Density profiles of the first halos & microhalo evolution through stellar encounters

M. Sten Delos
Max Planck Institute for Astrophysics

News from the Dark
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Cosmological signatures in the small-scale $P(k)$

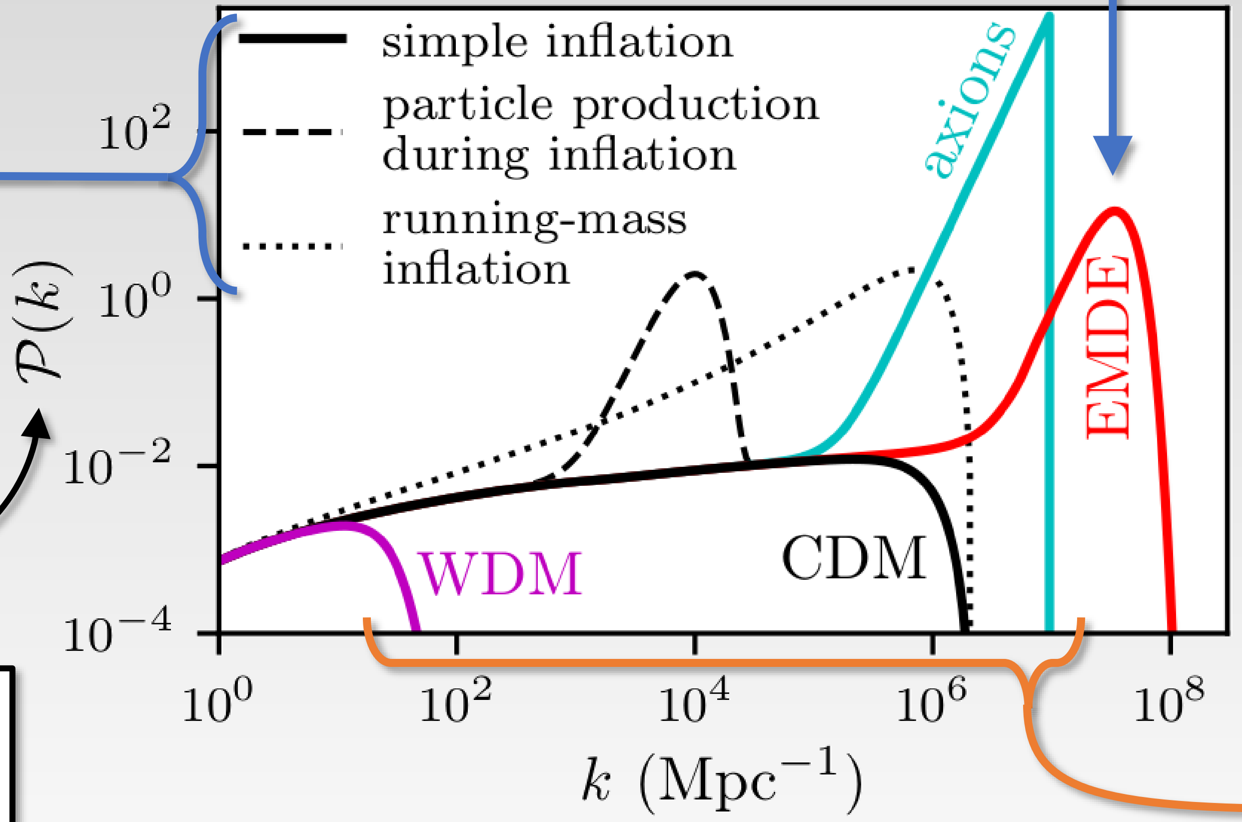
What happened after inflation?

Early matter domination boosts density variations.

[Early matter species clusters, carrying DM with it]

What drove inflation?

Dynamics of the inflaton field imprint on the primordial power spectrum.



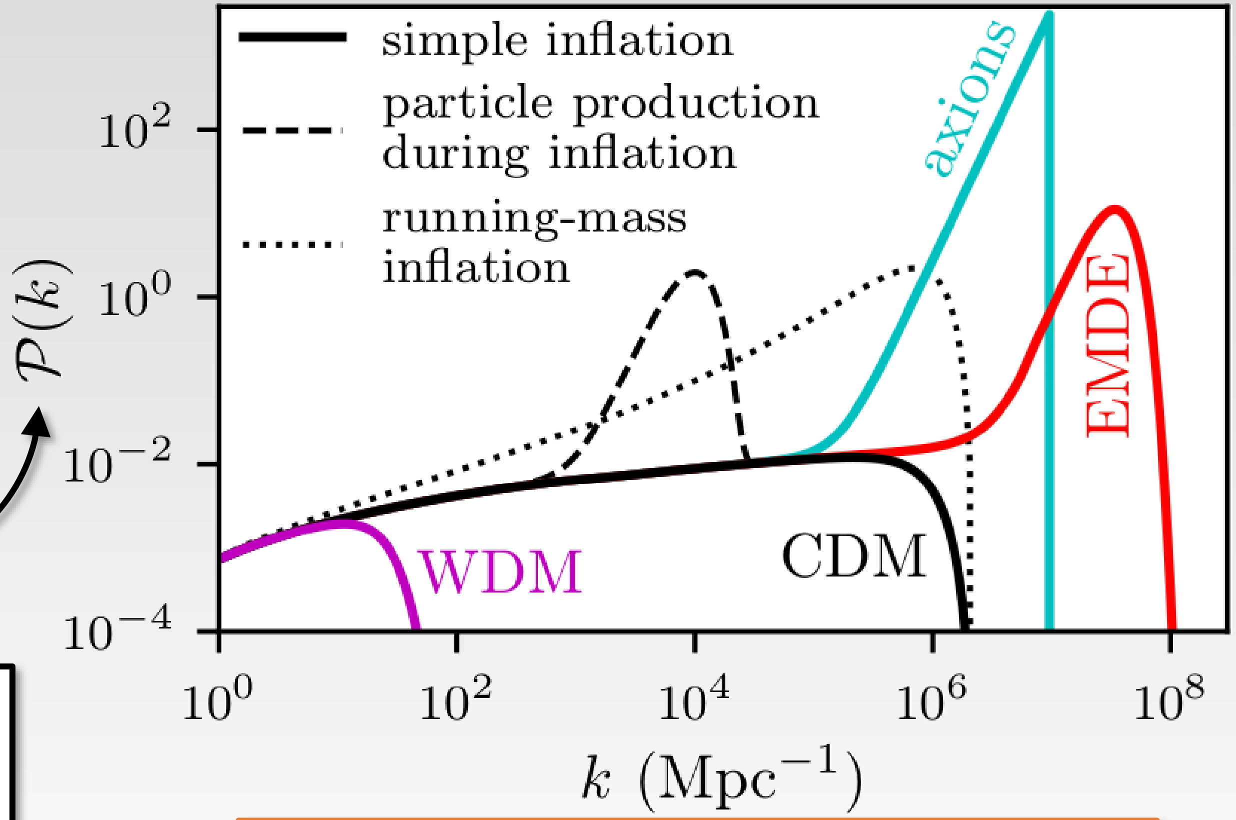
What is dark matter?

- Free streaming (CDM vs WDM)
- Poisson noise (axion, PBH)

$$\mathcal{P}(k) \equiv \frac{k^3}{2\pi^2} P(k)$$

Cosmological signatures in the small-scale $P(k)$

In these cases, we are interested in the largest-amplitude density variations

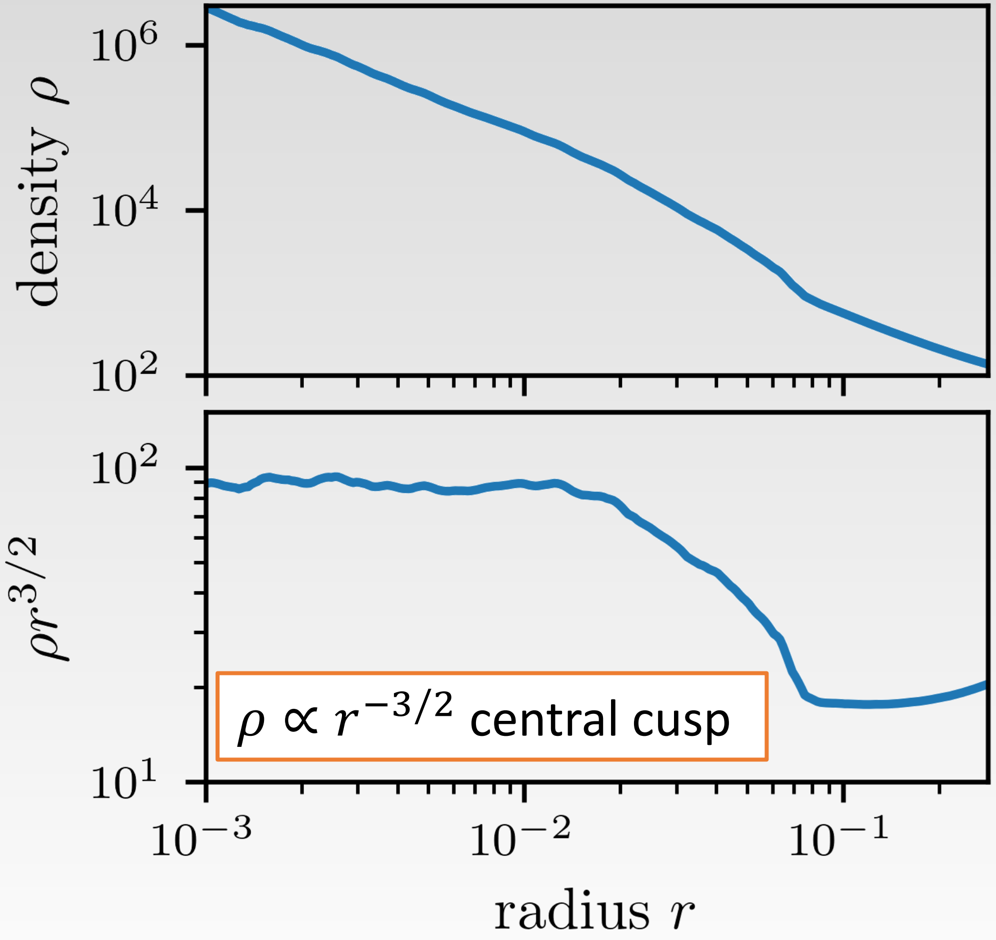


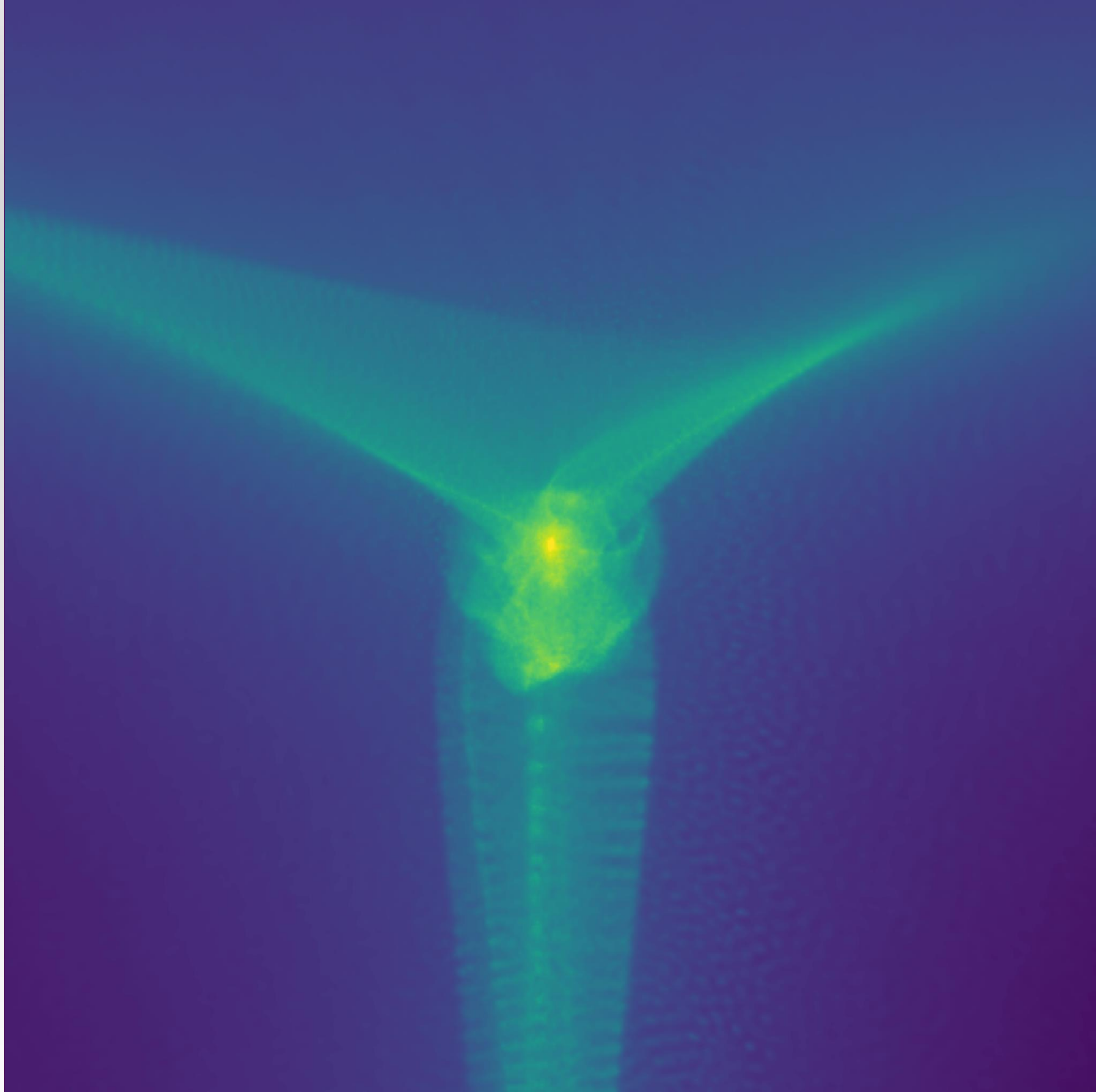
$$\mathcal{P}(k) \equiv \frac{k^3}{2\pi^2} P(k)$$

…and hence in the first halos

The first halos

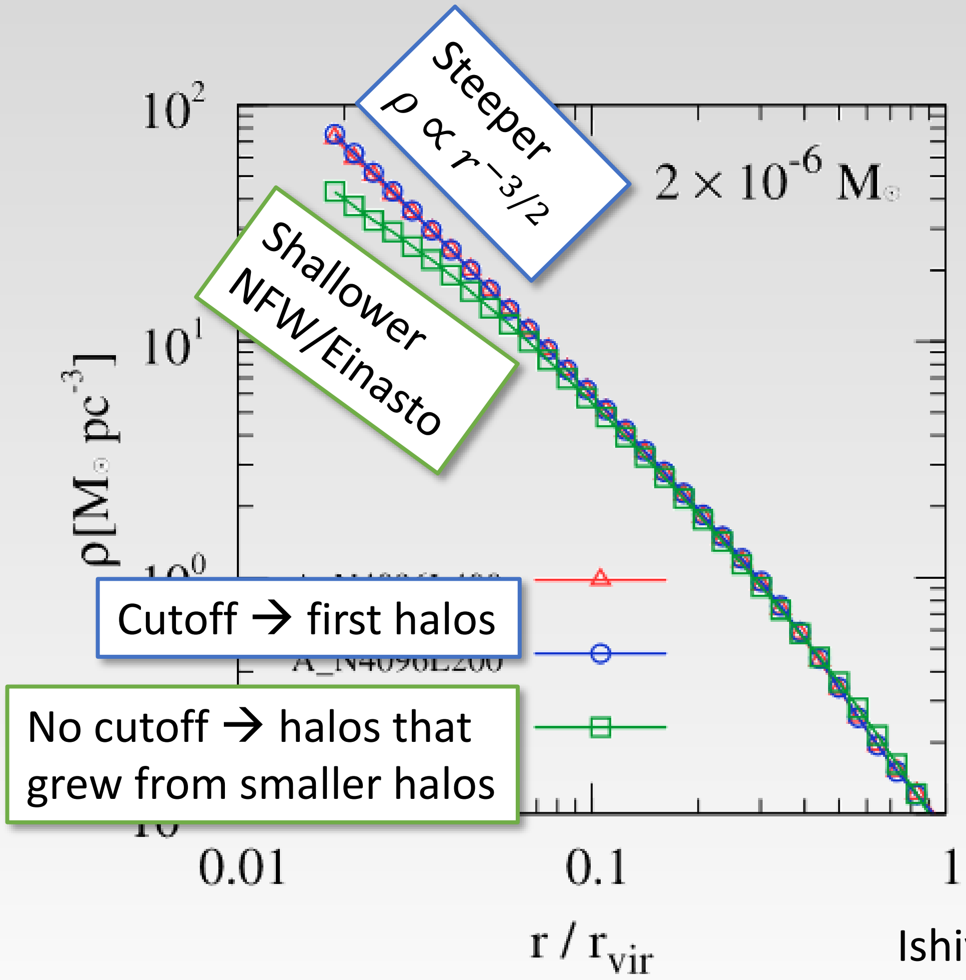
The first (and smallest) halos
collapse from smooth density peaks

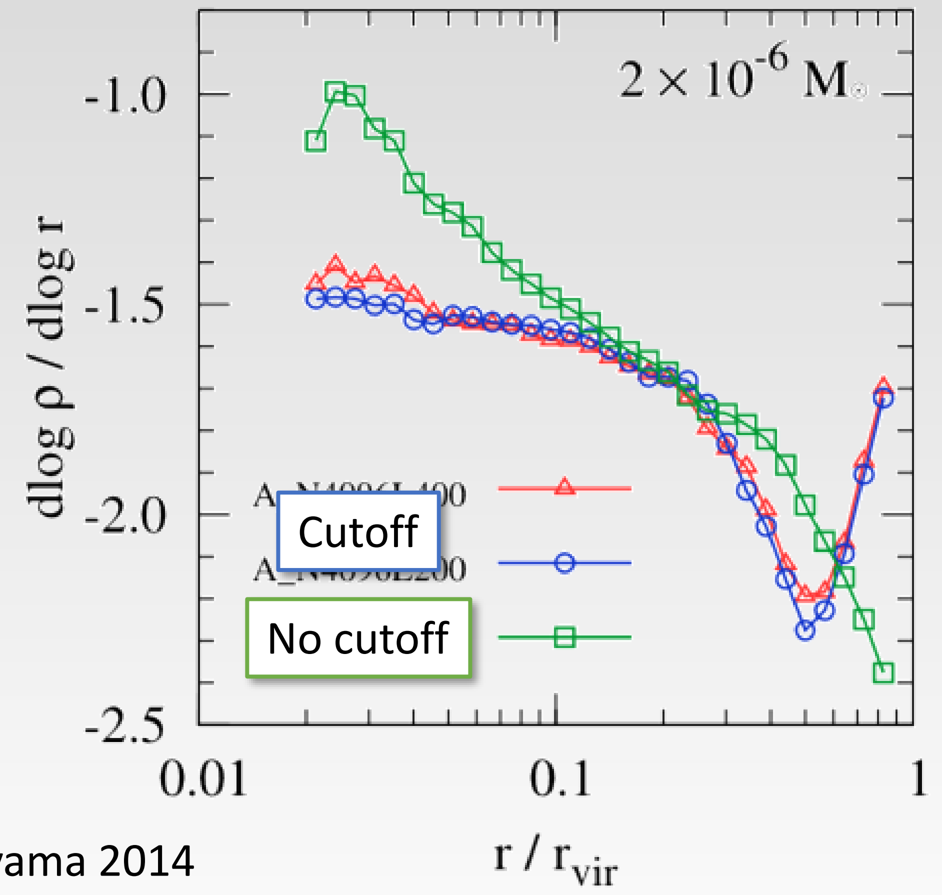




Density profiles of the first halos

It is well known that halos that form close to the cutoff scale in $P(k)$ develop steeper inner density profiles.





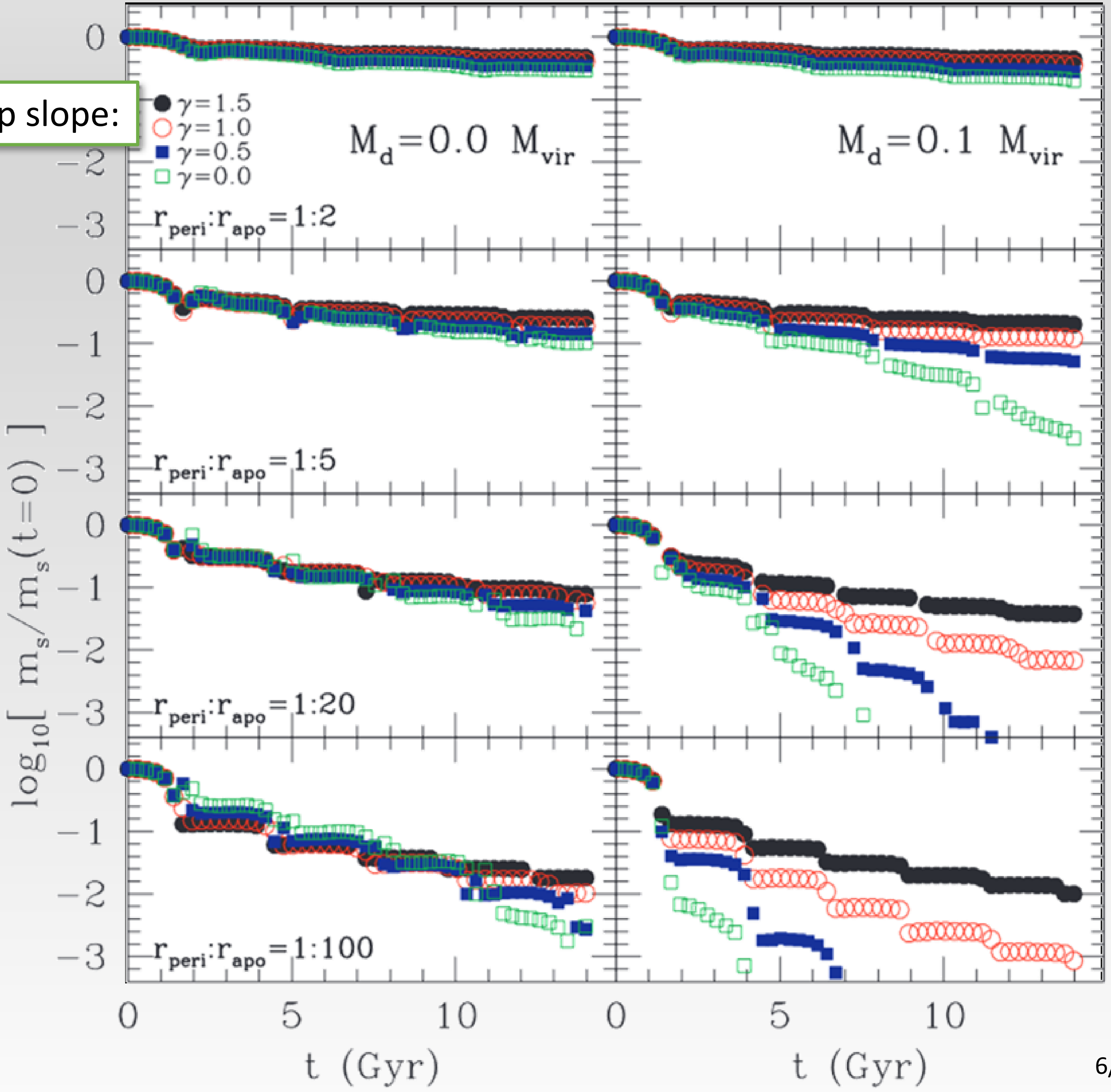
Ishiyama 2014

Impact of steeper cusps

Boosted subhalo survival:

Steeper cusps have a more resilient phase-space structure, so they are less susceptible to tidal stripping and heating.

Cusp slope:

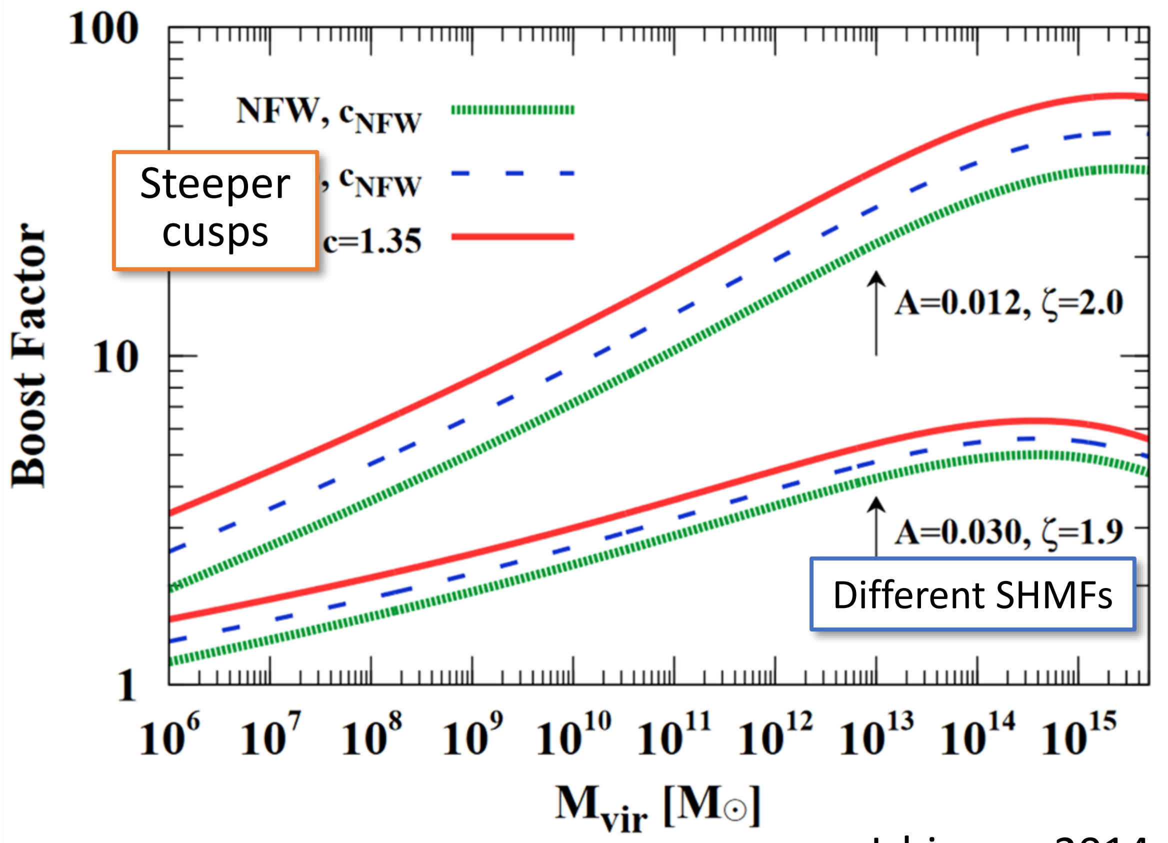


Peñarrubia et al 2010

Impact of steeper cusps

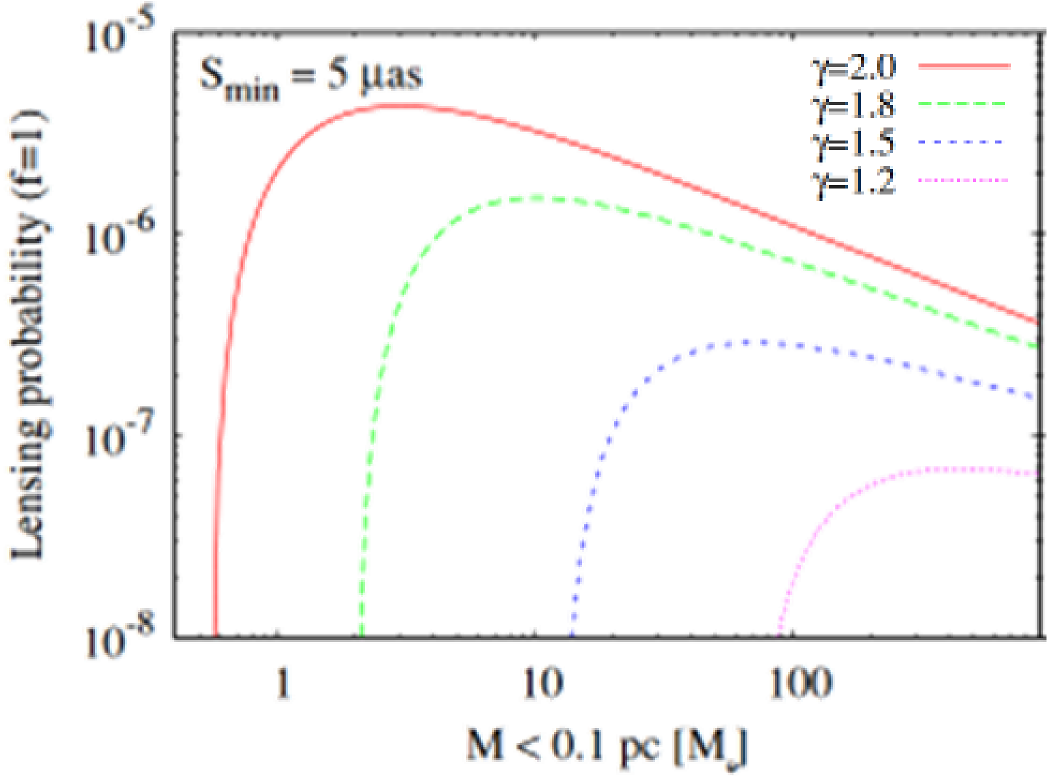
Boosted observational signatures, e.g.

Annihilation



Ishiyama 2014

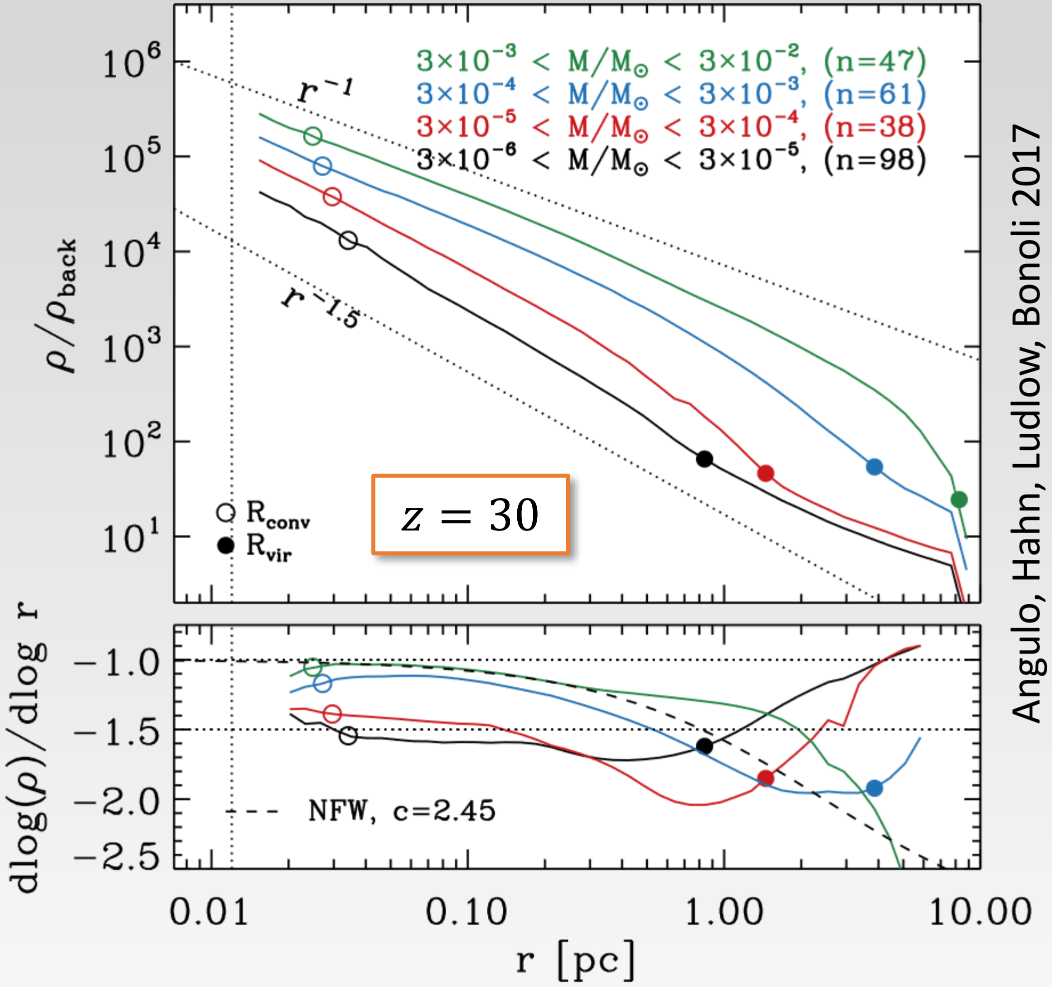
Lensing



Erickcek & Law 2011

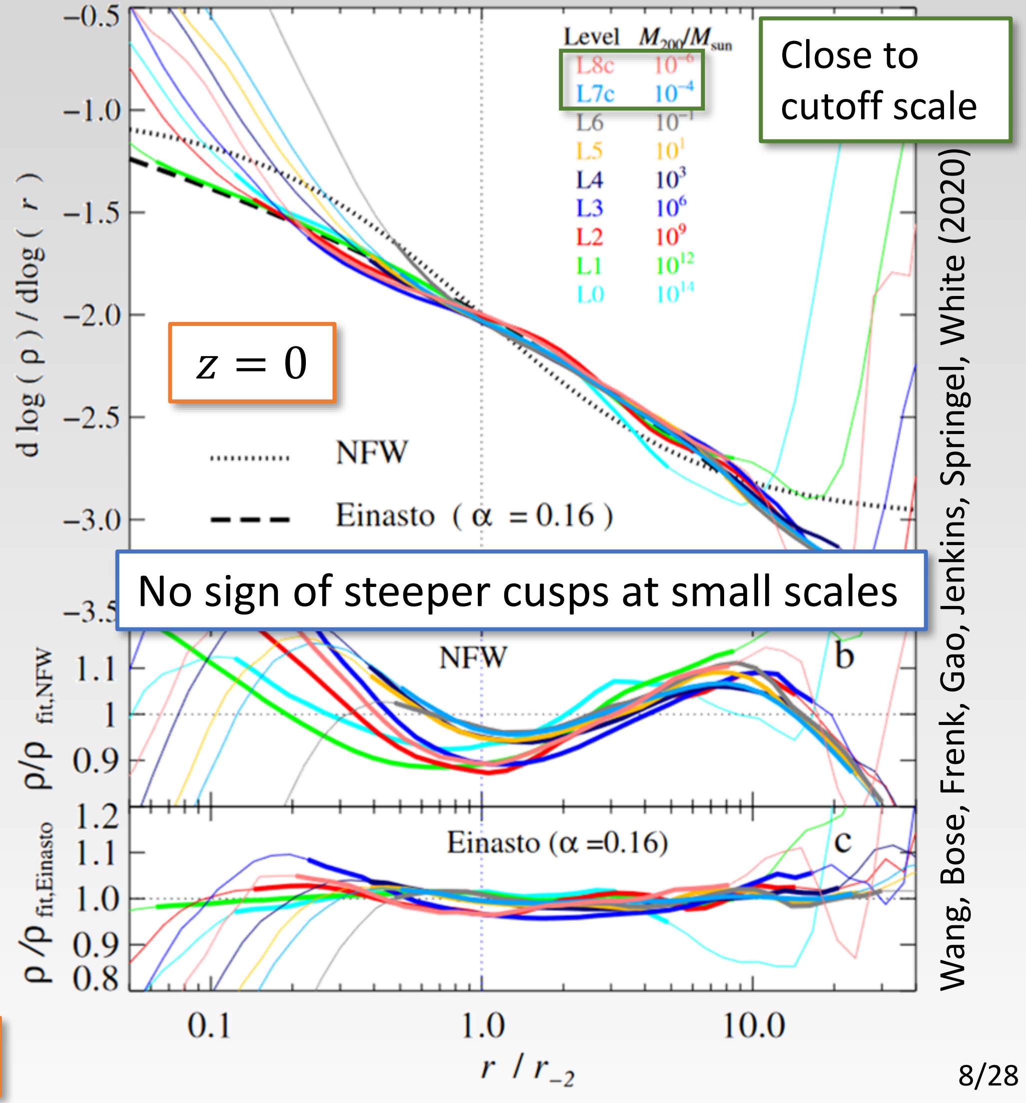
Do steep cusps survive?

Larger halos have shallower slopes



Angulo, Hahn, Ludlow, Bonoli 2017

Einasto profiles universal at $z = 0$?



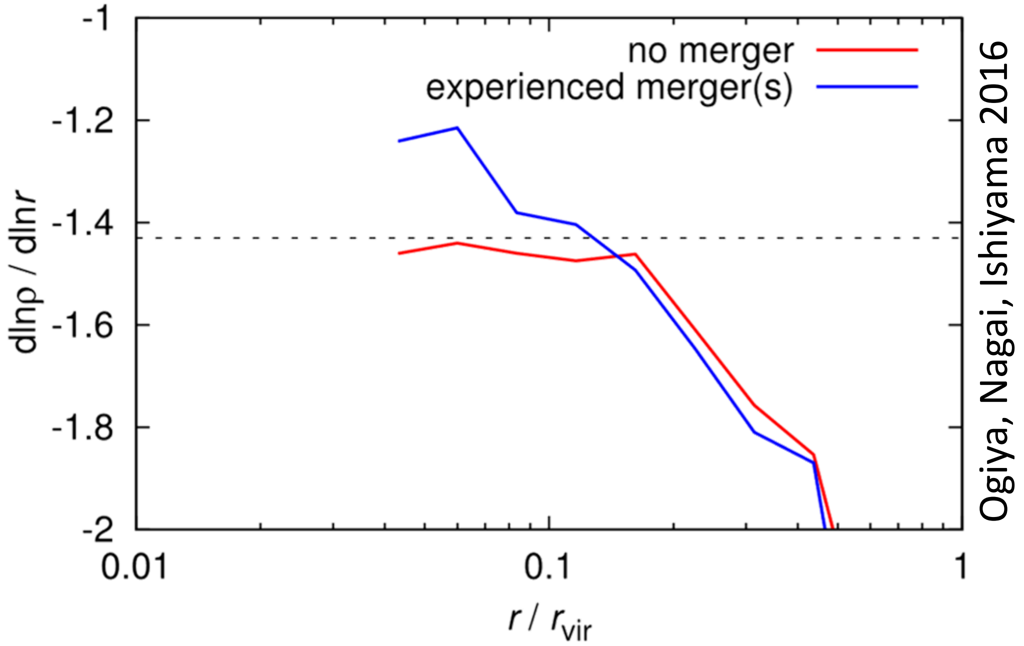
Wang, Bose, Frenk, Gao, Jenkins, Springel, White (2020)

Difficult to simulate over long time periods: halos grow too rapidly

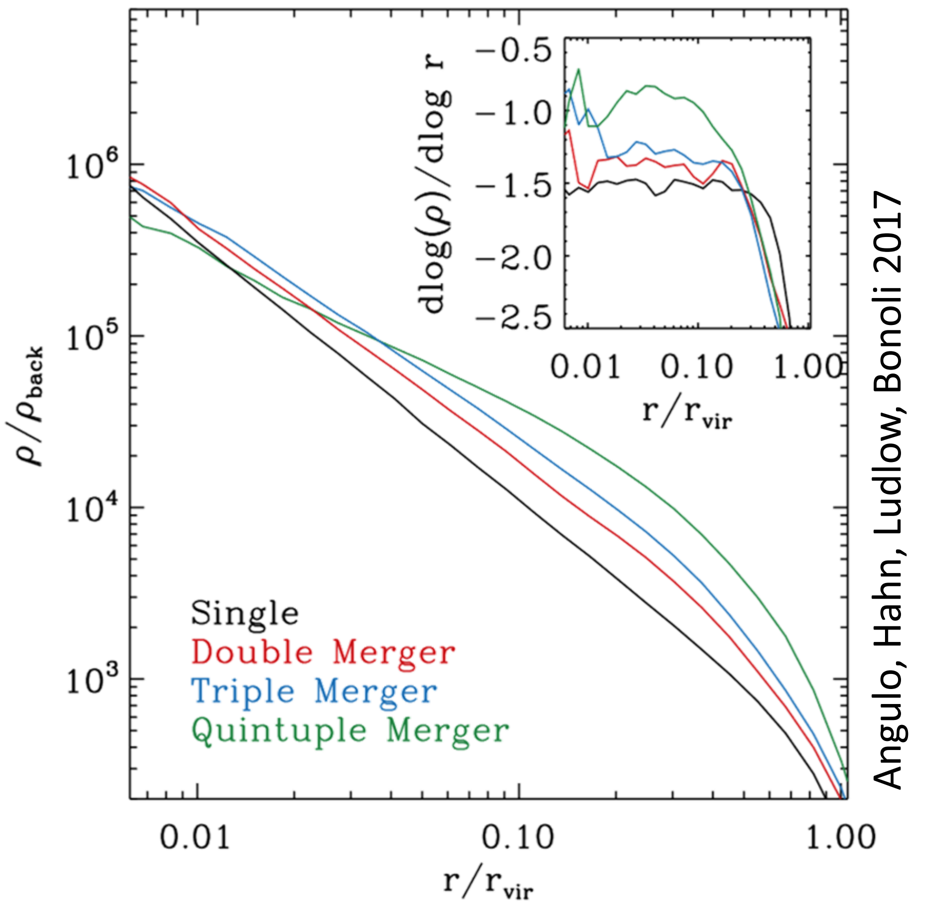
Cusps shallow due to mergers?

The common view is that mergers disrupt steep cusps

Correlation between mergers and shallow cusps

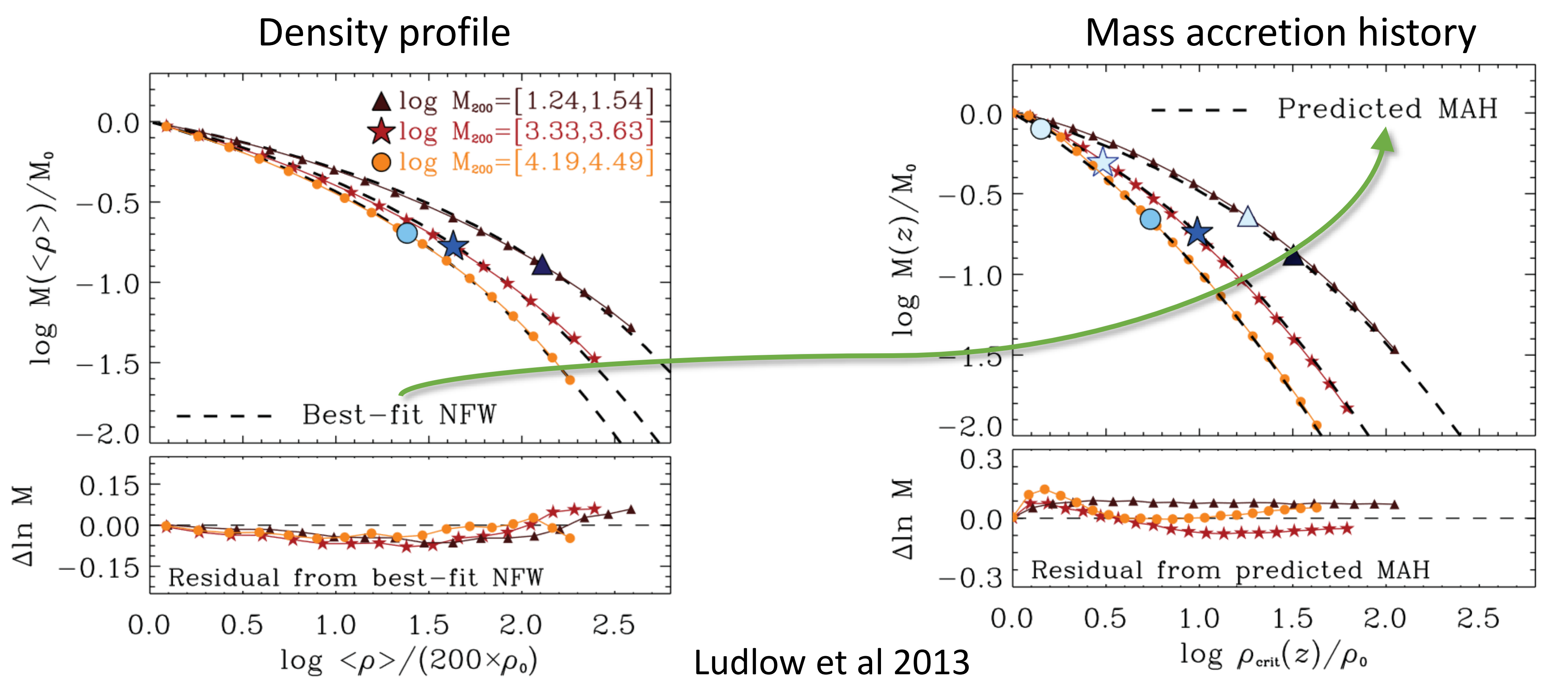


Shallowing in idealized merger simulations



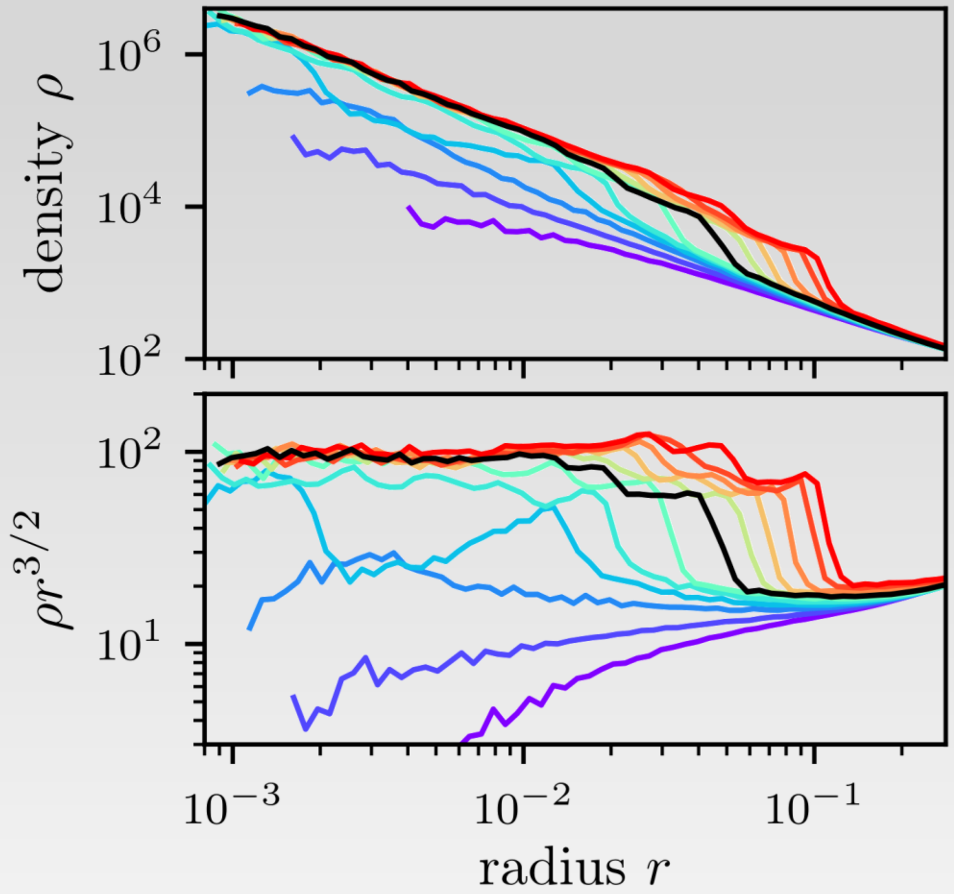
Cusps shallow due to mergers?

But CDM halo density profiles (NFW/Einasto) set by accretion history more than merger history.

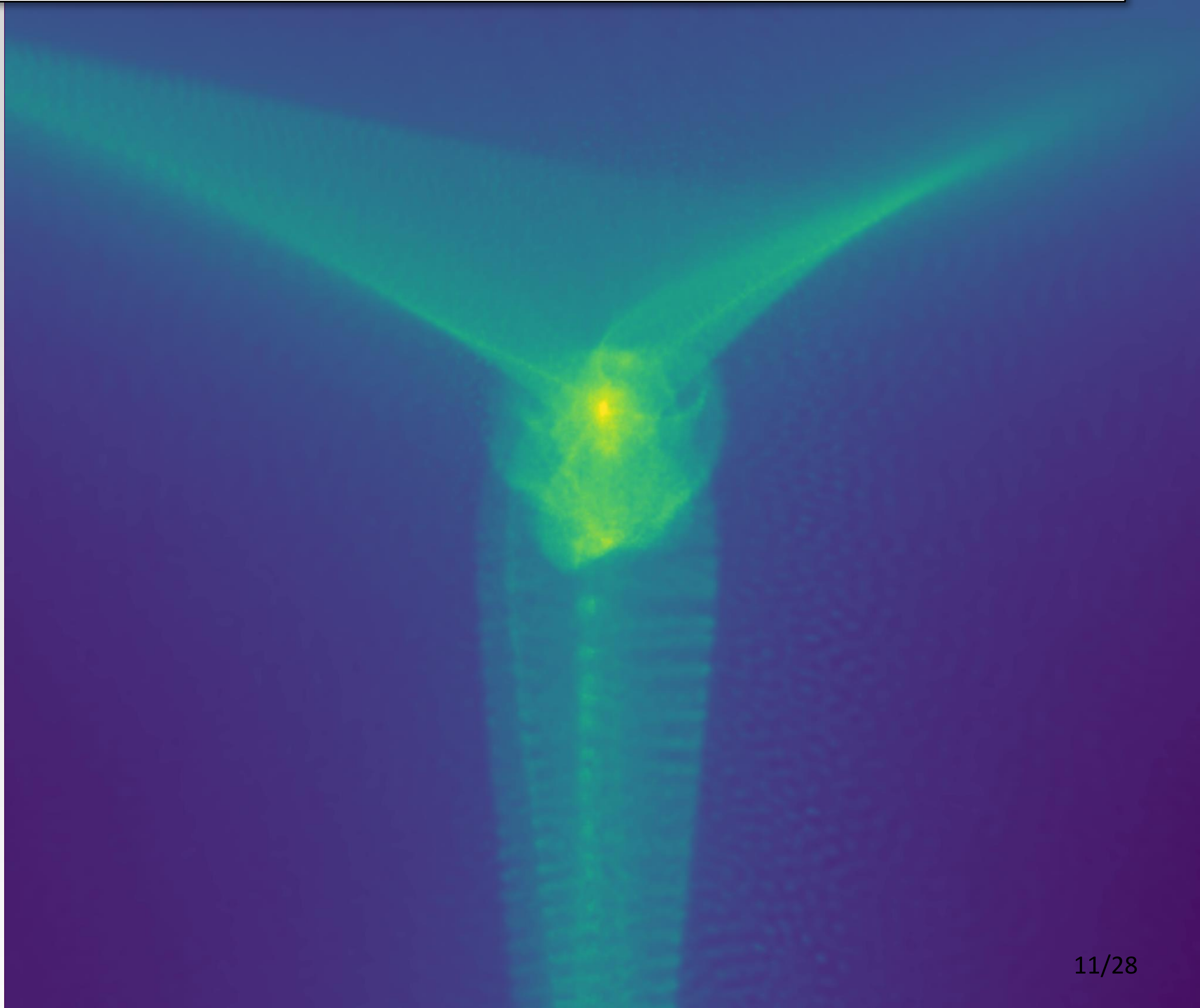


Ludlow et al 2013

Simulating an individual object at high resolution

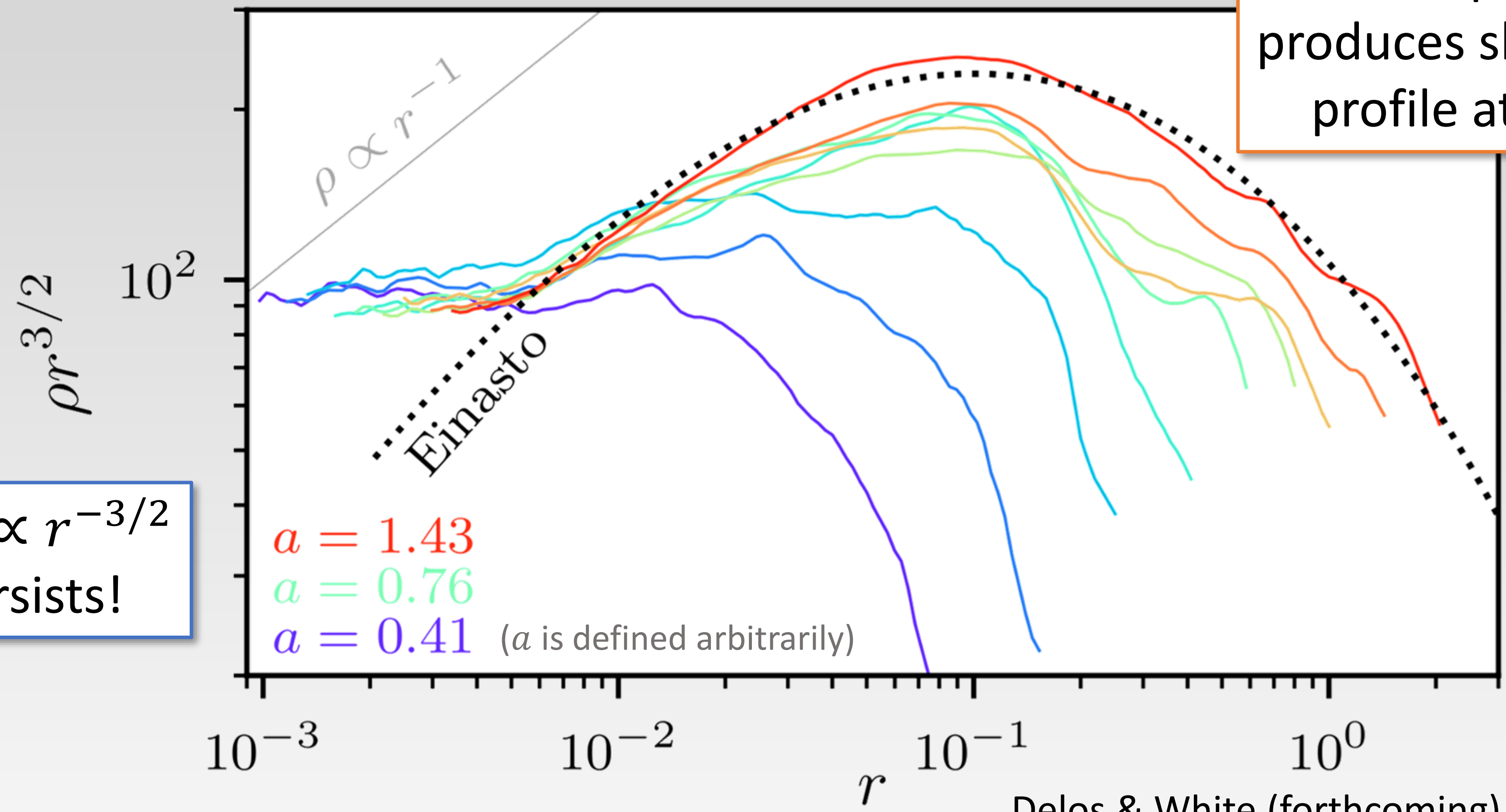


$\rho \propto r^{-3/2}$ cusp stabilizes immediately after formation



How a cusp shallows

Buildup of material produces shallow Einasto profile at larger radii



Delos & White (forthcoming)

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

Apparent shallowing of $\rho \propto r^{-3/2}$ cusps is not due to disruption after all?

Rapid accretion

Naturally yields shallow profiles

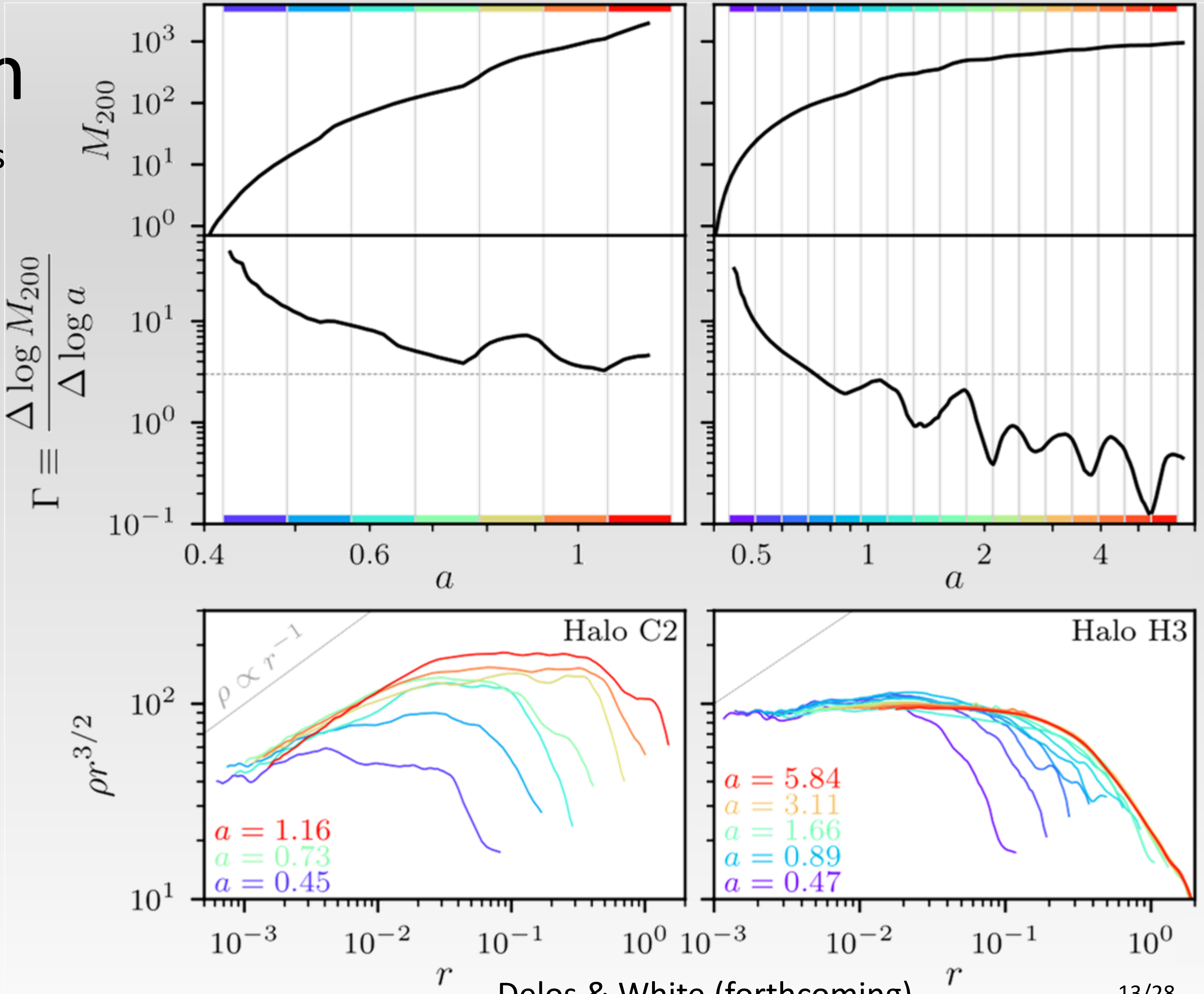
Models that connect accretion histories to density profiles
(e.g. Ludlow et al 2013)
predict that

$$\frac{\mathrm{d}\log\rho}{\mathrm{d}\log r} \gtrsim -\frac{3}{2}$$

if

$$\frac{\mathrm{d}\log M}{\mathrm{d}\log a} \gtrsim 3$$

This behavior is approximately borne out.



Delos & White (forthcoming)

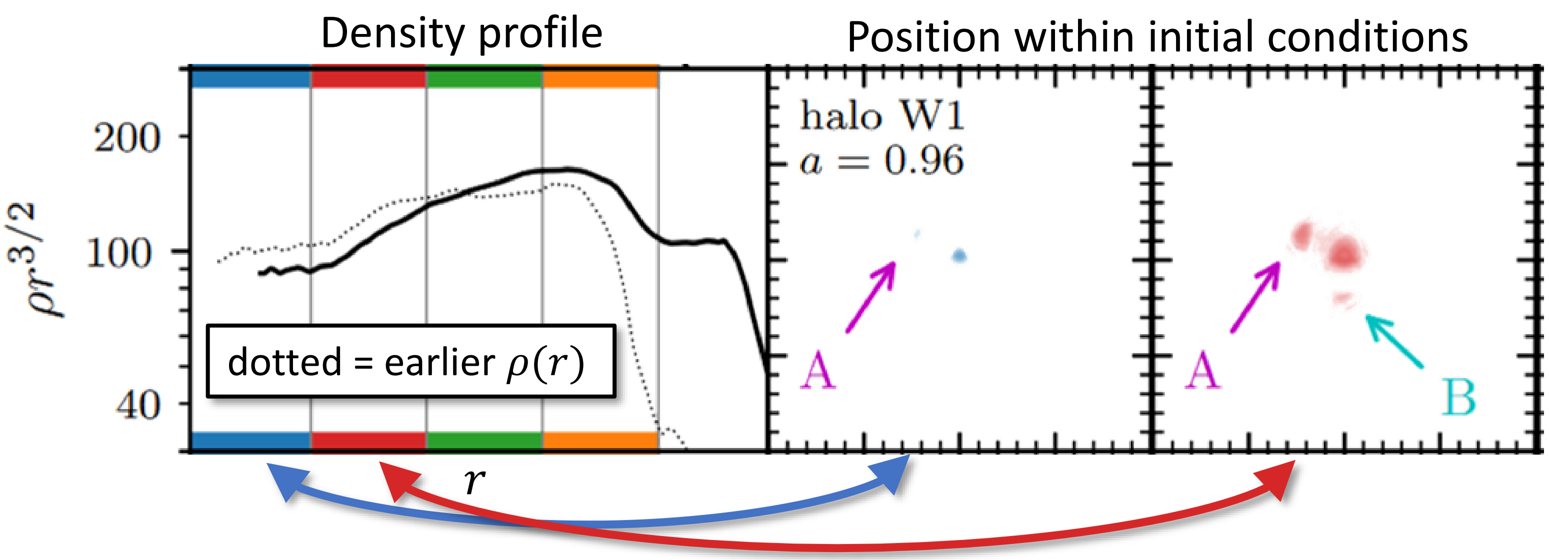
Mergers

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.

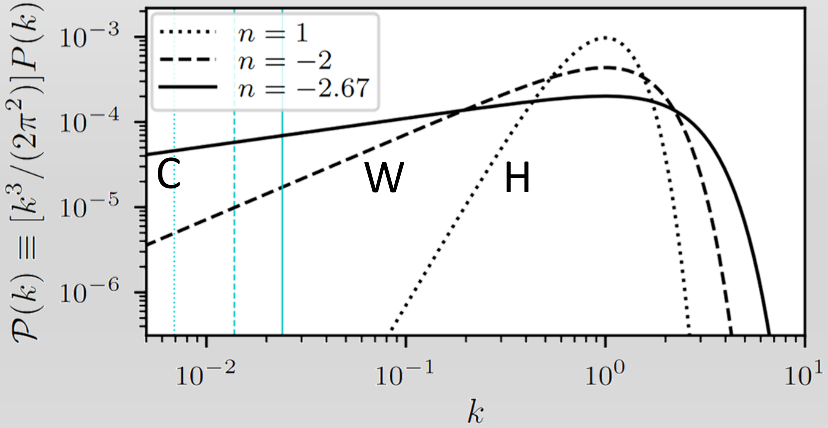
Merging halos 'A' and 'B' deposited material deep inside this halo…



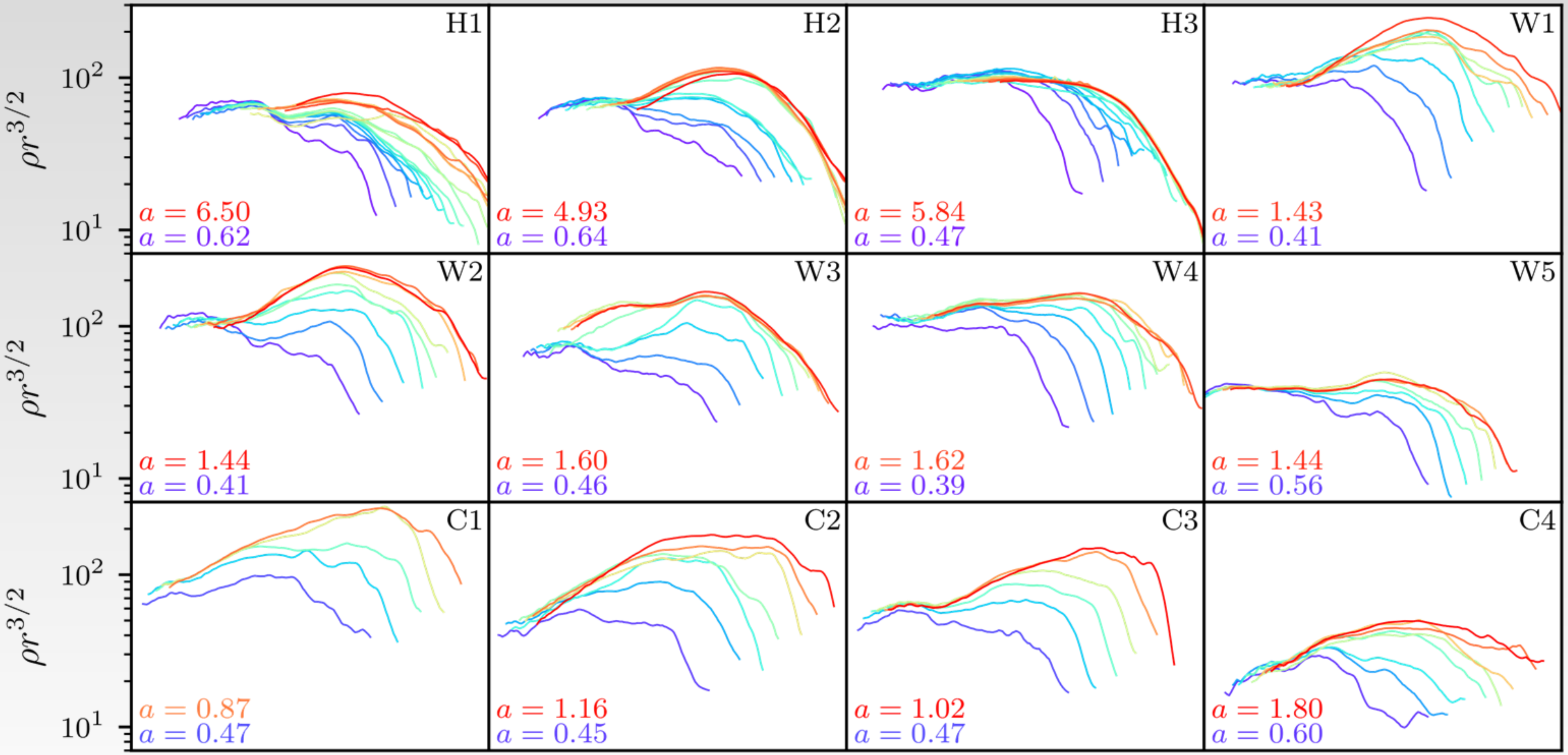
…which caused some disruption of the $\rho \propto r^{-3/2}$ cusp.

Delos & White (forthcoming)

No significant cusp disruption

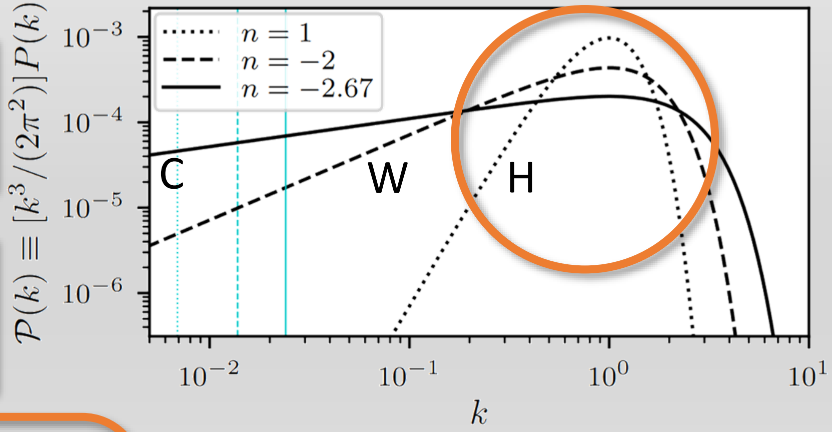


Twelve high-resolution halos from three power spectra: no significant cusp disruption (within resolution limits)

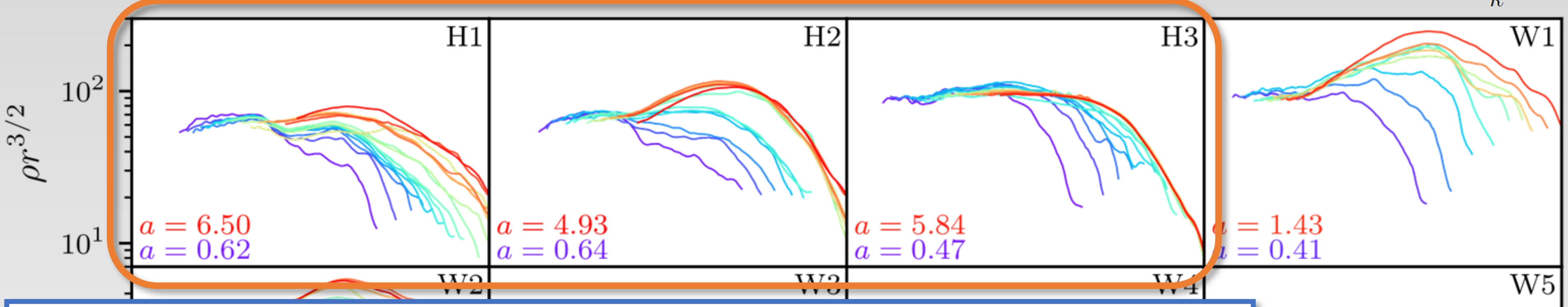


Delos & White (forthcoming)

Sharply peaked power spectra

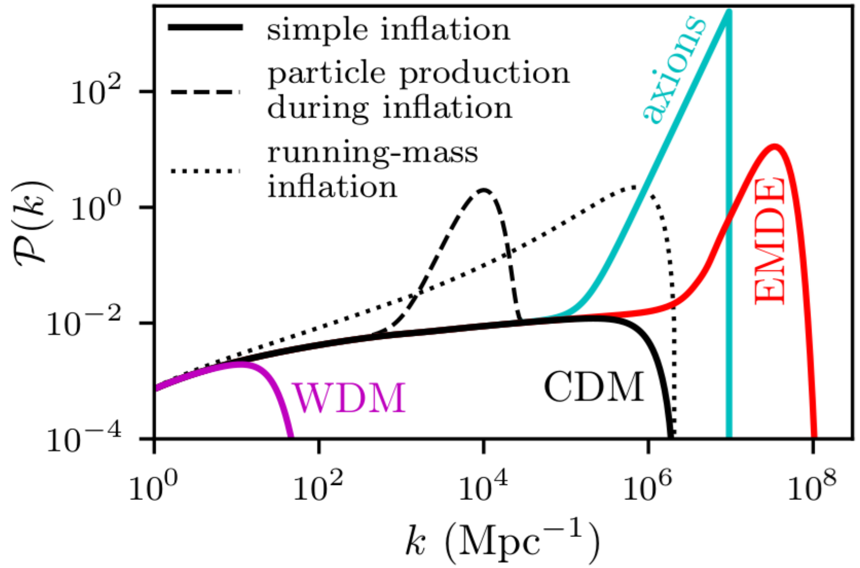


For the sharply peaked power spectrum 'H', accretion is slow
→ $\rho \propto r^{-3/2}$ cusps remain a large portion of the halo over a long time



Some cosmological scenarios yield boosted small-scale power spectra with similar forms!

$\rho \propto r^{-3/2}$ cusps may be particularly relevant to these cases.



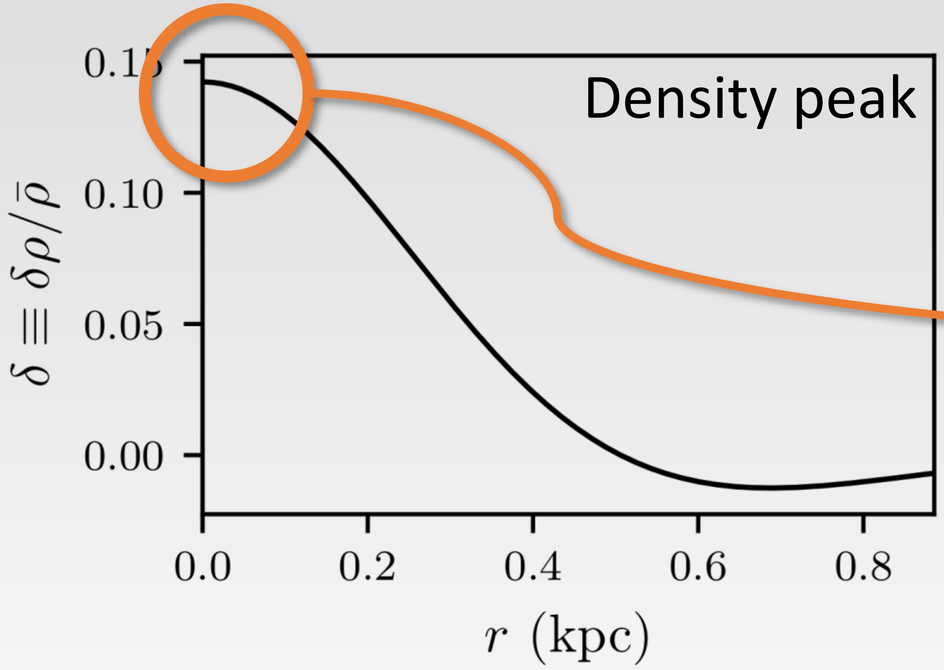
Delos & White (forthcoming)

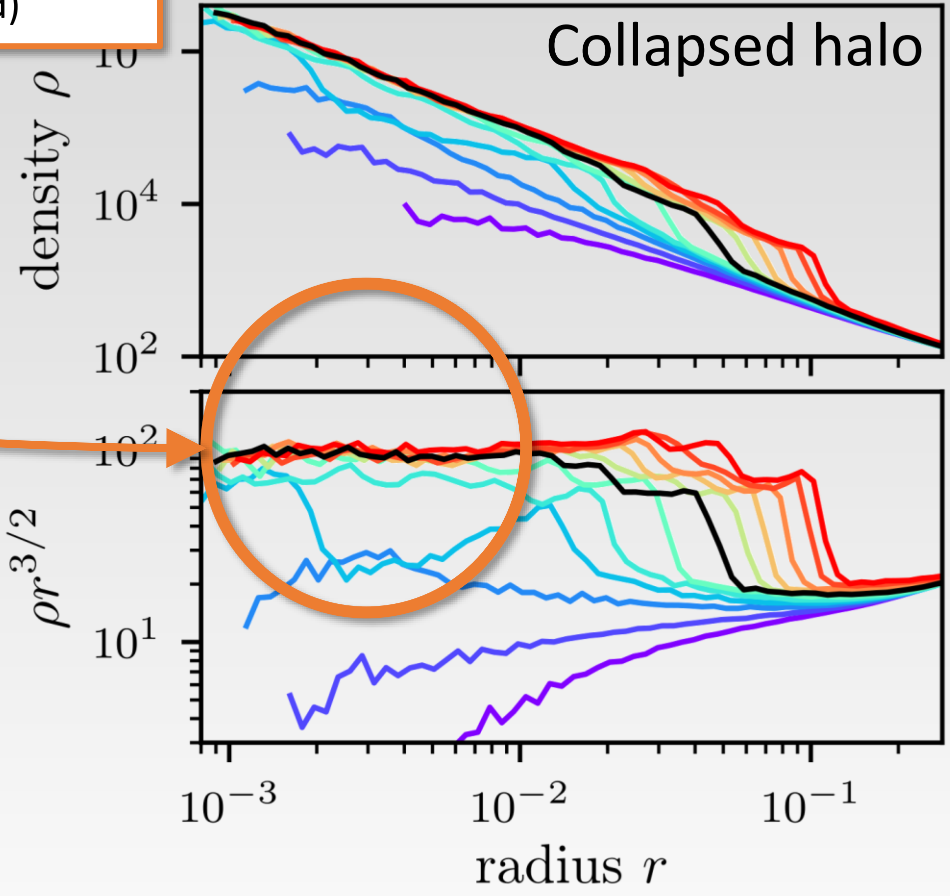
What sets the coefficient of the $\rho \propto r^{-3/2}$ cusp?

Inner asymptote set at formation time

∴ only sensitive to neighborhood of density peak

i.e., $\delta \equiv \delta\rho/\bar{\rho}$ and $\nabla^2\delta$ at peak (+ tidal field)





Predicting the coefficient of the $\rho \propto r^{-3/2}$ cusp

Peak has local properties
- Height $\delta = \delta\rho/\rho$
- Derivatives $\partial_i \partial_j \delta$

[w.r.t. comoving coordinates]

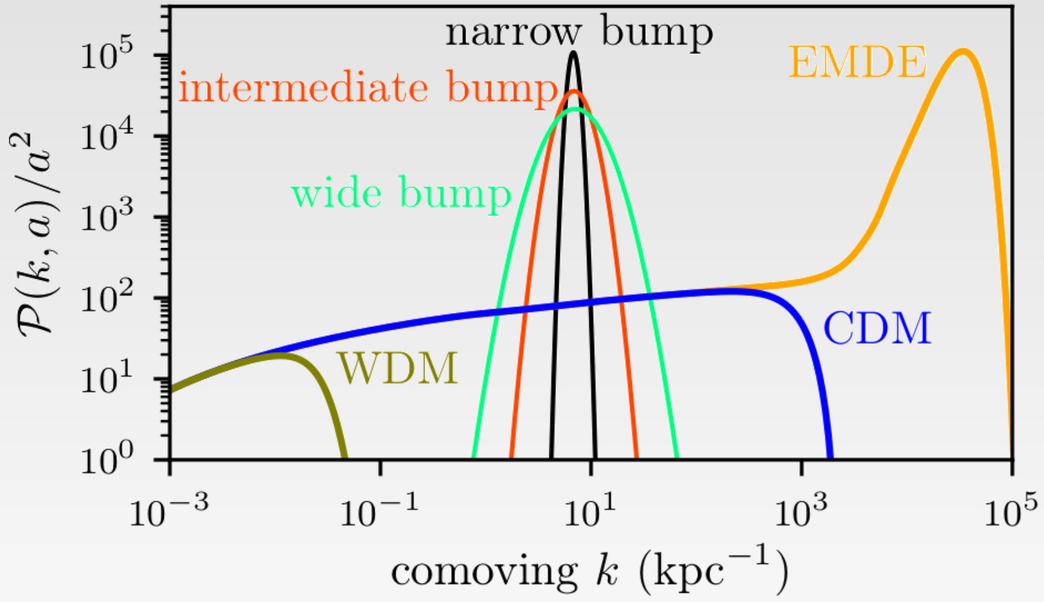
Halo has: $\rho = A r^{-3/2}$

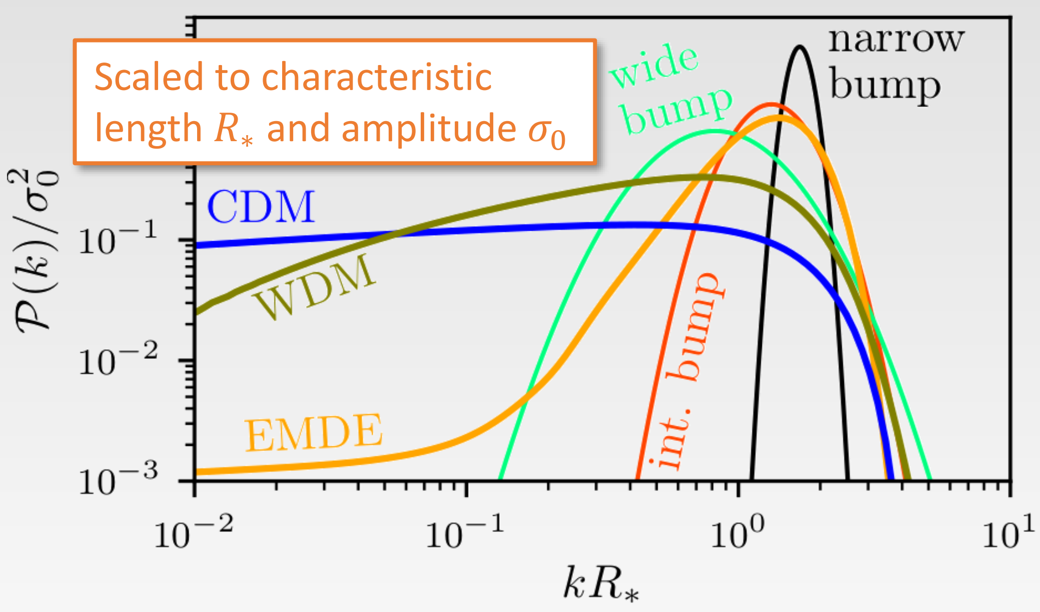
→ The connection:

$$A \propto \delta^3 \left[\delta^{-1} \left(\frac{\delta}{|\nabla^2 \delta|} \right)^{1/2} \right]^{3/2} \left[\frac{\delta_{\mathrm{ec}}(e,p)}{\delta_{\mathrm{sc}}} \right]^{-3/2}$$

- Density at collapse $\propto a_c^{-3} \propto \delta^3$
- Physical length scale at collapse $\propto a_c q \propto \delta^{-1} q$
- Comoving length scale q
- Tidal correction f_{ec}

Accurate for wildly disparate $\mathcal{P}(k)$ (i.e., cosmologies):





Delos, Bruff, Erickcek 2019

Predicting the coefficient of the $\rho \propto r^{-3/2}$ cusp

Peak has local properties
- Height $\delta = \delta\rho/\rho$
- Derivatives $\partial_i \partial_j \delta$ [w.r.t. comoving coordinates]

Halo has: $\rho = A r^{-3/2}$

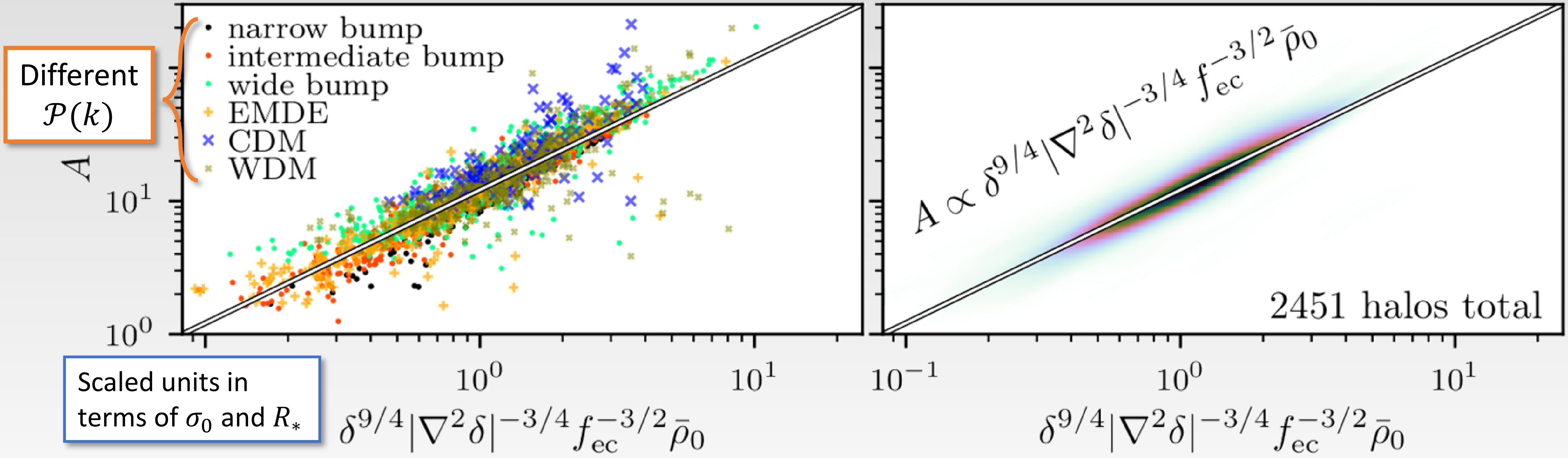
The connection: $A \propto \delta^3 \left[\delta^{-1}\left(\frac{\delta}{|\nabla^2\delta|}\right)^{1/2}\right]^{3/2}\left[\frac{\delta_{\rm ec}(e,p)}{\delta_{\rm sc}}\right]^{-3/2}$

Physical length scale at collapse $\propto a_c q \propto \delta^{-1} q$

Tidal correction $f_{\rm ec}$

Density at collapse $\propto a_c^{-3} \propto \delta^3$

Comoving length scale q

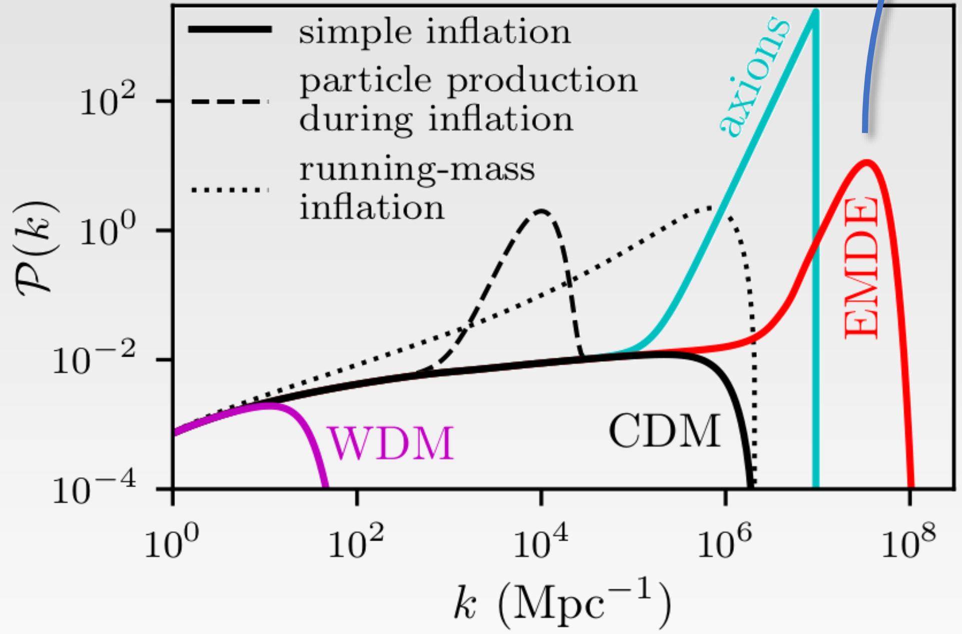


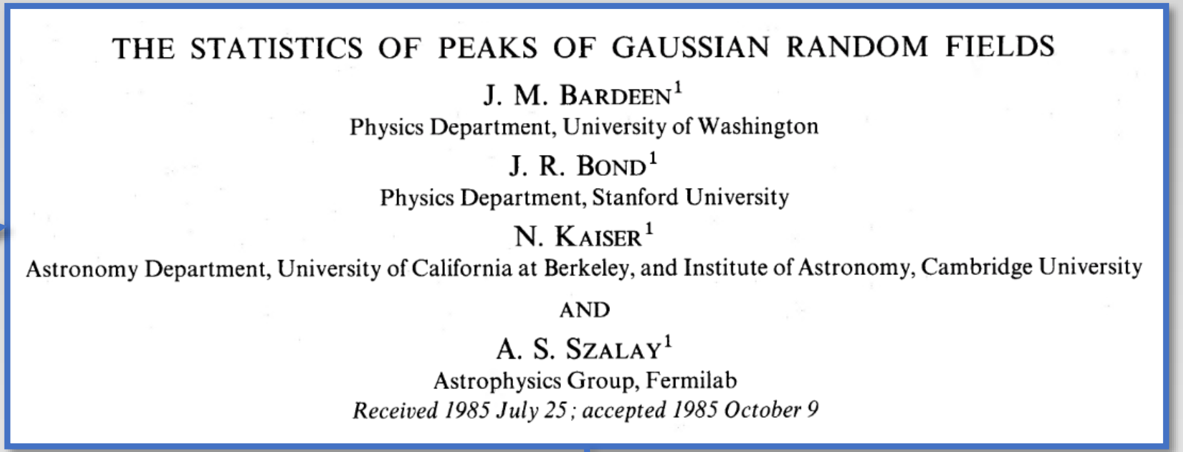
Delos, Bruff, Erickcek 2019

A single fitting parameter (the proportionality constant) → model accurate for all power spectra

Statistics of peaks

Connection between cusps and peaks is clear.
How do we relate this to the power spectrum?




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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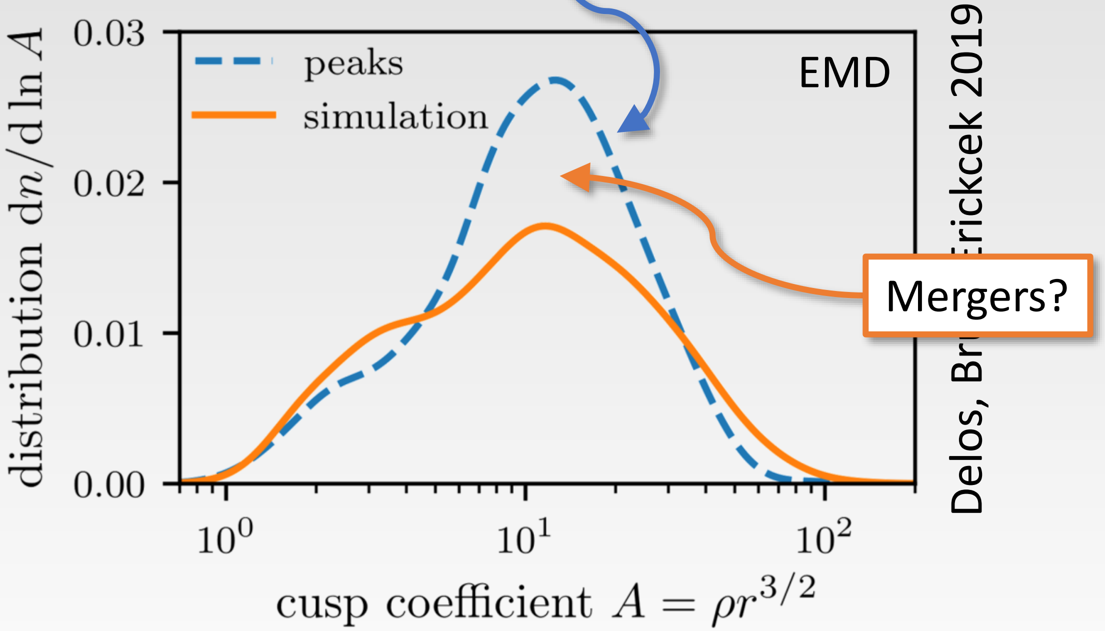


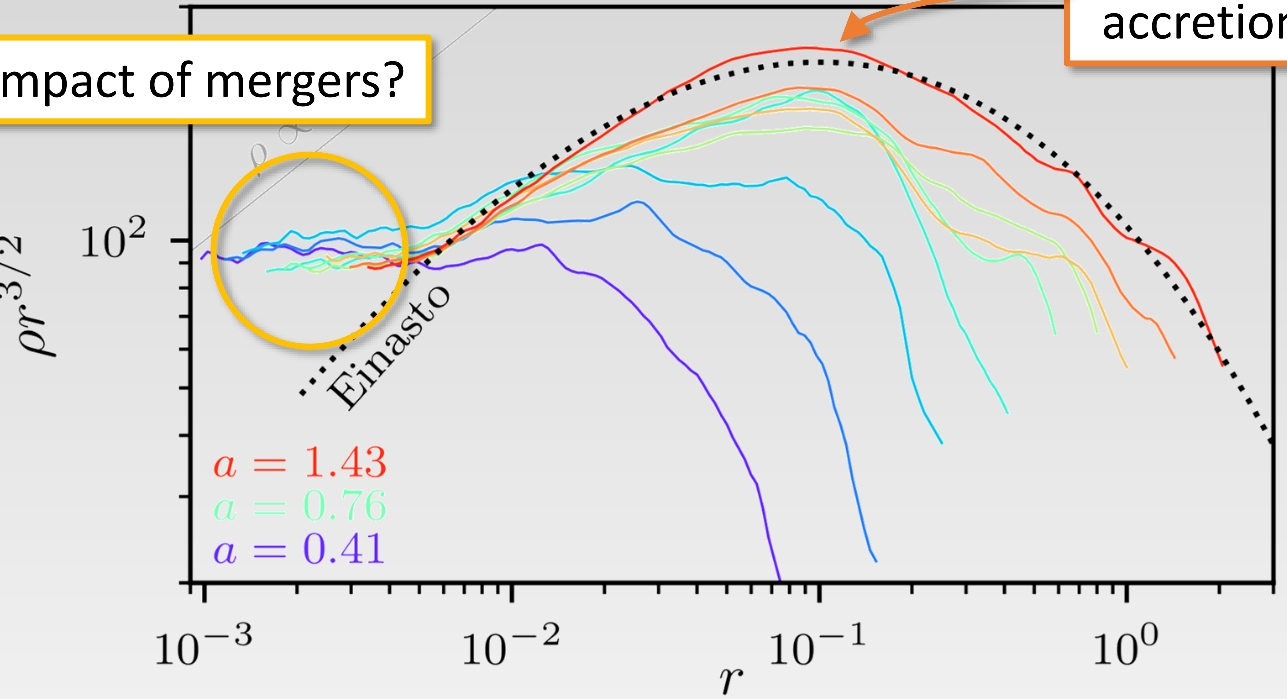
Delos, Br… Erickcek 2019

Halo evolution

Questions remain:

Precise impact of mergers?

Can we predict using an accretion history model?

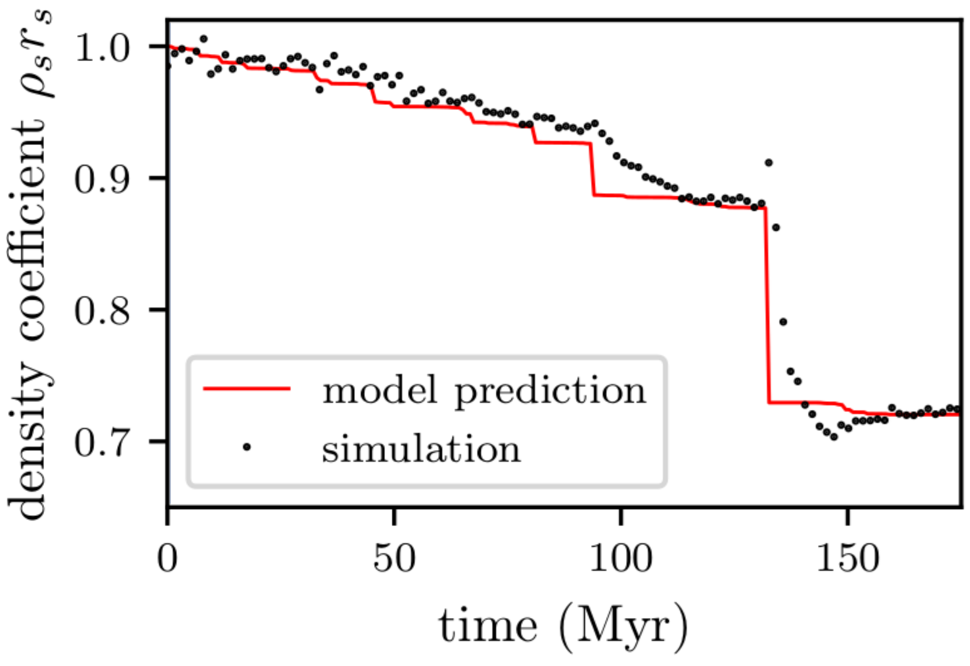


Also, subhalo evolution: tidal forces and impulsive encounters

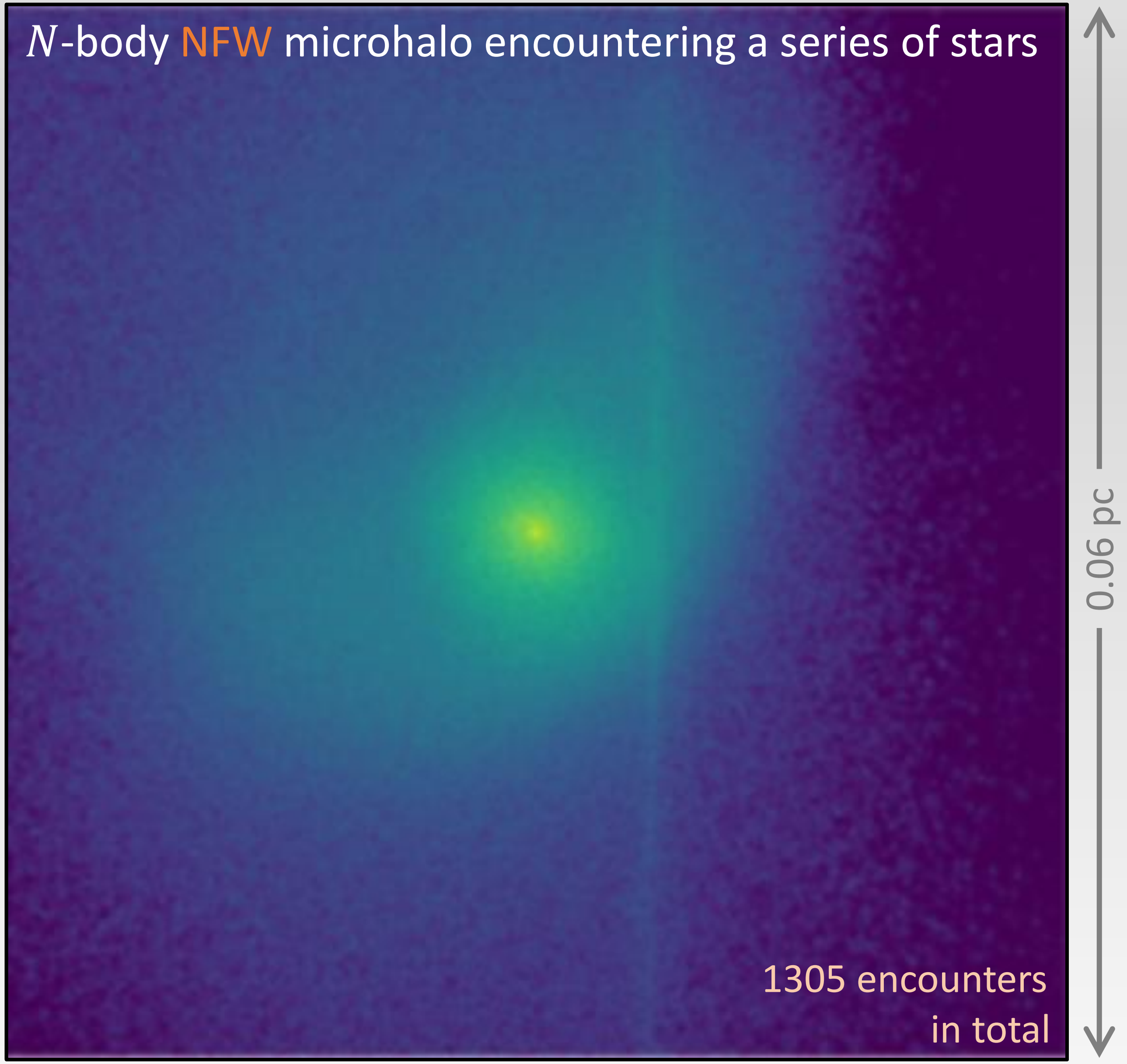
Stellar encounters

Apply $\Delta\vec{v}$ induced by a series of stellar encounters

Accurate predictive model:



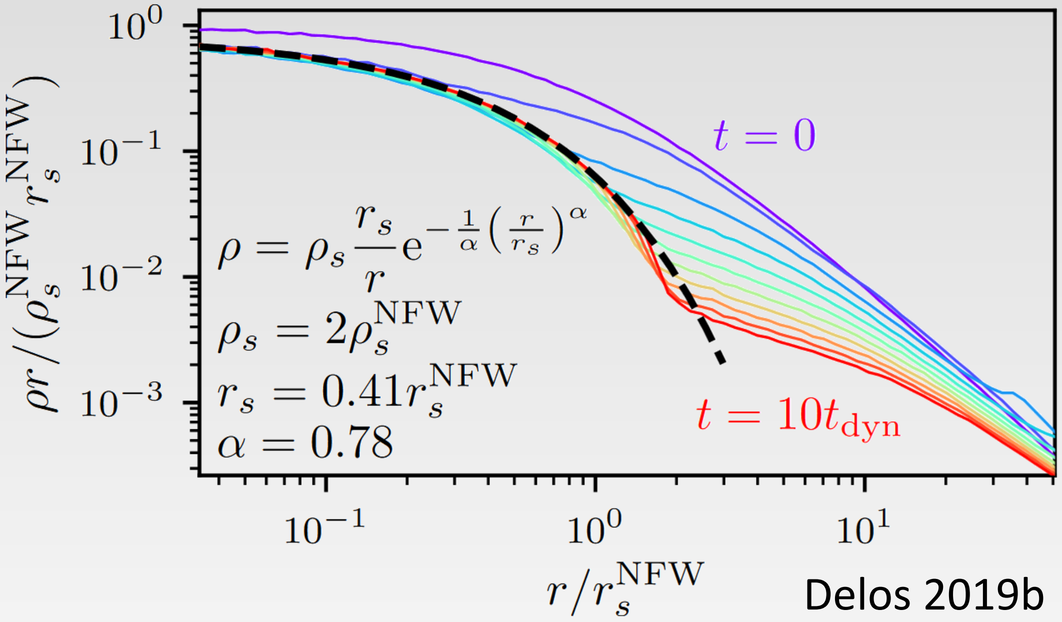
Delos 2019b



Density profile after stellar encounters

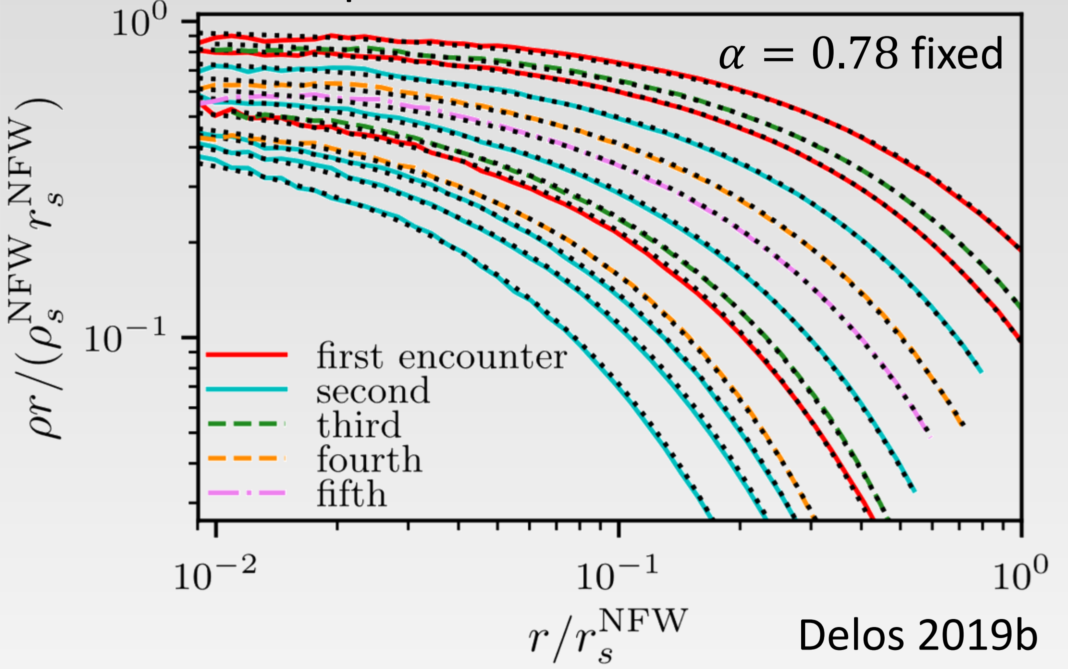
We start with an NFW profile.

Let's parametrize the density profile after an encounter:



Delos 2019b

This parametrization is universal!



Delos 2019b

(for most encounter parameters)

Thus, it's easy to handle successive encounters

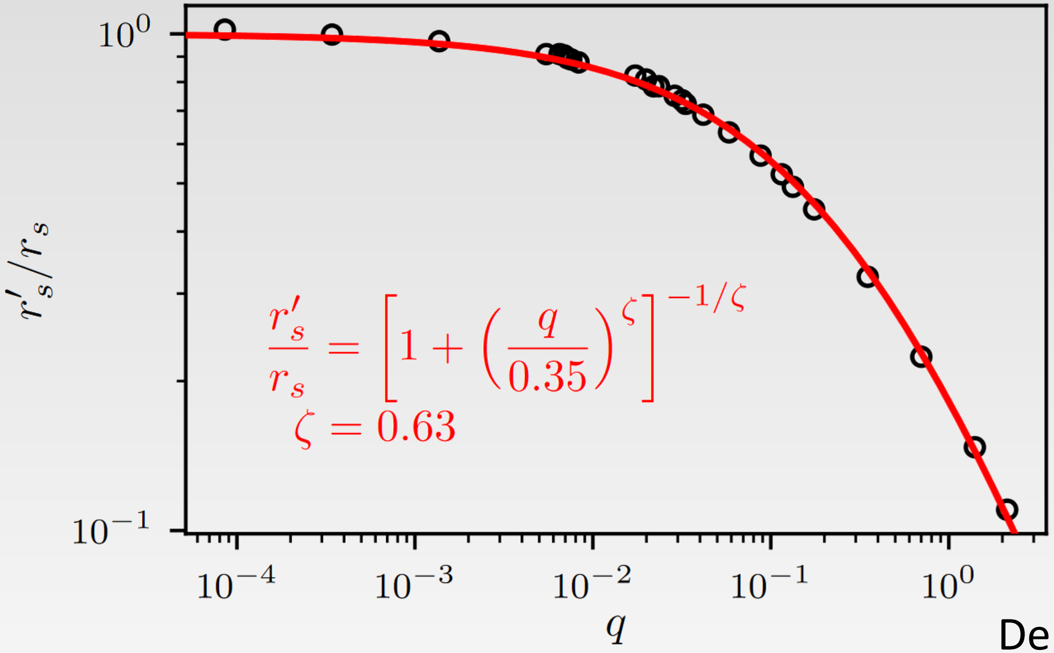
$$q = \frac{G}{2\pi} \frac{M_*^2}{\rho_s V^2 (b^4 + r_s^4)}$$

Modeling stellar encounters

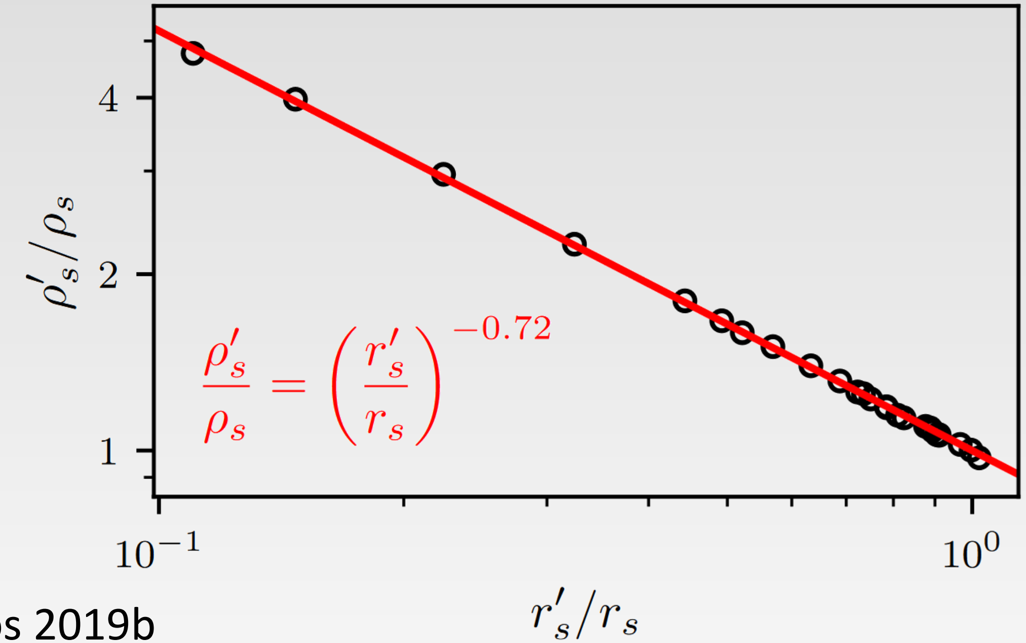
For most stellar encounters, a single parameter determines the halo's response: the characteristic relative energy injection q per particle

$$q \equiv \Delta E/|E_b|$$

Change in halo scale radius



Change in halo scale density



Delos 2019b

Each point is a different stellar encounter simulation. The connection to q is extremely tight → model is precise.

Limitations of the stellar encounter model

The model assumes:

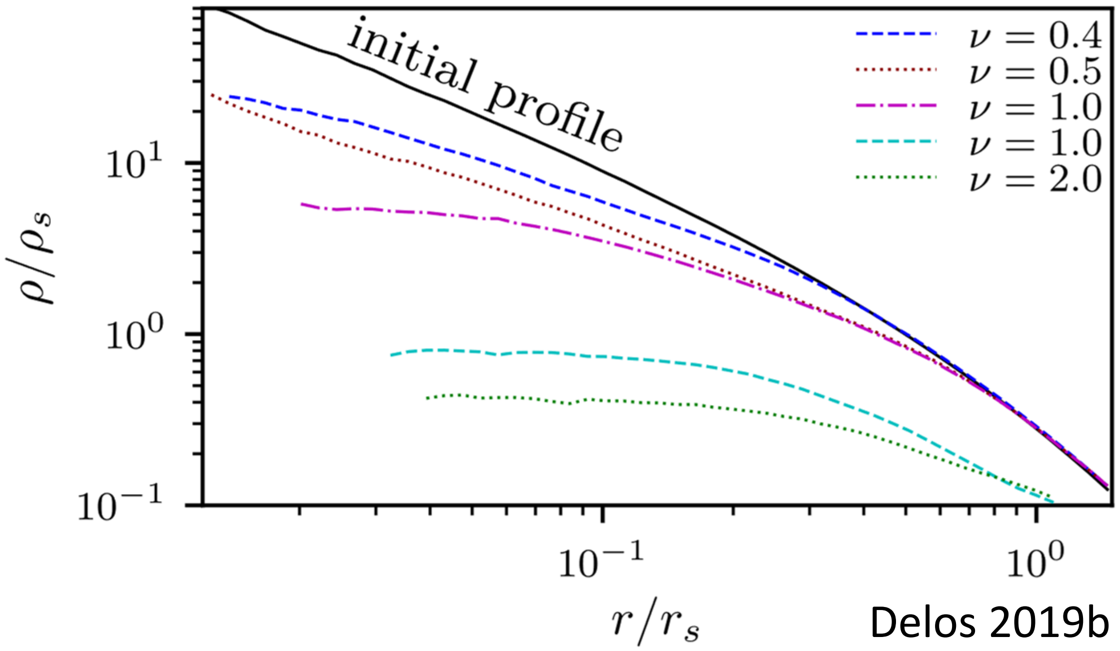
- NFW initial profiles
- the encounter is impulsive (accurate for CDM microhalos)
- impact parameter ≫ scale radius

However:
For CDM microhalos, any penetrative encounter with a star already effectively destroys the halo (since $q \sim b^{-4}$)
∴ a precise model of the outcome is not needed.

Penetrative encounters with

$$\nu \equiv \frac{r_s}{b}\left(1+q^{-1}\right)^{-1/2} \gtrsim 1$$

can alter the form of the density profile and even disrupt the central cusp:



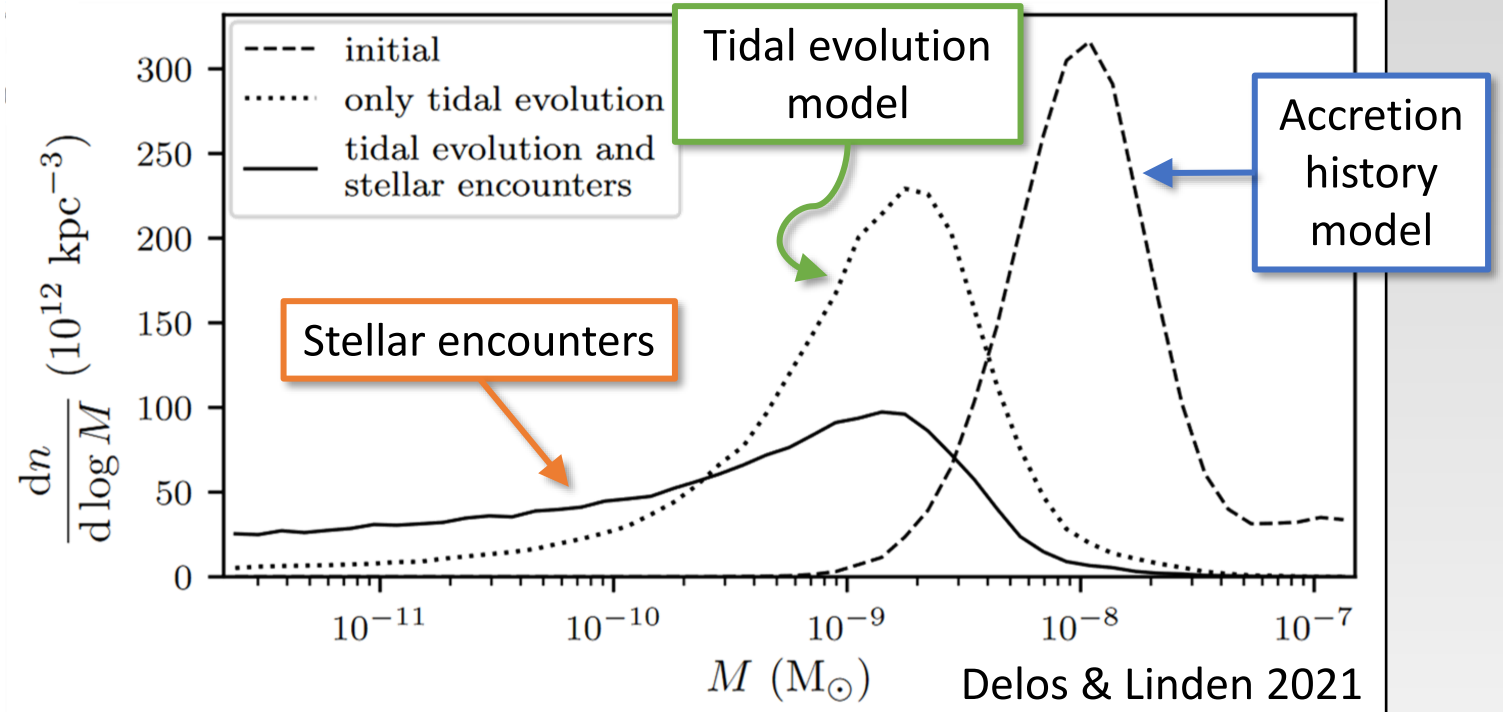
Delos 2019b

Impact of stellar encounters

Example calculation:

- Generate a halo distribution with random Galactic orbits
- Choose the stellar phase space distribution
- Sample stellar encounters along each orbit & apply model

Microhalos in the solar neighborhood due to early matter domination



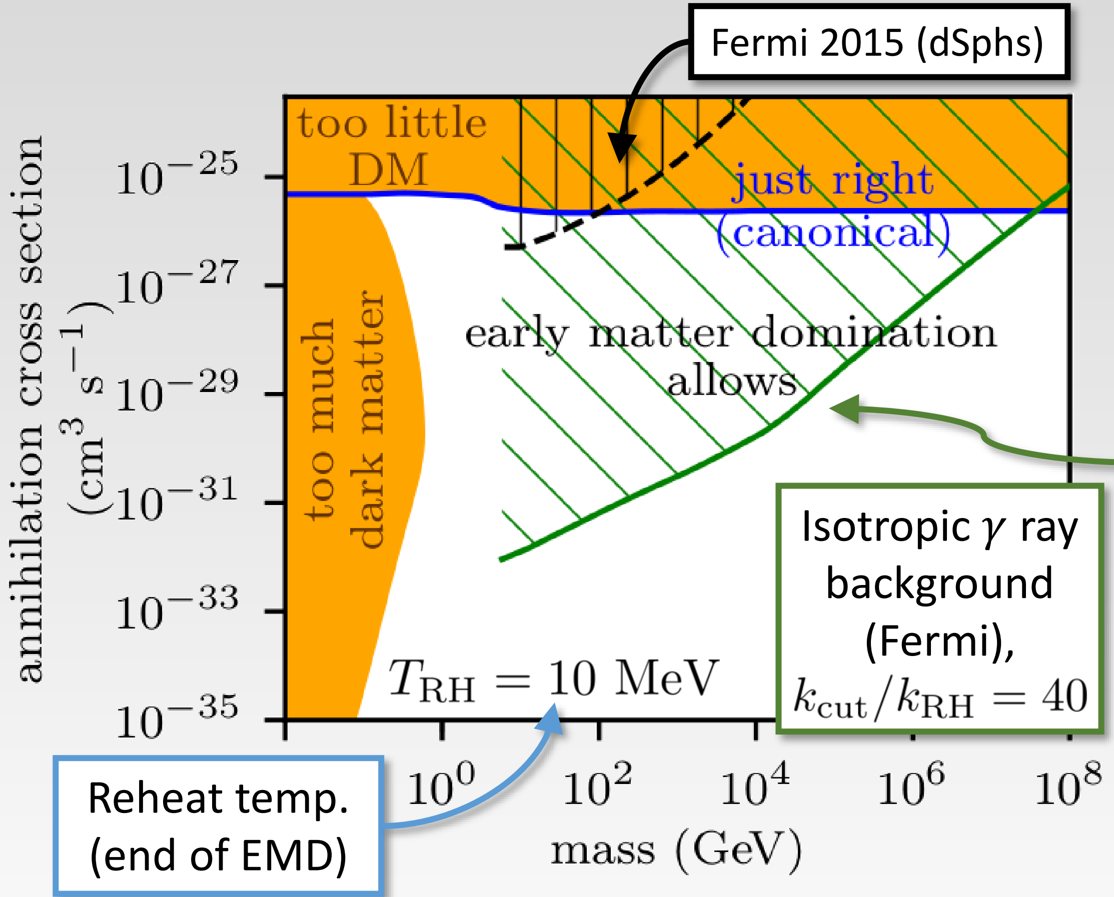
Delos & Linden 2021

Random nature of stellar encounters spreads out the mass distribution

Application: Breaking a dark degeneracy

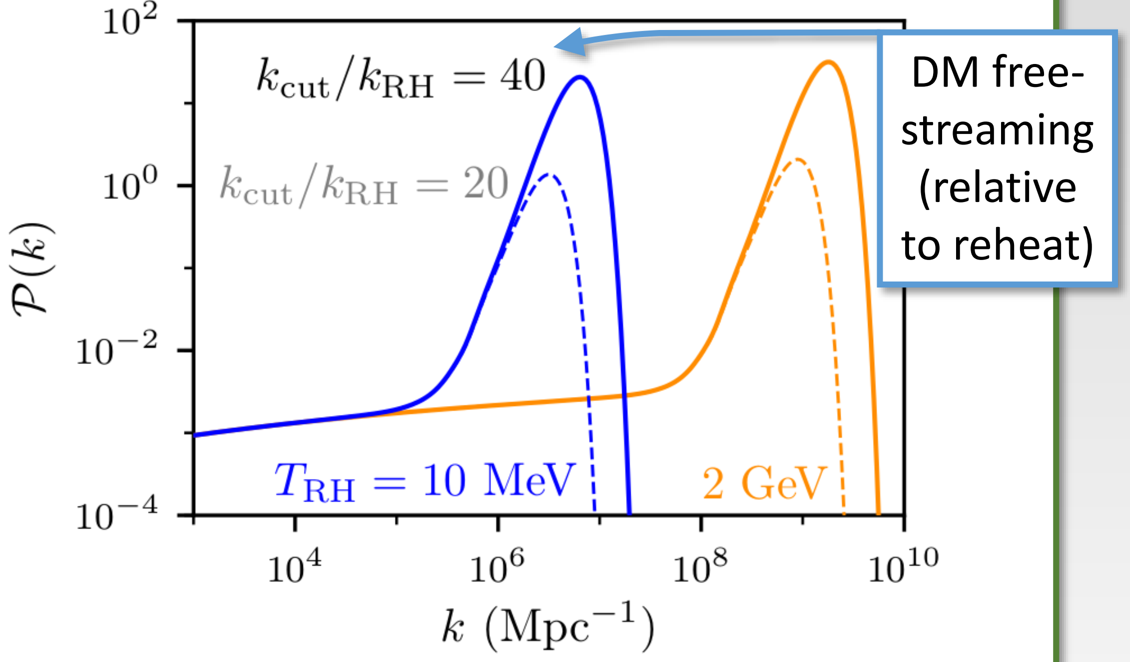
Early matter domination (domination by an unstable matter species prior to BBN)
broadens the range of viable dark matter parameters.

[Decay of early matter species sources radiation that dilutes the DM → need smaller $\langle \sigma v \rangle$ to produce more DM.]



Delos, Linden, Erickcek 2019

EMD boosts density variations [early matter clusters]

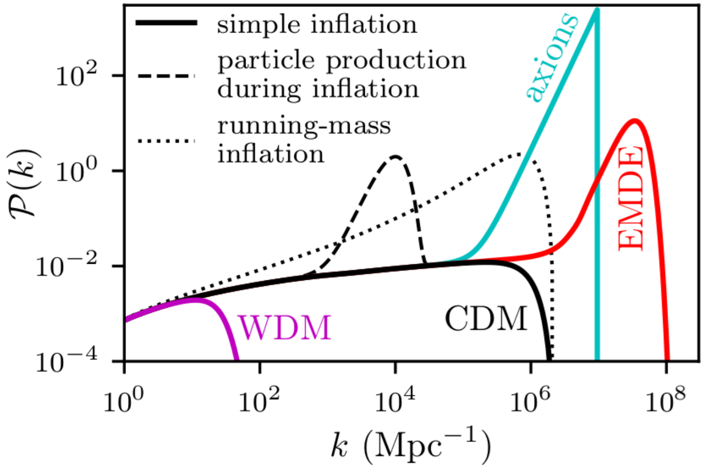


$\Longrightarrow$ Early, highly dense microhalos

$\Longrightarrow$ Improved indirect-detection bounds

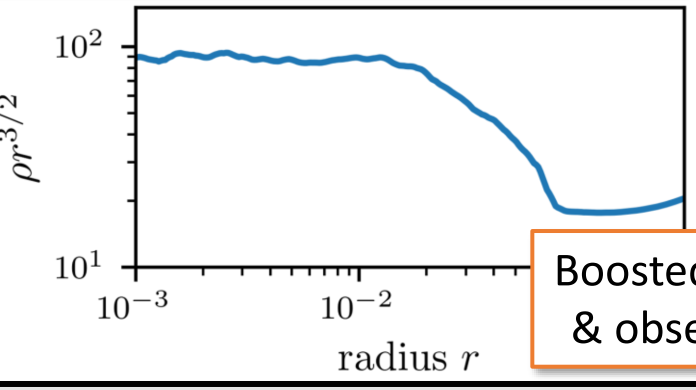
Summary

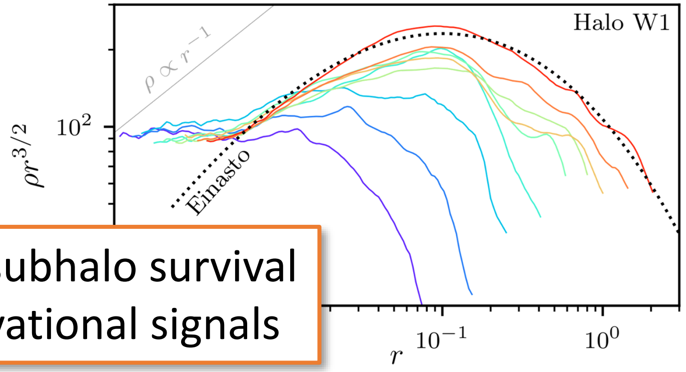
Key cosmological questions are connected to the small-scale (linear) matter $P(k)$…



…which manifests itself in the properties of the first and smallest halos.

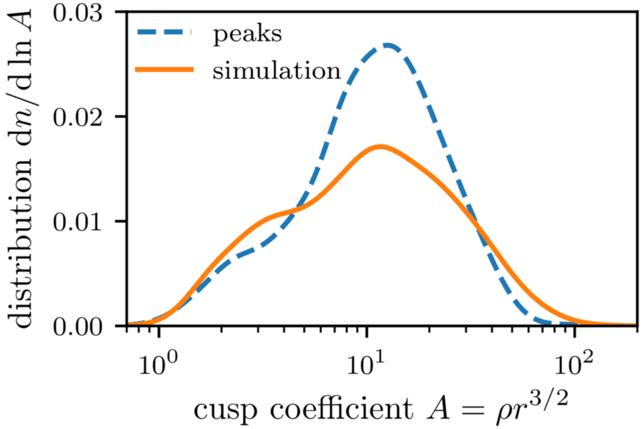
The first halos develop persistent steep $\rho \propto r^{-3/2}$ cusps





Boosted subhalo survival & observational signals

$A = \rho r^{3/2}$ can be predicted using statistics of peaks



We can predict the outcome of any sequence of stellar encounters