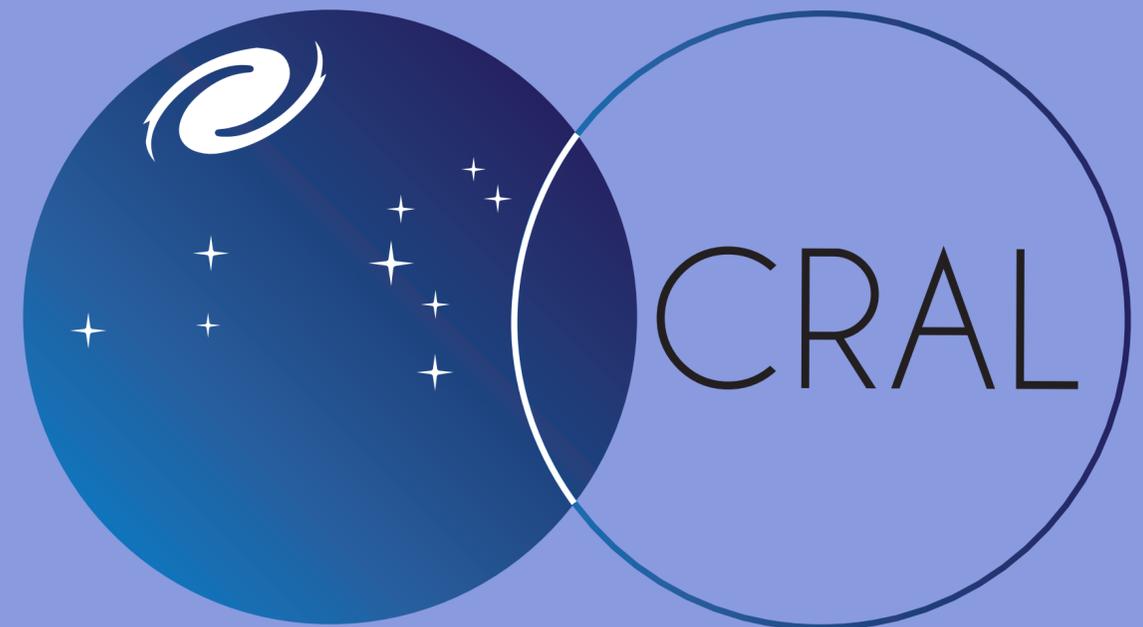# The first galaxies: cosmological simulations

Joki Rosdahl, CRAL
JWST school, ENS de Lyon, 13/01/2026

CRAL

CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

What is a galaxy?

Main ingredients

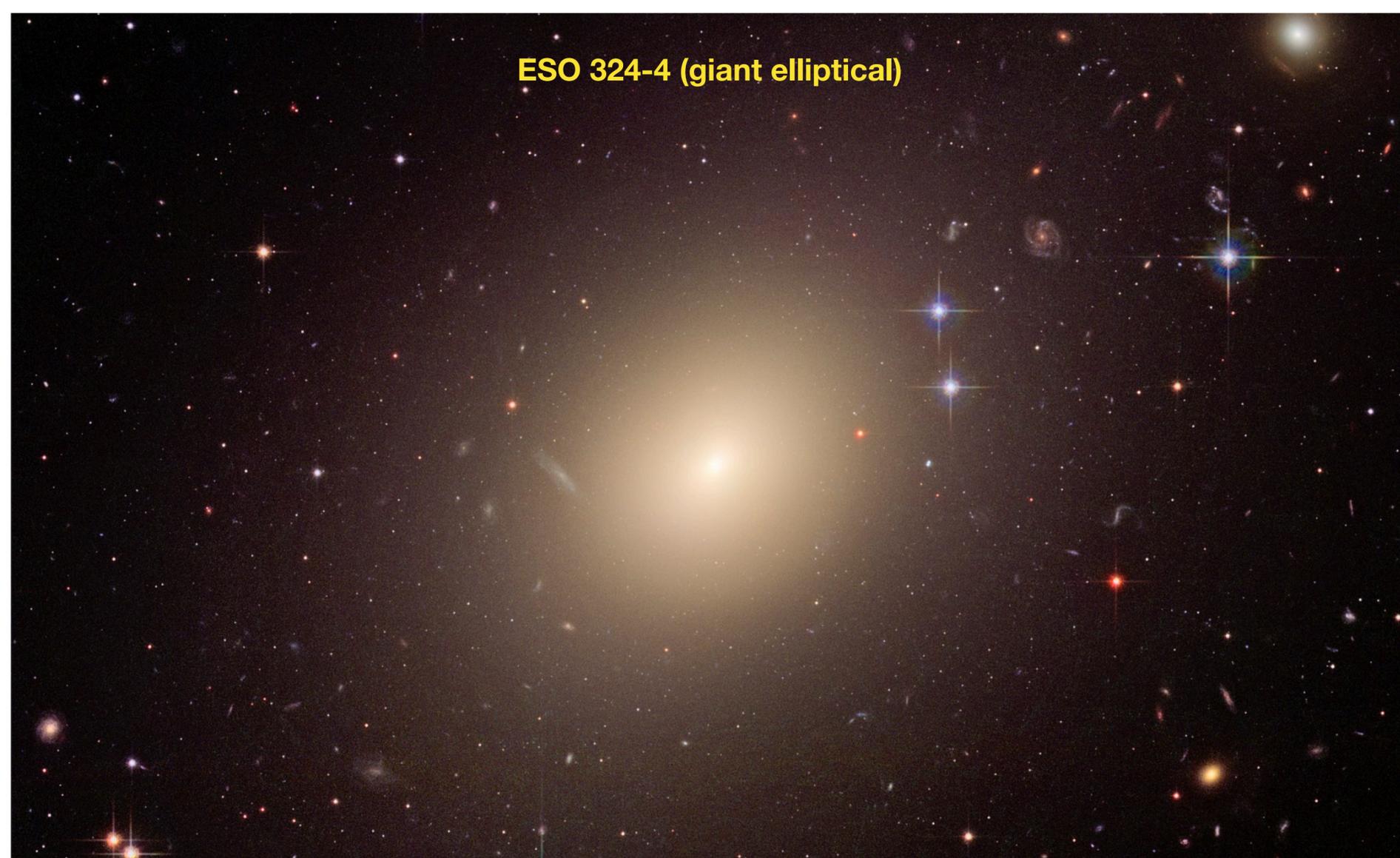# What is a galaxy?
Main ingredients

- **Gravity!**
  Holds everything together

What is a galaxy?
Main ingredients

- **Gravity!**
  Holds everything together

- **Stars** — what we see

ESO 324-4 (giant elliptical)

Andromeda (spiral)

UGC 11411 (dwarf galaxy)

What is a galaxy?
Main ingredients

- **Gravity!**
  Holds everything together

- **Stars** — what we see

- **Gas** (mostly hydrogen and helium) fuels star formation. Re-emits stellar radiation (Lyα, Hα)
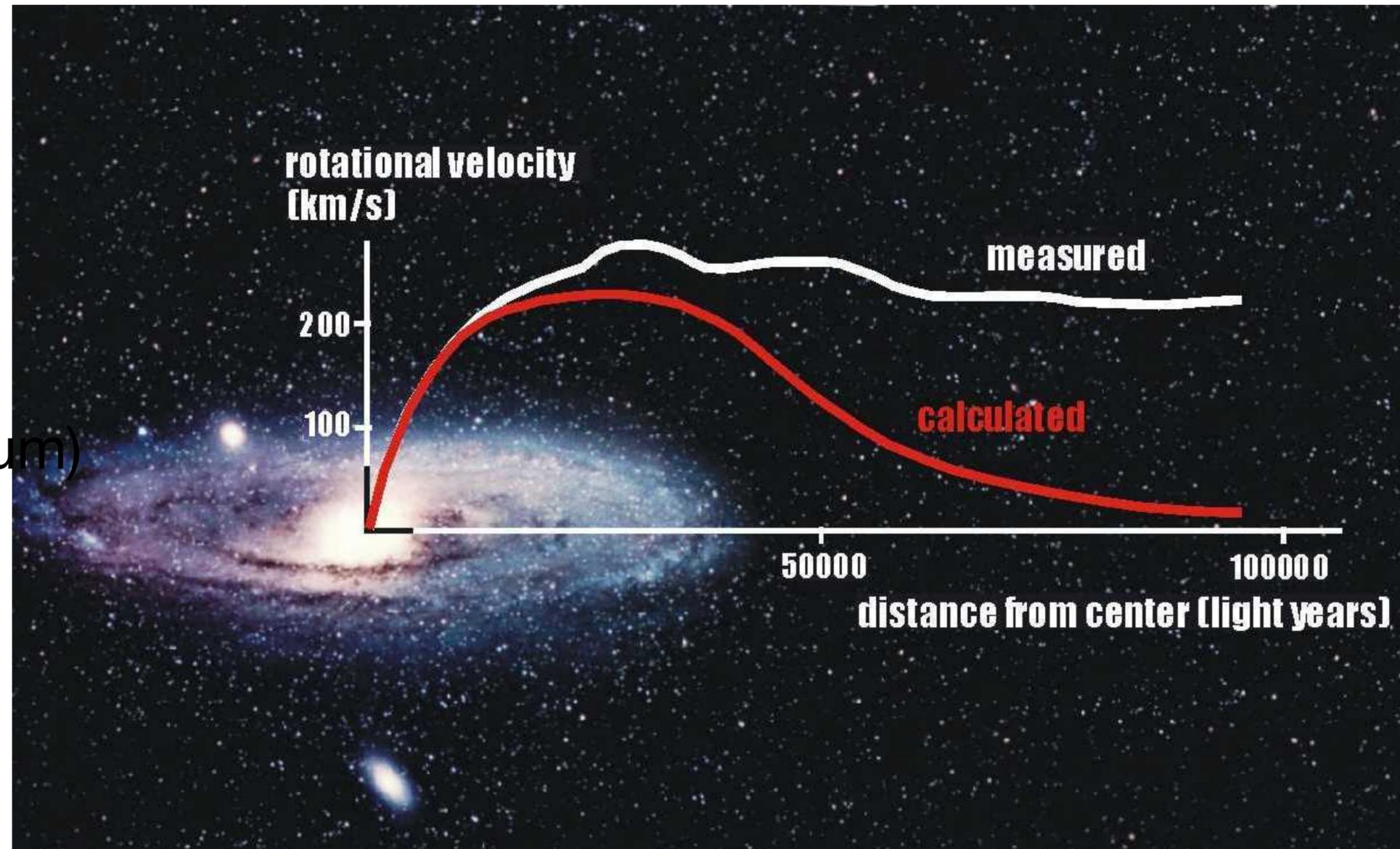
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- **Dark matter** halo
  Roughly 5/6th of the mass!
  But we don't know what it is!

What is a galaxy?
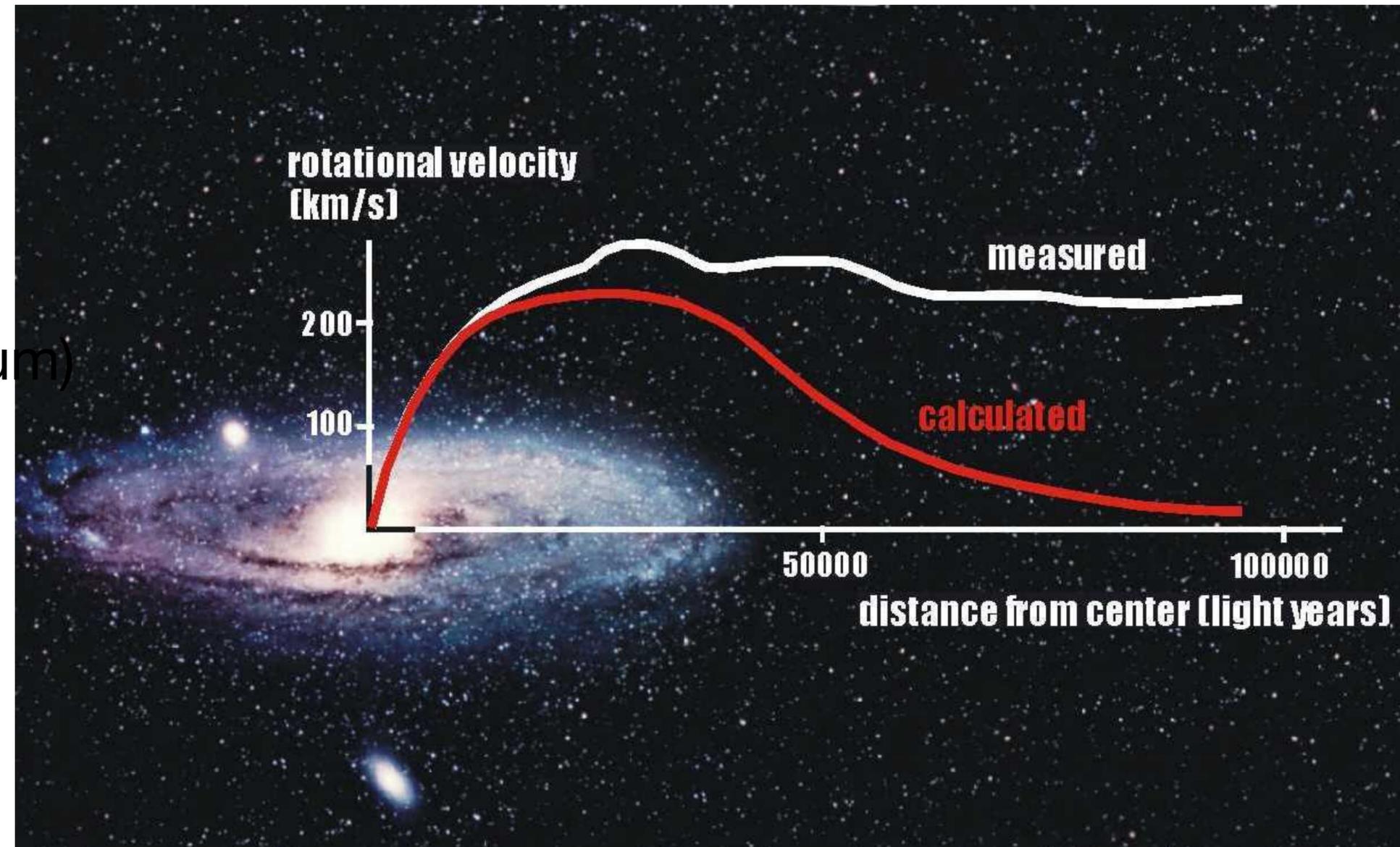
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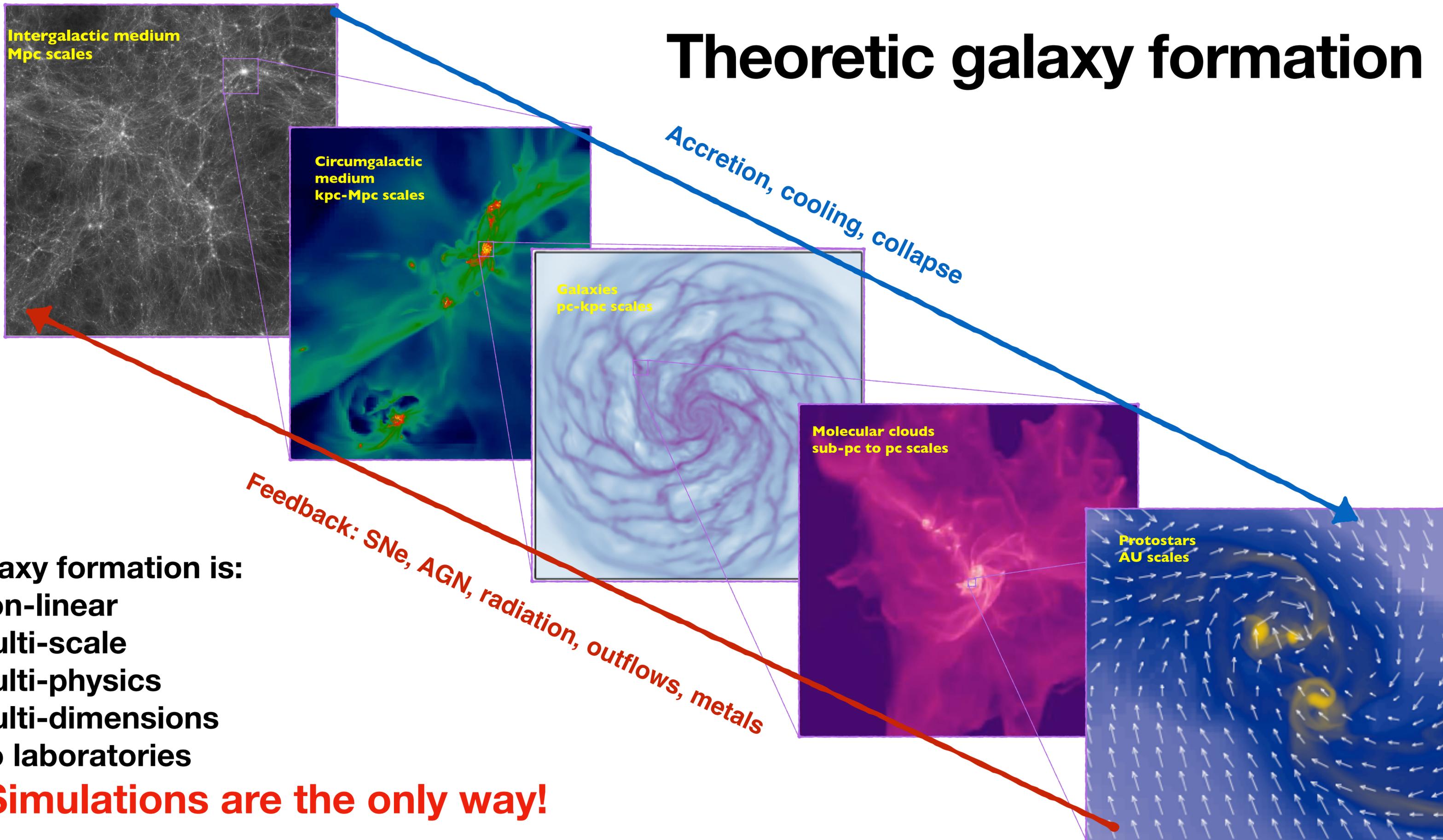 Roughly 5/6th of the mass!
  But we don't know what it is!

- Also black holes, dust, planets, ….

Theoretic galaxy formation

Intergalactic medium
Mpc scales

Circumgalactic
medium
kpc-Mpc scales

Galaxies
pc-kpc scales

Molecular clouds
sub-pc to pc scales

Protostars
AU scales

Accretion, cooling, collapse

Feedback: SNe, AGN, radiation, outflows, metals

Galaxy formation is:
· Non-linear
· Multi-scale
· Multi-physics
· Multi-dimensions
· No laboratories
➡ Simulations are the only way!

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4. Towards higher resolution and more physics

5. Reionization simulations

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8. Mock observations

First-order (and first) galaxy formation simulations

- To first-order, galaxy evolution is described by gravity

$$\vec{a}_i = -G \sum_{\substack{j=1 \\ j \neq i}}^{N} m_j \frac{\vec{r}_i - \vec{r}_j}{|\vec{r}_i - \vec{r}_j|^3}$$

- To simulate a galaxy, you integrate for each body:

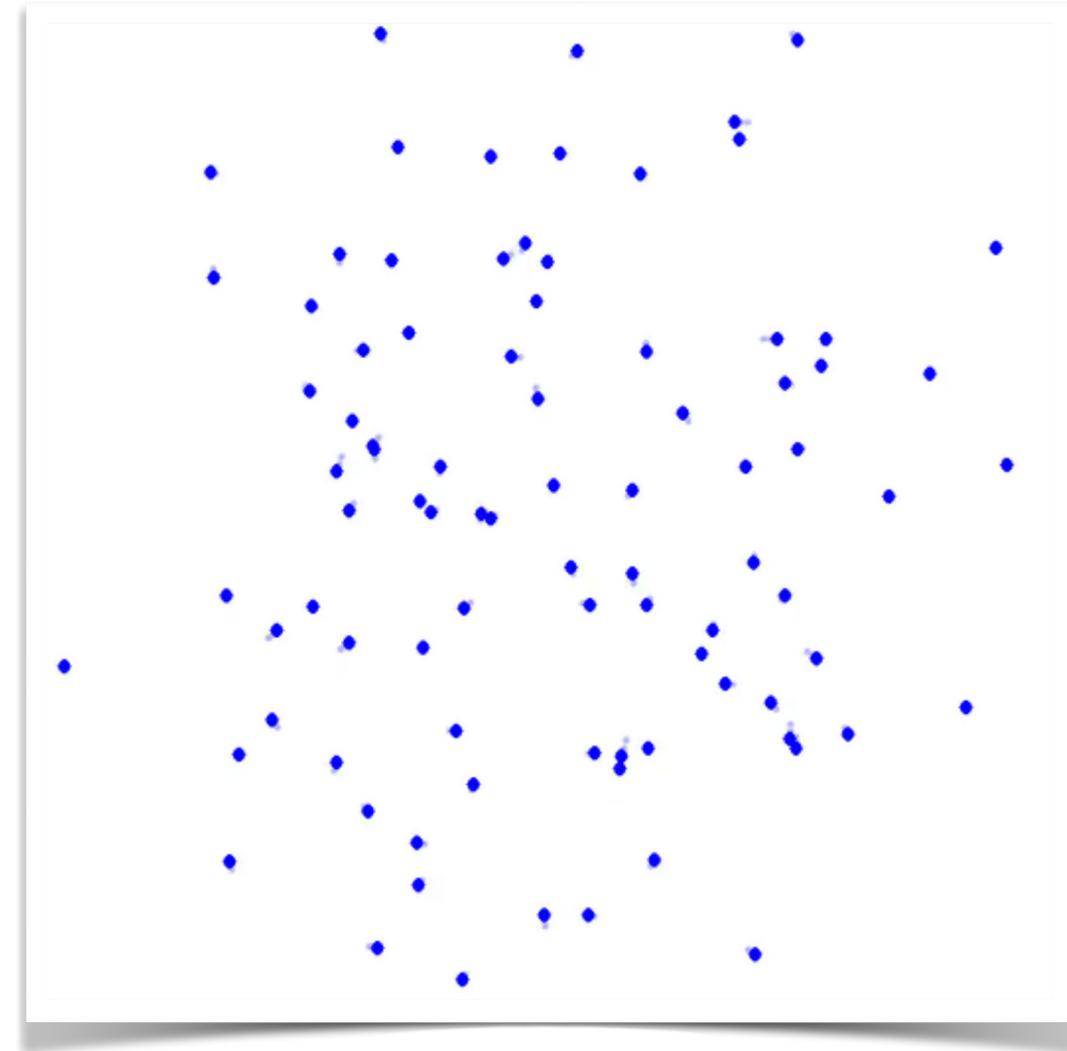$$\frac{d\vec{x}_i}{dt} = \vec{v}_i \qquad \frac{d\vec{v}_i}{dt} = \vec{a}_i$$

- e.g. with the *leap-frog scheme*:

$$\vec{v}_i\left(t + \frac{\Delta t}{2}\right) = \vec{v}_i(t) + \frac{\Delta t}{2} \cdot \vec{a}_i(t)$$

$$\vec{x}_i(t + \Delta t) = \vec{x}_i(t) + \Delta t \cdot \vec{v}_i\left(t + \frac{\Delta t}{2}\right)$$

$$\vec{a}_i(t + \Delta t) = \text{compute from } \vec{x}_i(t + \Delta t)$$

- Trivial, but N² force calculations $$\vec{v}_i(t + \Delta t) = \vec{v}_i(t + \frac{\Delta t}{2}) + \frac{\Delta t}{2} \cdot \vec{a}_i(t + \Delta t)$$

The first galaxy simulation
In 1941, with lightbulbs!

- The first documented N-body 'simulation' of galaxies was performed by Eric Holmberg in 1941

- Instead of a computer, he used 74 lightbulbs

  - Light flux $\propto r^{-2}$, just like gravity, so 'easy' to sum up forces

- Studied the effects of galaxy mergers on clustering and the formation of spiral arms
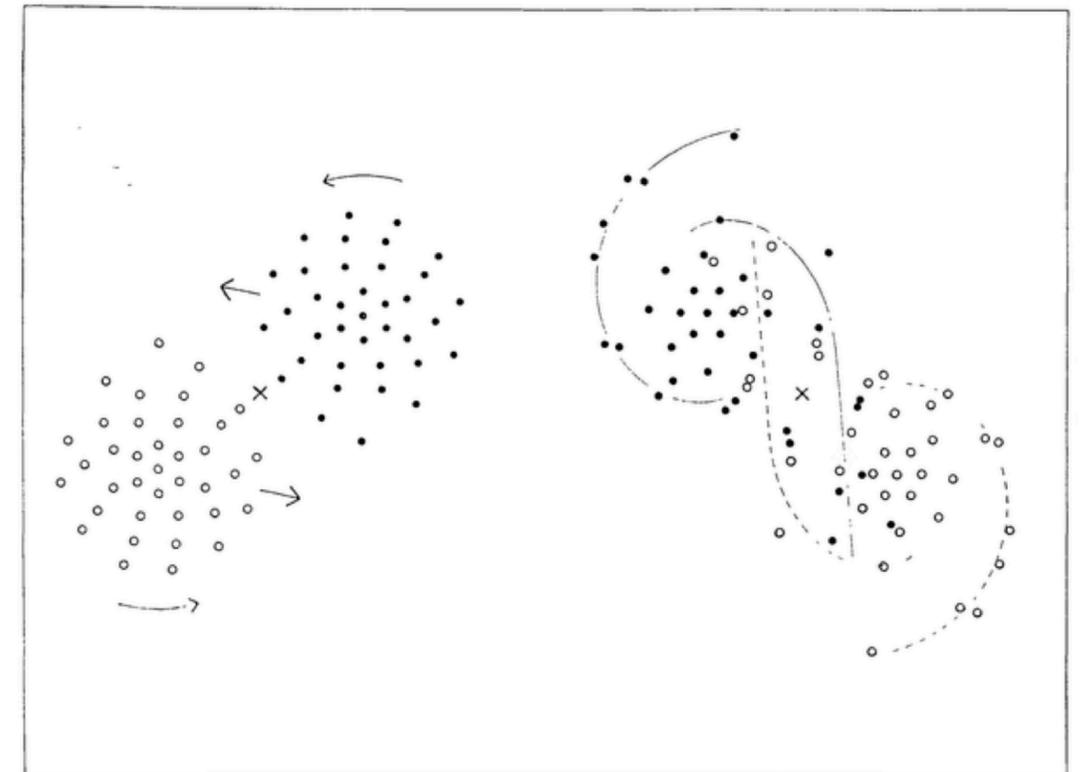
From Holmberg (1941)

The first simulations
From lightbulbs to computers

- Pure N-body, meaning particle-based and gravity only
- Non-cosmological

| Year	Name	Method	Description
1941	**Holmberg**	Analog (light bulbs)	First N-body galaxy interaction model
1960s	Von Hoerner	Digital (~10 particles)	First computer-based star cluster simulations
1968	Miller & Prendergast	Digital (~100 particles)	Bar formation in galaxies
1972	Toomre & Toomre	Restricted N-body	First realistic galaxy merger modeling

The first simulations
Towards cosmological simulations

- Cosmological N-body simulations with initial density fluctuations (random -> CDM)

- Demonstrated how tiny density fluctuations evolve into a cosmic web of galaxy clusters

Year	Researcher(s)	Particles	Significance
1970	Peebles	~300	First cosmological N-body simulation; showed clustering from small fluctuations
1979	Aarseth, Gott & Turner	~1000	Simulated galaxy clustering in an expanding universe
1981	Efstathiou & Eastwood	~10,000+	Efficient simulation of dark matter structure formation
1985	Efstathiou et al.	~64^3	Helped establish CDM as the leading model for large-scale structure

80s and 90s

- $\Lambda\mathrm{CDM}$ becomes established, better computational methods are developed, computers become bigger and faster

- Baryons enter the game and the **overcooling problem** is identified:
  without strong feedback, stellar populations form too efficiently
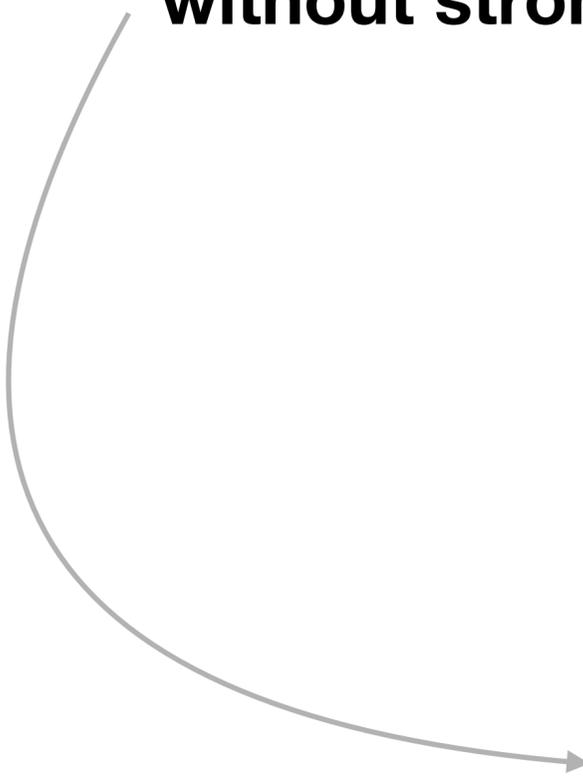
Year	Work / Group	Contribution
1986	Barnes & Hut	Introduced fast hierarchical tree code
1988	Efstathiou et al. (Virgo)	Large SCDM simulations, clustering statistics
1993	Davis, Efstathiou, Frenk & White	Seminal CDM structure formation simulation
1994	Katz, Hernquist & Weinberg	Early hydrodynamic simulations
1998	Jenkins et al. (Virgo)	Halo mass function, dark matter halo properties

Millennium simulation
in 2005

- **10 billion** DM particles

- Big success of (pure dark matter) cosmological simulations in reproducing the distribution of galaxies around us
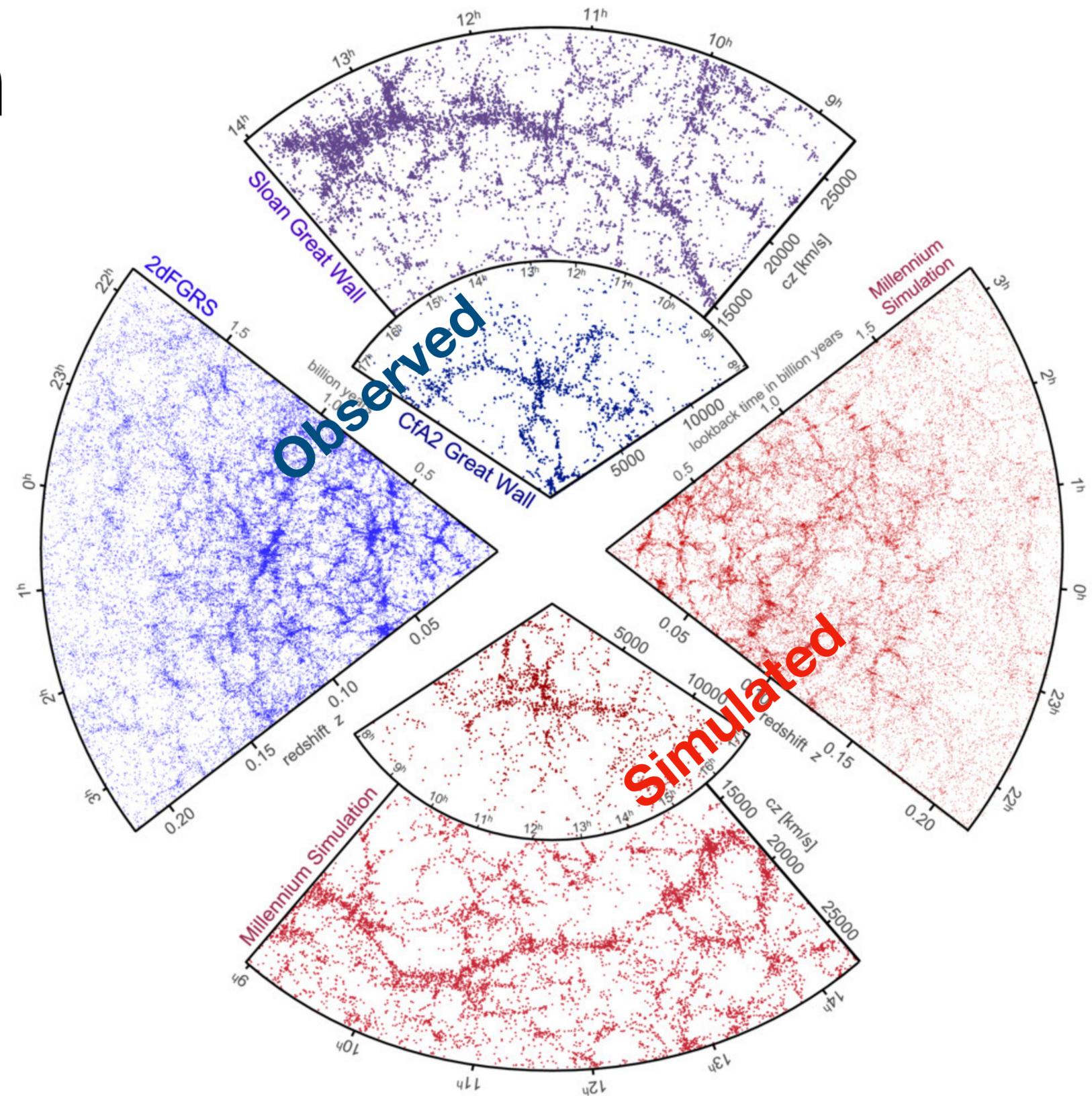
Springel+(2006)

2010s

- Era of cosmological **hydrodynamical** simulations

- 100 cMpc wide volumes with tens of thousands of galaxies

- Resolution of kiloparsecs and
$$10^4 - 10^7 \, M_\odot$$

- Great efforts to develop **sub-grid models** to overcome overcooling and reproduce observables, e.g:

     -SFR density
     -Stellar mass function
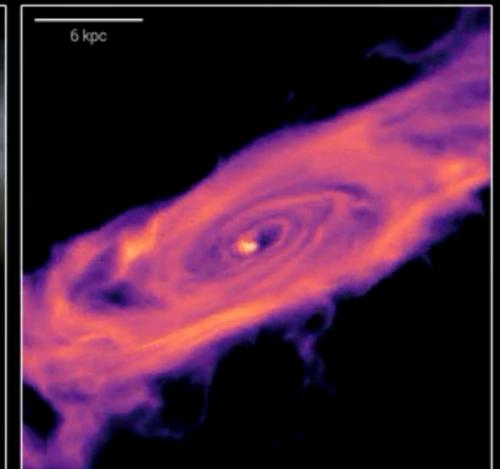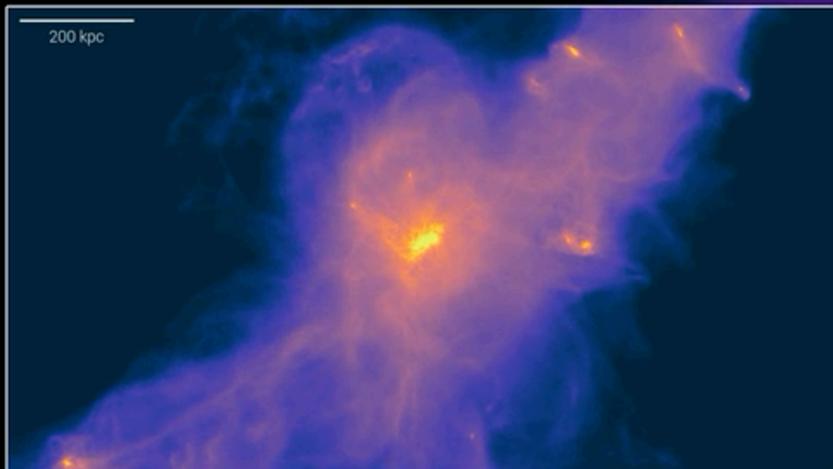   -Kennicutt-Schmidt
     -Stellar mass to halo mass
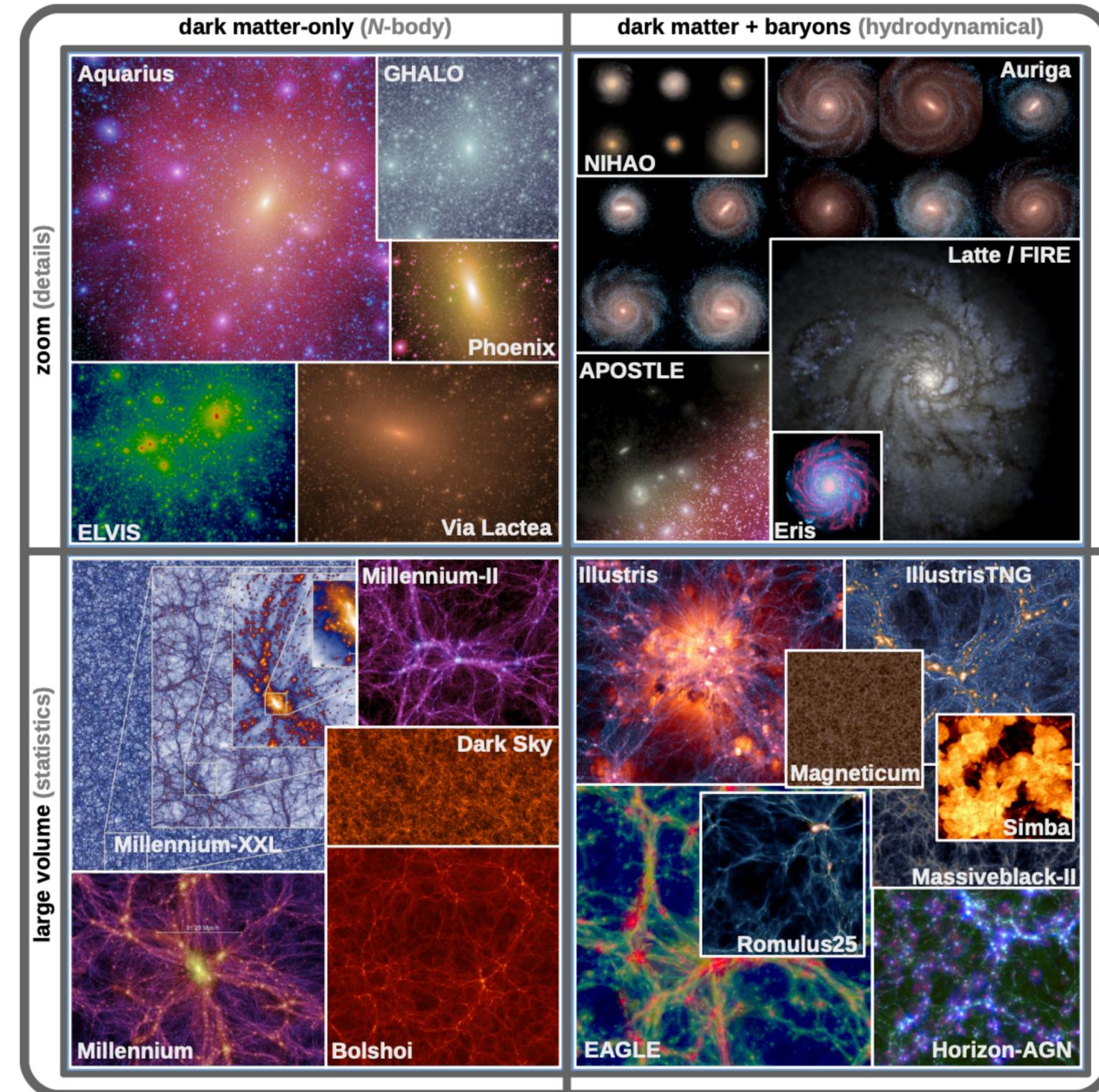
60 kpc

z = 0.58

Illustris TNG (Pillepich+18)

log M$_\star$ = 10.52

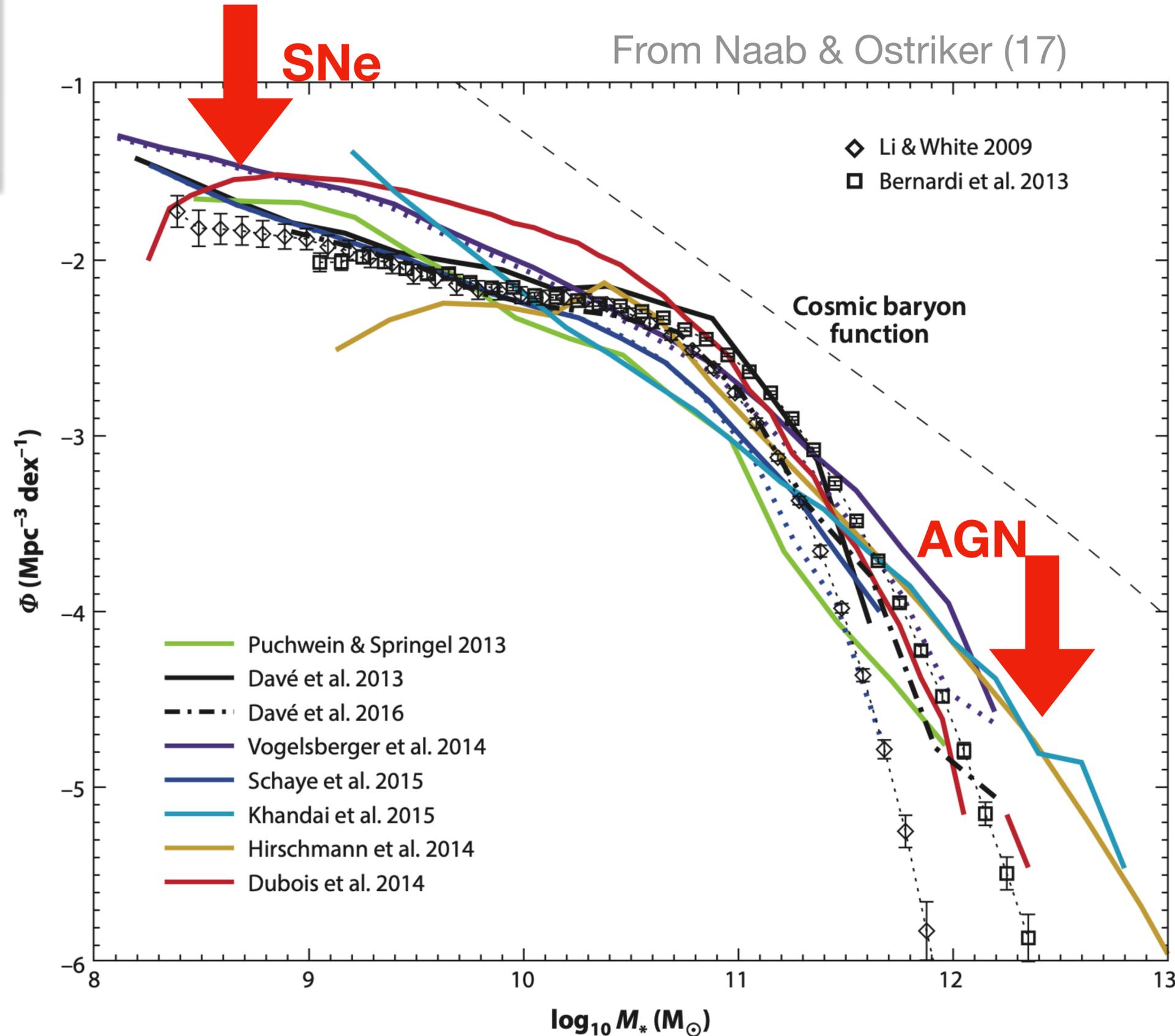SFR = 6.8 M$_\odot$ yr^{-1}

TNG50

200 kpc

6 kpc

Calibration

(the name you cannot name)

- With unresolved ISM, sub-grid models are *calibrated* to match observables — mainly the **inefficiency of star formation**

- It helps for understanding but unclear whether it masks lack of resolution or physics (see Schaye+15)

- It can take the *wrong* way to the *right* solution

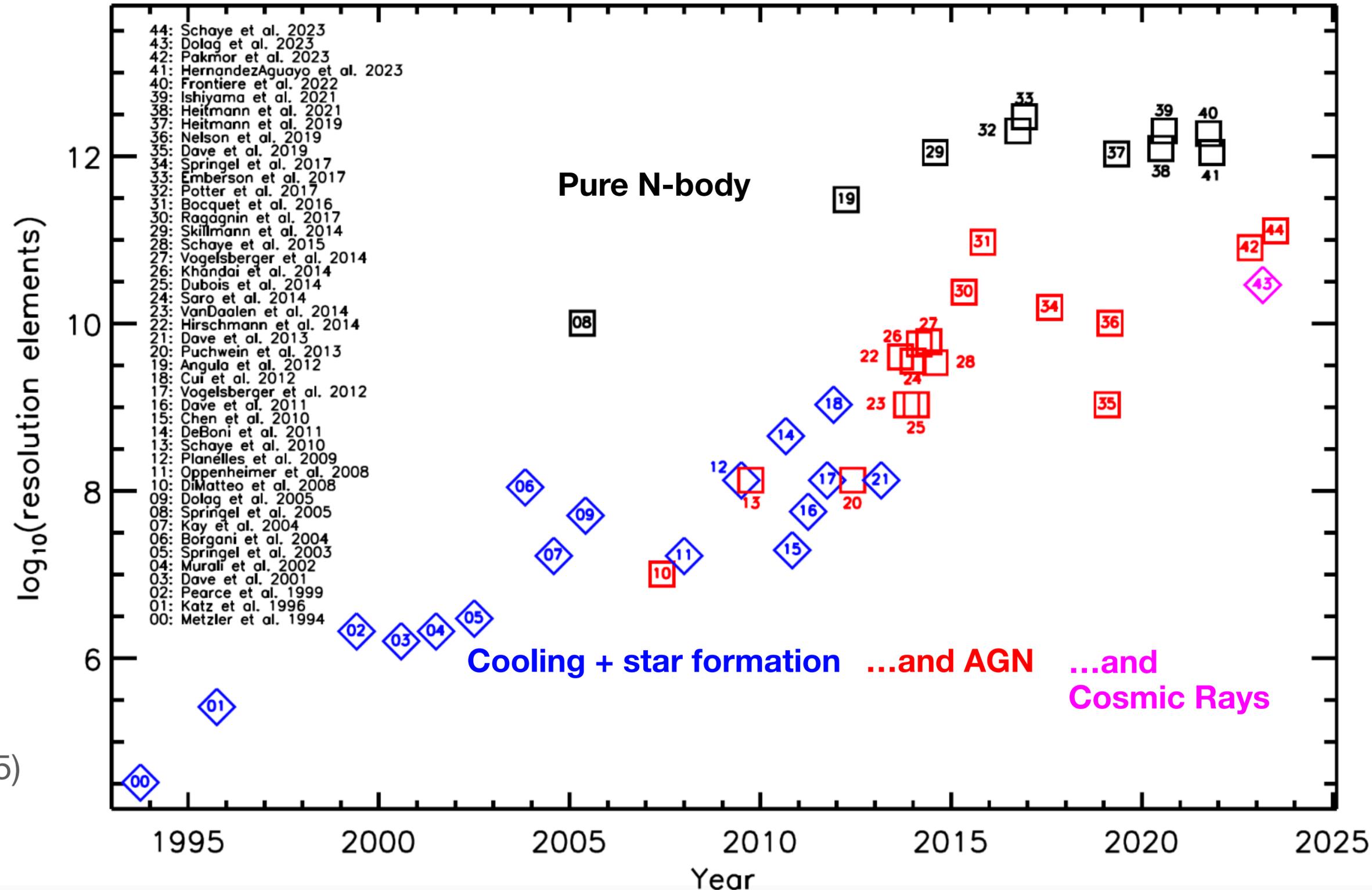- It is necessary, but (hopefully) decreasingly so with increased resolution

From Naab & Ostriker (17)

SNe

AGN

Cosmic baryon function

◇ Li & White 2009
▢ Bernardi et al. 2013

— Puchwein & Springel 2013
— Davé et al. 2013
-·- Davé et al. 2016
— Vogelsberger et al. 2014
— Schaye et al. 2015
— Khandai et al. 2015
— Hirschmann et al. 2014
— Dubois et al. 2014

Φ (Mpc^{-3} dex^{-1})

$\log_{10} M_*$ (M$_\odot$)

Improvements in methods and computational resources

This evolution is driven by:

- Increase in computational power

- Better computational methods and parallelism

From Valentini & Dolag (2025)

44: Schaye et al. 2023
43: Dolag et al. 2023
42: Pakmor et al. 2023
41: HernandezAguayo et al. 2023
40: Frontiere et al. 2022
39: Ishiyama et al. 2021
38: Heitmann et al. 2021
37: Heitmann et al. 2019
36: Nelson et al. 2019
35: Dave et al. 2019
34: Springel et al. 2017
33: Emberson et al. 2017
32: Potter et al. 2017
31: Bocquet et al. 2016
30: Ragagnin et al. 2017
29: Skillmann et al. 2014
28: Schaye et al. 2015
27: Vogelsberger et al. 2014
26: Khandai et al. 2014
25: Dubois et al. 2014
24: Saro et al. 2014
23: VanDaalen et al. 2014
22: Hirschmann et al. 2014
21: Dave et al. 2013
20: Puchwein et al. 2013
19: Angula et al. 2012
18: Cui et al. 2012
17: Vogelsberger et al. 2012
16: Dave et al. 2011
15: Chen et al. 2010
14: DeBoni et al. 2011
13: Schaye et al. 2010
12: Planelles et al. 2009
11: Oppenheimer et al. 2008
10: DiMatteo et al. 2008
09: Dolag et al. 2005
08: Springel et al. 2005
07: Kay et al. 2004
06: Borgani et al. 2004
05: Springel et al. 2003
04: Murali et al. 2002
03: Dave et al. 2001
02: Pearce et al. 1999
01: Katz et al. 1996
00: Metzler et al. 1994

Pure N-body

Cooling + star formation   ...and AGN   ...and Cosmic Rays

So where are we now?

- 10 years ago, everything seemed more or less solved

- But not really:

  - Resolution is ~kiloparsecs — the ISM is unresolved!

  - Sub-grid models, calibrated to z=0 and physics not understood

  - There were disagreements with high-z observations, which have been highlighted further with JWST observations

- With higher resolution and less calibration, simulations struggle more and more

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(Gravity and) Euler equations of hydrodynamics

Conservation of

- Mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$\rho = \text{density}$
$\mathbf{v} = \text{velocity}$

- Momentum

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \rho \mathbf{v}(\nabla \cdot \mathbf{v}) + \nabla P = -\rho \nabla \Phi$$

$P = \text{pressure}$
$\Phi = \text{grav . potential}$

- Energy

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[(E + P)\mathbf{v}\right] = -\rho \mathbf{v} \cdot \nabla \Phi + \Lambda$$

$E = \text{Total energy density}$
$\Lambda = \text{cooling}$

$$E = \frac{1}{2}\rho |\mathbf{v}|^2 + \varepsilon$$

$\varepsilon = \text{internal energy density}$

- Eq of state

$$P = (\gamma - 1)\varepsilon$$

$\gamma = \text{adiabatic index}$

Lagrangian vs Eulerian

- This is for the gas — DM and stars are always Lagrangian

- A combination is also possible

➡ Moving Mesh (Arepo — TNG simulations)

➡ ..and meshless methods (e.g. Gizmo — FIRE simulations)

From Valentini & Dolag (2025)

Simulation codes

Table 1: Major galaxy formation simulation codes

code name	gravity treatment[a]	hydrodynamics treatment[b]	parallelization technique[c]	code availability[d]	primary reference
ART	PM/ML	AMR	data-based	public	Kravtsov (1997)[27]
RAMSES	PM/ML	AMR	data-based	public	Teyssier (2002)[38]
GADGET-2/3	TreePM	SPH	data-based	public	Springel (2005)[39]
Arepo	TreePM	MMFV	data-based	public	Springel (2010)[40]
Enzo	PM/MG	AMR	data-based	public	Bryan et al. (2014)[41]
ChaNGa[e]	Tree/FM	SPH	task-based	public	Menon et al. (2015)[42–44]
GIZMO[f]	TreePM	MLFM/MLFV	data-based	public	Hopkins et al. (2015)[45]
HACC	TreePM/P^{3}M	CRK-SPH	data-based	private	Habib et al. (2016)[46]
PKDGRAV3	Tree/FM	–	data-based	public	Potter et al. (2017)[47]
Gasoline2	Tree	SPH	task-based	public	Wadsley et al. (2017)[48]
SWIFT	TreePM/FM	SPH	task-based	public	Schaller et al. (2018)[49]

[a] PM: particle-mesh; TreePM: tree + PM, FM: fast multipole, P^{3}M: particle-particle-particle-mesh; ML: multilevel; MG: multigrid

[b] SPH: smoothed particle hydrodynamics, CRK-SPH: conservative reproducing kernel smoothed particle hydrodynamics , AMR: adaptive-mesh-refinement, MMFV: moving-mesh finite volume, MLFM/MLFV: mesh-free finite mass / finite volume

[c] data-based: data parallelism focuses on distributing data across different nodes, which operate on the data in parallel; task-based: task parallelism focuses on distributing tasks concurrently performed

[d] private: private code; public: publicly available code (in some cases with limited functionality)

[e] gravity solver is based on PKDGRAV3

[f] based on the GADGET-3 code

SNO RAMSES

USING RAMSES   DEVELOPING RAMSES   COMMUNITY   RAMSES SNO   CREDITS   `SEARCH`

Ramses is an open source code to model astrophysical systems. It describes self-gravitating, magnetised, compressible, radiative fluid flows with Adaptive Mesh Refinement (AMR), and has been widely used for cosmological simulations of the Universe, isolated as well as cosmological resimulations of individual galaxies, simulations of molecular clouds, star formation, supernovae remnants, accretion disks around black holes and planets. Ramses was written by Romain Teyssier, and is now used and developed by a growing community of astrophysicists all around the world, with many groups in France, United Kingdom, Danemark, South Korea and the United States.

The goal of this website is to promote the activities of the Ramses community in France and internationally. It is edited by the RAMSES SNO (see this page for more details about this structure).

Get the newsletter

Events

RAMSES School for New Users

October 22, 2025

Paris (IAP)
Oct. 22-23

SNO days

News

RAMSES Developer School 2025

Projects

The VINTERGATAN project

The VINTERGATAN project (Milky Way in Swedish

(Eulerian) Discretization

- Infinitestimal δx becomes finite Δx — the width of the grid cell

- Infinitestimal δt beomes finite Δt, subject to **Courant condition**:

$$\Delta t \leq \frac{\Delta x}{\text{Highest speed, anywhere}}$$

- The exact same is done on the right boundary, and for y- and z-boundaries

- Repeat until $\Sigma \Delta t = t_{\text{Hubble}}$

- This is the *basics*. A lot of subtleties on how to interpolate the flux at cell boundaries.

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

$$\frac{\Delta \rho}{\Delta t} + \frac{(\Delta \rho v)}{\Delta x} = 0$$

Cell $i-1$ Cell i Cell $i+1$
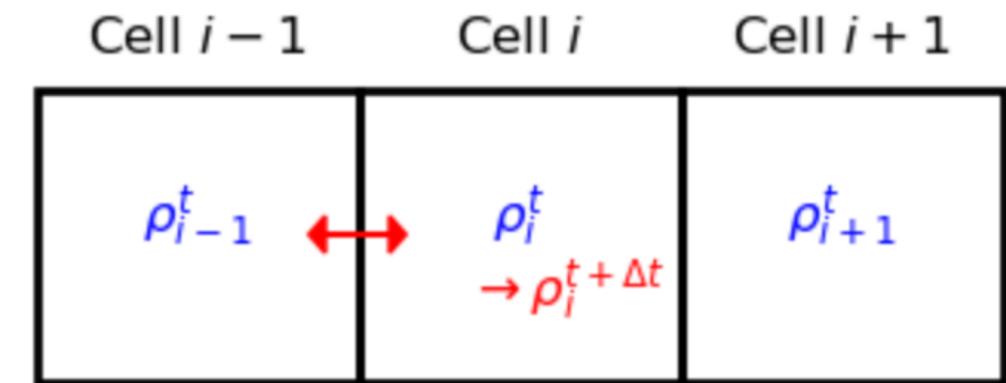
$$\frac{\rho_i^{t+\Delta t} - \rho_i^t}{\Delta t} + \frac{(\rho v)_i^t - (\rho v)_{i-1}^t}{\Delta x} = 0$$

$$\rho_i^{t+\Delta t} = \rho_i^t - \frac{\Delta t}{\Delta x} \left[(\rho v)_i^t - (\rho v)_{i-1}^t \right]$$

Adaptive refinement

- SPH codes have natural refinement on mass

- Grid codes use adaptive mesh refinement (AMR) — otherwise impossible to resolve galaxies in cosmological simulations

- A cell is 'split' into smaller children cells if its mass exceeds a threshold (typically 8 DM particles)
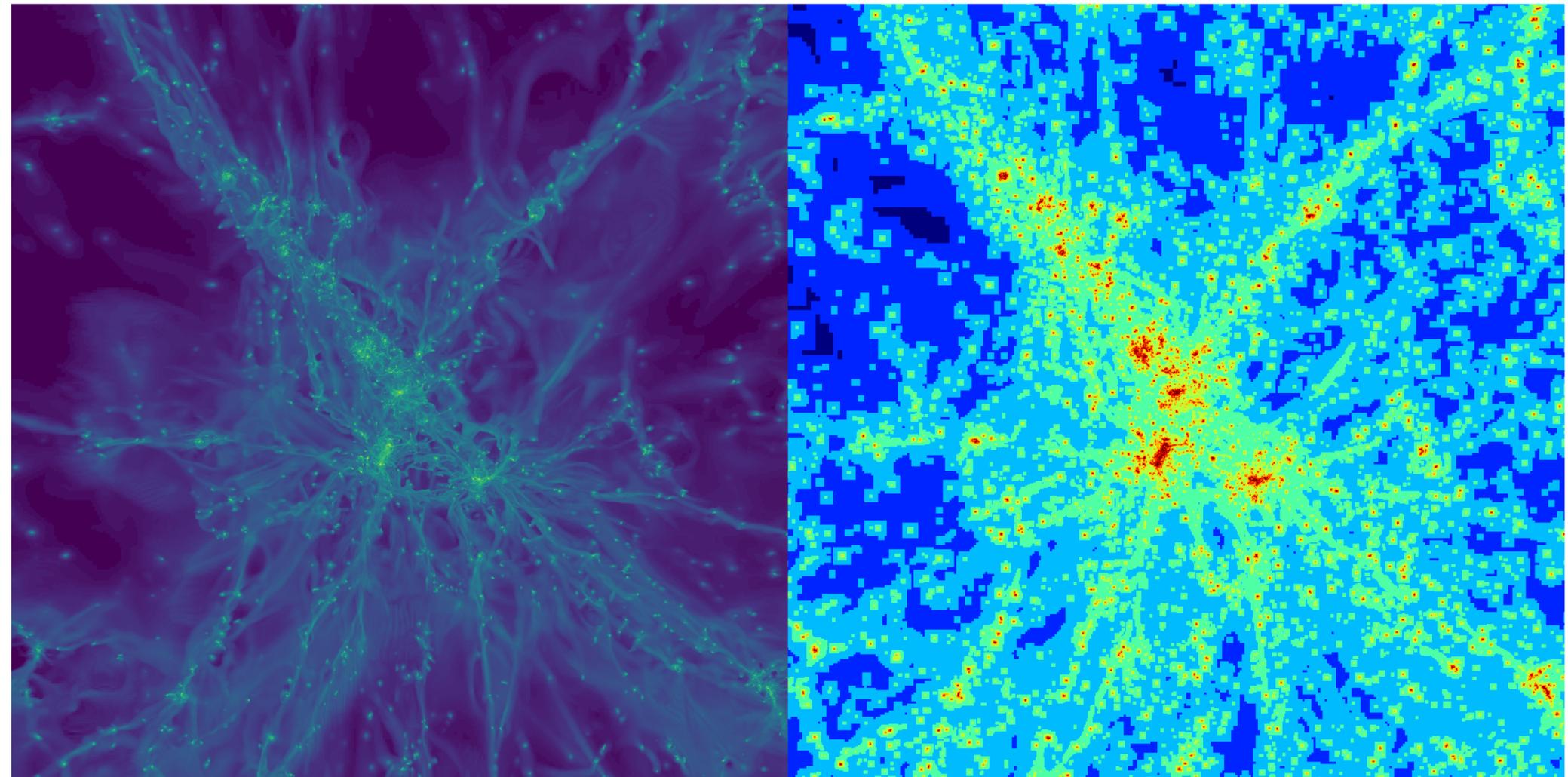
Gas density in a proto-cluster of galaxies (from SPHINX simulations)

Cell refinement level

Parallel computing

- Classically, the simulation volume is split into sub-domains, and each domain computed independently on a CPU

- CPUs then communicate flows over the boundaries between them

- Equal load-balancing of the CPUs is one of the biggest challenges of optimising a simulations code
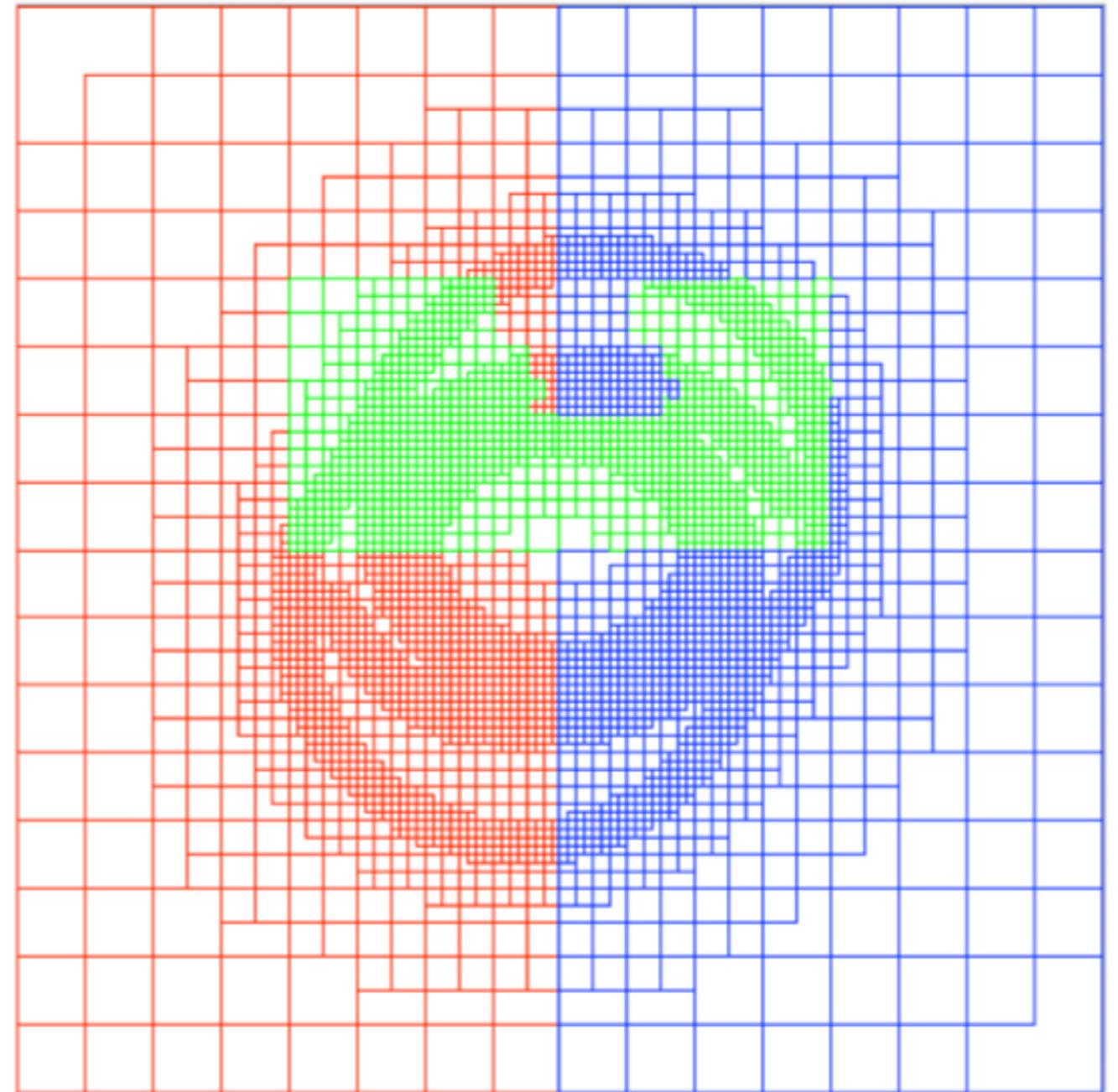
An AMR (RAMSES) run on 3 CPUs

Cosmological initial conditions

- Initial conditions have the same statistical properties as the CMB (power spectrum of density fluctuations)

- Several public codes exist to generate initial conditions with your favourite LCDM parameters (Ω_m, Ω_b, H_0, σ_8,), and a **random seed**
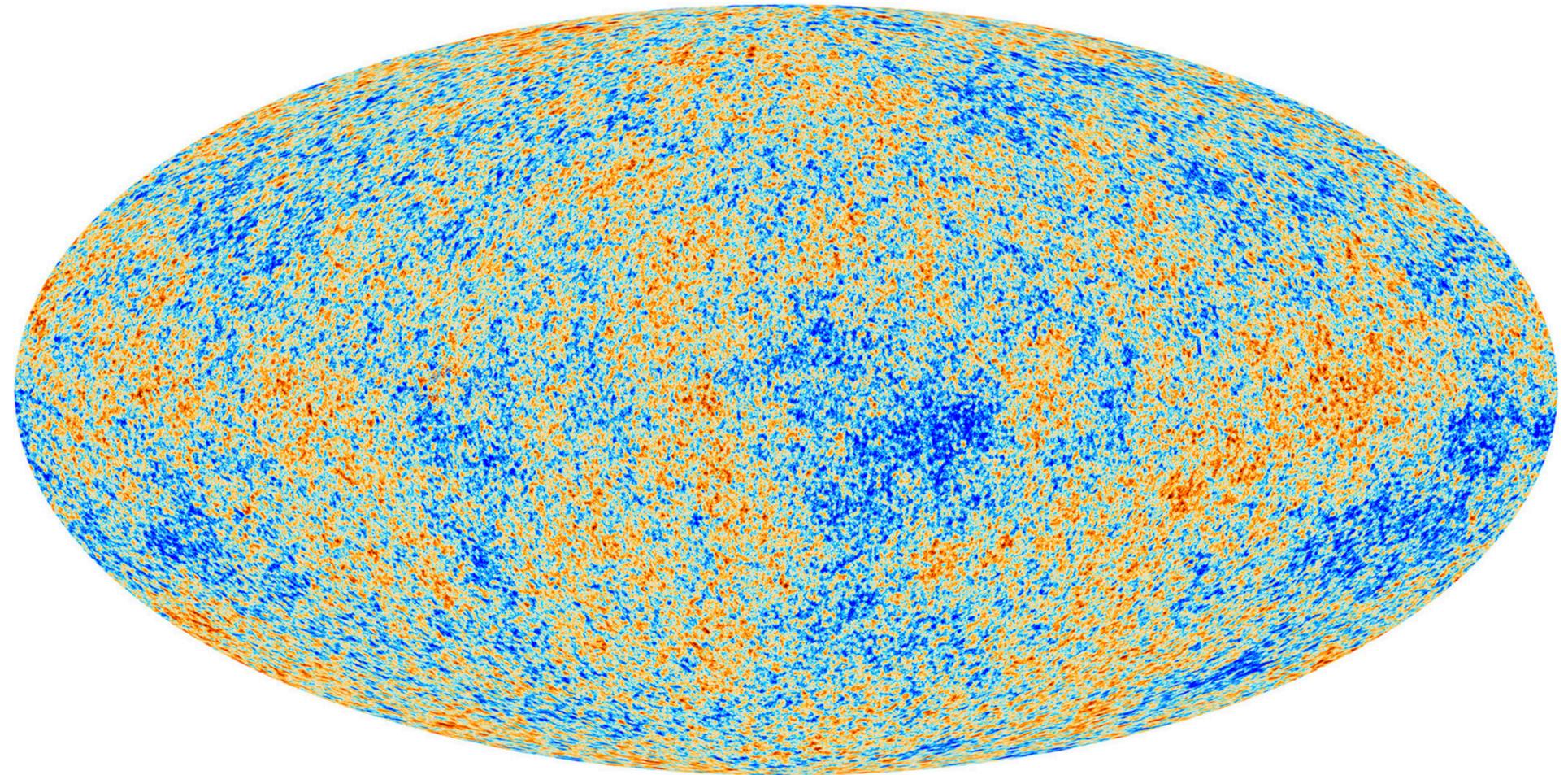
Cosmological box

- The initial conditions are 'extrapolated' to z~50-100

- Periodic boundary conditions

- Co-moving coordinates

- Can you spot the Milky-Way?
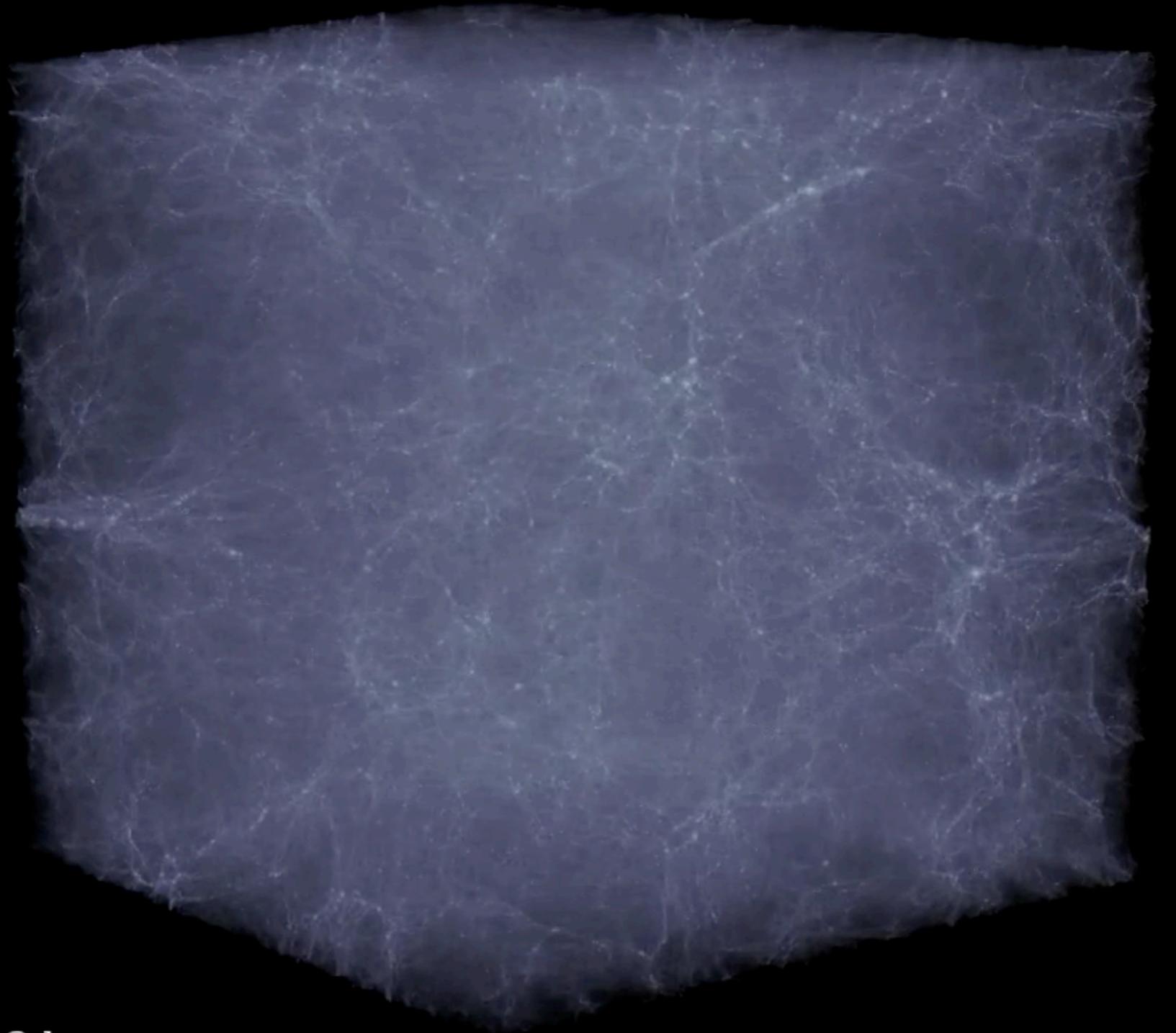
513 kpc

z=5.23

Cosmological zoom simulations

Mpc   z= 3.00   Mpc   z= 3.00   100 Kpc   z= 3.00
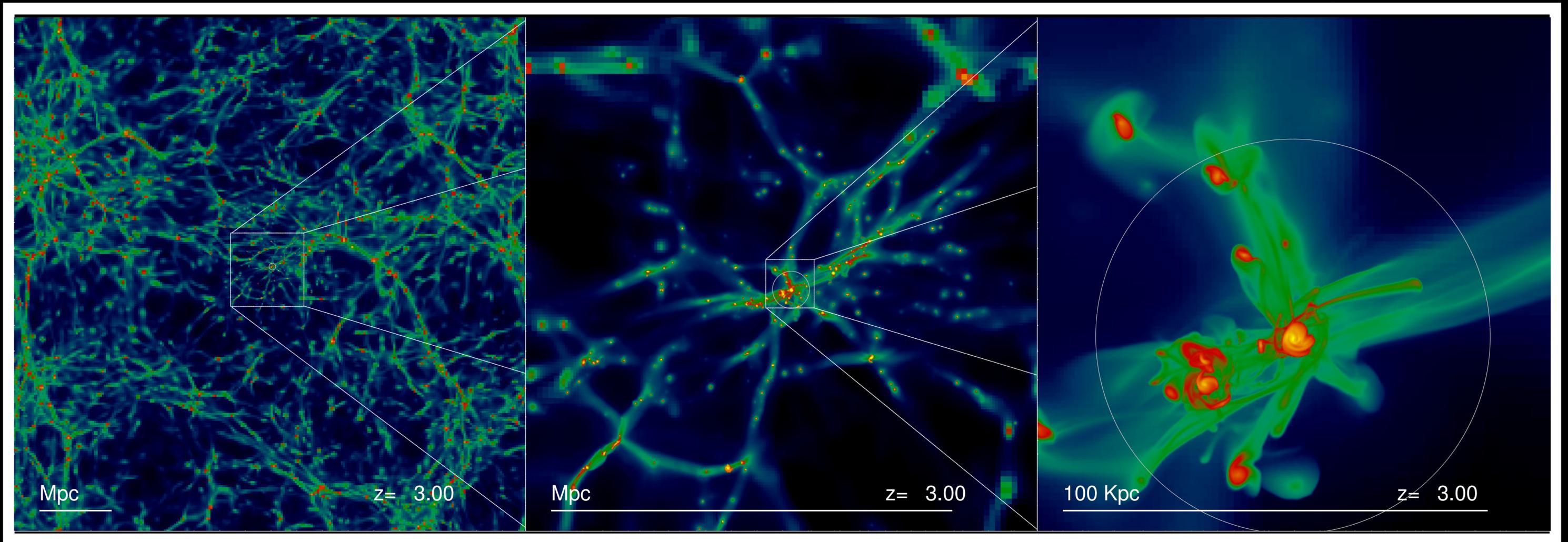
- Alternative to 'full' cosmological box

- Use low resolution in most of the volume and high resolution around a *targeted halo*

- Cheaper simulation and higher resolution, compared to full volume

- But scales much worse than full volume, i.e. runs on fewer CPUs

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Sub-grid physics

- **We 'resolve', on pc-kpc scales:**

  - Gravity

  - Hydrodynamics

- **We don't resolve:**

  - Gas cooling, chemistry

  - Star formation

  - Stellar feedback

  - Black hole creation, accretion, feedback

- **For the above, we use sub-grid physics to describe their effects on resolved scales —** **and they have many 'knobs'**

Cooling

Solar metallicity
z=0 UV background
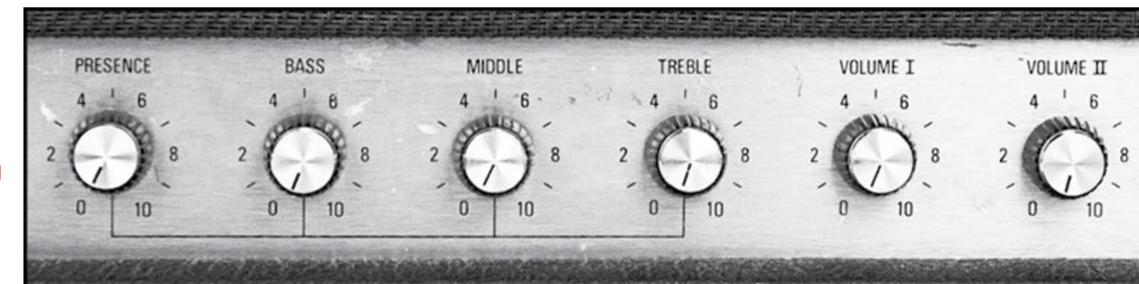
- Mostly $\Lambda \propto \rho^2$, with strong contribution from *metals*

- Cooling rates are usually **tabulated** as a function of T, ρ_{gas}, and redshift

- Metals are typically one or a few scalars

- We typically start with a (calibrated) **metallicity floor** of $Z \sim 10^{-5} \, Z_\odot$
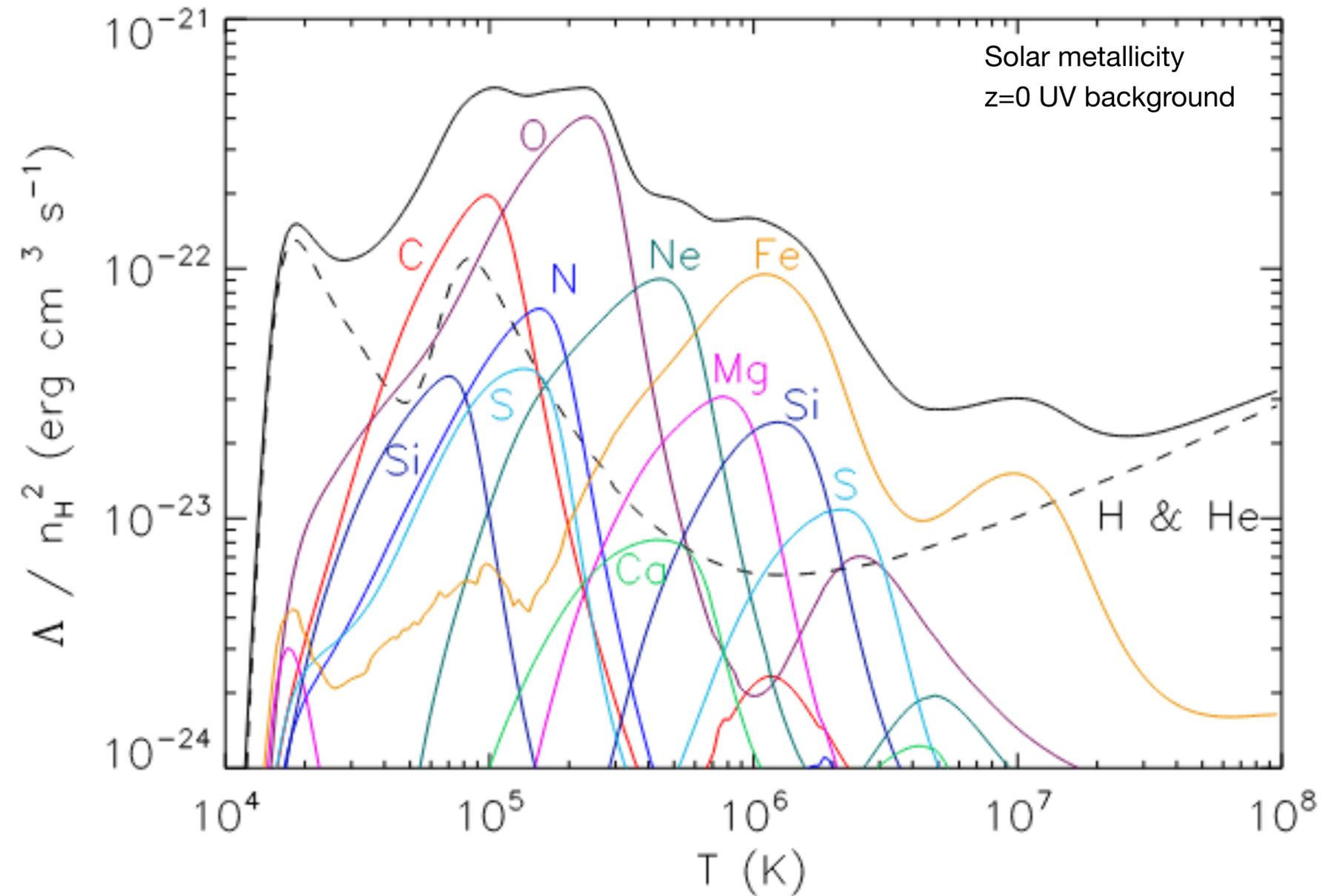
Star formation

- Stars are modelled as collisionless particles, much like DM

- Star particles represent stellar populations, typically $m_* = 10^3 - 10^8 \, M_\odot$

- Resolution is typically hundreds of parsecs, larger than molecular clouds!

- In each cell, stochastically sample $\boxed{\dfrac{\delta \dot{\rho}_*}{\delta t} = \epsilon_* \dfrac{\rho}{t_{\rm ff}}}$, with ϵ_* the star formation *efficiency*

- *ϵ_*=0.02 is the Universal value, but locally it can be much higher*

- Simulations vary a lot in their modelling of ϵ_*

  - ϵ_*=0.02 vs ϵ_*=1 vs locally varying ϵ_* — changes a lot the burstiness of SF

The 'general' overcooling problem
(Navarro & Benz, 1991)

- Realistic galaxies require *efficient supernova feedback*

- Without it, they are:
  - too compact, star forming
  - no outflows or fountains

- So SN explosions are *vital*
  - Primarily type II SNe, with 10-20 % of stellar mass exploding within 50 Myrs
  - Also: chemical enrichment
  But: a naive 'thermal dump' SN energy injection does not work

The 'special' overcooling problem

- SN feedback: instantaneous thermal energy injection
- The injected temperature $\propto (\Delta x)^3$
- ➡ **Stochastic** SN feedback in EAGLE simulations, injecting $T_{SN} = 10^{7.5}\,K$

From Wiersma+09

$$E_{SN} \approx 10^{51}\text{erg} \times \frac{m_*}{100\,M_\odot}$$

Solar metallicity
z=0 UV background
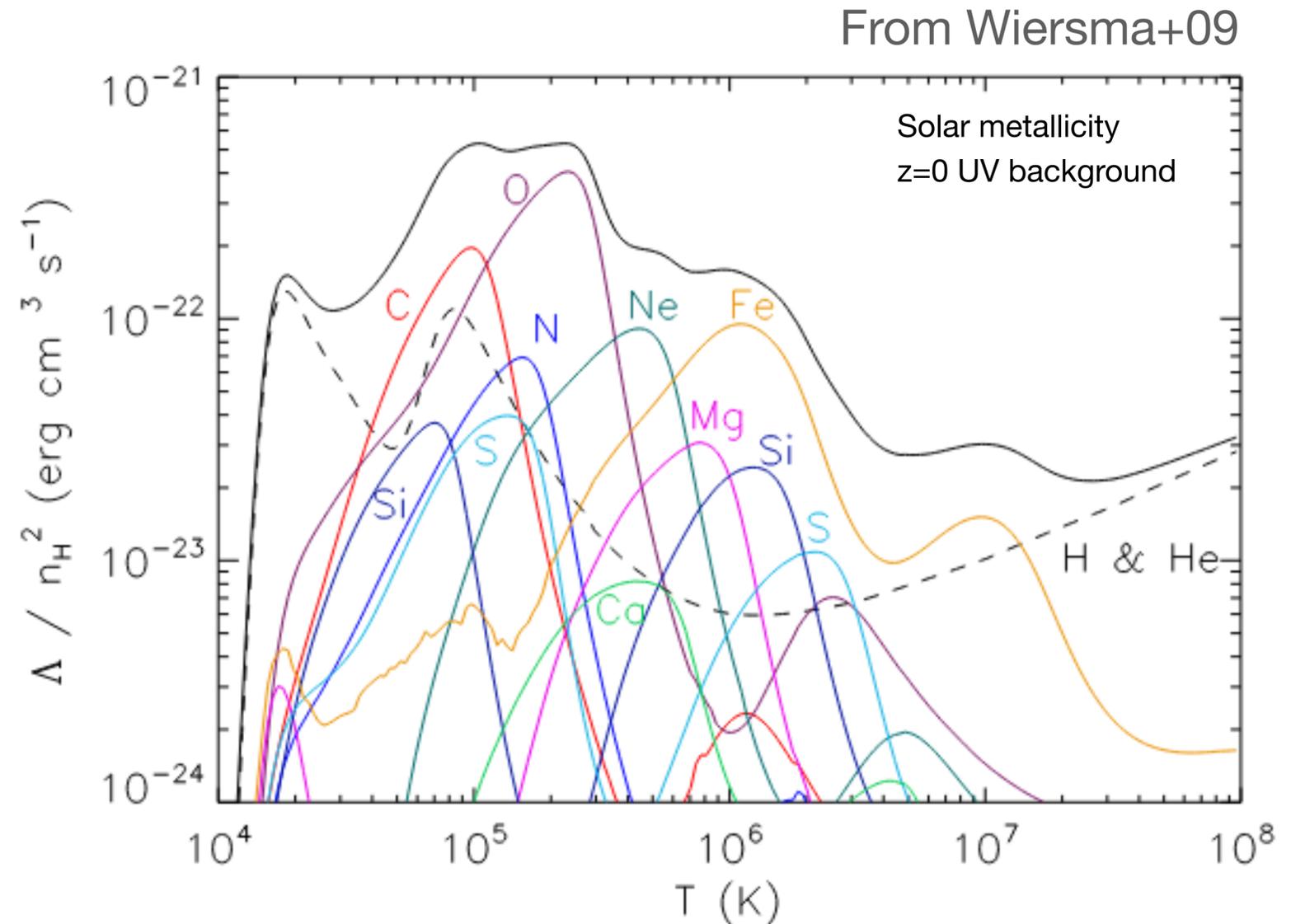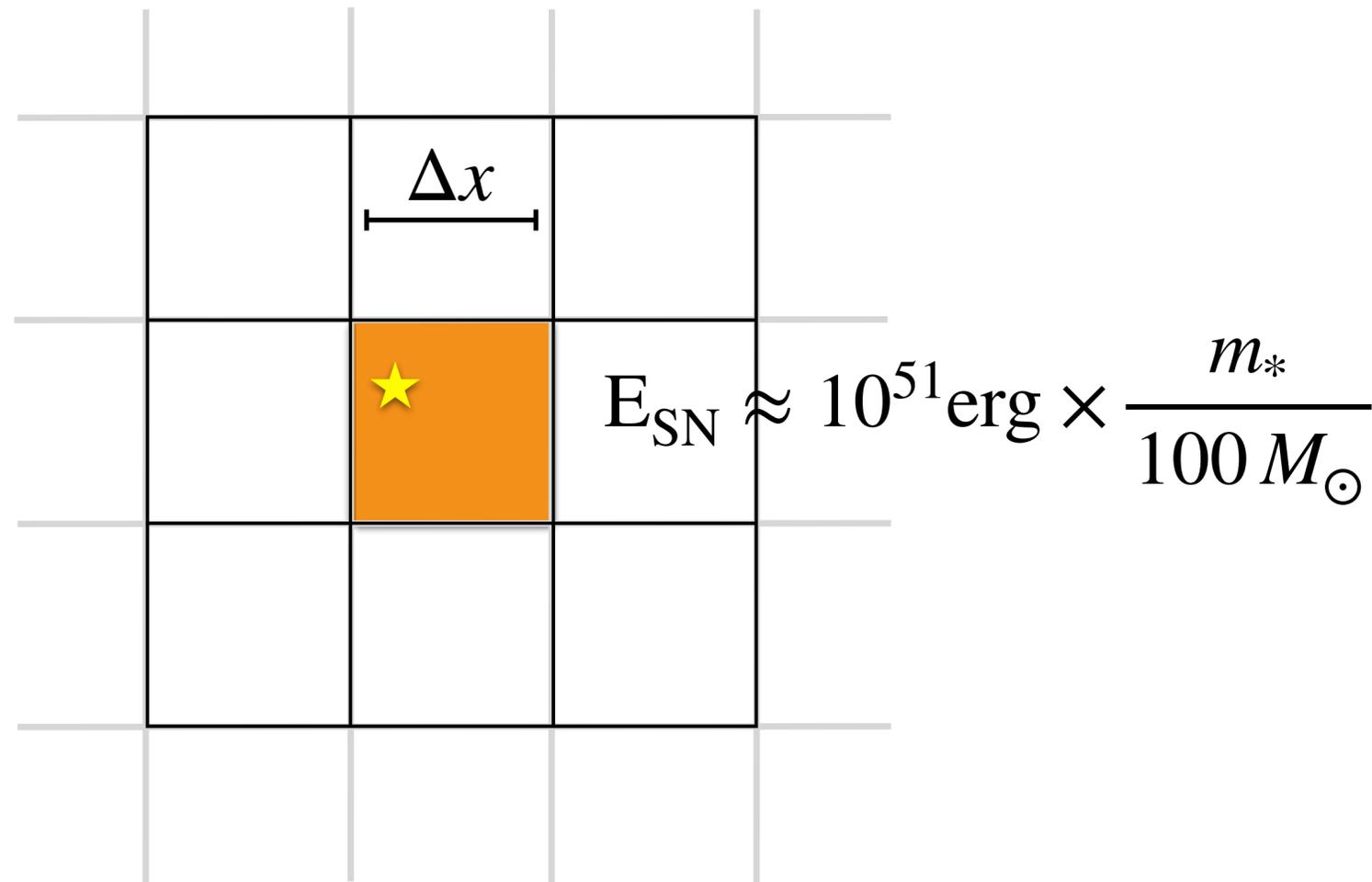
The 'special' overcooling problem

- SN feedback: instantaneous thermal energy injection
- One must resolve the adiabatic Sedov-Taylor phase: **~ 1 pc, 10³ yr**
➡**Momentum injection (Horizon, FIRE, many recent high-resolution simulations)**
➡**Or turn off cooling and calibrate the turn-off time (NIHAO, …)**
➡**Or decouple the SN ejecta until they are somewhere in the CGM (Illustris, TNG)**

From Haid+16
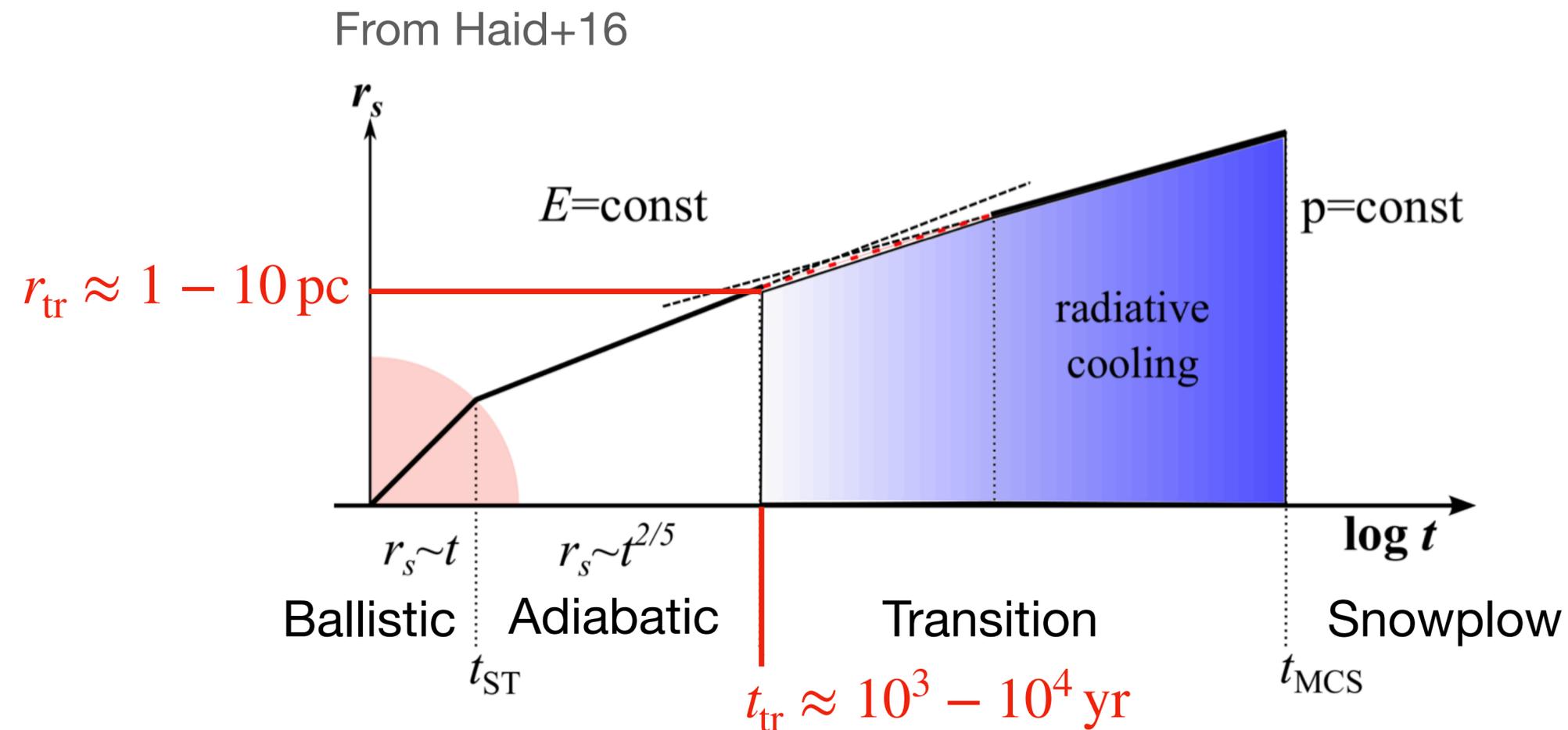
ISM equation of state

- In addition to depositing SN explosions from stars, we often replace cooling in dense gas with a density-dependent pressure (unresolved turbulence, early feedback)

- Necessary to prevent runaway cooling, too much star formation, and small timesteps

- But it prevents a multi-phase ISM from forming, which makes sense for ~kpc resolution

From Semenov+25
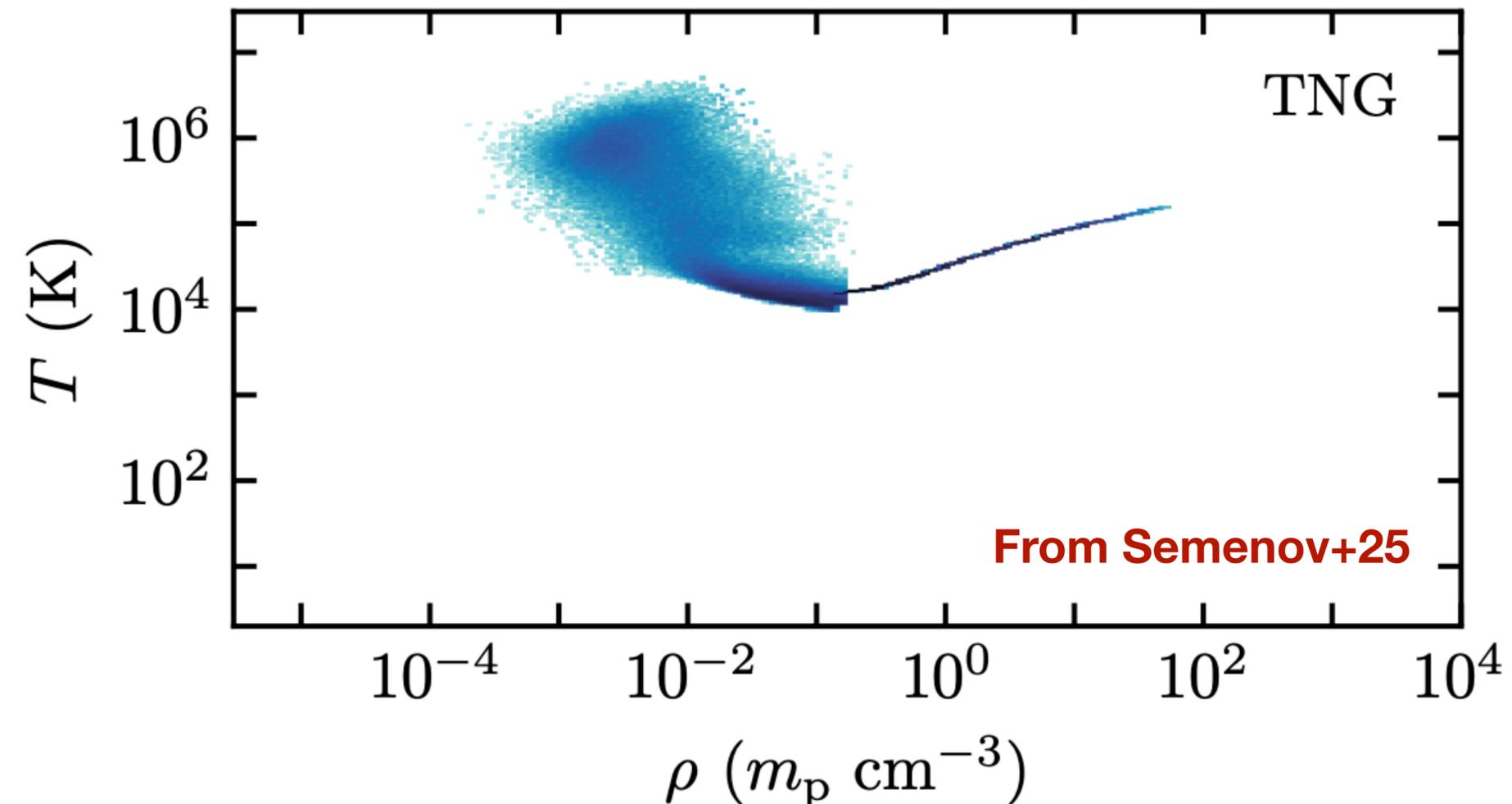
AGN

- Important in massive galaxies, $M_{\rm vir} \gtrsim 10^{12} M_{\odot}$ (or so we thought)

- In reality, an AGN is a black hole accreting from a surrounding disk, in turn surrounded by a torus. But none of that is resolved in cosmological simulations

- **Instead**: sink particle that accretes matter (with Bondi-Hoyle) from galaxy center

- A lot of variations in the accretion model:
  super-Eddington?
  How to form the black hole?
  How to get it to stick to the galaxy center

- This (and feedback) is calibrated against observations of the massive end of the stellar mass function
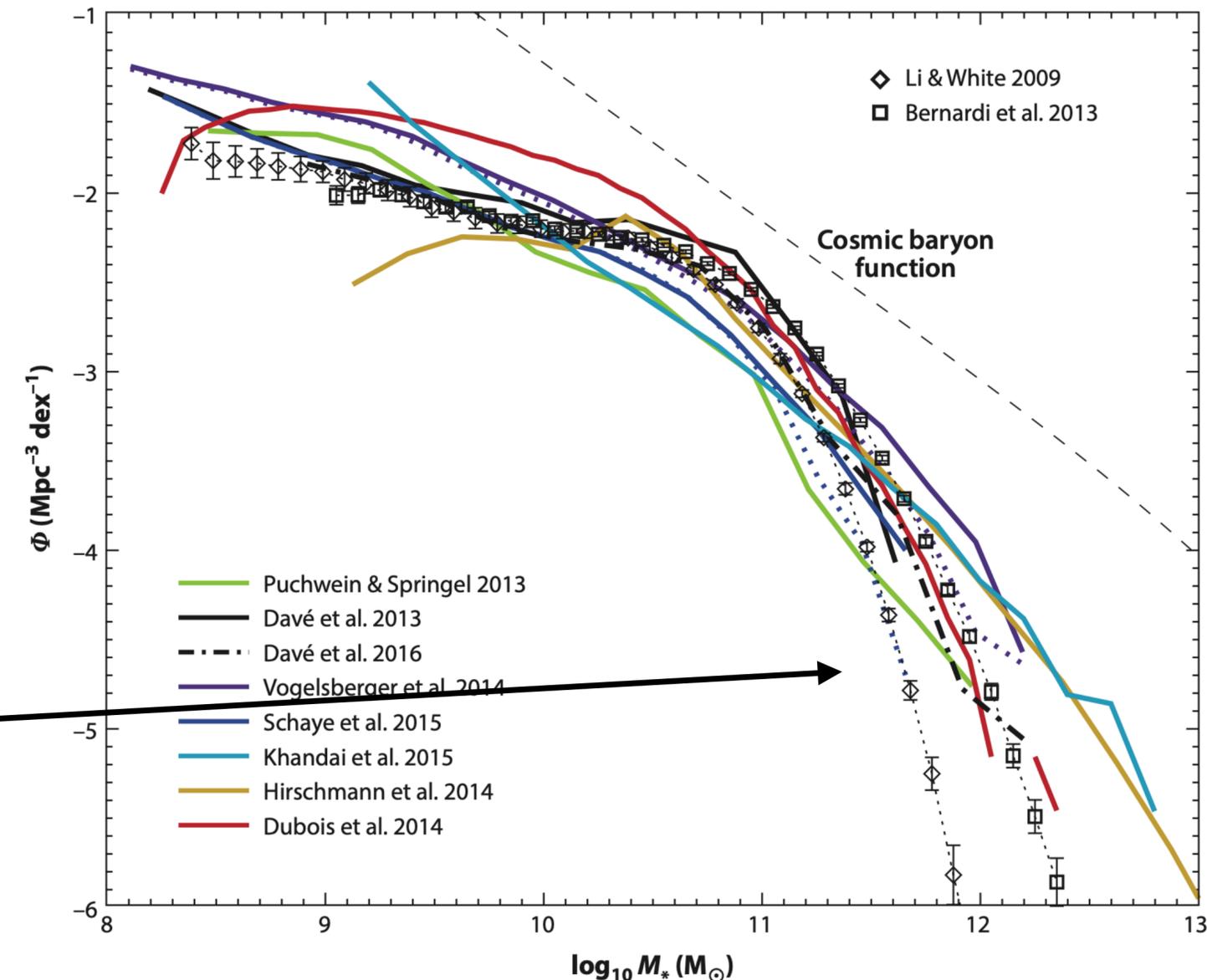
AGN feedback

- A fraction of the accretion luminosity is injected into surroundings

$$\dot{E} = \epsilon_{\mathrm{f}}\epsilon_{\mathrm{r}}\dot{M}_\bullet c^2$$

ϵ_{f} = feedback, or coupling, effiency (tuned)

$\epsilon_{\mathrm{r}} = 0.1$ = radiative effiency

From Valentini & Dolag (2025)

Magneticum/SLOW

BH seeding: halo stellar mass and gas to stellar mass fraction; BH mass at seeding scaled via M_{BH}/M_{star} relation

BH feeding: Bondi formula, boosted α=100; in some runs, hot and cold gas accretion, α=10 for hot, 100 for cold gas

BH dynamics: dynamical friction and boosted dynamical mass

feedback

$\dot{M}_\bullet = 0.01\dot{M}_{\mathrm{Edd}}$
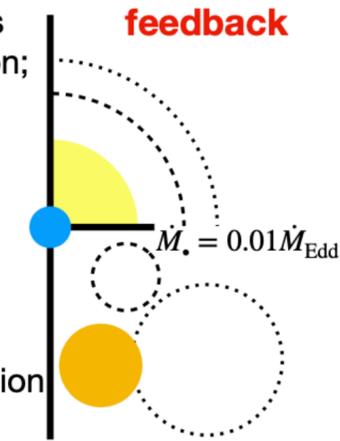
Illustris

BH seeding: halo mass > 7.1×10^{10} $M_\odot$ BH mass at seeding: 1.4×10^5 $M_\odot$

BH feeding: Bondi formula, α=100, accretion reduced if low gas pressure surrounding the BH

BH dynamics: repositioning, BH fixed to local potential minimum

feedback

radiative electro-magnetic AGN feedback changes gas cooling rate

$\dot{M}_\bullet = 0.05\dot{M}_{\mathrm{Edd}}$
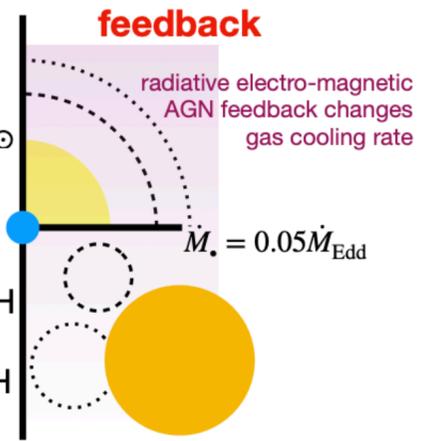
EAGLE

BH seeding: halo mass > 1.5×10^{10} $M_\odot$ BH mass at seeding: 1.5×10^5 $M_\odot$

BH feeding: Bondi formula, not boosted, reduced for gas with high angular momentum

BH dynamics: repositioning via pinning on minimum potential

feedback
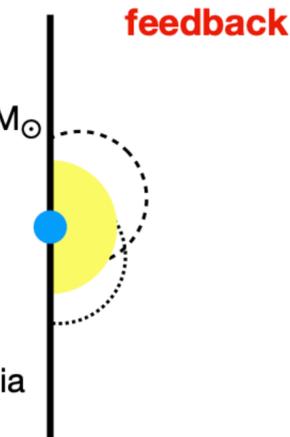
Illustris-TNG

BH seeding: halo mass > 7.4×10^{10} $M_\odot$ BH mass at seeding: 1.2×10^6 $M_\odot$

BH feeding: Bondi formula, unboosted

BH dynamics: repositioning via pinning on minimum potential

feedback

radiative electro-magnetic AGN feedback changes gas cooling rate

$\dot{M}_\bullet = f(M_{BH}), \leq 0.1\dot{M}_{\mathrm{Edd}}$
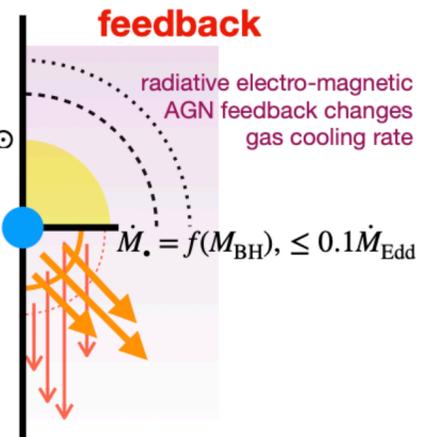
Simba

BH seeding: stellar mass in halo > $10^{9.5}$ $M_\odot$ BH mass at seeding: 1.4×10^4 $M_\odot$

BH feeding: torque-limited cold gas accretion capped to $3 \times \dot{M}_{\mathrm{Edd}}$ and Eddington limited Bondi accretion for hot gas (α=0.1)

BH dynamics: repositioning, BH fixed to local potential minimum

feedback

bipolar outflows, zero opening angle, // to angular momentum of the accretion disc

$\dot{M}_\bullet = 0.02\dot{M}_{\mathrm{Edd}}$

X-ray feedback heating gas

hot (T$_{vir}$) outflows
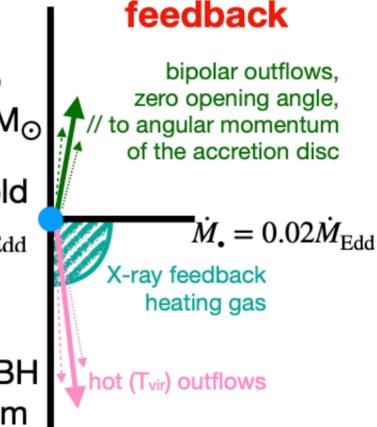
(New)Horizon-AGN

**BH seeding**: starforming gas, σ > 20-100 km/s BH mass at seeding: 10^5 $M_\odot$

BH feeding: Bondi formula, not boosted, Eddington-limited

BH dynamics: drag force of the gas onto BH and enforced mesh refinement around the BH

feedback

radiative and jet efficiencies, and jet direction depend on BH spin

$\dot{M}_\bullet = 0.01\dot{M}_{\mathrm{Edd}}$

bipolar, v=10^4 km/s
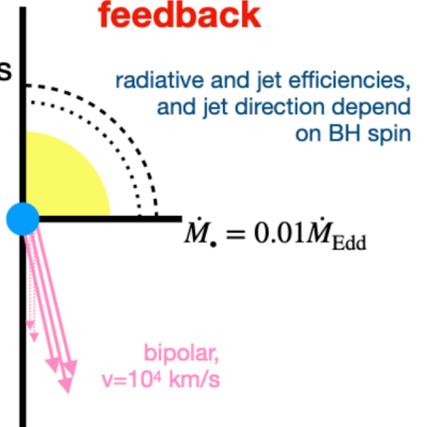
Different methods for star formation and feedback

- From Jung+25: same MW-like galaxy at z=2.8 with different methods for star formation and feedback

- Though different models are calibrated towards the same final galaxy mass, they produce very different galaxies (bursty vs steady, outflows vs gas reservoir)
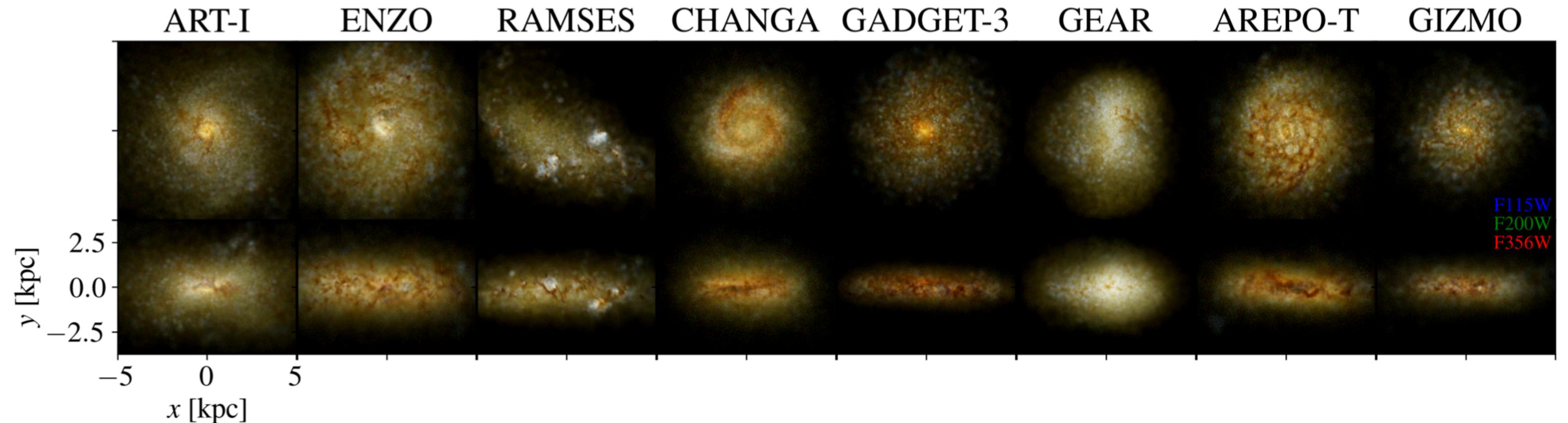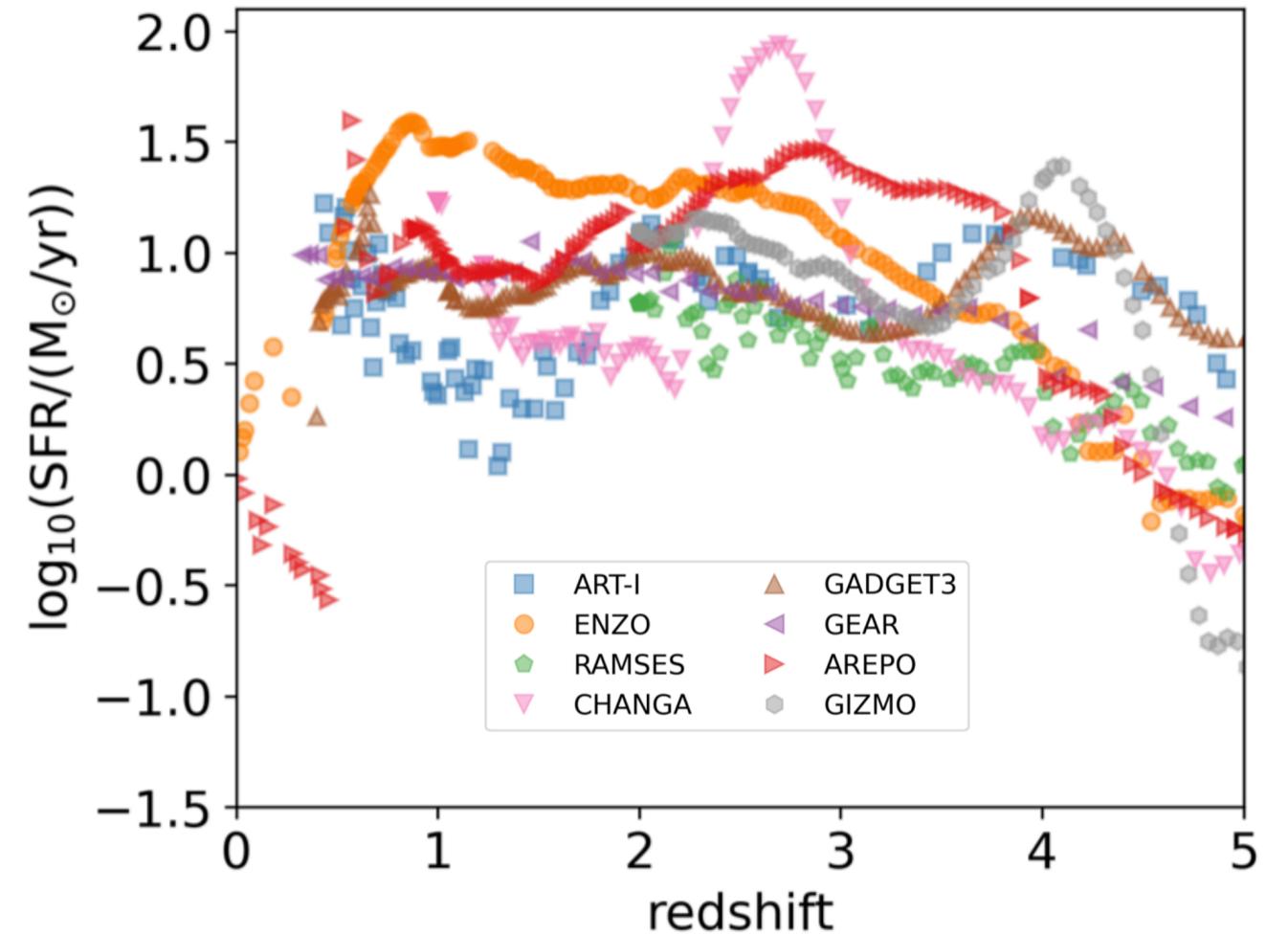
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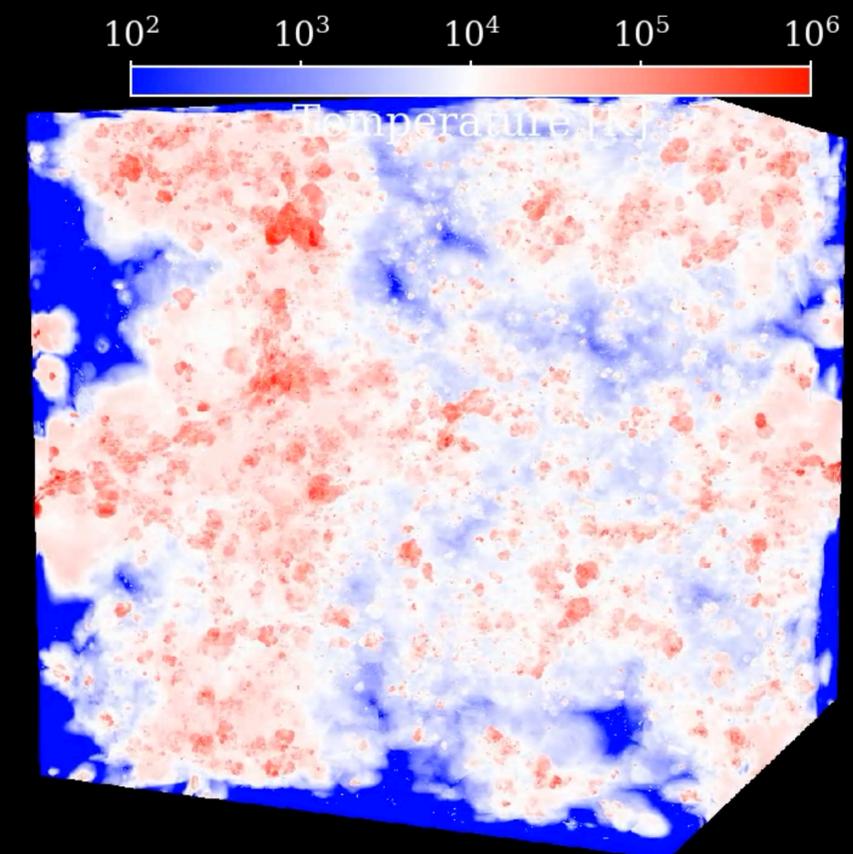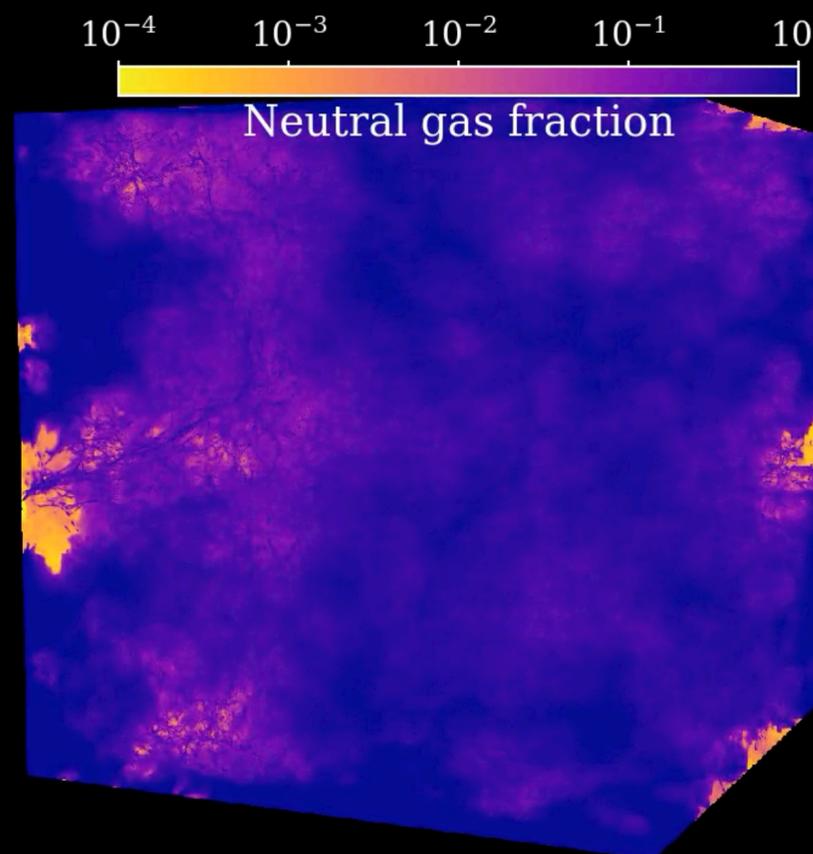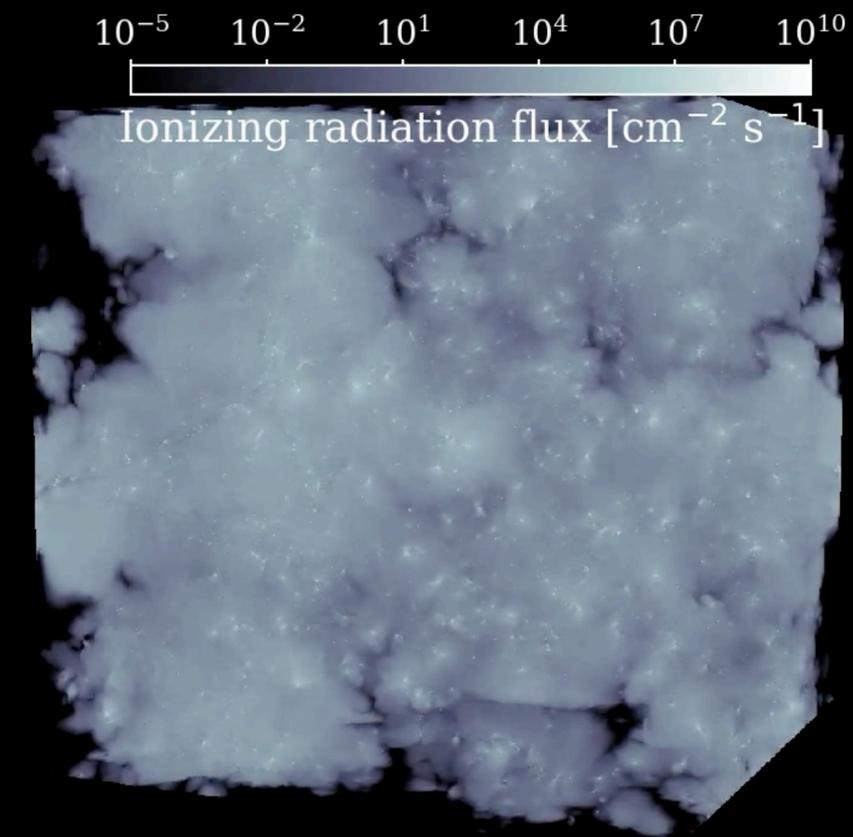
7. High-z galaxies and observations

8. Mock observations

Towards a resolved ISM

- In parallel with large cosmological simulation projects, there is a lot of work on (sub-) parsec resolution simulations of isolated galaxies and cosmological zooms

- Lower-temperature cooling, multi-phase ISM, and **less room for calibrations**

- These physically motivated simulations struggle to suppress SF (e.g. FIREBOX, THESAN-ZOOM, SPHINX, …)

- Is the problem (still) lack of resolution or physics?

➡ **Explorations of e.g. radiation feedback, cosmic rays**

44
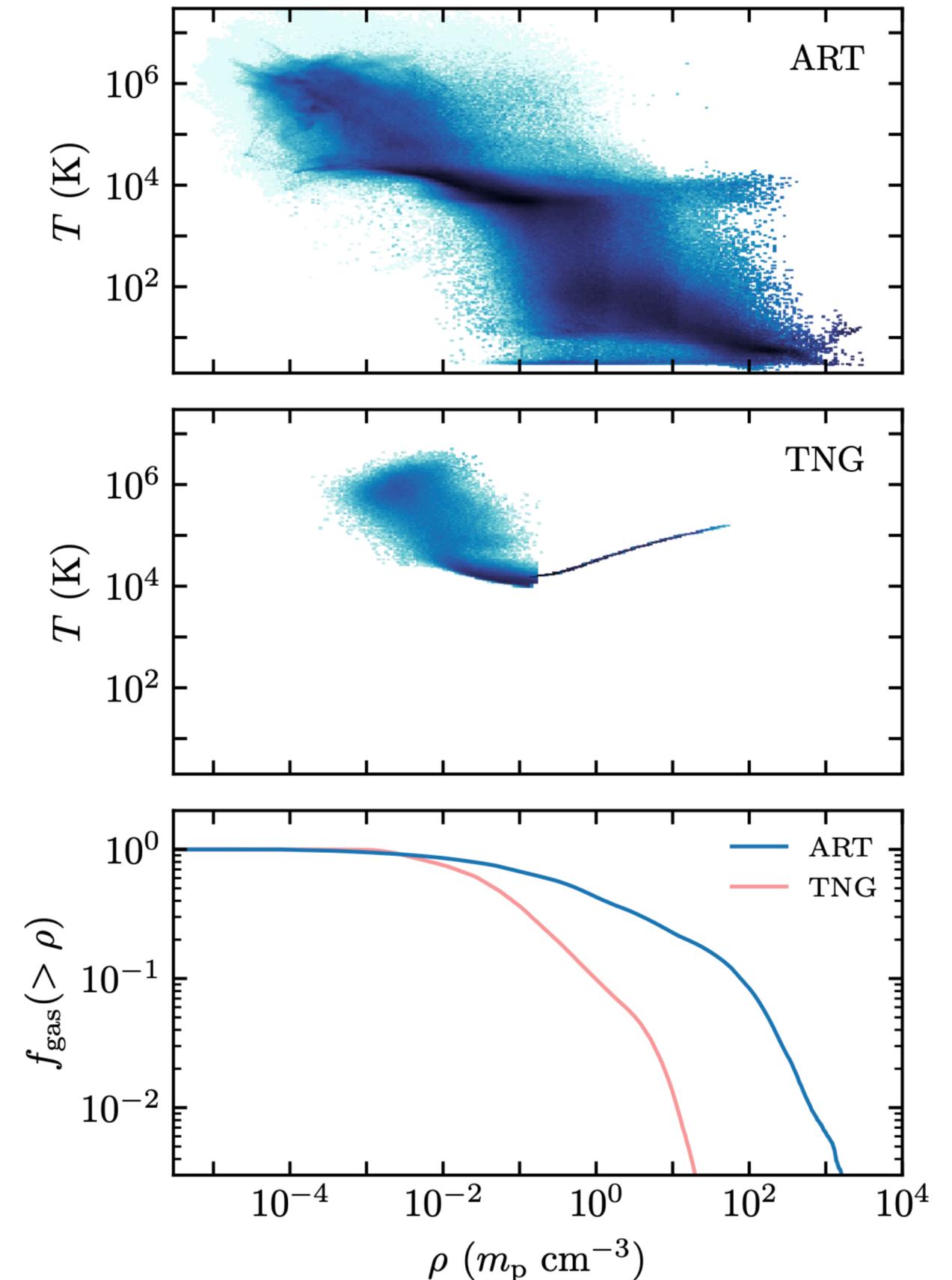
Radiative transfer

- Stellar radiation dominates the feedback energy

- This inspired sub-grid models for efficient radiation feedback (Agertz, Ceverino, FIRE, Nihao)

- But:
  - Continuous energy injection
  - Heats the as to ~10^4 K
  - Low in momentum
  - Not very strong coupling to the gas
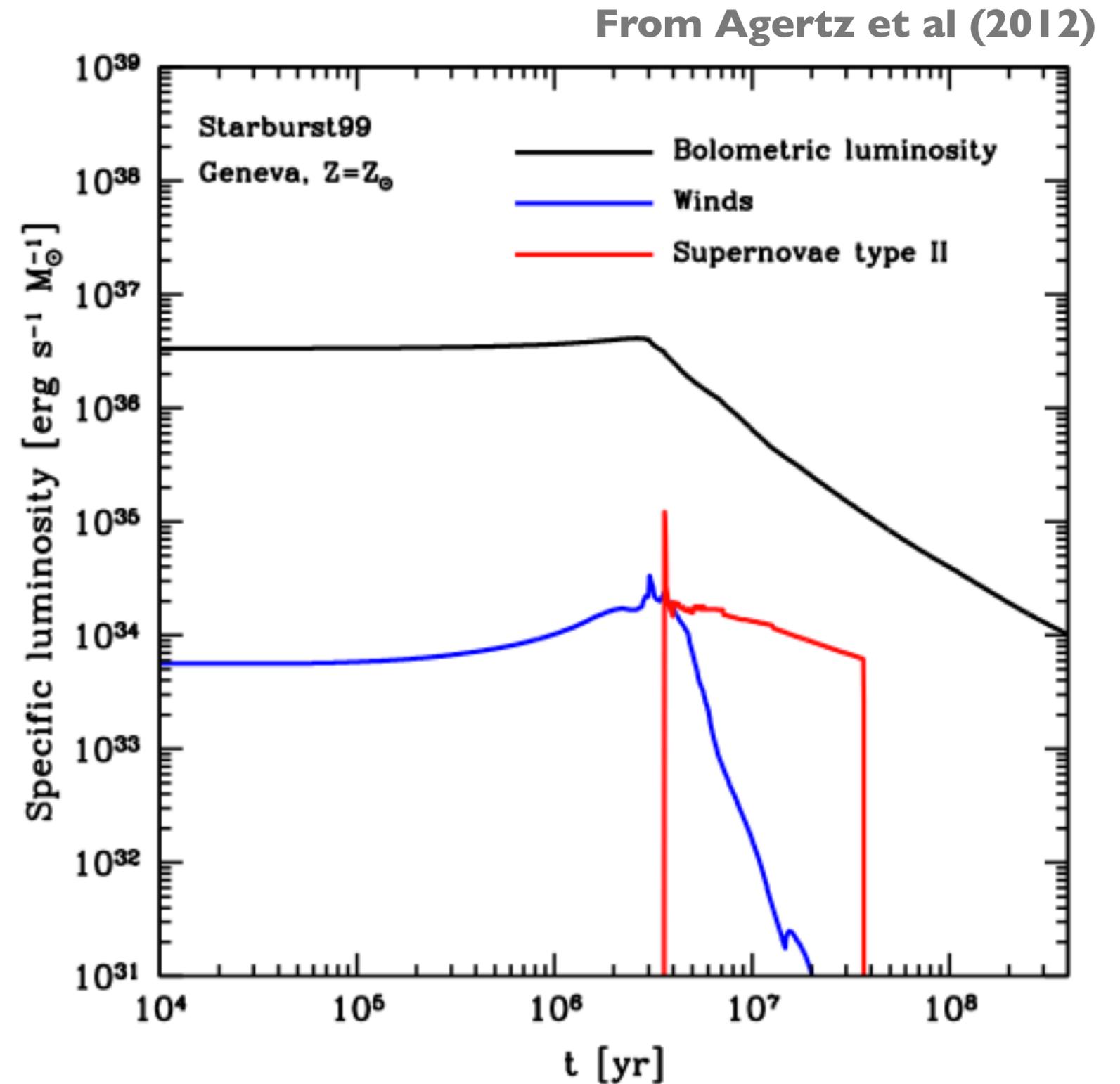
RHD simulations

In the 2010s, many codes had RHD implemented (very simplified and still quite expensive)

The results were underwhelming:
mild SF suppression in low-mass galaxies, smaller mass loading factors
(Rosdahl+15, Kannan+18, Emerick+18, Peters+16, Agertz+20, …)
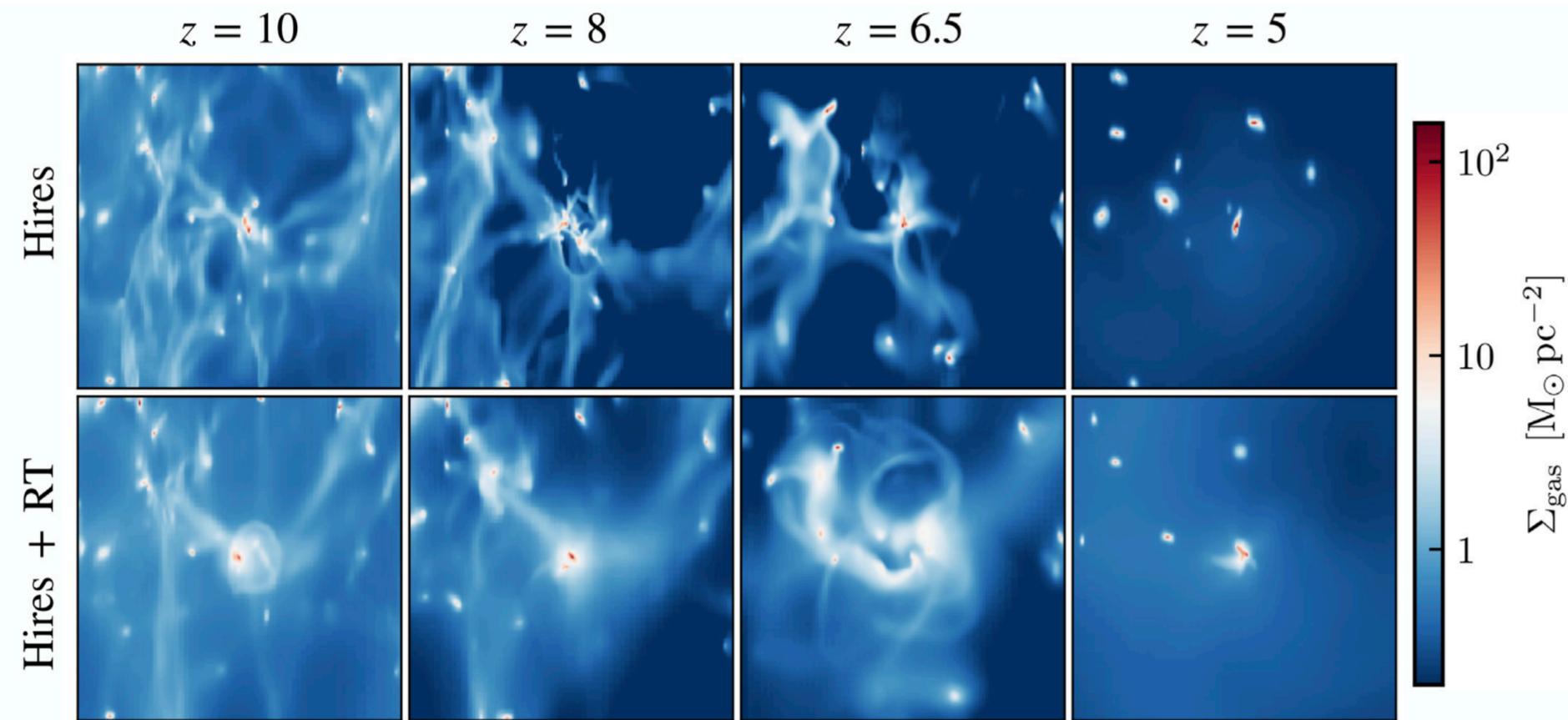
From Agertz et al (2020)
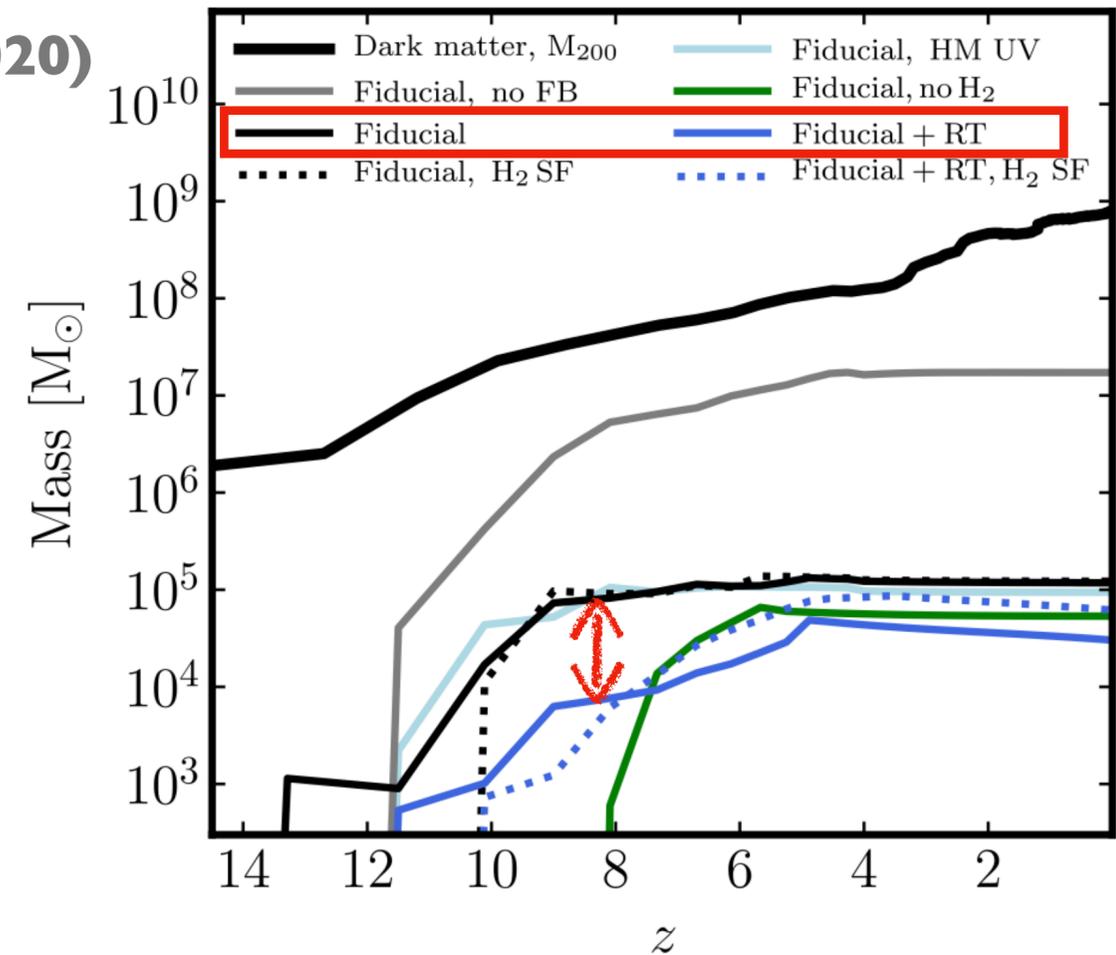
MHD simulations

- Magnetic pressure is very important on star-formation (AU) scales

- But not very important for galaxy formation in cosmological simulations

- And complicated, and expensive

- But it is important for the propagation of cosmic rays…

Cosmic rays simulations

- Charged particles, propagating along magnetic field lines

- Created in shocks (from SNe, AGN, ..)

- Push the gas: suppress star formation, enhance outflows

- Increasingly studied in simulations since the early 2010s

- But not very clear yet what exactly they do — still a lot of freedom in their energy budget and diffusion
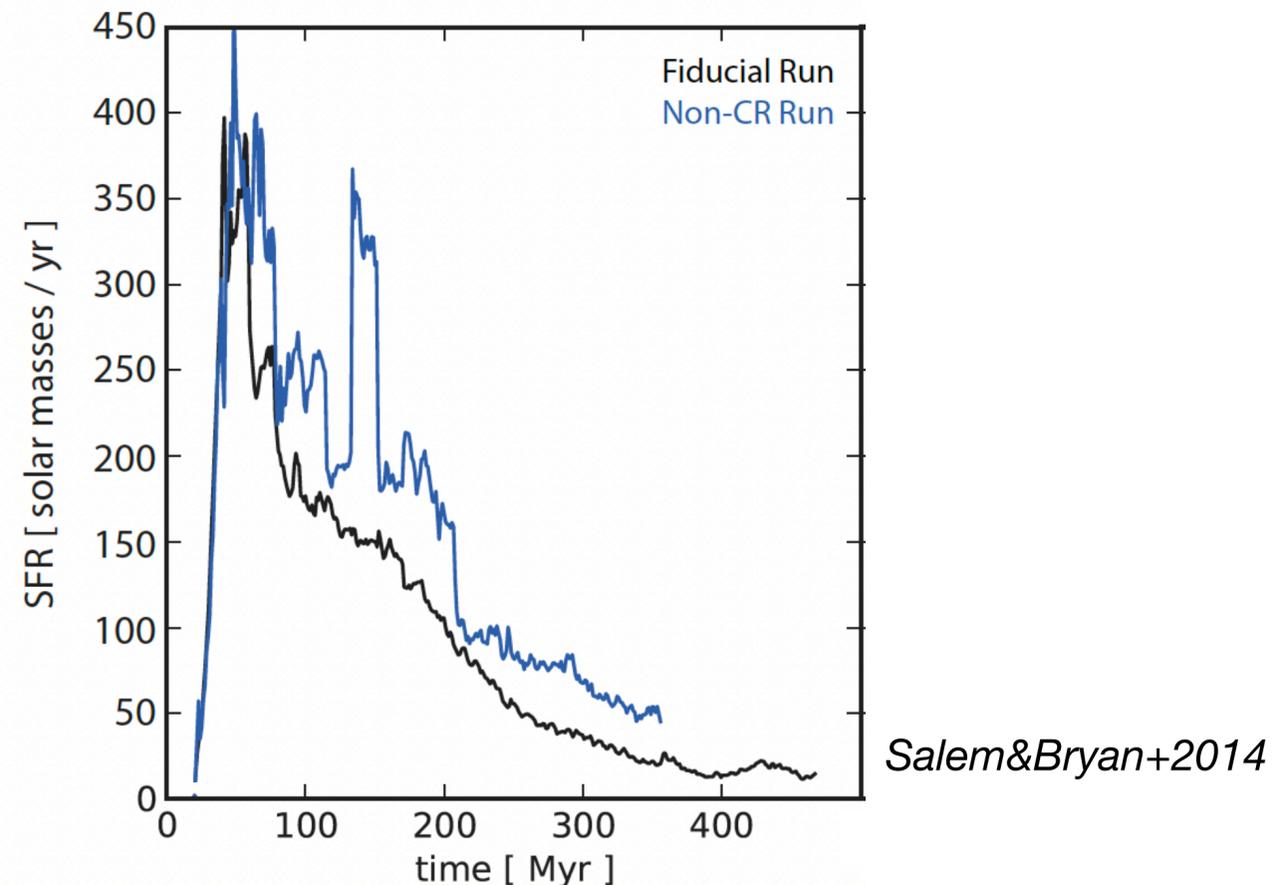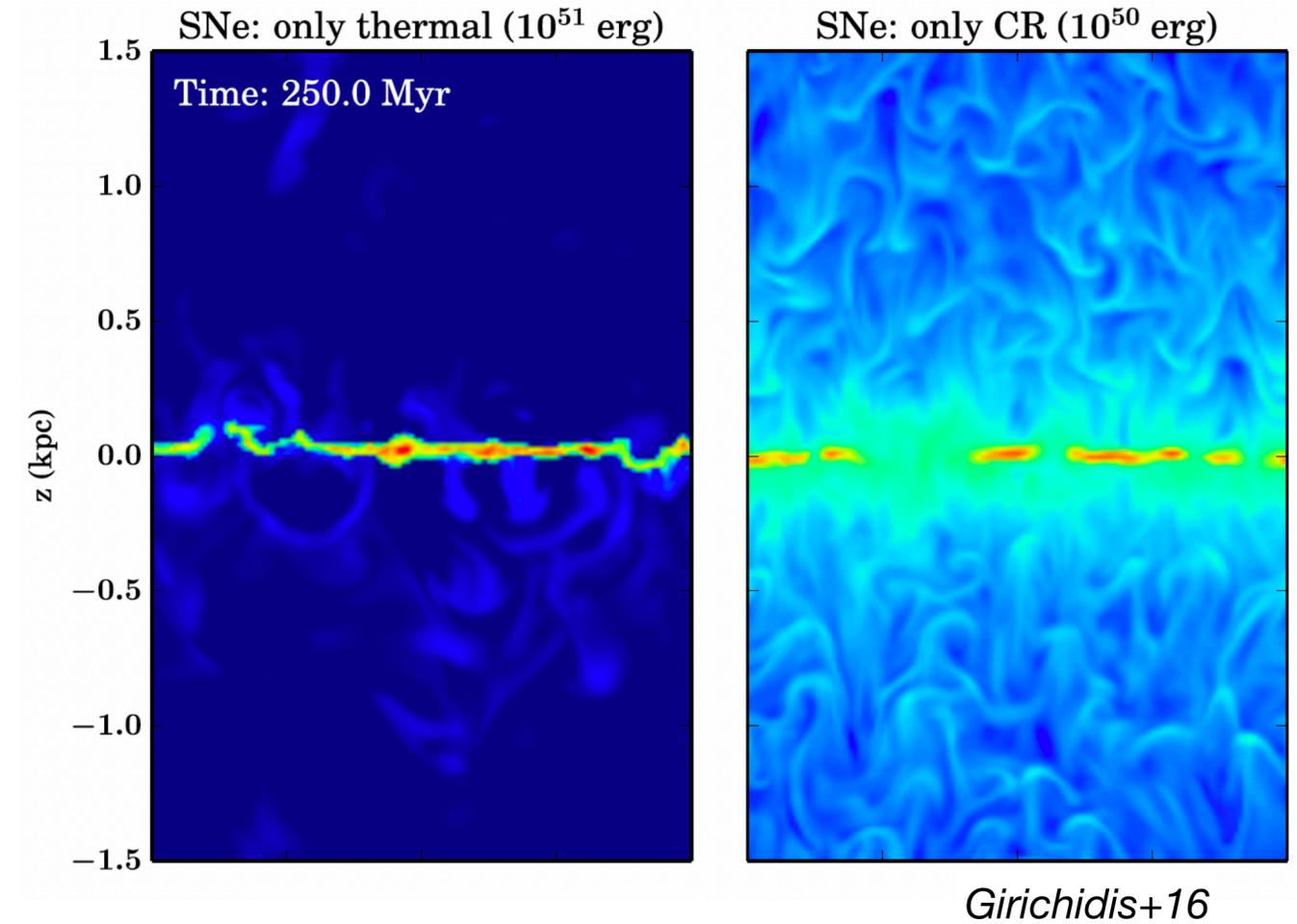
SNe: only thermal (10^{51} erg)   SNe: only CR (10^{50} erg)

Time: 250.0 Myr

Girichidis+16

Salem&Bryan+2014

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Cosmological simulations of reionization

- Usually require radiation-hydrodynamics

- Two classes of simulations:

  - Model the **sources** of reionization

  - Model the **process** of reionization

- My interest is the former:

  - What are the sources?
    f_{esc} vs galaxy (intrinsic & observational) properties

  - How does the LyC radiation get out?

  - How does reionization feedback work?
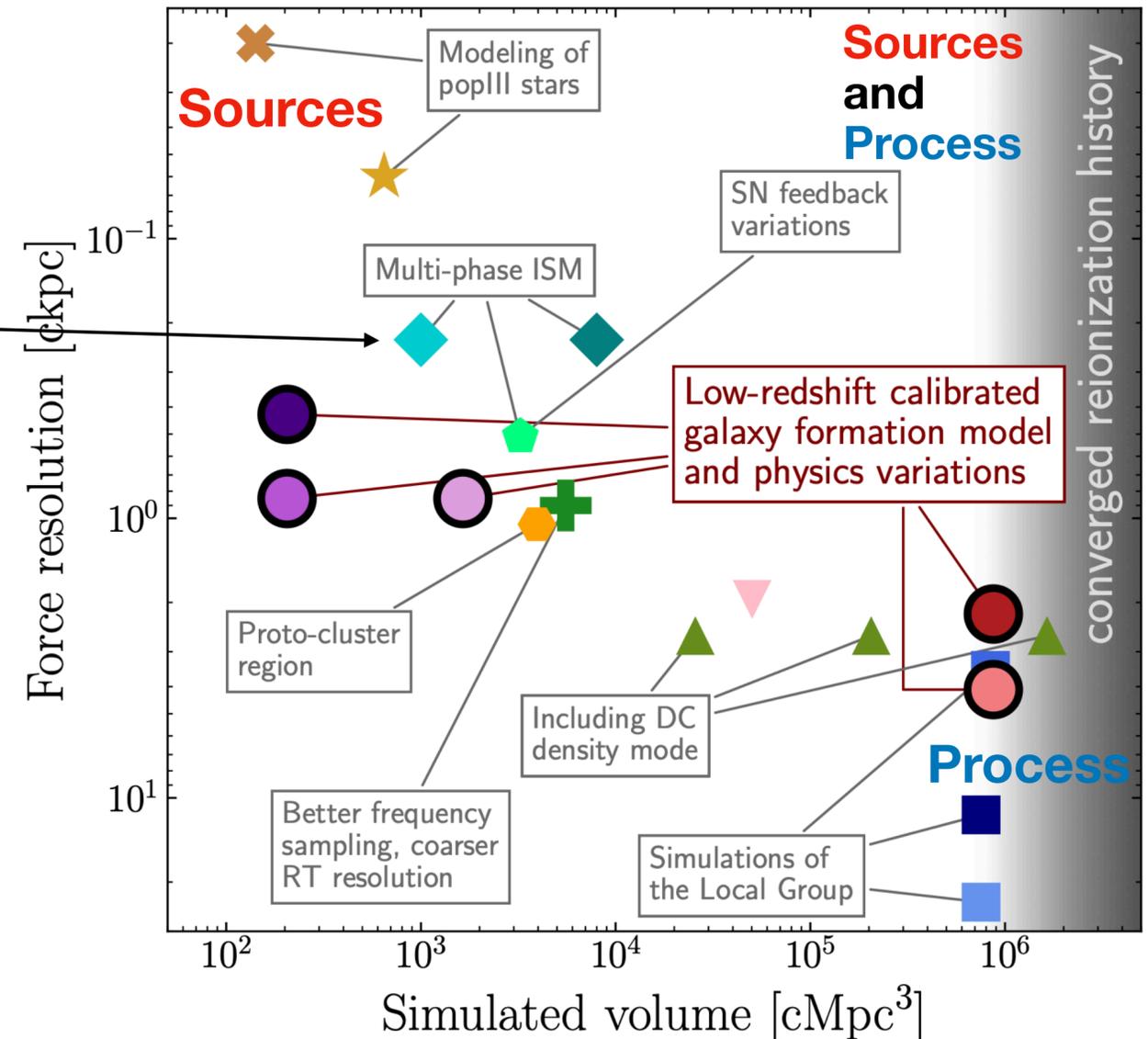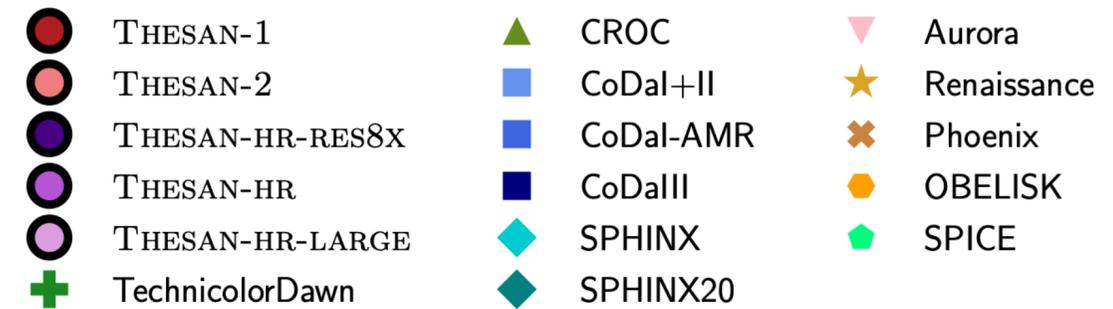
SPHINX²⁰ volume

- L_{box} = 20 cMpc

- Max 10 pc resolution

- BPASS SED model for LyC luminosities

- 32,000 star-forming galaxies at z=6

- ~5 billion adaptive refinement cells

- ~60 Mhrs of computing time

- ~200 TB of data

10^{-6} 10^{-4} 10^{-2} 10^{0}

Gas density [cm^{-3}]

392 kpc

743.2 Myr

10^{-5} 10^{-2} 10^{1} 10^{4} 10^{7} 10^{10}

Ionizing radiation flux [cm^{-2} s^{-1}]

10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}

Neutral gas fraction

10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

Temperature [K]
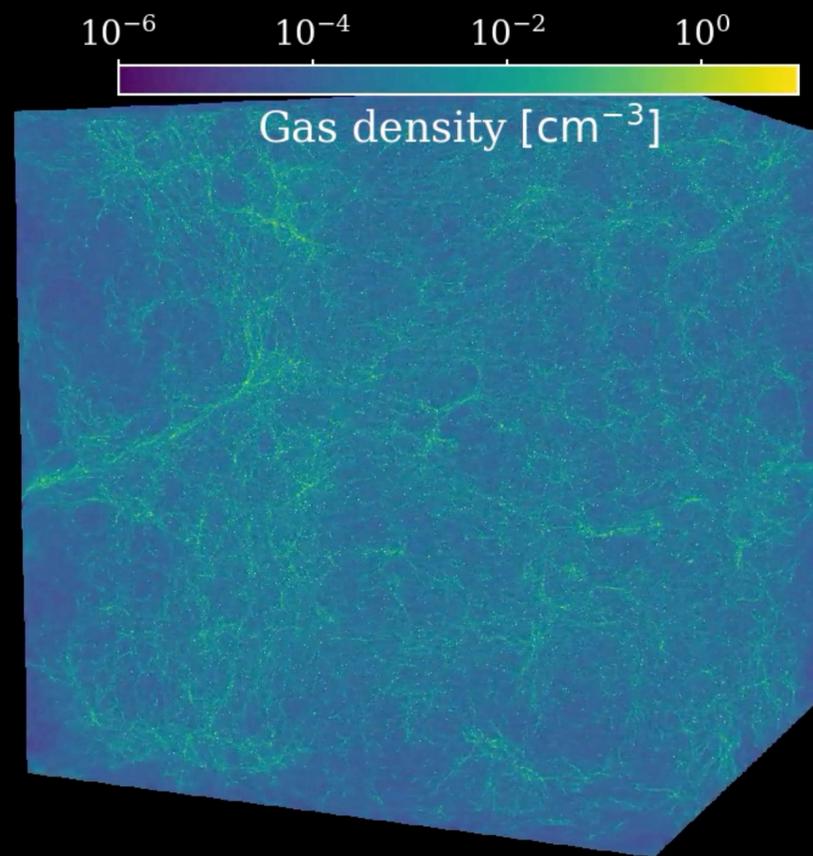
SPHINX²⁰ volume

close-up

- L_{box} = 20 cMpc

- Max 10 pc resolution

- BPASS SED model for LyC luminosities

- 32,000 star-forming galaxies at z=6

- ~5 billion adaptive refinement cells

- ~60 Mhrs of computing time

- ~200 TB of data

$z = 4.82$

Harley Katz, SPHINX Collaboration
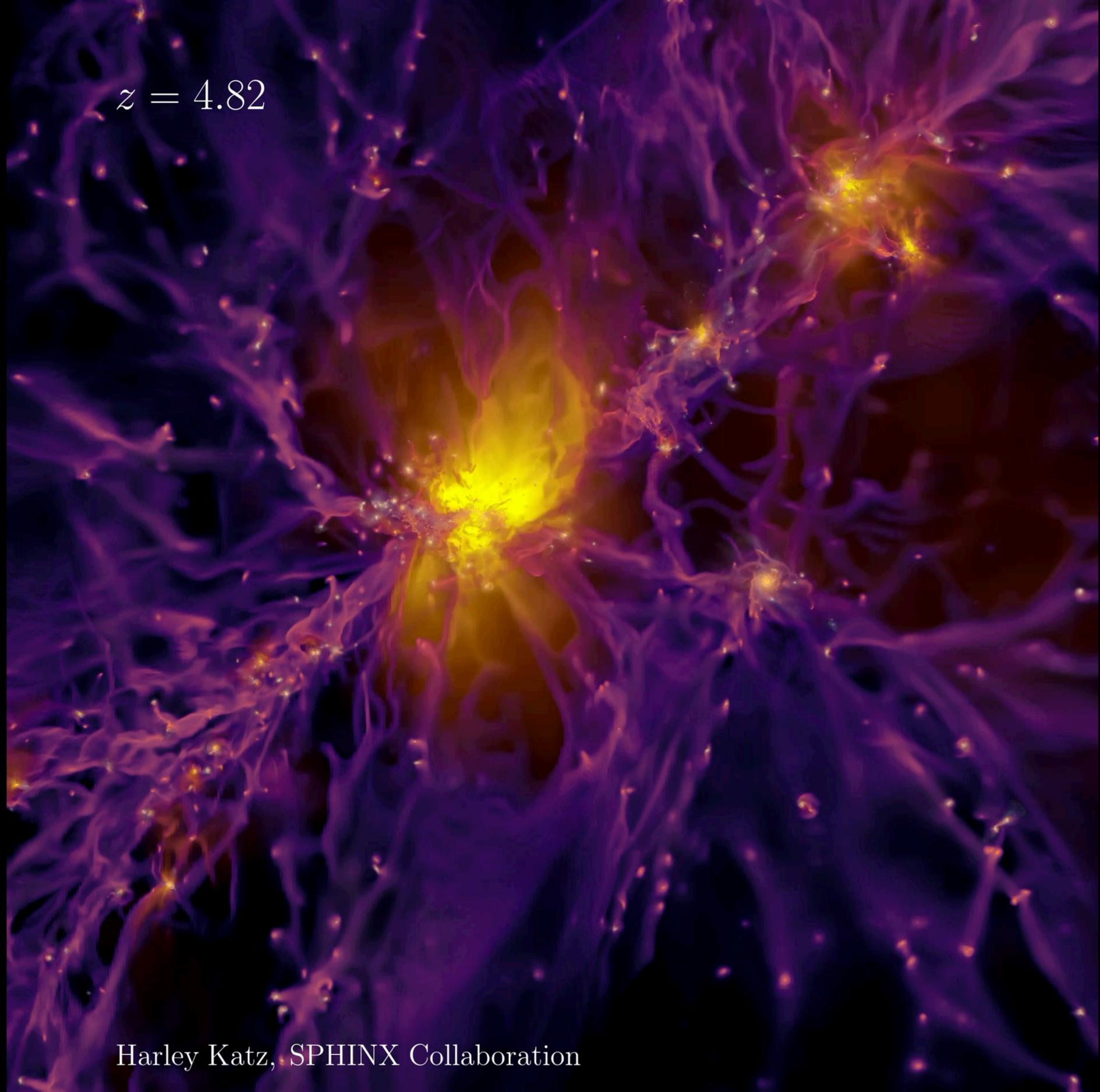
LyC escape fractions

- …are all over the place in simulations

- Yet all these simulations produce reasonable reionisation histories

- But f_{esc} is unresolved, to varying degrees (kpc to tens of pc resolution)

From Kostyuk+23 (TNG)
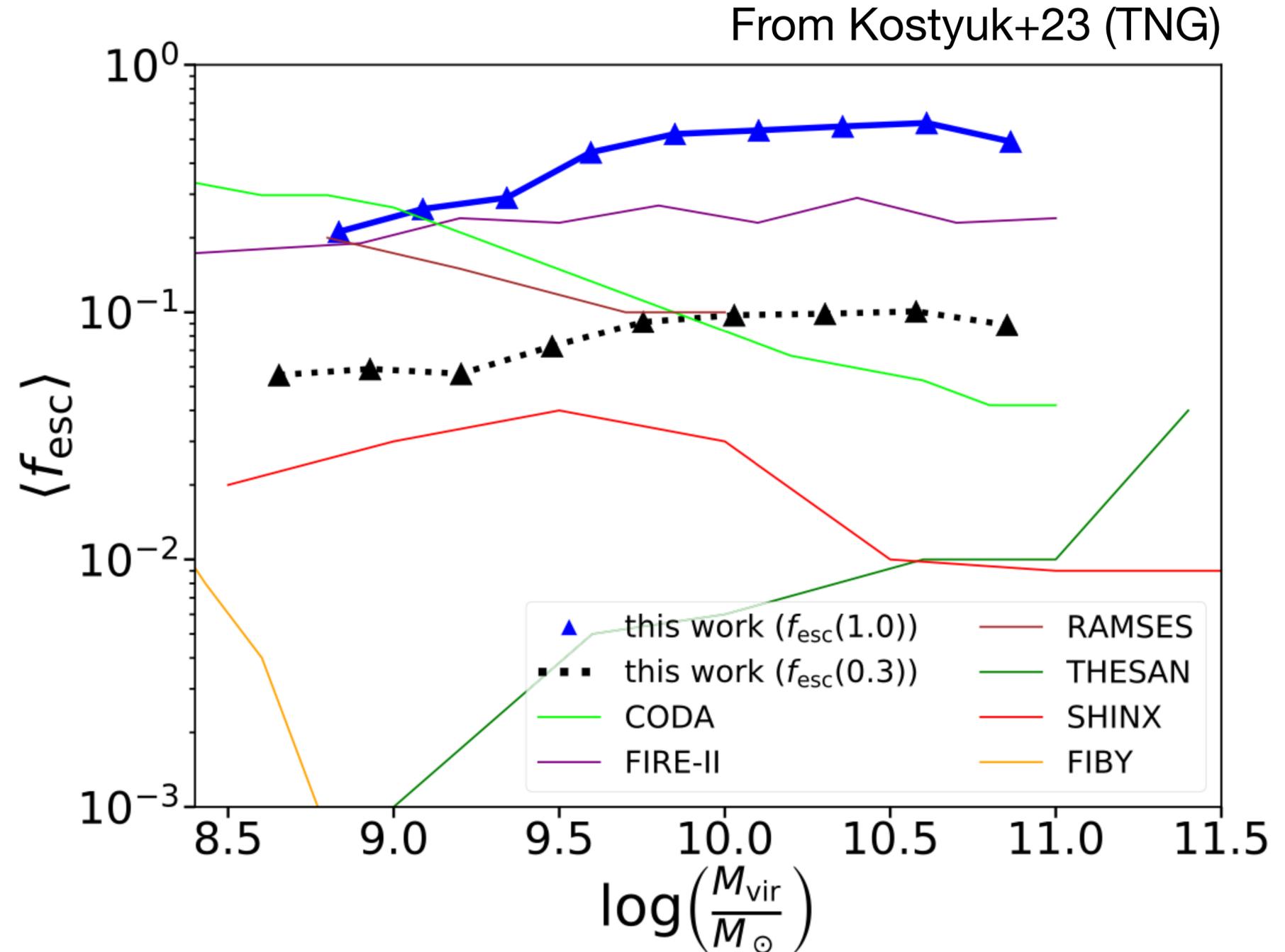
What happens at much higher resolution?

From Kimm+21

$f_{esc, LyC}$ vs Time [Myr]

- instant
- L-weight
- $N_{LyC}(t)$

$M_{cloud}=10^5\ M_\odot$
$M_{cloud}=10^6\ M_\odot$

$\Delta x=0.04$ pc
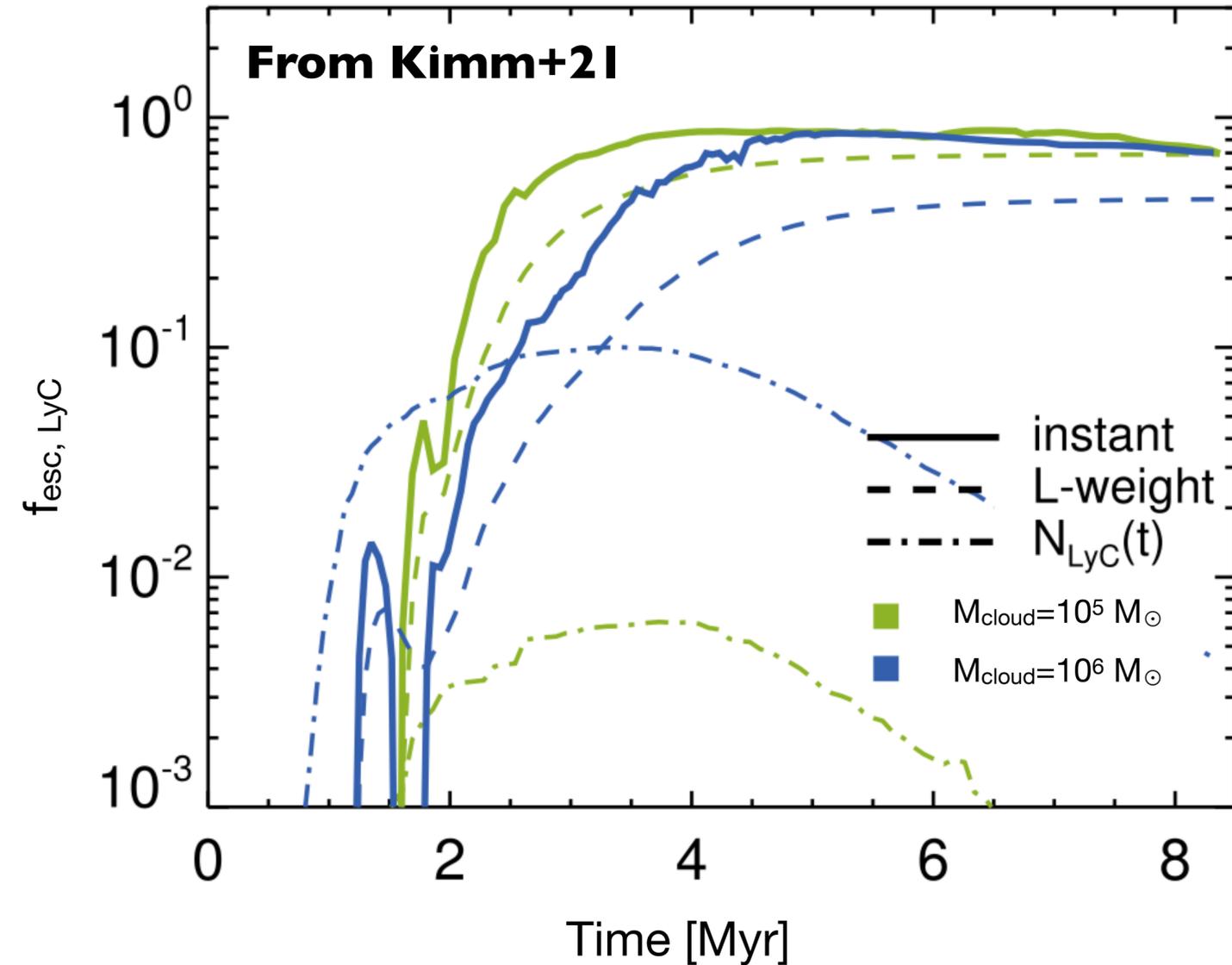
- *A lot of the radiation escapes the stellar nursery* *before SN explosions, due to radiation feedback*

- We need to capture this in galaxy simulations, with sub-pc resolution and samples of thousands of galaxies!!
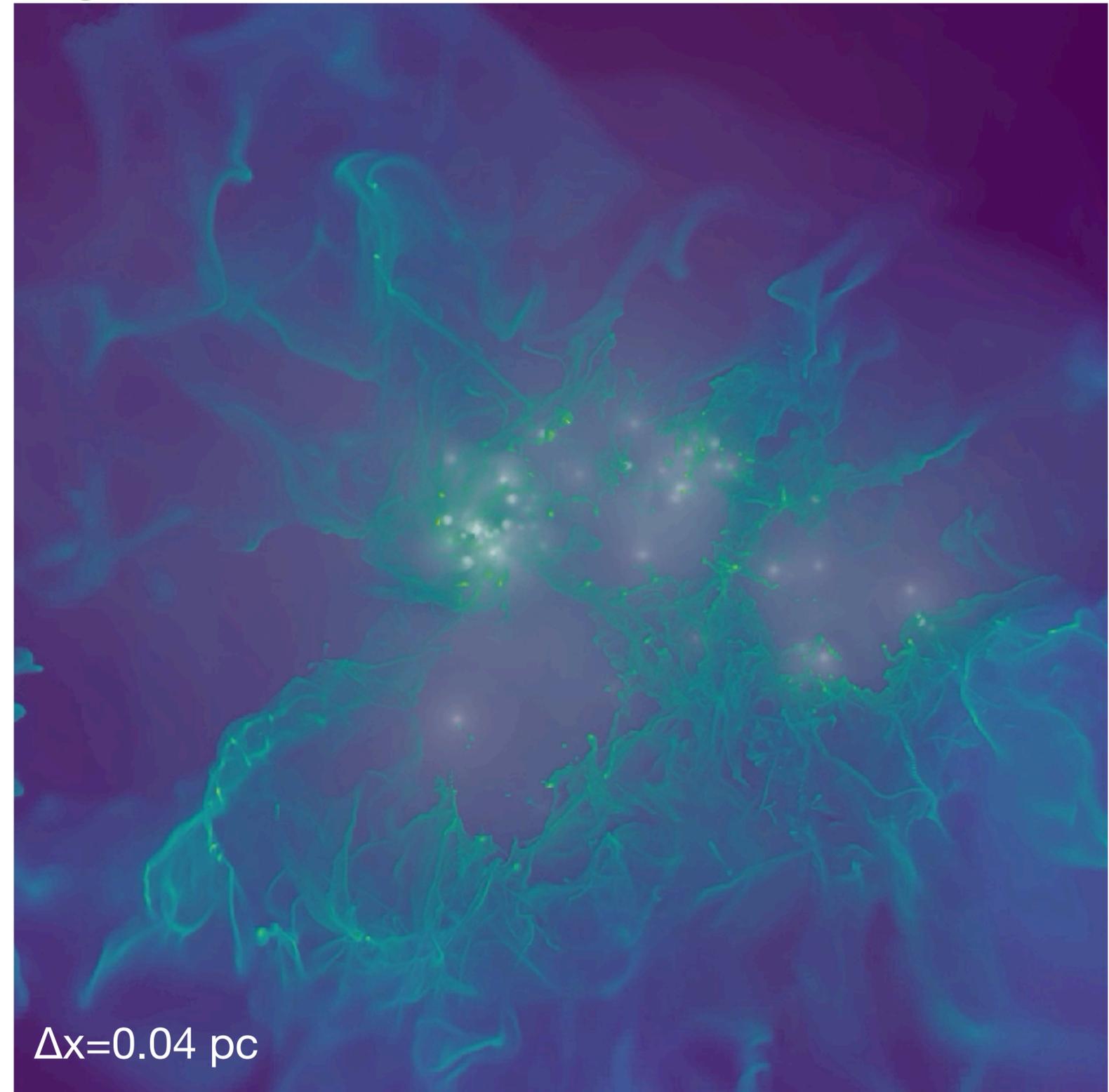
Reionization feedback

- Does reionization affect the growth of low-mass galaxies?

- It does, by evaporation and **starvation**
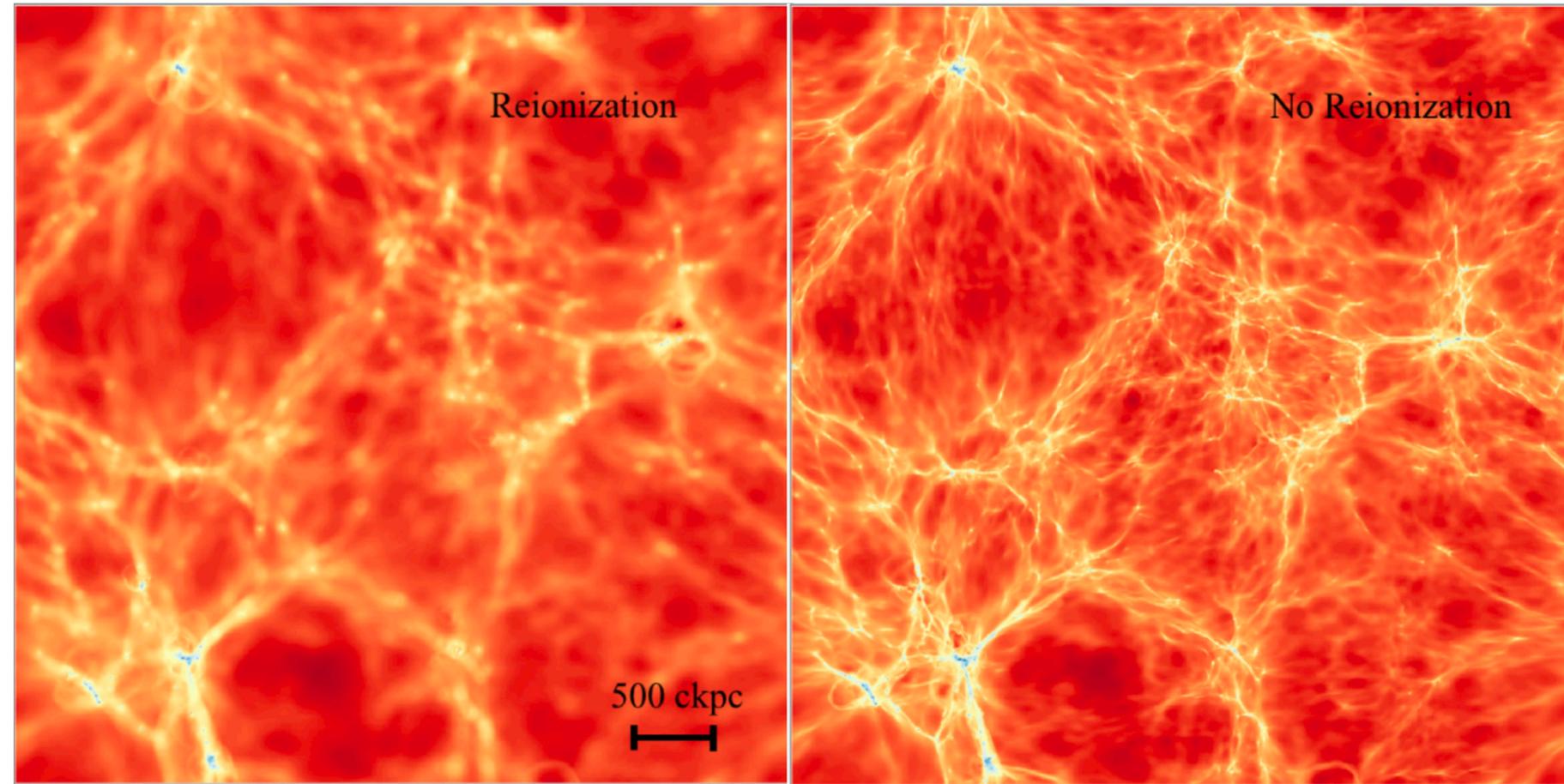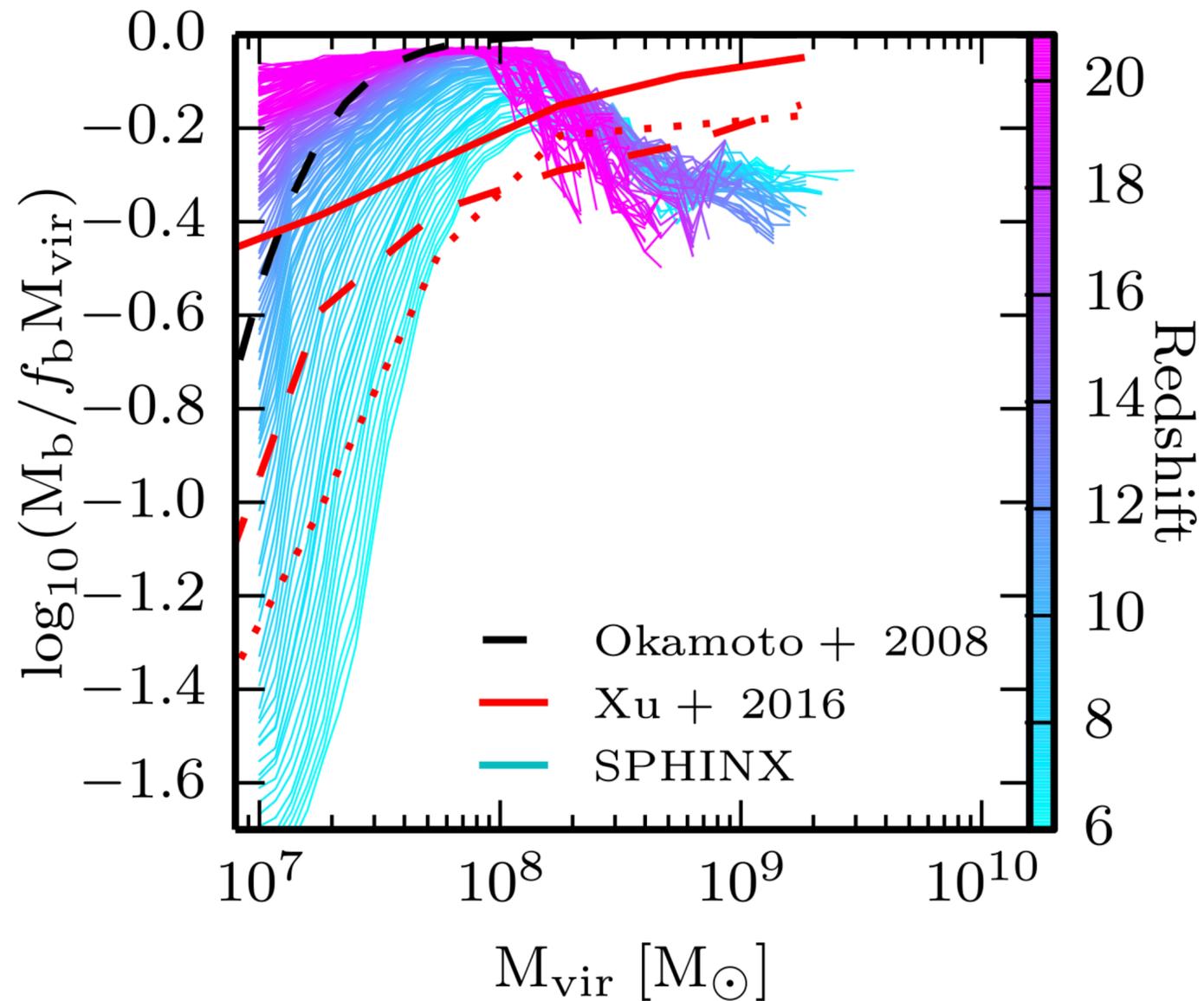
From Katz+20: 'How to Quench a Dwarf Galaxy'

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The First Stars

- **The big question is the IMF**

- Sets their luminosity (reionization), feedback, and enrichment (high-z galaxy evolution)

- To understand the IMF, we need idealised (non-cosmo) simulations

- …and a plethora of non-equilibrium network RMHD physical processes
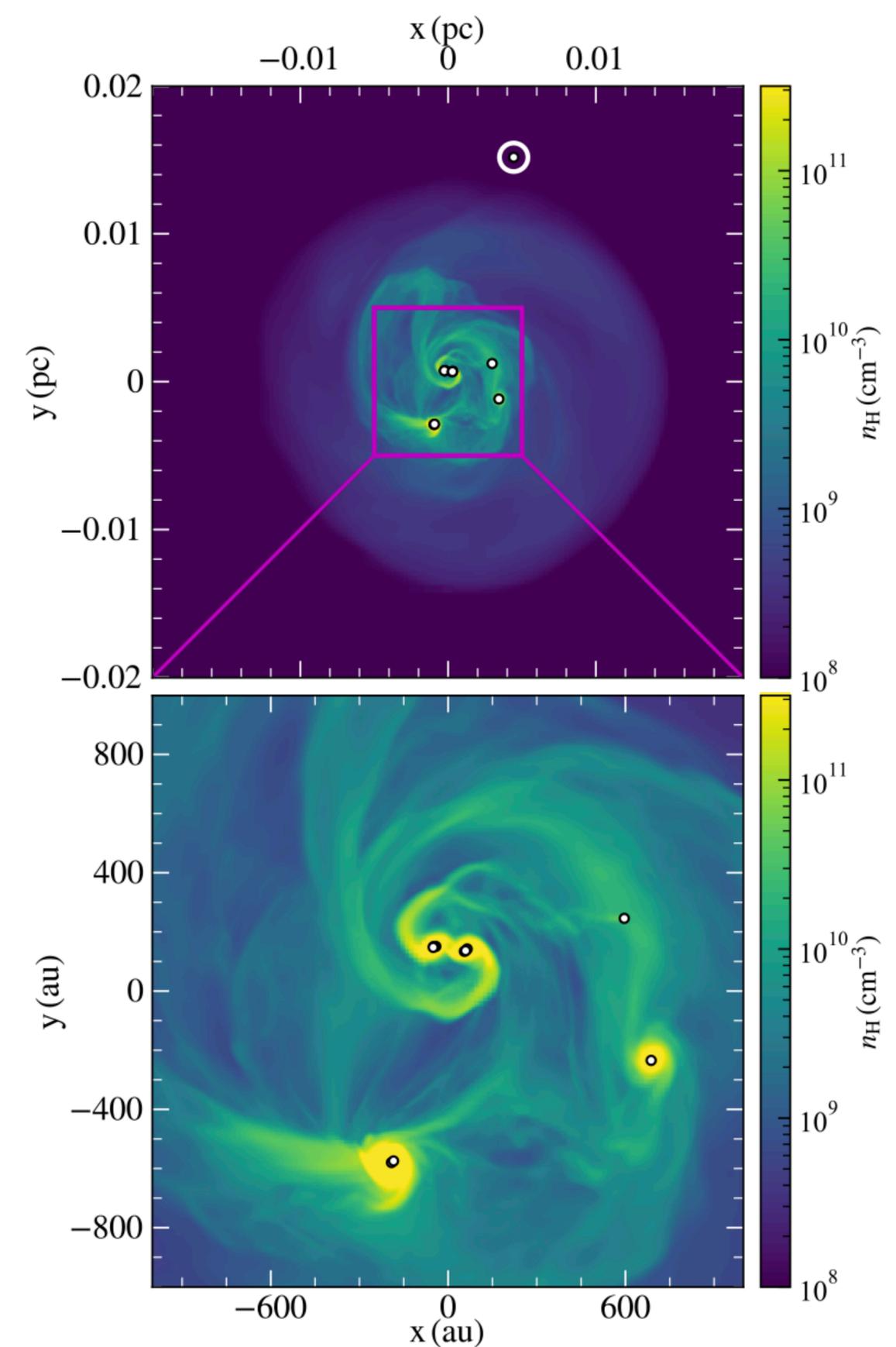
From Sharda & Menon (25)

The First Stars

- **The big question is the IMF**

- Sets their luminosity (reionization), feedback, and enrichment (high-z galaxy evolution)

- To understand the IMF, we need idealised (non-cosmo) simulations

- There is a lot of work but **little agreement**

- This improves as physical ingredients are added, but there are still barriers, such as knowledge of the primordial magnetic field
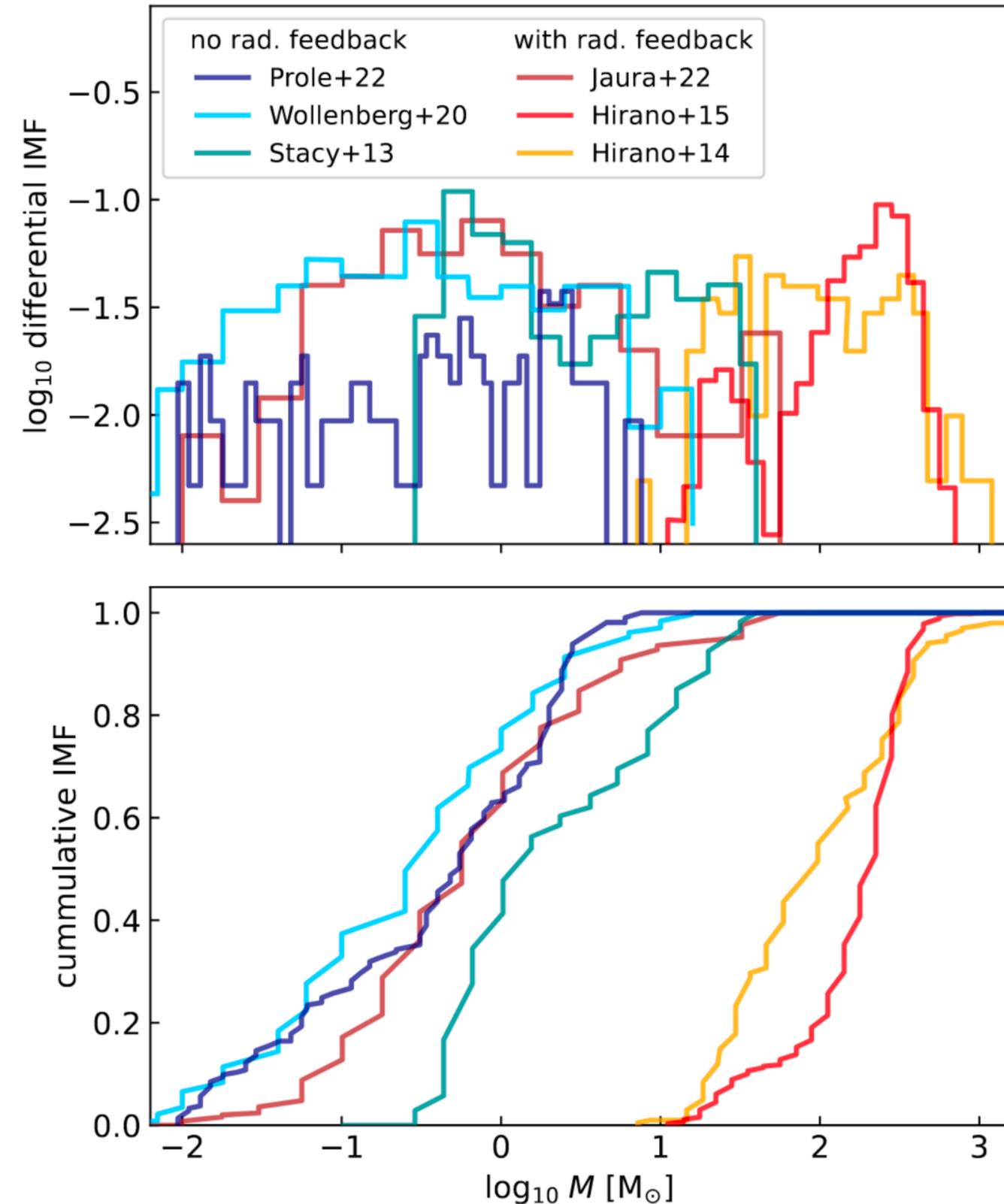
The First Stars in cosmological simulations

- We can use cosmological simulations to probe when and where the first stars form

- Most simulations agree on

$$z \approx 25 - 30$$

in halos with

$$M_{\mathrm{vir}} \approx 10^5 - 10^6 \, M_\odot$$

From Lenoble+24
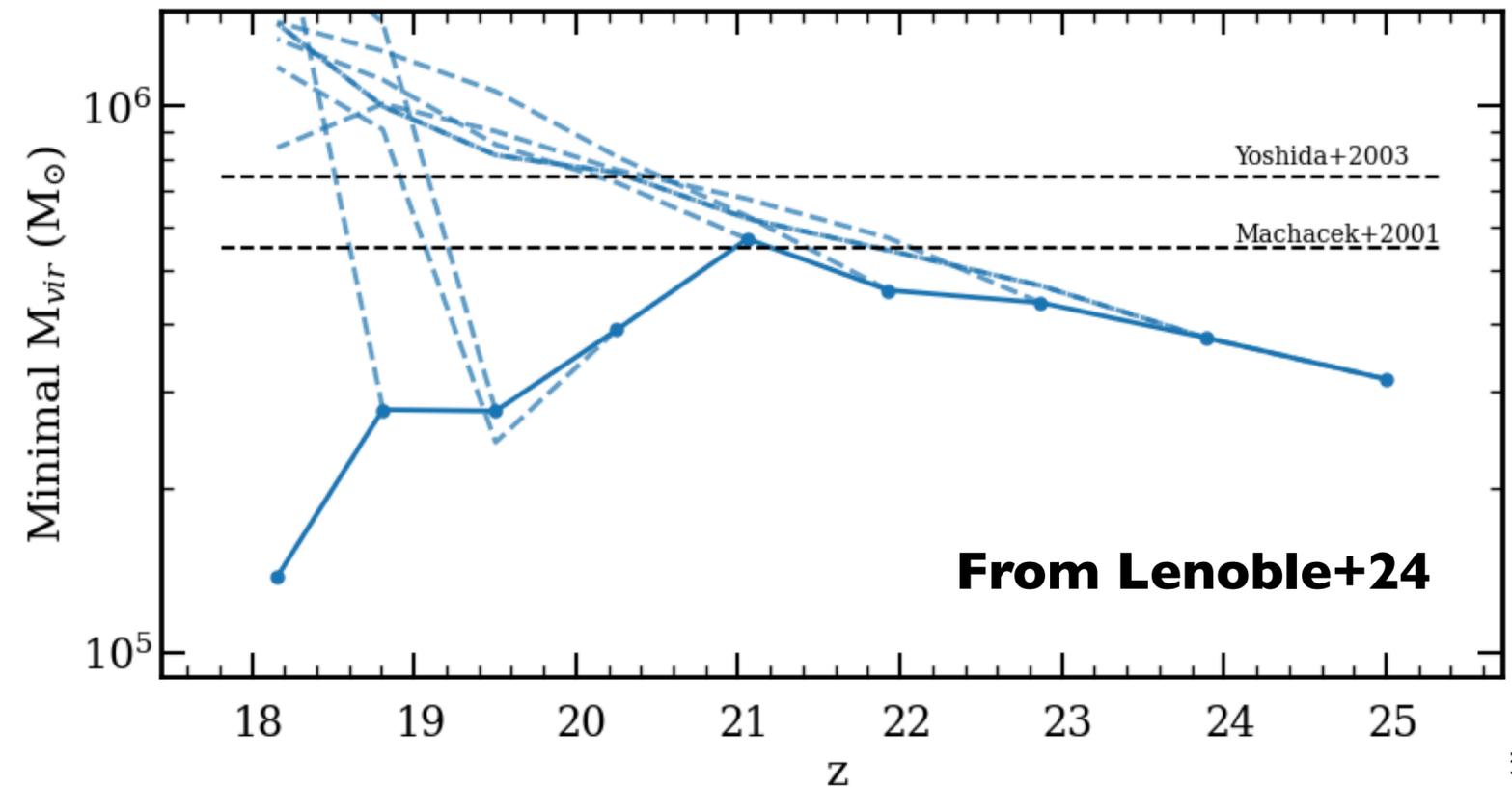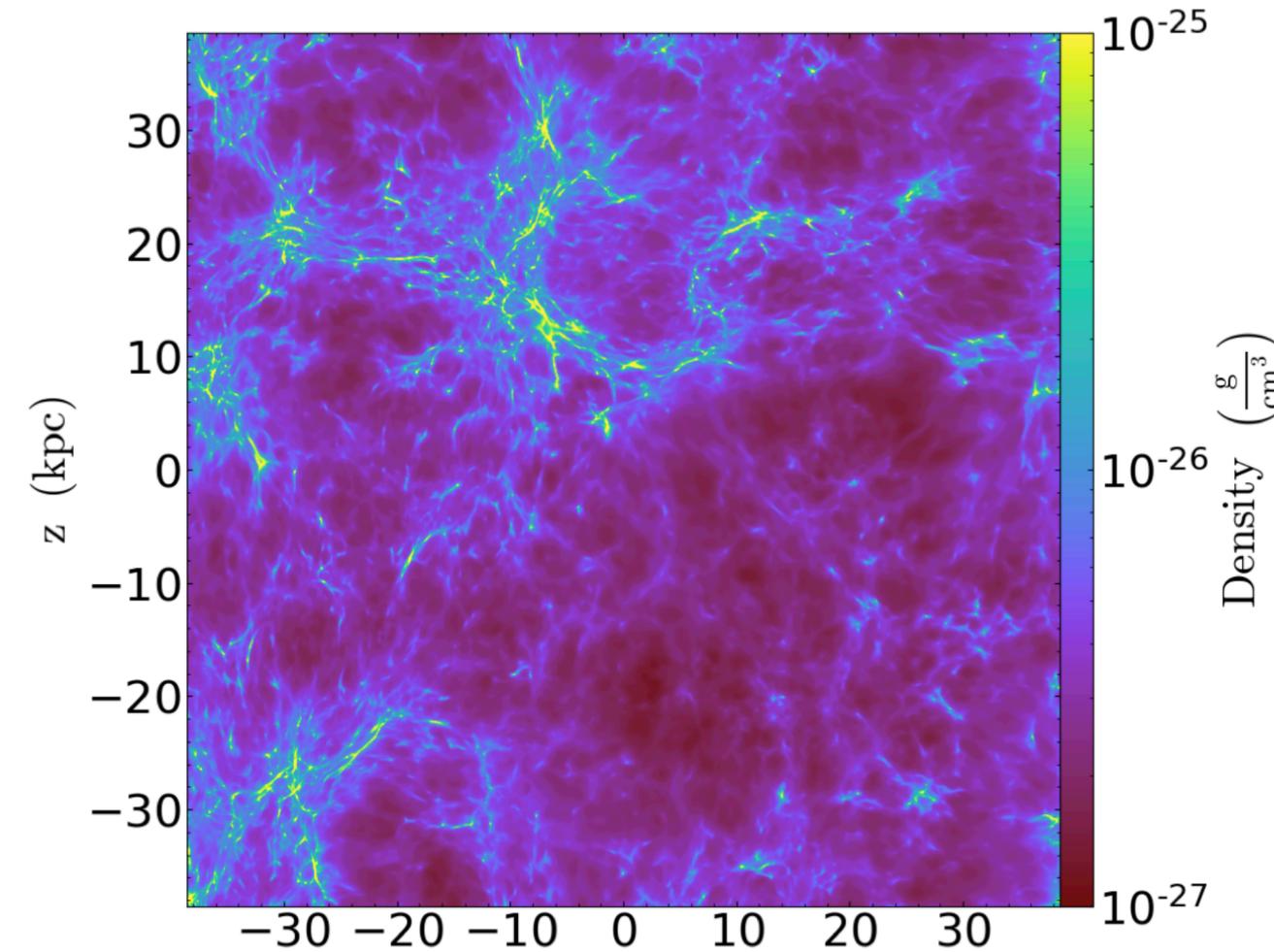
The First Stars may form down to z~5

- The timeframe for PopIII formation in a given galaxy is very short, due to fast enrichment

- Reionization shuts down the initiation of star formation in pristine low-mass halos by 'starving' them (e.g. Katz+20, Rey+20)

- So **reionization shuts down PopIII formation** (Zier+25)
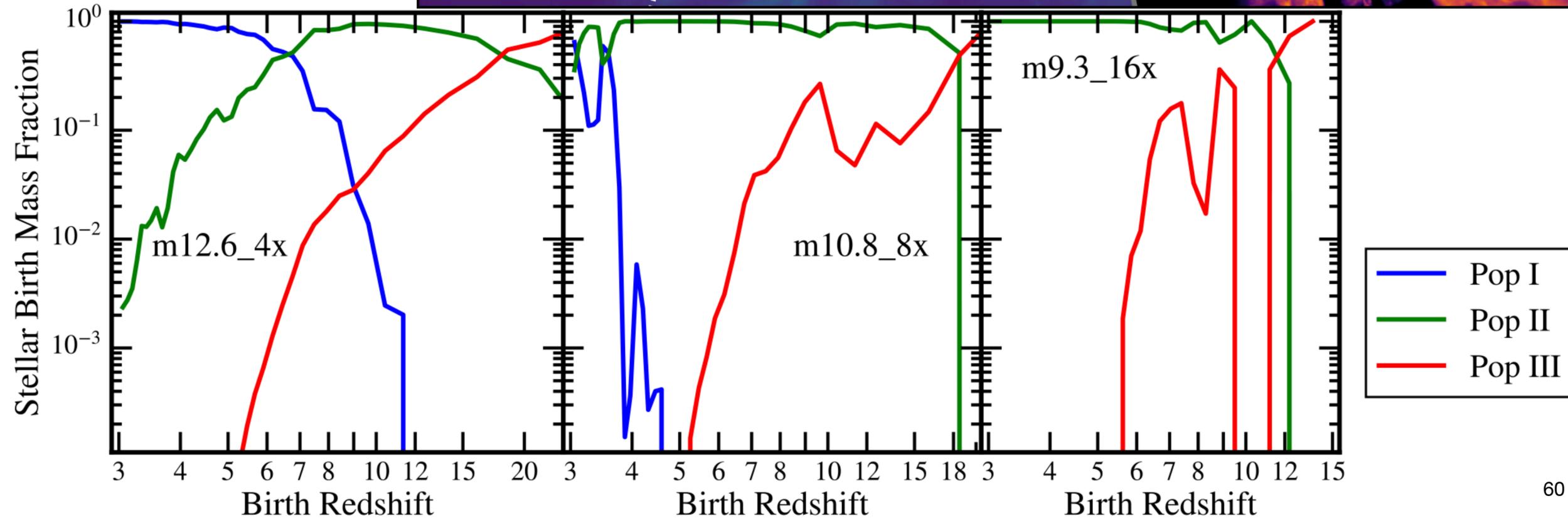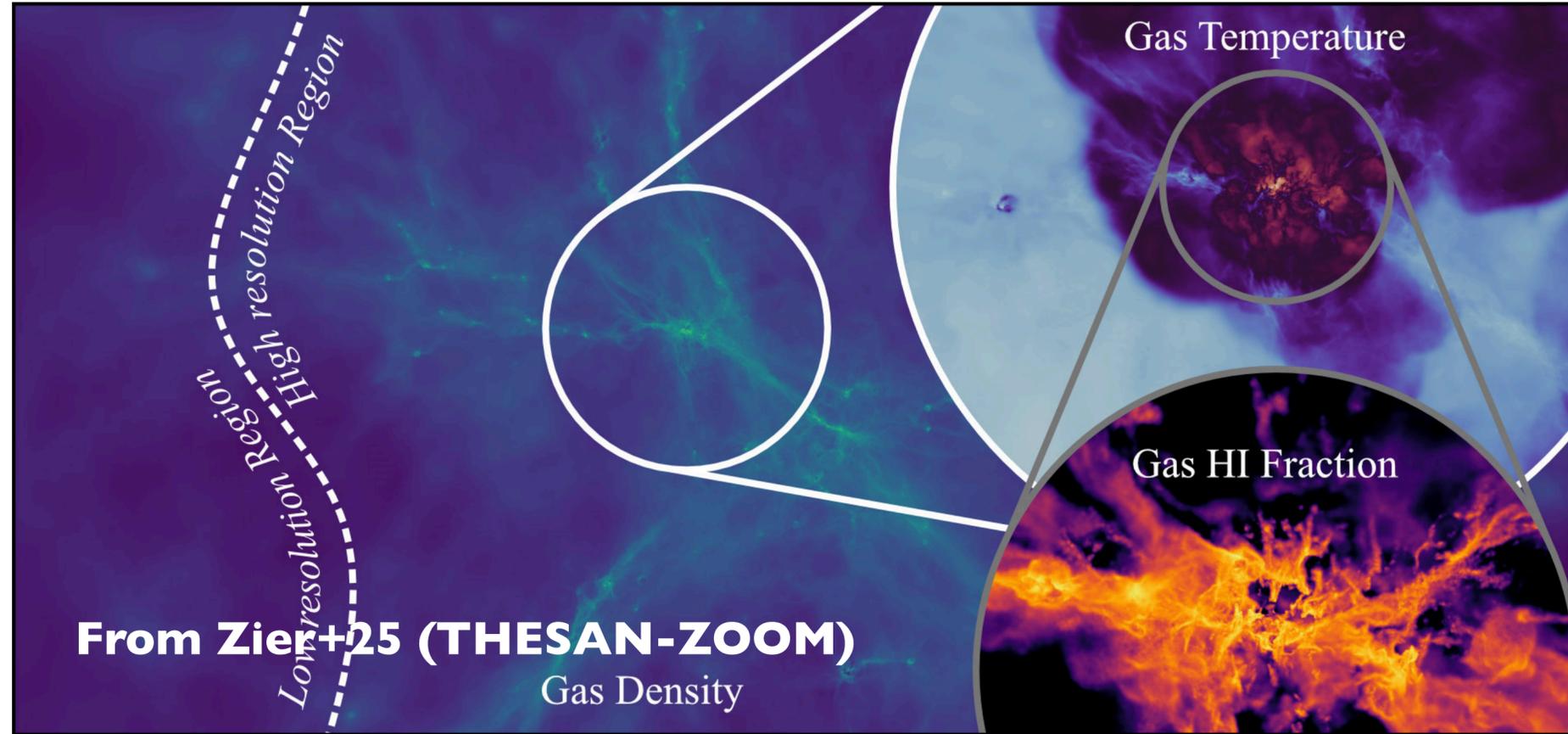
Gas Temperature

Low resolution Region   High resolution Region

Gas HI Fraction

From Zier+25 (THESAN-ZOOM)

Gas Density

m12.6_4x

m10.8_8x

m9.3_16x

Stellar Birth Mass Fraction

Birth Redshift

Pop I
Pop II
Pop III

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10 years ago…

- The focus was on low-z (where we had observations)

- Some looked at those simulations at high-z, but usually this didn't give favourable comparisons

- Already then hints of too strong SFR suppression at high-z

From Furlong+15 (EAGLE)
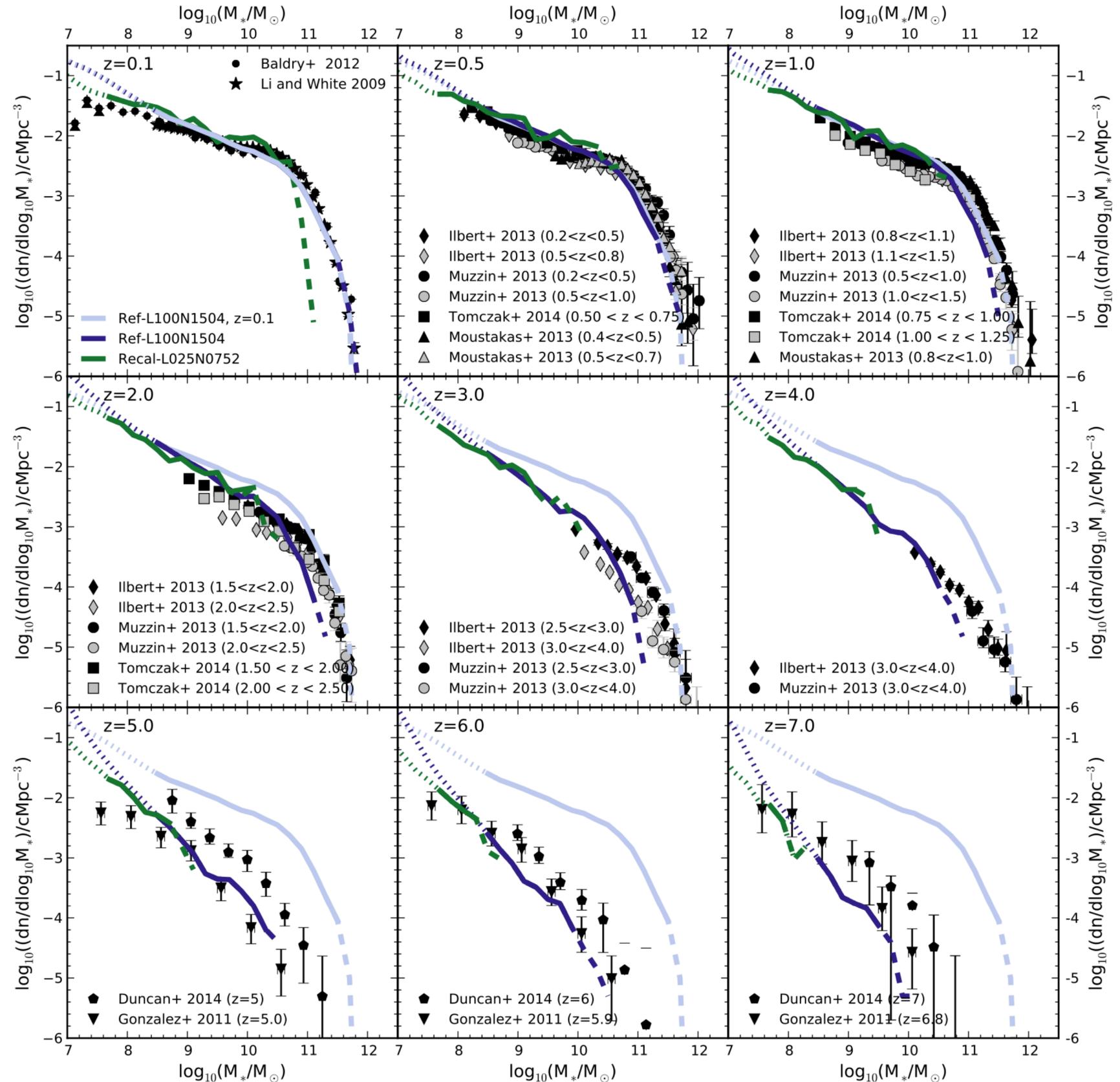
Massive extreme-z galaxies with CEERS

Labbé+23

- Early JWST observations revealed MW-plus galaxies at (photometric) z>6!
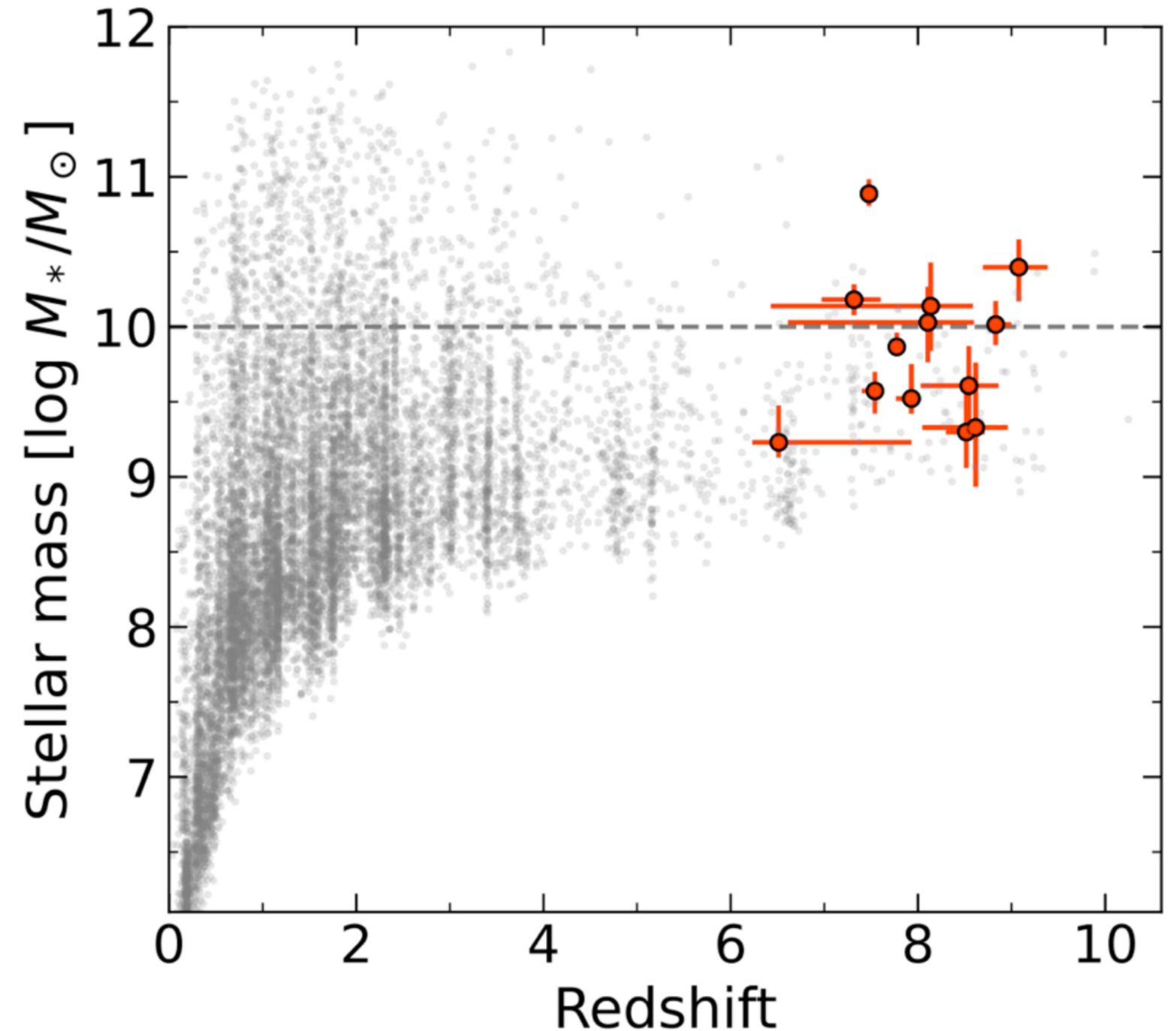
What does it mean?
Lovell+22 (and Boylan-Kolchin 23)

- Extreme Value Statistics and Press-Schechter

- The most extreme detections clearly broke ΛCDM — the galaxies form too many stars!

- The most extreme detections have largely gone, but high-z galaxies appear to form **fast** and have extreme SFRs!

A numerical modeller, having spent a decade on **suppressing** star formation
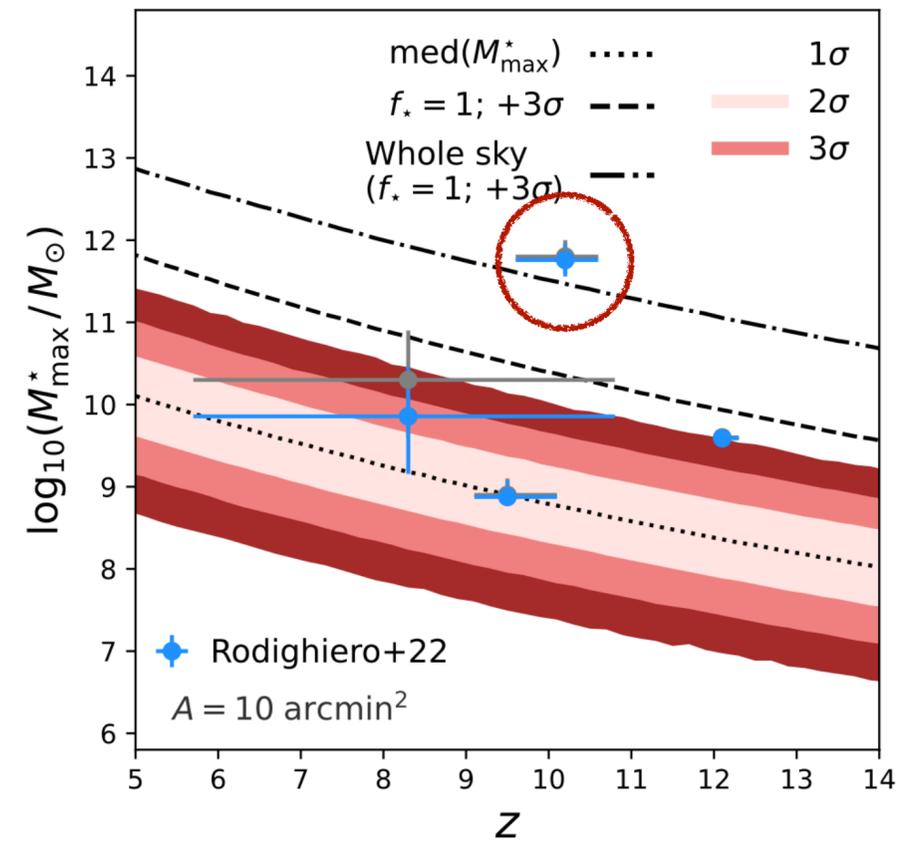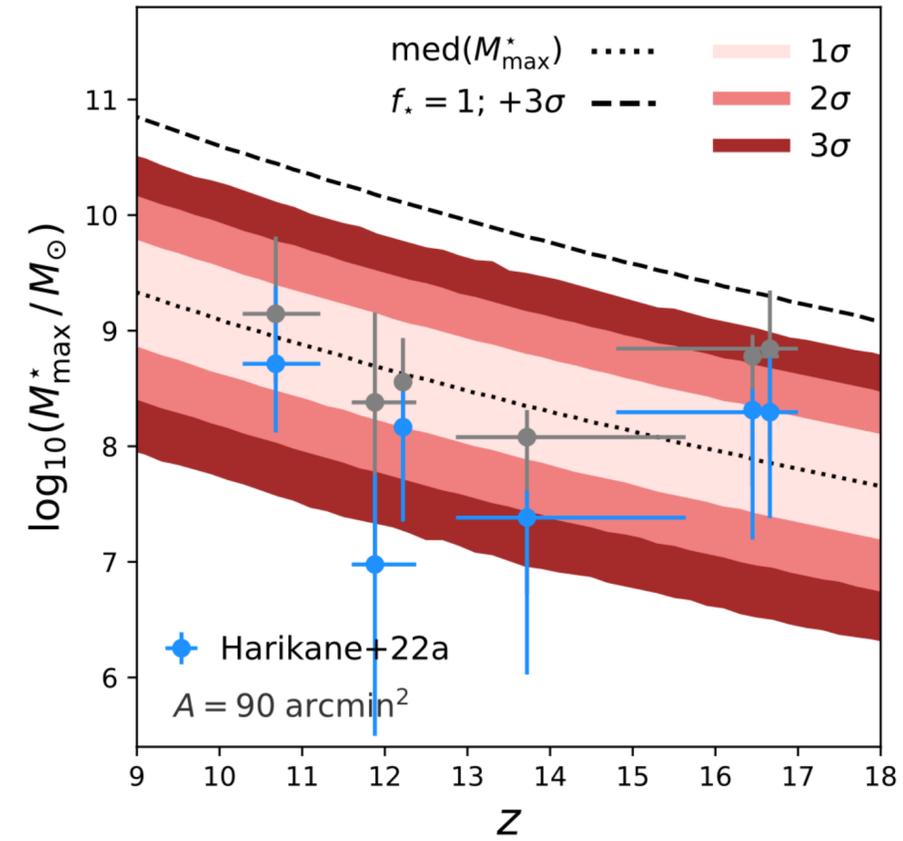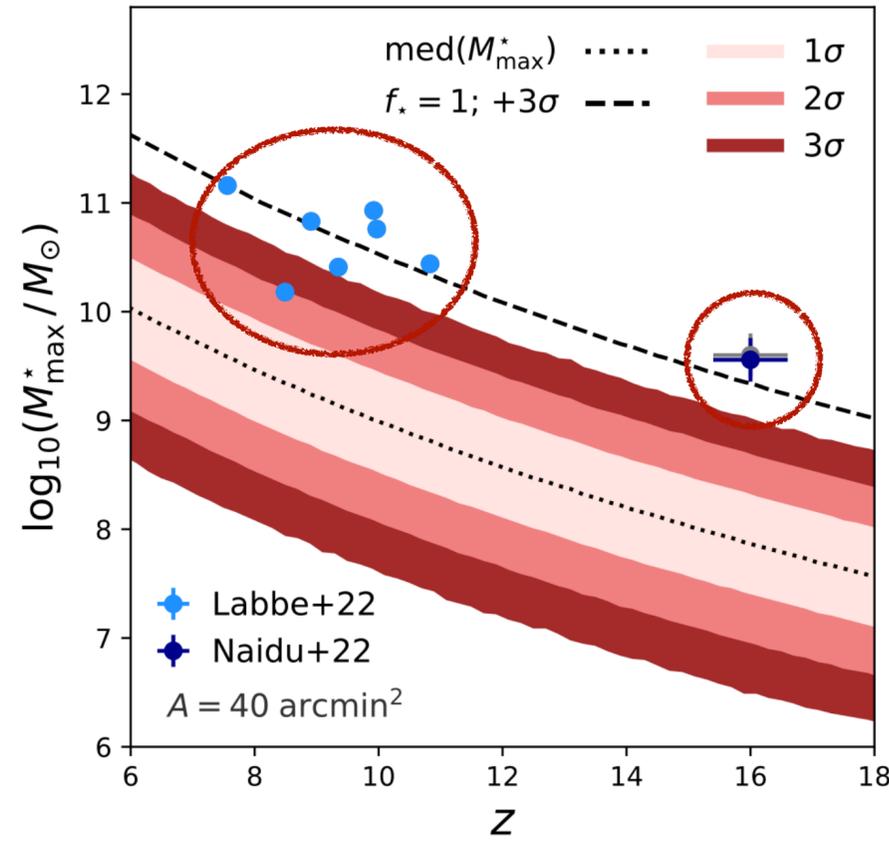
Circled objects have later moved to lower redshifts or become possible AGN

Photometry vs spectroscopy
(or NIRCam vs NIRSpec)

From Jiyoung Choe+25

- Galaxy **redshift** is determined from emission lines (e.g. Lya, Ha, OIII, NII etc)

- Most observations are ***photometric***, far from resolving these lines

- Photometric redshift estimation is done by **SED fitting**, finding the best-fitting magnitudes for an array of spectra given $(z, M_{\text{gal}}, \text{SFH}, Z, \text{dust})$

- Highly degenerate and sometimes completely wrong! (interlopers, impostors)

- Spectroscopic redshift is much more robust — but the observations are more expensive

Legend:
- Mock spectrum of a galaxy with $M_\star = 10^{7.7}\,M_\odot$
- JWST NIRCAM magnitudes
- Intrinsic stellar continuum
- Intrinsic nebular continuum

Axes: Flux [μJy] vs Observed wavelength [μm]

Filters: F115W, F150W, F200W, F277W, F356W, F444W
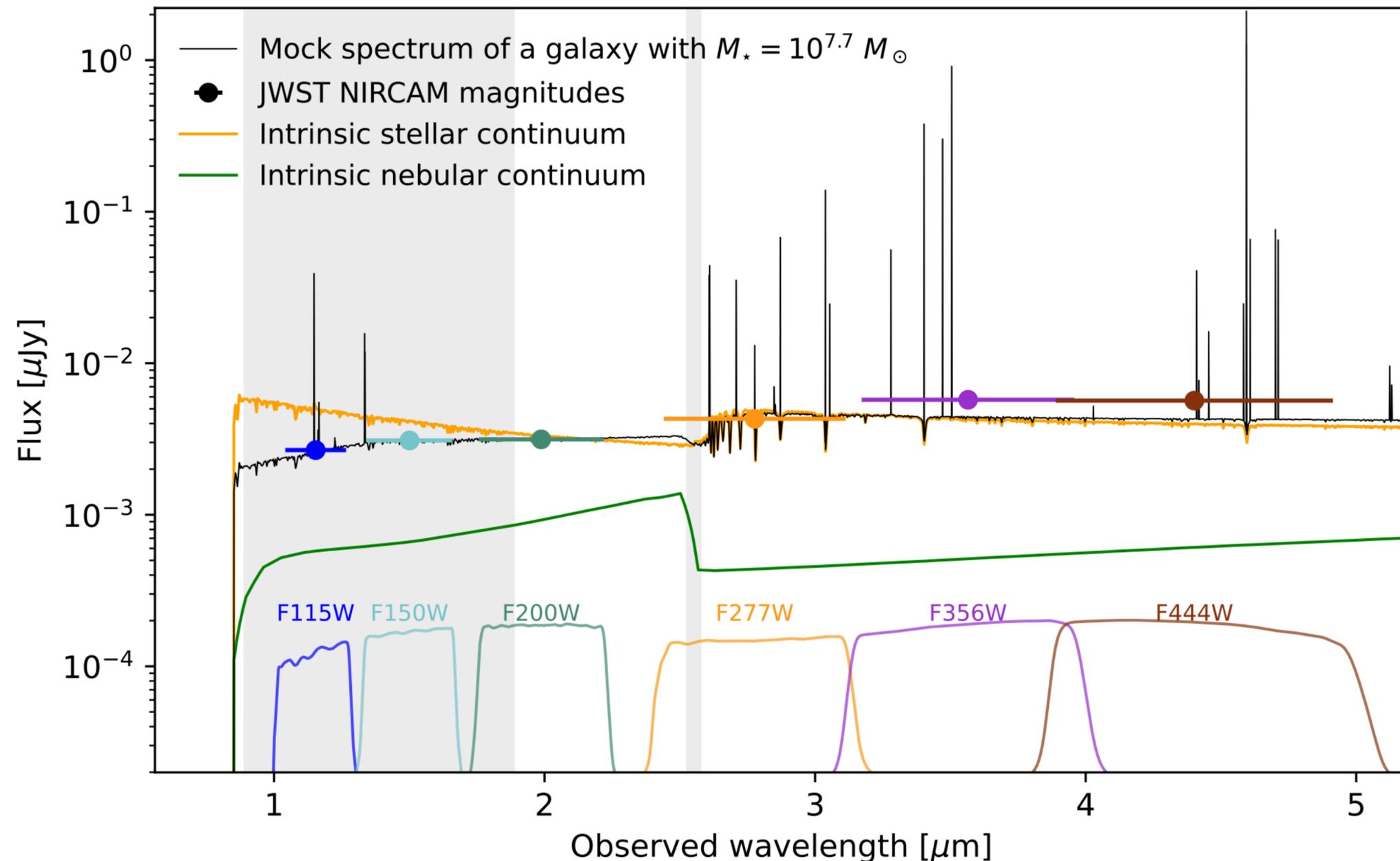
Has JWST Already Falsified Dark-matter-driven Galaxy Formation?

Moritz Haslbauer[1,2] (iD), Pavel Kroupa[1,3] (iD), Akram Hasani Zonoozi[4] (iD), and Hosein Haghi[4] (iD)

[1] Helmholtz-Institut für Strahlen- und Kernphysik (HISKP), University of Bonn, Nussallee 14−16, D-53115 Bonn, Germany; mhaslbauer@astro.uni-bonn.de
[2] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
[3] Astronomical Institute, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, CZ-180 00 Praha 8, Czech Republic
[4] Department of Physics, Institute for Advanced Studies in Basic Sciences (IASBS), Zanjan 45137-66731, Iran

- Comparison with EAGLE and IllustrisTNG

- This looks scary, but

  - CEERS-1749 is an impostor out and

  - …the ID galaxies may host AGN and

  - …the simulations are **calibrated to massive low-z galaxies**

- Yet, these early papers are still being cited (to advertise the failure of ΛCDM and promote alternative cosmologies, modified gravity, …)
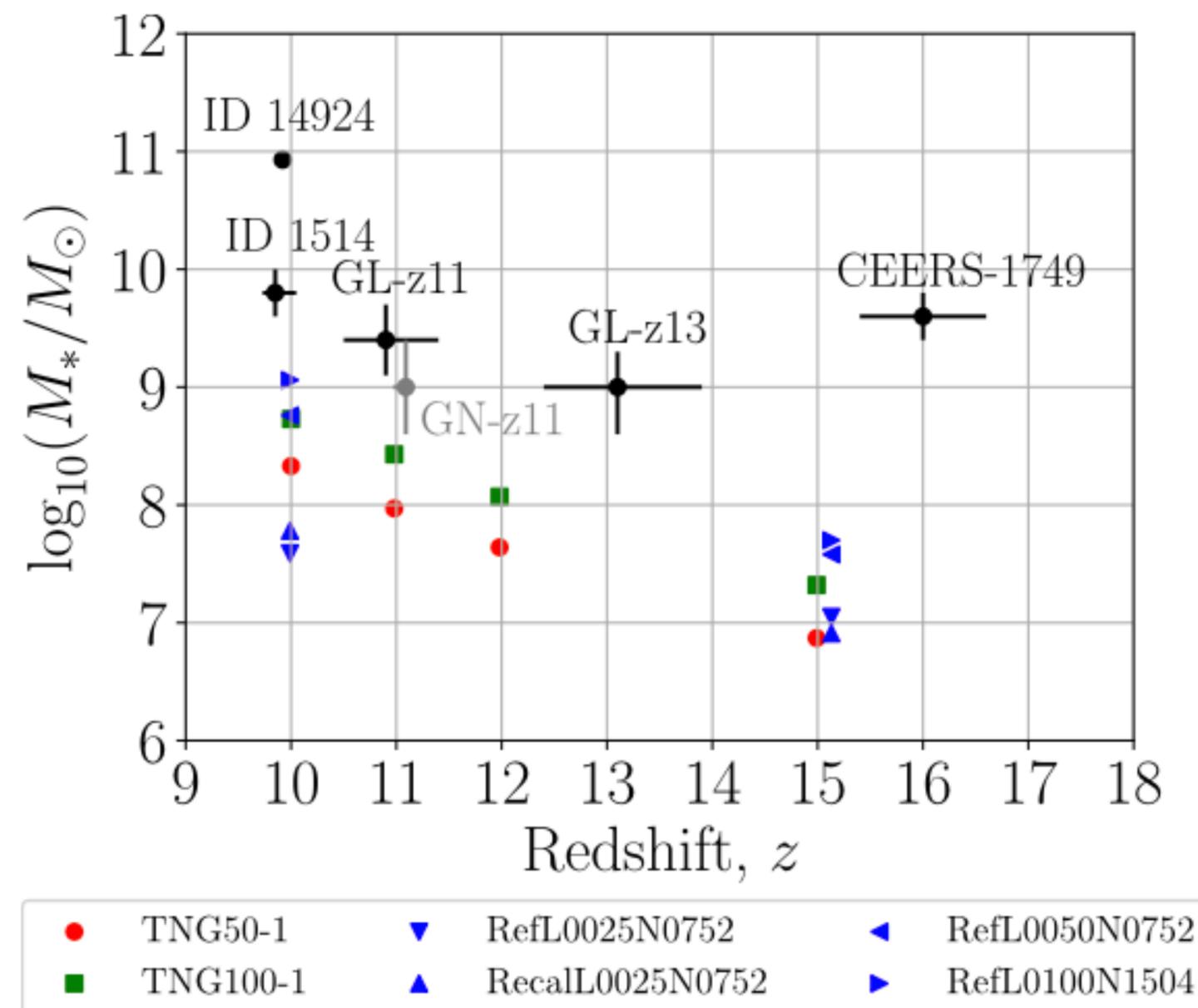
More pre-JWST simulation comparisons
Keller+22
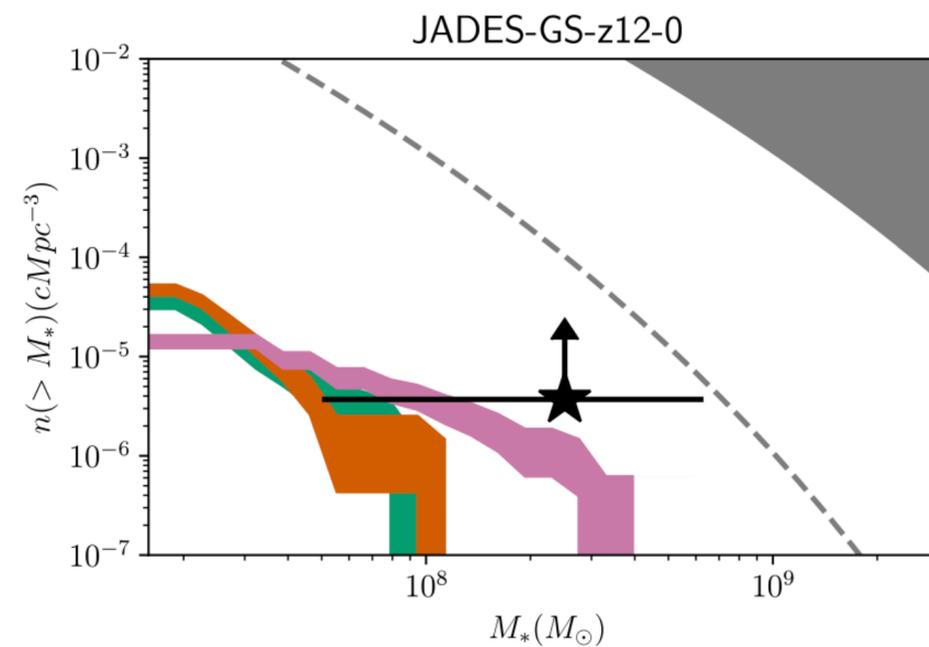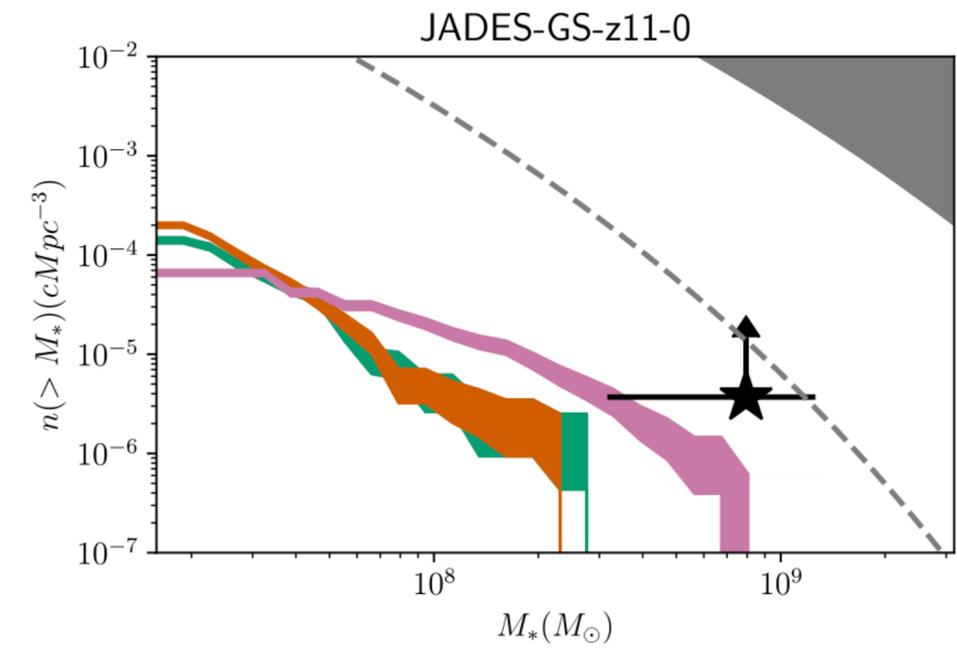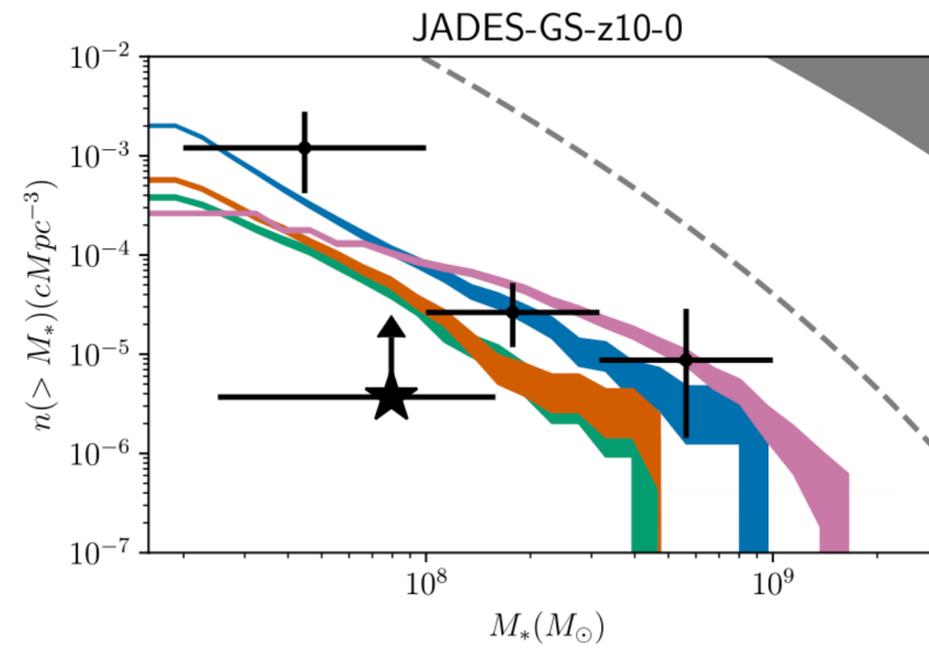
- Could simulations reproduce the *confirmed* massive high-z galaxies?

- Survey of recent cosmological simulations

- Some simulations *were* able to produce those massive galaxies

- Even if they are not 'built' for these redshifts
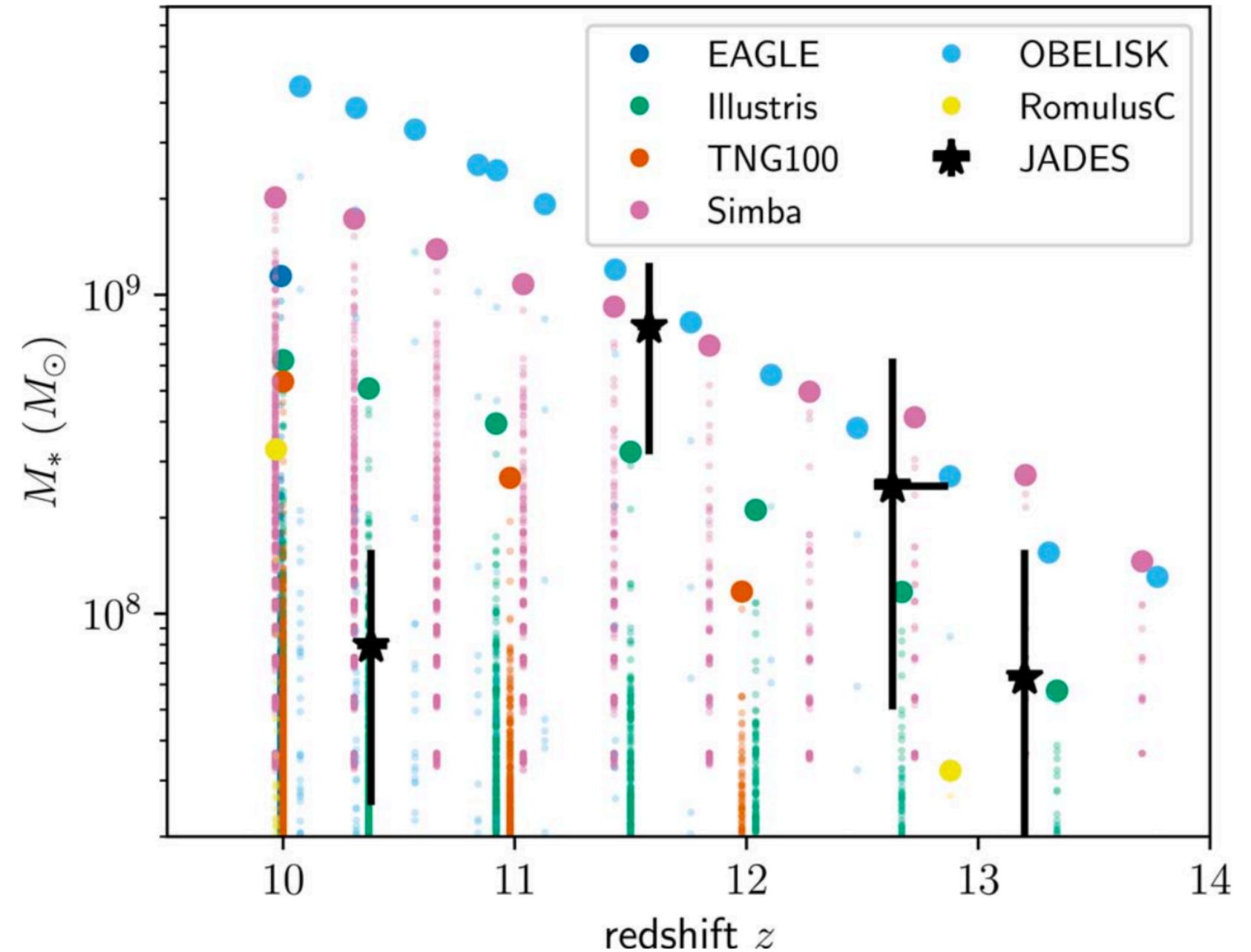
# More pre-JWST simulation comparisons
Keller+22

- Even in terms of number densities these 'old' simulations *were* not doing so bad
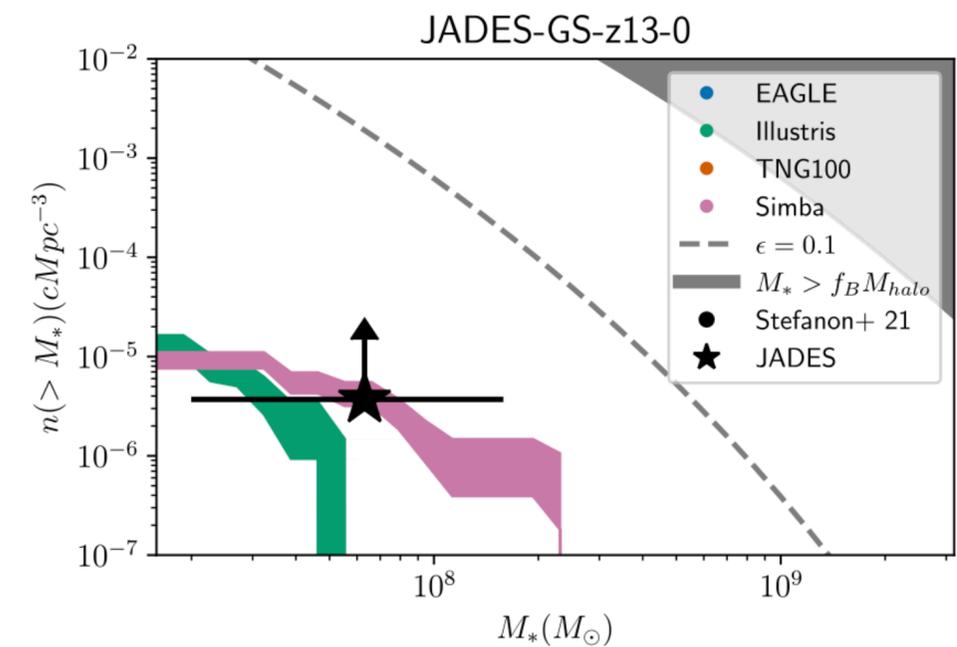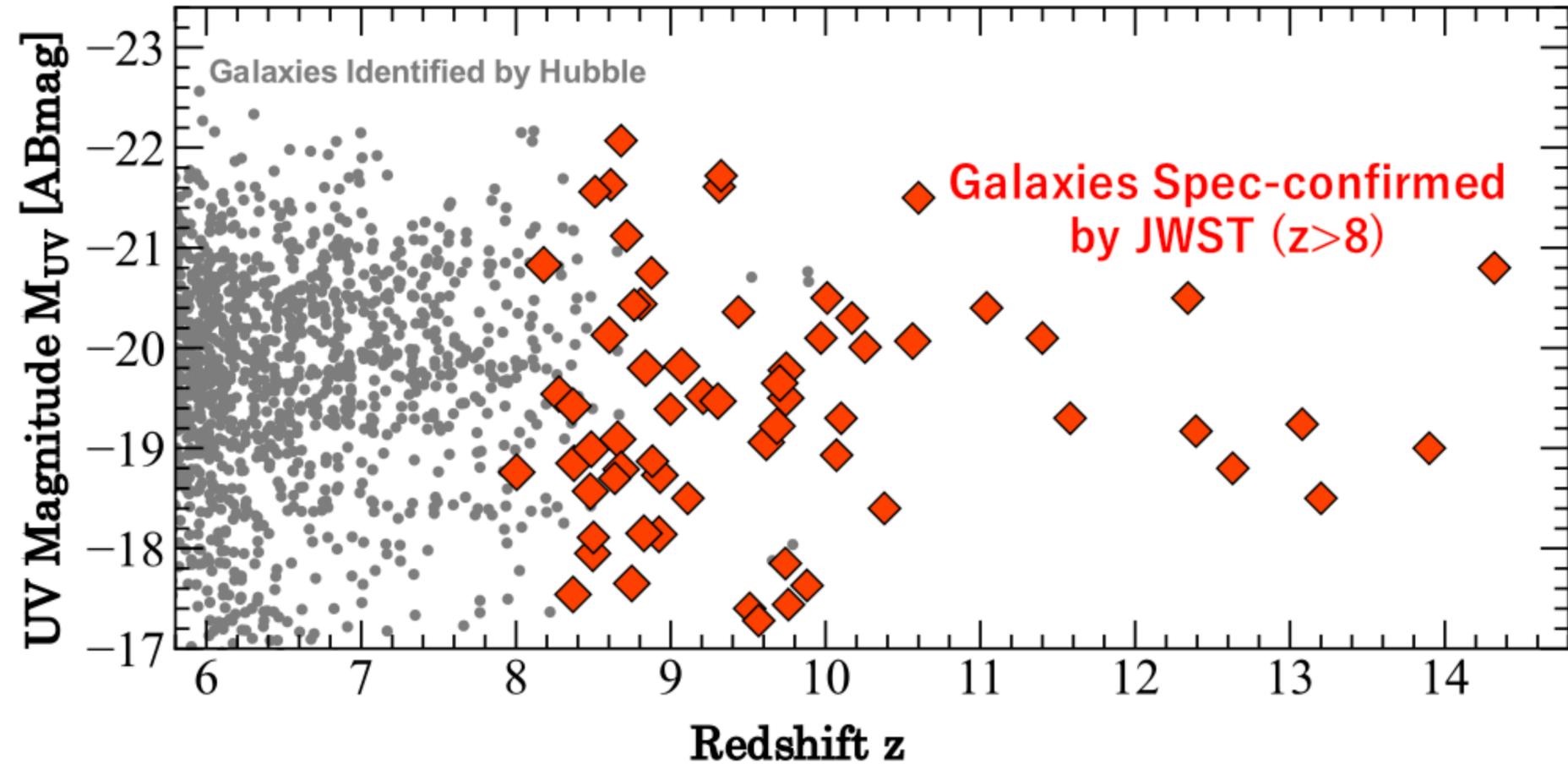
More (and less) blue monsters!
Harikane+24

- Spectroscopic follow-up of 25 high-z galaxies from multiple programs

- (And removal of some candidates)

- A bit hard to keep up with what is in and what is out, and many sources are still photometric

- Here 25 galaxies at z>8
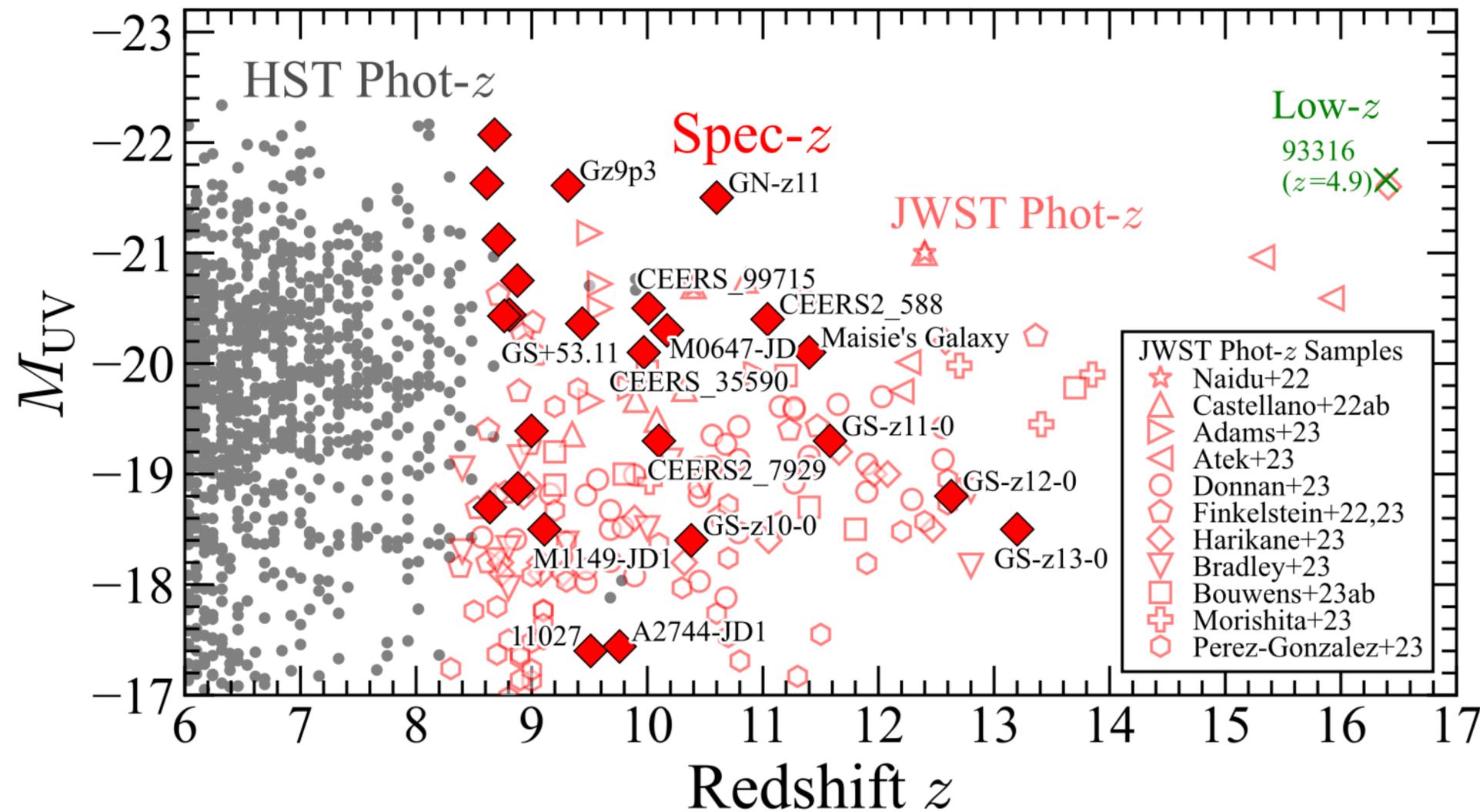
More (and less) blue monsters!
Harikane+25

- Update from last year

- Here 25 63 galaxies at z>8

More (and less) blue monsters!

Harikane+25

- Update from this year

- Here 63 galaxies at z>8

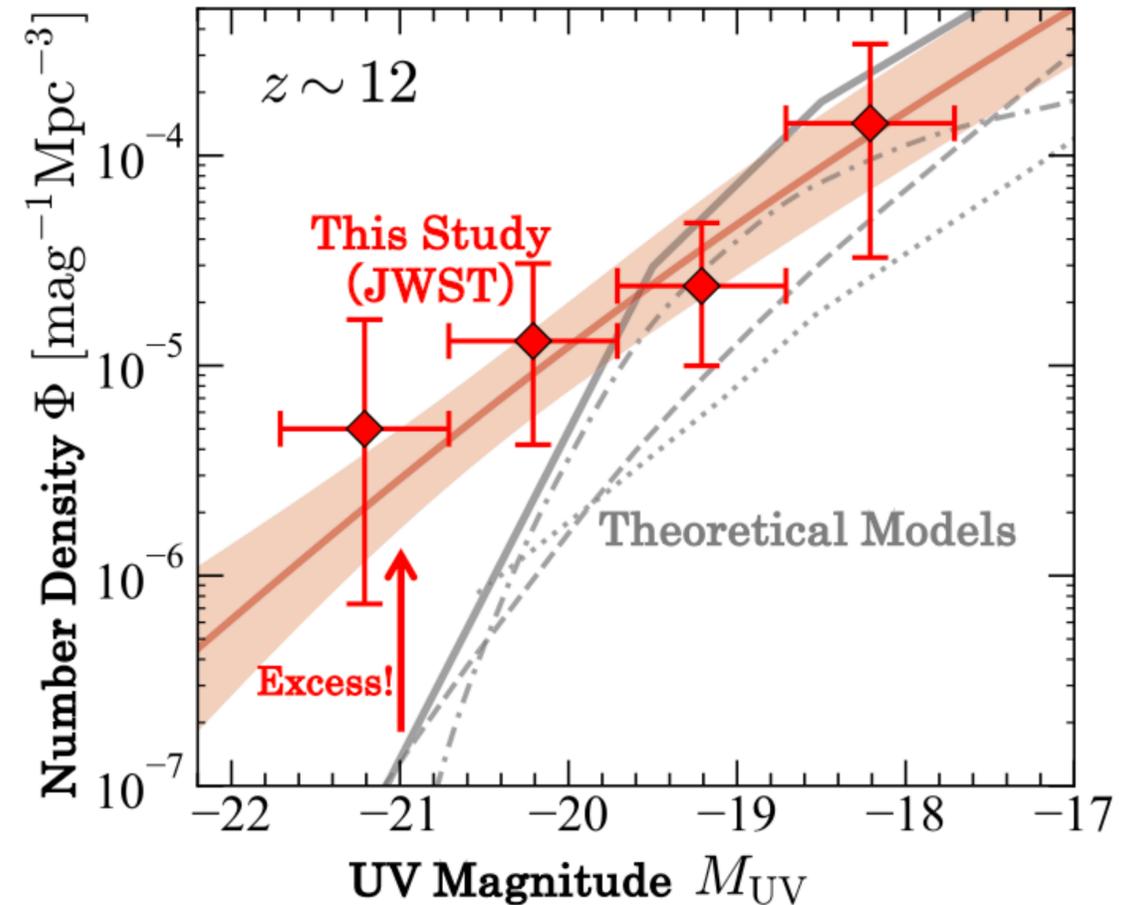- Not OK compared to (mostly analytic) theory!

Fig. 3 UV luminosity function at $z \sim 12$. The horizontal axis represents the UV absolute magnitude, while the vertical axis shows the galaxy number density. The red diamonds indicate the JWST results in Harikane et al. (2023a). The gray lines correspond to predictions from various theoretical models (Dayal et al. 2019: solid, Behroozi et al. 2020: dot-dashed, Yung et al. 2020: dotted, Mason et al. 2023: dashed), which underestimate the number density on the bright end, highlighting that the high number density of luminous galaxies at $z > 10$ was not expected before the JWST launch

Challenges at extreme redshifts

1. Abundance of bright galaxies (in previous slides)

2. Shallow slope of SFR density

3. Disky high-z galaxies

4. Likely AGN activity

5. Quenched galaxies at cosmic noon (z~4-5)

From Harikane+24b
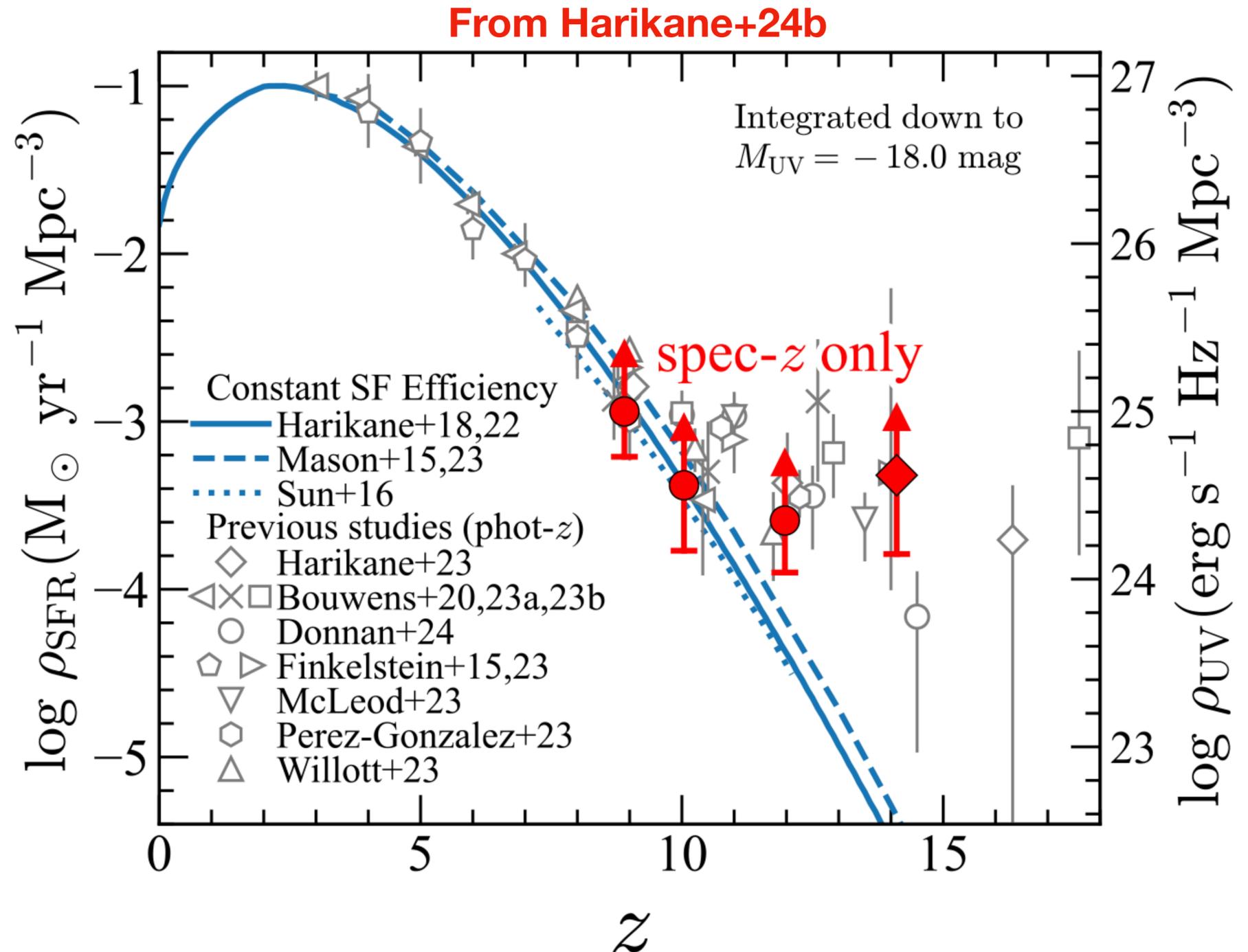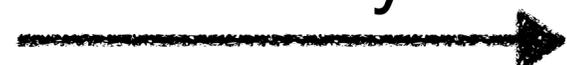
Models to explain high UVLF and very early SF

- ΛCDM alternatives (e.g. Early Dark Energy — Shen+24)

- Feedback-free early galaxies (Dekel+23, Ceverino+24, Li+24)

- Attenuation-free early galaxies (Ferrari+24)

- Top-heavy IMF (e.g. Chon+22, Katz+22, Mauerhofer+25)

- AGN!

- Bursty star formation -> fluctuating M_{UV}

- **...many of these models are fairly plausible and can act together**

- We need dedicated high-z simulations to explore these scenarios

High-z is great!

- **Simulating to z≈5 costs about a 10th of going to z=0 !!**

- (actually much less than a 10th)

- So can afford more physics and **much** higher resolution

Cosmic Time vs. Redshift in ΛCDM Cosmology
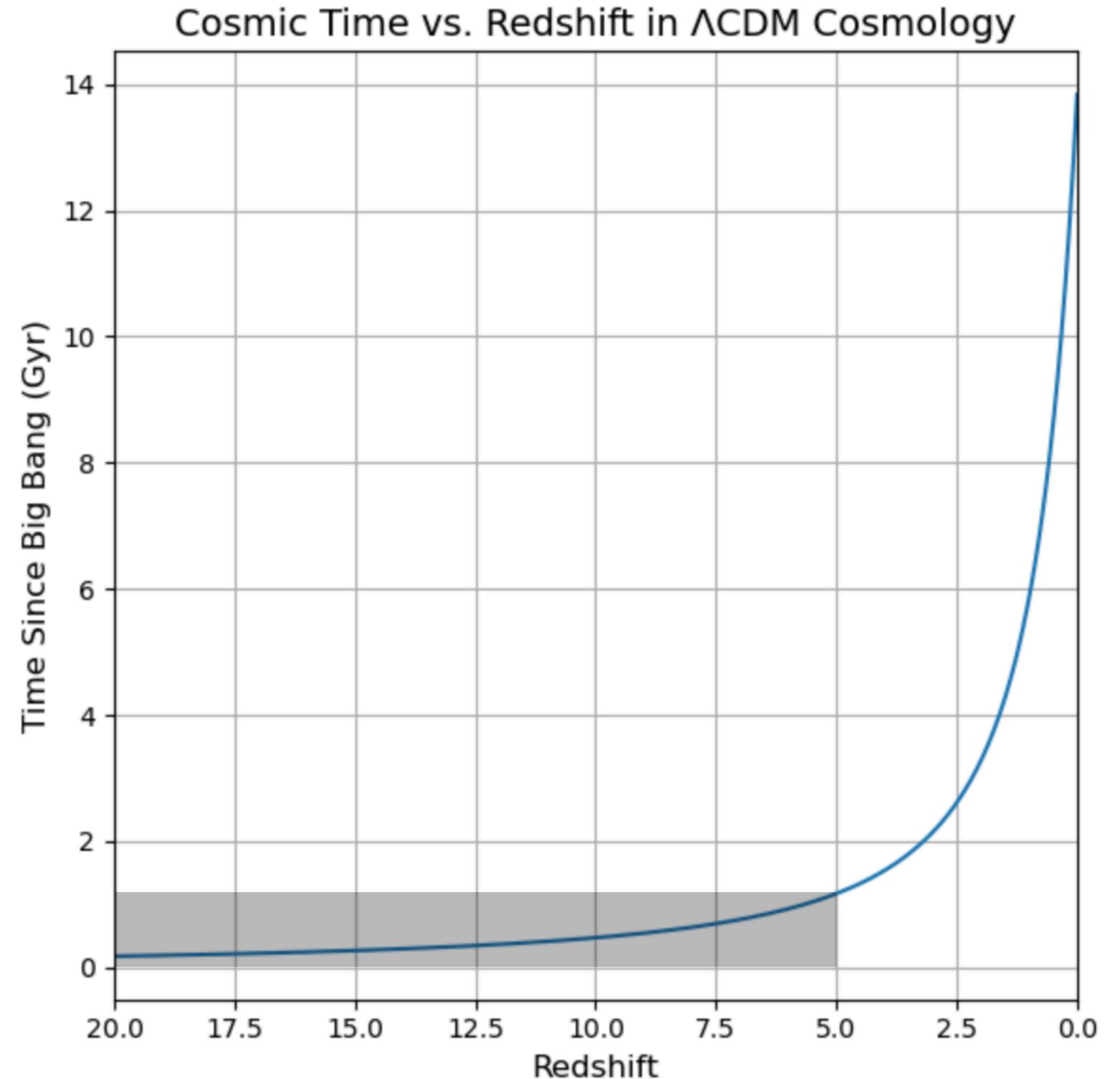
Dedicated extreme-z simulations

- Higher resolution needed — and possible — for high-z

- In **Semenov+25**, TNG halo re-simulated with higher resolution and more ISM physics (cooling, efficient star formation, ISM-coupled feedback)

- A bursty, multi-phase ISM can now form
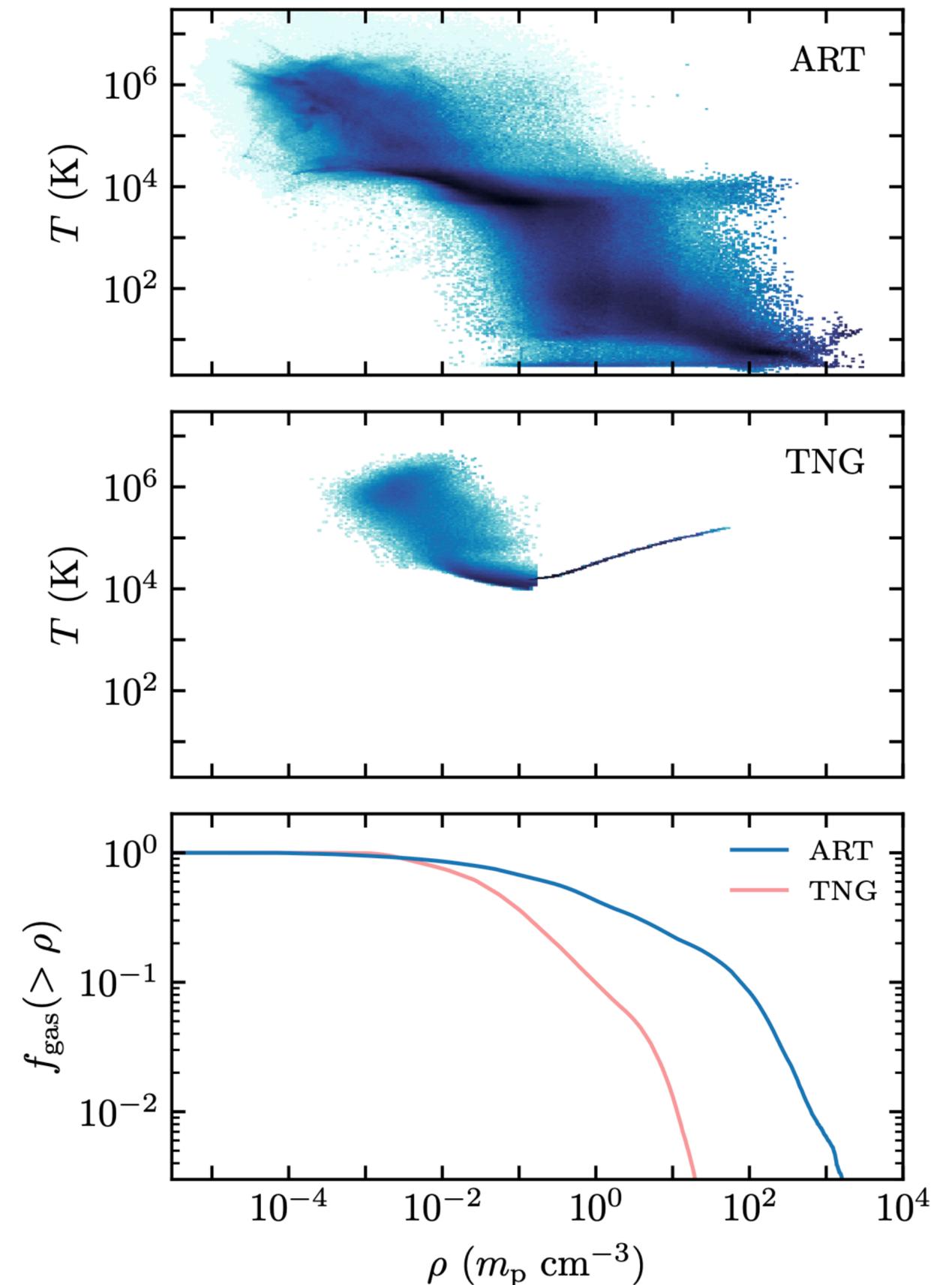
Dedicated extreme-z sims
Semenov+25

- Stellar disk forms at z=7 and bursty star formation, strongly contrasting TNG — and agreeing with observations

- The higher resolution and added physics boost star formation and UV brightness

- But the galaxy may 'fail' at low redshift, where TNG matches observational constraints

This is an ongoing 'feature' of extreme-z galaxy formation simulations — they don't make predictions for low-z, or make bad ones!
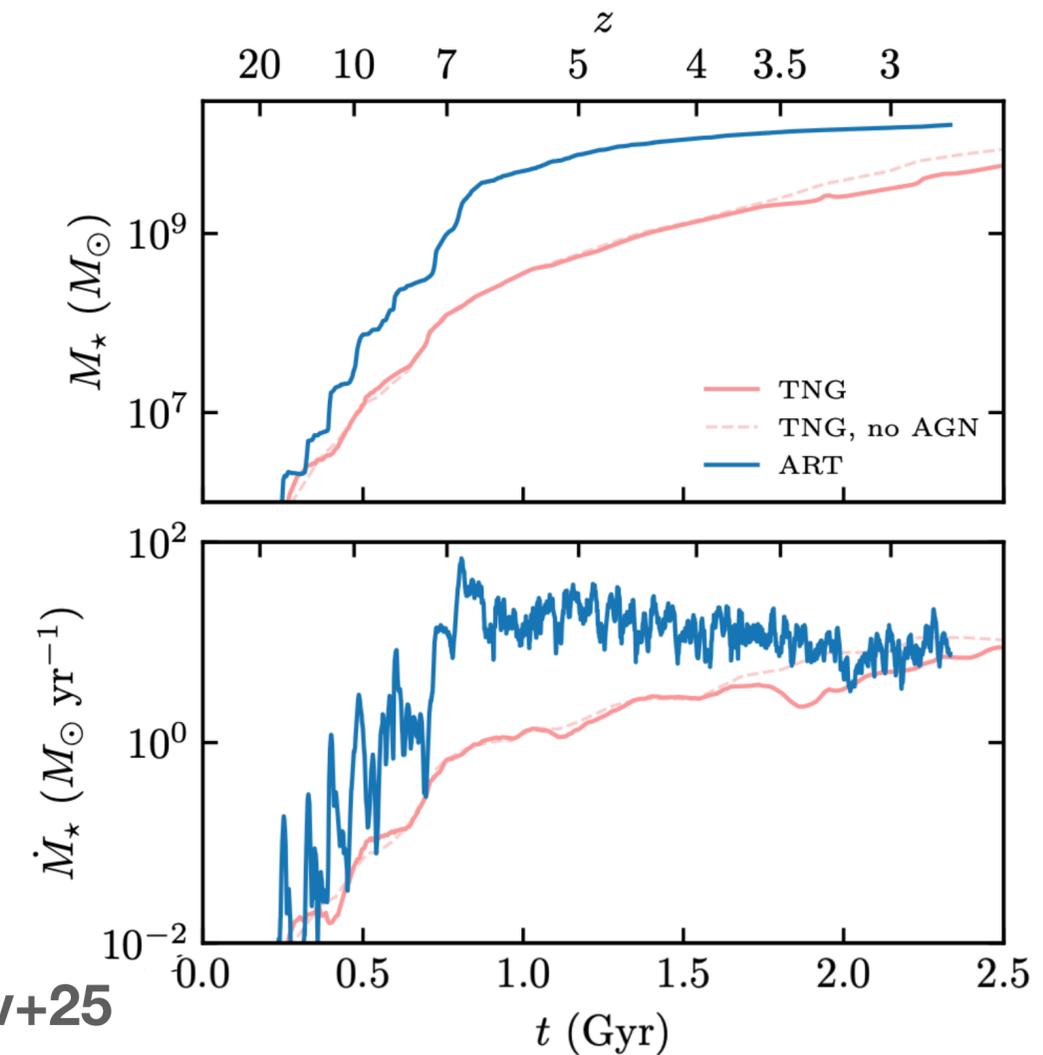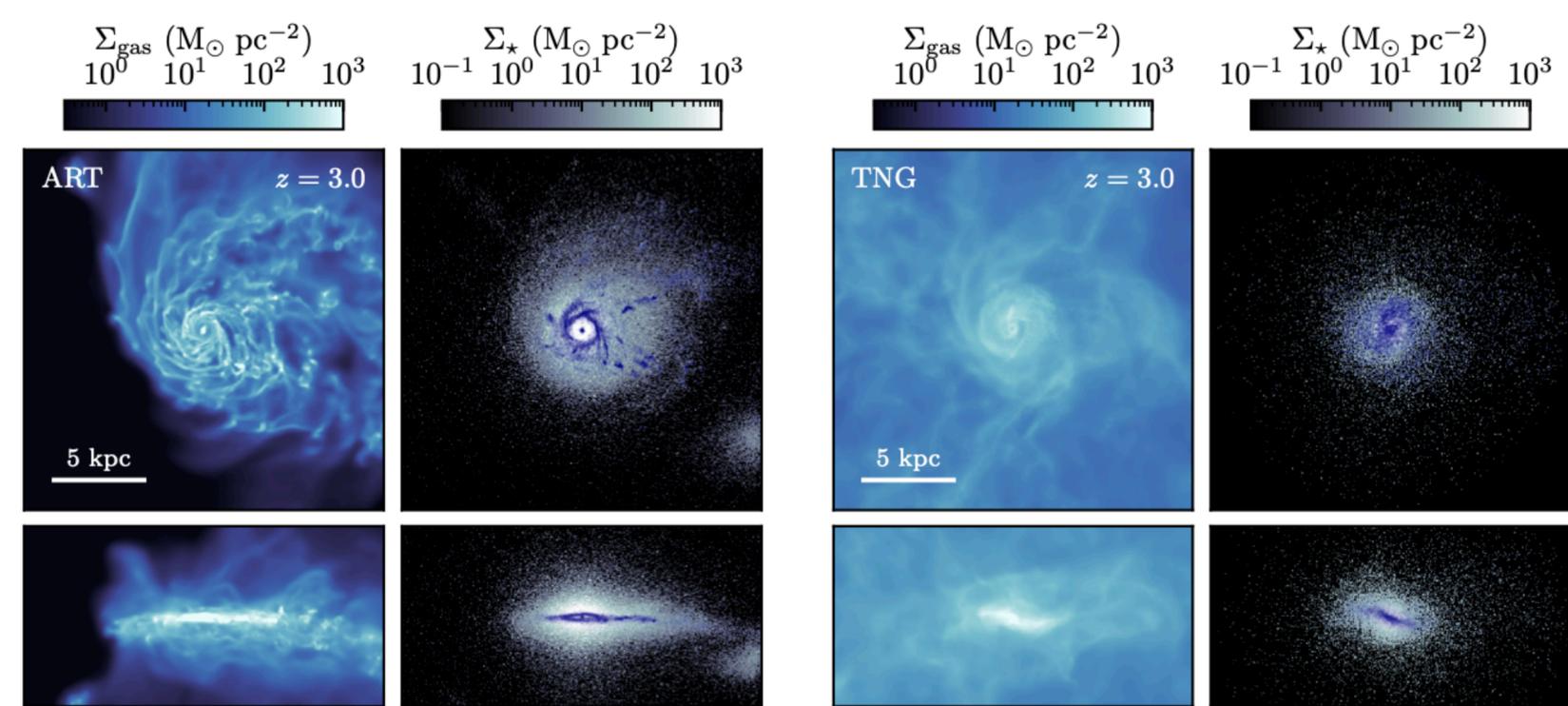

From Semenov+25

Dedicated extreme-z sims
## Semenov+25

- **This work, and many others with high resolution, include artificial feedback 'boosts'.** See also SPHINX (Rosdahl+), THESAN-ZOOM (Kannan+), FIREBOX (Feldman+).

- Here, 5 times the expected number of SNe from a Kroupa IMF and an additional 2x energy deposited as 'early feedback'

- May compensate (still) lack of resolved clustering, radiation, cosmic rays, stellar winds, …

- We don't know what it is, and we need more simulations, with more physics, to understand

From Semenov+25
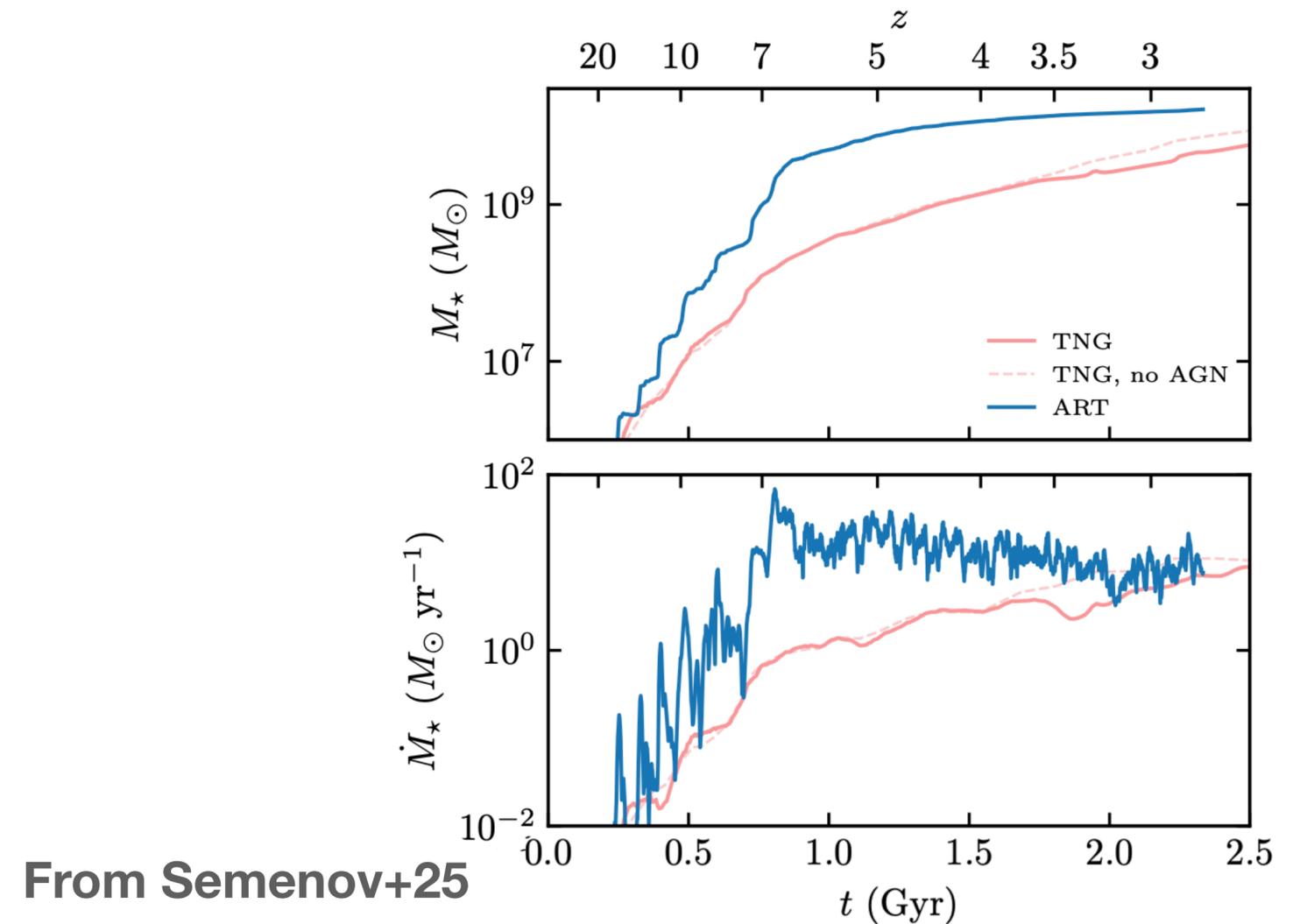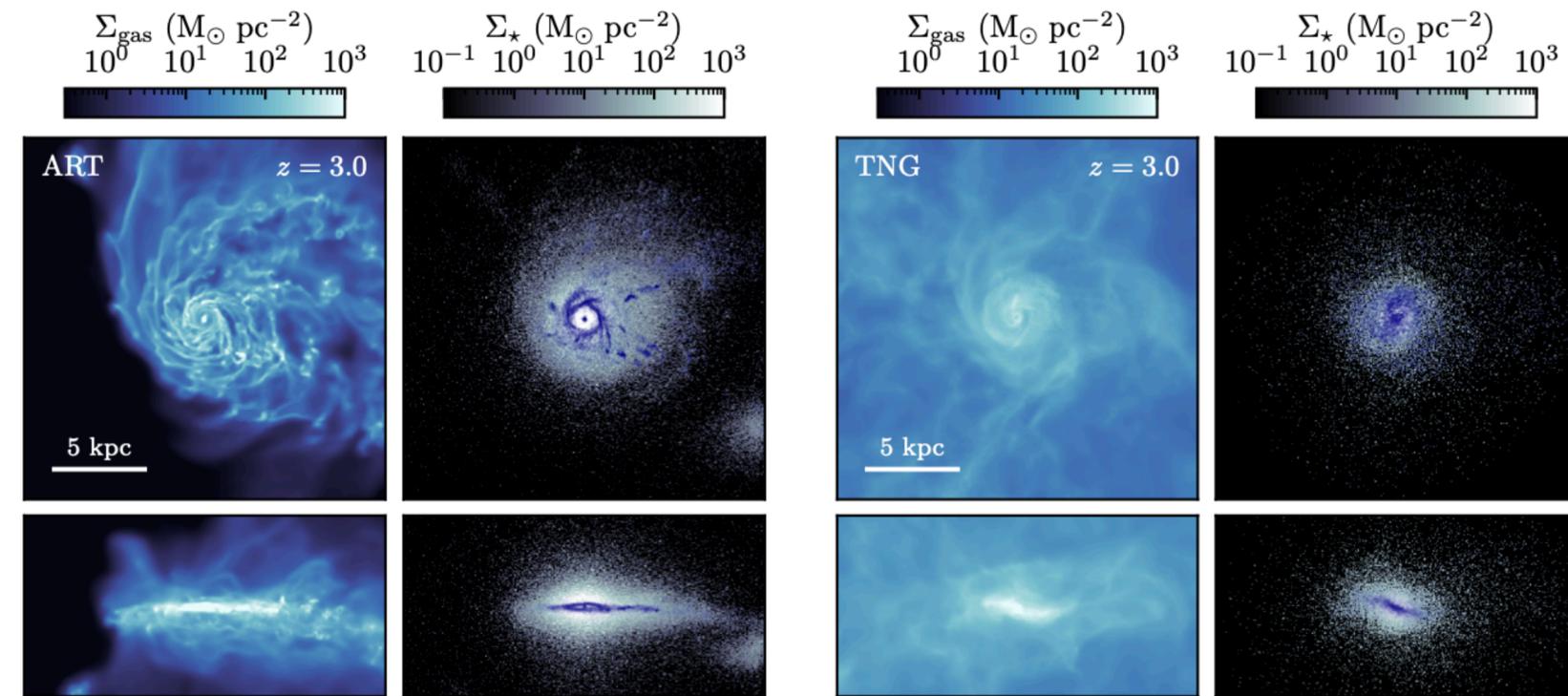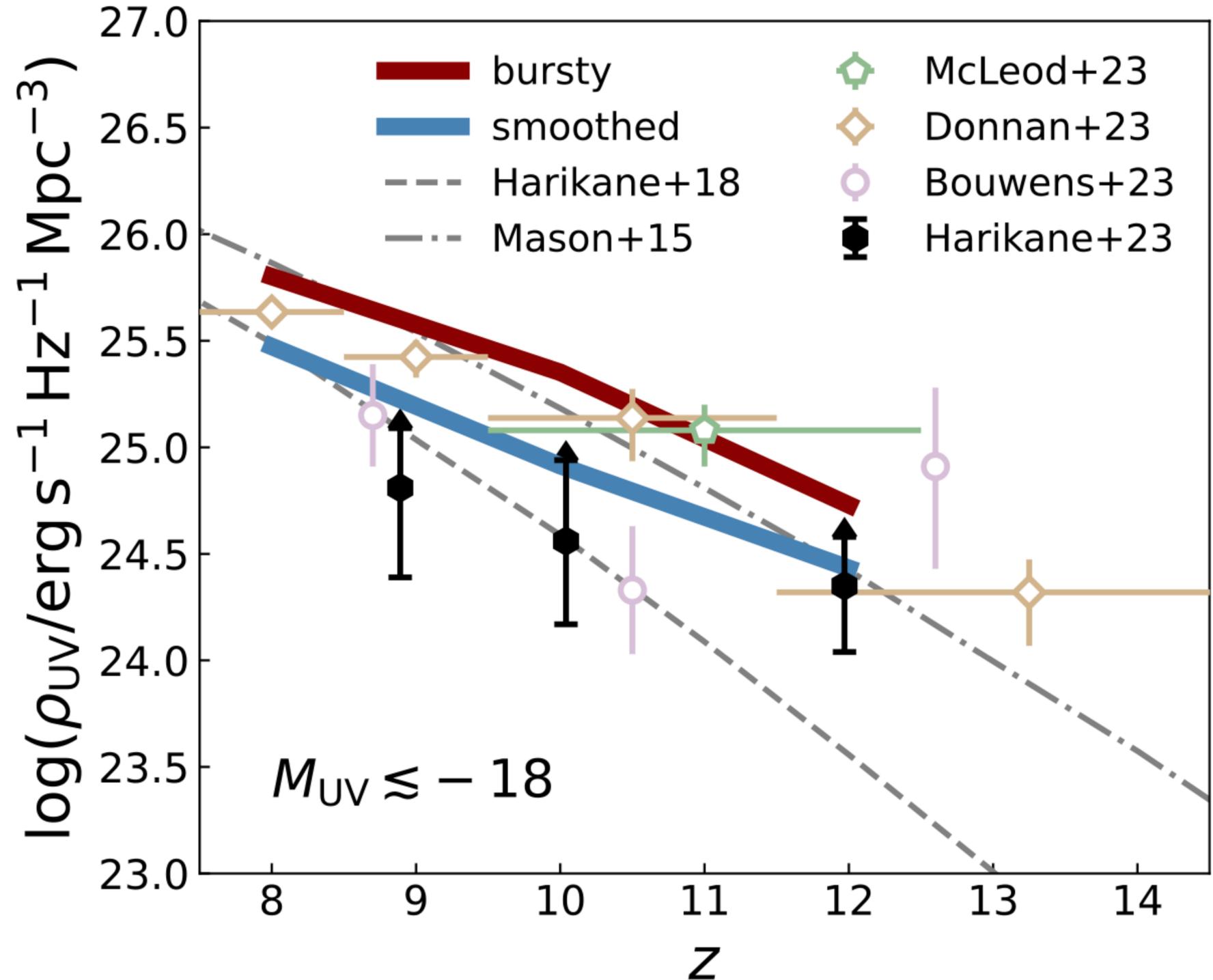
Bursty star formation

Sun+23

- FIRE simulations naturally produce bursty star formation

- The burstiness helps for the UVLF — a bit

- See also Kravtsov+24, Shen+24, McClymont+25

- JWST observations do indicate burstiness (e.g. Edsley+24, Ciesla+24, Looser+23)
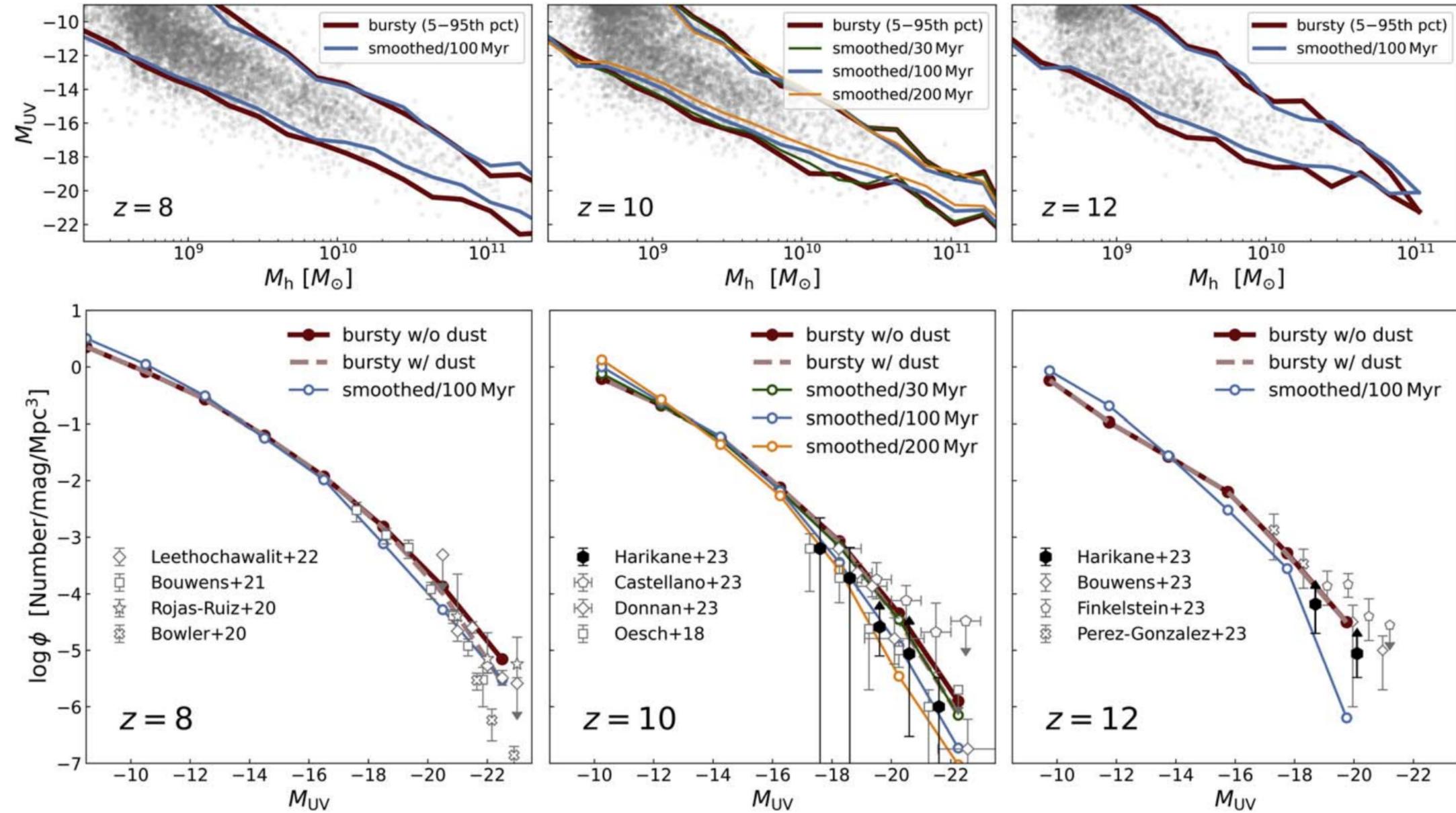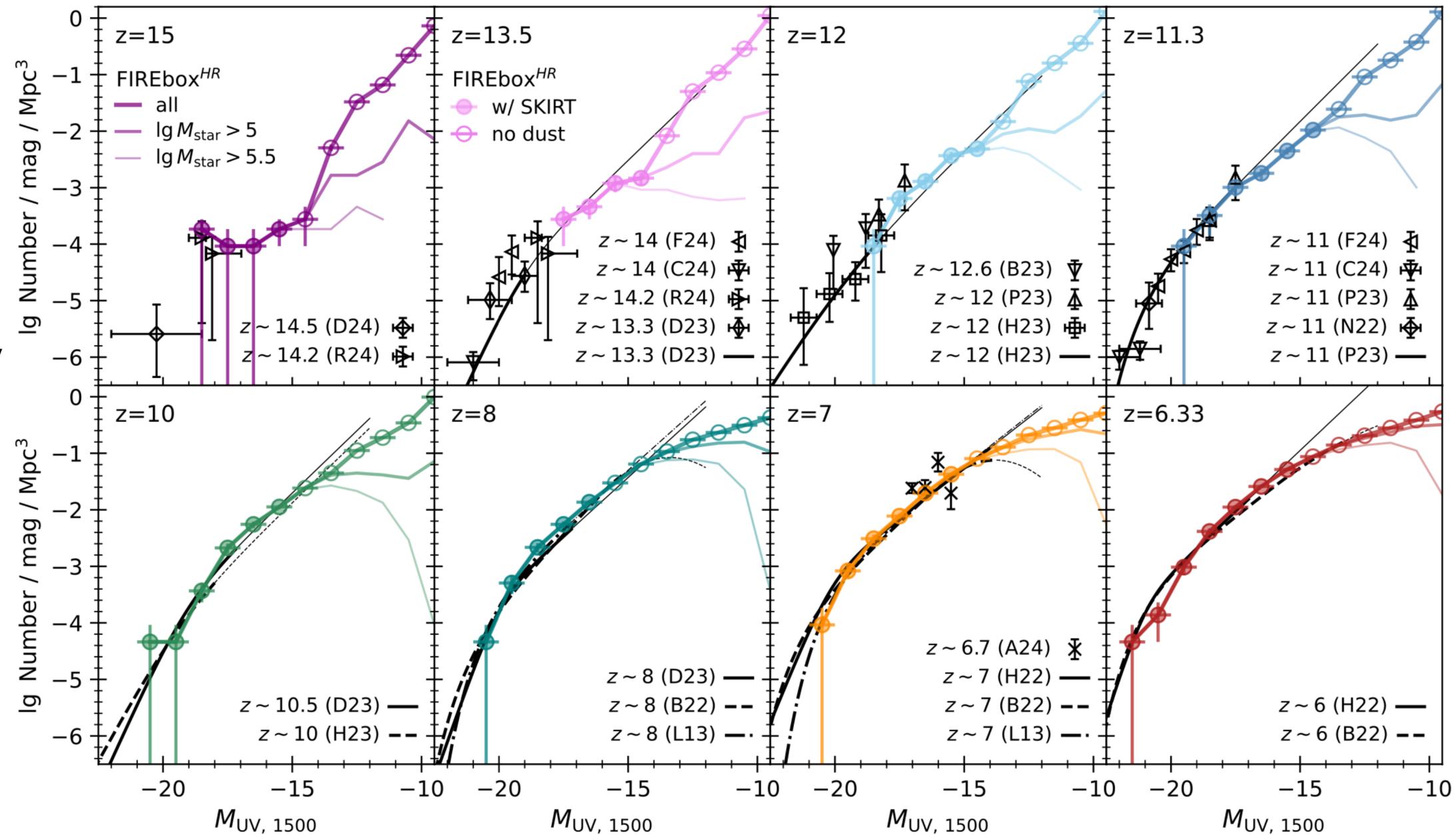
Bursty star formation

Sun+23

- The burstiness also helps to boost the observable SFR rate density at high-z
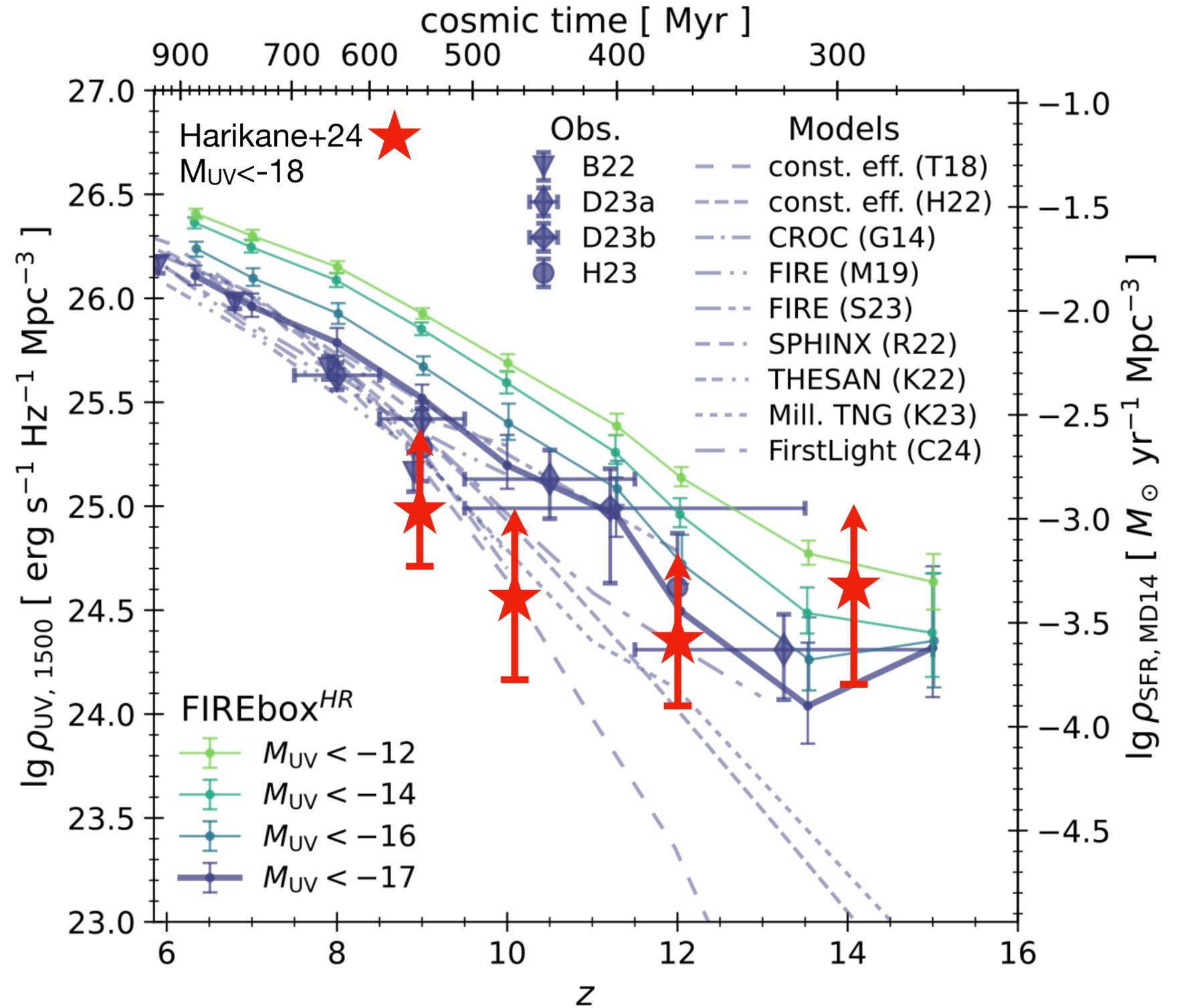
FIREBOX[HR]

Feldmann+25

- Full-volume FIRE simulations (20 cMpc)^3

- Good agreement, and no special ingredients: only bursty stellar feedback (no AGN)

- Only partly overlaps high-z results, due to small volume

- And very low statistics (hence weird shapes)

FIREBOX[HR]

Feldmann+25

- Observed gradual evolution of SFR with z is fairly well reproduced (*with low statistics on both sides*)

- Largely a feature of non-evolving star formation efficiency (SFE) with redshift, and insensitive to M_{halo}

FIREBOX^{HR}

FIREBOX^{HR}

Feldmann+23

- **But issues at low redshift**

- Contradiction to the FIRE (zoom) simulations, which have stronger suppression at low redshifts

- The discrepancy is unclear, perhaps related to a selection effect in zoom simulations
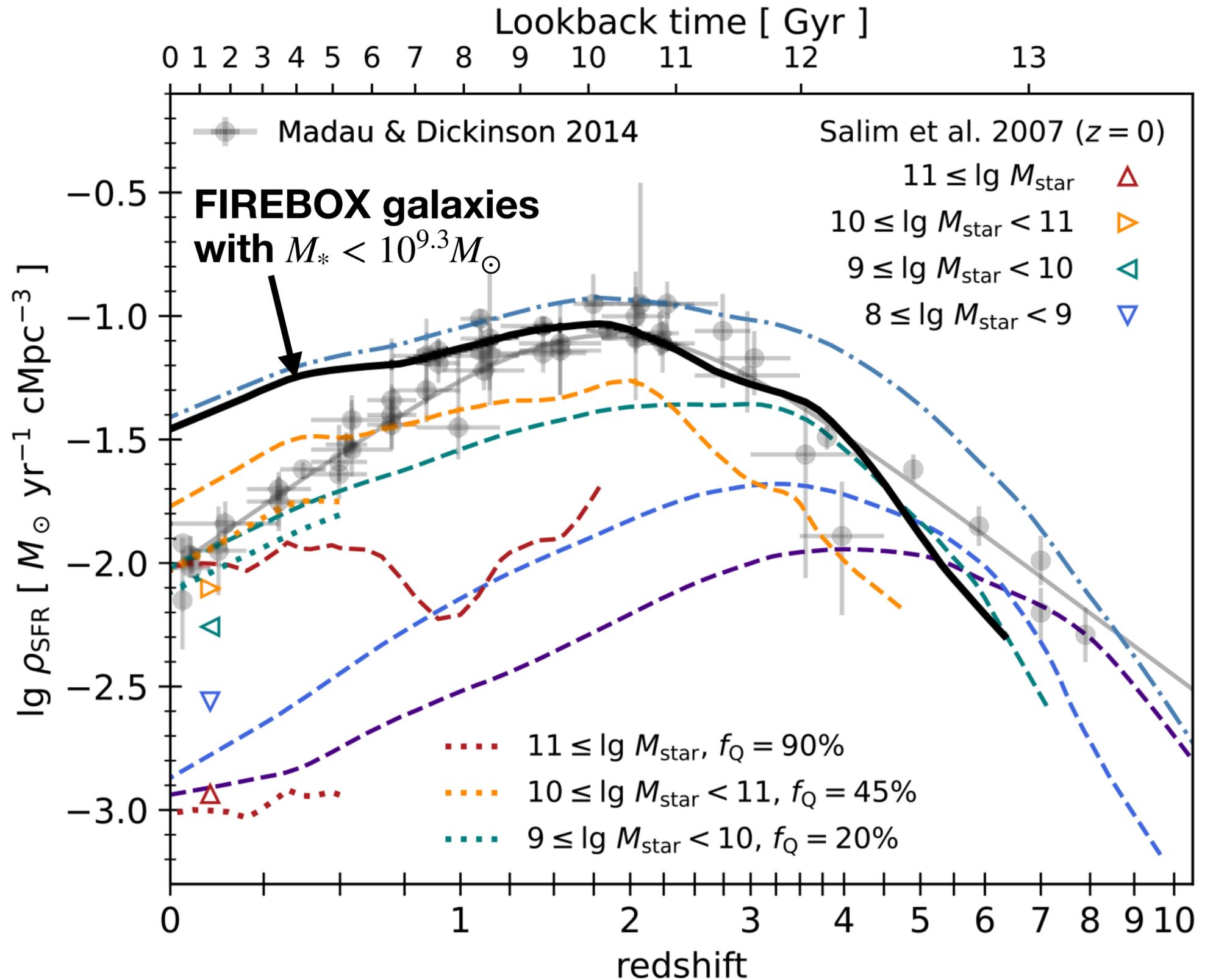
No DUST in simulations

- This is very complicated, hard to model, and difficult to constrain, especially at high redshift.

- The UV luminosities derived from the simulations above are all derived using rather ad-hoc dust models, in post-processing

# ~~No~~ DUST in simulations

- Dust formation and destruction models are being added to simulations

- Here, 'Species' dust model in FIRE simulations (Choban+22,25)

- Was shown to reproduce observed dust masses in z=0 galaxies

- But struggles at high z~5-10, due to slow dust accretion growth, regulated by bursty feedback, and, simply, low metallicities

From Choban+25
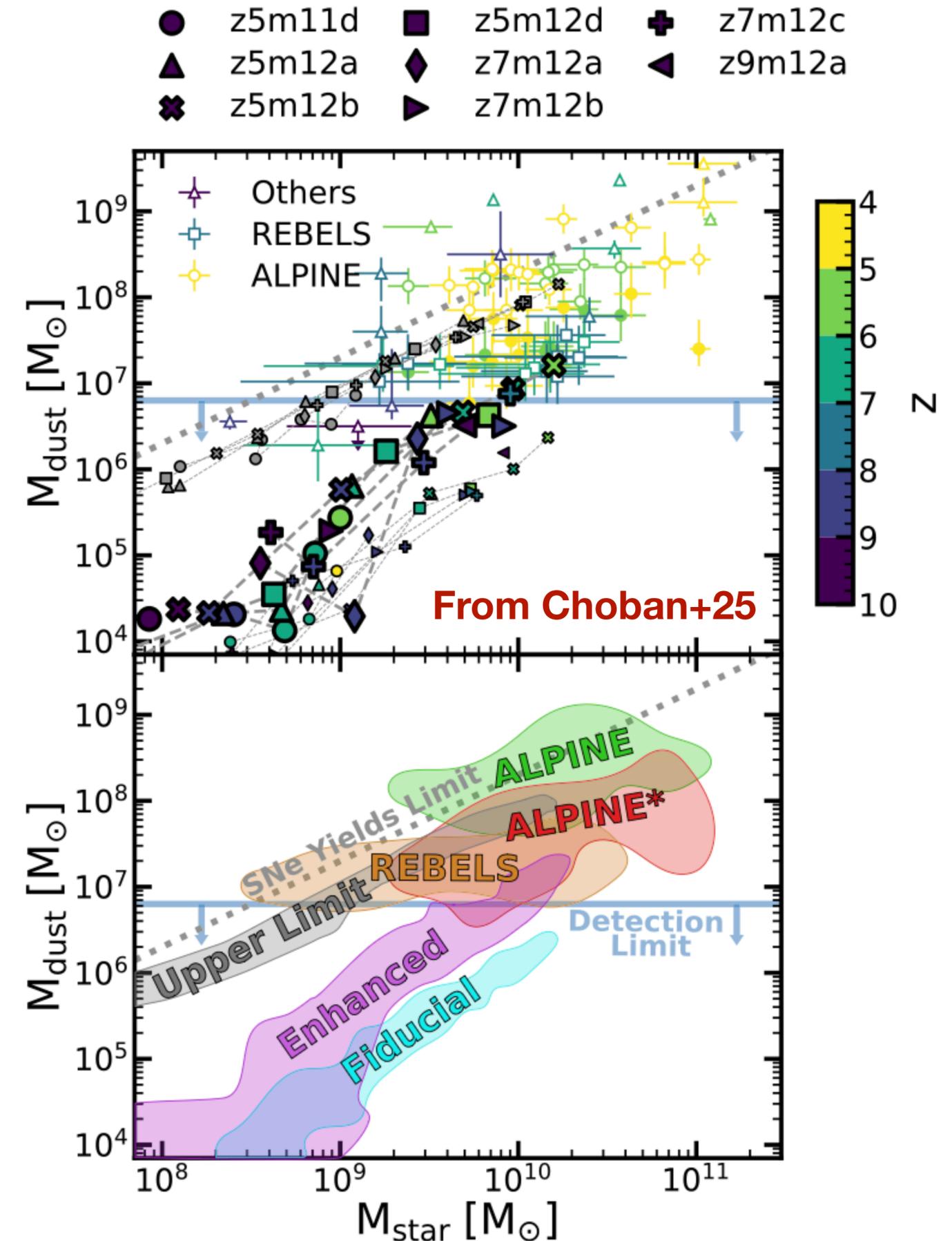
High-z AGN and quenched galaxies
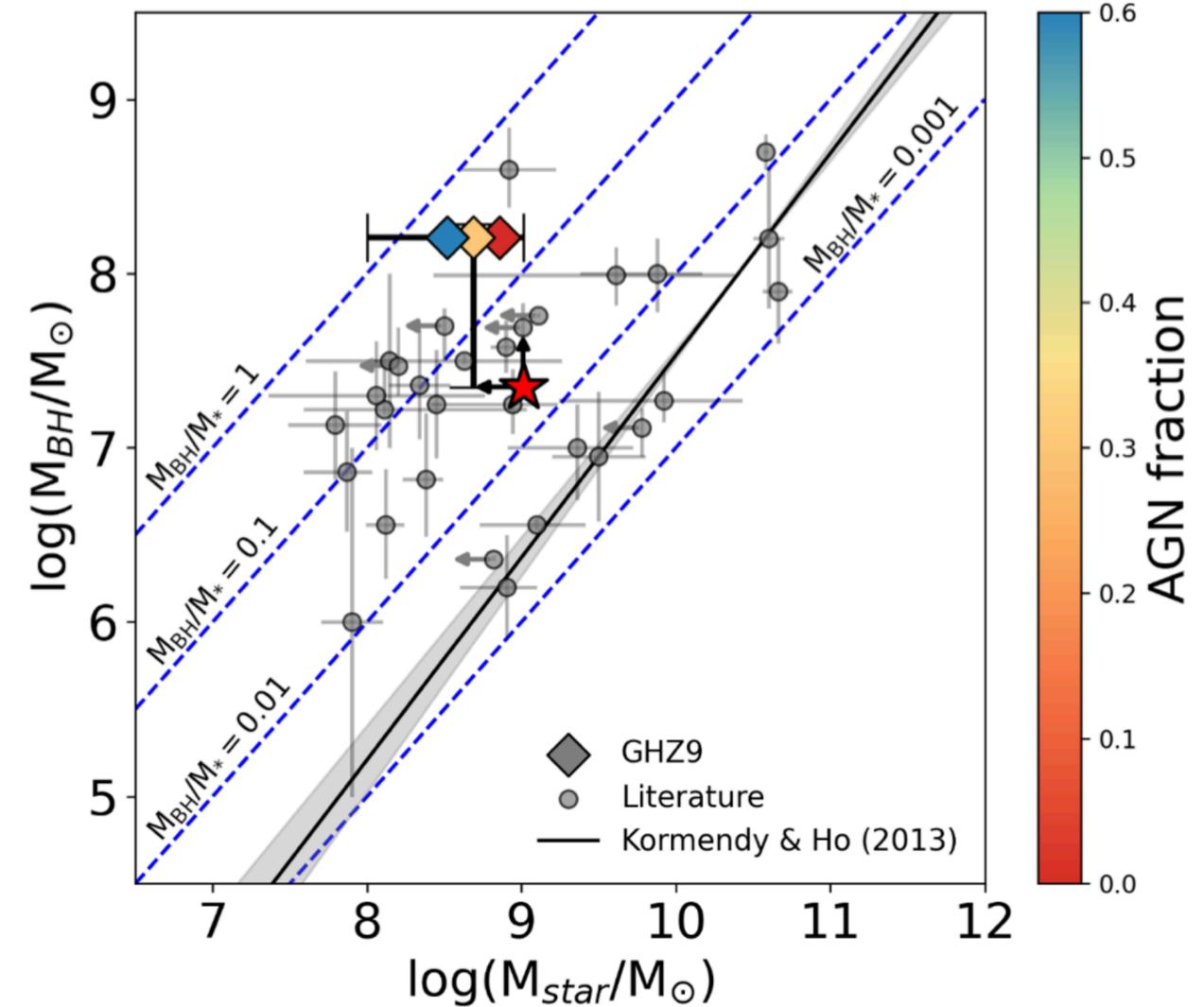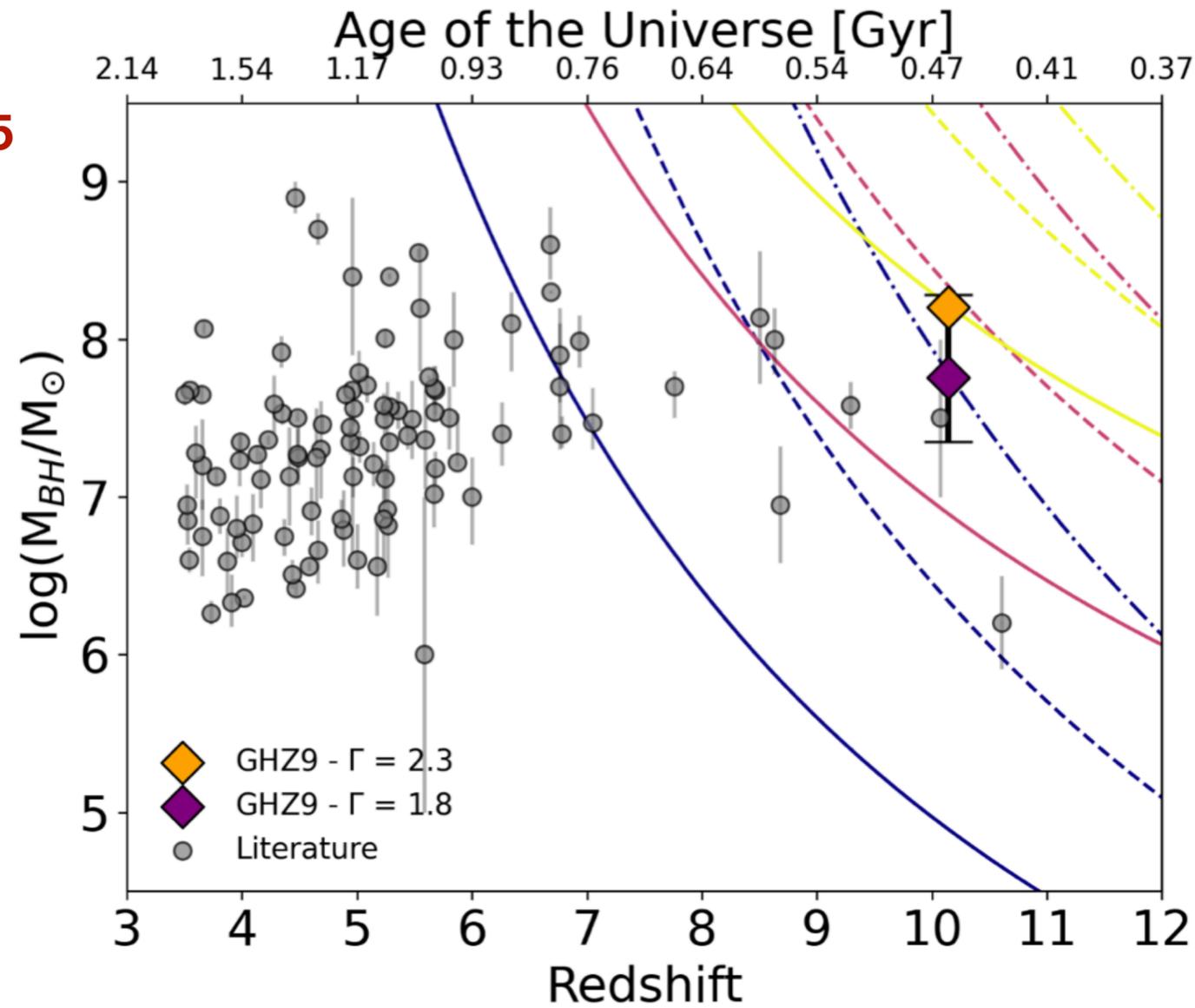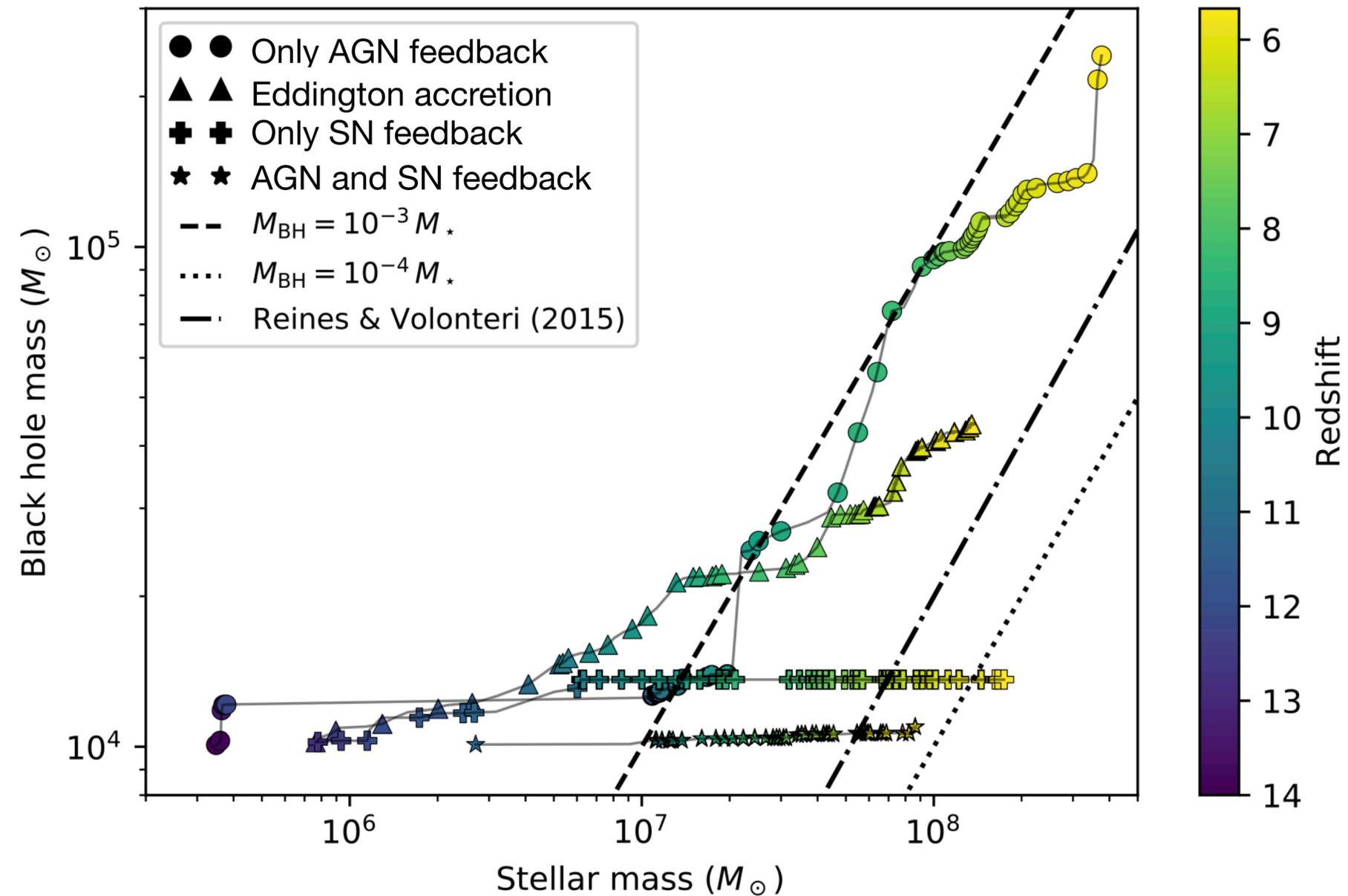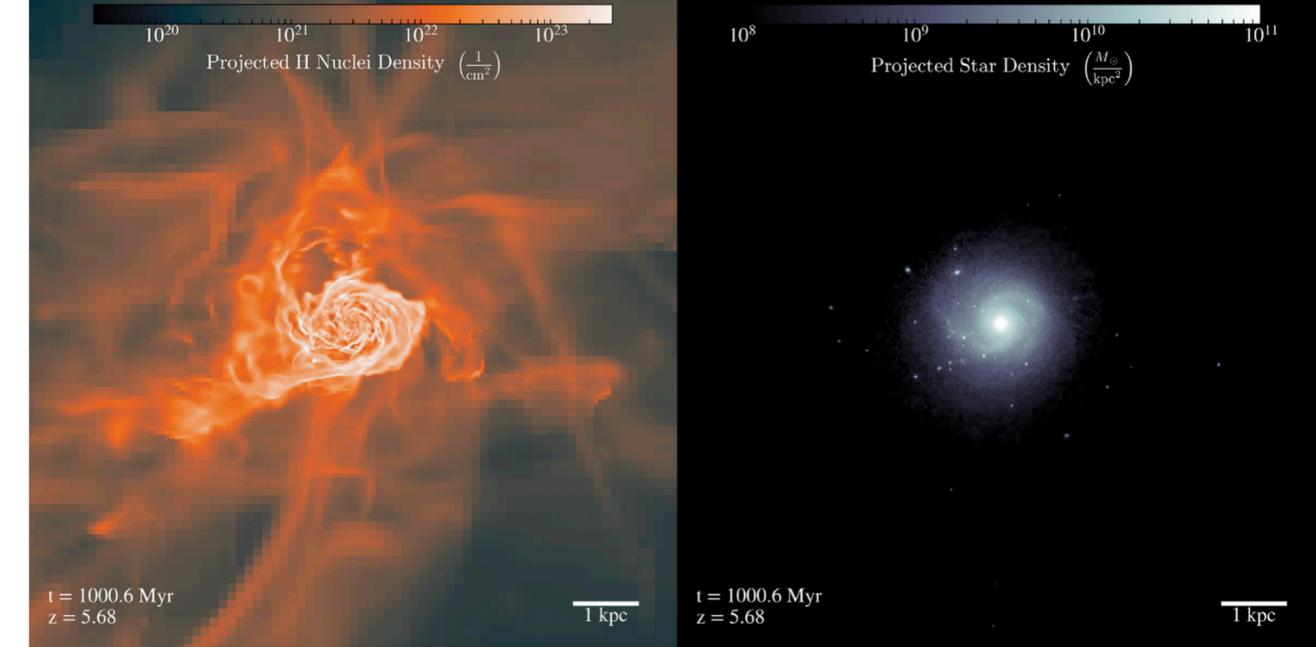
High-z AGN and quenched galaxies

- Both are very difficult to explain theoretically

- An extreme case from Napolitano+25 **GHz9: $M_{BH} \sim 10^9 \, M_\odot$, $M_* \sim 10^8$-$10^9 \, M_\odot$**

- Trebitsch+18 try to grow such an object, but find it very challenging to grow black holes in dwarf galaxies, due to stellar feedback. See also Petersson+25, Byrne+25, Koudmani+22

Conclusions on high-z simulations

- $\Lambda\mathrm{CDM}$ is not dead, but simulations struggle to reproduce JWST surprises:

  - Massive starbursting galaxies at z>6

  - Disky quenched galaxies at cosmic dawn

  - High-z AGN

  - Mainly, it is a very active time and difficult to keep up

- **A major challenge is to match observations at both high and low z, and efforts are needed**

Overview
High-z cosmological simulations

1. A bit of history

2. How to perform cosmological simulations — a crash course

3. Sub-grid recipes and their calibration

4. Towards higher resolution and more physics

5. Reionization simulations

6. The 1st stars

7. High-z galaxies and observations
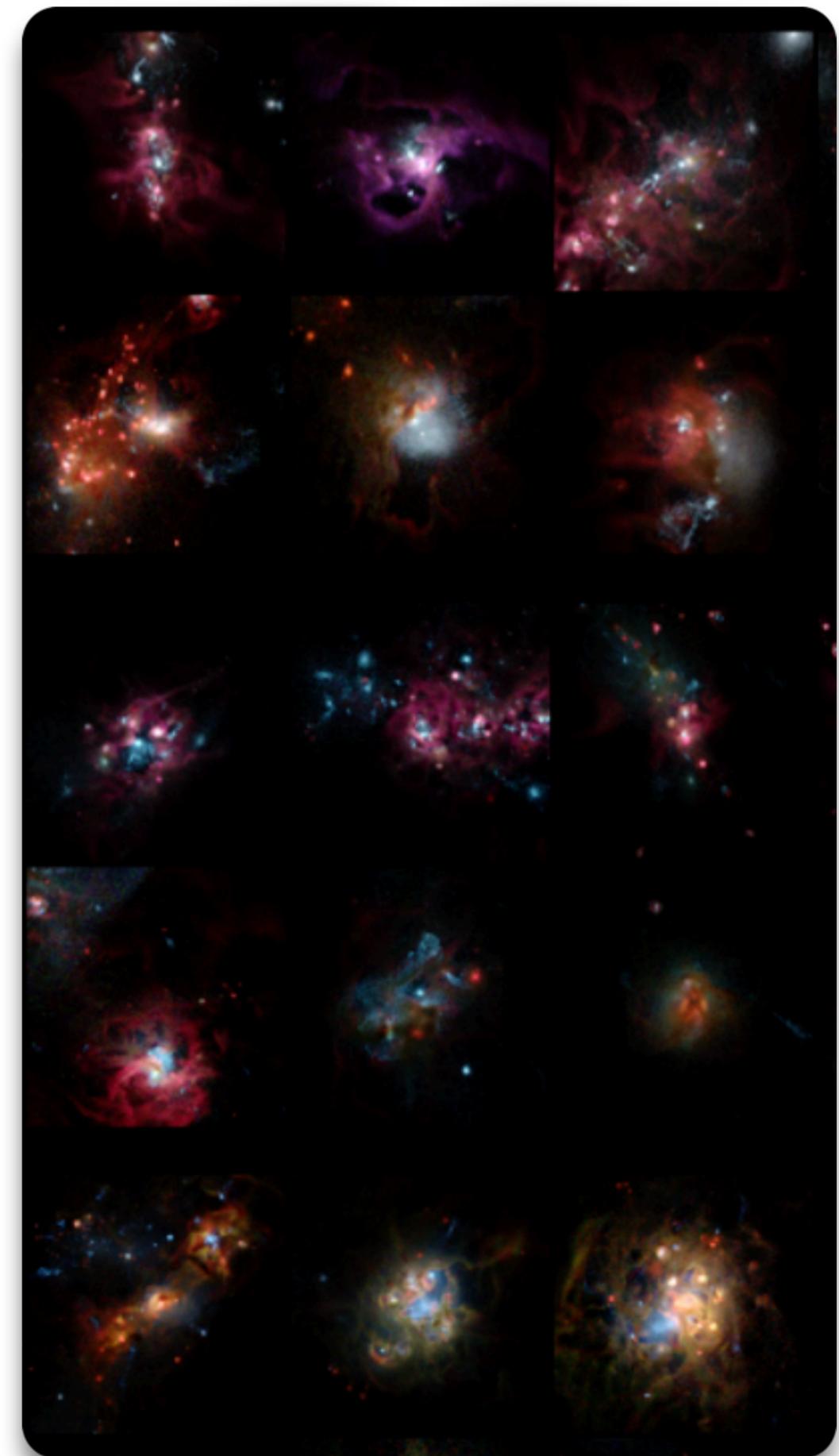
8. Mock observations

Mock observations

- **With increasing ISM physics and forward-modelling, mock observations become useful to**
  - Interpret observations
  - Test SED fitting codes
  - Derive physical properties like $f_{\rm esc}$ from observations

- **Method:**
  1. Run a cosmological simulation of a galaxy
  2. Post-process emission from simulated volume elements, e.g. with CLOUDY
  3. Ray-trace the emitted radiation with a Monte-Carlo code (RASCAS, SKIRT, COLT)
  4. Generate spectra

- **Data releases, in decreasing order of post-processing assumptions:**
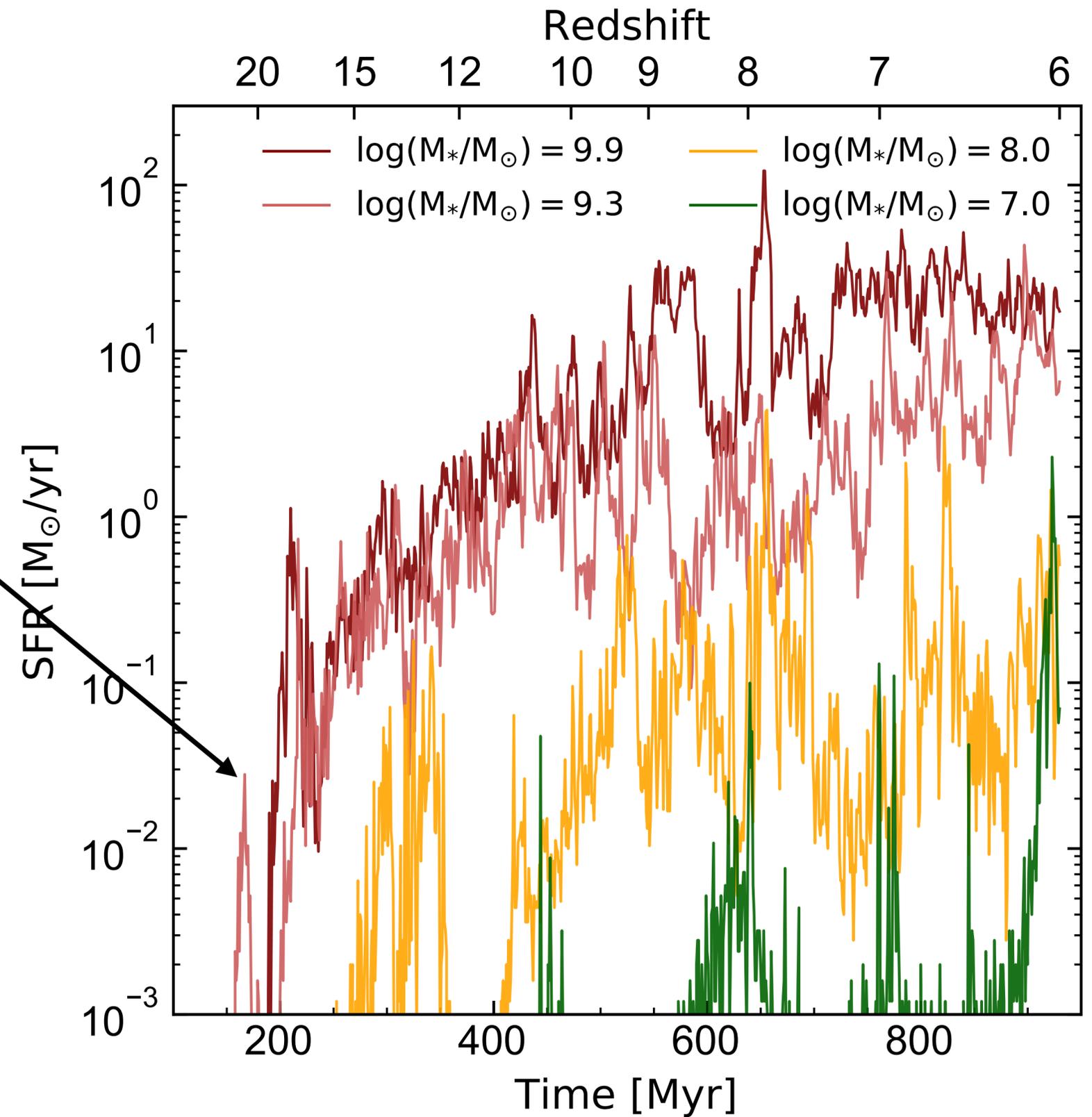 **Illustris(TNG), THESAN, SPHINX, MEGATRON (in prep)**

SPHINX data release
Katz+23

- Low-mass galaxies simulated in the first Gyr
- Sample of 1400 galaxies with SFR>0.3 $M_\odot$/yr
- Various galaxy properties (i.e. SFRs, masses, metallicities)
- Escape fractions
- Galaxy sizes and magnitudes
- Intrinsic and attenuated emission line luminosities
- Intrinsic and dust attenuated stellar continua
- UV slopes (dust attenuated)
- Dust extinction and colour excess
- Mock images

- Lya spectra, spatial profiles (z=4.64, 5.0, and 6 only)
- Ha spectra, spatial profiles (z=4.64, 5.0, and 6 only)
- Nebular continua

SPHINX data release
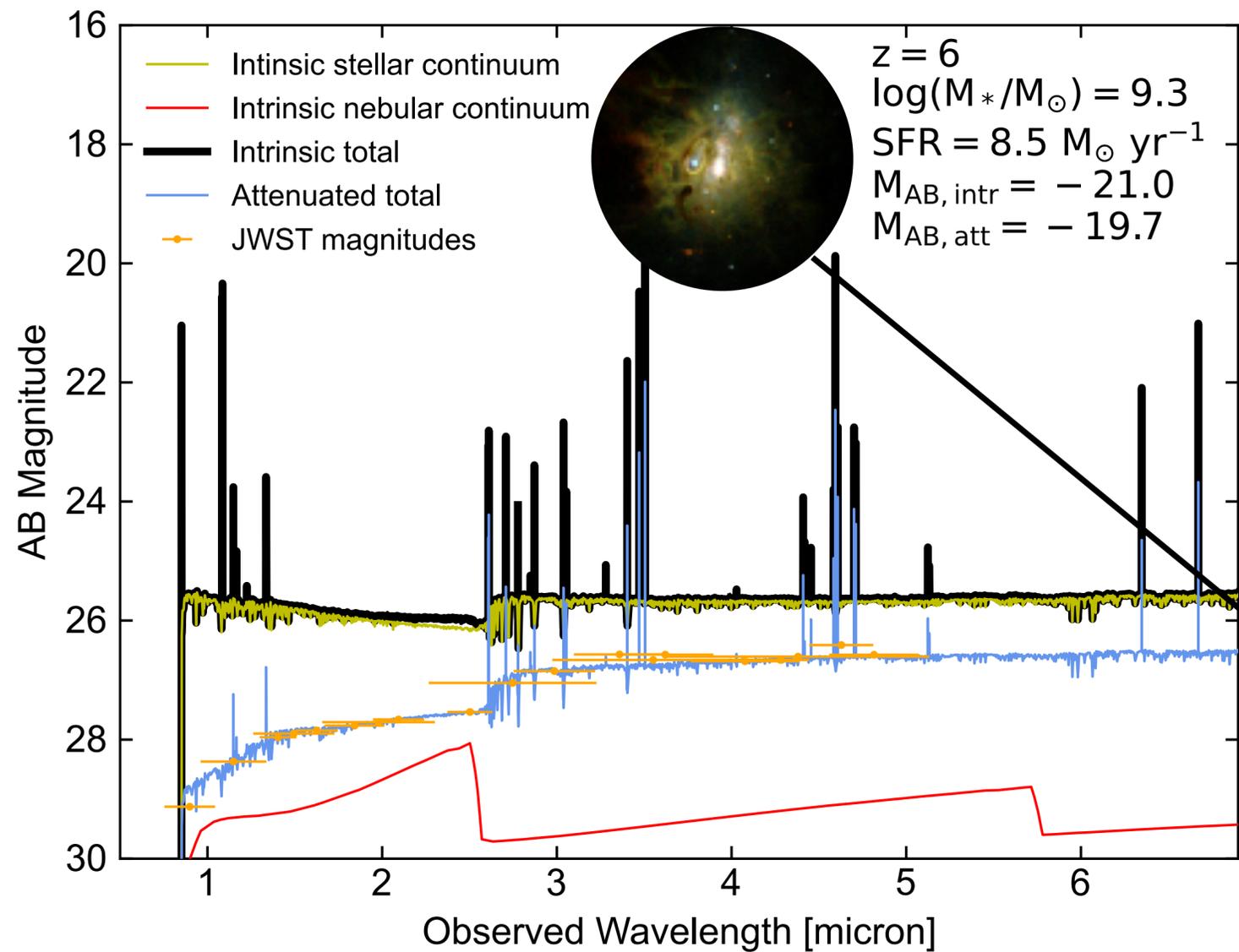
Left panel legend:
- Intinsic stellar continuum
- Intrinsic nebular continuum
- Intrinsic total
- Attenuated total
- JWST magnitudes

$z = 6$
$\log(M_*/M_\odot) = 9.3$
$SFR = 8.5\ M_\odot\ yr^{-1}$
$M_{AB,\,intr} = -21.0$
$M_{AB,\,att} = -19.7$

Left panel axes:
- y-axis: AB Magnitude
- x-axis: Observed Wavelength [micron]

Right panel legend:
- $\log(M_*/M_\odot) = 9.9$
- $\log(M_*/M_\odot) = 9.3$
- $\log(M_*/M_\odot) = 8.0$
- $\log(M_*/M_\odot) = 7.0$

Right panel axes:
- top: Redshift
- y-axis: SFR [$M_\odot$/yr]
- x-axis: Time [Myr]

Uncertainties in high-z galaxy properties inferred from SED fitting using JWST NIRCam photometry

Jiyoung Choe[1], Taysun Kimm[1]⋆ ⓘ, Harley Katz[2,3] ⓘ, Maxime Rey[1] ⓘ, Daniel Han[1] ⓘ, J. K. Jang[1], and Joki Rosdahl[4] ⓘ

- BAGPIPES SED fitting package used on SPHINX mock spectra

- Does BAGPIPES return the true galaxy masses, star formation histories (SFHs), metallicities?

- See also Cochrane+25, Narayanan+24, Ciesla+24

Uncertainties in high-z galaxy properties inferred from SED fitting using JWST NIRCam photometry

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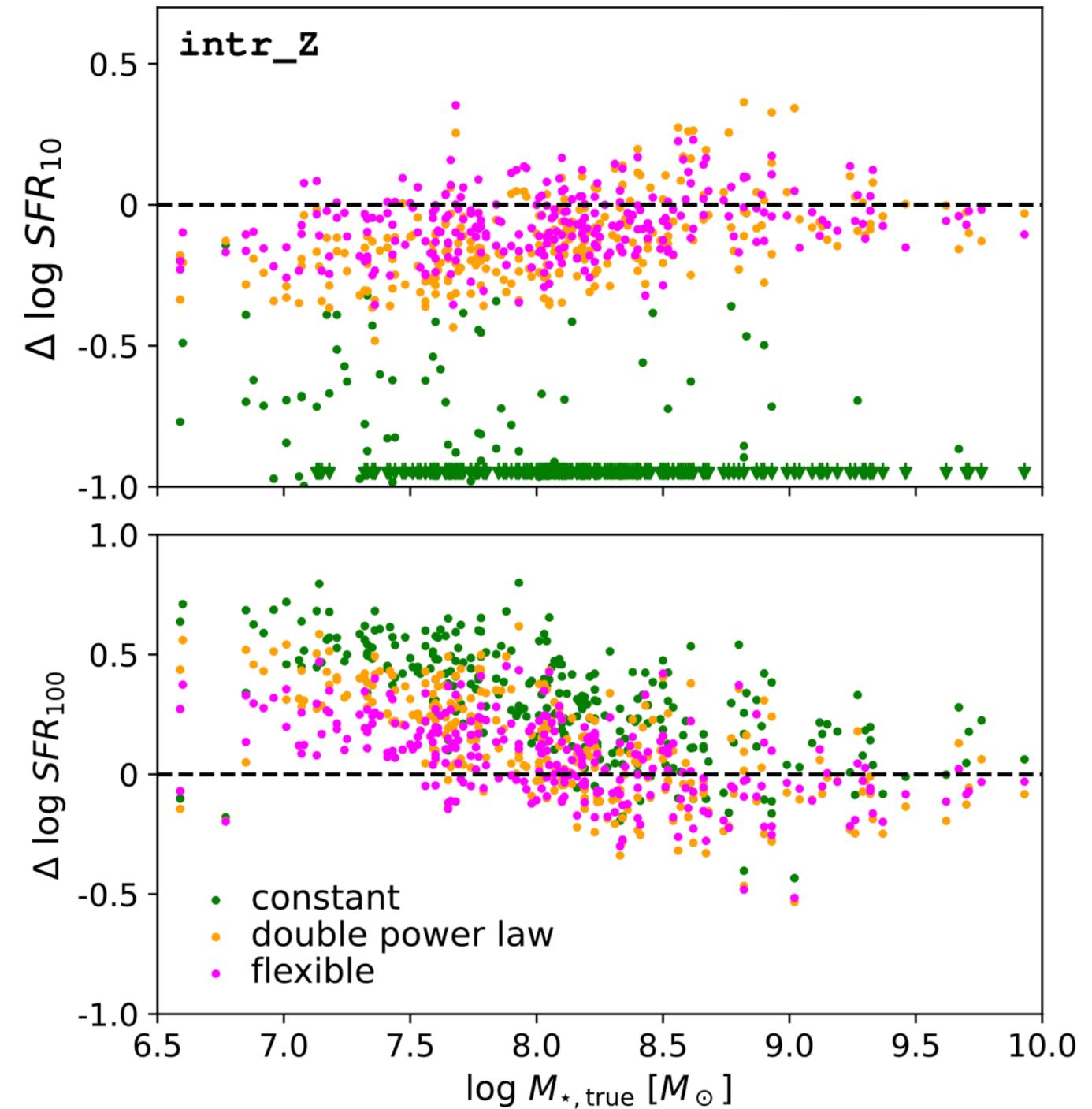
- SFH-Z-degeneracy (low-Z stars are brighter)

- SFHs favour old populations -> massive, metal-poor

Uncertainties in high-z galaxy properties inferred from SED fitting using JWST NIRCam photometry

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- SFH-Z-degeneracy

- SFHs favour old populations
-> massive, metal-poor
…and 'early-forming'

Uncertainties in high-z galaxy properties inferred from SED fitting using JWST NIRCam photometry

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- SFH-Z-degeneracy

- SFHs favour old populations

- **Accounting for dust attenuation makes things much worse!**
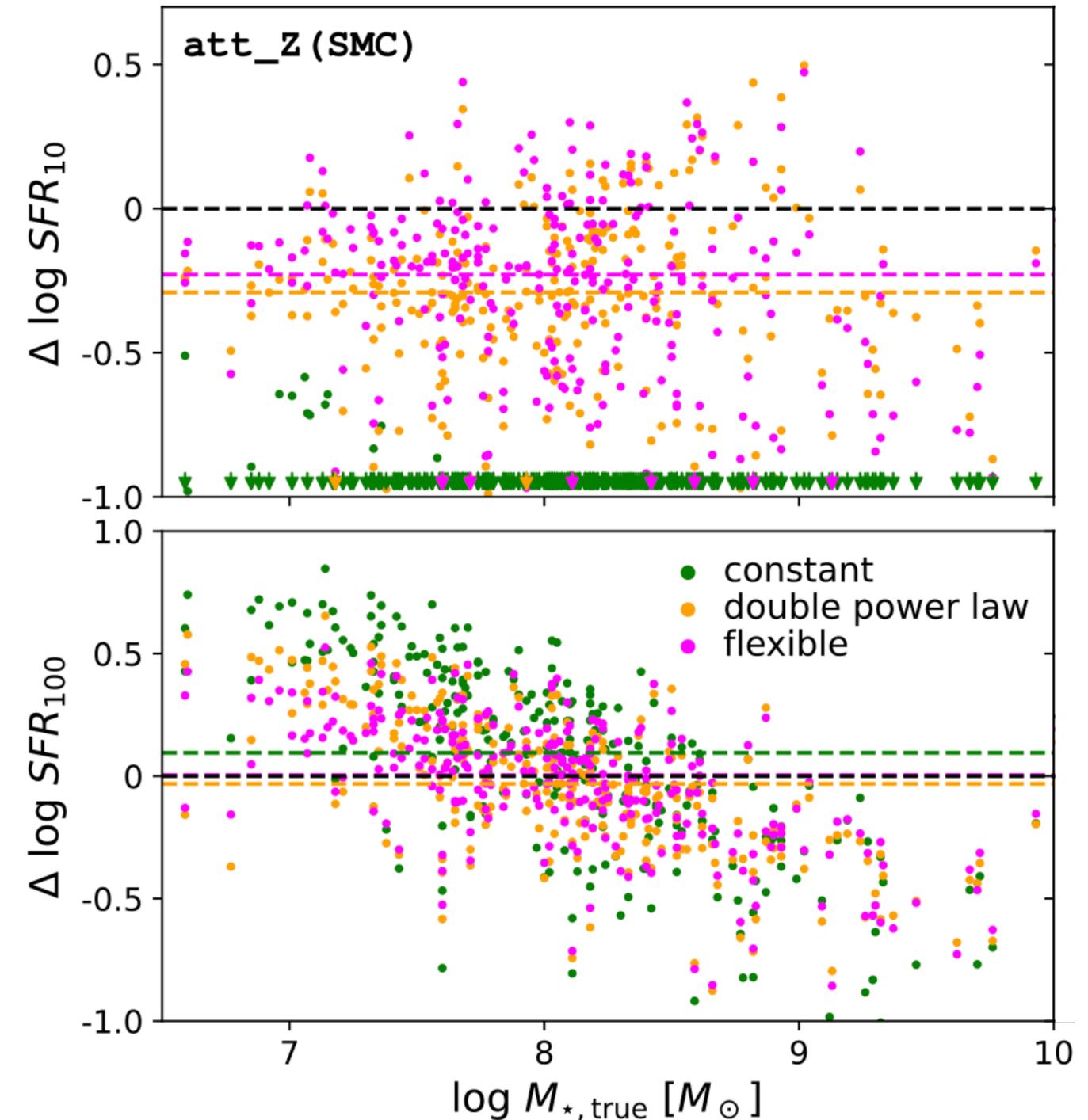
The future

- More physics, from first principles

- All redshifts

- Going further requires exa-scale facilities with large memory

- Supercomputers are evolving towards GPUs: many, but little memory

- It is a struggle to evolve the next generation of cosmological simulations codes for these new and future facilities. But it is happening!

That's it!

Now you know everything about high-z simulations!!