Title: Prompt cusps of dark matter

Speakers: Sten Delos

Series: Cosmology & Gravitation

Date: October 10, 2023 - 11:00 AM

URL: https://pirsa.org/23100055

Abstract: The onset of the formation of structure in the early universe was marked by the monolithic collapse of smooth peaks in the initial density field. This process creates prompt rho ~ r^-1.5 density cusps of dark matter, which persist largely unaltered through the subsequent growth of dark matter halos around them. Consequently, in the standard collisionless dark matter paradigm, these prompt cusps are expected to be enormously abundant, and one resides at the center of every halo and subhalo. Prompt cusps present new opportunities to test the nature of dark matter. In annihilating dark matter models, the abundance of these features and the high density inside them greatly influence the intensity and morphology of the annihilation signal. For example, if the Galactic Center gamma-ray excess is due to annihilating dark matter, then a matching signal from unresolved prompt cusps should be detectable elsewhere. Moreover, the properties of prompt cusps are closely linked to details of the primordial density field. In warm dark matter models, prompt cusps are expected to be large enough to influence stellar motions within galaxies at detectable levels.
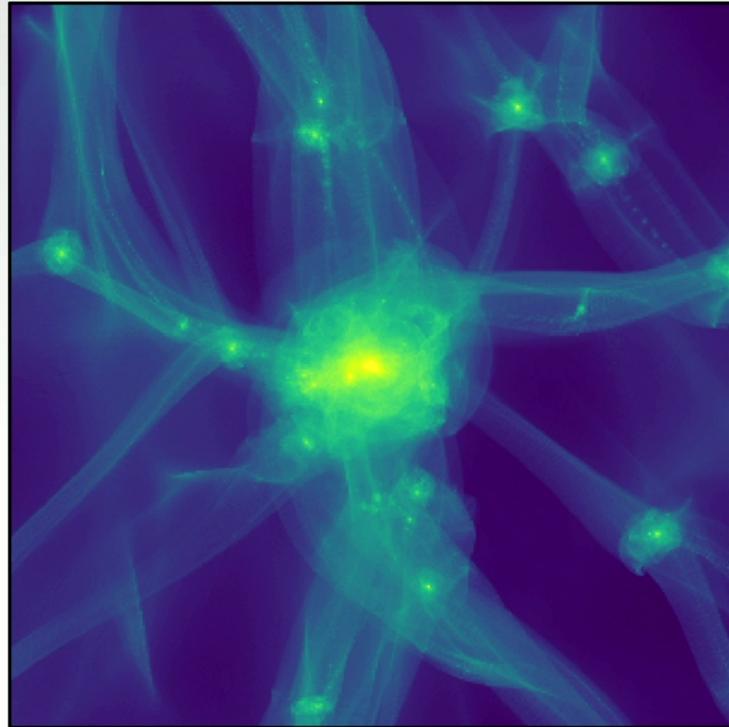

Zoom link: https://pitp.zoom.us/j/98307421845?pwd=V3BqZmtyQ09XcjBwNEltTzFPTHJPUT09

Dark matter halos

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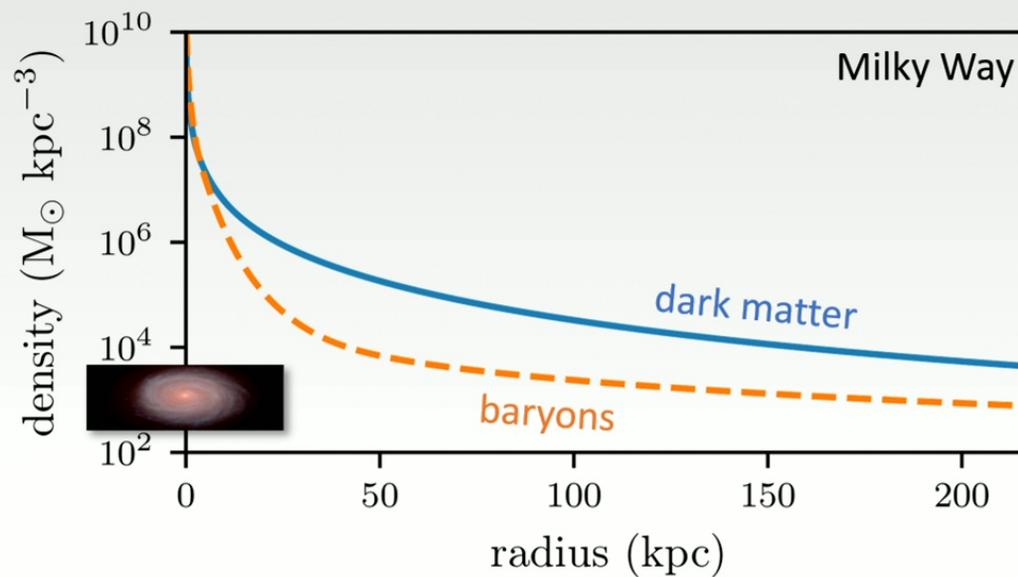- Dark matter drives gravitational structure formation

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

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

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Dark matter halos

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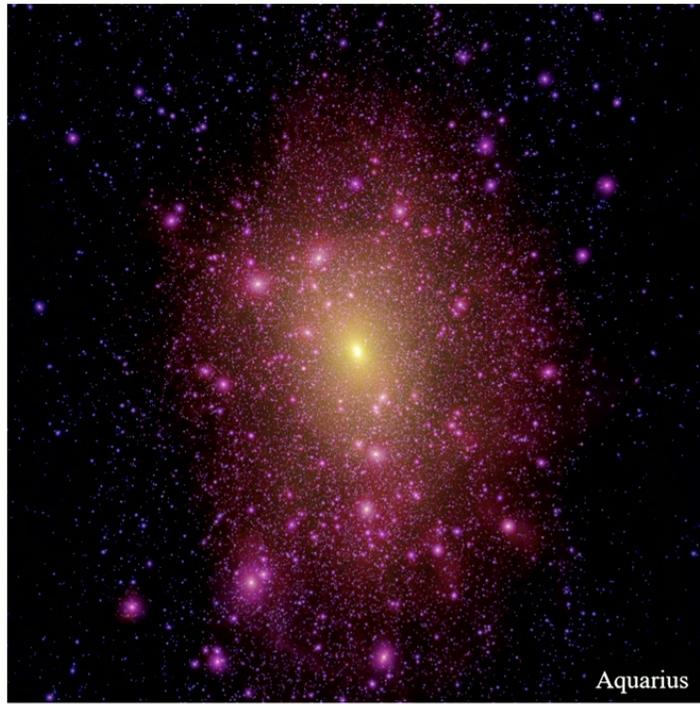- Dark matter drives gravitational structure formation

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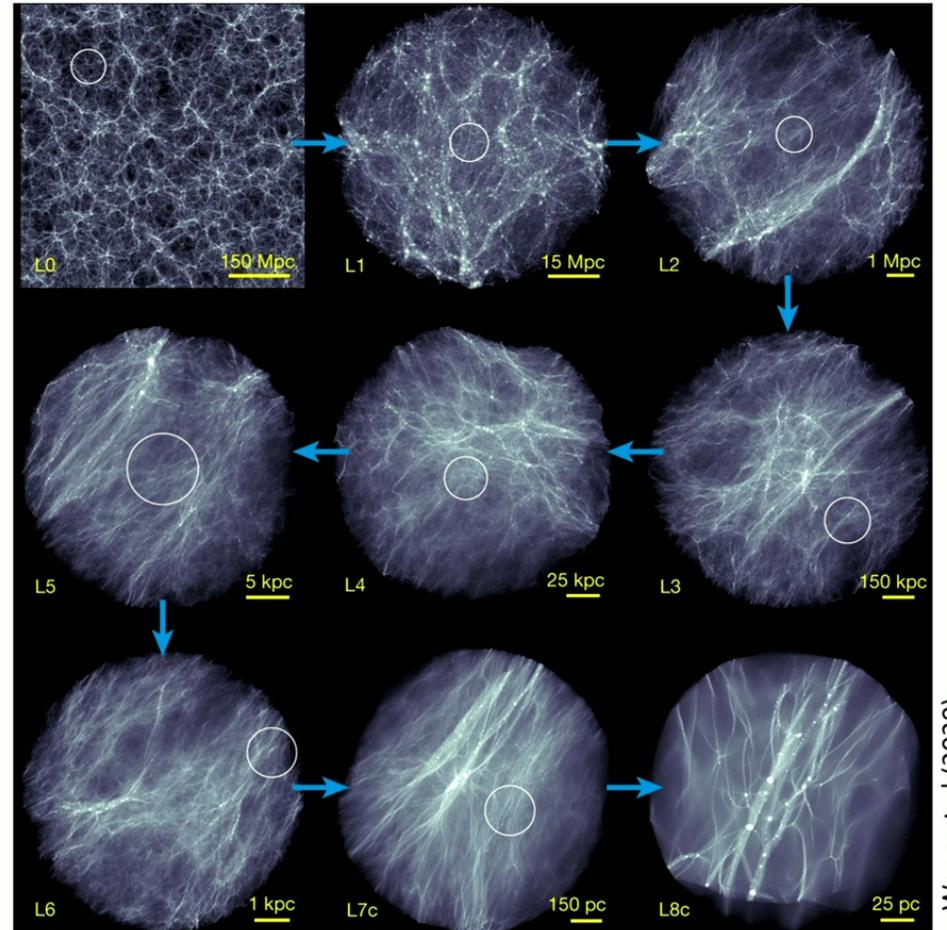picture of simulated MW-like galaxy: Grand et al (2021)

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Dark matter halos

Subhalos persist inside other halos:

Aquarius

Halos form at all scales:

L0   150 Mpc   L1   15 Mpc   L2   1 Mpc

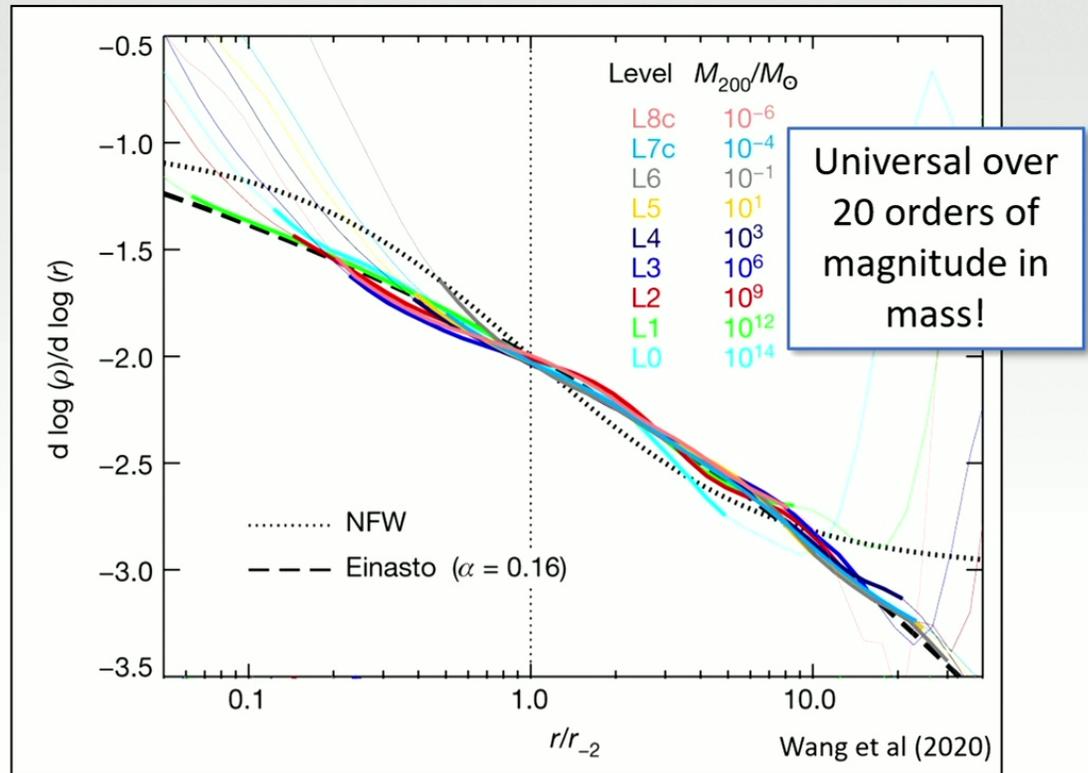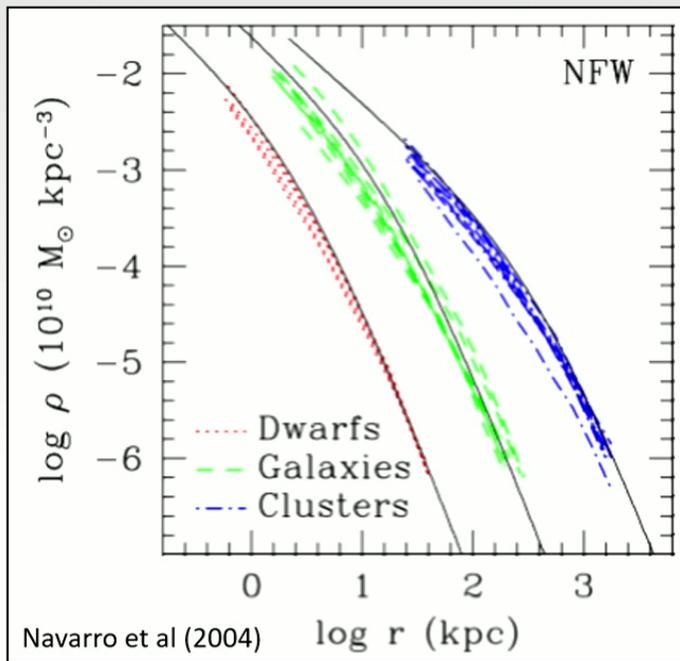L5   5 kpc   L4   25 kpc   L3   150 kpc

L6   1 kpc   L7c   150 pc   L8c   25 pc

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!

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Density profiles from accretion history

Universal density profiles follow from universal accretion history
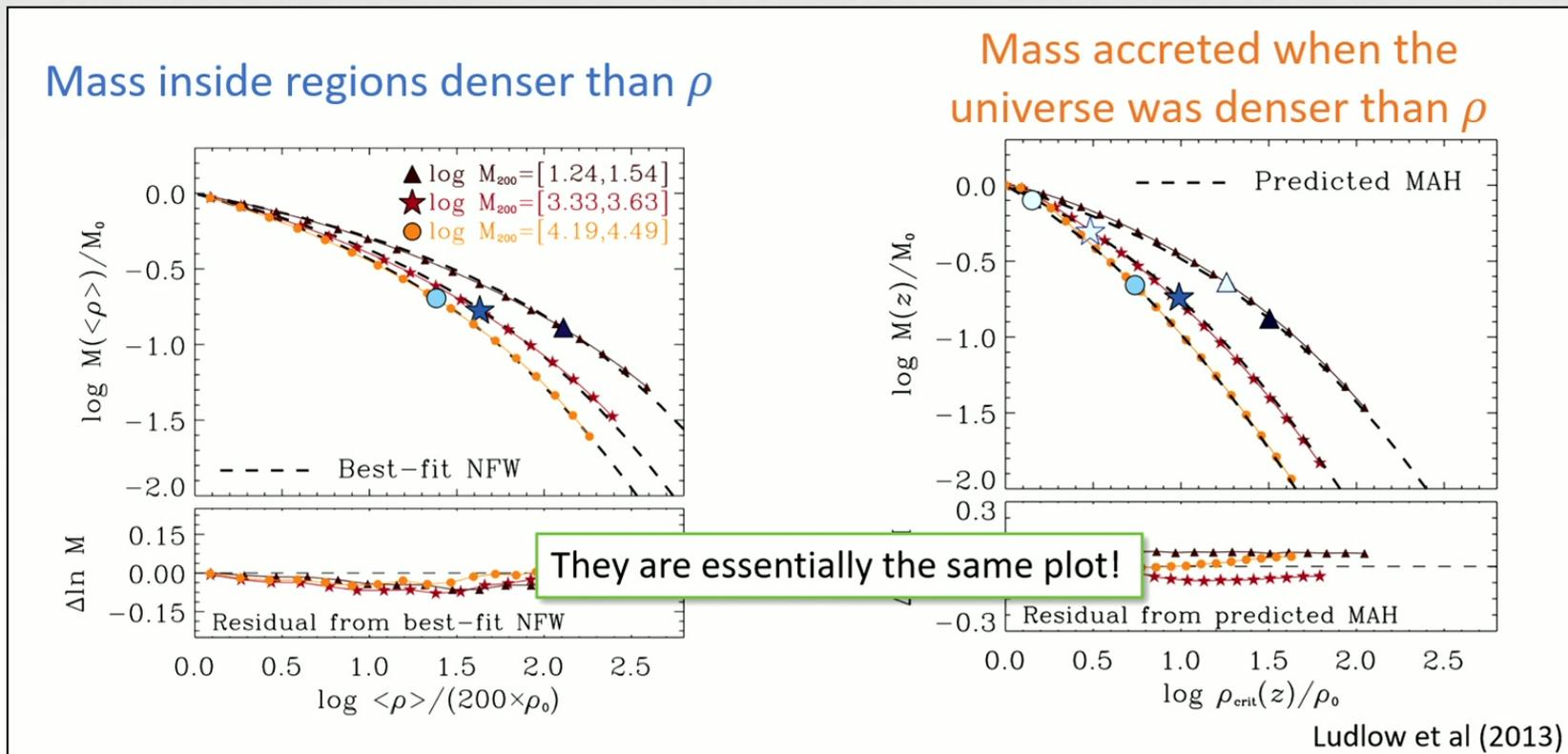
Mass inside regions denser than ρ

Mass accreted when the universe was denser than ρ

They are essentially the same plot!

Ludlow et al (2013)
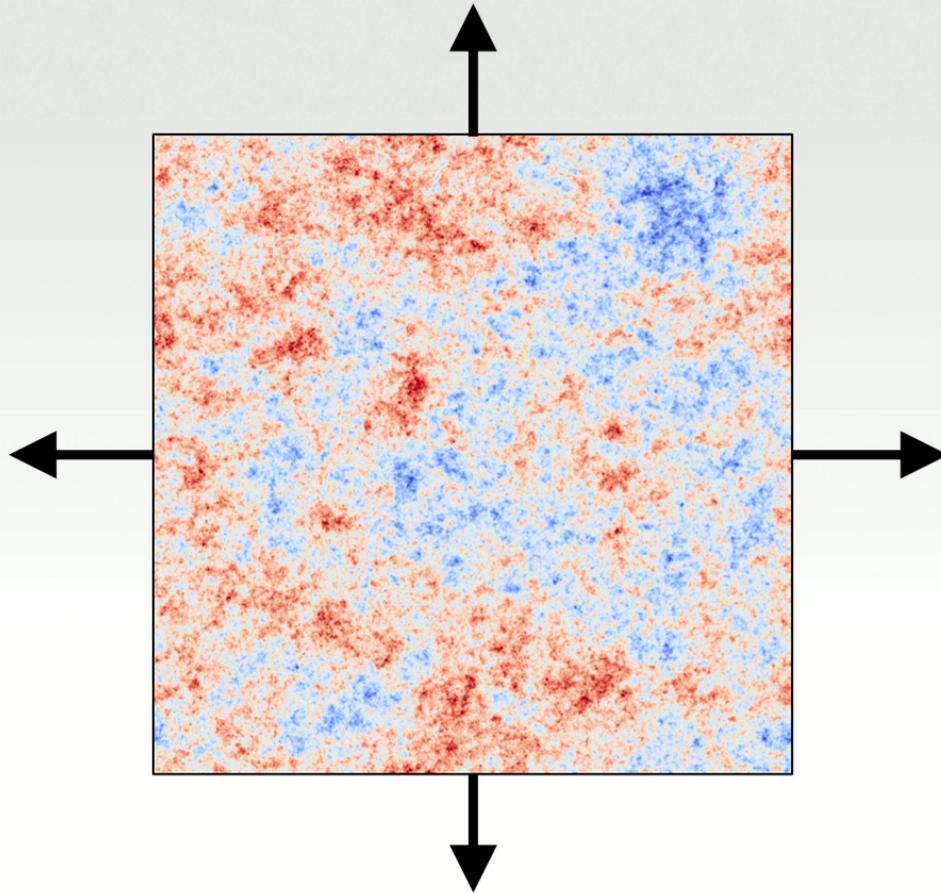
Outline

Dark matter halos

The cosmological initial conditions and prompt cusps

Survival of prompt cusps

Prompt cusps and dark matter annihilation
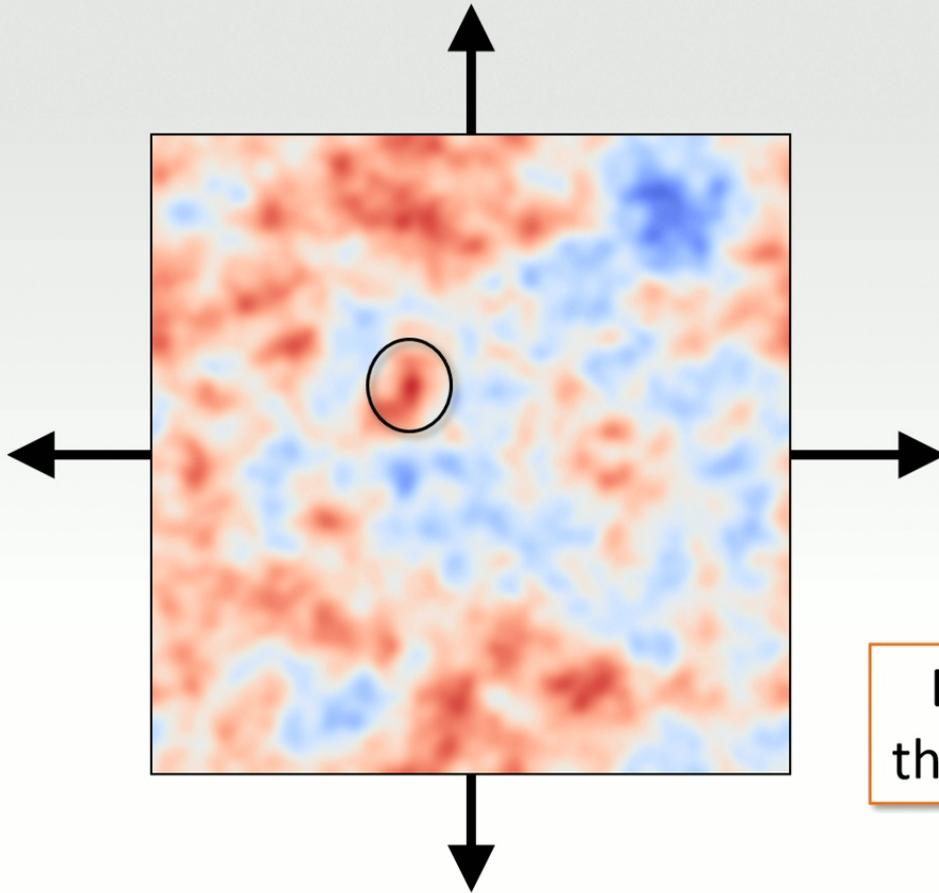
Prompt cusps of warm dark matter

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The cosmological initial conditions

A random density field

- Expanding over time
- Gravitationally amplified over time

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The cosmological initial conditions
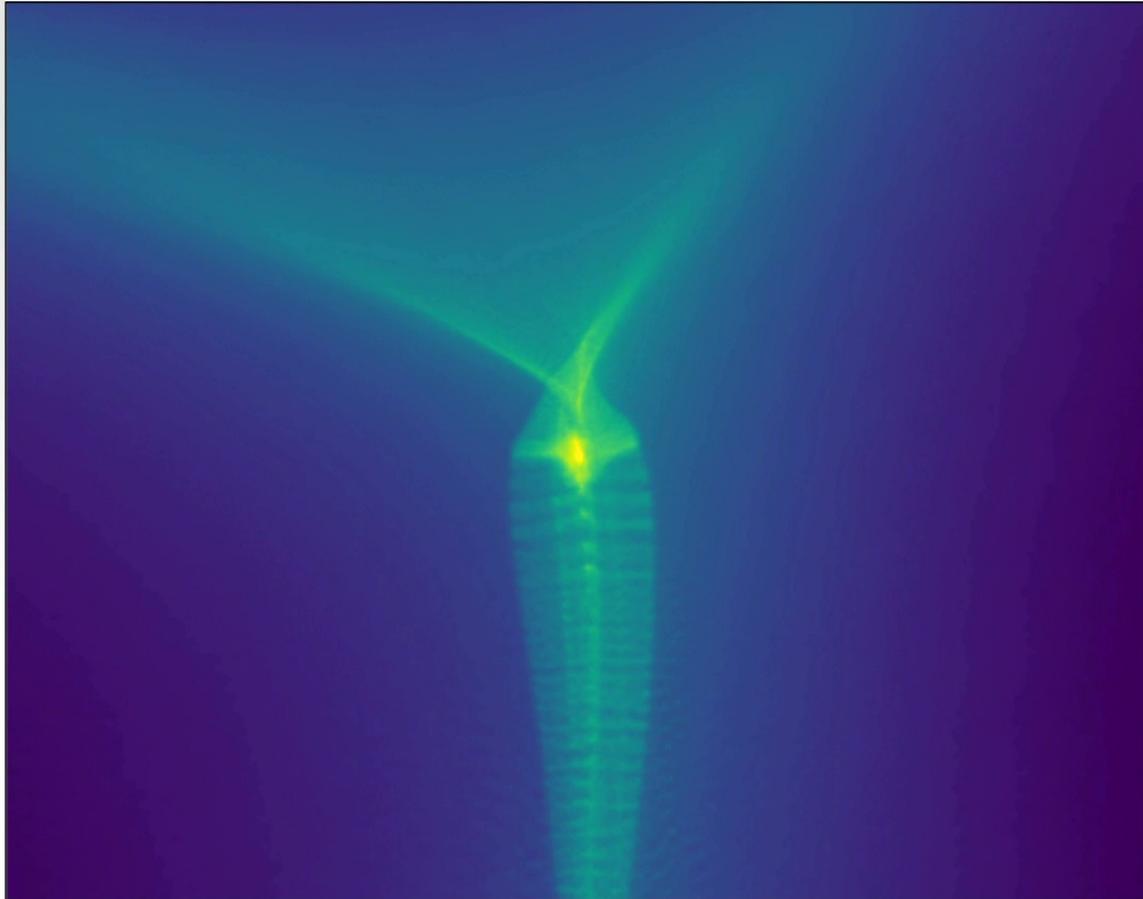

A random density field
- Expanding over time
- Gravitationally amplified over time
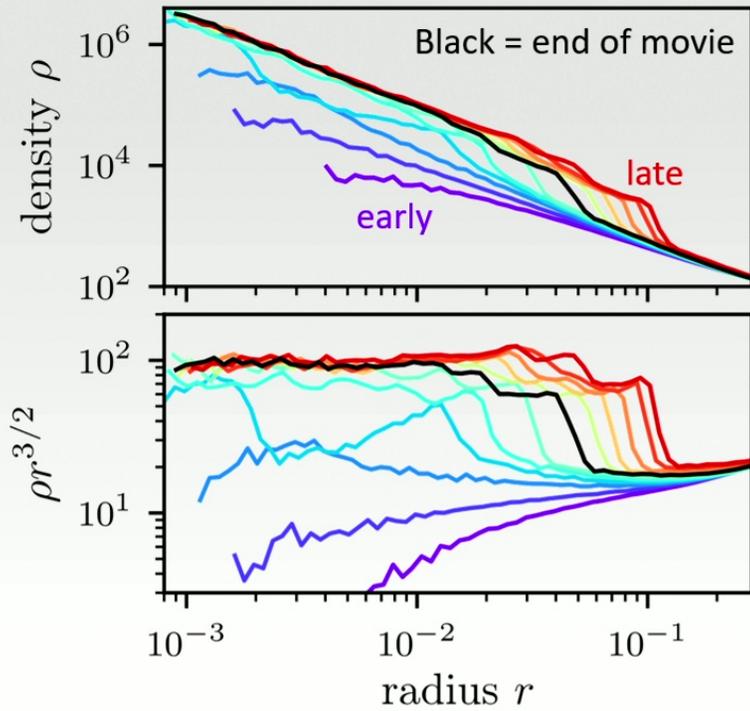
Smooth on sufficiently
small scales
e.g., due to thermal motion of
the dark matter

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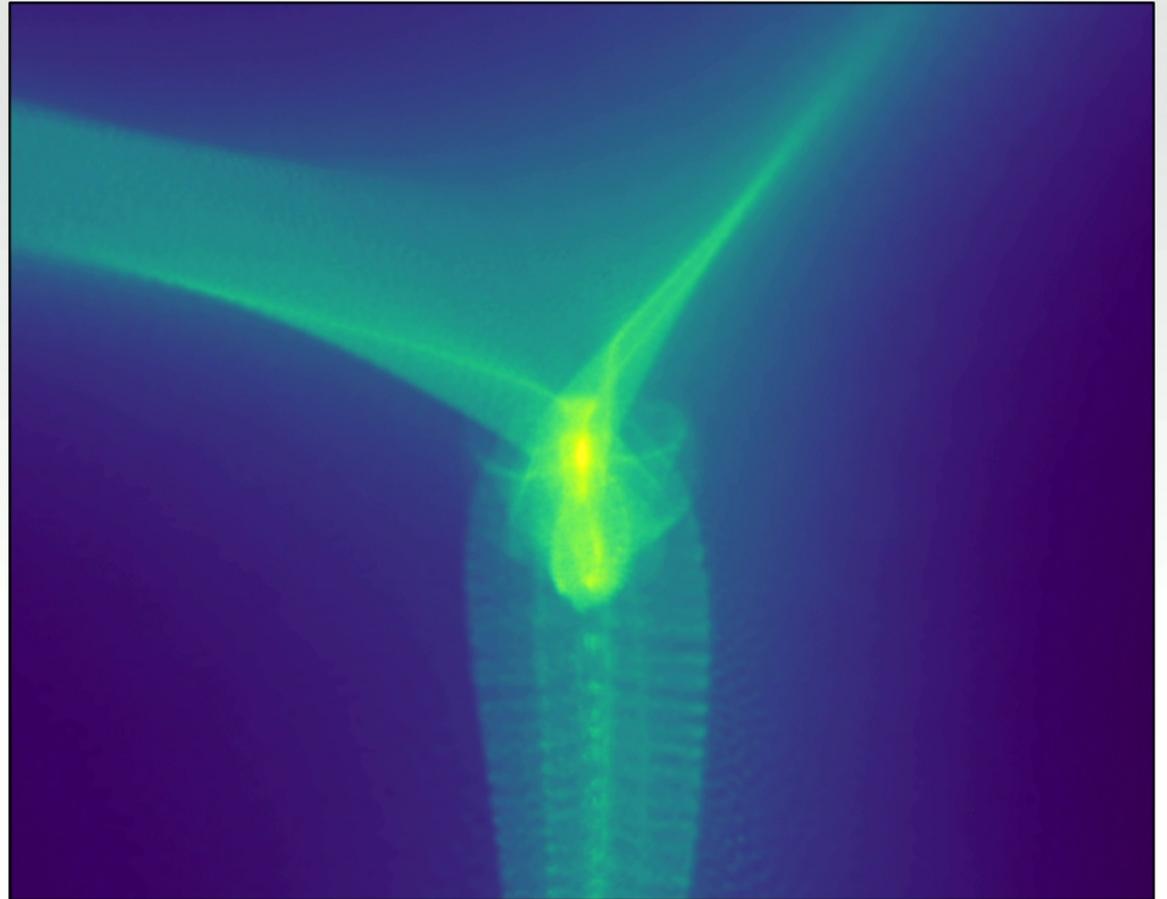the first places to gravitationally collapse

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Collapse at a density maximum
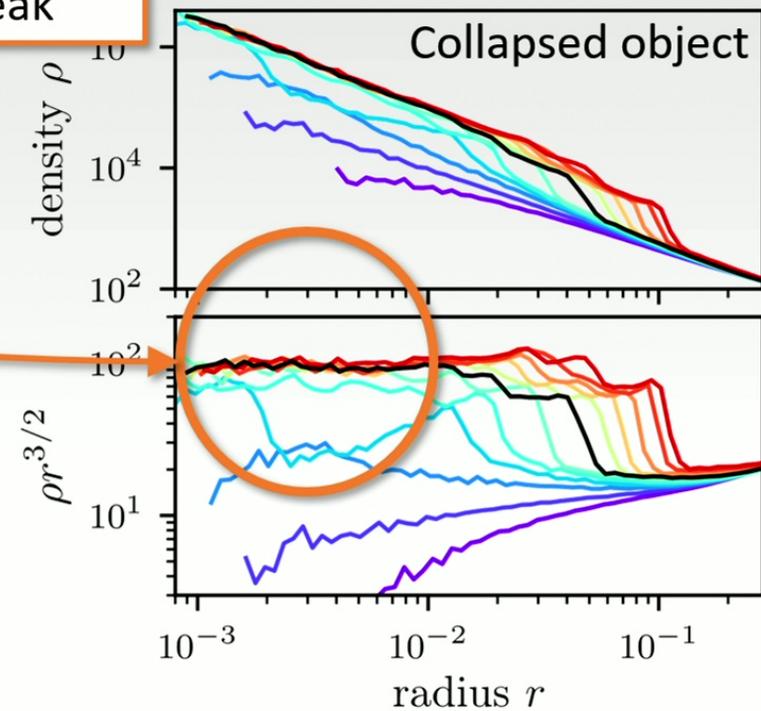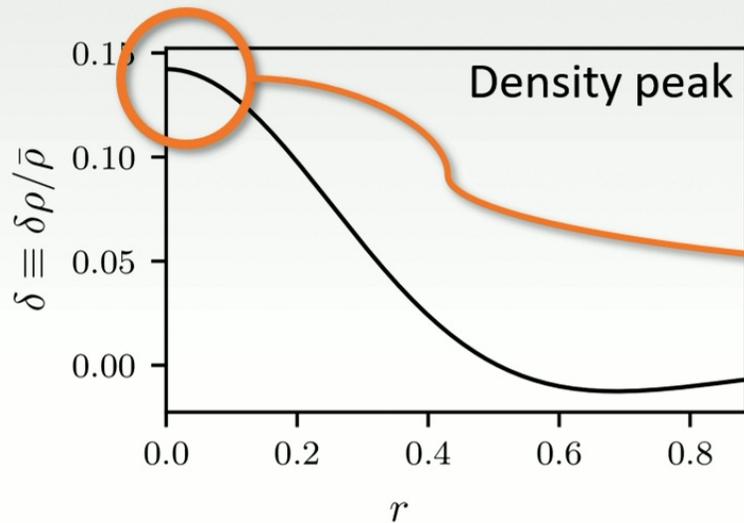

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"Prompt cusp"

$\rho \propto r^{-3/2}$ cusp stabilizes immediately after formation
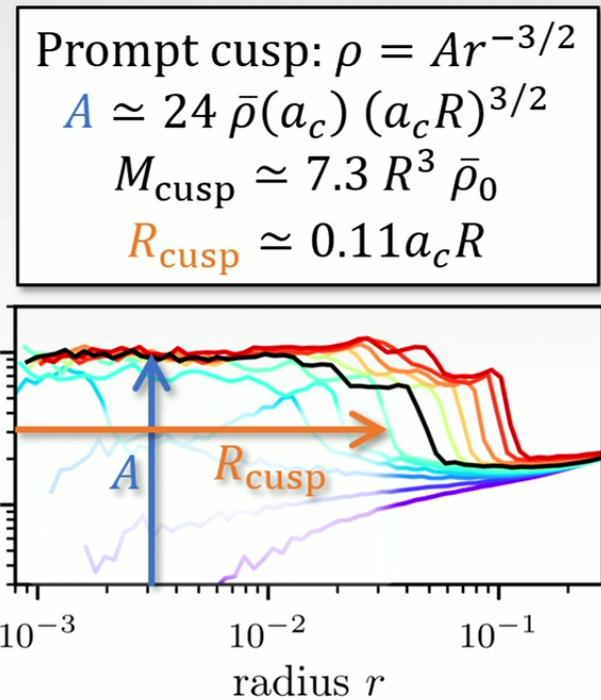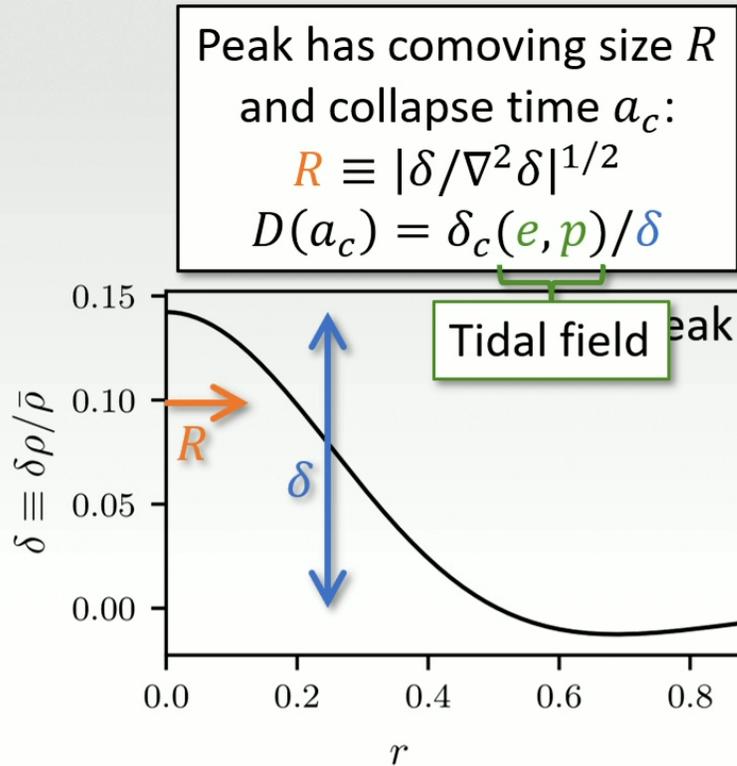
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What sets prompt cusp properties?

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

Peak has comoving size R
and collapse time a_c:
$$R \equiv |\delta/\nabla^2\delta|^{1/2}$$
$$D(a_c) = \delta_c(e,p)/\delta$$

Tidal field

Prompt cusp: $\rho = Ar^{-3/2}$
$$A \simeq 24\,\bar{\rho}(a_c)\,(a_c R)^{3/2}$$
$$M_{\rm cusp} \simeq 7.3\,R^3\,\bar{\rho}_0$$
$$R_{\rm cusp} \simeq 0.11 a_c R$$

MSD & White (2023); **MSD**, Bruff, Erickcek (2019)

Peak-cusp connection

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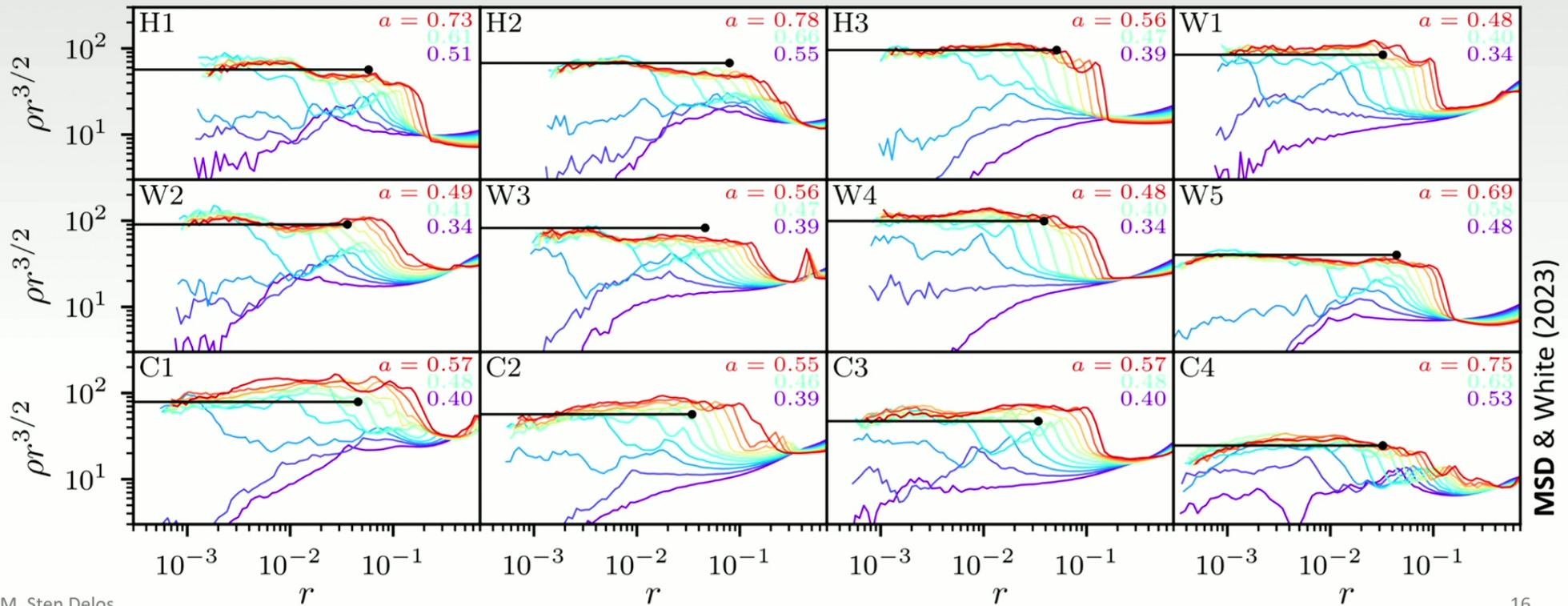
Statistics of peaks

Connection between cusps
and peaks is clear.
What is the distribution of peaks?

THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

J. M. BARDEEN[1]
Physics Department, University of Washington

J. R. BOND[1]
Physics Department, Stanford University

N. KAISER[1]
Astronomy Department, University of California at Berkeley, and Institute of Astronomy, Cambridge University
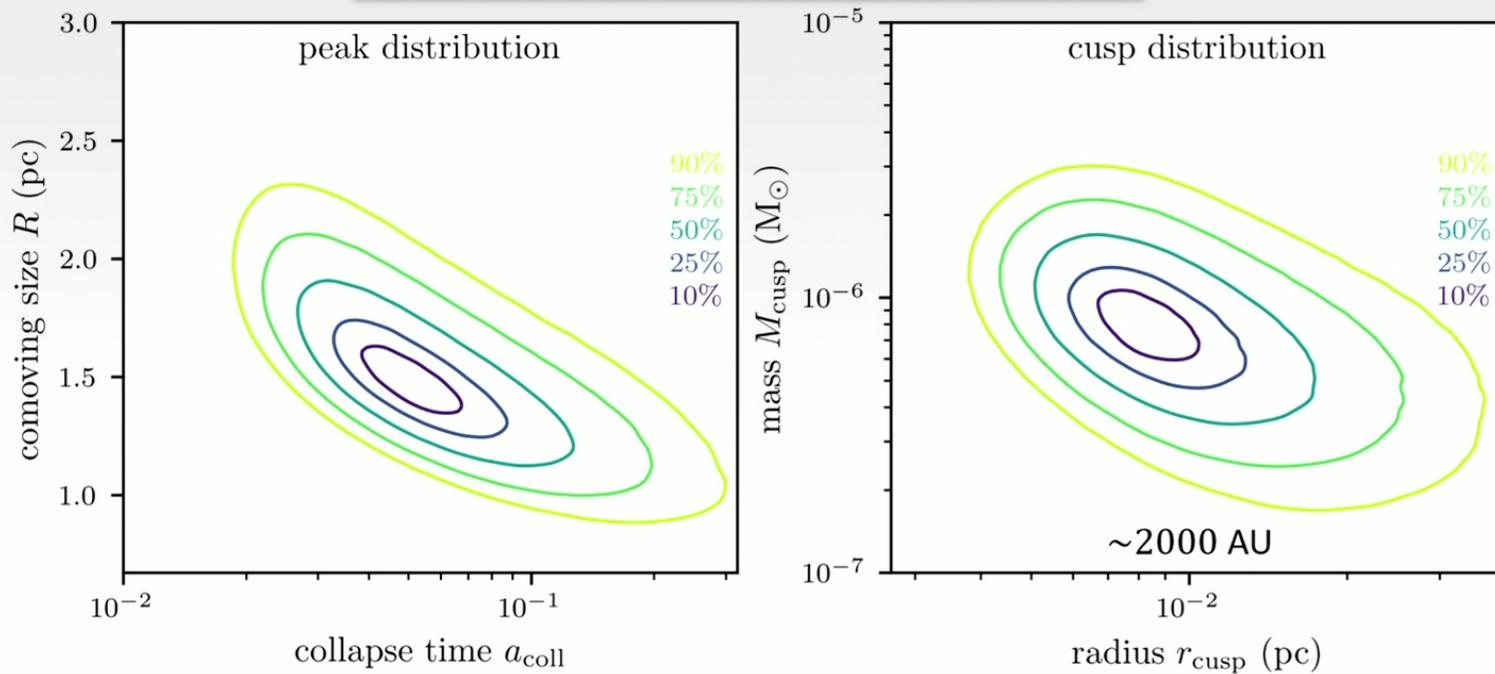
AND

A. S. SZALAY[1]
Astrophysics Group, Fermilab

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Statistics of prompt cusps

Example: 100 GeV WIMP (decoupling at 30 MeV)

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

Central cores

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

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

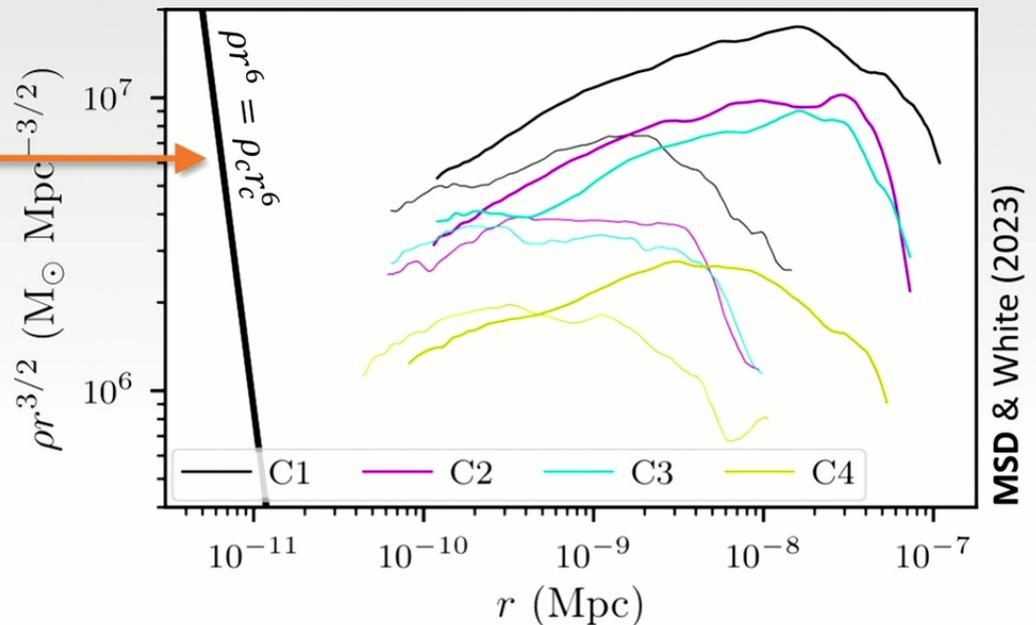Core radius r_c and density ρ_c

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

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

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

velocity dispersion

MSD & White (2023)

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

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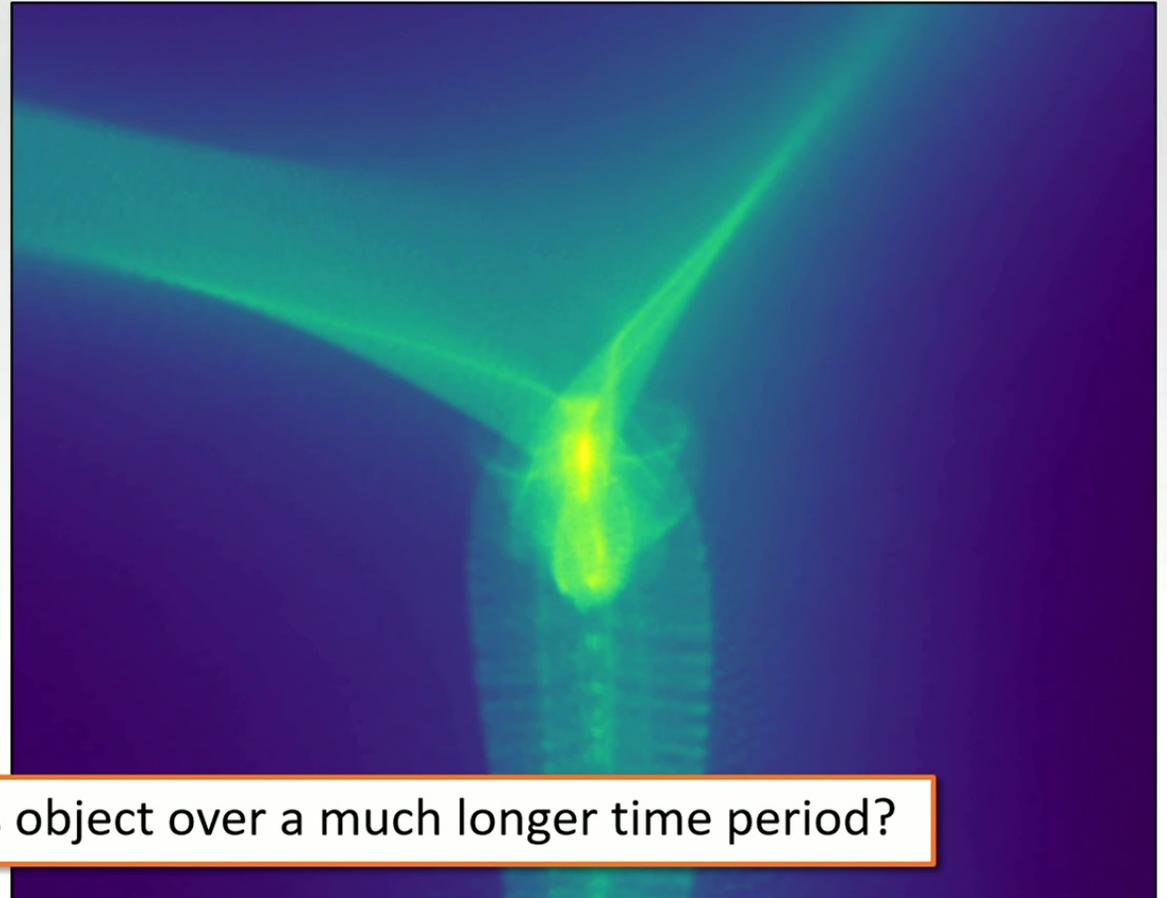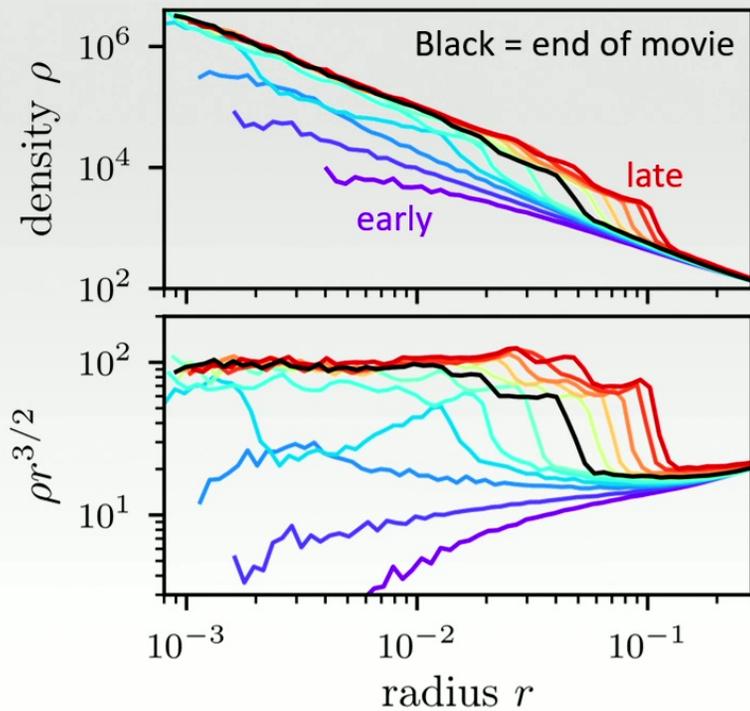
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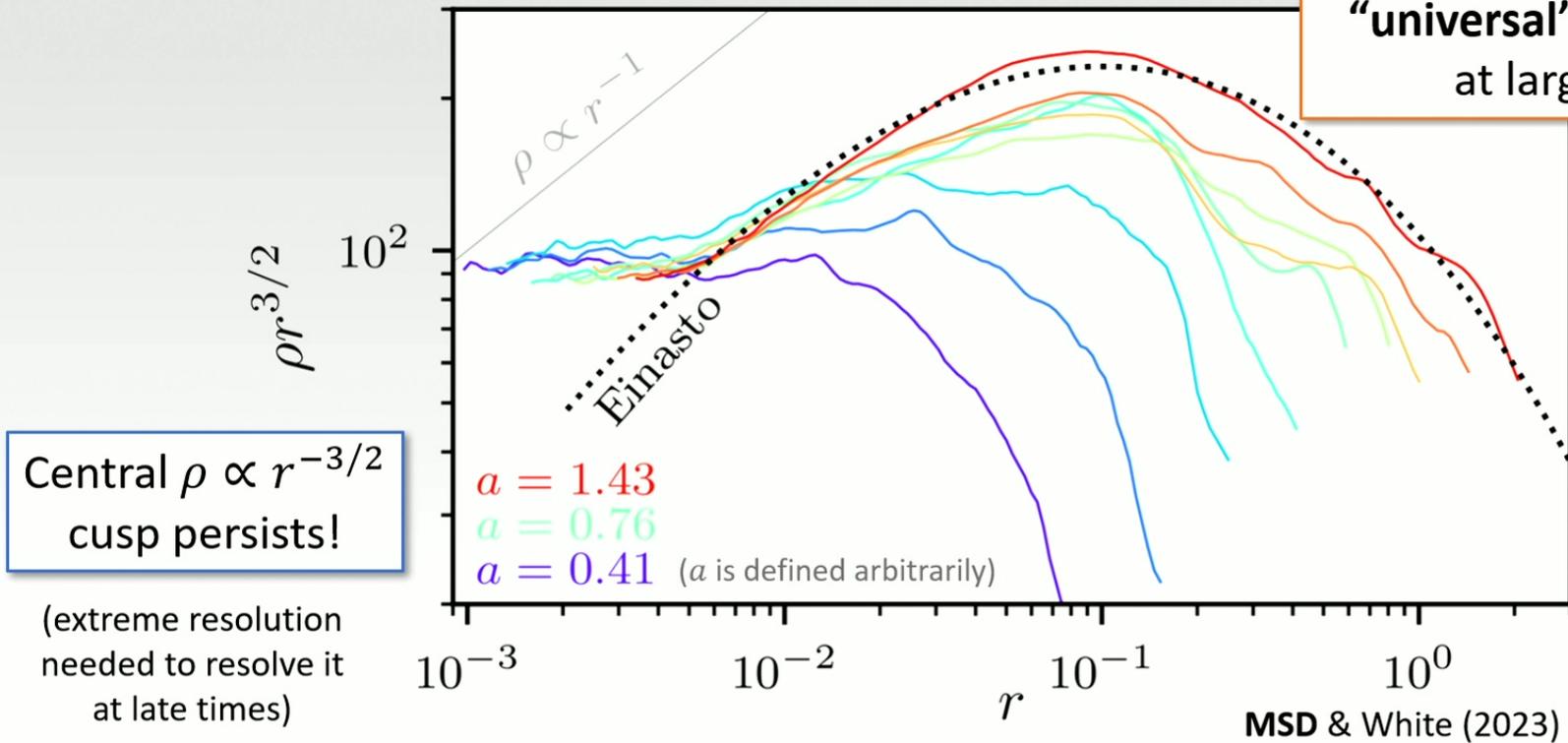
Prompt cusps of warm dark matter

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Do prompt cusps survive halo growth?

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

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Do prompt cusps survive halo growth?

Buildup of material makes **"universal" halo profile** at larger radii

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

(extreme resolution needed to resolve it at late times)

$\rho \propto r^{-1}$

Einasto

$a = 1.43$
$a = 0.76$
$a = 0.41$ (a is defined arbitrarily)

MSD & White (2023)

Outcome: standard DM halo density profile + prompt cusp

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Prompt cusp survival

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

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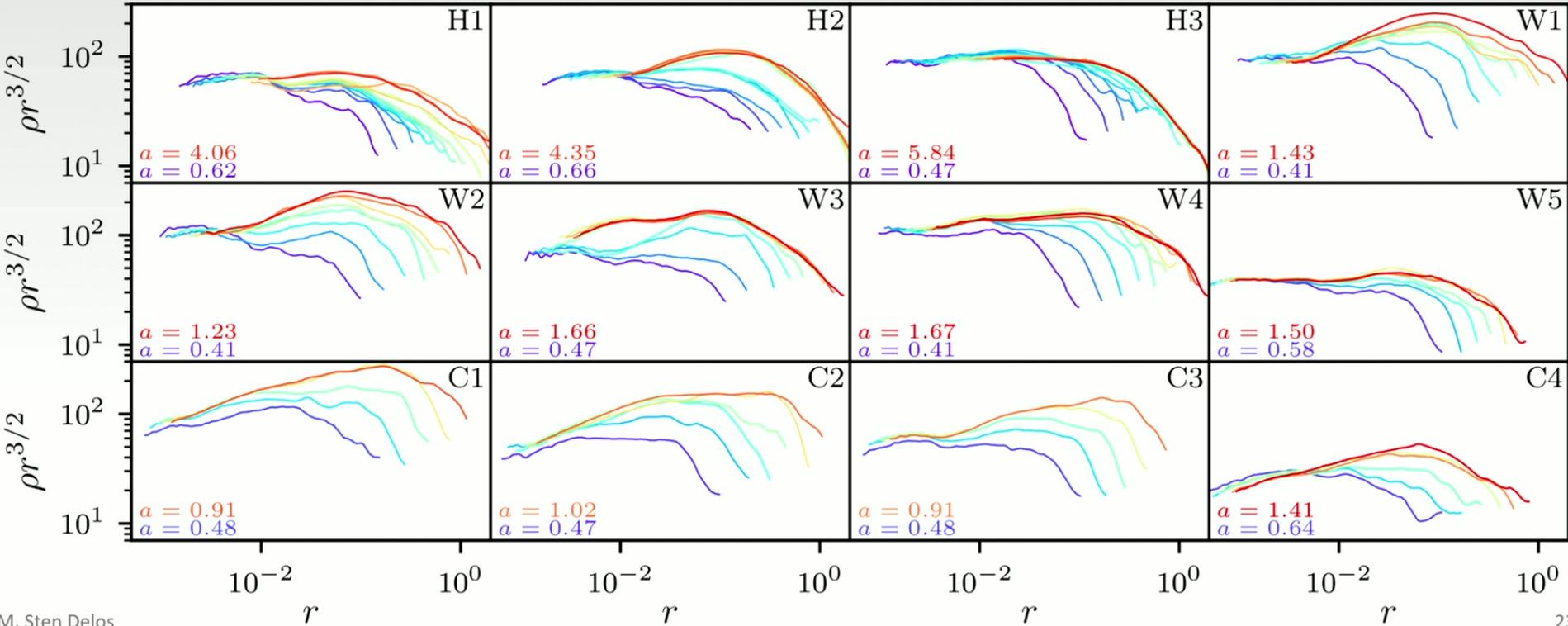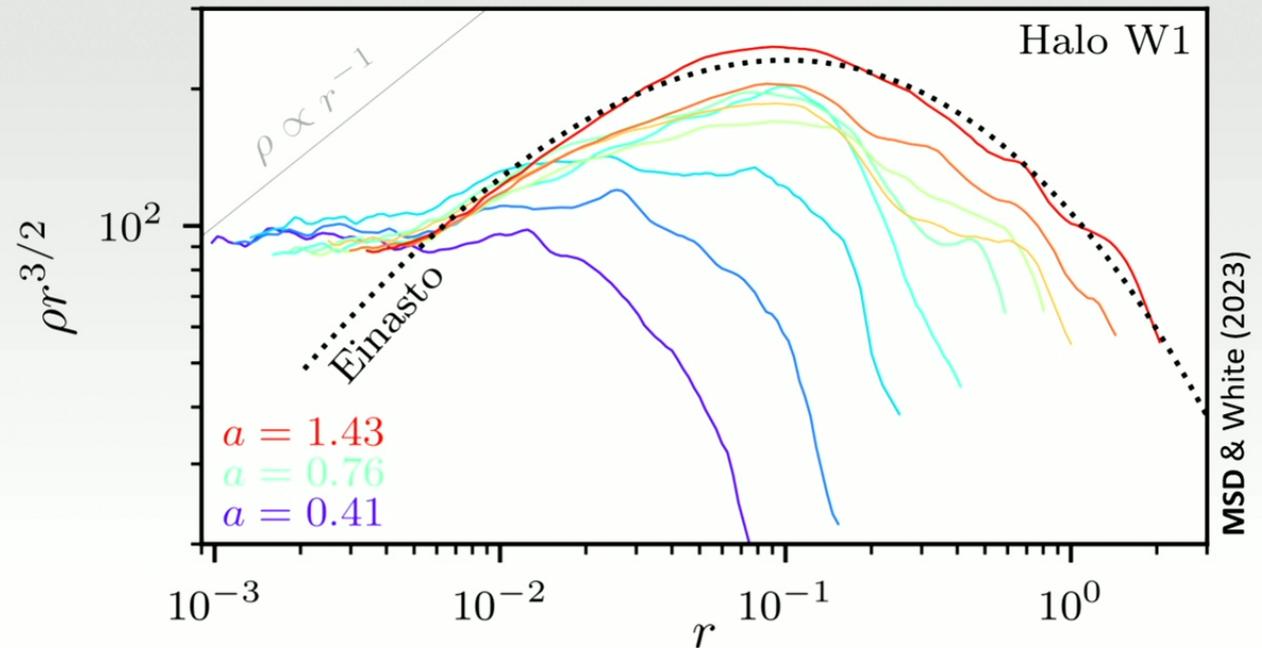
Prompt cusp persistence is natural

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

Halo W1

$\rho \propto r^{-1}$

Einasto

$a = 1.43$
$a = 0.76$
$a = 0.41$

$\rho r^{3/2}$

10^2

10^{-3} 10^{-2} 10^{-1} 10^0

r

MSD & White (2023)

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?

Simulation estimate:
match initial peaks to halos identified in simulation

MSD & White (2022)

initial field

forming halos

surviving halos

$\sigma_0(a) \propto a$ (time)

normalized number

Peaks incorporated into other structures before collapse

Central cusps merge

Cusps not really destroyed; numerical artifact
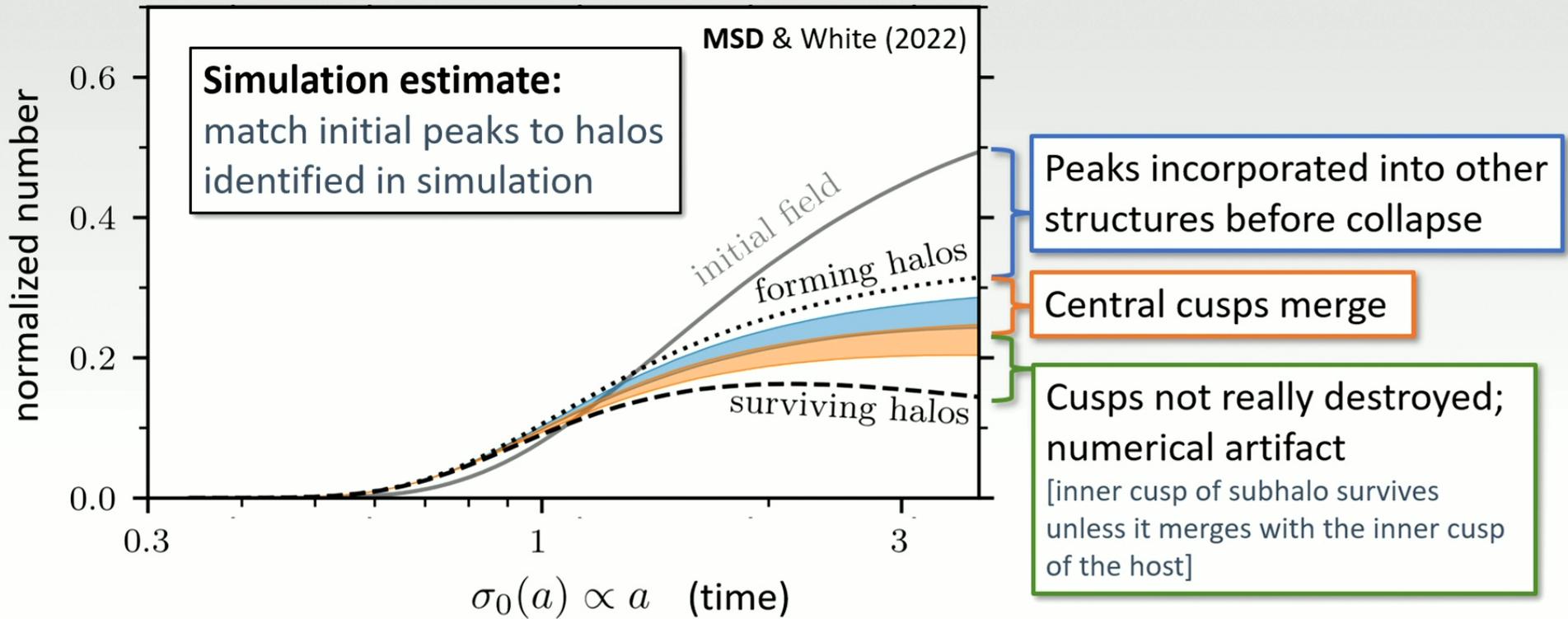[inner cusp of subhalo survives unless it merges with the inner cusp of the host]

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Can all peaks be associated with prompt cusps?

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MSD & White (2022)

initial field

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Peaks incorporated into other structures before collapse

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Cusps not really destroyed; numerical artifact
[inner cusp of subhalo survives unless it merges with the inner cusp of the host]

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

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Outline

Dark matter halos

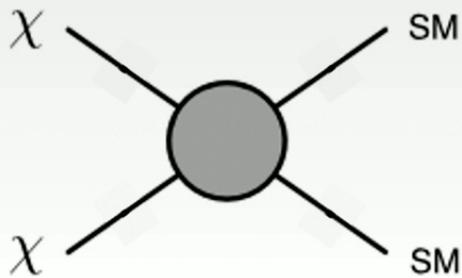The cosmological initial conditions and prompt cusps

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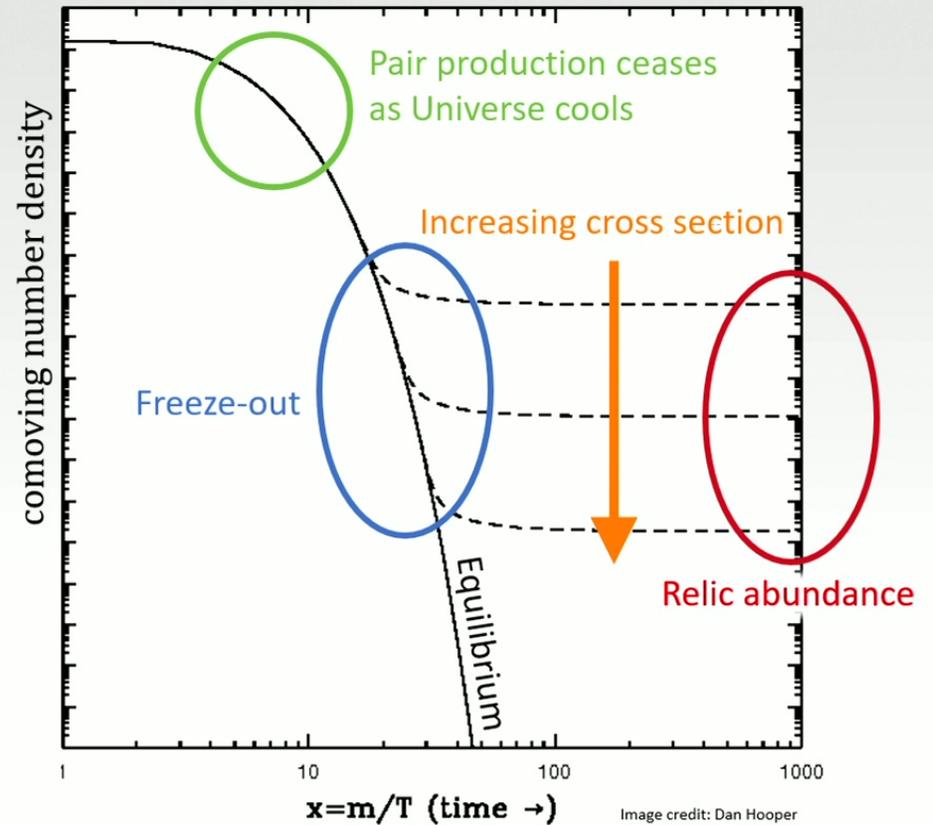
Prompt cusps of warm dark matter

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What is dark matter?

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

χ ———○——— SM
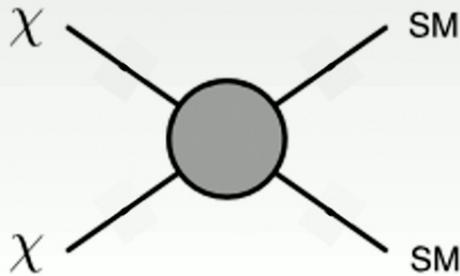
χ ———○——— SM

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

Image credit: Dan Hooper

comoving number density

Pair production ceases
as Universe cools

Increasing cross section

Freeze-out

Equilibrium

Relic abundance

$x=m/T$ (time →)

1   10   100   1000

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Indirect detection

Then dark matter can annihilate
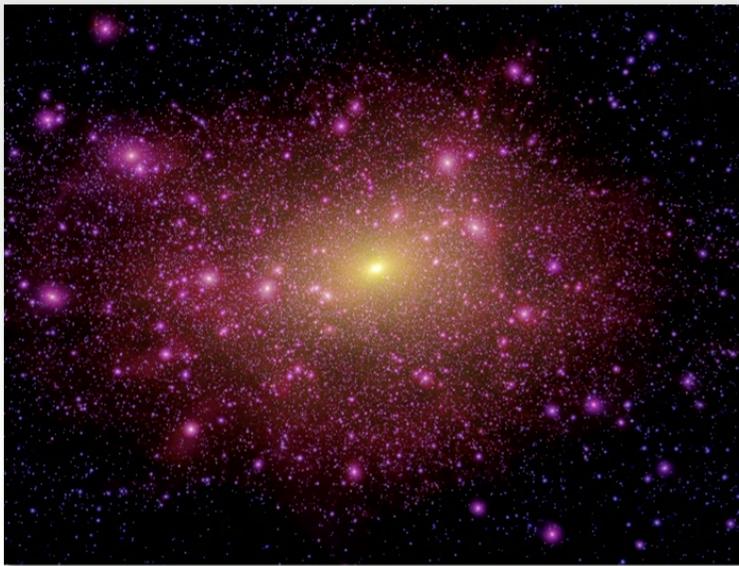into detectable SM particles today!

Annihilation rate $\propto \rho^2$:
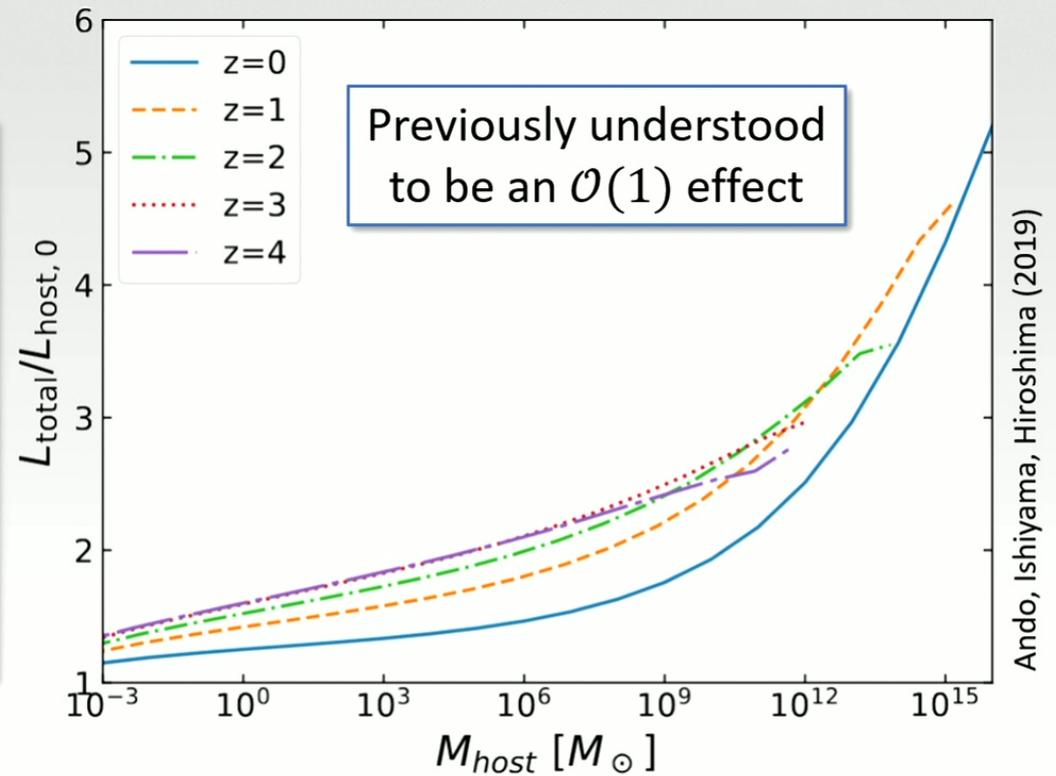**Search the dense centers of galaxies**

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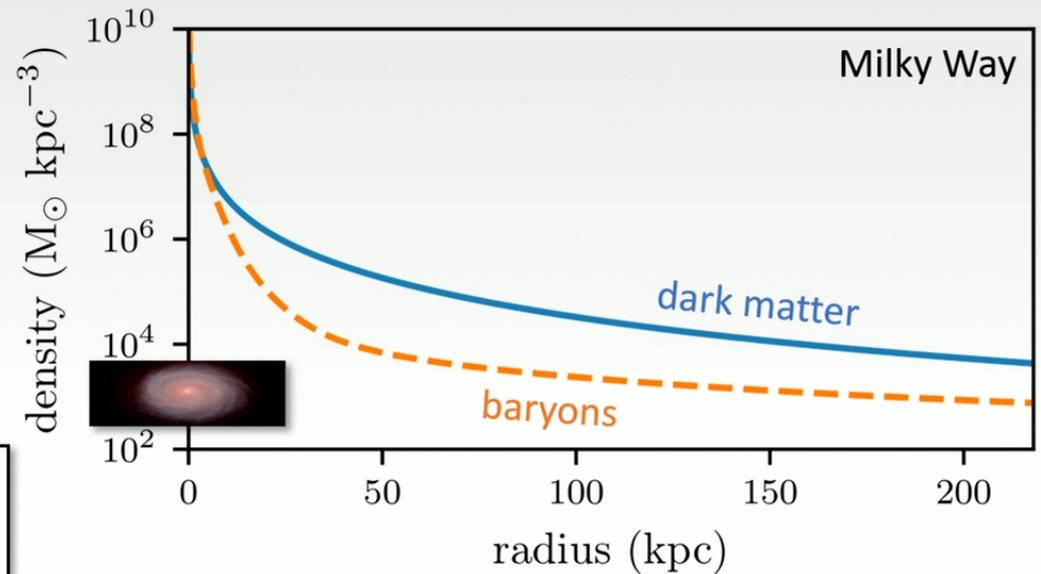
Substructure boost

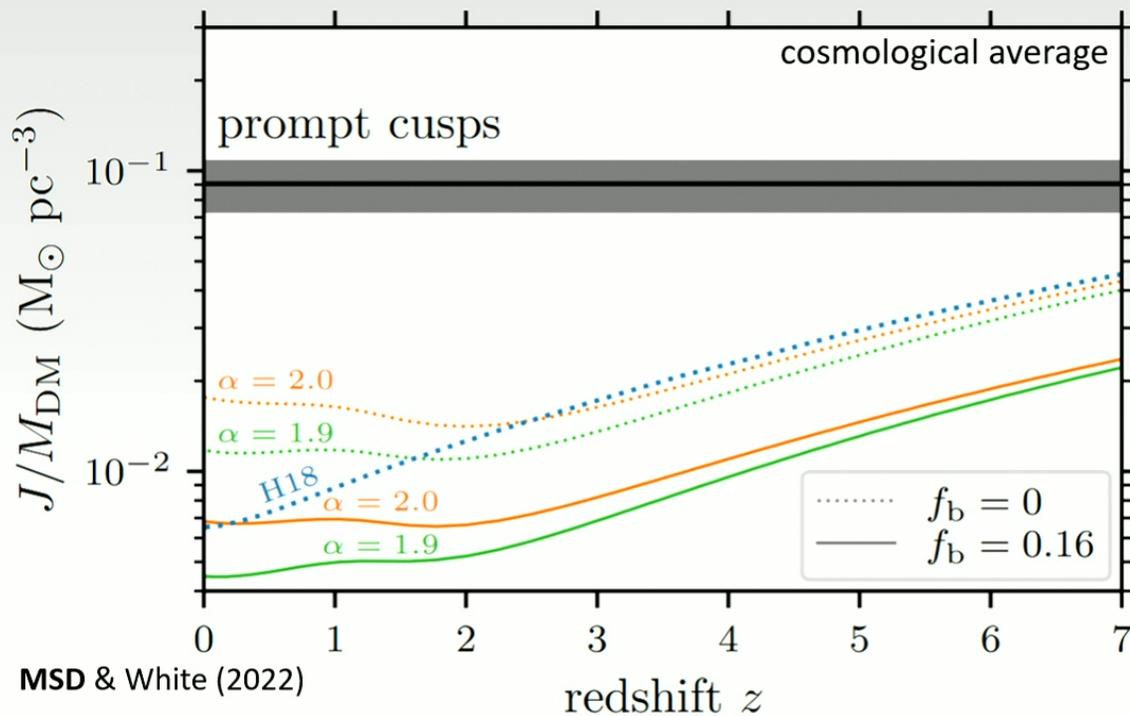The annihilation rate inside a halo is boosted by the presence of subhalos

(due to ρ^2 scaling)

Previously understood to be an $\mathcal{O}(1)$ effect

Ando, Ishiyama, Hiroshima (2019)

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Annihilation in prompt cusps

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

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

Directly from statistics of peaks & peak-cusp connection

Previous predictions:

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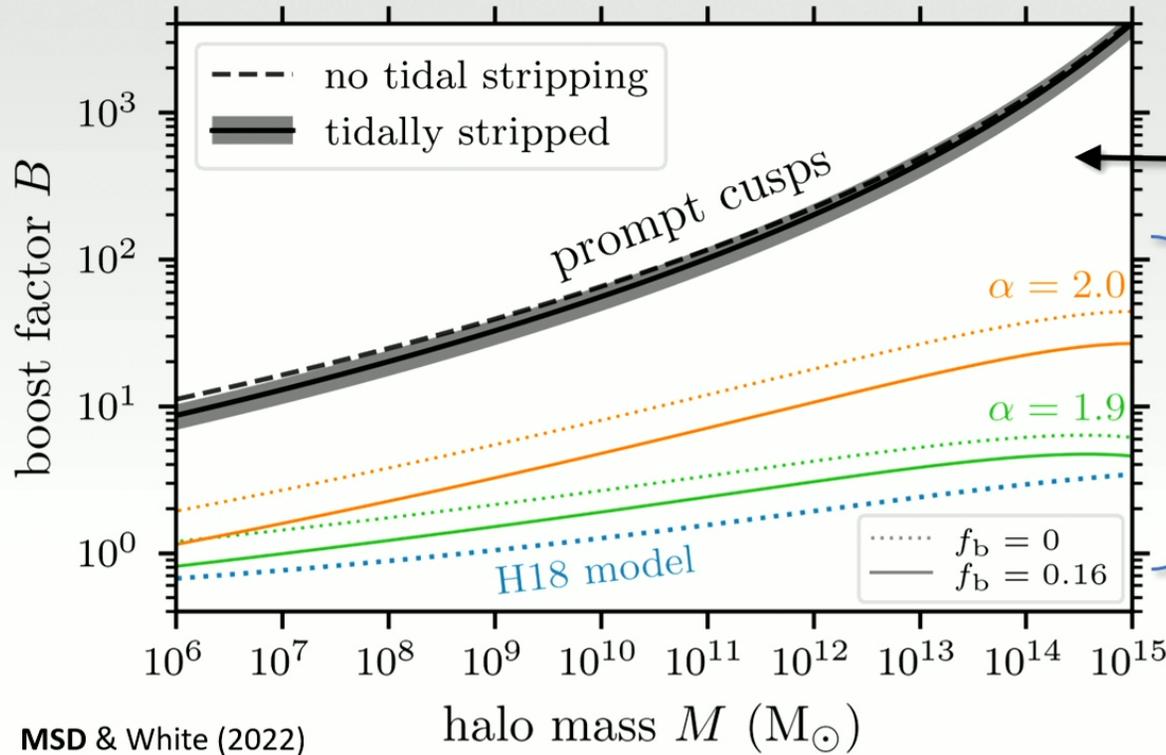- Semianalytic modeling (neglected baryons!)

MSD & White (2022)

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Annihilation in prompt cusps

Annihilation boost inside larger halos:

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

Directly from statistics of peaks & peak-cusp connection

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MSD & White (2022)

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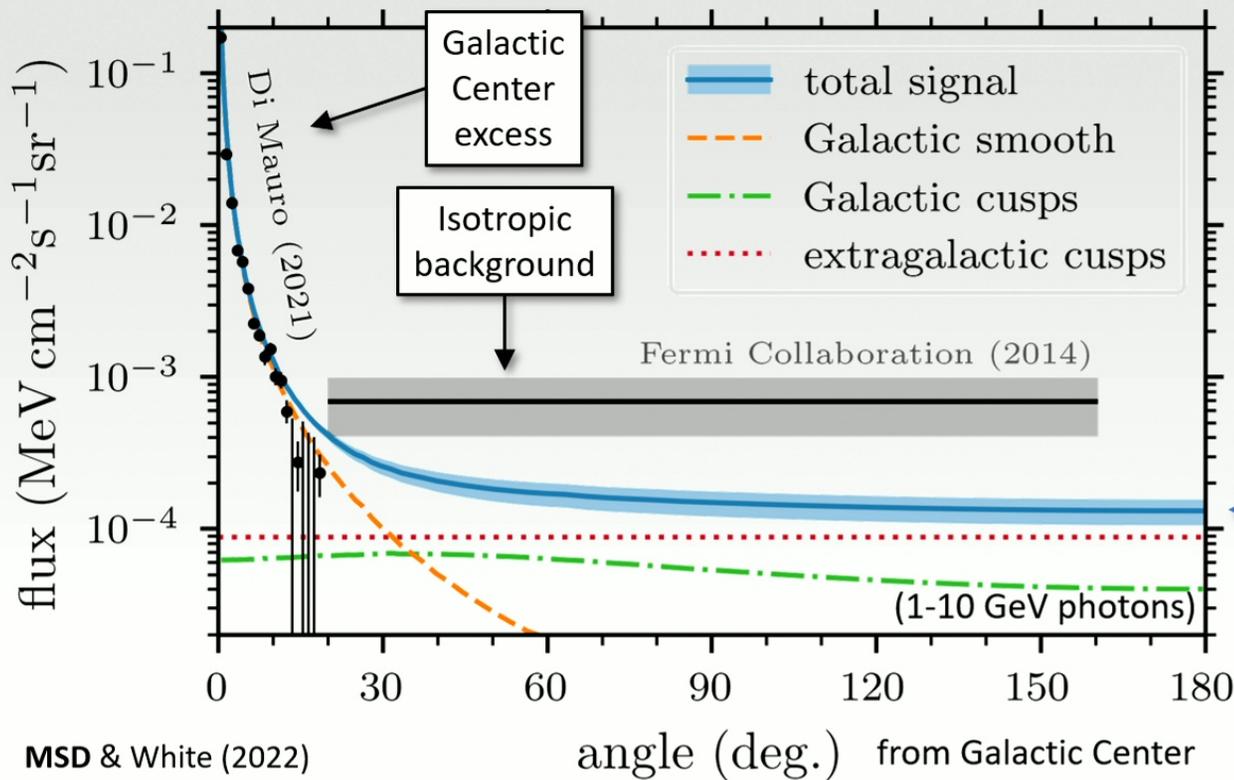
No annihilation boost in the centers of galactic halos (cusps disrupted & density already high), but annihilation everywhere else is greatly boosted.

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
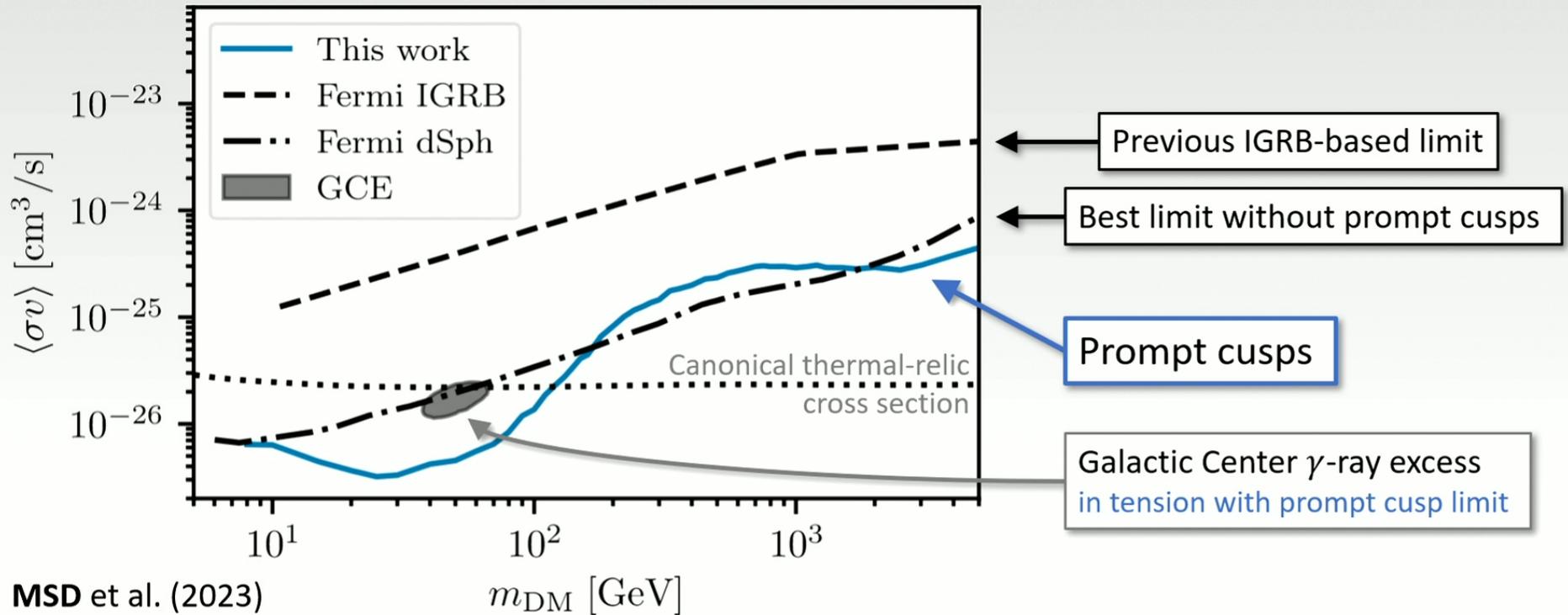
MSD et al. (2023)

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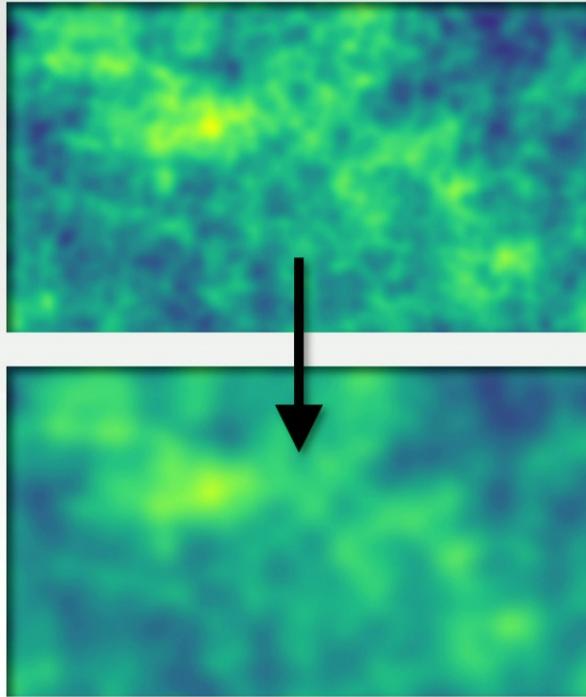
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Warm dark matter

Random particle motion smooths initial conditions
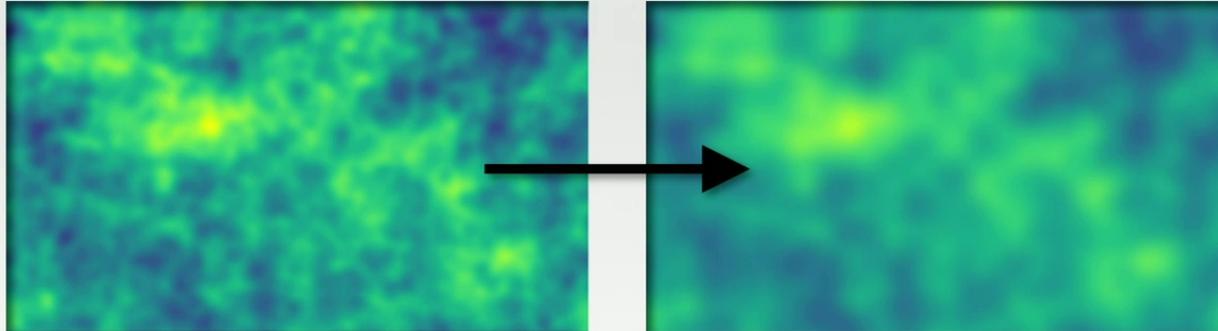
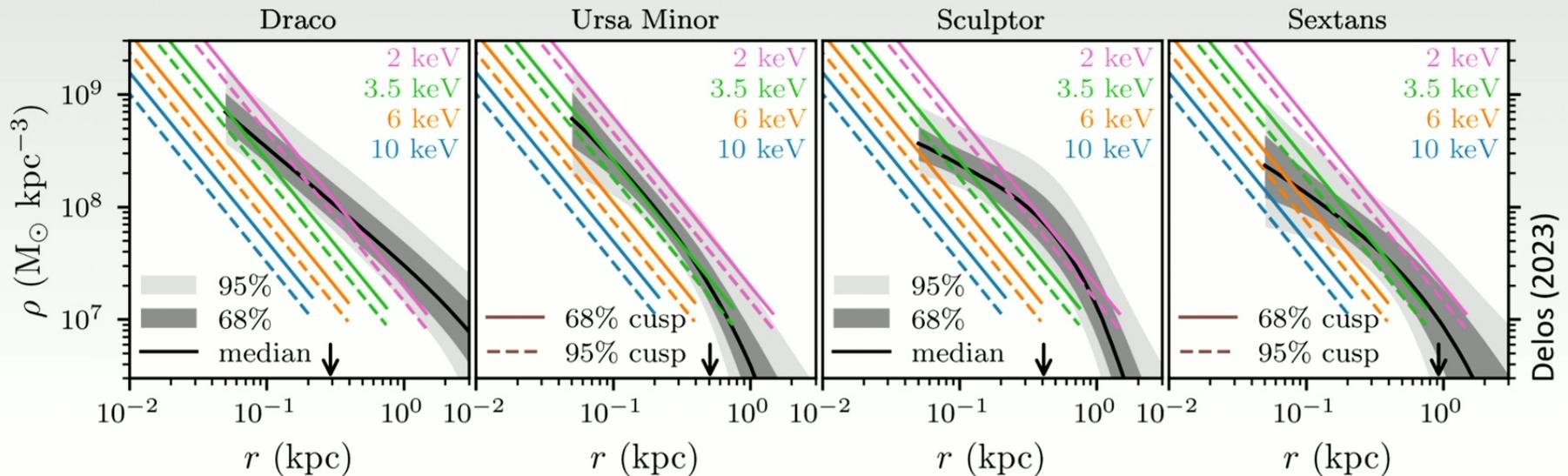which suppresses the abundance of low-mass halos:

cold dark matter

warm dark matter

Lovell et al (2014)

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Prompt cusps of warm dark matter

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

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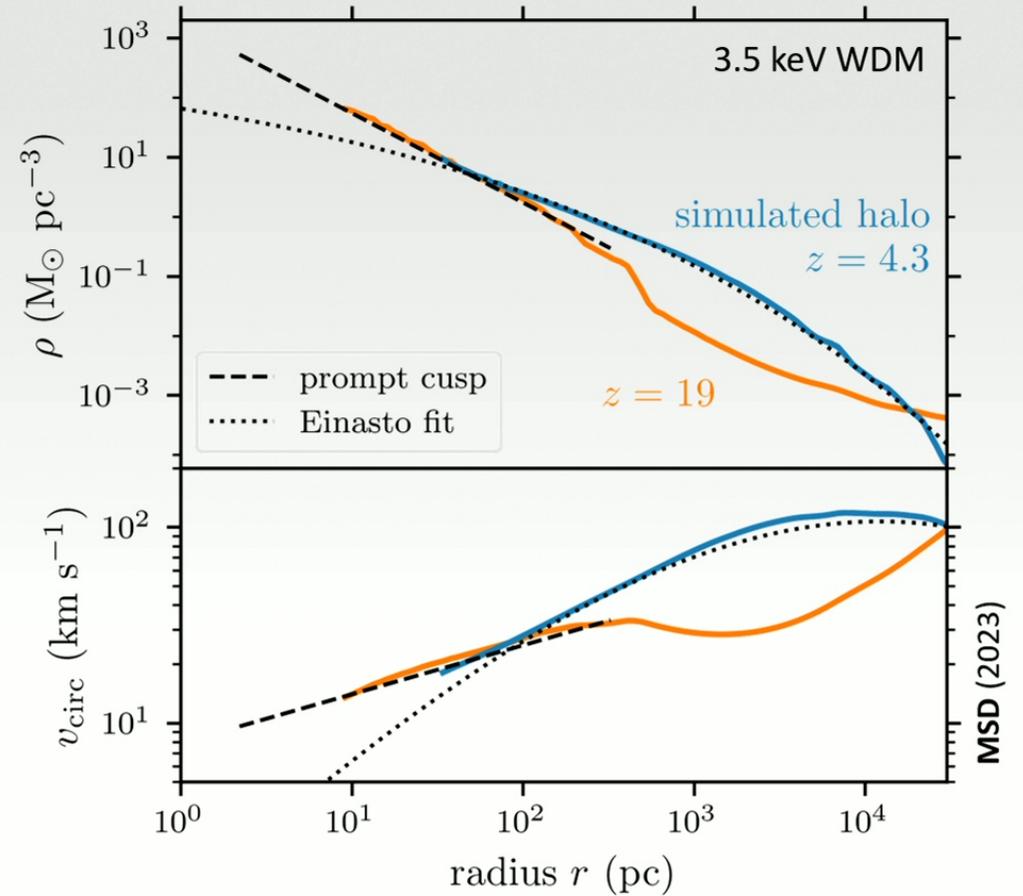
Searching for WDM prompt cusps

We can search for prompt cusps within nearby dwarf galaxies:

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

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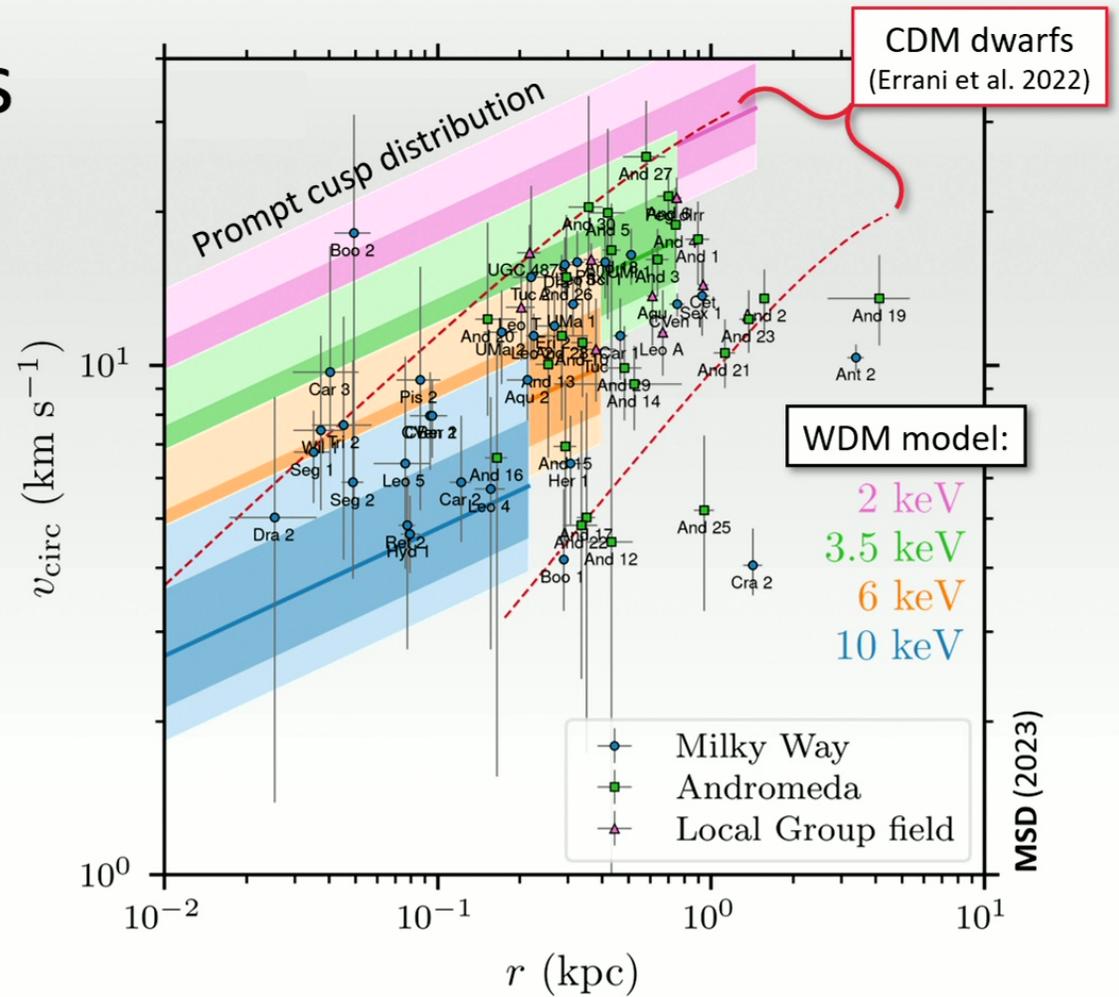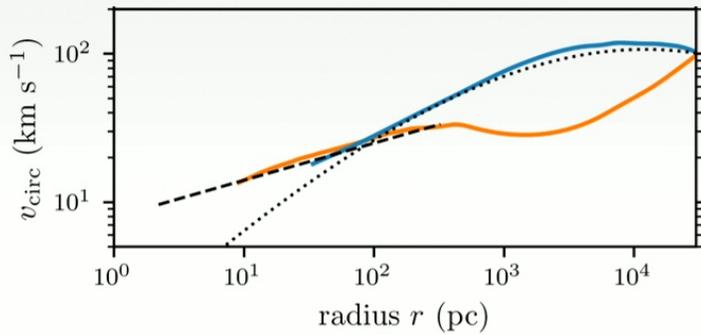
Comparison to kinematics of
Local Group dwarf galaxies
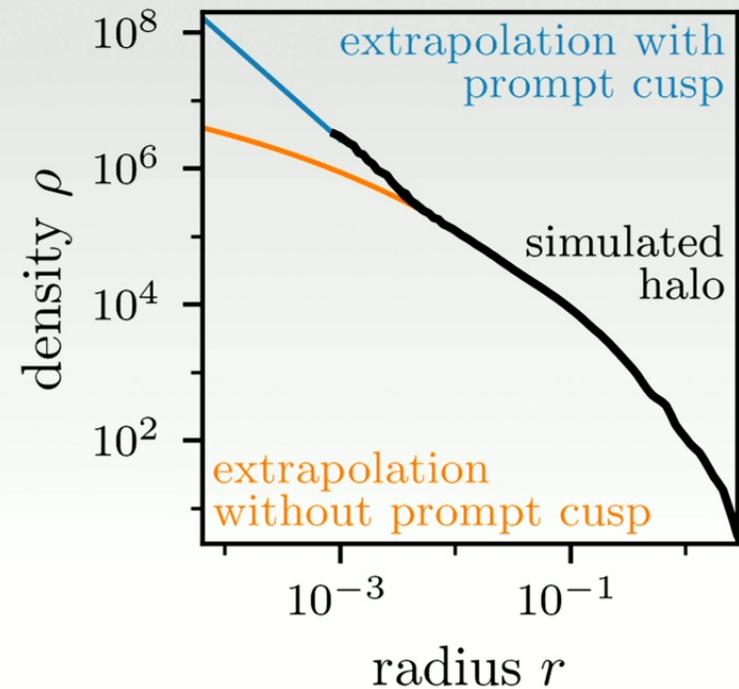[v_{circ} at half-light radius]

- 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.

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Power spectrum

$$k_{\mathrm{fs}} \simeq 1 \text{ pc}$$

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