High redshift galaxy formation with early dark energy (and some SIDM)

12/2025, MPA

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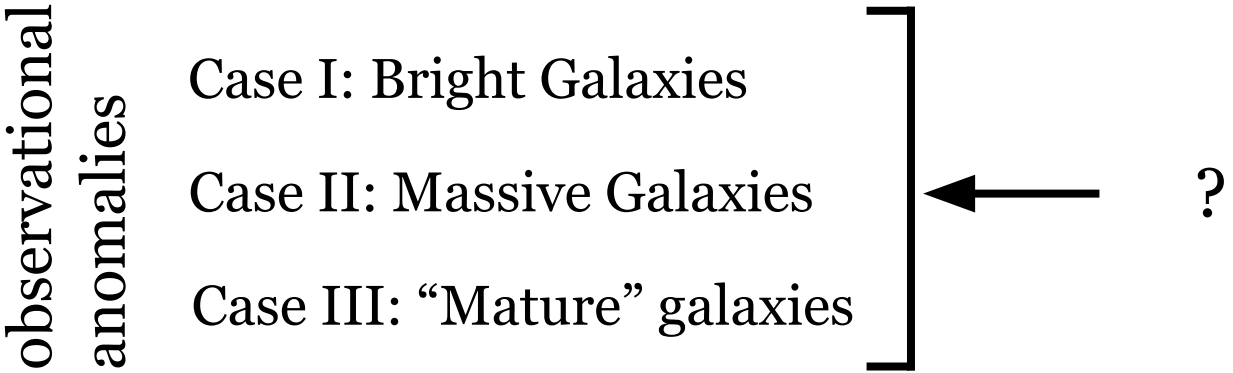
HARVARD & SMITHSONIAN

with Xuejian Shen, Mark Vogelsberger, Mike Boylan-Kolchin, Lars Hernquist, Sandro Tacchella, Rohan Naidu

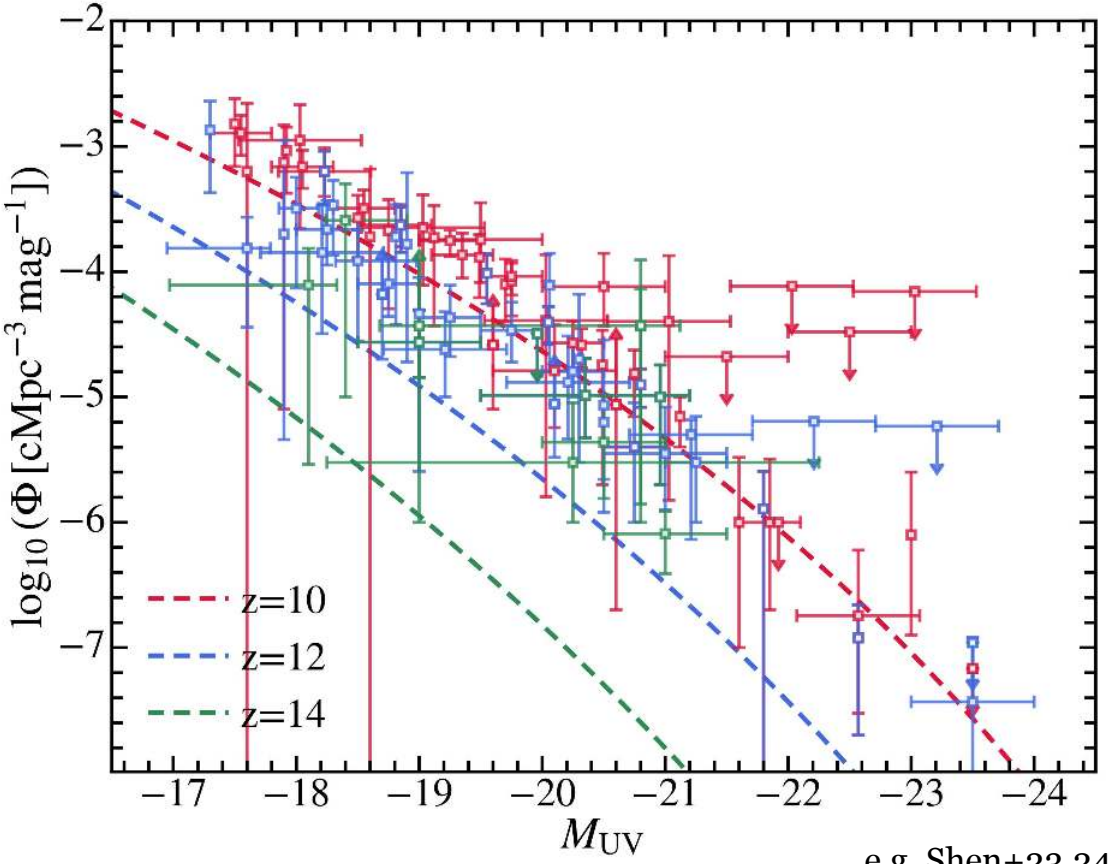
Outline


observational anomalies
Case I: Bright Galaxies
Case II: Massive Galaxies
Case III: “Mature” galaxies
?

Accelerated Structure Formation revealed by JWST

Case I: Bright Galaxies

pre-JWST model (dashed)
vs
observations



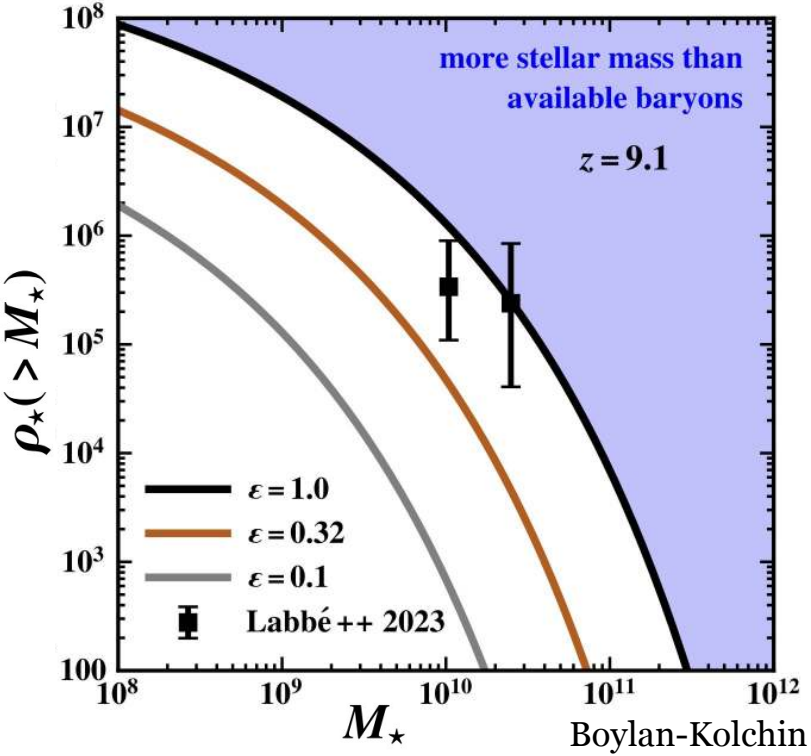
e.g. Shen+23,24

Accelerated Structure Formation revealed by JWST

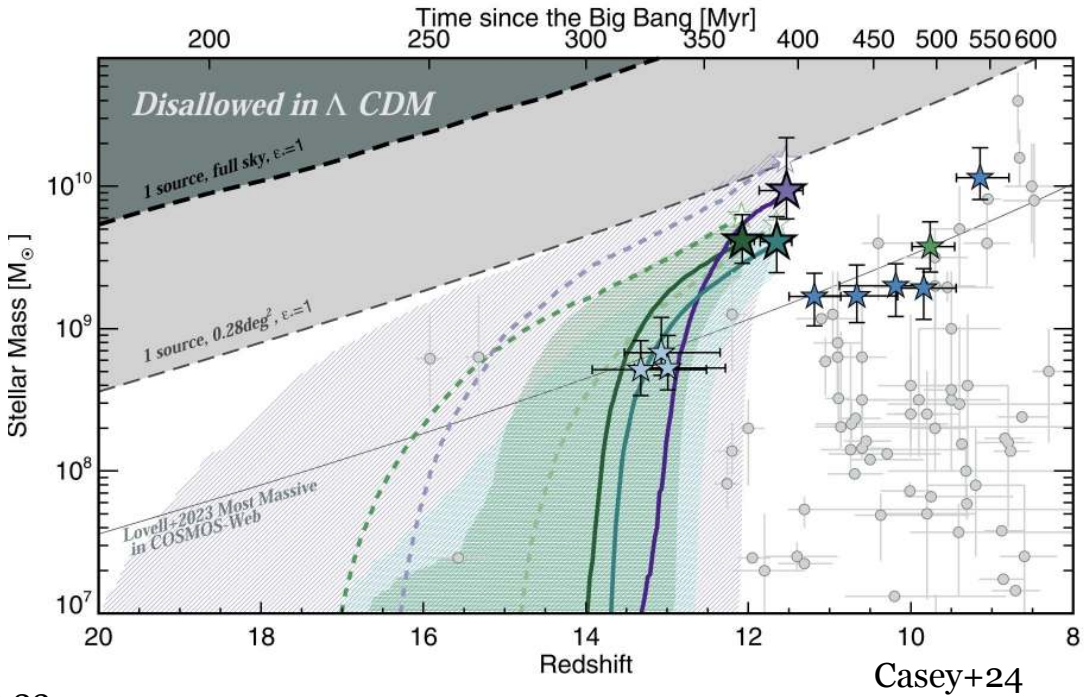
Case II: Massive Galaxies

"cosmic breakers"

— need to convert all baryons to stars to produce them



Boylan-Kolchin 23

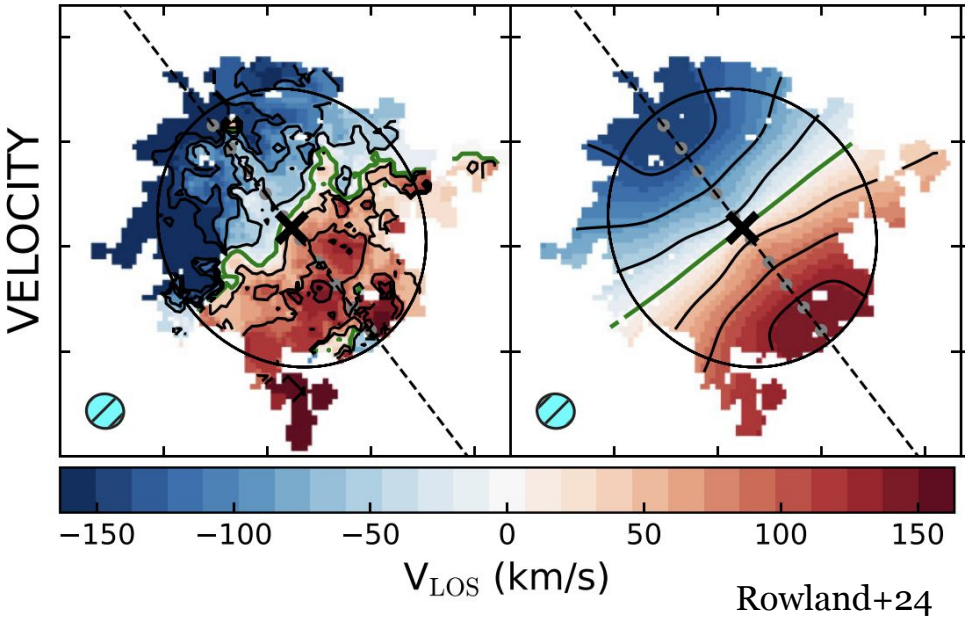


Casey+24

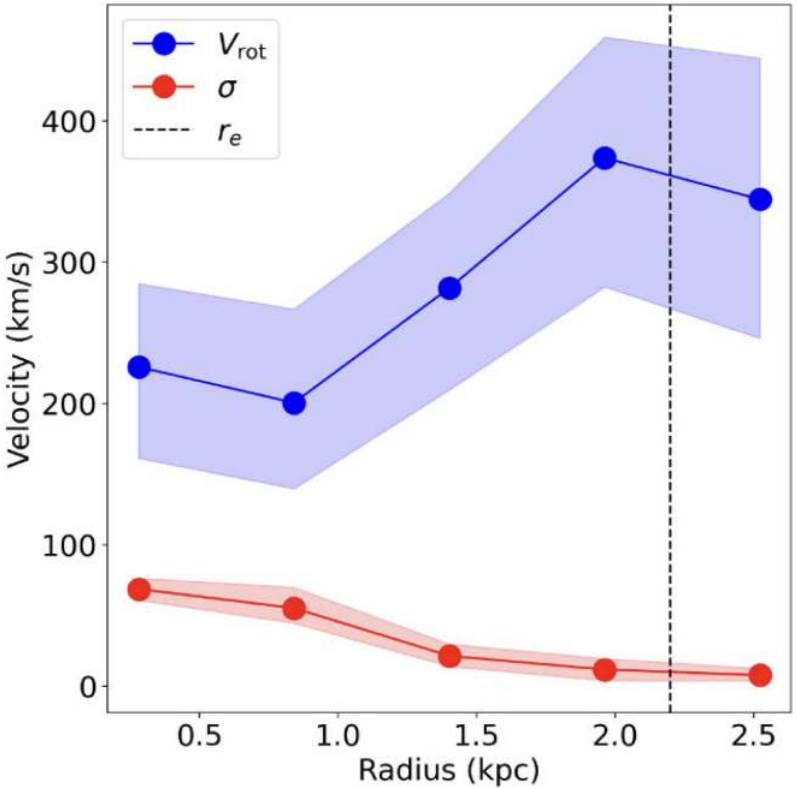
Accelerated Structure Formation revealed by JWST

Case III: Indirect evidences — (morphologically) “mature” galaxies

dynamically cold disky galaxies out to z~7.3



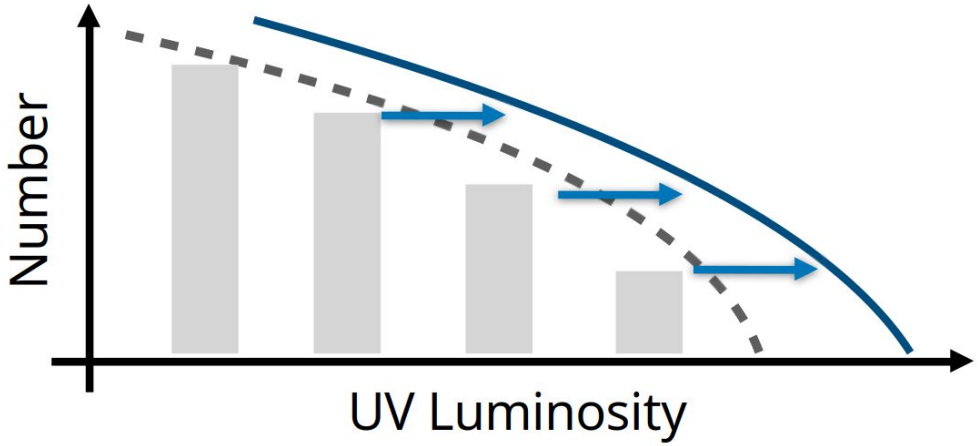
Rowland+24



Astrophysical Explanations

Enhanced star-formation efficiency
(e.g. Dekel+23, Li+24, Boylan-Kolchin+24)

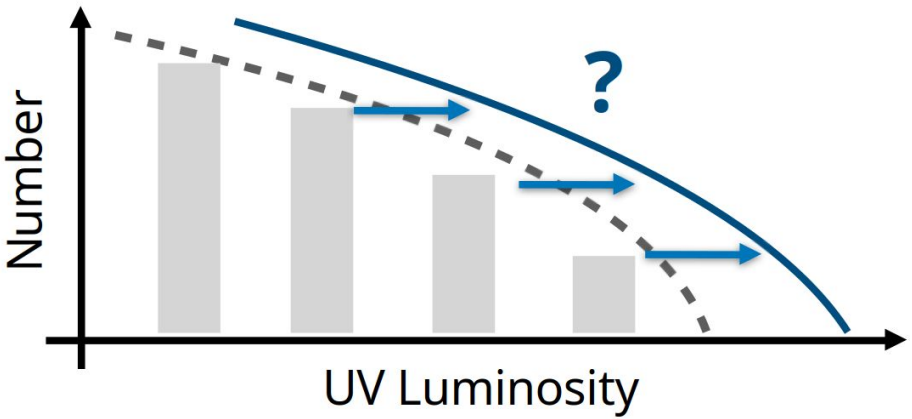
Weaker pre-supernovae stellar feedback at high redshifts
-> Feedback-free starburst: one-zone collapse before first supernovae



Astrophysical Explanations

Enhanced star-formation efficiency
(e.g. Dekel+23, Li+24, Boylan-Kolchin+24)

Top-heavier stellar initial mass function
(e.g. Inayoshi+22, Yung+23)



i.e. more massive stars given same total stellar mass

Increase the light-to-mass ratios
but also the feedback-to-mass ratios

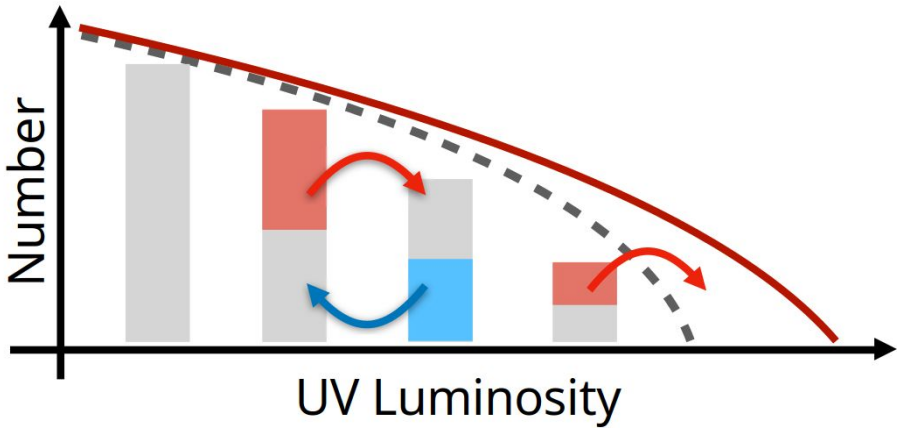
Astrophysical Explanations

Enhanced star-formation efficiency
(e.g. Dekel+23, Li+24, Boylan-Kolchin+24)

Top-heavier stellar initial mass function
(e.g. Inayoshi+22, Yung+23)

Bursty star-formation
(e.g. Shen+23, Sun+23)

...



Boost bright galaxy abundance through the Eddington bias

? Not enough burstiness found in observations?
Not that helpful regarding massive galaxies

A solution beyond the standard ΛCDM model

Early Dark Energy (EDE)

a solution to the Hubble tension!

(also an example of a more generic class of models moderately enhance small-scale power spectrum)

A solution beyond the standard ΛCDM model

Early Dark Energy (EDE)

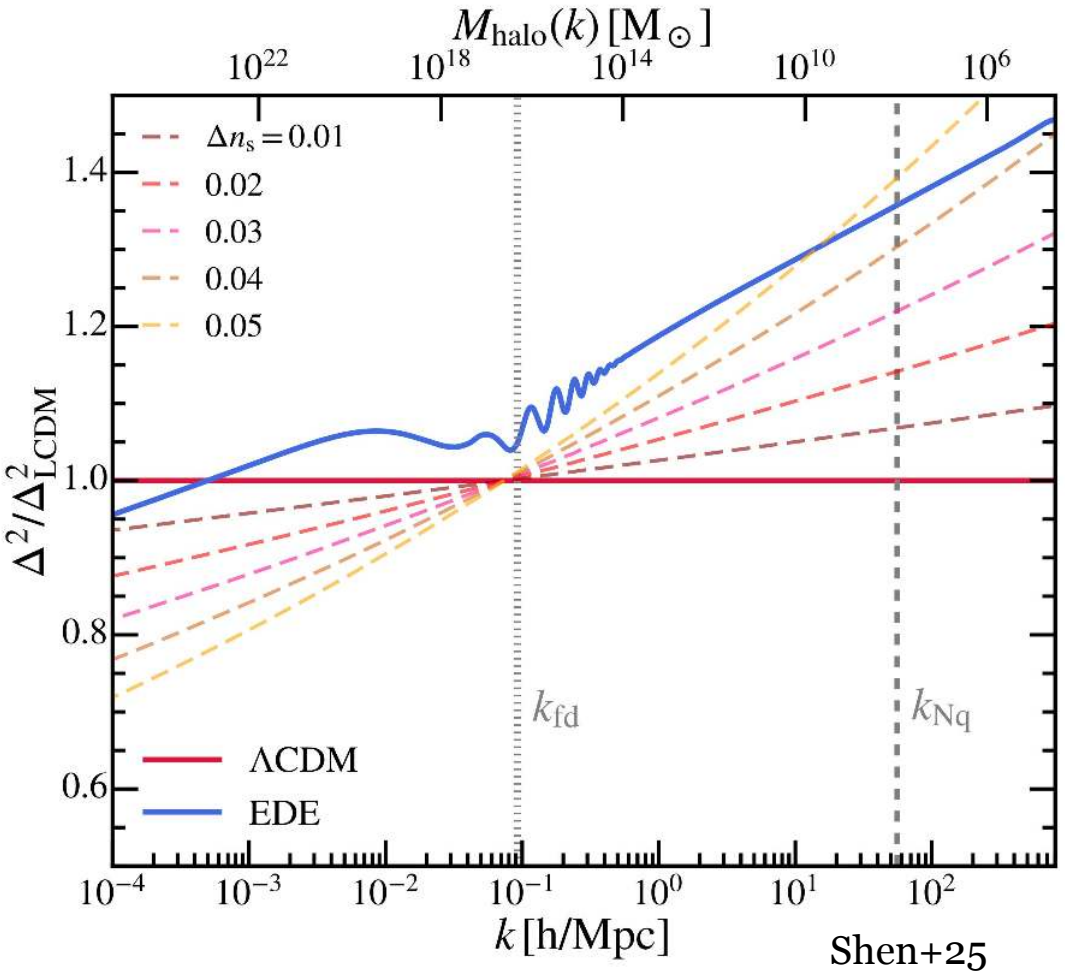
a hypothetical particle (field) with
- similar equation-of-state to dark energy (at a certain point)
- perturb the pre-recombination expansion history

$z \lesssim 100$

- no direct impact on structure formation
- Indirect impact: slight changes to other cosmological parameters
  e.g. higher $\sigma_8, n_s, \Omega_m h^2$

higher amplitude of primordial fluctuations at non-linear scales

higher matter densities



Shen+25

A solution beyond the standard ΛCDM model

Shen, Zier+25

large-volume cosmological hydro-dynamic simulations at z>3

$N_{\mathrm{part}} = 2{\times}1200^3$

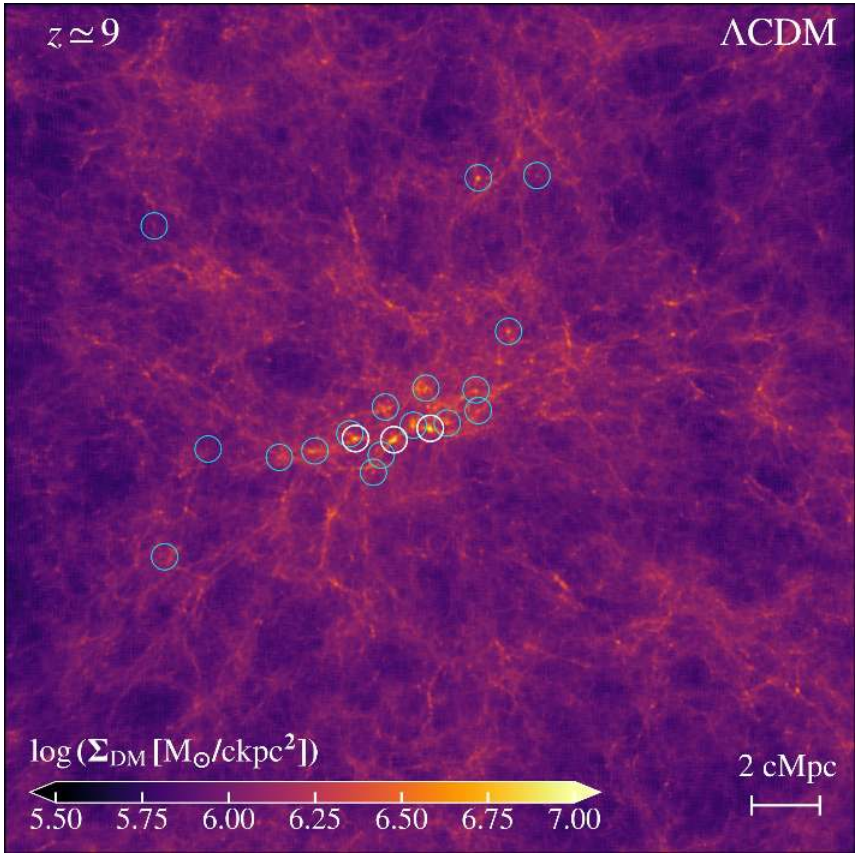
$L_{\mathrm{box}} = 100\mathrm{cMpc}$

$m_{\mathrm{b}} \sim 3{\times}10^6 \mathrm{M}_\odot$

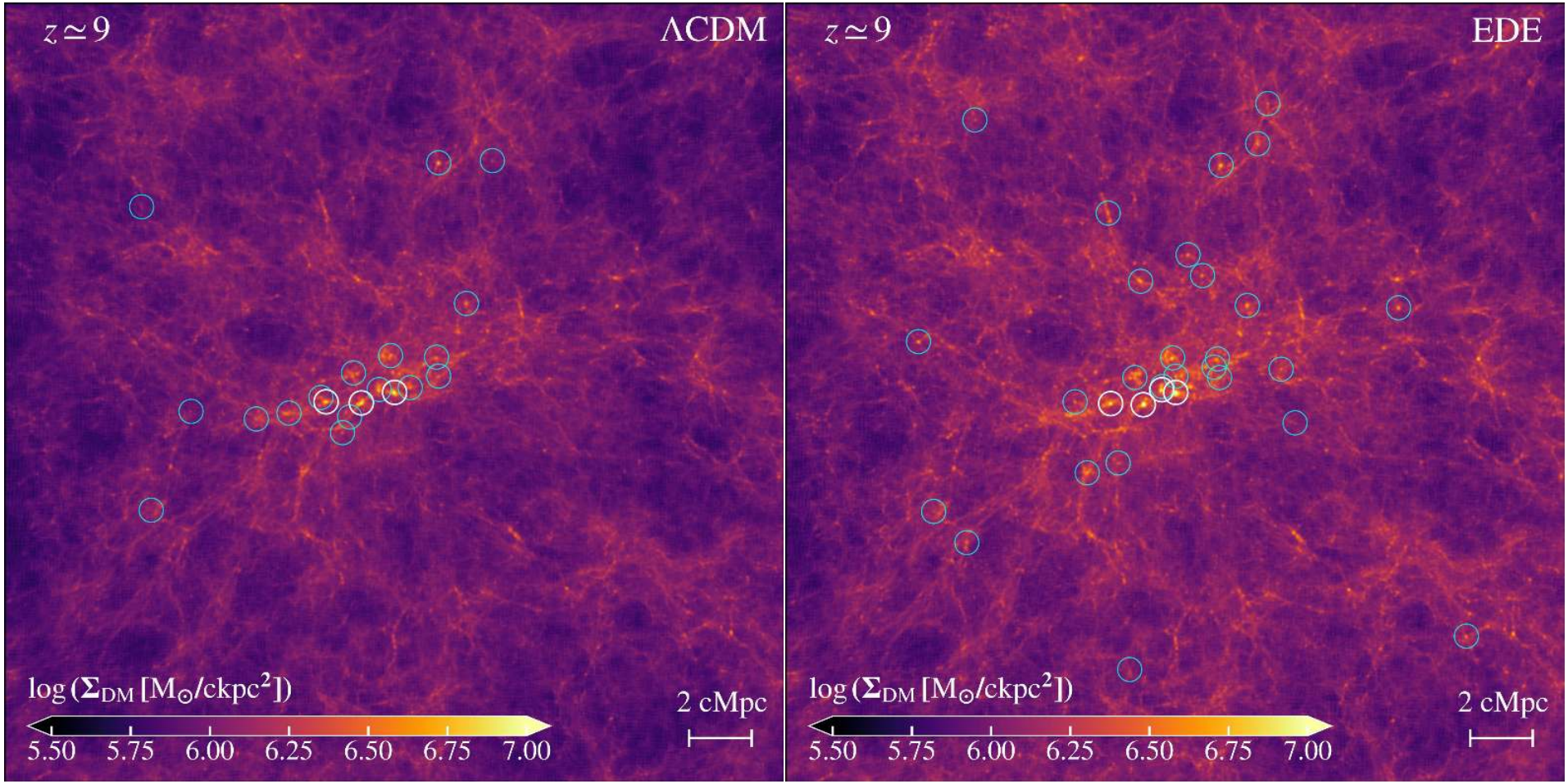
$r_{\mathrm{cell}}^{\mathrm{min}} \sim 18\mathrm{pc}$

using the moving-mesh code AREPO + IllustrisTNG galaxy formation model

Pillepich+18

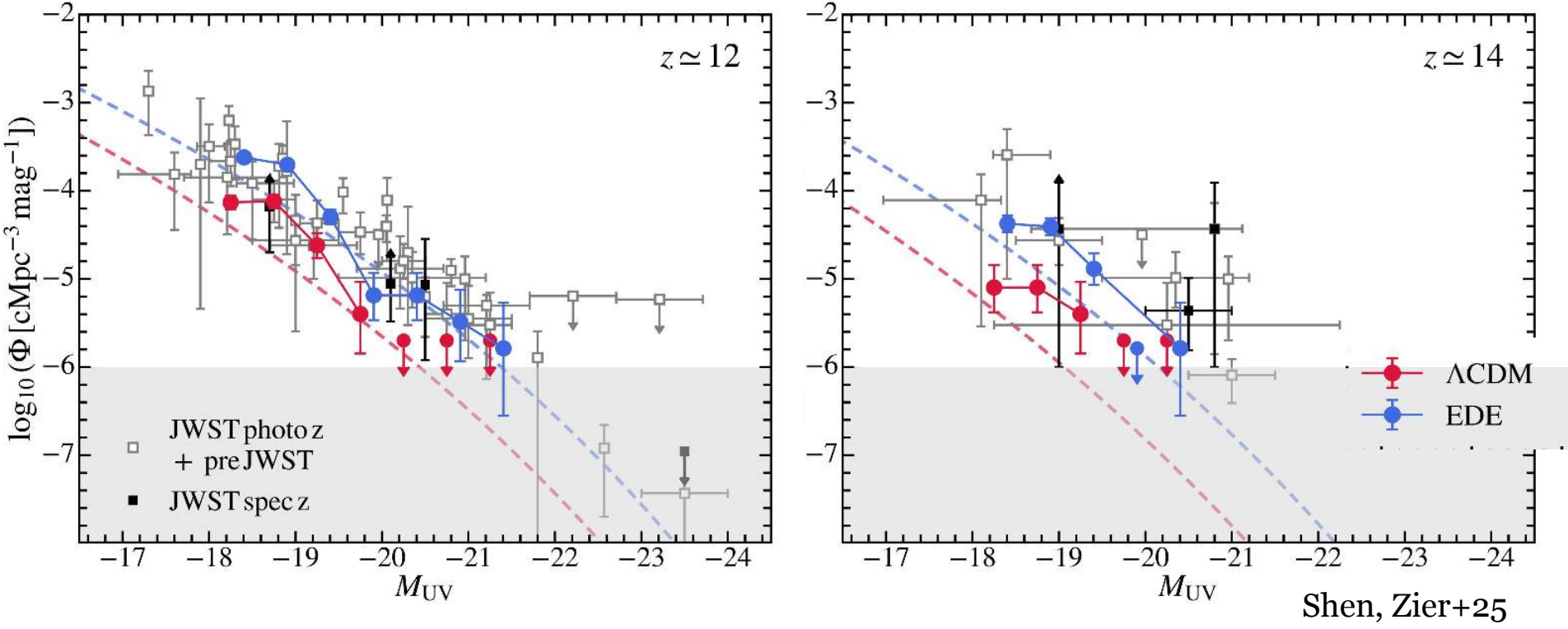


DM density field + bright galaxies marked by circles



A solution beyond the standard ΛCDM model

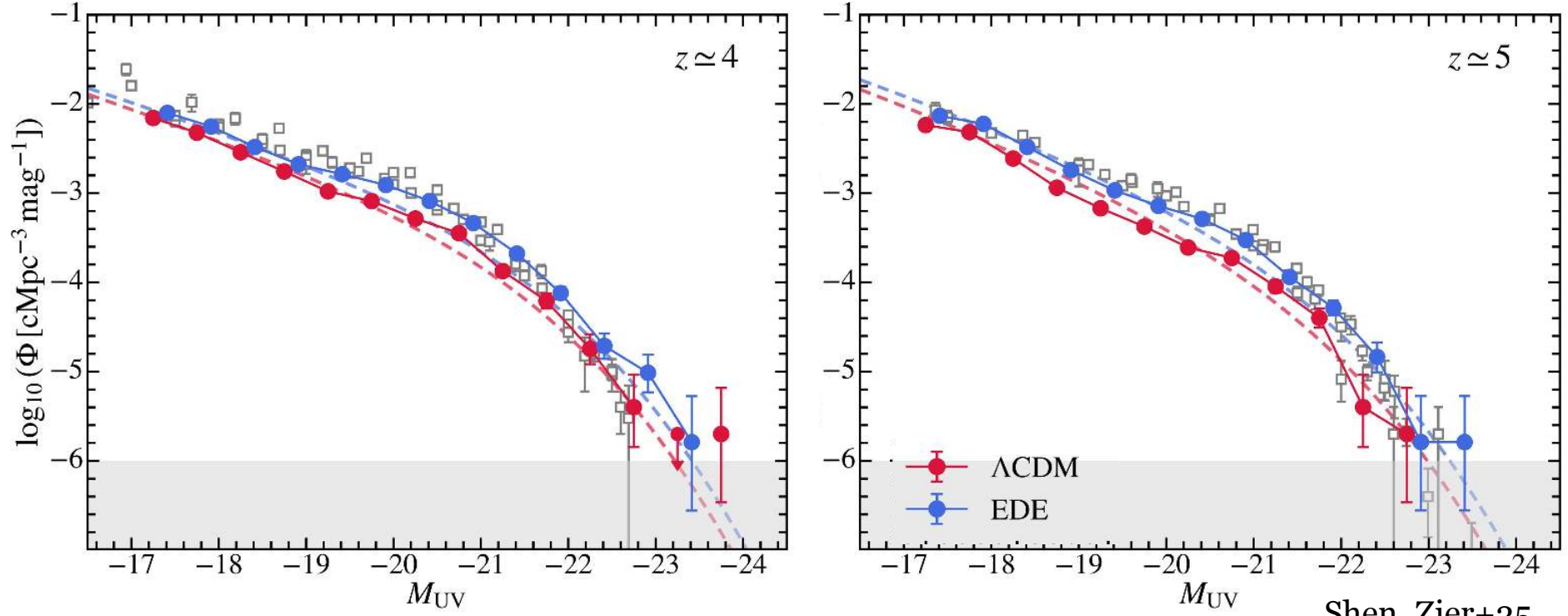
out-of-the-box EDE + IllustrisTNG gives:



Shen, Zier+25

A solution beyond the standard ΛCDM model

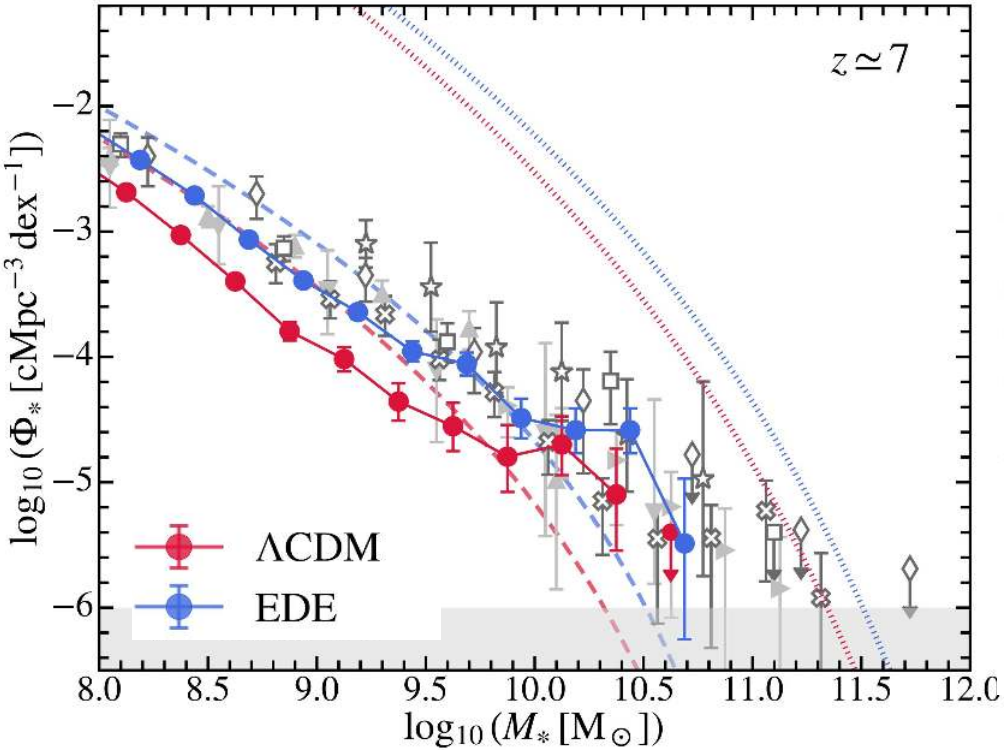
meanwhile at lower redshifts …



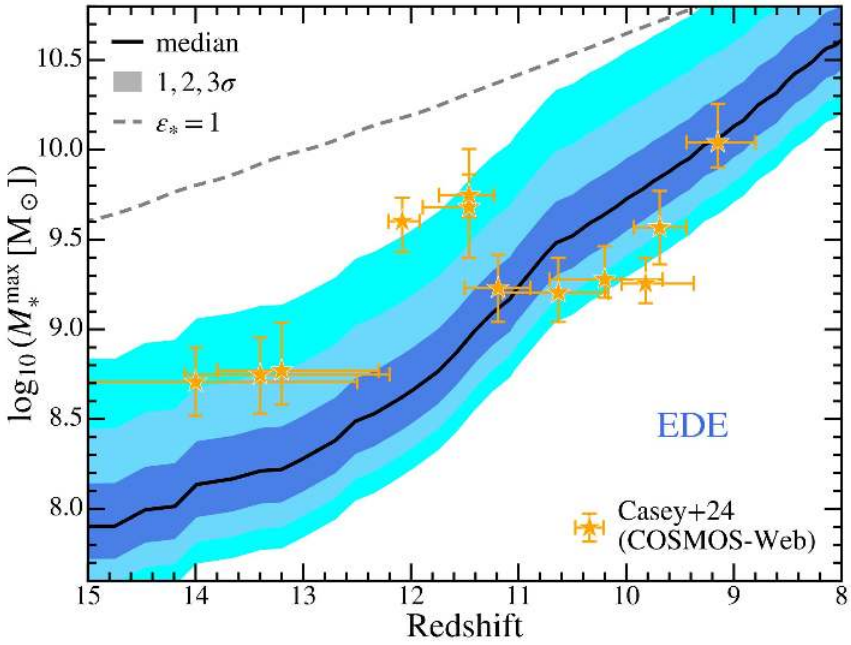
Shen, Zier+25

A solution beyond the standard ΛCDM model

how about the stellar mass function?



and the “cosmic breakers”?

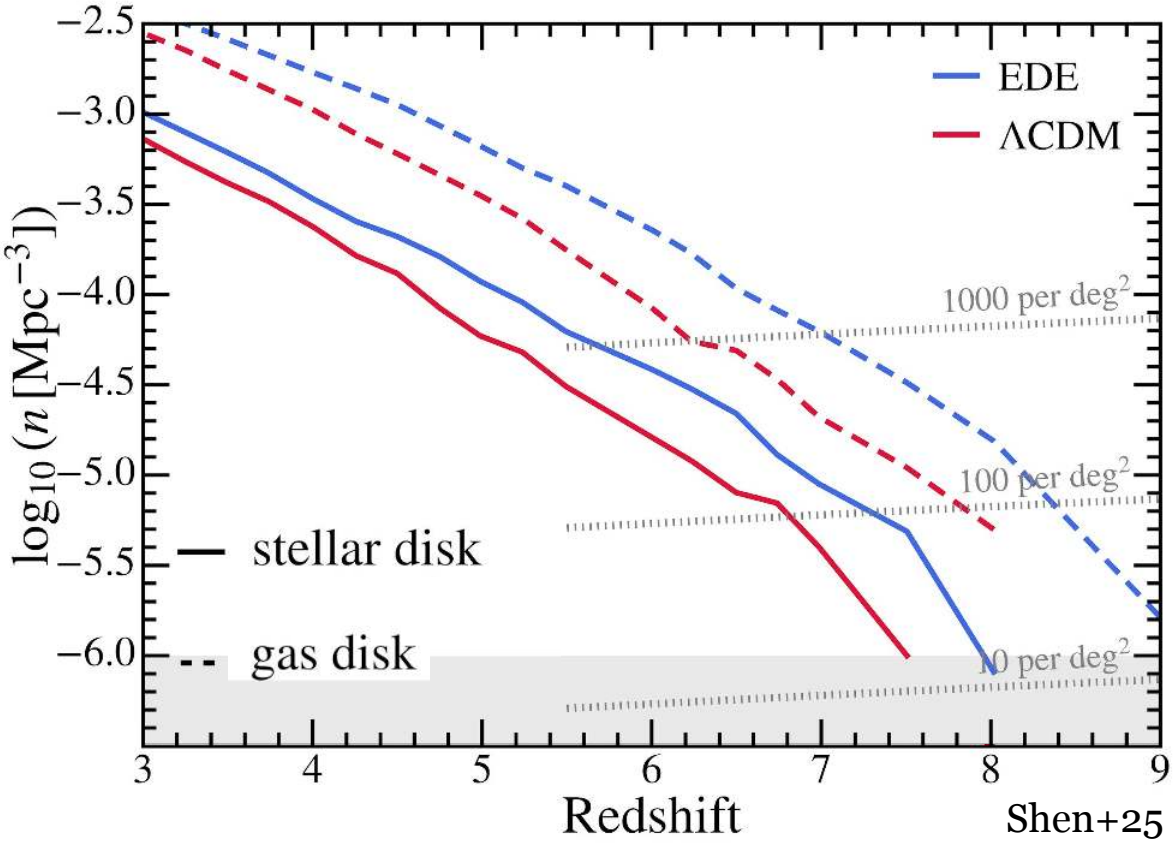


Shen, Zier+25

A solution beyond the standard ΛCDM model

earlier disky galaxies?

- morphology — stellar mass correlation not altered by cosmology
- more disk galaxies simply from more massive galaxies



Shen+25

Simulating SIDM with AREPO-2

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Self-Interacting Dark Matter

astrophysical implications/constraints

σ/m

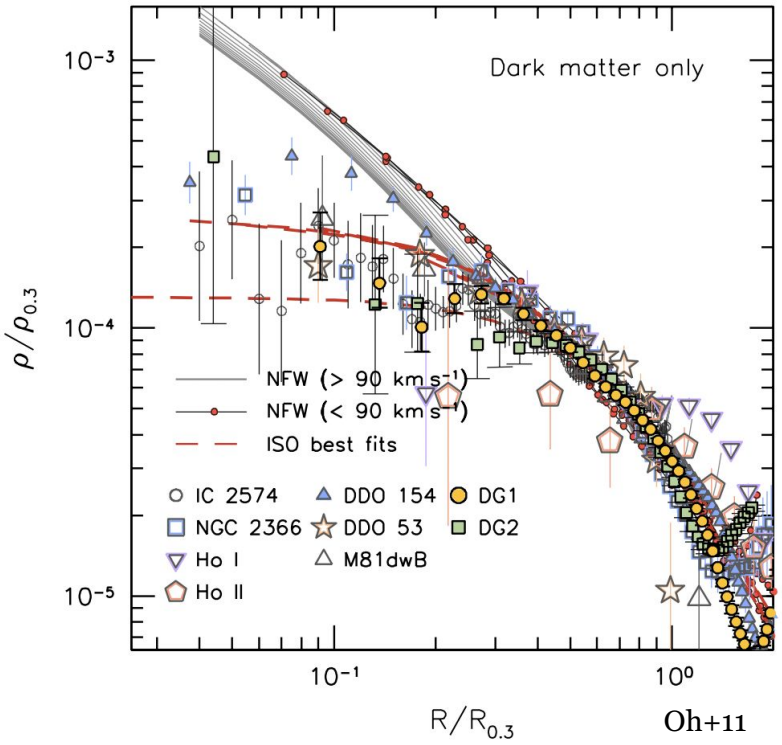
elastic interactions

$\sigma/m \sim 1\mathrm{cm}^2/\mathrm{g}$

original sweet spot of making "cores" to explain observed dwarf galaxy structure

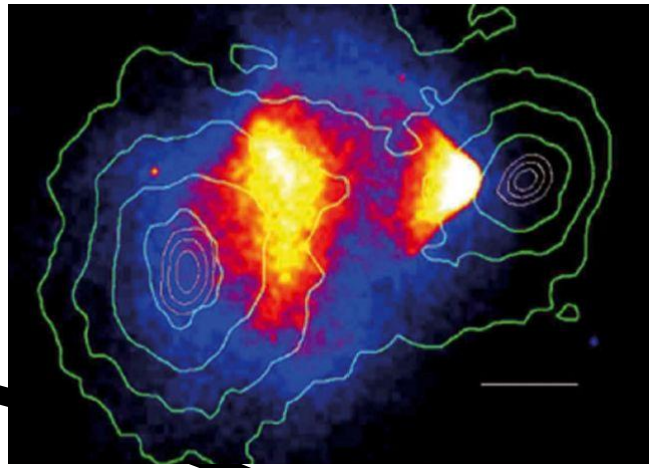
$v \lesssim 100\mathrm{km/s}$

velocity of DM particles, v



Self-Interacting Dark Matter

astrophysical implications/constraints



σ/m

$\sigma/m \lesssim 0.5\mathrm{cm}^2/\mathrm{g}$

constraints from colliding clusters

$v \sim 1000\mathrm{km/s}$

Harvey+15

velocity of DM particles, v

Self-Interacting Dark Matter

astrophysical implications/constraints

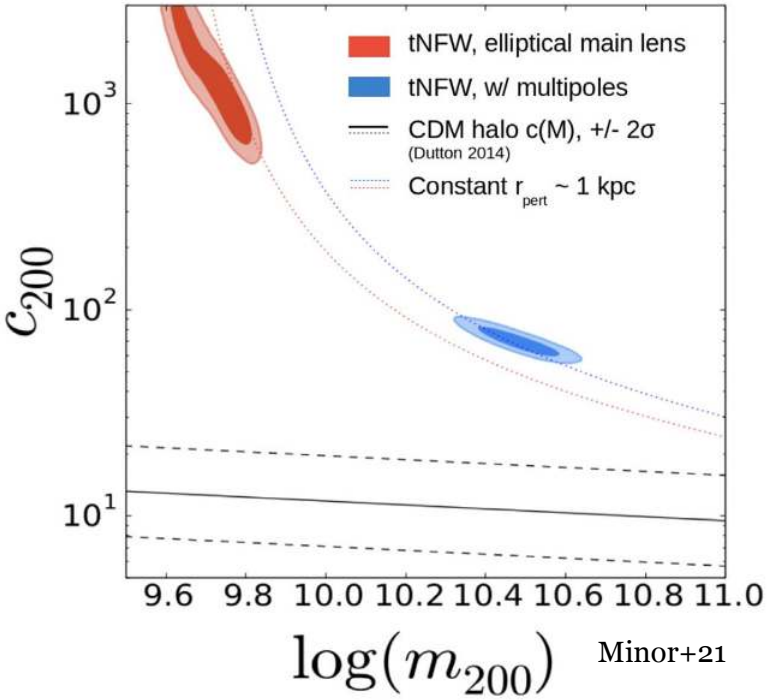
$\sigma/m \sim 30 - 200\mathrm{cm}^2/\mathrm{g}$

- diversity of dwarf galaxy structures
- strong lensing signals for ultra-compact substructures (e.g. Minor+21; Powell+25)
- ultra-dense perturber of stellar streams (e.g. Bonaca+19)

$v \lesssim 100\mathrm{km/s}$

σ/m

velocity of DM particles, v



Minor+21

Traditional implementation in AREPO (Vogelsberger 2012+)

use one sided SPH kernel overlap:

$$P_{ij} = \frac{m_i}{m_\chi} W(r_{ij}, h_i)\, \sigma_T(v_{ij}) v_{ij}\, \Delta t_i,$$

=> requires smoothing lengths => use gravity tree for neighbour search

momentum/energy conservation: requires updated state => no multi scattering => restrictive time step criterion

modifications to scattering requires knowledge of tree implementation

Implementation in AREPO-2

new ordered communication scheme:

- allows multi-scattering => less restrictive time step criterion
- trivial to extend to new pair wise interactions
- speed up with specialized neighbour search tree for DM

```
static void get_sidm_scatter_input_data(int p, input_scattering_data *in_data);
static void apply_sidm_scatter_output_data(int index, const output_scattering_data *out_data);
static void sidm_perform_scatter(const input_scattering_data *__restrict__ in_data_a,
                                 const input_scattering_data *__restrict__ in_data_b,
                                 output_scattering_data *__restrict__ out_data_a,
                                 output_scattering_data *__restrict__ out_data_b);
```

already implemented:

- elastic scattering
- state based SIDM
- inelastic scattering
- “frequent scattering” with angular dependence
- decaying dark matter

Main take-aways

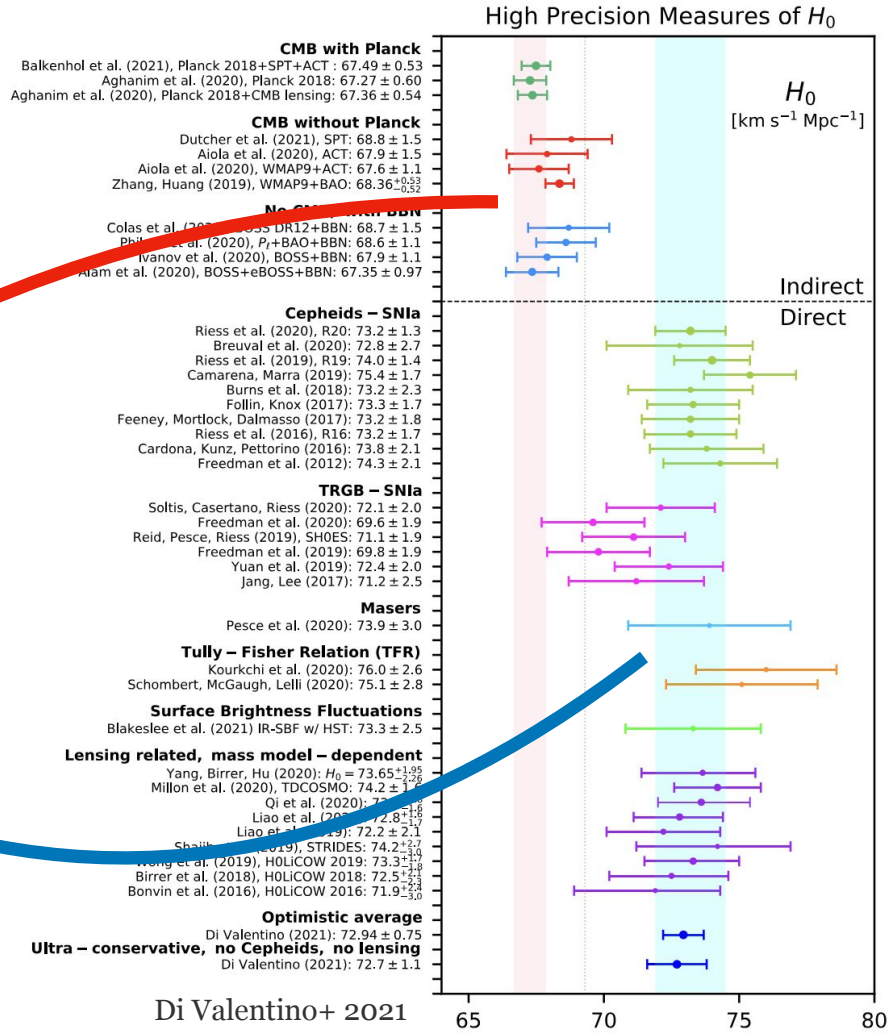
- Early dark energy could explain early structure formation at high z
- new optimized SIDM implementation in AREPO-2

Context: The Hubble Tension

"Early" constraints (e.g. CMB, BAO)
$H_0 \sim 68$km/s/Mpc

a$\sim 5\sigma$ tension ✕

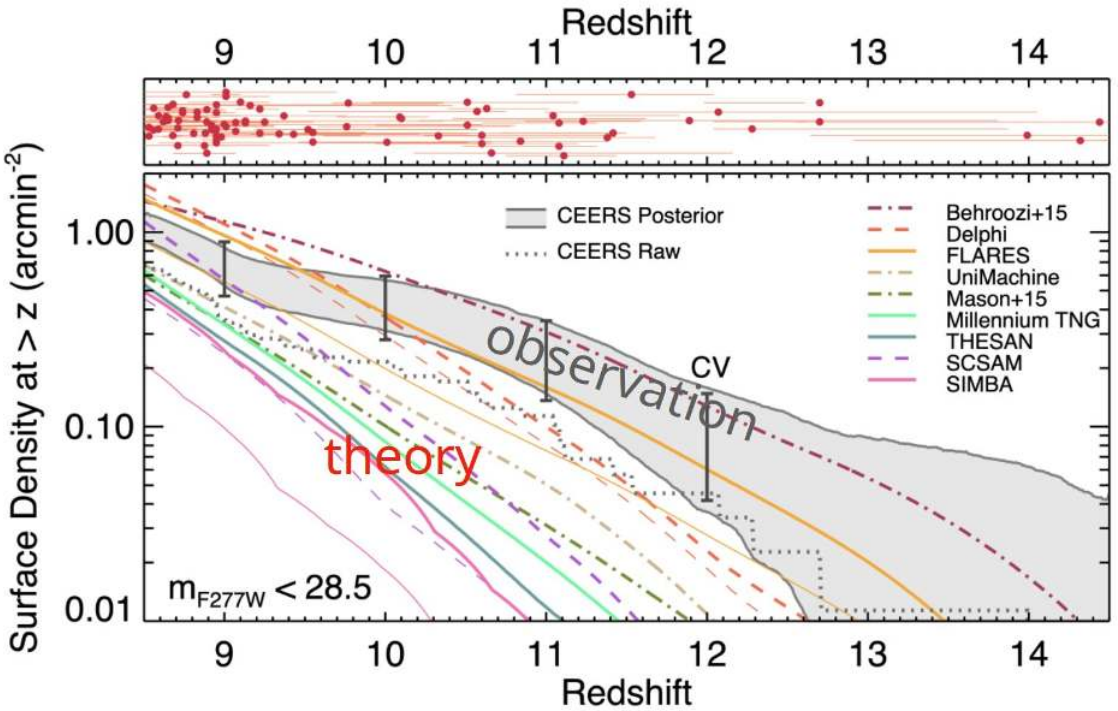
"Late" constraints (e.g. distance ladder)
$H_0 \sim 73$km/s/Mpc



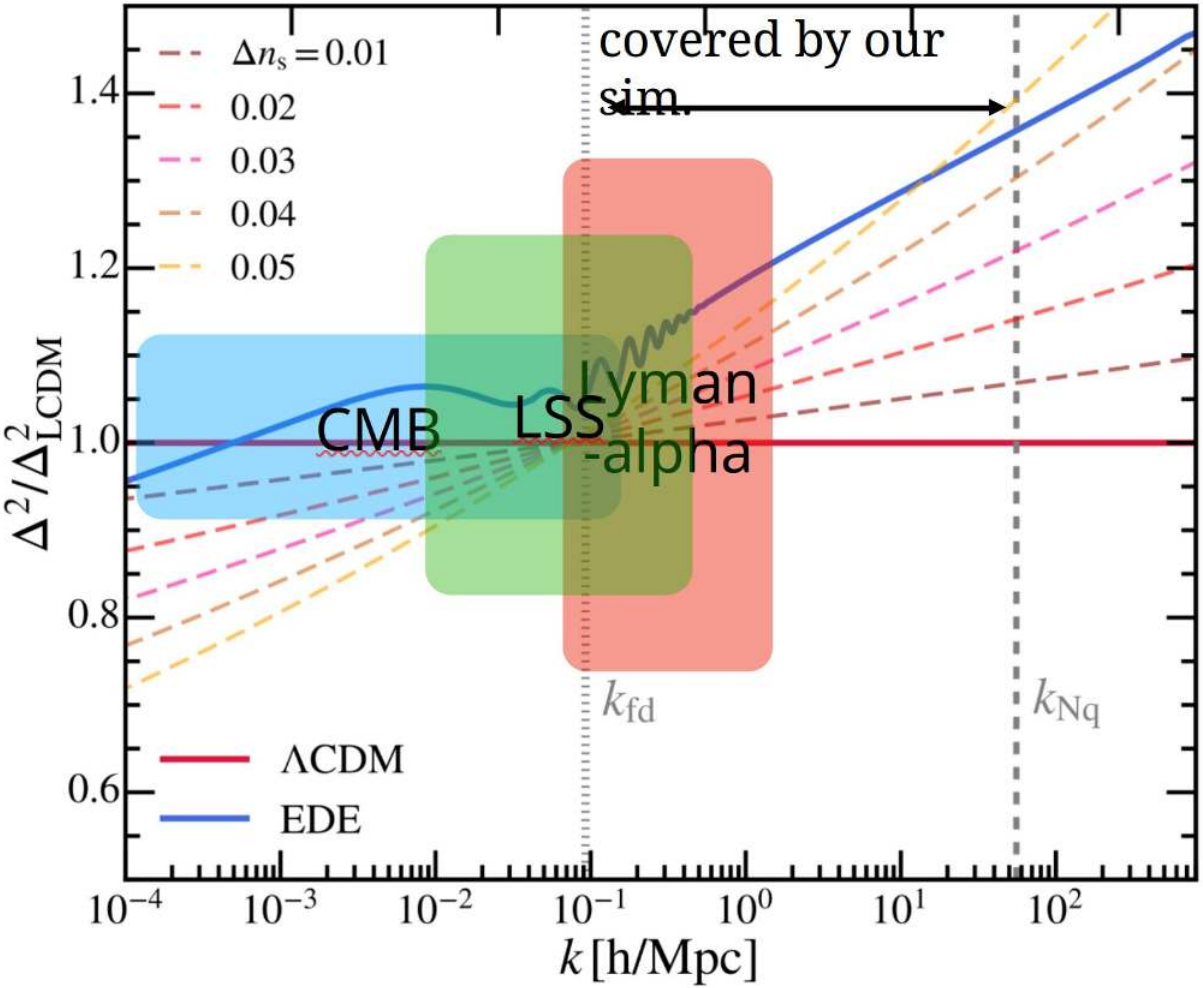
Di Valentino+ 2021

Accelerated Structure Formation revealed by JWST

Case I: Bright Galaxies



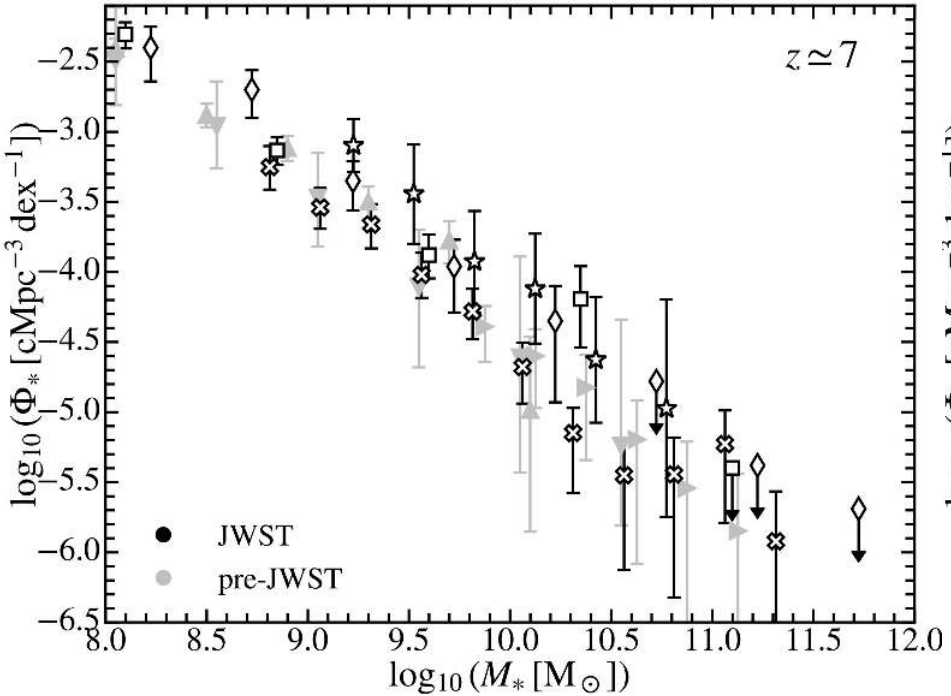
Finkelstein+2024, complete CEERS sample

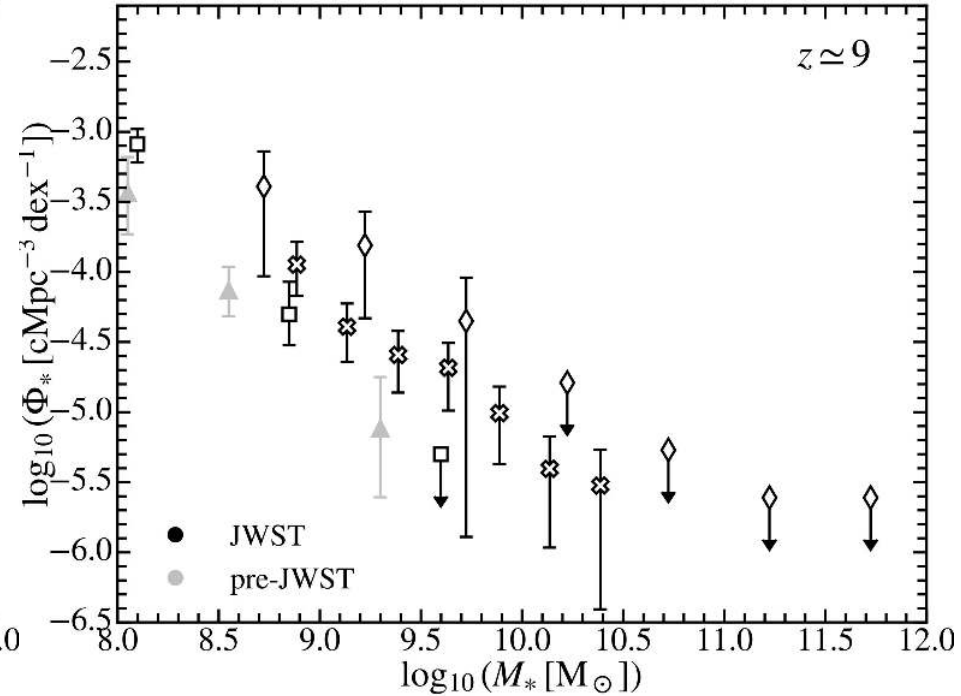

covered by our sim.
$\Delta n_s = 0.01$
0.02
0.03
0.04
0.05
CMB
LSS
Lyman -alpha
$k_{\rm fd}$
$k_{\rm Nq}$
ΛCDM
EDE
$\Delta^2/\Delta^2_{\rm LCDM}$
k [h/Mpc]
1.4
1.2
1.0
0.8
0.6
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

Accelerated Structure Formation revealed by JWST

Case II: Massive Galaxies

stellar mass functions (more robust)
pre-JWST vs post-JWST





Accelerated Structure Formation revealed by JWST

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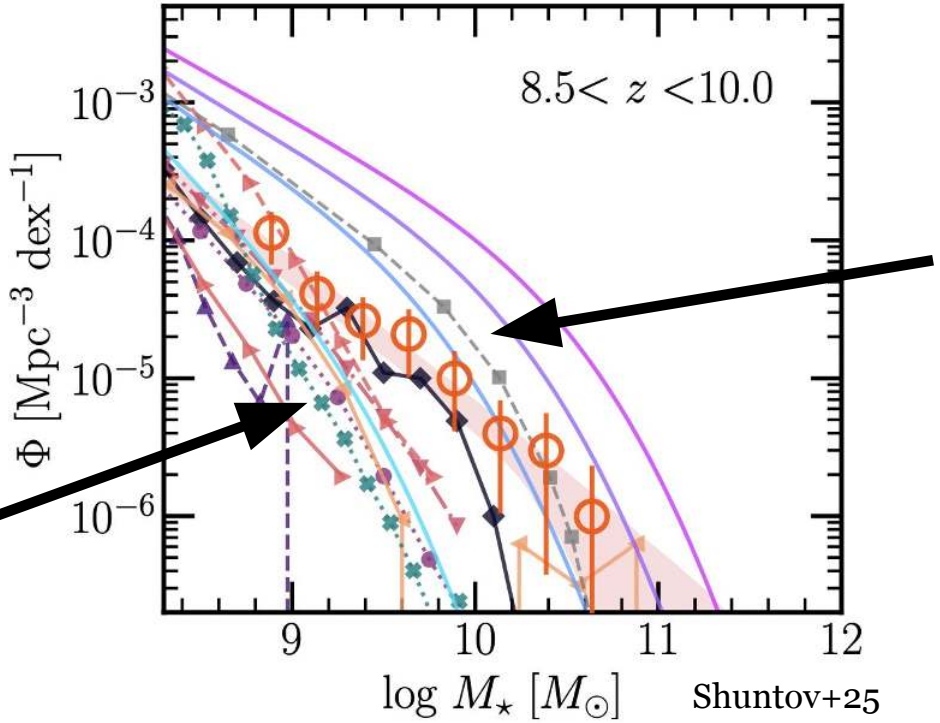

Post-JWST tweaks to galaxy formation/cosmology model

Pre-JWST models

Shuntov+25