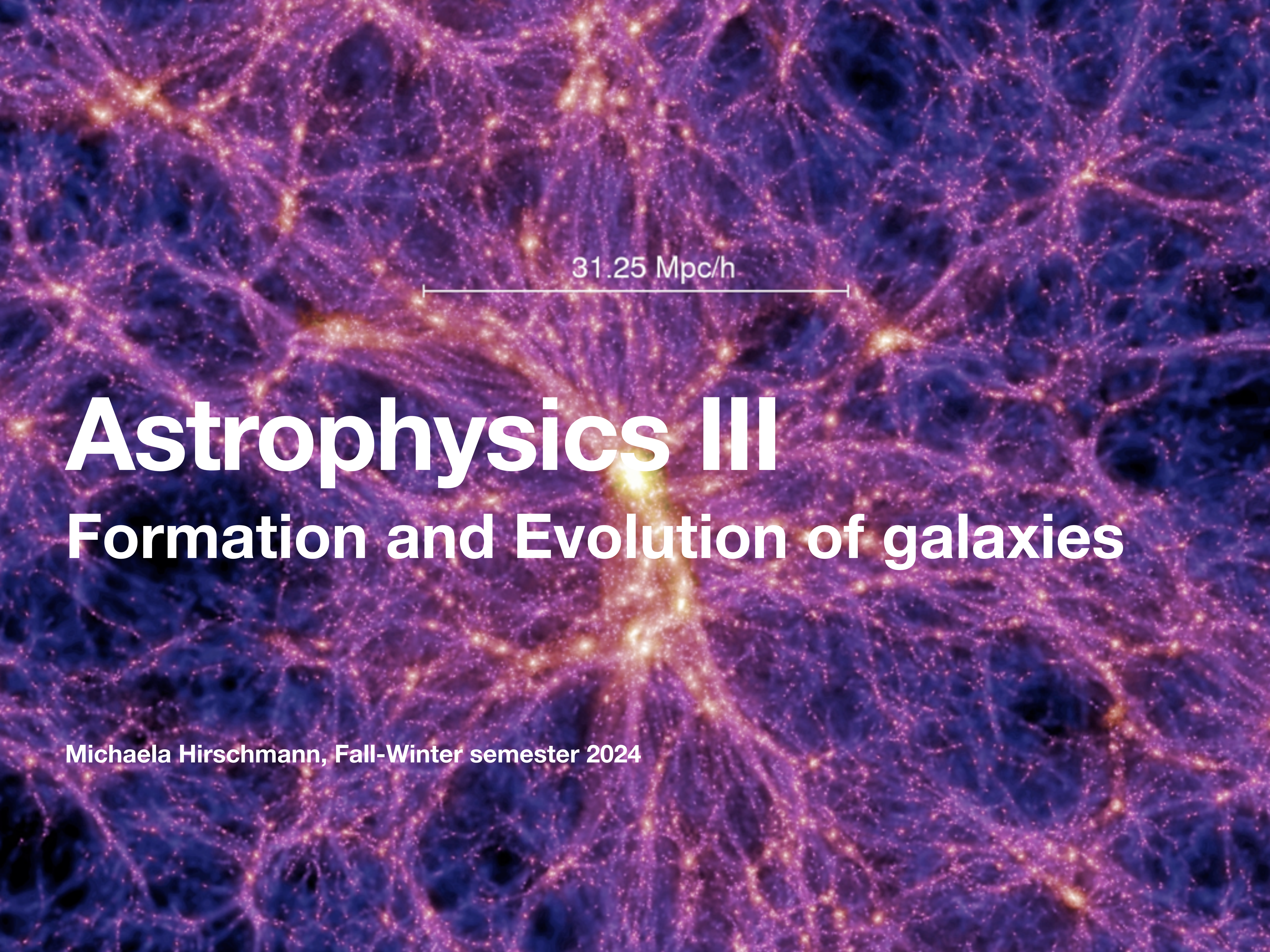


Astrophysics III

Formation and Evolution of galaxies

Michaela Hirschmann, Fall-Winter semester 2024

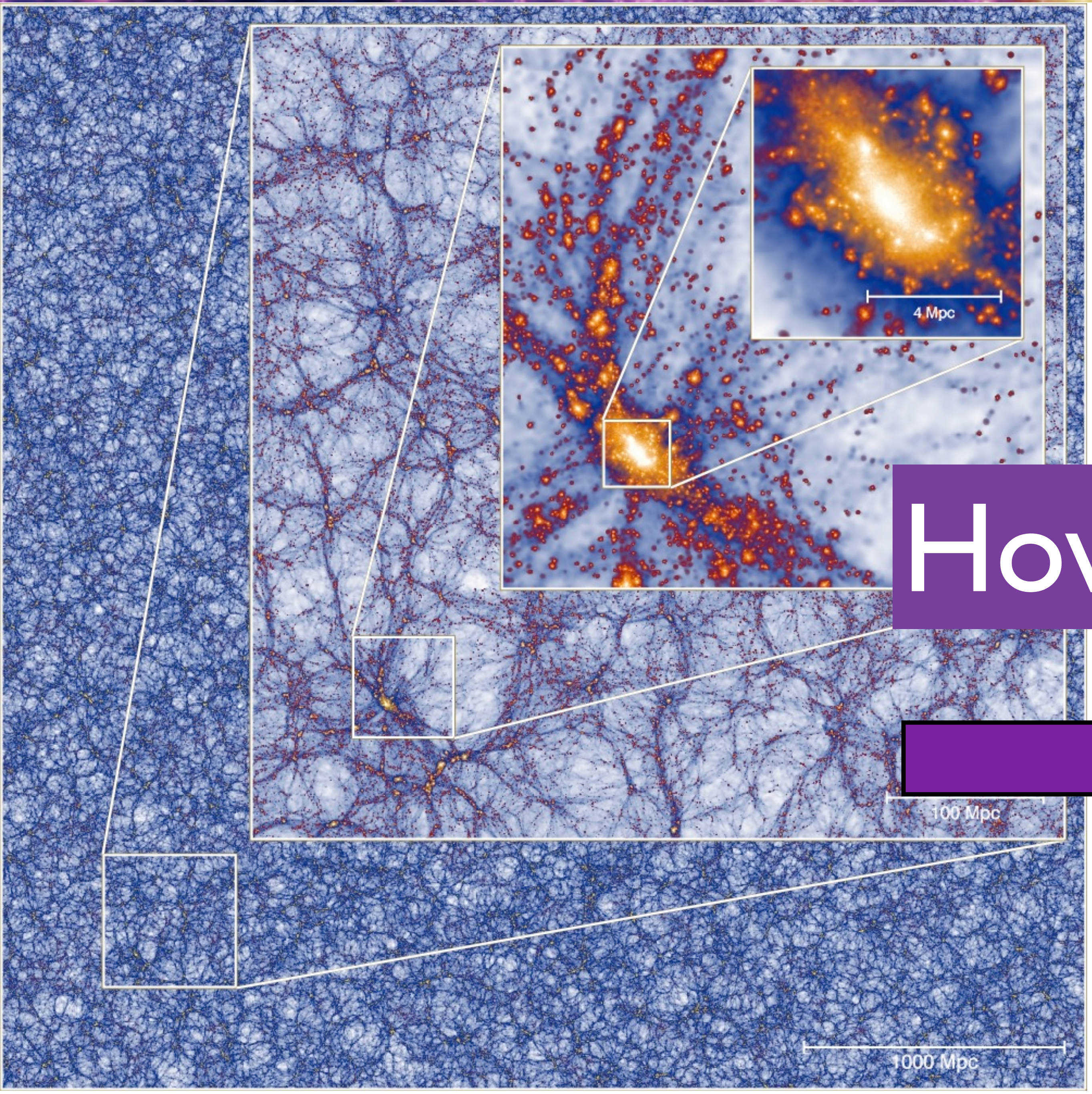
Lecture content and schedule

- *Chapter 1*: Introduction (galaxy definition, astronomical scales, observable quantities — repetition of Astro-I)
- *Chapter 2:* Brief review on stars
- *Chapter 3*: Radiation processes in galaxies and telescopes;
- *Chapter 4:* The Milky Way
- *Chapter 5*: The world of galaxies I
- *Chapter 6*: The world of galaxies II
- *Chapter 7:* Black holes and active galactic nuclei
- *Chapter 8:* Galaxies and their environment;
- *Chapter 9:* High-redshift galaxies
- *Chapter 10*:
    - Cosmology in a nutshell; Linear structure formation in the early Universe
- *Chapter 11*:
    - Dark matter and the large-scale structure
    - Cosmological N-body simulations of dark matter
- *Chapter 12*: Populating dark matter halos with baryons: Semi-empirical & semi-analytical models
- *Chapter 13:* Modelling the evolution of gas in galaxies: Hydrodynamics
- *Chapter 14*: Gas cooling/heating and star formation
- *Chapter 15*: Stellar feedback processes
- *Chapter 16*: Black hole growth & AGN feedback processes
- *Chapter 17*: Modern simulations & future prospects

Part I:
Observational basics & facts of galaxies
first 7 lectures

Part II:
Theory & models of
galaxy evolution processes
second 7 lectures

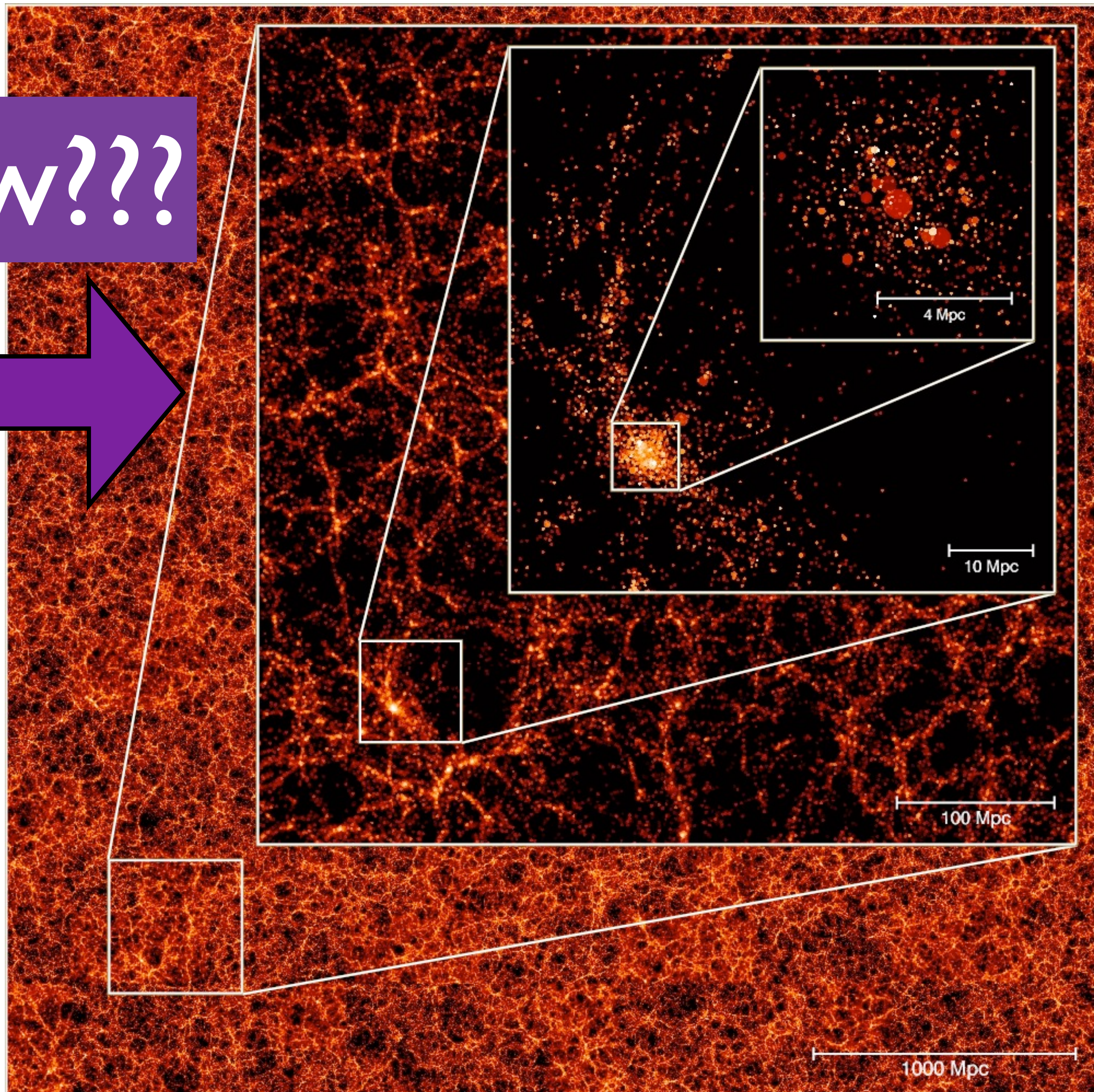
How to populate halos with galaxies?



Dark matter distribution
halo catalogues and halo
merger trees

How???

Galaxy distribution



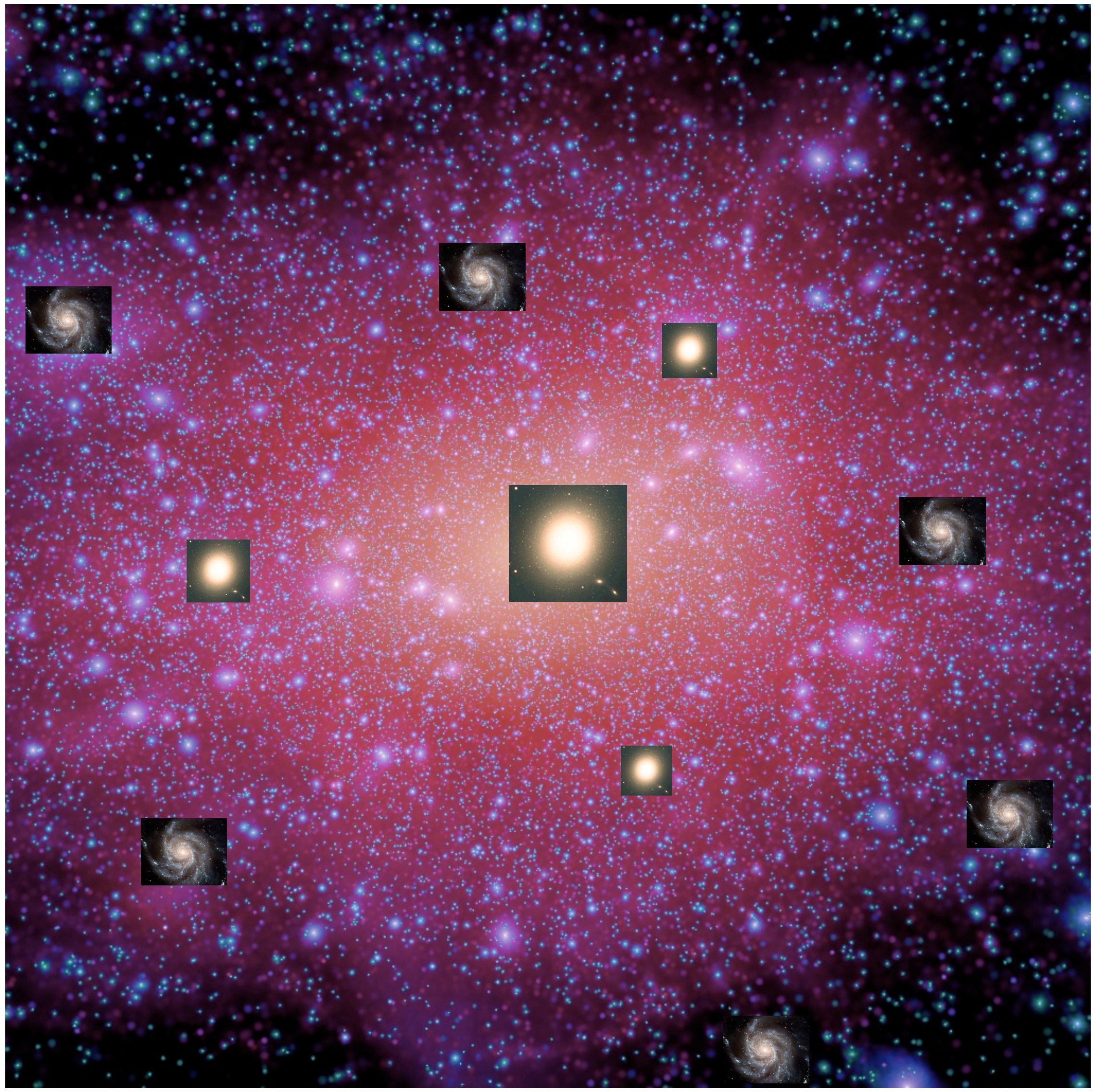
Outline of this lecture

- Different modelling approaches for baryons
- Semi-empirical models
  - Linking DM halos to observed galaxies
  - Main results
- Semi-analytic models
  - Physical models for baryons
  - Main results
  - Challenges and limitations

How to model baryons?

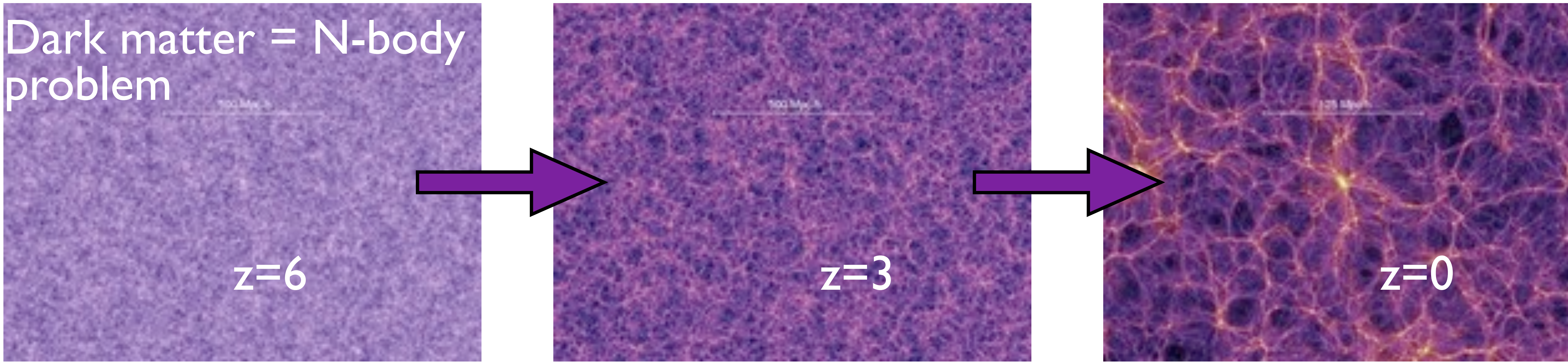
- Based on hierarchical evolution of DM halos in a CDM paradigm: due to gravitational interactions, baryons follow the evolution of dark matter
- Evolution of baryons much more complex due to gas-dynamical processes and variety of other baryonic processes
- Galaxy formation is a complex, self-regulated network of reactions and back-reactions

- **What are the main processes affecting galaxy evolution?**



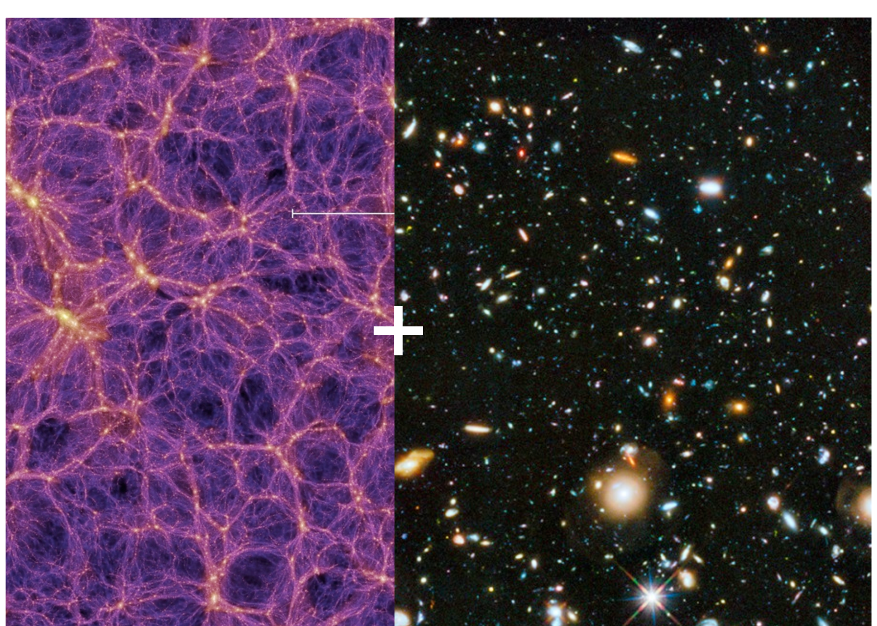
Cosmological galaxy formation simulations

Cosmological model + initial conditions + N-body simulation code = DM halos

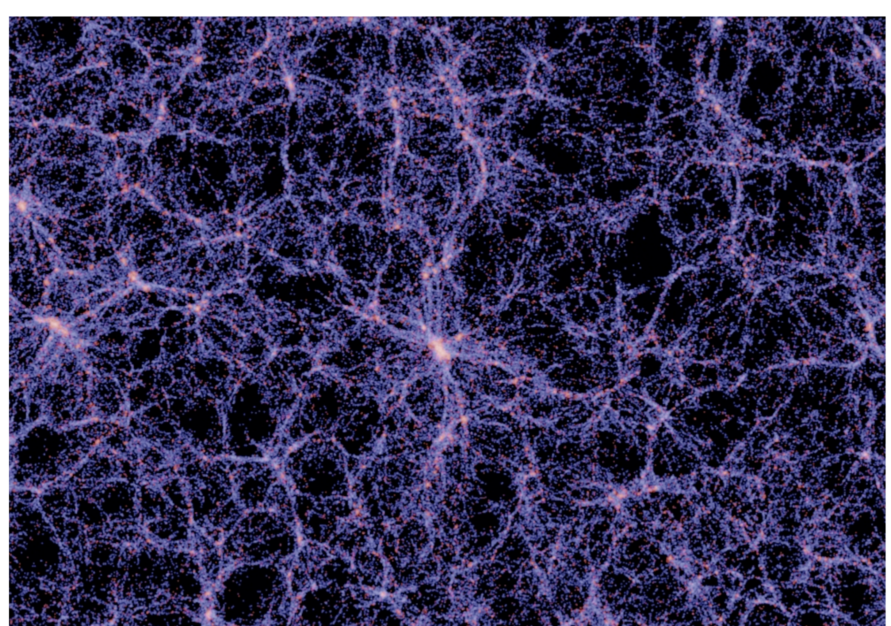


To populate DM halos with galaxies: model baryon physics via

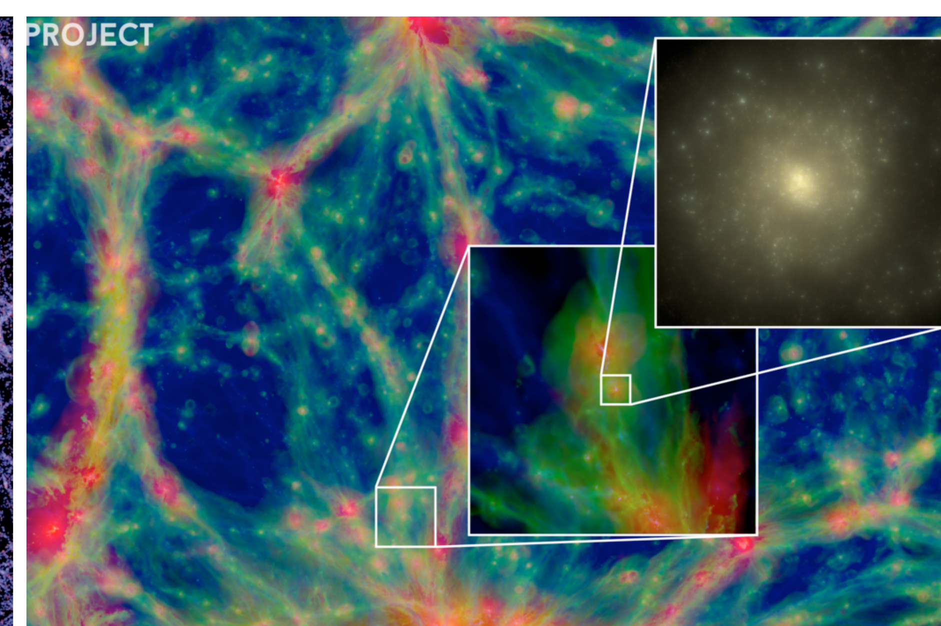
Semi-empirical models



Semi-analytic models

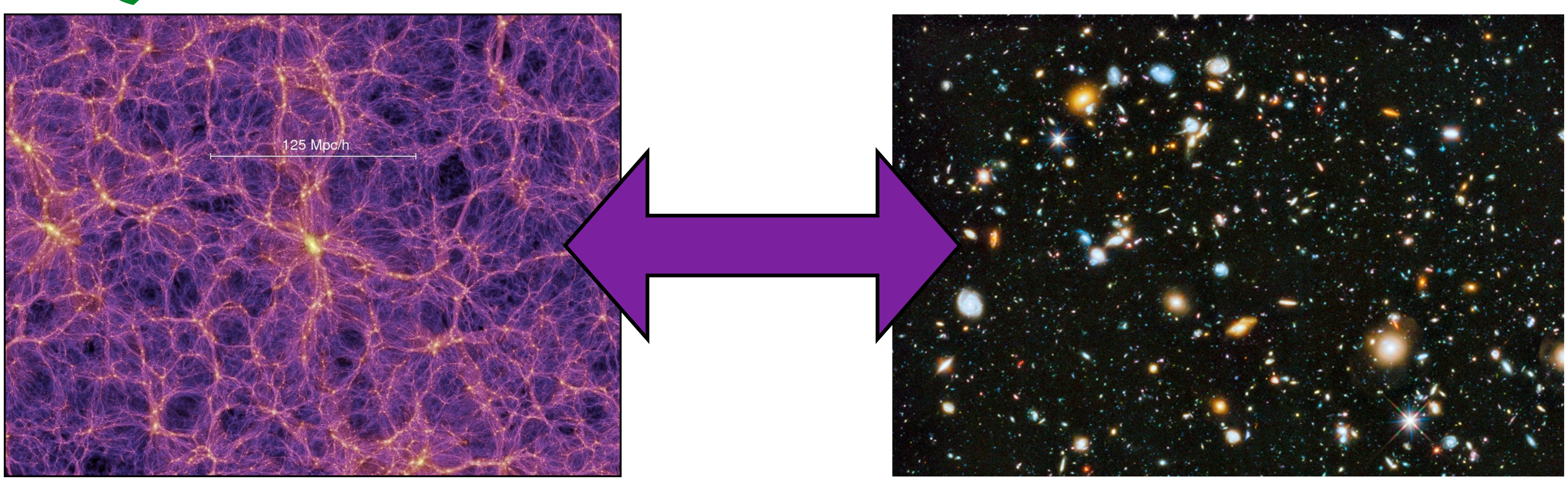


Hydrodynamic simulations



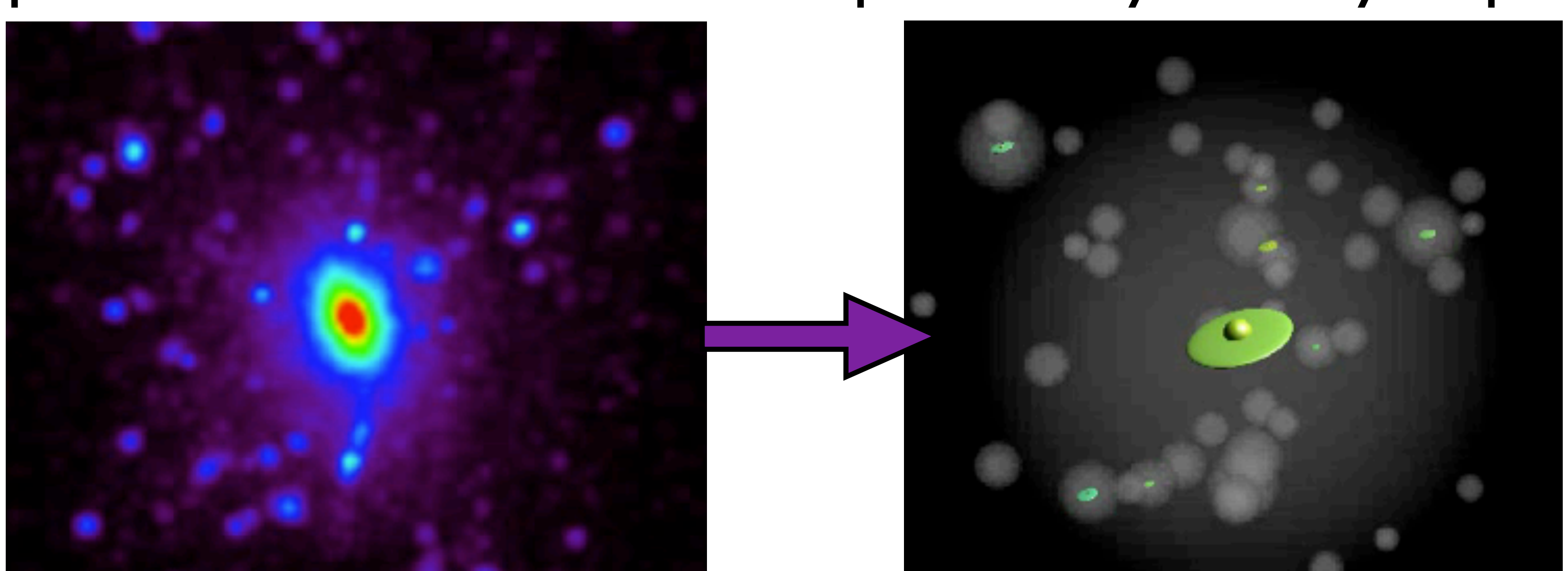
Different approaches for modelling baryons

- Mostly based on N-body simulations of dark matter
- Semi-empirical/abundance matching models:
  - Observed galaxy properties are coupled to depth of potential well of simulated halo mass
  - **No** direct modelling of baryonic physics
  - Using statistical observations of galaxies and statistically link halo masses (simulated) to (observed) galaxy masses or luminosities
  - Idea of how galaxies may evolve in the framework of hierarchically growing DM halos
  - **“Quasi”-observations with “undetectable” halo mass**



Different approaches for modelling baryons

- Mostly based on N-body simulations of dark matter
- Semi-empirical models
- Semi-analytic models:
  - **Approximation with physically motivated, but phenomenological analytic laws** to trace different baryonic reservoirs of a galaxy (cold gas, stars, hot gas, BH mass etc.)
  - Solving coupled sets of differential equations
  - +Powerful approach to assess *statistical galaxy properties*
  - +Low computational costs
  - +Perfect for a first *testing of different physical processes*
  - — *But* Simplified models with a large free parameter space
  - — No spatial resolution, other than spherical symmetry of profiles

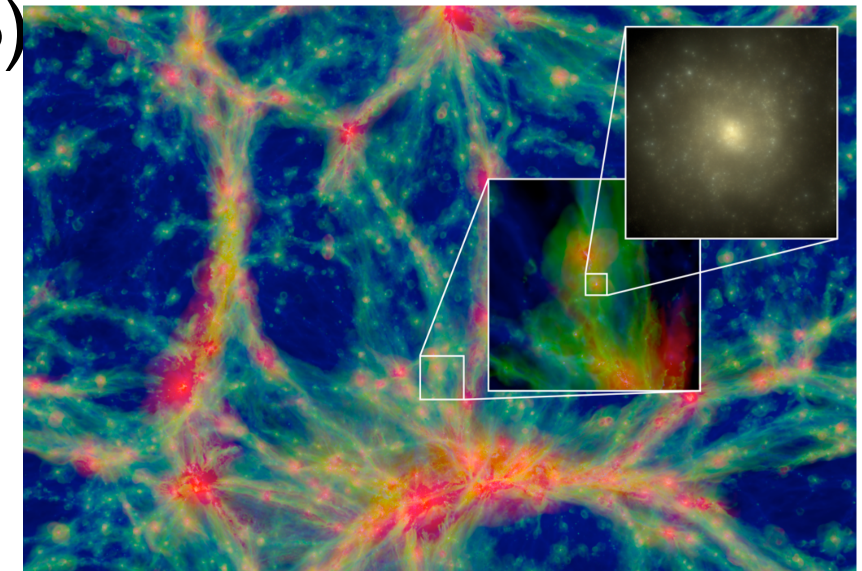


Different approaches for modelling baryons

- Mostly based on N-body simulations of dark matter
- Semi-empirical models
- Semi-analytic models
- (Cosmological) hydrodynamic simulations:
  - **Explicitly solving gas dynamical equations**: conservation laws for mass, momentum & energy, solved with Mesh-based/SPH techniques, see Chapter 13
  - + Most precise approach for modelling baryons up to now
  - + Spatial information accessible and self-consistently modelled
  - — High computational costs —> difficult to explore the effect of different physical processes and their parameter space
  - — Multi-scale problem: sub-resolution models very uncertain and strongly affect the results (see chapter 14-16)

$$\frac{\partial \boldsymbol{U}}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{F} = 0 \qquad \boldsymbol{U} = \begin{pmatrix} \rho \\ \rho \boldsymbol{v} \\ \rho e \end{pmatrix} = \begin{pmatrix} \rho \\ \rho \boldsymbol{v} \\ \rho u + \frac{1}{2}\rho \boldsymbol{v}^2 \end{pmatrix}$$

$$\boldsymbol{F}(\boldsymbol{U}) = \begin{pmatrix} \rho \boldsymbol{v} \\ \rho \boldsymbol{v}\boldsymbol{v}^T + P \\ (\rho e + P)\boldsymbol{v} \end{pmatrix} \qquad P = (\gamma - 1)\rho u$$



Outline of this lecture

- Different modelling approaches for baryons
- Semi-empirical models
  - Description
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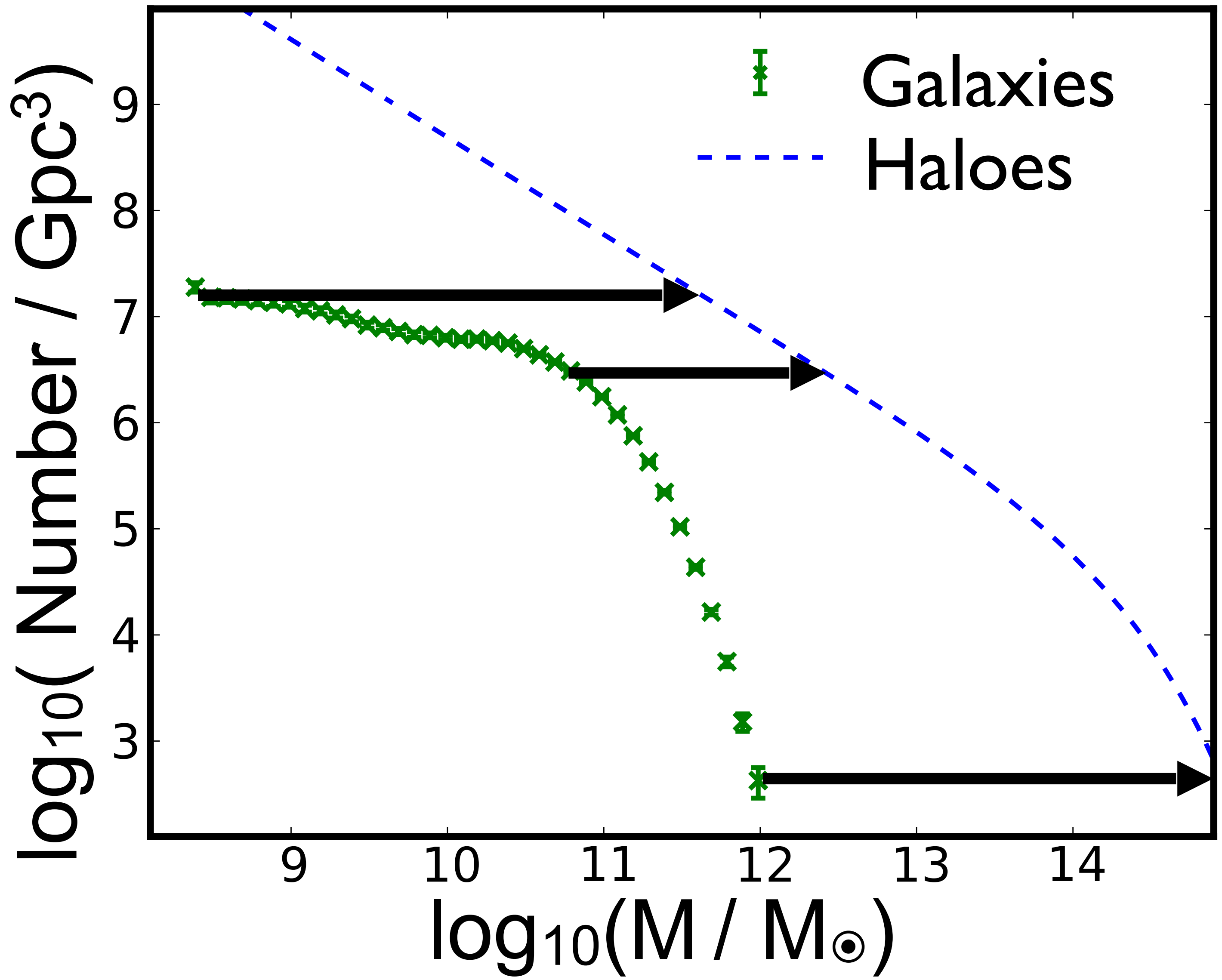
Abundance matching

- Extract positions and masses of halos from N-body simulations
- Take observed stellar mass function (SMF) of galaxies
- Link galaxies and halos using a simple assumption: most massive galaxies live in most massive halos

- Rank order halos by mass
- Generate galaxy catalogue from observed SMF and rank order galaxies by mass
- Link galaxies one-to-one
- Connection of stellar to halo mass can be done in two ways:
  - assuming a non-parametric monotonic relation
  - assuming parameterised functions

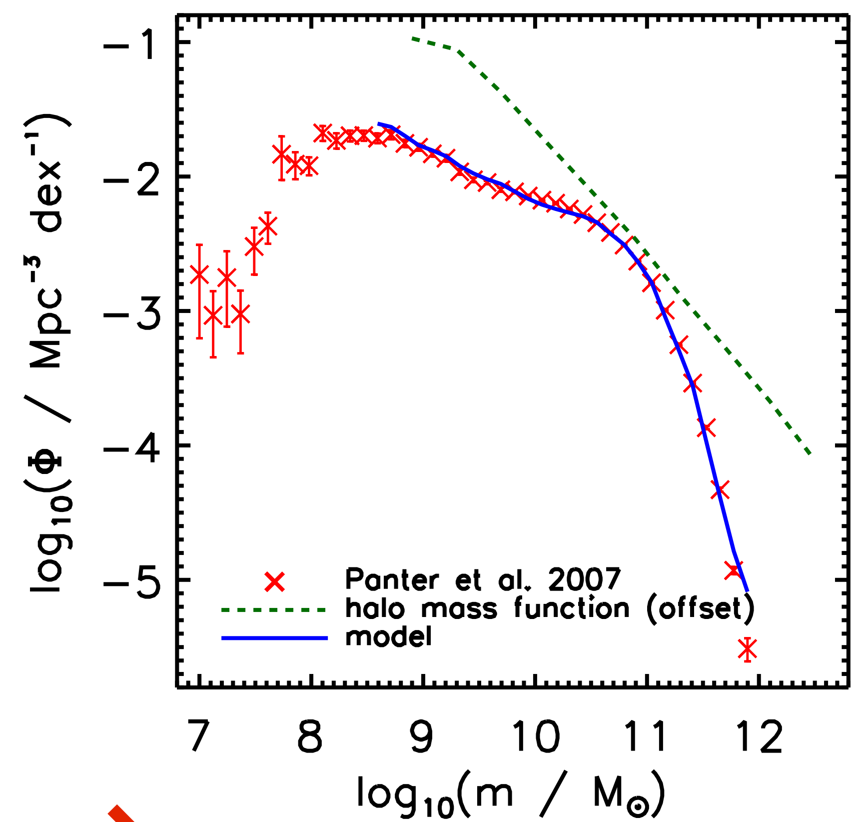


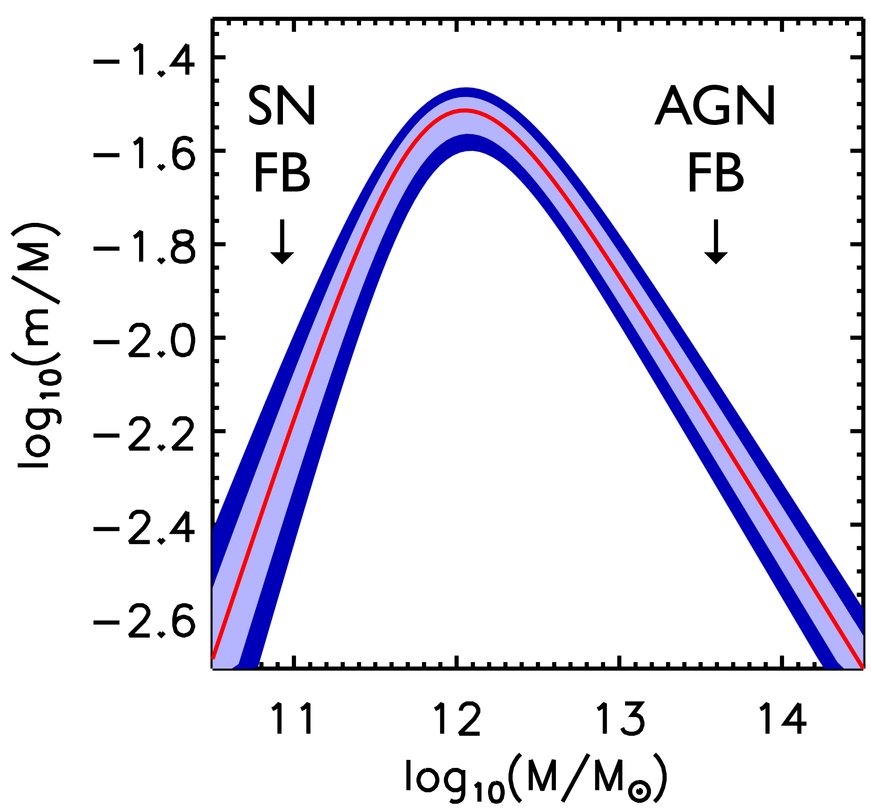
Populating halos

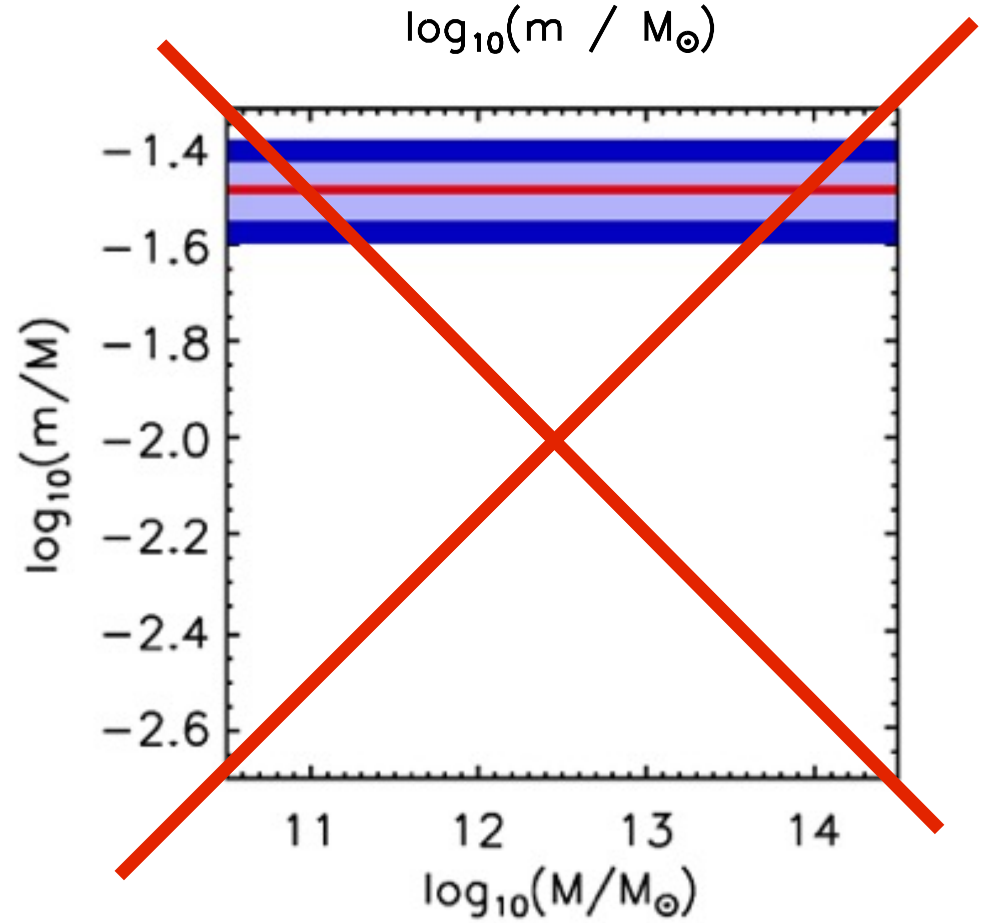
- Populate halos and subhalos
- Constant stellar-to-halo mass ratio does not work
- Use non-constant ratio like:

$$\frac{m_*}{M}(M) = 2N\left[\left(\frac{M}{M_1}\right)^{-\beta} + \left(\frac{M}{M_1}\right)^{\gamma}\right]$$

- Contains two slopes, characteristic mass and a normalisation
- Fit parameters to SMF



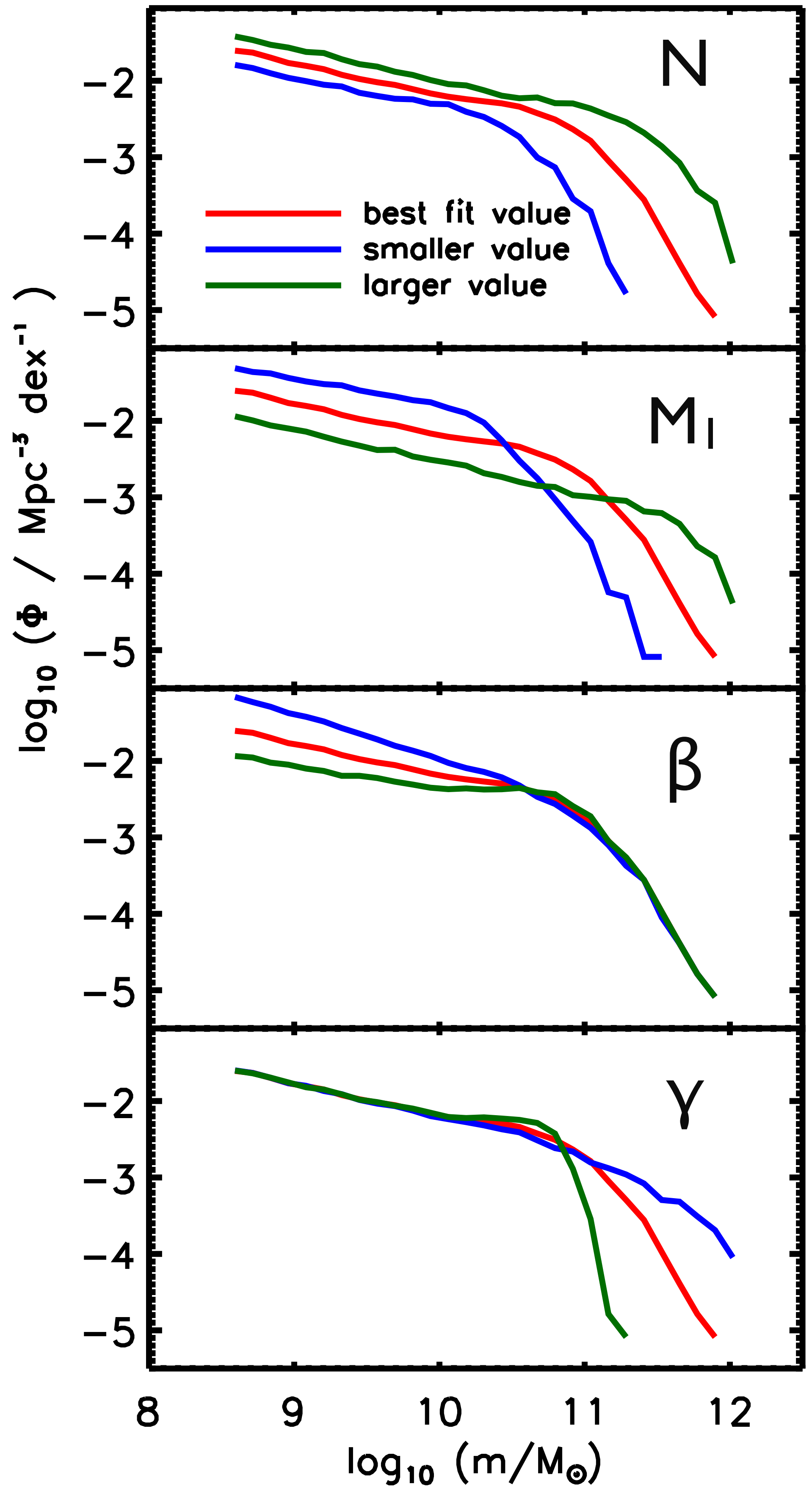




Meaning of parameters

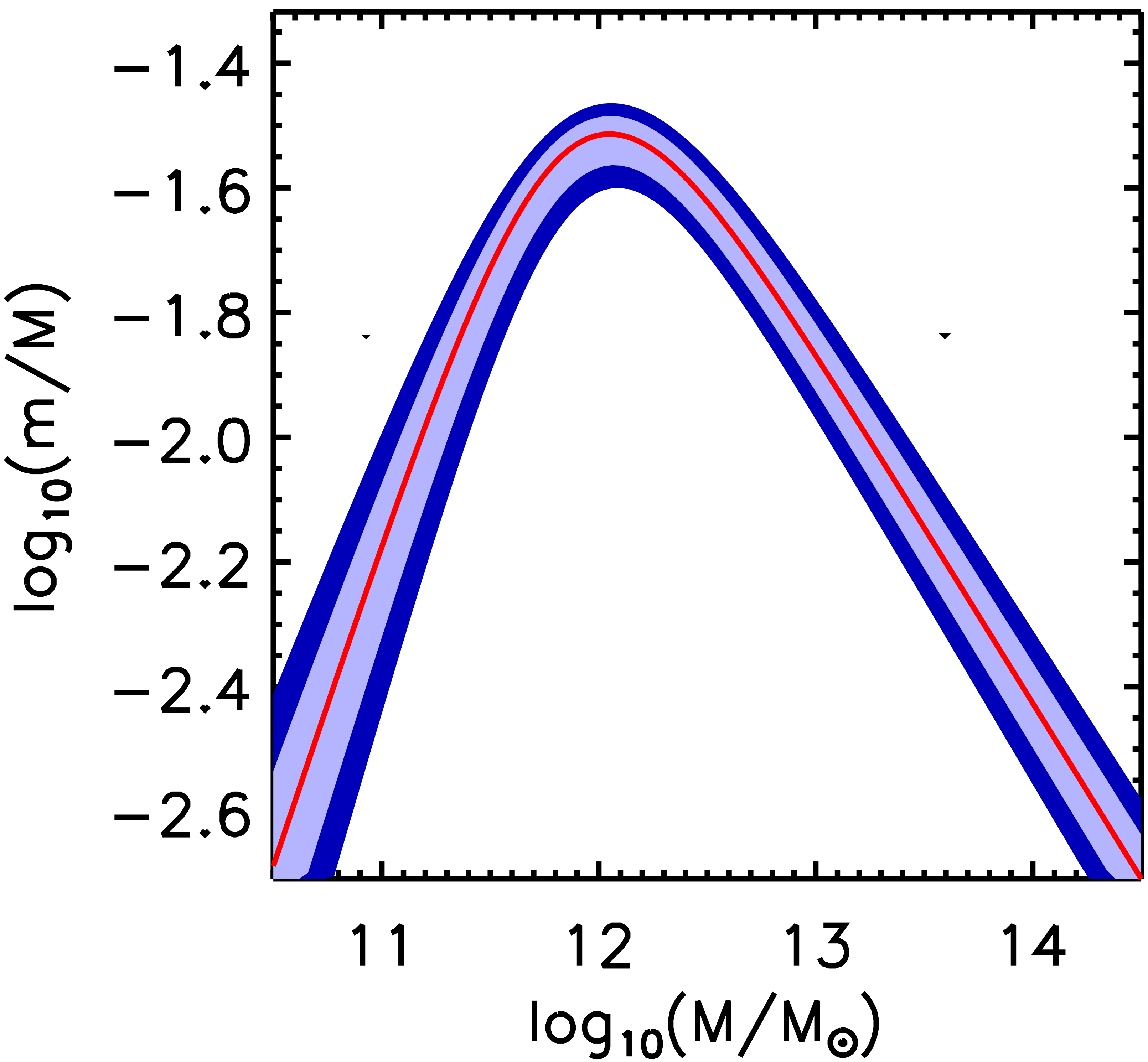
$$\frac{m_*}{M}(M) = 2N\left[\left(\frac{M}{M_1}\right)^{-\beta} + \left(\frac{M}{M_1}\right)^{\gamma}\right]$$

- Leave all parameters constant and change only one:
  - Normalization N determines the position on stellar mass axis
  - Characteristic mass M_1 sets the knee of the SMF
  - Low mass slope β affects the slope α of the Schechter fct
  - High mass slope γ determines the exponential "cut-off" of the SMF

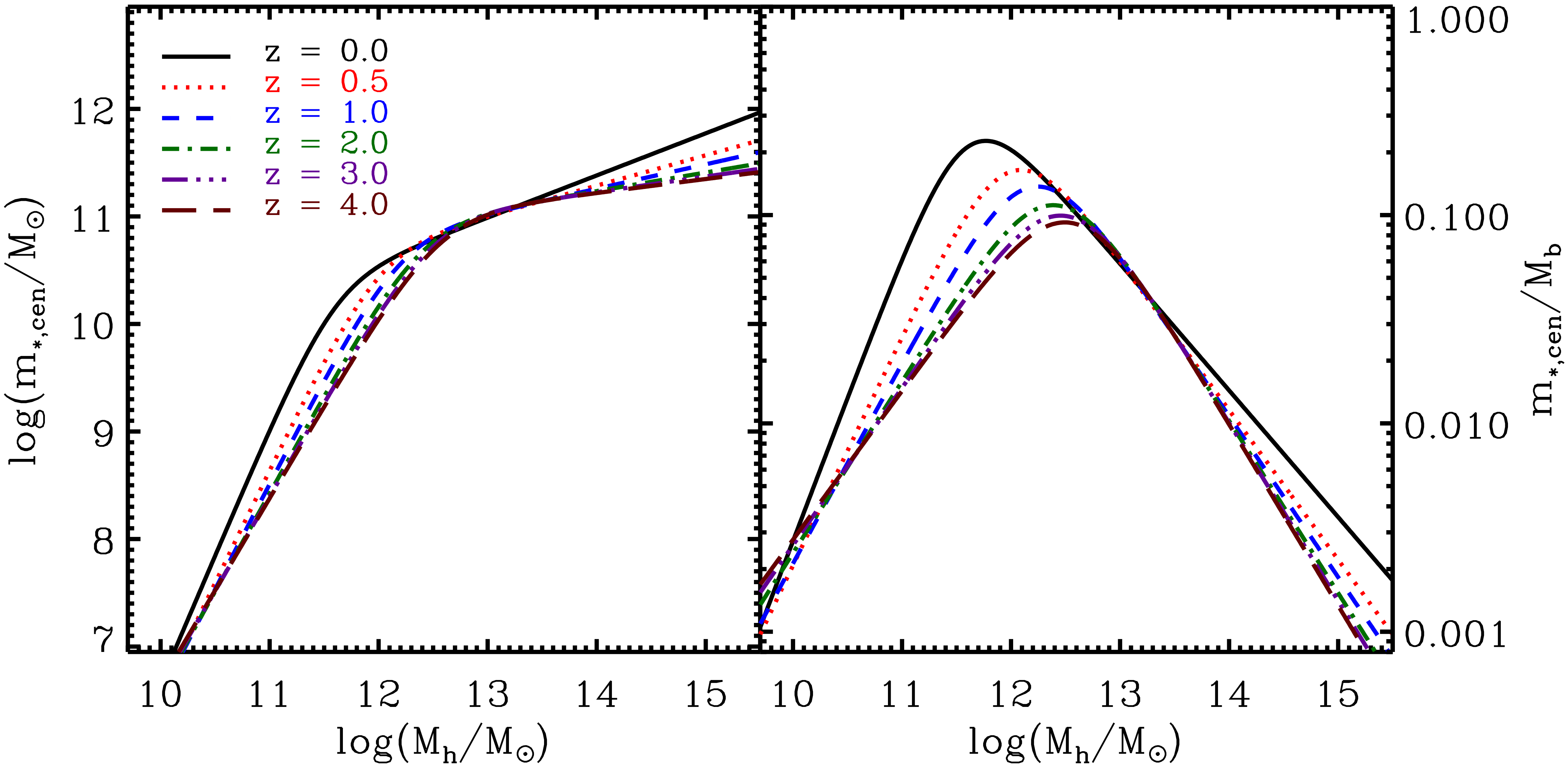


Stellar mass content versus halo mass

- At maximum, only 3-4% of matter in halo consists of luminous stars
- Implying that at maximum only ~20-30% of the universally expected baryon content is converted into stars
- lower efficiencies for low-mass and high-mass halos!



Results of the best-fit model



- Little evolution at high z (>2), moderate evolution at low z
- "Antihierarchical" trend visible: at higher z, baryon conversion efficiencies peak in more massive halos than at lower z

- Why is the stellar baryon conversion efficiency so low?
  - gas prevented from infall? — gas not forming stars? — gas ejected?

➡ Semi-empirical models ***cannot answer*** this question!

Constraints and predictions

Semi-empirical (abundance matching) models helpful for

- Predictions unbiased by assumption on baryon physics
- Getting an idea of how galaxies grow and assemble in hierarchically growing dark matter halos
- "Observational-like" constraints for semi-analytic models and hydro simulations to test their models for baryon physics within DM halos

BUT: Semi-empirical models only provide us with some trends with halos mass, but they DO NOT PROVIDE ANY PHYSICAL EXPLANATION!

Outline of this lecture

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A bit of history...

- Original "idea" by Fred Hoyle (1949): "Stellar evolution and the expanding Universe"

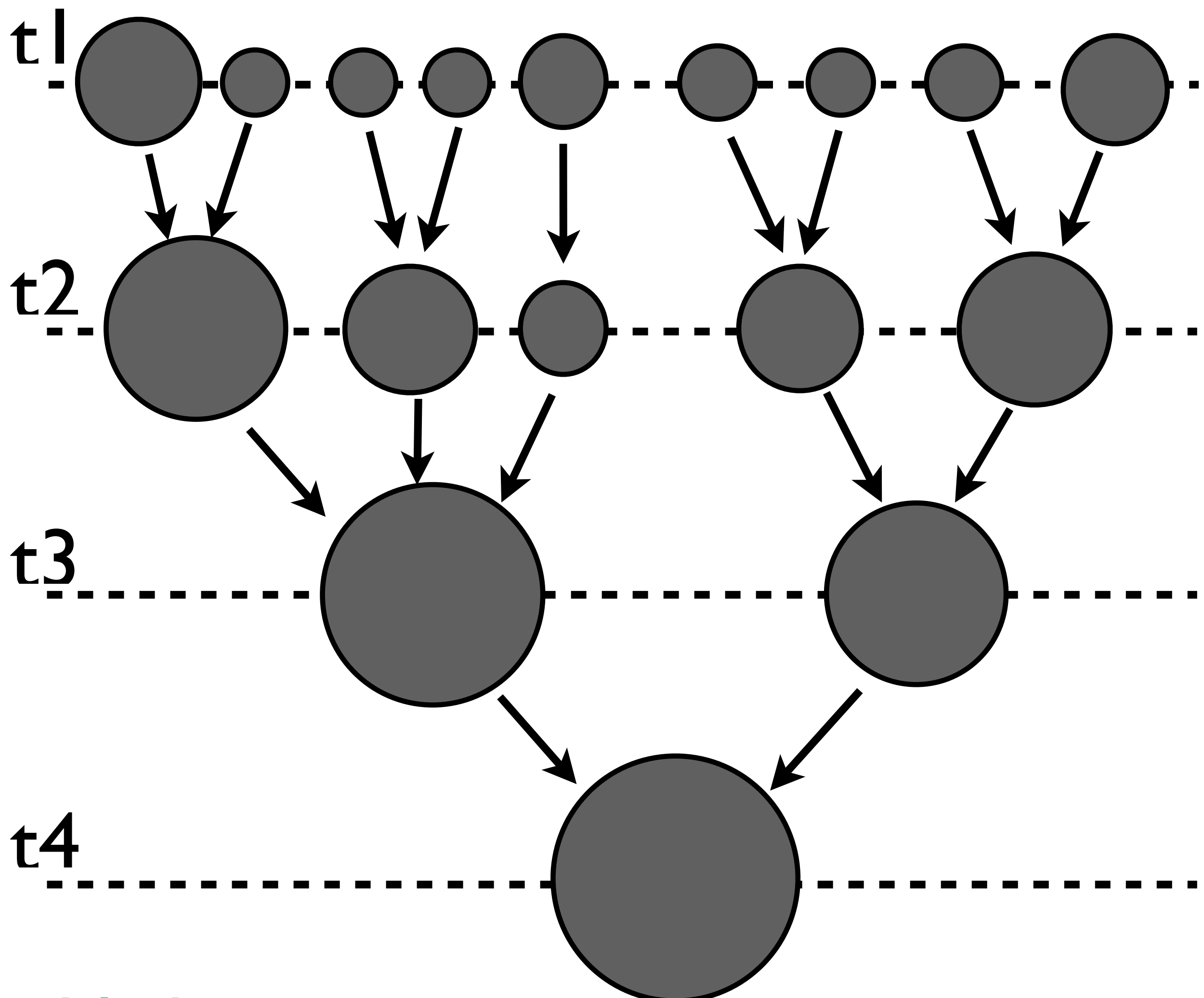
- White & Rees 1978: Galaxy formation as a two stage process
  - First, dark matter halos collapse and assemble
  - Then, gas cools in these halo potential, condenses in the center and forms stars

- Frenk & White 1991: "Grandparent" model for all future SAMs: further development, first semi-analytic model with cooling, SF, feedback, mergers etc.

- Since then, further refinement of physically motived models and development of many different semi-analytic models

Reminder: Merger trees

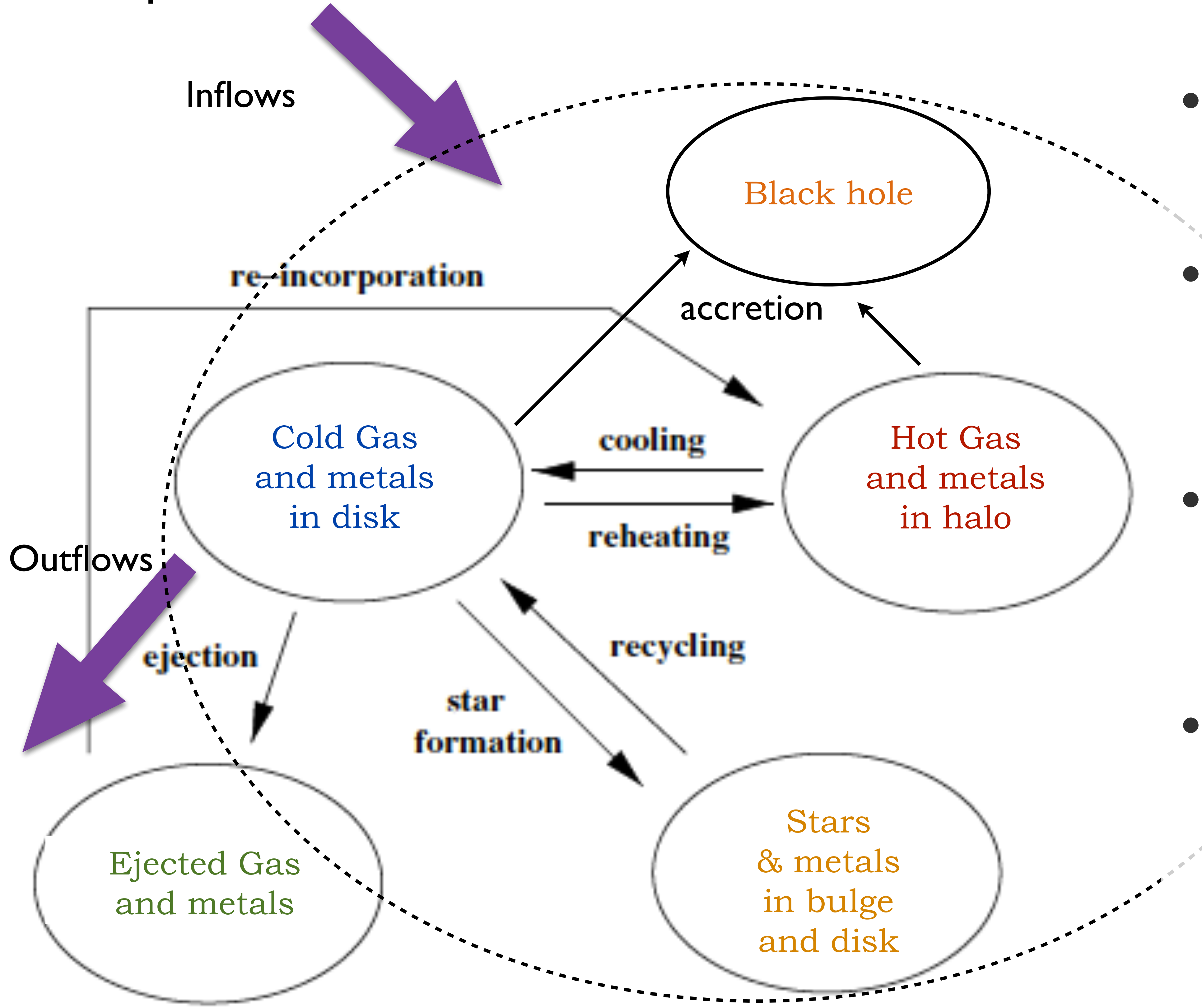
- Backbone is HIERARCHICAL structure formation, merging into larger and larger objects



- SAMs are built up-on the DM assembly history
    - When a halo for the first time "appears", hot gas is put in according to the universal baryon fraction of a halo of a given mass
    - Smooth accretion rate in dark matter is transformed into one for baryons (according to the universal baryon fraction)
    - Mergers are considered, and accretion onto larger halos (->sub-halos)

Baryon reservoirs in SAMs

- In practice, in SAMs, we follow the evolution of different baryonic reservoirs



- Recipes empirically motivated by observations
- *Problem*: small-scale physical processes not well understood —> free parameters
- Free parameters are "tuned" to match basic statistical galaxy properties at z~0
- Predictions of other statistical galaxy properties and confront them to observations

Gas cooling

- For simplicity, always assume spherical symmetry of halos and galaxies
- Gas is assumed to fall into DM halos and to shock heat to the virial temperature
- The gas density profile is assumed to follow an isothermal sphere

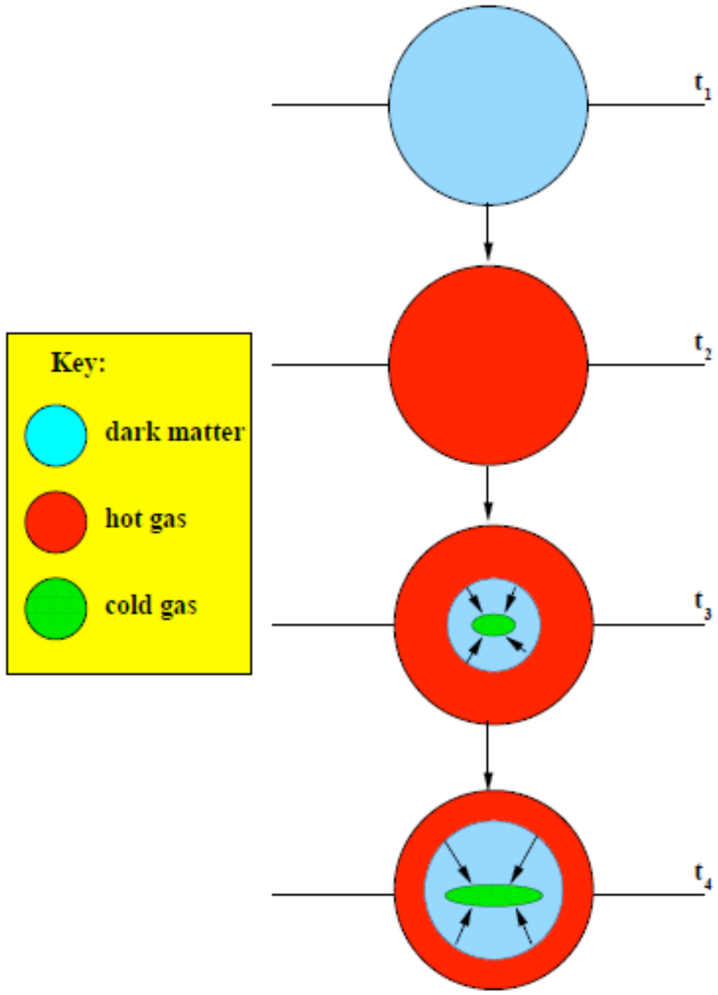
$$\rho_g(r) = m_{\rm hot}/(4\pi r_{vir} r^2)$$

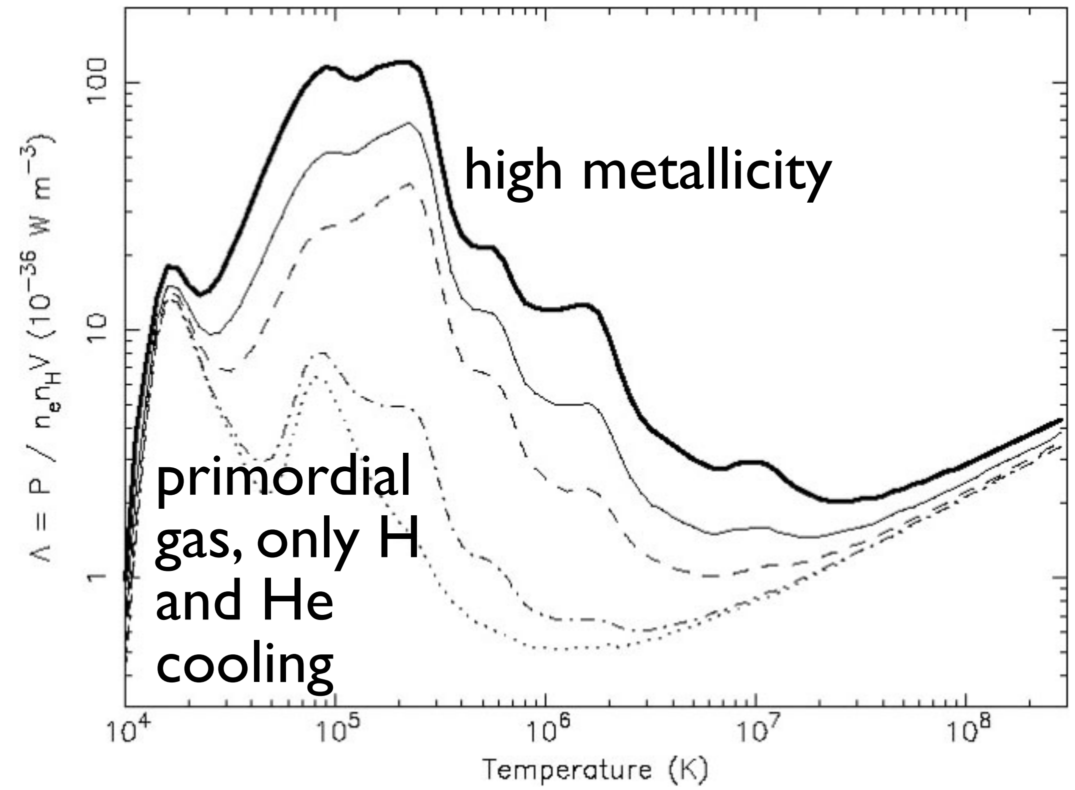
- Gas cools from this hot halo, looses P support, falls to the centre and forms a disc

$$t_{\rm cool} = \frac{3/2 \mu m_p k T}{\rho_g(r)\Lambda(T, Z_h)}$$

- Putting the density into the above equation, one can solve for the cooling radius $r_{\rm cool}$ with $t_{\rm cool}$
- Writing expression of the mass within $r_{\rm cool}$ and differentiate it —> rate at which gas can cool

$$\frac{{\rm d}m_{\rm cool}}{{\rm d}t} = \frac{1}{2} m_{\rm hot} \frac{r_{\rm cool}}{r_{\rm vir}} \frac{1}{t_{\rm cool}}$$





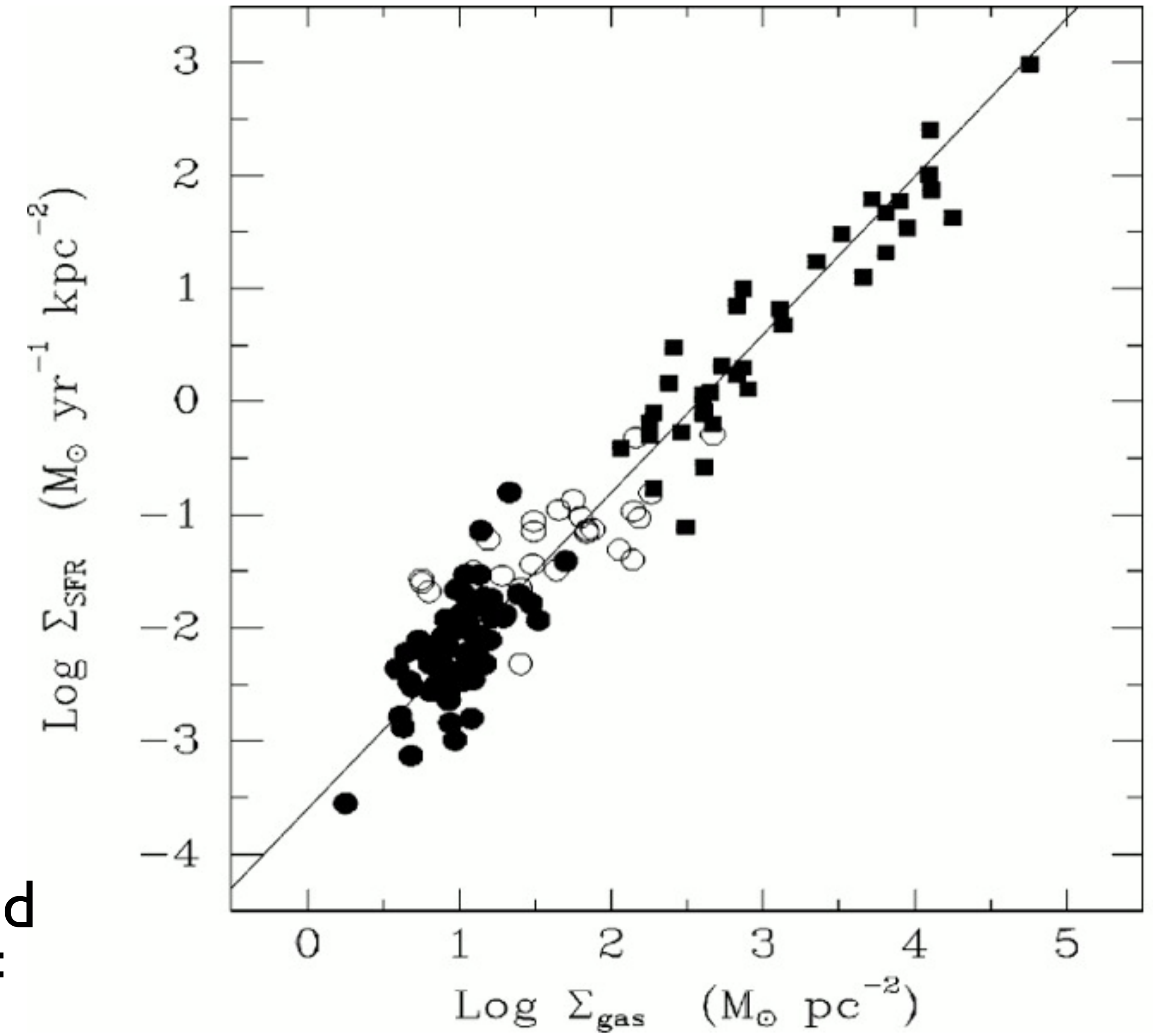
Star formation

- No full theory of star formation that gives SFR as a function of the ISM
- Phenomenological approach: calculate SFR following the observed Schmidt-Kennicutt relation
  - SFR surface density is related to the cold gas surface density

$$\Sigma_{\rm SFR} = A_{\rm Kenn}\Sigma_{\rm gas}^{N_K}$$

- Stars and cold gas are assumed to be distributed in an exponential disc
- Adopt a critical gas surface density, and calculate the corresponding critical SF radius (inside which gas is SF)

$$SFR = \int_0^{r_{\rm crit}} \dot{\Sigma}_* 2\pi r dr$$



- Remove mass of formed stars from cold gas reservoir and add it to the stellar component
- Details can vary from model to model…

Stellar feedback

- Due to Supernova explosions, a certain amount of energy is released

$$\dot{E}_{\rm thermal} = \epsilon \eta_{\rm SN} E_{\rm SN} \cdot SFR = \dot{M}_{\rm reheated} V_{\rm max}^2$$

- Thus, some cold gas is assumed to be re-heated

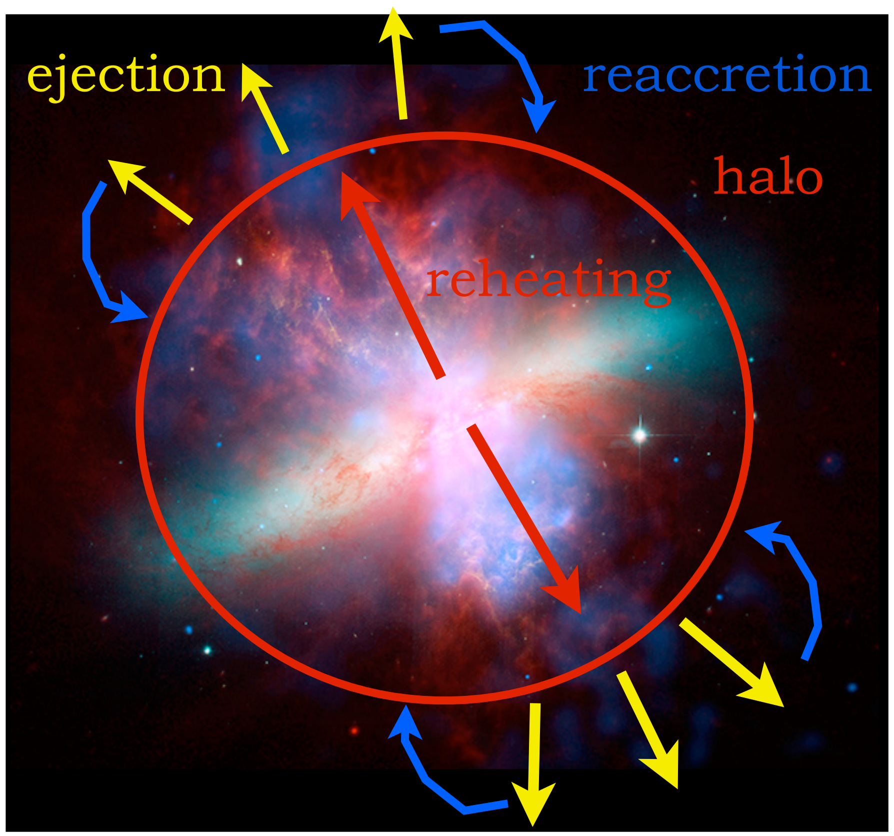
$$\dot{M}_{\rm reheated} = \epsilon \frac{\eta_{\rm SN} E_{\rm SN}}{V_{\rm max}^2} SFR$$

- In addition, a fraction of re-heated gas can be expelled out of the halo so that it is not available for cooling for some time

$$f_{\rm eject}(V_{\rm vir}) = \left[1 + \left(\frac{V_{\rm vir}}{V_{\rm eject}}\right)^{\alpha_{\rm eject}}\right]^{-1}$$

- After some time (typically a halo dynamical time scale), a fraction of the ejected gas is reincorporated back onto the halo

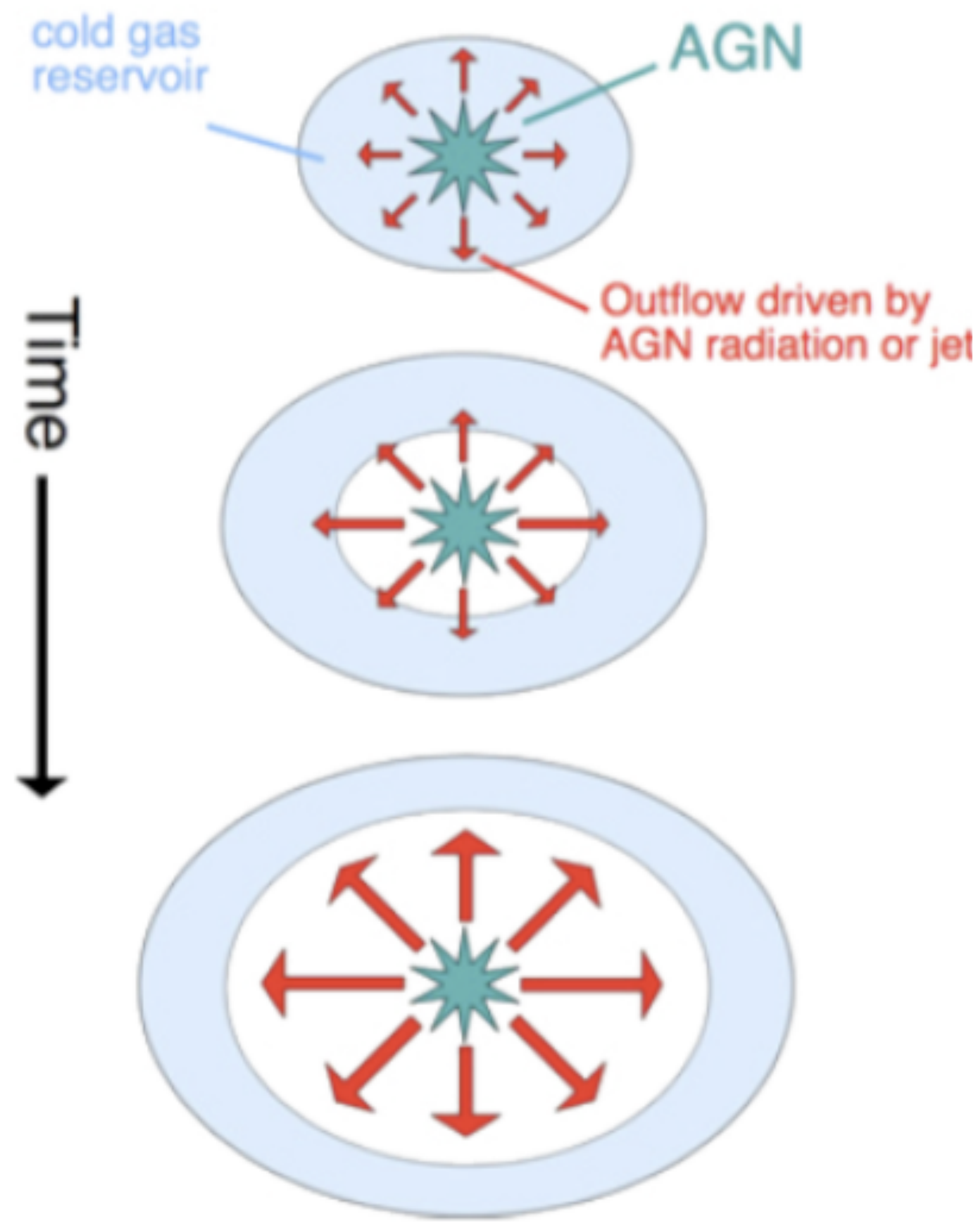
$$\dot{M}_{\rm reinc} = \gamma \; M_{\rm ejected}/t_{\rm dyn} = \gamma \; M_{\rm ejected} \frac{V_{\rm Vir}}{R_{\rm Vir}}$$



- Again, exact parametrisations vary from model to model due to our poor understanding of the underlying physics
- Other processes like radiation pressure, stellar winds may contribute to heating/expelling gas

BH growth & "quasar-mode" AGN feedback

- Every top-level halo contains a seed BH of 100-10^5 $M_\odot$
- Mostly assumed that BH grow via gas inflows through mergers (and secular evolution processes like disk instabilities)
- Accretion rates related to cold gas content and merger mass ratio, sometimes recipes for merger simulations used
- Some (but not many) SAMs account for quasar-driven outflows during phases of heavy gas accretion



$$f_{\rm eject} \propto L_{\rm quasar},$$

$$\text{where } L_{\rm quasar} = \epsilon_r \dot{M}_\bullet c^2$$

conversion efficiency of the loss of gravitational energy into radiation

“Jet-mode” AGN feedback

- Less efficient “hot gas accretion” once a static hot halo is present

$$\dot{m}_{\rm radio} = \pi (G M_{\rm BH})^2 \rho_0 c_s^{-3}$$

- “Radio-mode” feedback: energy due to jets released into hot halo
  - Mechanical heating power generated by BH accretion

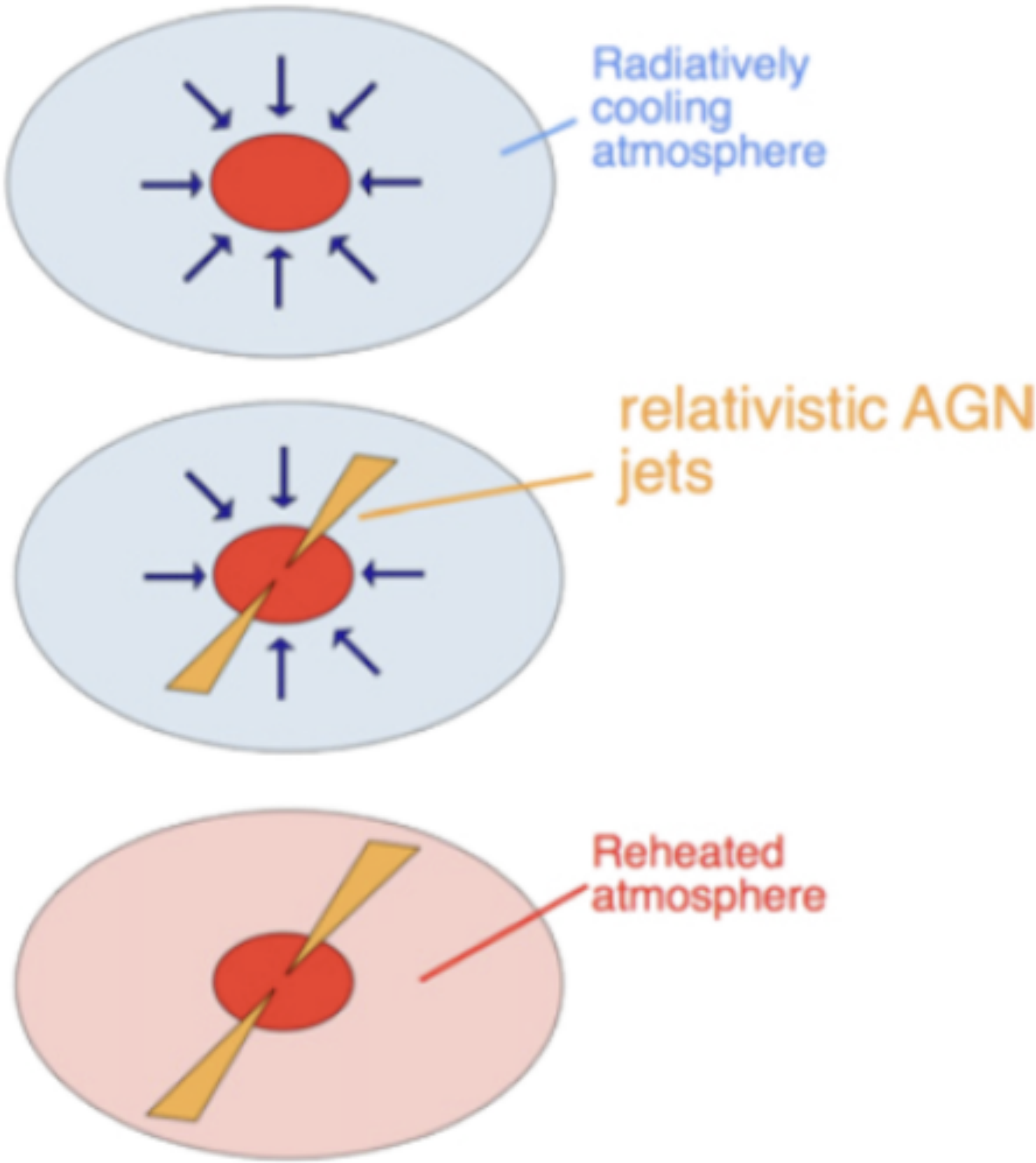
$$L_{\rm heat} = \kappa_{\rm heat}\, \eta_{\rm rad}\, \dot{m}_{\rm radio}\, c^2$$

$$\longrightarrow \dot{m}_{\rm heat} \propto L_{\rm heat}$$

- Modified, reduced cooling rate:

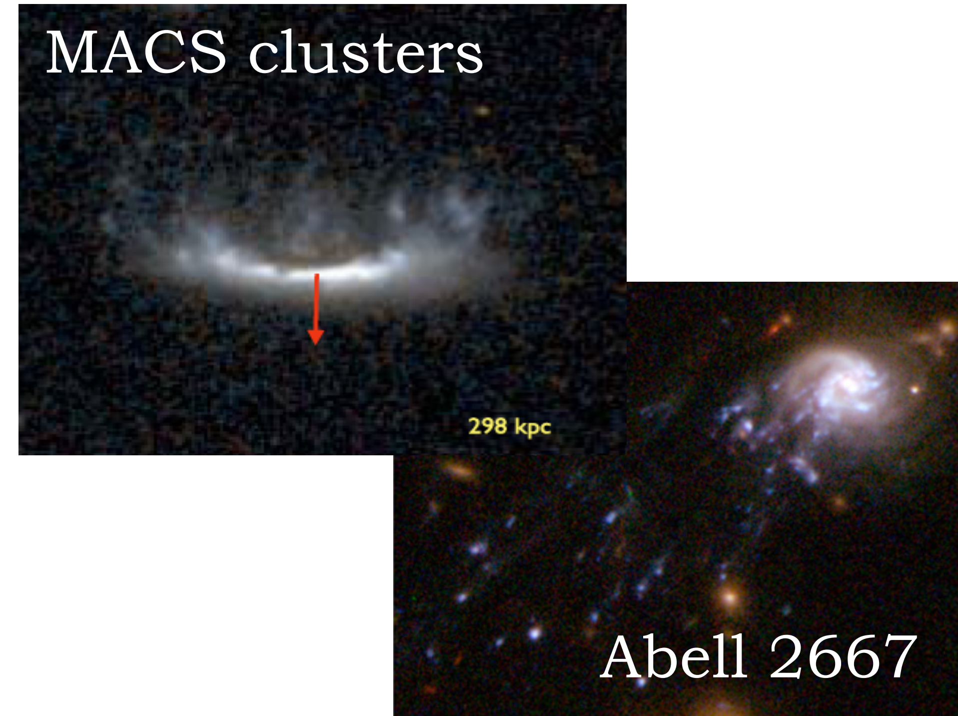
$$\dot{m}_{\rm cool,new} = \dot{m}_{\rm cool} - \dot{m}_{\rm heat}$$

Croton+06 explains the first implementation of such a scheme

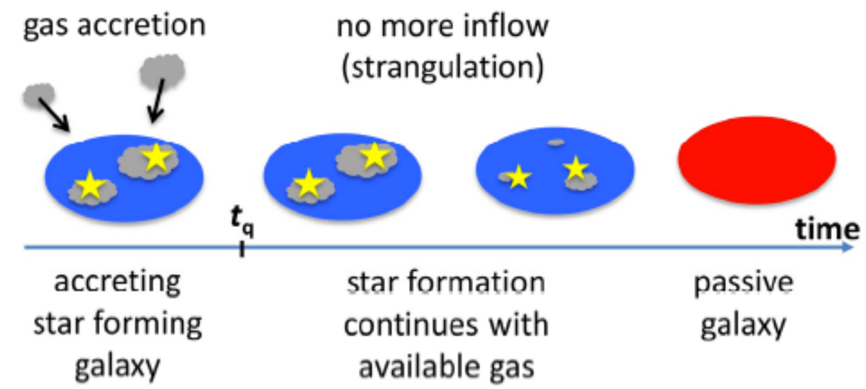


Mergers and environmental effects

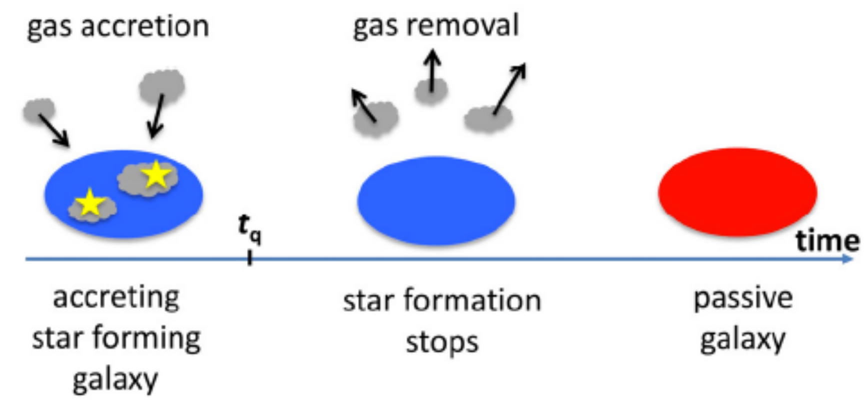
- Mergers lead to starbursts and morphological transformation
- Environmental effects mostly affecting satellites residing in dense regions:
  - Strangulation, Ram-pressure stripping: Interaction with hot/cold gas due to ram-pressure
- SAMs often assume an instantaneous strangulation, i.e. as soon as a galaxy becomes a satellite, its hot gaseous halo is entirely stripped (i.e. no further cooling)
- Sometimes more sophisticated approaches of delayed strangulation/stripping based on hydro-simulations



Strangulation



Ram-pressure stripping



taken from Peng+15

Free parameters for a typical SAM...

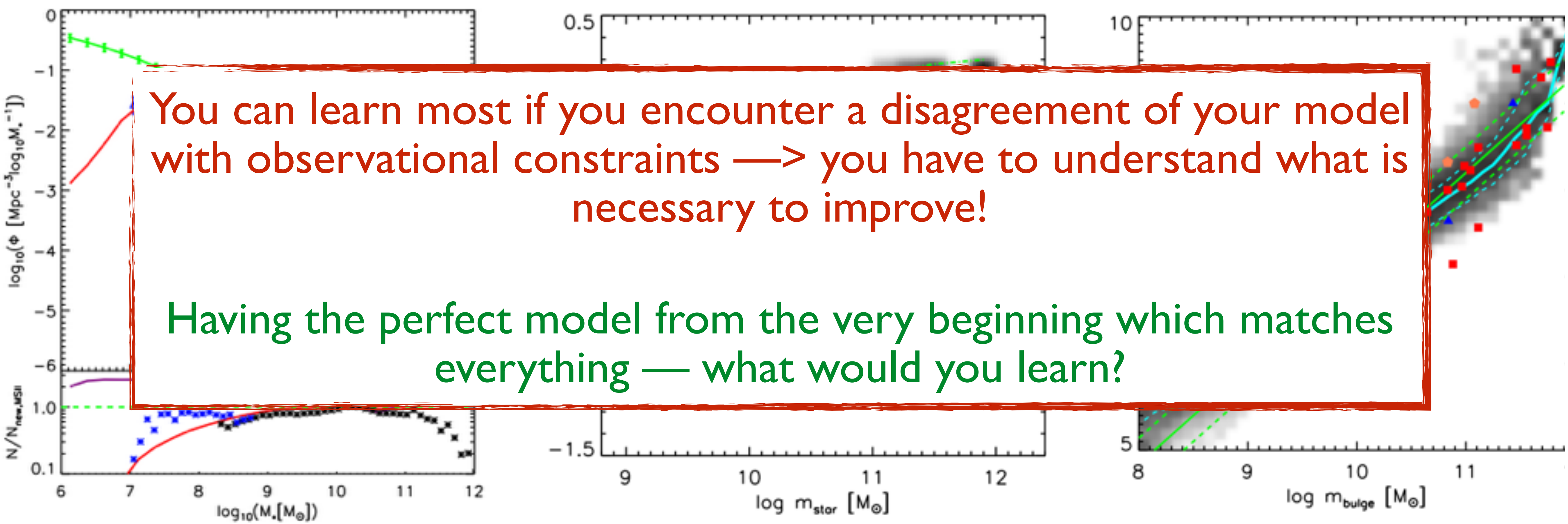
Parameter	Description
Quiescent star formation	
$A_{\rm KS}$	Normalization of Kennicutt law
N_K	Power-law index in Kennicutt law
$\Sigma_{\rm crit}$	Critical surface density
Burst star formation	
$\mu_{\rm crit}$	Critical mass ratio for burst activity
SN feedback	
$\epsilon^0_{\rm SN}$	Normalization of reheating fct
$\alpha_{\rm rh}$	Power-law slope of reheating fct
$V_{\rm eject}$	Velocity scale for ejecting gas
$\chi_{\rm re-infall}$	Time-scale for re-infall of ejected gas
Chemical evolution	
y	Chemical yield
Black hole growth	
$\eta_{\rm rad}$	Efficiency of conversion of rest mass to radiation
$M_{\rm seed}$	Mass of seed black hole
$f_{\rm BH,final}$	Scaling factor for mass after merger
$f_{\rm BH,crit}$	Scaling factor for critical BH mass
AGN-driven winds	
$\epsilon_{\rm wind}$	Coupling factor for AGN-driven winds
Radio-mode feedback	
$\kappa_{\rm radio}$	Normalization of 'radio mode' accretion rate
$\kappa_{\rm heat}$	Coupling efficiency of radio jets with hot gas

- This SAM (Somerville+08) has 16 free parameters

...tuned to...

- ...match a number of different observational data, mostly at the low redshift Universe, as SMF, BH-bulge mass relation, stellar metallicity
- Either tuned "by hand", or more modern SAMs use Monte-Carlo-Markov-Chains to explore all different combinations of free parameters
- Investigate predictions for other galaxy properties
- Sometimes tuning to some observational data set not possible (i.e. one cannot reproduce "everything" just by re-tuning free parameters)

  ➡This indicates the need for more fundamental modifications for some physical models

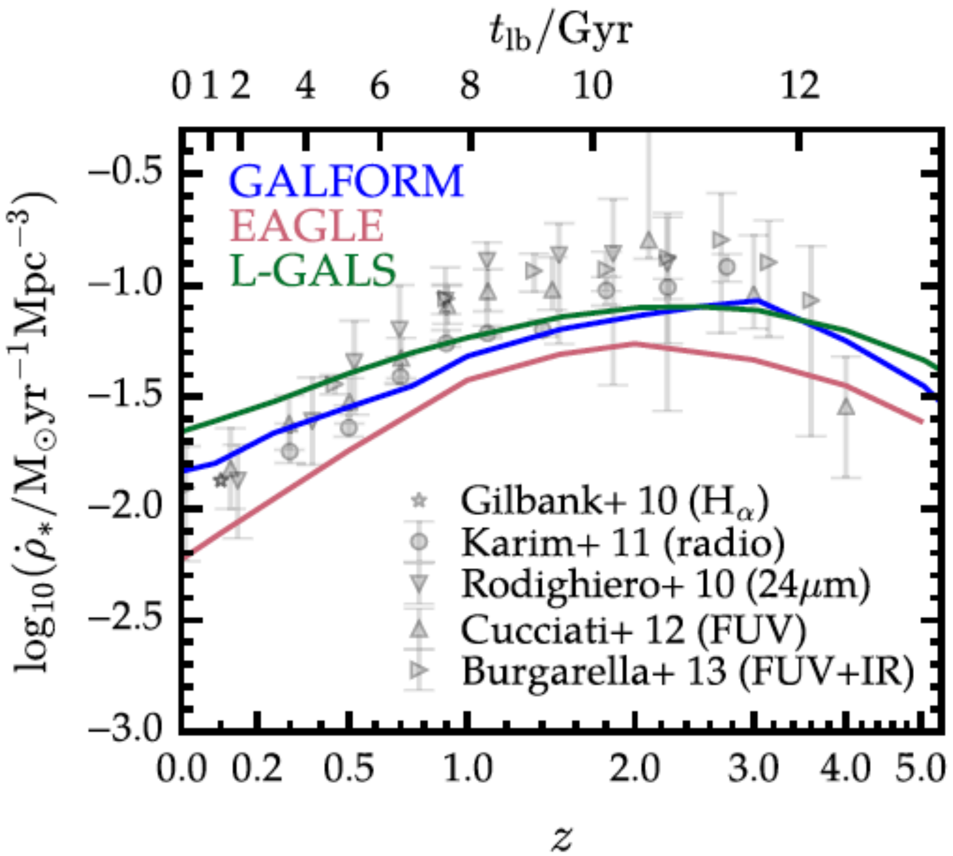


You can learn most if you encounter a disagreement of your model with observational constraints —> you have to understand what is necessary to improve!

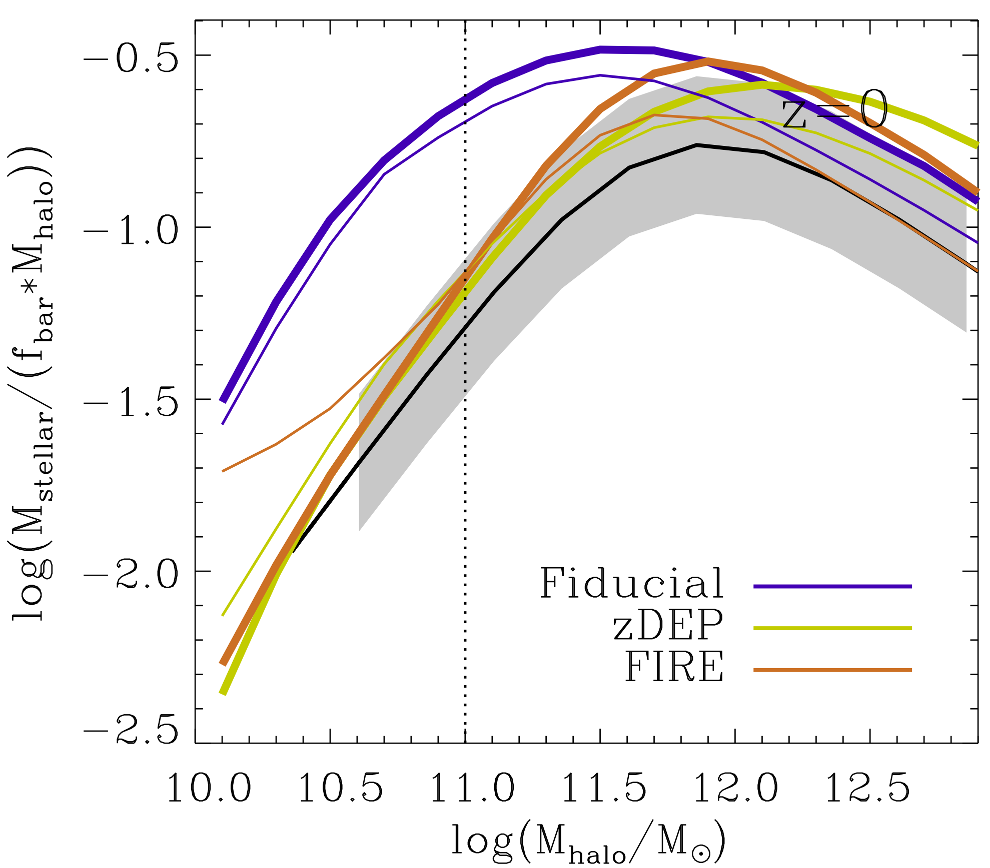
Having the perfect model from the very beginning which matches everything — what would you learn?

Lessons learned from SAMs…

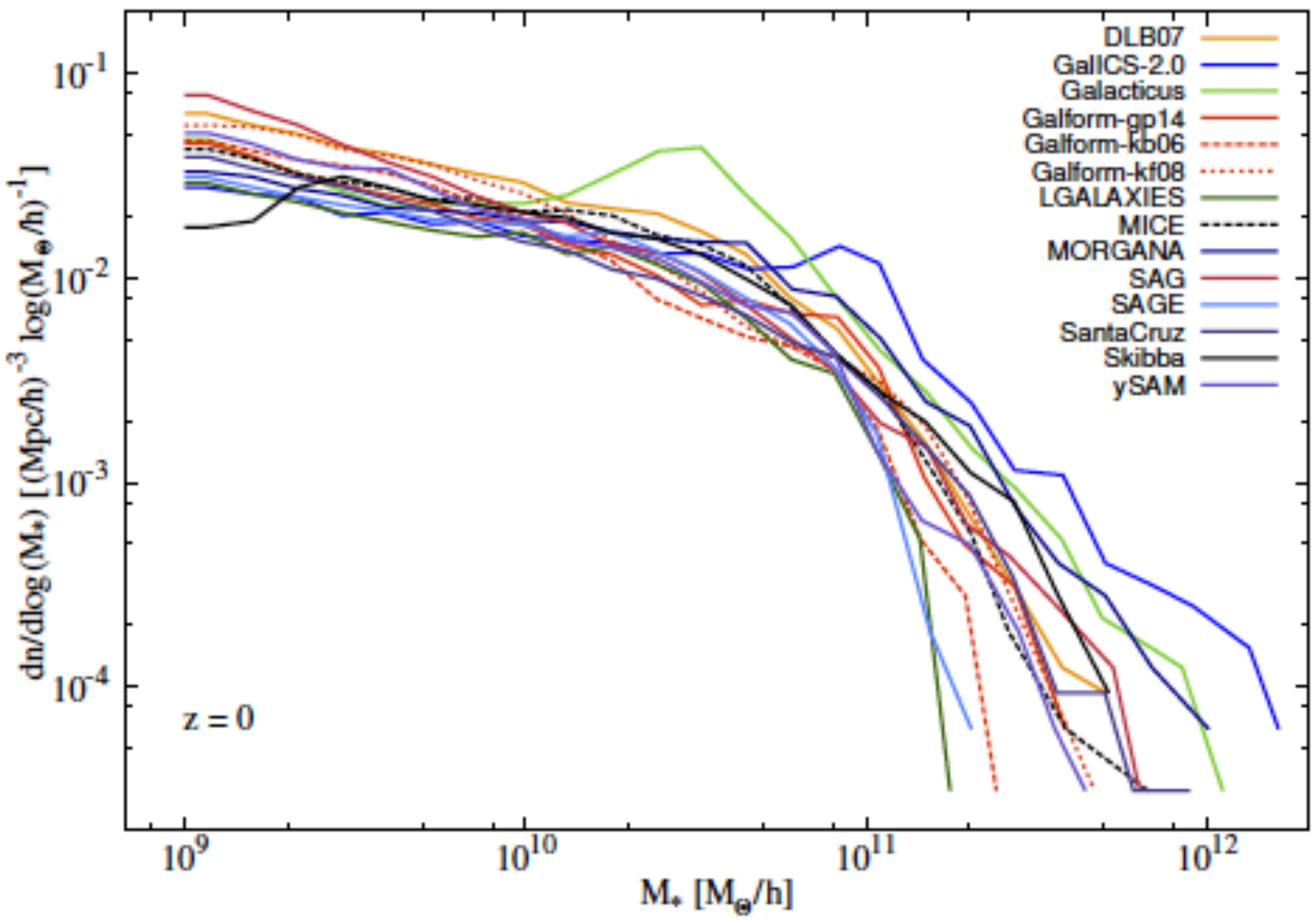
- Without any mechanism which prevents gas from cooling in massive halos (like jet-mode feedback), SAMs cannot be brought into agreement with the massive end of the stellar mass function and decline of SFR density at z<0



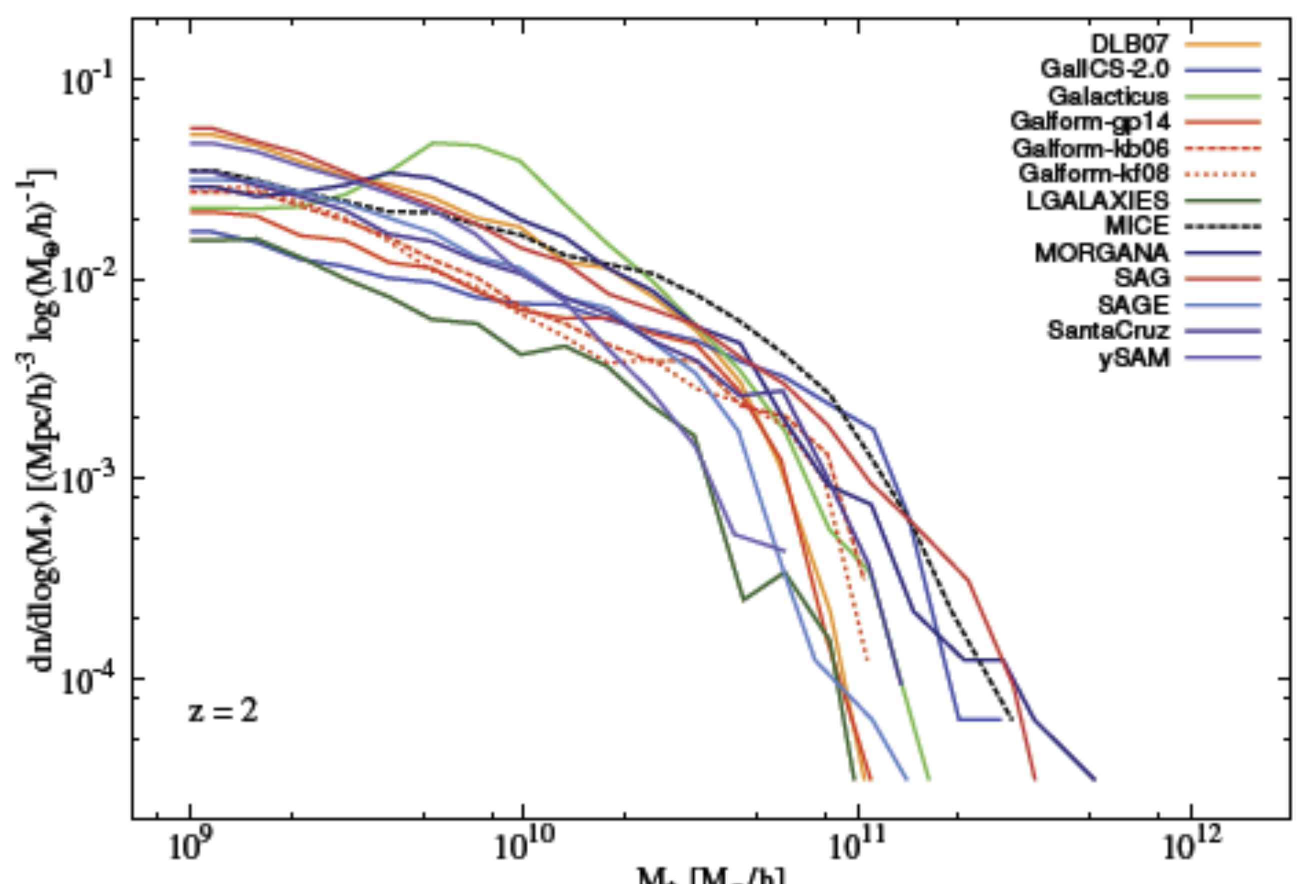
- In addition, SAMs show that stellar feedback is a possibility to suppress SF in low mass halos



Comparison studies of different SAMs



- Different SAMs applied to same merger trees based on same DM simulation
- Stellar mass function at z=0 and at z=2
- Large scatter at the massive end at z=0 and at all masses at z=2

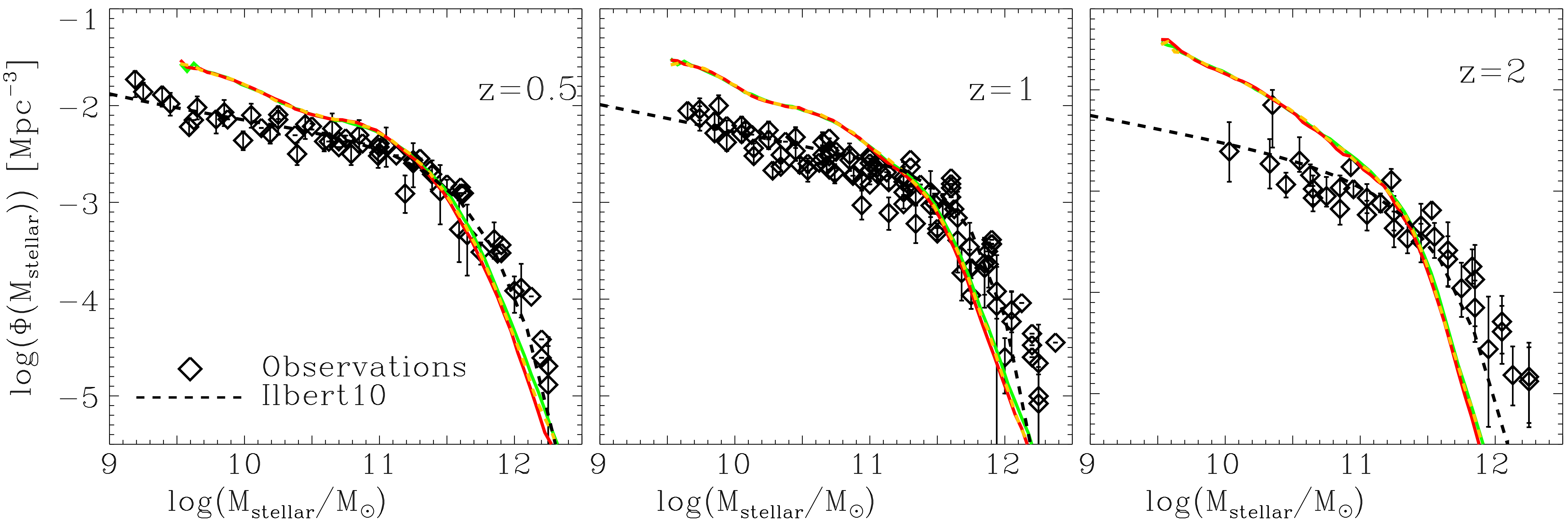


- Origin of large scatter is
  - the tuning to different observational data sets
  - **the uncertainty of how to model baryon physics**

What…

are the past and current main challenges to SAMs?

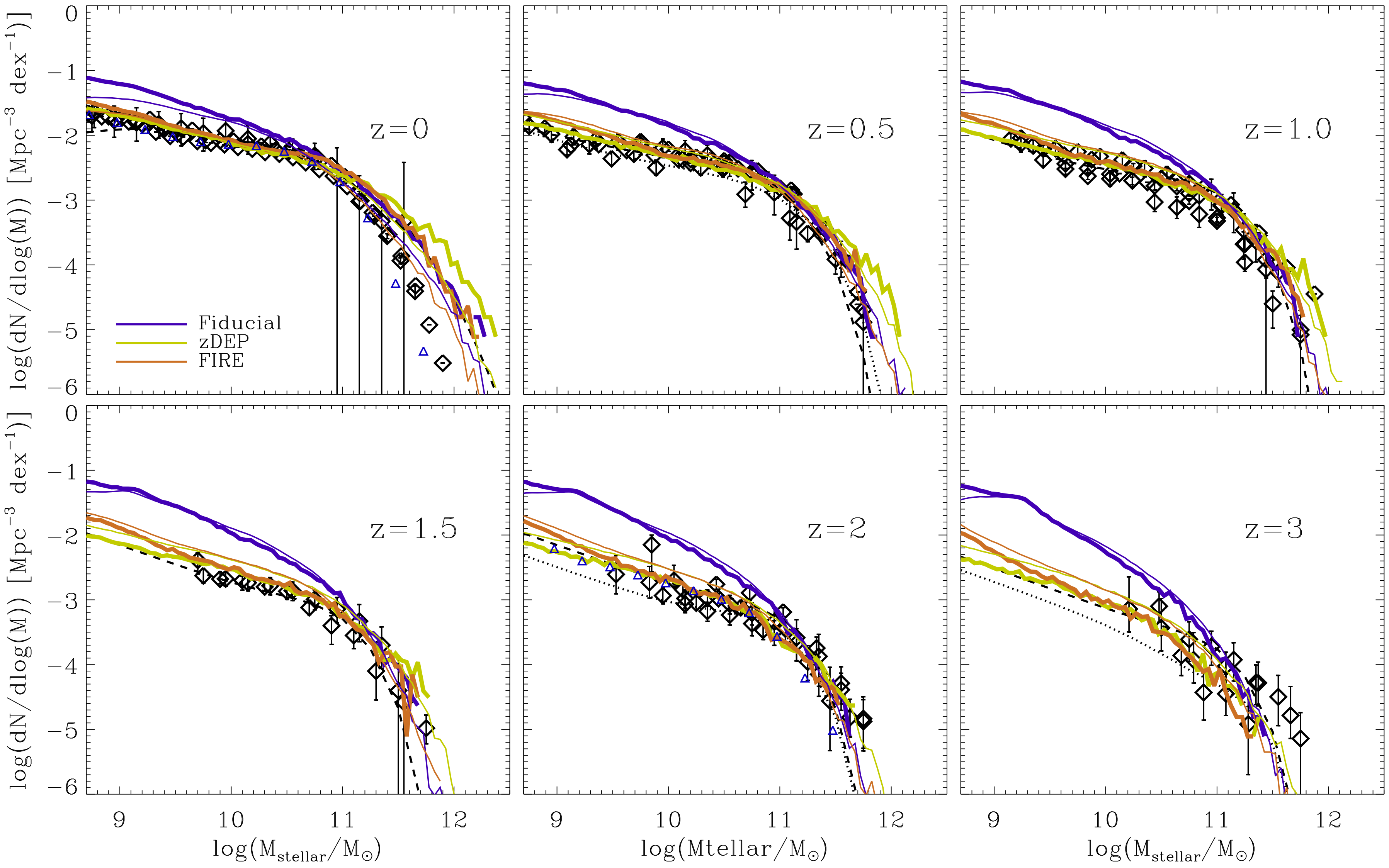
Past challenges... Evolution of the SMF



- Most SAMs (and simulations!!) had/have the problem that they over-estimate the amount of low-mass galaxies towards higher redshifts
- Observations instead indicate an antihierarchical behaviour
- Evolution of baryons too tightly coupled to hierarchical evolution of dark matter halos

Past challenges... Evolution of the SMF

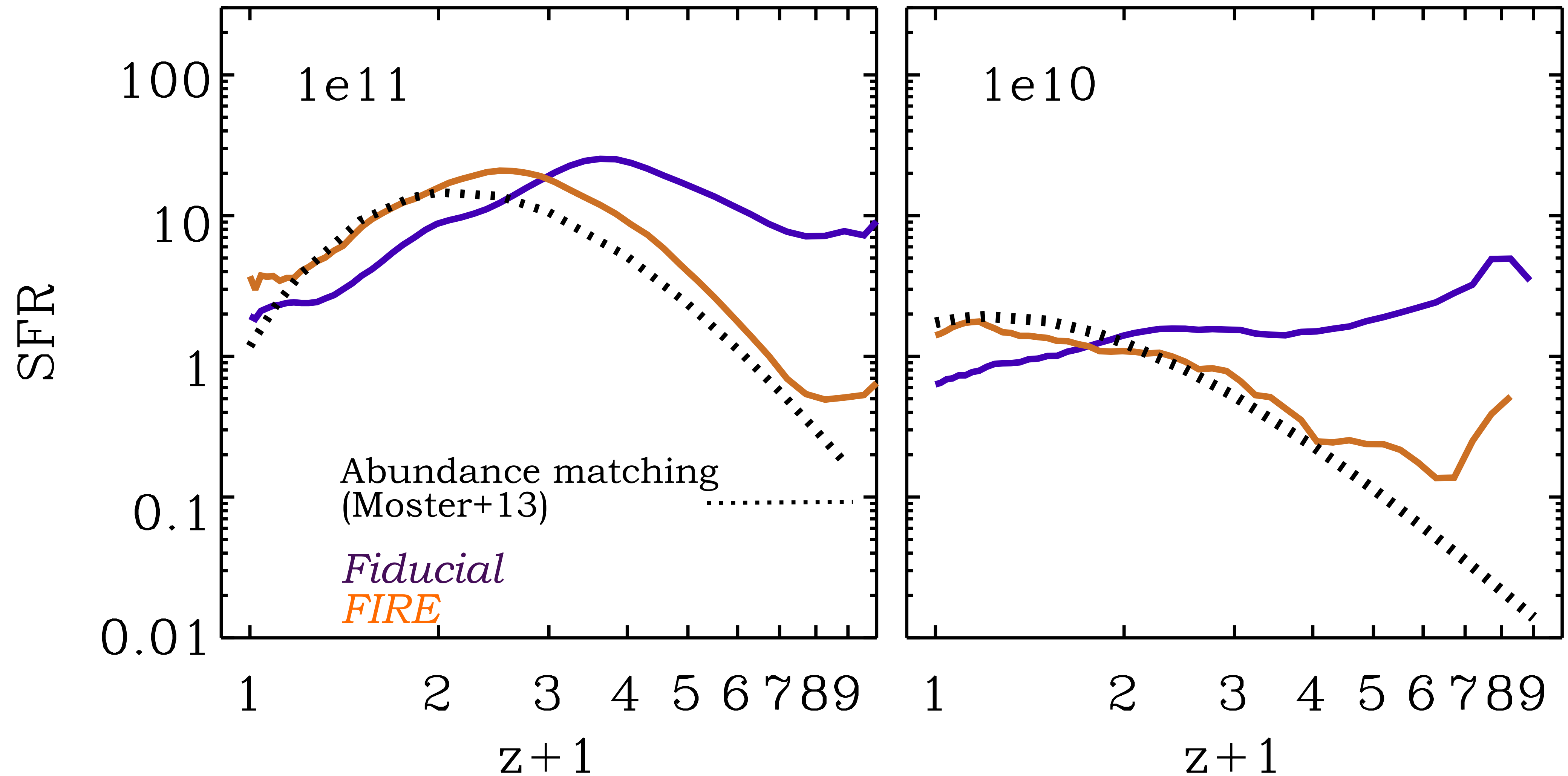
- Different solutions have been proposed over the past decade
- Strong stellar feedback: different scalings for re-heating and ejection following hydro-simulations



- Such mechanisms can help to de-couple the evolution of baryons from that of DM halos and to reproduce the anti-hierarchical trend

Past challenges... Evolution of the SFR

- This delayed stellar mass growth in case of strong stellar feedback can also be seen when looking at SFR:
  - SFRs of low mass galaxies peak at lower redshift than that of more massive galaxies (anti-hierarchical trend)
  - Consistent with abundance matching constraints/semi-empirical models

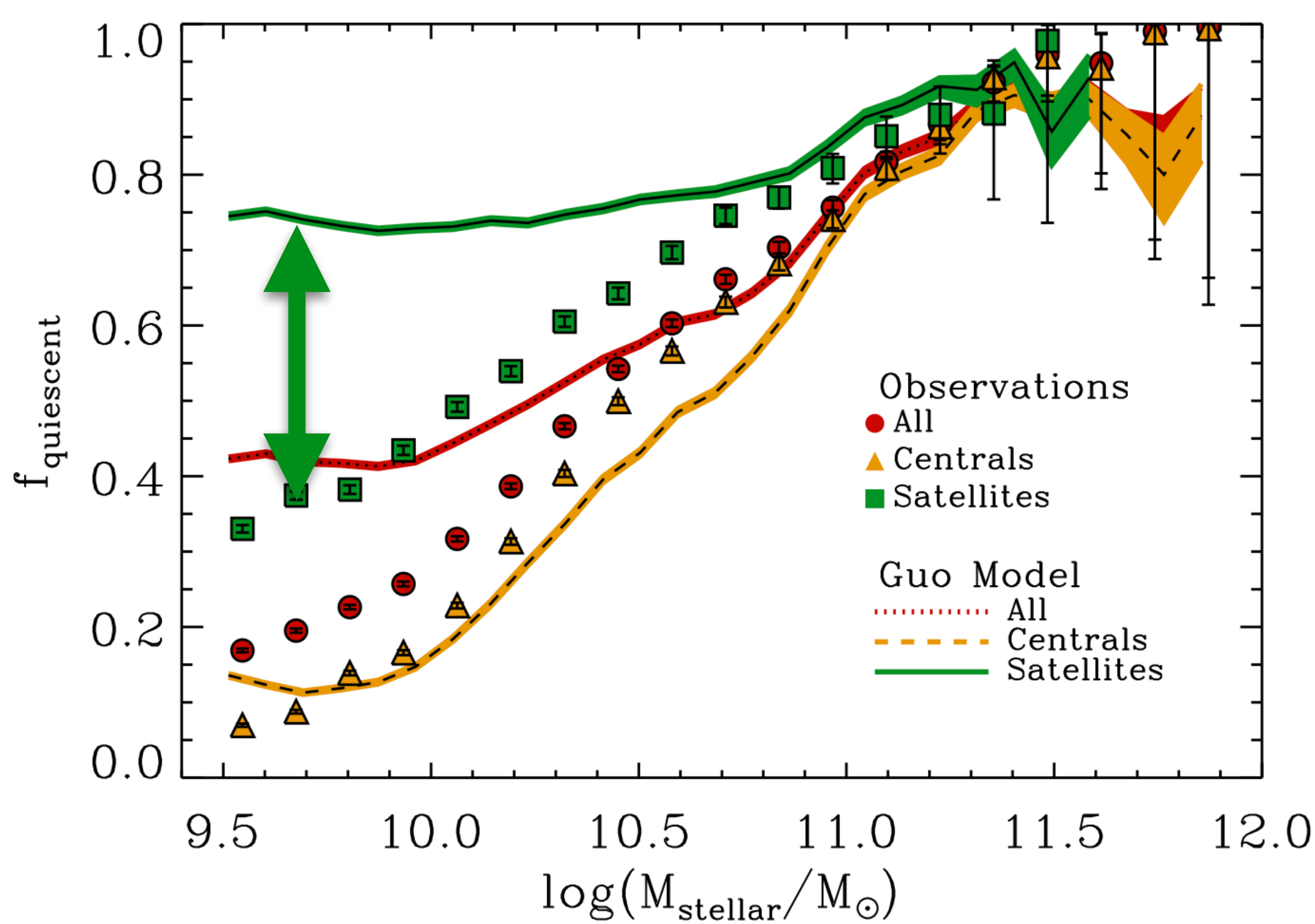


- **With SAMs, no conclusion on *origin* for strong outflows possible**

Past challenges... Quiescent fractions of sats

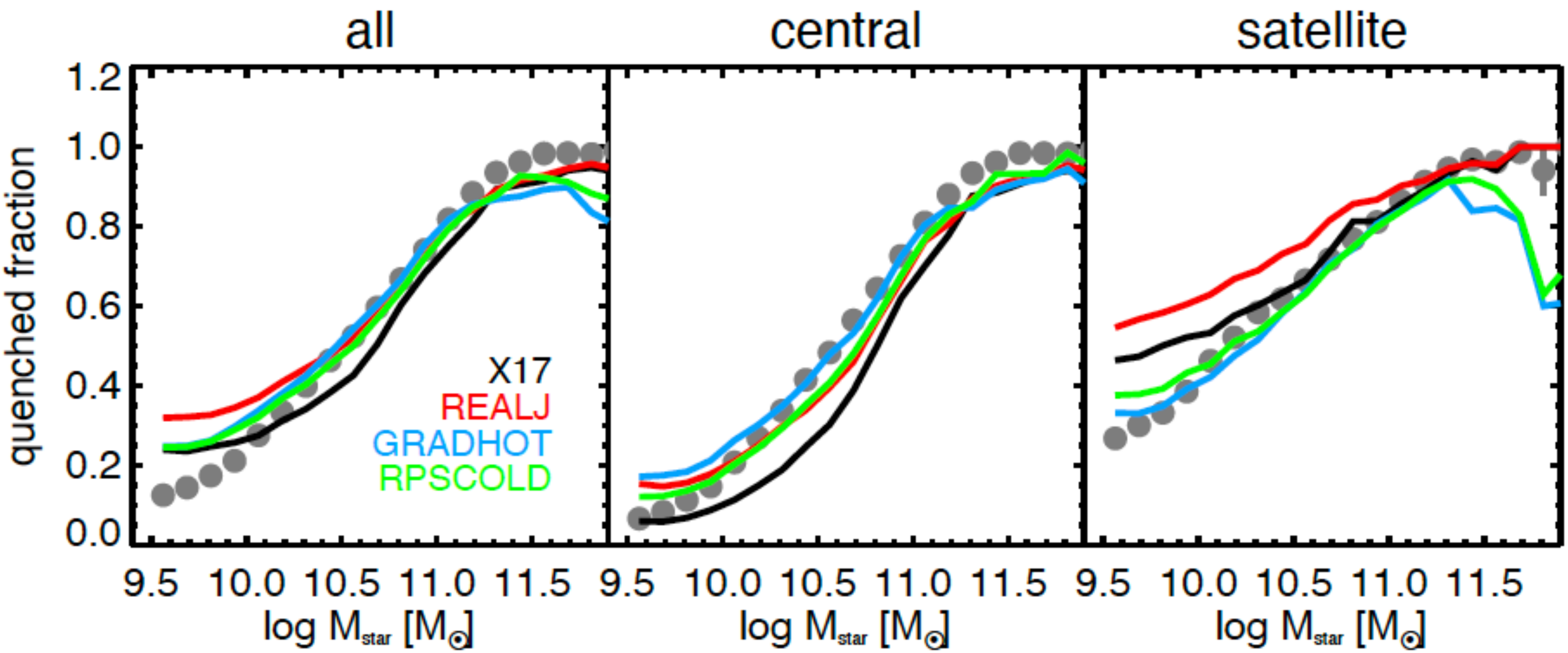
Another long-standing problem of most SAMs:

- Select quiescent galaxies according to their sSFR
- Quiescent fraction of (low-mass) satellites is significantly over-estimated
- Star formation is too fast quenched when a galaxy becomes a satellite —> too short quenching time-scales
- Partly related to the simplified assumptions of instantaneous strangulation



Past challenges... Quiescent fractions of sats

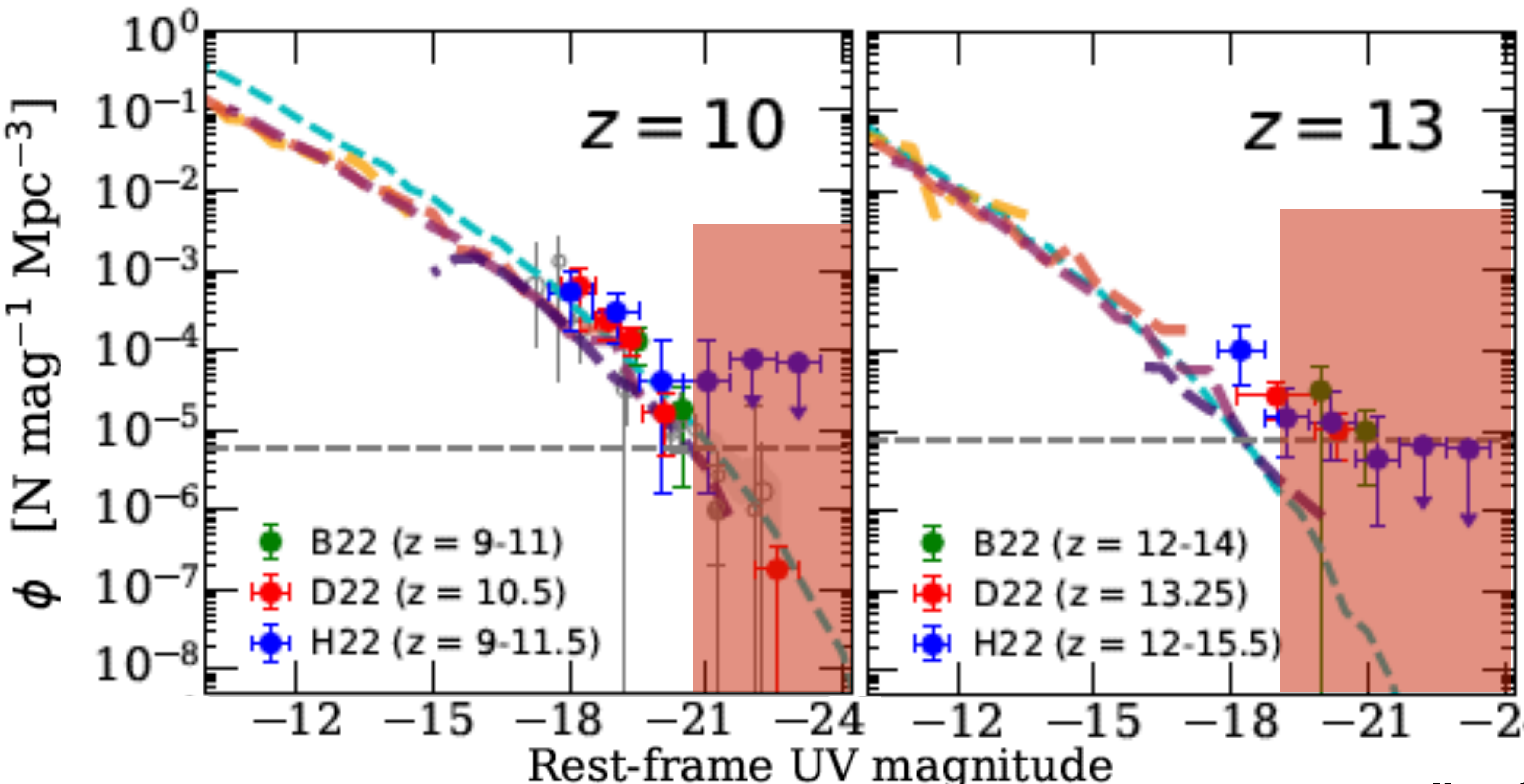
- Changing models stellar feedback and environment in GAEA reduces quiescent satellite fractions, in a better agreement with that observed



- Strong early stellar feedback makes the galaxies more gas-rich at time of infall —> longer/more SF while being a satellite
- *Gradual* stripping of hot gas, ram-pressure stripping of cold gas instead of *instantaneous* removal of hot gas when becoming a satellite

Challenges... UV luminosity function at z>10

- One of the main current challenges:
- SAMs fail to predict bright galaxies above z=10 newly observed with JWST!



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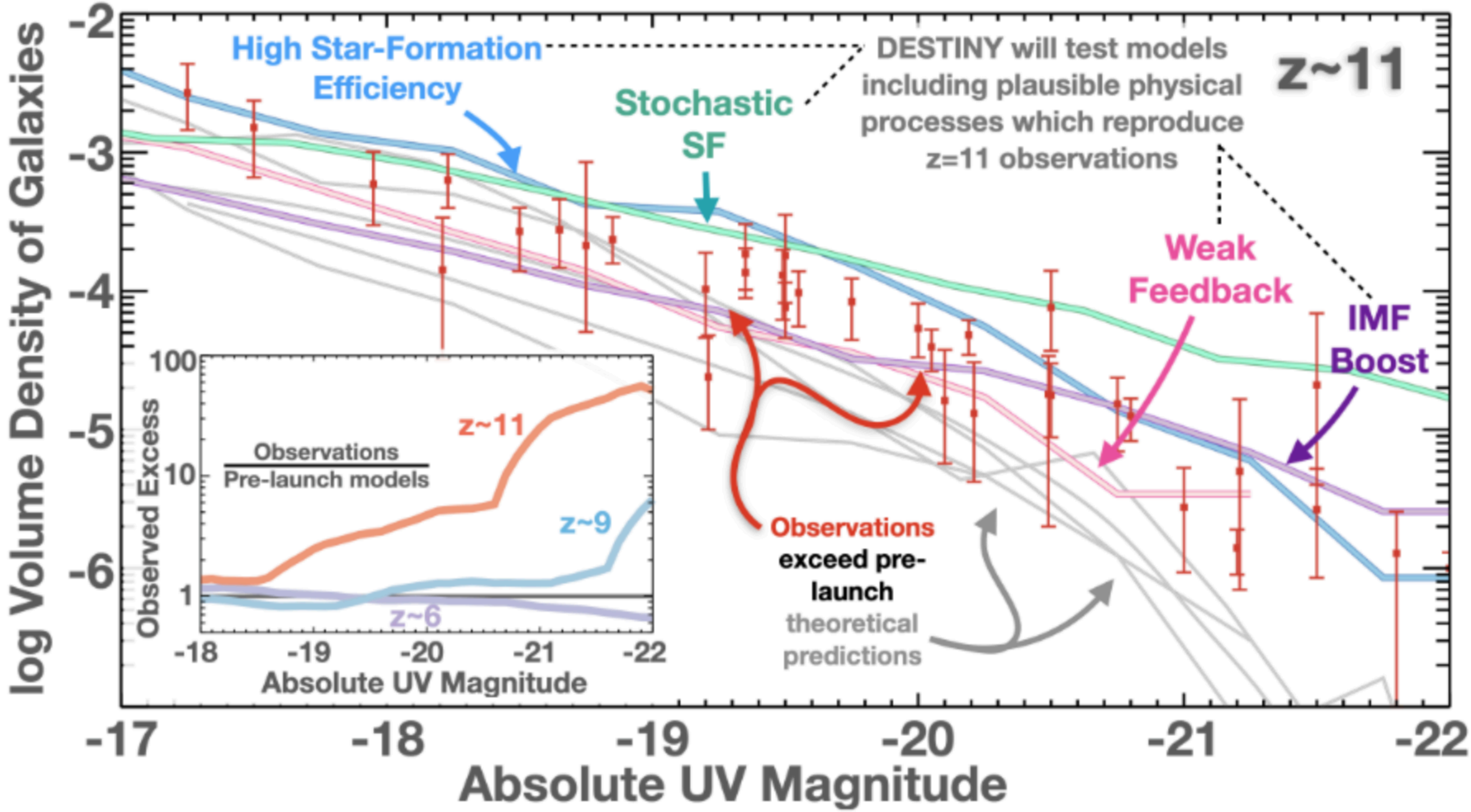
- What could be the reason for this mismatch?

Challenges… UV luminosity function at z>10

- Possible reasons: model deficiencies (SF efficiency, stochastic SF, weak stellar feedback, top-heavy IMF and/or observational uncertainties



➡ Continuous on-going improvement, but also higher level of complexity…

Pro's and con's of SAMs

PRO:

- SAMs are flexible in testing different recipes for different physical processes
- SAMs are fast in running over the merger trees
- and thus, they allow for large statistics with low computational costs

CON:

- Little to no spatial information
- Simplified approximations, no direct modelling of a gas fluid
- Many (often degenerate) free parameters
- No possibility of understanding the underlying physical processes leading to different, partly more successful recipes
- We can just capture "global trends", no physically based recipes available yet

Summary

- **Galaxies form in the potential wells of DM halos: gas gets trapped due to gravity, cools, condenses form stars…**
- **Galaxy evolution processes**: gas cooling, SF, stellar feedback, BH growth and feedback, mergers, environmental processes etc.
- Semi-empirical models helpful to interpret observations in the framework of hierarchically growing DM halos
  - Useful "observational-like" constraints for models with detailed baryon physics
  - No insights in the physical processes at all
- Semi-analytic models based on the DM halo merger trees and the evolution of baryons is estimated via phenomenologically motivated differential equations
  - Consistent with many observational constraints, but some unresolved issues remain
  - Information about *global* trends of baryon processes, but underlying physical driving mechanisms often unclear
  - Excellent for a fast testing physical processes in a large cosmological volume

Up next…

- *Chapter 1*: Introduction (galaxy definition, astronomical scales, observable quantities — repetition of Astro-I)
- *Chapter 2:* Brief review on stars
- *Chapter 3*: Radiation processes in galaxies and telescopes;
- *Chapter 4:* The Milky Way
- *Chapter 5*: The world of galaxies I
- *Chapter 6*: The world of galaxies II
- *Chapter 7:* Black holes and active galactic nuclei
- *Chapter 8:* Galaxies and their environment;
- *Chapter 9:* High-redshift galaxies
- *Chapter 10*:
  - Cosmology in a nutshell; Linear structure formation in the early Universe
- *Chapter 11*:
  - Dark matter and the large-scale structure
  - Cosmological N-body simulations of dark matter
- *Chapter 12*: Populating dark matter halos with baryons: Semi-empirical & semi-analytical models
- *Chapter 13:* Modelling the evolution of gas in galaxies: Hydrodynamics
- *Chapter 14*: Gas cooling/heating and star formation
- *Chapter 15*: Stellar feedback processes
- *Chapter 16*: Black hole growth & AGN feedback processes
- *Chapter 17*: Modern simulations & future prospects

Part I: Observational basics & facts of galaxies
first 7 lectures

Part II: Theory & models of galaxy evolution processes
second 7 lectures

Cosmological hydrodynamic simulation