Dark Matter Beyond
the Weak Scale II

25 March 2024

astrophysical tests of dark matter

on small scales

Sownak Bose

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Durham University

UK Research and Innovation

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astrophysical tests of dark matter

~~on small~~ scales
across many

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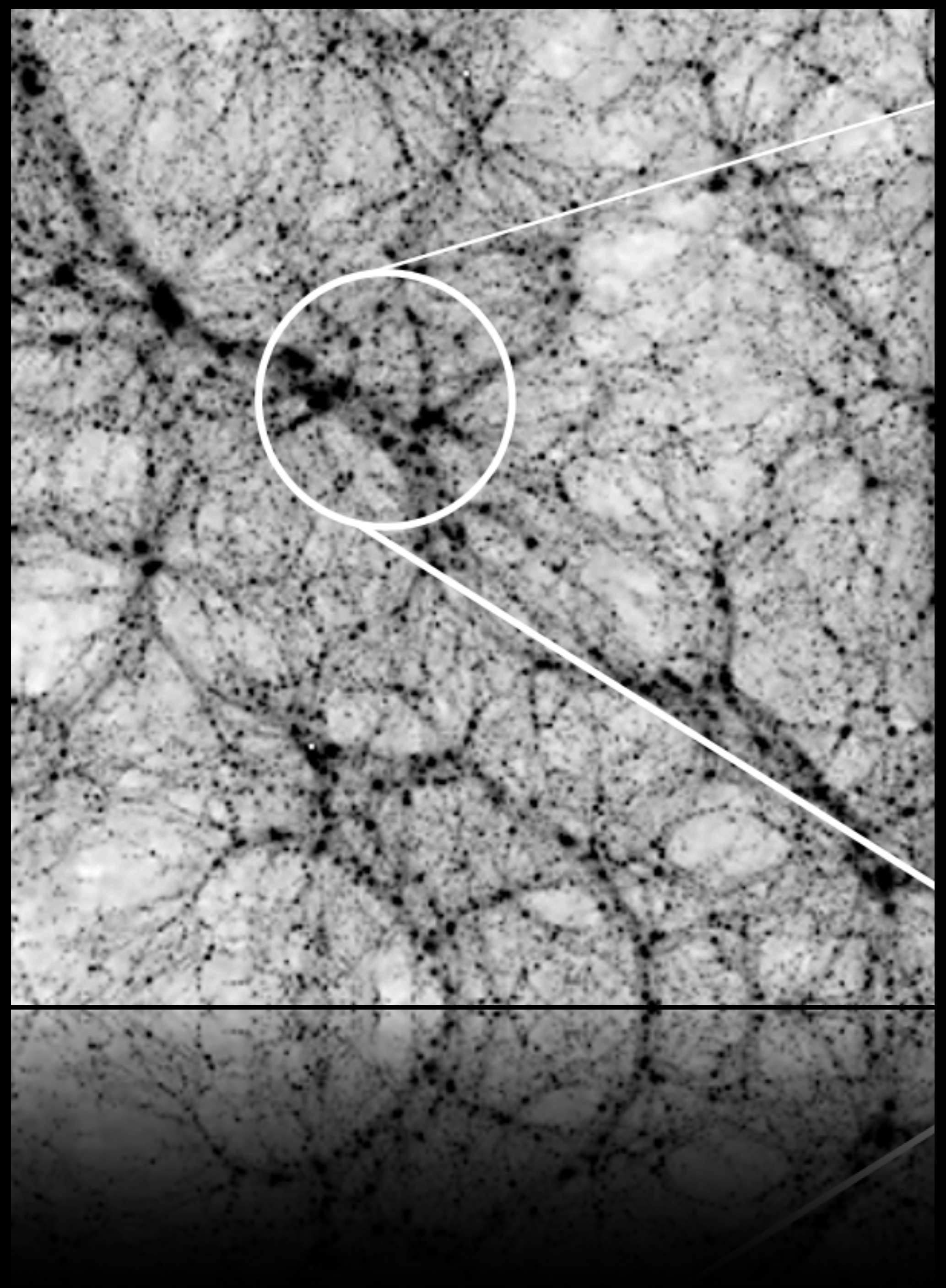
structures are **coupled** across multiple scales

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



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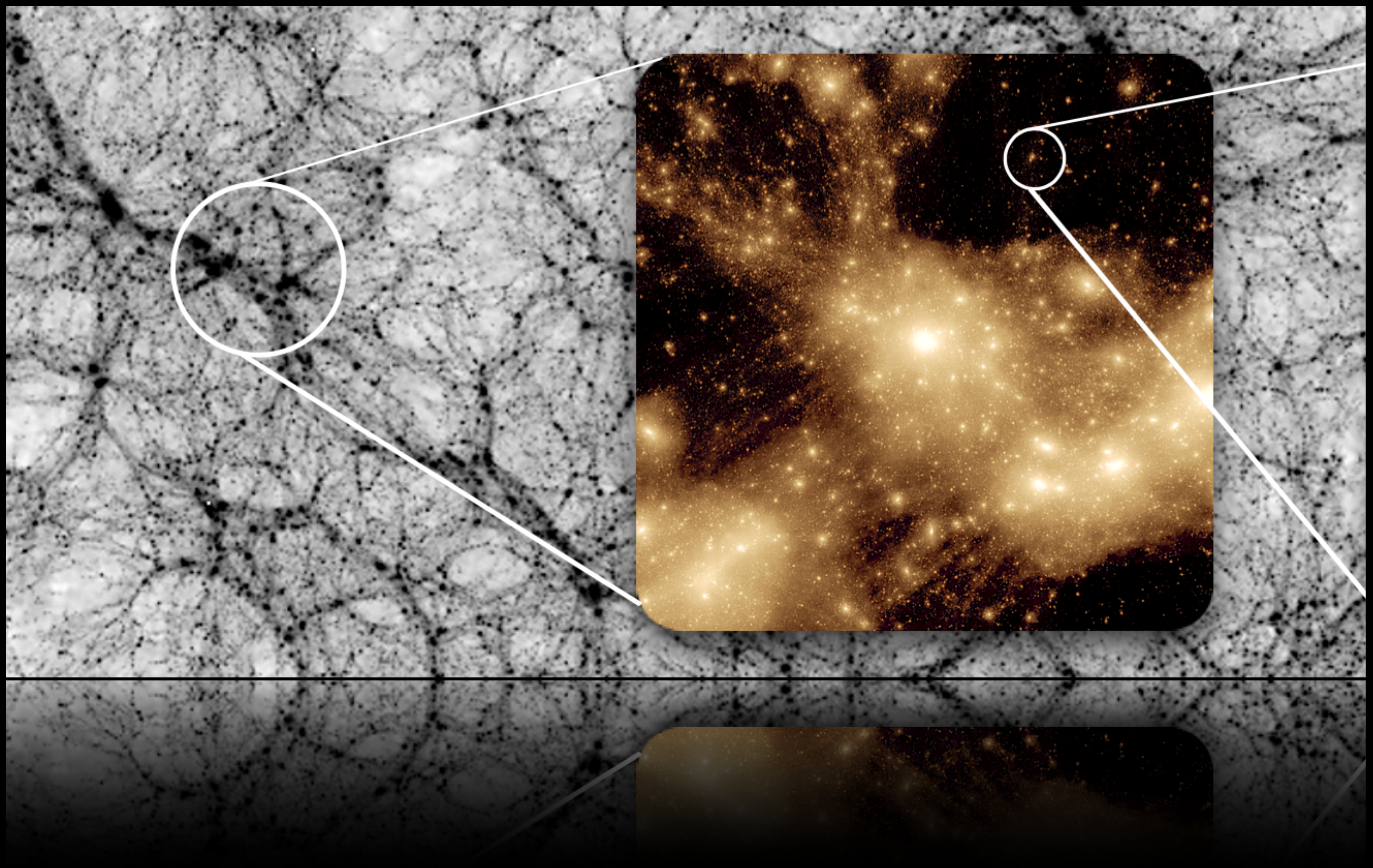
large-scale structure
[~ 10^9 light-years]

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

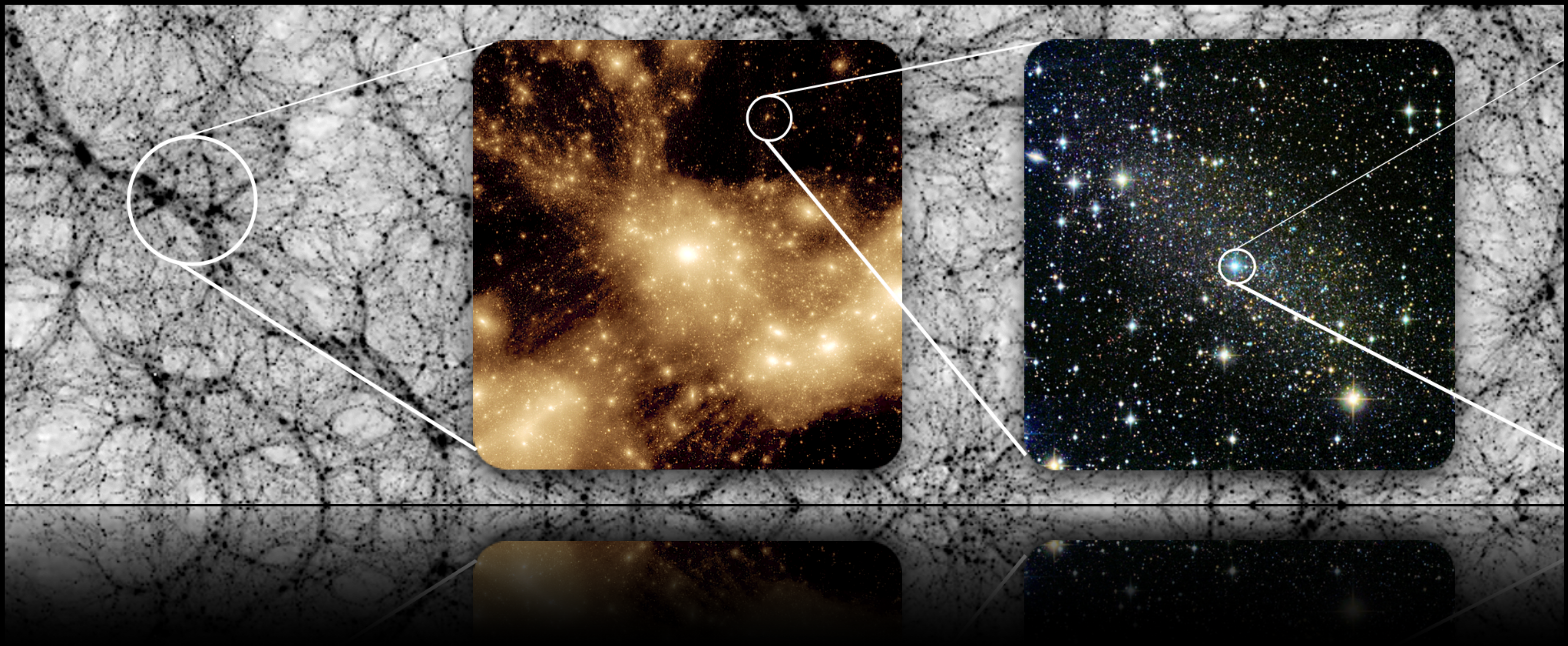


structures are coupled across multiple scales

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

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

galaxies
[~ 10^3 light-years]



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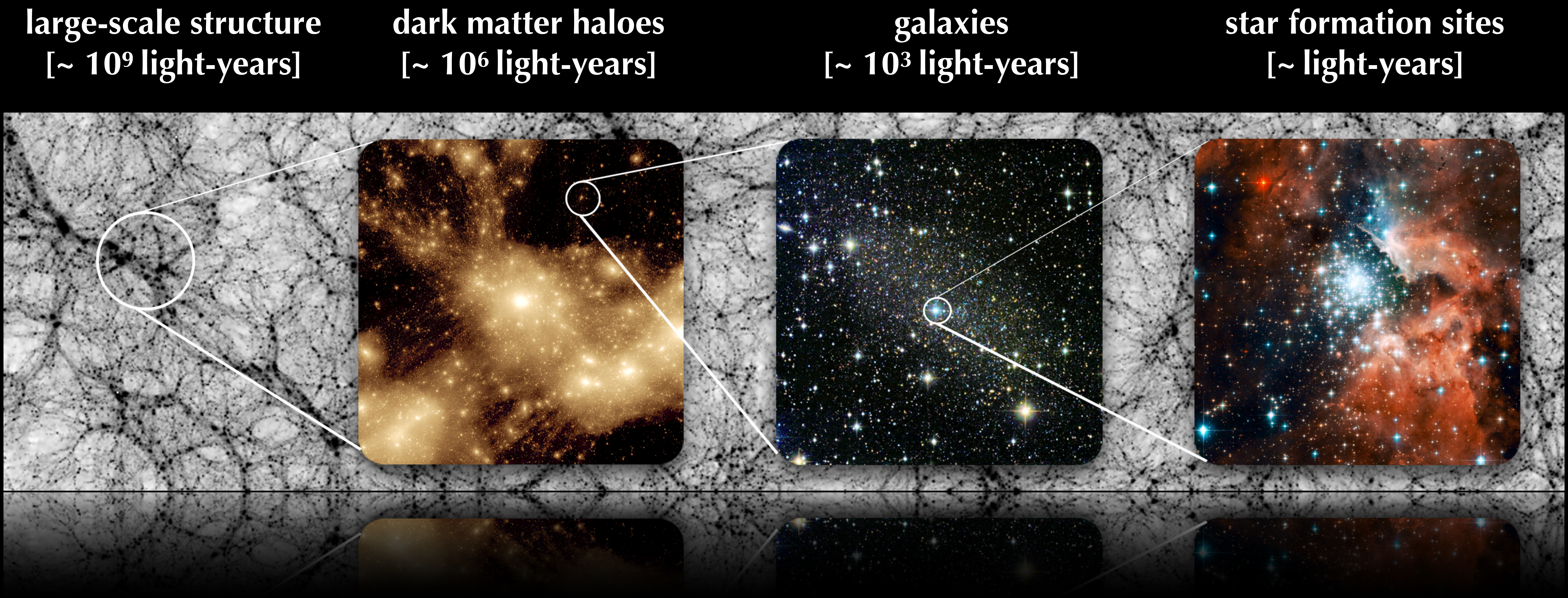
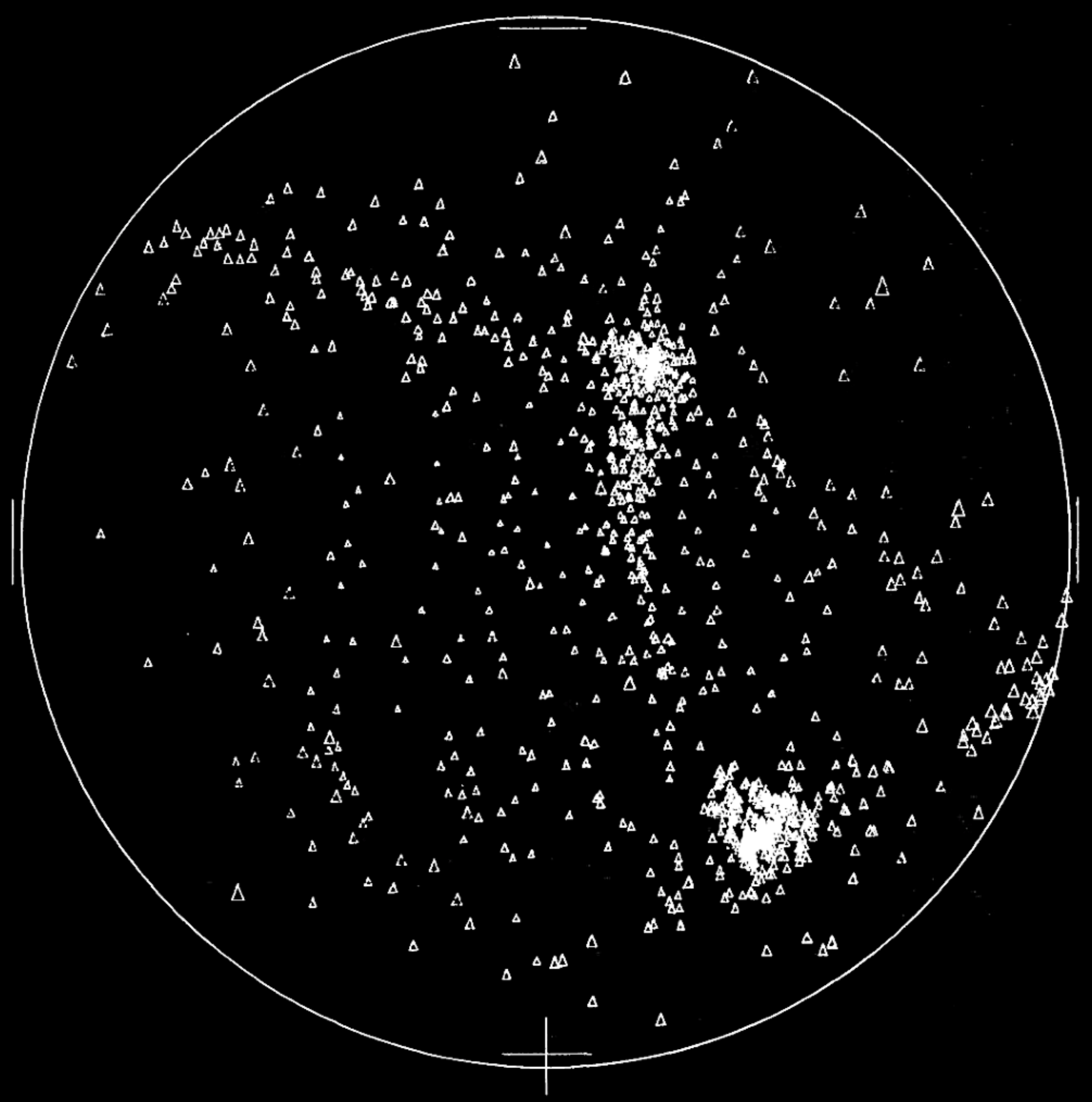
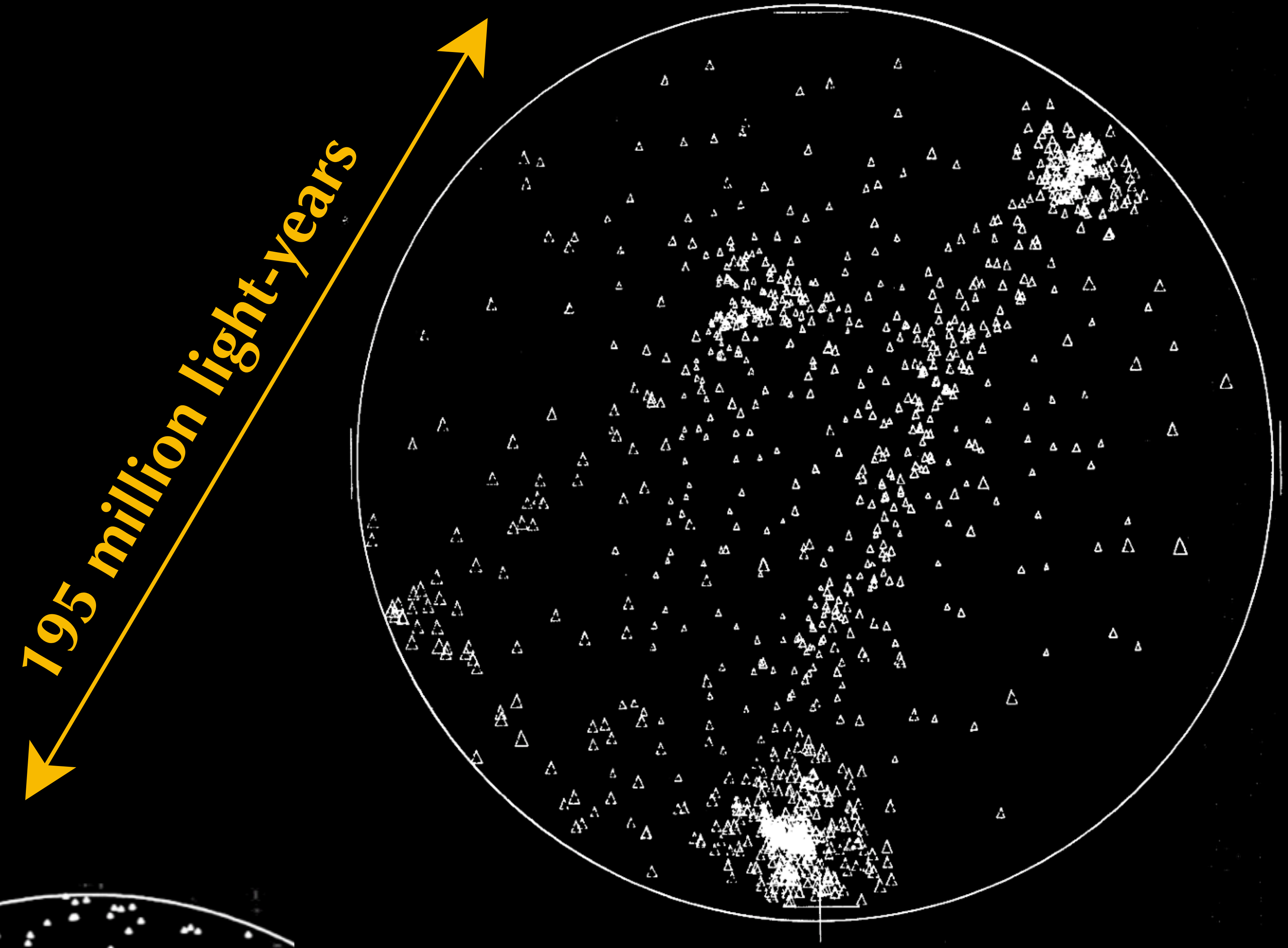
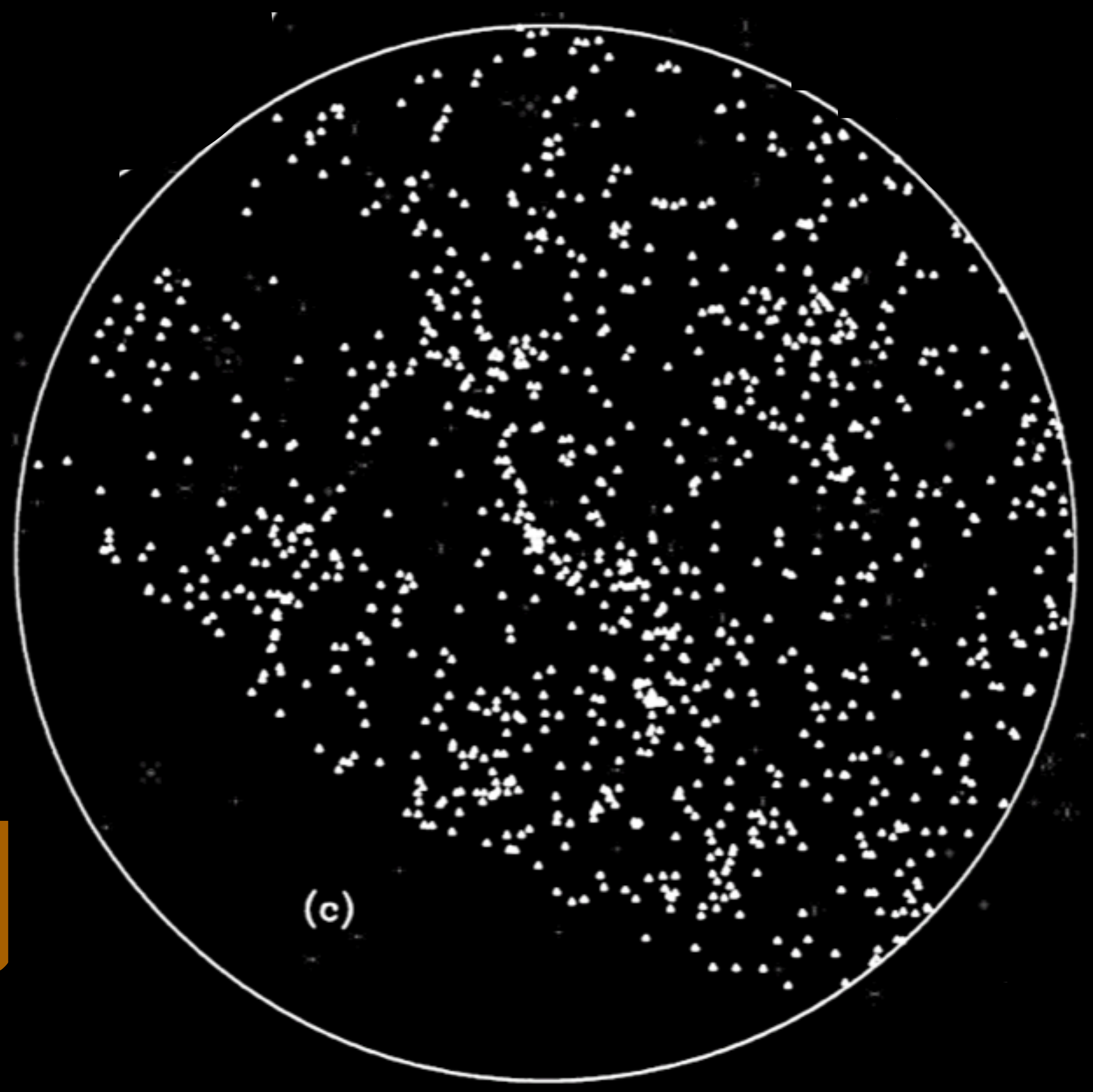


the role of **cosmological** simulations





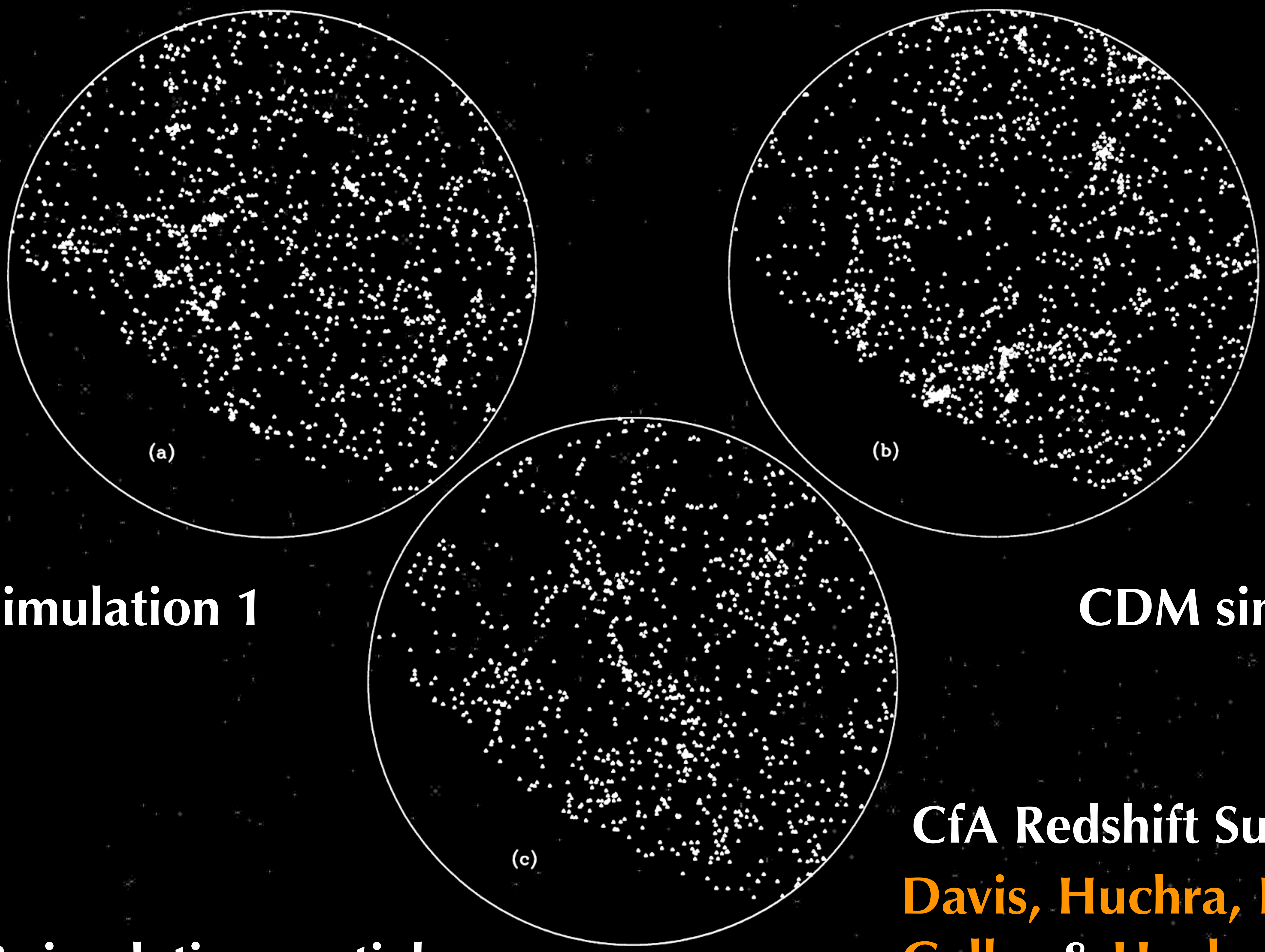


“hot” dark matter

CfA Galaxy Redshift survey

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

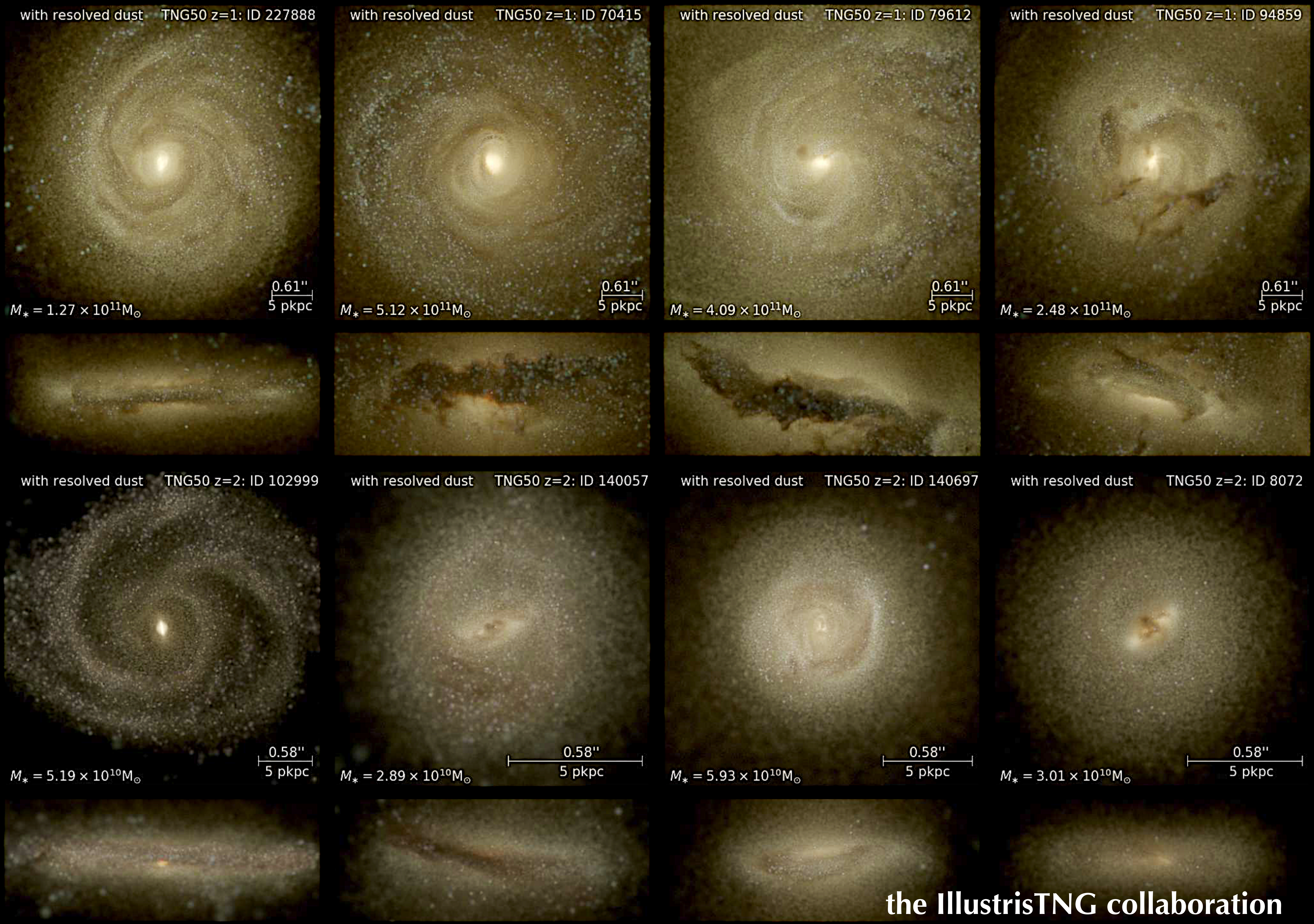

~ 512x larger computational volume
~ 300,000x more resolution elements (2160³ DM particles)

~ 512x larger computational volume

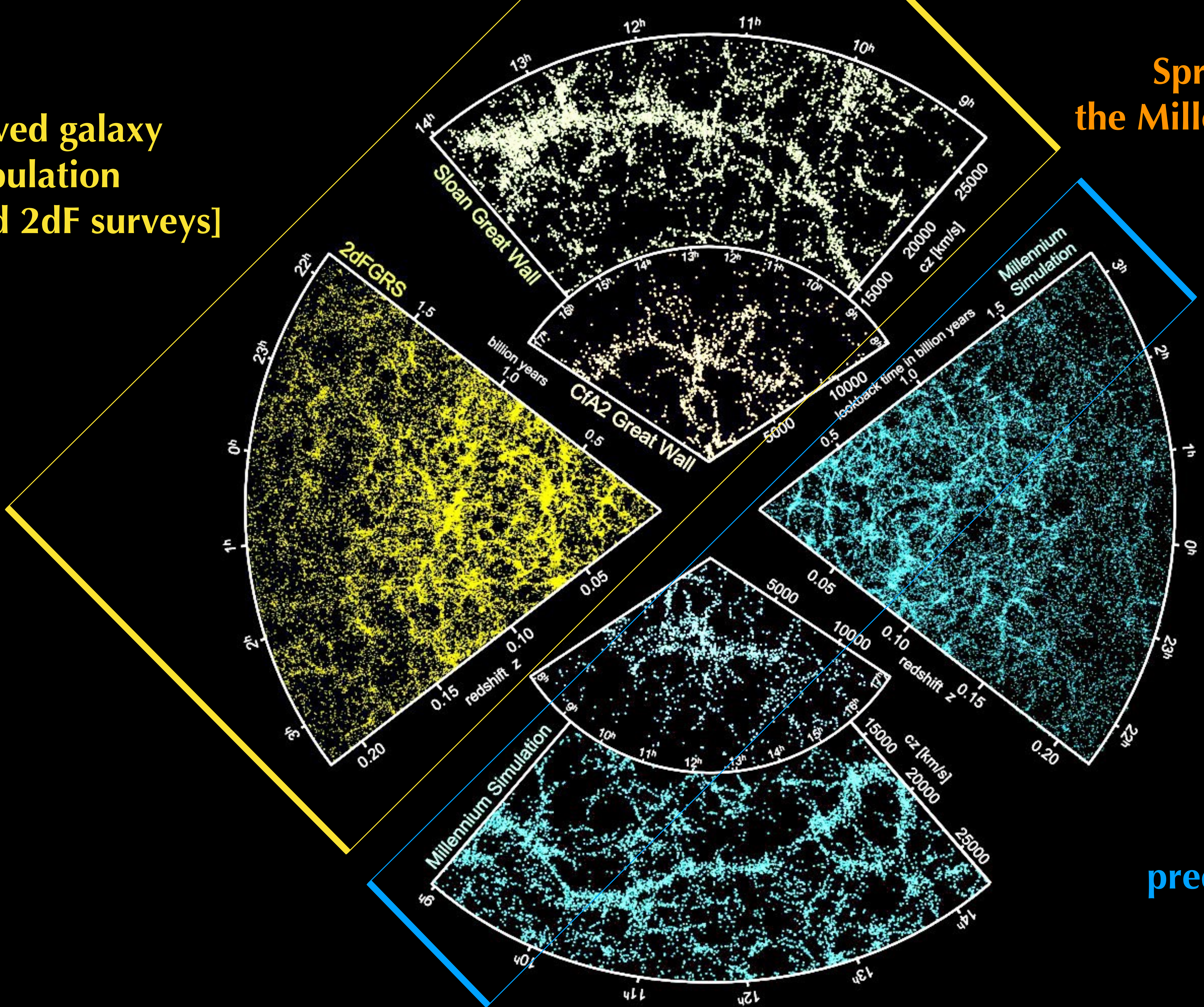
~ 300,000x more resolution elements (2160^3 DM particles)


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


30 kpc
z = 2.8
log M★ = 9.43
SFR = 3.5 M☉ yr⁻¹
80 kpc
3 kpc
TNG50

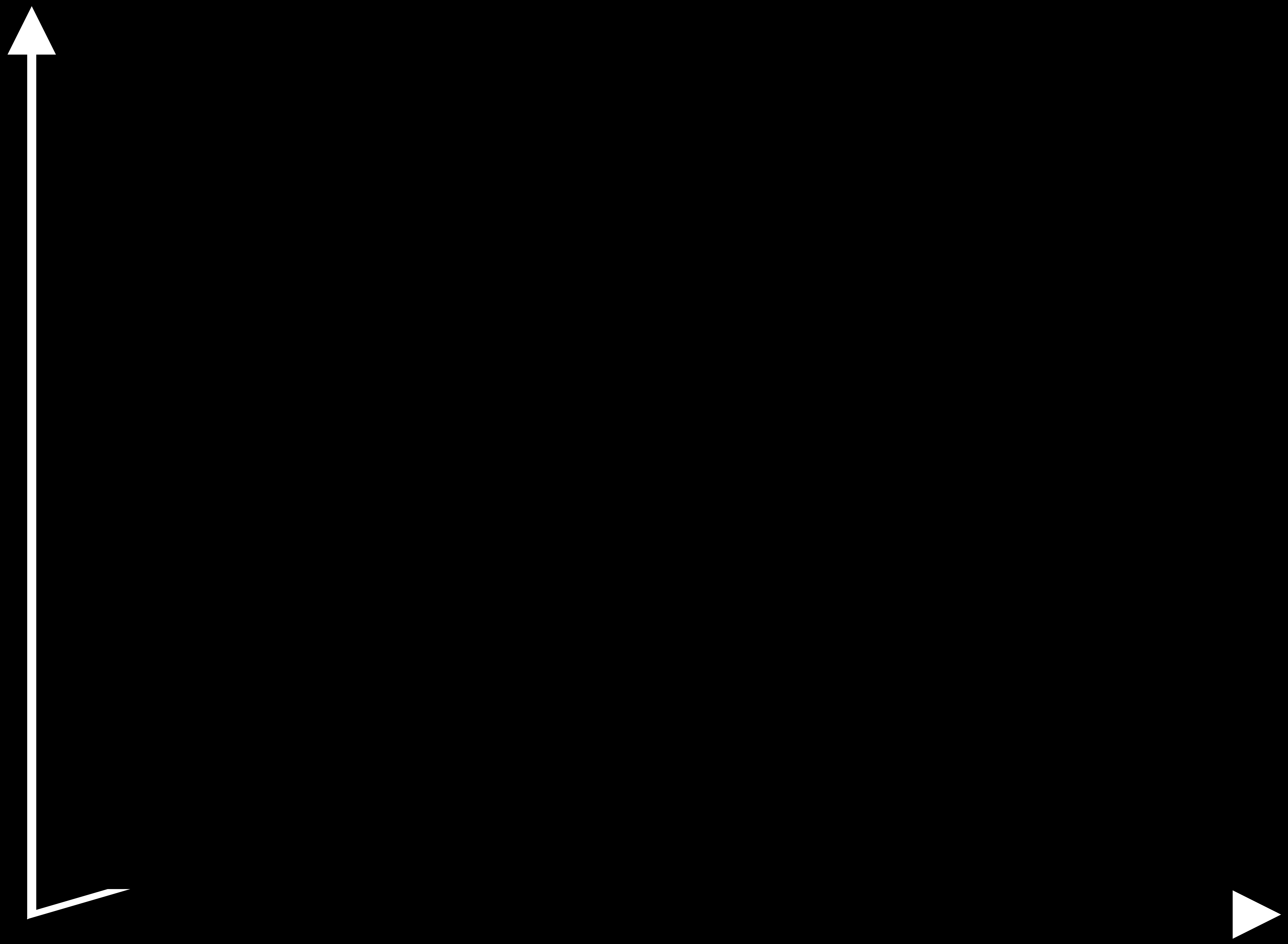

with resolved dust TNG50 z=1: ID 227888
$M_* = 1.27 \times 10^{11} M_\odot$
0.61''
5 pkpc
with resolved dust TNG50 z=1: ID 70415
$M_* = 5.12 \times 10^{11} M_\odot$
0.61''
5 pkpc
with resolved dust TNG50 z=1: ID 79612
$M_* = 4.09 \times 10^{11} M_\odot$
0.61''
5 pkpc
with resolved dust TNG50 z=1: ID 94859
$M_* = 2.48 \times 10^{11} M_\odot$
0.61''
5 pkpc
with resolved dust TNG50 z=2: ID 102999
$M_* = 5.19 \times 10^{10} M_\odot$
0.58''
5 pkpc
with resolved dust TNG50 z=2: ID 140057
$M_* = 2.89 \times 10^{10} M_\odot$
0.58''
5 pkpc
with resolved dust TNG50 z=2: ID 140697
$M_* = 5.93 \times 10^{10} M_\odot$
0.58''
5 pkpc
with resolved dust TNG50 z=2: ID 8072
$M_* = 3.01 \times 10^{10} M_\odot$
0.58''
5 pkpc
the IllustrisTNG collaboration

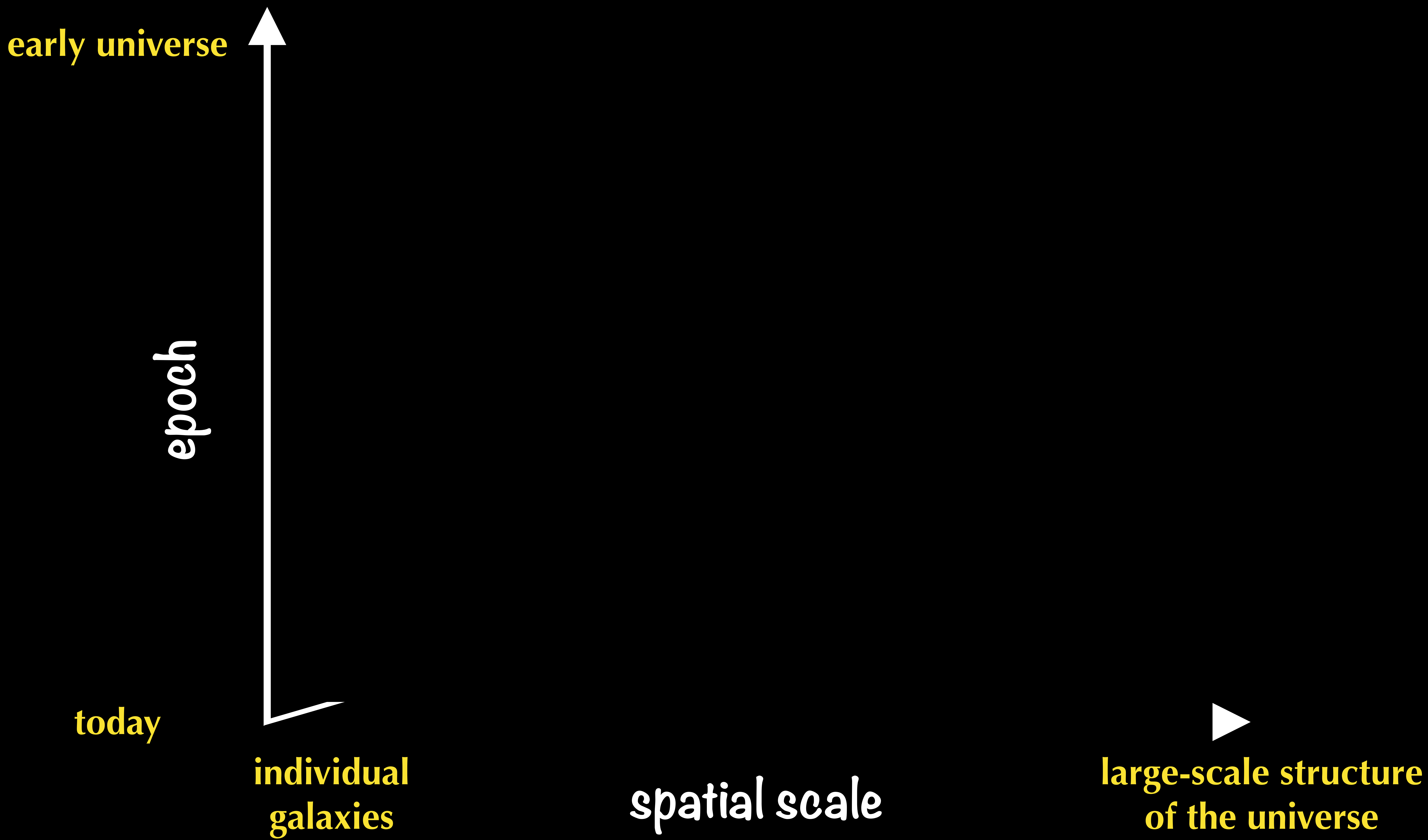
observed galaxy population
[SDSS and 2dF surveys]

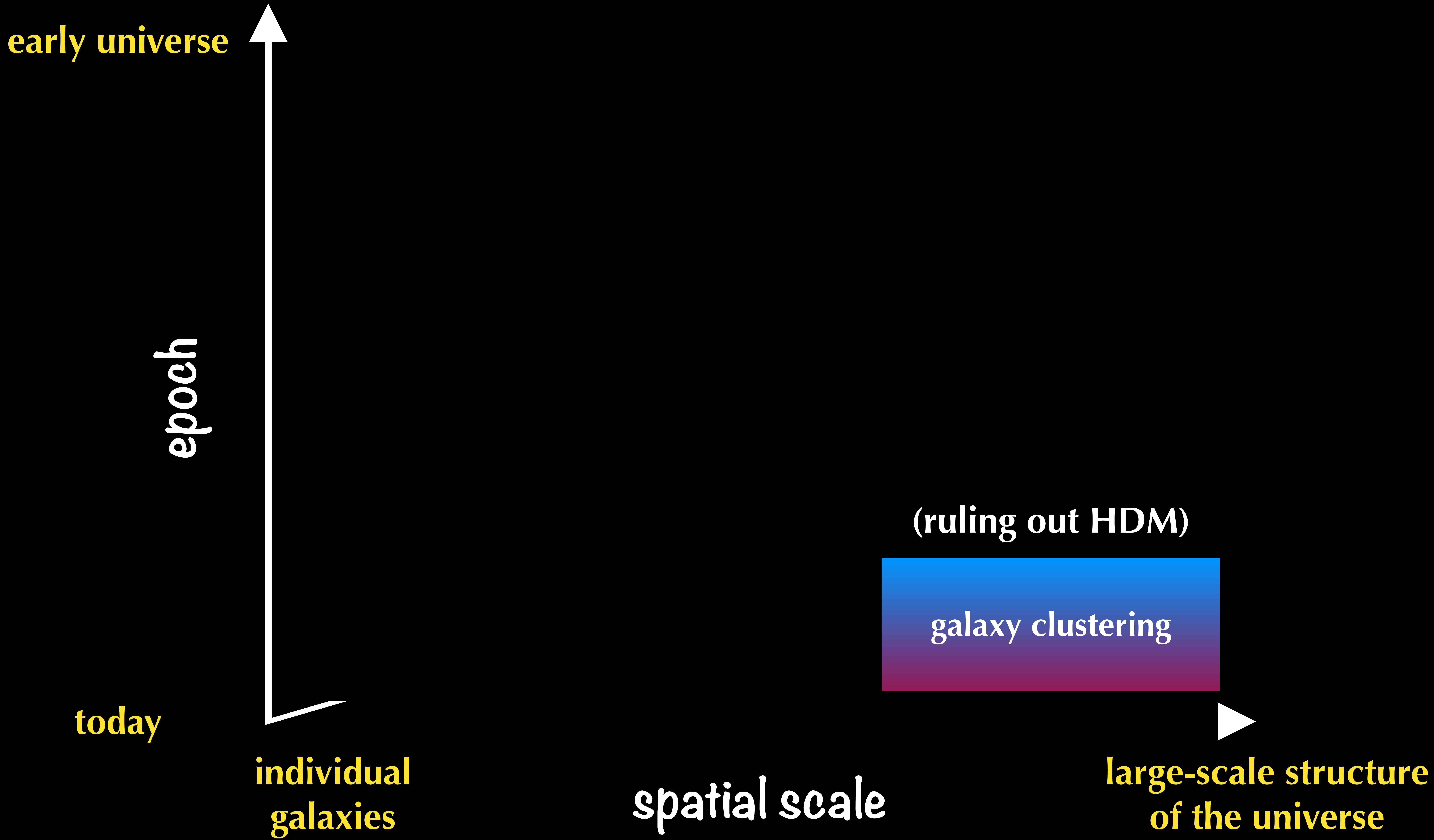


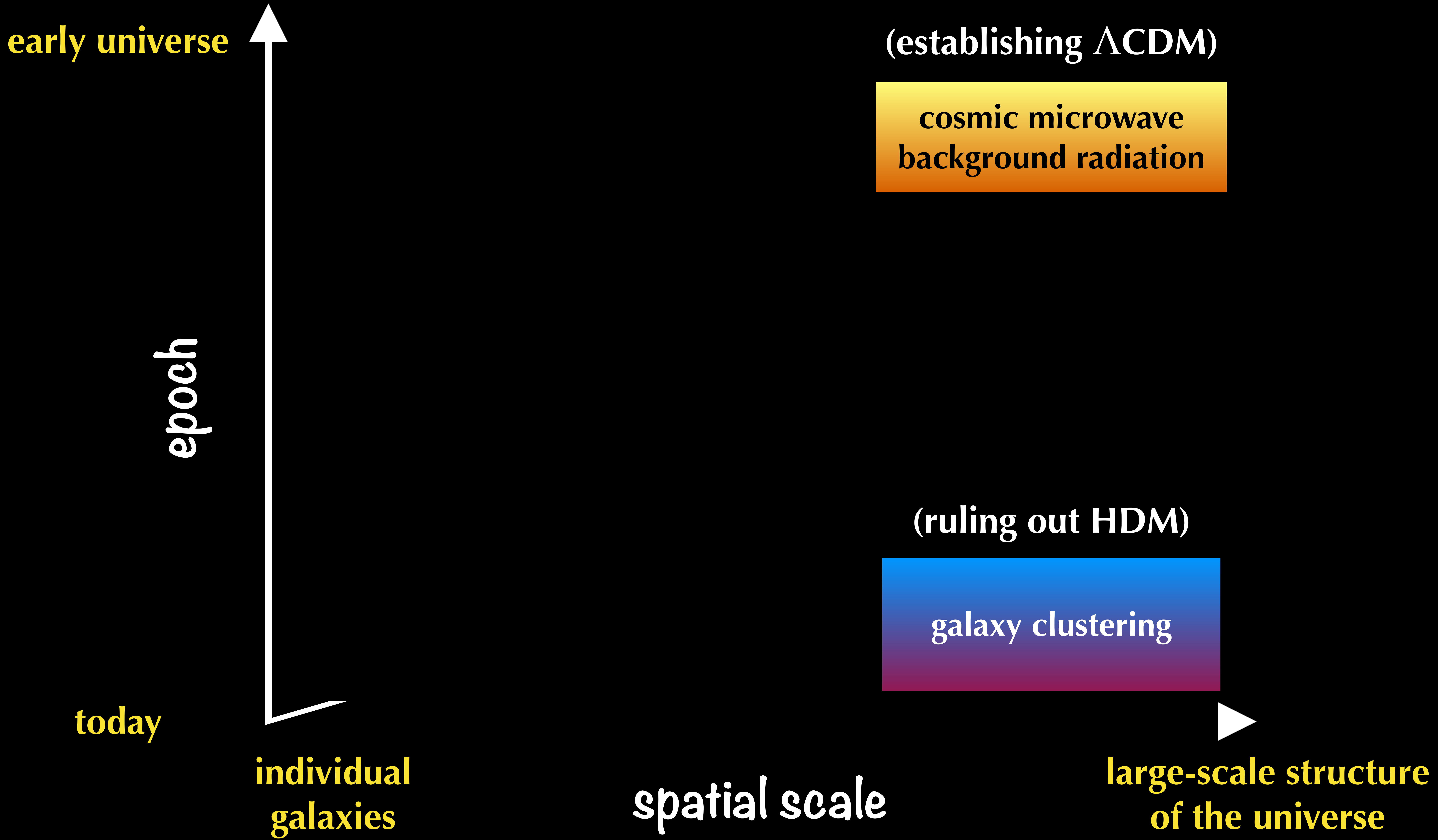
Springel+ (2005)
the Millennium simulation

prediction of the ΛCDM model




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


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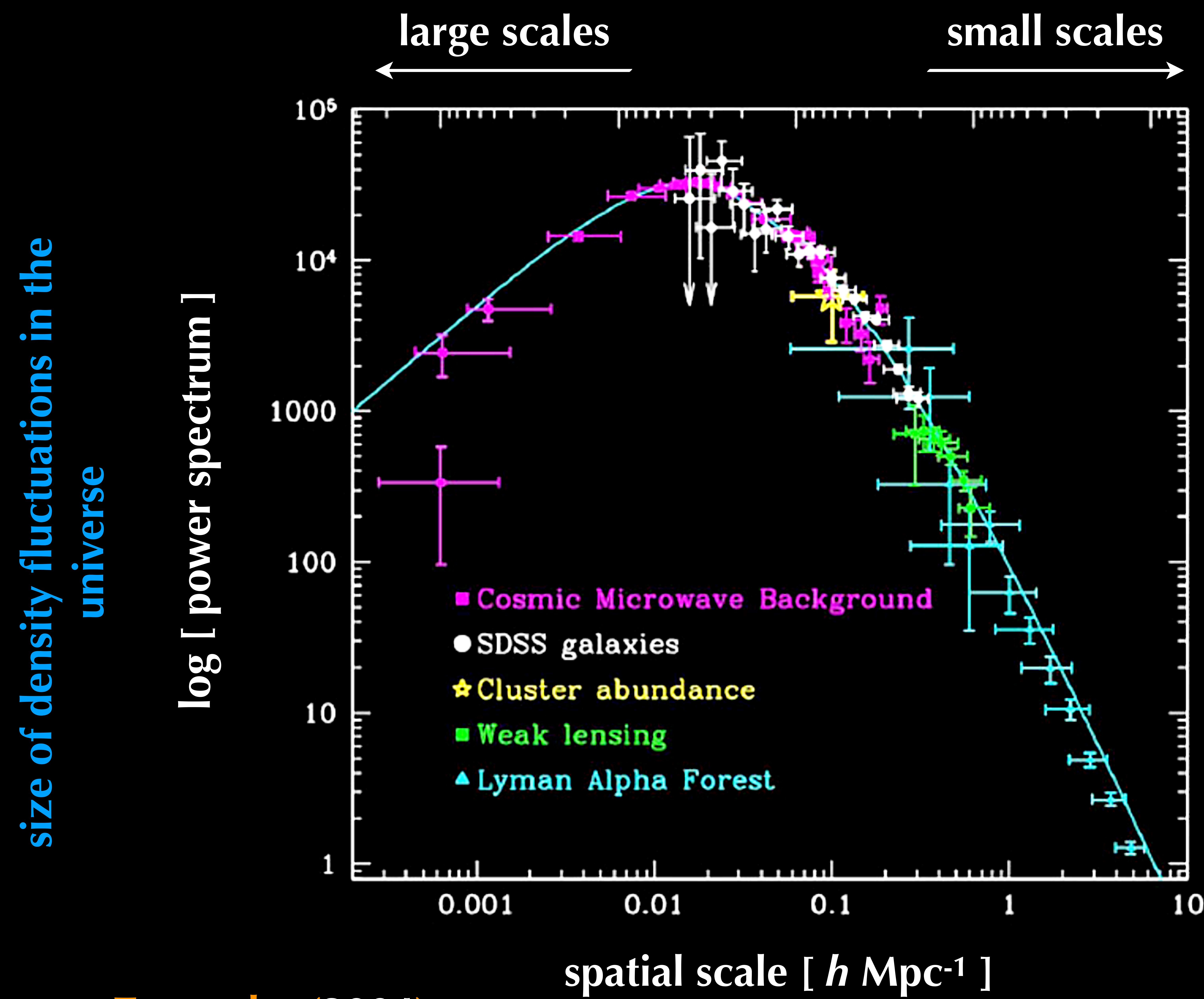


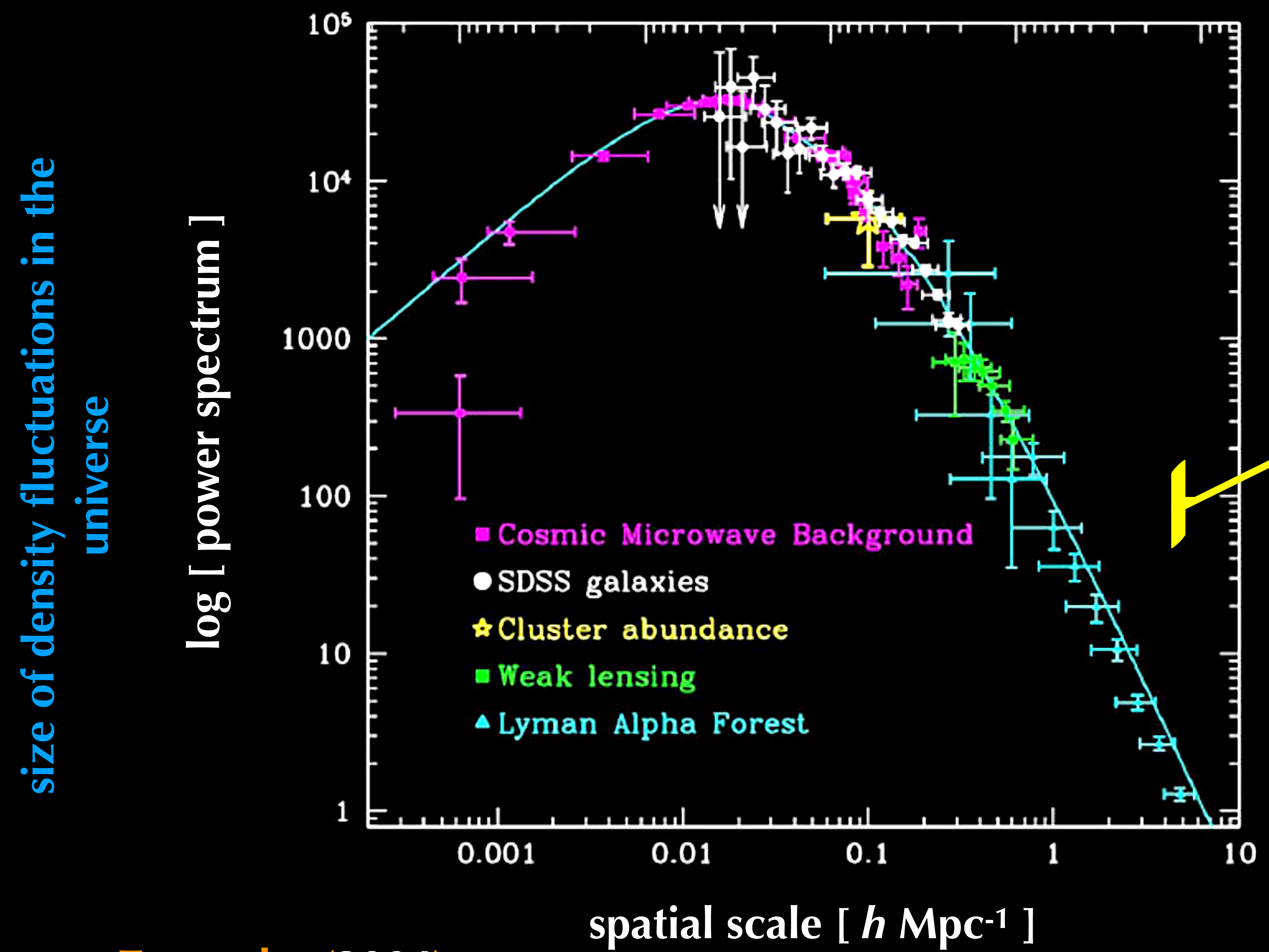
solid curve: ΛCDM prediction

symbols: data from multi-scale probes

Tegmark+ (2004)

large scales

small scales



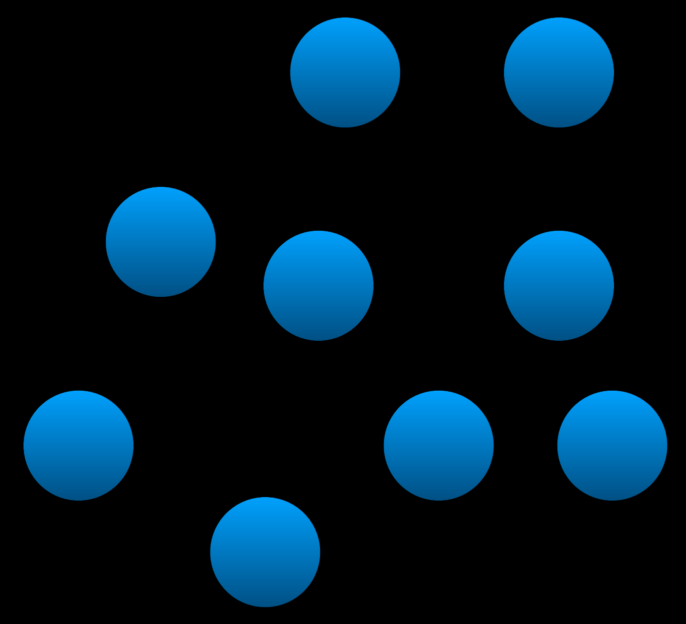
Tegmark+ (2004)

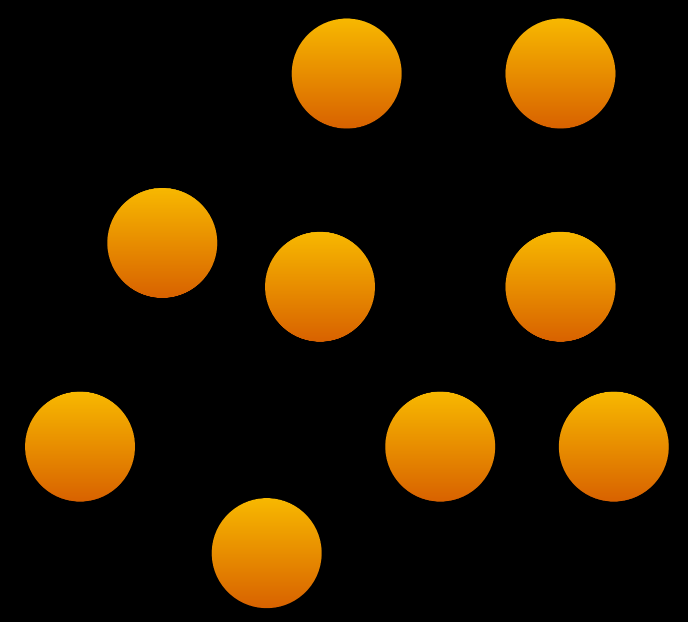
solid curve: ΛCDM prediction

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
[warm dark matter]

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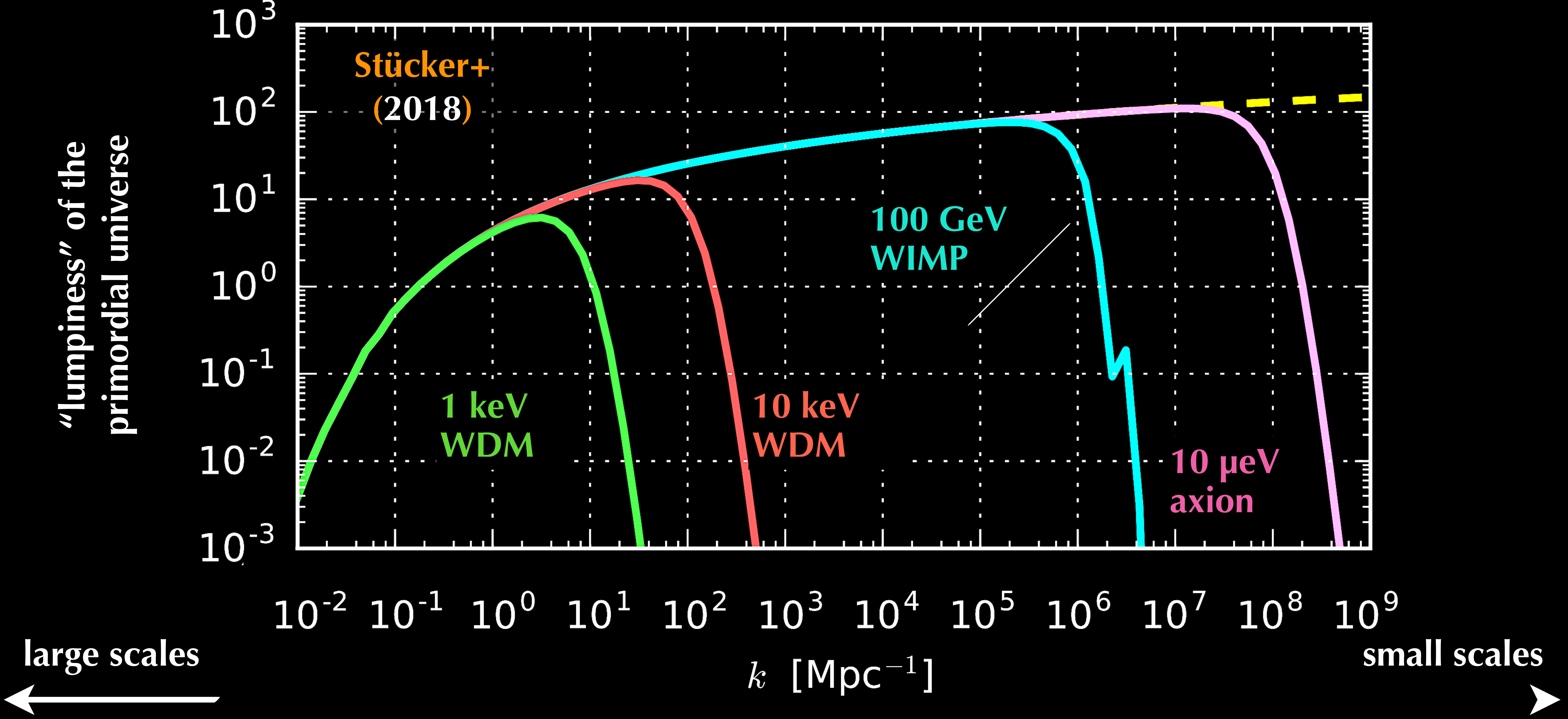
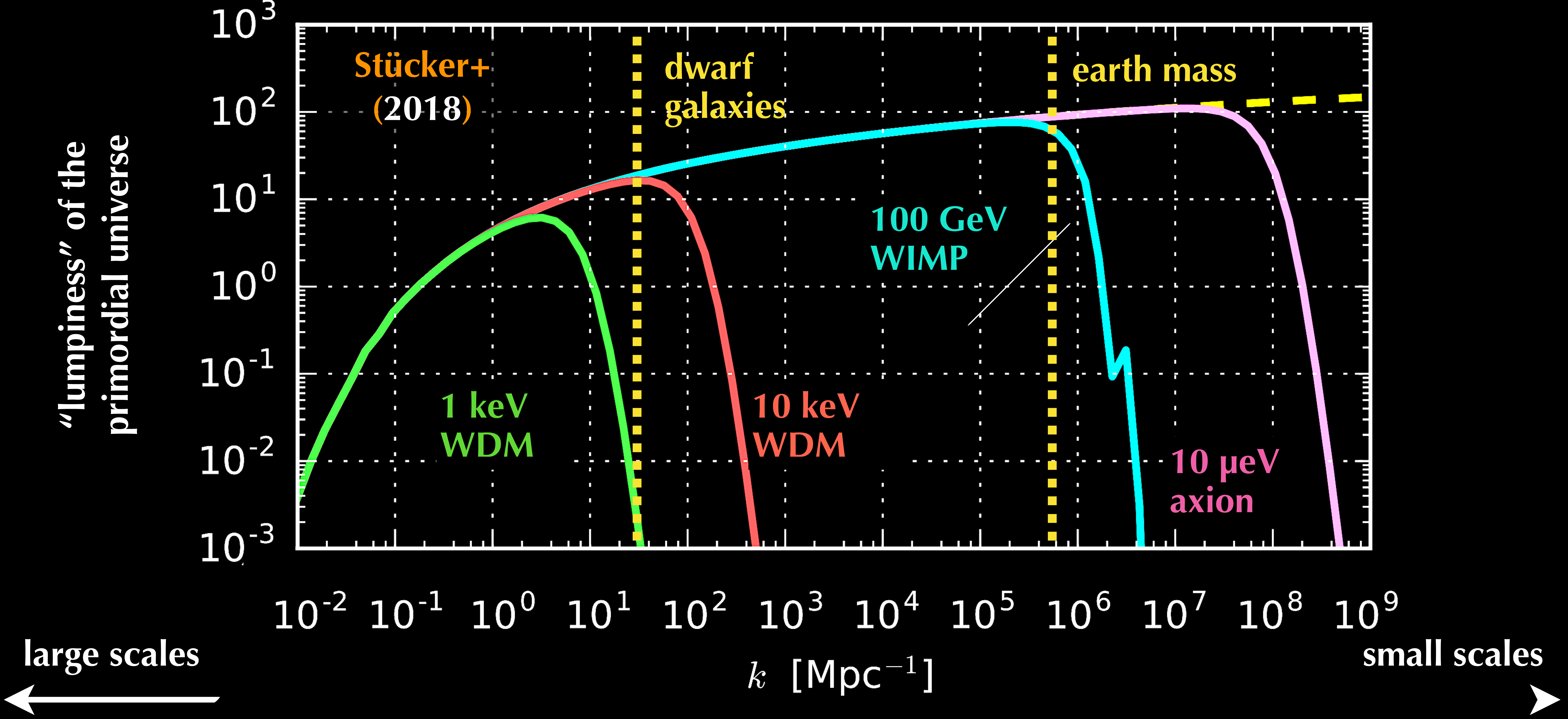
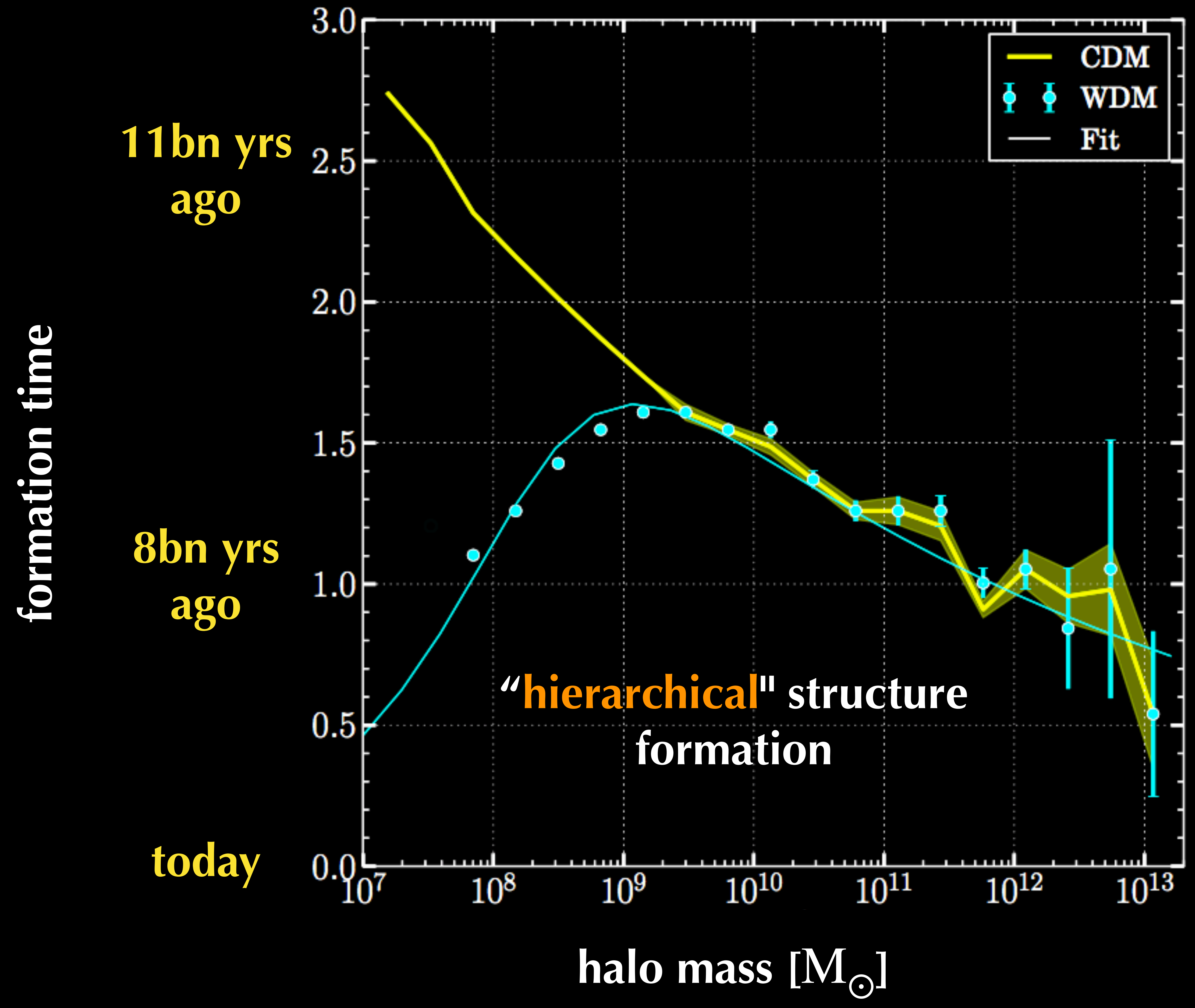
the power spectrum of structures

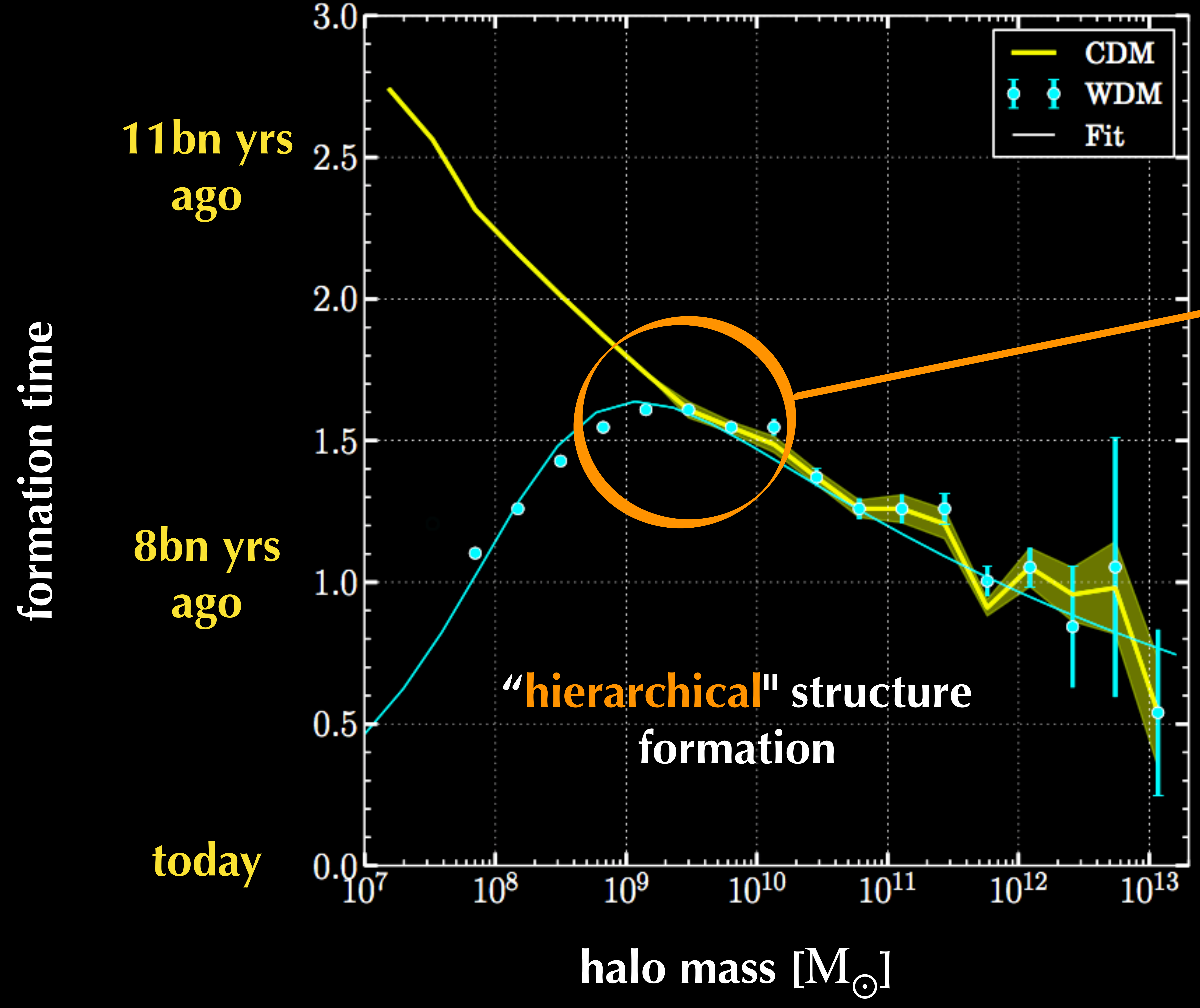


the **power spectrum** of structures



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





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

below a characteristic scale, halo formation is delayed relative to CDM

differences driven by this feature


movie: Mark Lovell
cold dark matter
warm dark matter


movie: Mark Lovell
cold dark matter
warm dark matter

movie: Mark Lovell

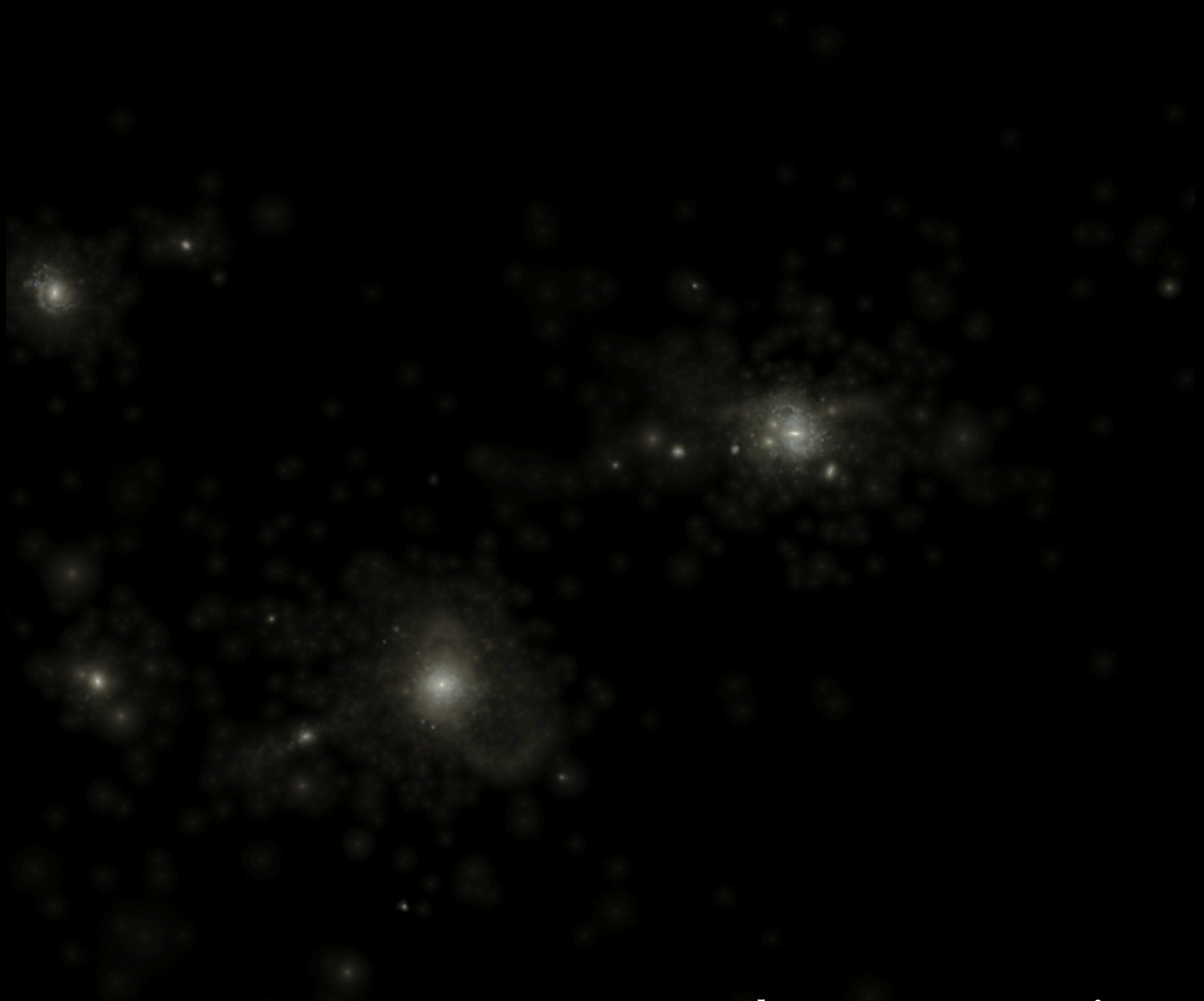
is it as simple as counting the number of satellite galaxies we observe orbiting the Milky Way?

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)]

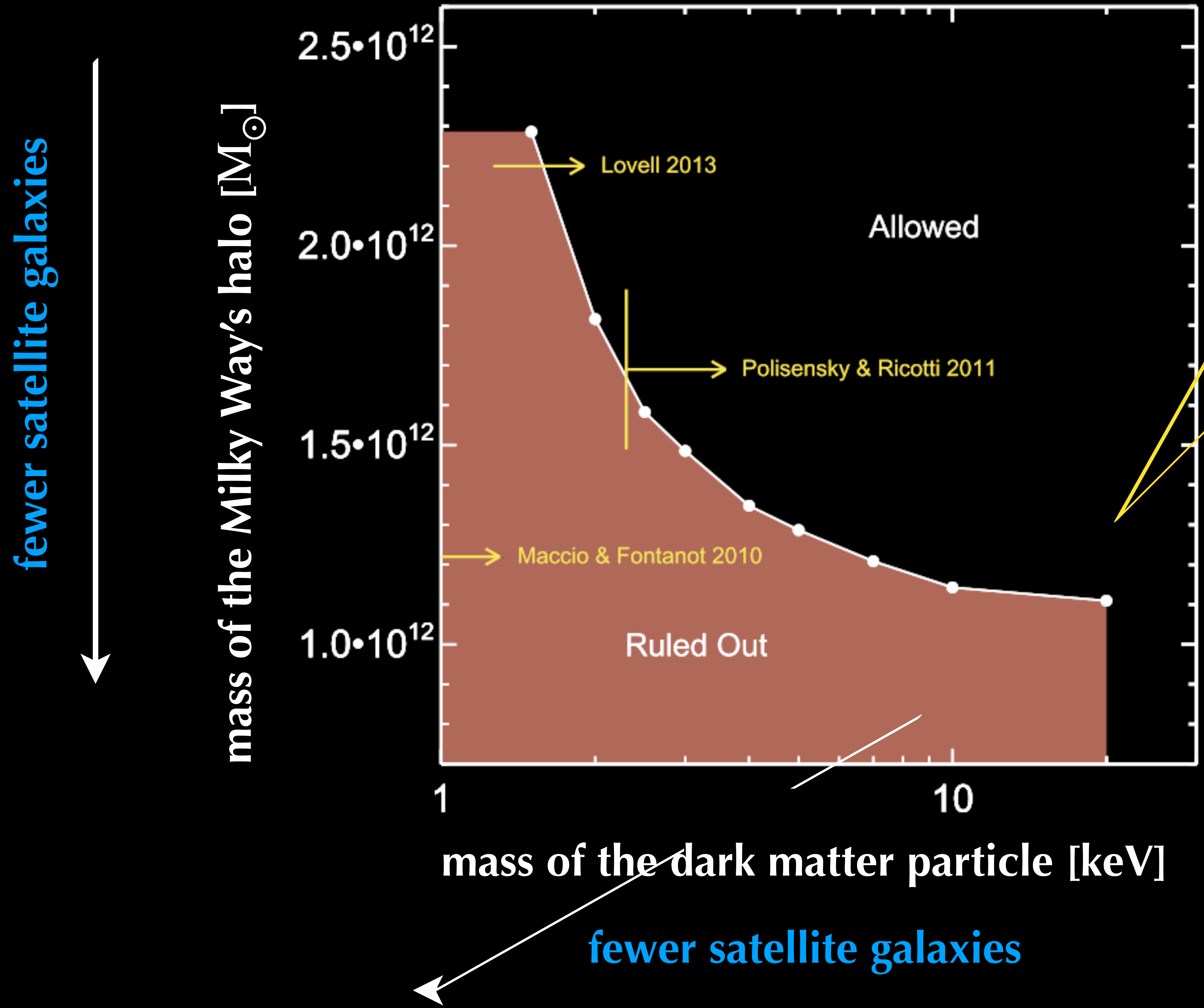
the APOSTLE Project
[Fattahi+ (2016); Sawala+ (2016)]



Galaxies

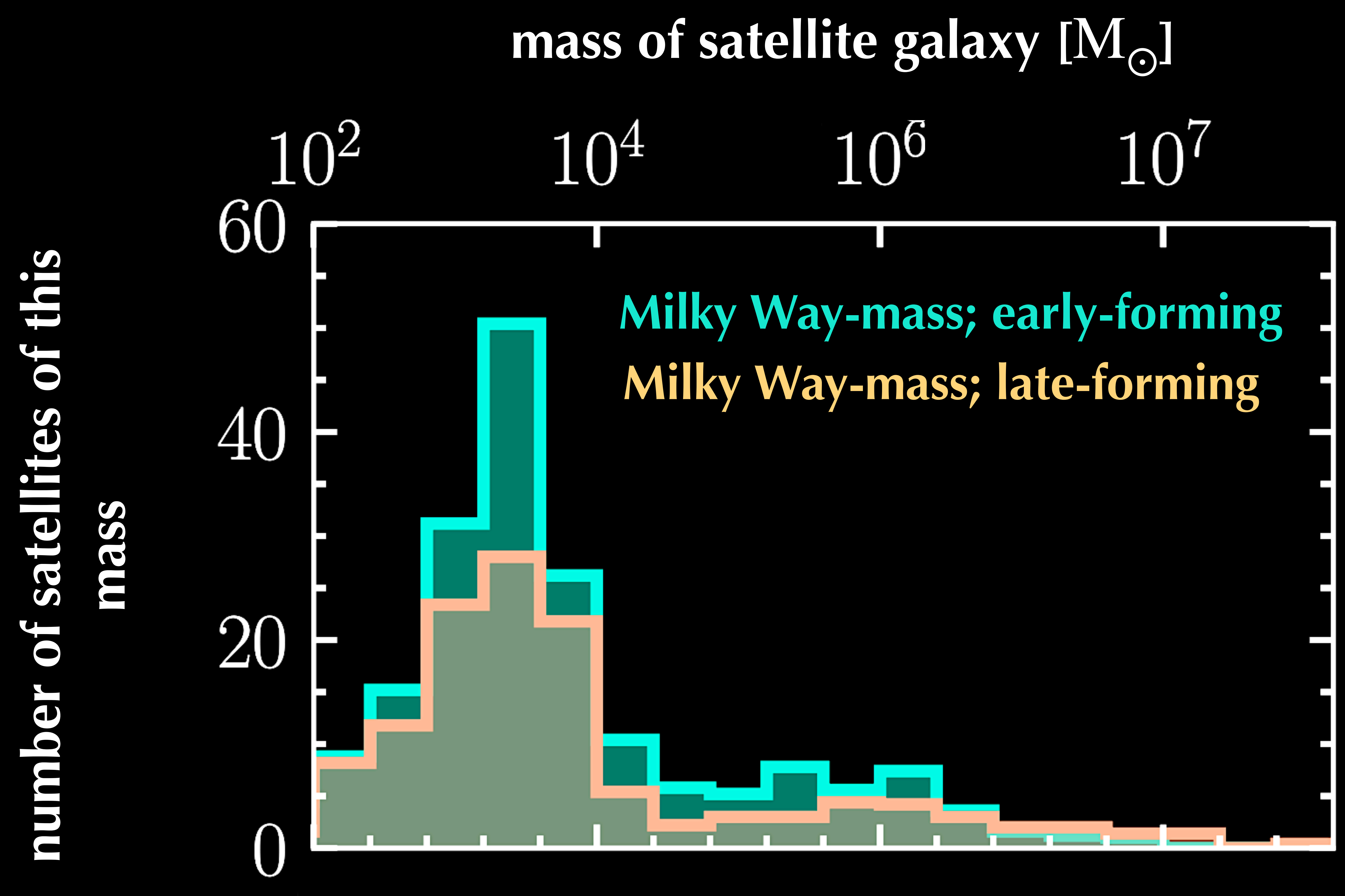
the APOSTLE Project
[Fattahi+ (2016); Sawala+ (2016)]

Kennedy+ (2014)
Bose, Frenk+ (2017b) [arXiv: 1604.07409]



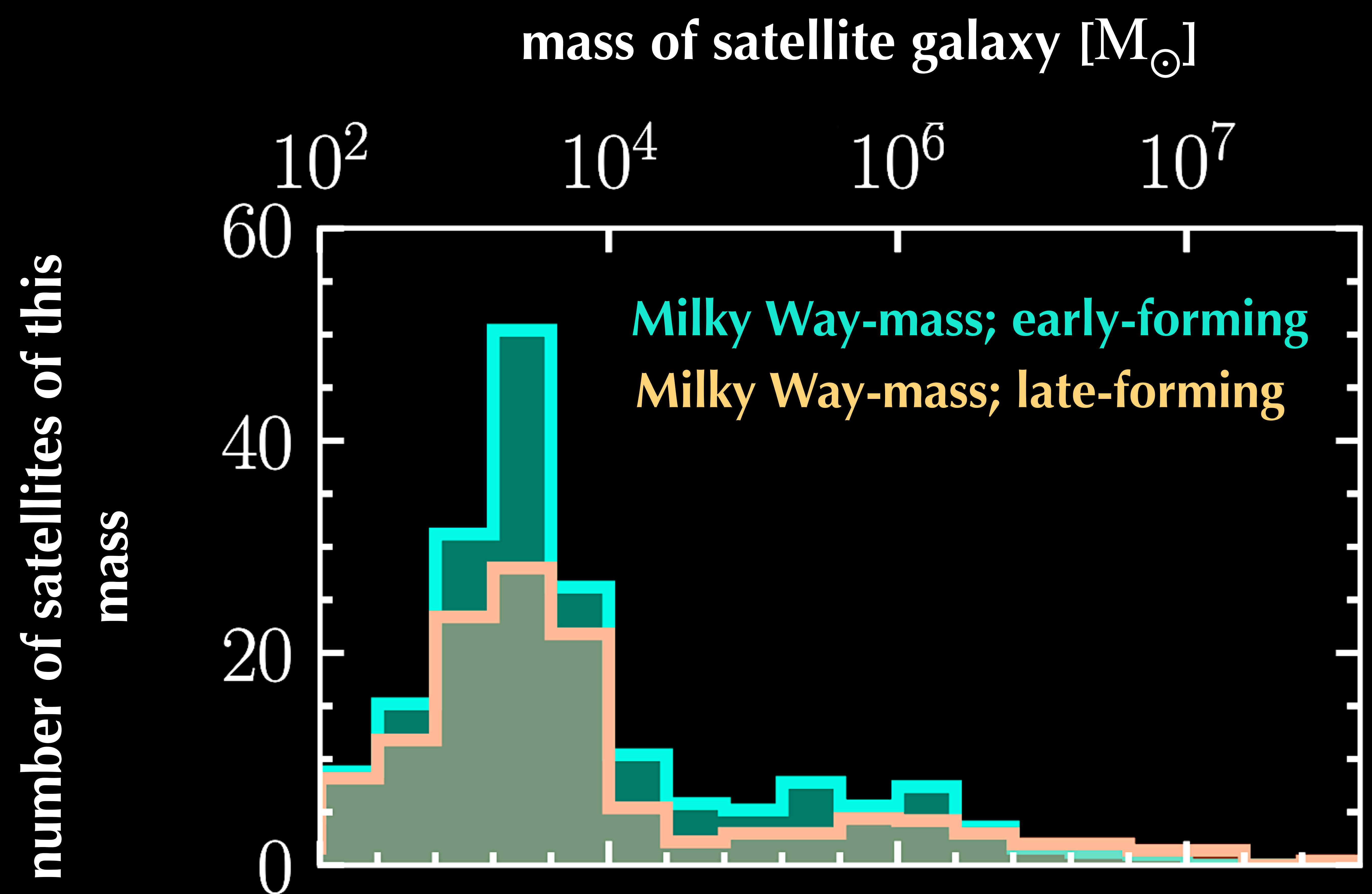
challenge: there is significant degeneracy between the particle nature of the dark matter, and our imperfect knowledge of how heavy the Milky Way is, how galaxy formation works etc.

the journey is as important as the destination



Bose, Deason+ (2020)
[arXiv: 1909.04039]

the journey is as important as the destination



Bose, Deason+ (2020)
[arXiv: 1909.04039]

- in addition to the mass of the DM particle & that of the Milky Way halo, the galaxy's assembly history also affects the final number of satellite galaxies predicted can we image dark matter structures directly?

can we **image** dark matter structures directly?

yes!

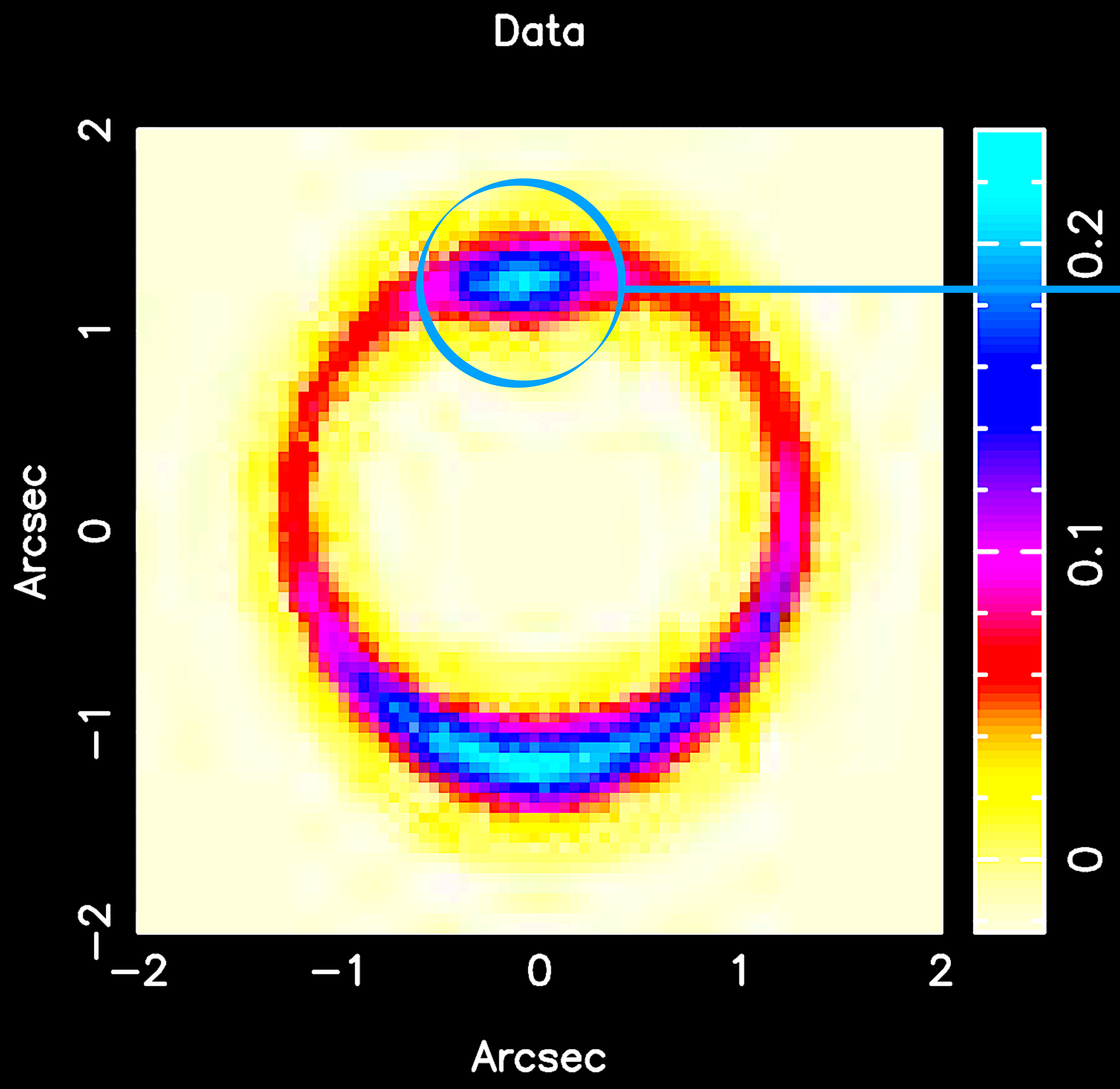
ESO

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??

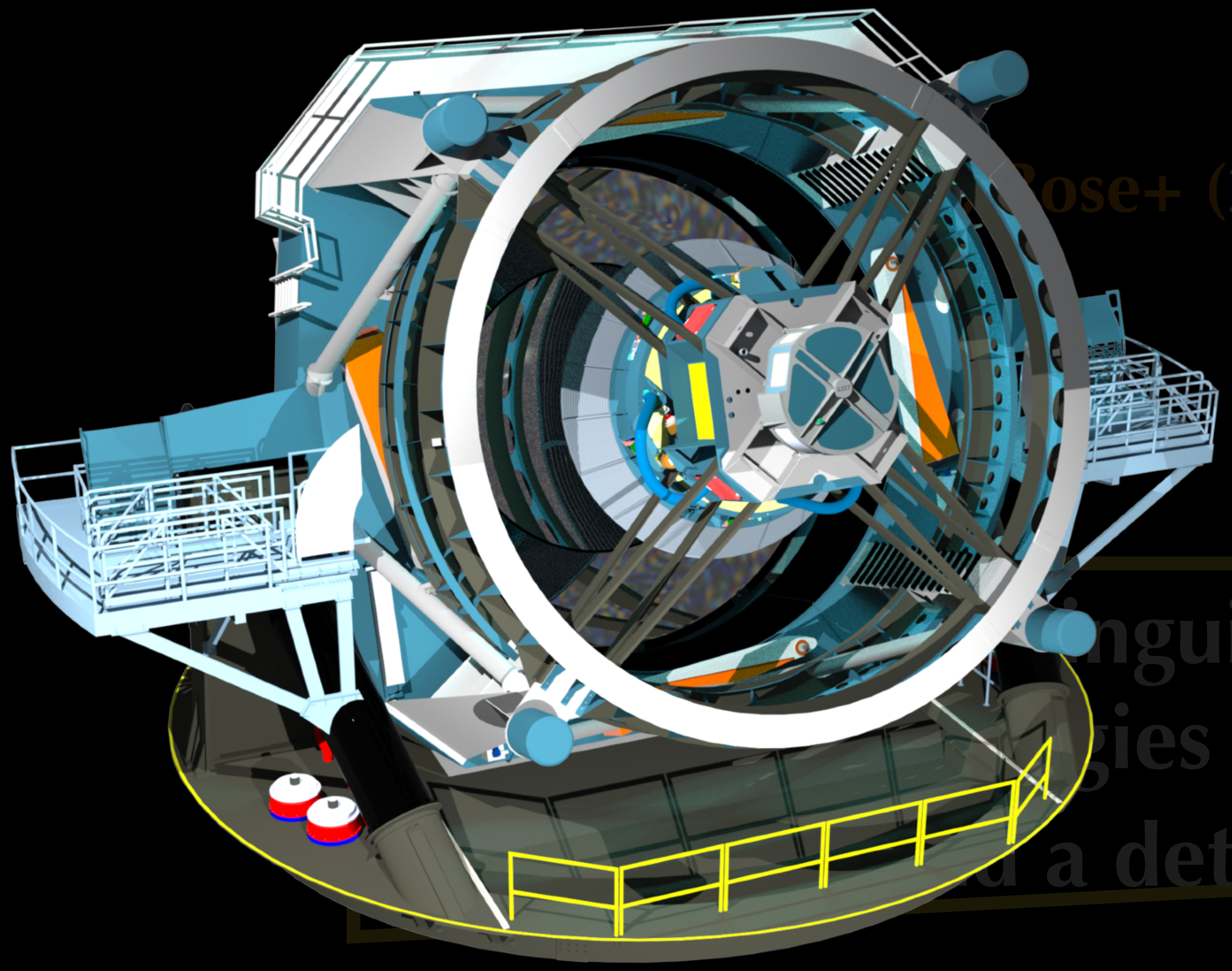
can use simulations of "different universes" to predict what these systems would look like in each

Li, Frenk, Bose+ (2016) [arXiv: 1512.06507]

can clearly distinguish between CDM & sterile neutrino cosmologies at high significance with 100 lens systems and a detection sensitivity of ~$10^7 \, M_\odot$

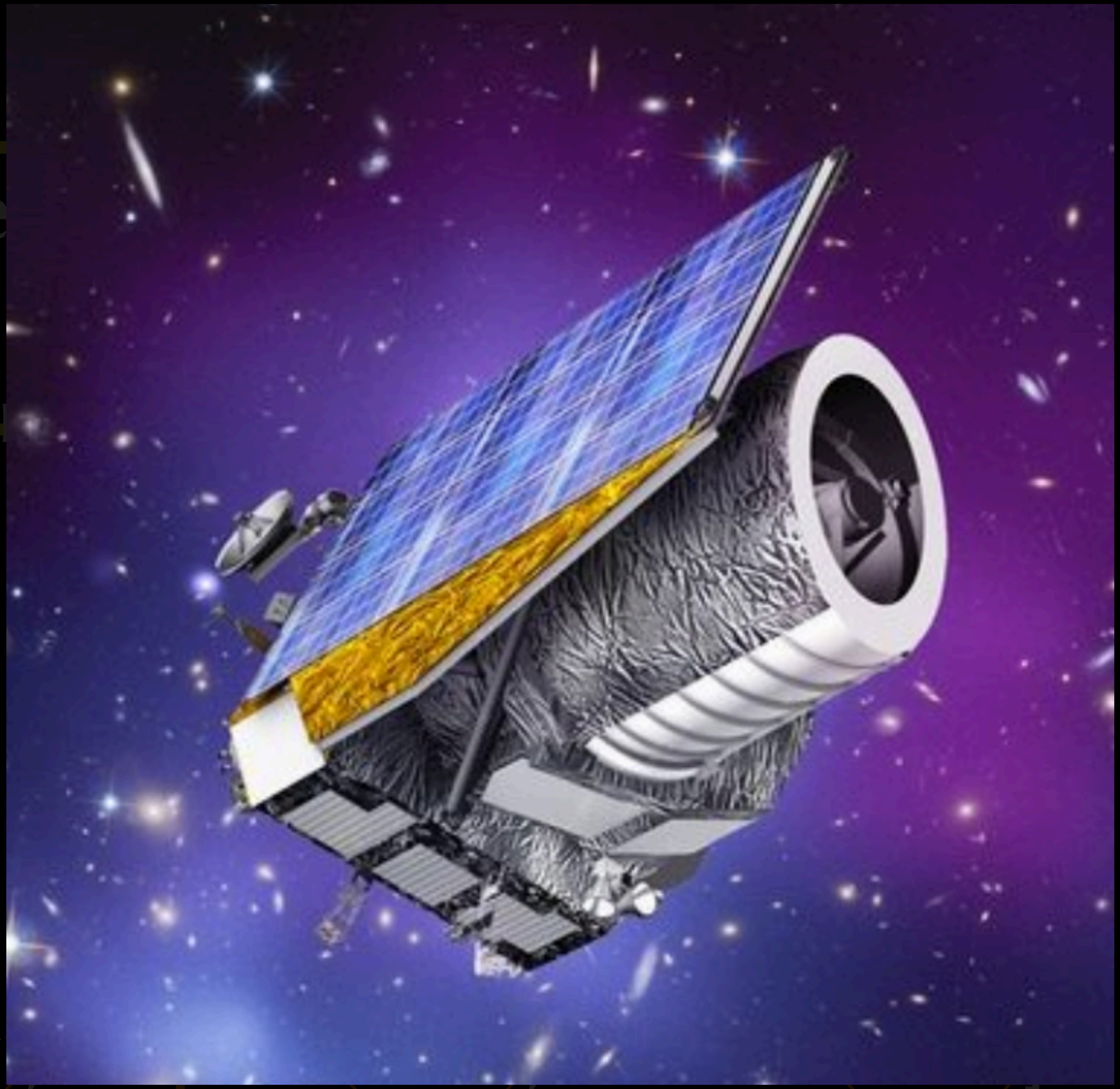
[see also Nierenberg+ (2017); Birrer+ (2017); Despali+ (2020); Gilman+ (2020)]

Rose+ (2016) [arXiv: 1512.06507]

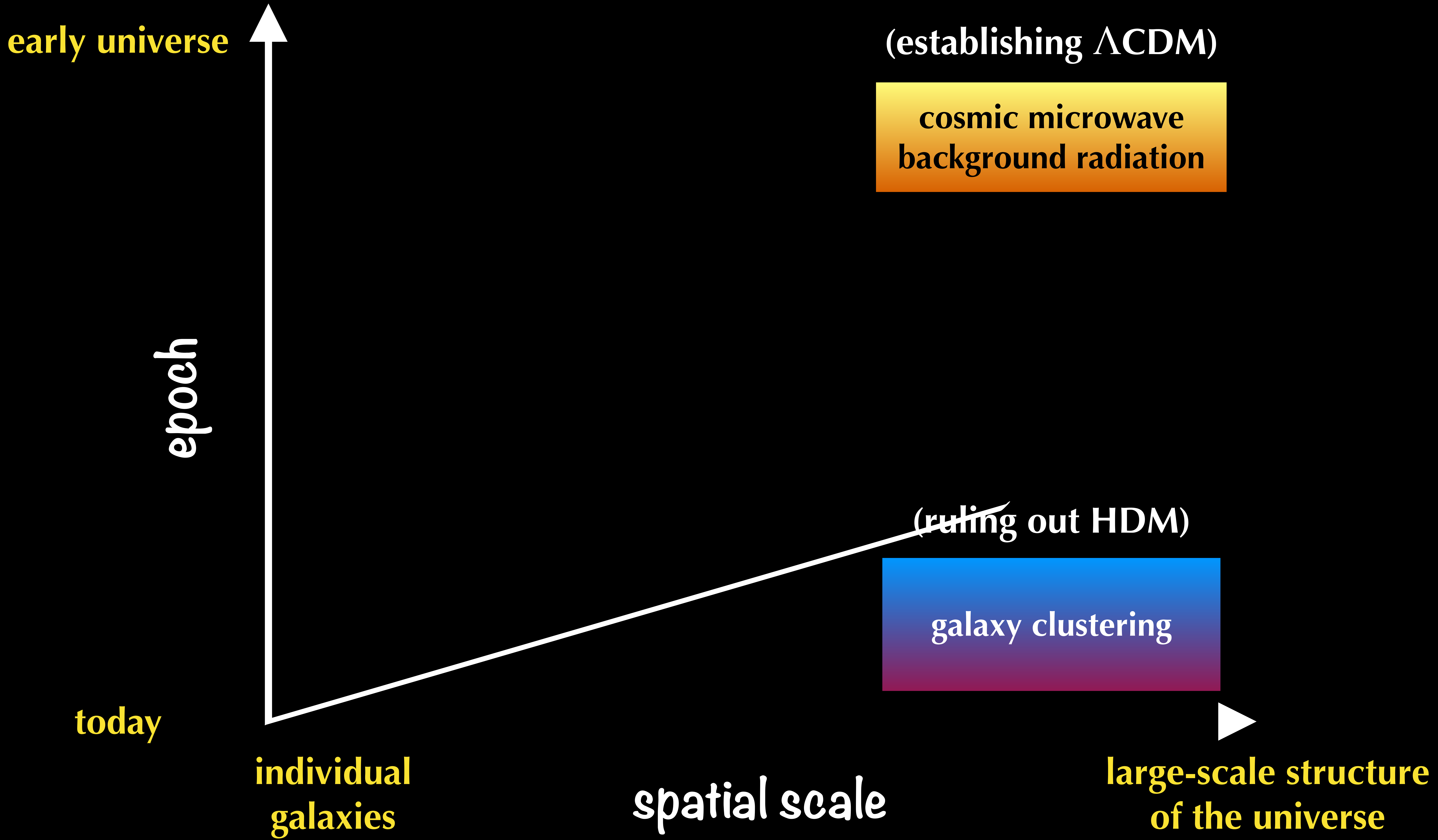


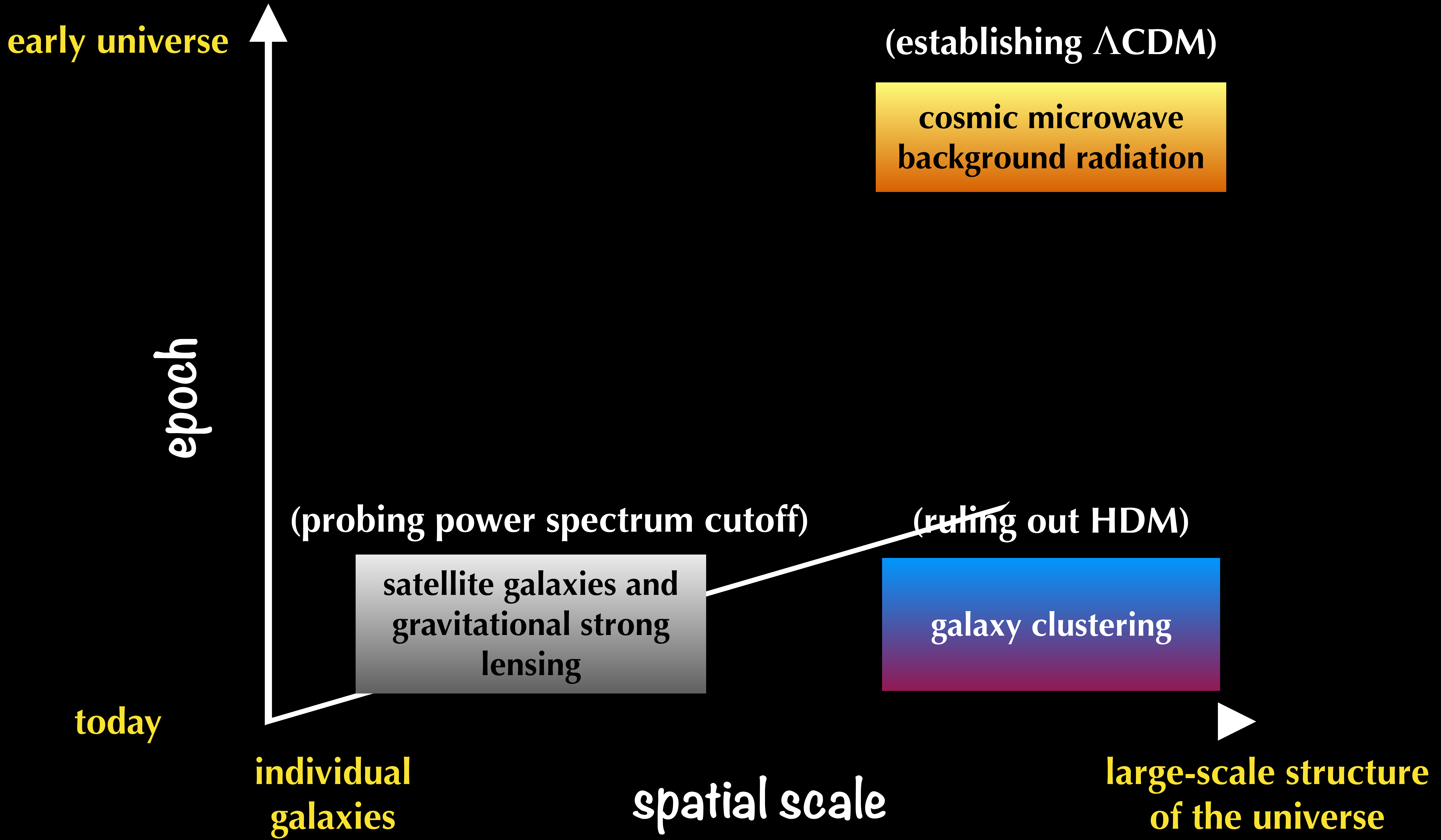
LSST/VRO [~ 2025]

Euclid [2023]



[see also Nierenberg+ (2017); Birrer+ (2017


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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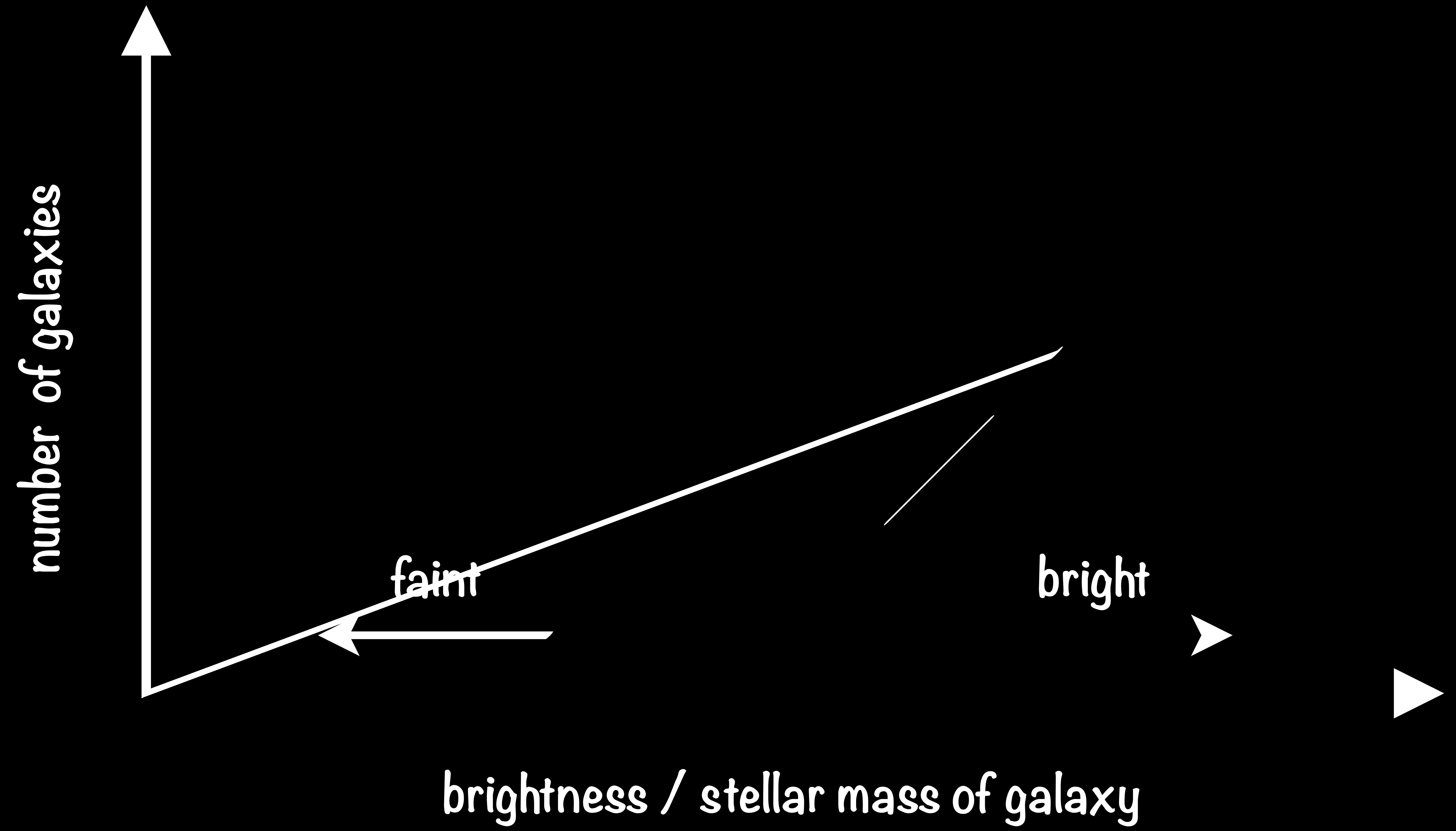
furthermore: we can use the early universe to our advantage

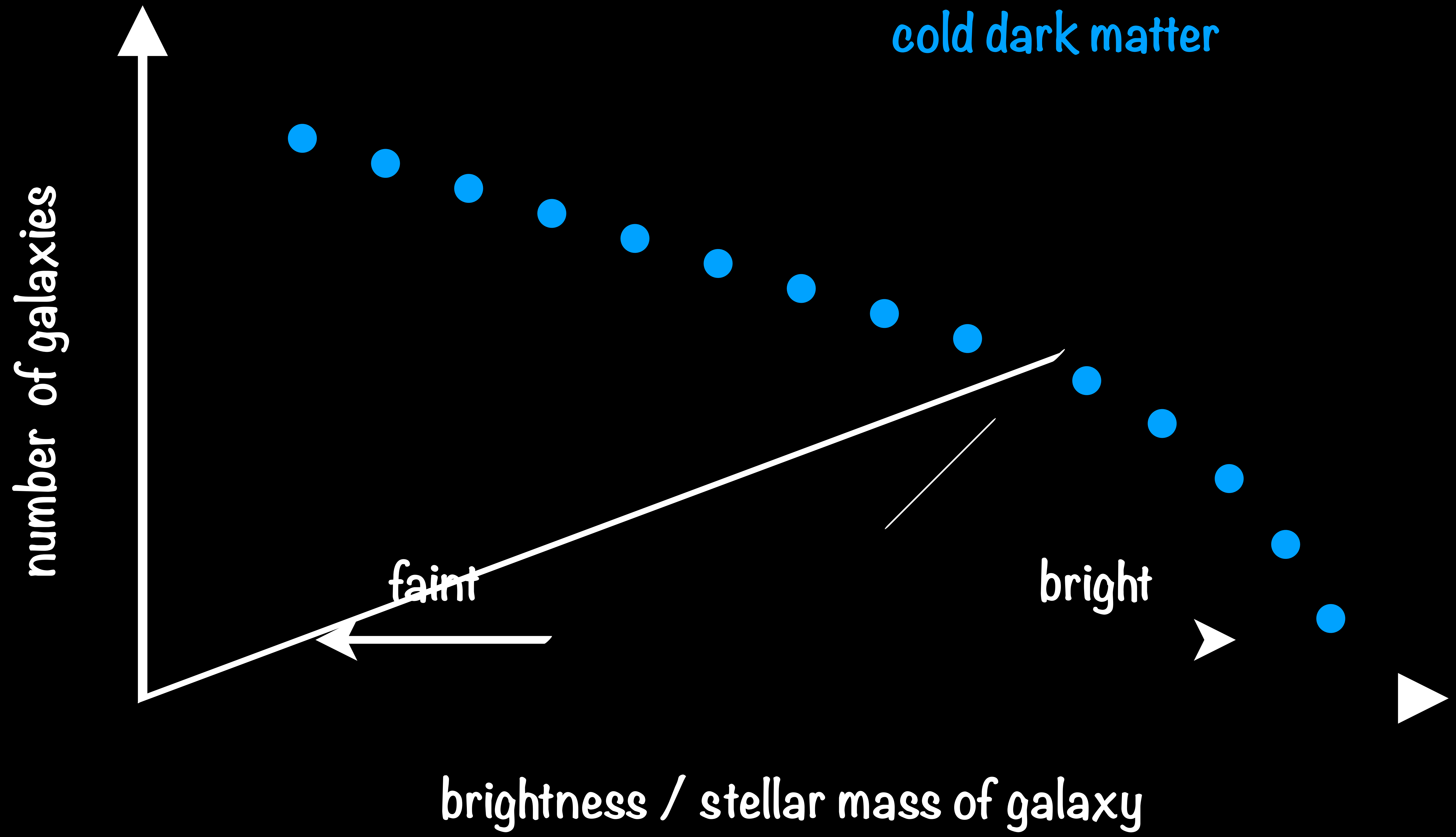
James Webb Space Telescope
[2021]

[Credit: NASA]

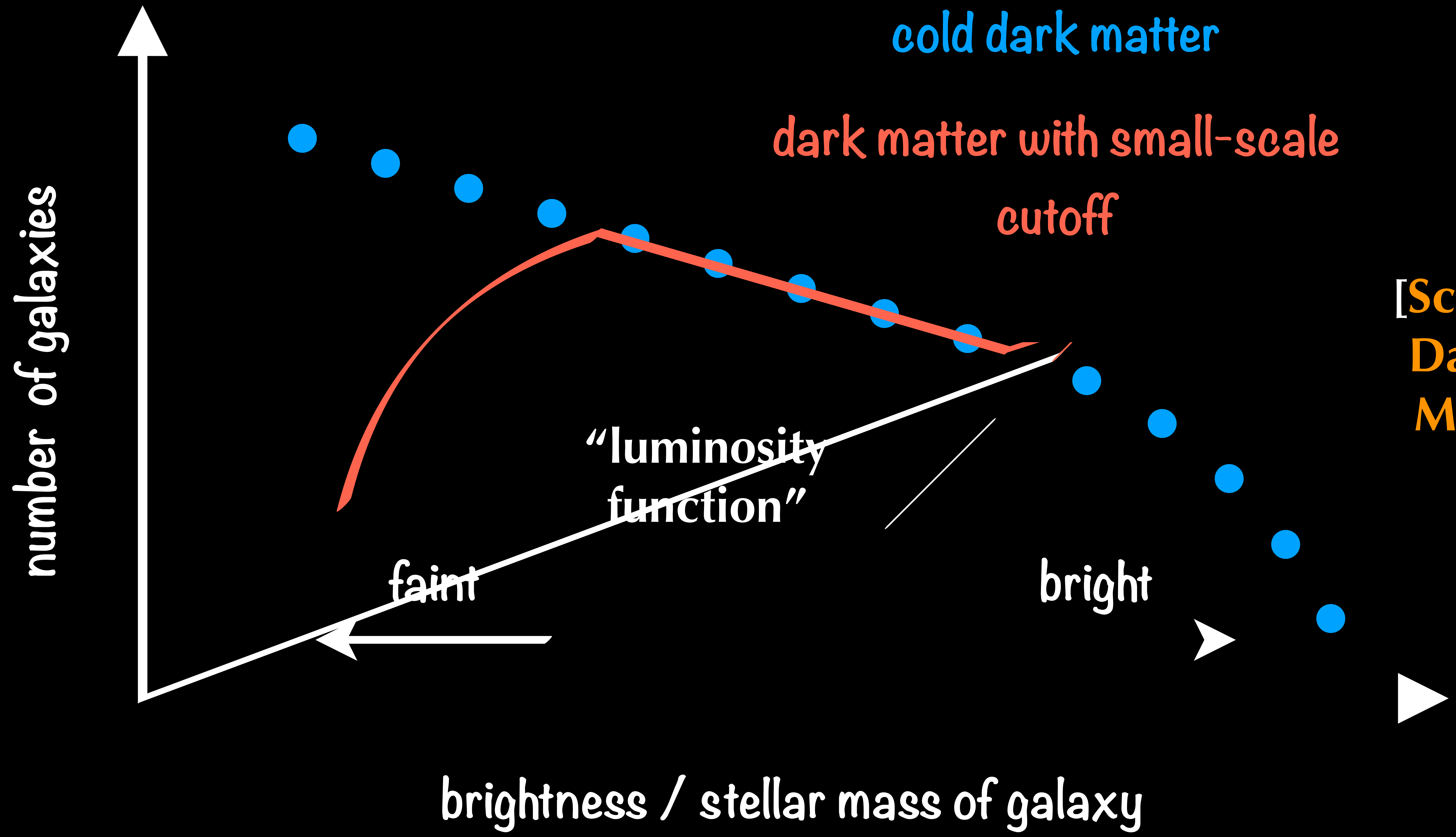
galactic **abundance** at early cosmic times



galactic **abundance** at early cosmic times

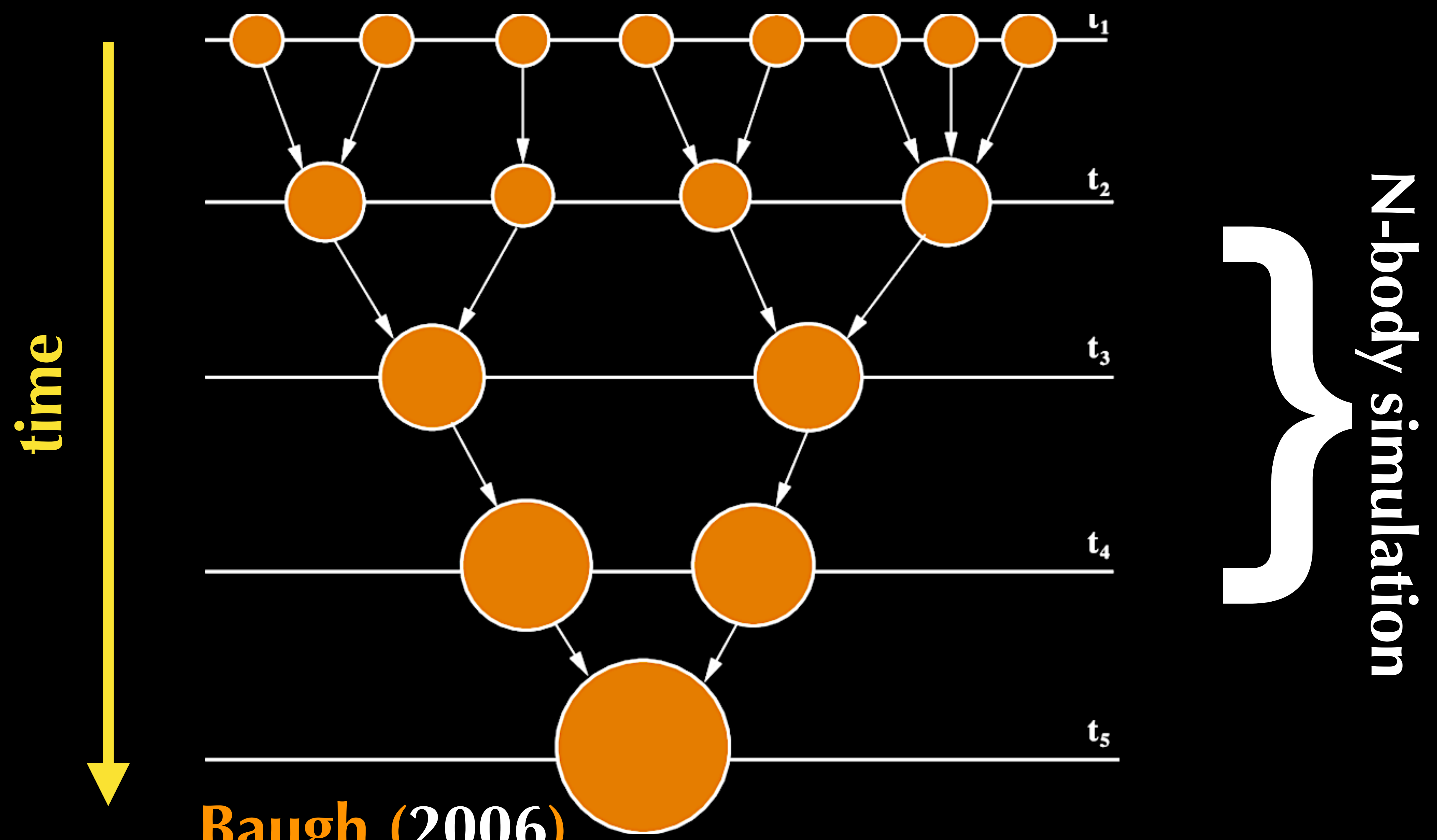


galactic abundance at early cosmic times



[Schulz+ (2014);
Dayal+ (2015);
Maio+ (2015)]

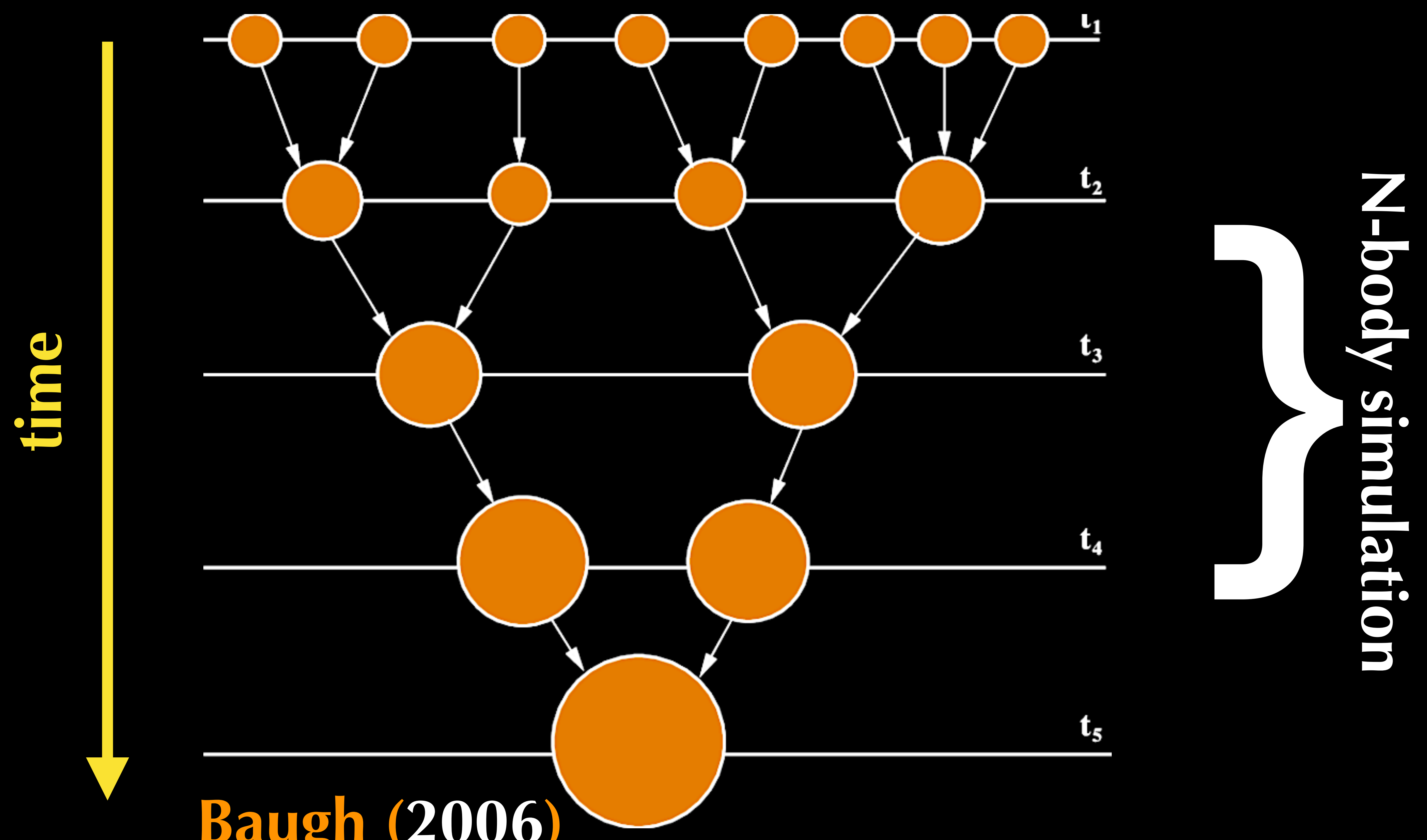
halo merger histories



Baugh (2006)

$$\mathrm{SFR}\left(M_{\mathrm{halo}}, z\right) = \varepsilon\left(M_{\mathrm{halo}}\right) \times f_B \times \frac{\mathrm{d}M_{\mathrm{halo}}}{\mathrm{d}t}$$

halo merger histories



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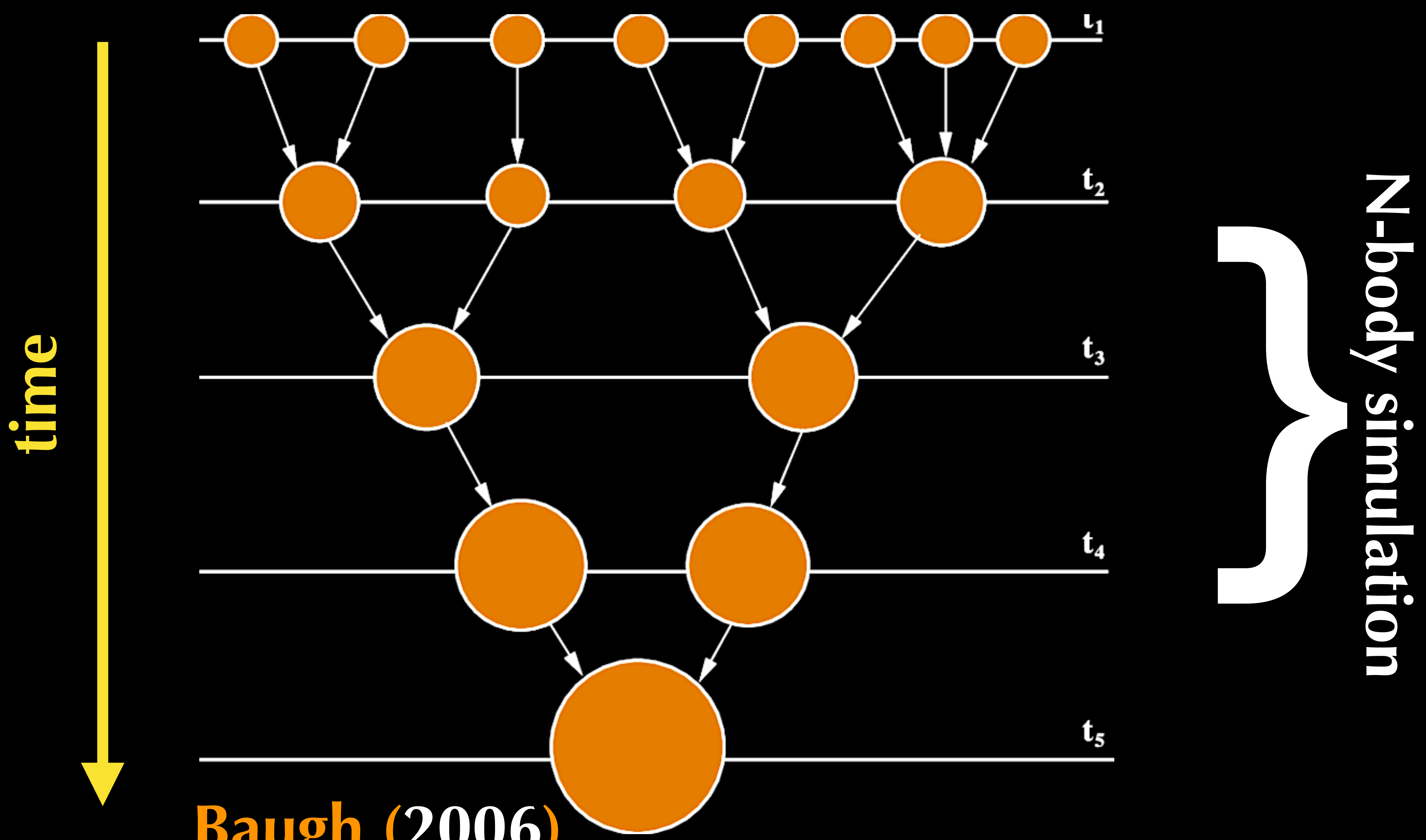
halo growth rate

halo merger histories

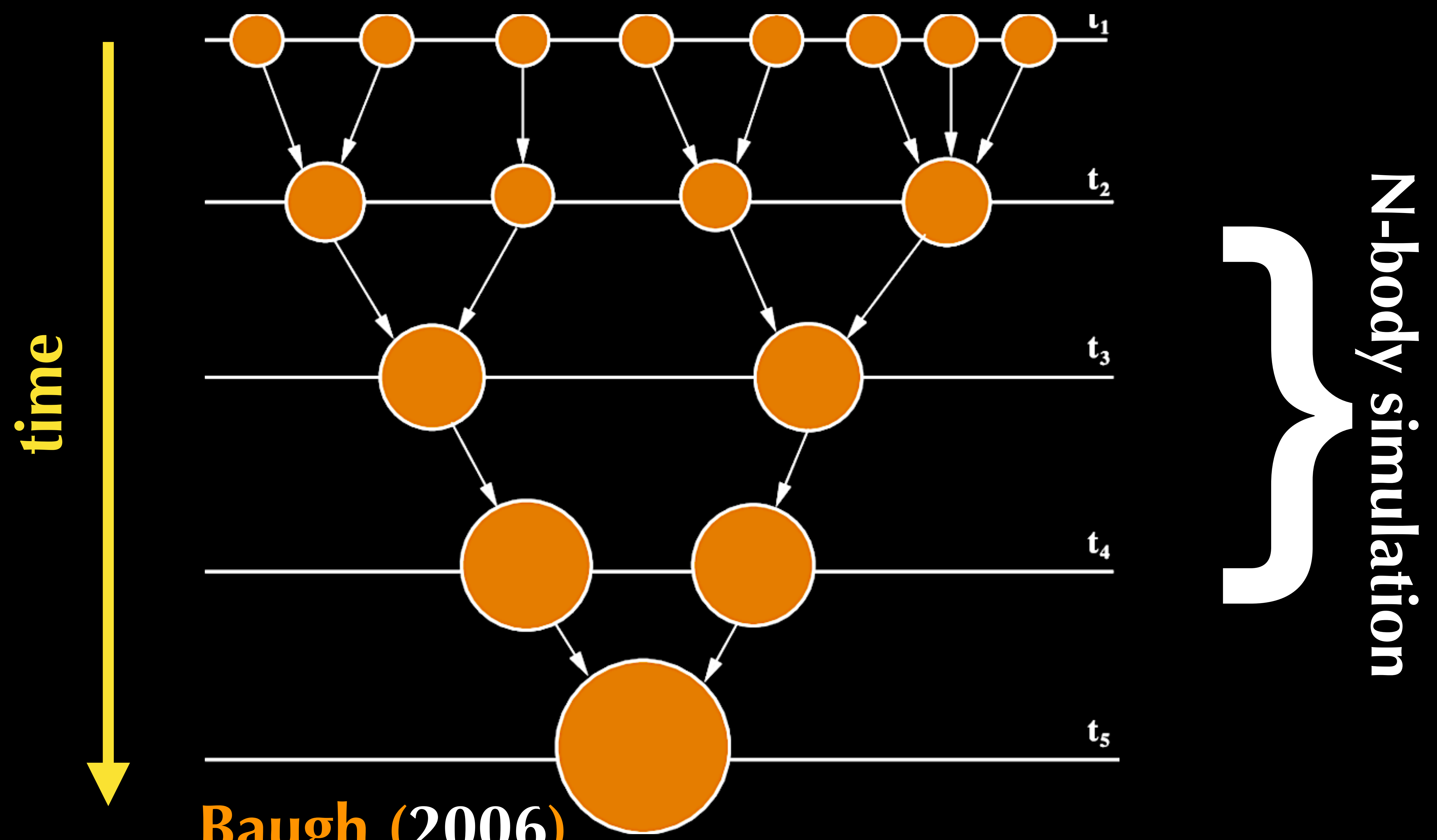


Baugh (2006)

$$\mathrm{SFR}\left(M_{\mathrm{halo}}, z\right) = \varepsilon\left(M_{\mathrm{halo}}\right) \times f_B \times \frac{\mathrm{d}M_{\mathrm{halo}}}{\mathrm{d}t}$$

baryon fraction

halo merger histories

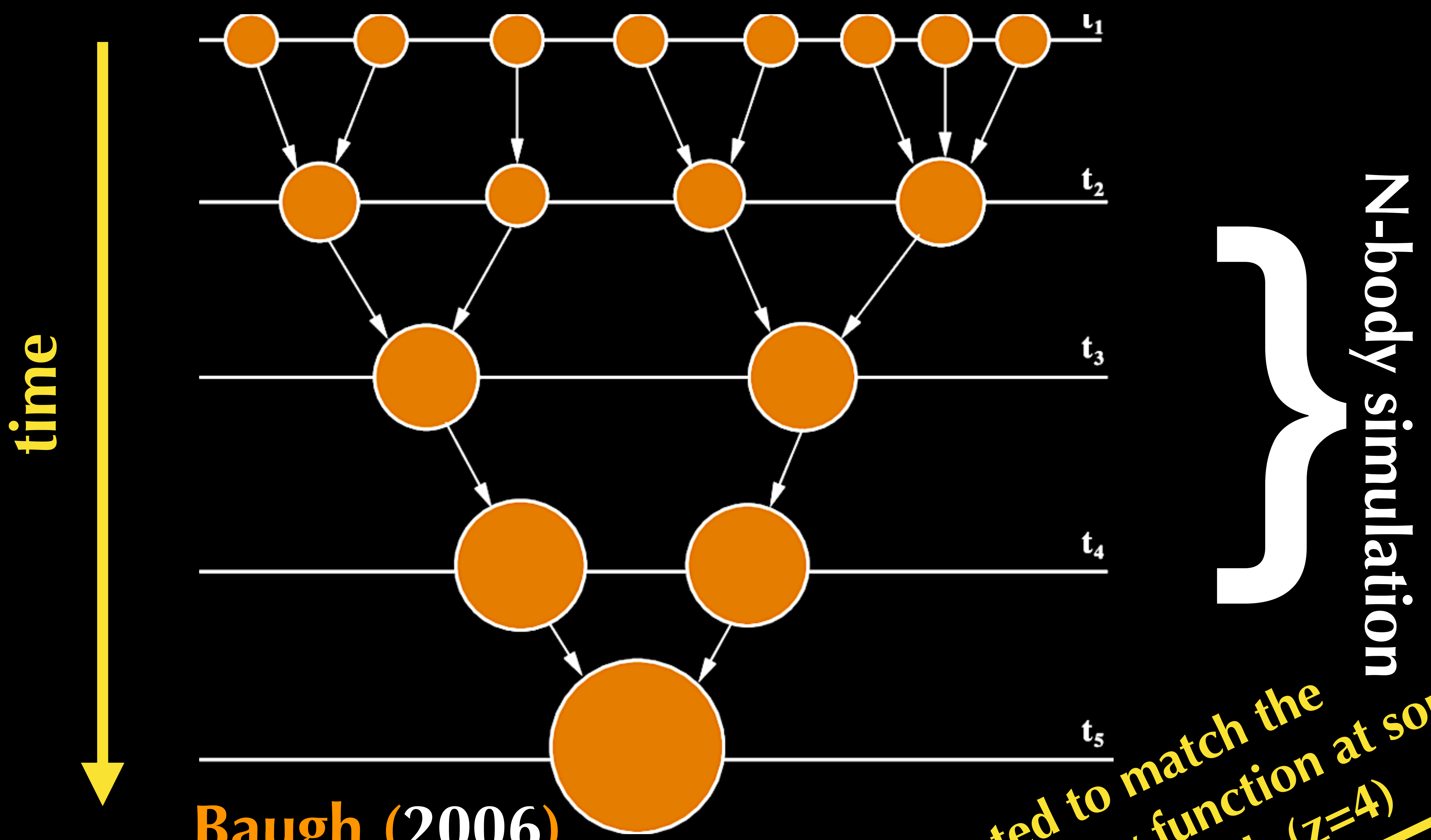


Baugh (2006)

$$\mathrm{SFR}\left(M_{\rm halo}, z\right) = \varepsilon\left(M_{\rm halo}\right) \times f_B \times \frac{\mathrm{d}M_{\rm halo}}{\mathrm{d}t}$$

efficiency of star formation

halo merger histories

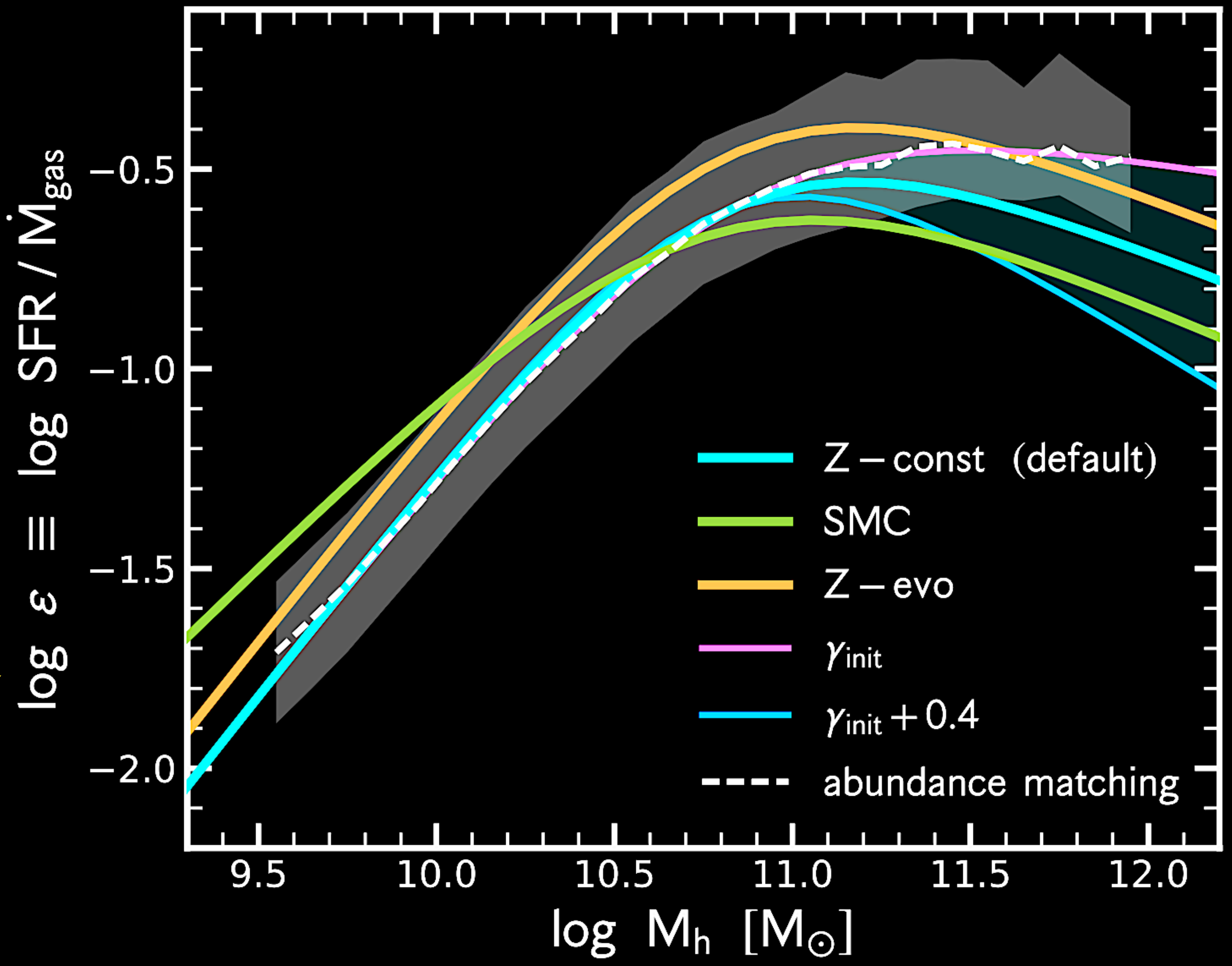


Baugh (2006)

calibrated to match the observed luminosity function at some intermediate epoch (z=4)

$$\mathrm{SFR}\left(M_{\rm halo}, z\right) = \varepsilon\left(M_{\rm halo}\right) \times f_B \times \frac{\mathrm{d}M_{\rm halo}}{\mathrm{d}t}$$

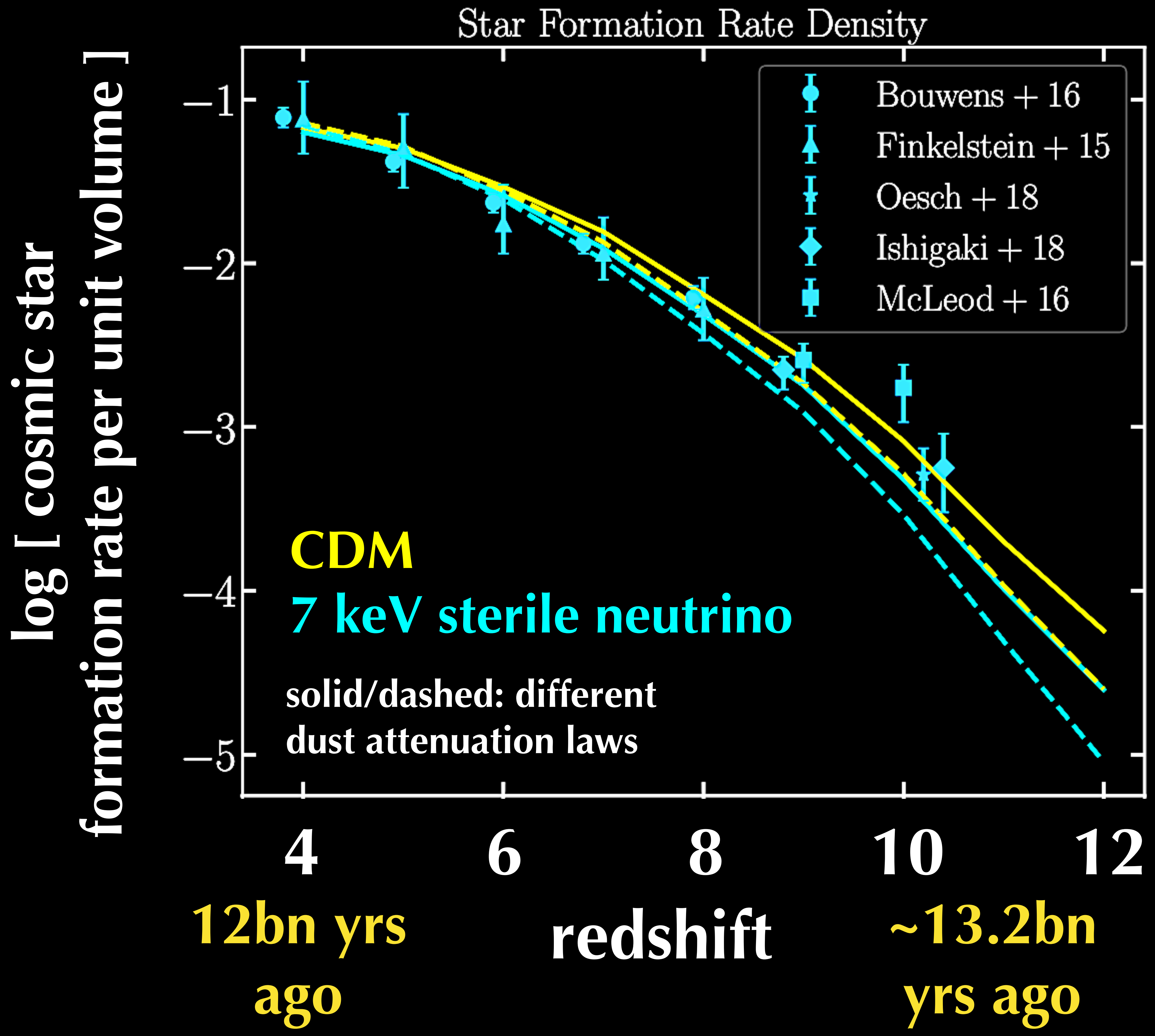
Tacchella, Bose, Conroy+ (2018)
[arXiv: 1806.03299]



[Conroy & Wechsler (2009); Mason+ (2015); Moster+ (2018); Behroozi+ (2019)]

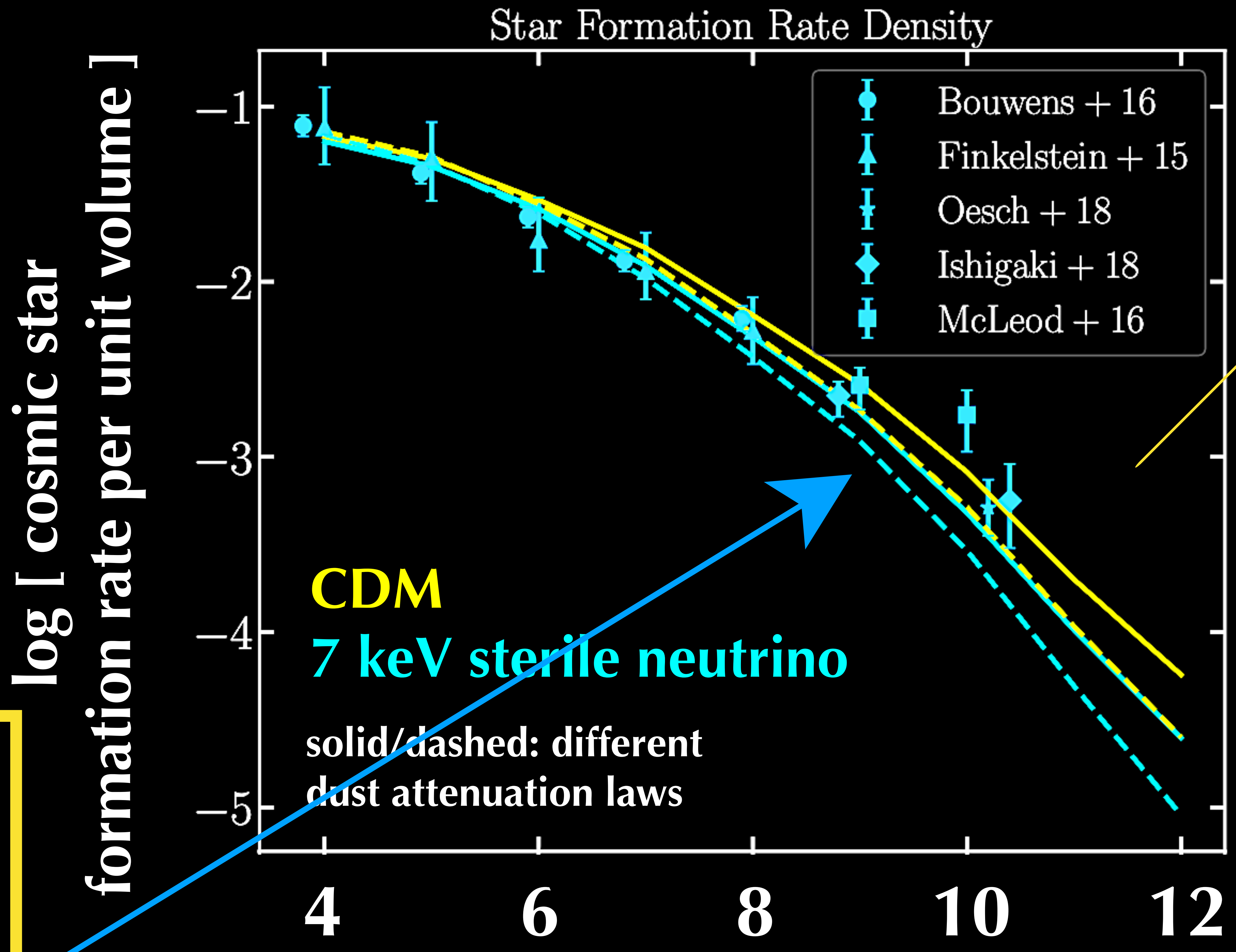
astrophysical degeneracies are significant even at high redshift

Diana Khimey



astrophysical degeneracies are significant even at high redshift

Diana Khimey



12bn yrs ago

redshift

~13.2bn yrs ago

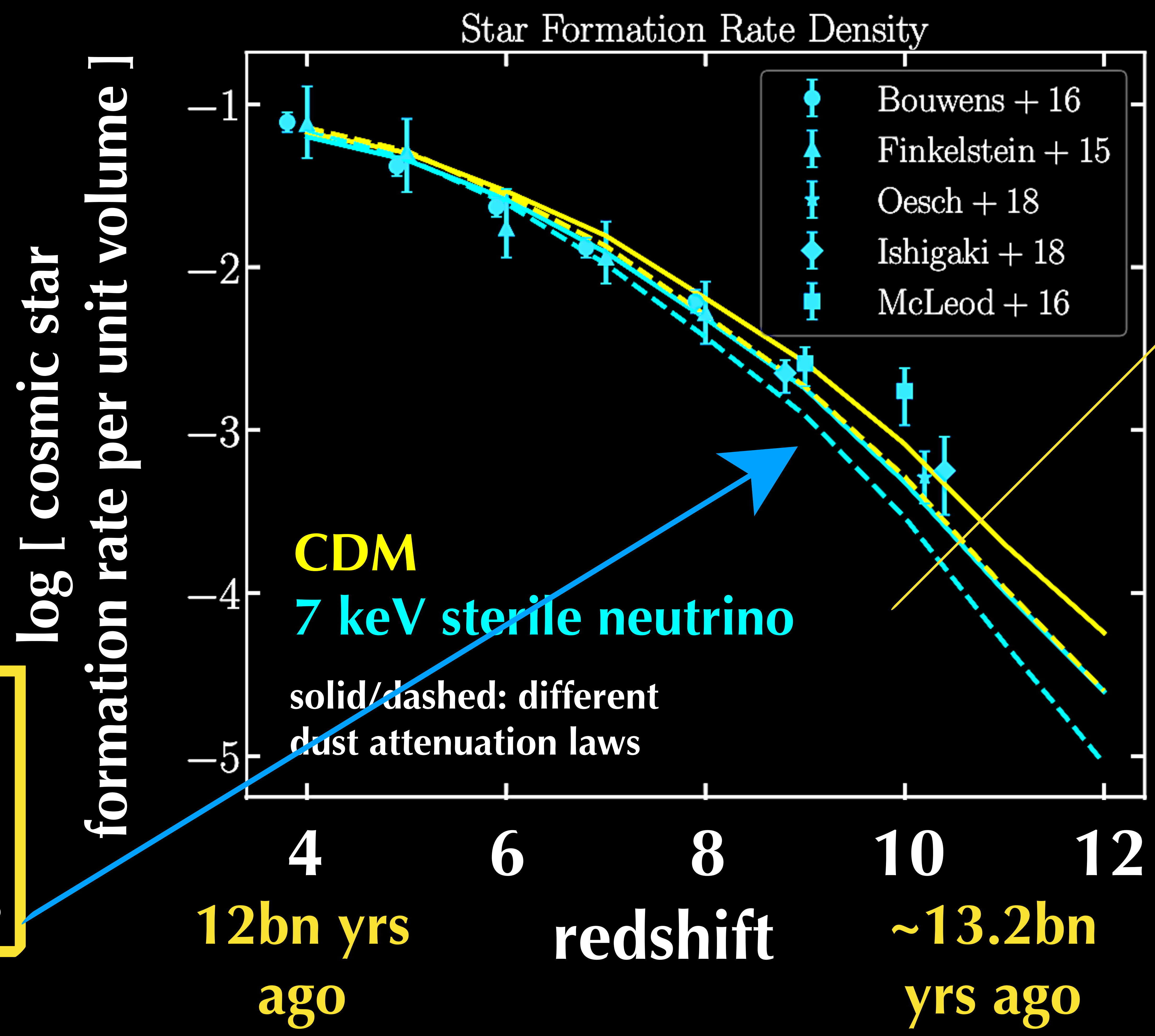
Khimey, Bose & Tacchella [arXiv: 2010.10520]

it's easy to make two different dark matter models look like one another even by with relatively small changes in model parameters

different dust attenuation laws result in different star formation efficiencies

astrophysical degeneracies are significant even at high redshift

Ali Kurmus



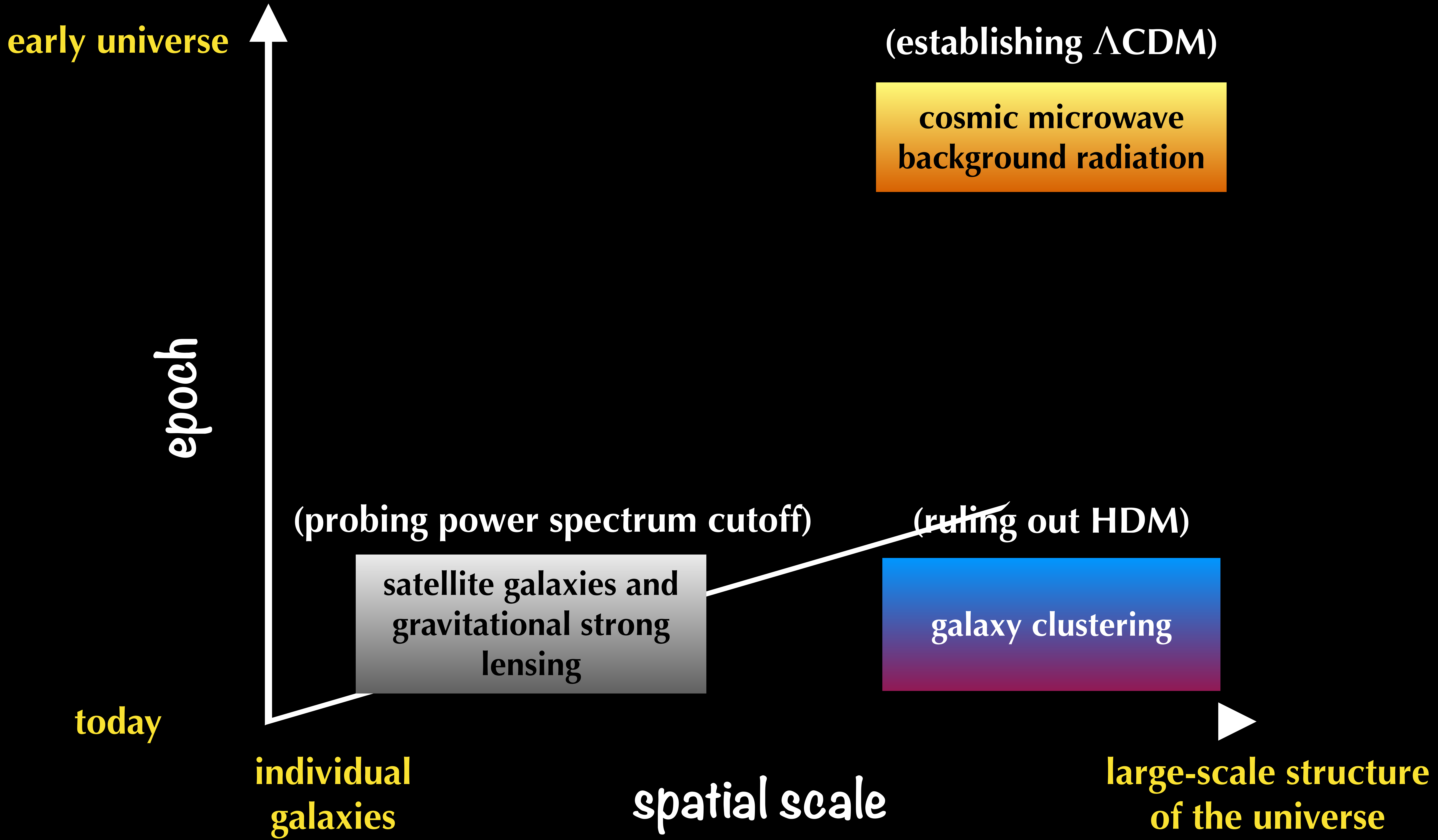
different dust attenuation laws result in different star formation efficiencies

Kurmus, Bose, Vogelsberger+
[arXiv: 2203.04985]

and, even in cases where differences relative to CDM persist, it's extremely challenging to determine what kind of particle physics is responsible (free-streaming / DM interactions / scattering etc.)

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


early universe
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more exotic small-scale behaviour

[interacting dark matter]

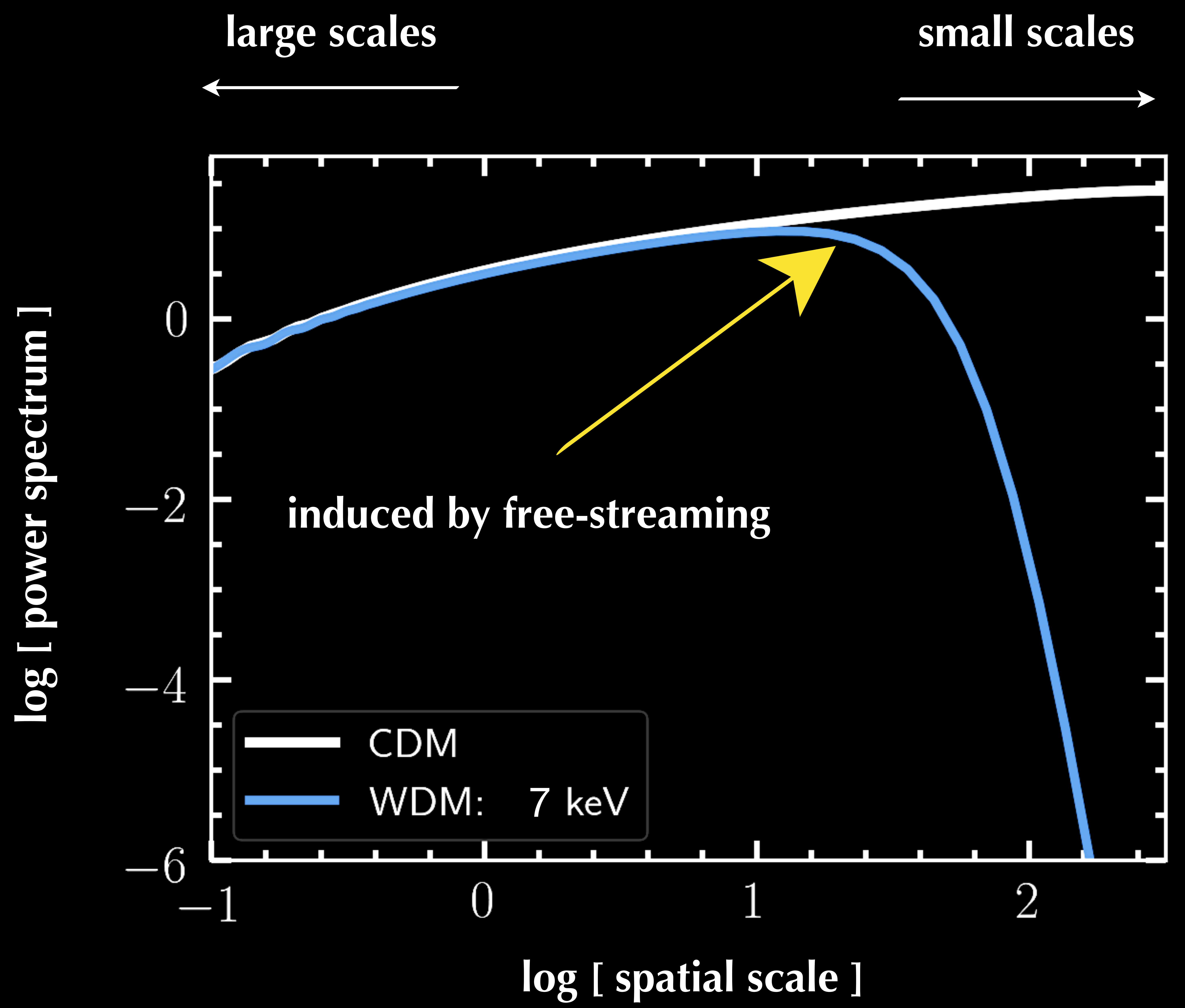
[Carlson+ (1992); Boehm+ (2002); Ackerman+ (2009); Cyr-Racine & Sigurdson (2013); Bringmann+ (2016)]

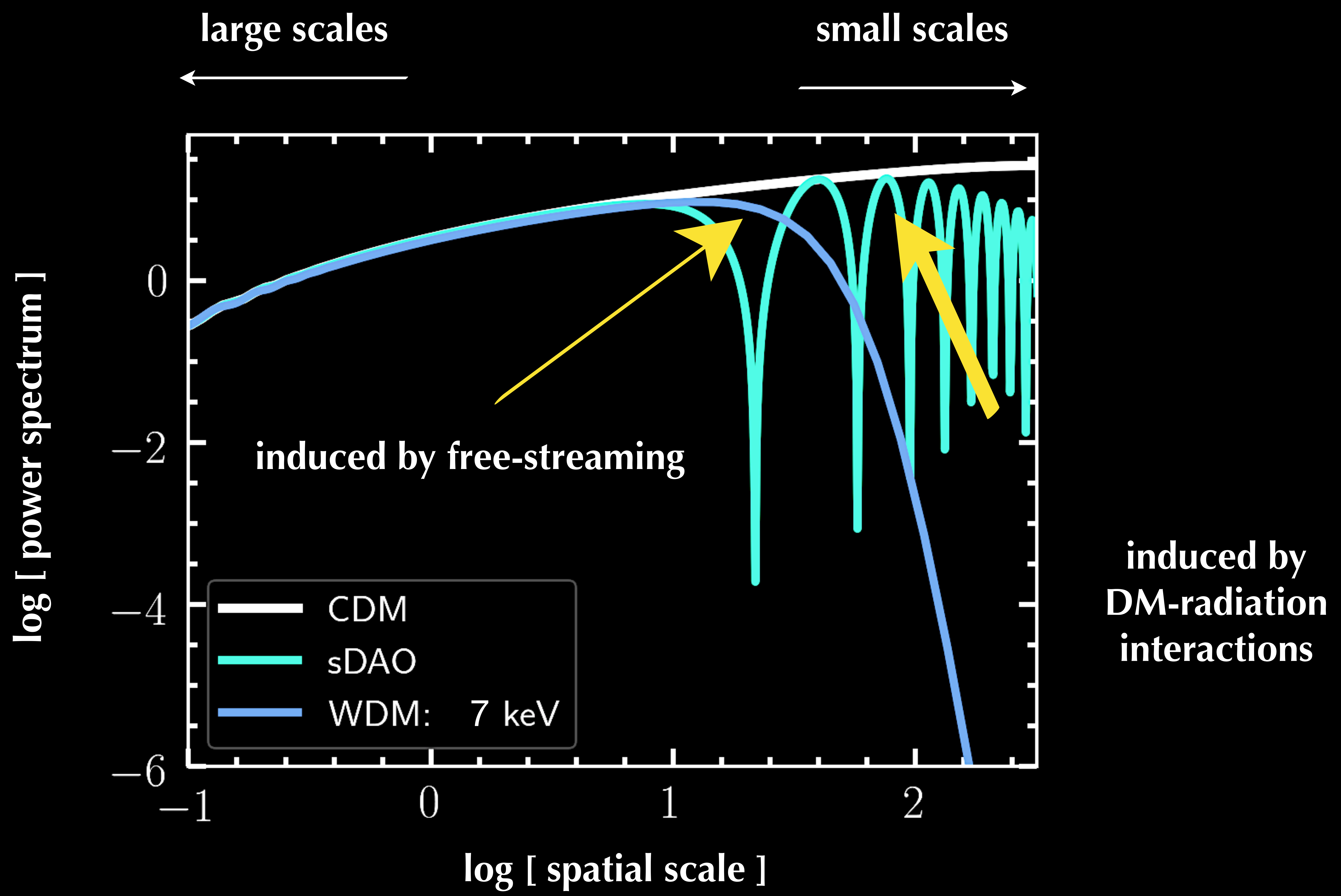
more exotic small-scale behaviour

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


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

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 ✓

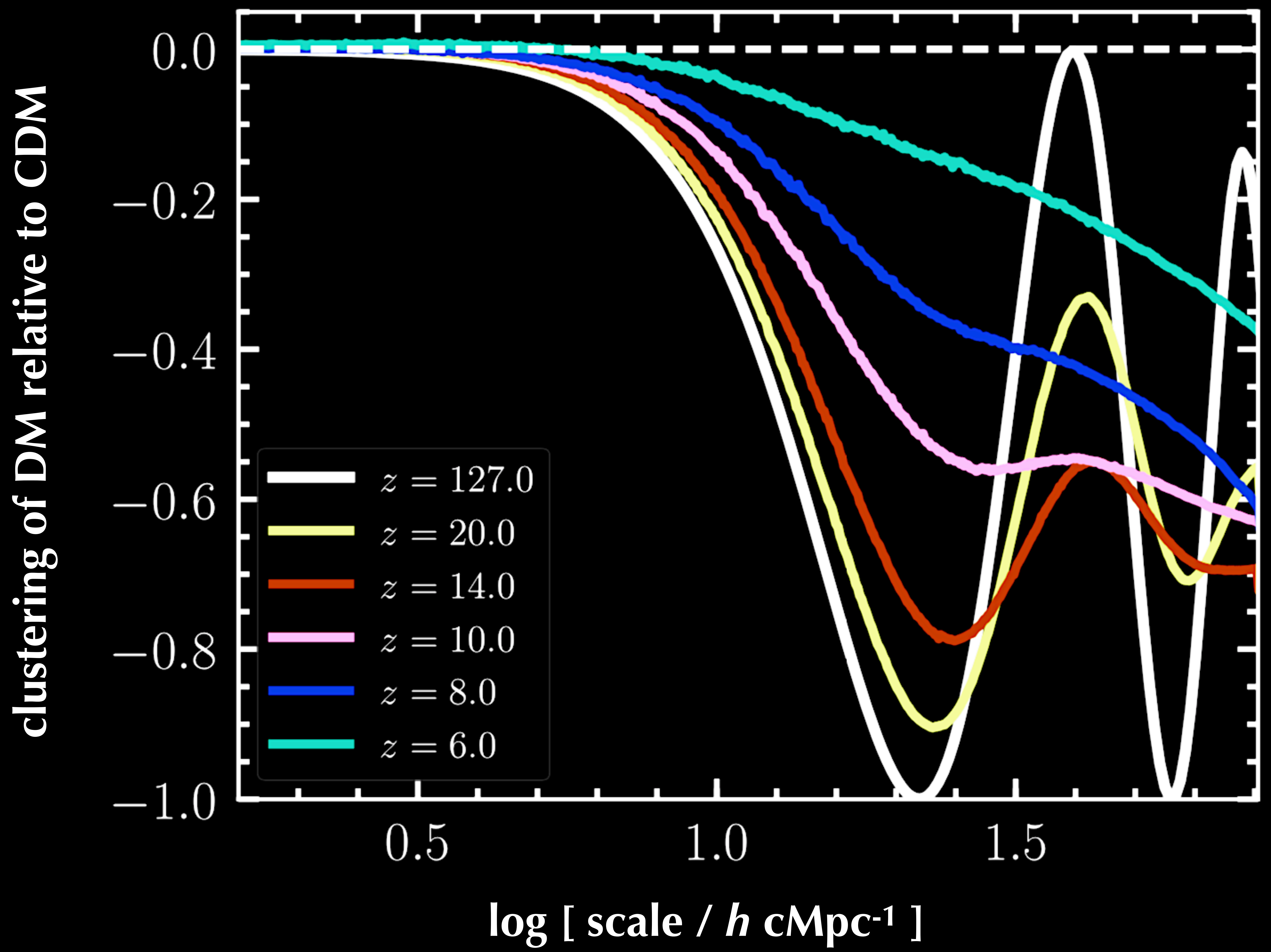
are signatures of "**dark acoustic oscillations**" imprinted in the galaxy distribution in an observable way?

no.

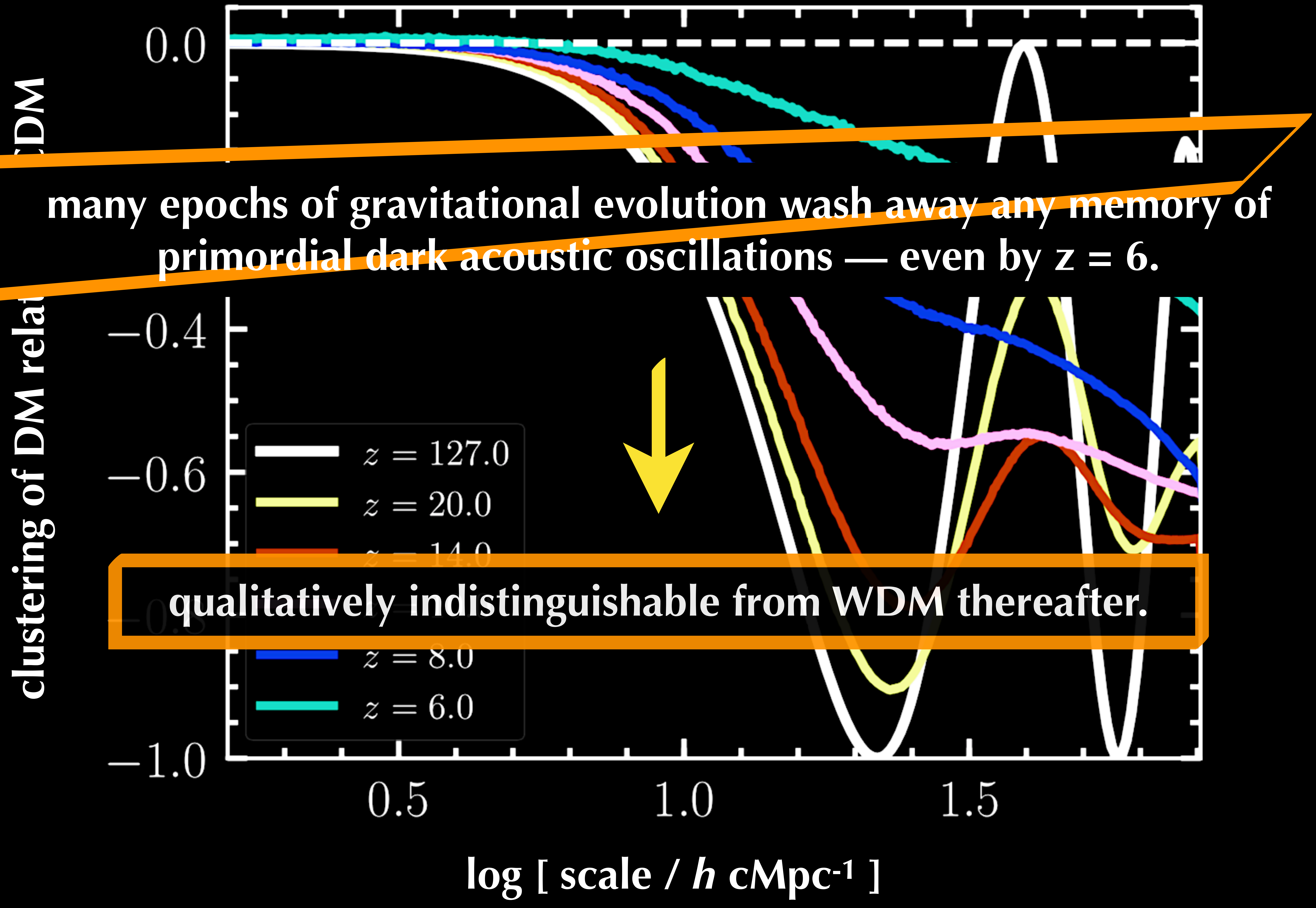
no.

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.

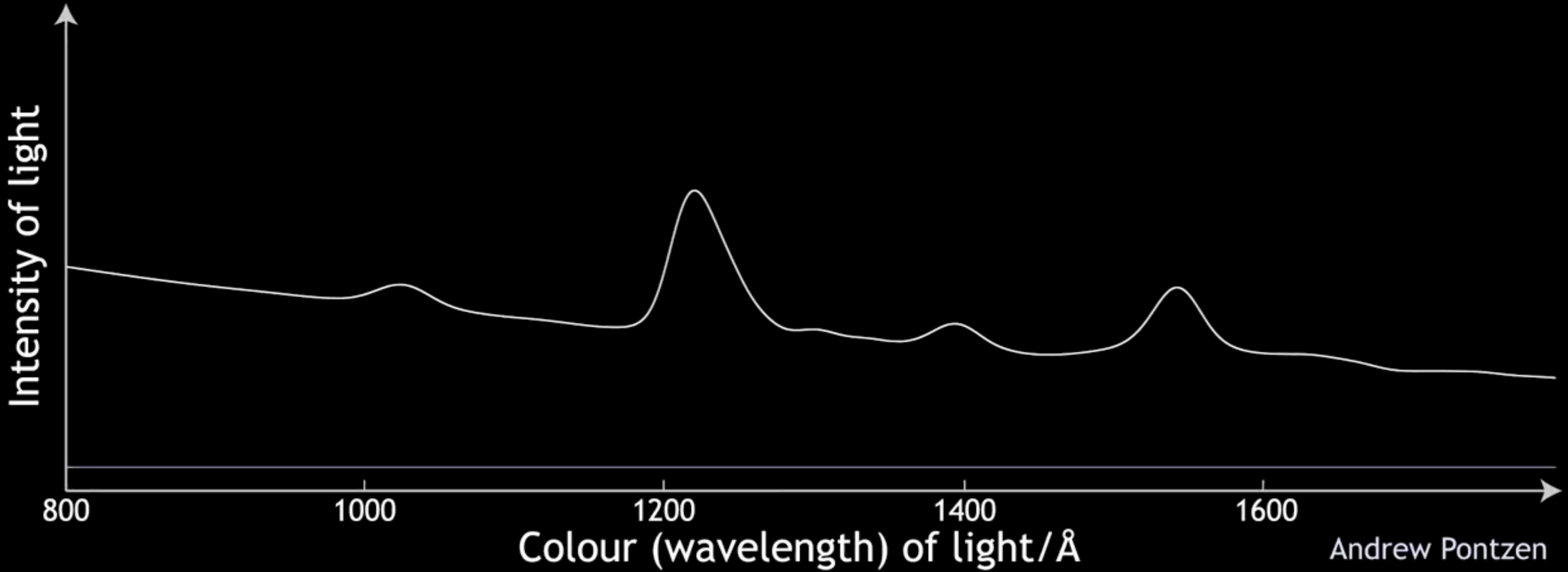
[see also Buckley+ (2014); Vogelsberger+ (2014)]

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)]

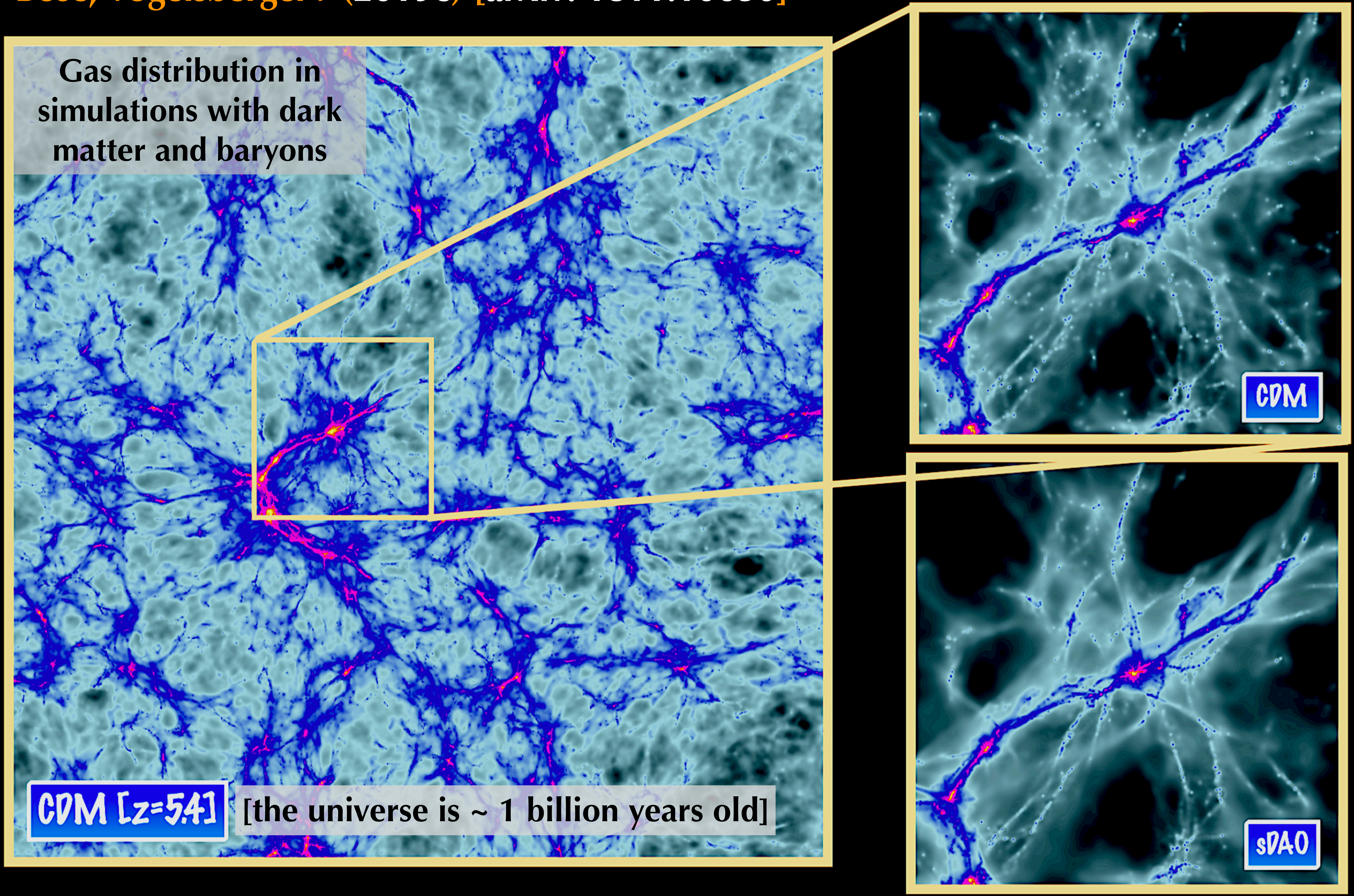

Intensity of light
800
1000
1200
1400
1600
Colour (wavelength) of light/Å
Andrew Pontzen



Andrew Pontzen

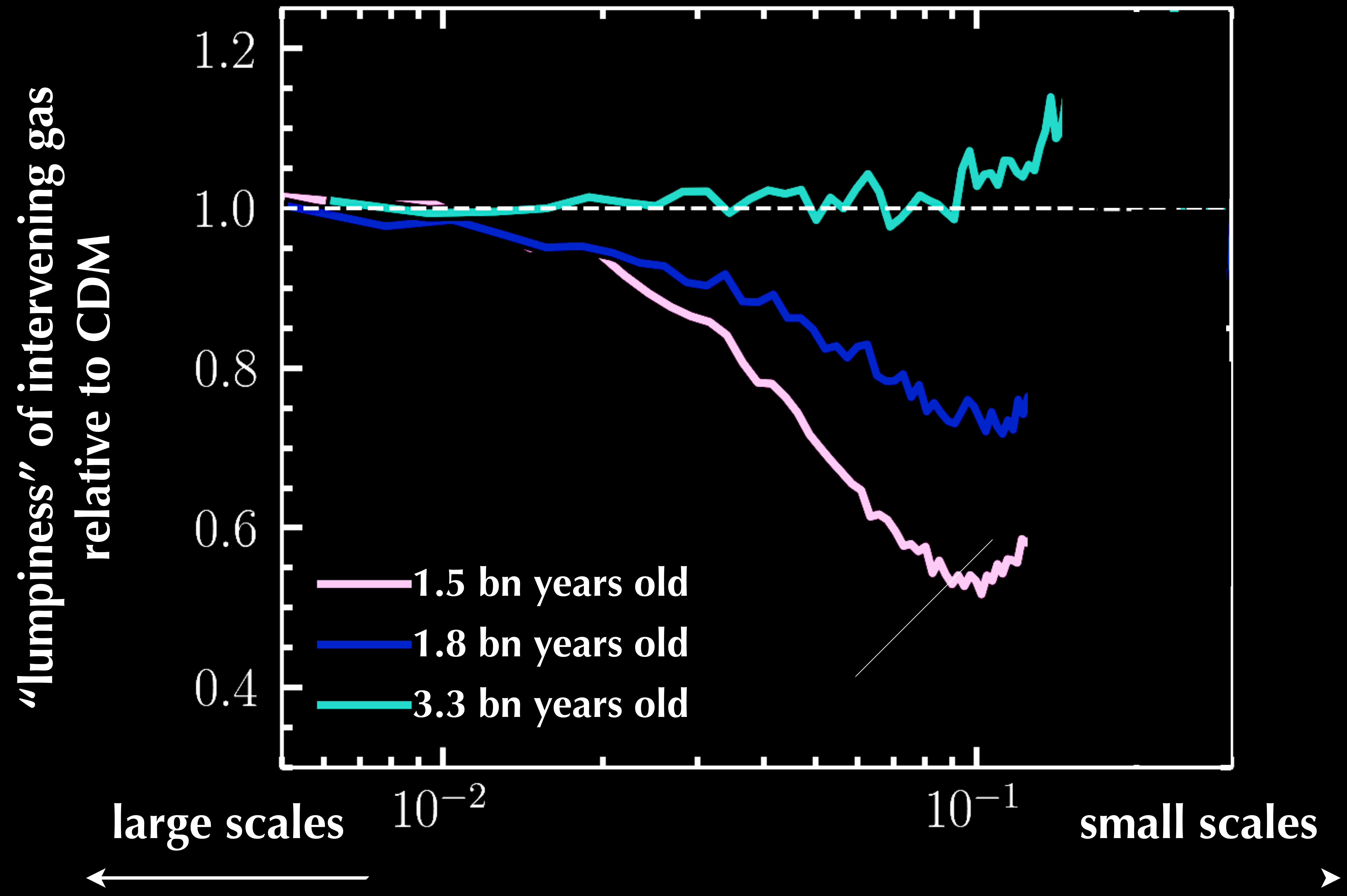
repeat this for ~1000s of lines-of-sight to develop a statistical map of neutral hydrogen in the early universe

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

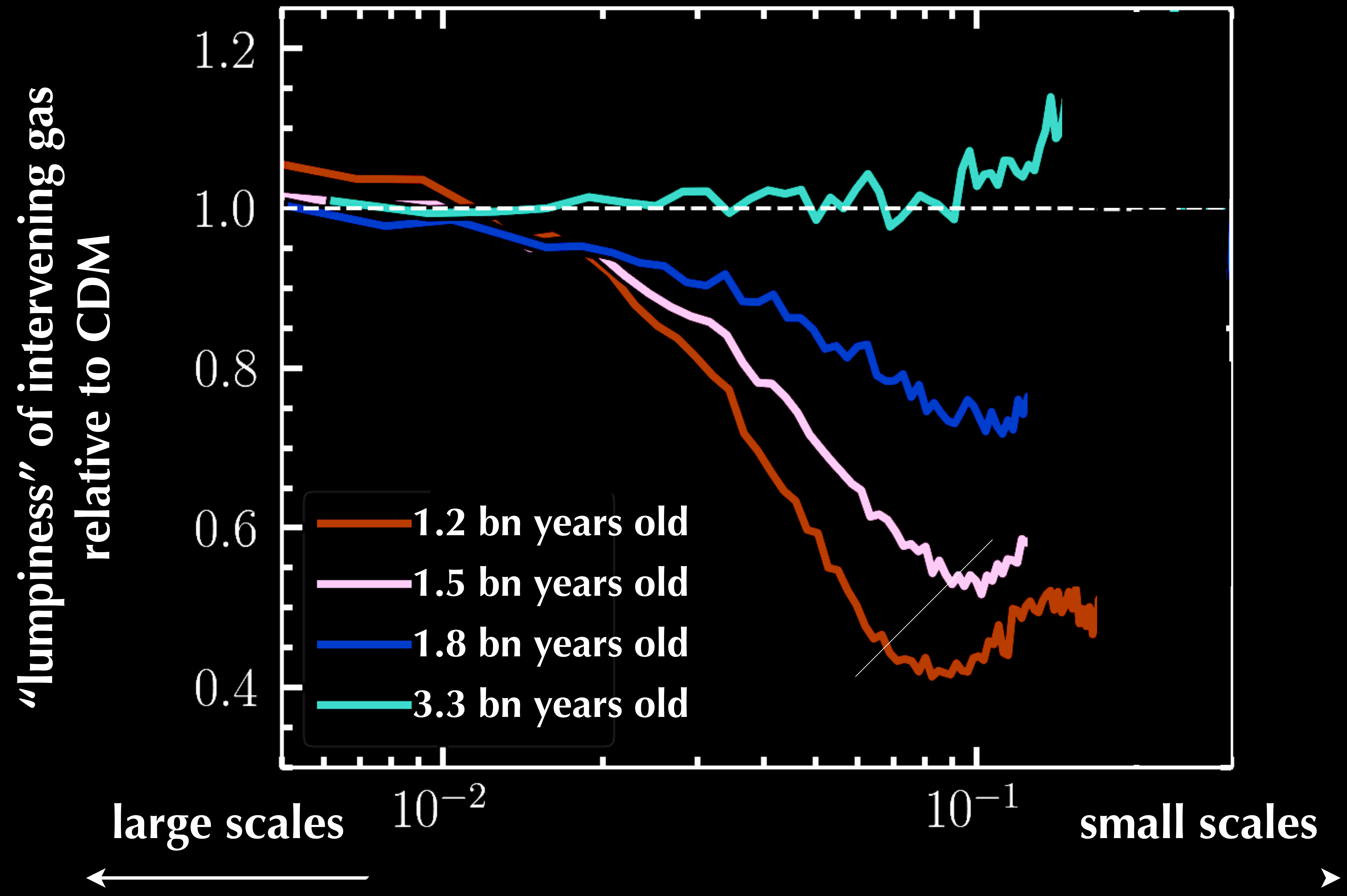


time evolution of the Lyman-alpha forest

Bose+ (2019c) [arXiv: 1811.10630]

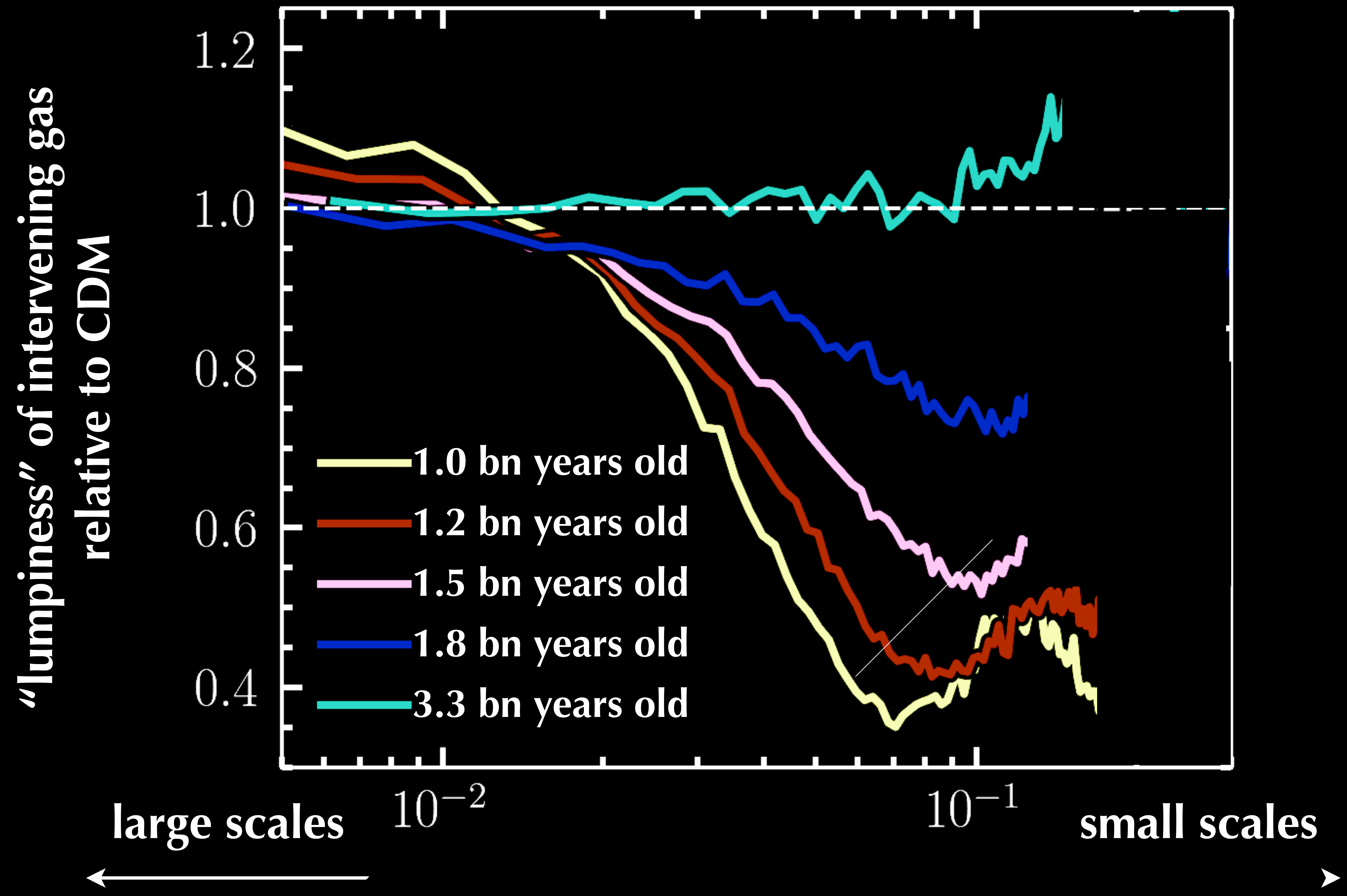


time evolution of the Lyman-alpha forest



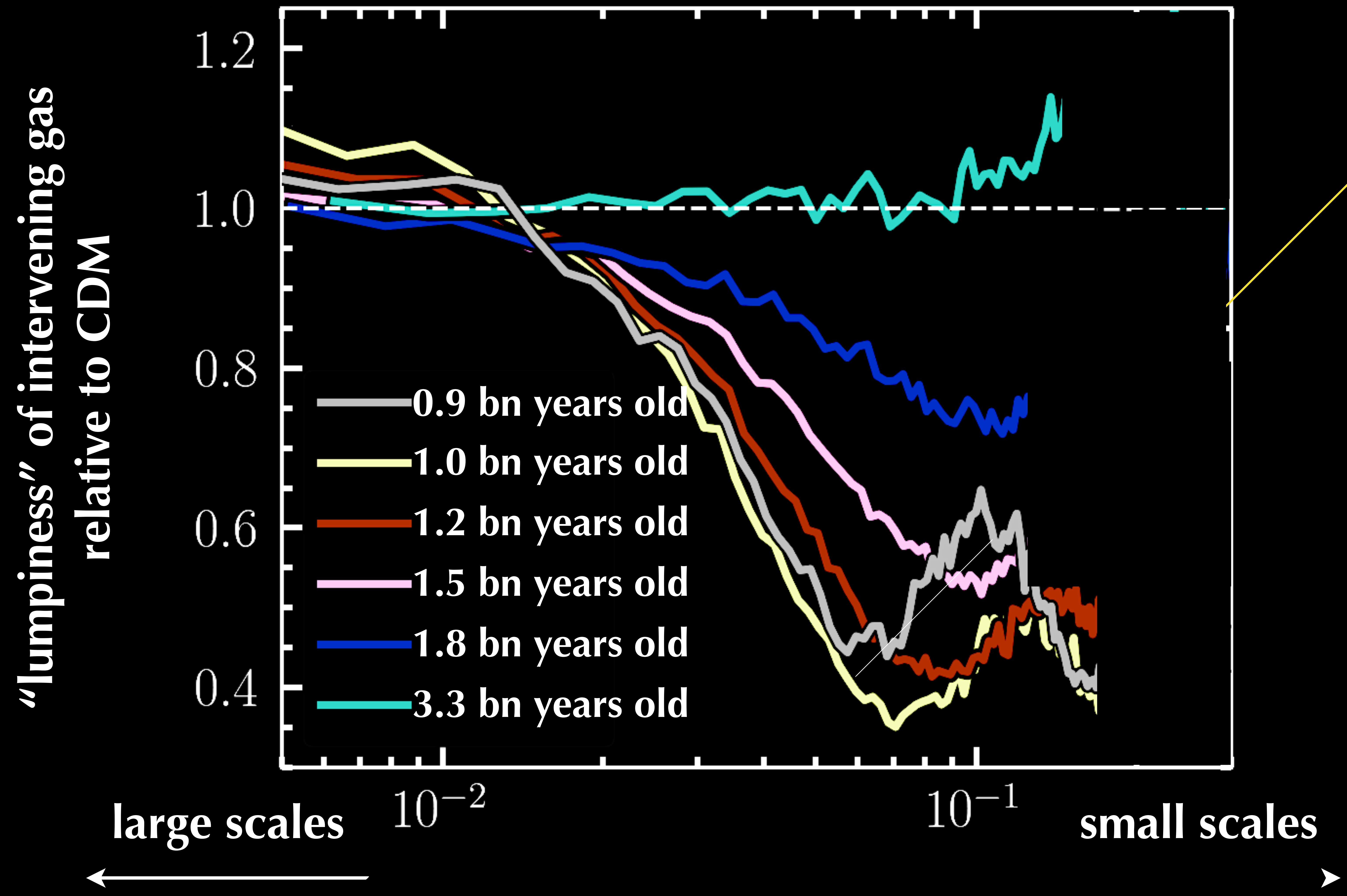
Bose+ (2019c) [arXiv: 1811.10630]

time evolution of the Lyman-alpha forest



Bose+ (2019c) [arXiv: 1811.10630]

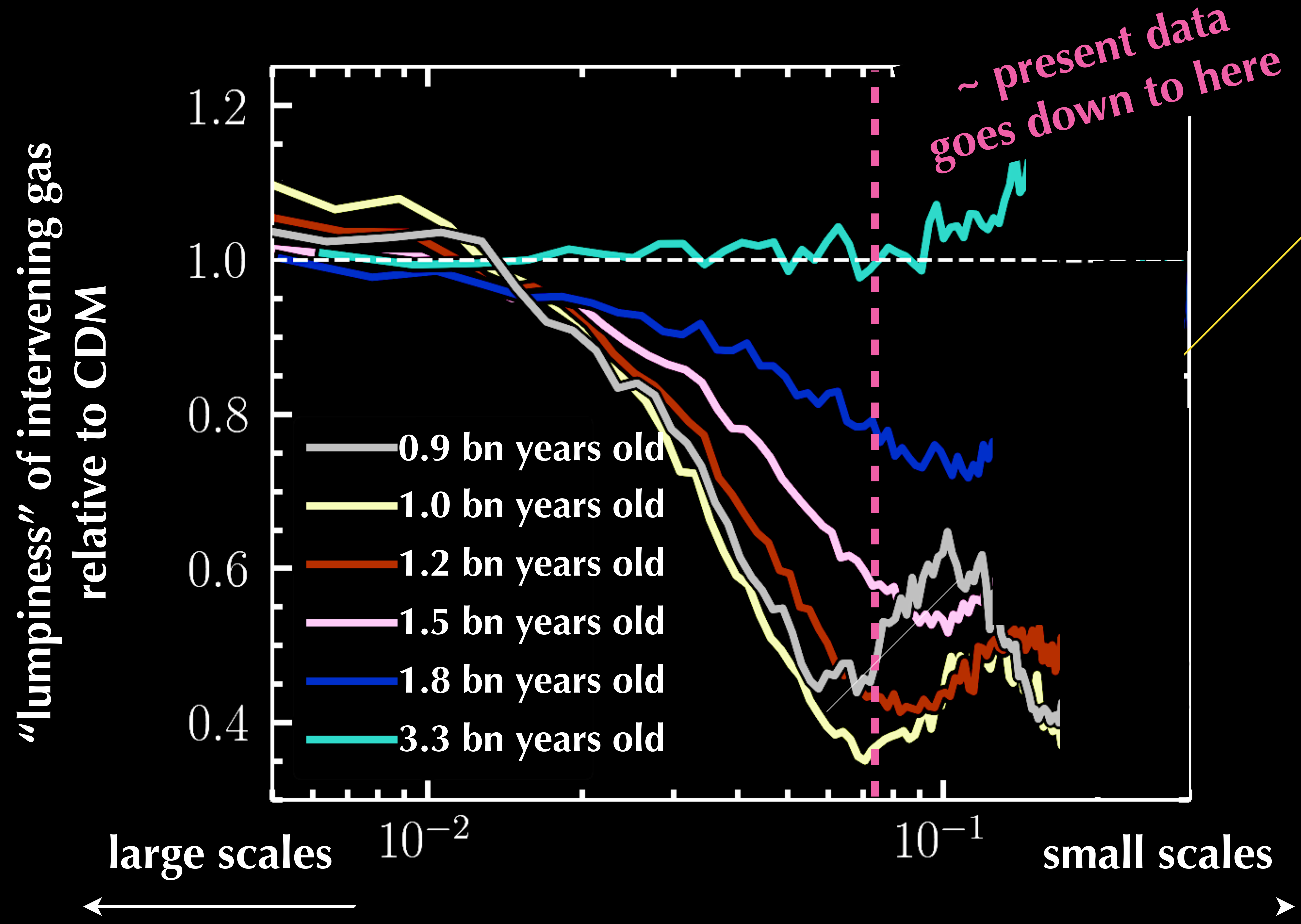
time evolution of the Lyman-alpha forest



Bose+ (2019c) [arXiv: 1811.10630]

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

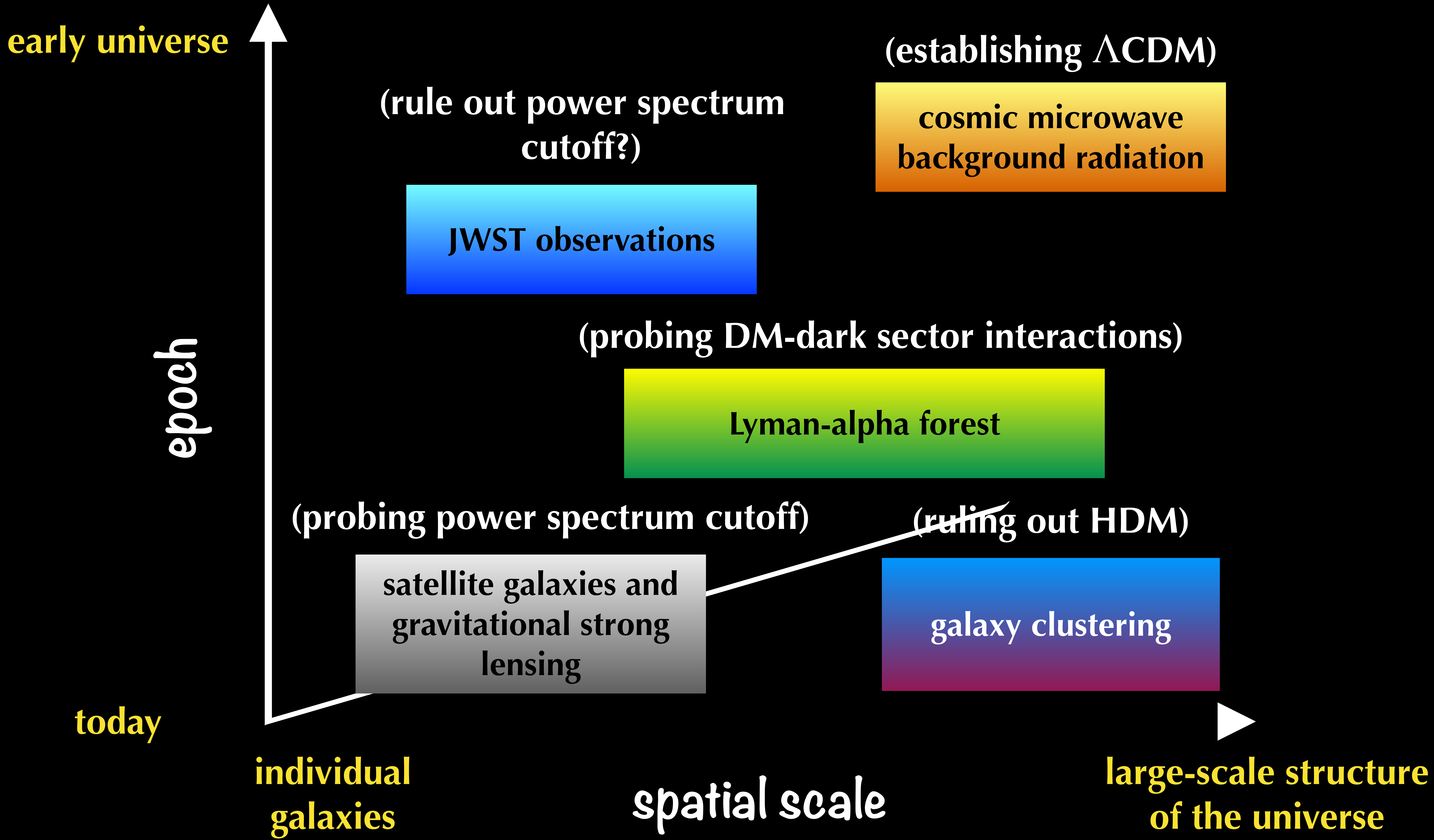
time evolution of the Lyman-alpha forest



Bose+ (2019c) [arXiv: 1811.10630]

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


early universe
(establishing ΛCDM)
(rule out power spectrum cutoff?)
cosmic microwave background radiation
JWST observations
epoch
(probing power spectrum cutoff)
(ruling out HDM)
satellite galaxies and gravitational strong lensing
galaxy clustering
today
individual galaxies
spatial scale
large-scale structure of the universe


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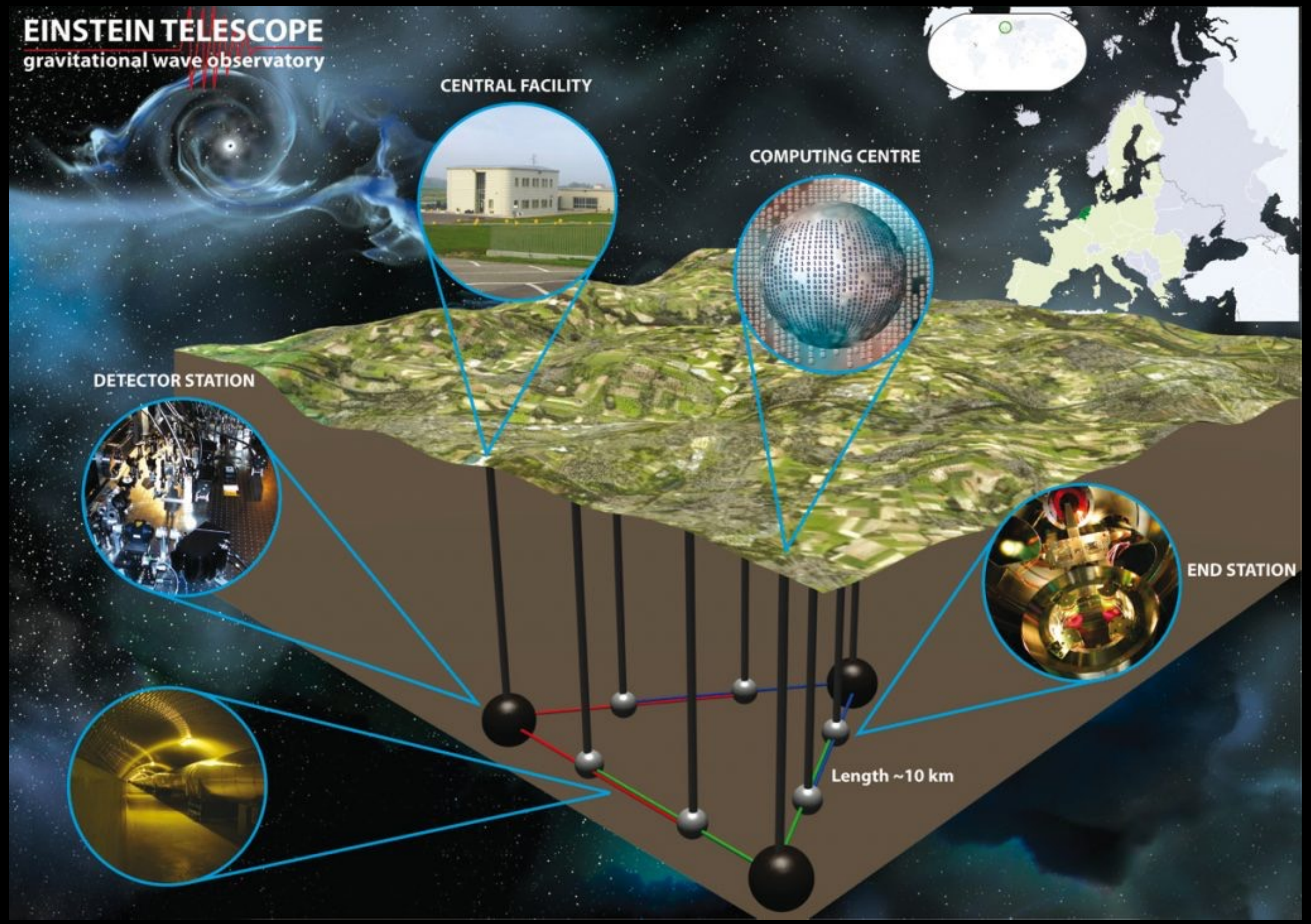
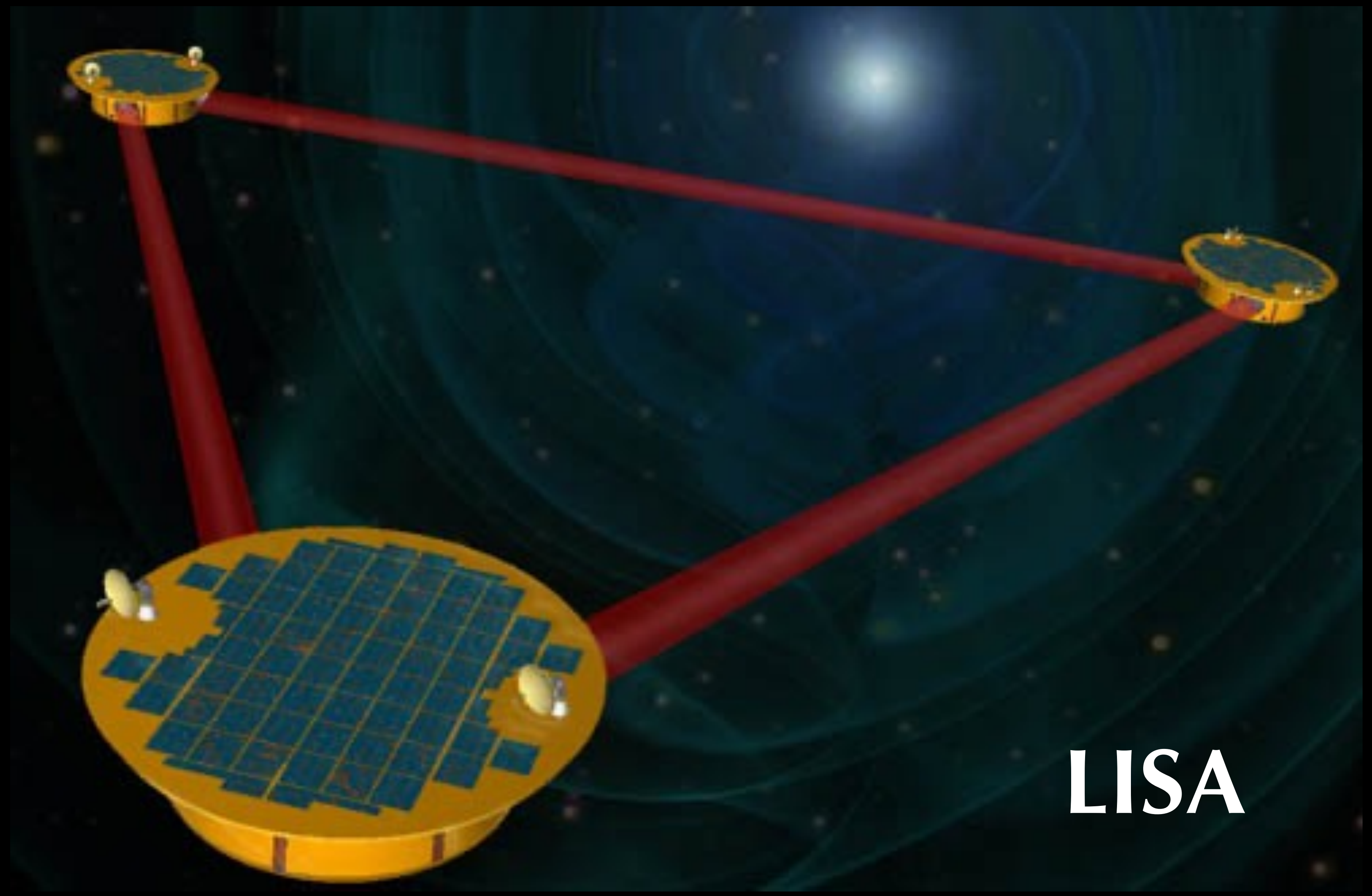
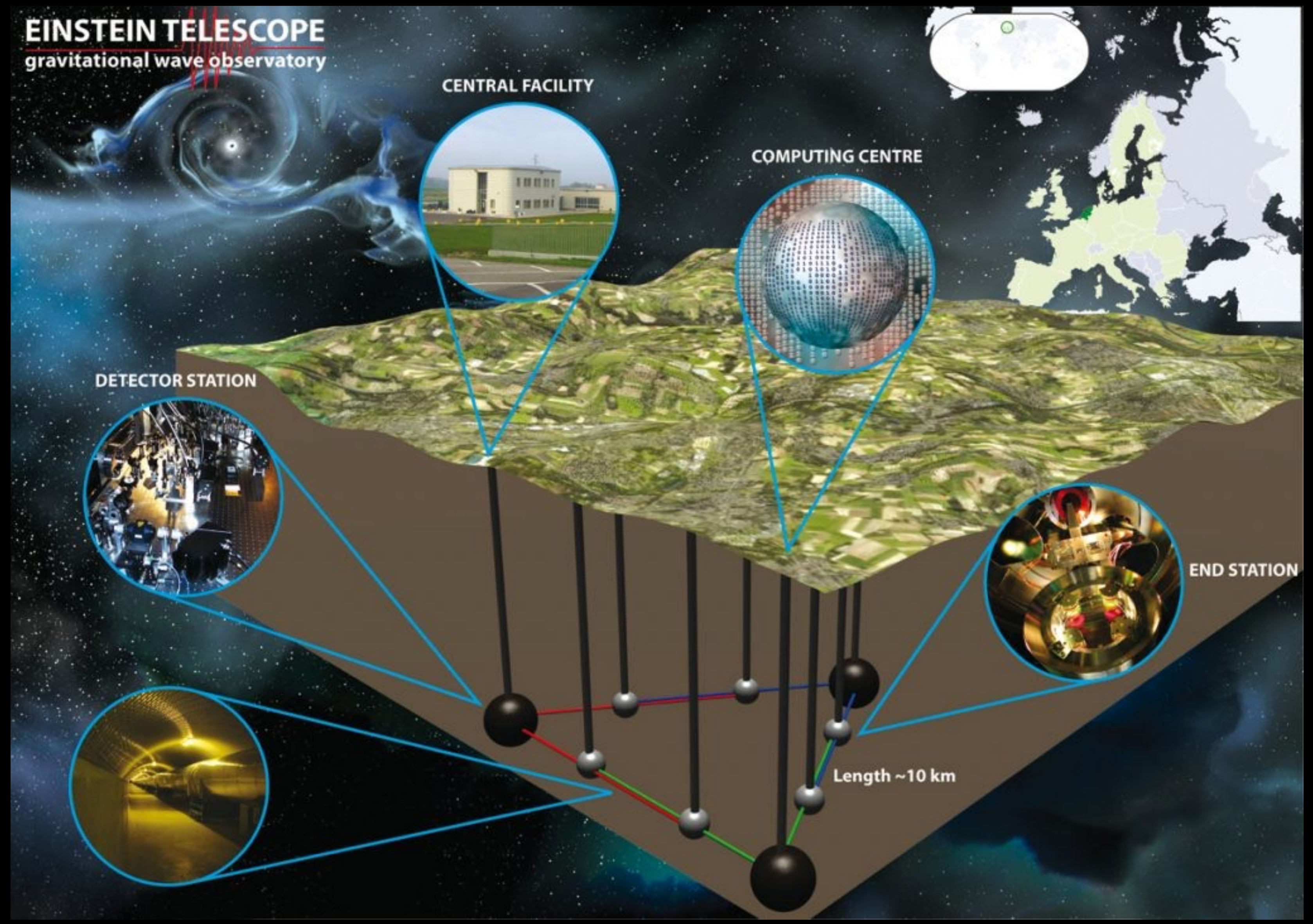
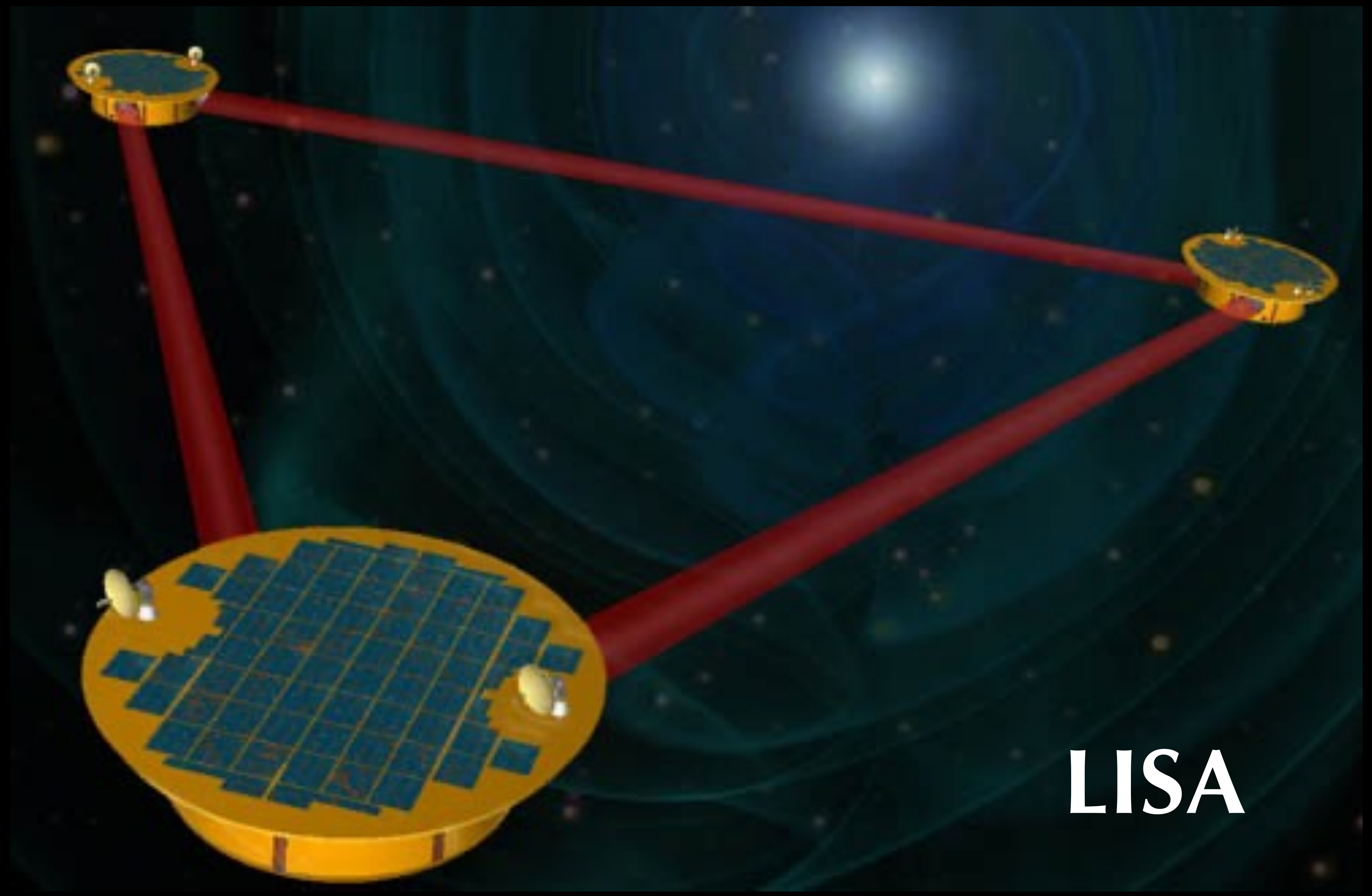
the early universe may offer some of the strongest tests of dark matter

what can we do besides counting galaxies?

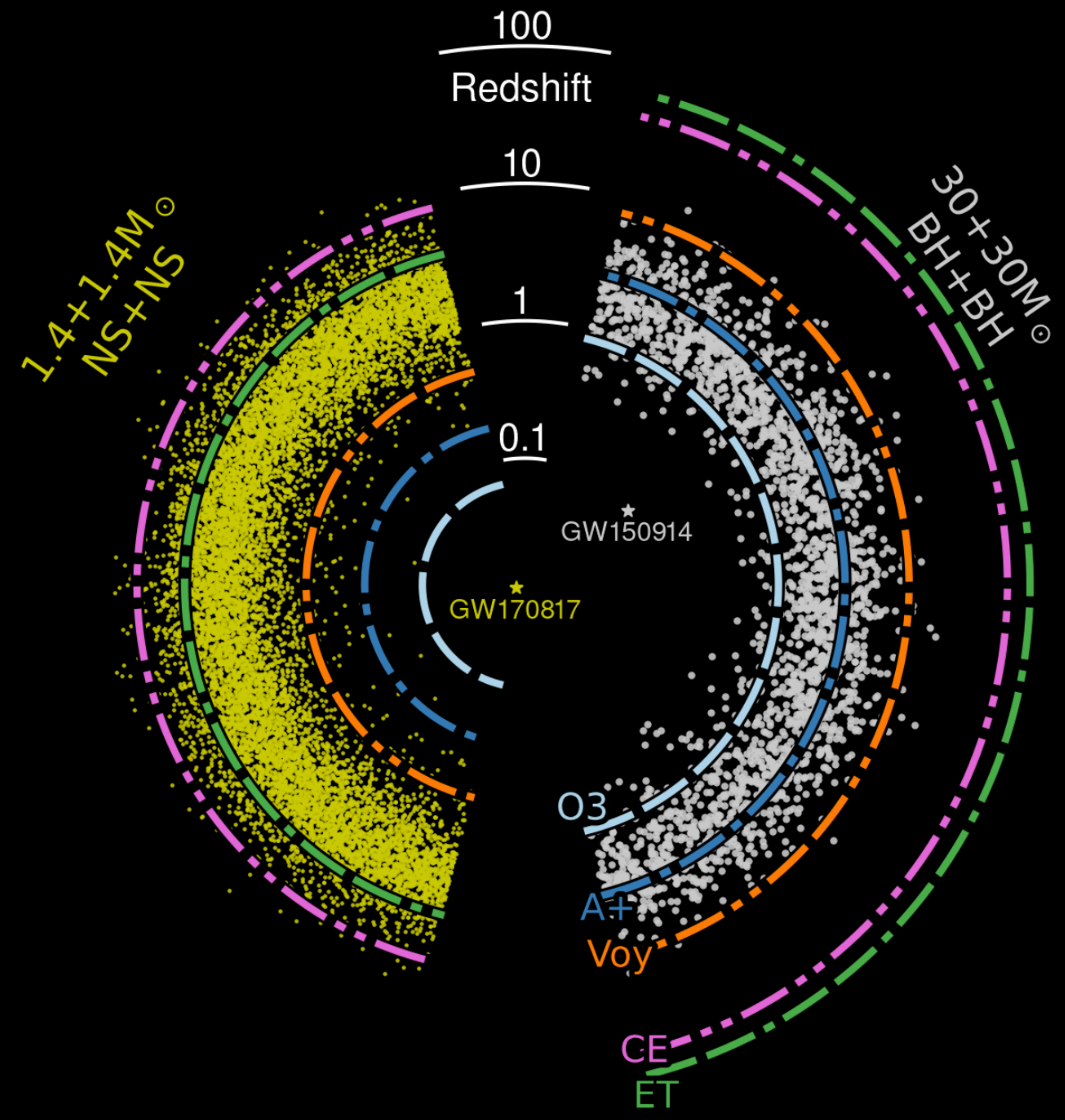

EINSTEIN TELESCOPE
gravitational wave observatory
CENTRAL FACILITY
COMPUTING CENTRE
DETECTOR STATION
END STATION
Length ~10 km


LISA

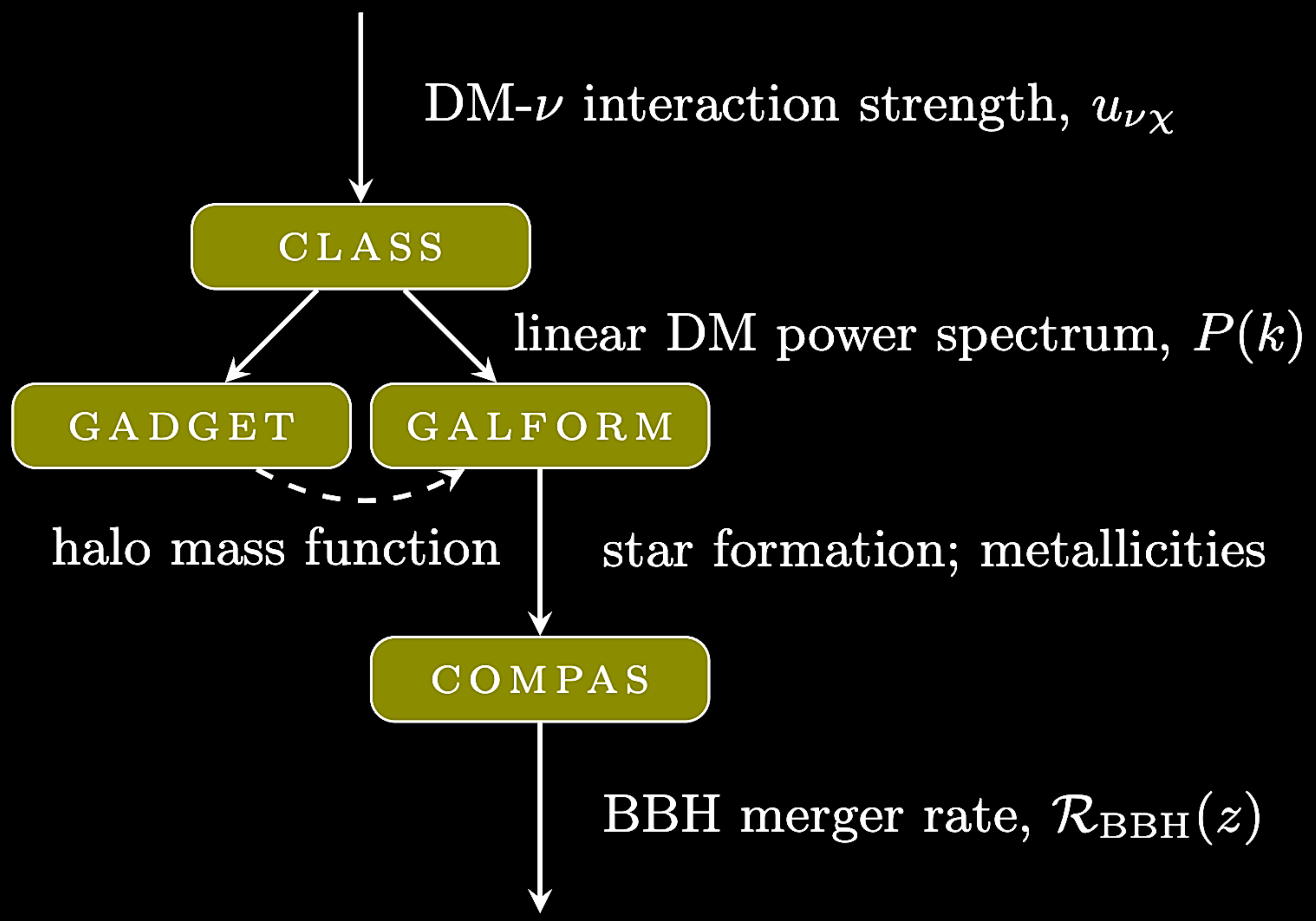




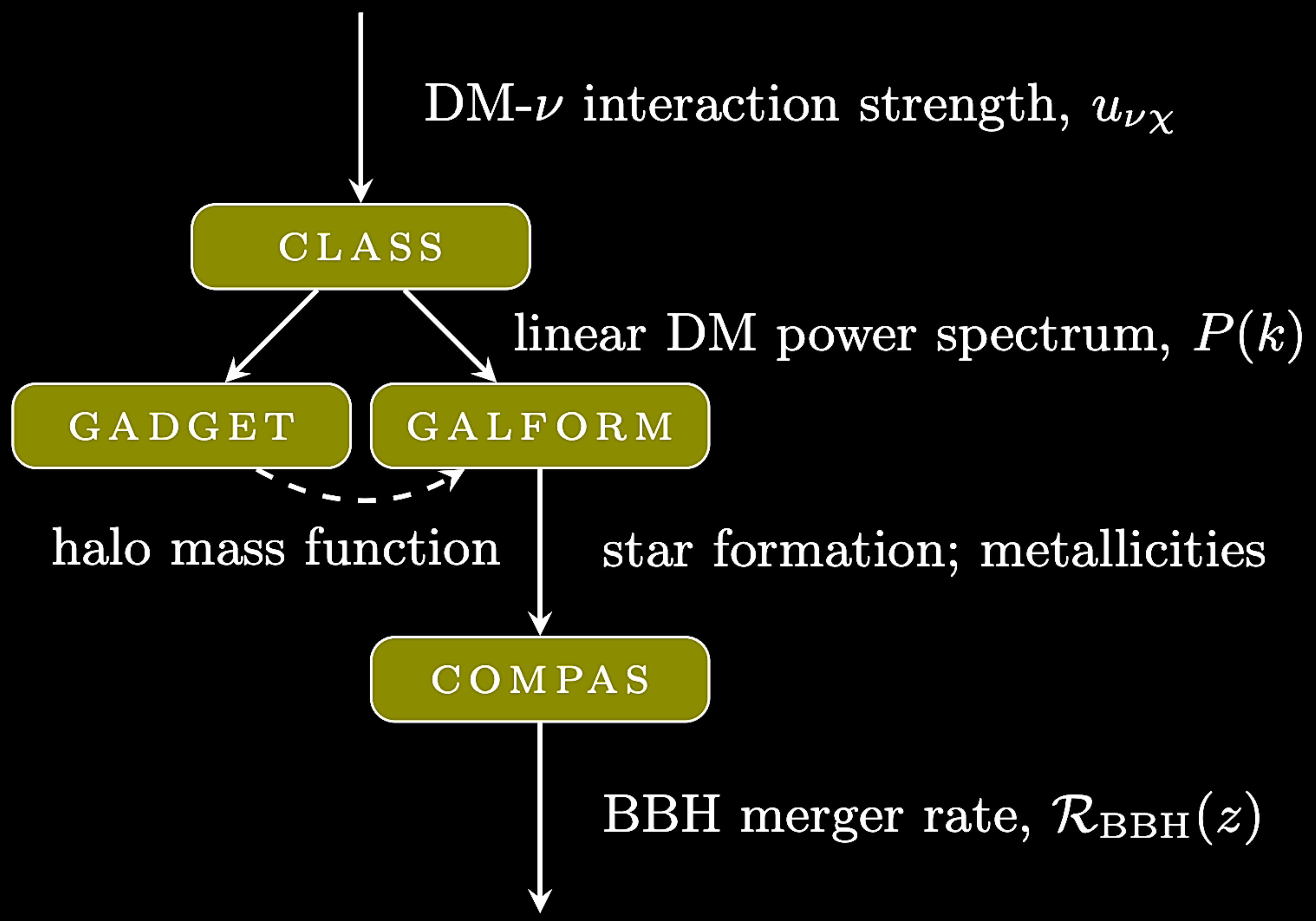
Cosmic Explorer technical report CE-P2100003-v7 (2021)

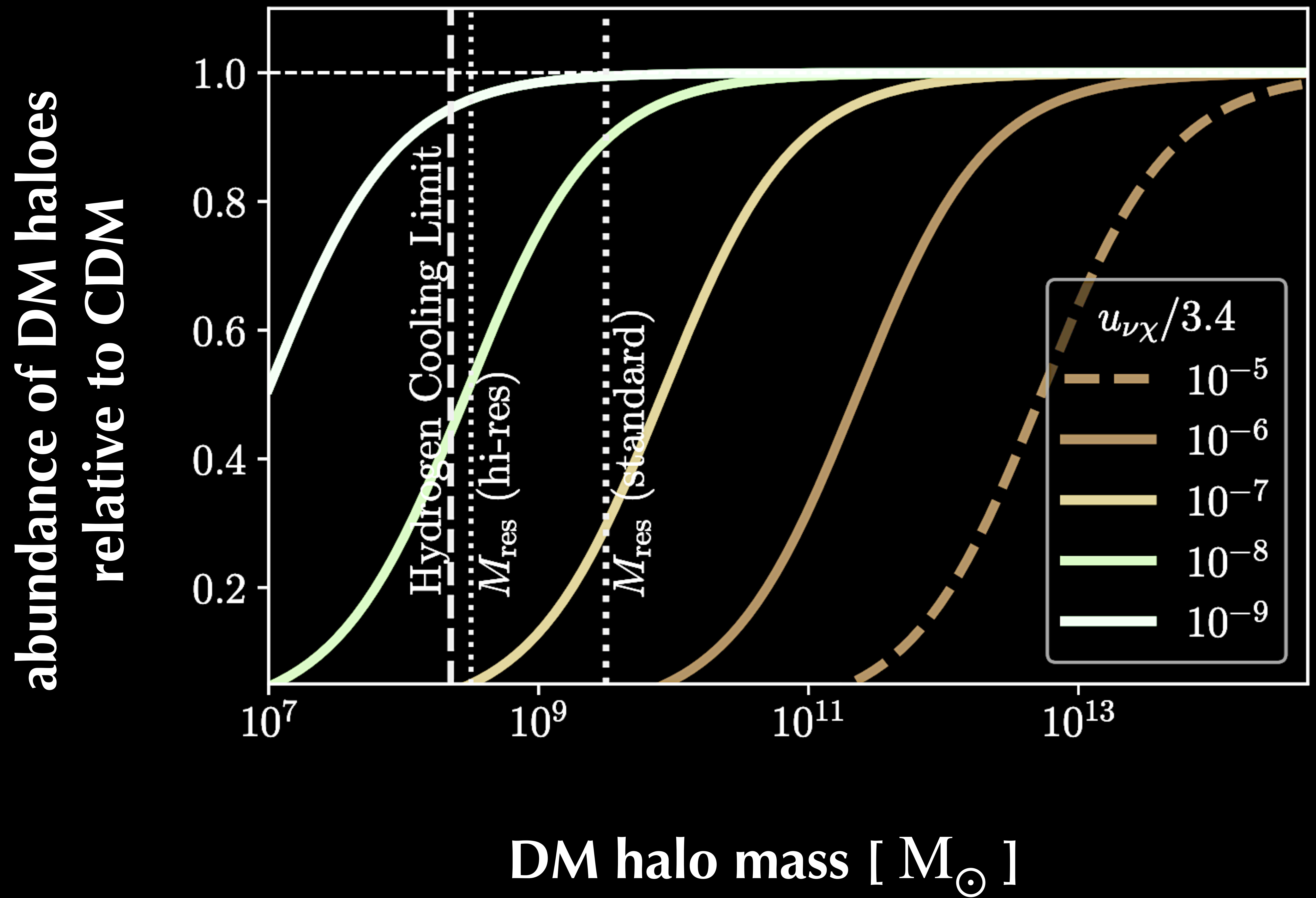


★ the merger rate of BHs is an (indirect) **tracer** of the **merger rate of galaxies**



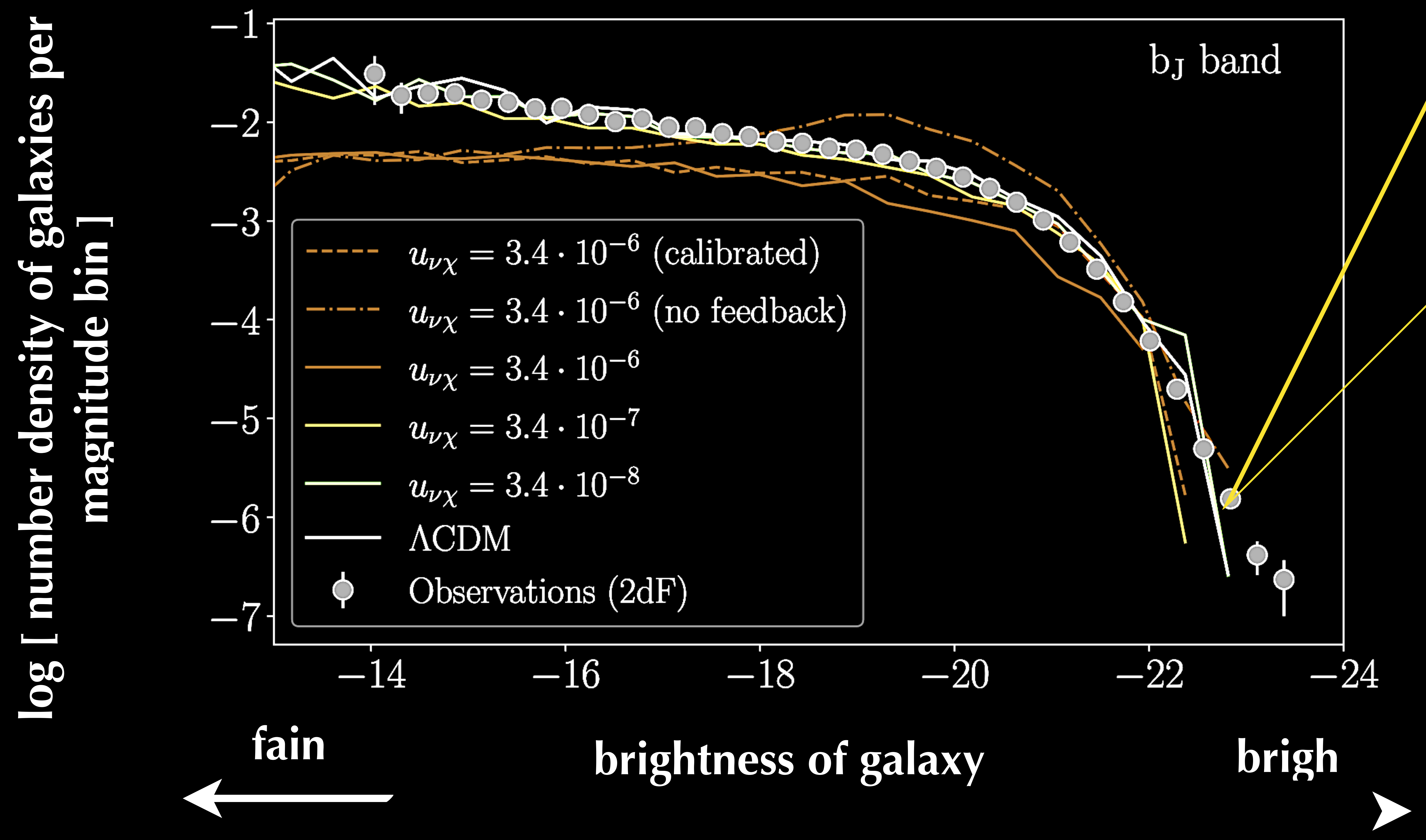
Mosbech, Jenkins, Bose+
[2021, arXiv: 2207.14126]



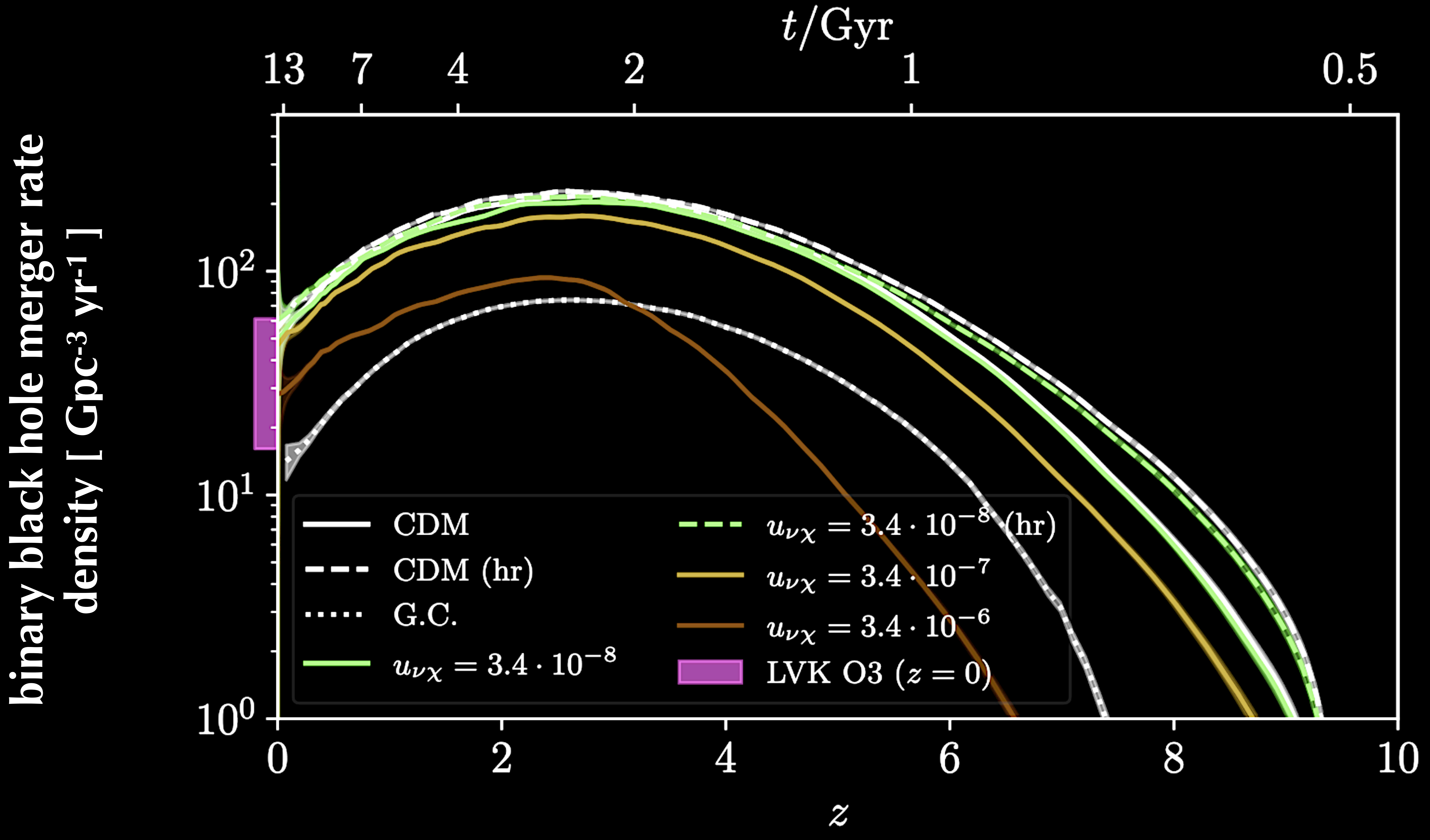


Mosbech, Jenkins, Bose+
[2021, arXiv: 2207.14126]

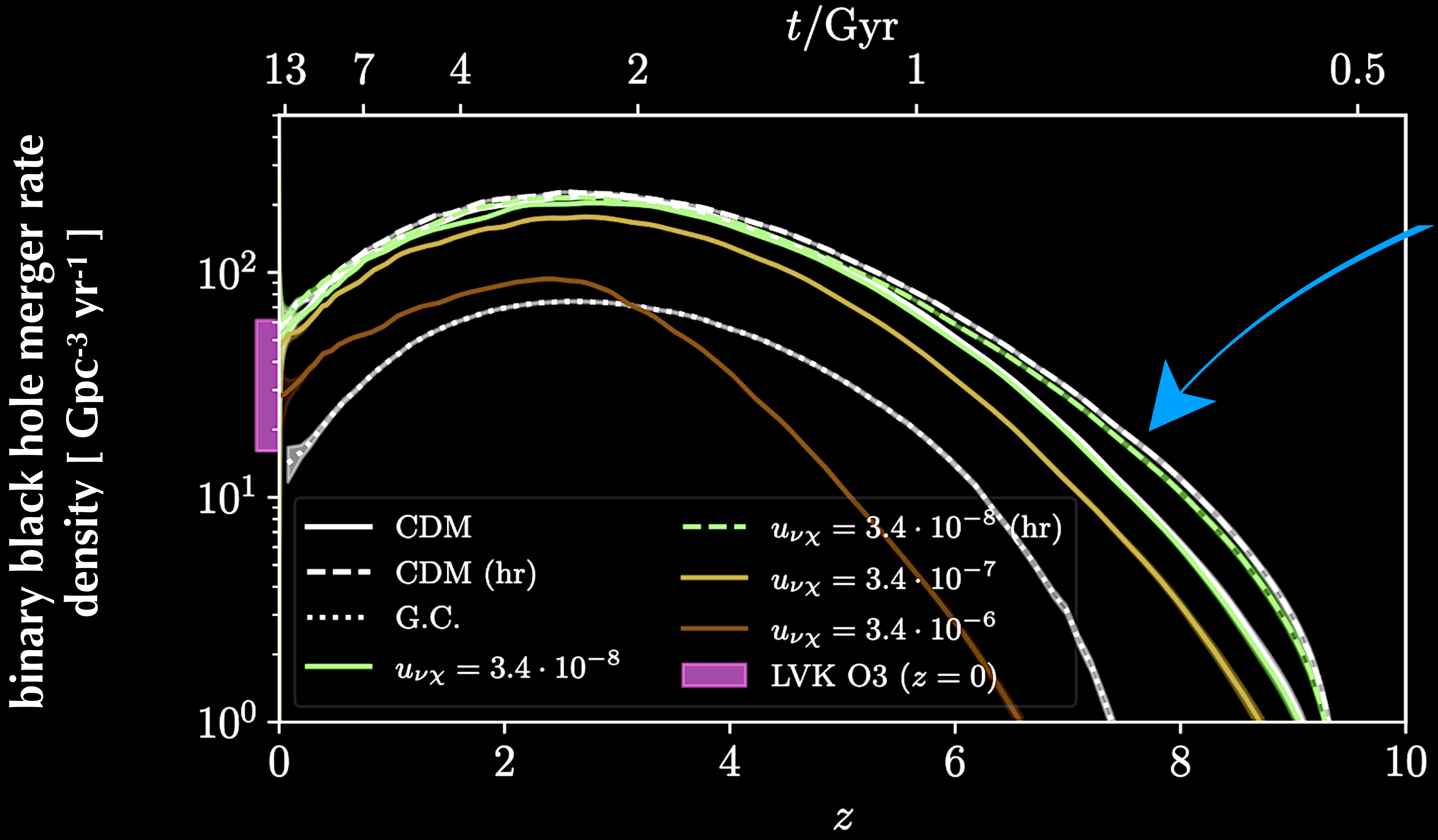
★ lower interaction strength —> closer to CDM



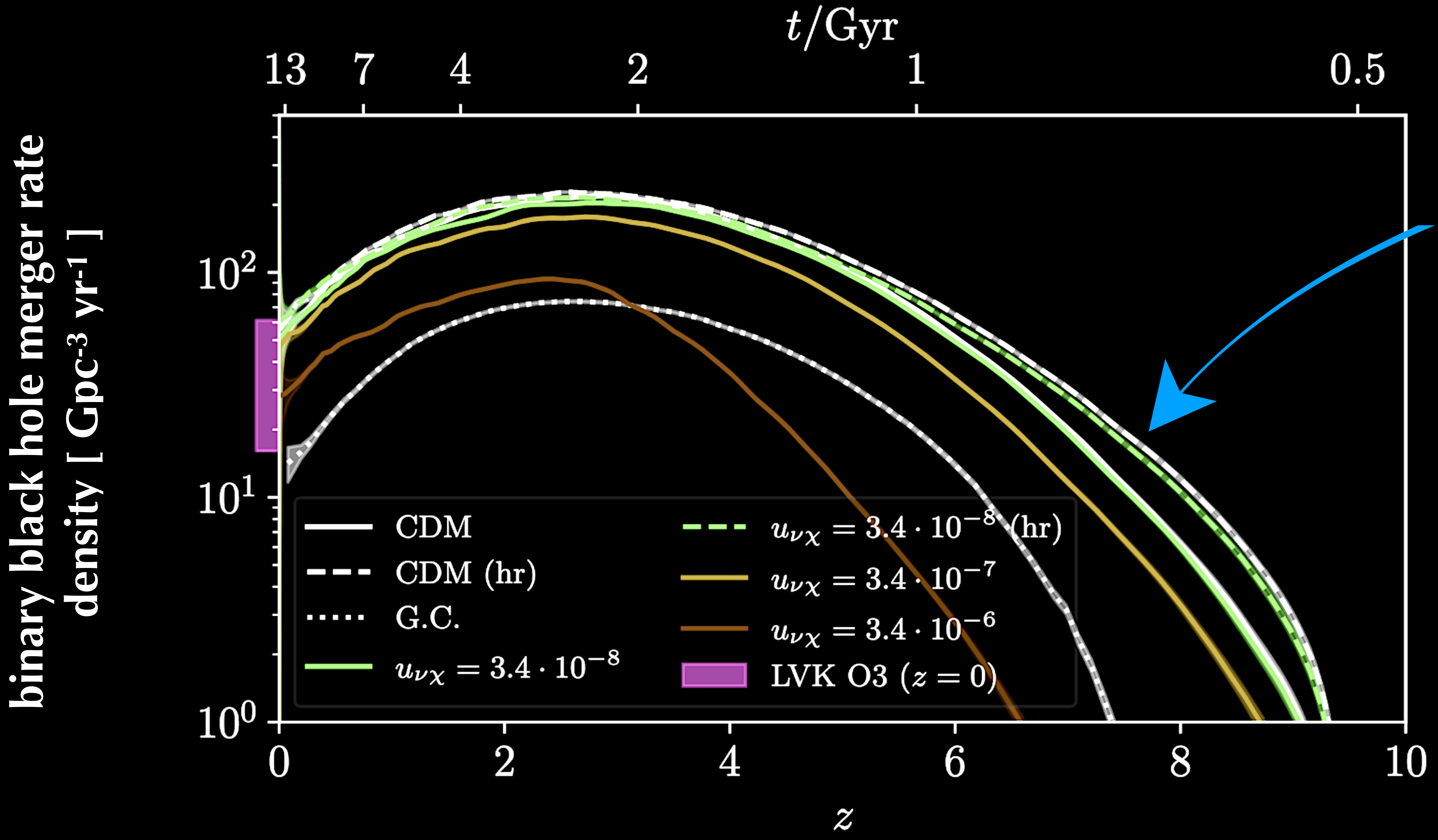
goal: generate "realistic" galaxy population for each model at present day and predict their BBH merger rates in the past. in extreme models, this calibration is not possible no matter what you do with astrophysics



t/Gyr
13
7
4
2
1
0.5
binary black hole merger rate density [Gpc-3 yr-1]
10^2
10^1
10^0
0
2
4
6
8
10
z
CDM
CDM (hr)
G.C.
$u_{\nu\chi} = 3.4 \cdot 10^{-8}$
$u_{\nu\chi} = 3.4 \cdot 10^{-8}$ (hr)
$u_{\nu\chi} = 3.4 \cdot 10^{-7}$
$u_{\nu\chi} = 3.4 \cdot 10^{-6}$
LVK O3 ($z = 0$)



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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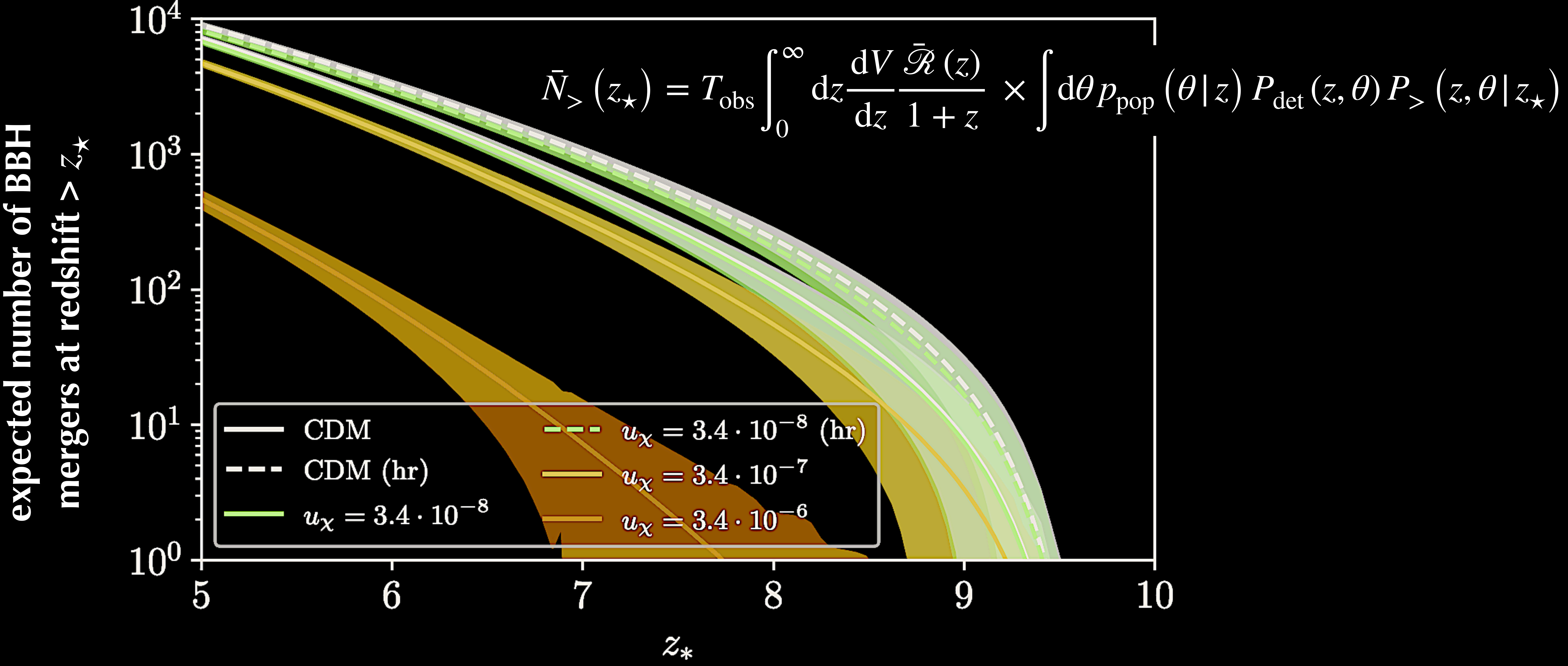
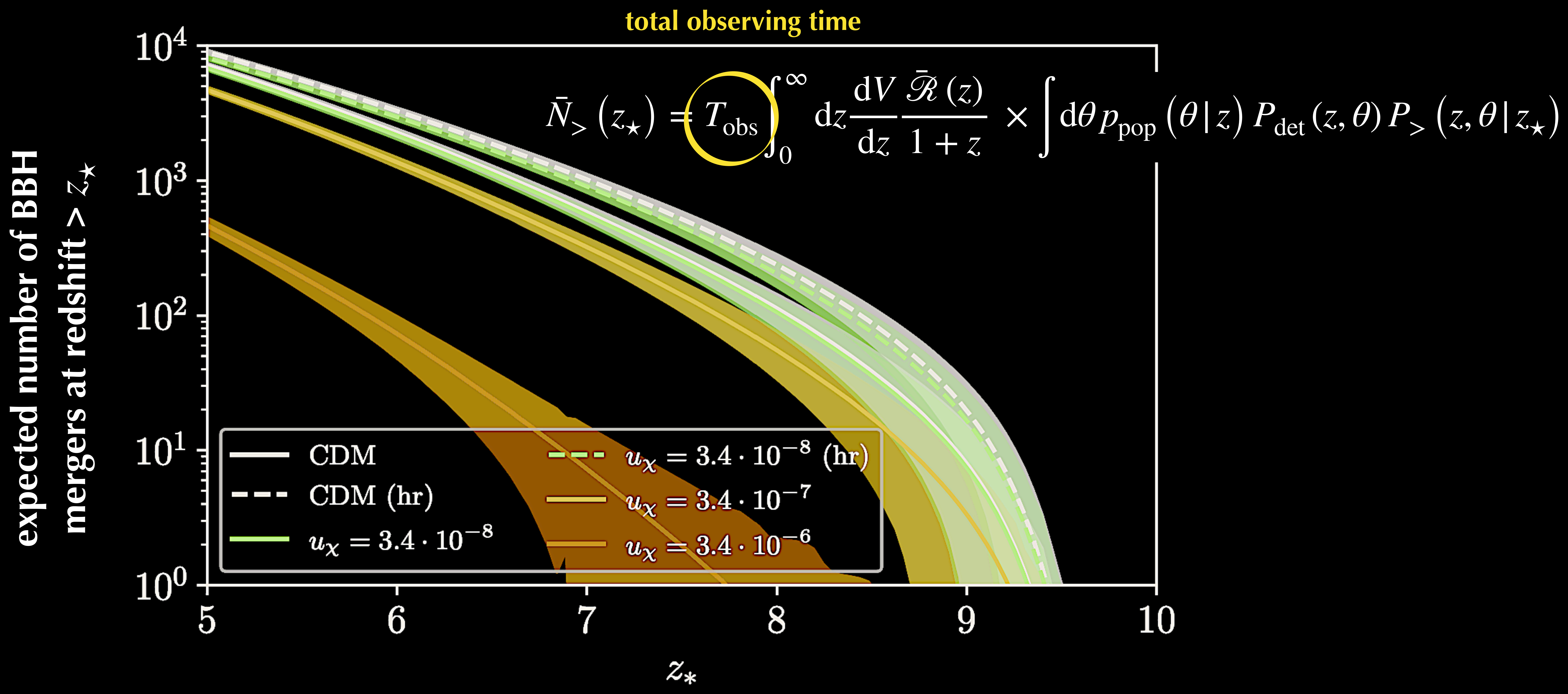
are these differences observable using future GW observatories?



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



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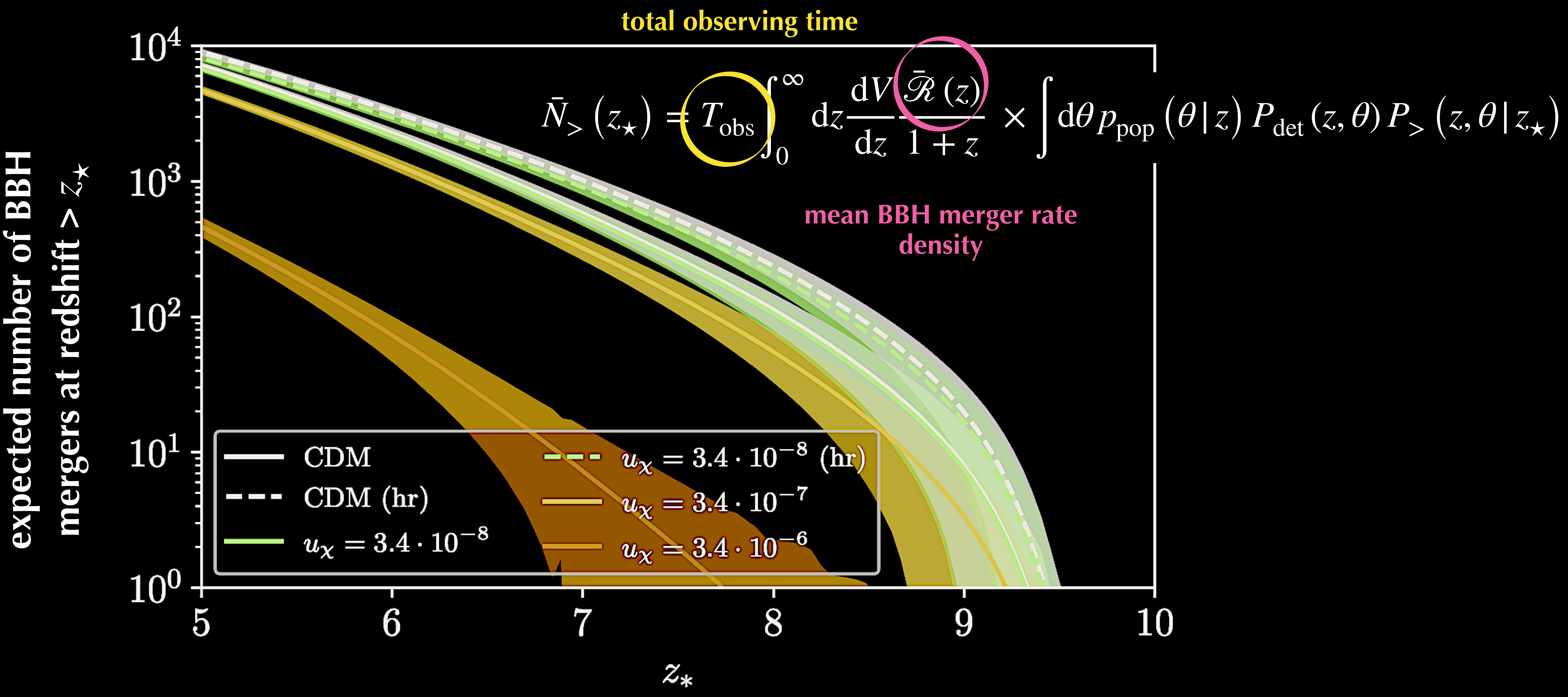


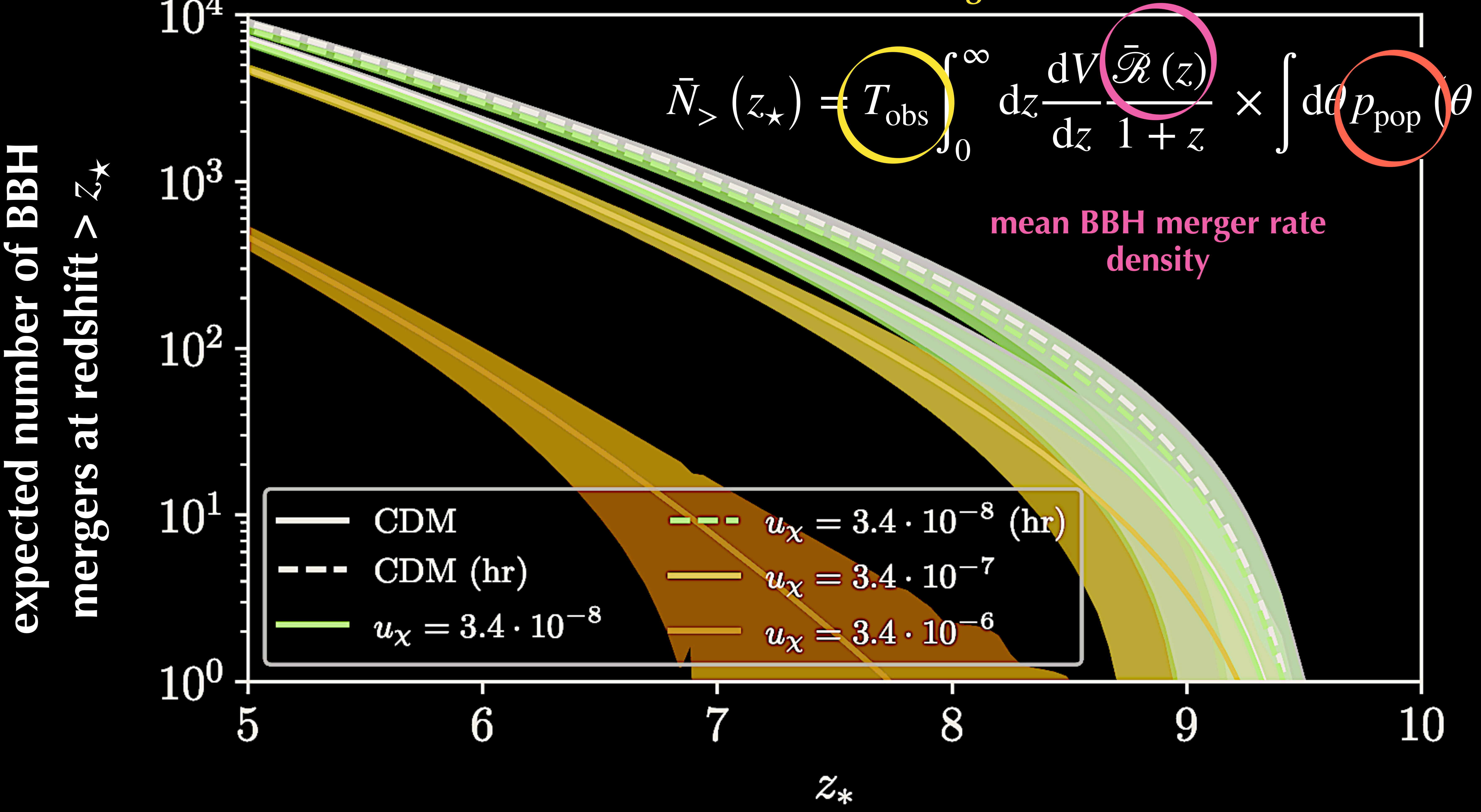
forecasts for one year of observations with Einstein Telescope + 2 Cosmic Explorers

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

total observing time

population distribution

mean BBH merger rate density



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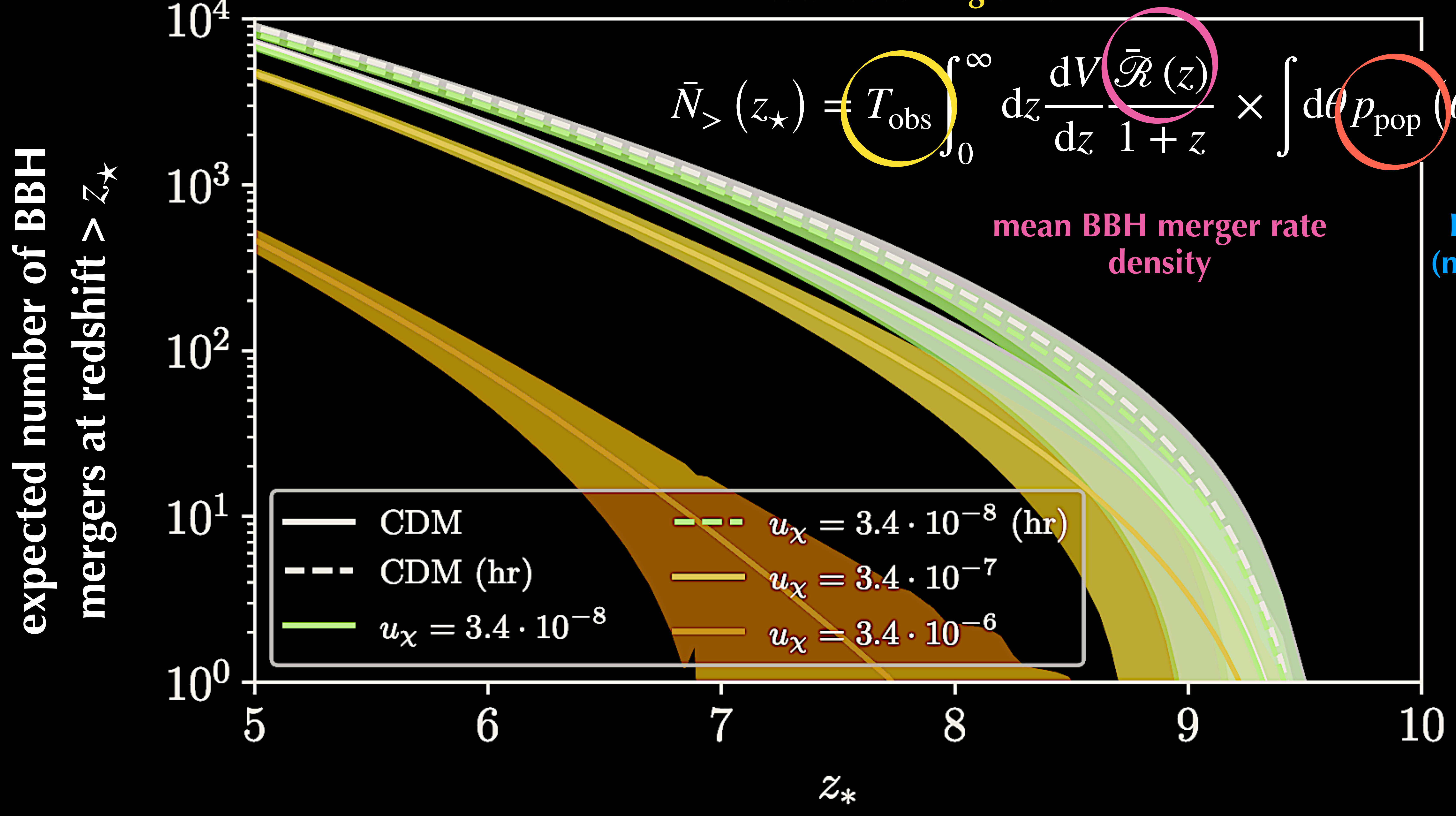

total observing time

population distribution

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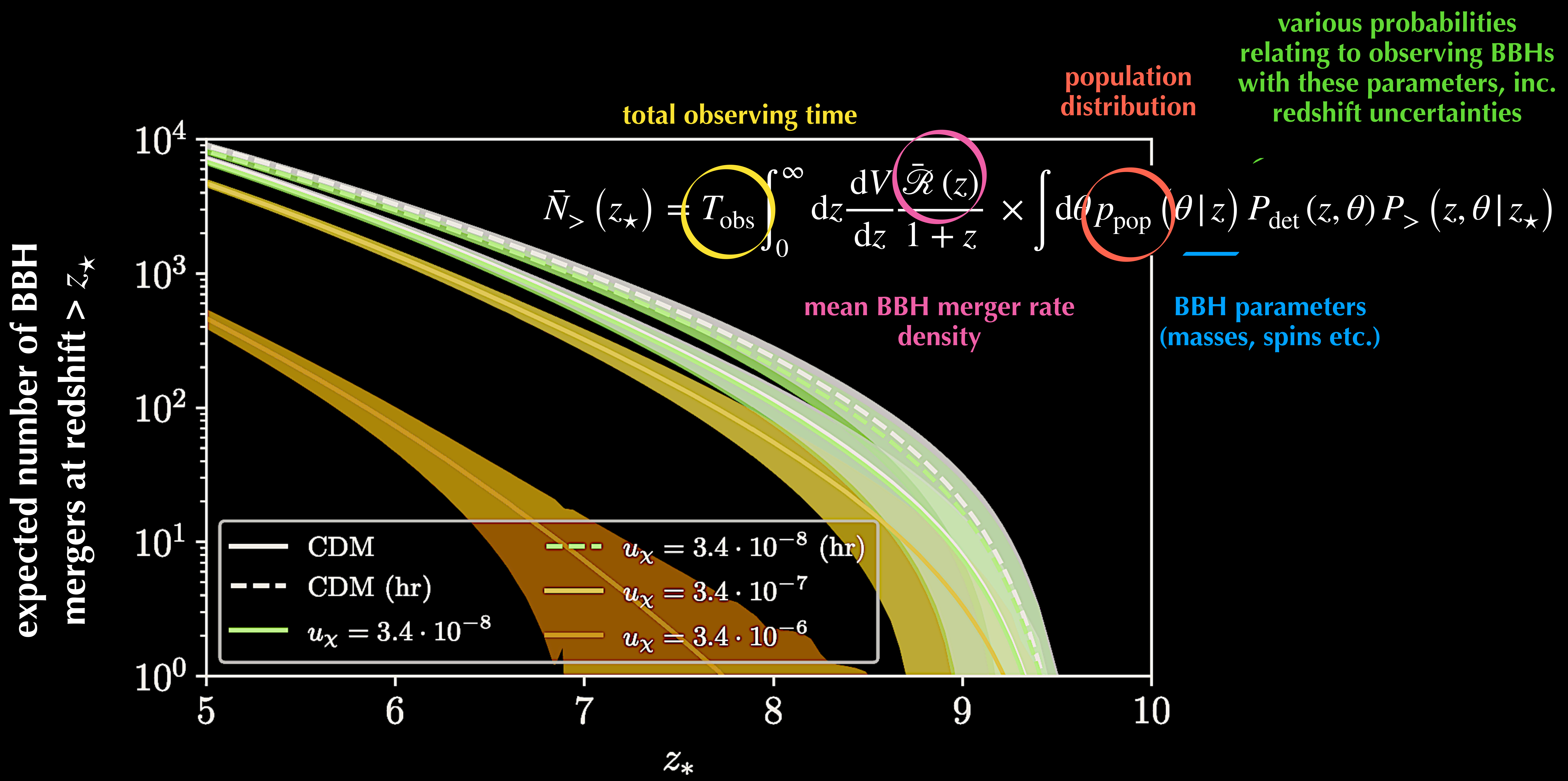
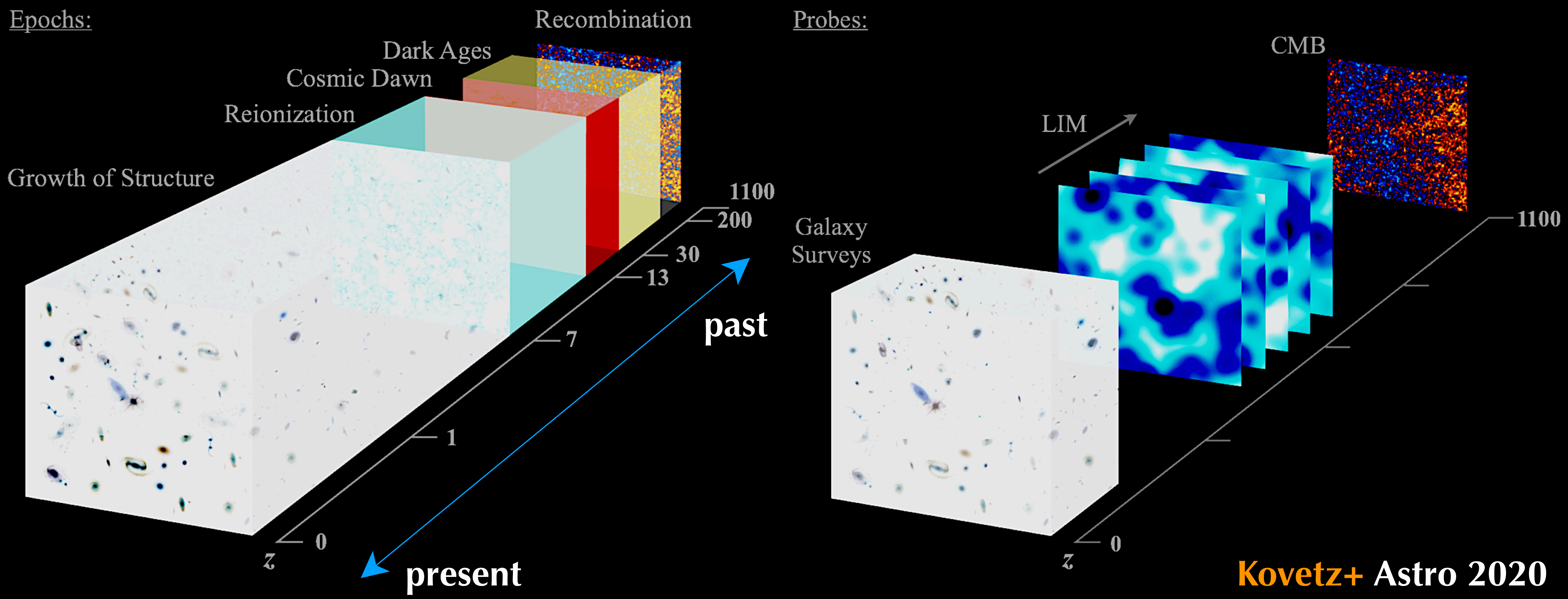
mean BBH merger rate density

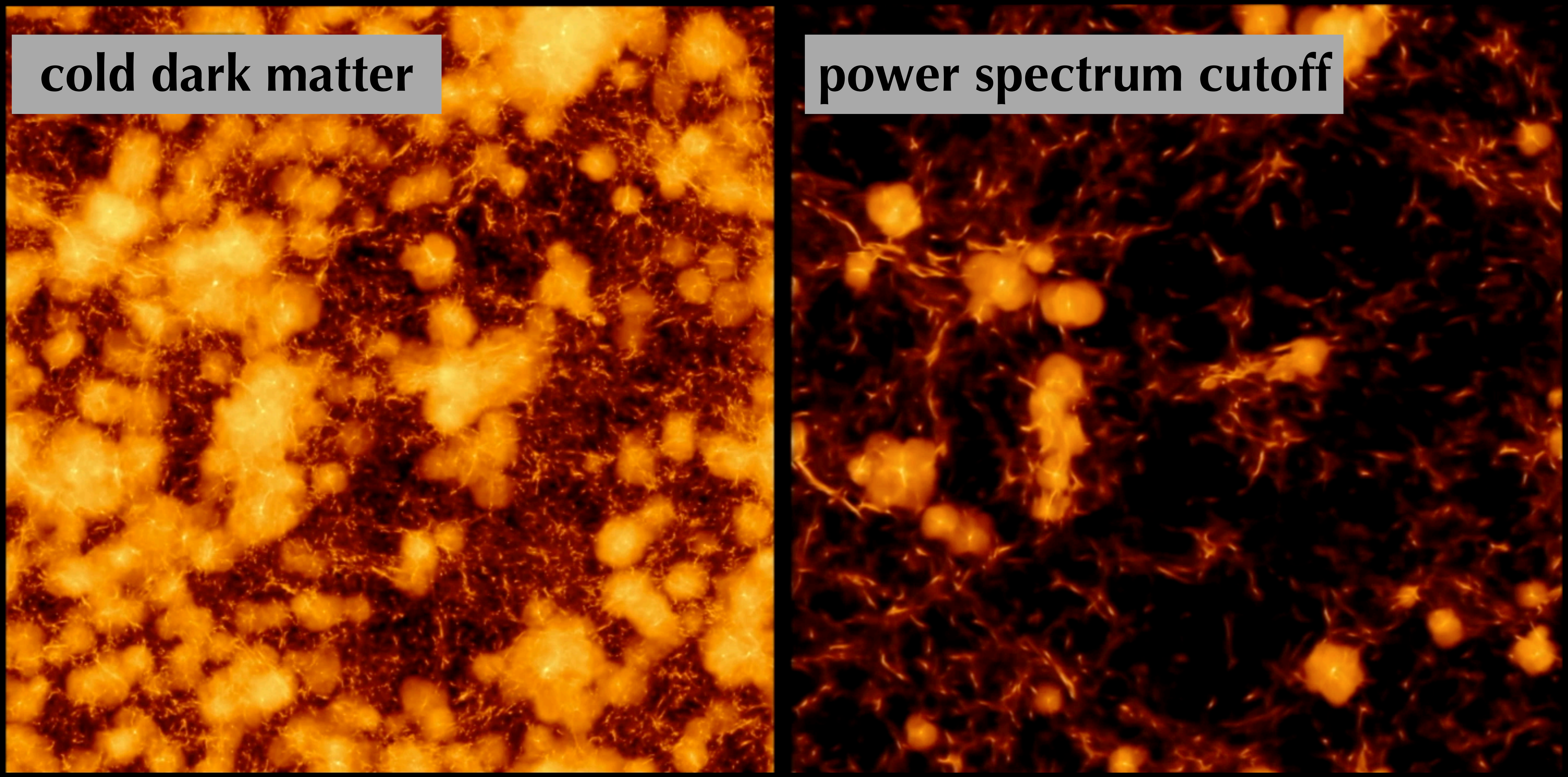
BBH parameters (masses, spins etc.)

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

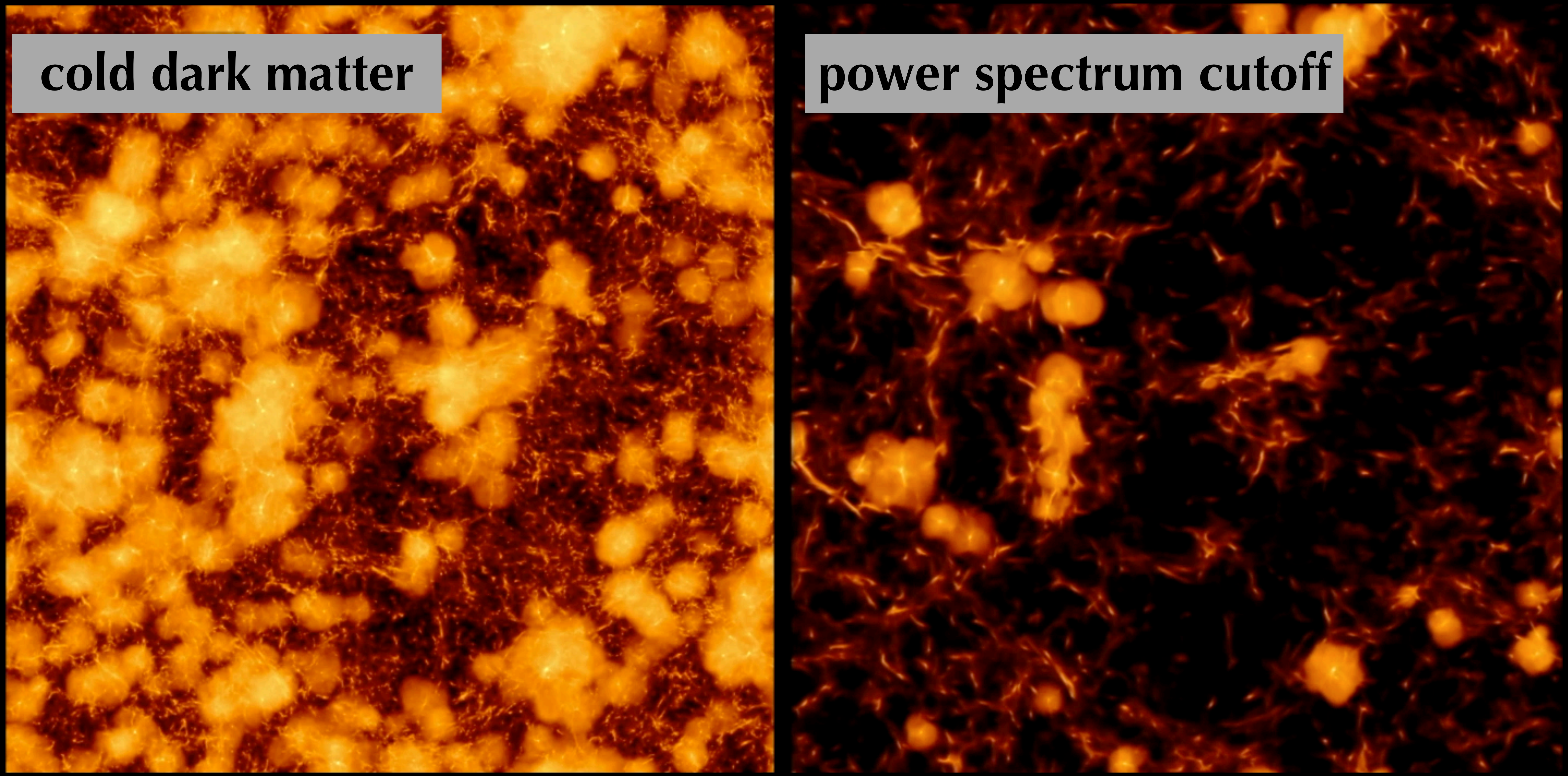


forecasts for one year of observations with Einstein Telescope + 2 Cosmic Explorers


Epochs:
Recombination
Dark Ages
Cosmic Dawn
Reionization
Growth of Structure
1100
200
30
13
7
1
0
z
past
present
Probes:
CMB
LIM
Galaxy Surveys
1100
0
z
Kovetz+ Astro 2020



★ mapping the topology of primordial ionisation fields will provide a completely novel (and orthogonal) constraint on the shape of the initial power spectrum.



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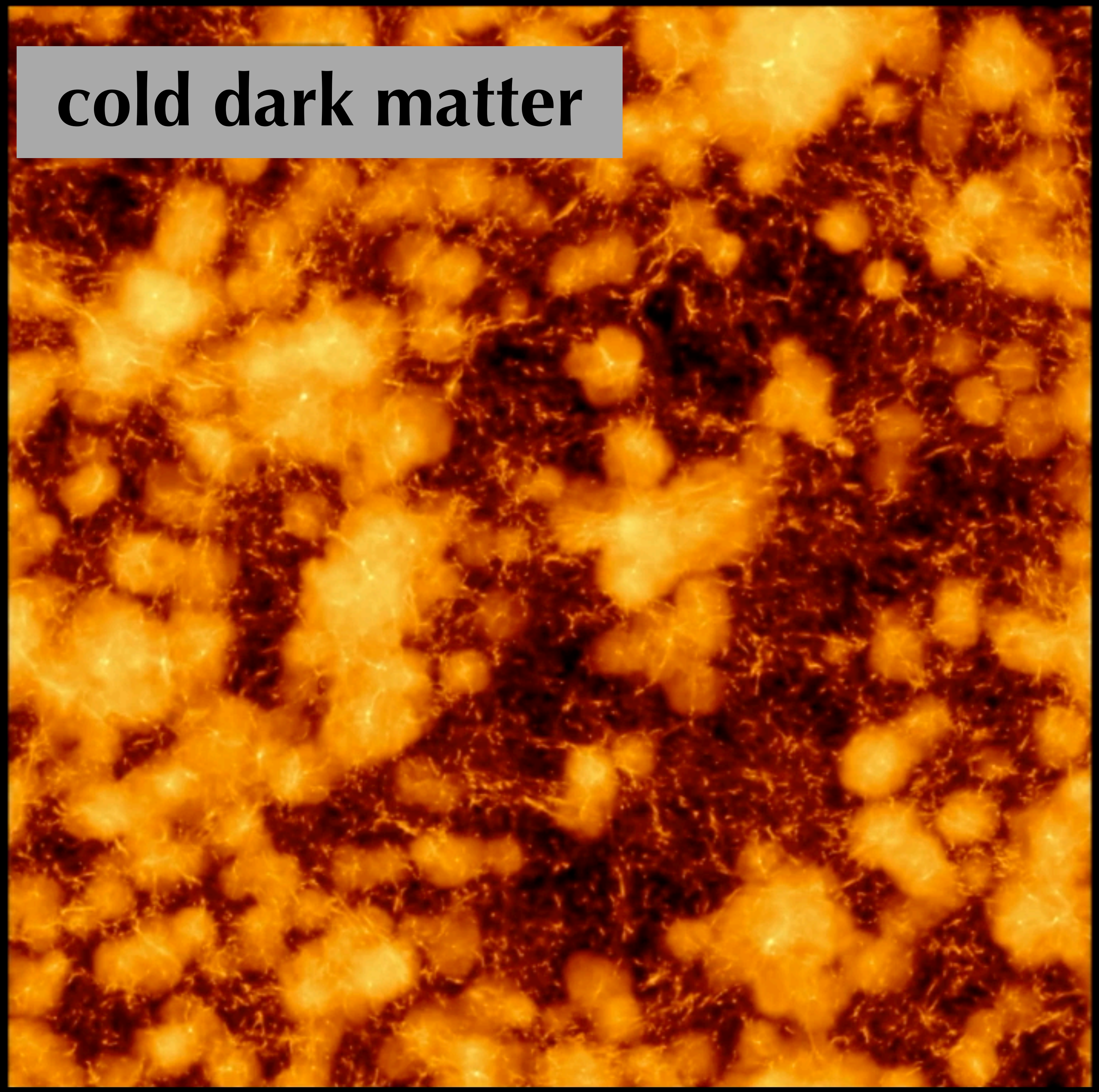
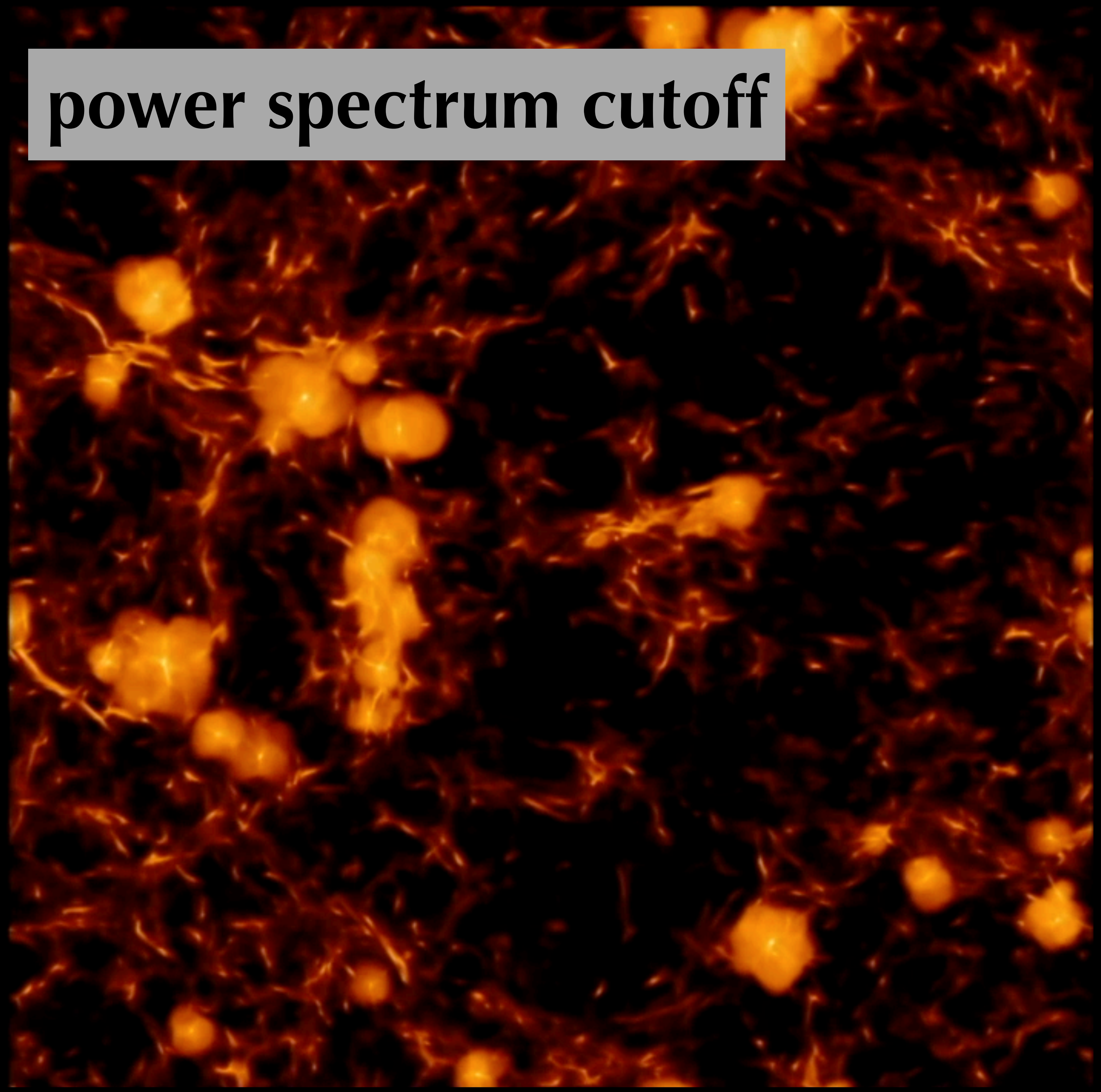


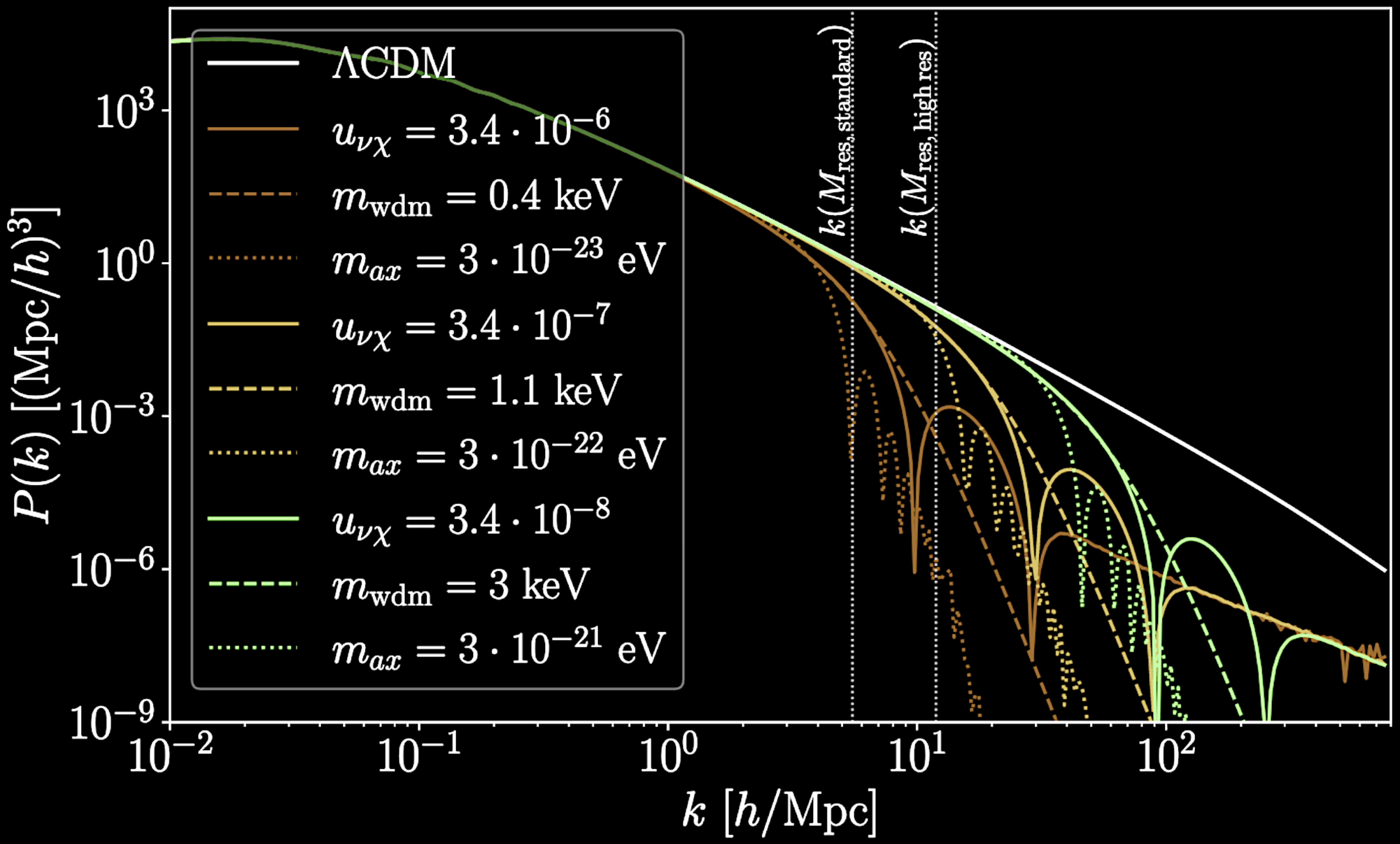


★ mapping the topology of primordial ionisation fields will provide a completely novel (and orthogonal) constraint on the shape of the initial power spectrum.

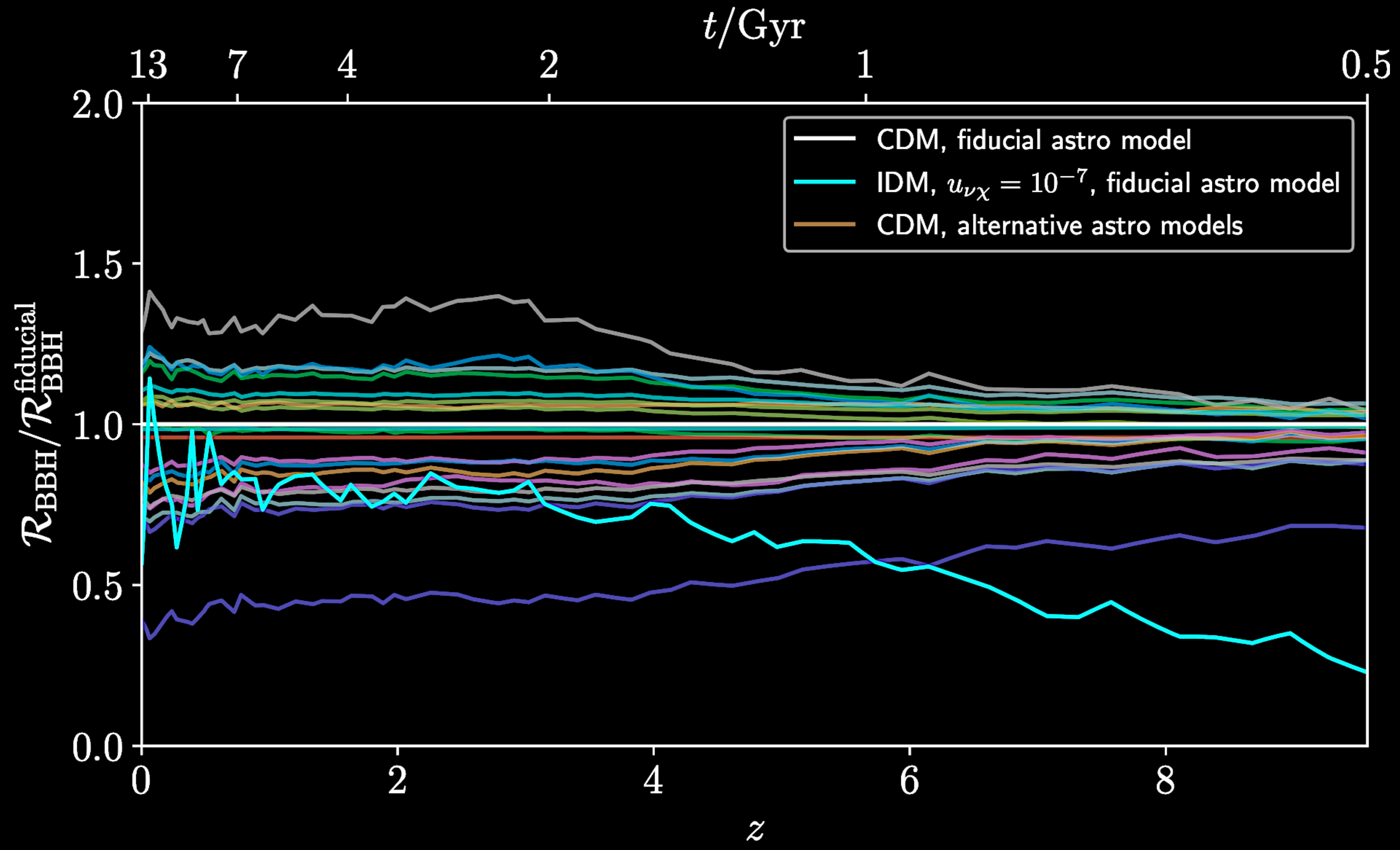
summary

- 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
- 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

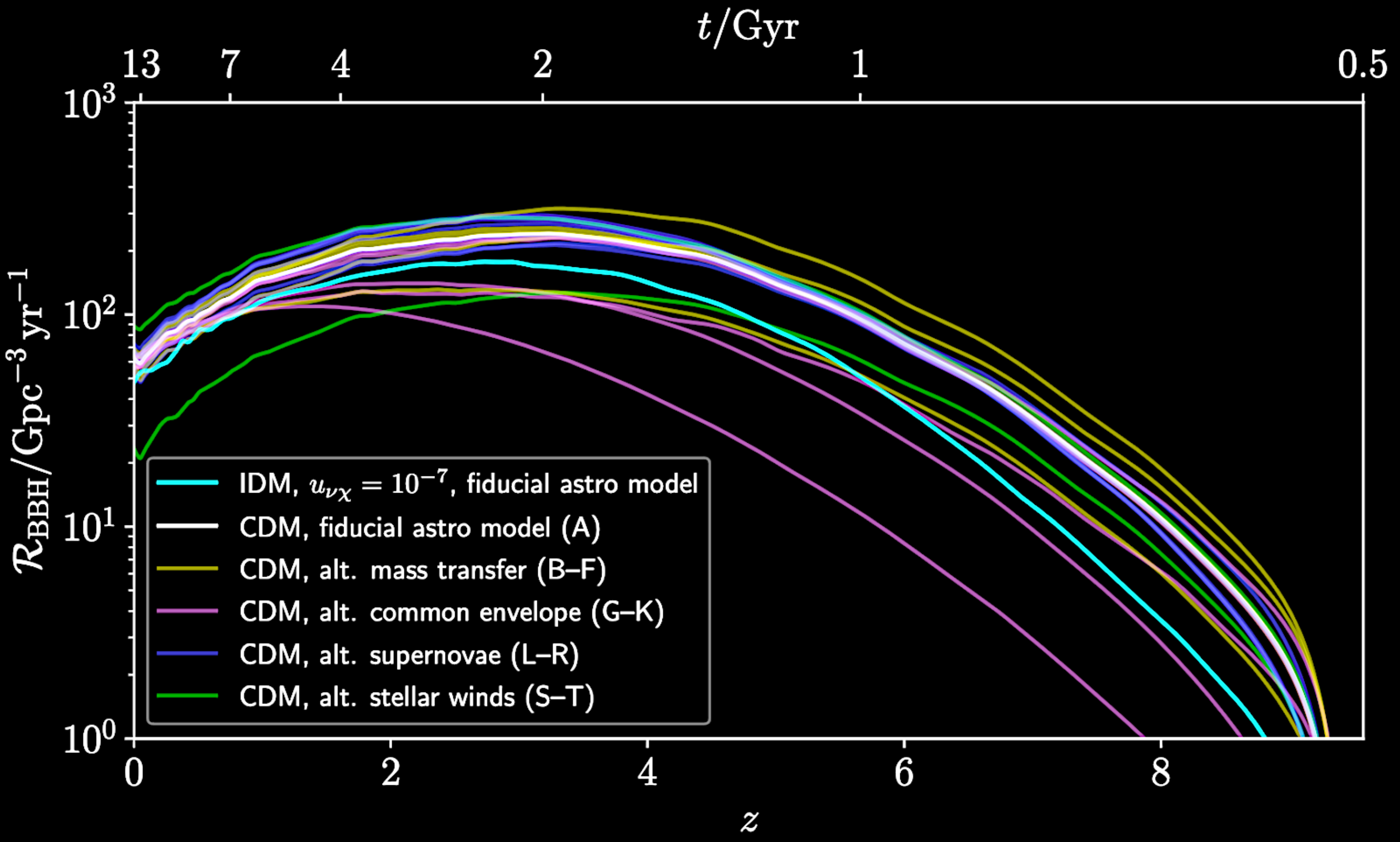
backup



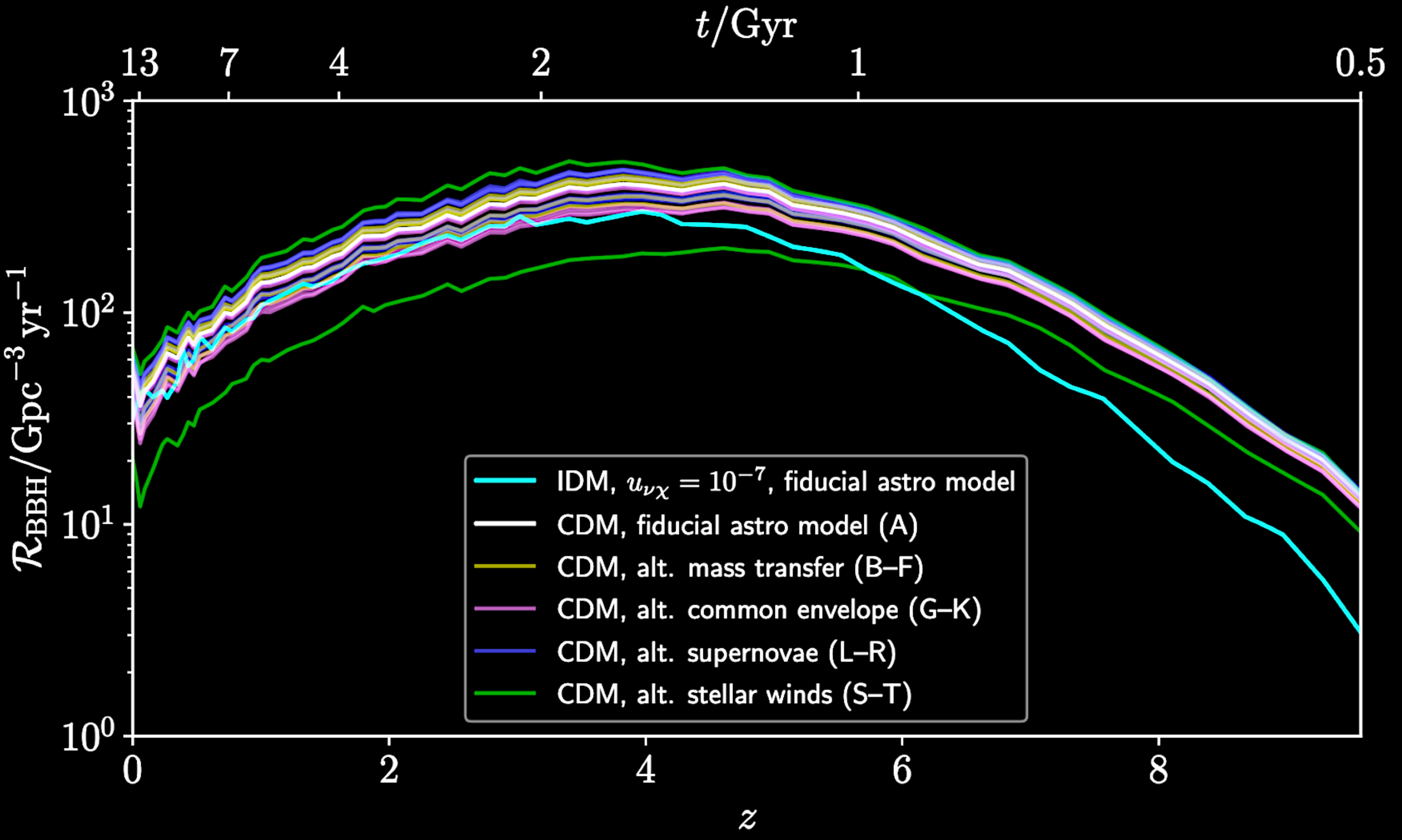
ΛCDM
$u_{\nu\chi} = 3.4 \cdot 10^{-6}$
$m_{\rm wdm} = 0.4$ keV
$m_{ax} = 3 \cdot 10^{-23}$ eV
$u_{\nu\chi} = 3.4 \cdot 10^{-7}$
$m_{\rm wdm} = 1.1$ keV
$m_{ax} = 3 \cdot 10^{-22}$ eV
$u_{\nu\chi} = 3.4 \cdot 10^{-8}$
$m_{\rm wdm} = 3$ keV
$m_{ax} = 3 \cdot 10^{-21}$ eV
$k(M_{\rm res, standard})$
$k(M_{\rm res, high\ res})$
$P(k)$ $[({\rm Mpc}/h)^3]$
k $[h/{\rm Mpc}]$
10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}



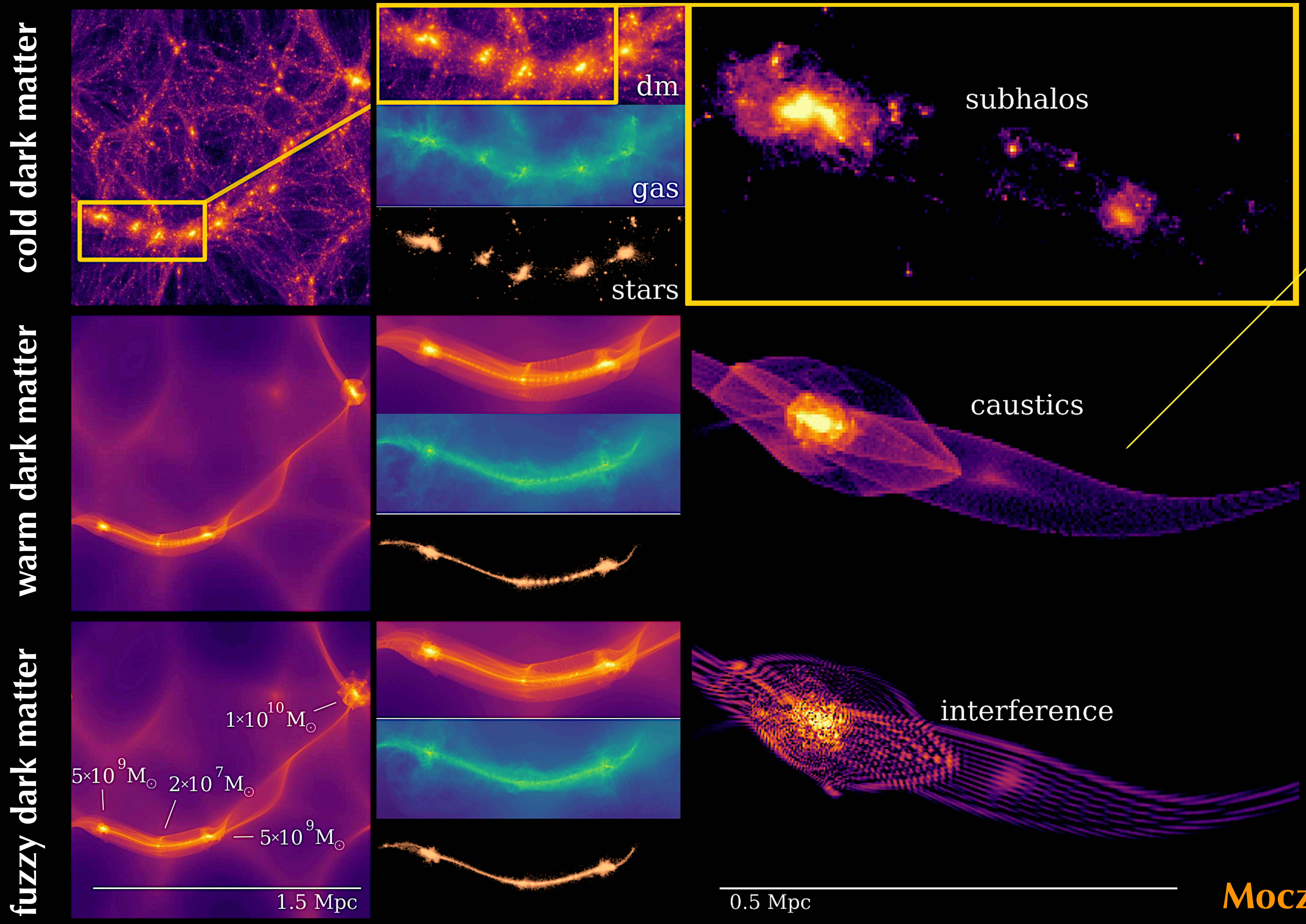
t/Gyr
13
7
4
2
1
0.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
z
$\mathcal{R}_{\mathrm{BBH}}/\mathcal{R}_{\mathrm{BBH}}^{\mathrm{fiducial}}$
CDM, fiducial astro model
IDM, $u_{\nu\chi} = 10^{-7}$, fiducial astro model
CDM, alternative astro models



t/Gyr
13
7
4
2
1
0.5
10^3
10^2
10^1
10^0
$\mathcal{R}_{\mathrm{BBH}}/\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
IDM, $u_{\nu\chi} = 10^{-7}$, fiducial astro model
CDM, fiducial astro model (A)
CDM, alt. mass transfer (B–F)
CDM, alt. common envelope (G–K)
CDM, alt. supernovae (L–R)
CDM, alt. stellar winds (S–T)
0
2
4
6
8
z



t/Gyr
13
7
4
2
1
0.5
10^3
10^2
10^1
10^0
$\mathcal{R}_{\mathrm{BBH}}/\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
IDM, $u_{\nu\chi} = 10^{-7}$, fiducial astro model
CDM, fiducial astro model (A)
CDM, alt. mass transfer (B–F)
CDM, alt. common envelope (G–K)
CDM, alt. supernovae (L–R)
CDM, alt. stellar winds (S–T)
0
2
4
6
8
z



cosmic web filaments — the seats of first star formation — show morphological variations with the particle nature of dark matter

Mocz, … Bose+ (2019 a, b)