

Prompt cusps of dark matter

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Outline

Dark matter halos

The cosmological initial conditions and prompt cusps

Survival of prompt cusps

Prompt cusps and dark matter annihilation

Prompt cusps of warm dark matter

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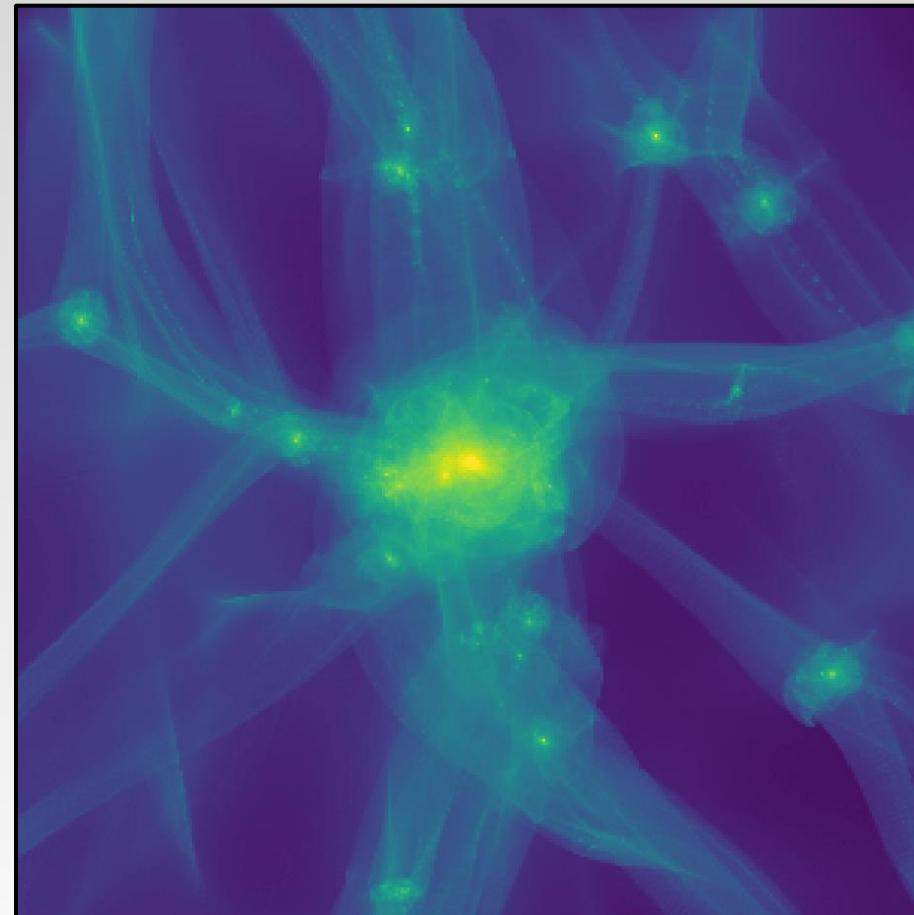
Prompt cusps of warm dark matter

Dark matter halos

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

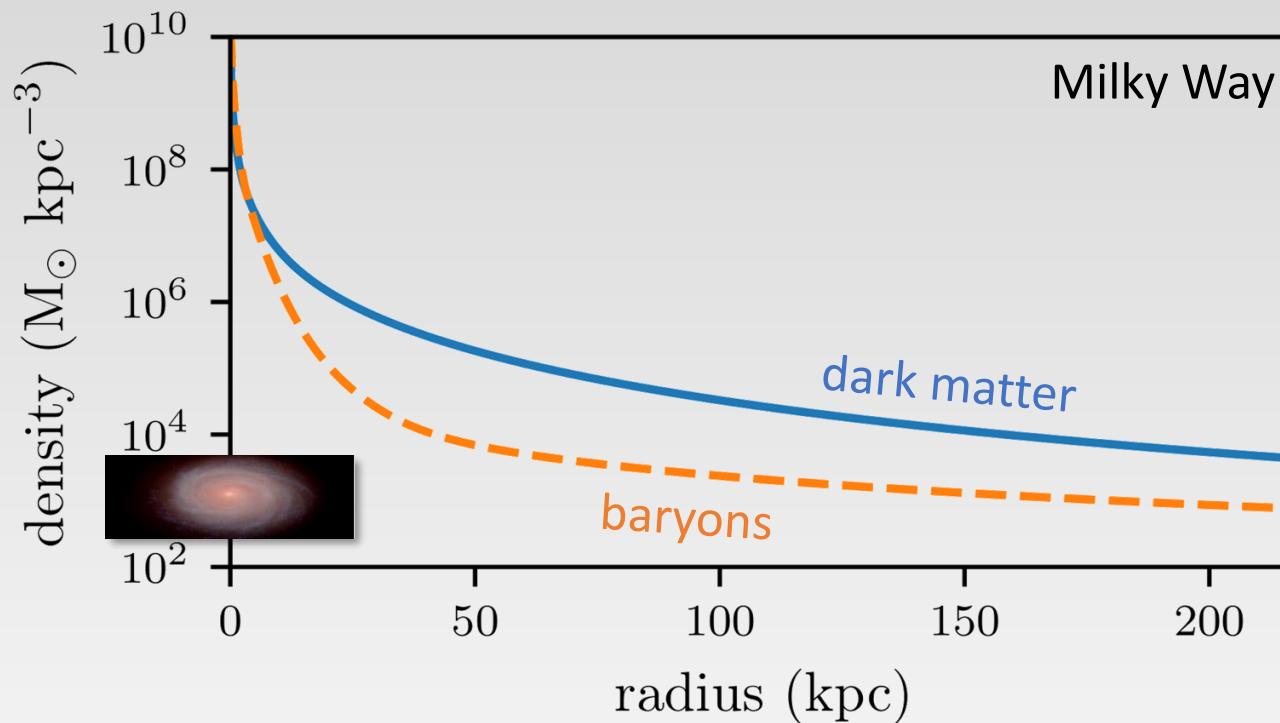
Regions with excess density
collapse under gravity to form
hot clouds of dark matter

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



Dark matter halos

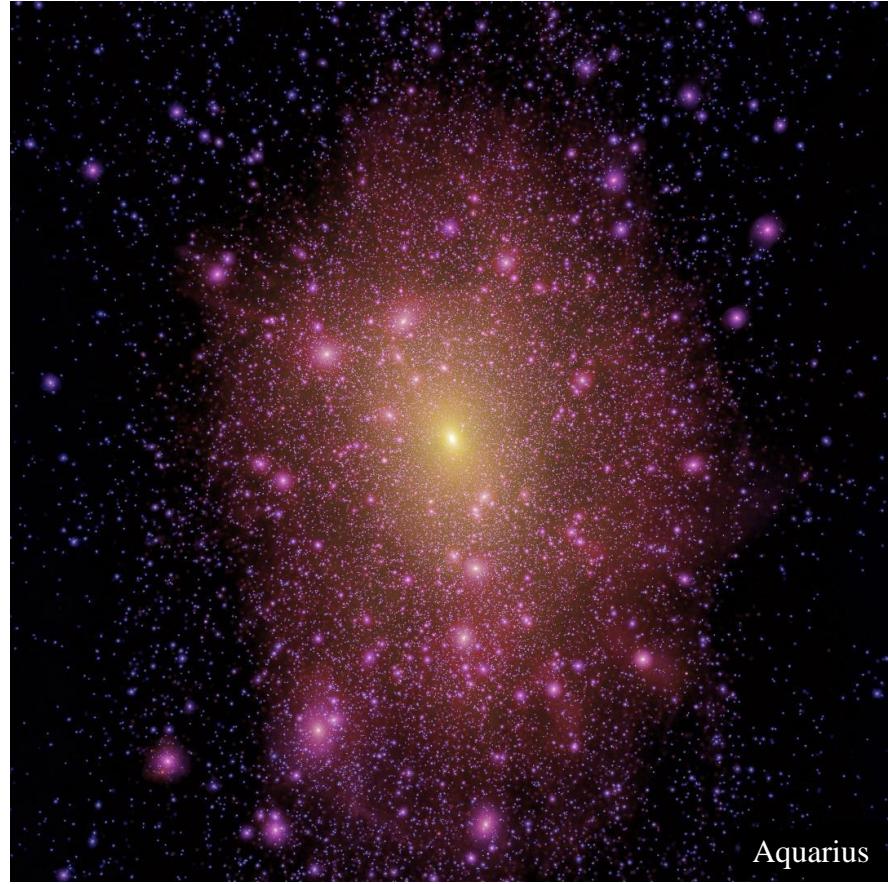
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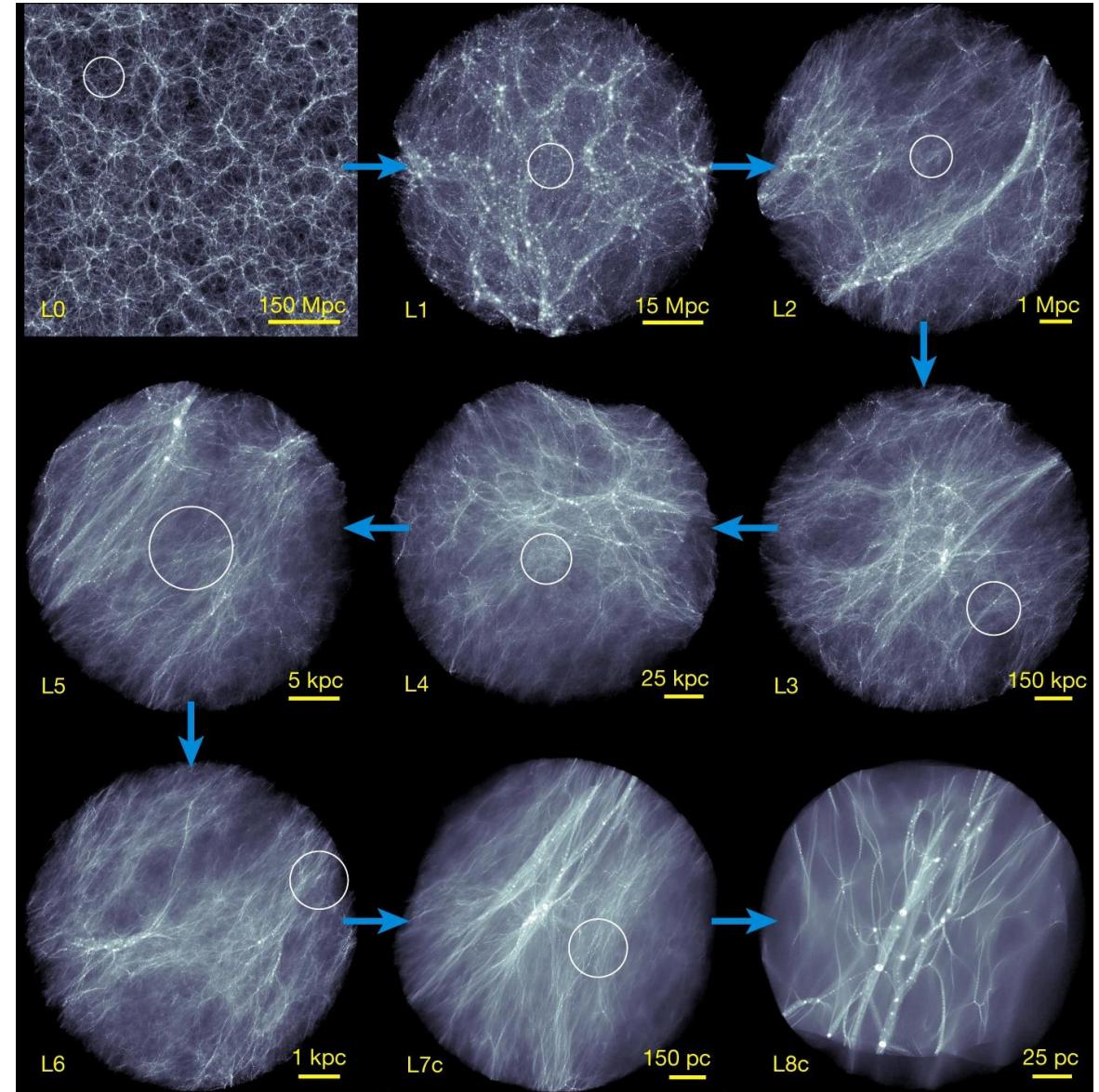
MW mass model: Cautun et al (2020)
picture of simulated MW-like galaxy: Grand et al (2021)

Dark matter halos

Subhalos persist inside other halos:

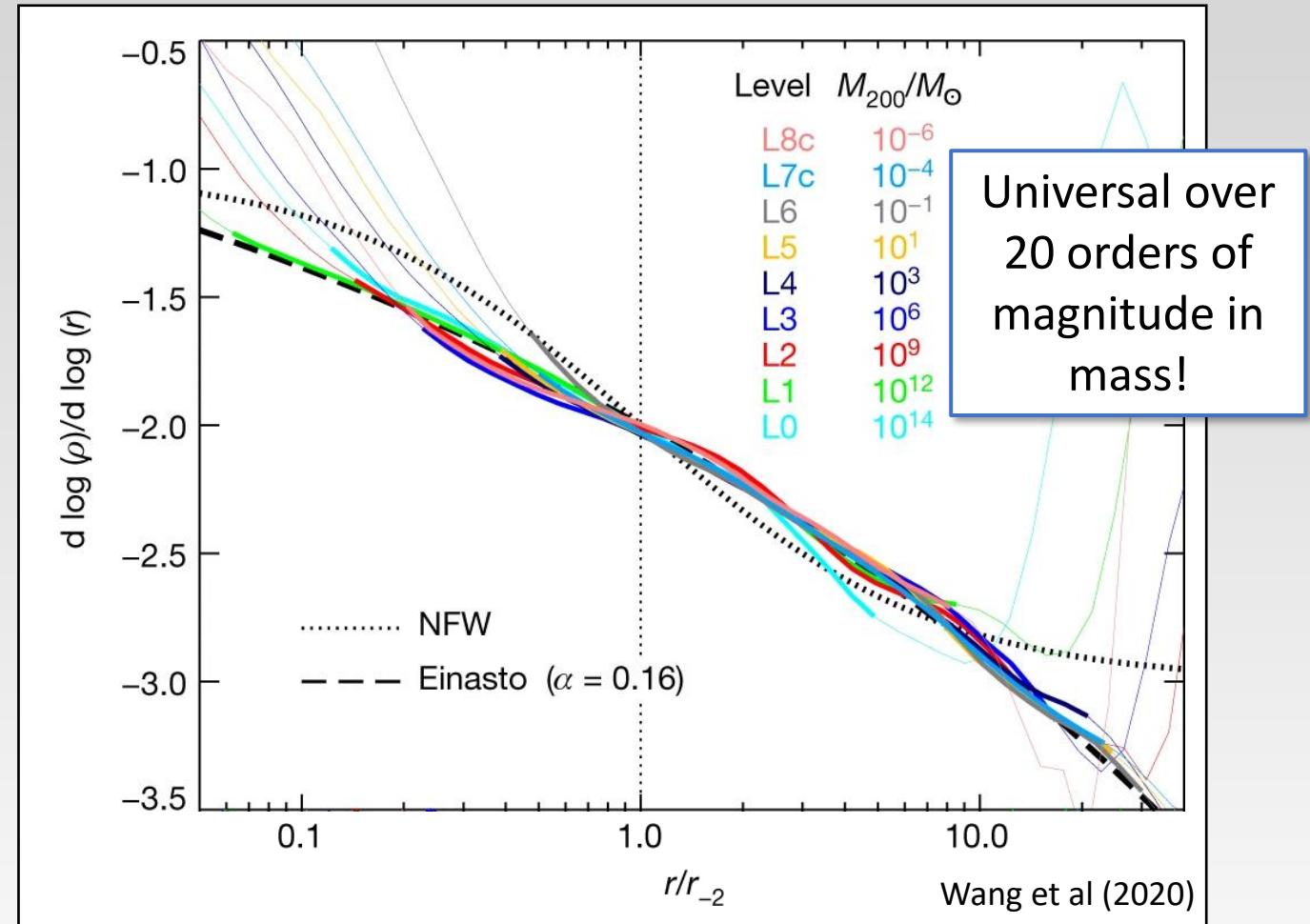
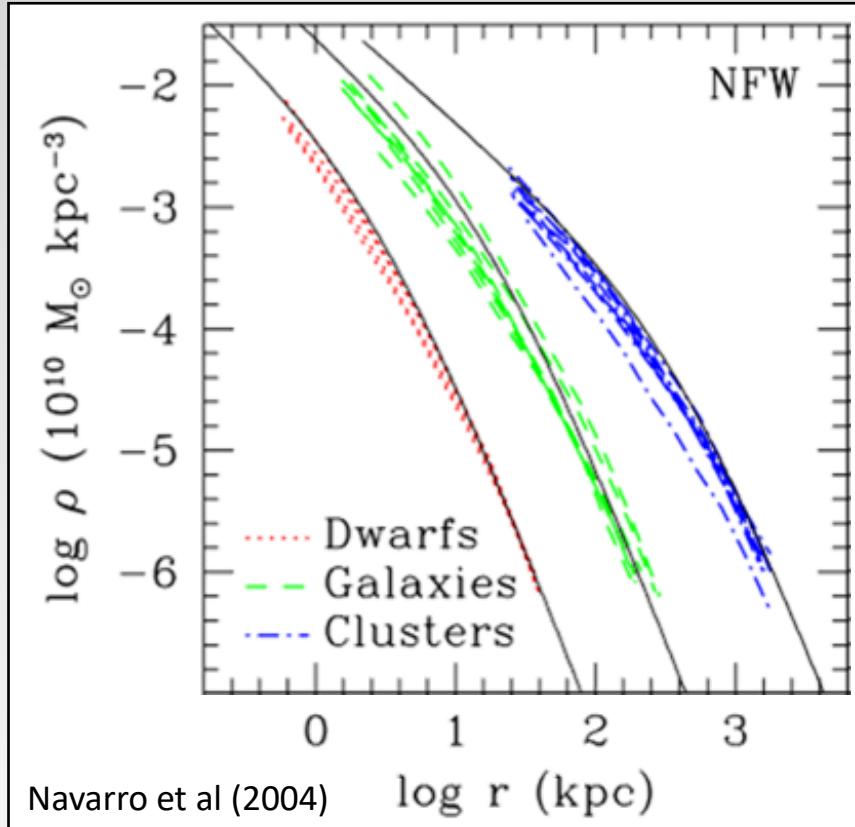


Halos form at all scales:



Halo density profiles

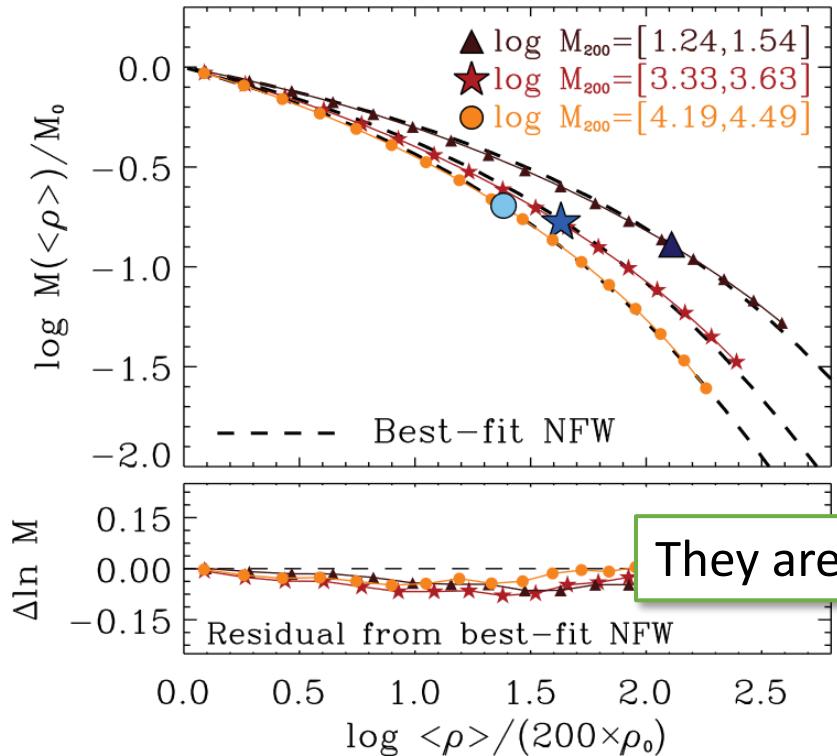
$\rho(r)$: shallow (logarithmic) decrease at small r , steep decrease at large r



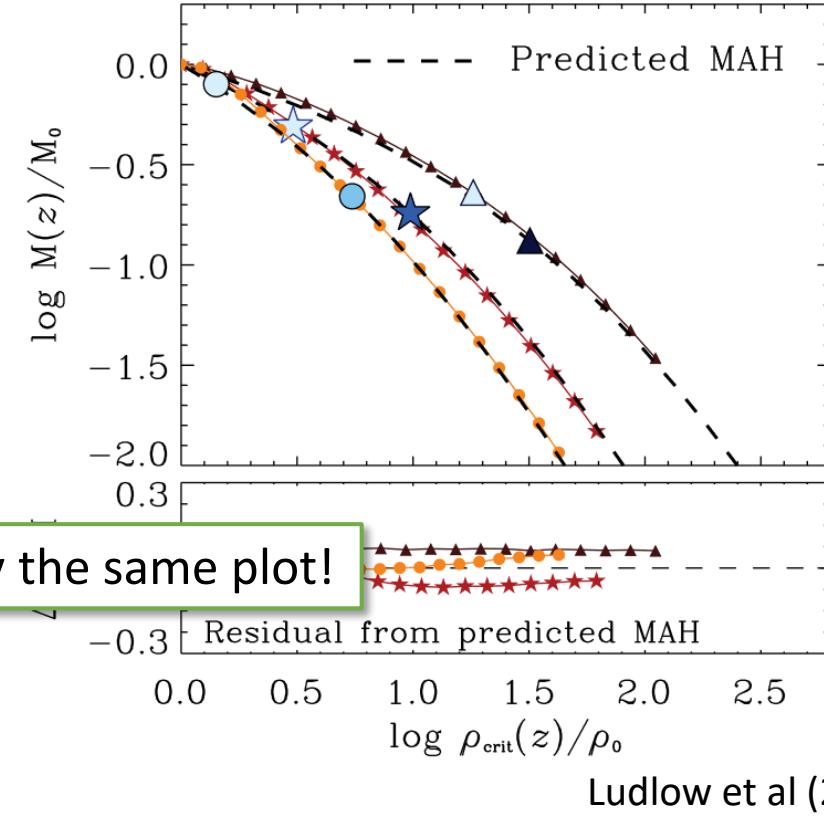
Density profiles from accretion history

Universal **density profiles** follow from universal **accretion history**

Mass inside regions denser than ρ



Mass accreted when the universe was denser than ρ



They are essentially the same plot!

Outline

Dark matter halos

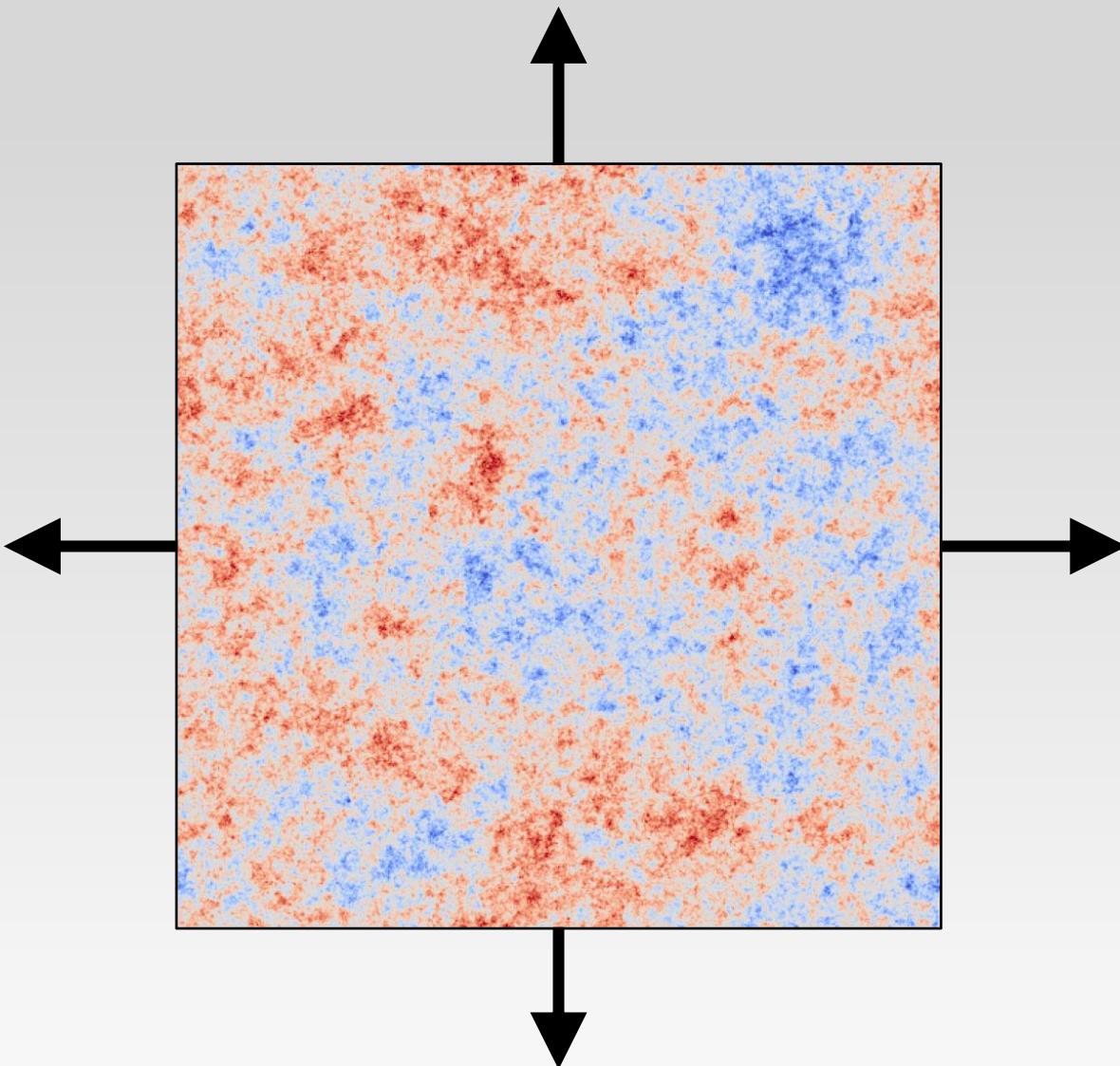
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Survival of prompt cusps

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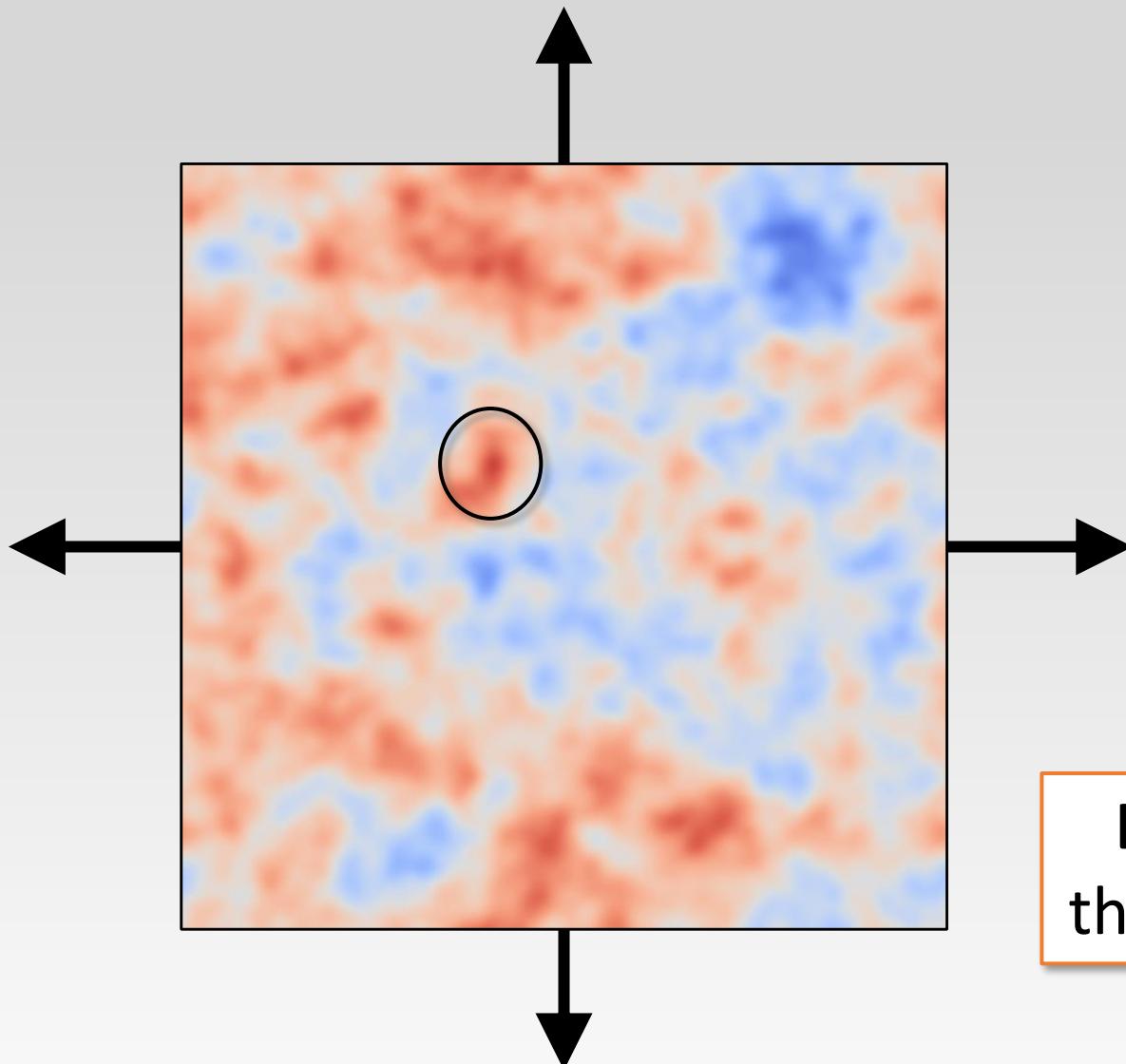
The cosmological initial conditions



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**

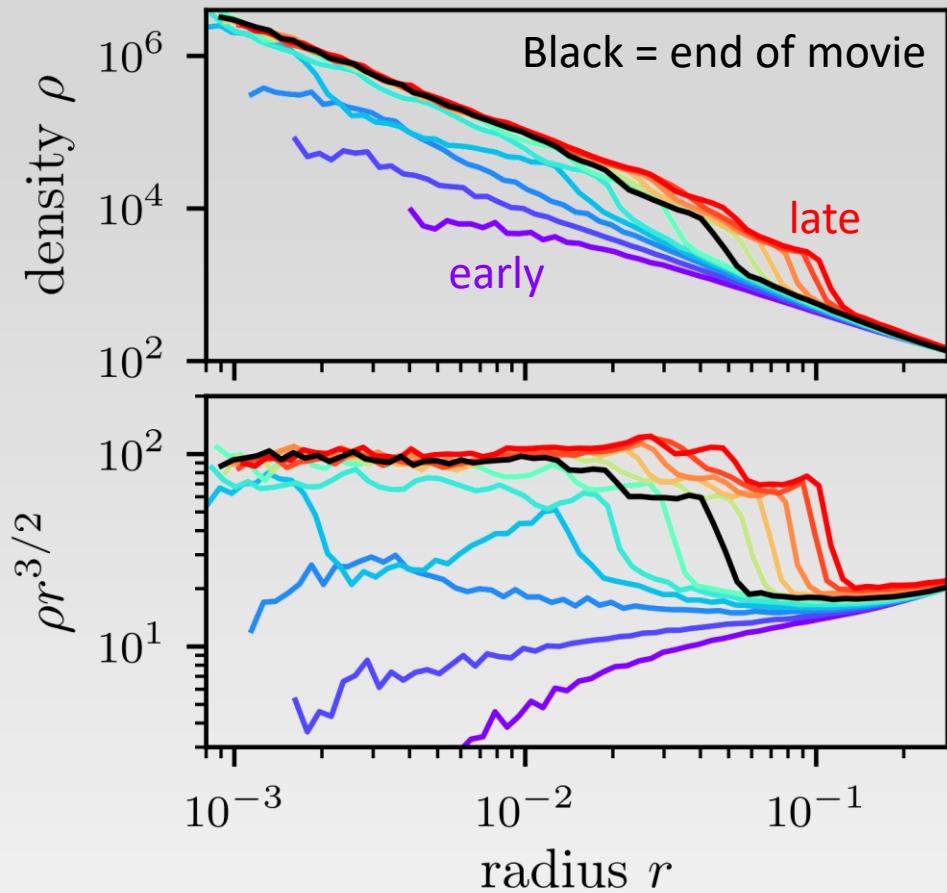
e.g., due to thermal motion of
the dark matter

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

Collapse at a density maximum

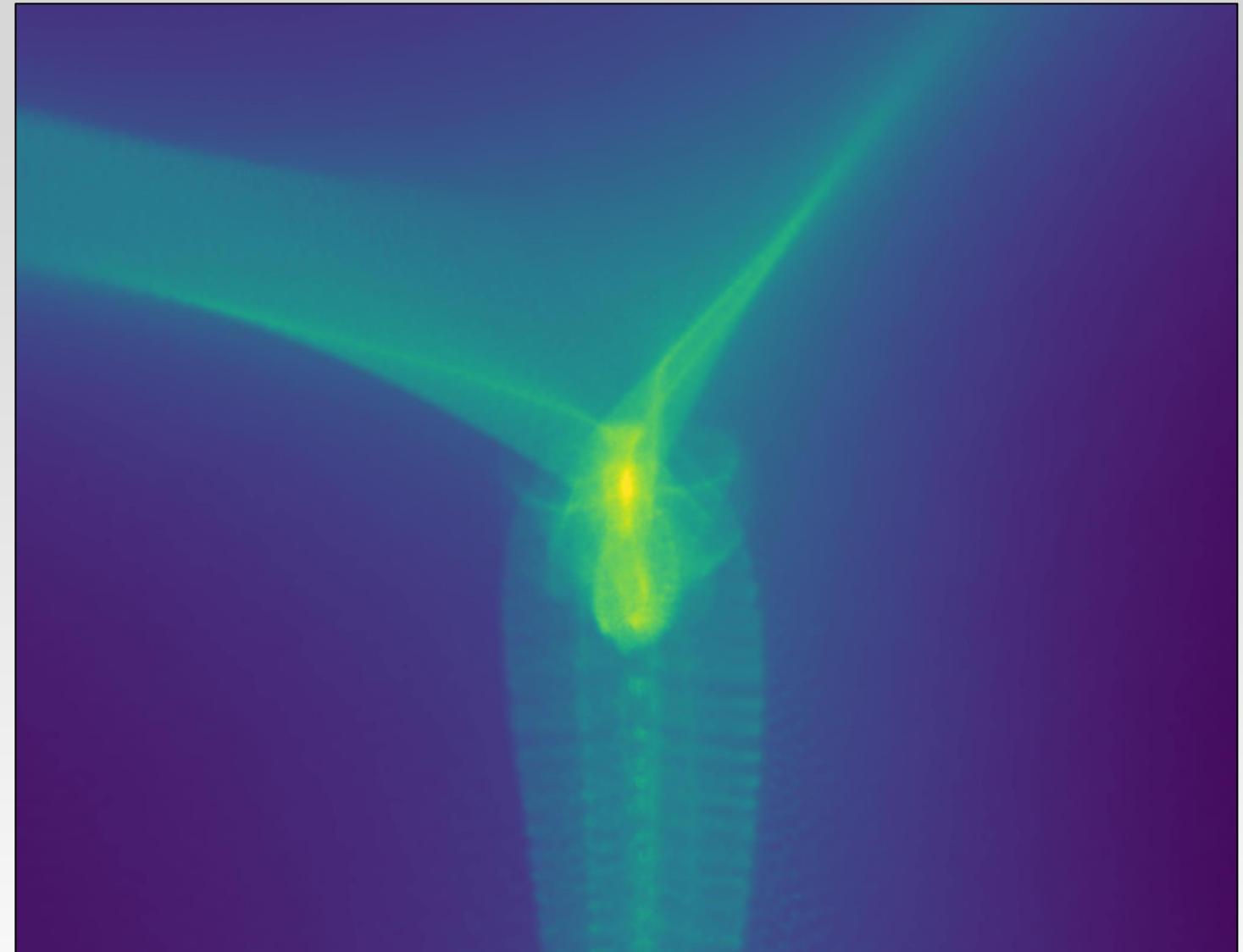


“Prompt cusp”



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

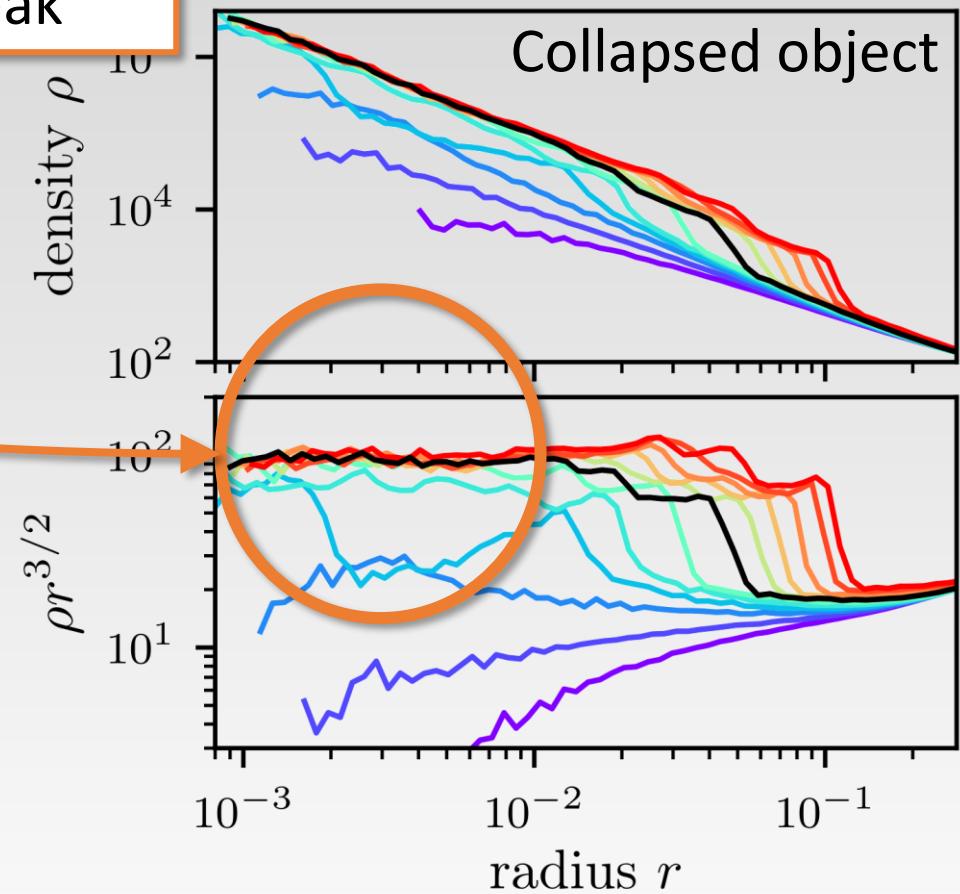
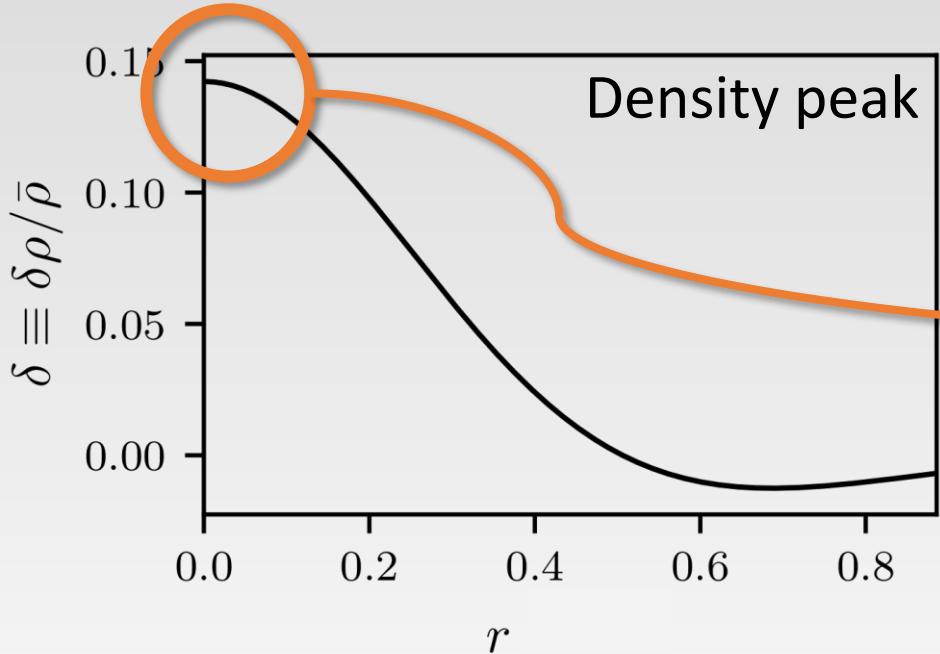
“prompt”



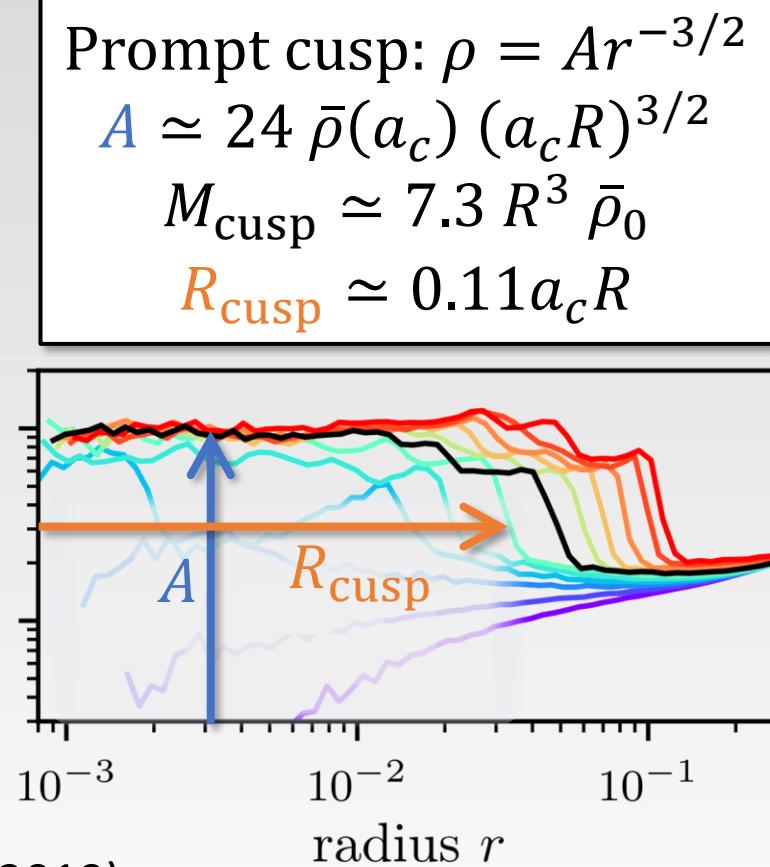
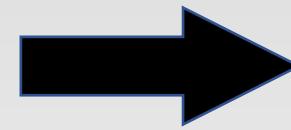
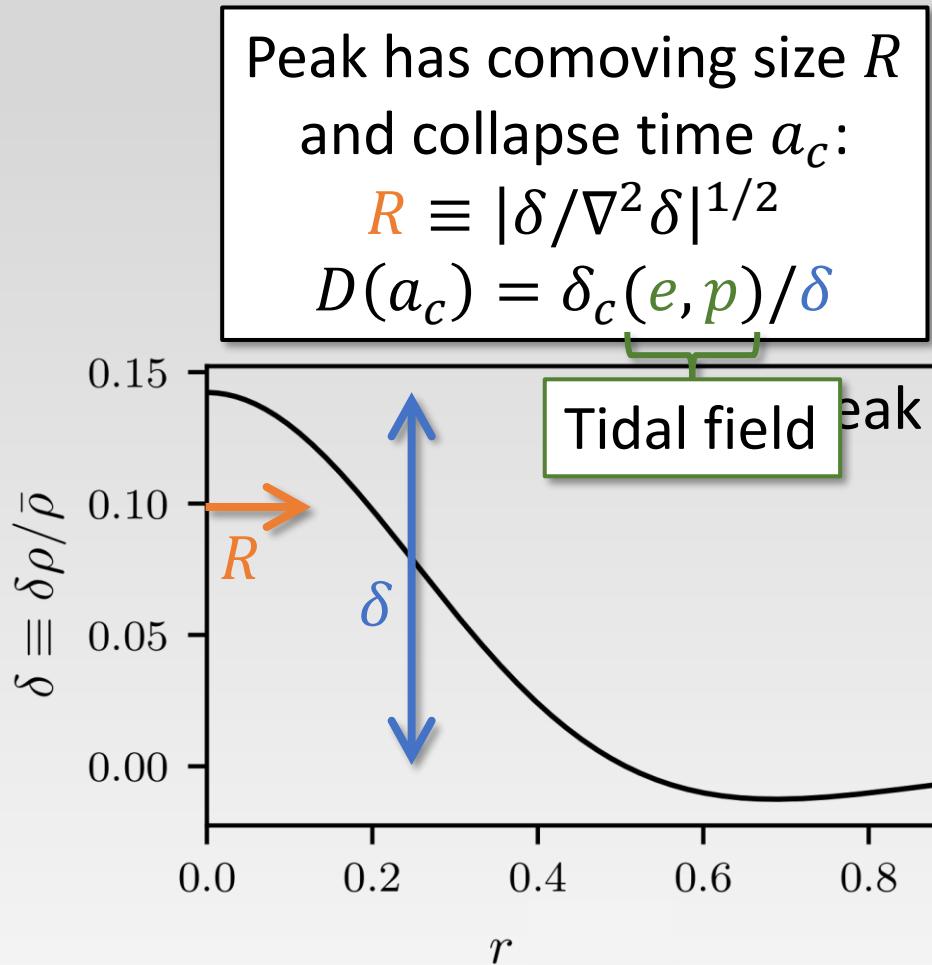
What sets prompt cusp properties?

Cusp set at formation time

∴ only sensitive to neighborhood of density peak
i.e., $\delta \equiv \delta\rho/\bar{\rho}$, $\nabla^2\delta$, and tidal field at peak



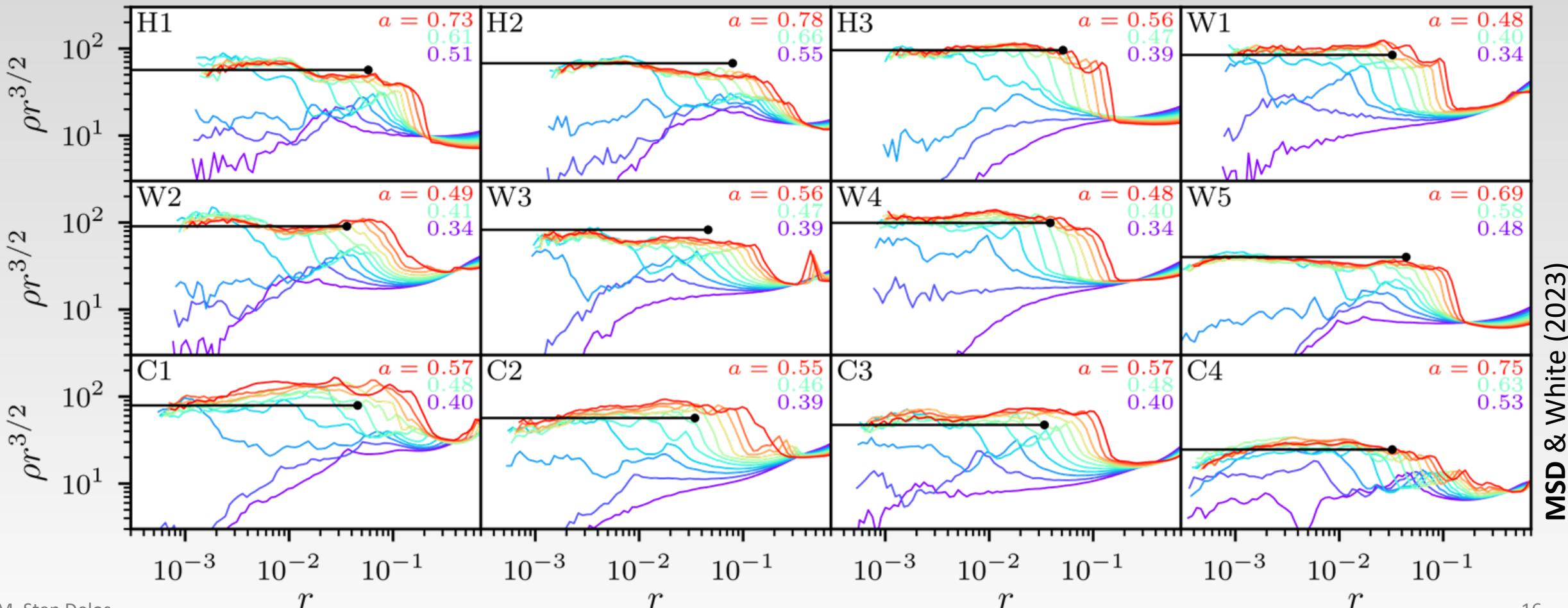
Peak-cusp connection



MSD & White (2023); based on MSD, Bruff, Erickcek (2019)

Peak-cusp connection

Twelve high-resolution halos from three power spectra:
Predictions [black] work well!



Statistics of peaks

Connection between cusps
and peaks is clear.

What is the distribution of peaks?

THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

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Physics Department, University of Washington

J. R. BOND¹

Physics Department, Stanford University

N. KAISER¹

Astronomy Department, University of California at Berkeley, and Institute of Astronomy, Cambridge University

AND

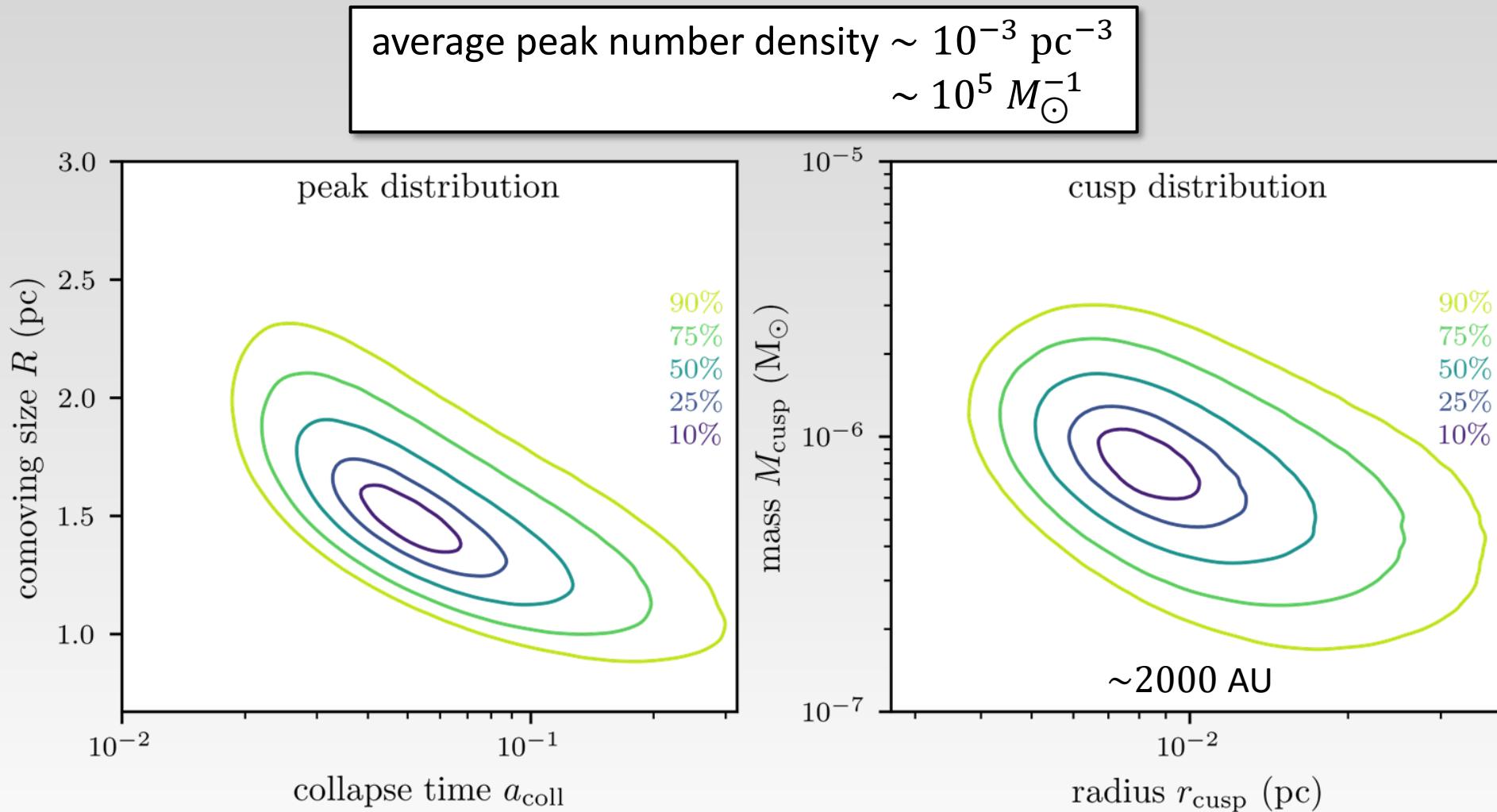
A. S. SZALAY¹

Astrophysics Group, Fermilab

Received 1985 July 25; accepted 1985 October 9

Statistics of prompt cusps

Example: 100 GeV WIMP (decoupling at 30 MeV)



Central cores

What about the influence of the dark matter's thermal motion?

Conservation of phase-space density → **finite-density core** at small radii

Core radius r_c and density ρ_c

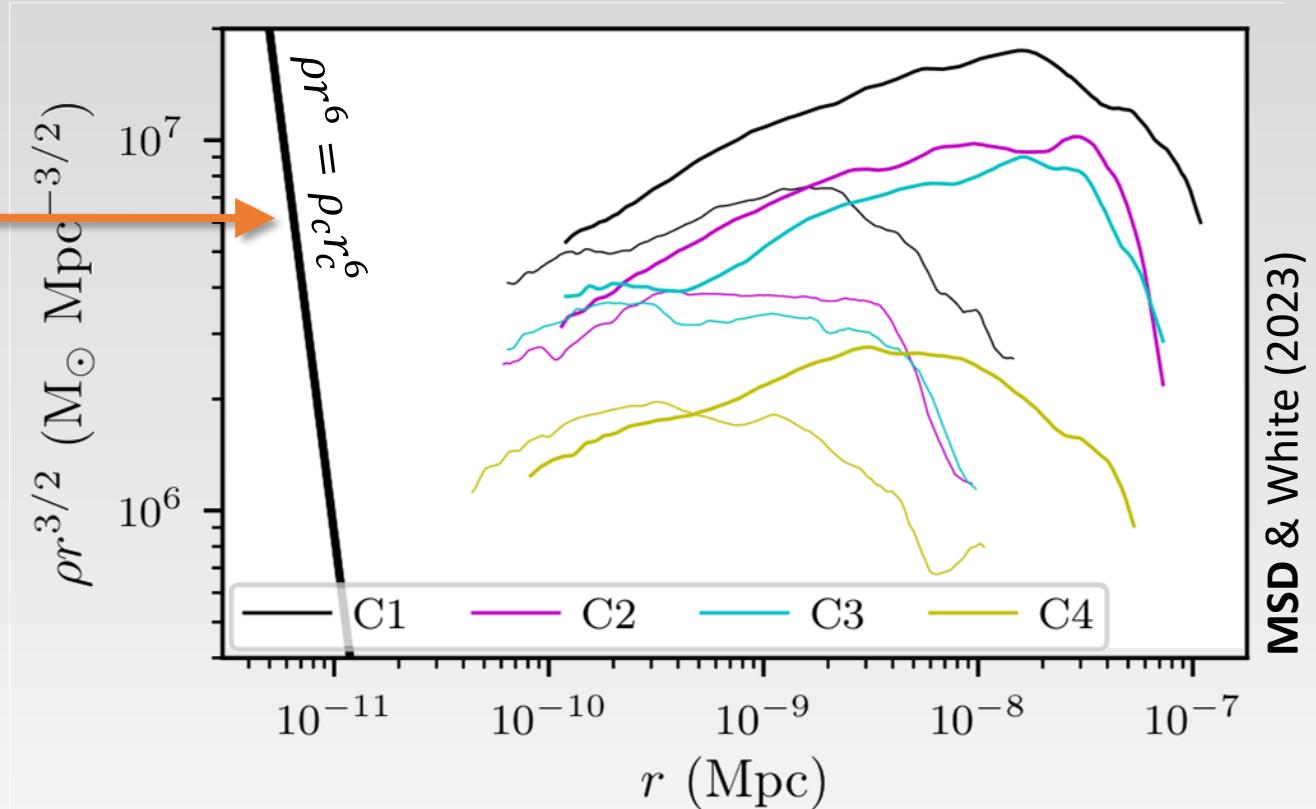
$$\rho_c r_c^6 \approx 3 \times 10^{-5} G^{-3} f_{\max}^{-2}$$

f_{\max} = phase-space density
of the early universe

$$\sim \bar{\rho}(a) \sigma(a)^{-3}$$



velocity dispersion



$\rho \propto r^{-3/2}$ cusps cover a factor of $R_{\text{cusp}}/r_c \sim 500$ in radius for typical cosmologies

Outline

Dark matter halos

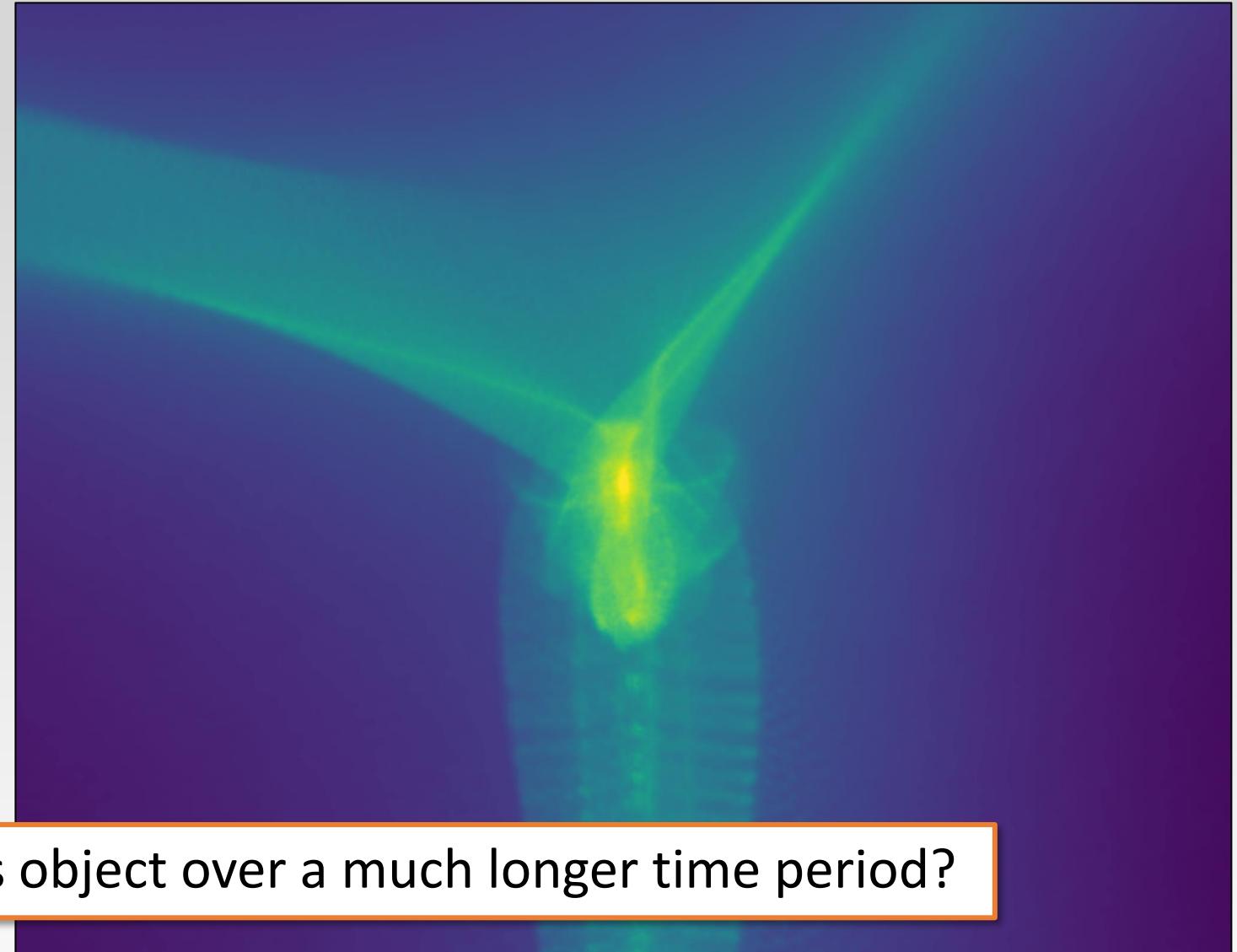
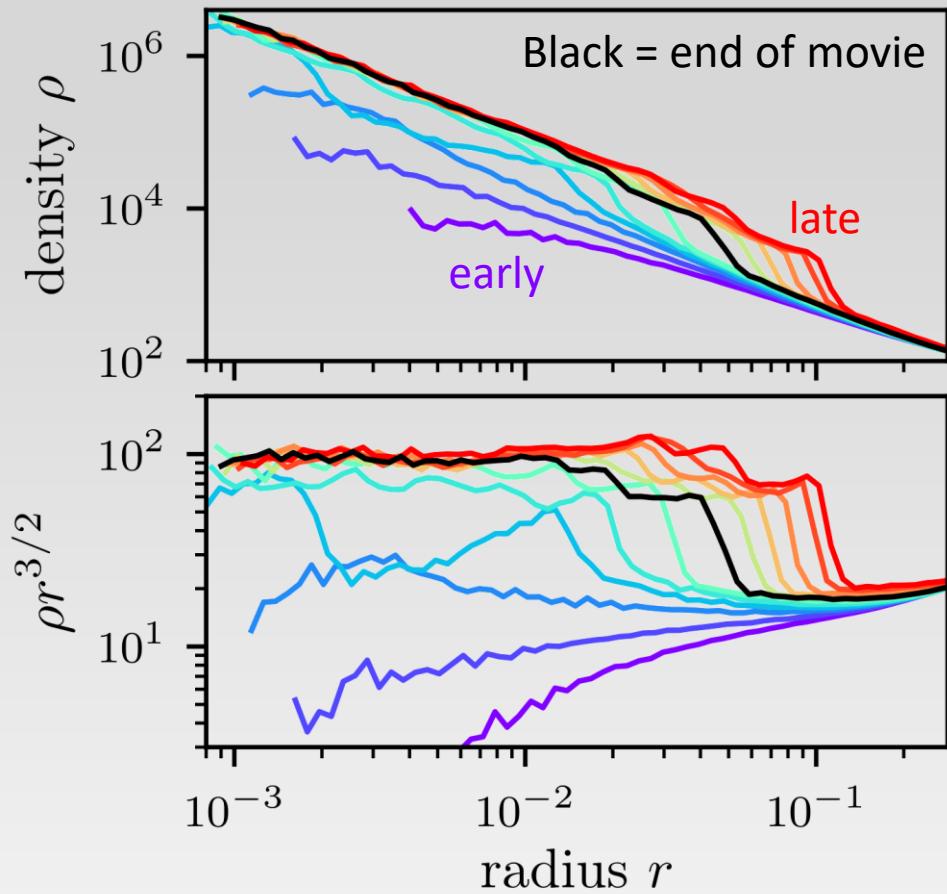
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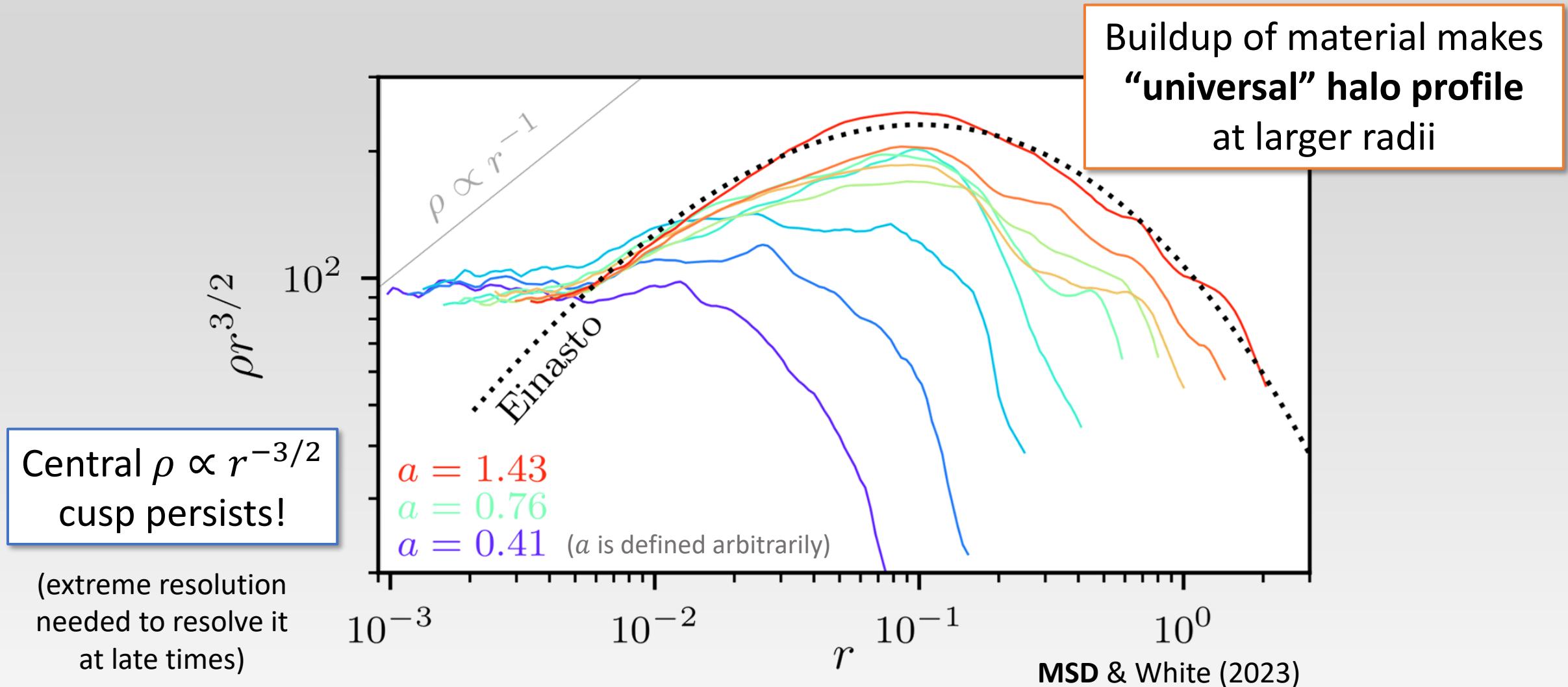
Prompt cusps of warm dark matter

Do prompt cusps survive halo growth?



What happens to this object over a much longer time period?

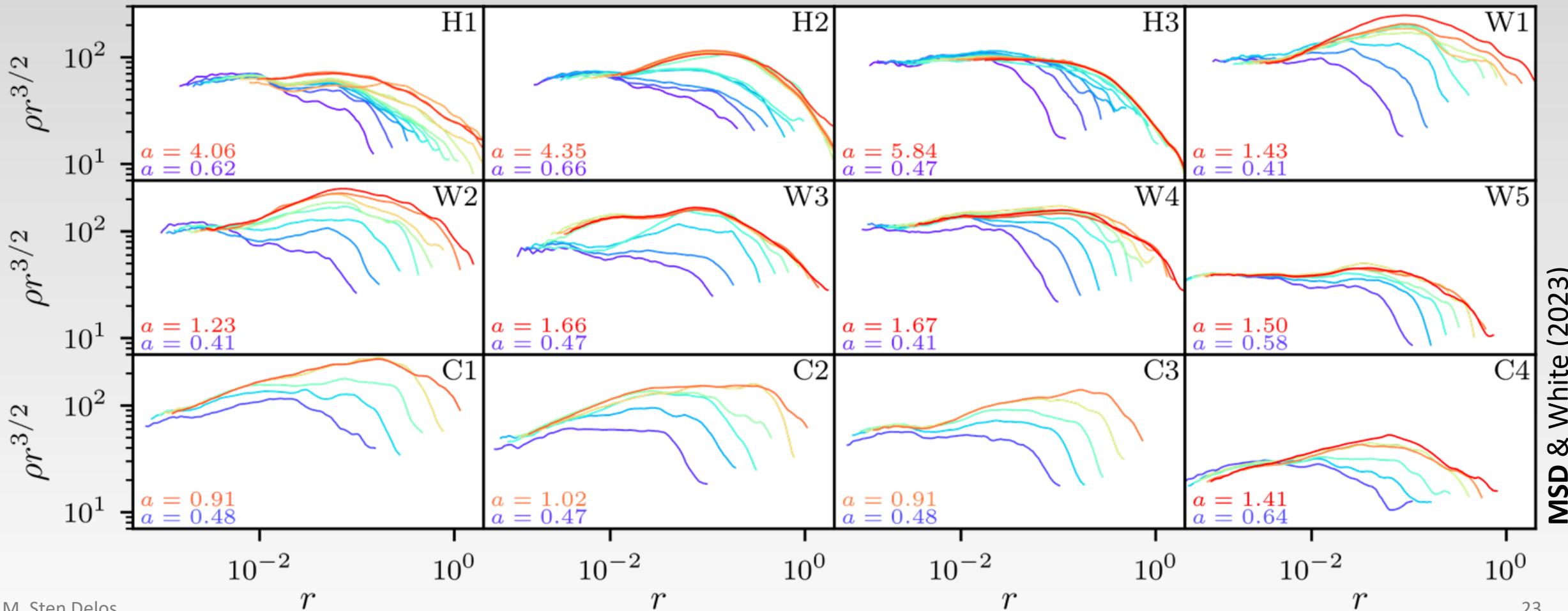
Do prompt cusps survive halo growth?



Outcome: standard DM halo density profile + prompt cusp

Prompt cusp survival

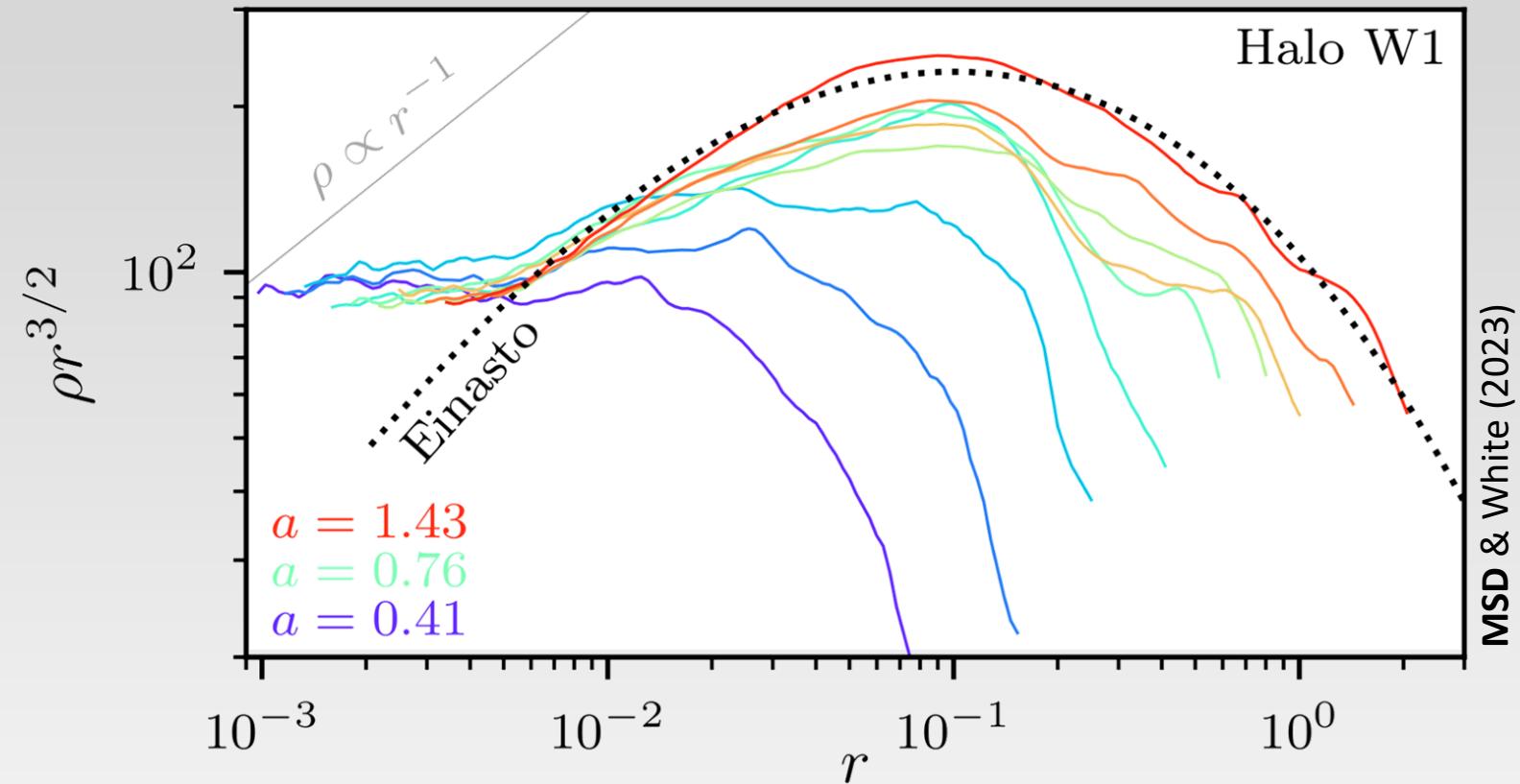
Twelve high-resolution halos from three cosmologies:
Prompt cusp forms at collapse; no evidence for disruption



Prompt cusp persistence is natural

Most new material has
too much energy and
angular momentum to
sink to the center

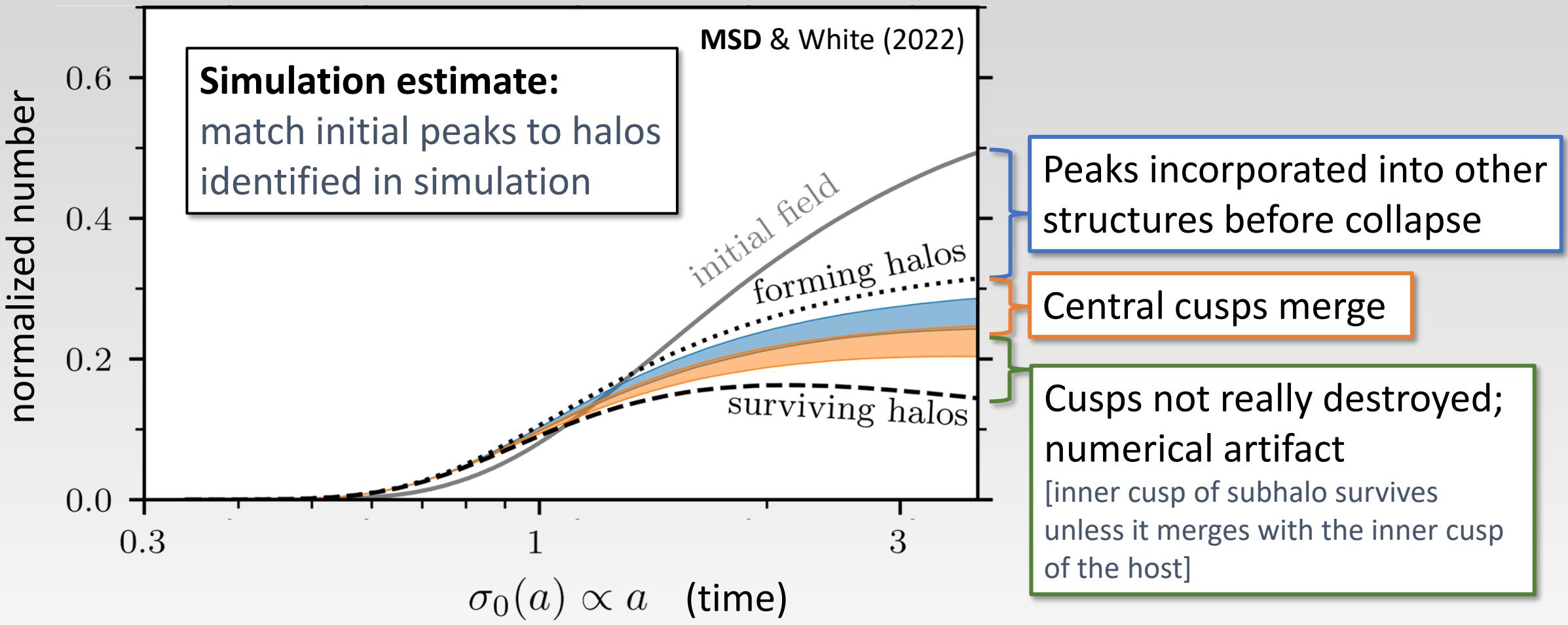
Only major mergers
can deposit material
into the center, but
impact is minor



Consequence: every (sub)halo has a central prompt cusp!

Can all peaks be associated with prompt cusps?

Prompt cusps survive halo growth. But do they survive halo clustering?



~ 1/2 of collapsed peaks can be associated with prompt cusps

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Dark matter halos

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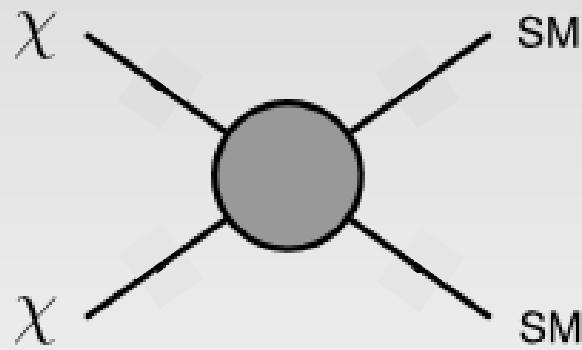
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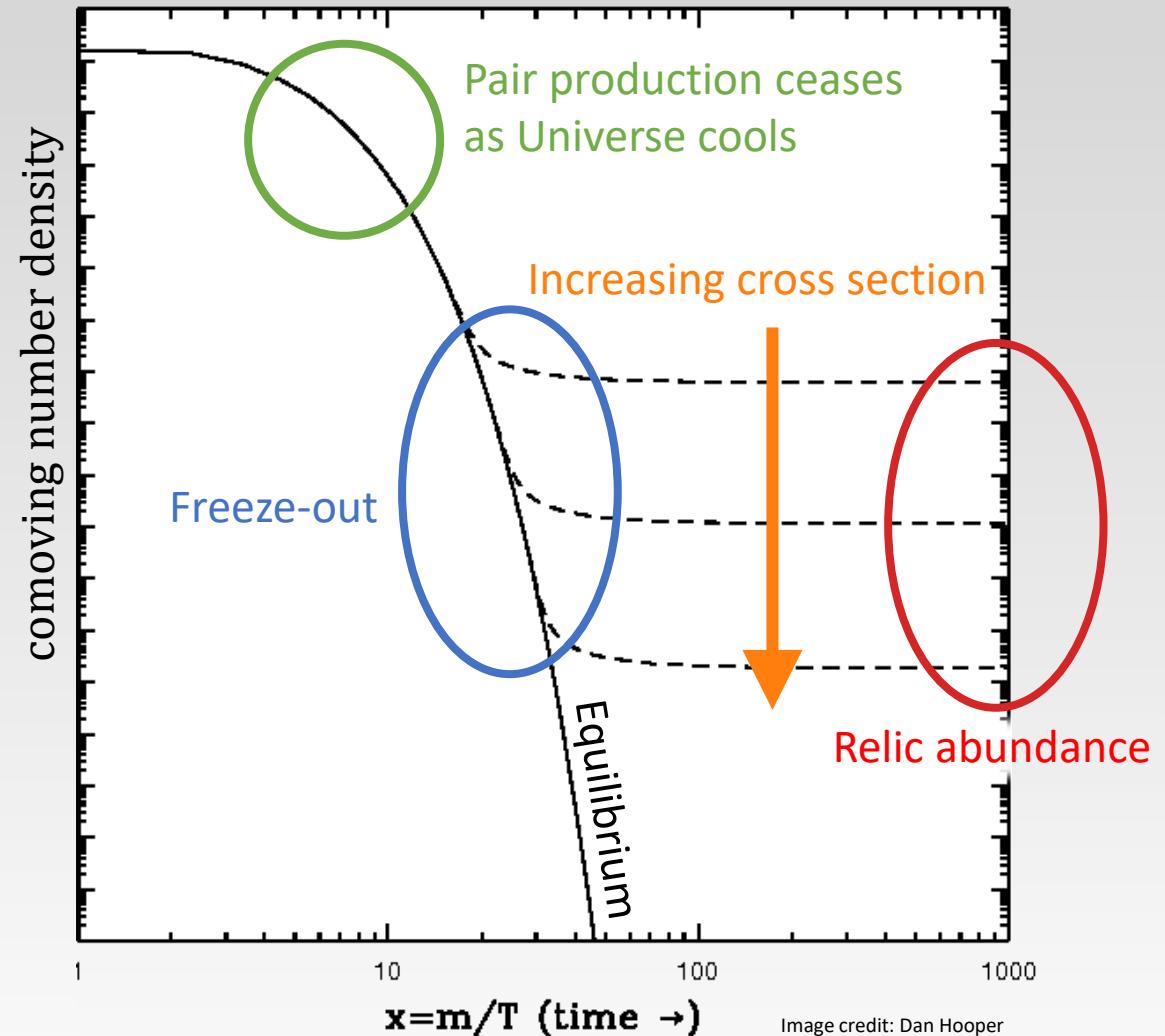
Prompt cusps of warm dark matter

What is dark matter?

Well motivated possibility:
thermal relic dark matter particle χ ,
pair-produced in the early universe.

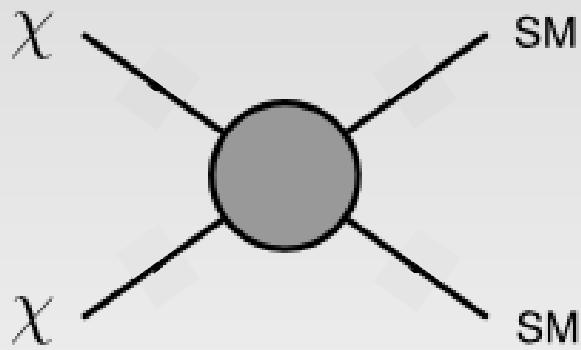


Thermal relic cross section:
 $\langle \sigma v \rangle \simeq 3 \times 10^{-26} \text{ cm}^3/\text{s}$



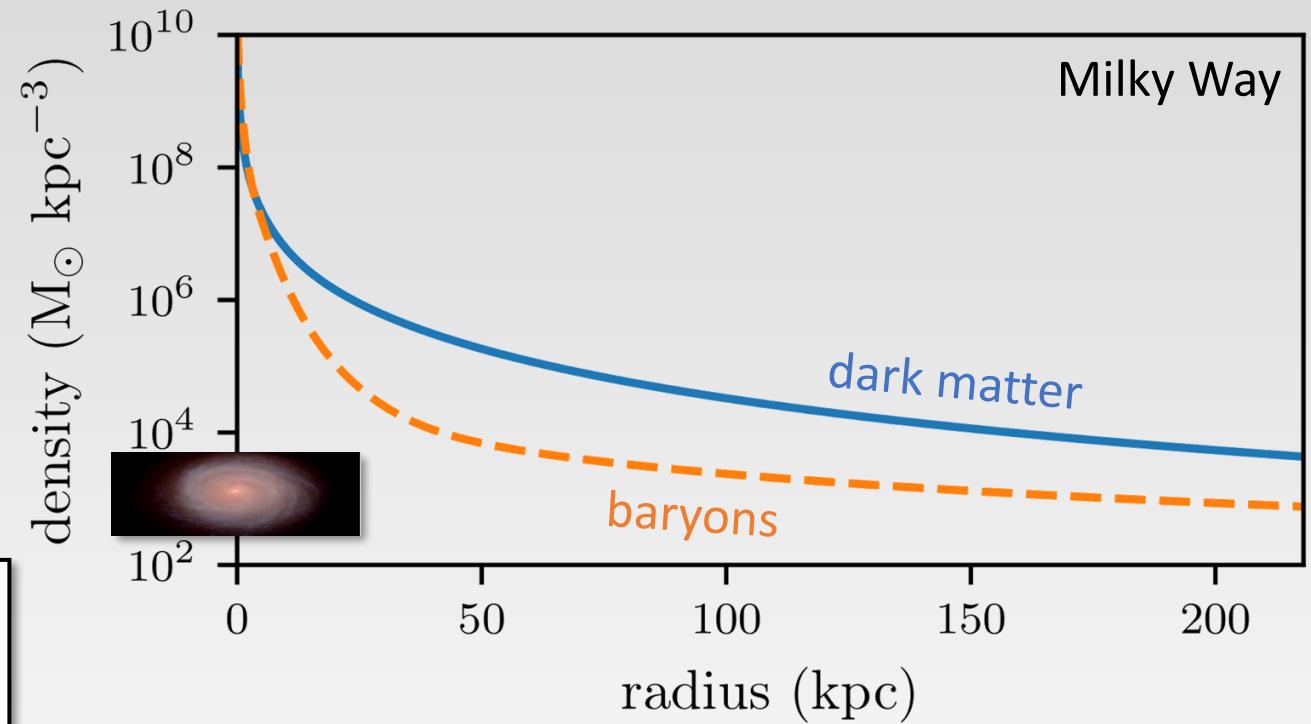
Indirect detection

Then dark matter can annihilate
into detectable SM particles today!



Annihilation rate $\propto \rho^2$:

Search the dense centers of galaxies

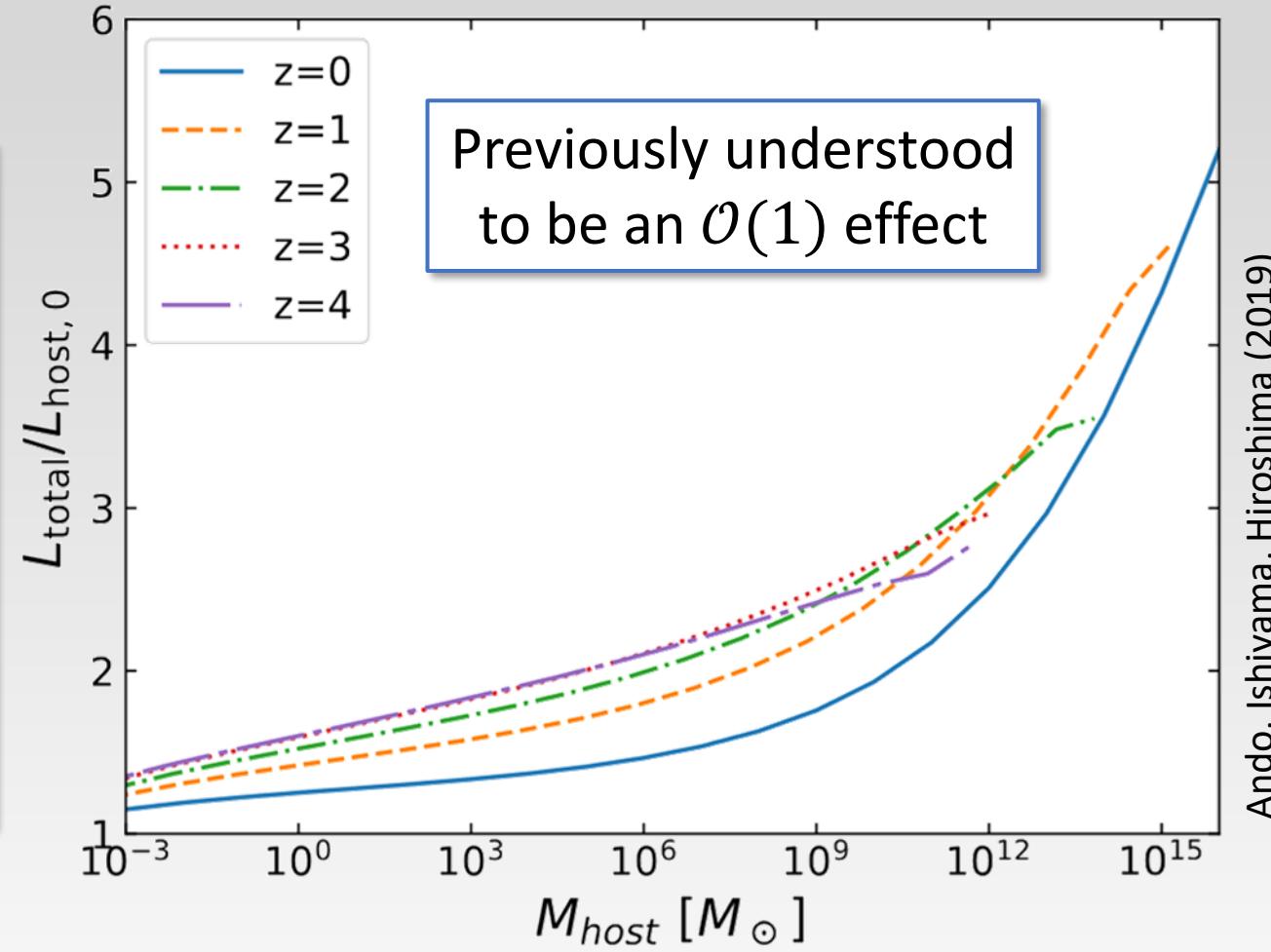


Substructure boost

The annihilation rate inside a halo is boosted by the presence of subhalos



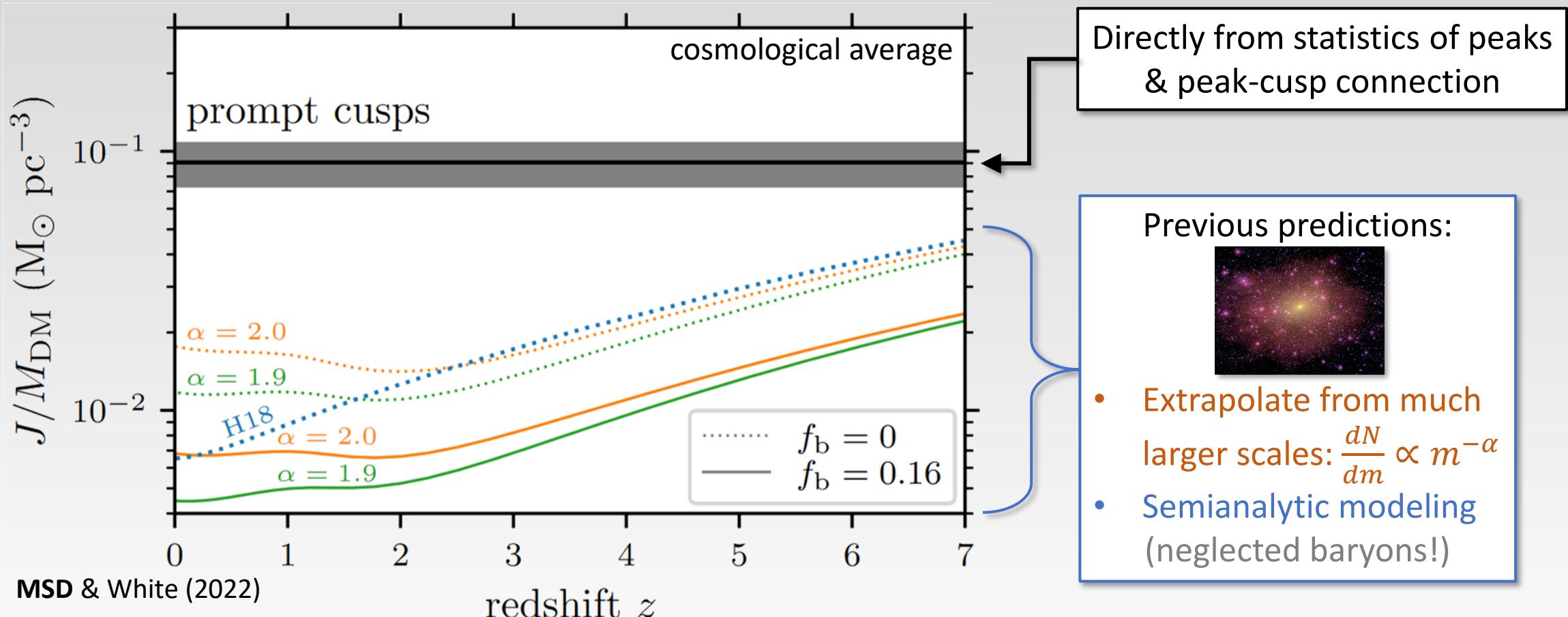
(due to ρ^2 scaling)



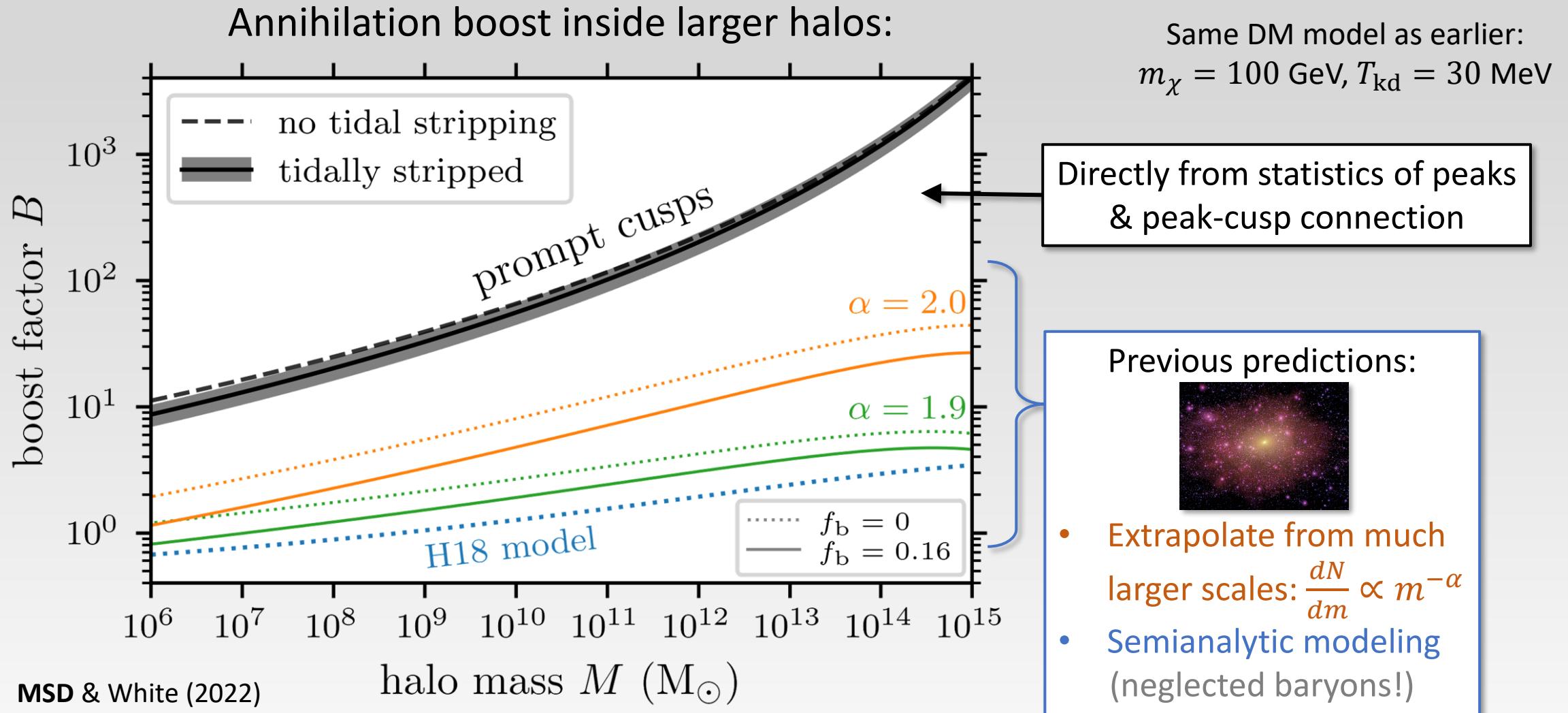
Annihilation in prompt cusps

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

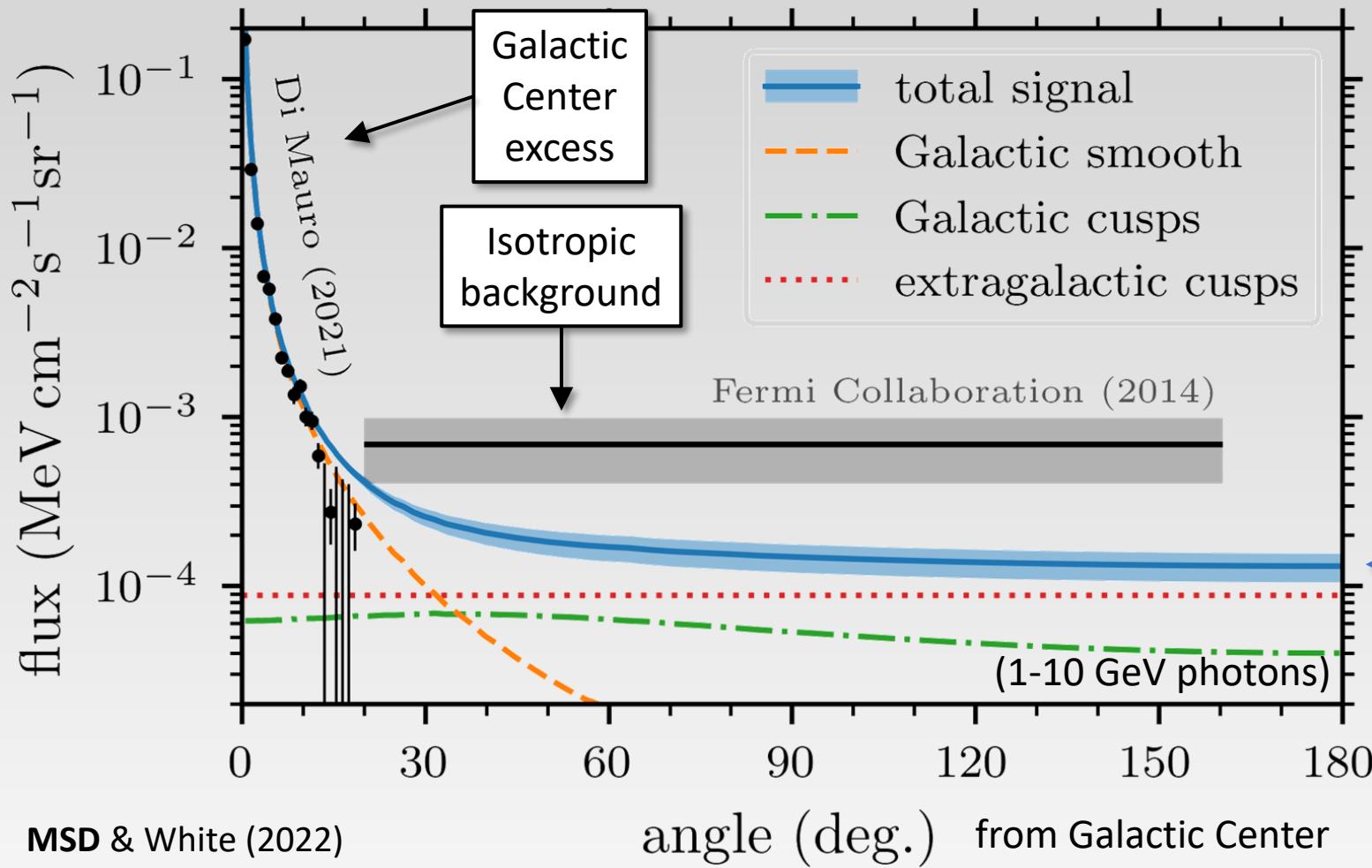
Same DM model as earlier:
 $m_\chi = 100 \text{ GeV}, T_{\text{kd}} = 30 \text{ MeV}$



Annihilation in prompt cusps



Annihilation in prompt cusps

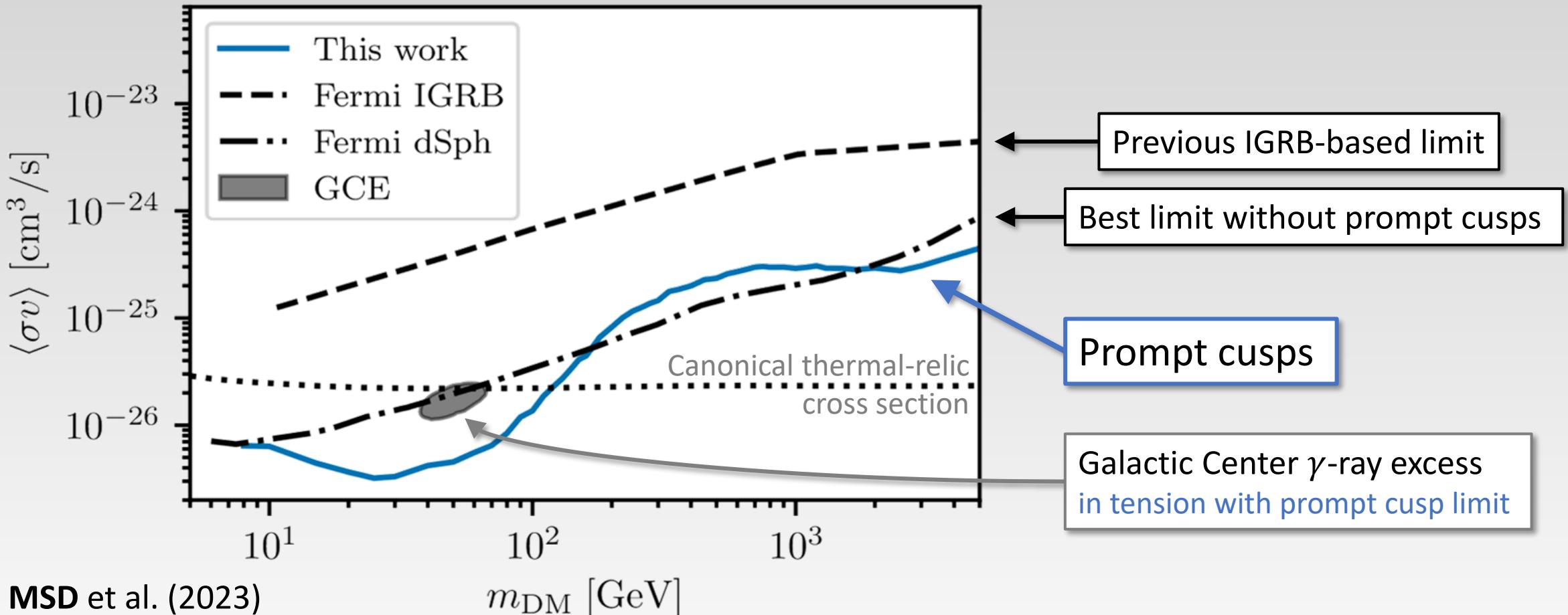


No annihilation boost in the centers of galactic halos (cusps disrupted & density already high), but **annihilation everywhere else is greatly boosted.**

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

Limits on dark matter annihilation

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



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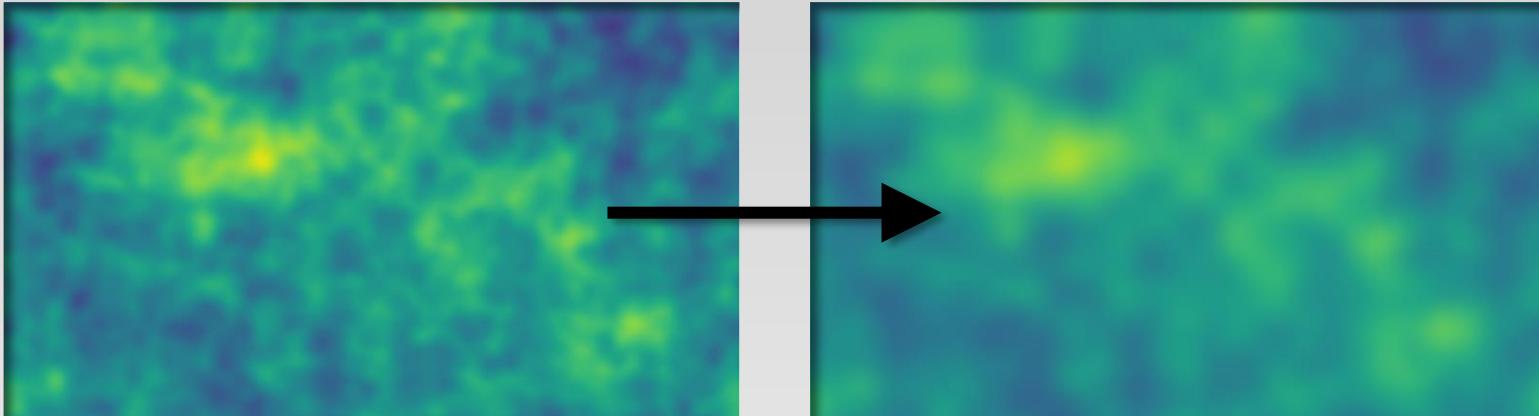
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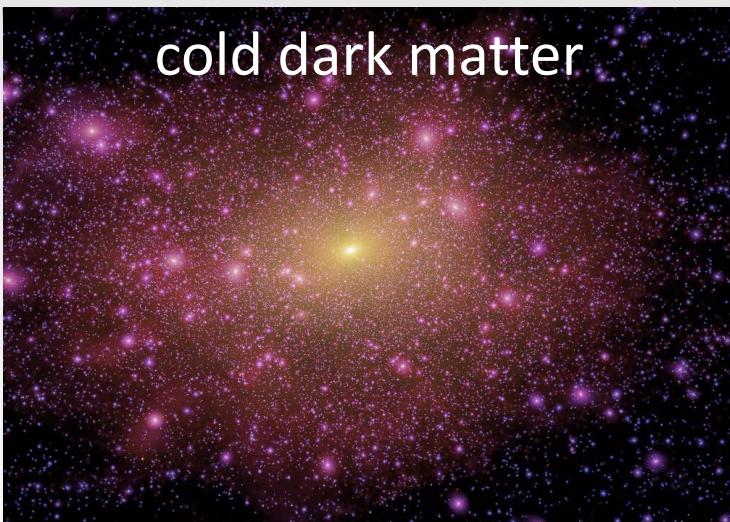
Prompt cusps of warm dark matter

Warm dark matter

Random particle motion smooths initial conditions



which suppresses the abundance of low-mass halos:



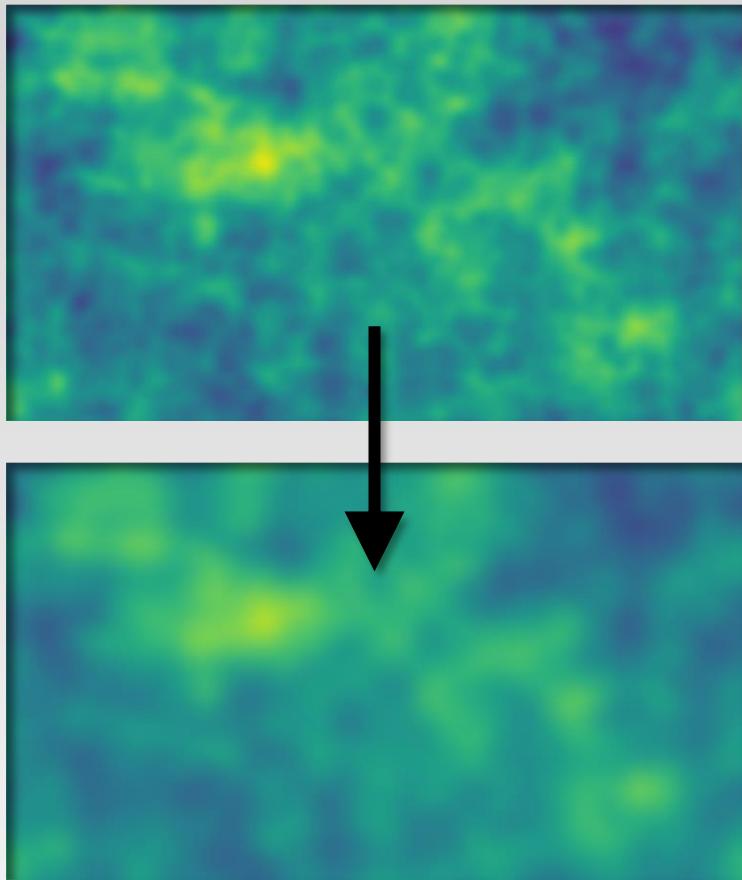
cold dark matter



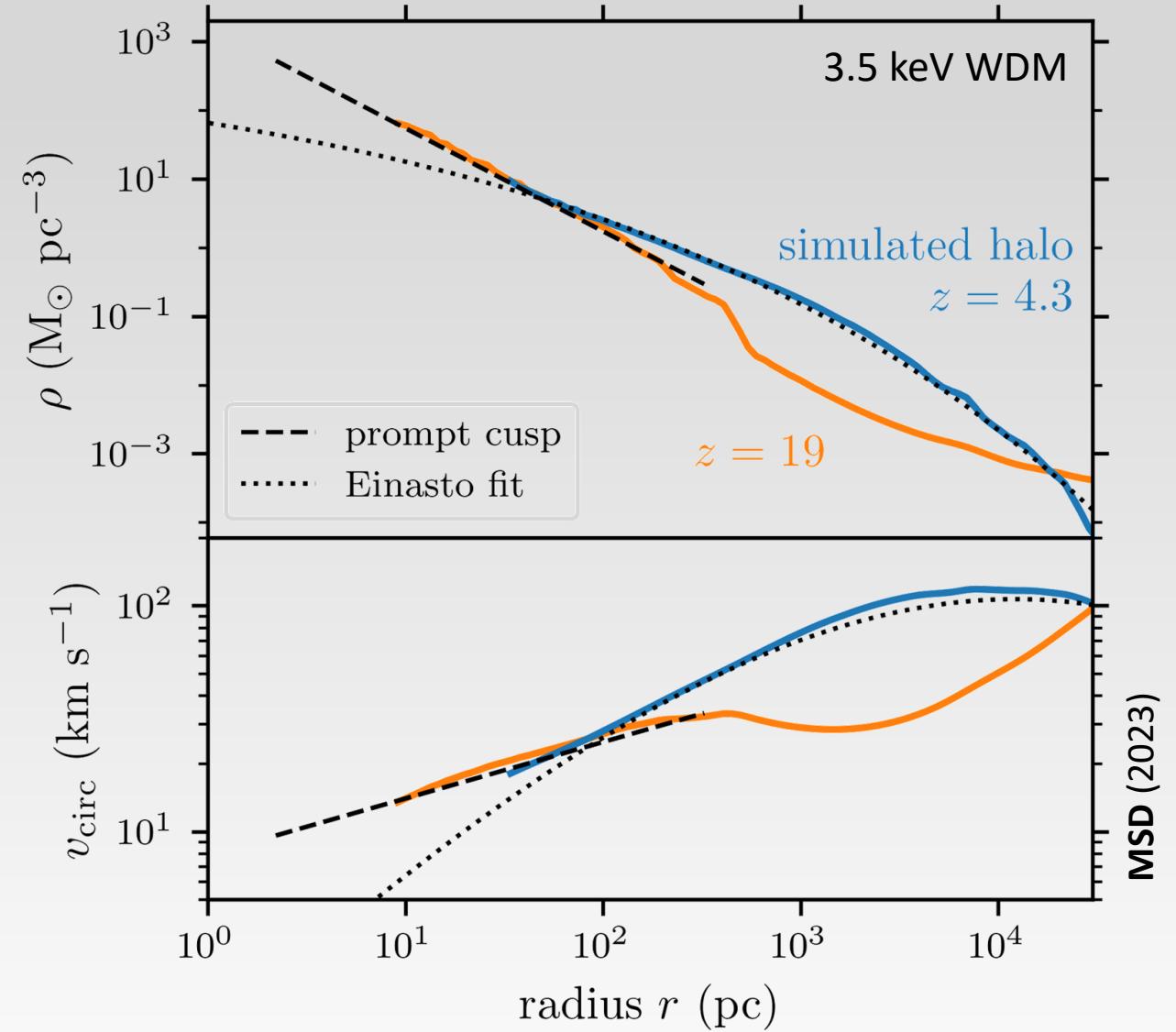
warm dark matter

Lovell et al (2014)

Prompt cusps of warm dark matter

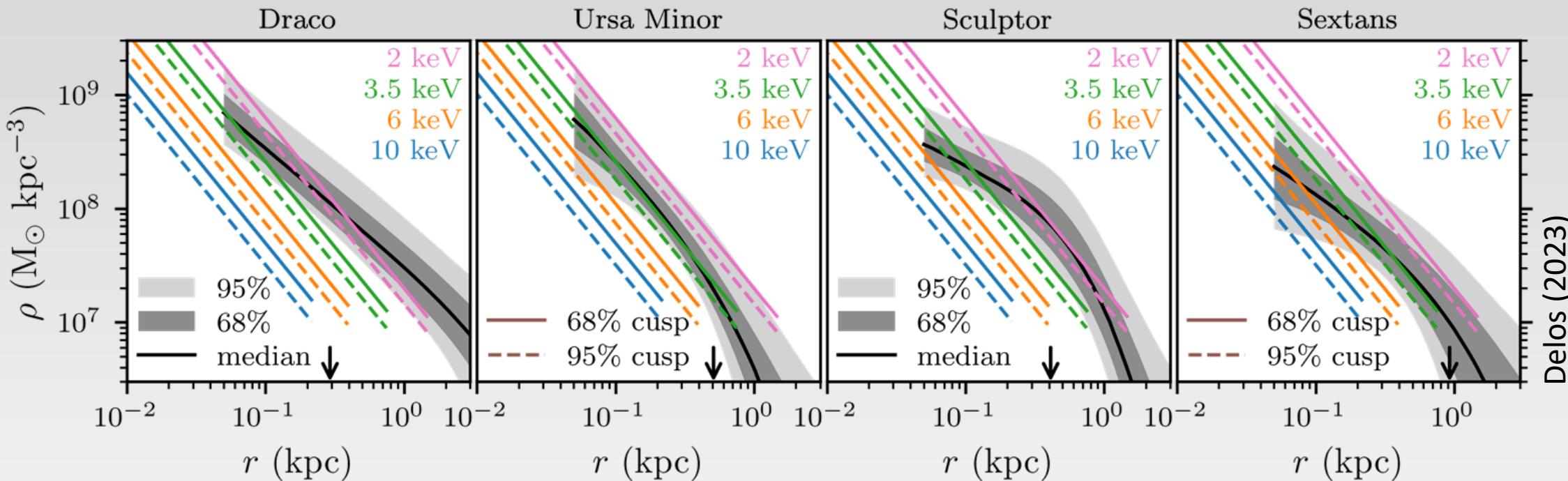


Initial density peaks are much larger
→ Prompt cusps are much larger



Searching for WDM prompt cusps

We can search for prompt cusps within nearby dwarf galaxies:



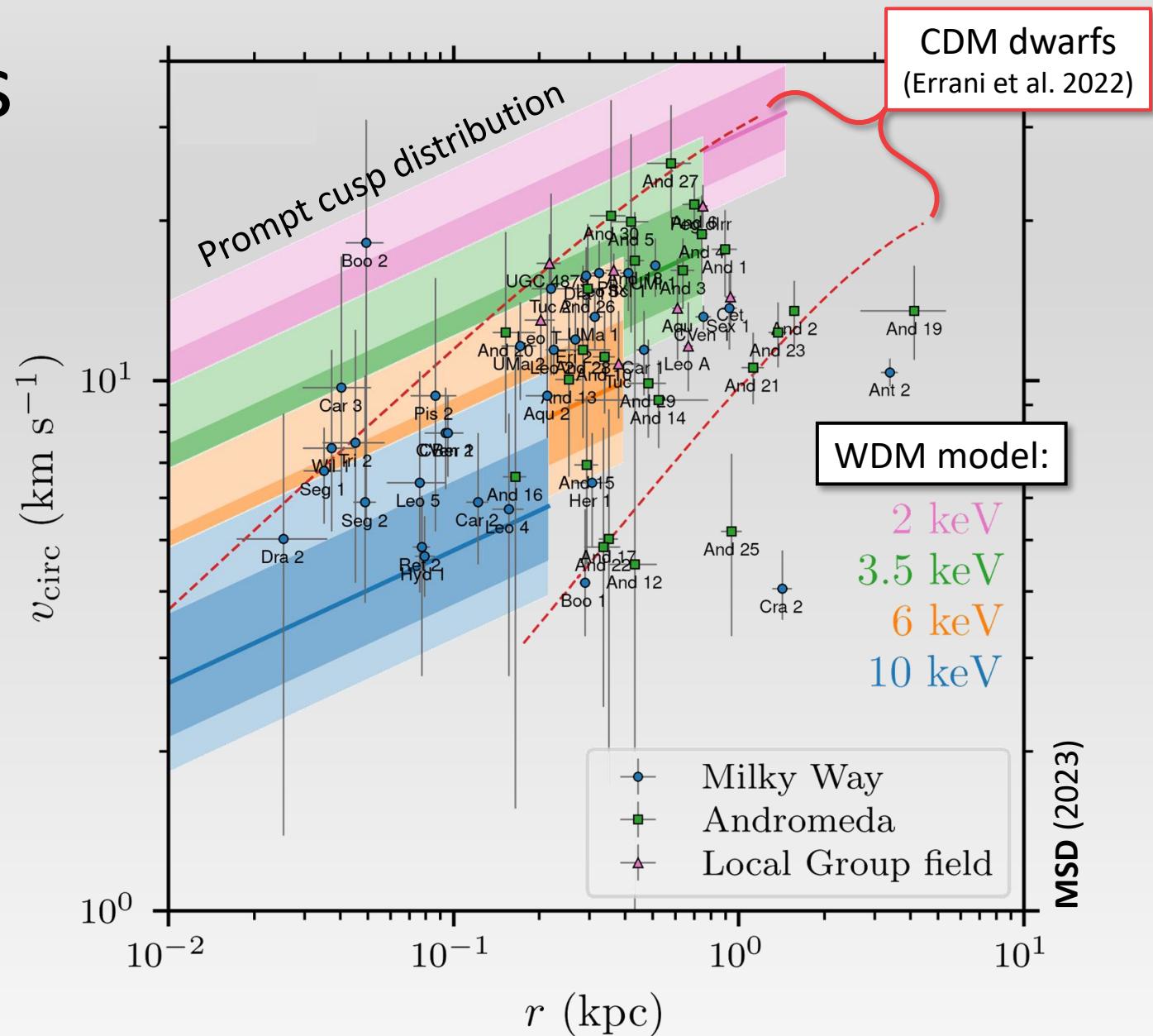
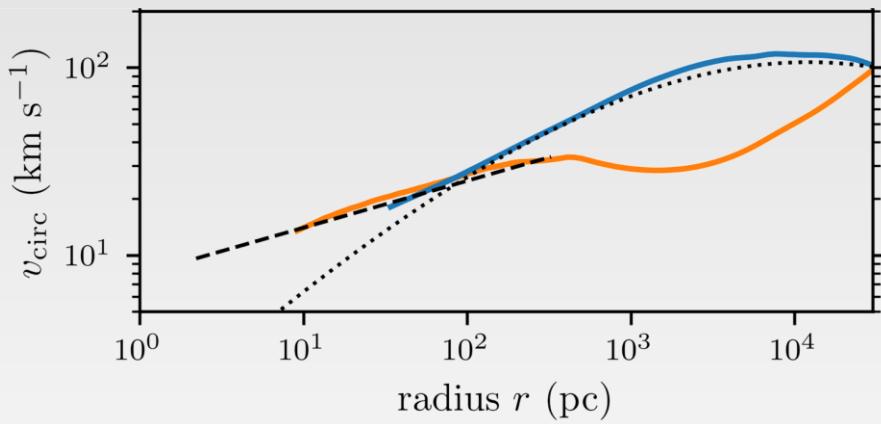
Interpretation: $\rho > \rho_{\text{cusp}}$ can be explained by halo growth, but $\rho < \rho_{\text{cusp}}$ is difficult to explain

Better constraints come from ultrafaints...

WDM prompt cusps

Comparison to kinematics of
Local Group dwarf galaxies
[v_{circ} at half-light radius]

- v_{circ} too high: can be explained by halo growth
- v_{circ} too low: difficult to explain



Summary

Gravitational collapse of smooth peaks in the initial density field produces **prompt** $\rho \propto r^{-1.5}$ **cusps**, which persist through halo growth.

- These features **greatly impact DM annihilation**. We expect an annihilation signal not only from the densest regions but from diffuse regions as well.
[If Galactic Center γ -ray excess is DM annihilation, a matching signal should appear in the isotropic γ -ray background.]
- If DM is warm, **prompt cusps should affect galactic kinematics** and potentially other observables.

