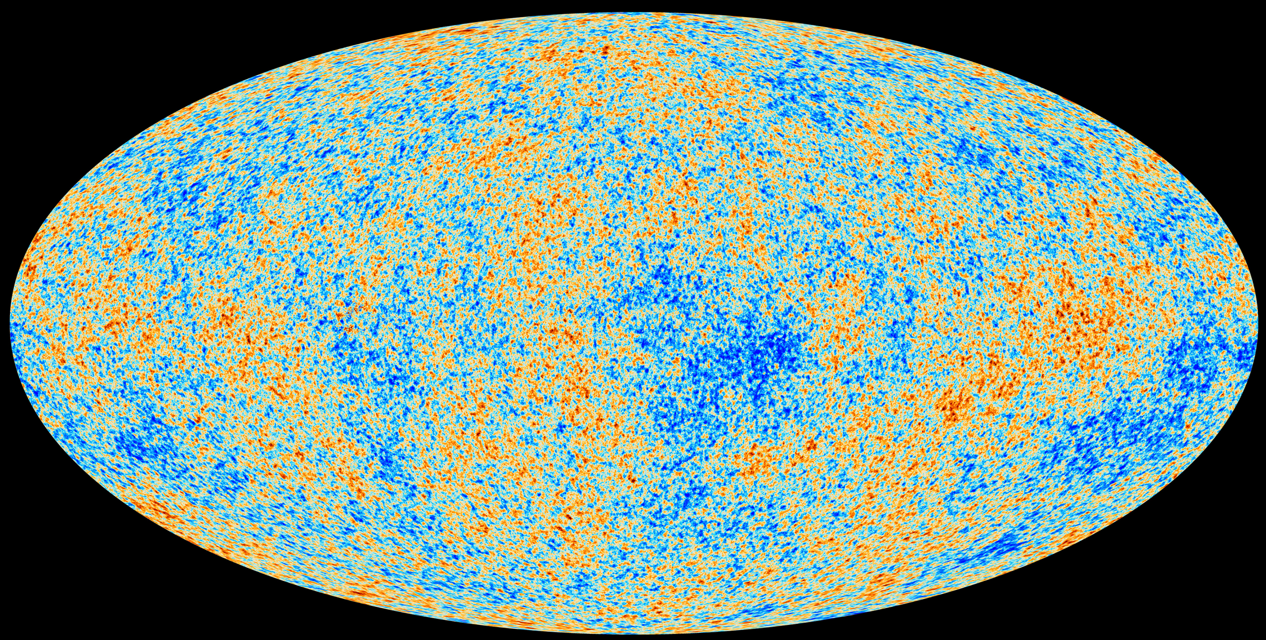
Structure Formation:

Putting ΛCDM to the test

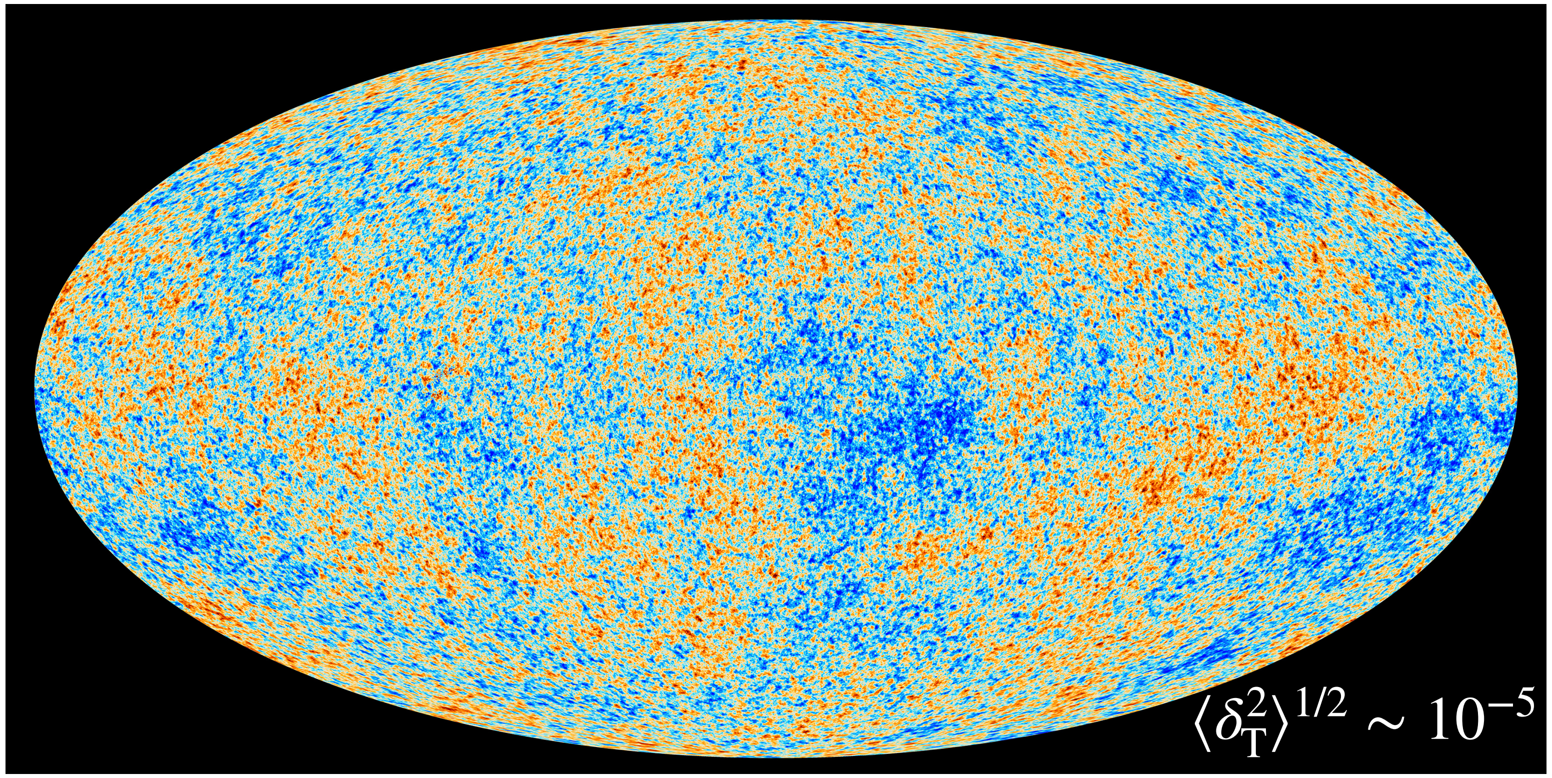


Mike Boylan-Kolchin

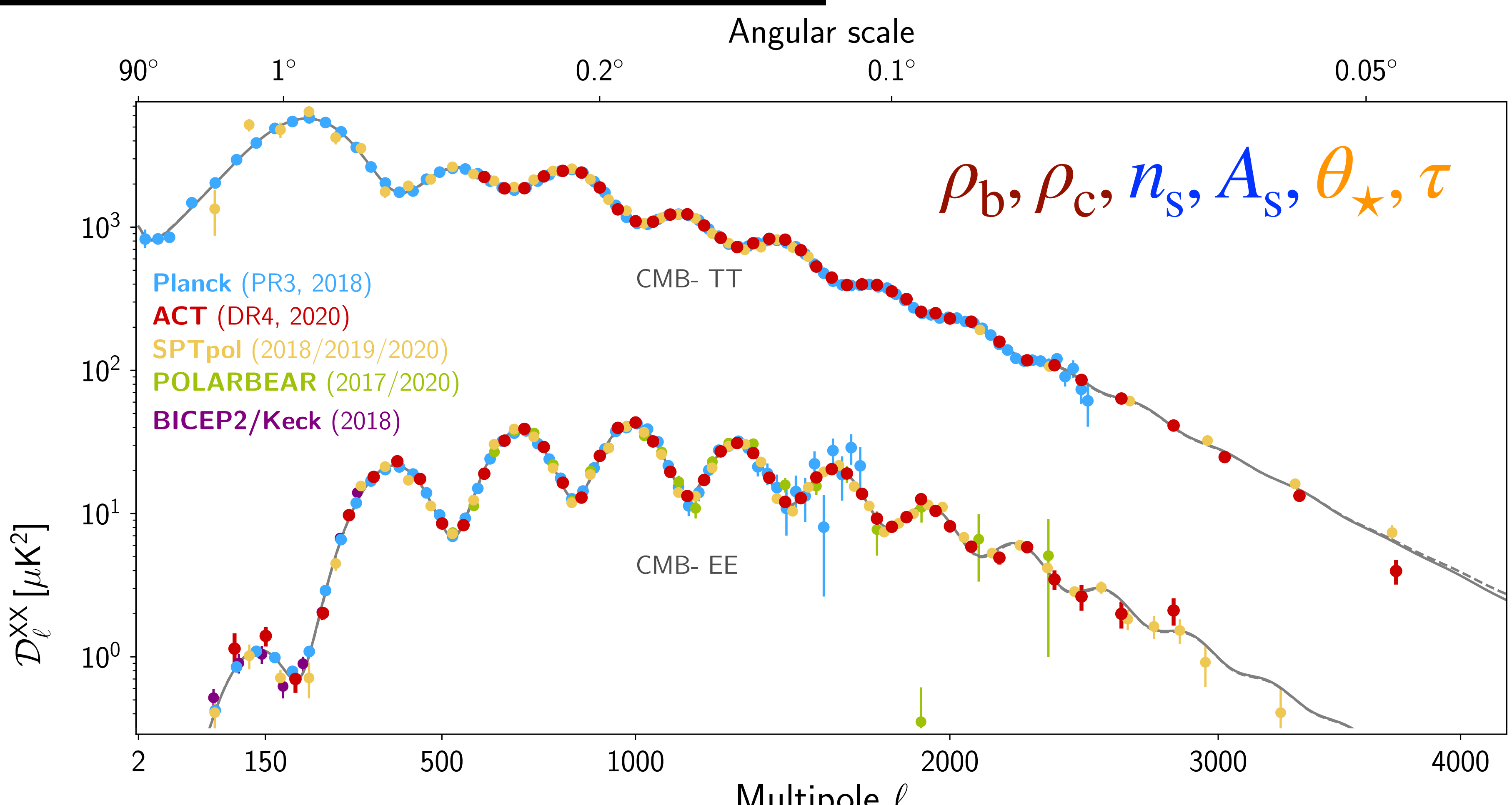
@mbkplus

The University of Texas at Austin

ΛCDM works. Really well.

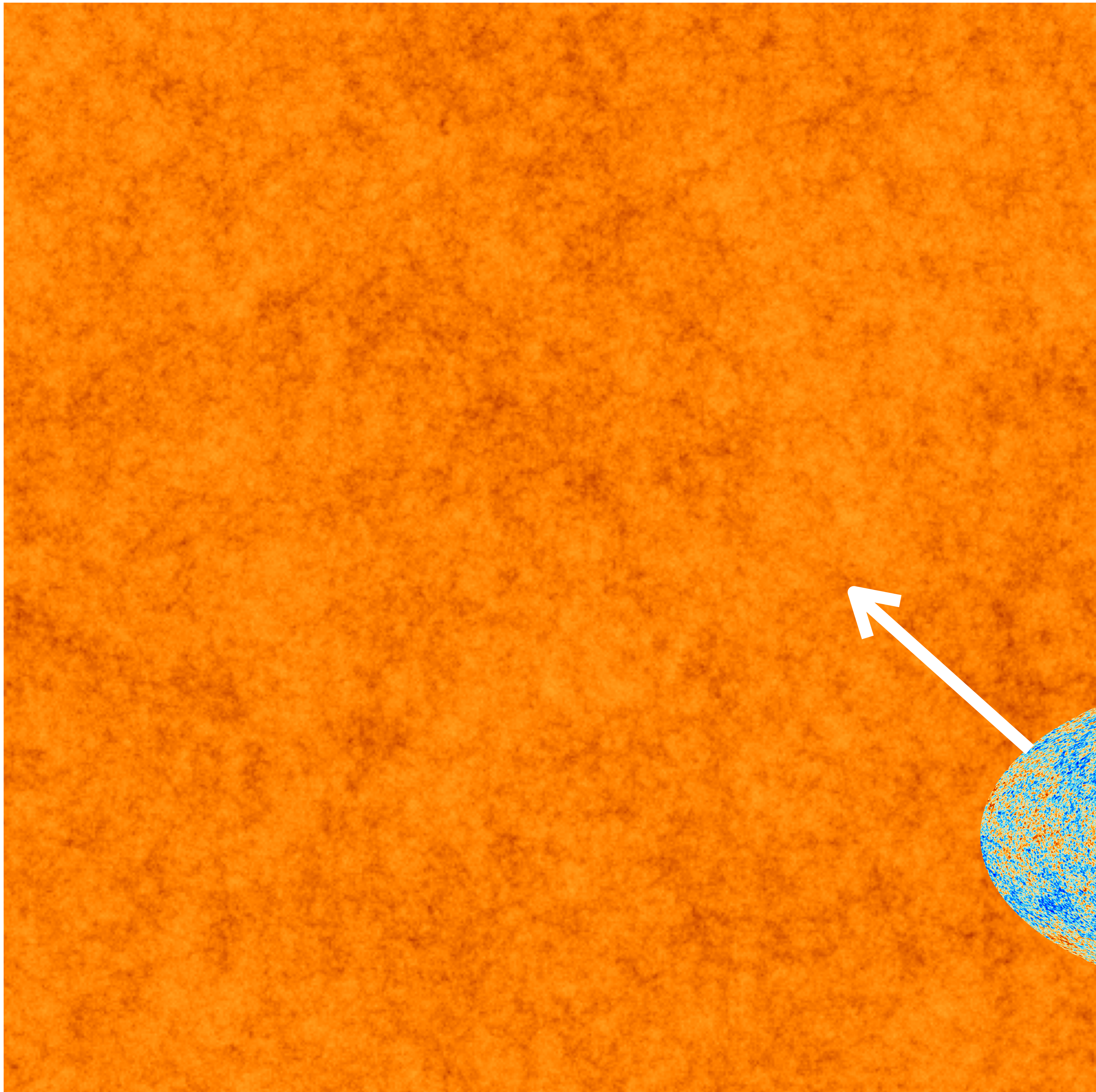


ΛCDM is a ***starting*** point for a predictive theory of our Universe



Choi et al. 2021

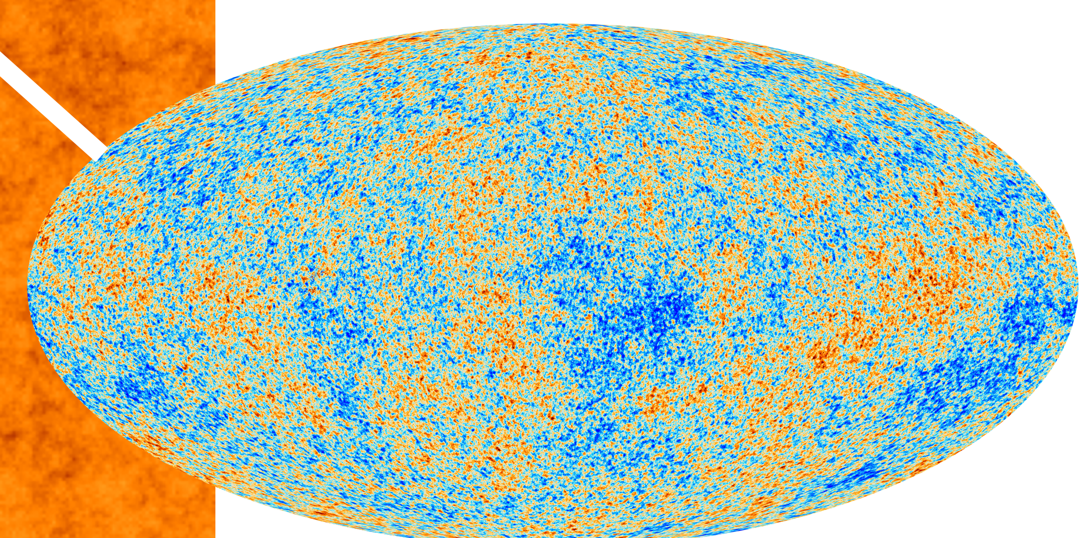
Linear theory: from $\delta_{\rm T}(z \approx 1100)$ to $\delta_\rho(z \approx 100)$



6* parameter model

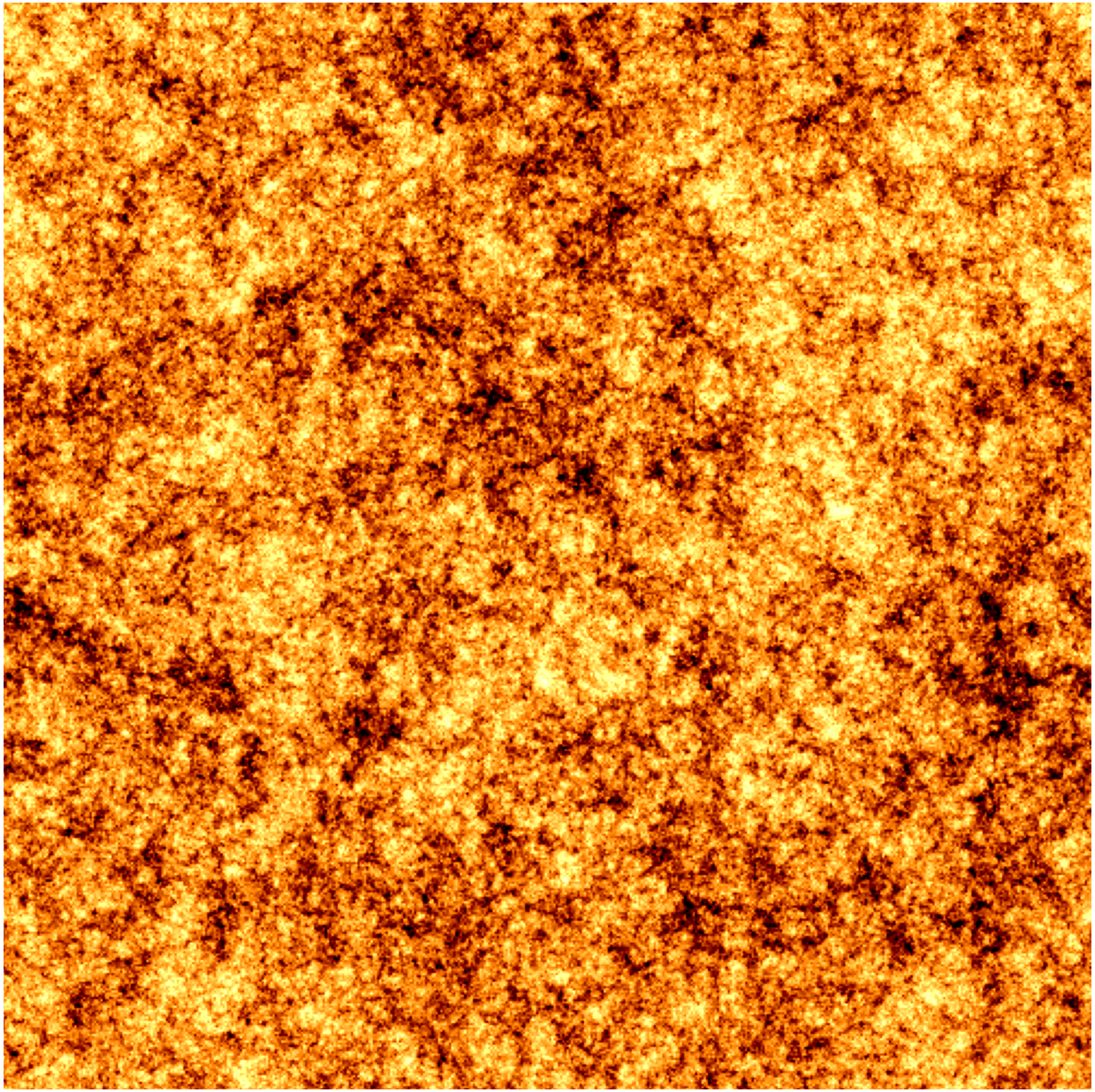
$\rho_{\rm b}, \rho_{\rm c}, n_{\rm s}, A_{\rm s}, \theta_\star, \tau$

extrapolated to $z = 127$
using linear theory



$\langle \delta_{\rm T}^2 \rangle^{1/2} \sim 10^{-5}$

Linear theory: from $\delta_{\rm T}(z \approx 1100)$ to $\delta_{\rho}(z = 0)$



6* parameter model

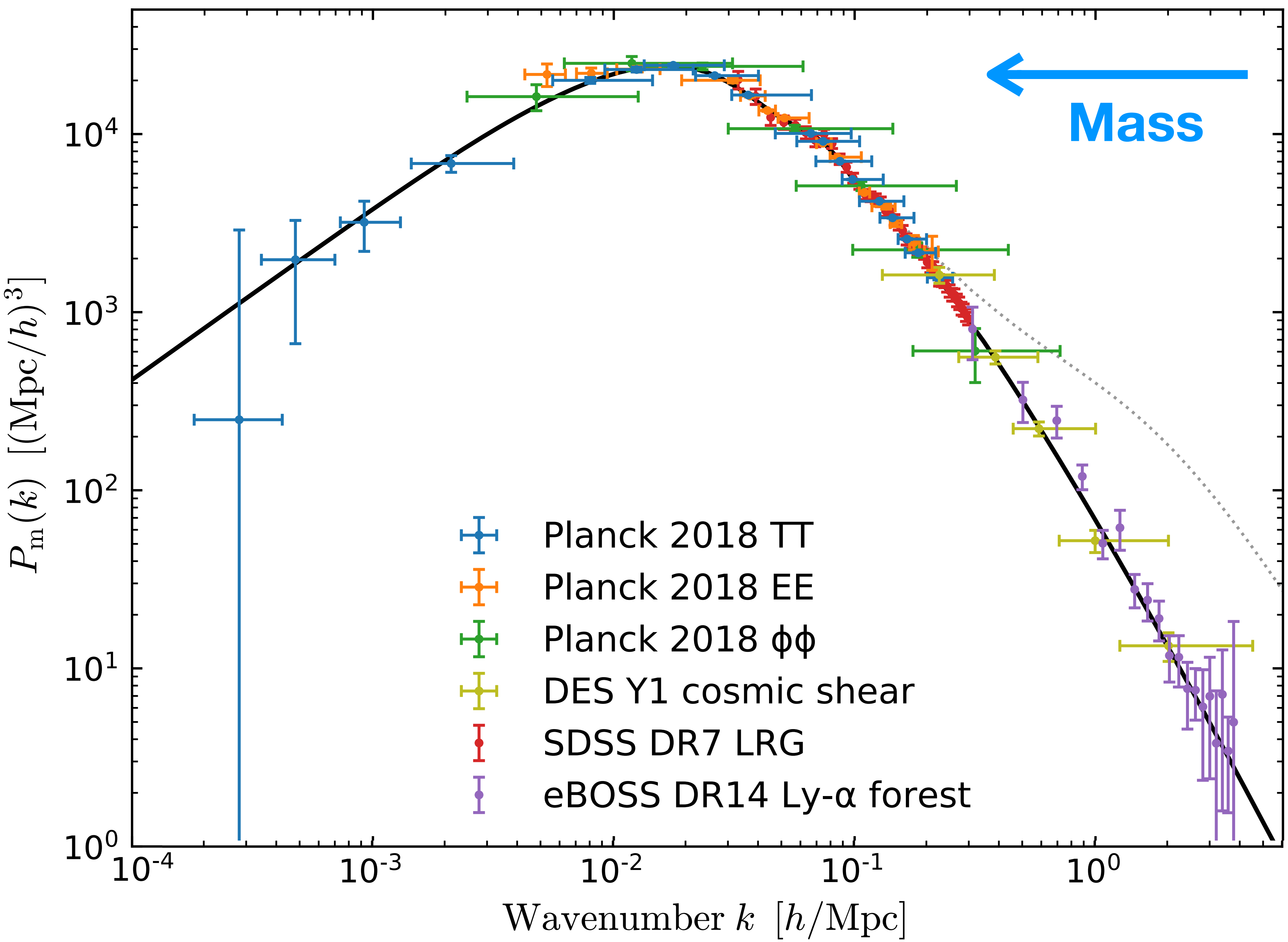
$\rho_{\rm b}, \rho_{\rm c}, n_{\rm s}, A_{\rm s}, \theta_{\star}, \tau$

extrapolated to $z = 0$
using linear theory

Best-tested predictions are on **linear** scales

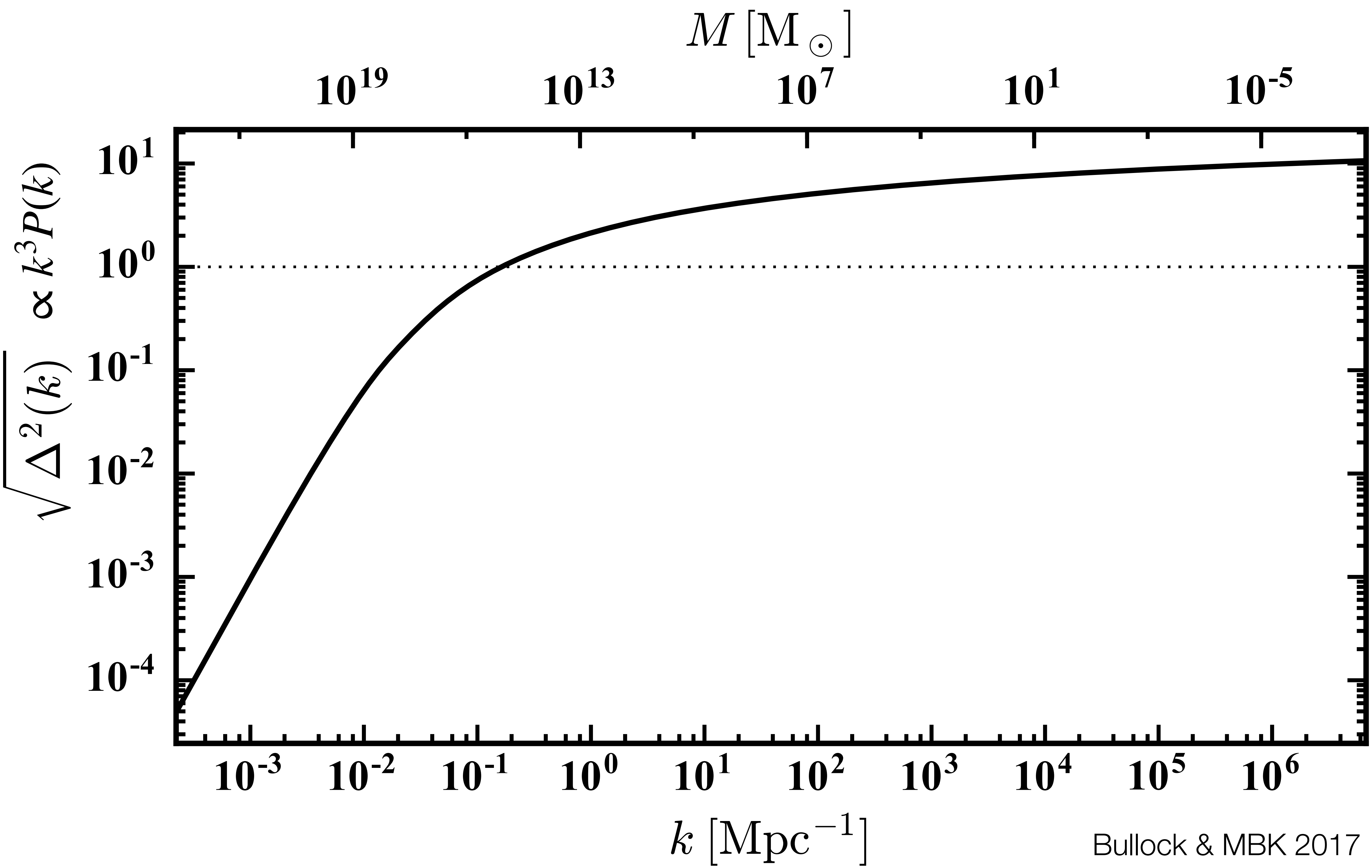
Fits a *wide* range of data with only 6 parameters: $\rho_b, \rho_c, n_s, A_s, \theta_\star, \tau$

Matter fluctuations described by (linear) matter power spectrum



Chabanier et al. 2019

ΛCDM covers a **vast** range of scales



Bullock & MBK 2017

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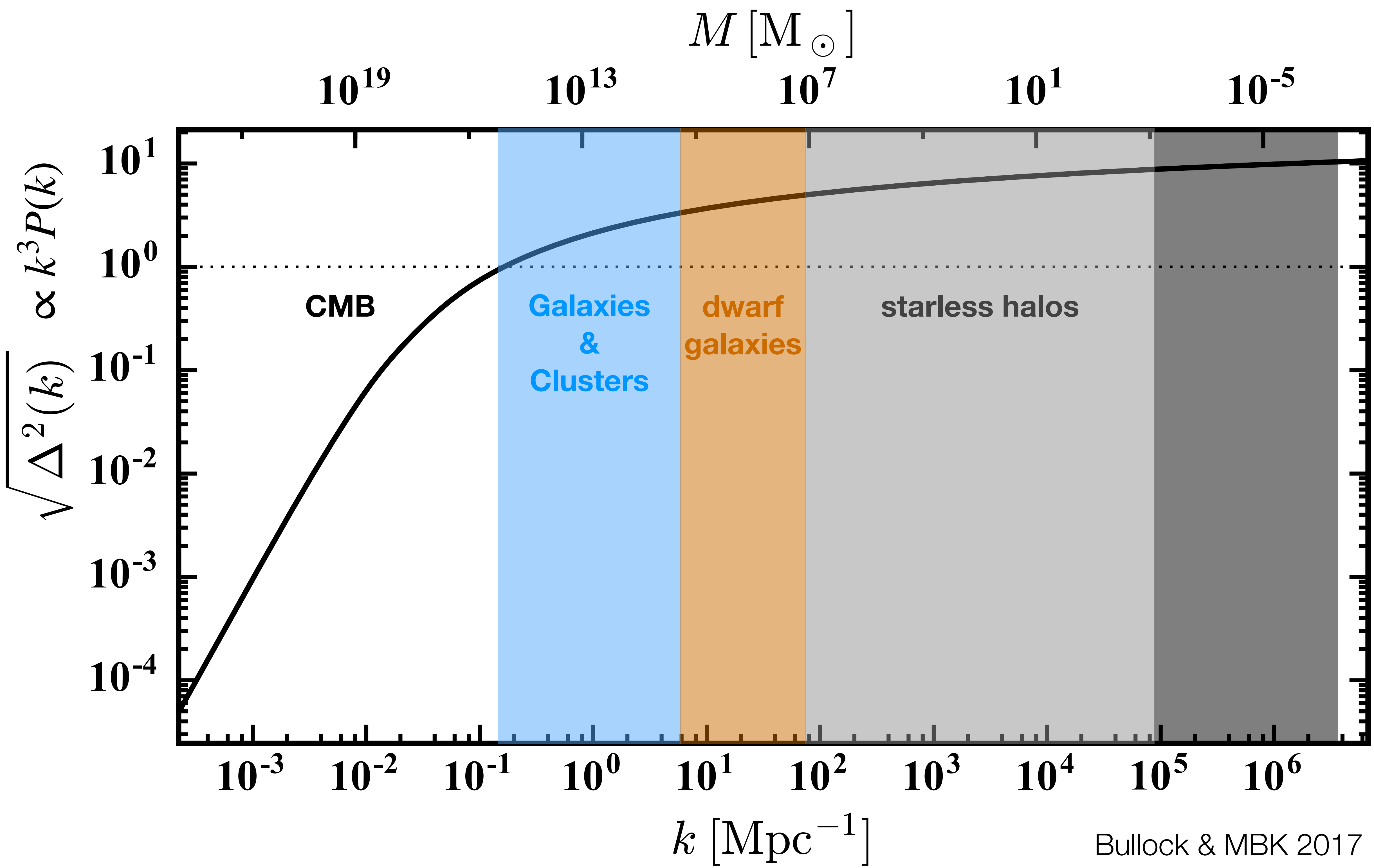

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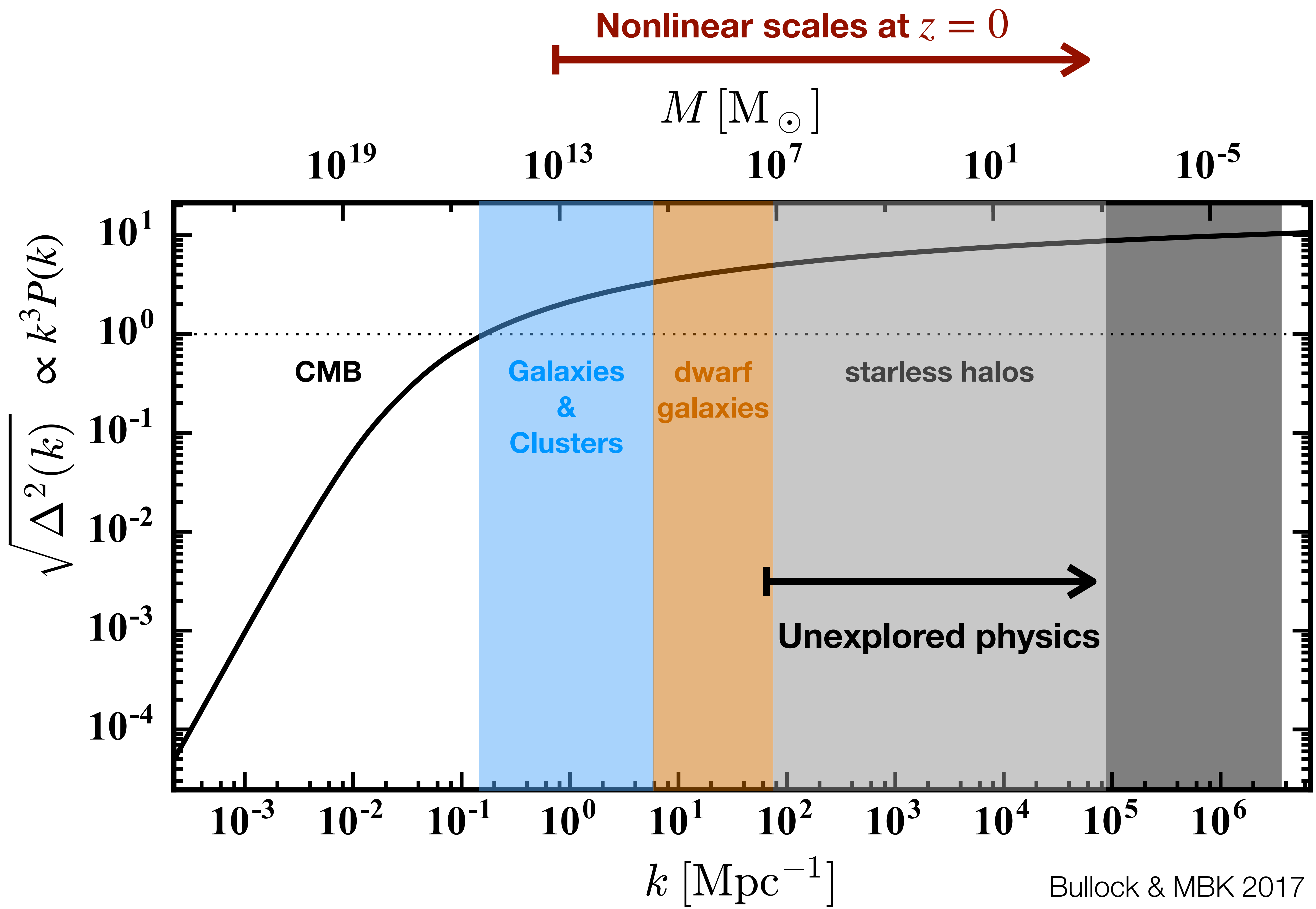
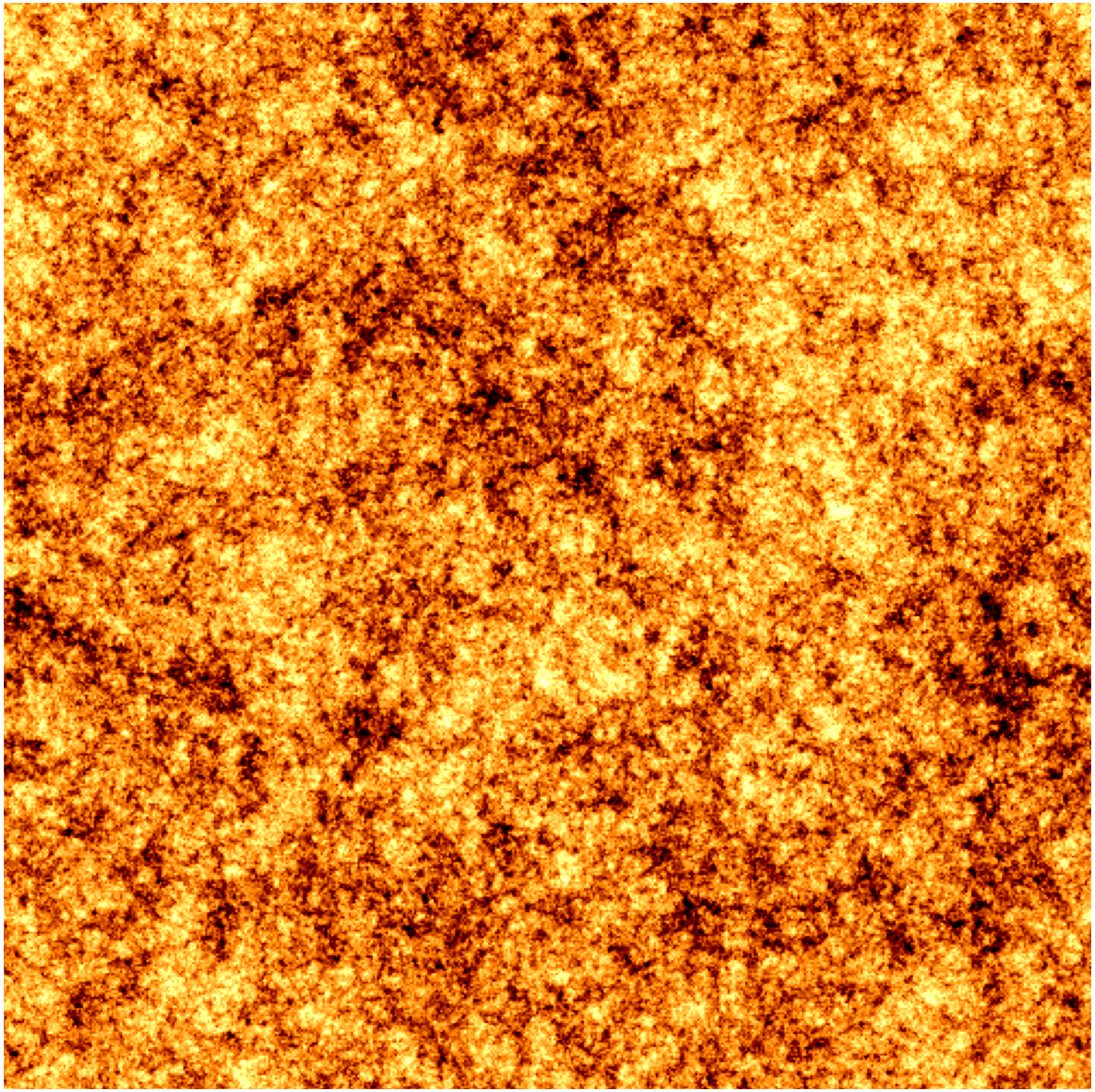


Bullock & MBK 2017

ΛCDM: we can use linear theory to $z = 0$...

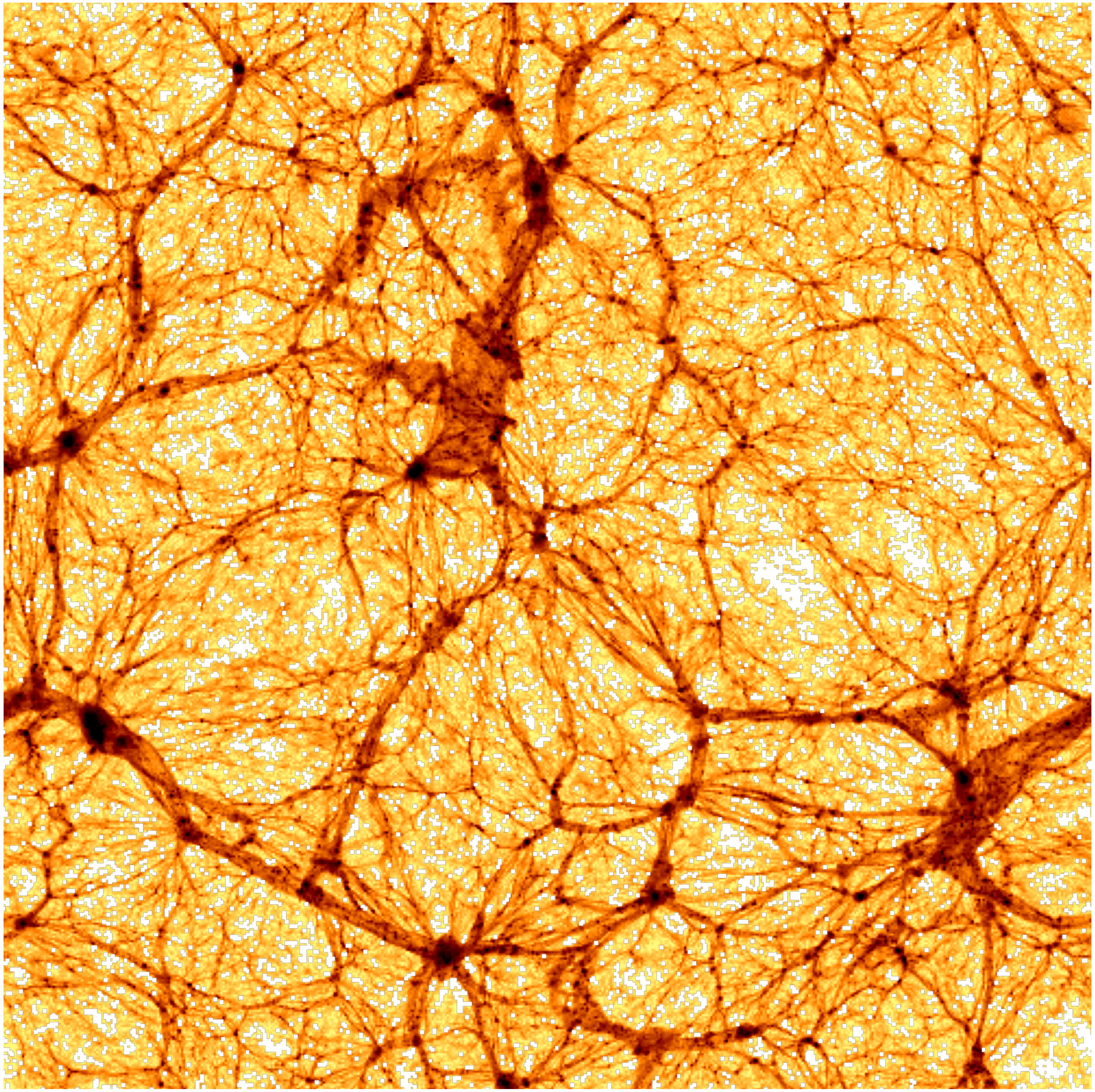


6 parameter model

$\rho_{\rm b}, \rho_{\rm c}, n_{\rm s}, A_{\rm s}, \theta_\star, \tau$

extrapolated to $z = 0$
using linear theory

…but the Universe does a different extrapolation



6 parameter model

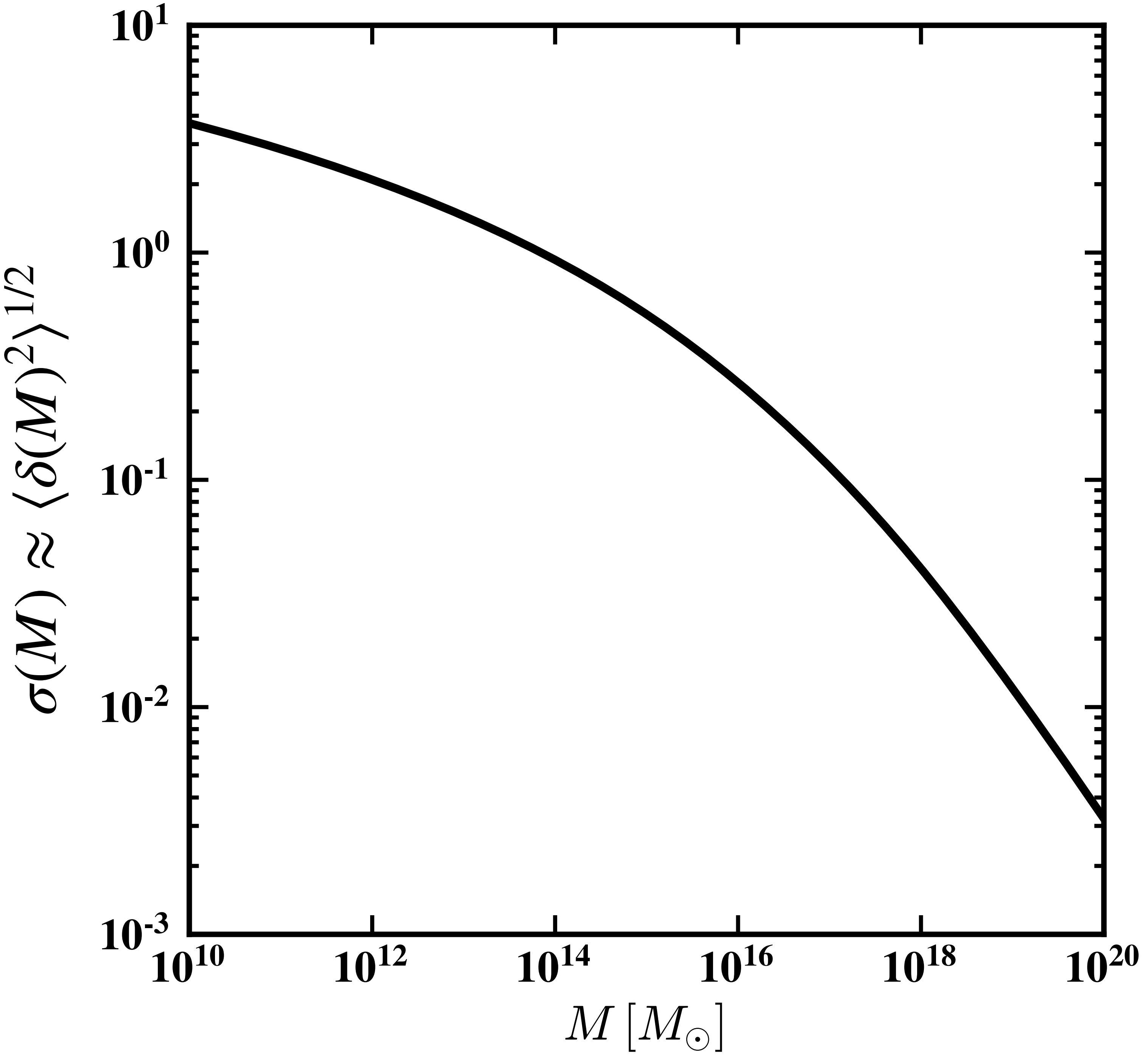
$\rho_{\rm b}, \rho_{\rm c}, n_{\rm s}, A_{\rm s}, \theta_{\star}, \tau$

evolved to $z = 0$ using really big computers

A clever way to go non-linear (Press & Schecter 1974)

Linear matter power spectrum contains information about statistics of ***non-linear*** fluctuations (dark matter halos):

$$\rho_{\rm b}, \rho_{\rm c}, n_{\rm s}, A_{\rm s}, \theta_\star, \tau \rightarrow \sigma(M,z) \rightarrow n(M,z)$$



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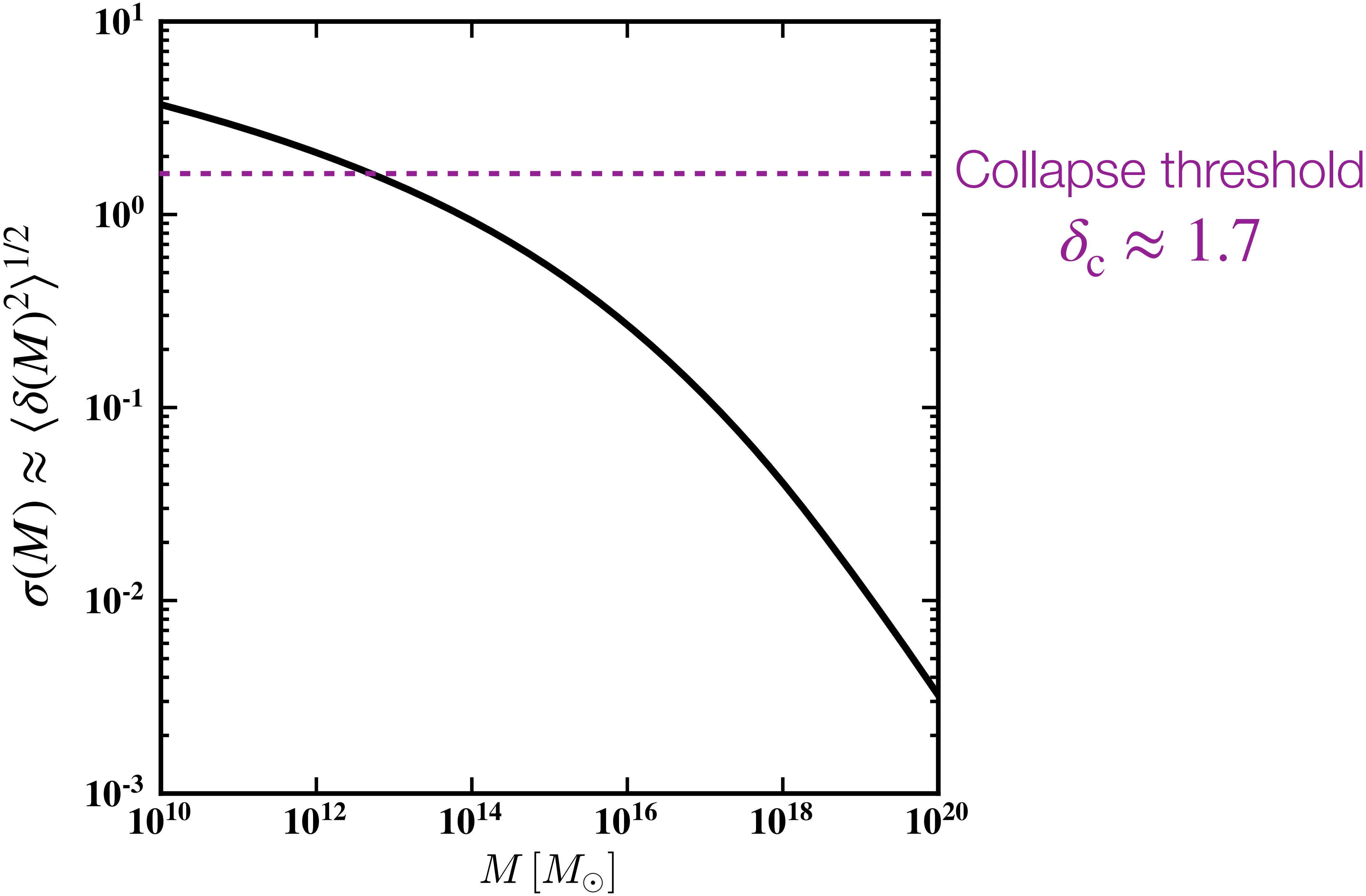

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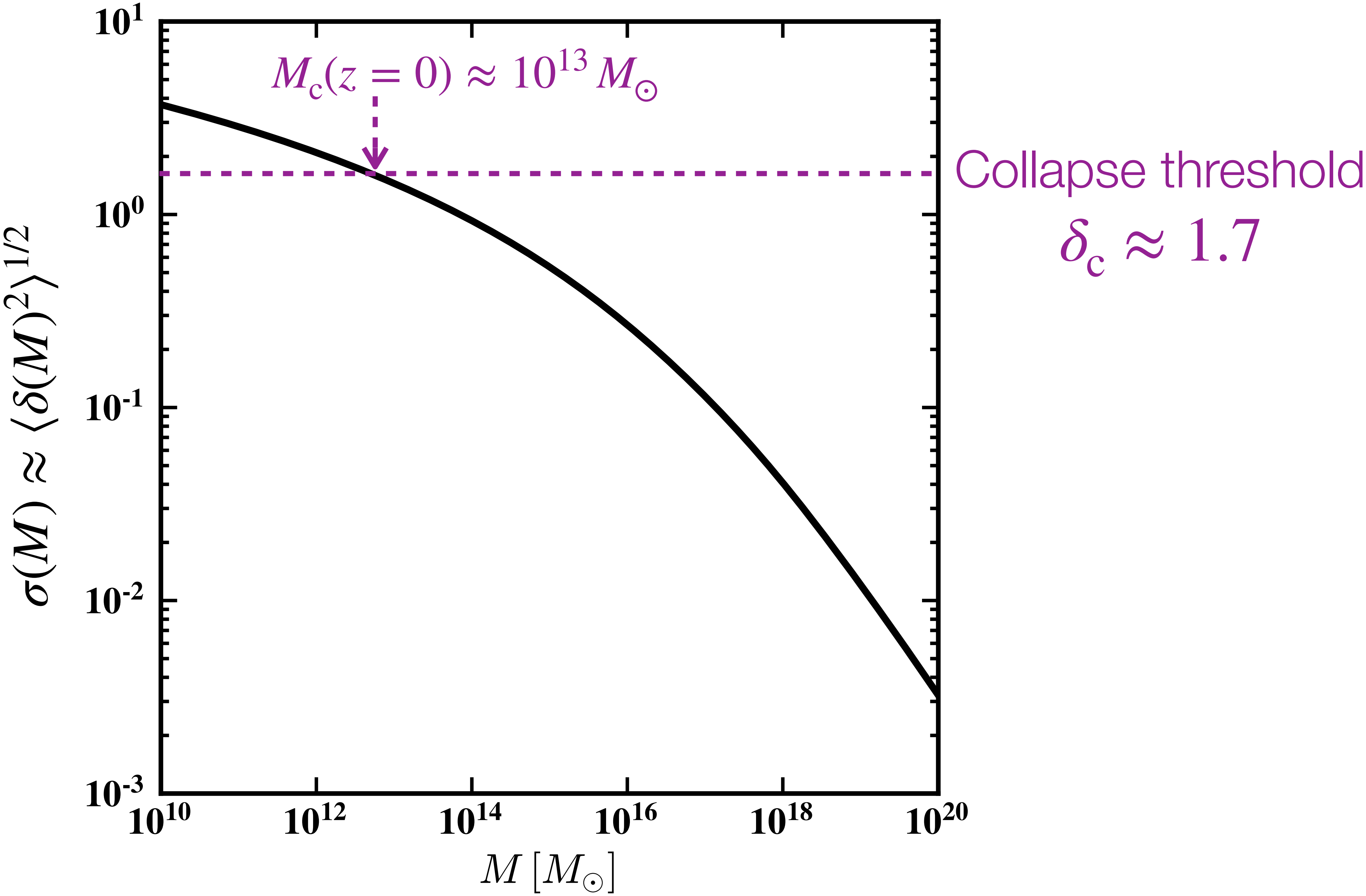

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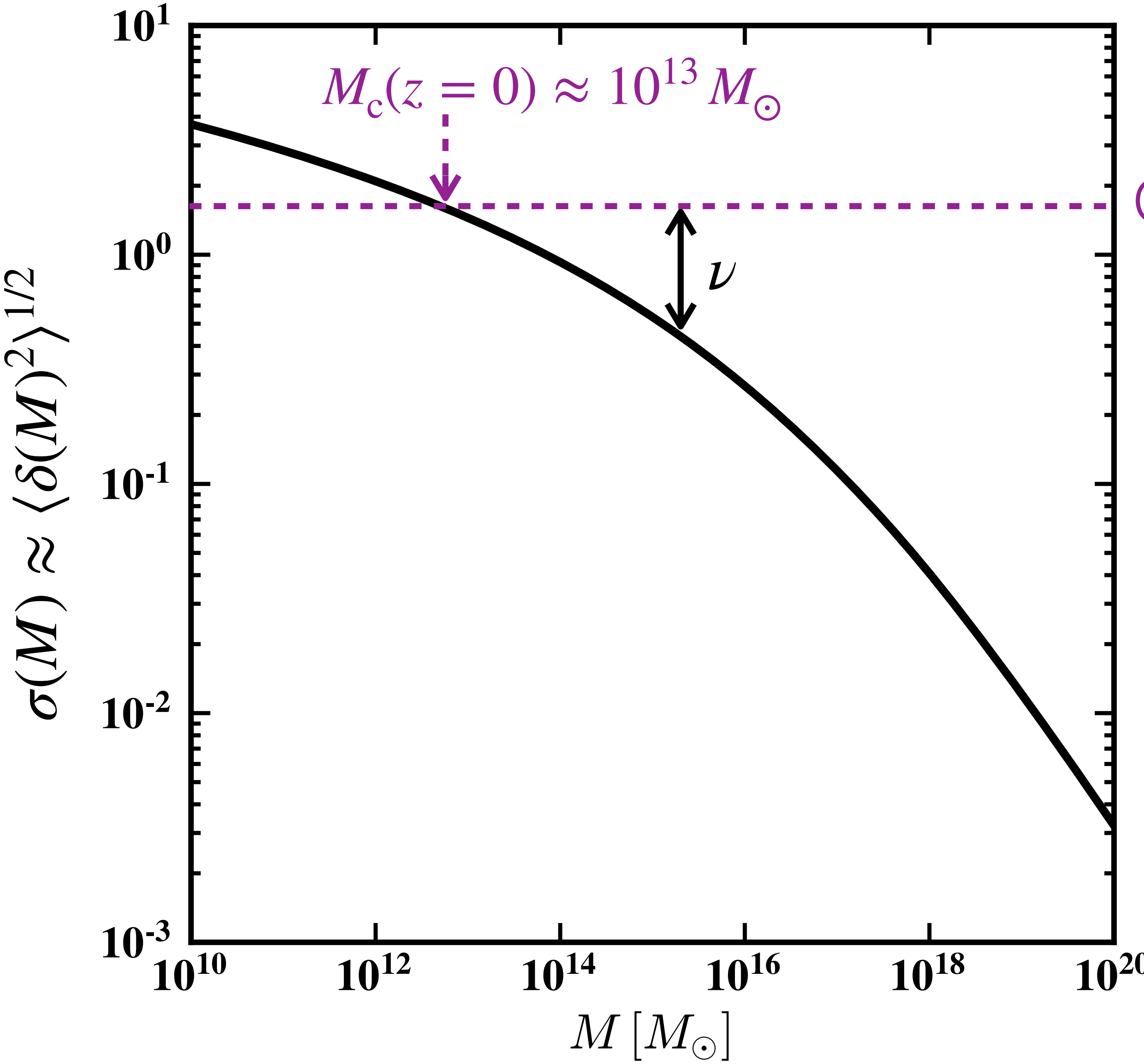

Collapse threshold

$\delta_c \approx 1.7$

Peak height:

$$\nu = \frac{\delta_c}{\sigma(M, z)}$$

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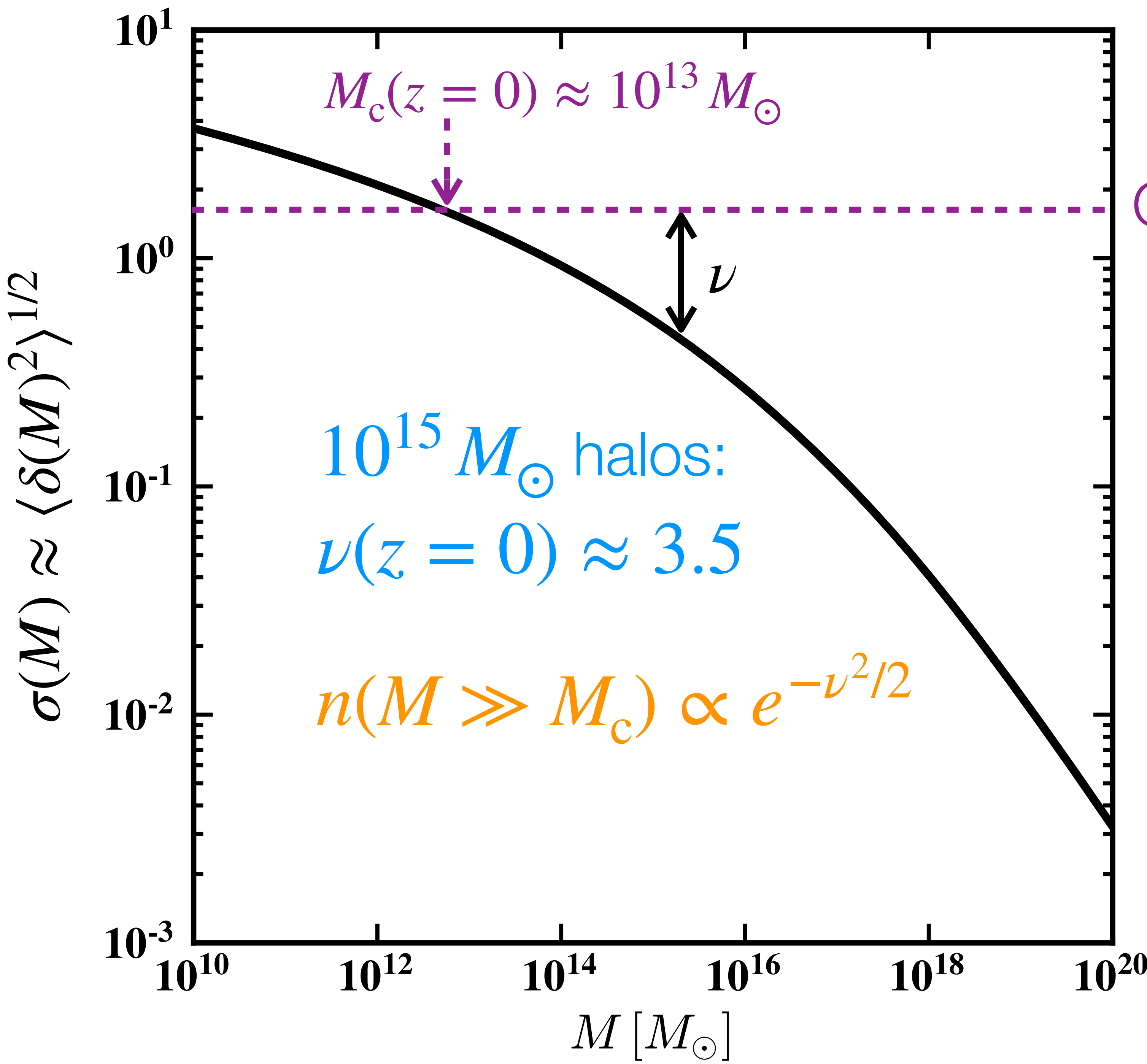

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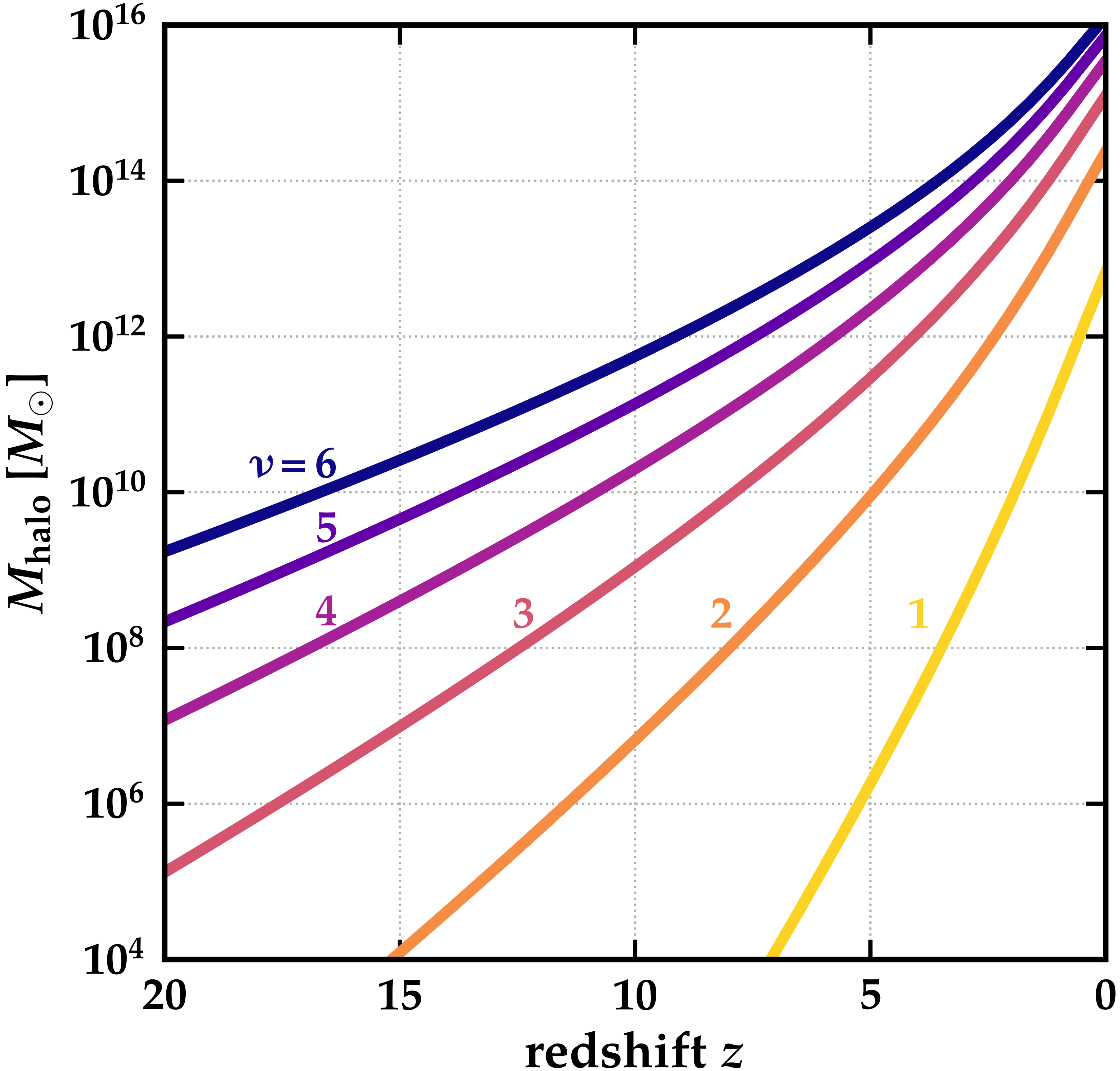
ΛCDM predictions for ***dark matter halos***

$\rho_b, \rho_c, n_s, A_s, \theta_\star, \tau \;\rightarrow n(M,z), \rho(>M,z)$



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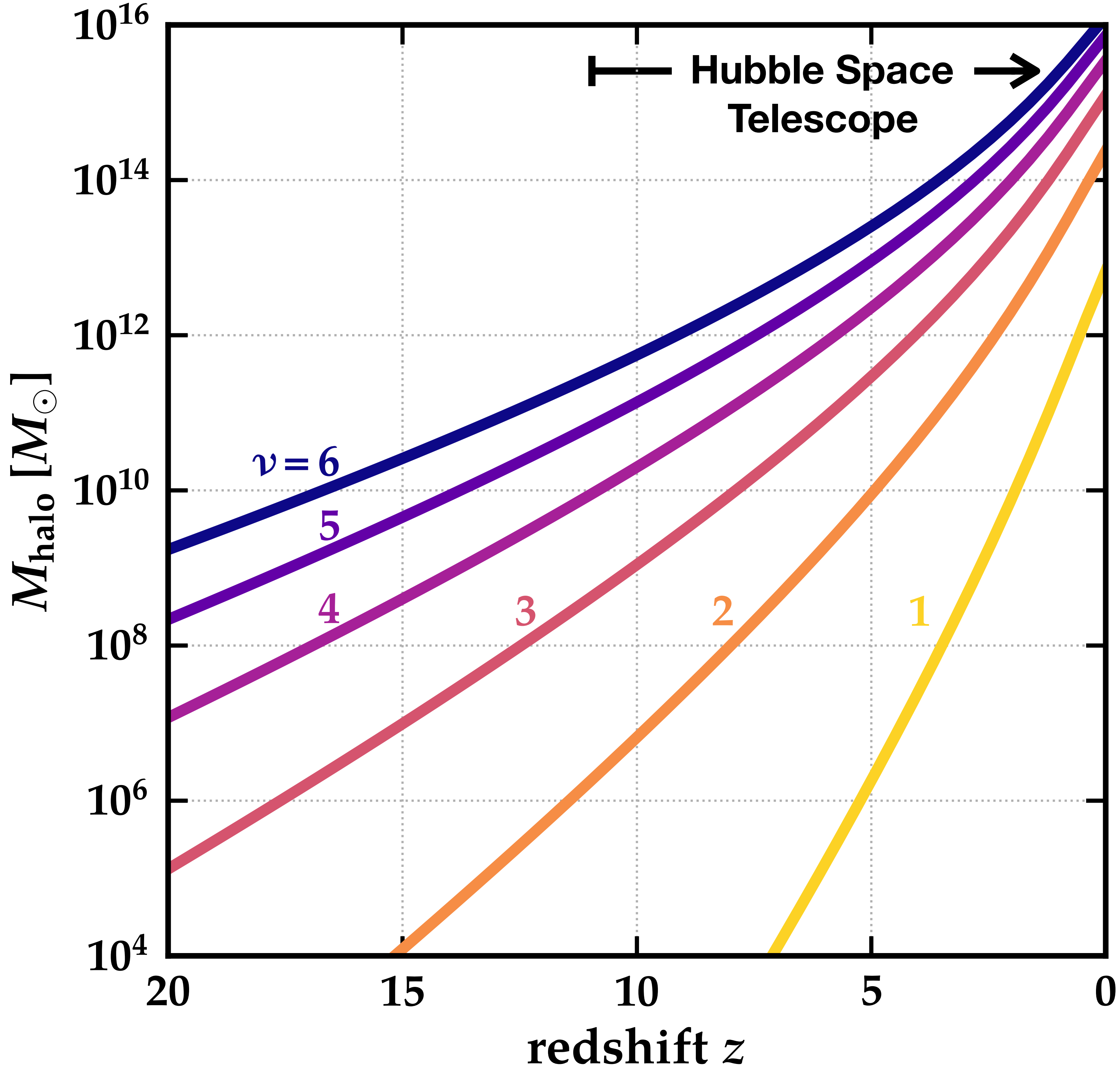

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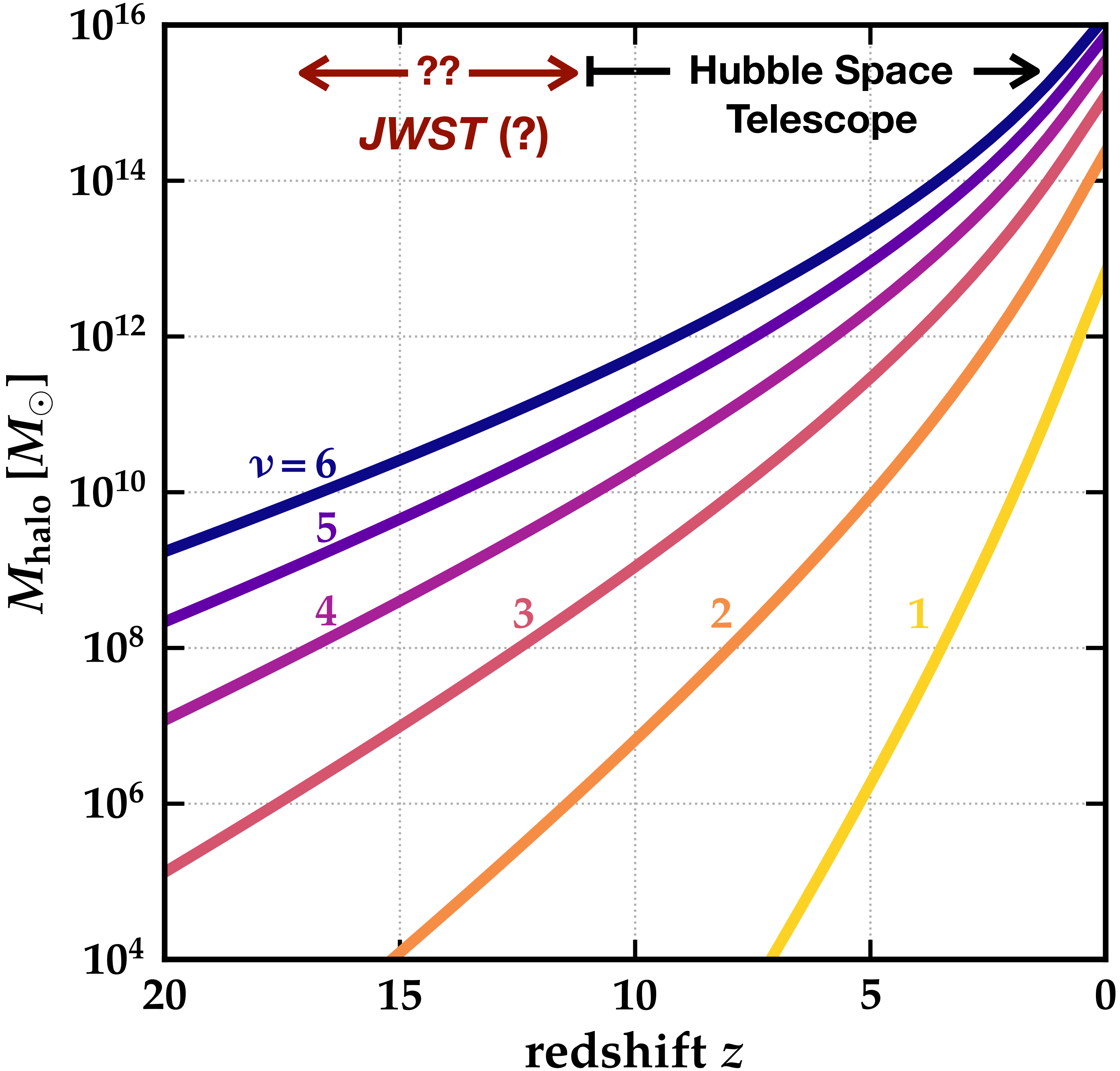
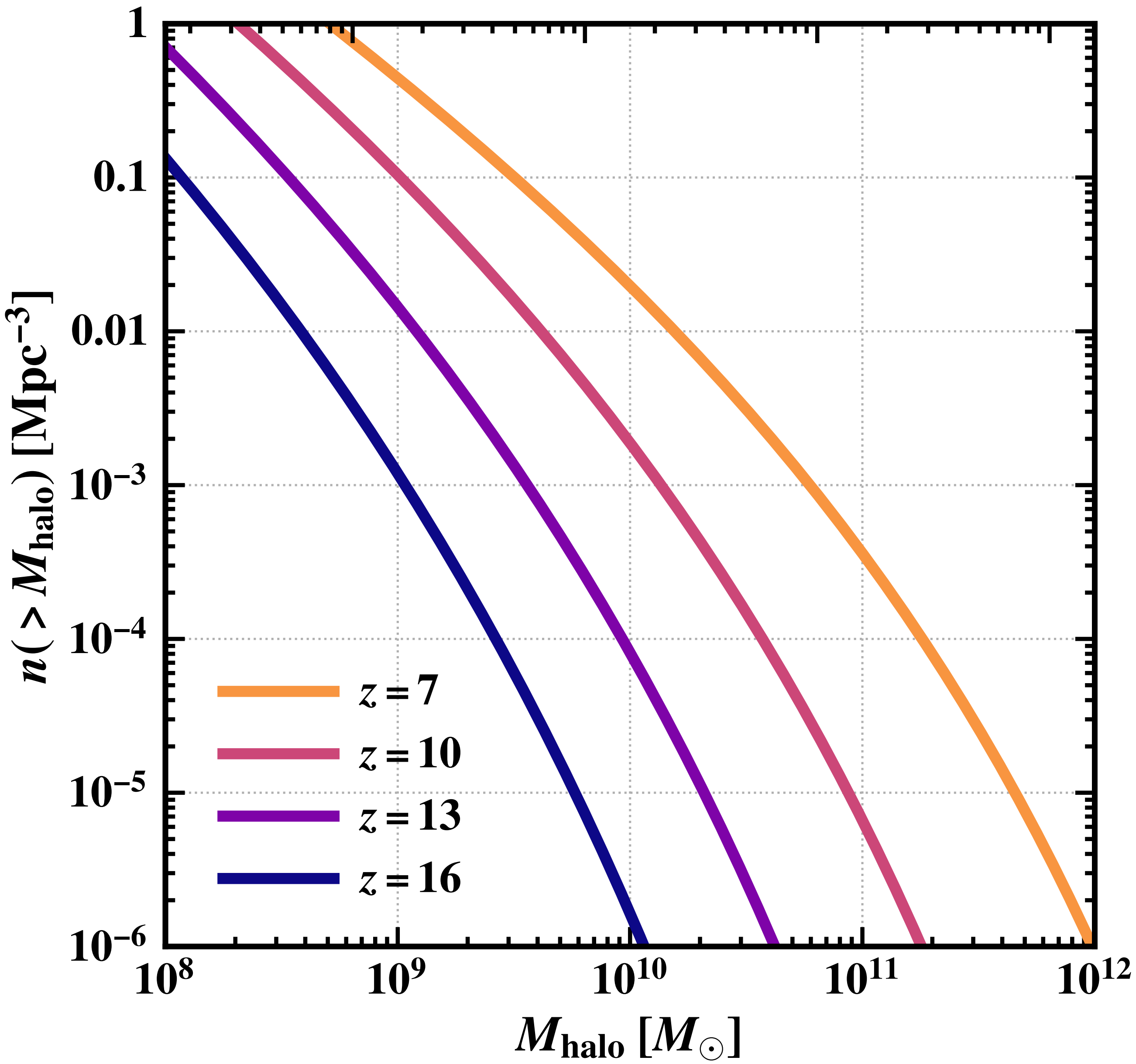


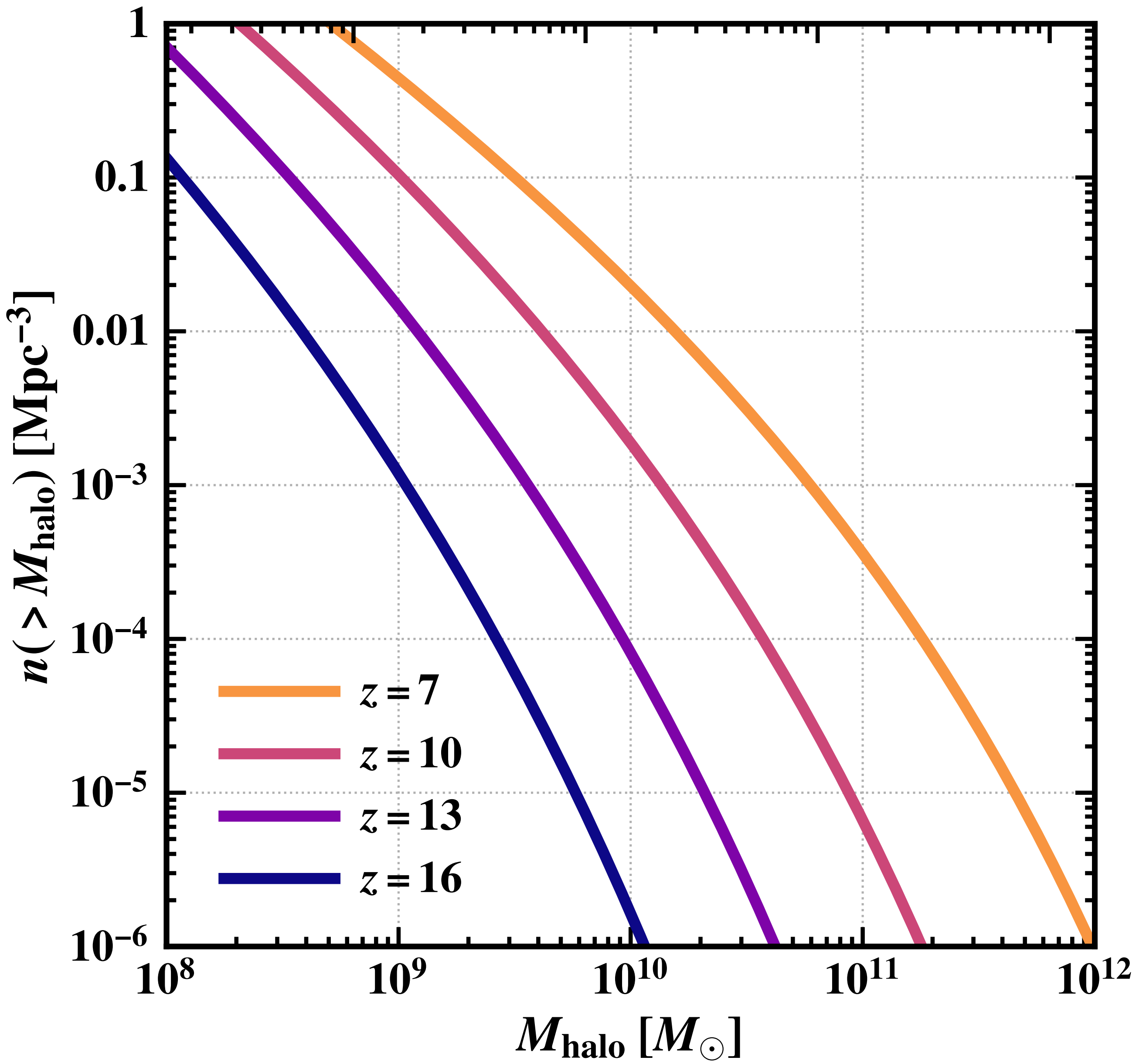
What should we expect with *JWST*?



Boylan-Kolchin 2023

What should we expect with *JWST*?

$$M_{\rm baryon} = \frac{\Omega_{\rm b}}{\Omega_{\rm m}} M_{\rm halo} = f_{\rm b} M_{\rm halo}$$



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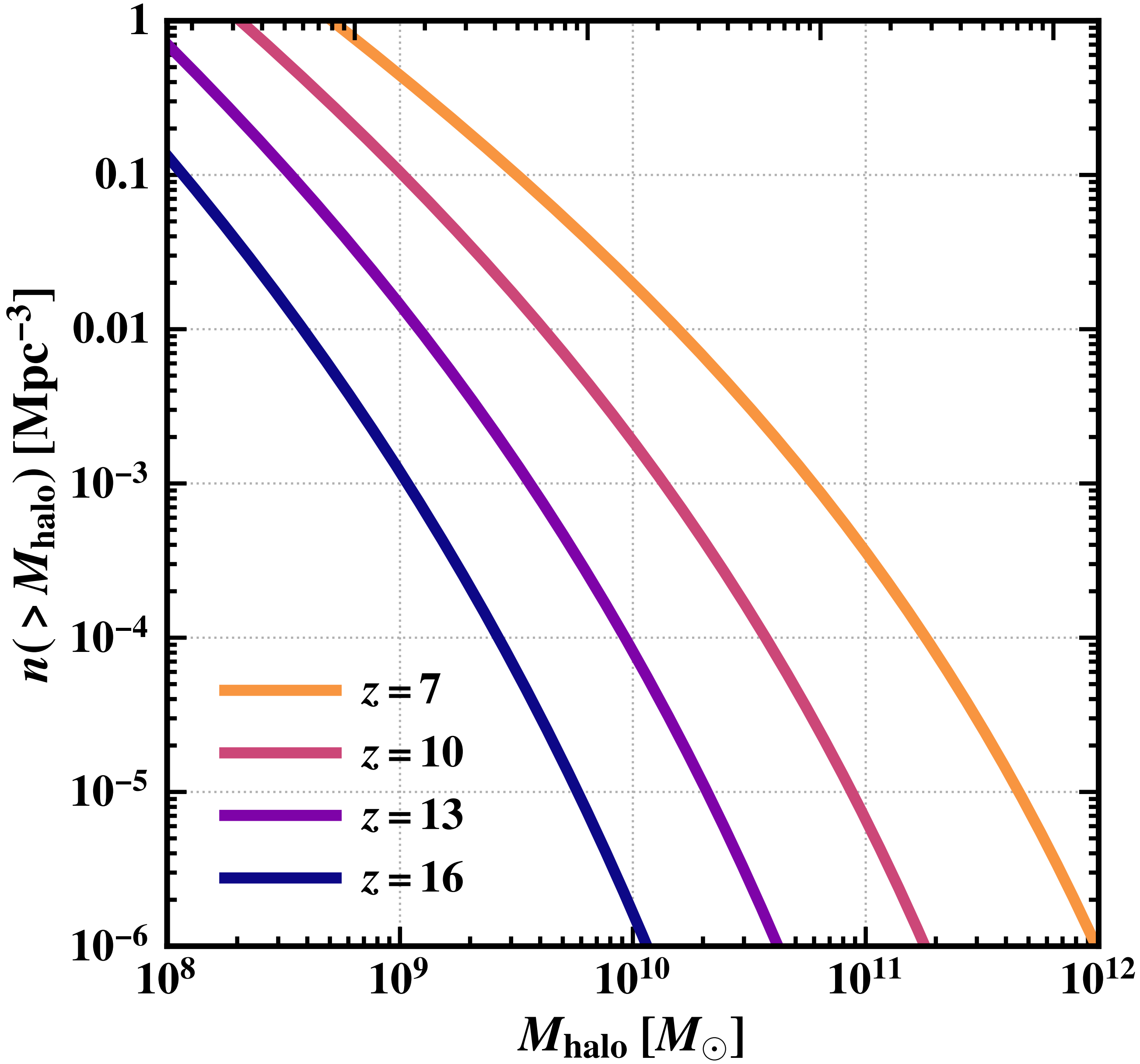

$$M_{\rm baryon} = \frac{\Omega_{\rm b}}{\Omega_{\rm m}} M_{\rm halo} = f_{\rm b} M_{\rm halo}$$

$$M_\star = \epsilon_\star f_{\rm b} M_{\rm halo} \leq M_{\rm baryon}$$

$$\left(\epsilon_\star = \frac{M_\star}{f_{\rm b} M_{\rm halo}} \leq 1\right)$$

star formation efficiency

Boylan-Kolchin 2023

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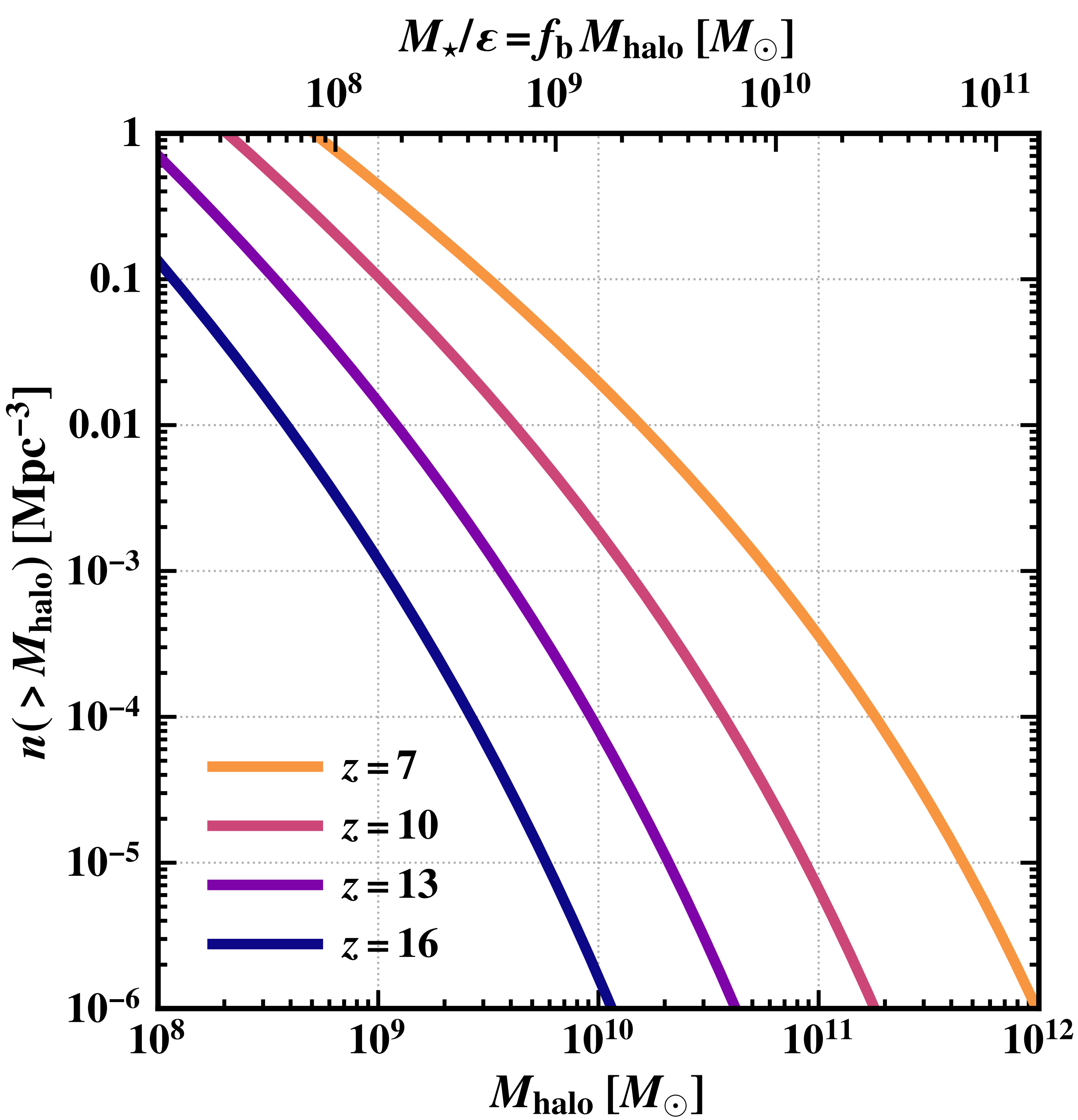


$$M_{baryon} = \frac{\Omega_b}{\Omega_m} M_{halo} = f_b\, M_{halo}$$

$$M_\star = \epsilon_\star f_b\, M_{halo} \le M_{baryon}$$

$$\left(\epsilon_\star = \frac{M_\star}{f_b\, M_{halo}} \le 1\right)$$

star formation efficiency

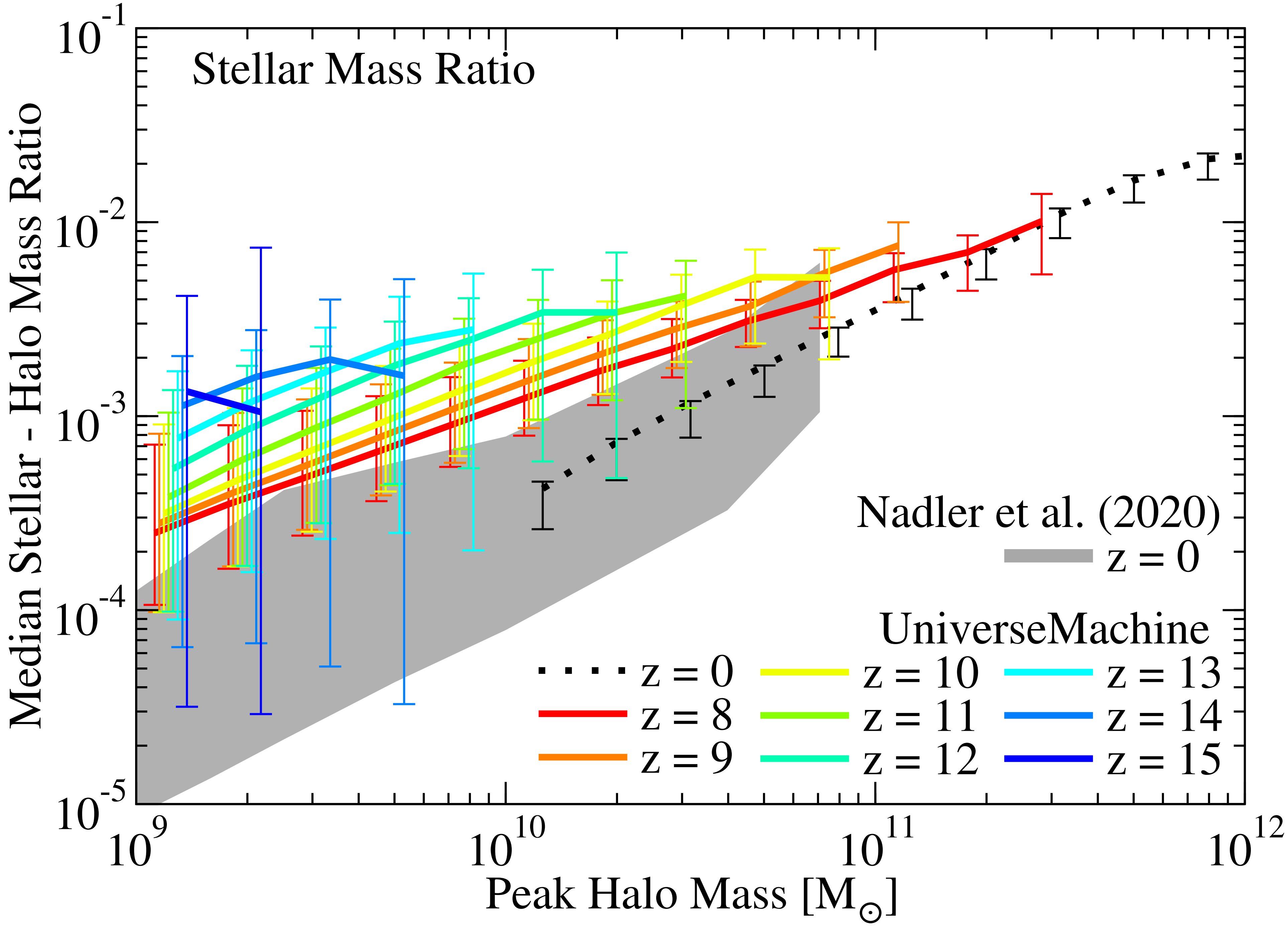
$$M_{halo} \ge \frac{M_\star}{f_b}, \quad M_\star \le f_b\, M_{halo}$$

$$\rho_\star(>M_\star) \le f_b\, \rho_m(>M_\star/f_b)$$

Boylan-Kolchin 2023

Expectations for $\epsilon_\star$: galaxy formation is **inefficient**

$$f_b = \frac{\Omega_b}{\Omega_m} \qquad \epsilon_\star = \frac{M_\star}{f_b\, M_{halo}} \leq 1$$



Behroozi et al. 2020

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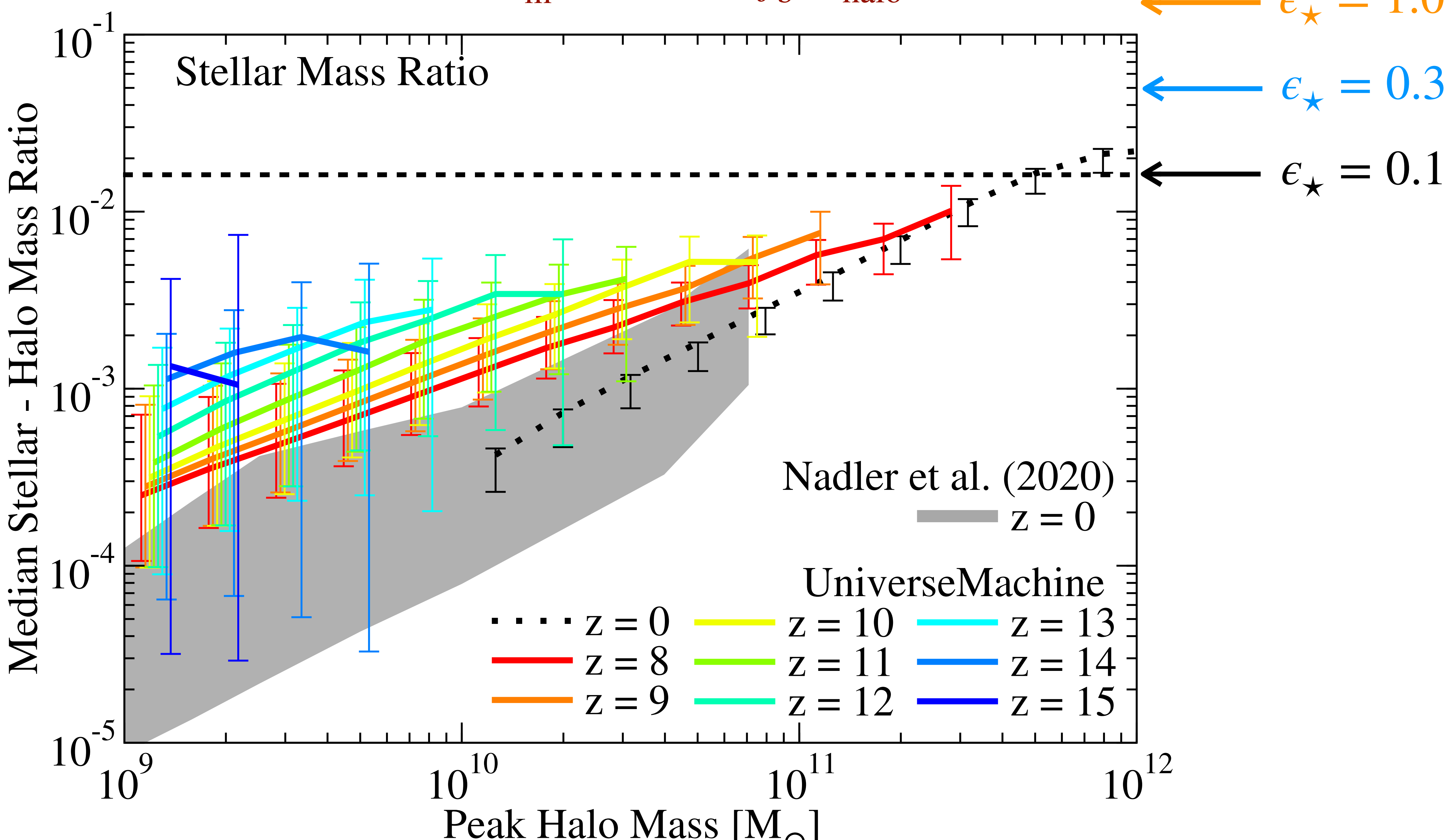
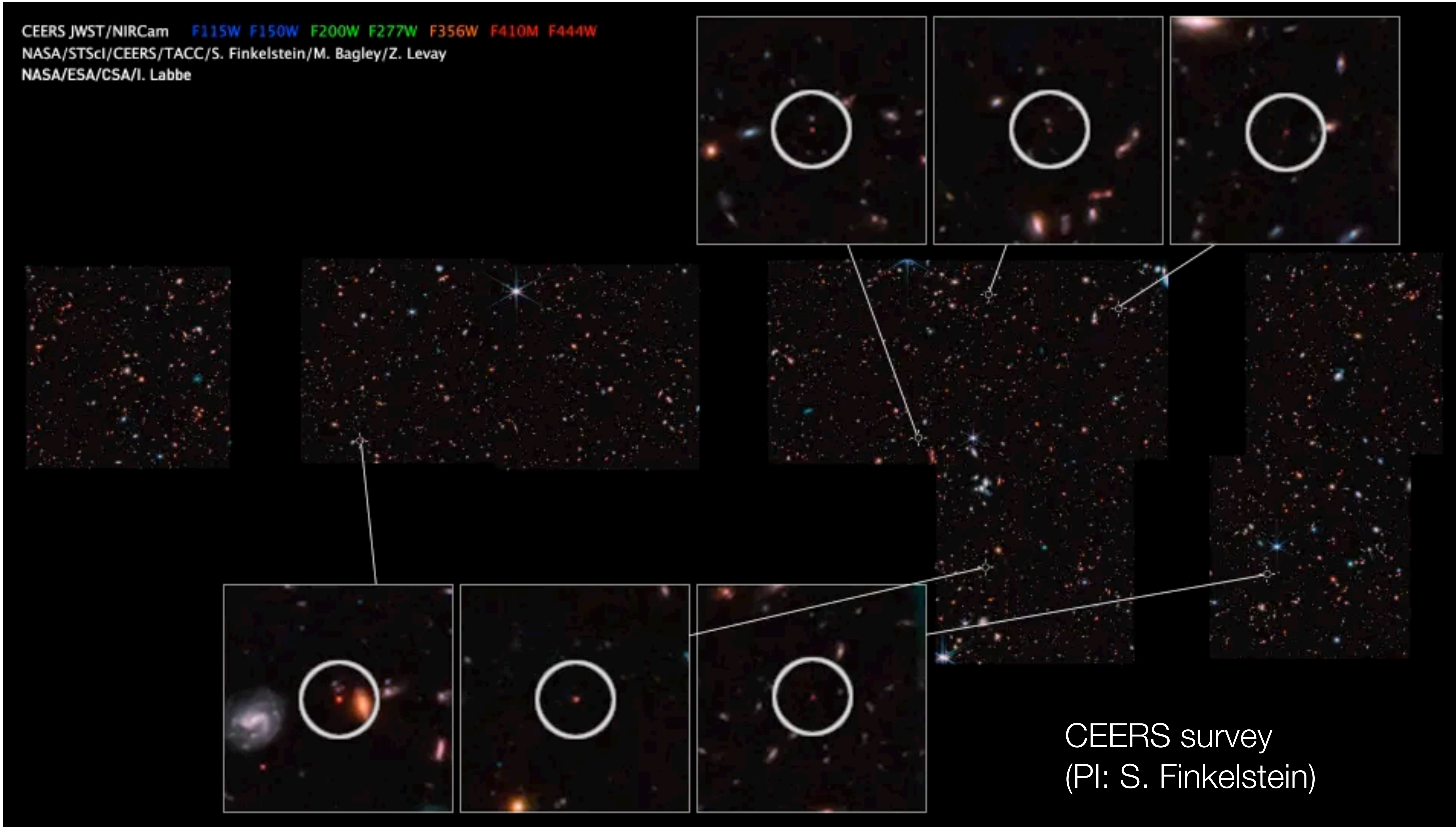


Behroozi et al. 2020

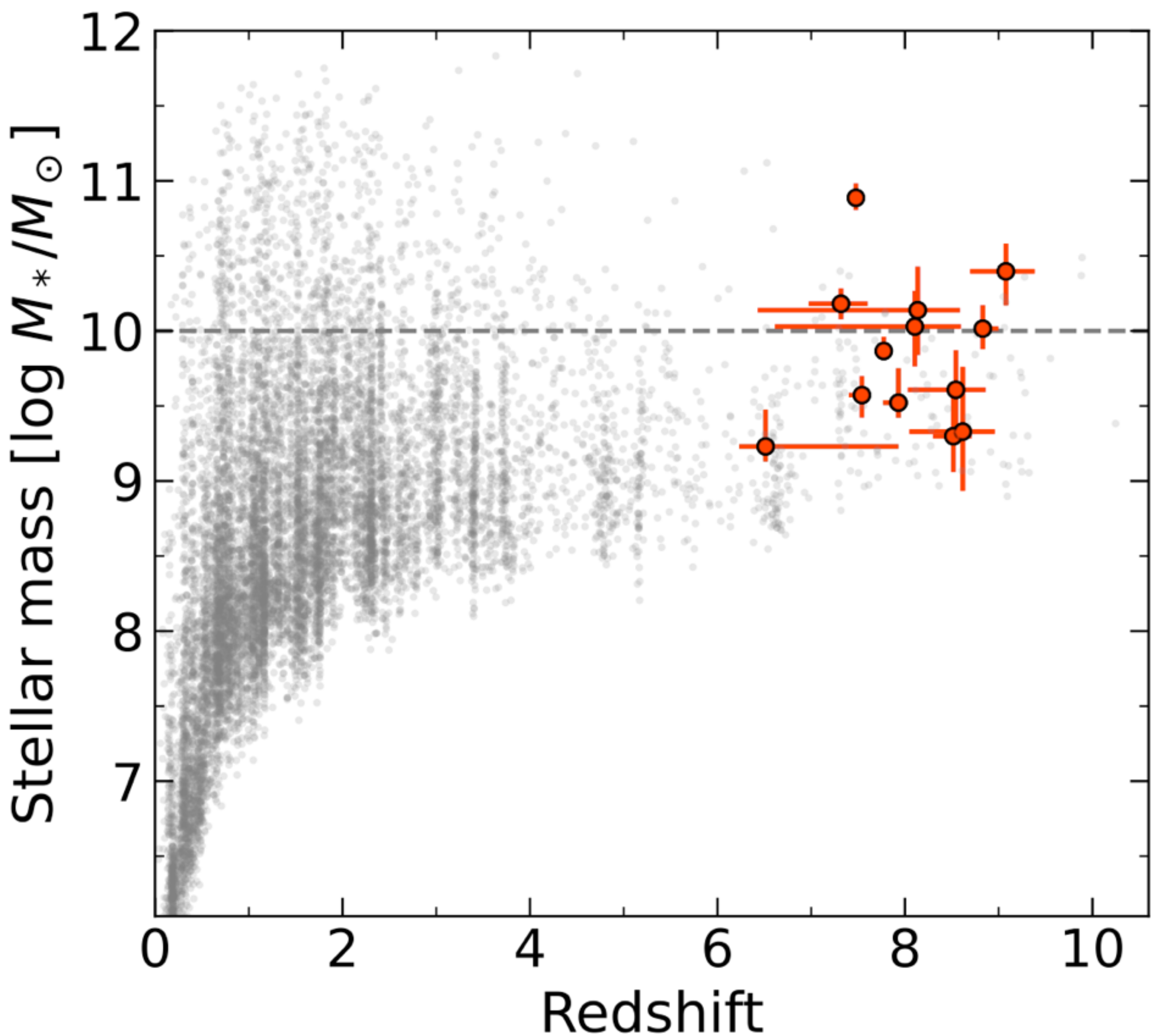
First results from *JWST*: galaxies everywhere



CEERS survey
(PI: S. Finkelstein)

First results from *JWST*: massive early galaxies

Galaxy candidates with $M_\star \approx 10^{10-11}\, M_\odot$ at $z \sim 8 - 10$ from CEERS



Labbé et al. 2023

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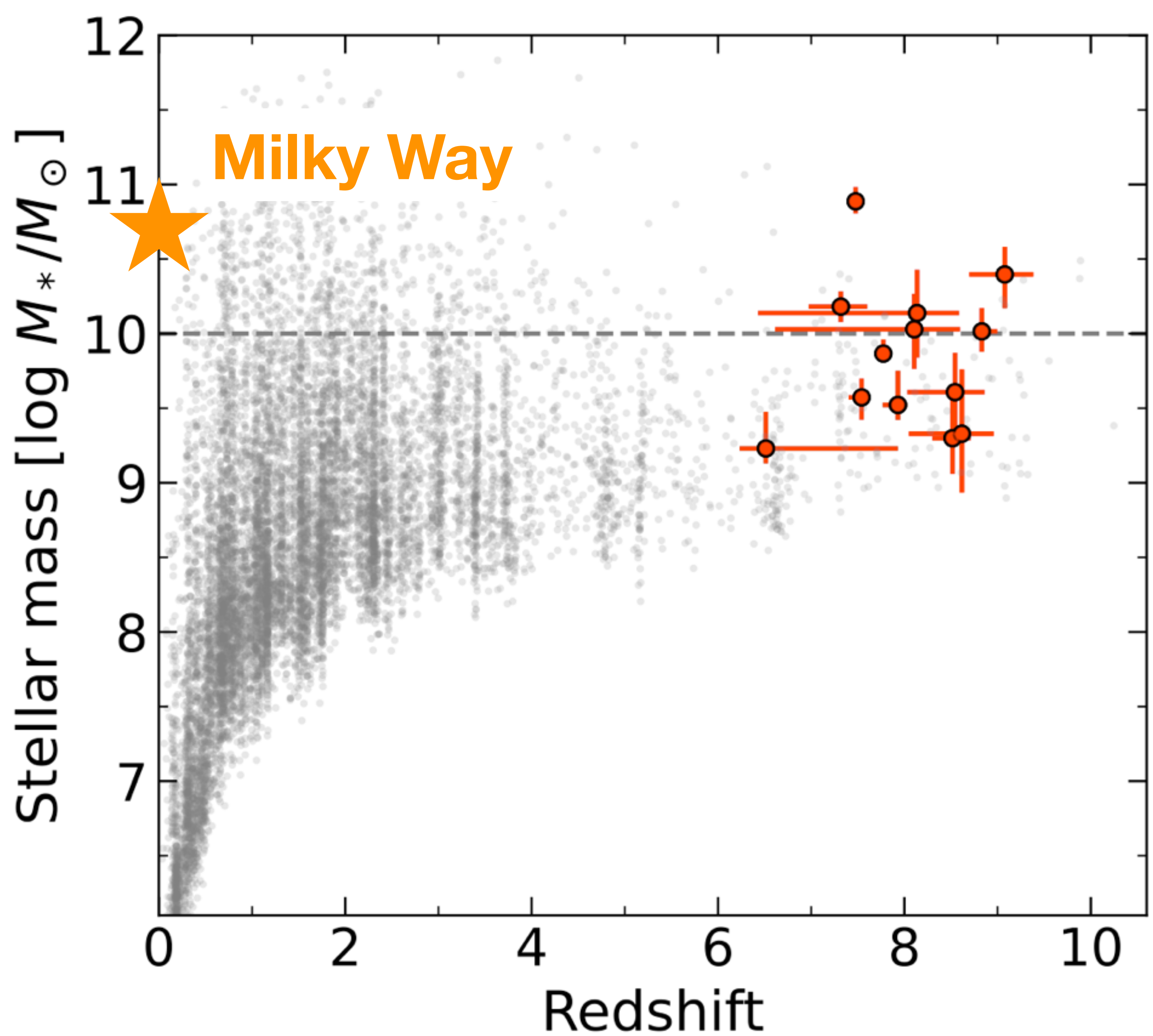

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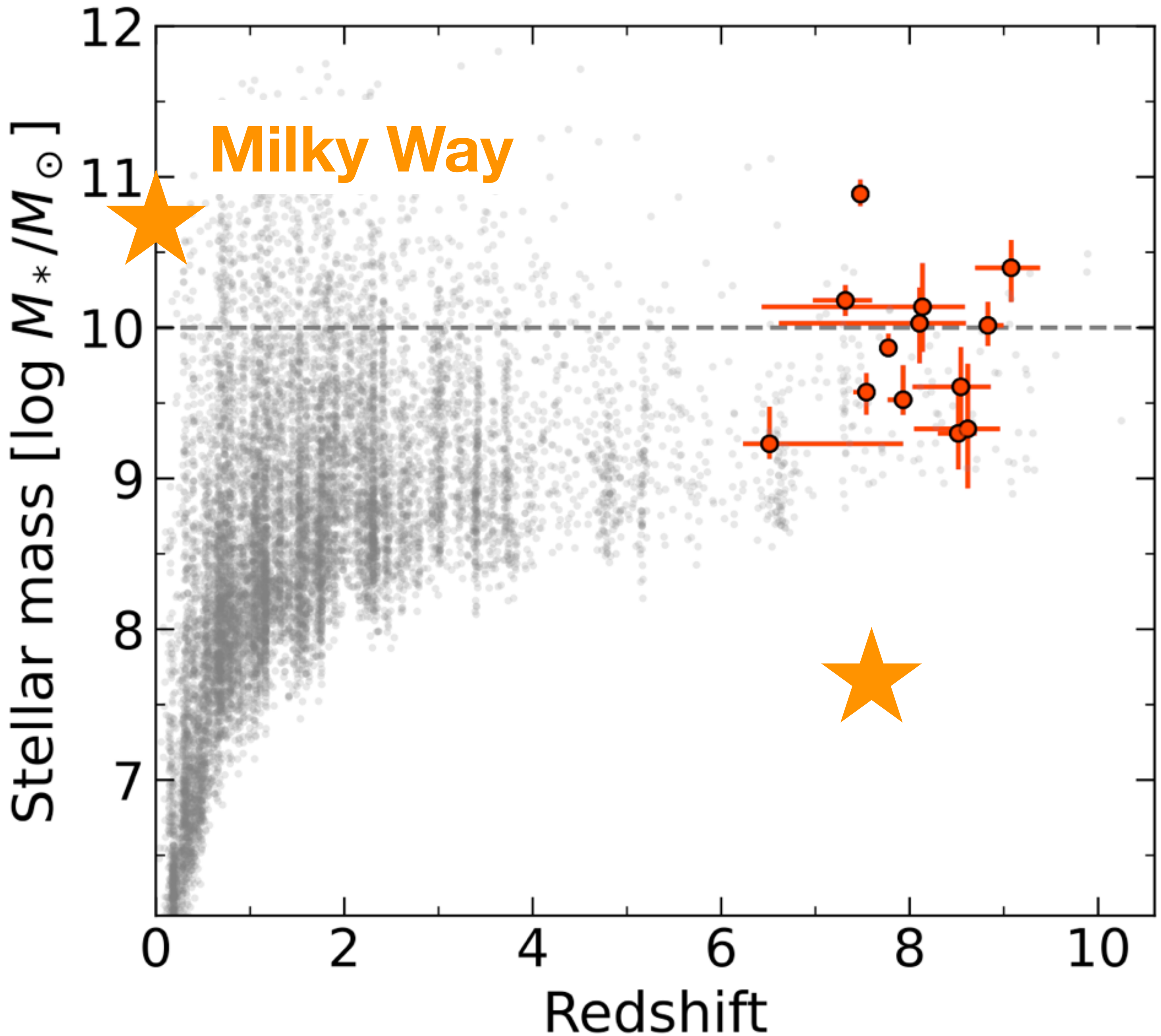
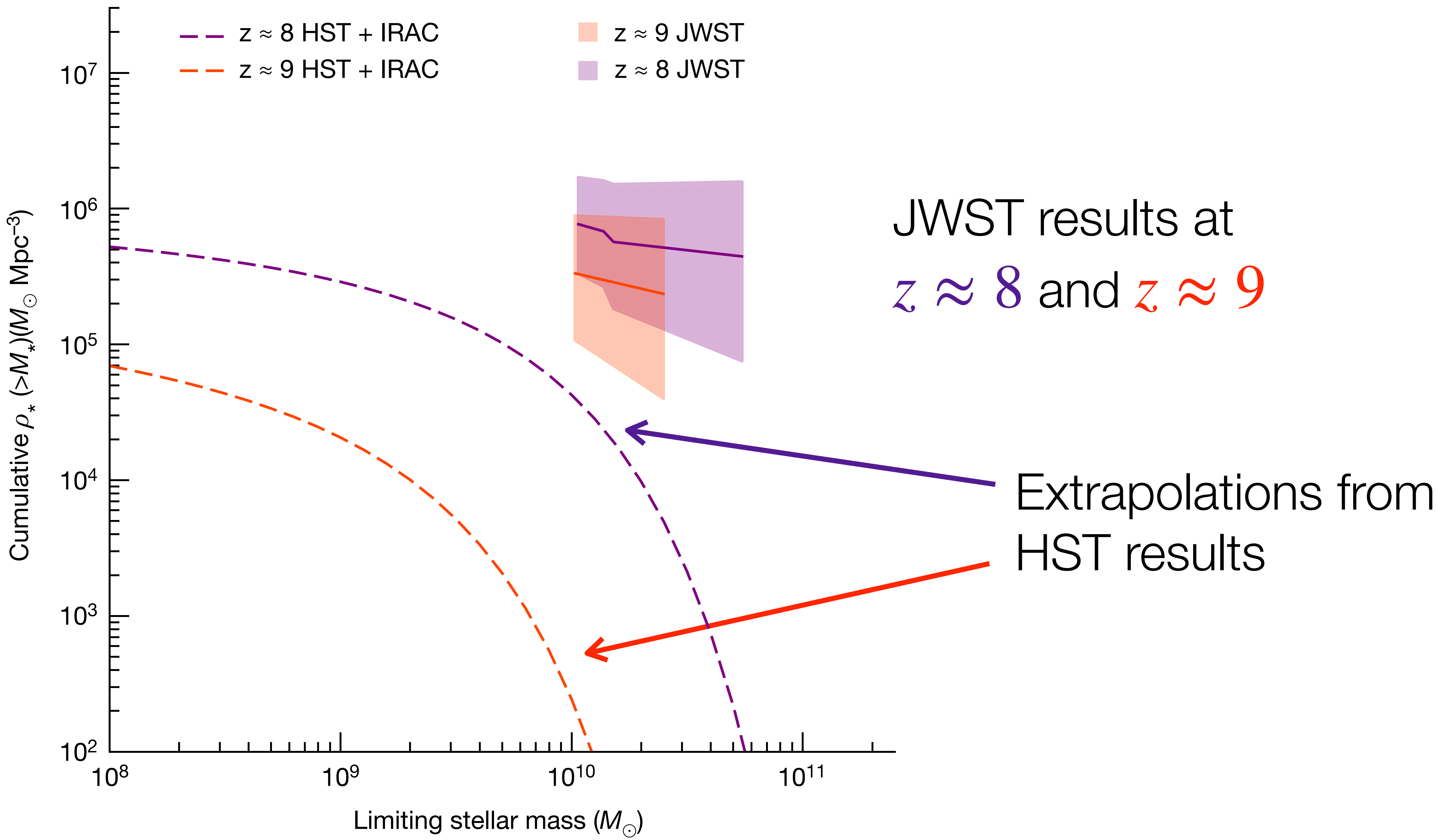


Labbé et al. 2023

First results from *JWST*: massive early galaxies

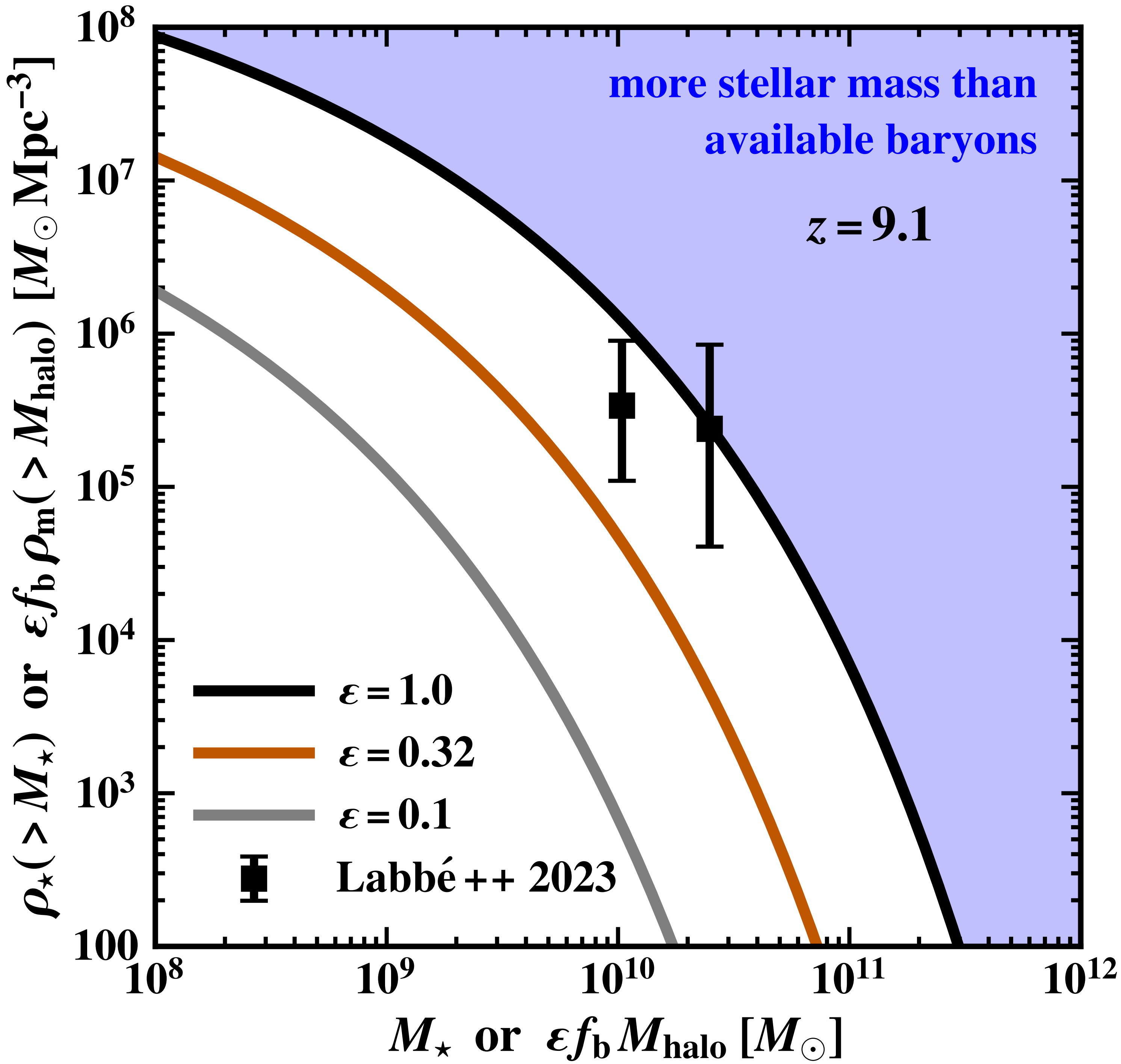
Galaxies with $M_\star \approx 10^{10-11}\, M_\odot$ at $z \sim 8 - 10$ imply *thousands* of times more stars per unit volume than expected based on *HST* results



Labbé et al. 2023

Massive early galaxies: in tension with ΛCDM

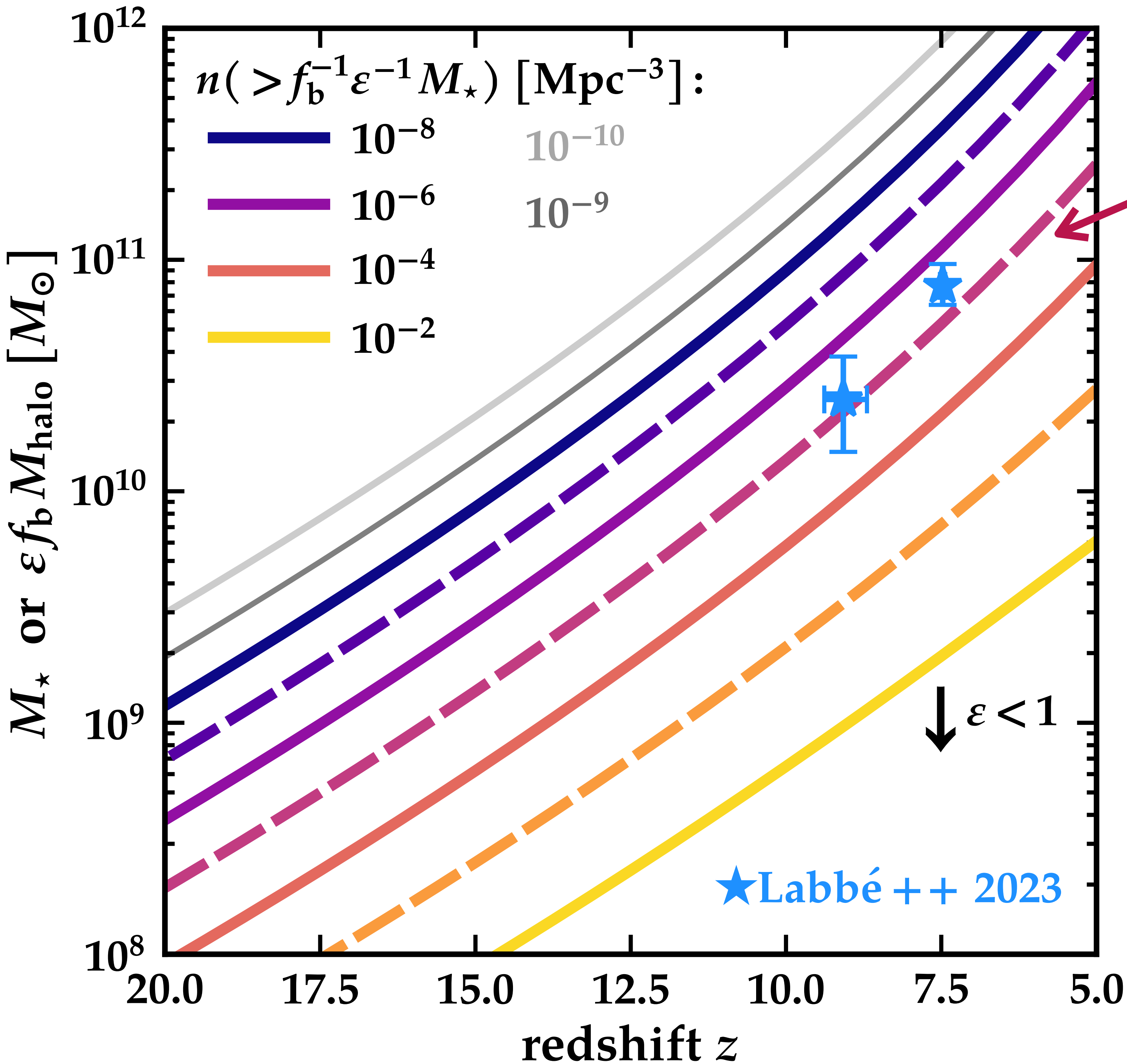
Uh oh: require *all* available baryons in the halo to be converted into stars in ΛCDM (i.e., $\epsilon_\star \approx 1$). *Note*: at $z = 0, \langle \epsilon_\star \rangle \lesssim 0.2$ at all halo masses



similar result at $z \approx 7.5$

Boylan-Kolchin 2023
arXiv:2208.01611

The implied dark matter hosts are *very* rare



n [Mpc^{-3}] :

$\approx 10^{-5}$ ($\epsilon = 1$),

$\approx 10^{-7}$ ($\epsilon = 0.32$), or

$\approx 10^{-9}$ ($\epsilon = 0.1$)

Survey volume:

38 arcmin^2 $\approx 10^5$ Mpc^3

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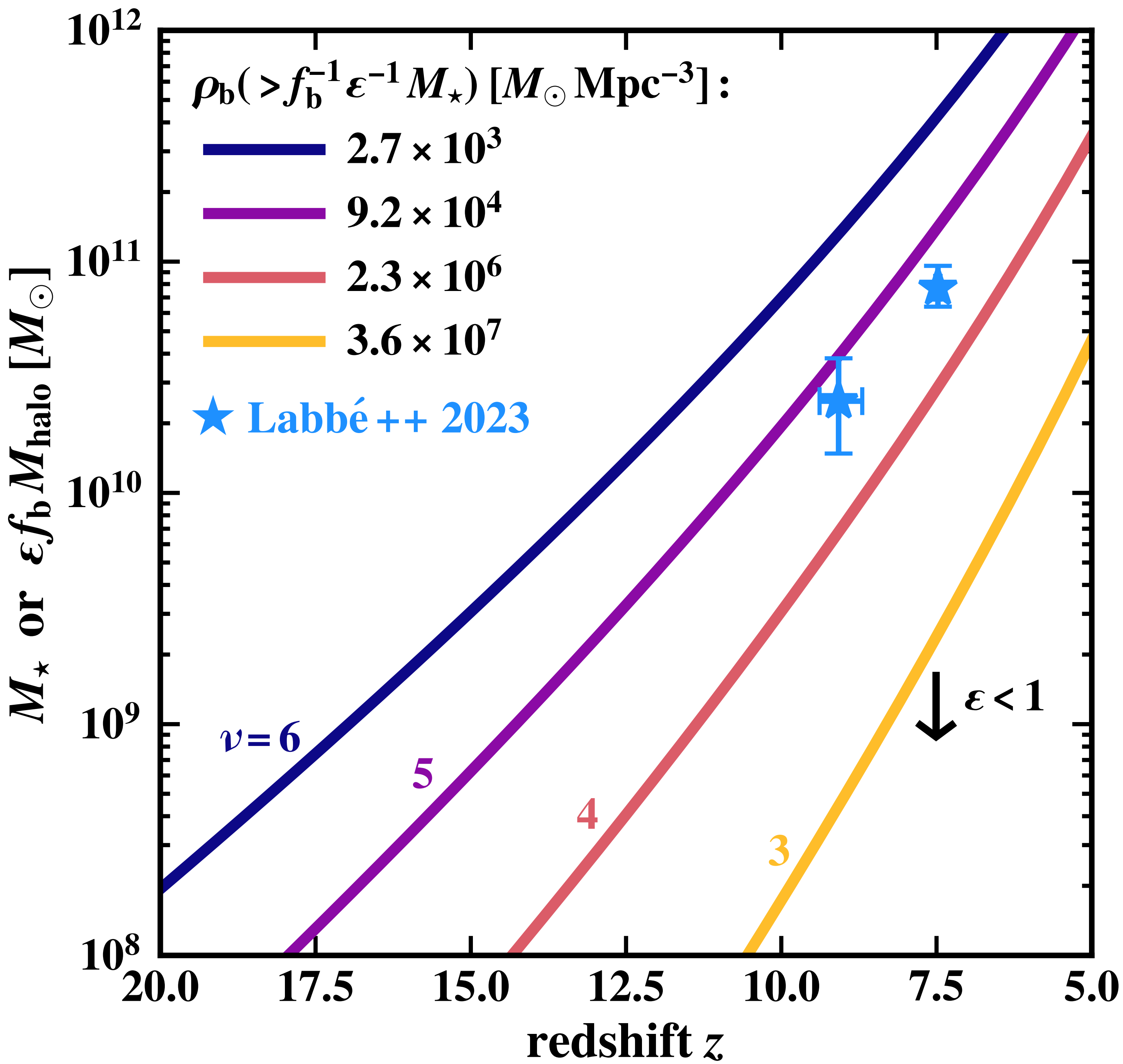

Find implied peak heights of

$$\nu \approx 4.5 \quad (\epsilon = 1),$$
$$\nu \approx 5.4 \quad (\epsilon = 0.32), \text{ or}$$
$$\nu \approx 6.4 \quad (\epsilon = 0.1)$$

$$\nu \approx 4.5 \longleftrightarrow M_{halo}(z=0) \approx 5\times10^{15}\,M_\odot$$

Survey volume:

38 arcmin^2 $\approx 10^5$ Mpc^3

Boylan-Kolchin 2023
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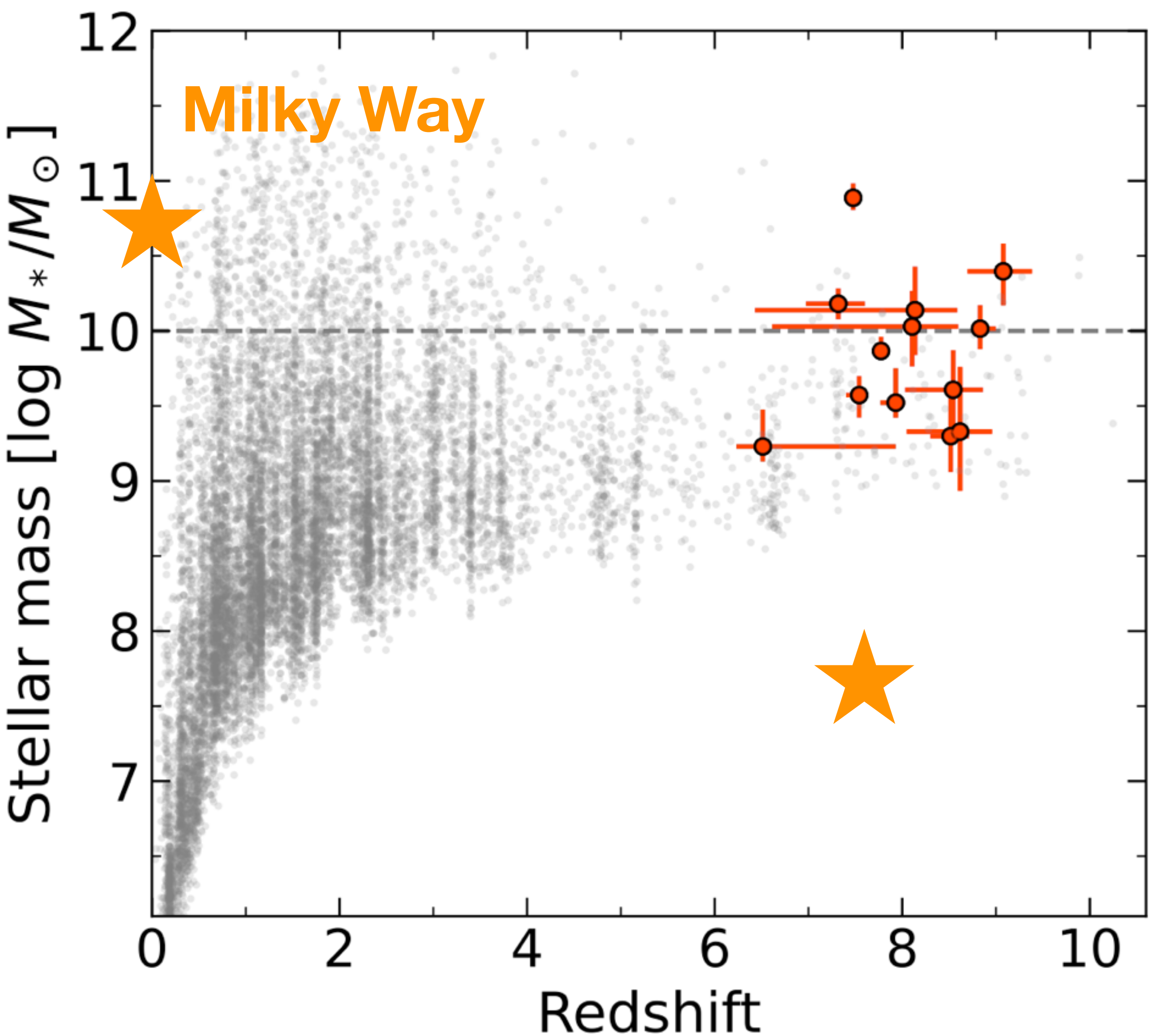
JWST: massive early galaxies at early cosmic times

Galaxy candidates with $M_\star \approx 10^{10.5-11}\,M_\odot$ at $z \sim 8-10$ from CEERS



Labbé et al. 2023

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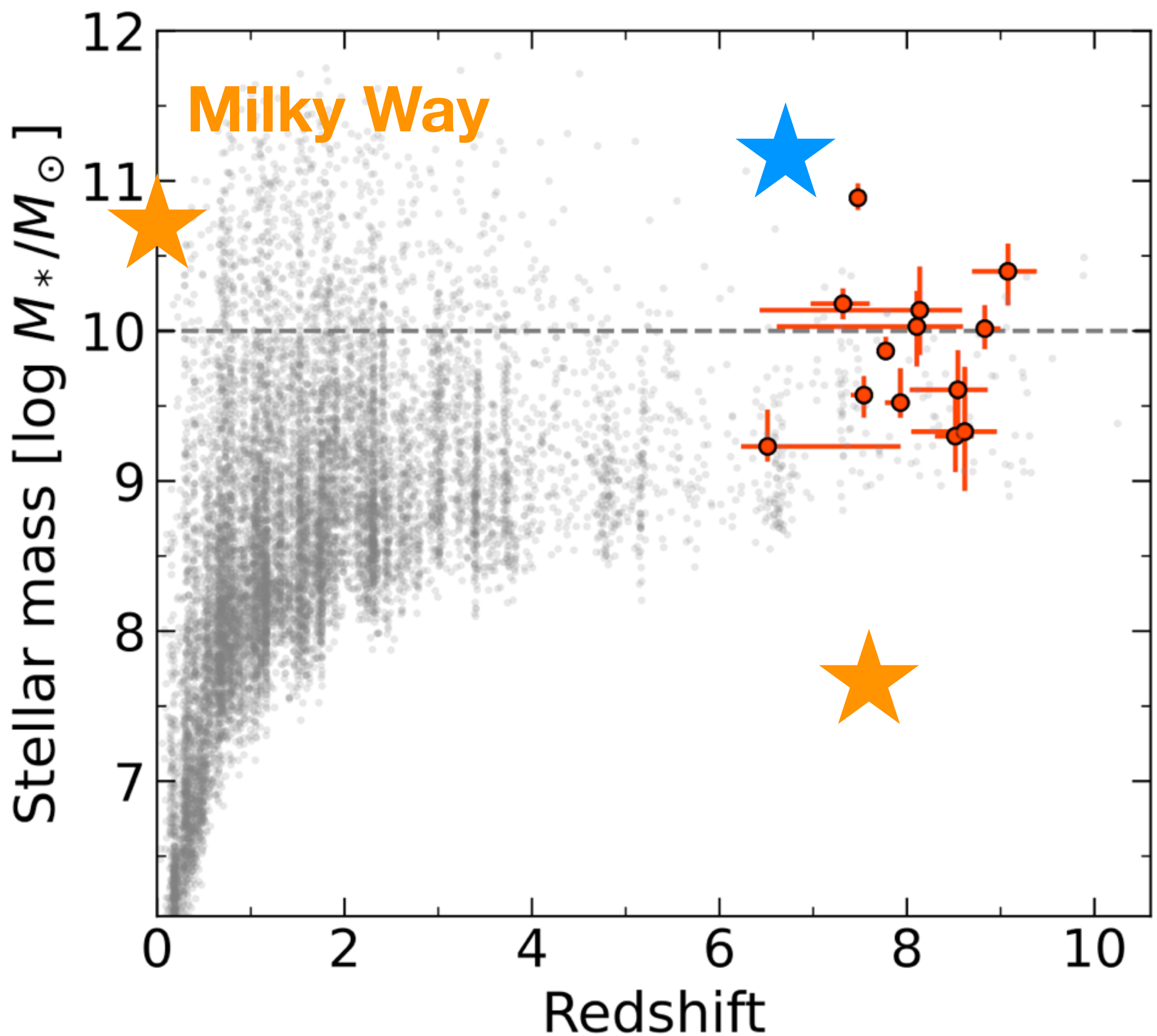

Labbé et al. 2023

HST+ALMA-detected galaxy at z=6.83 with:

$M_\star = 1.7 \times 10^{11}\, M_\odot$

$M_{\rm BH} \approx 1.5 \times 10^9\, M_\odot$

$\dot{M}_\star \approx 1300\, M_\odot\, {\rm yr}^{-1}$

Endsley et al. 2023

Too many stars too early in JWST data?

Problem: this means **all available baryons** throughout the halo must have been **converted into stars** in the standard ΛCDM cosmology

Implications: either the inferred **galaxy properties are wrong** (AGN "contamination"?), the observed portion of the Universe is **very atypical**, or there is an issue with our successful **cosmological model**

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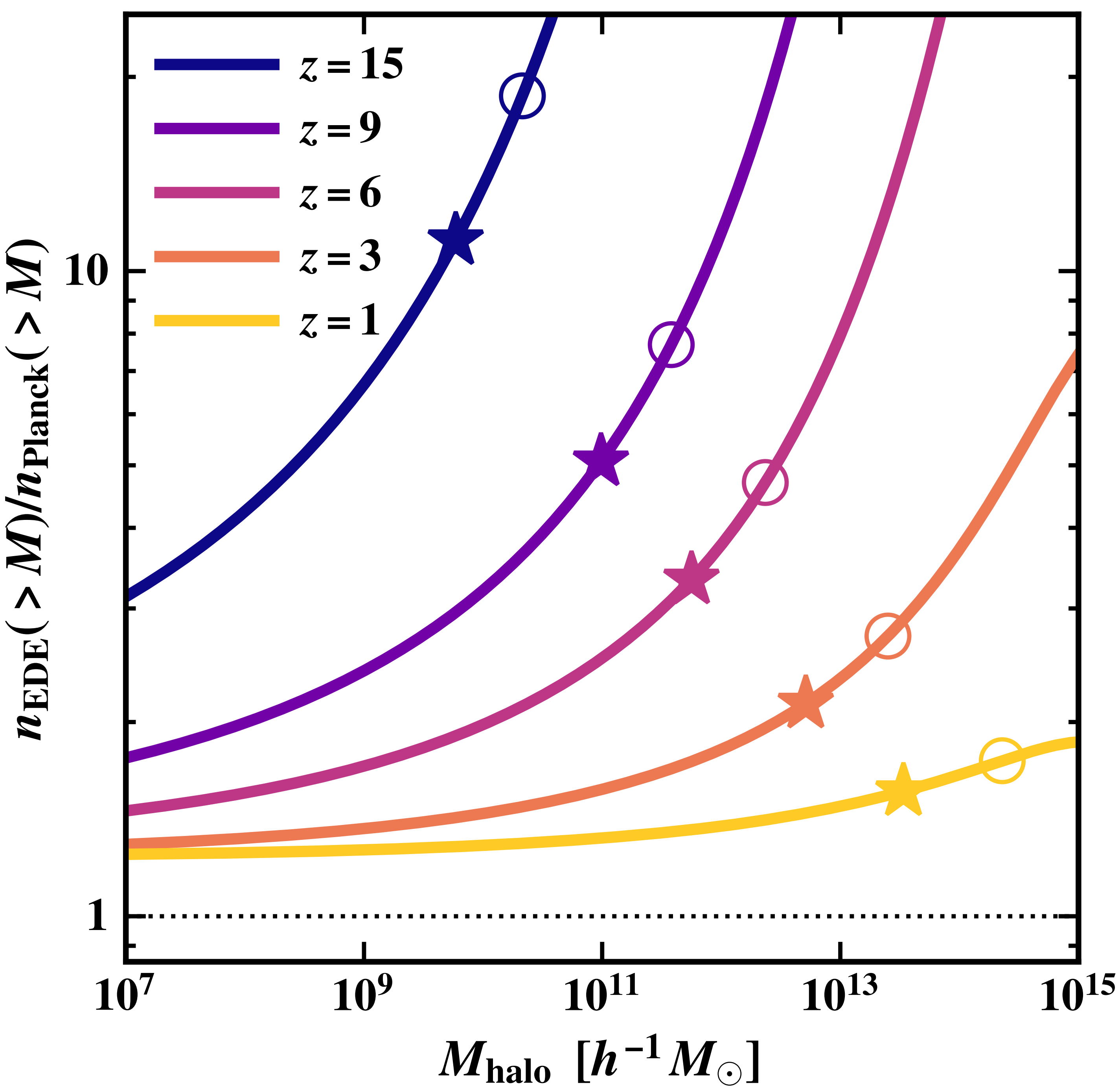
Implications: either the inferred **galaxy properties are wrong** (AGN "contamination"?), the observed portion of the Universe is **very atypical**, or there is an issue with our successful **cosmological model**

***If* it is a cosmology issue**: need more (faster) formation of cosmological structure at early times. **No wiggle room in base ΛCDM** — all parameters are known to $\lesssim 1\,\%$ precision. What about extensions?

- need higher ρ_m, σ_8, and/or n_s
- a small(ish) possible modification: a short period of **early dark energy** with $\Omega_\mathrm{EDE} \sim 0.1$ at $z \sim 3500$
  (Karwal++ 2016; Poulin++ 2018, 2019; Smith++ 2020, Riess & Kamionkowski 2022)

EDE leads to enhanced high-z structure formation

higher $\omega_{\rm m}$, σ_8, & $n_{\rm s}$ than base Planck model: **more high-z galaxies**
(Klypin et al. 2021)



$$n(M \gg M_{\rm c}) \propto e^{-\nu^2/2}$$

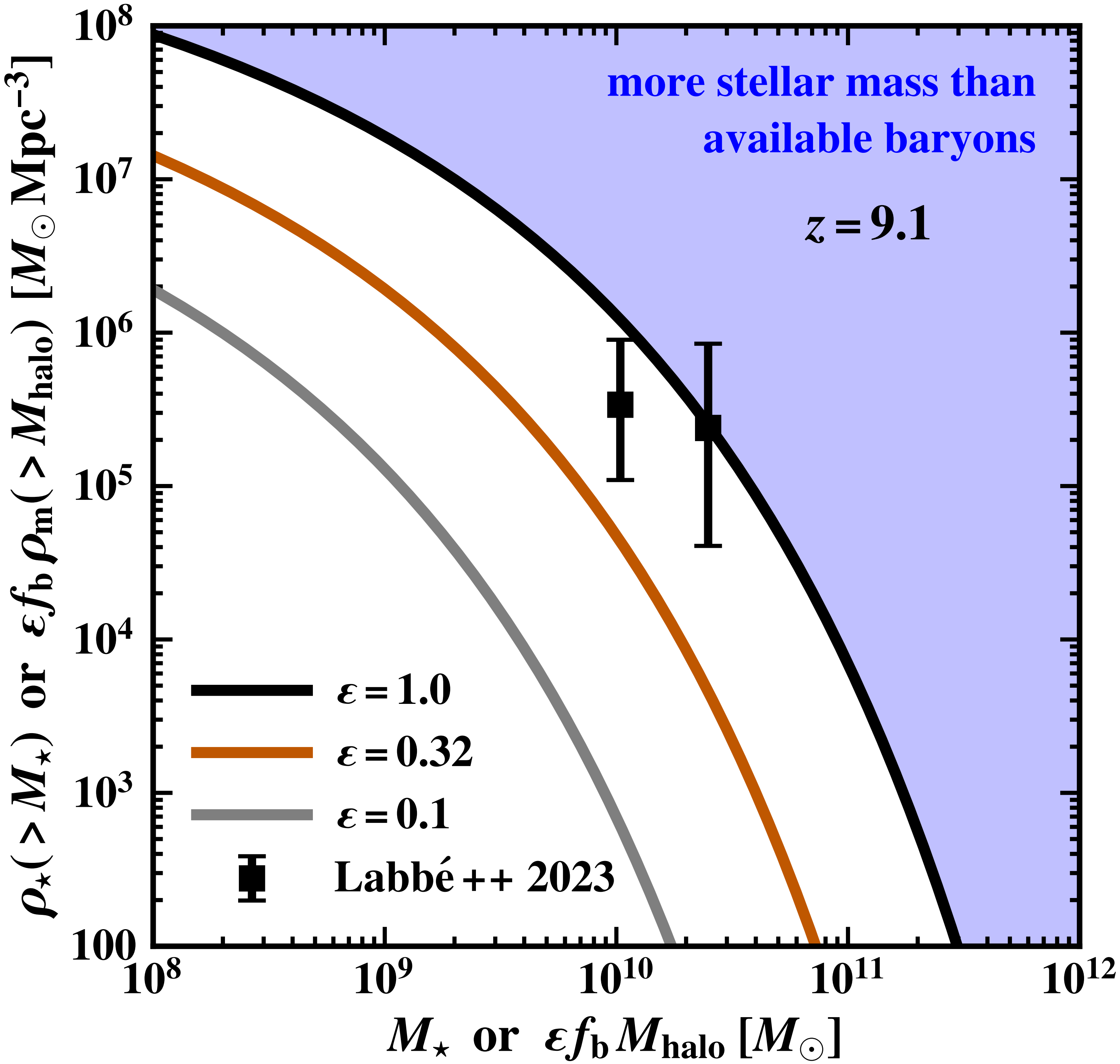
$$\nu = \frac{\delta_{\rm c}}{\sigma(M, z)}$$

○: $n_{\rm Planck}(>M; z) = 10^{-7}\,{\rm Mpc}^{-3}$
(COSMOS-Web)

★: $n_{\rm Planck}(>M; z) = 10^{-5}\,{\rm Mpc}^{-3}$
(CEERS)

EDE leads to enhanced high-z structure formation

requires higher ρ_m, σ_8, & n_s than base Planck model



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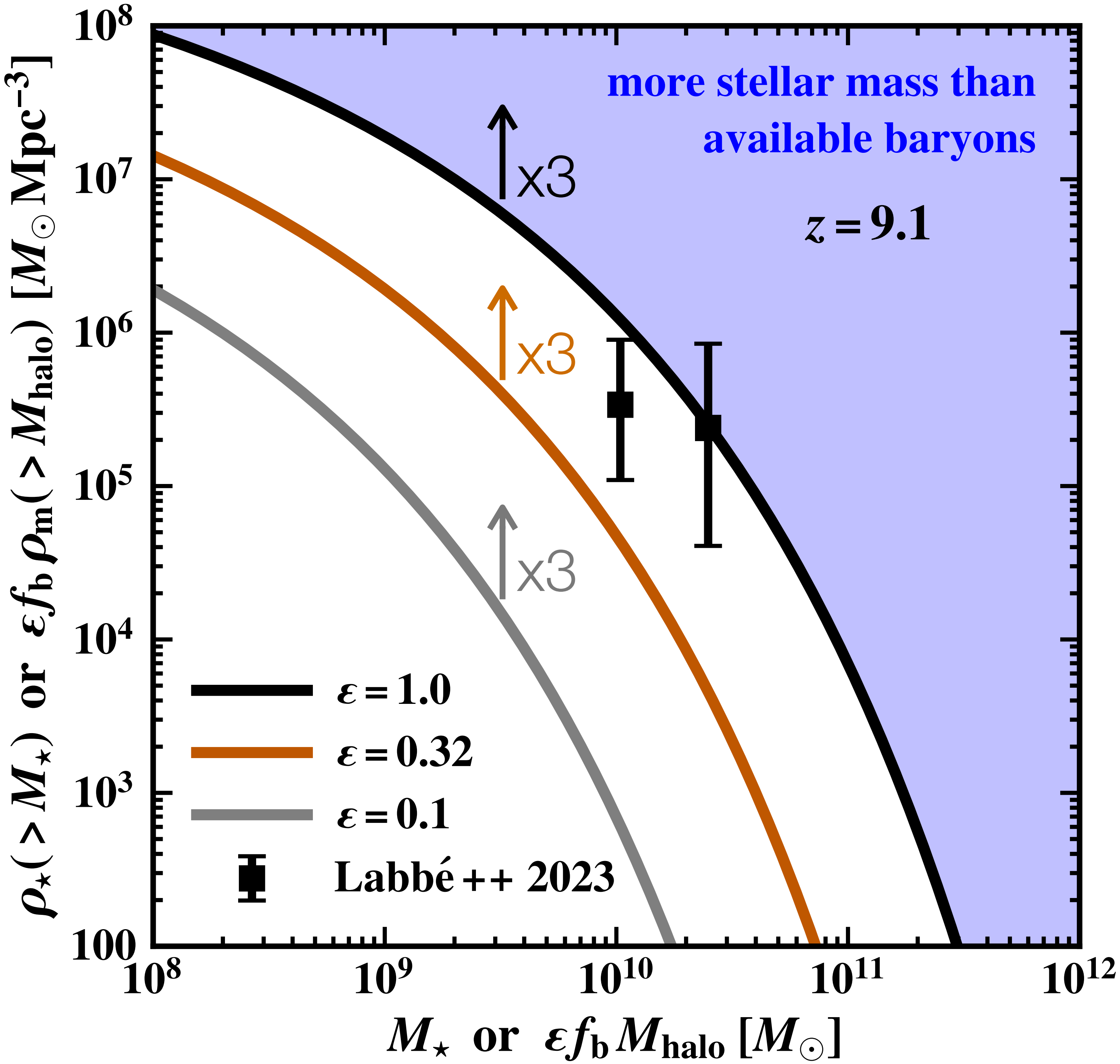

Boylan-Kolchin 2023
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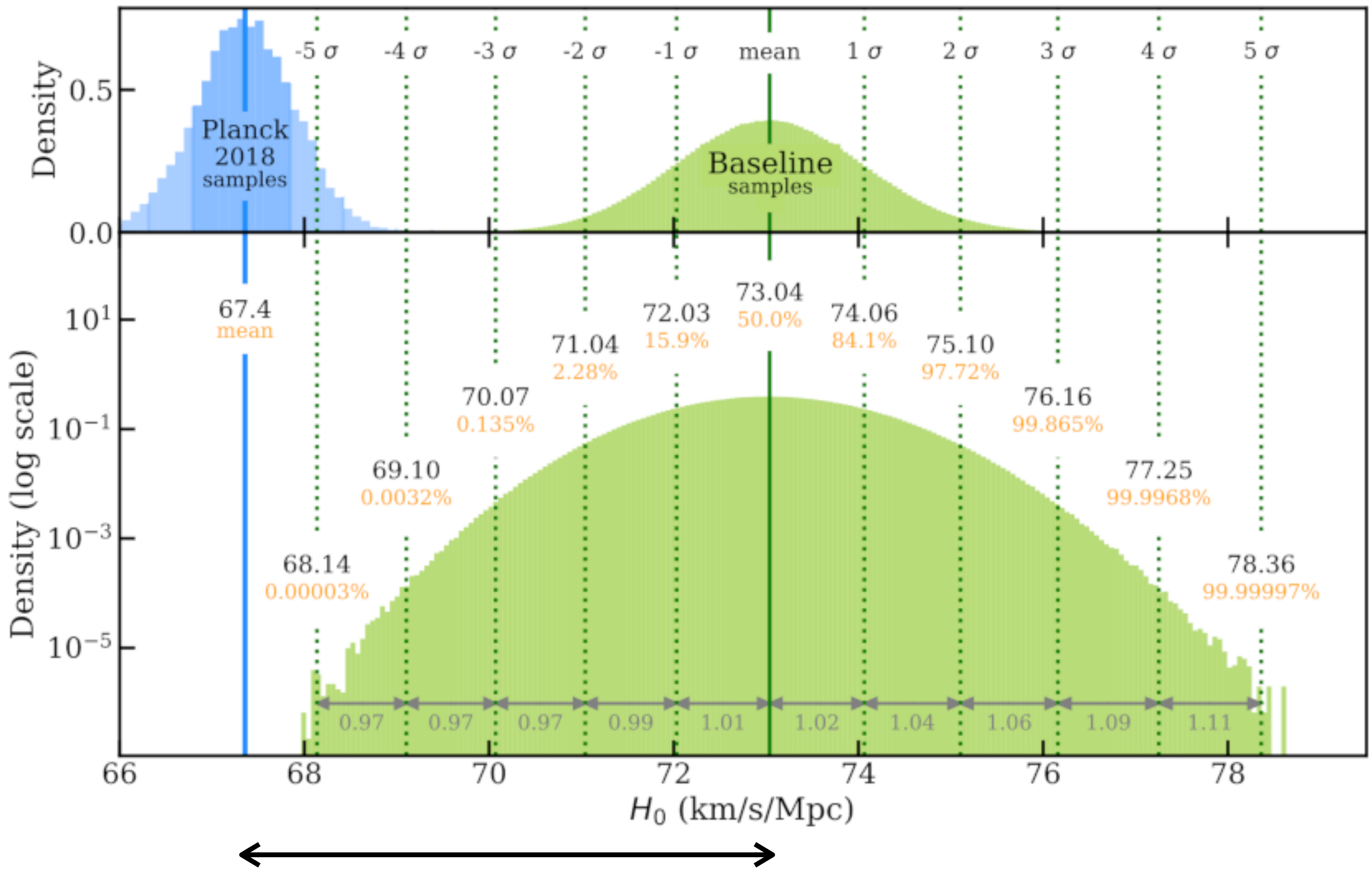
Original motivation for EDE: the Hubble tension

Riess et al. 2022



$> 5\,\sigma$ discrepancy (but see, e.g., Freedman et al.)

Original motivation for EDE: H_0 tension

faster expansion at $z > 1100$ → smaller $r_\star$ → larger H_0

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TRISTAN L. SMITH *et al.* PHYS. REV. D **106,** 043526 (2022)

TABLE I. The mean (best-fit) $\pm 1\sigma$ errors of the cosmological parameters reconstructed in the ΛCDM and EDE models from the analysis of the ACT DR4 + SPT-3G+*Planck* TT650TEEE dataset combination.

Model	ΛCDM	EDE
H_0 [km/s/Mpc]	$68.02(67.81)^{+0.64}_{-0.6}$	$74.2(74.83)^{+1.9}_{-2.1}$
$100\omega_b$	$2.253(2.249)^{+0.014}_{-0.013}$	$2.279(2.278)^{+0.018}_{-0.02}$
$\omega_{\rm cdm}$	$0.1186(0.1191)^{+0.0014}_{-0.0015}$	$0.1356(0.1372)^{+0.0053}_{-0.0059}$
$10^9 A_s$	$2.088(2.092)^{+0.035}_{-0.033}$	$2.145(2.146)^{+0.041}_{-0.04}$
n_s	$0.9764(0.9747)^{+0.0046}_{-0.0047}$	$1.001(1.003)^{+0.0091}_{-0.0096}$
$\tau_{\rm reio}$	$0.0510(0.0510)^{+0.0087}_{-0.0078}$	$0.0527(0.052)^{+0.0086}_{-0.0084}$
S_8	$0.817(0.821) \pm 0.017$	$0.829(0.829)^{+0.017}_{-0.019}$
Ω_m	$0.307(0.309)^{+0.008}_{-0.009}$	$0.289(0.287) \pm 0.009$
Age [Gyrs]	$13.77(13.78) \pm 0.023$	$12.84(12.75) \pm 0.27$
$\Delta\chi^2_{\rm min}$ (EDE − ΛCDM)	–	−16.2
Preference over ΛCDM	–	99.9% (3.3σ)

Original motivation for EDE: H_0 tension

faster expansion at $z > 1100$ $\rightarrow$ smaller $r_\star$ $\rightarrow$ larger H_0

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TABLE I. The mean (best-fit) $\pm 1\sigma$ errors of the cosmological parameters reconstructed in the ΛCDM and EDE models from the analysis of the ACT DR4 + SPT-3G+*Planck* TT650TEEE dataset combination.

Model	ΛCDM	EDE
H_0 [km/s/Mpc]	$68.02(67.81)^{+0.64}_{-0.6}$	$74.2(74.83)^{+1.9}_{-2.1}$
$100\omega_b$	$2.253(2.249)^{+0.014}_{-0.013}$	$2.279(2.278)^{+0.018}_{-0.02}$
$\omega_{\rm cdm}$	$0.1186(0.1191)^{+0.0014}_{-0.0015}$	$0.1356(0.1372)^{+0.0053}_{-0.0059}$
$10^9 A_s$	$2.088(2.092)^{+0.035}_{-0.033}$	$2.145(2.146)^{+0.041}_{-0.04}$
n_s	$0.9764(0.9747)^{+0.0046}_{-0.0047}$	$1.001(1.003)^{+0.0091}_{-0.0096}$
$\tau_{\rm reio}$	$0.0510(0.0510)^{+0.0087}_{-0.0078}$	$0.0527(0.052)^{+0.0086}_{-0.0084}$
S_8	$0.817(0.821) \pm 0.017$	$0.829(0.829)^{+0.017}_{-0.019}$
Ω_m	$0.307(0.309)^{+0.008}_{-0.009}$	$0.289(0.287) \pm 0.009$
Age [Gyrs]	$13.77(13.78) \pm 0.023$	$12.84(12.75) \pm 0.27$
$\Delta\chi^2_{\rm min}$ (EDE − ΛCDM)	–	−16.2
Preference over ΛCDM	–	99.9% (3.3σ)

Original motivation for EDE: H_0 tension

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Ongoing work: absolute ages of globular clusters

The Universe should be older than the oldest objects in it. A good place to look: globular clusters ($\approx 10^5 M_\odot$ collections of ancient, coeval stars)

Preliminary results:

- M92 has an age of 13.80 ± 0.75 Gyr;
- **dominant uncertainty is distance;** metallicity, nuclear reaction rates, opacities, etc. are much less important (M. Ying, B. Chaboyer, et al., including MBK).

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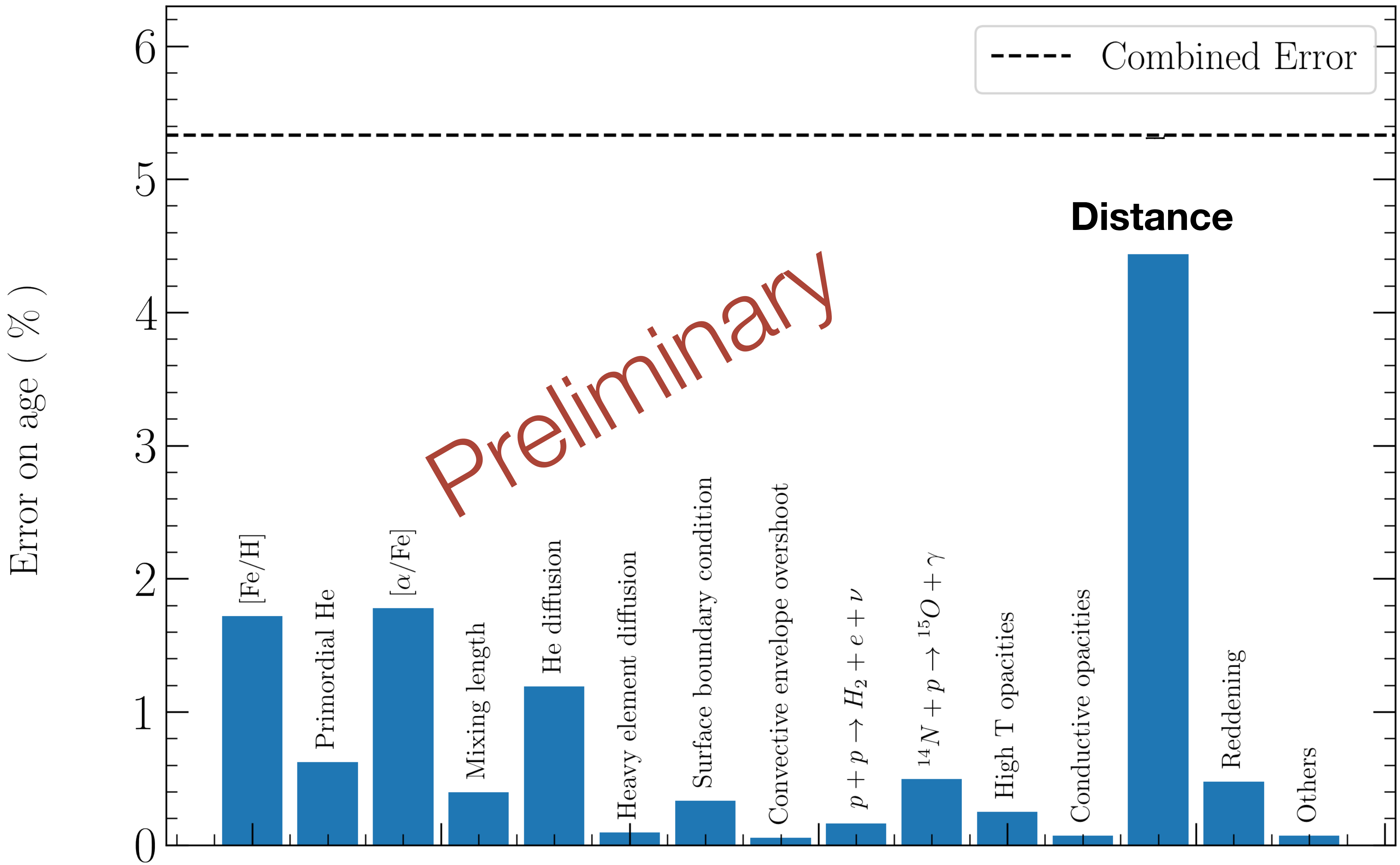

Ying et al. (2023, submitted)

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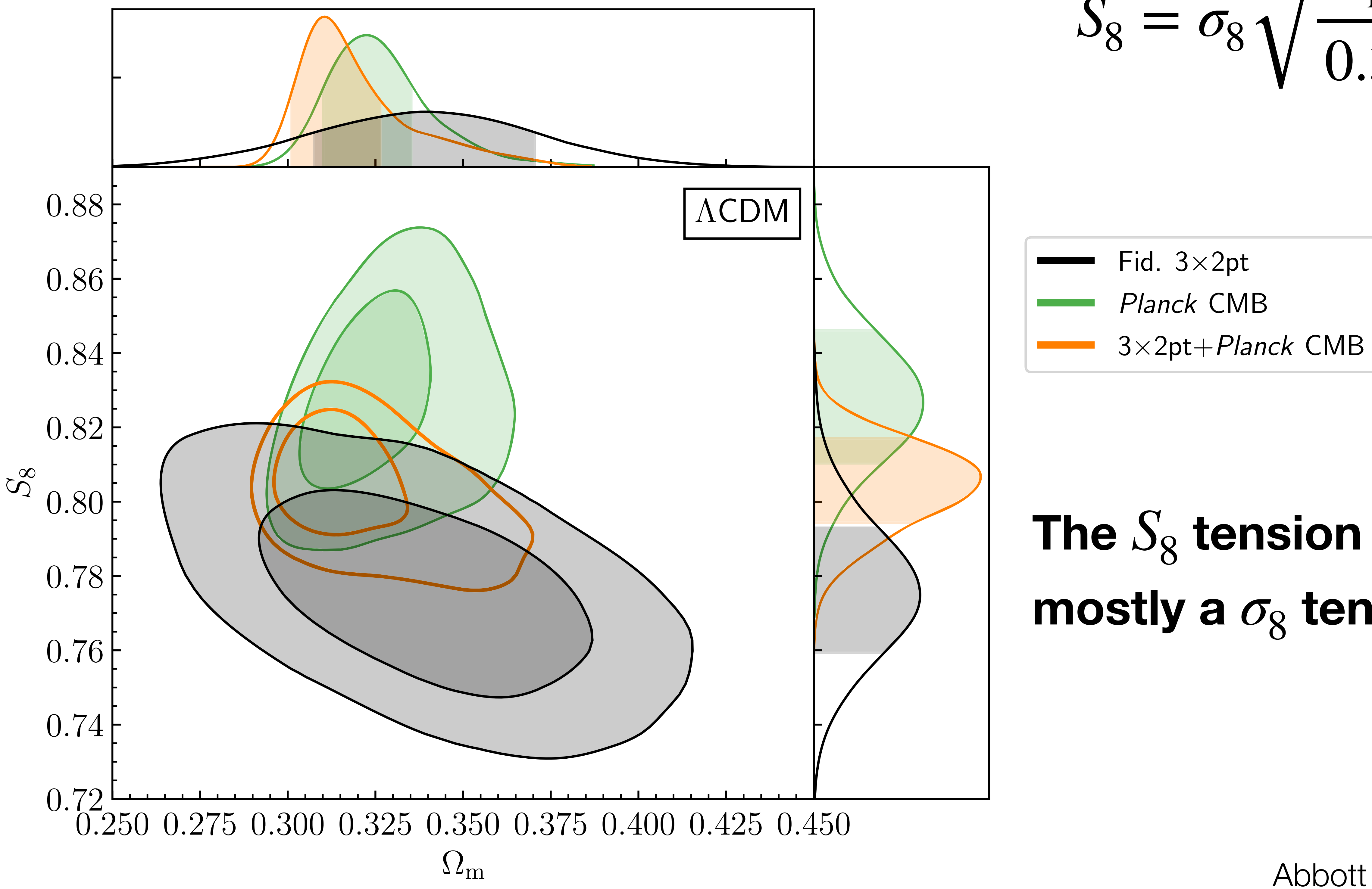
if we can reduce distance uncertainties, **globular cluster ages** can strongly constrain any resolution to Hubble tension that **modifies early Universe physics** (e.g., early dark energy).

- early solutions to H_0 tension ***generically*** predict a younger Universe

What about the S_8 tension?

no tension in Ω_m direction



$$S_8 = \sigma_8 \sqrt{\frac{\Omega_m}{0.3}}$$

The S_8 tension is mostly a σ_8 tension

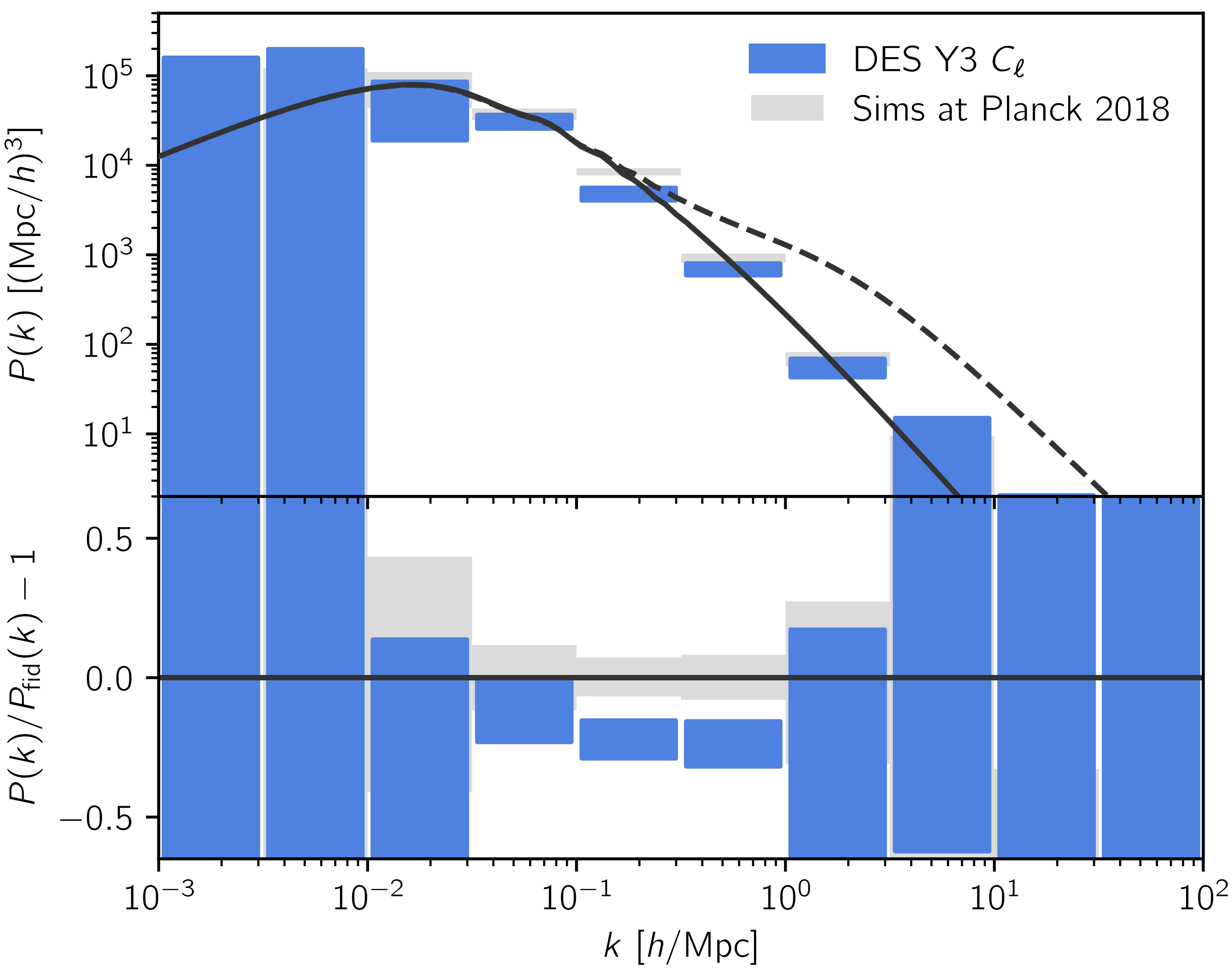
Abbott et al. (2022)

What can go wrong in measuring σ_8?

Linear theory predictions are clear

Observations of σ_8 include power from **non-linear** scales.

Significant effects from **baryonic physics** (e.g., AGN feedback)?



dashed: non-linear

solid: linear

Doux et al. 2022

Outlook

ΛCDM model: just a starting point for understanding our Universe

- 95% of the Universe is can be well described but is poorly understood
- Accurate cosmological is a prerequisite for a predictive theory of galaxy formation

Tensions are appearing in **many** places; may indicate the need for a revised cosmology or may be a sign of ΛCDM's maturity.

JWST observations are challenging our inference of **galaxy properties**, our understanding of **galaxy formation**, or our **cosmological model**

- Massive galaxy candidates require perfect conversion of baryons to stars for halos predicted by the base ΛCDM (arXiv:2208.01611)
- **if** it is an issue with cosmology, could it be related to the Hubble tension & EDE?
- A new era of stellar astrophysics may help us understand cosmology

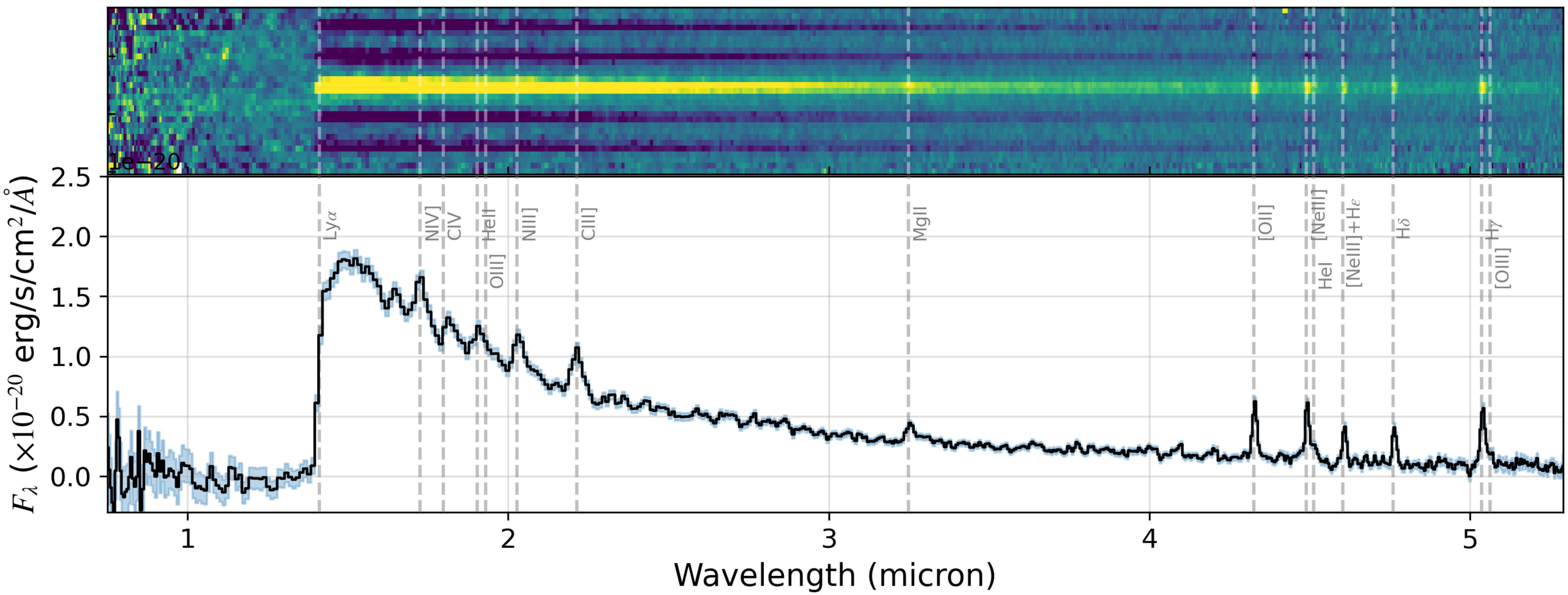
Data are pouring in; we should have a much better understanding of whether early galaxies truly challenge ΛCDM within the next 1-2 years

Spectroscopic data

$z = 10.6$ galaxy with $M_\star \approx 10^9\, M_\odot$

(one of the brightest high-redshift galaxies discovered with HST)

Bunker et al. 2023 (see also Tacchella et al. 2023)



JADES: 4 confirmed galaxies at $z = 10.4 - 13.2$ with $M_\star \approx 10^8 - 10^9\, M_\odot$

Robertson, Tacchella et al. 2022; Curtis-Lake, Carniani et al. 2022

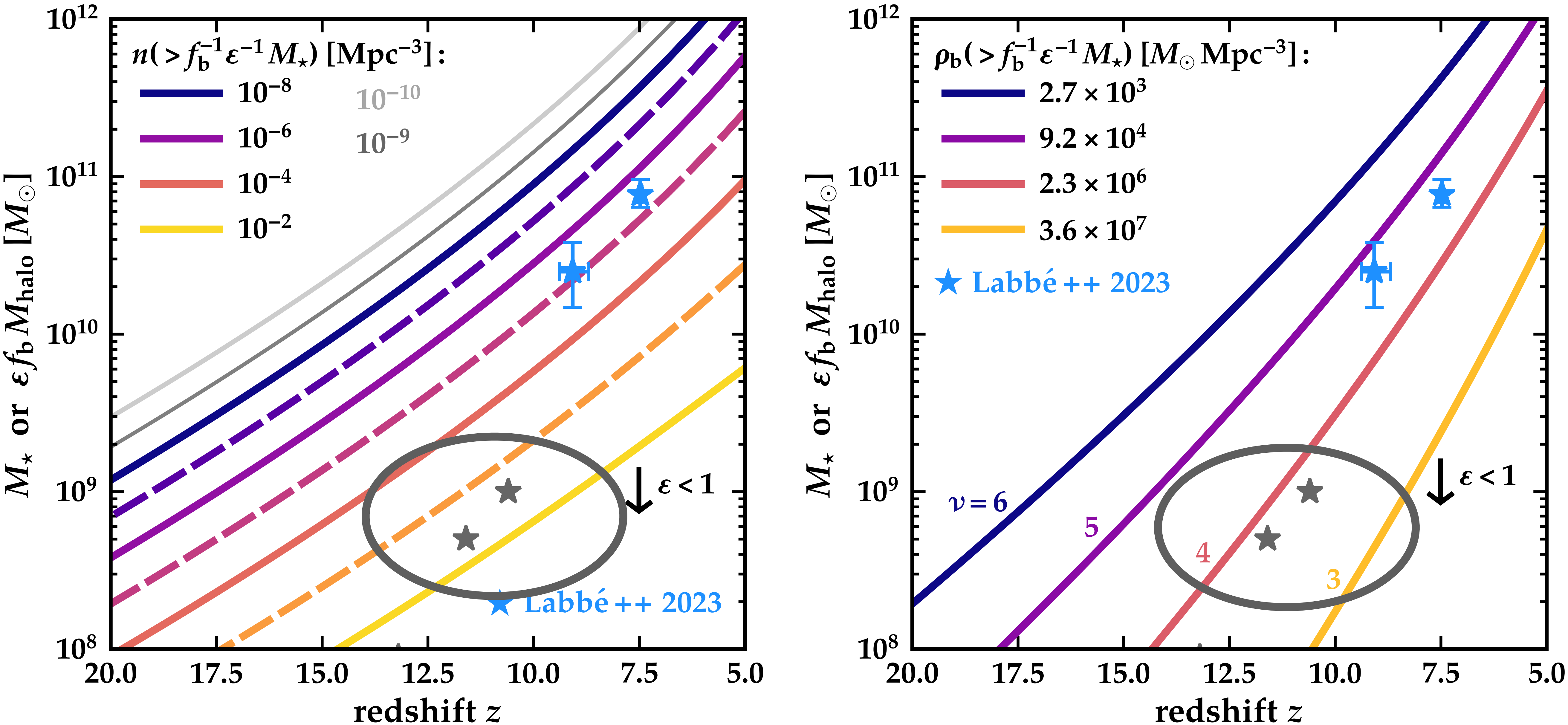
CEERS: 2 confirmed galaxies at $z = 10.1 - 11.4$ with $M_\star \approx 10^8 - 10^9\, M_\odot$

P. Arrabal Haro et al. 2023

Spectroscopically confirmed galaxies

Galaxies at $z \sim 10 - 13$ with $M_\star \approx 10^8 - 10^9\, M_\odot$

Very exciting, but **thus far** not cosmologically challenging



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space.com

COSMOS-Web: PIs Casey & Kartaltepe

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