

What is JWST telling us about cosmology?

JULIAN B. MUÑOZ

Based on:

Sabti, **JBM**, Kamionkowski PRL 2023

JBM, Mirocha, Sabti, Furlanetto MNRAS Lett 2023



CREDIT: NASA/STSCI/CEERS/TACC/
FINKELSTEIN/M. BAGLEY/R. LARSON/Z. LEVAY

What do we already know?

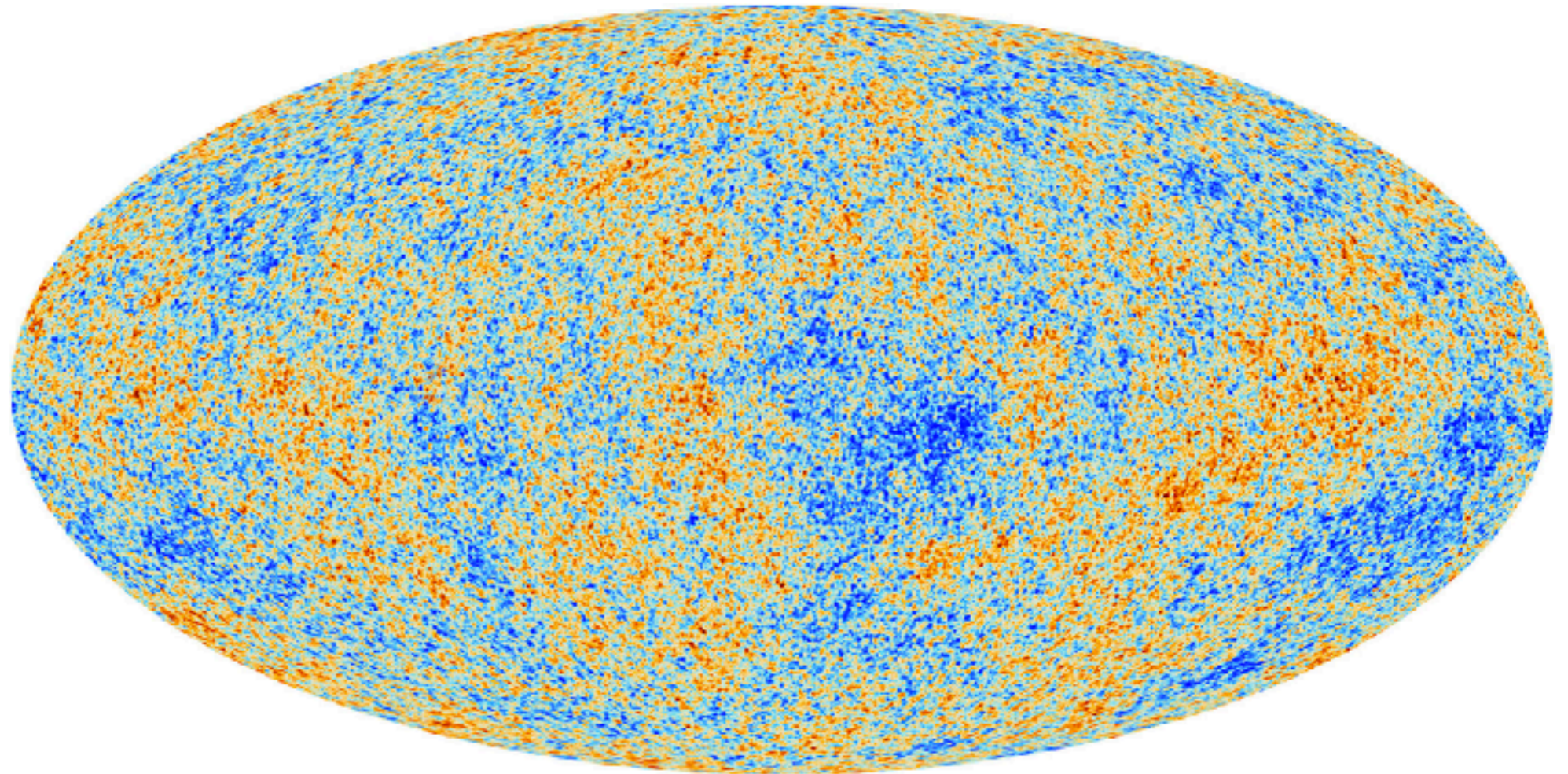
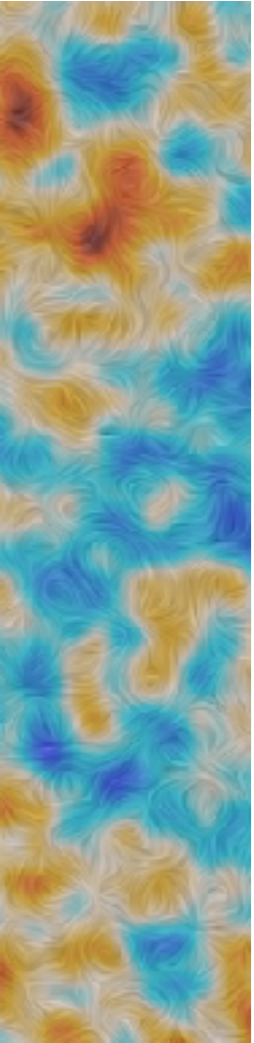
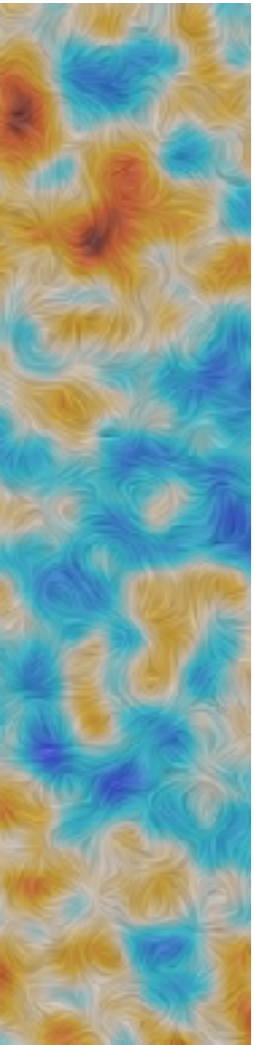


Image: ESA


What do we already know?

Image: ESA

CMB



$z \approx 10^3$


400,000

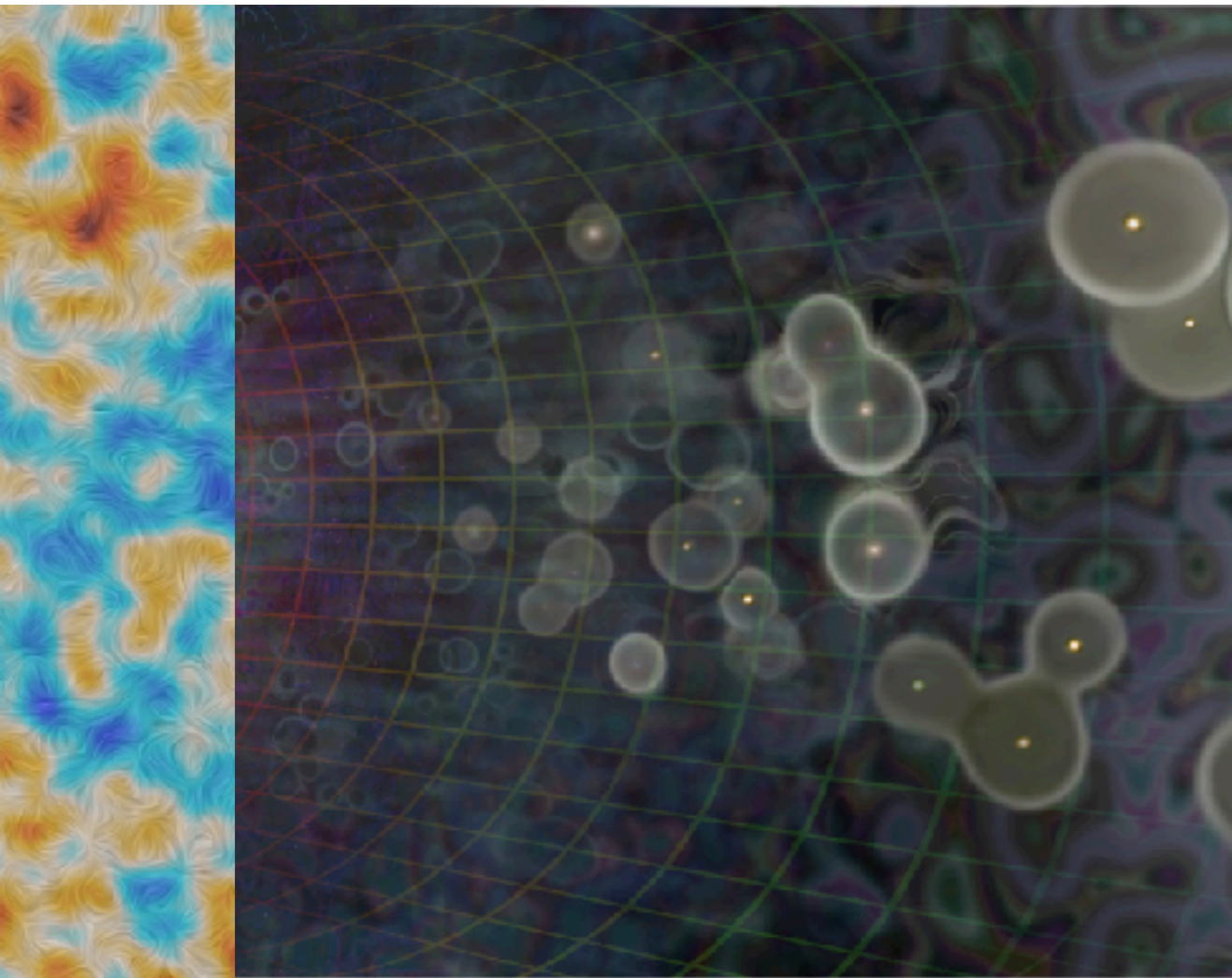
cosmic time [yr]

What do we already know?

Image: NASA/
CXC/M.WEISS

CMB

Cosmic Dawn



$z \approx 10^3$

$z \approx 30$

400,000  100 Myr

cosmic time [yr]

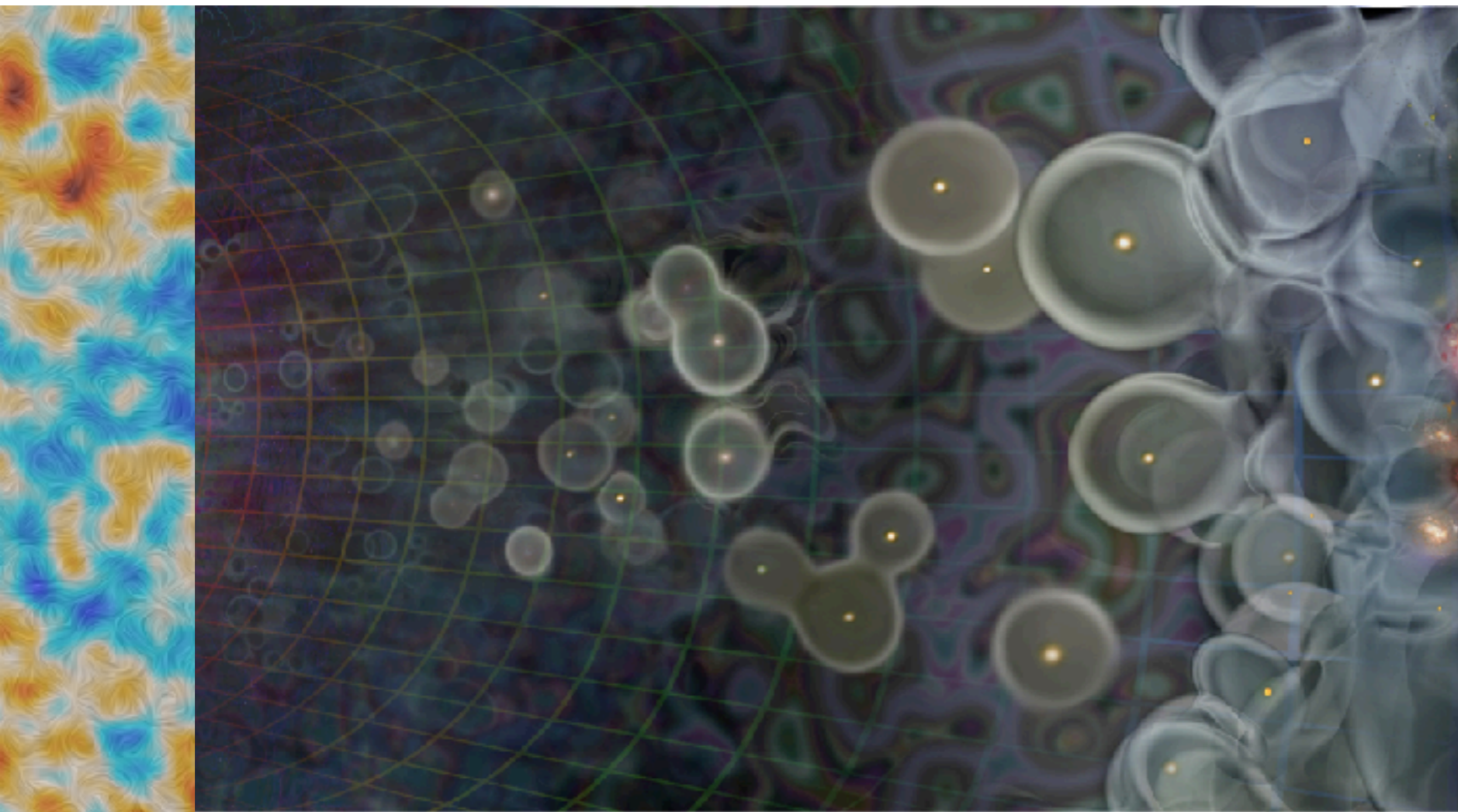
What do we already know?

Image: NASA/
CXC/M.WEISS

CMB

Cosmic Dawn

Reionization



$z \approx 10^3$

$z \approx 30$

$z \approx 5$

400,000 100 Myr 1 Byrs cosmic time [yr]

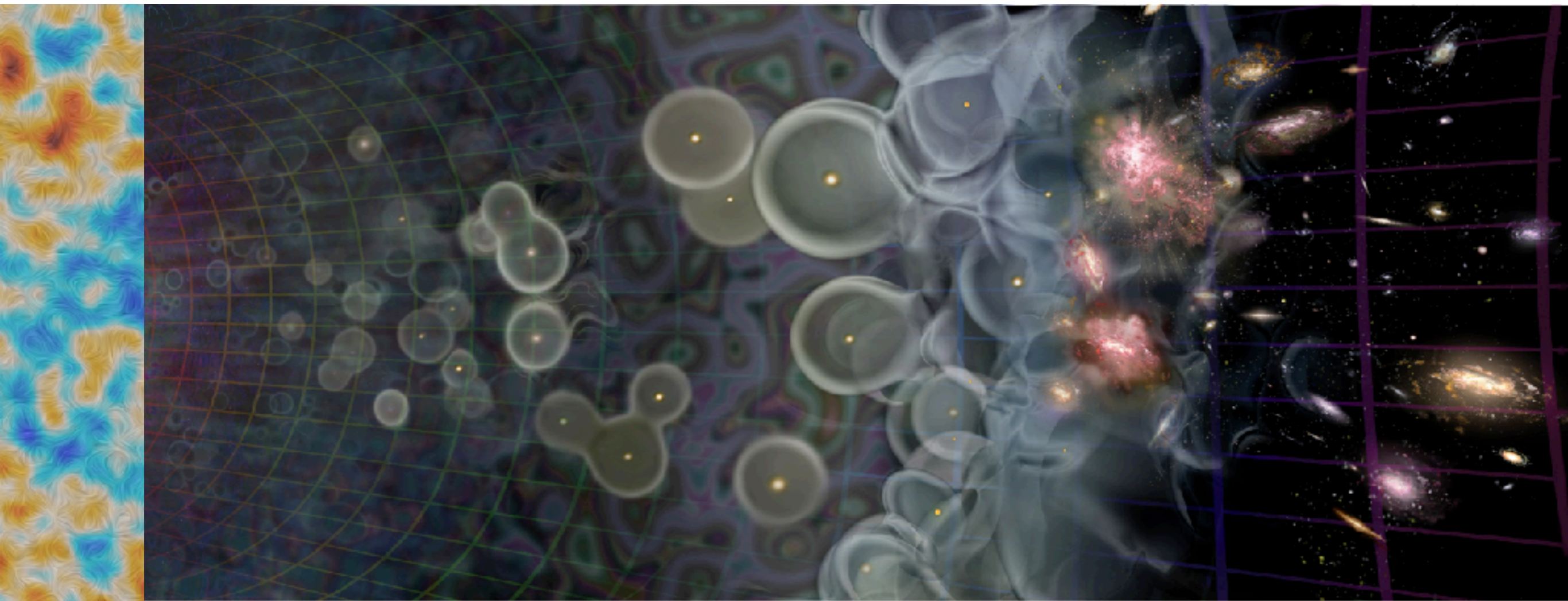
Image: NASA/
CXC/M.WEISS

CMB

Cosmic Dawn

Reionization

Today



$z \approx 10^3$

$z \approx 30$

$z \approx 5$

$z = 0$

cosmic time [yr]

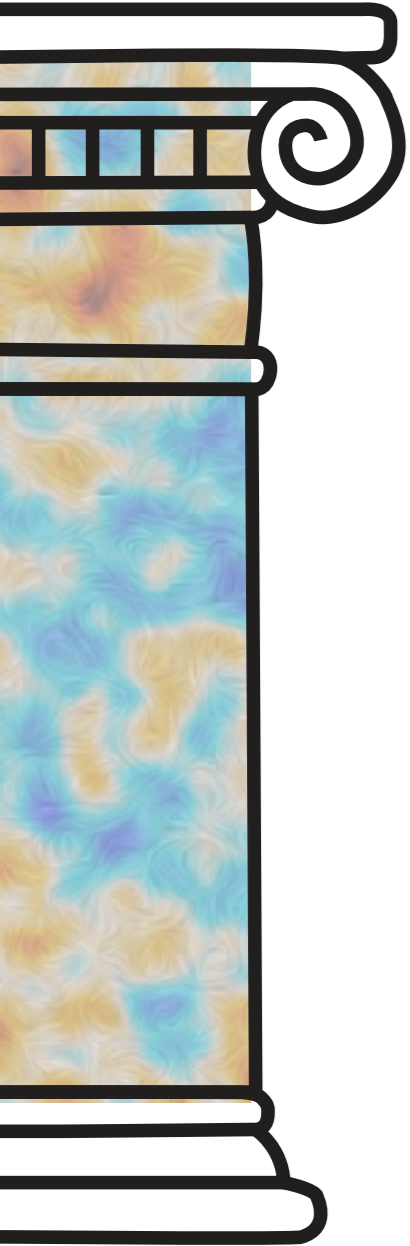
400,000

100 Myr

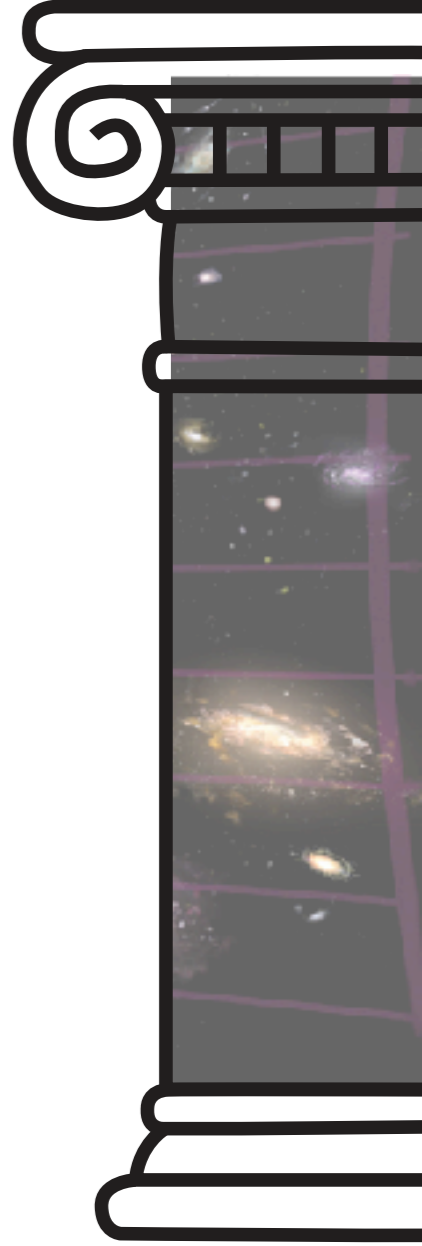
1 Byrs

14 Byrs

Cosmology

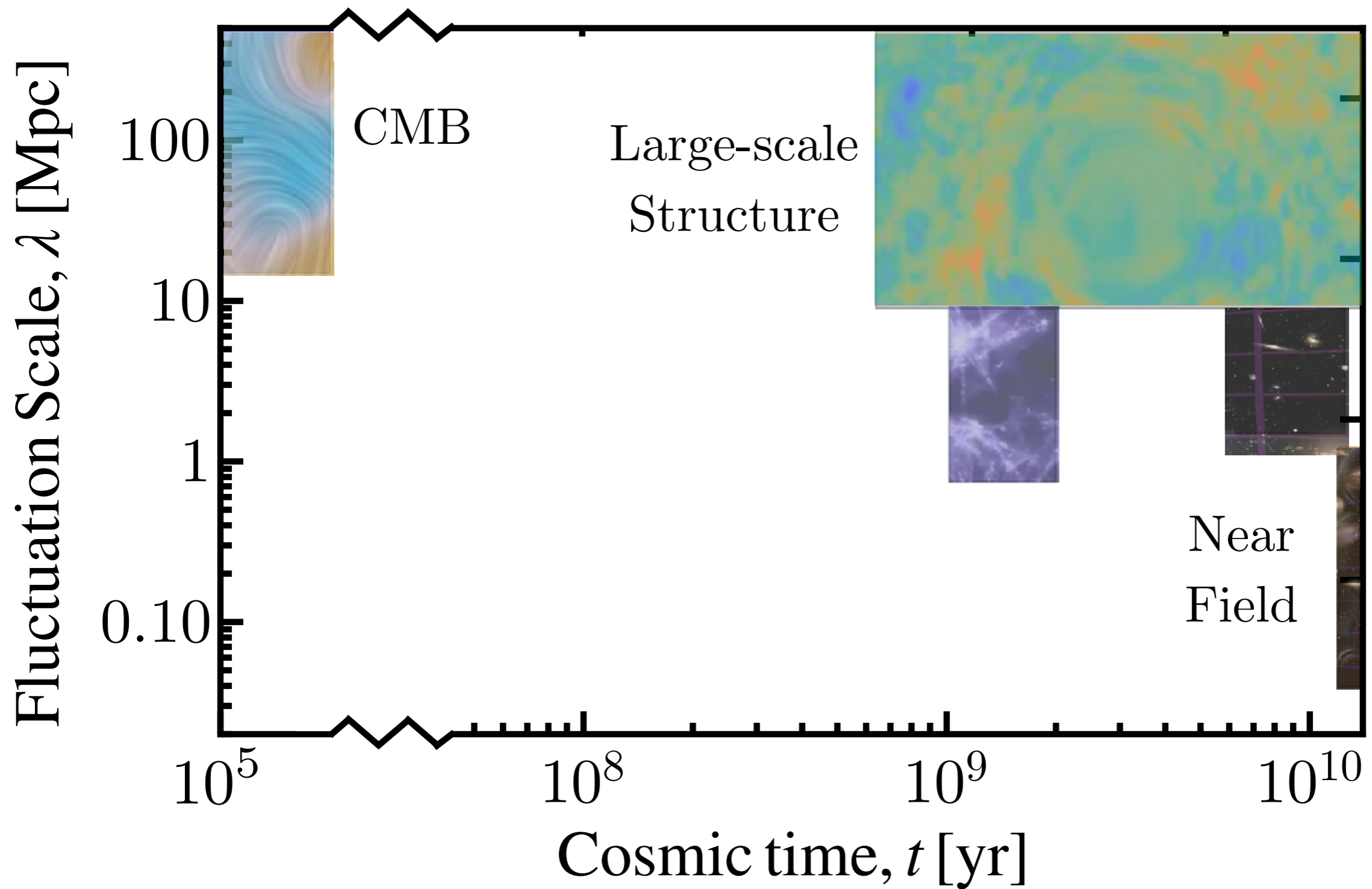


CMB

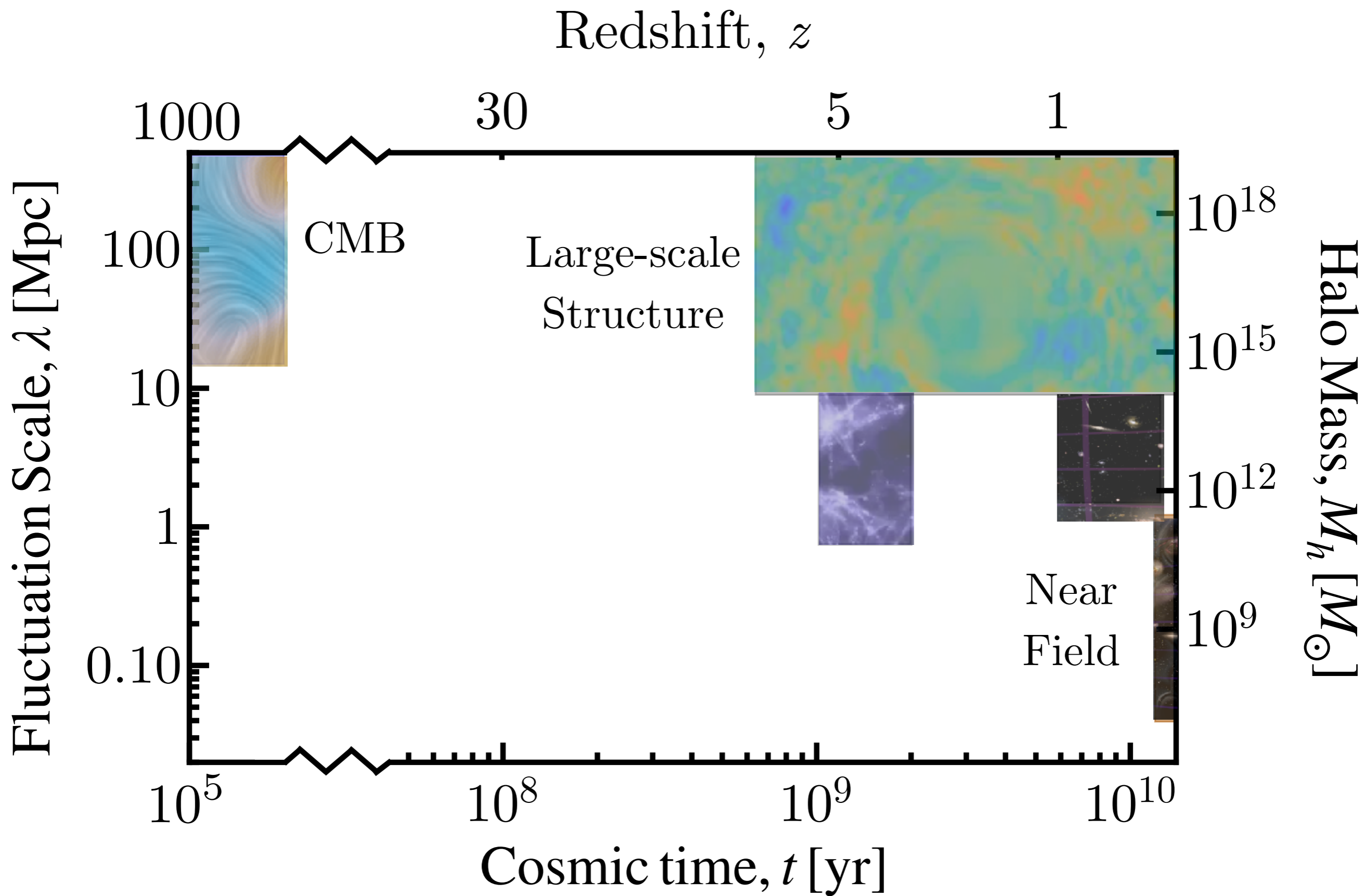


Today

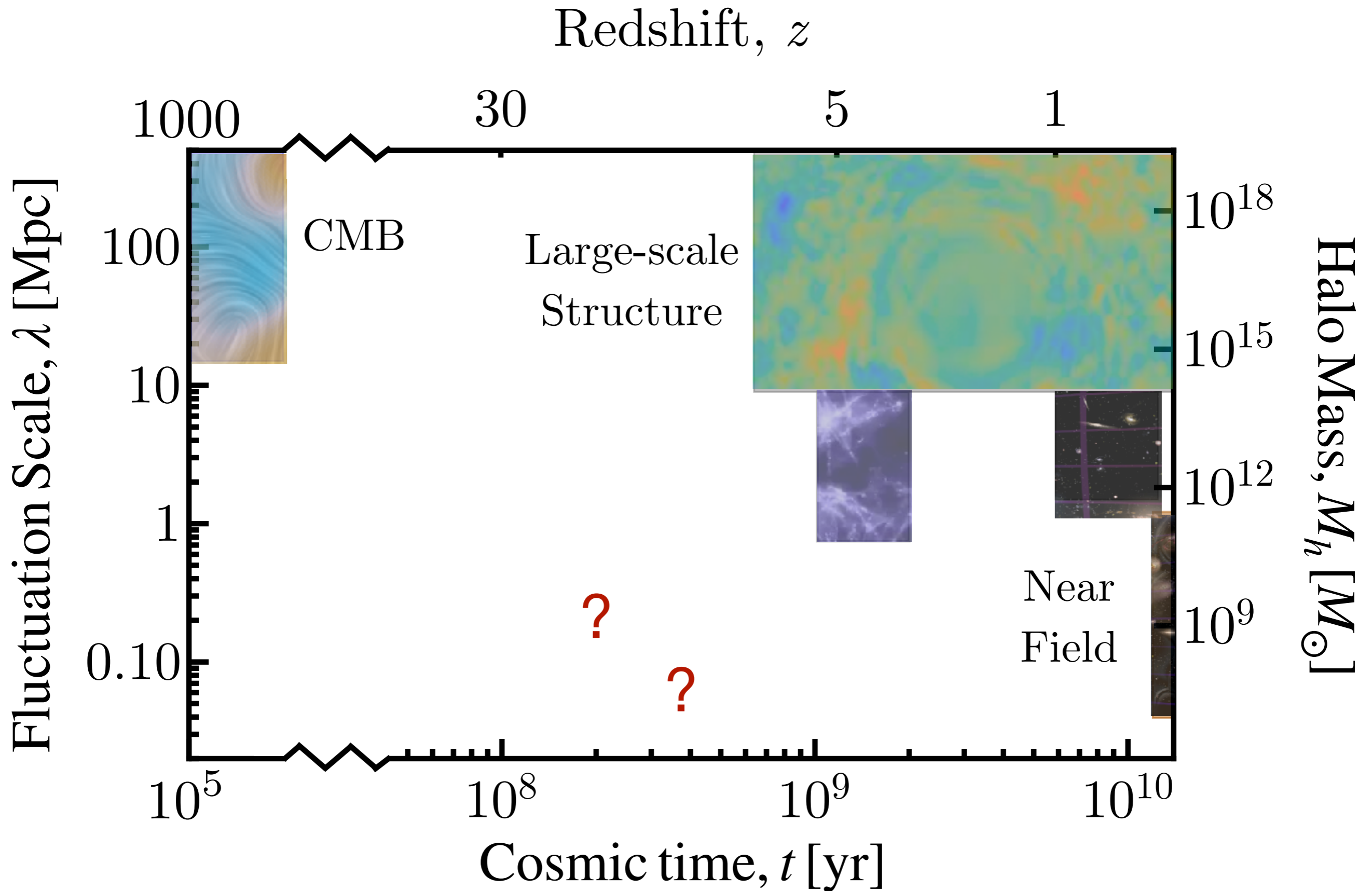
DM is cold ...



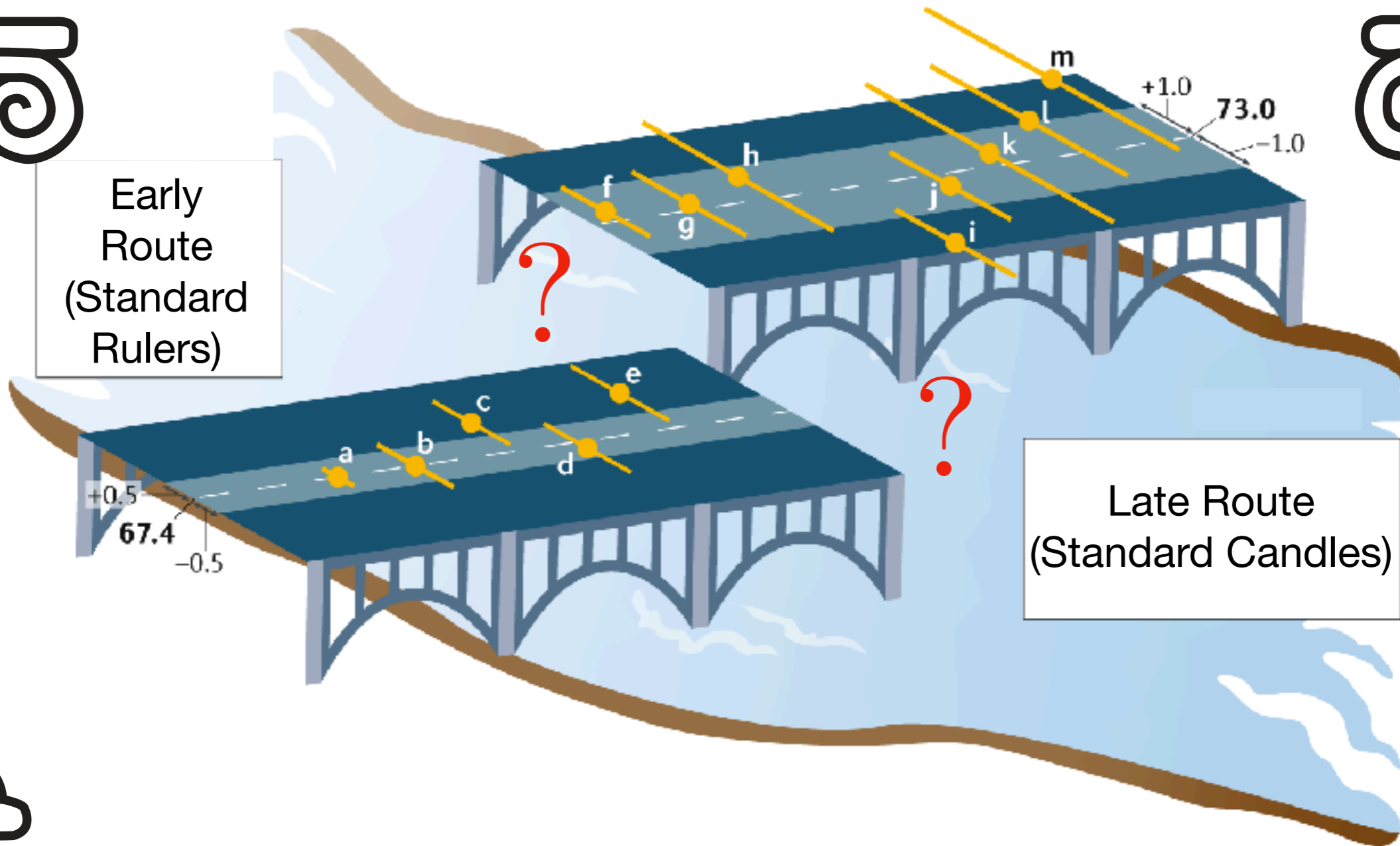
DM is cold ...



DM is cold as far as we can tell



What is the expansion rate?



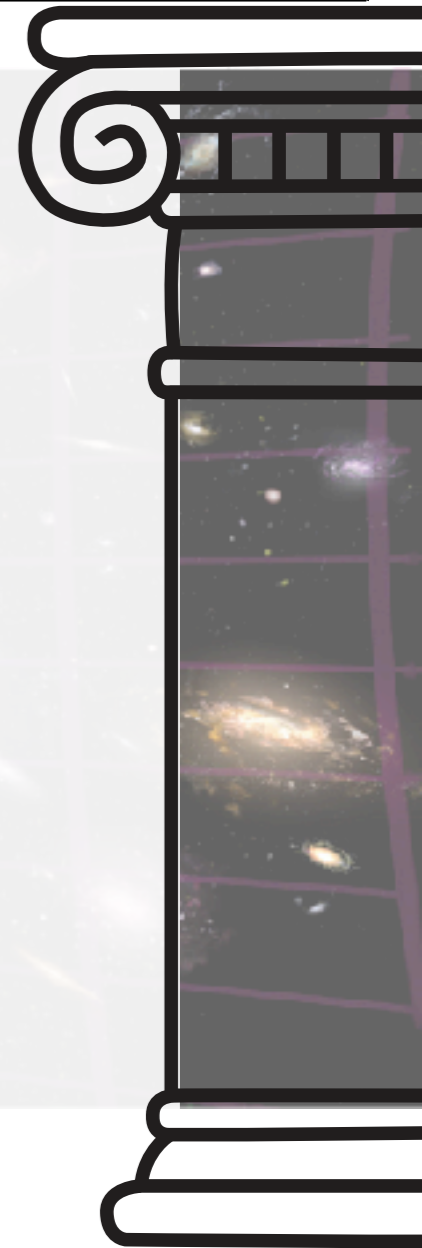
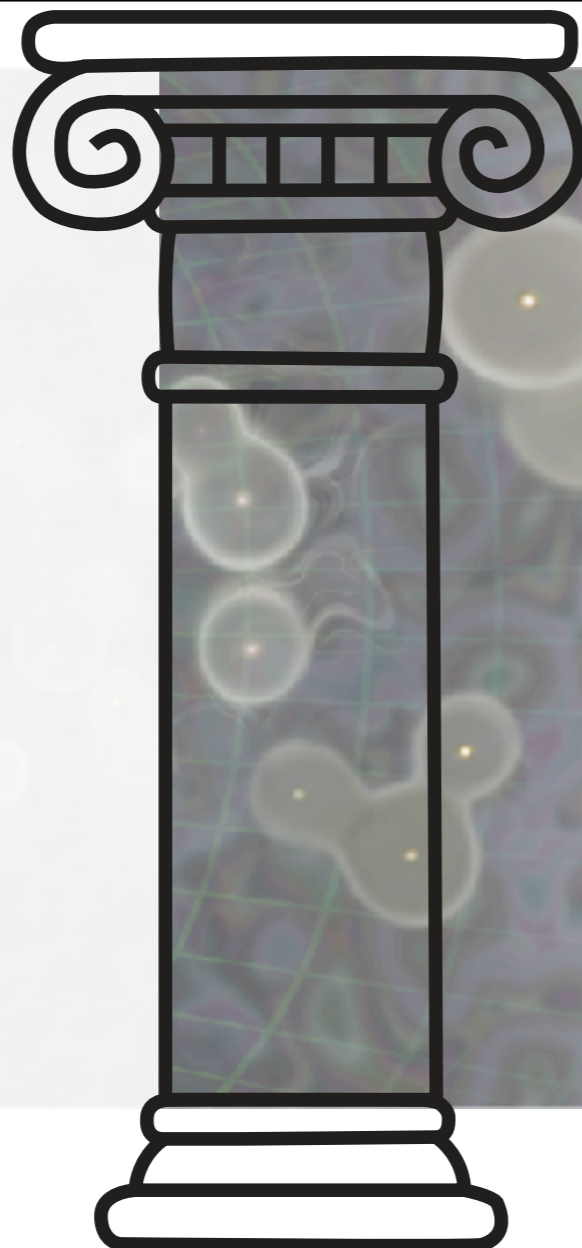
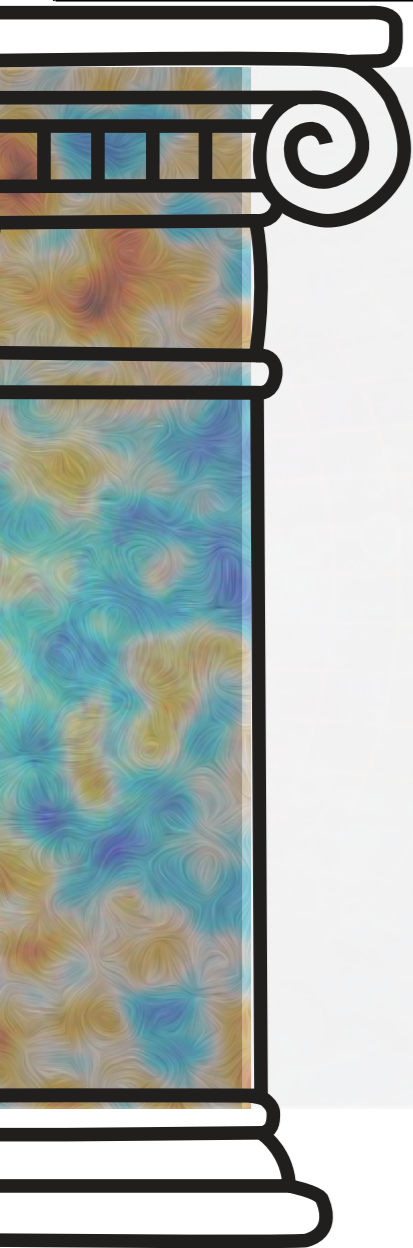
Early Route
(Standard Rulers)

Late Route
(Standard Candles)

CMB

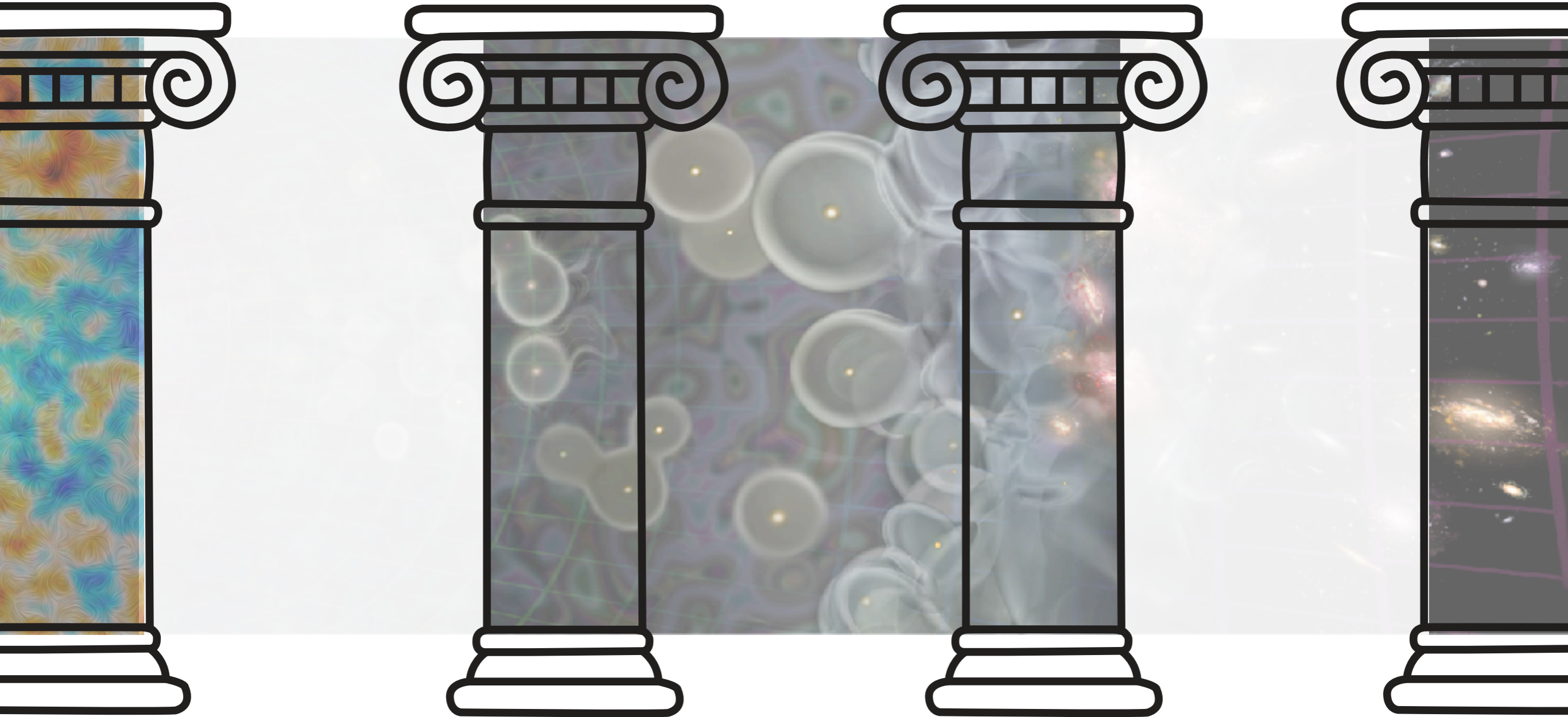
Today

New pillars of cosmology



Cosmic Dawn and Reionization

New pillars of cosmology



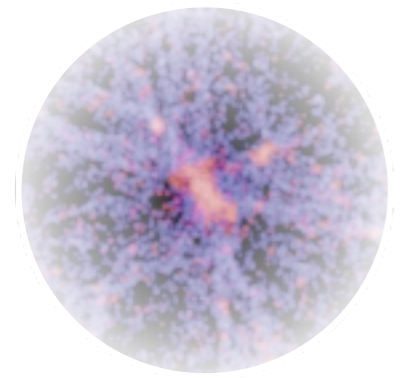
Cosmic Dawn and Reionization

JWST+HST, 21-cm → Cosmology (and astrophysics!)

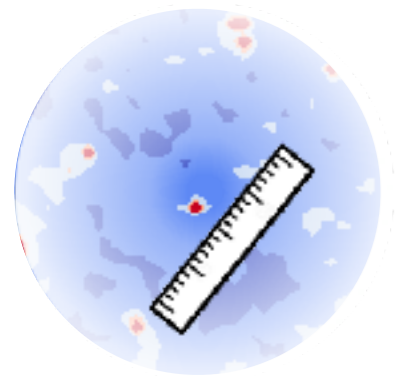
Outline



Does JWST break LCDM?

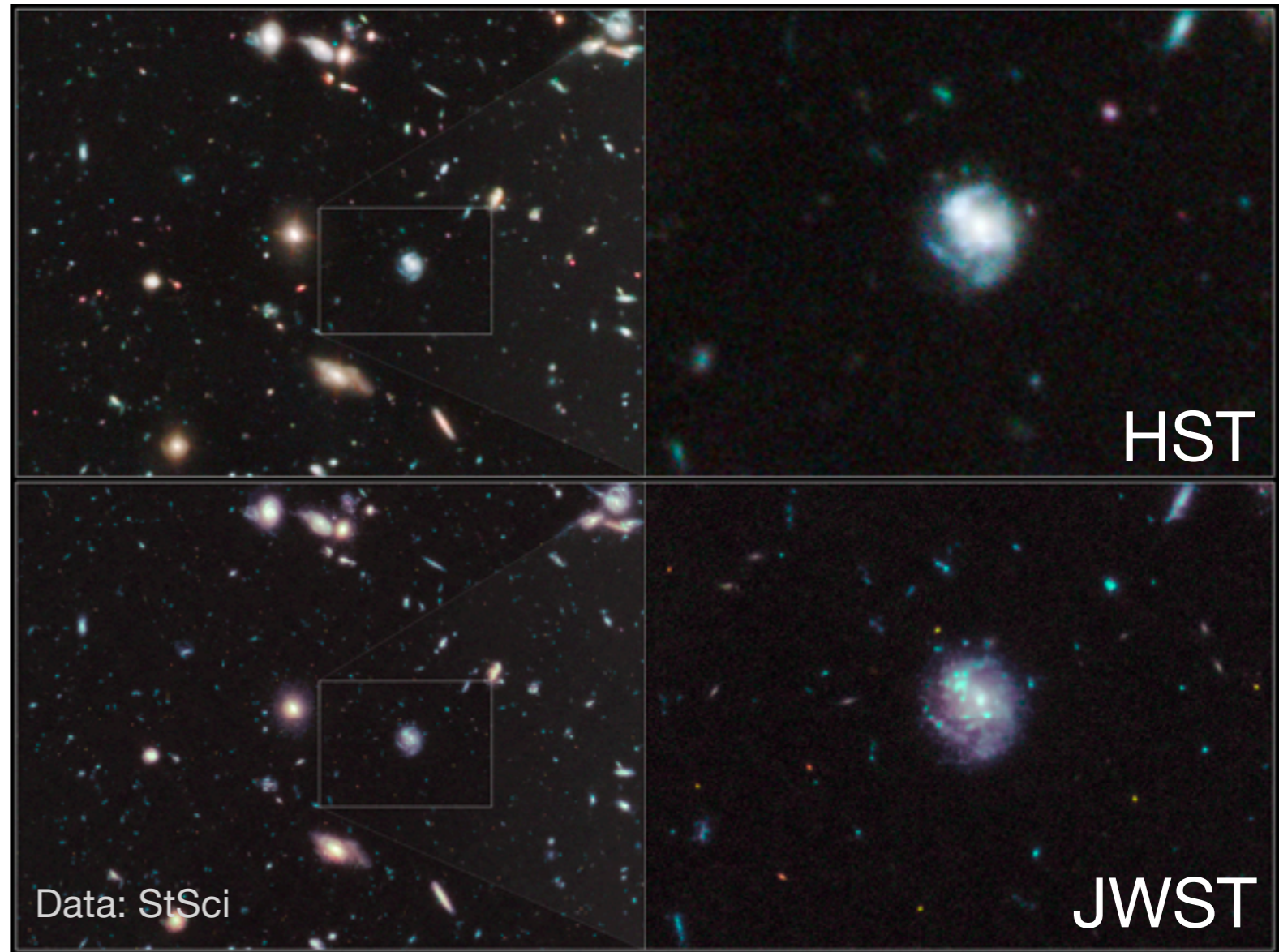


First galaxies: too many, too early

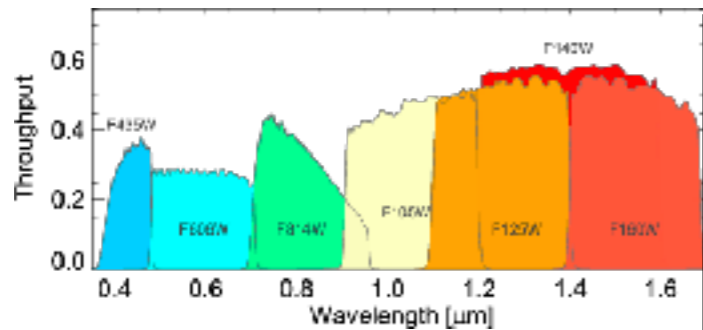


Hubble halfway to the CMB

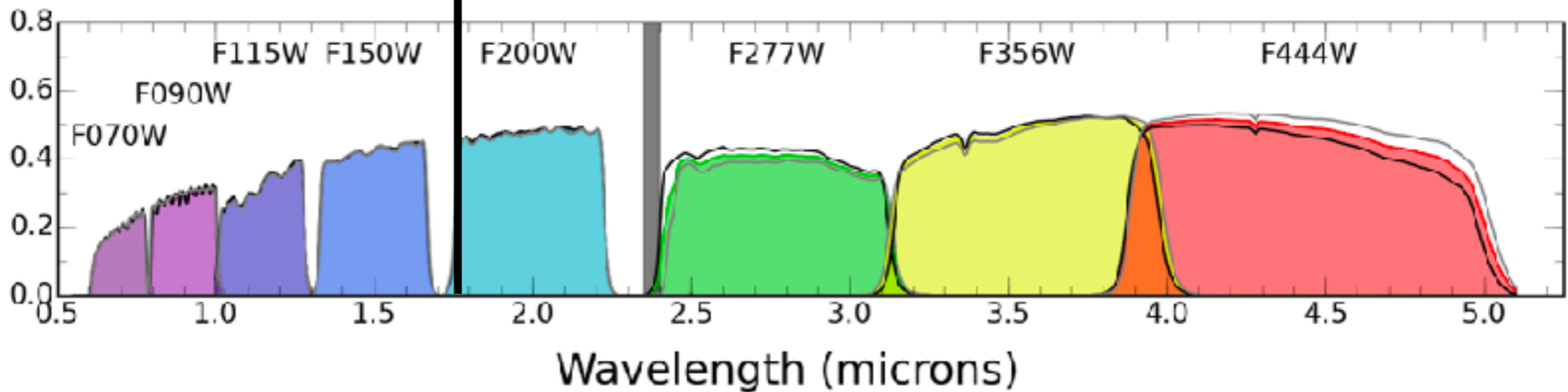
As a theorist, what does JWST do for us?



HST



JWST

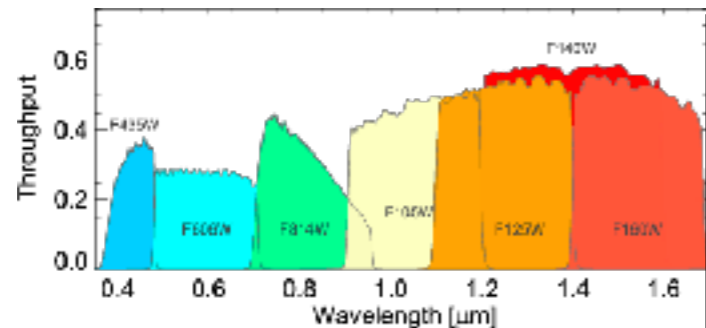


As a theorist, what does JWST do for us?

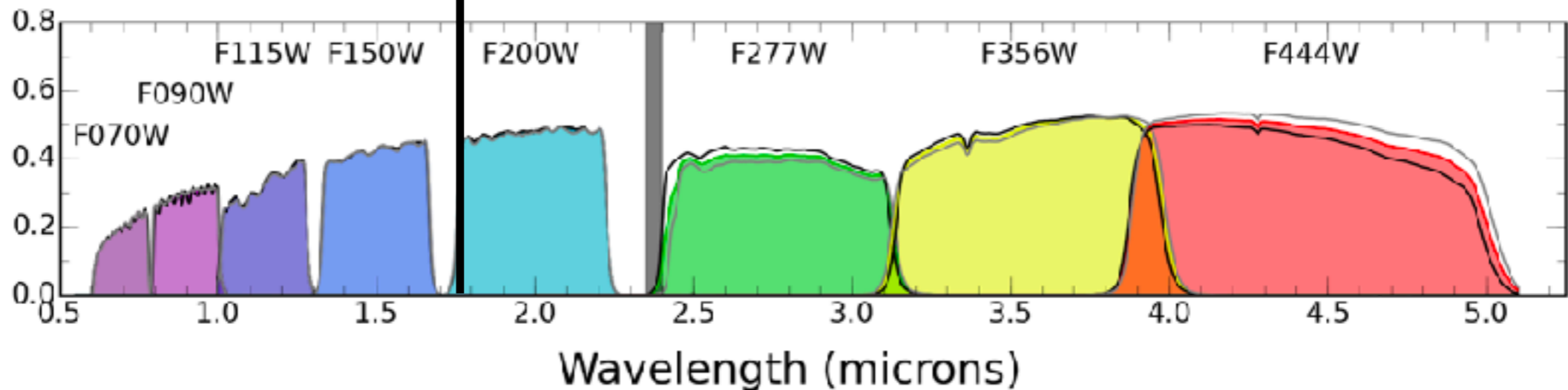
Measure rest-frame visible $\rightarrow M_{\star}, M_{\text{BH}}, \dots$

Reach higher redshifts \rightarrow UV at higher z

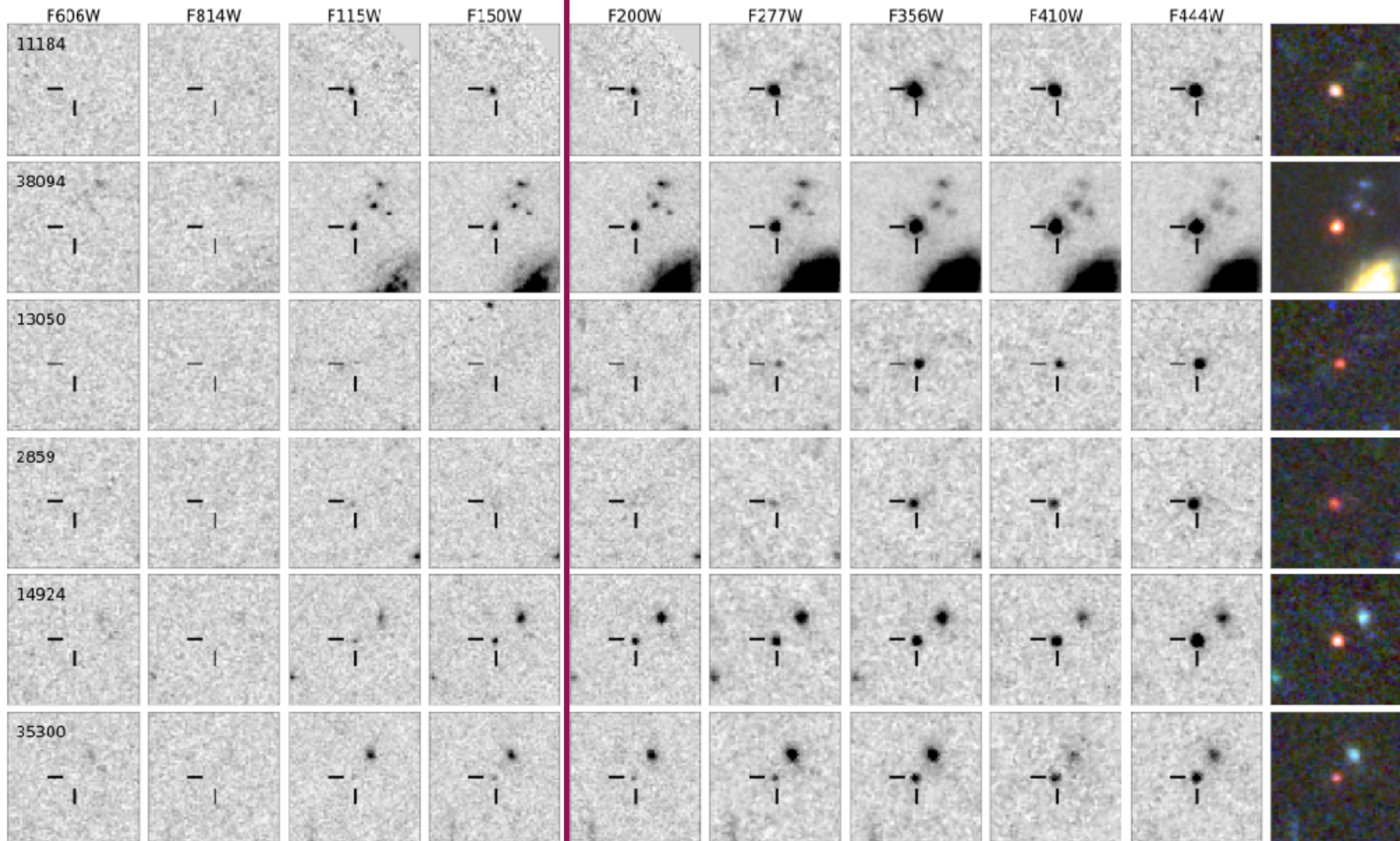
HST



JWST



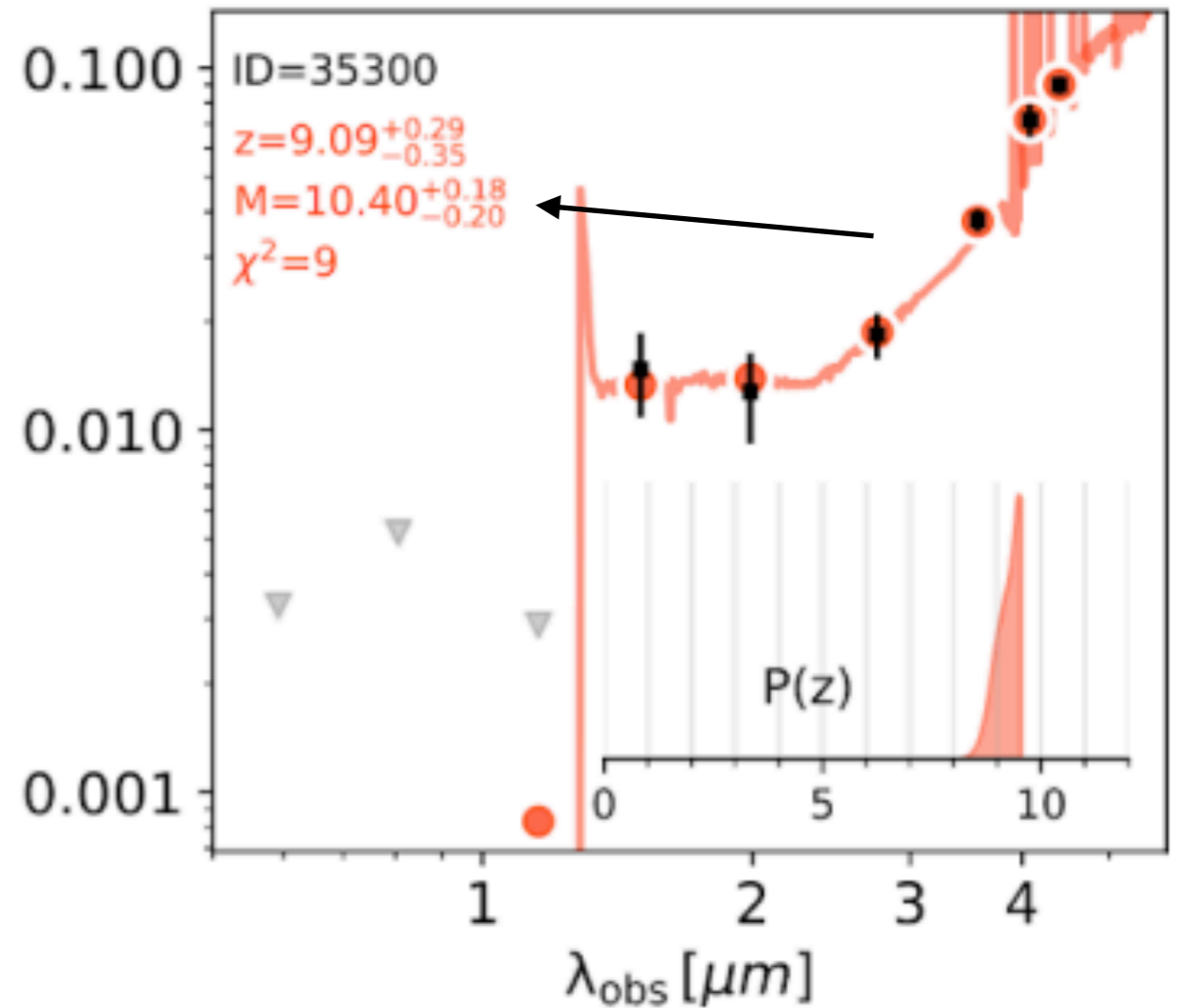
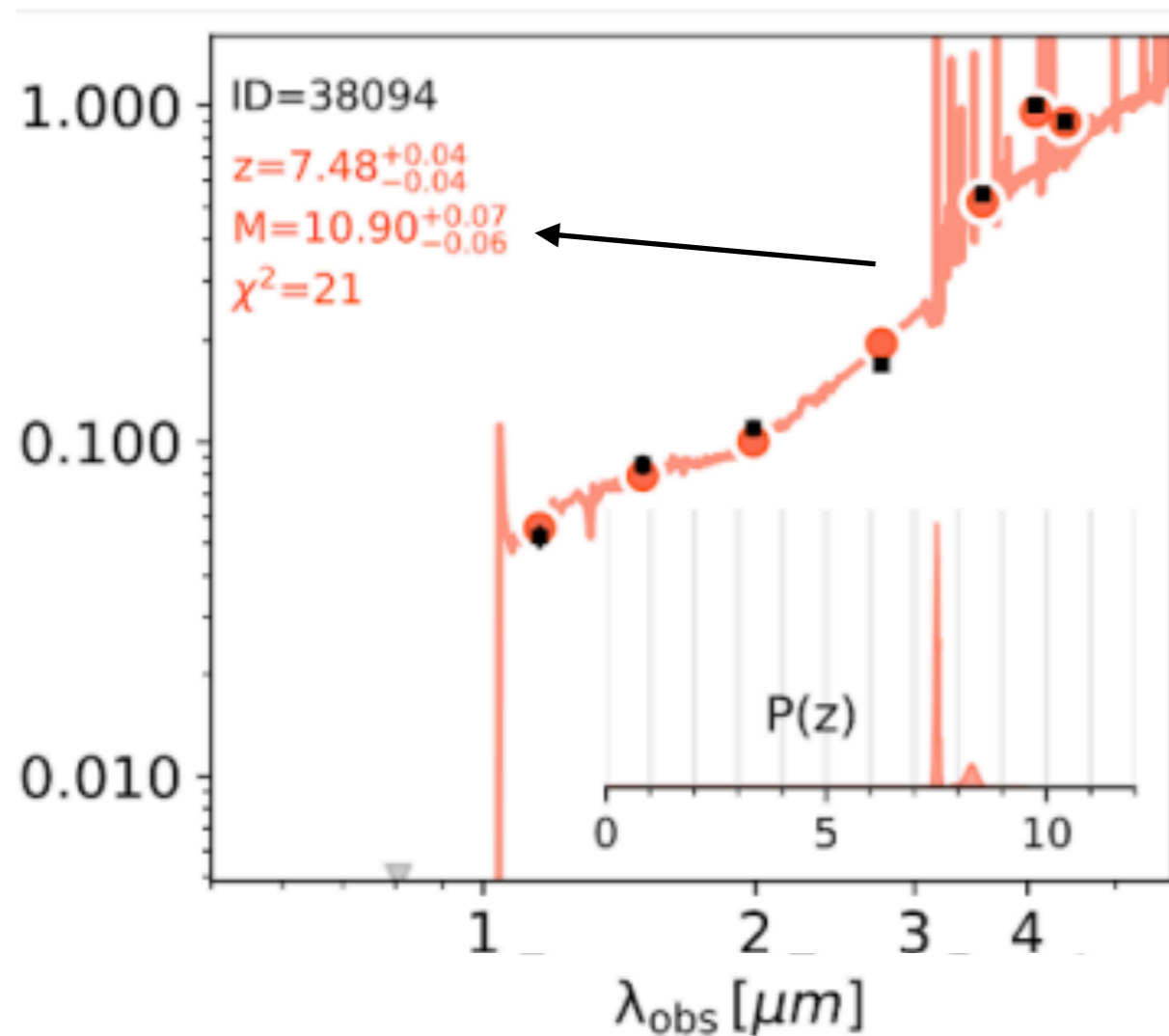
Ultramassive galaxies at high z



HST

Labbe+ Nature 23

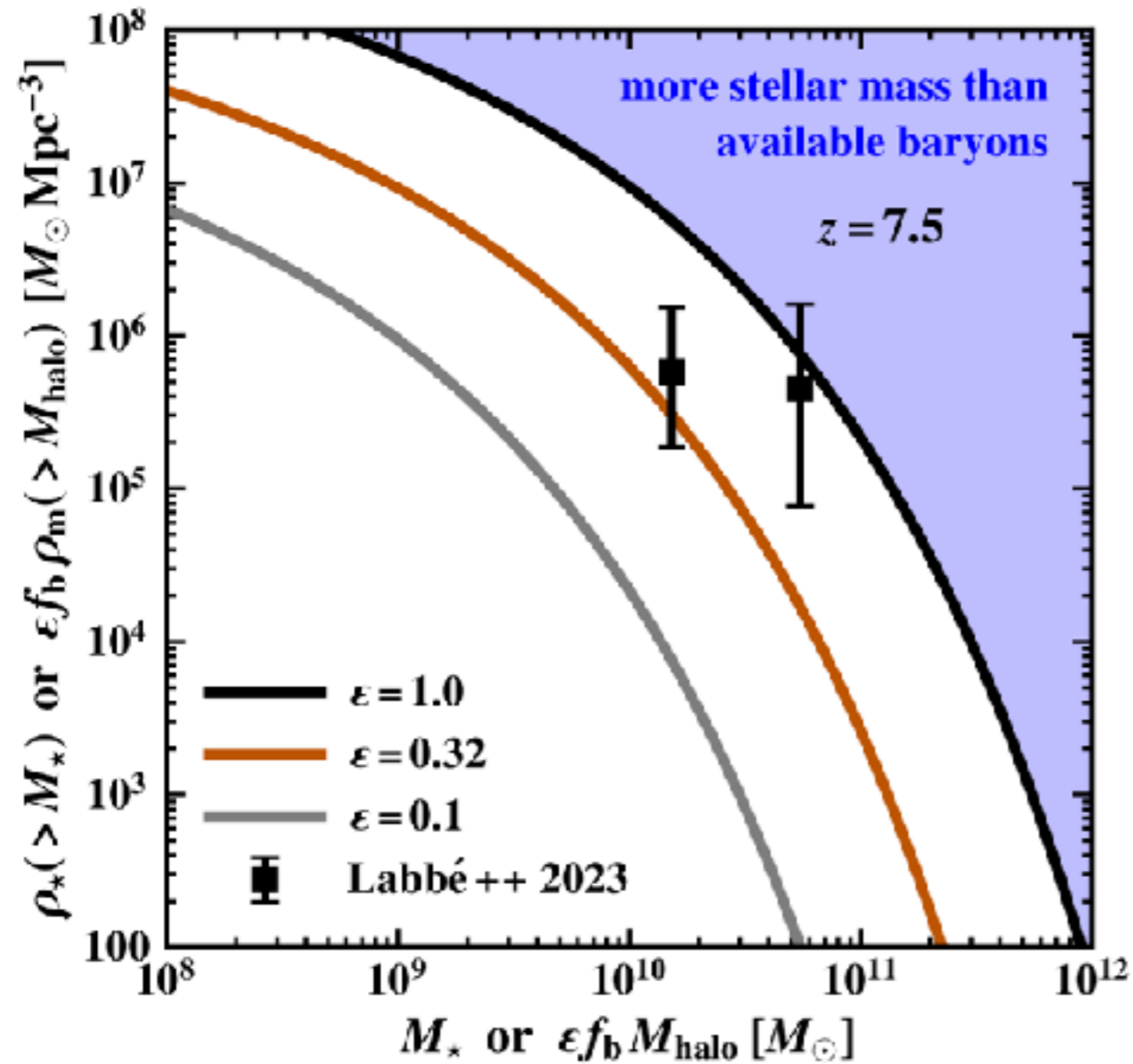
Ultramassive galaxies at high z



Top 2 massive galaxies. Only photometry*

Balmer break?

Do they break LCDM?

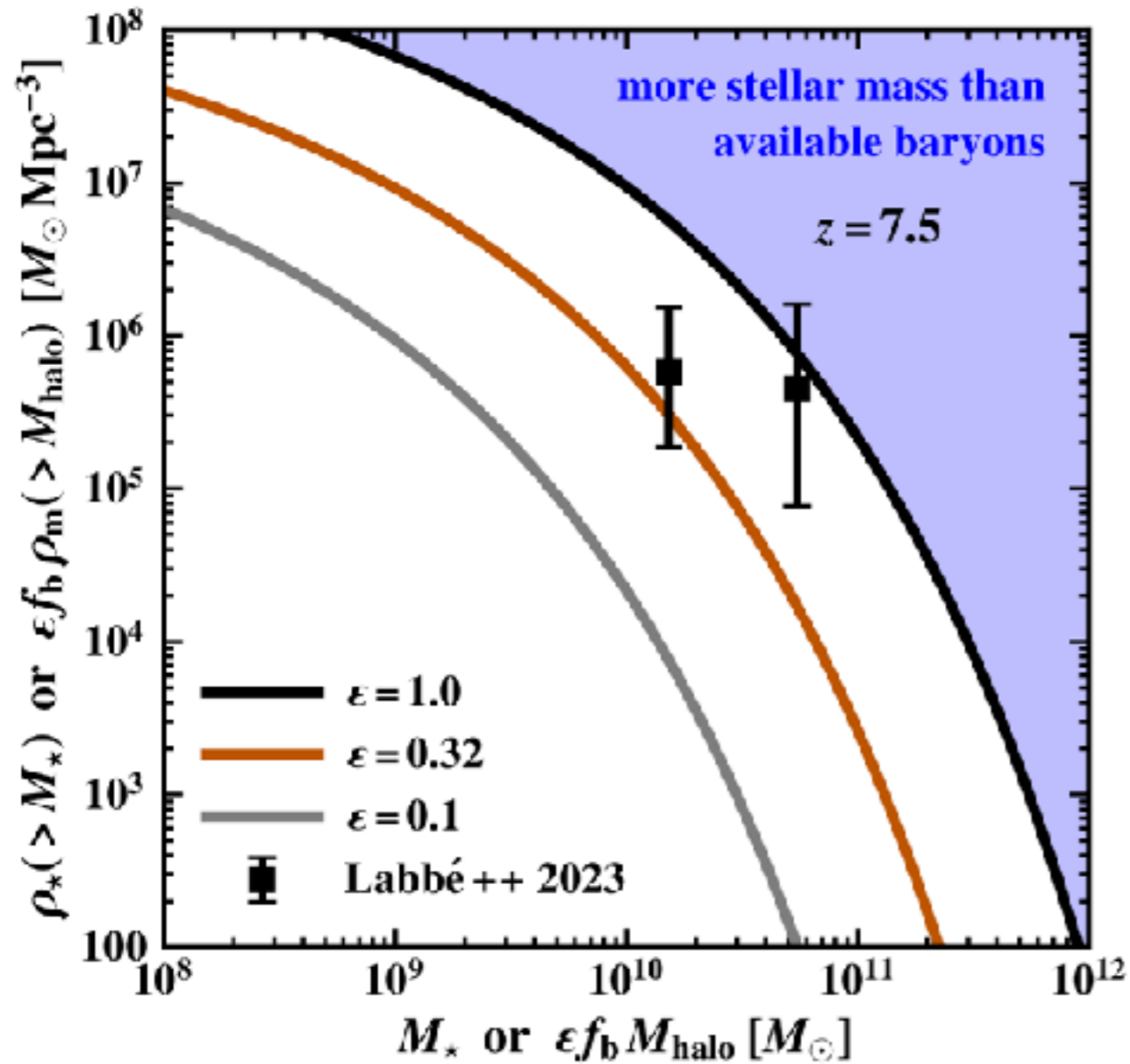


Boylan-Kolchin 23
(Data from Labbé+ 23)

$$N_{\text{gal}}(> M_\star) = \text{Vol} \times n_{\text{gal}}$$

$$n_{\text{gal}} = \int_{M_{h,\text{min}}} dM_h \frac{dn}{dM_h}$$

Do they break LCDM?



Boylan-Kolchin 23
(Data from Labbé+ 23)

$$n_{\text{gal}} \gtrsim 10^{-8} \text{Mpc}^{-3}$$

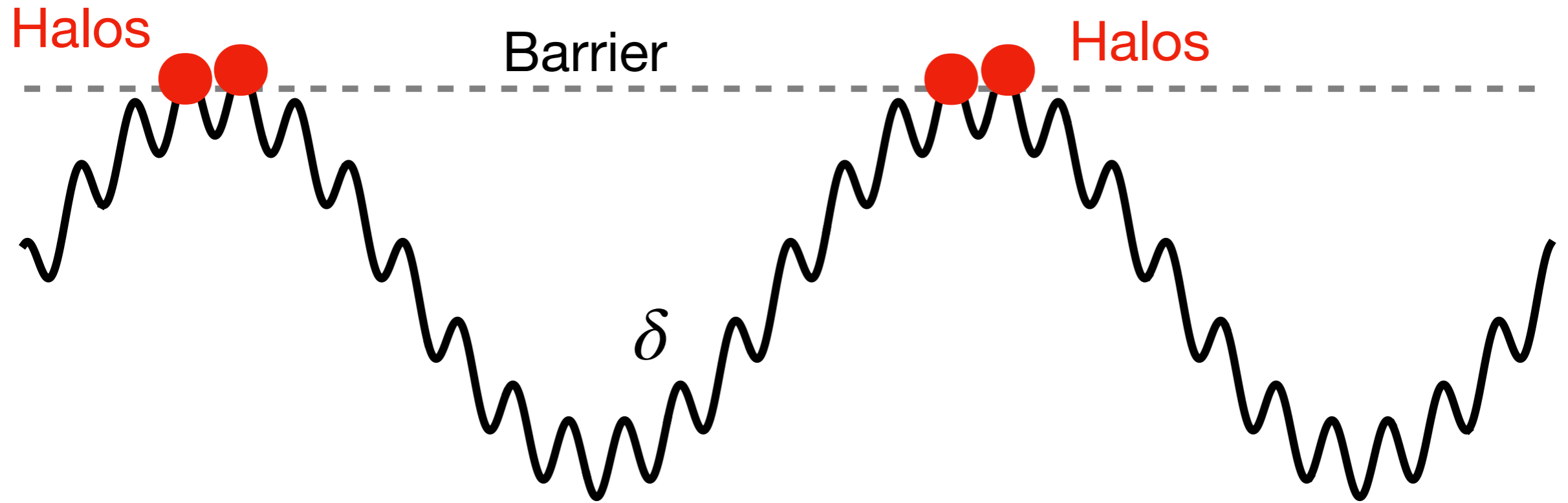
$$\text{Vol} \approx 10^5 \text{Mpc}^{-3}$$

Need more halos??

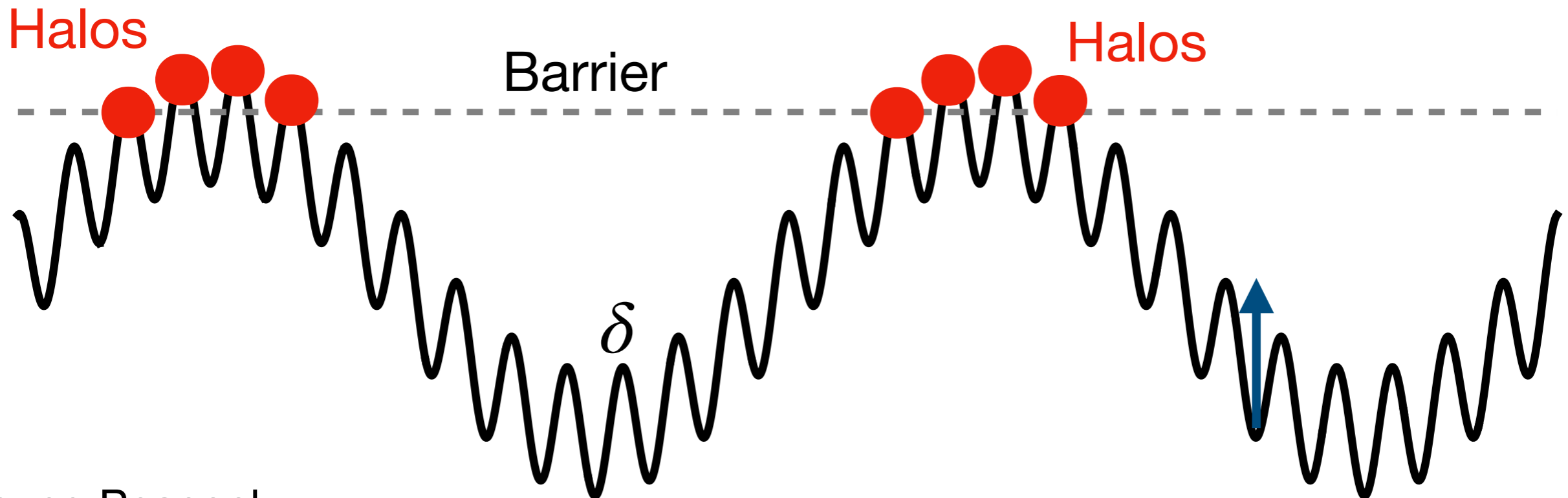
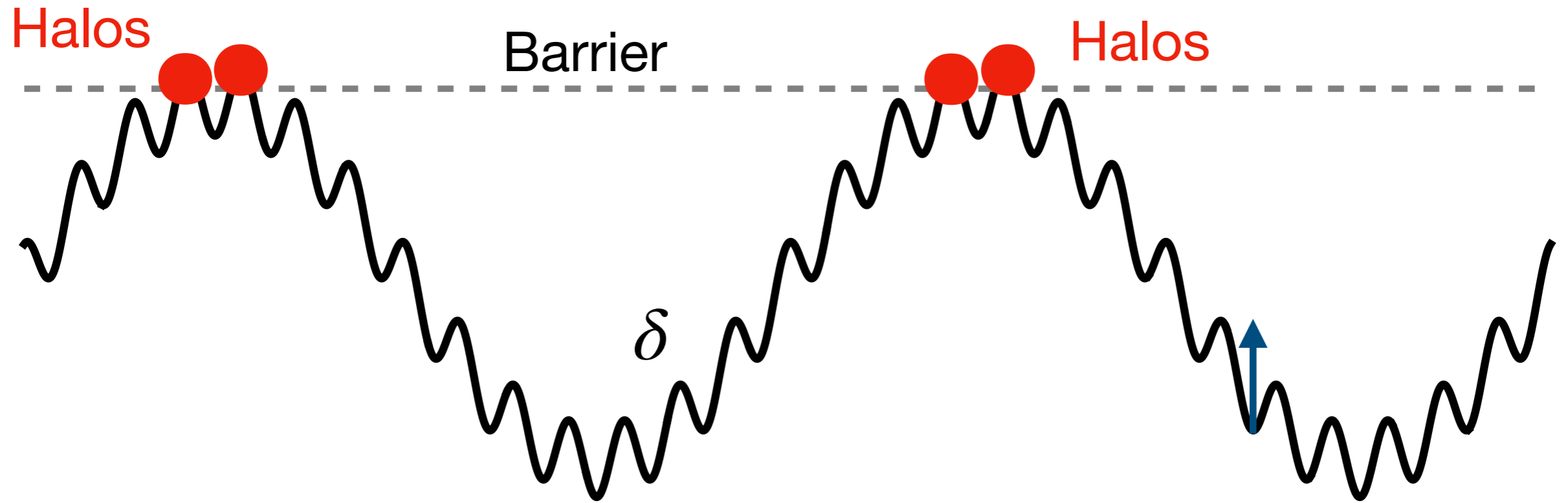
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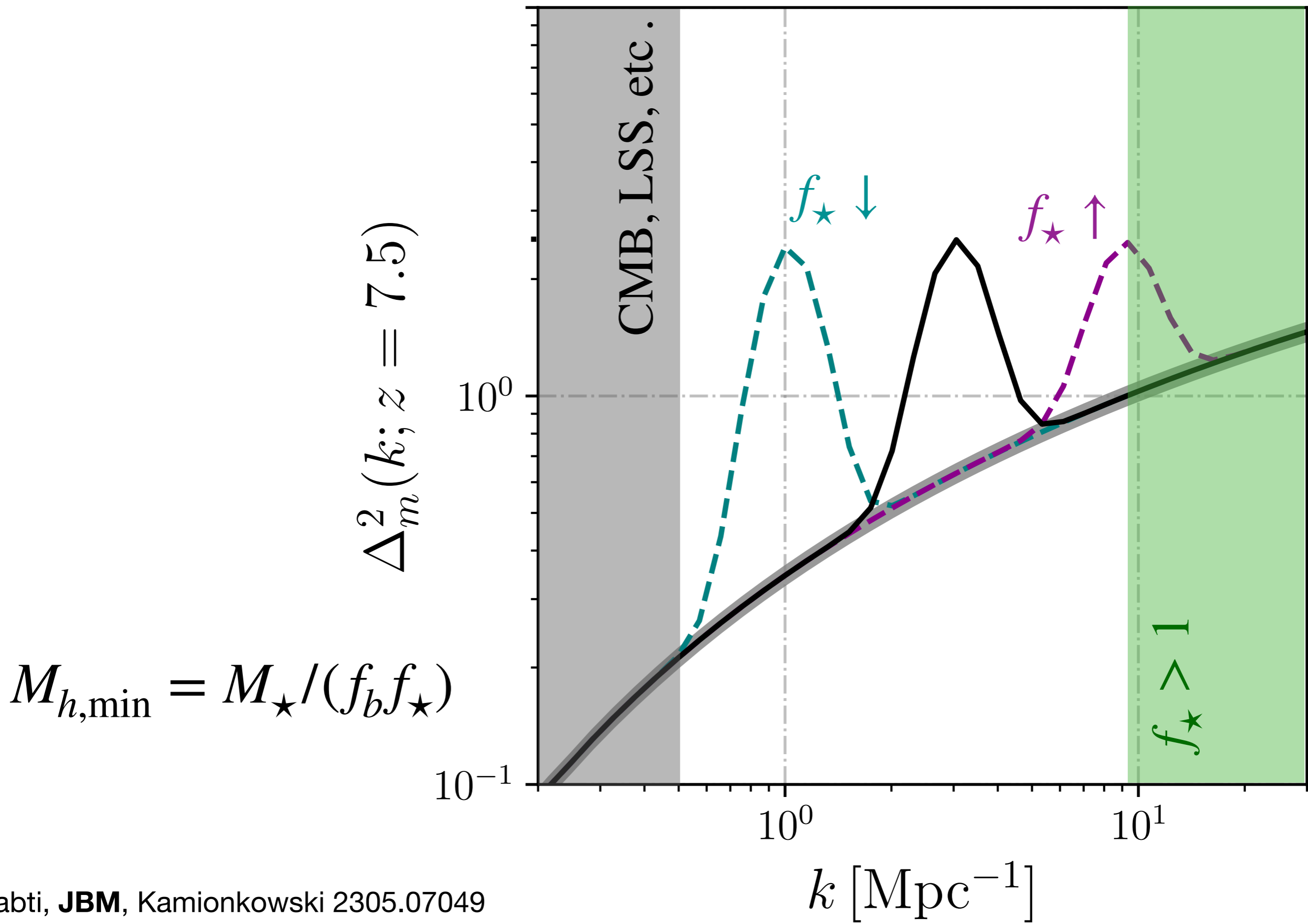
Halos from fluctuations

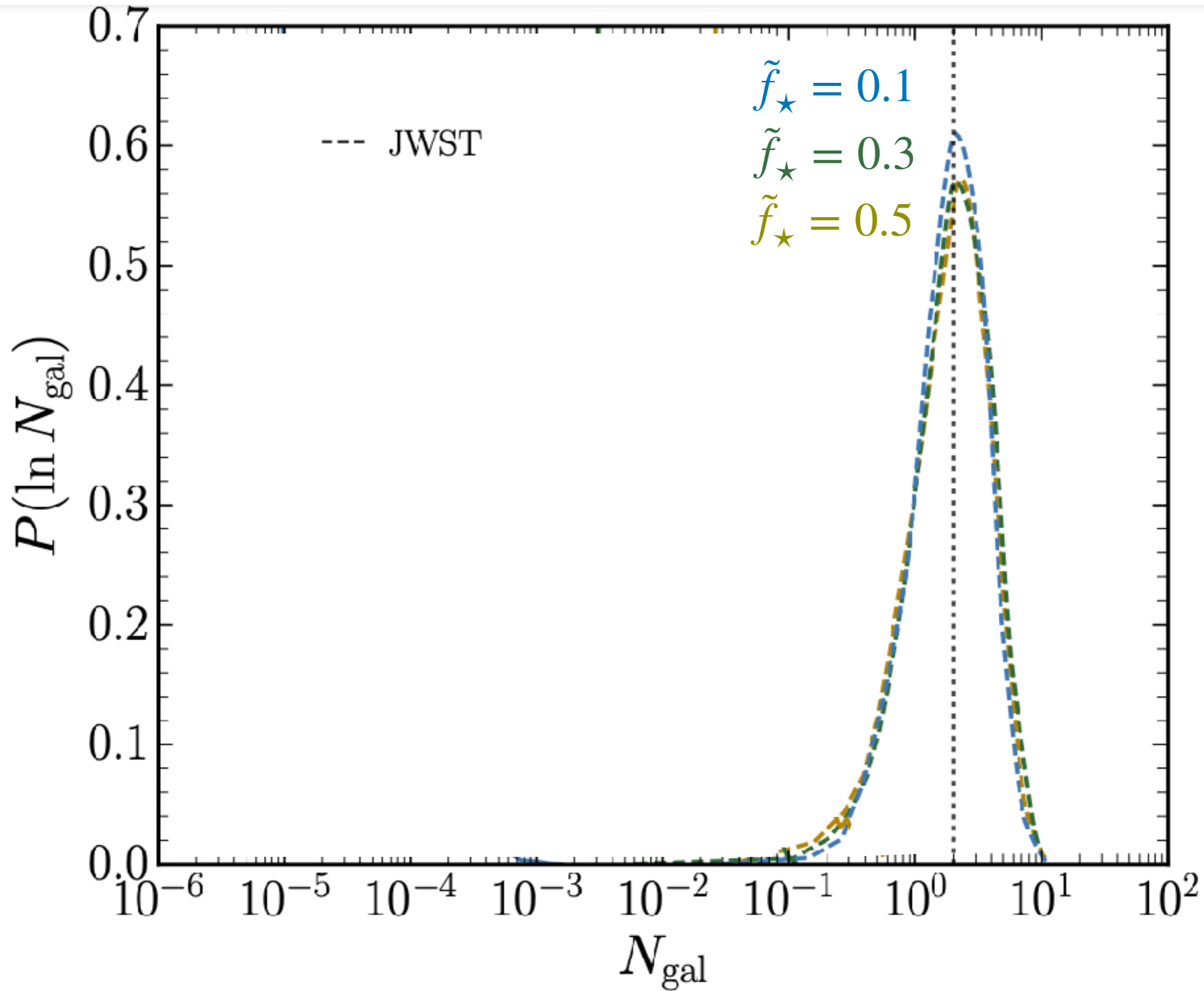


Halos from fluctuations

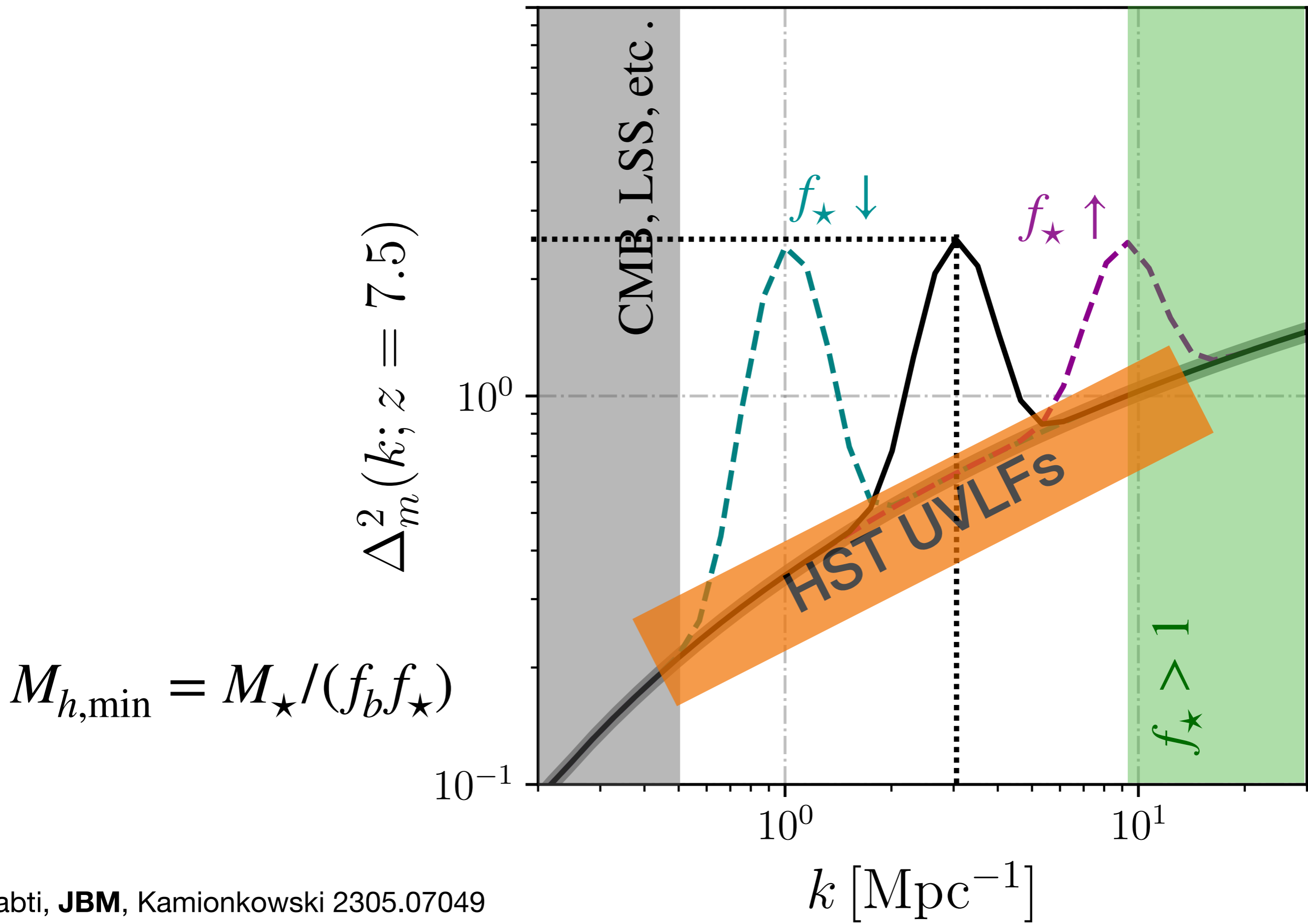


Is there more power?



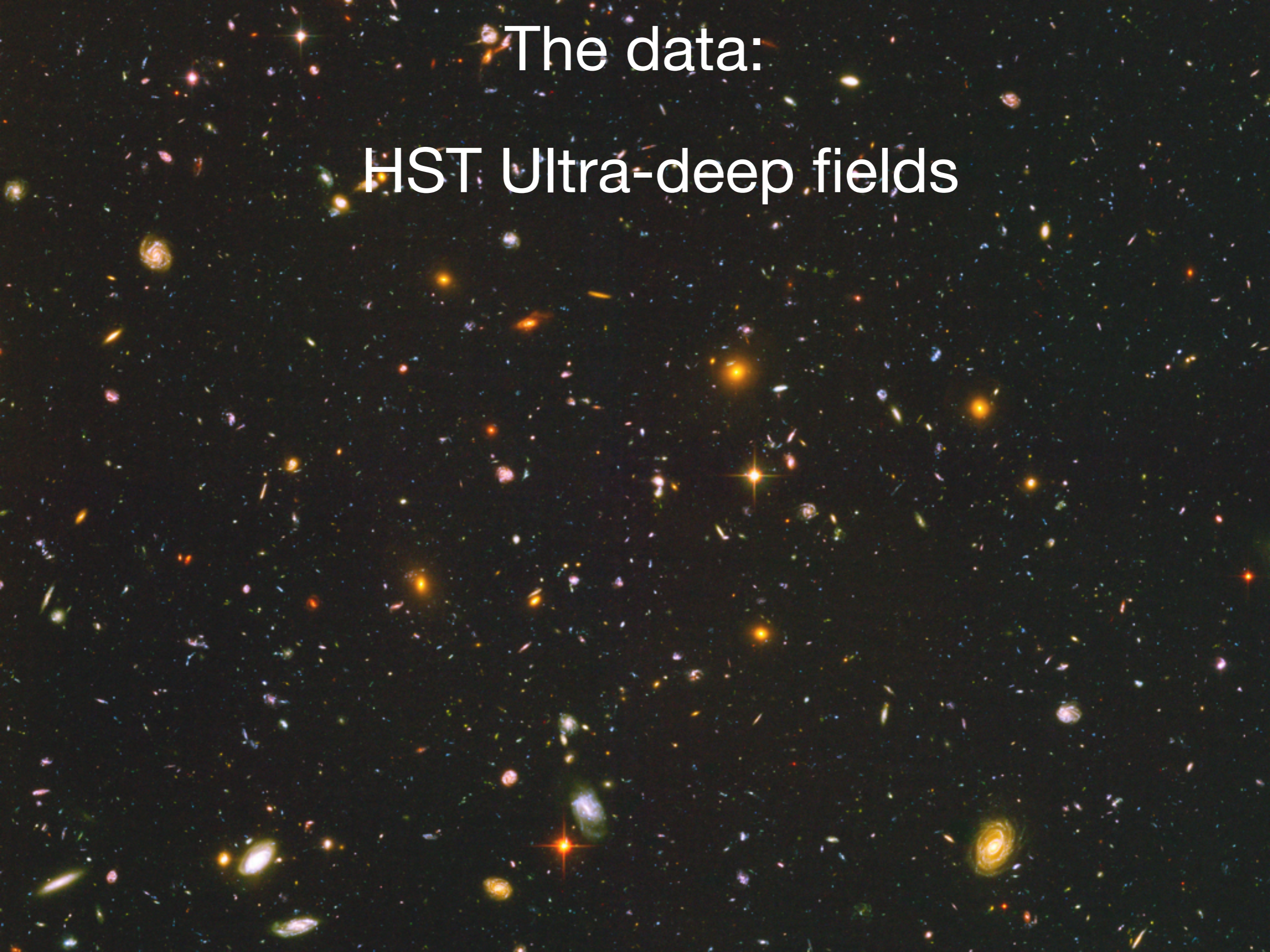


Is there more power?

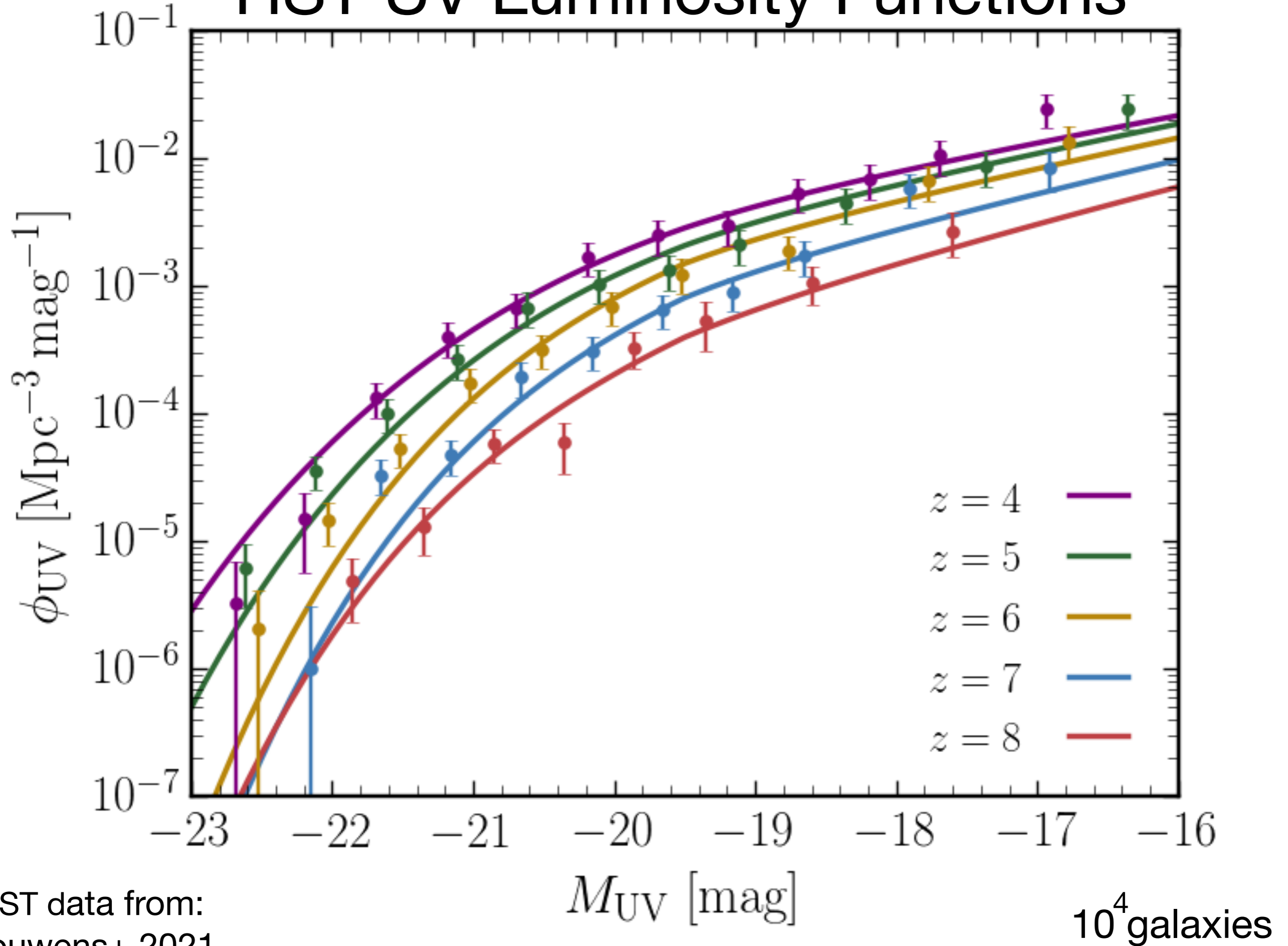


The data:

HST Ultra-deep fields

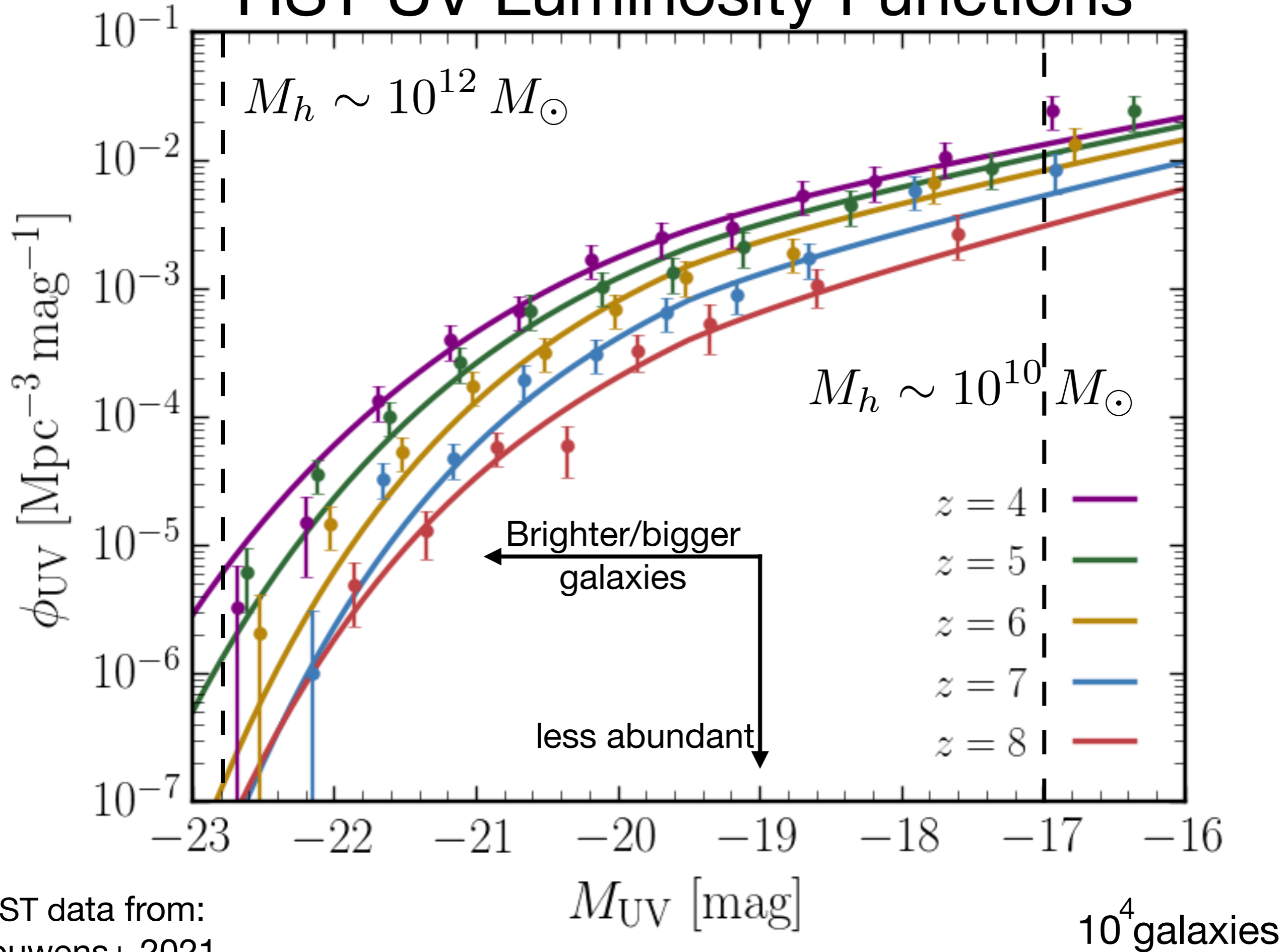


HST UV Luminosity Functions

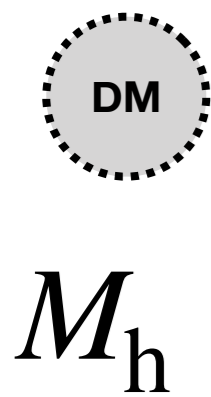


HST data from:
Bouwens+ 2021

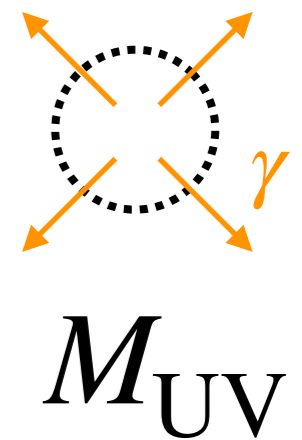
HST UV Luminosity Functions



HST UV Luminosity Functions (Simple theoretical model)

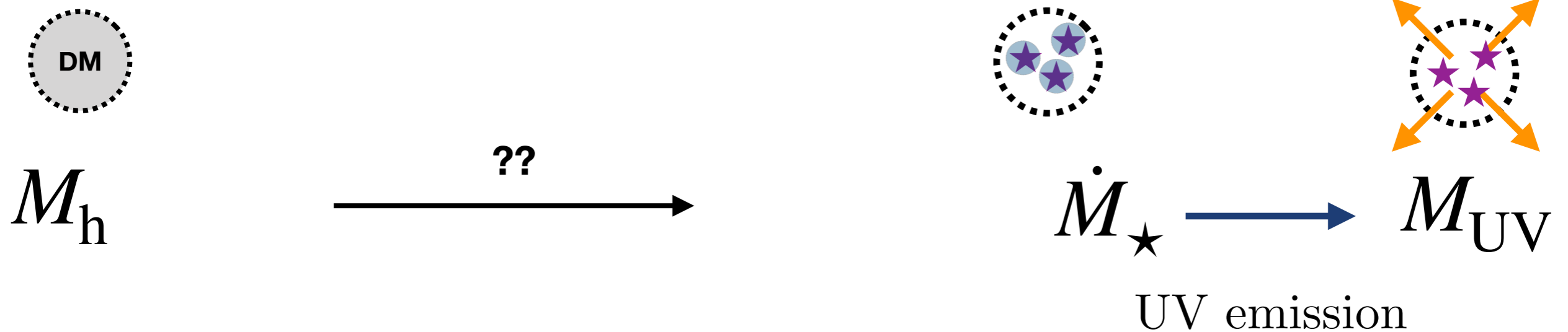


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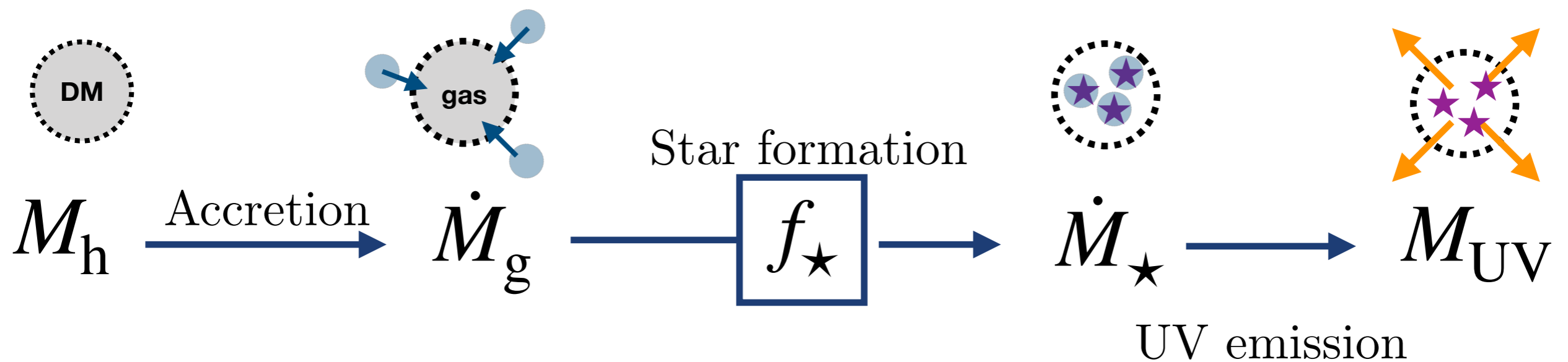
HST UV Luminosity Functions (Simple theoretical model)

Assumption 1: UV light comes from young stars

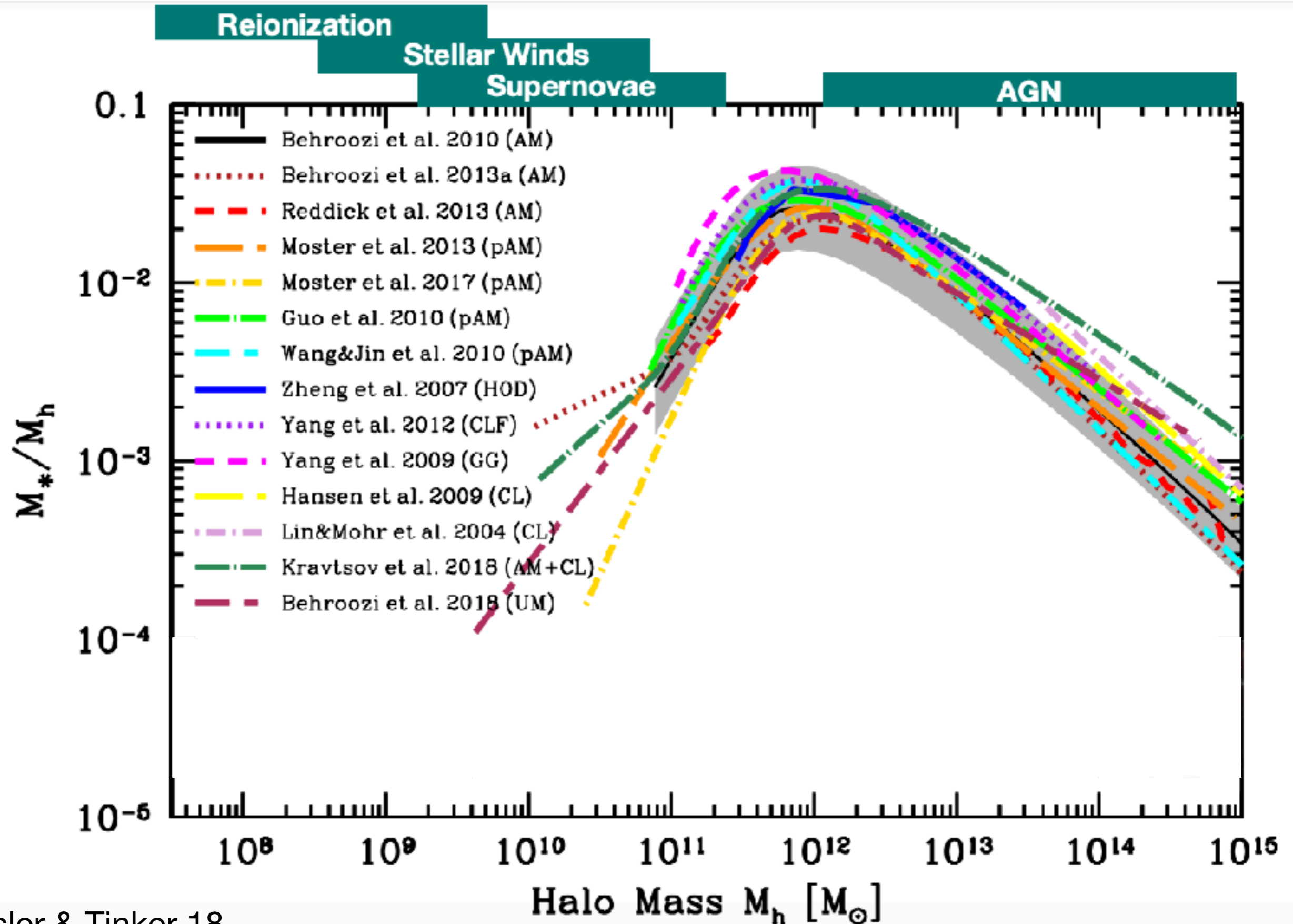


HST UV Luminosity Functions (Simple theoretical model)

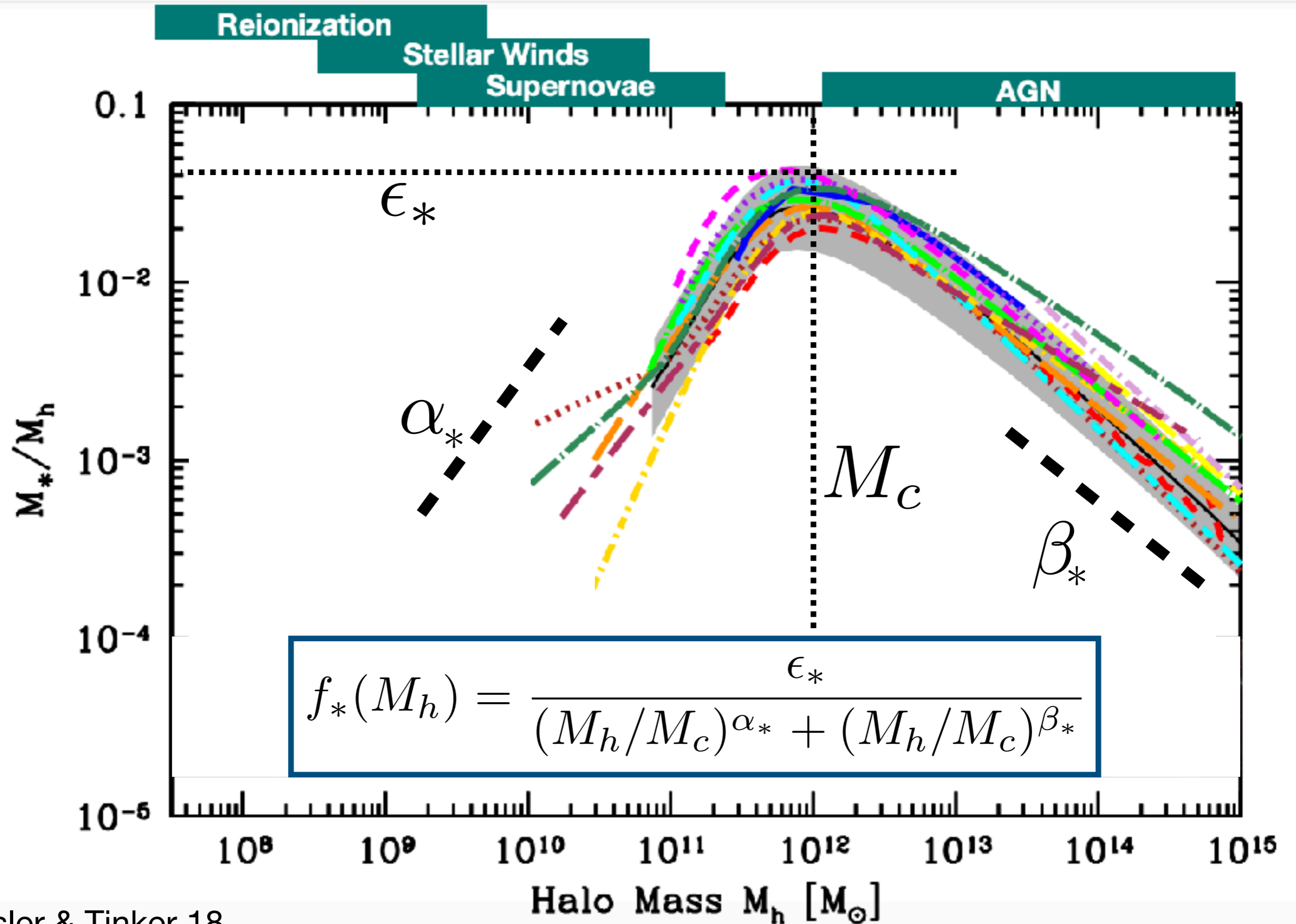
Assumption 2: \dot{M}_* is a parametric function of \dot{M}_h

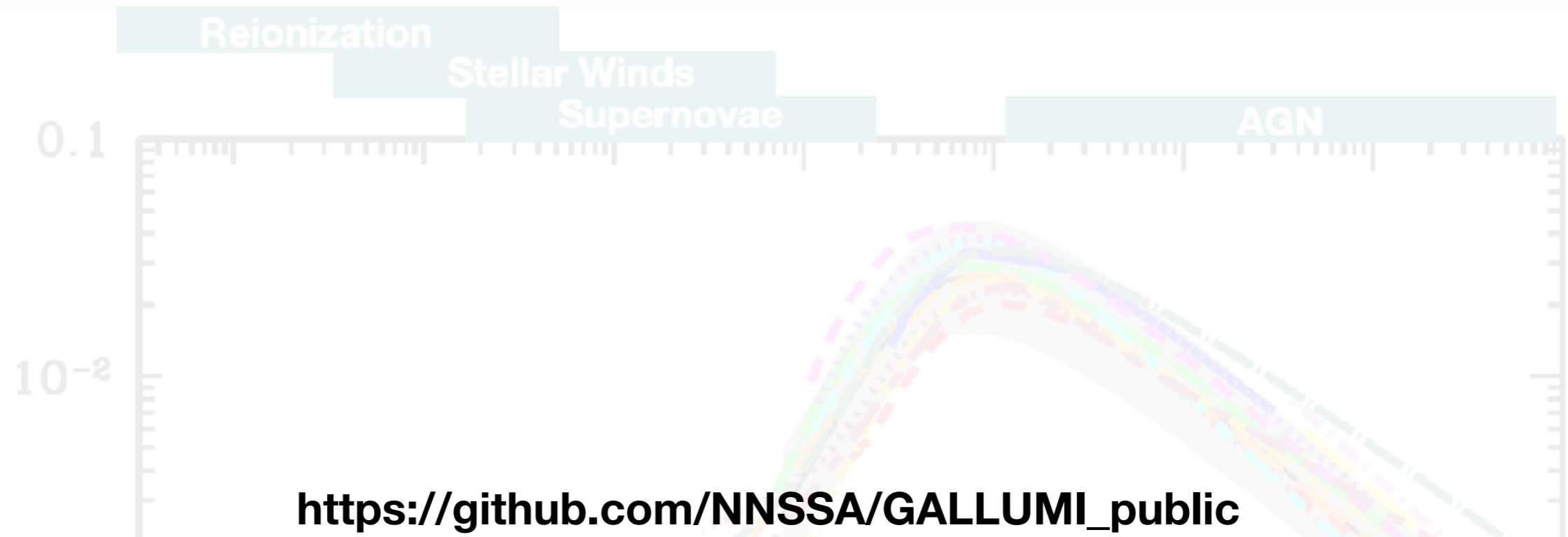


Halo-galaxy connection

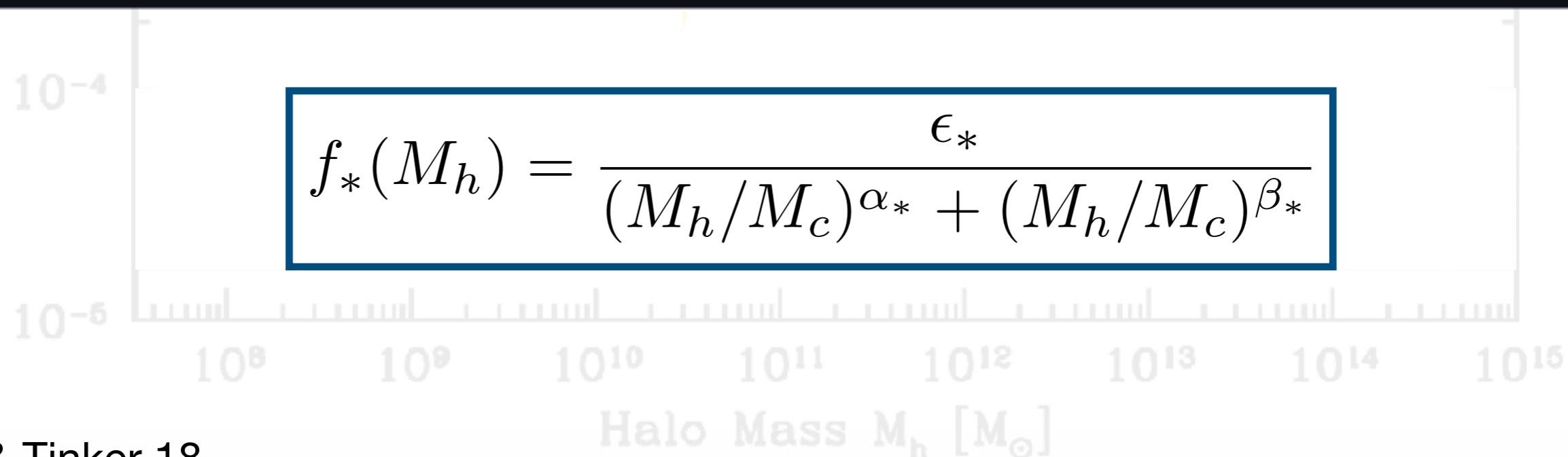


Halo-galaxy connection: a SAM





GALLUMI: A Galaxy Luminosity Function Pipeline for Cosmology and Astrophysics



GALLUMI

https://github.com/NNSSA/GALLUMI_public

Fast (~ 10 ms) SAM + likelihood

$$M_h \begin{matrix} \xrightarrow{\text{red}} \\ \xrightarrow{\text{blue}} \\ \xrightarrow{\text{green}} \end{matrix} M_{UV}$$

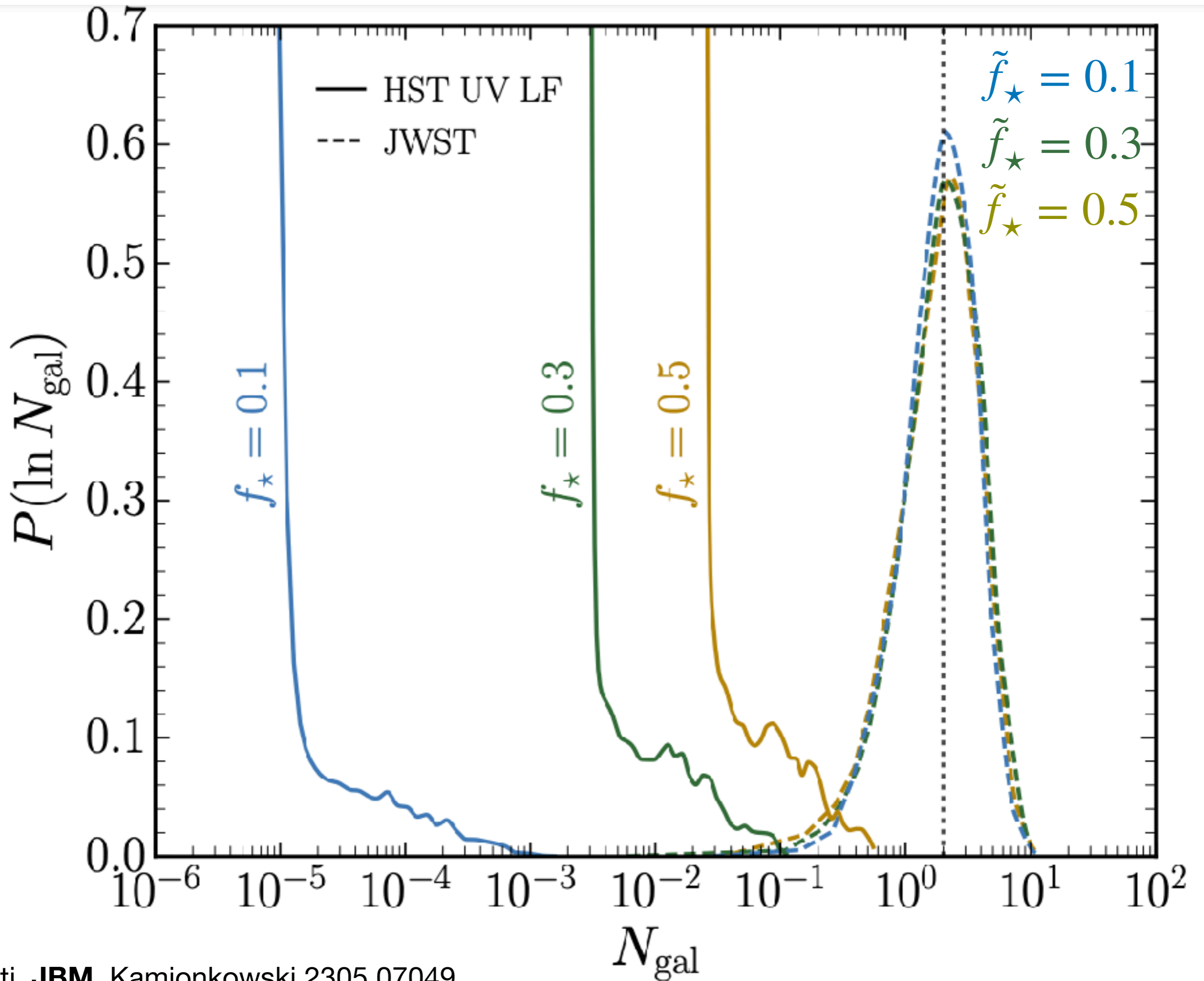
Three halo-galaxy connections, with **stochasticity**

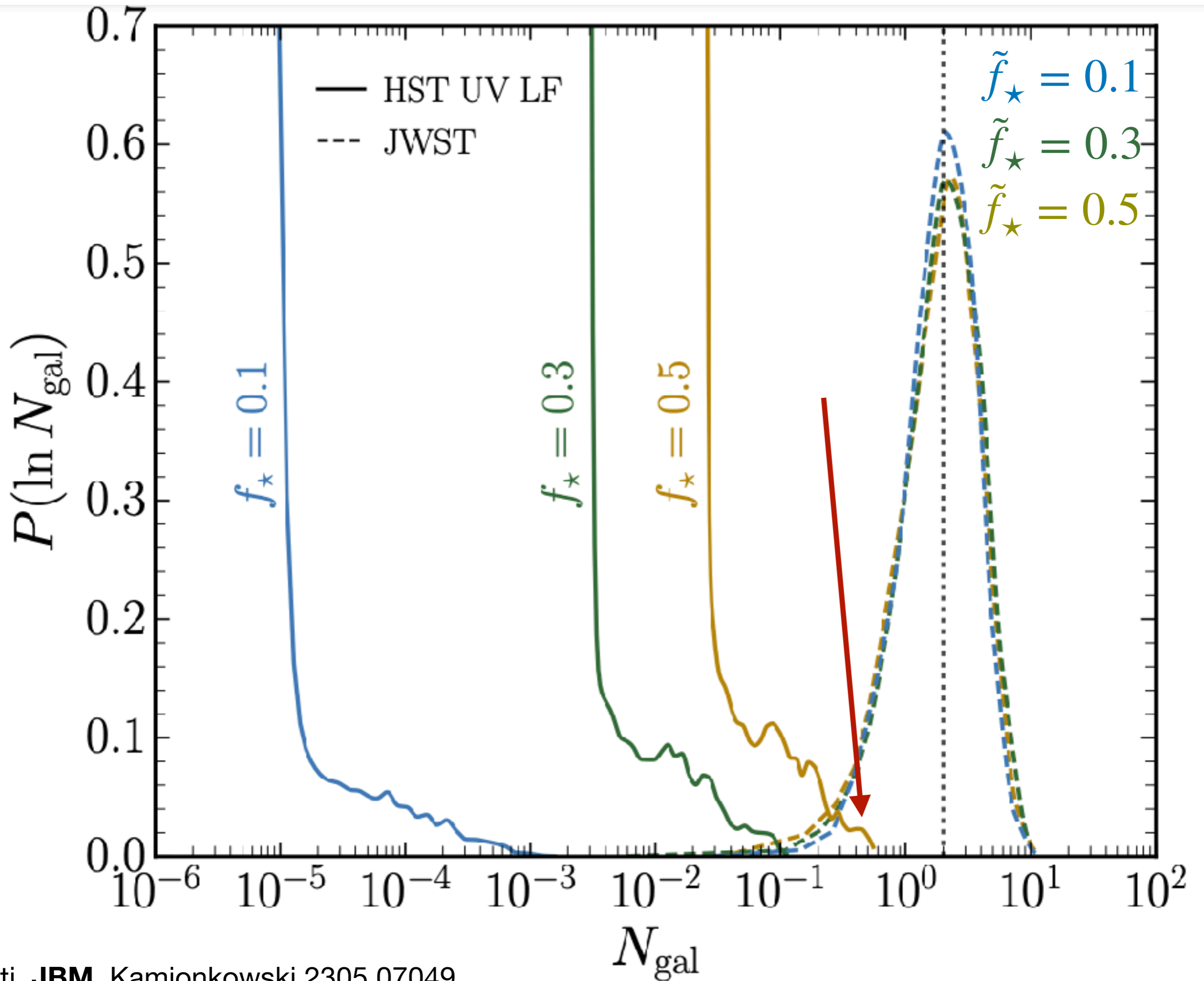
Different dust assumptions

Talks to Montepython 3 + public

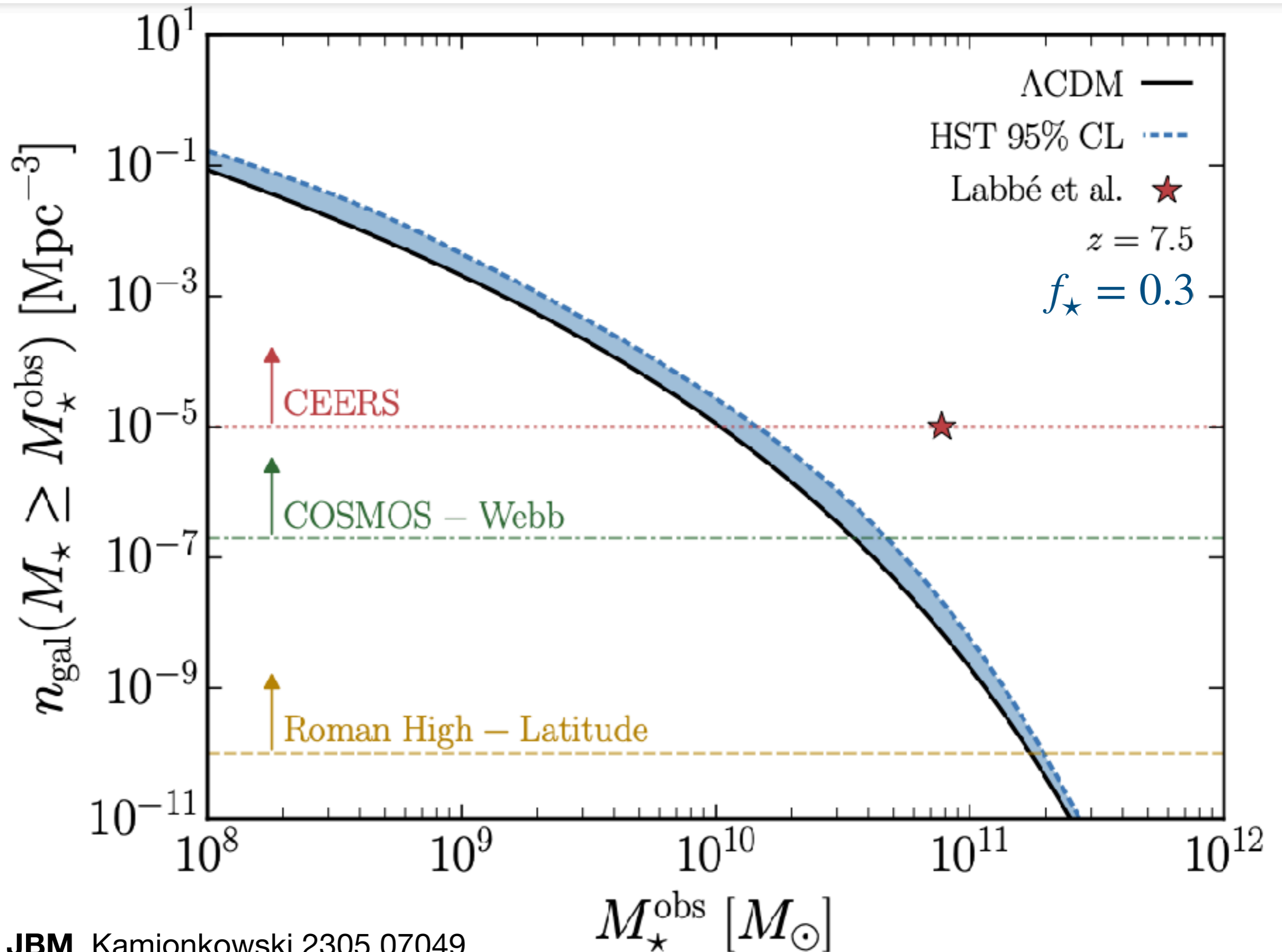
Sabti*, **JBM**,
Blas 2021a,b



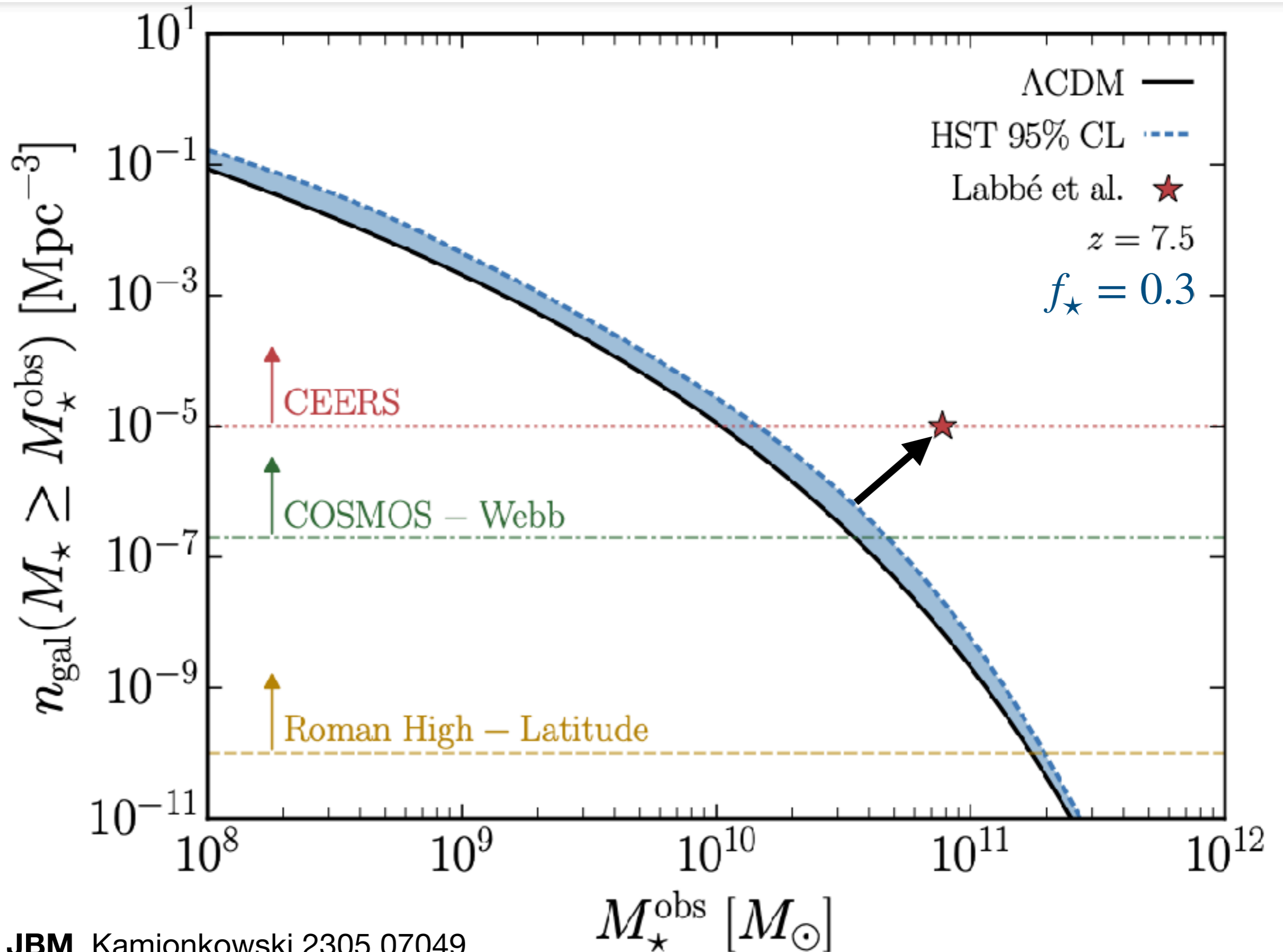




How many massive galaxies?



So what is it??



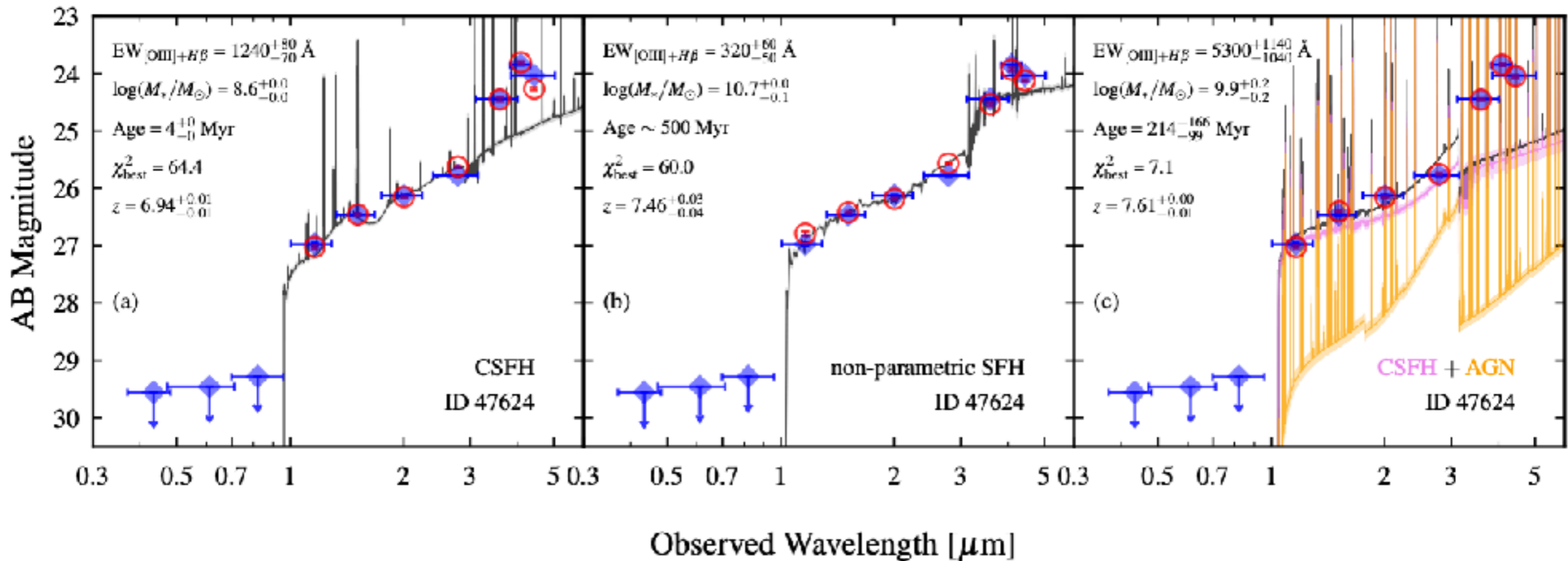
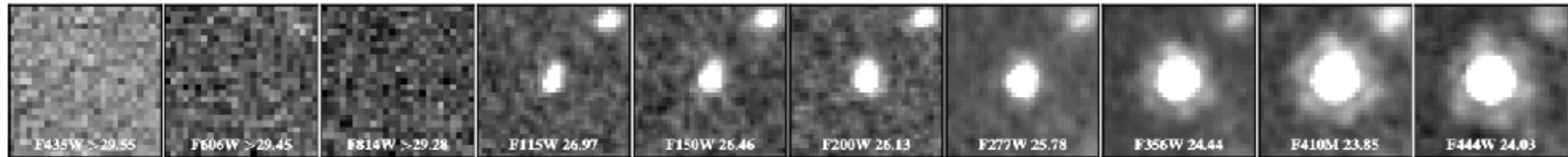
A lower mass from spectra

(At $z \sim 9$)

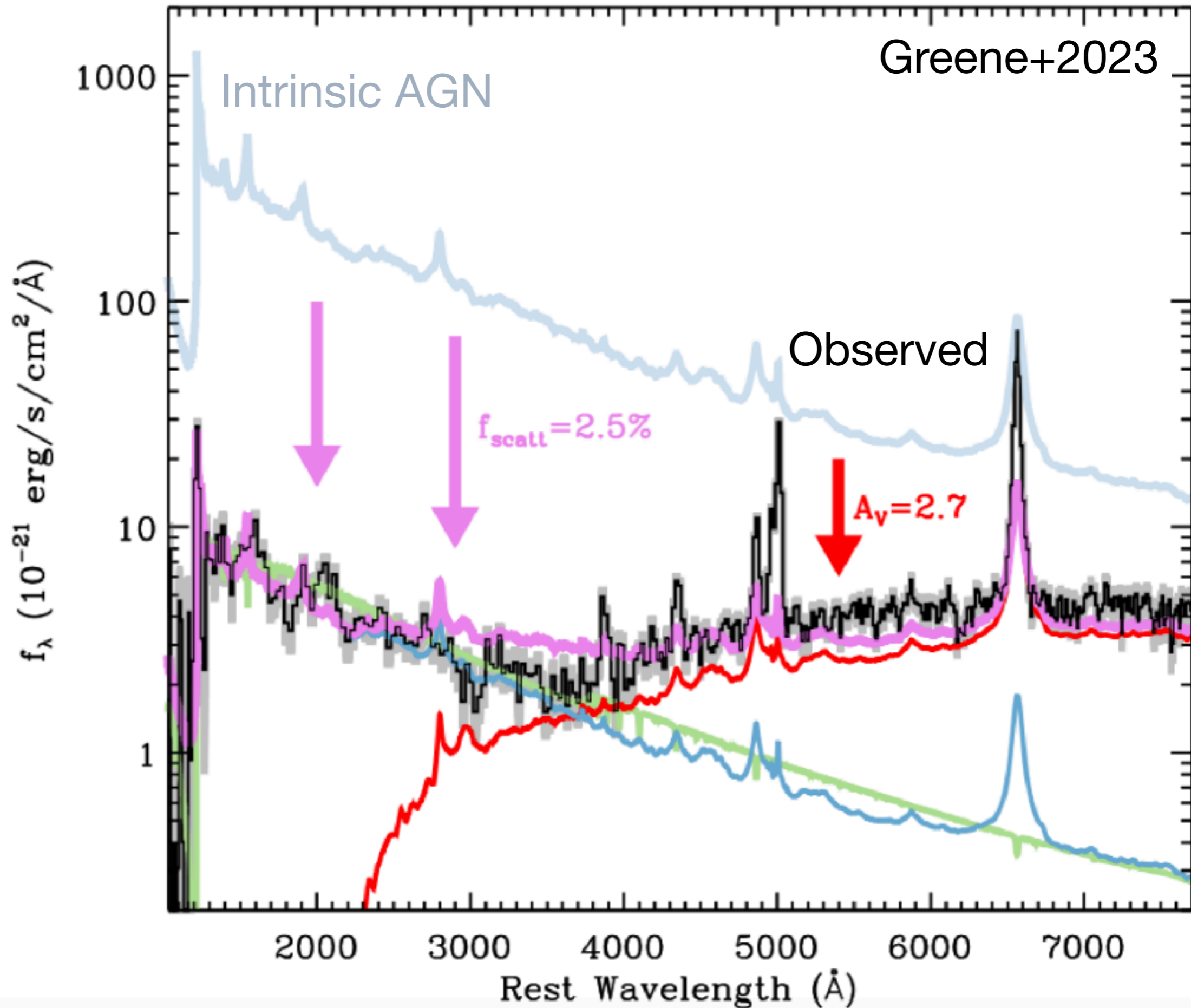
Table 2. Physical Properties of the NIRCам CEERS galaxies confirmed at $z \simeq 8 - 9$

MPT-ID	z_{spec}	M_{UV} (mag)	$E(B - V)$ (mag)	SFR ($M_{\odot} \text{ yr}^{-1}$)	M_{star} ($10^8 M_{\odot}$)	f_{burst}	EW([OIII]5008) (\AA)	EW(H β) (\AA)	R3	O32	Mode
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
2	8.807	-20.44	$0.03^{+0.03}_{-0.02}$	$3.2^{+1.1}_{-0.5}$	$1.2^{+0.8}_{-0.6}$	$0.12^{+0.18}_{-0.08}$	372 ± 112	< 150	> 2.5	> 8.2	P
3	8.005	-20.47	$0.15^{+0.04}_{-0.07}$	$9.8^{+2.9}_{-3.2}$	$2.0^{+1.7}_{-0.8}$	$0.25^{+0.21}_{-0.16}$	1022 ± 129	163 ± 62	6.3 ± 2.3	> 8.1	P
4	7.9932	-19.44	$0.33^{+0.12}_{-0.09}$	$16.3^{+21.0}_{-8.1}$	$8.7^{+6.3}_{-4.4}$	$0.10^{+0.18}_{-0.07}$	430 ± 69	< 166	> 2.6	... †	M
7	8.876	-20.75	$0.03^{+0.03}_{-0.02}$	$3.9^{+1.1}_{-0.6}$	$1.2^{+0.9}_{-0.6}$	$0.13^{+0.25}_{-0.09}$	895 ± 436	350 ± 194	2.6 ± 0.8	> 5.5	M
20	7.769	-18.55	$0.61^{+0.02}_{-0.18}$	$64.3^{+18.6}_{-50.8}$	$30.6^{+19.7}_{-13.0}$	$0.08^{+0.13}_{-0.06}$	109 ± 19	50 ± 16	2.2 ± 0.8	> 6.1	P
23	8.8805	-18.38	$0.06^{+0.1}_{-0.04}$	$0.8^{+0.7}_{-0.3}$	$0.2^{+0.2}_{-0.1}$	$0.21^{+0.23}_{-0.14}$	1195 ± 200	208 ± 121	5.8 ± 3.3	> 6.5	M
24	8.998	-19.08	$0.09^{+0.08}_{-0.06}$	$2.7^{+1.5}_{-1.0}$	$0.6^{+0.6}_{-0.3}$	$0.23^{+0.22}_{-0.15}$	989 ± 131	$173 \pm 51^{\dagger\dagger}$	5.7 ± 1.7	> 5.0	M

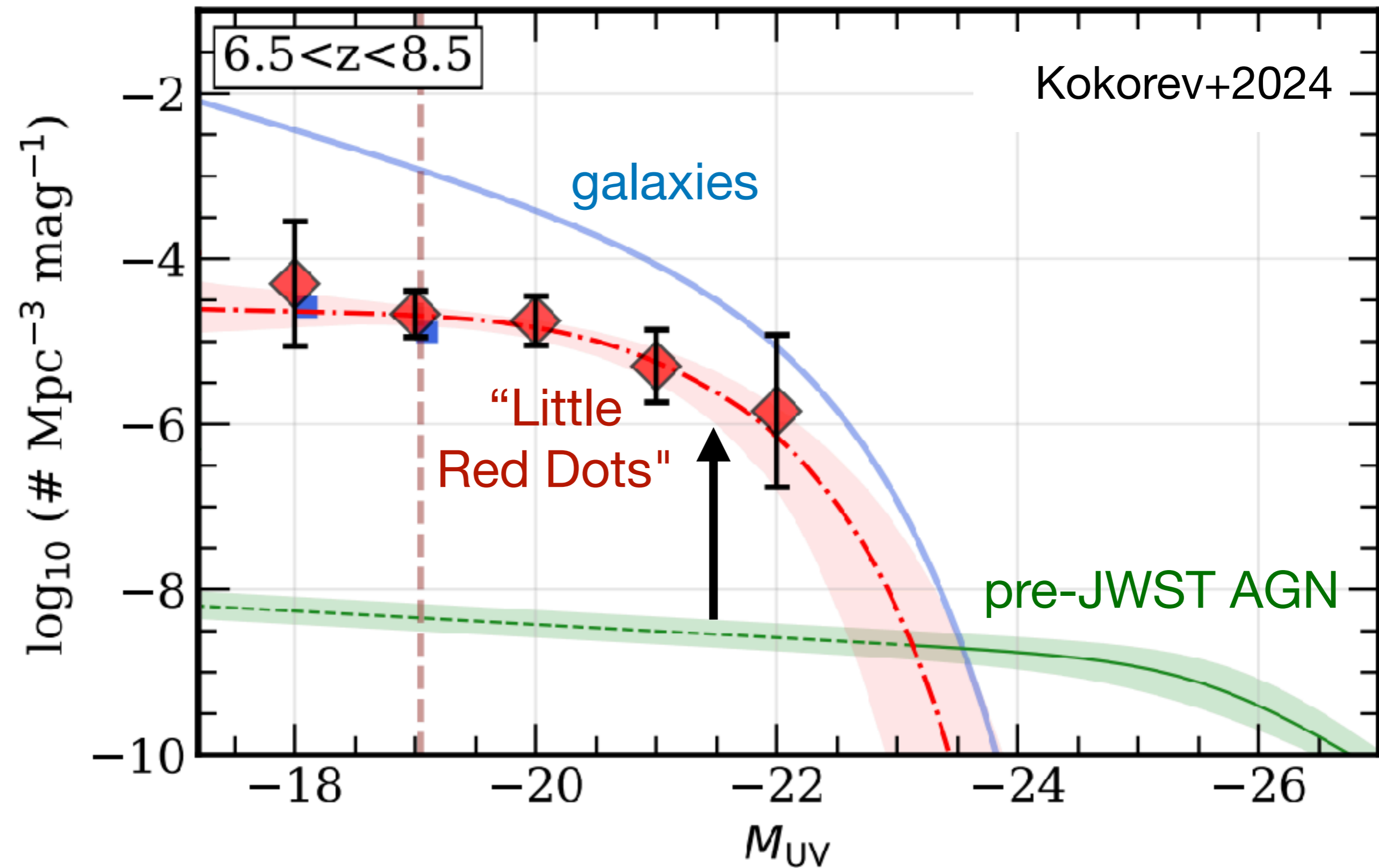
Perhaps one of them hosts a QSO? (At $z \sim 7.5$)



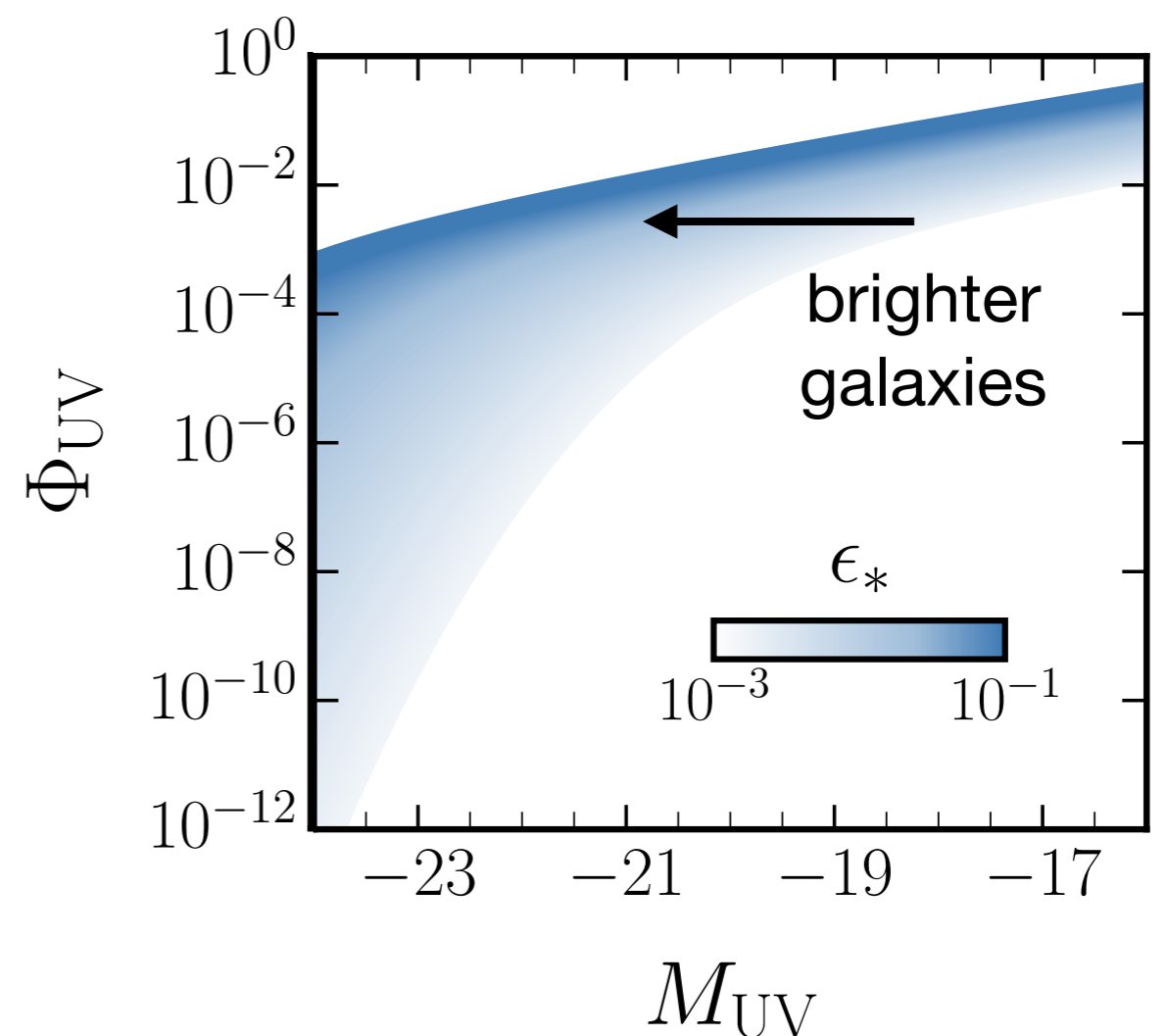
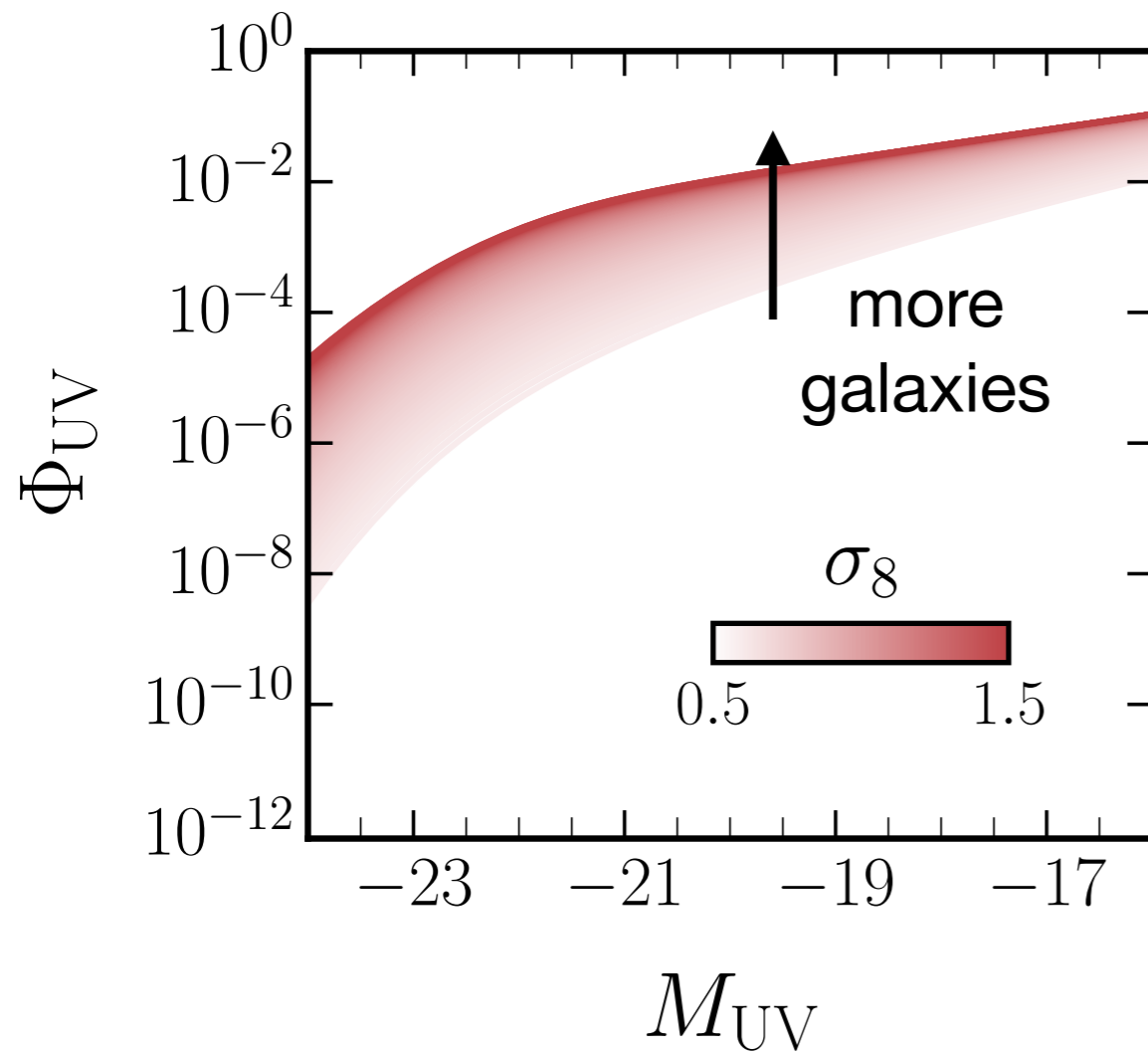
Detour: SMBHs??



Detour: SMBHs??

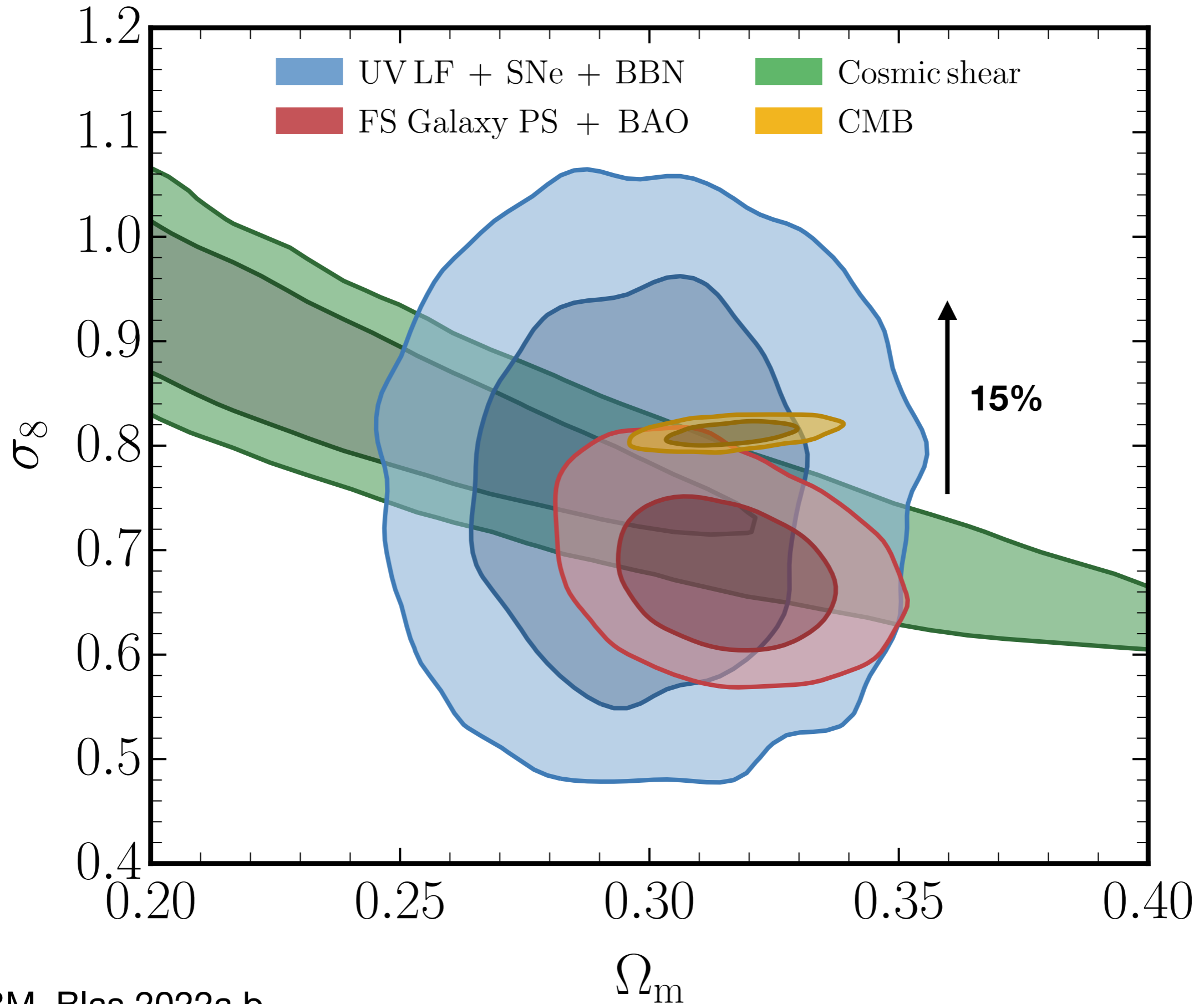


More broadly, what can we learn?

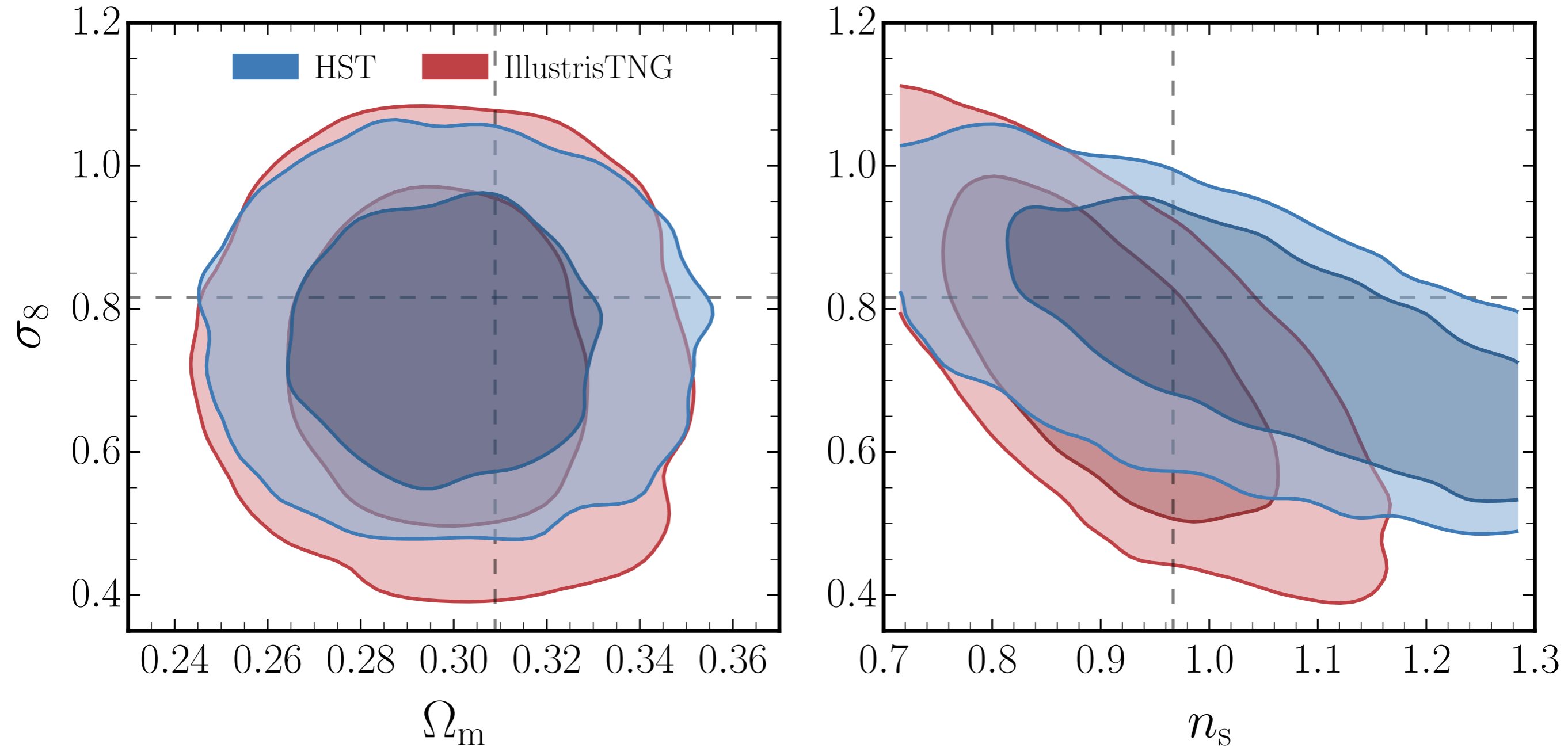


-Separate **cosmology** from **astrophysics**?

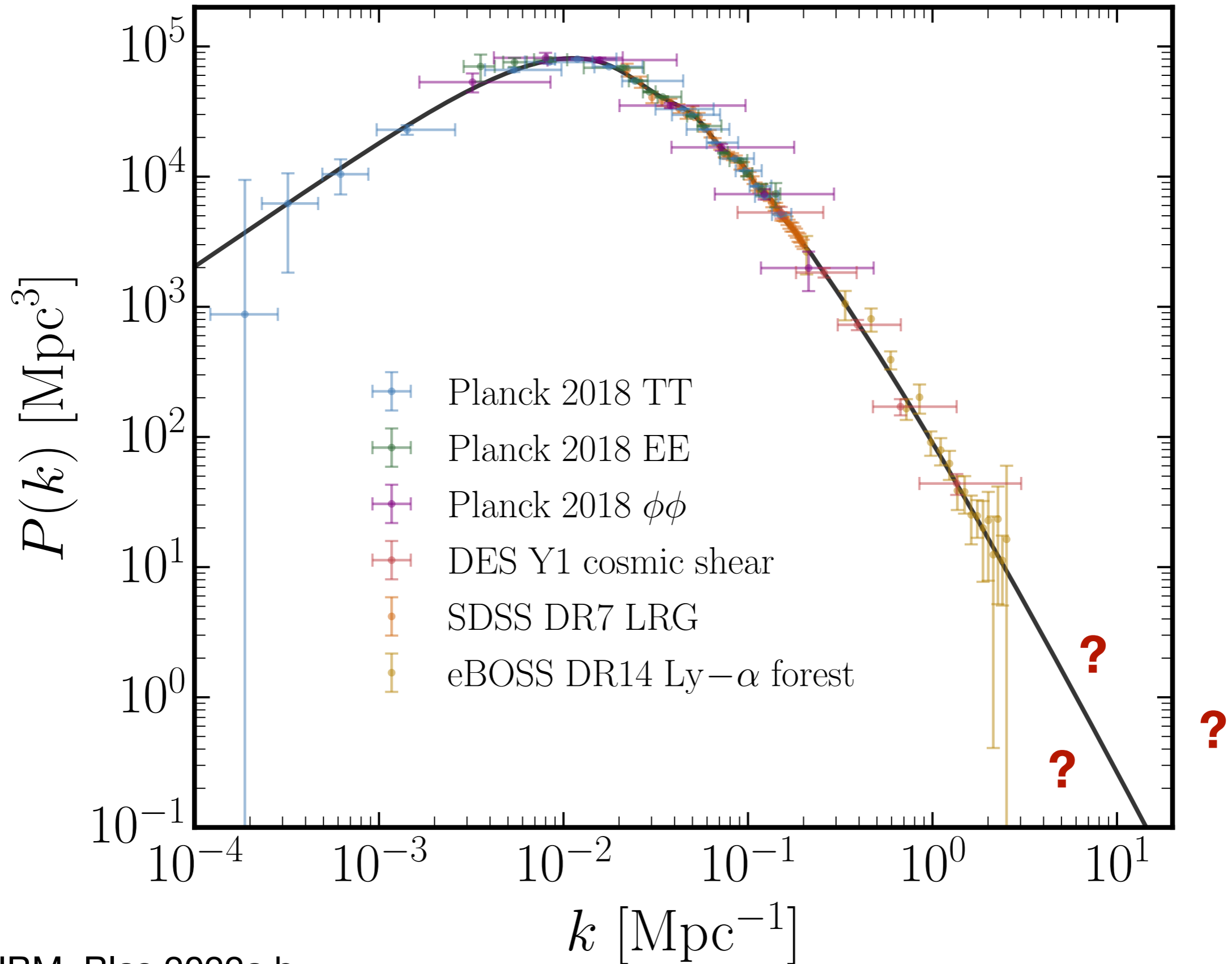
More broadly, what can we learn?



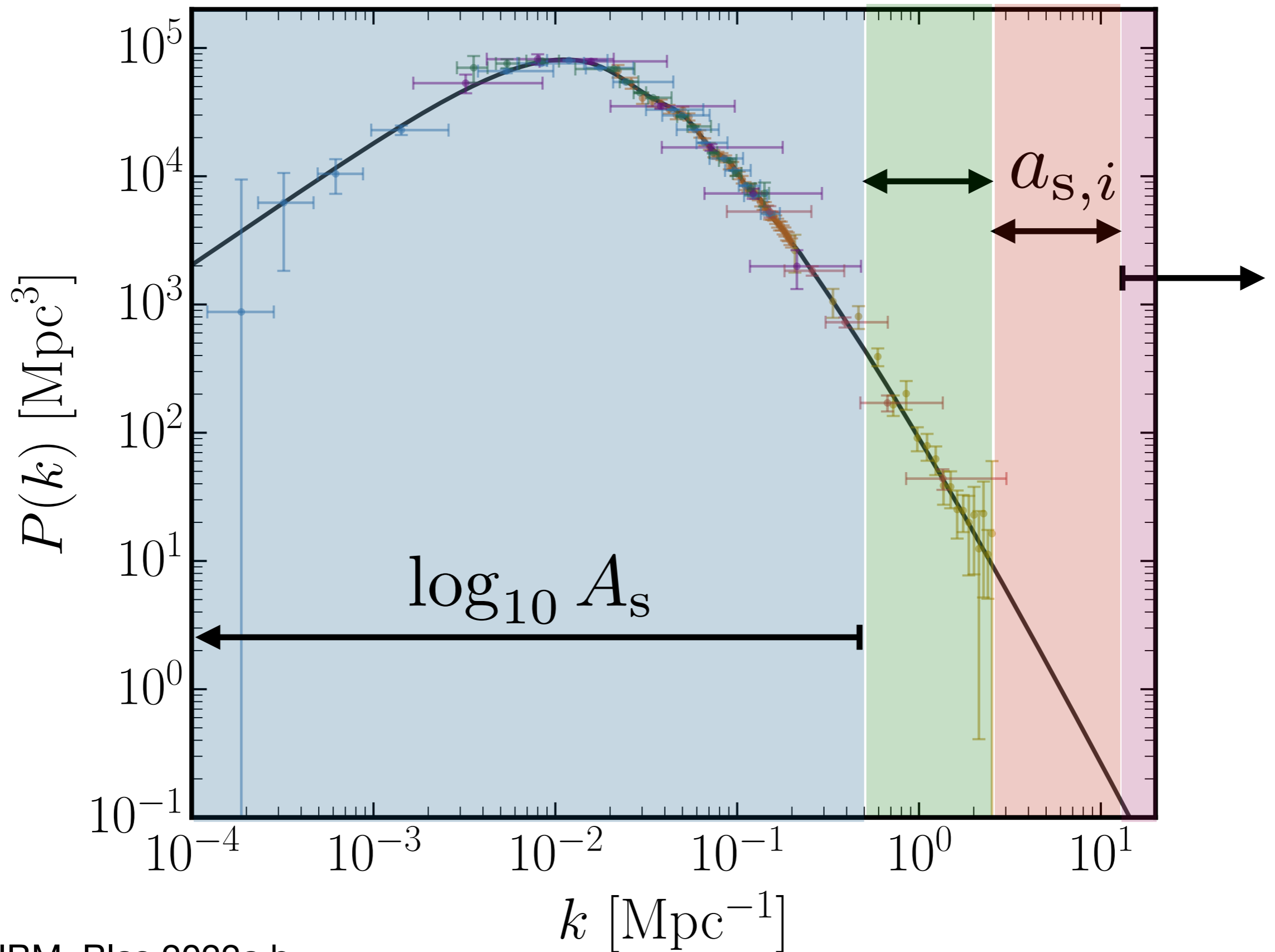
Cross check with IllustrisTNG



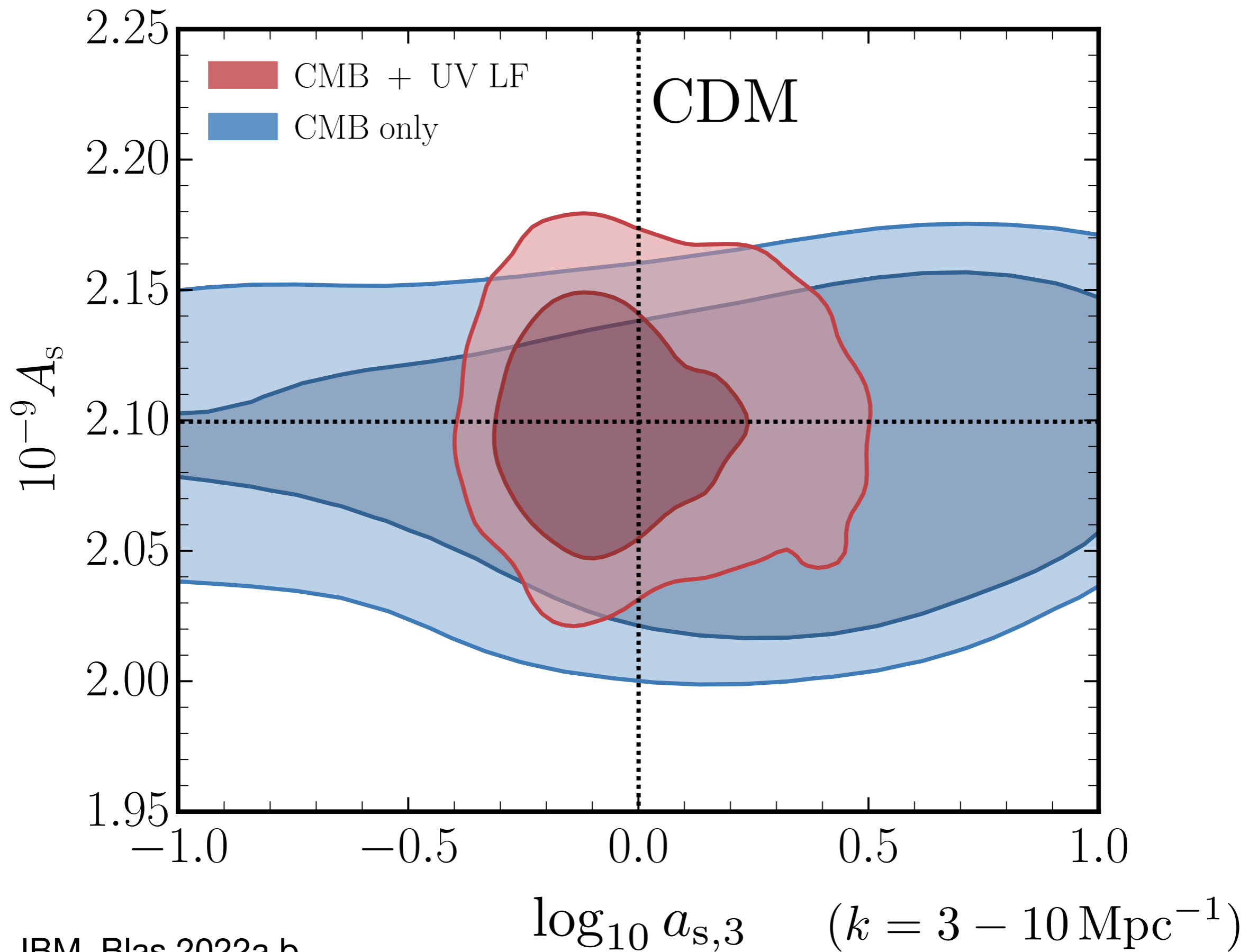
Smaller galaxies -> higher k



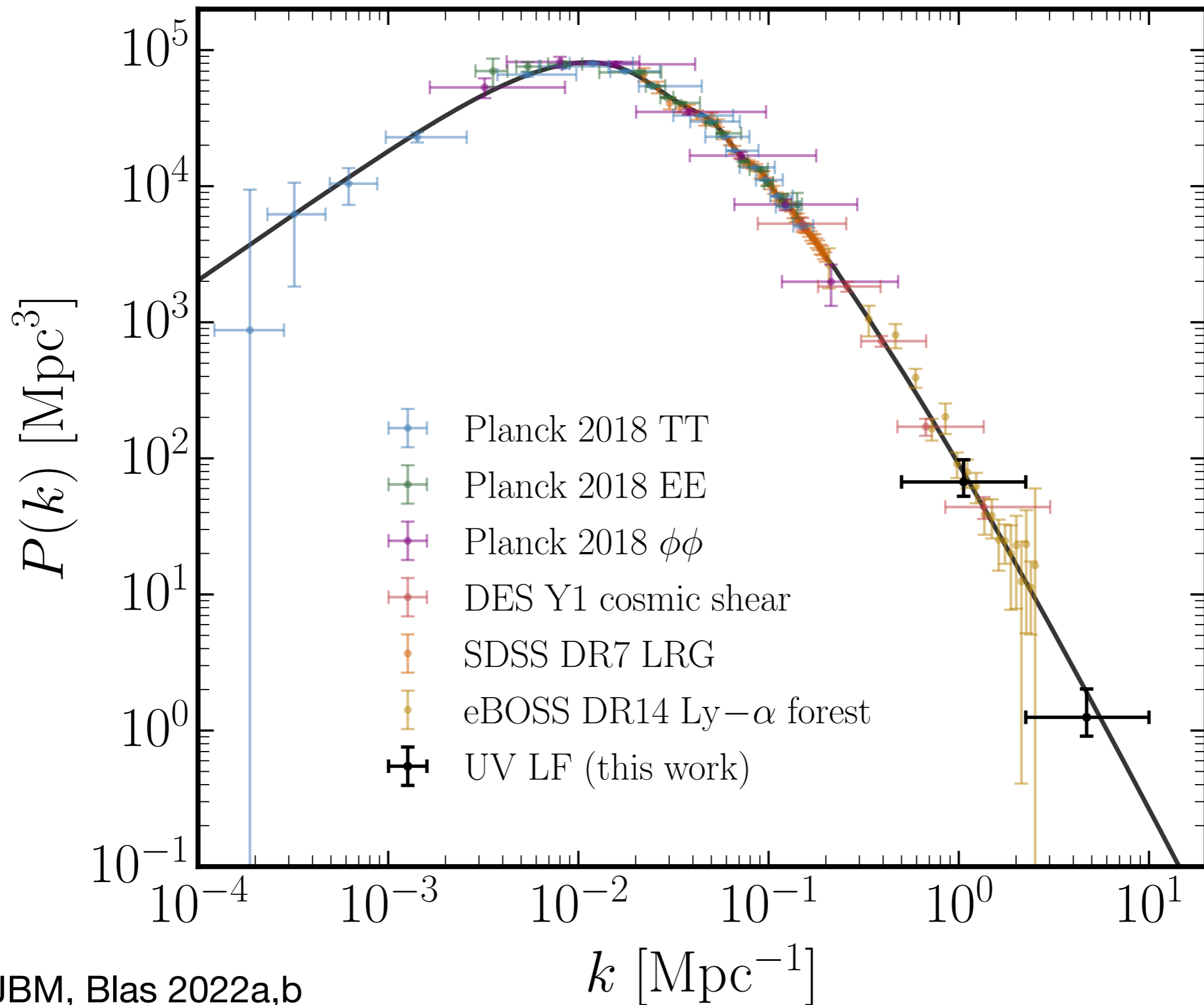
Smaller galaxies -> higher k



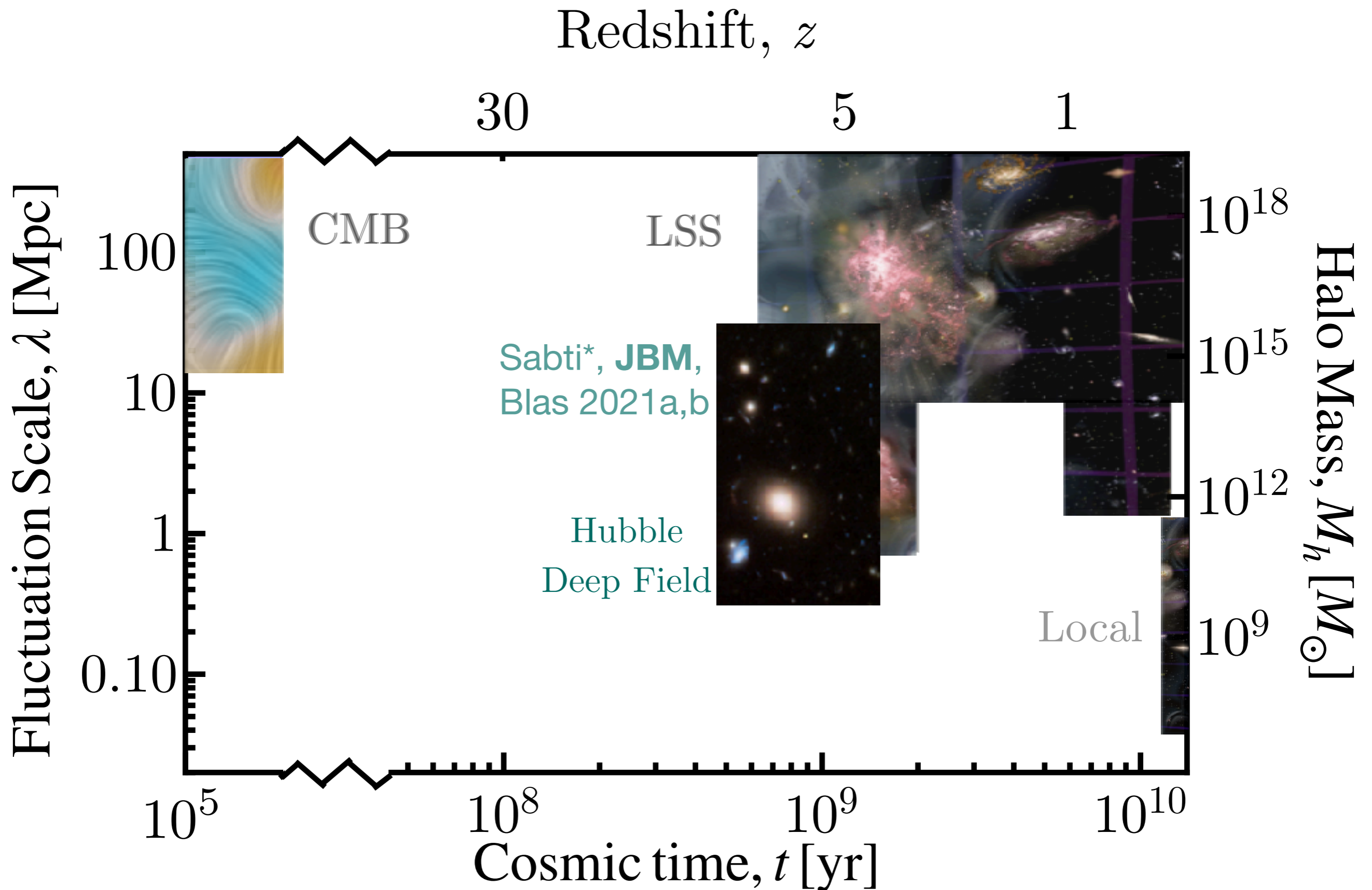
Smaller galaxies -> higher k



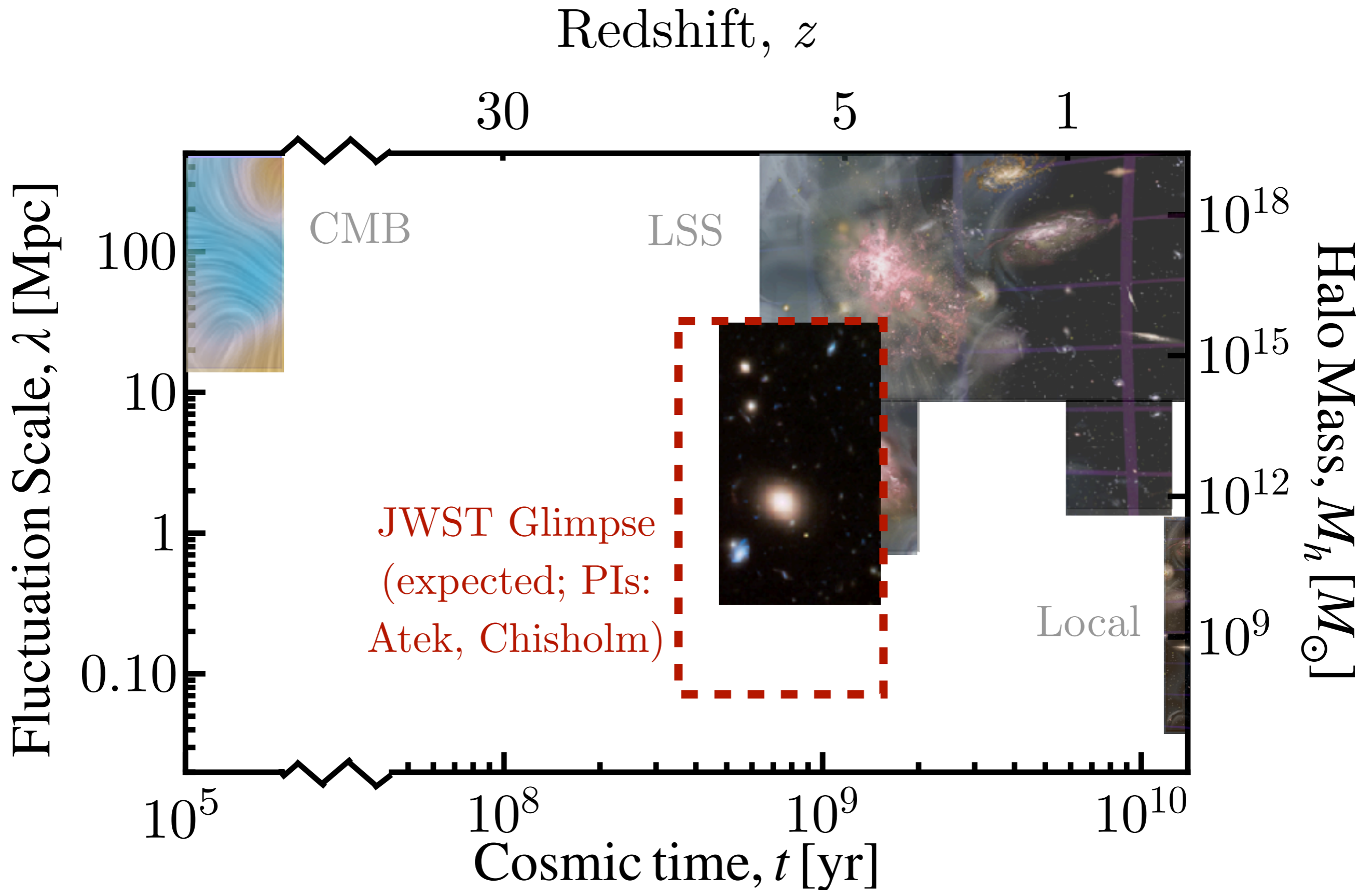
Smaller galaxies -> higher k



Smaller galaxies \rightarrow higher k



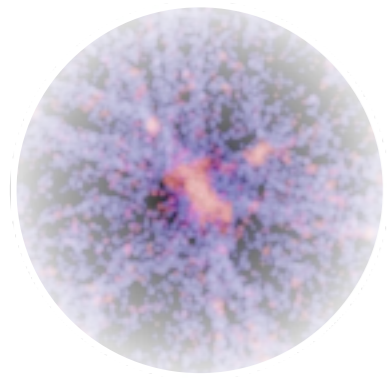
A *Glimpse* of the future



Outline



Does JWST break LCDM?



First galaxies: too many, too early



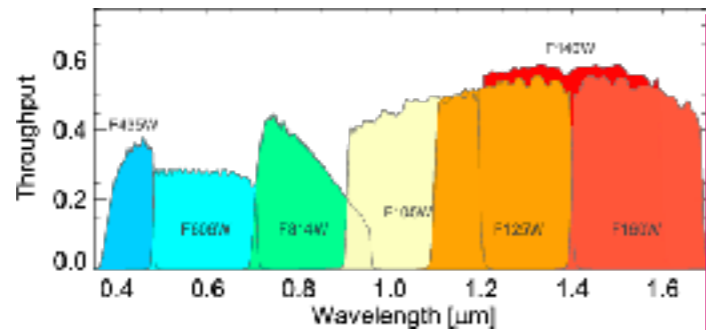
Hubble halfway to the CMB

What does JWST tell us about hi-z galaxies?

Measure rest-frame visible $\rightarrow M_{\star}$

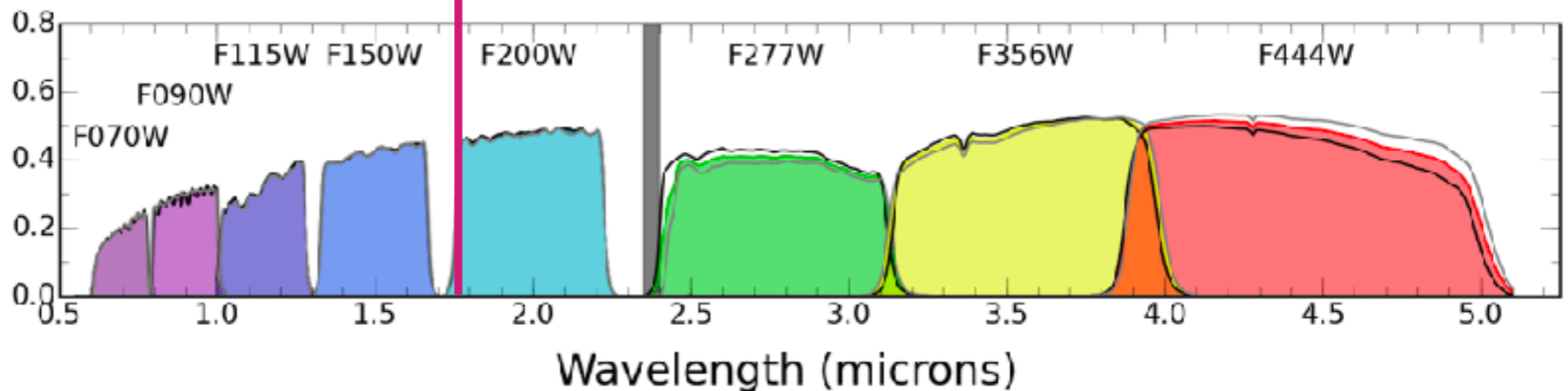
Reach higher redshifts \rightarrow UV at $z \gtrsim 10$

HST

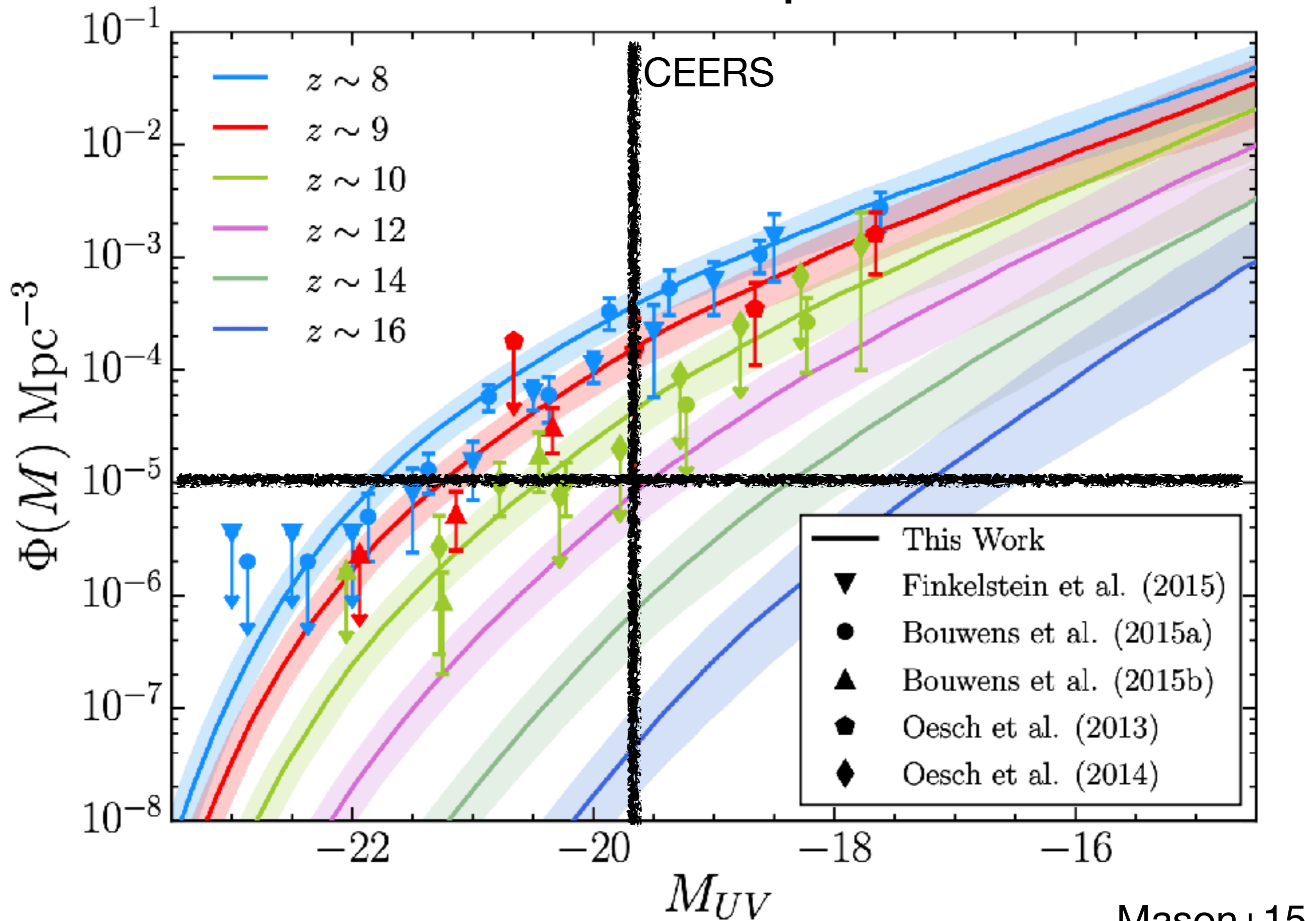


Push Lyman Break to higher z

JWST



What did we expect?



What did we **see**?

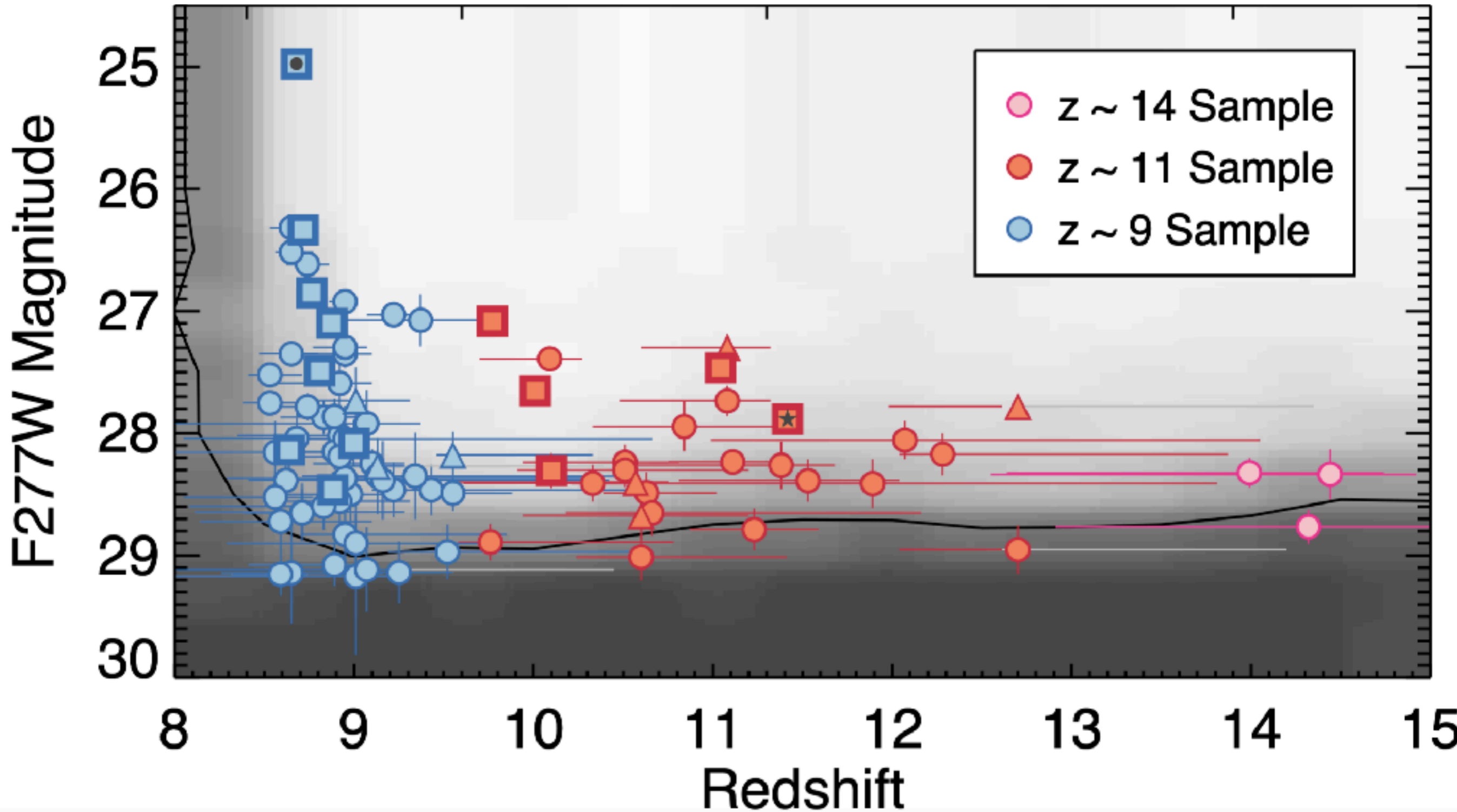
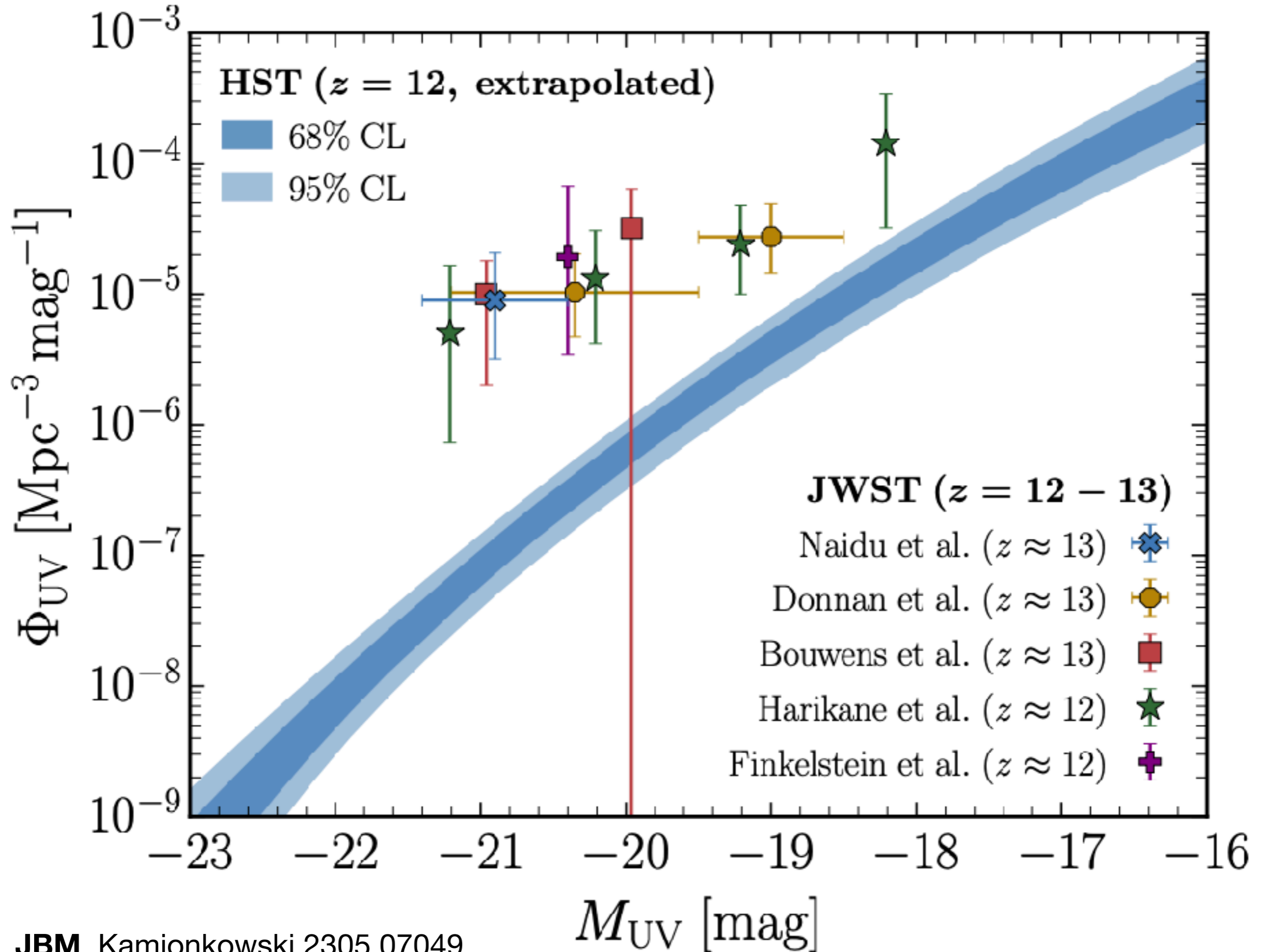


Photo-z only

Finkelstein+ 23 full CEERS catalogue

In more useful terms:



How to explain so many galaxies?

Option 1: More efficient UV emission (on average)

Eg. Steinhardt+22 Dekel+23

Option 2: Stochasticity (width of PDF, burstiness)

Eg. Mason+22 Mirocha+22

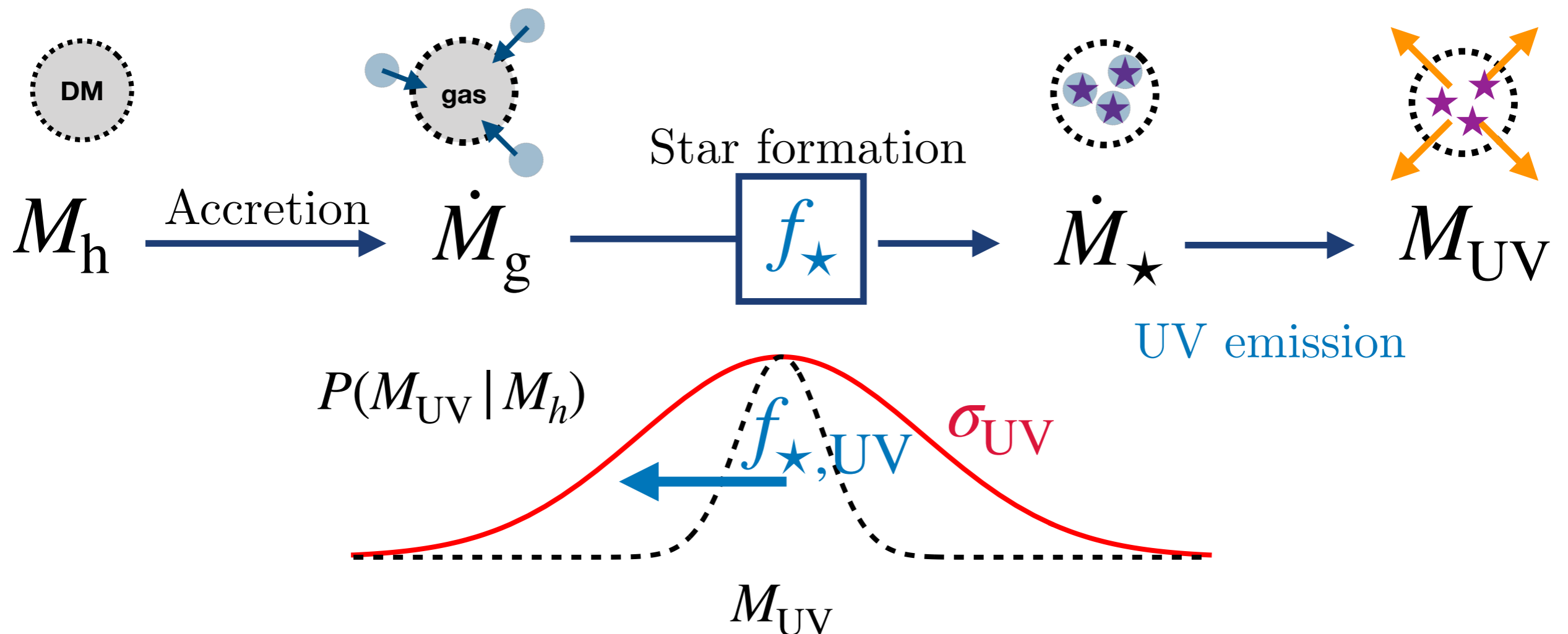
How to explain so many galaxies?

Option 1: More efficient UV emission (on average)

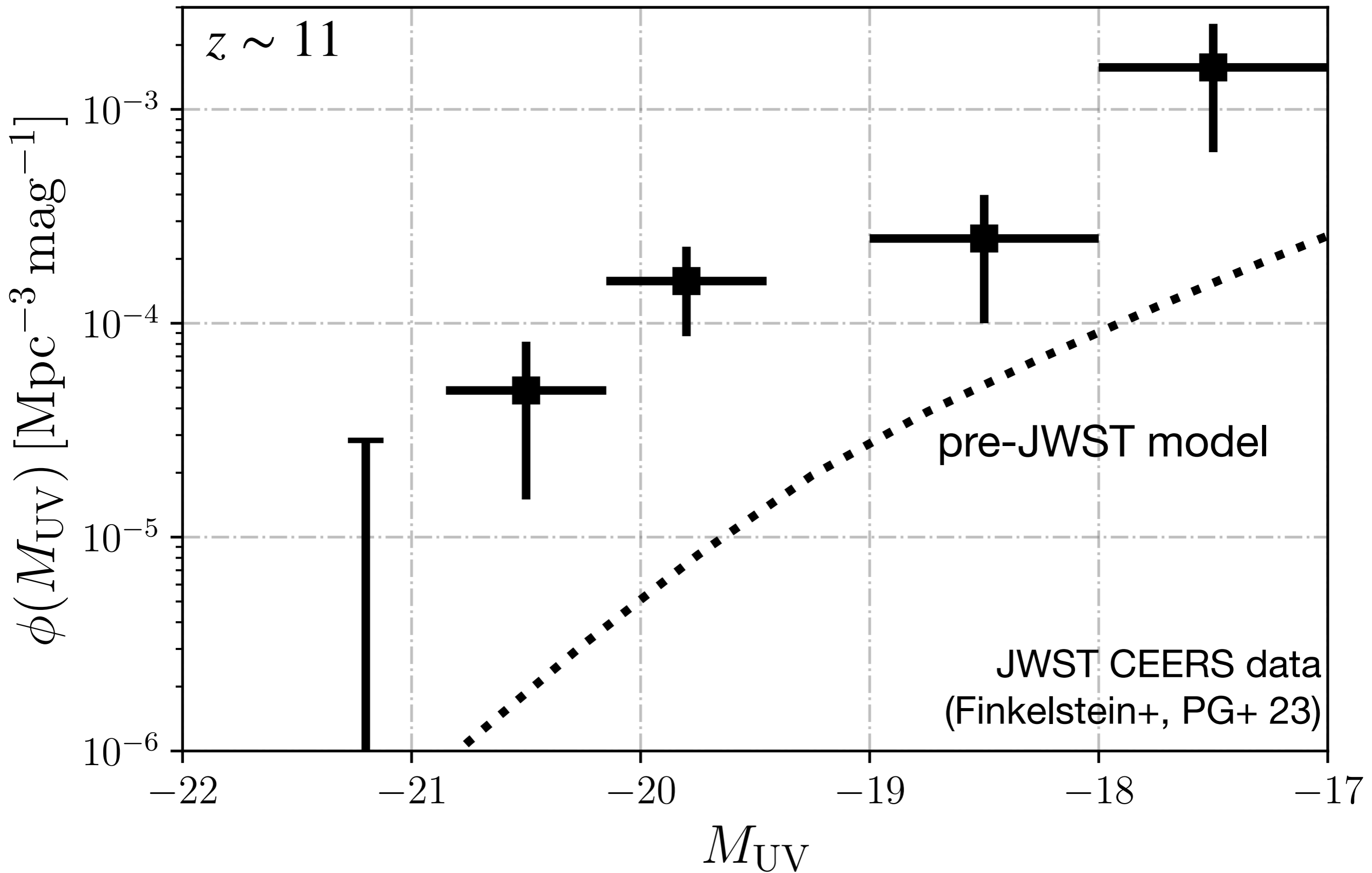
Eg. Steinhardt+22 Dekel+23

Option 2: Stochasticity (width of PDF, burstiness)

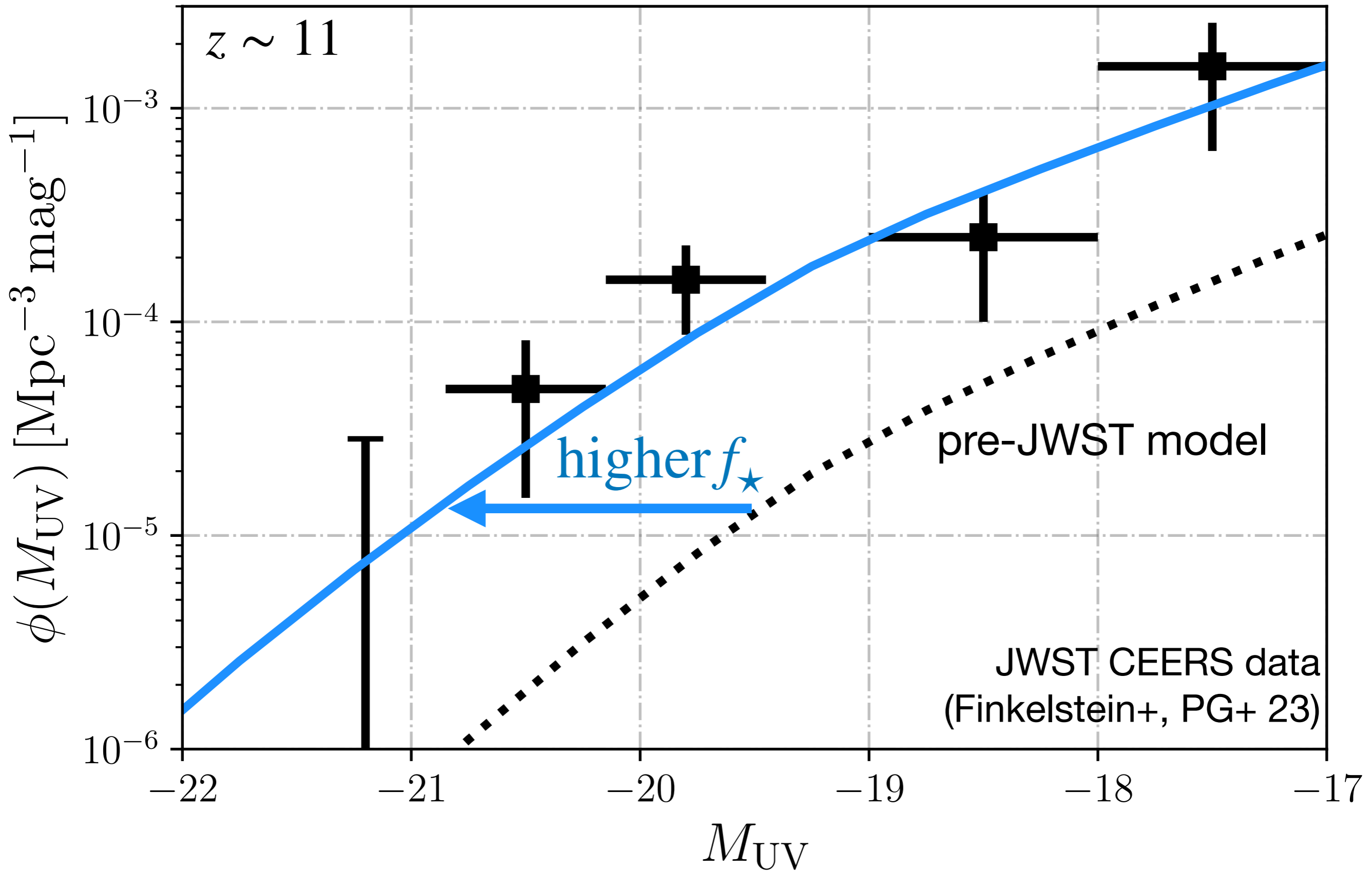
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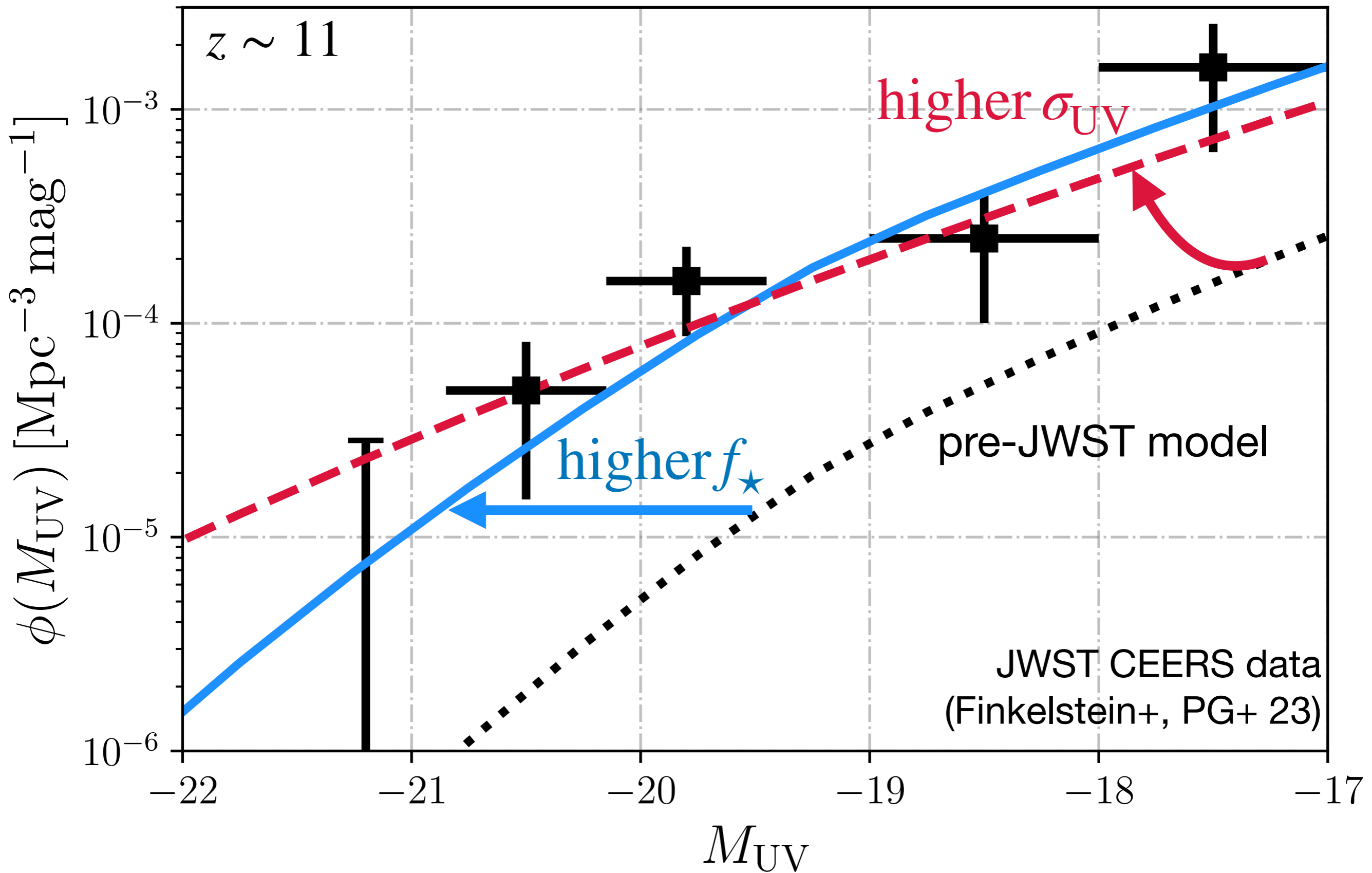
How to explain so many galaxies?



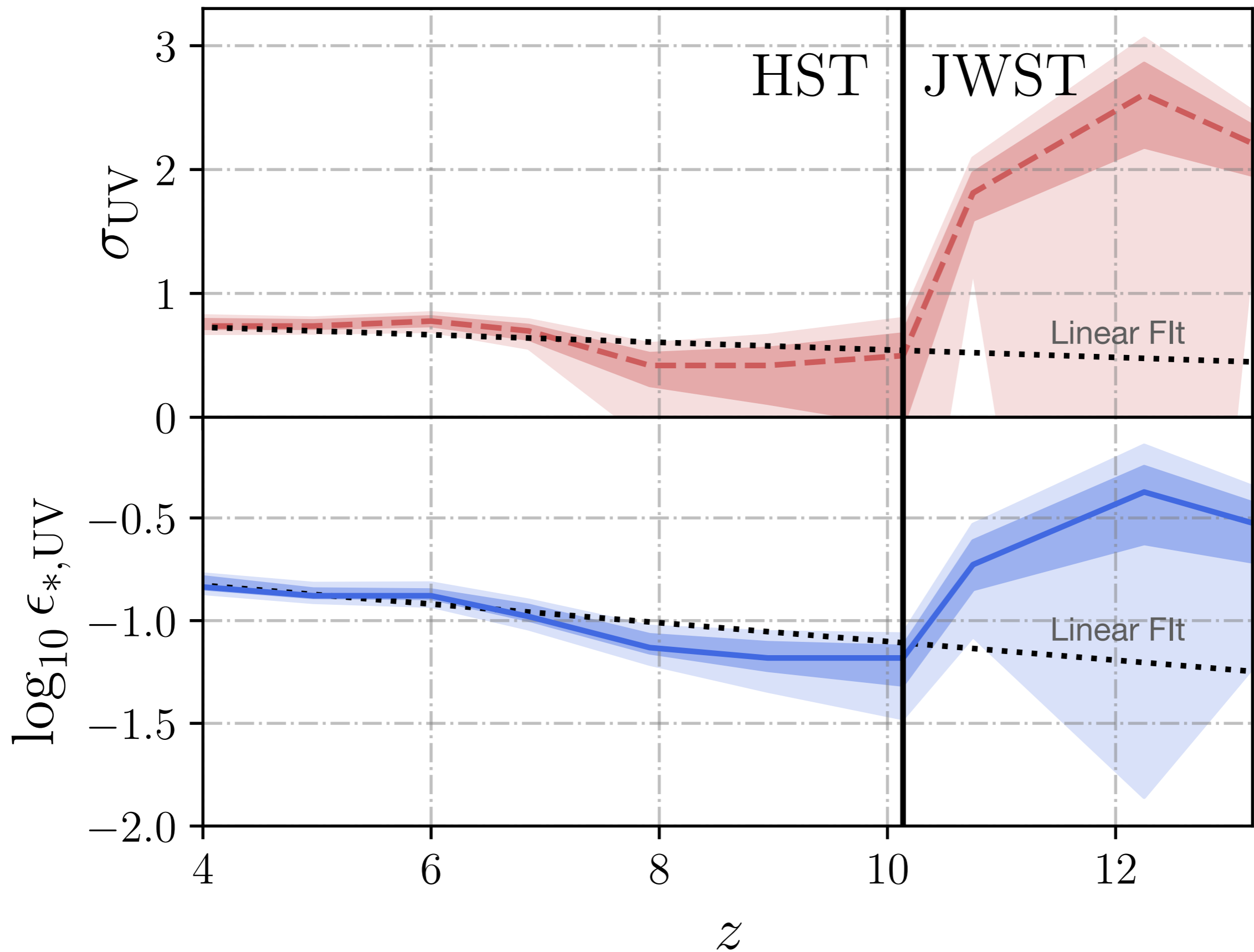
How to explain so many galaxies?



How to explain so many galaxies?



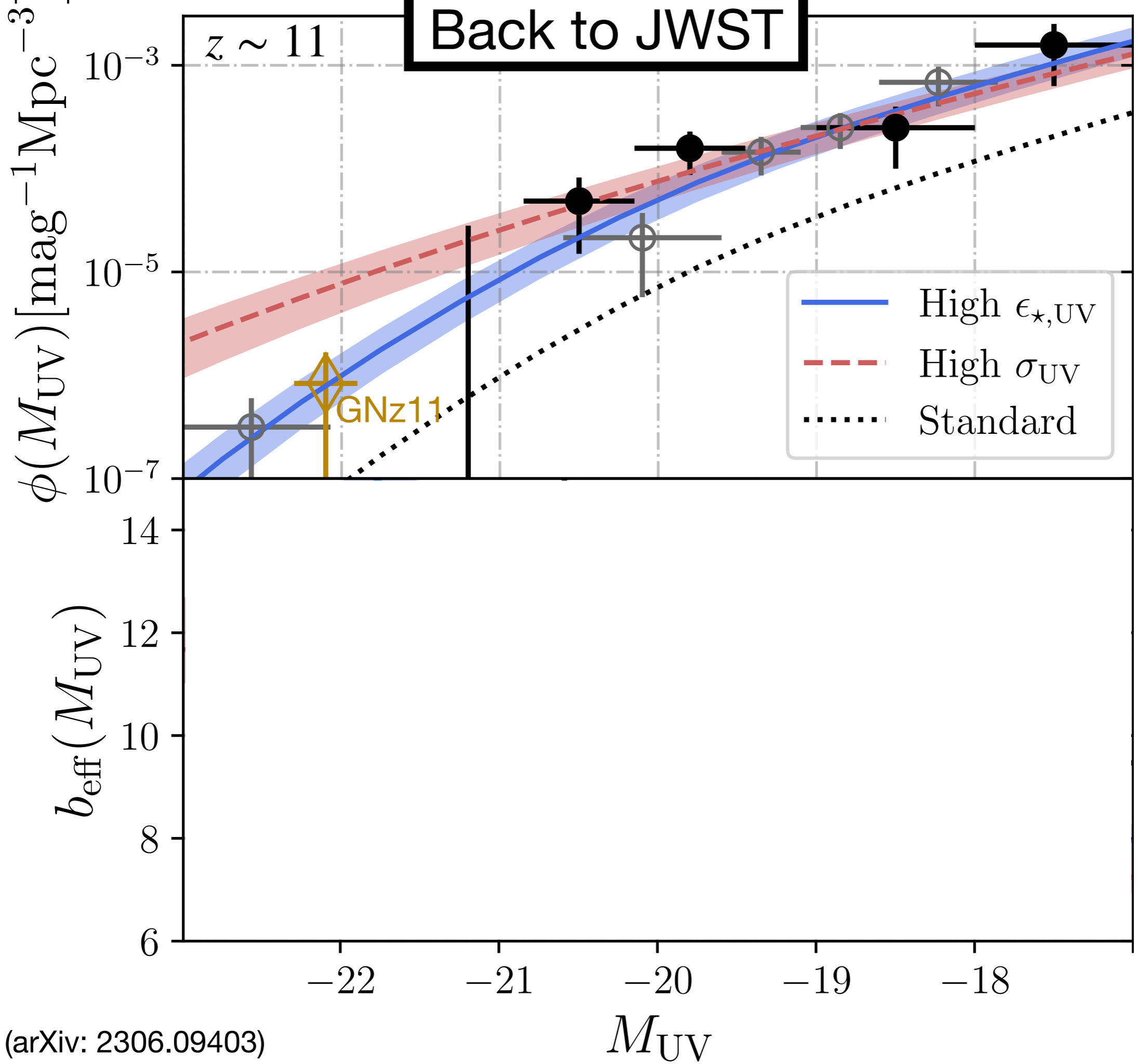
Let's fit these parameters at all z

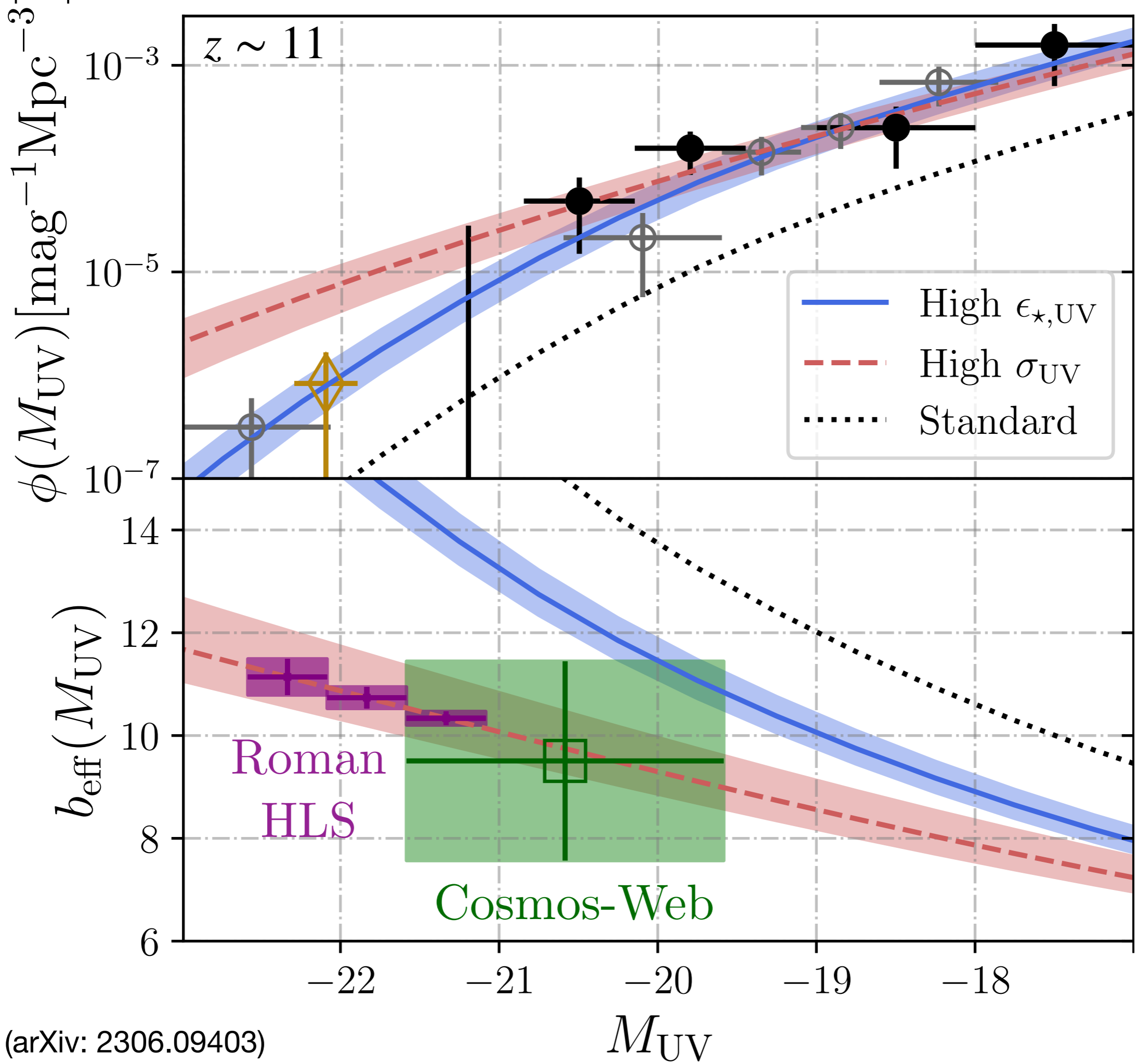


$$\Delta\chi^2(z > 10) \approx 2$$



How to distinguish?





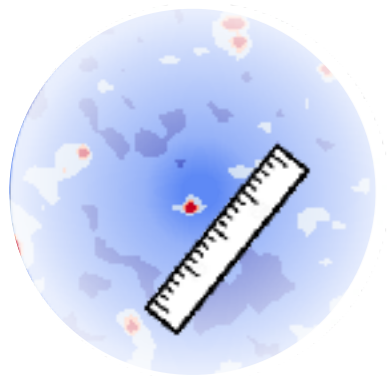
Outline



Does JWST break LCDM?

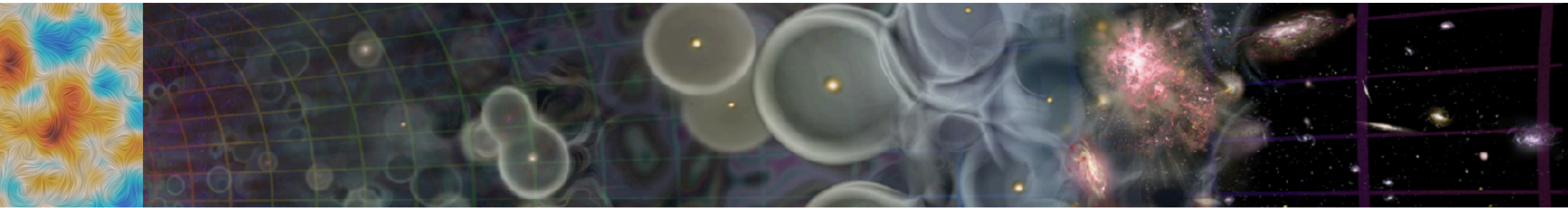


Early galaxies: too many, too early

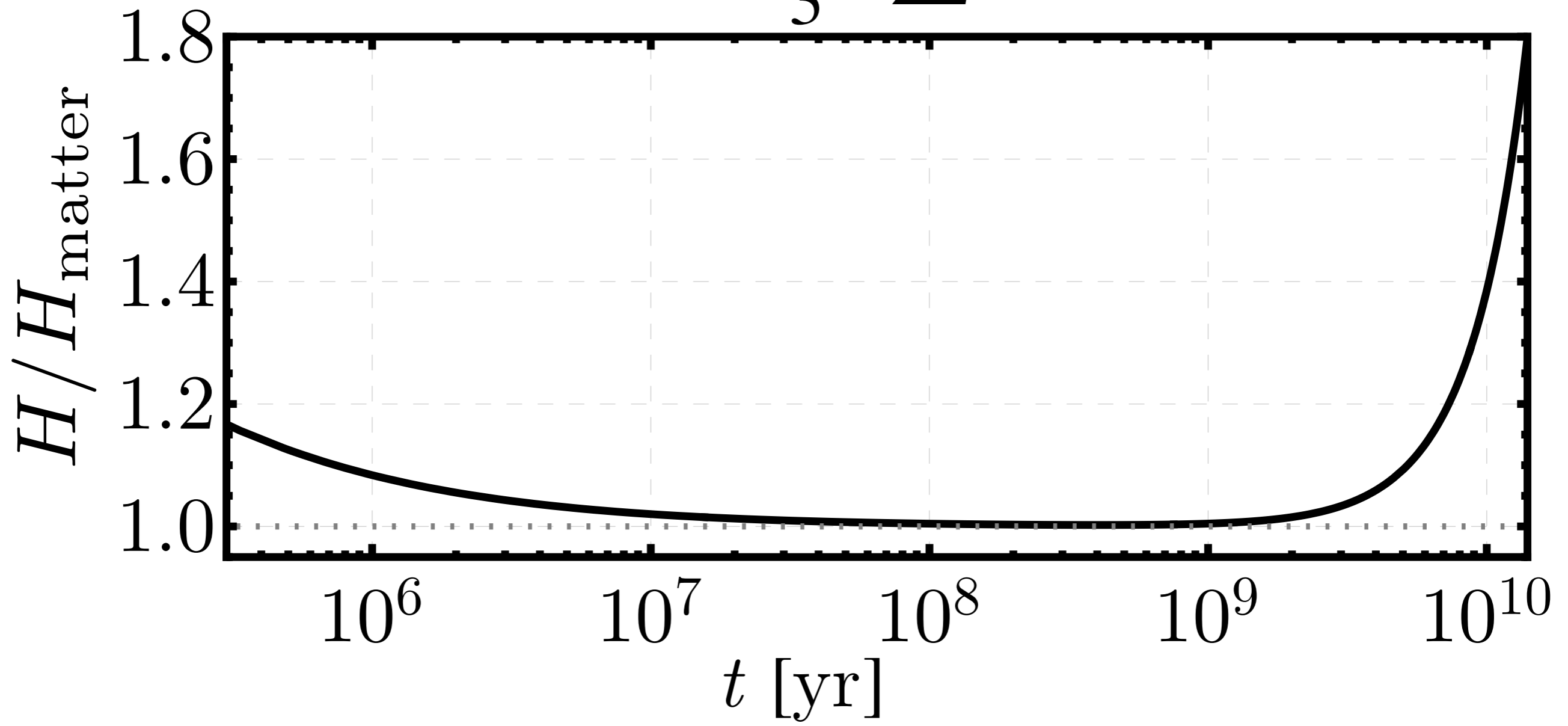


Hubble halfway to the CMB

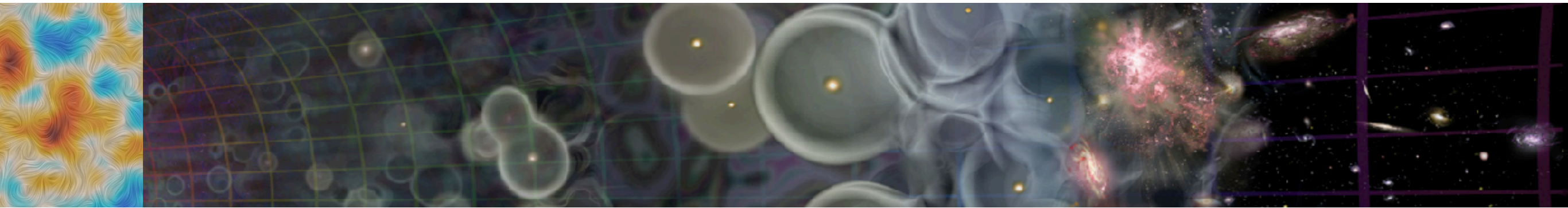
Expansion rate = Energy content



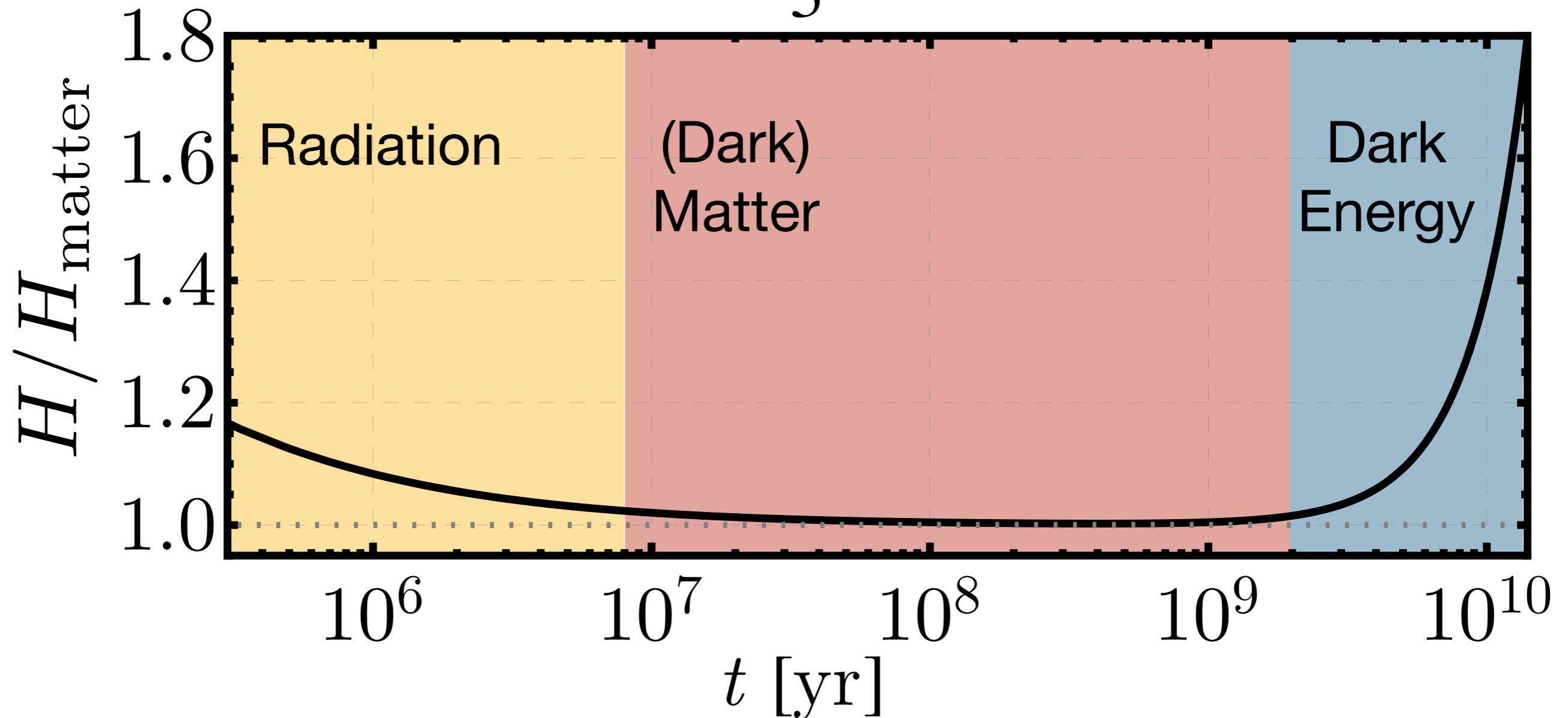
$$H^2(t) = \frac{8\pi G}{3} \sum \rho_i$$



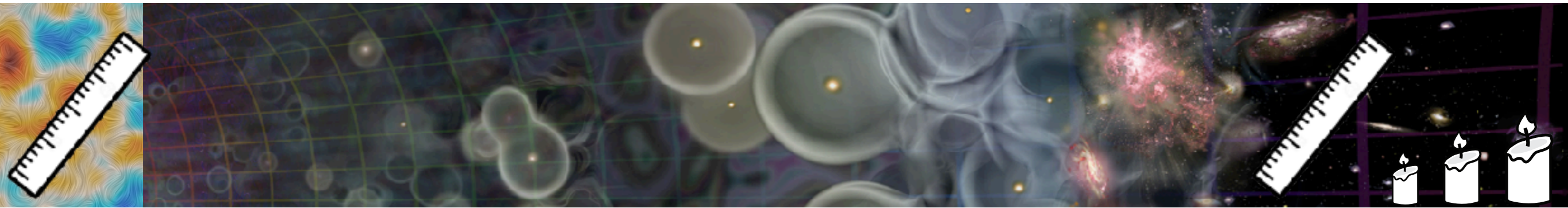
Expansion rate = Energy content



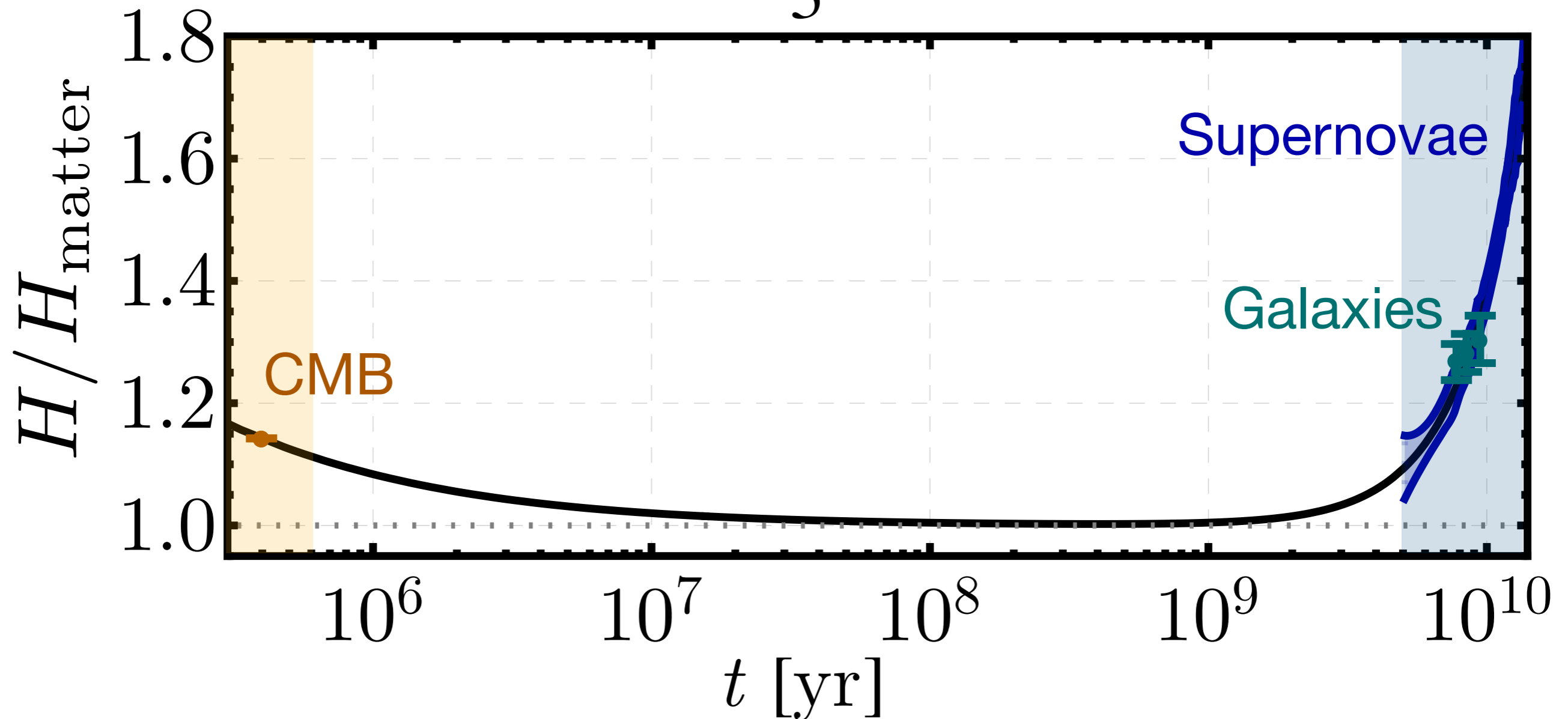
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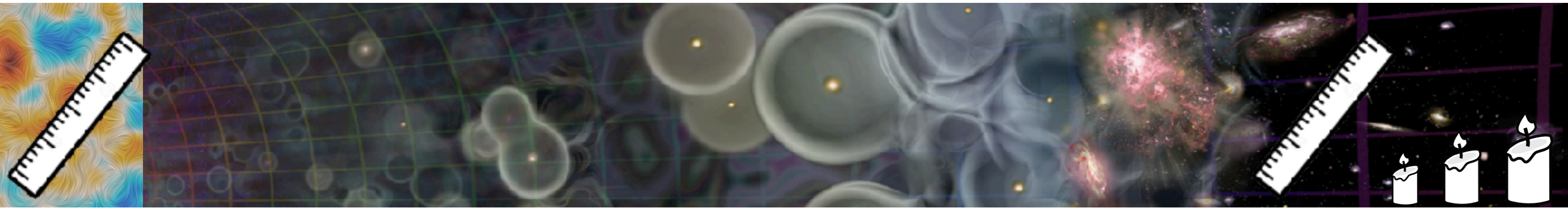
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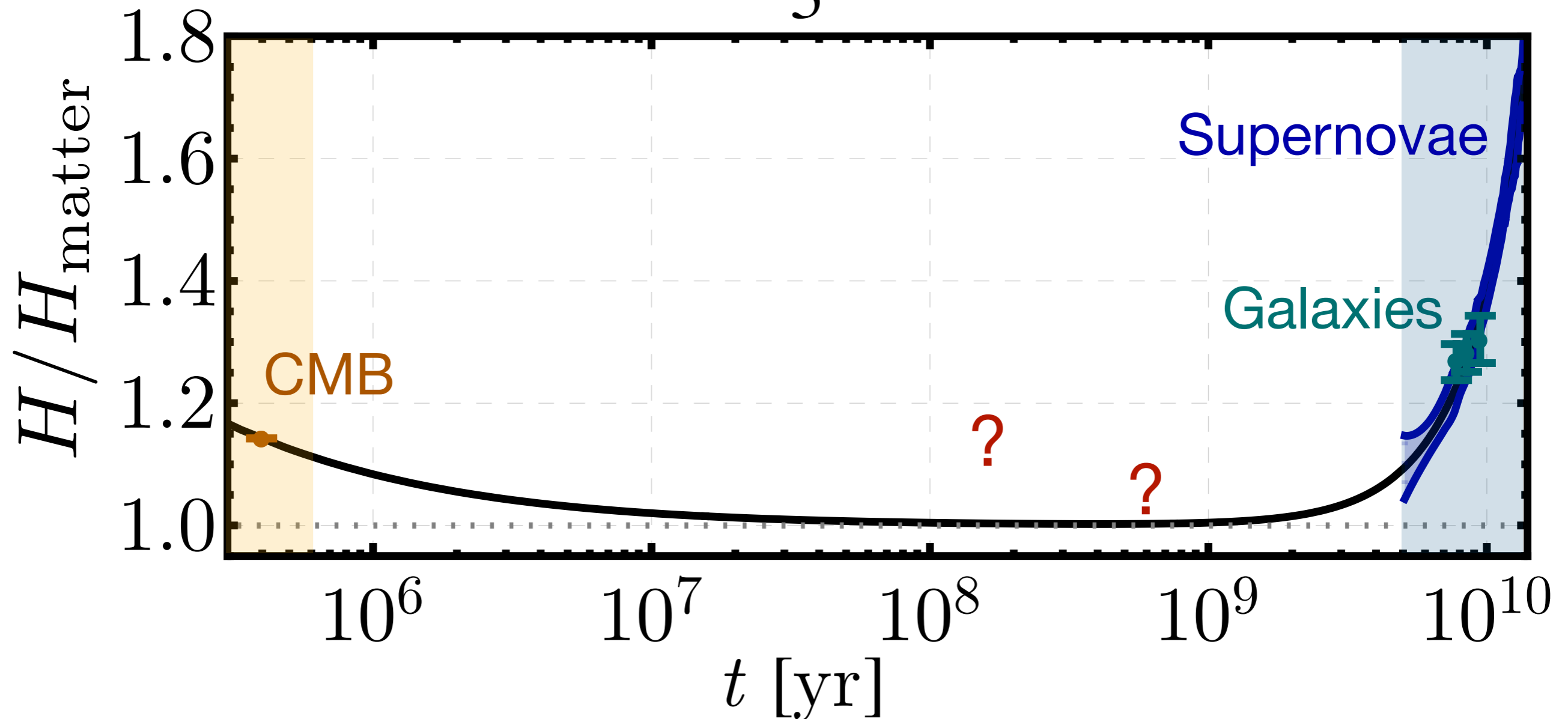
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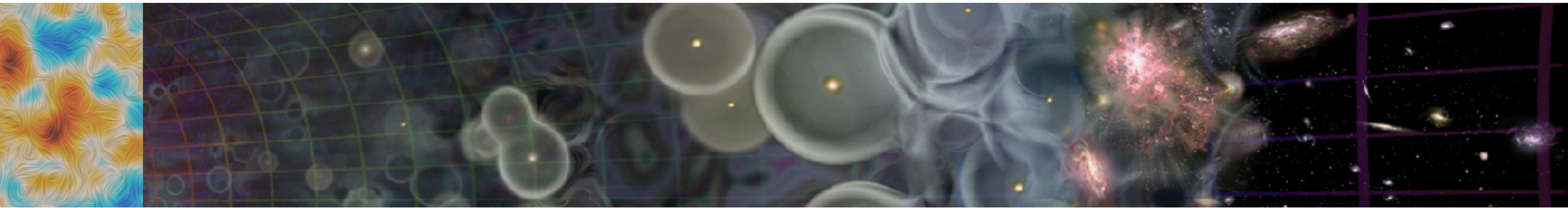
Expansion rate = Energy content



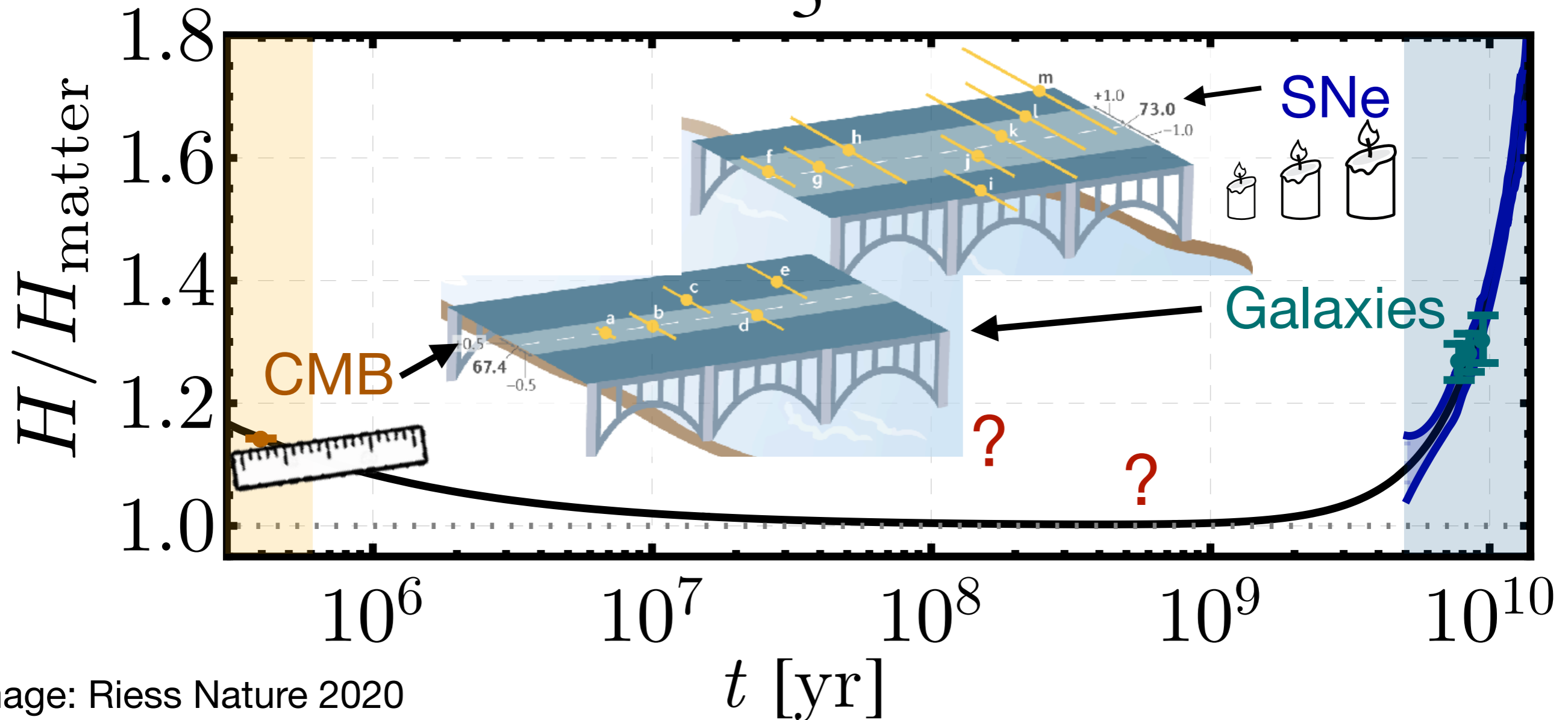
$$H^2(t) = \frac{8\pi G}{3} \sum \rho_i$$



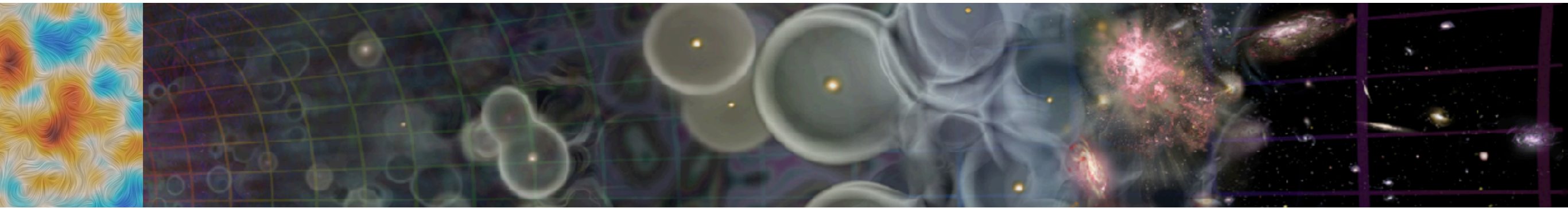
Expansion rate = Energy content



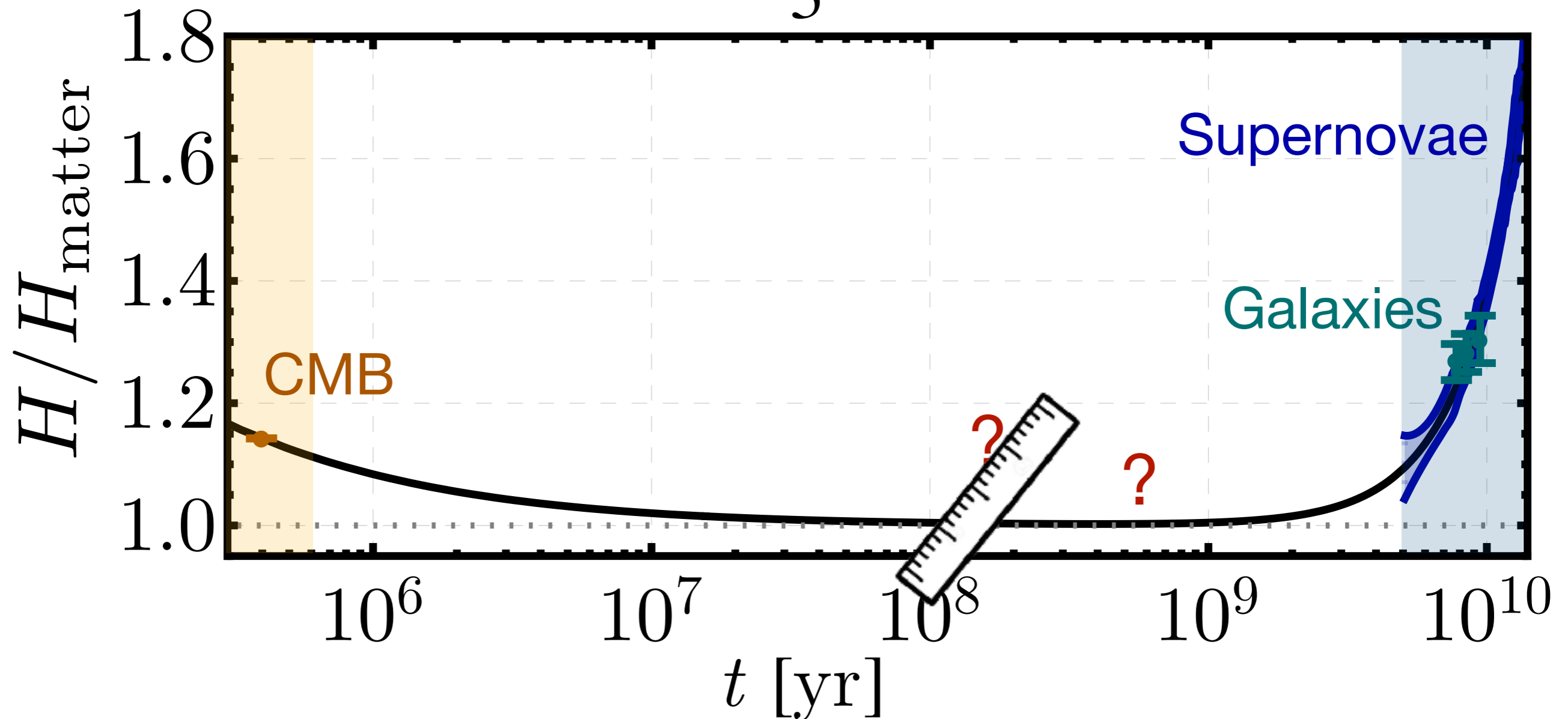
$$H^2(t) = \frac{8\pi G}{3} \sum \rho_i$$



Expansion rate = Energy content



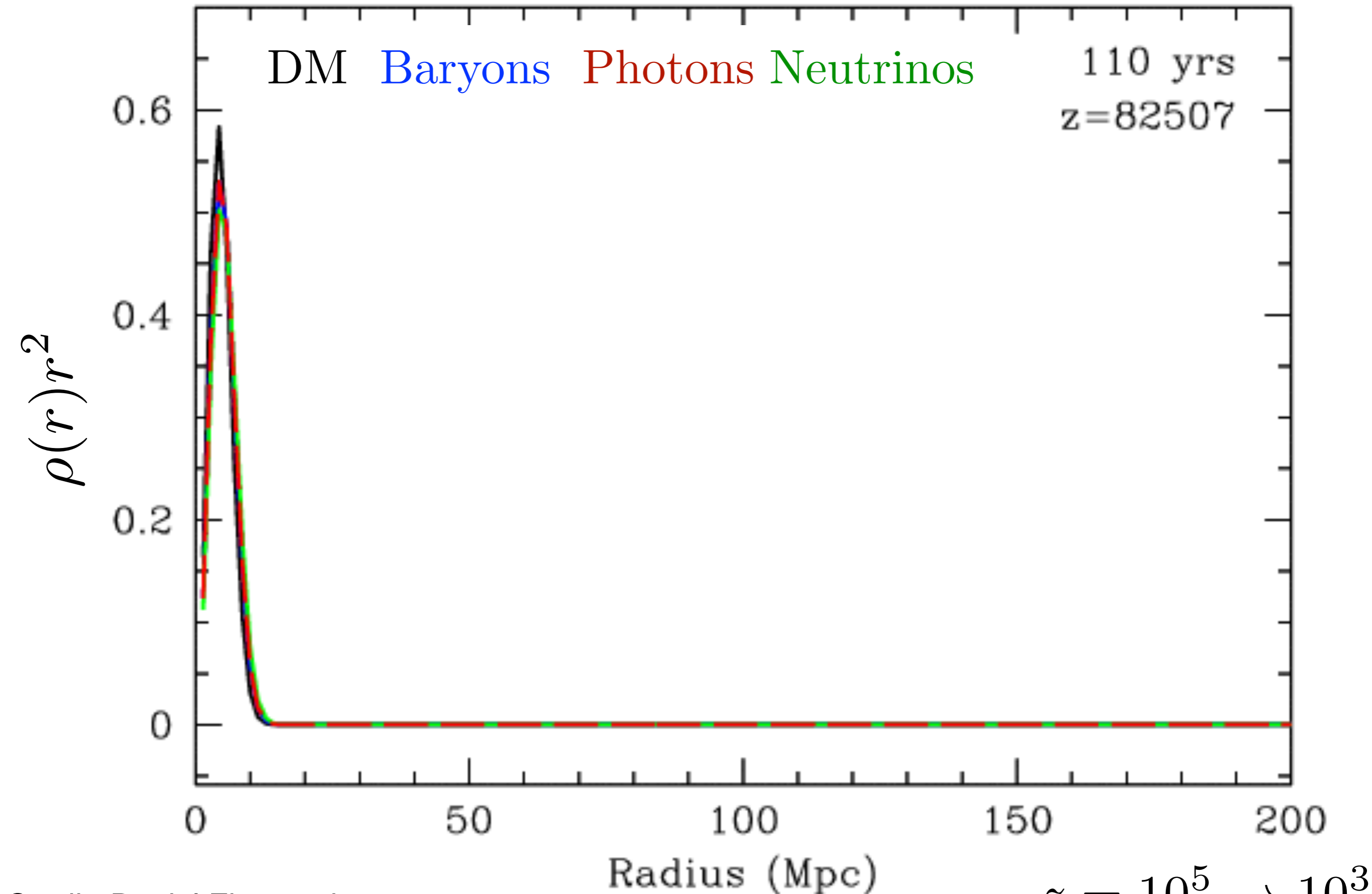
$$H^2(t) = \frac{8\pi G}{3} \sum \rho_i$$



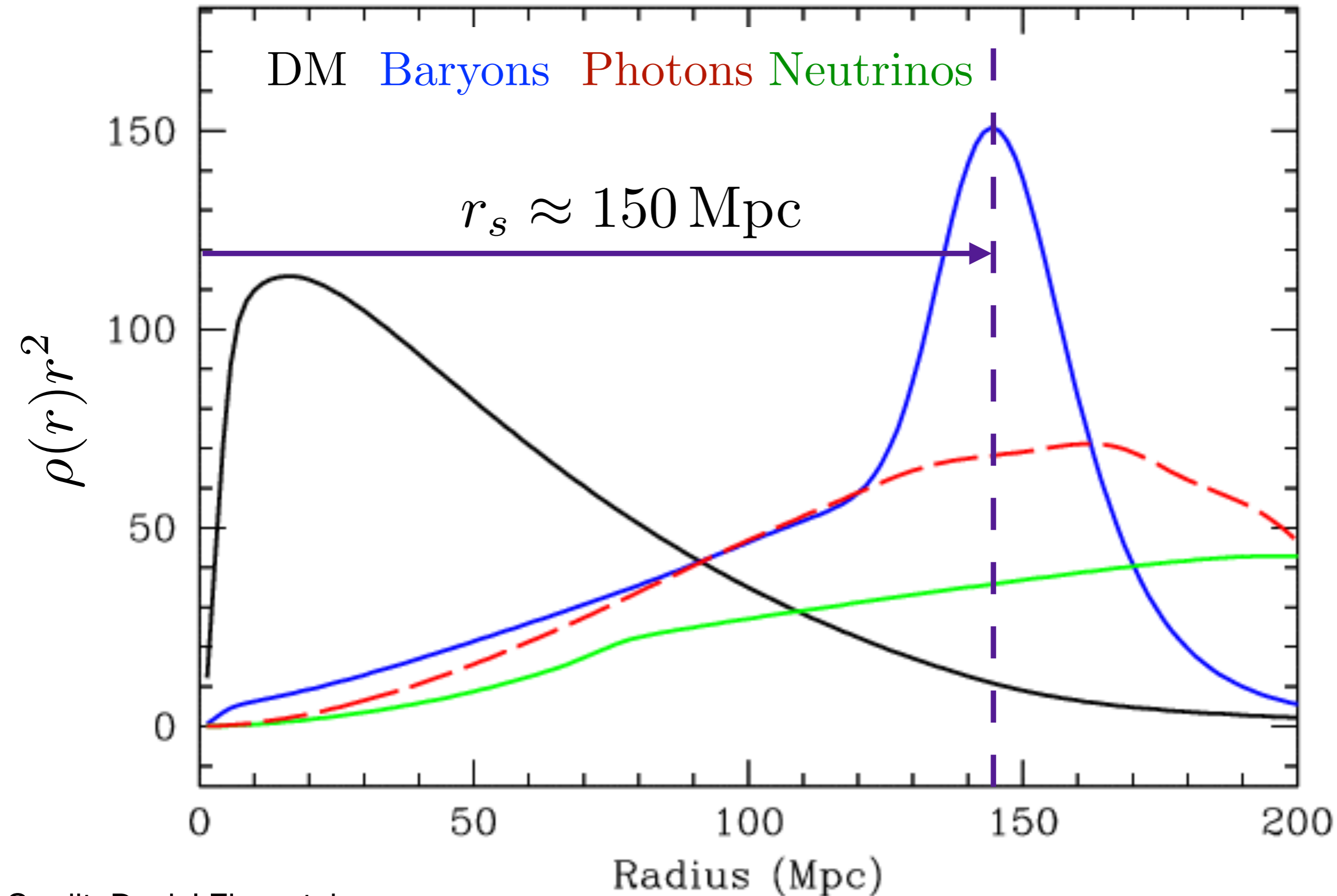
Baryon Acoustic Oscillations



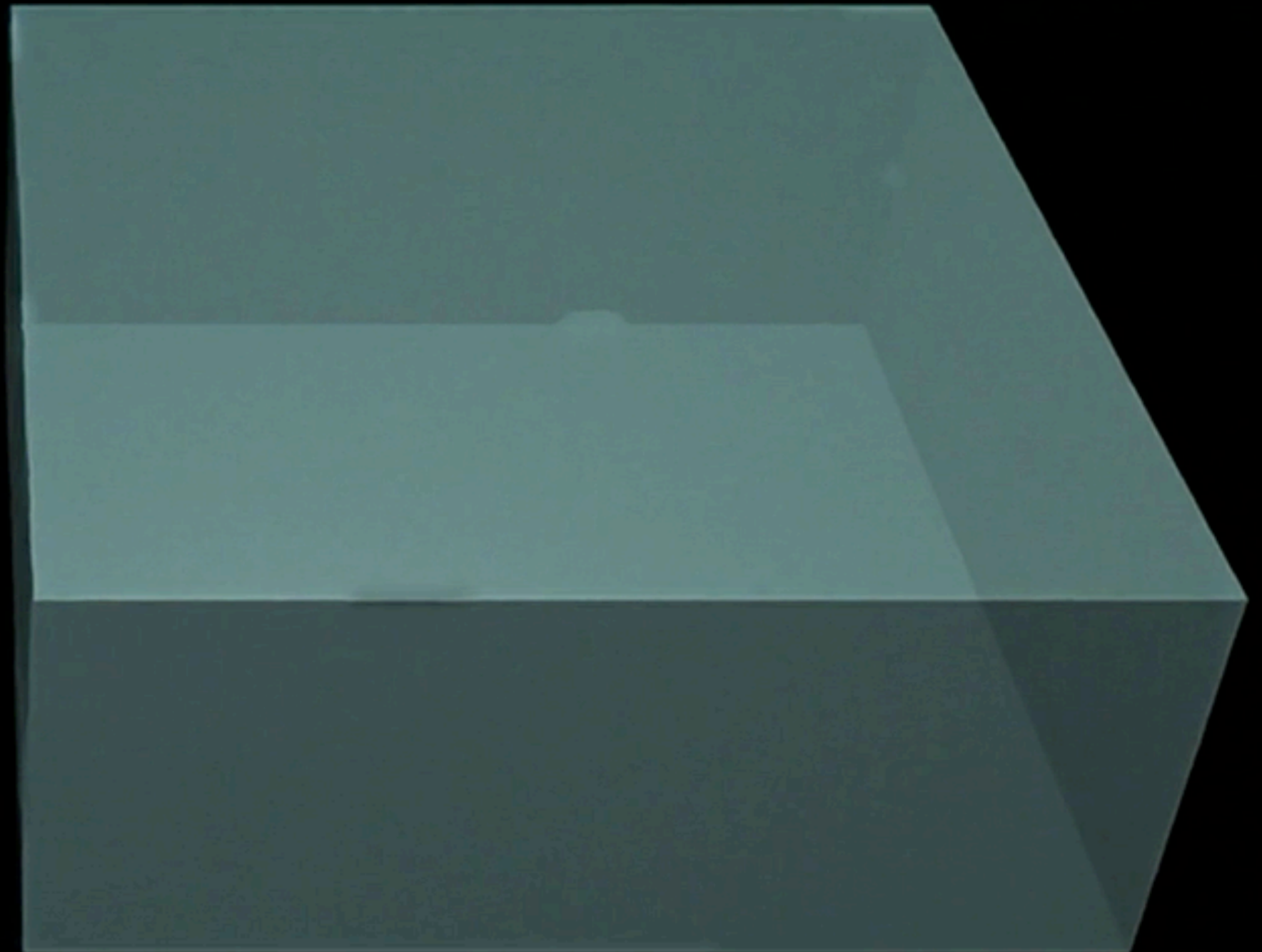
Baryon Acoustic Oscillations



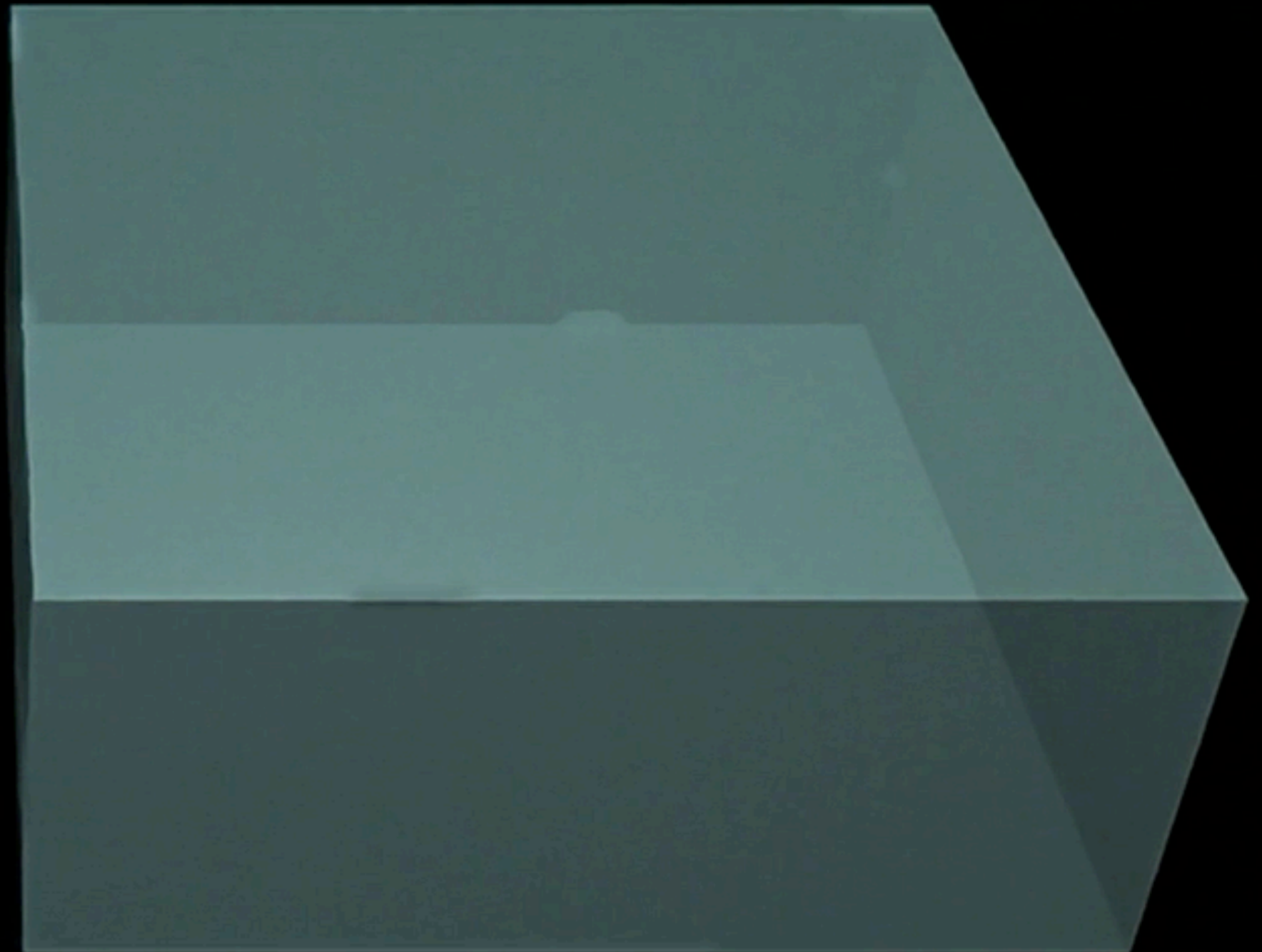
Baryon Acoustic Oscillations



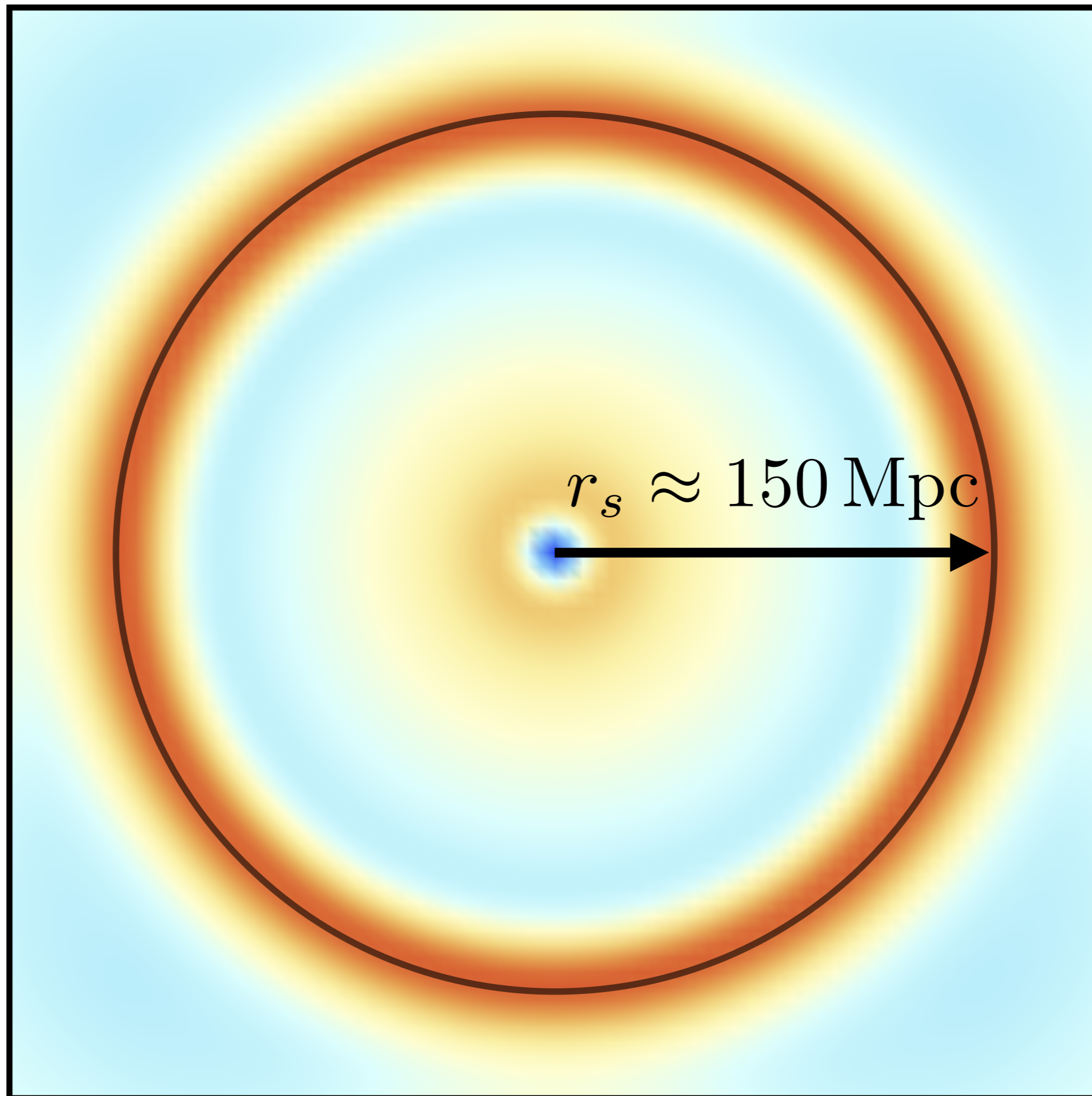
It's just waves!



It's just waves!



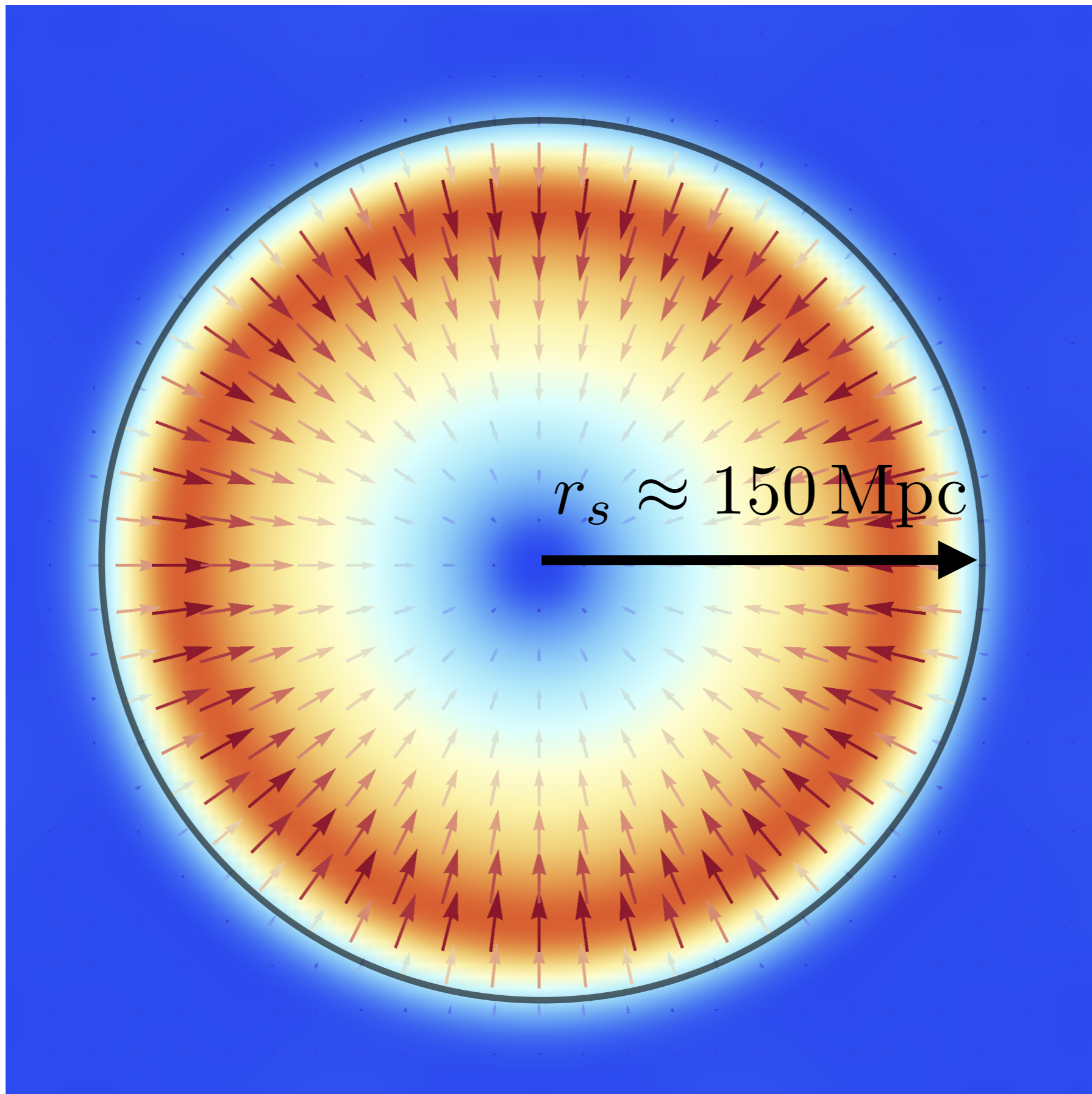
A preferred distance scale



Density

Tseliakhovich
& Hirata 2010

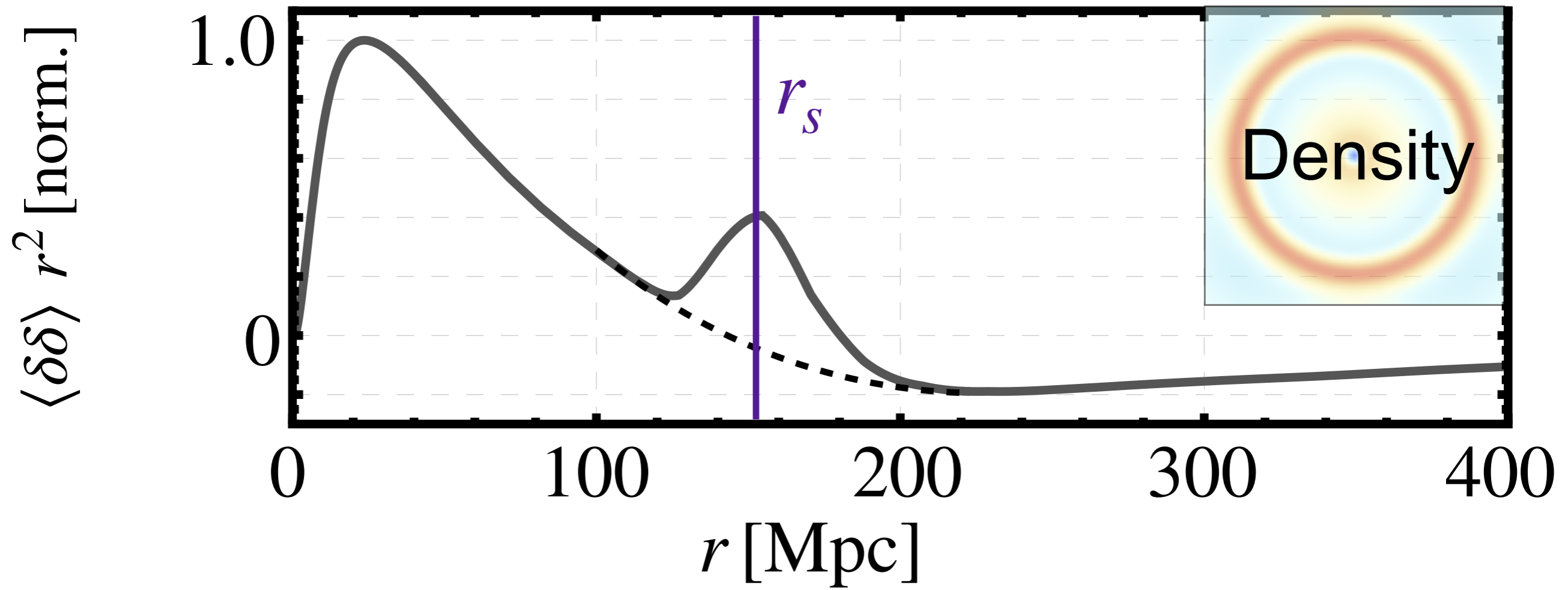
$$\mathbf{v}_{\text{DM},b} = \mathbf{v}_{\text{DM}} - \mathbf{v}_b$$



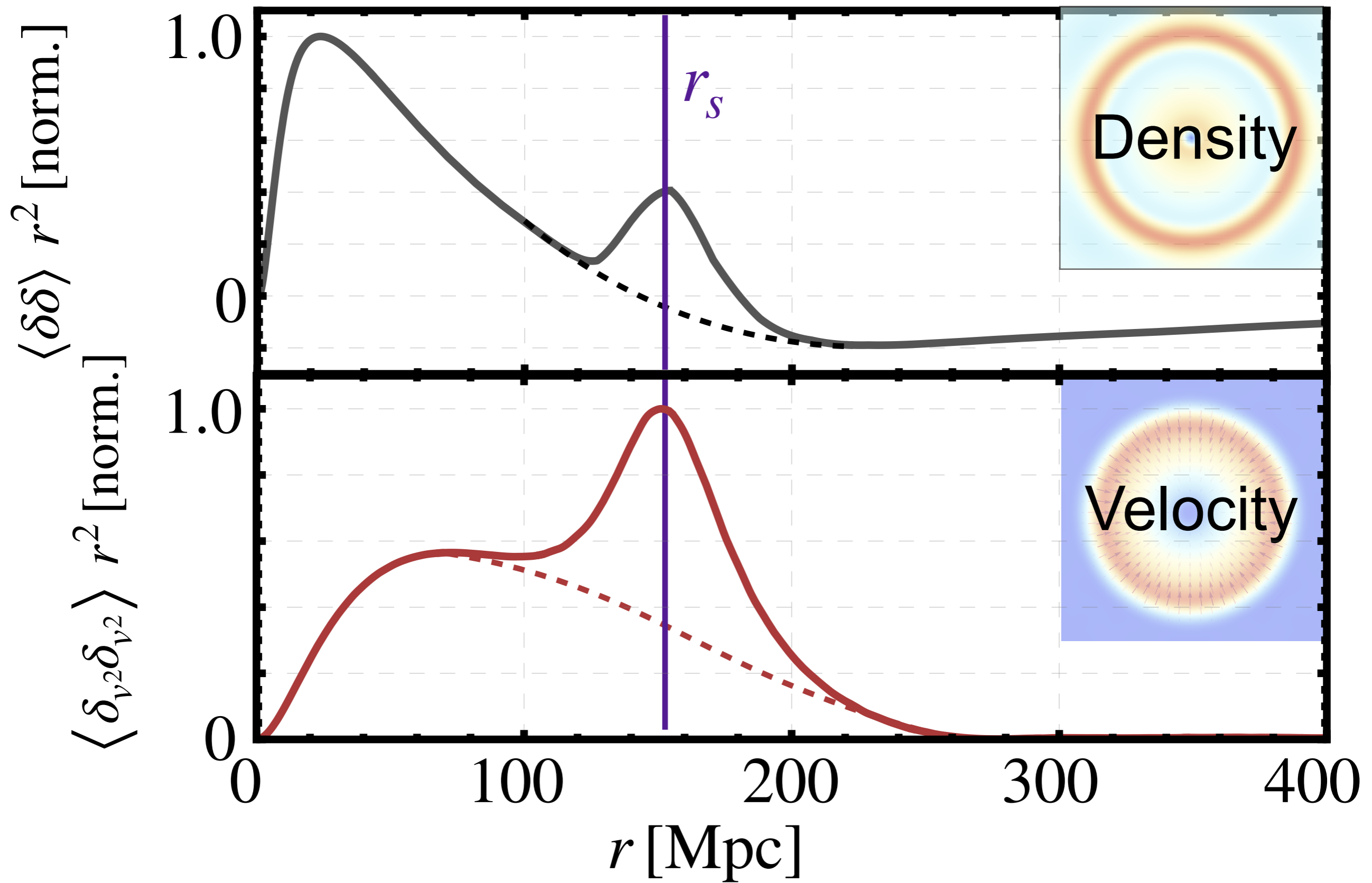
Velocity

Tselikhovich
& Hirata 2010

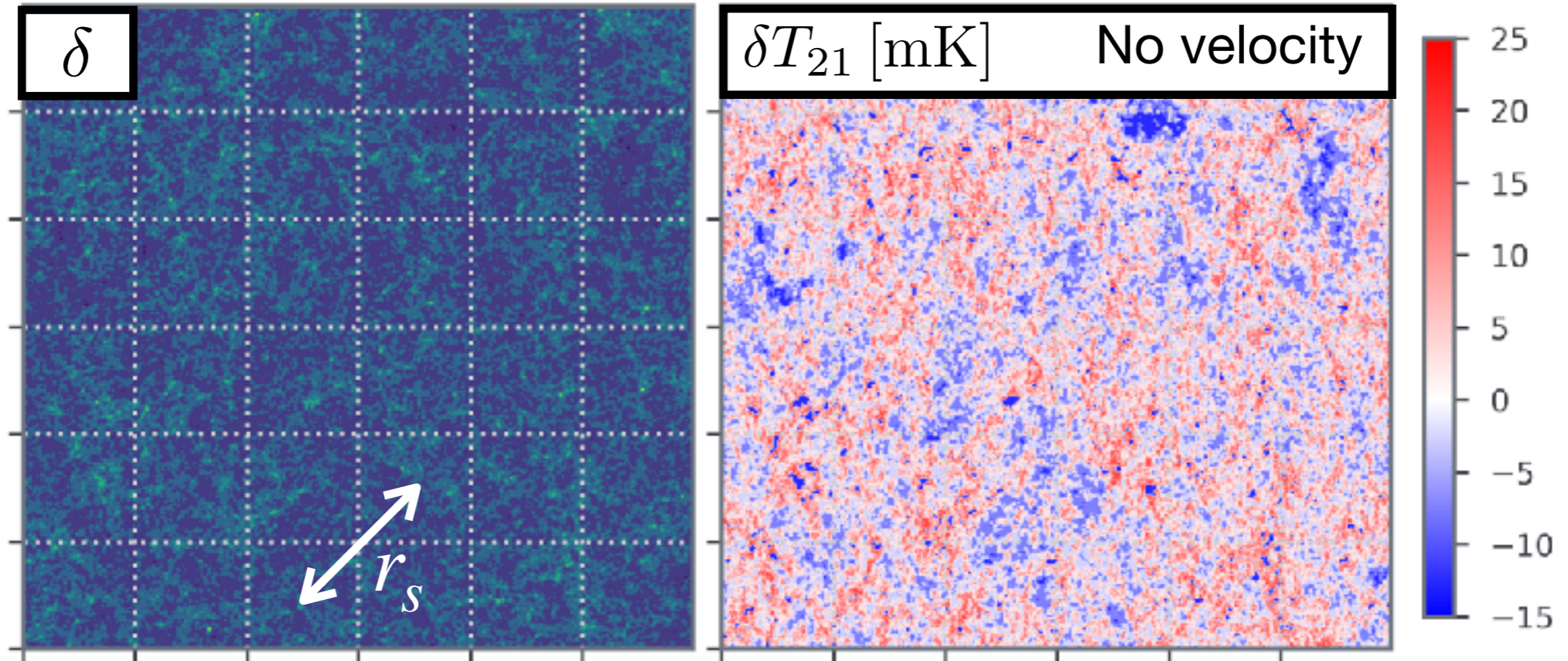
A preferred distance scale



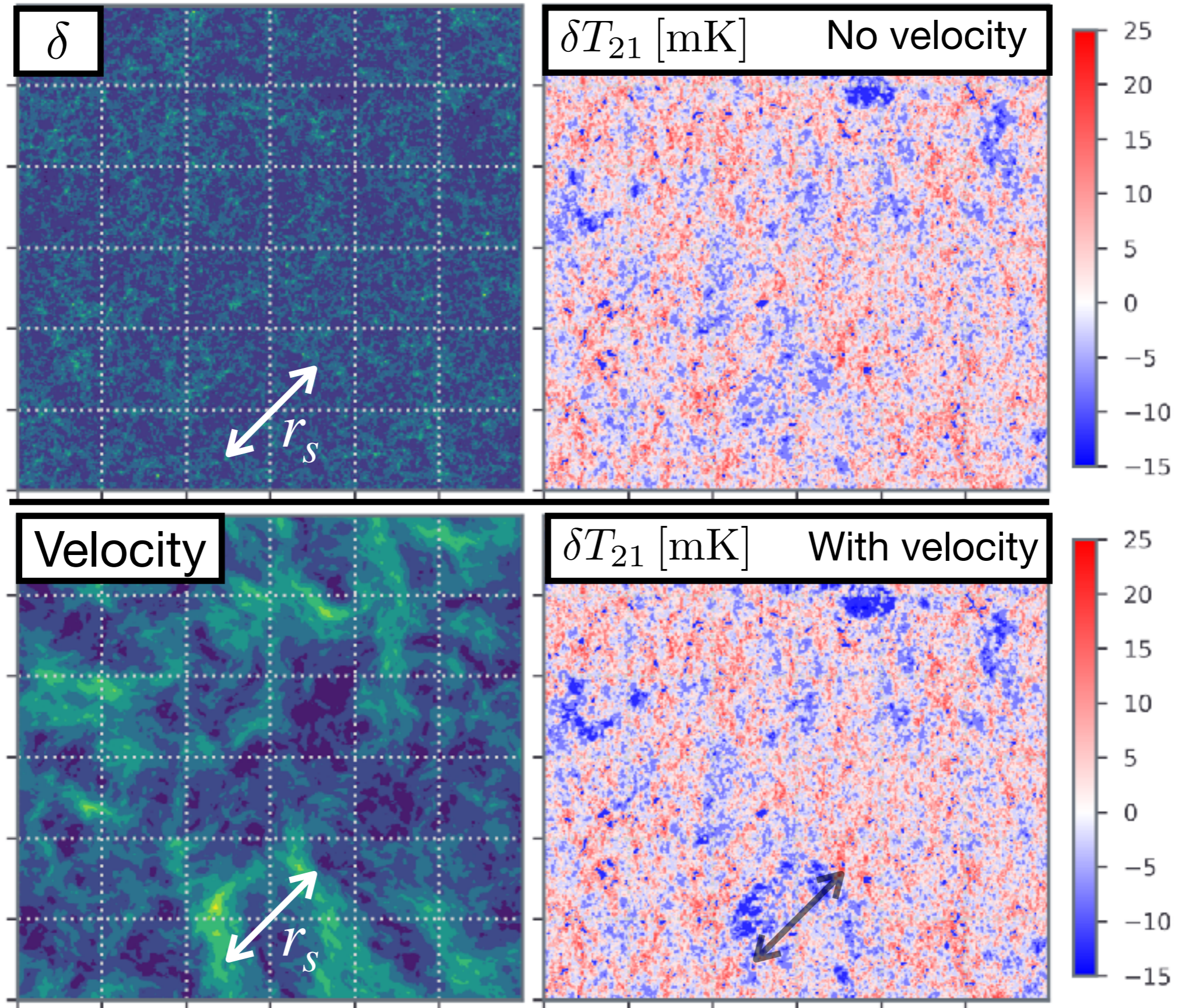
A preferred distance scale



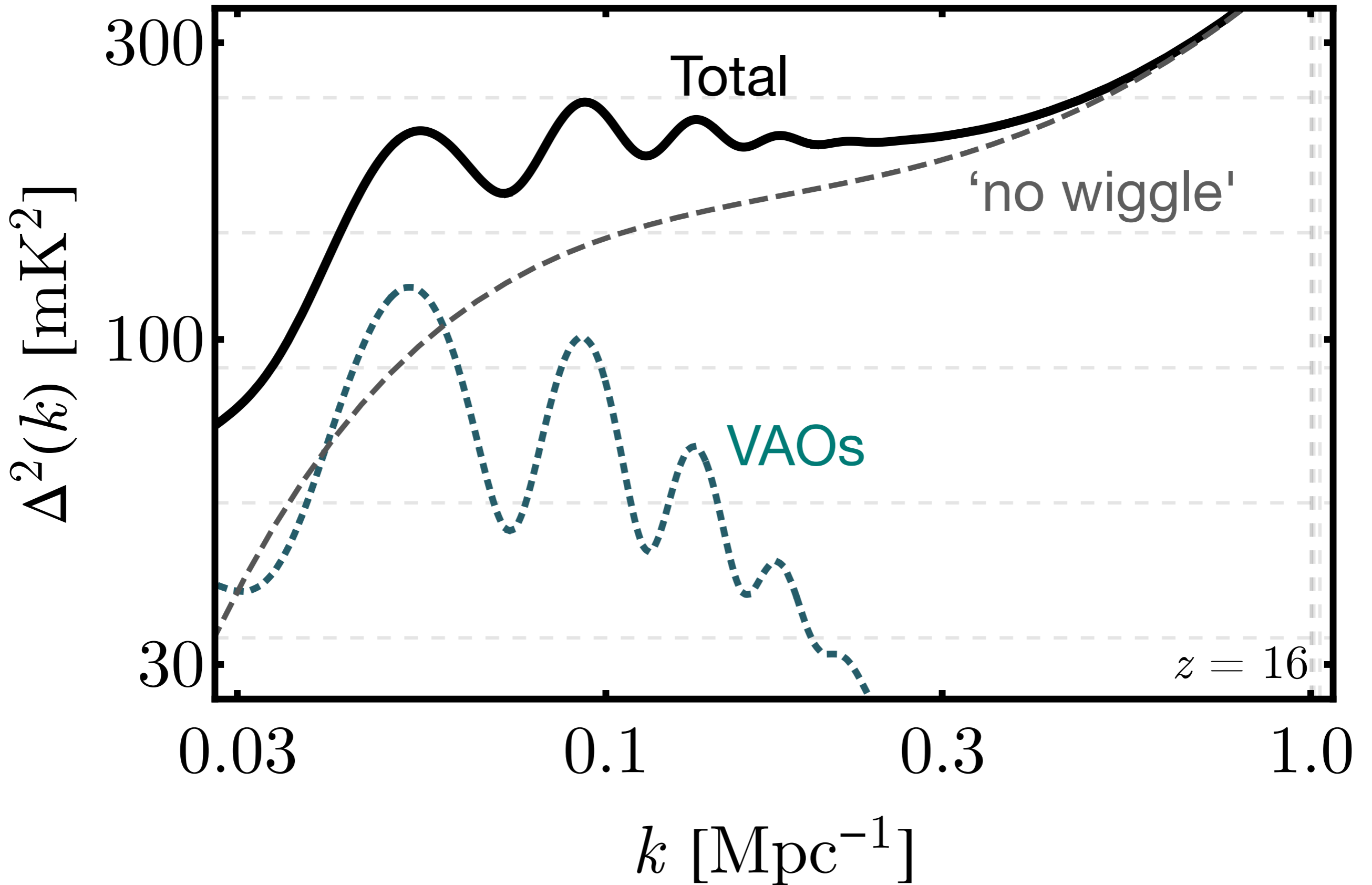
On the first galaxies



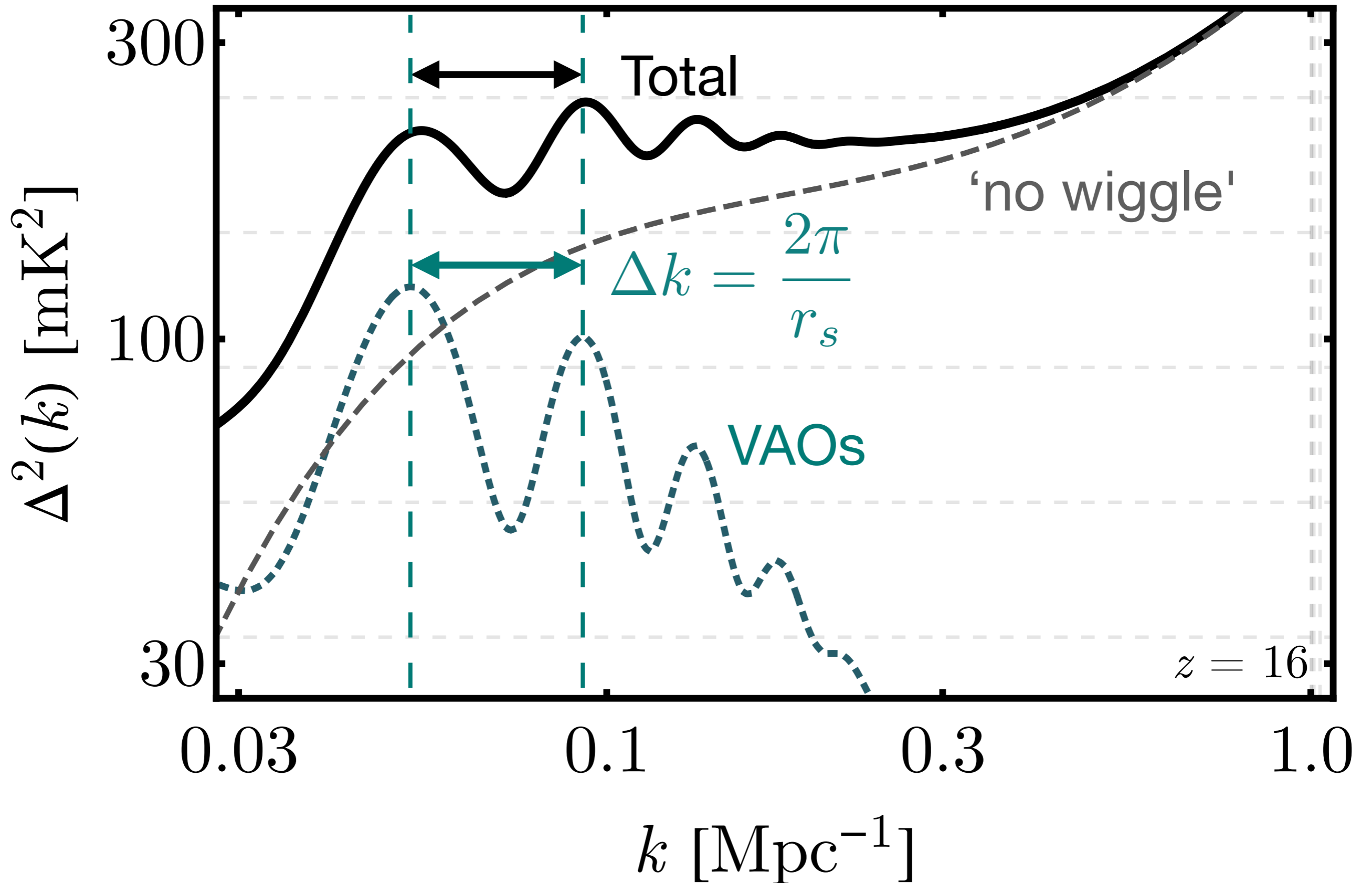
On the first galaxies

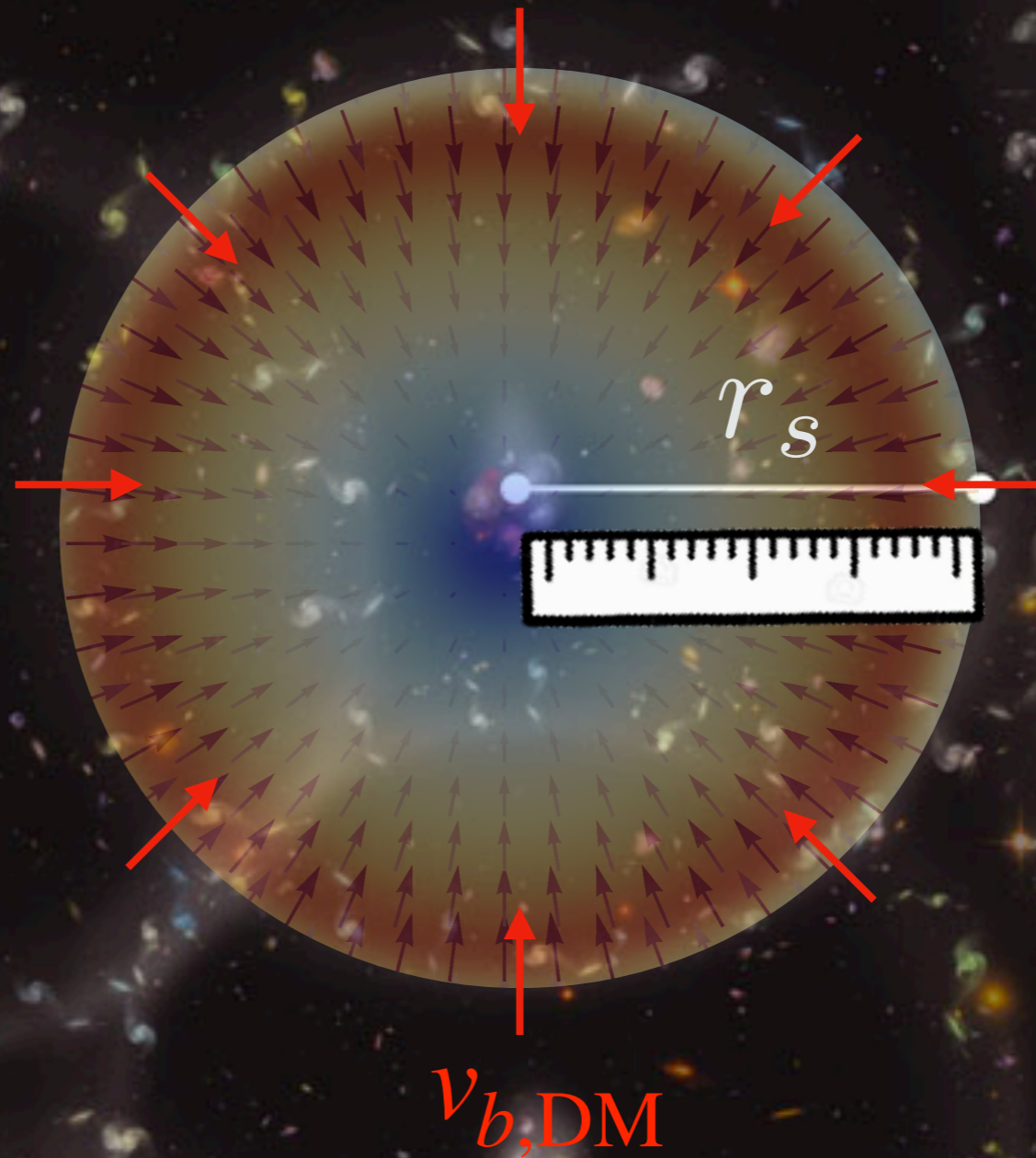


Velocity-induced Acoustic Oscillations



Velocity-induced Acoustic Oscillations

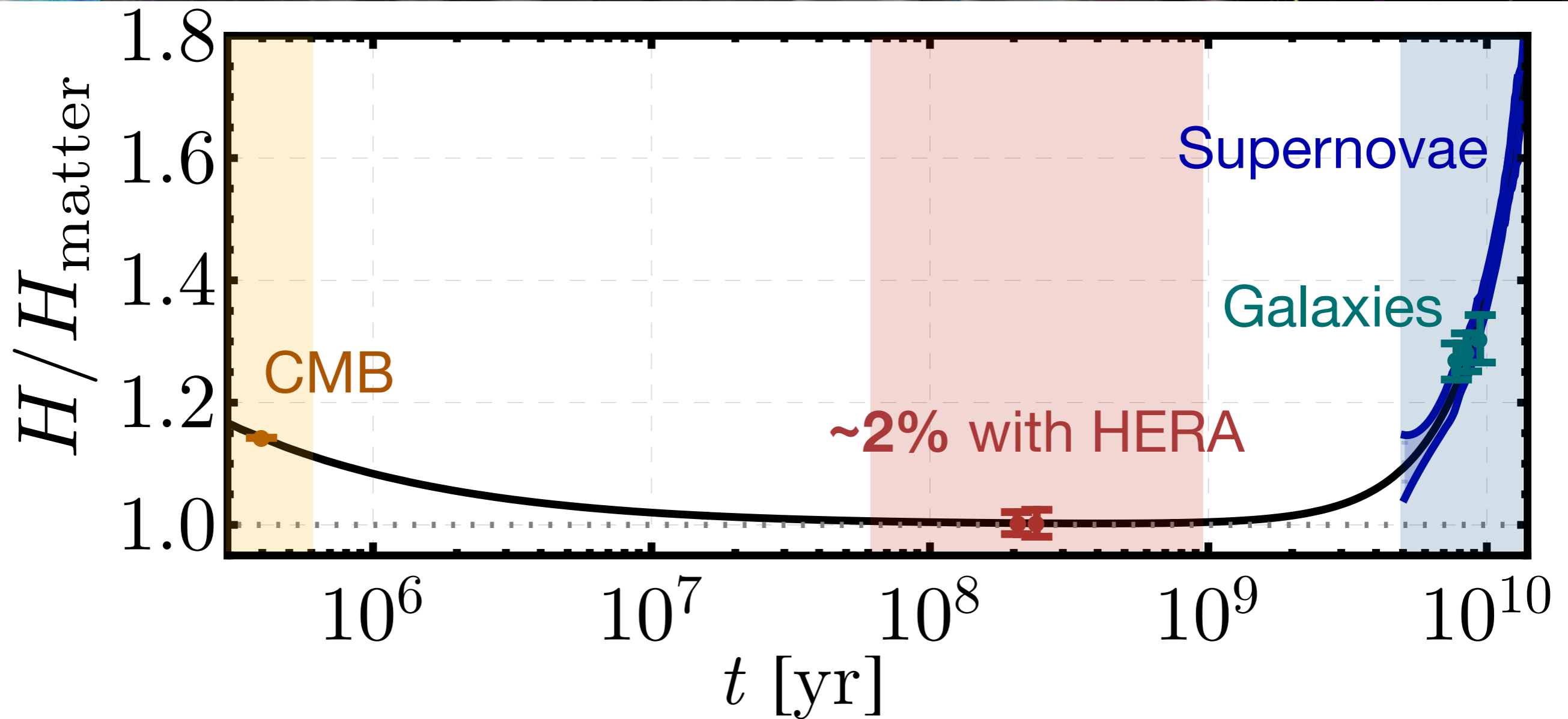
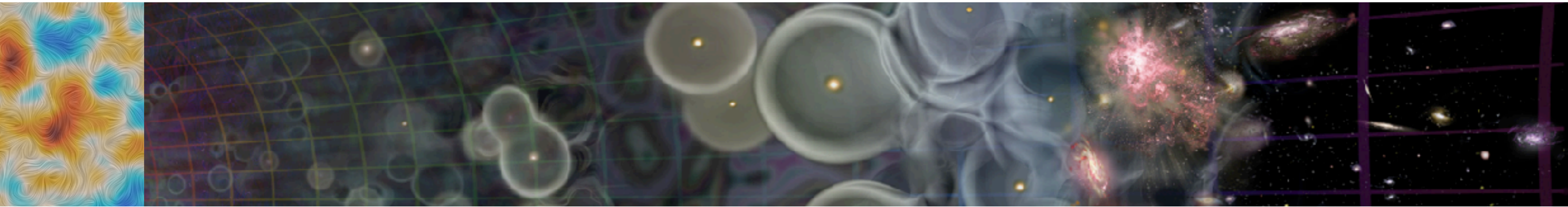




JBM PRL 2019

Velocity-induced Acoustic Oscillations (VAOs): A new standard ruler

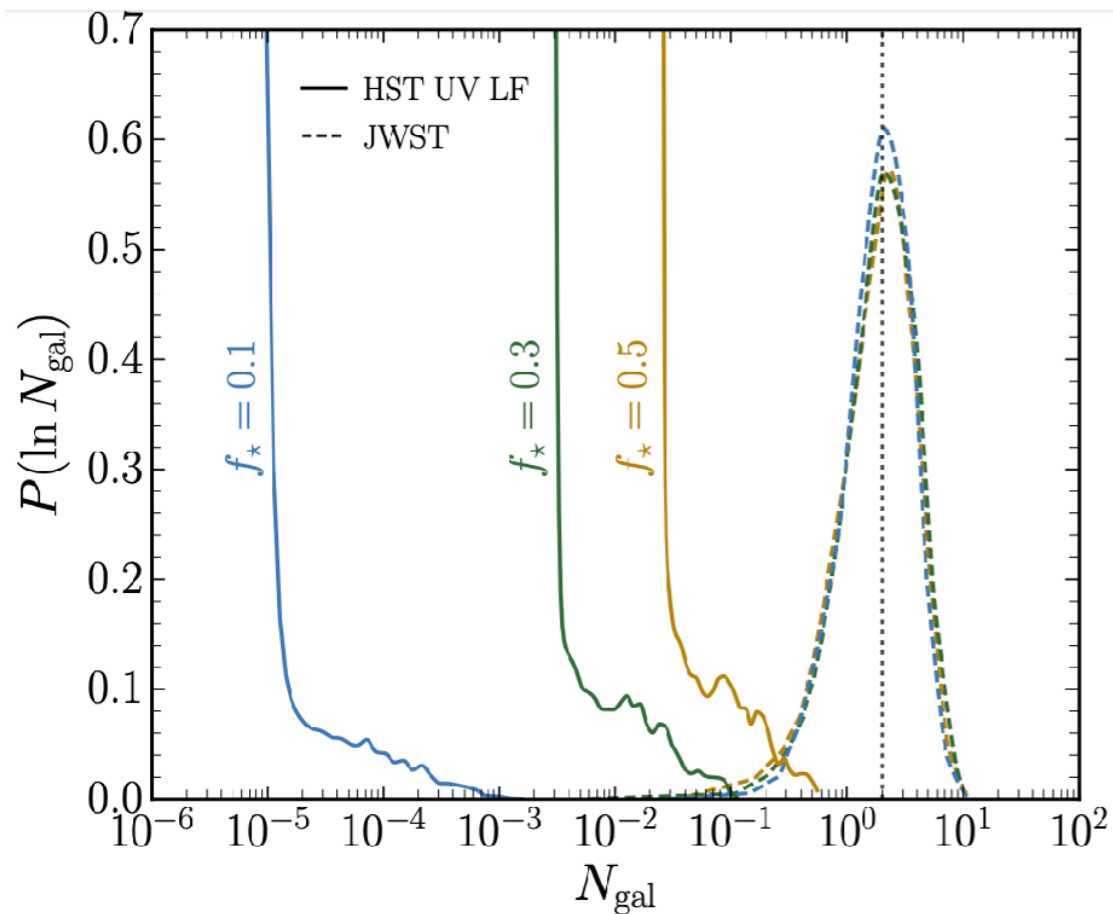
Expansion rate = Energy content



To summarize

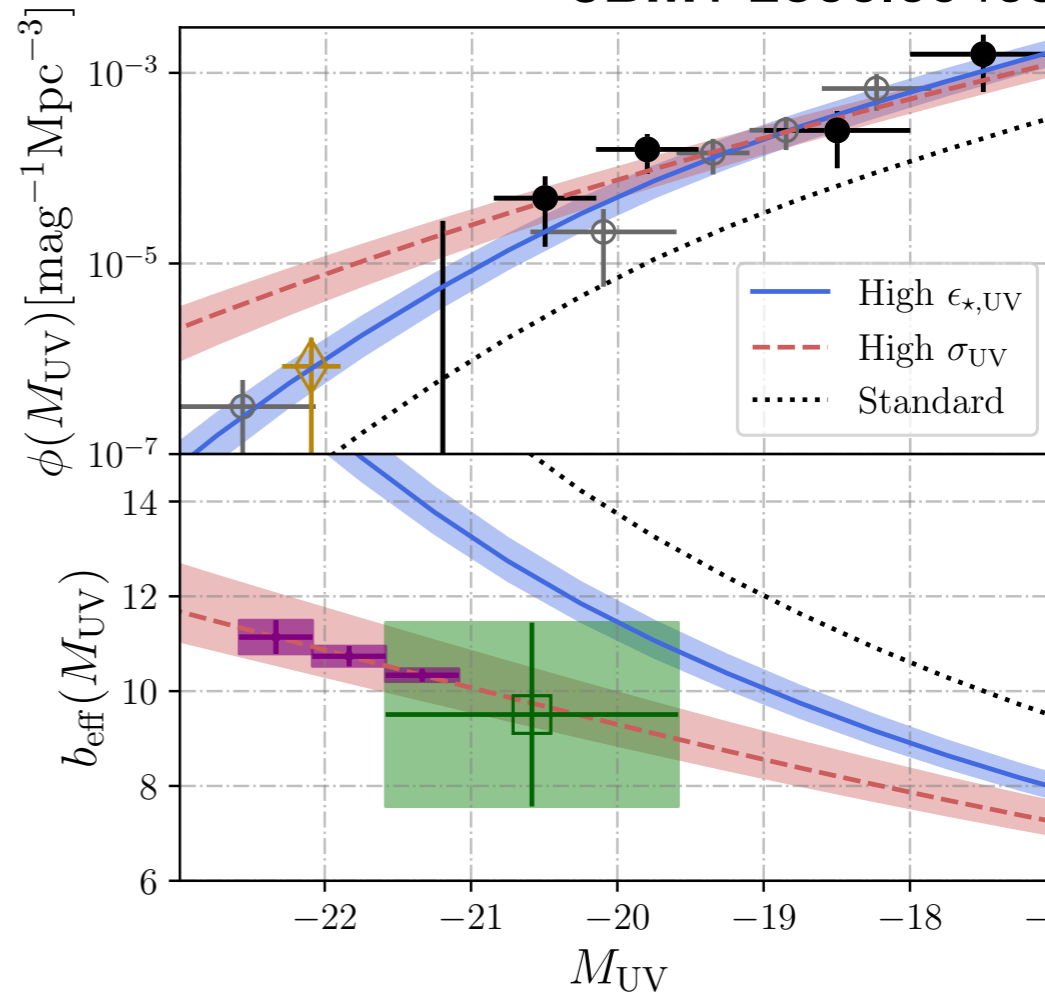
Too massive for LCDM?

Sabti, **JBM**, Kamionkowski 2305.07049



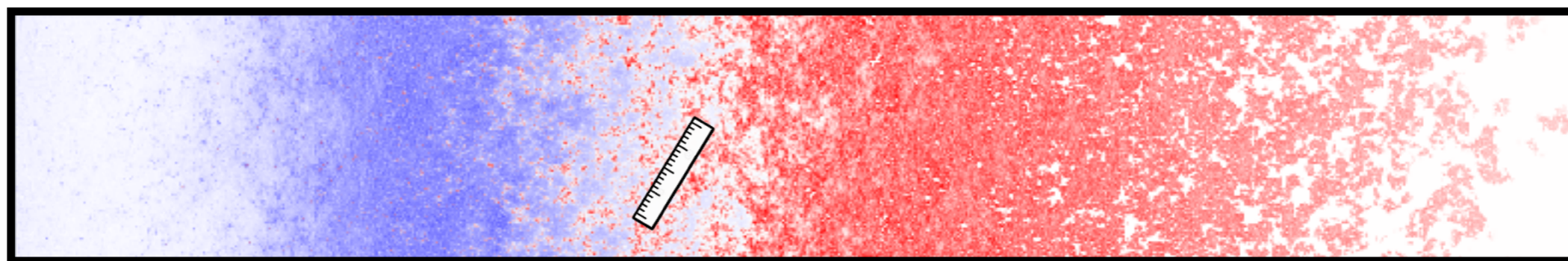
Tension beyond $z > 10$?

JBM+ 2306.09403



Hubble

@ $z \sim 10-20$



20

10

5

Redshift, z

JBM 1904.07868

JBM+ 2110.13919

