The smallest dark structures

M. Sten Delos

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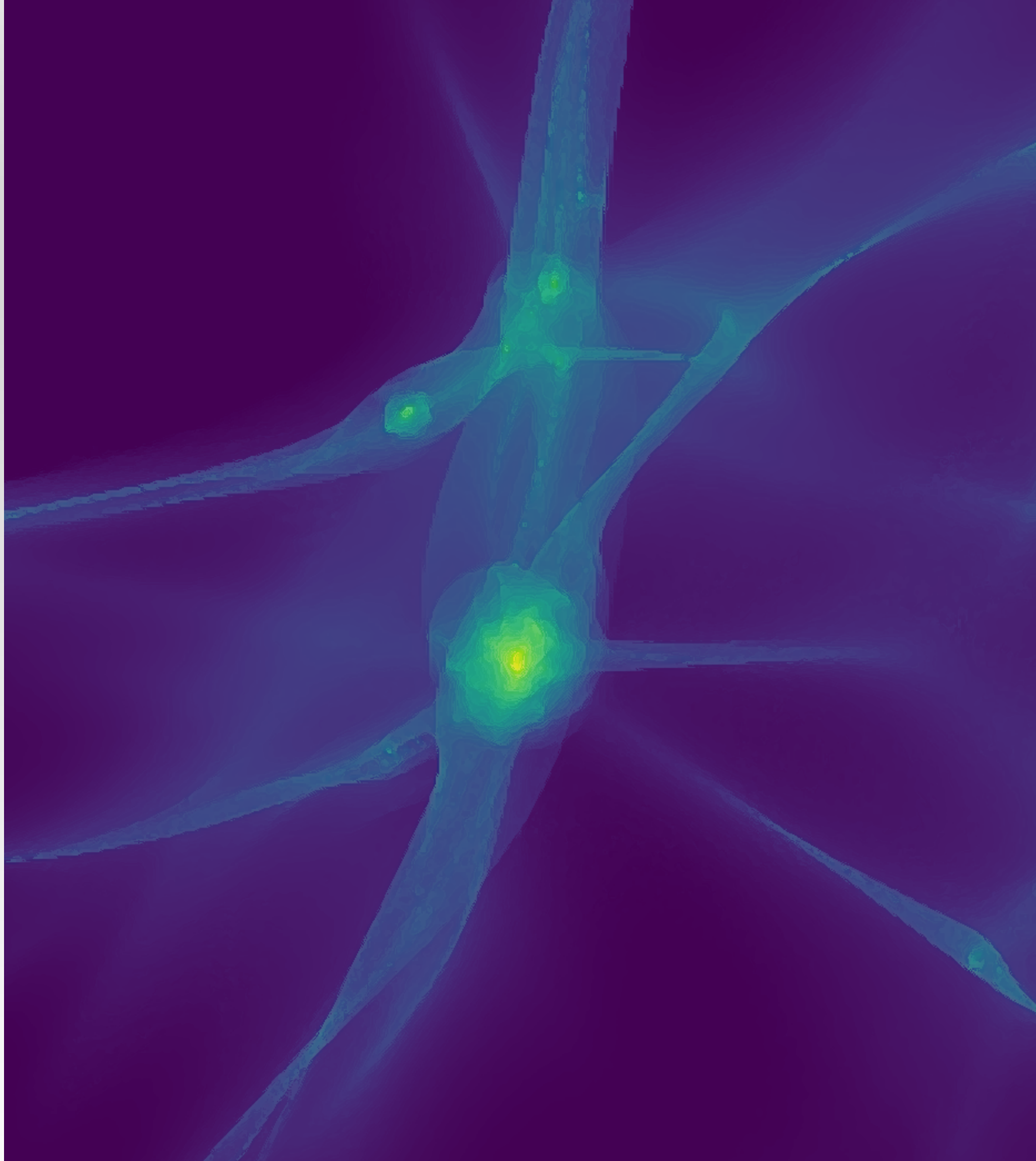

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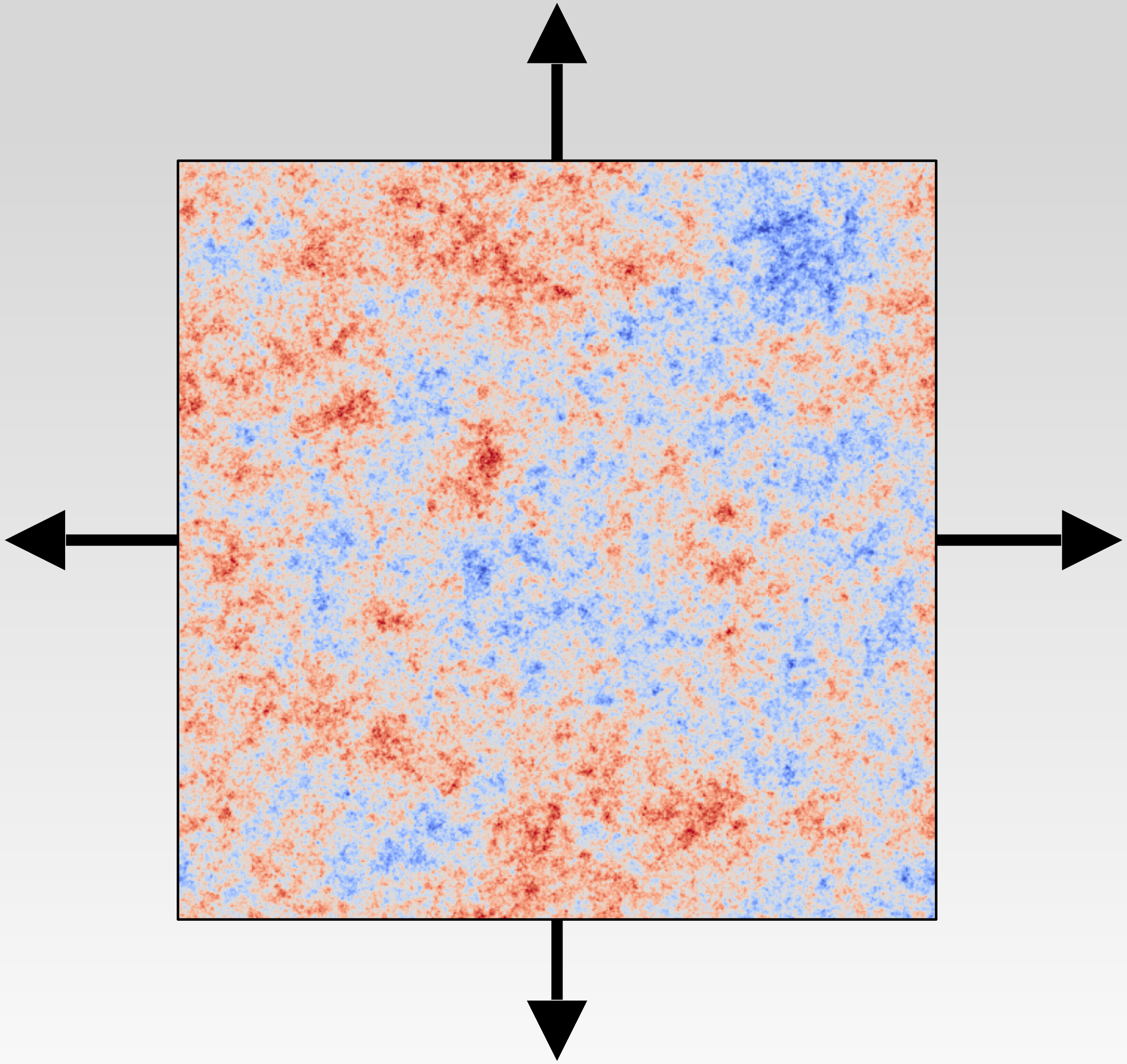
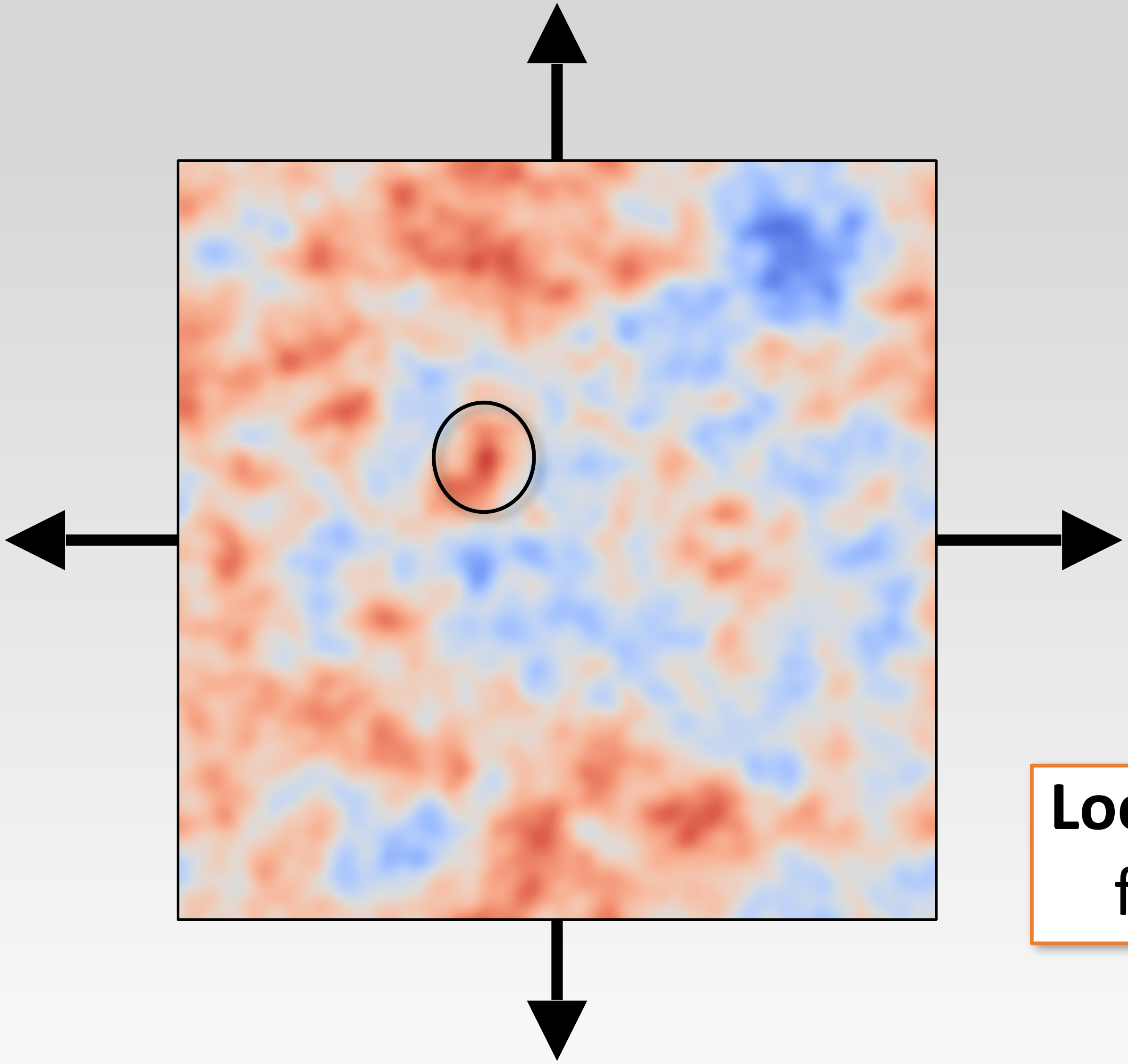
The cosmological initial conditions



A random density field

- Expanding over time
- Gravitationally amplified over time

The cosmological initial conditions



A random density field

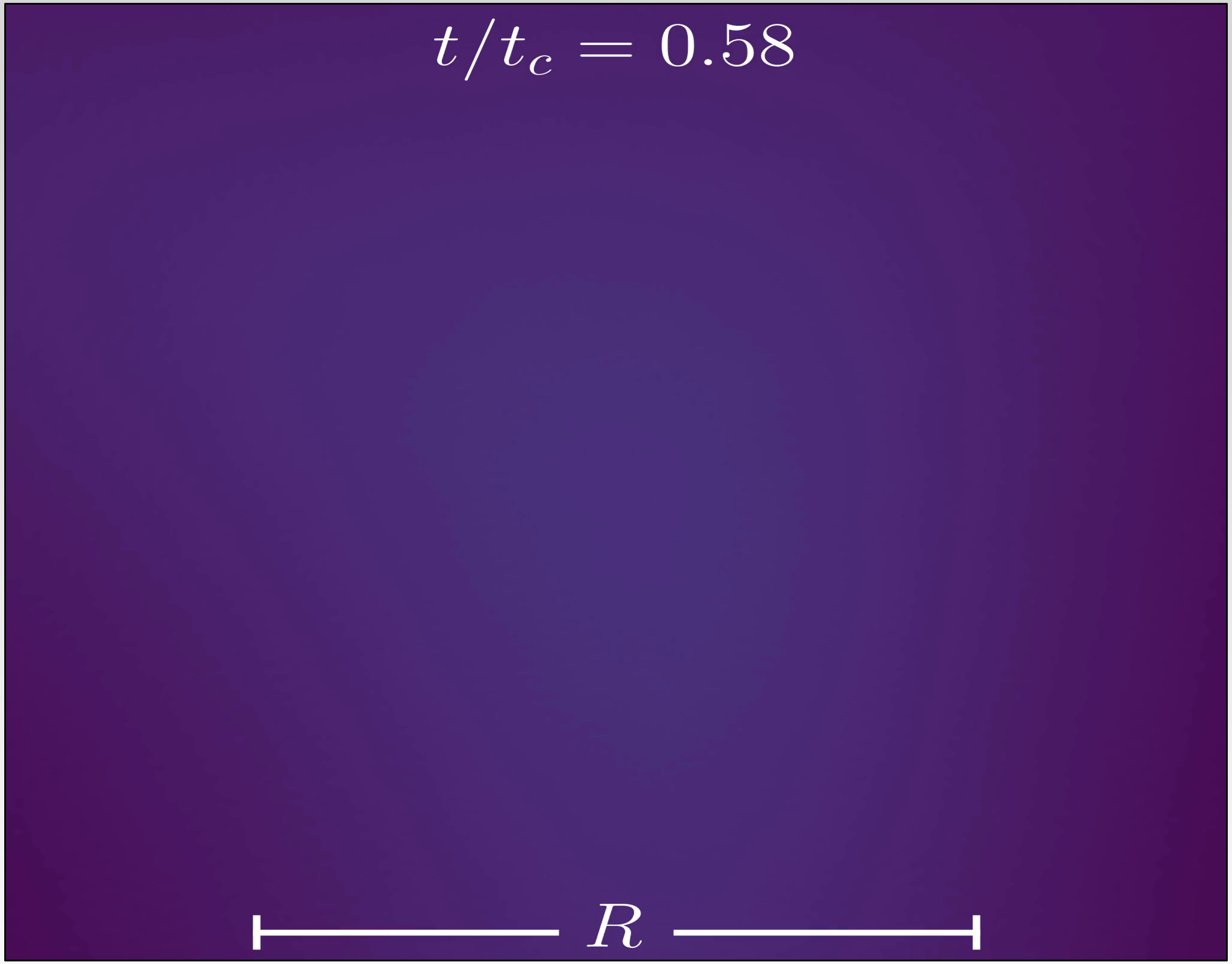
- Expanding over time
- Gravitationally amplified over time

Smooth on sufficiently small scales

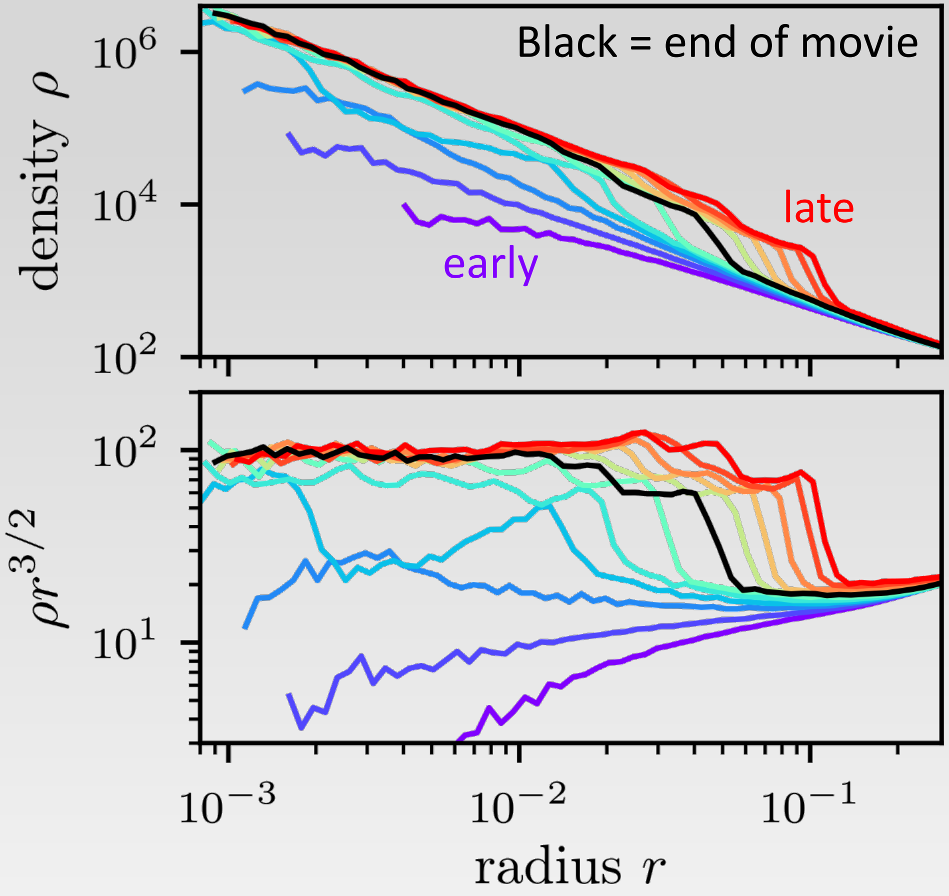
e.g., due to thermal motion of the dark matter

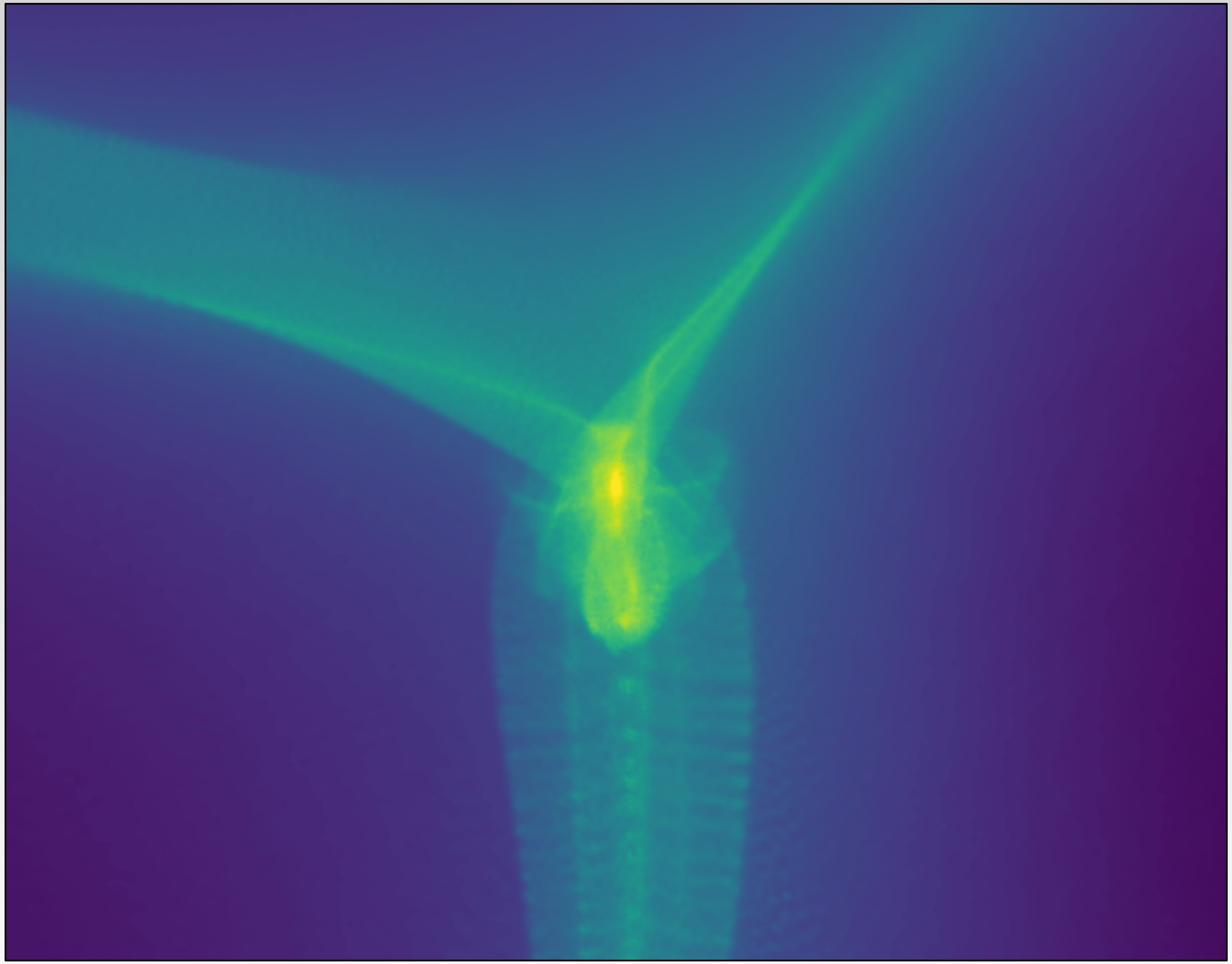
Local maxima in the density field are the first places to gravitationally collapse

Collapse at a density maximum



“Prompt cusp”





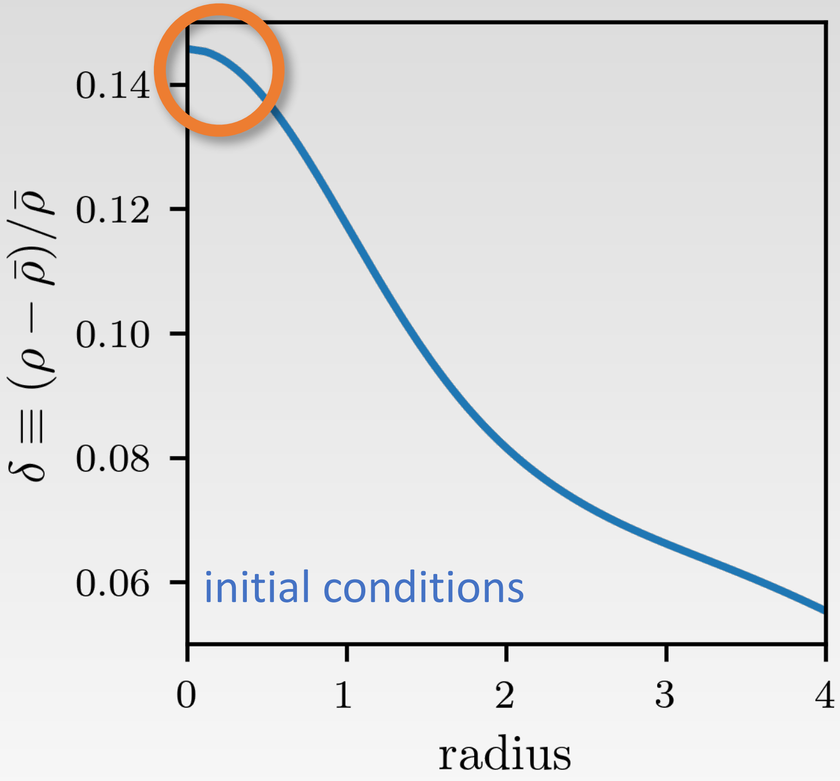
$\rho \propto r^{-3/2}$ cusp stabilizes immediately after formation

“prompt”

Prompt cusps set by peak properties

Cusp set at formation time

∴ only sensitive to neighborhood of density peak ($\delta \equiv \delta\rho/\bar{\rho}$, $\nabla^2\delta$, tides)



Peak with:

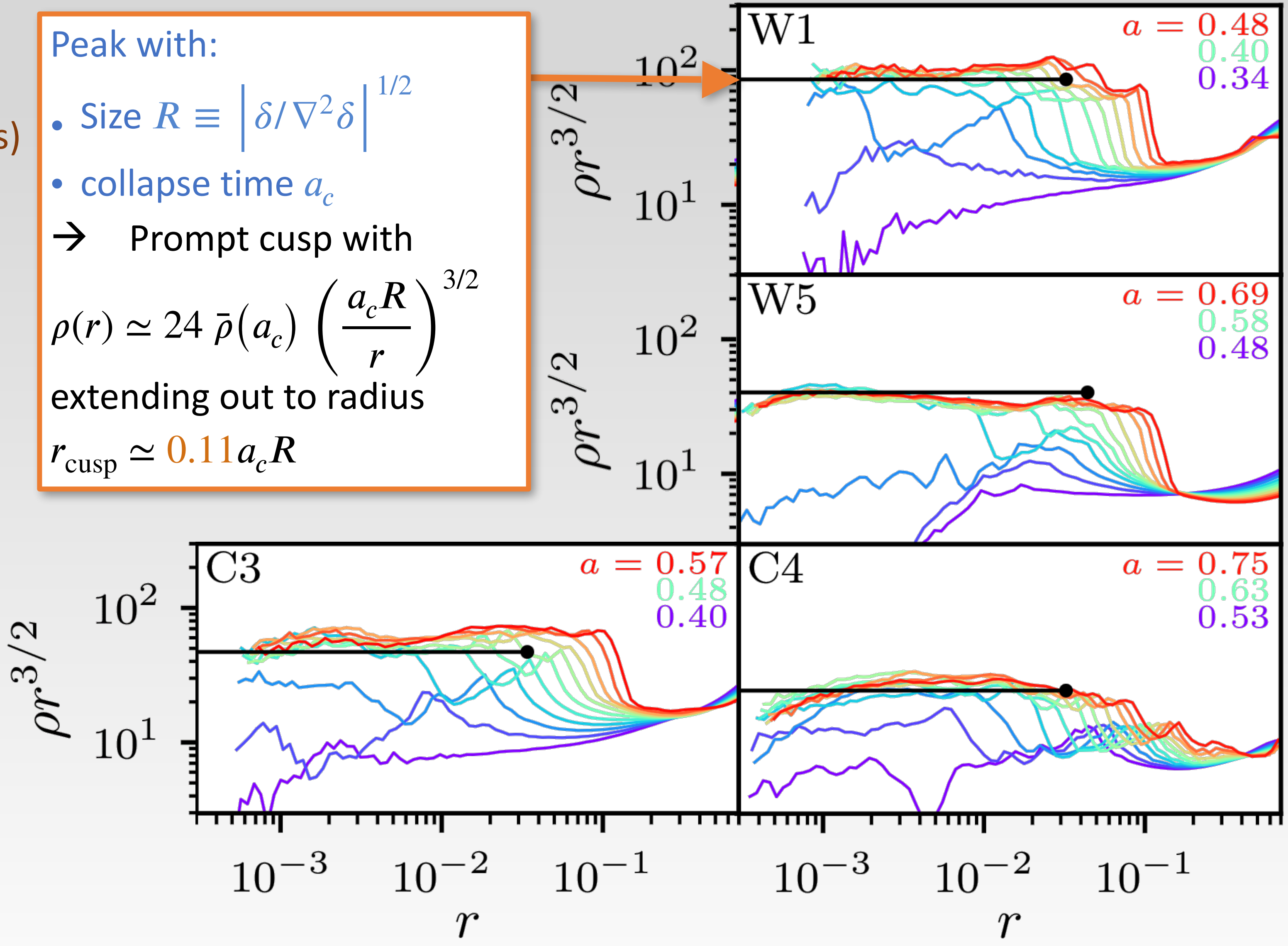
- Size $R \equiv \left|\delta/\nabla^2\delta\right|^{1/2}$
- collapse time a_c

→ Prompt cusp with

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

extending out to radius

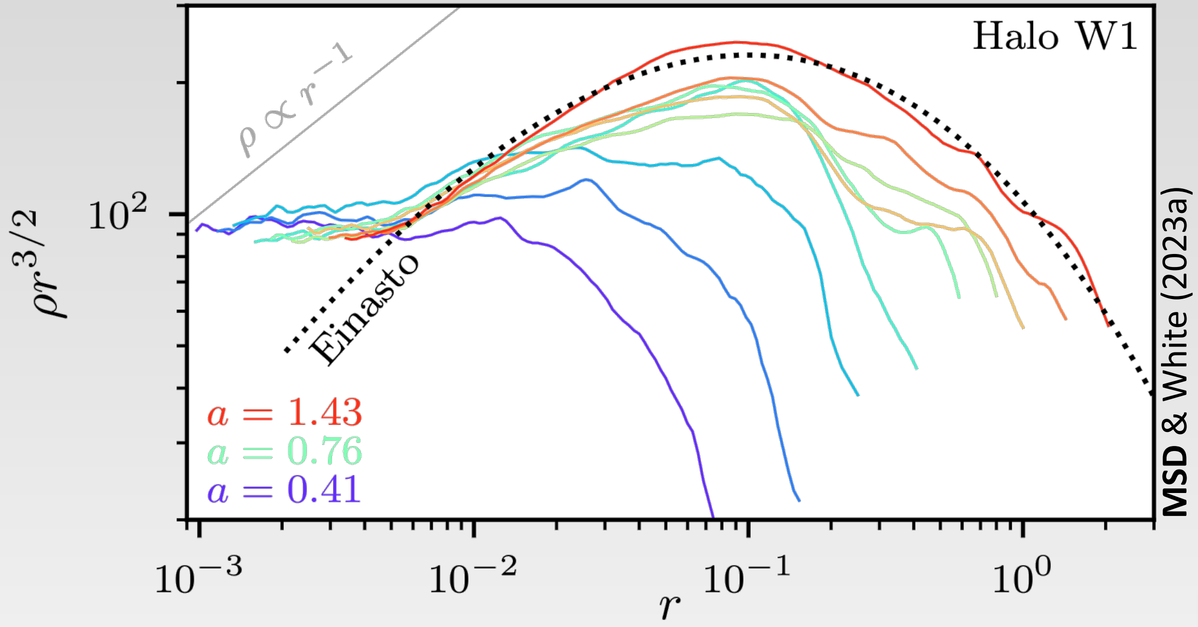
$r_{\rm cusp} \simeq 0.11 a_c R$



MSD & White (2023a)

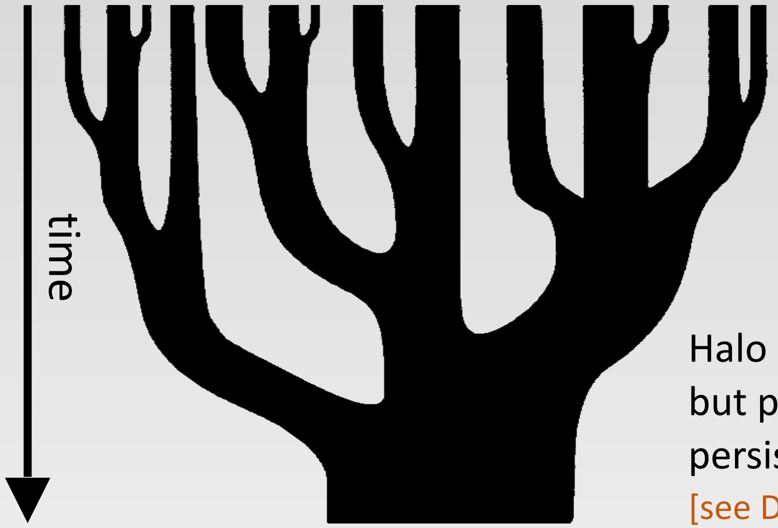
Prompt cusps and dark matter halos

Prompt cusps persist
even as halos grow around them



Every halo and subhalo should have a central prompt cusp!

$\sim 1/2$ of initial density maxima can be associated with surviving prompt cusps



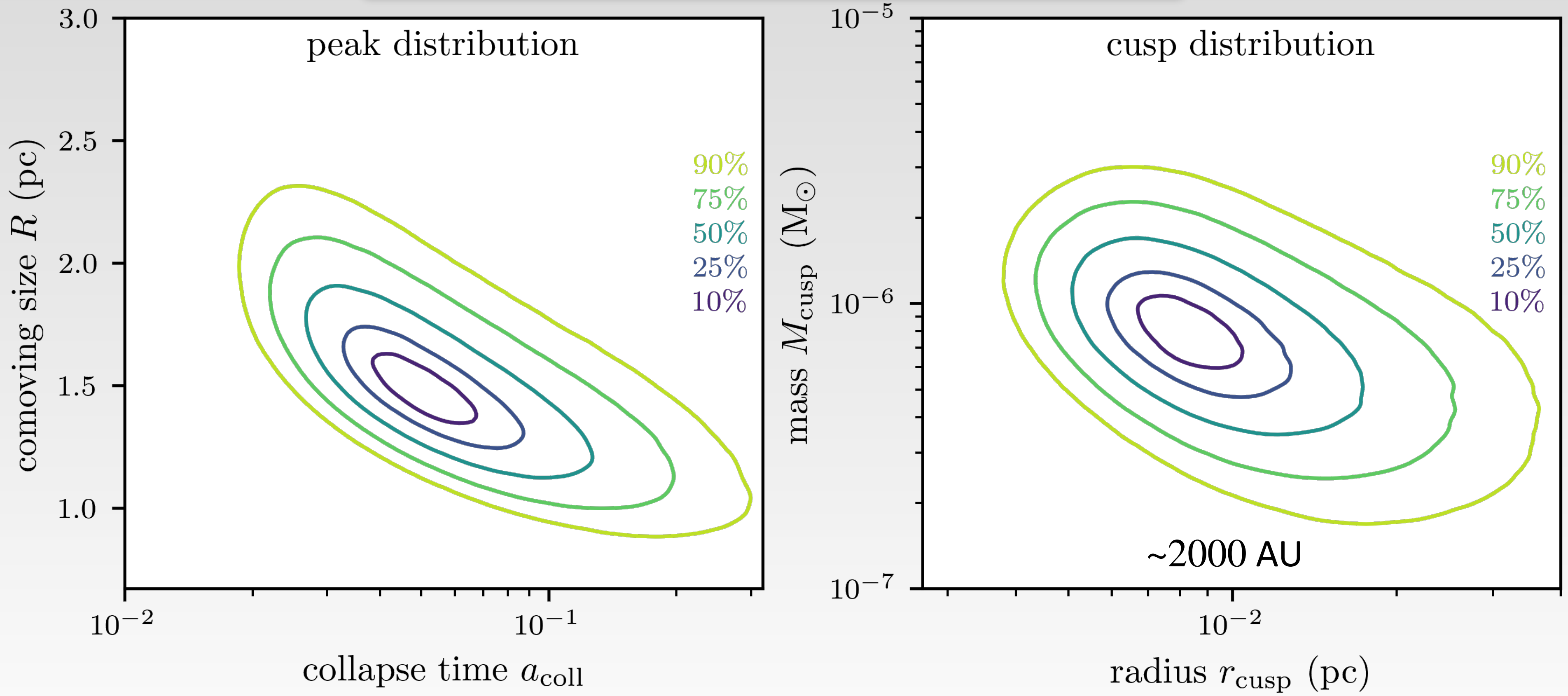
Halo count decreases, but prompt cusps persist as substructures [see Delos & White 2023b]

We can use the statistics of peaks in a Gaussian random field to directly predict the prompt cusp population

Abundance of prompt cusps today

Example: 100 GeV WIMP (decoupling at 30 MeV)

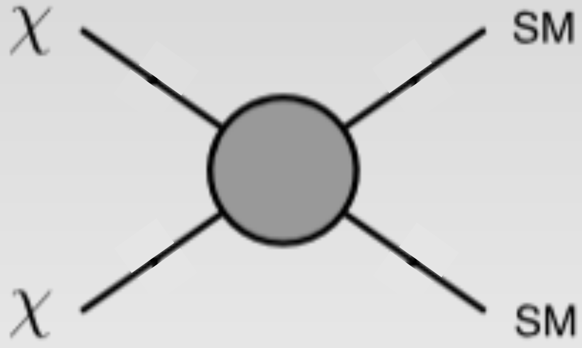
average peak number density $\sim 10^{-3}\ \mathrm{pc}^{-3}$
$\sim 10^{5}\ M_{\odot}^{-1}$



MSD & White (2023b)

Annihilating dark matter

dark matter particle χ pair-produced in the early universe



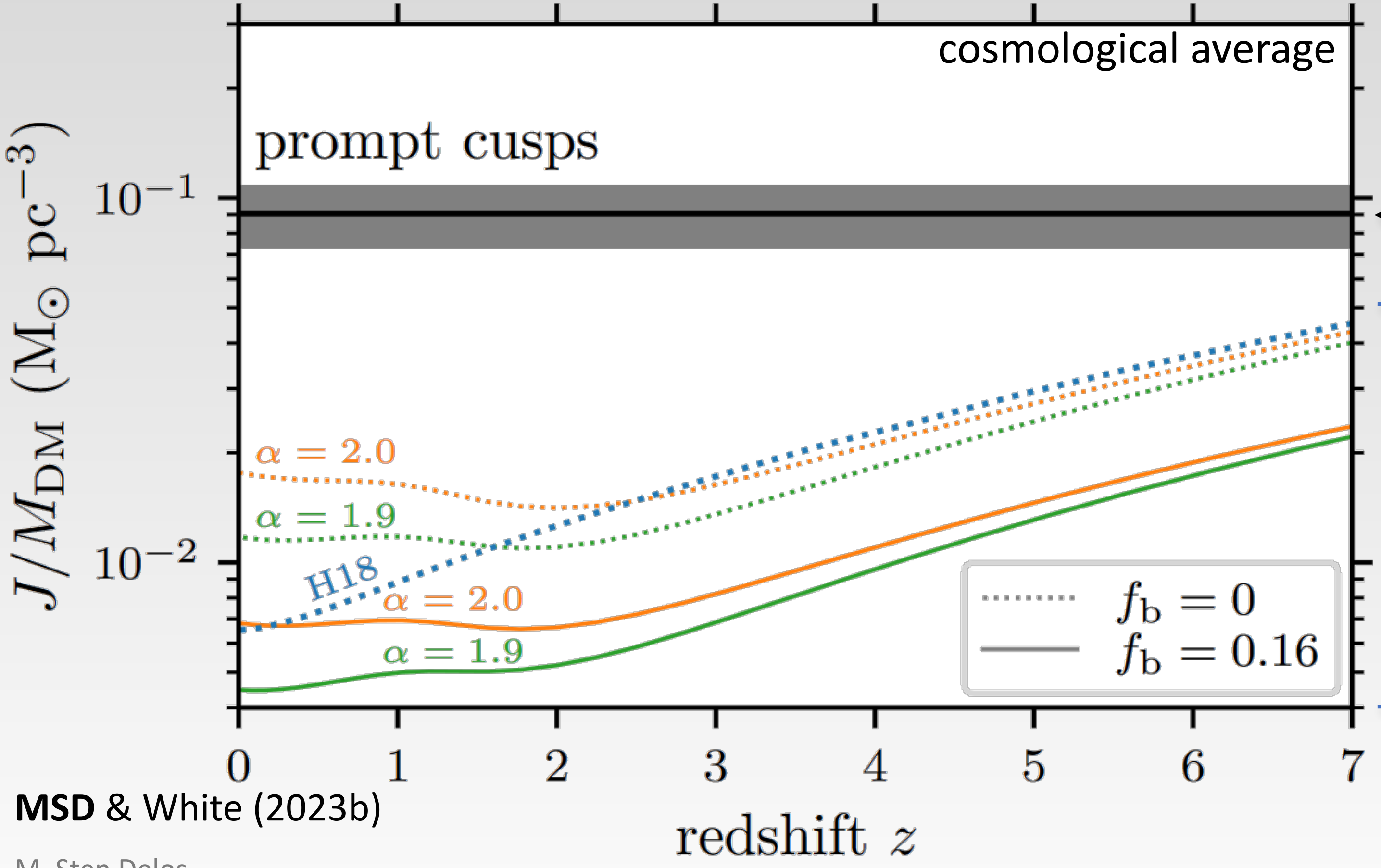
can annihilate into detectable SM particles today

Annihilation rate $\propto \rho^2 \rightarrow$ boosted by prompt cusps

Annihilation in prompt cusps

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

Same DM model as earlier:
$m_\chi = 100$ GeV, $T_{\rm kd} = 30$ MeV



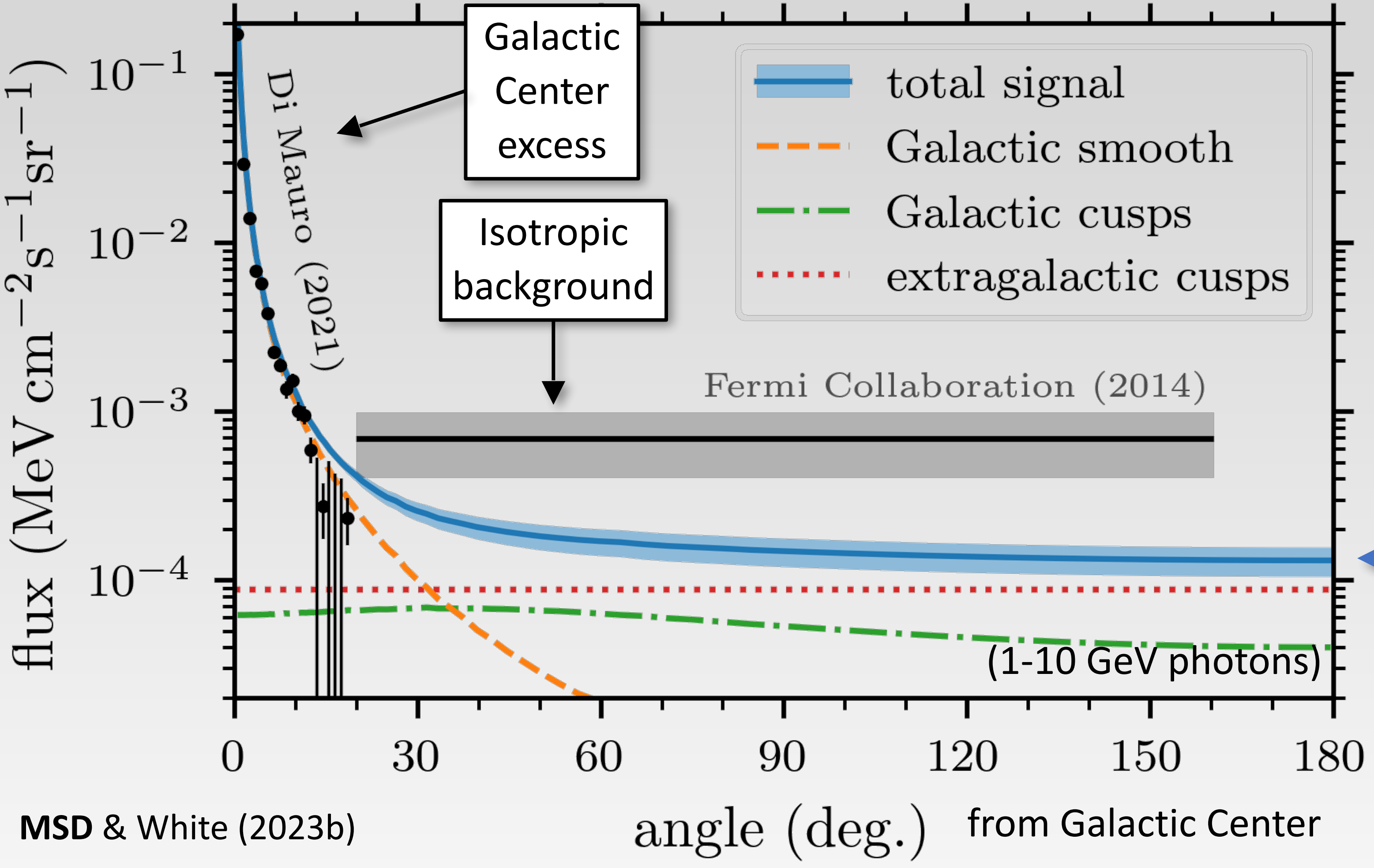
MSD & White (2023b)

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!)

Annihilation in prompt cusps



MSD & White (2023b)

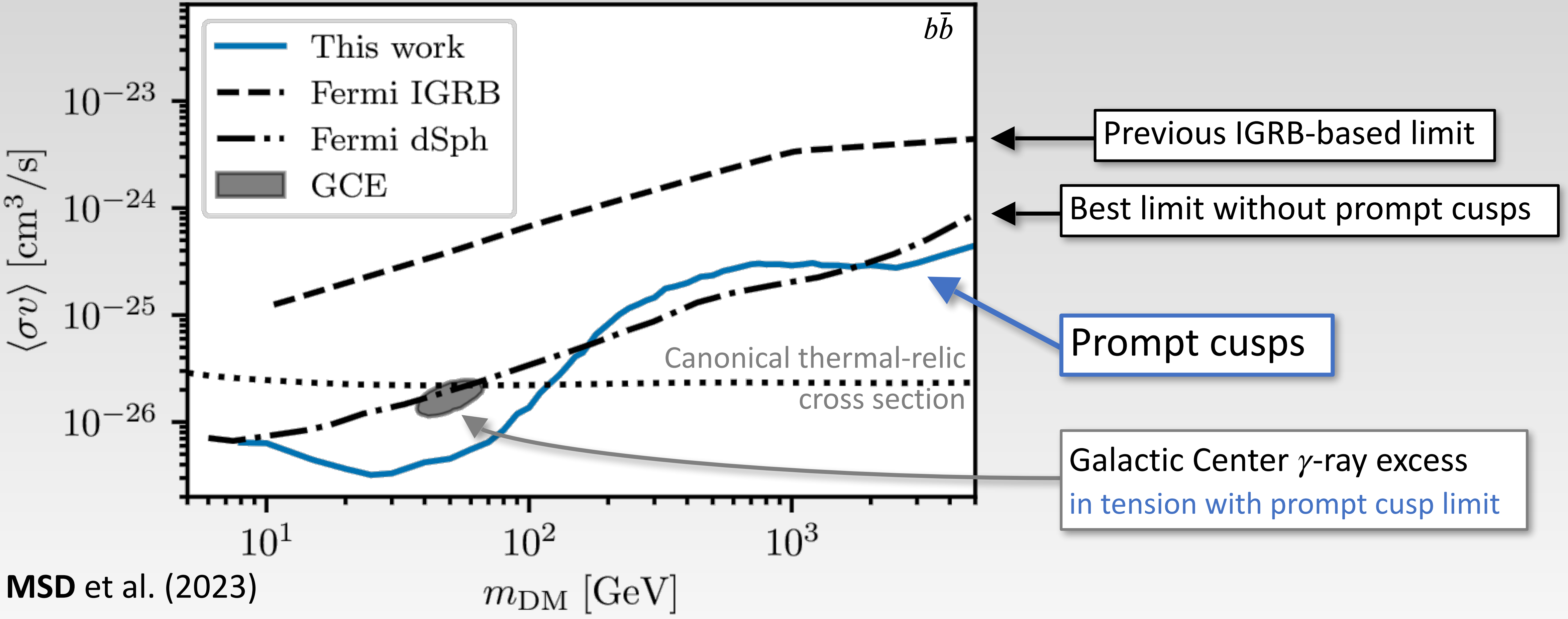
No annihilation boost in the centers of galactic halos (cusps disrupted & density already high), but annihilation everywhere else is greatly boosted.

If the Galactic Center excess is DM annihilation, a matching signal should appear in the isotropic gamma-ray background

Galactic cusps suppressed by tidal forces & stellar encounters per Stücker et al. (2023)

Limits on dark matter annihilation

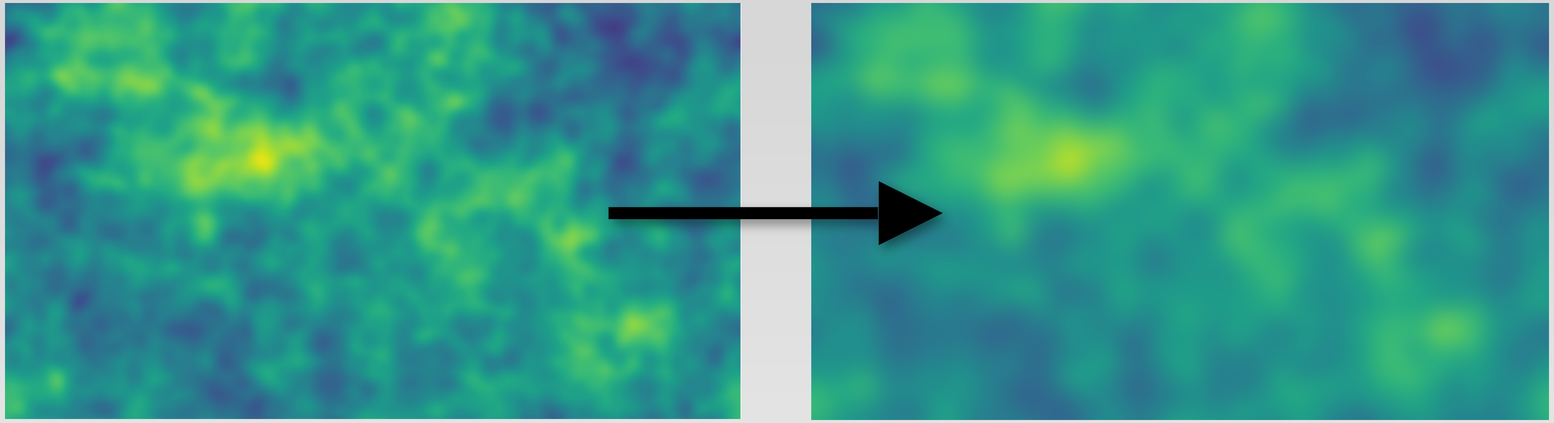
based on prompt cusp contribution to the isotropic γ-ray background



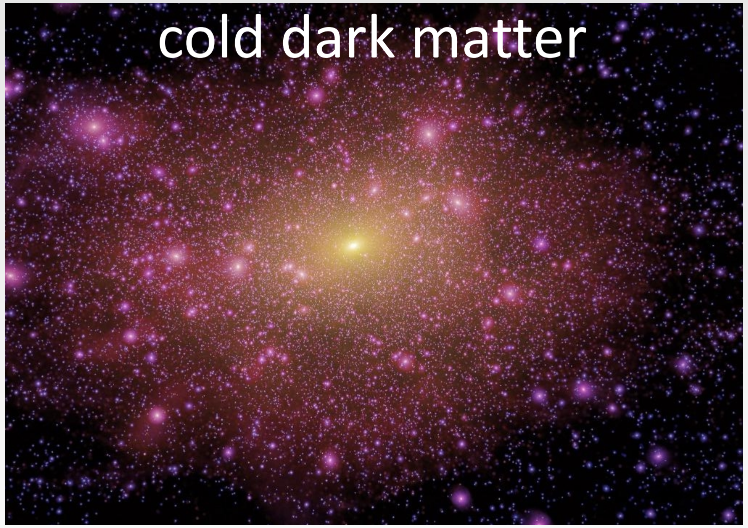
MSD et al. (2023)

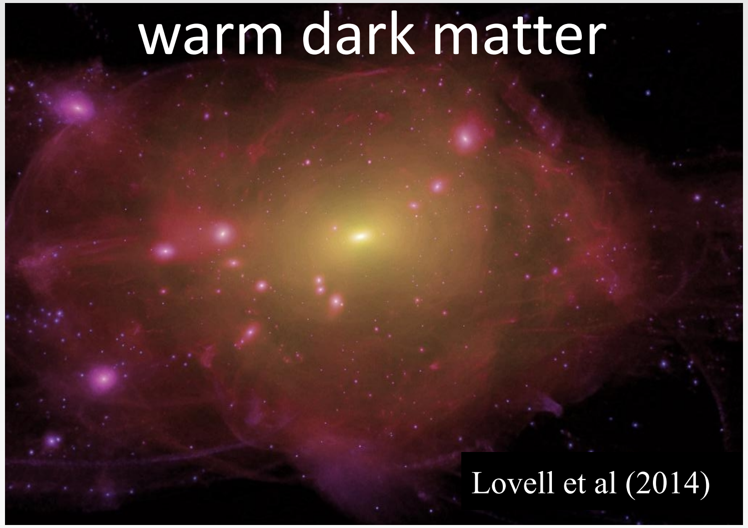
Warm dark matter

Random particle motion smooths initial conditions

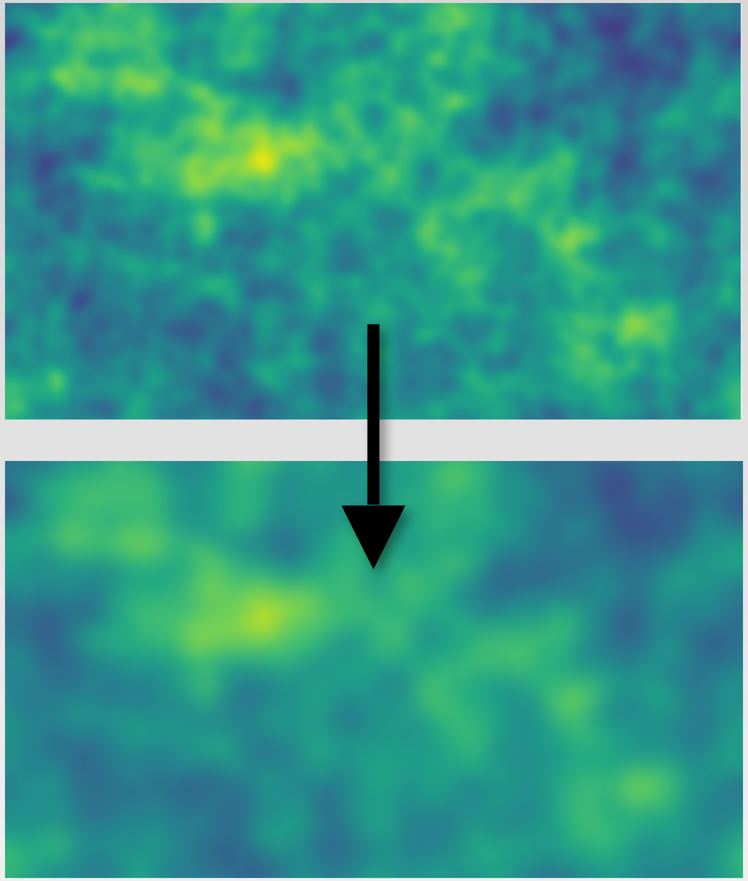


which suppresses the abundance of low-mass halos:



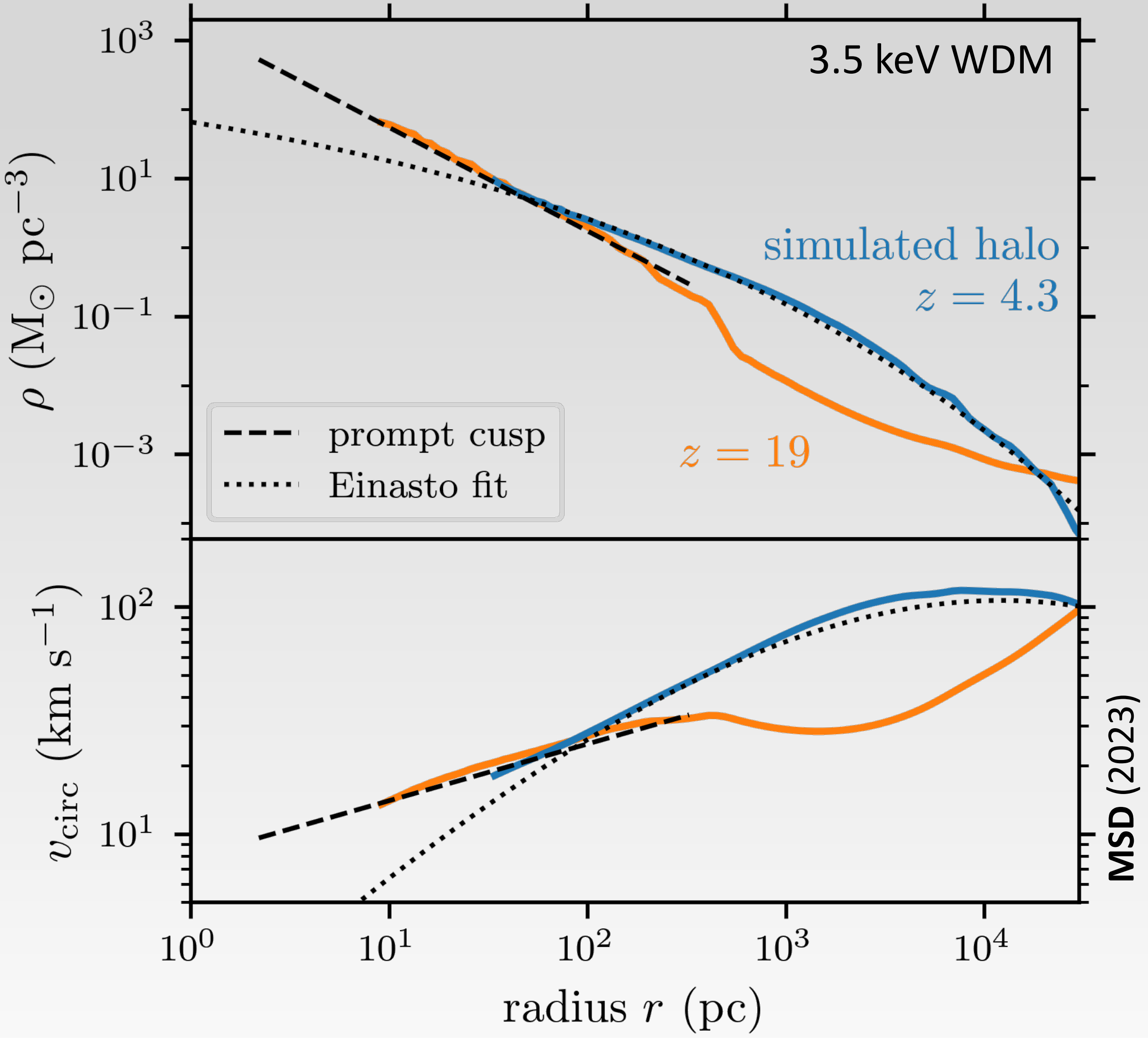


Prompt cusps of warm dark matter



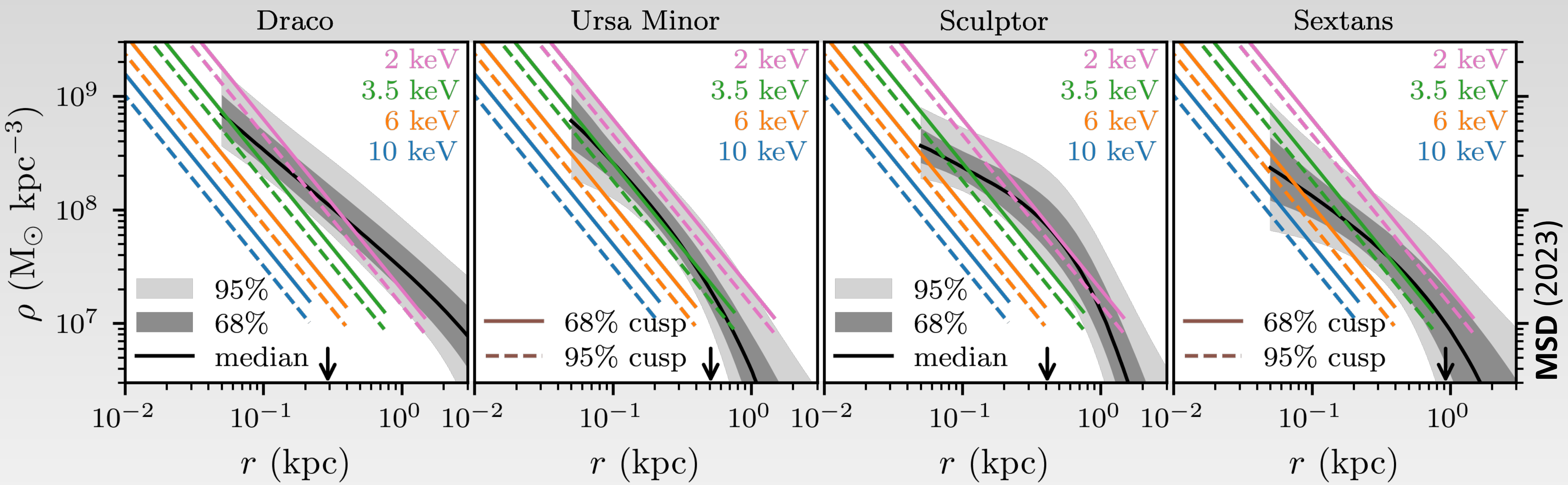
Initial density peaks are much larger

→ Prompt cusps are much larger



Searching for WDM prompt cusps

We can search for prompt cusps within nearby dwarf galaxies:

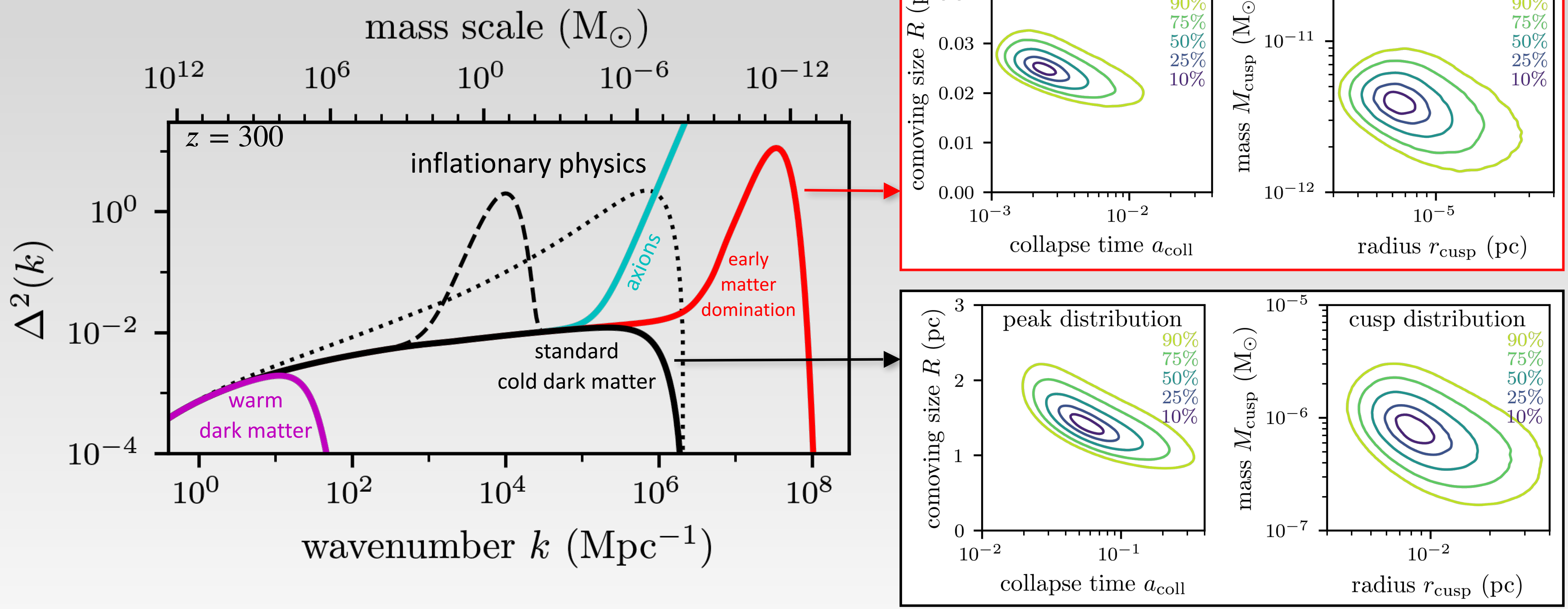


Inferred profiles from Hayashi et al. (2020)

Interpretation: $\rho > \rho_{\text{cusp}}$ can be explained by halo growth, but $\rho < \rho_{\text{cusp}}$ is difficult to explain

Better constraints come from ultrafaints, but plots are not as nice…

Broader picture



Summary

The smallest structures of collisionless dark matter are prompt $\rho \propto r^{-1.5}$ cusps, which:

- form from the gravitational collapse of smooth peaks in the initial density field and persist through halo growth and clustering;
- can be predicted straightforwardly from Gaussian statistics;
- dominate the overall DM annihilation rate, greatly boosting the expected signal outside the dense centers of galaxies;
- could affect galactic kinematics and other observables, if the DM is warm enough.