Prompt cusps of the first halos

(or why collisionless cold dark matter is still exciting)

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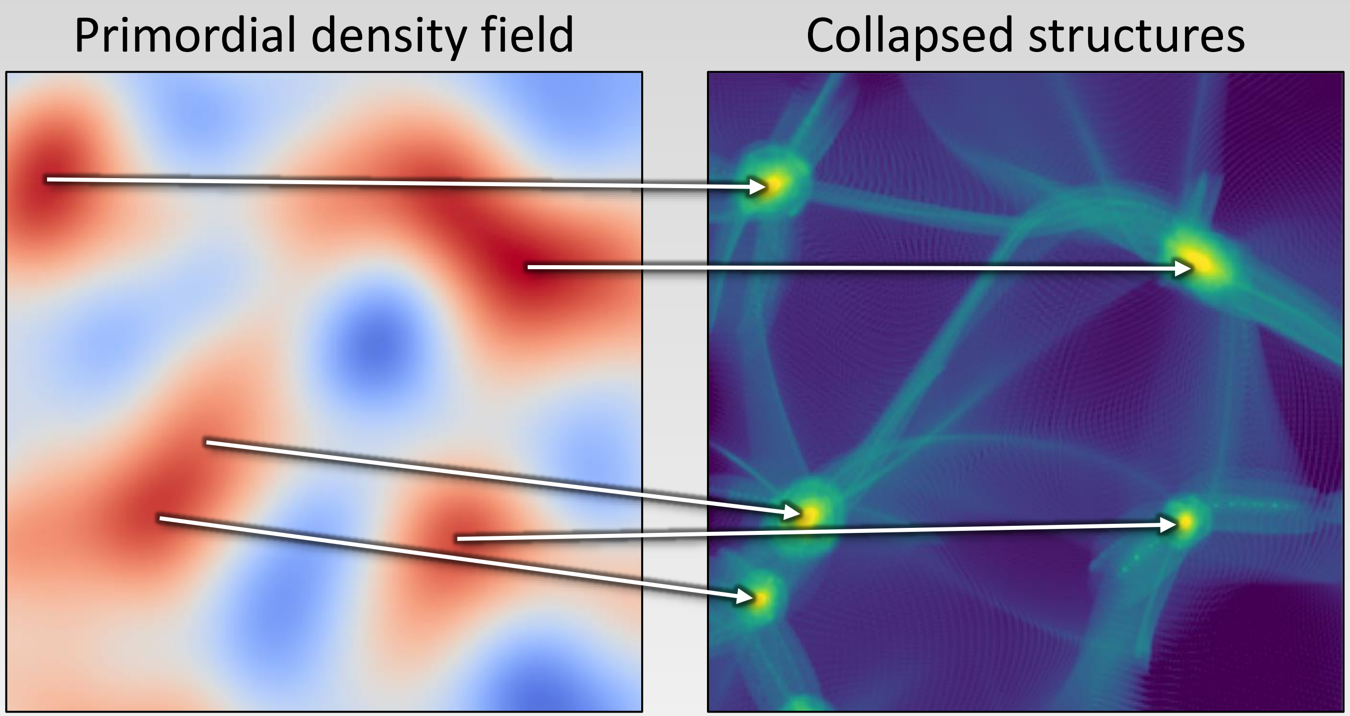
The first halos

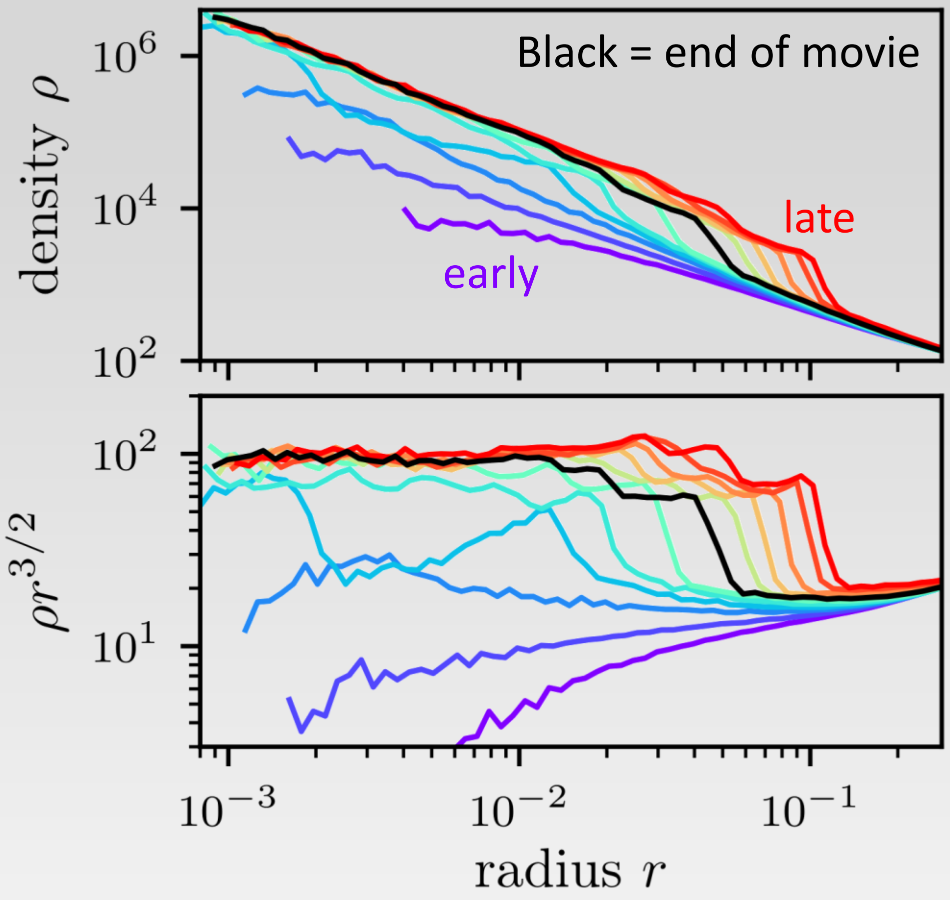
The first dark matter halos form from smooth density peaks.



(smoothed by free streaming)

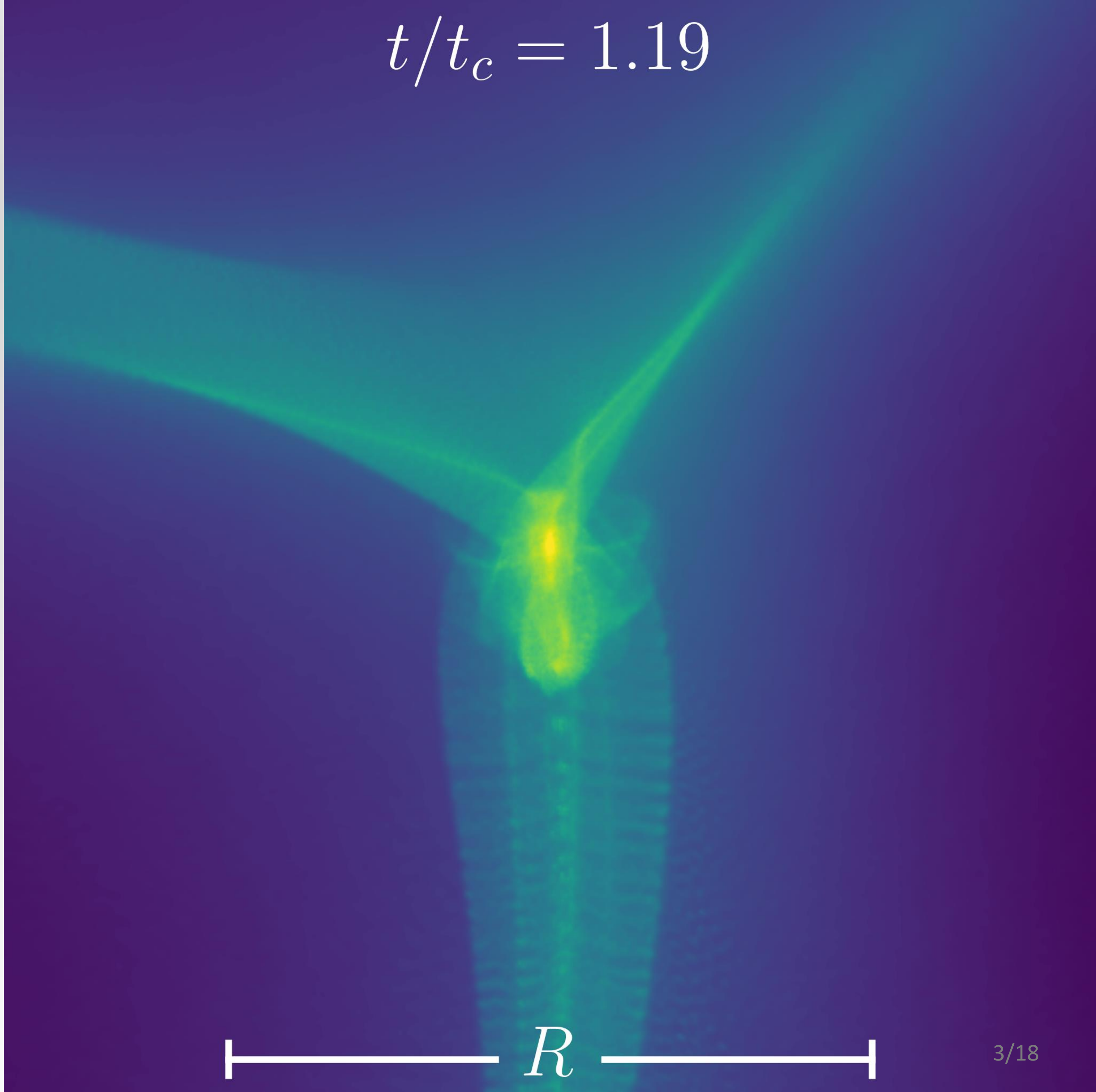
Normally not resolved in simulations [~earth mass]

Prompt cusps



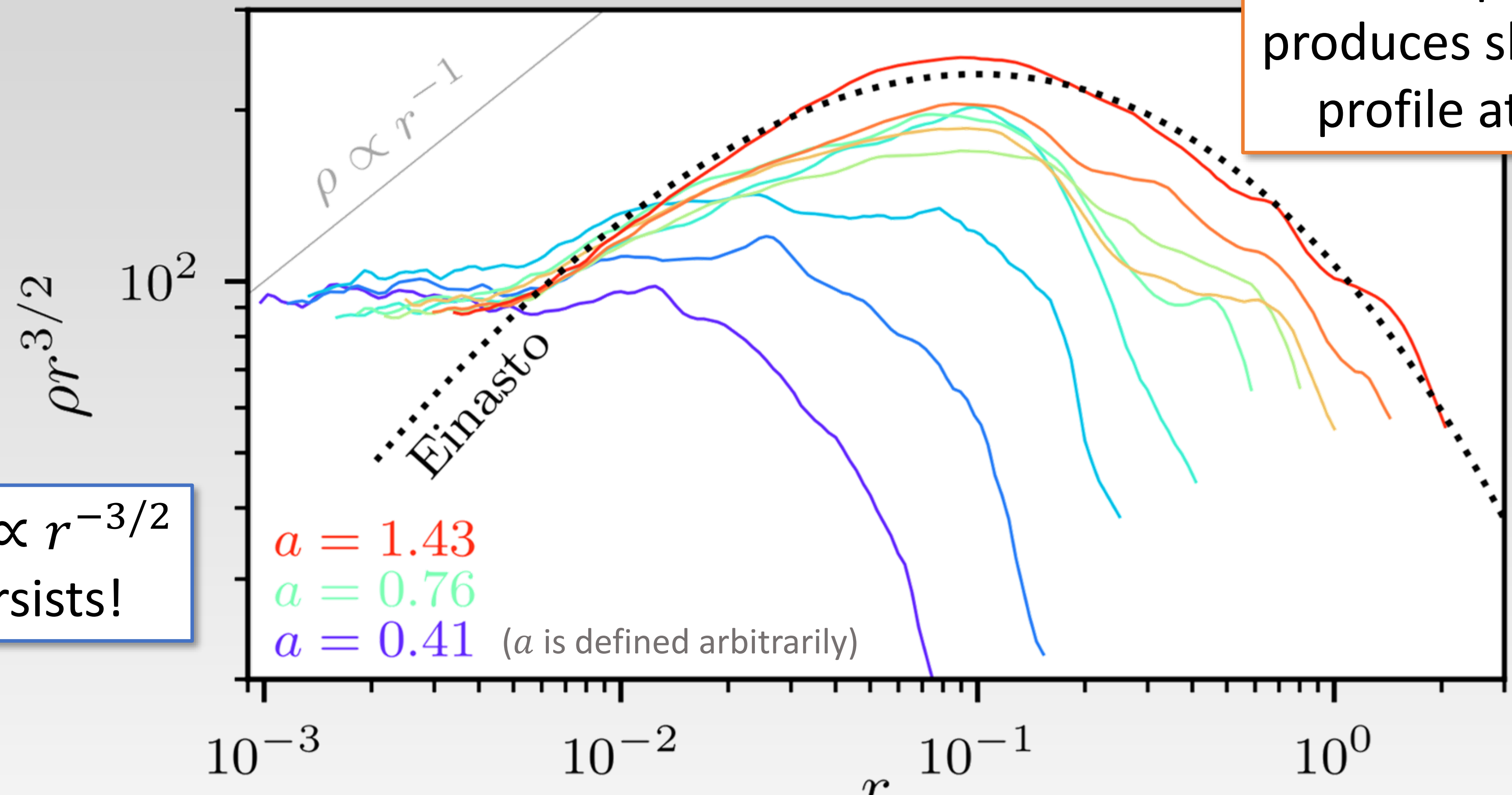
$\rho \propto r^{-3/2}$ cusp stabilizes immediately after formation

"prompt"



Prompt cusp persistence

Buildup of material produces shallow Einasto profile at larger radii

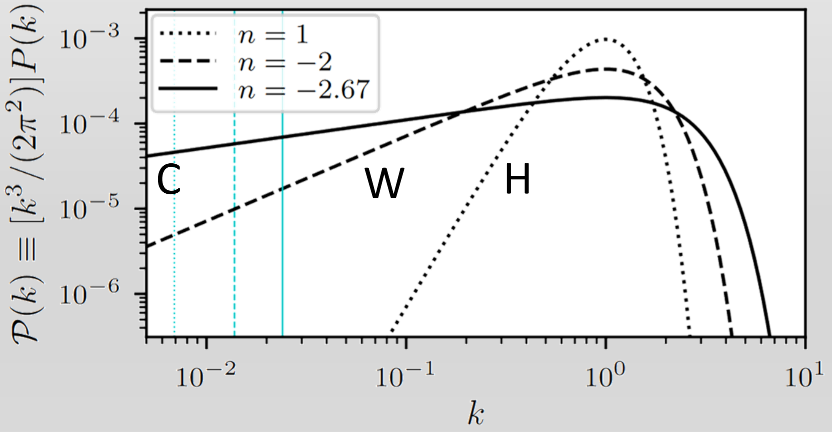


Central $\rho \propto r^{-3/2}$ cusp persists!

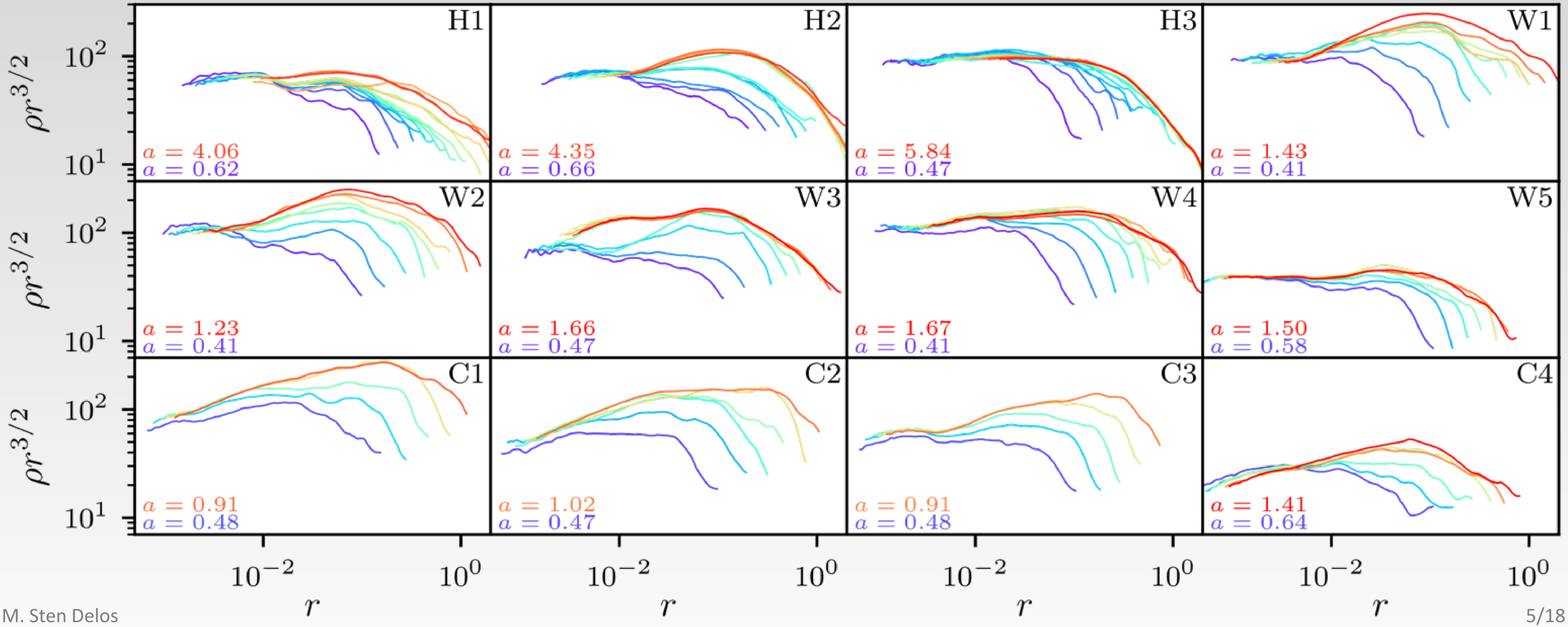
MSD & White (2022)

Outcome: standard CDM density profile + prompt cusp

Prompt cusps: broader picture



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

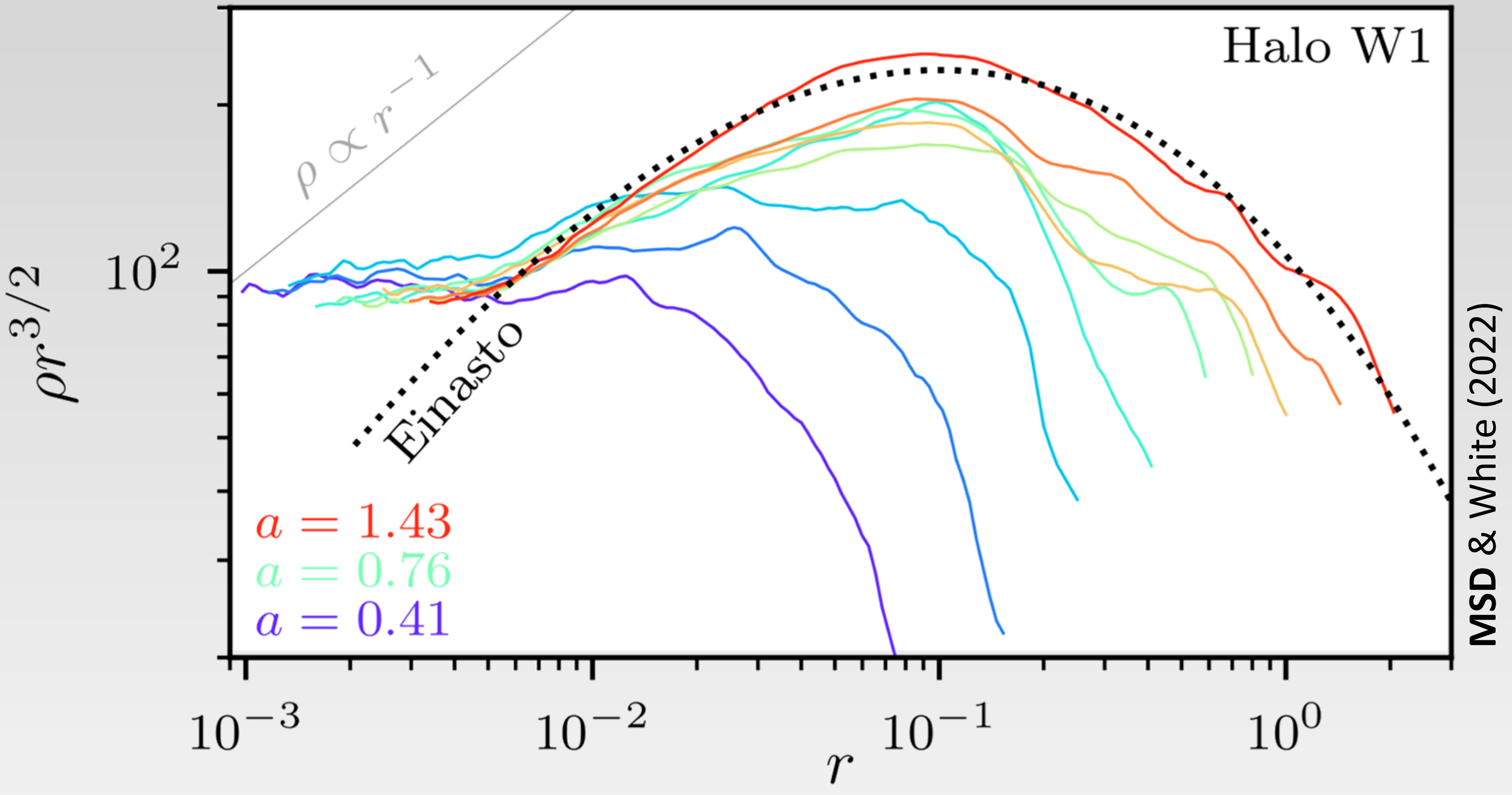


MSD & White (2022)

Prompt cusp persistence is natural

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

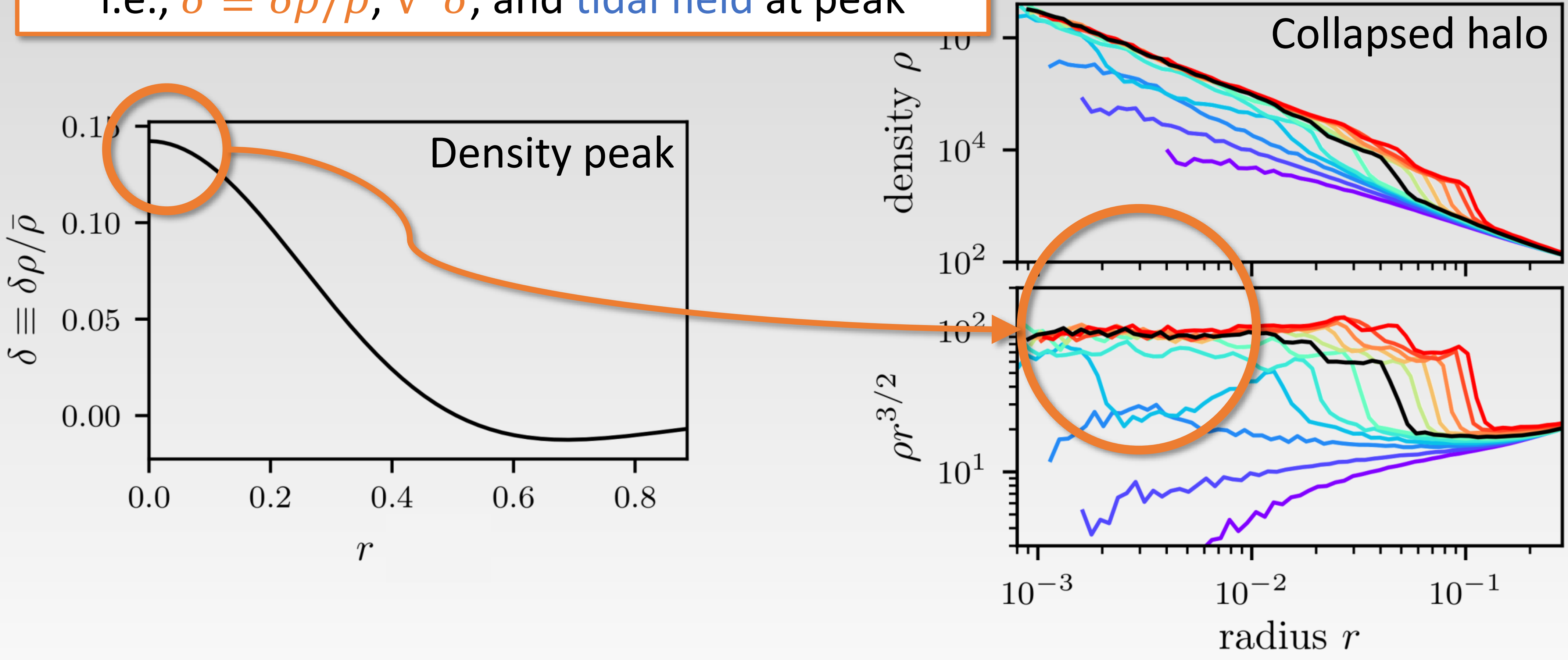
Only major mergers can deposit material into the center, but impact is minor



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

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



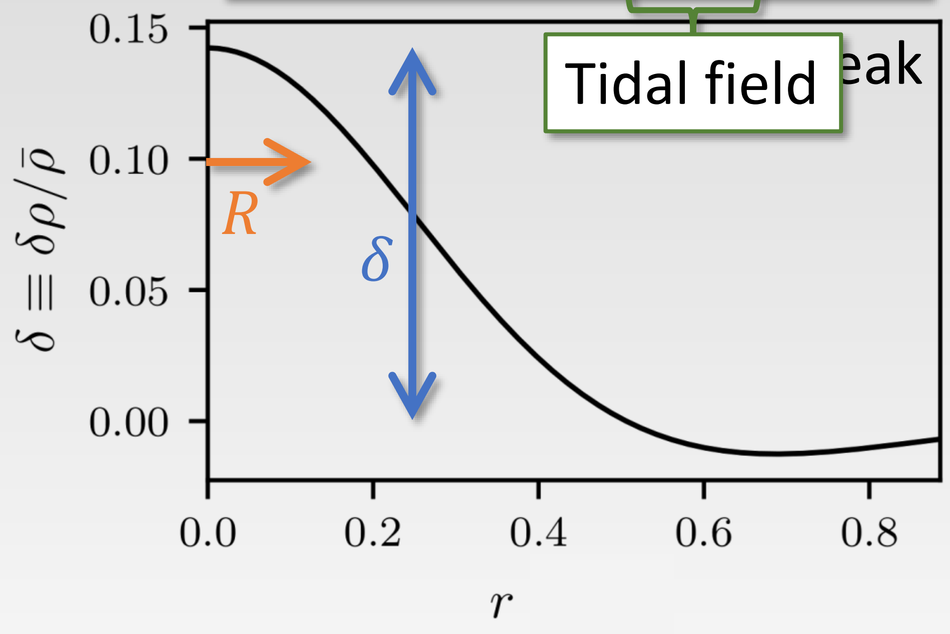
What sets prompt cusp properties?

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

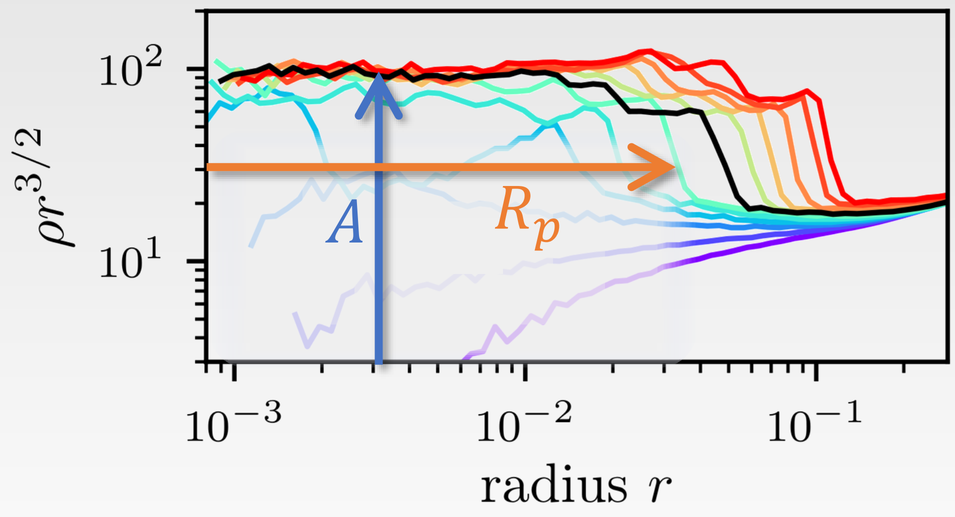


Prompt cusp: $\rho = Ar^{-3/2}$

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

$$M_p \simeq 7.3\,R^3\,\bar{\rho}_0$$

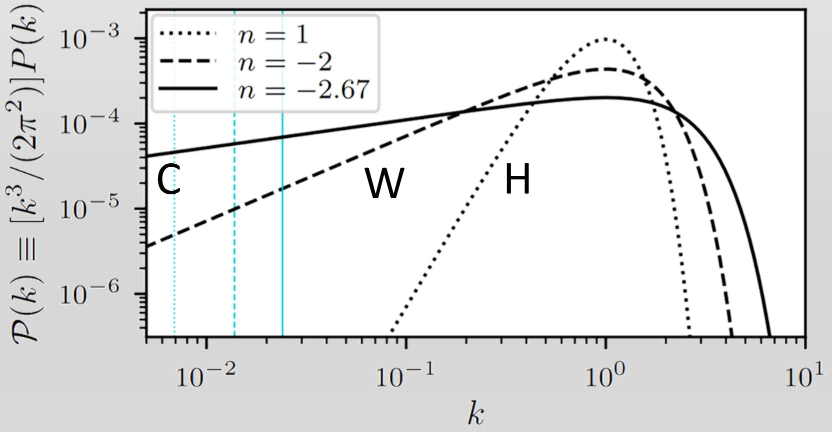
$$R_p \simeq 0.11 a_c R$$

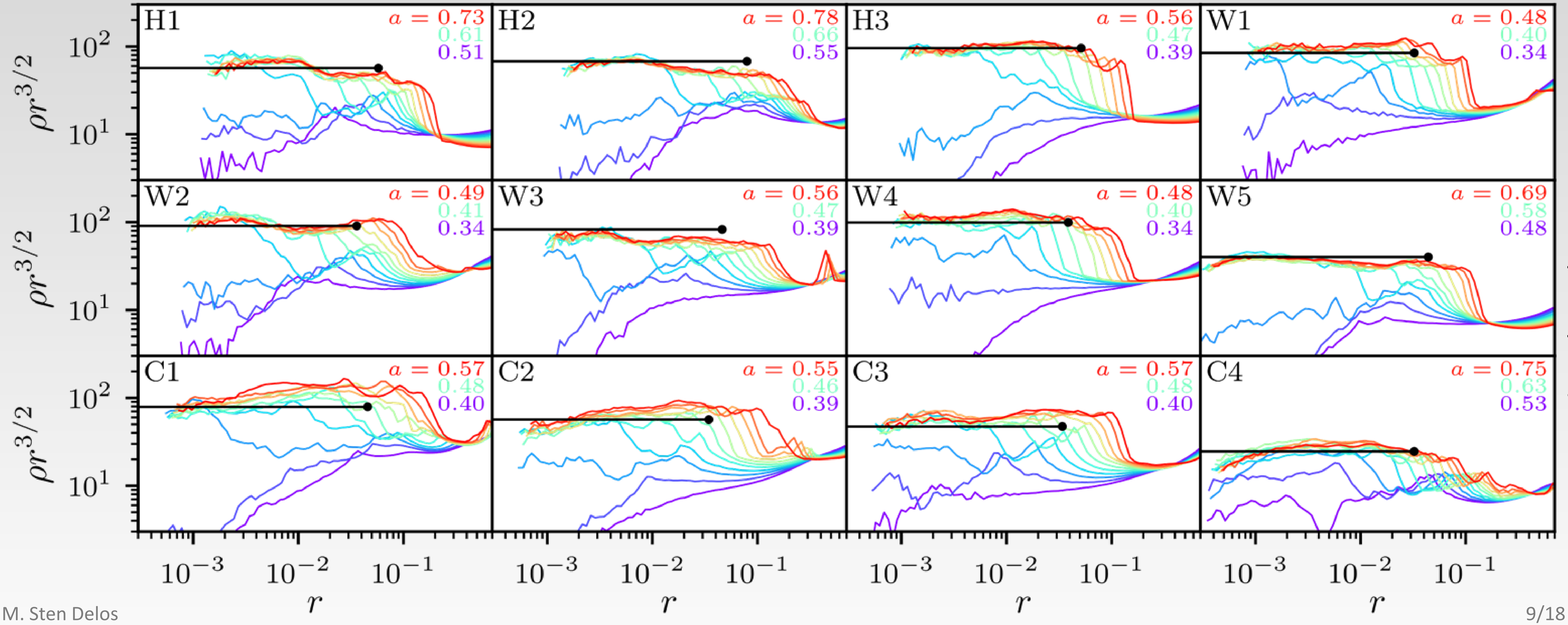


Cusp properties from peaks

Twelve high-resolution halos from three power spectra:

Predictions [black] work well!



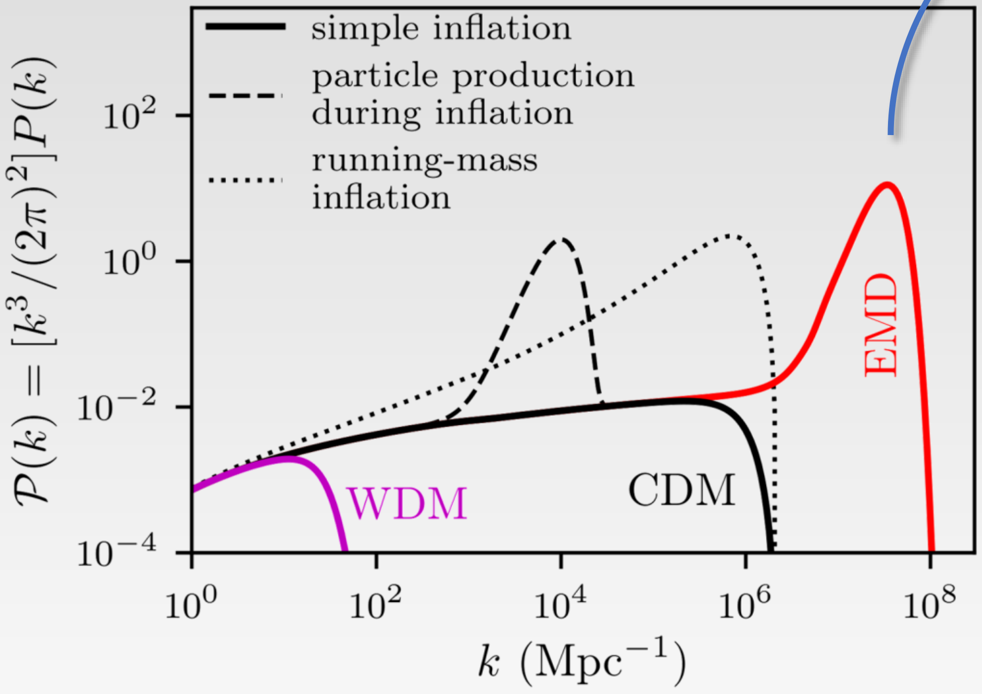


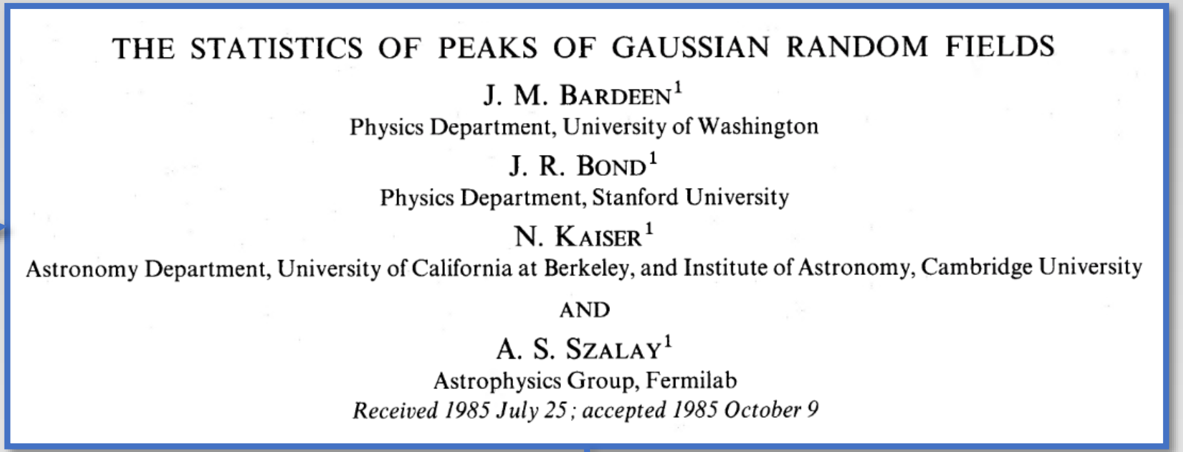
MSD & White (2022)

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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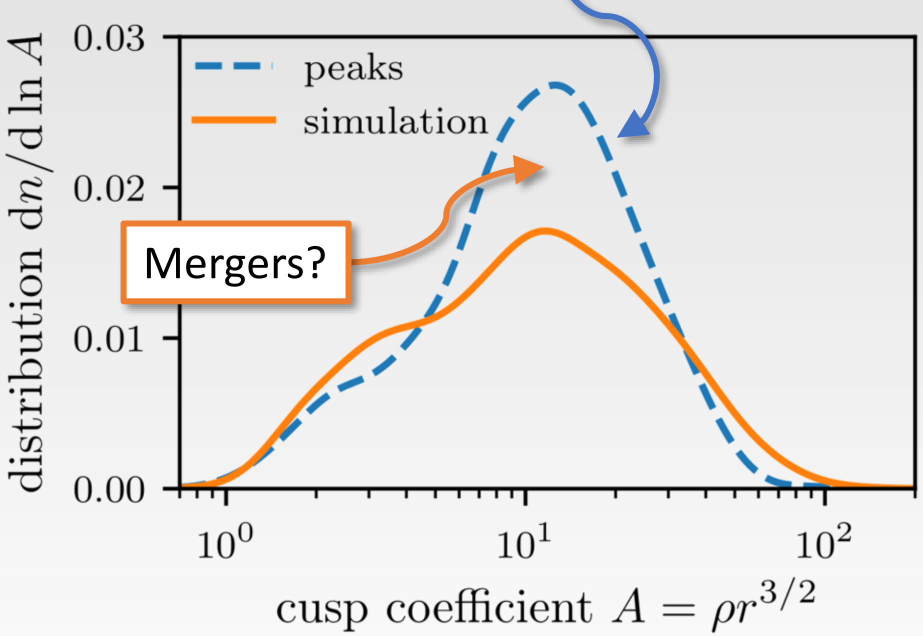


MSD, Bruff, Erickcek (2019)

Central cores

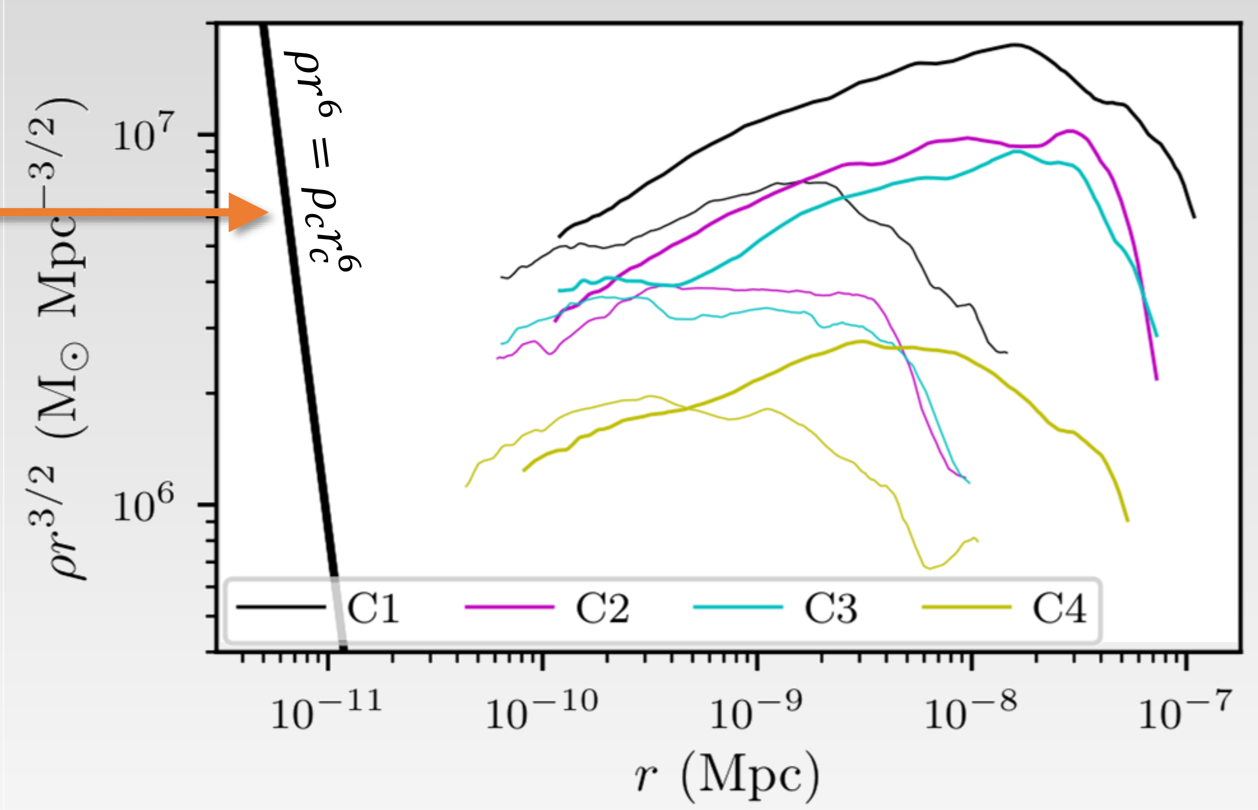
Any density cusp must give way to a finite-density core at small radii due to phase-space conservation

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

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



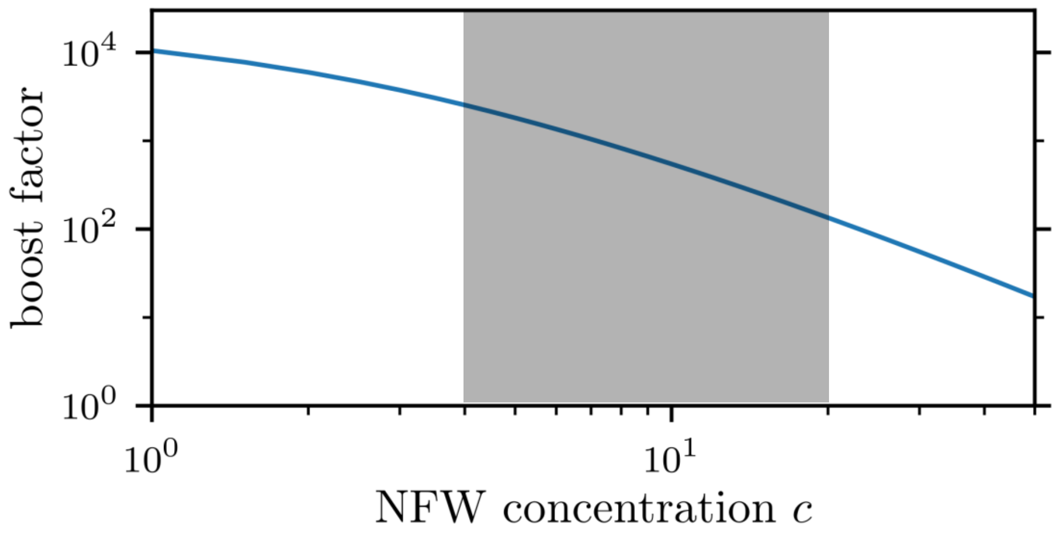
MSD & White (2022)

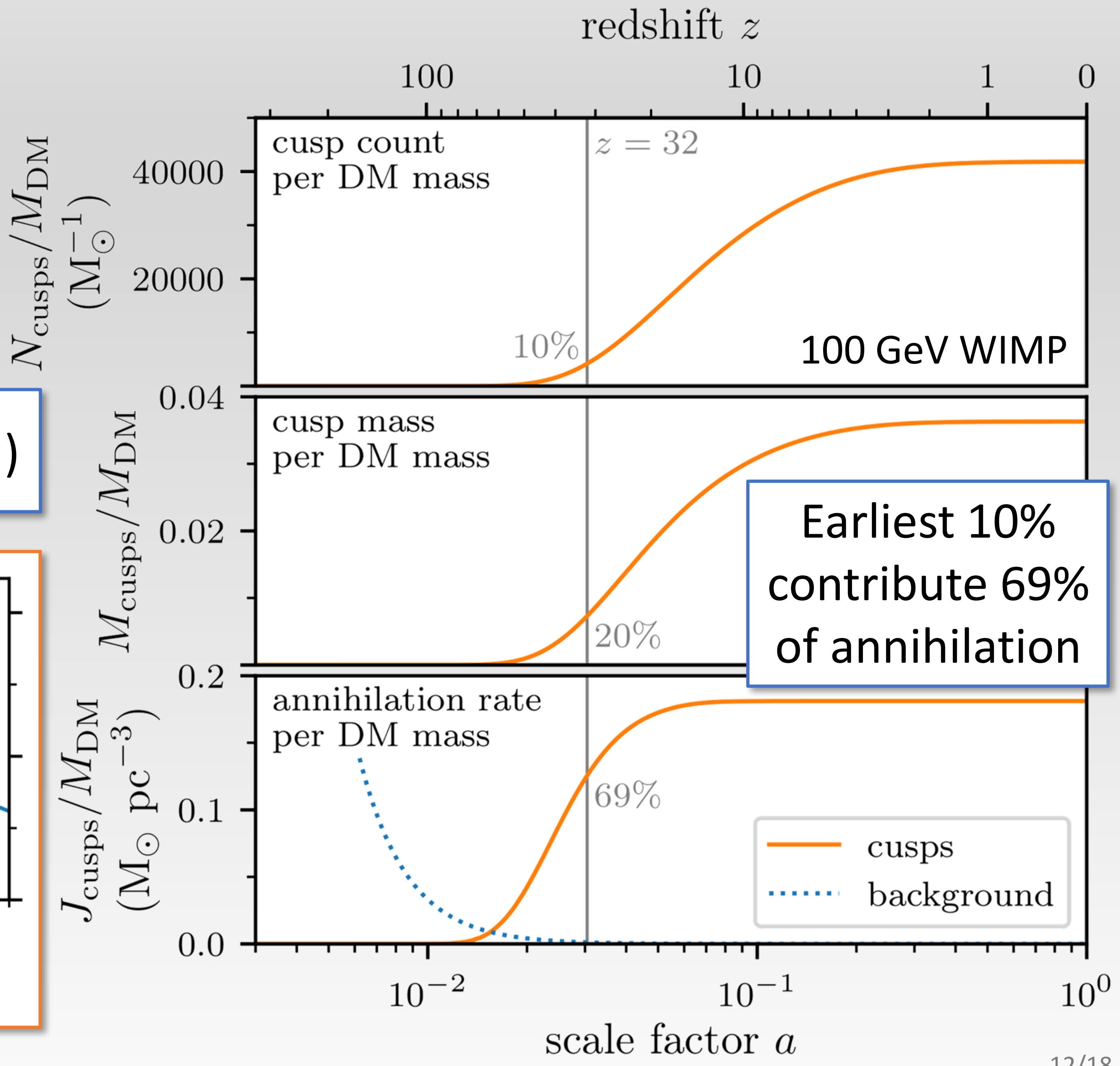
$\rho \propto r^{-3/2}$ cusps cover a factor of $R_p/r_c \sim 500$ in radius

Annihilation in prompt cusps

Prompt cusps greatly impact the DM annihilation rate

$$\frac{\text{annihilation rate}}{\text{DM mass}} \propto \frac{\int \rho dM}{M_{\mathrm{DM}}} \simeq 150\bar{\rho}(z=32)$$





Earliest 10% contribute 69% of annihilation

Prompt cusp survival

Subhalo evolution studies have focused on $\rho \propto r^{-1}$ cusps; steeper cusps are not well studied. However:

Theoretical studies

- Stücker et al 2022
- Drakos et al 2022
- Benson & Du 2022
- Amorisco 2021

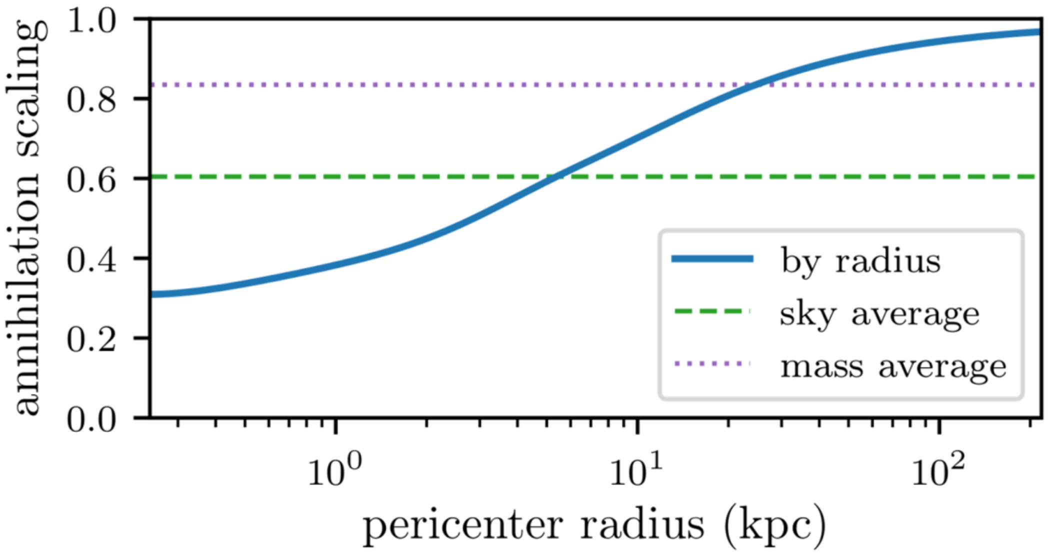
predict cusps are always preserved at sufficiently small radii

Steeper cusps are more resistant to tidal effects:

- More tightly bound
- Lower particle apocenters

Annihilation rate in a $\rho \propto r^{-3/2}$ cusp is only logarithmically sensitive to the outer radius

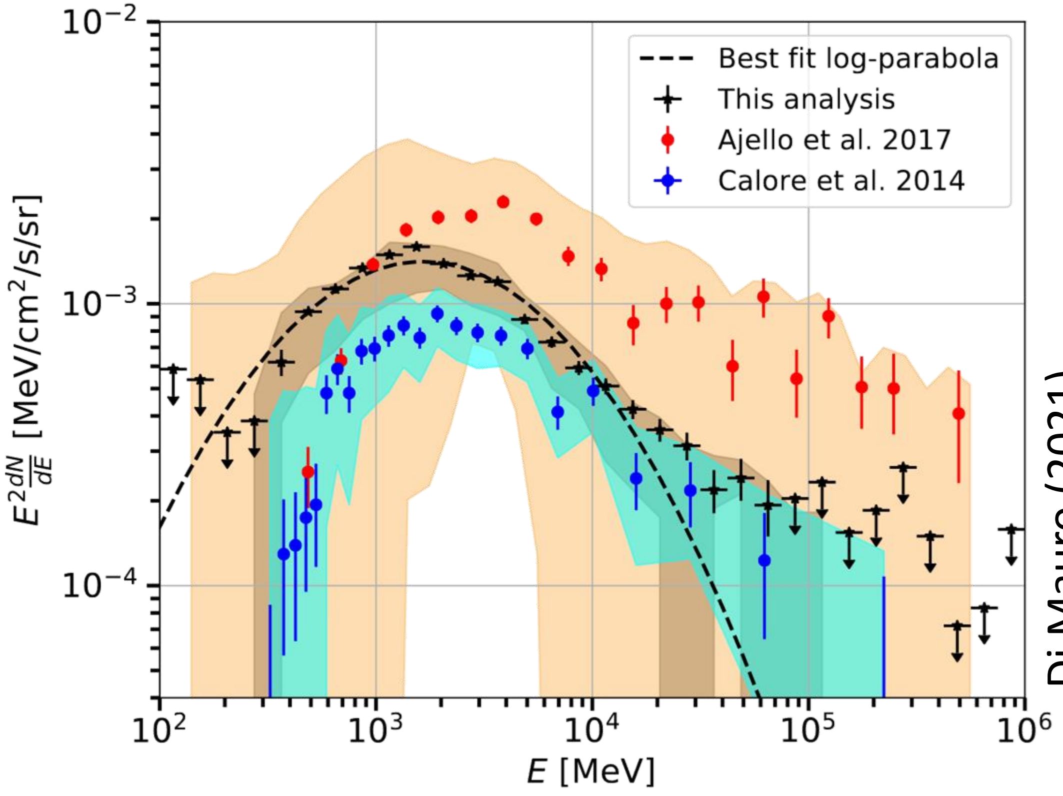
Adiabatic-tides (Stücker et al) prediction for prompt cusp survival in our Galactic halo:



The Galactic Center gamma-ray excess

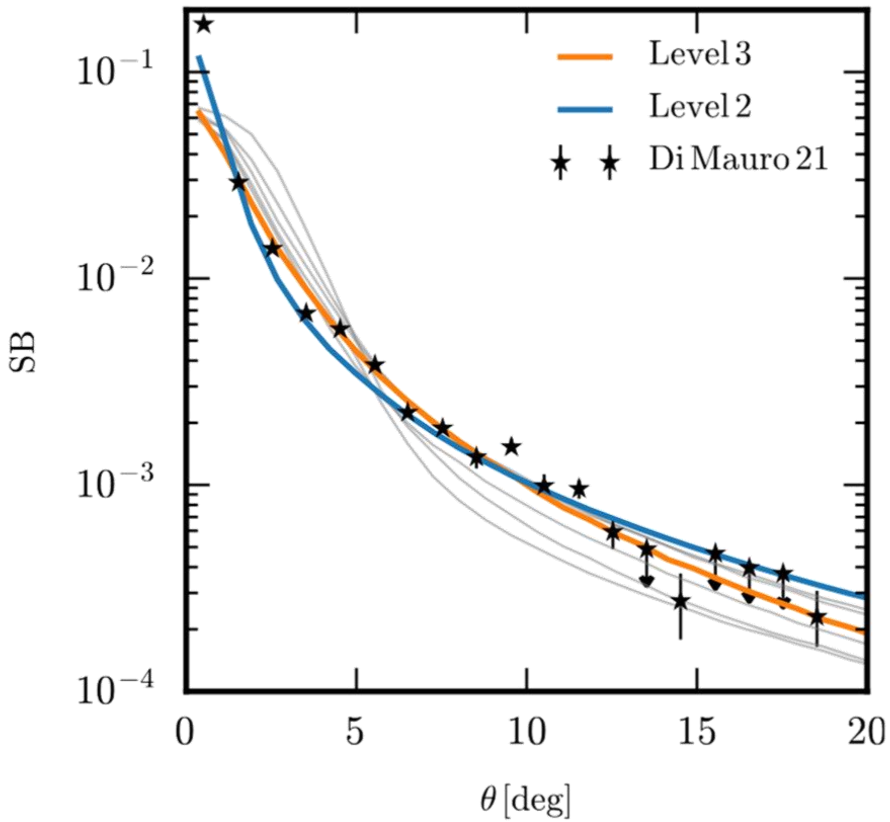
Spatial distribution of annihilation signal changes. Consider GCE as illustration:

Excess of γ rays detected by *Fermi* in the 1-10 GeV energy range



Di Mauro (2021)

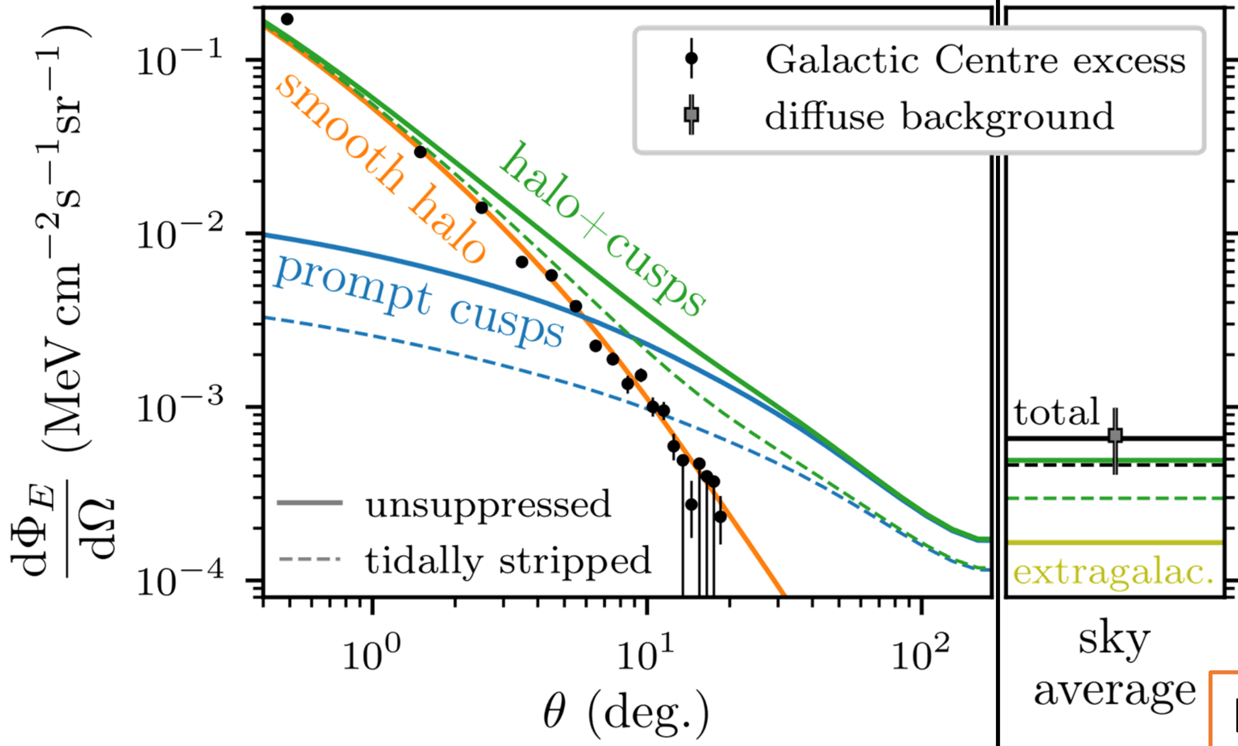
Morphology consistent with DM annihilation from a smooth Galactic halo



Grand & White (2022)

Prompt cusps and the Galactic Center excess

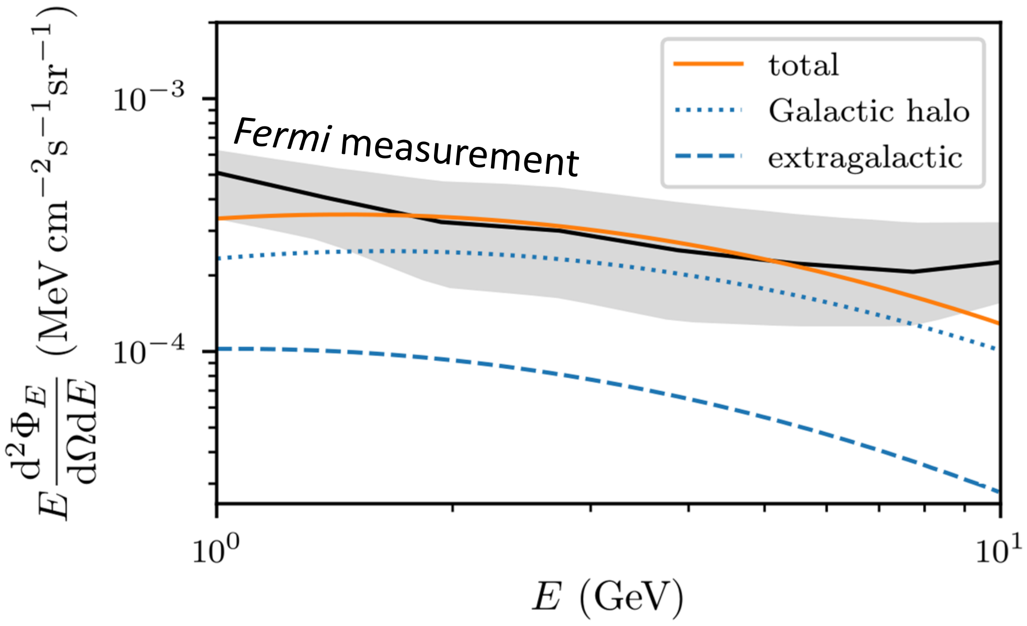
Prompt cusps alter the DM annihilation morphology (ρ, not ρ^2)



GCE is no longer consistent with annihilating DM.

Uncertainty about disruption by stars, though…

Prompt cusps boost the background annihilation signal



If GCE is annihilating DM, diffuse γ-ray background must also be mostly annihilating DM…

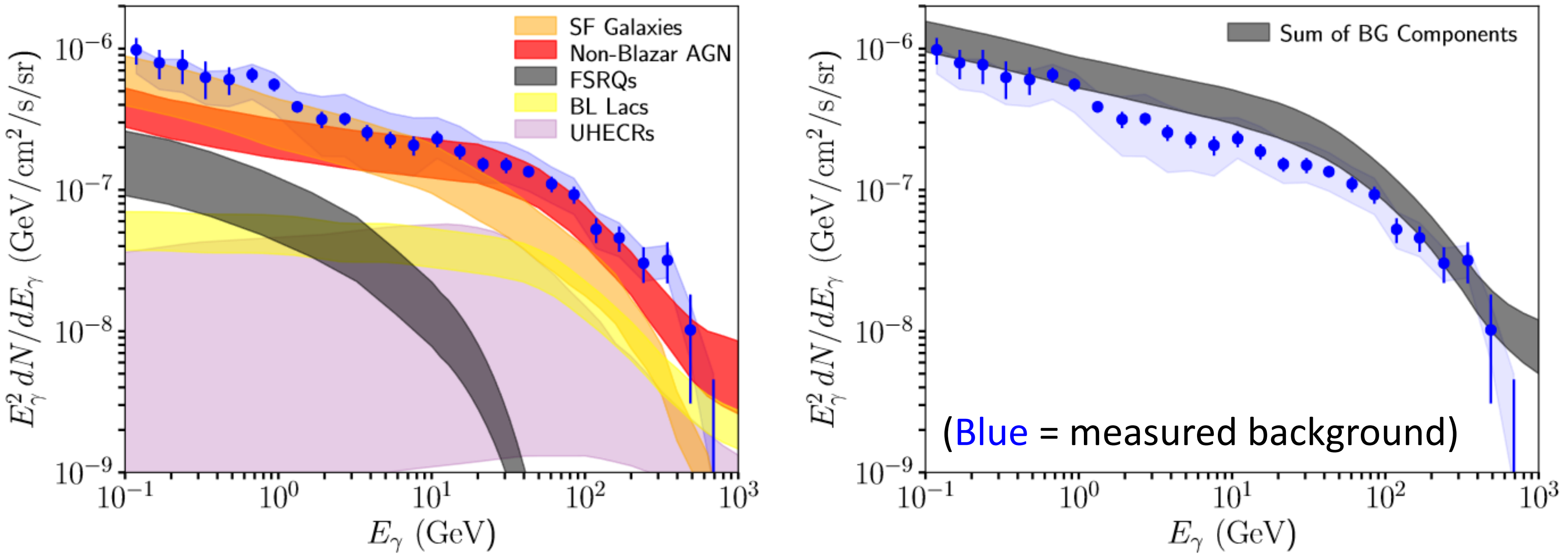
Galactic halo mass model: Cautun et al (2020)

Prompt cusps and the Galactic Center excess

If GCE is annihilating DM, diffuse γ-ray background must also be mostly annihilating DM…

Inconsistent with claims that almost all of the diffuse background comes from known astrophysical sources:

Blanco & Hooper (2019)

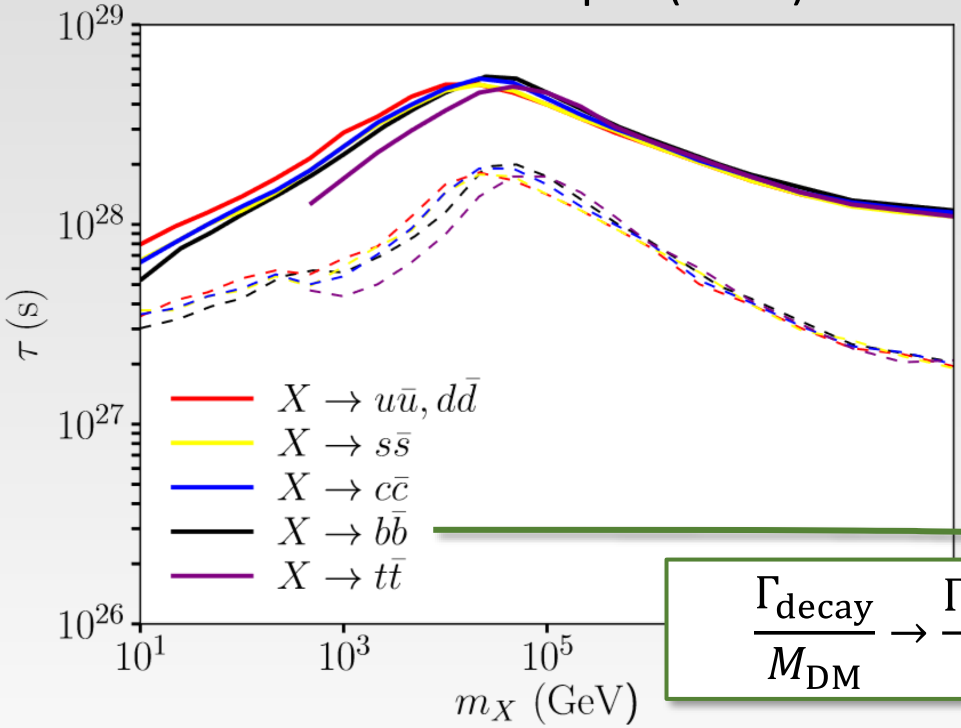


Limits on DM annihilation from the diffuse γ-ray background

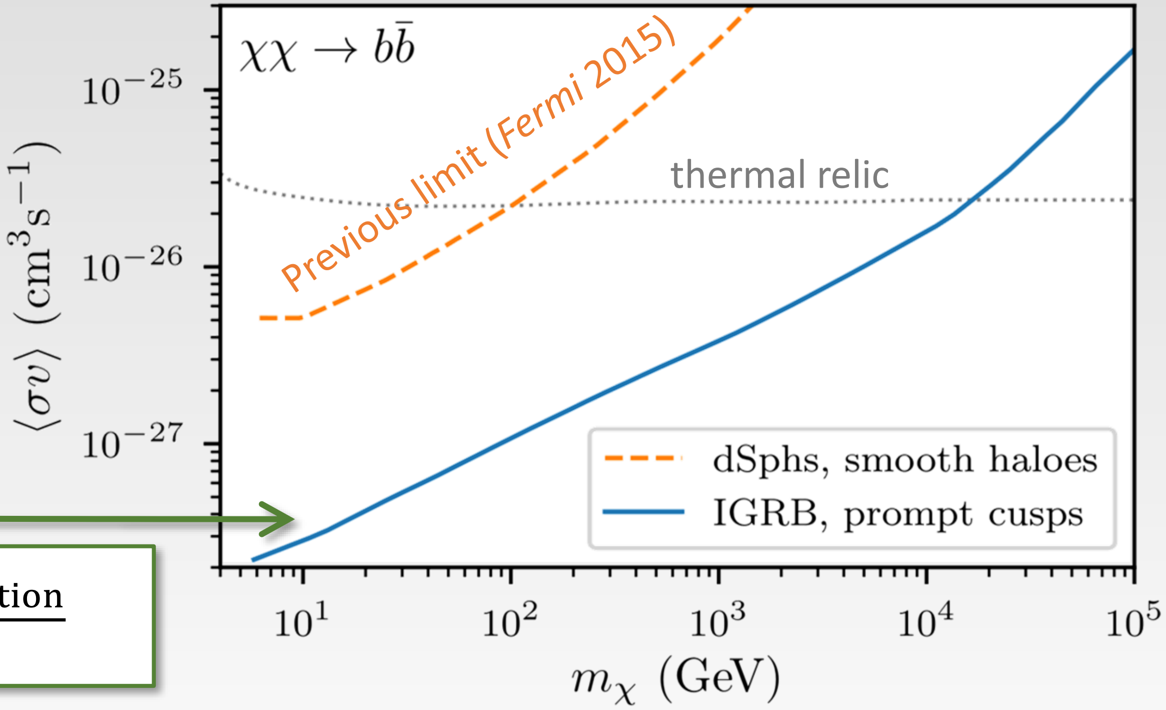
Signal from DM annihilation in unresolved prompt cusps ≃ signal from DM decay

so we can convert between them:

Blanco & Hooper (2019)



$$\frac{\Gamma_{\text{decay}}}{M_{\text{DM}}} \to \frac{\Gamma_{\text{annihilation}}}{M_{\text{DM}}}$$



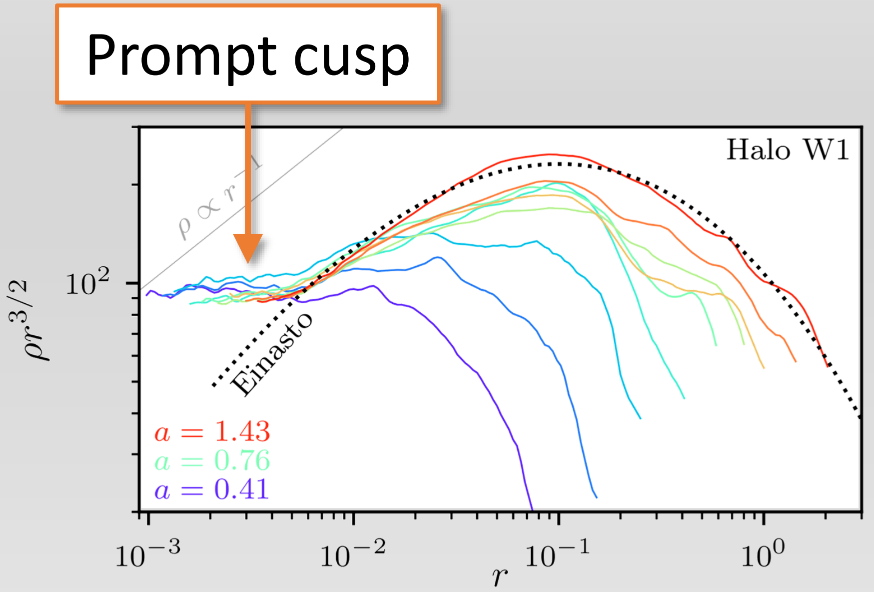
Summary

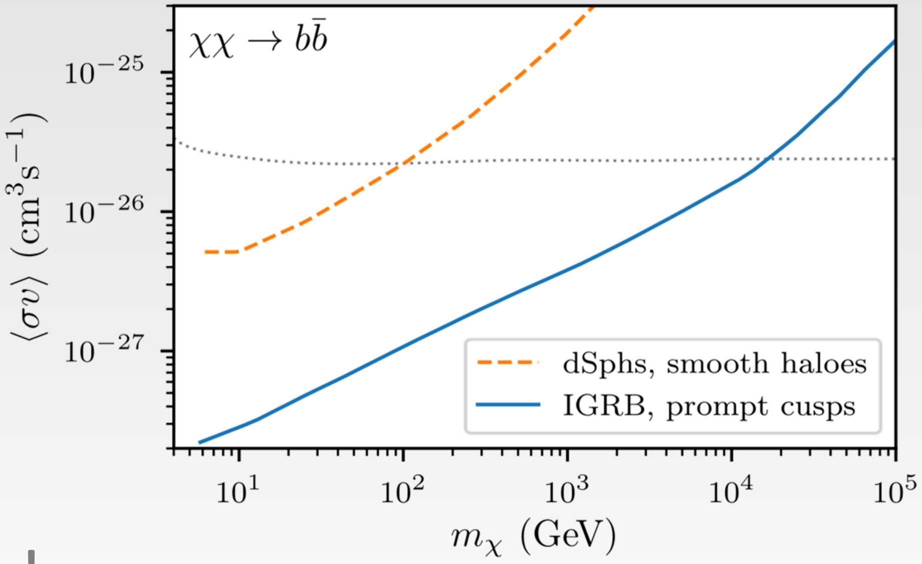
The first halos develop prompt $\rho \propto r^{-3/2}$ cusps, which

- persist through halo growth
- are particularly resistant to subhalo evolution
- have straightforwardly predictable properties

Prompt cusps have a major impact on DM annihilation

- Boost factors range from hundreds to thousands
- Different morphology: rate $\propto \rho$ instead of ρ^2
- Challenge to annihilation interpretation of GCE
- Unprecedentedly strong limits on annihilating DM



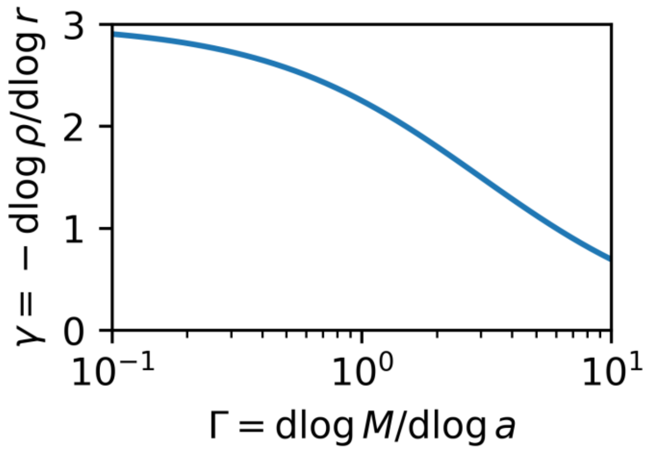


CDM is still exciting!

Rapid accretion

Shallow NFW/Einasto profiles follow from the accretion history

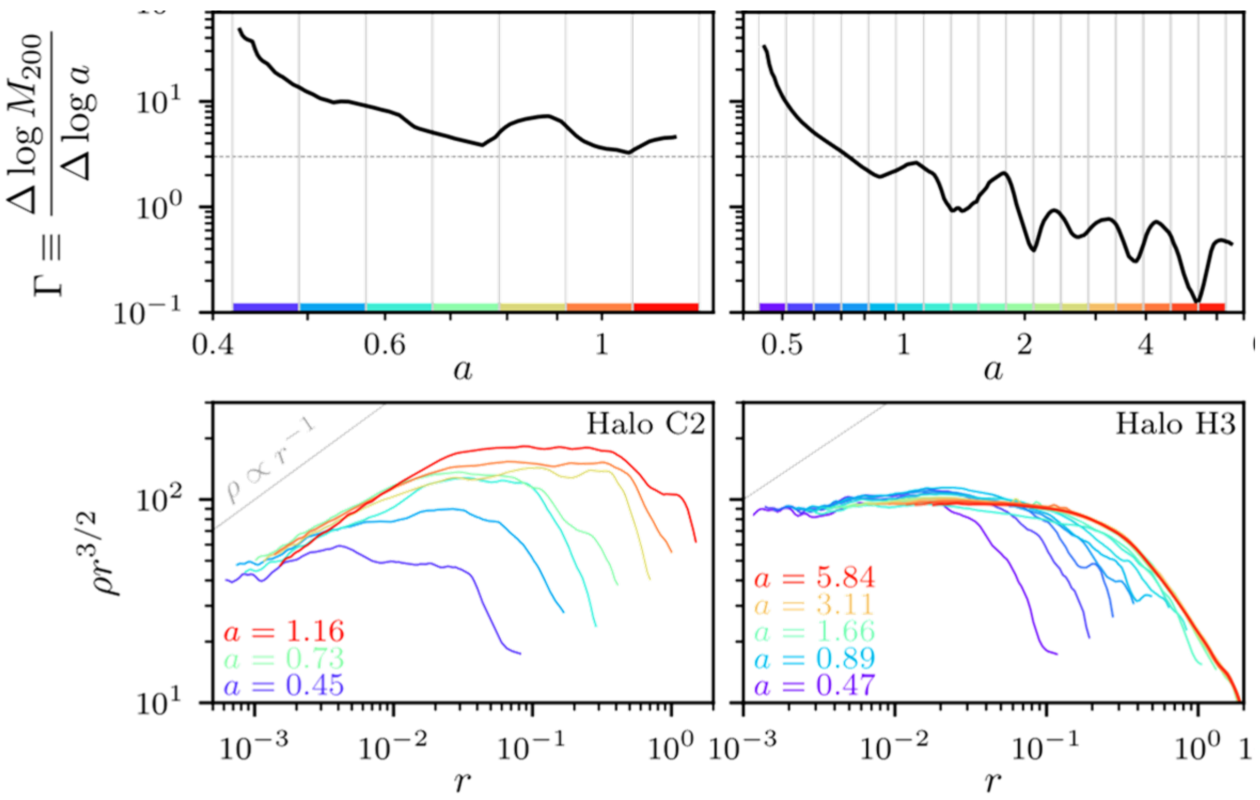
Self-similar models predict
faster accretion → shallower profile



Physically, new material
- builds up density at large radii
- contributes little to smaller radii

Same idea holds in more realistic models
(Ludlow et al 2013, Dalal et al 2010)

Behavior borne out in the first halos



MSD & White (2022)

Rapid accretion builds up large radii without disrupting smaller radii:
No destruction of prompt cusps

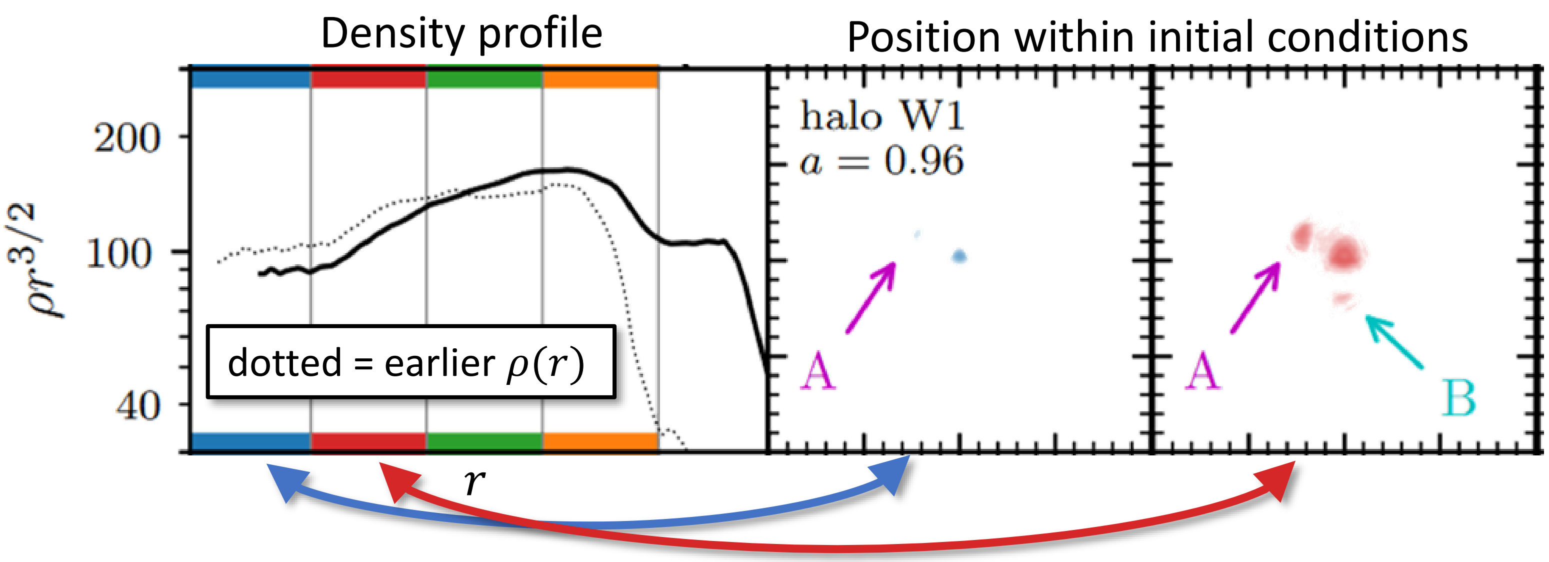
Mergers

Mergers can disturb central cusps:

A massive subhalo sinks due to dynamical friction and can thus disrupt the structure at small radii.

However, the disruption is minimal.

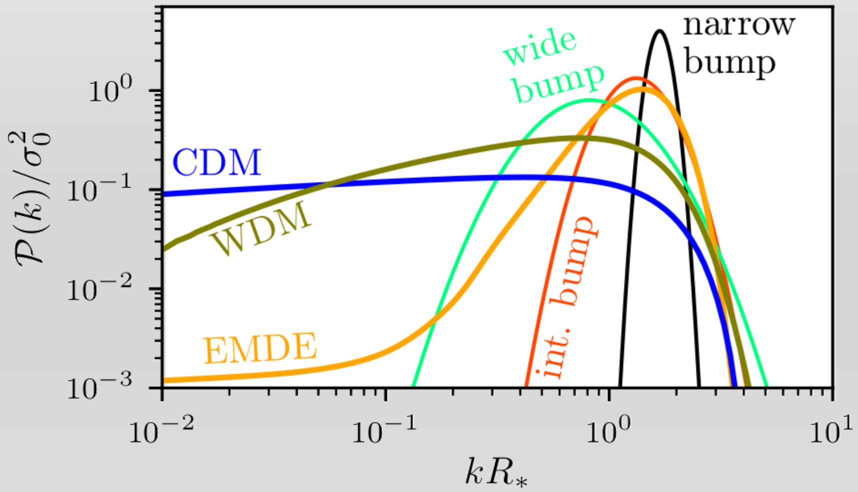
Merging halos ‘A’ and ‘B’ deposited material deep inside this halo…



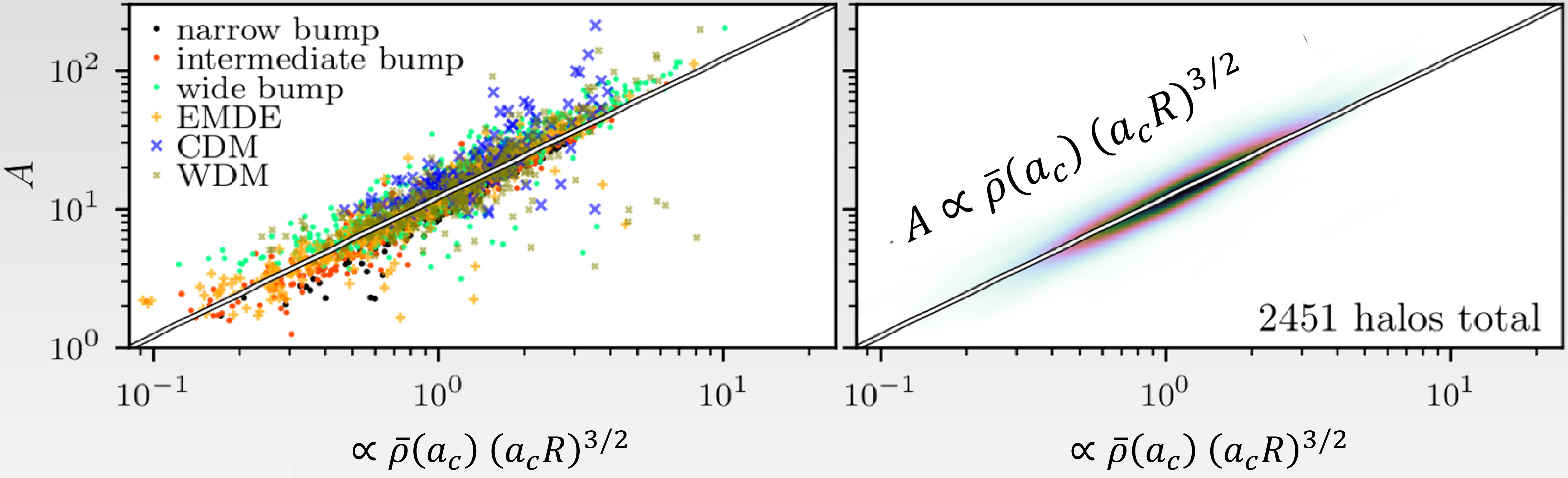
…which caused some disruption of the $\rho \propto r^{-3/2}$ cusp.

MSD & White (2022)

Cusp properties from peaks



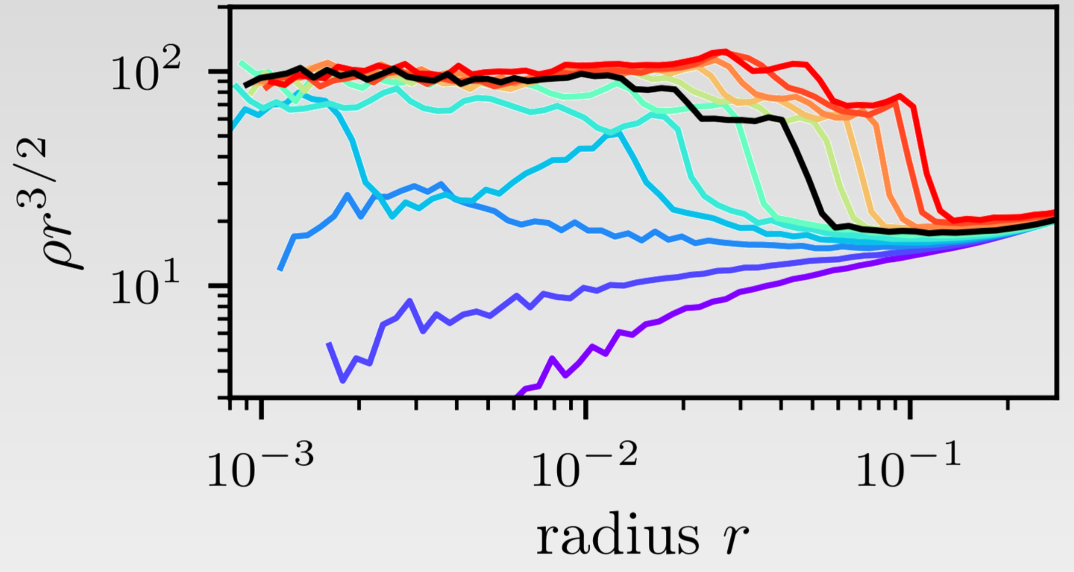
Prediction for $A = \rho r^{3/2}$ also validated using a much larger halo sample



MSD, Bruff, Erickcek (2019)

Universality?

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



Consistent with:

Universality in the structure of dark matter haloes over twenty orders of magnitude in halo mass

Wang, J.[1], Bose, S.[2], Frenk, C. S.[3], Gao, L.[1], Jenkins, A.[3], Springel, V.[4] & White, S. D. M.[4]