Prompt cusps and the dark matter annihilation signal

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Particle and Astroparticle Theory Seminar, MPIK
28 November 2022

Outline

Dark matter halos

Prompt cusps of the first halos

Dark matter annihilation and indirect detection

Annihilation in prompt cusps

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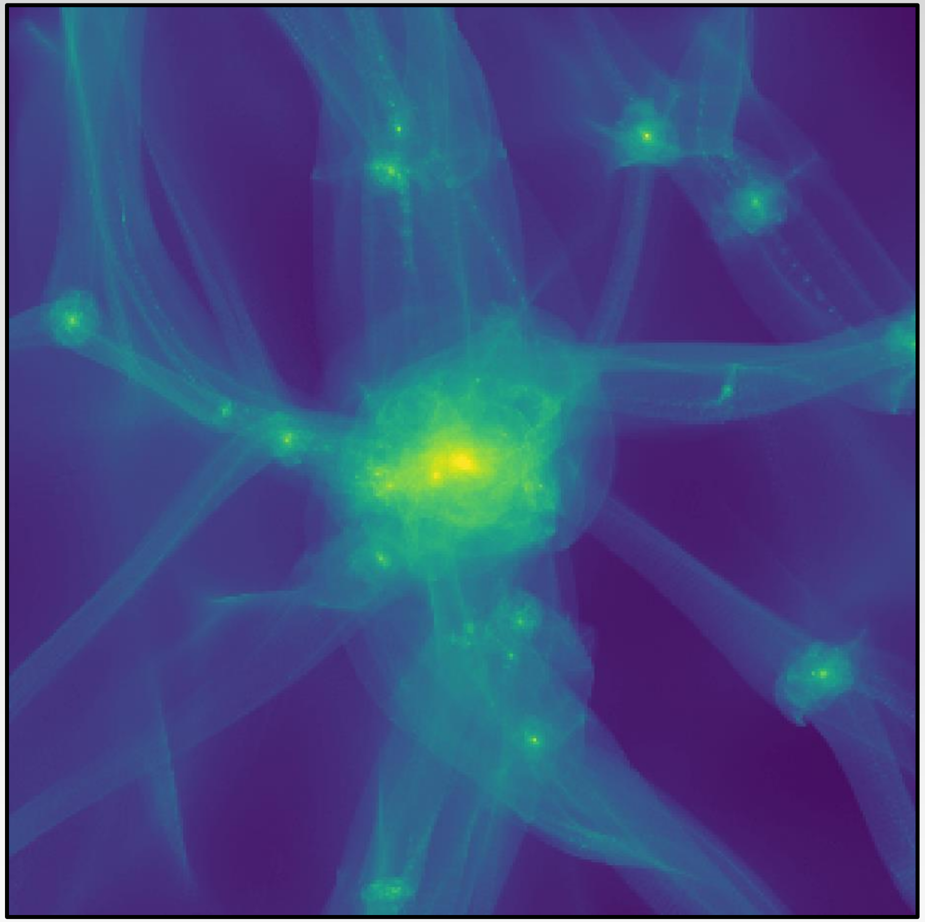
Dark matter halos

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

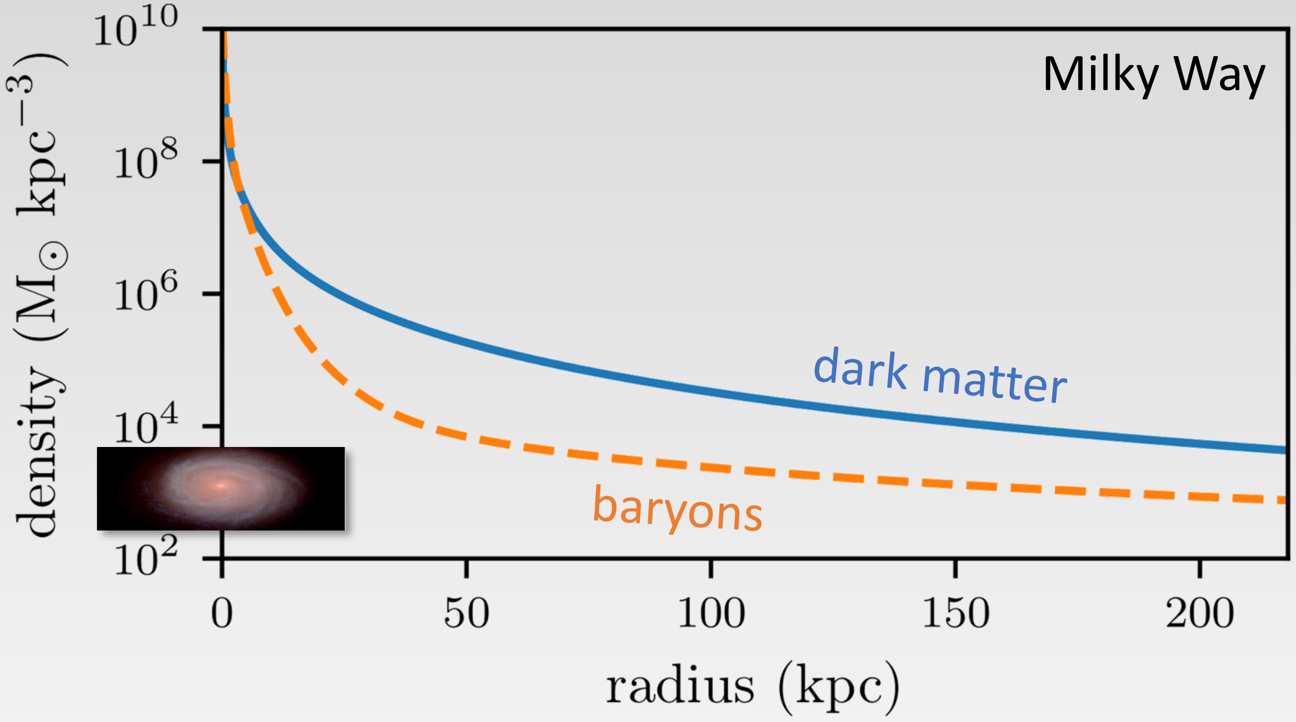
Regions with excess density collapse under gravity to form hot clouds of dark matter

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



Dark matter halos

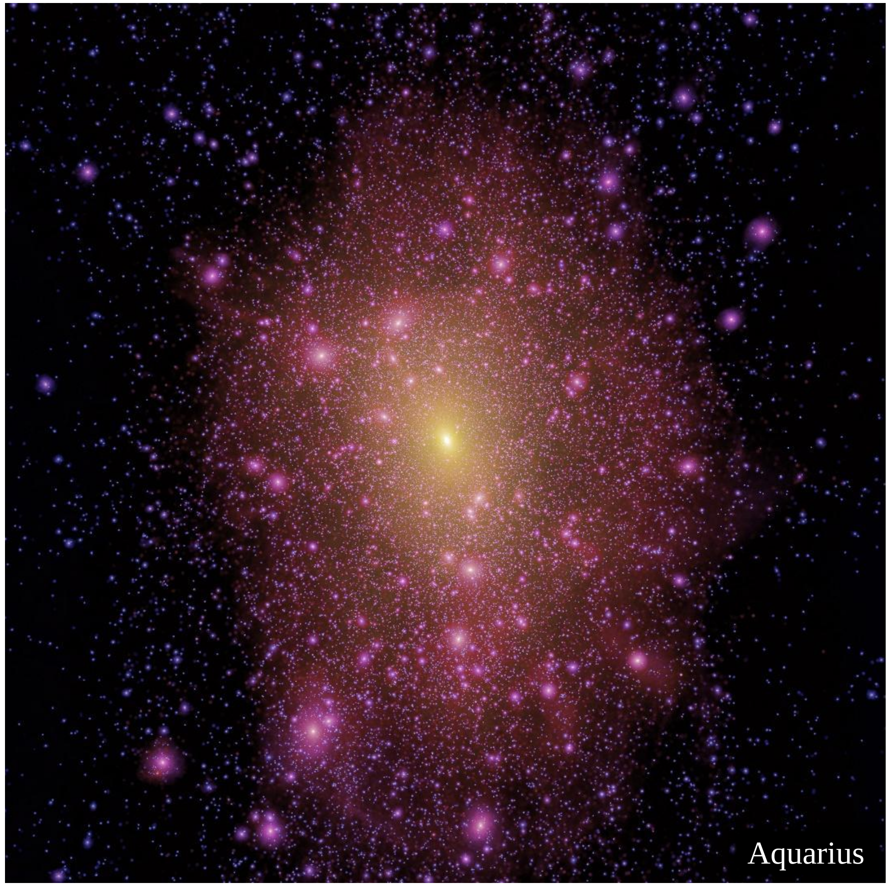
Galaxies form in the centers of these “halos”



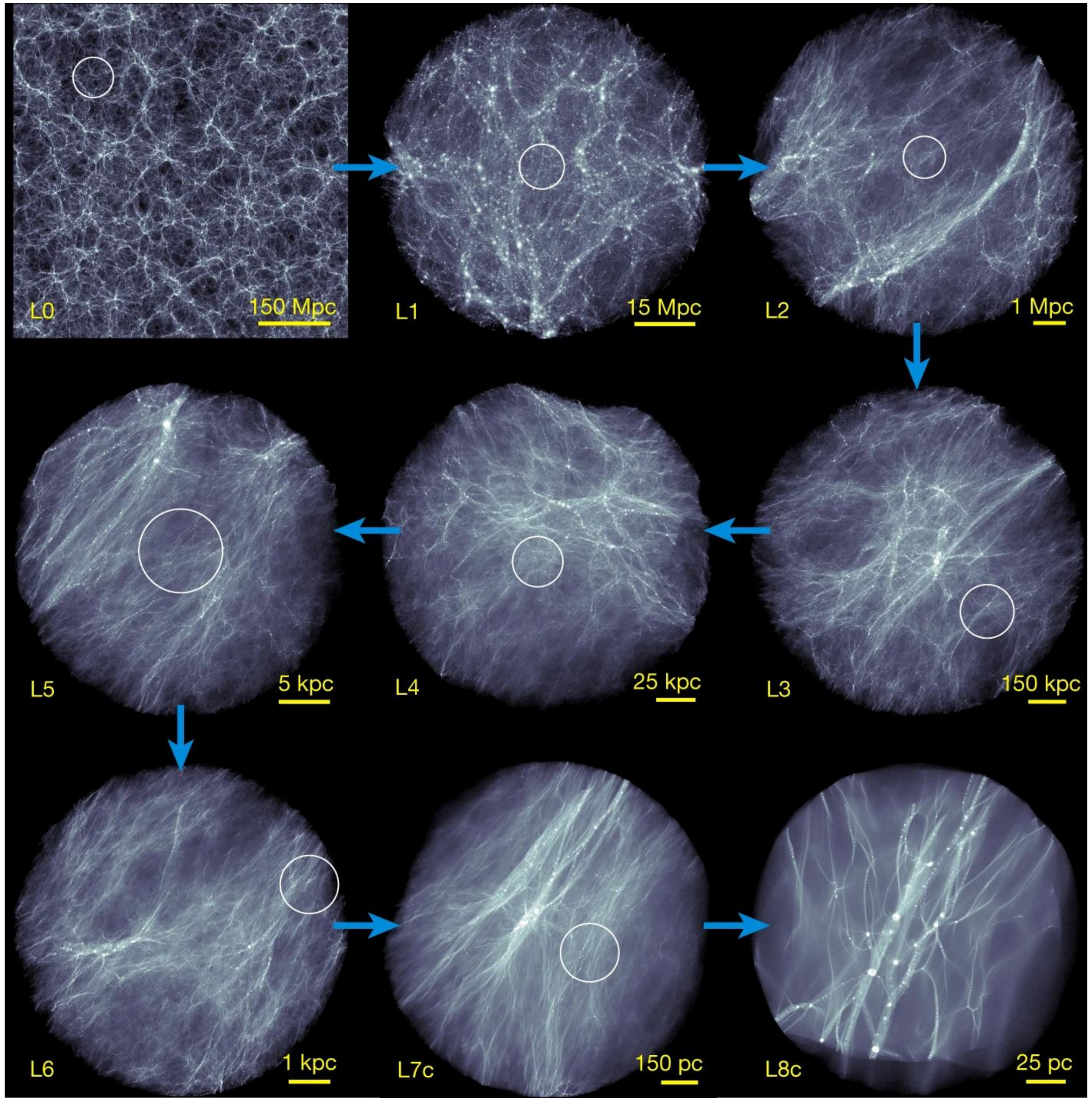
MW mass model: Cautun et al (2020)
picture of simulated MW-like galaxy: Grand et al (2021)

Dark matter halos

Subhalos persist inside other halos:



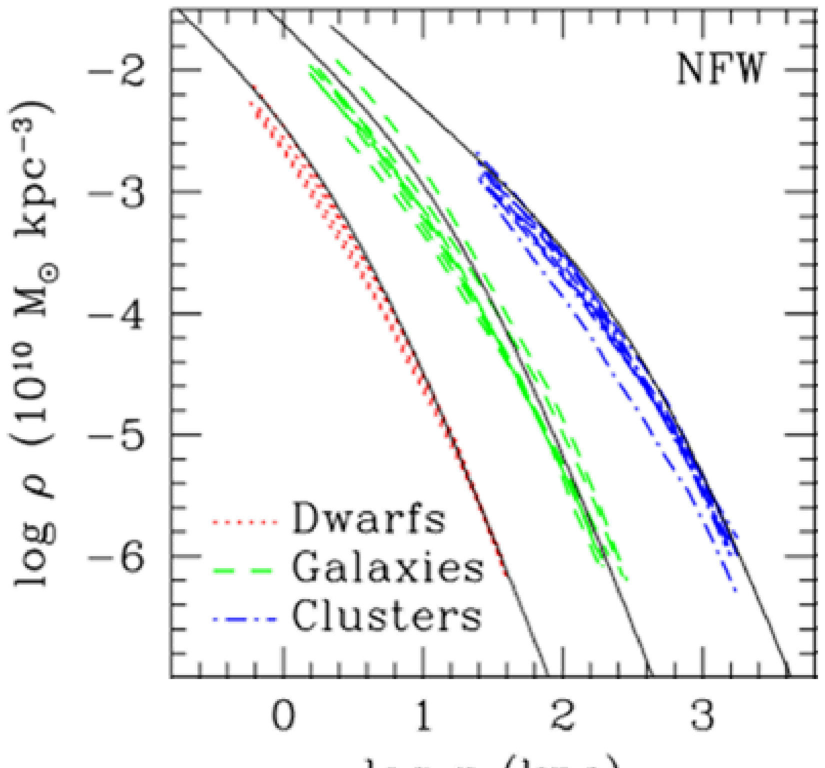
Halos form at all scales:



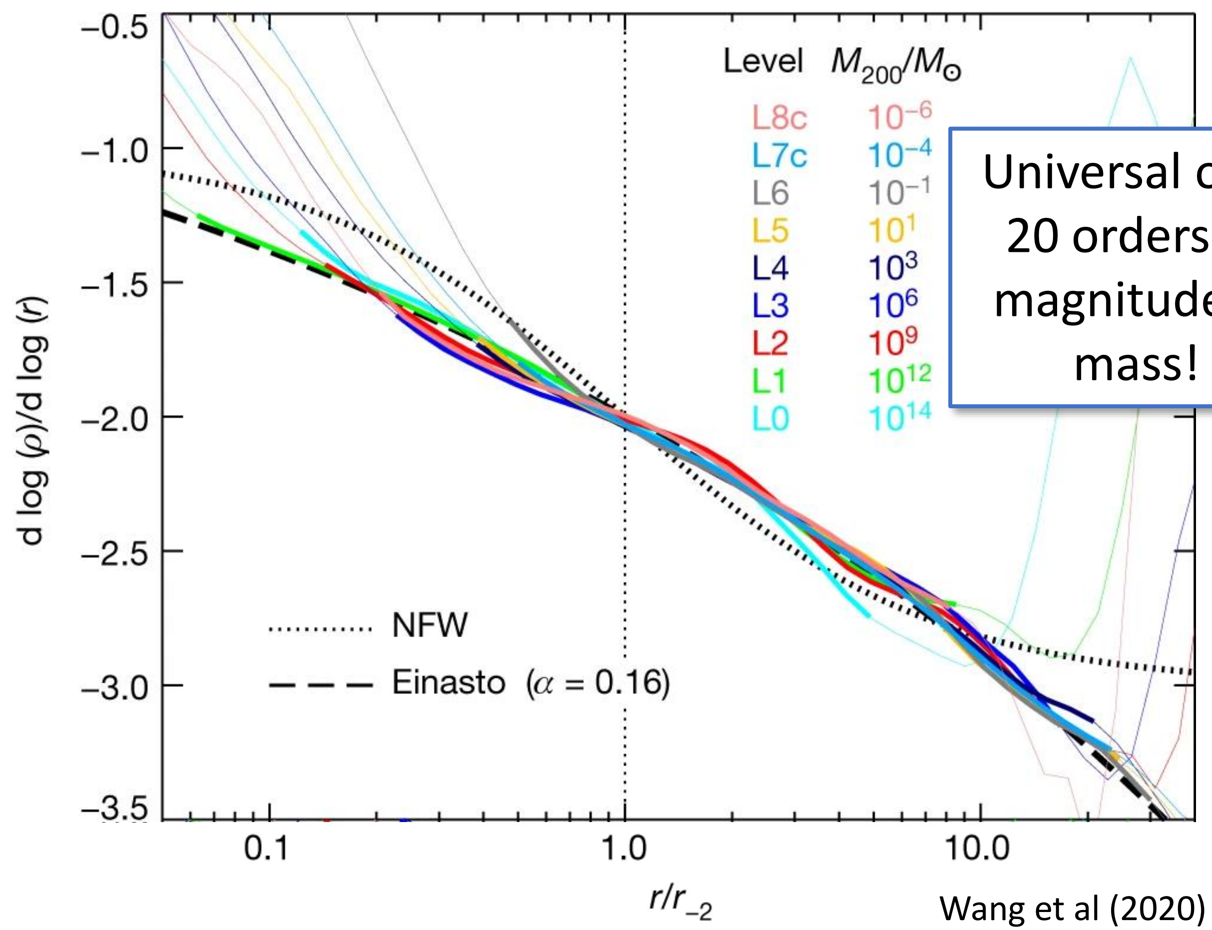
Wang et al (2020)

Halo density profiles

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



Navarro et al (2004)

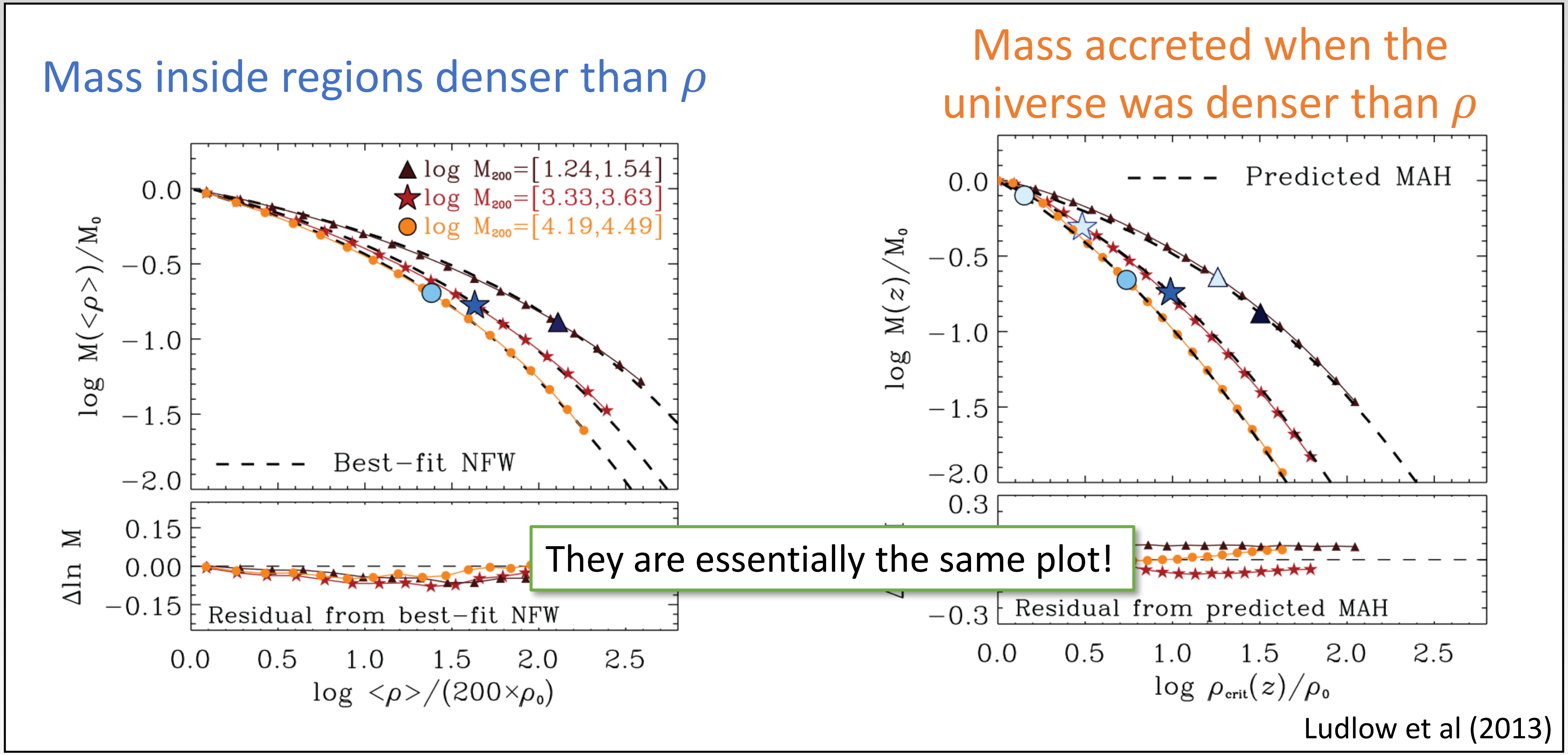


Wang et al (2020)

Universal over 20 orders of magnitude in mass!

Density profiles from accretion history

Universal density profiles follow from universal accretion history



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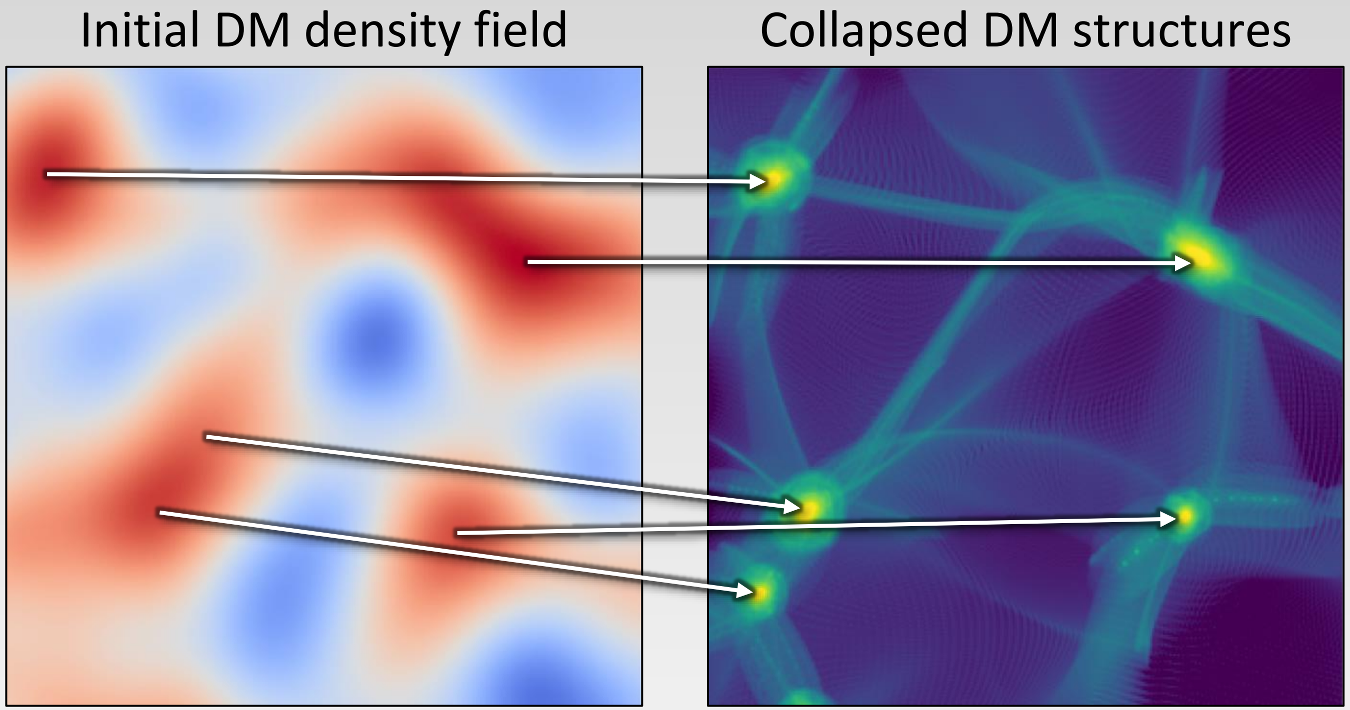
Annihilation in prompt cusps

The first halos

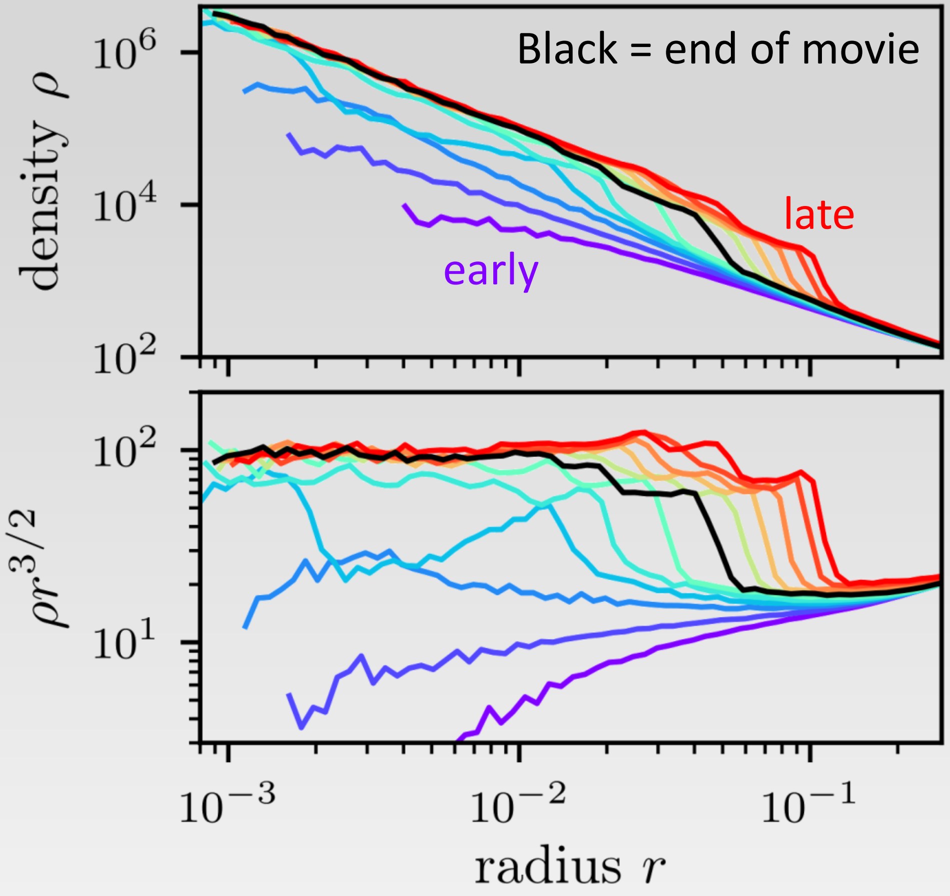
The first dark matter halos form from density peaks.



(smoothed by thermal motion)

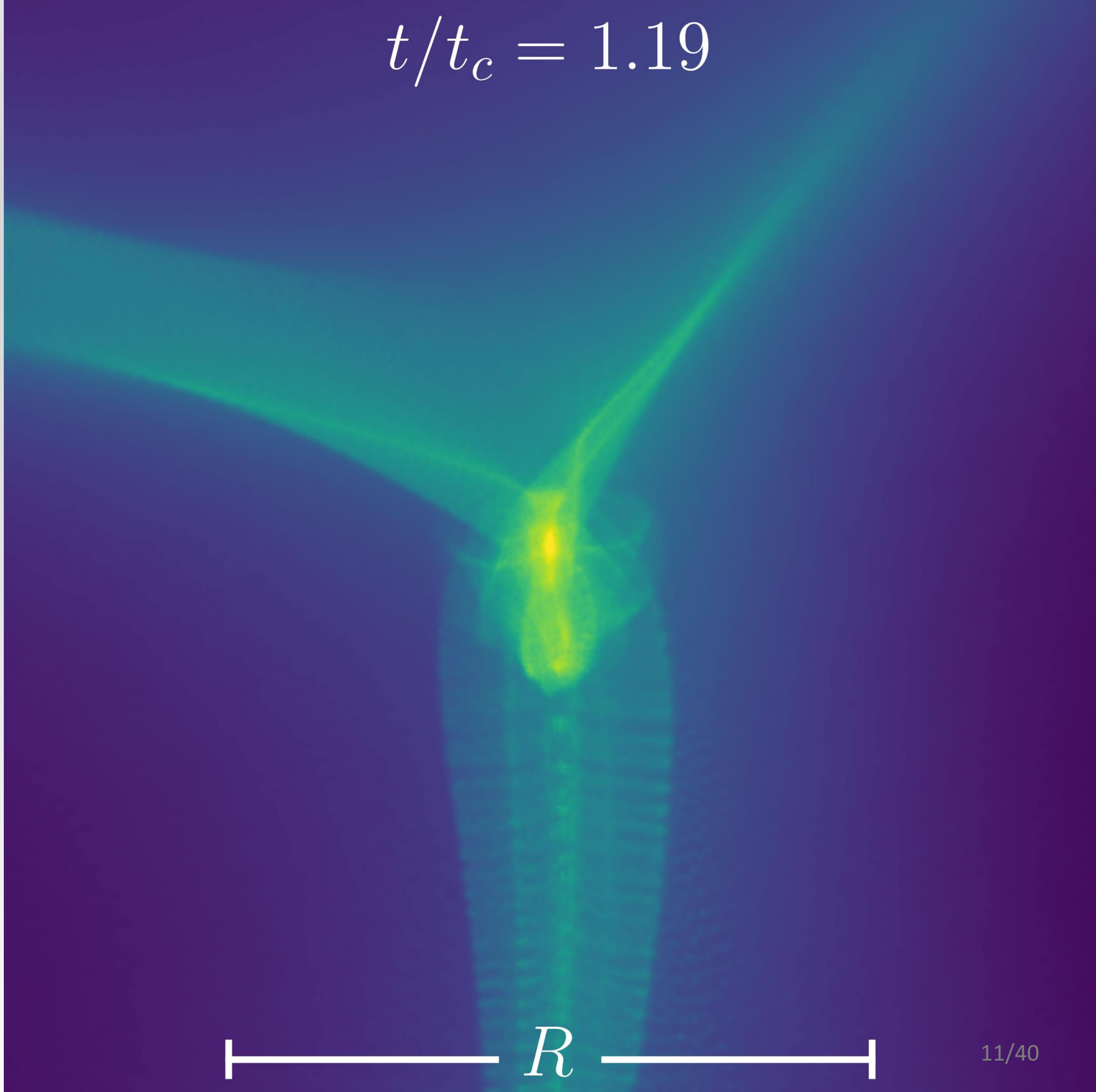
Normally not resolved in simulations [~earth mass]

Prompt cusps



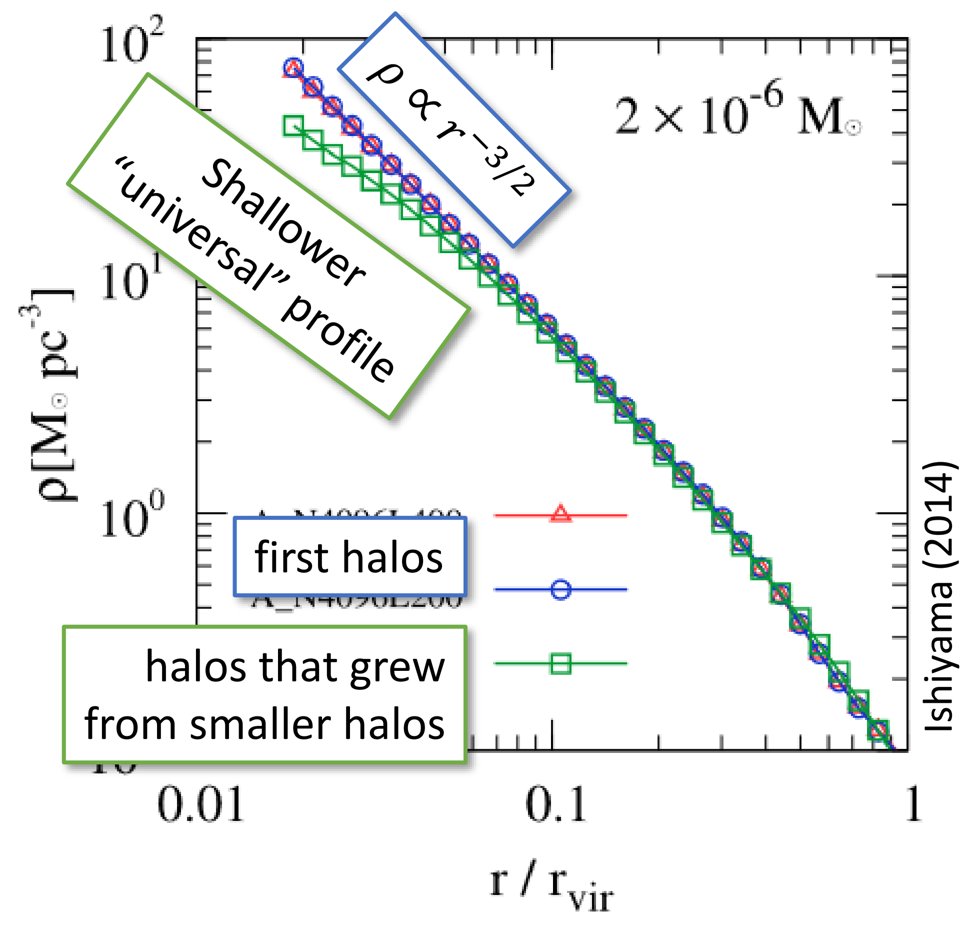
$\rho \propto r^{-3/2}$ cusp stabilizes immediately after formation

"prompt"



Do prompt cusps survive?

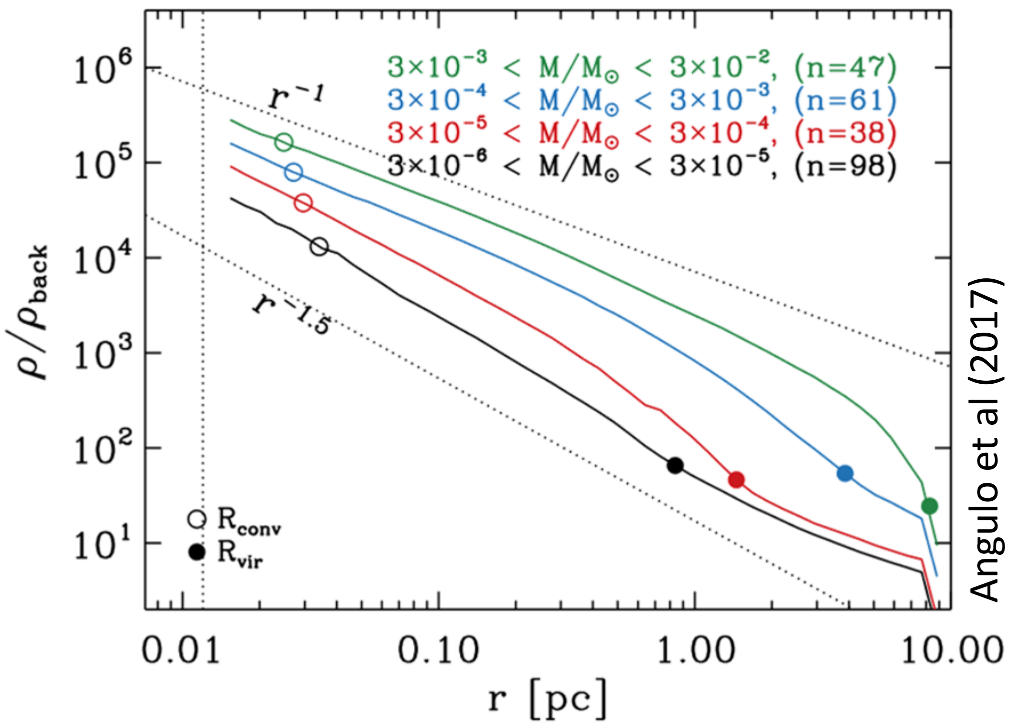
$\rho \propto r^{-3/2}$ cusps have been seen in simulations before…



Ishiyama (2014)

…but their survival was questioned

Halos converge to "universal" density profile as they grow?

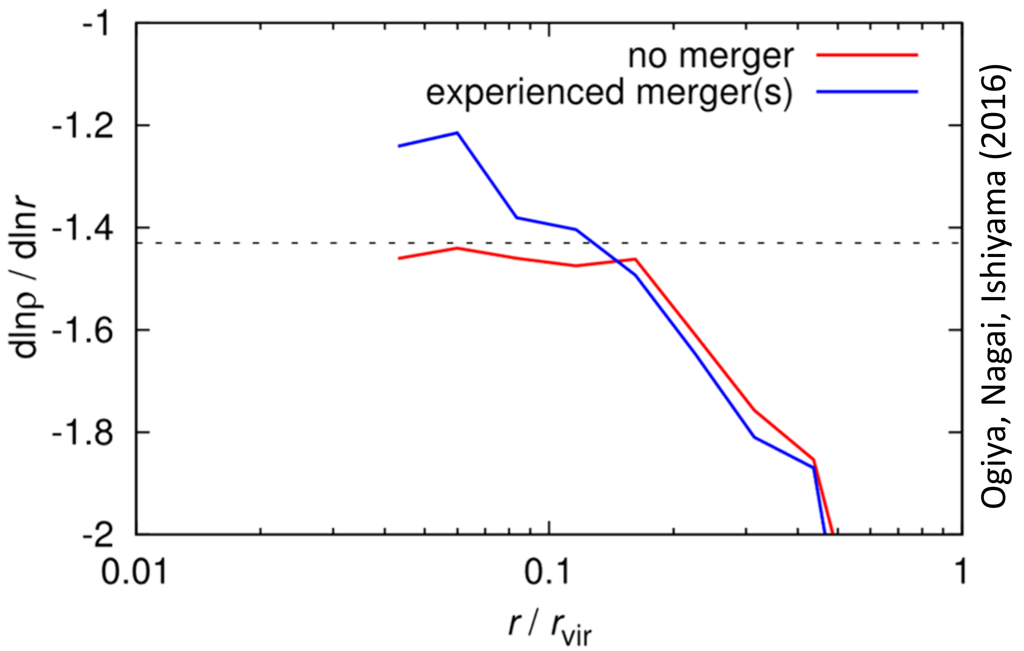


Angulo et al (2017)

Cusps shallow due to mergers?

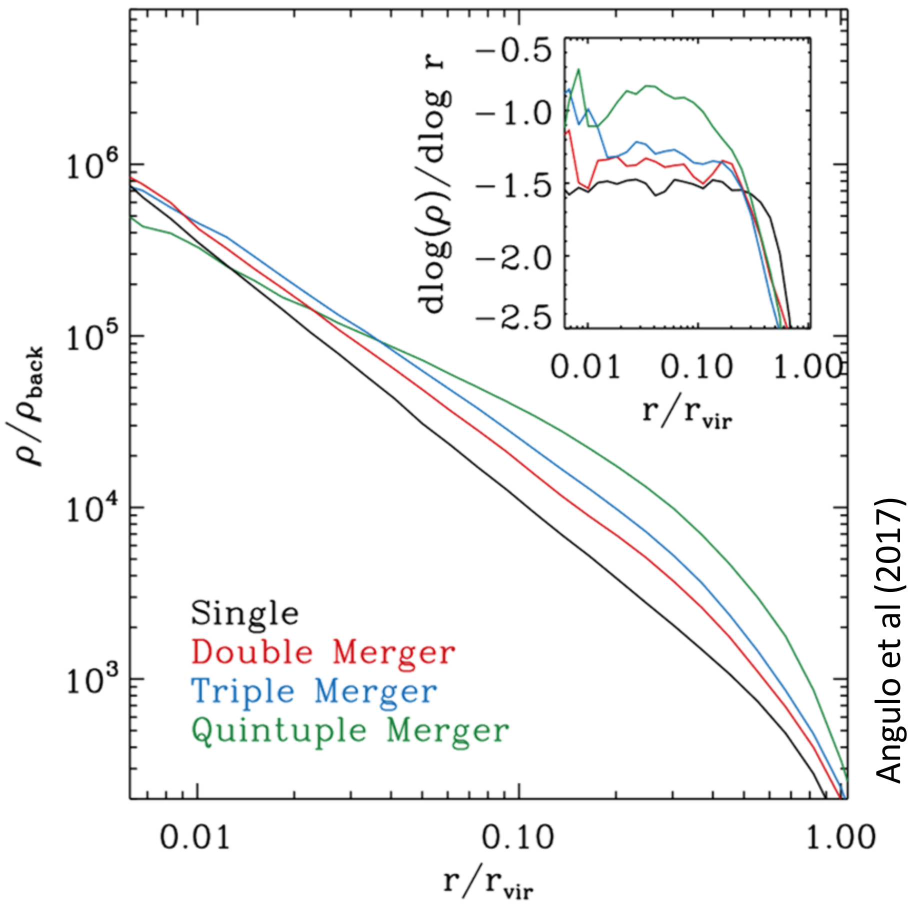
The common view was that mergers disrupt steep cusps

Correlation between mergers and shallow cusps



Ogiya, Nagai, Ishiyama (2016)

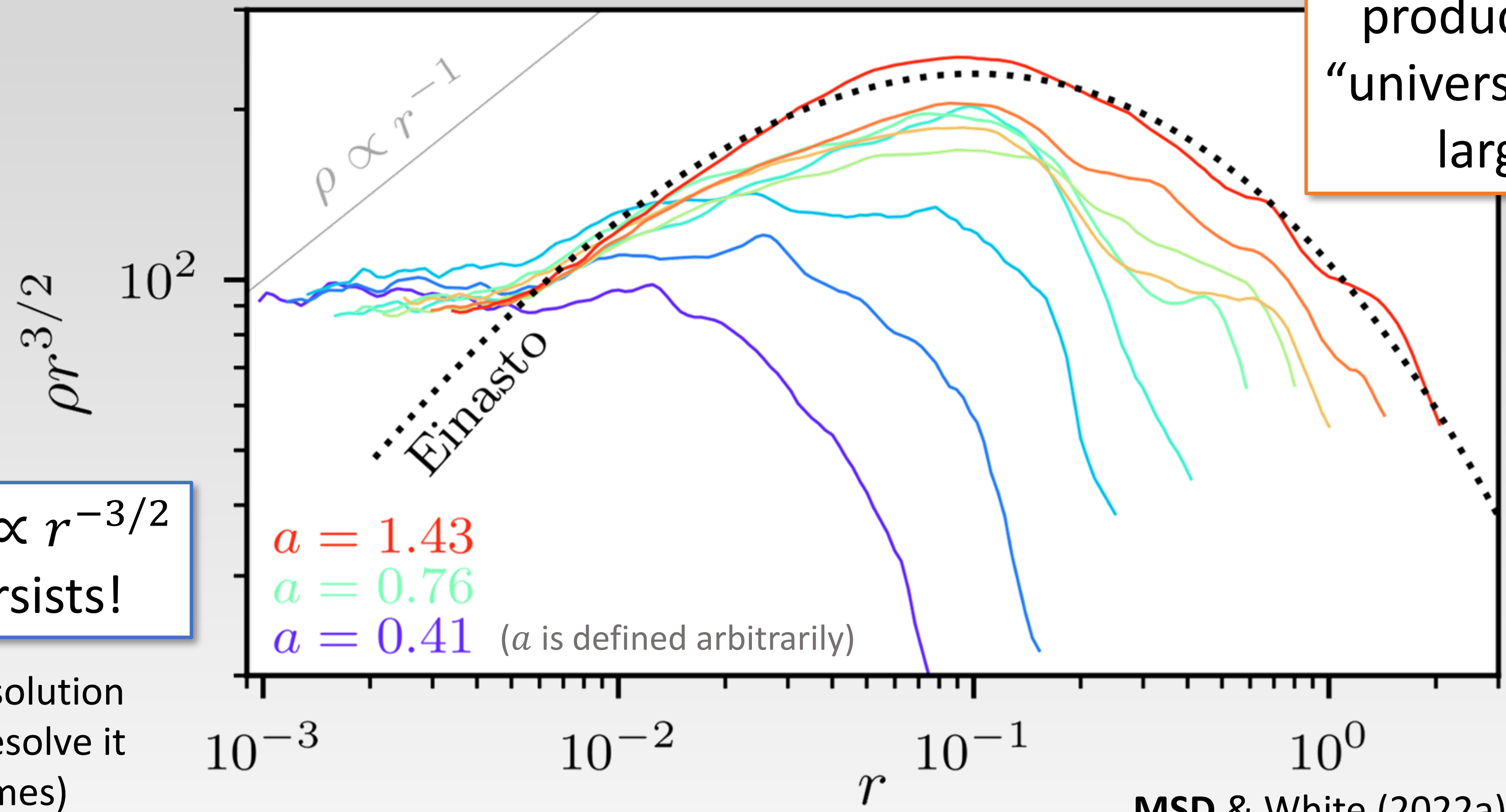
Shallowing in idealized merger simulations



Angulo et al (2017)

Prompt cusp persistence

Buildup of material produces shallow "universal" profile at larger radii



(a is defined arbitrarily)

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

(extreme resolution needed to resolve it at late times)

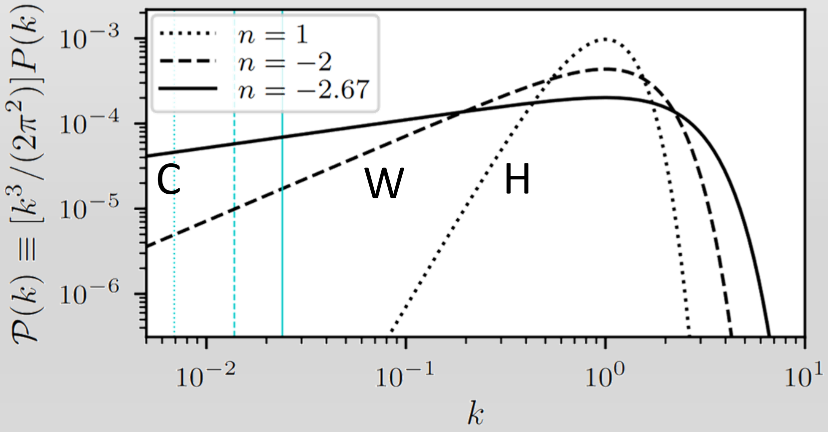
MSD & White (2022a)

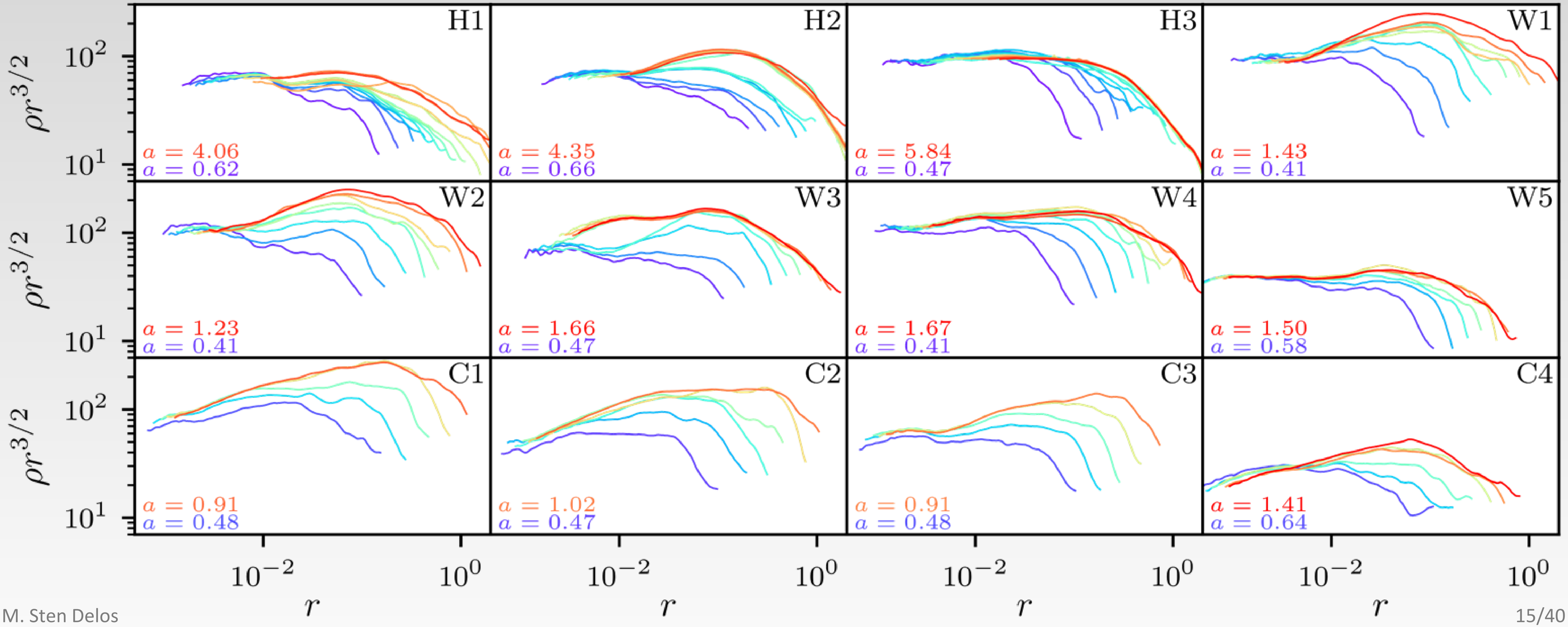
Outcome: standard DM density profile + prompt cusp

Prompt cusps: broader picture

Twelve high-resolution halos from three cosmologies:

Prompt cusp forms at collapse; no evidence for disruption



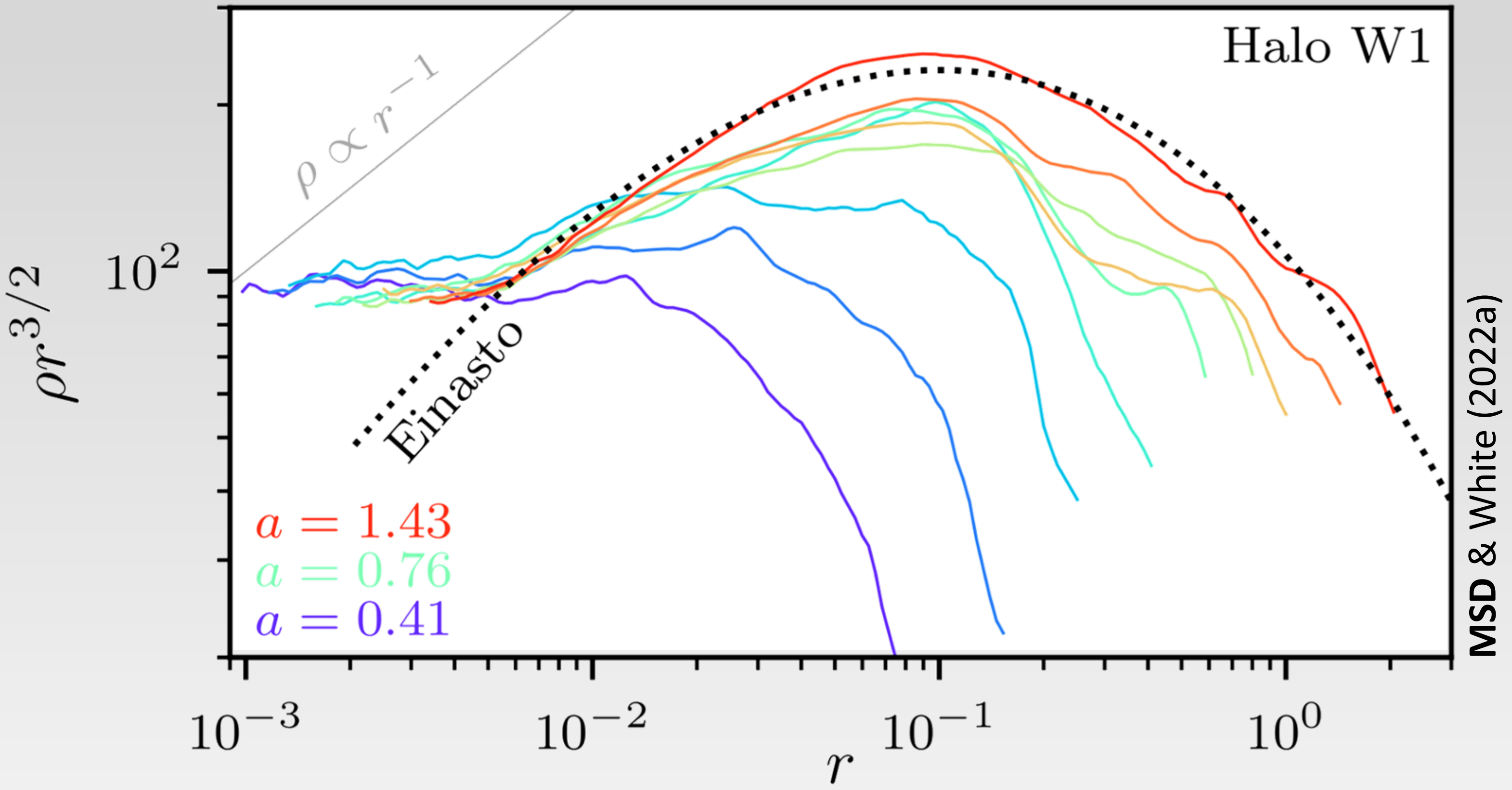


MSD & White (2022a)

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



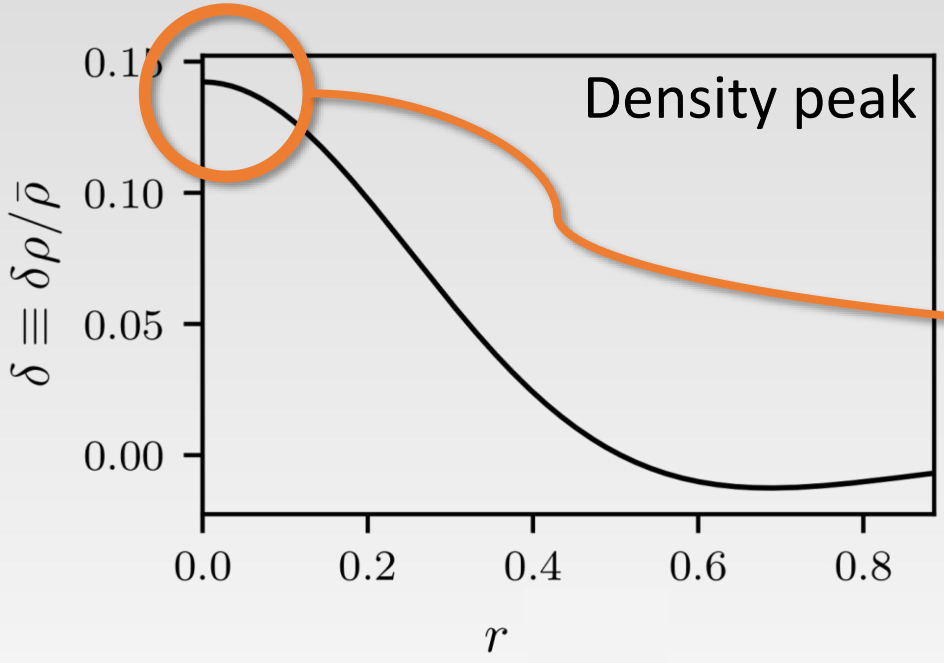
Consequence: every (sub)halo has a central prompt cusp!

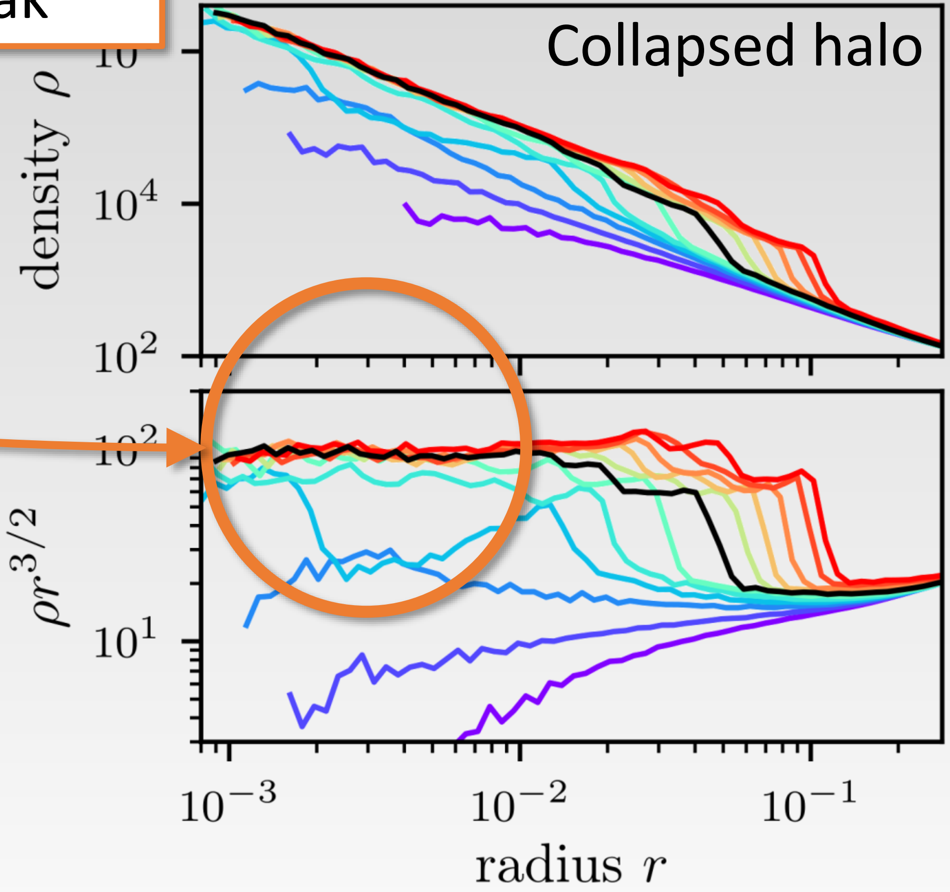
What sets prompt cusp properties?

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



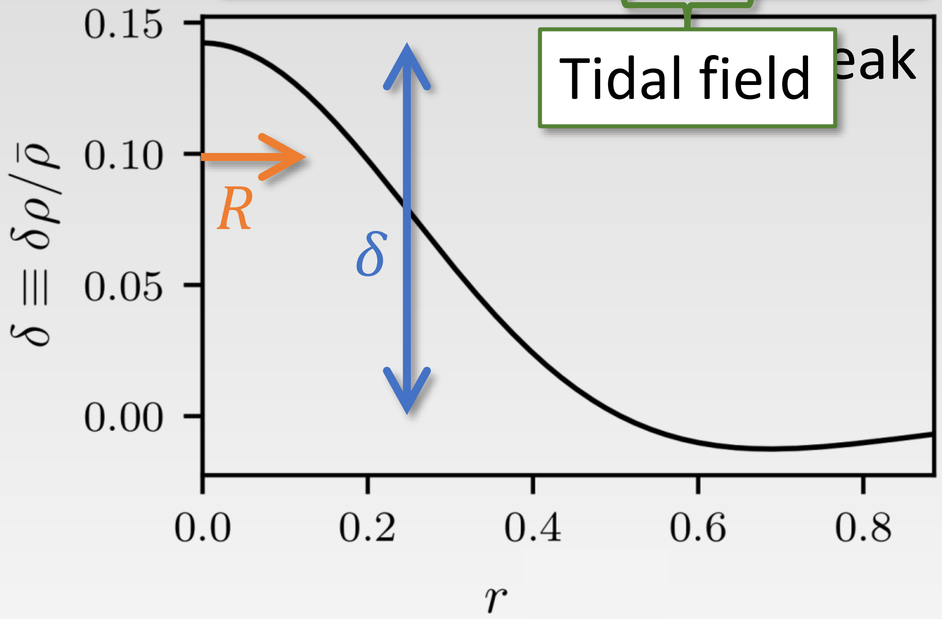


What sets prompt cusp properties?

Peak has comoving size R and collapse time a_c:

$$R \equiv |\delta/\nabla^2\delta|^{1/2}$$

$$D(a_c) = \delta_c(\underbrace{e, p}_{\text{Tidal field}})/\delta$$

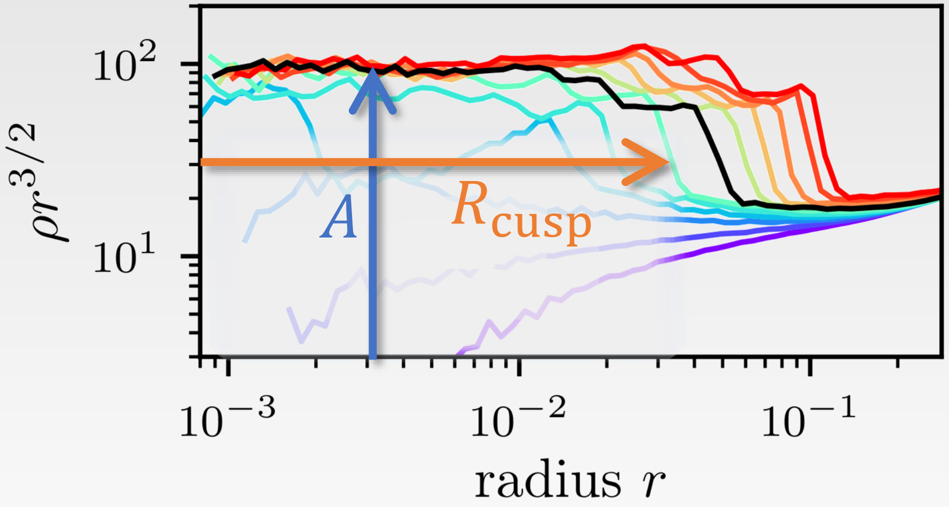


Prompt cusp: $\rho = Ar^{-3/2}$

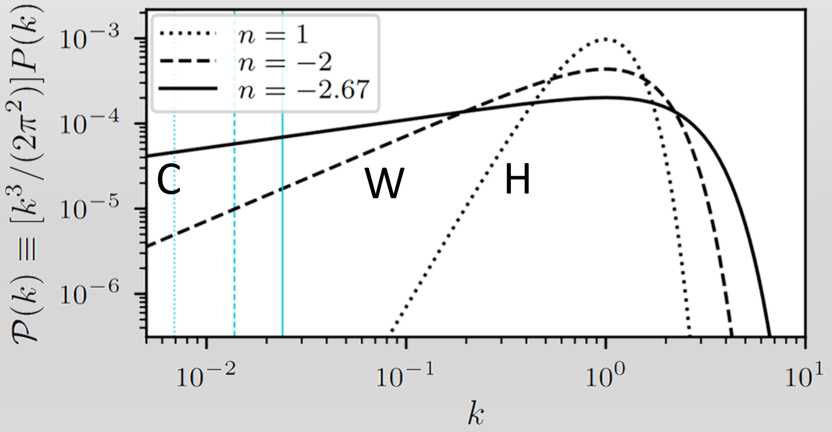
$$A \simeq 24\,\bar{\rho}(a_c)\,(a_c R)^{3/2}$$

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

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

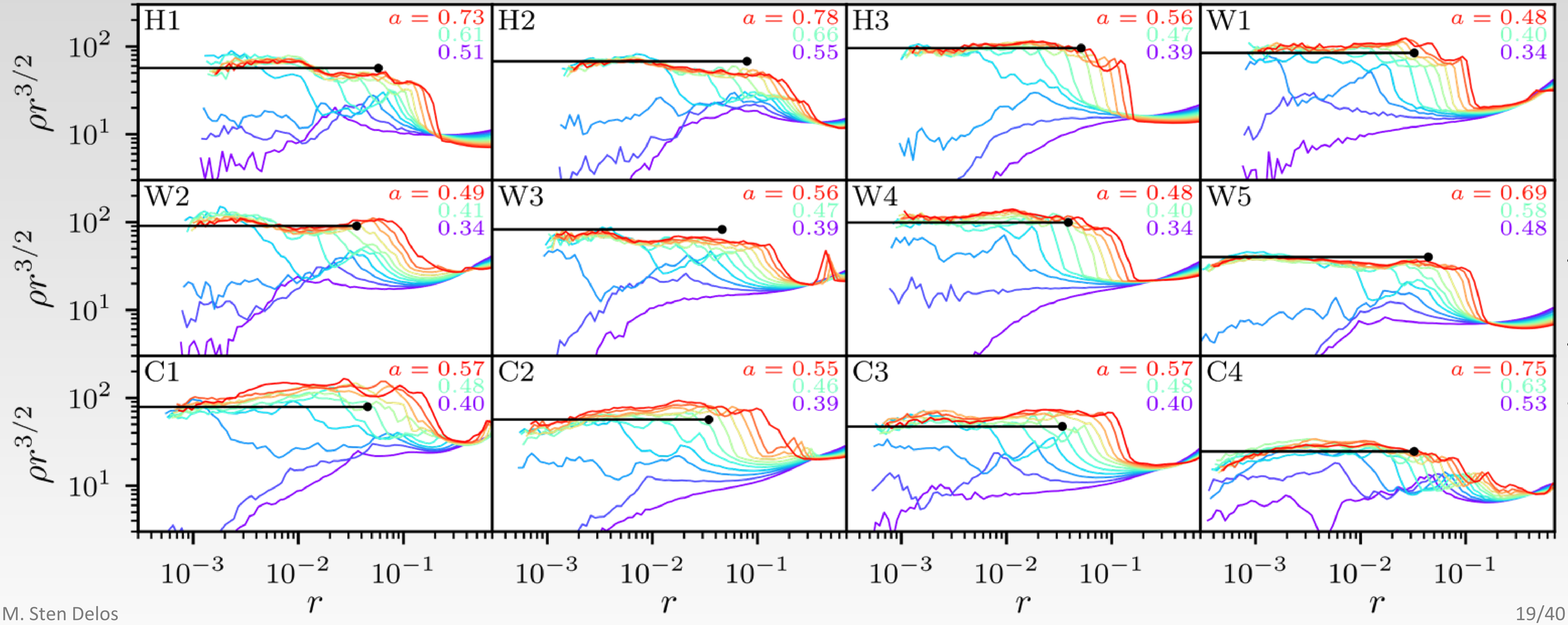


Cusp properties from peaks



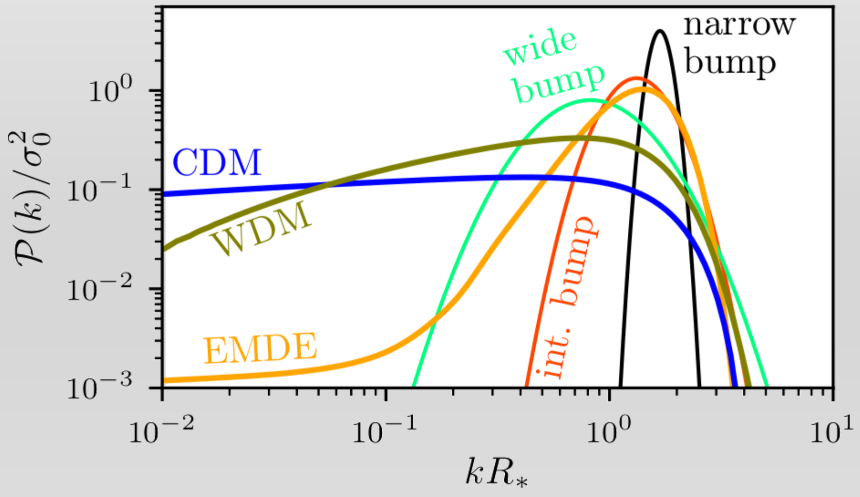
Twelve high-resolution halos from three cosmologies:

Predictions [black] work well!

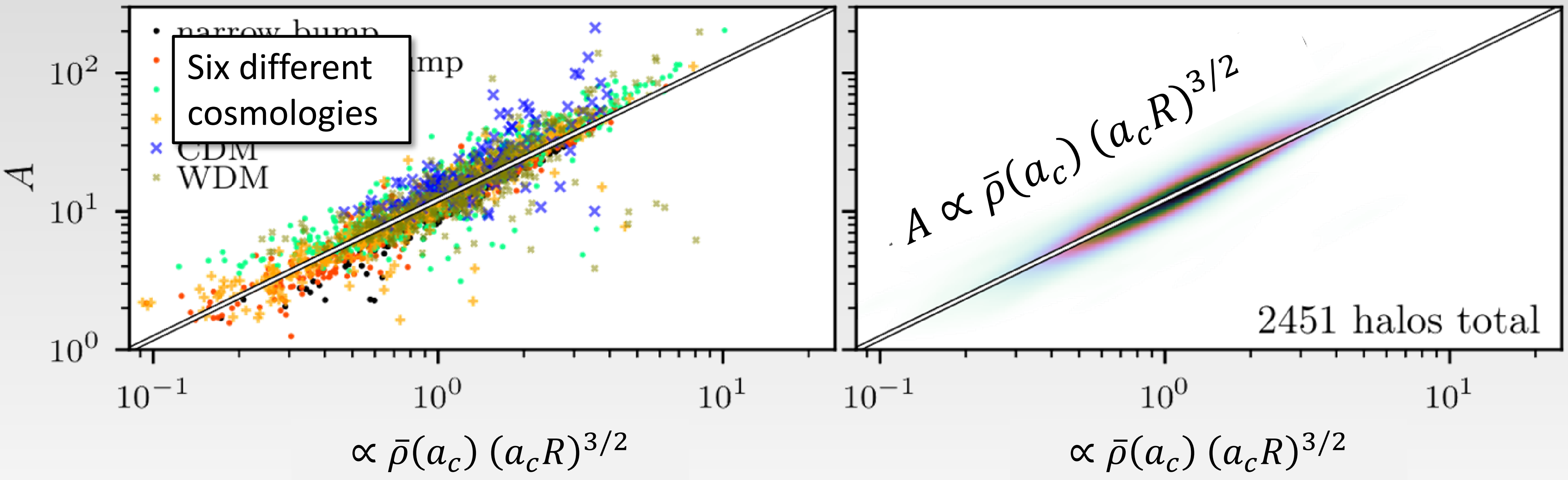


MSD & White (2022a)

Cusp properties from peaks



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

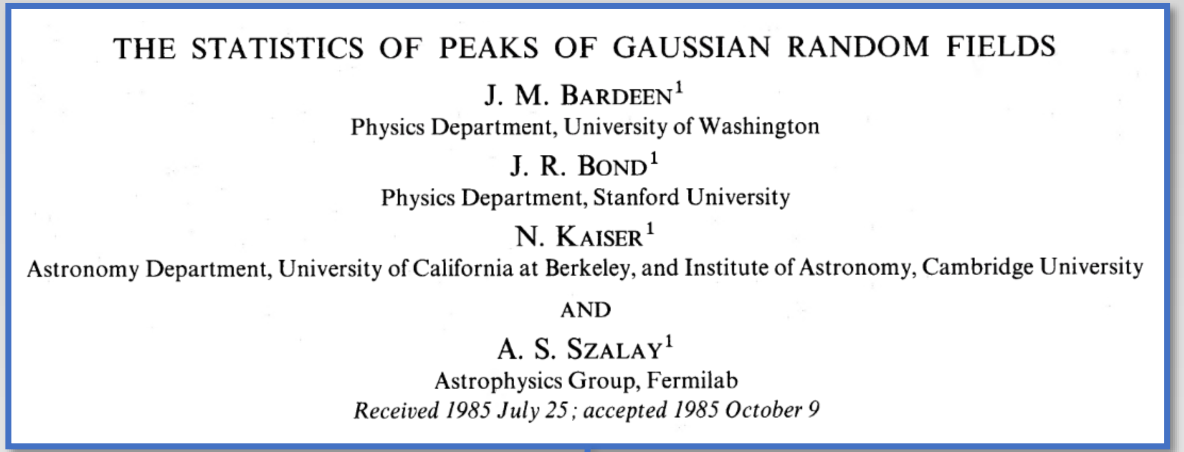


MSD, Bruff, Erickcek (2019)

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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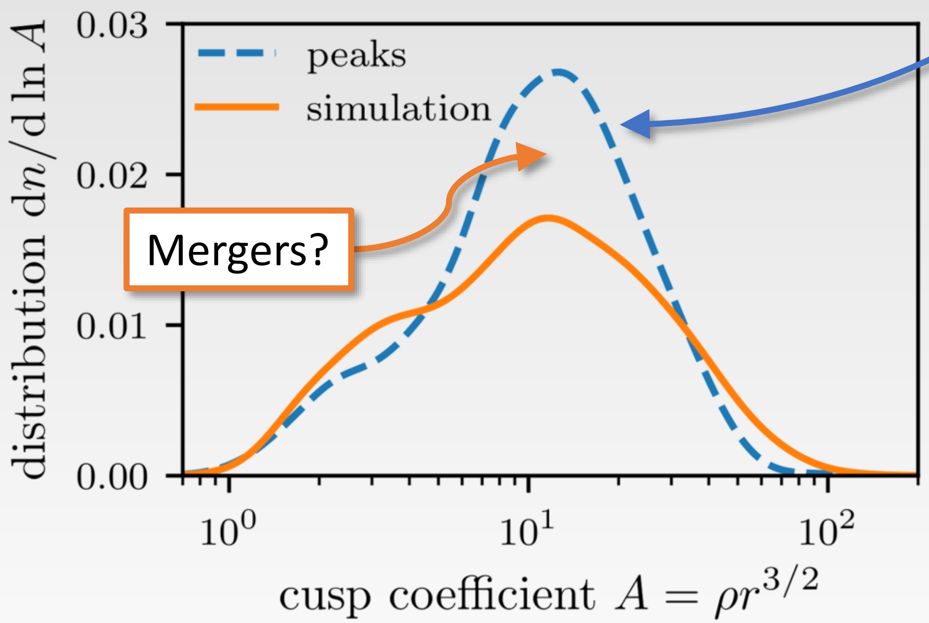


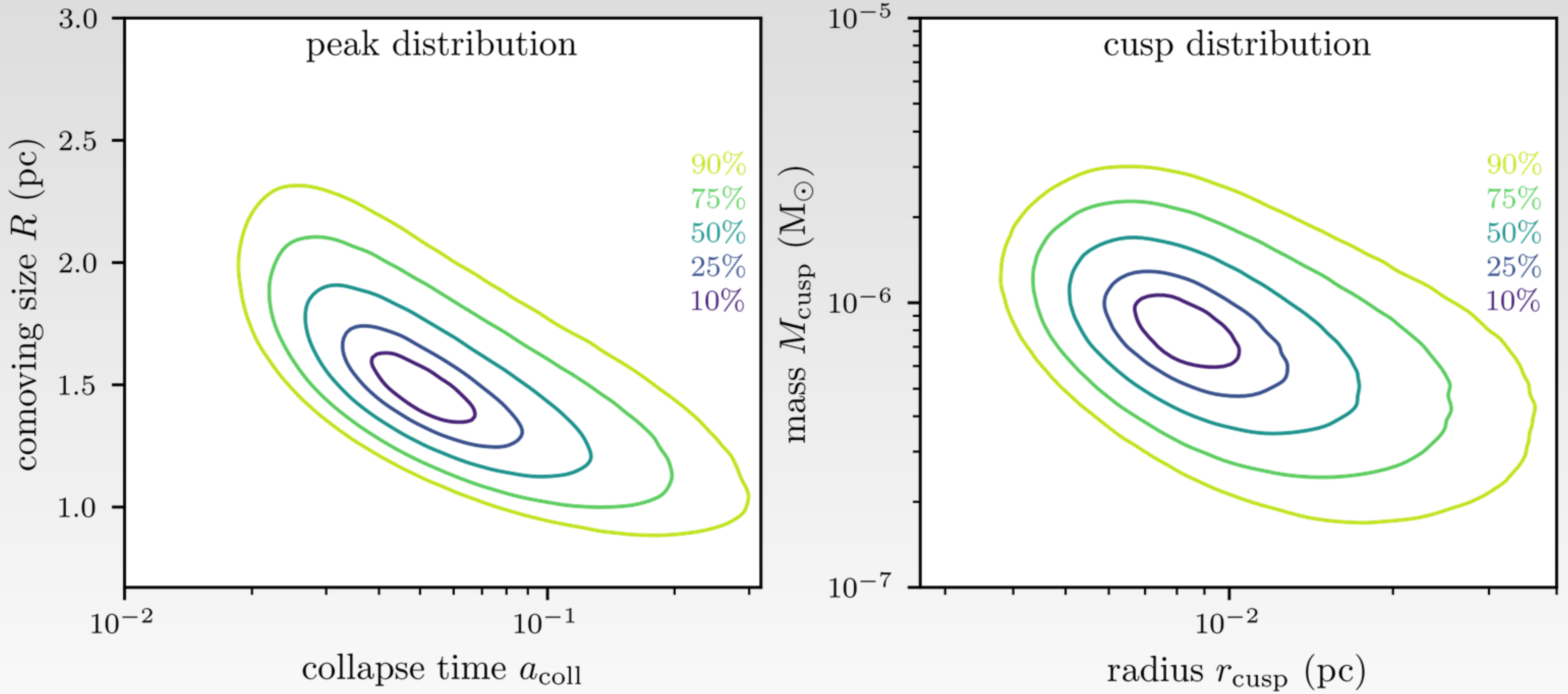
MSD, Bruff, Erickcek (2019)

Statistics of prompt cusps

Example: 100 GeV WIMP (decoupling at 30 MeV)

average peak/cusp number density $\simeq 10^{-3}\ \mathrm{pc}^{-3}$

$\sim 40000\ M_\odot^{-1}$



Central cores

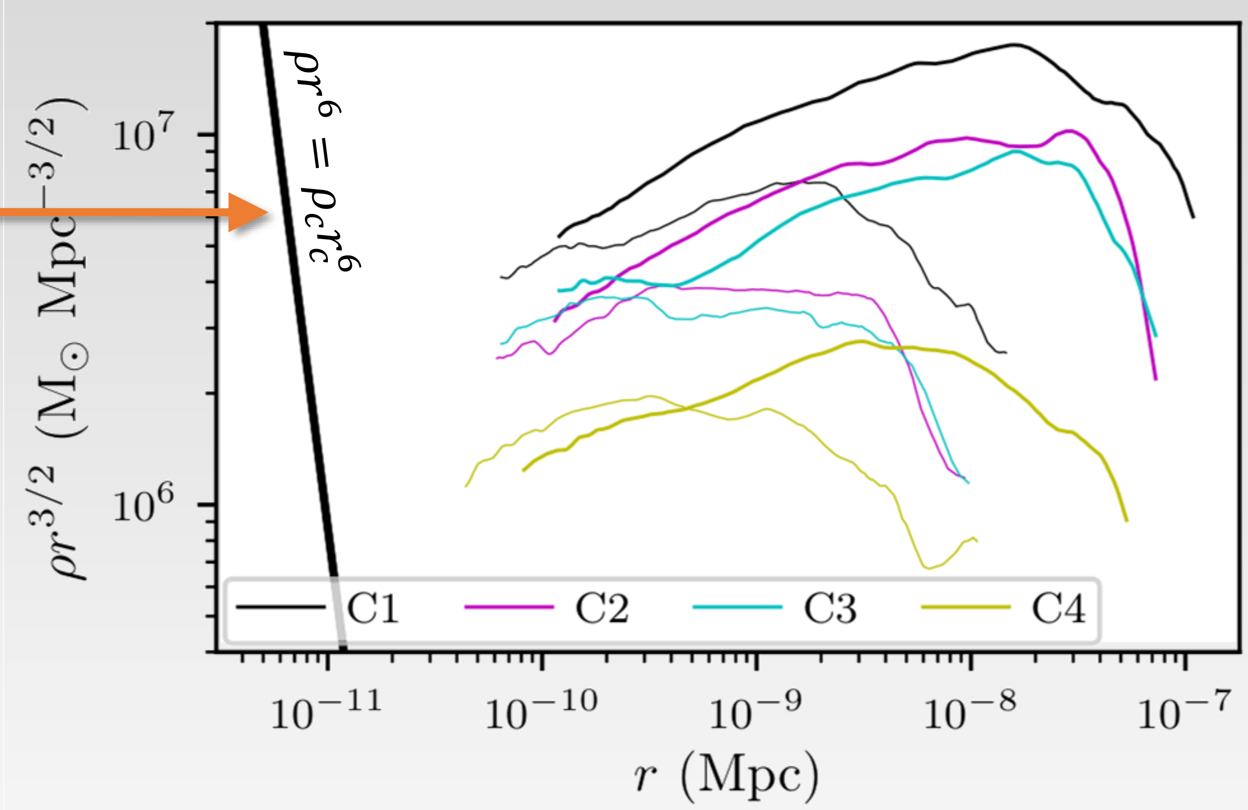
Any density cusp must give way to a finite-density core at small radii due to phase-space conservation

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 (2022a)

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

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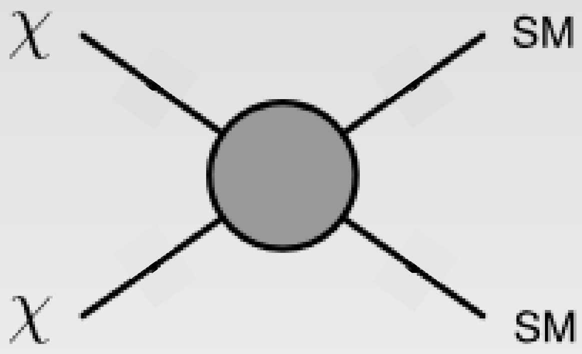
What is dark matter?

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



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

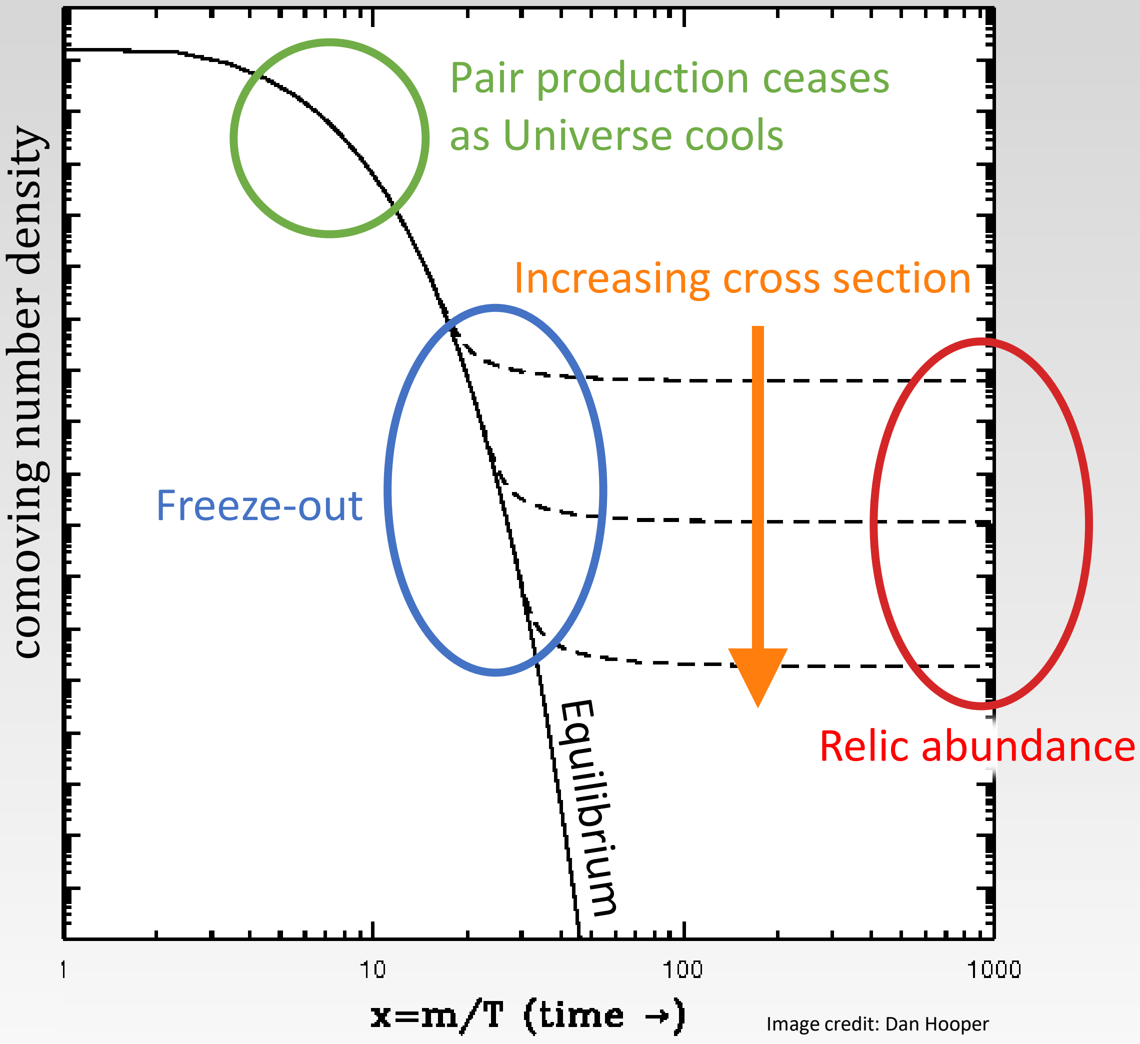
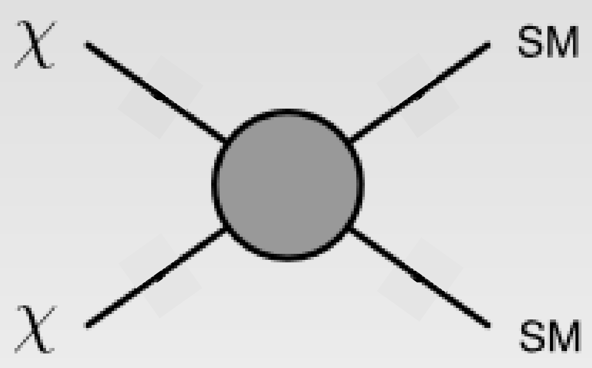


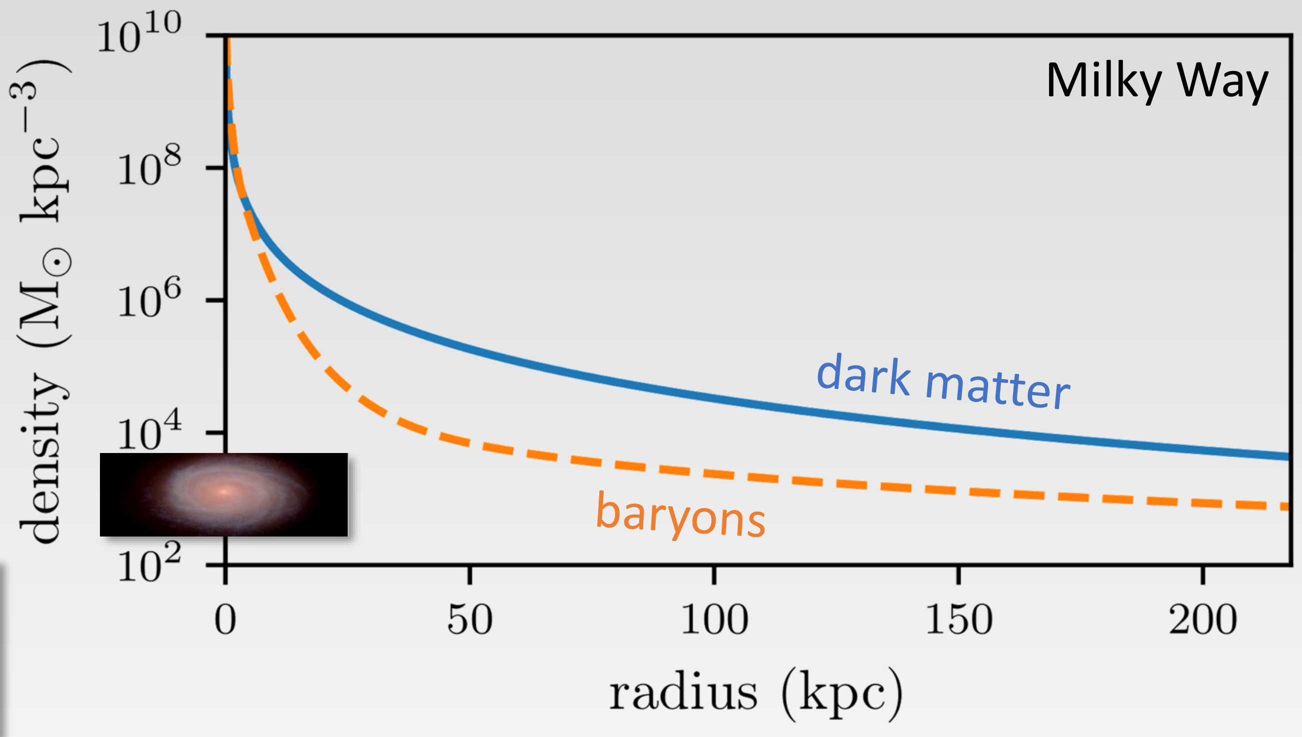
Image credit: Dan Hooper

Indirect detection

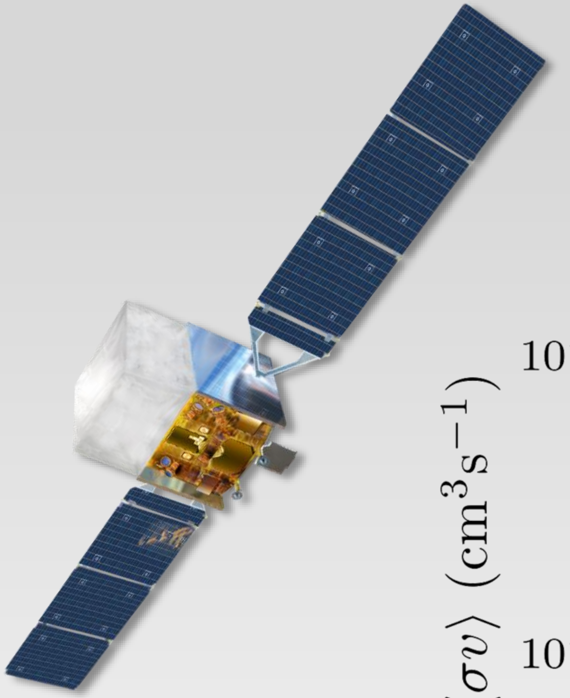
Then dark matter can annihilate into detectable SM particles today!



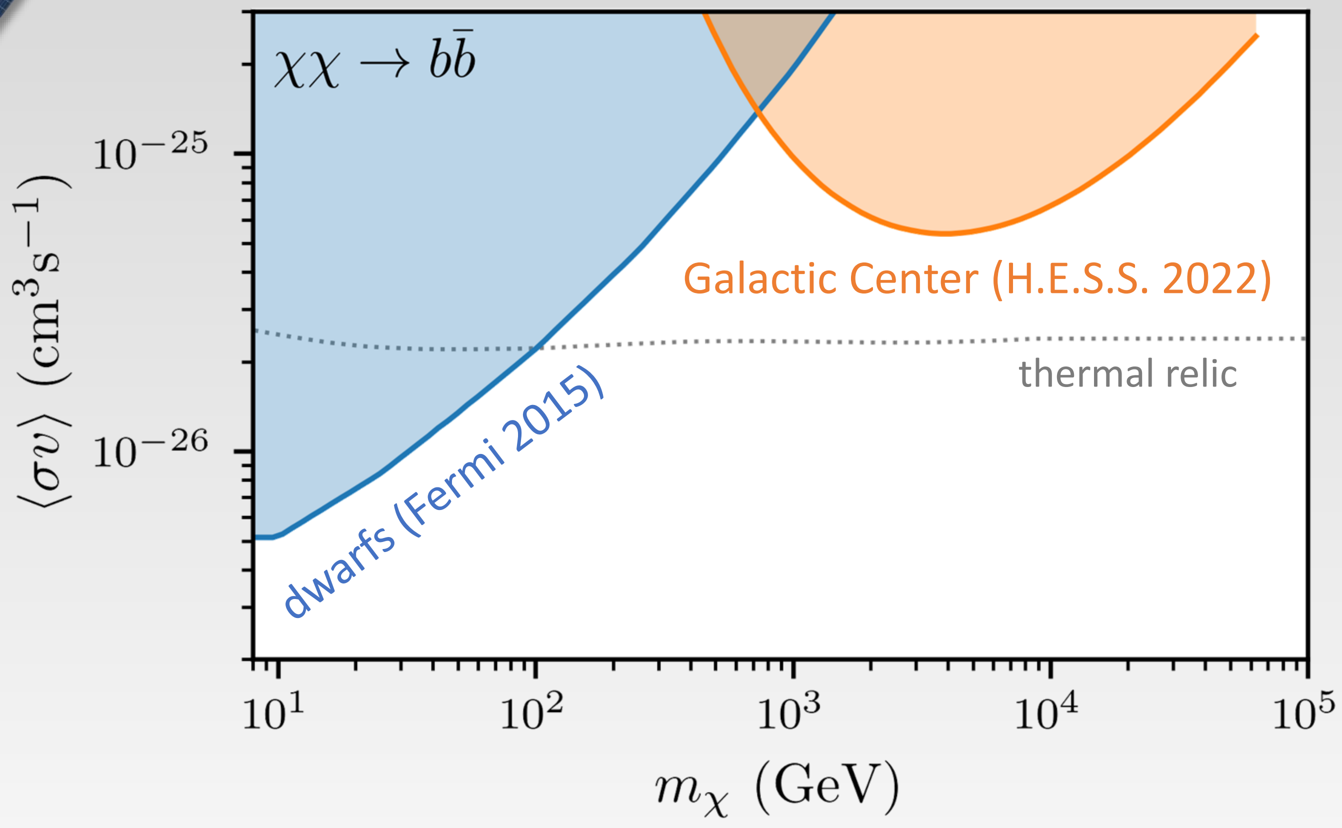
Annihilation rate ∝ ρ^2:
Search the dense centers of galaxies



Indirect-detection limits



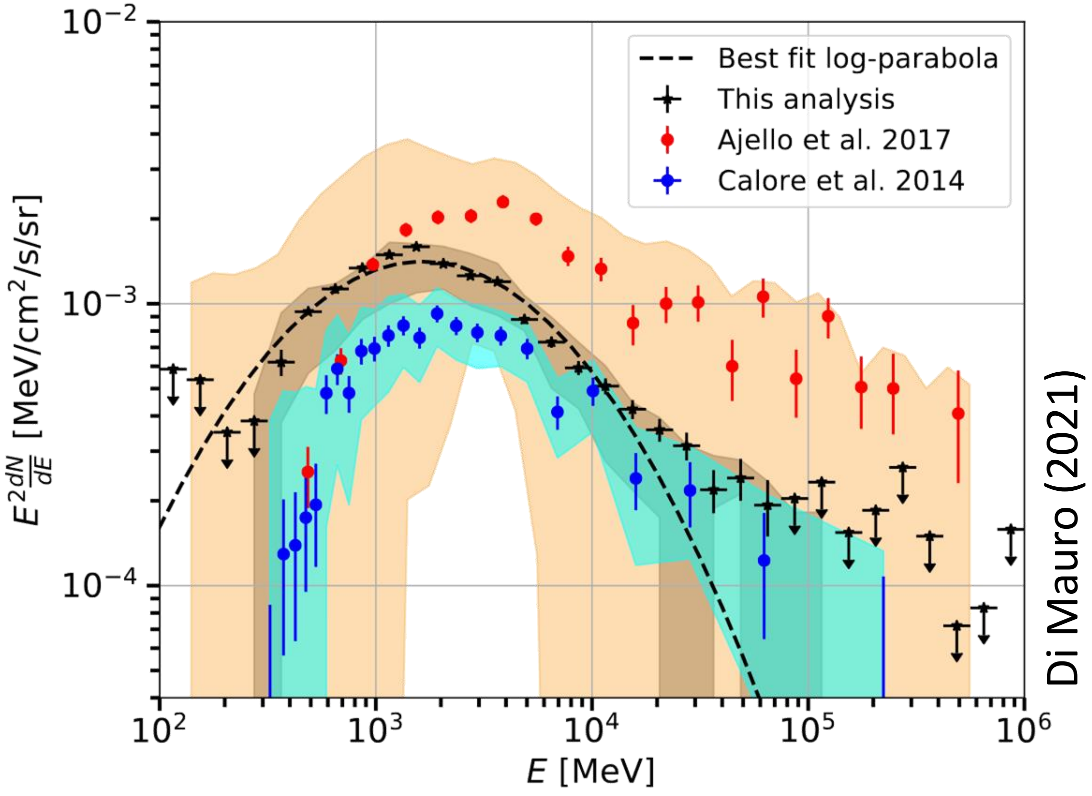
Limits from gamma-ray searches:



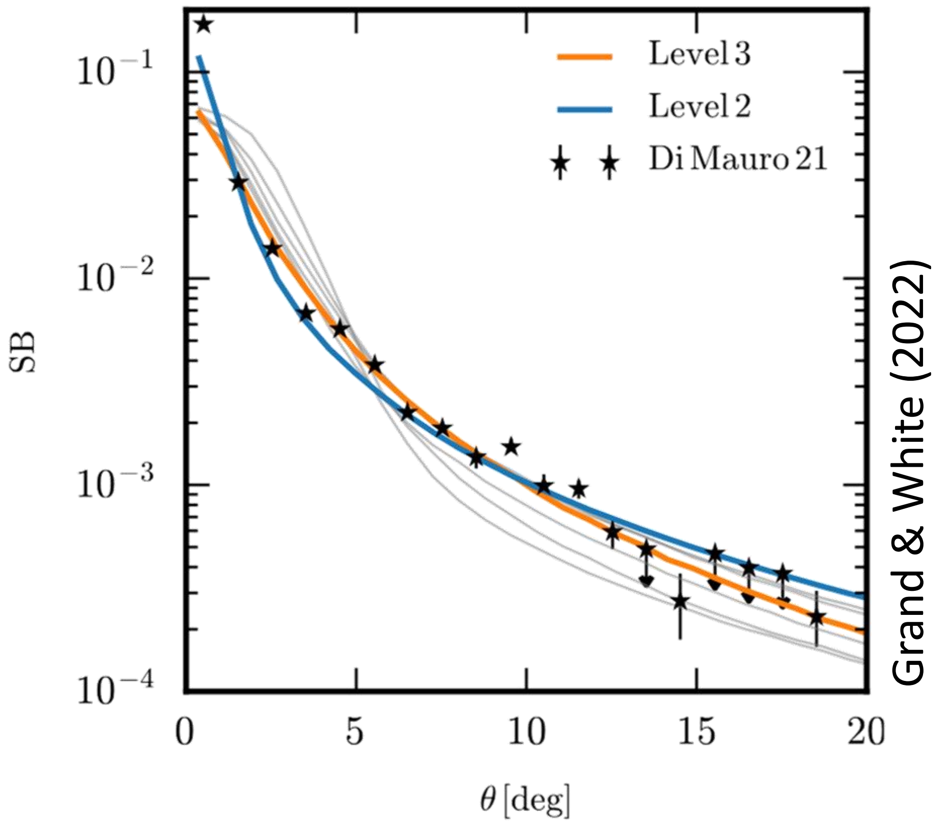
Indirect detection?

The Galactic Center gamma-ray excess

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

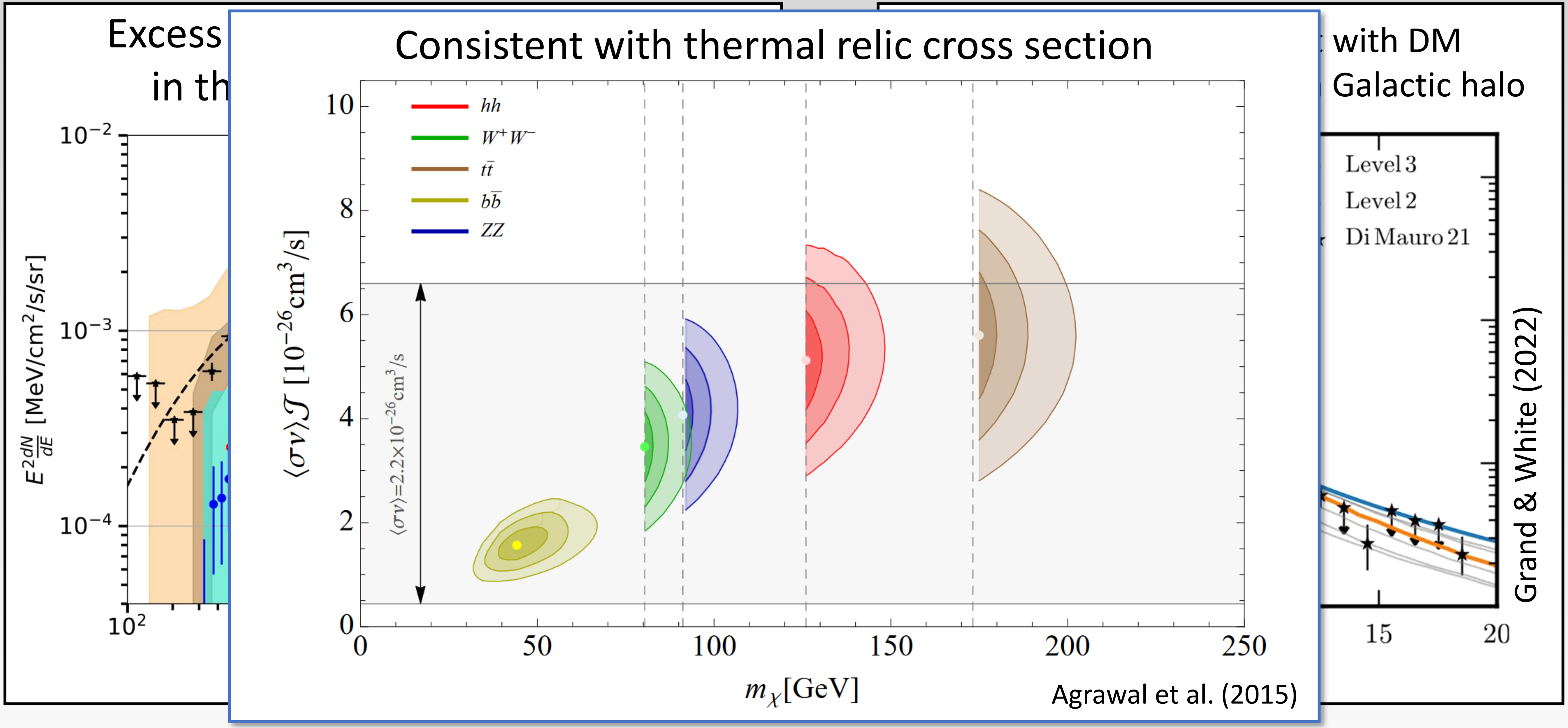


Morphology consistent with DM annihilation from a smooth Galactic halo



Indirect detection?

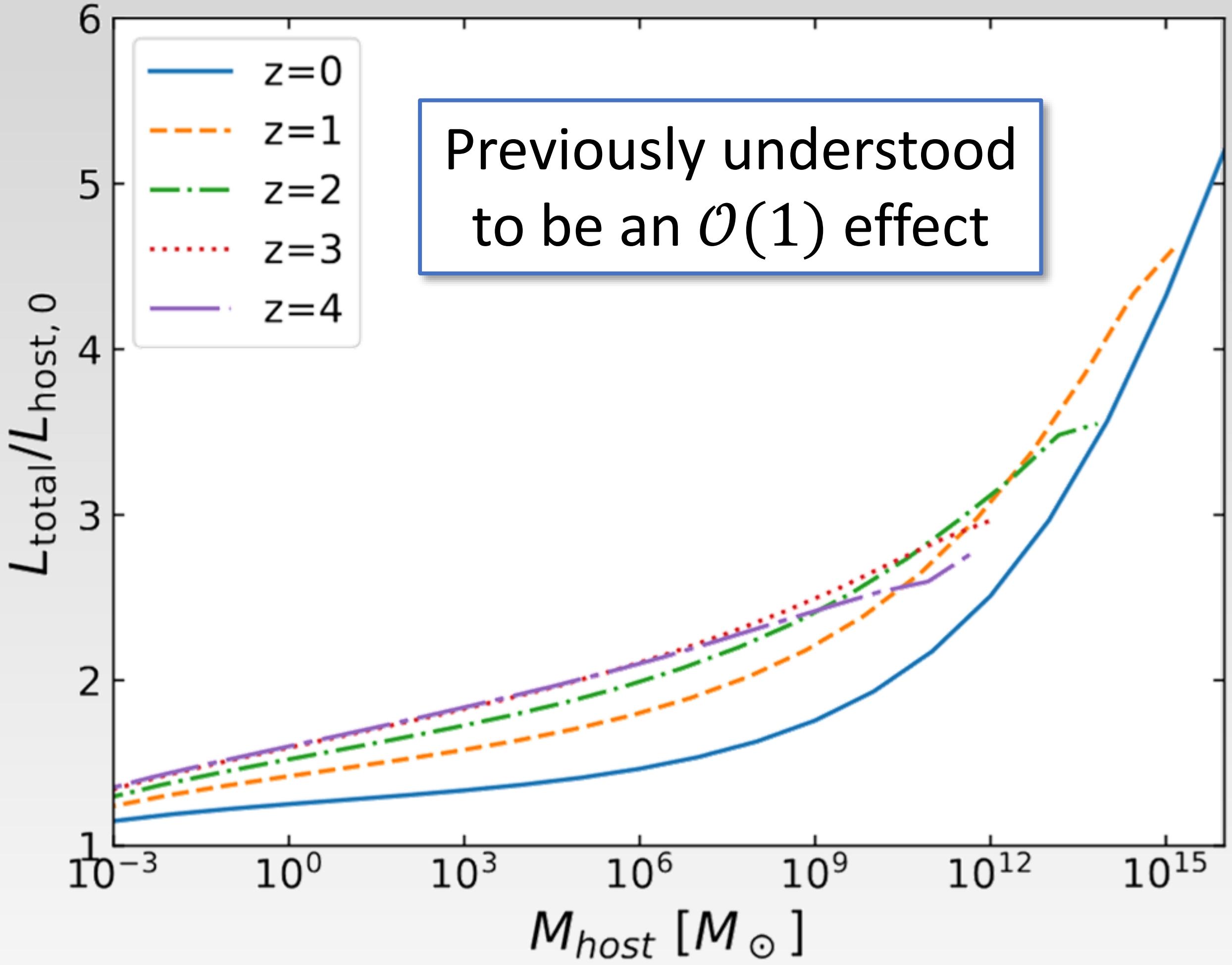
The Galactic Center gamma-ray excess



Substructure boost

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

(due to ρ^2 scaling)



Ando, Ishiyama, Hiroshima (2019)

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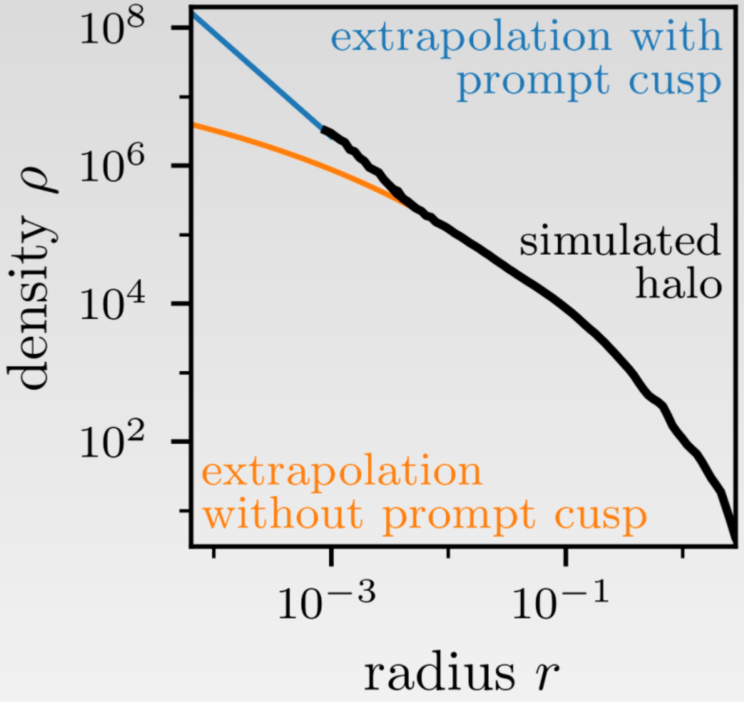
Prompt cusps and dark matter annihilation

Prompt cusp survival implies
every halo and subhalo has one

Extreme density inside prompt cusps
boosts the annihilation rate

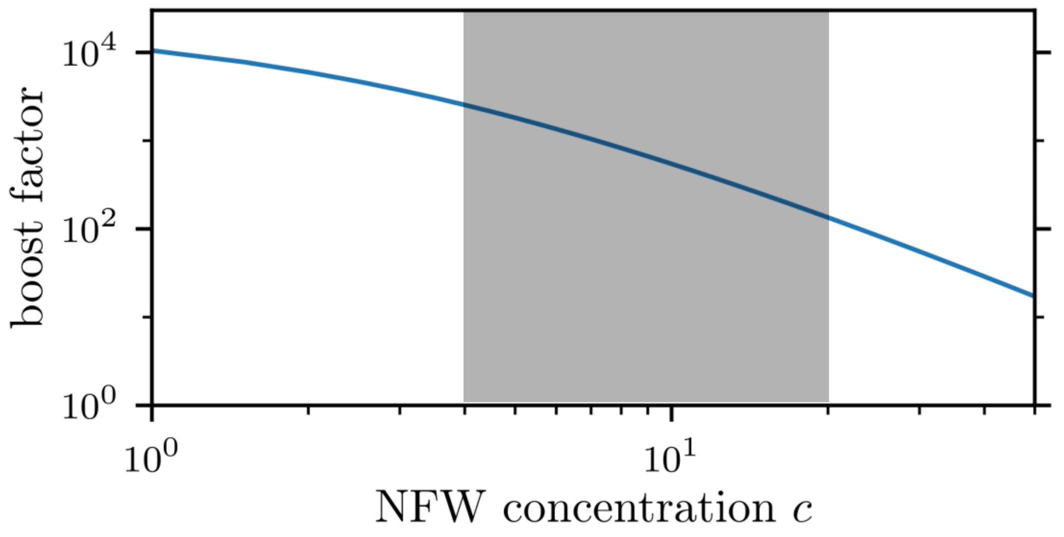


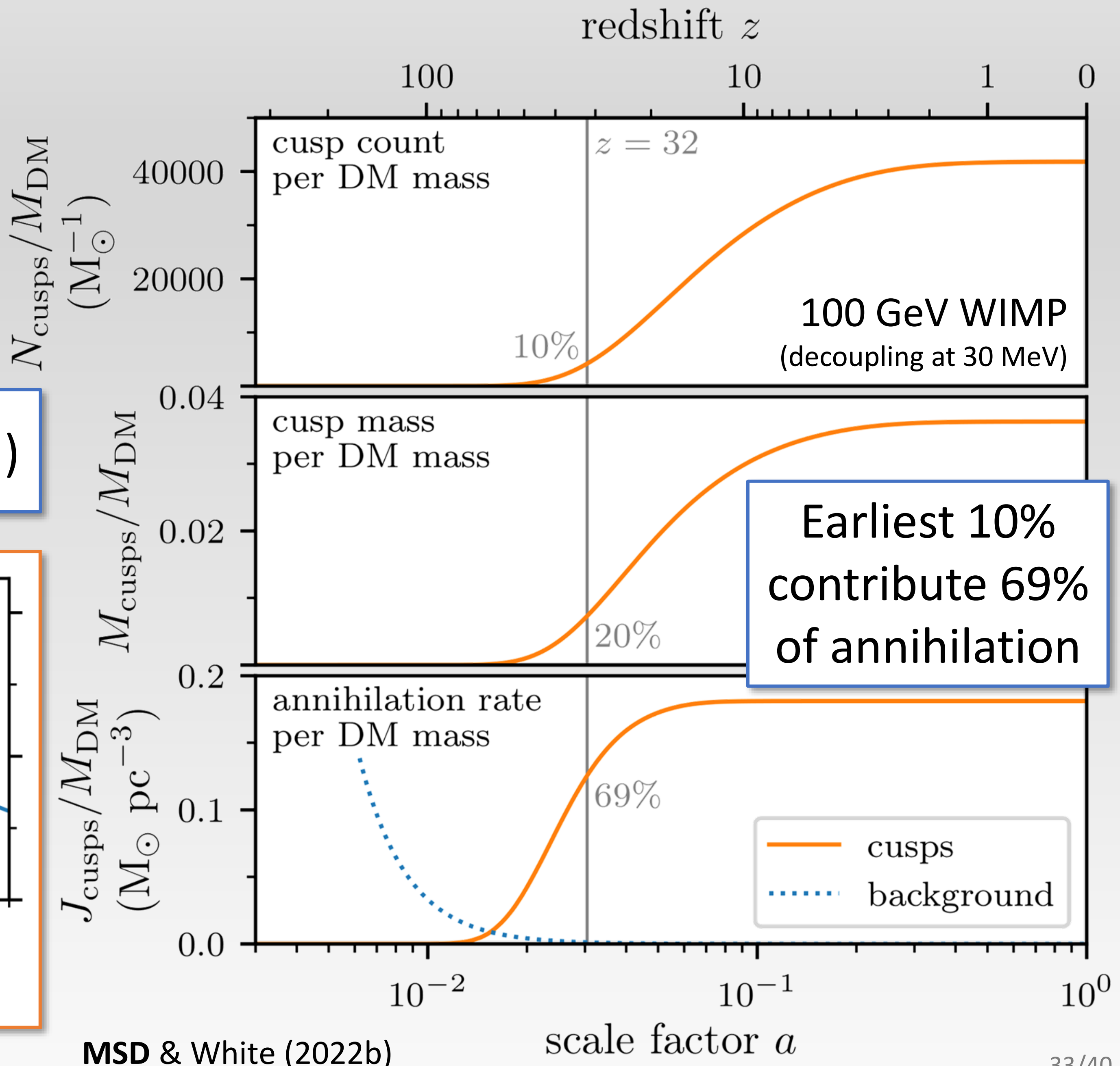
Egalitarian: every halo, no matter its size, has (roughly) **the same prompt cusp**

Annihilation in prompt cusps

Compute using peak statistics

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





Earliest 10% contribute 69% of annihilation

MSD & White (2022b)

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

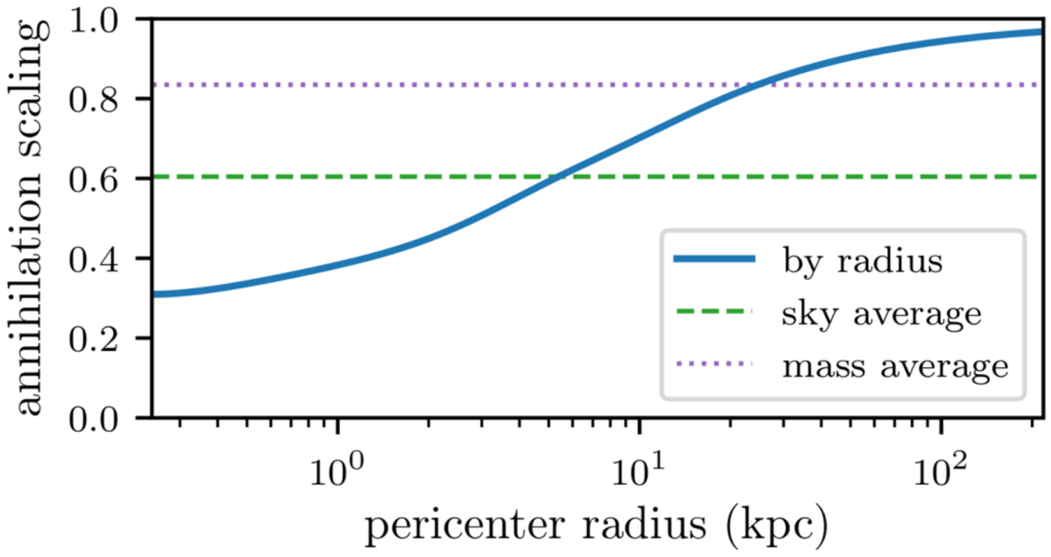
predict cusps are always preserved at sufficiently small radii

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

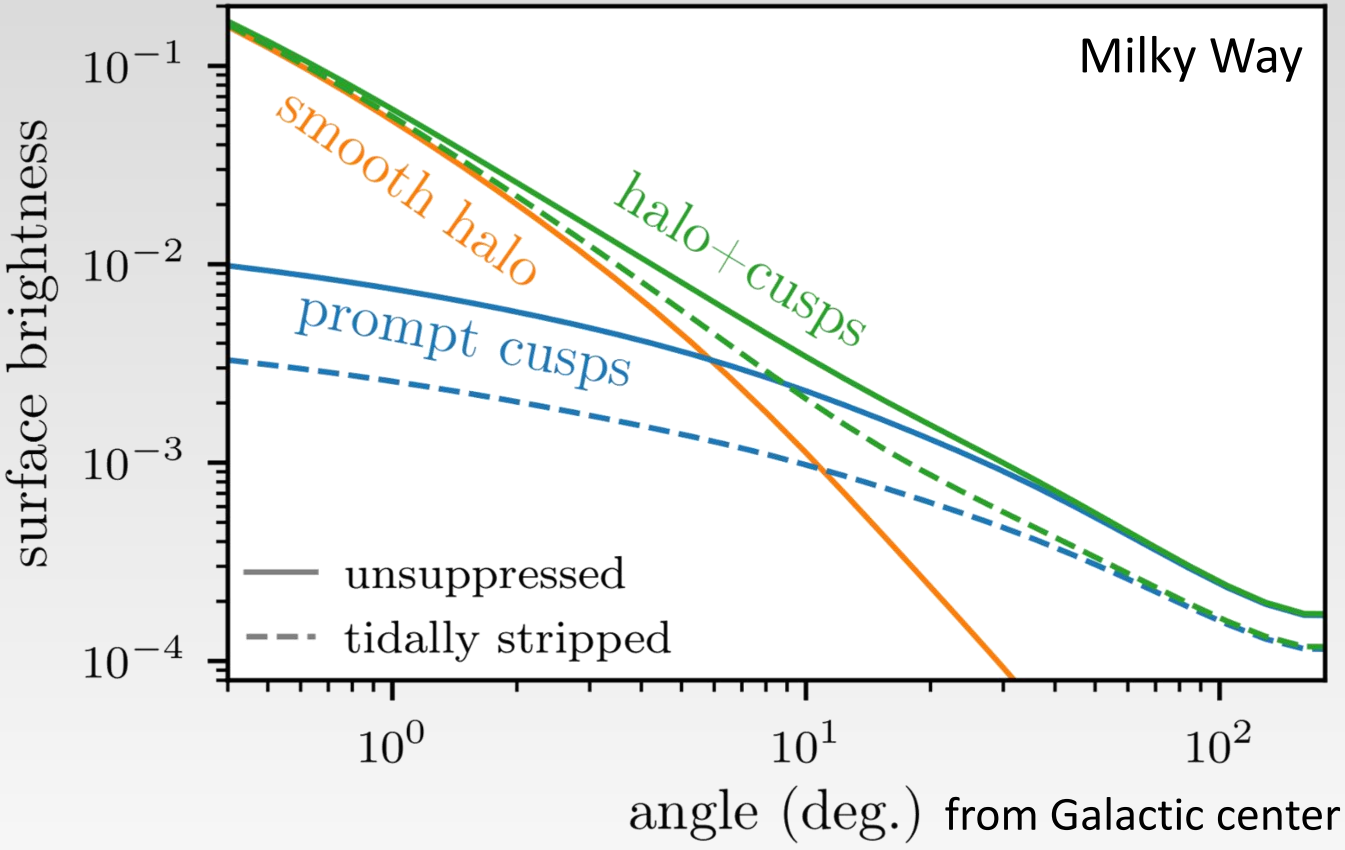
Adiabatic-tides (Stücker et al) prediction for prompt cusp survival in our Galactic halo:



MSD & White (2022b)

Annihilation signal

Spatial distribution of annihilation signal changes:
annihilation rate in prompt cusps $\propto$ smoothed density ρ, not ρ^2

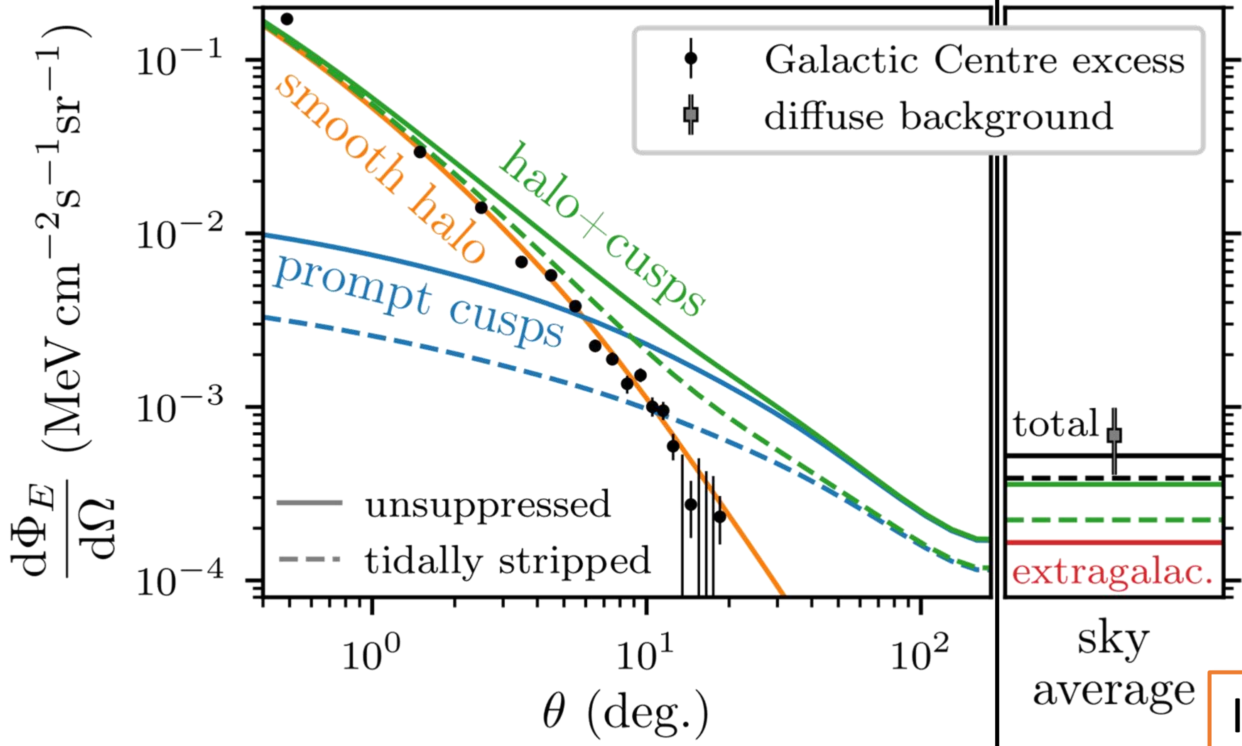


from Galactic center

Galactic halo mass model: Cautun et al (2020)

Prompt cusps and the Galactic Center excess

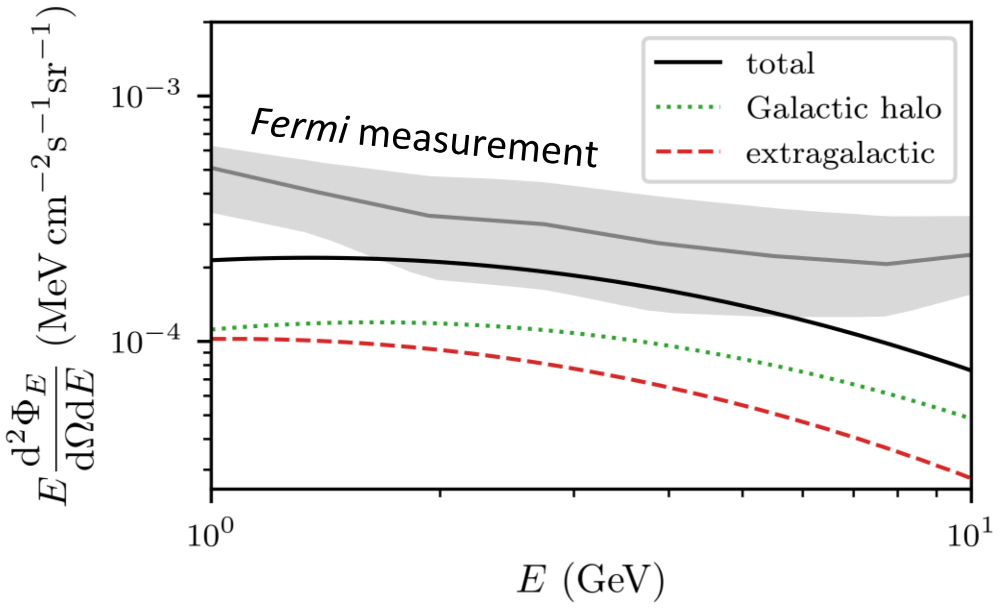
Prompt cusps alter the DM annihilation morphology (ρ, not ρ^2)



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 largely annihilating DM…

Galactic halo mass model: Cautun et al (2020)

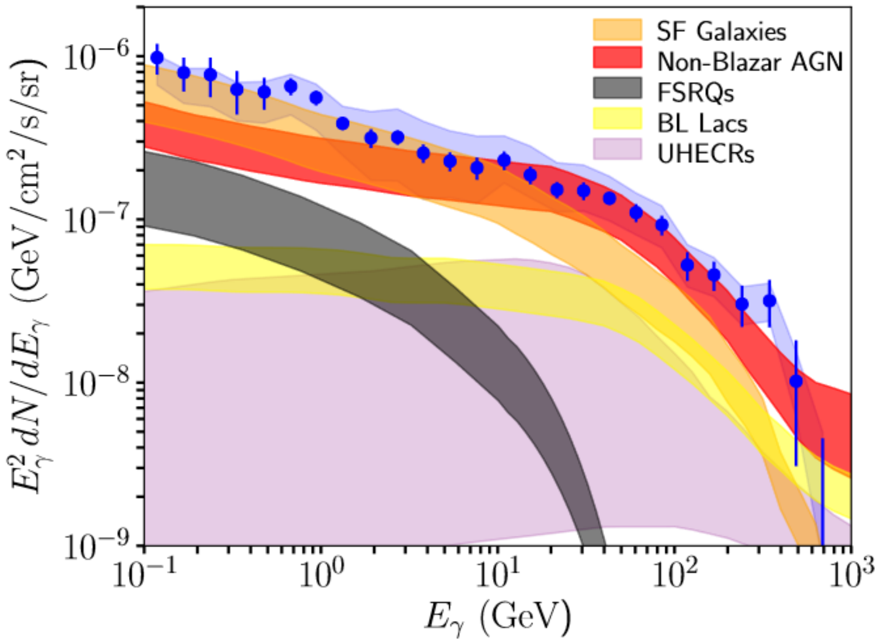
MSD & White (2022b)

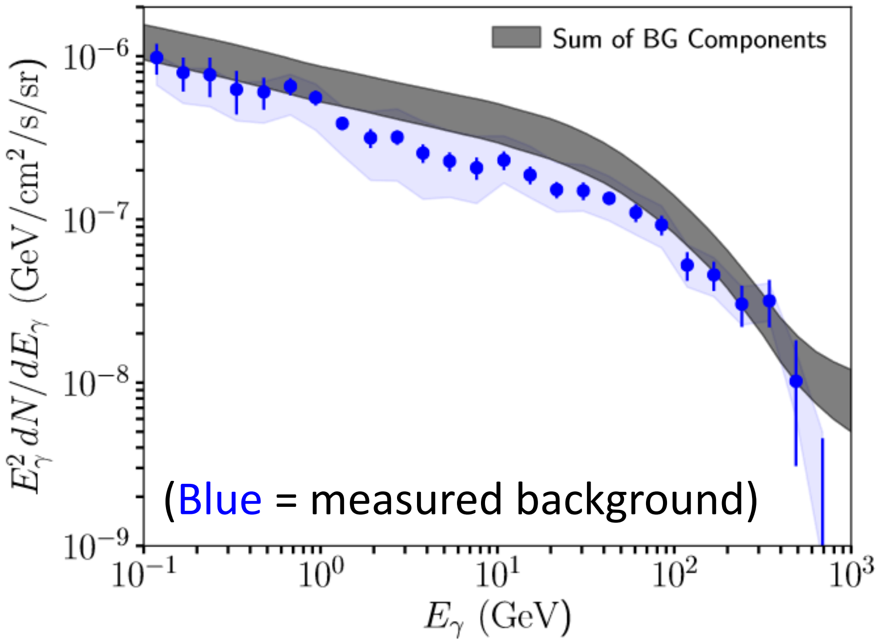
Prompt cusps and the Galactic Center excess

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

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

Blanco & Hooper (2019)



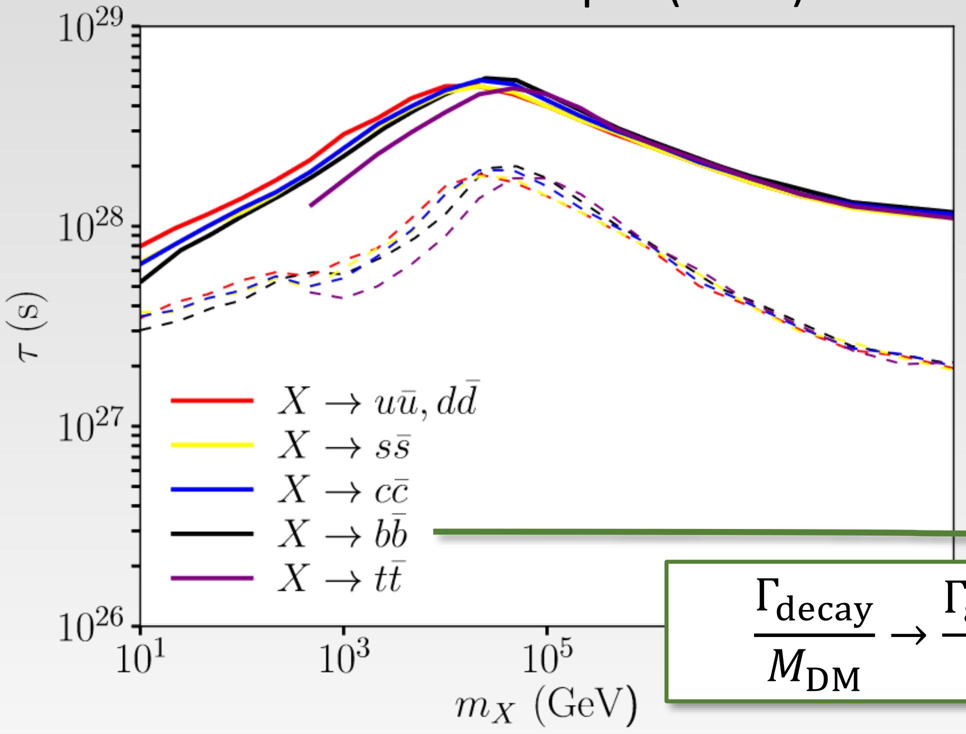


Limits on DM annihilation

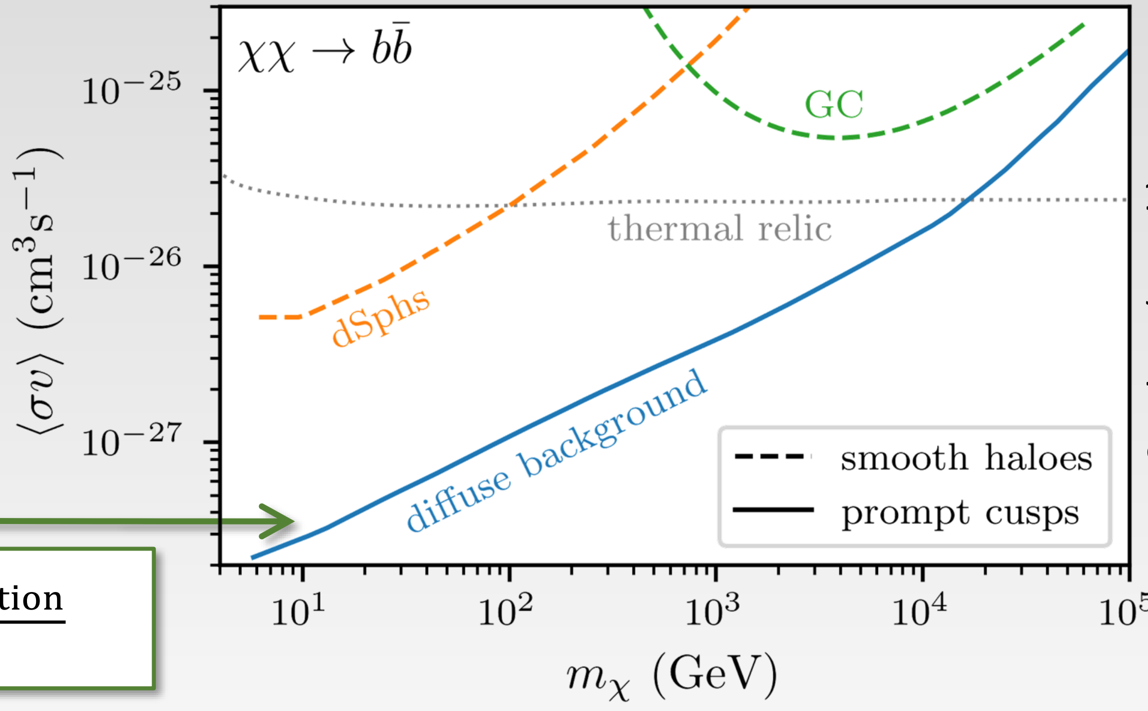
Signal from DM annihilation in unresolved prompt cusps ≃ signal from DM decay

so we can convert between them:

Blanco & Hooper (2019)



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

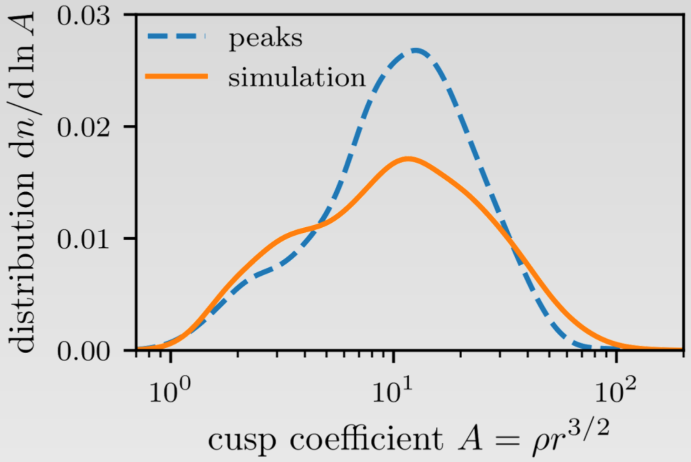


MSD & White (2022b)

(different DM candidate)

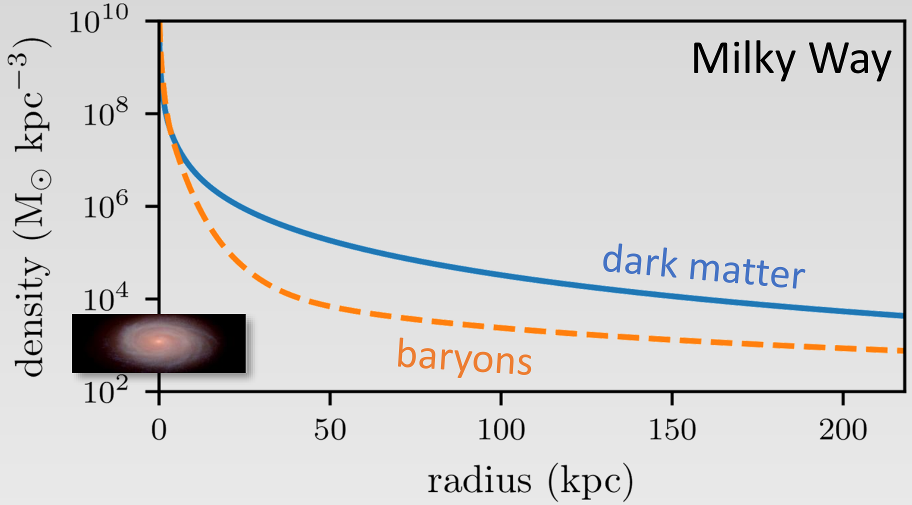
Outlook

Reduction in prompt cusp number due to mergers?



(highly unequal masses lead to subhalo, both cusps preserved)

How much disruption by stars?



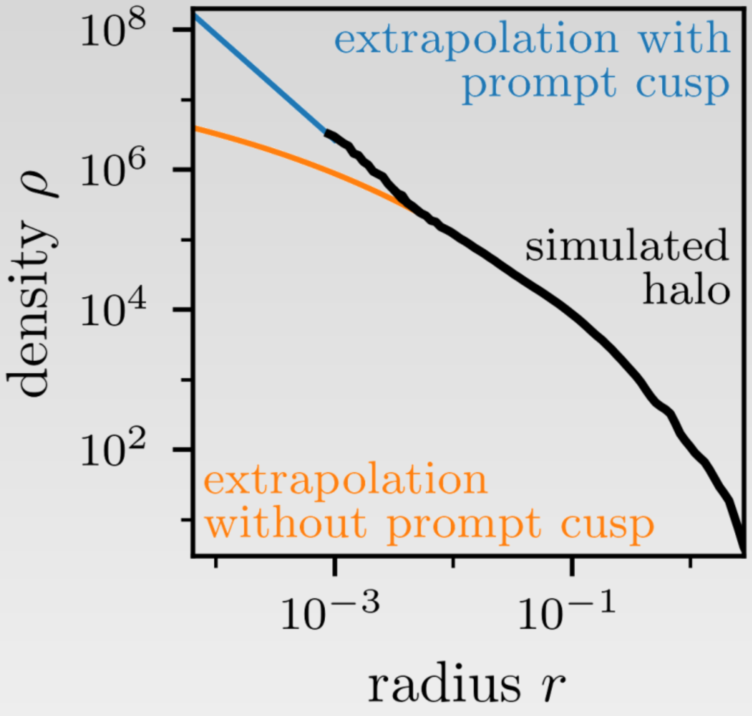
~30% of Galactic DM crosses disk

If DM is a thermal relic, expect an annihilation signal not only from the densest regions **but from diffuse regions as well**

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 can range from hundreds to thousands
- Different morphology: rate $\propto \rho$ instead of ρ^2
- Unprecedentedly strong limits on annihilating DM

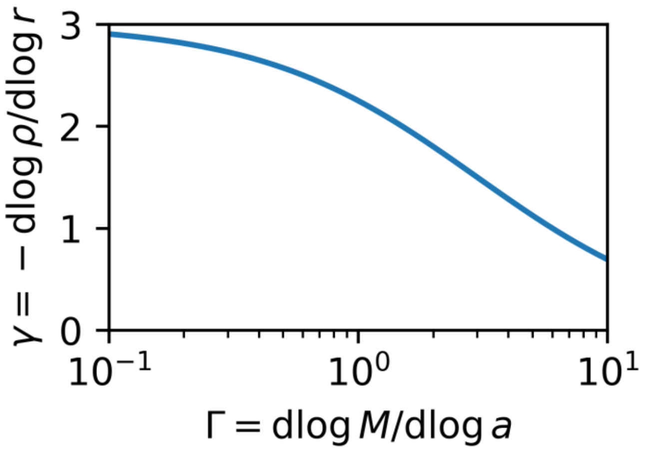
If DM is a thermal relic, expect an annihilation signal not only from the densest regions **but from diffuse regions as well**

Rapid accretion

Shallow NFW/Einasto profiles follow from the accretion history

Self-similar models predict

faster accretion → shallower profile



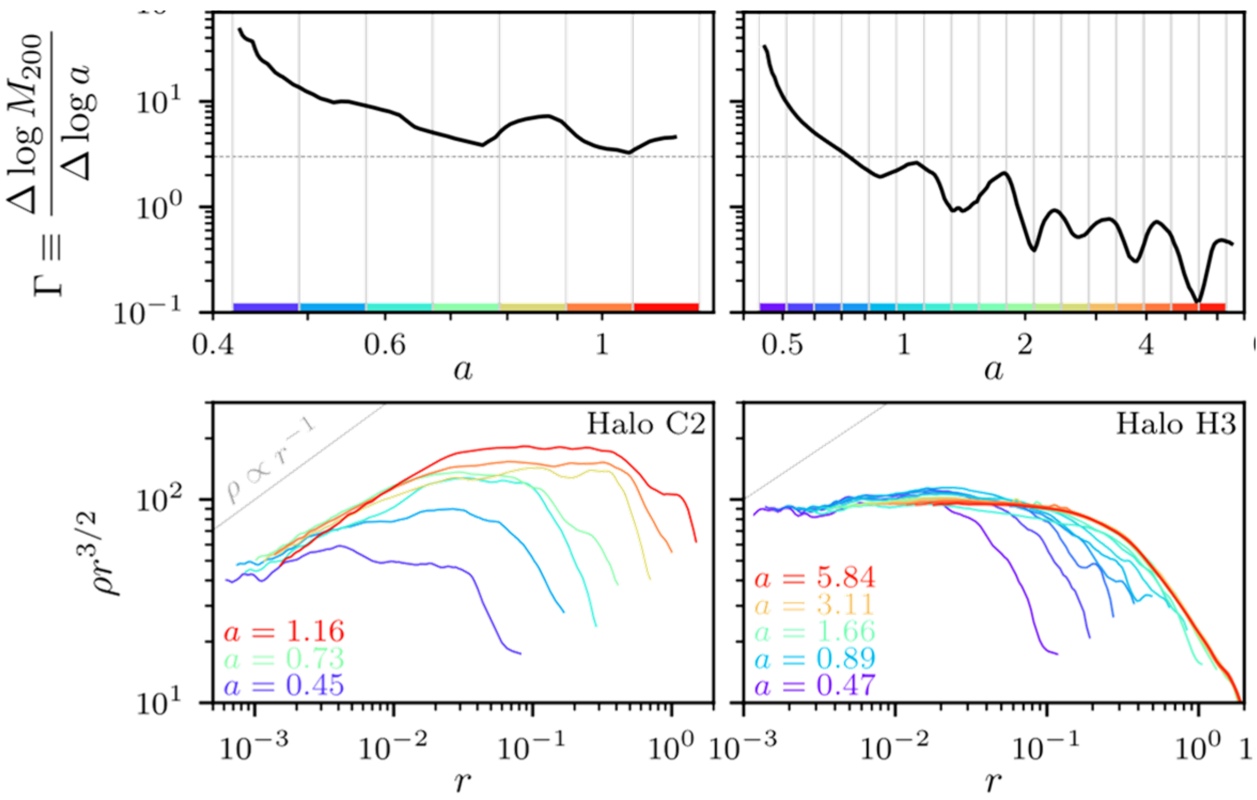
Physically, new material

- 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

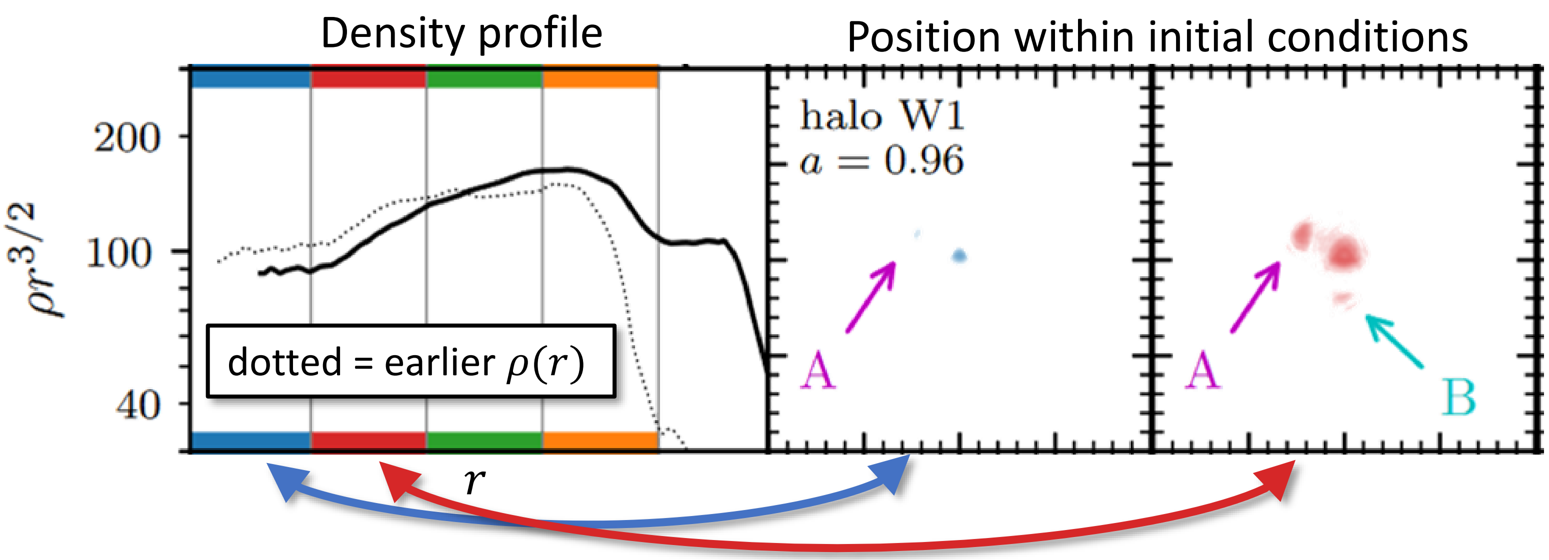
Mergers

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…

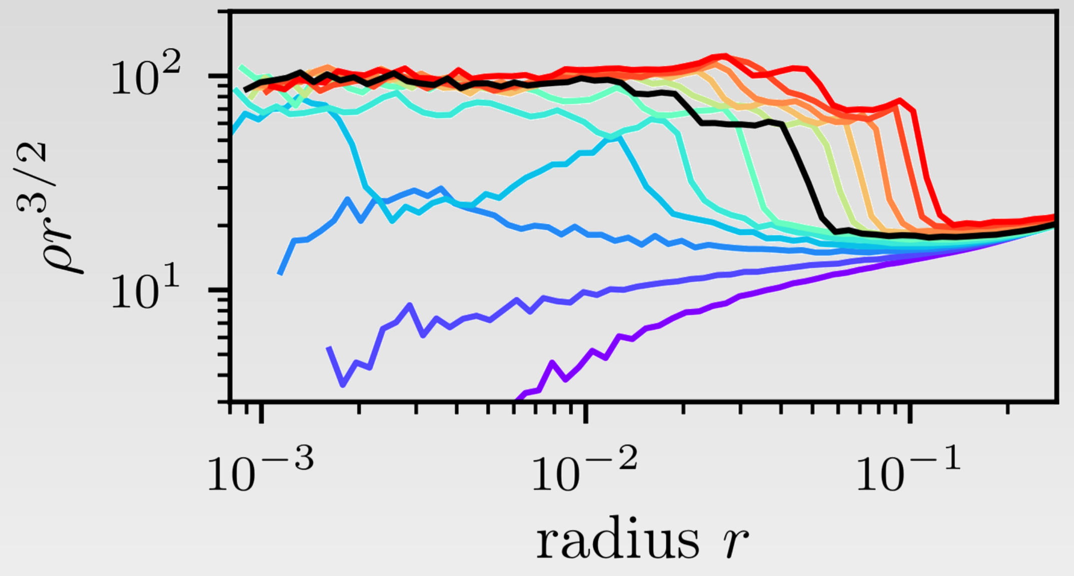


…which caused some disruption of the $\rho \propto r^{-3/2}$ cusp.

MSD & White (2022)

Universality?

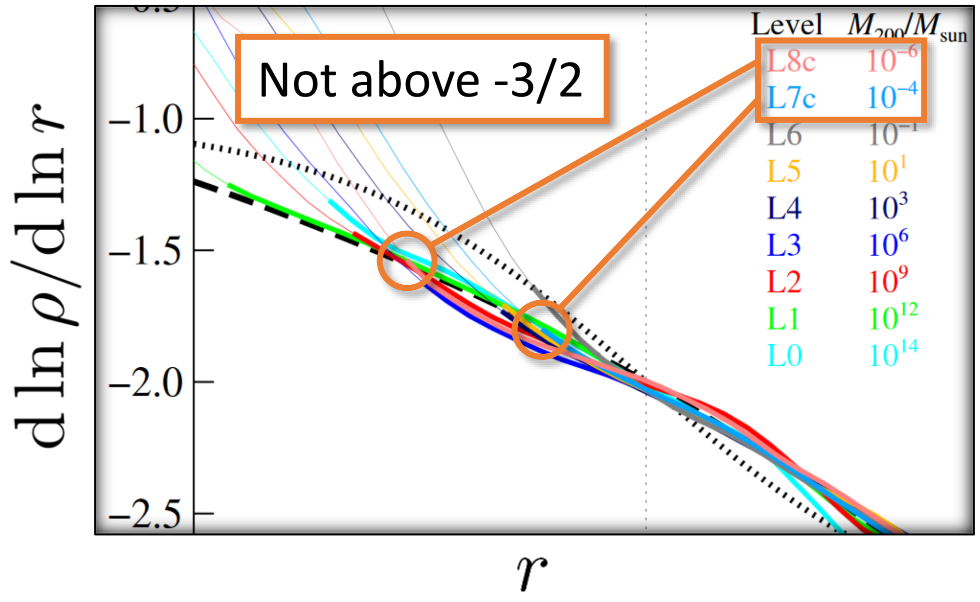
$\rho \propto r^{-3/2}$ cusp



Consistent with:

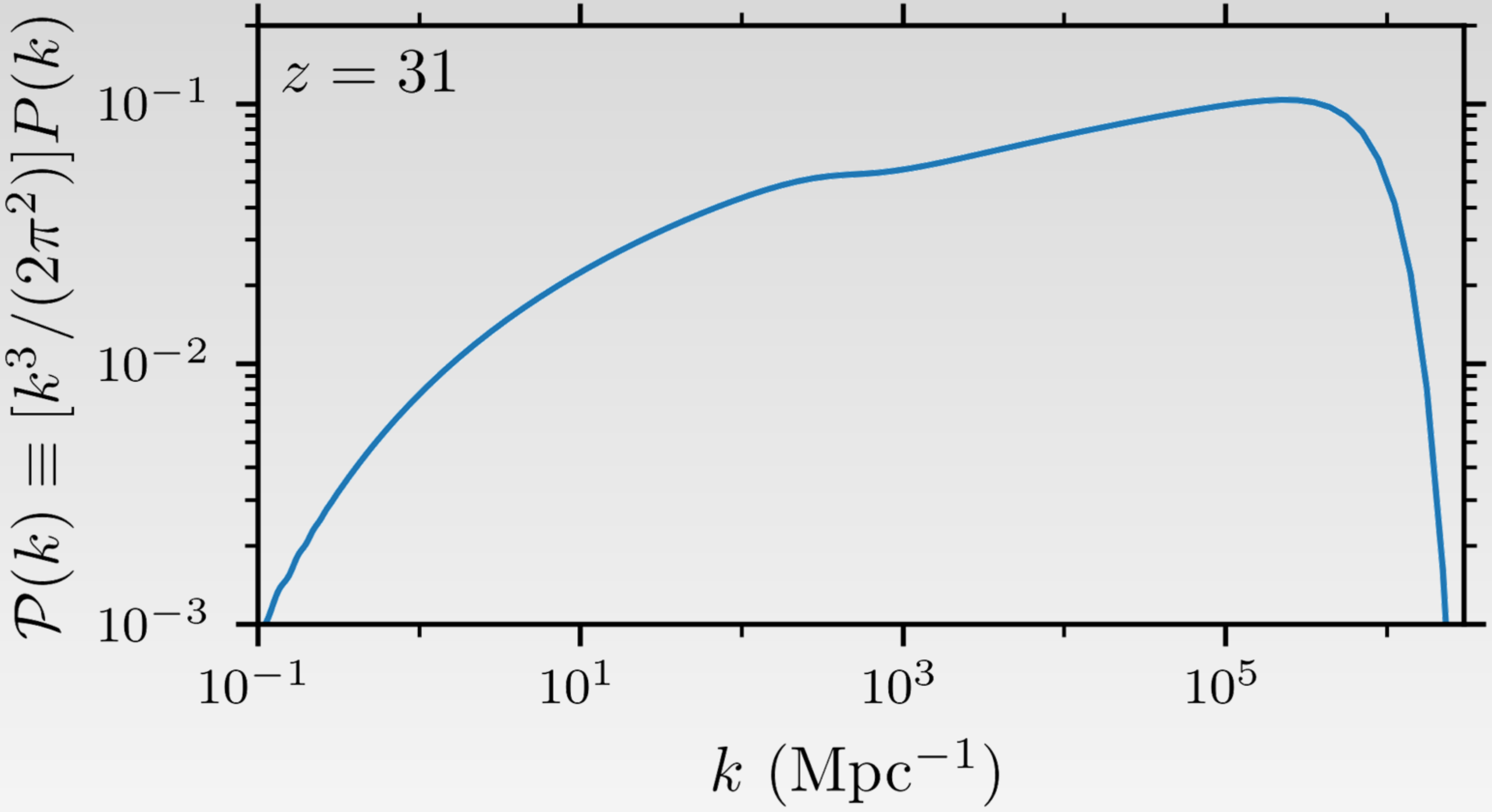
Universality in the structure of dark matter haloes over twenty orders of magnitude in halo mass

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



Power spectrum

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



Annihilation vs particle properties

$$\frac{J_{\mathrm{cusps}}}{M_{\mathrm{DM}}} = 0.08 \left[\log\left(\frac{m_\chi}{\mathrm{GeV}}\frac{T_{\mathrm{kd}}}{\mathrm{GeV}}\right) + 36\right]^5 \bar{\rho}_0$$

m_χ = DM particle mass
T_{kd} = DM kinetic decoupling temperature
$\bar{\rho}_0$ = mean DM density today