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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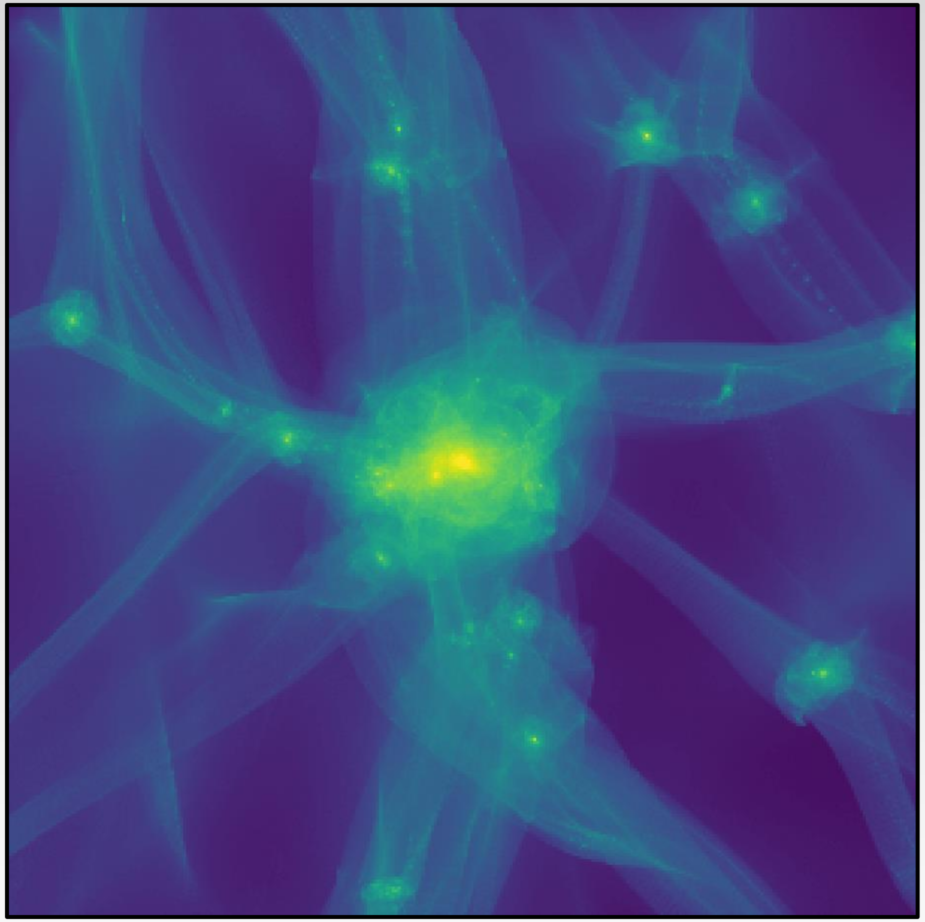
Dark matter halos

- 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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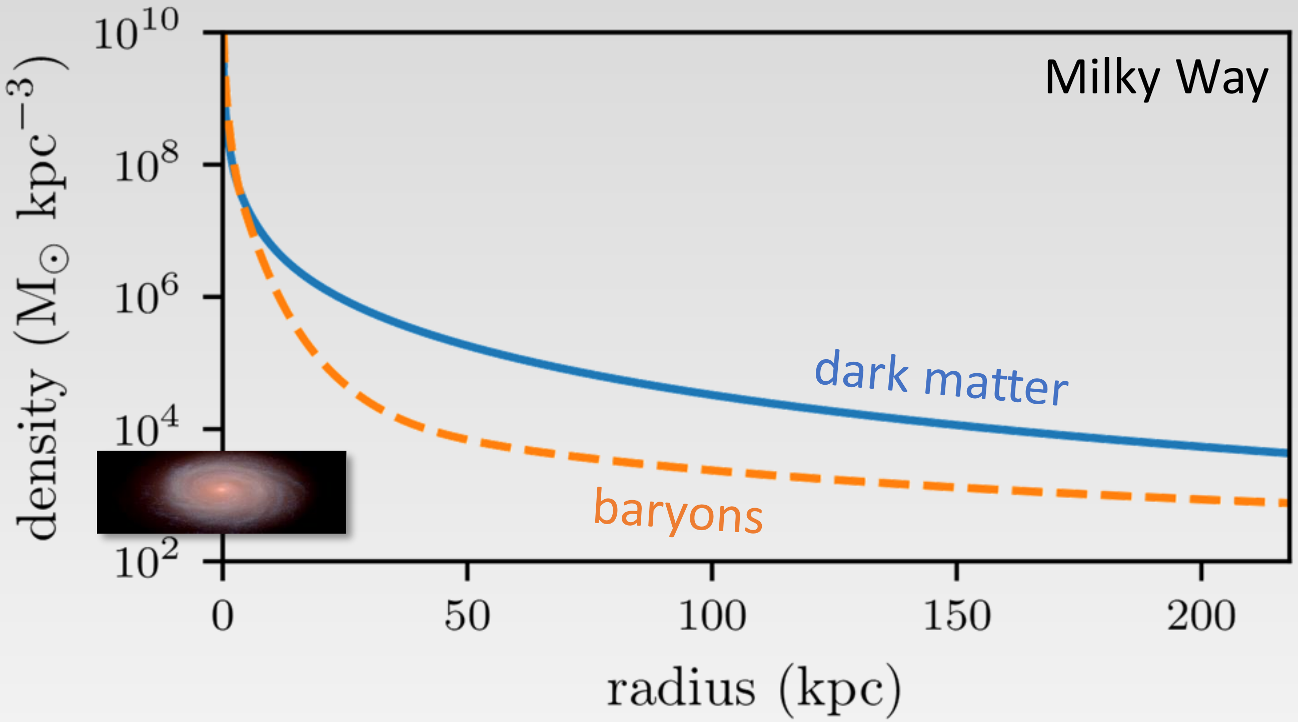
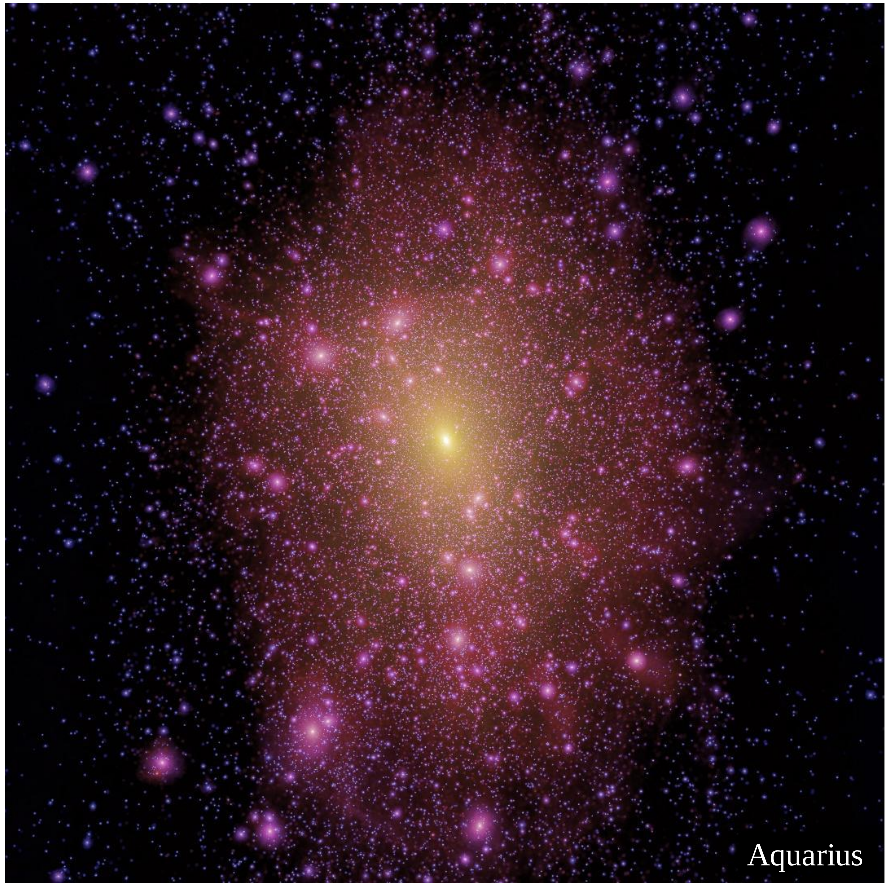


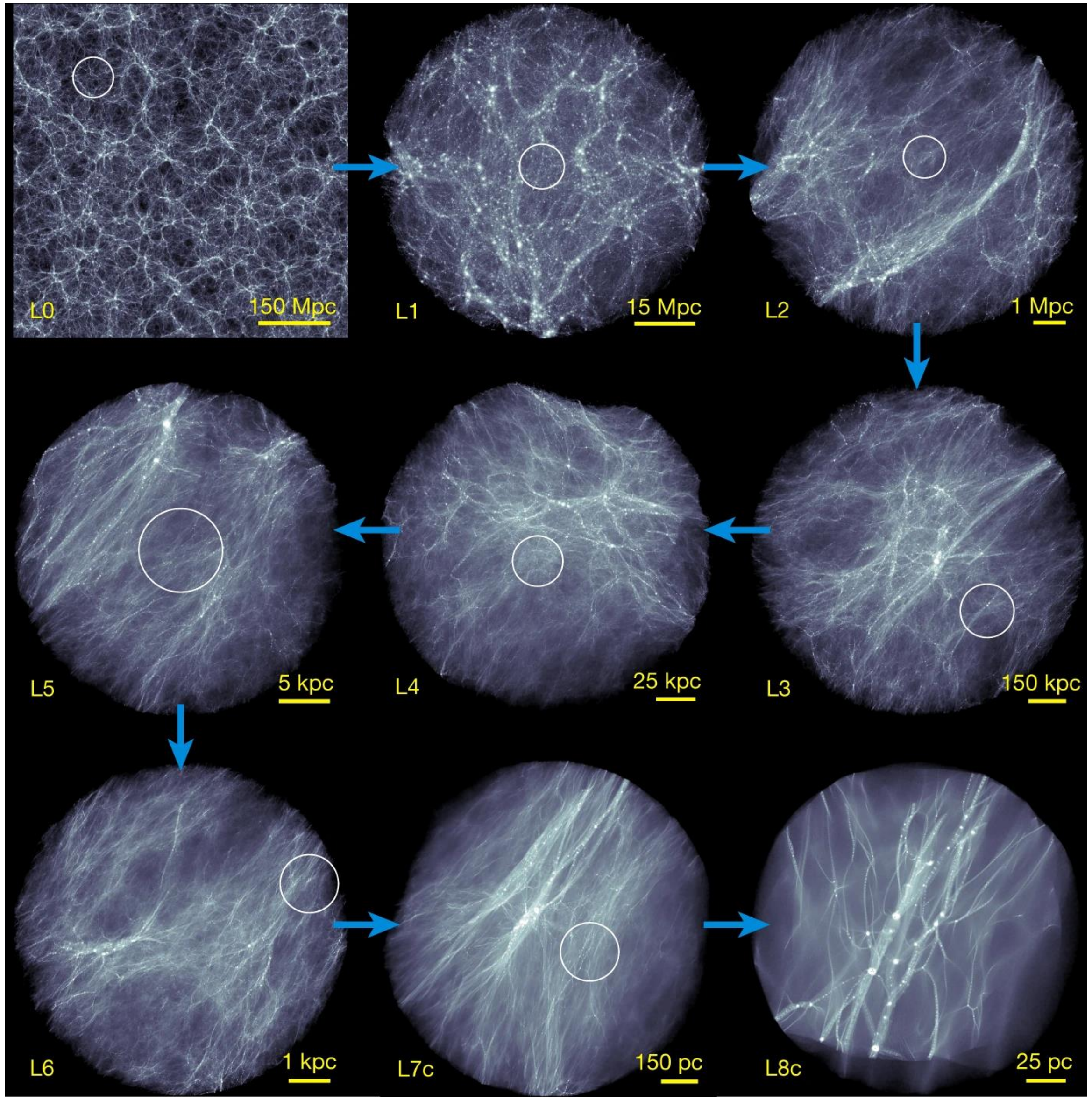
MW mass model: Cautun et al (2020)
picture of simulated MW-like galaxy: Grand et al (2021)

Dark matter halos

Subhalos persist inside other halos:



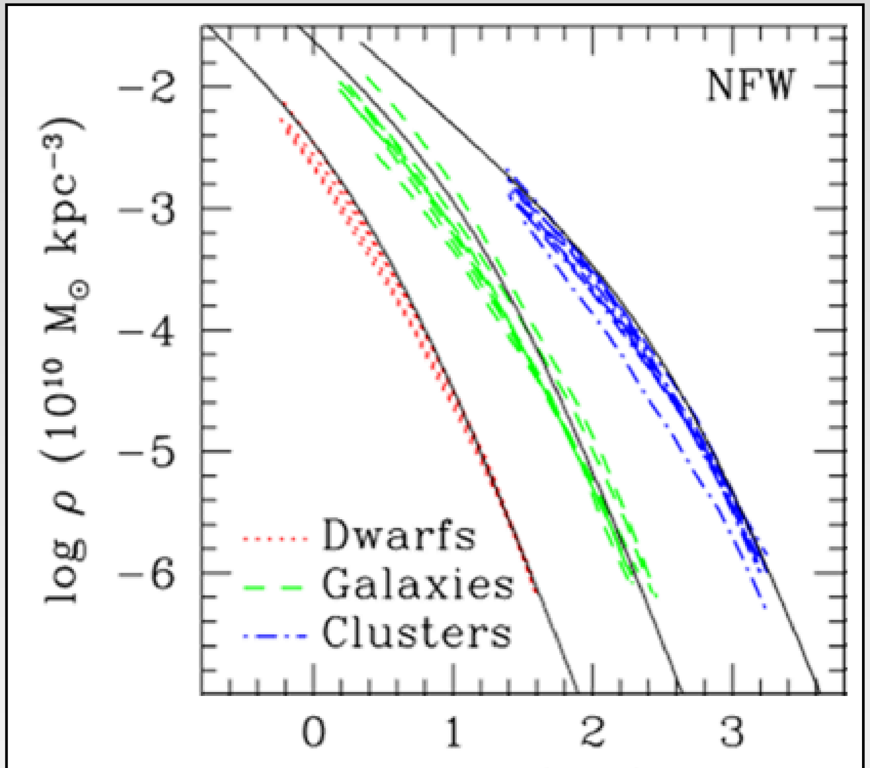
Halos form at all scales:



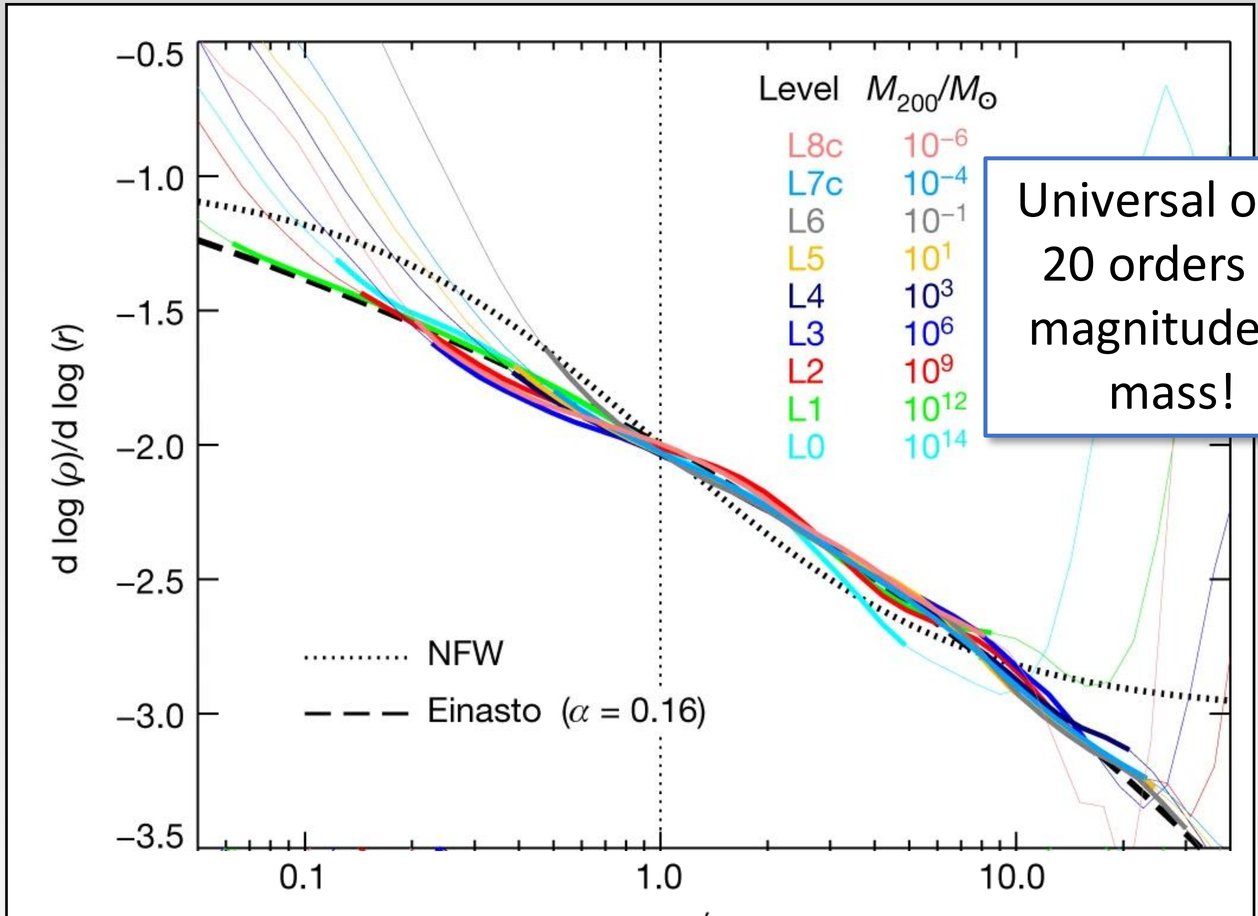
Wang et al (2020)

Halo density profiles

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



Navarro et al (2004)



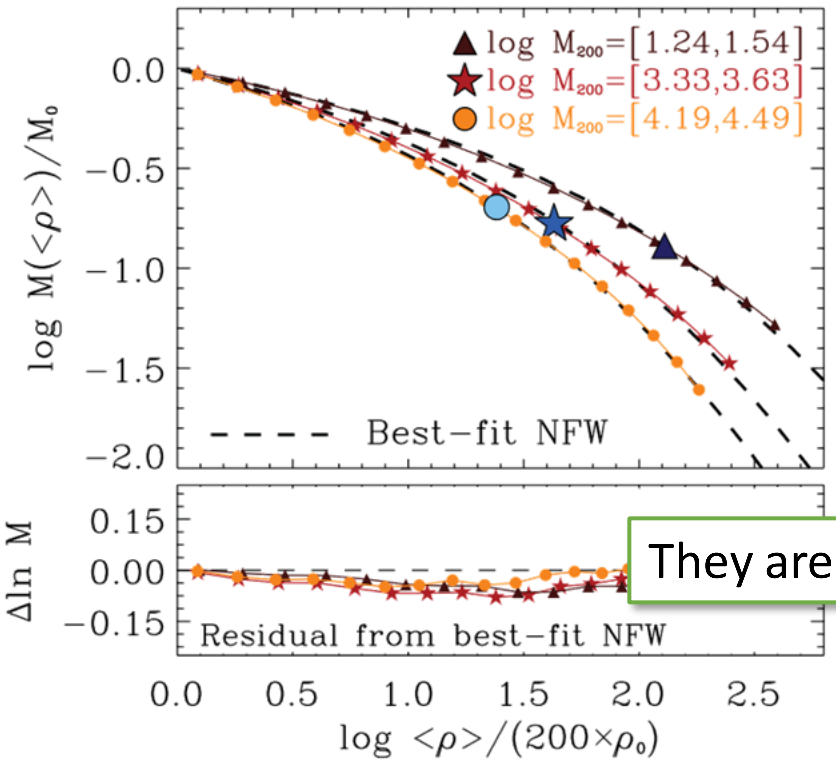
Wang et al (2020)

Universal over 20 orders of magnitude in mass!

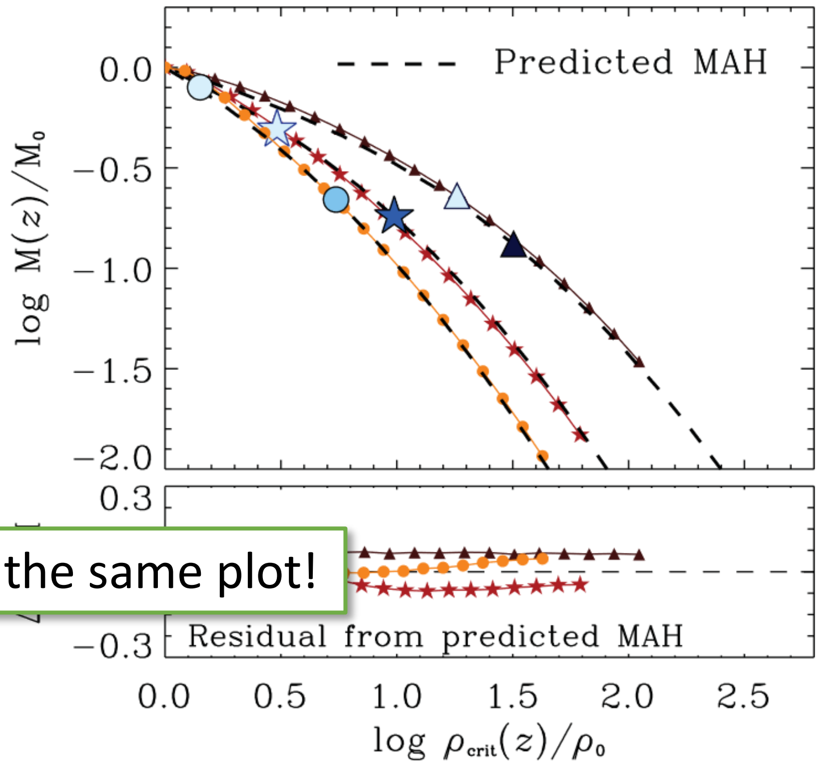
Density profiles from accretion history

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)

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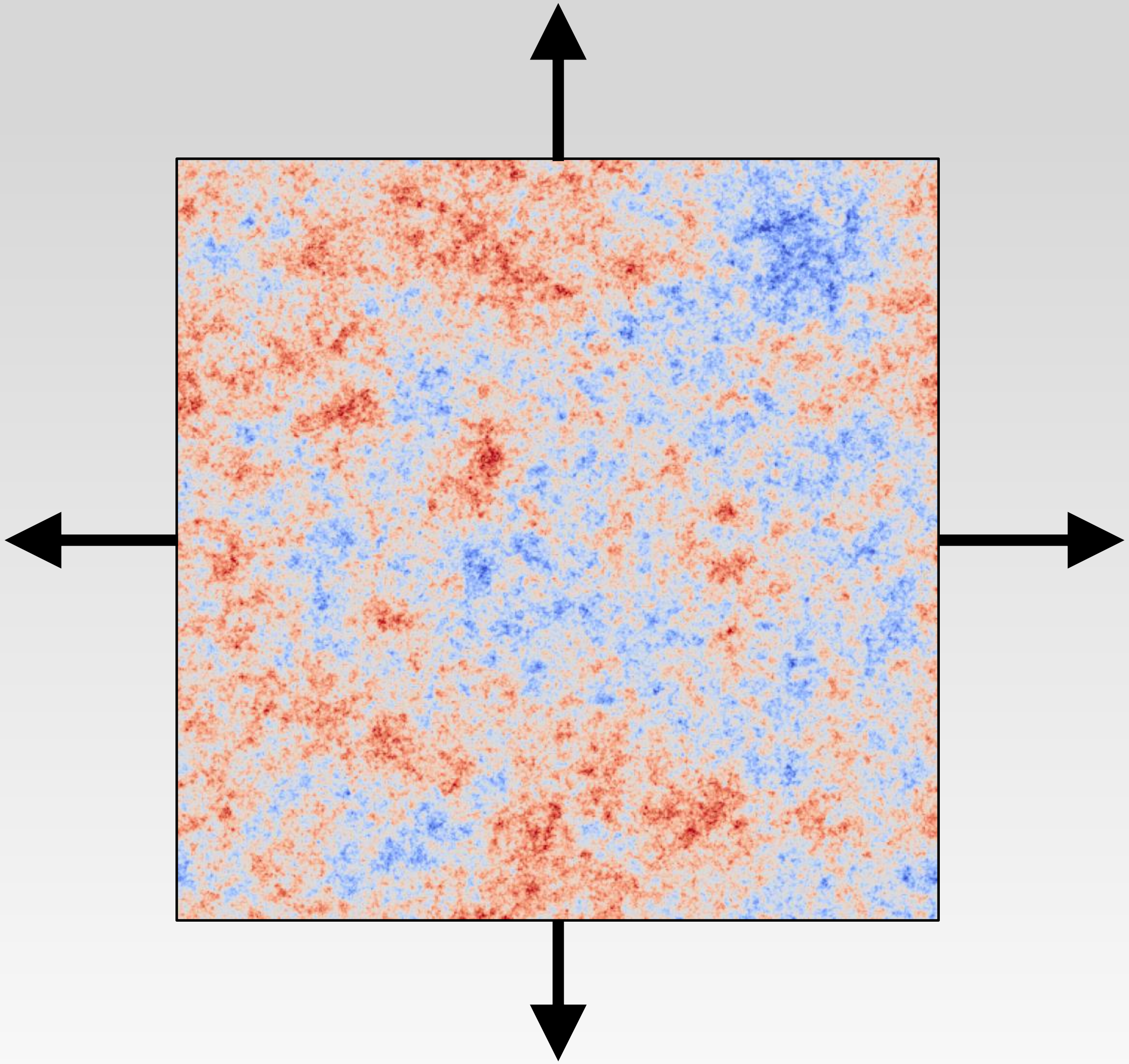
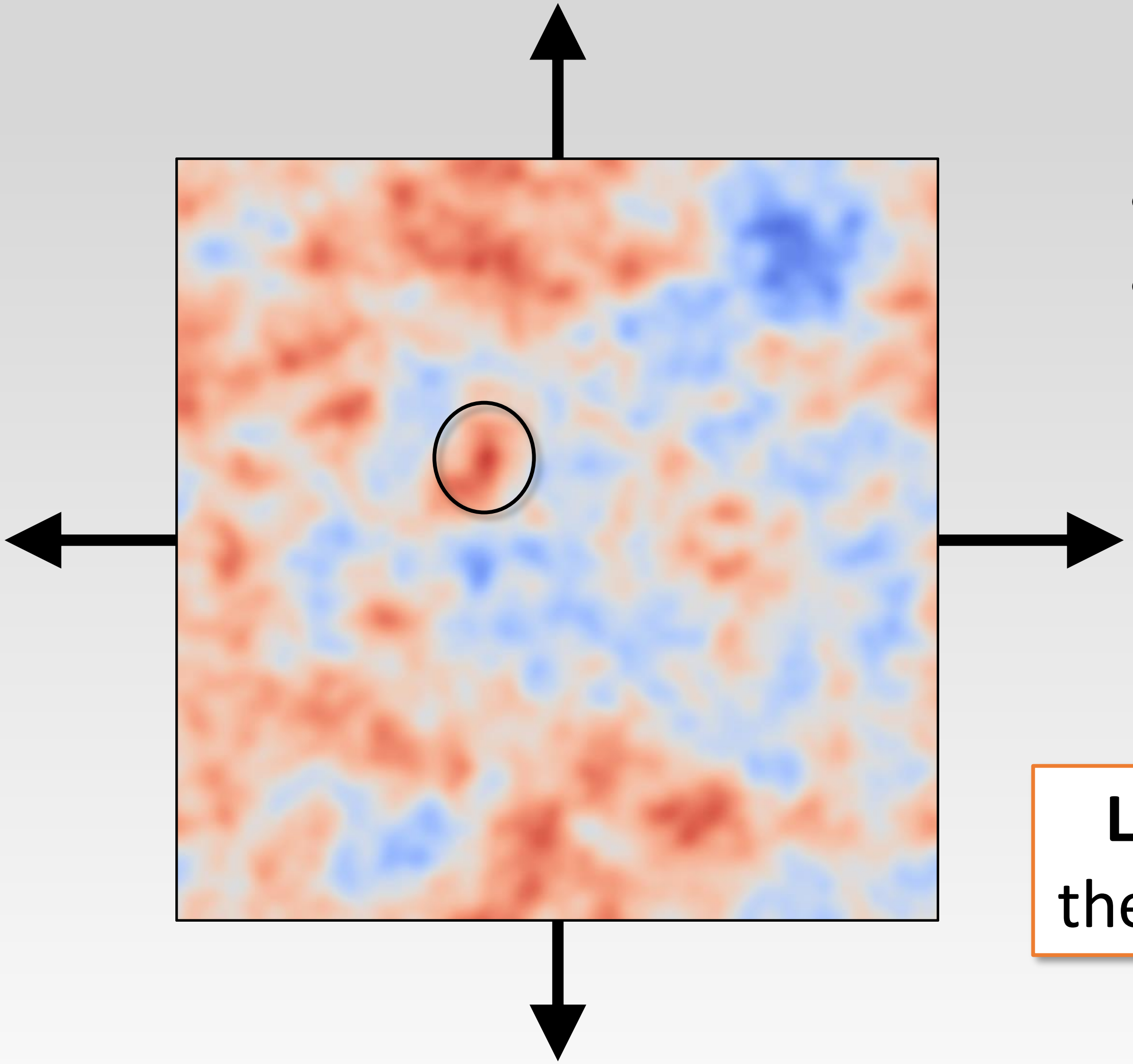
The cosmological initial conditions



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

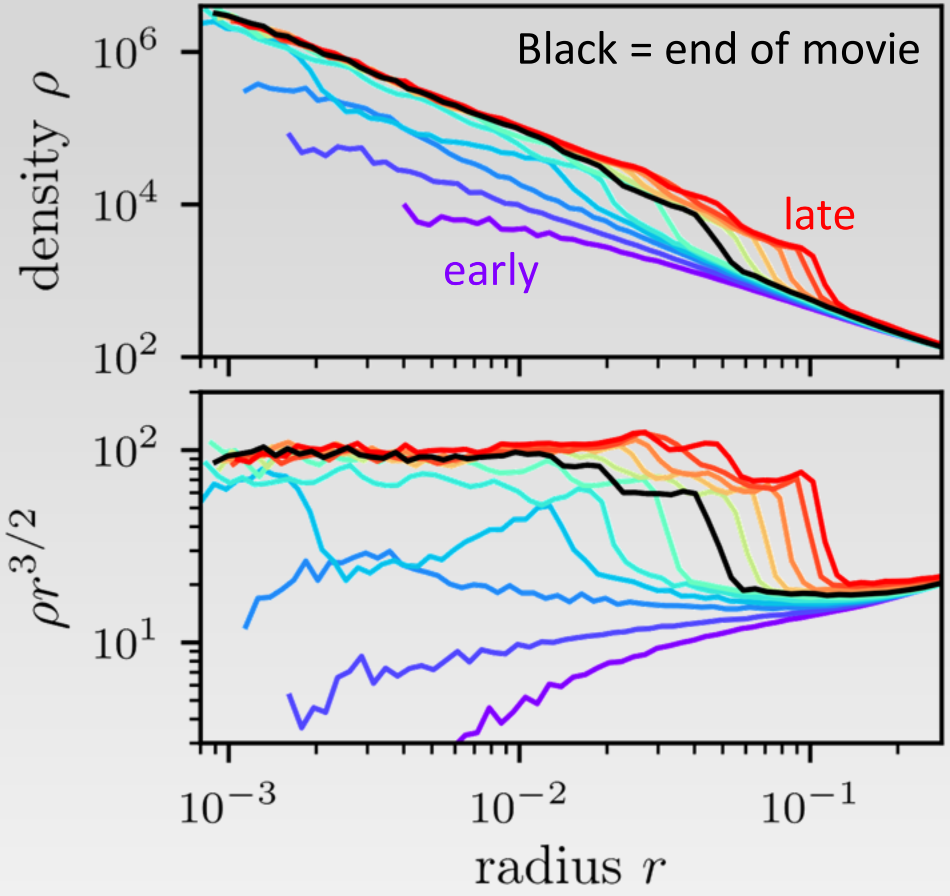
Smooth on sufficiently small scales

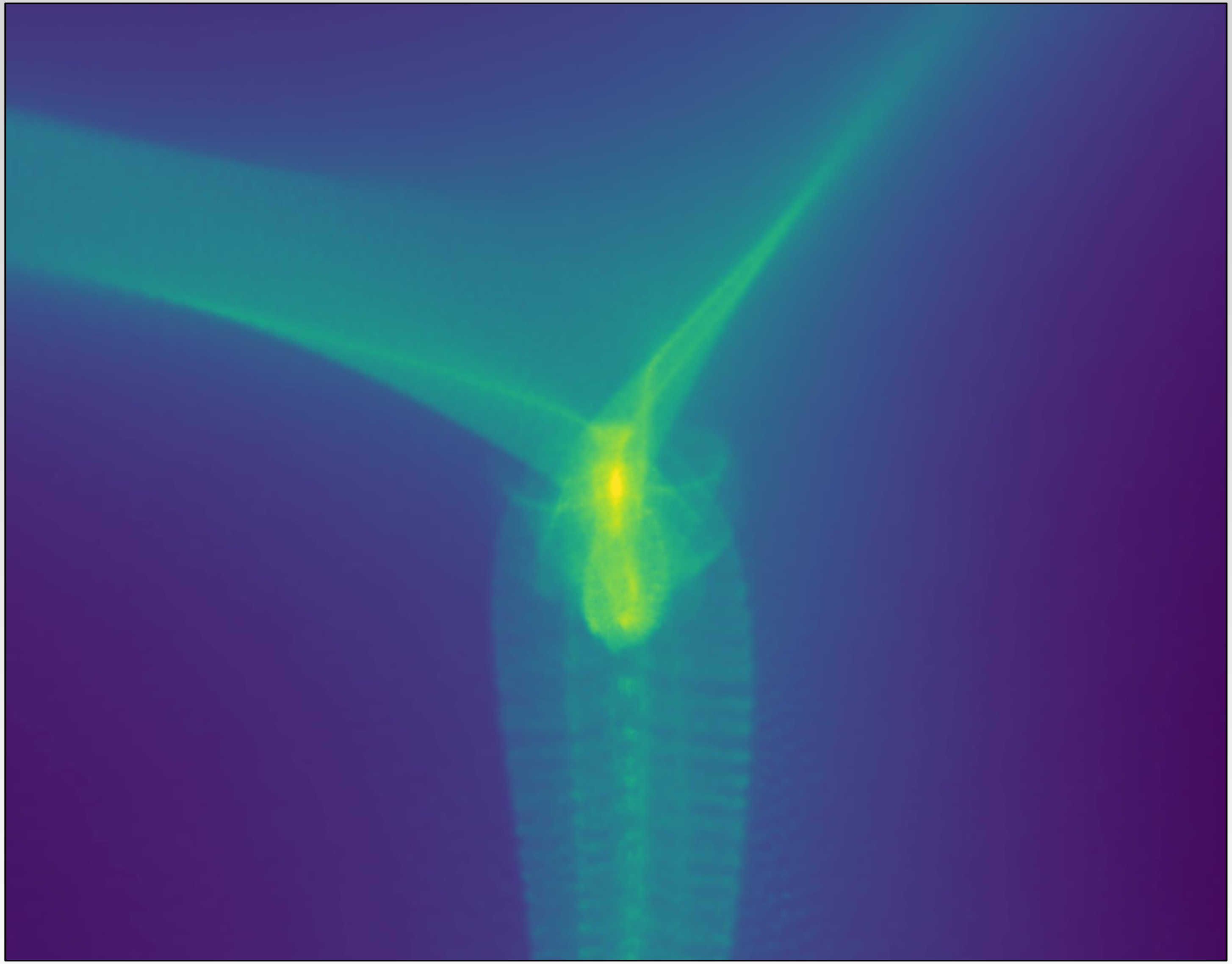
e.g., due to thermal motion of the dark matter

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

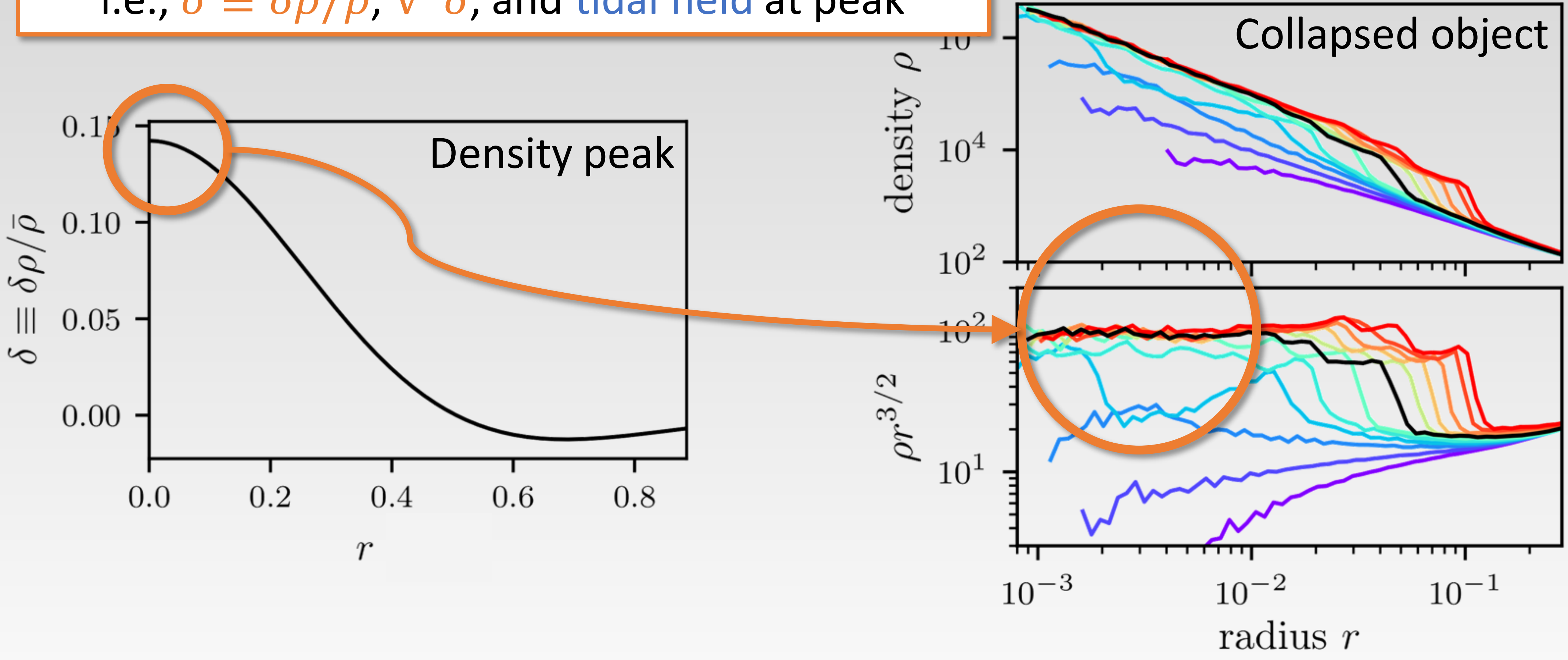
"prompt"

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



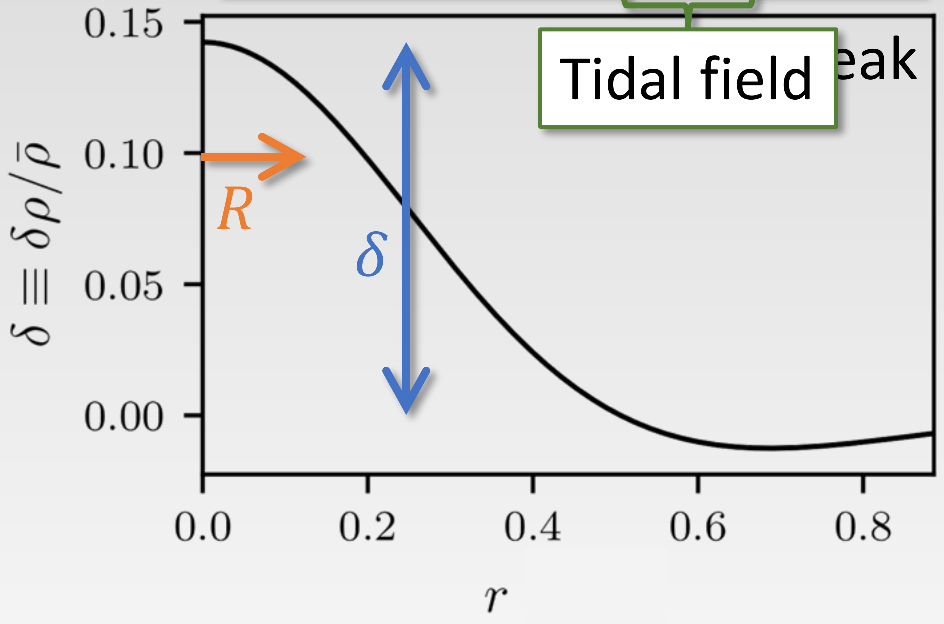
Peak-cusp connection

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

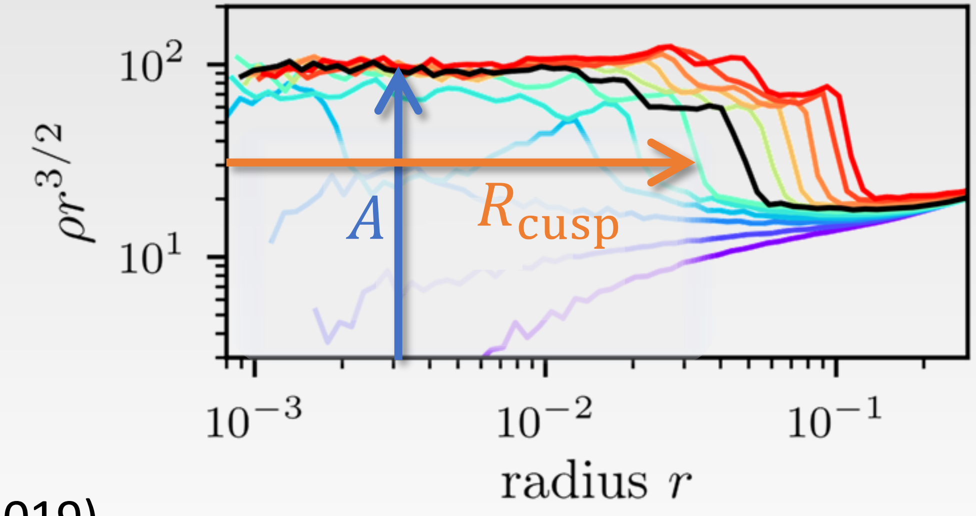


Prompt cusp: $\rho = Ar^{-3/2}$

$$A \simeq 24\,\bar{\rho}(a_c)\,(a_c R)^{3/2}$$

$$M_{\rm cusp} \simeq 7.3\,R^3\,\bar{\rho}_0$$

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

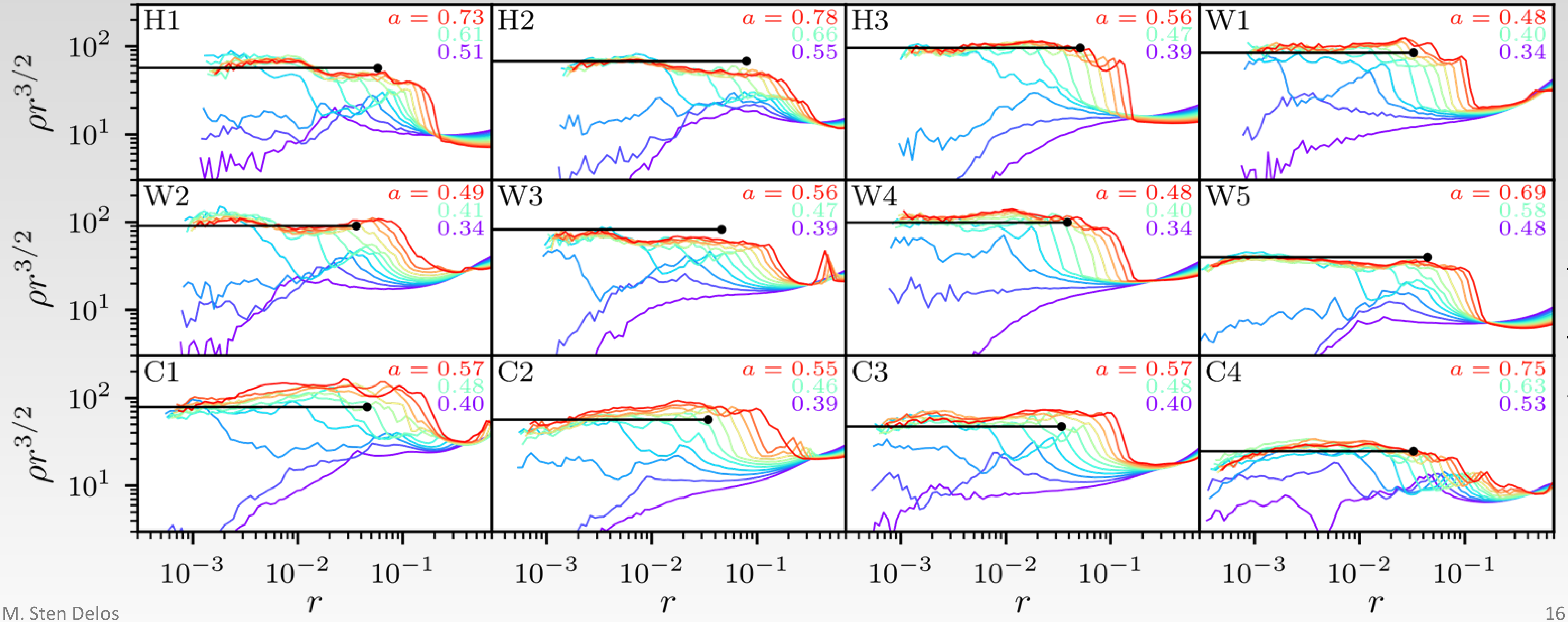


MSD & White (2023); **MSD**, Bruff, Erickcek (2019)

Peak-cusp connection

Twelve high-resolution halos from three power spectra:

Predictions [black] work well!



MSD & White (2023)

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
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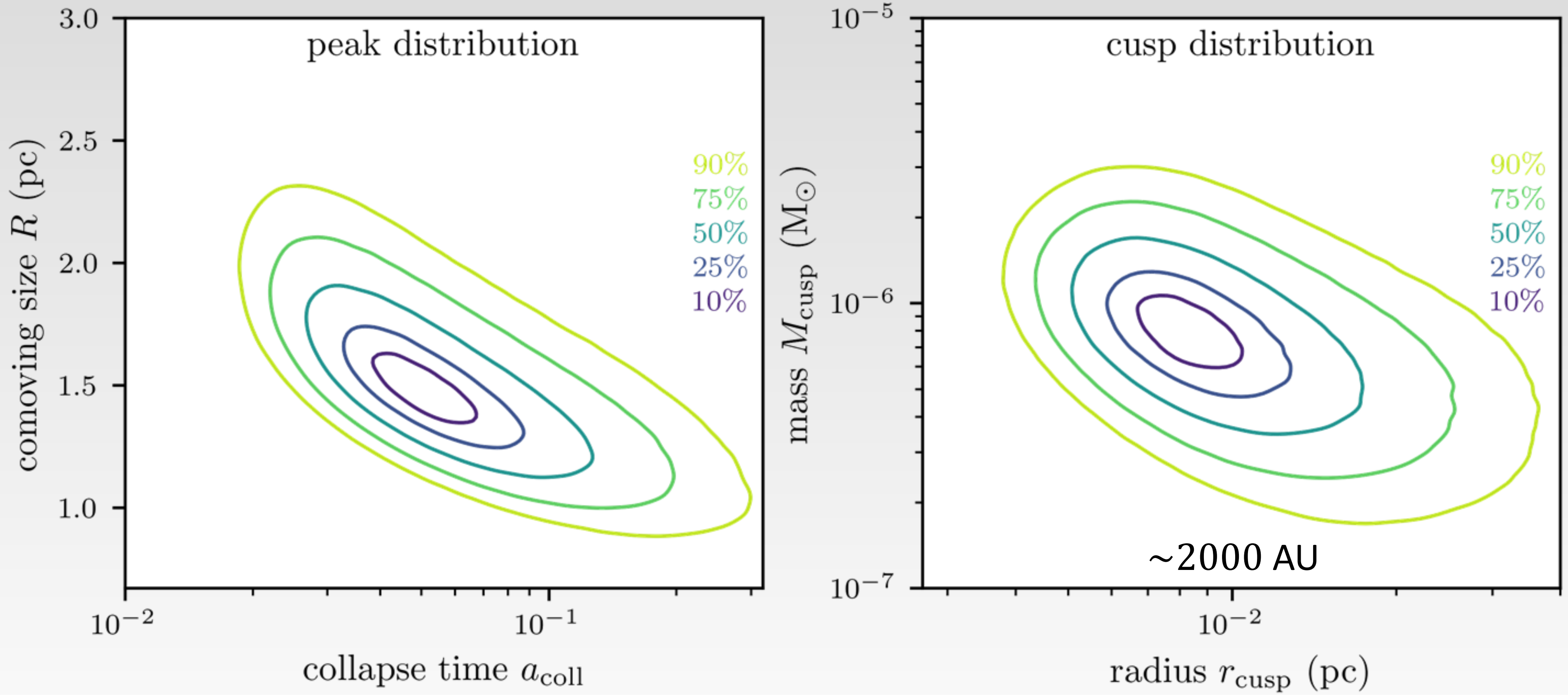
Astrophysics Group, Fermilab
Received 1985 July 25; accepted 1985 October 9

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

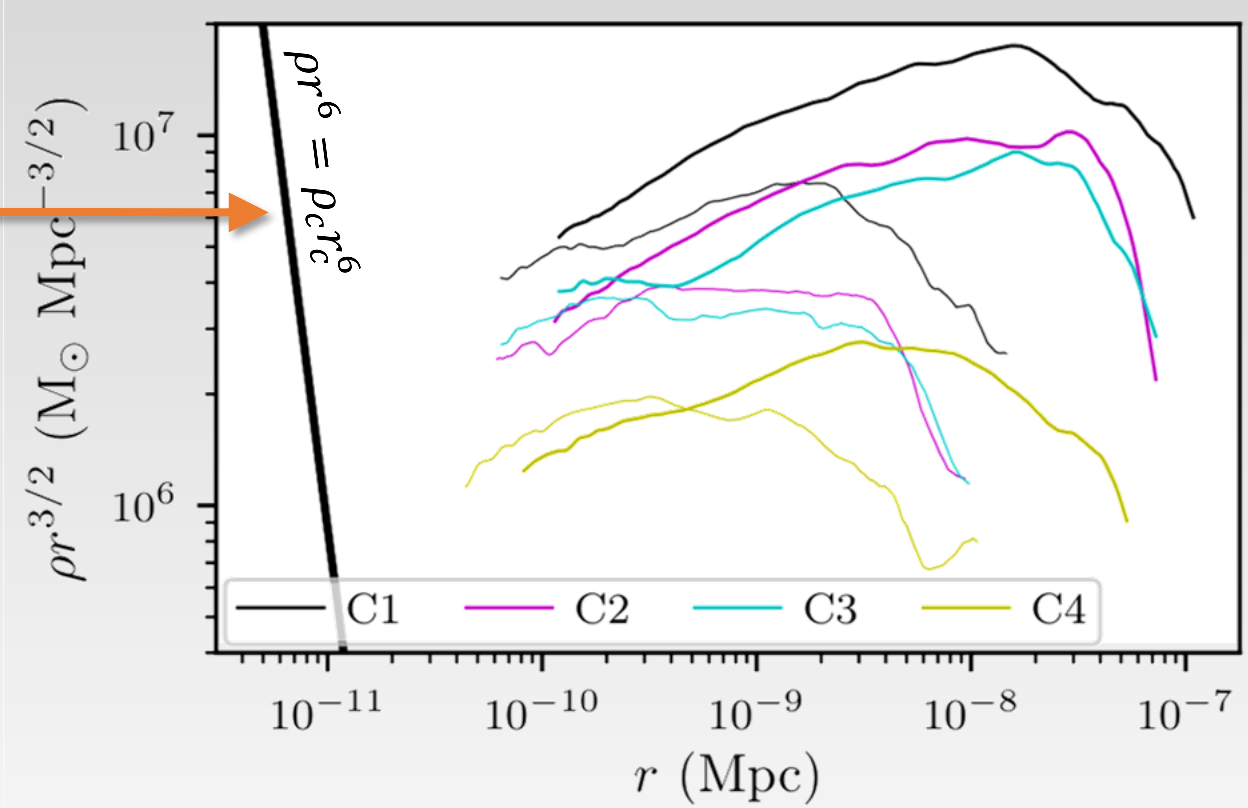
Core radius r_c and density ρ_c

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

$f_{\max}$ = 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 $R_{\rm cusp}/r_c \sim 500$ in radius for typical cosmologies

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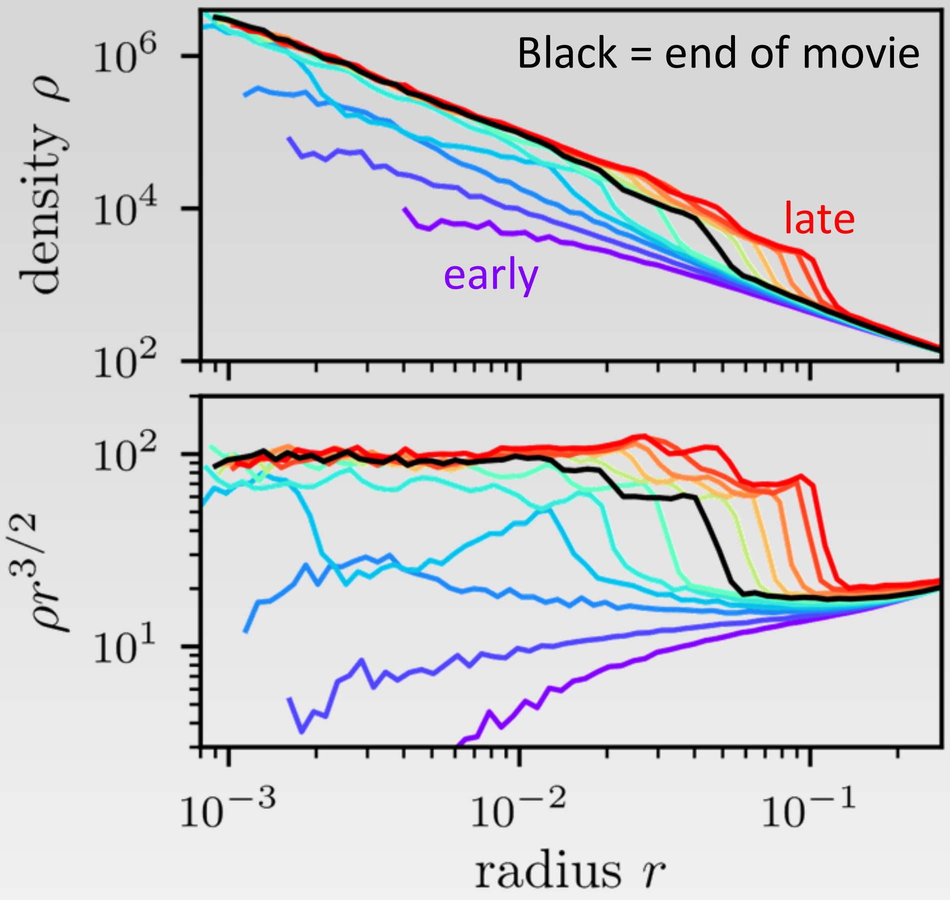
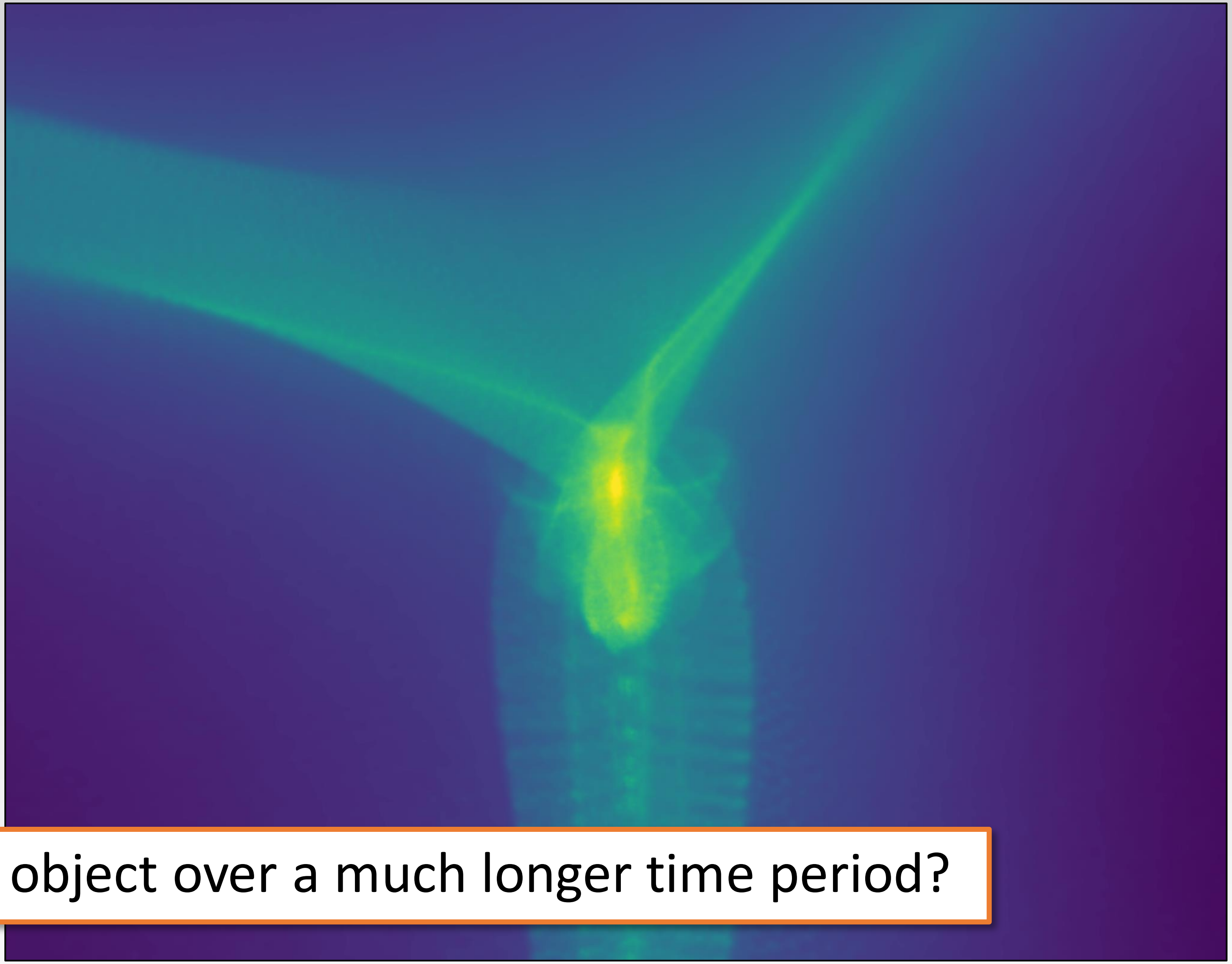
Do prompt cusps survive halo growth?

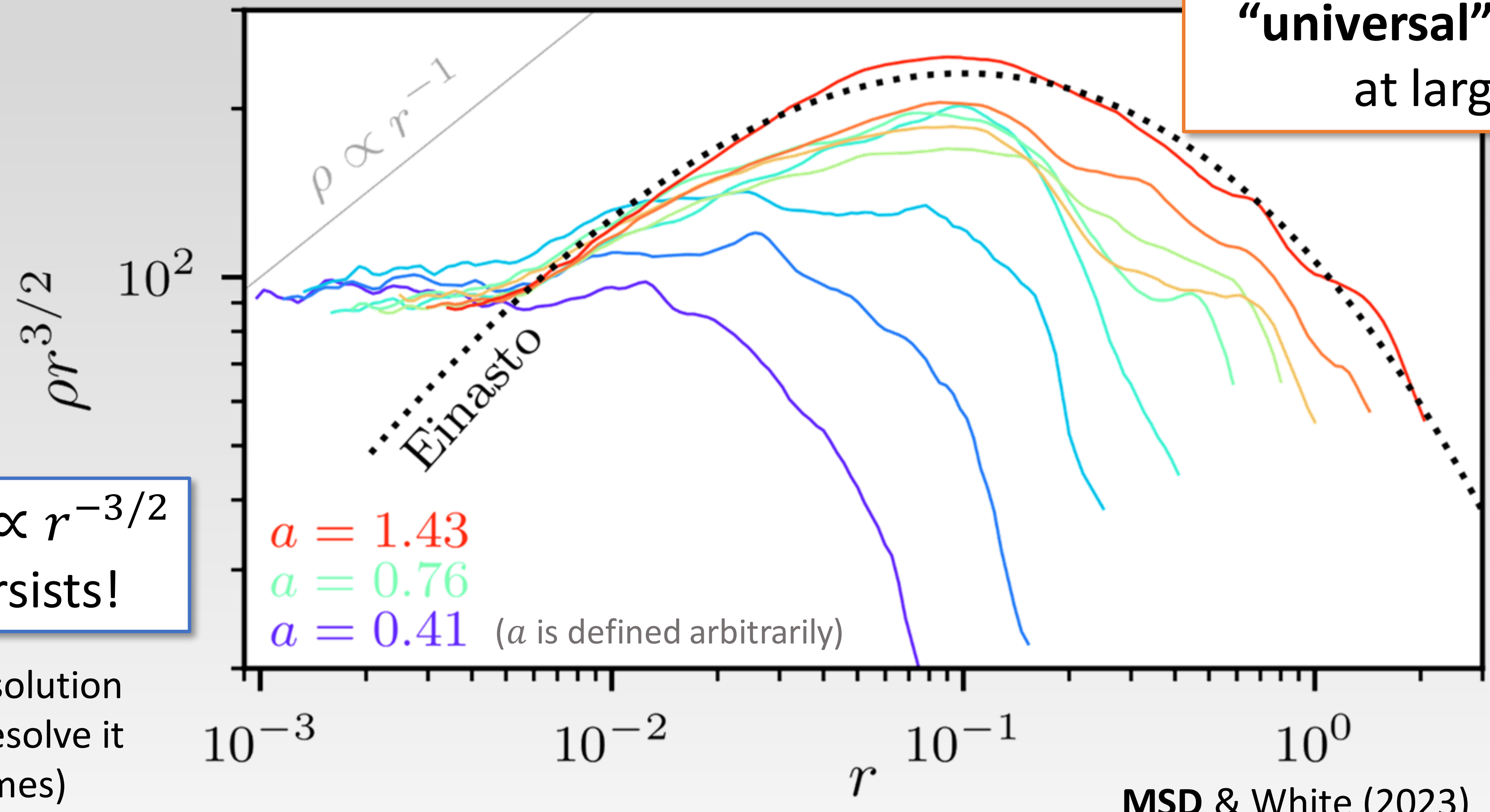




What happens to this object over a much longer time period?

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)

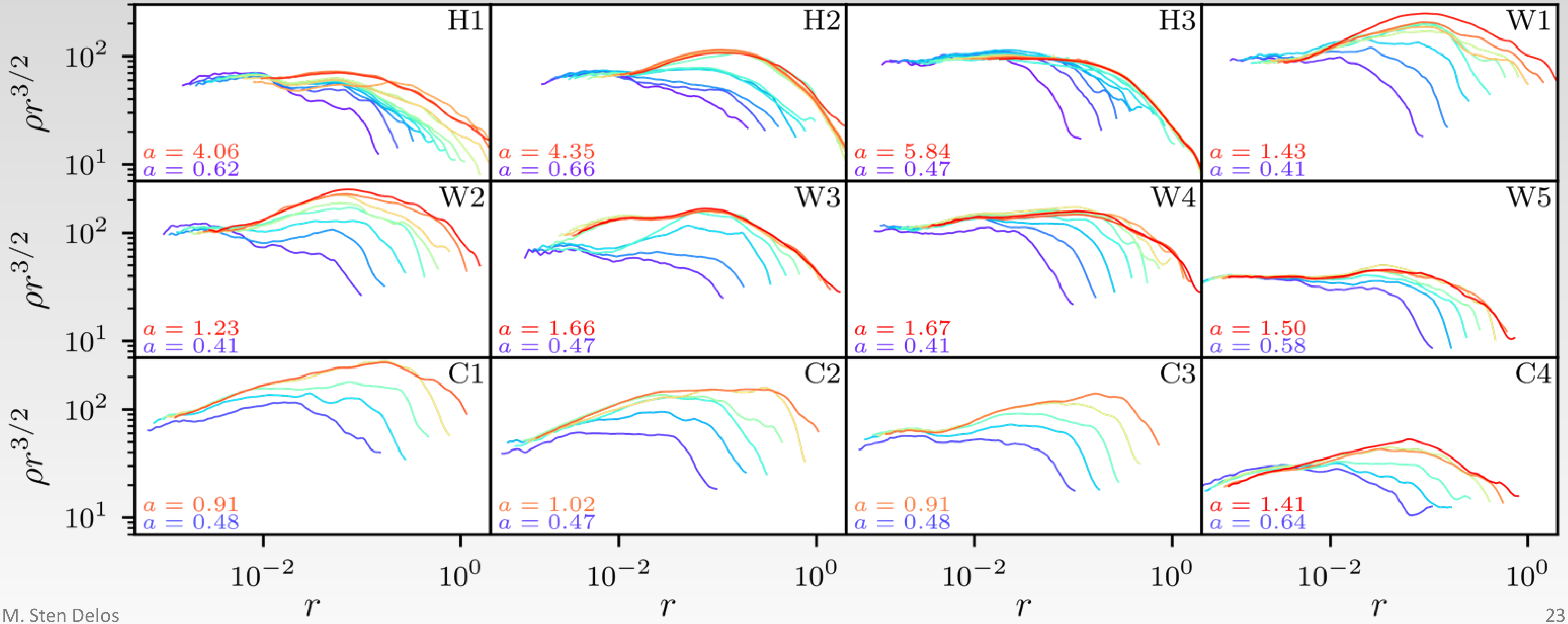
MSD & White (2023)

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

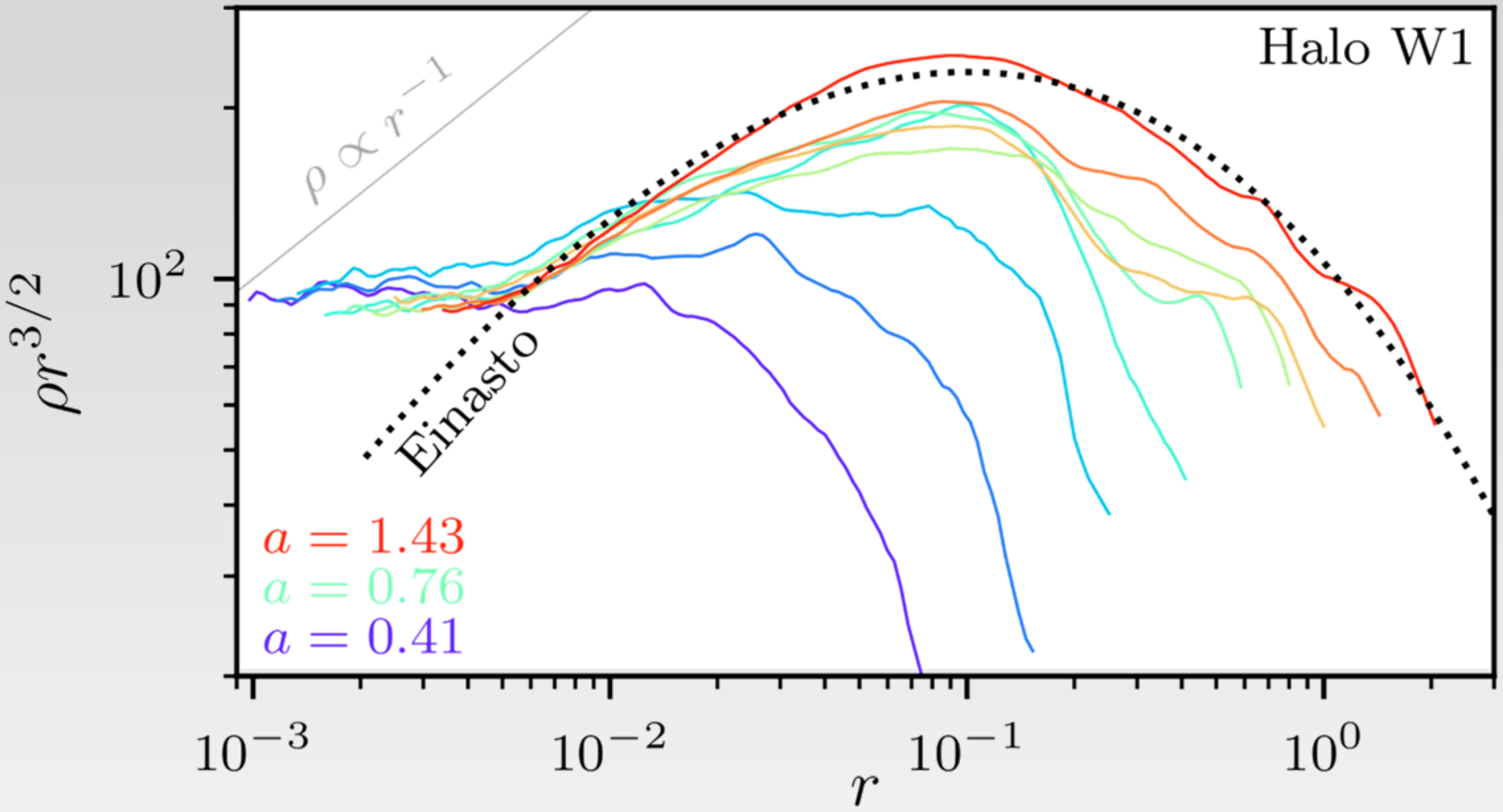


MSD & White (2023)

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

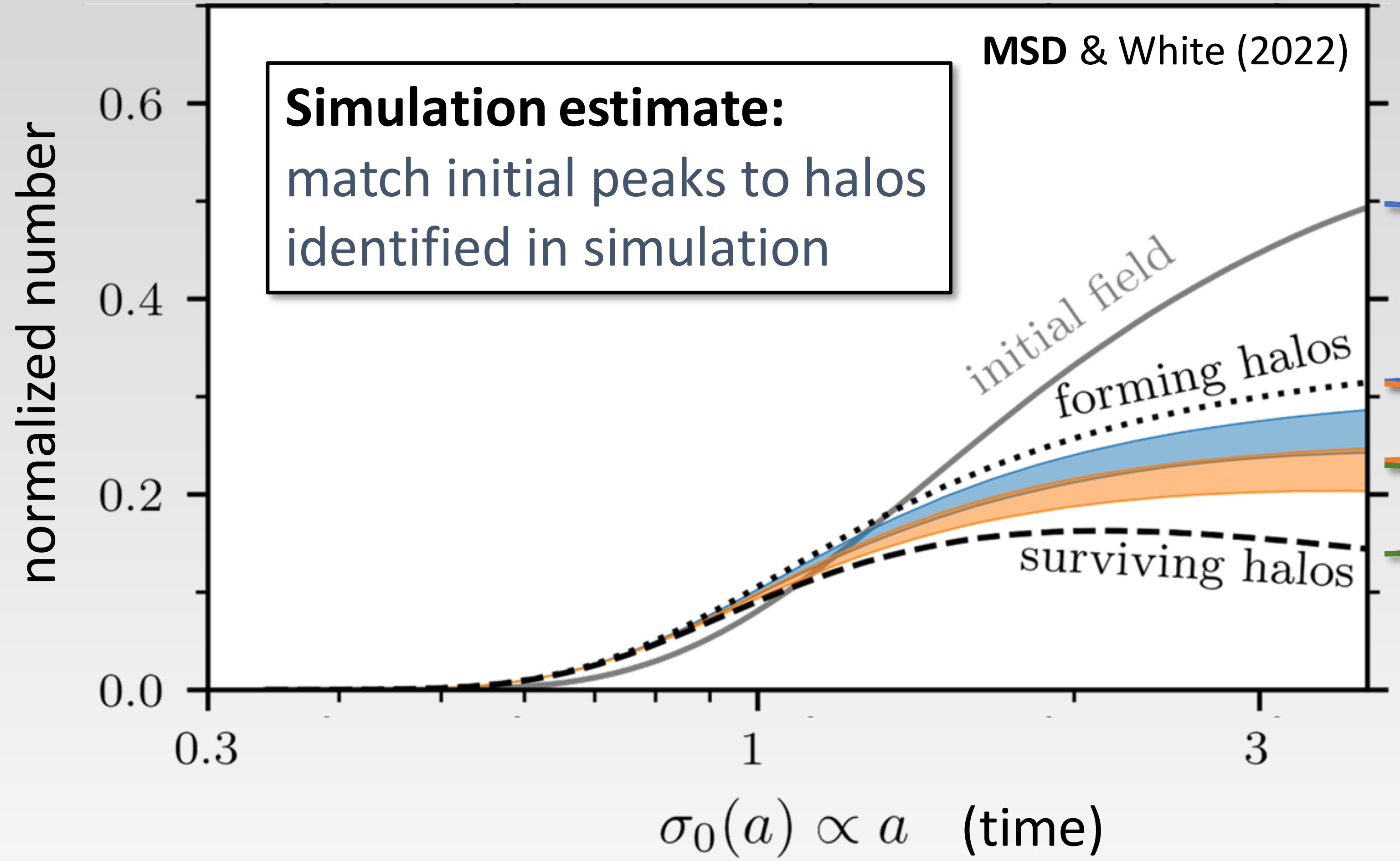


MSD & White (2023)

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?



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]

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

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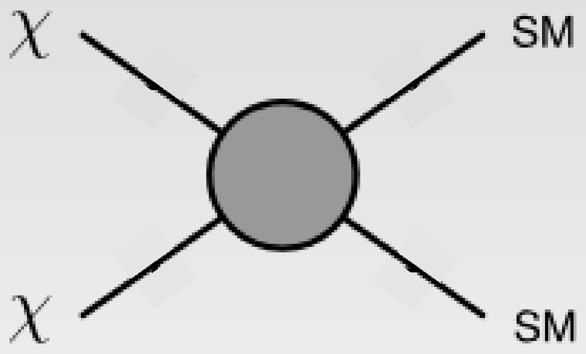
What is dark matter?

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



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

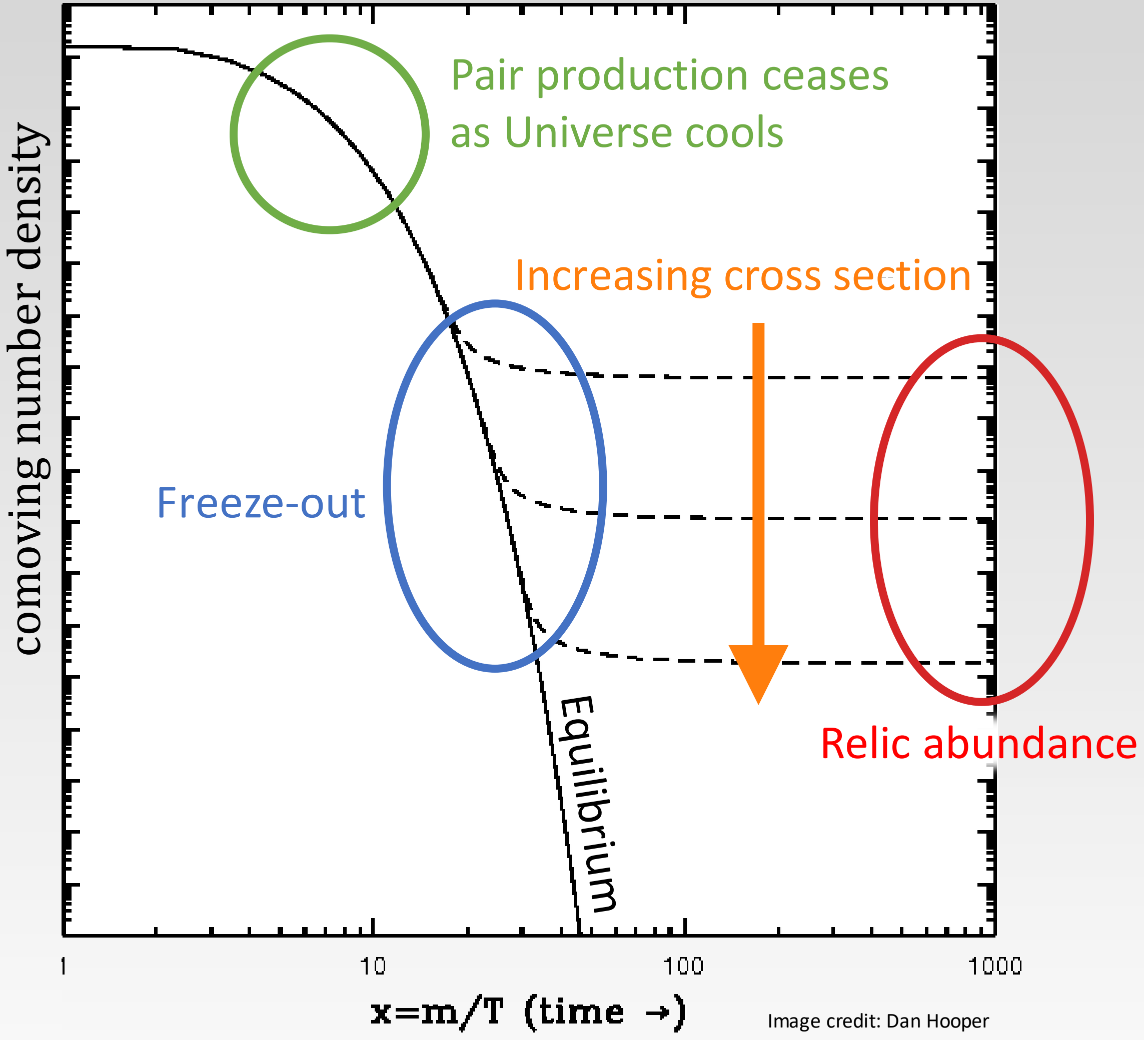
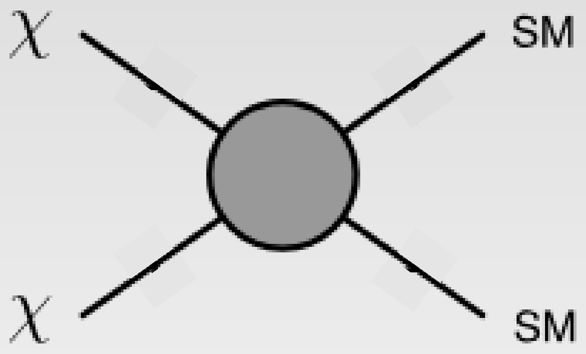


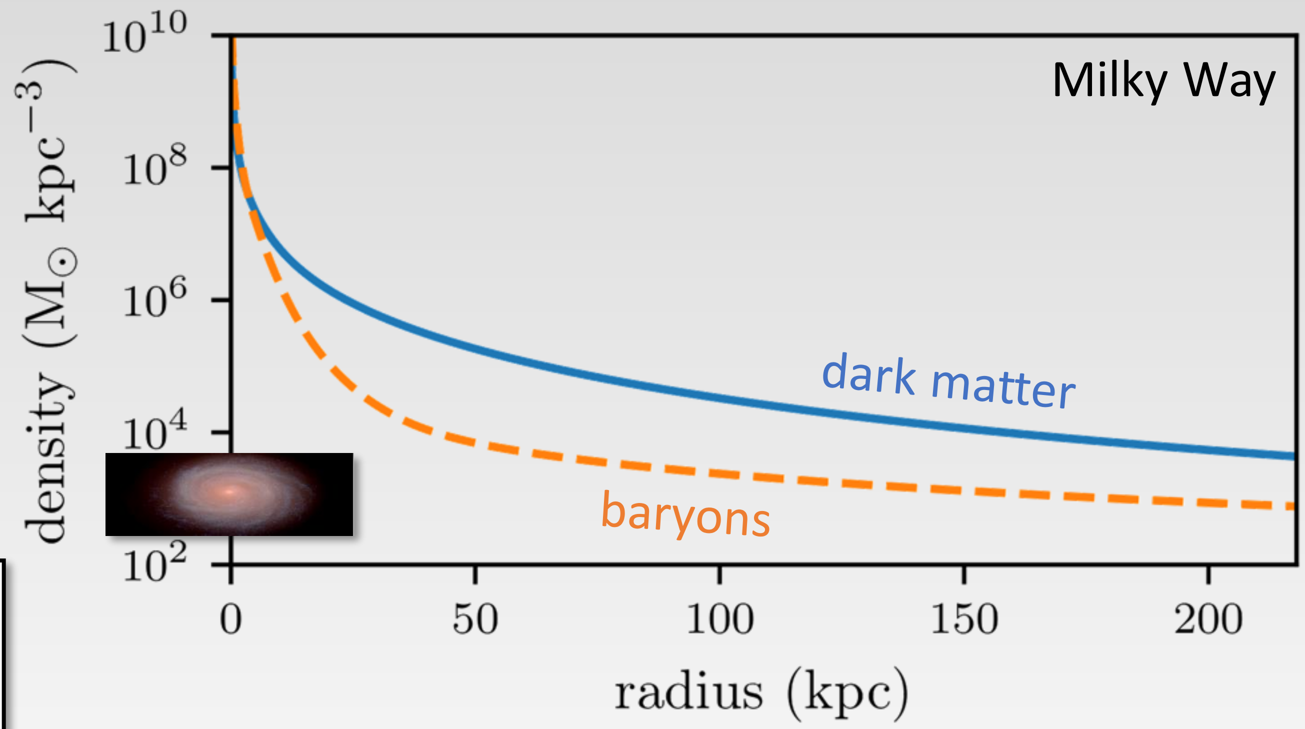
Image credit: Dan Hooper

Indirect detection

Then dark matter can annihilate into detectable SM particles today!



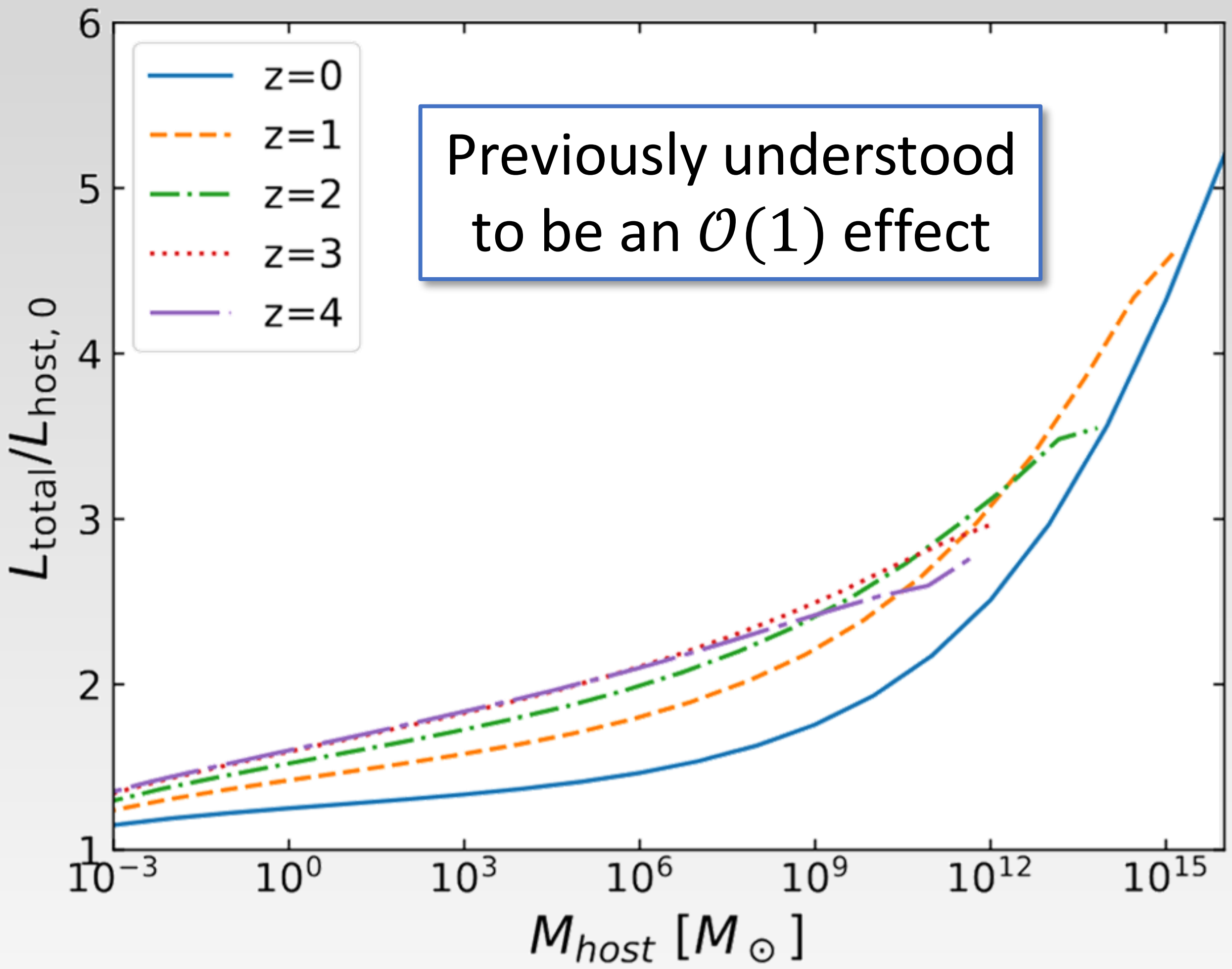
Annihilation rate $\propto \rho^2$:
Search the dense centers of galaxies



Substructure boost

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

(due to ρ^2 scaling)

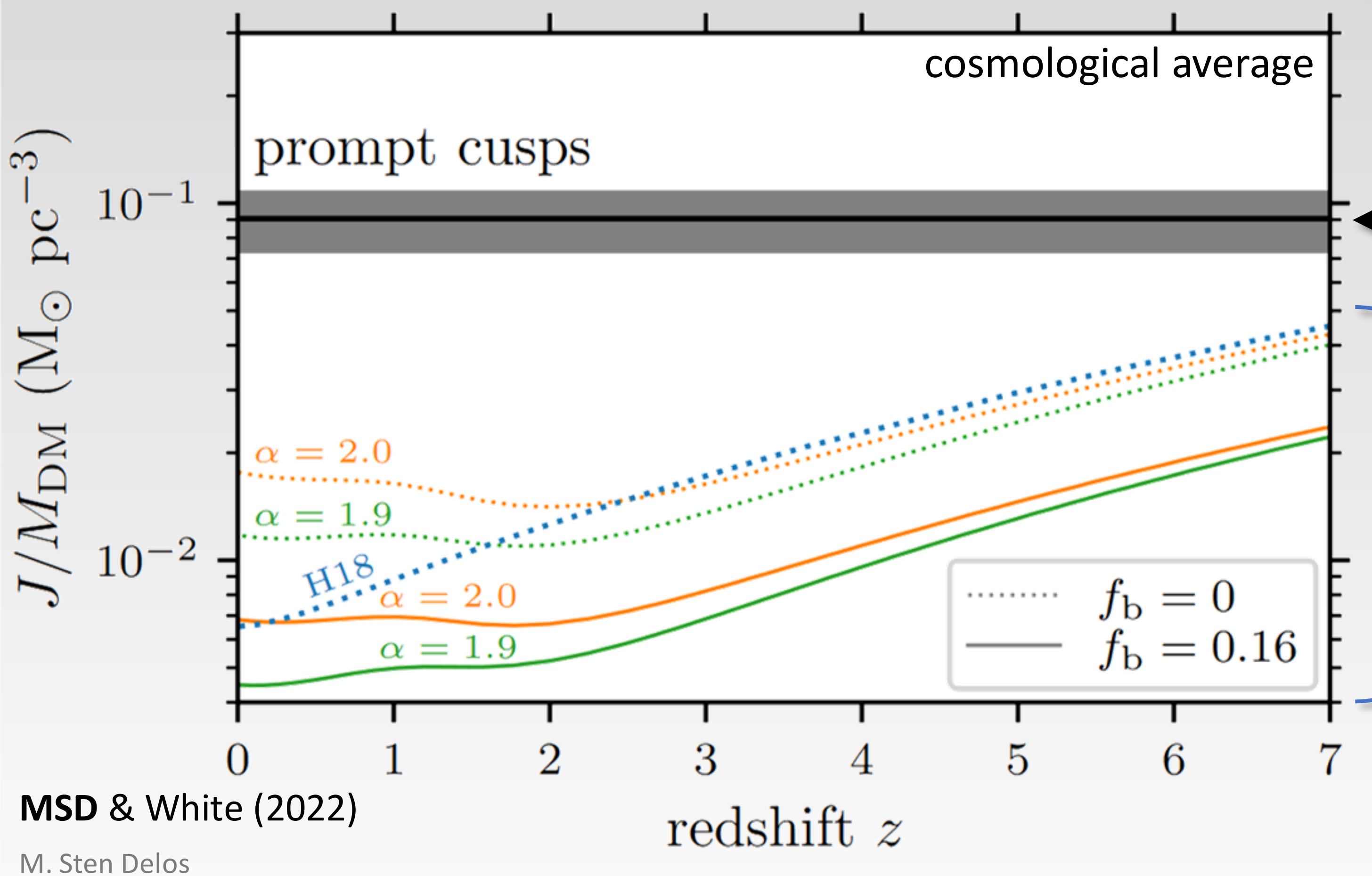


Ando, Ishiyama, Hiroshima (2019)

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 (2022)

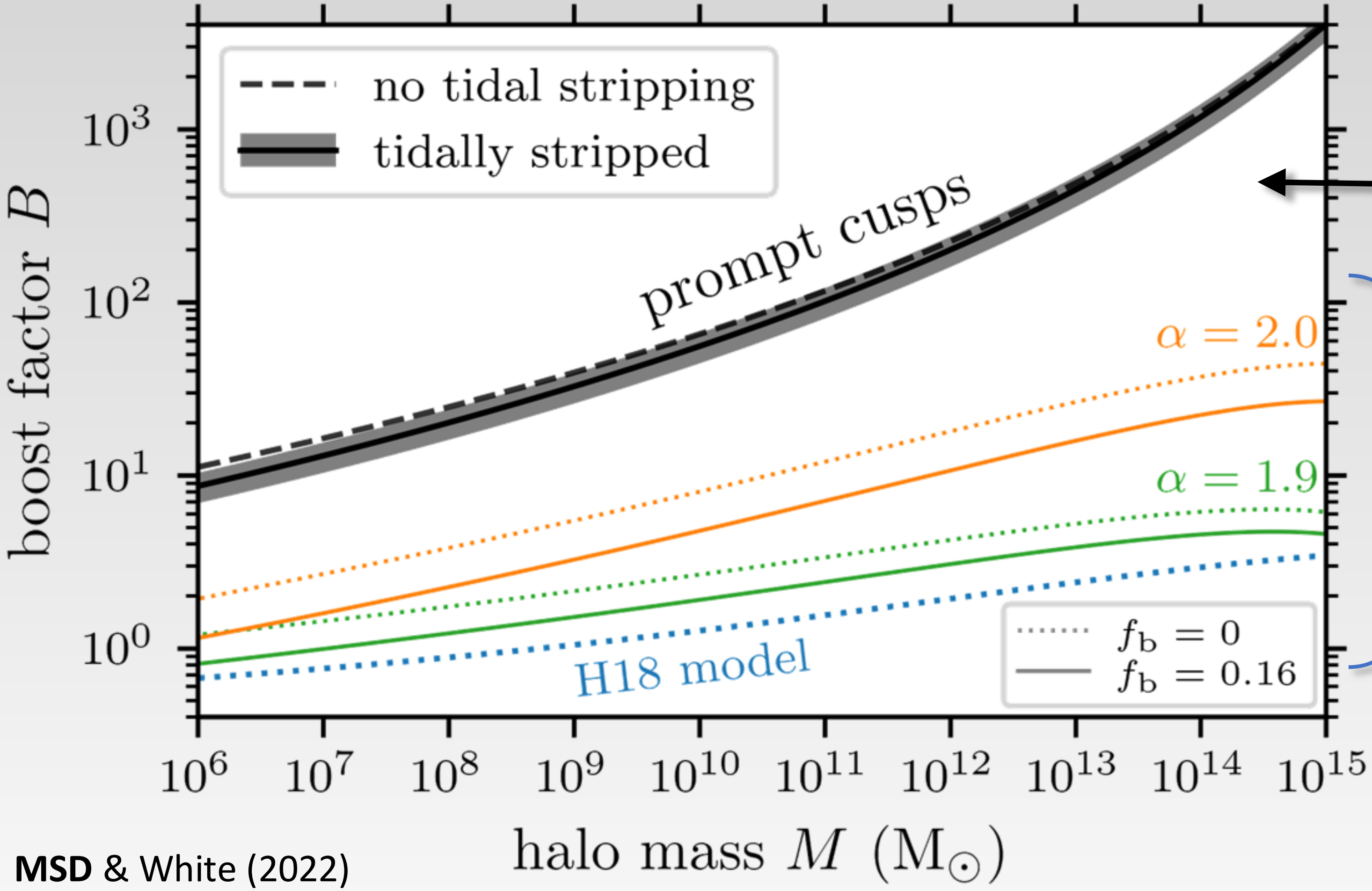
Directly from statistics of peaks & peak-cusp connection

Previous predictions:

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

Annihilation in prompt cusps

Annihilation boost inside larger halos:



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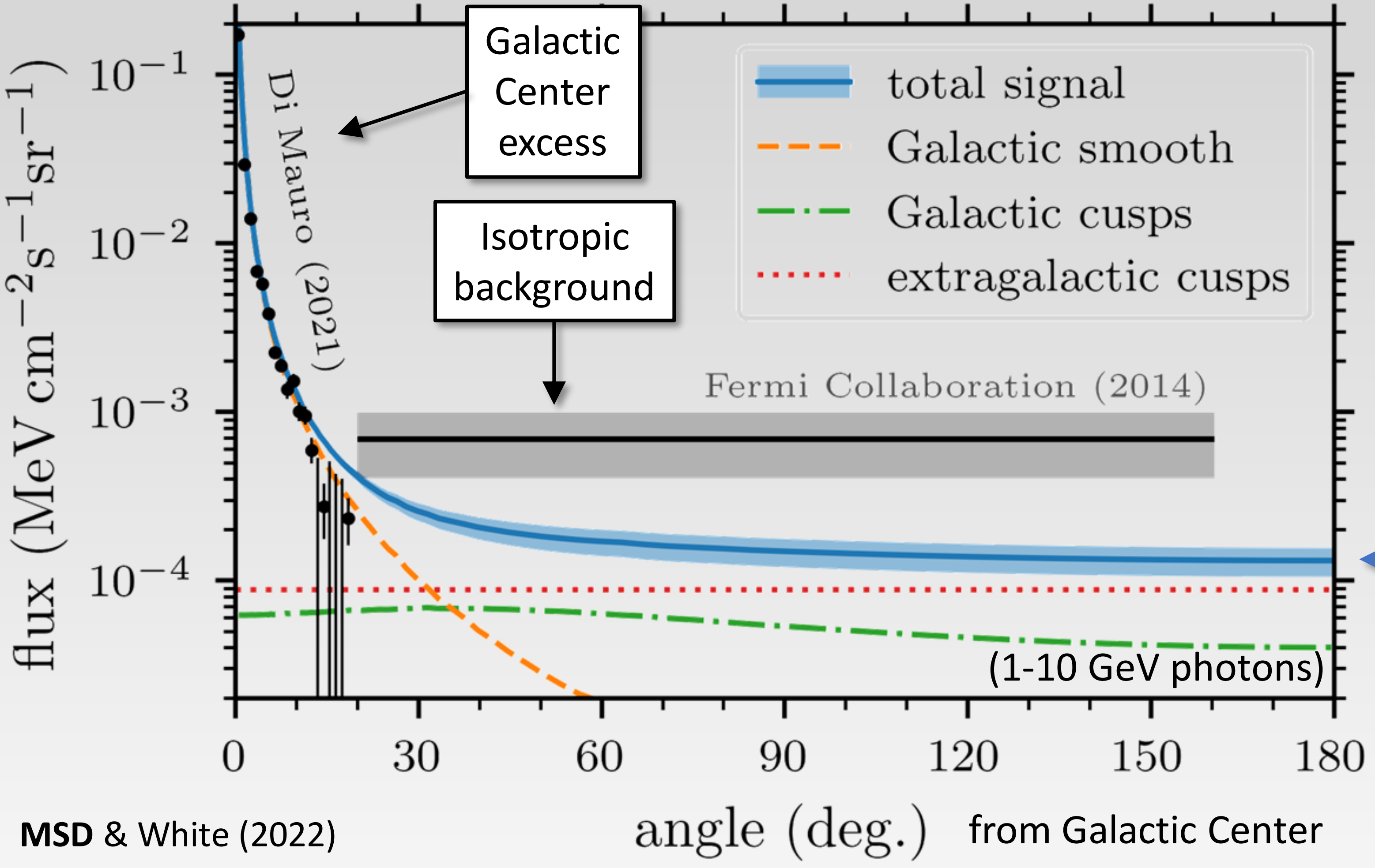


from Galactic Center

MSD & White (2022)

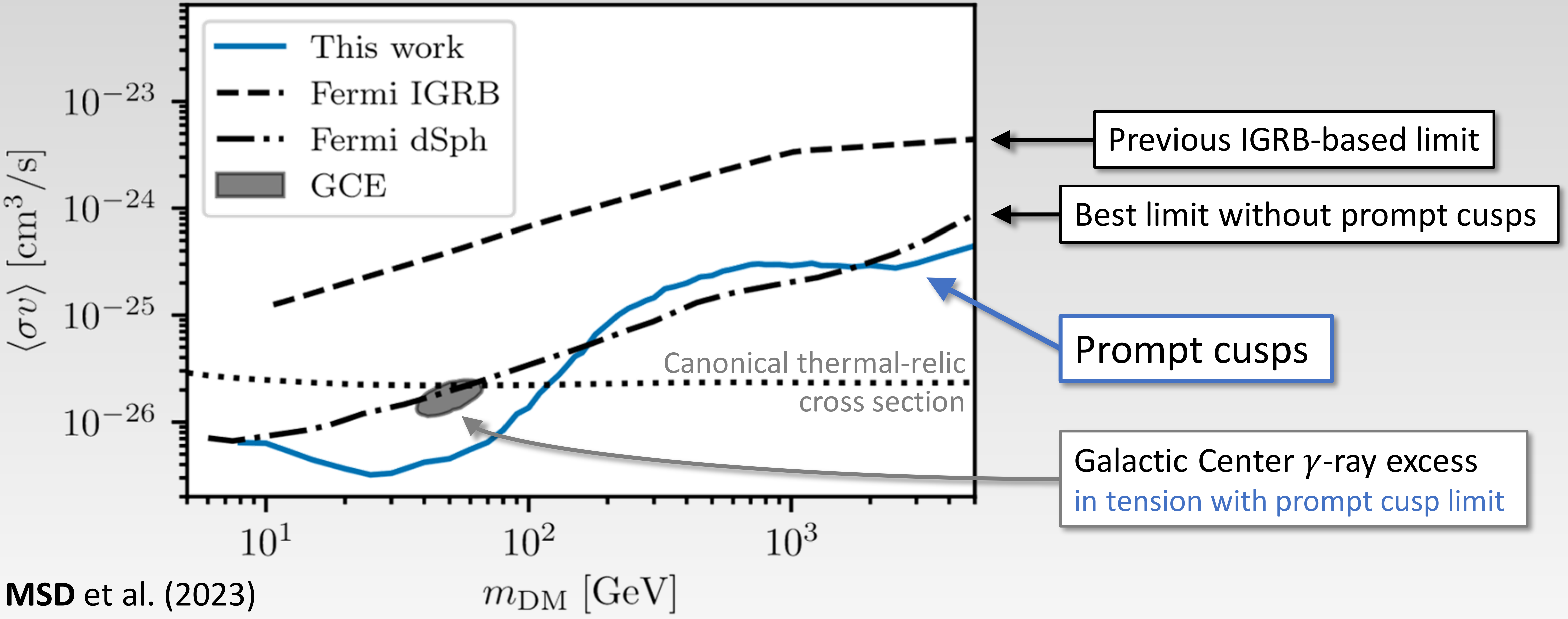
No annihilation boost in the centers of galactic halos (cusps disrupted & density already high), but annihilation everywhere else is greatly boosted.

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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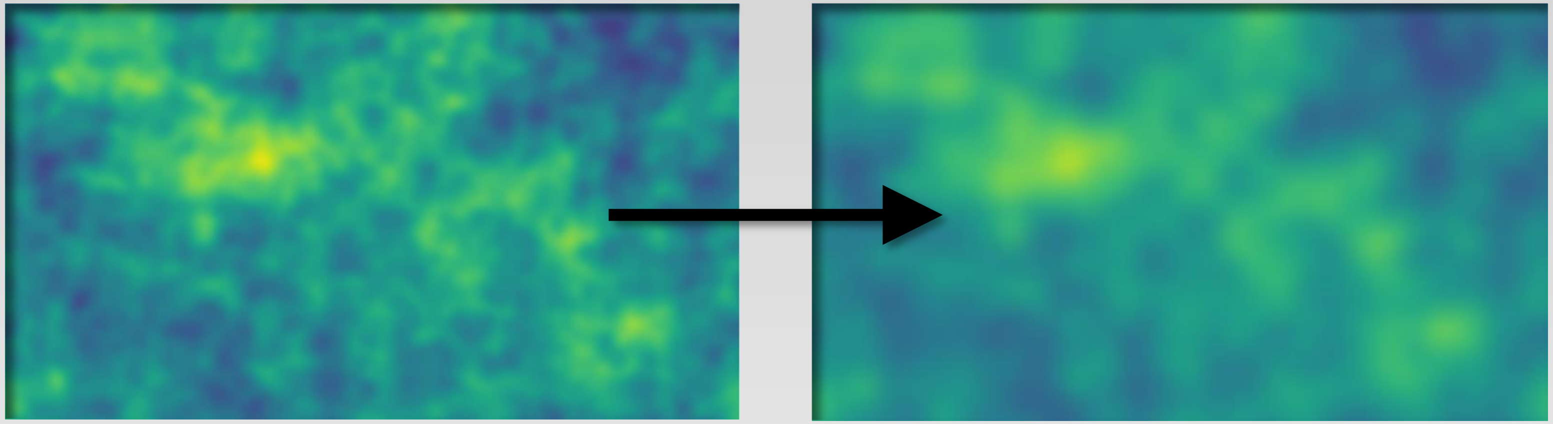
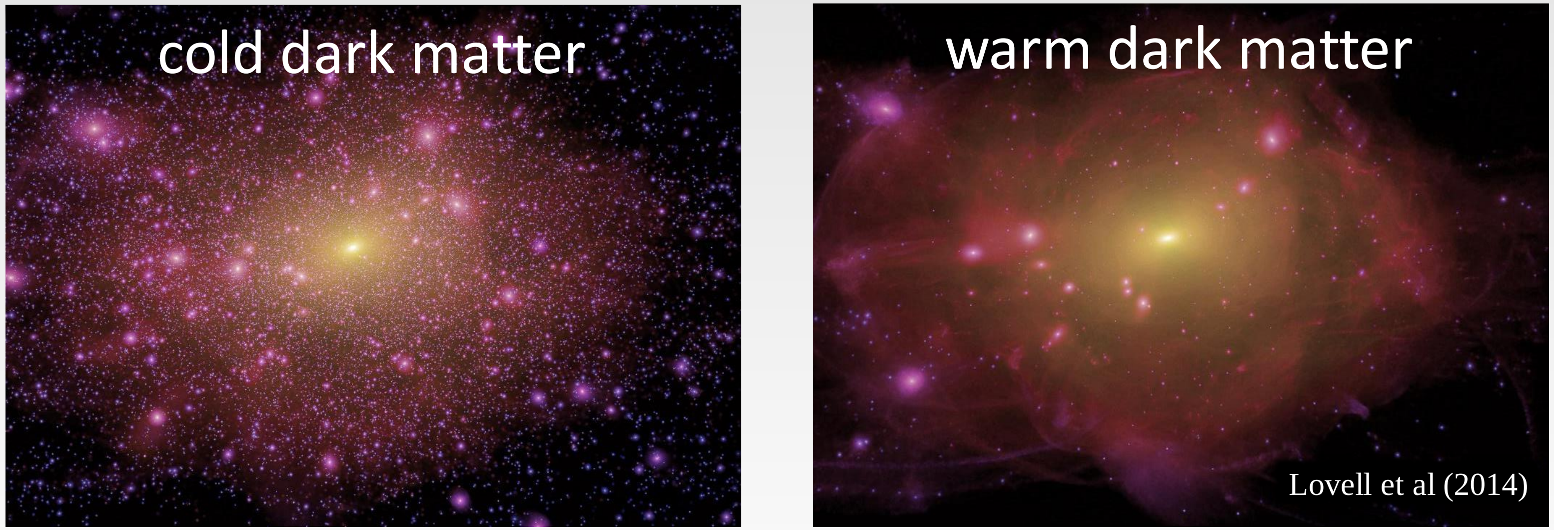
Warm dark matter

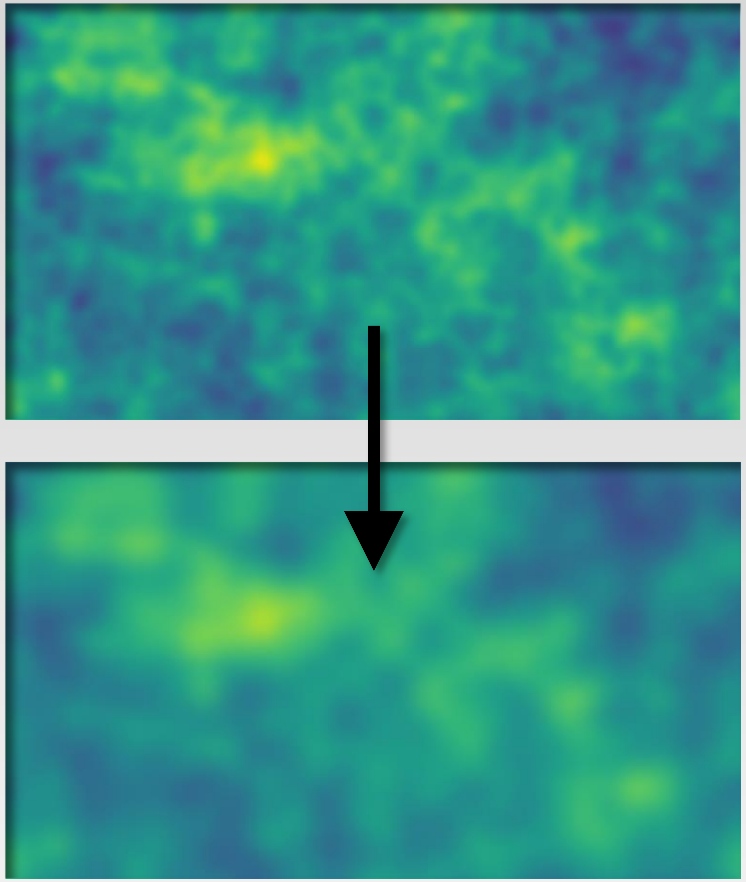
Random particle motion smooths initial conditions



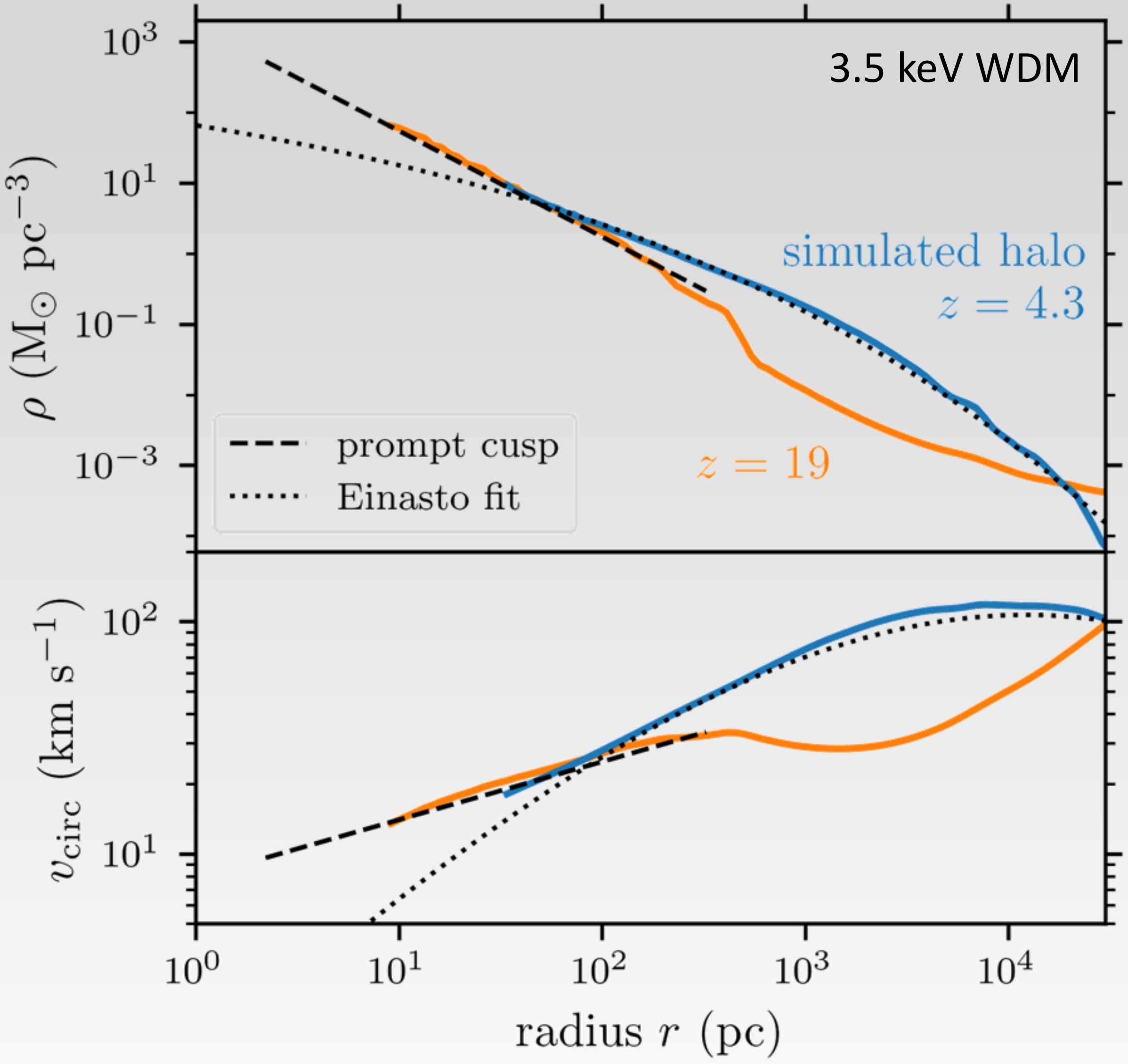
which suppresses the abundance of low-mass halos:



Prompt cusps of warm dark matter



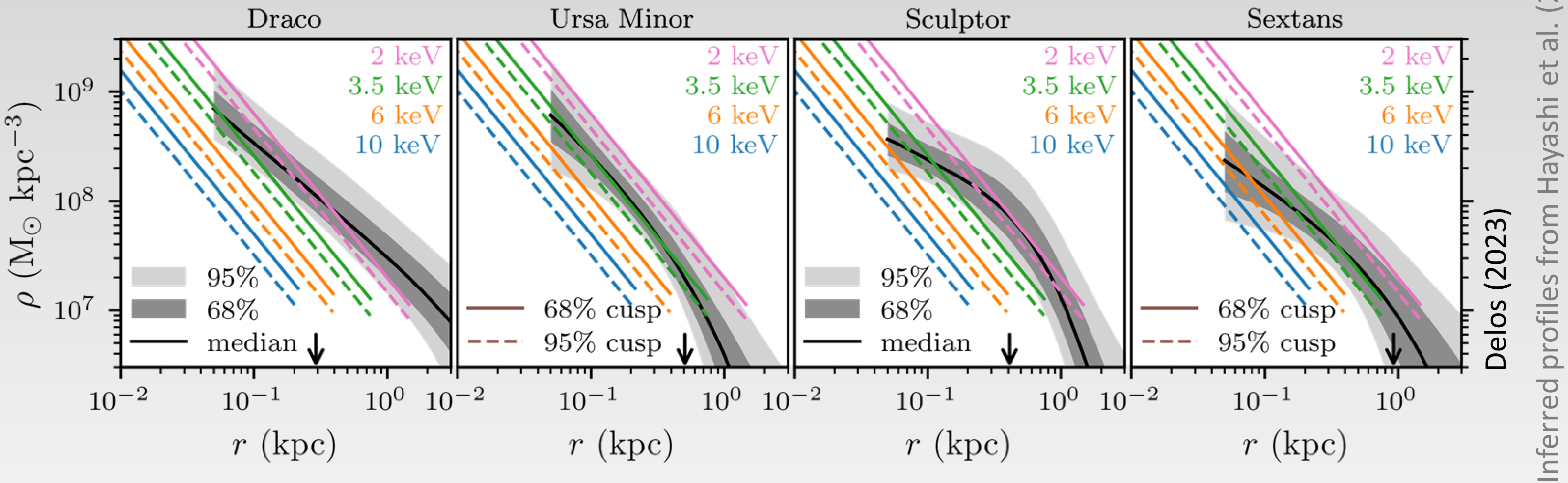
Initial density peaks are much larger
→ Prompt cusps are much larger



MSD (2023)

Searching for WDM prompt cusps

We can search for prompt cusps within nearby dwarf galaxies:



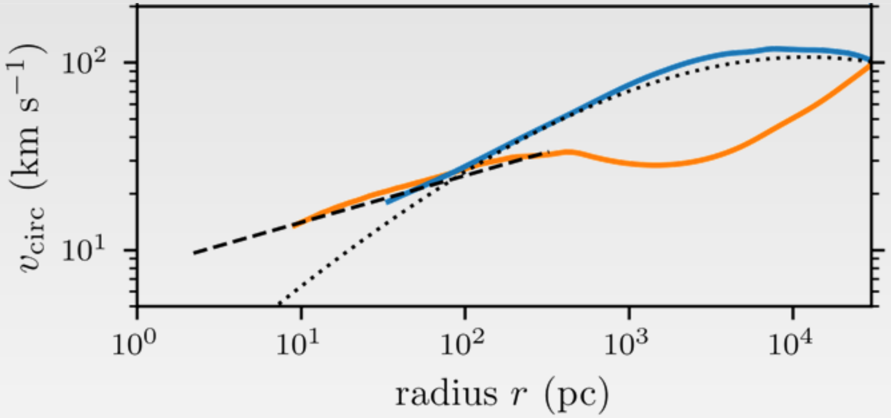
Interpretation: $\rho > \rho_{\mathrm{cusp}}$ can be explained by halo growth, but $\rho < \rho_{\mathrm{cusp}}$ is difficult to explain

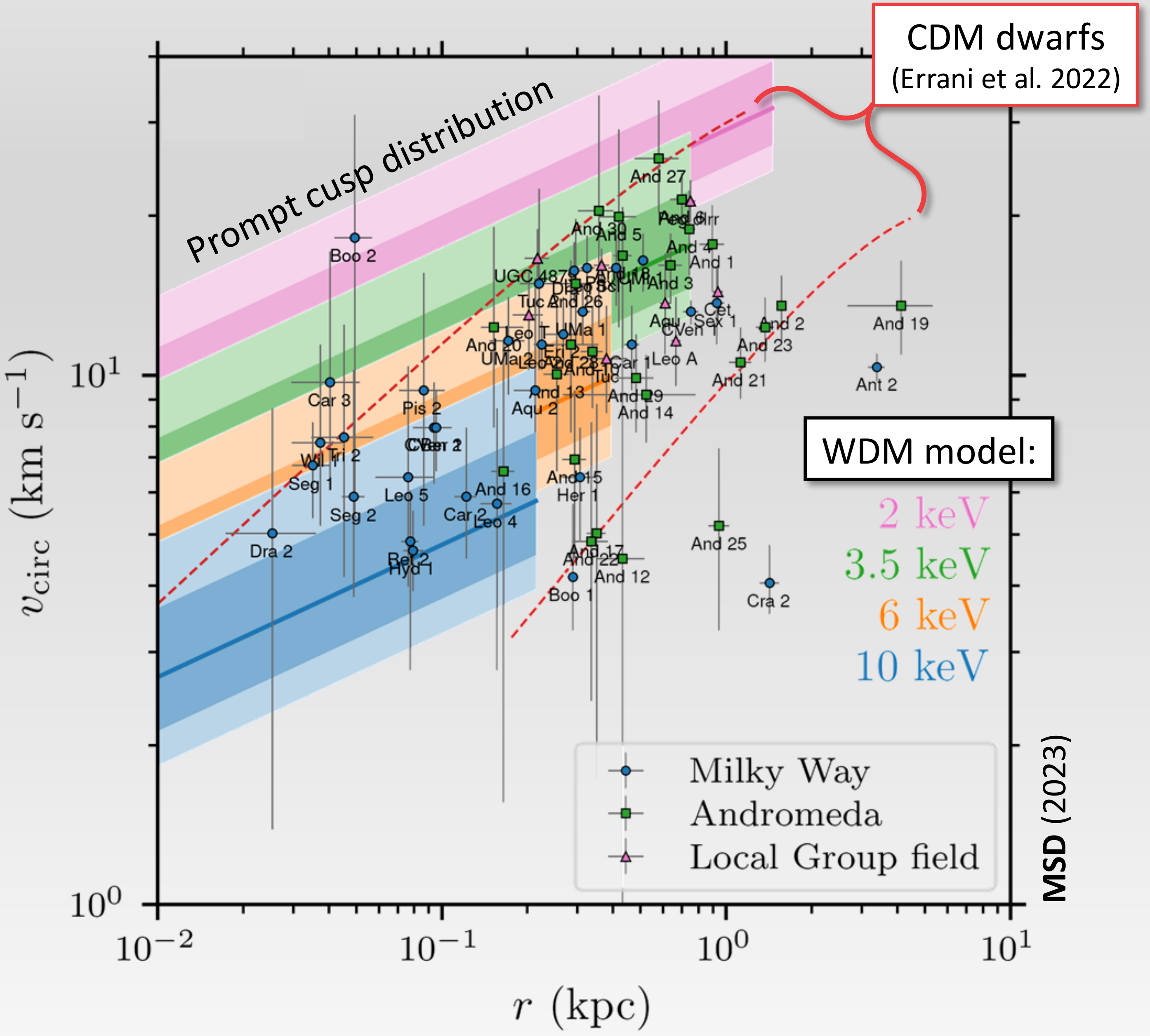
Better constraints come from ultrafaints…

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.