Modelling high redshift structure formation and reionization in the era of JWST

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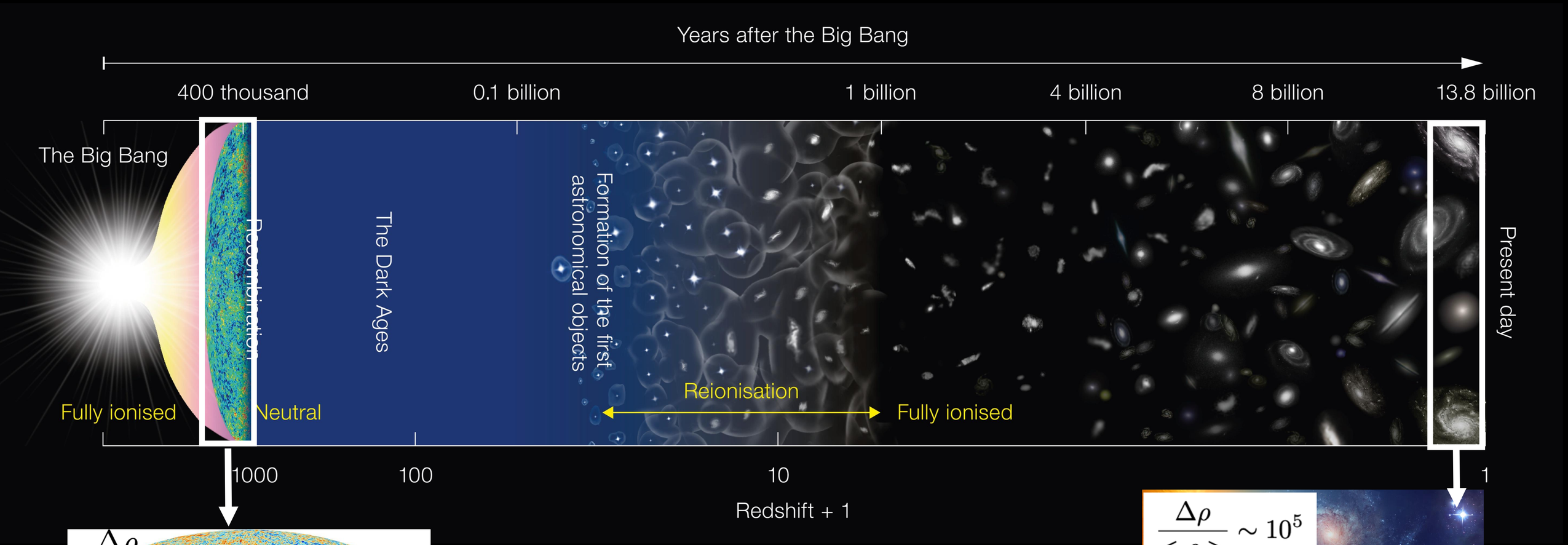
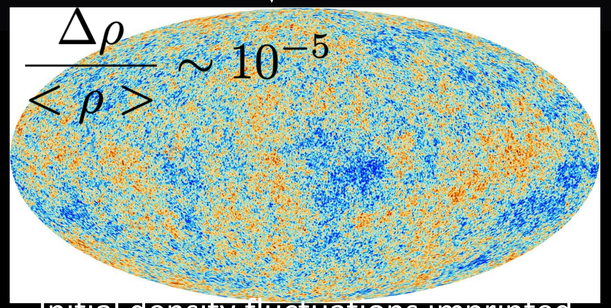
Cosmology 2025, Isola d'Elba
Sept 10, 2025

Cosmological structure formation

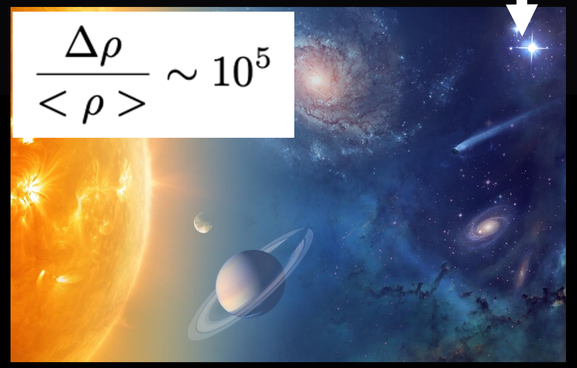




Initial density fluctuations imprinted on the cosmic microwave background

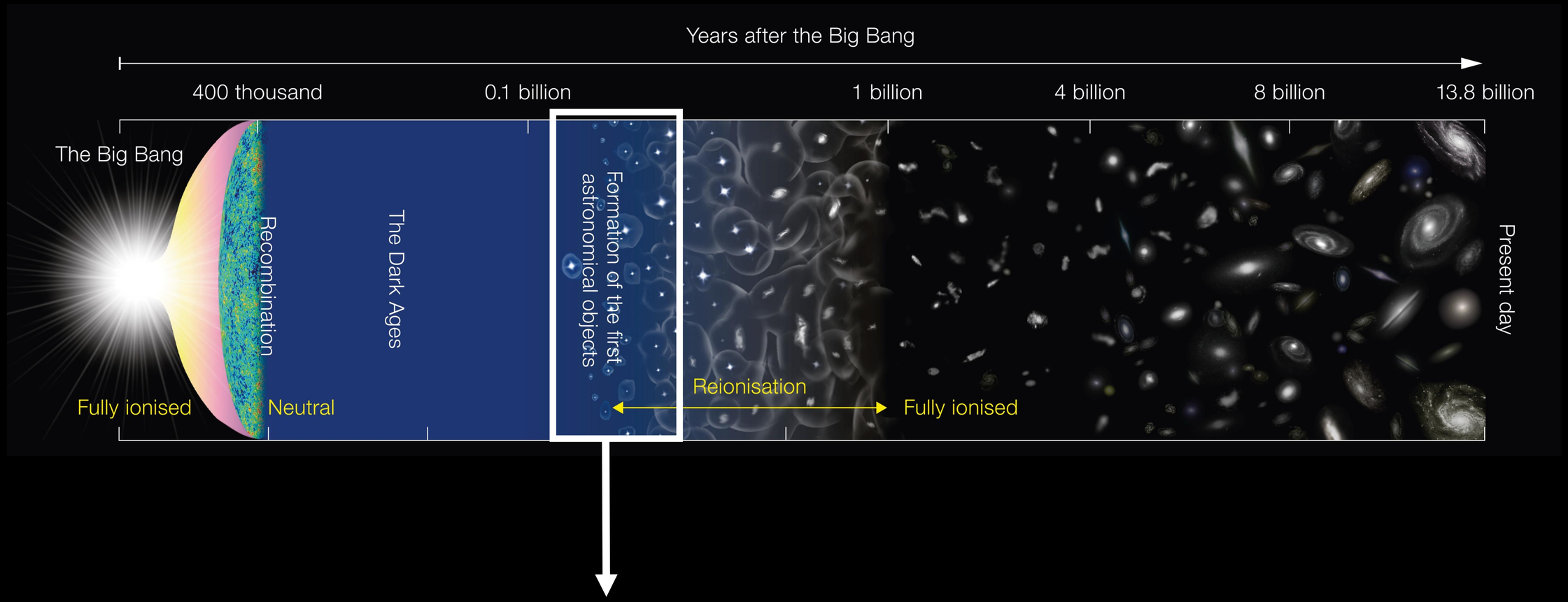
Gravity, (radiation-magneto) Hydrodynamics

Star & BH formation, Feedback



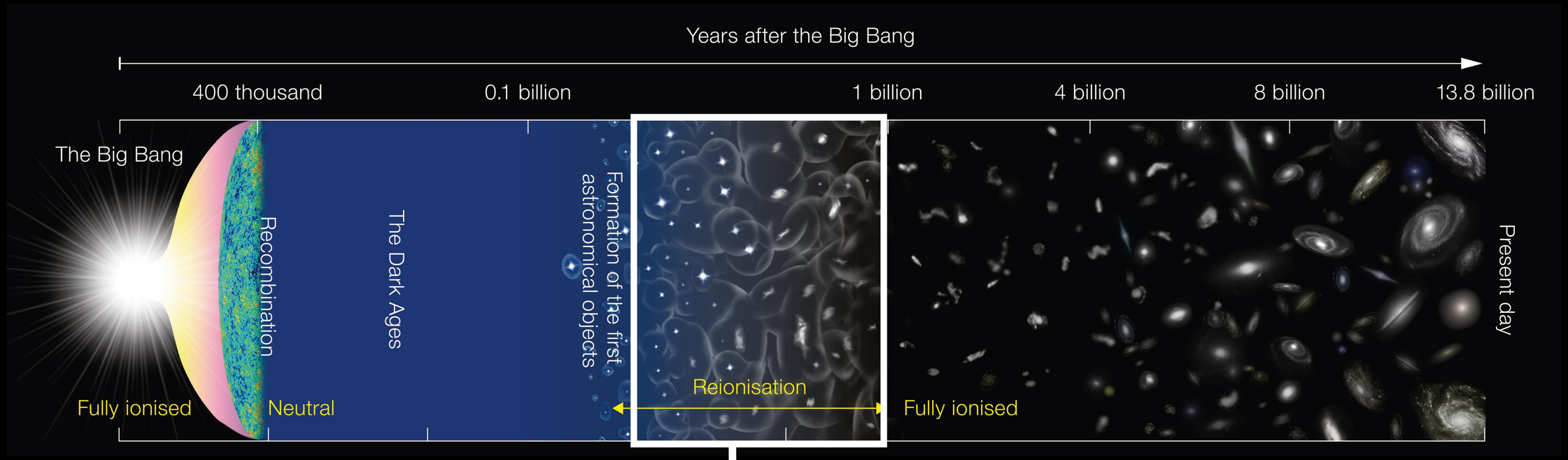
Complex structure seen today — galaxies, stars and planets

Cosmic Dawn (30>z>15)

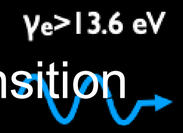


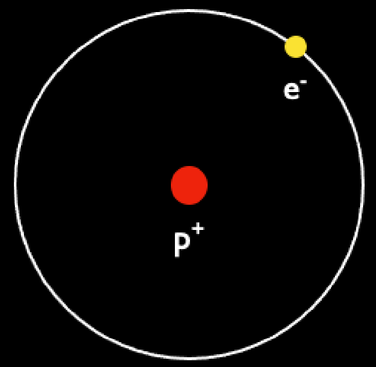
- The very first stars and galaxies start to form
- Start emitting light and begin ionizing low-density gas around them

Epoch of Reionization (15>z>5)



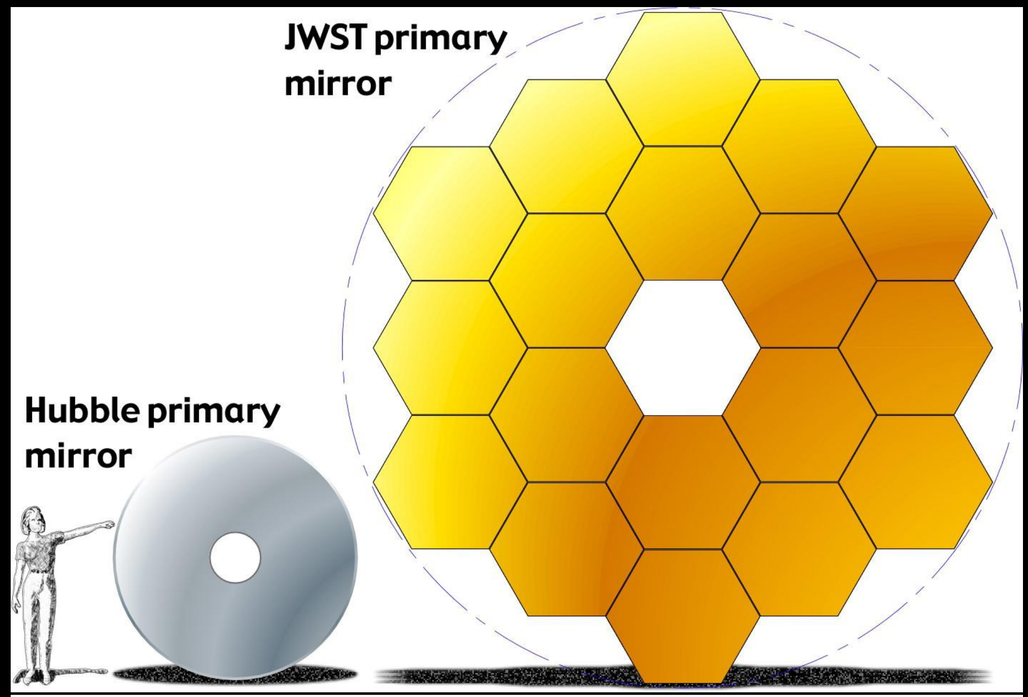
- Epoch of Reionization z=15-5 - Universe undergoes a phase transition
- All photons with energy > 13.6 eV have the ability to ionize hydrogen
- Radiation from first stars and galaxies ionizes the neutral Hydrogen in the Universe and heats up the gas to ~ 10,000 K

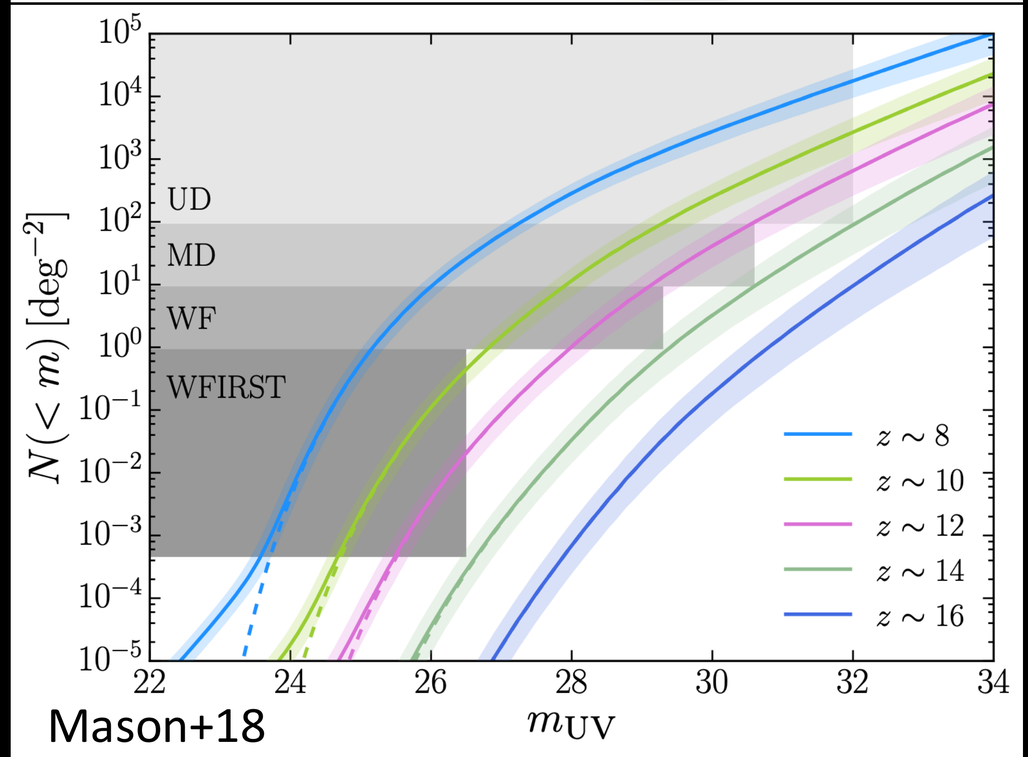




JWST has expanded the high redshift frontier (z~20)

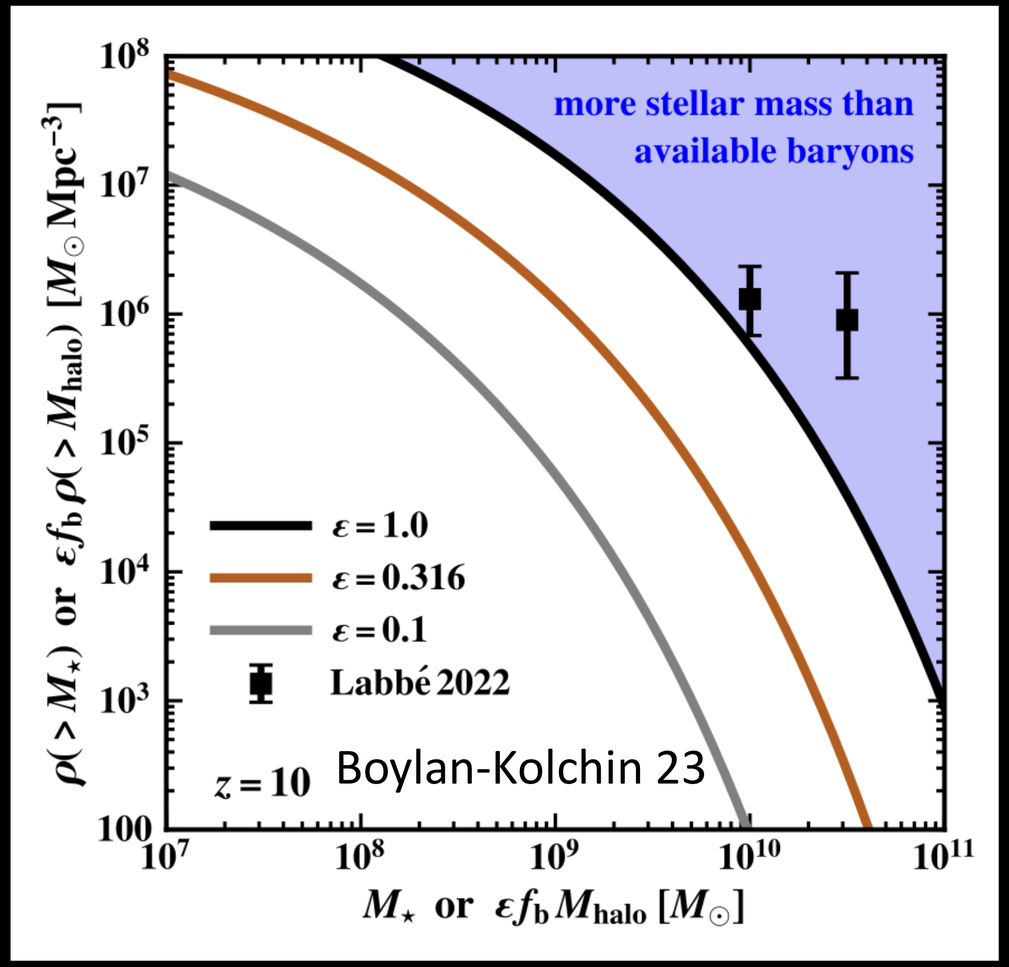
- JWST is a game-changer thanks to
  - Larger mirror
  - Larger frequency coverage
  - Detects the rest frame optical emission of galaxies in Cosmic Dawn and Epoch of Reionization
  - Galaxies detected up to z=25 with spectroscopic confirmation of galaxies up to z=14
  - Cosmic Dawn and Reionization have entered a new high-precision era



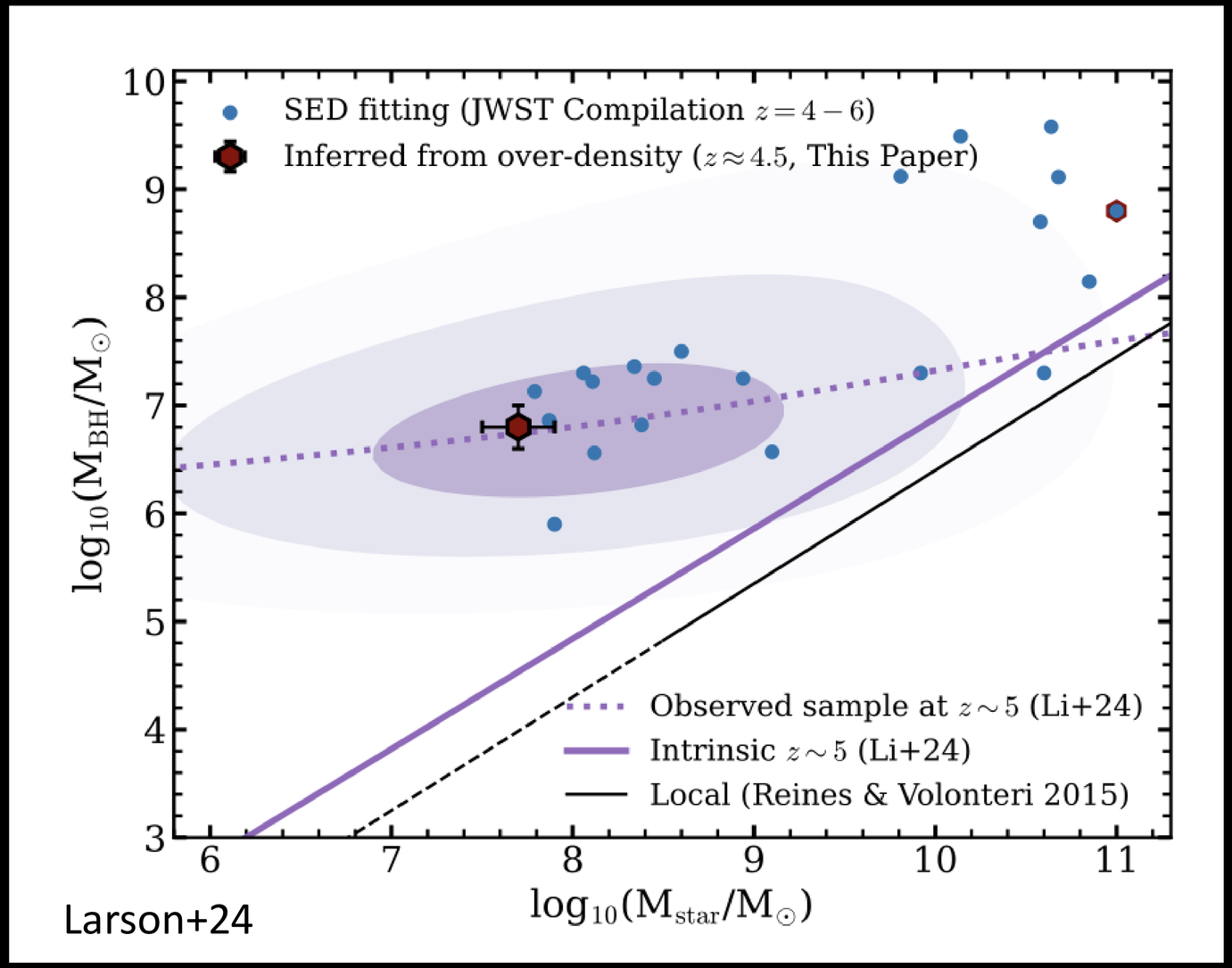


Mason+18

JWST thrown up surprises



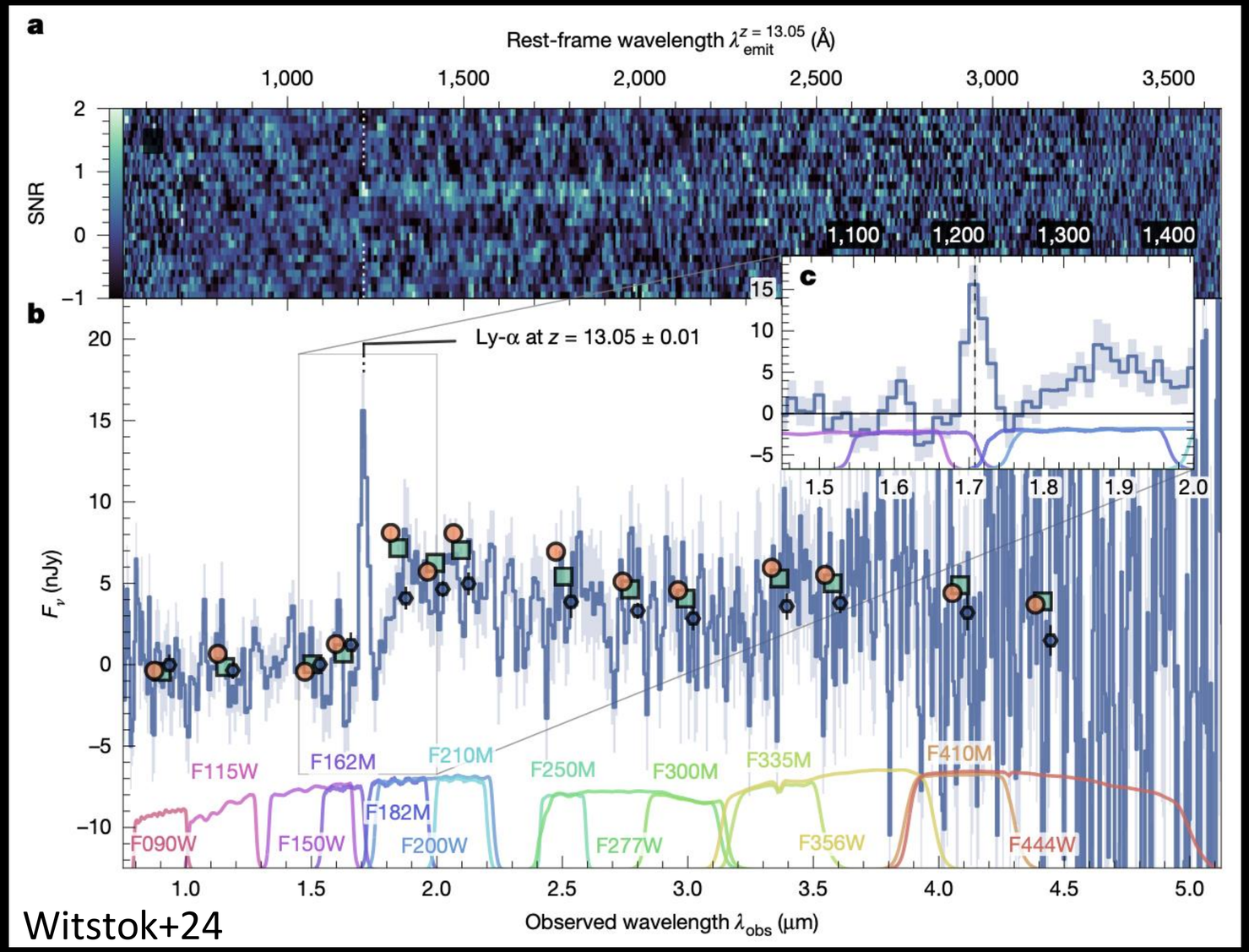
An abundance of massive bright galaxies



Overmassive BHs at high-z

JWST thrown up surprises

- Lyα emitter with EW of 40 A at z~13
- Stars and BHs in the galaxy must have created an ionized region around the galaxy
- Only way to prevent complete extinction of Lyα
- Able to detect the onset of reionization



Witstok+24

Exciting few years….

SEPTEMBER 14, 2022 | 13 MIN READ

JWST's First Glimpses of Early Galaxies Could Break Cosmology

The James Webb Space Telescope's first images of the distant universe shocked astronomers. Is the discovery of unimaginably distant galaxies a mirage or a revolution?

JWST finds cosmic monster ruling tiny early galaxy: Was it forged by black holes from the Big Bang?

News By Robert Lea published July 9, 2025

"Theories involving substantial formation of stars prior to or together with the black hole formation and growth are very unlikely."

MAY 22, 2025 The GIST

The new, farthest galaxy has been found by JWST, only 280 million years after the Big Bang

by Evan Gough, Universe Today

edited by Lisa Lock, reviewed by Andrew Zinin

6 MIN READ

Newfound Galaxy Class May Indicate Early Black Hole Growth, Webb Finds

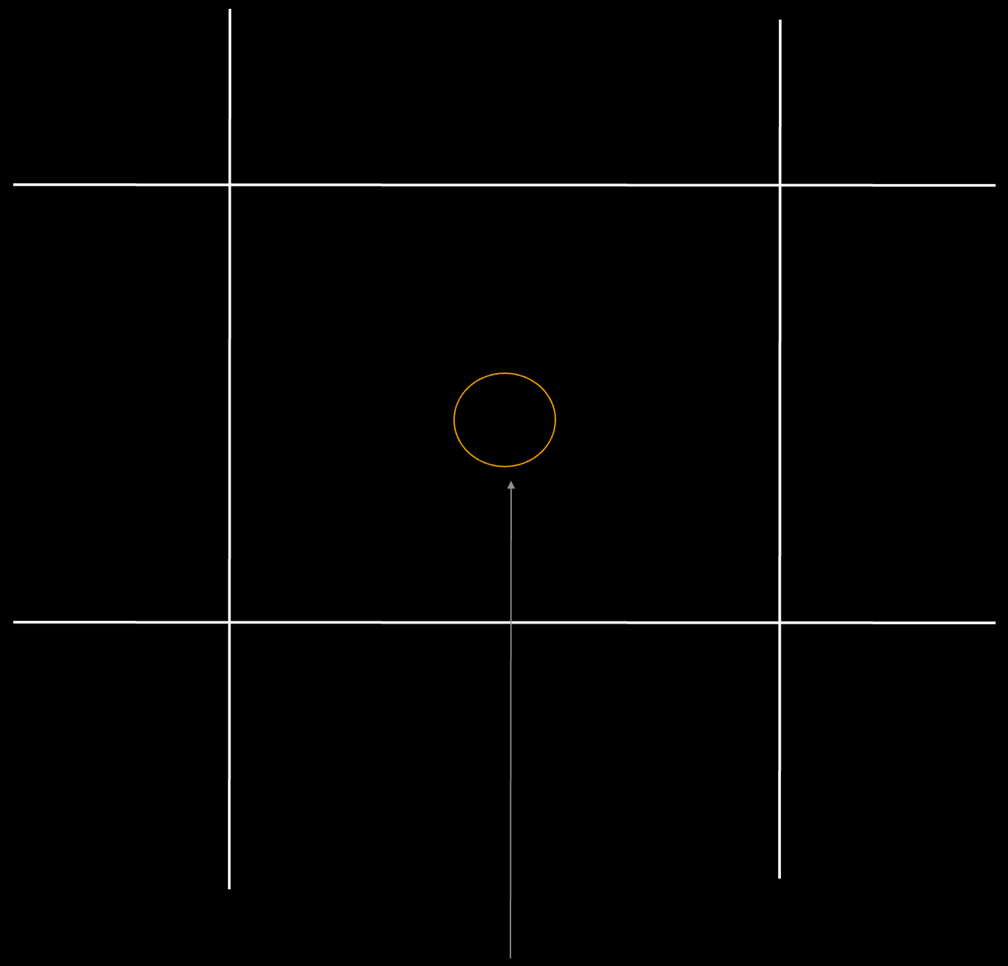
How to make sense of all of this?

Galaxy formation is a complex multi-scale — multi-physics problem

- Generally requires the solution of complex multi-physics and multi-scale systems to understand Reionization
- Requires accurate treatment of
  - Gravity
  - Hydrodynamics
  - Star and BH formation
  - Feedback processes
  - Self-consistent radiation hydrodynamics
  - Dust
  - Accurate source functions for stars and black holes

The need for subgrid models

- Feedback processes occur on small scales but impact the large scale properties of galaxies
- Any process occurring below the cell size in simulations in not modeled properly
- Consider a simulation of a representative patch of the Universe ~100 Mpc -- If you want to resolve stellar feedback physics then cell size ~ 0.1 pc -- Dynamic range ~ 10^9
- Need 10^{27} cells to achieve this resolution everywhere
- Need models that can capture the small scale physics and translate them onto the grid scale
- **Most current research in galaxy formation focuses on developing accurate and predictive subgrid models**

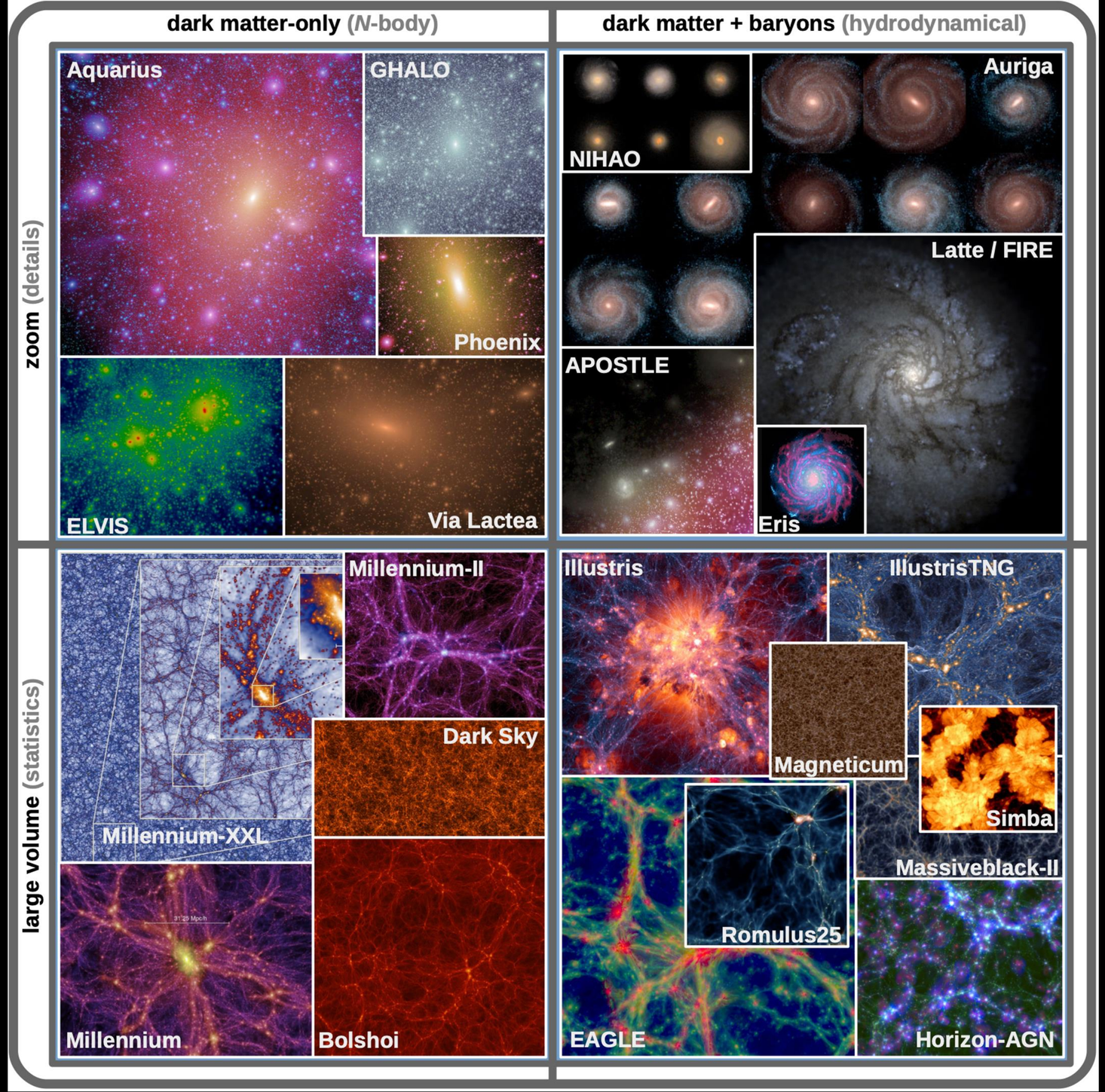


Sphere of influence for feedback << Grid size
(1 pc << 1kpc)

The simulation landscape

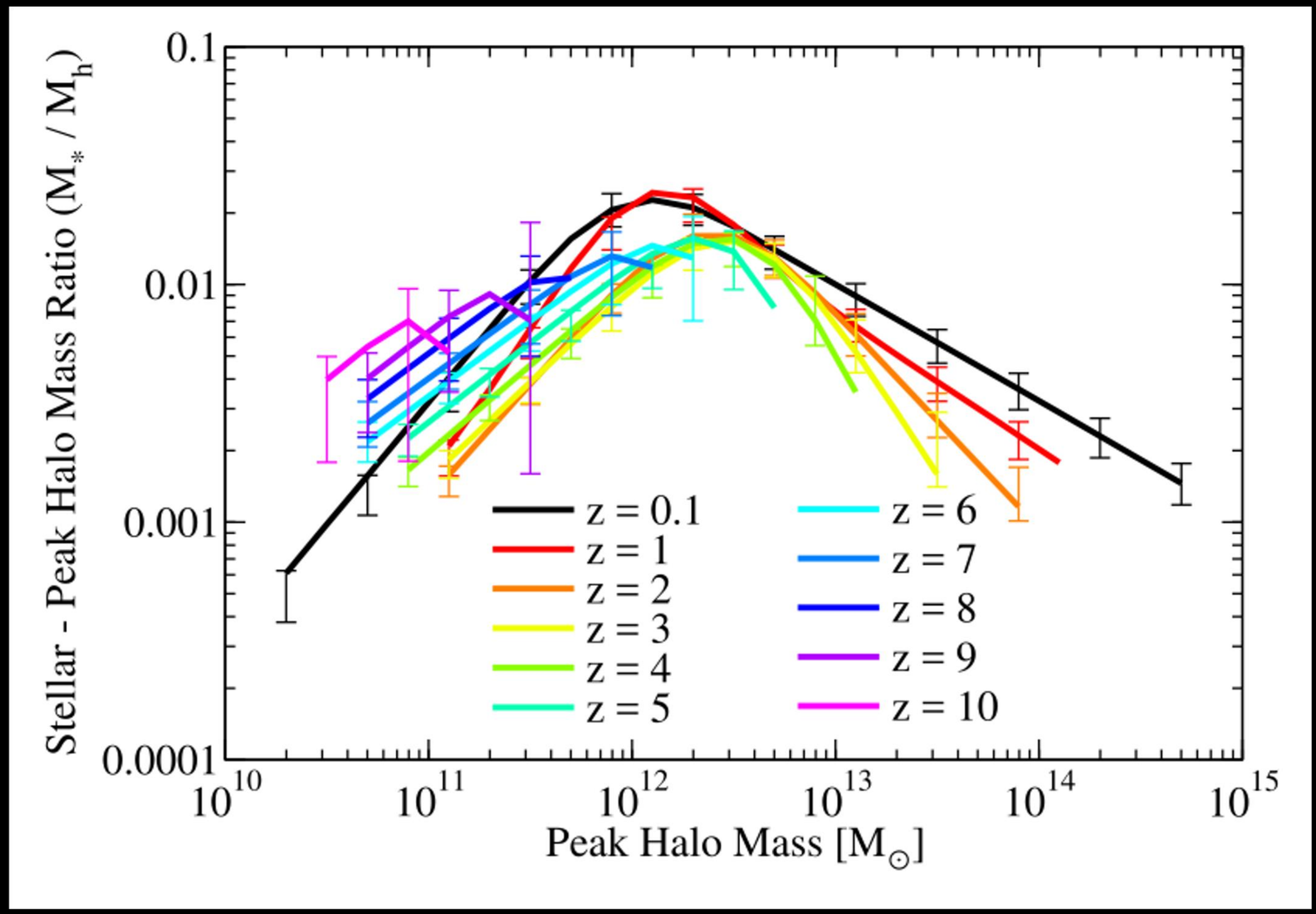
- A variety of simulation codes and techniques are used to model galaxies
- Interestingly, wildly different sub-grid models give rise to similar galaxy properties

Vogelsberger+20



Inefficiency of galaxy formation

- The star formation efficiency is about 1~2% at z=0 in MW mass halos
- The efficiency decreases up to z=5 and then increases again
- However, they are still quite small < 1 %

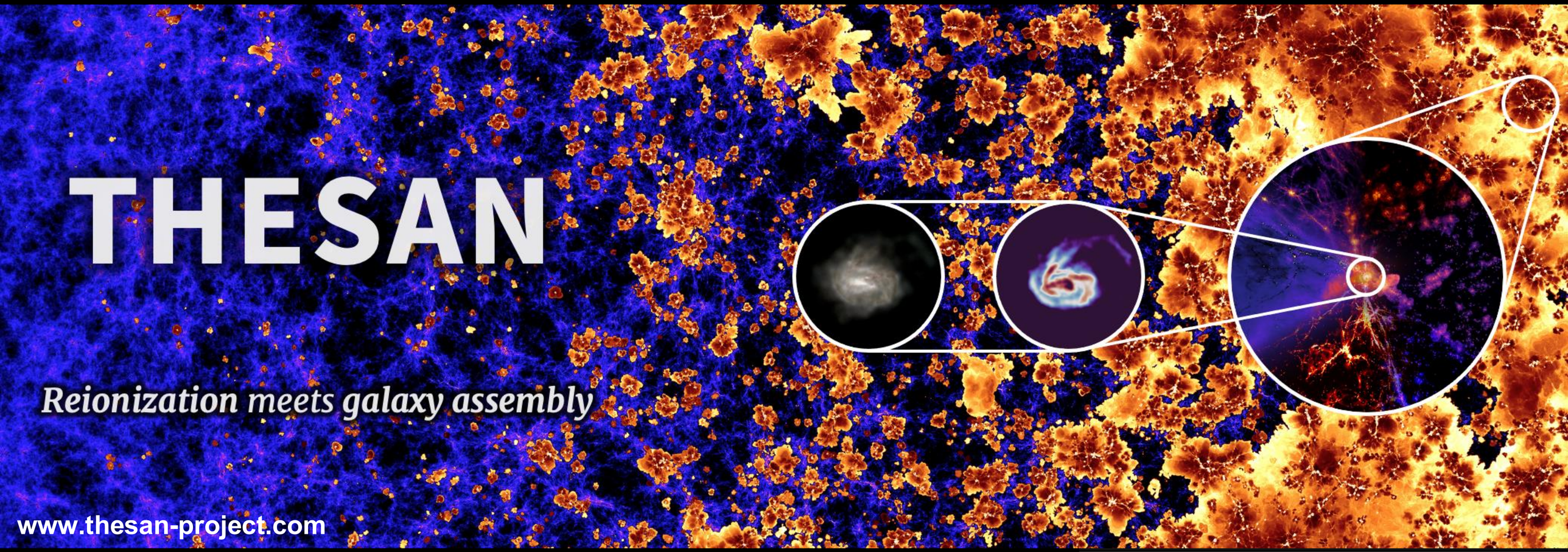


Behroozi+19

What about reionization?

- Generally requires the solution of complex multi-physics and multi-scale systems to understand Reionization
- Requires accurate treatment of
  - Gravity
  - Hydrodynamics
  - Star and BH formation
  - Feedback processes
  - Self-consistent radiation hydrodynamics - necessary for modelling reionization
  - Dust
  - Accurate source functions for stars and black holes

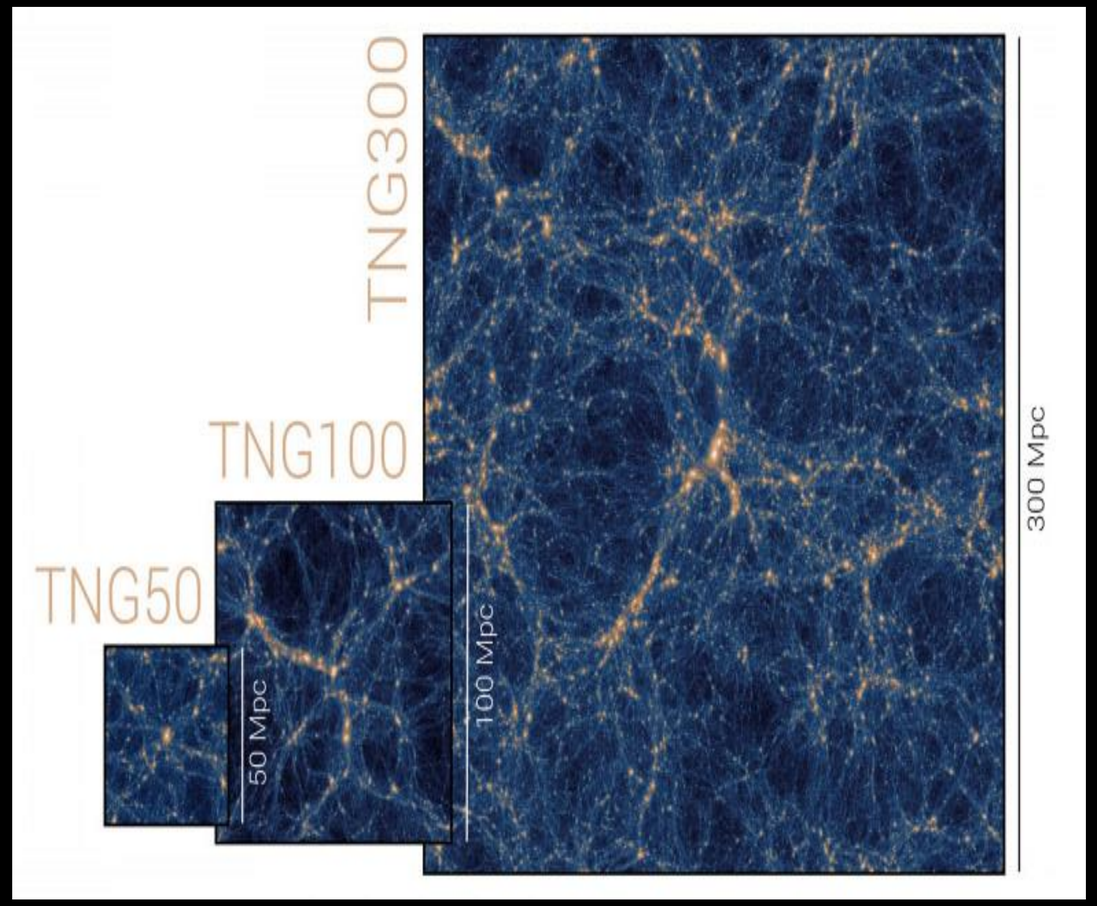
Coupled galaxy formation + RHD simulations



PI: Kannan+22a,b; Smith+22; Garaldi+22

- Can potentially model both the reionization process and the sources responsible for it
- On the fly, RHD is quite expensive
- The largest simulations have a linear size of about ~100 Mpc

Accurate galaxy formation model + RHD



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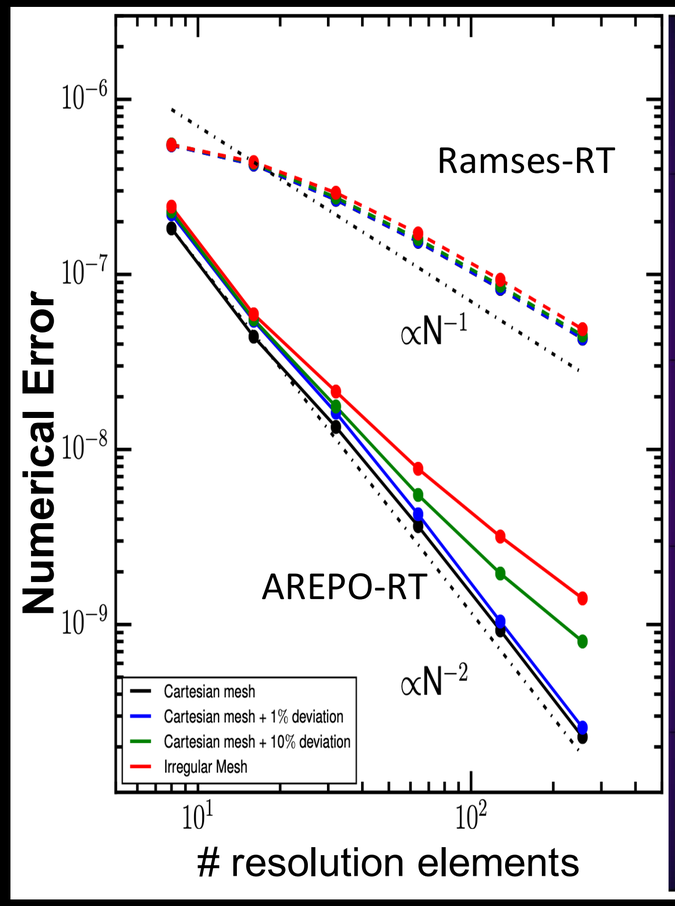
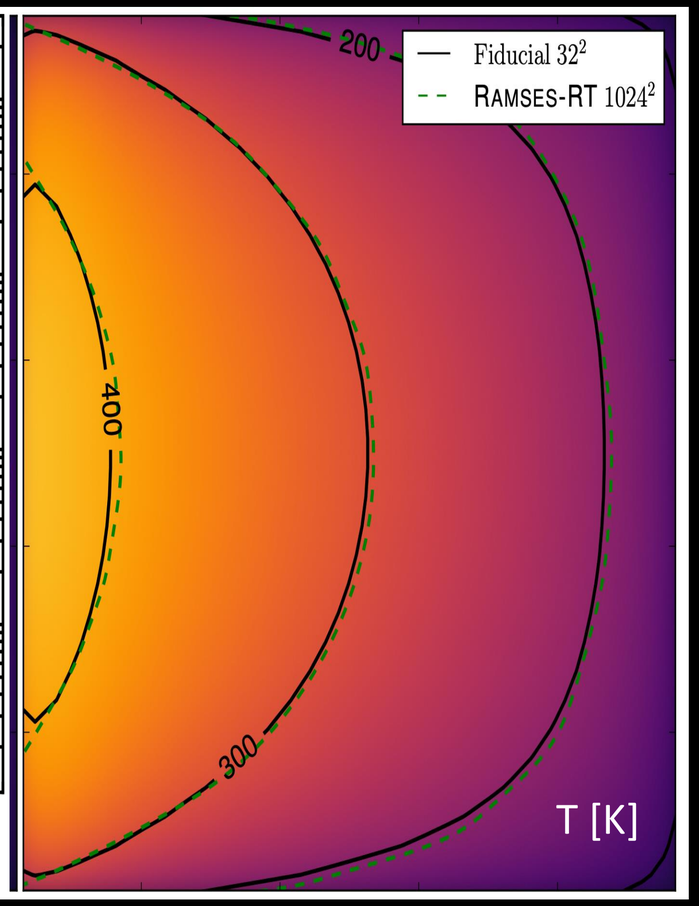




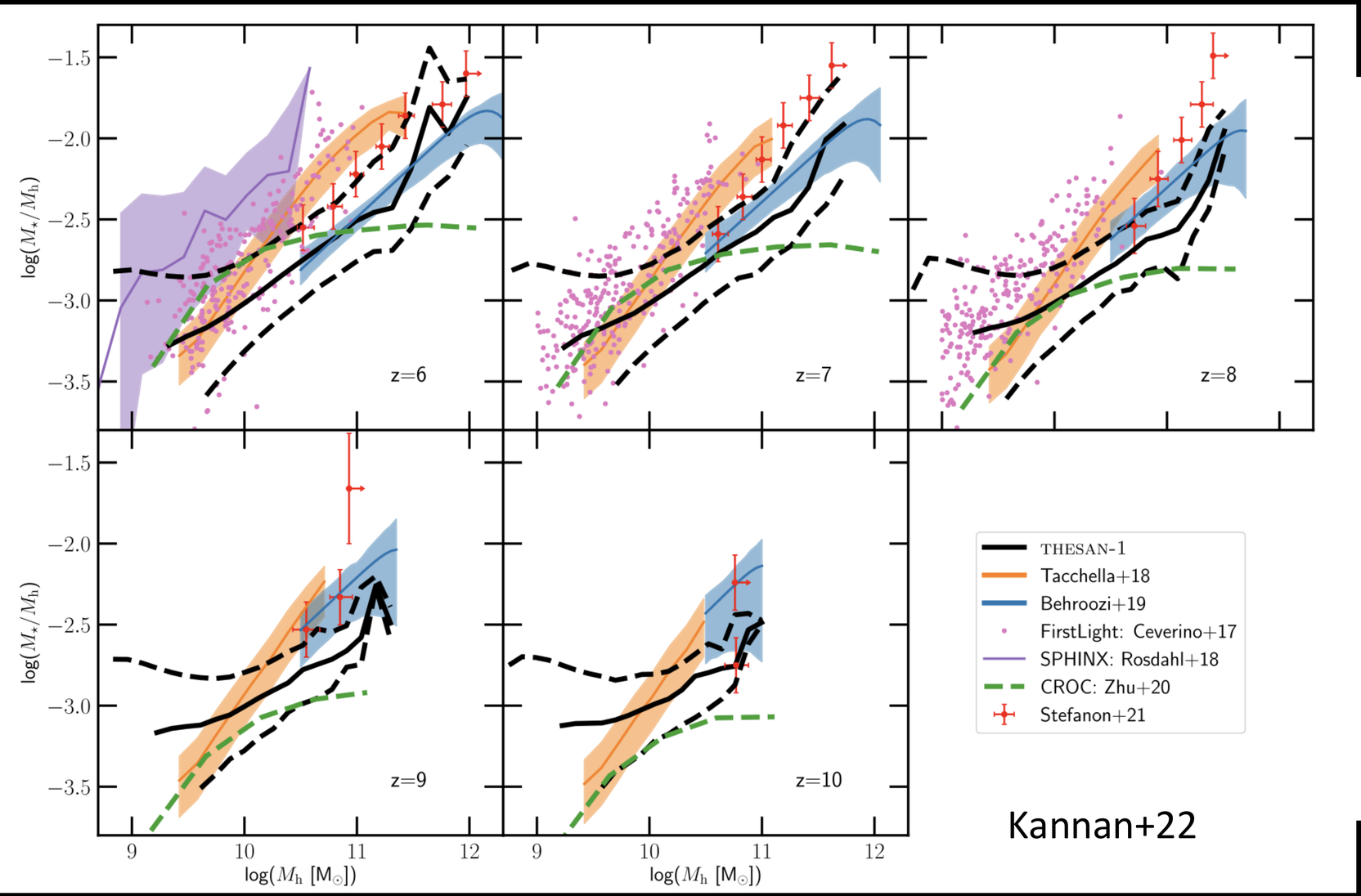
IllustrisTNG
(Springel+18)

- Well tested galaxy formation model, works extremely well down to z=0

AREPO-RT
(Kannan+19)

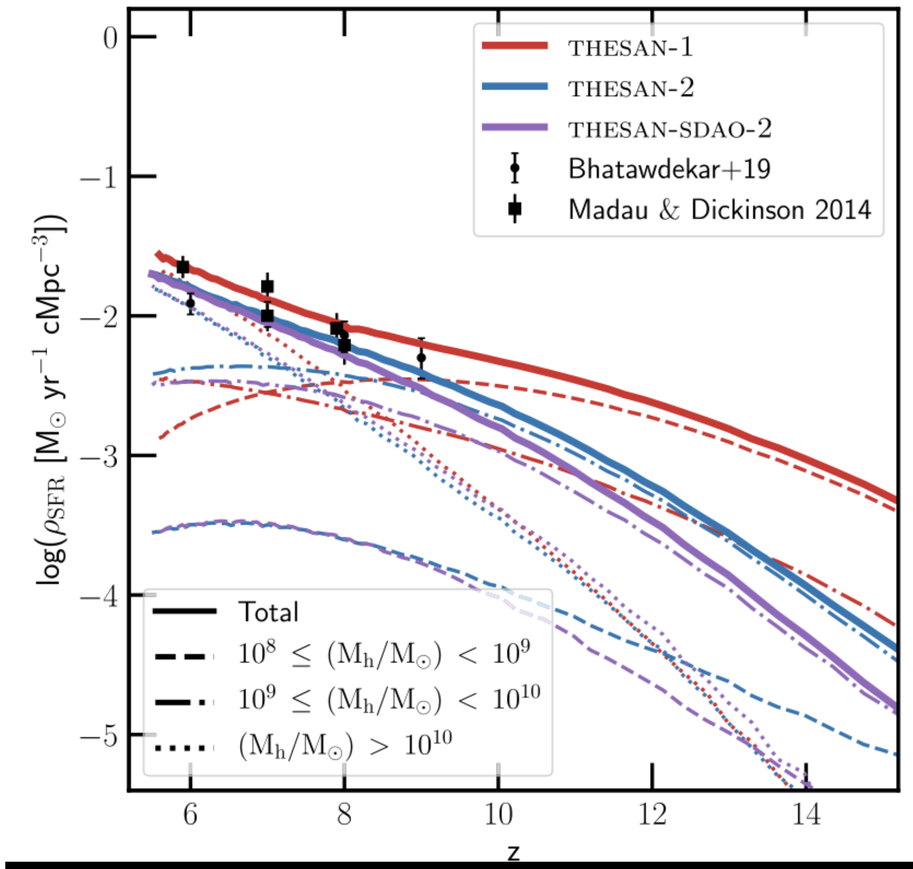
- Efficient and highly scalable radiation hydrodynamics module that solves the RT equations on the native Voronoi Mesh

Matches pre-JWST observations of star formation efficiency



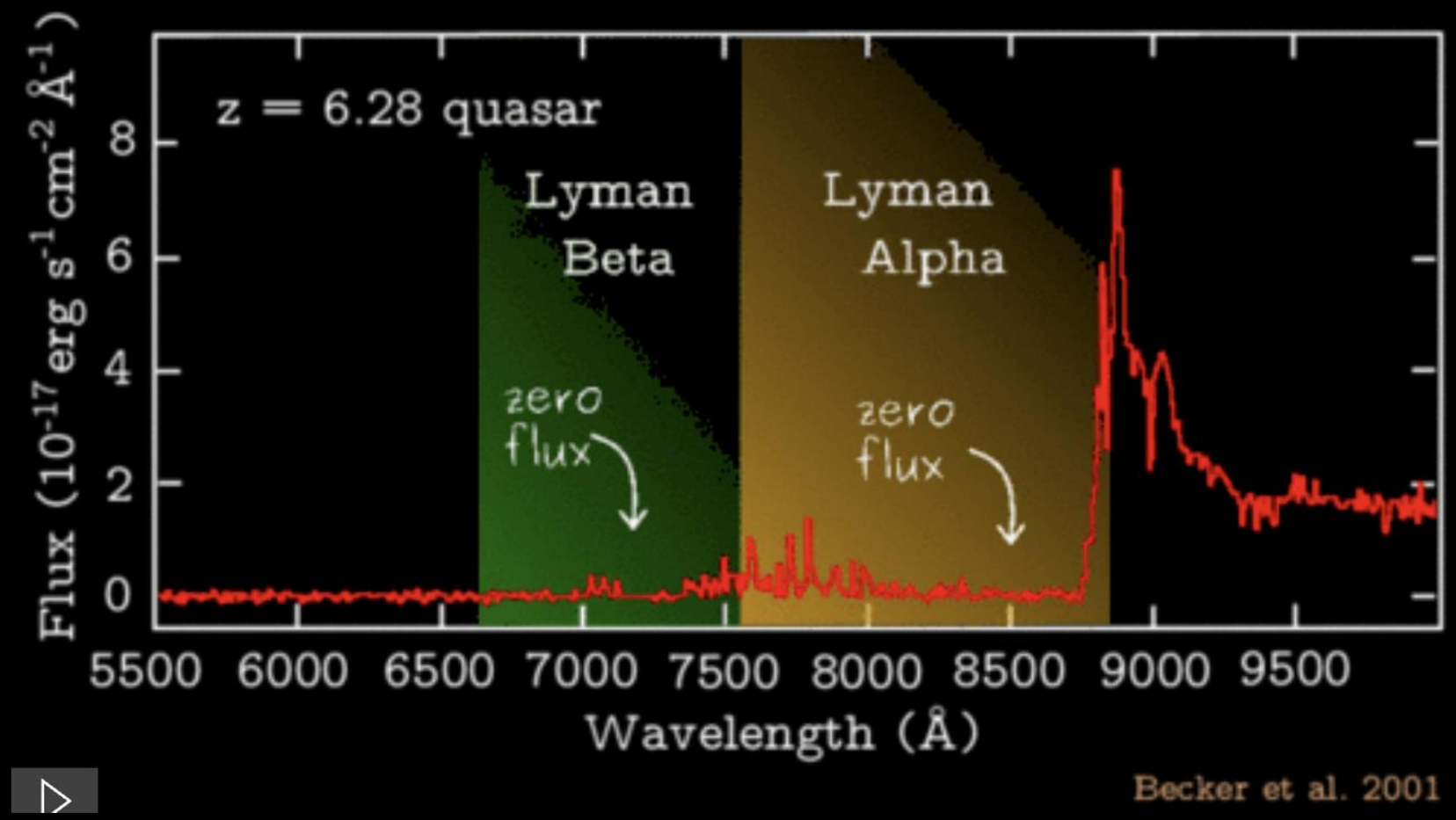
Kannan+22

Low star formation efficiency



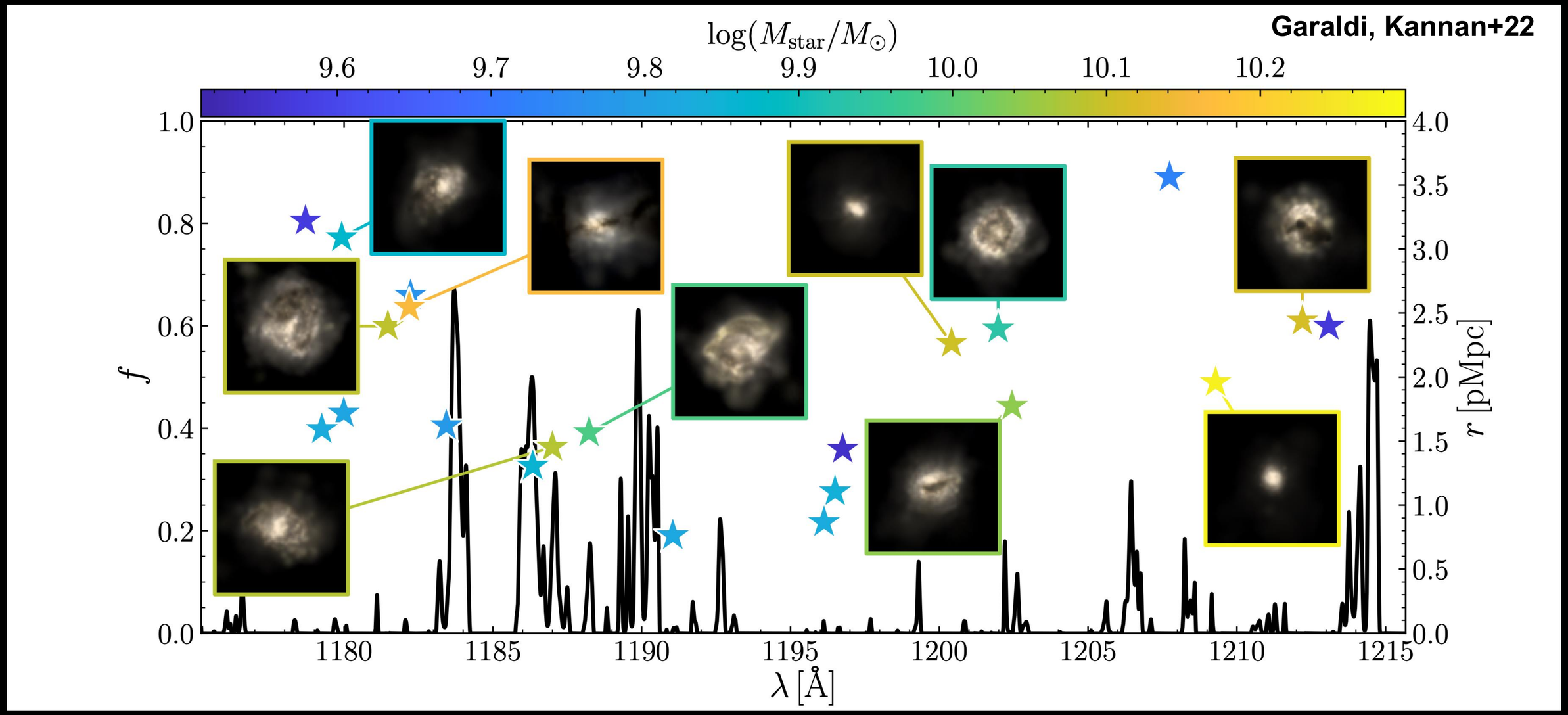
Star formation falls off quickly at high redshift

Galaxy-IGM Connection



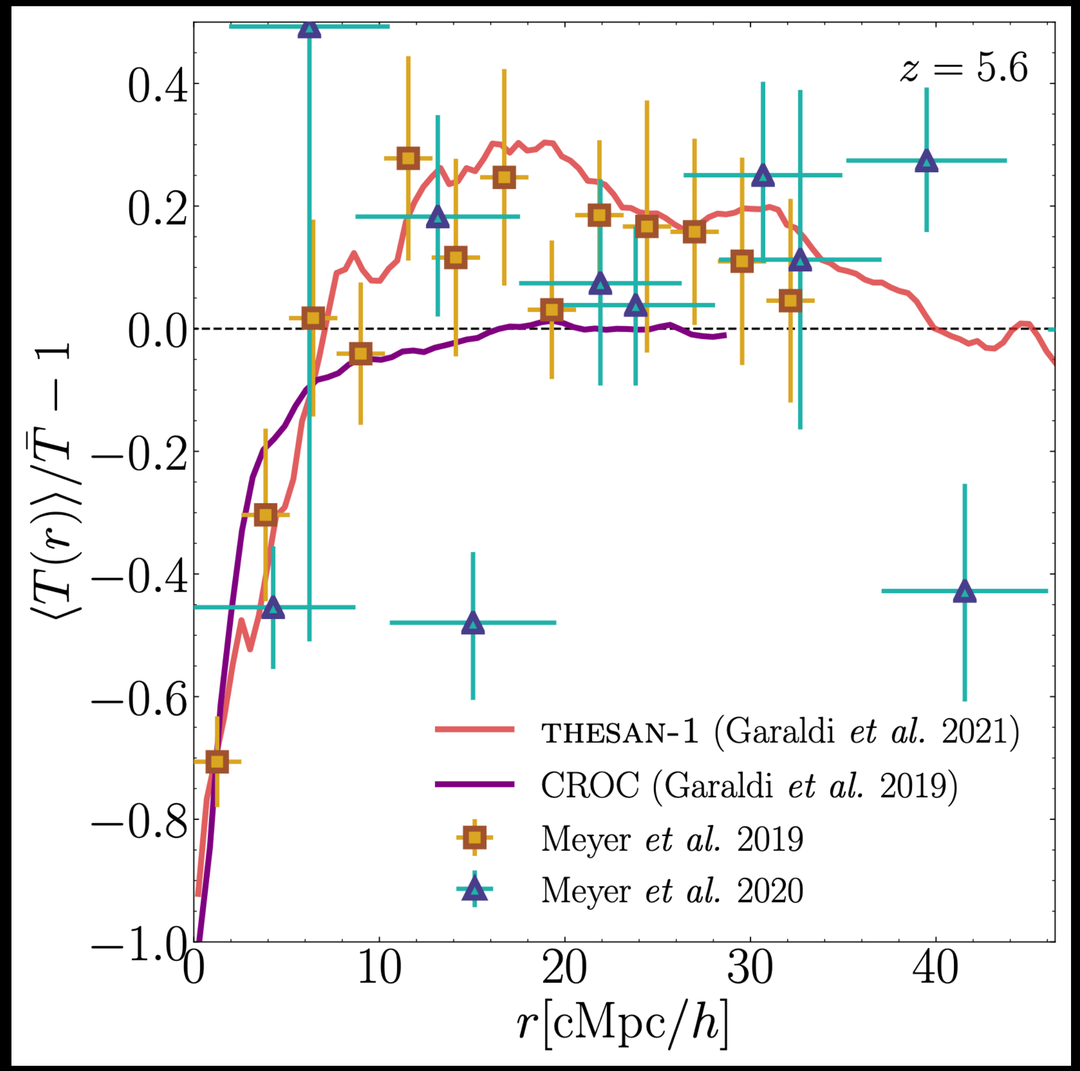
- In high redshift quasars (z~6), the spectra blueward of the Lyα line indicating presence of a large amount of neutral gas in the Universe
- However, any ionized regions around galaxies will show up as transmission spikes

IGM - Galaxy connection

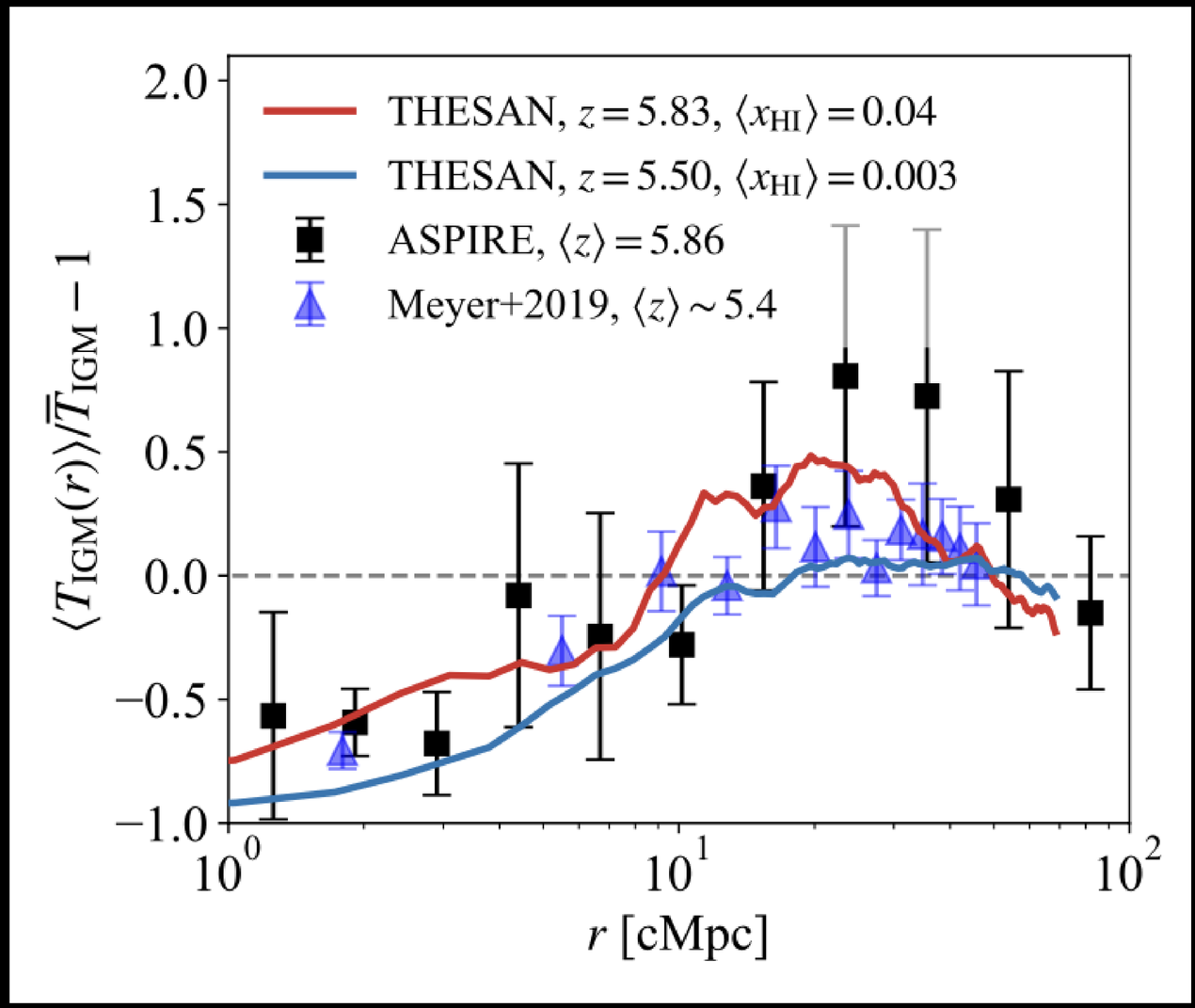


- The normalized transmission flux of the Lyα line around galaxies is an important observable
- Probes connection between the sources and their ionized bubbles

IGM - Galaxy connection

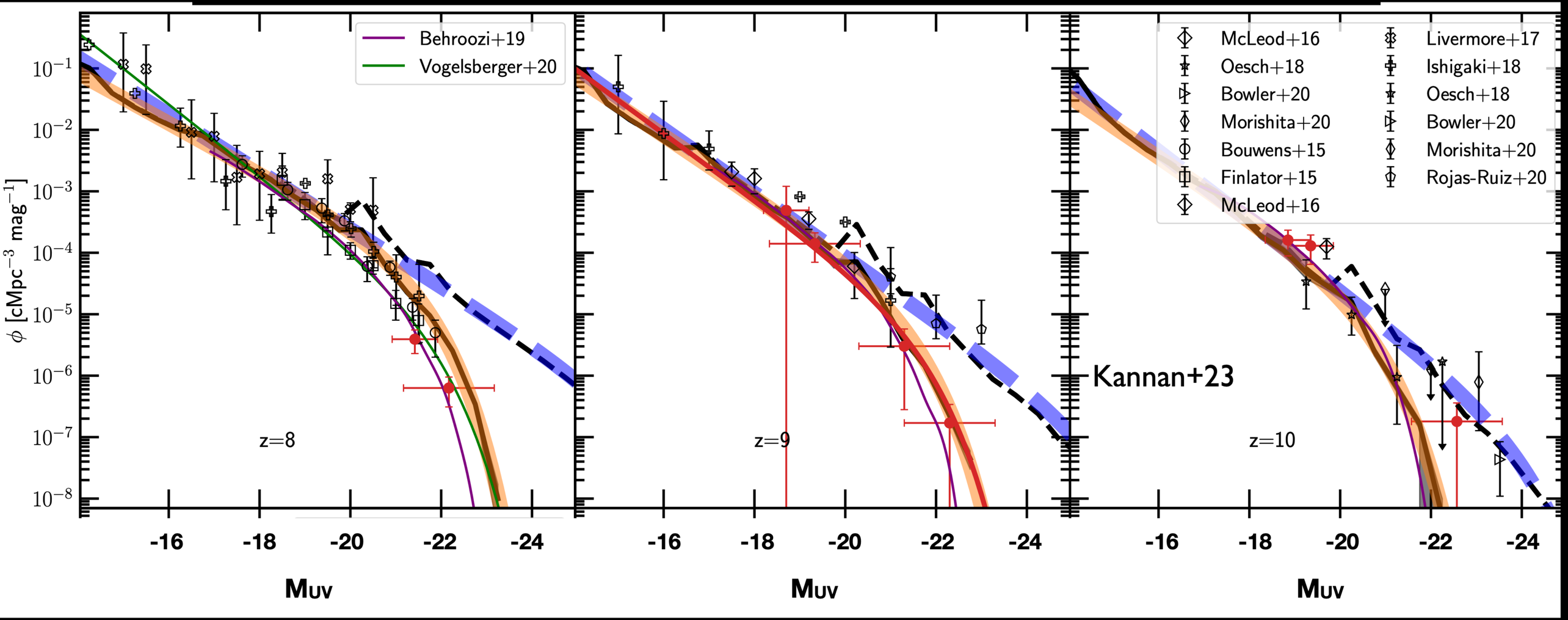


Garaldi, Kannan+22



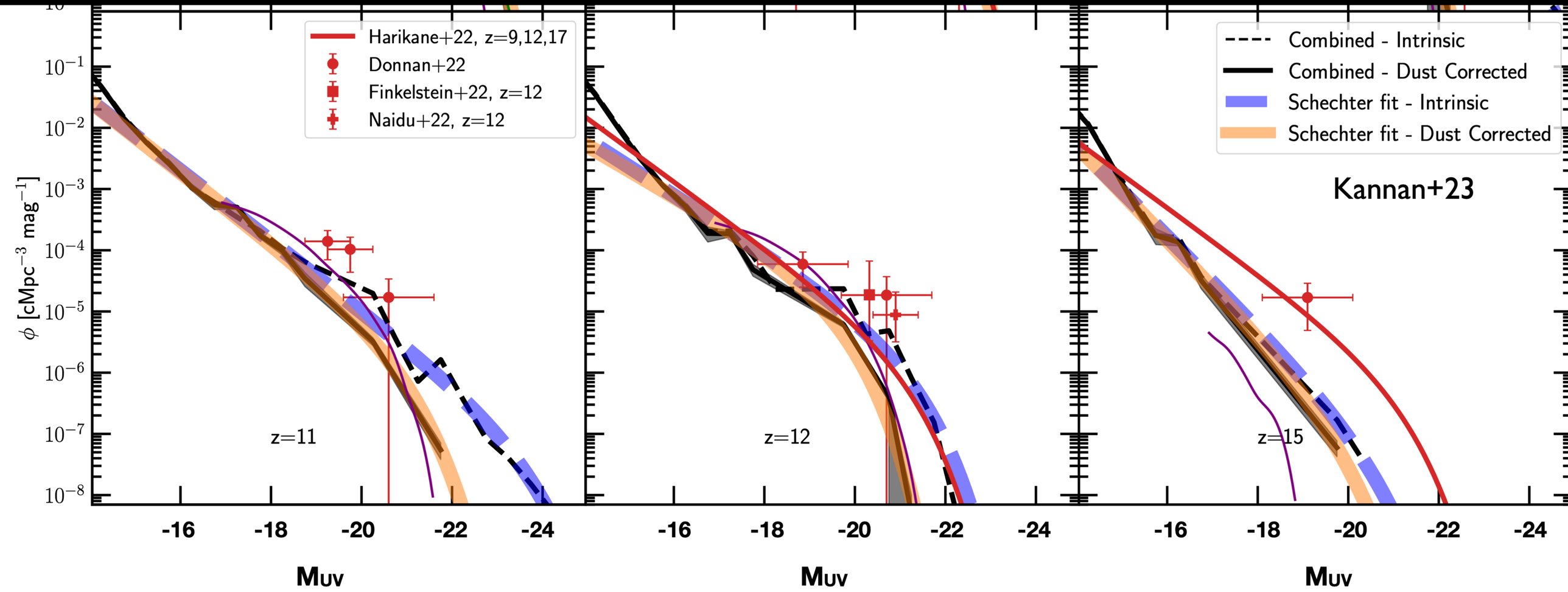
JWST ASPIRE - Lyα+[OIII] cross correlation
Kakiichi+2025 (incl. Kannan)

JWST's impact - what does THESAN (and THESAN-like models) predict?



- z=8 & z=9 observations match the simulated dust attenuated UV luminosity function
- z=10 - both HST and JWST observations seem to prefer a galaxy population that is largely dust-free

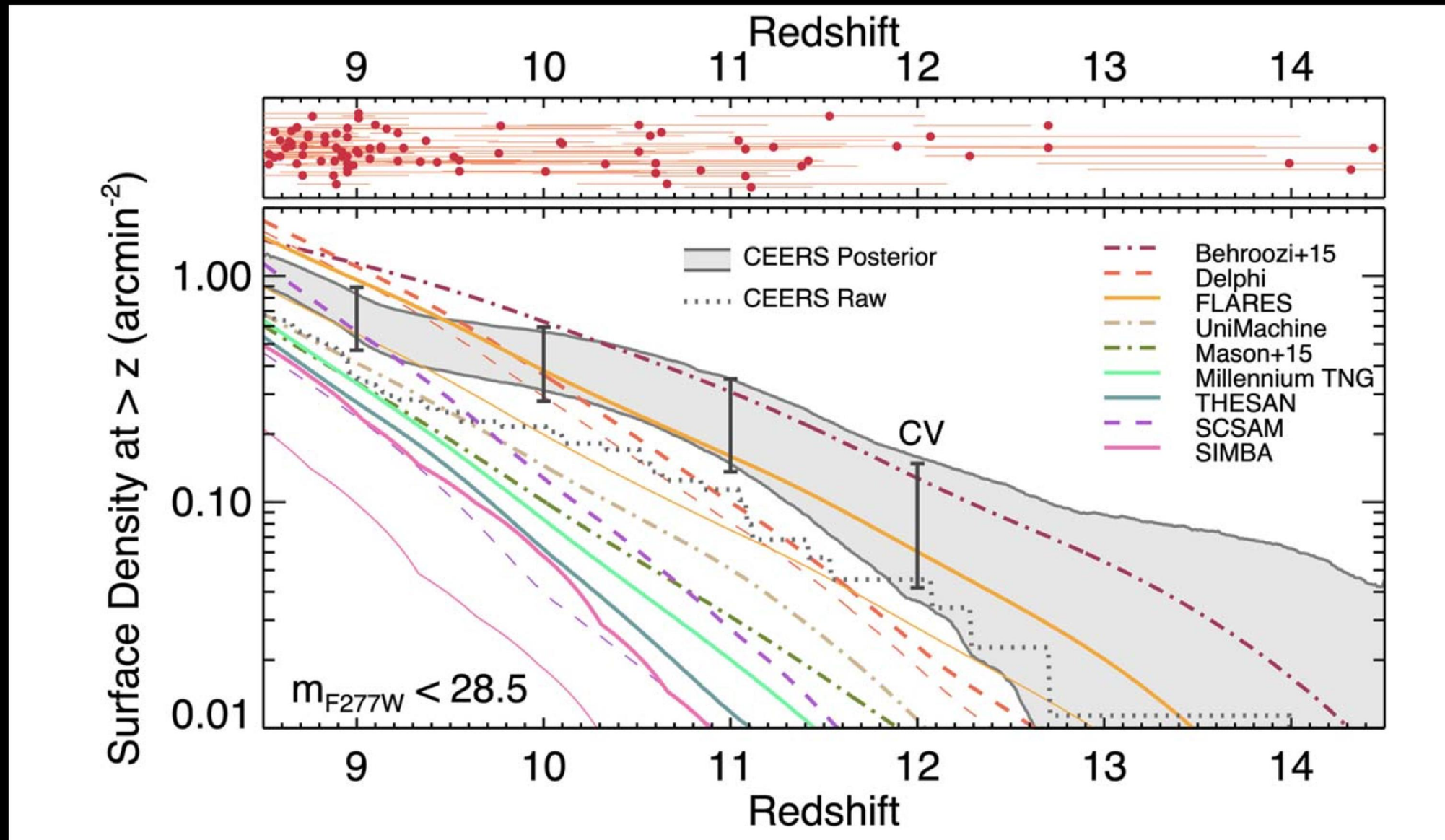
JWST's impact - what does THESAN (and THESAN-like models) predict?



- z=11 & z=12 observations show slightly large number of luminous galaxies (still consistent with simulations)
- z>12 - The simulated UVLF is about a factor of 5-10 lower

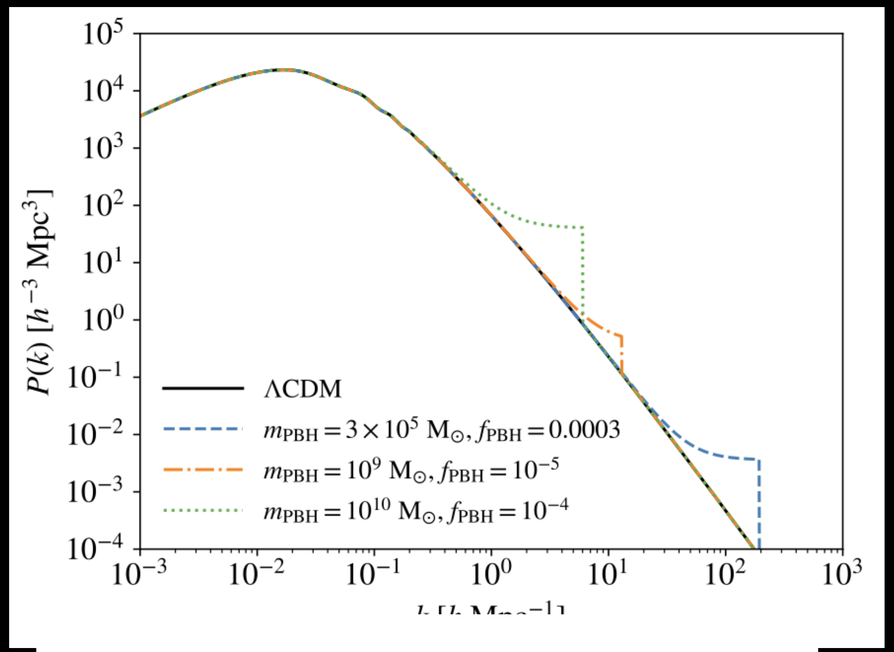
Current galaxy formation models are in tension with JWST

- Almost all simulations/models underpredict the abundance of massive galaxies beyond z=9

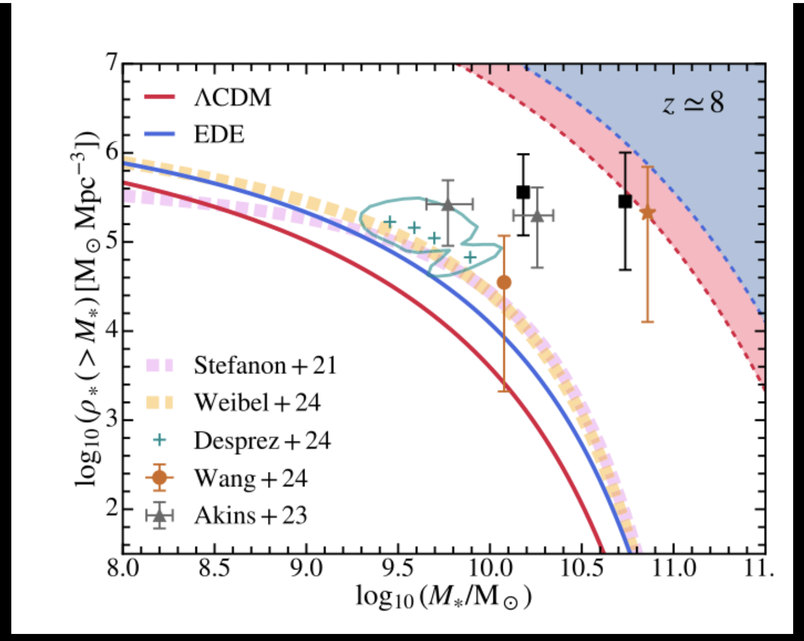


Finkelstein+24

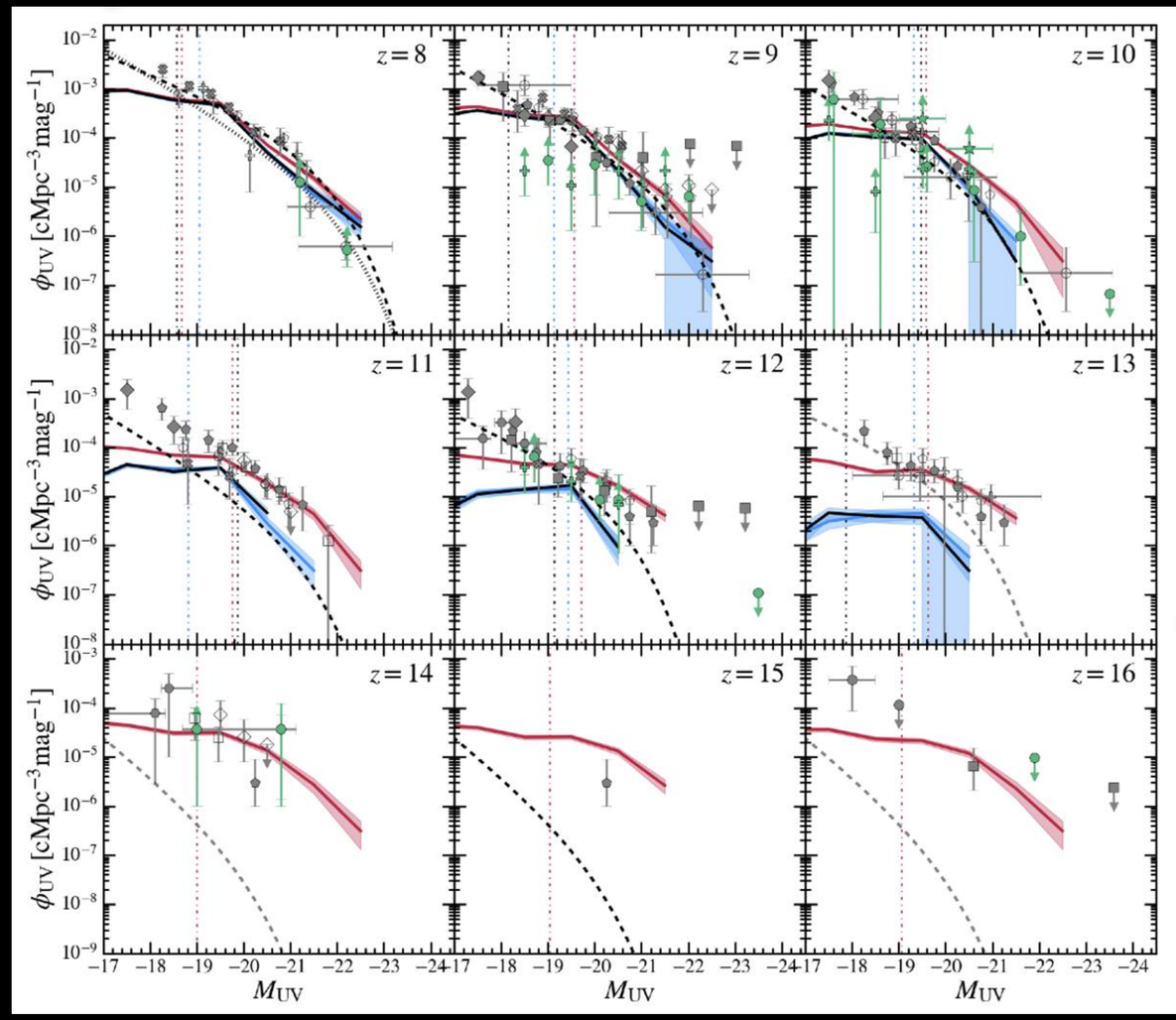
Potential Cosmological Solutions



- Primordial BHs can increase power on small scales and seed structures at early times (Liu+22)



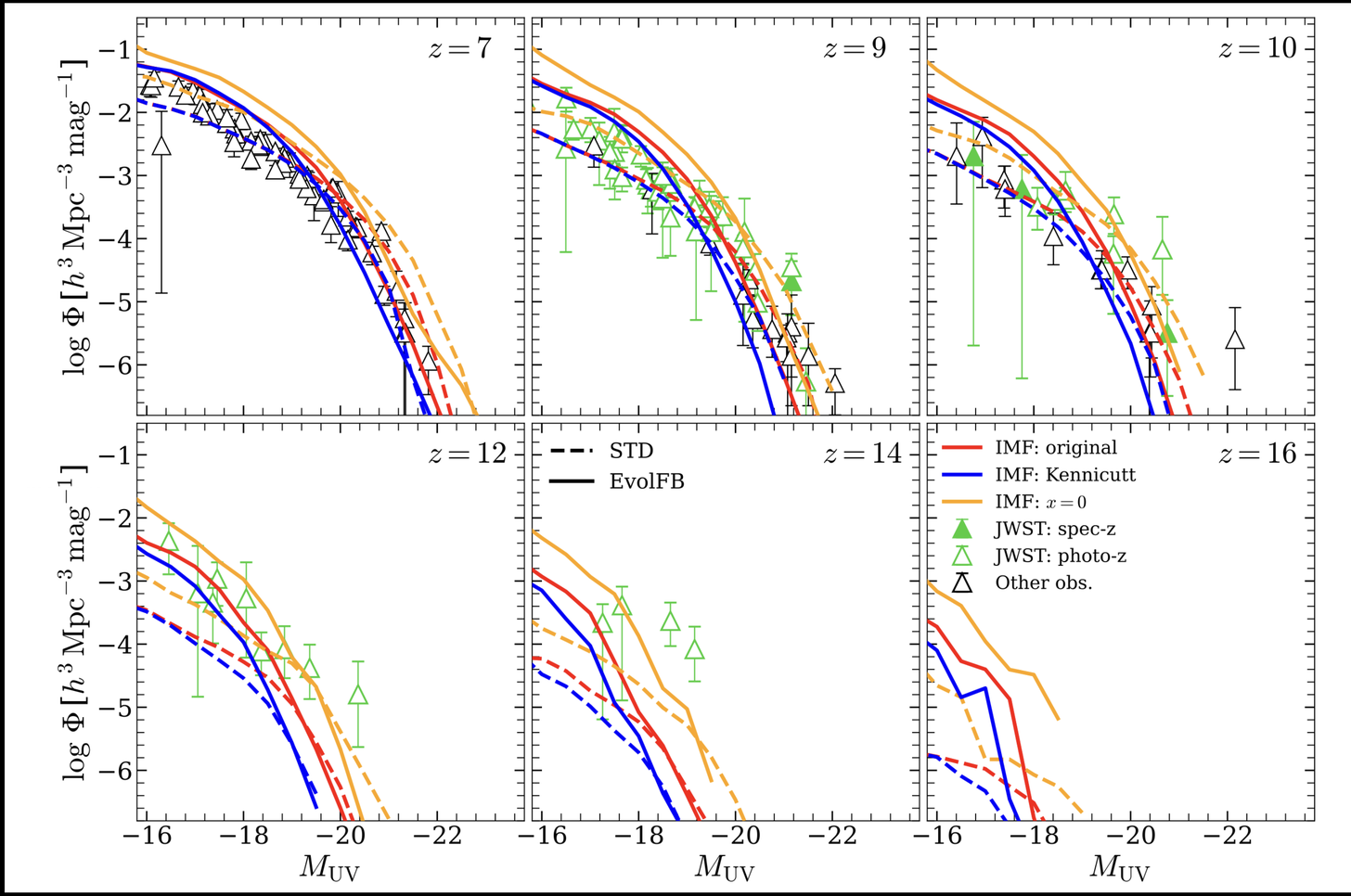
- Early Dark Energy accelerates structure growth at early times, while also providing a solution to the Hubble tension (Shen+24)



- Cosmic strings provide additional seeds for structure formation at early times (z>12), but retains LCDM predictions at low-z (Koehler, Hao, Kannan+24)

Potential astrophysical solution - Variable IMF?

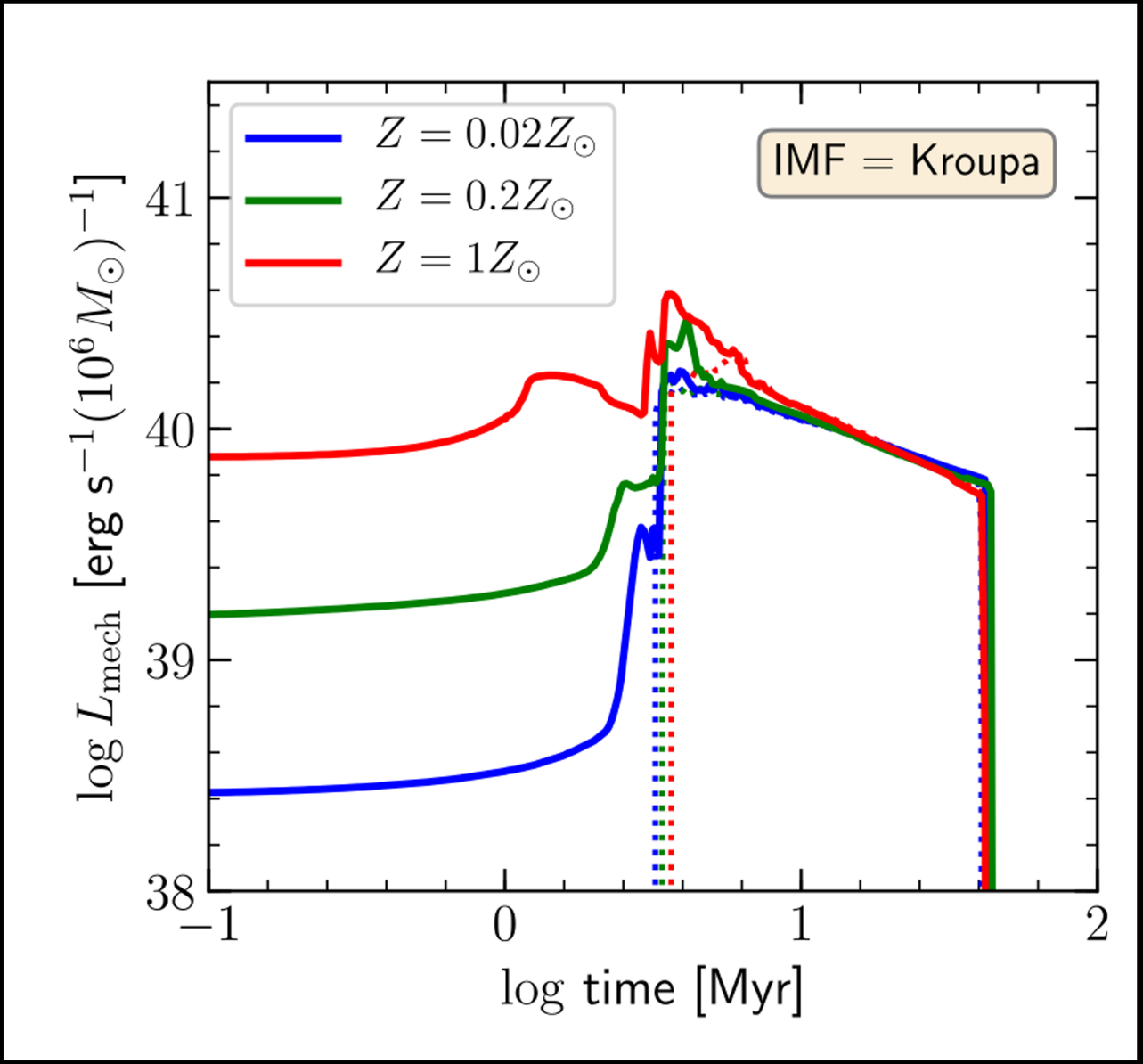
- Variable IMF can potentially explain this discrepancy
- Especially if a top heavy IMF is preferred in high gas density environments and high redshift environments (Steinhardt+23)
- The light to mass ratio increases compared to (for e.g.) Chabrier IMF
- Variable IMF combined with lack of dust can explain JWST data (Lu+25)



Lu+25 , Steinhardt+23

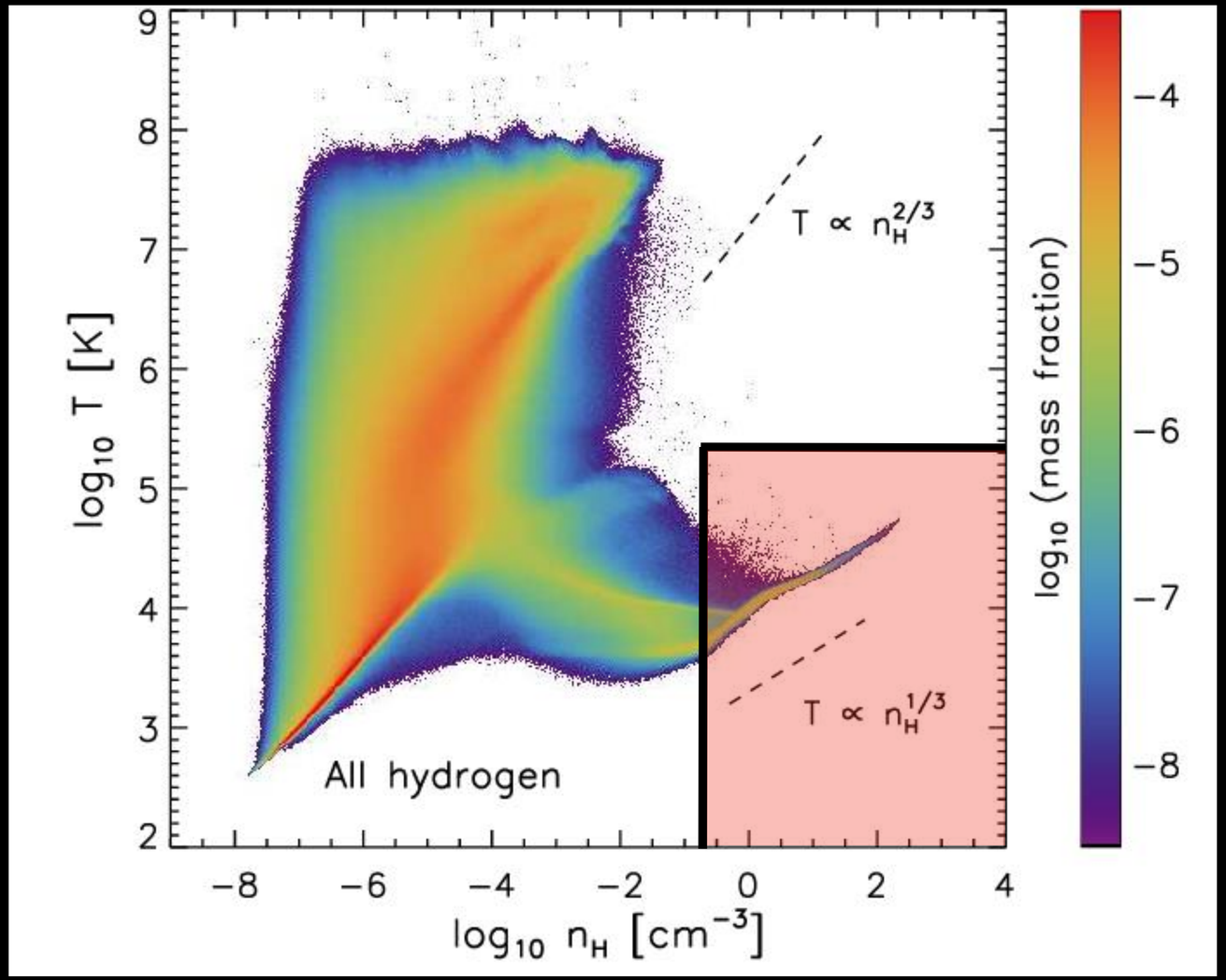
Potential astrophysical solution- Reduced efficiency of feedback

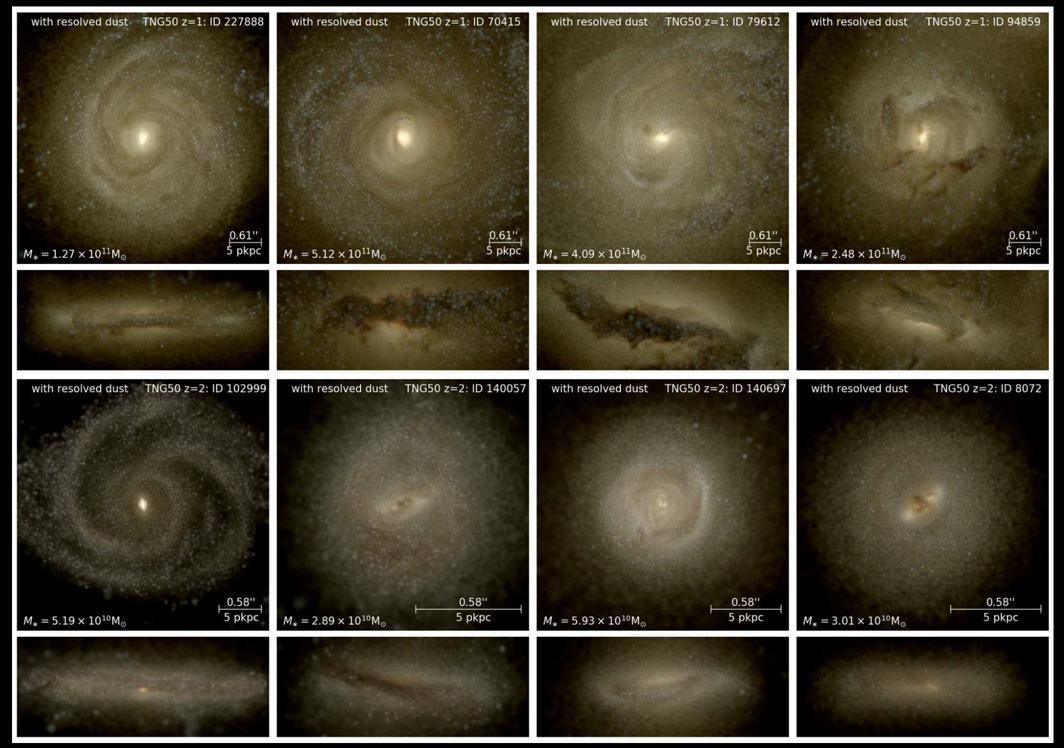
- Stellar winds are launched by radiation pressure of resonant metal absorption lines on the surface of the star
- As the metallicity of the star decreases, the abundance of these metal ions in its atmosphere decreases
- The energy output of lower metallicity stars is therefore much lower
- So there is a delay between the star forming and it going SN (few Myrs)



Dekel+23

THESAN (& IllustrisTNG & EAGLE) limitation - ISM modelled by an effective equation of state



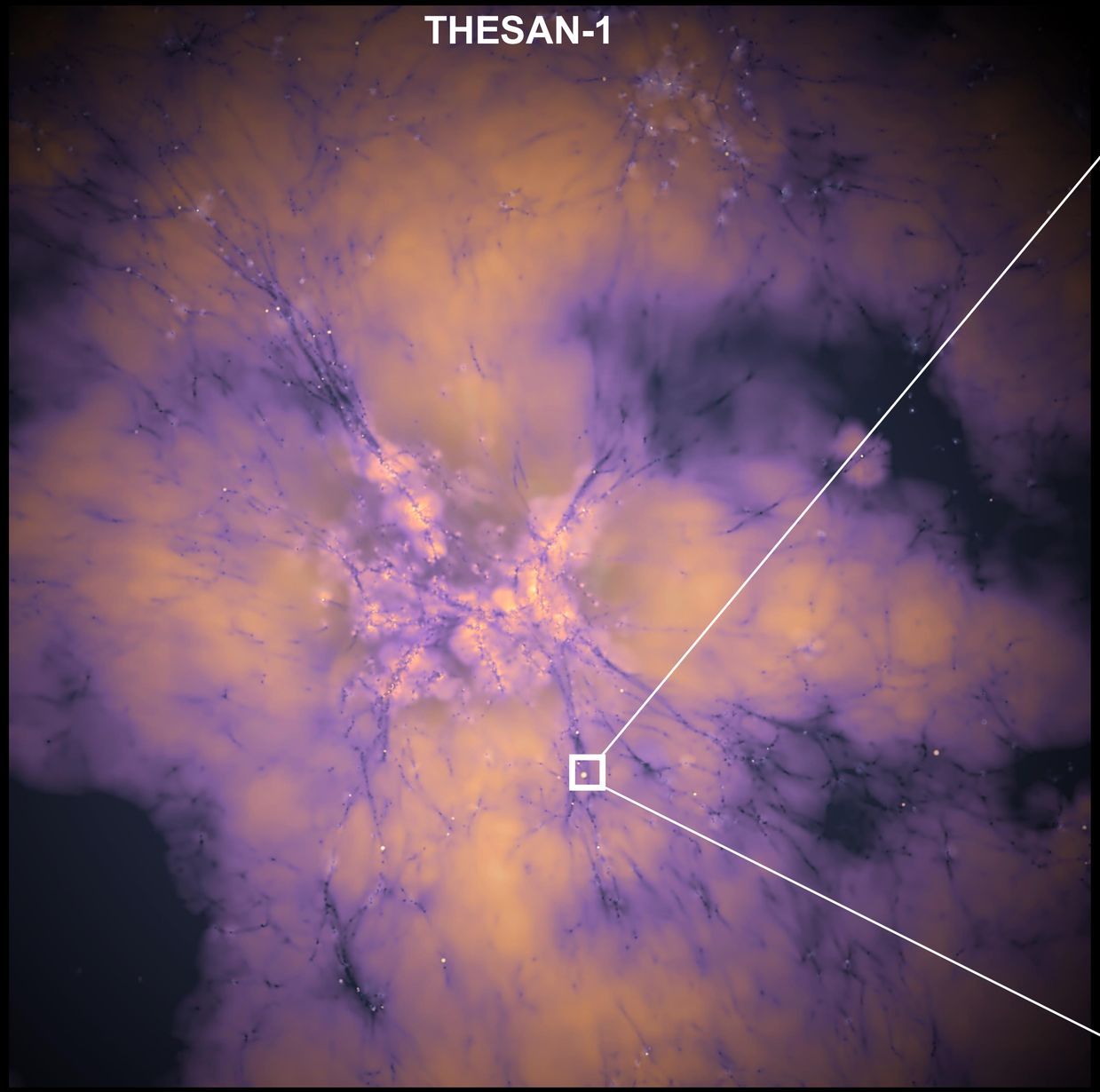


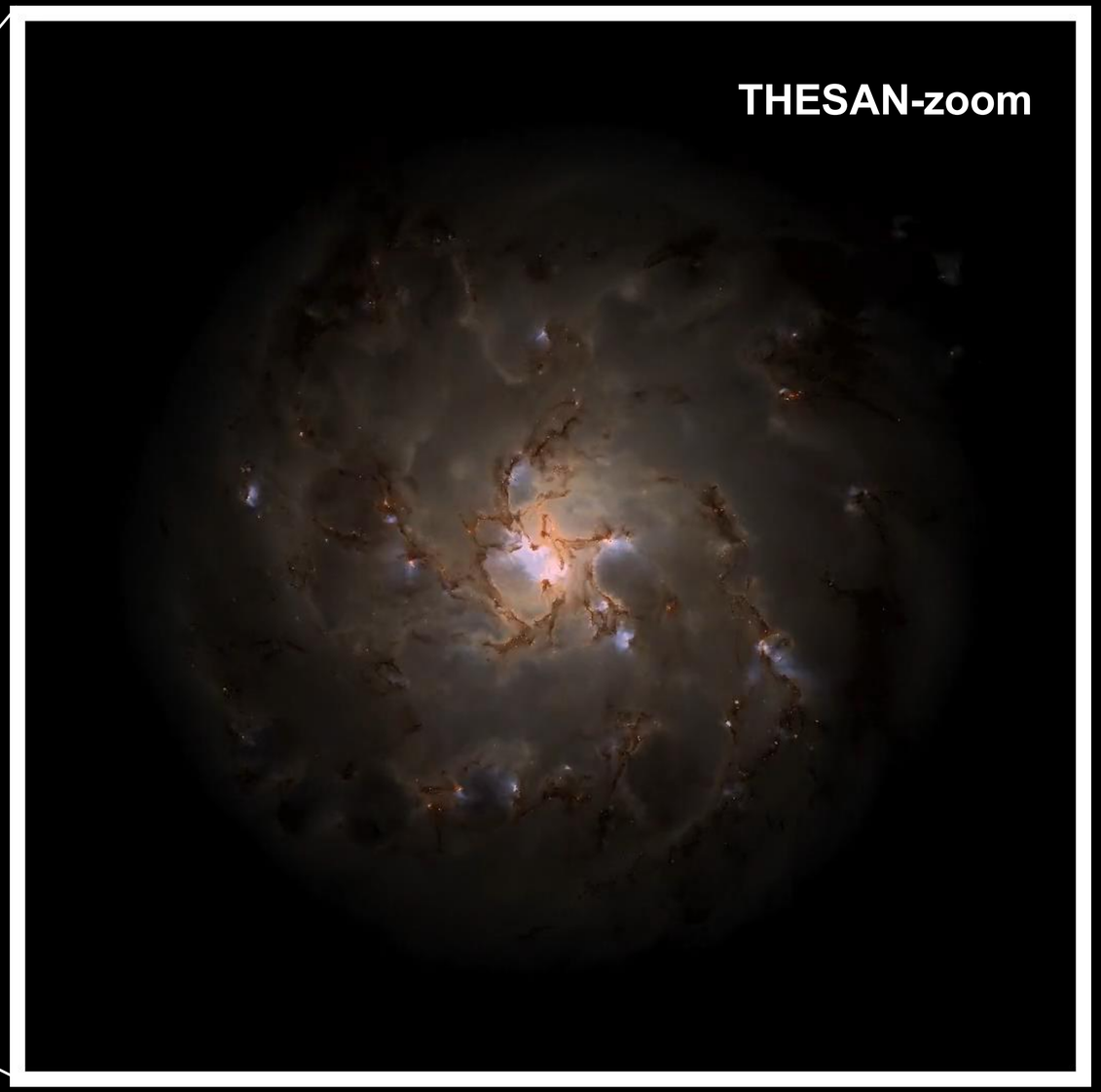
Springel+2018

The ISM is not resolved, i.e., cold dense gas is unresolved. Assume artificial equation of state

Illustris, EAGLE, MillenniumTNG: get the large scale properties of galaxies right

Improvements to the THESAN model - THESAN zoom

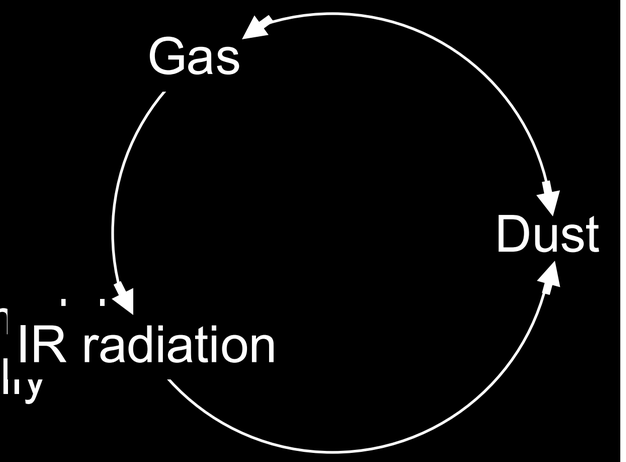


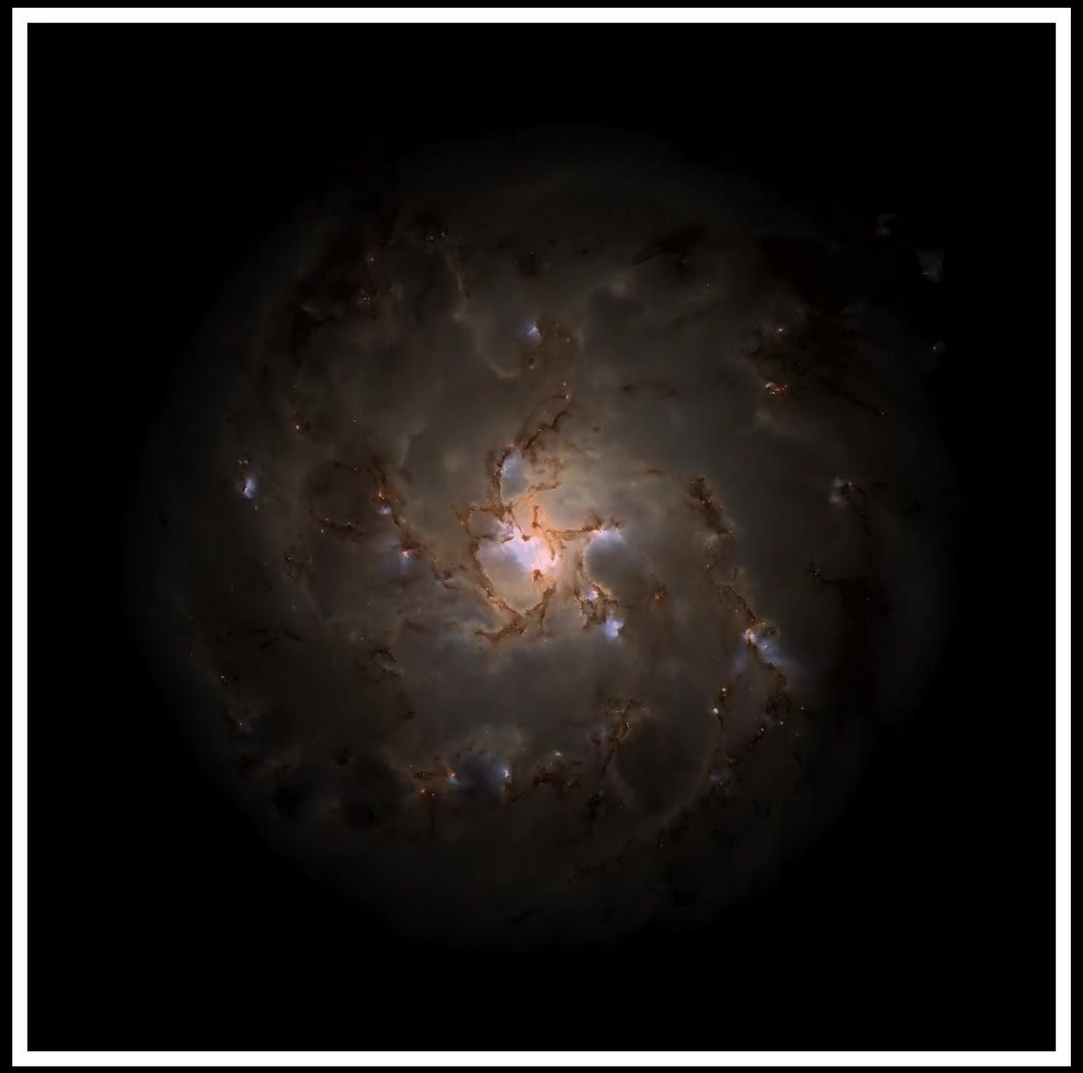


Salient features of Multi-Phase ISM model

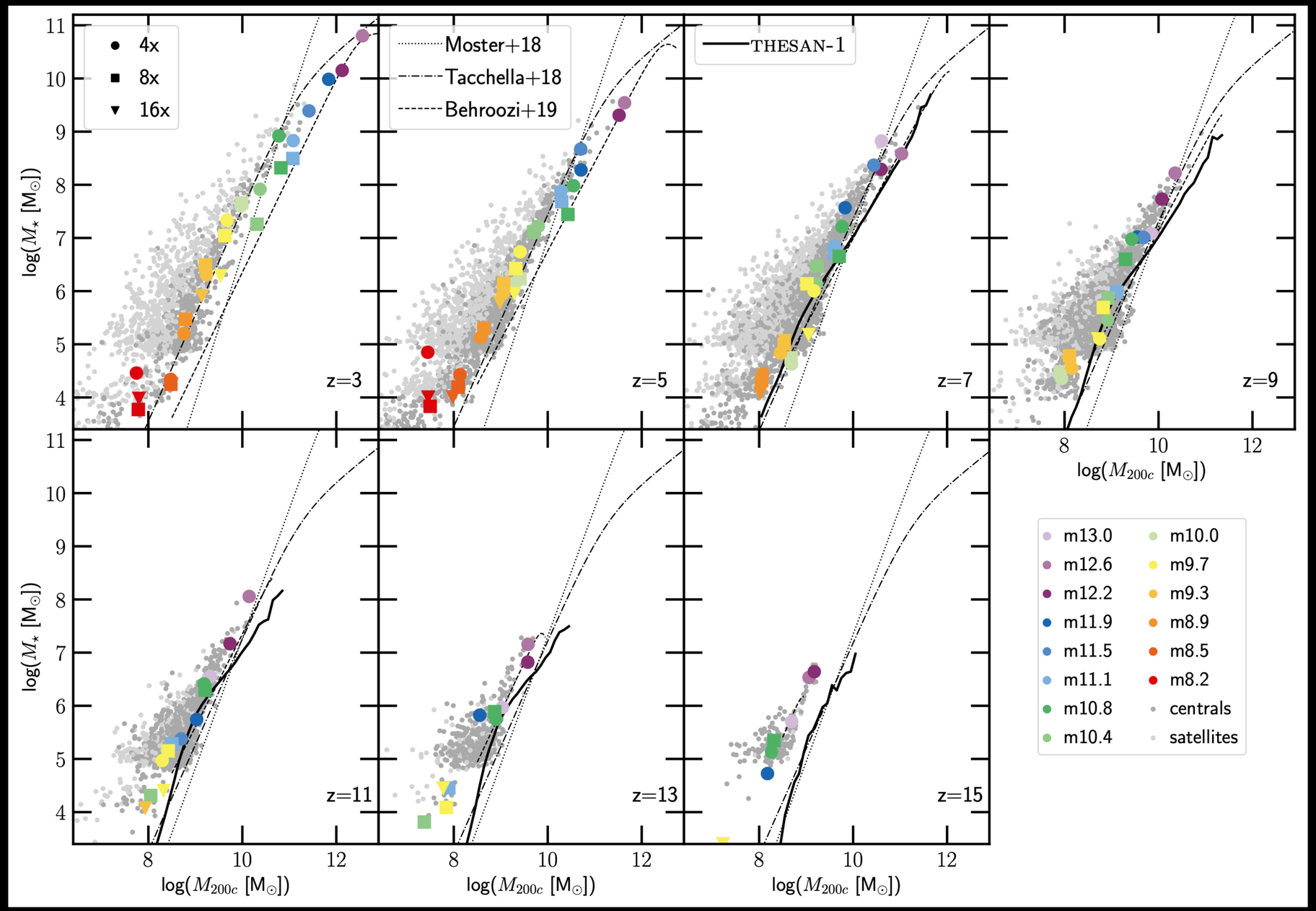
Kannan+20b, 21a

- Radiation fields included using AREPO-RT
- Better low-temperature cooling - follows non-equilibrium thermochemistry of molecular hydrogen (H_2)
- H_2 formation on dust grains
- A dust production and destruction m that is both thermally and dynamical coupled to gas and radiation
- Ionization states of HII regions and PDRs are calculated self-consistently (modulo resolution effects)
- Boosted momentum injection to model SN feedback (Kim+16, Martizzi+16)





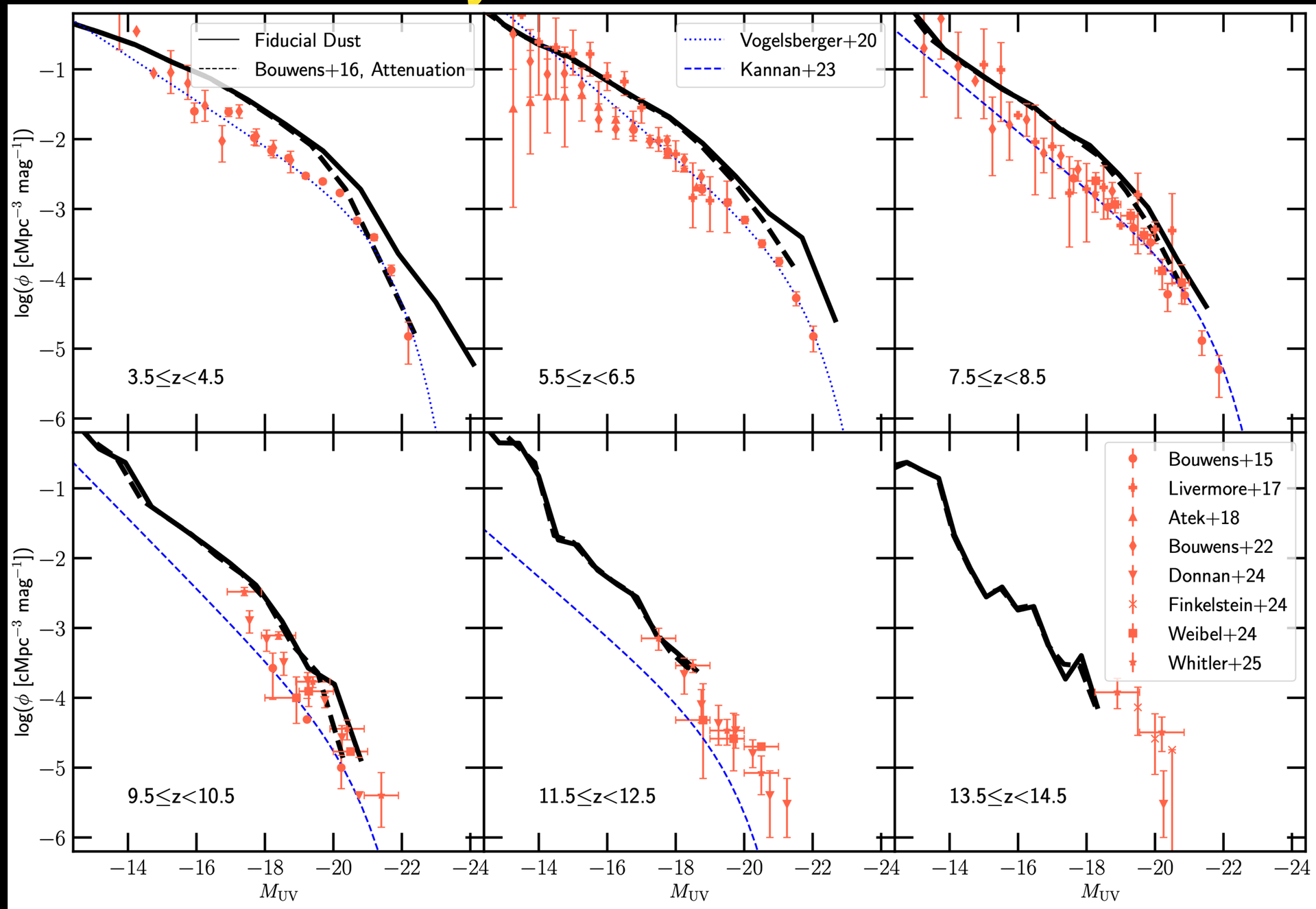
The Stellar-Halo Mass Function



Kannan+2025

UV luminosity functions

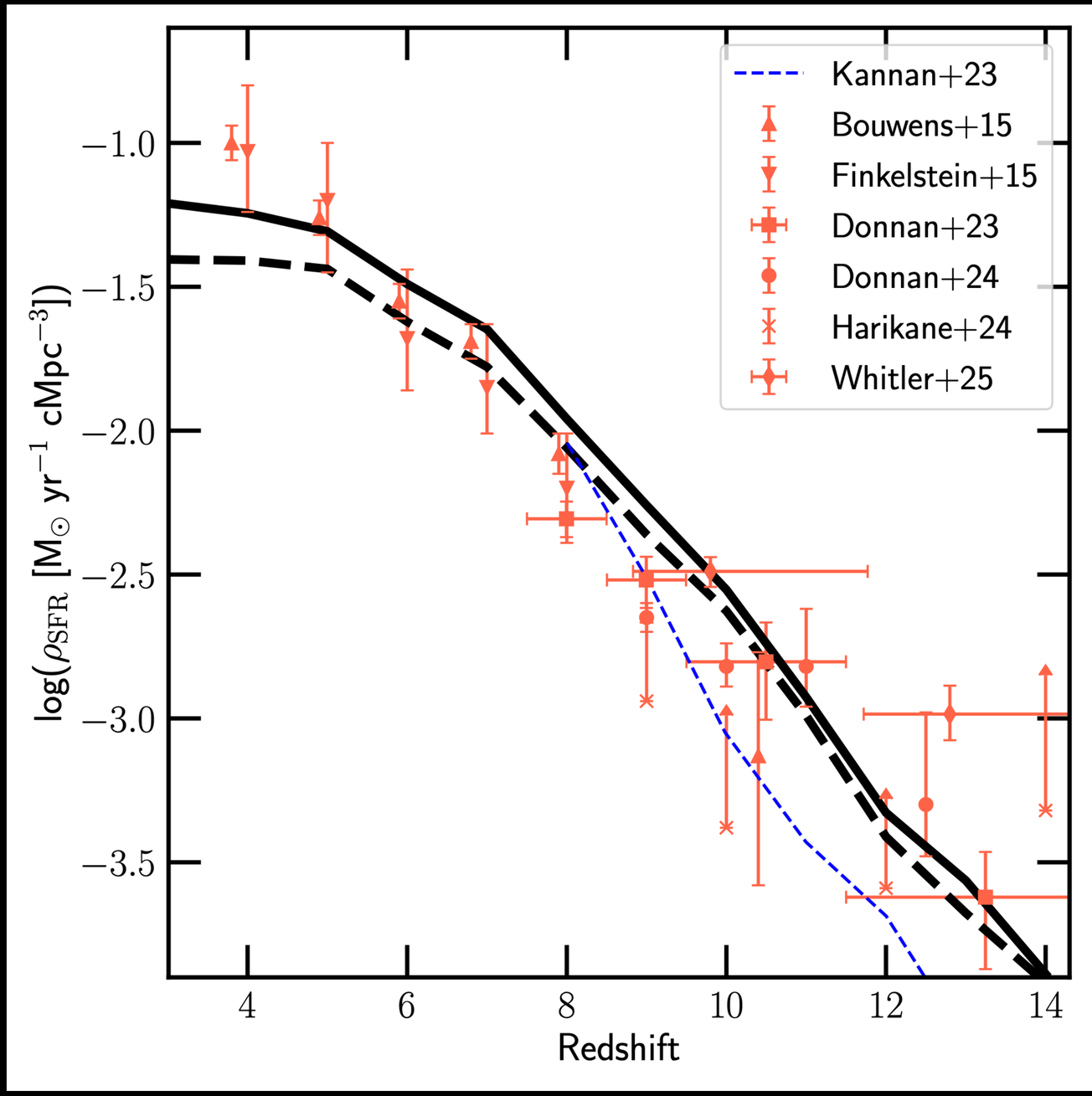
- Slightly higher abundances at intermediate luminosities
- High mass end matches observations, modulo the dust



Kannan+2025

Evolution of SFRD

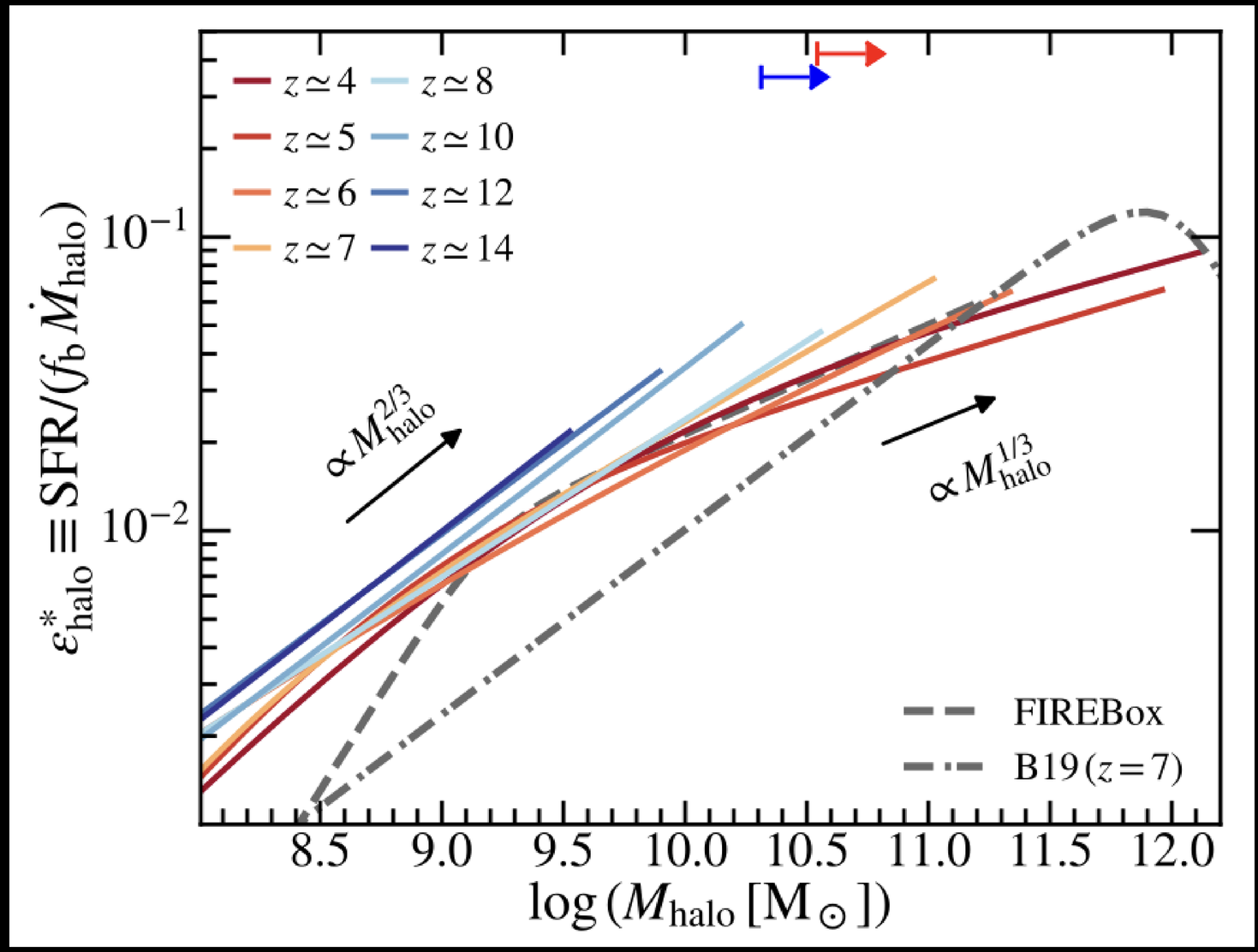
- Matches the SFRD from z=3-14



Kannan+2025

Why do we reproduce (sort of) the right properties of early galaxies?

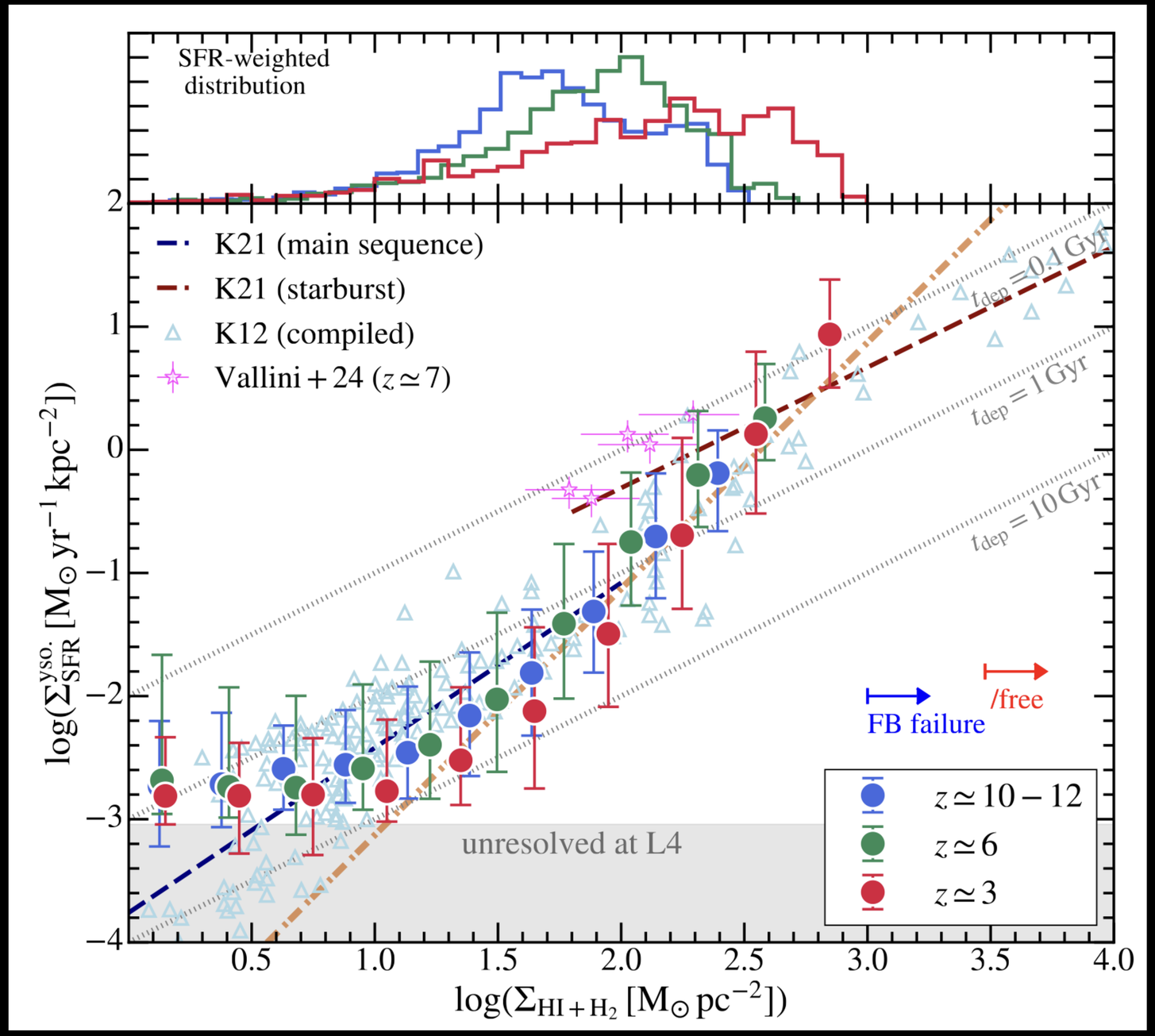
- The halo scale star formation efficiency computed from the Thesan-Zoom simulations is about 2-3 times higher than commonly assumed in empirical galaxy formation models



Shen,Kannan+25

Why do we reproduce (sort of) the right properties of early galaxies?

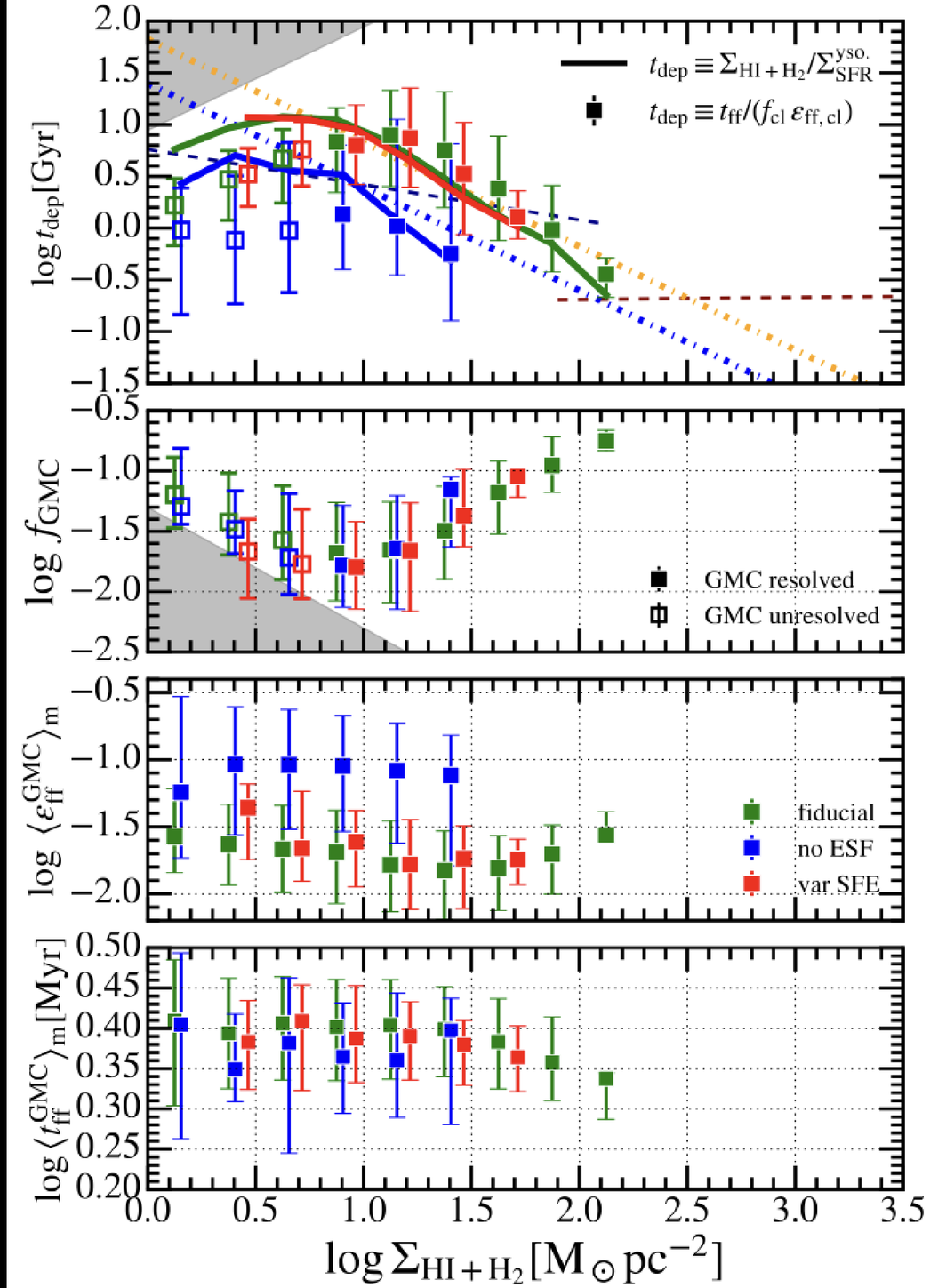
- At low gas surface densities, the star formation efficiencies are pretty low (τ_{dep} ~ 1-10 Gyrs)
- As the gas surface density increases, the gas depletion time falls rapidly and reaches < 0.1 Gyrs



Shen,Kannan+25

Why d owe reproduce (sort of) the right properties of early galaxies?

- The efficiency of star formation in GMCs does not seem to increase
- However, the fraction of the ISM in GMCs increases with increasing gas (surface) density
- This leads to a lowering of gas depletion times

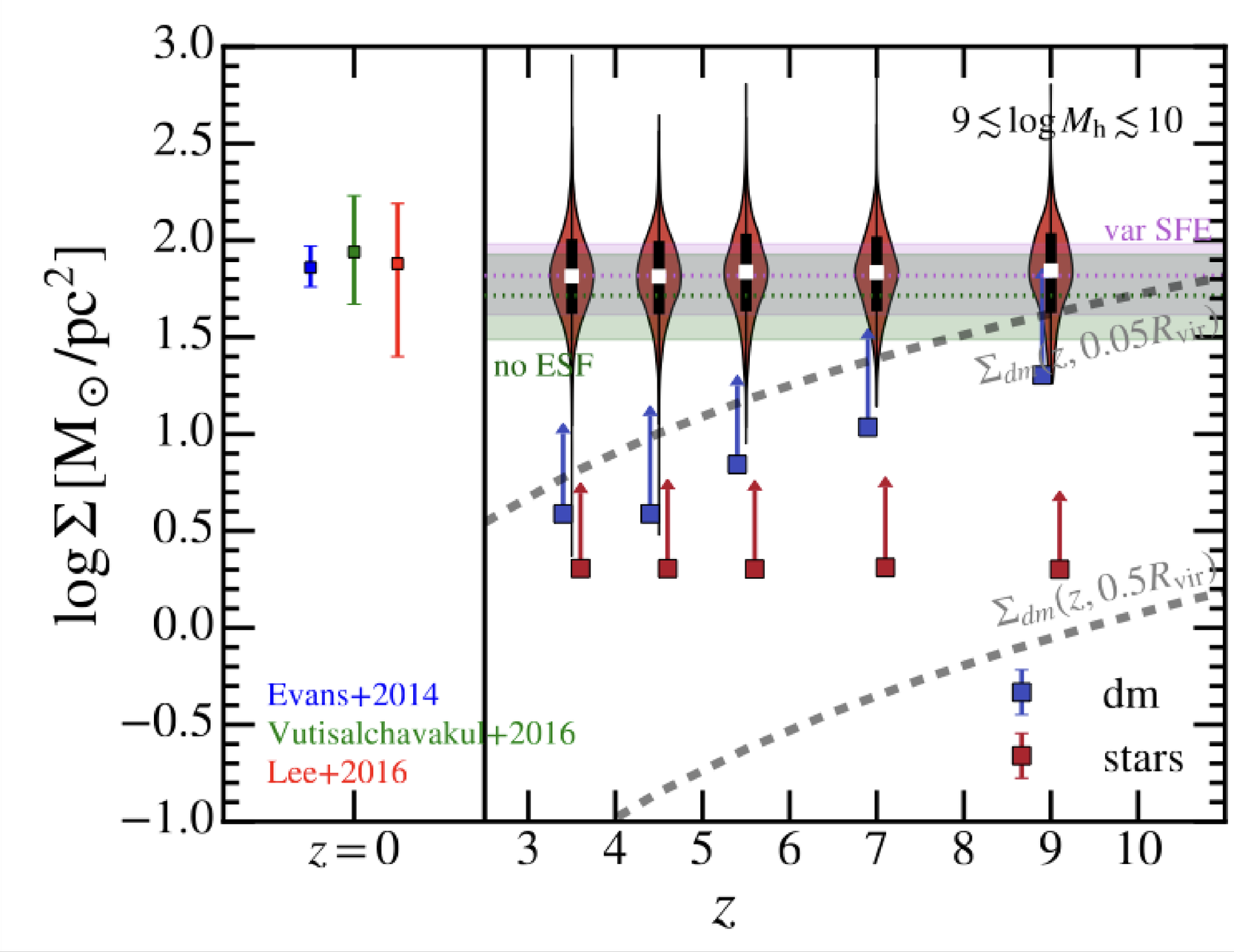


Wang (incl. Kannan)+25

Why do we reproduce (sort of) the right properties of early galaxies?

- The DM fraction of the GMCs also increases with redshift
- This increases the gravitational forces, reducing the free-fall time
- This also helps increase the efficiency of star formation
- Need to simulate higher mass galaxies to properly probe the galaxies observed by JWST

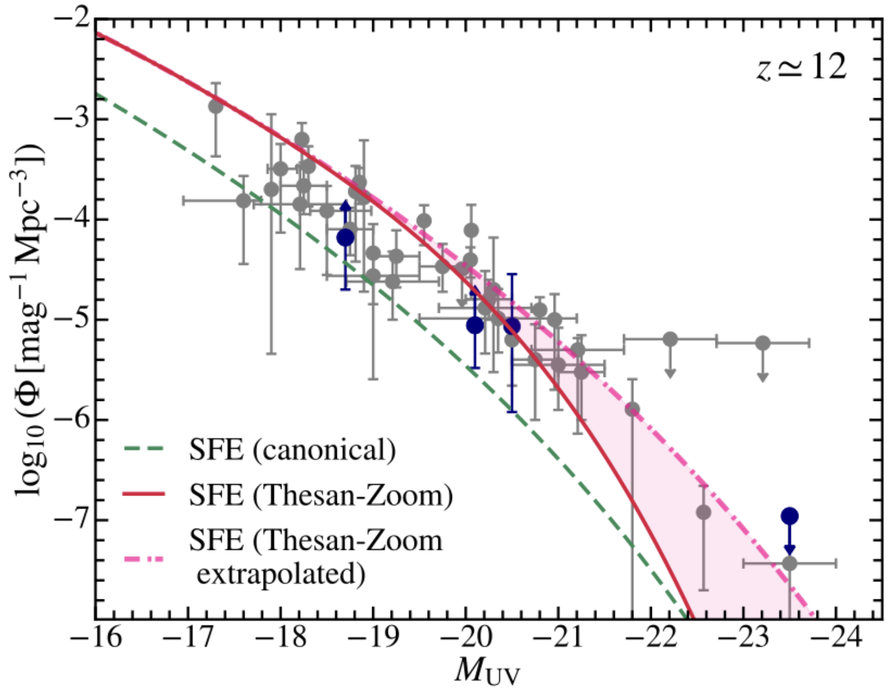
Wang (incl. Kannan)+25

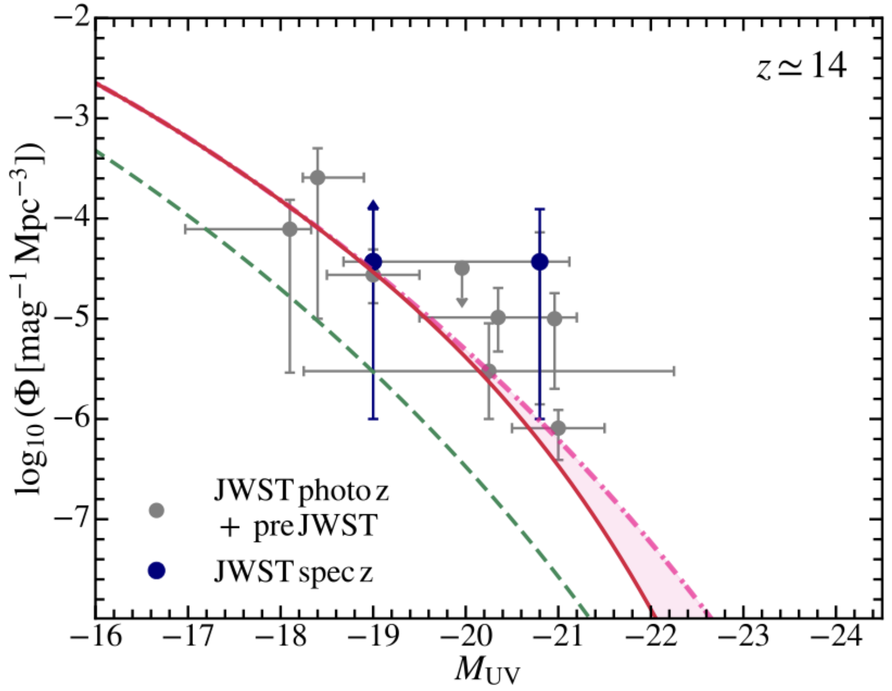


Why do we reproduce (sort of) the right properties of early galaxies?

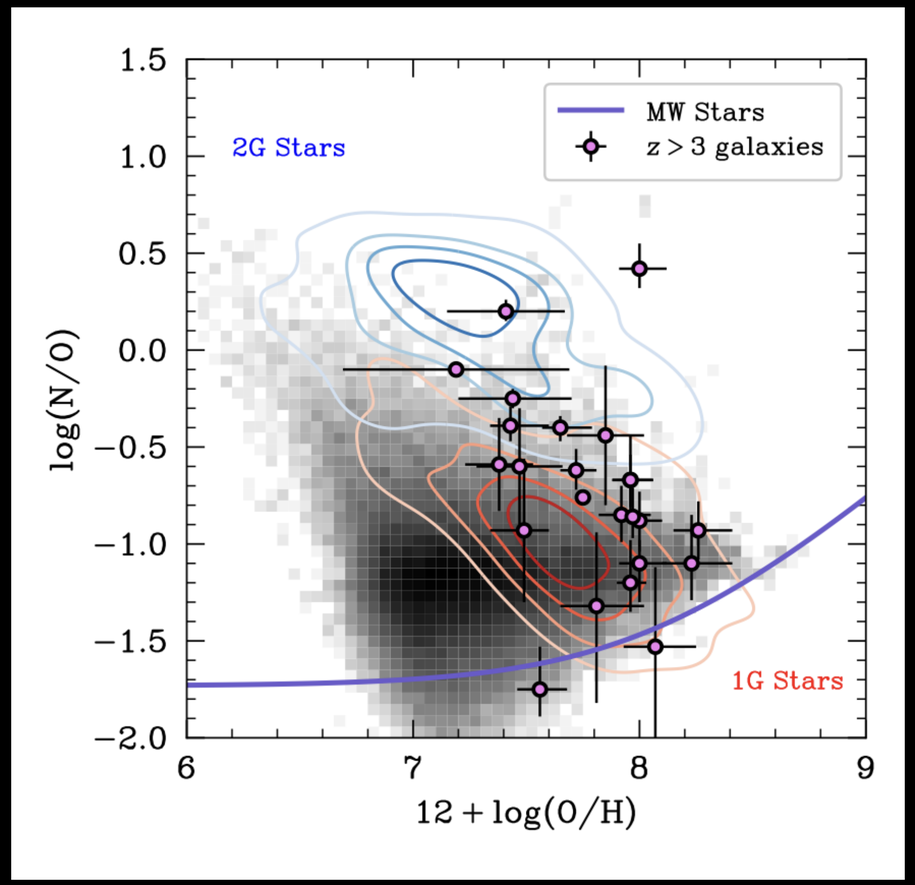
- The increased star formation efficiency can potentially explain the presence of bright galaxies at high-z
- Thesan-Zoom simulations only reach about Mhal~10^{10} Msun at z~12, so we cannot probe the high mass regime
- Simple extrapolation shows we can match results at z=12, but still below what is necessary for z=14

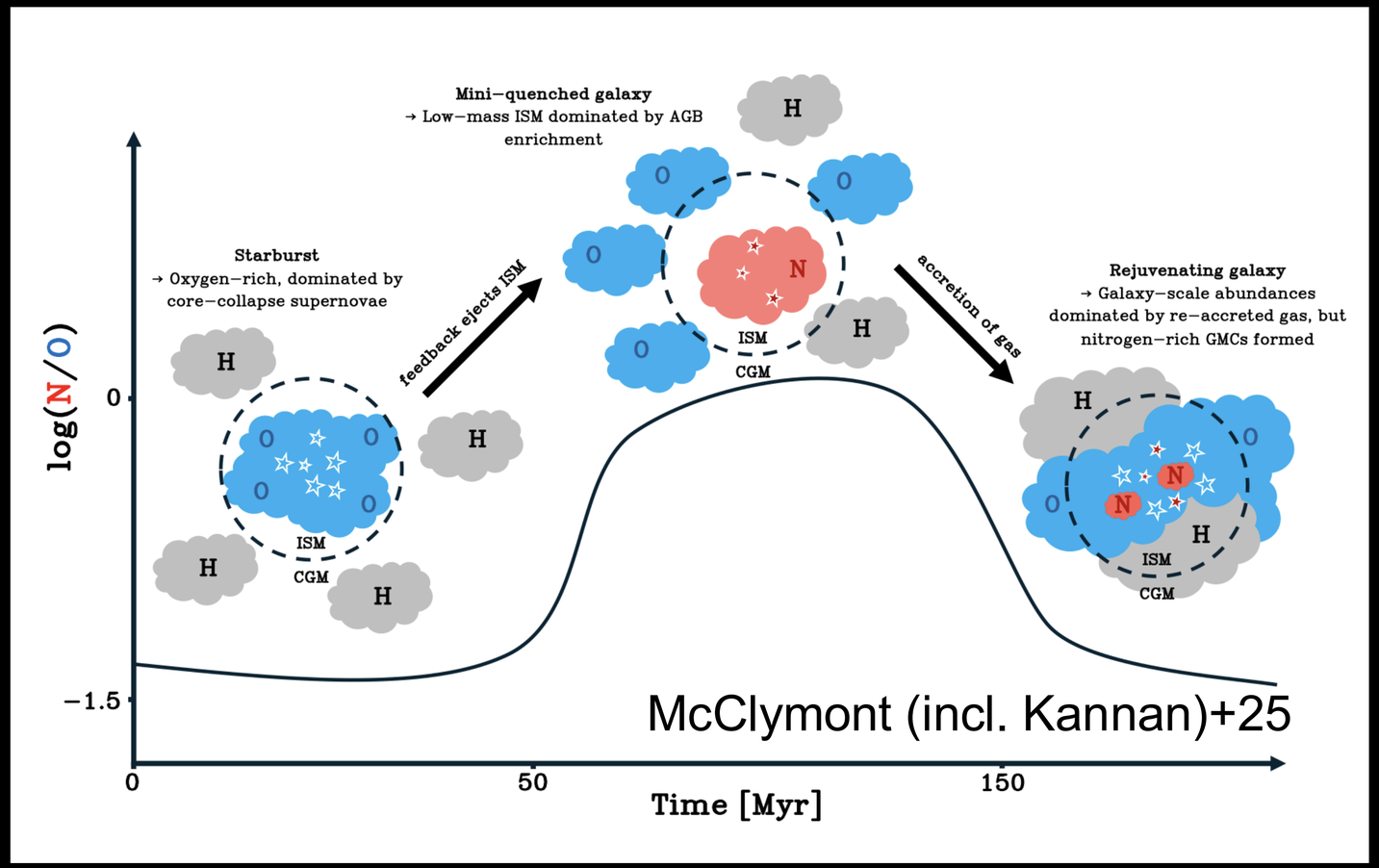
Shen, Kannan+25





Can explain high-z N/O ratios without resorting to exotic yields

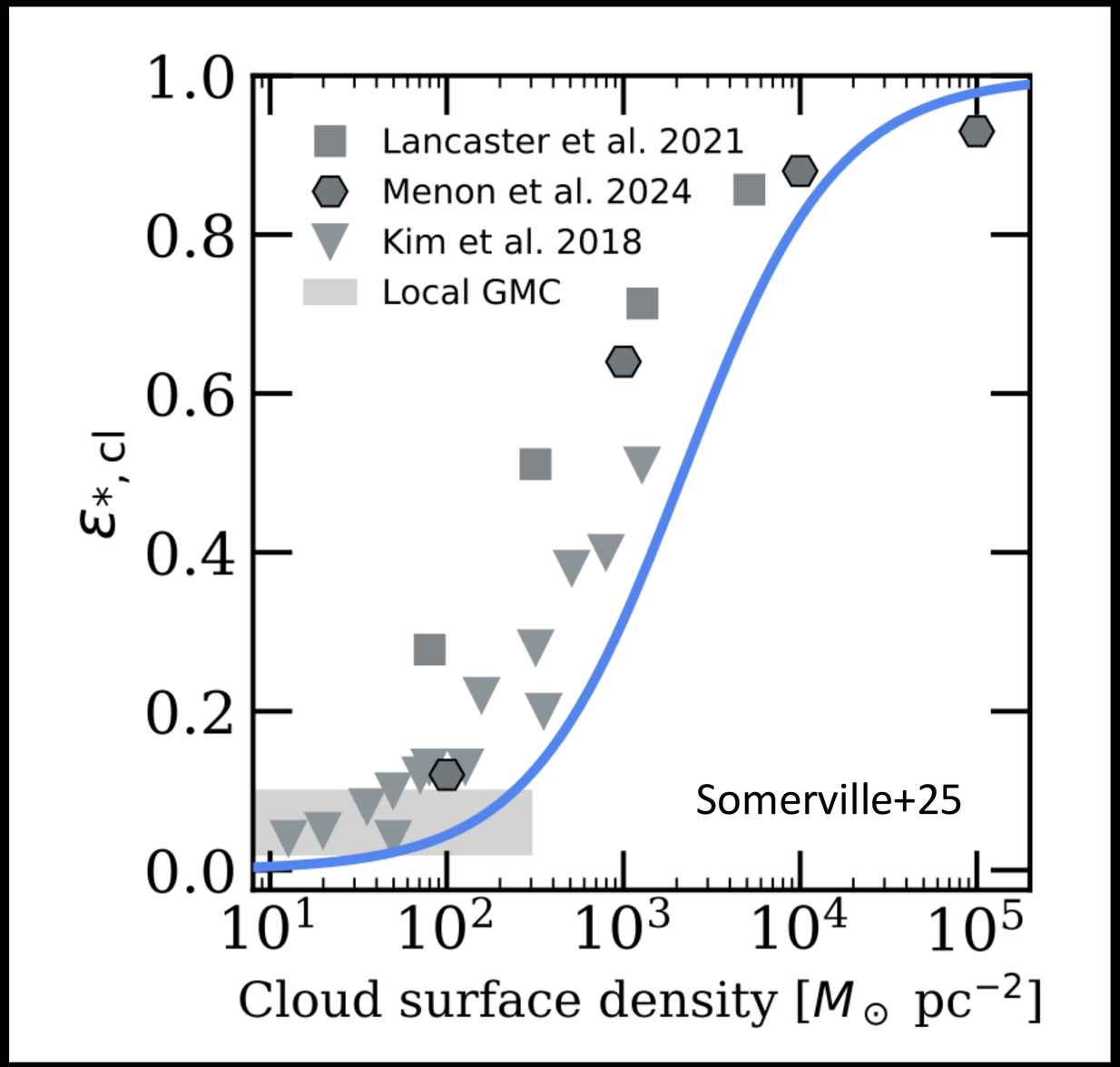




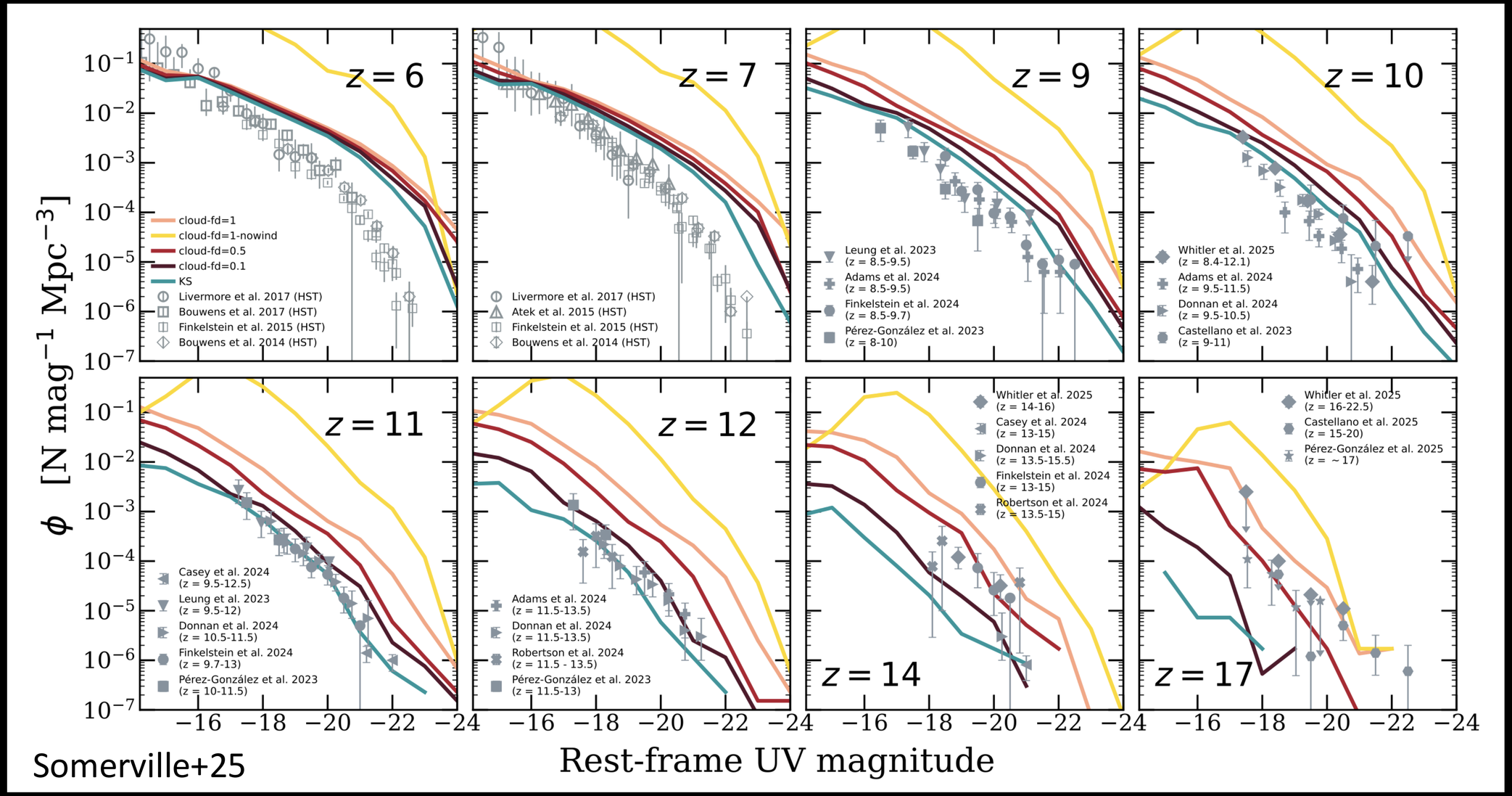
- Bursty star formation naturally generates order-of-magnitude excursions in N/O on $\lesssim$100 Myr timescales
- After a starburst, stellar feedback expels gas, leaving a large population of asymptotic-giant-branch stars to dominate the enrichment of the relatively low-mass interstellar medium

The GMC scale star formation efficiency also increases

- High-resolution GMC simulations that include feedback such as photoheating and radiation pressure show an increased SFE as the cloud surface density increases



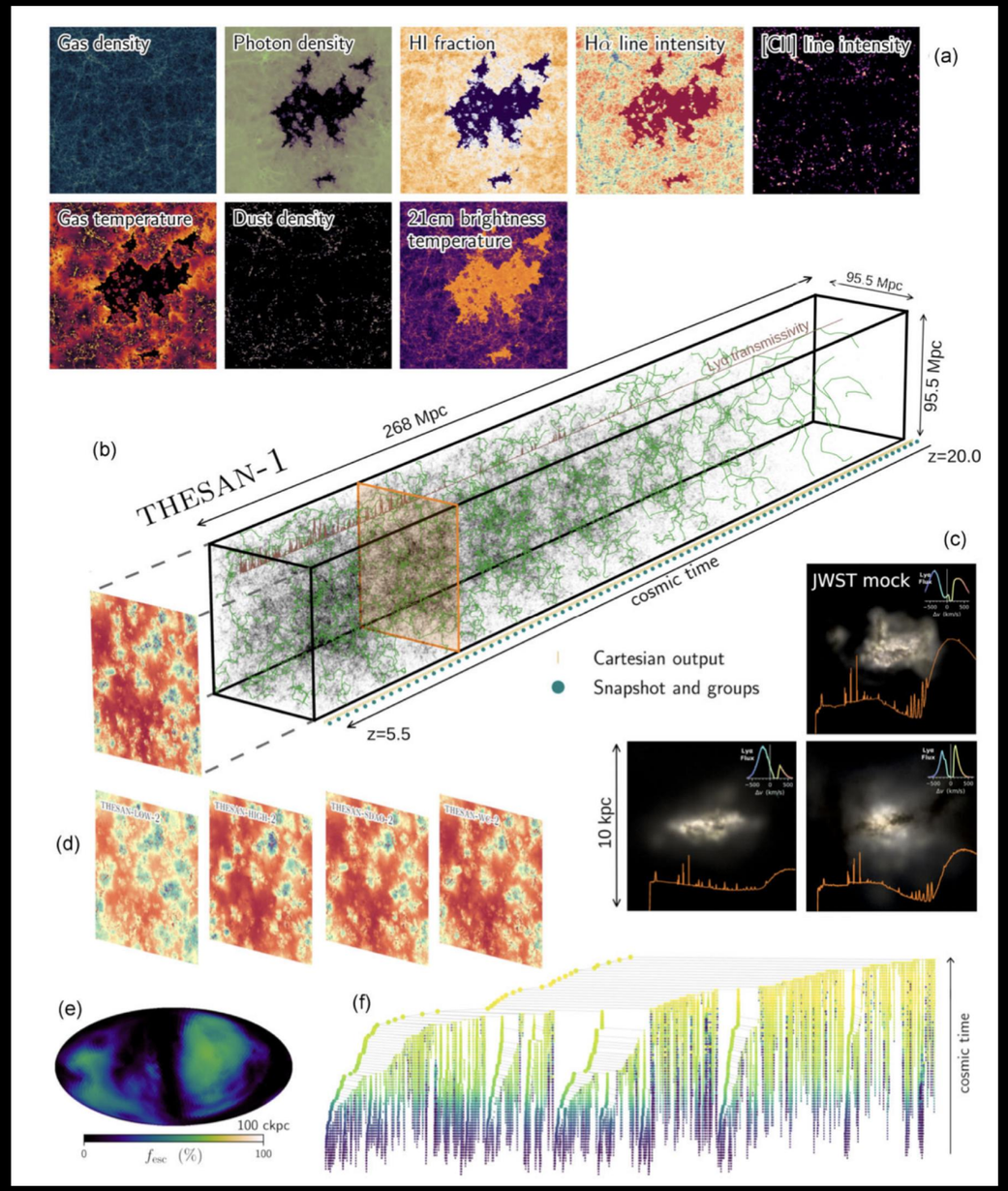
The GMC scale star formation efficiency also increases



- Need a large fraction (50-100%) of the ISM to be in the form of dense molecular clouds to replicate observed UVLF
- Thesan-Zoom simulations shows evidence for this at high gas surface densities

Conclusions

- JWST observations have thrown up a lot of surprises
- The models that worked at low redshift seem to fail in the high redshift environments
- Fundamentally different environment - high gas fractions, low metallicities and lot more mergers
- A variety of both astrophysical and cosmological solutions have been put forward to explain the observations
- While THESAN and THESAN-ZOOM simulations provide a theoretical framework to interpret these results, a lot of work needs to done to understand this early epoch



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Data publicly available at www.thesan-project.com