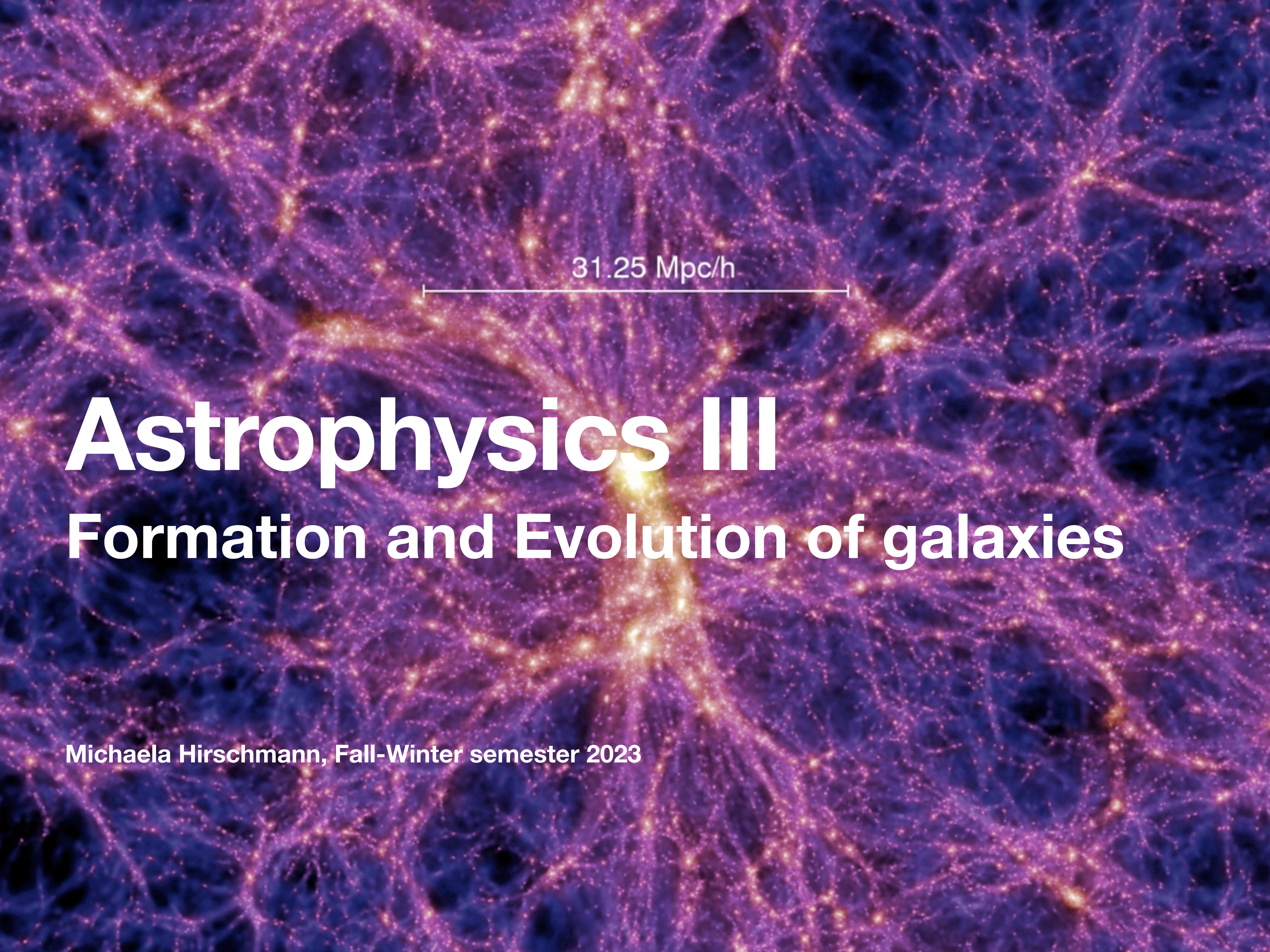

Astrophysics III

Formation and Evolution of galaxies

Michaela Hirschmann, Fall-Winter semester 2023

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
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- *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

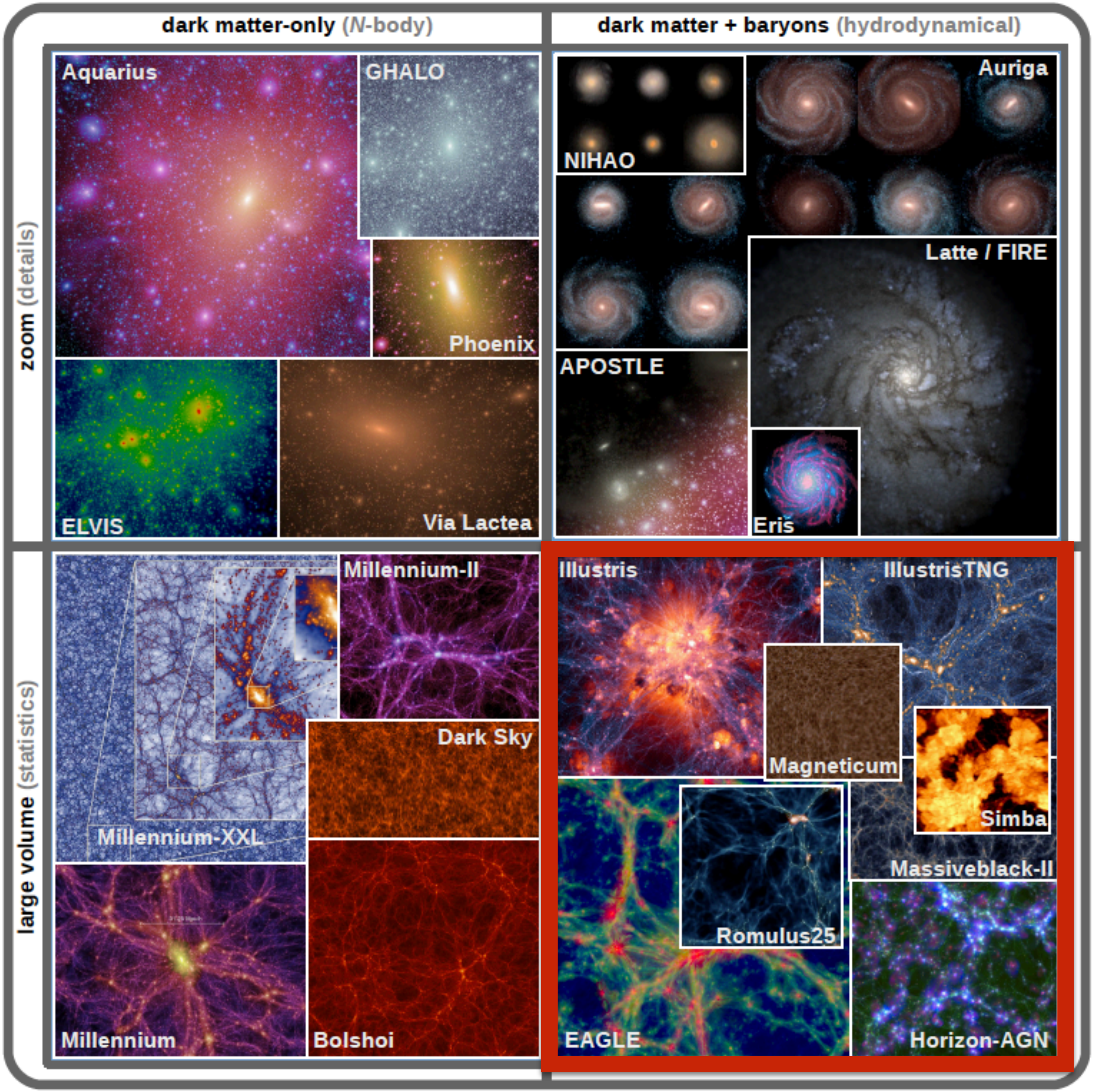
Part I: Observational basics & facts of galaxies first 7 lectures

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

Outline of this lecture

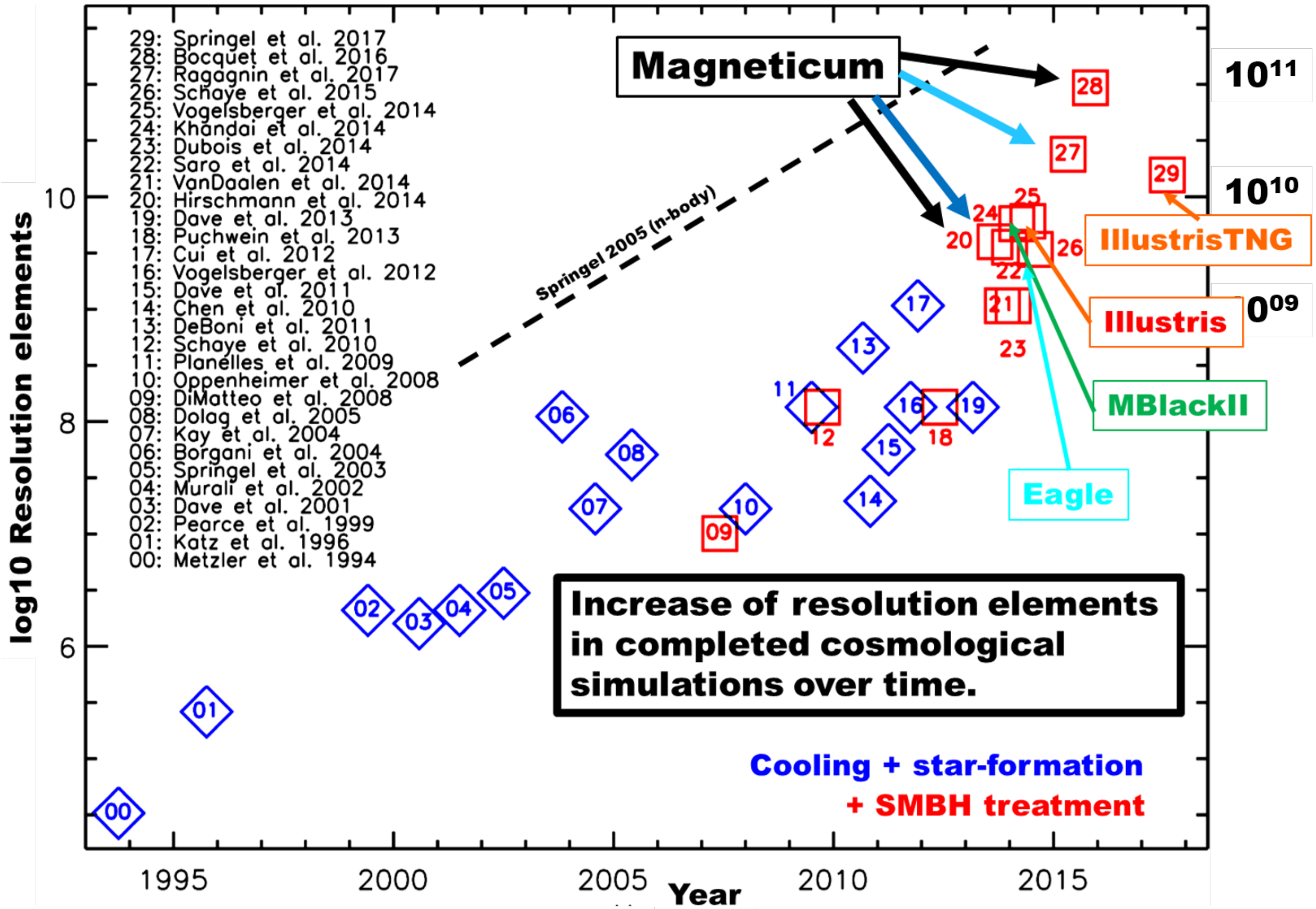
- Success of state-of-the-art cosmological simulations
  - IllustrisTNG, EAGLE, (MassiveBlack), Magneticum, HorizonAGN
- Challenges of state-of-the-art cosmological simulations
  - Limited predicted power
  - High-redshift Universe
  - Missing processes
- Future directions

The variety of cosmological simulations



Large cosmological hydrodynamic simulations

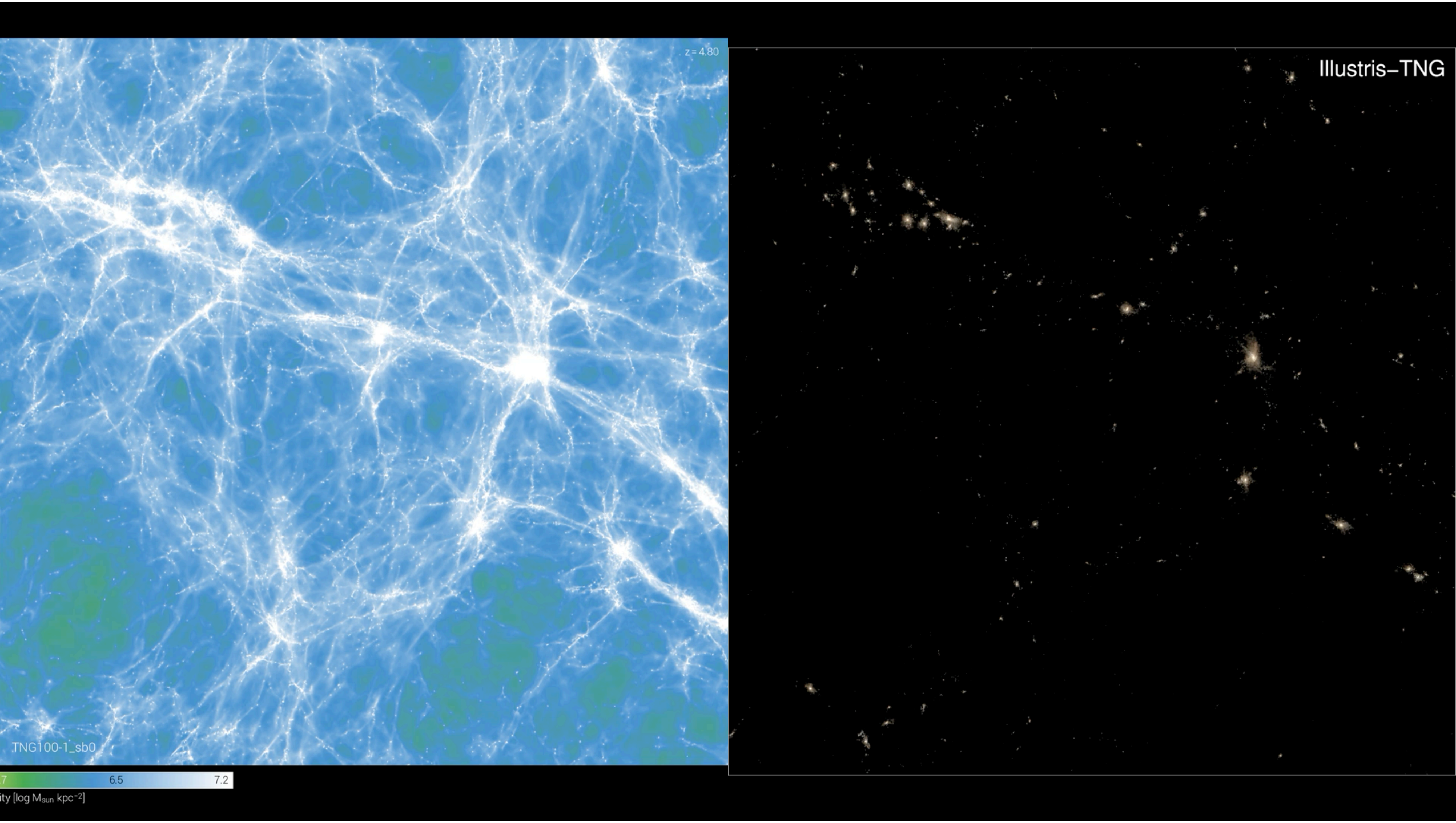
- Significant development during the last 5-10 years thanks to increased computational power
- Full hydrodynamic simulation of statistically representative cosmological volume possible (box length ~ 50-500Mpc)



Large cosmological hydrodynamic simulations

- Significant development during the last 5-10 years thanks to increased computational power
- Full hydrodynamic simulation of statistically representative cosmological volume possible (box length ~ 50-500Mpc)
- Statistical sample of galaxies which can be compared to large observational data sets like SDSS
- Learn how *millions of galaxies* form and evolve in a hierarchically evolving Universe, e.g.
  - Structure, stellar populations and kinematics
  - Gaseous content, gas flows, enrichment of the CGM
  - BHs and AGN, co-evolution with their host galaxies
- Most well-known and to date largest simulations:
  - IllustrisTNG, EAGLE, Magneticum, HorizonAGN, Simba, MassiveBlack

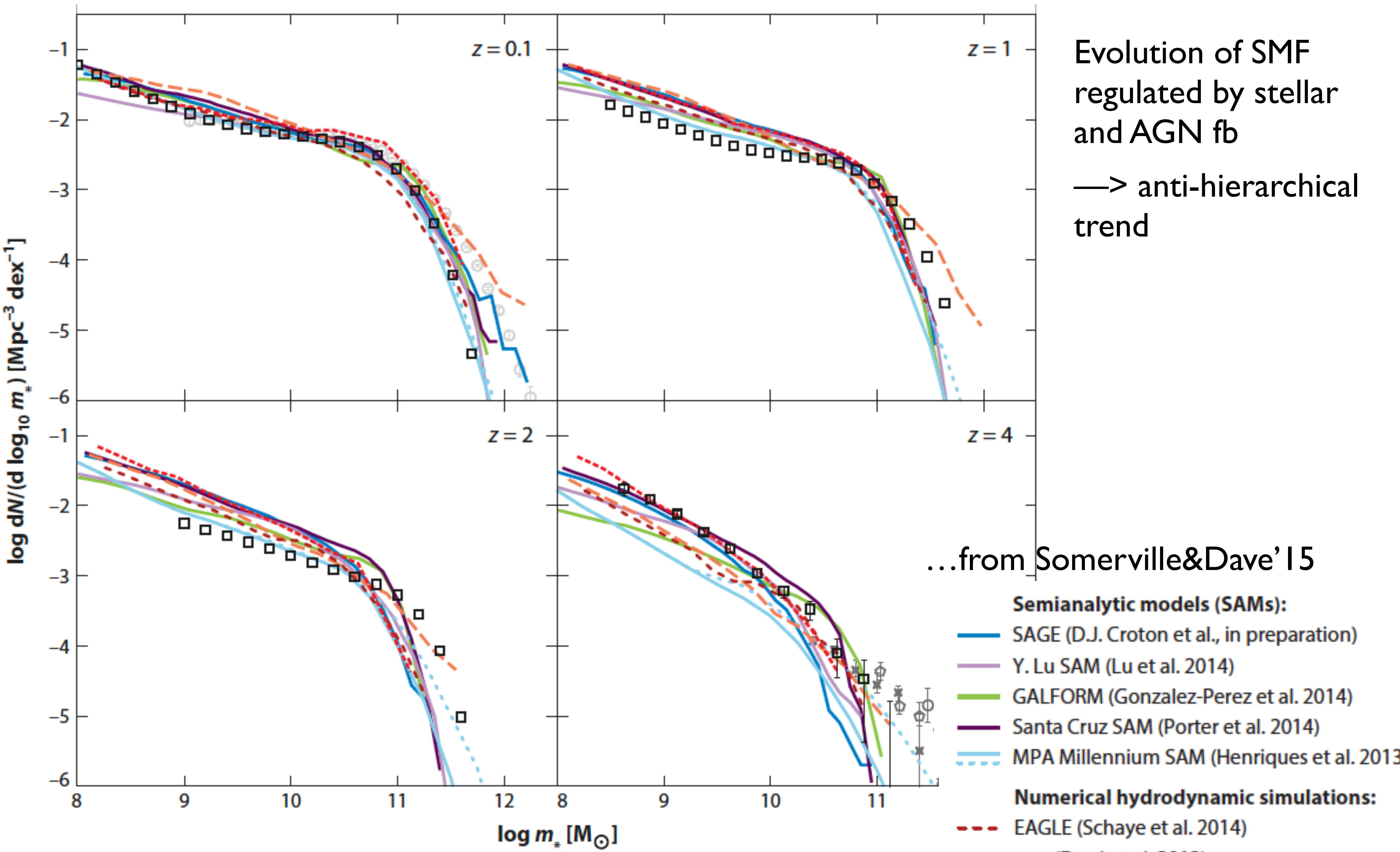
Movie of IllustrisTNG



Success of cosmological simulations

- Evolution of stellar mass function and anti-hierarchical trend
- Cosmic SFR history and SFR-Mstar relation
- Morphologies: spiral and elliptical galaxies
- Realistic sizes and mass-size relations
- Low-redshift BH and AGN populations

Stellar mass function

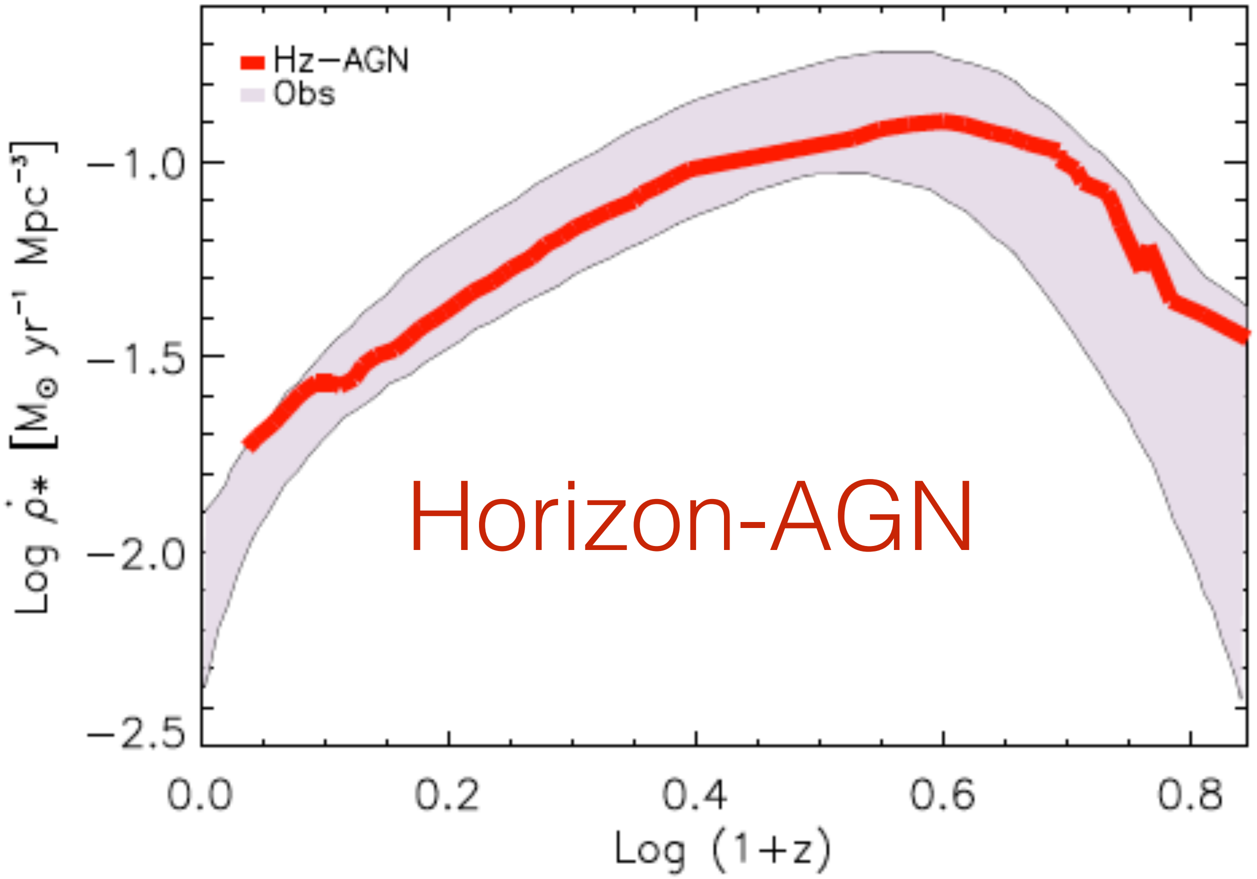


Evolution of SMF regulated by stellar and AGN fb

—> anti-hierarchical trend

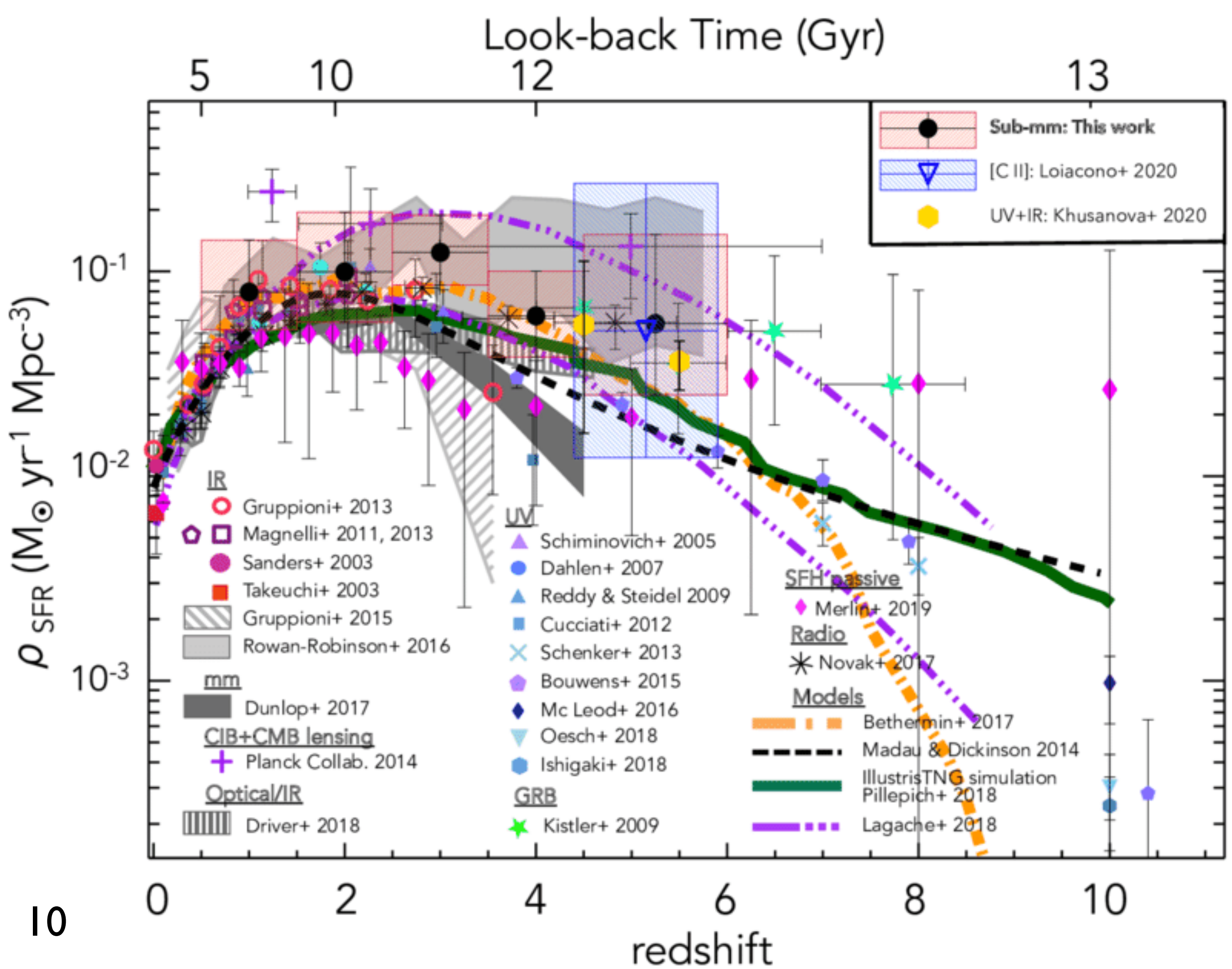
…from Somerville&Dave'15

Cosmic Star formation rate density

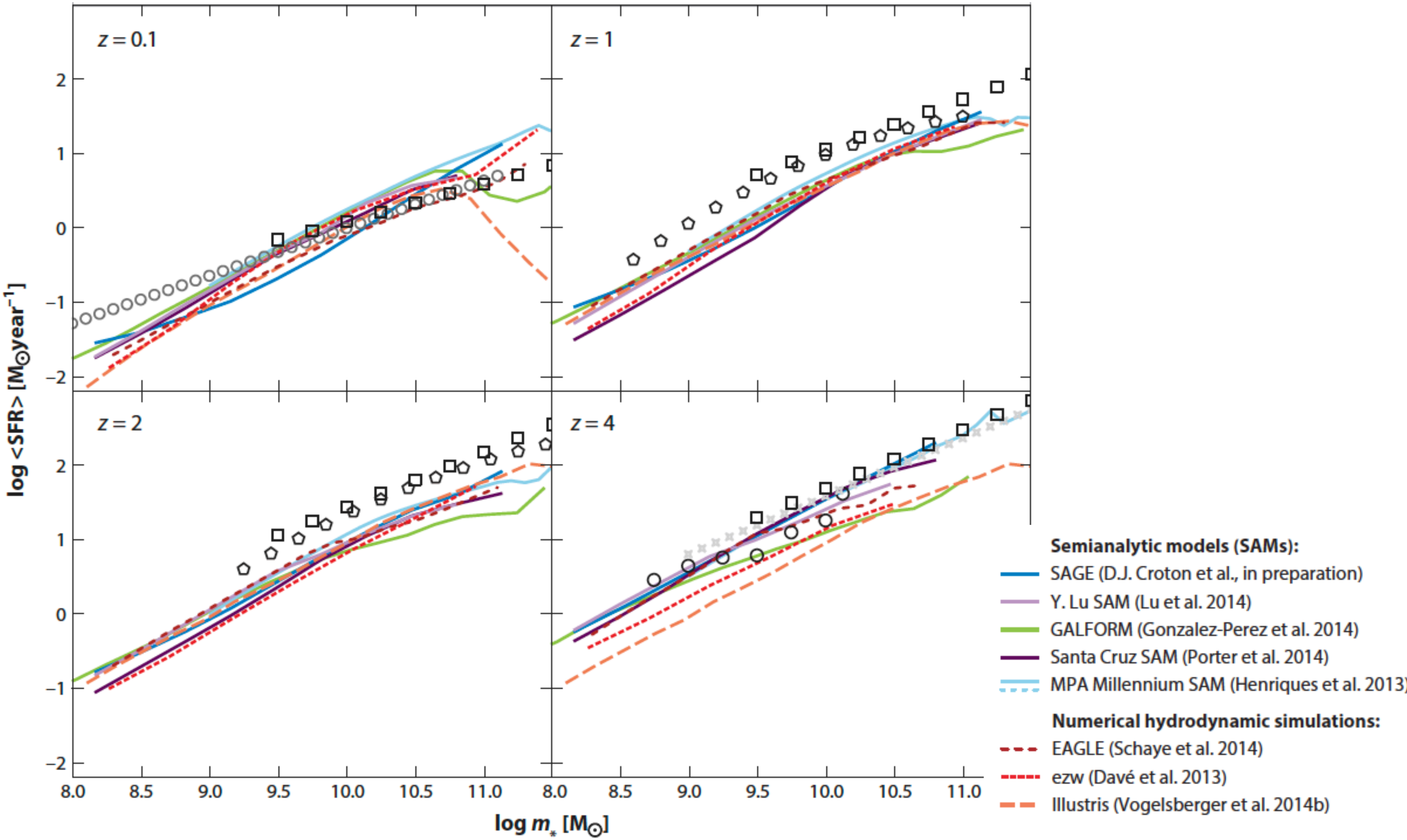


- Decline of cosmic SFR density due to gas consumption via SF and due to AGN feedback
- Large uncertainty of SFR density at z>6

Illustris-TNG

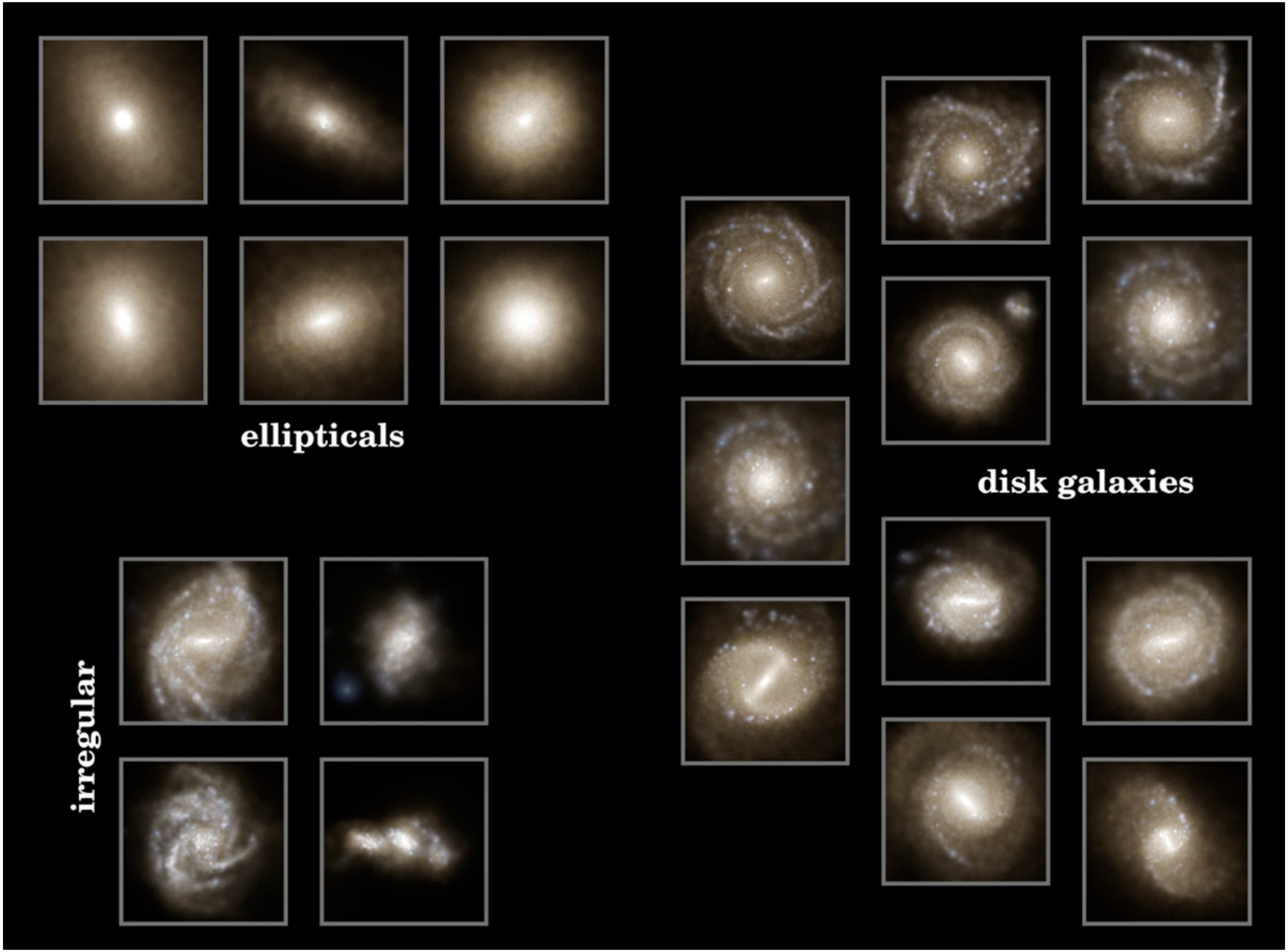


Main sequence of SF galaxies



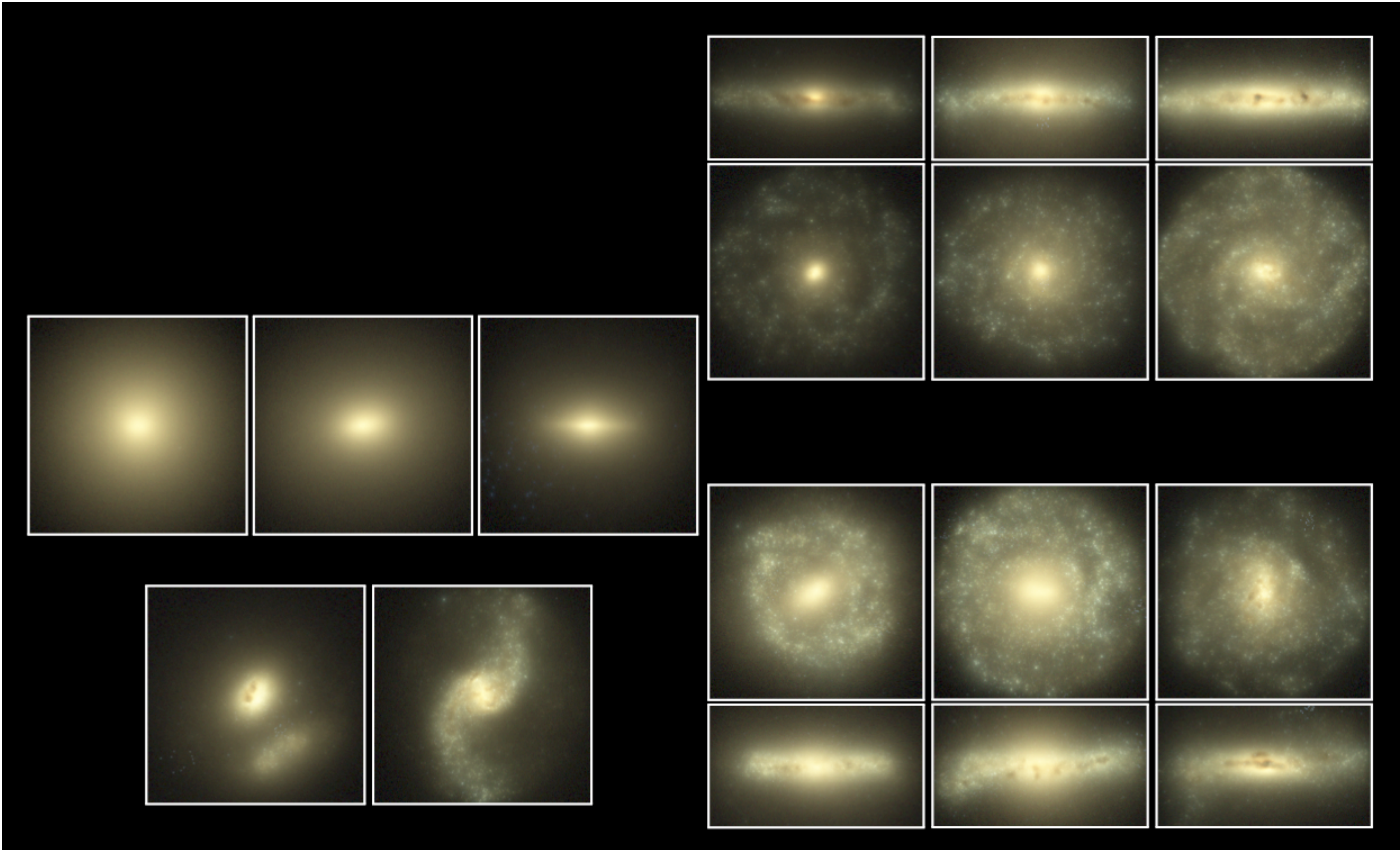
- Overall good agreement with observations
- Tendency that SFRs of low mass galaxies are slightly underestimated

Morphologies of Illustris(TNG)



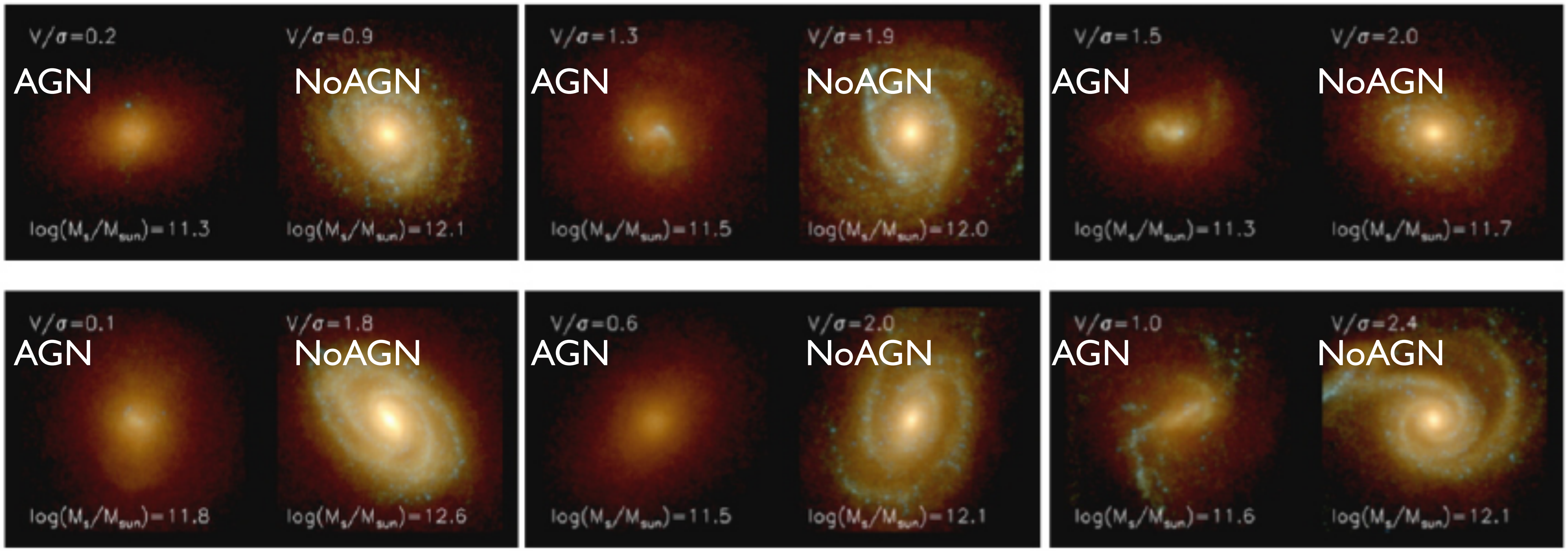
Morphologies of EAGLE

- Hubble sequence

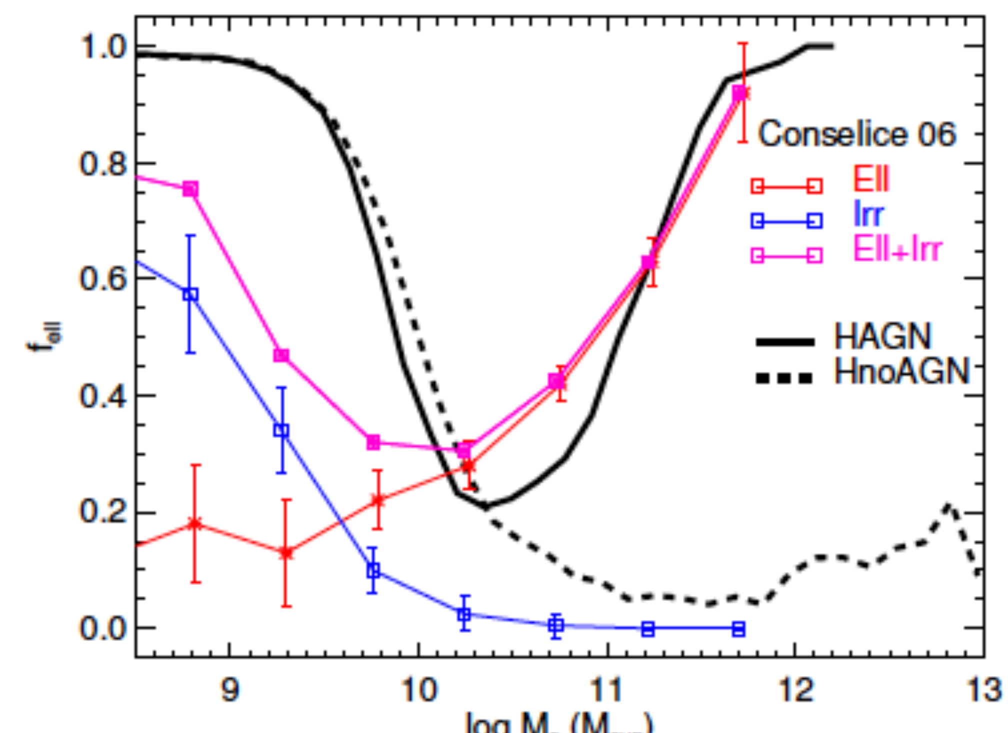


Morphologies of HorizonAGN

- Morphologies



- AGN feedback helps to transform spiral into elliptical galaxies due to suppression of late insitu SF
- Good agreement with observed elliptical fraction



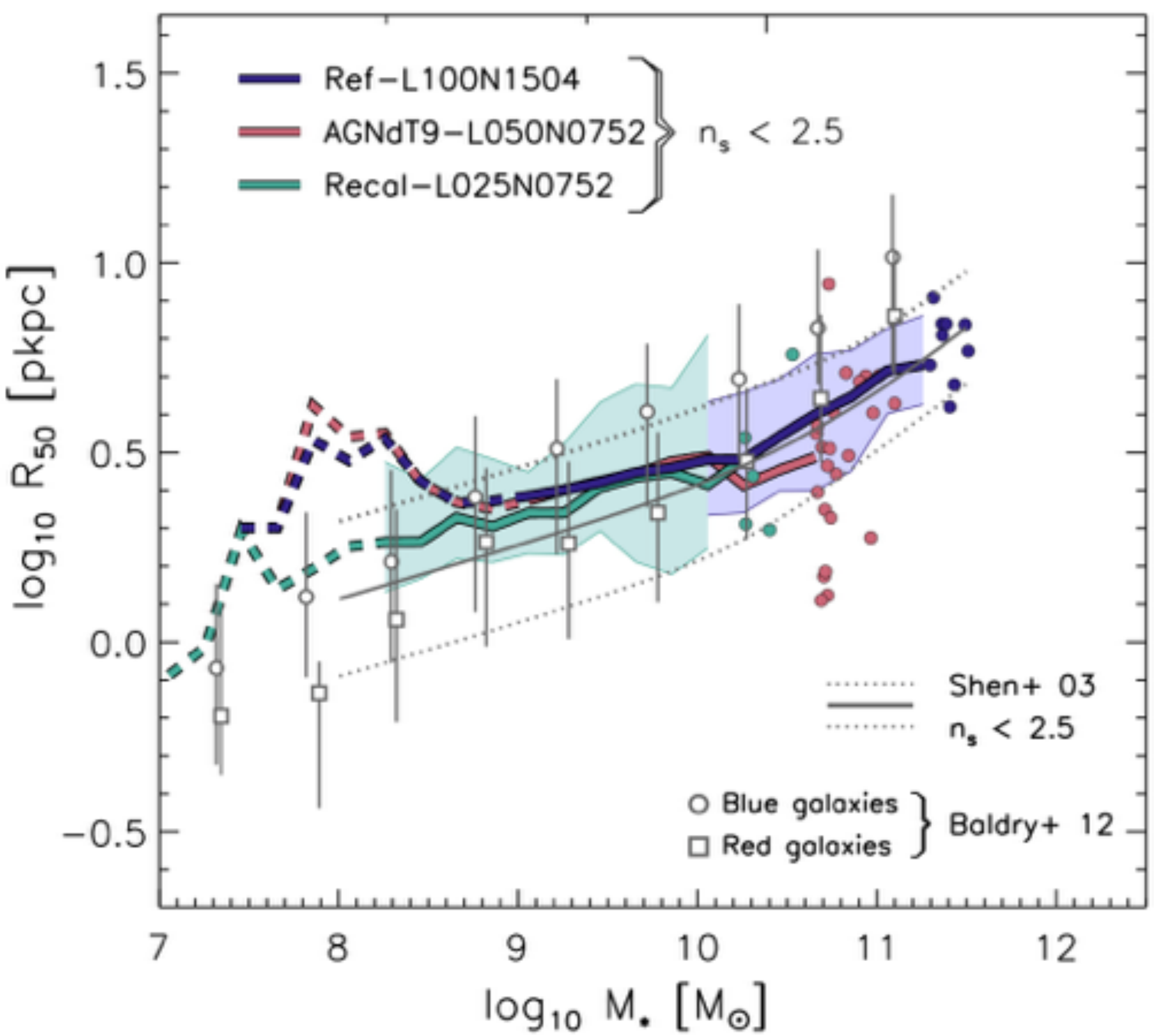
Elliptical and spiral galaxies in simulations

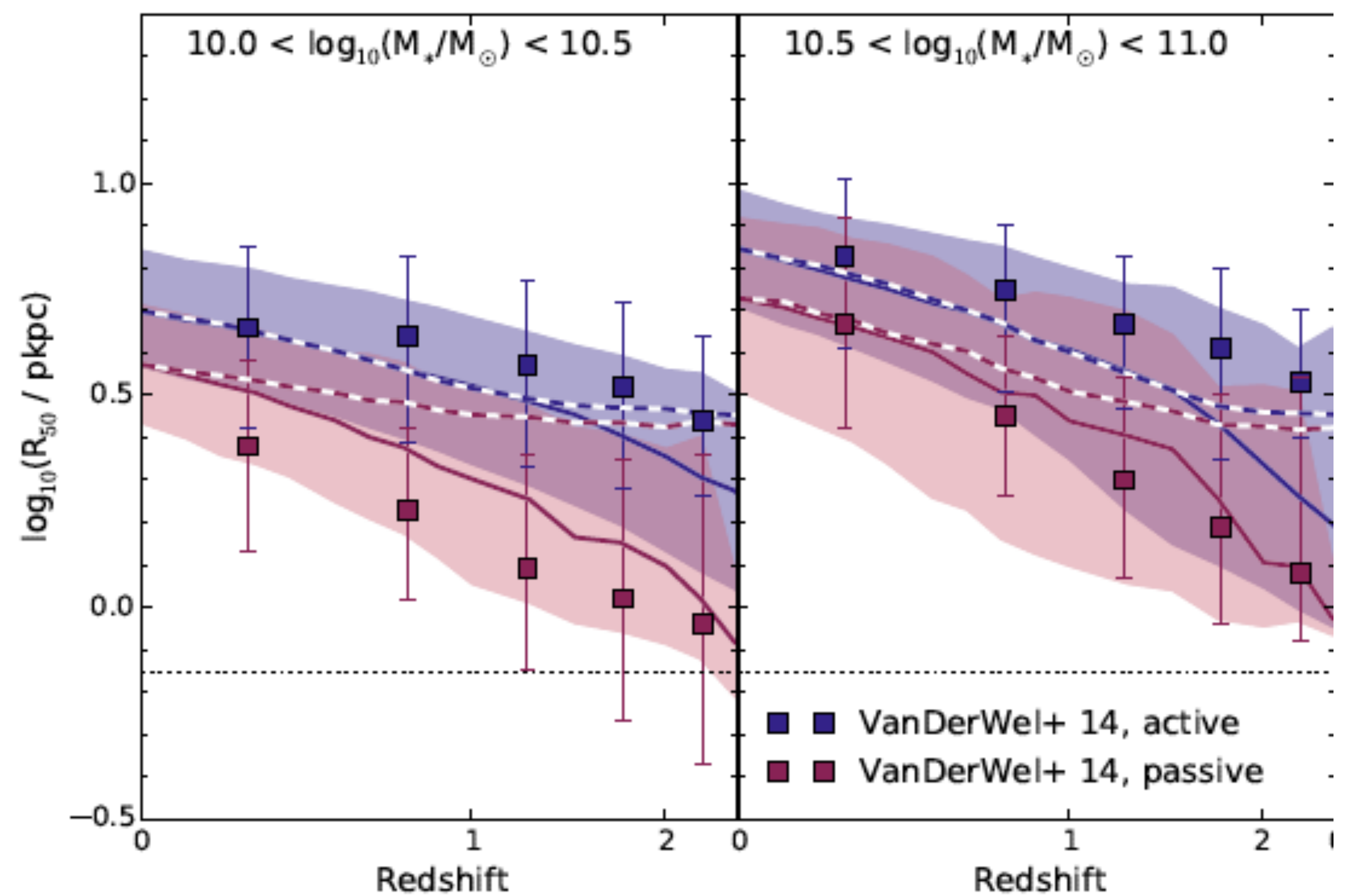
- Key processes for the formation of Spiral galaxies
- Rather quiet merger history, no major merger at late times
- Strong stellar feedback: early removal of low-angular momentum gas —> late re-accretion as high-angular momentum gas —> build-up of spiral structure

- Key processes for the formation of Elliptical galaxies
- Major mergers destroy spiral structure
- AGN feedback suppresses late gas accretion which could lead to a build-up of a young stellar disk
- Minor merger/late accretion low-mass satellites

Sizes of EAGLE

- Mass-size relation and size evolution of active/passive galaxies

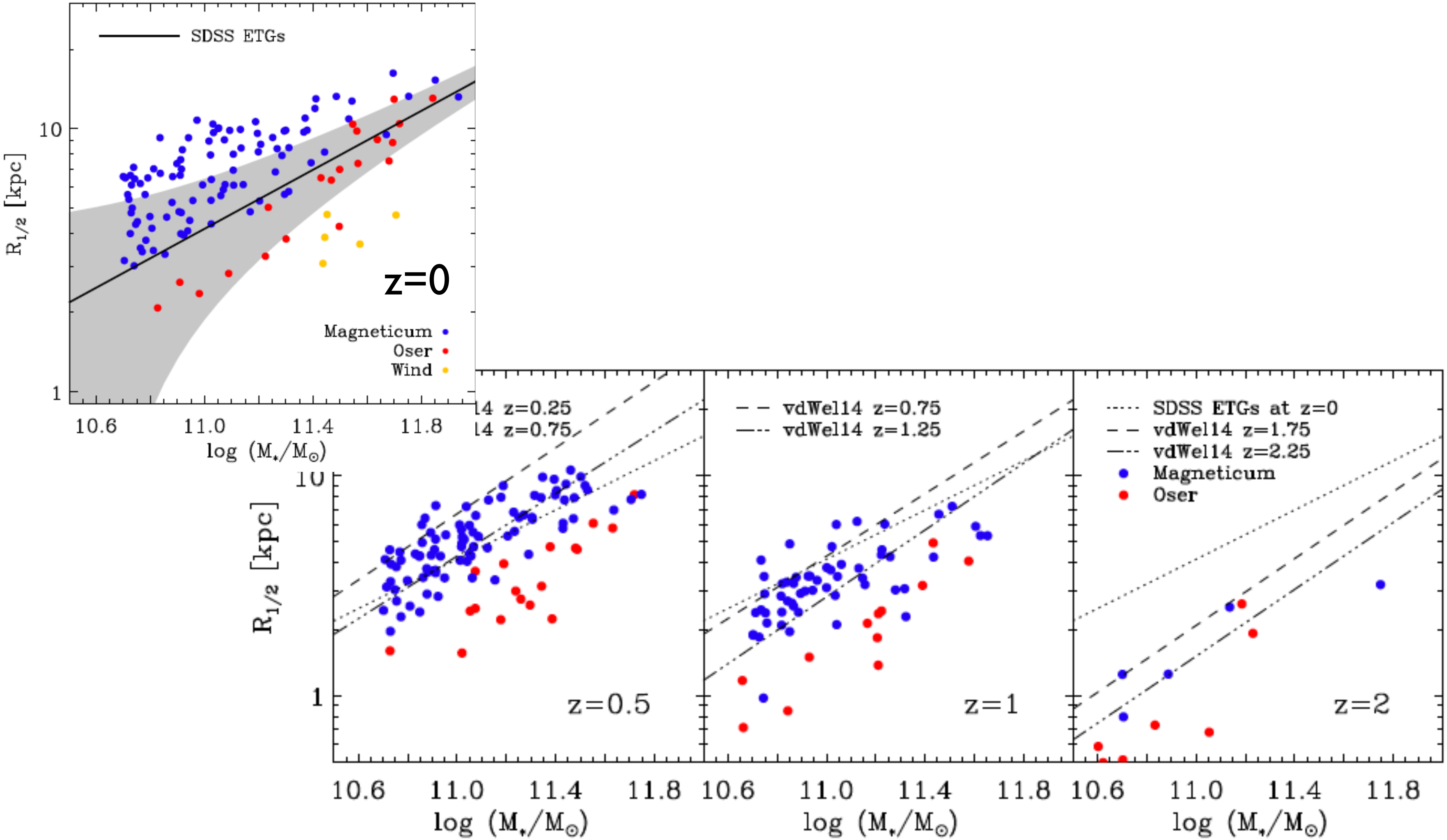




- Reference run over-predicts sizes of low-mass galaxies
- Size evolution is reproduced fairly well (role of minor mergers and SF)

Sizes of Magneticum

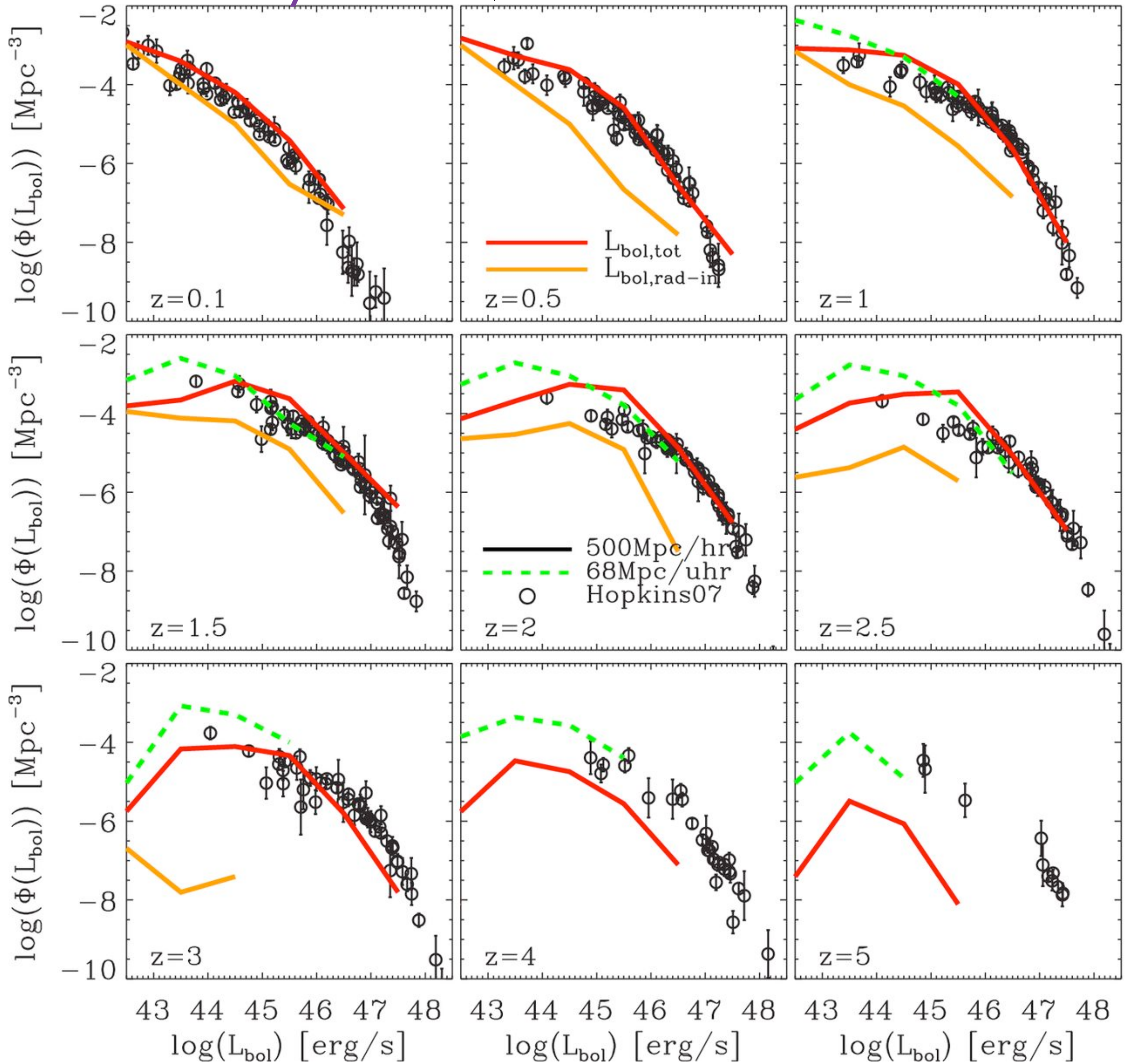
- Evolution of the mass-size relation of early-type galaxies



- Magneticum captures the observed evolution fairly well

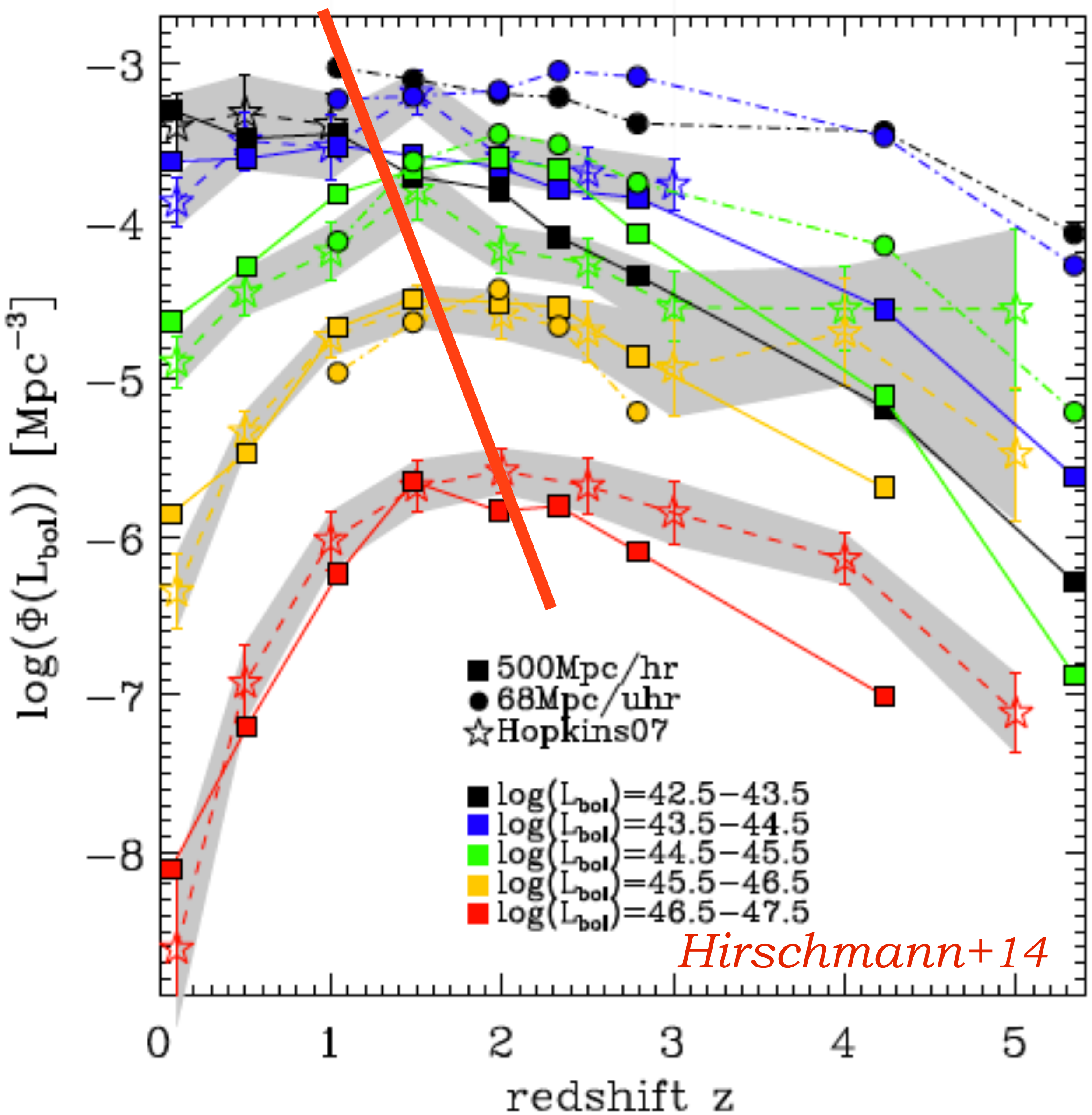
Results of Magneticum

- Evolution of AGN luminosity function, first simulation which can access the luminous end



Results of Magneticum

- Implying anti-hierarchical trend in BH growth is automatically captured



- The simplified schemes of BH accretion are able to capture the essence of BH growth in reality
- Moderately luminous AGN at low z have large contribution from massive BHs accreting way below their peak luminosities -- WHY?

Mainly gas density around the BHs governs BH accretion:

Decreasing ρ_{gas} with decreasing z & increasing M_{BH} due to SF & AGN fb

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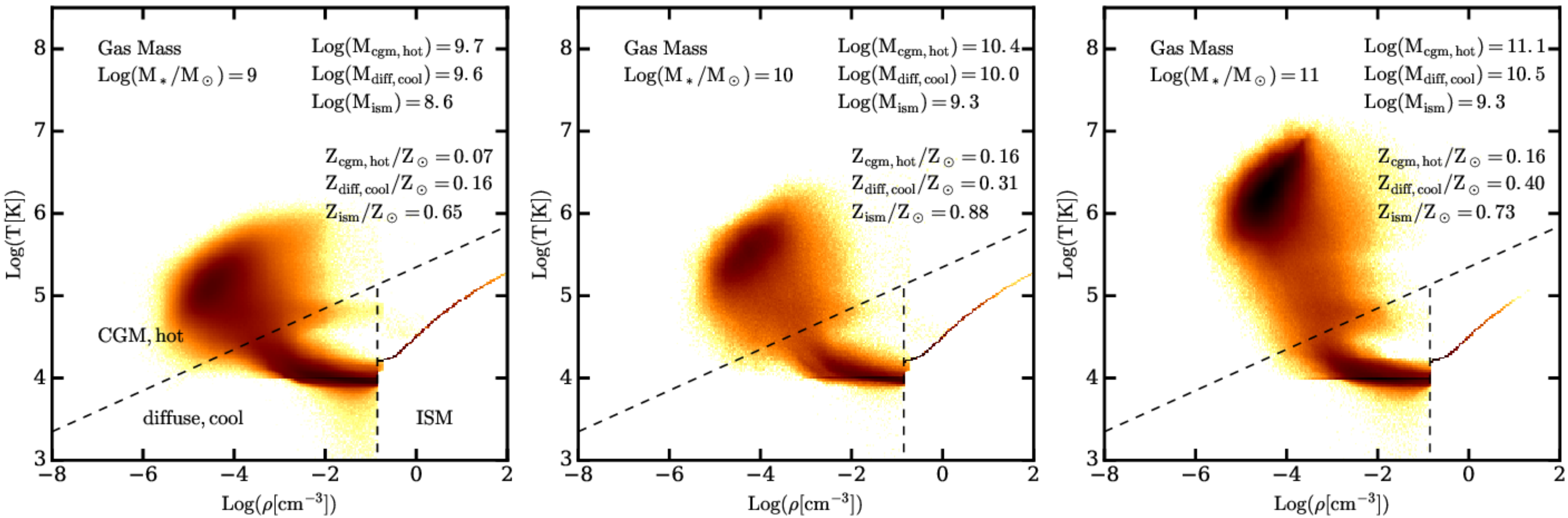
Challenges of cosmological simulations

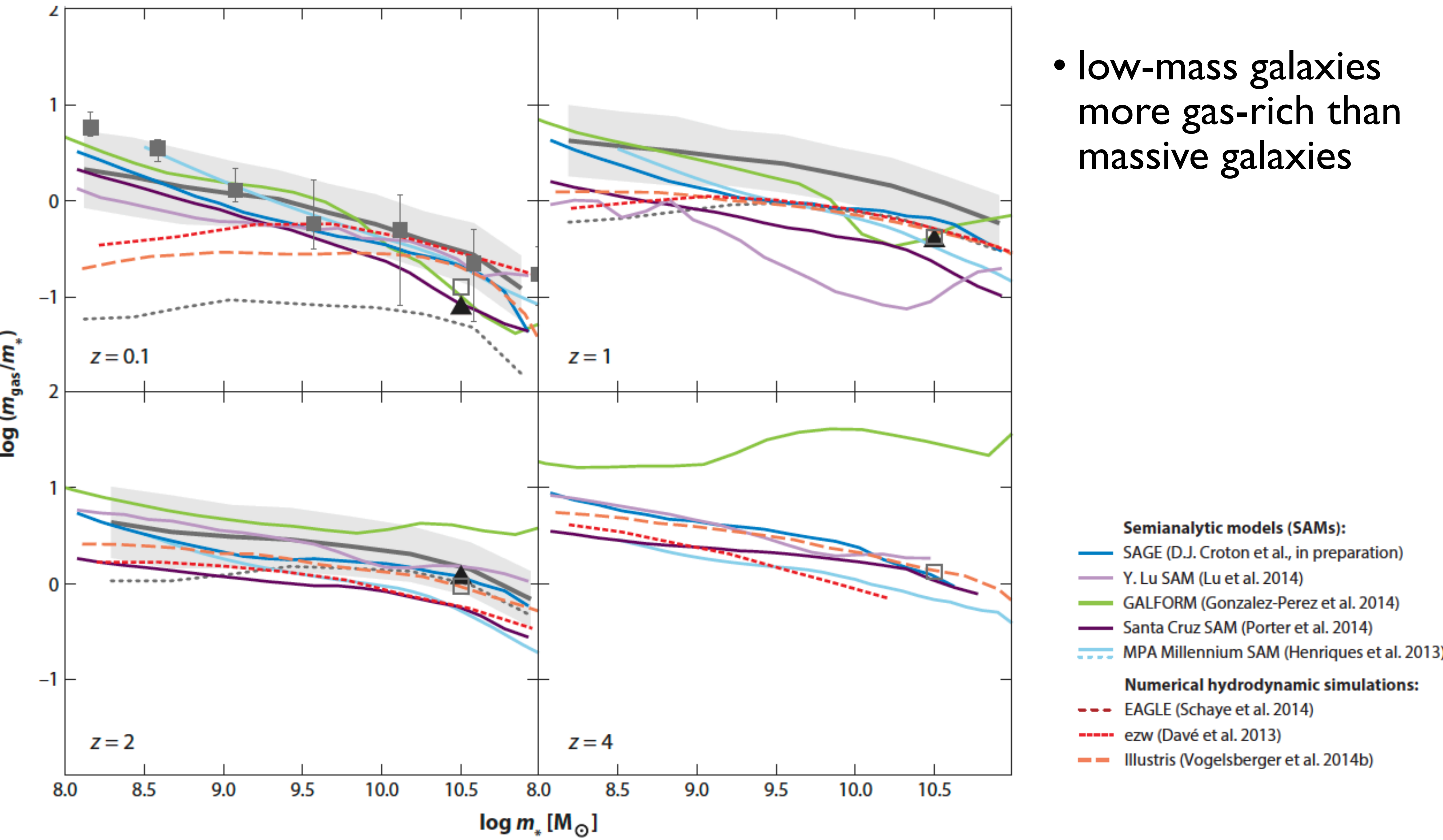
- Multi-phase ISM/Cold gas content
- Often simplified, ad-hoc sub-grid models
  - limited predictive power
  - impede a detailed understanding of the impact of some physical processes
  - large scatter in chemical enrichment history and mass metallicity relation
  - large diversity for high-redshift galaxy and BH populations
- Missing physical processes

The limited multi-phase ISM



- No gas below 100K, SF gas artificially pressurised —> unrealistic
- No realistic predictions for neutral/molecular gas

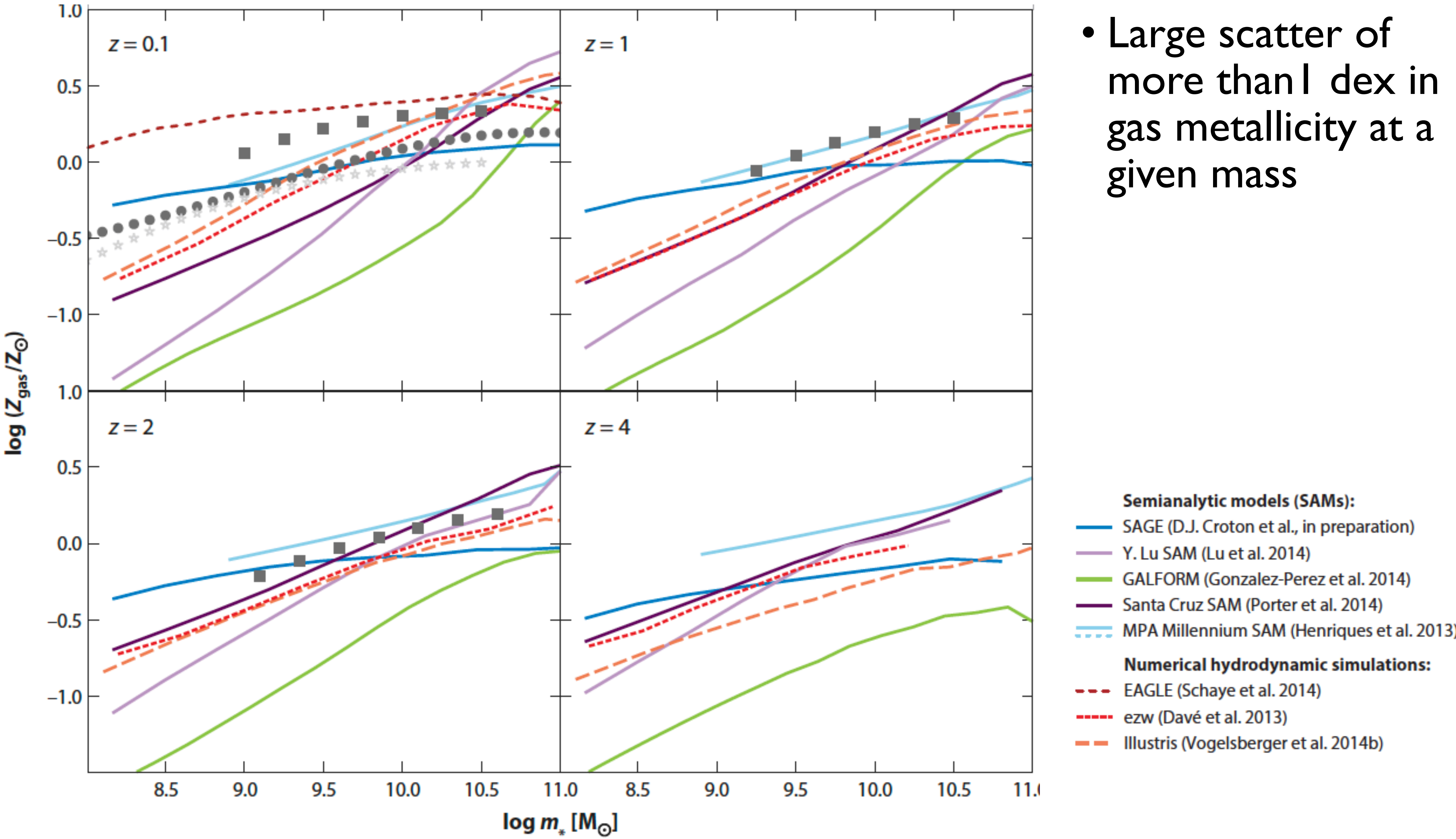
"Cold" gas fractions



- low-mass galaxies more gas-rich than massive galaxies

- Low-mass galaxies at low z in simulations too gas poor, perhaps related to stellar fb model and/or resolution

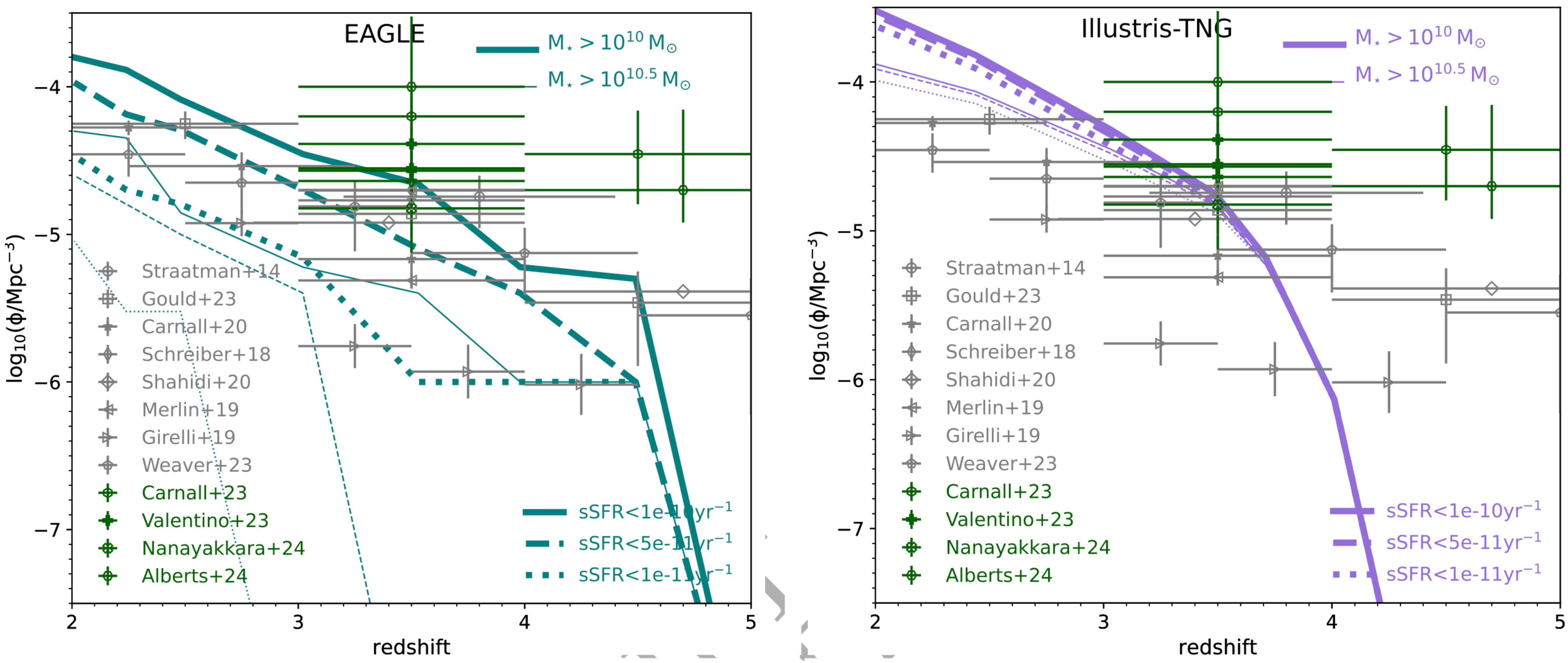
Cold gas metallicity



- Large scatter of more than1 dex in gas metallicity at a given mass

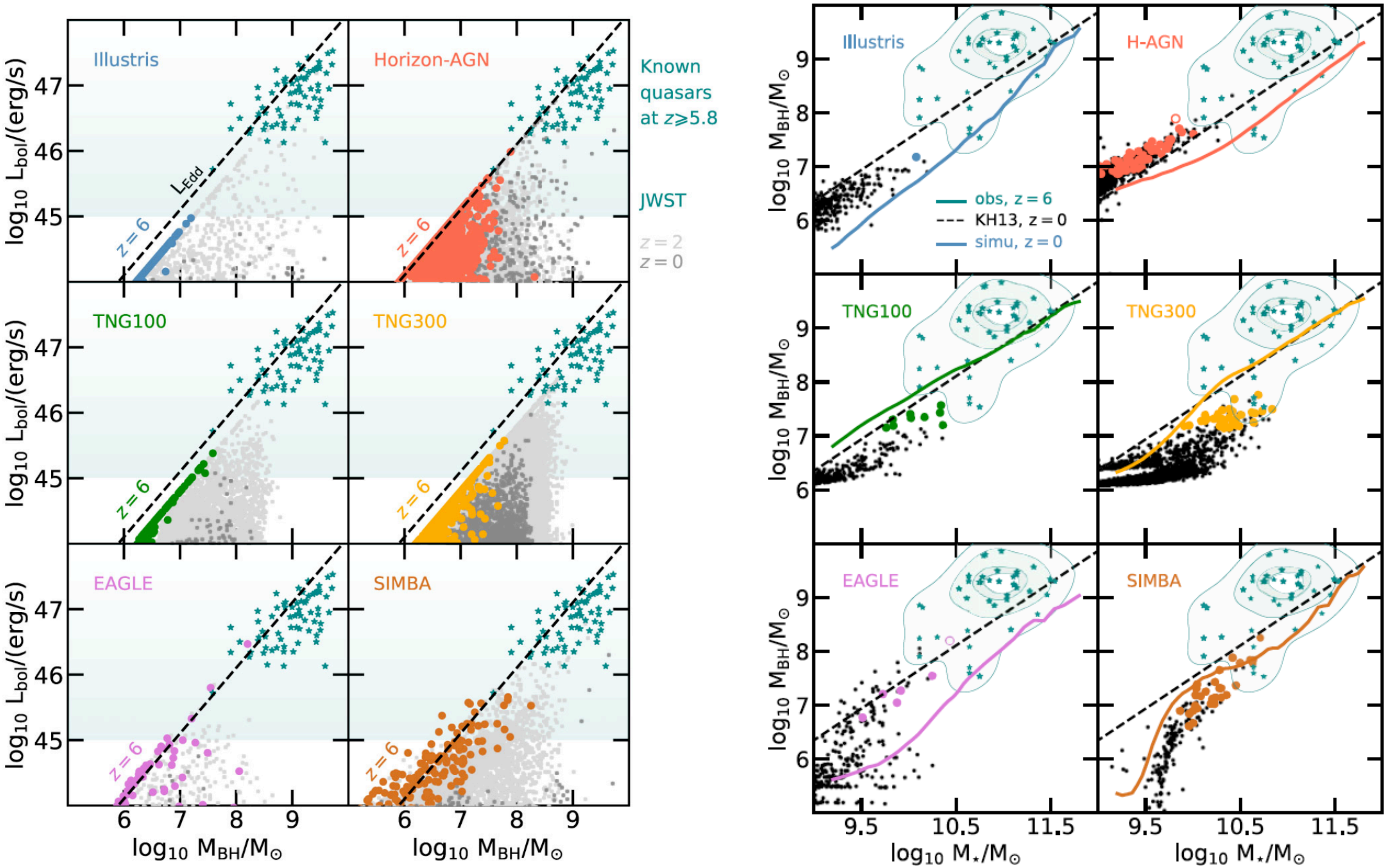
- Reflect large variety of uncertain feedback models regulating SF, in- and outflows

High-redshift galaxy populations



- Scatter in predicted number density of massive, quiescent galaxies at z>3
- No massive quiescent galaxies predicted above z~4
- How can the SF of massive galaxies be suppressed within only 2Gyrs after BB?

High-redshift black hole/AGN populations



- Reflecting uncertain, and large variety of models BH seeding, growth and feedback; how do BHs form?

Non-thermal feedback

Modelling magnetic field and cosmic ray feedback

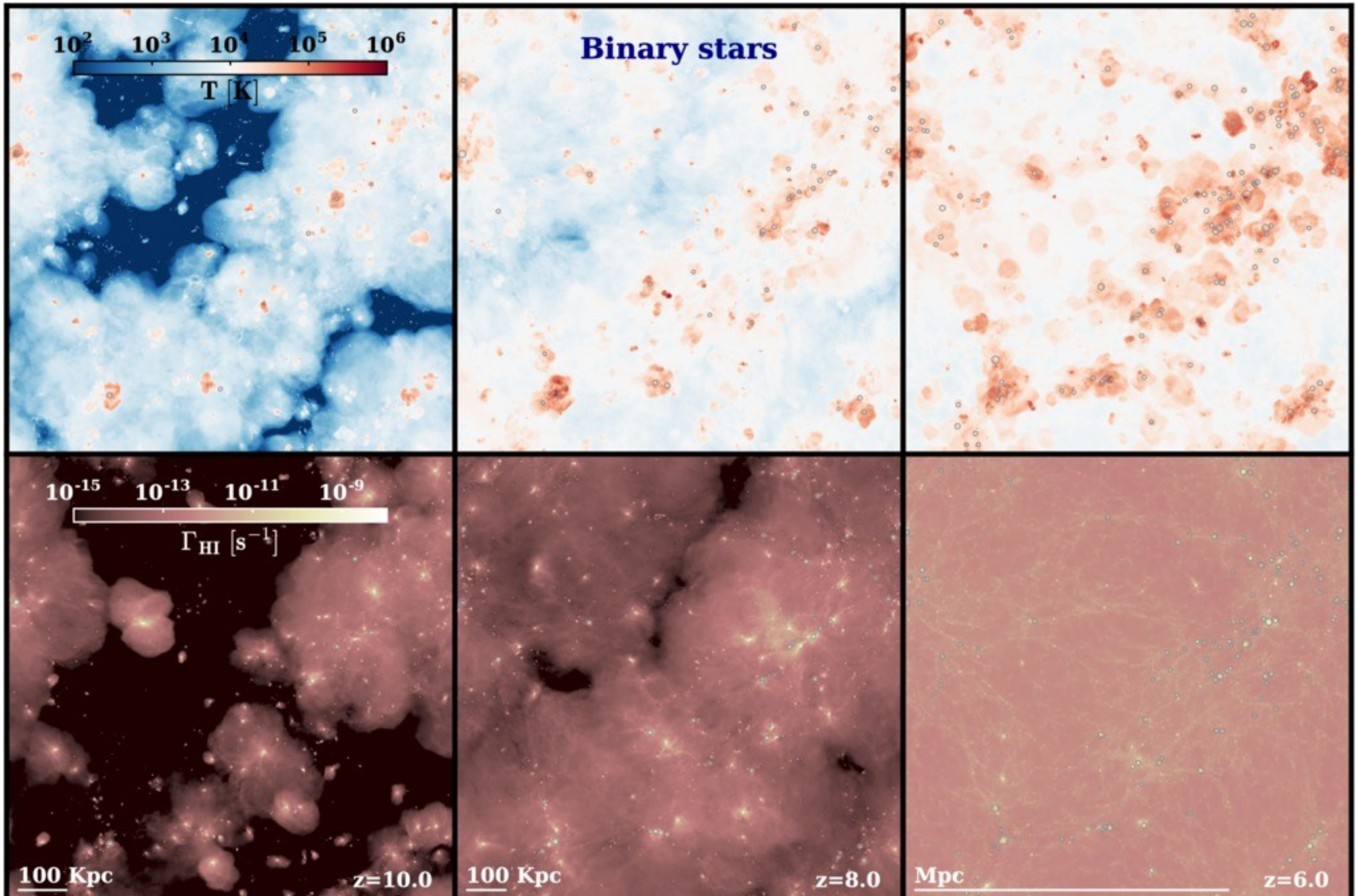
- Cosmic rays are composed of high-energy protons (and ions) produced in shocks of e.g. SN explosions, and AGN jets
    - As charged particles they move along magnetic field lines
    - Can be modelled as additional fluid
- Fraction of energy stored in cosmic rays is highly uncertain
- First simulations of isolated galaxies indicate that cosmic rays might have a non-negligible effect on driving outflows:
    - Particles can easily escape the high-dense regions and introduce a pressure gradient —> drives gas outflows
    - Excite so called "Alfven" waves (=magnetohydrodynamic wave in which ions oscillate in response to a restoring force provided by an effective tension on the magnetic field lines) which can result in some additional energy input into the surrounding gas
- Speculation: Less stellar feedback necessary if additional cosmic ray feedback added? Might that help to keep high-z disk more intact?

Radiation hydrodynamics

- **Model radiative feedback from young stars and AGN** and also the re-ionisation of Universe fully self-consistently by using radiation-hydrodynamics
- Capturing the interplay between photons and baryons by solving modified hydrodynamic equations (very complex)
- Computationally very demanding —> hardly possible to include that into cosmological simulations so far (only at high z)
- However, recent progress with GPU programming and doing simulations of the re-ionisation of the Universe, but galaxies are treated as point-like objects
- In isolated galaxies or smaller-scale simulations, radiation-hydro codes are used and the impact of feedback can be tested
- Understand the role/relevance of radiation pressure from AGN/stars, their contribution to re-ionisation of the neutral H content in the IGM!

The Sphinx simulation

The first radiation-hydro simulations to simultaneously capture large-scale reionization & the escape of ionizing radiation from 1000s of resolved galaxies



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Future directions…

- Increase the predictive power of galaxy simulations via **identifying physically motivated sub-resolution models**
  - Take advantage of accurate, high-fidelity small-scale simulations —> bright the gap to cosmological scales
  - Push towards high resolution in zooms to resolve the multi-phase medium, formation of individual stars etc (~1pc and ~10 Msolar)

- **Add often neglected physical processes**
  - Explore the role of non-thermal feedback processes, e.g. cosmic rays, in a cosmological context
  - Model radiative processes (e.g. feedback for stars and AGN) self-consistently using radiation hydrodynamics (computationally very demanding) —> Exascale computing, GPUs, improved algorithms

- Take advantage of new data from revolutionary telescopes like JWST, Euclid, Alma, etc., to **put novel, observational constraints** on uncertain processes for the formation of first galaxies out to and beyond the epoch of re-ionisation

Future directions…

Combining simulations with observations to address major outstanding questions:

- How are different feedback processes regulating the baryon cycle of galaxies over cosmic time (using spatially resolved observations)?
- Formation and evolution of faintest, dwarf galaxies? Nature of dark matter ?
- How do first galaxies form and evolve?
- How to black holes come into existence in galaxy centres?
- Next-generation observational facilities: SKA (radio), ELT, (optical-NIR), ATHENA (X-ray), LISA/ET (Grav. waves)

Exciting times ahead of us!!

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first 7 lectures

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