Primordial black holes and ultradense halos

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Outline

Primordial perturbations

Primordial black holes

Dark matter halos

Ultradense halos forming during the radiation epoch

Growth and evolution of the smallest halos

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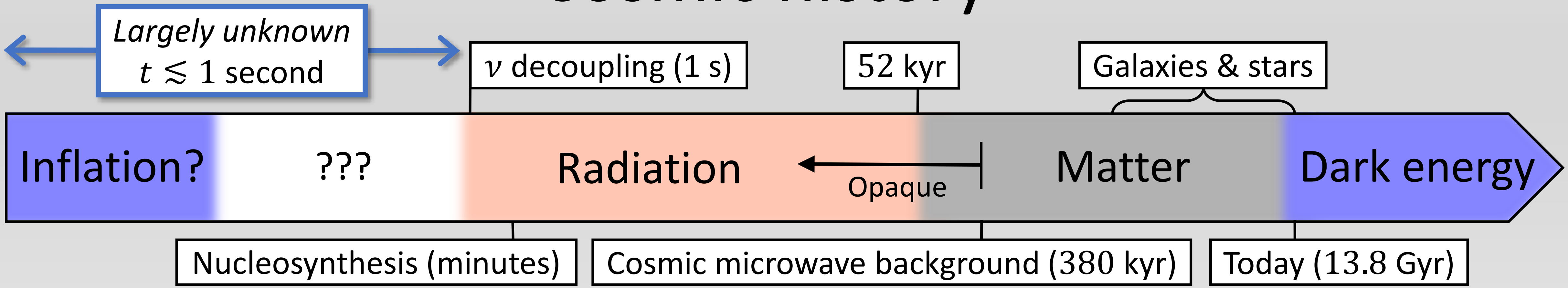
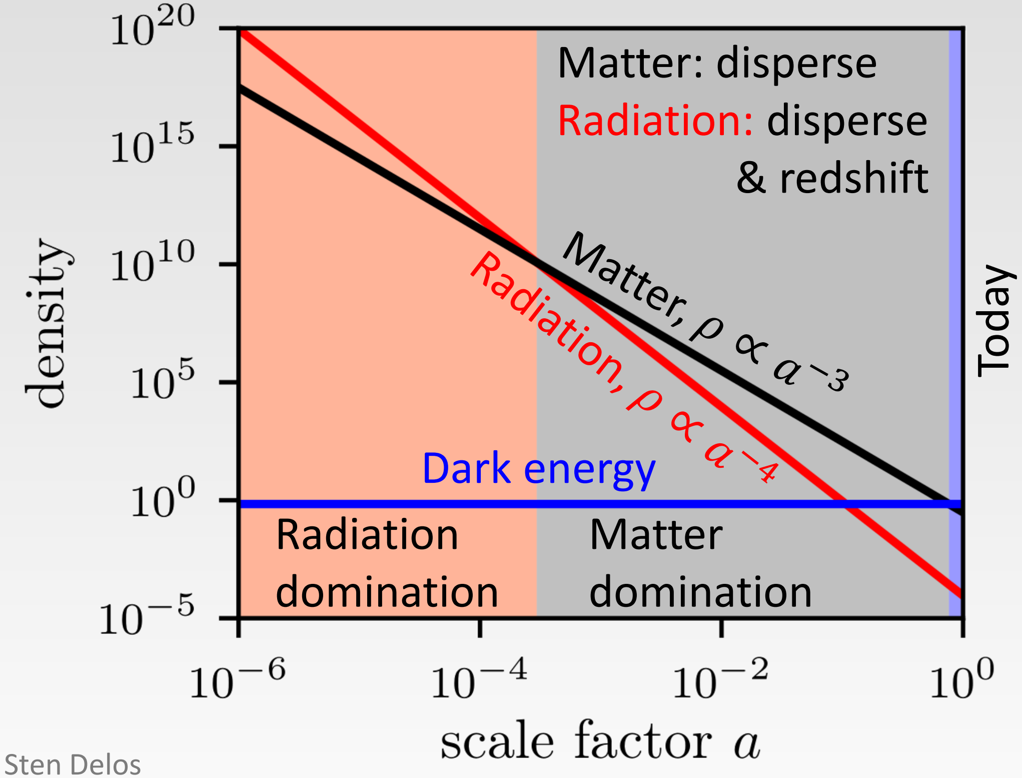
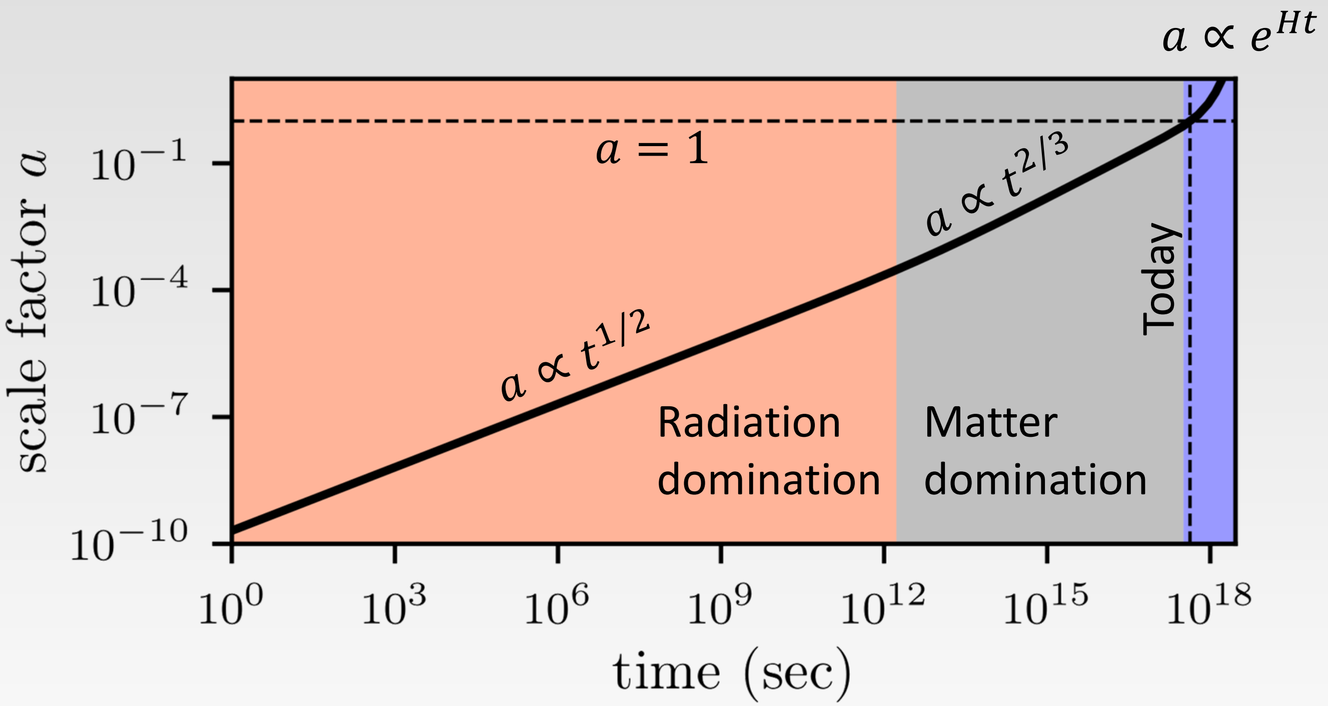
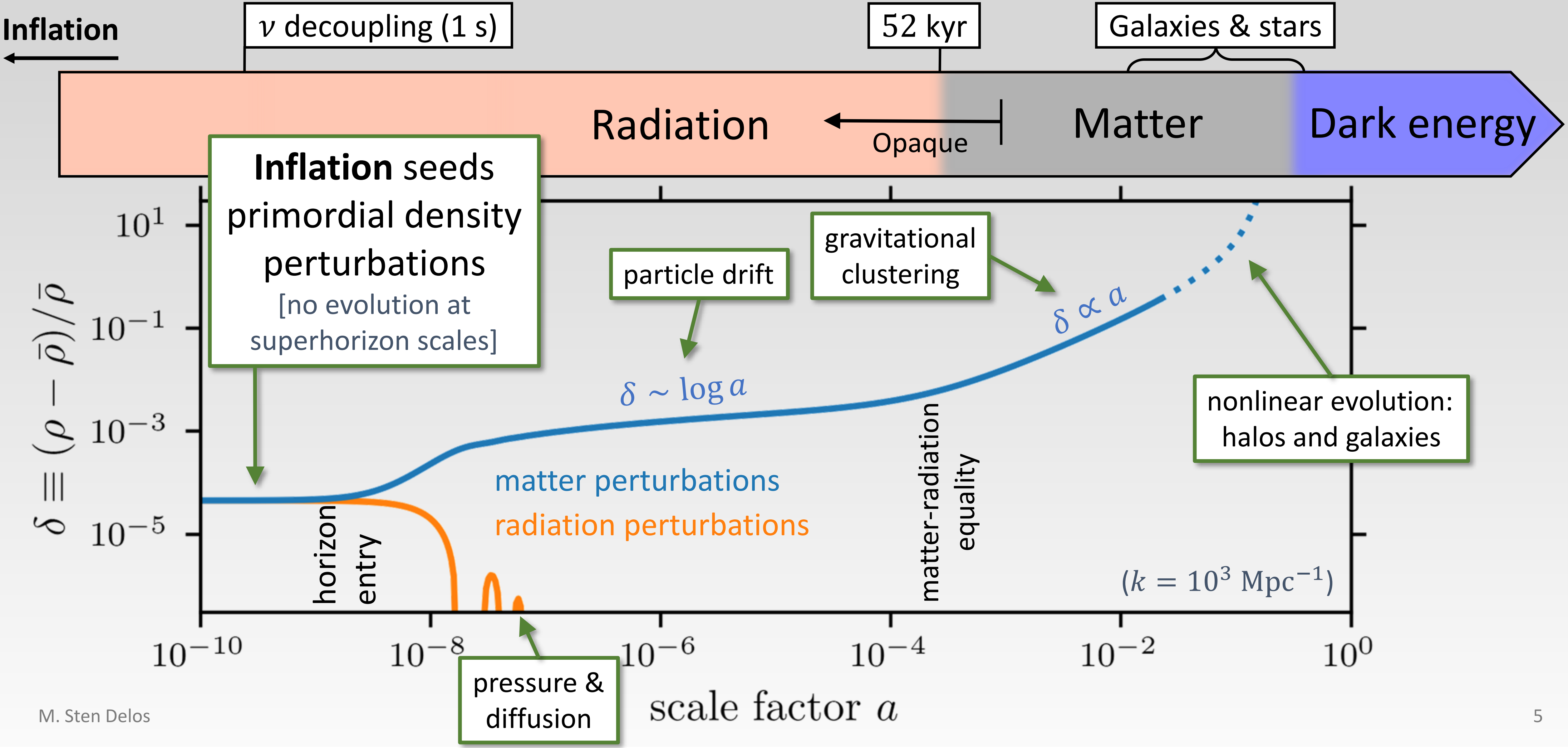
Cosmic history





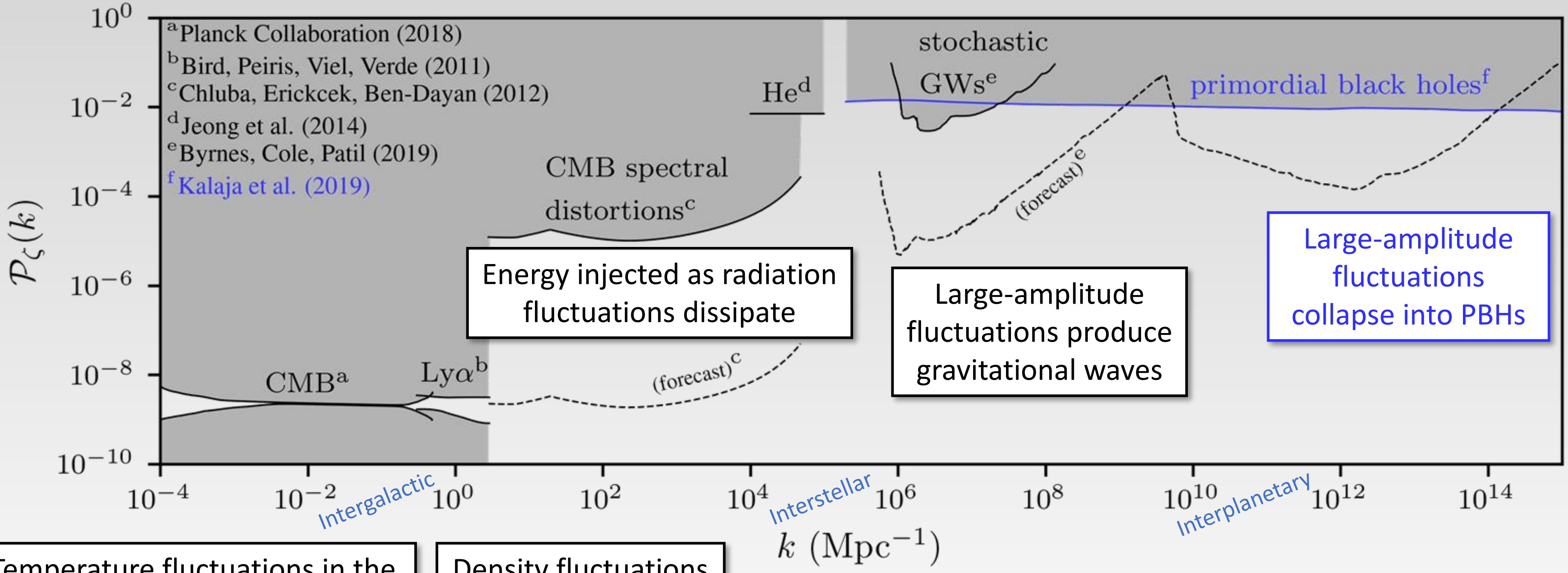


Growth of perturbations



Primordial perturbations

Superhorizon (primordial) perturbations are tightly constrained **only at large scales:**

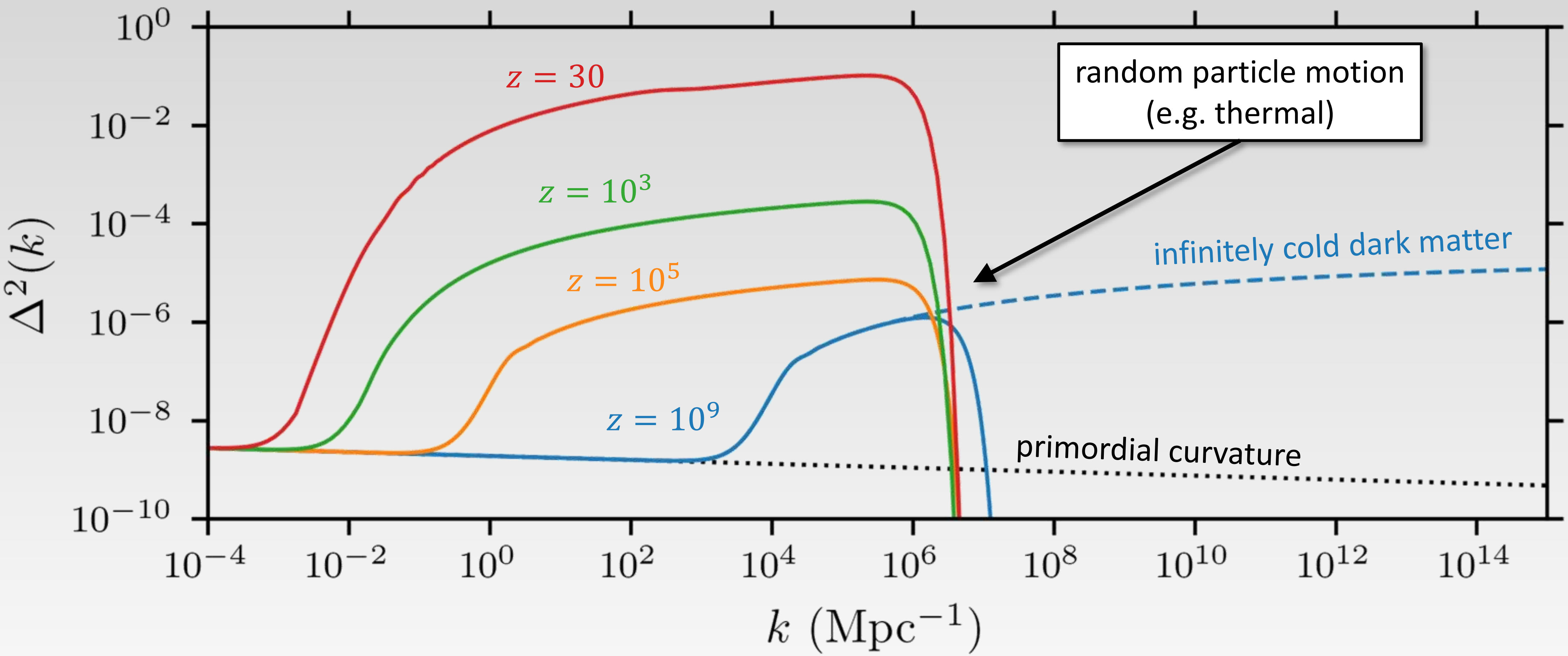


Temperature fluctuations in the cosmic microwave background

Density fluctuations in intergalactic gas

Matter perturbations

Consider a power-law primordial power spectrum that is consistent with CMB measurements



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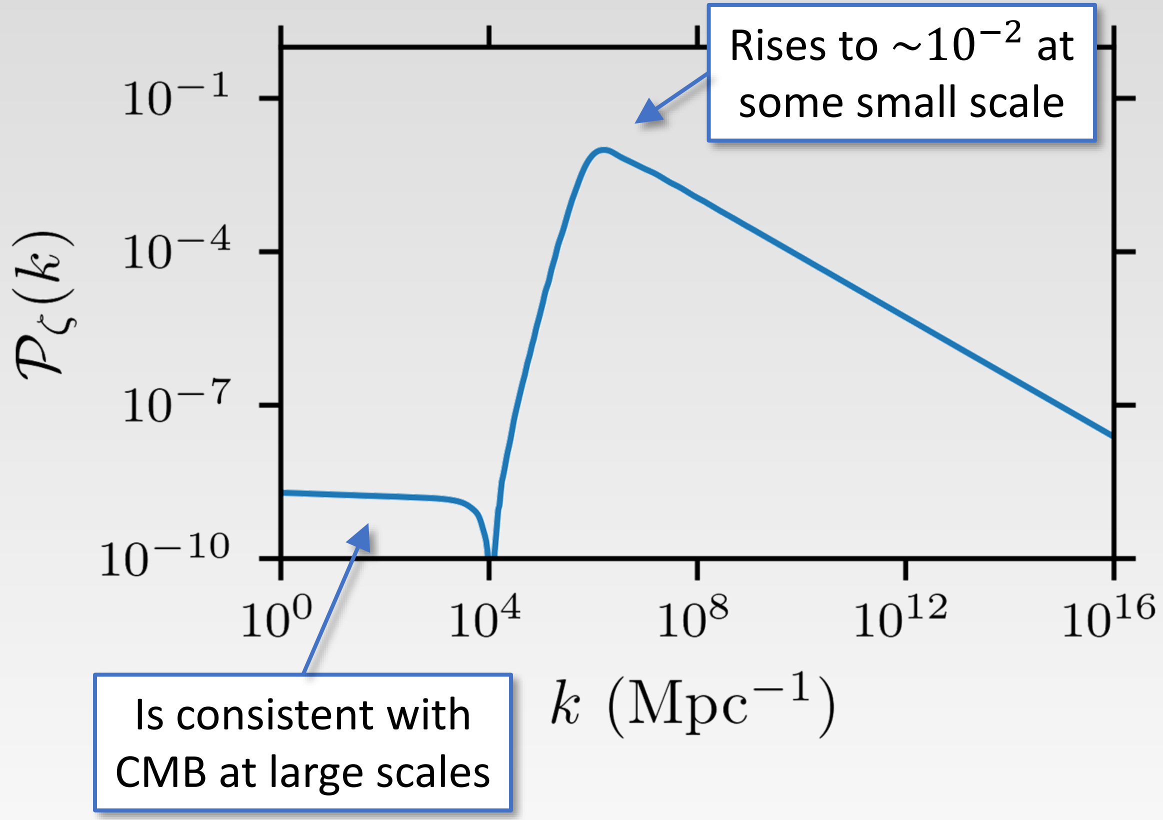
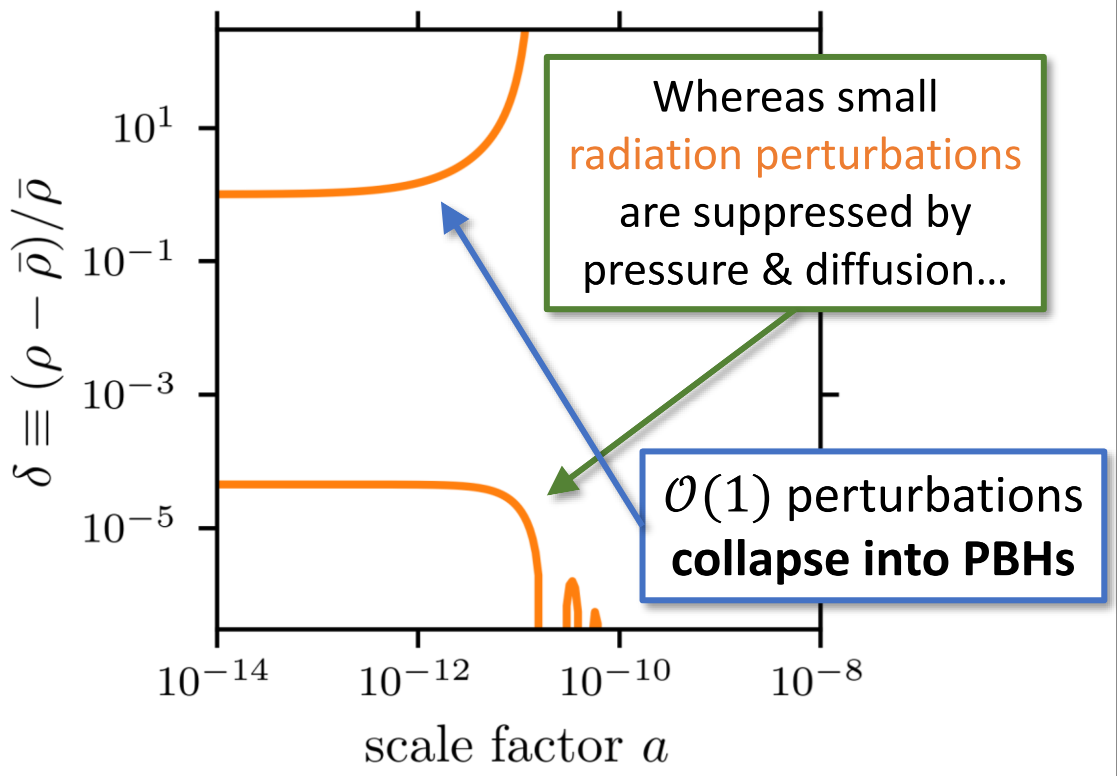
Primordial black holes

Consider a primordial power spectrum that…



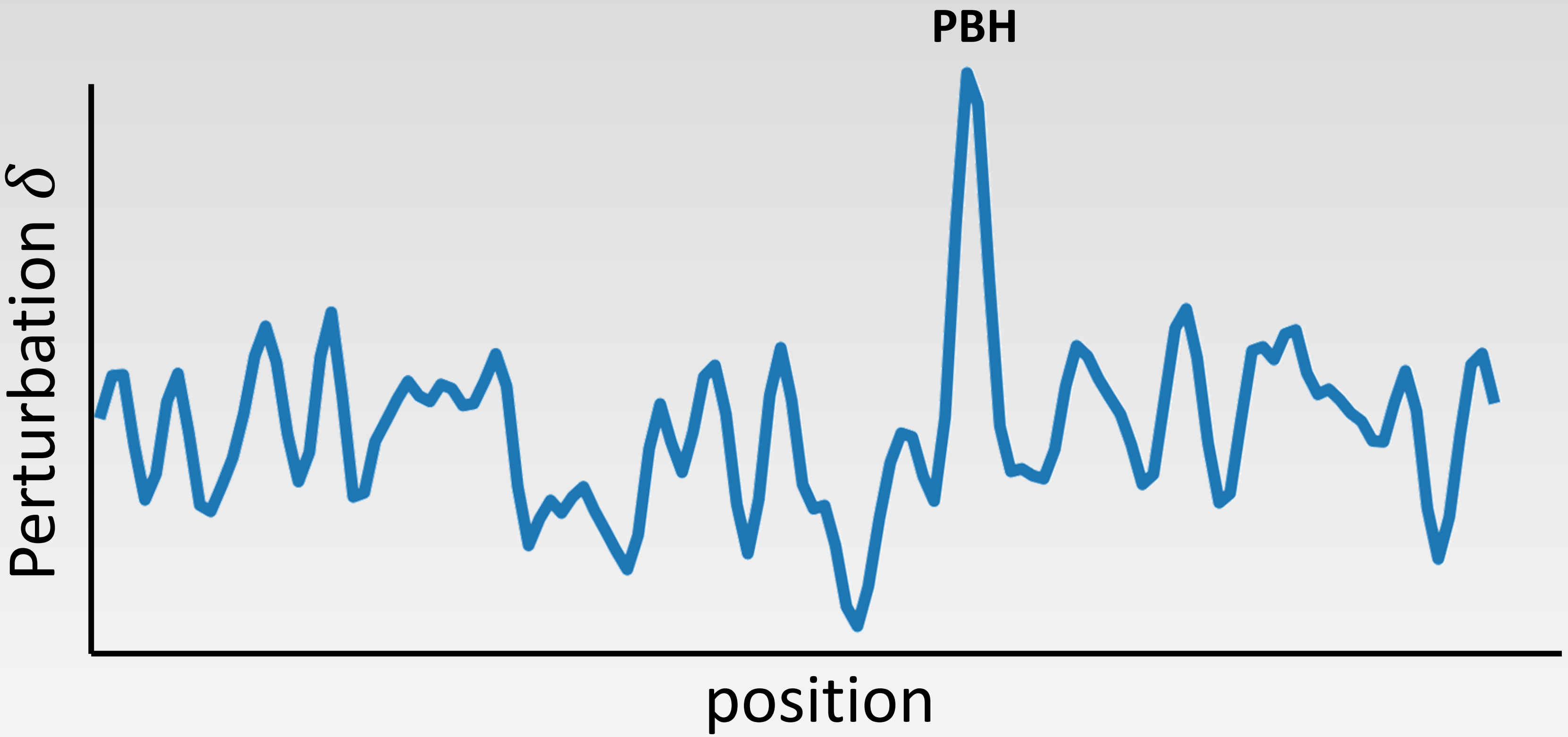
$\mathcal{O}(1)$ primordial perturbations can arise at that scale



Primordial black holes

Only the most extreme initial density excesses produce PBHs

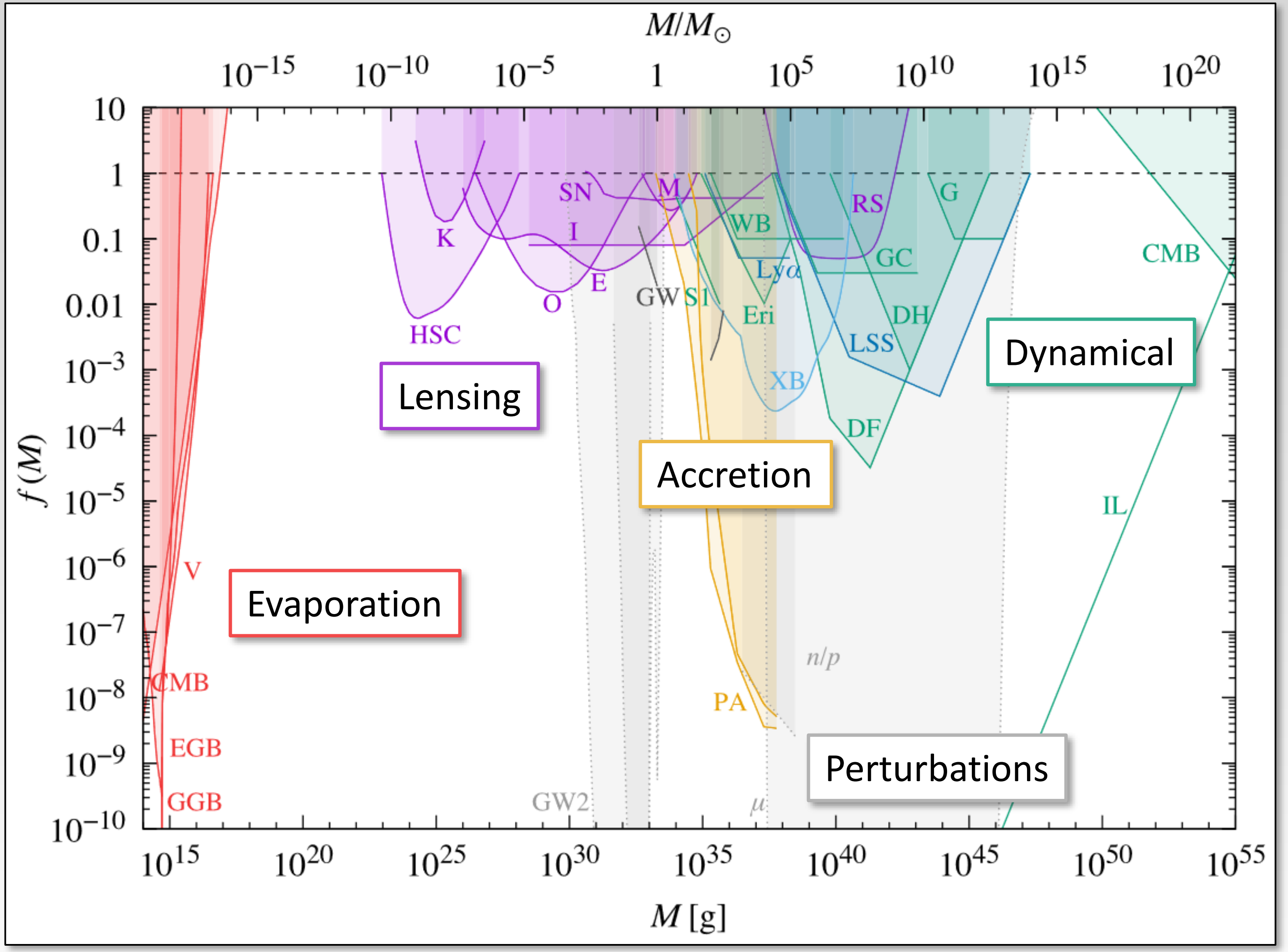
[otherwise PBHs would be overproduced]



Constraints on primordial black holes

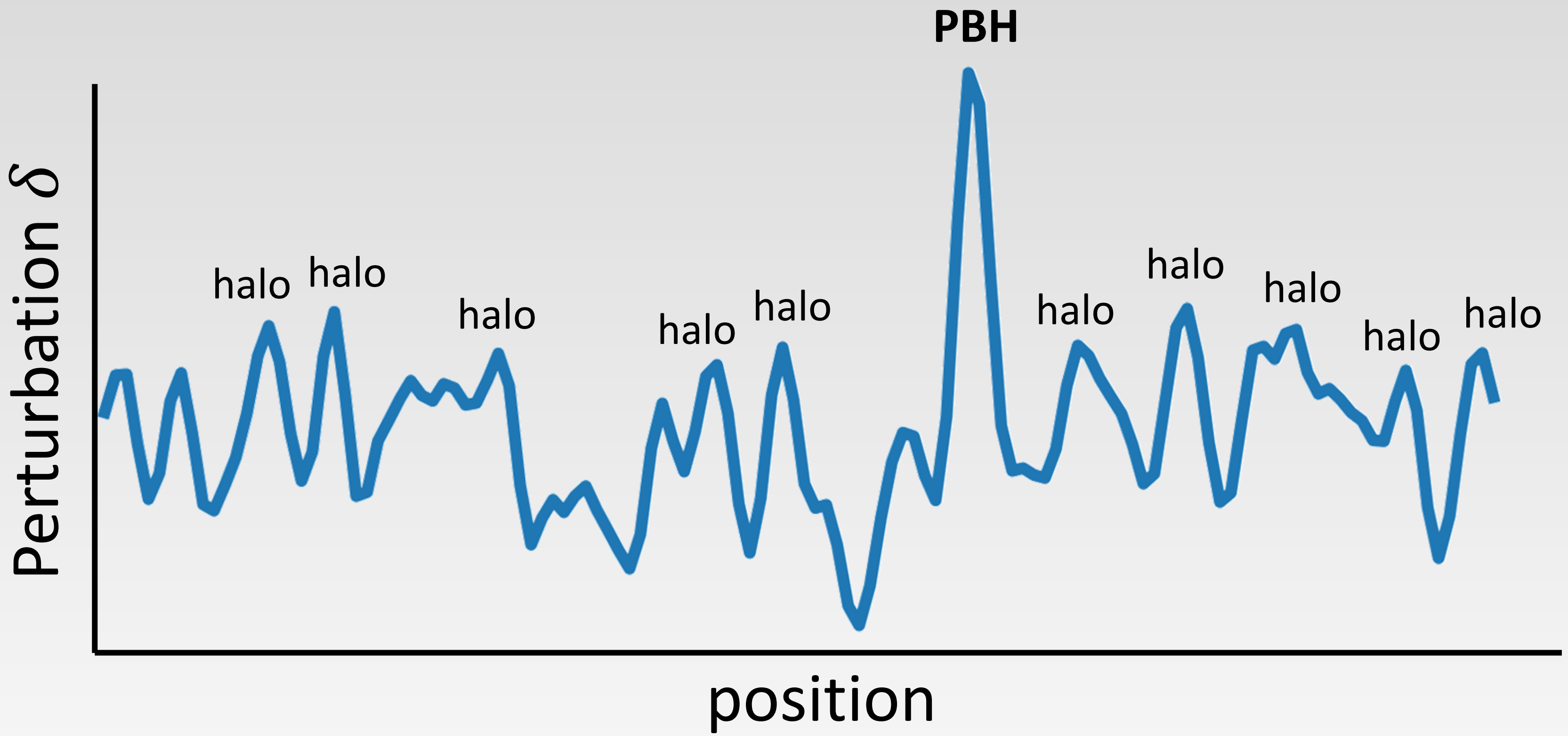
PBHs could be detected through their lensing, dynamical, or accretion signatures. Low-mass PBHs could be detected through their evaporation. Perturbations of sufficient amplitude to produce PBHs would also produce other signatures.

PBHs in a narrow mass range probably cannot comprise all of the dark matter
[except in the asteroid-mass window]



Primordial black holes and dark matter halos

If PBHs are not all of the dark matter, then the same perturbation spectrum that produces PBHs **also produces many more dark matter halos**



The halos consist of particle dark matter (or much smaller PBHs)

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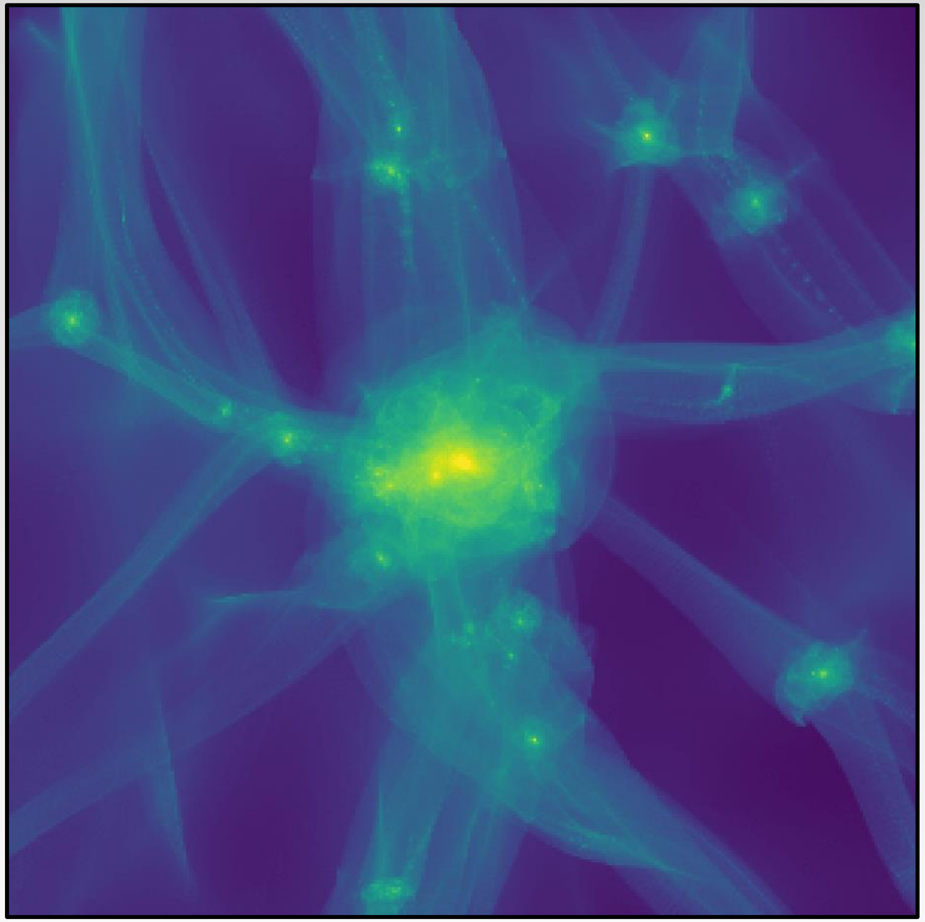
Dark matter halos

- There is ~ 5 times more dark matter than baryons
- Dark matter drives gravitational structure formation

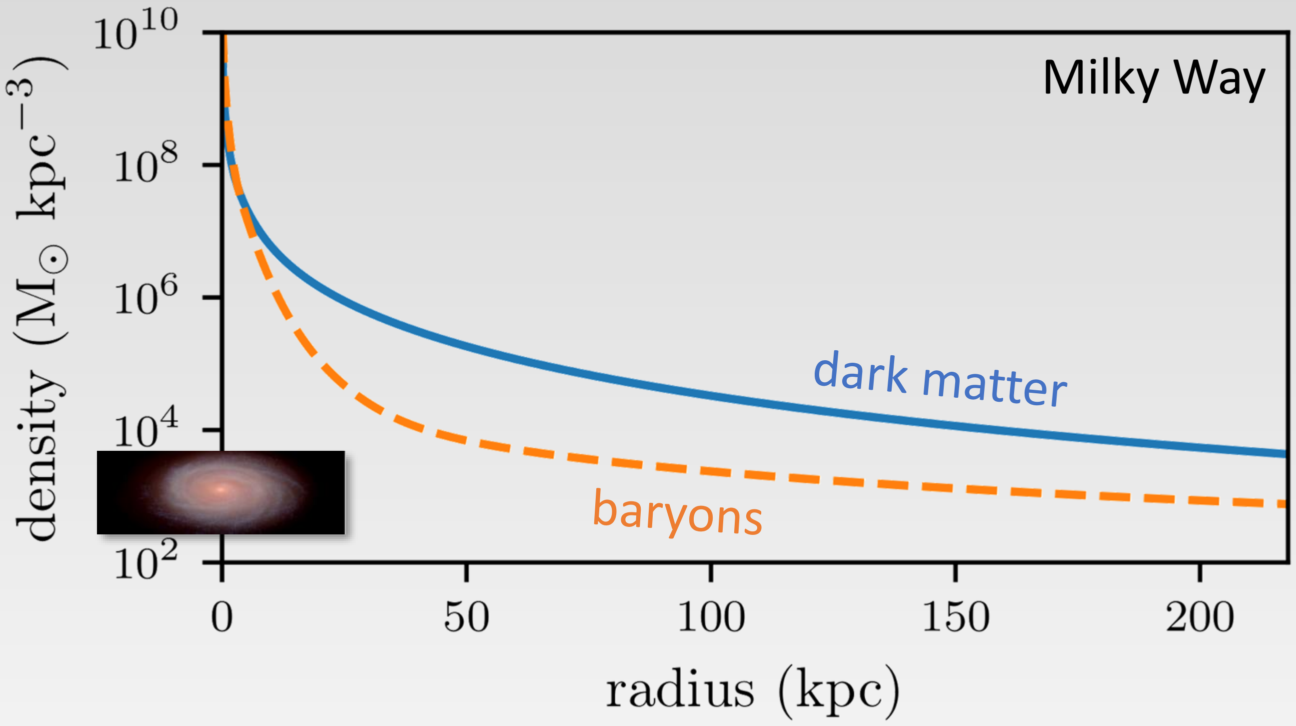
Regions with excess density collapse under gravity to form hot clouds of dark matter

[Unlike visible matter, DM is essentially collisionless and cannot cool]



Dark matter halos

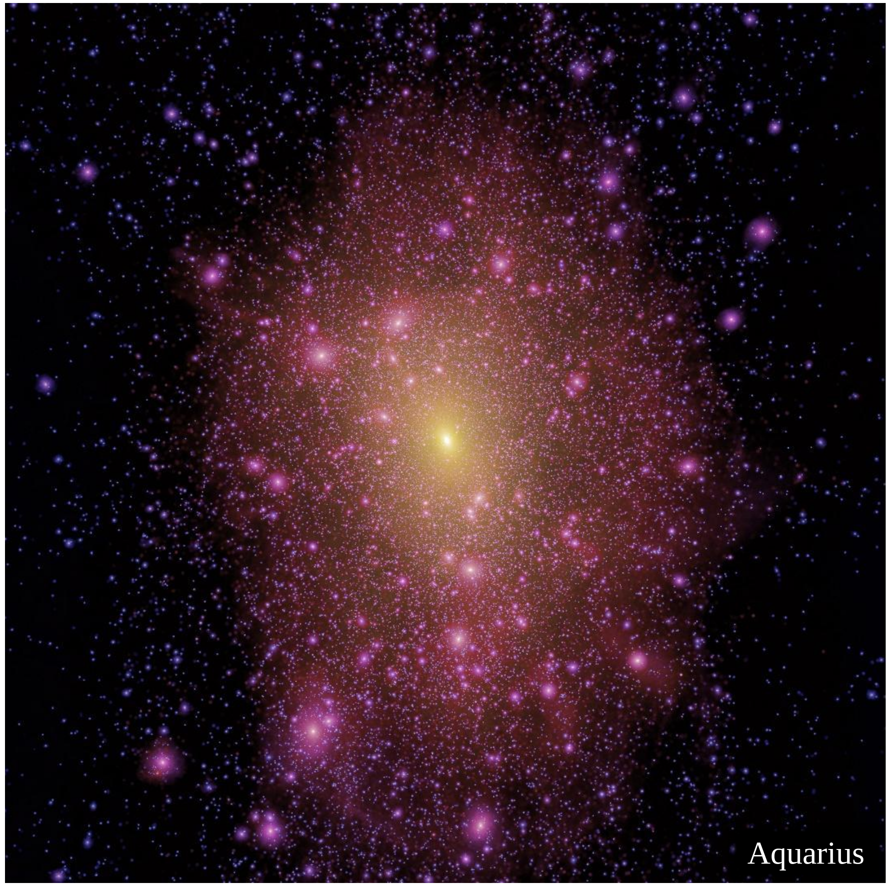
- There is $\sim$5 times more dark matter than baryons
- Dark matter drives gravitational structure formation



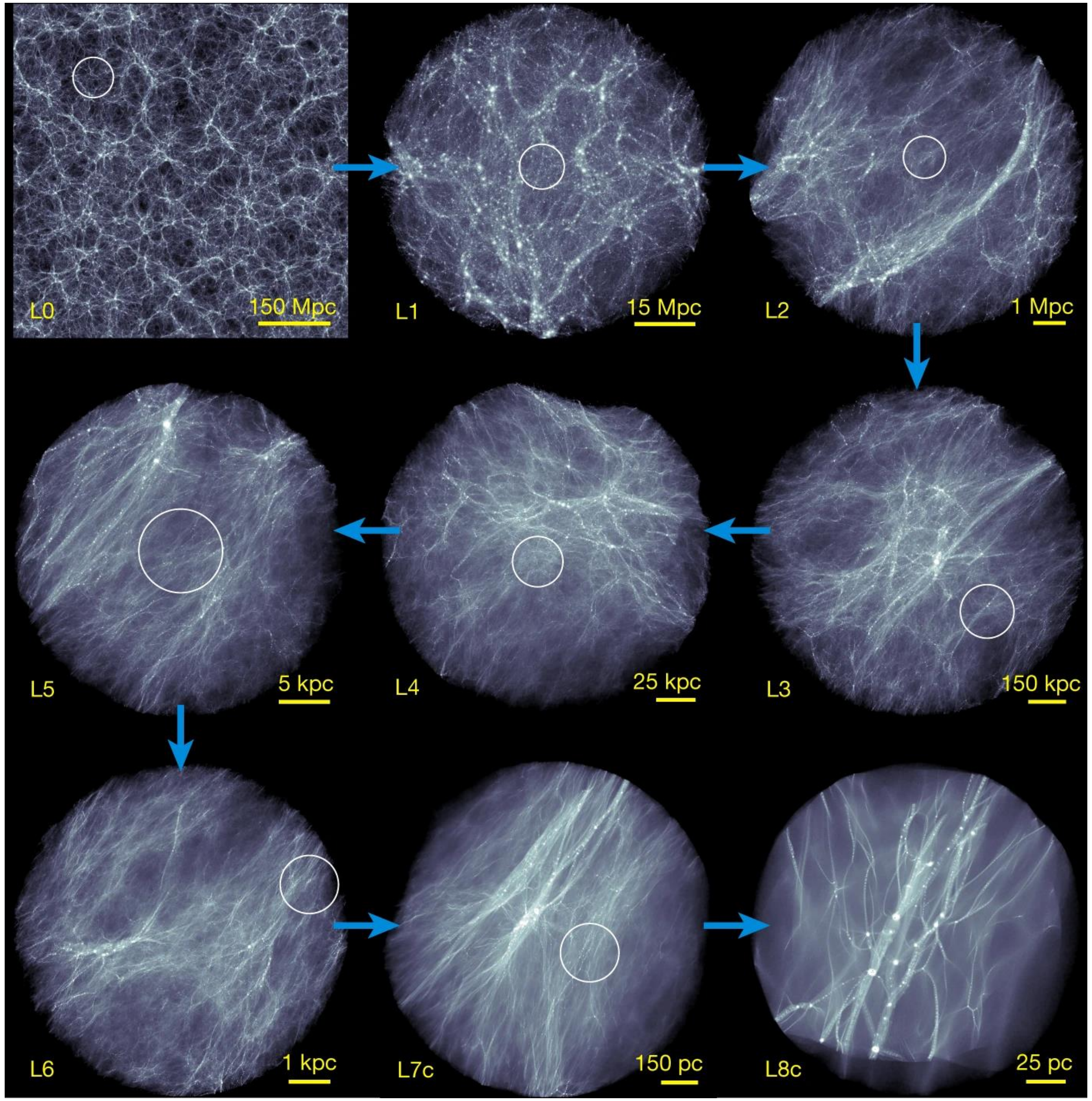
MW mass model: Cautun et al (2020)
picture of simulated MW-like galaxy: Grand et al (2021)

Dark matter halos

Subhalos persist inside other halos:



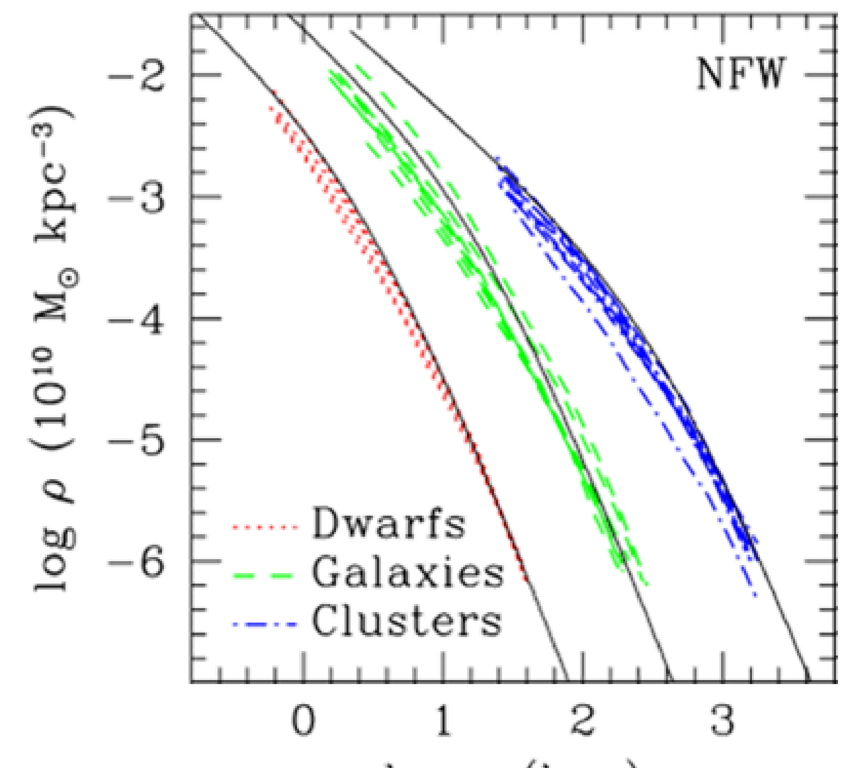
Halos form at all scales:



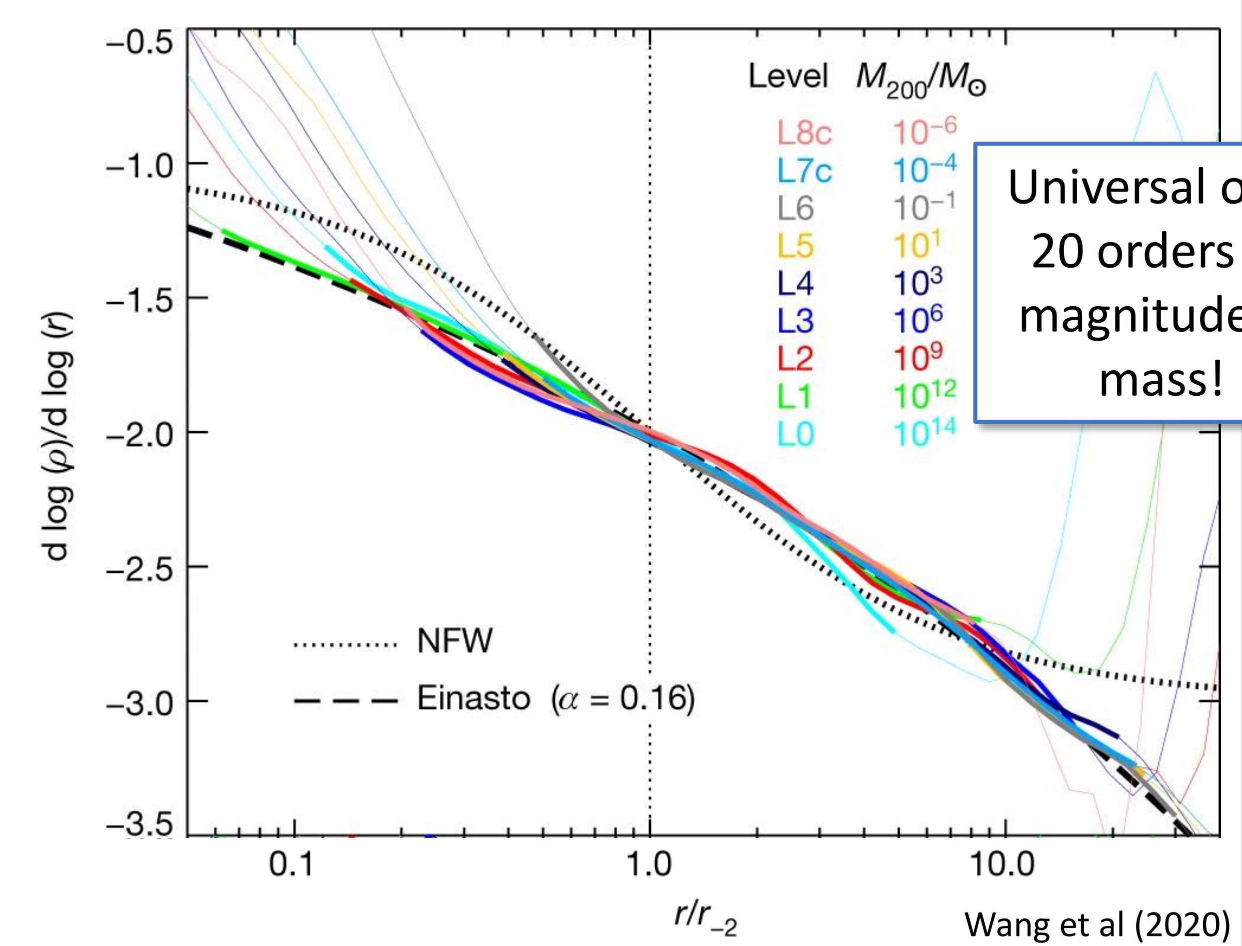
Wang et al (2020)

Halo density profiles

$\rho(r)$: shallow (logarithmic) decrease at small r, steep decrease at large r



Navarro et al (2004)

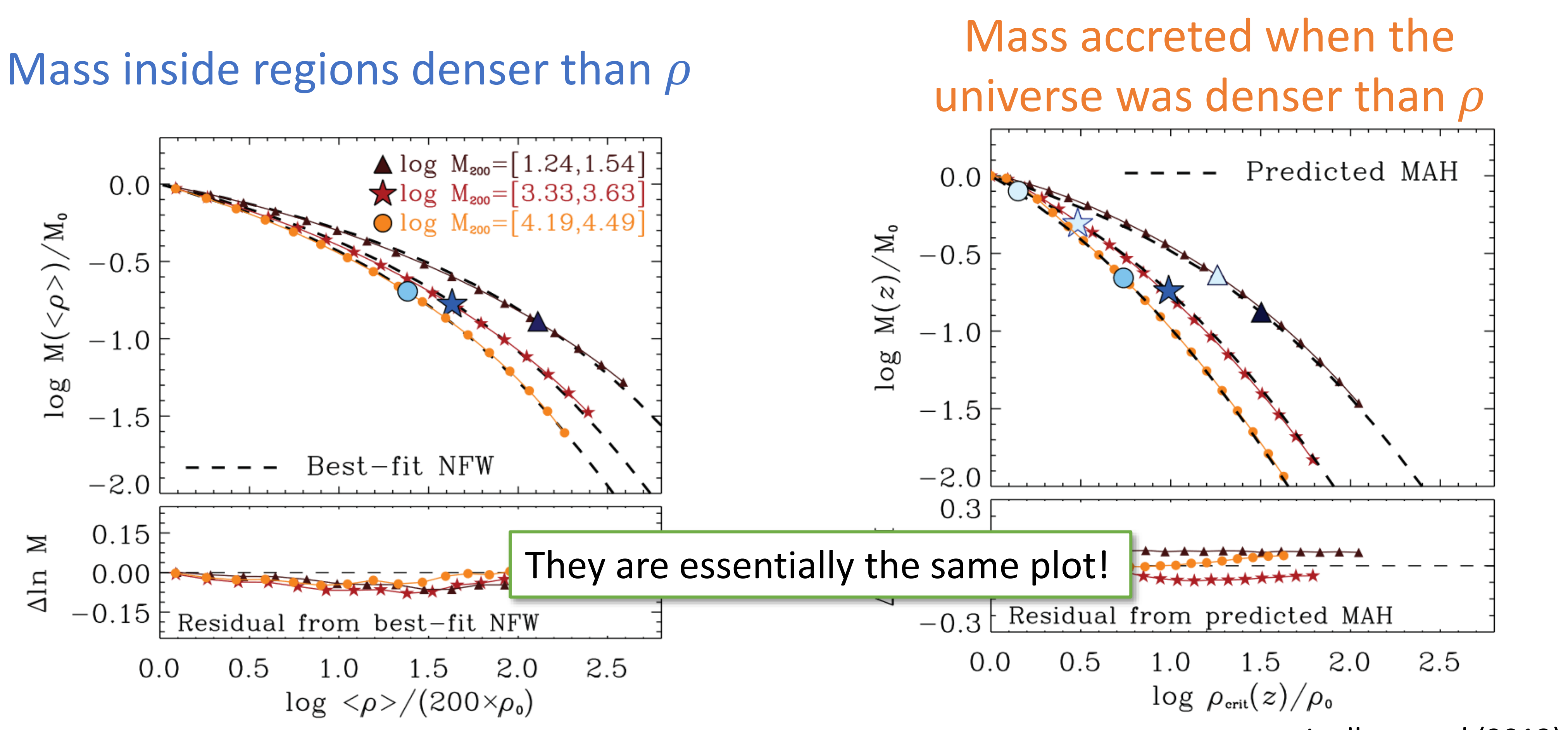


Wang et al (2020)

Universal over 20 orders of magnitude in mass!

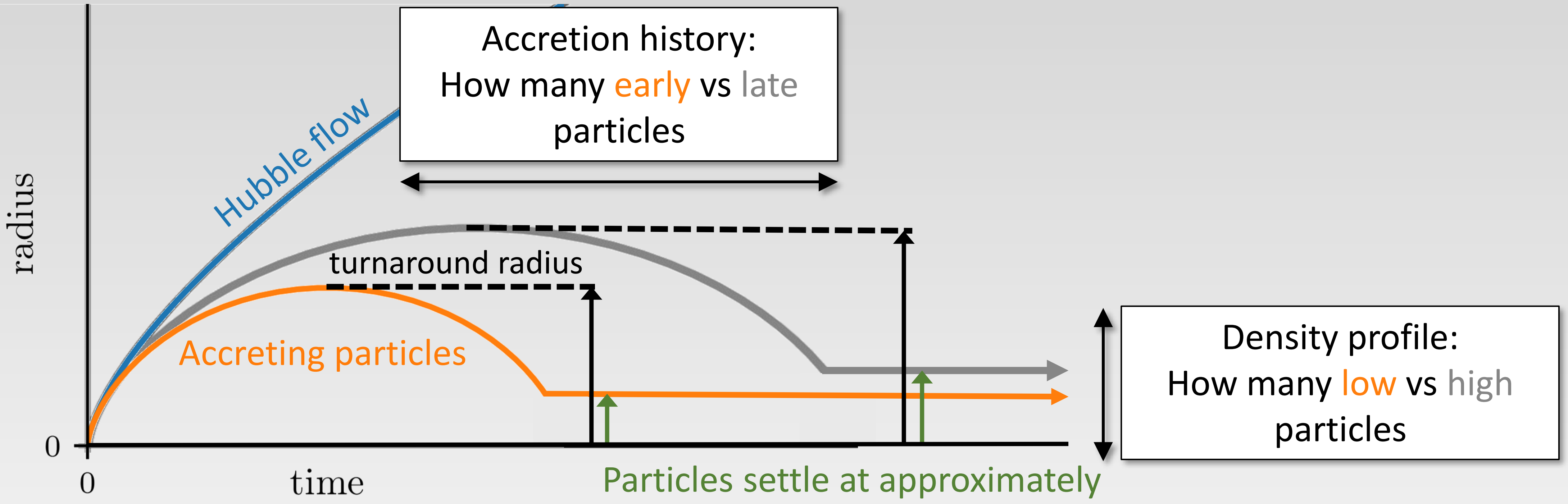
Density profile from accretion history

Density profiles are linked to accretion histories



Ludlow et al (2013)

Density profile from accretion history



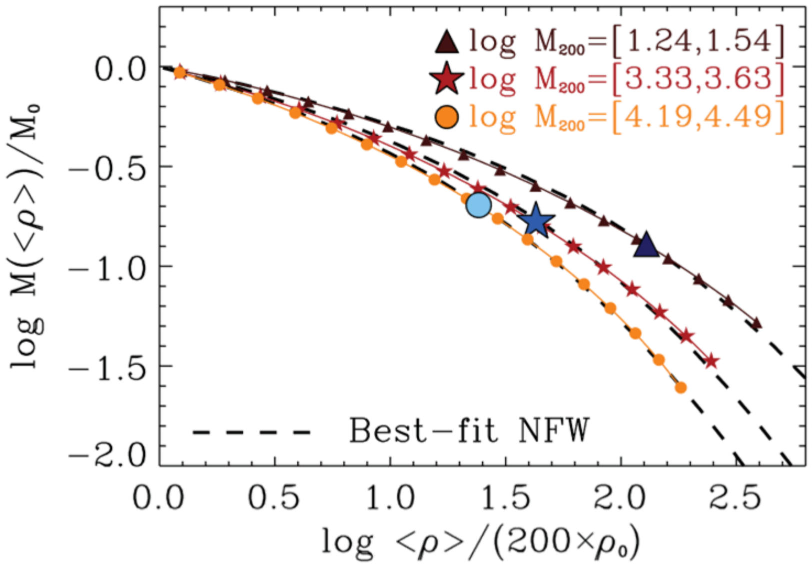
Particles settle at approximately fixed fraction of turnaround radius (average radius of stable orbits)

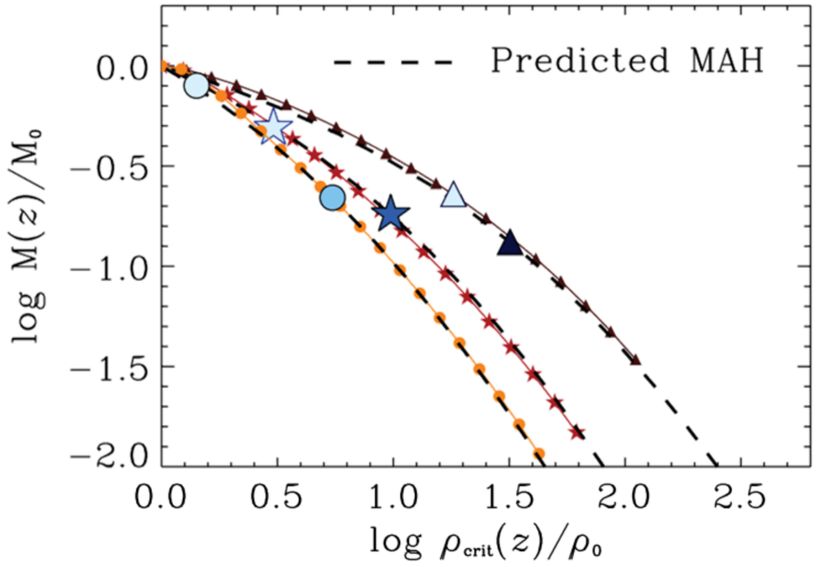
Thus, accretion history $\simeq$ density profile

Density profile from accretion history

Key point: within a halo,

Mass inside regions denser than $\sim 800\rho$ $\simeq$ Mass accreted when the universe was denser than ρ





Thus,

earlier halo formation → halos of higher internal density

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Early halo formation

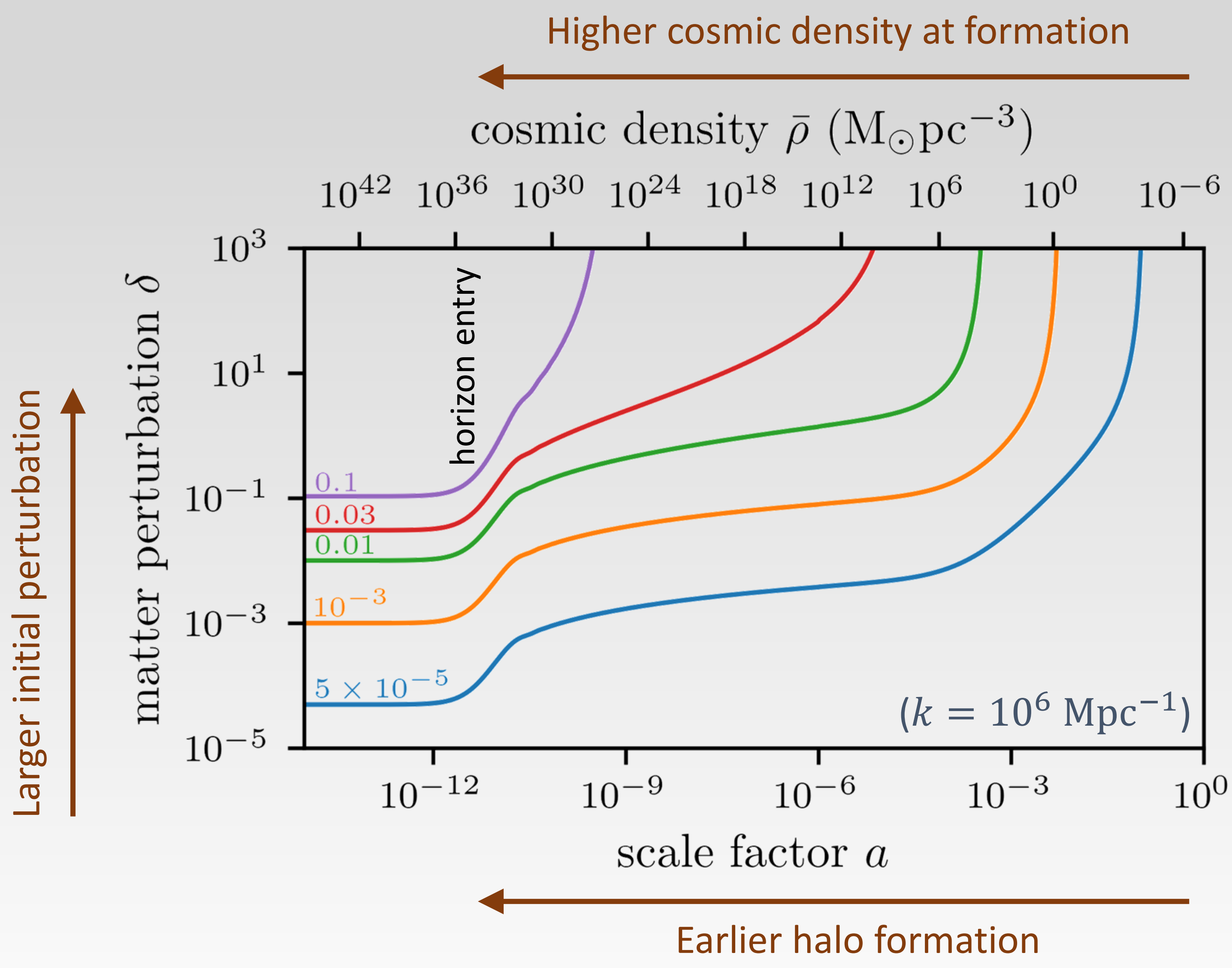
Large initial perturbations lead to early halo formation

⇩

high cosmic density at halo formation time

⇩

high density within halo



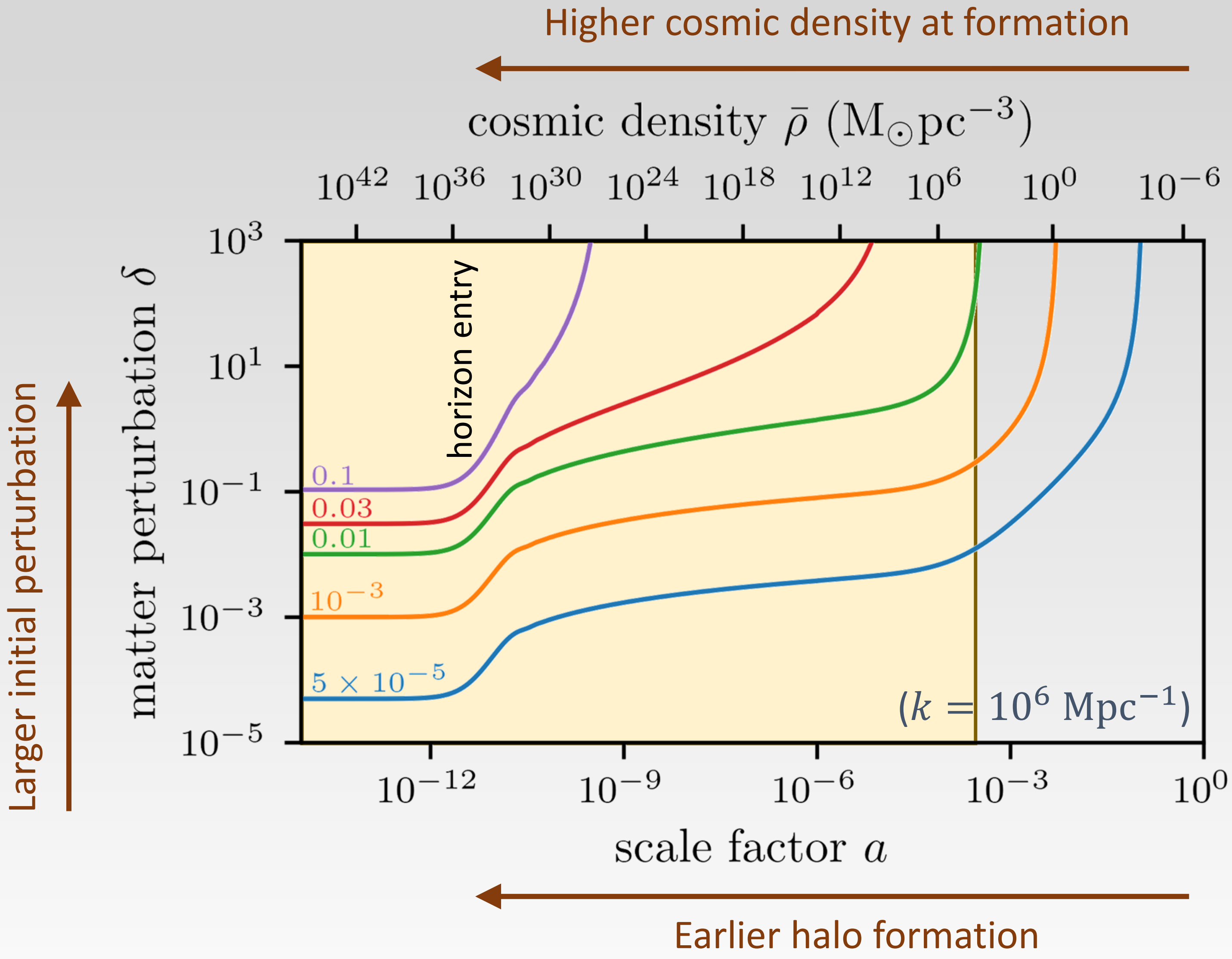
Early halo formation

Can halos form during the radiation era?

If so, they could be extraordinarily dense

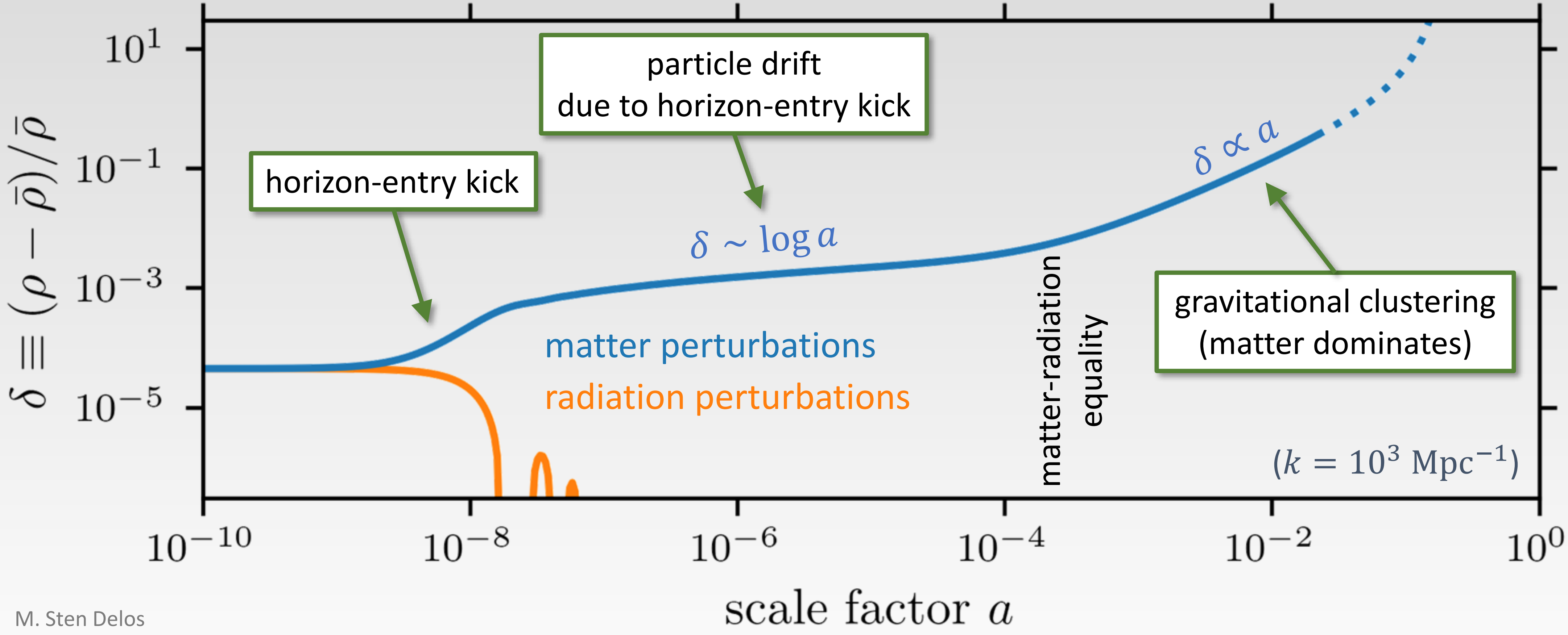
Recall:

Mass inside regions denser than $\sim 800\rho$	$\simeq$	Mass accreted when the universe was denser than ρ



Halo formation during the radiation epoch

No peculiar gravitational forces where radiation dominates,
only DM particle drift from initial conditions [horizon-entry kick].



Halo formation during the radiation epoch

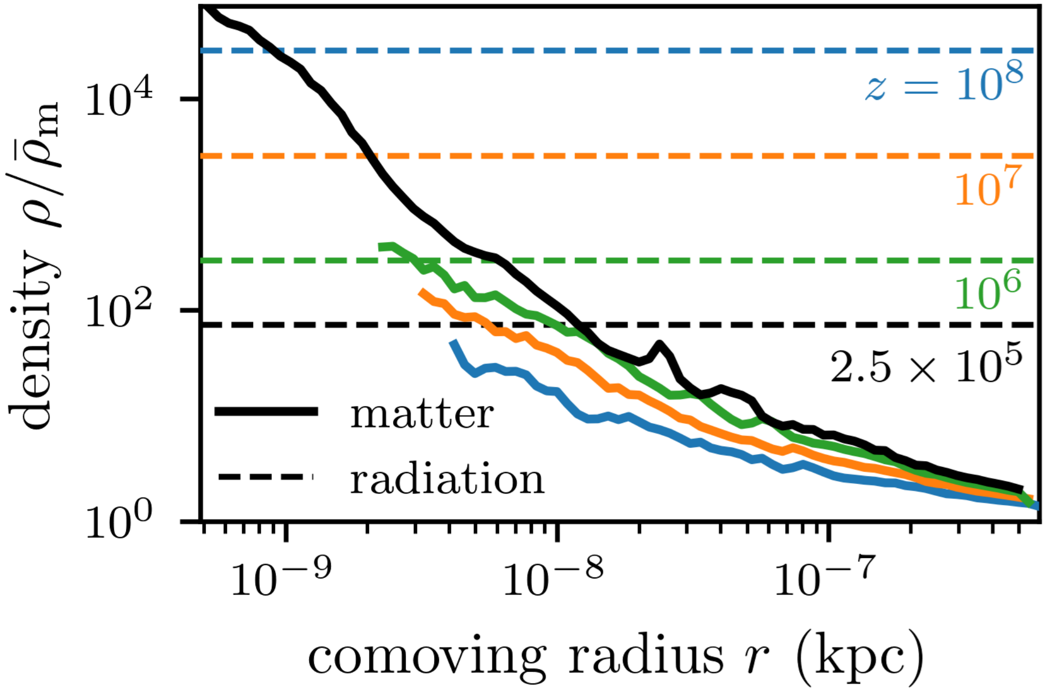
No peculiar gravitational forces where radiation dominates,
only DM particle drift from initial conditions [horizon-entry kick].

However, for sufficiently spherical initial perturbations, drift can make locally matter dominated regions, **forming halos deep in the radiation epoch**

Formation time: $a \sim e^2 a_{\mathrm{eq}}$

"ellipticity", typically $e \sim 0.1$ to 0.3

Idealized simulation:



Blanco, **MSD**, Erickcek, Hooper (2019)

Hence $a \sim 10^{-5}$

Halo formation during the radiation epoch

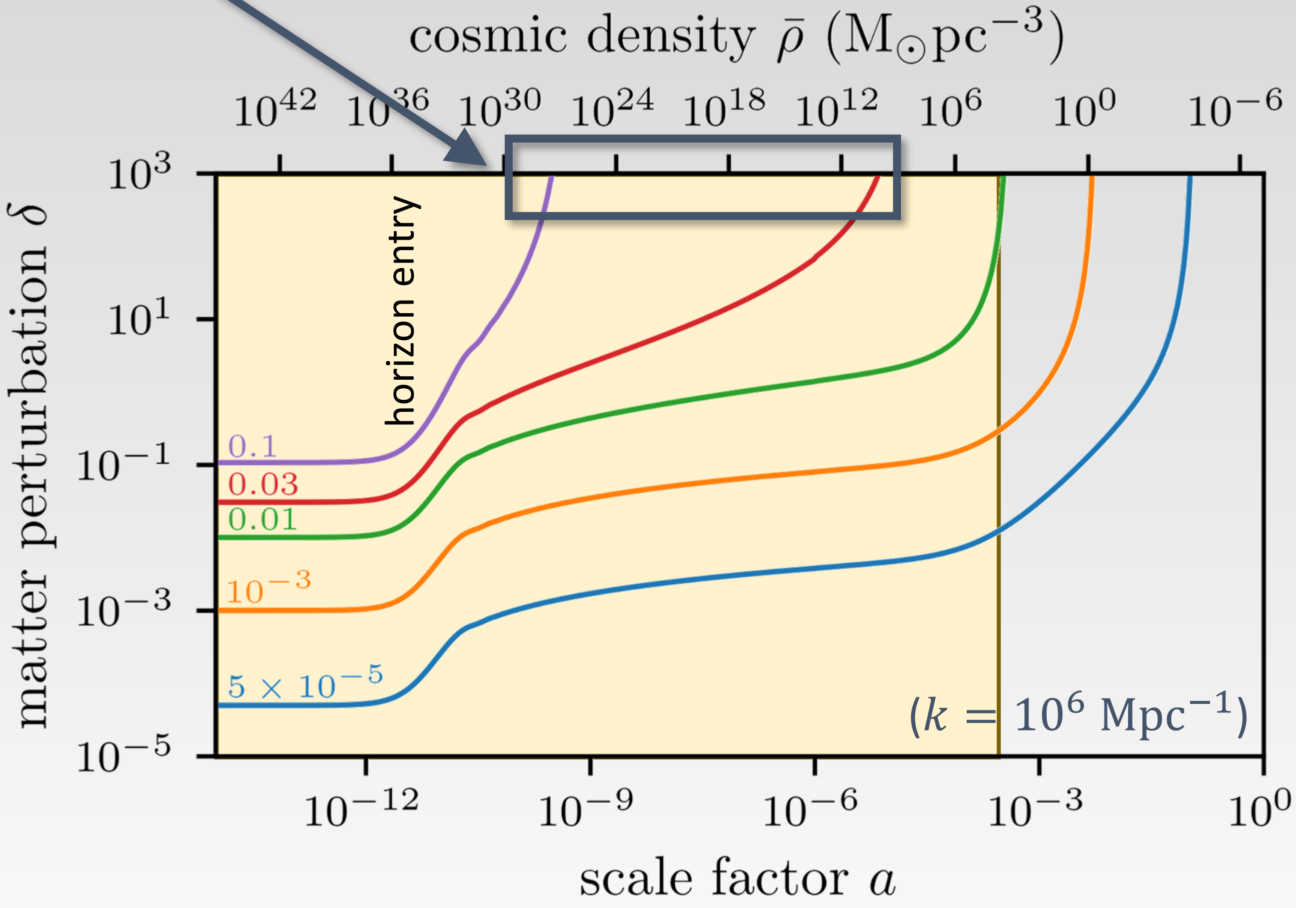
Halo forms around $a \sim 10^{-5}$ even if collapse occurs earlier.
Earlier collapse simply overshoots.

Recall:

Mass inside regions denser than $\sim 800\rho$	$\simeq$	Mass accreted when the universe was denser than ρ

$a \sim 10^{-5} \rightarrow \bar{\rho} \sim 10^9\ M_\odot pc^{-3}$

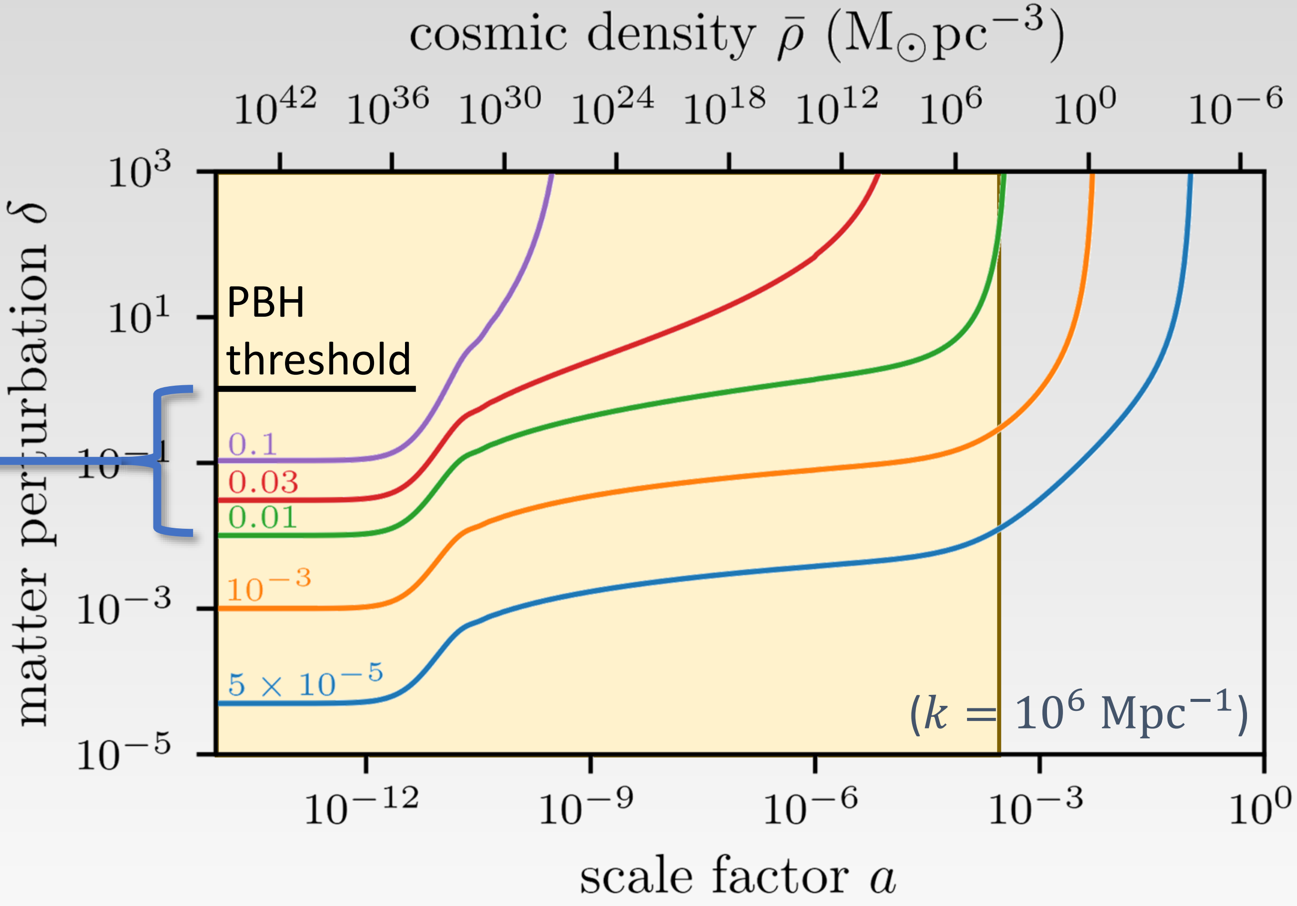
$\rightarrow \rho_\mathrm{halo} \sim 10^{12}\ M_\odot pc^{-3}$



Primordial black holes and ultradense halos

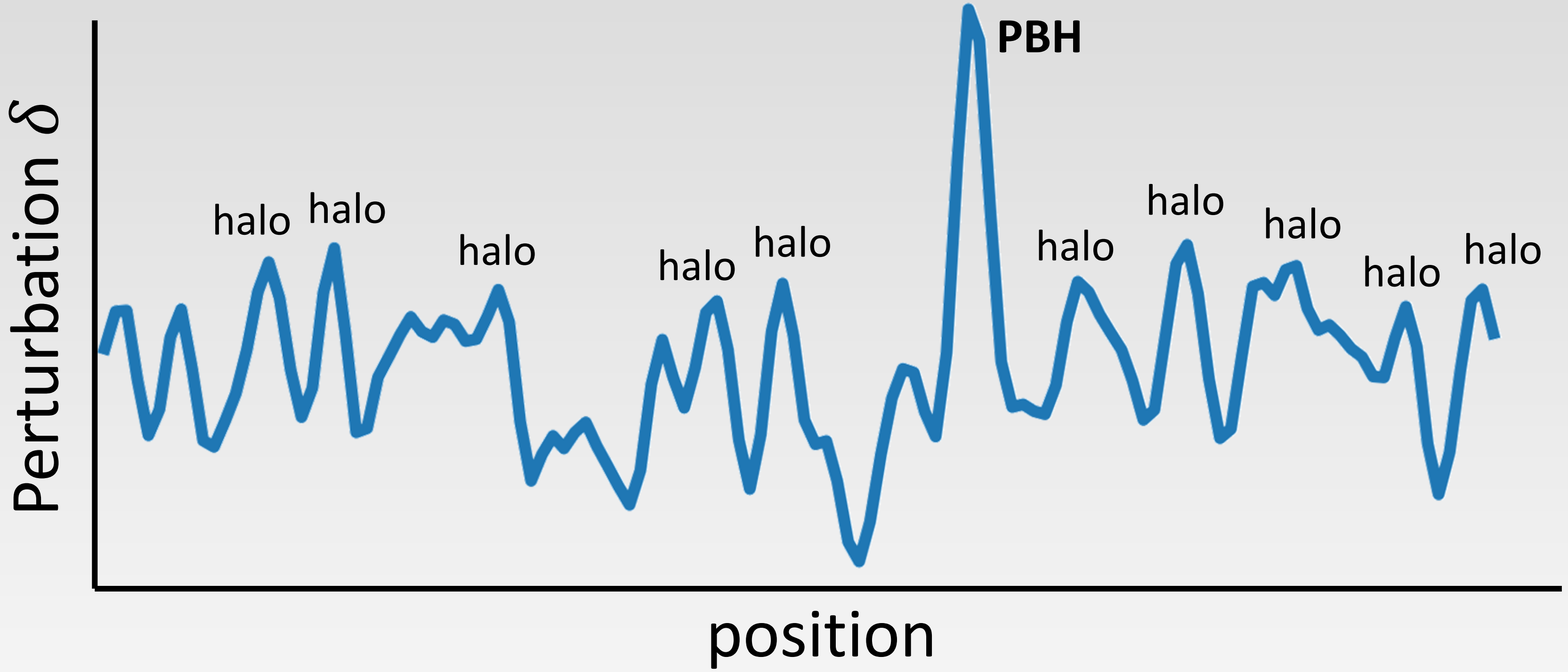
PBHs require $\mathcal{O}(1)$ perturbations.
Much lower perturbations can still collapse during the radiation epoch.

Too low to make a PBH, but still sufficient to make an ultradense halo during the radiation epoch



Primordial black holes and ultradense halos

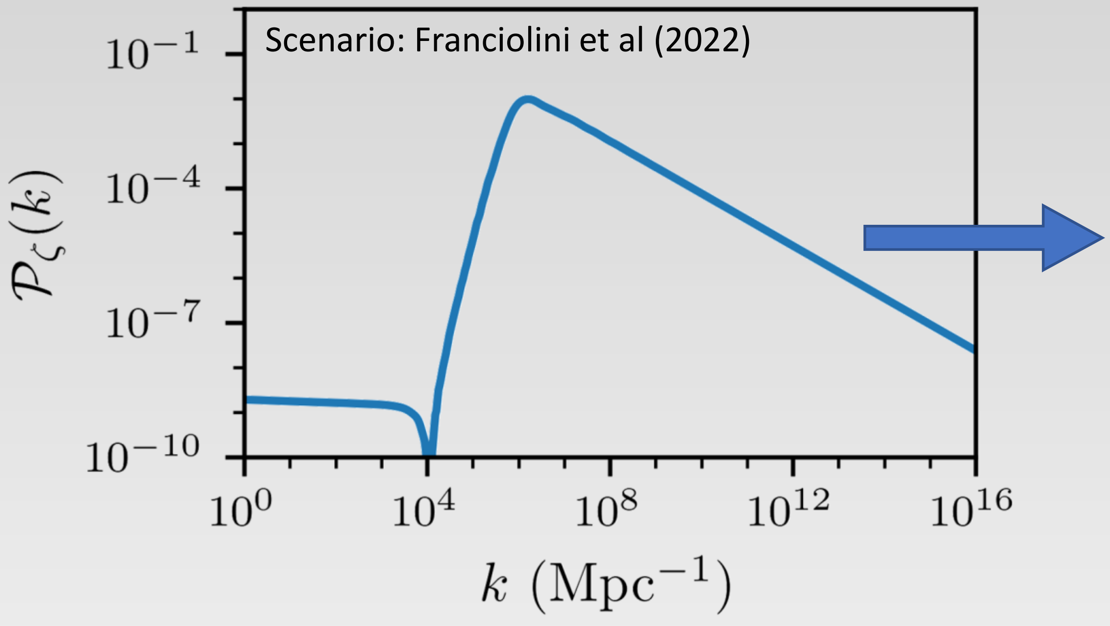
The same perturbation spectrum that produces PBHs
also produces many more lower-amplitude perturbations that are
still sufficient to collapse during the radiation epoch

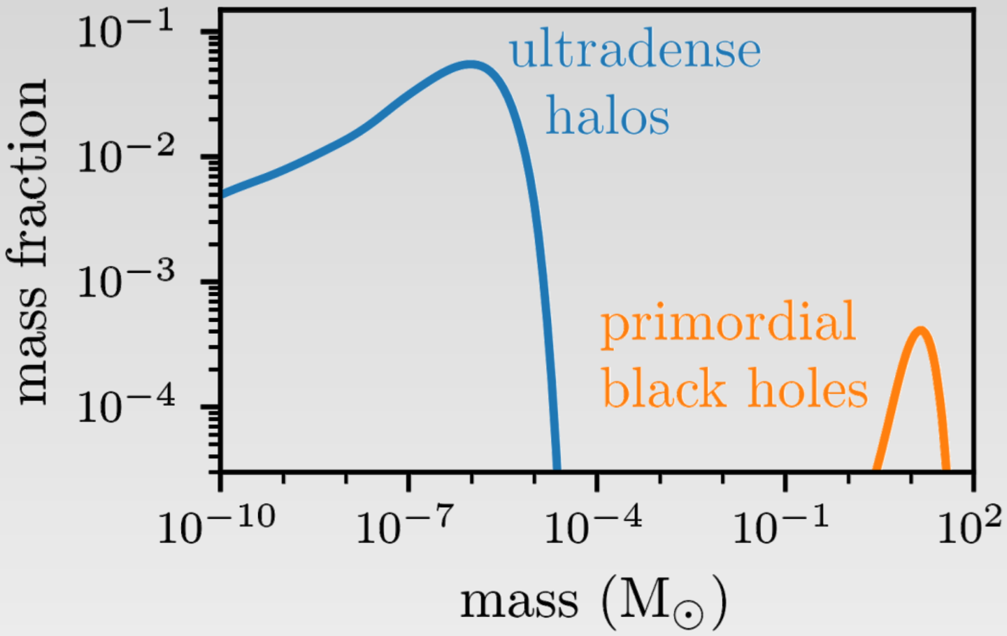


So the resulting ultradense halos vastly outnumber PBHs!

Primordial black holes and ultradense halos

Example calculation:





MSD & Silk (2023); **MSD & Franciolini (2023)**

Halos vastly outnumber PBHs:
$f_{\mathrm{halo}} \sim 10^{-1}$ while $f_{\mathrm{PBH}} \sim 10^{-3}$

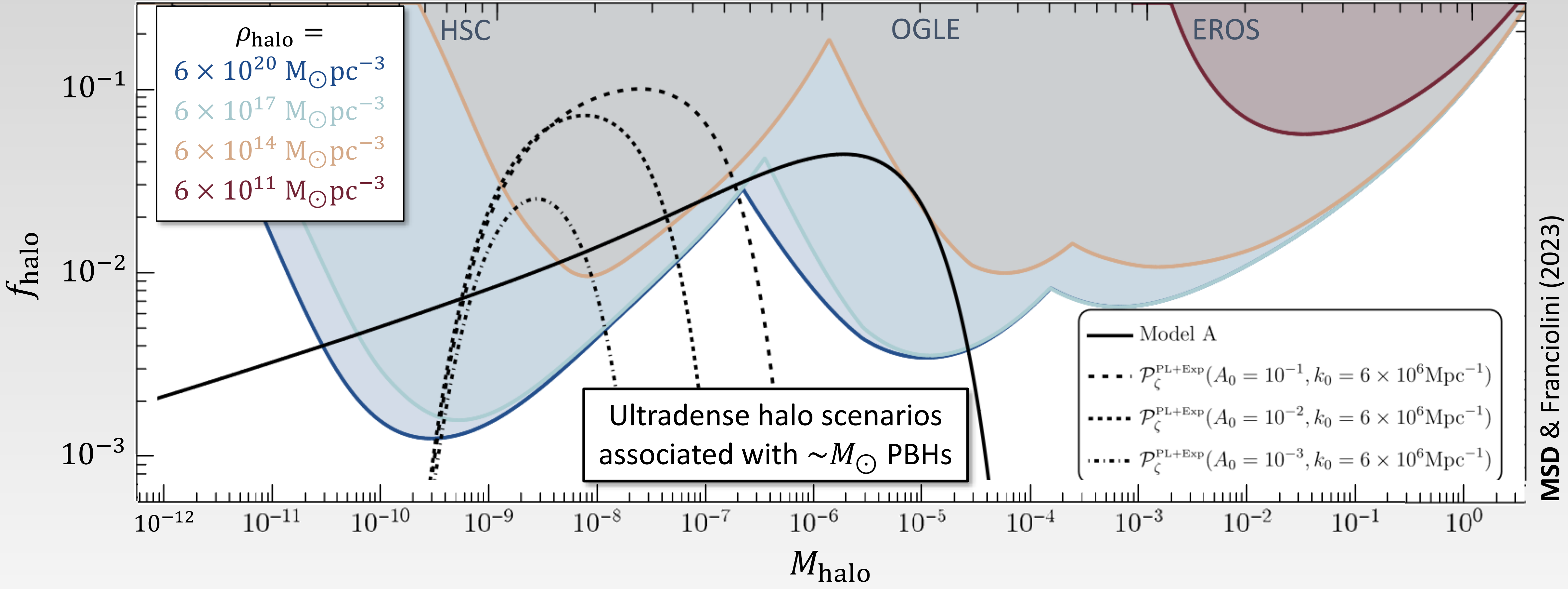
$M_{\mathrm{halo}} < M_{\mathrm{PBH}}$ because halos form from matter while PBHs form from radiation:

$$M_{\mathrm{halo}} \sim M_{\mathrm{PBH}}^{3/2} M_{\mathrm{eq}}^{-1/2}$$

($M_{\mathrm{eq}} \simeq 3 \times 10^{17} \mathrm{M}_\odot$ is the horizon mass at equality)

Lensing of ultradense halos

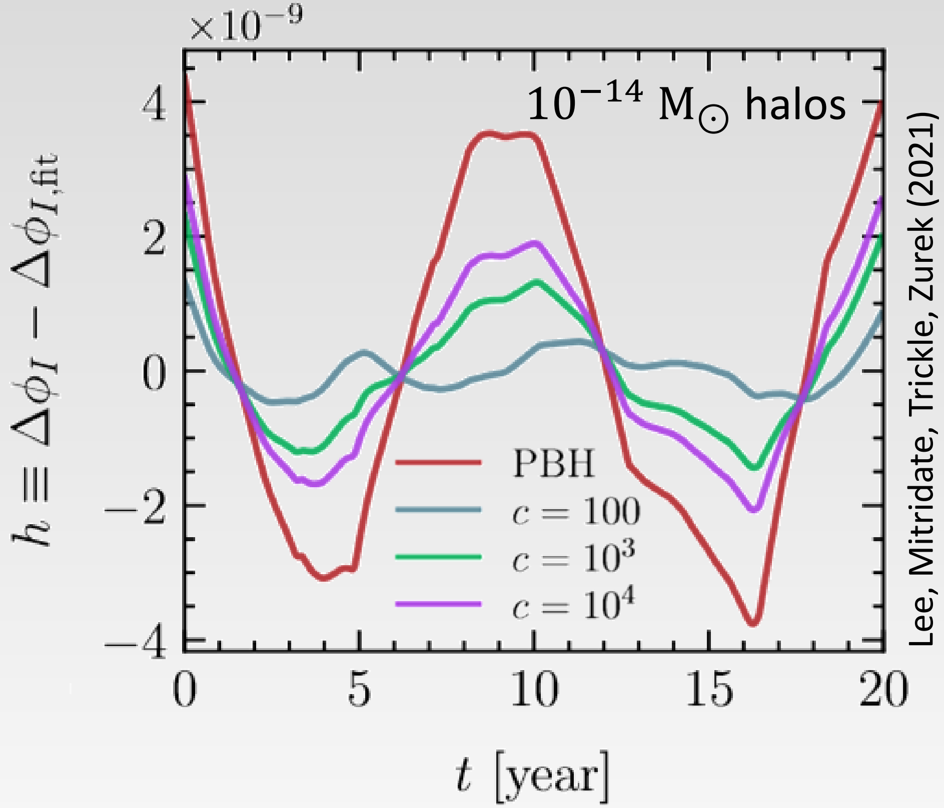
Can halos forming during radiation domination be dense enough to be detected with microlensing?



Need to know $\rho_{\rm halo}$ ($\sim 10^{12}{\rm M_\odot pc^{-3}}$) more precisely [simulations?]

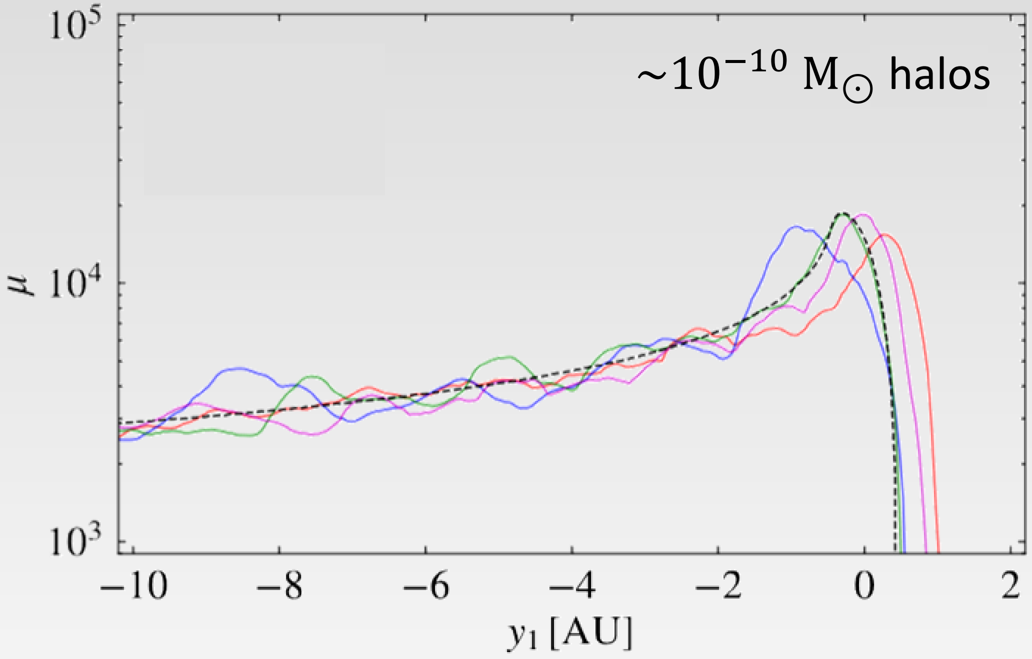
Other microhalo probes

Pulsar timing:
Doppler shift due to passing halos



Lee, Mitridate, Trickle, Zurek (2021)

Caustic crossing events:
Distortions in the light curve of a star crossing a lens caustic



Dai & Miralda-Escude (2020)

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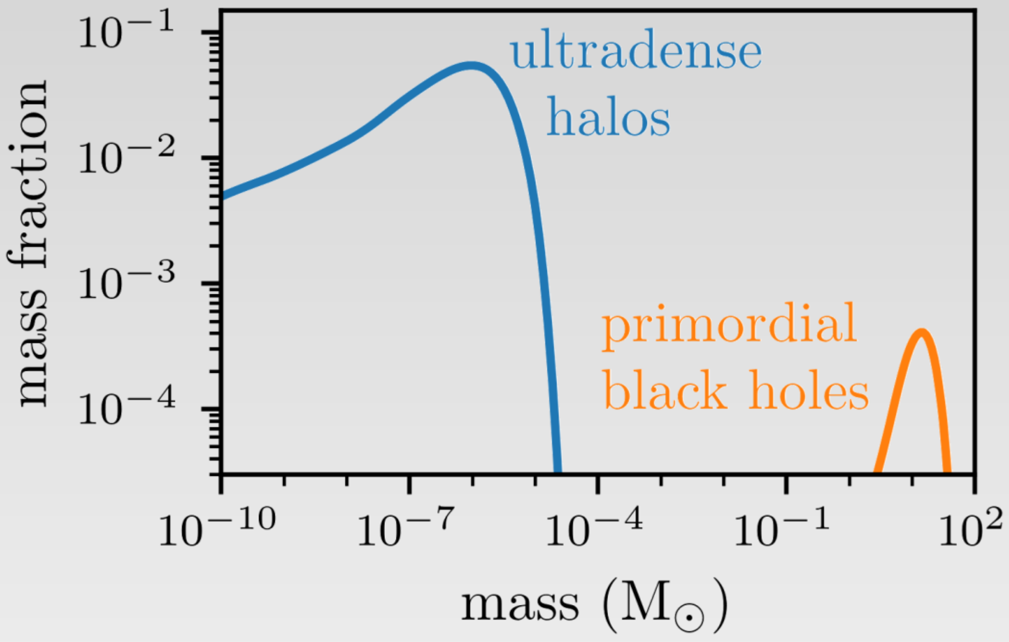
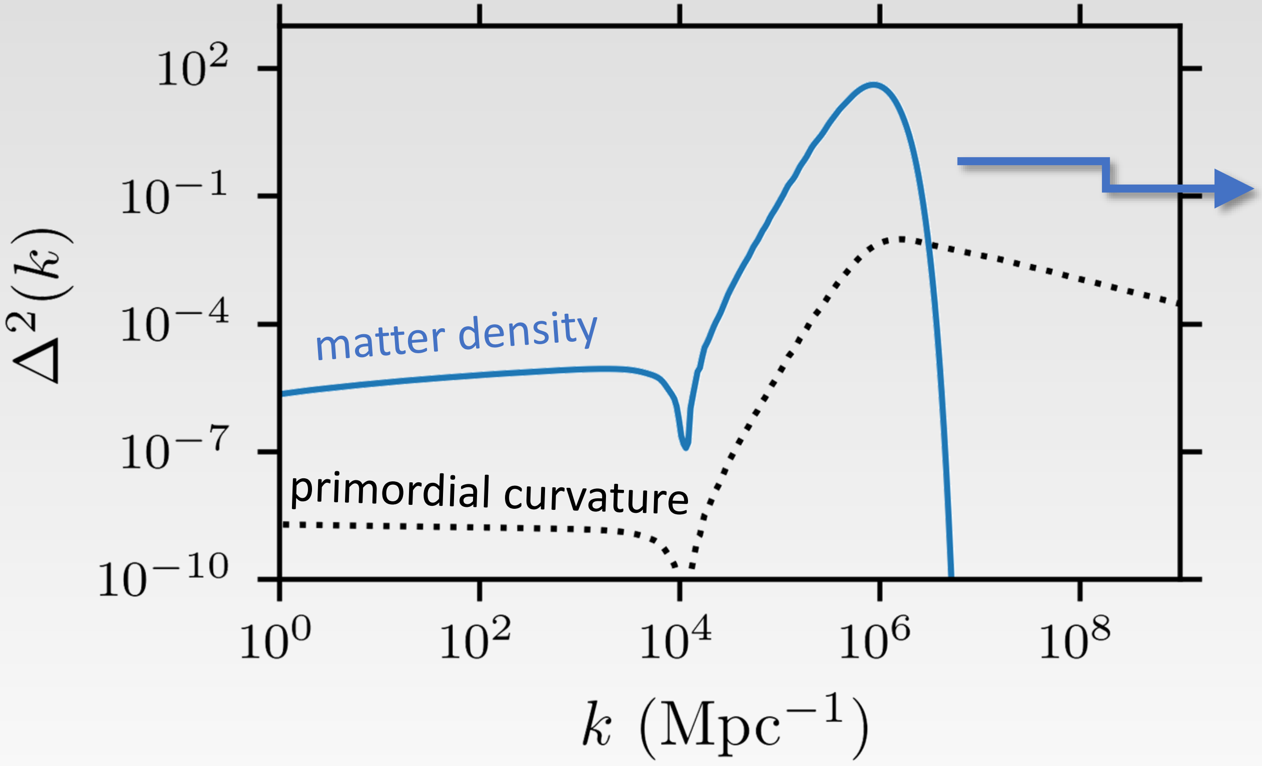
Ultradense halos today

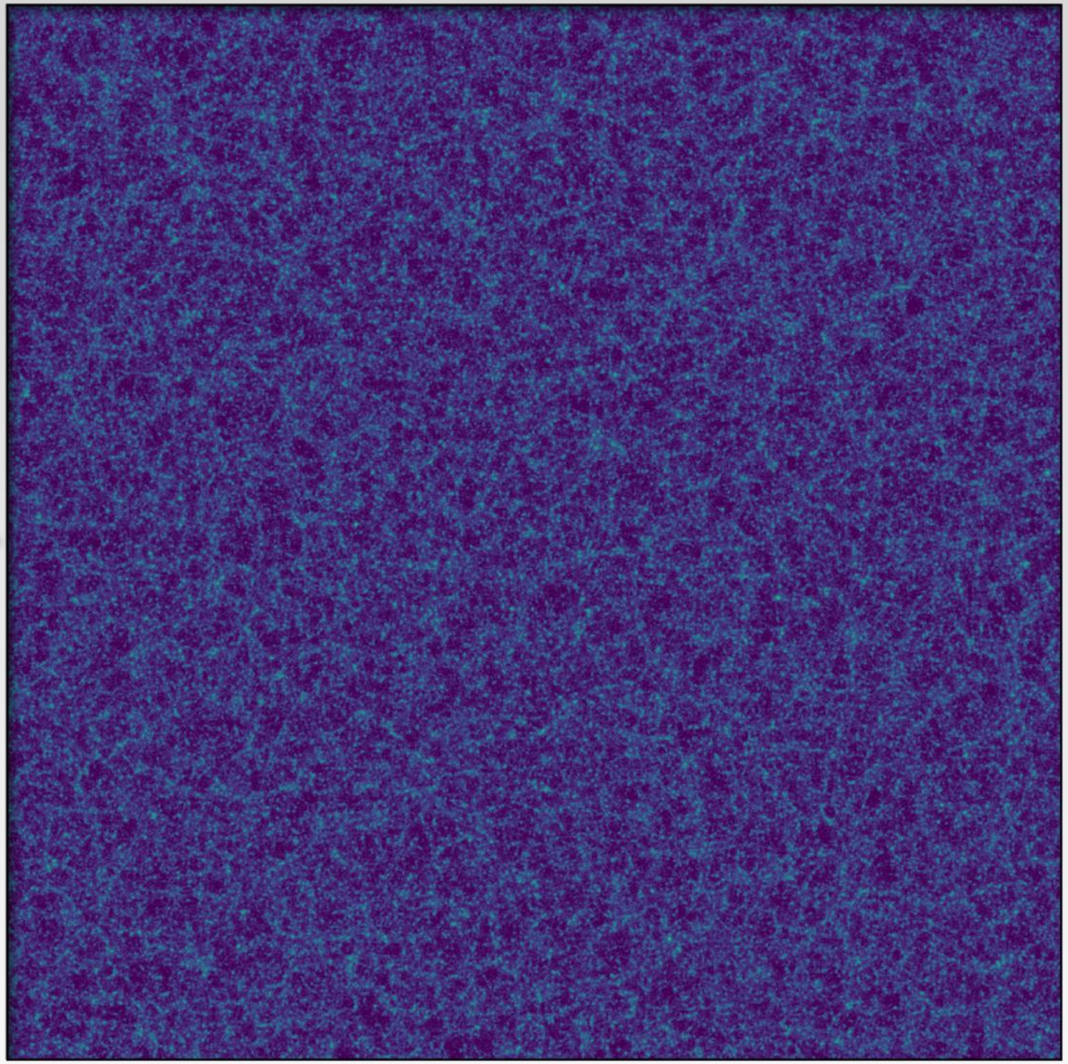


Evaluated at $a = 10^{-5}$. How is this representative of the present-day distribution?

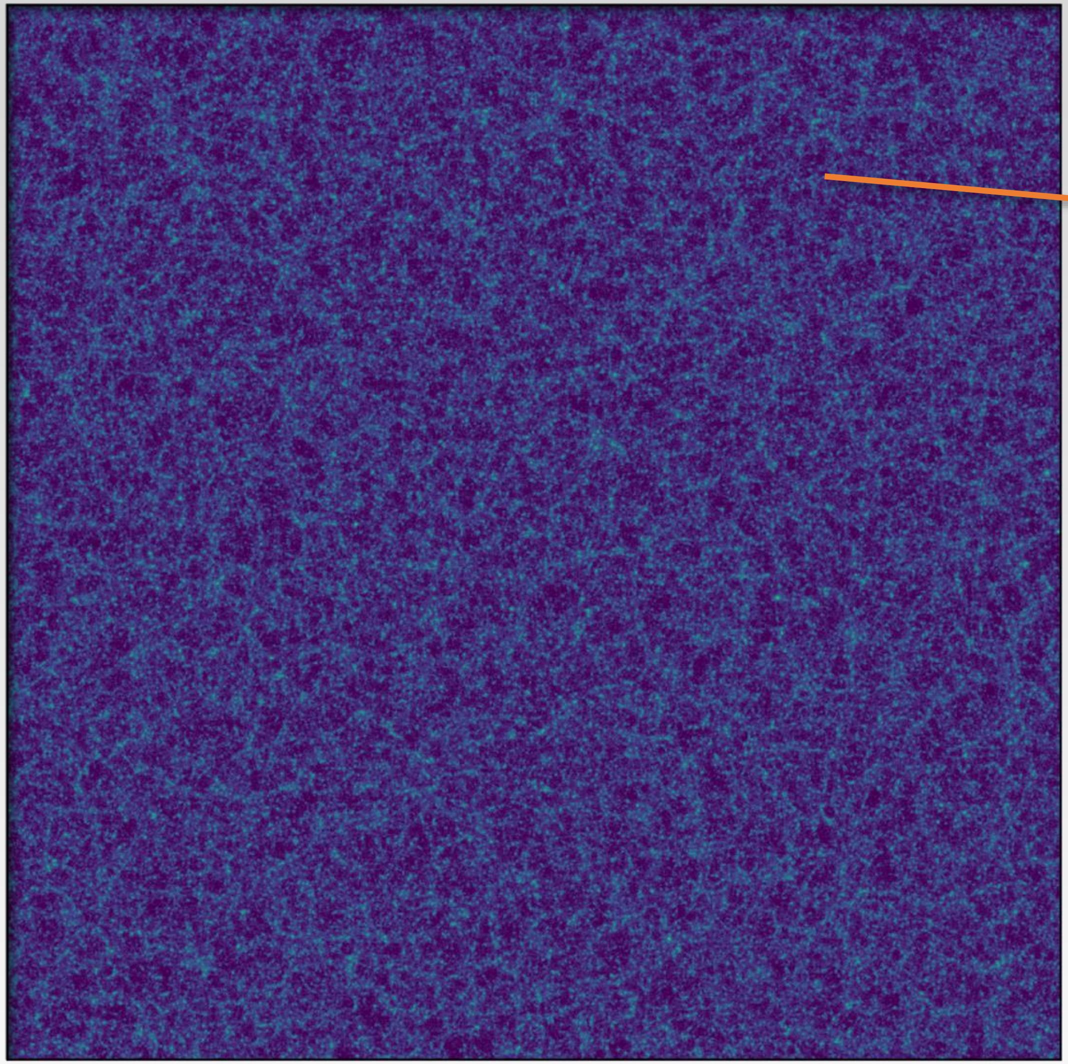
Microhalos from amplified small-scale power

A bump in the power spectrum at small scales produces a nearly uniform distribution of tiny halos

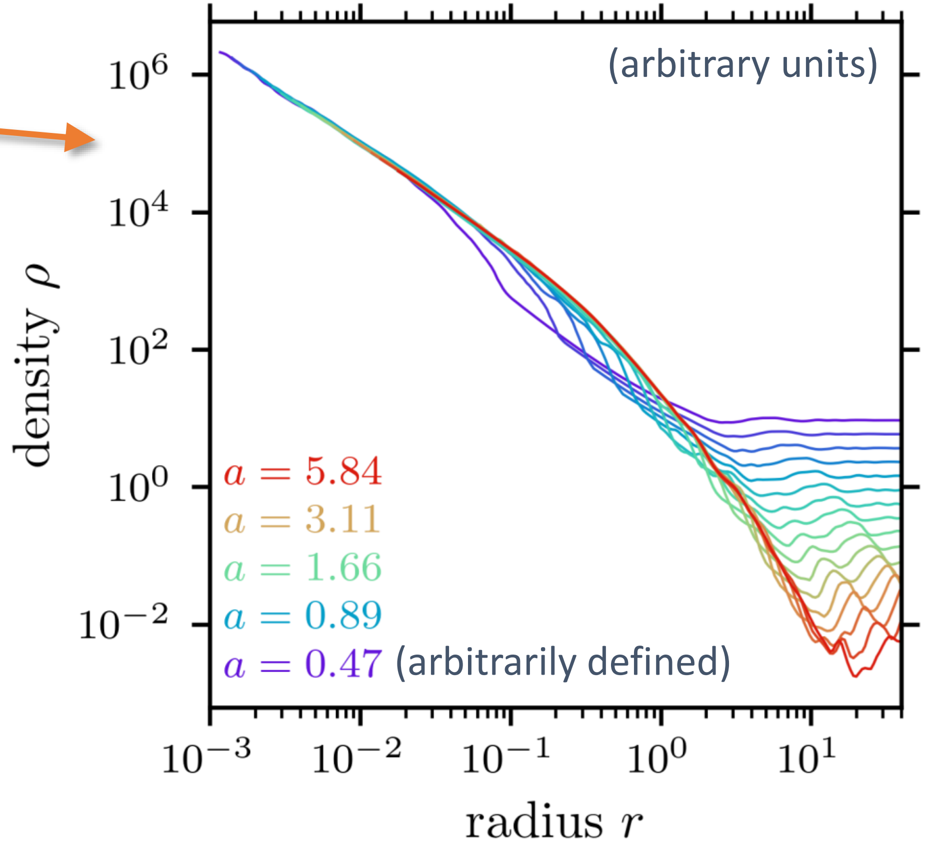




Microhalos from amplified small-scale power



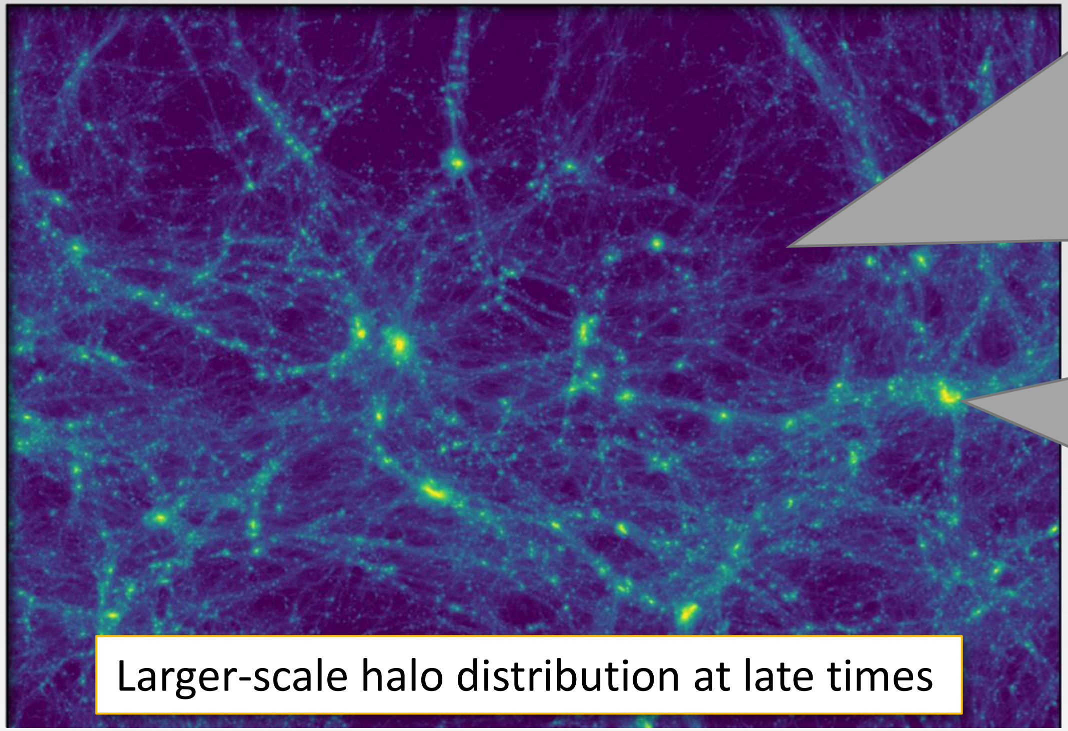
These microhalos grow slowly and merge rarely…

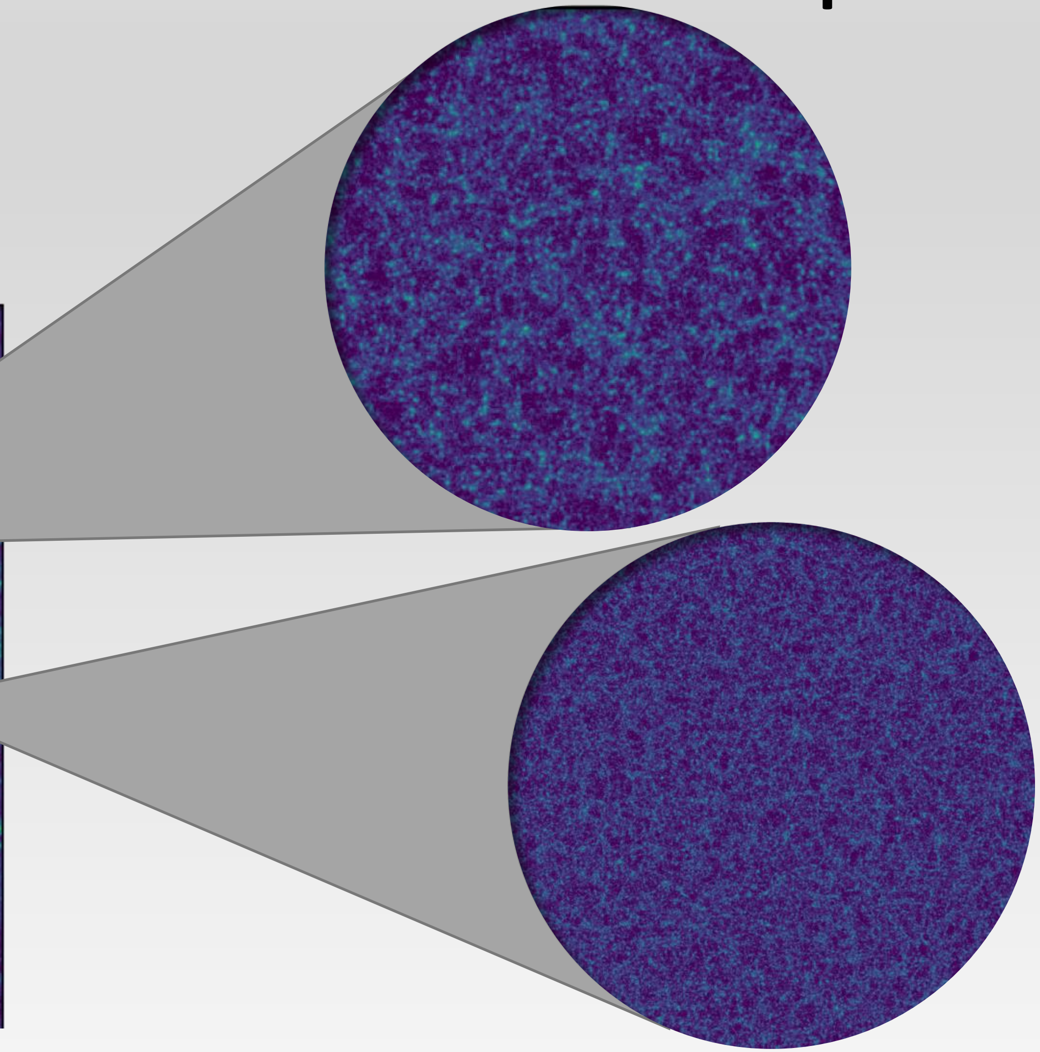


…until much later times, when they exceed the background density by such a great margin that they are difficult to destroy

Microhalos from amplified small-scale power

Thus, microhalos should underly the dark matter distribution everywhere…





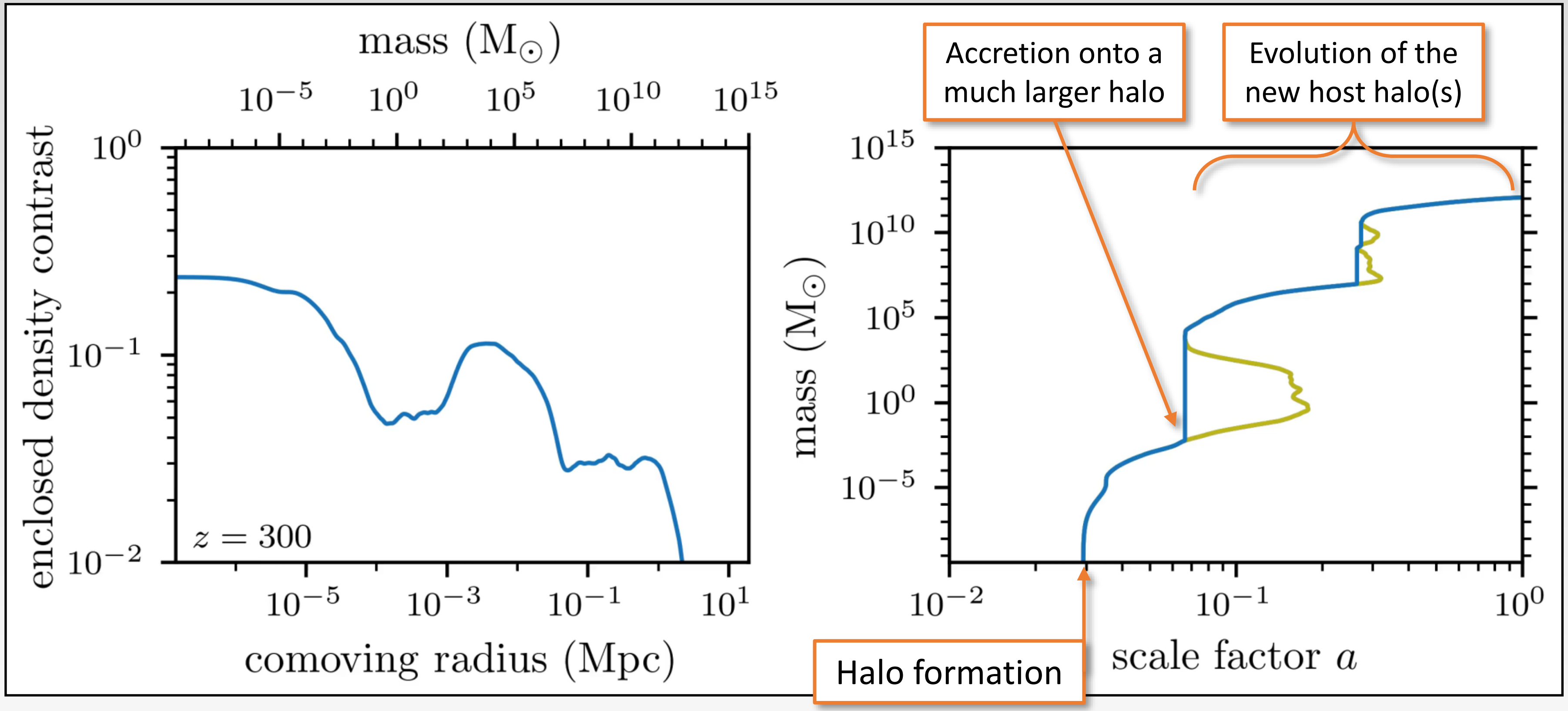
…but can we quantify this behavior more directly?

Halo growth history

Consider the mean density excess $\bar{\delta}$ enclosed within radius r about a density peak in the initial conditions

→ mass M

Rotate the picture:
Halo mass M as a function of scale factor $a \sim \delta_c/\bar{\delta}$



Straightforward to sample using Gaussian statistics (**MSD**, Bruff, Erickcek 2019)

Halo growth history

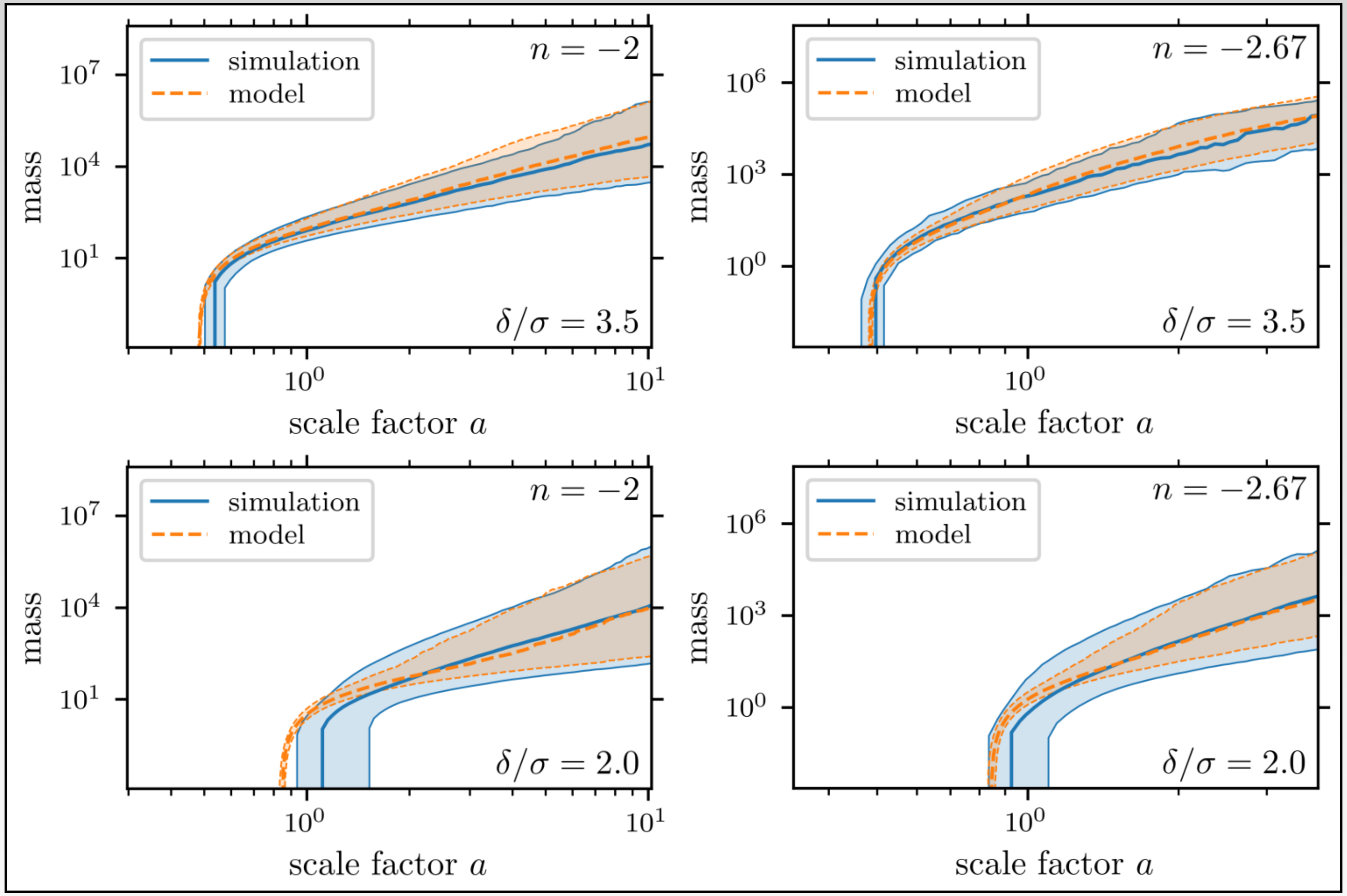
Model works well for halo populations

Plot:
median and 68% band

Simulation statistics:
200 to 35000 halos

Model:
1000 random $\bar{\delta}(r)$ samples

Aggregate halos

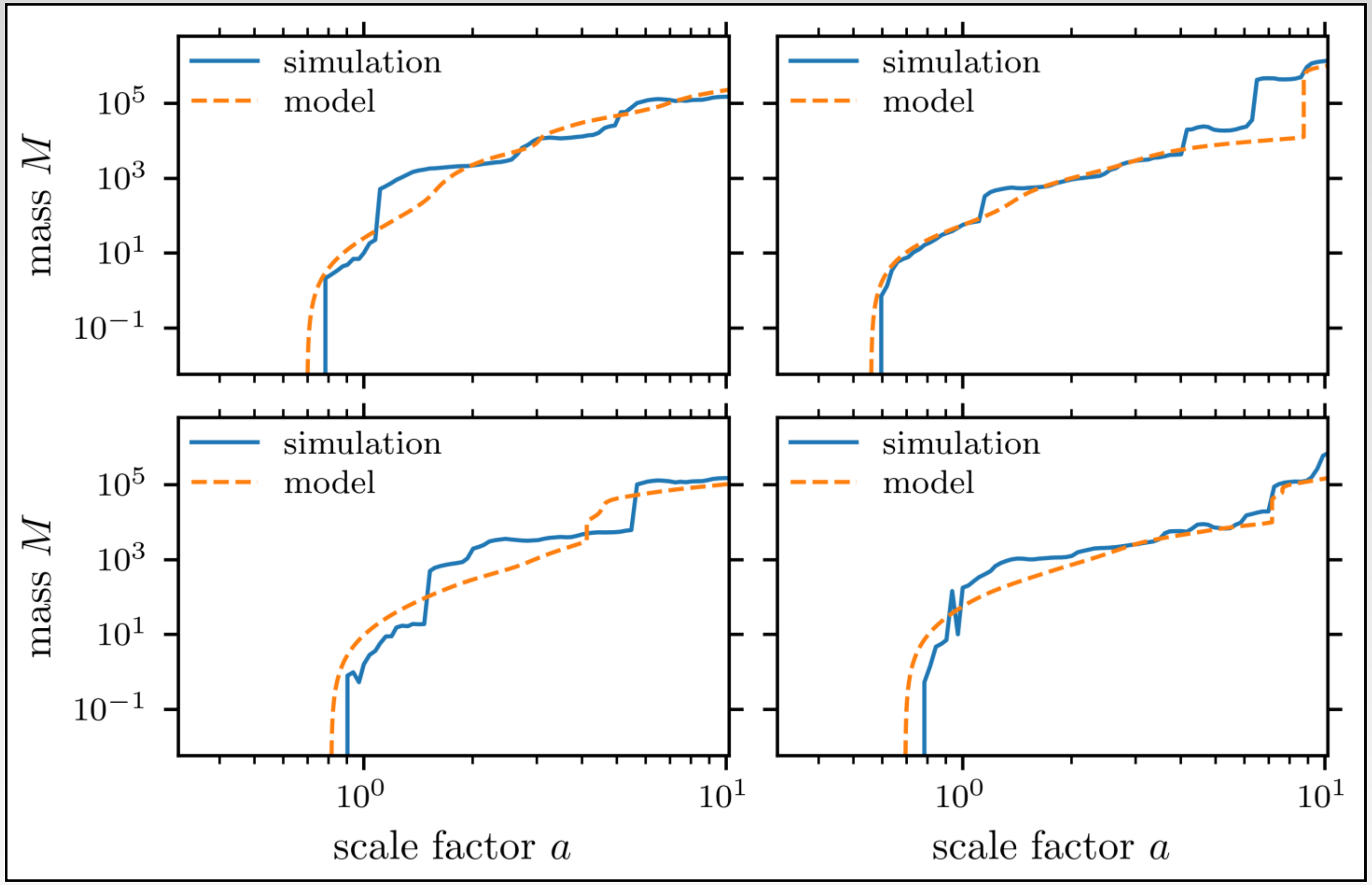


(arbitrary units and scale factor reference)

Halo growth history

Model works reasonably well for individual halos

Individual halos



(arbitrary units and scale factor reference)

Summary

If primordial black holes are only a fraction of the dark matter, they will be vastly outnumbered by ultradense halos that could form prior to the matter epoch.

These halos may be so internally dense ($\sim 10^{12} \mathrm{M}_{\odot} \mathrm{pc}^{-3}$) that they can be detected with microlensing.

Growth of such halos into larger objects can be accurately and efficiently predicted using the statistics of random fields.