

Multi-Asset Noisy Rational Expectations Equilibrium with Contingent Claims*

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Abstract

We study a noisy rational expectations equilibrium in a multi-asset economy populated by informed and uninformed investors and noise traders. The assets can include state contingent claims such as Arrow-Debreu securities, assets with only positive payoffs, options or other derivative securities. The probabilities of states depend on an aggregate shock, which is observed only by the informed investor. We derive a three-factor CAPM with asymmetric information, establish conditions under which asset prices reveal information about the shock, and show that information asymmetry amplifies the effects of payoff skewness on asset returns. We also find that volatility derivatives make incomplete markets effectively complete, and their prices quantify market illiquidity and shadow value of information to uninformed investors.

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1. Introduction

Informed investors in financial markets often use their private information to extract gains from trading in a multitude of financial assets, such as stocks, corporate bonds, and derivative securities. This information can be partially learned from asset prices by uninformed investors for their own advantage. Learning from asset prices in realistic multi-asset economies is complicated by the joint effects of non-normality of asset payoff distributions, complex payoff structures of derivative securities, and interdependence of asset prices arising because each price may contain information about the payoffs of other assets. Therefore, despite the fact that asymmetry of information across investors is a prominent feature of financial markets, its impact on equilibrium asset prices in multi-asset economies remains relatively unexplored.

In this paper, we develop a new tractable approach for studying asset prices in multi-asset noisy rational expectations equilibrium (REE) economies with realistic asset payoffs and asymmetric information. Our approach provides a bridge between risk-neutral asset pricing and models with asymmetric information, and sheds new light on the effects of information asymmetry on asset prices. In particular, we derive a three-factor extension of the standard Capital Asset Pricing Model (CAPM), show that aggregate volatility is priced in the cross-section of asset returns, derive conditions under which prices of assets (such as debt, equity, and derivatives) reveal information about an aggregate economic shock, and demonstrate that information asymmetry amplifies the effects of higher order moments of asset payoffs on asset returns. We also uncover a unique economic role of volatility derivatives. We show that these derivatives make incomplete markets effectively complete, and their prices quantify both market illiquidity and the shadow value of information for uninformed investors. The latter results complement the widely-used interpretation of market volatility indices such as VIX (i.e., the risk-neutral volatility of S&P500 stock index) as “fear gauges” of financial markets.

We consider a multi-asset economy with two dates and a finite but arbitrary number of random states. The probabilities of states are exponential-linear functions of an aggregate shock normalized to sum up to one, where the shock has a certain conjugate prior distribution. The shocks are multiplied by realizations of a state-dependent aggregate risk factor, such as aggregate output or weather conditions, which quantifies shock impacts on state probabilities. The tradable assets can be state contingent claims such as Arrow-Debreu securities, assets with only positive payoffs, and derivatives. The economy is populated by two types of price-taking rational investors, informed and uninformed, with constant abso-

lute risk aversion (CARA) preferences over terminal wealth. There are also noise traders with exogenous jointly normally distributed asset demands. The investors trade assets at the initial date, and asset prices are determined from the market clearing conditions. The informed investors observe the shock, whereas the uninformed investors use asset prices to extract information about the shock, which is obfuscated by noise traders.

We begin the analysis by studying markets where the number of states equals the number of assets, henceforth complete markets. Our unique setup allows us to extend the methods of risk-neutral valuation and portfolio choice to complete markets with asymmetric information. We show that the risk-neutral probability measure is unique and obtain closed-form asset prices and investors' portfolios of assets. Asset prices are given by expected discounted payoffs with respect to risk-neutral probabilities.

We then derive an approximate three-factor model that extends the standard CAPM by linearizing the state price density in the economy. This three-factor model helps us isolate the effects of asymmetric information on asset returns. The first factor in the model is the payoff of the market portfolio, as in the standard CAPM. The second and third factors are the aggregate risk factor and its volatility. In the special case in which the market portfolio is proportional to the aggregate risk factor, our model (26) is consistent with the empirical findings showing that market volatility is priced in the cross-section of asset returns [e.g., Ang, Hodrick, Xing, and Zhang (2006); Cremers, Halling, and Weinbaum (2015)]. The model may also contribute towards explaining findings in Savor and Wilson (2014) who show that market betas are strongly related to expected returns only during periods of macroeconomic announcements. Our model implies that reduced asymmetry of information during such announcements reduces the effect of information-related factors on asset returns, and hence, expected returns are mainly determined by market betas.

Next, we extend our analysis to a subset of realistic incomplete-market economies, where the number of states exceeds the number of assets. These economies include economies with one risky asset studied in the previous literature [e.g., Grossman and Stiglitz (1980), Breon-Drish (2015)], the latter economies with added derivatives, and economies with risky corporate debt and equity, among others. Asset prices in these economies solve a system of non-linear equations and are less tractable than in the economies with complete markets. We prove the existence and uniqueness of equilibrium in these economies using a new method that relies only on well-known results of basic calculus.

We provide several further applications of our model that shed light on the effects of information asymmetry on asset prices. First, we provide an answer to a fundamental question: which assets help mitigate the information asymmetry in the economy? We

show that the information about the aggregate shock is impounded into asset prices only via the informed investor's demand for those assets that make up a replicating portfolio for the aggregate risk factor. Investing in this replicating portfolio allows the informed investor to hedge exposure to the aggregate risk factor in response to information by transferring more wealth to more likely states. The amount of wealth invested in this portfolio depends on the aggregate shock. The information about the shock then becomes incorporated into asset prices via the market clearing conditions. The assets which are not included in the replicating portfolio are informationally irrelevant in the sense that adding them to the economy does not reveal any additional information. For example, we show that adding derivatives to the economies with one risky asset in Grossman and Stiglitz (1980) and Breon-Drish (2015) does not reveal any additional information about the underlying asset, provided that noises across markets are uncorrelated. Similarly, we demonstrate an informational analogue of the irrelevance of capital structure according to which, absent additional frictions, the information jointly revealed by the prices of risky corporate debt and equity does not depend on the face value of debt.

We also identify realistic situations when securities are not informationally irrelevant. In particular, we consider an economy with costly defaults on corporate debt that destroy a fraction of the firm's value, and allow investors to trade Arrow-Debreu securities on default states, similar to credit default swaps. We find that the informativeness of prices (measured by the posterior variance of the aggregate shock) is a decreasing function of the face value of debt and the cost of default. The intuition is that as the face value of debt increases, default becomes more likely. Therefore, more Arrow-Debreu securities are needed for hedging and more information is revealed through their prices. Our findings are consistent with the empirical literature showing that credit default swaps reveal information about cash flow distributions of underlying firms [e.g., Blanco, Brennan, and Marsh (2005); Longstaff, Mithal, and Neis (2005)]. Other realistic situations where derivatives are not informationally redundant include the cases in which noise trader demands are correlated across markets or derivatives help hedge the exposure to the aggregate risk factor.

The multi-asset nature of our setup also allows us to unravel the important economic role of volatility derivatives. These derivatives are widely traded in financial markets, and adding them to our model makes it both more realistic and tractable. The analysis of these derivatives when the payoff of the underlying asset is not normally distributed is unique to our model. Specifically, we study a security with a payoff equal to the squared payoff of the underlying, which we interpret as a volatility derivative. We show that introducing this security in an incomplete market with one risky underlying asset makes this market

effectively complete, that is, allows informed and uninformed investors to achieve Pareto optimal asset allocations. Moreover, the asset prices in the resulting effectively complete market are available in closed form.

Furthermore, we show that the prices of volatility derivatives, given by risk-neutral variances of asset payoffs, determine the shadow value of information and illiquidity in financial markets. We define the shadow value of information as the amount of wealth that an uninformed investor is willing to give up to become informed. When the market is complete, the value of information is proportional to the risk-neutral variance of the aggregate risk factor, which can be interpreted as the price of a volatility derivative. When the market is incomplete, the value of information is reduced by the measure of market incompleteness defined as the Kullback-Leibler divergence of two risk-neutral measures given by real probabilities weighted by marginal utilities of investors. The intuition is that the benefits of information are smaller in incomplete markets due to restricted risk sharing and fewer tradable assets.

We define market illiquidity as the matrix of asset price sensitivities to noise trader demands, and show that illiquidity is proportional to the risk-neutral variance-covariance matrix of asset payoffs. Such a relationship between illiquidity and risk-neutral variance is in line with empirical findings. In particular, Chung and Chuwonganant (2014) show that liquidity (defined as the inverse of the illiquidity) is negatively related to VIX, and Nagel (2012) shows that the returns of liquidity provision are high when VIX is high.

We build on the role of volatility derivatives discussed above to develop a new method for studying the effects of asymmetric information on asset prices. We consider an incomplete market with a single risky asset and then make it effectively complete by adding a volatility derivative. To facilitate the comparison of incomplete and effectively complete markets, we exclude noise traders from trading the derivative; even then we show that the equilibrium is not fully revealing because the derivative is informationally irrelevant (in this particular case). For several broad classes of asset payoff distributions we find asset prices in the effectively complete market in closed-form. Using our new method, we also derive a new relationship between asset prices and higher moments of their payoff distributions. We show that asset risk premia are decreasing functions of payoff skewness, and the asymmetry of information amplifies the sensitivity of risk premia to skewness.

Finally, we demonstrate the generality of our methodology and robustness of results by extending our baseline analysis in several directions. First, we show that when the market is complete the model can be solved for general probabilities of states and distributions of shocks and noise trader demands. We then extend the analysis to economies where noise

traders are replaced by noisy endowments of investors, and show that the equilibrium prices have the same structure and the quadratic derivatives play the same role as in the baseline analysis. Next, we study economies with multiple heterogeneously informed investors, and show that quadratic derivatives make the market effectively complete, prove the existence and uniqueness of a symmetric equilibrium, and derive prices in closed form. Finally, we extend the analysis to the case of multidimensional economic shocks. As in other extensions, the prices are available in closed form and have the same structure as in the baseline analysis. Moreover, the security that completes the market has payoffs given by quadratic forms of the aggregate risk factor in the economy.

Related Literature. Our paper is related to a large literature on noisy REE models, which was pioneered by Grossman (1976), Grossman and Stiglitz (1980) and Hellwig (1980). These early works typically consider economies with CARA investors and one risky asset with normally distributed payoffs. Admati (1985) extends these models to the case of multiple securities and Wang (1993) develops a dynamic model. Pálvölgyi and Venter (2014) prove the uniqueness of equilibrium in Grossman and Stiglitz (1980) in the class of continuous prices and find multiple equilibria with discontinuous prices. Diamond and Verrecchia (1981), Vives (2008), García and Urošević (2013) and Kurlat and Veldkamp (2013) discuss further extensions and applications of CARA-normal models. Davila and Parlato (2019) study the effect of trading costs on the acquisition and aggregation of information. Cespa and Foucault (2014) study an economy in which investors learn information about an asset also from the information about other assets and show that such learning may lead to liquidity crashes. In contrast to this literature, we allow for multiple assets with more general payoff distributions.

Breon-Drish (2015) studies an economy with CARA investors and one risky asset without normality. He obtains a general characterization of prices in terms of inverse functions and proves the existence and uniqueness of equilibrium when the asset payoff conditional on the informed investor's signal has a distribution from the exponential family. He also obtains closed-form exponential-linear asset prices when payoffs have a binomial distribution, and uses conjugate prior for the economic shock similar to ours. Relative to the latter paper, we study a multi-asset economy with multinomial distributions. We show that (effective) market completeness offers significant additional tractability and closed-form prices. We provide new economic results on the informational irrelevance of assets, the role of quadratic derivatives, effective completeness, value of information, and liquidity.

Malamud (2015) studies an REE with Arrow-Debreu securities in a continuous-space complete-market economy and shows that the equilibria with non-CARA preferences are

fully revealing. Albagli, Hellwig, and Tsyvinski (2013) consider a noisy REE model where the information is dispersed across all investors, preferences are general, and investors face position limits. Our model differs from their setup in that our investors are either informed or uninformed and their trades are unconstrained. Han (2018) studies numerically dynamic information acquisition with ex ante identical investors but without derivative securities, and shows that the marginal cost of information precision is proportional to risk-neutral variance. In contrast to Han (2018), we derive the value of information and show that this value is reduced by market incompleteness. Although our model is one-period, investors are not ex-ante identical and solutions are in closed form.

Bernardo and Judd (2000) solve models with general distributions and preferences numerically and demonstrate that the REE in Grossman and Stiglitz (1980) is not robust to parametric assumptions. Breugem and Buss (2019) study portfolio and information choice of investors concerned about their performance relative to an index. Other related models that do not rely on the normality of asset payoffs include Barlevy and Veronesi (2000), Peress (2004), and Yuan (2005) among others.

Our model is also related to works on the informational role of derivatives. Brennan and Cao (1996) consider a CARA-normal model with one risky underlying asset and a quadratic derivative written on it. They show that the derivative effectively completes the market and does not reveal any information which is not already in the price of the underlying asset. We show that the latter result extends to economies without payoff normality. Moreover, the quadratic derivative in our model plays a unique role by allowing us to obtain closed-form prices whereas in their work introducing this derivative does not affect the price of the underlying asset. Other related models in this literature include Back (1993), Biais and Hillion (1994), Vanden (2008), and Huang (2014) among others.

2. Model

2.1. Securities Markets and Information Structure

We consider an economy with two dates $t = 0$ and $t = T$, and N states $\omega_1, \dots, \omega_N$ at the terminal date, where $N \geq 2$. The probabilities $\pi_n(\varepsilon)$ of states ω_n are normalized exponential functions of the *aggregate shock* $\varepsilon \in \mathbb{R}$ adopted from logit models in econometrics:

$$\pi_n(\varepsilon) = \frac{e^{a_n + b_n \varepsilon}}{\sum_{j=1}^N e^{a_j + b_j \varepsilon}}, \quad n = 1, \dots, N, \quad (1)$$

where a_n and b_n are state-dependent variables. Variable b_n determines the effect of shocks on probabilities and can be interpreted as an *aggregate risk factor* of global importance for the economy, such as aggregate output. With such interpretation, probabilities (1) intuitively imply that, for example, bad shock $\varepsilon < 0$ makes states with higher output b_n less likely than states with lower output. We also interpret variables b_n as the *sensitivities* of probabilities $\pi_n(\varepsilon)$ to shock ε . Below, we discuss economic settings where probabilities (1) arise endogenously and factor b emerges as a source of information asymmetry. By $b(\omega)$ we denote a corresponding random variable with realizations b_n in states ω_n .

There are $M \geq 2$ assets traded in the economy: a riskless bond in perfectly elastic supply paying \$1 at date T and $M - 1$ state-contingent risky assets in zero net supply with terminal payoff $C_m(\omega)$ in state ω , where $m = 1, \dots, M - 1$. The risky assets may include Arrow-Debreu securities, assets with only positive payoffs, options or other derivatives. All assets are non-redundant in the sense that each asset's terminal payoff cannot be replicated by trading in other assets. We denote the vector of $M - 1$ risky asset payoffs in state ω by $C(\omega) = (C_1(\omega), \dots, C_{M-1}(\omega))^\top$, and use C_m and C as shorthand notation for $C_m(\omega)$ and $C(\omega)$. The bond price is set to $p_0 = e^{-rT}$, where r is an exogenous risk-free interest rate. We denote the vector of observed date-0 prices of the risky assets by $p = (p_1, \dots, p_{M-1})^\top$. These prices are determined in equilibrium, defined below.

The economy is populated by three types of investors, informed and uninformed, labeled I and U , and noise traders. There is a continuum of identical investors of each type that act as price-takers. Fraction $h/2$ of all investors are informed and fraction $(1 - h)/2$ are uninformed, where $h \in (0, 1)$, and fraction $1/2$ are noise traders. Investors I and U have CARA preferences over terminal wealth with risk aversions γ_I and γ_U , respectively. Noise traders submit exogenous normally distributed demands $\nu = (\nu_1, \dots, \nu_{M-1})^\top \sim \mathcal{N}(0, \Sigma_\nu)$ for risky assets, where $\Sigma_\nu \in \mathbb{R}^{(M-1) \times (M-1)}$ is a symmetric positive-definite matrix.

Both investors I and U know all asset payoffs in all states, $C_m(\omega_n)$. Before the markets open, investor I observes shock ε . Investor U observes only asset prices p at date $t = 0$ and knows how the equilibrium prices, given by some function $P(\varepsilon, \nu) \in \mathbb{R}^{M-1}$, depend on shock ε and noises ν . Investor U has the following conjugate prior probability density function (PDF) over ε :

$$\varphi_\varepsilon(x) = \frac{\left(\sum_{j=1}^N e^{a_j + b_j x}\right) e^{-0.5(x - \mu_0)^2 / \sigma_0^2}}{\int_{-\infty}^{\infty} \left(\sum_{j=1}^N e^{a_j + b_j x}\right) e^{-0.5(x - \mu_0)^2 / \sigma_0^2} dx}. \quad (2)$$

Below, we discuss economies where PDF $\varphi_\varepsilon(x)$ arises endogenously.

For fixed parameters a_n and b_n , we choose μ_0 and σ_0^2 such that ε has any desired mean

μ_ε and variance σ_ε^2 . We refer to the distribution of ε as *generalized normal* $\widehat{\mathcal{N}}(\mu_\varepsilon, \sigma_\varepsilon^2)$ with mean $\mathbb{E}[\varepsilon] = \mu_\varepsilon$ and variance $\text{var}[\varepsilon] = \sigma_\varepsilon^2$, and note that it can be rewritten as a weighted average of PDFs of normally distributed random variables. The relationship between (μ_0, σ_0^2) and $(\mu_\varepsilon, \sigma_\varepsilon^2)$ is given by equations (A.1) and (A.2) in the Appendix.

Our economy also has an equivalent interpretation as an economy where the aggregate risk factor b has an arbitrary prior distribution $\tilde{\pi}_n$ and the informed investor receives a conditionally normal signal $\varepsilon = b\sigma_0^2 + u$, where $u \sim \mathcal{N}(\mu_0, \sigma_0^2)$. Then, Bayes' law and the formula for total probability give rise to probabilities (1) and distribution (2), where $a_n = \ln(\tilde{\pi}_n) - 0.5\sigma_0^2 b_n^2$. According to this interpretation, learning via ε about factor b is the source of the asymmetry of information, which justifies the interpretation of b as an aggregate risk factor.

Allowing shocks ε to be conditionally normal and noise trader demands ν normal variables captures in a tractable way the fact that these variables can be either positive or negative, which makes their normality less restrictive than the normality of asset payoffs in the related literature. Moreover, ν and ε in reality are likely to be sums of smaller zero-mean shocks, in which case they are approximately normal by the central limit theorem. The normality of noise ν is in line with the empirical evidence in Peress and Schmidt (2018) who show that noise trader demands are normally distributed at monthly and quarterly frequencies. In Section IA1 of the Internet Appendix, we study an economy with general continuous probabilities $\pi_n(\varepsilon)$, shock distribution $\varphi_\varepsilon(x)$ and noise distribution $\varphi_\nu(x)$ with finite moments. The latter economy admits closed-form solutions for the complete market case when $M = N$ (which is the main focus of this paper), albeit these solutions are less tractable than the solutions in our baseline economy.

Finally, we provide another interpretation of probabilities (1). The investors believe that true probabilities π_n are in the vicinity of benchmark probabilities $\tilde{\pi}_n = e^{a_n} / \sum_{j=1}^N e^{a_j}$. The informed investors directly observe or estimate the expected value of the aggregate risk factor $\sum_{n=1}^N \pi_n b_n = \bar{b}$ but do not observe probabilities π_n . The informed investors find probabilities π_n that minimize the Kullback-Leibler divergence $\sum_{n=1}^N \pi_n \ln(\pi_n / \tilde{\pi}_n)$, often interpreted as a distance between two probability measures [see MacKay (2017, p. 34)], subject to constraints $\sum_{n=1}^N \pi_n b_n = \bar{b}$ and $\sum_{n=1}^N \pi_n = 1$. Using the method of Lagrange multipliers, it can be verified that the optimal probabilities are given by equation (1), where ε is a Lagrange multiplier that depends on $\bar{b}$, and hence, is observed only by informed investors. Therefore, shock ε describes the deviation of optimal probabilities from benchmark probabilities in response to the inflow of information about factor b .

2.2. Investors' Optimization and Definition of Equilibrium

Each investor $i = I, U$ is endowed with initial wealth $W_{i,0}$, and allocates it to buy α_i units of the riskless asset and $\theta_{i,m}$ units of the risky asset m . By $\theta_i = (\theta_{i,1}, \dots, \theta_{i,M-1})^\top$ we denote the vector of units of risky assets purchased by investor i . After observing prices p , the uninformed investor updates the prior PDF (2) conditioning on the information that shock ε and noise ν satisfy equation $P(\varepsilon, \nu) = p$. Investors I and U maximize their expected utilities over terminal wealth:

$$\max_{\theta_I} \mathbb{E} \left[-e^{-\gamma_I W_{I,T}} \middle| \varepsilon, p \right], \quad (3)$$

$$\max_{\theta_U} \mathbb{E} \left[-e^{-\gamma_U W_{U,T}} \middle| P(\varepsilon, \nu) = p \right], \quad (4)$$

respectively, subject to their self-financing budget constraints

$$W_{i,T} = W_{i,0}e^{rT} + (C - e^{rT}p)^\top \theta_i, \quad i = I, U. \quad (5)$$

Definition of Equilibrium. A competitive noisy rational expectations equilibrium is a vector of risky asset prices $P(\varepsilon, \nu)$ and investor portfolios $\theta_I^*(p; \varepsilon)$ and $\theta_U^*(p)$ that solve optimization problems (3) and (4) subject to self-financing budget constraints (5), taking asset prices as given, and satisfy the market clearing condition:

$$h\theta_I^*(P(\varepsilon, \nu); \varepsilon) + (1-h)\theta_U^*(P(\varepsilon, \nu)) + \nu = 0. \quad (6)$$

Remark 1 (Particular Cases). Our model incorporates the economies with one risky asset in Grossman and Stiglitz (1980) and Breon-Drish (2015) for particular choices of distribution parameters a_n and b_n in equation (1) in the limit $N \rightarrow \infty$. Lemma A.2 in the Appendix demonstrates that the latter economy is a limiting case of our N -state economy with asset payoffs $C_1(\omega_n) = \underline{C}_N + (\overline{C}_N - \underline{C}_N)(n-1)/(N-1)$ and distribution parameters

$$a_n = -\frac{C_1(\omega_n)^2}{2\sigma_0^2} - \frac{\mu_0 C_1(\omega_n)}{\sigma_0^2} + \ln[\varphi_C(C_1(\omega_n))], \quad b_n = \frac{C_1(\omega_n)}{\sigma_0^2}, \quad (7)$$

where $\underline{C}_N$ and $\overline{C}_N$ converge to the lower and upper limits of payoff C_1 with PDF $\varphi_C(x)$.

3. Characterization of Equilibrium

In this section, we first consider our baseline economy where the number of assets equals the number of states, $M = N$, and find the equilibrium in closed form. Then, we consider a more general economy with $M \leq N$ assets and derive the equilibrium in terms of inverse functions. We use the latter economy to establish conditions for the effective completeness of financial markets and to study the impact of market incompleteness on asset prices.

3.1. Economy with $M = N$ Securities

We start with an economy where the number of assets equals the number of states, that is, $M = N$, which we label as a *complete-market economy*.¹ Our methodological contribution is to show that market completeness substantially simplifies the derivation of equilibrium, so that asset prices and investors' portfolios are available in closed form.

Due to market completeness, we look for equilibrium prices p in the following form:

$$p = \left[\pi_1^{\text{RN}} C(\omega_1) + \pi_2^{\text{RN}} C(\omega_2) + \dots + \pi_N^{\text{RN}} C(\omega_N) \right] e^{-rT}, \quad (8)$$

where π_n^{RN} are the *risk-neutral* probabilities of states ω_n . The risk-neutral probabilities exist and are unique in equilibrium because investors I and U are unconstrained and can eliminate any arising arbitrage opportunities [e.g., Duffie (2001, p. 4)].

Informed and uninformed investors agree on the risk-neutral probabilities because these probabilities are uniquely determined from equation (8) as functions of prices p . However, investors assign different real probabilities to states ω_n . In particular, investor U 's real *posterior probabilities* are given by $\pi_n^U(p) = \mathbb{E}[\pi_n(\varepsilon) | P(\varepsilon, \nu) = p]$. The expression for $\pi_n^U(p)$ can be obtained by rewriting investor U 's expected utility (4) as follows:

$$\begin{aligned} \mathbb{E}[-e^{-\gamma_U W_{U,T}} | P(\varepsilon, \nu) = p] &= -\sum_{n=1}^N \left(\mathbb{E}[\pi_n(\varepsilon) | P(\varepsilon, \nu) = p] e^{-\gamma_U W_{U,T,n}} \right) \\ &= -\sum_{n=1}^N \pi_n^U(p) e^{-\gamma_U W_{U,T,n}}. \end{aligned} \quad (9)$$

Taking probabilities $\pi_n(\varepsilon)$ and $\pi_n^U(p)$ as given, investors' optimizations can be solved using the methods of complete-market portfolio choice. The informed and uninformed investors have different state price densities (SPDs), which are given by discounted ratios of risk-neutral and their real probabilities [e.g., Duffie (2001, p. 11)]: $\pi_n^{\text{RN}} e^{-rT} / \pi_n(\varepsilon)$ and $\pi_n^{\text{RN}} e^{-rT} / \pi_n^U(p)$, respectively. The first order conditions (FOCs) of investors equate their marginal utilities and SPDs [e.g., Duffie (2001, p. 5)] and are given by:

$$\gamma_I e^{-\gamma_I W_{I,T,n}} = \ell_I \frac{\pi_n^{\text{RN}} e^{-rT}}{\pi_n(\varepsilon)}, \quad \gamma_U e^{-\gamma_U W_{U,T,n}} = \ell_U \frac{\pi_n^{\text{RN}} e^{-rT}}{\pi_n^U(p)}, \quad (10)$$

where ℓ_i are Lagrange multipliers for investors' budget constraints. From equations (10), we find optimal wealths $W_{i,T}$. Then, we use these wealths to recover optimal portfolios from budget constraints (5). Lemma 1 below reports investor I 's portfolio in closed form.

¹The realizations of shock ε can be interpreted as a continuum of states of the economy in addition to states ω_n . However, N non-redundant assets still suffice to replicate any contingent claim in our economy because the payoffs of such claims do not vary across ε for a fixed state ω_n . In other words, ε -states can be clumped together so that only ω_n states matter for replication. Furthermore, noise trader demands do not contribute to market incompleteness because they affect date-0 prices but do not affect future payoffs.

Lemma 1 (Investor I 's optimal portfolio). *Investor I 's optimal portfolio is given by:*

$$\theta_I^*(p; \varepsilon) = \frac{\lambda \varepsilon}{\gamma_I} - \frac{\Omega^{-1}(\tilde{v}(p) - \tilde{a})}{\gamma_I}, \quad (11)$$

where $\Omega \in \mathbb{R}^{(N-1) \times (N-1)}$ is a matrix of excess payoffs with elements $\Omega_{n,k} = C_k(\omega_n) - C_k(\omega_N)$, $\lambda = \Omega^{-1}(b_1 - b_N, \dots, b_{N-1} - b_N)^\top \in \mathbb{R}^{N-1}$, $\tilde{a} = (a_1 - a_N, \dots, a_{N-1} - a_N)^\top \in \mathbb{R}^{N-1}$, and $\tilde{v}(p) \in \mathbb{R}^{N-1}$ is the vector of log ratios of risk-neutral probabilities, given by:

$$\tilde{v}(p) = \left(\ln \left(\frac{\pi_1^{\text{RN}}}{\pi_N^{\text{RN}}} \right), \dots, \ln \left(\frac{\pi_{N-1}^{\text{RN}}}{\pi_N^{\text{RN}}} \right) \right)^\top. \quad (12)$$

Equation (11) decomposes portfolio $\theta_I^*(p; \varepsilon)$ into two terms, which we label as *information-sensitive* and *information-insensitive* demands, respectively. The information-sensitive demand is linear in shock ε , and the portfolio is separable in ε and prices p , as in the related literature [e.g., Grossman and Stiglitz (1980), Breon-Drish (2015)]. The information-insensitive demand depends on risk-neutral probabilities, which can be found analytically as functions of prices p by solving risk-neutral pricing equations (8). Hence, portfolio (11) is in closed form in terms of shock ε and price p , which are observable by investor I .

Vector λ in portfolio (11) has the following interpretation. The definition of λ in Lemma 1 implies that λ satisfies equations $b_n = \lambda_0 + C(\omega_n)^\top \lambda$, where λ_0 is a constant. Therefore, λ is a replicating portfolio for the aggregate risk factor b , up to a constant λ_0 . In Section 3.3 below, we provide detailed discussion of portfolio λ and separability of portfolio (11) in shock ε and price p in a more general incomplete-market economy.

Substituting $\theta_I^*(p; \varepsilon)$ and $\theta_U^*(p)$ into the market clearing condition (6), we find that

$$\frac{h\lambda\varepsilon}{\gamma_I} + \nu + H(p) = 0, \quad (13)$$

where $H(p)$ is a function of asset prices p , discussed below, which is given by:

$$H(p) = (1 - h)\theta_U^*(p) - \frac{h}{\gamma_I}\Omega^{-1}(\tilde{v}(p) - \tilde{a}), \quad (14)$$

and $\tilde{v}(p)$, $\tilde{a}$ are as in Lemma 1.

Investor U uses equation (13) to infer information about shock ε . Substituting prices p into this equation, investor U learns *sufficient statistic* $s = h\lambda\varepsilon/\gamma_I + \nu$, which is equal to $-H(p)$. Therefore, function $H(p)$ reveals information in prices, and hence, we label it *the informational content of prices*. Next, investor U finds posterior probabilities of states given by the conditional expectation $\pi_n^U(p) = \mathbb{E}[\pi_n(\varepsilon) | h\lambda\varepsilon/\gamma_I + \nu = -H(p)]$. The

derivation of probabilities $\pi_n^U(p)$ is simplified by the structures of probabilities $\pi_n(\varepsilon)$ in (1) and the prior distribution $\varphi_\varepsilon(x)$ of shock ε in (2). Lemma 2 reports these probabilities.

Lemma 2 (Posterior probabilities of states). *The posterior probabilities of states ω_n conditional on observing the sufficient statistic $s = h\lambda\varepsilon/\gamma_I + \nu$ are given by:*

$$\pi_n^U(p) = \frac{1}{G(p)} \exp \left\{ a_n + \frac{1}{2} \frac{b_n^2 + 2b_n(\mu_0/\sigma_0^2 - h\lambda^\top \Sigma_\nu^{-1} H(p)/\gamma_I)}{h^2 \lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2 + 1/\sigma_0^2} \right\}, \quad (15)$$

where function $H(p)$ is given by equation (14), and $G(p)$ is a normalizing function.

We observe that probabilities (15) are proportional to an exponent of a quadratic function of sensitivities b_n , which is similar to a moment generating function $\mathbb{E}[e^{b_n z}]$ of a normally distributed variable z . This similarity emerges because, as discussed in Section 2.1, noise ν and shock ε are (conditionally) normally distributed, and state probability $\pi_n(\varepsilon)$ has an exponential-linear form. Consequently, Bayesian updating of the latter probability gives exponential-quadratic posterior probability (15).

We then find the equilibrium as follows. From the FOC (10) for investor U we find investor U 's optimal portfolio $\theta_v^*(p)$ in terms of probabilities (15), similar to finding investor I 's portfolio (11). We observe, that probabilities (15) themselves depend on portfolio $\theta_v^*(p)$ via the informational content of prices $H(p)$. Hence, portfolio $\theta_v^*(p)$ solves a fixed-point problem [equation (A.15) in the Appendix], which we do not show here for brevity. The fixed-point problem turns out to be linear, and hence, we find portfolio $\theta_v^*(p)$ in closed form. Then, we find the equilibrium risk-neutral probabilities and asset prices from the market clearing condition (13). In this paper, we focus on equilibria in which asset prices are continuous functions of the sufficient statistic s , and the sufficient statistic is the only information revealed by prices.² Proposition 1 reports the equilibrium.

Proposition 1 (Equilibrium with $M = N$ assets).

i) *There exists unique equilibrium in which prices only reveal the sufficient statistic $s = h\lambda\varepsilon/\gamma_I + \nu$. In this equilibrium, the vector of risky asset prices $P(\varepsilon, \nu)$ and risk-neutral probabilities π_n^{RN} are given by:*

$$P(\varepsilon, \nu) = \left[\pi_1^{\text{RN}} C(\omega_1) + \pi_2^{\text{RN}} C(\omega_2) + \dots + \pi_N^{\text{RN}} C(\omega_N) \right] e^{-rT}, \quad (16)$$

$$\pi_n^{\text{RN}} = \frac{e^{v_n}}{\sum_{j=1}^N e^{v_j}}, \quad (17)$$

²Pálvölgyi and Venter (2015) show that our complete market equilibrium is unique among all equilibria with continuous prices. However, Pálvölgyi and Venter (2014) demonstrate the existence of multiple discontinuous equilibria in a Grossman and Stiglitz (1980) economy, which may also exist in our model. Finding such equilibria in multi-asset economies is a challenging task and is beyond the scope of our work.

where probability parameters v_n are given in closed form by:

$$v_n = a_n + \frac{1}{2} \frac{(1-h)/\gamma_U}{h/\gamma_I + (1-h)/\gamma_U} \frac{b_n^2 + 2(\mu_0/\sigma_0^2)b_n}{h^2\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2} + \frac{C(\omega_n)^\top (E+Q)s}{h/\gamma_I + (1-h)/\gamma_U}, \quad (18)$$

$$Q = \frac{h(1-h)}{\gamma_I\gamma_U} \frac{\lambda\lambda^\top \Sigma_\nu^{-1}}{h^2\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2}, \quad (19)$$

where E is an identity matrix, $Q, E \in \mathbb{R}^{(N-1) \times (N-1)}$, and $\lambda = \Omega^{-1}(b_1 - b_N, \dots, b_{N-1} - b_N)^\top$.

ii) Portfolio $\theta_I^*(p; \varepsilon)$ is given by equation (11) and portfolio $\theta_U^*(p)$ is given by

$$\theta_U^*(p) = (E+Q)^{-1} \left(\frac{hQ\Omega^{-1}(\tilde{v}(p) - \tilde{a})}{(1-h)\gamma_I} - \frac{\Omega^{-1}(\tilde{v}(p) - \hat{a})}{\gamma_U} + \frac{\mu_0/(\gamma_U\sigma_0^2)\lambda}{h^2\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2} \right), \quad (20)$$

where $\tilde{v}(p) \in \mathbb{R}^{N-1}$ is given by (12) and has elements $v_n - v_N$ in equilibrium, and $\tilde{a}, \hat{a} \in \mathbb{R}^{N-1}$ have elements $a_n - a_N$ and $a_n - a_N + 0.5(b_n^2 - b_N^2)/(h^2\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2)$, respectively.

Proposition 1 extends the no-arbitrage valuation approach to economies with asymmetric information and provides asset prices in closed form in terms of expected discounted payoffs under risk-neutral probabilities, familiar from the asset-pricing literature. The equilibrium prices are non-linear functions of shock ε and noise ν , in contrast to CARA-normal noisy REE models [e.g., Grossman and Stiglitz (1980); Admati (1985), among others]. The tractability of equilibrium prices and portfolios allows us to study the slopes of asset demands with respect to prices p , which we report in Proposition 2 below.

Proposition 2 (Slopes of asset demands). *The comparative statics for investors' portfolios with respect to prices p are as follows:*

$$\frac{\partial \theta_I^*(p; \varepsilon)}{\partial p} = -\frac{1}{\gamma_I} (\text{var}^{\text{RN}}[C])^{-1} e^{rT}, \quad (21)$$

$$\frac{\partial \theta_U^*(p)}{\partial p} = -\left(\frac{1}{\gamma_U} E - \frac{(h/\gamma_I + (1-h)/\gamma_U)h\lambda\lambda^\top \Sigma_\nu^{-1}}{\gamma_U\gamma_I(h^2\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2) + h(1-h)\lambda^\top \Sigma_\nu^{-1}\lambda} \right) (\text{var}^{\text{RN}}[C])^{-1} e^{rT}, \quad (22)$$

where $\text{var}^{\text{RN}}[\cdot]$ is the variance-covariance matrix under the risk-neutral probability measure. Furthermore, informed investor's demand for risky asset m is a downward-sloping function of that asset's price p_m , holding other prices fixed.

Equations (21) and (22) show the sensitivities of investors' asset demands to prices. The informed investor's demand (21) is determined by the inverse risk-neutral variance-covariance matrix. Hence, the informed investor's demand for risky asset m is a downward sloping function of that asset's own price p_m because the elements on the main diagonal of a positive-definite matrix $(\text{var}^{\text{RN}}[C])^{-1}$ are all positive [see proof of Proposition 2].

The sensitivity of portfolio $\theta_U^*(p)$ to prices p in equation (22) has two terms that capture the substitution and information effects, respectively. Investor U 's demand for asset m can be an upward sloping function of p_m because the product of the matrices in (22), in general, is not positive-definite. Intuitively, high asset prices can be interpreted as positive information about shock ε , in which case the uninformed demand for asset m may increase despite high price p_m through this information effect. Admati (1985) finds a similar result in a multi-asset CARA-normal model. Our analysis extends the finding of Admati (1985) to economies without normality and reveals the important roles of portfolio λ and the risk-neutral variance of asset payoffs in generating these effects.

Similar to Admati (1985), the equilibrium is unique despite possibly upward sloping uninformed demand. The intuition is that for the uninformed demand to be upward sloping there should be a sufficiently large fraction of informed investors in the economy so that the information effect is sufficiently strong. However, as shown in Proposition 2, the informed investors have downward sloping demands. As a result, the aggregate demand is downward sloping because the information effect is subdued by the substitution effect after aggregation. At a more technical level, the equilibrium is unique because uninformed portfolios and log-ratios of risk-neutral probabilities solve a linear system of equations that has a unique solution [see the proof of Proposition 1].

3.2. Capital Asset Pricing Model with Asymmetric Information

In this Section, we derive a capital asset pricing model (CAPM) with asymmetric information and study its economic implications. Our CAPM provides a bridge between risk-based models of asset pricing in the no-arbitrage tradition and models with asymmetric information, and also highlights how information aggregation alters asset returns. The existence of the state price density allows us to derive this CAPM as a simple corollary of the results in Section 6.1 of Cochrane (2005), which we report below.

Corollary 1 (Asymmetric information CAPM). *Let $R_i = C_i/P_i$ be the gross return of asset i . In the effectively complete market the asset risk premia are given by*

$$\mathbb{E}^U[R_i] - e^{rT} = -\text{cov}^U\left(R_i, \frac{\pi^{\text{RN}}}{\pi^U}\right), \quad (23)$$

where π^{RN}/π^U is the ratio of risk-neutral and investor U 's probabilities of states, and the covariance is computed under investor U 's probability measure π^U . Furthermore, let R^* be the projection of the rescaled state price density $(\pi^{\text{RN}}/\pi^U)/\mathbb{E}^{\text{RN}}[\pi^{\text{RN}}/\pi^U]$ on the space of

tradable assets in the Euclidean space with scalar product $\mathbb{E}^U[XY]$. Then

$$\mathbb{E}^U[R_i] - e^{rT} = \frac{\text{cov}^U(R_i, R^*)}{\text{var}^U[R^*]} (\mathbb{E}^U[R^*] - e^{rT}). \quad (24)$$

Corollary 1 presents the CAPM from the point of view of an uninformed investor or an econometrician, and demonstrates that the asset risk premia are determined by the covariance of returns with the state price density and admit a beta representation (24), similar to standard risk-based models discussed in Cochrane (2005, pp. 101-102). Following Cochrane (2005, p. 109), we note that return R^* in (24) can be interpreted as a return of a factor-mimicking portfolio for the state price density.

The risk-premia in (24) non-linearly depend on the aggregate risk factor b , which complicates the analysis of asset returns. To isolate the effects of asymmetric information on the risk premia, following Cochrane (2005, p. 161), we derive an approximate linear three-factor model by linearizing the SPD. Corollary 2 reports our results.

Corollary 2 (Three-factor CAPM). *Suppose, either γ_I or γ_U are small. Then,*

$$\frac{\pi_n^{\text{RN}}}{\pi_n^U} e^{-rT} \approx g_0(s) \left(1 + \frac{C(\omega_n)^\top \mathbb{E}[-\nu|s]}{(1-h)/\gamma_U + h/\gamma_I} - \frac{1}{2} \frac{h/\gamma_I}{(1-h)/\gamma_U + h/\gamma_I} \frac{b_n^2 - 2b_n \mathbb{E}^U[b]}{h^2 \lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2 + 1/\sigma_0^2} \right), \quad (25)$$

where $g_0(s)$ does not depend on state ω_n , and asset risk premia are given by:

$$\mathbb{E}^U[R_i] - e^{rT} \approx \beta_{1i} \Lambda_1 + \beta_{2i} \Lambda_2 + \beta_{3i} \Lambda_3, \quad (26)$$

where β_{1i} , β_{2i} , and β_{3i} are the multiple regression coefficients of R_i on factors $C(\omega)^\top \mathbb{E}[-\nu|s]$, b , b^2 and a constant, and the factor risk premia are given by $\Lambda_1 = (\mathbb{E}^U[C(\omega_n)] - p e^{rT})^\top \mathbb{E}[-\nu|s]$, $\Lambda_2 = \mathbb{E}^U[b] - \mathbb{E}^{\text{RN}}[b]$, $\Lambda_3 = \mathbb{E}^U[b^2] - \mathbb{E}^{\text{RN}}[b^2]$.

The three-factor model (26) is the main result of this section. The betas in (26) can be interpreted as time-series regression coefficients of asset returns on factors in a setting where returns each period are determined from our one-period model, as in the mean-variance CAPM. We also note that model (26) is conditional on the investors' ability to observe the sufficient statistic s . Hence, betas should be estimated as functions (e.g., polynomials) of s , similar to Cochrane (2005, p. 144).

Next, we discuss the factors. The first factor $C(\omega)^\top \mathbb{E}[-\nu|s]$ is analogous to the payoff of the market portfolio in our model. In particular, from the market clearing condition (6), the exogenous supply of risky assets in the economy is given by $-\nu$. The uninformed investor does not observe $-\nu$, and hence, evaluates the payoff of the market portfolio by

using the best estimate $\mathbb{E}[-\nu|s]$. The other two factors, the aggregate risk factor b and the volatility factor b^2 , capture the effects of asymmetric information on the SPD.³

The three-factor model (26) reduces to the standard mean-variance CAPM in three special cases of our model in which 1) there are no informed traders ($h = 0$), 2) exogenous asset supply is deterministic ($\Sigma_\nu = 0$), and 3) shock ε is known to everyone ($\sigma_0 = 0$). This is because factors b and b^2 cancel out in the SPD (25) in these three special cases when $h = 0$, $\lambda^\top \Sigma_\nu^{-1} \lambda \rightarrow \infty$, or $\sigma_0 \rightarrow 0$, respectively. Hence, these factors would have zero betas.

Three-factor CAPM (26) is consistent with the empirical findings in Ang, Hodrick, Xing, and Zhang (2006) and Cremers, Halling, and Weinbaum (2015) showing that market volatility measured by VIX is priced in the cross-section of asset returns. In particular, in a special case of our model studied in Section 4.1 in which b is proportional to C_1 and $\nu_i = 0$ for $i \geq 2$, risk factor b and its volatility are proportional to the market portfolio payoff and its volatility. Our model may also contribute towards explaining findings in Savor and Wilson (2014) who show that market betas are strongly related to average returns only during periods of macroeconomic announcements such as news about inflation, unemployment, and FOMC interest rate decisions. Their explanation is that announcements provide a clearer signal about aggregate risk and expected future market returns due to reduced noise or disagreement. CAPM (26) shows that, in line with this explanation, reduced asymmetry of information during macroeconomic announcements decreases the effect of information-related factors on asset returns, and hence, expected returns are mainly determined by market betas.

Finally, we evaluate the contribution of the information-specific factors to asset returns. For tractability, we focus on the returns of Arrow-Debreu (AD) securities. We also assume that the informed and uninformed investors have the same risk aversion so that the effects of information asymmetry are not confounded by other sources of investor heterogeneity. Lemma 3 presents the expected returns and comparative statics.

Lemma 3 (Expected returns of Arrow-Debreu securities). *Suppose, both investors have identical risk aversions, $\gamma_I = \gamma_U = \gamma$. Then, the expected return of the Arrow-Debreu security with payoff $1_{\{\omega=\omega_n\}}$ is given by:*

$$\mathbb{E}^U[R_n] = \frac{\pi_n^U}{\pi_n^{\text{RN}}} e^{rT} = \frac{\exp\{-\gamma C(\omega_n)^\top \mathbb{E}[-\nu|s] + 0.5t(b_n - \mathbb{E}^U[b])^2 + rT\}}{\mathbb{E}^{\text{RN}}[\exp\{-\gamma C(\omega)^\top \mathbb{E}[-\nu|s] + 0.5t(b - \mathbb{E}^U[b])^2\}]}, \quad (27)$$

where $t = h/(h^2 \lambda^\top \Sigma_\nu^{-1} \lambda / \gamma^2 + 1/\sigma_0^2)$ quantifies the asymmetry of information. Moreover, $\partial \mathbb{E}^U[R_n] / \partial t > 0$ if and only if $(b_n - \mathbb{E}^U[b])^2 > \text{var}^U[b]$.

³As noted in Cochrane (2005), the factor representation is not unique. Three is the maximum number of independent factors in our model, but they can be combined in two or one factor, as in equation (24).

Equation (27) disentangles the effects of risk attitudes and information asymmetry on expected returns, which are captured by terms $\gamma C(\omega_n)^\top \mathbb{E}[-\nu|s]$ and $t(b_n - \mathbb{E}^U[b])^2$, respectively. Parameter t quantifies information asymmetry. Larger t corresponds to more information asymmetry and $t = 0$ to no asymmetry, in which case either there are no informed investors ($h = 0$), or asset supply is deterministic ($\Sigma_\nu = 0$), or shock ε is known to everyone ($\sigma_0 = 0$). When $t = 0$, expected returns are only determined by risk aversion γ and market portfolio payoffs $C(\omega_n)^\top (-\nu)$. Equation (27) allows for simple comparative statics showing that if two states have the same market portfolio payoffs then, in the presence of information asymmetry, the AD security of the state with higher squared deviation $(b - \mathbb{E}^U[b])^2$ has higher return, and the effect is stronger with larger parameter t .

The risk premia of AD securities are given by $\mathbb{E}^U[R_n] - e^{rT} = (\pi_n^U/\pi_n^{\text{RN}} - 1)e^{rT}$. There are always AD securities with positive and negative risk premia because assuming that, e.g., all risk premia are positive, $\pi_n^U/\pi_n^{\text{RN}} - 1 > 0$, leads to a contradiction $1 = \sum_{i=1}^N \pi_n^U > \sum_{i=1}^N \pi_n^{\text{RN}} = 1$. Next, we find out which AD securities have positive risk premia. From equation (27) we observe that $\pi_n^U > \pi_n^{\text{RN}}$ for sufficiently large $|b_n|$ because the ratio $\pi_n^U/\pi_n^{\text{RN}}$ is mainly determined by the quadratic term $(b_n - \mathbb{E}^U[b])^2$. Therefore, posterior probabilities π_n^U are higher than risk-neutral ones for tail risks (i.e, when $|b_n|$ is large), and hence, corresponding AD securities have positive risk premia. The latter effects are stronger with larger asymmetry parameter t .

3.3. General Economy with $M \leq N$ Securities

In this section, we study an economy with M securities, where $M \leq N$, which subsumes complete and incomplete market economies as special cases. For tractability, we focus on a subset of economies which satisfy the following condition.

Informational spanning condition: *There exists a replicating portfolio for the risk factor b . That is, there exist constant λ_0 and vector $\lambda = (\lambda_1, \dots, \lambda_{M-1})^\top$ such that*

$$b_n = \lambda_0 + C(\omega_n)^\top \lambda. \quad (28)$$

We provide several plausible economies that satisfy condition (28). First example is a complete-market economy, where $M = N$, and hence, there always exist constant λ_0 and vector λ satisfying equation (28). Second example is an incomplete-market economy with only one risky asset with payoff $C_1 = b/\lambda_1$, where λ_1 is a constant. Lemma A.2 in the Appendix shows that single risky asset economies in Grossman and Stiglitz (1980) and Breon-Drish (2015) satisfy condition $C_1 = b/\lambda_1$. Third example is an economy with an

asset paying $C_1 = b/\lambda_1$, and call options on C_1 with payoffs $C_2 = \max(C_1 - K_2, 0), \dots, C_{M-1} = \max(C_1 - K_{M-1}, 0)$, in which case $\lambda_0 = 0$, $\lambda = (\lambda_1, 0, \dots, 0)^\top$. Fourth example is an economy with a firm that has cash flow b and issues risky debt and equity with payoffs $\min(b, K)$ and $\max(b - K, 0)$, where K is the face value of debt. It is easy to verify that in this last example $\lambda_0 = 0$ and $\lambda = (1, 1)^\top$ because $b = \min(b, K) + \max(b - K, 0)$.

We begin with the derivation of informed investor's portfolio in Lemma 4 below.

Lemma 4 (Investor I 's optimal portfolio). i) *The portfolio choice of the informed investor is equivalent to the following mean-entropy optimization:*

$$\max_{\theta_I} \theta_I^\top (\tilde{\mathbb{E}}[C] - pe^{rT}) - \frac{\tilde{\kappa}(b\varepsilon - \gamma_I \theta_I^\top C)}{\gamma_I}, \quad (29)$$

where expectation $\tilde{\mathbb{E}}[\cdot]$ is under investor I 's benchmark probability measure $\tilde{\pi}_n = \pi_n(0)$, and $\tilde{\kappa}(X) \equiv \ln(\tilde{\mathbb{E}}[e^X]) - \tilde{\mathbb{E}}[X]$ is the entropy of random variable $\exp(X)$ under this measure.

ii) *If Condition (28) is satisfied, then investor I 's demand is linear in ε , and given by*

$$\theta_I^*(p; \varepsilon) = \frac{\lambda \varepsilon}{\gamma_I} - \frac{\hat{\theta}_I^*(p)}{\gamma_I}, \quad (30)$$

where vector λ is such that Condition (28) is satisfied, and $\hat{\theta}_I^*(p)$ is a function of p .

Lemma 4 shows that portfolio (30) is separable in shock ε and price p and linear in ε when condition (28) is satisfied. We label the first and second terms of (30) as *information-sensitive* and *information-insensitive* demands, respectively. Next, we provide intuition for portfolio (30) and condition (28).

First, we discuss the portfolio choice. Lemma 4 shows that the portfolio choice is equivalent to a risk-return tradeoff (29), which is similar to mean-variance optimization except that risk is measured by entropy rather than variance. This similarity can be seen from the expansion of entropy in terms of cumulants [see Campbell (2018, p. 100)]:

$$\tilde{\kappa}(X) = \frac{\text{var}[X]}{2!} + \frac{\text{skewness}[X]}{3!} + \dots$$

If variable X is normally distributed, then $\tilde{\kappa}(X) = 0.5 \text{var}[X]$, and hence the entropy term in (29) becomes $0.5\gamma_I \text{var}[b\varepsilon/\gamma_I - \theta_I^\top C]$, and we obtain the mean-variance objective. If higher order cumulants are small, we obtain an approximate mean-variance objective.

The entropy term of the objective function (29) explicitly demonstrates that investor I hedges uncertainty arising due to the variation of risk factor $b\varepsilon$ across states, because this variation affects the probabilities of states $\pi_n(\varepsilon)$. We now show that the economic role of condition (28) is to ensure perfect hedging of $b\varepsilon$. To focus on pure hedging, we first

consider a partial equilibrium portfolio choice with zero excess payoffs $\tilde{\mathbb{E}}[C] - pe^{rT} = 0$. Then, optimization (29) reduces to the minimization of entropy $\tilde{\kappa}(b\varepsilon - \gamma_I \theta_I^\top C)$, and hence, investor I replicates risk factor $b\varepsilon$ in the best possible way. Perfect hedging with zero entropy is feasible if and only if condition (28) is satisfied, in which case the optimal information-sensitive hedge is given by $\lambda\varepsilon/\gamma_I$. The latter portfolio perfectly tracks $b\varepsilon$ and allows the investor to have more wealth in more likely states.

Next, we show how perfect hedging (equivalently, condition (28)) leads to the separability of shock ε and prices p in portfolio (30). If perfect hedging is feasible, the investor hedges exposures $b\varepsilon$ by including a perfect hedge $\lambda\varepsilon/\gamma_I$ in the total portfolio θ_I^* . Residual uncertainty then no longer depends on $b\varepsilon$ and the information-insensitive demand solves the optimization problem for the case $\varepsilon = 0$. Consequently, the information-based trading is localized in the hedging portfolio $\lambda\varepsilon/\gamma_I$.

The separability of portfolio θ_I^* in shock ε and price p is not feasible without perfect hedging because speculation and hedging decisions become intertwined. Consider, for example, a single-asset economy where condition (28) is violated because $b = C - C^2$, and assume without loss of generality that $\tilde{\mathbb{E}}[C] - pe^{rT} > 0$ and $\varepsilon > 0$. Then, investing $\theta_I > 0$ in the risky asset allows the investor to take advantage of the excess payoff $\tilde{\mathbb{E}}[C] - pe^{rT} > 0$. However, the optimal portfolio cannot balance two irreconcilable hedging objectives of having 1) more wealth in more likely states and 2) less wealth in less likely states. Specifically, portfolio $\theta_I > 0$ allocates more wealth to more likely states with $b\varepsilon > 0$ when C is low, in line with the hedging incentive, but more wealth to less likely states with $b\varepsilon < 0$ when C is high and b takes negative values, contrary to the hedging incentive.

Finally, we comment on the role of distributions and preferences in the portfolio choice. We observe that probabilities $\pi_n(\varepsilon)$ in (1) and preferences of investor I are conjugates because both have an exponential form. Consequently, risk factor $b\varepsilon$ and portfolio payoffs $\theta_I^\top C$ are perfect substitutes such that one unit decrease of $b_n\varepsilon$ can be offset by the increase of portfolio payoff $\theta_I^\top C(\omega_n)$ in the investor's optimization. This substitutability gives rise to the additivity of $b\varepsilon$ and portfolio payoff $\theta_I^\top C$ in the optimization (29).

Equation (1) for real probabilities and condition (28) imply that the PDF of the payoff vector $C(\omega)$ conditional on shock ε belongs to a multivariate exponential family distribution $\varphi_{C|\varepsilon}(x) = H(\varepsilon) \exp(A(x) + B(x)\varepsilon)$ [Casella and Berger (2002, p. 114)] with a linear function $B(x) = \lambda^\top x$. Breon-Drish (2015) demonstrates that the latter exponential family distribution with a linear function $B(x)$ is necessary and sufficient for the separability of portfolio θ_I^* in the signal and prices in a single risky asset economy. The separability of portfolio θ_I^* in the multi-asset case can be demonstrated along the same lines as in

Breon-Drish (2015), and without mean-entropy optimization (29). In Section IA2 of the Internet Appendix, we show that the informational spanning condition (28), and hence the linearity of function $B(x)$, can be relaxed in a setting where noise trader demands are replaced with random endowments, and show the robustness of our results in that setting.

Substituting portfolio (30) into the market clearing condition, similar to the complete-market economy, we obtain $h\lambda\varepsilon/\gamma_I + \nu + \widehat{H}(p) = 0$, where $\widehat{H}(p) \equiv (1-h)\theta_U^*(p) - h\widehat{\theta}_I^*(p)/\gamma_I$ is the informational content of prices. Investor U finds the posterior probabilities following the same steps as in the complete-market case. Given these probabilities, we derive the portfolios of investors, and then the asset prices from the market clearing condition. Proposition 3 reports the equilibrium.

Proposition 3 (Equilibrium with $M \leq N$ assets).

i) *Let the informational spanning condition (28) be satisfied. Then, there exists unique price vector $P(\varepsilon, \nu)$ that is a continuous, differentiable, and invertible on its range function of sufficient statistic $s = h\lambda\varepsilon/\gamma_I + \nu$. Price vector $P(\varepsilon, \nu)$ is the unique solution of equation*

$$\frac{hf_I^{-1}(e^{r^T}P(\varepsilon, \nu))}{\gamma_I} + \frac{(1-h)f_U^{-1}(e^{r^T}P(\varepsilon, \nu))}{\gamma_U} = (E + Q)s + \frac{(1-h)\mu_0/(\gamma_U\sigma_0^2)\lambda}{h^2\lambda^\top\Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2}, \quad (31)$$

where E is the identity matrix, Q is a matrix given by equation (19), $E, Q \in \mathbb{R}^{(M-1) \times (M-1)}$, and functions $f_I, f_U : \mathbb{R}^{M-1} \rightarrow \mathbb{R}^{M-1}$ are invertible on their ranges and given by

$$f_I(x) = \frac{\sum_{j=1}^N C(\omega_j) \exp\{a_j + C(\omega_j)^\top x\}}{\sum_{j=1}^N \exp\{a_j + C(\omega_j)^\top x\}}, \quad (32)$$

$$f_U(x) = \frac{\sum_{j=1}^N C(\omega_j) \exp\{a_j + \frac{1}{2} \frac{b_j^2}{h^2\lambda^\top\Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2} + C(\omega_j)^\top x\}}{\sum_{j=1}^N \exp\{a_j + \frac{1}{2} \frac{b_j^2}{h^2\lambda^\top\Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2} + C(\omega_j)^\top x\}}. \quad (33)$$

ii) *The informed and uninformed investors' optimal portfolios are given by*

$$\theta_I^*(p; \varepsilon) = \frac{\lambda\varepsilon}{\gamma_I} - \frac{f_I^{-1}(e^{r^T}p)}{\gamma_I}, \quad (34)$$

$$\theta_U^*(p) = (E + Q)^{-1} \left(\frac{hQf_I^{-1}(e^{r^T}p)}{(1-h)\gamma_I} - \frac{f_U^{-1}(e^{r^T}p)}{\gamma_U} + \frac{\mu_0/(\gamma_U\sigma_0^2)\lambda}{h^2\lambda^\top\Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2} \right). \quad (35)$$

Portfolios (34) and (35) have similar structure as the complete-market portfolios. Furthermore, both in incomplete and complete markets prices are non-linear functions of the sufficient statistic $h\lambda\varepsilon/\gamma_I + \nu$. However, in incomplete markets, in general, the prices are

not available in closed form and satisfy non-linear equations (31). Solving and analyzing these equations, in general, is a challenging task when the number of unknowns is large. The intractability of the incomplete-market equilibrium is in stark contrast with our complete-market equilibrium where prices are available in closed form.

Another contribution of Proposition 3 is the proof of the existence of equilibrium. This proof is complicated by market incompleteness and the multiplicity of risky assets. As a result, proofs in the related models with a single risky asset [e.g., Pálvölgyi and Venter (2014), Breon-Drish (2015)], which are based on the intermediate value theorem, do not apply in our model. Our proof in the Appendix relies on well-known results of basic calculus such as Weierstrass's compactness theorem [e.g., Rudin (1976, Theorem 2.42)] and an implicit function theorem [e.g., Rudin (1976, Theorem 9.28)]. Although the latter theorem guarantees only local existence and uniqueness, using Weierstrass's theorem and the fact that functions $f_I(x)$ and $f_U(x)$ in (32) and (33) have globally invertible Jacobians, we show that the solution can be extended globally.

Next, we introduce two *measures of market incompleteness* which we use in our analysis below. Risk-neutral probabilities in incomplete markets (i.e., $M < N$), in general, are not unique. In particular, consider the following two probability measures:

$$\pi_n^{\text{RN},I} = \frac{\pi_n(\varepsilon) \exp\{-\gamma_I W_{I,T,n}\}}{\sum_{j=1}^N \pi_j(\varepsilon) \exp\{-\gamma_I W_{I,T,j}\}}, \quad \pi_n^{\text{RN},U} = \frac{\pi_n^U(p) \exp\{-\gamma_U W_{U,T,n}\}}{\sum_{j=1}^N \pi_j^U(p) \exp\{-\gamma_U W_{U,T,j}\}}. \quad (36)$$

The first order conditions for investor optimizations (3) and (4) imply that $p = e^{-rT} \mathbb{E}^{\text{RN},I}[C]$ and $p = e^{-rT} \mathbb{E}^{\text{RN},U}[C]$, respectively, where the expectations are under the measures (36). Hence, probabilities (36) can be interpreted as risk-neutral probabilities.

The first measure of market incompleteness is the Kullback-Leibler (KL) divergence (also called relative entropy) of the two risk-neutral measures (36), defined as

$$\kappa^U = \mathbb{E}^{\text{RN},U} \left[\ln \left(\frac{\pi^{\text{RN},U}}{\pi^{\text{RN},I}} \right) \right], \quad (37)$$

and the second measure is the symmetric KL divergence, given by

$$\hat{\kappa} = \mathbb{E}^{\text{RN},U} \left[\ln \left(\frac{\pi^{\text{RN},U}}{\pi^{\text{RN},I}} \right) \right] + \mathbb{E}^{\text{RN},I} \left[\ln \left(\frac{\pi^{\text{RN},I}}{\pi^{\text{RN},U}} \right) \right]. \quad (38)$$

The KL divergences (37) and (38) are always non-negative, and take zero value if and only if the probability measures (36) coincide [e.g., MacKay (2017)]. Lemma A.9 in the Appendix shows that the probability measures (36) and divergences κ^U and $\hat{\kappa}$ are functions of the sufficient statistic s , and hence, are observed by both investors I and U . Lemma A.9 also presents κ^U for the CARA-normal economy.

We now relate the measures of market incompleteness to the probability-weighted ratio of marginal utilities. In incomplete markets, this ratio varies across states, and hence,

$$\frac{\pi_n(\varepsilon) \exp\{-\gamma_I W_{I,T,n}\}}{\pi_n^U(p) \exp\{-\gamma_U W_{U,T,n}\}} = e^{\bar{\ell} + \ell_n}, \quad (39)$$

where $\bar{\ell}$ and $\ell_n = \ell(\omega_n)$ are a state-independent and a state-dependent variables, respectively. Using simple algebra, it can be shown that our measure of incompleteness (37) equals the entropy of the random variable $\exp\{\ell(\omega)\}$ under the measure $\pi^{\text{RN},U}$, given by $\kappa^U = \ln(\mathbb{E}^{\text{RN},U}[e^{\ell(\omega)}]) - \mathbb{E}^{\text{RN},U}[\ell(\omega)]$. Hence, ratio (39) does not depend on state ω_n if and only if $\kappa^U = 0$ (equivalently, $\hat{\kappa} = 0$). In the latter case, the market is *effectively complete*, that is, the investors achieve Pareto-optimal allocations [e.g., Amershi (1985); Brennan and Cao (1996)]. Lemma 5 below, derives $\hat{\kappa}$ in terms of risk-neutral variances.

Lemma 5 (Measure of market incompleteness). *The measure of market incompleteness defined as the symmetric KL divergence (38) of the informed and uninformed investors' risk-neutral probabilities is equal to*

$$\hat{\kappa} = \frac{\text{var}^{\text{RN},U}[b] - \text{var}^{\text{RN},I}[b]}{h^2 \lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2 + 1 / \sigma_0^2}, \quad (40)$$

where the variances are under the risk-neutral probabilities (36), respectively.

Lemma 5 has several implications. The first implication is that the asymmetry of information is in itself an important source of market incompleteness. It is known that without the asymmetry of information the market is effectively complete even when investors have different risk aversions and $M < N$ [see Rubinstein (1974)]. Second, equation (40) shows that the extent of the risk-sharing imperfection is characterized by the wedge between the risk-neutral variances of the risk factor b under the risk-neutral measures of investors U and I . Third, Lemma 5 implies that $\text{var}^{\text{RN},U}[b] \geq \text{var}^{\text{RN},I}[b]$ because $\hat{\kappa} \geq 0$, and hence, investor U faces higher uncertainty. Finally, Lemma 5 implies that the risk-neutral measures (36) coincide if and only if $\text{var}^{\text{RN},U}[b] = \text{var}^{\text{RN},I}[b]$ because then $\hat{\kappa} = 0$.

Lemma 5 sheds light on risk-sharing in the economy. First, we note that the informational spanning condition (28) and the risk-neutral measures (36) imply that $\mathbb{E}^{\text{RN},U}[b] = \mathbb{E}^{\text{RN},I}[b] \equiv \tilde{p}$, and hence, investors U and I agree on the valuation of the replicating portfolio for the risk factor b . Next, we observe that the risk-neutral variances $\text{var}^{\text{RN},U}[b]$ and $\text{var}^{\text{RN},I}[b]$ in (40) can be interpreted as the informed and uninformed investors' subjective valuations of a non-tradable quadratic derivative with payoff $(b - \tilde{p})^2$, respectively. Therefore, because $\text{var}^{\text{RN},U}[b] \geq \text{var}^{\text{RN},I}[b]$, as discussed above, there are potential gains from trade if investor I could sell this derivative to investor U . Equation (40) then implies that

market incompleteness arises due to the different subjective valuations of this derivative and inability to trade it. The intuition is that buying the quadratic derivative at a price lower than $\text{var}^{\text{RN},U}[b]$ compensates investor U for the disutility of facing higher uncertainty due to being uninformed. Consistent with this intuition, in Section 4.2 below, we show that allowing investors to trade quadratic derivatives makes the market effectively complete and it is the informed investor who sells the quadratic derivative to the uninformed.

4. Economic Applications

In this section, we provide several applications of our model to market microstructure, corporate finance, and asset pricing. In Section 4.1 we study the informativeness of derivative prices and introduce a new concept of informationally irrelevant securities. There we also explore the informational content of corporate debt and equity. Then, in Section 4.2, we study volatility derivatives and show that they make financial markets effectively complete, quantify the value of information, and indicate by how much the informed investors are better off than the uninformed ones. In Section 4.3 we derive new closed-form asset prices in effectively complete markets. We also derive expansion for asset prices in terms of higher order moments of asset payoffs and use it to study the effect of payoff skewness on prices. In Section 4.4, we study the effect of financial innovation on market liquidity.

4.1. Information Revelation in Asset Markets

In this section, we study how the information about the aggregate shock revealed by the prices depends on the type of traded assets. We start with the analysis of the informed investor's portfolio in equation (30). This equation implies that the informed investor's demand for asset m depends on shock ε if and only if $\lambda_m \neq 0$, where λ_m is the m^{th} component of vector λ . Otherwise, if $\lambda_m = 0$, the informed investor's demand for asset m does not contain any information about ε , and hence, asset m is *informationally irrelevant*.

The informational irrelevance of derivatives is a generic property of economies with one underlying asset with payoff $C_1 = b/\lambda_1$ and derivative securities written on this asset. In such economies, the informational spanning condition (28) is satisfied with the replicating portfolio $\lambda = (\lambda_1, 0, \dots, 0)^\top$. As demonstrated in Lemma A.2 in the Appendix, condition $C_1 = b/\lambda_1$ is satisfied in the single risky asset economies of Grossman and Stiglitz (1980) and Breon-Drish (2015). Consequently, adding any non-redundant securities to these economies does not reveal more information about ε (provided that noises ν are uncorrelated across assets, as elaborated below).

To illustrate informational irrelevance, we consider an economy with a risky asset with payoff $C_1 = b/\lambda_1$. Then, we add $M - 2$ derivative securities written on that asset and assume that all noises ν_m are i.i.d. In this economy, $\lambda = (\lambda_1, 0, \dots, 0)^\top$. Prices then reveal sufficient statistic $\lambda\varepsilon/\gamma_I + \nu = (\lambda_1\varepsilon/\gamma_I + \nu_1, \nu_2, \dots, \nu_{M-1})^\top$. However, because noises ν_m are i.i.d., only the first element $\lambda_1\varepsilon/\gamma_I + \nu_1$ of the sufficient statistic provides information about ε . Hence, the number of assets does not affect the posterior distribution of ε and posterior probabilities $\pi_n^U(p)$. The derivative securities are thus informationally irrelevant.⁴ Informational irrelevance also implies that derivatives prices are not fully revealing when noise traders do not trade in derivatives markets, that is, when $\nu_i = 0$ for $i \geq 2$.

As shown in Section 3, assets with $\lambda_m \neq 0$ are used by investor I for hedging the aggregate risk factor $b\varepsilon$. From equations (34) and (35) we observe that assets with $\lambda_m = 0$ are still held by investors for reasons unrelated to information, such as trading against noise traders. Moreover, we note that portfolio λ does not depend on payoff distributions.⁵

The informativeness of prices also depends on the correlations of noises. Consider an example with two risky assets and perfectly correlated noises $\nu_1 = \nu_2$. Taking the difference of the market clearing conditions (13) for the two markets we find that $(\lambda_1 - \lambda_2)\varepsilon/\gamma_I + (\nu_1 - \nu_2) + (1, -1)^\top H(p) = 0$. Shock ε can then be perfectly learned from prices if $\lambda_1 \neq \lambda_2$ and is given by $\varepsilon = \gamma_I(-1, 1)^\top H(p)/(\lambda_1 - \lambda_2)$. The effects of the informed investor's demand and noise correlations on the learning from prices by investor U are captured by vector λ and matrix Σ_ν in equation (15) for investor U 's posterior probabilities, respectively.

We now apply the results of this section to study the informational content of risky debt and equity. Consider a firm with cash flow b_n in state ω_n . The real probabilities of states $\pi_n(\varepsilon)$ and PDF $\varphi_\varepsilon(x)$ of shock ε are given by equations (1) and (2), respectively. Suppose, investors trade the firm's debt and equity with payoffs $\min(b, K)$ and $\max(b - K, 0)$, respectively, where $K > 0$ is the face value of debt. The informational spanning condition

⁴The empirical literature on price discovery in financial markets finds that the prices and trading volumes of derivative securities reveal information about the payoffs of the underlying asset [e.g., Easley, O'Hara, and Srinivas (1998); Chakravarty, Gulen, and Mayhew (2004); Pan and Poteshman (2006)]. This evidence is consistent with our model when the derivatives help replicate the economic factor b or noise trader demands are correlated. The latter situation may arise when factor b represents the aggregate output in the economy and ε is a market shock that makes states with high output less (more) likely when $\varepsilon < 0$ ($\varepsilon > 0$). If, for example, informed investors know that $\varepsilon < 0$ they would hedge by investing in assets and derivatives that have higher payoffs in bad times (e.g., put options, gold). The latter assets are sensitive to information, and hence, would have $\lambda_m \neq 0$.

⁵Consider, for example, a firm with cash flows b and three tradable securities with payoffs $C_1 = b - g_1(b)$, $C_2 = g_1(b) - g_2(b)$, $C_3 = g_2(b)$, where $g_1(b)$ and $g_2(b)$ are arbitrary continuous functions. The replicating portfolio for cash flow b is given by $\lambda = (1, 1, 1)^\top$, because $b = C_1 + C_2 + C_3$, and does not depend on the distribution of cash flow b or functions $g_1(b)$ and $g_2(b)$. The latter result is similar to how replicating portfolios for options in a binomial model do not depend on real probabilities of states of the economy.

is satisfied for debt and equity with the replicating portfolio $\lambda = (1, 1)^\top$ because $b = \min(b, K) + \max(b - K, 0)$. The prices of debt and equity can be obtained by solving equation (31). Portfolio $\lambda = (1, 1)^\top$ does not depend on K , and hence, the sufficient statistic, the posterior distribution of ε , and the posterior probabilities of states also do not depend on K . As a result, the face value of debt K is irrelevant for the amount of information jointly revealed by the prices of debt and equity.

Our irrelevance result is not a mere consequence of the Modigliani–Miller theorem because of a market imperfection in the form of informational asymmetry. This result emerges because investor I buys the same number of units of debt and equity to replicate the risk factor b , which is similar to buying directly a security with payoff b . Such portfolio composition of investor I is difficult to anticipate without our theory because, in general, the uninformed investor may want to purchase less informationally sensitive securities such as debt $\min(b, K)$ when K is small. Then, the informed investor would hold more equity than debt in equilibrium.

Similar to the Modigliani–Miller theorem, the economic value of the irrelevance conditions is that they help identify plausible situations when the capital structure is relevant for the informativeness of asset prices. For example, our analysis of debt and equity relies on costless default on debt whereas in reality firms may face considerable bankruptcy costs [e.g., Altman (1984); Andrade and Kaplan (1998)]. Hence, the irrelevance result breaks down in the presence of costly defaults, as we show below.⁶

Consider a firm with cash flow b_n in state ω_n such that $b_1 < b_2 < \dots < b_N$. The firm loses fraction χ of its value in the case of default so that the final payoffs of debt and equity are given by $\min(b, K) - \chi b 1_{\{b < K\}}$ and $\max(b - K, 0)$, respectively. The cash flow b can no longer be replicated by trading only debt and equity. In addition to debt and equity, we allow the investors to trade Arrow–Debreu (AD) securities with payoffs $1_{\{\omega = \omega_n\}}$, where $n \leq N - 2$. These securities help achieve protection in default states, and in this respect are similar to credit default swaps. The firm cash flow can be replicated as follows:

$$b = \chi \sum_{n: b_n < K} b_n 1_{\{\omega = \omega_n\}} + \underbrace{(\min(b, K) - \chi b 1_{\{b < K\}})}_{\text{debt with costly default}} + \underbrace{\max(b - K, 0)}_{\text{equity}},$$

⁶Another realistic example where the capital structure affects the informativeness of prices is an economy with an interplay between investment decisions and security payoffs. Consider, for example, an economy where raising capital K by issuing debt changes the probabilities of states so that $\pi_n(\varepsilon) = \exp\{a_n + (b_n + g(K)b_n^2)\varepsilon\} / \sum_{j=1}^N \exp\{a_j + (b_j + g(K)b_j^2)\varepsilon\}$, where $g(K)$ is an increasing function of K . Thus, investing K increases the probability of high payoffs when $\varepsilon > 0$, and hence, the investment decision reveals information about ε . Assuming that investors can trade a derivative with payoff b^2 , the risk factor can be replicated as $b + g(K)b^2 = \min(K, b) + \max(b - K, 0) + g(K)b^2$. Therefore, the replicating portfolio $\lambda = (1, 1, g(K))$ depends on K and the amount of information is affected by debt K , similar to the example below. More detailed investigation of this interplay we reserve for future research.

and hence, the replicating portfolio is given by $\lambda = (\chi b_1, \dots, \chi b_{\bar{n}}, 0, \dots, 0, 1, 1)^\top$, where $\bar{n}$ is the largest integer such that $b_n < K$. We then evaluate the informativeness of prices using the posterior variance of shock ε , which is reported in Lemma 6 below.

Lemma 6 (Posterior variance of shock ε). *The posterior variance of ε is given by:*

$$\text{var}[\varepsilon|s] = \frac{1}{h^2 \lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2 + 1 / \Sigma_0^2} + \frac{\text{var}^U[b]}{(h^2 \lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2 + 1 / \Sigma_0^2)^2}. \quad (41)$$

From equation (41), we see that defaults affect the informativeness of prices because the replicating portfolio λ depends on both the cost of default χ and the face value of debt K . To simplify the exposition, we assume that $\Sigma_\nu = \sigma_\nu^2 E$, where E is an identity matrix. We further assume that σ_0^2 is small and/or b_n has low variability, so that the second term in (41) is small. Then, keeping only the first term in (41) for tractability, we find that

$$\text{var}[\varepsilon|s] \approx \frac{1}{h^2(2 + \chi^2 \sum_{b_n < K} b_n^2) / (\gamma_I^2 \sigma_\nu^2) + 1 / \sigma_0^2}. \quad (42)$$

Equation (42) reveals that the posterior variance of shock ε is a decreasing function of the face value of debt K and the cost of default χ . The intuition is that default becomes more likely as the face value of debt K increases, and hence, more AD securities are needed for hedging and more information is revealed through their prices. The latter result is consistent with the empirical evidence showing that credit default swaps reveal information about cash flow distributions of underlying firms [e.g., Blanco, Brennan, and Marsh (2005); Longstaff, Mithal, and Neis (2005)].

4.2. Effective Completeness and Volatility Derivatives

We now apply our model to study the economic role of volatility derivatives. These derivatives are widely traded in financial markets, and hence, adding them to our analysis makes it more realistic. We show that introducing volatility derivatives to incomplete markets makes these markets effectively complete and, moreover, their prices quantify the value of information to uninformed investors. As discussed in Section 3.3, effective completeness requires that the measure of market incompleteness (37) is zero, $\kappa^U = 0$. Proposition 4 below provides necessary and sufficient conditions for effective completeness.

Proposition 4 (Conditions for effective completeness).

i) *Suppose, the market is incomplete, that is, $M < N$, and the informational spanning condition (28) is satisfied. Then, the market is effectively complete if and only if there exists a replicating portfolio for squared risk factor b_n^2 . That is, there exist constant $\tilde{\lambda}_0$ and vector $\tilde{\lambda} \in \mathbb{R}^{M-1}$ such that $b_n^2 = \tilde{\lambda}_0 + C(\omega_n)^\top \tilde{\lambda}$, for all $n = 1, \dots, N$.*

- ii) If the quadratic derivative with payoffs b_n^2 is tradable, then the informed investor holds a short position and the uninformed investor holds a long position in this derivative
- iii) If the market is effectively complete, the prices of risky assets are given by equation (16), as in a complete market, with the only difference that vectors λ , ν , and matrices Ω , E and Q are of lower dimensions: $\lambda, \nu \in \mathbb{R}^{M-1}$, $\Omega \in \mathbb{R}^{(N-1) \times (M-1)}$, and $E, Q \in \mathbb{R}^{(M-1) \times (M-1)}$. Moreover, the CAPMs in Corollaries 1 and 2 also hold in the effectively complete markets.

Proposition 4 confirms the risk sharing analysis in Section 3.3. As discussed in Section 3.3, the measure of market incompleteness (40) implies that investors U and I have different subjective valuations of assets with quadratic payoffs b^2 in incomplete markets. Moreover, investor U has higher valuation of this derivative than investor I in the incomplete market. Consequently, allowing informed investors to sell securities with such payoffs to uninformed investors generates gains from trade. Proposition 4.ii verifies that investor I sells a quadratic derivative to investor U .

We demonstrate the implications of Proposition 4 in a simple economy with one asset that has payoff $C_1 = b/\lambda_1$. The proposition implies that the market can be effectively completed by introducing a derivative security with a quadratic payoff such as C_1^2 or $(C_1 - \mathbb{E}^{\text{RN}}[C_1])^2$. The last security is similar to a simple variance swap (SVIX) introduced in Martin (2013). The prices of this security and the underlying asset are then given in closed form by $\text{var}^{\text{RN}}[C_1]e^{-rT}$ and $\mathbb{E}^{\text{RN}}[C_1]e^{-rT}$, respectively. Therefore, we interpret assets with quadratic payoffs as volatility derivatives.

Next, we explain the importance of volatility derivatives for achieving effective completeness. Taking logs on both sides of equation (39) for the marginal rates of substitution, after simple algebra, we find that the market is effectively complete [i.e., $\ell_n = 0$ in equation (39)] if and only if $\gamma_U W_{U,T,n} - \gamma_I W_{I,T,n} - \bar{\ell} = \ln(\pi_n^U(p)/\pi_n(\varepsilon))$. The expression $\gamma_U W_{U,T,n} - \gamma_I W_{I,T,n} - \bar{\ell}$ can be interpreted as the payoff of a portfolio that invests in bonds and $\gamma_U \theta_U^* - \gamma_I \theta_I^*$ units of the risky assets. Hence, effective completeness is feasible if only if the log-ratio of probabilities $\ln(\pi_n^U(p)/\pi_n(\varepsilon))$ can be replicated by a portfolio of tradable assets [see Lemma A.8 in the Appendix]. Moreover, the log-probability $\ln(\pi_n^U(p))$ is a quadratic function of b_n [see equations (15) and (A.29)], and hence, Pareto allocations of wealth are quadratic functions of b_n . Therefore, the existence of a replicating portfolio for b_n^2 is essential for Pareto optimality.

Previous literature has noted that introducing contracts and securities with quadratic payoffs can lead to Pareto-optimality in CARA-normal models of syndicates with belief heterogeneity [e.g., Wilson (1968)] and REE models of asset markets [e.g., Brennan and Cao (1996)]. However, CARA-normal models have very restrictive structure of asset pay-

offs, and there is no indication or anticipation in this literature that the latter property of quadratic derivatives might hold in more general models. Moreover, quadratic derivatives do not play any methodological role in CARA-normal models because the asset prices in these models are available in closed form and do not depend on whether the quadratic derivatives are traded or not [see Lemma 7 below]. Our methodological contribution is to show that quadratic derivatives significantly enhance the tractability of models where the normality of asset payoffs is relaxed. Introducing these derivatives gives rise to analytical asset prices [studied in Section 4.3 below]. We observe that incomplete market prices, in general, solve nonlinear equations (31) in terms of inverse functions, and are difficult to compute in multi-asset settings even by numerical methods. We also contribute to the literature by uncover a simple yet general approach for completing markets by introducing a security that replicates the log-ratio of investors' probabilities. This approach works not only for our REE model but also for models where investors have heterogeneous beliefs.

Finally, we study the implications of volatility derivatives for the valuation of information. Conditional on observing the sufficient statistic s , we define the shadow value of information as the amount of wealth $\widehat{W}$ that the uninformed investor is willing to give up to become informed. Although we primarily focus on the complete-market economy, we derive $\widehat{W}$ in a more general incomplete market economy. Proposition 5 reports our result.

Proposition 5 (Shadow value of information). *The amount of wealth that the uninformed investor is willing to give up to become informed is given by*

$$\widehat{W} = \frac{1}{2\gamma_U} \frac{\text{var}^{\text{RN},U}[b]}{h^2 \lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2 + 1/\sigma_0^2} - \frac{\kappa^U}{\gamma_U}, \quad (43)$$

where $\kappa^U \geq 0$ is the measure of market incompleteness given by (37), and the variance is computed under the risk-neutral measure of investor U in (36).

Proposition 5 sheds further light on the economic role of volatility derivatives. When the volatility derivatives are traded, and hence, the market is effectively complete, the measure of market incompleteness is zero, $\kappa^U = 0$. Moreover, in the effectively complete market the variance in equation (43) is computed under the unique risk-neutral measure (17), which coincides with the incomplete-market measures (36). In particular, consider an effectively complete market with two securities with payoffs C_1 and $(C_1 - \mathbb{E}^{\text{RN}}[C_1])^2$. Then, the price of the second asset quantifies the value of information and by how much investor I is better off than investor U . The latter result also complements the widespread use of the volatility index VIX as the “fear gauge” in financial markets, which increases during times of uncertainty when information is more valuable.

Proposition 5 also sheds light on the value of information in the incomplete market. In

such markets, the volatility index is not traded, and hence, the value of information cannot be inferred from the prices of tradable securities. However, this value still features the risk-neutral variance of risk factor b computed under the risk-neutral measure of investor U . Moreover, equation (43) shows that the value of information is reduced by the measure of market incompleteness κ^U because market incompleteness constrains the use of information to fewer assets, which makes the information less valuable.

4.3. Closed Form Asset Prices and Higher Order Moments

In this section, for a broad class of payoff distributions, we derive new analytic expressions for asset prices in effectively complete markets and study the effects of higher order moments on asset prices. Because volatility derivatives are actively traded in financial markets, our method based on effectively complete markets provides an economically realistic and tractable tool for studying asset pricing with asymmetric information.

Our benchmark is the economy with one risky asset with payoff C_1 that has a continuous unconditional PDF $\varphi_C(x)$. The informed investor observes signal $\varepsilon = C_1 + u$, where $u \sim \mathcal{N}(\mu_0, \sigma_0^2)$. The uninformed investor learns about ε from prices, and noise traders submit exogenous demand ν_1 . This economy is a special limiting case of our economy in Section 2 with distribution parameters a_n and b_n given by equations (7) when $N \rightarrow \infty$, as noted in Remark 1 and demonstrated in Lemma A.2 in the Appendix. From equations (7) we observe that the informational spanning condition is satisfied because $b_n = C_1(\omega_n)/\sigma_0^2$.

Following Section 4.2, we make the economy effectively complete by adding a volatility derivative with payoff C_1^2 . To facilitate the comparison of the economies with and without the volatility derivative, we assume that the noise traders do not trade in the derivative. As a result, the prices in the incomplete and effectively complete markets depend on the same scalar sufficient statistic $s = h\varepsilon/(\gamma_I\sigma_0^2) + \nu_1$. The equilibrium is not fully revealing because the derivative is informationally irrelevant⁷ (as defined in Section 4.1), that is, $b = C_1/\sigma_0^2 + 0 \cdot C_1^2$. Proposition 6 below reports asset prices in the two economies.

Proposition 6 (Equilibrium prices). *The prices of the asset with payoff C_1 that has PDF $\varphi_C(x)$ in the effectively complete and incomplete markets are given by*

$$P_{com}(s) = P_C(\gamma_I\sigma_0^2 s/h - \mu_0, \sigma_{com}) e^{-rT}, \quad P_{inc}(s) = P_C(\gamma_I\sigma_0^2 \hat{s}(s)/h - \mu_0, \sigma_0) e^{-rT}, \quad (44)$$

⁷The volatility derivative is made informationally irrelevant only to facilitate the comparison between complete and incomplete markets in this application. However, in general, the volatility derivative does not need to be informationally irrelevant as, for example, when $b = C_1/\sigma_0^2 + C_1^2$.

respectively, where the pricing function $P_C(\mu, \sigma)$ is given by equation

$$P_C(\mu, \sigma) = \frac{\mathbb{E} \left[C_1 \exp \left(-\frac{(C_1 - \mu)^2}{2\sigma^2} \right) \right]}{\mathbb{E} \left[\exp \left(-\frac{(C_1 - \mu)^2}{2\sigma^2} \right) \right]}, \quad (45)$$

$\mathbb{E}[\cdot]$ is the expectation with respect to PDF $\varphi_C(x)$, $s = h\varepsilon/(\gamma_I\sigma_0^2) + \nu_1$, $\hat{s}(s)$ in the equation for $P_{inc}(s)$ is an increasing implicit function of s satisfying equation

$$P_C \left(\gamma_I\sigma_0^2\hat{s}(s)/h - \mu_0, \sigma_0 \right) = P_C \left(\gamma_I\sigma_0^2s/h - \mu_0 + \gamma_U\sigma_{inc}^2(s - \hat{s}(s))/(1-h), \sigma_{inc} \right), \quad (46)$$

and the volatility parameters σ_{com} and σ_{inc} are given by:

$$\sigma_{com} = \frac{\sigma_0}{\sqrt{1 - \frac{(1-h)/\gamma_U}{h/\gamma_I + (1-h)/\gamma_U} \frac{1}{1 + h^2/(\gamma_I^2\sigma_U^2\sigma_0^2)}}}, \quad \sigma_{inc} = \frac{\sigma_0}{\sqrt{1 - \frac{1}{1 + h^2/(\gamma_I^2\sigma_U^2\sigma_0^2)}}}. \quad (47)$$

Moreover, both prices $P_{com}(s)$ and $P_{inc}(s)$ are increasing functions of s .

Equations (44) show that the price of an asset with payoff C_1 admits similar representations in terms of pricing function (45) both in the effectively complete and incomplete markets. Price $P_{com}(s)$ is given in closed form in the sense that finding this price does not require solving any equations and it is in terms of only exogenous parameters specified in Section 2. Price $P_{inc}(s)$ in the incomplete market is less tractable because it is given in terms of an implicit function $\hat{s}(s)$, which solves non-linear equation (46). The latter equation is a consistency condition, which makes informed and uninformed investors agree on the incomplete-market price, as shown in the proof of Proposition 6 in the Appendix.

To further highlight the role of quadratic derivatives in achieving tractability, we derive the equilibrium prices in a CARA-normal economy. Lemma 7 reports our results.

Lemma 7. *In the case of normally distributed asset payoff $C_1 \sim \mathcal{N}(\mu_C, \sigma_C^2)$ the price of this asset is the same in incomplete and complete markets, is linear in s , and is given by:*

$$P(s) = \frac{\sigma_{com}^2\sigma_C^2}{\sigma_C^2 + \sigma_{com}^2} \left(\frac{\gamma_I\sigma_0^2s/h - \mu_0}{\sigma_{com}^2} + \frac{\mu_C}{\sigma_C^2} \right) e^{-rT}, \quad (48)$$

where volatility σ_{com}^2 is given in the first equation in (47).

Lemma 7 shows that adding a quadratic derivative to an incomplete-market CARA-normal economy does not affect the price of the underlying asset. The latter result is in contrast to Proposition 6, which shows that, for more general distributions, complete-market prices are available in closed-form whereas incomplete-market prices are not.

As the first application of Proposition 6, we derive an expansion of the price $P_{com}(s)$ in terms of higher order moments of the cash flow C_1 . Proposition 7 reports the result.

Proposition 7 (Expansion in terms of moments). Let $m_n = \mathbb{E}\left[\left(\frac{C_1 - \mu_C}{\sigma_C}\right)^n\right]$ be the standardized moments under the PDF $\varphi_C(x)$. The pricing function (45) is then given by

$$P_C(\mu, \sigma) = \mu_C + \sigma_C \frac{\sum_{n=0}^{\infty} H_n\left(\frac{\mu - \mu_C}{\sigma_C}\right) \left(\frac{\sigma_C}{\sigma}\right)^n \frac{m_{n+1}}{n!}}{\sum_{n=0}^{\infty} H_n\left(\frac{\mu - \mu_C}{\sigma_C}\right) \left(\frac{\sigma_C}{\sigma}\right)^n \frac{m_n}{n!}}, \quad (49)$$

where $H_n(x)$ are Hermite polynomials satisfying a recursive equation $H_{n+1}(x) = xH_n(x) - nH_{n-1}(x)$ with the initial conditions $H_1(x) = x$ and $H_0(x) = 1$.

Equation (49) provides an explicit link between the asset price and the higher-order moments. We now evaluate the impact of payoff skewness on the asset risk premia by linearizing equation (49) assuming that volatility σ_C is small. We derive the unconditional risk premium $\overline{\mathbb{E}^U[C_1]} - P_{com}(s)e^{rT}$, averaged over different values of s , which captures the effects of skewness that do not depend on particular realizations of s . To focus on the effects of the asymmetry of information, we assume that the informed and uninformed investors have the same risk aversion γ . Corollary 3 reports our result.

Corollary 3. Suppose, $\gamma_I = \gamma_U = \gamma$ and σ_C^2 is small. Then, the unconditional risk premium of the risky asset, averaged over the realizations of s , is given by:

$$\overline{\mathbb{E}^U[C_1]} - P_{com}(s)e^{rT} \approx -\frac{m_3\sigma_C^3}{2} \left(\gamma^2\sigma_\nu^2 + \frac{h(1-h)}{\sigma_0^2 + h^2/(\gamma^2\sigma_\nu^2)} \right), \quad (50)$$

where m_3 is the skewness of cash flow C_1 under the prior cash flow distribution $\varphi_C(x)$.

Equation (50) reveals that the risk premium is a decreasing function of skewness and that assets with negative (positive) skewness on average have a positive (negative) risk premium. The two components in brackets on the right-hand side of the equation decompose the skewness effect into two terms, the effect of the random asset supply and the effect of asymmetric information, respectively. The first term implies that the relationship between the risk premium and skewness holds due to noisy asset supply even without the asymmetry of information. However, the second term demonstrates that the asymmetry of information amplifies the sensitivity of the risk premium to skewness.

The relationship between the risk premium and skewness arises because positive skewness makes low payoffs less likely, and hence, makes holding the security less risky and decreases the risk premium. Similarly, negative skewness increases the risk premium. The latter effect is amplified by learning from prices. For example, in the case of positive skewness, the uninformed investors would attribute a large negative sufficient statistic s to noises ν_1 and u rather than to low cash flow C_1 , and hence, would require lower risk premium than in the absence of learning.

Albagli, Hellwig, and Tsyvinski (2013) find similar results in a model with risk-neutral investors, position limits, and heterogeneously informed investors. They also discuss large empirical literature documenting a negative relation between the risk premium and skewness. Breon-Drish (2015) considers a single-asset binomial model with more general distributions for ε and supply shocks and derives conditions under which uninformed demand curves bend backwards, in which case asset prices react more strongly than in a setting in which all traders are informed. Our Corollary 3 complements the latter results by showing that the relationship between the risk premium and skewness also holds in a no-arbitrage setting with risk averse and asymmetrically informed investors and for general payoff distributions.

Next, as a second application of Proposition 6, we provide analytic pricing functions (45) for the following payoff distributions:

$$\varphi_C(x) = \sum_{l=1}^L w_l \frac{1}{\sqrt{2\pi}\hat{\sigma}_{C,l}} \exp\left(-\frac{(x - \hat{\mu}_{C,l})^2}{2\hat{\sigma}_{C,l}^2}\right), \quad x \in \mathbb{R}, \quad (\text{Mixture of Normals}), \quad (51)$$

$$\varphi_C(x) = \frac{1}{\Lambda} x^{k-1} \exp\left(-\frac{x^2}{2\hat{\sigma}_C^2} - \delta x\right), \quad x \geq 0, \quad (\text{Generalized Gamma}), \quad (52)$$

$$\varphi_C(x) = \frac{2}{\sqrt{2\pi}\hat{\sigma}_C} \exp\left(-\frac{(x - \hat{\mu}_C)^2}{2\hat{\sigma}_C^2}\right) \Phi\left(\alpha \frac{x - \hat{\mu}_C}{\hat{\sigma}_C}\right), \quad x \in \mathbb{R}, \quad (\text{Skew-normal}), \quad (53)$$

respectively, where $w_1 + \dots + w_L = 1$, $w_l \geq 0$, Λ is a normalizing constant, $\hat{\sigma}_{C,l} > 0$ and $\hat{\sigma}_C > 0$ are scale parameters, $\hat{\mu}_{C,l}$, δ and $\hat{\mu}_C$ are shift parameters, and $k \geq 1$ is an integer power, α is a skewness parameter, and $\Phi(x)$ is the standard normal cumulative distribution function (CDF). We note that: mixture of normals (51) is widely employed for non-parametric estimation of general PDFs [Greene (2008, p. 416)]; generalized gamma (52) has positive support and incorporates exponential ($k = 1$, $\hat{\sigma}_C \rightarrow \infty$), gamma ($\hat{\sigma}_C \rightarrow \infty$), Rayleigh ($k = 2$), and truncated normal ($k = 1$) distributions; and the skew-normal distribution (53) extends the normal distribution to allow for skewness [Azzalini (1985)]. Proposition 8 reports pricing functions (45) for distributions (51)–(53).

Proposition 8 (Pricing functions in analytic form).

i) When $\varphi_C(x)$ is a mixture of normals (51), the pricing function $P_C(\mu, \sigma)$ is given by:

$$P_C(\mu, \sigma) = \frac{\sum_{l=1}^L w_l \frac{\mu \hat{\sigma}_{C,l}^2 + \hat{\mu}_{C,l} \sigma^2}{(\hat{\sigma}_{C,l}^2 + \sigma^2)^{3/2}} \exp\left(-\frac{1}{2} \frac{(\mu - \hat{\mu}_{C,l})^2}{\hat{\sigma}_{C,l}^2 + \sigma^2}\right)}{\sum_{l=1}^L w_l \frac{1}{\sqrt{\hat{\sigma}_{C,l}^2 + \sigma^2}} \exp\left(-\frac{1}{2} \frac{(\mu - \hat{\mu}_{C,l})^2}{\hat{\sigma}_{C,l}^2 + \sigma^2}\right)}. \quad (54)$$

ii) When $\varphi_C(x)$ is a generalized gamma PDF (52) with an integer power k the pricing function $P_C(\mu, \sigma; k)$ is given in terms of $P_C(\mu, \sigma; k-1)$ by the following recursive formula:

$$P_C(\mu, \sigma; k) = \begin{cases} \frac{\hat{\sigma}_C^2 \sigma^2}{\hat{\sigma}_C^2 + \sigma^2} \left(\frac{\mu}{\sigma^2} - \delta + \frac{k-1}{P_C(\mu, \sigma; k-1)} \right), & \text{if } k > 1, \\ \frac{\hat{\sigma}_C^2 \sigma^2}{\hat{\sigma}_C^2 + \sigma^2} \left(\frac{\mu}{\sigma^2} - \delta \right) + \frac{\hat{\sigma}_C \sigma}{\sqrt{\hat{\sigma}_C^2 + \sigma^2}} \hat{\Phi} \left(\frac{\hat{\sigma}_C \sigma}{\sqrt{\hat{\sigma}_C^2 + \sigma^2}} \left(\frac{\mu}{\sigma^2} - \delta \right) \right), & \text{if } k = 1, \end{cases} \quad (55)$$

where $\hat{\Phi}(x) = \exp(-0.5x^2) / (\sqrt{2\pi}\Phi(x))$, and $\Phi(x)$ is the standard normal CDF.

iii) When $\varphi_C(x)$ is a skew-normal PDF (53) the pricing function $P_C(\mu, \sigma)$ is given by:

$$P_C(\mu, \sigma) = \frac{\mu \hat{\sigma}_C^2 + \hat{\mu}_C \sigma^2}{\hat{\sigma}_C^2 + \sigma^2} + \frac{\hat{\sigma}_C^2 \sigma^2}{\hat{\sigma}_C^2 + \sigma^2} \frac{\text{sgn}(\alpha)}{\sqrt{\frac{\hat{\sigma}_C^2}{\alpha^2} + \frac{\hat{\sigma}_C^2 \sigma^2}{\hat{\sigma}_C^2 + \sigma^2}}} \hat{\Phi} \left(\frac{\hat{\sigma}_C^2}{\hat{\sigma}_C^2 + \sigma^2} \frac{\text{sgn}(\alpha)(\mu - \hat{\mu}_C)}{\sqrt{\frac{\hat{\sigma}_C^2}{\alpha^2} + \frac{\hat{\sigma}_C^2 \sigma^2}{\hat{\sigma}_C^2 + \sigma^2}}} \right), \quad (56)$$

where $\hat{\Phi}(x) = \exp(-0.5x^2) / (\sqrt{2\pi}\Phi(x))$, $\Phi(x)$ is the standard normal CDF, and $\text{sgn}(x) = x/|x|$ when $x \neq 0$ and $\text{sgn}(0) = 0$.

The pricing function (54) for the mixture of normals is derived in terms of elementary functions, and pricing functions (55) and (56) for the generalized gamma and the skew-normal distribution are in terms of the inverse Mills ratio $\hat{\Phi}(x) = \exp(-0.5x^2) / (\sqrt{2\pi}\Phi(x))$, widely employed in statistics. The pricing functions (54)–(56) then give rise to analytic complete-market price $P_{com}(s)$ in (44) of the asset with payoff C_1 , which is in terms of basic and widely used functions. Pricing functions also facilitate the computation of incomplete-market price $P_{inc}(s)$ in (44), which involves solving non-linear equation (46) numerically.

Panels (a), (b), and (c) of Figure 1 plot complete-market prices $P_{com}(s)$ when asset payoff C is drawn from distributions (51)–(53), respectively. Panels (a) and (b) show that non-normality of payoff C_1 makes asset prices non-linear functions of the sufficient statistic $s = h\varepsilon/(\gamma_I \sigma_0^2) + \nu_1$. In particular, panel (a.i) demonstrates that even a small change in s can lead to large price changes [see also Breon-Drish (2010)]. Therefore, more general distributions give rise to effects that are not captured by CARA-normal models, where prices are linear functions of s .

Panel (c) of Figure 1 plots price $P_{com}(s)$ for the standard normal distribution with zero skewness and the skew-normal distribution for which the distribution parameters are chosen in such a way that payoff C_1 has mean $\mu_C = 0$ and variance $\sigma_C^2 = 1$, as for the

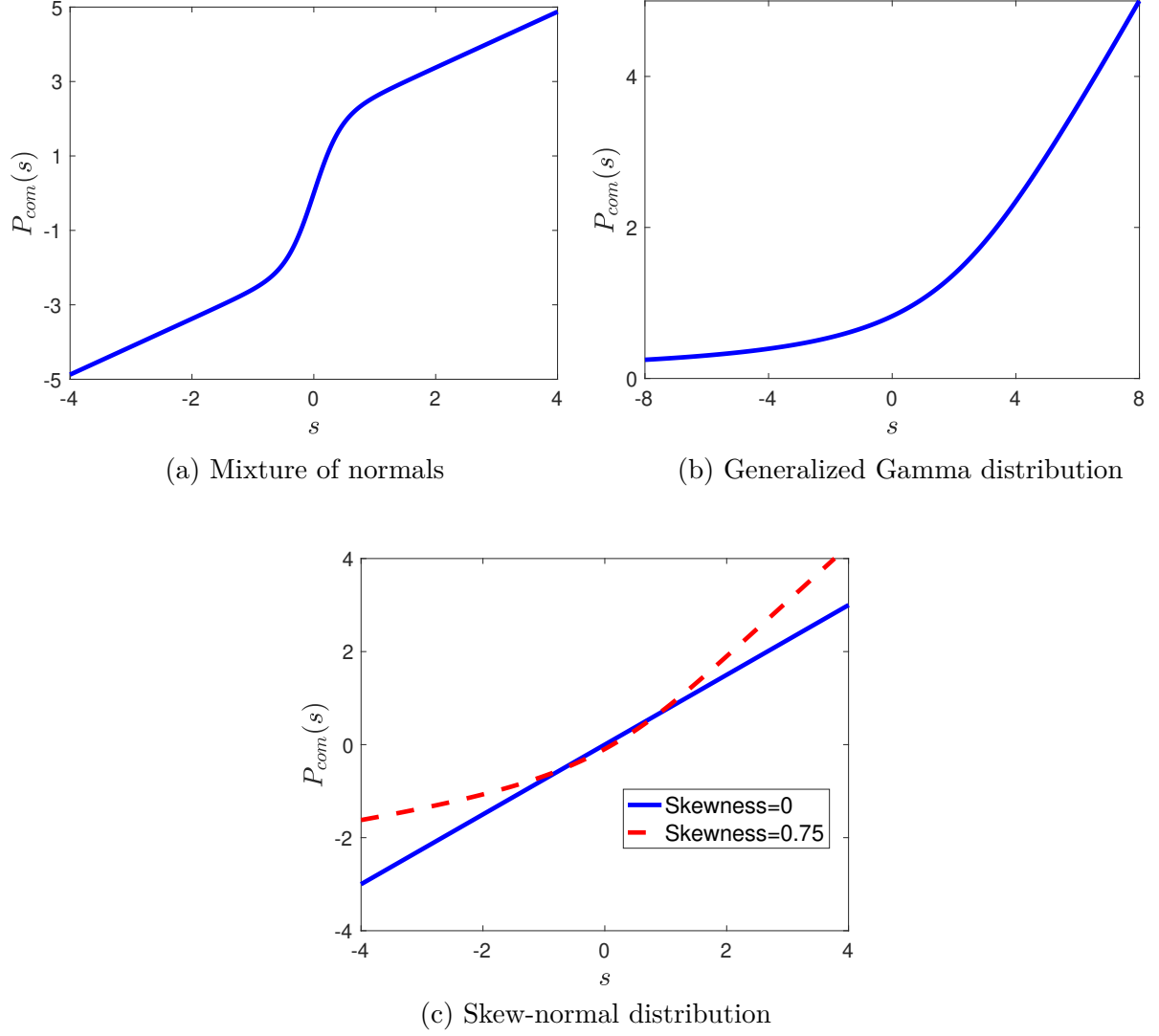


Figure 1: Asset prices in effectively complete markets.

Panels (a), (b), and (c) show the effectively complete market price $P_{com}(s)$ when payoff PDF $\varphi_C(x)$ is a mixture of normals (51), a generalized gamma (52), and a skew-normal (53), respectively. Panel (c) shows price $P_{com}(s)$ for the case of zero skewness (solid blue line) and positive skewness 0.75 (dashed red line). For panel (a) $\hat{\sigma}_{C,1} = \hat{\sigma}_{C,2} = 1$, $\hat{\mu}_{C,1} = -\hat{\mu}_{C,2} = 3$, $w_1 = w_2 = 0.5$; for panel (b) $\hat{\sigma}_C = 1$, $\delta = 2$, $k = 3$; for panel (c) $\mu_C = 0$, $\sigma_C^2 = 1$. The remaining parameters are: $\mu_0 = 0$, $\sigma_0 = 1$, $\sigma_\nu = 1$, $h = 0.5$, $\gamma_I = \gamma_U = 1$, $r = 0$, $T = 1$.

standard normal, but has skewness of 0.75.⁸ Equation (56) decomposes the pricing function $P_C(\mu, \sigma)$ for the skew-normal distribution (53) into two terms, where the first term is the

⁸The mean, variance, and skewness of a skew-normal random variable are given by $\mu_C = \hat{\mu}_C + \hat{\sigma}_C \sqrt{2/\pi} \hat{\alpha}$, $\sigma_C^2 = \hat{\sigma}_C^2 (1 - 2\hat{\alpha}^2/\pi)$, skew = $0.5(4 - \pi) (\hat{\alpha} \sqrt{2/\pi})^3 / (1 - \hat{\alpha}^2 2/\pi)^{3/2}$, respectively, where $\hat{\alpha} = \alpha / \sqrt{1 + \alpha^2}$ [e.g., Azzalini (1985)]. We calibrate the parameters so that $\mu_C = 0$, $\sigma_C = 1$, and skew = 0.75.

pricing function for a normally distributed payoff and the second term isolates the effect of skewness and shows that skewness is priced. The comparison of prices on panel (c) shows that skewness introduces non-linearity and convexity in asset prices and gives rise to higher prices than in the case of normally distributed payoffs when $|s|$ is large. These higher prices are in line with lower risk premia implied by equation (50).

4.4. Liquidity and Financial Innovation

In this Section, we study the effects of asymmetric information and financial innovation on market liquidity. We first define market illiquidity as the price impact of the noisy supply given by a Jacobian matrix $[\partial P/\partial \nu]$ with elements $\partial P_m/\partial \nu_l$, similar to the literature [e.g., Vayanos and Wang (2012), Cespa and Foucault (2014)]. We derive the price impacts in the effectively complete and incomplete markets in Proposition 9.

Proposition 9 (Price impacts). *The price impact matrices of the noise traders in the effectively complete and incomplete markets are given by:*

$$\left[\frac{\partial P_{com}}{\partial \nu} \right] = \frac{e^{-rT} \text{var}^{\text{RN}}[C](E + Q)}{h/\gamma_I + (1-h)/\gamma_U}, \quad (57)$$

$$\left[\frac{\partial P_{inc}}{\partial \nu} \right] = e^{-rT} \left(\frac{h}{\gamma_I} \text{var}^{\text{RN},I}[C]^{-1} + \frac{(1-h)}{\gamma_U} \text{var}^{\text{RN},U}[C]^{-1} \right)^{-1} (E + Q), \quad (58)$$

where matrix Q is given by equation (19).

Equation (57) demonstrates that the price impact of noise traders is proportional to the risk-neutral variance-covariance matrix $\text{var}^{\text{RN}}[C]$ when the market is effectively complete. For example, in a simple market with only two tradable assets C_1 and C_1^2 and no noise traders in the market for the quadratic derivative the first asset's illiquidity is proportional to $\text{var}^{\text{RN}}[C_1]$. For this asset, we define its liquidity as the reciprocal of illiquidity, given by $1/\text{var}^{\text{RN}}[C_1]$. The novelty of our analysis is that it links liquidity directly to the risk-neutral rather than physical variance as in the related literature [e.g., Vayanos and Wang (2012)]. The inverse relationship between liquidity and risk-neutral volatility is in line with empirical findings. In particular, Chung and Chuwonganant (2014) show that liquidity is negatively related to VIX, and Nagel (2012) shows that the returns of liquidity provision are high when VIX is high, which may lead to evaporation of liquidity.

The price impact of noise traders can be decomposed into substitution and learning effects, which correspond to terms $\text{var}^{\text{RN}}[C]$ and $\text{var}^{\text{RN}}[C]Q$ in equation (57), respectively. The first term shows that a demand shock ν_l to asset l affects prices of all assets correlated with asset l . This is because the change in the price of asset l leads to portfolio rebalancing

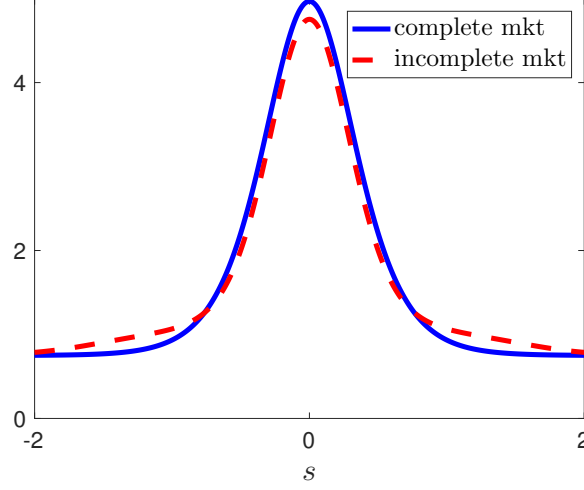


Figure 2: Price impact of noise traders when C_1 drawn from a mixture of normals. The Figure shows the noise traders' price impacts in the effectively complete and incomplete markets, $\partial P_{com}/\partial \nu$ and $\partial P_{inc}/\partial \nu$, as functions of the sufficient statistic s when cash flow C_1 PDF is a mixture of normals (51) with parameters $\hat{\sigma}_{C,1} = \hat{\sigma}_{C,2} = 1$, $\hat{\mu}_{C,1} = -\hat{\mu}_{C,2} = 3$, $w_1 = w_2 = 0.5$. The remaining parameters are: $\mu_0 = 0$, $\sigma_0 = 1$, $\sigma_\nu = 1$, $h = 0.5$, $\gamma_I = \gamma_U = 1$, $r = 0$, $T = 1$.

across all assets. For example, if shock ν_l is positive, the price of asset l increases, and hence, investors partially substitute asset l with asset m positively correlated with asset l . This substitution then increases the price of asset m .

The second term, $\text{var}^{\text{RN}}[C]Q$, arises due to the difficulty of disentangling the effects of noise ν and shock ε . If noisy demand ν_l increases the prices of some assets, such increases may be partially attributed to a positive shock ε . Hence, noisy demand ν_l affects the posterior distribution of ε , and through this distribution affects the prices of assets other than l . Thus, learning from prices generates contagions by spreading demand shocks across assets. The latter effect of learning is similar to the mechanism in Cespa and Foucault (2014) where investors learn information about an asset from the information about other assets, which may lead to liquidity crashes. Finally, we observe that matrix Q given by equation (19) has a hump-shaped coefficient proportional to $h(1-h)$. Consequently, the learning effect vanishes when investors have the same information (i.e., $h = 0$ or $h = 1$).

Next, we compute the price impacts in the economy of Section 4.3 where investors trade a single risky asset with cash flows C_1 and the informed investor receives a signal $\varepsilon = C_1 + u$, $u \sim N(\mu_0, \sigma_0^2)$. Investors can also complete the market by introducing a security with quadratic payoff C_1^2 . Figure 2 shows the price impacts of noise traders in the effectively complete and incomplete markets when the cash flow C_1 is drawn from a mixture of normal distributions (51). We observe that the effect of introducing a quadratic

derivative has an ambiguous effect on liquidity, which goes up or down depending on the sufficient statistic s . We attribute this ambiguity to two forces pushing liquidity in different direction. On one hand, as discussed in Section 4.2, introducing a quadratic derivative compensates the uninformed investor for the uncertainty in the market, and hence allows this investor to trade more in the risky asset. On the other hand, part of the trading volume shifts from the underlying to the quadratic derivative, which reduces trading and liquidity in the underlying asset. Finally, we observe that in a CARA-normal economy financial innovation does not affect the liquidity of the underlying asset because, as shown in Lemma 7, completing the CARA-normal economy does not affect the price of the underlying asset.

5. Extensions and Robustness

Noisy signals of shock ε . Our baseline model in Section 2.1 assumes that the informed investors observe the realization of economic shock ε . In reality, the informed investors may only observe a noisy signal about ε . We here extend our model to economies where the informed investor observes a signal given by $\hat{\varepsilon} = \varepsilon + z$, where $z \sim \mathcal{N}(0, \sigma_z^2)$. Lemma A.11 in the Appendix shows that the latter economy is equivalent to our baseline economy where the probabilities of states and the distribution of shock are given by

$$\pi_n(\hat{\varepsilon}) = \frac{e^{\hat{a}_n + \hat{b}_n \hat{\varepsilon}}}{\sum_{j=1}^N e^{\hat{a}_j + \hat{b}_j \hat{\varepsilon}}}, \quad \varphi_{\hat{\varepsilon}}(x) = \frac{\left(\sum_{j=1}^N e^{\hat{a}_j + \hat{b}_j x} \right) e^{-0.5(x - \mu_0)^2 / (\sigma_0^2 + \sigma_z^2)}}{\int_{-\infty}^{\infty} \left(\sum_{j=1}^N e^{\hat{a}_j + \hat{b}_j x} \right) e^{-0.5(x - \mu_0)^2 / (\sigma_0^2 + \sigma_z^2)} dx}, \quad (59)$$

where $\hat{a}_n = a_n + 0.5(b_n + \mu_0/\sigma_0^2)^2 / (1/\sigma_z^2 + 1/\sigma_0^2)$ and $\hat{b}_n = b_n / (1 + \sigma_z^2/\sigma_0^2)$. We observe that probabilities and the shock distribution in (59) have the same structure as in the baseline analysis. Moreover, the economic factor $\hat{b}$ is proportional to b . Therefore, all our results remain valid in this extended model.

Complete markets with general distributions. In Section IA2 of the Internet Appendix, we extend our no-arbitrage complete-market methodology to an economy with general probabilities of states $\pi_n(\varepsilon)$, distribution $\varphi_{\varepsilon}(x)$ of the aggregate shock, and distribution $\varphi_{\nu}(x)$ of noise trader demands. We obtain closed-form solutions in the general case. We also consider a special case where noise trader demand is drawn from a mixture of normal distributions (51). Using analytical expressions, we show that in the latter economy the asset price is a non-monotone function of the sufficient statistic and also identify a security which makes an incomplete market effectively complete.

Noisy endowments and financial innovation. In Section IA2 of the Internet Appendix, we extend our analysis to economies in which noise traders are replaced with

noisy endowments at the final date. These endowments prevent prices from fully revealing the shock ε that determines state probabilities $\pi_n(\varepsilon)$. The main advantage of this new setting is that it allows us to analyze the welfare effects of a financial innovation. Moreover, this setting also allows us to relax the informational spanning condition (28).

We assume that the state probabilities $\pi_n(\varepsilon)$ are given by equation (1) and that there are no noise traders in the economy. The informed investor receives state-dependent noisy income at date T , which is generated by claims to non-tradable assets, and is given by

$$e_{I,n} = \widetilde{W}_{0,I}(\alpha + \beta b_n + \eta), \quad (60)$$

where α is a constant, $\beta \sim \mathcal{N}(0, \sigma_\beta^2)$, $\eta \sim \mathcal{N}(0, \sigma_\eta^2)$, where variables β and η are uncorrelated with each other and with shock ε . The structure of endowments (60) is motivated by the CAPM and captures the endowment's exposure to the aggregate risk factor b . The exposure coefficient β (analogous to CAPM beta) is known to the informed investors but not to the uninformed investors. The endowment may represent a net asset or liability. Therefore, β can have either sign, and we model it as a normally distributed variable.

First, we show that a quadratic security with payoff b^2 effectively completes the market and the asset prices, derived in Proposition IA2.1 of the Internet Appendix, are analogous to those in our main analysis. Hence, our results on the effect of asymmetric information and the role of quadratic derivatives are robust to introducing noisy endowments. Second, in Proposition IA2.2 we derive equilibrium in an incomplete market and replace the informational spanning condition with a weaker condition $C = g(b)$, where $g(x)$ is a monotone function. We also compute investors' welfare and study the welfare effects of financial innovation that effectively completes the market.

Information aggregation with multiple types of investors. In Section IA3 of the Internet Appendix, we study an economy with K types of investors that have different risk aversions and each type receives a signal $e_i = \varepsilon + x_i$, where $x_i \sim \mathcal{N}(0, 1/\tau_i)$, and τ_i is the signal precision. The investors maximize their expected CARA utility conditional on observing asset prices p and the private signal e_i .

We conjecture and verify that investors' optimal portfolios are separable in prices p and signals e_i , and can be decomposed as $\theta_i^*(p; e_i) = \theta_{1,i}(p) + \lambda \kappa_i e_i$. We show that asset prices in this setting are functions of the sufficient statistic given by $\widehat{s} = \lambda \sum_{i=1}^k k_i e_i + \lambda$, where constants k_i solve a system of non-linear equation. We show that this system of equations has at least one solution, and exactly one solution in the symmetric equilibrium where investors' risk aversions γ_i and signal precisions τ_i are exactly the same.

Similar to our baseline setting, we show that the quadratic derivative makes the finan-

cial market effectively complete. Moreover, asset prices in the latter market are available in closed form and have similar structure to asset prices in our baseline setting. When the market is incomplete, asset prices can be characterized in terms of inverse functions, similar to Proposition 3 in our baseline analysis.

Multidimensional shock ε . In Section IA4 of the Internet Appendix, we generalize our model to incorporate multidimensional shocks $\varepsilon \in \mathbb{R}^K$. We consider an economy where the probabilities of states $\pi_n(\varepsilon)$ and the prior PDF of shock ε are given by

$$\pi_n(\varepsilon) = \frac{e^{a_n + b_n^\top \varepsilon}}{\sum_{j=1}^N e^{a_j + b_j^\top \varepsilon}}, \quad n = 1, \dots, N,$$

$$\varphi_\varepsilon(x) = \frac{\left(\sum_{j=1}^N e^{a_j + b_j^\top x} \right) e^{-0.5(x - \mu_0)^\top \Sigma_0^{-1}(x - \mu_0)}}{\int_{\mathbb{R}^K} \left(\sum_{j=1}^N e^{a_j + b_j^\top x} \right) e^{-0.5(x - \mu_0)^\top \Sigma_0^{-1}(x - \mu_0)} dx},$$

where $\varepsilon, b_n, \mu_0 \in \mathbb{R}^K$, and $\Sigma_0 \in \mathbb{R}^{K \times K}$ is a positive-definite matrix. When the market is complete, we show that the risk-neutral probabilities, asset prices, and investor portfolios have the same structure as in our baseline analysis in Section 3, with the main difference that the replicating portfolio λ is replaced by a matrix Λ .

Similar to the baseline setting, we impose the informational spanning condition when the market is incomplete. This condition guarantees the existence of K tradable portfolios that replicate the aggregate risk factor b , and is given by

$$b_n^\top = \Lambda_0 + C(\omega_n)^\top \Lambda, \quad (61)$$

where $\Lambda_0 \in \mathbb{R}^K$ and $\Lambda \in \mathbb{R}^{(M-1) \times K}$.

We show that despite the multidimensionality of shock ε only one security is needed to effectively complete the market. The payoffs of this security are quadratic forms of the risk factor realizations $b_n \in \mathbb{R}^K$ and are given by $b_n^\top (h^2 \Lambda^\top \Sigma_\nu^{-1} \Lambda / \gamma_I^2 + \Sigma_0^{-1})^{-1} b_n$, where Λ is the matrix of replicating portfolios such that condition (61) is satisfied. In the economy with a scalar shock ($K = 1$) the latter payoff reduces to a quadratic derivative $b_n^2 / (h^2 \lambda^\top \Sigma_\nu^{-1} \lambda + 1/\sigma_0^2)$, as in Section 4.2.

6. Conclusion

We develop a tractable REE model with multiple risky assets with realistic payoff structures. Our model provides a tractable setting for studying the effects of information aggregation on asset prices where prices and portfolios are available in closed form. We

derive a three-factor CAPM with asymmetric information, which provides a bridge between standard risk-based models of asset pricing and models with asymmetric information.

Our results yield necessary and sufficient conditions under which the informed demands for derivative securities reveal information about the underlying asset. Absent any additional frictions other than the asymmetry of information, these conditions imply the irrelevance of the face value of debt for the total amount of information revealed by the debt and equity of a firm. The conditions for the irrelevance of the capital structure also help identify situations in which the capital structure is not informationally redundant. In particular, we show that the irrelevance of capital structure breaks down in the presence of bankruptcy costs. Our analysis also uncovers an important role of volatility derivatives. These derivatives make incomplete markets effectively complete, and their prices quantify market illiquidity and the shadow value of information for uninformed investors.

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Appendix: Proofs

Lemma A.1 (Prior mean and prior variance of ε and prior probabilities). *Let ε have PDF (2). Then, its mean μ_ε and variance σ_ε^2 in terms of (μ_0, σ_0^2) are given by:*

$$\mu_\varepsilon = \frac{\sum_{j=1}^N \exp\left(a_j + \frac{\mu_j^2}{2\sigma_0^2}\right) \mu_j}{\sum_{j=1}^N \exp\left(a_j + \frac{\mu_j^2}{2\sigma_0^2}\right)}, \quad (\text{A.1})$$

$$\sigma_\varepsilon^2 = \sigma_0^2 + \left[\frac{\sum_{j=1}^N \exp\left(a_j + \frac{\mu_j^2}{2\sigma_0^2}\right) \mu_j^2}{\sum_{j=1}^N \exp\left(a_j + \frac{\mu_j^2}{2\sigma_0^2}\right)} - \frac{\left(\sum_{j=1}^N \exp\left(a_j + \frac{\mu_j^2}{2\sigma_0^2}\right) \mu_j\right)^2}{\left(\sum_{j=1}^N \exp\left(a_j + \frac{\mu_j^2}{2\sigma_0^2}\right)\right)^2} \right], \quad (\text{A.2})$$

where $\mu_j = b_j \sigma_0^2 + \mu_0$.

Proof of Lemma A.1. We compute $\mu_\varepsilon = \mathbb{E}[\varepsilon]$ and $\sigma_\varepsilon^2 = \text{var}[\varepsilon]$ with PDF $\varphi_\varepsilon(x)$ given by (2), and after straightforward integration, we obtain equations (A.1) and (A.2). ■

Lemma A.2 (Special Cases). *Let payoff C_1 have general unconditional continuous PDF $\varphi_C(x)$. Suppose, the informed investor receives signal $\varepsilon = C_1 + u$, where $u \sim \mathcal{N}(\mu_0, \sigma_0^2)$. Then, the latter economy is a limiting case (when $N \rightarrow \infty$) of our N -state economy with $C_1(\omega_n) = \underline{C}_N + (\overline{C}_N - \underline{C}_N)(n-1)/(N-1)$ and distribution parameters*

$$a_n = -\frac{C_1(\omega_n)^2}{2\sigma_0^2} - \frac{\mu_0 C_1(\omega_n)}{\sigma_0^2} + \ln[\varphi_C(C_1(\omega_n))], \quad b_n = \frac{C_1(\omega_n)}{\sigma_0^2}, \quad (\text{A.3})$$

when $N \rightarrow \infty$ and $\underline{C}_N$ and $\overline{C}_N$ converge to lower and upper limits of payoff C_1 .

Proof of Lemma A.2. Consider a discretized economy with one risky asset with payoff $C_1(\omega_n) = \underline{C}_N + (\overline{C}_N - \underline{C}_N)(n-1)/(N-1)$, where $n = 1, \dots, N$, and let the informed investor receive signal $\varepsilon = C_1(\omega) + u$, where $u \sim \mathcal{N}(\mu_0, \sigma_0^2)$. The unconditional probabilities of $C_1(\omega_n)$ are given by $\text{Prob}(C_1(\omega_n)) = \varphi_C(C_1(\omega_n)) / \left(\sum_{n=1}^N \varphi_C(C_1(\omega_n))\right)$. The original continuous-space economy is a limiting case of the latter economy because as $N \rightarrow \infty$, the distributions $\text{Prob}(C_1(\omega) \leq x)$ and $\text{Prob}(C_1(\omega) \leq x | \varepsilon)$ converge pointwise to the respective continuous-space distributions. We show that the latter discretized economy is a special case of ours when parameters a_n and b_n are given by equations (A.3) by verifying that in our economy $\text{Prob}(C_1(\omega_n)) = \varphi_C(C_1(\omega_n)) / \left(\sum_{n=1}^N \varphi_C(C_1(\omega_n))\right)$ and $\varepsilon = C_1(\omega) + u$.

Consider the unconditional probability $\text{Prob}(C_1(\omega_n))$ in the model of Section 2:

$$\text{Prob}(C_1(\omega_n)) = \int_{-\infty}^{\infty} \pi_n(x) \varphi_\varepsilon(x) dx = \frac{1}{\Lambda} \int_{-\infty}^{\infty} e^{a_n + b_n x - 0.5(x - \mu_0)^2 / \sigma_0^2} dx = \frac{1}{\Lambda} e^{a_n + 0.5(\mu_0 + b_n \sigma_0^2)^2 / \sigma_0^2},$$

where Λ and $\tilde{\Lambda}$ are constants. Substituting a_n and b_n from equations (A.3) into the above equation, after some algebra, we verify that $\text{Prob}(C_1(\omega_n)) = \varphi_C(C_1(\omega_n)) / \sum_{n=1}^N \varphi_C(C_1(\omega_n))$.

Next, we verify that $\varepsilon = C_1(\omega) + u$, where $u \sim \mathcal{N}(\mu_0, \sigma_0^2)$. Substituting a_n and b_n from (A.3) into equation (2) for PDF $\varphi_\varepsilon(x)$, after some algebra, we obtain:

$$\varphi_\varepsilon(x) = \frac{\sum_{n=1}^N e^{-0.5(x - C_1(\omega_n) - \mu_0)^2 / \sigma_0^2} \varphi_C(C_1(\omega_n))}{\int_{-\infty}^{\infty} \left(\sum_{n=1}^N e^{-0.5(x - C_1(\omega_n) - \mu_0)^2 / \sigma_0^2} \varphi_C(C_1(\omega_n)) \right) dx}.$$

The above PDF is the convolution of the unconditional distributions of $C_1(\omega)$ and a normal distribution $\mathcal{N}(\mu_0, \sigma_0^2)$, and hence is the PDF of $\varepsilon = C_1(\omega) + u$, where $u \sim \mathcal{N}(\mu_0, \sigma_0^2)$. ■

Proof of Lemma 1. Taking log on both sides of investor I 's FOC (10), and substituting wealth $W_{I,T,n}$ from the budget constraint (5), we obtain:

$$(\theta_I^*)^\top (C(\omega_n) - e^{rT} p) = \frac{1}{\gamma_I} \left(\ln(\pi_n(\varepsilon)) - \ln(\pi_n^{\text{RN}}) \right) + \text{const}, \quad n = 1, \dots, N, \quad (\text{A.4})$$

where const is a constant. Subtracting equation (A.4) for $n = N$ from the other equations in (A.4), we obtain a system of $N - 1$ equations with $N - 1$ unknown components of θ_I^* :

$$(\theta_I^*)^\top (C(\omega_n) - C(\omega_N)) = \frac{1}{\gamma_I} \left(\ln \left(\frac{\pi_n(\varepsilon)}{\pi_N(\varepsilon)} \right) - \ln \left(\frac{\pi_n^{\text{RN}}}{\pi_N^{\text{RN}}} \right) \right), \quad n = 1, \dots, N - 1, \quad (\text{A.5})$$

Solving the system of equations (A.5), we obtain investor I 's optimal portfolio

$$\theta_I^*(p; \varepsilon) = \frac{\Omega^{-1}}{\gamma_I} \left\{ \left(\ln \left(\frac{\pi_1(\varepsilon)}{\pi_N(\varepsilon)} \right), \dots, \ln \left(\frac{\pi_{N-1}(\varepsilon)}{\pi_N(\varepsilon)} \right) \right) - \left(\ln \left(\frac{\pi_1^{\text{RN}}}{\pi_N^{\text{RN}}} \right), \dots, \ln \left(\frac{\pi_{N-1}^{\text{RN}}}{\pi_N^{\text{RN}}} \right) \right) \right\}^\top. \quad (\text{A.6})$$

Finally, substituting $\pi_n(\varepsilon)$ from (1) into the above equation, we obtain portfolio (11). ■

Proof of Lemma 2. Let $s \equiv h\lambda\varepsilon/\gamma_I + \nu$ denote the sufficient statistic. From Bayes rule, the PDF of ε conditional on s is given by:

$$\varphi_{\varepsilon|s}(x|y) = \frac{\varphi_{s|\varepsilon}(y|x) \varphi_\varepsilon(x)}{\int_{-\infty}^{\infty} \varphi_{s|\varepsilon}(y|x) \varphi_\varepsilon(x) dx}. \quad (\text{A.7})$$

Because $\nu \sim \mathcal{N}(0, \Sigma_\nu)$, $s = h\lambda\varepsilon/\gamma_I + \nu$ conditional on ε has a multivariate normal distribution $\mathcal{N}(h\lambda\varepsilon/\gamma_I, \Sigma_\nu)$. Hence, substituting $\varphi_{s|\varepsilon}(y|x)$ into equation (A.7), we have

$$\varphi_{\varepsilon|s}(x|y) = \frac{\exp\left\{-0.5\left(y - h\lambda x/\gamma_I\right)^\top \Sigma_\nu^{-1}\left(y - h\lambda x/\gamma_I\right)\right\} \varphi_\varepsilon(x)}{G_1(y)}, \quad (\text{A.8})$$

where $G_1(y)$ normalizes the density. Next, to find probability $\pi_n^U(p)$, from the market clearing condition (13), we note that in equilibrium $s = -H(p)$. We focus on equilibrium where prices only reveal the sufficient statistic s . Hence, $\pi_n^U(p) = \mathbb{E}[\pi_n(\varepsilon)|P(\varepsilon, \nu) = p] = \mathbb{E}[\pi_n(\varepsilon)|s = -H(p)]$. Calculating the last conditional expectation, we obtain:

$$\begin{aligned}\pi_n^U(p) &= \mathbb{E}[\pi_n(\varepsilon)|s = -H(p)] \\ &= \int_{-\infty}^{\infty} \frac{e^{a_n + b_n x}}{\sum_{j=1}^N e^{a_j + b_j x}} \varphi_{\varepsilon|s}(x| -H(p)) dx = \frac{1}{G_1(y)} \int_{-\infty}^{\infty} e^{d_n(x)} dx,\end{aligned}\quad (\text{A.9})$$

where $d_n(x)$ is a quadratic function of x given by:

$$\begin{aligned}d_n(x) &= a_n + b_n x - 0.5 \left(h\lambda x / \gamma_I + H(p) \right)^\top \Sigma_\nu^{-1} \left(h\lambda x / \gamma_I + H(p) \right) - 0.5(x - \mu_0)^2 / \sigma_0^2 \\ &= - \frac{h^2(\lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2) + 1/\sigma_0^2}{2} \left(x - \frac{\mu_0/\sigma_0^2 + b_n - h\lambda^\top \Sigma_\nu^{-1} H(p) / \gamma_I}{h^2(\lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2) + 1/\sigma_0^2} \right)^2 \\ &\quad + a_n + \frac{1}{2} \frac{b_n^2 + 2b_n(\mu_0/\sigma_0^2 - h\lambda^\top \Sigma_\nu^{-1} H(p) / \gamma_I)}{h^2(\lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2) + 1/\sigma_0^2} + g(p),\end{aligned}\quad (\text{A.10})$$

where $g(p)$ is a normalizing function. Substituting $d_n(x)$ from equation (A.10) into integral (A.9) and integrating, we obtain equation (15) for $\pi_n^U(p)$. ■

Proof of Proposition 1. First, we find the optimal portfolios of investors, and then recover the equilibrium prices from the market clearing condition. The portfolio of investor I is given by equation (11) in Lemma 1. To find investor U 's portfolio $\theta_U^*(p)$, we follow similar steps as in Lemma 1: 1) take the log of both sides of investor U 's FOC (10); 2) subtract the N^{th} equation from the rest; 3) solve the $N - 1$ equations for the $N - 1$ positions of U 's portfolio. This gives $\theta_U^*(p)$ in terms of investor U 's probabilities $\pi_n^U(p)$

$$\theta_U^*(p) = \frac{1}{\gamma_U} \Omega^{-1} \left\{ \left(\ln \left(\frac{\pi_1^U(p)}{\pi_N^U(p)} \right), \dots, \ln \left(\frac{\pi_{N-1}^U(p)}{\pi_N^U(p)} \right) \right)^\top - \tilde{v}(p) \right\}, \quad (\text{A.11})$$

where $\tilde{v}$ is given by equation (12). Substituting $\pi_n^U(p)$ from (15) into (A.11) we obtain:

$$\theta_U^*(p) = \frac{1}{\gamma_U} \Omega^{-1} \left\{ \tilde{a} + \frac{1}{2} \frac{\tilde{b}^{(2)} - 2\tilde{b}(h\lambda^\top \Sigma_\nu^{-1} H(p) / \gamma_I - \mu_0/\sigma_0^2)}{h^2\lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2 + 1/\sigma_0^2} - \tilde{v}(p) \right\}, \quad (\text{A.12})$$

where vectors $\tilde{a}, \tilde{b}, \tilde{b}^{(2)} \in \mathbb{R}^{N-1}$ are given by:

$$\tilde{a} = (a_1 - a_N, \dots, a_{N-1} - a_N), \quad \tilde{b} = (b_1 - b_N, \dots, b_{N-1} - b_N), \quad (\text{A.13})$$

$$\tilde{b}^{(2)} = (b_1^2 - b_N^2, \dots, b_{N-1}^2 - b_N^2). \quad (\text{A.14})$$

Substituting $\lambda = \Omega^{-1}\tilde{b}$ and $H(p) = (1-h)\theta_u^* - h\Omega^{-1}(\tilde{v} - \tilde{a})/\gamma_I$ from (14) into (A.12), we obtain:

$$\begin{aligned}\theta_u^*(p) &= \frac{\Omega^{-1}(\tilde{a} - \tilde{v}(p))}{\gamma_u} + \frac{\mu_0/(\gamma_u\sigma_0^2)\lambda}{h^2\lambda^\top\Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2} - QH(p), \\ &= \frac{hQ\Omega^{-1}(\tilde{v}(p) - \tilde{a})}{(1-h)\gamma_I} - \frac{\Omega^{-1}(\tilde{v}(p) - \tilde{a})}{\gamma_u} + \frac{\mu_0/(\gamma_u\sigma_0^2)\lambda}{h^2\lambda^\top\Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2} - Q\theta_u^*(p),\end{aligned}\quad (\text{A.15})$$

where $\tilde{a}$ and matrix Q are given by:

$$\tilde{a} = \tilde{a} + \frac{0.5\tilde{b}^{(2)}}{h^2\lambda^\top\Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2}, \quad Q = \frac{h(1-h)}{\gamma_u\gamma_I} \frac{\lambda\lambda^\top\Sigma_\nu^{-1}}{h^2\lambda^\top\Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2}. \quad (\text{A.16})$$

Solving linear equation (A.15) for portfolio $\theta_u^*(p)$, we obtain portfolio $\theta_u^*(p)$ in (20).

Next, we find the equilibrium prices. Substituting optimal portfolios $\theta_I^*(p; \varepsilon)$ and $\theta_u^*(p)$ from equations (11) and (20) into the market clearing condition $h\theta_I^*(p; \varepsilon) + (1-h)\theta_u^*(p) + \nu = 0$, after rearranging terms, we obtain the following equation for vector $\tilde{v}(p)$:

$$\begin{aligned}(E + Q)^{-1} \left(\frac{hQ\Omega^{-1}(\tilde{v}(p) - \tilde{a})}{\gamma_I} - \frac{(1-h)\Omega^{-1}(\tilde{v}(p) - \tilde{a})}{\gamma_u} + \frac{(1-h)\mu_0/(\gamma_u\sigma_0^2)\lambda}{h^2\lambda^\top\Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2} \right) \\ - \frac{h\Omega^{-1}(\tilde{v}(p) - \tilde{a})}{\gamma_I} + \frac{h\lambda\varepsilon}{\gamma_I} + \nu = 0.\end{aligned}\quad (\text{A.17})$$

The above equation can be further simplified by noting that

$$\begin{aligned}(E + Q)^{-1} \frac{1}{\gamma_I} Q\Omega^{-1}(\tilde{v}(p) - \tilde{a}) &= (E + Q)^{-1}(E + Q - E) \frac{1}{\gamma_I} \Omega^{-1}(\tilde{v}(p) - \tilde{a}) \\ &= \frac{1}{\gamma_I} \Omega^{-1}(\tilde{v}(p) - \tilde{a}) - (E + Q)^{-1} \frac{1}{\gamma_I} \Omega^{-1}(\tilde{v}(p) - \tilde{a}).\end{aligned}$$

Substituting the latter expression into equation (A.17), canceling like terms, substituting $\tilde{a}$ from equation (A.16) into equation (A.17), and solving it for $\tilde{v}(p) - \tilde{a}$ we obtain

$$\tilde{v}(p) = \tilde{a} + \frac{1}{2} \frac{(1-h)/\gamma_u}{h/\gamma_I + (1-h)/\gamma_u} \frac{\tilde{b}^{(2)} + 2(\mu_0/\sigma_0^2)\tilde{b}}{h^2\lambda^\top\Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2} + \frac{\Omega(E + Q)s}{h/\gamma_I + (1-h)/\gamma_u}, \quad (\text{A.18})$$

where $\tilde{a}$, $\tilde{b}$, and $\tilde{b}^{(2)}$ are given by (A.13) and (A.14), or element-wise for $n = 1, \dots, N-1$:

$$\tilde{v}_n = a_n - a_N + \frac{1}{2} \frac{(1-h)/\gamma_u}{h/\gamma_I + (1-h)/\gamma_u} \frac{(b_n^2 - b_N^2) + 2(\mu_0/\sigma_0^2)(b_n - b_N)}{h^2\lambda^\top\Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2} + \frac{(C(\omega_n) - C(\omega_N))^\top (E + Q)s}{h/\gamma_I + (1-h)/\gamma_u}.$$

Let v_n be given by equation (18). Then, vector $\tilde{v}(p) \in \mathbb{R}^{N-1}$ has elements $v_n - v_N$. From the definition of vector $\tilde{v}$ in equation (12), we find that $\pi_n^{\text{RN}} = e^{v_n - v_N} / \left(\sum_{j=1}^N e^{v_j - v_N} \right)$ for $n = 1, \dots, N$. Canceling e^{-v_N} , we obtain probabilities (17).

Finally, we show that $P(\varepsilon, \nu)$ is an invertible on its range function of $s = h\lambda\varepsilon/\gamma_I + \nu$, and hence, observing prices reveals unique s . First, because the risk-neutral probabilities are unique, there is a one-to-one mapping between these probabilities and prices. From equation (12) we observe that there is an one-to-one mapping between $\tilde{v}$ and the vector of risk-neutral probabilities. Finally, from equation (A.18) there is an one-to-one mapping between $\tilde{v}$ and s , which, by transitivity, completes the proof. ■

Proof of Proposition 2. We now find the derivatives of portfolios θ_i^* with respect to prices p . Substituting $\pi_N^{\text{RN}} = 1 - \pi_1^{\text{RN}} - \dots - \pi_{N-1}^{\text{RN}}$ into the risk-neutral valuation equation (8), we obtain:

$$p_m = \left[\pi_1^{\text{RN}} (C_m(\omega_1) - C_m(\omega_N)) + \dots + \pi_{N-1}^{\text{RN}} (C_m(\omega_{N-1}) - C_m(\omega_N)) + C_m(\omega_N) \right] e^{-rT}, \quad (\text{A.19})$$

where $m = 1, \dots, N-1$. From the definition of vector $\tilde{v}$ in (12) we observe that $\pi_n^{\text{RN}} = e^{\tilde{v}_n} / (1 + \sum_{n=1}^{N-1} e^{\tilde{v}_n})$. First, we need to compute $\partial \tilde{v} / \partial p$. To do this, we find the Jacobian $J_p = \partial p / \partial \tilde{v}$ and then by the inverse function theorem we have $\partial \tilde{v} / \partial p = J_p^{-1}$. Let J_π be the Jacobian of vector $(\pi_1^{\text{RN}}, \dots, \pi_{N-1}^{\text{RN}})^\top$, that is, a matrix with (n, k) element given by $\partial \pi_n^{\text{RN}} / \partial \tilde{v}_k$. Differentiating equation (A.19) we find that $J_p = \Omega^\top J_\pi e^{-rT}$, and hence

$$J_p \Omega e^{rT} = \Omega^\top J_\pi \Omega. \quad (\text{A.20})$$

To find J_π we first calculate $\partial \pi_n^{\text{RN}} / \partial \tilde{v}_k$, where π_n^{RN} is given by equation (17):

$$\frac{\partial \pi_n^{\text{RN}}}{\partial \tilde{v}_k} = \frac{\partial \pi_n^{\text{RN}}}{\partial v_k} = \begin{cases} -\pi_n^{\text{RN}} \pi_k^{\text{RN}}, & \text{if } n \neq k, \\ \pi_n^{\text{RN}} - (\pi_n^{\text{RN}})^2, & \text{if } n = k. \end{cases} \quad (\text{A.21})$$

for $n, k = 1, \dots, N-1$, where the first equality follows from $\tilde{v}_k = v_k - v_N$. From equation (A.21) we find $J_\pi = \text{diag}\{\pi_1^{\text{RN}}, \dots, \pi_{N-1}^{\text{RN}}\} - (\pi_1^{\text{RN}}, \dots, \pi_{N-1}^{\text{RN}})^\top (\pi_1^{\text{RN}}, \dots, \pi_{N-1}^{\text{RN}})$, where $\text{diag}\{\dots\}$ is a diagonal matrix. Substituting J_π into equation (A.20) we obtain:

$$J_p \Omega e^{rT} = \Omega^\top \left(\text{diag}\{\pi_1^{\text{RN}}, \dots, \pi_{N-1}^{\text{RN}}\} - (\pi_1^{\text{RN}}, \dots, \pi_{N-1}^{\text{RN}})^\top (\pi_1^{\text{RN}}, \dots, \pi_{N-1}^{\text{RN}}) \right) \Omega. \quad (\text{A.22})$$

Recalling that Ω is a matrix with rows $(C(\omega_n) - C(\omega_N))^\top$, and denoting $\tilde{C}_n = (C_n(\omega_1) - C_n(\omega_N), \dots, C_n(\omega_{N-1}) - C_n(\omega_N))^\top$, we find that the (n, k) element of matrix $J_p \Omega e^{rT}$ is:

$$\begin{aligned} \{J_p \Omega e^{rT}\}_{n,k} &= \tilde{C}_n^\top \text{diag}\{\pi_1^{\text{RN}}, \dots, \pi_{N-1}^{\text{RN}}\} \tilde{C}_k - \tilde{C}_n^\top (\pi_1^{\text{RN}}, \dots, \pi_{N-1}^{\text{RN}})^\top (\pi_1^{\text{RN}}, \dots, \pi_{N-1}^{\text{RN}}) \tilde{C}_k \\ &= \sum_{i=1}^N (C_n(\omega_i) - C_n(\omega_N)) (C_k(\omega_i) - C_k(\omega_N)) \pi_i^{\text{RN}} \\ &\quad - \left(\sum_{i=1}^N (C_n(\omega_i) - C_n(\omega_N)) \pi_i^{\text{RN}} \right) \left(\sum_{i=1}^N (C_k(\omega_i) - C_k(\omega_N)) \pi_i^{\text{RN}} \right) \\ &= \text{cov}^{\text{RN}}(C_n, C_k), \end{aligned}$$

where to derive the second equality we added zero terms $(C_n(\omega_N) - C_n(\omega_N))(C_k(\omega_N) - C_k(\omega_N))\pi_N^{\text{RN}}$, $(C_n(\omega_N) - C_n(\omega_N))\pi_N^{\text{RN}}$ and $(C_k(\omega_N) - C_k(\omega_N))\pi_N^{\text{RN}}$ to summations, and then removed constants $C_n(\omega_N)$ and $C_k(\omega_N)$, because they do not affect covariances.

Therefore, we conclude that $J_p \Omega e^{rT} = \text{var}^{\text{RN}}[C]$. Then, by the inverse function theorem, we now find that $\Omega^{-1} \partial \tilde{v} / \partial p = (\text{var}^{\text{RN}}[C])^{-1} e^{rT}$. Using the latter equality and differentiating optimal portfolios (11) and (20) with respect to p we obtain that the first of these two partial derivatives is given by equation (21) and the second is given by:

$$\frac{\partial \theta_U^*(p)}{\partial p} = \frac{1}{1-h} \left(\frac{h}{\gamma_I} E - \left(\frac{h}{\gamma_I} + \frac{1-h}{\gamma_U} \right) (E+Q)^{-1} \right) (\text{var}^{\text{RN}}[C])^{-1} e^{rT}. \quad (\text{A.23})$$

We note the following equation for the inverse matrix $(E+Q)^{-1}$:

$$(E+Q)^{-1} = E - \frac{h\lambda\lambda^\top \Sigma_\nu^{-1}}{\gamma_U \gamma_I (h^2 \lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2 + 1/\sigma_0^2) + h(1-h)\lambda^\top \Sigma_\nu^{-1} \lambda},$$

which can be verified by multiplying both sides of the latter equation by $E+Q$. Substituting $(E+Q)^{-1}$ above into equation (A.23), we obtain equation (22) for $\partial \theta_U^*(p) / \partial p^\top$.

Finally, we demonstrate that $\theta_{I,m}^*(p; \varepsilon)$ is downward sloping in p_m . This result follows from the fact that matrix $(\text{var}^{\text{RN}}[C])^{-1}$ is positive-definite (as the inverse of a positive-definite matrix), and its element m of the diagonal is given by $e_m^\top (\text{var}^{\text{RN}}[C])^{-1} e_m > 0$, where $e_m = (0, 0, \dots, 1, \dots, 0)^\top$ is a vector with m^{th} element equal to 1 and other elements equal to zero. Then, from equation (21) it follows that $\partial \theta_{I,m}^*(p; \varepsilon) / \partial p_m < 0$. ■

Proof of Corollary 1. Let $m = \pi^{\text{RN}} / \pi^U e^{-rT}$. Then, equation (23) follows from equation (1.12) in Cochrane (2005, p. 14), and equation (24) is derived analogously to equation (6.4) in Cochrane (2005, p. 102) in the proof of a theorem in Cochrane (2005, p. 101). ■

Proof of Corollary 2. From equations (17) and (15) for the probabilities π^{RN} and π^U , we obtain

$$\frac{\pi_n^{\text{RN}}}{\pi_n^U} = G(s) \exp \left\{ -\frac{1}{2} \frac{h/\gamma_I}{(1-h)/\gamma_U + h/\gamma_I} \frac{b_n^2 + 2b_n(\mu_0/\sigma_0 + h\lambda^\top \Sigma_\nu^{-1} s/\gamma_I)}{h^2 \lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2 + 1/\sigma_0^2} + \frac{C(\omega_n)^\top s}{(1-h)/\gamma_U + h/\gamma_I} \right\}, \quad (\text{A.24})$$

where $G(s)$ does not depend on state ω . Next, we express s in terms of $\mathbb{E}[\nu|s]$. We note that $\mathbb{E}[\nu|s] = \mathbb{E}[s - h\lambda\varepsilon/\gamma_I|s]$. Then, using equation (A.49) for $\mathbb{E}[\varepsilon|s]$, we obtain

$$s = \mathbb{E}[\nu|s] + \frac{h\lambda \mu_0/\sigma_0^2 + \mathbb{E}^U[b_n] + h\lambda^\top \Sigma_\nu^{-1} s/\gamma_I}{\gamma_I (h^2 (\lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2) + 1/\sigma_0^2)}. \quad (\text{A.25})$$

Substituting s from the above equation into equation (A.24) and then using the informa-

tional spanning condition $b_n = \lambda_0 + C(\omega_n)^\top \lambda$, we obtain:

$$\frac{\pi_n^{\text{RN}}}{\pi_n^U} = g_0(s) \exp \left\{ -\frac{1}{2} \frac{h/\gamma_I}{(1-h)/\gamma_U + h/\gamma_I} \frac{b_n^2 - 2b_n \mathbb{E}^U[b]}{h^2 \lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2 + 1/\sigma_0^2} + \frac{C(\omega_n)^\top \mathbb{E}[\nu|s]}{(1-h)/\gamma_U + h/\gamma_I} \right\}. \quad (\text{A.26})$$

Assuming that either γ_I or γ_U is small, and using approximation $e^x \approx 1 + x$ for small x , from the above equation we obtain equation (25). Three-factor model (26) and the interpretations of β_{ki} follow from the theorem in Cochrane (2005, p. 107). The expressions for the risk premia Λ_i are given in Cochrane (2005, p. 108). ■

Proof of Lemma 3. The price of an Arrow-Debreu security is given by $\mathbb{E}^{\text{RN}}[1_{\{\omega=\omega_n\}}]e^{-rT} = \pi_n^{\text{RN}}e^{-rT}$. Hence, the return is given by $\mathbb{E}^U[1_{\{\omega=\omega_n\}}]/(\pi_n^{\text{RN}}e^{-rT}) = \pi_n^U/\pi_n^{\text{RN}}e^{rT}$. Equation (27) follows, after some algebra, from equation (A.26). Differentiating (27) w.r.t. t , we obtain:

$$\begin{aligned} \frac{\partial \mathbb{E}^U[R_n]}{\partial t} &= (b_n - \mathbb{E}^U[b])^2 \mathbb{E}^U[R_n] - \mathbb{E}^U[R_n] \mathbb{E}^{\text{RN}}[(b - \mathbb{E}^U[b])^2 \frac{\pi^U}{\pi^{\text{RN}}}] \\ &= (b_n - \mathbb{E}^U[b])^2 \mathbb{E}^U[R_n] - \mathbb{E}^U[R_n] \mathbb{E}^U[(b - \mathbb{E}^U[b])^2] \\ &= [(b_n - \mathbb{E}^U[b])^2 - \text{var}^U[b]] \mathbb{E}^U[R_n]. \quad \blacksquare \end{aligned}$$

Proof of Lemma 4. i) Using simple algebra, it can be easily observed that the portfolio choice of the informed investor is equivalent to solving the following problem:

$$\begin{aligned} \max_{\theta_I} - \sum_{j=1}^N \pi_j(0) \exp\{b_j \varepsilon - \gamma_I \theta_I^\top (C(\omega_j) - e^{rT} p)\} = \\ \max_{\theta_I} - \exp\{\tilde{\mathbb{E}}[b] \varepsilon - \gamma_I \theta_I^\top (\tilde{\mathbb{E}}[C] - e^{rT} p) + \tilde{\kappa}(b \varepsilon - \gamma_I \theta_I^\top C)\}, \end{aligned}$$

where $\tilde{\kappa}(X) = \ln(\tilde{\mathbb{E}}[e^X]) - \tilde{\mathbb{E}}[X]$. The above problem is equivalent to (29).

ii) Suppose, condition (28) is satisfied. Then, substituting portfolio (30) into (29) and using simple algebra, we find that $b\varepsilon$ cancels out from the second term of (29) and $\hat{\theta}_I^*$ solves optimization problem that does not depend on ε :

$$\max_{\hat{\theta}_I} e^{rT} p^\top \hat{\theta}_I - g_I(\hat{\theta}_I), \quad (\text{A.27})$$

where $g_I(\hat{\theta}_I) = \ln(\sum_{i=1}^N \exp\{a_i + C(\omega_i)^\top \hat{\theta}_I\})$. Hence, $\hat{\theta}_I^*$ only depends on prices p . ■

Proof of Proposition 3.

Step 1 (Portfolio of investor I). Investor I 's optimization problem (A.27) yields the FOC for the optimal $\hat{\theta}_I^* = \lambda \varepsilon - \gamma_I \theta_I^*$:

$$f_I(\hat{\theta}_I^*) = e^{rT} p, \quad (\text{A.28})$$

where $f_I(x) \equiv g'_I(x)$ is given by (32). Assuming that $f_I(\cdot)$ is invertible (as verified below), gives $\hat{\theta}_I^* = f_I^{-1}(e^{rT}p)$. Then, using $\hat{\theta}_I^* = \lambda\varepsilon - \gamma_I\theta_I^*$, we find portfolio $\theta_I^*(p; \varepsilon)$ in (34).

Step 2 (Posterior probabilities and portfolio of investor U). Substituting investor I 's portfolio (30) into the market clearing condition, we obtain: $h\lambda\varepsilon/\gamma_I + \nu + \widehat{H}(p) = 0$, where $\widehat{H}(p) = -hf_I^{-1}(e^{rT}p)/\gamma_I + (1-h)\theta_U^*(p)$, analogous to condition (13) for complete markets. Hence, the posterior probabilities can be found similar to Lemma 2, and are given by equation (15) in which $H(p)$ is replaced by $\widehat{H}(p)$. Substituting $b_n = \lambda_0 + C(\omega_n)^\top \lambda$ from Condition (28) into equation (15) with $\widehat{H}(p)$ instead of $H(p)$, we obtain:

$$\pi_n^U(p) = \frac{1}{G_3(p)} \exp \left(a_n + \frac{1}{2} \frac{b_n^2 + 2C(\omega_n)^\top (\lambda\mu_0/\sigma_0^2 - h\lambda\lambda^\top \Sigma_\nu^{-1} \widehat{H}(p)/\gamma_I)}{h^2(\lambda^\top \Sigma_\nu^{-1} \lambda/\gamma_I^2) + 1/\sigma_0^2} \right), \quad (\text{A.29})$$

where $G_3(p)$ is a normalizing function. Substituting probabilities $\pi_n^U(p)$ into investor U 's objective function (9), after some algebra, we obtain:

$$\begin{aligned} & -\sum_{n=1}^N \pi_n^U(p) \exp \left\{ -\gamma_U \left(W_{U,0} e^{rT} + \left(C(\omega_n) - e^{rT}p \right)^\top \theta_U \right) \right\} \\ & = -\frac{1}{G_4(p)} \exp \left(\gamma_U e^{rT} p^\top \theta_U + g_U \left(\frac{\lambda\mu_0/\sigma_0^2 - h\lambda\lambda^\top \Sigma_\nu^{-1} \widehat{H}(p)/\gamma_I}{h^2(\lambda^\top \Sigma_\nu^{-1} \lambda/\gamma_I^2) + 1/\sigma_0^2} - \gamma_U \theta_U \right) \right), \end{aligned} \quad (\text{A.30})$$

where $G_4(p)$ is some function of prices and $g_U : \mathbb{R}^{M-1} \rightarrow \mathbb{R}$ is a function given by:

$$g_U(x) = \ln \left(\sum_{j=1}^N \exp \left\{ a_j + \frac{1}{2} \frac{b_j^2}{h^2(\lambda^\top \Sigma_\nu^{-1} \lambda/\gamma_I^2) + 1/\sigma_0^2} + C(\omega_j)^\top x \right\} \right).$$

From equation (A.30), we find that investor U 's optimization problem becomes

$$\min_{\theta_U} \gamma_U e^{rT} p^\top \theta_U + g_U \left(\frac{\lambda\mu_0/\sigma_0^2 - h\lambda\lambda^\top \Sigma_\nu^{-1} \widehat{H}(p)/\gamma_I}{h^2(\lambda^\top \Sigma_\nu^{-1} \lambda/\gamma_I^2) + 1/\sigma_0^2} - \gamma_U \theta_U \right).$$

Let $f_U(x) \equiv g'_U(x)$, then the FOC for investor U 's optimal portfolio θ_U^* is,

$$f_U \left(\frac{\lambda\mu_0/\sigma_0^2 - h\lambda\lambda^\top \Sigma_\nu^{-1} \widehat{H}(p)/\gamma_I}{h^2(\lambda^\top \Sigma_\nu^{-1} \lambda/\gamma_I^2) + 1/\sigma_0^2} - \gamma_U \theta_U^* \right) = e^{rT} p.$$

Assuming that f_U is invertible (as verified below), and $e^{rT}p$ belongs to its range, we obtain

$$\frac{\lambda\mu_0/\sigma_0^2 - h\lambda\lambda^\top \Sigma_\nu^{-1} \widehat{H}(p)/\gamma_I}{h^2(\lambda^\top \Sigma_\nu^{-1} \lambda/\gamma_I^2) + 1/\sigma_0^2} - \gamma_U \theta_U^* = f_U^{-1}(e^{rT}p). \quad (\text{A.31})$$

Substituting for $\widehat{H}(p) = -hf_I^{-1}(e^{rT}p)/\gamma_I + (1-h)\theta_U^*(p)$ and factoring out $\gamma_U \theta_U^*(p)$ we have

$$\frac{\lambda\mu_0/\sigma_0^2 + h^2\lambda\lambda^\top \Sigma_\nu^{-1} f_I^{-1}(e^{rT}p)/\gamma_I}{h^2(\lambda^\top \Sigma_\nu^{-1} \lambda/\gamma_I^2) + 1/\sigma_0^2} - \gamma_U \theta_U^*(p) (E + Q) = f_U^{-1}(e^{rT}p),$$

where E is the identity matrix and matrix Q is given in (A.16). Solving for $\theta_v^*(p)$ yields

$$\begin{aligned}\theta_v^*(p) &= \frac{1}{\gamma_v} (E + Q)^{-1} \left(\frac{\lambda \mu_0 / \sigma_0^2 + h^2 \lambda \lambda^\top \Sigma_v^{-1} f_I^{-1}(e^{rT} p) / \gamma_I^2}{h^2 (\lambda^\top \Sigma_v^{-1} \lambda / \gamma_I^2) + 1 / \sigma_0^2} - f_v^{-1}(e^{rT} p) \right) \\ &= (E + Q)^{-1} \left(\frac{h Q f_I^{-1}(e^{rT} p)}{(1 - h) \gamma_I} - \frac{f_v^{-1}(e^{rT} p)}{\gamma_v} + \frac{\mu_0 / (\gamma_v \sigma_0^2) \lambda}{h^2 \lambda^\top \Sigma_v^{-1} \lambda / \gamma_I^2 + 1 / \sigma_0^2} \right).\end{aligned}\quad (\text{A.32})$$

Step 3 (Invertibility of $f_I(x)$ and $f_v(x)$). Functions $f_I(x)$ and $f_v(x)$ are special cases of function $f(x; t)$ in equation (A.36) below for $t = 0$ and $t = 0.5 / (h^2 \lambda^\top \Sigma_v^{-1} \lambda / \gamma_I^2 + 1 / \sigma_0^2)$. Function $f(x; t)$ has positive-definite and invertible Jacobian by Lemma A.3 below. Hence, by Lemma A.4 below, $f_I(x)$ and $f_v(x)$ are invertible on their ranges.

Step 4 (Equation for asset prices). Substituting θ_I^* and θ_v^* from equations (34) and (35) into the market clearing condition $h\theta_I^*(p; \varepsilon) + (1 - h)\theta_v^*(p) + \nu = 0$ yields, after some algebra, equation (31) for price vector $P(\varepsilon, \nu)$.

Step 5 (Existence of Equilibrium). Finally, we show that there exists unique vector of prices satisfying equation (31). Denote $x_I = f_I^{-1}(e^{rT} P(\varepsilon, \nu))$ and $x_v = f_v^{-1}(e^{rT} P(\varepsilon, \nu))$. Hence, $f_I(x_I) = f_v(x_v) = e^{rT} P(\varepsilon, \nu)$. From the latter equation and equation (31) for $P(\varepsilon, \nu)$, we obtain the following system of equations for x_I and x_v :

$$\frac{hx_I}{\gamma_I} + \frac{(1 - h)x_v}{\gamma_v} = (E + Q)s + \frac{(1 - h)\mu_0 / (\gamma_v \sigma_0^2) \lambda}{h^2 \lambda^\top \Sigma_v^{-1} \lambda / \gamma_I^2 + 1 / \sigma_0^2}, \quad (\text{A.33})$$

$$f_I(x_I) = f_v(x_v). \quad (\text{A.34})$$

From equations (A.28) and (A.31), we note that x_I and x_v are related to portfolios:

$$x_I = \lambda \varepsilon - \gamma_I \theta_I^*, \quad x_v = \frac{\lambda \mu_0 / \sigma_0^2 - h \lambda \lambda^\top \Sigma_v^{-1} \widehat{H}(p) / \gamma_I}{h^2 (\lambda^\top \Sigma_v^{-1} \lambda / \gamma_I^2) + 1 / \sigma_0^2} - \gamma_v \theta_v^*. \quad (\text{A.35})$$

From (A.33), we find that $x_v = \bar{x} - \eta x_I$, where $\eta = \gamma_v h / (\gamma_I (1 - h))$ and $\bar{x}$ is given by

$$\bar{x} = \frac{\gamma_v (E + Q)s}{1 - h} + \frac{(\mu_0 / \sigma_0^2) \lambda}{h^2 \lambda^\top \Sigma_v^{-1} \lambda / \gamma_I^2 + 1 / \sigma_0^2}.$$

Substituting $x_v = \bar{x} - \eta x_I$ into equation (A.34), we find that x_I solves $f_I(x_I) = f_v(\bar{x} - \eta x_I)$. The latter equation is a special case of equation $f(x; 0) = f(\bar{x} - \eta x; t)$ in (A.39) below with $t = 0.5 / (h^2 (\lambda^\top \Sigma_v^{-1} \lambda / \gamma_I^2) + 1 / \sigma_0^2)$, because $f(x; 0) = f_I(x)$, $f(x; t) = f_v(x)$. Hence, by Lemma A.5, equation $f_I(x_I) = f_v(\bar{x} - \eta x_I)$ has a unique, continuous, and differentiable solution x_I . Because $P(\varepsilon, \nu) = e^{-rT} f_I(x_I)$, price exists, is unique, continuous, differentiable, and invertible on its range function of $\bar{x}$, and hence, also of the sufficient statistic s . ■

Lemma A.3.

i) Consider function $f(x; t) : \mathbb{R}^{M-1} \times \mathbb{R} \rightarrow \mathbb{R}^{M-1}$ given by:

$$f(x; t) = \frac{\sum_{j=1}^N C(\omega_j) \exp\{a_j + tb_j^2 + C(\omega_j)^\top x\}}{\sum_{j=1}^N \exp\{a_j + tb_j^2 + C(\omega_j)^\top x\}}. \quad (\text{A.36})$$

Then, for all x and t , $f(x; t)$ has an invertible positive-definite Jacobian given by:

$$\frac{\partial f(x; t)}{\partial x} = \text{var}^\pi[C], \quad (\text{A.37})$$

where $\text{var}^\pi[C]$ is a variance-covariance matrix under a certain probability measure $\pi(x; t)$.

ii) Consider function $\hat{f}(x; t) = f(x; 0) - f(\bar{x} - \eta x; t)$ for a fixed $\bar{x}$ and $\eta > 0$. Then, this function also has a positive-definite and invertible Jacobian $\partial \hat{f}(x; t) / \partial x$ for all x and t .

Proof of Lemma A.3. i) Differentiating function $f(x; t)$ with respect to x , we obtain:

$$\begin{aligned} \frac{\partial f(x; t)}{\partial x} &= \frac{\sum_{j=1}^N C(\omega_j) C(\omega_j)^\top \exp\{a_j + tb_j^2 + C(\omega_j)^\top x\}}{\sum_{j=1}^N \exp\{a_j + tb_j^2 + C(\omega_j)^\top x\}} \\ &\quad - \frac{\sum_{j=1}^N C(\omega_j) \exp\{a_j + tb_j^2 + C(\omega_j)^\top x\}}{\sum_{j=1}^N \exp\{a_j + tb_j^2 + C(\omega_j)^\top x\}} \frac{\sum_{j=1}^N C(\omega_j)^\top \exp\{a_j + tb_j^2 + C(\omega_j)^\top x\}}{\sum_{j=1}^N \exp\{a_j + tb_j^2 + C(\omega_j)^\top x\}} \quad (\text{A.38}) \\ &= \text{var}^\pi[C], \end{aligned}$$

where the variance $\text{var}^\pi[C]$ is computed under a probability measure given by $\pi_j(x; t) = \exp\{a_j + tb_j^2 + C(\omega_j)^\top x\} / \left(\sum_{j=1}^N \exp\{a_j + tb_j^2 + C(\omega_j)^\top x\} \right)$.

Matrix $\text{var}^\pi[C]$ has elements $\text{cov}^\pi(C_i, C_j)$. It is positive-definite and invertible because all assets are non-redundant. Suppose, $\text{var}^\pi[C]$ is not invertible. Then, the columns of this matrix are linearly dependent, and hence, there exist constants λ_m such that $\text{cov}^\pi(\lambda_1 C_1 + \dots \lambda_{M-1} C_{M-1}, C_m) = 0$ for all $m = 1, \dots, M-1$. Multiplying the latter equalities by λ_m and summing up, we obtain $\text{var}^\pi[\lambda_1 C_1 + \dots \lambda_{M-1} C_{M-1}] = 0$. Hence, $\lambda_1 C_1 + \dots \lambda_{M-1} C_{M-1}$ is a constant, which contradicts non-redundancy of the riskless asset.

ii) Function $\hat{f}(x; t)$ has Jacobian $\partial f(x; 0) / \partial x + \eta \partial f(\bar{x} - \eta x; t) / \partial x$, which is the sum of positive-definite and invertible matrices, and hence is positive-definite and invertible. ■

Lemma A.4 (Gale and Nikaidô). Let $f(x) : \mathbb{R}^{M-1} \rightarrow \mathbb{R}^{M-1}$ be a continuous differentiable function with a positive-definite Jacobian. Then, function $f(x)$ is injective, that is, invertible on its range, so that $\forall x_1, x_2 \in \mathbb{R}^{M-1}$ such that $f(x_1) = f(x_2)$ we have $x_1 = x_2$.

Proof of Lemma A.4. See the proof of Theorem 6 in Gale and Nikaidô (1965). ■

Lemma A.5 Consider function $f(x; t) : \mathbb{R}^{M-1} \times \mathbb{R} \rightarrow \mathbb{R}^{M-1}$ given by equation (A.36). Then, for all fixed $\bar{x} \in \mathbb{R}^{M-1}$, $\eta > 0$ and $t \in \mathbb{R}$ there exists unique x which solves equation

$$f(x; 0) = f(\bar{x} - \eta x; t). \quad (\text{A.39})$$

Moreover, solution $x(t; \bar{x})$ is continuous and differentiable in t and $\bar{x}$.

Proof of Lemma A.5. The proof proceeds in three steps.

Step 1. Let us fix $\bar{x}$ and show that the solution of equation (A.39) exists for all t . For $t = 0$ equation (A.39) has solution $x_0 = \bar{x}/(1 + \eta)$. Function $\hat{f}(x; t) \equiv f(x; 0) - f(\bar{x} - \eta x; t)$ is continuously differentiable and has an invertible Jacobian with respect to x by Lemma A.3. Hence, by the implicit function theorem (Theorem A.1 below), there exists a unique continuously differentiable function $x(t)$ that solves (A.39) in some interval $t \in (-t_-, t_+)$, where $t_{\pm} > 0$. Next, we show that $t_+ = +\infty$, and the proof that $t_- = +\infty$ is analogous.

Suppose, t_+ is finite. Let $(-t_-, t_+)$ be the largest open interval in which a unique solution exists. We show in steps 2 and 3 below that there exists a unique solution of equation $\hat{f}(x; t_+) = 0$. Because $\hat{f}(x; t)$ has a positive definite and invertible Jacobian [see Lemma A.3], by the implicit function theorem, the solution can be extended to some $t > t_+$, which contradicts the fact that $(-t_-, t_+)$ is the largest interval in which a unique solution exists. Therefore, this leads to a contradiction, and hence, $t_+ = +\infty$.

Step 2. We show that $\hat{f}(x; t_+) = 0$ has a unique solution, which implies that $t_+ = +\infty$, as shown above. Consider a sequence $t_k \uparrow t_+$ and solutions x_k such that

$$f(x_k; 0) = f(\bar{x} - \eta x_k; t_k). \quad (\text{A.40})$$

Suppose, x_k are bounded by some constant A , i.e., $|x_k| < A$. Then, by Weierstrass Theorem [e.g., Rudin (1976, Theorem 2.42)], there exists a convergent subsequence such that $x_{k_n} \rightarrow x^*$ as $n \rightarrow +\infty$. Taking limit $k_n \rightarrow \infty$ in equation (A.40), by the continuity of $f(x; t)$ we find that $\hat{f}(x^*; t_+) = 0$. This solution is unique by Lemma A.4 because $f(x; 0) - f(\bar{x} - \eta x; t)$ has positive-definite Jacobian by Lemma A.3. Hence, $t_+ = +\infty$.

Step 3. It remains to prove that x_k is indeed bounded. Suppose, x_k is unbounded, i.e., there exist indices k_n such that $|x_{k_n}| \rightarrow \infty$, as $k_n \rightarrow \infty$. We renumber elements k_n by k , and hence, assume that $|x_k| \rightarrow \infty$. Let $j(k) = \arg \max_j C(\omega_j)^\top x_k$. Because $j(k)$ takes only finite number of values from 1 to N , there exists index j^* such that $j^* = j(k_n)$ for an infinite sequence of $k_n \rightarrow \infty$. Without loss of generality, we assume that $j^* = 1$ (otherwise, we relabel states ω_n accordingly) and also focus on subsequence k_n and relabel its elements

by k . Hence, $C(\omega_1)^\top x_k \geq C(\omega_j)^\top x_k$ for all $j = 1, \dots, N$. Similarly, we find a subsequence x_k such that $C(\omega_1)^\top x_k \geq C(\omega_2)^\top x_k \geq C(\omega_j)^\top x_k$ for all $j = 2, \dots, N$. Similarly, there exists x_k such that

$$C(\omega_1)^\top x_k \geq \dots \geq C(\omega_m)^\top x_k > C(\omega_{m+1})^\top x_k \geq \dots \geq C(\omega_N)^\top x_k, \quad (\text{A.41})$$

for all k , where m is the first index for which $C(\omega_m)^\top x_k - C(\omega_{m+1})^\top x_k \rightarrow +\infty$ as $k \rightarrow \infty$. The existence of such an index m is guaranteed by Lemma A.7 below.

Next, we take the limit $k \rightarrow \infty$ in equation (A.40). Ordering (A.41) simplifies the computation of this limit. Consider the following probability measure $\pi_j(x; t)$:

$$\pi_j(x; t) = \frac{\exp\{a_j + tb_j^2 + C(\omega_j)^\top x\}}{\sum_{j=1}^N \exp\{a_j + tb_j^2 + C(\omega_j)^\top x\}}. \quad (\text{A.42})$$

Because $0 \leq \pi_j(x_k; t) \leq 1$, by Weierstrass theorem there exists a subsequence x_k such that $\pi_j(x_k; 0) \rightarrow \pi_j^+$ and $\pi_j(\bar{x} - \eta x_k; t_k) \rightarrow \pi_j^-$ for all $j = 1, \dots, N$, where $\sum_{j=1}^N \pi_j^+ = \sum_{j=1}^N \pi_j^- = 1$, $0 \leq \pi_j^+ \leq 1$ and $0 \leq \pi_j^- \leq 1$. Next, we demonstrate that

$$\pi_j^+ = 0, \text{ for } j = m+1, \dots, N, \quad (\text{A.43})$$

$$\pi_j^- = 0, \text{ for } j = 1, \dots, m. \quad (\text{A.44})$$

To derive equalities (A.43) and (A.44), we use inequalities (A.41) and the fact that $C(\omega_m)^\top x_k - C(\omega_{m+1})^\top x_k \rightarrow +\infty$ as $k \rightarrow \infty$, to obtain for all $j > m$:

$$\pi_j^+ = \lim_{k \rightarrow +\infty} \pi_j(x_k; 0) \leq \lim_{k \rightarrow +\infty} \frac{\exp\{a_j + C(\omega_j)^\top x_k\}}{\exp\{a_m + C(\omega_m)^\top x_k\}} \leq \lim_{k \rightarrow +\infty} \frac{\exp\{a_j + C(\omega_{m+1})^\top x_k\}}{\exp\{a_m + C(\omega_m)^\top x_k\}} = 0.$$

Similarly, for all $j \leq m$ we obtain:

$$\begin{aligned} \pi_j^- &= \lim_{k \rightarrow +\infty} \pi_j(\bar{x} - \eta x_k; t_k) \leq \lim_{k \rightarrow +\infty} \frac{\exp\{a_j + t_k b_j^2 + C(\omega_j)^\top \bar{x} - \eta C(\omega_j)^\top x_k\}}{\exp\{a_{m+1} + t_k b_{m+1}^2 + C(\omega_{m+1})^\top \bar{x} - \eta C(\omega_{m+1})^\top x_k\}} \\ &\leq \lim_{k \rightarrow +\infty} \frac{\exp\{a_j + t_k b_j^2 + C(\omega_j)^\top \bar{x} - \eta C(\omega_m)^\top x_k\}}{\exp\{a_m + t_k b_m^2 + C(\omega_{m+1})^\top \bar{x} - \eta C(\omega_{m+1})^\top x_k\}} = 0. \end{aligned}$$

Using equations (A.43) and (A.44) and taking the limit $k \rightarrow +\infty$ in (A.40), we obtain:

$$\pi_{m+1}^+ C(\omega_{m+1}) + \dots + \pi_N^+ C(\omega_N) = \pi_1^- C(\omega_1) + \dots + \pi_m^- C(\omega_m).$$

Transposing both sides of the above equation and multiplying by x_k , we obtain:

$$\pi_{m+1}^+ C(\omega_{m+1})^\top x_k + \dots + \pi_N^+ C(\omega_N)^\top x_k = \pi_1^- C(\omega_1)^\top x_k + \dots + \pi_m^- C(\omega_m)^\top x_k. \quad (\text{A.45})$$

From the fact that $\sum_{j=1}^N \pi_j^+ = \sum_{j=1}^N \pi_j^- = 1$, demonstrated above, equations (A.43)–(A.45), and inequality (A.41), we obtain:

$$\begin{aligned} \pi_{m+1}^+ C(\omega_{m+1})^\top x_k + \dots + \pi_N^+ C(\omega_N)^\top x_k &\leq C(\omega_{m+1})^\top x_k < C(\omega_m)^\top x_k \\ &\leq \pi_1^- C(\omega_1)^\top x_k + \dots + \pi_m^- C(\omega_m)^\top x_k. \end{aligned} \quad (\text{A.46})$$

Inequalities (A.46) contradict equation (A.45). Consequently, x_k is bounded. Hence, as shown in step 2 above, $t_+ = +\infty$, which proves the global existence of $x(t; \bar{x})$. The continuity and differentiability of $x(t; \bar{x})$ follows from the implicit function theorem. ■

Theorem A.1 (Implicit Function Theorem). *Consider a continuously differentiable function $\hat{f}(x; t) : \mathbb{R}^{M-1} \times \mathbb{R} \rightarrow \mathbb{R}^{M-1}$. Suppose, $\hat{f}(x_0; t_0) = 0$ and the Jacobian $\partial \hat{f}(x_0; t_0) / \partial x$ is invertible. Then, there exist open sets U and V such that $x_0 \in U$, $t_0 \in V$, and a unique continuously differentiable function $x(t) : V \rightarrow U$ such that $\hat{f}(x(t); t) = 0$.*

Proof of Theorem A.1. This is a special case of Theorem 9.28 in Rudin (1976). ■

Lemma A.6. *Consider a sequence x_k such that $|x_k| \rightarrow \infty$ as $k \rightarrow \infty$. Then, there exists index m such that sequence $|C(\omega_m)^\top x_k|$ is unbounded.*

Proof of Lemma A.6. Suppose, on the contrary, there exists constant A such that $|C(\omega_m)^\top x_k| < A$ for all m and k . Because all securities are non-redundant, the matrix with columns $C(\omega_n)$, $n = 1, \dots, N$ has rank $M-1$ and vectors $C(\omega_n)$ span $\mathbb{R}^{M-1}$. Without loss of generality, assume that the $M-1$ vectors $C(\omega_1), \dots, C(\omega_{M-1})$ form a basis in $\mathbb{R}^{M-1}$.

Consider vector $e_l = (0, \dots, 0, 1, 0, \dots, 0)^\top \in \mathbb{R}^{M-1}$ with l^{th} element equal to 1 and all other elements equal to 0. Then, there exist constants $\alpha_{m,l}$ such that $e_l = \alpha_{1,l} C(\omega_1) + \dots + \alpha_{M-1,l} C(\omega_{M-1})$. It can be easily observed that x_k is bounded, because for all l

$$|e_l^\top x_k| \leq |\alpha_{1,l}| |C(\omega_1)^\top x_k| + \dots + |\alpha_{M-1,l}| |C(\omega_{M-1})^\top x_k| \leq A(M-1) \max_{m,l} |\alpha_{m,l}|,$$

which contradicts $|x_k| \rightarrow \infty$. Hence, $|C(\omega_m)^\top x_k|$ is unbounded for some m . ■

Lemma A.7. *Consider a sequence x_k such that $|x_k| \rightarrow \infty$ as $k \rightarrow \infty$. Then, there exists index m such that sequence $|C(\omega_m)^\top x_k - C(\omega_{m+1})^\top x_k|$ is unbounded.*

Proof of Lemma A.7. Suppose, on the contrary, sequence $|C(\omega_m)^\top x_k - C(\omega_{m+1})^\top x_k|$ is bounded for all m . The latter easily implies that $|C(\omega_i)^\top x_k - C(\omega_j)^\top x_k| < A$ for all i and j and some constant A . Because all assets are non-redundant, vectors $(C(\omega_n)^\top, 1)^\top \in \mathbb{R}^M$,

where $n = 1, \dots, N$, span $\mathbb{R}^M$. Without loss of generality, assume that the first M vectors $(C(\omega_n)^\top, 1)^\top$ form a basis in $\mathbb{R}^M$. Hence, there exist unique $(\alpha_1, \dots, \alpha_M)^\top$ such that:

$$\begin{aligned}\alpha_1 C(\omega_1) + \dots + \alpha_M C(\omega_M) &= 0, \\ \alpha_1 + \dots + \alpha_M &= 1.\end{aligned}\tag{A.47}$$

We solve equations (A.47) and for an arbitrary index m we obtain:

$$\begin{aligned}|C(\omega_m)^\top x_k| &= |(\alpha_1 + \dots + \alpha_M)C(\omega_m)^\top x_k - (\alpha_1 C(\omega_1)^\top x_k + \dots + \alpha_M C(\omega_M)^\top x_k)| \\ &\leq |\alpha_1| |C(\omega_m)^\top x_k - C(\omega_1)^\top x_k| + \dots + |\alpha_M| |C(\omega_m)^\top x_k - C(\omega_M)^\top x_k| \\ &\leq A \max_l |\alpha_l|,\end{aligned}$$

contradicting the result of Lemma A.6 that $|C(\omega_m)^\top x_k|$ is unbounded for some m . ■

Proof of Lemma 5. Substituting the risk-neutral probabilities (36) into (38), and noting that due to the properties of risk-neutral distributions $\mathbb{E}^{\text{RN},i}[W_{i,T}] = W_{i,0}e^{rT}$, we obtain:

$$\hat{\kappa} = \mathbb{E}^{\text{RN},U}\left[\ln\left(\frac{\pi^U(p)}{\pi(\varepsilon)}\right)\right] + \mathbb{E}^{\text{RN},I}\left[\ln\left(\frac{\pi(\varepsilon)}{\pi^U(p)}\right)\right].$$

Substituting $\pi(\varepsilon)$ from (1) and $\pi^U(p)$ from (A.29) into the above equation, we find:

$$\hat{\kappa} = 0.5\mathbb{E}^{\text{RN},U}\left[\frac{b^2 + 2b(\mu_0/\sigma_0^2 + h\lambda^\top \Sigma_\nu^{-1}s/\gamma_I)}{h^2(\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2) + 1/\sigma_0^2} - b\varepsilon\right] - 0.5\mathbb{E}^{\text{RN},I}\left[\frac{b^2 + 2b(\mu_0/\sigma_0^2 + h\lambda^\top \Sigma_\nu^{-1}s/\gamma_I)}{h^2(\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2) + 1/\sigma_0^2} - b\varepsilon\right].$$

Using the fact that under the risk-neutral probabilities the price of a portfolio with payoff b is given by $\mathbb{E}^{\text{RN},U}[b] = \mathbb{E}^{\text{RN},I}[b]$, we simplify the above expression for $\hat{\kappa}$ as follows:

$$\hat{\kappa} = \frac{1}{2} \frac{\mathbb{E}^{\text{RN},U}[b^2] - \mathbb{E}^{\text{RN},I}[b^2]}{h^2(\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2) + 1/\sigma_0^2} = \frac{1}{2} \frac{\text{var}^{\text{RN},U}[b] - \text{var}^{\text{RN},I}[b]}{h^2(\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2) + 1/\sigma_0^2}. \quad \blacksquare$$

Proof of Lemma 6. Using the conditional PDF (A.8), we obtain

$$\mathbb{E}[\varepsilon^k|s] = \int_{-\infty}^{\infty} x^k \varphi_{\varepsilon|s}(x|s) dx = \frac{1}{G_1(s)} \sum_{n=1}^N \int_{-\infty}^{\infty} x^k e^{d_n(x)} dx, \tag{A.48}$$

where $\varphi_{\varepsilon|s}(x|s)$ is given by (A.8), $G_1(s)$ is a normalization function, and $d_n(x)$ is given by equation (A.10). Computing the integral (A.48) for $k = 1$ and $k = 2$, we obtain:

$$\mathbb{E}[\varepsilon|s] = \sum_{n=1}^N \frac{\mu_0/\sigma_0^2 + b_n + h\lambda^\top \Sigma_\nu^{-1}s/\gamma_I}{h^2(\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2) + 1/\sigma_0^2} \pi_n^U(p) = \frac{\mu_0/\sigma_0^2 + E^U[b_n] + h\lambda^\top \Sigma_\nu^{-1}s/\gamma_I}{h^2(\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2) + 1/\sigma_0^2}, \tag{A.49}$$

$$\mathbb{E}[\varepsilon^2|s] = \frac{1}{h^2(\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2) + 1/\sigma_0^2} + \mathbb{E}^U\left[\left(\frac{\mu_0/\sigma_0^2 + b_n + h\lambda^\top \Sigma_\nu^{-1}s/\gamma_I}{h^2(\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2) + 1/\sigma_0^2}\right)^2\right]. \tag{A.50}$$

Combining (A.49) and (A.50), we obtain the conditional variance (41). ■

Lemma A.8. i) *The market is effectively complete if and only if there exists a portfolio that replicates $\ln(\pi_n(\varepsilon)/\pi_n^U(p))$, that is, there exist ω -independent $\hat{\lambda}_0 \in \mathbb{R}$ and $\hat{\lambda} \in \mathbb{R}^{M-1}$ such that*

$$\ln\left(\frac{\pi_n(\varepsilon)}{\pi_n^U(p)}\right) = \hat{\lambda}_0 + C(\omega_n)^\top \hat{\lambda}. \quad (\text{A.51})$$

ii) *The equilibrium Pareto efficient portfolios are given by:*

$$\theta_I^* = \frac{1}{\gamma_I} \frac{\hat{\lambda}(1-h)/\gamma_U - \nu}{h/\gamma_I + (1-h)/\gamma_U}, \quad (\text{A.52})$$

$$\theta_U^* = -\frac{1}{\gamma_U} \frac{\hat{\lambda}h/\gamma_I + \nu}{h/\gamma_I + (1-h)/\gamma_U}. \quad (\text{A.53})$$

Proof of Lemma A.8. i) Suppose, the market is effectively complete. Taking logs on both sides of the equation (39) with $\ell_n = 0$, and rearranging terms, we find that $\gamma_U W_{U,T,n} - \gamma_I W_{I,T,n} - \bar{\ell} = \ln(\pi_n^U(p)/\pi_n(\varepsilon))$. Hence, the log-ratio of probabilities can be replicated by a portfolio of $\gamma_U \theta_U^* - \gamma_I \theta_I^*$ units of risky assets and $\gamma_U(W_{U,0} - p^\top \theta_U^*)e^{rT} - \gamma_I(W_{I,0} - p^\top \theta_I^*)e^{rT} - \bar{\ell}$ units of bond.

Suppose, there exist $\lambda_0 \in \mathbb{R}$ and $\hat{\lambda} \in \mathbb{R}^{M-1}$ such that (A.51) holds. Hence, $\pi_n(\varepsilon) = \pi_n^U(p) \exp(\hat{\lambda}_0 + C(\omega_n)^\top \hat{\lambda})$. Substituting $\pi_n(\varepsilon)$ into investor I 's optimization (3), we obtain:

$$\max_{\theta_I} \mathbb{E}\left[-e^{-\gamma_I W_{I,T}} \mid \varepsilon, p\right] = \max_{\theta_I} \left[-\sum_{n=1}^N \pi_n^U(p) e^{\hat{\lambda}_0 + C(\omega_n)^\top \hat{\lambda} - \gamma_I W_{I,T,n}}\right]. \quad (\text{A.54})$$

Substituting wealth $W_{I,T,n}$ from the budget constraint (5) into optimization (A.54), and rearranging terms, we observe that this optimization is equivalent to maximizing

$$\max_{\theta_I} \left[-\sum_{n=1}^N \pi_n^U(p) e^{-\gamma_I(C(\omega_n) - e^{rT}p)^\top (\theta_I - \hat{\lambda}/\gamma_I)}\right] = \max_{\hat{\theta}} \left[-\sum_{n=1}^N \pi_n^U(p) e^{-\gamma_U(C(\omega_n) - e^{rT}p)^\top \hat{\theta}}\right], \quad (\text{A.55})$$

where, by a change of variable, $\hat{\theta} = (\theta_I - \hat{\lambda}/\gamma_I)(\gamma_I/\gamma_U)$. The second optimization in (A.55) is the same as that of investor U . Hence, $\theta_U^* = \hat{\theta}^* = (\theta_I^* - \hat{\lambda}/\gamma_I)(\gamma_I/\gamma_U)$, or, equivalently:

$$\gamma_I \theta_I^* - \gamma_U \theta_U^* = \hat{\lambda}. \quad (\text{A.56})$$

Multiplying (A.56) by $(C(\omega_n) - e^{rT}p)$, we obtain $\gamma_I(C(\omega_n) - e^{rT}p)^\top \theta_I^* - \gamma_U(C(\omega_n) - e^{rT}p)^\top \theta_U^* = (C(\omega_n) - e^{rT}p)^\top \hat{\lambda}$. The latter equation and budget constraints (5) then imply $\gamma_U W_{U,T,n} - \gamma_I W_{I,T,n} - \bar{\ell} = \ln(\pi_n^U(p)/\pi_n(\varepsilon))$, where $\bar{\ell}$ does not depend on ω_n , which is equivalent to the Pareto efficiency condition (39) with $\ell_n = 0$.

ii) The equilibrium Pareto efficient portfolios satisfy the market clearing condition (6) and efficiency condition (A.56). Solving the latter two equations with two unknowns, we obtain portfolios (A.52) and (A.53). ■

Proof of Proposition 4. i) Substituting $\pi_n(\varepsilon)$ from (1) and $\pi_n^U(p)$ from (A.29) into $\ln(\pi_n(\varepsilon)/\pi_n^U(p))$, and using market clearing $\widehat{H}(p) = -s$, where $s = (h\lambda\varepsilon/\gamma_I + \nu)$, we find:

$$\ln\left(\frac{\pi_n(\varepsilon)}{\pi_n^U(p)}\right) = b_n\varepsilon - \frac{1}{2} \frac{b_n^2 + 2b_n(\mu_0/\sigma_0^2 + h\lambda^\top \Sigma_\nu^{-1}(h\lambda\varepsilon/\gamma_I + \nu)/\gamma_I)}{h^2\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2} + \text{const}, \quad (\text{A.57})$$

where *const* does not depend on state ω_n . The log-ratio of probabilities in (A.57) is a quadratic function of b_n . Hence, by Lemma A.8, the optimal portfolios are Pareto efficient if and only if there exists a portfolio that replicates b_n^2 .

ii) Substituting $b_n = \lambda_0 + C(\omega_n)^\top \lambda$ from (28) and $b_n^2 = \tilde{\lambda}_0 + C(\omega_n)^\top \tilde{\lambda}$ from the conditions of Proposition 4 into (A.57), we find that the replicating portfolio $\hat{\lambda}$ in (A.51) for the ratio $\ln(\pi_n(\varepsilon)/\pi_n^U(p))$ is given by:

$$\hat{\lambda} = \lambda \left(\varepsilon - \frac{\mu_0/\sigma_0^2 + h\lambda^\top \Sigma_\nu^{-1}s/\gamma_I}{h^2\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2} \right) - \frac{0.5\tilde{\lambda}}{h^2\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2}. \quad (\text{A.58})$$

Substituting (A.58) into equation (A.52) for the portfolio of the informed investor, we observe that investor I shorts portfolio $\tilde{\lambda}$, which replicates the quadratic derivative. Consequently, investor I sells the quadratic derivative to investor U .

iii) From the FOC of investor I (A.28), we find that $P(\varepsilon, \nu) = f_I(\lambda\varepsilon - \gamma_I\theta_I^*)$. Using the expression for $f_I(x)$ in (32), we obtain:

$$P(\varepsilon, \nu) = \frac{\sum_{j=1}^N C(\omega_j) \exp\{a_j + C(\omega_j)^\top (\lambda\varepsilon - \gamma_I\theta_I^*)\}}{\sum_{j=1}^N \exp\{a_j + C(\omega_j)^\top (\lambda\varepsilon - \gamma_I\theta_I^*)\}}. \quad (\text{A.59})$$

Using θ_I^* from (A.52), and the spanning condition $b_n = \lambda_0 + C(\omega_n)^\top \lambda$, we obtain:

$$C(\omega_n)^\top (\lambda\varepsilon - \gamma_I\theta_I^*) = (b_n - \lambda_0)\varepsilon - \frac{(1-h)/\gamma_U C(\omega_n)^\top \hat{\lambda}}{h/\gamma_I + (1-h)/\gamma_U} + \frac{1}{h/\gamma_I + (1-h)/\gamma_U} C(\omega_n)^\top \nu, \quad (\text{A.60})$$

where $\hat{\lambda}$ is such that $\ln(\pi_n(\varepsilon)/\pi_n^U(p)) = \hat{\lambda}_0 + C(\omega_n)^\top \hat{\lambda}$. Hence, $C(\omega_n)^\top \hat{\lambda} = \ln(\pi_n(\varepsilon)/\pi_n^U(p)) - \hat{\lambda}_0$. Substituting $C(\omega_n)^\top \hat{\lambda}$ and $\ln(\pi_n(\varepsilon)/\pi_n^U(p))$ from (A.57) into (A.60), after some algebra, we find that $a_n + C(\omega_n)^\top (\lambda\varepsilon - \gamma_I\theta_I^*) = v_n + \text{const}$, where v_n is given by (18) in which $\lambda, \nu \in \mathbb{R}^{M-1}$, $\Omega \in \mathbb{R}^{(N-1) \times (M-1)}$, and $E, Q \in \mathbb{R}^{(M-1) \times (M-1)}$, and *const* does not depend on ω_n . Substituting $a_n + C(\omega_n)^\top (\lambda\varepsilon - \gamma_I\theta_I^*)$ into (A.59), we find the price. ■

Proof of Proposition 5. Consider an atomistic uninformed investor that becomes informed and has risk aversion γ_U and wealth $\widetilde{W}_I$. The prices are not affected by this investor becoming informed. From equation (34) for the trading strategy of the informed investor, we see that $\gamma_I\theta_I^*$ does not depend on γ_I . Hence, $\gamma_I W_I$ is the same for all informed investors,

up to a constant. Therefore, equation (39) for the marginal rate of substitution also holds (albeit with a different constant $\tilde{\ell}$) for the informed investor with risk aversion γ_U . Taking conditional expectation $\mathbb{E}[\cdot|s]$ on both sides of the latter equation, we obtain:

$$\frac{\mathbb{E}[\pi_n(\varepsilon) \exp\{-\gamma_U \widetilde{W}_{I,T,n}\}|s]}{\pi_n^U(p) \exp\{-\gamma_U W_{U,T,n}\}} = e^{\tilde{\ell} + \ell_n}, \quad (\text{A.61})$$

where $\tilde{\ell}$ does not depend on ω_n . We note that ℓ_n is not affected by taking conditional expectations on both sides of (39) since it does not depend on ε [see Lemma A.9 below].

Let $J_I(W_0)$ be the expected utility of the atomistic uninformed investor who becomes informed, under probabilities $\pi_n(\varepsilon)$, and $J_U(W_0)$ be the expected utility of the uninformed investor. From the uninformed investor's point of view, the expected utility of the informed investor is $\mathbb{E}[J_I|s]$. Using equation (A.61), we obtain:

$$\begin{aligned} \mathbb{E}[J_I|s] &= -\mathbb{E}[\sum_{n=1}^N \pi_n(\varepsilon) \exp\{-\gamma_U \widetilde{W}_{I,T,n}\}|s] = -\sum_{n=1}^N \pi_n^U(p) \exp\{-\gamma_U W_{U,T,n} + \tilde{\ell} + \ell_n\} \\ &= -\sum_{n=1}^N \pi_n^{\text{RN},U}(p) \exp\{\tilde{\ell} + \ell_n\} \sum_{n=1}^N \pi_n^U(p) \exp\{-\gamma_U W_{U,T,n}\} \\ &= \exp\{\tilde{\ell}\} \mathbb{E}^{\text{RN},U}[\exp\{\ell_n\}] J_U = \exp\{\hat{\ell} + \kappa^U\} J_U, \end{aligned} \quad (\text{A.62})$$

where $\hat{\ell} = \tilde{\ell} - \mathbb{E}^{\text{RN},U}[\ell_n]$, where J_U is the expected utility of investor U , and $\mathbb{E}^{\text{RN},U}[\cdot]$ is the expectation under the risk-neutral measure of investor U in (36). Let $\widehat{W}$ be the amount of wealth that investor U is willing to give up to become informed, so that $\mathbb{E}[J_I(W_0 - \widehat{W})|s] = J_U(W_0)$. We note that $\mathbb{E}[J_I(W_0 - \widehat{W})|s] = \mathbb{E}[J_I(W_0)|s] \exp\{\gamma_U \widehat{W}\}$. Therefore, $\mathbb{E}[J_I(W_0 - \widehat{W})|s] = \exp\{\gamma_U \widehat{W} + \hat{\ell} + \kappa^U\} J_U(W_0)$, and hence, $\widehat{W} = -(\hat{\ell} + \kappa^U)/\gamma_U$. It remains now to find $\hat{\ell}$.

Define function $F(z) = \mathbb{E}[\exp\{z\varepsilon\}/\sum_{j=1}^N \exp\{a_j + b_j\varepsilon\}]$. Substituting $\pi_n(\varepsilon)$, $\pi_n^U(p) = \mathbb{E}[\pi_n(\varepsilon)|s]$, and θ_I^* from (30) into (A.61), we obtain:

$$\exp\{(\widehat{\theta}_I^*(p) + \gamma_U \theta_U^*)^\top (C(\omega_n) - e^{rT} p)\} \frac{F(\lambda_0 + e^{rT} \lambda^\top p)}{F(b_n)} = \exp\{\tilde{\ell} + \ell_n\}. \quad (\text{A.63})$$

Using the informational spanning condition (28), we find that $\lambda_0 + e^{rT} \lambda^\top p = \lambda_0 + \lambda^\top \mathbb{E}^{\text{RN},U}[C(\omega_n)] = \mathbb{E}^{\text{RN},U}[b_n]$. Using the latter fact, equation (A.63) for function $F(z)$ in Lemma A.10 below, and taking logs on both sides of equation (A.63), we obtain:

$$\begin{aligned} &(\widehat{\theta}_I^*(p) + \gamma_U \theta_U^*)^\top (C(\omega_n) - e^{rT} p) + \frac{(h\lambda^\top \Sigma_\nu^{-1} s/\gamma_I + \mu_0/\sigma_0 + \mathbb{E}^{\text{RN},U}[b_n])^2}{h^2 \lambda^\top \Sigma_\nu^{-1} \lambda/\gamma_I^2 + 1/\sigma_0^2} \\ &- \frac{(h\lambda^\top \Sigma_\nu^{-1} s/\gamma_I + \mu_0/\sigma_0 + b_n)^2}{h^2 \lambda^\top \Sigma_\nu^{-1} \lambda/\gamma_I^2 + 1/\sigma_0^2} = \hat{\ell} + (\ell_n - \mathbb{E}^{\text{RN},U}[\ell(\omega)]). \end{aligned}$$

Next, we take expectation $\mathbb{E}^{\text{RN},U}[\cdot]$ on both sides of the above equation, and notice that its first term cancels because $\mathbb{E}^{\text{RN},U}[C(\omega_n)] = e^{rT}p$. Then, after some algebra, we obtain

$$\hat{\ell} = -\frac{1}{2} \frac{\text{var}^{\text{RN},U}[b_n]}{h^2 \lambda^\top \Sigma_\nu^{-1} \lambda / \gamma_I^2 + 1/\sigma_0^2}.$$

As shown above, $\widehat{W} = -(\hat{\ell} + \kappa^U)/\gamma_U$, and hence, we obtain equation (43). ■

Lemma A.9. 1) *The measure of market incompleteness κ^U given by equation (37) and the time-varying parameter ℓ_n of the probability-weighted ratio of marginal utilities (39) are functions of the sufficient statistic s , and depend on ε only via s .*

2) *If $C \sim \mathcal{N}(\mu_C, \sigma_C^2)$, then the measure of market incompleteness (37) is given by:*

$$\kappa^U = \frac{1}{2} \left(\frac{1/\sigma_0^2 + 1/\sigma_C^2}{1/\sigma_{inc}^2 + 1/\sigma_C^2} - 1 - \ln \left(\frac{1/\sigma_0^2 + 1/\sigma_C^2}{1/\sigma_{inc}^2 + 1/\sigma_C^2} \right) \right), \quad (\text{A.64})$$

where σ_{inc} is given in (47).

Proof of Lemma A.9. 1) Substituting θ_I^* from (30) into wealth W_I , we find that the probability $\pi_n^{\text{RN},I}$ in (36) is given by:

$$\pi_n^{\text{RN},I} = \frac{\exp\{a_n + b_n \varepsilon - (\lambda \varepsilon - \hat{\theta}_I^*(p))^\top C(\omega_n)\}}{\sum_{j=1}^N \exp\{a_j + b_j \varepsilon - (\lambda \varepsilon - \hat{\theta}_I^*(p))^\top C(\omega_j)\}} = \frac{\exp\{a_n + \hat{\theta}_I^*(p)^\top C(\omega_n)\}}{\sum_{j=1}^N \exp\{a_j + \hat{\theta}_I^*(p)^\top C(\omega_j)\}},$$

where the second equality uses $\lambda^\top C(\omega_n) = b_n - \lambda_0$ from the informational spanning condition (28). Hence, $\pi_n^{\text{RN},I}$ only depends on s via the asset prices p . Probability $\pi_n^{\text{RN},U}$ in (36) depends only on s because investor U does not observe ε . Hence, κ^U in (37) does not depend on ε . Finally, from equations (36) for the risk-neutral measures and the ratio of probability-weighted marginal utilities (39) we observe that ℓ_n can be chosen such that $\exp\{\ell_n\} = \pi_n^{\text{RN},I} / \pi_n^{\text{RN},U}$, and then ℓ_n does not depend on ε as shown above.

2) Next, we derive the measure of market incompleteness in a setting where $C \sim N(\mu_C, \sigma_C^2)$ and $\varepsilon = C + u$, where $u \sim N(\mu_0, \sigma_0^2)$. Equation (46) for the asset prices in incomplete markets implies that the risk-neutral measures of investor I and U are given by:

$$\pi^{\text{RN},i} = \frac{\exp\{-0.5(C_1 - \mu_i)^2/\sigma_i^2\} - 0.5(C_1 - \mu_C)^2/\sigma_C^2}{\int_{-\infty}^{\infty} \exp\{-0.5(C_1 - \mu_i)^2/\sigma_i^2\} - 0.5(C_1 - \mu_C)^2/\sigma_C^2 dC_1}, \quad i = I, U, \quad (\text{A.65})$$

where $\sigma_I = \sigma_0$, $\sigma_U = \sigma_{inc}$ given by (47), and

$$\mu_I = \hat{s}(s)/h - \mu_0, \quad \mu_U = \gamma_I \sigma_0^2 s/h - \mu_0 + \gamma_U \sigma_{inc}^2 (s - \hat{s}(s))/(1-h), \quad (\text{A.66})$$

and $\hat{s}(s)$ solves the consistency equation (46). Simplifying equation (A.65) we obtain:

$$\pi^{\text{RN},i} = \frac{\exp\left\{-0.5\left(1/\sigma_i^2 + 1/\sigma_C^2\right)\left(C_1 - \frac{\mu_i/\sigma_i^2 + \mu_C/\sigma_C^2}{1/\sigma_i^2 + 1/\sigma_C^2}\right)\right\}}{\sqrt{2\pi} \sqrt{\sigma_i^2 \sigma_C^2 / (\sigma_i^2 + \sigma_C^2)}}. \quad (\text{A.67})$$

Moreover, the consistency equation (46) takes the form:

$$\frac{\mu_I/\sigma_I^2 + \mu_C/\sigma_C^2}{1/\sigma_I^2 + 1/\sigma_C^2} = \frac{\mu_U/\sigma_U^2 + \mu_C/\sigma_C^2}{1/\sigma_U^2 + 1/\sigma_C^2}. \quad (\text{A.68})$$

Then, substituting measures (A.67) into the measure of incompleteness (37) and using (A.68), after some algebra, we find that κ^U is given by equation (A.64). ■

Lemma A.10. *Let $F(z) = \mathbb{E}[\exp\{z\varepsilon\}/\sum_{j=1}^N \exp\{a_j + b_j\varepsilon\}]$. Then, $F(z)$ is given by*

$$F(z) = \exp\left\{\frac{(h\lambda^\top \Sigma_\nu^{-1}s/\gamma_I + \mu_0/\sigma_0 + z)^2}{h^2\lambda^\top \Sigma_\nu^{-1}\lambda/\gamma_I^2 + 1/\sigma_0^2}\right\} \frac{1}{\widehat{G}(s)}, \quad (\text{A.69})$$

where $\widehat{G}(s)$ does not depend on z .

Proof of Lemma A.10. Using conditional PDF (A.8), we obtain:

$$F(z) = \int_{-\infty}^{\infty} \exp\{z\varepsilon - 0.5(s - h\lambda\varepsilon/\gamma_I)^\top \Sigma_\nu^{-1}(s - h\lambda\varepsilon/\gamma_I - 0.5(\varepsilon - \mu_0)^2/\sigma_0^2)\} \frac{d\varepsilon}{G(s)},$$

where $G(s)$ does not depend on z . Integrating, we obtain equation (A.69). ■

Proof of Proposition 6. By Lemma A.2, the model is a limiting case of a discrete model with parameters a_n and b_n given by Equations (7) when $N \rightarrow \infty$. Therefore, we derive prices for the discrete state-space case and then take the limit $N \rightarrow \infty$.

First, consider an effectively complete market with a quadratic derivative $C_1(\omega_n)^2$. Because $b_n = C_1(\omega_n)/\sigma_0^2$, we obtain that $\lambda = (1/\sigma_0^2, 0)^\top$, where λ is defined in Condition (28), and hence, $C_1(\omega_n)^2$ is informationally irrelevant. By Proposition 4, the asset prices are given by equation (16) in terms of v_n in (18). Because, by assumption, there is no noise in the market for $C_1(\omega_n)^2$, we take the limit in which noise $\nu_2 \rightarrow 0$ in the equation for prices.⁹ Substituting a_n and b_n from (7) and $\lambda = (1/\sigma_0^2, 0)^\top$ in equation (18) for v_n , taking limit $\nu_2 \rightarrow 0$ and denoting $s = h\varepsilon/(\gamma_I\sigma_0^2) + \nu_1$, after some algebra, we obtain:

$$\begin{aligned} v_n = & -\frac{C_1(\omega_n)^2}{2\sigma_{com}^2} - C_1(\omega_n) \left(\frac{\mu_0}{\sigma_{com}^2} - \frac{1}{h/\gamma_I + (1-h)/\gamma_U} \left(1 + \frac{h(1-h)/(\gamma_I\gamma_U\sigma_\nu^2\sigma_0^2)}{1+h^2/(\gamma_I^2\sigma_\nu^2\sigma_0^2)} \right) s \right) \\ & + \ln[\varphi_C(C_1(\omega_n))] = -\frac{(C_1(\omega_n) - (\gamma_I\sigma_0^2s/h - \mu_0))^2}{2\sigma_{com}^2} + \ln[\varphi_C(C_1(\omega_n))] + \frac{(\gamma_I\sigma_0^2s/h - \mu_0)^2}{2\sigma_{com}^2}, \end{aligned}$$

where volatility parameter σ_{com}^2 is given in (47). Substituting v_n into Equations (17) and

⁹When $\nu_2 = 0$ the same prices $P(\varepsilon, \nu)$ can be obtained directly without taking the limit.

(16) for the risk-neutral probabilities and prices, we obtain:

$$\begin{aligned}
P_{com}(s) &= \frac{\sum_{n=1}^N C_1(\omega_n) \exp\left(-\frac{(C_1(\omega_n) - \gamma_I \sigma_0^2 s/h + \mu_0)^2}{2\sigma_{com}^2}\right) \varphi_C(C_1(\omega_n))}{\sum_{n=1}^N \exp\left(-\frac{(C_1(\omega_n) - \gamma_I \sigma_0^2 s/h + \mu_0)^2}{2\sigma_{com}^2}\right) \varphi_C(C_1(\omega_n))} e^{-rT} \\
&= \frac{\mathbb{E}\left[C_1 \exp\left(-\frac{(C_1 - \gamma_I \sigma_0^2 s/h + \mu_0)^2}{2\sigma_{com}^2}\right)\right]}{\mathbb{E}\left[\exp\left(-\frac{(C_1 - \gamma_I \sigma_0^2 s/h + \mu_0)^2}{2\sigma_{com}^2}\right)\right]} e^{-rT} \equiv P_C(\gamma_I \sigma_0^2 s/h - \mu_0, \sigma_{com}) e^{-rT}.
\end{aligned} \tag{A.70}$$

Equation (A.70) gives the price $P_{com}(s)$ in (44) for the discrete state-space, and it also holds for continuous state-space by taking the limit $N \rightarrow \infty$.

Next, we turn to the incomplete-market case with one risky asset and derive prices using $P(\varepsilon, \nu) = f_I(x_I)e^{-rT} = f_U(x_U)e^{-rT}$, which follows from FOC (A.28) and condition (A.34). Substituting $f_I(x)$ and $f_U(x)$ from Equations (32) and (33) into the equation for $P(\varepsilon, \nu)$ and observing that $\Sigma_\nu = \sigma_\nu^2$, we obtain:

$$\begin{aligned}
P_{inc}(s)e^{rT} &= \frac{\sum_{n=1}^N C_1(\omega_n) \exp\{a_n + C_1(\omega_n)x_I\}}{\sum_{n=1}^N \exp\{a_n + C_1(\omega_n)x_I\}} \\
&= \frac{\sum_{n=1}^N C_1(\omega_n) \exp\{a_n + \frac{1}{2} \frac{b_n^2}{h^2 \lambda^2 / (\gamma_I^2 \sigma_\nu^2) + 1 / \sigma_0^2} + C_1(\omega_n)x_U\}}{\sum_{n=1}^N \exp\{a_n + \frac{1}{2} \frac{b_n^2}{h^2 \lambda^2 / (\gamma_I^2 \sigma_\nu^2) + 1 / \sigma_0^2} + C_1(\omega_n)x_U\}},
\end{aligned}$$

where x_I and x_U solve the system of equations (A.33) and (A.34). Substituting $\lambda = 1/\sigma_0^2$, a_n and b_n from (7) into the above equation for $P_{inc}(s)$, similarly to (A.70) we obtain:

$$P_{inc}(s) = P_C(\sigma_0^2 x_I - \mu_0, \sigma_0) e^{-rT} = P_C(\sigma_{inc}^2 x_U - \mu_0 \sigma_{inc}^2 / \sigma_0^2, \sigma_{inc}) e^{-rT}, \tag{A.71}$$

where volatility σ_{inc} is given in (47). Next, from equation (A.33), we express x_U in terms of x_I and, after some algebra, we find that $\sigma_{inc}^2 x_U - \mu_0 \sigma_{inc}^2 / \sigma_0^2 = \gamma_I \sigma_0^2 s/h - \mu_0 + \gamma_U \sigma_{inc}^2 (s - hx_I/\gamma_I)/(1-h)$. Substituting the latter equality into the second equation in (A.71) and denoting $\hat{s}(s) \equiv hx_I/\gamma_I$, we obtain price $P_{inc}(s)$ in (44), and also equation (46) for $\hat{s}(s)$.

Differentiating $P_C(\mu, \sigma)$ with respect to μ , after some algebra, we obtain:

$$\frac{\partial P_C(\mu, \sigma)}{\partial \mu} = \frac{\mathbb{E}\left[C_1^2 \exp\left(-\frac{(C_1 - \mu)^2}{2\sigma^2}\right)\right]}{\sigma^2 \mathbb{E}\left[\exp\left(-\frac{(C_1 - \mu)^2}{2\sigma^2}\right)\right]} - \left(\frac{\mathbb{E}\left[C_1 \exp\left(-\frac{(C_1 - \mu)^2}{2\sigma^2}\right)\right]}{\sigma \mathbb{E}\left[\exp\left(-\frac{(C_1 - \mu)^2}{2\sigma^2}\right)\right]}\right)^2 = \frac{\widehat{\text{var}}[C_1]}{\sigma^2} > 0,$$

where variance $\widehat{\text{var}}[C_1]$ is calculated under the new probability measure, which is given by $\varphi_C(C_1) \exp(-(C_1 - \mu)^2/(2\sigma^2)) / \mathbb{E}[\exp(-(C_1 - \mu)^2/(2\sigma^2))]$. Therefore, $P_C(\mu, \sigma)$ is an increasing function of μ , and hence, $P_{com}(s)$ is increasing in s . Differentiating equation (46) with respect to s and solving for $\hat{s}'(s)$, we find that:

$$\hat{s}'(s) = \frac{\gamma_I \sigma_0^2 (\partial P_C(\mu_U(s), \sigma_{inc}) / \partial \mu)}{\gamma_I \sigma_0^2 (\partial P_C(\mu_I(s), \sigma_0) / \partial \mu) + \gamma_U \sigma_{inc}^2 (\partial P_C(\mu_U(s), \sigma_{inc}) / \partial \mu)} > 0,$$

where $\mu_I(s) = \gamma_I \sigma_0^2 \hat{s}(s)/h - \mu_0$ and $\mu_U(s) = \gamma_I \sigma_0^2 s/h - \mu_0 + \gamma_U \sigma_{inc}^2 (s - \hat{s}(s))/(1-h)$. Hence, $P_{inc}(s) = P_C(\gamma_I \sigma_0^2 \hat{s}(s)/h - \mu_0, \sigma_{inc})$ is an increasing function of s . ■

Proof of Proposition 7. From formula 8.957 in Gradshteyn and Ryzhik (2007)

$$e^{xt-0.5t^2} = \sum_{n=0}^{\infty} H_n(x) \frac{t^n}{n!}, \quad (\text{A.72})$$

where $H_{n+1}(x) = 2xH_n(x) - 2nH_{n-1}(x)$ (formula 8.952 in Gradshteyn and Ryzhik (2007)). Then, we note that

$$\exp\left(-\frac{(C_1 - \mu)^2}{2\sigma^2}\right) = \exp\left(-\frac{(C_1 - \mu_C)^2}{2\sigma_C^2} \frac{\sigma_C^2}{\sigma^2} + \frac{C_1 - \mu_C}{\sigma_C} \frac{\sigma_C}{\sigma} \frac{\mu - \mu_C}{\sigma} - \frac{(\mu - \mu_C)^2}{2\sigma^2}\right). \quad (\text{A.73})$$

Next, we expand (A.73) using (A.72), and then substituting the result into equation (45), we obtain the expansion (49). ■

Proof of Corollary 3. Similar to the derivation of the prices in incomplete and complete markets in Proposition 7, we find that $\mathbb{E}^U[C_1] = P_C(\gamma_I \sigma_0^2 s/h - \mu_0, \sigma_{inc})$, where σ_{inc} is given in equation (47). Next, we consider the expansion (49) and retain only terms that have the order of magnitude $1/\sigma_0$ and $1/\sigma_0^2$. We note that when $1/\sigma_0^2$ is small then $1/\sigma^2$, where σ is either σ_{com} or σ_{inc} is even smaller. Hence, from the expansion (49) we obtain the following approximation:

$$P_C(\mu, \sigma) \approx \mu_C + \frac{\sigma_C^2}{\sigma^2} (\mu - \mu_C) + \frac{\sigma_C^3}{2\sigma^2} \left[\left(\frac{\mu - \mu_C}{\sigma} \right)^2 - 1 \right]. \quad (\text{A.74})$$

Using equation (A.74), we obtain the following expression for the risk premium:

$$\begin{aligned} \mathbb{E}^U[C] - P_{com}(s)e^{rT} &= P_C(\gamma_I \sigma_0^2 s/h - \mu_0, \sigma_{inc}) - P_C(\gamma_I \sigma_0^2 s/h - \mu_0, \sigma_{com}) \\ &\approx \frac{\sigma_C^2}{\sigma_{inc}^2} (\gamma_I \sigma_0^2 s/h - \mu_0 - \mu_C) + \frac{\sigma_C^3}{2\sigma_U^2} \left[\left(\frac{\gamma_I \sigma_0^2 s/h - \mu_0 - \mu_C}{\sigma_U} \right)^2 - 1 \right] \\ &\quad - \frac{\sigma_C^2}{\sigma_{com}^2} (\gamma_I \sigma_0^2 s/h - \mu_0 - \mu_C) - \frac{\sigma_C^3}{2\sigma_{com}^2} \left[\left(\frac{\gamma_I \sigma_0^2 s/h - \mu_0 - \mu_C}{\sigma_{com}} \right)^2 - 1 \right], \end{aligned}$$

where σ_{inc} and σ_{com} are given in (47). The above expression depends on a random sufficient statistic s . Next, we take the expectation with regard to s , and taking into account that $\mathbb{E}[\gamma_I \sigma_0^2 s/h - \mu_0 - \mu_C] = 0$ and $\text{var}[s] = h^2 \sigma_\varepsilon^2 / (\gamma_I^2 \sigma_0^4) + \sigma_\nu^2$, we obtain:

$$\overline{\mathbb{E}^U[C] - P_{com}(s)e^{rT}} \approx -\frac{m_3 \sigma_C^3}{2} \frac{h/\gamma_I}{h/\gamma_I + (1-h)/\gamma_U} \left(\frac{\sigma_C^2}{\sigma_{inc}^2} + \frac{1}{\sigma_{com}^2} \right) \frac{1}{1 + h^2/(\gamma_I^2 \sigma_\nu^2 \sigma_0^2)} + \frac{\gamma_I^2 \sigma_0^2 \sigma_\nu^2 / h^2}{\sigma_{com}^2}.$$

The above expression shows that $\overline{\mathbb{E}^U[C] - P_{com}(s)e^{rT}} \approx -m_3 \sigma_C^3 A(h)$, where $A(h) > 0$. To further simplify the expression for the risk premium, we ignore terms of the order σ_C^5 , and

assume that $\gamma_U = \gamma_I = \gamma$. Then, after some algebra, we obtain:

$$\begin{aligned}\overline{\mathbb{E}^U[C] - P_{com}(s)e^{rT}} &\approx -\frac{m_3\sigma_C^3}{2} \frac{h/\gamma_I}{h/\gamma_I + (1-h)/\gamma_U} \left(\frac{\gamma_I^2\sigma_0^2\sigma_\nu^2/h^2}{\sigma_{com}^2} \right) \\ &= -\frac{m_3\sigma_C^3}{2} \left(\gamma^2\sigma_\nu^2 + \frac{h(1-h)}{\sigma_0^2 + h^2/(\gamma^2\sigma_\nu^2)} \right). \blacksquare\end{aligned}$$

Proof of Proposition 8. i) We derive equation (54) by substituting PDF (51) into equation (45), and then finding the expectations in equation (45) in closed form.

ii) Rewriting the expectations under the generalized gamma distribution (52) in the pricing function (45) as integrals, after simple algebra, we obtain:

$$P_C(\mu, \sigma; k) = \frac{\int_0^{+\infty} C_1^k \exp \left\{ -\frac{1}{2} \left(\frac{1}{\hat{\sigma}_C^2} + \frac{1}{\sigma_0^2} \right) C_1^2 + \left(\frac{\mu}{\sigma^2} - \delta \right) C_1 \right\} dC_1}{\int_0^{+\infty} C_1^{k-1} \exp \left\{ -\frac{1}{2} \left(\frac{1}{\hat{\sigma}_C^2} + \frac{1}{\sigma_0^2} \right) C_1^2 + \left(\frac{\mu}{\sigma^2} - \delta \right) C_1 \right\} dC_1}. \quad (\text{A.75})$$

For the case $k = 1$ the above pricing function can be easily computed in closed form, and is given in equation (55) for $k = 1$. For general integer $k > 1$, denote the integrals in the numerator and the denominator of (A.75) by I_k and I_{k-1} , respectively. Using integration by parts, we obtain the following recursive equation for I_k :

$$\begin{aligned}I_k &= \frac{\hat{\sigma}_C^2\sigma^2}{\hat{\sigma}_C^2 + \sigma^2} \left[\left(\frac{\mu}{\sigma^2} - \delta \right) I_{k-1} - \int_0^{+\infty} C_1^{k-1} \left(\exp \left\{ -\frac{1}{2} \left(\frac{1}{\hat{\sigma}_C^2} + \frac{1}{\sigma_0^2} \right) C_1^2 + \left(\frac{\mu}{\sigma^2} - \delta \right) C_1 \right\} \right)' dC_1 \right] \\ &= \frac{\hat{\sigma}_C^2\sigma^2}{\hat{\sigma}_C^2 + \sigma^2} \left(\left(\frac{\mu}{\sigma^2} - \delta \right) I_{k-1} + (k-1)I_{k-2} \right).\end{aligned}$$

Dividing both sides by I_{k-1} and using $P_C(\mu, \sigma; k) = I_k/I_{k-1}$, we obtain equation (55).

iii) Under the skew-normal distribution (53) the pricing function (45) becomes:

$$P_C(\mu, \sigma) = \frac{\int_{-\infty}^{+\infty} C_1 \exp \left\{ -\frac{(C_1 - \mu)^2}{2\sigma^2} - \frac{(C_1 - \hat{\mu}_C)^2}{2\hat{\sigma}_C^2} \right\} \Phi \left(\alpha \frac{C_1 - \hat{\mu}_C}{\hat{\sigma}_C} \right) dC_1}{\int_{-\infty}^{+\infty} \exp \left\{ -\frac{(x - \mu)^2}{2\sigma^2} - \frac{(C_1 - \hat{\mu}_C)^2}{2\hat{\sigma}_C^2} \right\} \Phi \left(\alpha \frac{C_1 - \hat{\mu}_C}{\hat{\sigma}_C} \right) dC_1}. \quad (\text{A.76})$$

Denote by J_1 and J_0 the integrals in the numerator and the denominator, respectively.

After some algebra and integration by parts, we obtain:

$$\begin{aligned}J_1 &= \exp \left\{ -\frac{1}{2} \frac{(\mu - \hat{\mu}_C)^2}{\hat{\sigma}_C^2 + \sigma^2} - \frac{1}{2} \frac{(\hat{\mu} - \mu)^2}{\hat{\sigma}_C^2/\alpha^2 + \hat{\sigma}^2} \right\} \frac{\text{sgn}(\alpha)\hat{\sigma}^3}{\sqrt{\hat{\sigma}_C^2/\alpha^2 + \hat{\sigma}^2}} + \frac{\hat{\sigma}_C^2\mu + \sigma^2\hat{\mu}_C}{\hat{\sigma}_C^2 + \sigma^2} J_0, \\ J_0 &= \exp \left\{ -\frac{1}{2} \frac{(\mu - \hat{\mu}_C)^2}{\hat{\sigma}_C^2 + \sigma^2} \right\} \int_{-\infty}^{\infty} \exp \left\{ -\frac{(x - \hat{\mu})^2}{2\hat{\sigma}^2} \right\} \Phi \left(\alpha \frac{x - \hat{\mu}_C}{\hat{\sigma}_C} \right) dx \\ &= \sqrt{2\pi}\hat{\sigma} \exp \left\{ -\frac{1}{2} \frac{(\mu - \hat{\mu}_C)^2}{\hat{\sigma}_C^2 + \sigma^2} \right\} \Phi \left(\frac{\text{sgn}(\alpha)(\hat{\mu} - \hat{\mu}_C)}{\sqrt{\hat{\sigma}_C^2/\alpha^2 + \hat{\sigma}^2}} \right),\end{aligned}$$

where $\hat{\sigma} = \hat{\sigma}_C^2 \sigma^2 / (\hat{\sigma}_C^2 + \sigma^2)$, $\hat{\mu} = (\hat{\sigma}_C^2 \mu + \sigma^2 \hat{\mu}_C) / (\hat{\sigma}_C^2 + \sigma^2)$, and the computation of J_0 uses the following integral 8.259.1 in Gradshteyn and Ryzhik (2007): $\int_{-\infty}^{\infty} \exp(-px^2) \operatorname{erf}(a+bx) dx = (\sqrt{\pi/p}) \operatorname{erf}(a\sqrt{p}/\sqrt{b^2+p})$, where the error function is given by $\operatorname{erf}(x) \equiv 2\Phi(x\sqrt{2}) - 1$. After some algebra, we obtain $P_C(\mu, \sigma) = J_1/J_0$ given by equation (56). ■

Proof of Lemma 7. For the case of $C_1 \sim \mathcal{N}(\mu_C, \sigma_C^2)$ from equation (54) with $L = 1$, we observe that $P_C(\mu, \sigma) = (\mu\sigma_C^2 + \mu_C\sigma^2)/(\sigma_C^2 + \sigma^2)$. Consequently, equation (46) for $\hat{s}(s)$ becomes linear. Solving the latter equation, we obtain:

$$\hat{s}(s) = \frac{\sigma_C^2 + \sigma_0^2}{\sigma_{com}^2 + \sigma_C^2} s + \frac{\mu_0 + \mu_C}{\sigma_{com}^2 + \sigma_C^2} \frac{\sigma_{com}^2 - \sigma_0^2}{\gamma_I \sigma_0^2 / h}, \quad (\text{A.77})$$

where σ_{com} is given in (47). Substituting (A.77) into (44), after some algebra, we obtain:

$$P_{inc}(s) = \frac{(\gamma_I \sigma_0^2 \hat{s}(s)/h - \mu_0) \sigma_C^2 + \mu_C \sigma_0^2}{\sigma_C^2 + \sigma_0^2} = \frac{(\gamma_I \sigma_0^2 s/h - \mu_0) \sigma_C^2 + \mu_C \sigma_{com}^2}{\sigma_{com}^2 + \sigma_0^2} = P_{com}(s), \quad (\text{A.78})$$

and hence, the two prices coincide. After some algebra, we obtain equation (48) for the price. ■

Proof of Proposition 8. Differentiating equation (31) for the incomplete market price, we obtain

$$\frac{\partial}{\partial \nu} \left(\frac{h f_I^{-1}(e^{rT} P)}{\gamma_I} + \frac{(1-h) f_U^{-1}(e^{rT} P)}{\gamma_I} \right) = E + Q. \quad (\text{A.79})$$

Next, we use the fact that $\partial f^{-1}(y)/\partial y = f'(x)^{-1}$. Differentiating functions $f_I(x)$ and $f_U(x)$, and noting that $x_I = f_I^{-1}(e^{rT} P)$ and $x_U = f_U^{-1}(e^{rT} P)$ are given by equations (A.35), we obtain that $f'_I(x_I) = \operatorname{var}^{\text{RN}, I}[C]$ and $f'_U(x_U) = \operatorname{var}^{\text{RN}, U}[C]$. Substituting the expressions for derivatives into equation (A.79), after some algebra, we obtain the expression for $\partial P/\partial \nu$ for the incomplete market in equation (58). Equation (57) for the complete market can be obtained as a special case of (58) when $\operatorname{var}^{\text{RN}, I}[C] = \operatorname{var}^{\text{RN}, U}[C] = \operatorname{var}^{\text{RN}}[C]$, because the risk-neutral measure in the complete market is unique. ■

Lemma A.11. *Consider an economy where the probabilities of states are given by equation (1) and the distribution of shocks is given by (2). Suppose, the informed investor observes a noisy signal $\hat{\varepsilon} = \varepsilon + z$, where $z \sim \mathcal{N}(0, \sigma_z^2)$. Then, the economy is equivalent to the baseline economy where the probabilities of states and the shock distribution are as in (59) and the informed investor observes shock $\hat{\varepsilon}$.*

Proof of Lemma A.11. Using Bayes' law, we observe that

$$\varphi_{\varepsilon|\hat{\varepsilon}}(x|y) = \frac{\varphi_{\hat{\varepsilon}|\varepsilon}(y|x) \varphi_{\varepsilon}(x)}{\varphi_{\hat{\varepsilon}}(y)} = \frac{\sum_{j=1}^N \exp\{a_n + b_n x\} \exp\{-0.5(y-x)^2/\sigma_z^2 - 0.5(x-\mu_0)^2/\sigma_0^2\}}{\varphi_{\hat{\varepsilon}}(y)}.$$

Using the law of total probability, after some algebra, we find that

$$\pi_n(\hat{\varepsilon}) = \int_{-\infty}^{\infty} \pi_n(x) \varphi_{\varepsilon|\hat{\varepsilon}}(x|\hat{\varepsilon}) dx = \frac{e^{\hat{a}_n + \hat{b}_n \hat{\varepsilon}}}{\sum_{j=1}^N e^{\hat{a}_j + \hat{b}_j \hat{\varepsilon}}},$$

$$\varphi_{\varepsilon}(y) = \int_{-\infty}^{\infty} \varphi_{\varepsilon|\varepsilon}(x|y) \varphi_{\varepsilon}(x) dx = \frac{\left(\sum_{j=1}^N e^{\hat{a}_j + \hat{b}_j y} \right) e^{-0.5(y-\mu_0)^2/(\sigma_0^2 + \sigma_z^2)}}{\int_{-\infty}^{\infty} \left(\sum_{j=1}^N e^{\hat{a}_j + \hat{b}_j y} \right) e^{-0.5(y-\mu_0)^2/(\sigma_0^2 + \sigma_z^2)} dy},$$

where $\hat{a}_n = a_n + 0.5(b_n + \mu_0/\sigma_0^2)^2/(1/\sigma_z^2 + 1/\sigma_0^2)$ and $\hat{b}_n = b_n/(1 + \sigma_z^2/\sigma_0^2)$. Investor U learns $\hat{\varepsilon}$ from asset prices in the same way as in the baseline model. ■

Internet Appendix

“Multi-Asset Noisy Rational Expectations Equilibrium with Contingent Claims”

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In this Internet Appendix, we present several extensions of our model to demonstrate the robustness of our methodology and results to various alternative specifications. In Section IA1, we examine a complete market economy where probabilities of states, and distributions of shock ε and noise trader demands ν are general. In Section IA2, we extend our analysis to the economy with random endowment shocks and without noise traders. In Section IA3, we consider a model of information aggregation with multiple heterogeneously informed investors. Finally, in Section IA4, we generalize our results to the case of multidimensional shocks ε .

IA1 Complete Markets with General Distributions

In this section, we extend the analysis of Section 3.1 to a complete-market economy with general probabilities of states $\pi_n(\varepsilon)$, distribution $\varphi_\varepsilon(x)$ of the aggregate shock, and distribution $\varphi_\nu(z)$ of noise trader demands. For the simplicity of exposition, we assume that informed and uninformed investors and noise traders all have the same mass 0.5, so that the mass parameter is $h = 0.5$. We find asset prices $P(\varepsilon, \nu)$ and investor I 's portfolio $\theta_I^*(p; \varepsilon)$ in closed form in terms of simple integrals, and investor U 's portfolio $\theta_U^*(p)$ as a solution of a fixed-point problem. First, we derive portfolio $\theta_I^*(p; \varepsilon)$ below.

Lemma IA1.1 (Investor I 's optimal portfolio). *Investor I 's optimal portfolio is*

$$\theta_I^*(p; \varepsilon) = \frac{1}{\gamma_I} \Omega^{-1} \left(\tilde{\xi}(\varepsilon) - \tilde{v}(p) \right), \quad (\text{IA.1})$$

where $\Omega \in \mathbb{R}^{(N-1) \times (N-1)}$ is a matrix of excess payoffs with elements $\Omega_{n,k} = C_k(\omega_n) - C_k(\omega_N)$, and $\tilde{\xi}(\varepsilon) \in \mathbb{R}^{N-1}$ and $\tilde{v}(p) \in \mathbb{R}^{N-1}$ are the vectors of log ratios of real and risk-neutral probabilities, respectively, given by:

$$\tilde{\xi}(\varepsilon) = \left(\ln \left(\frac{\pi_1(\varepsilon)}{\pi_N(\varepsilon)} \right), \dots, \ln \left(\frac{\pi_{N-1}(\varepsilon)}{\pi_N(\varepsilon)} \right) \right)^\top, \quad (\text{IA.2})$$

$$\tilde{v}(p) = \left(\ln \left(\frac{\pi_1^{\text{RN}}}{\pi_N^{\text{RN}}} \right), \dots, \ln \left(\frac{\pi_{N-1}^{\text{RN}}}{\pi_N^{\text{RN}}} \right) \right)^\top. \quad (\text{IA.3})$$

Portfolio $\theta_I^*(p; \varepsilon)$ is still available in closed form but is no longer a linear function of ε .¹ Nonetheless, it remains separable in shock ε and prices p . Substituting $\theta_I^*(p; \varepsilon)$ into the market clearing condition (6), we obtain:

$$\frac{\Omega^{-1}\tilde{\xi}(\varepsilon)}{\gamma_I} + \nu + \tilde{H}(p) = 0, \quad (\text{IA.4})$$

where $\tilde{H}(p) = \theta_U^*(p) - \Omega^{-1}\tilde{v}(p)/\gamma_U$. As in the main text, we focus on equilibrium prices that reveal the sufficient statistic $\Omega^{-1}\tilde{\xi}(\varepsilon)/\gamma_I + \nu$. The derivation of equilibrium proceeds in the same way as in Section 3. Proposition IA1.1 reports the result.

Proposition IA1.1 (Equilibrium with $M = N$, general case). *Let probabilities $\pi_n(\varepsilon)$ and PDFs $\varphi_\varepsilon(x)$ and $\varphi_\nu(z)$ of shock ε and noise ν be continuous and bounded functions on $\mathbb{R}$ and $\mathbb{R}^{M-1}$, respectively. Then, the following statements hold.*

i) *If there exists an REE, then the vector of asset prices $P(\varepsilon, \nu)$ and risk-neutral probabilities π_n^{RN} are given by:*

$$P(\varepsilon, \nu) = \left[\pi_1^{\text{RN}} C(\omega_1) + \pi_2^{\text{RN}} C(\omega_2) + \dots + \pi_N^{\text{RN}} C(\omega_N) \right] e^{-rT}, \quad (\text{IA.5})$$

$$\pi_n^{\text{RN}} = \frac{e^{v_n}}{\sum_{j=1}^N e^{v_j}}, \quad (\text{IA.6})$$

where probability parameters v_n are given by:

$$v_n = \frac{\gamma_I}{\gamma_I + \gamma_U} \Psi_n \left(-\frac{\Omega^{-1}\tilde{\xi}(\varepsilon)}{\gamma_I} - \nu \right) + \frac{\gamma_I \gamma_U}{\gamma_I + \gamma_U} C(\omega_n)^\top \left(\frac{\Omega^{-1}\tilde{\xi}(\varepsilon)}{\gamma_I} + \nu \right), \quad (\text{IA.7})$$

where function Ψ_n is given by the following integral:

$$\Psi_n(z) = \ln \left(\int_{-\infty}^{+\infty} \pi_n(x) \varphi_\varepsilon(x) \varphi_\nu \left(-\frac{\Omega^{-1}\tilde{\xi}(x)}{\gamma_I} - z \right) dx \right), \quad (\text{IA.8})$$

and vector $\tilde{\xi}(\varepsilon)$ is given by equation (IA.2). Investor I 's portfolio is given by equation (IA.1) and investor U 's portfolio solves the following fixed point equation:

$$\theta_U^*(p) = \frac{1}{\gamma_U} \Omega^{-1} \left(\tilde{\Psi} \left(\theta_U^*(p) - \frac{\Omega^{-1}\tilde{v}(p)}{\gamma_I} \right) - \tilde{v}(p) \right), \quad (\text{IA.9})$$

¹It is easy to show that in our complete market the distribution of asset payoffs conditional on ε is from the exponential family, that is, has the following form:

$$\text{Prob}(C(\omega_n)|\varepsilon) = \exp \left\{ C(\omega_n)^\top \Omega^{-1}\tilde{\xi}(\varepsilon) - \ln \left[\sum_{i=1}^N \exp \left(C(\omega_i)^\top \Omega^{-1}\tilde{\xi}(\varepsilon) \right) \right] \right\}, \text{ for } n = 1, \dots, N.$$

We are grateful to Bradyn Breon-Drish for pointing this out to us.

where $\tilde{v}(p) \in \mathbb{R}^{N-1}$ has elements $v_n - v_N$, and $\tilde{\Psi}(z) \in \mathbb{R}^{N-1}$ has elements $\Psi_n(z) - \Psi_N(z)$.

ii) The REE in which investor U observes only asset prices exists if and only if $\tilde{\Psi}(s)/\gamma_U - \Omega s : \mathbb{R}^{M-1} \rightarrow \mathbb{R}^{M-1}$ is an invertible function on its range, or equivalently, the price vector $P(\varepsilon, \nu)$ is an invertible function of the sufficient statistic $\Omega^{-1}\tilde{\xi}(\varepsilon)/\gamma_I + \nu$ on its range.

Proposition IA1.1 provides tractable equilibrium prices (IA.5). Finding these prices does not involve solving any equations but may require numerical integration. Investor U 's portfolio $\theta_U^*(p)$ solves a fixed-point equation. The equilibrium is derived in terms of function $\tilde{\Psi}(z)$, which is the vector of log ratios of posterior probabilities of investor U , as shown in the proof of Proposition IA1.1 below. When shock ε has PDF (2) and ν is normally distributed, $\tilde{\Psi}(z)$ becomes a linear function of z . Then, equation (IA.9) for $\theta_U^*(p)$ can be solved in closed form, and the equilibrium coincides with that in Proposition 1.

Proposition IA1.1 provides a necessary and sufficient condition for the existence of equilibrium in which investor U observes only the asset prices. The condition requires function $\tilde{\Psi}(s)/\gamma_U - \Omega s$ to be invertible or, equivalently, price $P(\varepsilon, \nu)$ to be an invertible function of the sufficient statistic on its range. When this condition is satisfied, investor U can infer the sufficient statistic from the prices and calculate posterior probabilities, accordingly. When function $P(\varepsilon, \nu)$ is not invertible, observing $P(\varepsilon, \nu)$ does not reveal the sufficient statistic. This last fact is not consistent with the existence of equilibrium because observing prices reveals the sufficient statistic from the market clearing condition (IA.4). Similar non-existence of equilibrium occurs in a model with one risky asset in Breon-Drish (2010) when the asset price is a non-monotone function of the sufficient statistic. The intuition is that the informed and uninformed investors may trade assets in opposite directions, which makes prices less informative than the sufficient statistic because informed demands are offset by uninformed demands. This may happen when noise trader demands lead to higher asset prices that investor U may confuse with good news about the realization of ε .

When prices $P(\varepsilon, \nu)$ do not reveal the sufficient statistic $\Omega^{-1}\tilde{\xi}(\varepsilon)/\gamma_I + \nu$, it can still be inferred in economies where investor U additionally observes the residual demand of the informed investor and noise traders, $\hat{\Theta} \equiv \theta_I^*(p; \varepsilon) + \nu$. In particular, using the informed demand (IA.1), we find that $\Omega^{-1}\tilde{\xi}(\varepsilon)/\gamma_I + \nu = \hat{\Theta} + \Omega^{-1}\tilde{v}(p)/\gamma_I$. Hence, the residual demand $\hat{\Theta}$ may reveal additional information that is not in prices. The information in $\hat{\Theta}$ is redundant only when prices reveal the sufficient statistic. In that case, $\hat{\Theta}$ can be inferred by substituting prices p into the market clearing condition $\hat{\Theta} + \theta_U^*(p) = 0$. Such inference is not possible when prices are less informative than $\hat{\Theta}$ because investor U 's portfolio $\theta_U^*(p; \hat{\Theta})$ becomes a function of $\hat{\Theta}$, as shown below, and cannot be found without knowing $\hat{\Theta}$.

The assumption that investor U observes the residual demand $\hat{\Theta}$ is similar to that in the literature on microstructure theory [e.g., Kyle (1985)] where an uninformed market maker observes $\hat{\Theta}$. Allowing investor U to observe $\hat{\Theta}$ restores the existence of equilibrium, as shown in Breon-Drish (2010) in economies with one risky asset. Proposition IA1.2 below derives the equilibrium in a multi-asset economy where investor U can observe the residual demand $\hat{\Theta}$ and demonstrates its existence.

Proposition IA1.2 (Equilibrium when $\theta_I^*(p; \varepsilon) + \nu$ can be observed). *If investor U can learn about shock ε both from asset prices p and the residual demand of informed and noise traders $\hat{\Theta} = \theta_I^*(p; \varepsilon) + \nu$, then there exists unique REE with asset prices and risk-neutral probabilities given by equations (IA.5) and (IA.6). The informed investor's portfolio is given by equation (IA.1), and the uninformed investor's portfolio is given by:*

$$\theta_U^*(p; \hat{\Theta}) = \frac{1}{\gamma_U} \Omega^{-1} \left(\tilde{\Psi} \left(-\hat{\Theta} - \frac{\Omega^{-1} \tilde{v}(p)}{\gamma_I} \right) - \tilde{v}(p) \right), \quad (\text{IA.10})$$

where $\tilde{\Psi}(z)$ is a vector with elements $\Psi_n(z) - \Psi_N(z)$, and $\Psi_n(z)$ are given by (IA.8).

Next, we provide an example of an economy where asset prices are available in analytic form and are non-invertible functions of the sufficient statistic. Specifically, we consider an economy where probabilities $\pi_n(\varepsilon)$ and PDF of the aggregate shock $\varphi_\varepsilon(x)$ are given by Equations (1) and (2), respectively, as in the baseline analysis. The market is complete, and investors can trade an underlying asset with payoffs $C_1(\omega_n) = b_n/\lambda_1$, $N-2$ informationally irrelevant state contingent claims, and a bond. We assume that the noise traders only trade in the market for the underlying asset. However, in contrast to our baseline analysis in Section 3.1, the noise trader demand ν_1 in the market for the underlying asset is non-normal, and its PDF is a mixture of normals given by:

$$\varphi_\nu(x) = \frac{w}{\sqrt{2\pi}\sigma_\nu} \exp\left(-\frac{(x - \mu_{\nu,1})^2}{2\sigma_\nu^2}\right) + \frac{1-w}{\sqrt{2\pi}\sigma_\nu} \exp\left(-\frac{(x - \mu_{\nu,2})^2}{2\sigma_\nu^2}\right), \quad (\text{IA.11})$$

where $0 \leq w \leq 1$, $\sigma_\nu > 0$, and $\mu_{\nu,1}, \mu_{\nu,2} \in \mathbb{R}$. Proposition IA1.3 presents the asset prices.

Proposition IA1.3 (Asset Prices when Noise is a Mixture of Normals). *Let $\pi_n(\varepsilon)$, φ_ε , and φ_ν be given by Equations (1), (2), and (IA.11), respectively. Then the price of the asset with payoff $C_1(\omega) = b/\lambda_1$ in the above economy is a function of $s = \lambda_1 \varepsilon / \gamma_I + \nu_1$ and is given by equation (IA.5), where risk-neutral probabilities π_n^{RN} are given by:*

$$\pi_n^{\text{RN}} = \frac{e^{\hat{v}_n} \left(w e^{\hat{v}_{1,n}} + (1-w) e^{\hat{v}_{2,n}} \right)^{\frac{\gamma_I}{\gamma_I + \gamma_U}}}{\sum_{j=1}^N e^{\hat{v}_j} \left(w e^{\hat{v}_{1,j}} + (1-w) e^{\hat{v}_{2,j}} \right)^{\frac{\gamma_I}{\gamma_I + \gamma_U}}}, \quad (\text{IA.12})$$

and parameters $\hat{v}_n$, $\hat{v}_{1,n}$ and $\hat{v}_{2,n}$ are as follows:

$$\hat{v}_n = a_n + \frac{1}{2} \frac{\gamma_I}{\gamma_I + \gamma_U} \frac{b_n^2 + 2(\mu_0/\sigma_0^2)b_n}{\lambda_1^2/(\sigma_U^2\gamma_I^2) + 1/\sigma_0^2} + \frac{\gamma_I\gamma_U}{\gamma_I + \gamma_U} \left(1 + \frac{\lambda_1^2/(\gamma_U\gamma_I\sigma_U^2)}{\lambda_1^2/(\sigma_U^2\gamma_I^2) + 1/\sigma_0^2} \right) \frac{b_n s}{\lambda_1}, \quad (\text{IA.13})$$

$$\hat{v}_{l,n} = -\frac{1}{\gamma_I} \frac{\mu_{\nu,l}}{2\sigma_0^2\sigma_\nu^2} \frac{\gamma_I(\mu_{\nu,l} - 2s) + 2\lambda_1(\mu_0 + b_n\sigma_0^2)}{\lambda_1^2/(\sigma_U^2\gamma_I^2) + 1/\sigma_0^2}, \quad l = 1, 2. \quad (\text{IA.14})$$

Figure IA.1 shows the price of the underlying asset with cash flow C_1 when the noise trader demand PDF is a mixture of normals, given by equation (IA.5) with risk-neutral probabilities (IA.12), for calibrated parameters. We observe that the price is a non-monotone function of the sufficient statistic s .

When $w = 0$ or $w = 1$ and $\mu_{\nu,1} = \mu_{\nu,2} = 0$, the model reduces to the baseline model in Section 3.1, and the risk-neutral probability parameter $\hat{v}_n$ in equation (IA.13) coincides with parameter v_n in equation (18) in the baseline model for $h = 0.5$. We now look at a particular example in which the underlying asset has payoffs $C_1(\omega_n) = \underline{C}_N + (\bar{C}_N - \underline{C}_N)(n-1)/(N-1)$ and distribution parameters a_n and b_n are as follows:

$$a_n = -\frac{C_1(\omega_n)^2}{2\sigma_0^2} - \frac{\mu_0 C_1(\omega_n)}{\sigma_0^2} + \ln[\varphi_C(C_1(\omega_n))], \quad b_n = \frac{C_1(\omega_n)}{\sigma_0^2}, \quad (\text{IA.15})$$

where $\varphi_C(x) = x^{k-1} \exp(-x^2/\hat{\sigma}_C^2 - \delta x)/\Lambda$, $x > 0$, is a generalized gamma distribution, $\Lambda > 0$ is a normalizing constant, $k \geq 1$ is a power parameter, and δ is a drift parameter. As demonstrated in Lemma A.2 in the Appendix, in the limit $N \rightarrow \infty$, the economy with parameters (IA.15) converges to an economy where payoff C_1 has continuous PDF $\varphi_C(x)$, and ε is a signal given by $\varepsilon = C_1 + u$, where $u \sim N(\mu_0, \sigma_0^2)$. Figure IA.1 plots the price of the underlying asset $P_{com}(s)$ as a function of sufficient statistic s for specific model parameters given in the legend of the figure. The figure demonstrates that the price is a non-monotone function of sufficient statistic s , and hence, the equilibrium only exists if the uninformed investor can observe the residual demand.

We note that when the market is incomplete, the conditions for its effective completeness remain the same as in Sections 3.2 and 4.2 of the paper. That is, the market is effectively complete if the probability-weighted ratio of marginal utilities is constant across the states of the economy:

$$\frac{\pi_n(\varepsilon) \exp\{-\gamma_I W_{I,T,n}\}}{\pi_n^U(p) \exp\{-\gamma_U W_{U,T,n}\}} = e^{\bar{l}}. \quad (\text{IA.16})$$

Following the analysis in Section 4.2, taking logs on both sides of equation (IA.16) we find that $\gamma_U W_{U,T,n} - \gamma_I W_{I,T,n} - \bar{l} = \ln(\pi_n^U(p)/\pi_n(\varepsilon))$. Lemma A.8 in the paper shows that the

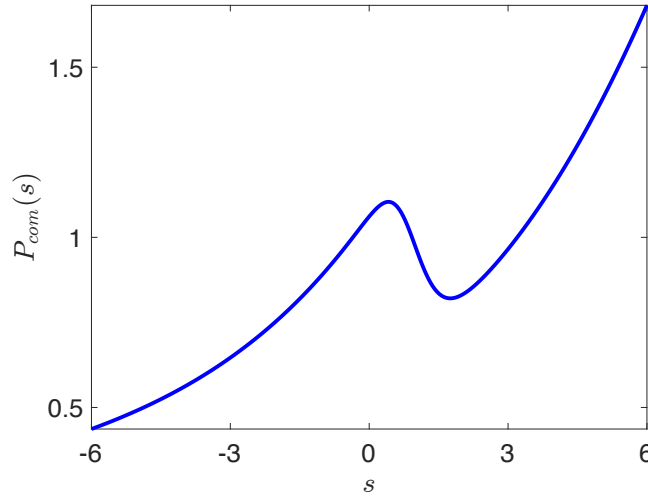


Figure IA.1: Price of the Underlying Asset when Noise is Mixture of Normals.

This Figure shows the complete market price of the underlying asset $P_{com}(s)$ as a function of the sufficient statistic $s = \lambda_1 \varepsilon / \gamma_I + \nu_1$ in a model where distribution parameters a_n and b_n are given by (IA.15). Noise trader demand has mixture of normals PDF (IA.11) with weight $w = 0.5$. The other distribution and preferences parameters are: $\mu_0 = 0$, $\sigma_0 = 1$, $\sigma_\nu = 0.5$, $\hat{\sigma}_C = 1$, $k = 3$, $\delta = 2$, $\mu_{\nu,1} = -\mu_{\nu,2} = 4$, $N = 1000$, $\gamma_I = \gamma_U = 1$, $r = 0$, and $T = 1$.

latter equation implies that the market is effectively complete if there exists a portfolio that replicates $\ln(\pi_n^U(p)/\pi_n(\varepsilon))$. The latter lemma does not make any distributional assumptions about ε and ν . Therefore, we can use this lemma to identify the security that completes the market when the noise trader demand is not normally distributed. Lemma IA.2 below, derives this security for the above economy where the noise trader demand has the mixture of normals PDF given by (IA.11).

Lemma IA.2 (Effective Completeness). *Let $\pi_n(\varepsilon)$, φ_ε , and φ_ν be given by Equations (1), (2), and (IA.11), respectively. Suppose, there is only one risky asset with the payoff $C_{1n} = b_n/\lambda_1$ traded in the economy. Then, the market becomes effectively complete if and only if a security or portfolio with the following payoff becomes available for trading:*

$$C_{2n} = \frac{1}{2} \frac{b_n^2}{\lambda_1^2 / (\sigma_\nu^2 \gamma_I^2) + 1 / \sigma_0^2} + \ln \left(w e^{\hat{v}_{1,n}} + (1 - w) e^{\hat{v}_{2,n}} \right), \quad (\text{IA.17})$$

where $\hat{v}_{i,n}$ are given by (IA.14).

IA1.1 Proofs

Proof of Lemma IA1.1. Investor I 's optimal portfolio in equation (A.6) in the proof of Lemma 1 holds for general probabilities $\pi_n(\varepsilon)$. Hence, substituting $\tilde{\xi}(\varepsilon)$ from equation

(IA.2) into equation (A.6), we obtain equation (IA.1). ■

Proof of Proposition IA1.1. i) Suppose, the equilibrium exists. First, we find the posterior probabilities. Let $s = \Omega^{-1}\tilde{\xi}(\varepsilon)/\gamma_I + \nu$. Similar to equation (A.7), by Bayes rule,

$$\varphi_{\varepsilon|s}(x|y) = \frac{\varphi_{\nu}\left(y - \Omega^{-1}\tilde{\xi}(x)/\gamma_I\right)\varphi_{\varepsilon}(x)}{\int_{-\infty}^{+\infty} \varphi_{\nu}\left(y - \Omega^{-1}\tilde{\xi}(x)/\gamma_I\right)\varphi_{\varepsilon}(x)dx}. \quad (\text{IA.18})$$

From the market clearing condition (IA.4) we note that in equilibrium $s = -\tilde{H}(p)$. Then, similar to the proof of Lemma 2, investor U 's posterior probabilities $\pi_n^U(p)$ are given by:

$$\begin{aligned} \pi_n^U(p) &= \int_{-\infty}^{+\infty} \pi_n(x) \varphi_{\varepsilon|s}(x | -\tilde{H}(p)) dx \\ &= \frac{1}{G_1(p)} \int_{-\infty}^{+\infty} \pi_n(x) \varphi_{\varepsilon}(x) \varphi_{\nu}\left(-\frac{\Omega^{-1}\tilde{\xi}(x)}{\gamma_I} - \tilde{H}(p)\right) dx = \frac{\exp\{\Psi_n(\tilde{H}(p))\}}{G_1(p)}, \end{aligned} \quad (\text{IA.19})$$

where $G_1(p)$ is a normalizing function and $\Psi_n(\cdot)$ is given by (IA.8). The integrals in Equations (IA.18) and (IA.19) exist because $\varphi_{\nu}(\cdot)$ and $\varphi_{\varepsilon}(\cdot)$ are bounded and continuous.

Next, we derive investor U 's portfolio. Equation (A.11) in the proof of Proposition 1 derives this portfolio for general posterior and risk-neutral probabilities. From equation (IA.19), we obtain that $\ln(\pi_n^U/\pi_N^U) = \Psi_n(\tilde{H}(p)) - \Psi_N(\tilde{H}(p)) = \tilde{\Psi}_n(\tilde{H}(p))$. Substituting this expression in equation (A.11), we have

$$\theta_v^*(p) = \frac{1}{\gamma_v} \Omega^{-1} \left(\tilde{\Psi}(\tilde{H}(p)) - \tilde{v}(p) \right). \quad (\text{IA.20})$$

Substituting $\tilde{H}(p) = \theta_v^*(p) - \Omega^{-1}v(p)/\gamma_I$ into equation (IA.20), we obtain equation (IA.9).

Then, we find vector $\tilde{v}(p)$. Subtracting $\Omega^{-1}\tilde{v}(p)/\gamma_I$ from both sides of (IA.20), multiplying both sides by Ω , using $\tilde{H}(p) = -\Omega^{-1}\tilde{\xi}(\varepsilon)/\gamma_I - \nu$, and rearranging terms we obtain:

$$\frac{1}{\gamma_v} \tilde{\Psi} \left(-\frac{\Omega^{-1}\tilde{\xi}(\varepsilon)}{\gamma_I} - \nu \right) + \Omega \left(\frac{\Omega^{-1}\tilde{\xi}(\varepsilon)}{\gamma_I} + \nu \right) = \frac{\gamma_I + \gamma_v}{\gamma_I \gamma_v} \tilde{v}(p). \quad (\text{IA.21})$$

After some algebra, we obtain components of vector $\tilde{v}(p) \in \mathbb{R}^{N-1}$ from equation (IA.21):

$$\begin{aligned} \tilde{v}_n &= \frac{\gamma_I \gamma_v}{\gamma_I + \gamma_v} \left(\frac{1}{\gamma_v} \Psi_n \left(-\frac{\Omega^{-1}\tilde{\xi}(\varepsilon)}{\gamma_I} - \nu \right) - \frac{1}{\gamma_v} \Psi_N \left(-\frac{\Omega^{-1}\tilde{\xi}(\varepsilon)}{\gamma_I} - \nu \right) \right. \\ &\quad \left. + (C(\omega_n) - C(\omega_N))^{\top} \left(\frac{\Omega^{-1}\tilde{\xi}(\varepsilon)}{\gamma_I} + \nu \right) \right). \end{aligned}$$

where $n = 1, \dots, N - 1$. From the fact that $\tilde{v}_n = \ln(\pi_n^{\text{RN}}/\pi_N^{\text{RN}})$ we obtain:

$$\pi_n^{\text{RN}} = \begin{cases} \frac{e^{\tilde{v}_n}}{1 + \sum_{i=1}^{N-1} e^{\tilde{v}_i}}, & n = 1, \dots, N - 1, \\ \frac{1}{1 + \sum_{i=1}^{N-1} e^{\tilde{v}_i}}, & n = N. \end{cases} \quad (\text{IA.22})$$

It can be easily verified that $\tilde{v}_n = v_n - v_N$, where v_n is defined in equation (IA.7). Substituting $\tilde{v}_n = v_n - v_N$ into equation (IA.22), after simple algebra, we obtain risk-neutral probabilities (IA.6). The prices are then given by equation (IA.5) because of the absence of arbitrage. This completes the derivation of equilibrium when it exists.

ii) Suppose, there exists an REE. First, we show that $\tilde{\Psi}(s)/\gamma_U - \Omega s$ is invertible on its range. Suppose, it is not. Then, there exist s' and s'' such that $\tilde{\Psi}(s')/\gamma_U - \Omega s' = \tilde{\Psi}(s'')/\gamma_U - \Omega s''$ but $s' \neq s''$. Pick (ε', ν') and (ε'', ν'') such that $s' = \Omega^{-1}\tilde{\xi}(\varepsilon')/\gamma_I + \nu'$ and $s'' = \Omega^{-1}\tilde{\xi}(\varepsilon'')/\gamma_I + \nu''$. From equation (IA.21) we observe that vector $\tilde{v}(p)$, and, hence, also the risk-neutral probabilities (IA.22), are the same for (ε', ν') and (ε'', ν'') . Then, from equation (IA.5) for $P(\varepsilon, \nu)$, we find that $P(\varepsilon', \nu') = P(\varepsilon'', \nu'')$. Hence, $P(\varepsilon, \nu)$ is not injective. In Lemma IA.2 below, we prove that the price vector is injective if an REE exists, which leads to a contradiction. Therefore, $\tilde{\Psi}(s)/\gamma_U - \Omega s$ is invertible on its range.

Let $\tilde{\Psi}(s)/\gamma_U - \Omega s$ be invertible on its range. Then, we show that the fixed-point equation (IA.9) has a unique solution. Subtracting $\Omega^{-1}\tilde{v}(p)/\gamma_I$ from both sides of equation (IA.9) and then multiplying both sides by Ω , after some algebra, we find that $\theta_U^*(p)$ satisfies

$$\frac{1}{\gamma_U} \tilde{\Psi} \left(\theta_U^*(p) - \frac{\Omega^{-1}\tilde{v}(p)}{\gamma_I} \right) - \Omega \left(\theta_U^*(p) - \frac{\Omega^{-1}\tilde{v}(p)}{\gamma_I} \right) = \frac{\gamma_I + \gamma_U}{\gamma_I \gamma_U} \tilde{v}(p). \quad (\text{IA.23})$$

Equation (IA.23) has a unique solution $\theta_U^*(p)$, which is an implicit function of $\tilde{v}(p)$, because $\tilde{\Psi}(s)/\gamma_U - \Omega s$ is invertible on its range and because the right-hand side of (IA.23) belongs to this range when v_n is given by equation (IA.7). By construction, $\theta_I^*(p; \varepsilon)$ and $\theta_U^*(p)$ are optimal. Then, it can be easily verified that the market clearing condition (IA.4) is also satisfied when the risk-neutral probabilities are given by equation (IA.6). Hence, the equilibrium exists.

Finally, we show that $\tilde{\Psi}(s)/\gamma_U - \Omega s$ is invertible on its range if and only if the price vector $P(\varepsilon, \nu)$ is an invertible function of the sufficient statistic on its range. Consider equation $P(\varepsilon, \nu) = p$. Next, we find unique corresponding risk-neutral probabilities π_n^{RN} and unique vector $\tilde{v}(p) = (\ln(\pi_1^{\text{RN}}/\pi_N^{\text{RN}}), \dots, \ln(\pi_{N-1}^{\text{RN}}/\pi_N^{\text{RN}}))^{\top}$ from (IA.5) and (IA.6). Then, we find unique sufficient statistic by solving equation (IA.21), which has unique solution because $\tilde{\Psi}(s)/\gamma_U - \Omega s$ is invertible. Hence, $P(\varepsilon, \nu)$ is an invertible function of the sufficient statistic. ■

Lemma IA.2 *If there exists an REE then the vector of risky asset prices $P(\varepsilon, \nu)$ is an injective function of the sufficient statistic $\Omega^{-1}\tilde{\xi}(\varepsilon)/\gamma_I + \nu$.*

Proof of Lemma IA.2. First, we observe that if $P(\varepsilon', \nu') = P(\varepsilon'', \nu'')$ then $\tilde{v}(P(\varepsilon', \nu')) = \tilde{v}(P(\varepsilon'', \nu''))$, where $\tilde{v}(p) = \left(\ln(\pi_n^{\text{RN}}/\pi_N^{\text{RN}}), \dots, \ln(\pi_{N-1}^{\text{RN}}/\pi_N^{\text{RN}})\right)^\top$. This is because the risk-neutral probabilities are unique solutions of the risk-neutral pricing equations (8) due to the absence of arbitrage, and they uniquely determine vector $\tilde{v}(p)$.

The rest is similar to the proof of Lemma B.1 in Breon-Drish (2010). Suppose, $P(\varepsilon, \nu)$ is not injective. Then, there exist (ε', ν') and (ε'', ν'') such that $P(\varepsilon', \nu') = P(\varepsilon'', \nu'')$ but $\Omega^{-1}\tilde{\xi}(\varepsilon')/\gamma_I + \nu' \neq \Omega^{-1}\tilde{\xi}(\varepsilon'')/\gamma_I + \nu''$. We denote the latter and the former statistics by s'' and s' , respectively. Then, from the market clearing condition (IA.4), we obtain:

$$\begin{aligned} 0 &= s' + \theta_U^*(P(\varepsilon', \nu')) - \frac{\Omega^{-1}\tilde{v}(P(\varepsilon', \nu'))}{\gamma_I} = s' + \theta_U^*(P(\varepsilon'', \nu'')) - \frac{\Omega^{-1}\tilde{v}(P(\varepsilon'', \nu''))}{\gamma_I} \\ &= s' - s'' + s'' + \theta_U^*(P(\varepsilon'', \nu'')) - \frac{\Omega^{-1}\tilde{v}(P(\varepsilon'', \nu''))}{\gamma_I} = s' - s''. \end{aligned}$$

Hence, $s' = s''$, which leads to a contradiction. ■

Proof of Proposition IA1.2. Investor U observes prices p and the combined demand $\hat{\Theta} = \theta_I^*(p; \varepsilon) + \nu$. Investor U then infers the sufficient statistic from the equation $\Omega^{-1}\tilde{\xi}(\varepsilon)/\gamma_I + \nu = \hat{\Theta} + \Omega^{-1}\tilde{v}(p)/\gamma_I$, which can be easily proven by substituting in $\hat{\Theta}$ and $\theta_I^*(p; \varepsilon)$ from equation (IA.1). Next, following similar steps as in the proof of Proposition IA1.1 we find that the posterior probabilities are given by $\pi_n^U(p; \hat{\Theta}) = \exp\{\Psi_n(-\hat{\Theta} - \Omega^{-1}\tilde{v}(p)/\gamma_I)\}/G_1(p)$, where $\Psi_n(z)$ is given by equation (IA.8) and $G_1(p)$ is a normalizing function. The rest of the proof follows the proof of part (i) of Proposition IA1.1. The prices are not required to be invertible functions of the sufficient statistic because investor U learns the sufficient statistic from the additional variable $\hat{\Theta}$. ■

Proof of Proposition IA1.3. The sufficient statistic is given by $\Omega^{-1}\tilde{\xi}(\varepsilon)/\gamma_I + \nu$, where $\tilde{\xi}(\varepsilon) = \tilde{a} + \tilde{b}\varepsilon$, and $\tilde{a}$ and $\tilde{b}$ are vectors with elements $a_n - a_N$ and $b_n - b_N$, respectively. Because noise traders only trade in the market for the underlying asset, $\nu = (\nu_1, 0, \dots, 0)^\top$. Substituting $\tilde{\xi}(\varepsilon)$ and ν into the sufficient statistic we obtain: $\Omega^{-1}\tilde{\xi}(\varepsilon)/\gamma_I + \nu = se_1 + \Omega^{-1}\tilde{a}/\gamma_I$, where $s = \lambda_1\varepsilon/\gamma_I + \nu_1$ is a one-dimensional statistic and $e_1 = (1, 0, \dots, 0)^\top$. Therefore, only the first component of vector $\Omega^{-1}\tilde{\xi}(\varepsilon)/\gamma_I + \nu$ is random, and hence, the sufficient statistic is effectively one-dimensional and given by $s + c_1$, where c_1 is the first component of vector $\Omega^{-1}\tilde{a}/\gamma_I$. Hence, we use this one-dimensional statistic in the proof.

First, we compute function $\Psi_n(z)$ in equation (IA.8). Substituting $\pi_n(\varepsilon)$ from (1),

$\varphi_\varepsilon(x)$ from (2), and $\varphi_\nu(x)$ from (IA.11), we find that the expression under the integral in equation (IA.8) is given by:

$$\begin{aligned}\widehat{\varphi}(x) = & \frac{\exp(a_n + b_n x)}{G} \exp\left(-\frac{(x - \mu_0)^2}{2\sigma_0^2}\right) \left(w \exp\left(-\frac{(c_1 + z + \lambda_1 x / \gamma_I + \mu_{\nu,1})^2}{2\sigma_\nu^2}\right) \right. \\ & \left. + (1 - w) \exp\left(-\frac{(c_1 + z + \lambda_1 x / \gamma_I + \mu_{\nu,2})^2}{2\sigma_\nu^2}\right) \right),\end{aligned}$$

where G is a constant. Integrating $\widehat{\varphi}(x)$ and taking log, we obtain $\Psi_n(z)$ as follows:

$$\begin{aligned}\Psi_n(z) = & \ln\left(\int_{-\infty}^{+\infty} \widehat{\varphi}(x) dx\right) \\ = & g + a_n + \frac{1}{2} \frac{b_n^2 + 2b_n(\mu_0/\sigma_0^2 - (c_1 + z)\lambda_1/(\sigma_\nu^2\gamma_I))}{\lambda_1^2/(\sigma_\nu^2\gamma_I^2) + 1/\sigma_0^2} \\ & + \ln\left\{ w \exp\left(-\frac{\mu_{\nu,1}}{2\sigma_0^2\sigma_\nu^2\gamma_I} \frac{\gamma_I(\mu_{\nu,1} + 2(c_1 + z)) + 2\lambda_1(\mu_0 + b_n\sigma_0^2)}{\lambda_1^2/(\sigma_\nu^2\gamma_I^2) + 1/\sigma_0^2}\right) \right. \\ & \left. + (1 - w) \exp\left(-\frac{\mu_{\nu,2}}{2\sigma_0^2\sigma_\nu^2\gamma_I} \frac{\gamma_I(\mu_{\nu,2} + 2(c_1 + z)) + 2\lambda_1(\mu_0 + b_n\sigma_0^2)}{\lambda_1^2/(\sigma_\nu^2\gamma_I^2) + 1/\sigma_0^2}\right) \right\},\end{aligned}\tag{IA.24}$$

where g is a constant. Then, the parameters v_n in equation (IA.6) are given by:

$$\begin{aligned}v_n = & \frac{\gamma_I}{\gamma_I + \gamma_U} \Psi_n(-c_1 - s) + \frac{\gamma_U}{\gamma_I + \gamma_U} a_n + \frac{\gamma_I \gamma_U}{\gamma_I + \gamma_U} \frac{b_n s}{\lambda_1} \\ = & \widehat{g} + \widehat{v}_n + \frac{\gamma_I}{\gamma_I + \gamma_U} \ln\left(we^{\widehat{v}_{1,n}} + (1 - w)e^{\widehat{v}_{2,n}}\right),\end{aligned}$$

where $\widehat{v}_n$ and $\widehat{v}_{l,n}$ are given by Equations (IA.13) and (IA.14), respectively, and $\widehat{g}$ is a constant. Substituting v_n in equation (IA.6) for the risk-neutral probabilities, we note that constant $\widehat{g}$ cancels out and we obtain risk-neutral probabilities (IA.12). ■

Proof of Lemma IA.2. The sufficient statistic in the incomplete market remains the same as in the economy studied in Proposition IA1.3. Therefore, equation (IA.19) for the uninformed probability π_n^U , and equation (IA.24) for function $\Psi_n(z)$ remain the same. Consequently, the log-ratio of probabilities becomes:

$$\ln\left(\frac{\pi_n^U}{\pi_n(\varepsilon)}\right) = g_1 + g_2 b_n + C_{2n},$$

where C_{2n} is given by (IA.17). We note that b_n can be replicated by trading the available risky asset with payoff $C_{1n} = b_n/\lambda_1$. Hence, by Lemma A.8, the market is complete if and only if a security with payoff C_{2n} is tradable. ■

IA2 Noisy Endowments and Financial Innovation

We extend our analysis to economies in which noise traders are absent and the informed investors receive noisy endowments. These endowments prevent prices from being fully revealing and allow us to analyze the welfare effects of a financial innovation when a new security is introduced to an incomplete-market economy. Moreover, noisy endowments allow us to replace the informational spanning condition (28) with a weaker condition.

The state probabilities $\pi_n(\varepsilon)$ are given by equation (1), as in the main analysis, and there are no noise traders in the economy. The informed investor receives state-dependent noisy income at date T , which is generated by claims to non-tradable assets, given by

$$e_{I,n} = \widetilde{W}_{0,I}(\alpha + \beta b_n + \eta), \quad (\text{IA.25})$$

where α is a constant, $\beta \sim \mathcal{N}(0, \sigma_\beta^2)$, $\eta \sim \mathcal{N}(0, \sigma_\eta^2)$, where random variables β and η are uncorrelated with each other and with shock ε . The structure of endowments (IA.25) is inspired by the CAPM. It implies that the informed investors are exposed to the aggregate risk factor b . The exposure to that factor, denoted by β (analogously to CAPM), is known to the informed investors but not to the uninformed investors. Exposure β performs the same role as noise trader demand in our main analysis, and prevents uninformed investors from observing shock ε . The endowment may represent a net liability, in which case β can be negative. Therefore, because β can have either sign, we model it as a normally distributed variable. Constant return α and shock η are added to complete the analogy with the CAPM. They do not play any role in our analysis and do not affect the results. Consequently, without loss of generality, we set $\alpha = 0$, $\eta = 0$, and $\widetilde{W}_{0,I} = 1$.

The informed and uninformed investors solve the following optimization problems:

$$\max_{\theta_I} \mathbb{E} \left[-e^{-\gamma_I W_{I,T}} \middle| \varepsilon, \beta, p \right], \quad (\text{IA.26})$$

$$\max_{\theta_U} \mathbb{E} \left[-e^{-\gamma_U W_{U,T}} \middle| P(\varepsilon, \beta) = p \right], \quad (\text{IA.27})$$

respectively, where $P(\varepsilon, \beta)$ is the vector of risky asset prices, subject to their self-financing budget constraints

$$W_{i,T} = W_{i,0}e^{rT} + (C - e^{rT}p)^\top \theta_i + e_i, \quad i = I, U. \quad (\text{IA.28})$$

For the simplicity of exposition, we assume that the uninformed investors do not have any endowment, $e_U = 0$. The total mass of informed investors is h . Because there are no noise traders in the economy, the market clearing condition is given by

$$h\theta_I^* + (1 - h)\theta_U^* = 0. \quad (\text{IA.29})$$

First, we derive the equilibrium in a market with two risky assets with payoffs b and b^2 , and show that this market is effectively complete. Proposition IA2.1 reports the results.

Proposition IA2.1 (Effectively complete-market equilibrium). *Suppose, the investors trade two assets with payoffs $C_{1n} = b_n$ and $C_{2n} = b_n^2$. Then, the market is effectively complete, the asset prices and risk-neutral probabilities are given by*

$$P(\varepsilon, \nu) = \left[\pi_1^{\text{RN}} C(\omega_1) + \pi_2^{\text{RN}} C(\omega_2) + \dots + \pi_N^{\text{RN}} C(\omega_N) \right] e^{-rT}, \quad (\text{IA.30})$$

$$\pi_n^{\text{RN}} = \frac{e^{v_n}}{\sum_{j=1}^N e^{v_j}}, \quad (\text{IA.31})$$

where $C(\omega_n) = (C_{1n}, C_{2n})^\top$ and probability parameters v_n are given in closed form by:

$$v_n = a_n + \frac{1}{2} \frac{(1-h)/\gamma_U}{h/\gamma_I + (1-h)/\gamma_U} \frac{b_n^2 + 2(\mu_0/\sigma_0^2)b_n}{1/(\gamma_I^2\sigma_\beta^2) + 1/\sigma_0^2} + \frac{b_n(1+Q)hs}{h/\gamma_I + (1-h)/\gamma_U}, \quad (\text{IA.32})$$

$$Q = \frac{(1-h)}{\gamma_I\gamma_U h} \frac{1/\sigma_\beta^2}{1/(\gamma_I^2\sigma_\beta^2) + 1/\sigma_0^2}. \quad (\text{IA.33})$$

The trading strategies of investors are given by:

$$\theta_I^* = \frac{(1-h)/\gamma_U}{h/\gamma_I + (1-h)/\gamma_U} \frac{1}{1 + \sigma_0^2/(\gamma_I^2\sigma_\beta^2)} \left(\frac{\gamma_I s - \mu_0}{\gamma_I}, -\frac{\sigma_0^2}{2\gamma_I} \right)^\top, \quad (\text{IA.34})$$

$$\theta_U^* = \frac{h/\gamma_I}{h/\gamma_I + (1-h)/\gamma_U} \frac{1}{1 + \sigma_0^2/(\gamma_I^2\sigma_\beta^2)} \left(\frac{\mu_0 - \gamma_I s}{\gamma_U}, \frac{\sigma_0^2}{2\gamma_U} \right)^\top. \quad (\text{IA.35})$$

From Proposition IA2.1, we observe that the expression for the asset prices (IA.30) is the same as in a model with noise traders described in Proposition 4 where the market is effectively complete, $h\lambda = 1$, and the noise trader demand is zero in the market for the quadratic derivative b^2 . Consequently, the economic implications of asymmetric information and the quadratic derivatives are the same as in the analysis with noise traders.

Next, we turn to the analysis of the incomplete-market equilibrium. In the economy with noisy endowments the informational spanning condition (28) in our main analysis can be replaced by a weaker condition. In particular, substituting probabilities $\pi_n(\varepsilon)$ from equation (1) and the wealth (IA.28) into the objective function (IA.26), we observe that the optimization problem of the informed investor reduces to the following problem:

$$\max_{\theta_I} - \sum_{n=1}^N \exp\{a_n + \gamma_I b_n(\varepsilon/\gamma_I - \beta) - \gamma_I (C - e^{rT} p)^\top \theta_I\}, \quad (\text{IA.36})$$

and hence, the optimal strategy is a function of the sufficient statistic $s = \varepsilon/\gamma_I - \beta$ even if condition (28) is violated. Consequently, if the REE exists, the asset price is also a function

of the statistic s . Proposition IA2.2 below characterizes the equilibrium and demonstrates its existence under a weaker condition than the informational spanning condition (28). For simplicity, we focus on an economy with a single risky asset.

Proposition IA2.2 (Incomplete-market equilibrium). *Suppose, the state- ω_n asset payoffs are given by $C_n = g(b_n)$, where $g(x)$ is a monotone continuously differentiable function. Then, there exists a REE in which the asset price is a monotone function of the sufficient statistic $s = \varepsilon/\gamma_I - \beta$, and solves the following nonlinear equation:*

$$\frac{hf_I^{-1}(e^{rT}P(s))}{\gamma_I} + \frac{(1-h)f_U^{-1}(e^{rT}P(s))}{\gamma_U} = 0, \quad (\text{IA.37})$$

where functions $f_I(x)$ and $f_U(x)$ are invertible and given by

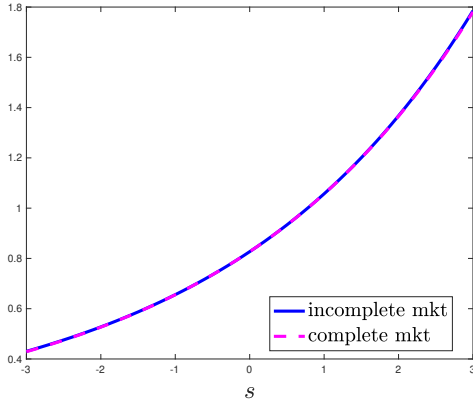
$$f_I(x) = \frac{\sum_{j=1}^N C(\omega_j) \exp \{a_j + \gamma_I s b_n + C_j x\}}{\sum_{j=1}^N \exp \{a_j + \gamma_I s b_n + C_j x\}}, \quad (\text{IA.38})$$

$$f_U(x) = \frac{\sum_{j=1}^N C(\omega_j) \exp \{a_j + \frac{1}{2} \frac{b_j^2 + 2b_j(\mu_0/\sigma_0^2 + s/(\gamma_I \sigma_\beta^2))}{1/(\gamma_I^2 \sigma_\beta^2) + 1/\sigma_0^2} + C_j x\}}{\sum_{j=1}^N \exp \{a_j + \frac{1}{2} \frac{b_j^2 + 2b_j(\mu_0/\sigma_0^2 + s/(\gamma_I \sigma_\beta^2))}{1/(\gamma_I^2 \sigma_\beta^2) + 1/\sigma_0^2} + C_j x\}}. \quad (\text{IA.39})$$

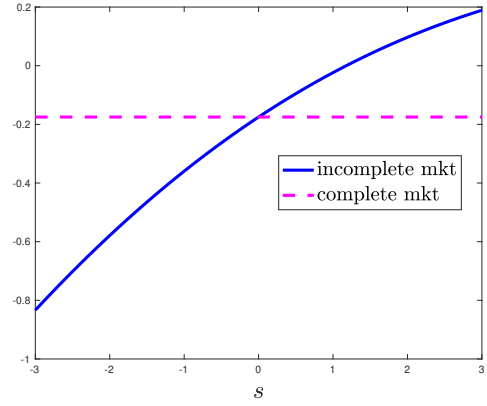
The investors' trading strategies are given by $\theta_i^* = -f_i^{-1}(e^{rT}P(s))/\gamma_i$, where $i = I, U$.

We use Proposition IA2.2 to compute the equilibrium without the informational spanning condition by solving equation (IA.37) numerically. Figure IA.2a shows the price of the quadratic derivative C_1^2 , where $C_1 = b > 0$, in an incomplete market economy where this derivative is the only traded asset, and also in the effectively complete market where the underlying with payoff C_1 is additionally traded. In the first of these economies the informational spanning condition is violated because the economic factor b is not spanned by payoff C_1^2 . Nevertheless, we observe that the prices of C_1^2 in the incomplete and complete markets are very close and difficult to distinguish on a graph. Figure IA.2b shows investor I 's trading strategy in the quadratic derivative in both markets. We observe that the strategy is non-linear in sufficient statistic s in the incomplete market, and a constant when the market is complete.

The main advantage of the model with noisy endowments is that it allows us to analyze investor welfare gains/losses from completing the market without the need to account for noise traders' welfare. To make the value function of investor I comparable to that of investor U , we use conditional expectation $\mathbb{E}[J_I|s]$ instead of value function J_I , because J_I additionally depends on shock ε which is not observed by uninformed investors. Expectation $\mathbb{E}[J_I|s]$ evaluates investor I 's welfare from the viewpoint of investor U , and



(a) Price of volatility derivative C_1^2



(b) I 's trading strategy in volatility derivative

Figure IA.2: Prices and trading strategies for the volatility derivative C_1^2 .

Panel (a) shows the price of the volatility derivative C_1^2 in the incomplete and complete markets. Panel (b) shows investor I 's trading strategy in this derivative both in incomplete and complete markets. The cash flow C_1 has a generalized gamma PDF (52) with parameters $\hat{\sigma}_C = 1$, $\delta = 2$, $k = 3$. The other parameters are: $\mu_0 = 0$, $\sigma_0 = 1$, $\sigma_\nu = 1$, $h = 0.5$, $\gamma_I = \gamma_U = 1$, $r = 0$, $T = 1$.

an uninformed econometrician or a policy maker. Lemma IA2.1 below reports the value functions.

Lemma IA2.1 (Welfare). *The expected value functions of investors conditional on observing the sufficient statistic s are given by:*

$$\mathbb{E}[J_I|s] = -\frac{\sum_{n=1}^N \exp\{a_n + \gamma_I b_n s - \gamma_I (C(\omega_n) - e^{rT} p)^\top \theta_I^*\}}{\sum_{n=1}^N \exp\left\{a_n + \frac{1}{2} \frac{b_n^2 + 2b_n(s/(\gamma_I \sigma_\beta^2) + \mu_0/\sigma_0^2)}{1/(\gamma_I^2 \sigma_\beta^2) + 1/\sigma_0^2}\right\}}, \quad (\text{IA.40})$$

$$J_U = -\frac{\sum_{n=1}^N \exp\left\{a_n + \frac{1}{2} \frac{b_n^2 + 2b_n(s/(\gamma_I \sigma_\beta^2) + \mu_0/\sigma_0^2)}{1/(\gamma_I^2 \sigma_\beta^2) + 1/\sigma_0^2} - \gamma_U (C(\omega_n) - e^{rT} p)^\top \theta_U^*\right\}}{\sum_{n=1}^N \exp\left\{a_n + \frac{1}{2} \frac{b_n^2 + 2b_n(s/(\gamma_I \sigma_\beta^2) + \mu_0/\sigma_0^2)}{1/(\gamma_I^2 \sigma_\beta^2) + 1/\sigma_0^2}\right\}}. \quad (\text{IA.41})$$

We use the results in Lemma IA2.1 to evaluate the welfare implications of completing the market by comparing the value functions (IA.40) and (IA.41) in the incomplete and effectively complete markets. Figures IA.3a–IA.3b show welfare gains of investors I and U , respectively, from completing the market by adding an asset C_1^2 to the economy with asset C_1 . Figures IA.3c–IA.3d show welfare gains from adding an asset C_1 to the economy with asset C_1^2 , and Figures IA.3e–IA.3f show welfare gains from adding an asset C_1^2 to the economy with assets C_1 and C_1^4 . The underlying asset payoff C_1 has a generalized gamma PDF (52). The parameters of the PDF and investor risk aversions are described in the legend of Figure IA.3.

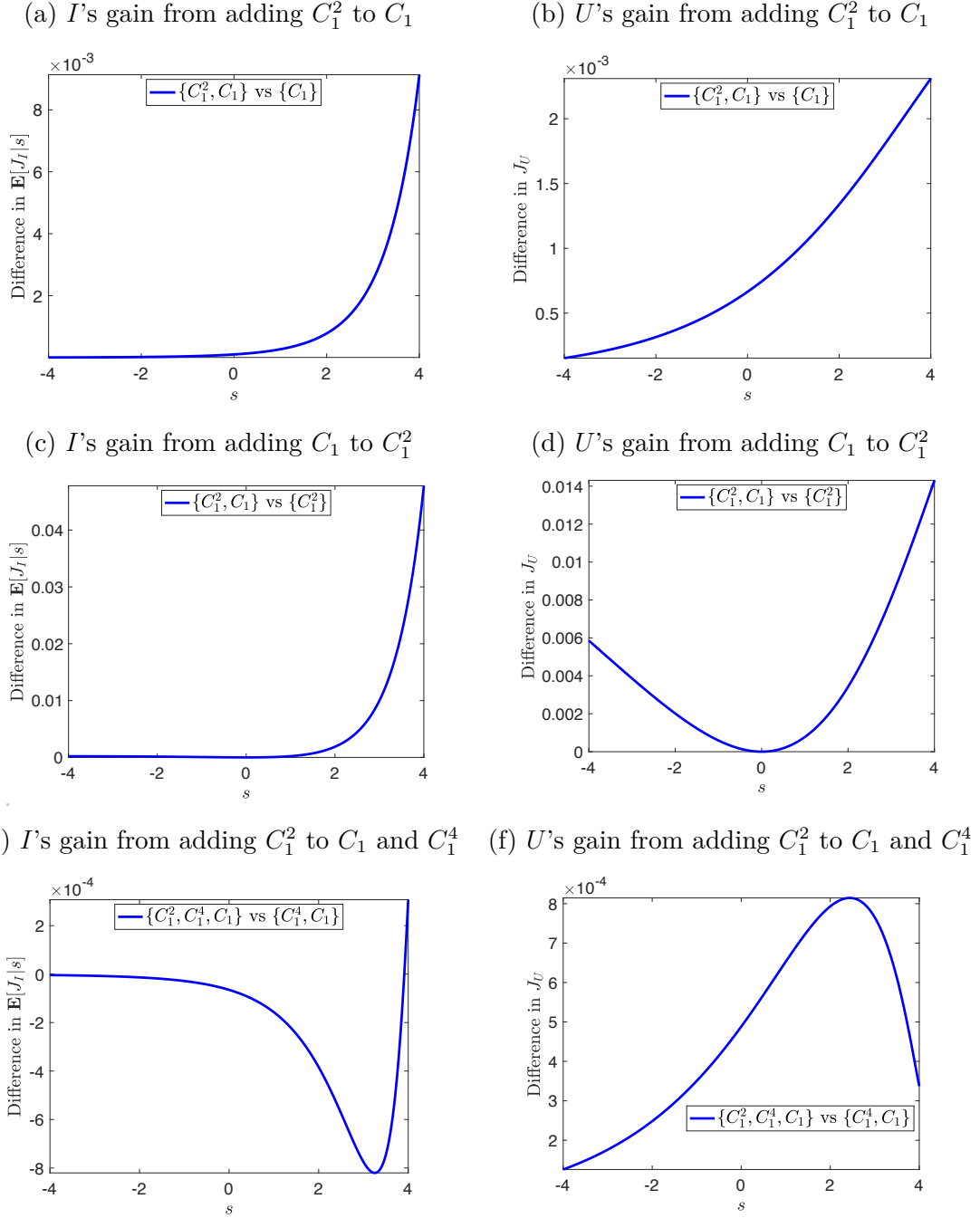


Figure IA.3: Welfare gain from financial innovation.

This Figure shows the welfare gains of investors I and U from adding securities to various incomplete markets. Panels (a)–(b) show the welfare gains from adding a security with payoff C_1^2 to the market with security C_1^2 , Panels (c)–(d) show gains from adding C_1 to C_1^2 , and Panels (e)–(f) show gains from adding C_1^2 to C_1 and C_1^4 . Cash flow C_1 has a generalized gamma PDF (52) with parameters $\hat{\sigma}_C = 1$, $\delta = 2$, $k = 3$. The remaining parameters are: $\mu_0 = 0$, $\sigma_0 = 1$, $\sigma_\nu = 1$, $h = 0.5$, $\gamma_I = 1$ and $\gamma_U = 2$, $r = 0$, $T = 1$.

From Figure IA.3, we observe that completing single-asset economies with asset payoffs C_1 and C_1^2 , respectively, improves the welfare of both investors, and hence, is Pareto improving. Moreover, because the welfare improves for all values of the sufficient statistic s , the ex-ante welfare before investors observe any signals and endowments also improves when the market becomes complete. We also observe that the informed investor gains more than the uninformed investor when the new security is introduced. However, we observe that completing an economy with two assets C_1 and C_1^4 results in a lower welfare of investor I (for most s) and higher welfare of investor U (for all s). The latter result also holds if we compare ex-ante welfares before observing the signals and endowments.

Our results on the welfare effects of financial innovation are consistent with the theoretical results in Elul (1999), who shows that in a single consumption good incomplete-market economy at least one of the investors is better off due to financial innovation. Therefore, it is not feasible to construct a security adding which to the market makes all investors worse off.

IA2.1 Proofs

Proof of Proposition IA2.1. The derivation of equilibrium in the case when both assets b and b^2 are traded and the demonstration of the effective completeness can be obtained following the same steps as in the proof of Proposition 4 in our main analysis. ■

Proof of Proposition IA2.2. Suppose, price $P(s)$ is monotone in s (as verified below), and hence, investor U can extract s from prices and filter out the information about shock ε . Then, following the same steps as in the derivation of posterior probabilities (15) in the main analysis, we find that the posterior probabilities are given by:

$$\pi_n^U(p) = \frac{1}{G(p)} \exp \left\{ a_n + \frac{1}{2} \frac{b_n^2 + 2b_n(\mu_0/\sigma_0^2 + s/(\gamma_I\sigma_\beta^2))}{1/(\gamma_I^2\sigma_\beta^2) + 1/\sigma_0^2} \right\}. \quad (\text{IA.42})$$

We substitute probabilities (IA.42) and $\pi_n(\varepsilon)$ into the objective functions (IA.26) and (IA.27), solving the optimization problems, we obtain the following first order conditions:

$$f_I(-\gamma_I\theta_I^*) = f_U(-\gamma_U\theta_U^*) = e^{rT}p. \quad (\text{IA.43})$$

The latter equation and the market clearing condition (IA.29) then imply equation (IA.37) for the asset price, and the expressions for the optimal strategies.

From the market clearing condition, we obtain that $\theta_I^* = -(1-h)/h\theta_U^*$. Substituting θ_I^* into (IA.43), we rewrite the FOC as an equation for θ_U^* given by $f_I(\gamma_I(1-h)\theta_U^*/h) =$

$f_U(-\gamma_U \theta_U^*)$. The existence of the solution θ_U^* and the invertibility of functions $f_i(x)$ can be proven in the same way as in the proof of Proposition 3 in our main analysis.

It remains to prove the monotonicity of function $P(s)$. Differentiating equation $f_I(\gamma_I(1-h)\theta_U^*/h) = f_U(-\gamma_U \theta_U^*)$ w.r.t. s , we obtain the derivative $(\theta_U^*(s))'$:

$$(\theta_U^*(s))' = \frac{\hat{\lambda} \text{cov}^{\text{RN},U}(C, b) - \gamma_I \text{cov}^{\text{RN},I}(C, b)}{\gamma_U h \text{var}^{\text{RN},U}(C) + \gamma_I(1-h) \text{var}^{\text{RN},I}(C)} h, \quad (\text{IA.44})$$

where $\hat{\lambda} = 1/(\gamma_I \sigma_\beta^2)/(1/(\gamma_I^2 \sigma_\beta^2) + 1/\sigma_0^2)$, and the covariances are computed under the risk-neutral probability measures of investors I and U , respectively.

From (IA.43), the price is given by $P(s) = f_U(-\gamma_U \theta_U^*)e^{-rT}$. Differentiating the price, and then substituting in the expression for $(\theta_U^*(s))'$ from equation (IA.44), we obtain:

$$\begin{aligned} e^{rT} P'(s) &= \hat{\lambda} \text{cov}^{\text{RN},U}(C, b) - \gamma_U \theta_U'(s) \text{var}^{\text{RN},U}(C) \\ &= \frac{1/(\gamma_I \sigma_\beta^2)}{1/(\gamma_I^2 \sigma_\beta^2) + 1/\sigma_0^2} \frac{\gamma_I(1-h) \text{var}^{\text{RN},I}(C)}{\gamma_U h \text{var}^{\text{RN},U}(C) + \gamma_I(1-h) \text{var}^{\text{RN},I}(C)} \text{cov}^{\text{RN},U}(C, b) \\ &\quad + \gamma_I \frac{\gamma_U h \text{var}^{\text{RN},U}(C)}{\gamma_U h \text{var}^{\text{RN},U}(C) + \gamma_I(1-h) \text{var}^{\text{RN},I}(C)} \text{cov}^{\text{RN},I}(C, b). \end{aligned} \quad (\text{IA.45})$$

Next, we use the following result from Schmidt (2003): if $g_1(x)$ and $g_2(x)$ are increasing functions, then $\text{cov}(g_1(b), g_2(b)) \geq 0$. From this result, it easily follows that if $C = g(b)$, where $g(x)$ is a monotone function, then $\text{cov}^{\text{RN},i}(C, b) \geq 0$ (≤ 0) if $g(x)$ is an increasing (decreasing) function. Consequently, equation (IA.45) and the monotonicity of payoff $C = g(b)$ imply that $P(s)$ is a monotone function, and hence, the uninformed investor can observe the sufficient statistic s by inverting function $P(s)$. ■

Proof of Lemma IA2.1. First, we derive the distribution of shock ε conditional on observing statistic s . Following exactly the same steps as in Lemma 2 in the main analysis, we obtain:

$$\varphi_{\varepsilon|s}(x|y) = \frac{\exp\left\{-\frac{(y-x/\gamma_I)^2}{2\sigma_\beta^2} - \frac{(x-\mu_0)^2}{2\sigma_0^2}\right\} \sum_{n=1}^N \exp\{a_n + b_n x\}}{G_0(y) \sum_{n=1}^N \exp\left\{a_n + \frac{1}{2} \frac{b_n^2 + 2b_n(s/(\gamma_I \sigma_\beta^2) + \mu_0/\sigma_0^2)}{1/(\gamma_I^2 \sigma_\beta^2) + 1/\sigma_0^2}\right\}}, \quad (\text{IA.46})$$

where $G_0(y)$ is given by:

$$G_0(y) = \int_{-\infty}^{\infty} \exp\left\{-\frac{(y-x/\gamma_I)^2}{2\sigma_\beta^2} - \frac{(x-\mu_0)^2}{2\sigma_0^2}\right\} dx.$$

Substituting probabilities $\pi_n(\varepsilon)$ into the objective function of investor I , we compute the expected value function of investor I as follows

$$\mathbb{E}[J_I|s] = - \int_{-\infty}^{\infty} \frac{\sum_{n=1}^N \exp\{a_n + \gamma_I b_n s - \gamma_I(C(\omega_n) - e^{rT} p)^\top \theta_I^*\}}{\sum_{n=1}^N \exp\{a_n + b_n x\}} \varphi_{\varepsilon|s}(x|s) dx. \quad (\text{IA.47})$$

Substituting distribution (IA.46) into the latter equation, after some simplifications, we obtain the expected value function (IA.40). Equation (IA.41) for J_U can be obtained by substituting probabilities (IA.42) into investor U 's objective function (IA.27). ■

IA3 Information Aggregation

In this section, we extend our solution approach to models of information aggregation by heterogeneously informed investors à la Hellwig (1980). We show that similar to our baseline setting, such models can be solved in closed form when the financial market is complete and volatility derivatives with payoffs given by quadratic functions of asset cash flows make the financial markets effectively complete.

We consider an economy with the same set of assets, probabilities of states $\pi_n(\varepsilon)$, distribution $\varphi_\varepsilon(x)$ of the aggregate shock, and distribution $\varphi_\nu(z)$ of noise trader demands as in Section 2.1 of our baseline setting. The difference with our baseline setting is in the types of agents and their information. There are K types of investors with risk aversions γ_i and normally distributed signals over shock ε :

$$e_i = \varepsilon + x_i, \quad (\text{IA.48})$$

where all $x_i \sim \mathcal{N}(0, 1/\tau_i)$ are independent from each other and of ε, ν , for $i = 1, \dots, K$. As in our baseline setting in Section 2.1, investors maximize their expected utilities over terminal wealth, given by

$$\max_{\theta_i} \mathbb{E} \left[-e^{-\gamma_i W_{i,T}} \middle| e_i, p \right], \quad (\text{IA.49})$$

subject to their self-financing budget constraints

$$W_{i,T} = W_{i,0}e^{rT} + (C - e^{rT}p)^\top \theta_i, \quad i = 1, \dots, K. \quad (\text{IA.50})$$

By $P(e, \nu)$ we denote the equilibrium asset prices as functions of the vector of signals $e \equiv (e_1, \dots, e_K)^\top$ and noise trader demands ν . The prices are determined from the market clearing condition. The definition of equilibrium is as follows.

Definition of Equilibrium. *A competitive noisy rational expectations equilibrium is a vector of risky asset prices $P(e, \nu)$ and investor portfolios $\theta_i^*(p; e_i)$ that solve optimization problems (IA.49) subject to self-financing budget constraints (IA.50), taking asset prices as given, for $i = 1, \dots, K$, and satisfy the market clearing condition:*

$$\sum_{i=1}^K \theta_i^* (P(e, \nu); e_i) + \nu = 0. \quad (\text{IA.51})$$

IA3.1 Economy with $M = N$ securities

We start with the complete-market case with $M = N$. All K investors agree on risk-neutral probabilities because these probabilities are uniquely determined from the pricing equation (8) as functions of observed prices p . However, investors assign different real probabilities to states ω_n . In particular, investor i 's real posterior probabilities are given by $\pi_n^i(p; e_i) = \mathbb{E}[\pi_n(\varepsilon) | P(e, \nu) = p, e_i]$. The latter expression for $\pi_n^i(p; e_i)$ can be obtained by rewriting investor i 's expected utility (IA.49) as follows:

$$\mathbb{E} \left[-e^{-\gamma_i W_{i,T}} | e_i, P(e, \nu) = p \right] = - \sum_{n=1}^N \pi_n^i(p; e_i) e^{-\gamma_i W_{i,T,n}}. \quad (\text{IA.52})$$

Moreover, as before, the first order conditions of investors equate their marginal utilities and SPDs [e.g., Duffie (2001, p. 5)] and are given by:

$$\gamma_i e^{-\gamma_i W_{i,T,n}} = \ell_i \frac{\pi_n^{\text{RN}} e^{-rT}}{\pi_n^i(p; e_i)} \quad (\text{IA.53})$$

where ℓ_i are Lagrange multipliers for the budget constraints. From Equations (IA.53), we find optimal wealths $W_{i,T}$, and recover optimal portfolios from budget constraints (IA.50).

To find the posterior probabilities, similar to the single asset cases in Hellwig (1980) and Breon-Drish (2015), we conjecture (and later verify) that investors' optimal portfolios $\theta_i^*(p; e_i)$, $i = 1, \dots, K$ are additively separable in prices p and signals e_i :

$$\theta_i^*(p; e_i) = \theta_{1,i}(p) + \lambda k_i e_i, \quad (\text{IA.54})$$

where k_i are investor-specific constants, and λ is a replicating portfolio for the risk factor b , given by $\lambda = \Omega^{-1}(b_1 - b_N, \dots, b_{N-1} - b_N)^\top$, as in our baseline analysis in Section 3.1. Substituting portfolios (IA.54) into the the market clearing condition (IA.51), we obtain

$$\widehat{H}(p) + \lambda \sum_{i=1}^K k_i \cdot e_i + \nu = 0, \quad (\text{IA.55})$$

where $\widehat{H}(p)$ is a function of prices, given by

$$\widehat{H}(p) \equiv \sum_{i=1}^K \theta_{1,i}(p). \quad (\text{IA.56})$$

The market clearing condition (IA.55) then implies that, if the equilibrium exists, investors can infer the following sufficient statistic from asset prices:

$$\widehat{s} \equiv \lambda \sum_{i=1}^K k_i \cdot e_i + \nu. \quad (\text{IA.57})$$

The posterior probabilities are given by $\pi_n^i(p; e_i) = \mathbb{E}[\pi_n(\varepsilon)|\hat{s}, e_i]$, and can be solved as in our baseline setting. These probabilities are reported in the Lemma below.

Lemma IA3.1 (Posterior probabilities of states). *The posterior probabilities of states ω_n conditional on observing the sufficient statistic $\hat{s}$ are given by:*

$$\pi_n^i(p; e_i) = \frac{1}{G_i(p; e_i)} \exp \left\{ a_n + \frac{1}{2} \frac{b_n^2 + 2b_n \left(\mu_0/\sigma_0^2 - \tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} (\widehat{H}(p), -e_i)^\top \right)}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} \right\}, \quad (\text{IA.58})$$

$i = 1, \dots, K$, where function $\widehat{H}(p)$ is given by equation (IA.56), $G_i(p; e_i)$ is a normalizing function, $\tilde{\lambda} \equiv \left(\lambda_1 \sum_{j=1}^K k_j, \dots, \lambda_{N-1} \sum_{j=1}^K k_j, 1 \right)^\top$, and

$$\tilde{\Sigma}_i \equiv \begin{bmatrix} (\lambda \lambda^\top \sum_{j=1}^K k_j^2 / \tau_j + \Sigma_\nu) & \lambda k_i / \tau_i \\ \lambda^\top k_i / \tau_i & 1 / \tau_i \end{bmatrix} \quad (\text{IA.59})$$

is the variance-covariance matrix of the vector $(\hat{s}, e_i)^\top$ conditional on ε .

From Lemma IA3.1 we observe that, in contrast to our baseline analysis, the sufficient statistic $\hat{s}$ and signal e_i are correlated because investor i 's information affects all prices, and hence also the sufficient statistic. Therefore, each investor has a different posterior not only via the private signal e_i but also because of the variance-covariance matrix $\tilde{\Sigma}_i$. The expression for the posterior probabilities (IA.58) are very similar to the uninformed investor's posterior probabilities (15) in our baseline setting, and can be obtained from the latter probabilities by replacing $h\lambda/\gamma_I$, Σ_ν , and $H(p)$ with $\tilde{\lambda}$, $\tilde{\Sigma}_i$, and $(\widehat{H}(p), -e_i)^\top$.

We then find the equilibrium as follows. From the FOC (IA.53) for investor i , we find optimal portfolios $\theta_i^*(p; e_i)$ in terms of probabilities (IA.58). After that, we construct the information function $\widehat{H}(p)$ in equation (IA.56). Similar to our baseline setting, the information function $\widehat{H}(p)$ depends on probabilities (IA.58), and hence, solves a linear fixed-point problem, which we are able to solve in closed form. Proposition IA3.1 reports the equilibrium.

Proposition IA3.1 (Equilibrium with $M = N$ assets and Heterogeneous Agents).

i) *In the class of equilibria with separable demand functions (IA.54) and for a given set of constants k_i , $i = 1, \dots, K$ there exists unique equilibrium in which prices only reveal the sufficient statistic $\hat{s}$. In this equilibrium, the vector of risky asset prices $P(\hat{s}) \equiv P(e, \nu)$ and risk-neutral probabilities π_n^{RN} are given by:*

$$P(\hat{s}) = \left[\pi_1^{\text{RN}} C(\omega_1) + \pi_2^{\text{RN}} C(\omega_2) + \dots + \pi_N^{\text{RN}} C(\omega_N) \right] e^{-rT}, \quad (\text{IA.60})$$

$$\pi_n^{\text{RN}} = \frac{e^{v_n}}{\sum_{j=1}^N e^{v_j}}, \quad (\text{IA.61})$$

where probability parameters v_n are given in closed form by:

$$v_n = a_n + \left(\sum_{j=1}^K \frac{1}{\gamma_j} \right)^{-1} \left(\frac{1}{2} \sum_{j=1}^K \frac{b_n^2 + 2b_n \mu_0 / \sigma_0^2}{\gamma_j (\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2)} + C(\omega_n)^\top \left(E + \sum_{j=1}^K \hat{Q}_j \right) \hat{s} \right), \quad (\text{IA.62})$$

$$\hat{Q}_i = \frac{1}{\gamma_i} \frac{1}{\tau_i + 1/\sigma_0^2} \frac{\lambda \lambda^\top \Sigma_\nu^{-1} \sum_{j \neq i} k_j / \lambda^\top \Sigma_\nu^{-1} \lambda}{1/\lambda^\top \Sigma_\nu^{-1} \lambda + \sum_{j \neq i} k_j^2 / \tau_j + \left(\sum_{j \neq i} k_j \right)^2 / (\tau_i + 1/\sigma_0^2)}, \quad (\text{IA.63})$$

where E is an identity matrix, $\hat{Q}_i, E \in \mathbb{R}^{(N-1) \times (N-1)}$, $\lambda = \Omega^{-1}(b_1 - b_N, \dots, b_{N-1} - b_N)^\top$, $\tilde{\lambda} = (\lambda_1 \sum_{j=1}^K k_j, \dots, \lambda_{N-1} \sum_{j=1}^K k_j, 1)^\top$, and $\tilde{\Sigma}_i$ is defined in equation (IA.59).

ii) Portfolios $\theta_i^*(p; e_i)$, $i = 1, \dots, N-1$ are given by

$$\theta_i^*(p; e_i) = \Omega^{-1} \frac{A_i}{\gamma_i} + \frac{\lambda \mu_0 / \sigma_0^2}{\gamma_i (\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2)} - \hat{Q}_i \hat{H}(p) + \lambda k_i e_i, \text{ where} \quad (\text{IA.64})$$

$$\hat{H}(p) = \left(E + \sum_{j=1}^K \hat{Q}_j \right)^{-1} \left(\sum_{j=1}^K \Omega^{-1} \frac{A_j}{\gamma_j} + \sum_{j=1}^K \frac{\lambda \mu_0 / \sigma_0^2}{\gamma_j (\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2)} \right), \quad (\text{IA.65})$$

where $A_i = \tilde{a} + 0.5 \tilde{b}^{(2)} / (\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2) - \tilde{v}(p) \in \mathbb{R}^{N-1}$, $\tilde{v} = (v_1 - v_N, \dots, v_{N-1} - v_N)$, $\tilde{a} = (a_1 - a_N, \dots, a_{N-1} - a_N)$, and $\tilde{b}^{(2)} = (b_1^2 - b_N^2, \dots, b_{N-1}^2 - b_N^2)$.

iii) Constants k_i , $i = 1, \dots, K$ solve the system of fixed point equations:

$$k_i = \frac{1}{\gamma_i} \frac{\tau_i}{\tau_i + 1/\sigma_0^2} \frac{1/\lambda^\top \Sigma_\nu^{-1} \lambda + \sum_{j \neq i} k_j^2 / \tau_j - \sum_{j \neq i} k_j k_i / \tau_i}{1/\lambda^\top \Sigma_\nu^{-1} \lambda + \sum_{j \neq i} k_j^2 / \tau_j + \left(\sum_{j \neq i} k_j \right)^2 / (\tau_i + 1/\sigma_0^2)}. \quad (\text{IA.66})$$

These equations have a solution that satisfies the bound:

$$0 < k_i < \frac{1}{\gamma_i} \frac{\tau_i}{\tau_i + 1/\sigma_0^2}, \quad i = 1, \dots, K. \quad (\text{IA.67})$$

Proposition IA3.1 extends the no-arbitrage valuation approach to economies with heterogeneous information á la Hellwig (1980) and provides asset prices in closed form in terms of expected discounted payoffs under risk-neutral probabilities, familiar from the asset-pricing literature. As in our baseline setting of Section 3.1 (Proposition 1) prices are non-linear functions of a sufficient statistic. This non-linearity is in contrast to the single-asset CARA-normal noisy REE model with heterogeneous information of Hellwig (1980), where prices are linear functions of the sufficient statistic, but akin to the single-asset model of Breon-Drish (2015, sec. 6) for asset payoffs belonging to the exponential family. Finally, the equations (IA.66) for k_i 's are very similar (with trivial notational differences)

to those in Hellwig (1980, eqs. 8a) and in Breon-Drish (2015, eqs. A.39). Below we present two special cases of this general setup for which we can find solutions for the constants k_i 's in closed form.

Remark IA3.1 (Particular Cases).

1. *Informed & Uninformed investors.* Note that we can retrieve our baseline setup by setting $K = 2$, $\gamma_1 = \gamma_I/h$, $\tau_1 = \infty$, $\gamma_2 = \gamma_U/(1-h)$, $\tau_2 = 0$. Then it is easy to see that from Equations (IA.66) $k_1 = 1/\gamma_1 = h/\gamma_I$ and $k_2 = 0$. This implies that $\hat{s} = h\lambda\varepsilon/\gamma_I + \nu$, since investor I has perfect information and embeds it in prices by trading, while investor U only has the prior information.

2. *Symmetric investors.* In the special case where $\tau_i = \tau$, $\gamma_i = \gamma$ we look for a symmetric solution $k_i = k$ for all $i = 1, \dots, K$. Equations (IA.66) reduce to a single cubic equation:

$$k^3(K-1)\left(K + 1/(\tau\sigma_0^2)\right)\lambda^\top \Sigma_\nu^{-1} \lambda / \tau + k\left(1 + 1/(\tau\sigma_0^2)\right) - 1/\gamma = 0,$$

which has a unique solution because the left-hand side is an increasing function of k .

IA3.2 General Economy with $M \leq N$ Securities

In this section, we study incomplete markets with $M \leq N$. As in Section 3.2 of our baseline analysis, we impose the informational spanning condition (28), which requires that the aggregate risk factor b_n can be replicated by a portfolio of assets, that is,

$$b_n = \lambda_0 + C(\omega_n)^\top \lambda, \quad (\text{IA.68})$$

where λ_0 is a constant and $\lambda = (\lambda_1, \dots, \lambda_{M-1})^\top$. As in the previous section, we conjecture that portfolios $\theta_i^*(p; e_i)$ are separable in price p and signal e_i [see equation (IA.54)]. Consequently, following the same steps as in the complete-market case $M = N$, we find that the equilibrium prices are functions of the same sufficient statistic $\hat{s}$. Hence, because investors i observe the same information as in the complete-market case, their posterior beliefs $\pi_n^i(p; e_i)$ are given by equation (IA.58). Given these probabilities, we derive the optimal portfolios, and then the asset prices from the market clearing condition. Proposition IA3.2 reports the equilibrium.

Proposition IA3.2 (Equilibrium with $M \leq N$ assets and Heterogeneous Agents).

i) *Let the informational spanning condition (IA.68) be satisfied. In the class of equilibria with separable demand functions (IA.54) and for a given set of constants k_i , $i = 1, \dots, K$ there exists unique continuously differentiable and invertible on its range price function*

$P(\hat{s})$ that is the unique solution of equation

$$\sum_{j=1}^K \frac{f_j^{-1}(e^{rT} P(\hat{s}))}{\gamma_j} = \left(E + \sum_{j=1}^K \hat{Q}_j\right) \hat{s} + \sum_{j=1}^K \frac{\lambda \mu_0 / \sigma_0^2}{\gamma_j (\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1 / \sigma_0^2)}, \quad (\text{IA.69})$$

where E is an identity matrix, $\hat{Q}_i$ is given by equation (IA.63), $\hat{Q}_i, E \in \mathbb{R}^{(M-1) \times (M-1)}$, $\lambda = (\lambda_1, \dots, \lambda_{M-1})^\top$, $\tilde{\lambda} = (\lambda_1 \sum_{j=1}^K k_j, \dots, \lambda_{M-1} \sum_{j=1}^K k_j, 1)^\top$, and $\tilde{\Sigma}_i$ is given by equation (IA.59). Functions $f_i : \mathbb{R}^{M-1} \rightarrow \mathbb{R}^{M-1}$ for $i = 1, \dots, K$ are invertible on their ranges and given by

$$f_i(x) = \frac{\sum_{j=1}^N C(\omega_j) \exp \left\{ a_j + \frac{1}{2} \frac{b_j^2}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1 / \sigma_0^2} + C(\omega_j)^\top x \right\}}{\sum_{j=1}^N \exp \left\{ a_j + \frac{1}{2} \frac{b_j^2}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1 / \sigma_0^2} + C(\omega_j)^\top x \right\}}. \quad (\text{IA.70})$$

ii) The optimal portfolios for each $i = 1, \dots, K$ are given by

$$\theta_i^*(p; e_i) = -\frac{f_i^{-1}(e^{rT} p)}{\gamma_i} + \frac{\lambda \mu_0 / \sigma_0^2}{\gamma_i (\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1 / \sigma_0^2)} - \hat{Q}_i \hat{H}^{inc}(p) + \lambda k_i e_i, \text{ where } (\text{IA.71})$$

$$\hat{H}^{inc}(p) = \left(E + \sum_{j=1}^K \hat{Q}_j \right)^{-1} \left(-\sum_{j=1}^K \frac{f_j^{-1}(e^{rT} p)}{\gamma_j} + \sum_{j=1}^K \frac{\lambda \mu_0 / \sigma_0^2}{\gamma_j (\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1 / \sigma_0^2)} \right). \quad (\text{IA.72})$$

iii) Constants k_i , $i = 1, \dots, K$ solve the same system of fixed point equations (IA.66) that have a solution satisfying bounds (IA.67).

Portfolios (IA.71) have similar structure as the complete-market portfolios. Furthermore, both in incomplete and complete markets, with heterogeneous agents, prices are non-linear functions of the sufficient statistic $\hat{s}$. However, in incomplete markets, in general, the prices are not available in closed form and satisfy non-linear equations (IA.69).

IA3.3 Effective Completeness and Volatility Derivatives

We now apply the model to study the role of volatility derivatives as in Section 4.2. We show that adding volatility derivatives to incomplete markets makes these markets *effectively complete*, that is, allows investors to achieve Pareto-optimal allocations. In a setting where investors have different probabilities of states Pareto optimality requires the marginal rate of substitution (MRS) across states n, m to be the same for investors i, j [see., Amershi (1985); Brennan and Cao (1996)]:

$$\frac{\pi_n^i(p; e_i) \exp\{-\gamma_i W_{i,T,n}\}}{\pi_m^i(p; e_i) \exp\{-\gamma_i W_{i,T,m}\}} = \frac{\pi_n^j(p; e_j) \exp\{-\gamma_j W_{j,T,n}\}}{\pi_m^j(p; e_j) \exp\{-\gamma_j W_{j,T,m}\}}, \quad (\text{IA.73})$$

for all $n \neq m$ and all $i \neq j$, or equivalently, for all states n and all $i \neq j$:

$$\frac{\pi_n^i(p; e_i) \exp\{-\gamma_i W_{i,T,n}\}}{\pi_n^j(p; e_j) \exp\{-\gamma_j W_{j,T,n}\}} = \ell, \quad (\text{IA.74})$$

where ℓ does not depend on the state ω_n (but may depend on i, j and signals). Proposition IA3.3 below provides necessary and sufficient conditions for effective completeness.

Proposition IA3.3 (Effective Completeness with Heterogeneous Agents).

- i) Suppose, the market is incomplete, that is, $M < N$, and the informational spanning condition (IA.68) is satisfied. Then, the market is effectively complete if and only if there exists a replicating portfolio for squared risk factor realizations b_n^2 , that is, there exist constant $\hat{\lambda}_0$ and vector $\hat{\lambda} \in \mathbb{R}^{M-1}$ such that $b_n^2 = \hat{\lambda}_0 + C(\omega_n)^\top \hat{\lambda}$, for all $n = 1, \dots, N$.
- ii) If the market is effectively complete, the prices of risky assets are given by equation (IA.60), as in a complete market, with the only difference that vectors $\lambda, \tilde{\lambda}, \nu$, and matrices $\Omega, E, \Sigma_\nu, \tilde{\Sigma}_i$ and $\hat{Q}_i$ are of lower dimensions: $\lambda, \tilde{\lambda}, \nu \in \mathbb{R}^{M-1}$, $\Omega \in \mathbb{R}^{(N-1) \times (M-1)}$, and $E, \Sigma_\nu, \tilde{\Sigma}_i, \hat{Q}_i \in \mathbb{R}^{(M-1) \times (M-1)}$, for all $i = 1, \dots, K$.

As in the baseline setting with uninformed and informed investors, the proposition implies that the market can be effectively completed by introducing a derivative security with a quadratic payoff such as C_1^2 or $(C_1 - \mathbb{E}^{\text{RN}}[C_1])^2$. The prices of this security and the underlying asset are then given in closed form by $\text{var}^{\text{RN}}[C_1]e^{-rT}$ and $\mathbb{E}^{\text{RN}}[C_1]e^{-rT}$, respectively.

IA3.4 Proofs

Proof of Lemma IA3.1: Let $\tilde{s}_i = (\hat{s}, e_i)^\top$. Then, from Bayes rule, the PDF of ε conditional on observing $\tilde{s}_i$ is given by

$$\varphi_{\varepsilon|\tilde{s}_i}(e|s, y) = \frac{\varphi_{\tilde{s}_i|\varepsilon}(s, y|e)\varphi_\varepsilon(e)}{\int \varphi_{\tilde{s}_i|\varepsilon}(s, y|e)\varphi_\varepsilon(e)de}. \quad (\text{IA.75})$$

From equation (IA.48), the signal is conditionally normal, and given by $e_i = \varepsilon + x_i$. Hence, $e_i|\varepsilon \sim \mathcal{N}(\varepsilon, 1/\tau_i)$. The sufficient statistic is given by $\hat{s} = \lambda \sum_{j=1}^K k_j e_j + \nu$, which implies that $\text{cov}(\hat{s}, e_i|\varepsilon) = \lambda k_i/\tau_i$. Therefore, the sufficient statistic is conditionally normal and is given by $\hat{s} = \lambda \sum_{j=1}^K k_j \varepsilon + \lambda \sum_{j \neq i} k_j \cdot x_j + \lambda k_i \cdot x_i + \nu$. Then, vector $\tilde{s}_i$ is also conditionally normal, and after computing its moments, we obtain $\tilde{s}_i|\varepsilon \sim \mathcal{N}(\tilde{\lambda}\varepsilon, \tilde{\Sigma}_i)$, where matrix $\tilde{\Sigma}_i$ is given by equation (IA.59), and vector $\tilde{\lambda}$ is given by

$$\tilde{\lambda} = \left(\lambda_1 \sum_{j=1}^K k_j, \dots, \lambda_{N-1} \sum_{j=1}^K k_j, 1 \right)^\top. \quad (\text{IA.76})$$

Hence, substituting normal PDF $\varphi_{\tilde{s}_i|\varepsilon}(s, y|e)$ into equation (IA.75), we obtain

$$\varphi_{\varepsilon|\tilde{s}_i}(e|s, y) = \frac{\exp \left\{ -0.5 \left((s, y)^\top - \tilde{\lambda}\varepsilon \right)^\top \tilde{\Sigma}_i^{-1} \left((s, y)^\top - \tilde{\lambda}\varepsilon \right) \right\} \varphi_\varepsilon(e)}{G_{1,i}(s, y)}, \quad (\text{IA.77})$$

where $G_{1,i}(s, y)$ normalizes the density.

Next, we find probability $\pi_n^i(p; e_i)$ given by $\pi_n^i(p; e_i) = \mathbb{E}[\pi_n(\varepsilon)|\hat{s} = -\widehat{H}(p), e_i]$. Calculating the latter conditional expectation, we obtain:

$$\pi_n^i(p; e_i) = \int_{-\infty}^{+\infty} \frac{e^{a_n + b_n e}}{\sum_{j=1}^N e^{a_j + b_j e}} \varphi_{\varepsilon|\tilde{s}_i}(e|s = -\widehat{H}(p), e_i = y) de = \frac{1}{G_{1,i}(\hat{s}, y)} \int_{-\infty}^{+\infty} e^{d_n^i(e)} de, \quad (\text{IA.78})$$

where $d_n^i(e)$ is a quadratic function of e given by:

$$\begin{aligned} d_n^i(e) &= a_n + b_n \cdot e - 0.5 \left(\tilde{\lambda}e + \begin{pmatrix} \widehat{H}(p) \\ -y \end{pmatrix} \right)^\top \tilde{\Sigma}_i^{-1} \left(\tilde{\lambda}e + \begin{pmatrix} \widehat{H}(p) \\ -y \end{pmatrix} \right) - 0.5(e - \mu_0)^2 / \sigma_0^2 \\ &= -\frac{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2}{2} \left(e - \frac{\mu_0/\sigma_0^2 + b_n - \tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} (\widehat{H}^{inc}(p), -e_i)^\top}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} \right)^2 + a_n \\ &\quad + \frac{1}{2} \frac{b_n^2 + 2b_n \left(\mu_0/\sigma_0^2 - \tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} (\widehat{H}^{inc}(p), -e_i)^\top \right)}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} + g(p, y), \end{aligned} \quad (\text{IA.79})$$

where $g(p, y)$ is a normalizing function. Substituting $d_n^i(e)$ from equation (IA.79) into integral (IA.78) and integrating, we obtain equation (IA.58) for $\pi_n^i(p; e_i)$. ■

Proof of Proposition IA3.1: Below we adapt the proof of Proposition 1 in the case of heterogeneous agents: namely, first we find the optimal portfolios of investors, and then recover the equilibrium prices from the market clearing condition. In particular, we use that now investors have different posterior probabilities $\pi_n^i(p; e_i)$ [see equation (IA.58)] to get the analogue of equation (A.12)

$$\theta_i^* = \underbrace{\frac{\Omega^{-1}}{\gamma_i} \left(\tilde{a} + \frac{1}{2} \frac{\tilde{b}^{(2)} + 2\tilde{b}\mu_0/\sigma_0^2}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} - \frac{\tilde{b}\Lambda_{1,i}\widehat{H}(p)}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} - \tilde{v}(p) \right)}_{\theta_{1,i}} + \underbrace{\lambda \frac{\Lambda_{2,i}/\gamma_i}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} e_i}_{\lambda k_i e_i}, \quad (\text{IA.80})$$

where $\tilde{v}(p)$, $\tilde{a}$, $\tilde{b}$, $\tilde{b}^{(2)} \in \mathbb{R}^{N-1}$ are defined in Equations (12), (A.13), (A.14), respectively. Furthermore, recall that $\lambda = \Omega^{-1}\tilde{b}$, $\tilde{\lambda} = [\sum_{j=1}^k k_j \lambda^\top, 1]^\top$, $\tilde{\Sigma}_i$ is defined in equation (IA.59), and $\Lambda_{1,i}$, $\Lambda_{2,i}$ are defined in equation (IA.86) of Lemma IA3.4.1 (presented below).

We conjectured in equation (IA.54) that $\theta_i^* = \theta_{1,i} + \lambda k_i e_i$, hence the notation above. Therefore, k_i 's solve the fixed point equations:

$$k_i = \frac{\Lambda_{2,i}/\gamma_i}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2}, \quad i = 1, \dots, K.$$

Now, substituting for $\Lambda_{2,i}$ from equation (IA.86) and using equation (IA.83) for $\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda}$ in terms of $\lambda^\top \Sigma_\nu^{-1} \lambda$ we have after some algebra that for each i :

$$k_i = \frac{\tau_i}{\gamma_i} \frac{1 + \lambda^\top \Sigma_\nu^{-1} \lambda \left(\sum_{j \neq i} k_j^2 / \tau_j - \sum_{j \neq i} k_j k_i / \tau_i \right)}{\lambda^\top \Sigma_\nu^{-1} \lambda \left(\sum_{j \neq i} k_j \right)^2 + (\tau_i + 1/\sigma_0^2) \left(1 + \lambda^\top \Sigma_\nu^{-1} \lambda \sum_{j \neq i} k_j^2 / \tau_j \right)}.$$

Furthermore, if we factor out $\lambda^\top \Sigma_\nu^{-1} \lambda$ from the numerator and denominator we arrive to equation (IA.66). Lemma IA3.4.2 below establishes the existence of a solution and the corresponding bounds reported in Proposition IA3.1-iii).

Now, we can sum up the identified $\theta_{1,i}$ in equation (IA.80) and use definition (IA.56) $\widehat{H}(p) = \sum_{j=1}^K \theta_{1,j}$ to solve for $\widehat{H}(p)$:

$$\begin{aligned} \widehat{H}(p) &= \sum_{j=1}^K \left\{ \frac{\Omega^{-1}}{\gamma_j} \left(\tilde{a} + \frac{1}{2} \frac{\tilde{b}^{(2)} + 2\tilde{b}\mu_0/\sigma_0^2}{\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2} - \frac{\tilde{b}\Lambda_{1,j}\widehat{H}(p)}{\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2} - \tilde{v}(p) \right) \right\} \\ \Rightarrow \widehat{H}(p) &= \left(E + \sum_{j=1}^K \lambda \underbrace{\frac{\Lambda_{1,j}}{\gamma_j (\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2)}}_{\widehat{Q}_j} \right)^{-1} \sum_{j=1}^K \frac{\Omega^{-1}}{\gamma_j} \underbrace{\left(\tilde{a} + \frac{1}{2} \frac{\tilde{b}^{(2)} + 2\tilde{b}\mu_0/\sigma_0^2}{\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2} - \tilde{v}(p) \right)}_{A_j}. \end{aligned} \quad (\text{IA.81})$$

Using the definitions of $\widehat{Q}_j$ and A_j , as indicated above, in equation (IA.81) we arrive to equation (IA.65). Substituting (IA.65) in equation (IA.80) leads to the expression of the optimal portfolios in equation (IA.64). We can further simplify $\widehat{Q}_j$ defined above by substituting for $\Lambda_{1,j}$ from equation (IA.86) and $\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda}$ in terms of $\lambda^\top \Sigma_\nu^{-1} \lambda$ from equation (IA.83). After some algebra, we arrive to equation (IA.63).

Next, we find the equilibrium prices. Substituting $\widehat{H}(p)$ from equation (IA.81) into the market clearing condition (IA.55), after rearranging terms, we obtain the following for vector $\tilde{v}(p)$, which is the analogue of equation (A.17) in the main text:

$$\begin{aligned} \sum_{j=1}^K \frac{1}{\gamma_j} \left(\tilde{a} + \frac{1}{2} \frac{\tilde{b}^{(2)} + 2\tilde{b}\mu_0/\sigma_0^2}{\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2} \right) - \sum_{j=1}^K \frac{1}{\gamma_j} \tilde{v}(p) + \Omega \left(E + \sum_{j=1}^K \lambda \frac{\Lambda_{1,j}}{\gamma_j (\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2)} \right) \widehat{s} &= 0 \\ \Rightarrow \tilde{v}(p) &= \left(\sum_{j=1}^K \frac{1}{\gamma_j} \right)^{-1} \sum_{j=1}^K \frac{1}{\gamma_j} \left(\tilde{a} + \frac{1}{2} \frac{\tilde{b}^{(2)} + 2\tilde{b}\mu_0/\sigma_0^2}{\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2} \right) \end{aligned}$$

$$+ \left(\sum_{j=1}^K \frac{1}{\gamma_j} \right)^{-1} \Omega \left(E + \sum_{j=1}^K \lambda \underbrace{\frac{\Lambda_{1,j}}{\gamma_j (\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2)}}_{\hat{Q}_j} \right) \hat{s}. \quad (\text{IA.82})$$

Writing the above element-wise for $n = 1, \dots, N$ leads to (IA.62). From the definition of vector $\tilde{v}$ in equation (12), we find that $\pi_n^{\text{RN}} = e^{v_n - v_N} / \left(\sum_{j=1}^N e^{v_j - v_N} \right)$ for $n = 1, \dots, N$. Canceling e^{-v_N} , we obtain probabilities (IA.61). Following similar arguments to Proposition 1, we can verify that $P(\hat{s})$ is an invertible on its range function of $\hat{s} = \lambda \sum_{j=1}^K k_j e_j + \nu = \lambda \sum_{j=1}^K k_j \varepsilon + \lambda \sum_{j=1}^K k_j x_j + \nu$, and hence, observing prices reveals unique $\hat{s}$. ■

Lemma IA3.4.1 (Posterior precision). *The effect on posterior probabilities stemming from noisy supply $\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda}$ can be decomposed as*

$$\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} = \frac{\lambda^\top \Sigma_\nu^{-1} \lambda \left(\sum_{j \neq i} k_j \right)^2}{1 + \lambda^\top \Sigma_\nu^{-1} \lambda \sum_{j \neq i} k_j^2 / \tau_j} + \tau_i, \quad (\text{IA.83})$$

where $\lambda = \Omega^{-1}(b_1 - b_N, \dots, b_{N-1} - b_N)^\top$ and $\tilde{\lambda}$ is given by (IA.76).

Proof of Lemma IA3.4.1: Let $\hat{\Sigma} \equiv \lambda \lambda^\top \sum_{j=1}^K k_j^2 / \tau_j + \Sigma_\nu$. It is easy to verify that

$$\hat{\Sigma}^{-1} = \Sigma_\nu^{-1} - \Sigma_\nu^{-1} \lambda \left(1 / \left(\sum_{j=1}^K k_j^2 / \tau_j \right) + \lambda^\top \Sigma_\nu^{-1} \lambda \right)^{-1} \lambda^\top \Sigma_\nu^{-1}. \quad (\text{IA.84})$$

Furthermore, it can be directly verified that

$$\tilde{\Sigma}_i^{-1} = \frac{1}{1 - \lambda^\top \hat{\Sigma}^{-1} \lambda k_i^2 / \tau_i} \begin{bmatrix} \hat{\Sigma}^{-1} \left(1 - \lambda^\top \hat{\Sigma}^{-1} \lambda k_i^2 / \tau_i \right) + \hat{\Sigma}^{-1} \lambda \lambda^\top \hat{\Sigma}^{-1} k_i^2 / \tau_i & -\hat{\Sigma}^{-1} \lambda k_i \\ -\lambda^\top \hat{\Sigma}^{-1} k_i & \tau_i \end{bmatrix}. \quad (\text{IA.85})$$

Using equation (IA.85), equation (IA.84), and $\tilde{\lambda}$ in equation (IA.76), we obtain:

$$\begin{aligned} \tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} &= \frac{1}{1 - \lambda^\top \hat{\Sigma}^{-1} \lambda k_i^2 / \tau_i} \left[\lambda^\top \hat{\Sigma}^{-1} \left(\sum_{j=1}^K k_j - k_i \right), \tau_i - \sum_{j=1}^K k_j k_i \lambda^\top \hat{\Sigma}^{-1} \lambda \right] \\ &\equiv \begin{bmatrix} \Lambda_{1,i} & \Lambda_{2,i} \end{bmatrix}, \end{aligned} \quad (\text{IA.86})$$

and

$$\begin{aligned} \tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} &= \frac{\lambda^\top \hat{\Sigma}^{-1} \lambda \sum_{j=1}^K k_j \left(\sum_{j=1}^K k_j - k_i \right) + \tau_i - \sum_{j=1}^K k_j k_i \lambda^\top \hat{\Sigma}^{-1} \lambda}{1 - \lambda^\top \hat{\Sigma}^{-1} \lambda k_i^2 / \tau_i} \\ &= \lambda^\top \hat{\Sigma}^{-1} \lambda \left(\sum_{j=1}^K k_j - k_i \right)^2 \frac{1}{1 - \lambda^\top \hat{\Sigma}^{-1} \lambda k_i^2 / \tau_i} + \tau_i \\ &= \frac{\lambda^\top \Sigma_\nu^{-1} \lambda \left(\sum_{j=1}^K k_j - k_i \right)^2}{1 + \lambda^\top \Sigma_\nu^{-1} \lambda \left(\sum_{j=1}^K k_j^2 / \tau_j - k_i^2 / \tau_i \right)} + \tau_i. \quad \blacksquare \end{aligned}$$

Lemma IA3.4.2 (Existence of solution and bounds for k_i). Equations (IA.66) for k_i , $i = 1, \dots, K$ have a solution that satisfies bounds (IA.67).

Proof of Lemma IA3.4.2: The proof essentially replicates Hellwig (1980, proof of Lemma 3.1) and by association Breon-Drish (2015, proof of Lemma A15). We first prove the bounds. We start with the lower bound. Assume there exists non-empty set $I^- \equiv \{i \in \{1, \dots, K\} : k_i \leq 0\}$. Then let $i_0 \equiv \arg \max_{i \in I^-} k_i/\tau_i$. Observe that for i_0 :

$$\begin{aligned} 1/\lambda^\top \Sigma_\nu^{-1} \lambda + \sum_{j \neq i_0} k_j^2/\tau_j - \sum_{j \neq i_0} k_j k_{i_0}/\tau_{i_0} &= 1/\lambda^\top \Sigma_\nu^{-1} \lambda + \sum_{j=1}^K k_j^2/\tau_j - \sum_{j=1}^K k_j k_{i_0}/\tau_{i_0} \\ &> \sum_{j=1}^K k_j^2/\tau_j - \sum_{j=1}^K k_j k_{i_0}/\tau_{i_0} \\ &> \sum_{j \in I^-} k_j^2/\tau_j - \sum_{j \in I^-} k_j k_{i_0}/\tau_{i_0} \\ &= \sum_{j \in I^-} k_j (k_j/\tau_j - k_{i_0}/\tau_{i_0}) \geq 0, \end{aligned}$$

where the first equality follows from adding and subtracting $k_{i_0}^2/\tau_{i_0}$, the first inequality follows because $1/\lambda^\top \Sigma_\nu^{-1} \lambda$ is positive, the second from the definition of I^- , and the last from the definitions of i_0 and I^- . The above implies that the numerator in the last fraction of (IA.66) is positive and hence also k_{i_0} since the denominator and the rest of the fractions are trivially positive. But this is a contradiction to $i_0 \in I^-$ and so $I^- = \emptyset$ and $k_i > 0$ for all i . From $k_i > 0$ we also have that the last fraction of (IA.66) is less than one and hence we get the upper bound on k_i . Given these bounds we will show existence of a solution.

Define mappings $T_0 : \times_{j=1}^K \Gamma_j \rightarrow \mathbb{R}^K$ and $T_1 : \times_{j=1}^K \Gamma_j \rightarrow \times_{j=1}^K \Gamma_j$, where

$$\Gamma_i \equiv \left[0, \frac{1}{\gamma_i} \frac{\tau_i}{\tau_i + 1/\sigma_0^2} \right],$$

as follows:

$$(T_0 k)_i = \frac{1}{\gamma_i} \frac{\tau_i}{\tau_i + 1/\sigma_0^2} \frac{1/\lambda^\top \Sigma_\nu^{-1} \lambda + \sum_{j \neq i} k_j^2/\tau_j - \sum_{j \neq i} k_j k_i/\tau_i}{1/\lambda^\top \Sigma_\nu^{-1} \lambda + \sum_{j \neq i} k_j^2/\tau_j + \left(\sum_{j \neq i} k_j \right)^2 / (\tau_i + 1/\sigma_0^2)}, \quad i = 1, \dots, K,$$

$$(T_1 k)_i = \begin{cases} 0, & \text{if } (T_0 k)_i < 0, \\ (T_0 k)_i, & \text{if } (T_0 k)_i \in \Gamma_i, \\ \frac{1}{\gamma_i} \frac{\tau_i}{\tau_i + 1/\sigma_0^2}, & \text{if } (T_0 k)_i > \frac{1}{\gamma_i} \frac{\tau_i}{\tau_i + 1/\sigma_0^2}. \end{cases}$$

The product of compact sets Γ_i is compact and mapping T_1 is continuous and maps $\times_{j=1}^K \Gamma_j$ into itself. Then by Brouwer's fixed point theorem T_1 has a fixed point in $\times_{j=1}^K \Gamma_j$.

It remains to verify that the fixed point let k^* is in the interior of $\times_{j=1}^K \Gamma_j$. Suppose first that there is i such that $k_i^* = 0$. Then

$$(T_0 k^*)_i = \frac{1}{\gamma_i} \frac{\tau_i}{\tau_i + 1/\sigma_0^2} \frac{1/\lambda^\top \Sigma_\nu^{-1} \lambda + \sum_{j \neq i} k_j^{*2}/\tau_j}{1/\lambda^\top \Sigma_\nu^{-1} \lambda + \sum_{j \neq i} k_j^{*2}/\tau_j + \left(\sum_{j \neq i} k_j^*\right)^2/(\tau_i + 1/\sigma_0^2)} \in \left(0, \frac{1}{\gamma_i} \frac{\tau_i}{\tau_i + 1/\sigma_0^2}\right),$$

hence $(T_1 k^*)_i = (T_0 k^*)_i > 0 = k_i^*$, which is a contradiction since we should have $k_i^* = (T_1 k^*)_i$. Since, $k_i^* > 0$ for all i it follows that $(T_0 k^*)_i < \tau_i/(\gamma_i(\tau_i + 1/\sigma_0^2))$ and hence also $(T_1 k^*)_i < \tau_i/(\gamma_i(\tau_i + 1/\sigma_0^2))$ for all i . Thus the fixed point is in the interior of $\times_{j=1}^K \Gamma_j$. ■

Proof of Proposition IA3.2. Below we adapt the proof of Proposition 3 in the case of heterogeneous agents. The only substantial point of departure from that proof is existence of equilibrium where we adopt an alternative technique suggested by a referee.

Step 1 (Posterior probabilities and portfolio of investor i). As mentioned given conjecture (IA.54) the market clearing condition with incomplete markets is analogous to condition (IA.55) for complete markets. The posterior probabilities can be found similar to Lemma IA3.1, and are given by equation (IA.58) in which $\widehat{H}(p)$ is replaced by $\widehat{H}^{inc}(p)$.

Substituting probabilities $\pi_n^i(p; e_i)$ into investor i 's objective function (IA.52), after some algebra, we obtain the FOC for investor i 's optimal portfolio θ_i^* and the analogue to equation (A.30),

$$f_i \left(\frac{\lambda \mu_0 / \sigma_0^2 - \lambda \tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} (\widehat{H}^{inc}(p), -e_i)^\top}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} - \gamma_i \theta_i^* \right) = e^{rT} p \Rightarrow$$

$$\frac{\lambda \mu_0 / \sigma_0^2 - \lambda \tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} (\widehat{H}^{inc}(p), -e_i)^\top}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} - \gamma_i \theta_i^* = f_i^{-1}(e^{rT} p). \quad (\text{IA.87})$$

Above we use the fact that functions f_i , defined in equation (IA.70), are invertible in their ranges [as special cases of $f(x; t)$ in equation (A.36), see Lemmas A.3-A.4] and assume that $e^{rT} p$ belongs to the range of f_i . Hence, solving for θ_i^* in equation (IA.87) we have:

$$\theta_i^* = \frac{1}{\gamma_i} \left(\underbrace{-f_i^{-1}(e^{rT} p) + \frac{\lambda \mu_0 / \sigma_0^2}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} - \frac{\lambda \Lambda_{1,i} \widehat{H}^{inc}(p)}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2}}_{\theta_{1,i}} + \underbrace{\lambda \frac{\Lambda_{2,i} / \gamma_i}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} e_i}_{\lambda k_i e_i} \right) \quad (\text{IA.88})$$

where $\Lambda_{1,i}$, $\Lambda_{2,i}$ are defined in equation (IA.86) of Lemma IA3.2. Again, we conjectured that $\theta_i^* = \theta_{1,i} + \lambda k_i e_i$, hence the notation above. Importantly, as we can see, k_i 's solve the same fixed point Equations (IA.66) as in the complete market case. Hence, solutions

exist from Lemma IA3.4.1, and satisfy bounds (IA.67). Proceeding, we use the definition of $\widehat{H}^{inc}(p) = \sum_{j=1}^K \theta_{1,j}$ and equation (IA.88) and after some algebra we get equation (IA.72) for $\widehat{H}^{inc}(p)$. Then substituting equation (IA.72) back in equation (IA.88), we arrive at equation (IA.71) for θ_i^* , where $\widehat{Q}_i$ is defined in equation (IA.63) but now has lower dimension $\widehat{Q}_i \in \mathbb{R}^{(M-1) \times (M-1)}$.

Step 2 (Equation for asset prices). Substituting $\widehat{H}^{inc}(p)$ from equation (IA.72) into the market clearing condition $\widehat{H}^{inc}(p) + \widehat{s} = \widehat{H}^{inc}(p) + \lambda \sum_{j=1}^K k_j e_j + \nu = 0$ yields, after some algebra, equation (IA.69) for price vector $P(\widehat{s})$.

Step 3 (Existence of Equilibrium). Finally, we show that there exists unique vector of prices satisfying equation (IA.69).² We aim to show that the left-hand-side (LHS) of equation (IA.69) is globally invertible using the Hadamard's Global Inverse Function Theorem. From Lemma IA3.4.2 below this amounts to showing that the LHS is a continuously differentiable function with a non-zero determinant of the Jacobian matrix and proper.

First, note that since the distribution of cash flows is supported on a finite set of points, the domain of f_i is all of $\mathbb{R}^{M-1}$. As the domain is open, Barndorff-Nielsen (2014, Theorem 9.2) implies that the range is $\mathcal{A} = \text{int}(\text{conv}(\text{support}(C(\omega))))$, which, given the assumption of no redundant assets, is the set of prices that do not admit arbitrage.

Second, let the LHS of equation (IA.69) (i.e., the sum of the inverse of the price sensitive parts of investors' portfolios weighted by one over their risk aversion parameter) be denoted by $\bar{f}(e^{rT}P(\widehat{s}))$. Since each f_i has positive definite Jacobian [see Lemma A.3] and is continuously differentiable [see equation (IA.70)] the same properties are inherited by each inverse f^{-1} . So also their weighted sum $\bar{f}$ is a continuously differentiable function and has a non-zero determinant of the Jacobian matrix.

Third, take any compact set $\mathcal{K} \subset \mathbb{R}^{M-1}$. Because $\bar{f}$ is continuous it is immediate that the pre-image $\bar{f}^{-1}(\mathcal{K})$ is closed and furthermore, since the domain $\mathcal{A}$ of $\bar{f}$ is bounded $\bar{f}^{-1}(\mathcal{K})$ is necessarily bounded. Hence, $\bar{f}^{-1}(\mathcal{K})$ is compact. So $\bar{f}$ is proper.

Therefore, from the Hadamard's Global Inverse Function Theorem $\bar{f}$ is a bijection and has a continuously differentiable inverse. Hence, prices exist and are given by:

$$P(\widehat{s}) = e^{-rT} \bar{f}^{-1} \left(\left(E + \sum_{j=1}^K \widehat{Q}_j \right) \left(\lambda \sum_{j=1}^K k_j e_j + \nu \right) + \sum_{j=1}^K \frac{1}{\gamma_j} \frac{\lambda \mu_0 / \sigma_0^2}{\widetilde{\lambda}^\top \widetilde{\Sigma}_j^{-1} \widetilde{\lambda} + 1 / \sigma_0^2} \right);$$

where P is a unique, continuous, differentiable, and invertible on its range function of the right-hand-side of equation (IA.69), and so, also of sufficient statistic $\widehat{s}$. ■

²We thank an anonymous referee for this proof of existence.

Lemma IA3.4.2 (Hadamard's Global Inverse Function Theorem). *Let $\mathcal{B}_1, \mathcal{B}_2 \subset \mathbb{R}^N$ be connected, open sets. A continuously differentiable function $g : \mathcal{B}_1 \rightarrow \mathcal{B}_2$ is a bijection and has a continuously differentiable inverse if and only if the determinant of the Jacobian matrix is everywhere nonzero and g is proper (i.e., the pre-image g^{-1} maps compact sets to compact sets).*

Proof of Lemma IA3.4.2: See Krantz and Parks (2012, Chapter 6). ■

Lemma IA3.4.3. *The market with heterogeneous agents is effectively complete if and only if for all $i \neq j$ there exists a portfolio that replicates $\ln(\pi_n^i(p; e_i)/\pi_n^j(p; e_j))$, that is, there exist (i, j) -dependent but ω -independent $\bar{\lambda}_0 \in \mathbb{R}$ and $\bar{\lambda} \in \mathbb{R}^{M-1}$ such that*

$$\ln \left(\frac{\pi_n^i(p; e_i)}{\pi_n^j(p; e_j)} \right) = \bar{\lambda}_0 + C(\omega_n)^\top \bar{\lambda}. \quad (\text{IA.89})$$

Proof of Lemma IA3.4.3: The proof follows identical steps to that of Lemma A.8-i). However, in contrast to having two separate Equations (A.54) and (A.55) for I and U , respectively, using equation (IA.89) we now have that for each i optimization becomes:

$$\max_{\theta_i} \left[- \sum_{n=1}^N \pi_n^j(p; e_j) e^{-\gamma_i(C(\omega_n) - e^{rT}p)^\top (\theta_i - \bar{\lambda}/\gamma_i)} \right] = \max_{\hat{\theta}} \left[- \sum_{n=1}^N \pi_n^j(p; e_j) e^{-\gamma_j(C(\omega_n) - e^{rT}p)^\top \hat{\theta}} \right], \quad (\text{IA.90})$$

where $\hat{\theta} \equiv (\theta_i - \bar{\lambda}/\gamma_i)(\gamma_i/\gamma_j)$. The second optimization in (IA.90) is the same as that of investor j . Hence, $\theta_j^* = \hat{\theta}^* = (\theta_i^* - \bar{\lambda}/\gamma_i)(\gamma_i/\gamma_j)$, or, equivalently:

$$\gamma_i \theta_i^* - \gamma_j \theta_j^* = \bar{\lambda}, \quad (\text{IA.91})$$

which is the counterpart of equation (A.56). So following the same steps as Lemma A.8-i), by using equation (IA.91) and budget constraints (IA.50) we have $\gamma_j W_{j,T,n} - \gamma_i W_{i,T,n} - \ln(\ell) = \ln(\pi_n^j(p; e_j)/\pi_n^i(p; e_i))$, where ℓ does not depend on ω_n (though depends on i, j), which is equivalent to the Pareto efficiency condition (IA.74). ■

Proof of Proposition IA3.3: i) The proof follows identical steps to that of Proposition 4-i). Substituting $\pi_n^i(p; e_i)$ and $\pi_n^j(p; e_j)$ from (IA.58) into the log-ratio $\ln(\pi_n^i(p; e_i)/\pi_n^j(p; e_j))$, and using the fact that by market clearing $\widehat{H}^{inc}(p) = -\widehat{s}$ we have that the log-ratio of probabilities is a quadratic function of b_n . Recall that $b_n = \lambda_0 + C(\omega_n)^\top \lambda$ by equation (IA.68). Hence, by Lemma IA3.4.3, the optimal portfolios are Pareto efficient if and only if there exists a portfolio that also replicates b_n^2 .

ii) If the market is effectively complete equation (IA.73) by definition holds for all $i \neq j$ and between states n and say N . Let us focus on the MRS of investor i . We substitute probabilities from equation (IA.58) and wealth from the budget constraint (IA.50), and after some algebra we arrive at:

$$\frac{\pi_n^i(p; e_i) \exp\{-\gamma_i W_{i,T,n}\}}{\pi_N^i(p; e_i) \exp\{-\gamma_i W_{i,T,N}\}} = \exp\left\{\tilde{a}_n + \frac{1}{2} \frac{\tilde{b}_n^2 + 2\tilde{b}_n \left(\mu_0/\sigma_0^2 - \tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} (\widehat{H}^{inc}(p), -e_i)^\top\right)}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} - \gamma_i (C(\omega_n) - C(\omega_N))^\top \theta_i^*\right\}, \quad (\text{IA.92})$$

Multiply equation (IA.87) by $(C(\omega_n) - C(\omega_N))^\top$ bearing in mind the definition of $\tilde{b}_n$:

$$\gamma_i (C(\omega_n) - C(\omega_N))^\top \theta_i^* = \frac{b_n (\mu_0/\sigma_0^2 - \tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} (\widehat{H}^{inc}(p), -e_i)^\top)}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} - (C(\omega_n) - C(\omega_N))^\top f_i^{-1}(e^{rT} p).$$

Substituting for $\gamma_i (C(\omega_n) - C(\omega_N))^\top \theta_i^*$ from the last equation to equation (IA.92) yields:

$$\frac{\pi_n^i(p; e_i) \exp\{-\gamma_i W_{i,T,n}\}}{\pi_N^i(p; e_i) \exp\{-\gamma_i W_{i,T,N}\}} = \exp\left\{\tilde{a}_n + \frac{1}{2} \frac{\tilde{b}_n^2}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} - (C(\omega_n) - C(\omega_N))^\top f_i^{-1}(e^{rT} p)\right\}. \quad (\text{IA.93})$$

If we repeat the same calculations we did to reach equation (IA.93) for j , then condition (IA.73) implies that for all $i \neq j$, using also $\tilde{b}_n^2 = (C(\omega_n) - C(\omega_N))^\top \hat{\lambda}$:

$$\frac{1}{2} \frac{\hat{\lambda}}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} - f_i^{-1}(e^{rT} p) = \frac{1}{2} \frac{\hat{\lambda}}{\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2} - f_j^{-1}(e^{rT} p). \quad (\text{IA.94})$$

Now, in equation (IA.94) multiply both sides by $1/\gamma_j$ and sum over j . Then use equation (IA.69) to substitute for $\sum_{j=1}^K f_j^{-1}/\gamma_i$ to arrive at:

$$\sum_{j=1}^K \frac{1}{\gamma_j} \frac{1}{2} \frac{\hat{\lambda}}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} - \sum_{j=1}^K \frac{1}{\gamma_j} f_i^{-1}(e^{rT} p) = \sum_{j=1}^K \left(\frac{1}{\gamma_j} \frac{1}{2} \frac{\hat{\lambda}}{\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2} \right) - R(\hat{s}), \quad (\text{IA.95})$$

where $R(\hat{s})$ is the right-hand-side (RHS) of equation (IA.69). Solving for the equilibrium price function $P(\hat{s}) = p$ in equation (IA.95) we have that for all $i \in 1, \dots, K$:

$$P(\hat{s}) = e^{-rT} f_i \left(\left(\sum_{j=1}^K \frac{1}{\gamma_j} \right)^{-1} \sum_{j=1}^K \left(\frac{1}{\gamma_j} \frac{1}{2} \frac{\hat{\lambda}}{\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2} \right) - \left(\sum_{j=1}^K \frac{1}{\gamma_j} \right)^{-1} R(\hat{s}) - \frac{1}{2} \frac{\hat{\lambda}}{\tilde{\lambda}^\top \tilde{\Sigma}_i^{-1} \tilde{\lambda} + 1/\sigma_0^2} \right), \quad (\text{IA.96})$$

Now, using the definition of f_i in equation (IA.70) the price in equation (IA.96) is the discounted expectation $P(\hat{s}) = e^{-rT} \sum_{n=1}^N q_n C(\omega_n)$ with respect to probability

$$q_n \equiv \frac{\exp\left\{a_n + \frac{1}{2}\left(\sum_{j=1}^K \frac{1}{\gamma_j}\right)^{-1} \sum_{j=1}^K \left(\frac{b_n^2}{\gamma_j \left(\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2\right)}\right) - \left(\sum_{j=1}^K \frac{1}{\gamma_j}\right)^{-1} C(\omega_n)^\top R(\hat{s})\right\}}{\sum_{m=1}^N \exp\left\{a_m + \frac{1}{2}\left(\sum_{j=1}^K \frac{1}{\gamma_j}\right)^{-1} \sum_{j=1}^K \left(\frac{b_m^2}{\gamma_j \left(\tilde{\lambda}^\top \tilde{\Sigma}_j^{-1} \tilde{\lambda} + 1/\sigma_0^2\right)}\right) - \left(\sum_{j=1}^K \frac{1}{\gamma_j}\right)^{-1} C(\omega_m)^\top R(\hat{s})\right\}}, \quad (\text{IA.97})$$

where we again used the fact that $b_n^2 = \hat{\lambda}_0 + C(\omega_n)^\top \hat{\lambda}$. Note that probabilities q_n in equation (IA.97) are the unique risk-neutral probabilities under effective completeness in the incomplete market case. Now, if we substitute $R(\hat{s})$ from the RHS of equation (IA.69) after some algebra we see that $q_n = \pi_n^{\text{RN}}$, where π_n^{RN} are the risk-neutral probabilities in the complete market case [see equation (IA.61)]. The only difference is that vectors $\lambda, \tilde{\lambda}, \nu$, and matrices $\Omega, E, \Sigma_\nu, \tilde{\Sigma}_i$ and $\hat{Q}_i$ are of lower dimensions: $\lambda, \tilde{\lambda}, \nu \in \mathbb{R}^{M-1}$, $\Omega \in \mathbb{R}^{(N-1) \times (M-1)}$, and $E, \Sigma_\nu, \tilde{\Sigma}_i, \hat{Q}_i \in \mathbb{R}^{(M-1) \times (M-1)}$, for all $i = 1, \dots, K$. Therefore, prices are given by equation (IA.60) as in a complete market. ■

IA4 Multidimensional Shock

In this section, we extend our analysis to economies with a multidimensional aggregate shock $\varepsilon \in \mathbb{R}^K$, where $K > 1$. We derive equilibrium in the complete market case, where the number of securities is equal to the number of states, $M = N$, and also obtain derivatives that make incomplete markets with $M < N$ effectively complete. We show that asset prices have similar structure to the prices in our baseline setting in Section 3.

We consider an economy with the same set of assets, distribution $\varphi_\nu(z)$ of noise trader demands, and informed and uninformed investors as in Section 2.1. The difference with our baseline setting is that shock ε and the aggregate risk factor b_n of the probabilities of states are now K -dimensional vectors. In this new setting, the probabilities of states $\pi_n(\varepsilon)$ and the prior shock distribution $\varphi_\varepsilon(x)$ are now given by:

$$\pi_n(\varepsilon) = \frac{e^{a_n + b_n^\top \varepsilon}}{\sum_{j=1}^N e^{a_j + b_j^\top \varepsilon}}, \quad n = 1, \dots, N, \quad (\text{IA.98})$$

$$\varphi_\varepsilon(x) = \frac{\left(\sum_{j=1}^N e^{a_j + b_j^\top x}\right) e^{-0.5(x - \mu_0)^\top \Sigma_0^{-1}(x - \mu_0)}}{\int_{\mathbb{R}^K} \left(\sum_{j=1}^N e^{a_j + b_j^\top x}\right) e^{-0.5(x - \mu_0)^\top \Sigma_0^{-1}(x - \mu_0)} dx}, \quad (\text{IA.99})$$

where $\varepsilon, b_n, \mu_0 \in \mathbb{R}^K$, and $\Sigma_0 \in \mathbb{R}^{K \times K}$ is a positive-definite matrix. Equations (IA.98) and (IA.99) are multidimensional extensions of the probabilities of states (1) and shock

distributions (2) in our baseline setting. The optimization problems of investors I and U , their corresponding budget constraints, and the definition of equilibrium are the same as in Section 2.2 [see equations (3)–(6)].

IA4.1 Economy with $M = N$ securities

Here we derive the equilibrium in the complete market case with $M = N$ following the same steps as in our baseline setting. In particular, the first order conditions are given by equations (10) as before. These conditions allow us to find the trading strategy of the informed investor in terms of shock ε and risk-neutral probabilities of states. Lemma IA4.1 reports this trading strategy in closed form.

Lemma IA4.1 (Investor I 's optimal portfolio with multidimensional shock).
Investor I 's optimal portfolio is given by:

$$\theta_I^*(p; \varepsilon) = \frac{\Lambda \varepsilon}{\gamma_I} - \frac{\Omega^{-1}(\tilde{v}(p) - \tilde{a})}{\gamma_I}, \quad (\text{IA.100})$$

where $\Omega \in \mathbb{R}^{(N-1) \times (N-1)}$ is a matrix of excess payoffs with elements $\Omega_{n,k} = C_k(\omega_n) - C_k(\omega_N)$, $\Lambda = \Omega^{-1} \tilde{B}^\top \in \mathbb{R}^{N-1 \times K}$, with $\tilde{B} \in \mathbb{R}^{K \times N-1}$ and elements $\tilde{B}_{k,n} = b_{k,n} - b_{k,N}$, $\tilde{a} = (a_1 - a_N, \dots, a_{N-1} - a_N)^\top \in \mathbb{R}^{N-1}$, and $\tilde{v}(p) \in \mathbb{R}^{N-1}$ is the vector of log ratios of risk-neutral probabilities, given by:

$$\tilde{v}(p) = \left(\ln \left(\frac{\pi_1^{\text{RN}}}{\pi_N^{\text{RN}}} \right), \dots, \ln \left(\frac{\pi_{N-1}^{\text{RN}}}{\pi_N^{\text{RN}}} \right) \right)^\top. \quad (\text{IA.101})$$

The optimal portfolio (IA.100) has the same structure as portfolio (11) in the baseline setting, with the only difference that the replicating portfolio λ in the baseline setting is now a matrix Λ with K rows corresponding to K replicating portfolios. These K portfolios help allocate more wealth to more likely states. Substituting equation (IA.100) in the market clearing condition (6) yields the sufficient statistic $s = h\Lambda\varepsilon/\gamma_I + \nu$. Below we report the posterior state probabilities of U after observing prices p .

Lemma IA4.2 (Posterior probabilities of states with multidimensional shock).
The posterior probabilities of states ω_n conditional on observing the sufficient statistic $s = h\Lambda\varepsilon/\gamma_I + \nu$ are given by:

$$\pi_n^U(p) = \frac{1}{G(p)} \exp \left\{ a_n + \frac{1}{2} \left(b_n^\top \hat{\Sigma}^{-1} b_n + 2b_n^\top \hat{\Sigma}^{-1} (\Sigma_0^{-1} \mu_0 + h\Lambda^\top \Sigma_\nu^{-1} s / \gamma_I) \right) \right\}, \quad (\text{IA.102})$$

where $\hat{\Sigma} = h^2 \Lambda^\top \Sigma_\nu^{-1} \Lambda / \gamma_I^2 + \Sigma_0^{-1} \in \mathbb{R}^{K \times K}$, and $G(p)$ is a normalizing function.

Equation (IA.102) is a multi-dimensional extension of posterior probabilities (15) in our baseline setting. Next, we find the risk-neutral probabilities and asset prices in the economy following the same steps as in Section 3. Proposition IA4.1 reports the results.

Proposition IA4.1 (Equilibrium with $M = N$ assets with multidimensional shock). i) *There exists unique equilibrium in which prices only reveal the sufficient statistic $s = h\Lambda\varepsilon/\gamma_I + \nu$. In this equilibrium, the vector of risky asset prices $P(\varepsilon, \nu)$ and risk-neutral probabilities π_n^{RN} are given by:*

$$P(\varepsilon, \nu) = \left[\pi_1^{\text{RN}} C(\omega_1) + \pi_2^{\text{RN}} C(\omega_2) + \dots + \pi_N^{\text{RN}} C(\omega_N) \right] e^{-rT}, \quad (\text{IA.103})$$

$$\pi_n^{\text{RN}} = \frac{e^{v_n}}{\sum_{j=1}^N e^{v_j}}, \quad (\text{IA.104})$$

where probability parameters v_n are given in closed form by:

$$v_n = a_n + \frac{1}{2} \frac{(1-h)/\gamma_U}{h/\gamma_I + (1-h)/\gamma_U} \left(b_n^\top \hat{\Sigma}^{-1} b_n + 2b_n^\top \hat{\Sigma}^{-1} \Sigma_0^{-1} \mu_0 \right) + \frac{C(\omega_n)^\top (E + Q)s}{h/\gamma_I + (1-h)/\gamma_U}, \quad (\text{IA.105})$$

$$Q = \frac{h(1-h)}{\gamma_I \gamma_U} \Lambda \hat{\Sigma}^{-1} \Lambda^\top \Sigma_\nu^{-1}, \quad (\text{IA.106})$$

$$\hat{\Sigma} = h^2 \Lambda^\top \Sigma_\nu^{-1} \Lambda / \gamma_I^2 + \Sigma_0^{-1}, \quad (\text{IA.107})$$

where E is an identity matrix, $Q, E \in \mathbb{R}^{(N-1) \times (N-1)}$, $\hat{\Sigma} \in \mathbb{R}^{K \times K}$, $\Lambda = \Omega^{-1} \tilde{B}^\top \in \mathbb{R}^{N-1 \times K}$, and $\tilde{B} \in \mathbb{R}^{K \times N-1}$ is a matrix with elements $\tilde{B}_{k,n} = b_{k,n} - b_{k,N}$.

ii) *Portfolio $\theta_I^*(p; \varepsilon)$ is given by equation (IA.100) and portfolio $\theta_U^*(p)$ is given by*

$$\theta_U^*(p) = (E + Q)^{-1} \left(\frac{hQ\Omega^{-1}(\tilde{v}(p) - \tilde{a})}{(1-h)\gamma_I} - \frac{\Omega^{-1}(\tilde{v}(p) - \hat{a})}{\gamma_U} + \Lambda \hat{\Sigma}^{-1} \Sigma_0^{-1} \mu_0 / \gamma_U \right), \quad (\text{IA.108})$$

where $\tilde{v}(p) \in \mathbb{R}^{N-1}$ is given by (IA.101) and has elements $v_n - v_N$ in equilibrium, and $\tilde{a}, \hat{a} \in \mathbb{R}^{N-1}$ have elements $a_n - a_N$ and $a_n - a_N + 0.5(b_n^\top \hat{\Sigma}^{-1} b_n - b_N^\top \hat{\Sigma}^{-1} b_N)$, respectively.

The expressions for the risk-neutral probabilities, asset prices, and the portfolio of the uninformed investor in our baseline setting derived in Proposition 1 are simple special cases of those in Proposition IA4.1 when shock ε is a scalar, that is, $K = 1$. Moreover, the corresponding expressions in Proposition 1 and Proposition IA4.1 have the same structure.

IA4.2 Effective Completeness

In this section, we derive securities such that opening up trading in these securities makes incomplete markets with $M < N$ effectively complete. Similar to our baseline analysis, we

impose the informational spanning condition

$$b_n^\top = \Lambda_0 + C(\omega_n)^\top \Lambda, \quad (\text{IA.109})$$

where $\Lambda_0 \in \mathbb{R}^K$, $\Lambda \in \mathbb{R}^{(M-1) \times K}$, and $b_n \in \mathbb{R}^K$ is a vector of aggregate risk factors in state ω_n . Similar to our baseline setting, condition (IA.109) guarantees the existence of K replicating portfolios for the aggregate risk factors. Condition (IA.109) facilitates tractability by making the portfolio of the informed investor separable in shock ε and prices p . For brevity, we do not study the incomplete-market equilibrium, which can be derived as in our baseline setting.

Our focus here is to understand which assets effectively complete the market in the case $M < N$. As demonstrated in Section 3, the market is effectively complete if and only if the log-ratio of the investors' probabilities $\ln(\pi_n(\varepsilon)/\pi_n^U(p))$ can be replicated by a portfolio of traded assets. The latter result remains valid in our extension with multidimensional shocks, because the first order conditions of investors and the condition for the effective completeness are not affected by the dimensionality of shock ε .

Proposition IA4.2 (Effective completeness with multidimensional shock).

Suppose, the market is incomplete, that is, $M < N$, and the informational spanning condition (IA.109) is satisfied. Then, the market is effectively complete if and only if there exists a replicating portfolio for $b_n^\top \hat{\Sigma}^{-1} b_n$, that is, there exist constant $\hat{\lambda}_0$ and vector $\hat{\lambda} \in \mathbb{R}^{M-1}$ such that $b_n^\top \hat{\Sigma}^{-1} b_n = \hat{\lambda}_0 + C(\omega_n)^\top \hat{\lambda}$, for all $n = 1, \dots, N$, where $\hat{\Sigma}$ is given by (IA.107). The asset prices and risk-neutral probabilities are given by the same equations (IA.103)–(IA.104) as in the complete market case.

The main economic implication of Proposition IA4.2 is that, despite the multidimensionality of shock ε , only one extra derivative is needed to complete the market and the payoff of this derivative in state ω_n is a quadratic form of b_n given by $b_n^\top \hat{\Sigma}^{-1} b_n$. Proposition IA4.2 is a generalization of Proposition 4 in our baseline setting, which establishes the conditions for the effective completeness in economies with scalar shocks ε . In particular, for the special case of a scalar shock ε matrix $\hat{\Sigma}$ becomes a constant, and hence, we recover the main result of Proposition 4 that the market is effectively complete if and only if a portfolio with payoffs b_n^2 is traded in the market.

Proposition IA4.2 and the informational spanning condition (IA.109) imply that the market can be completed by introducing a derivative with payoffs given by $(C(\omega_n) - \mathbb{E}^{\text{RN}}[C(\omega_n)])^\top \Lambda \hat{\Sigma}^{-1} \Lambda^\top (C(\omega_n) - \mathbb{E}^{\text{RN}}[C(\omega_n)])$, because these payoffs can be equivalently rewritten as quadratic forms of b_n using condition (IA.109). The value of the latter deriva-

tive is then given by

$$\mathbb{E}^{\text{RN}}[(C - \mathbb{E}^{\text{RN}}[C])^\top \Lambda \hat{\Sigma}^{-1} \Lambda^\top (C - \mathbb{E}^{\text{RN}}[C])] e^{-rT} = \text{tr}(\text{var}^{\text{RN}}[C] \Lambda \hat{\Sigma}^{-1} \Lambda^\top) e^{-rT}, \quad (\text{IA.110})$$

where $\text{tr}(\cdot)$ is a matrix trace, and we use the fact that for column vectors a and b we have that $a^\top b = \text{tr}(ba^\top)$.

Next, we consider an example where matrix Λ of replicating portfolios is diagonal, $\Lambda = \text{diag}\{\lambda_1, \dots, \lambda_K\}$, and assume that $K = M - 1$. In this case, the informational spanning condition (IA.109) implies that $b_{k,n} = \lambda_k C_k(\omega_n)$, and hence, for each shock ε_k the corresponding sensitivity can be replicated by a tradable asset. For further tractability, we assume that $\Sigma_\nu = \sigma_\nu^2 E_{M-1}$ and $\Sigma_0 = \sigma_0^2 E_K$, where E_i is the $\mathbb{R}^{i \times i}$ identity matrix. Then, matrix $\Lambda \hat{\Sigma} \Lambda^\top$ is a diagonal matrix with elements $1/(h^2/(\gamma_I^2 \sigma_\nu^2) + 1/(\lambda_k^2 \sigma_0^2))$, and hence, the price of the quadratic derivative is given by

$$\sum_{k=1}^K \frac{\text{var}^{\text{RN}}[C_k] e^{-rT}}{h^2/(\gamma_I^2 \sigma_\nu^2) + 1/(\lambda_k^2 \sigma_0^2)}. \quad (\text{IA.111})$$

We observe that price (IA.111) alternatively can be viewed as a price of a volatility index, defined as a portfolio of quadratic derivatives with payoffs $(C(\omega_k) - \mathbb{E}[C(\omega_k)])^2$.

IA4.3 Proofs

Proof of Lemma IA4.1: The proof follows identical steps as that of Lemma 1, with the only differentiation that ε is a vector so that we need to introduce matrices Λ and $\tilde{B}$ instead of vectors λ and $\tilde{b}$. ■

Proof of Lemma IA4.2: The proof follows identical steps as that of Lemma 1. In particular Equation (A.7) holds as is for $\varepsilon, x \in \mathbb{R}^K$, while (A.8) becomes:

$$\varphi_{\varepsilon|s}(x|y) = \frac{\exp\left\{-0.5\left(y - h\Lambda x/\gamma_I\right)^\top \Sigma_\nu^{-1}\left(y - h\Lambda x/\gamma_I\right)\right\} \varphi_\varepsilon(x)}{G_1(y)}, \quad (\text{IA.112})$$

where $G_1(y)$ normalizes the density. The integral in Equation (A.9) is now K -th dimensional, where the exponent is:

$$d_n(x) = a_n + b_n^\top x - 0.5\left(h\Lambda x/\gamma_I + H(p)\right)^\top \Sigma_\nu^{-1}\left(h\Lambda x/\gamma_I + H(p)\right) - 0.5(x - \mu_0)^\top \Sigma_0^{-1}(x - \mu_0), \quad (\text{IA.113})$$

where $H(p) = (1 - h)\theta_v^*(p) - h\Omega^{-1}(\tilde{v}(p) - \tilde{a})/\gamma_I$ is the informational contents of prices, and $H(p) = -s$ from the market clearing condition. After a bit of algebra, substituting $d_n(x)$ from Equation (IA.113) into the K -th dimensional version of integral (A.9) and integrating, we obtain Equation (IA.102) for $\pi_n^U(p)$. ■

Proof of Proposition IA4.1: The proof follows identical steps as that of Proposition 1, with the only difference that ε , b_n , and μ_0 are now vectors rather than scalars, and we have matrices Λ and Σ_0 instead of vector λ and scalar σ_0^2 . ■

Proof of Proposition IA4.2: The uninformed probabilities π_n^U in the incomplete market are still given by the same equation (IA.102), as in the complete market, because the sufficient statistics remains the same as in the complete market. Substituting $\pi_n(\varepsilon)$ from (IA.98) and π_n^U from (IA.102) into $\ln(\pi_n(\varepsilon)/\pi_n^U)$, we find:

$$\ln \left(\frac{\pi_n(\varepsilon)}{\pi_n^U(p)} \right) = b_n^\top \varepsilon - \frac{1}{2} \left(b_n^\top \hat{\Sigma}^{-1} b_n + 2b_n^\top \hat{\Sigma}^{-1} \left(\Sigma_0^{-1} \mu_0 + h\Lambda^\top \Sigma_\nu^{-1} (h\Lambda \varepsilon / \gamma_I + \nu) / \gamma_I \right) \right) + const, \quad (\text{IA.114})$$

where *const* does not depend on state ω_n . The log-ratio of probabilities in (IA.114) is a function of $b_n^\top \hat{\Sigma}^{-1} b_n$. Hence, by Lemma A.8, which holds unchanged for multidimensional shock ε , the optimal portfolios are Pareto efficient if and only if there exists a portfolio that replicates $b_n^\top \hat{\Sigma}^{-1} b_n$. ■

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