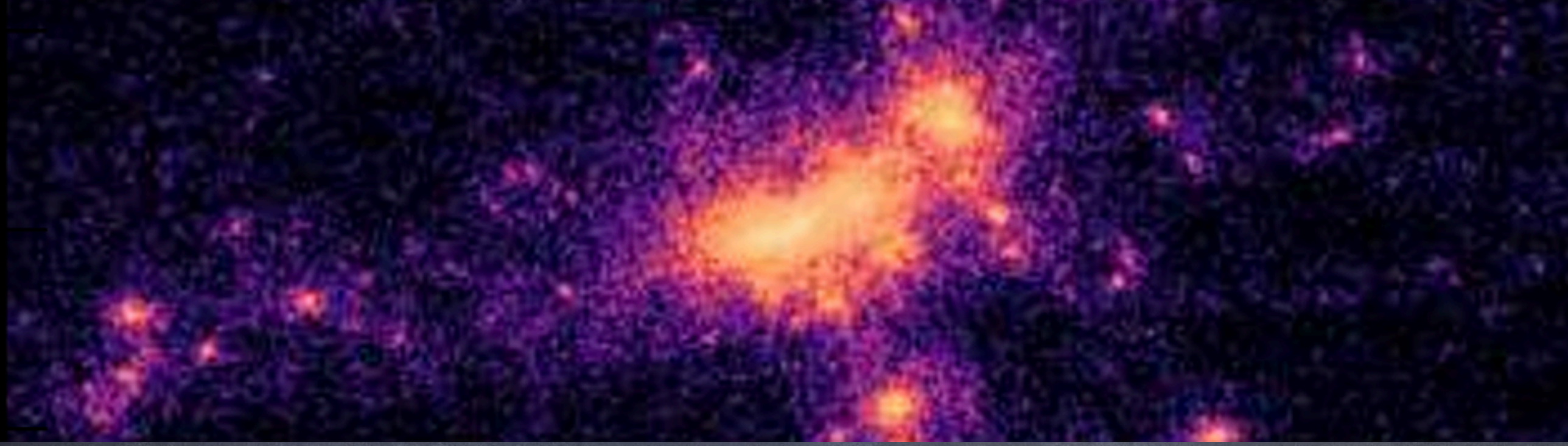

Outer Halo Profiles as Probes of beyond-CDM models

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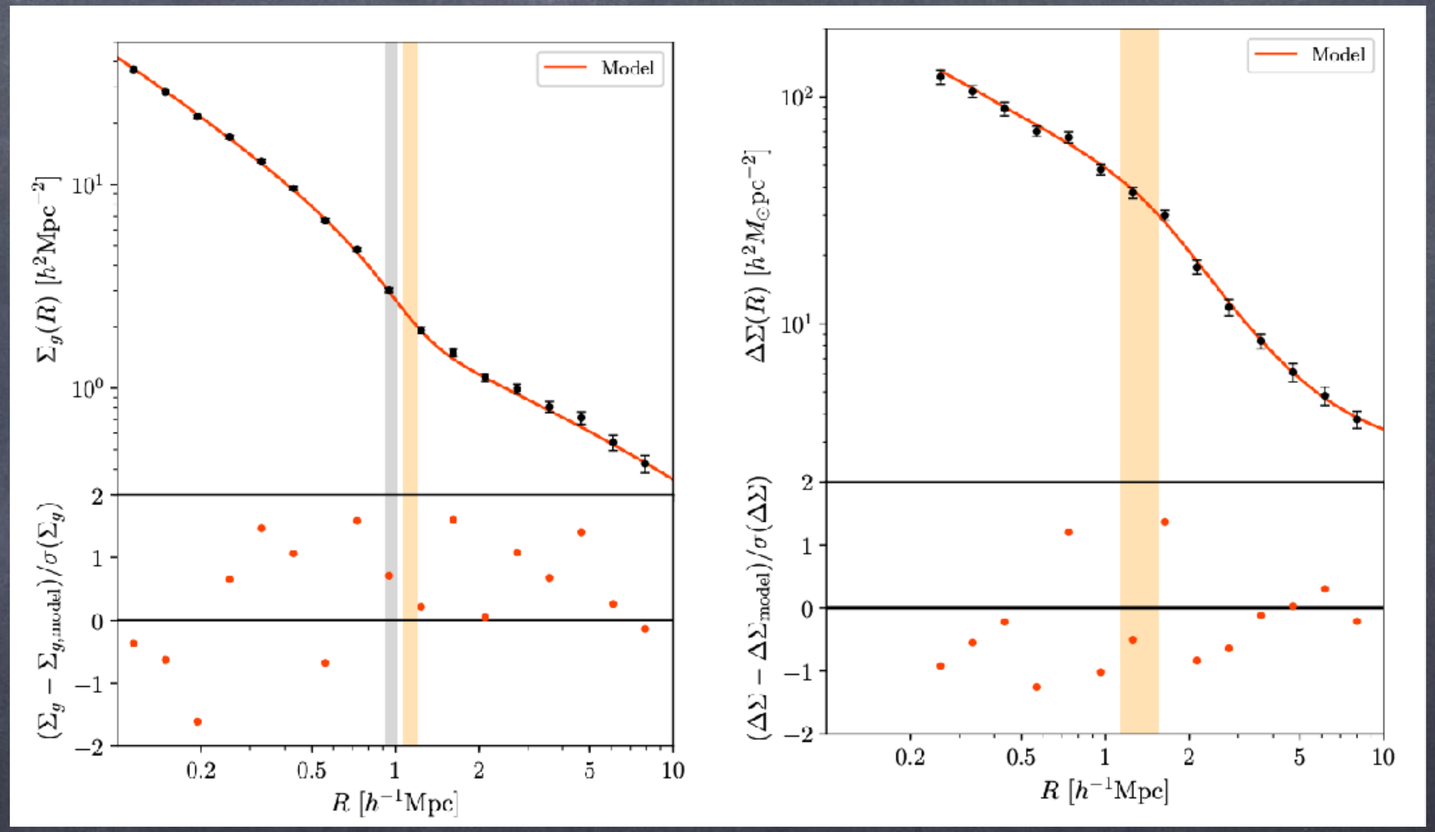
Mapping the outer profiles of clusters

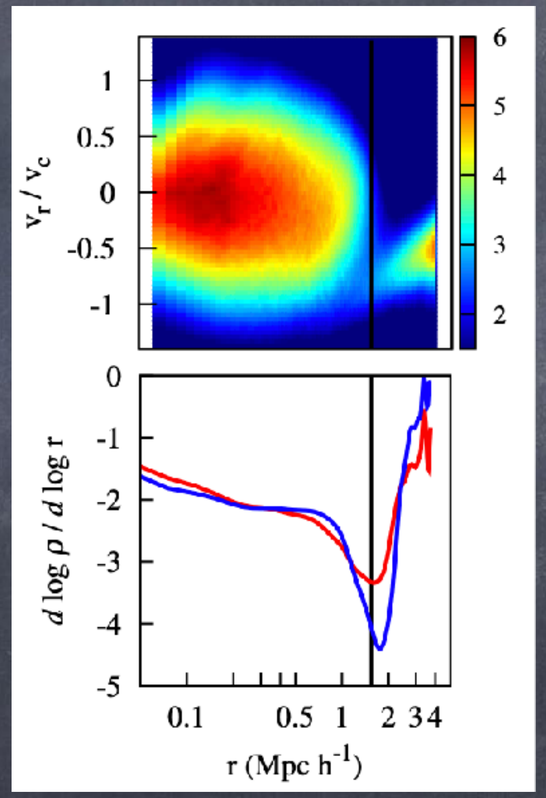
- With larger photometric surveys, weak lensing and satellite counts allow for precise mapping of the average outer profiles of massive clusters.
- Low S/N for individual objects, statistical power comes from the total number of clusters in some mass range.



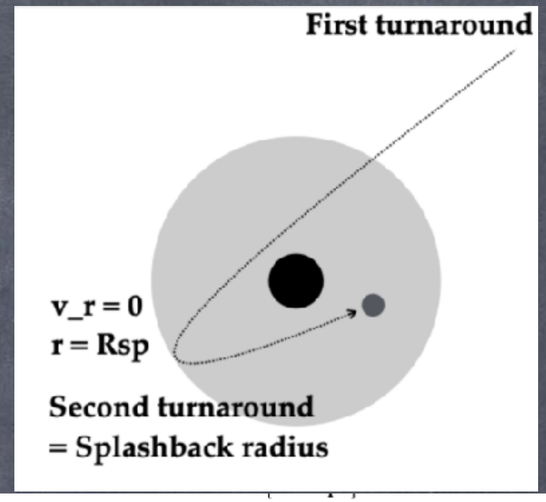
Chang et al, 2017

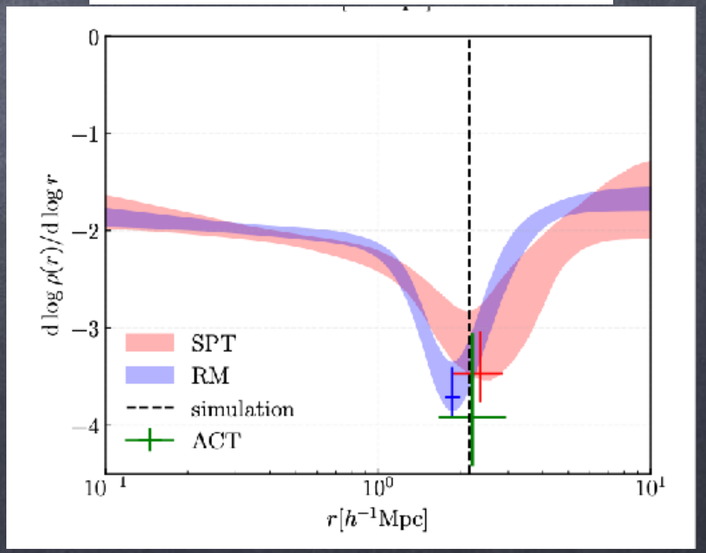
Splashback radius or the “edge” of a Dark Matter halo

- The edge of the virialized regions of halos corresponds to a steep drop in the slope of the density profile.
- The feature remains even after stacking over many halos in a mass range.
- Has been detected robustly in several studies.
- Can we use these measurements to constrain the dark sector?



Adhikari et al, 2014





Shin et al, 2018

SIDM Simulations

- Simulations run with a modified version of Gadget-2. We considered various scenarios for the differential cross-section:
  - Velocity-independent and isotropic.
  - Velocity-independent but with angular dependence:

$$\frac{d\sigma}{d\Omega} \propto \frac{1+\cos^2\theta}{1-\cos^2\theta}$$

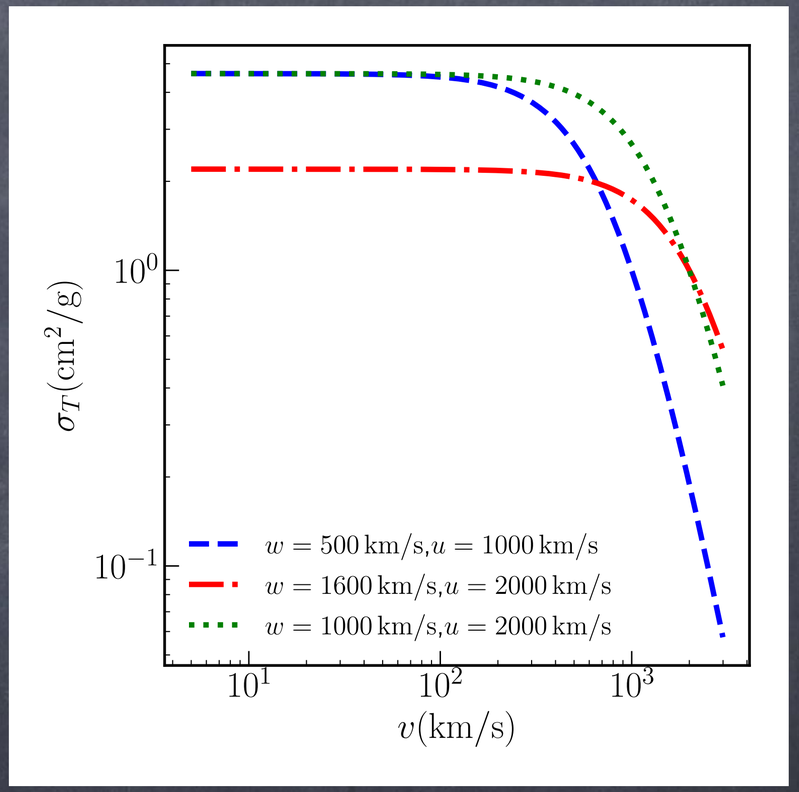
Kahlhofer et al, 2013

  - Velocity and angle-dependent:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\sigma_0}{2\left[1+\frac{v^2}{w^2}\sin^2\left(\frac{\theta}{2}\right)\right]^2}$$

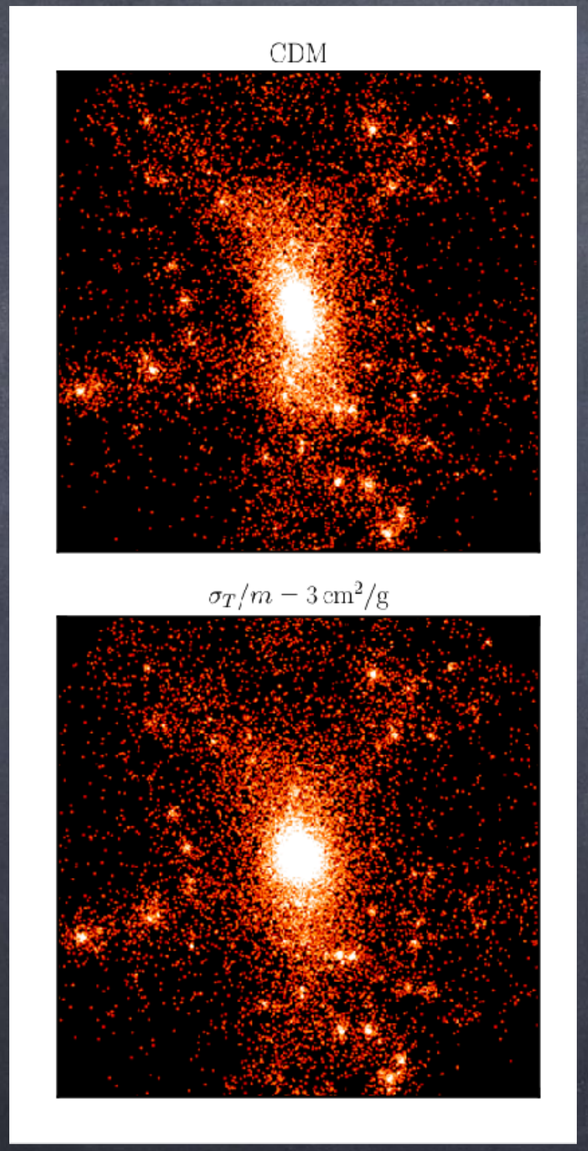
Tulin et al, 2017

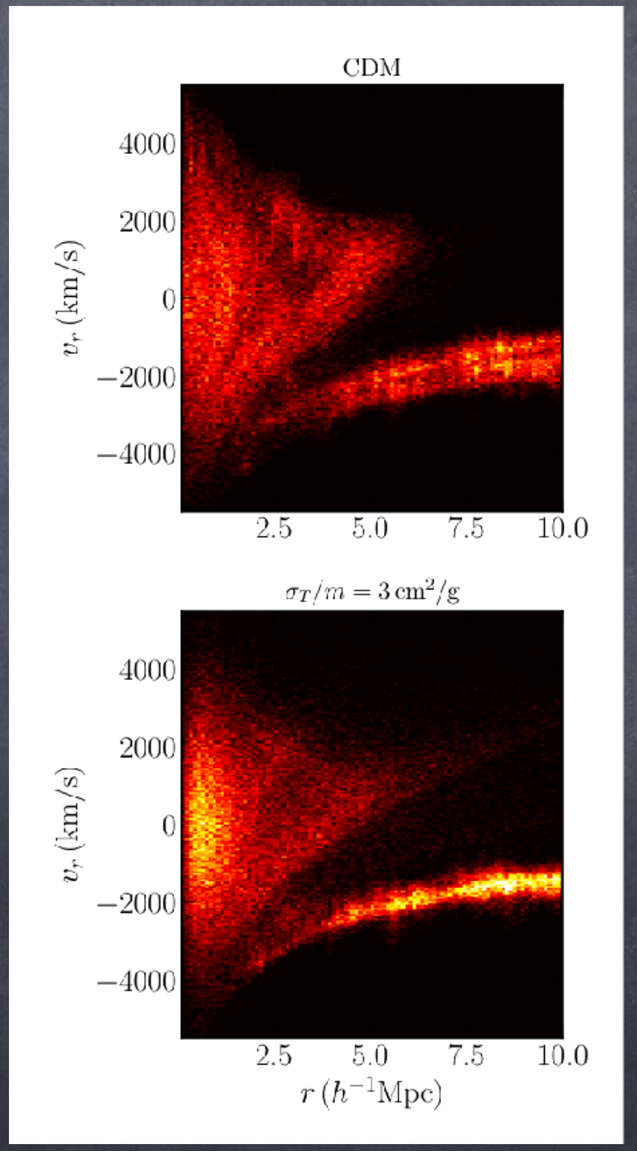
- Ran cosmological sims with volume (1 Gpc/h)3. Concentrated on halos in the mass range (1e14-2e14) Msun/h. Approximately 20000 objects in each simulation.



Banerjee et al, 2020

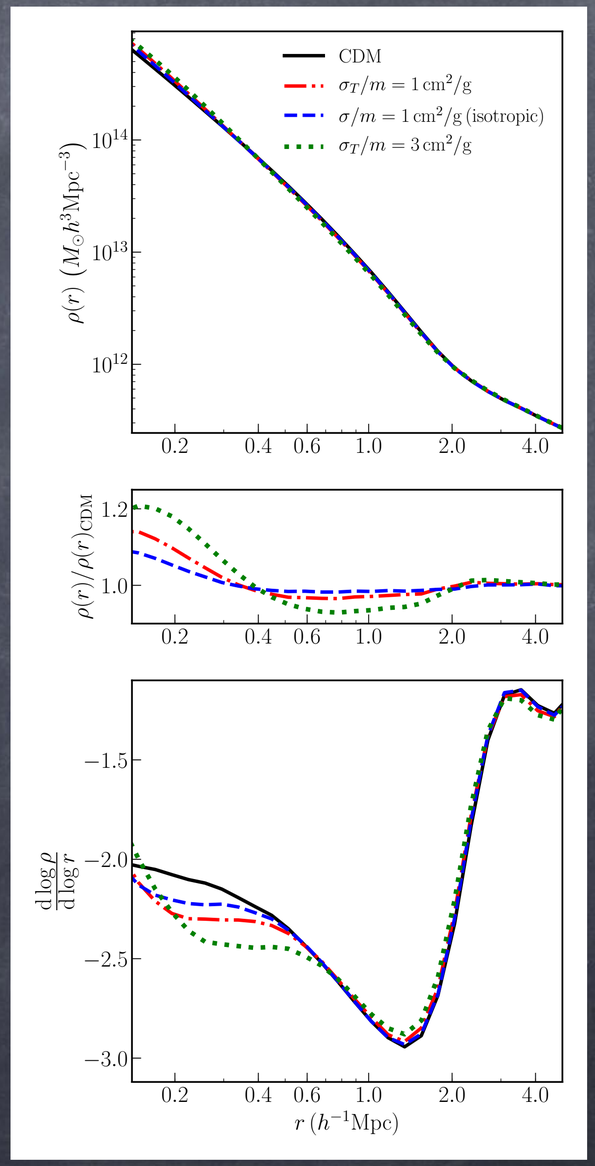
SIDM simulations: Most Massive Halo





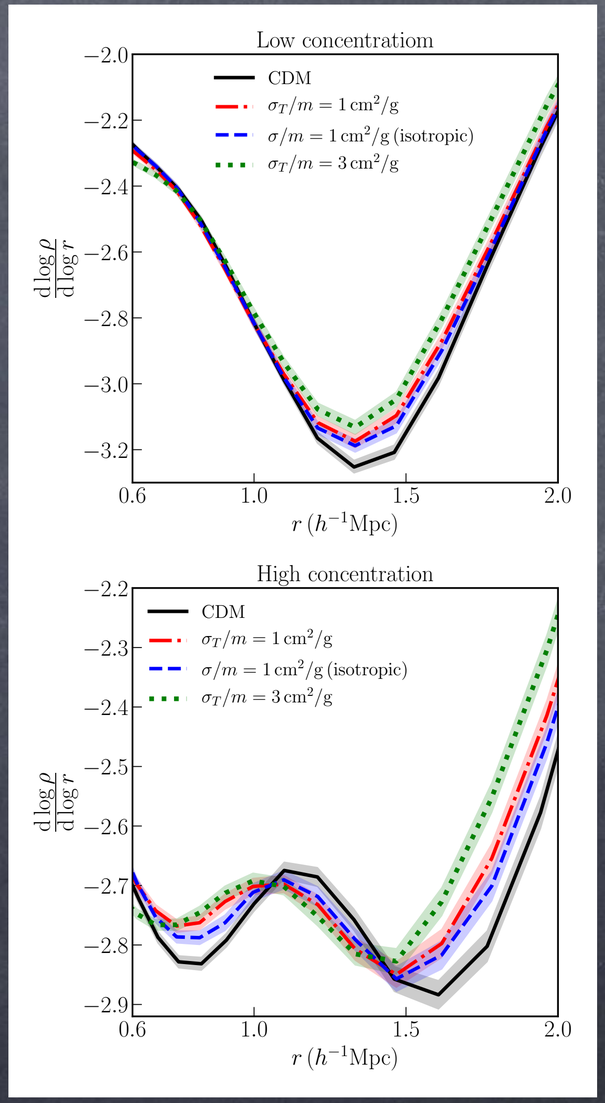
SIDM effects on the 3-d stacked density profiles

- Effects of self-interactions persist close to the virial radius and are measurable in the stacked density profiles.
- The splashback radius does not show any significant movement for the full population.



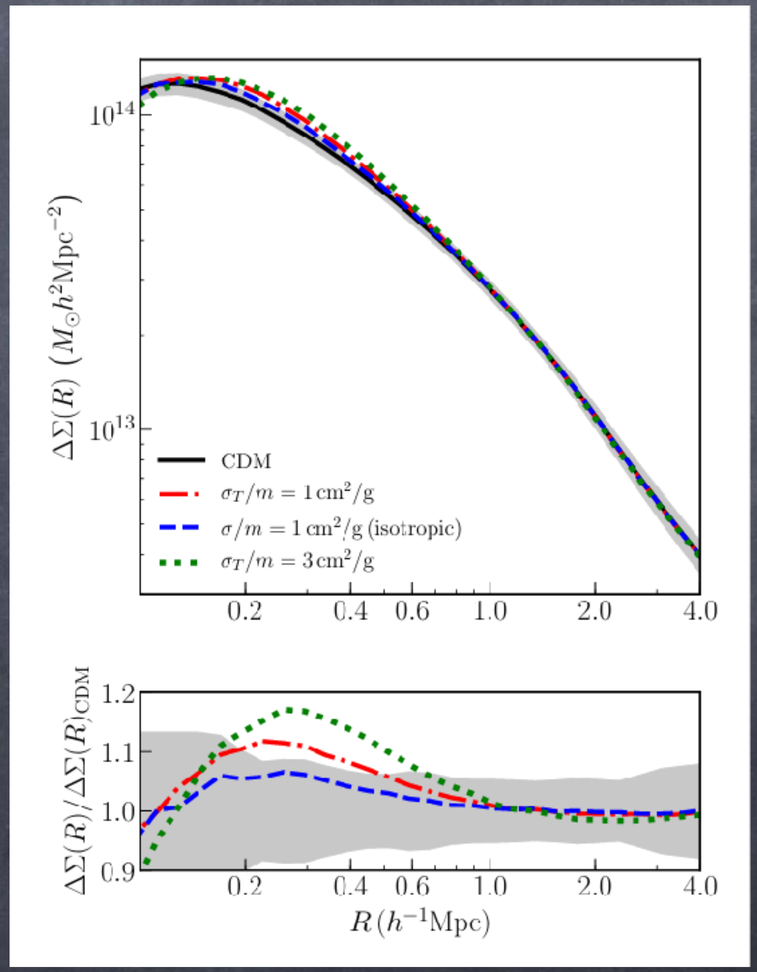
Trends in splashback radius with concentration

- When halos are split on concentration (of the CDM counterpart), self-interactions can change the splashback radius.
- Low concentration (late-forming) halos do not show any movement in the splashback radius.
- High concentration (early-forming) halos clearly show a trend with interaction strength.



Effects on cluster lensing signals

- We plot the $\Delta\Sigma(R)$ profiles relevant for weak lensing measurements.
- The grey shaded region represents error bars on the measurement from DES Y1.

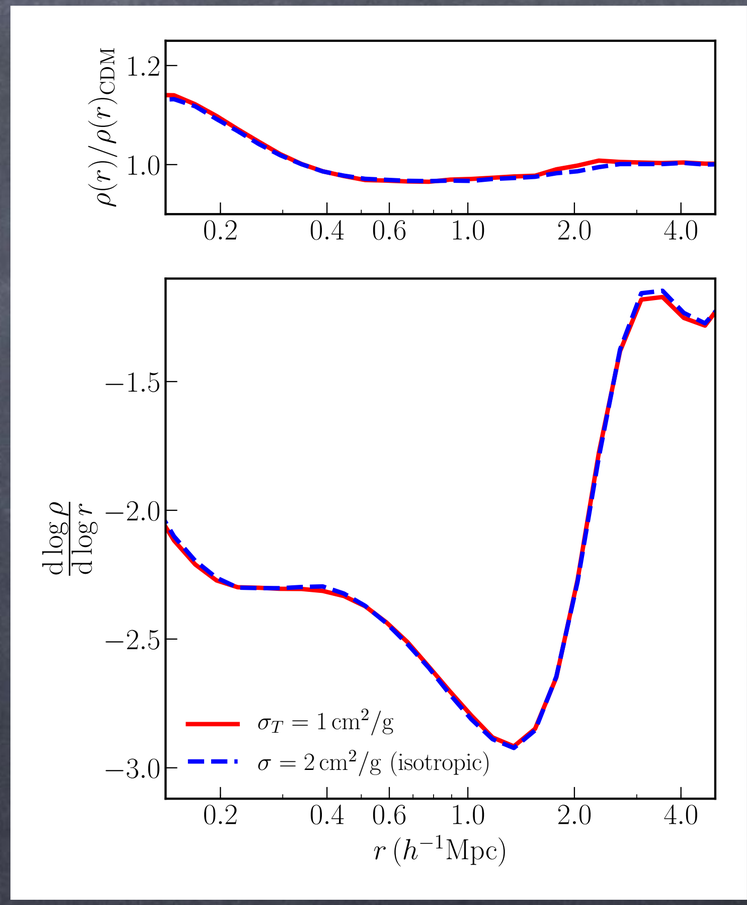


Angular dependence of self-interactions

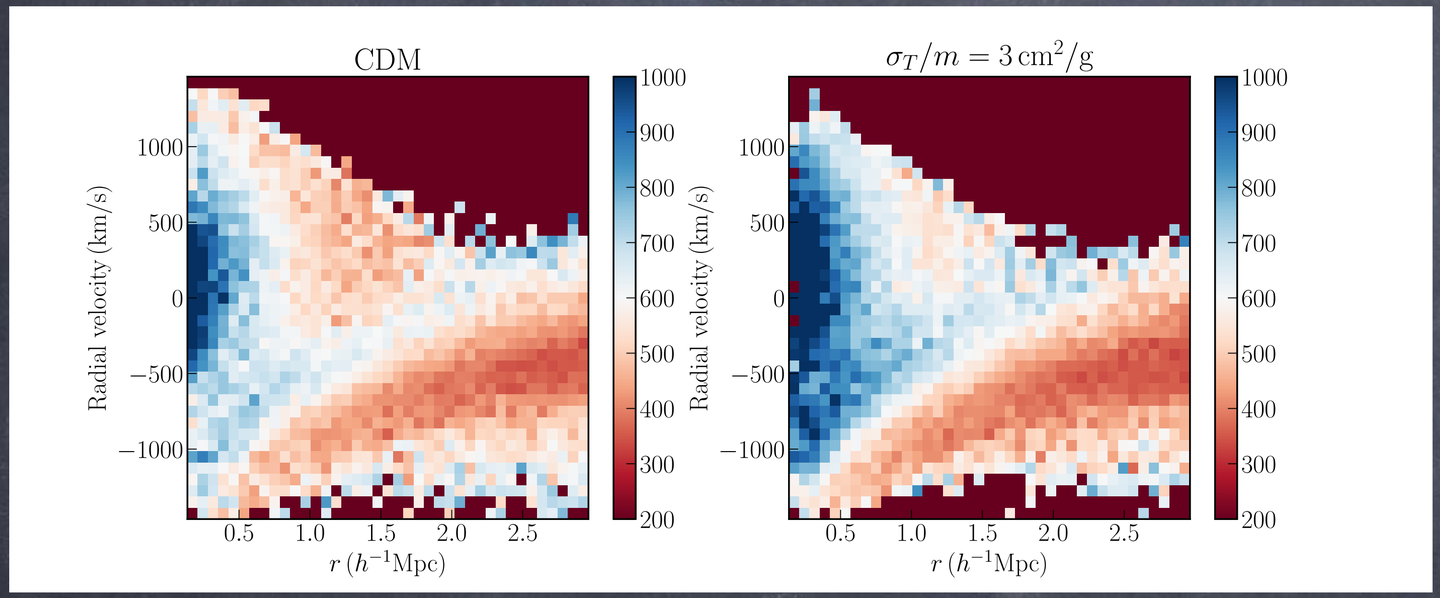
- We match the momentum transfer cross section:

$$\sigma_{\rm T} = \int \frac{{\rm d}\sigma}{{\rm d}\Omega}(1 - |\cos\theta|){\rm d}\Omega \,.$$

- We find no strong evidence that the exact angle-dependence of the differential cross section affects the stacked density or subhalo profiles.



Effects on subhalos/galaxies



Also see: 10.3847/1538-4357/ac68e9

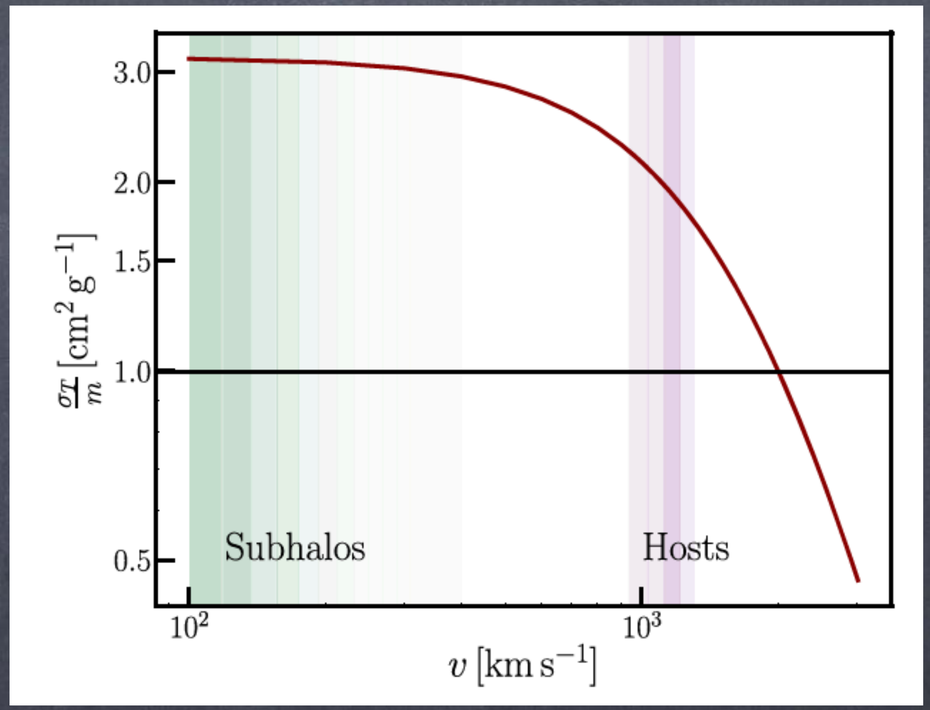
The Astrophysical Journal, 932:90 (18pp), 2022 June 10 https://doi.org/10.3847/1538-4357/ac68e9

The Signatures of Self-interacting Dark Matter and Subhalo Disruption on Cluster Substructure

Joy Bhattacharyya[1,2,3], Susmita Adhikari[4,5,6], Arka Banerjee[4,6,7], Surhud More[8,9], Amit Kumar[8], Ethan O. Nadler[6,10,11,12], and Suchetana Chatterjee[2]

Moving to smaller halo masses

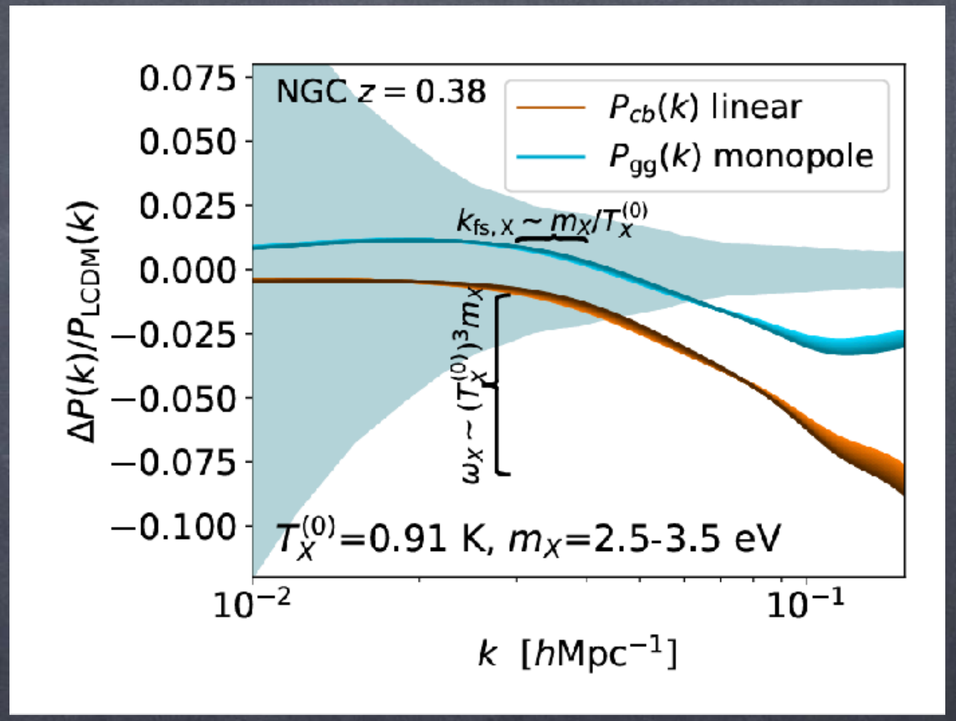
- There are many attempts to measure stacked lensing profiles around groups, Milky Way-sized halos, and even smaller hosts. E.g., DES, Merian, LSST.
- In the SIDM context, it is important to pin down any velocity-dependence as it relates directly to the underlying particle physics model.
- Important to repeat this analysis across other halo mass ranges and interaction strengths.
- Consider other models - e.g. dissipative dark matter.



Bhattacharya et al, 2022

Cosmology with Light but Massive relics (LiMRs)

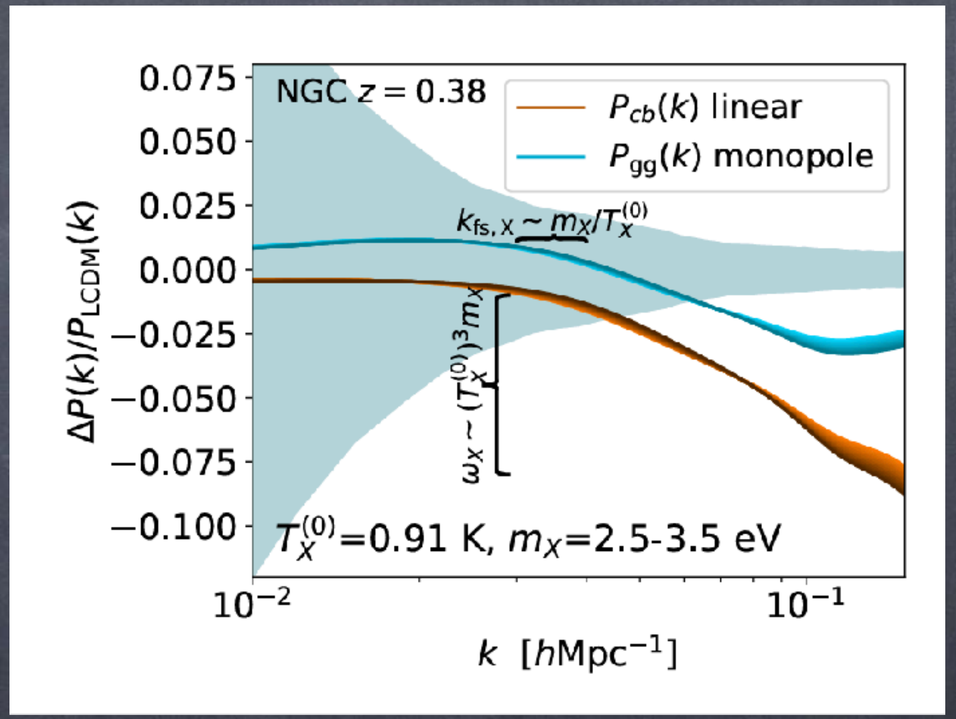
- Many dark sector models include a light but massive relic. Shows up as $\Delta N_{\rm eff}$ in CMB data. Will be tightly constrained at SO, CMB S4.
- Will also affect late time structure formation depending on mass and temperature.
- Linear scale effects are being explored.
- What about effects on small, nonlinear scales?



Xu, Munoz, and Dvorkin, 2022

Cosmology with Light but Massive relics (LiMRs)

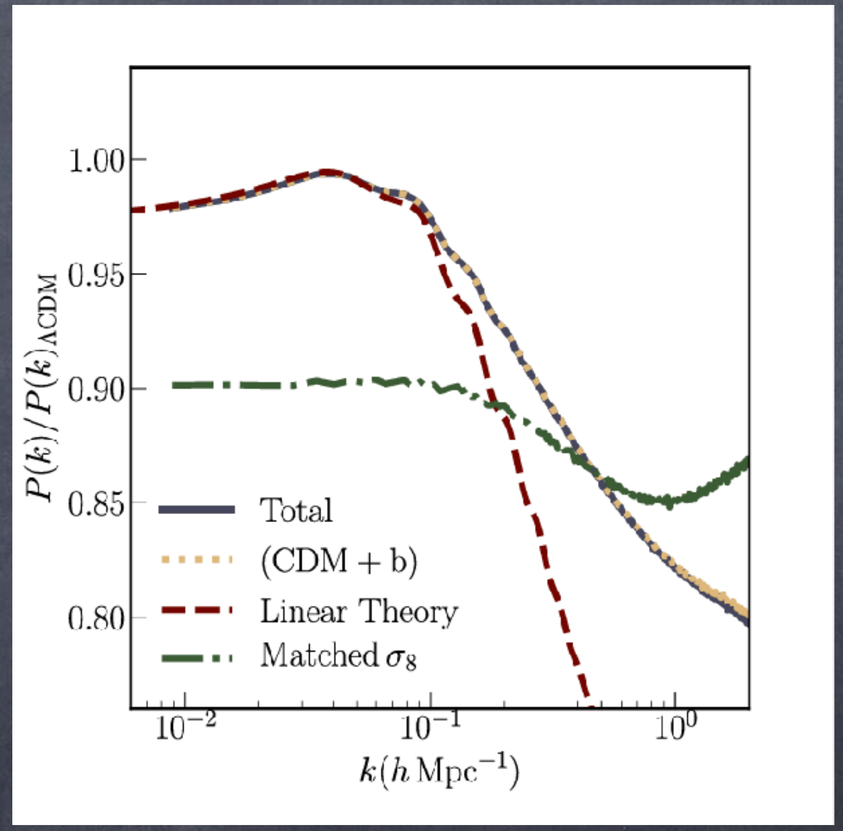
- What about effects on small, nonlinear scales?
  - Linear evolution depends on the total energy and sound speed (moments). Two distributions with these quantities matched will produce similar effects on linear scales.
  - If the LiMR component is “cold” enough to be captured and virialized in halos, the full distribution starts to matter.
- Needs a systematic simulation suite. Work in progress...



Xu, Munoz, and Dvorkin, 2022

Nonthermal decay model: Effect on power spectrum

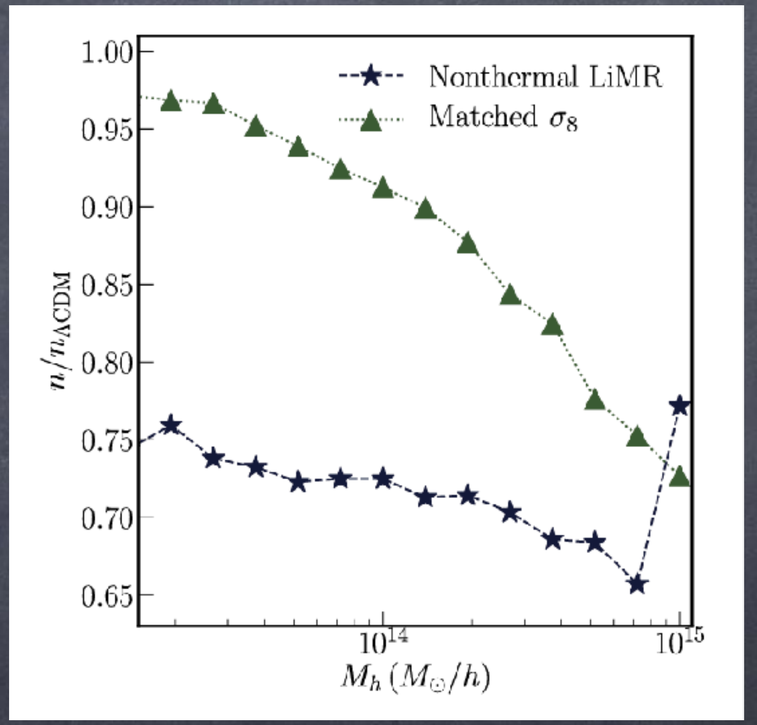
- Unlike SIDM, matter power spectrum is damped out to quasi-linear scales.
- Interestingly, the small-scale suppression has a shape that is a potential (nonlinear) solution to the "σ_8 tension". (See Efstahiou and Amon, 2022)



Banerjee et al, 2022

Nonthermal decay model: Halo mass function

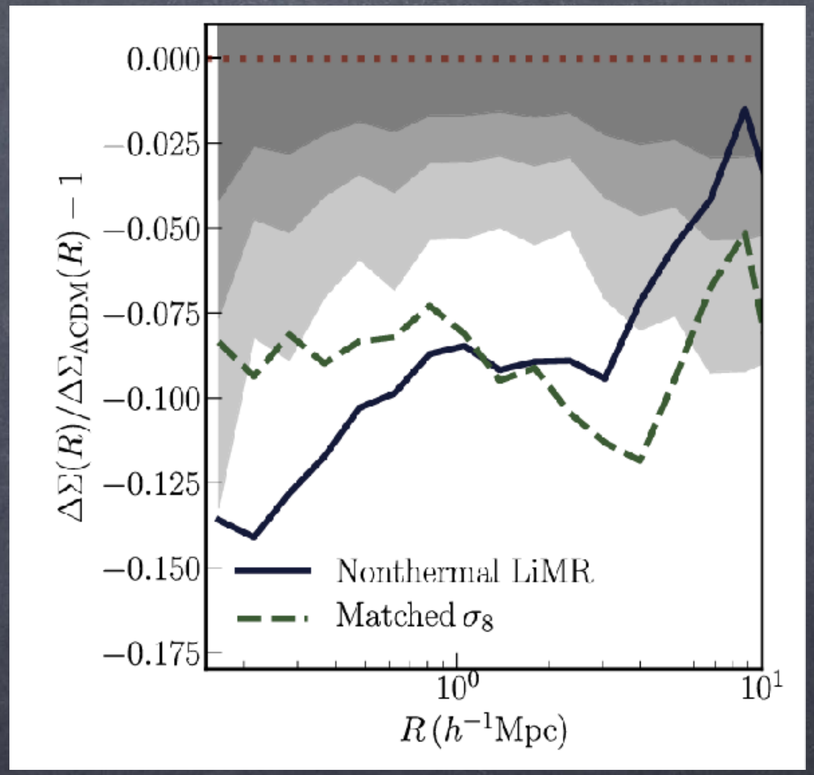
- On smaller scales, the halo mass function is affected in a non-trivial way compared to changing the amplitude of the primordial power spectrum.



Banerjee et al, 2022

Nonthermal decay model: Cluster lensing

- Compare lensing profiles ($\Delta\Sigma(R)$) around the 20,000 most massive halos in the simulation box.
- The signal includes the contribution to the lensing mass from LiMR particles as well.
- Again, we find a distinctive signal compared to a change in the amplitude of the primordial power spectrum.



Banerjee et al, 2022

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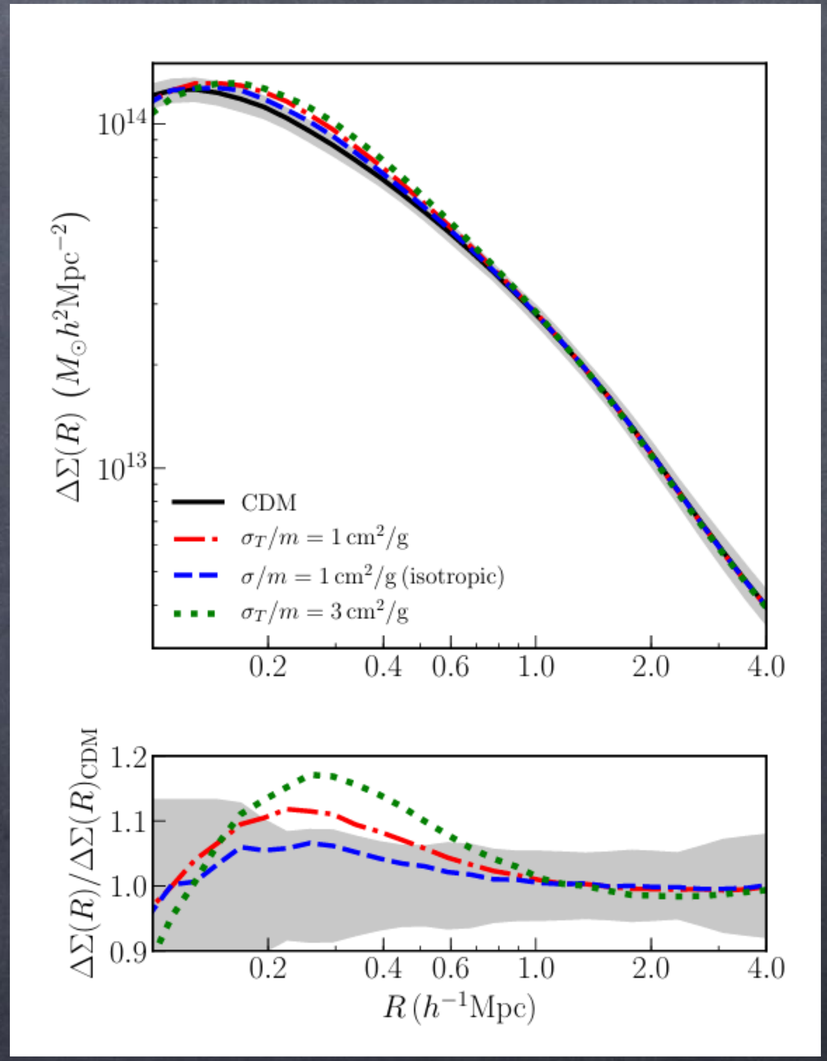

Summary

- Outer profiles of Dark Matter halos are starting to be measured very precisely, and can be used to study models of Dark Matter or the extended dark sector.
- Effects of SIDM on the lensing profile of clusters can extend out close to the virial radius, even when stacked.
- Splashback radius, as defined in matter, does not change for a mass-selected population. However, if we split on halo history within the mass bin, splashback is affected by self-interactions.
- In cosmological models with light, massive relics, lensing measurements around halos, in conjunction with other nonlinear observables, are the only avenue to determine the momentum distribution of these additional species.

Thank you!