

Title: How Dense is Early Dark Matter Structure?

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Collection: Dark Matter, First Light

Date: February 27, 2024 - 2:15 PM

URL: <https://pirsa.org/24020078>

Abstract: Recent work on the formation of the first dark matter halos suggests they may have had systematically different density profiles, with stronger cusps and higher densities than those predicted at low redshift. I will review recent work on the first generation(s) of dark matter halos, and discuss the implications for dark matter annihilation and structure formation in general.

# How Dense is Early Dark Matter Structure?

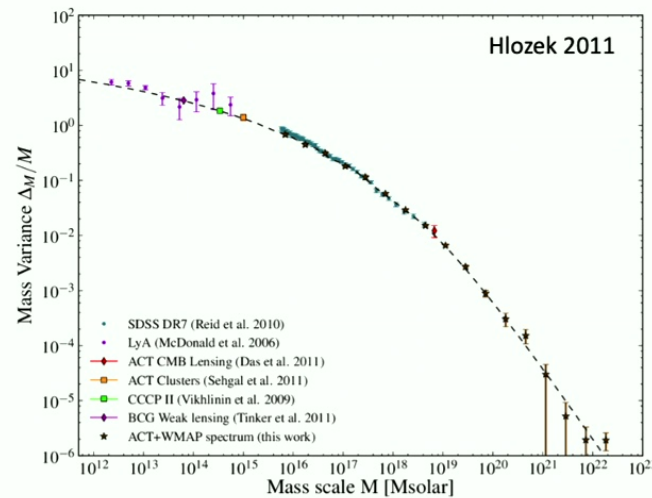
James Taylor – Waterloo Centre for Astrophysics

Chiamaka Okoli & Niayesh Afshordi (PI), Nicole Drakos (Hawaii), [Justin Marchioni](#) (Waterloo)

Dark Matter, First Light – Perimeter Institute – February 27 2024

# Introduction: the Importance of Small-scale Structure

On **large scales**, the matter distribution is known empirically; CDM models match obs. at % level



To test modified DM models, SIDM, ADM, or to interpret CDM direct detection, indirect detection results, usually need to know clustering on **all scales**

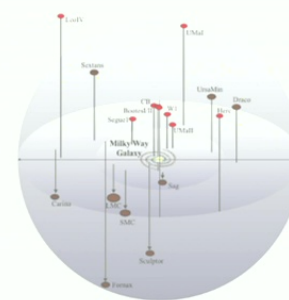
(Note new probes – GWs, pulsar timing, substructure lensing, 21cm – may help?)

On **small scales**, where hierarchical structure reaches highest densities, situation more complicated due to baryons

(1Mpc: 30%; 10kpc: x2-3; 100 pc ??)



Aquarius simulation – Springel et al.



Local Group dwarfs

So what densities does DM structure reach on the smallest scales?

# Physical limits on dark matter density

**Dynamical Role of Light Neutral Leptons in Cosmology**  
Scott Tremaine  
*W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125,  
and Institute of Astronomy, Cambridge, England*  
and  
James E. Gunn  
*W. K. Kellogg Radiation Laboratory, Hale Observatories, California Institute of Technology, Pasadena,  
California 91125, and Carnegie Institution of Washington, Washington, D. C. 20005*  
(Received 21 May 1978)

Historically, well-known constraints on light DM candidates from **phase-space density** conservation [the Tremaine-Gunn limit – TG79]. But what about **real-space** density?

e.g. measure local density around each dark matter particle, averaged on say the thermal scale; consider the cumulative distribution of this local density (CDD), for all particles; how does this evolve with time?

## **Basic Hypothesis: (central) density conservation**

(cf. “stable clustering” hypothesis in phase-space – Zavala & Afshordi 2014)

- \* matter is assembled into halos from linear fluctuations in a predictable way (PS formalism)
- \* it is assembled into halos with some  $\sim$  universal profile
- \* when halos merge, density distribution cannot drop (much?)  
e.g. tidal stripping only works in dense regions

As a result, the high-density end of the CDD grows monotonically.

# The usual approach: the concentration-mass-redshift relation

For boost factor etc. calculations, previous work considered halo concentration vs. mass, redshift

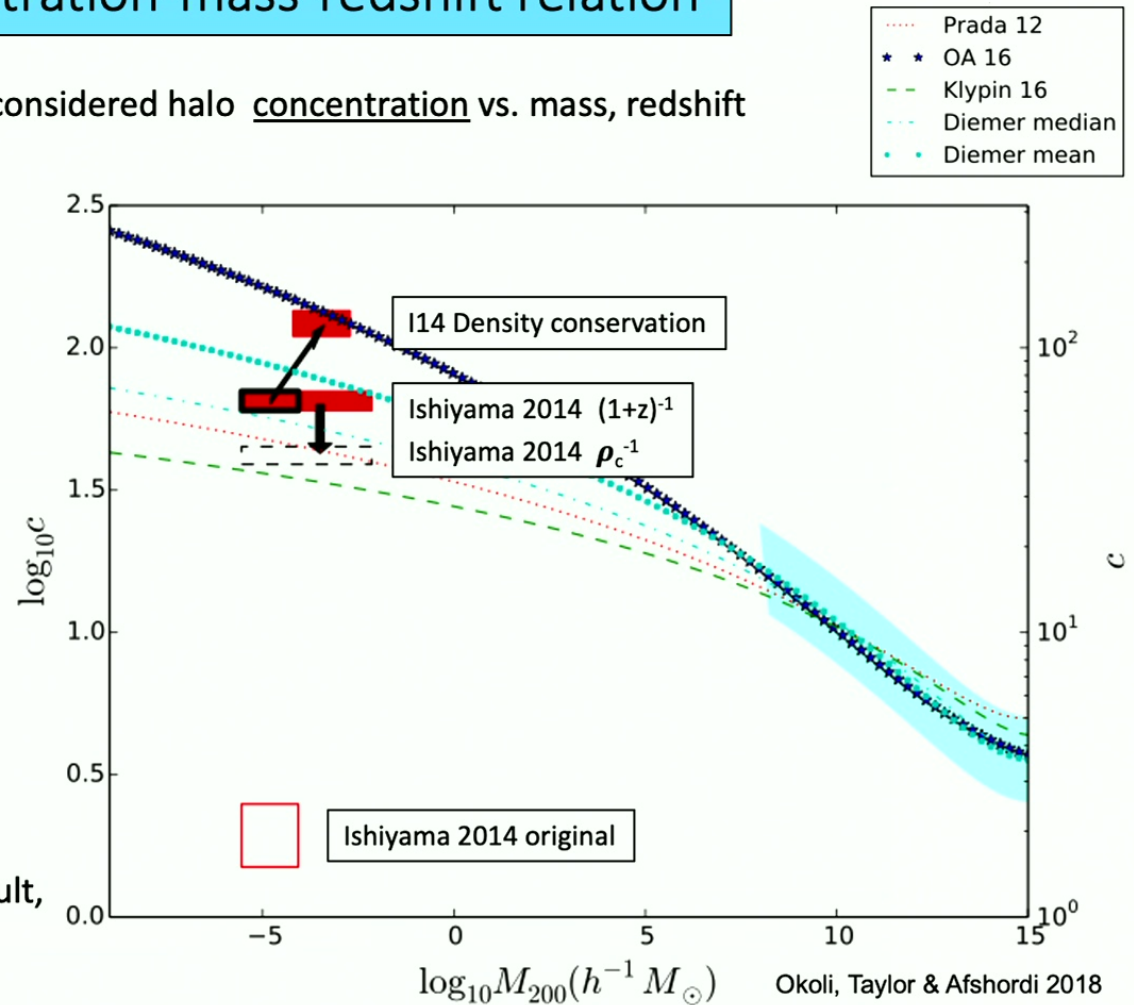
## Problems w. concentration:

- several possible definitions beyond  $r_s/r_{\text{vir}}$   
+ profile-dependent
- usually measured at low  $z$  and extrapolated as  $(1+z)^{-1}$  or  $\rho_c^{-1}$   
(based on evolution of  $r_{200}$ )
- this evolution ignores change in mass

## Afshordi + Okoli 2016:

Alternative analytic prediction based on energy conservation during collapse

**Simple density conservation:** predicts similar result,  
**6-8x denser than usual  $c(z,M)$  prediction**

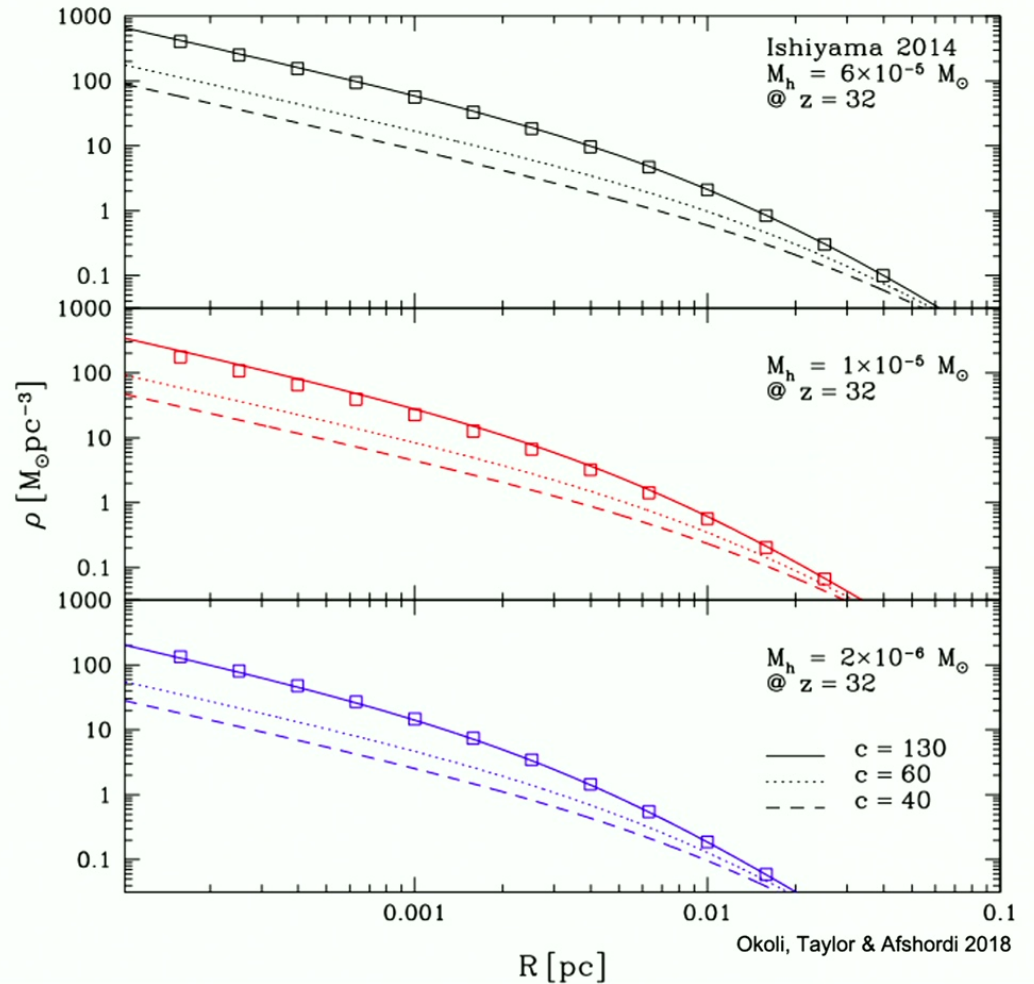


# What densities did the original high-z structures have?

**Ishiyama 2014 (open squares):**  
measured densities for halos evolved to  $z=32$

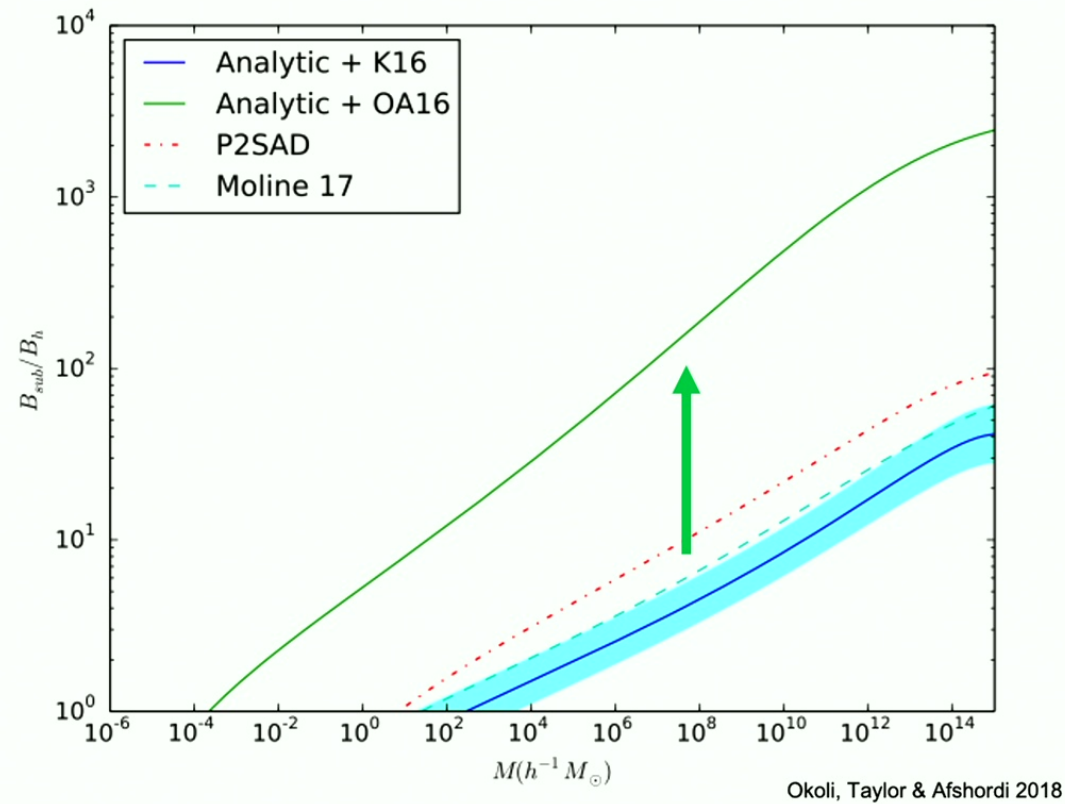
**solid curves:** halo profiles assuming mass grows by average amount ( $\sim 9x$ ) between  $z=32$  and  $z=0$ , for various  $z=0$  concentrations

**Conclusion:** The central density of the smallest halos is  $\sim 6-8$  times higher than predicted by low-redshift concentration-mass relations



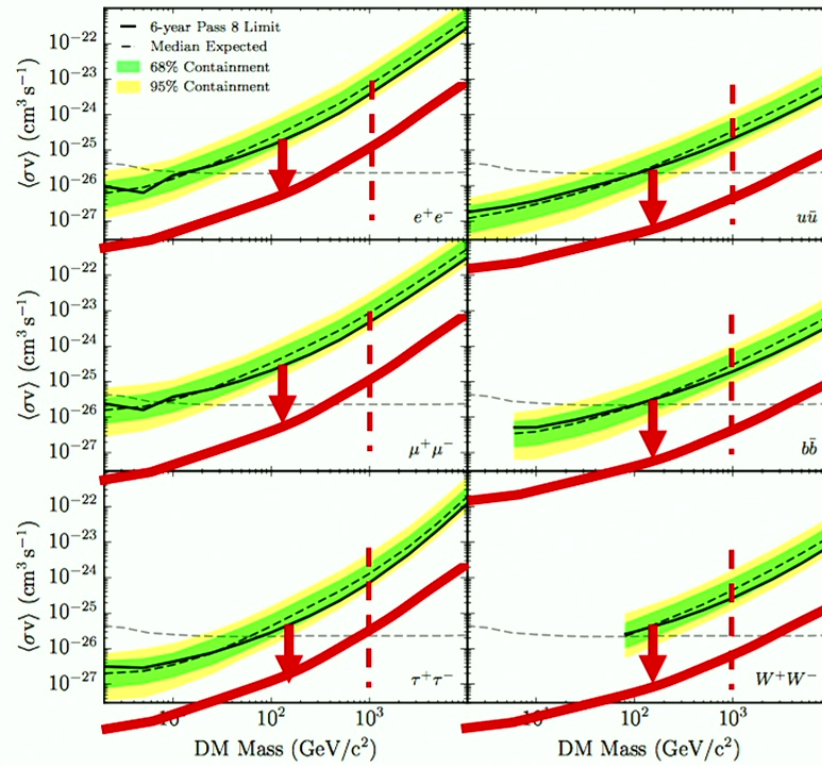
## N.B. Implications for the Boost Factor

If high DM densities are conserved to low redshift, the boost factor is 30-90 times larger than anticipated!



# N.B. Implications for the Boost Factor

Boost factors this high would rule out most annihilating SUSY WIMPs w. standard cross-sections below 1 TeV!



Fermi-LAT constraints  
(Ackermann et al. 2015)  
arXiv:1503.02641



## So how do we explain the discrepancy between high/low-z results?

### Three possibilities:

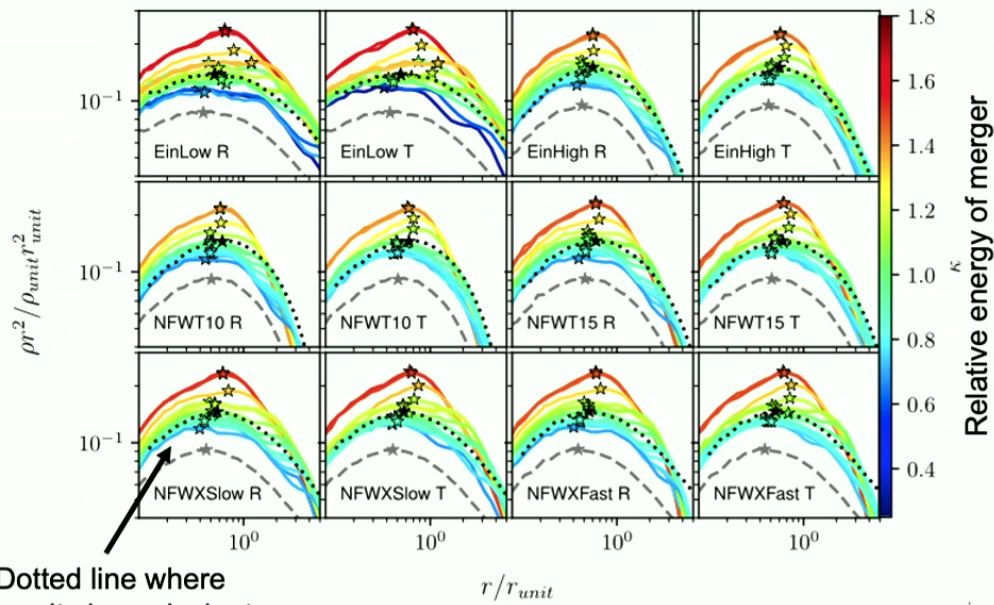
- high-z simulations wrong (unlikely at this point; multiple sims/authors, well-resolved)
- density profile of low-z halos is not NFW, but contains a denser central region
- some process causes the central density to decrease as halos evolve

Assume the latter; candidate mechanisms to reduce central density:

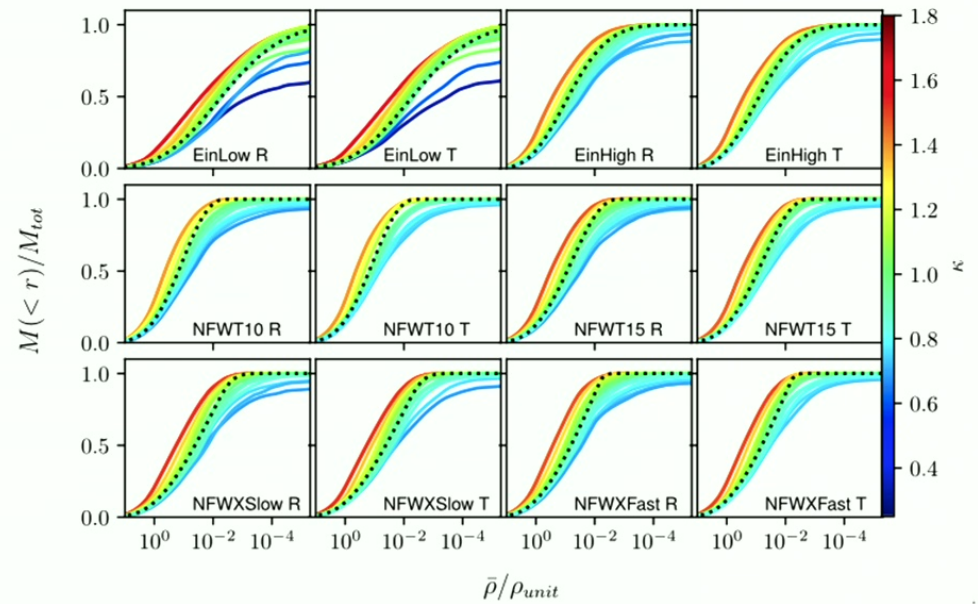
- ★ major mergers?
- ★ tidal stripping?
- ★ minor mergers?

# Major Mergers?

**Drakos+ 2019A, B:** how does the halo density profile change in equal-mass mergers?



(Dotted line where density is equivalent before/after merger)



Drakos, Taylor, Berrouet, Robotham & Power 2019

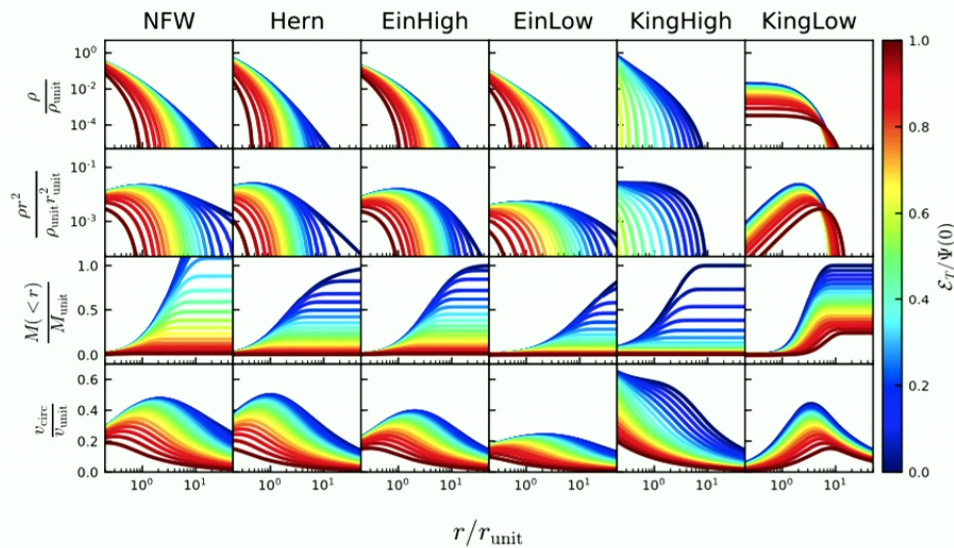
**Conclusion:** Typical mergers barely change the CDD; in particular, only the most violent mergers reduce it.

# Tidal Stripping?

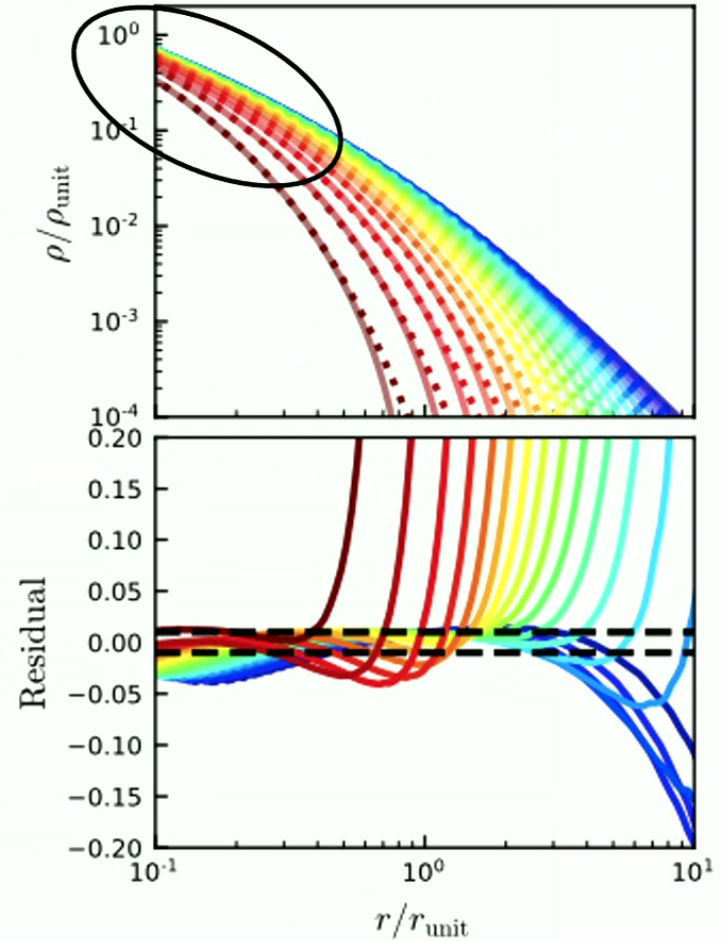
**Drakos, Taylor & Benson 2018, 2020, 2022:**

Tidal stripping stratified in energy space; inside-out

For any cuspy profile, preserves central density during most of mass loss



Central density  $\sim$  conserved down to 99% mass loss

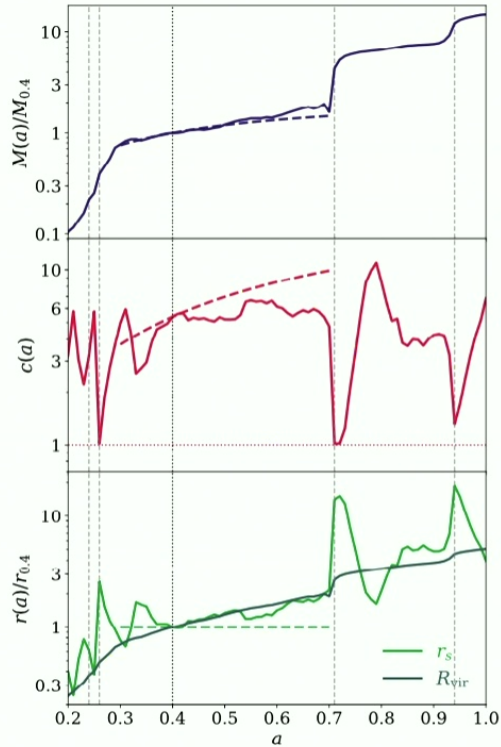


# Minor Mergers?

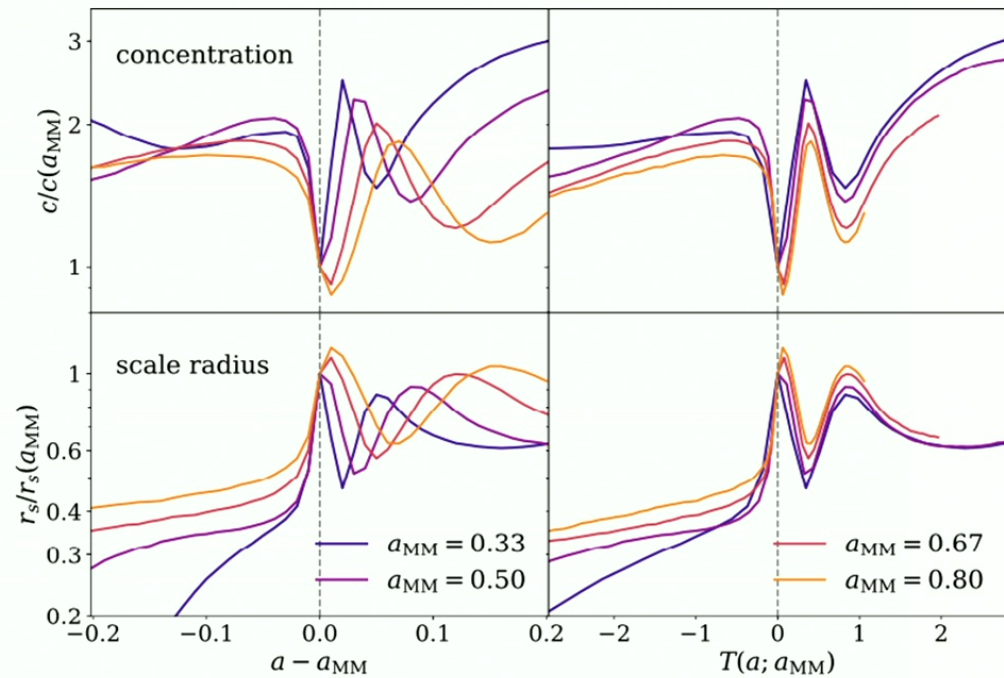
## Concentrations of Dark Haloes Emerge from Their Merger Histories

Kuan Wang,<sup>1,2\*</sup> Yao-Yuan Mao,<sup>3†</sup> Andrew R. Zentner,<sup>1,2</sup> Johannes U. Lange,<sup>4,5</sup>  
 Frank C. van den Bosch,<sup>6</sup> Risa H. Wechsler<sup>5,7</sup> MNRAS 2020 498, 4450

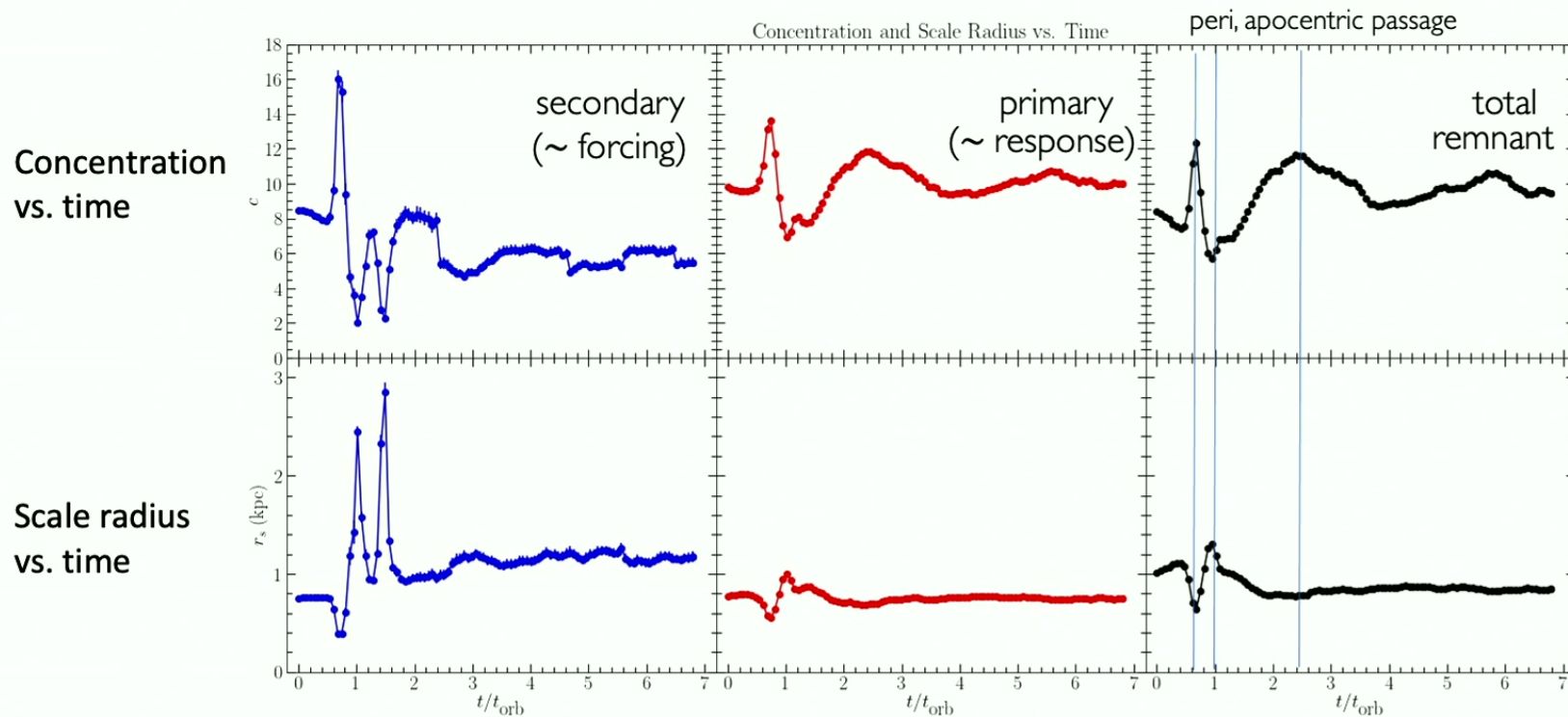
Evolution in a single case:



Calculating median of large sample of mergers:



## How does the central halo respond in asymmetric/minor mergers?



In test cases, see basic pattern in main system (black), but note background particles also respond (red)  
 So large oscillations in concentration; final density does not seem to change much, however...

## Conclusions

### **Basic question in structure formation: what is the highest density DM ever reaches?**

- ❖ Thinking about **cumulative density distribution** probably better path than concentration-mass relations
- ❖ Issues with concentration: profile assumed, halo/subhalo, redshift evolution, short-term oscillations...
  
- ❖ There is **residual uncertainty in the maximum DM density**, even in plain vanilla CDM cases
- ❖ Still not clear if the  $z=0$  profile wrong, or early density reduced by some unknown mechanism
- ❖ If high densities conserved, **indirect detection constraints get much stronger...**
  
- ❖ Further complications: main halos vs subhalos, relationship to initial cusp (Diemand, Moore & Stadel 2005; Ishiyama, Makino & Ebisuzaki 2010; Anderhalden & Diemand 2013; Ishiyama 2014; Polisensky & Ricotti 2015; Angulo et al. 2017; Ogiya & Hahn 2018; Colombi 2021; Delos & White 2023, Ondaro-Mallea+ 2024), also PBH/enhanced small-scale power, dissipation...

Thanks!