Dark matter at the smallest scales

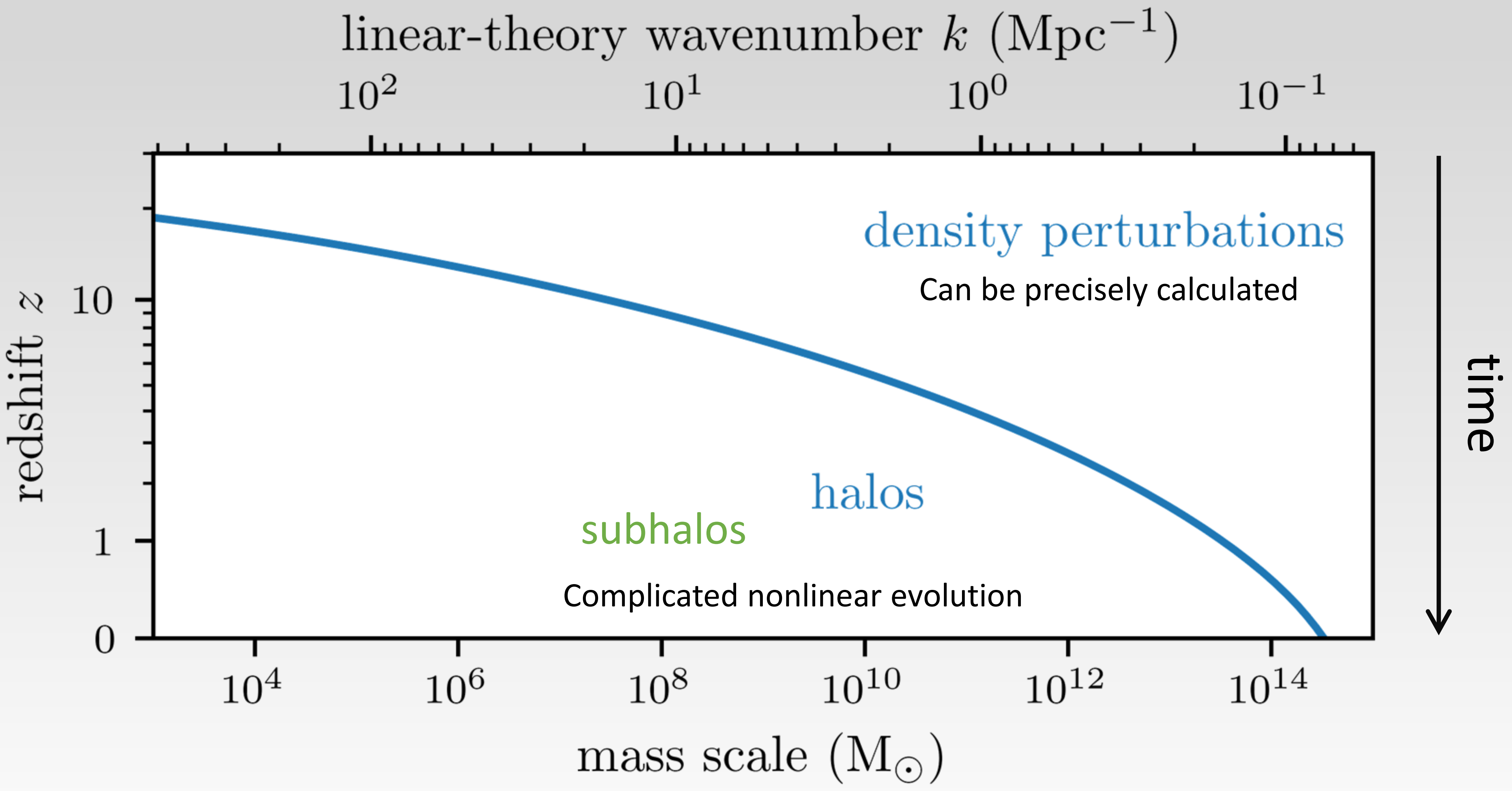
New signatures of particle dark matter and primordial black holes

M. Sten Delos (Carnegie Observatories)

Beyond WIMPs
24 March 2026

CARNEGIE SCIENCE | Observatories

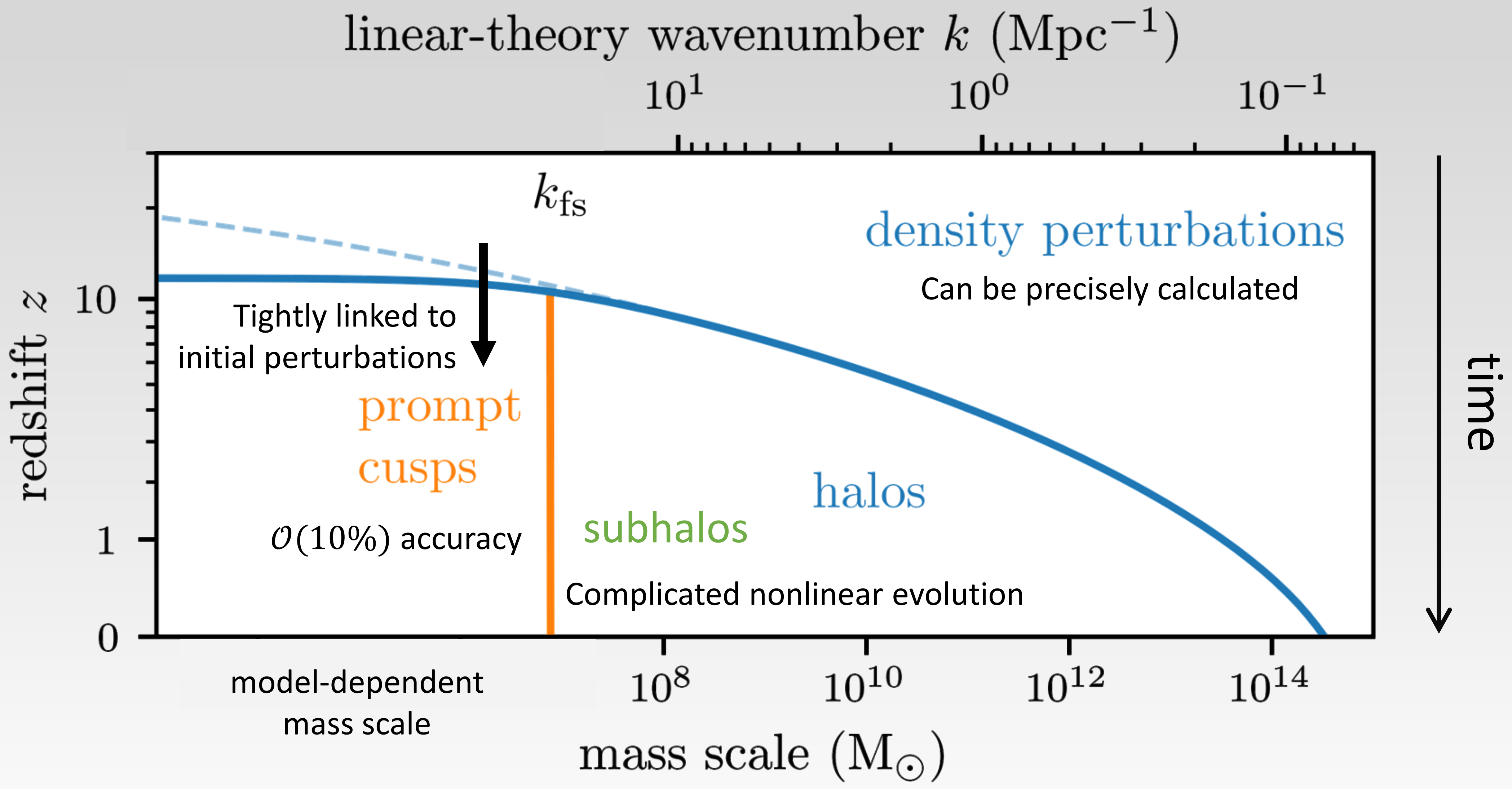
Phases of cosmic structure



Can be precisely calculated

Complicated nonlinear evolution

Phases of cosmic structure



Can be precisely calculated

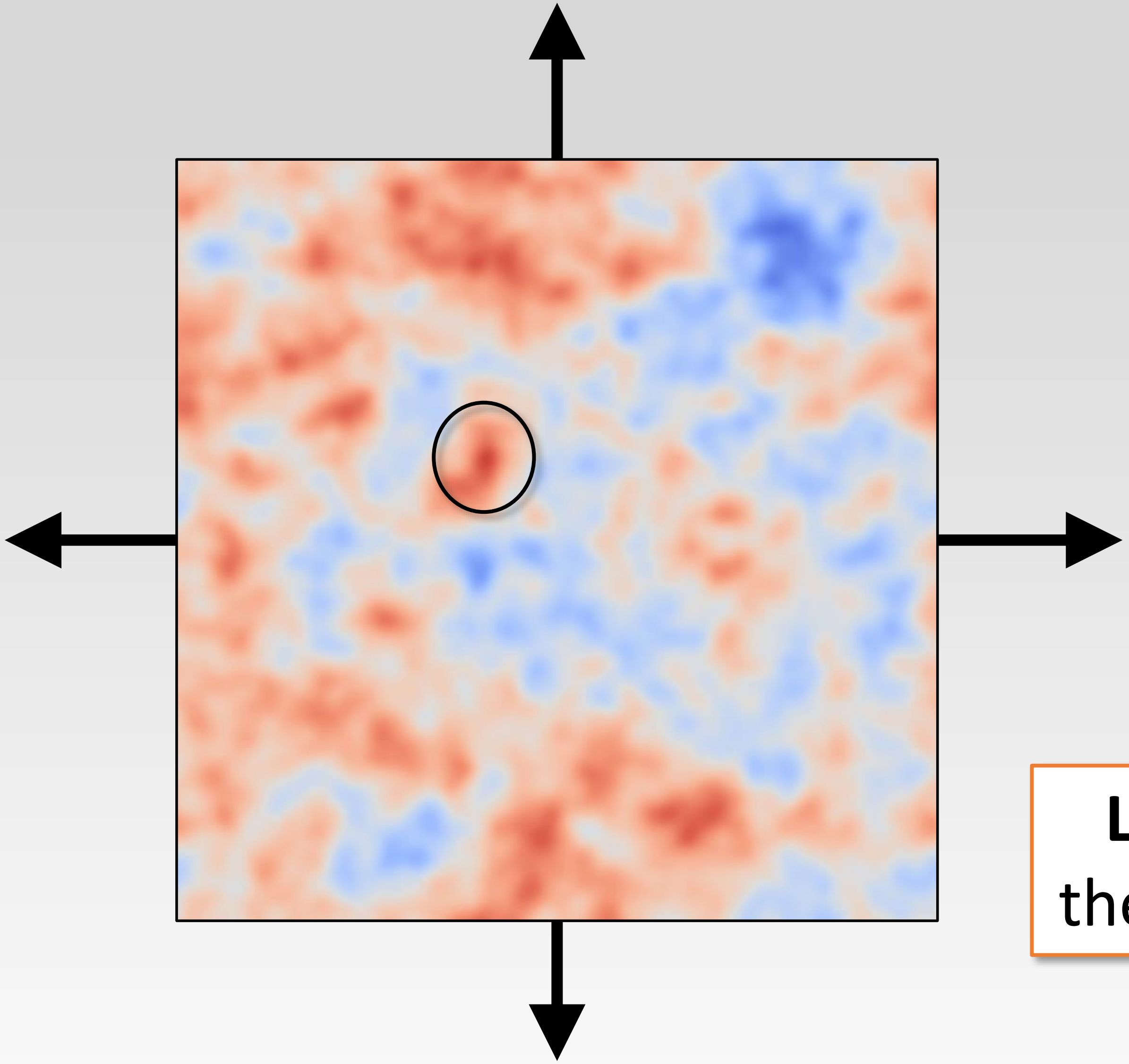
Tightly linked to initial perturbations

$\mathcal{O}(10\%)$ accuracy

Complicated nonlinear evolution

model-dependent mass scale

The cosmological initial conditions



A random density field

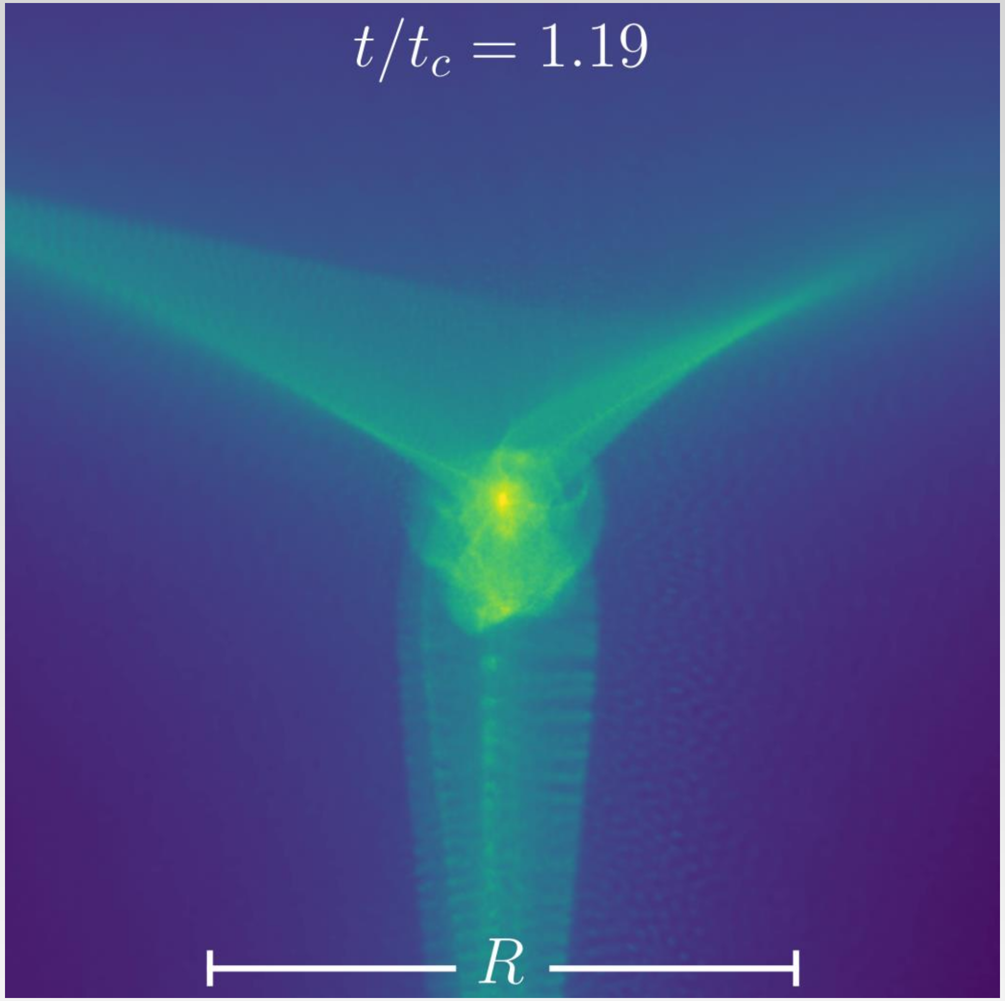
- Expanding over time
- Gravitationally amplified over time

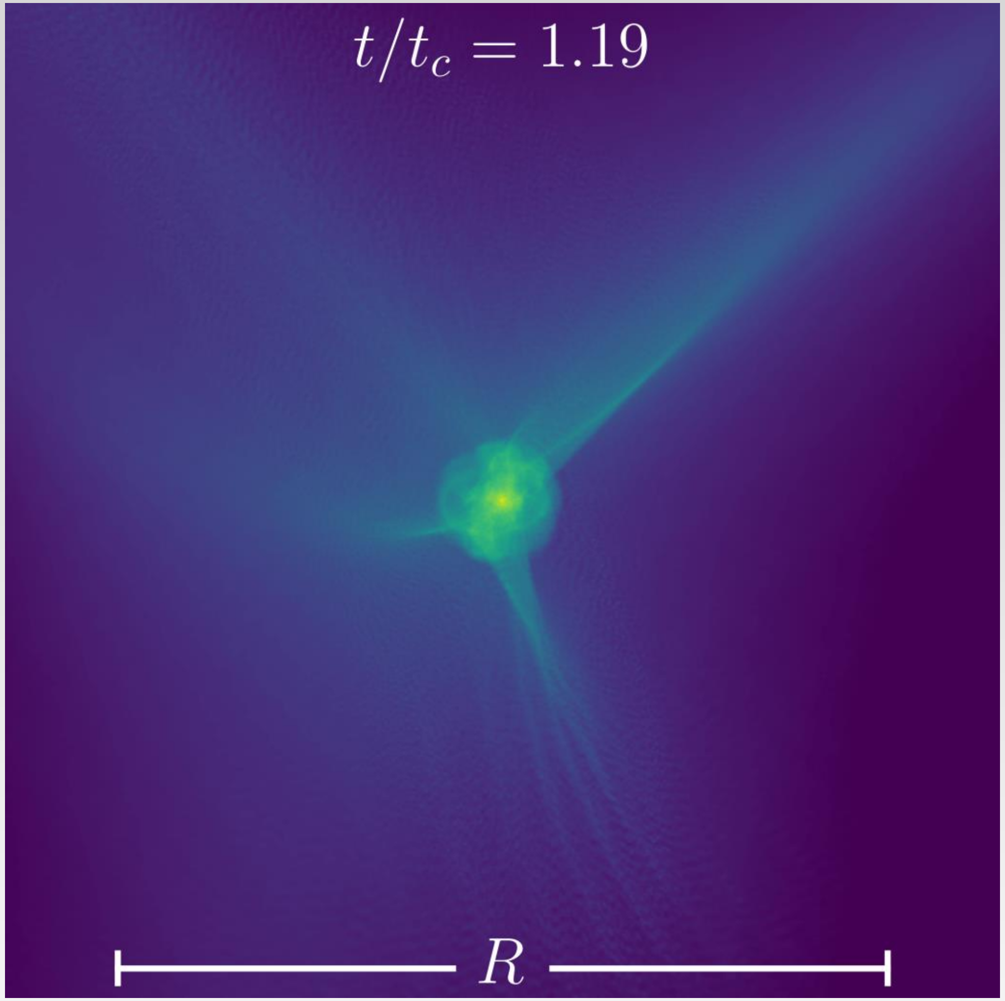
Smooth on sufficiently small scales

e.g., due to thermal motion of the dark matter

Local maxima in the density field are the first places to gravitationally collapse

Collapse of density maxima

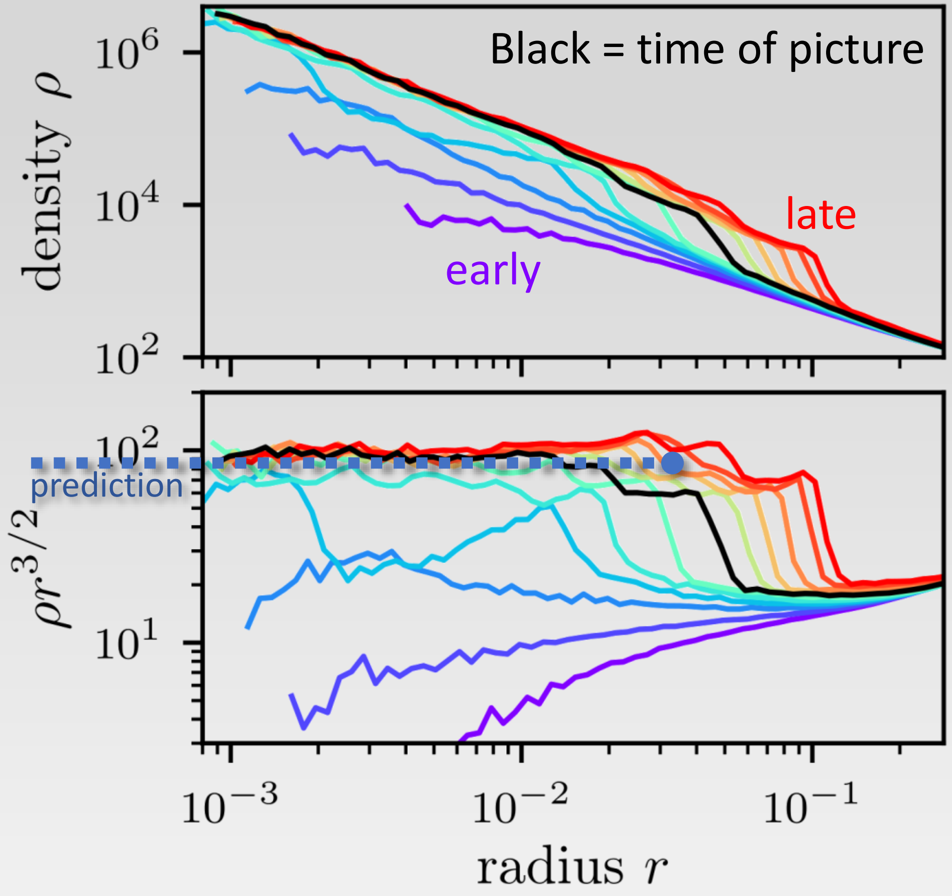




t_c = ellipsoidal collapse time

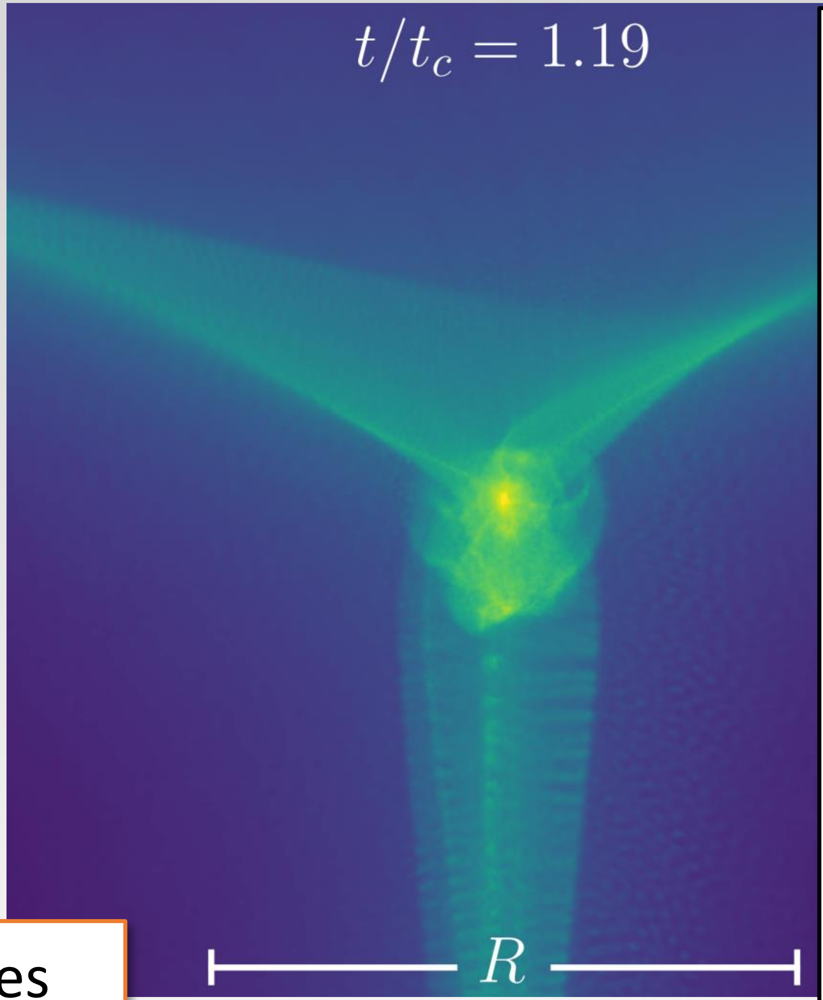
$R = \sqrt{-\delta/\nabla^2\delta}$

"Prompt cusp"



$\rho \propto r^{-3/2}$ cusp stabilizes immediately after formation

"prompt"



t_c = ellipsoidal collapse time

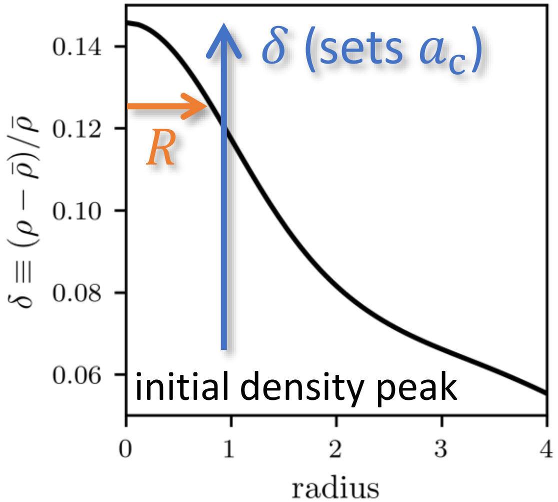
$$R = \sqrt{-\delta/\nabla^2\delta}$$

Cusp can only depend on immediate density peak (size R, collapse time a_c)

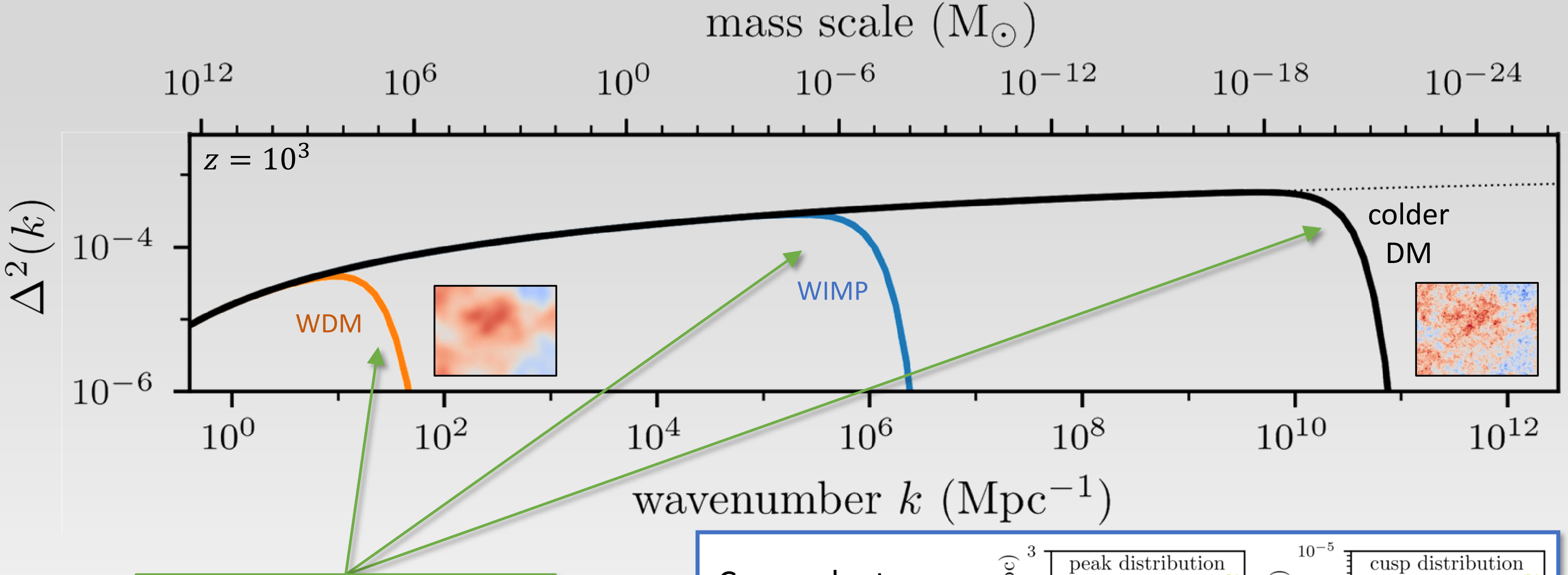
$$\rho(r) \simeq 24\,\bar{\rho}(a_c)\left(\frac{a_c R}{r}\right)^{3/2}$$

$$r_{\text{cusp}} \simeq 0.11 a_c R$$

MSD, Bruff, Erickcek (2019)
MSD & White (2023a)

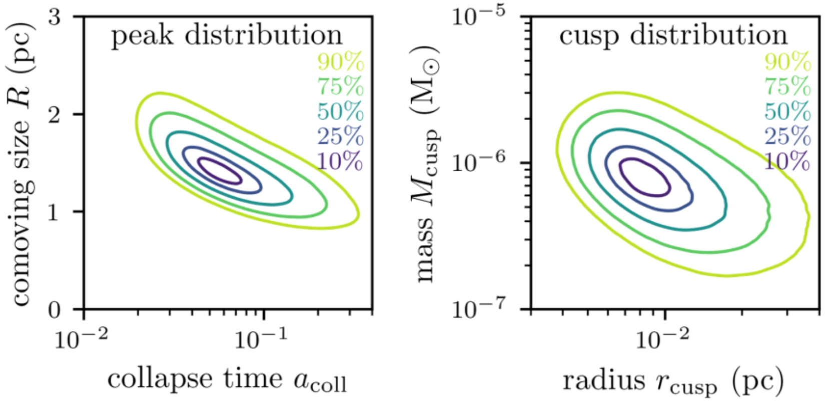


Statistics of prompt cusps

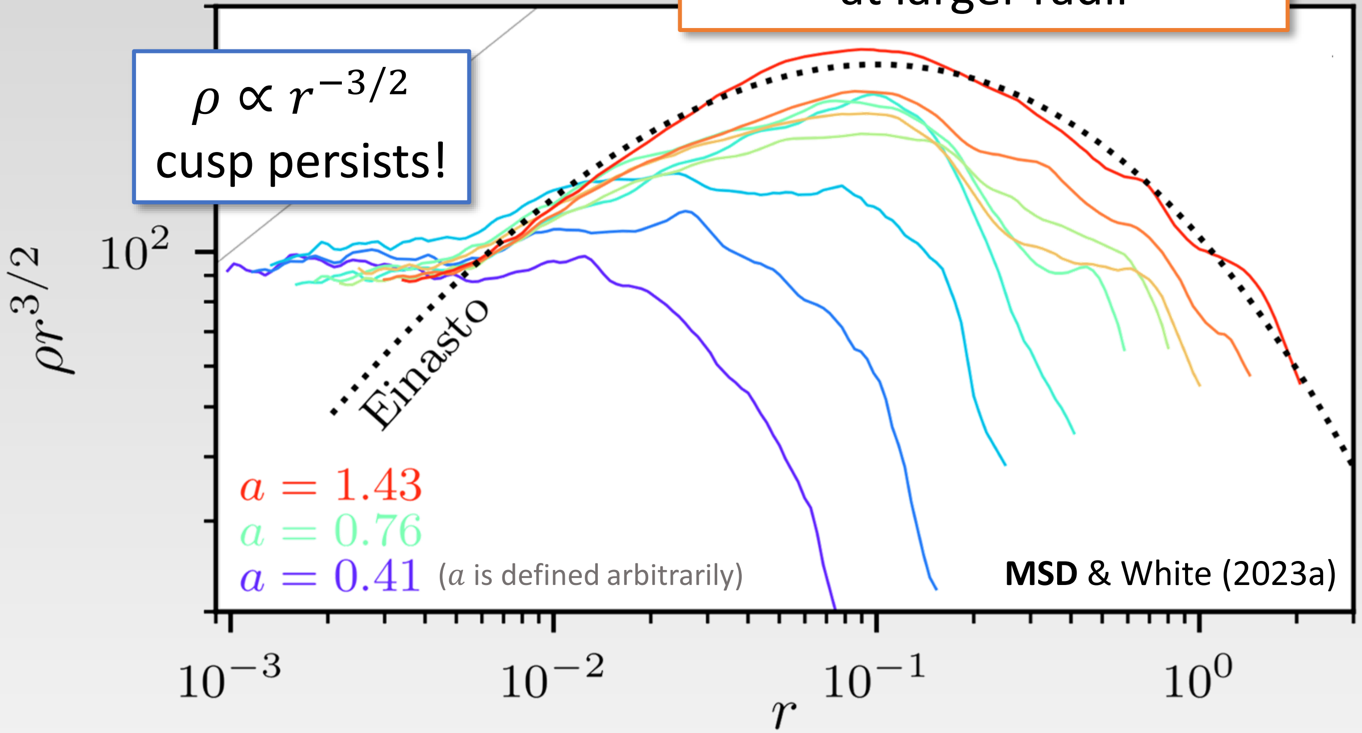


prompt cusps form at the smoothing scale

Can evaluate prompt cusp distribution directly from statistics of peaks:



Cusps and halos

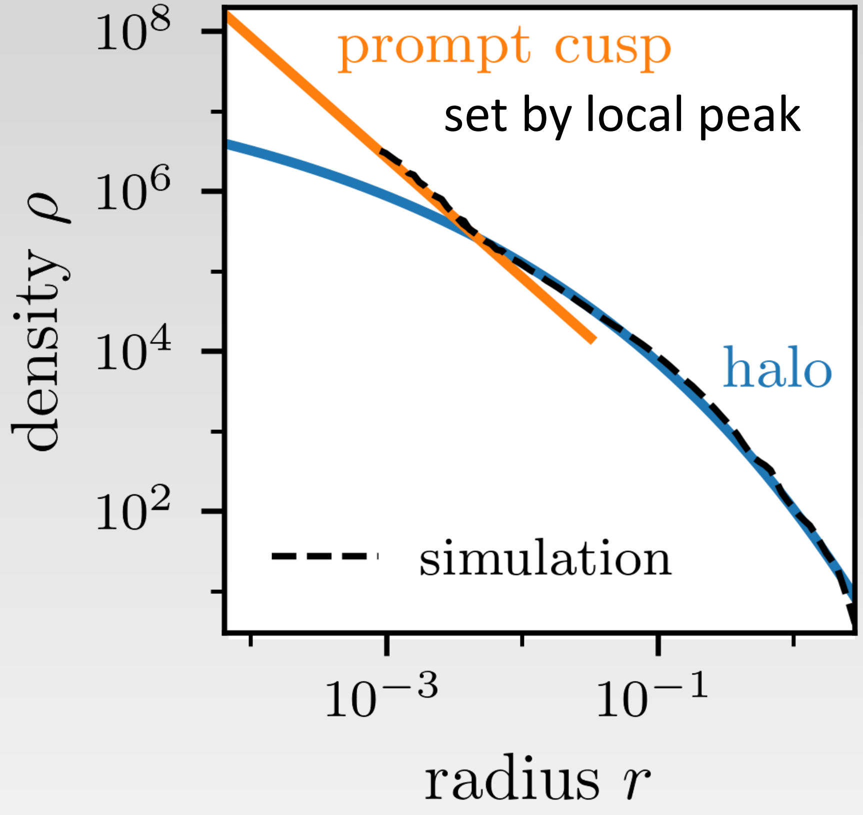


Buildup of material makes **standard halo profile** at larger radii

$\rho \propto r^{-3/2}$ cusp persists!

(a is defined arbitrarily)

MSD & White (2023a)



set by local peak

set by growth over time

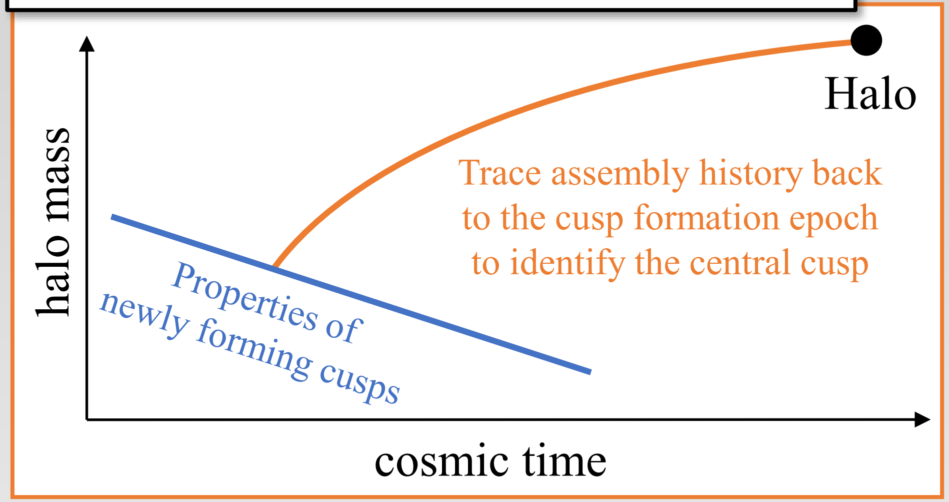
accreted “atmosphere” of initial cusp

- Most new material has too much energy and angular momentum to reach the central cusp
- Major mergers can affect the center, but effect appears to be small

Every halo/subhalo should have a central prompt cusp!

How to describe halo with central prompt cusp?

What is the central cusp of a given halo?



Full prescription for influence of smoothing scale on halo structures:

- arXiv:2506.03240
- https://github.com/delos/cusp-halo-relation

Prediction from:

- Initial peak → cusp (Delos et al. 2019)
- Growth history → halo (Ludlow et al. 2013)

What is the density profile of a halo with a central prompt cusp?

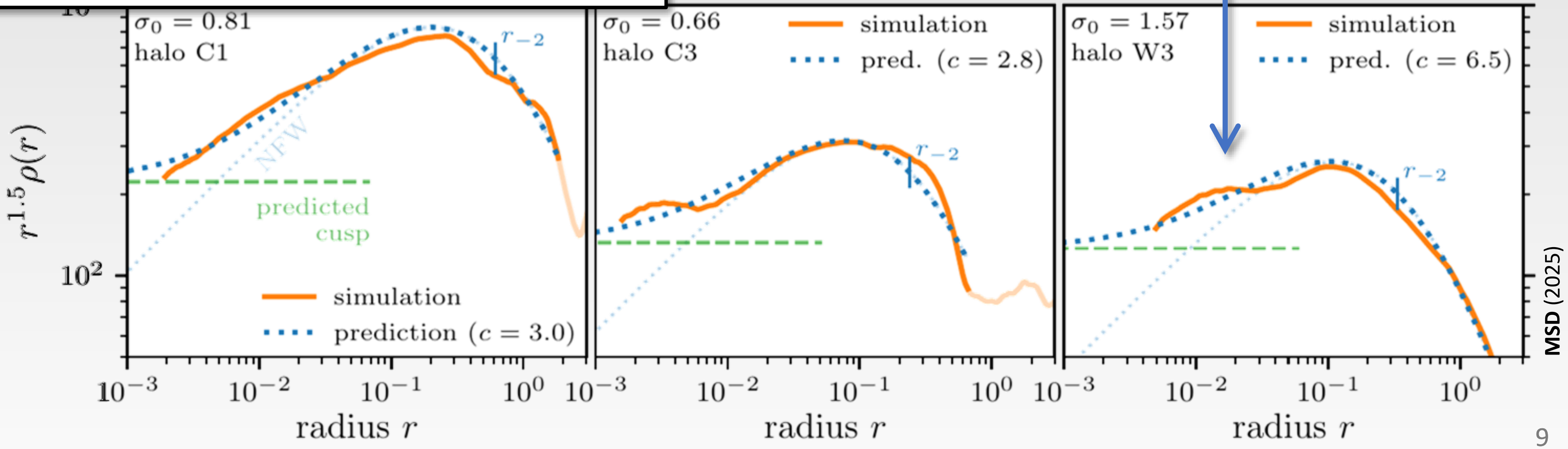
"cusp-NFW"

$$\rho(r) = \frac{\sqrt{y^2 + x}}{x^{1.5}(1+x)^2}\rho_\mathrm{s},$$

$$x = r/r_\mathrm{s}, \qquad y = A/(\rho_\mathrm{s} r_\mathrm{s}^{1.5})$$

$$0 \leq y \leq 1$$

NFW pure cusp

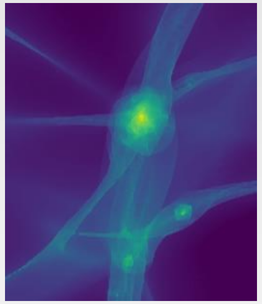


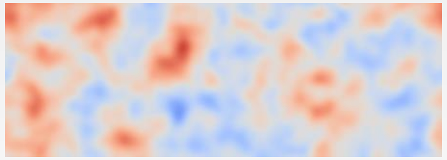
MSD (2025)

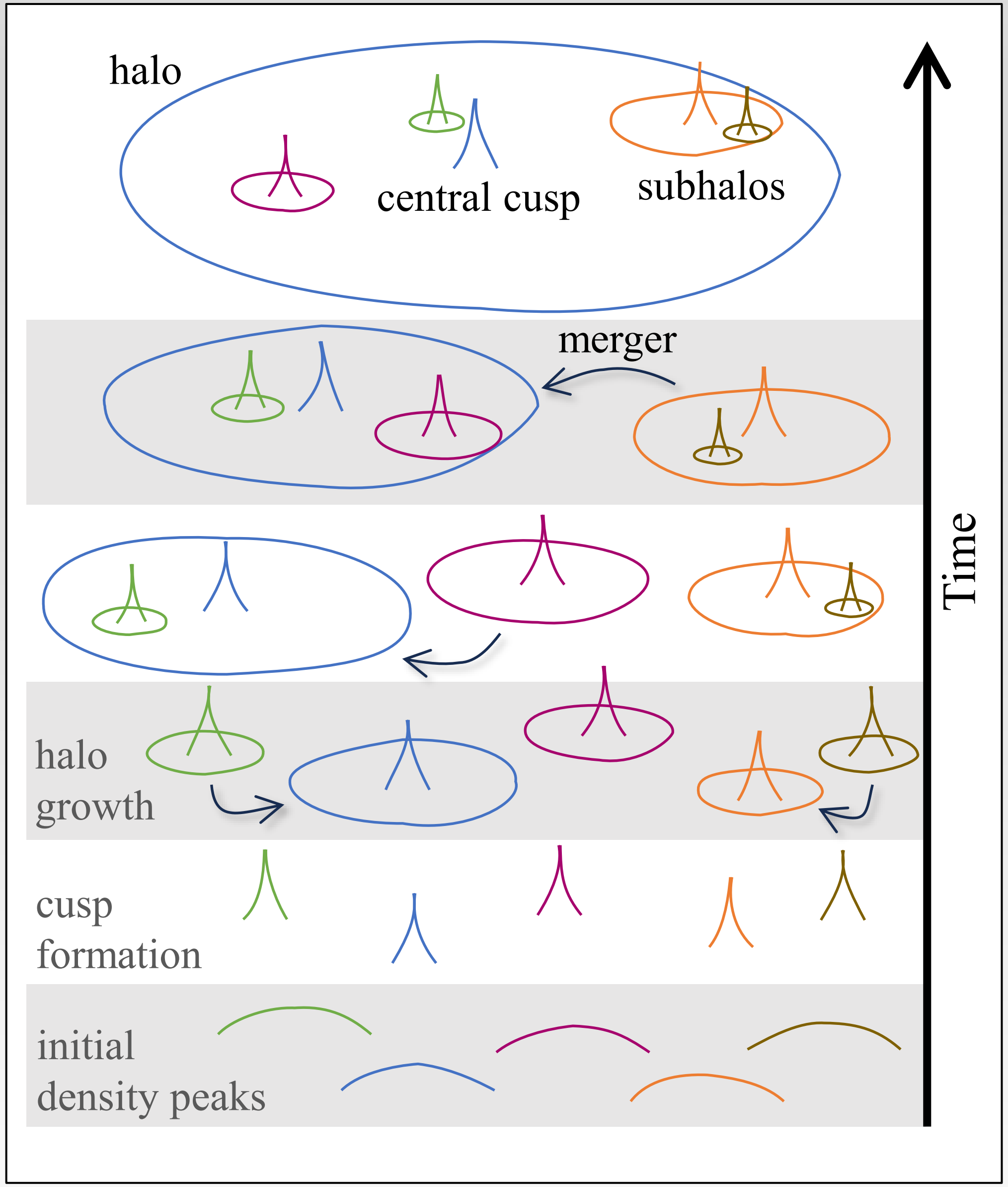
Hierarchical assembly of cosmic structure

Halos grow by merging with other halos

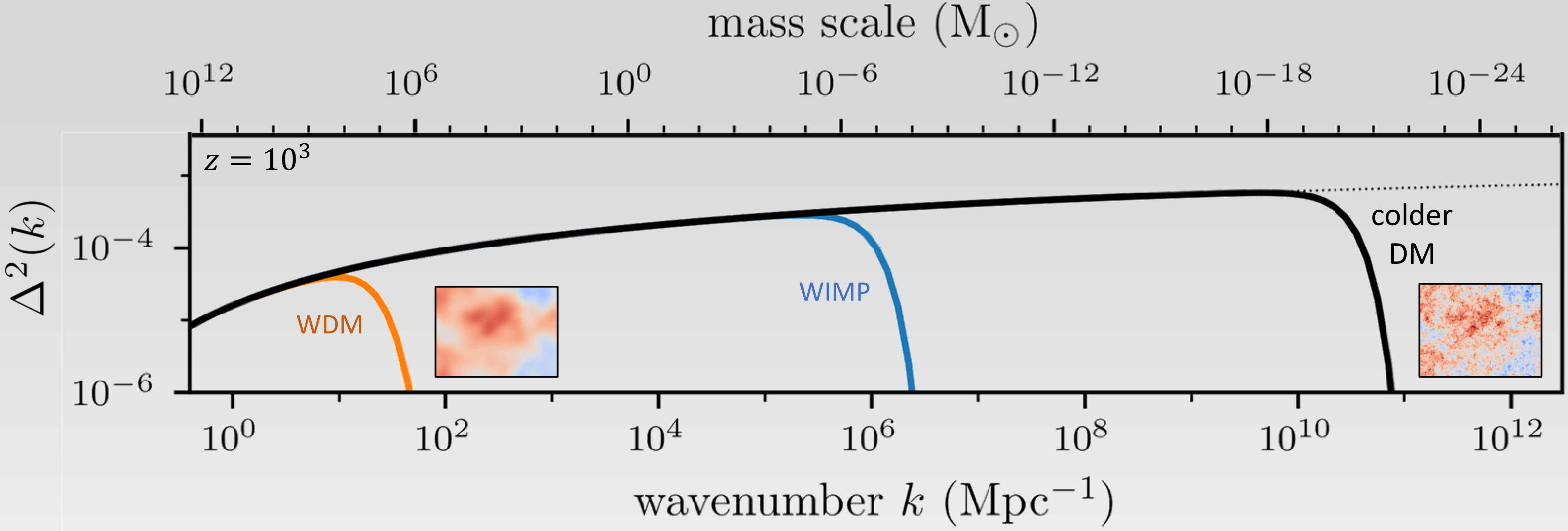
- Early universe was smooth (no halos)
- Prompt cusps: 1st stage of cosmic structure
- Prompt cusps persist at halo centers
  (but halo can grow much bigger than the initial cusp)
- Most cusps survive hierarchical assembly
  (as substructures)







Cosmology with prompt cusps



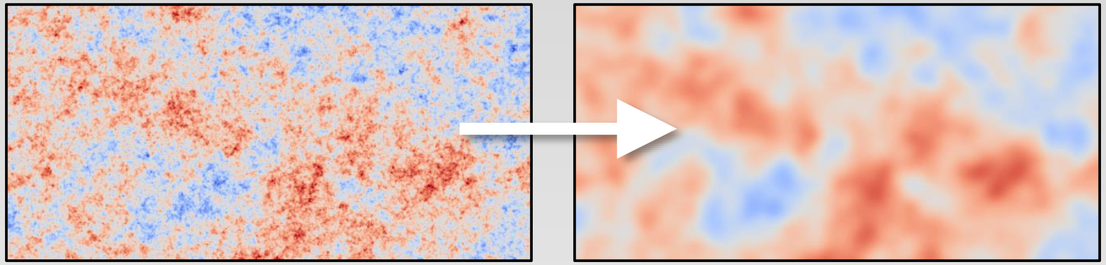
Prompt cusps are a signature of the smoothing scale (e.g., from thermal motion)

Prompt cusps of warm dark matter would affect dwarf galaxy structures

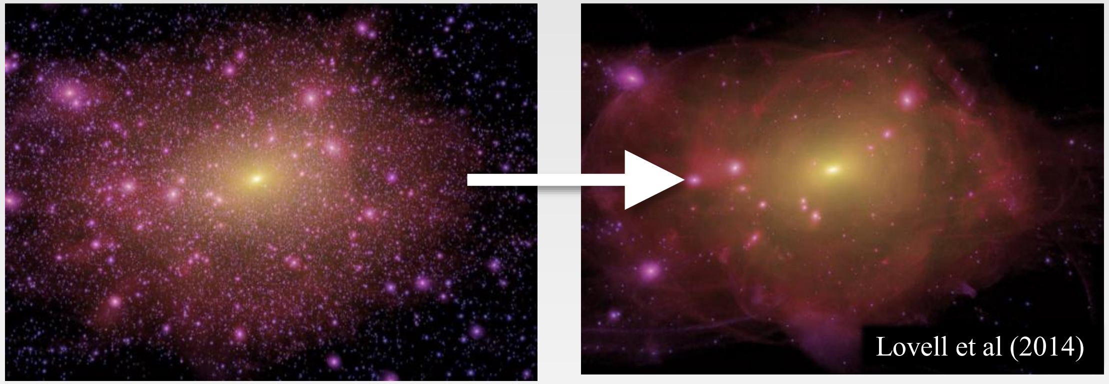
Warm or interacting dark matter

Random particle motion smooths initial conditions

- DM production mechanism?
- Interactions with Standard Model?



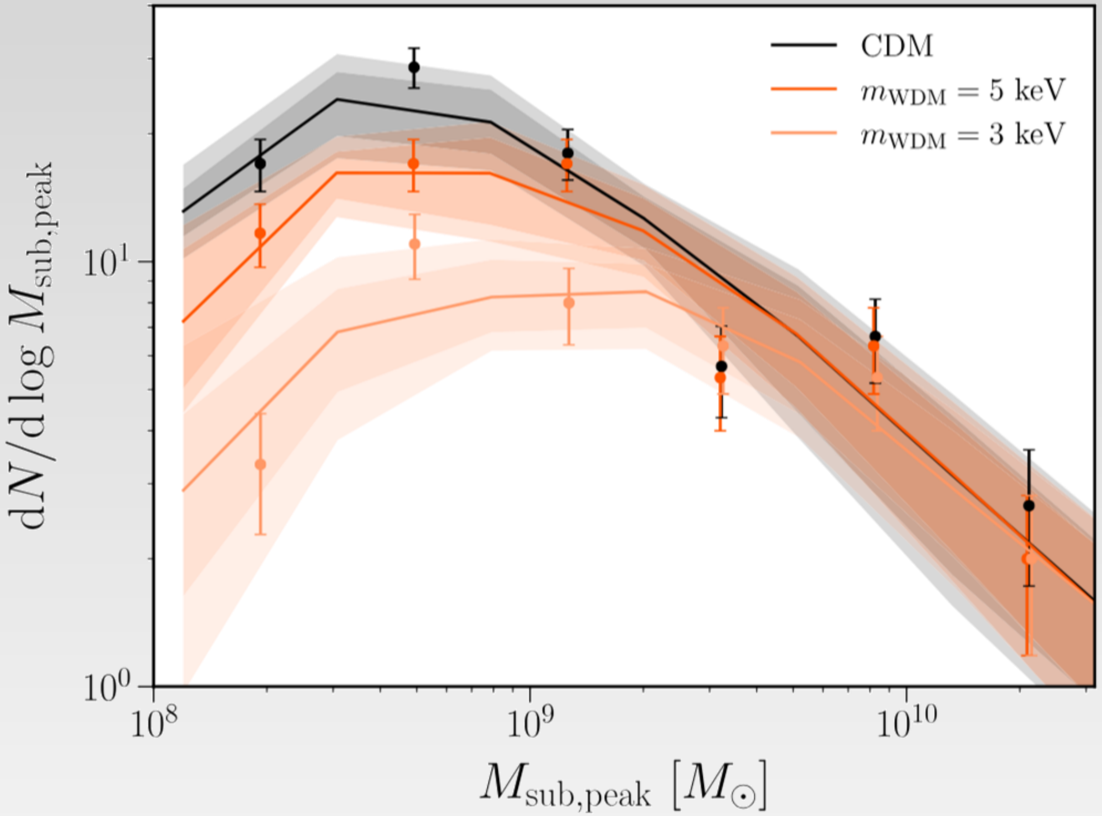
which suppresses the abundance of low-mass halos:



Lovell et al (2014)

Initial density peaks are much larger
→ Prompt cusps are much more massive

number of satellite galaxies

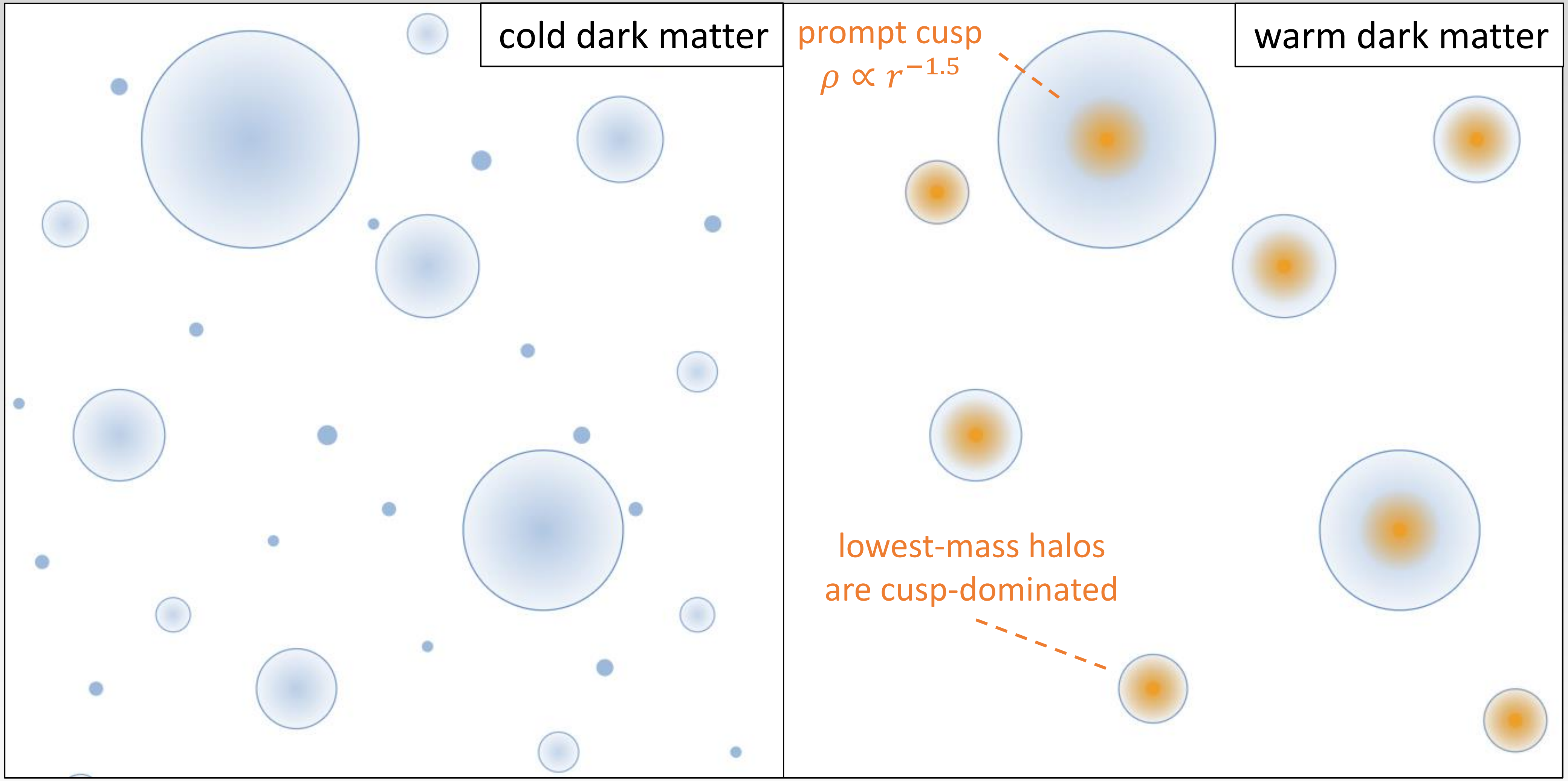


Nadler, An, Gluscevic, Benson, Du (2025)

$m_{\mathrm{WDM}} > 5.9$ keV (95% confidence).

Prompt cusps and warm dark matter

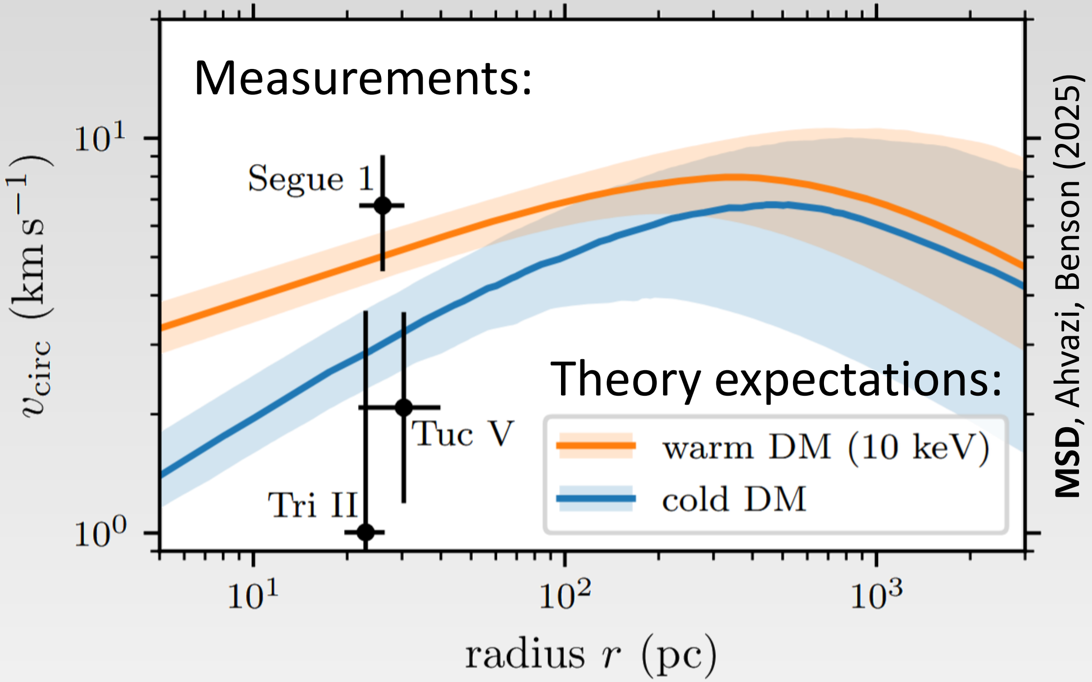
prompt cusp mass $\simeq$ minimum halo mass



Prompt cusps of ultrafaint dwarfs

Compare v_{circ} at half-light radius for the 3 faintest confirmed galaxies

- faint → baryonic feedback is unlikely to be relevant
- measurement most robust at half-light radius



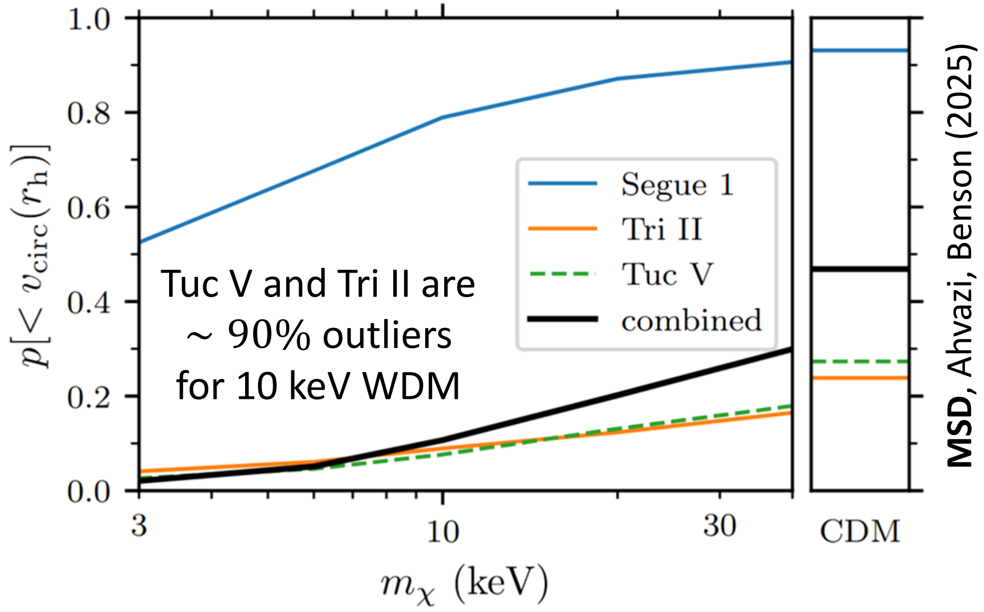
Measurements:

Theory expectations:

MSD, Ahvazi, Benson (2025)

Warm DM: prompt cusp concentrates mass at center → higher orbit speeds

Cold DM: prompt cusps are too low-mass to be relevant

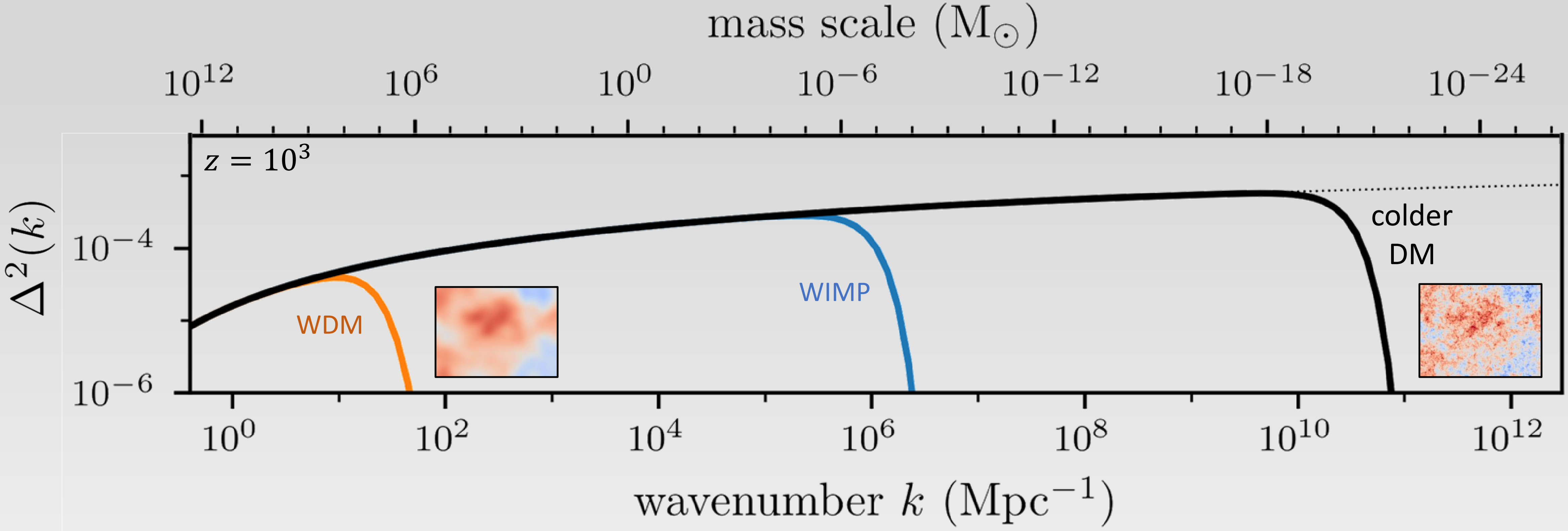


Tuc V and Tri II are ~ 90% outliers for 10 keV WDM

MSD, Ahvazi, Benson (2025)

Combined:
$m_\chi > 5.8$ keV at 95% confidence
$m_\chi > 9.4$ keV at 90% confidence

Cosmology with prompt cusps



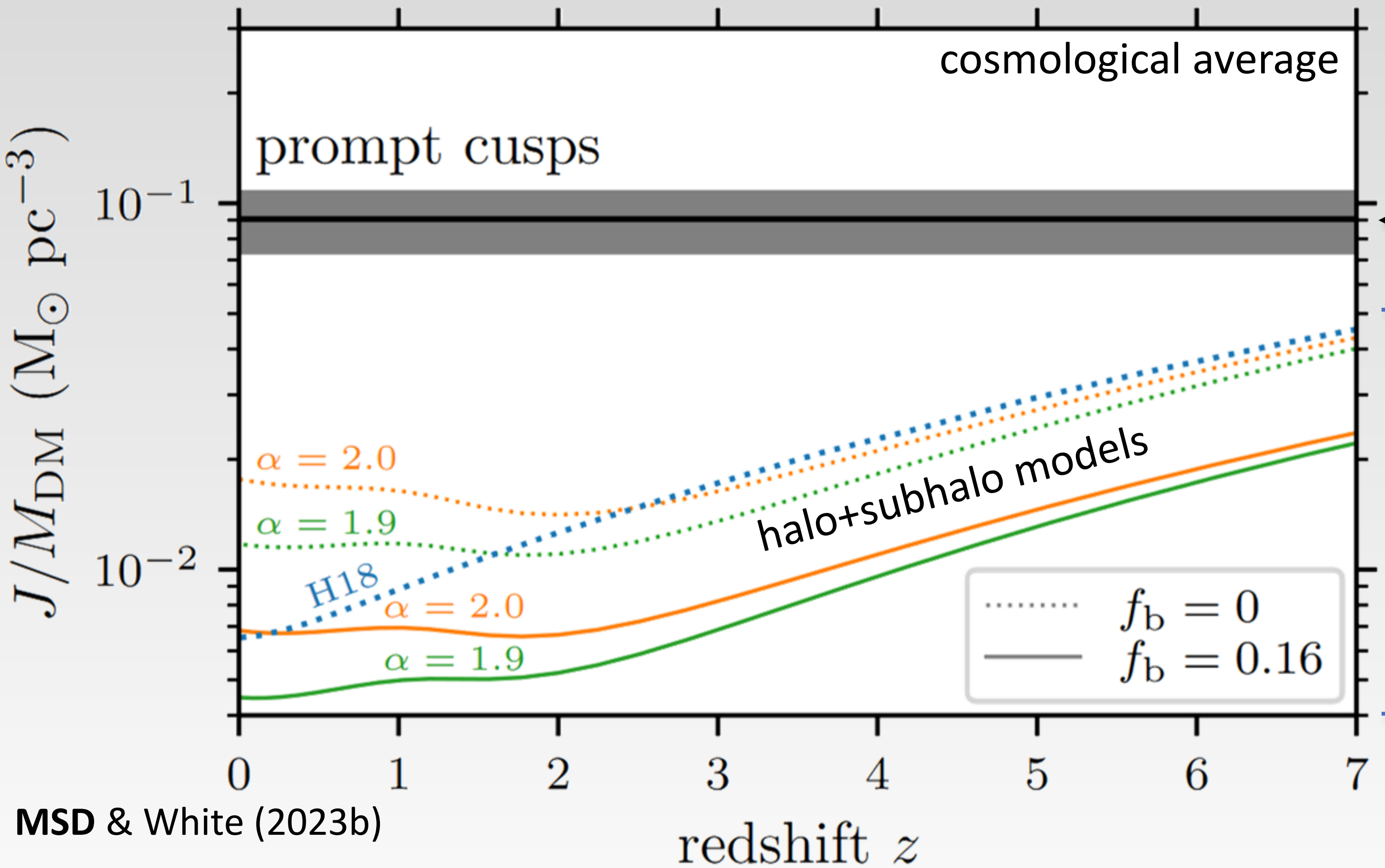
Prompt cusps are a signature of the smoothing scale (e.g., from thermal motion)

Prompt cusps of warm dark matter would affect dwarf galaxy structures

Prompt cusps boost dark matter annihilation by a factor of ~ 10

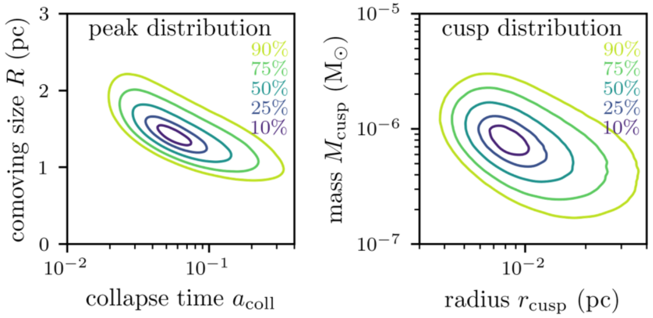
Annihilation in prompt cusps

Abundance and internal density of prompt cusps greatly boost the annihilation rate



MSD & White (2023b)

Directly from statistics of peaks & peak-cusp connection*



Previous predictions:
halo & subhalo models

- Extrapolate from much larger scales: $\frac{dN}{dm} \propto m^{-\alpha}$
- Semianalytic modeling (neglected baryons!)

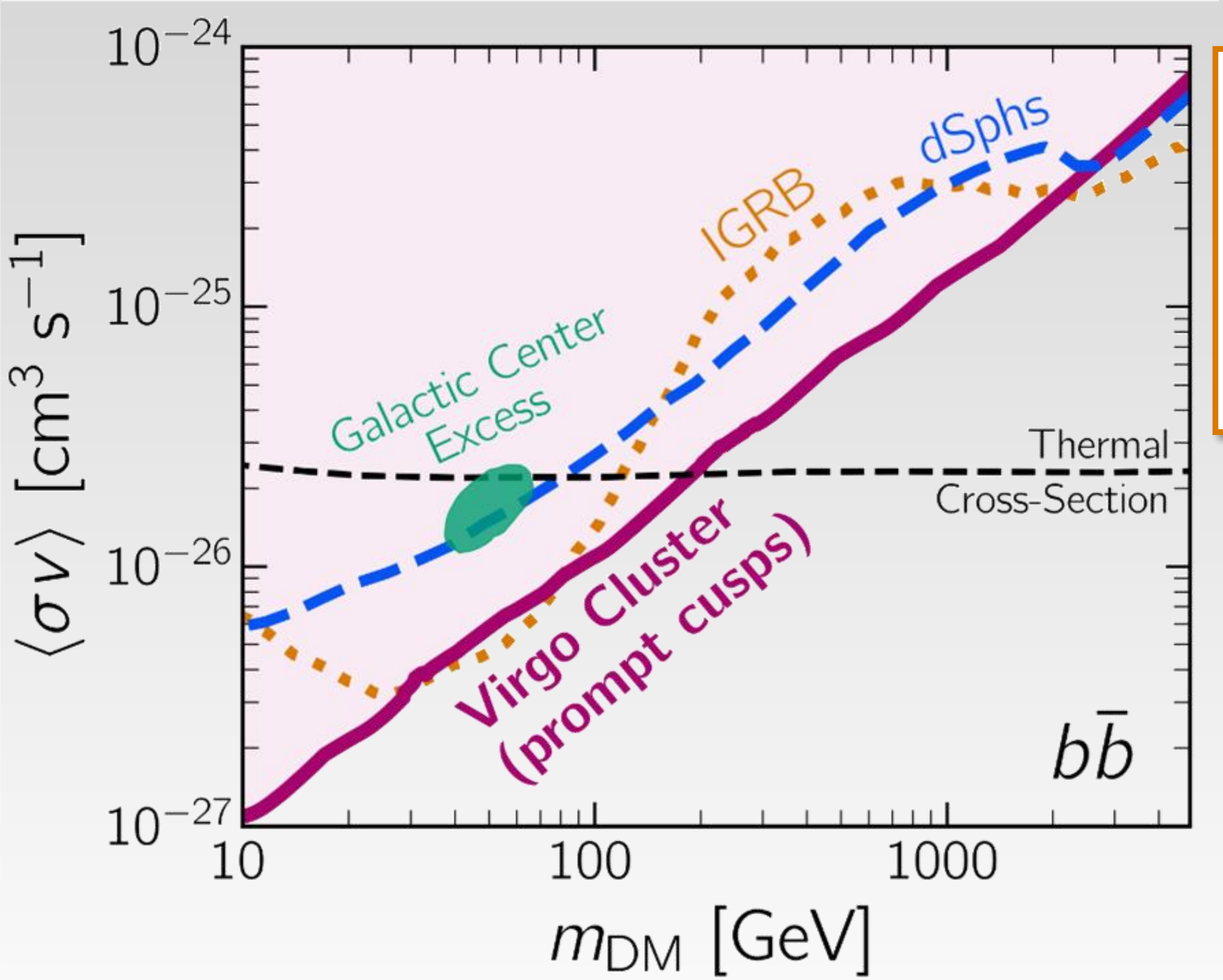
*about 1/2 of initial peaks can be associated with cusps due to halo clustering

Limits on dark matter annihilation

Annihilation rate ∝ number of cusps ∝ total mass of DM

No large annihilation boost in Galactic Center & nearby satellite galaxies:

- Density already high in smooth halo
- Substructure tidally disrupted



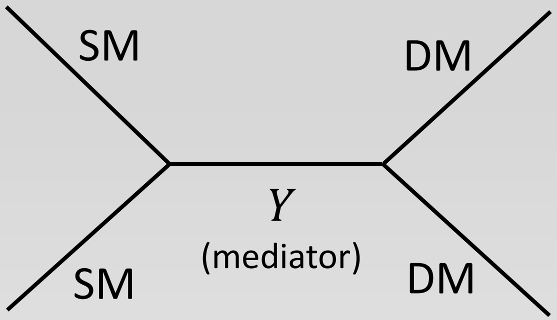
from prompt cusps contributing to isotropic γ-ray background (IGRB)

(**MSD**, Korsmeier, Widmark, Blanco, Linden, White 2024)

from prompt cusps in nearby galaxy clusters

(Crnogorčević, **MSD**, Kuritzén, Linden 2025)

Limits on hidden-sector dark matter

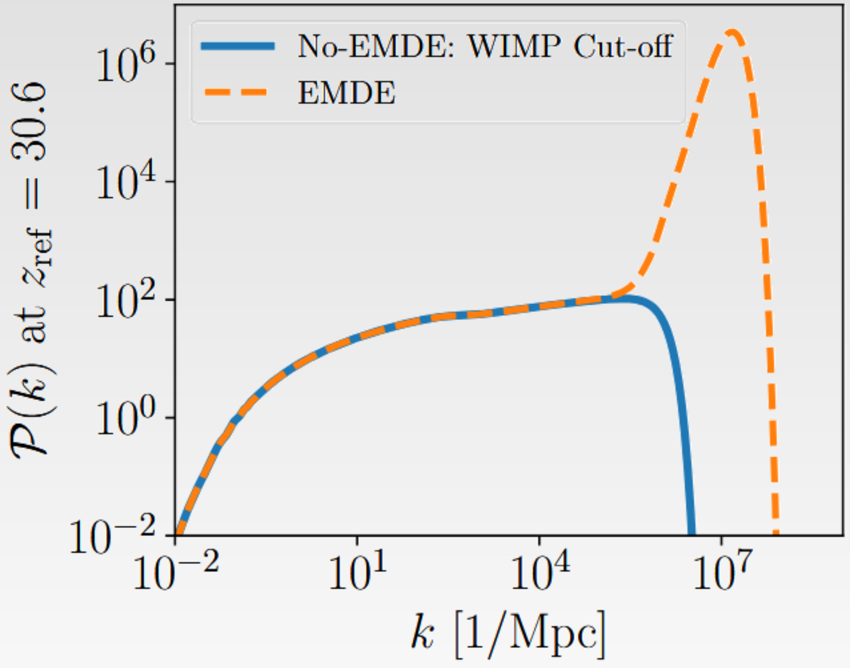


Idea: produce DM thermally while evading colliders/direct detection
(e.g. Berlin, Hooper, Krnjaic 2016)

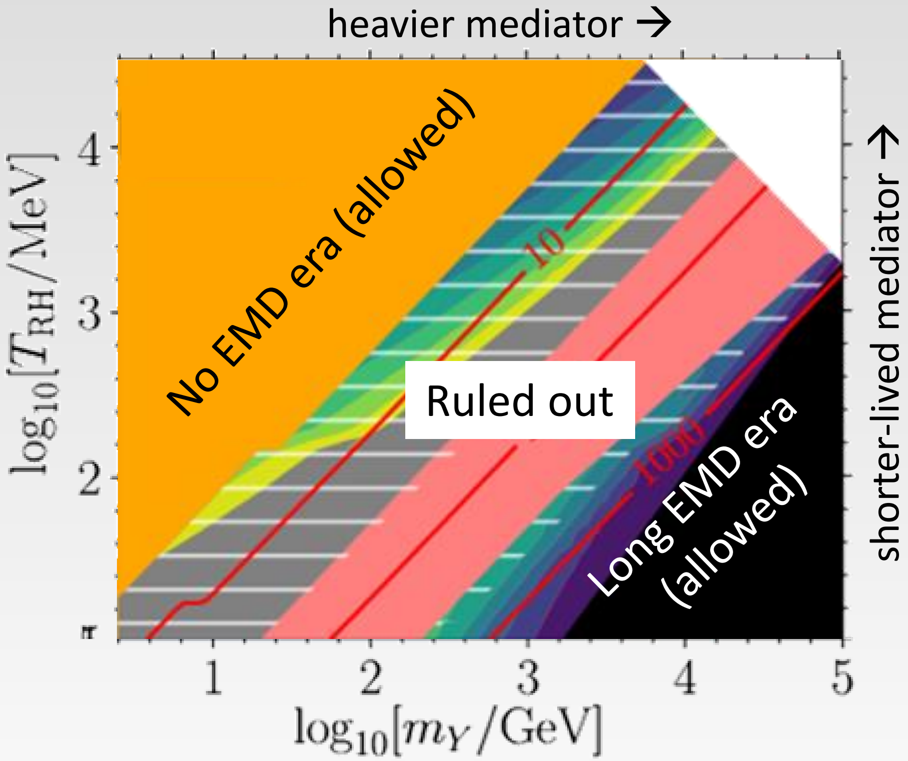
Himanish Ganjoo
(Paris Observatory)

Mediator Y can drive early matter-dominated era depending on mass/lifetime

- hugely boosted annihilation rates
- **strong indirect-detection constraints**



Ganjoo & **MSD** (2025)



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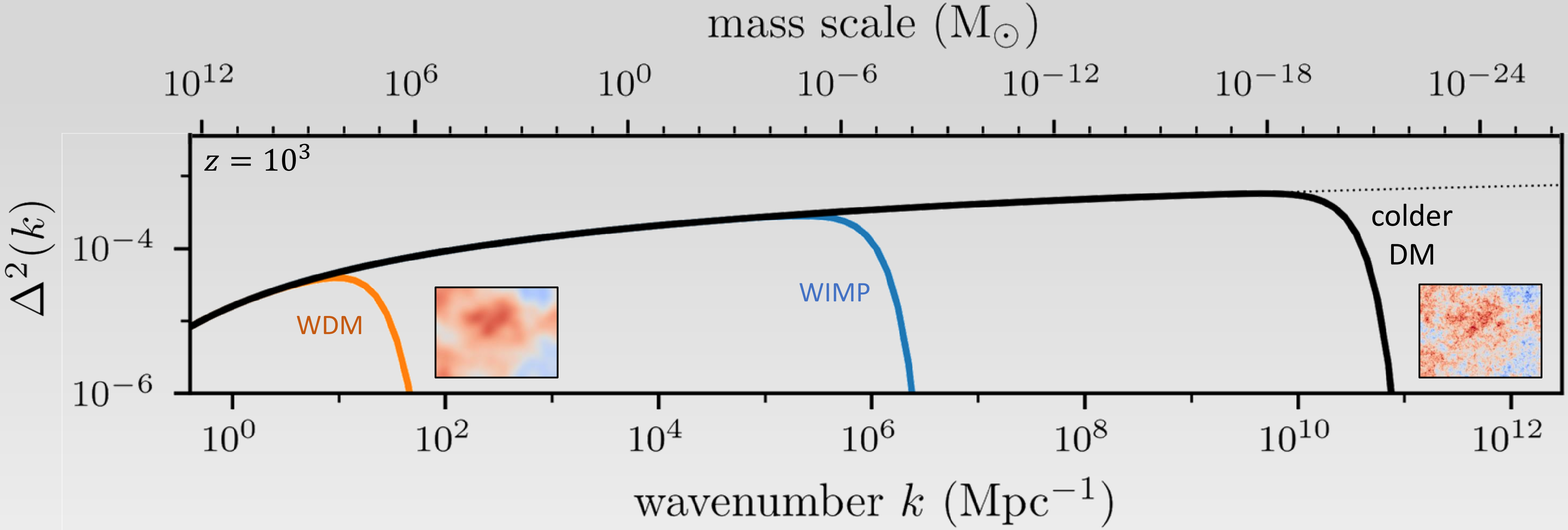
Cosmology with prompt cusps



Prompt cusps are a signature of the smoothing scale (e.g., from thermal motion)

Prompt cusps of warm dark matter would affect dwarf galaxy structures

Prompt cusps boost dark matter annihilation by a factor of ~ 10

For very cold DM, prompt cusps would pass continuously through the Solar System

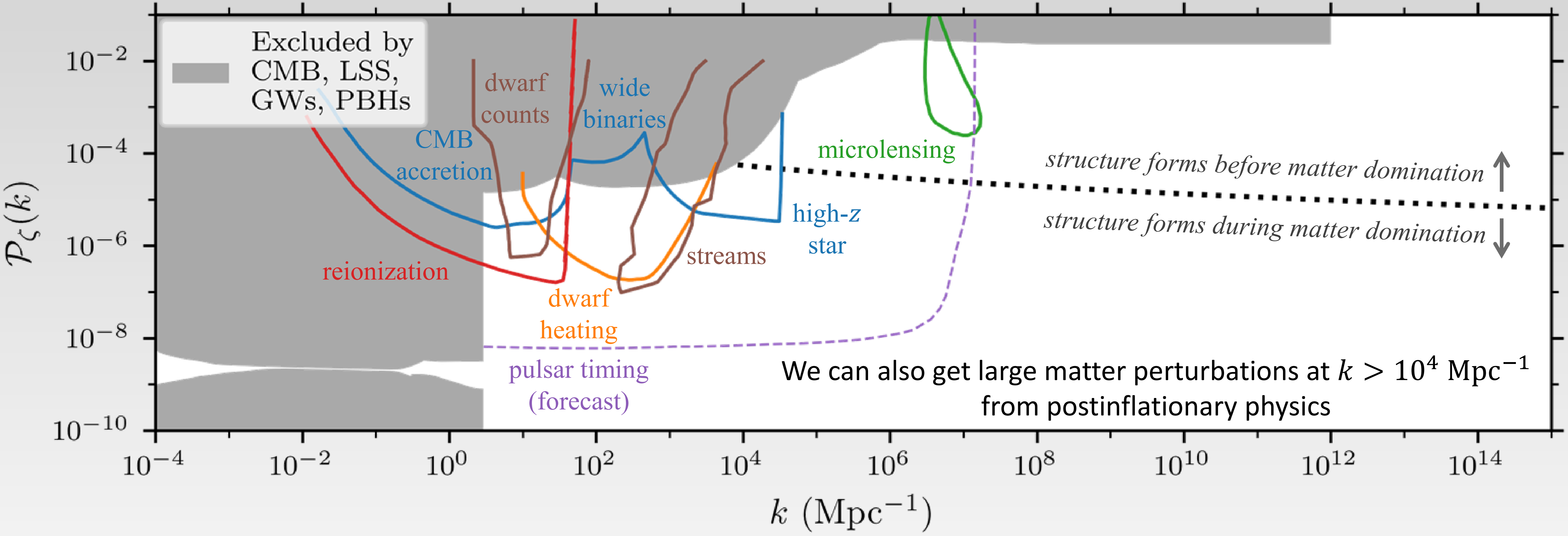
(dense enough to survive stellar encounters)

Outline

- Structure formation from smooth initial conditions:
  prompt cusps and constraints on particle dark matter
- **Structure formation in the radiation era**
  and constraints on large initial perturbations
- Structure formation with primordial black holes:
  influence of short-range and relativistic dynamics

Constraints on the primordial power spectrum

(colors are from small-scale structure)



We can also get large matter perturbations at $k > 10^4$ Mpc^{-1} from postinflationary physics

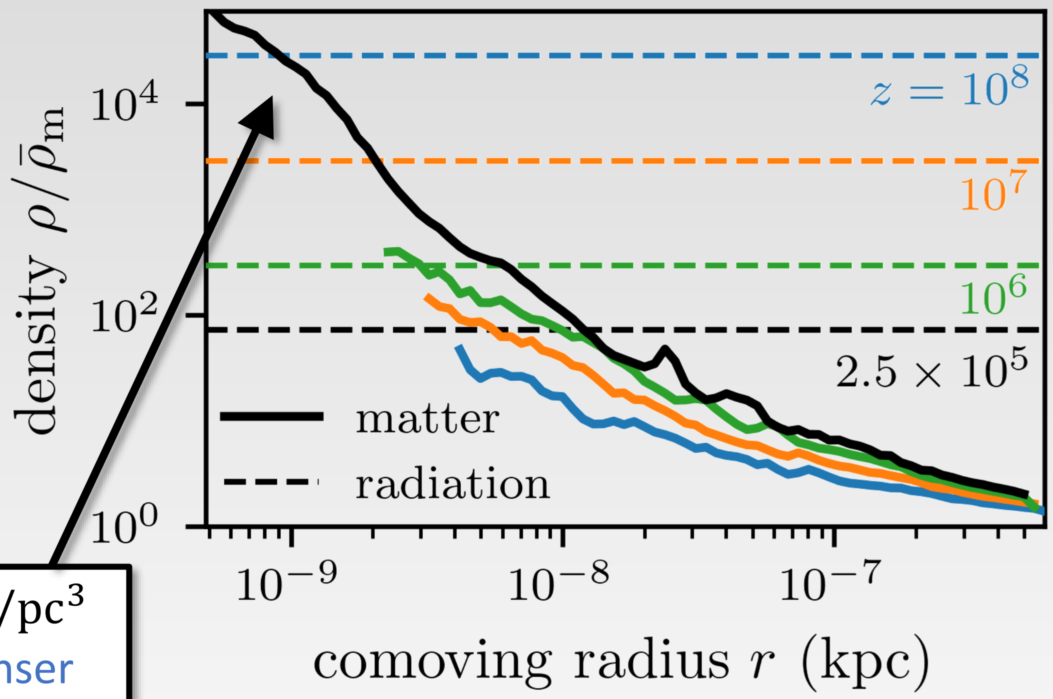
For $\mathcal{P}_\zeta \gtrsim 10^{-5}$, we need to consider structure formation prior to the matter-dominated era

Halo formation during the radiation era

No peculiar gravitational forces where radiation dominates,
only DM particle drift from initial conditions.

However, drift alone can make locally matter dominated regions, **forming halos deep in the radiation epoch**

simulation

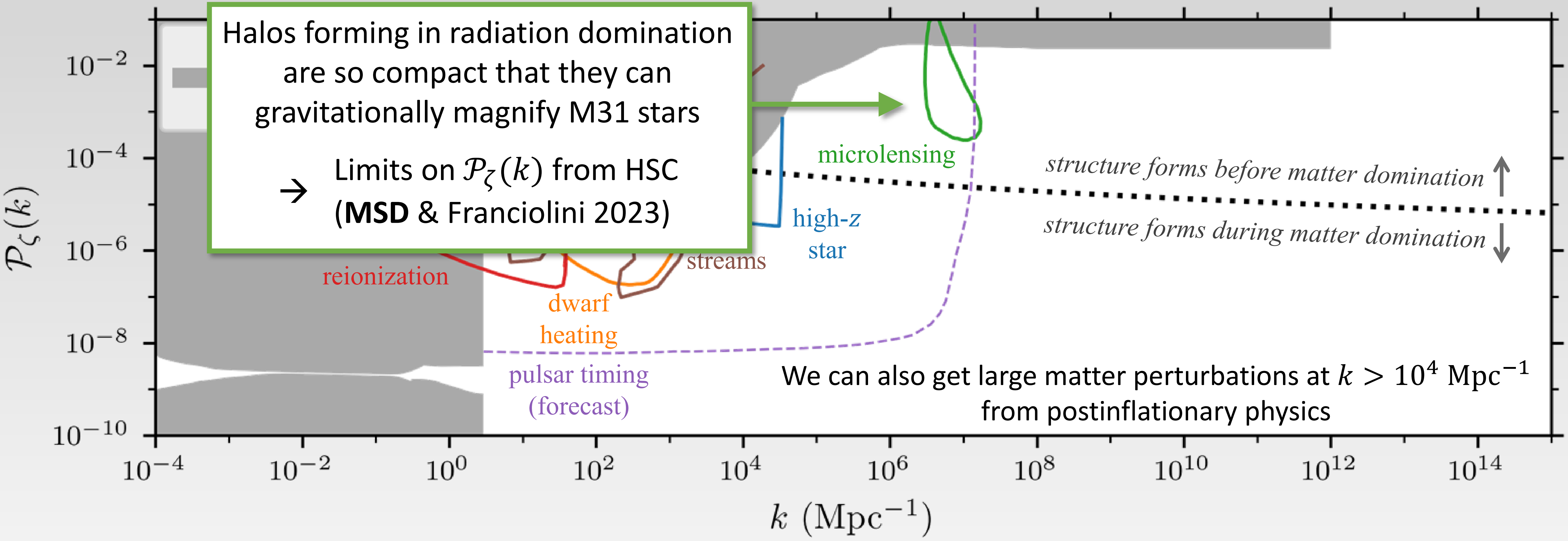


Blanco, **MSD**, Erickcek, Hooper (2019)

$\sim 10^{12}\ \mathrm{M}_\odot/\mathrm{pc}^3$
$\sim 10^{14}\times$ denser than galactic halos

Constraints from microlensing

(colors are from small-scale structure)



Halos forming in radiation domination are so compact that they can gravitationally magnify M31 stars

→ Limits on $\mathcal{P}_\zeta(k)$ from HSC (**MSD** & Franciolini 2023)

We can also get large matter perturbations at $k > 10^4$ Mpc^{-1} from postinflationary physics

For $\mathcal{P}_\zeta \gtrsim 10^{-5}$, we need to consider structure formation prior to the matter-dominated era

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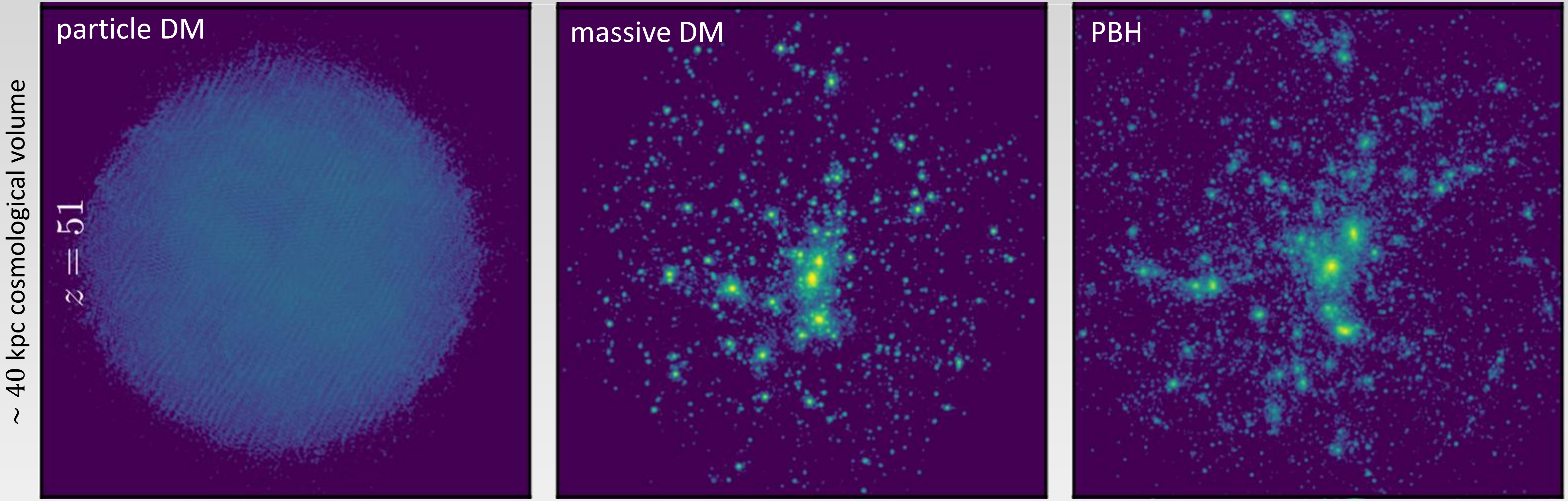
Primordial black hole dark matter

First cosmological simulation with PBH DM that fully resolves collisional+relativistic dynamics



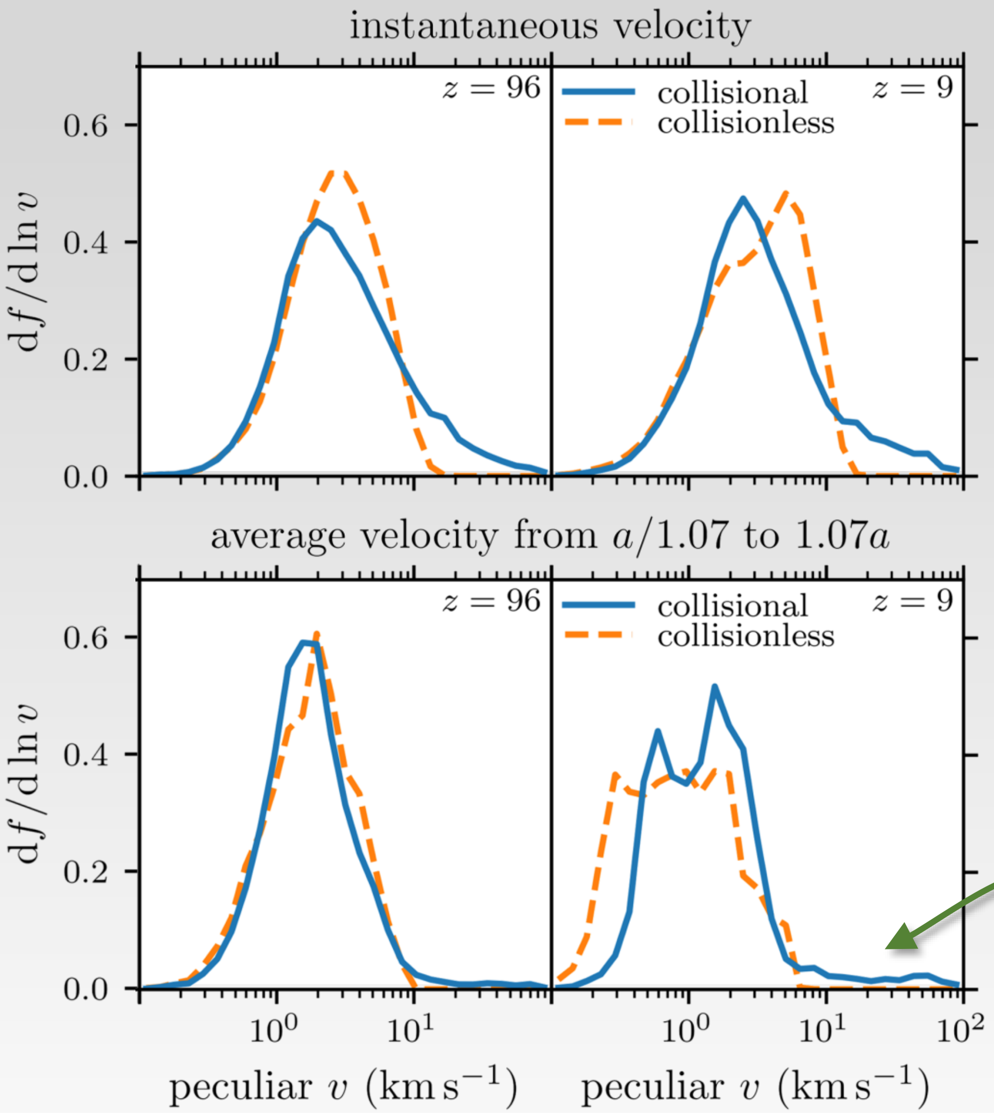
MSD, Rantala, Young, Schmidt (2024)

Poisson noise due to independently distributed particles ($\sim 10\ \mathrm{M}_\odot$)

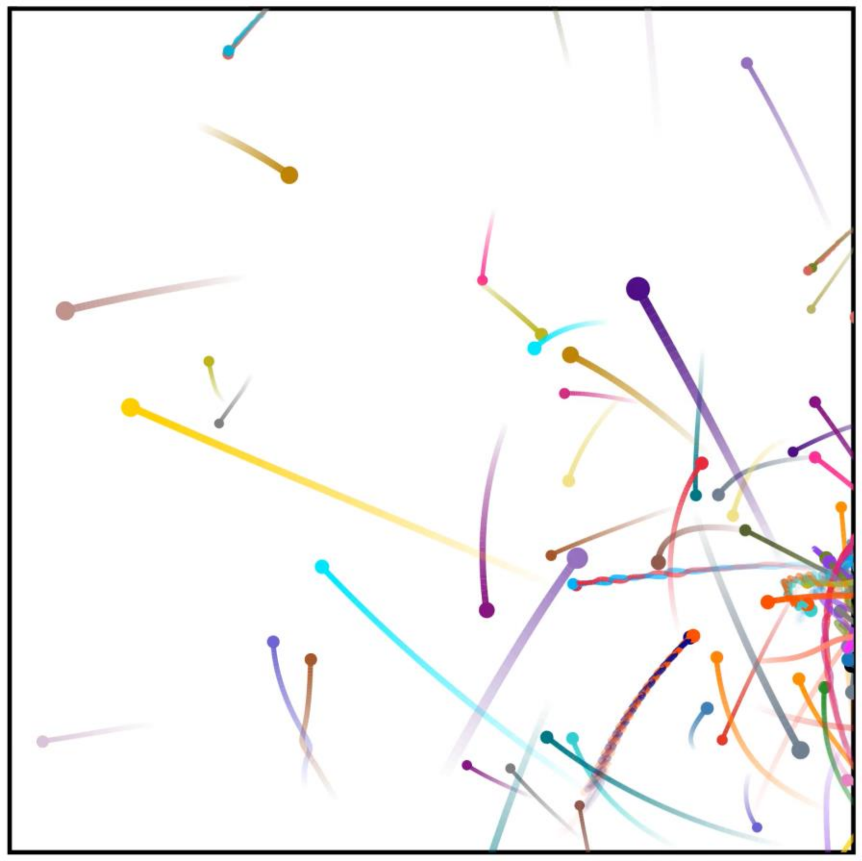
interparticle dynamics:

- large-angle scattering
- binaries
- relativistic gravity
- etc.

Collisional heating



Binary orbital motion contributes to velocity distribution



Through interactions, this can turn into streaming motion

Hot dark matter component, which would suppress structure growth up to billion-PBH scales

MSD, Rantala, Young, Schmidt (2024)

Binary mergers

Pairs of PBHs can merge, producing detectable gravitational radiation

Predictions for GWs from PBHs consider
merge times from relativistic orbital decay

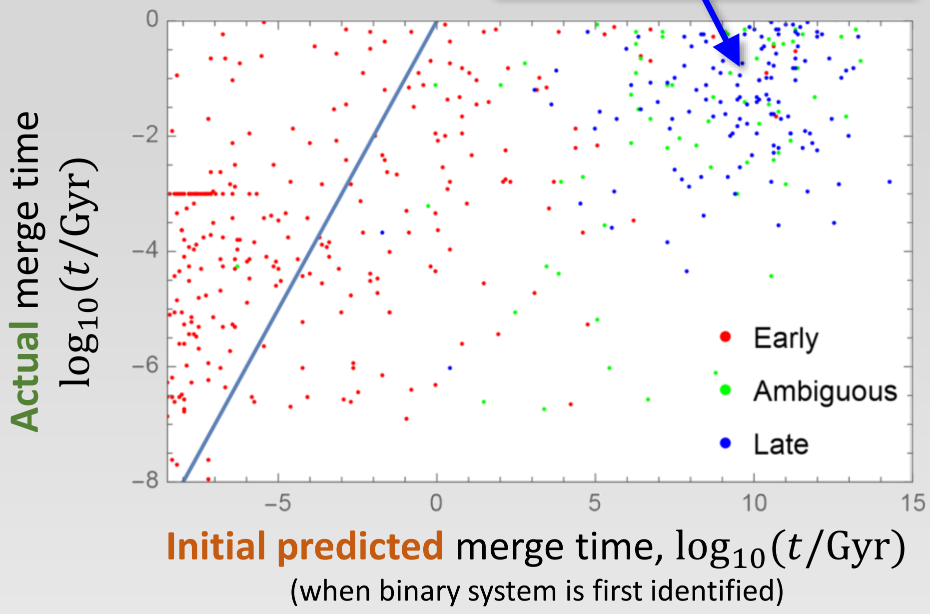
$$\tau = \frac{3}{85}\frac{c^5}{G^3}\frac{r_{\mathrm{a}}^4 j^7}{m_1 m_2 (m_1 + m_2)}$$

(for $j \to 0$ limit; j is normalized angular momentum)

In a cosmological simulation we find

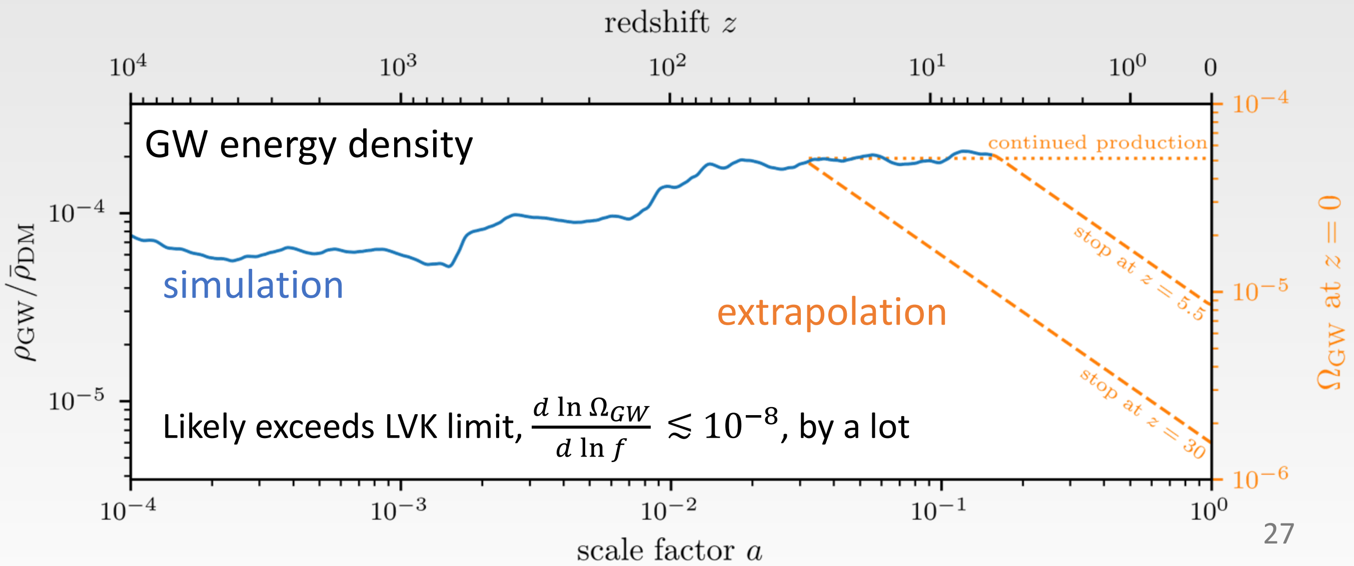
- no correlation between **initial prediction** and **actual** merge time
- certain populations not predicted to merge soon, but they do

Mergers are highly stochastic due to randomization of j in collisions?
(already recognized by the star cluster community)



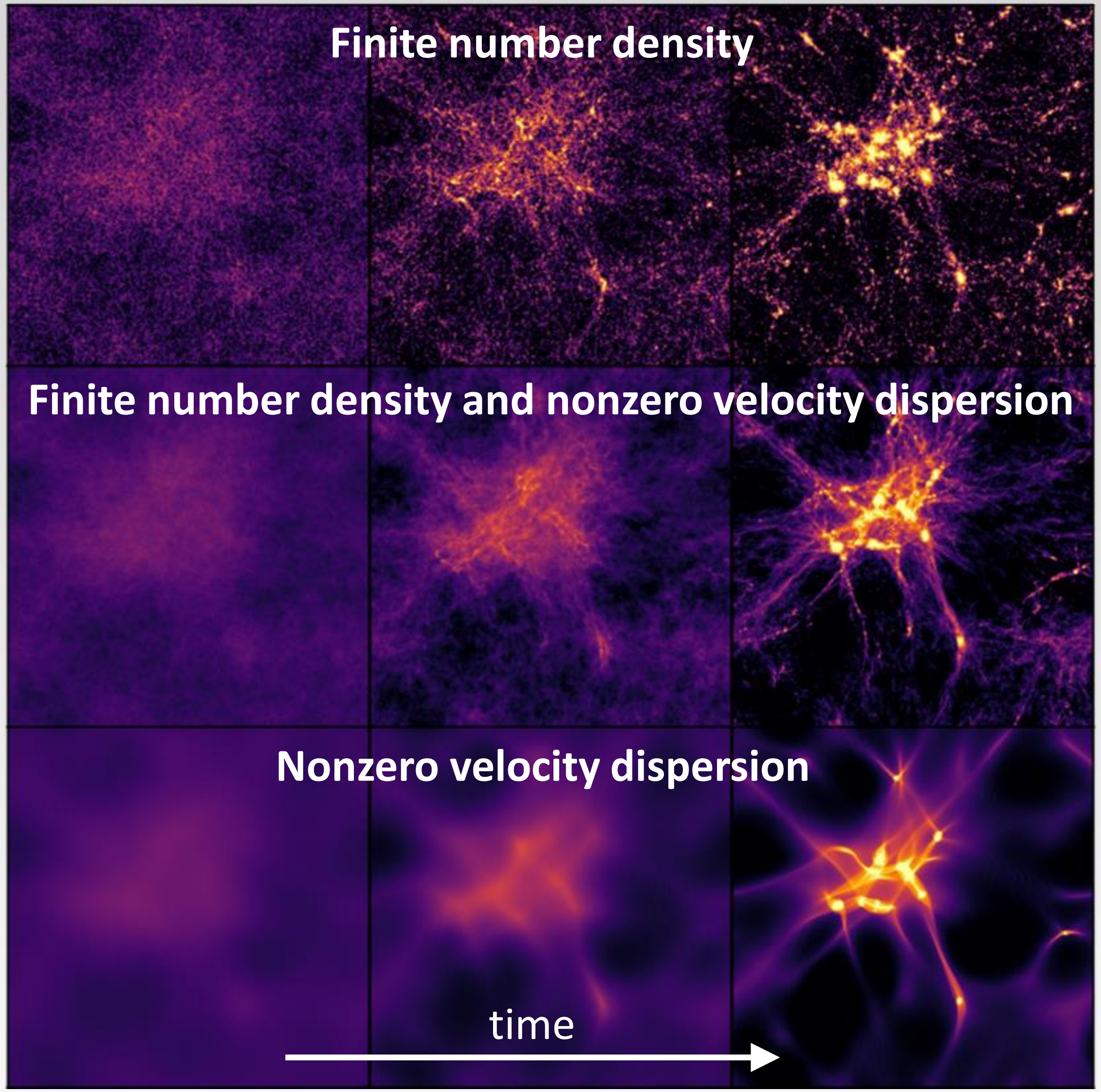
At no point are these predicted to merge soon

MSD, Rantala, Young, Schmidt (2024)



Likely exceeds LVK limit, $\frac{d\ln\Omega_{GW}}{d\ln f} \lesssim 10^{-8}$, by a lot

PBHs vs particle dark matter



Amin, **MSD**, Mirbabayi (2025)

≃ primordial black holes

(m large, $\sigma \to 0$)

How to do cosmological perturbation theory in the intermediate case?

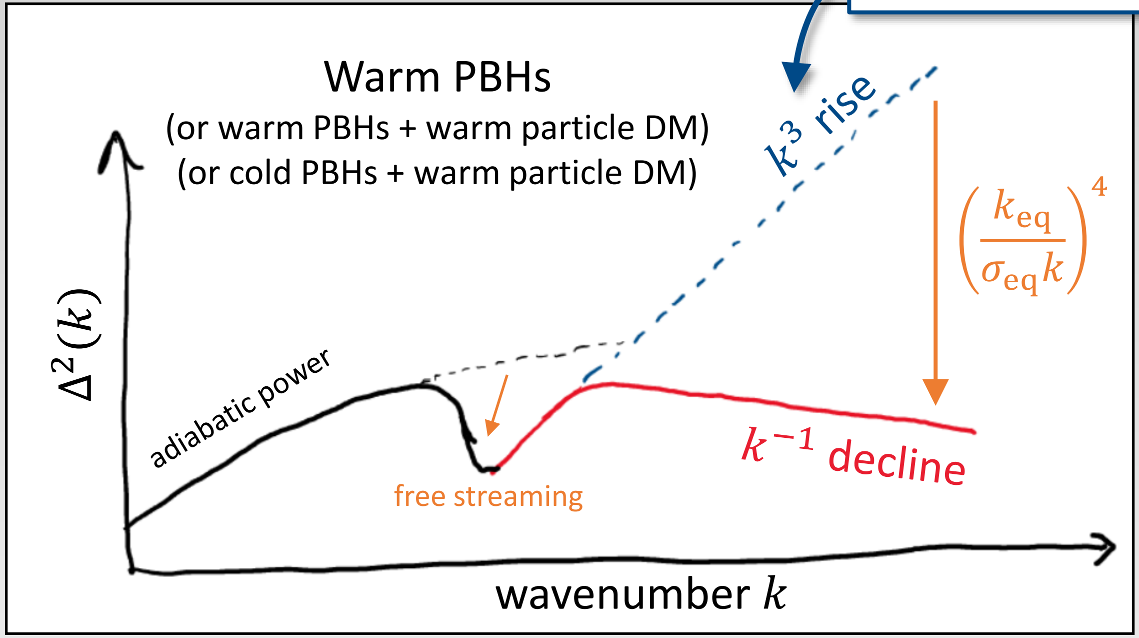
(warm PBHs? very cold particle DM?)

≃ particle dark matter (including most CDM)

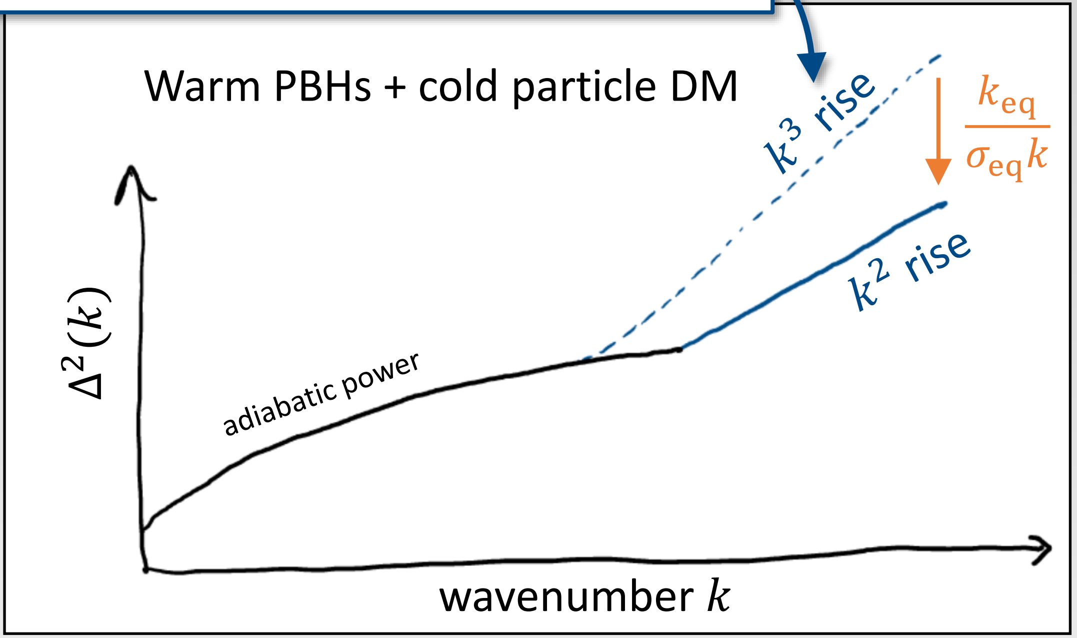
($m \to 0$, σ large)

Structure formation with finite n and σ

Poisson noise due to independently distributed particle positions



Amin, **MSD**, Mirbabayi (2025)



Amin, **MSD**, Yang (2025)

Velocity dispersion delays growth of perturbations

Velocity dispersion suppresses PBH → CDM seeding of perturbations

Based on a new formulation of cosmological perturbation theory using BBGKY hierarchy

(Amin, **MSD**, Mirbabayi 2025)

$$P_\delta(y,k) = \underbrace{P_{\delta_{\rm ad}}(y_0,k)\left[\mathcal{T}_k^{\rm ad}(y,y_0)\right]^2}_{\text{adiabatic IC + evolution}} + \underbrace{\frac{1}{\bar{n}}\left[1+3\int_{y_0}^{y}\frac{dy'}{\sqrt{1+y'}}\mathcal{T}_k^{(a)}(y,y')\mathcal{T}_k^{(b)}(y,y')\right]}_{\text{white noise IC + evolution}}$$

($\mathcal{T}$ = growth function × free-streaming cutoff)

Summary

Particle dark matter

Prompt $\boldsymbol{\rho \propto r^{-1.5}}$ cusps form at the onset of structure formation and persist at halo centers. They:

- Influence dwarf galaxy kinematics
  → constraints on warm dark matter
- Dominate the annihilation rate
  → constraints on symmetric DM
- Are dense enough to survive near us
  → detection prospects for cold DM

Large initial perturbations can form halos in the radiation era, which are dense enough to be constrained with microlensing

Black-hole dark matter

N-body dynamics:

- make a component of hot dark matter (suppressing structure on 10^9-BH scales)
- randomize binary orbits (changing predictions for GW production)

Initially nonzero velocity dispersion:

- Completely changes structure formation (new perturbation theory to calculate)
- Conceptually connects BH dark matter with particle dark matter