19th Patras workshop on
axions, WIMPs, and WISPs

17 September 2024

astrophysical tests of dark matter

across many scales

Sownak Bose

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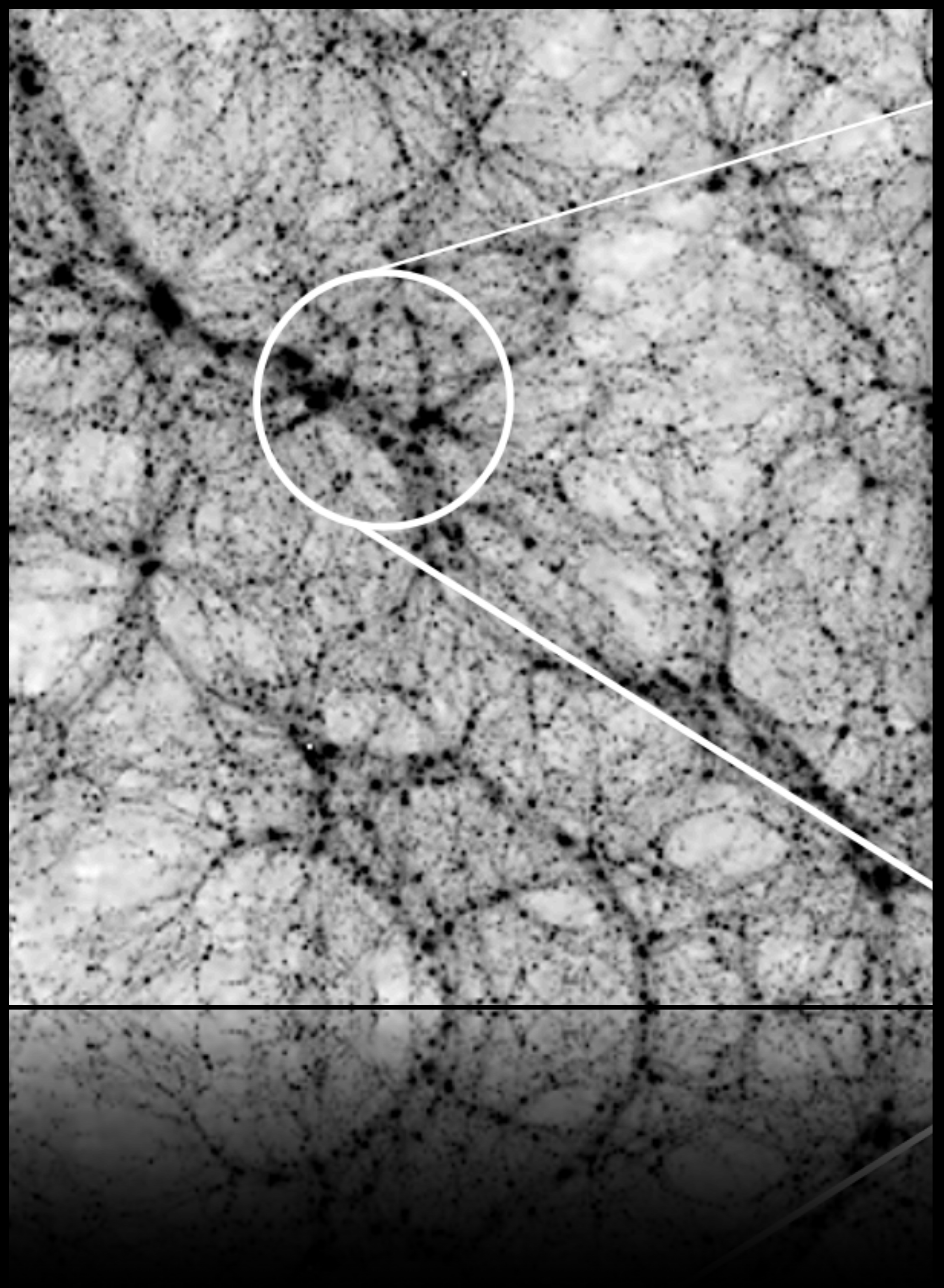
@Swnk16

Durham University

UK Research and Innovation

structures are **coupled** across multiple scales

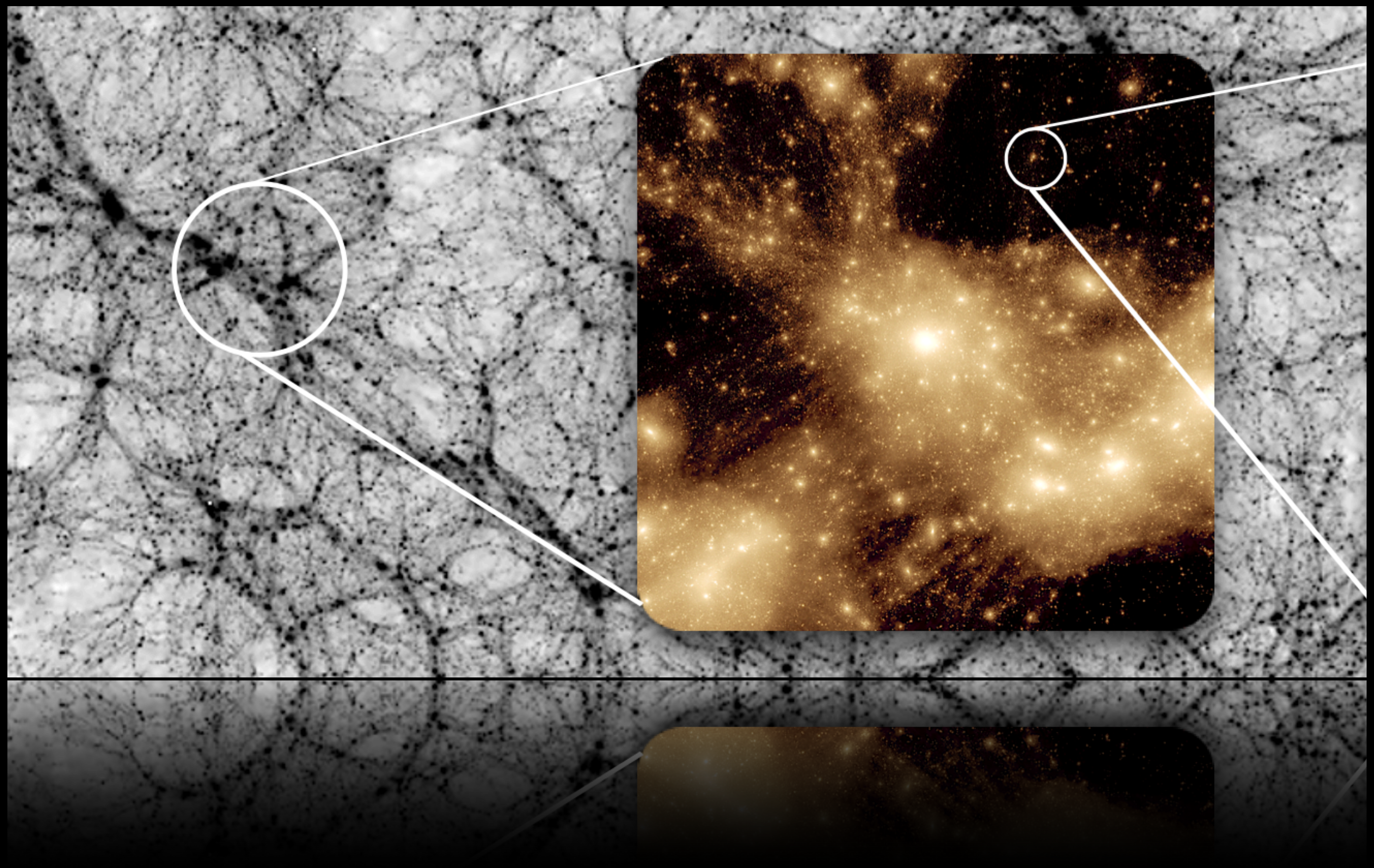
large-scale structure
[~ 10^9 light-years]



structures are coupled across multiple scales

large-scale structure
[~ 10^9 light-years]

dark matter haloes
[~ 10^6 light-years]

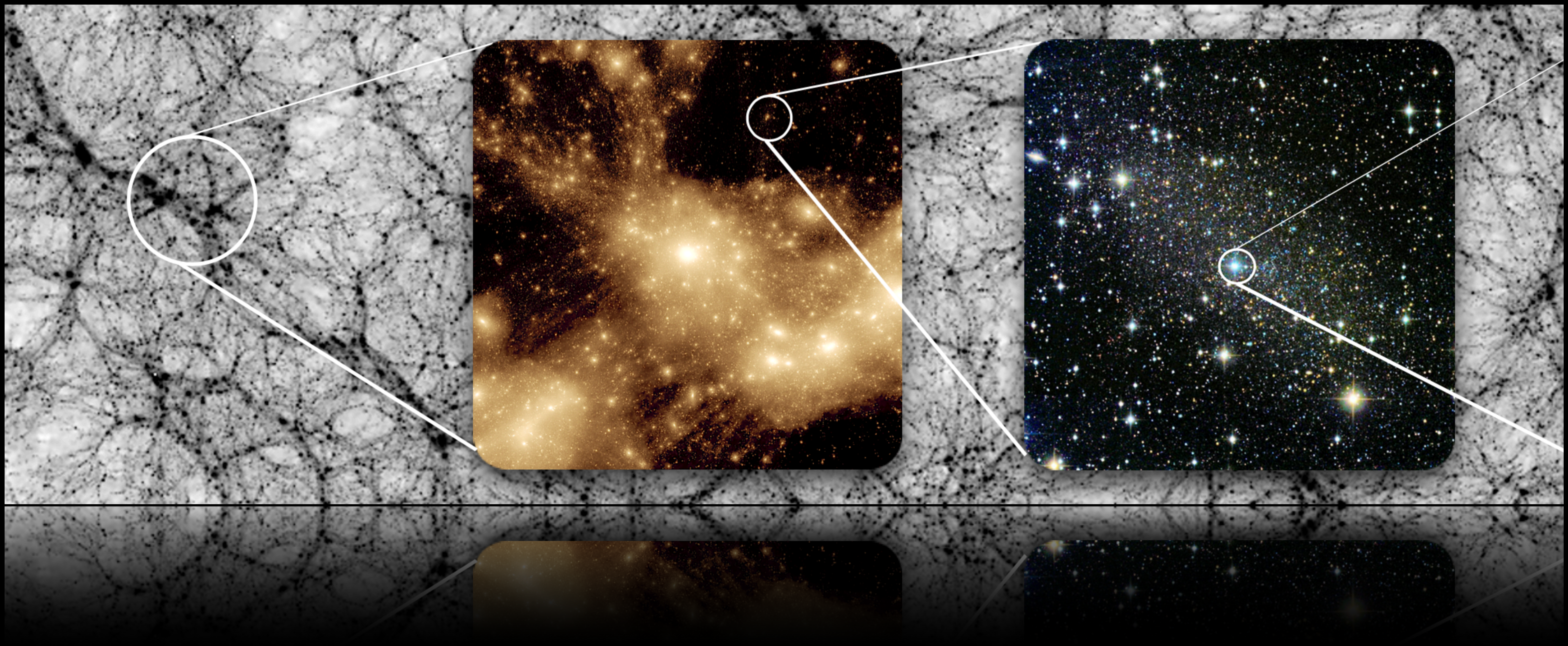


structures are **coupled** across multiple scales

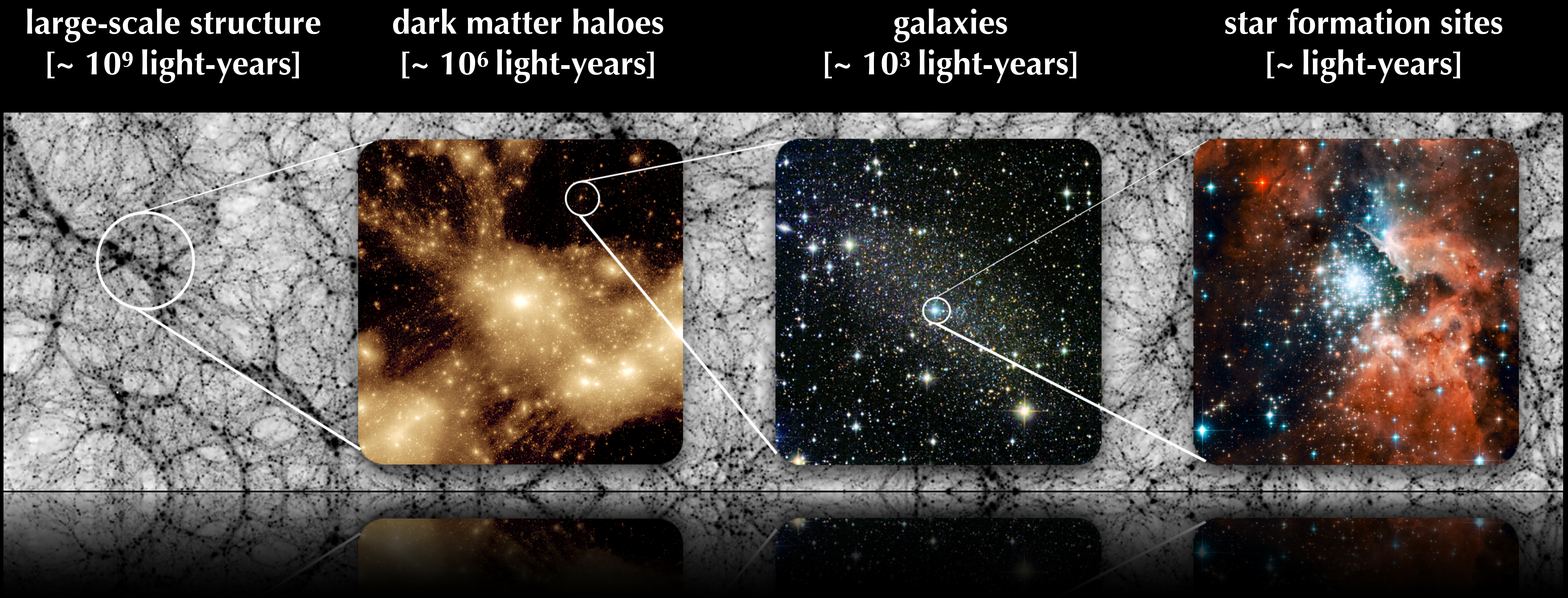
large-scale structure
[~ 10^9 light-years]

dark matter haloes
[~ 10^6 light-years]

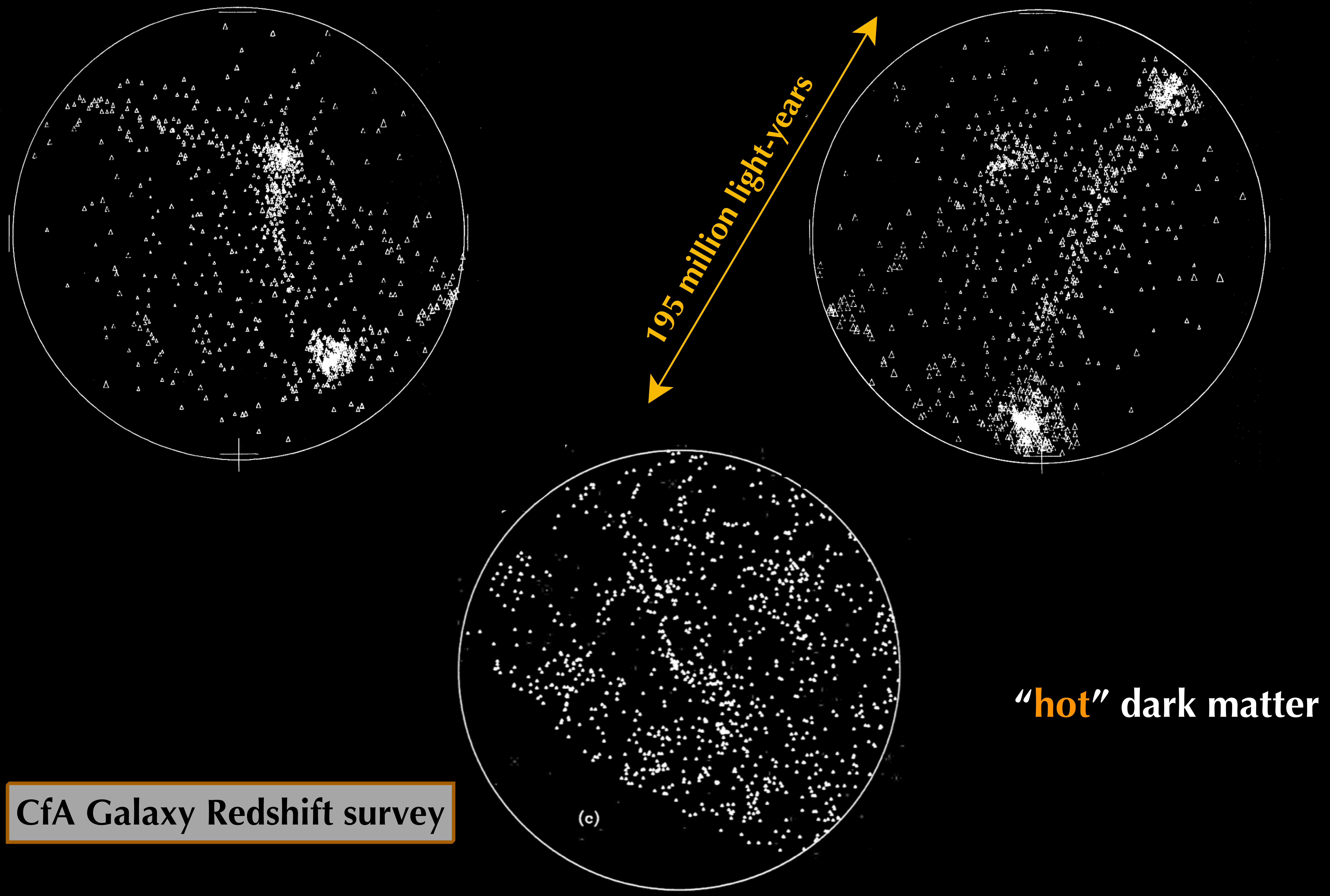
galaxies
[~ 10^3 light-years]



structures are coupled across multiple scales

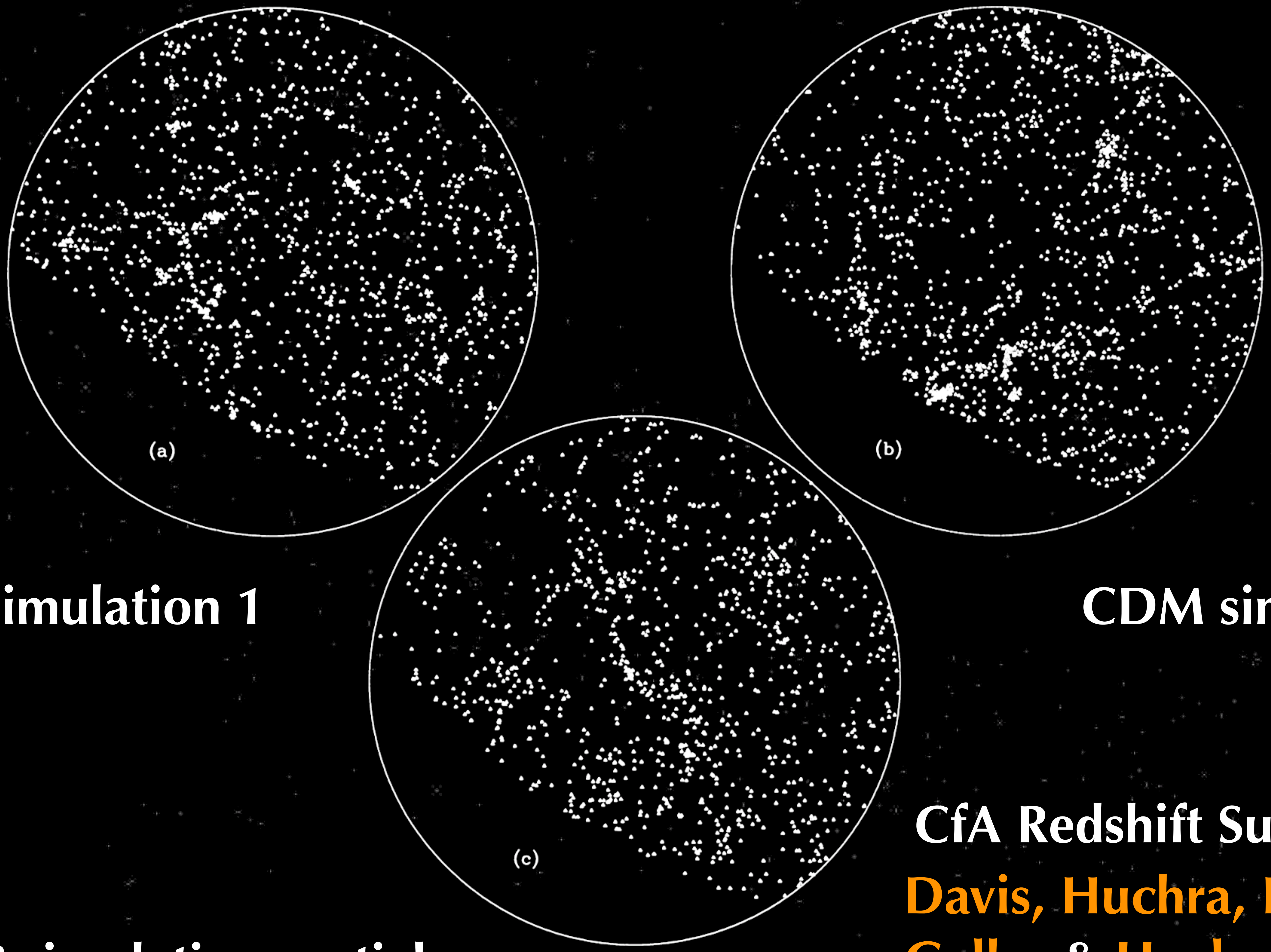


the role of cosmological simulations



Klypin & Shandarin (1983); 32^3 simulation particles

the emergence of cold dark matter



CDM simulation 1

CDM simulation 2

CfA Redshift Survey

Davis, Huchra, Latham & Tonry (1982)
Geller & Huchra (1983)

Davis+ (1985); 32^3 simulation particles


~ 512x larger computational volume
~ 300,000x more resolution elements (2160^3 DM particles)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~ 300,000x more resolution elements (2160³ DM particles)

30 kpc
z = 2.8
log $M_\star$ = 9.43
SFR = 3.5 $M_\odot$ yr^{-1}
TNG50
80 kpc
3 kpc


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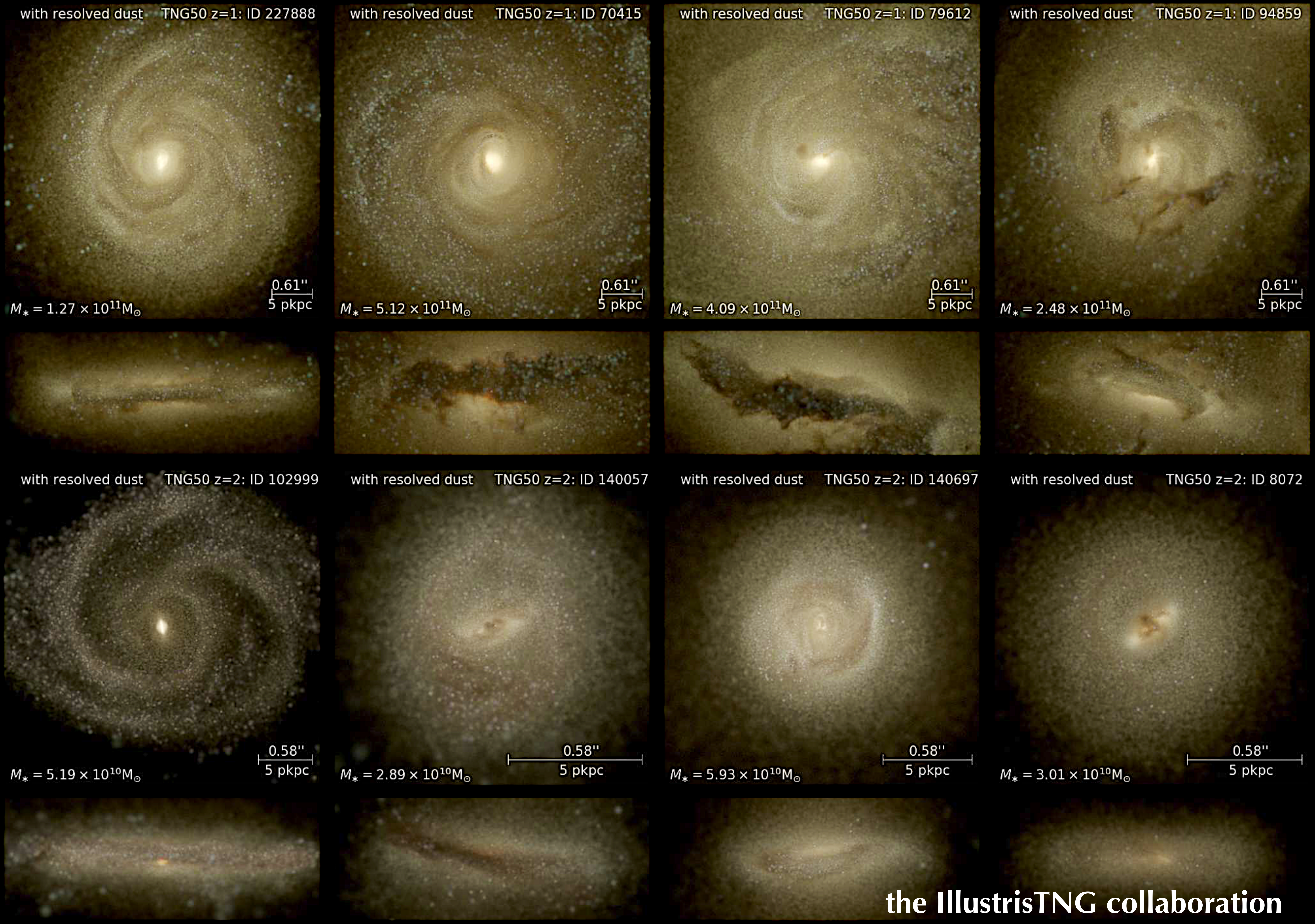
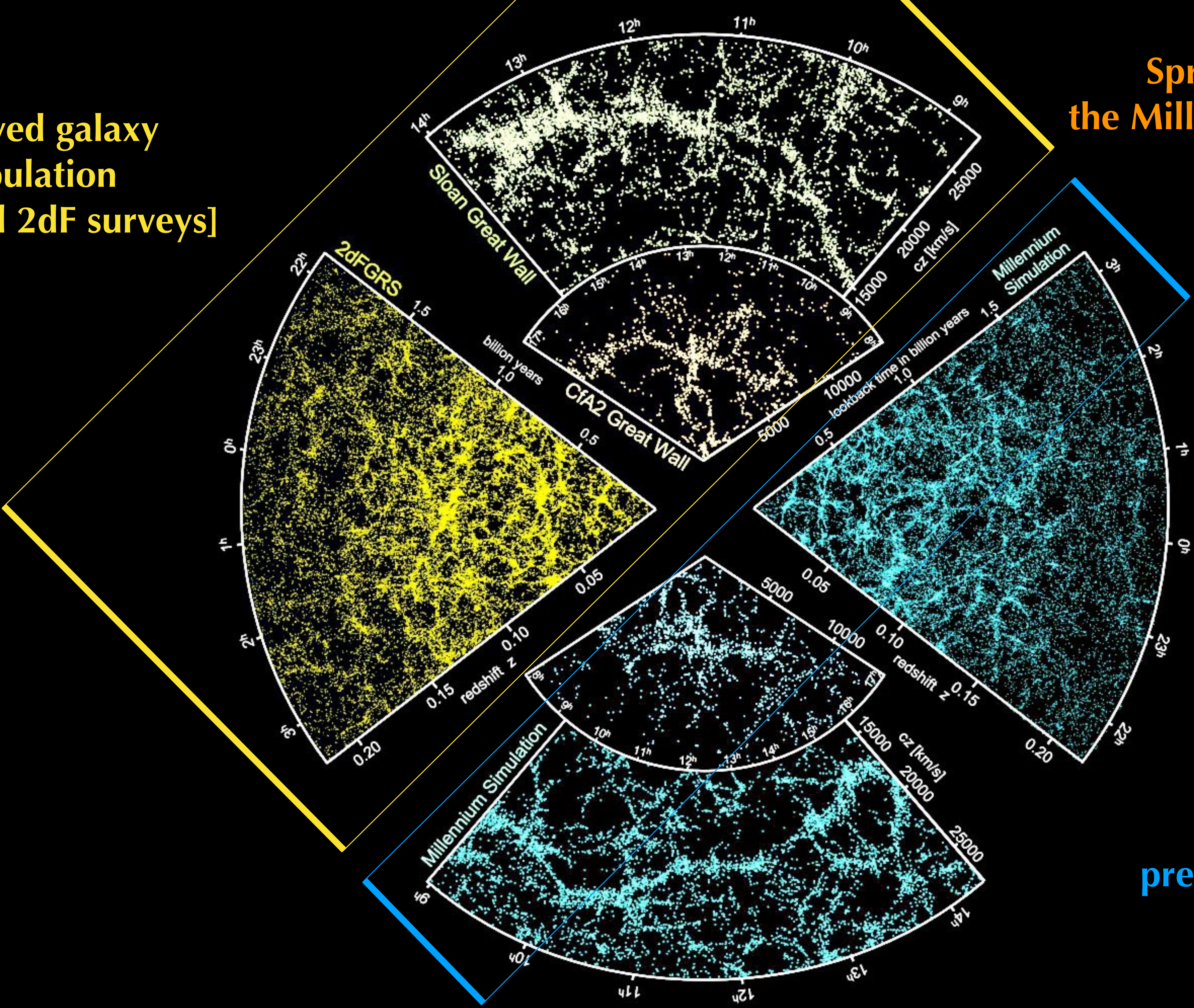
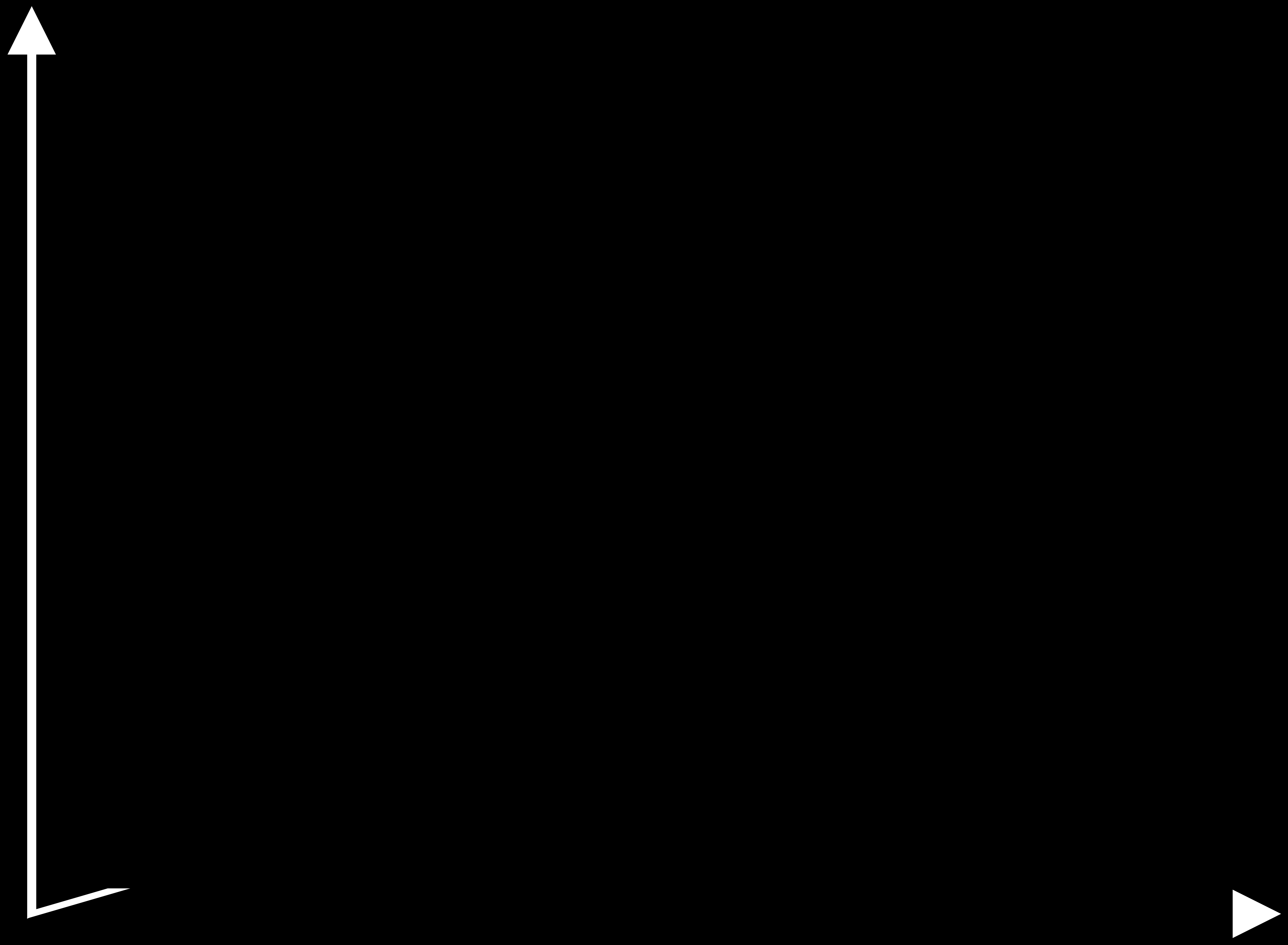

with resolved dust
TNG50 z=1: ID 227888
0.61''
5 pkpc
M* = 1.27 × 10^11 M☉
with resolved dust
TNG50 z=1: ID 70415
0.61''
5 pkpc
M* = 5.12 × 10^11 M☉
with resolved dust
TNG50 z=1: ID 79612
0.61''
5 pkpc
M* = 4.09 × 10^11 M☉
with resolved dust
TNG50 z=1: ID 94859
0.61''
5 pkpc
M* = 2.48 × 10^11 M☉
with resolved dust
TNG50 z=2: ID 102999
0.58''
5 pkpc
M* = 5.19 × 10^10 M☉
with resolved dust
TNG50 z=2: ID 140057
0.58''
5 pkpc
M* = 2.89 × 10^10 M☉
with resolved dust
TNG50 z=2: ID 140697
0.58''
5 pkpc
M* = 5.93 × 10^10 M☉
with resolved dust
TNG50 z=2: ID 8072
0.58''
5 pkpc
M* = 3.01 × 10^10 M☉
the IllustrisTNG collaboration

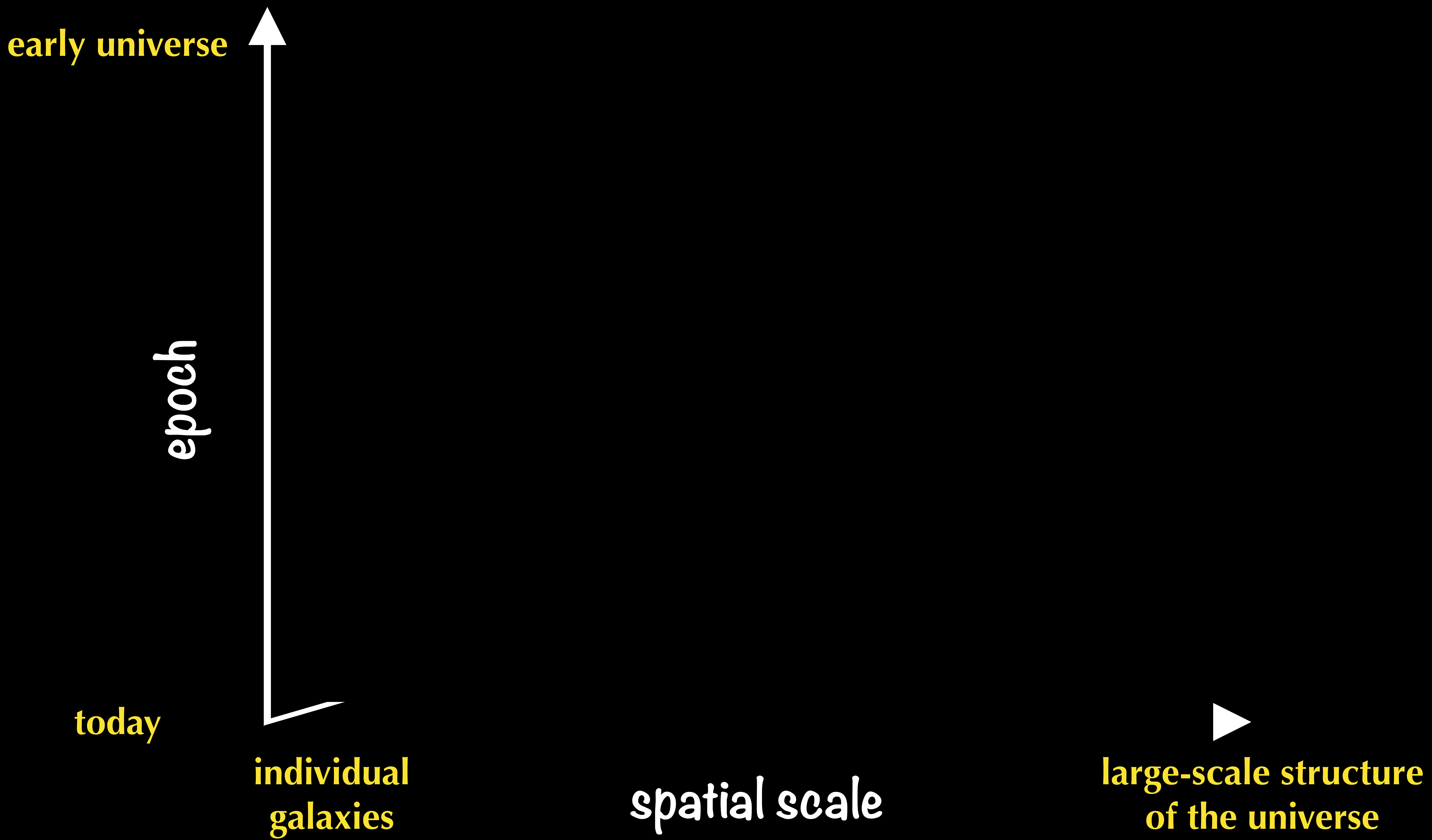
observed galaxy population
[SDSS and 2dF surveys]

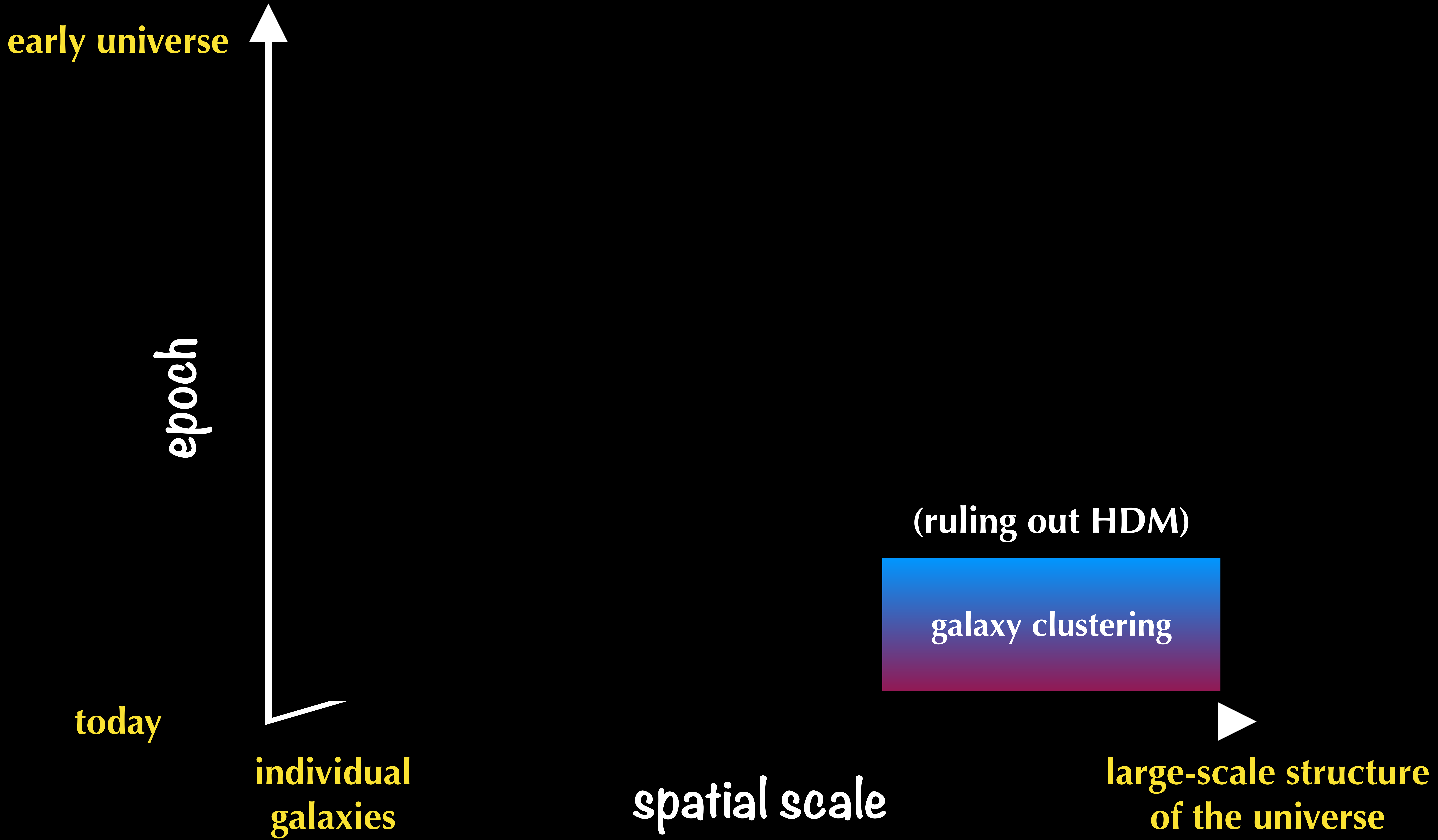
Springel+ (2005)
the Millennium simulation

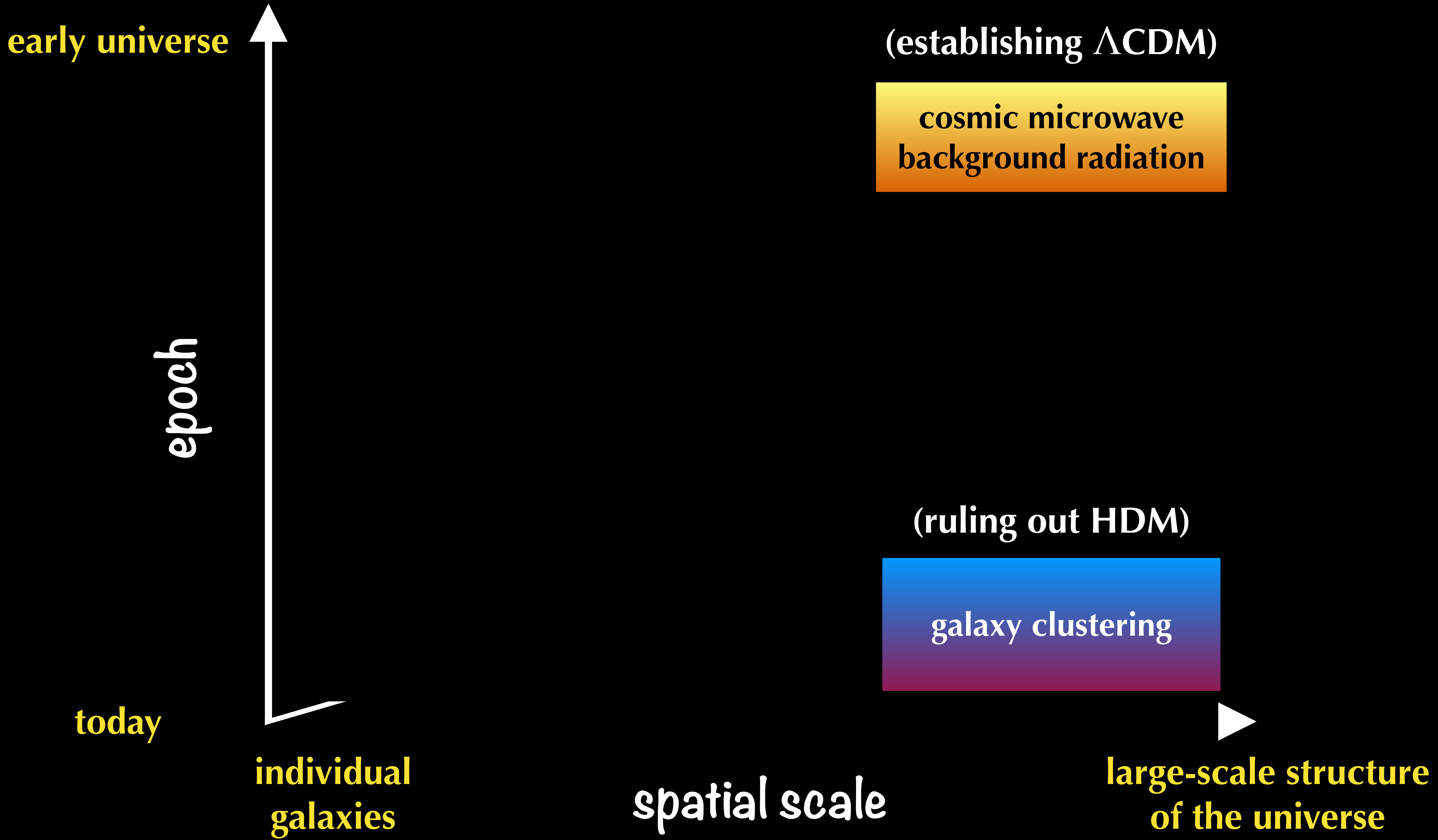


prediction of the ΛCDM model



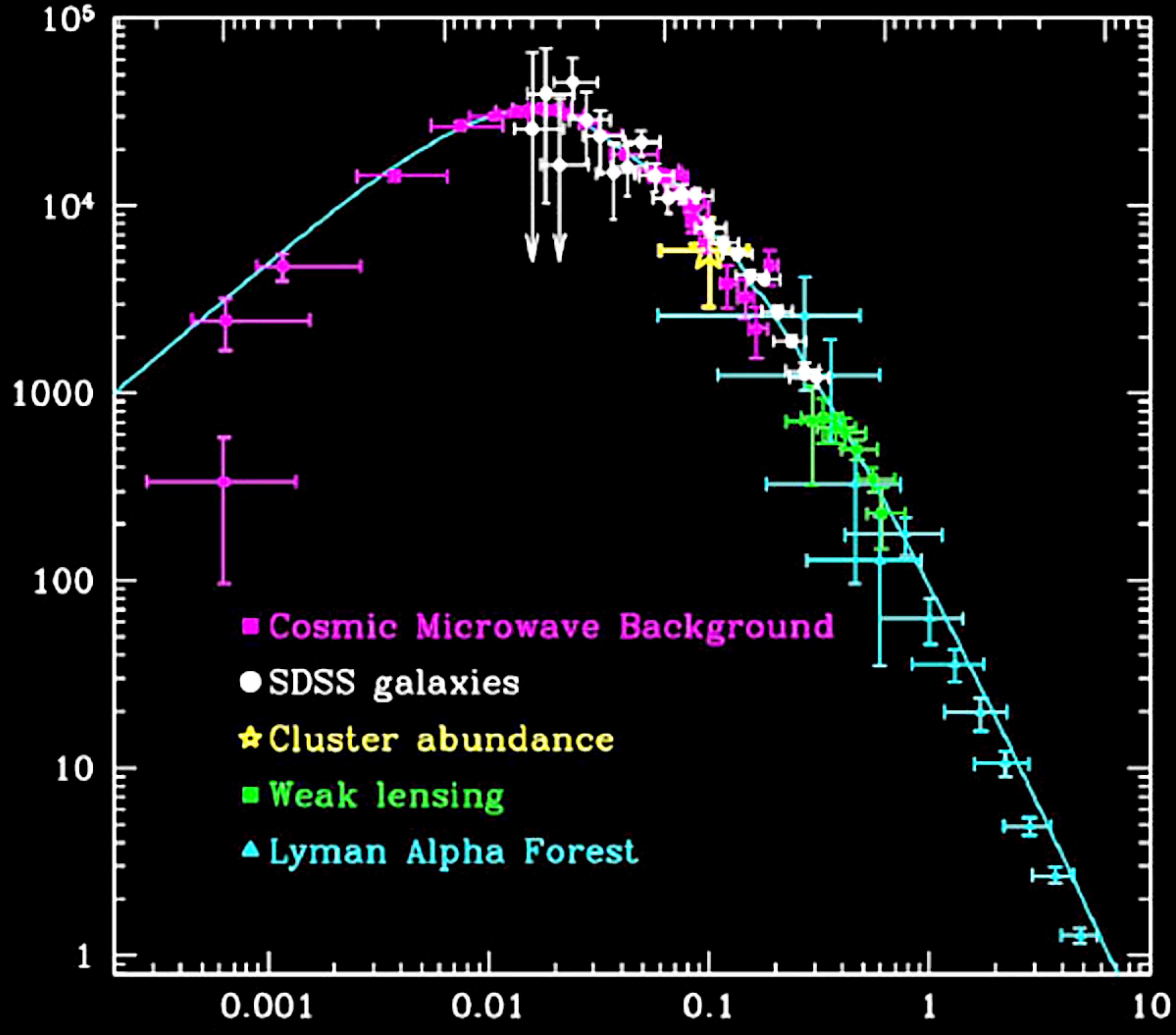

early universe
epoch
today
individual galaxies
spatial scale
large-scale structure of the universe


early universe
epoch
(ruling out HDM)
galaxy clustering
today
individual galaxies
spatial scale
large-scale structure of the universe


early universe
(establishing ΛCDM)
cosmic microwave background radiation
epoch
(ruling out HDM)
galaxy clustering
today
individual galaxies
spatial scale
large-scale structure of the universe

large scales

small scales



spatial scale [h Mpc^{-1}]

size of density fluctuations in the universe

solid curve: ΛCDM prediction
symbols: data from multi-scale probes

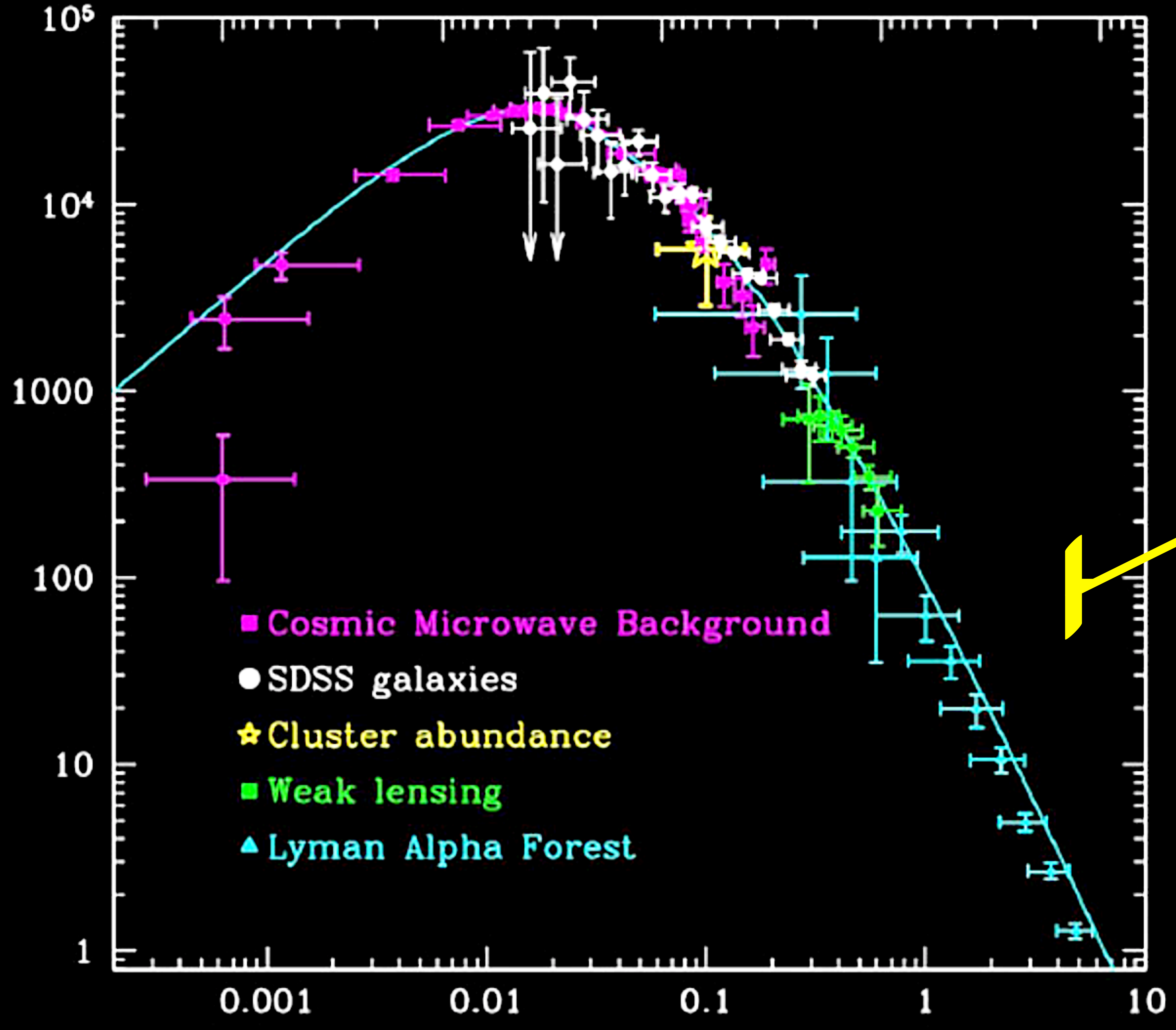
Tegmark+ (2004)

large scales ←

→ small scales

size of density fluctuations in the universe

log [power spectrum]



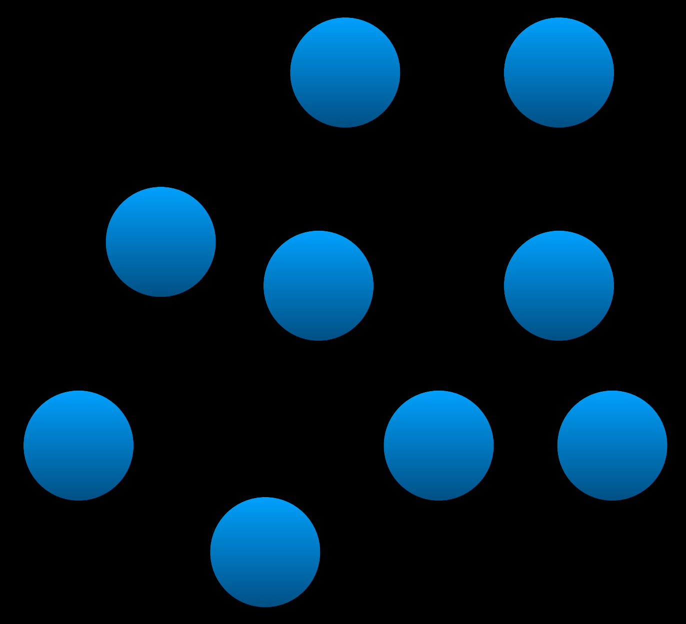
spatial scale [*h* Mpc^{-1}]

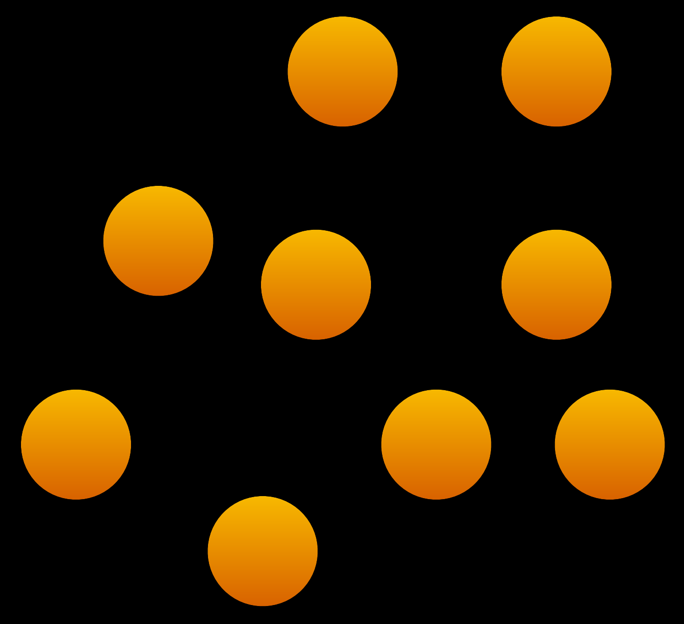
Tegmark+ (2004)

solid curve: ΛCDM prediction
symbols: data from multi-scale probes

this is the regime where we have most freedom to experiment with DM phenomenology:

dwarf galaxies





sterile neutrinos

[warm dark matter]

(~ keV mass)

[Dodelson & Widrow (1994); Abazajian+ (2001); Dolgov & Hansen (2002); Asaka & Shaposhnikov (2005); Boyarsky+ (2009)]

sterile neutrinos
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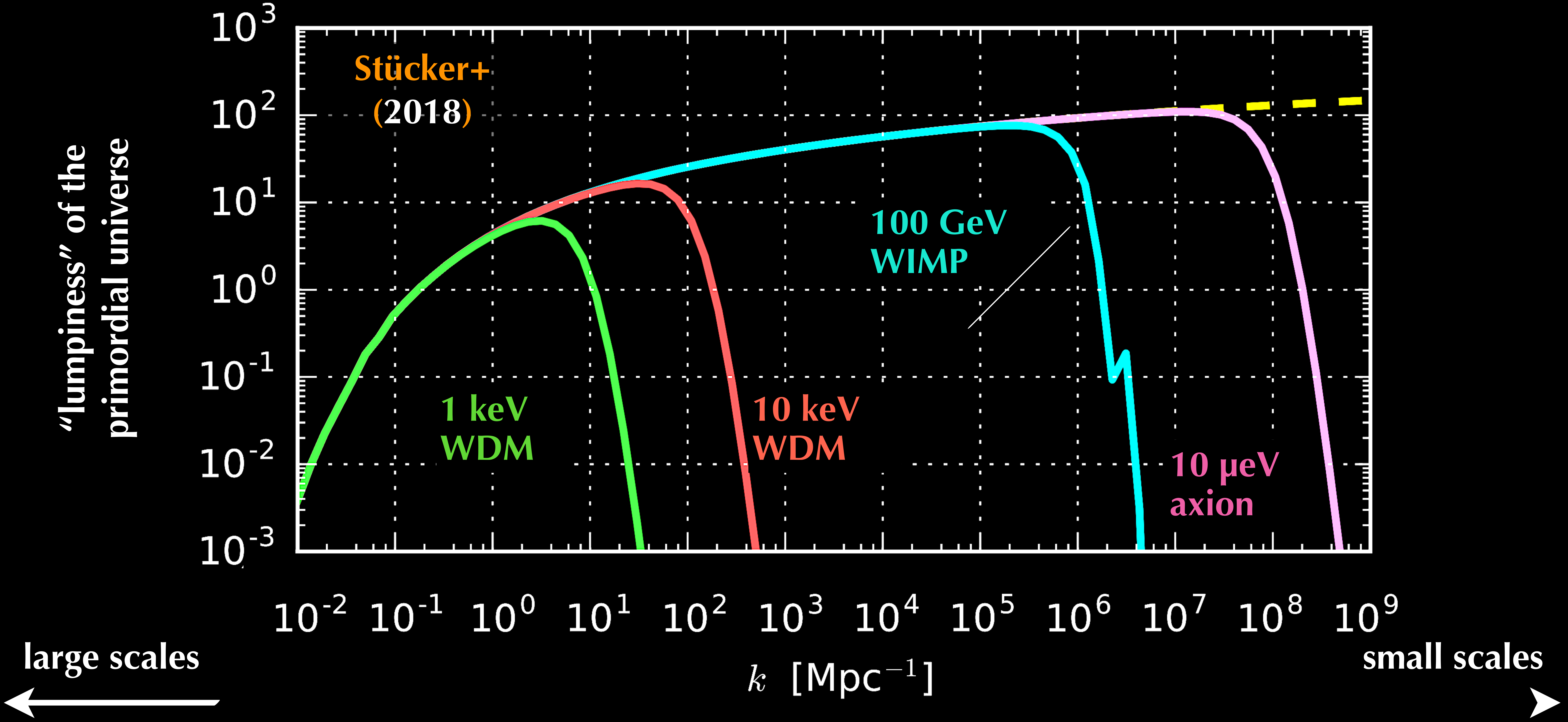
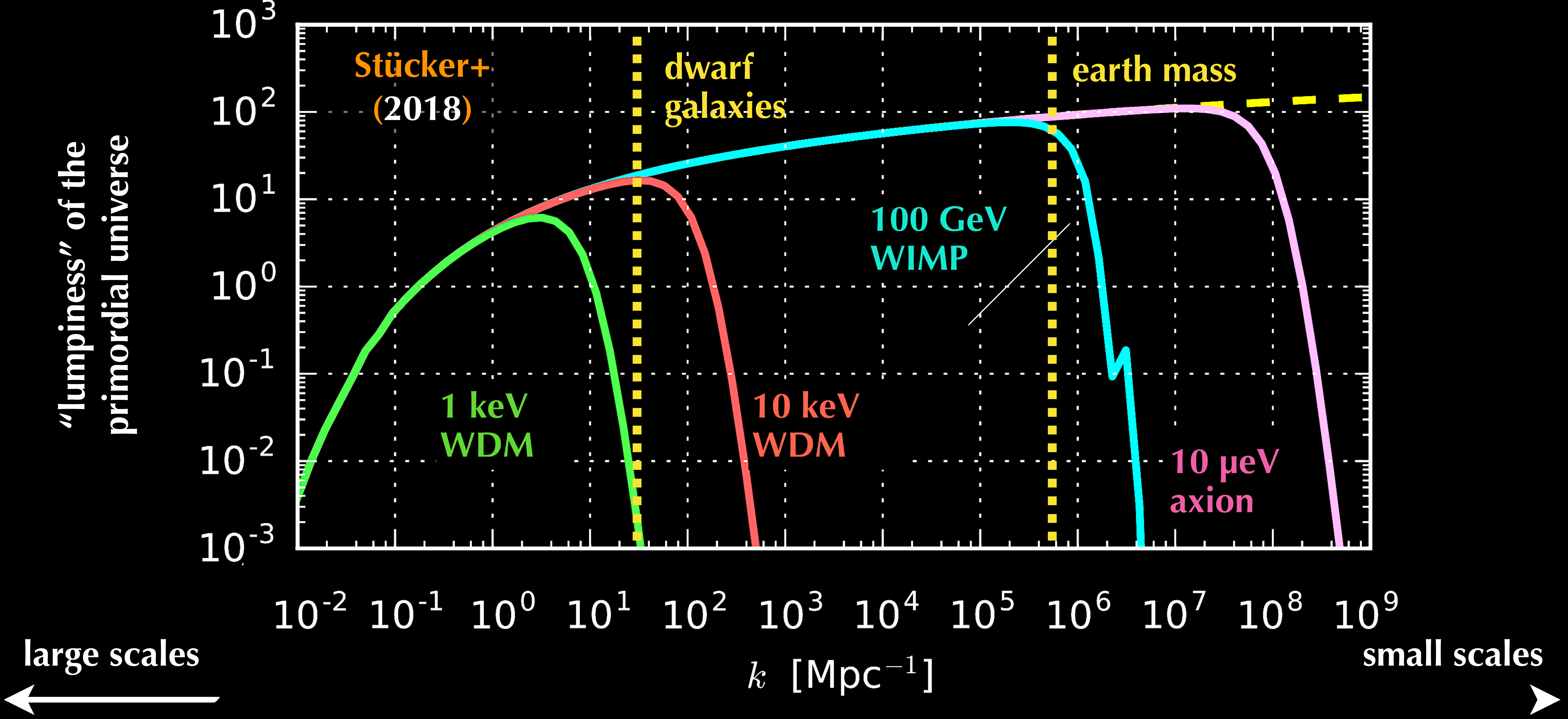
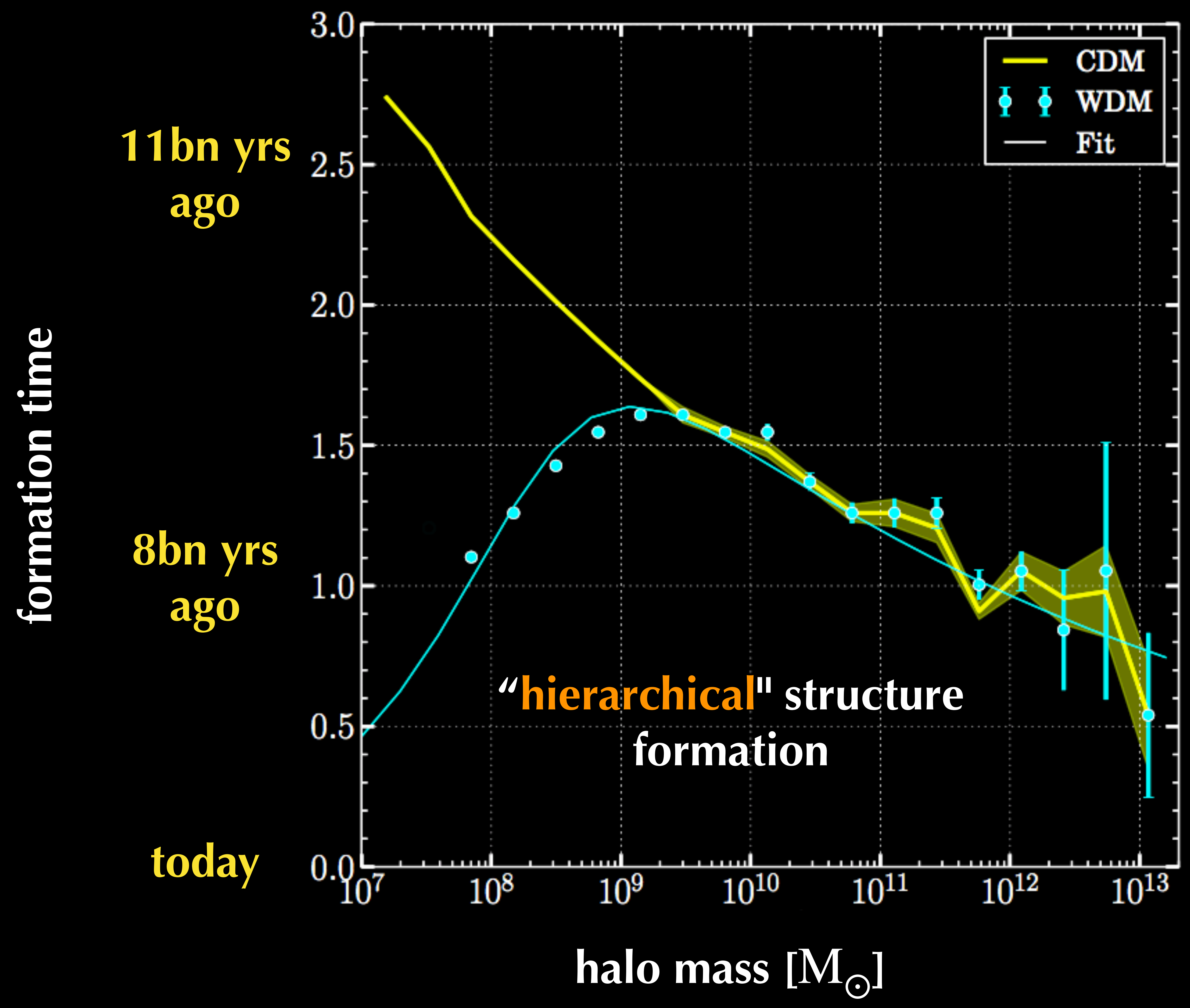
the power spectrum of structures



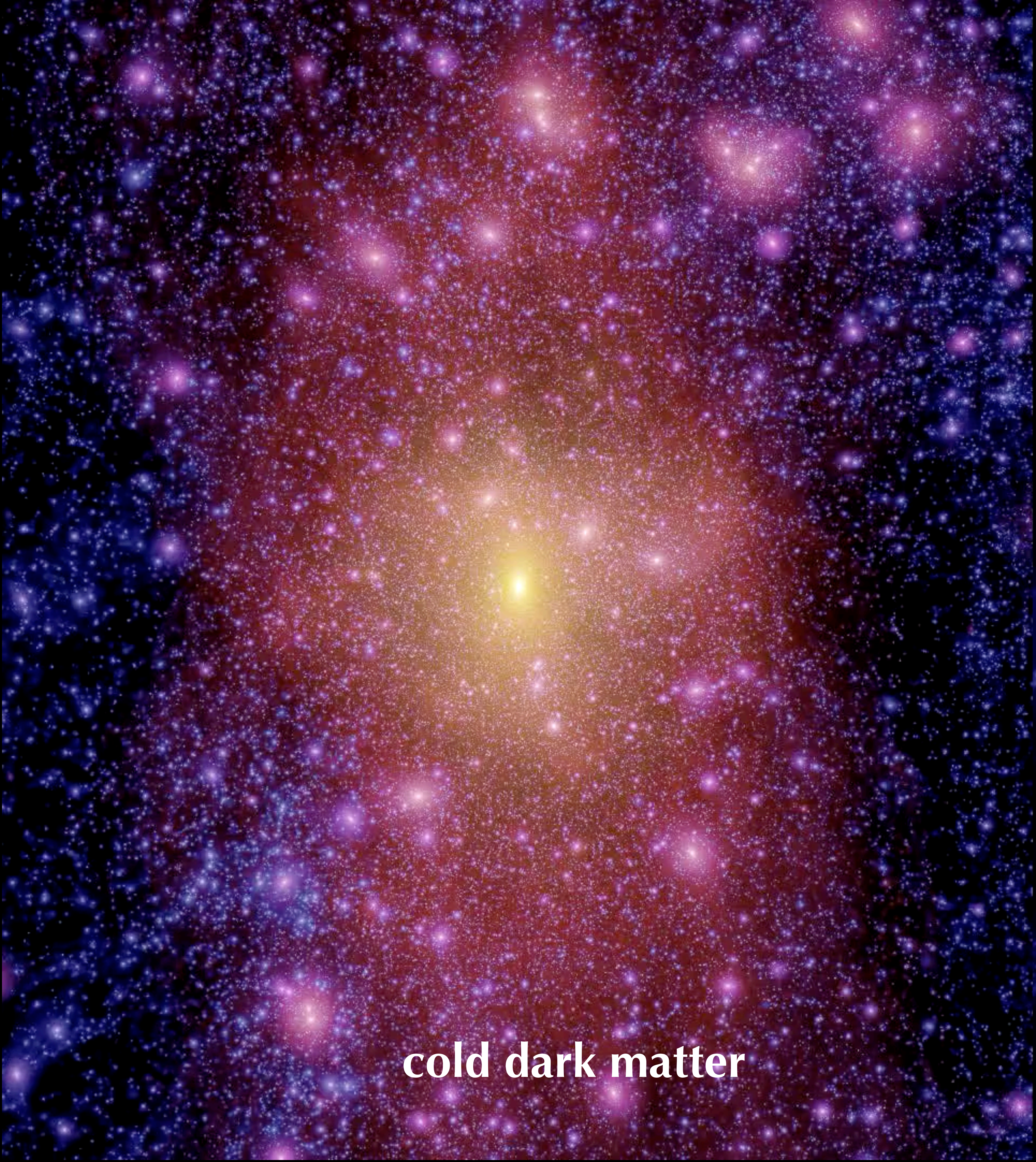
the power spectrum of structures

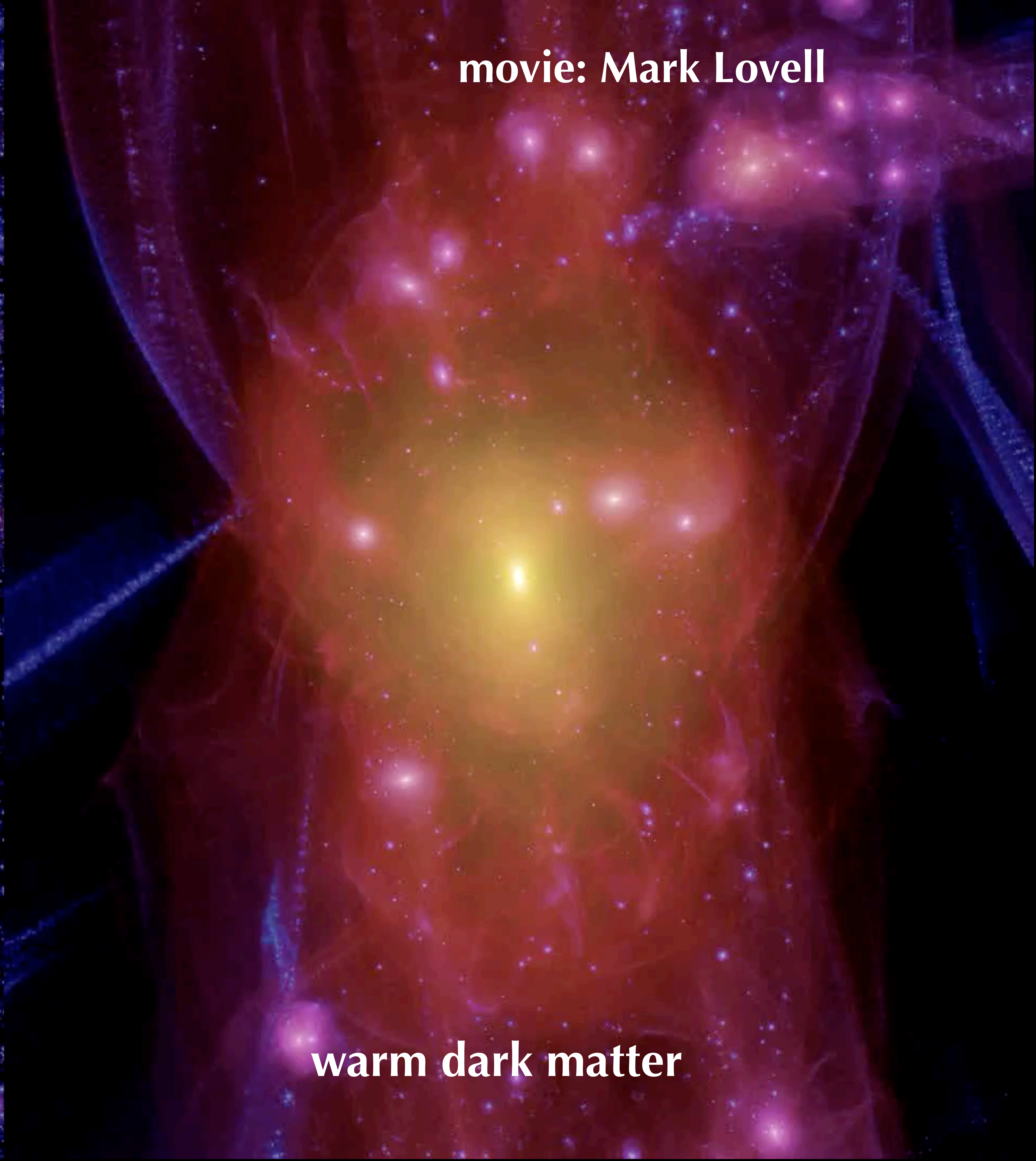


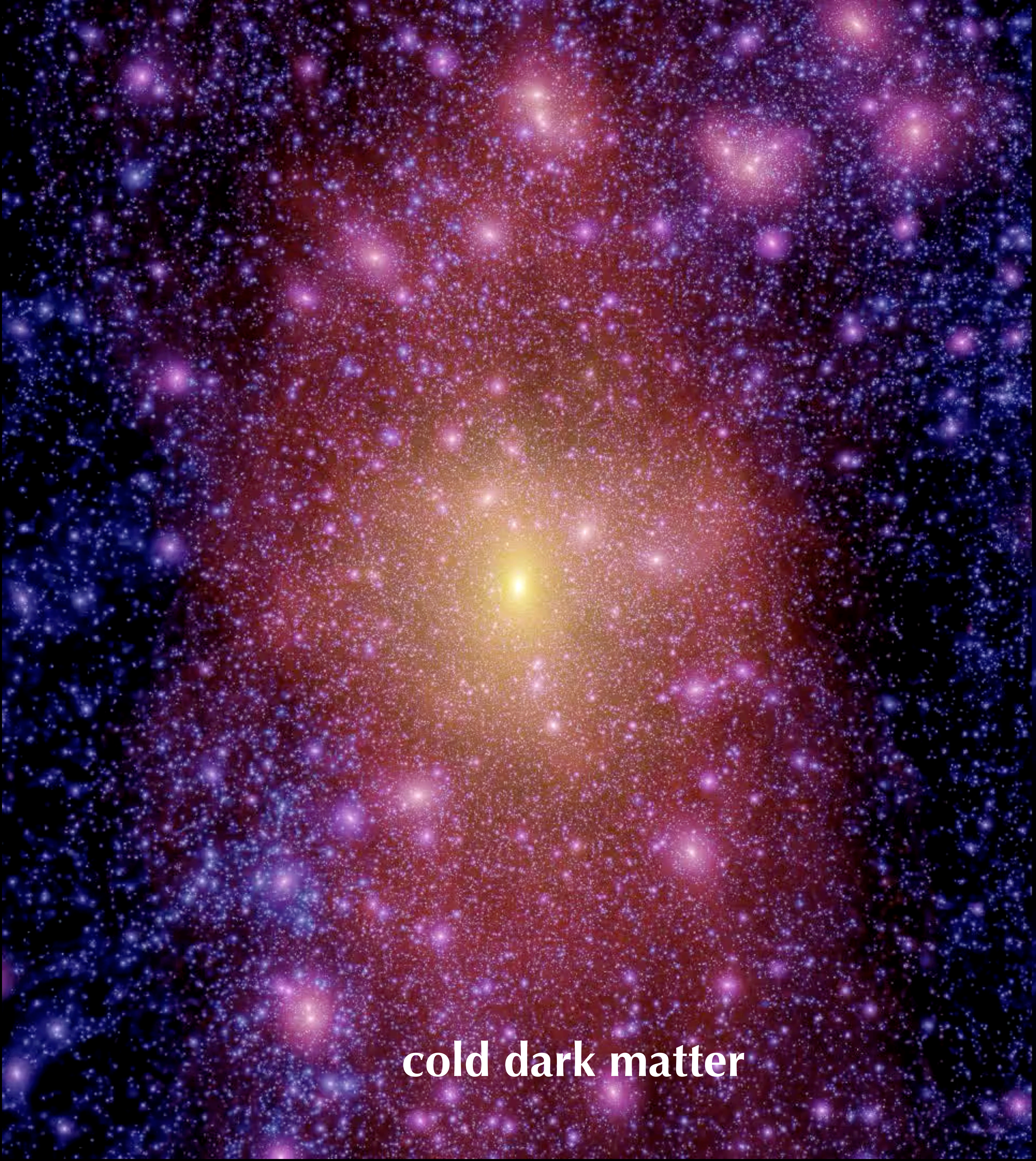
Bose, Hellwing+ (2016) [arXiv: 1507.01998]

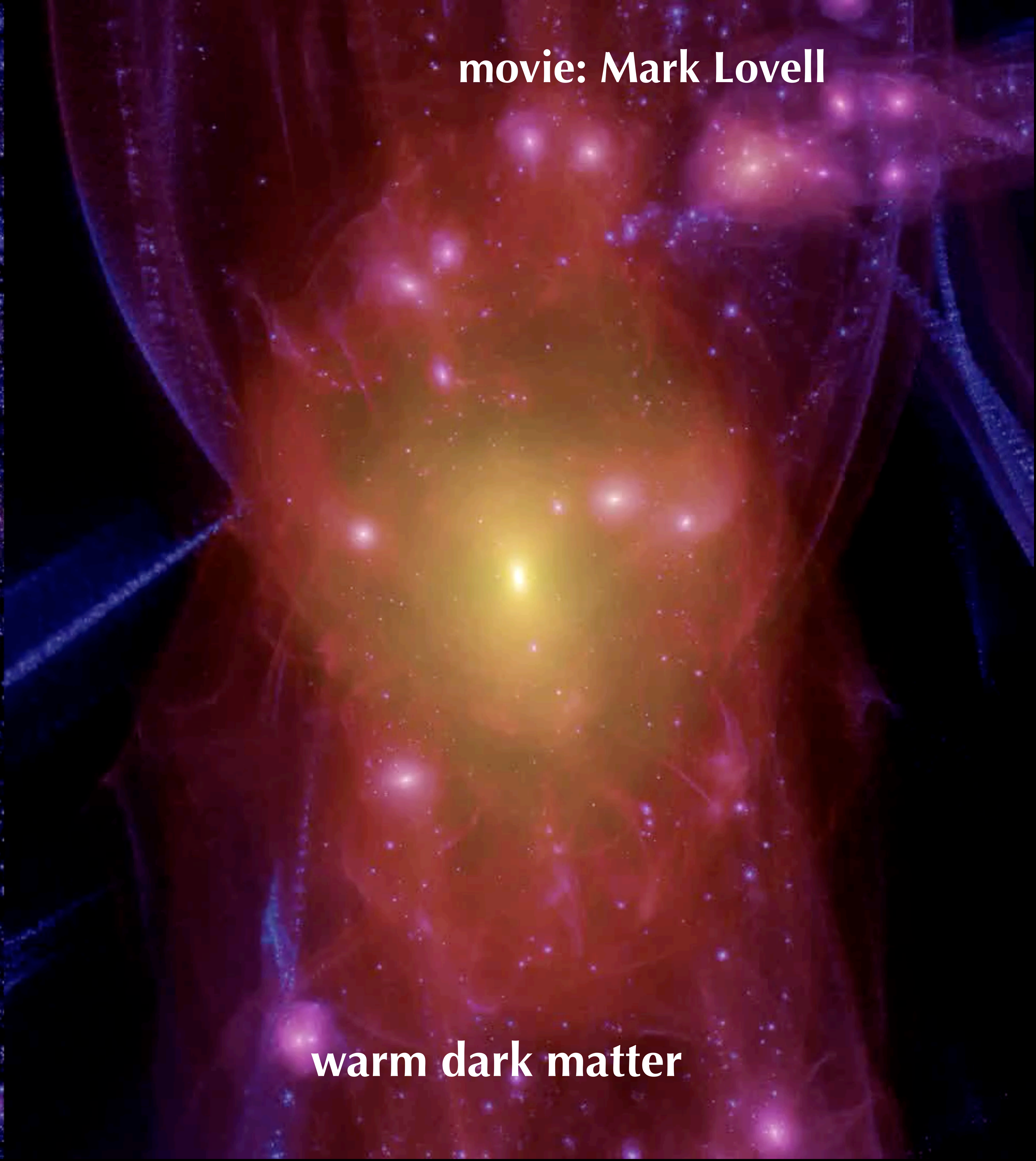



Bose, Hellwing+ (2016) [arXiv: 1507.01998]
CDM
WDM
Fit
11bn yrs ago
8bn yrs ago
today
formation time
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
halo mass [$M_\odot$]
"hierarchical" structure formation
below a characteristic scale, halo formation is delayed relative to CDM
differences driven by this feature


cold dark matter


movie: Mark Lovell
warm dark matter

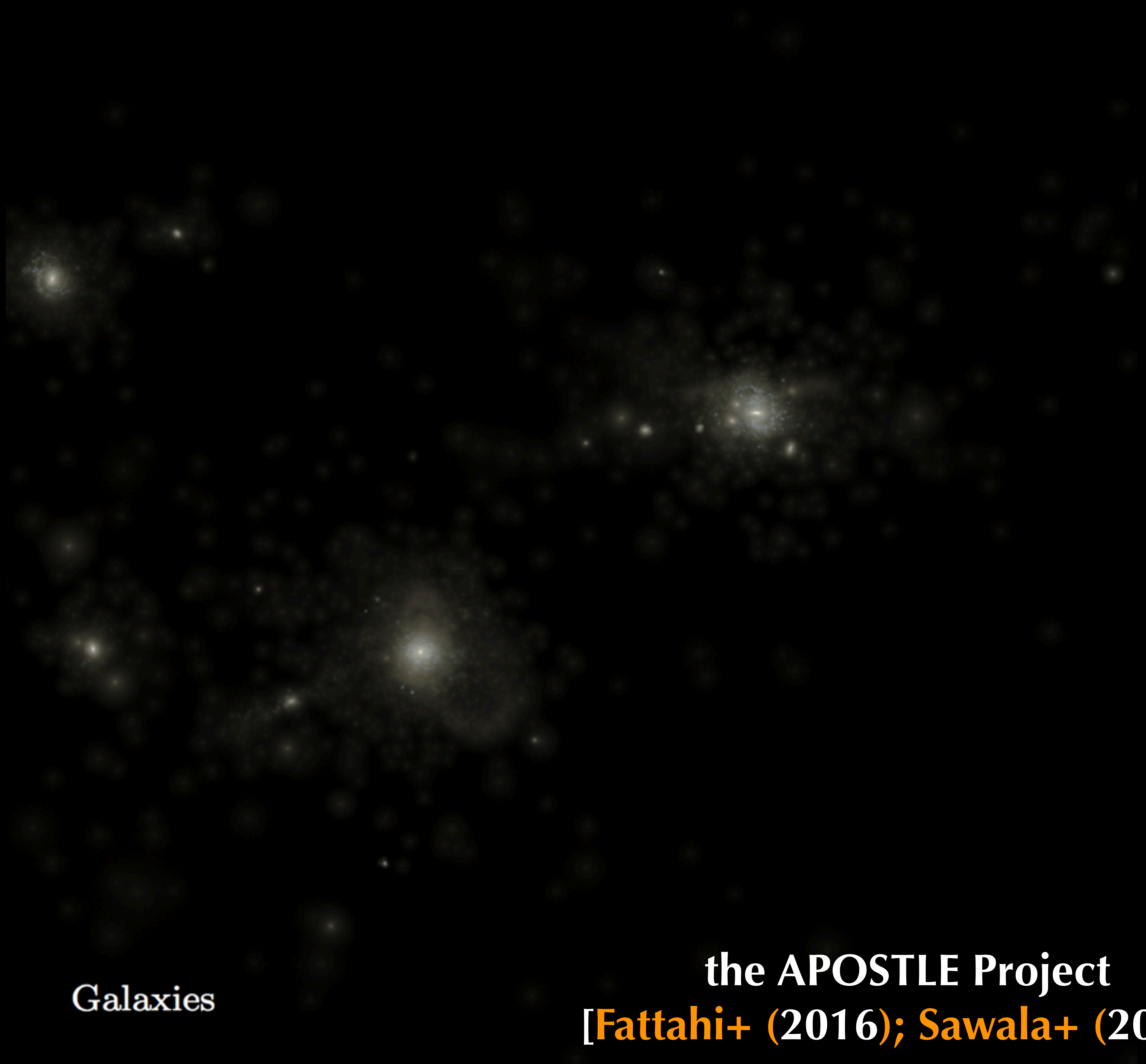

cold dark matter


movie: Mark Lovell
warm dark matter


movie: Mark Lovell
is it as simple as counting the number of satellite galaxies we observe orbiting the Milky Way?
cold dark matter
warm dark matter


movie: Mark Lovell
is it as simple as counting the number of satellite galaxies we observe orbiting the Milky Way? Yes! … and no.
[Maccio & Fontanot (2010); Polisensky & Ricotti (2011); Lovell+ (2012); Nierenberg+ (2013)]

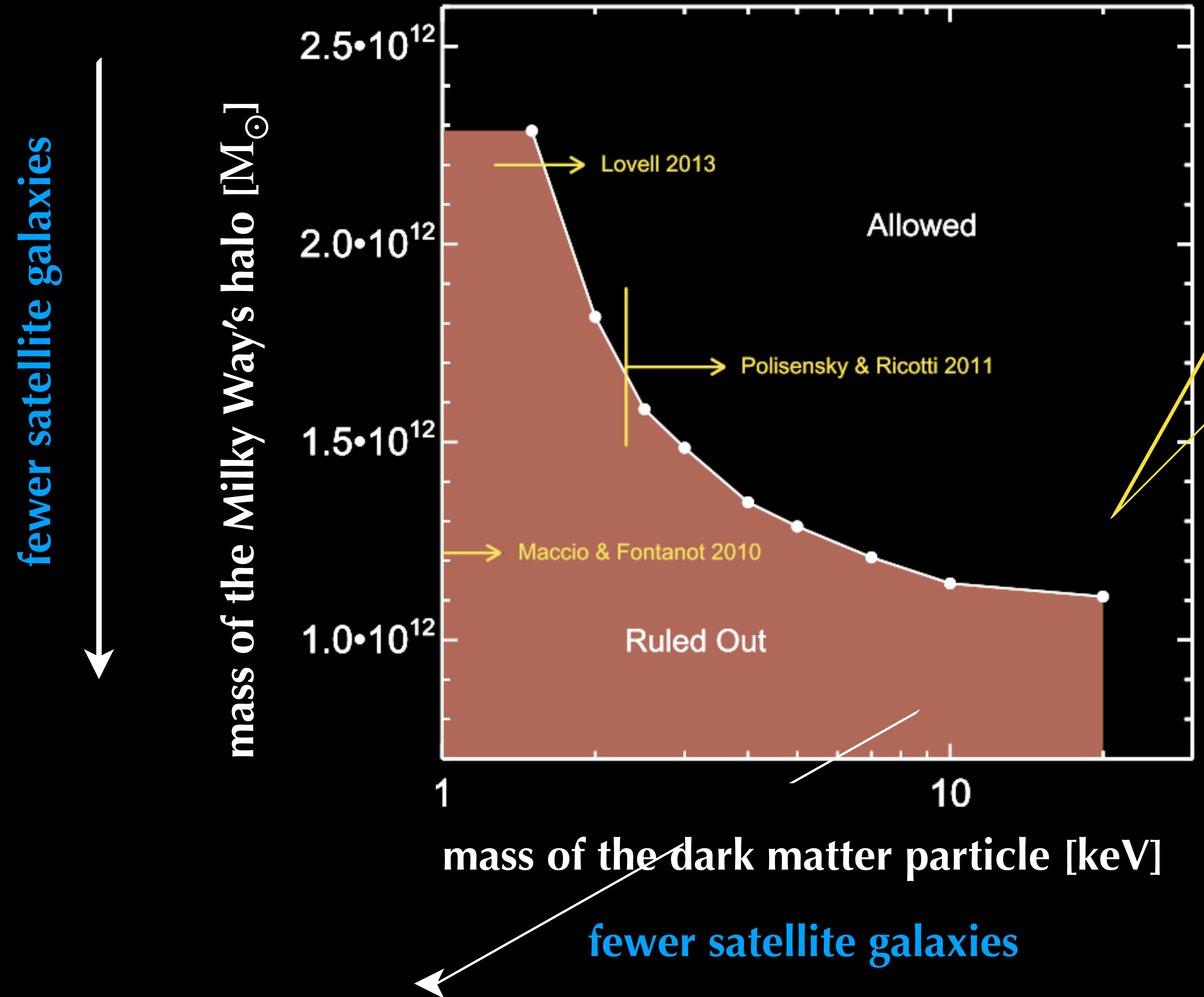

Dark matter
the APOSTLE Project
[Fattahi+ (2016); Sawala+ (2016)]



the APOSTLE Project
[Fattahi+ (2016); Sawala+ (2016)]

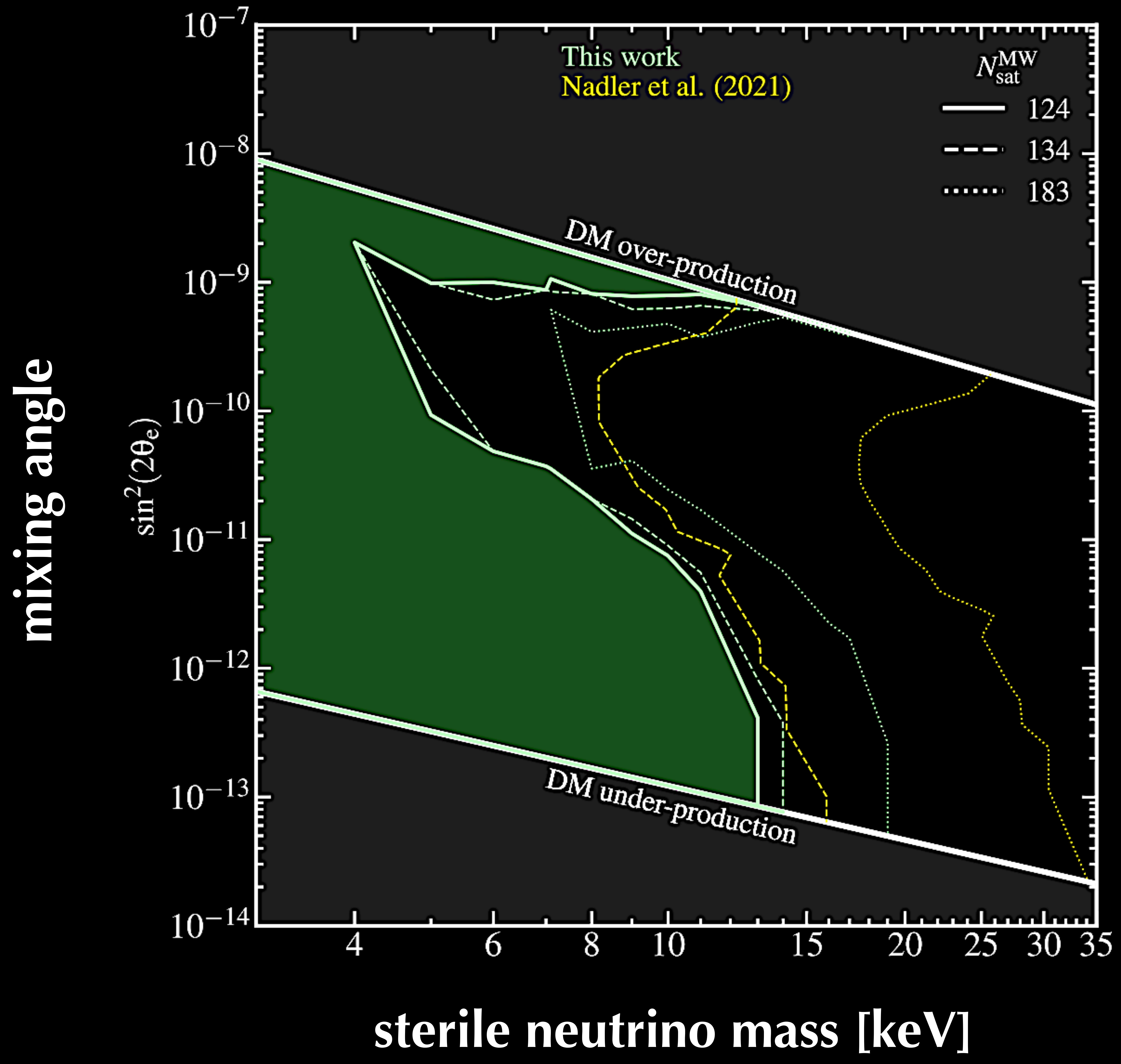
Kennedy+ (2014)

Bose, Frenk+ (2017) [arXiv: 1604.07409]



challenge: there is significant degeneracy between the particle nature of the dark matter, and our imperfect knowledge of how heavy the Milky Way is, how galaxy formation works etc.

Newton+ (2024)



} different total estimates for # of satellites around the Milky Way

these constraints all assume that sterile neutrinos make up 100% of the DM in the universe. different groups approach this seemingly straightforward problem in slightly different ways — yet, these lead to disagreement about how much of the sterile neutrino parameter space is ruled out!

can we image dark matter structures directly?

can we image dark matter structures directly?

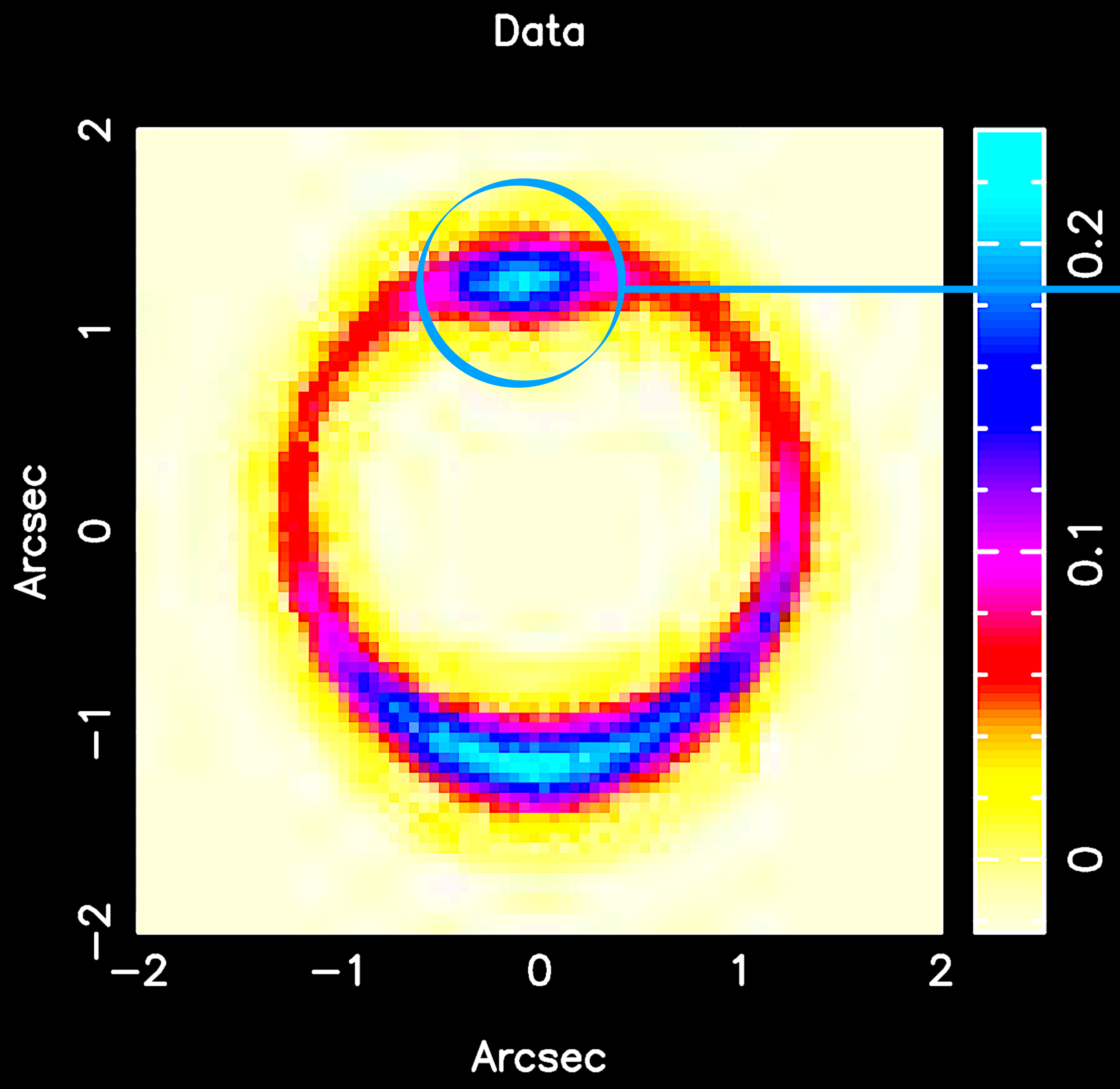
yes!

www.eso.org

https://www.youtube.com/watch?v=GPfUdpBe6j0 www.eso.org

https://www.youtube.com/watch?v=GPfUdpBe6j0

using gravitational lensing to image dark matter

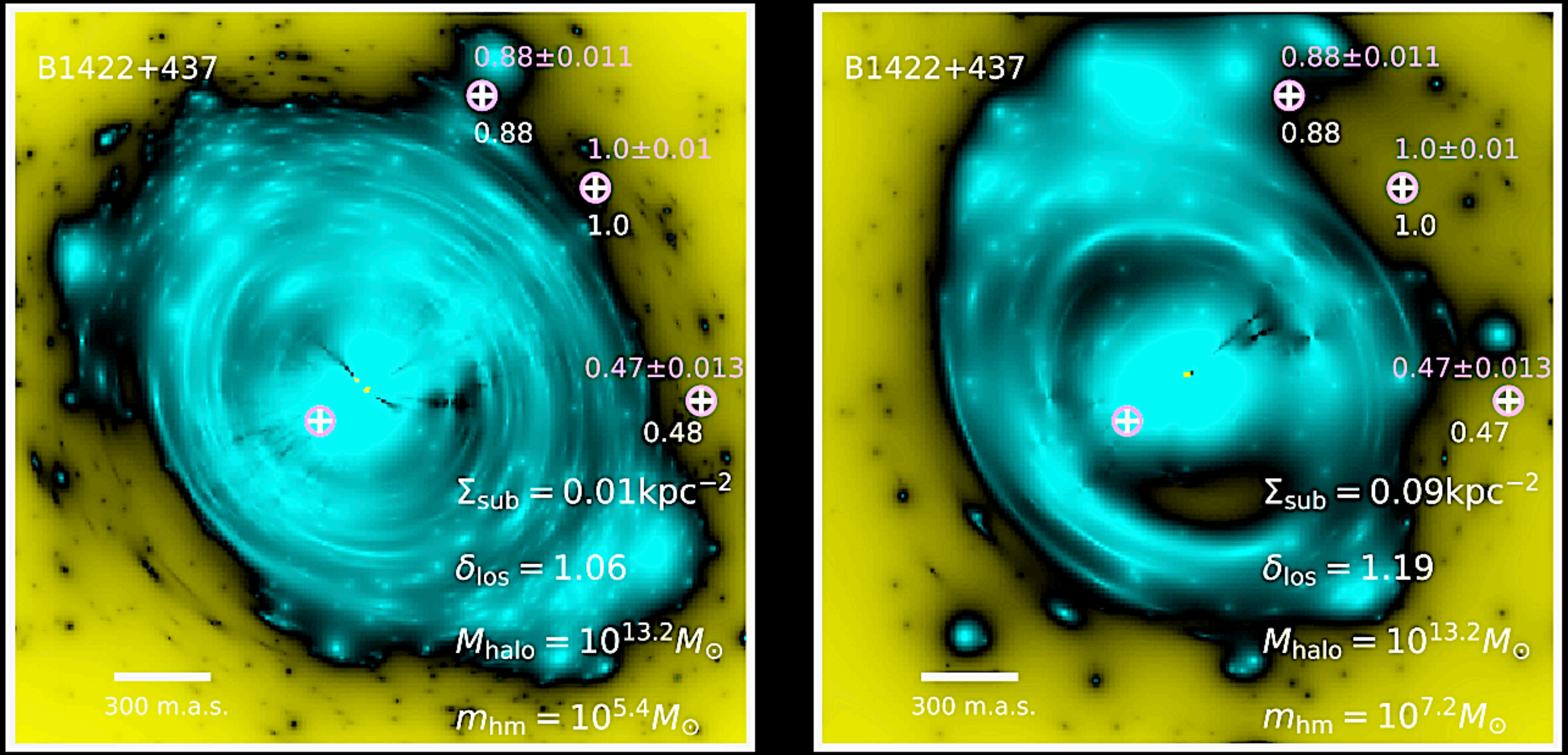


Vegetti & Koopmans (2009)

"lumpiness" in a
smooth matter distribution
= DM substructure??

can use simulations of "different universes" to predict what these systems would look like in each more suppressed small-scale structure

$M_{\rm hm} = 10^{5.4}\,\mathrm{M}_\odot$ $M_{\rm hm} = 10^{7.2}\,\mathrm{M}_\odot$

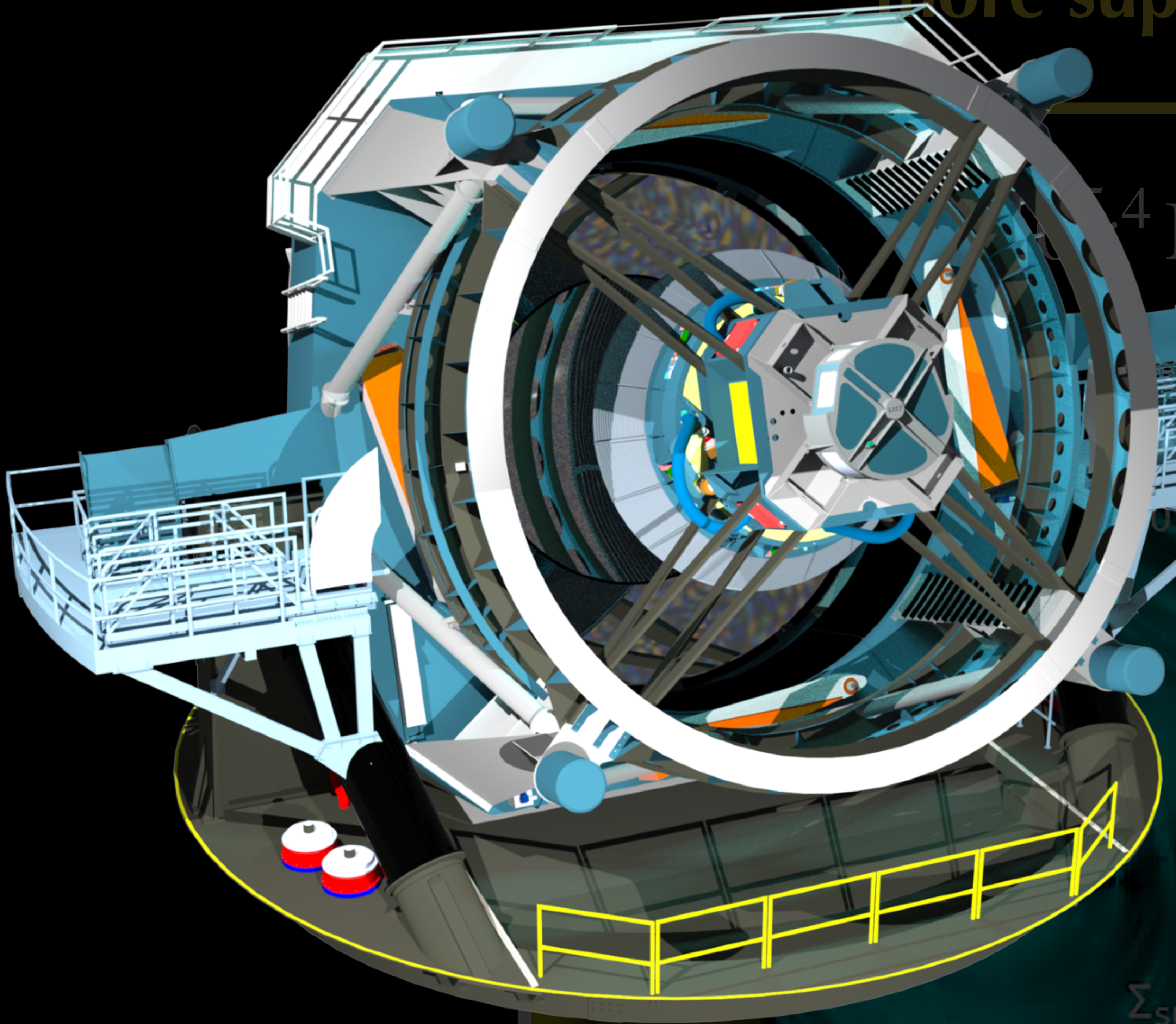


Gilman+ (2020)

[see also Li+ (2016); Nierenberg+ (2017); Birrer+ (2017); Despali+ (2020)]

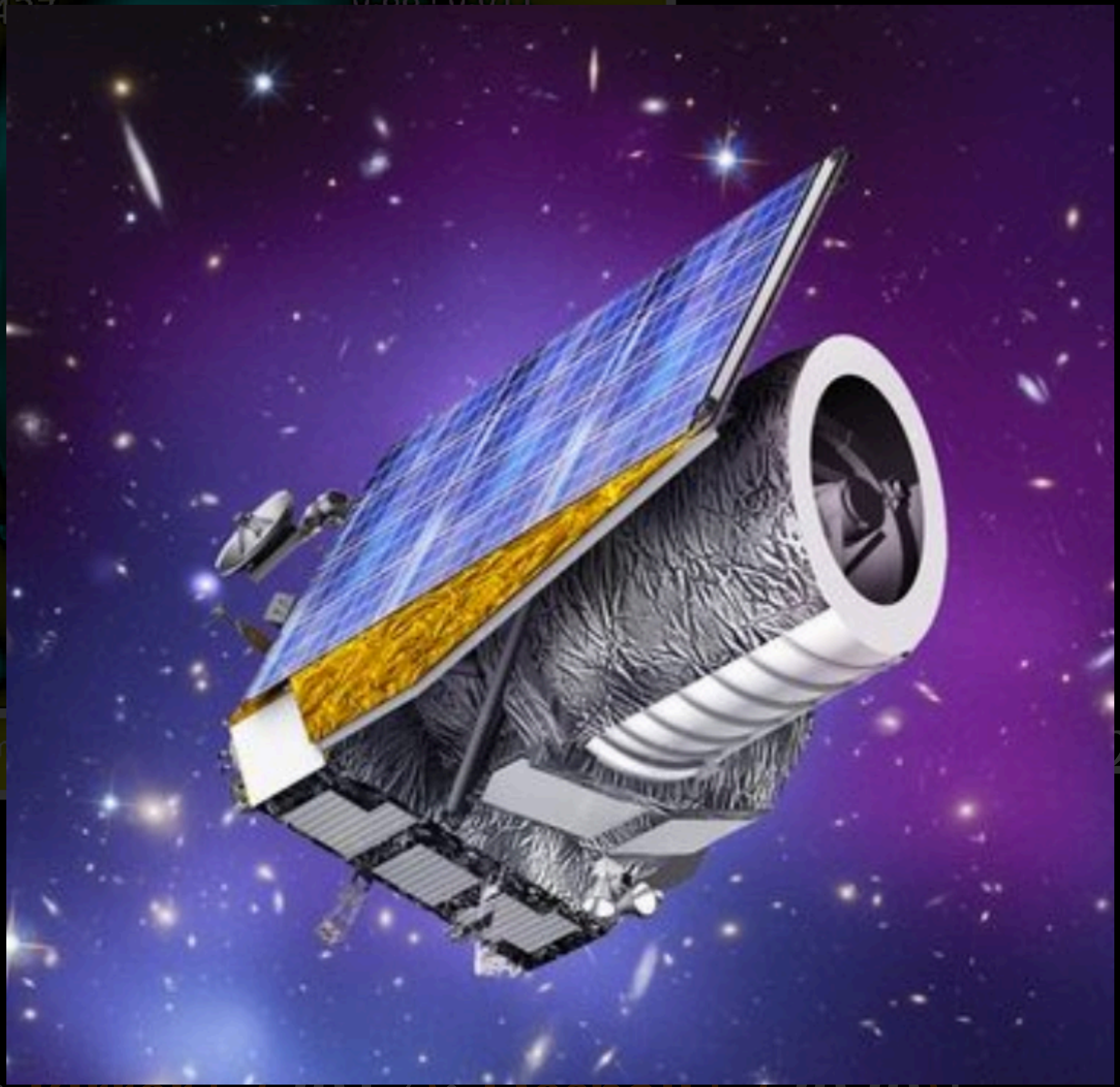
more suppressed small-scale structure

$M_{\rm hm} = 10^{7.2}\,{\rm M}_\odot$

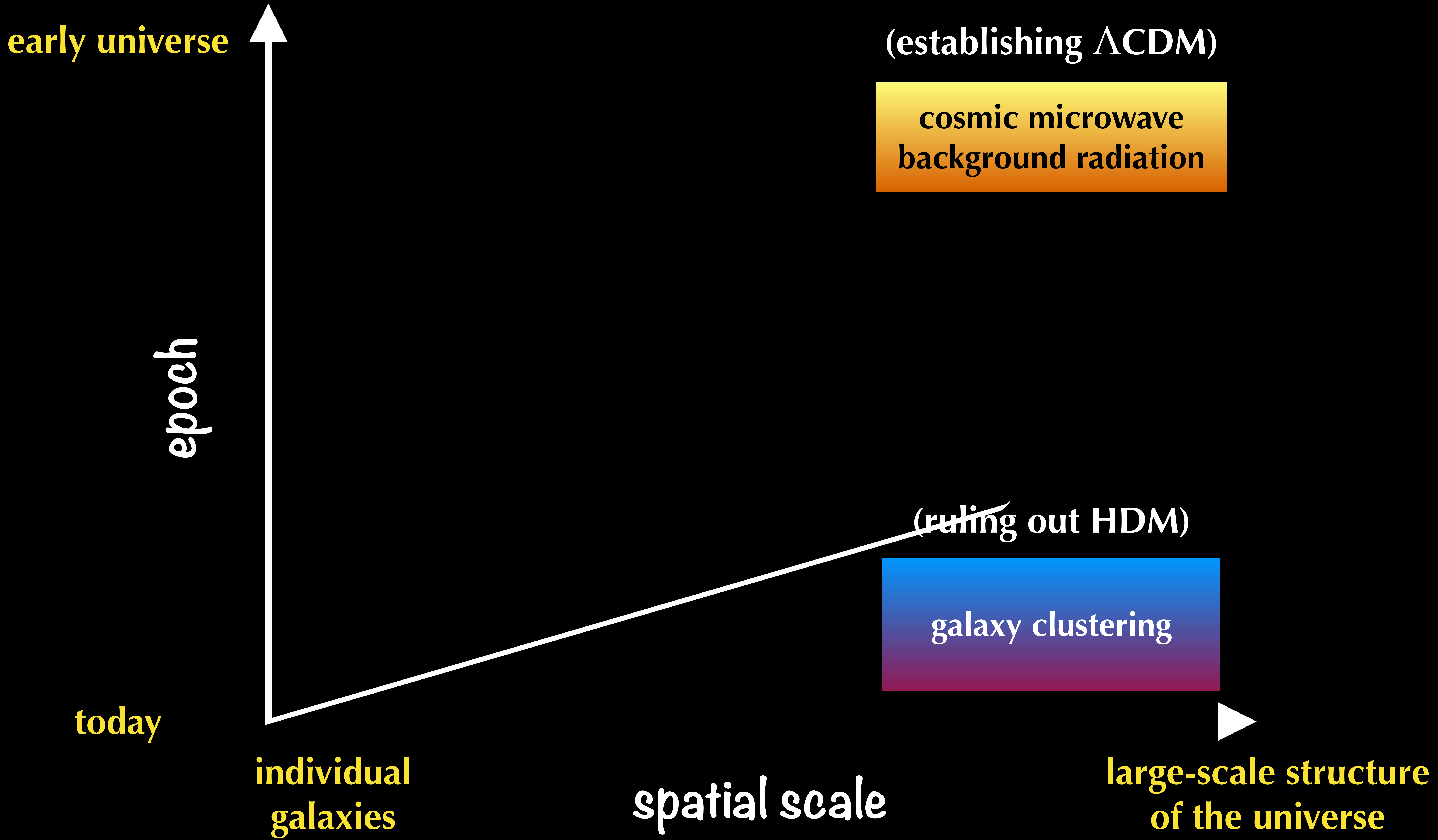


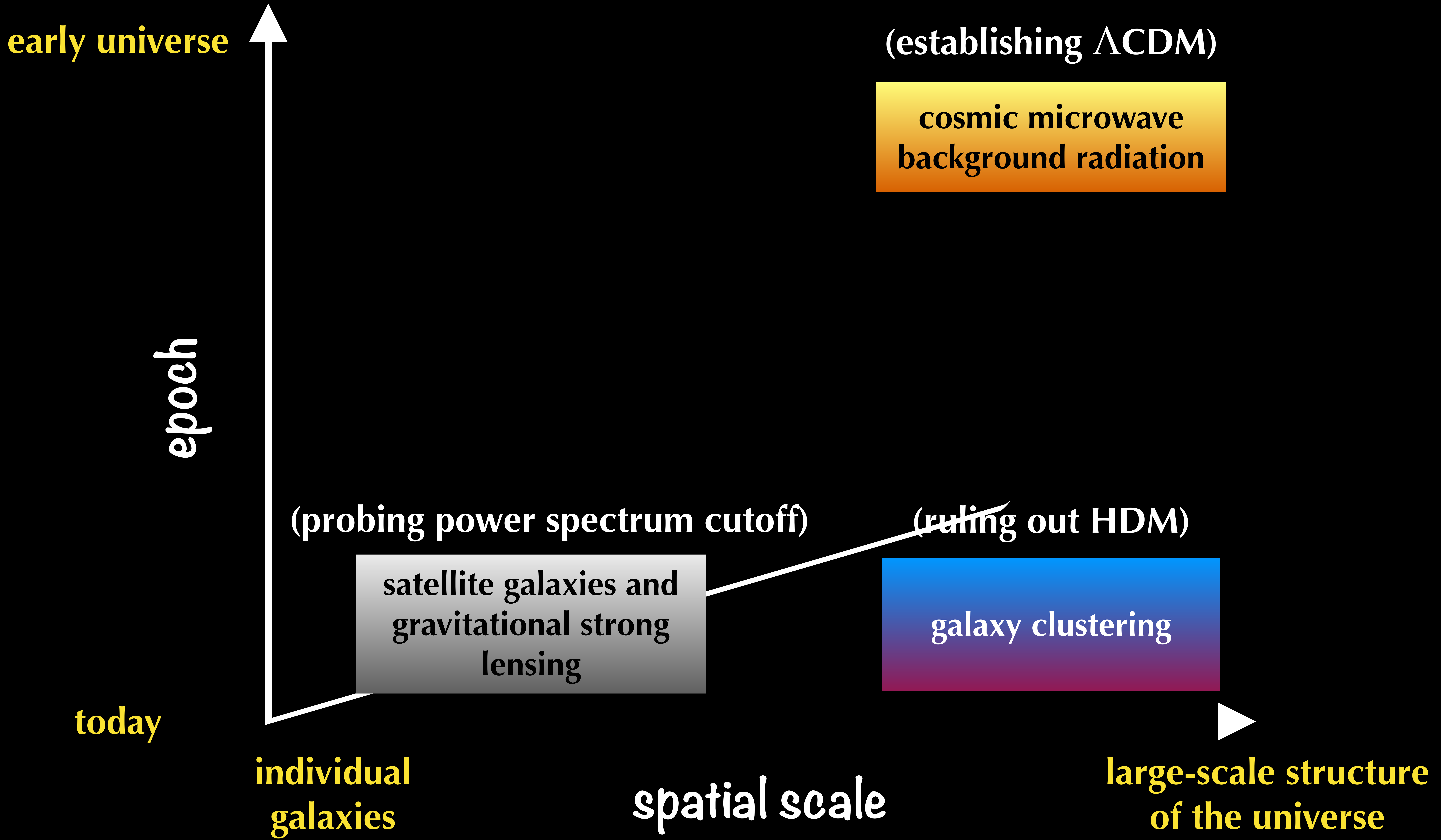
LSST/VRO [~2025]

Euclid [2023—]



[see also Li+ (2016); Nierenberg+ (2017); Birrer+ (2017); Despali+ (2020)]


early universe
(establishing ΛCDM)
cosmic microwave
background radiation
epoch
(ruling out HDM)
galaxy clustering
today
individual
galaxies
spatial scale
large-scale structure
of the universe


early universe
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(probing power spectrum cutoff)
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satellite galaxies and gravitational strong lensing
galaxy clustering
today
individual galaxies
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more exotic small-scale behaviour

[interacting dark matter]

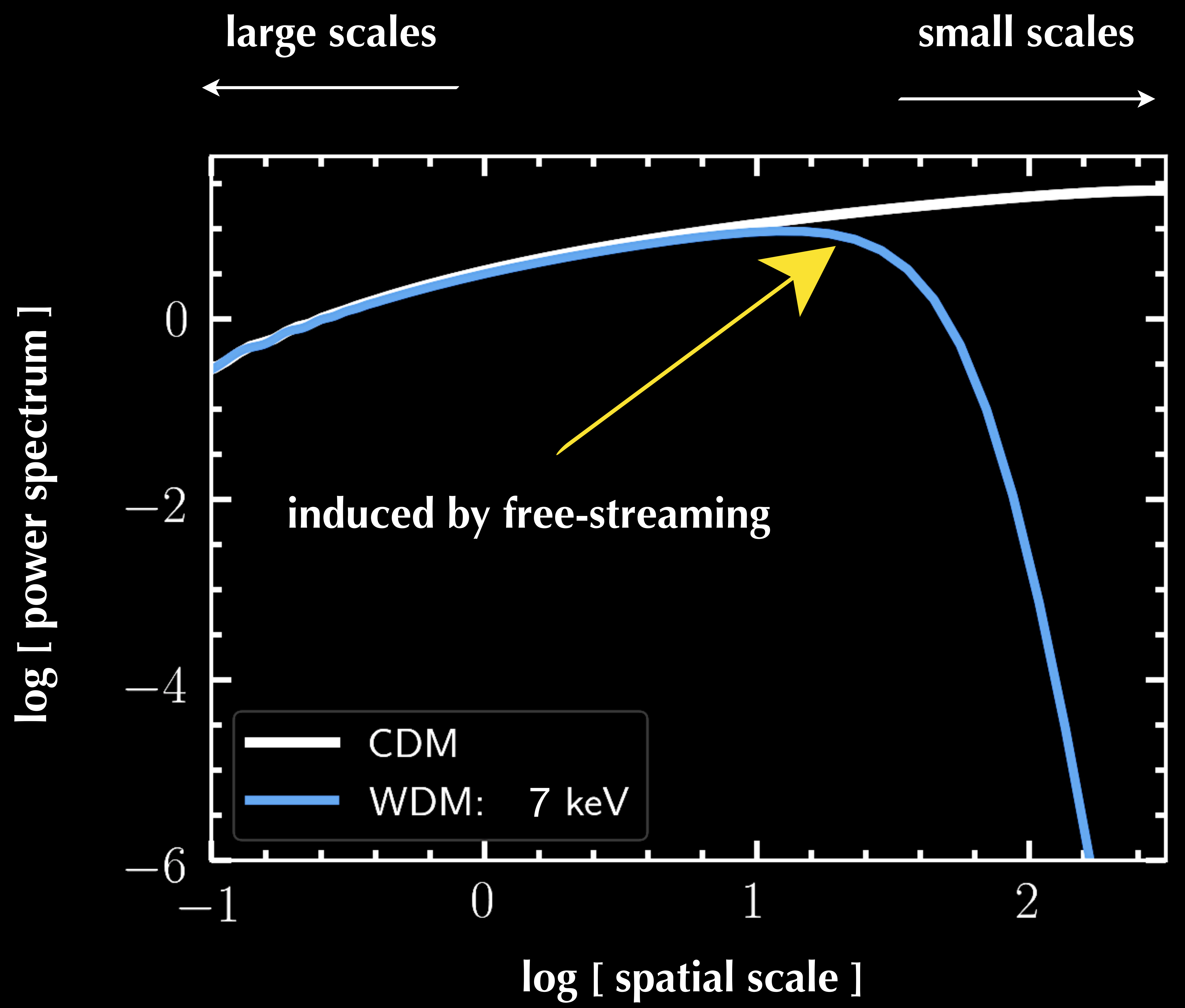
[Carlson+ (1992); Boehm+ (2002); Ackerman+ (2009); Cyr-Racine & Sigurdson (2013); Bringmann+ (2016)]

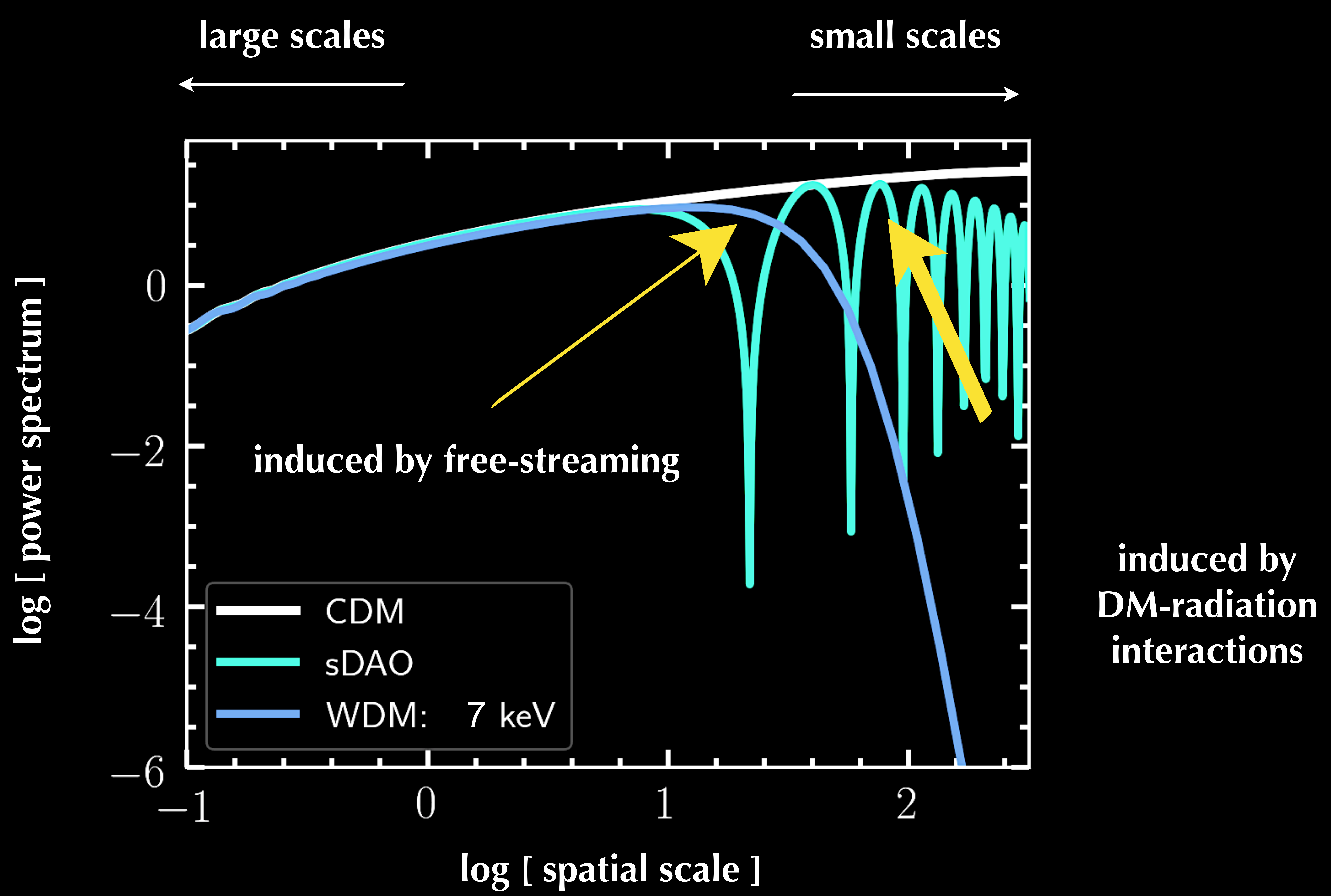
more exotic small-scale behaviour

[interacting dark matter]

tight coupling between the dark matter and a relativistic species at early times

[Carlson+ (1992); Boehm+ (2002); Ackerman+ (2009); Cyr-Racine & Sigurdson (2013); Bringmann+ (2016)]


large scales
small scales
log [power spectrum]
0
−2
−4
−6
−1
0
1
2
induced by free-streaming
CDM
WDM: 7 keV
log [spatial scale]



large scales
small scales
induced by free-streaming
induced by DM-radiation interactions
CDM
sDAO
WDM: 7 keV
0
−2
−4
−6
−1
0
1
2
log [power spectrum]
log [spatial scale]

phenomenology of a cutoff in the power spectrum

- delayed structure formation ✓
- faster galaxy assembly than in CDM ✓
- abundance of faint galaxies is reduced ✓
- at fixed halo mass, galaxies are brighter in their luminosity than in CDM ✓

phenomenology of a cutoff in the power spectrum

- delayed structure formation ✓
- faster galaxy assembly than in CDM ✓
- abundance of faint galaxies is reduced ✓
- at fixed halo mass, galaxies are brighter in their luminosity than in CDM ✓

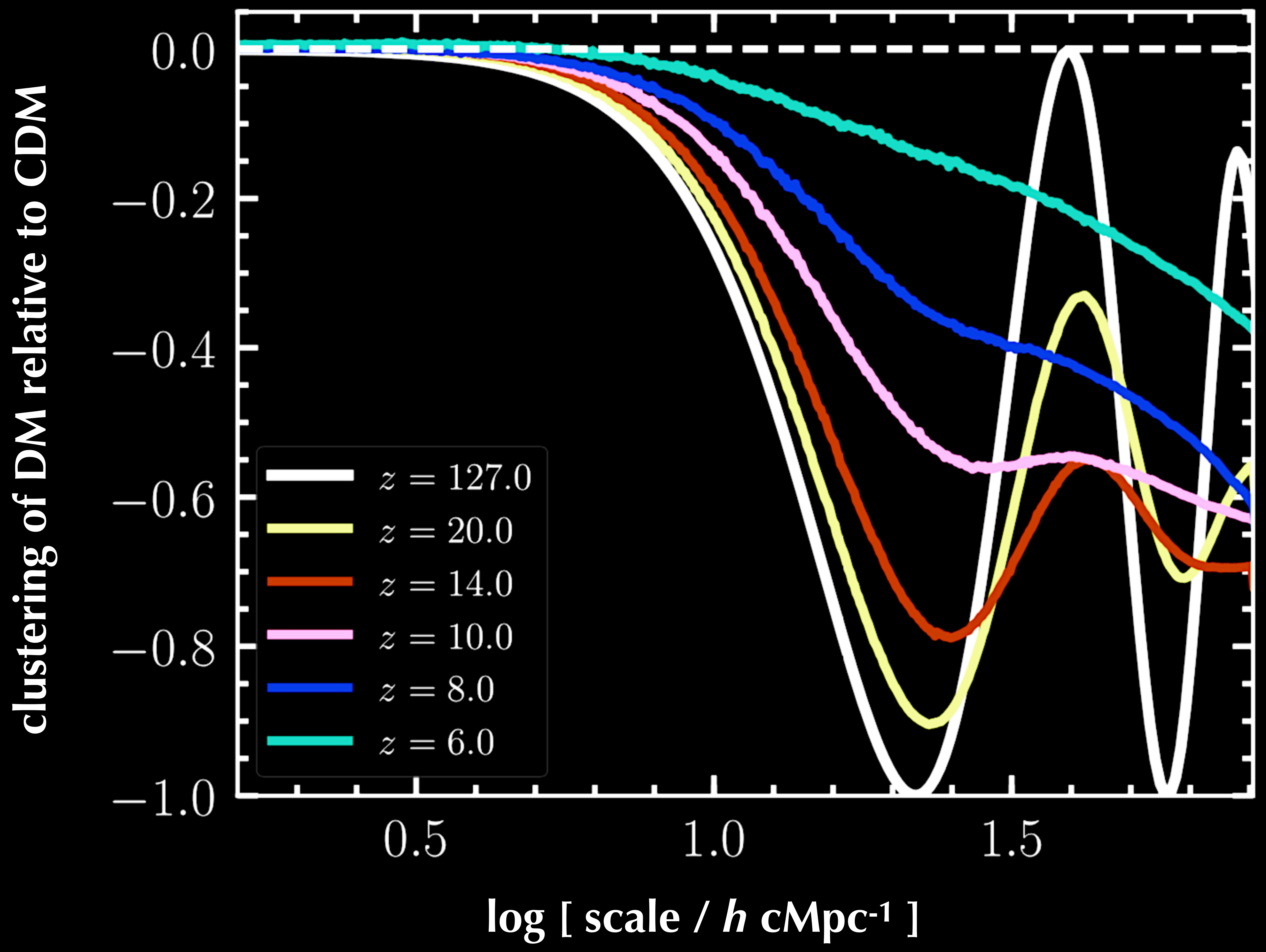
are signatures of "dark acoustic oscillations" imprinted in the galaxy distribution in an observable way?

no.

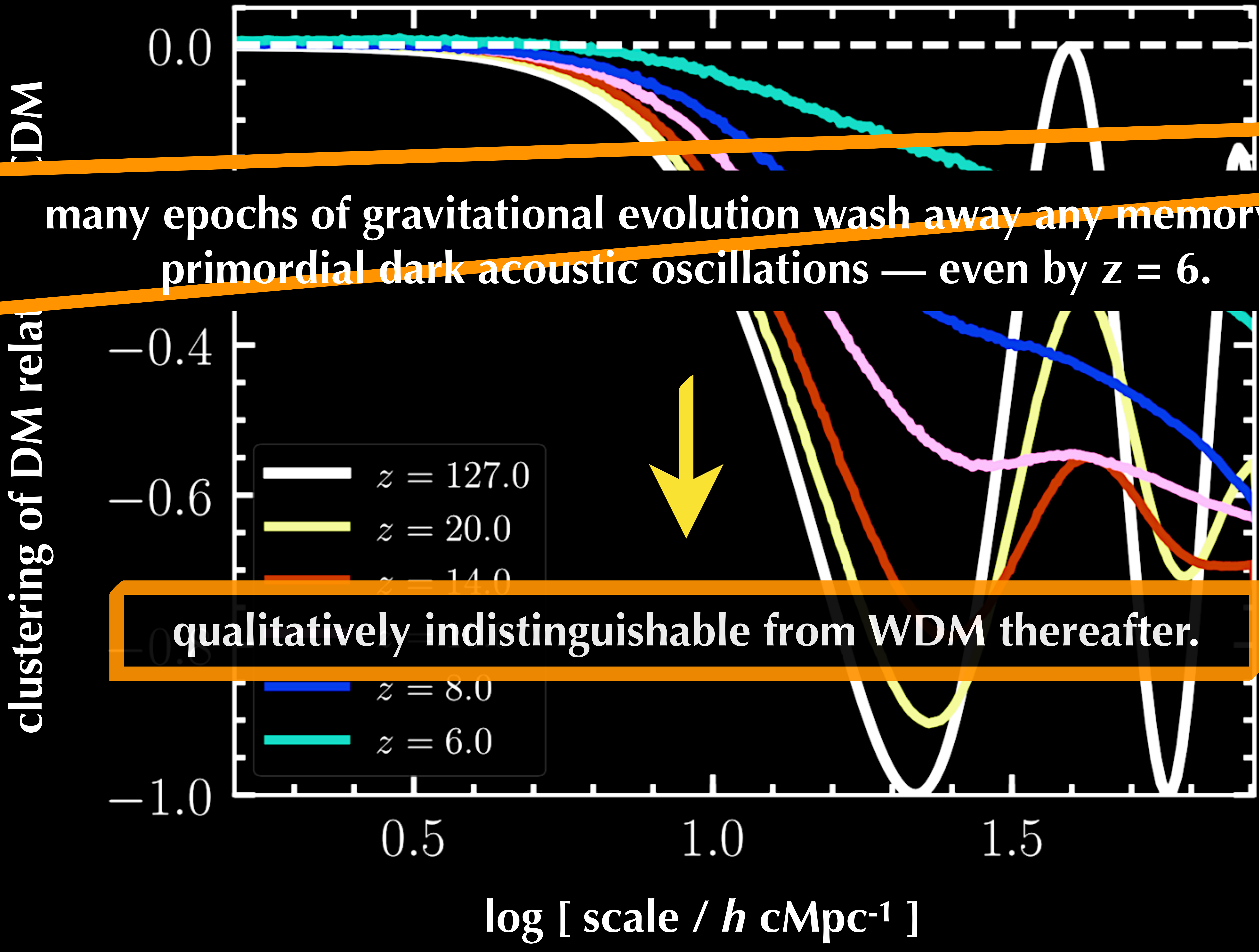
no.

problem: the distribution of galaxies looks identical in an iDM universe as in a WDM universe

Bose, Vogelsberger+ (2019c) [arXiv: 1811.10630] [see also Buckley+ (2014); Vogelsberger+ (2014)]



[see also Buckley+ (2014); Vogelsberger+ (2014)]



many epochs of gravitational evolution wash away any memory of primordial dark acoustic oscillations — even by z = 6.

qualitatively indistinguishable from WDM thereafter.

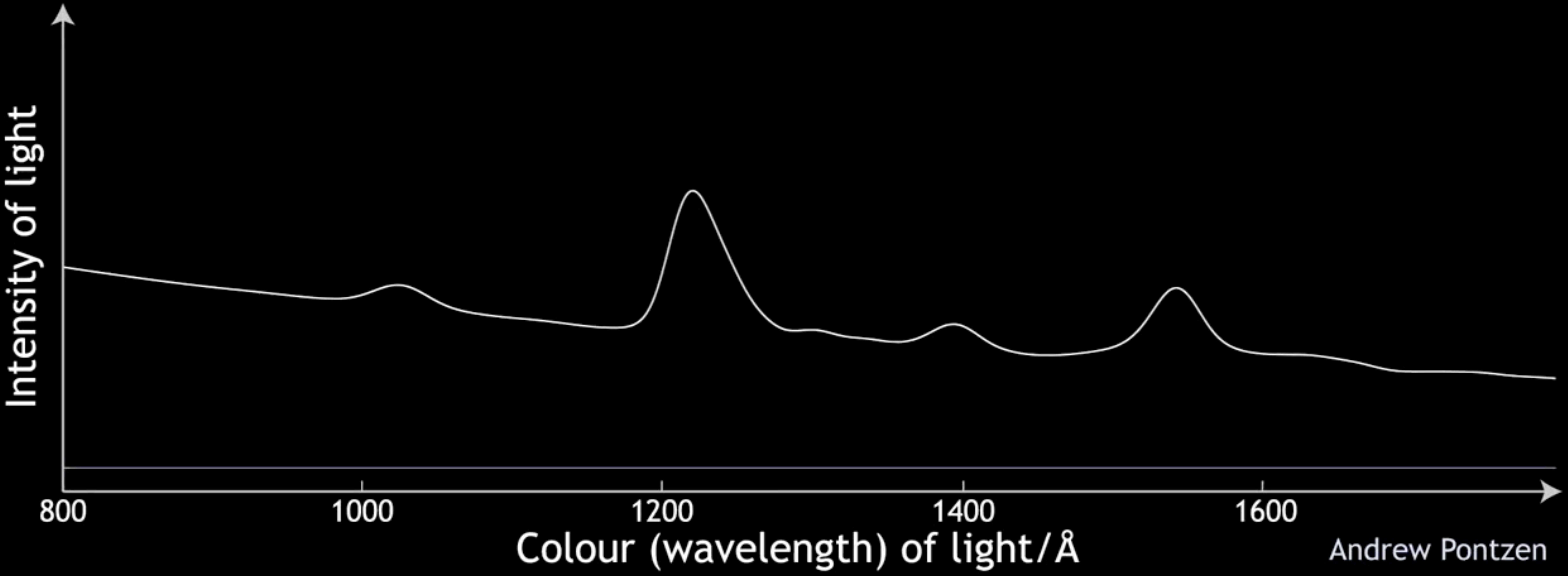
[see also Buckley+ (2014); Vogelsberger+ (2014)]

solution: probing structure in the early universe

with the Lyman-alpha forest

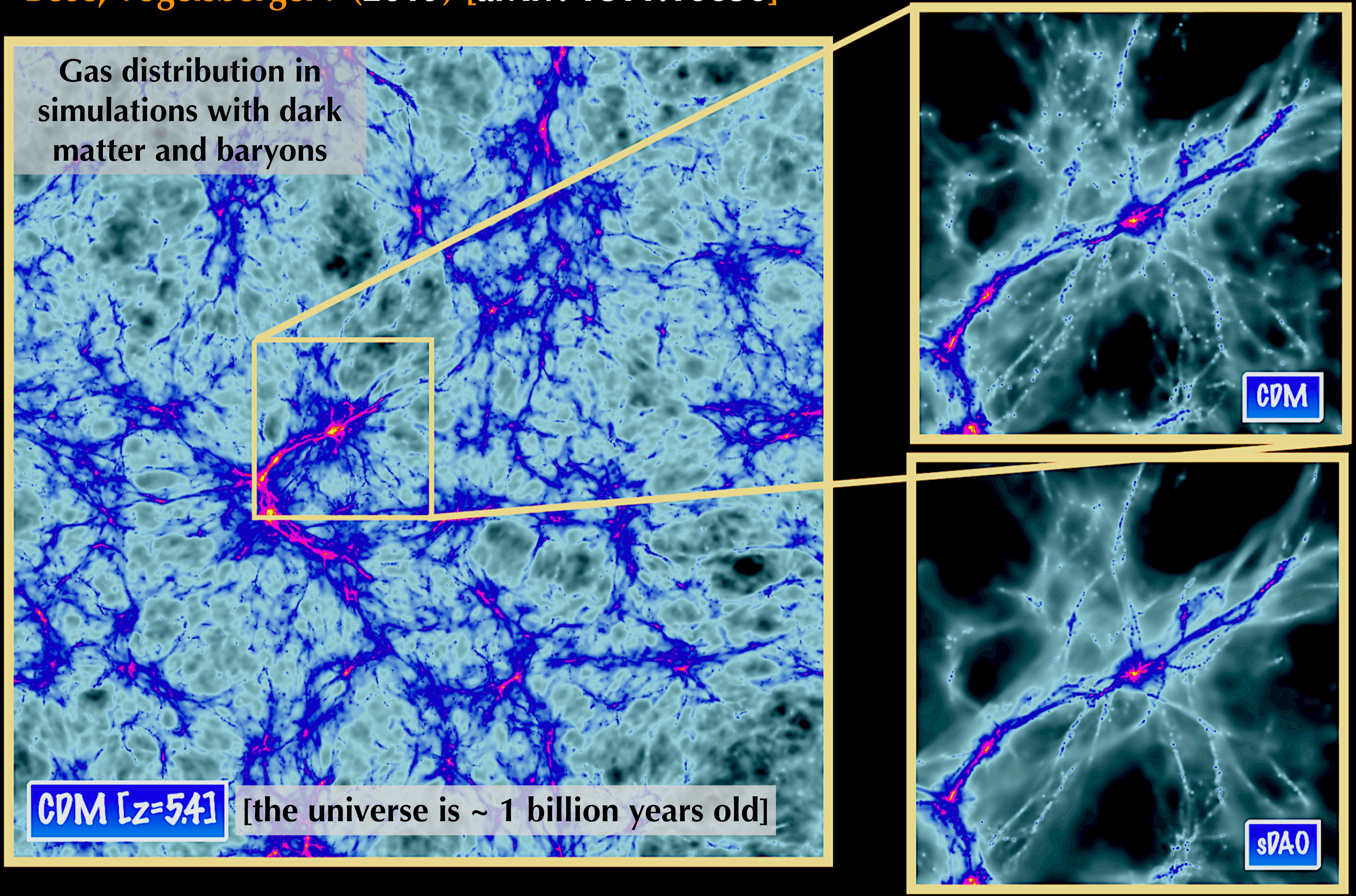
[Viel+ (2005); Seljak+ (2006); Viel+ (2013); Baur+ (2016); Irsic+ (2017); Kobayashi+ (2017); Murgia+ (2018); Nori+ (2018); Garzilli+ (2018)]


Intensity of light
800
1000
1200
1400
1600
Colour (wavelength) of light/Å
Andrew Pontzen

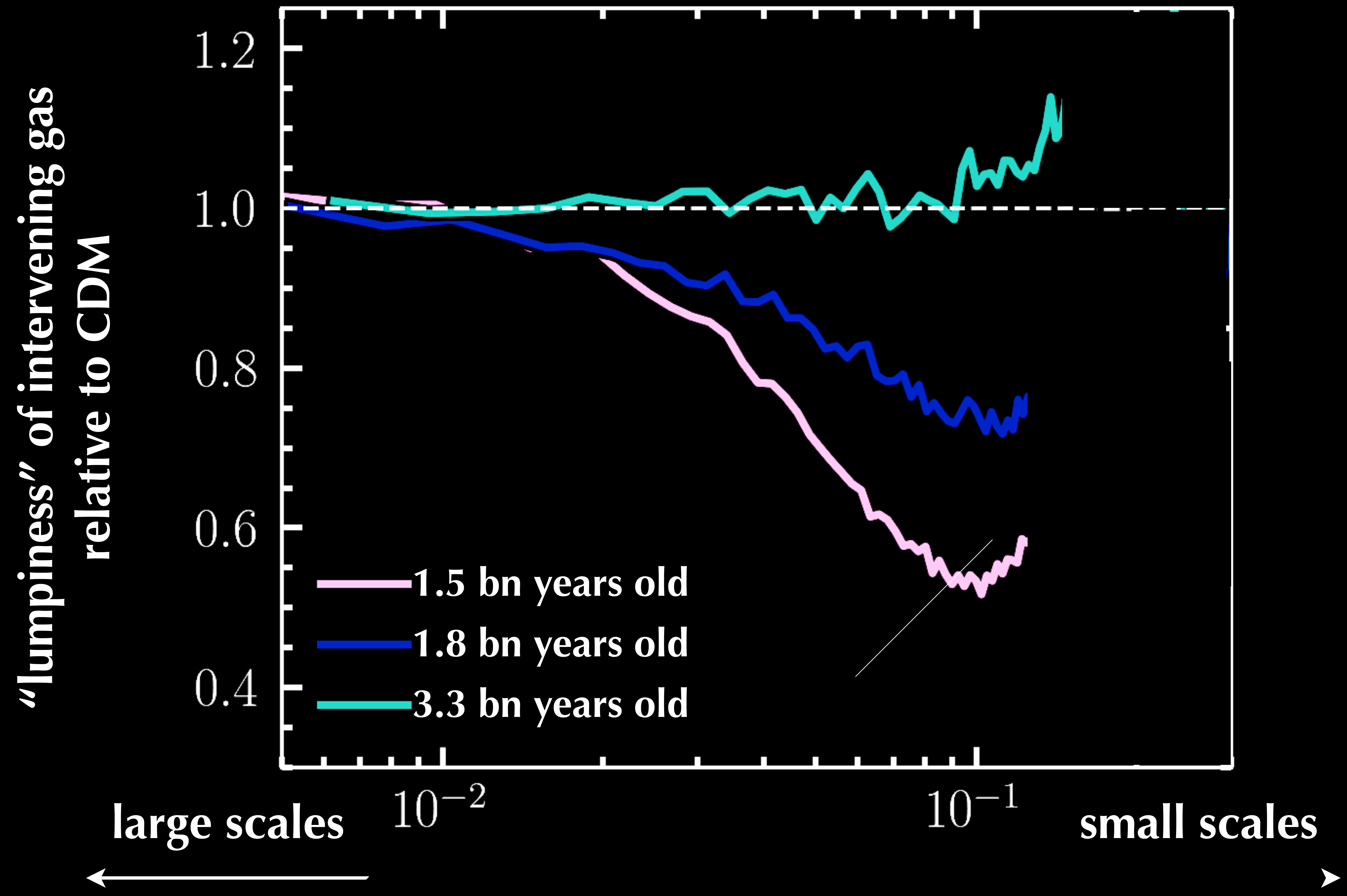

Intensity of light
800
1000
1200
1400
1600
Colour (wavelength) of light/Å
Andrew Pontzen


repeat this for ~1000s of lines-of-sight to develop a statistical map of neutral hydrogen in the early universe
Intensity of light
800
1000
1200
1400
1600
Colour (wavelength) of light/Å
Andrew Pontzen

Bose, Vogelsberger+ (2019) [arXiv: 1811.10630]

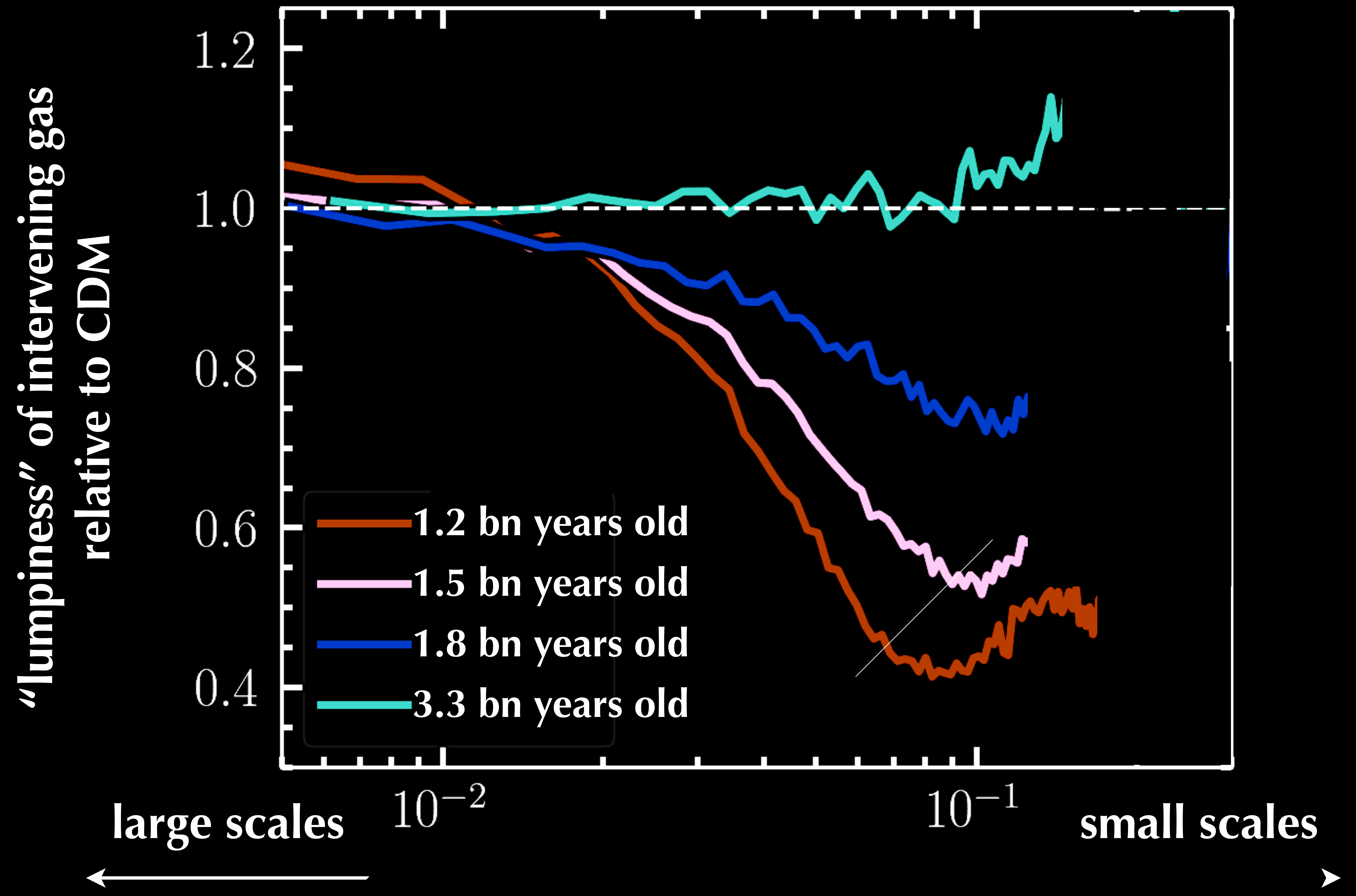


time evolution of the Lyman-alpha forest



Bose+ (2019) [arXiv: 1811.10630]

time evolution of the Lyman-alpha forest



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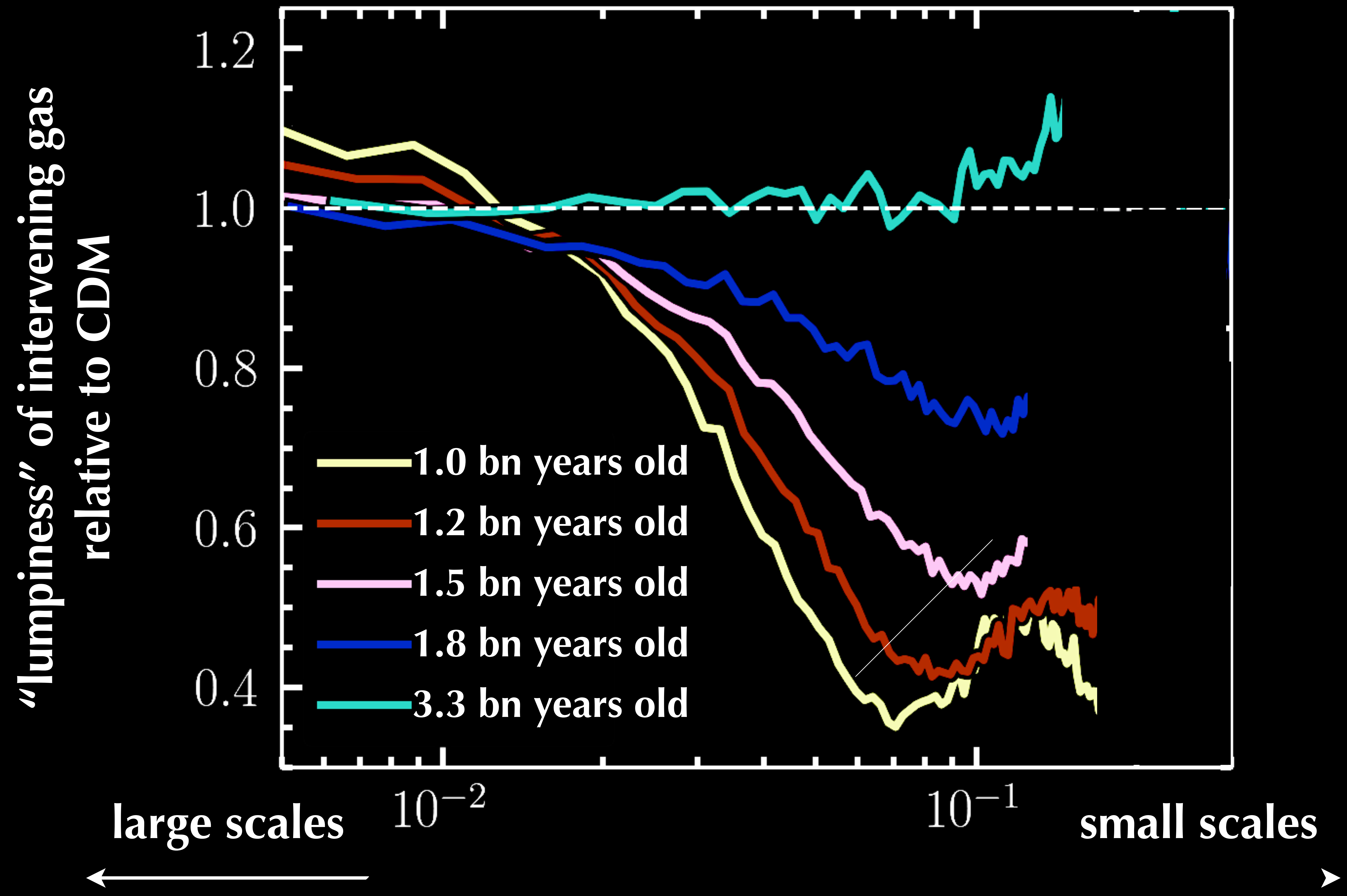
time evolution of the Lyman-alpha forest



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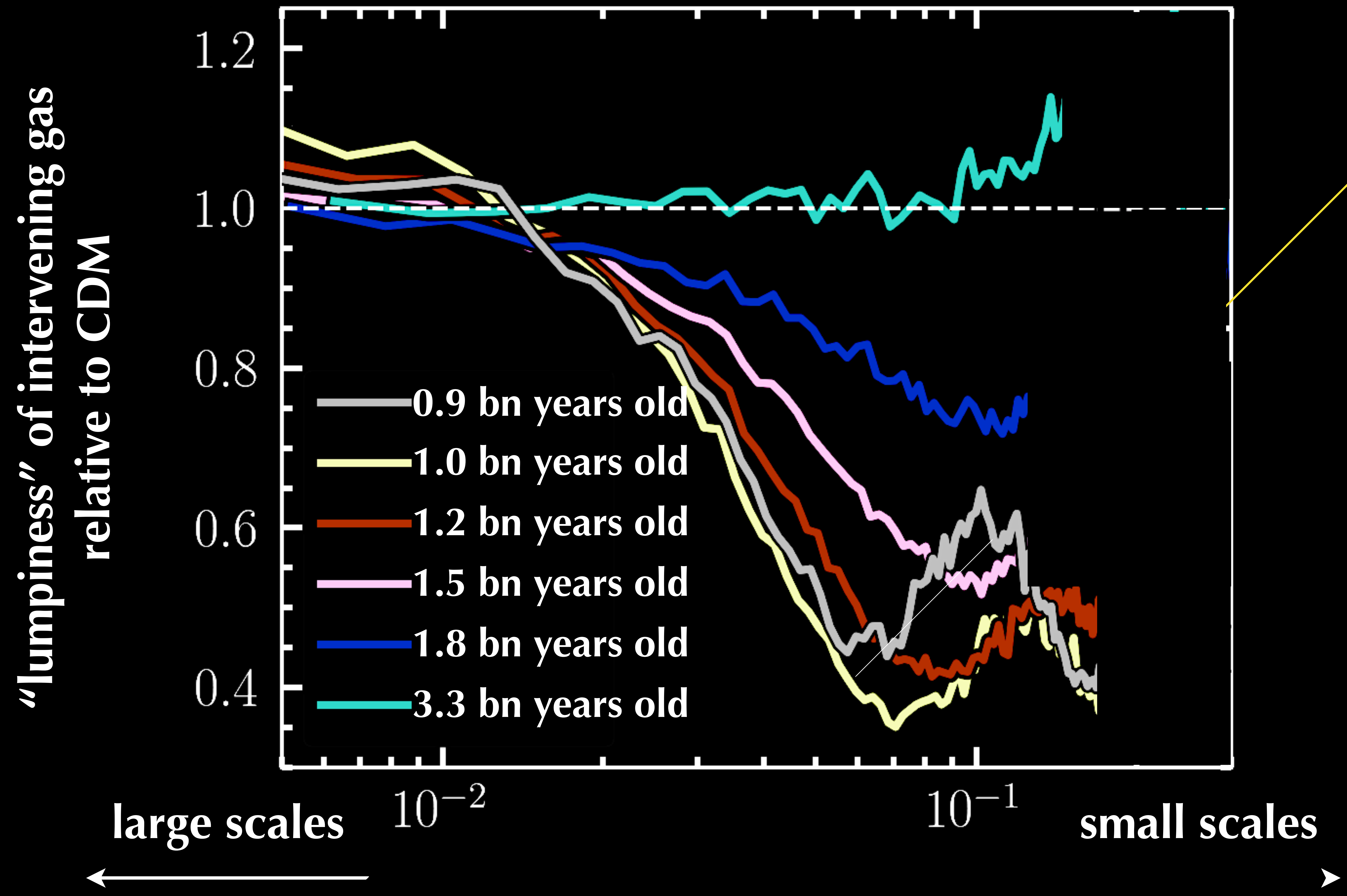
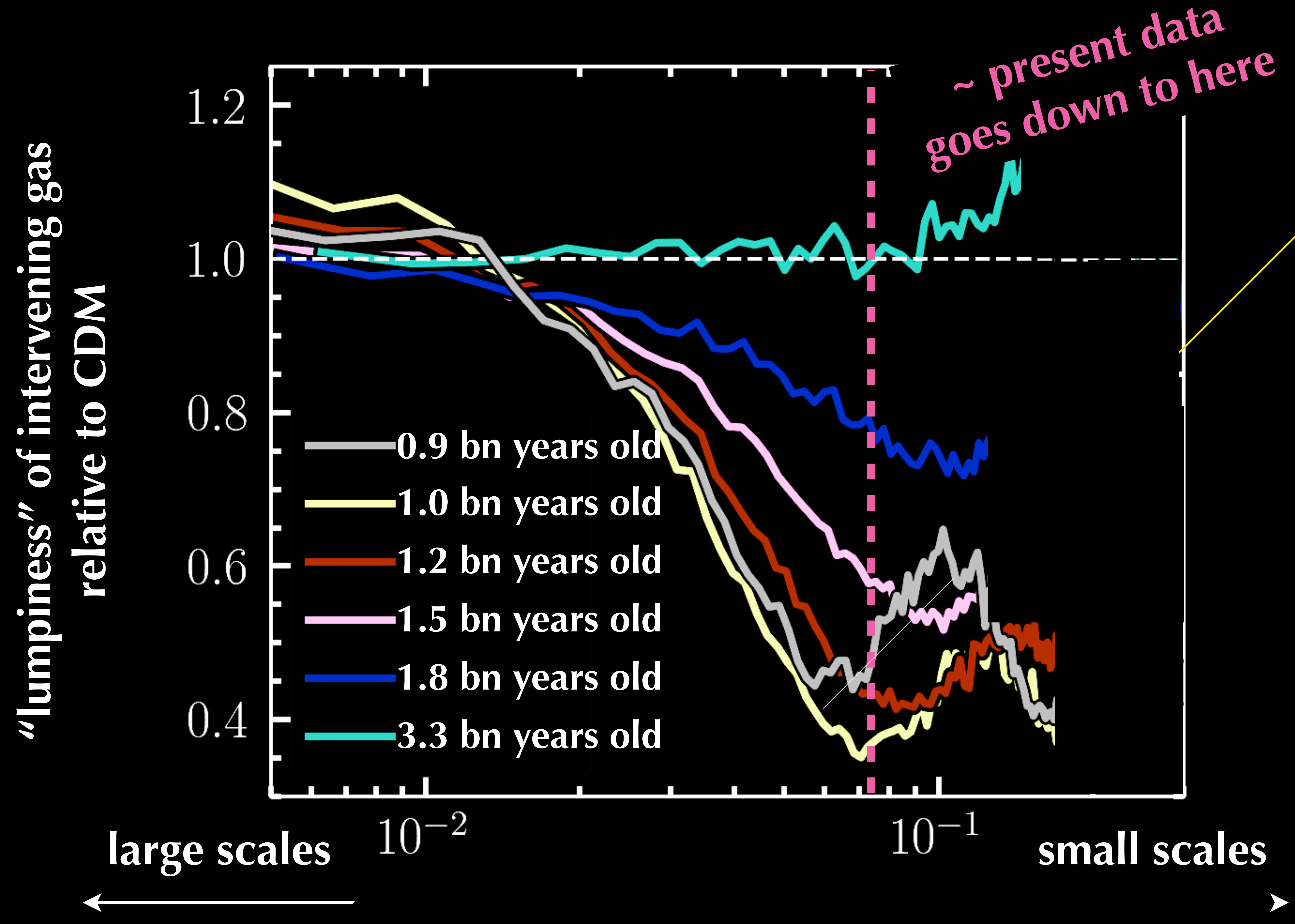


Bose+ (2019) [arXiv: 1811.10630]

the neutral intergalactic medium retains memory of the initial conditions of the cosmos long after they have been "forgotten" by galaxies

time evolution of the Lyman-alpha forest



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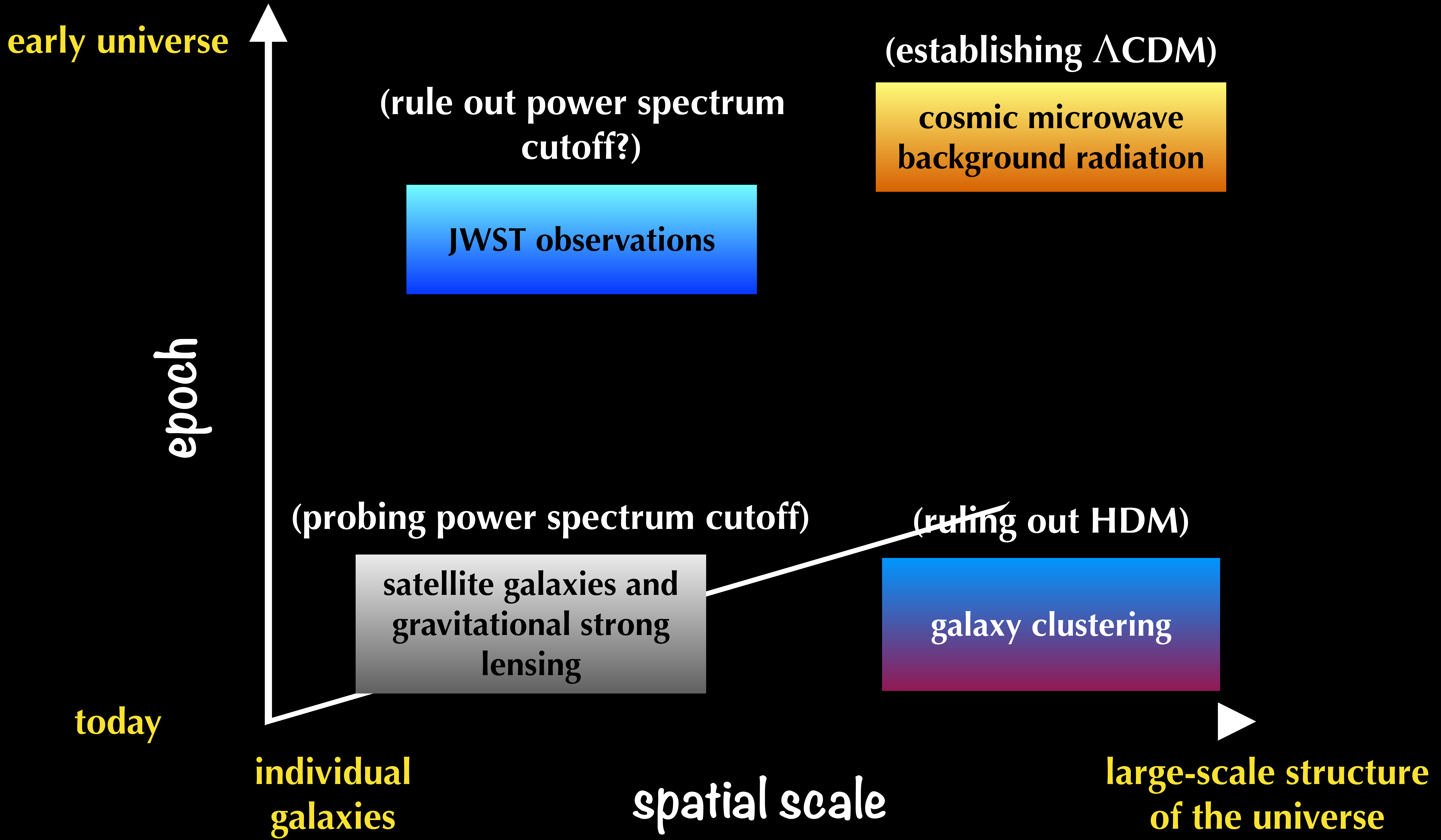
the neutral intergalactic medium retains memory of the initial conditions of the cosmos long after they have been "forgotten" by galaxies


early universe
epoch
today
(rule out power spectrum cutoff?)
JWST observations
(establishing ΛCDM)
cosmic microwave background radiation
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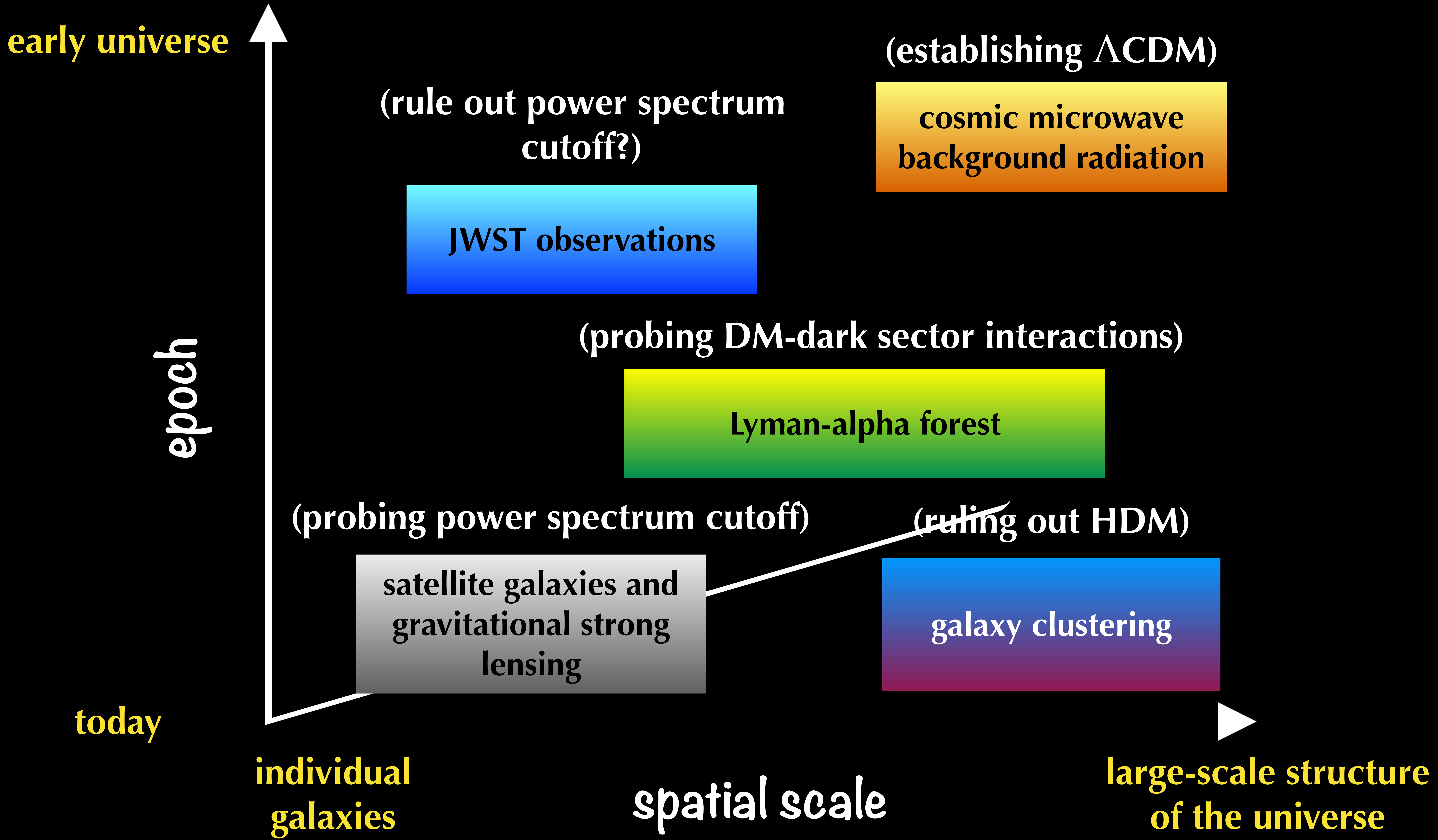
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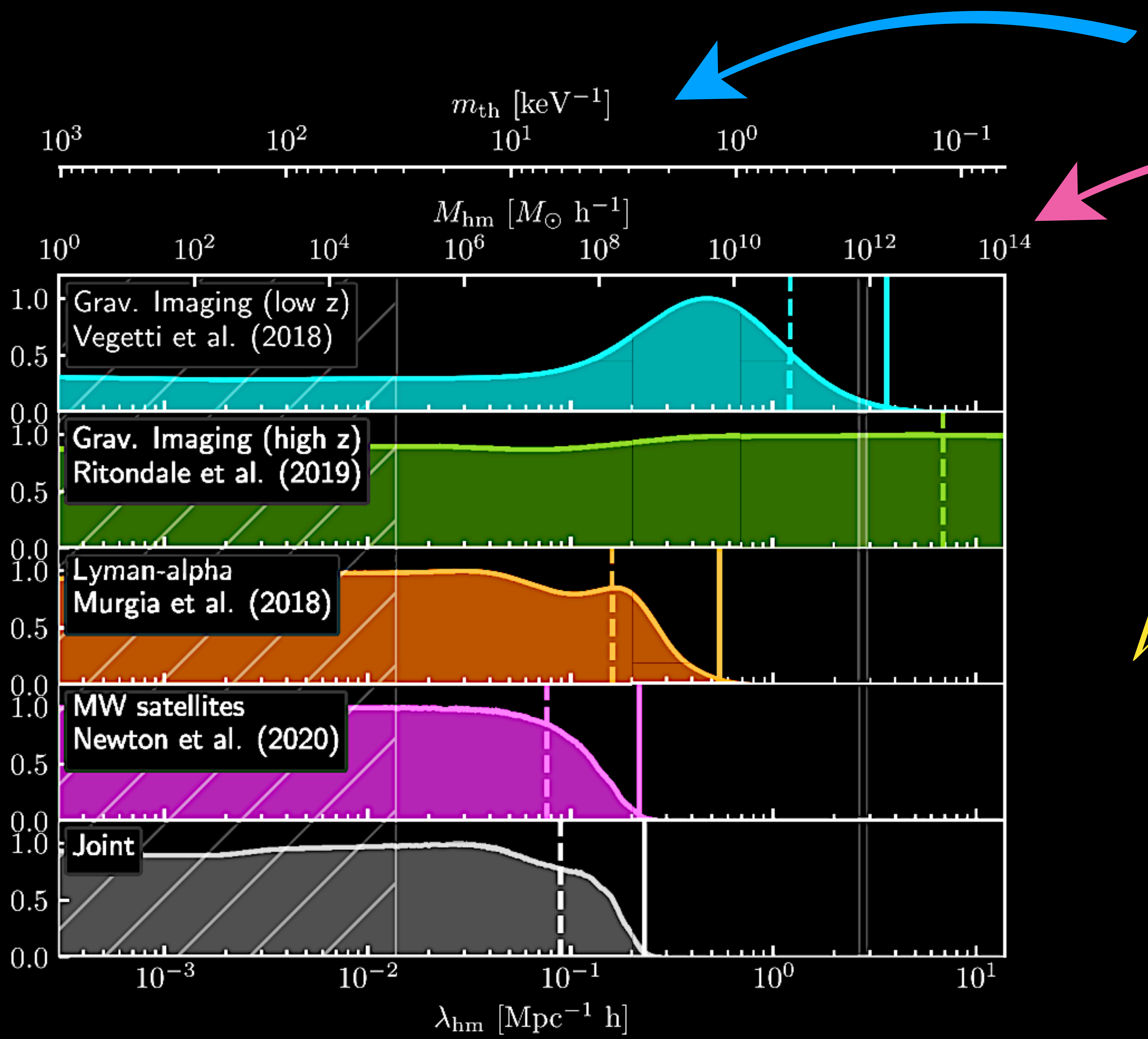
spatial scale
large-scale structure of the universe

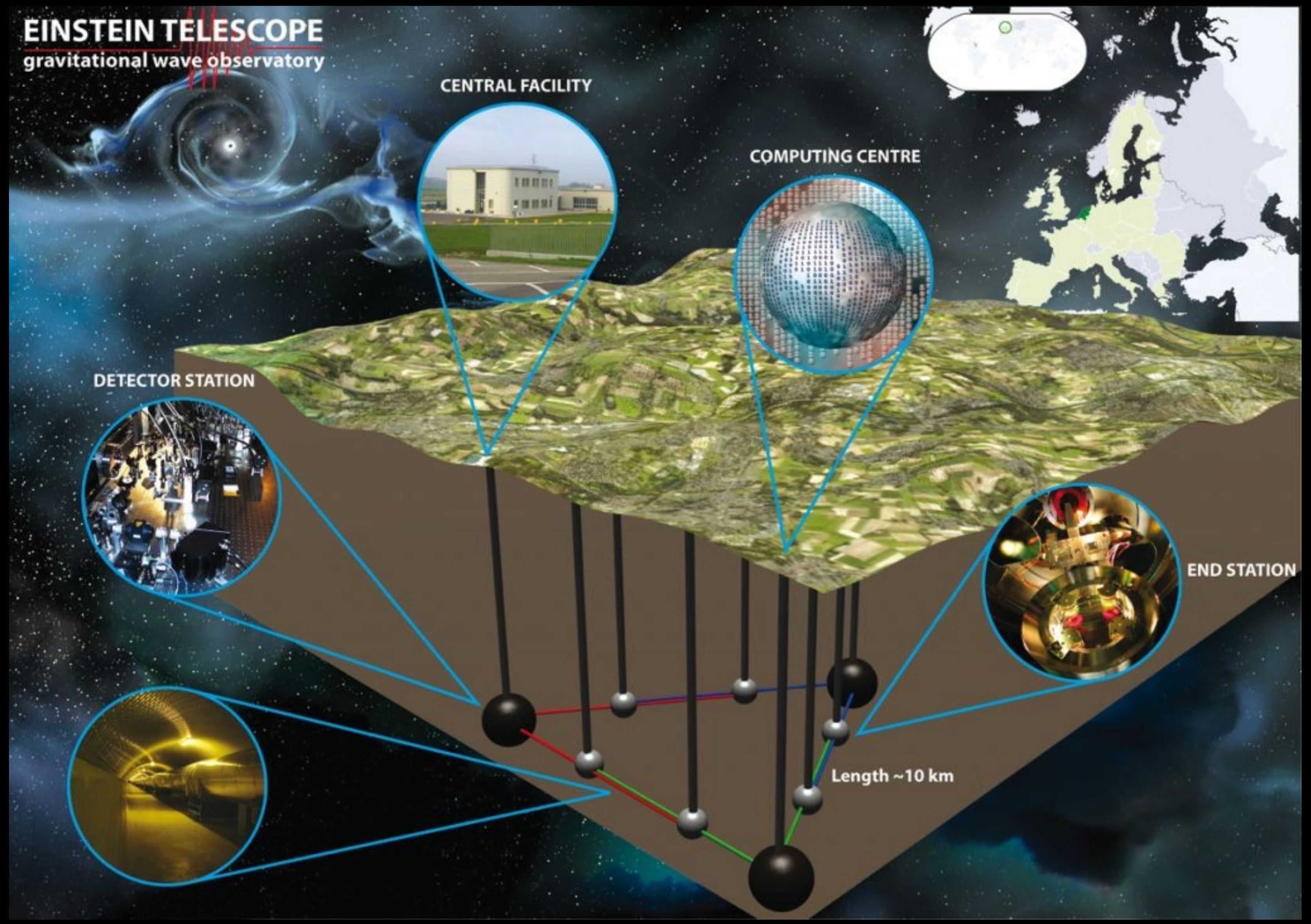


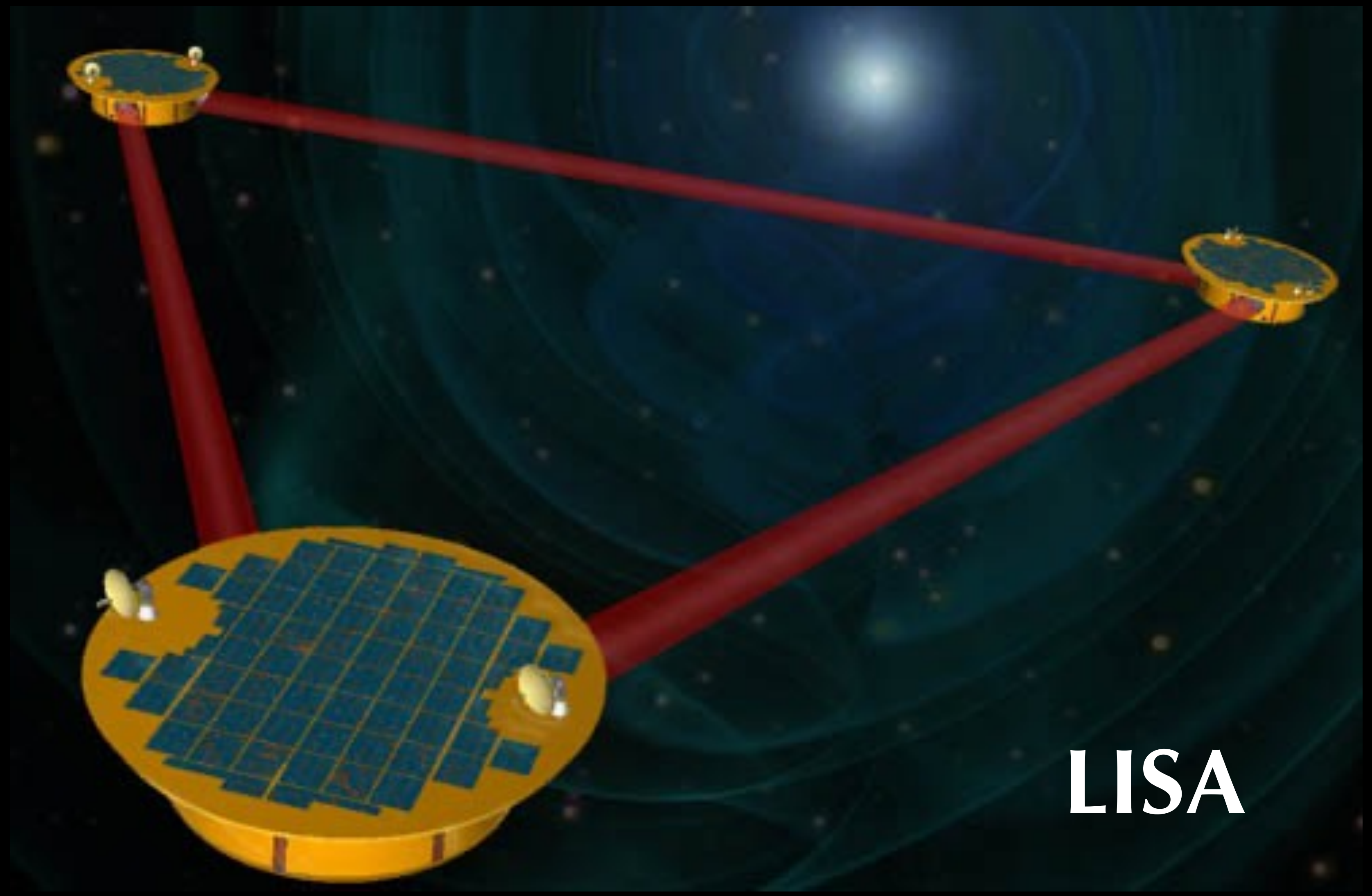
joint constraints—using different probes that exhibit different systematics—offer the best promise for setting limits on the small-scale cutoff in the initial power spectrum

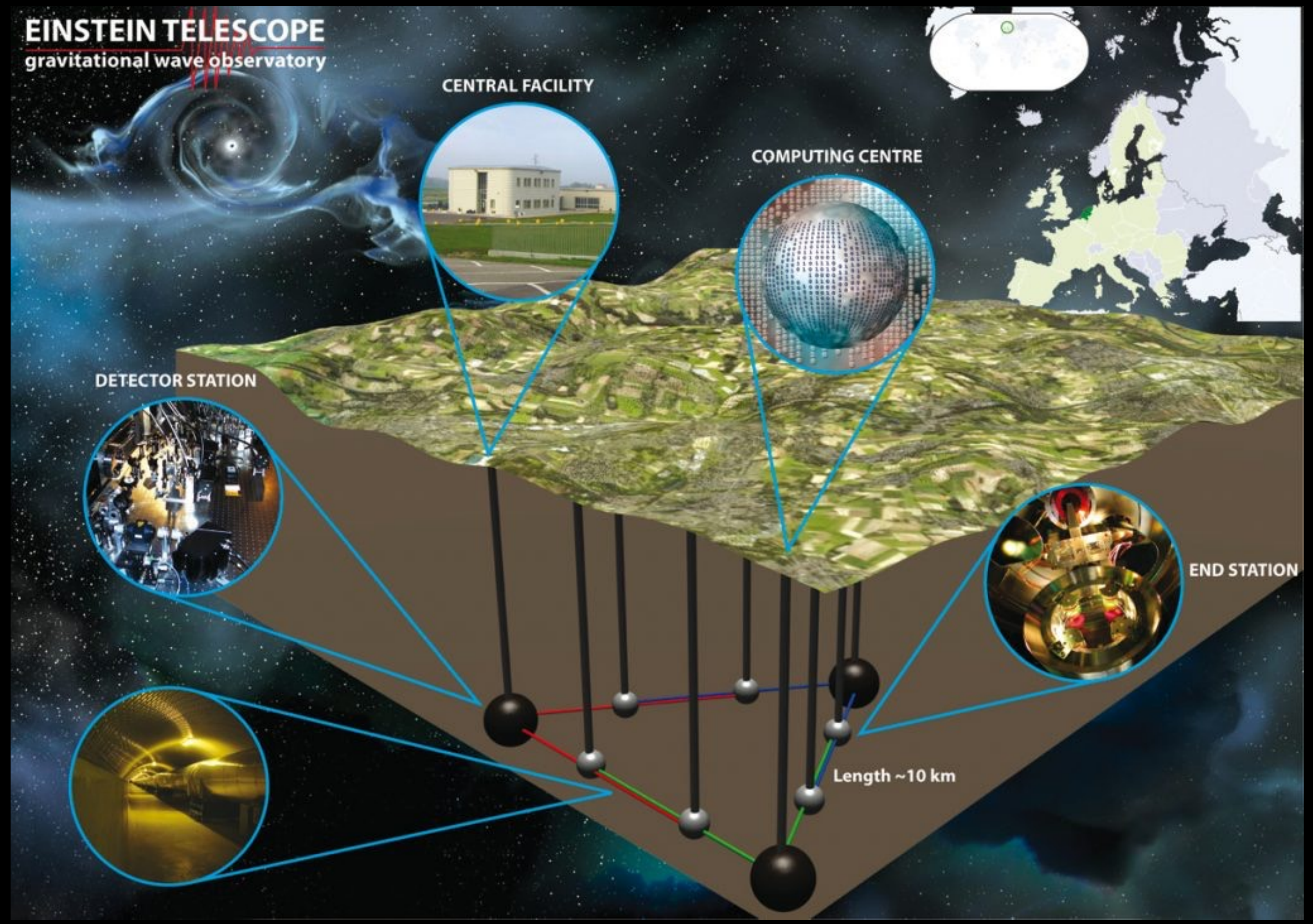
Enzi+ (2021)

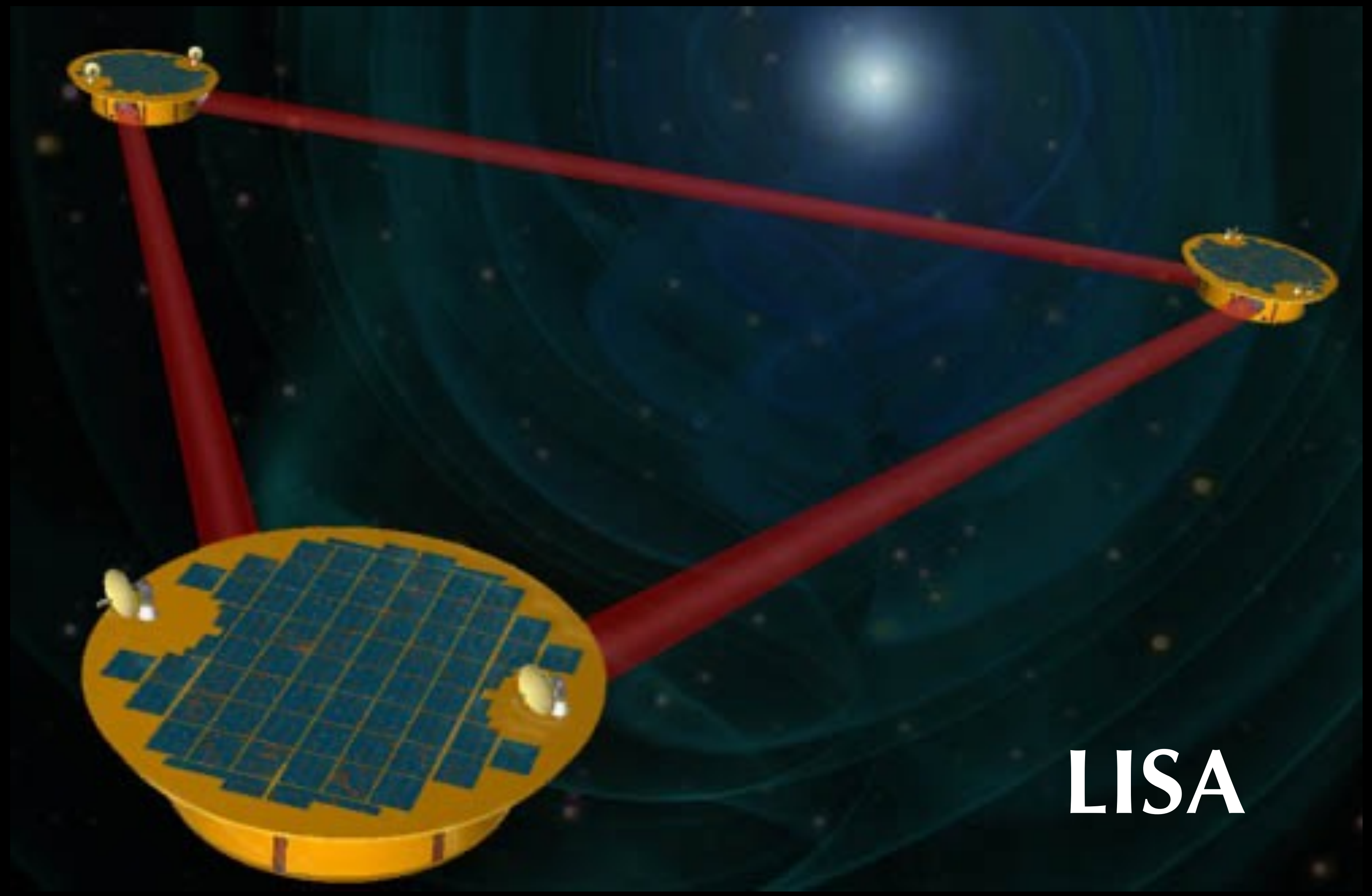
the early universe may offer some of the strongest tests of dark matter

what can we do besides counting galaxies?

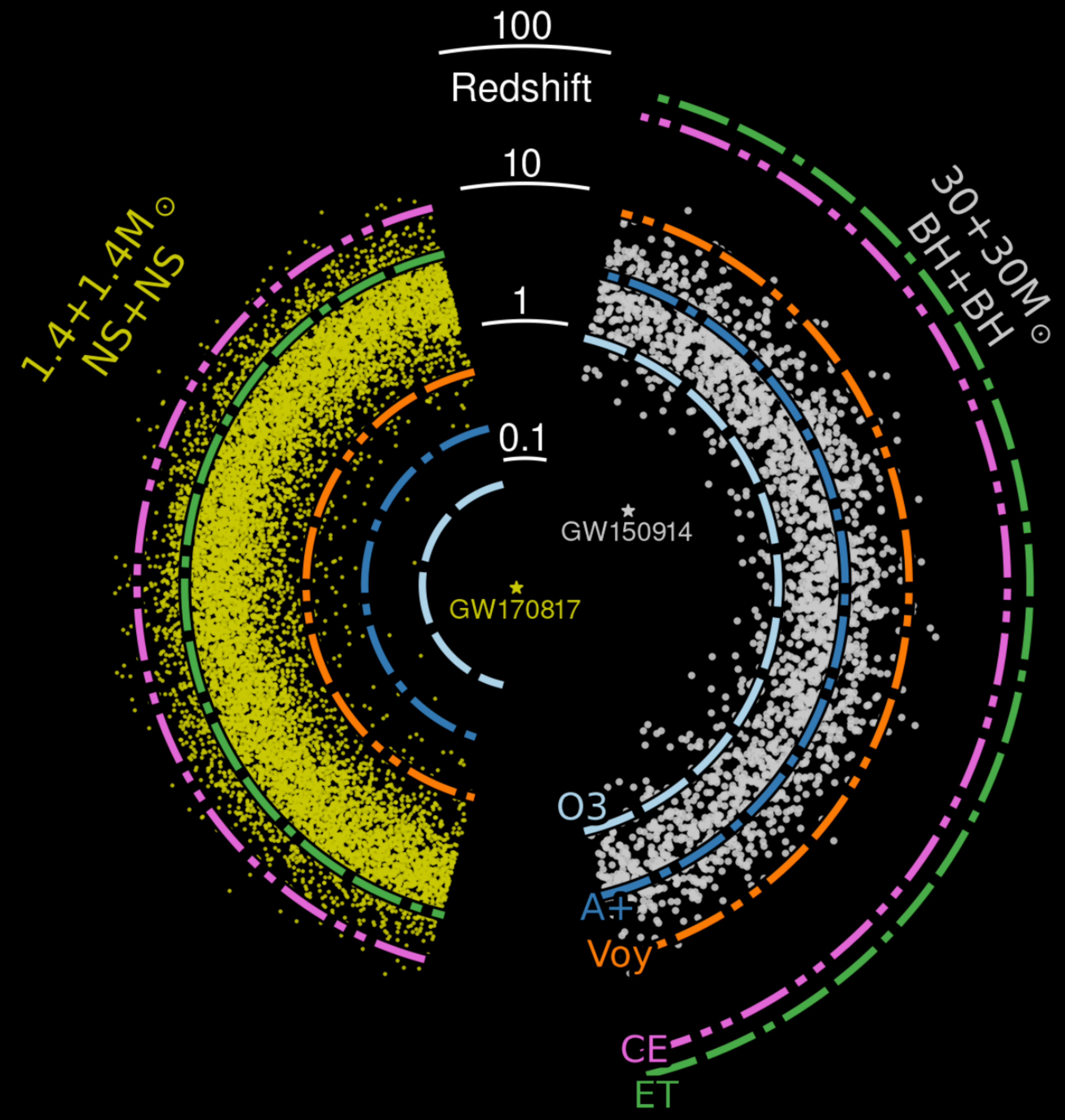

EINSTEIN TELESCOPE
gravitational wave observatory
CENTRAL FACILITY
COMPUTING CENTRE
DETECTOR STATION
END STATION
Length ~10 km


LISA

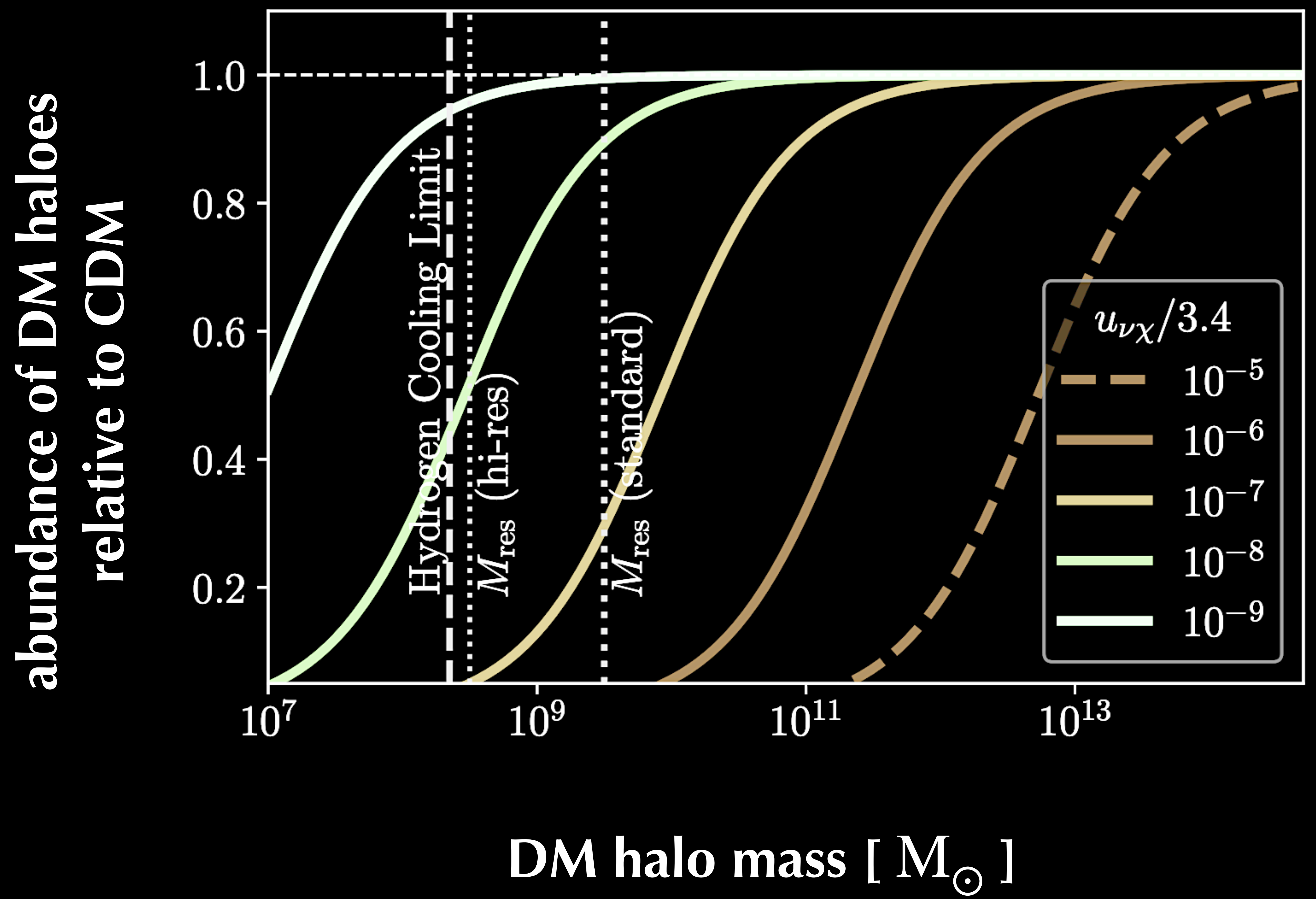




Cosmic Explorer technical report CE-P2100003-v7 (2021)

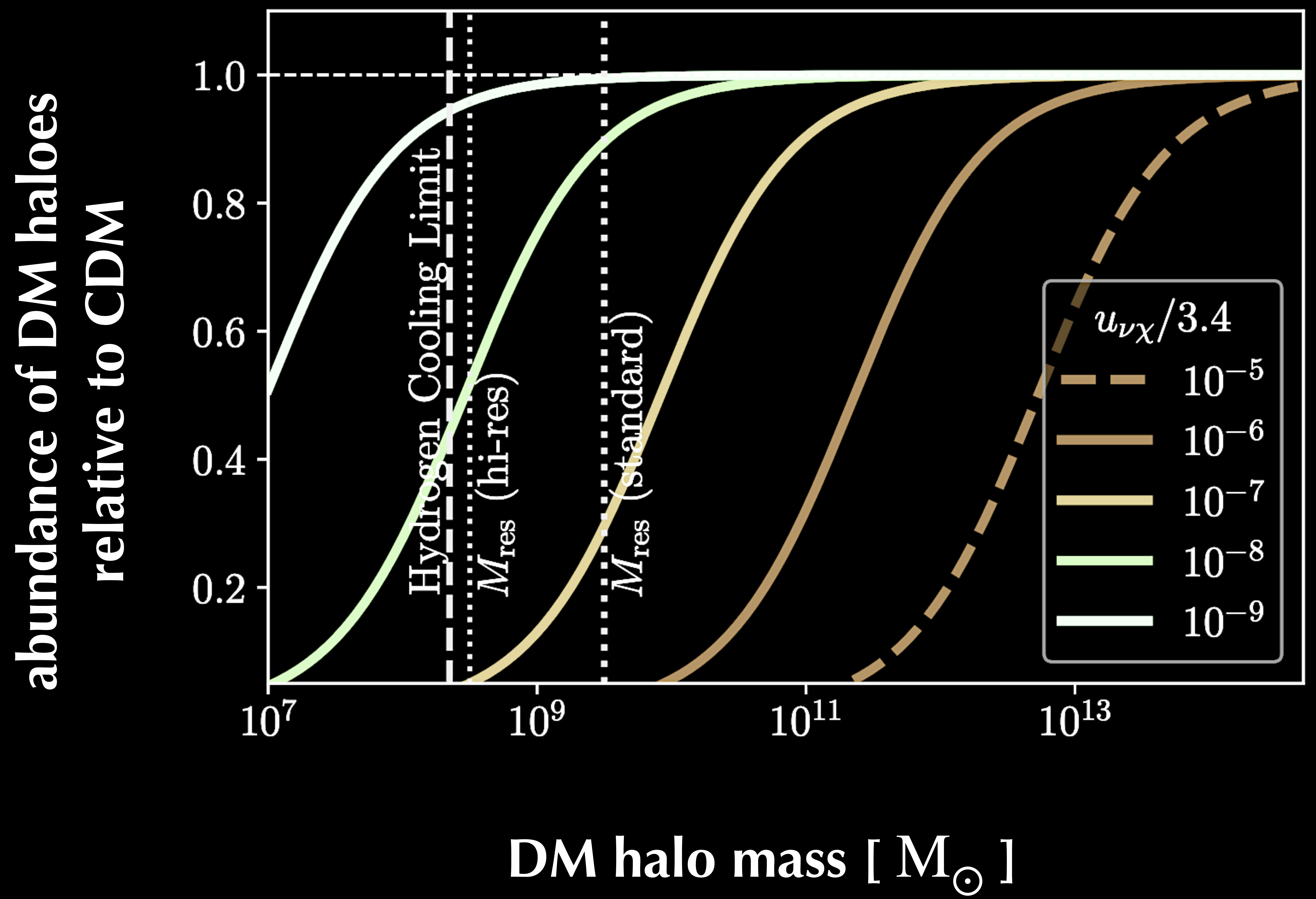


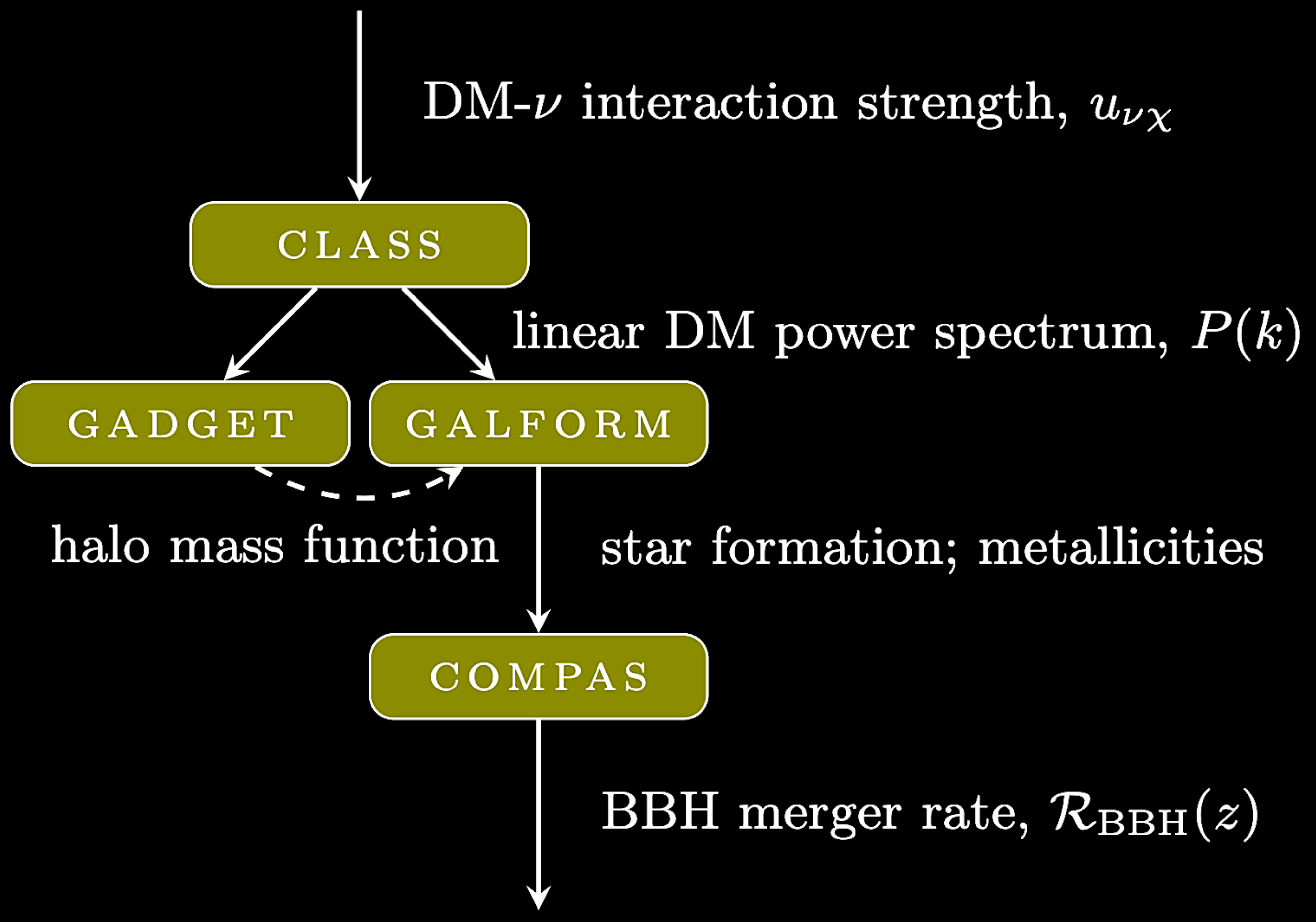
★ the merger rate of BHs is an (indirect) tracer of the merger rate of galaxies



★ lower interaction strength —> closer to CDM

Mosbech, Jenkins, SB+
[2023, arXiv: 2207.14126]





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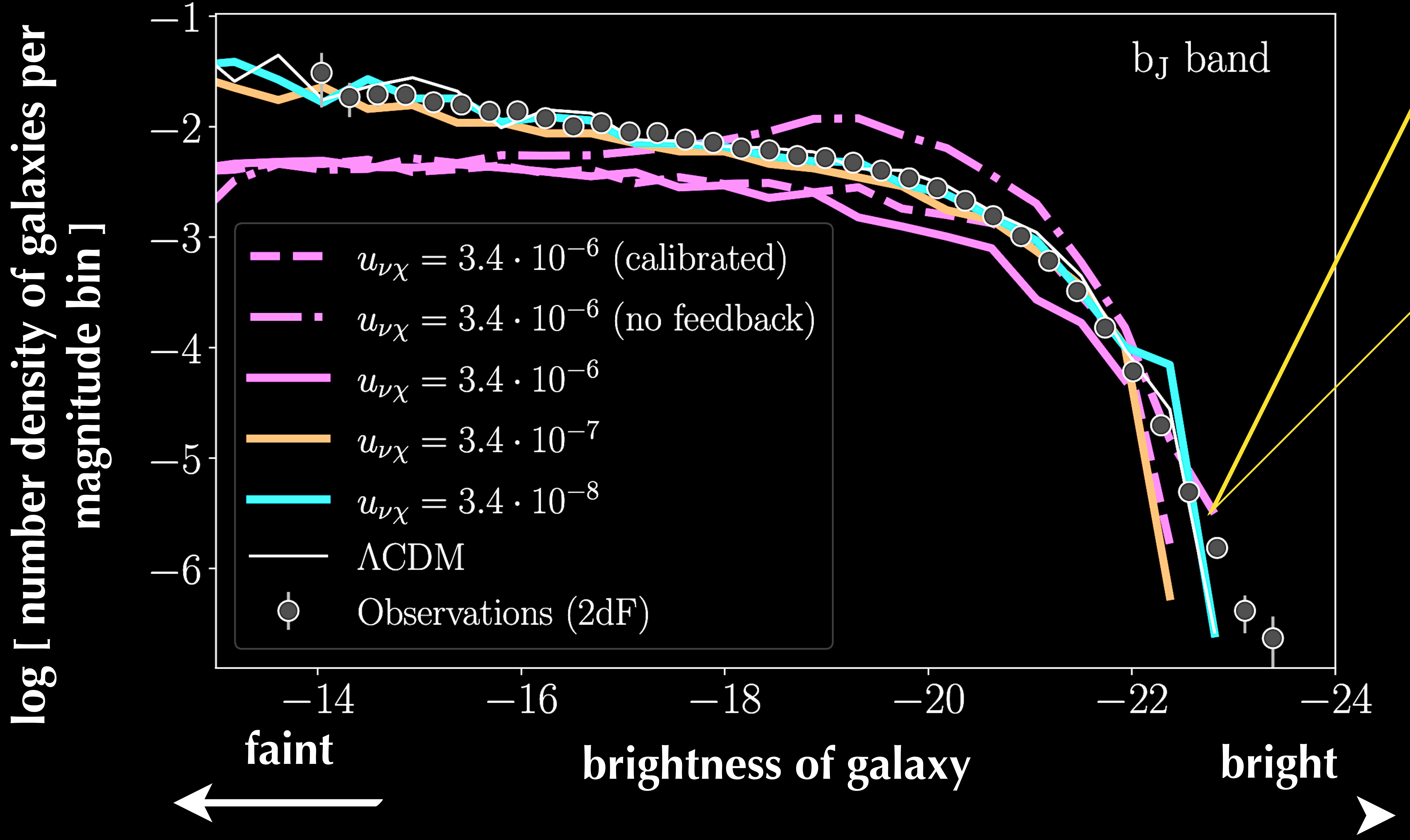
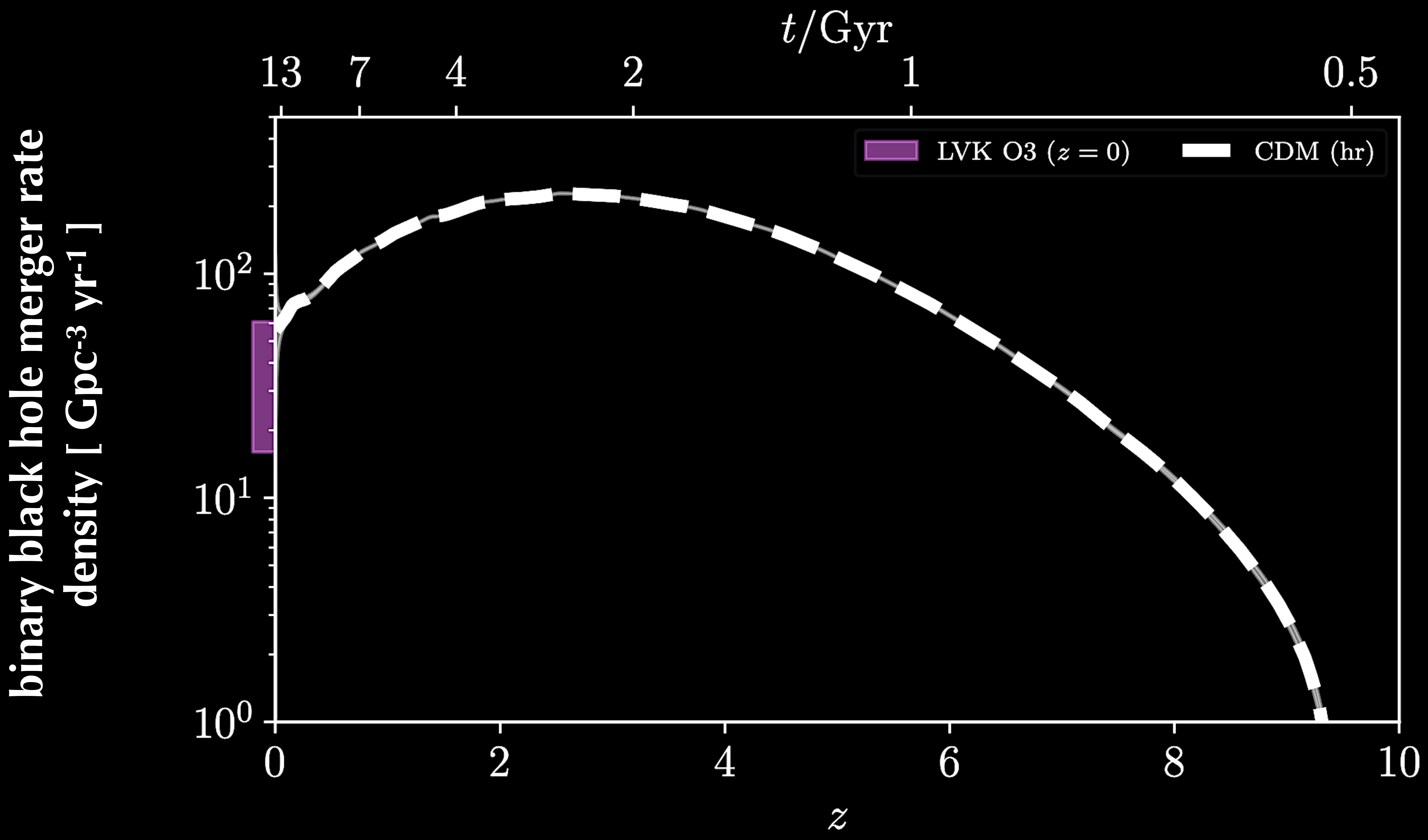
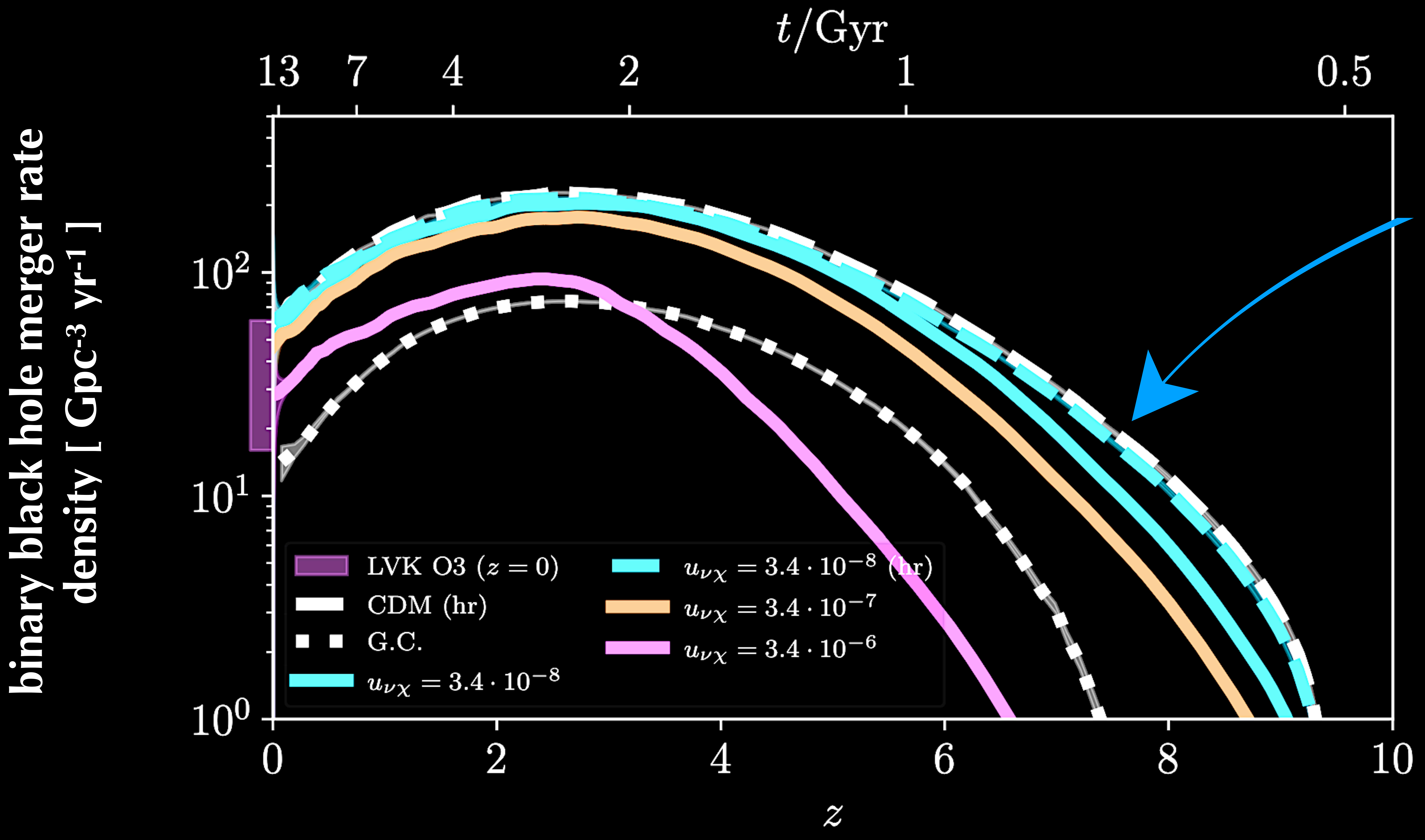


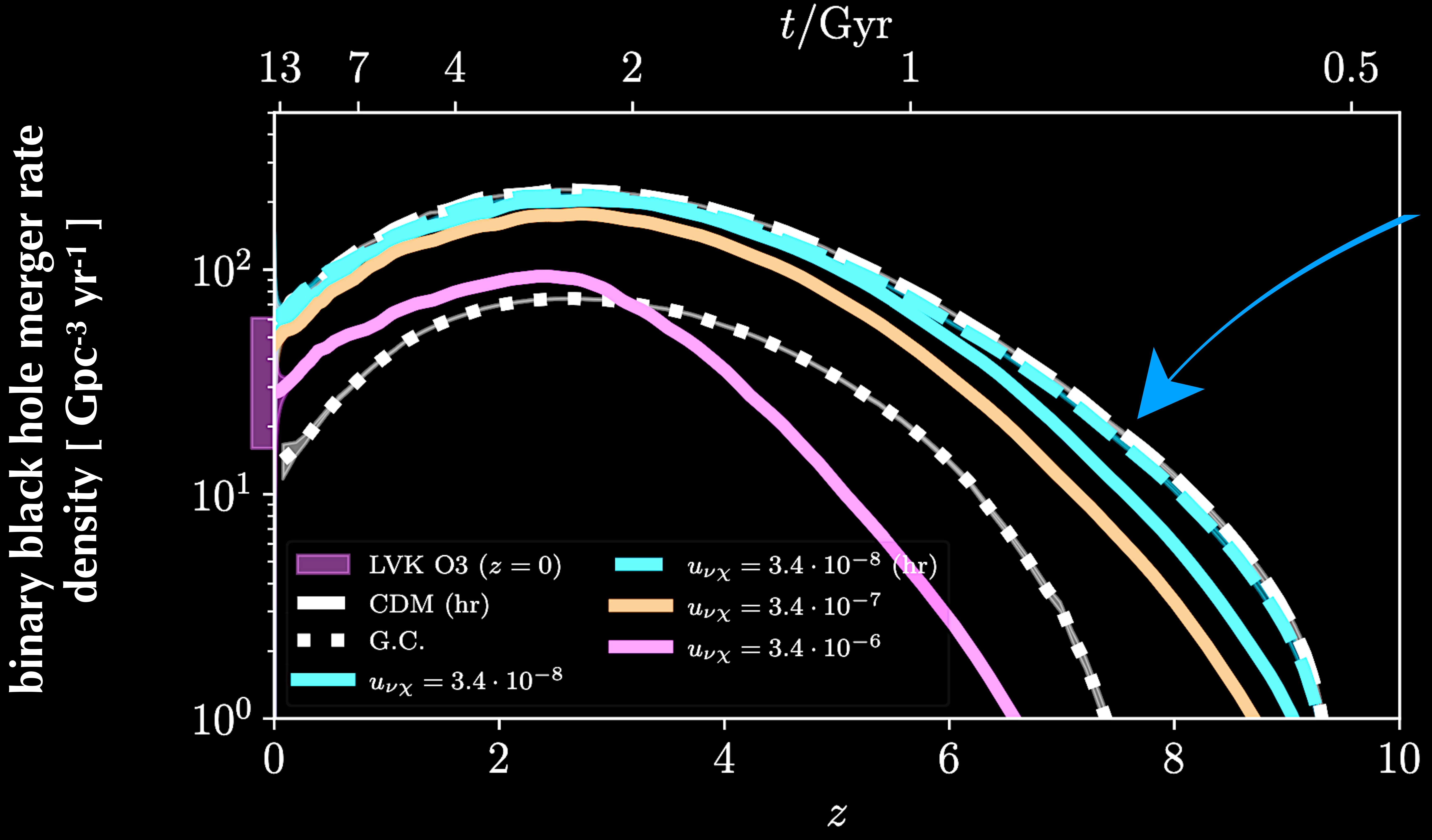
goal: generate "realistic" galaxy population for each model at present day and predict their BBH merger rates in the past. in extreme models, this calibration is not possible no matter what you do with astrophysics



t/Gyr
13
7
4
2
1
0.5
LVK O3 (z = 0)
CDM (hr)
binary black hole merger rate density [Gpc-3 yr-1]
10^2
10^1
10^0
0
2
4
6
8
10
z



merger rates are substantially lower in iDM models at early times, but "catch up" towards present day — a generic feature of models with a primordial suppression of small-scale power



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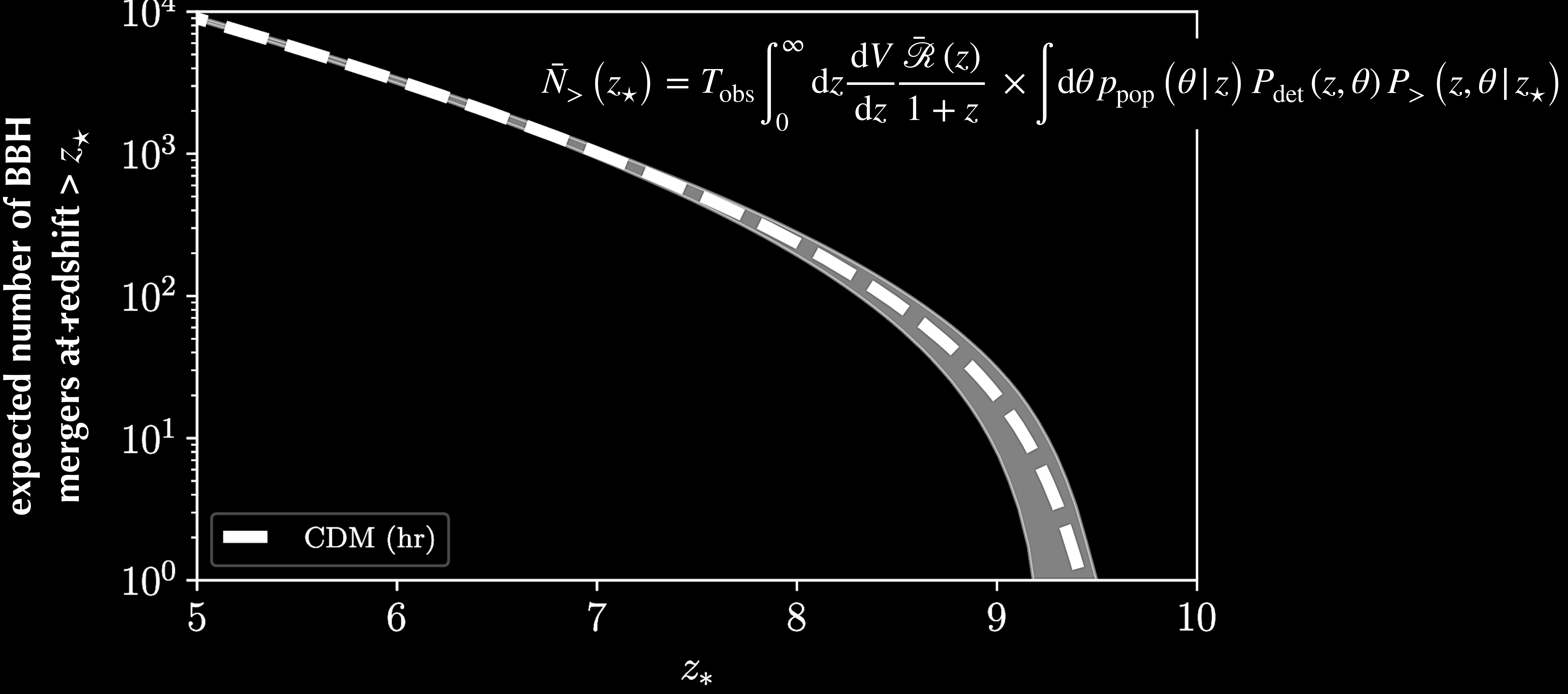
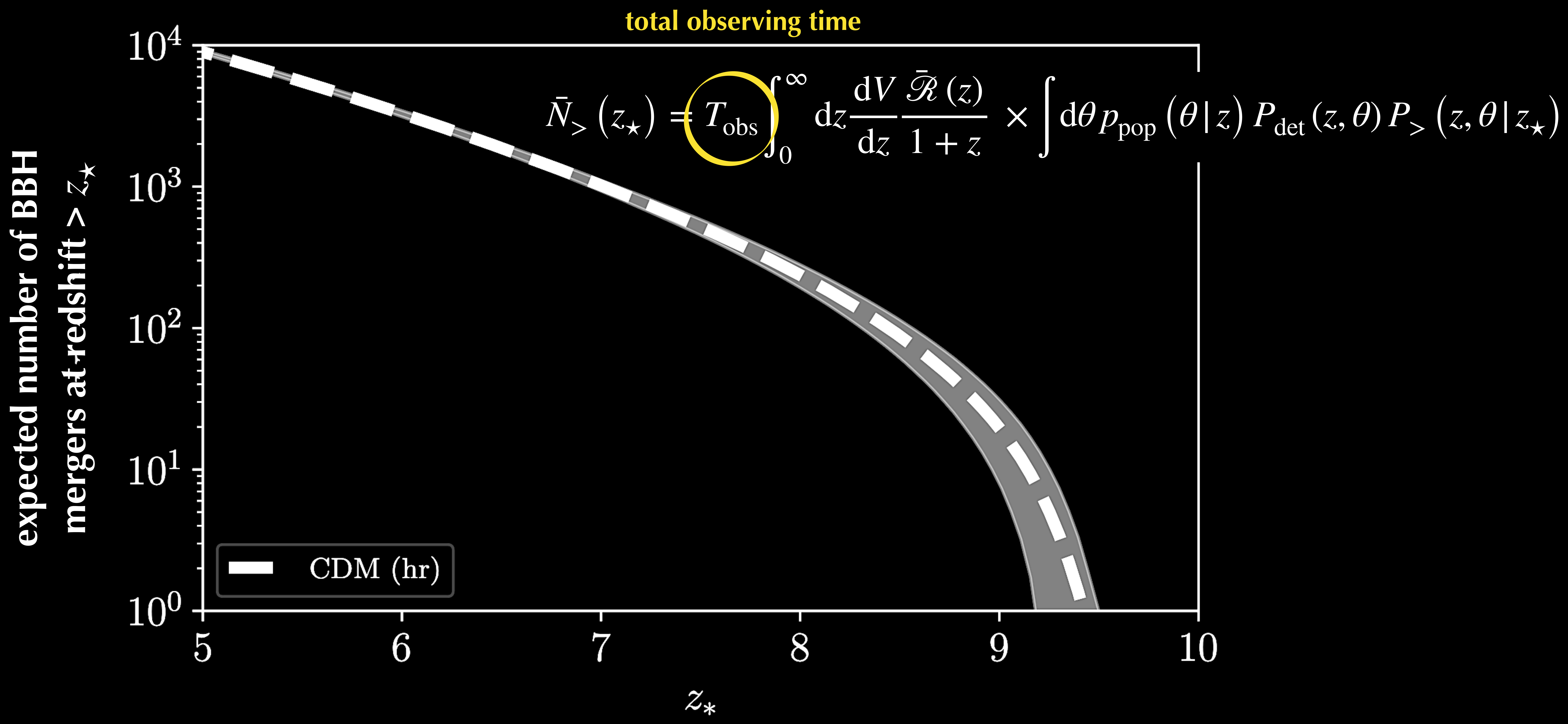
are these differences observable using future GW observatories?



forecasts for one year of observations with Einstein Telescope + 2 Cosmic Explorers



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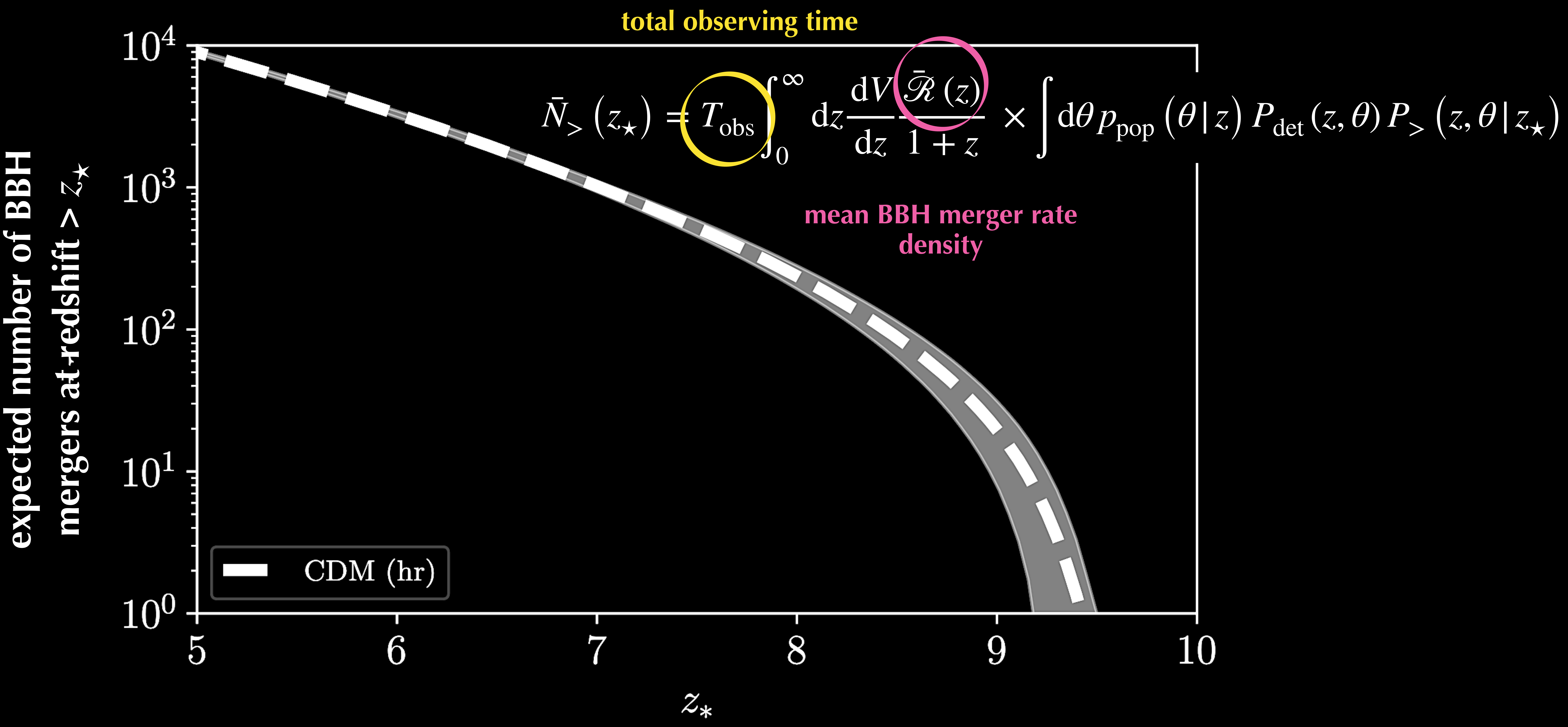

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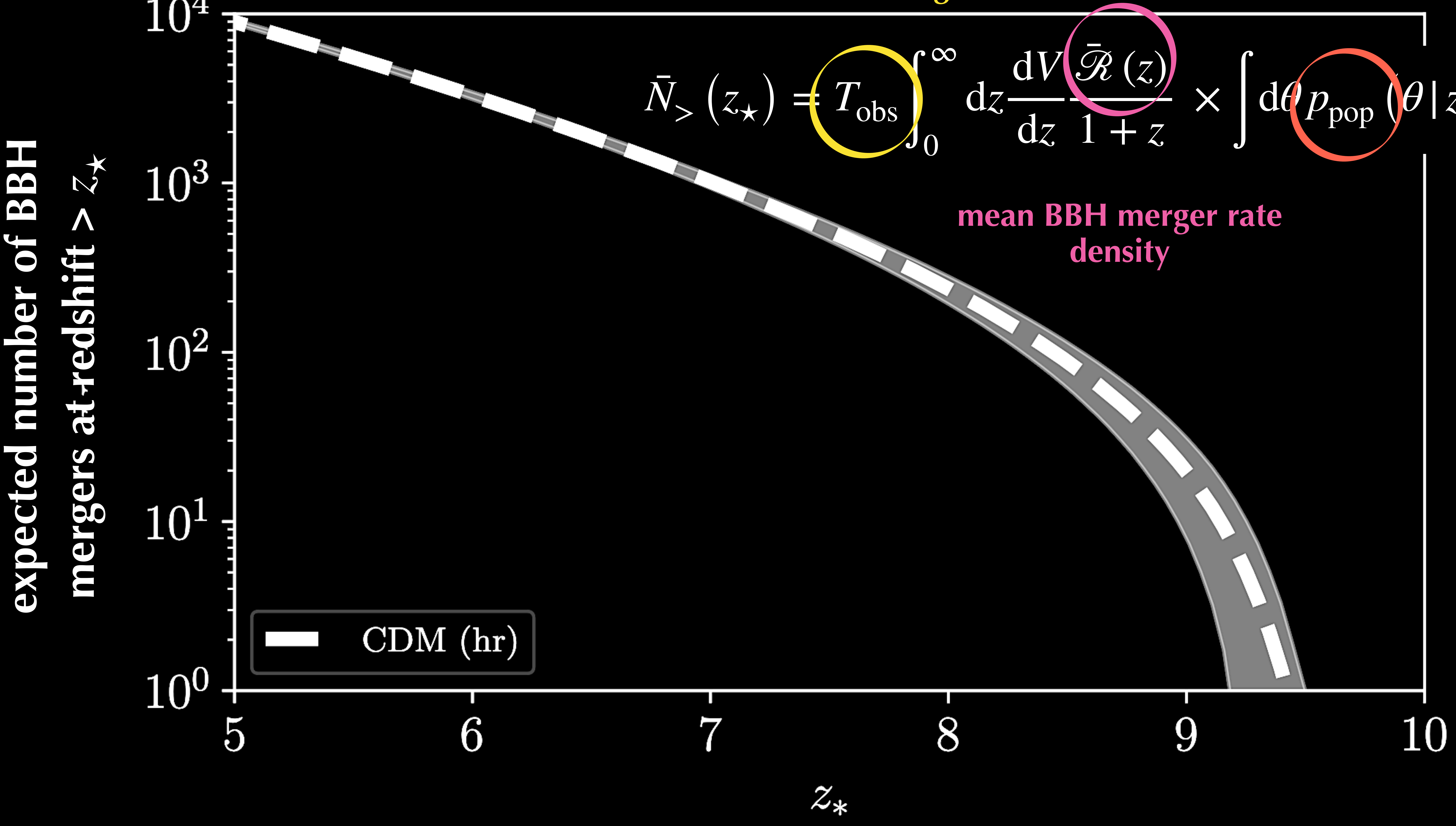


total observing time

population distribution

$$\bar{N}_>(z_\star) = T_{\rm obs}\int_0^\infty \mathrm{d}z\,\frac{\mathrm{d}V}{\mathrm{d}z}\,\frac{\bar{\mathcal{R}}(z)}{1+z} \times \int \mathrm{d}\theta\, p_{\rm pop}(\theta\,|\,z)\, P_{\rm det}(z,\theta)\, P_>(z,\theta\,|\,z_\star)$$

mean BBH merger rate density

forecasts for one year of observations with Einstein Telescope + 2 Cosmic Explorers

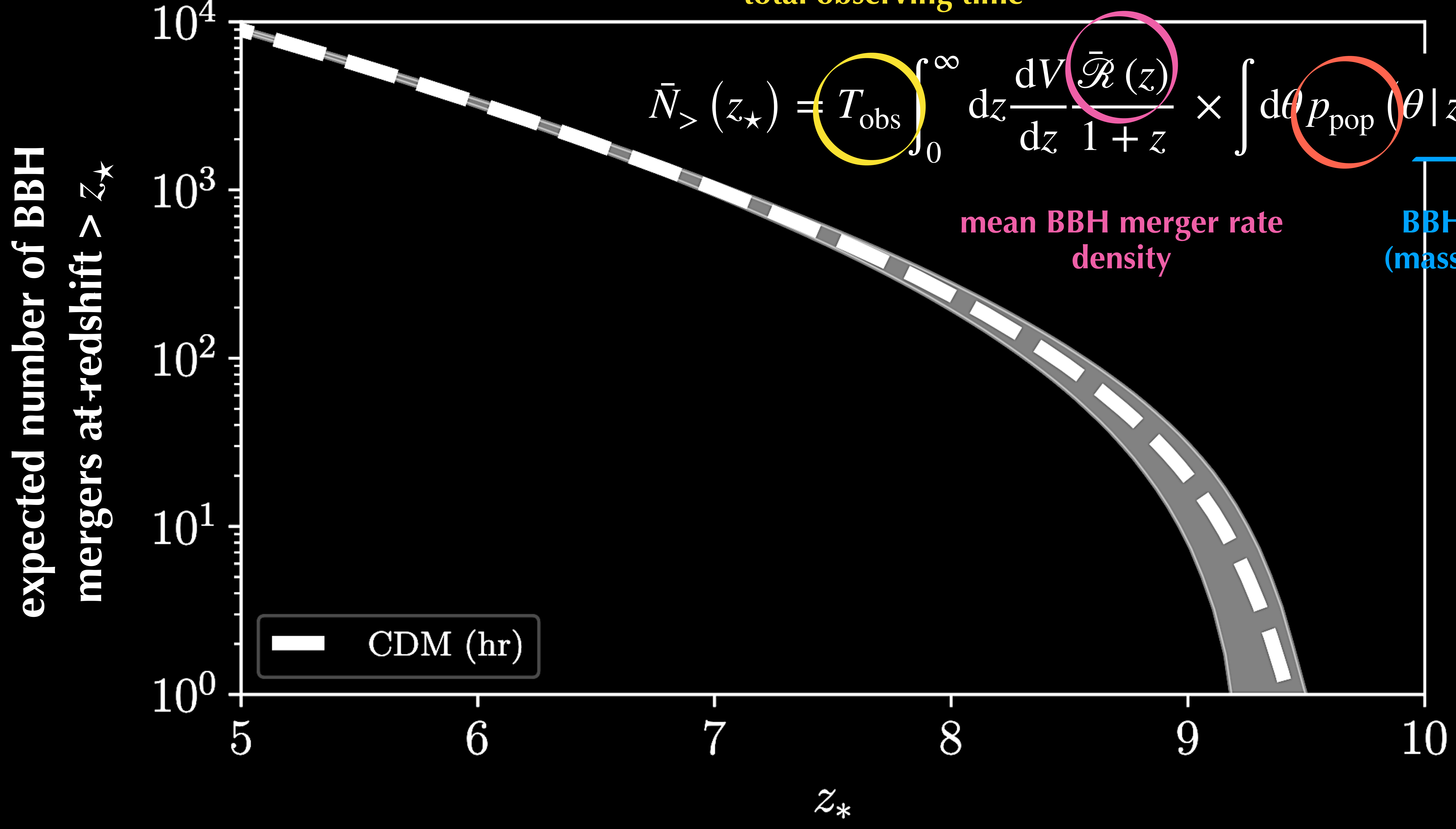
total observing time

population distribution

$$\bar{N}_{>}(z_\star) = T_{\rm obs} \int_0^\infty \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z} \frac{\bar{\mathscr{R}}(z)}{1+z} \times \int \mathrm{d}\theta \, p_{\rm pop}(\theta \,|\, z) \, P_{\rm det}(z, \theta) \, P_{>}(z, \theta \,|\, z_\star)$$

mean BBH merger rate density

BBH parameters (masses, spins etc.)



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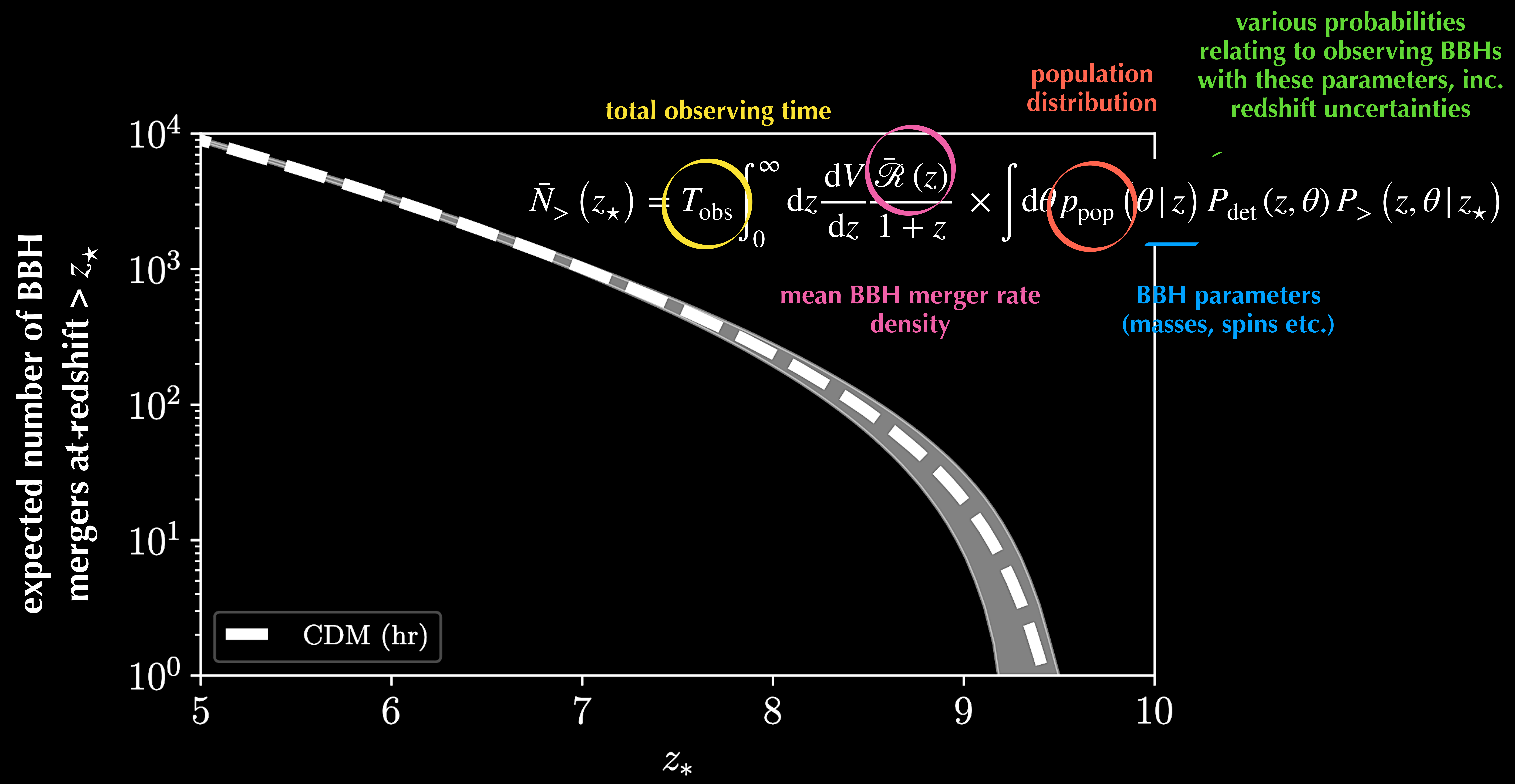

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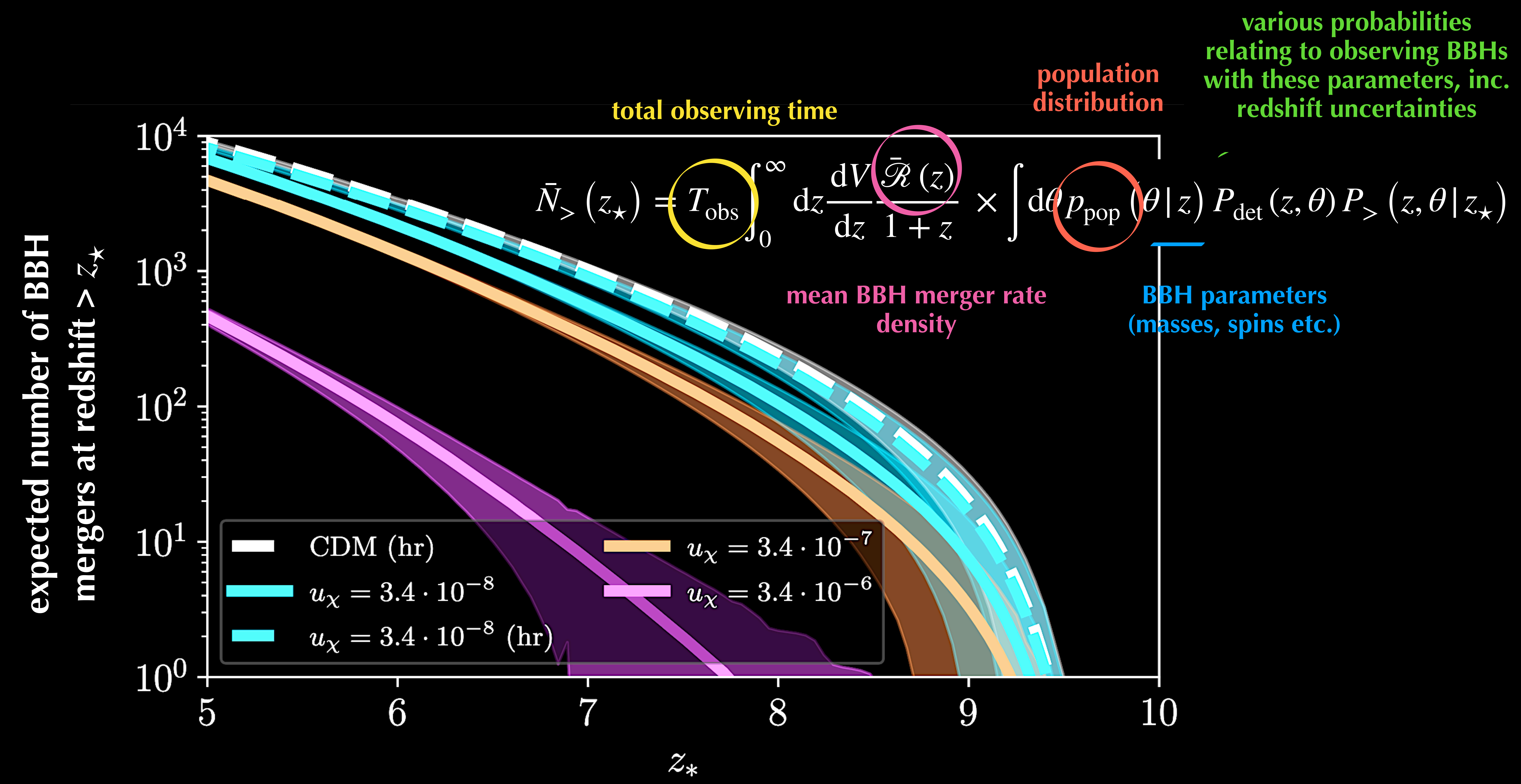

forecasts for one year of observations with Einstein Telescope + 2 Cosmic Explorers

summary

- it's always worthwhile thinking about well-motivated alternatives to the standard paradigm
- for a large class of models, which may originate from very different particle physics mechanisms, the astrophysical phenomenology is very similar
- this makes it important to setup targeted campaigns that identify *physical* scales associated with these theories
- for constraining the cutoff scale (if there is one): early generations of galaxies, faint galaxies and probes that image the dark matter directly (e.g. strong lensing). for features that may be otherwise lost in the matter field: Lyman-alpha forest
- for constraints on the (self-)interaction cross-section of DM: kinematics of galaxies, inferences of dwarf/cluster density profiles
- there are exciting prospects involving future observatories (e.g. intensity mapping, GW detections) that provide a statistical inference of the mass function of DM haloes, below the scales accessible to galaxy surveys