# Prompt cusps of dark matter halos


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Cosmology from Home, 2023


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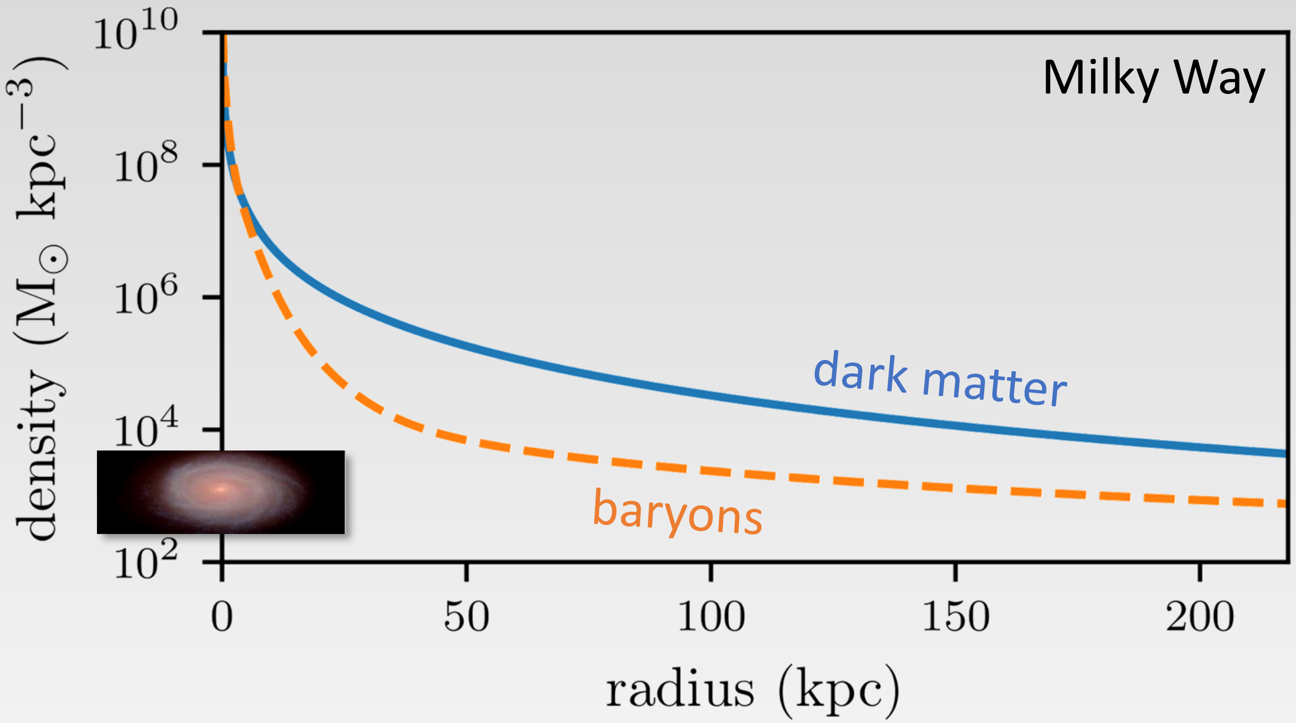
# Dark matter halos

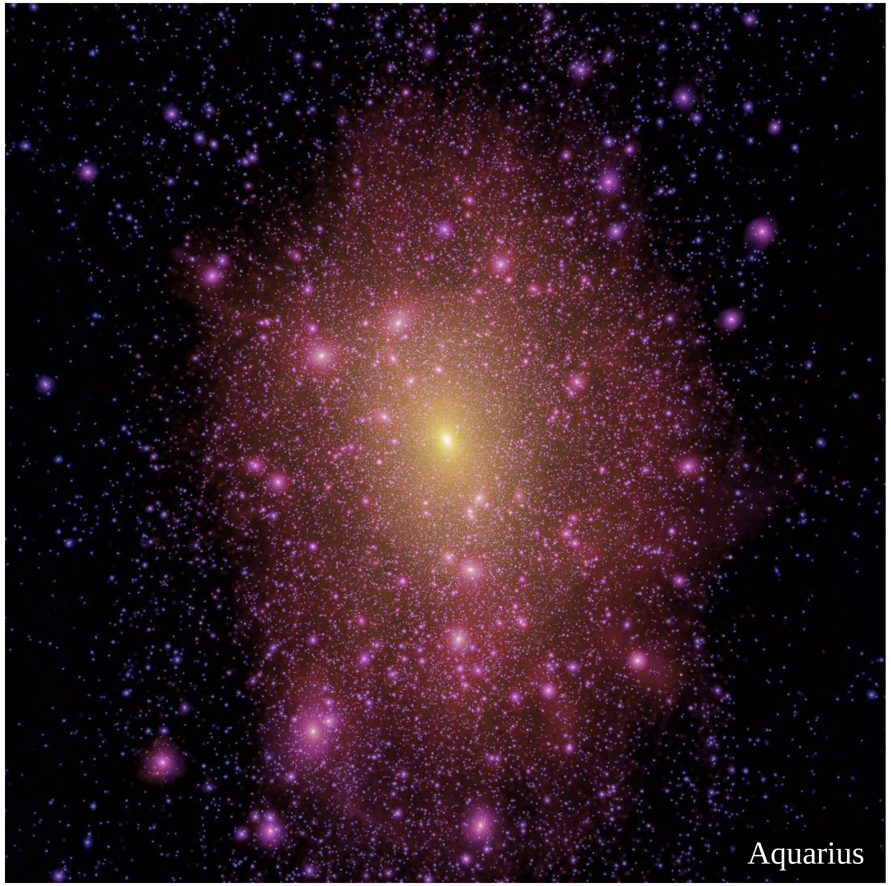
- There is ~5 times more dark matter than baryons
- Dark matter drives gravitational structure formation



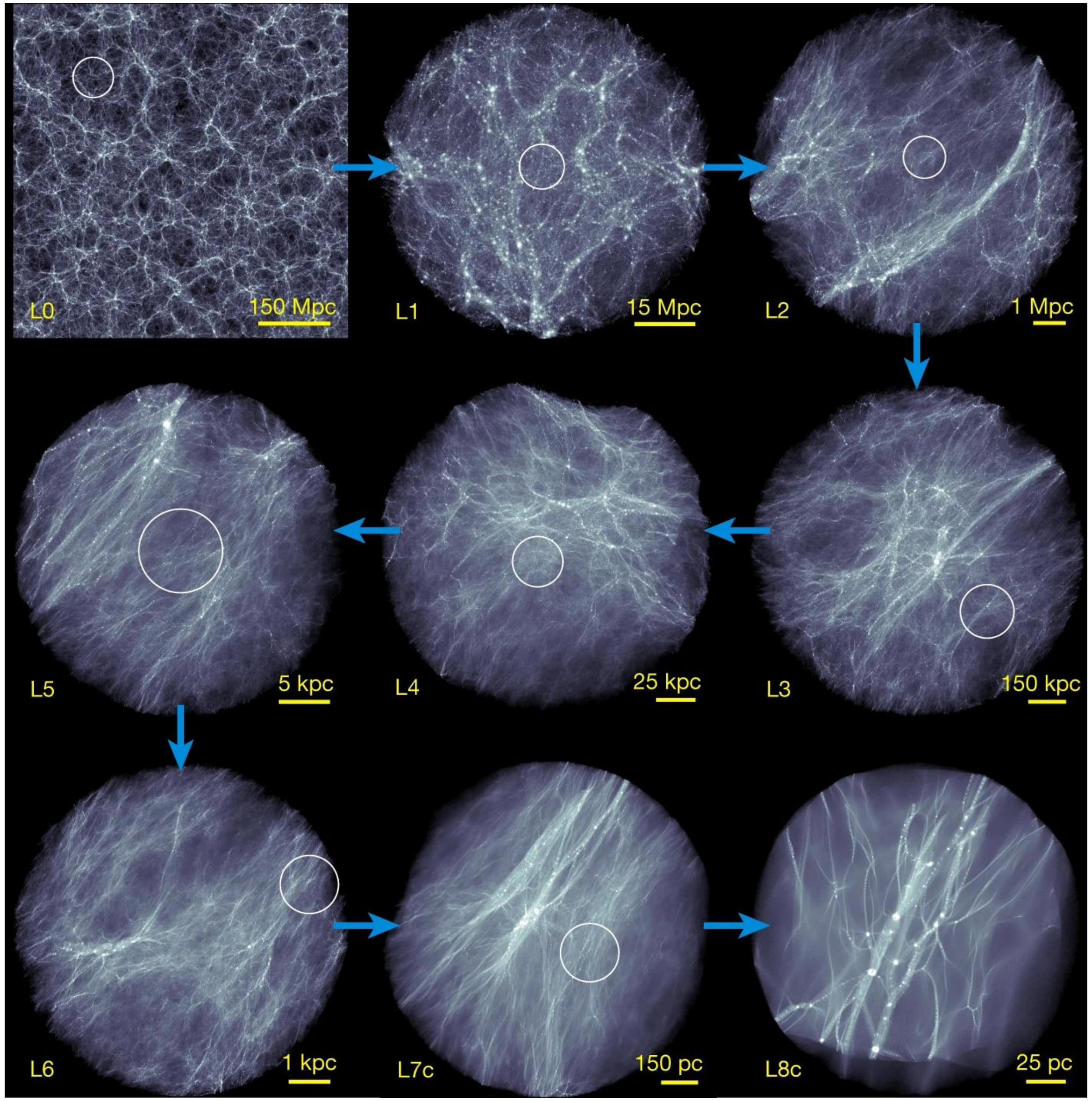

MW mass model: Cautun et al (2020)
picture of simulated MW-like galaxy: Grand et al (2021)

# Dark matter halos

Subhalos persist inside other halos:



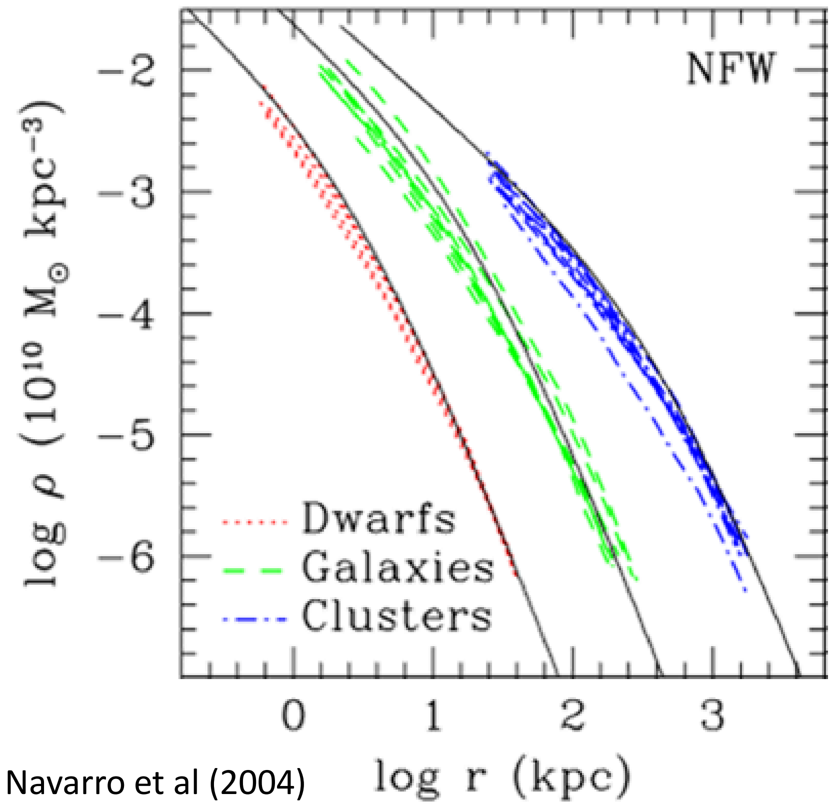

Halos form at all scales:



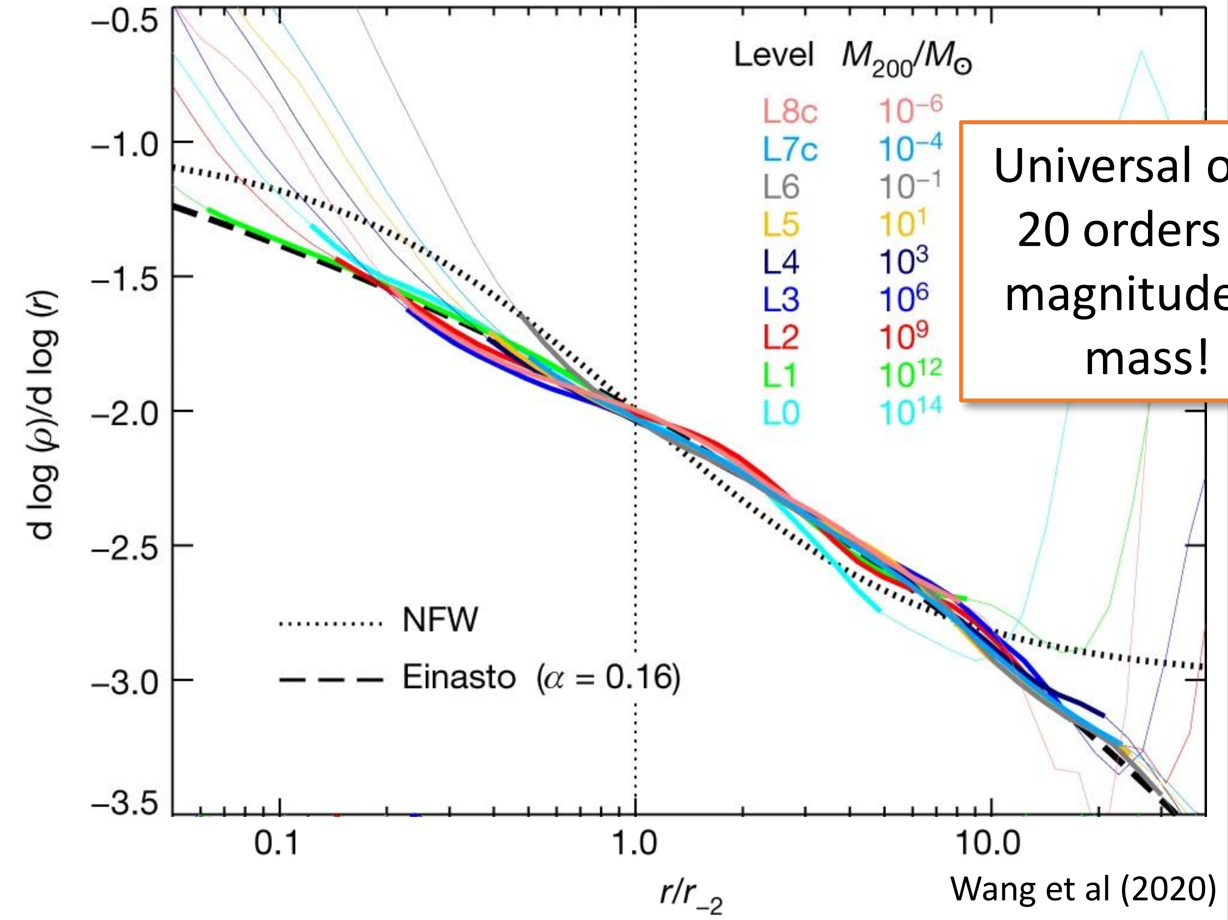

Wang et al (2020)

# Halo density profiles

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




Navarro et al (2004)



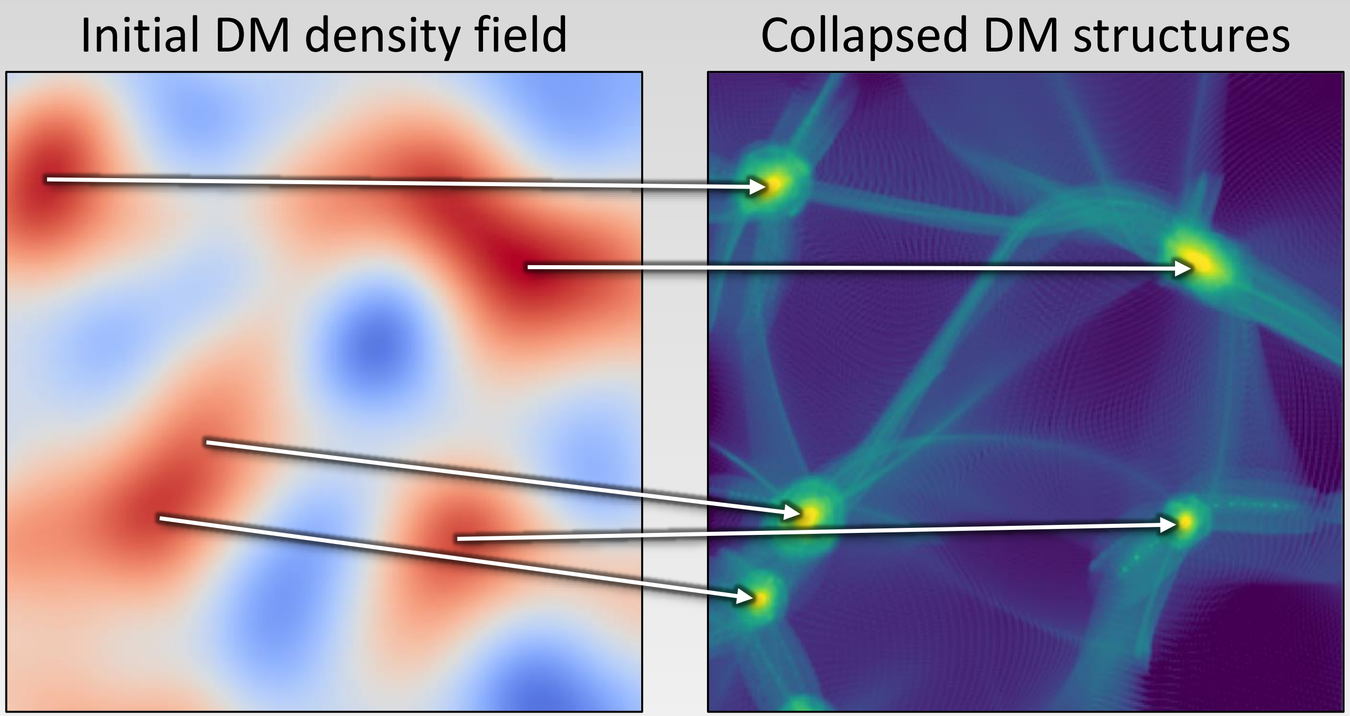

Wang et al (2020)

Universal over 20 orders of magnitude in mass!

…because all have the same formation mechanism: growth from a smaller halo (e.g. Ludlow et al 2013)

# The first halos

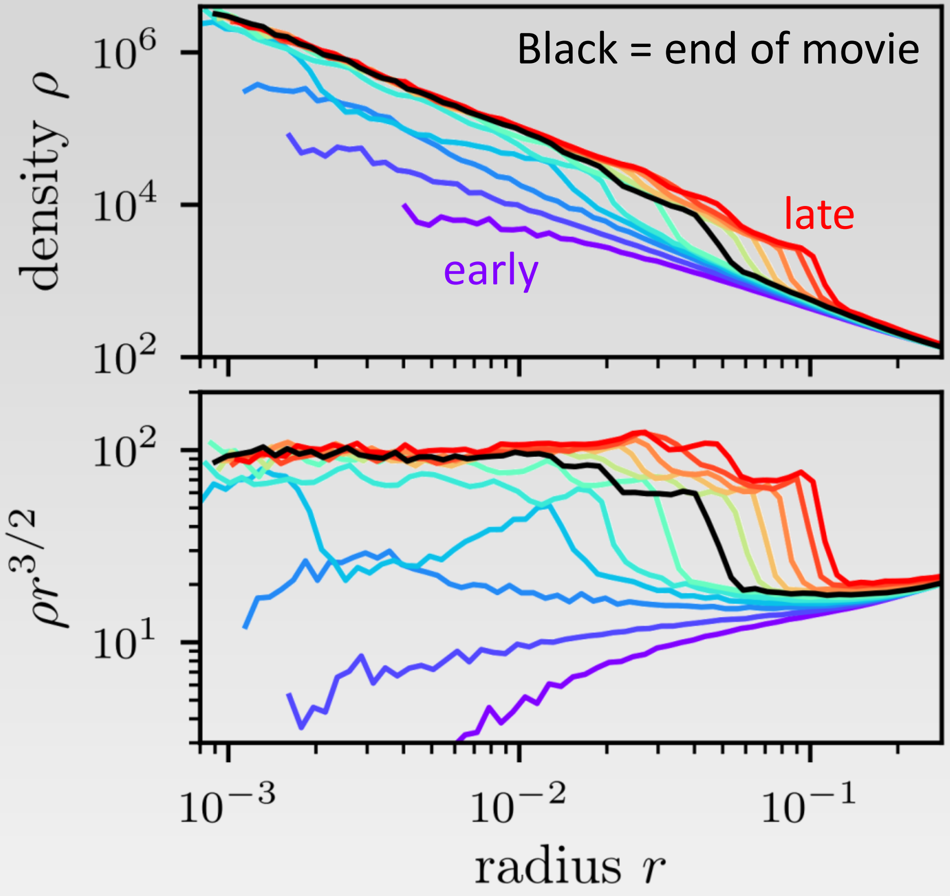
The first dark matter halos form from density peaks.




(smoothed by thermal motion)

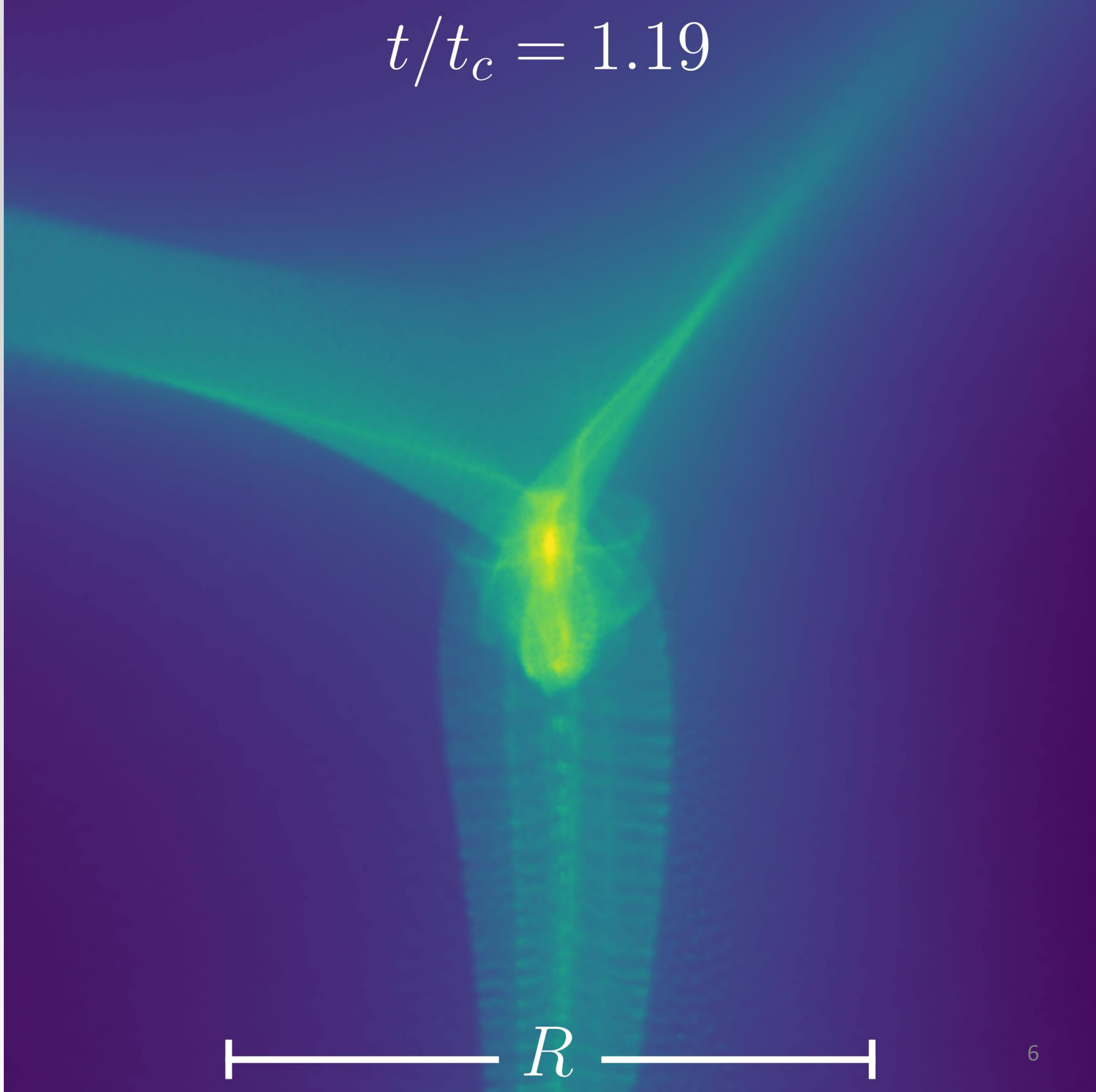
Normally not resolved in simulations [~earth mass]

# "Prompt cusps"




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

"prompt" (White 2022)

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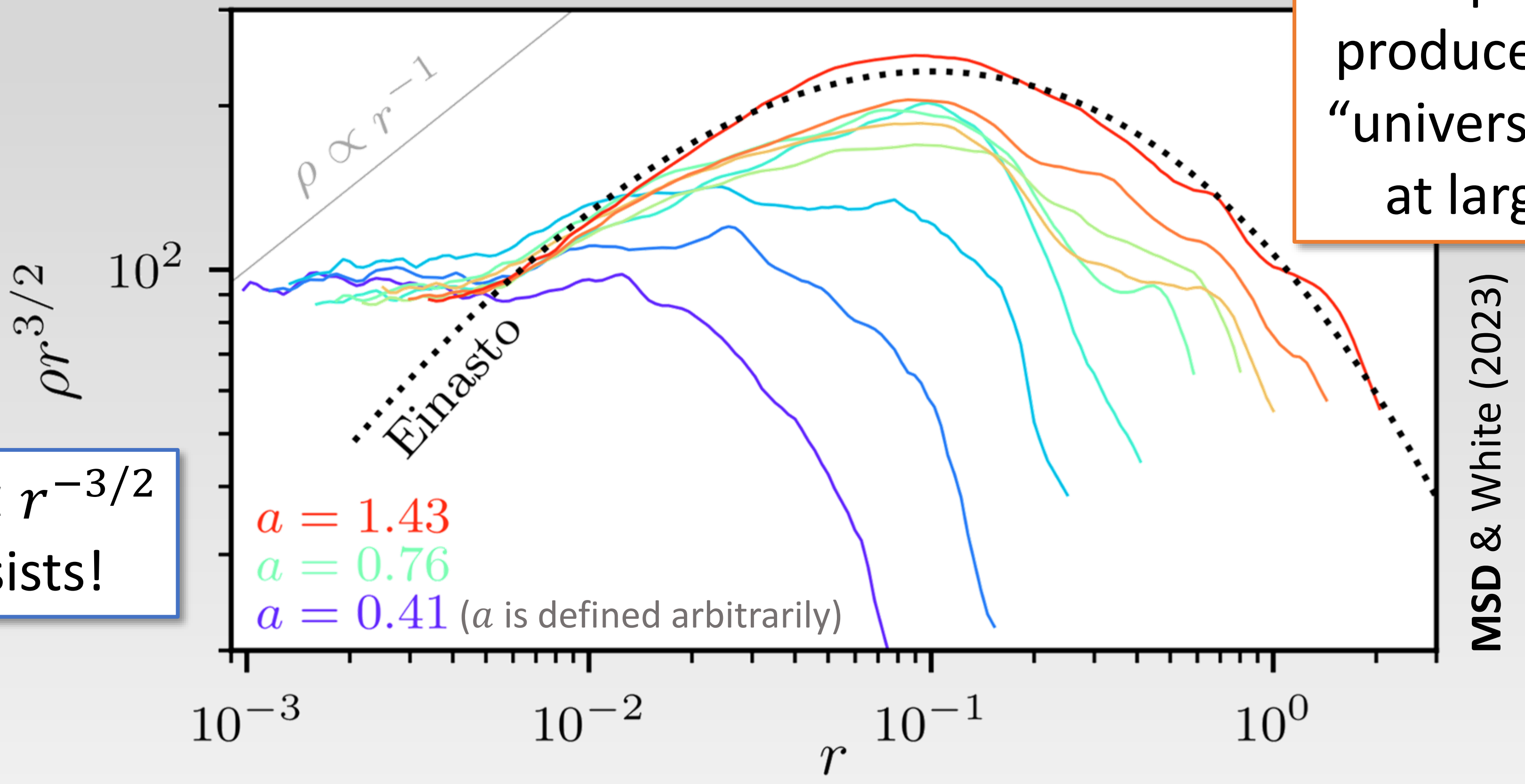
# Prompt cusp persistence




Buildup of material produces shallow “universal” profile at larger radii

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

Outcome: standard DM density profile + prompt cusp

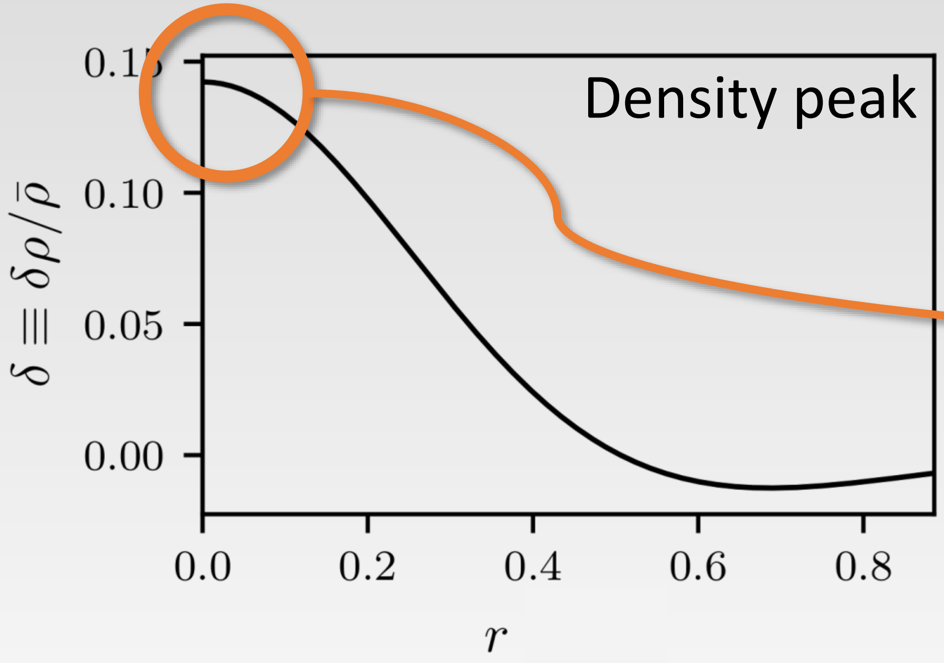
- Verified for a sample of other halos arising in a range of cosmologies
- Unsurprising: new material has too much $E$, $L$ to disturb the center

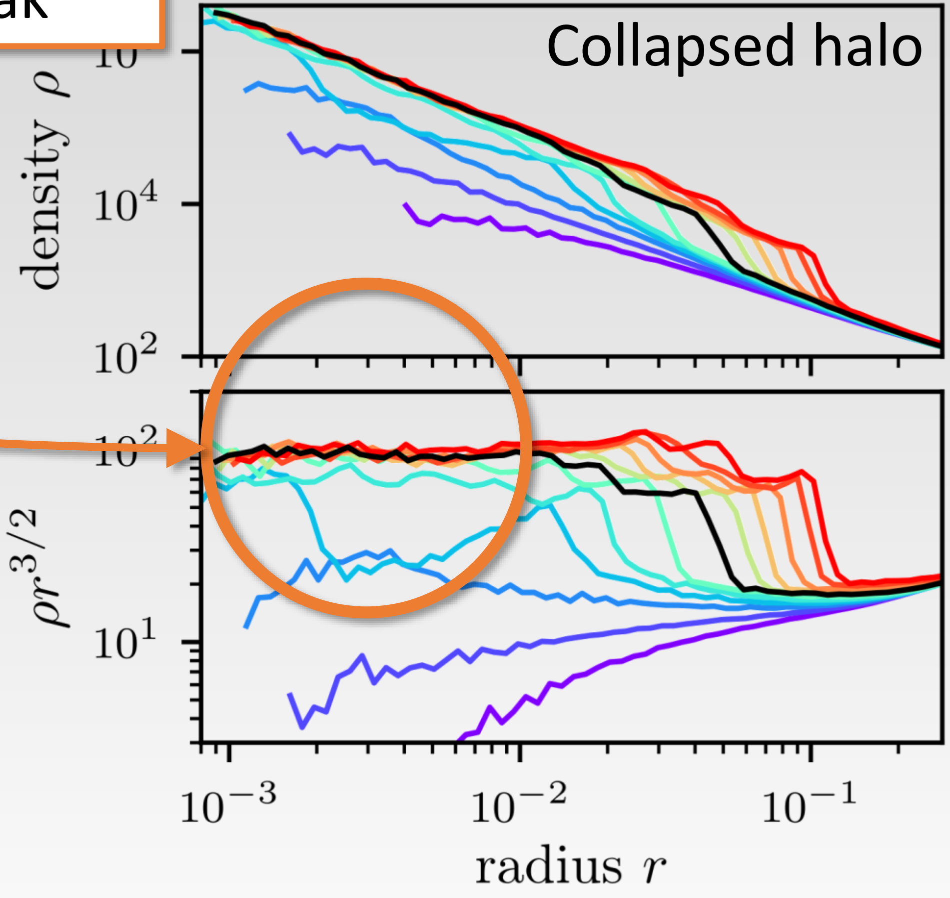
# What sets prompt cusp properties?

**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



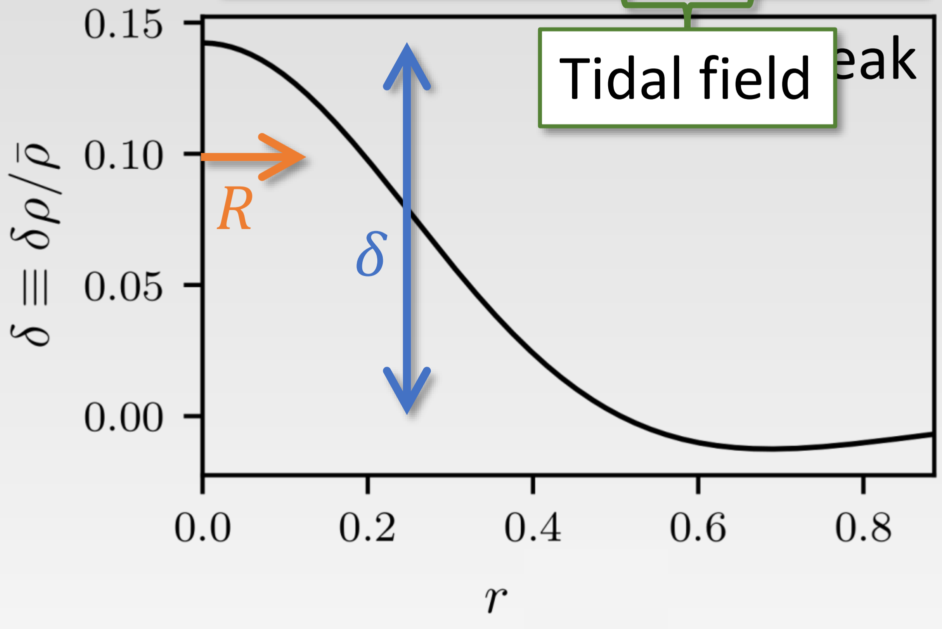
# What sets prompt cusp properties?

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

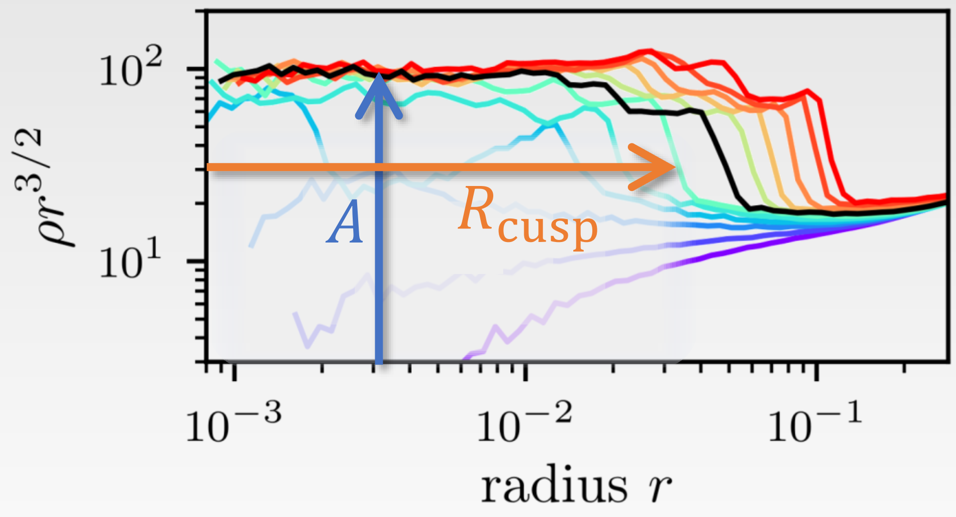



Prompt cusp: $\rho = Ar^{-3/2}$

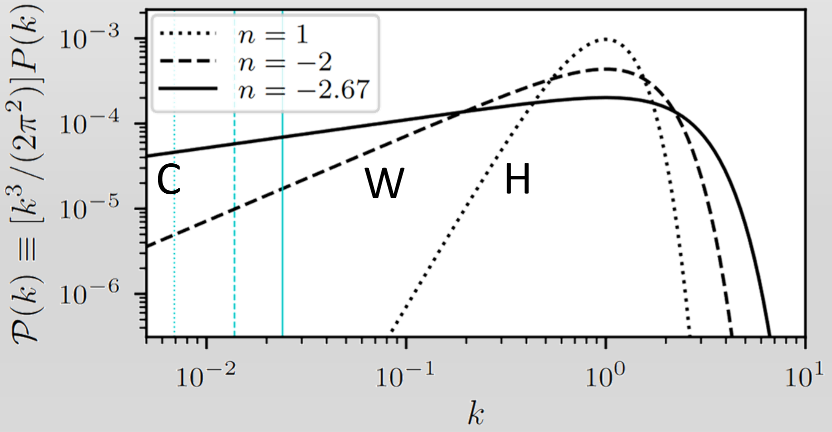
$A \simeq 24\,\bar{\rho}(a_c)\,(a_c R)^{3/2}$

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

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

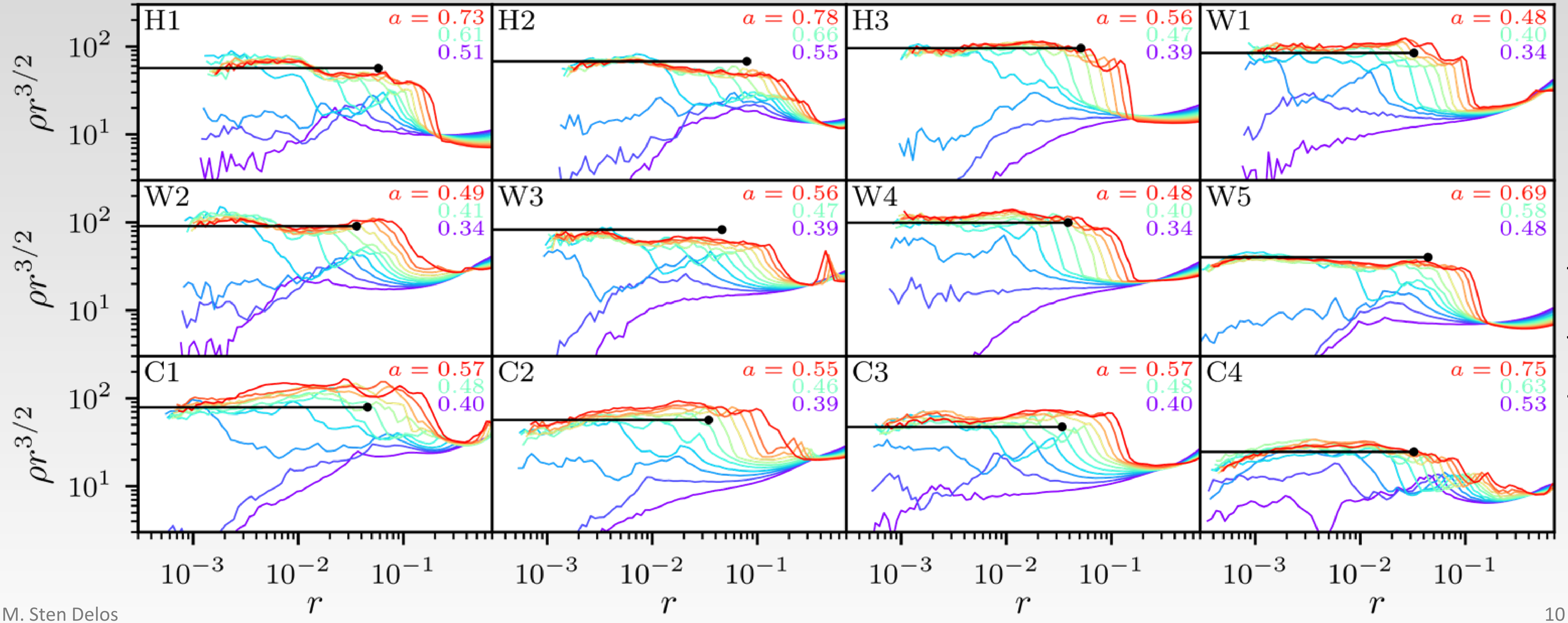


# Cusp properties from peaks




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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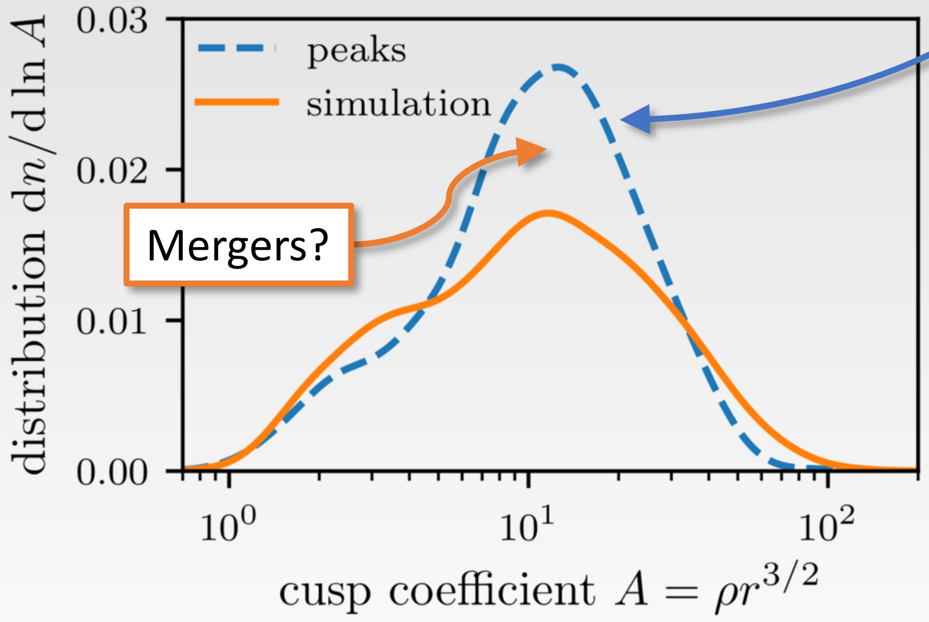
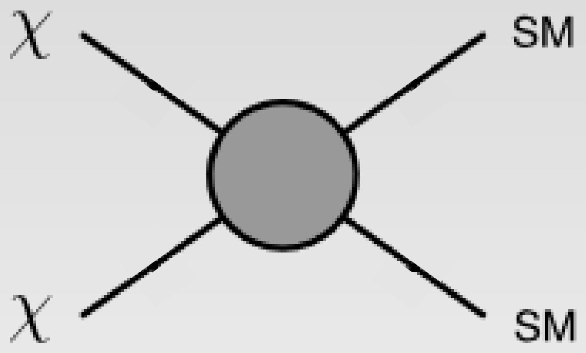



**MSD**, Bruff, Erickcek (2019)

# What is dark matter?

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



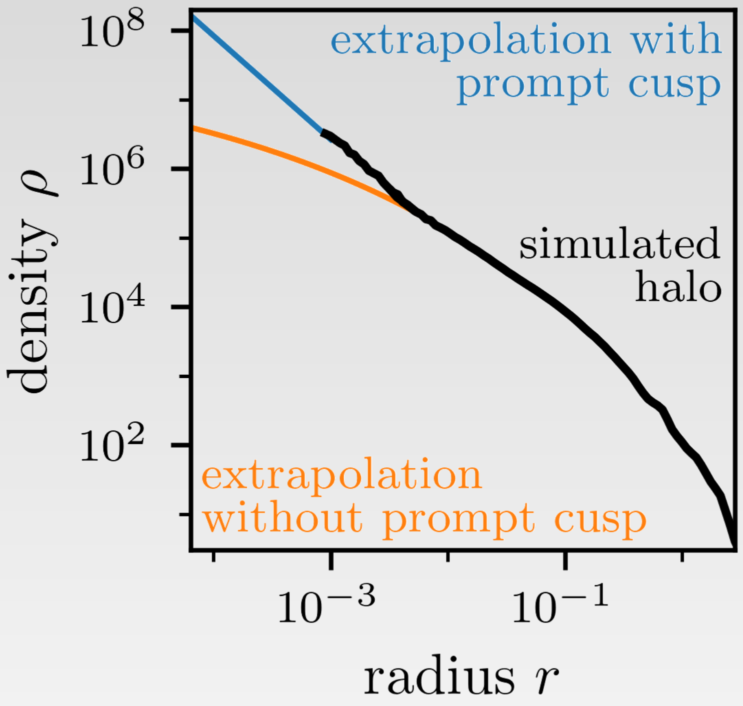

Then dark matter can annihilate into detectable SM particles today!

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

# Prompt cusps and dark matter annihilation

Prompt cusp survival implies **every halo and subhalo** has one

Extreme density inside prompt cusps boosts the annihilation rate ($\propto \rho^2$)



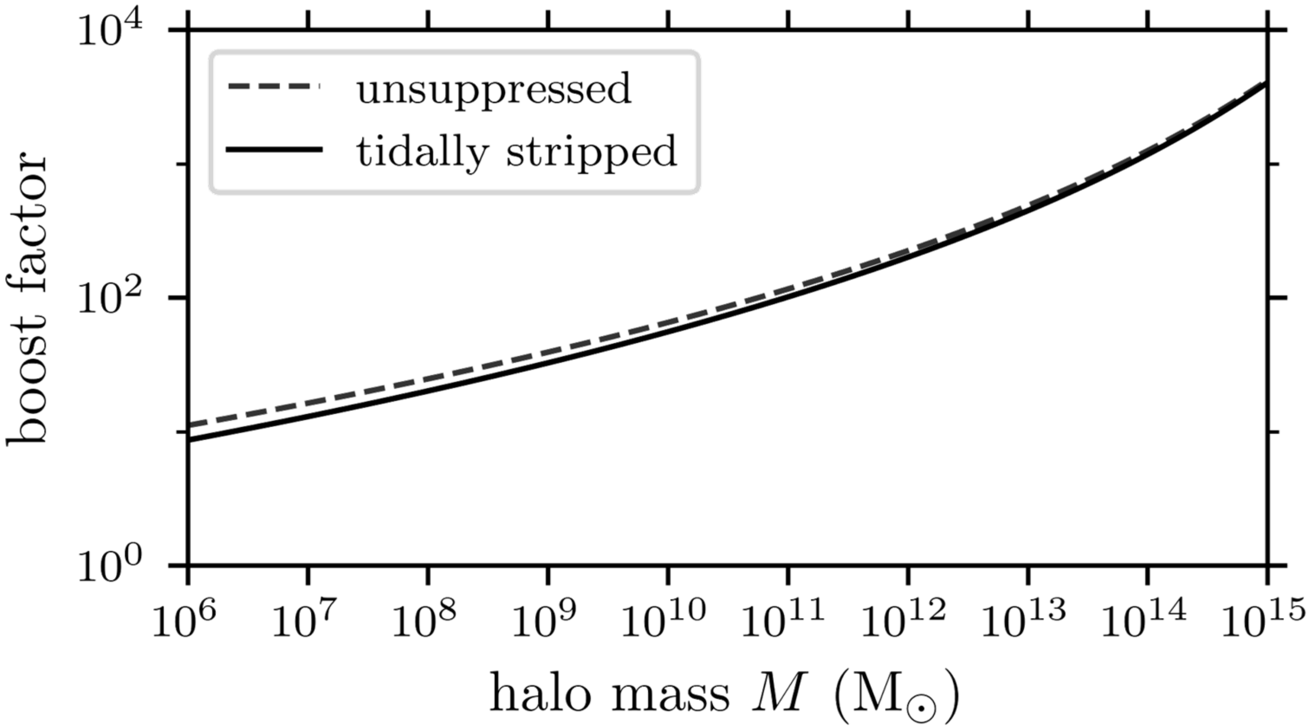

Egalitarian: every halo, no matter its size, has (roughly) **the same prompt cusp**

# Annihilation in prompt cusps

Example: 100 GeV WIMP (decoupling at 30 MeV)

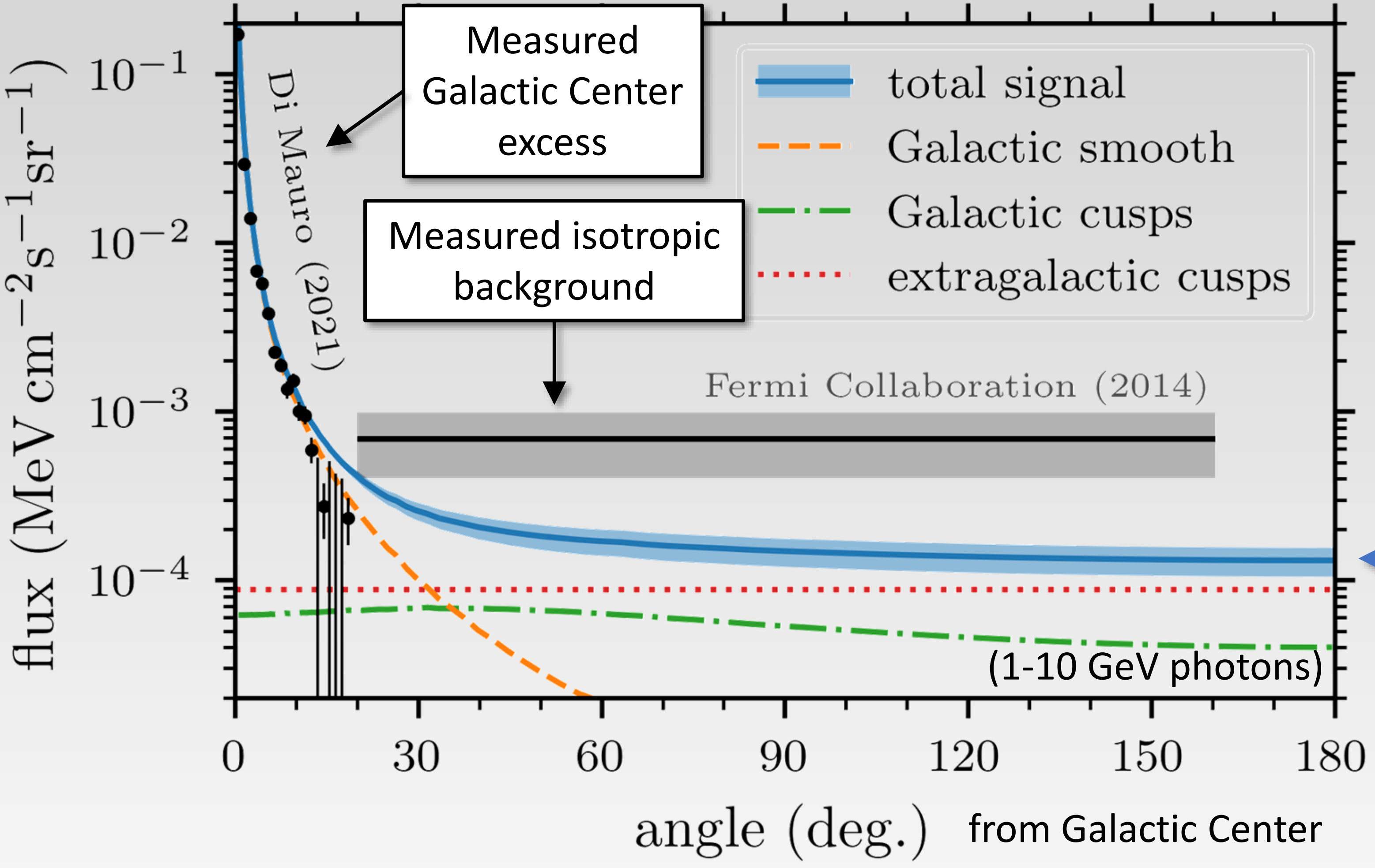
Statistics of peaks $\Rightarrow \sim 20000$ sub-earth-mass cusps per $\mathrm{M}_\odot$ of DM

Annihilation boost inside larger halos:




Also, different spatial distribution $\sim \rho$ (not $\rho^2$)

# Annihilation in prompt cusps



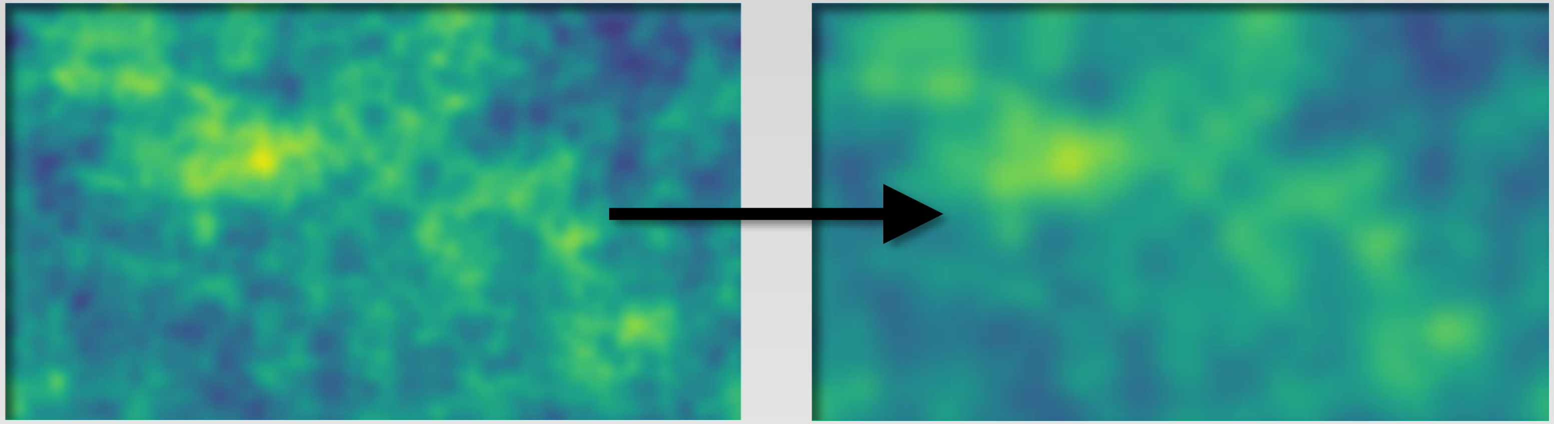

No annihilation boost in the centers of galactic halos (cusps disrupted & density already high), but annihilation everywhere else is greatly boosted.

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

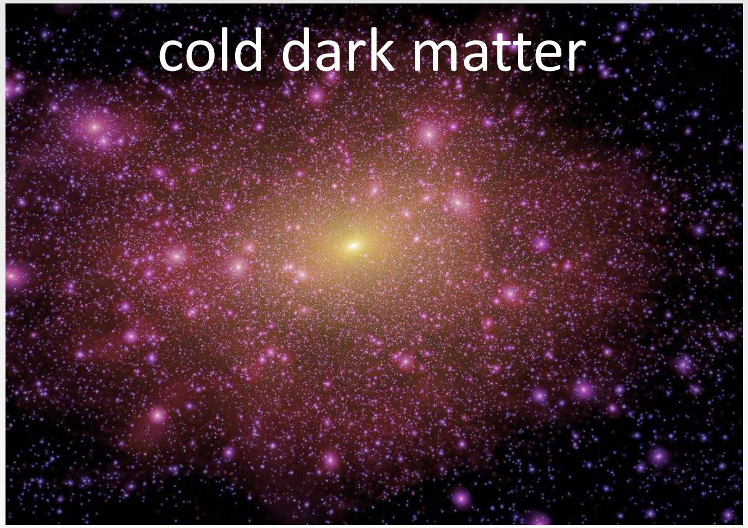
Galactic cusps suppressed by tidal forces & stellar encounters per Stücker et al. (2023)

# Warm dark matter

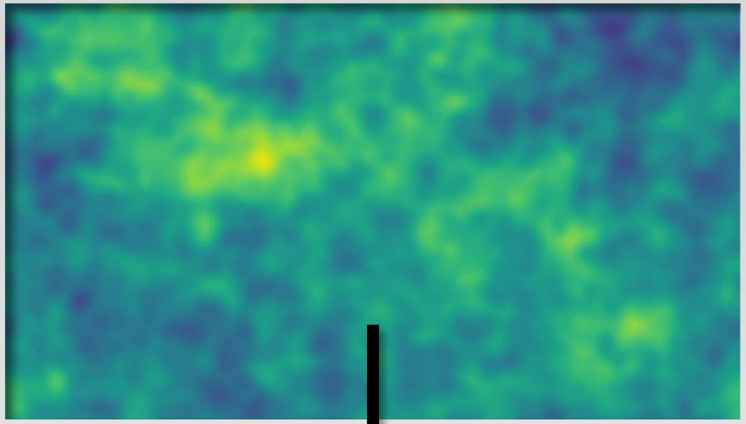
Random particle motion smooths initial conditions

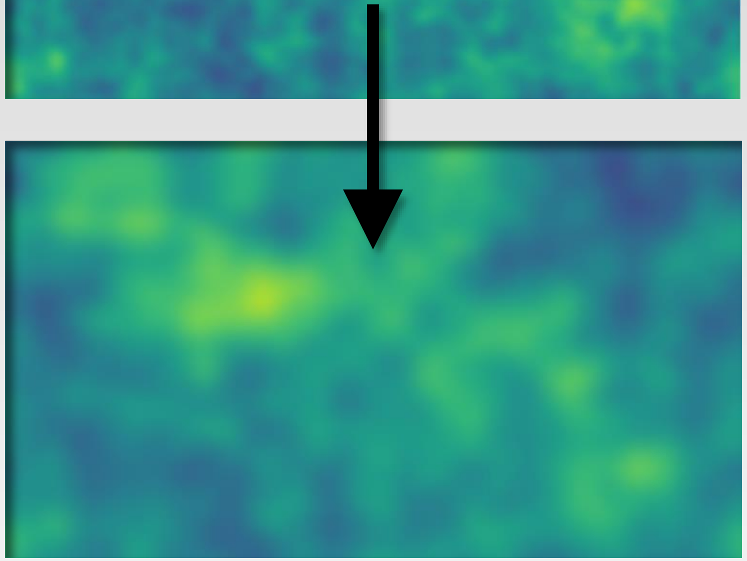


which suppresses the abundance of low-mass halos:

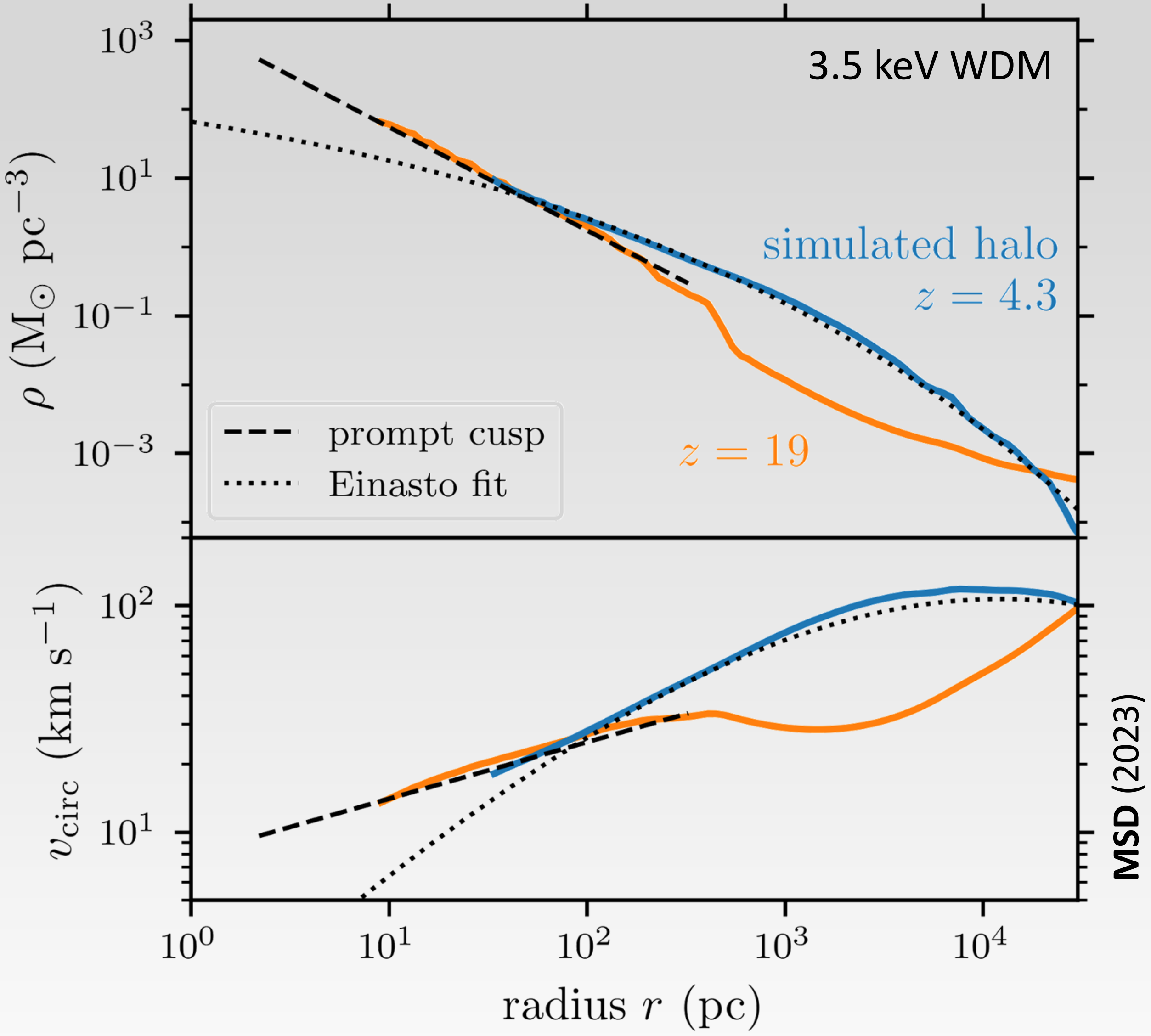



# Prompt cusps of warm dark matter



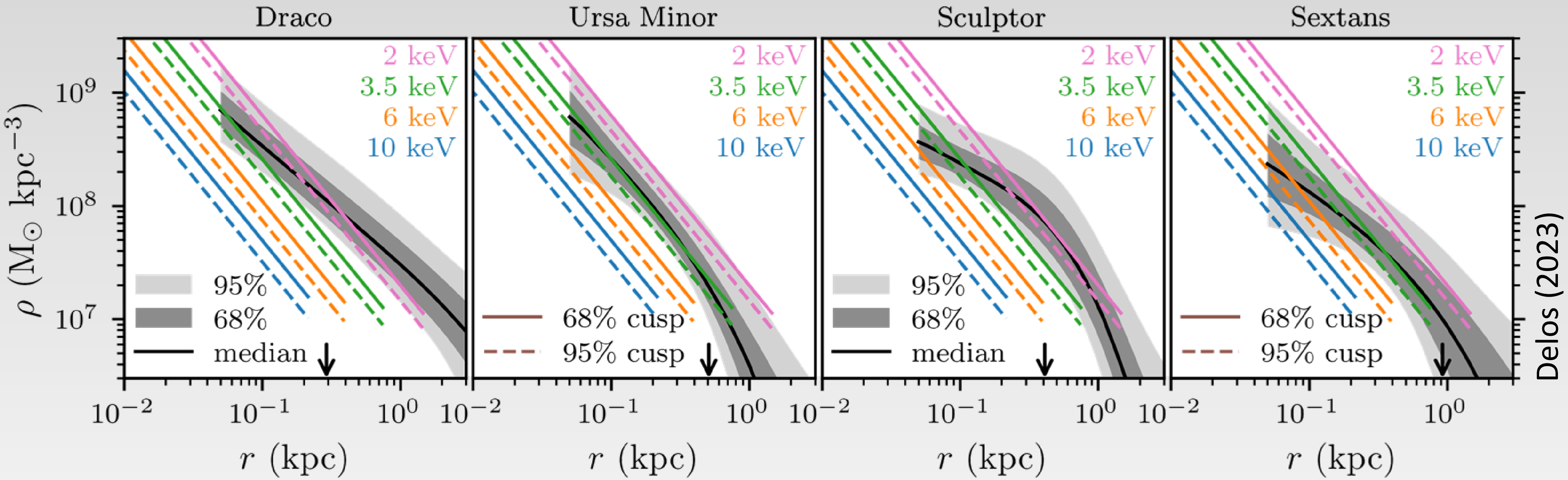


Initial density peaks are much larger
→ Prompt cusps are much larger



# Searching for WDM prompt cusps

We can search for prompt cusps within nearby dwarf galaxies:




Better constraints come from ultrafaints (Delos 2023), but plots don't look as nice

Inferred profiles from Hayashi et al. (2020)

# Summary

Gravitational collapse 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 DM is warm, prompt cusps should affect galactic kinematics and potentially other observables.