How Dense is Early Dark Matter Structure?

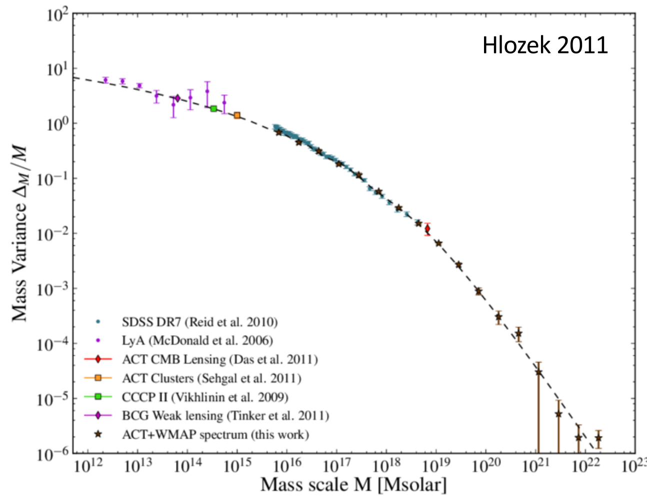
James Taylor – Waterloo Centre for Astrophysics

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

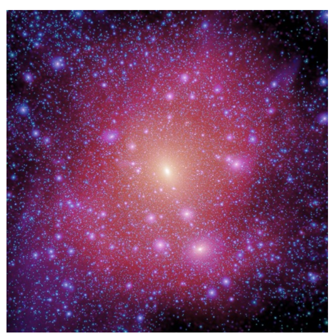


To test modified DM models, SIDM, ADM, or to interpret CDM direct detection, indirect detection results, usually need to know clustering on **all scales**

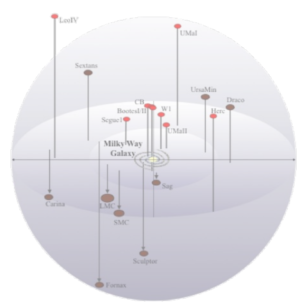
(Note new probes – GWs, pulsar timing, substructure lensing, 21cm – may help?)

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 31 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?

<u>Basic Hypothesis</u>: (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 ~ 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

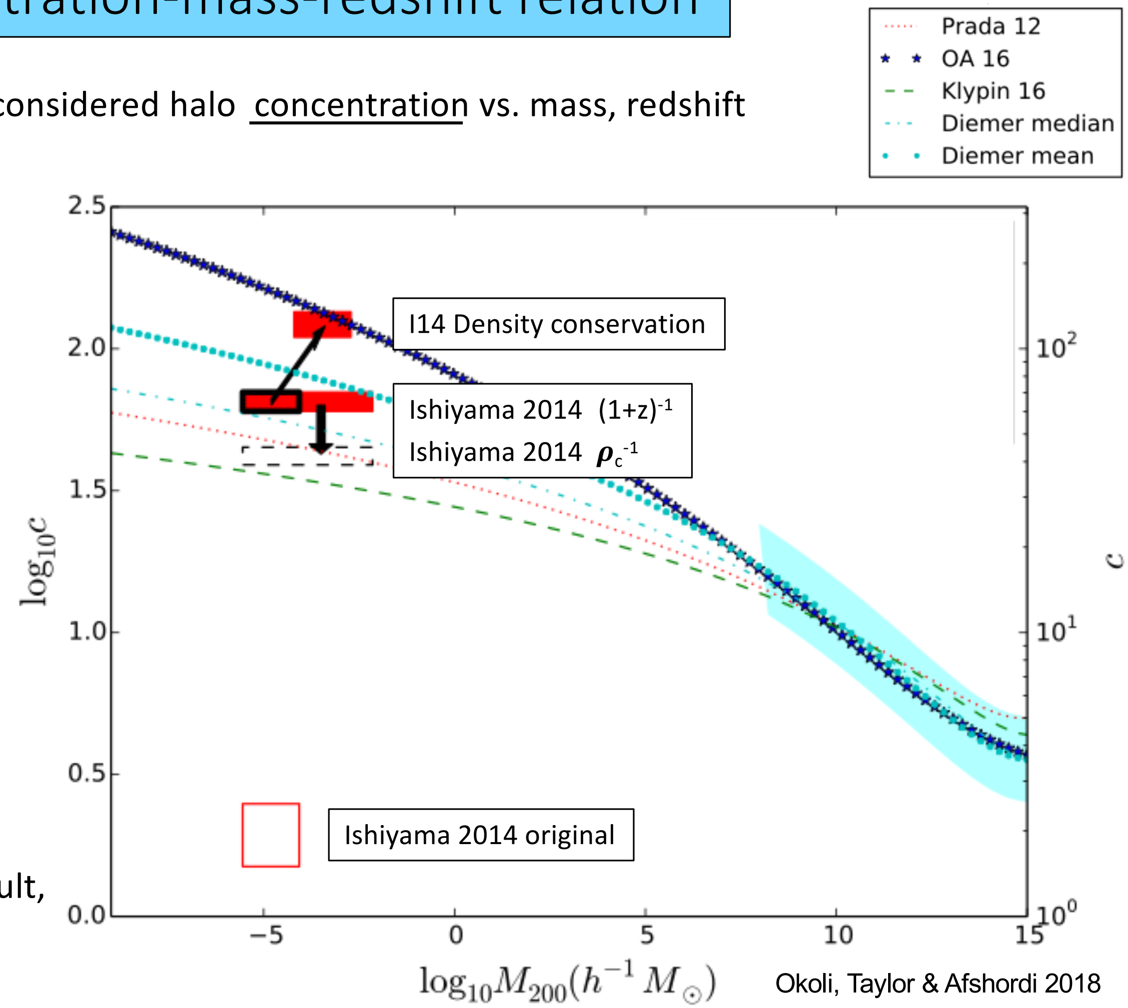
For boost factor etc. calculations, previous work considered halo concentration vs. mass, redshift

Problems w. concentration:

– several possible definitions beyond r_s/r_{vir}
+ profile-dependent

– usually measured at low z and
extrapolated as $(1+z)^{-1}$ or ρ_c^{-1}
(based on evolution of r_{200})

– this evolution ignores change in mass



Okoli, Taylor & Afshordi 2018

Afshordi + Okoli 2016:

Alternative analytic prediction based on energy conservation during collapse

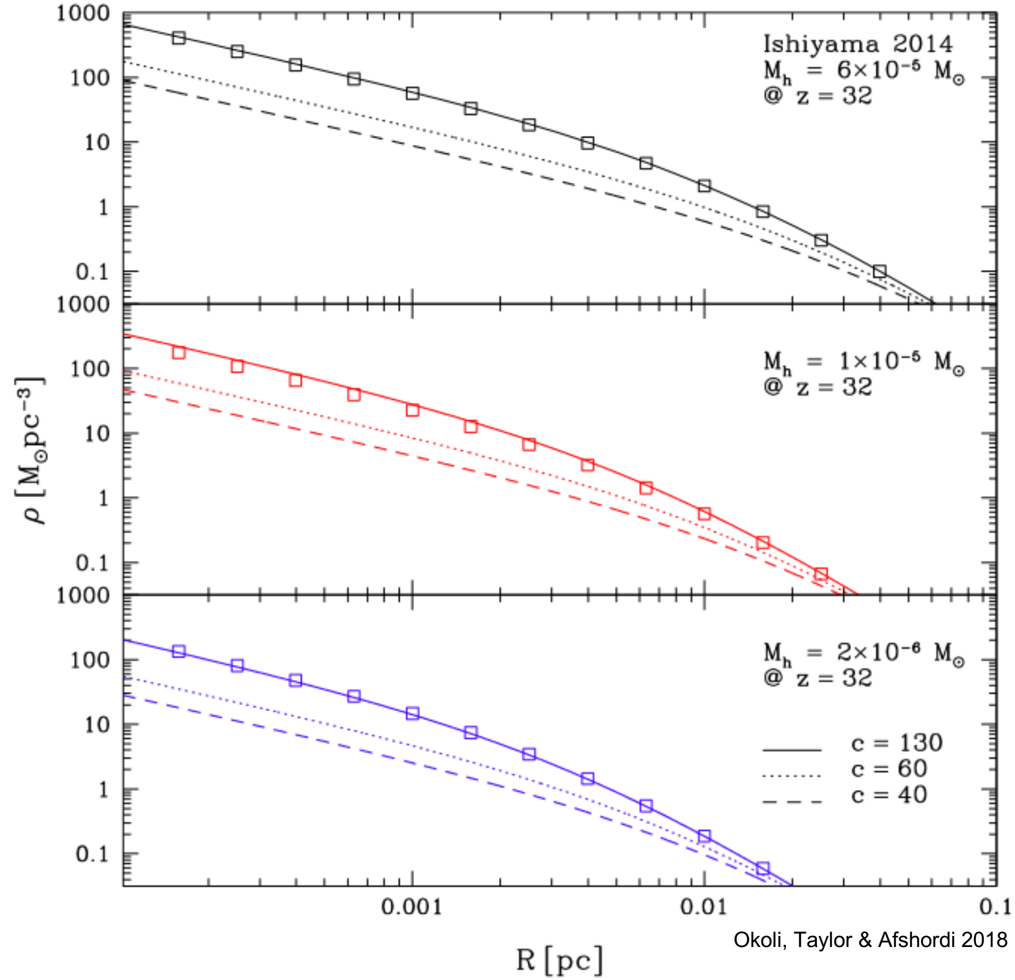
Simple density conservation: predicts similar result,
6-8x denser than usual c(z,M) prediction

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 (~ 9x) between z=32 and z=0, for various z=0 concentrations

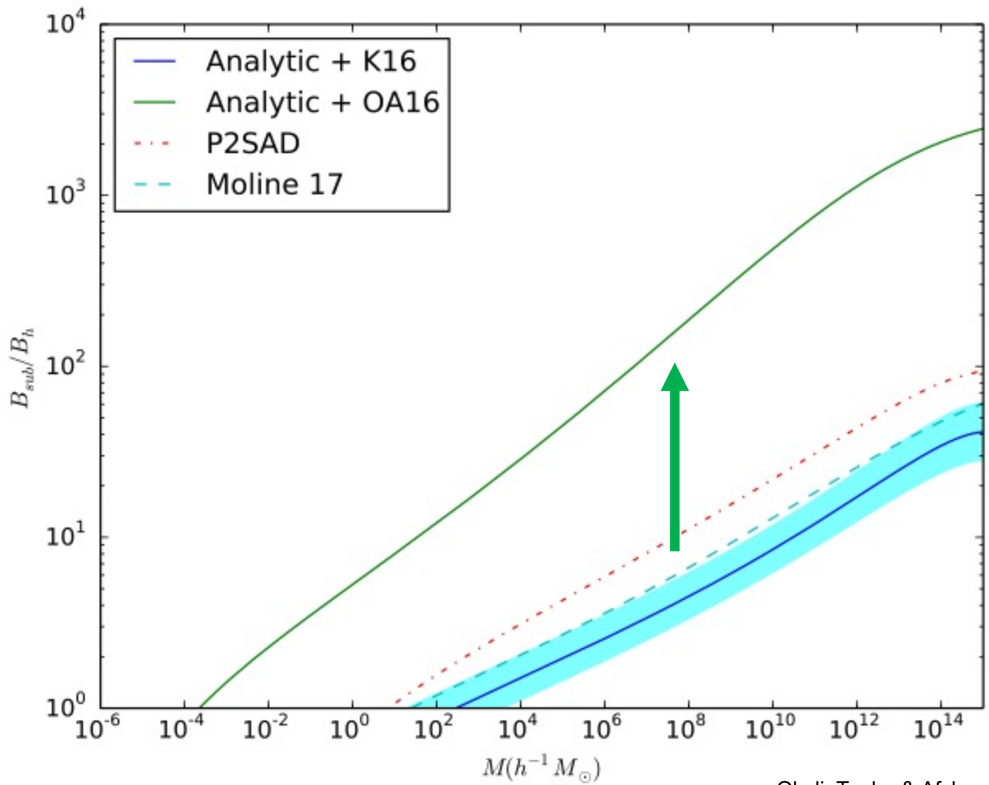
Conclusion: The central density of the smallest halos is ~6-8 times higher than predicted by low-redshift concentration-mass relations



Okoli, Taylor & Afshordi 2018

N.B. Implications for the Boost Factor

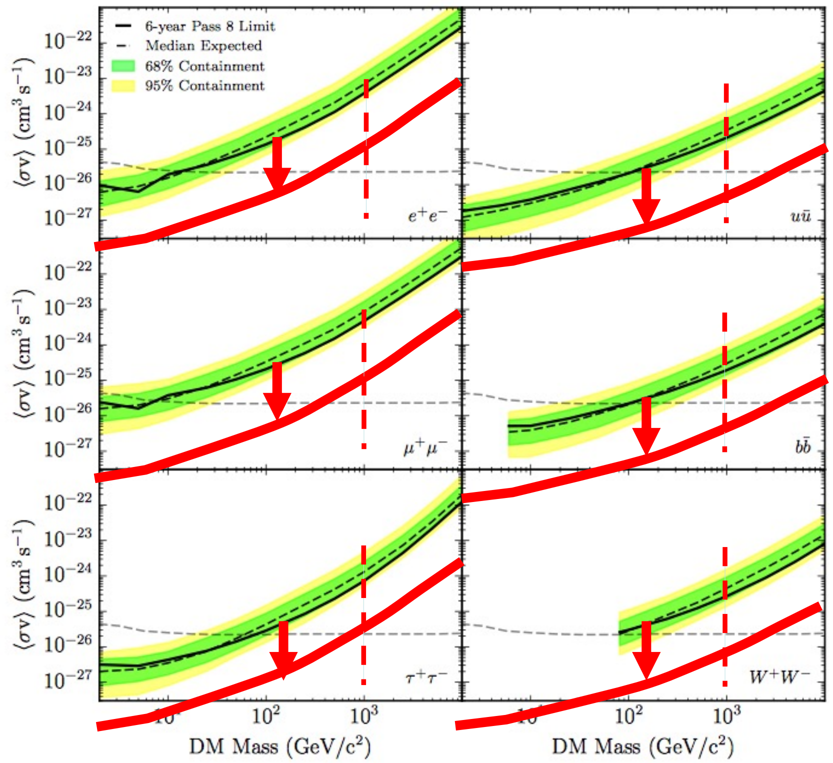
If high DM densities are conserved to low redshift, the boost factor is 30-90 times larger than anticipated!



Okoli, Taylor & Afshordi 2018

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:

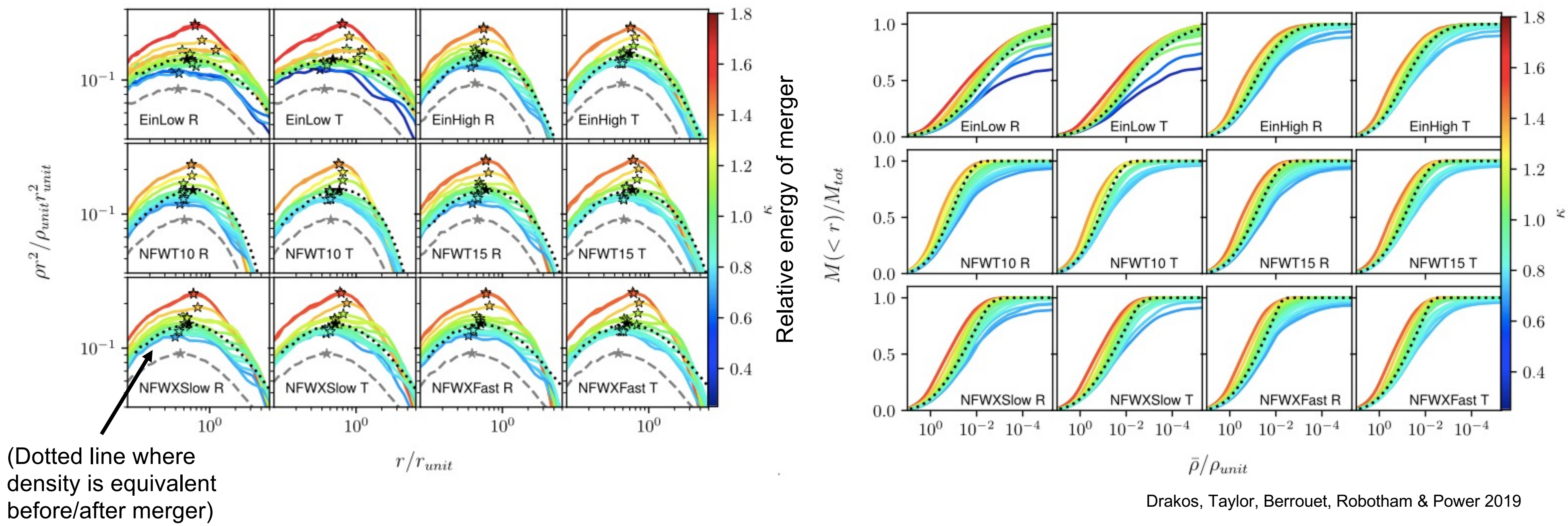
★ major mergers?

★ tidal stripping?

★ minor mergers?

Major Mergers?

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



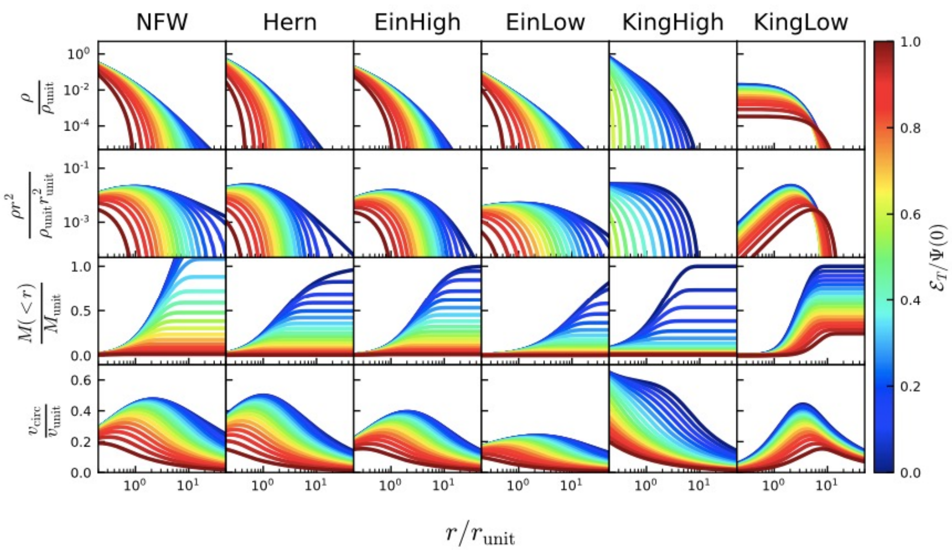
Drakos, Taylor, Berrouet, Robotham & Power 2019

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

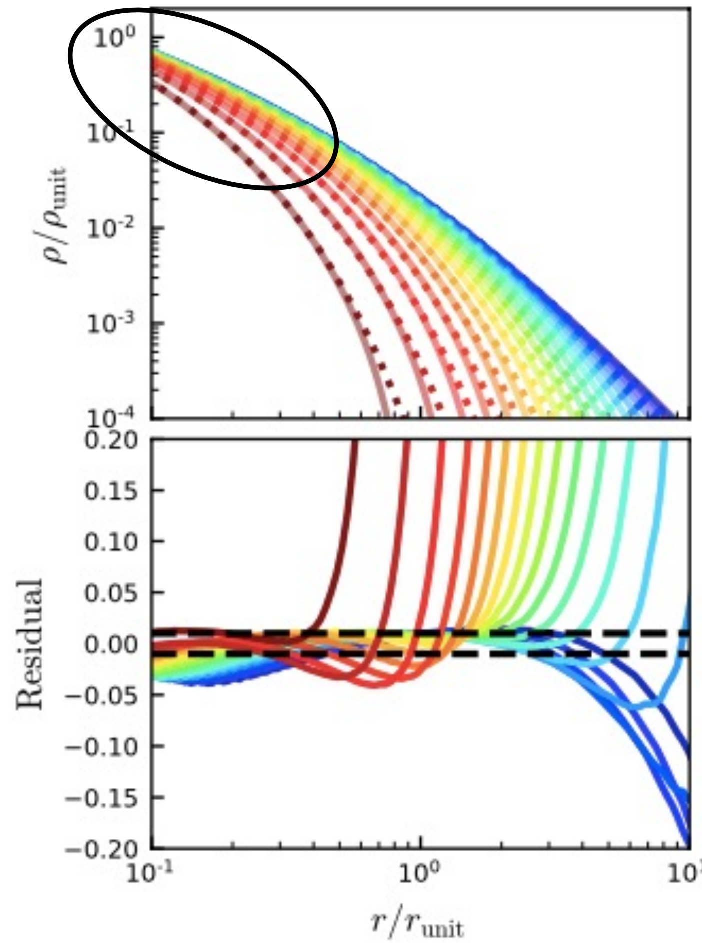
Tidal Stripping?

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 ~ conserved down to 99% mass loss

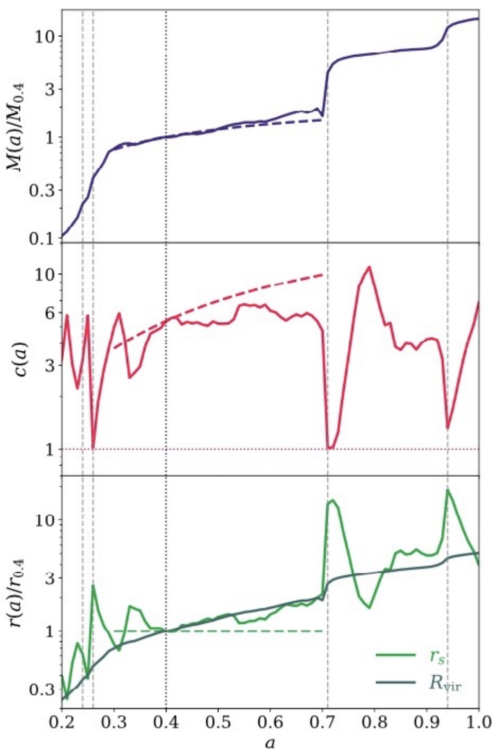


Minor Mergers?

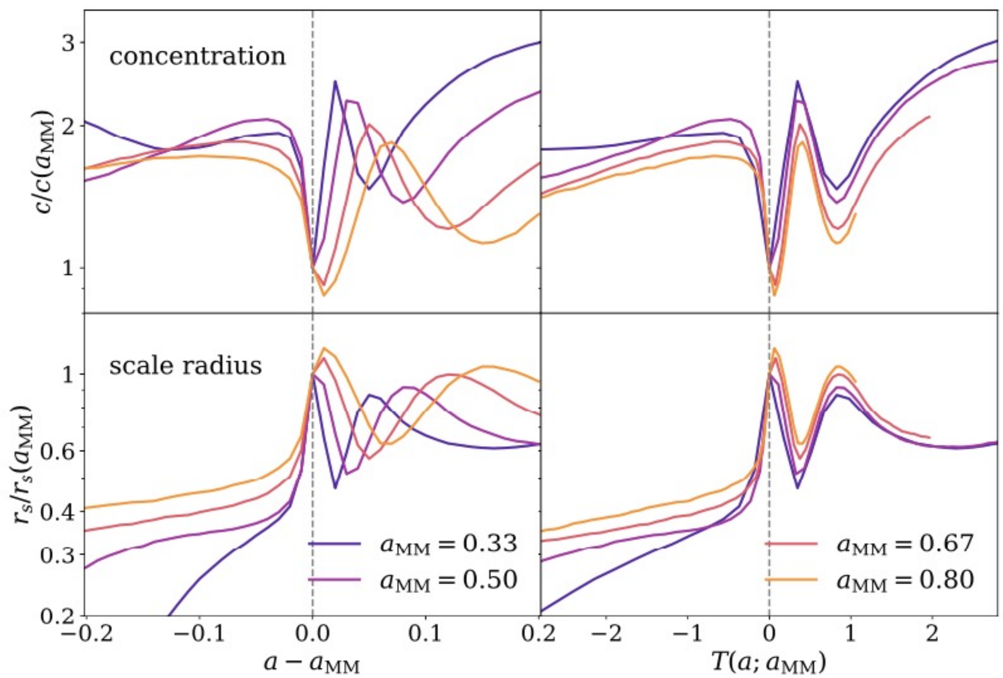
Concentrations of Dark Haloes Emerge from Their Merger Histories

Kuan Wang,[1,2★] Yao-Yuan Mao,[3†] Andrew R. Zentner,[1,2] Johannes U. Lange,[4,5]
Frank C. van den Bosch,[6] Risa H. Wechsler [5,7] MNRAS 2020 498, 4450

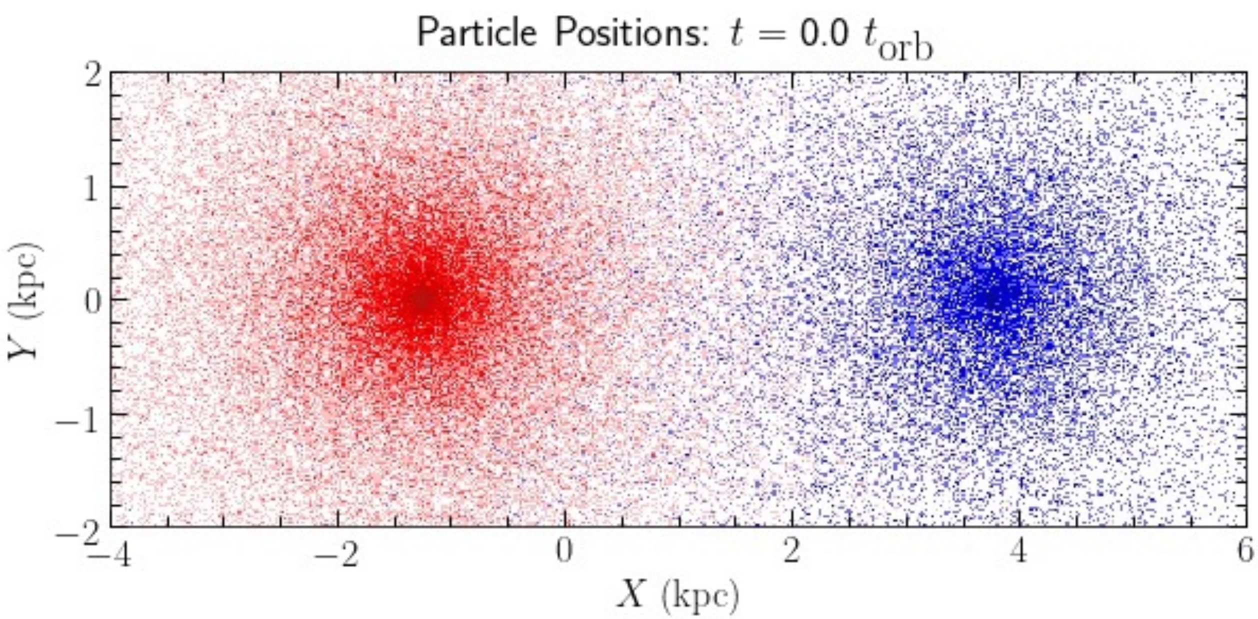
Evolution in a single case:



Calculating median of large sample of mergers:



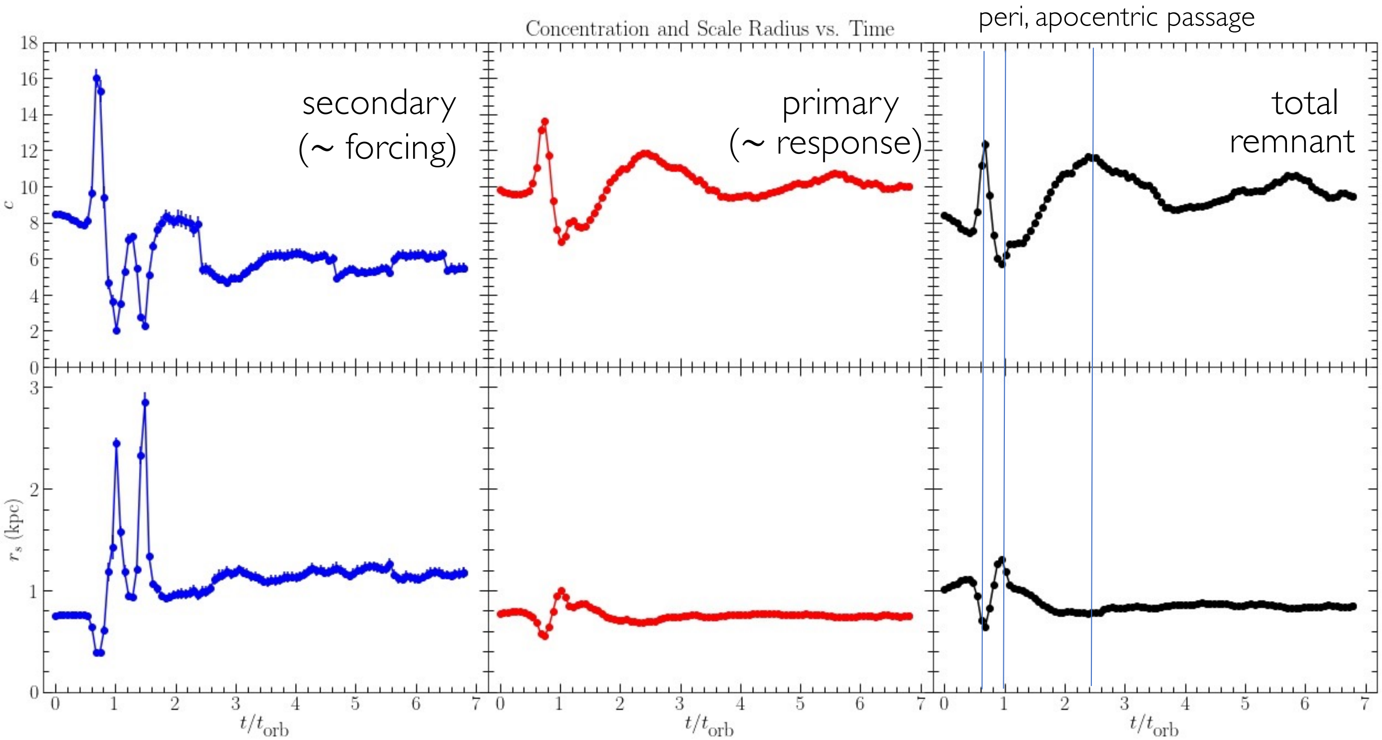
How does the central halo respond in asymmetric/minor mergers?



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

Concentration vs. time

Scale radius vs. time



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!