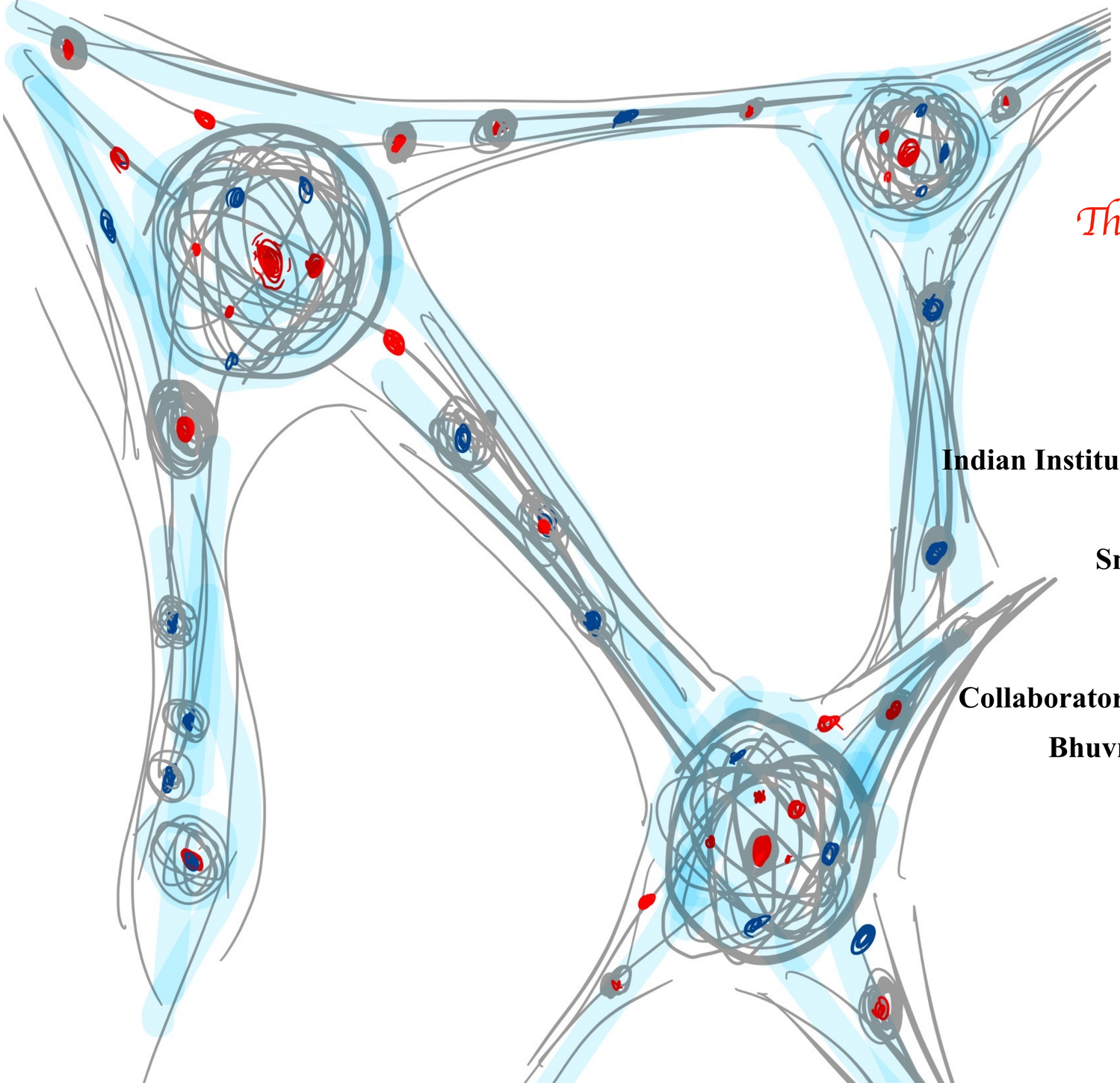


The mass and galaxy distribution in dark matter halos - Galaxy clusters

Susmita Adhikari

Indian Institute of Science Education and Research (IISER), Pune

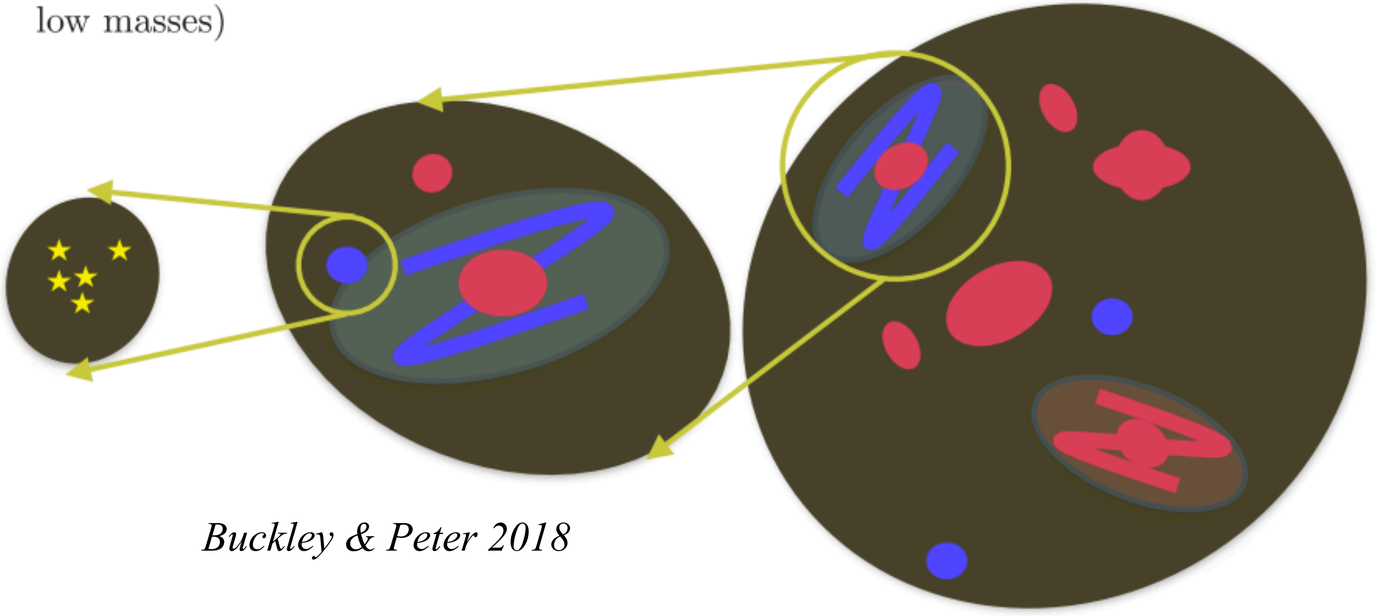
Small scale structure and SIDM, Valencia, June, 2025

Collaborators - Tae Hyeon Shin, Yiming Zhong, Arka Banerjee, Bhuvnesh Jain , Chihway Chang, Eric Baxter. and others

IISER PUNE

$z = 0$	**Dwarf**	**Galaxy**	**Cluster**
$M_{\rm vir}$ (central) :	$\sim 10^8 - 10^{11}\, M_\odot$	$\sim 10^{11} - 10^{14}\, M_\odot$	$\sim 10^{14} - 10^{15}\, M_\odot$
M_* (central) :	$\sim 10^2 - 10^9\, M_\odot$	$\sim 10^9 - 10^{11}\, M_\odot$	$\sim 10^{12}\, M_\odot$
M_* (total) :	$\sim 10^{-4}\, M_{\rm vir}$ (steeply falling at low masses)	$\sim 0.03\, M_{\rm vir}$	$\sim 0.01\, M_{\rm vir}$

← Dark



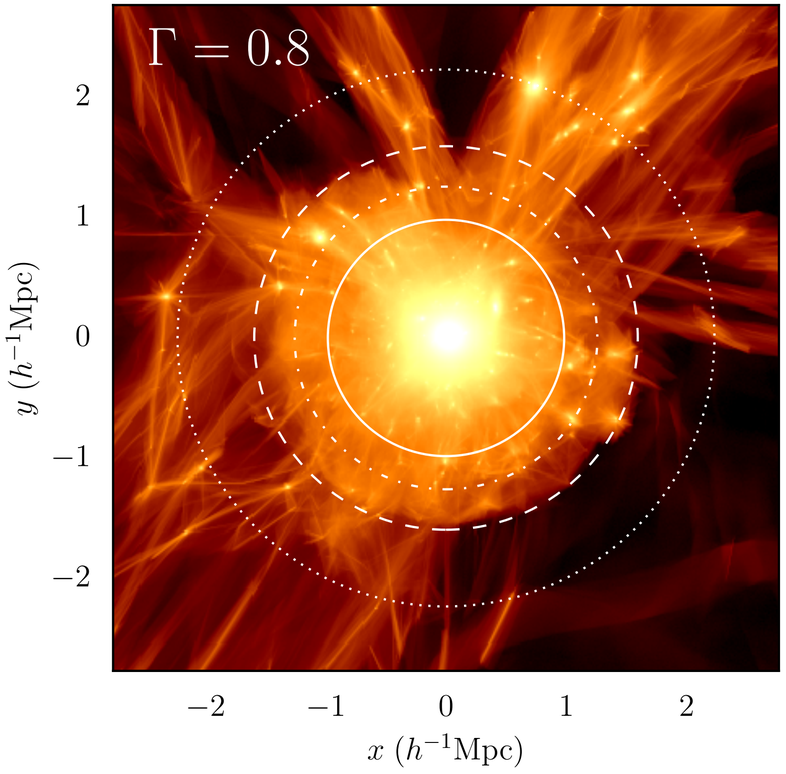
Buckley & Peter 2018

→ Nothing Larger Virialized

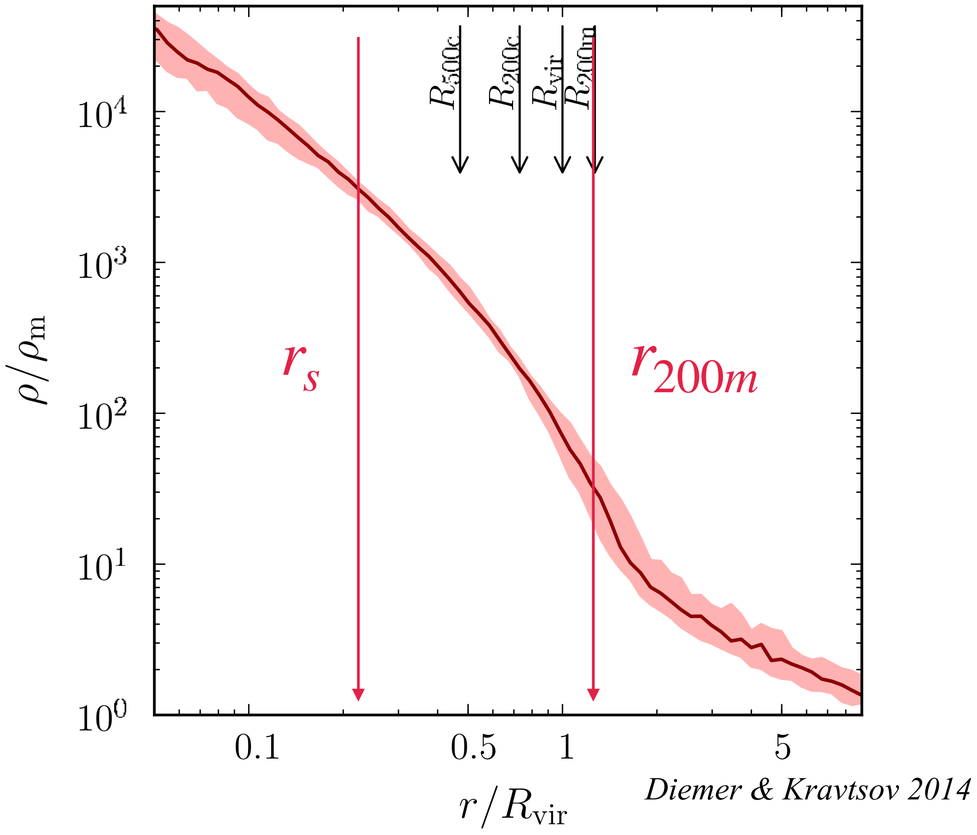
$v_{\rm vir} \sim M_{\rm vir}^{1/3}$:	$10 - 1000$ km/s	$100 - 1000$ km/s	$1000 - 2000$ km/s
$R_{\rm vir} \sim M_{\rm vir}^{1/3}$:	$10 - 100$ kpc	$100 - 1000$ kpc	$1 - 2$ Mpc
$R_* \sim 0.02 R_{\rm vir}$:	$\sim 0.1 - 1$ kpc	$\sim 1 - 10$ kpc	~ 20 kpc
$k_{\rm hm} \sim M_{\rm vir}^{-1/3}$:	$\sim 4 - 40$ Mpc^{-1}	$\sim 0.4 - 4$ Mpc^{-1}	$\sim 0.2 - 0.4$ Mpc^{-1}

Inner structure of dark matter halos and the halo boundary

Galaxy clusters we can probe a large range of scales that are important for different physical effects

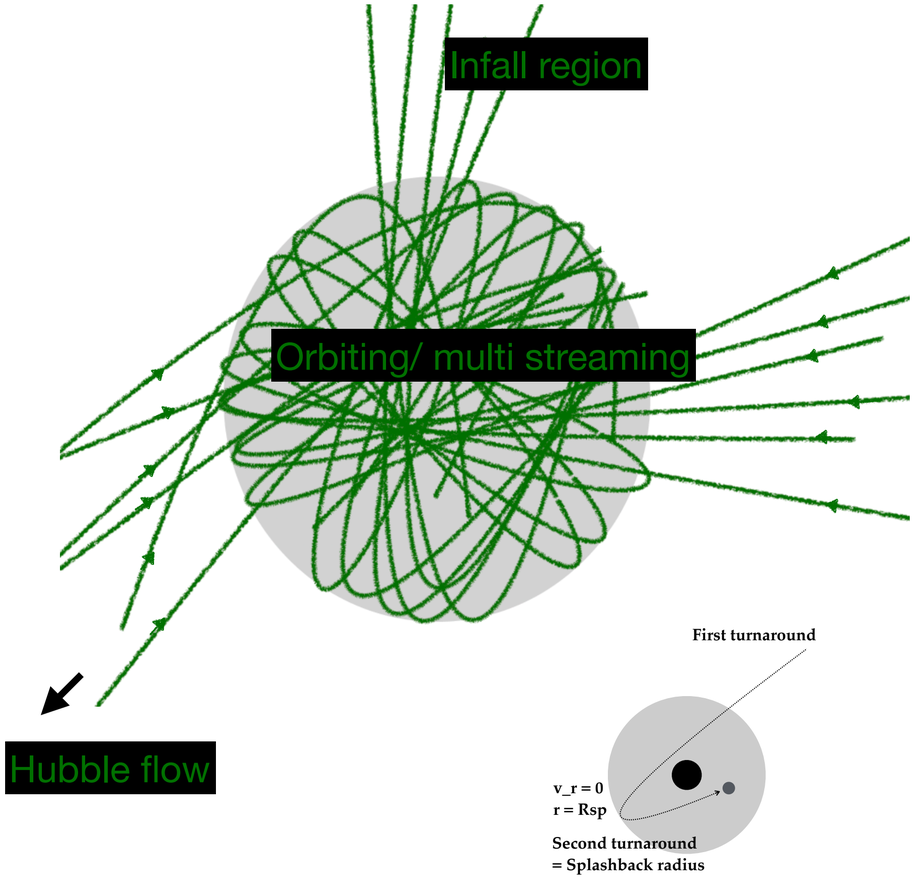


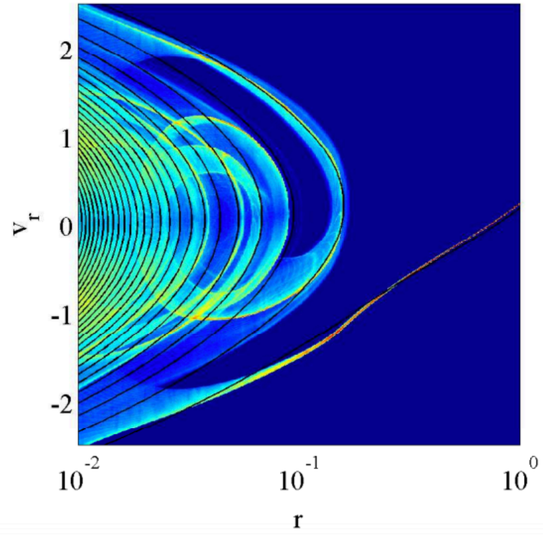
More et al. 2015



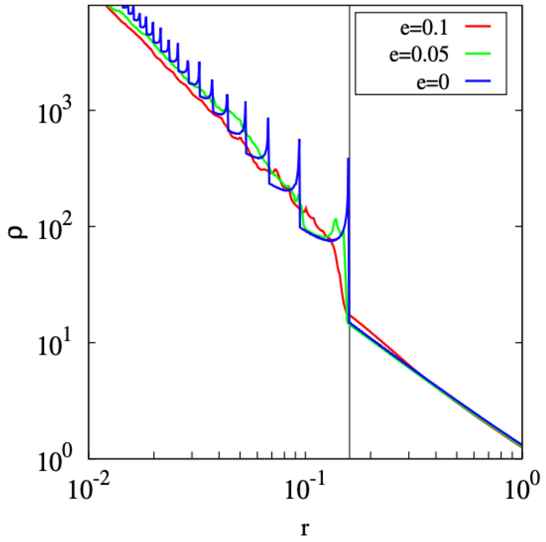
Diemer & Kravtsov 2014

Internal structure of the dark matter halo can be significantly informative





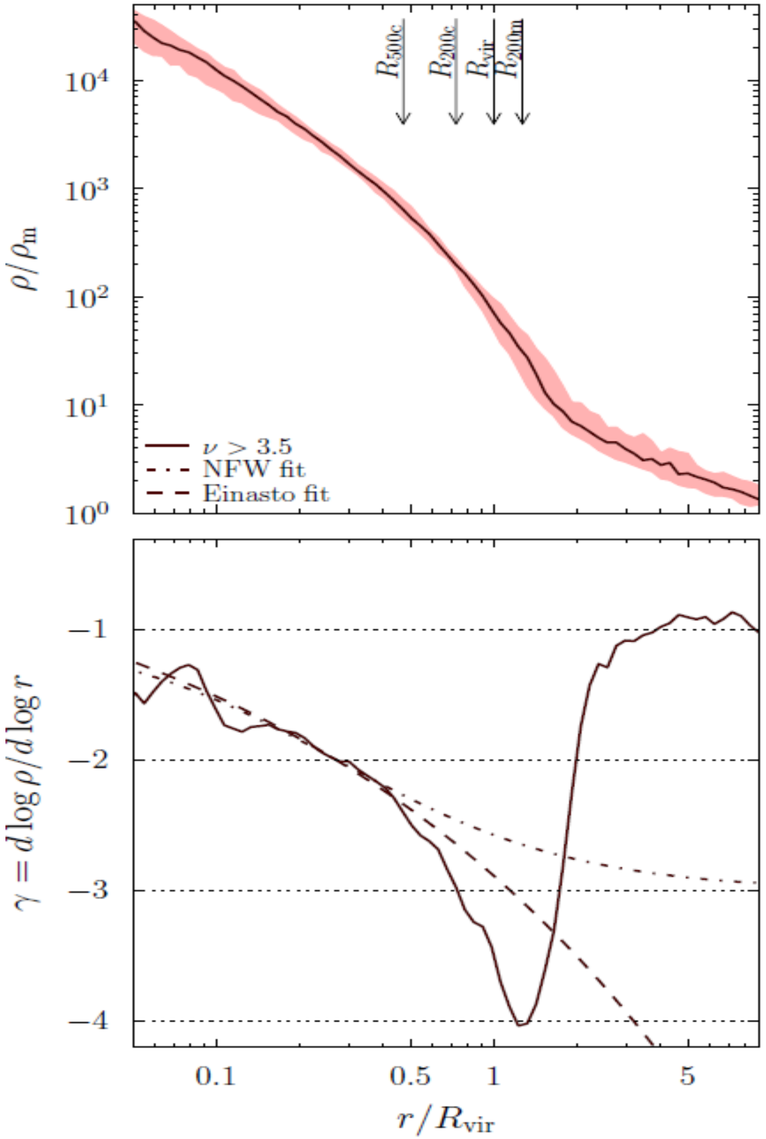
Phase space of a halo
In idealised self-similar simulations



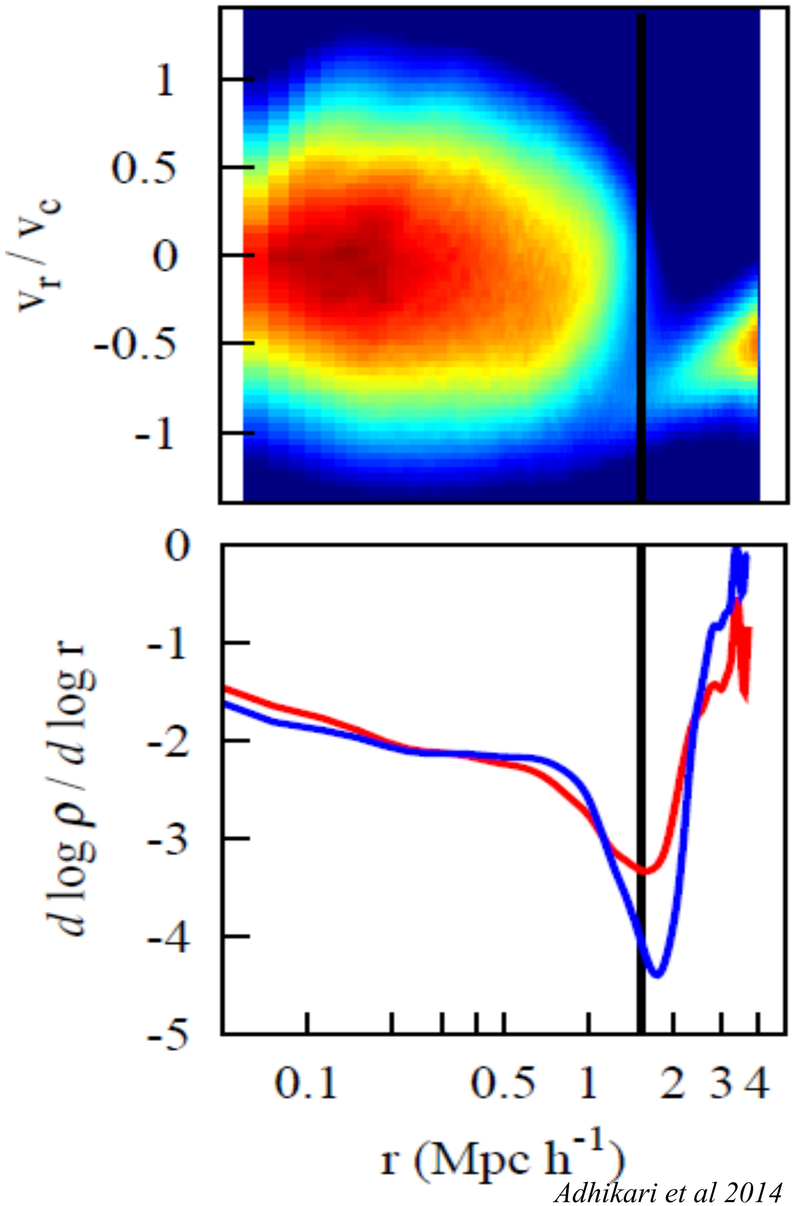
Density around a halo

Adhikari et al 2014

Outer density profiles of Dark Matter Halos

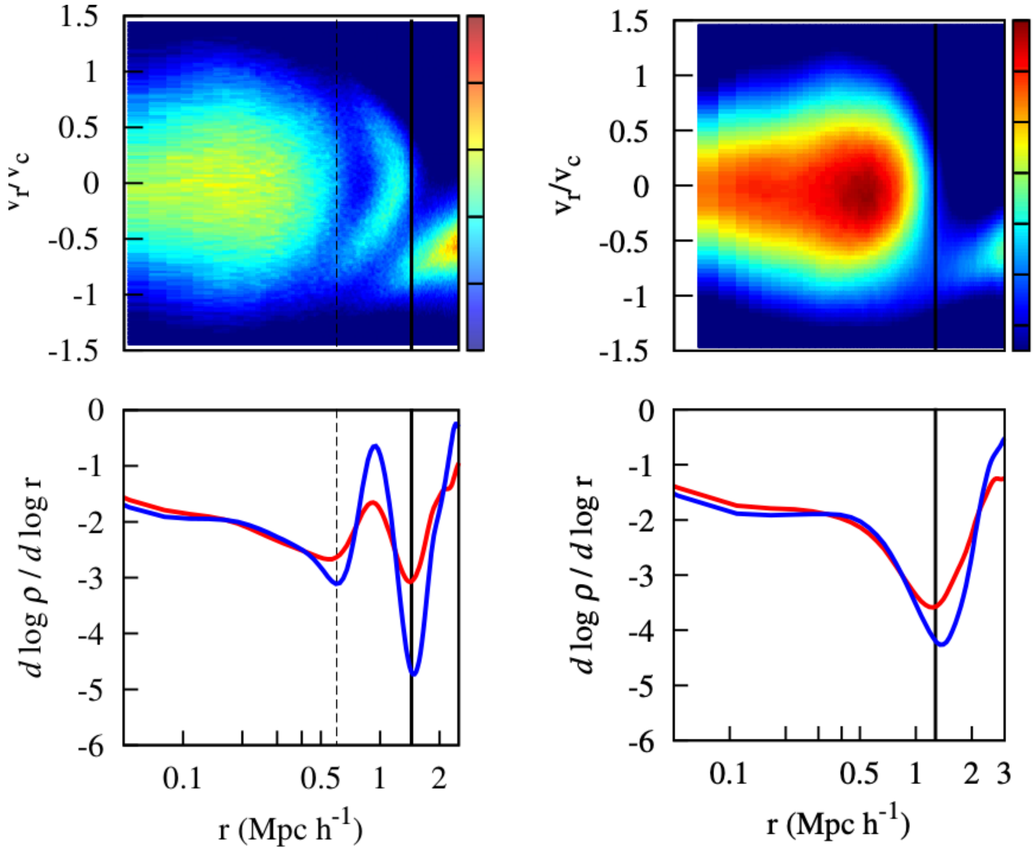


Diemer & Kravtsov 2014



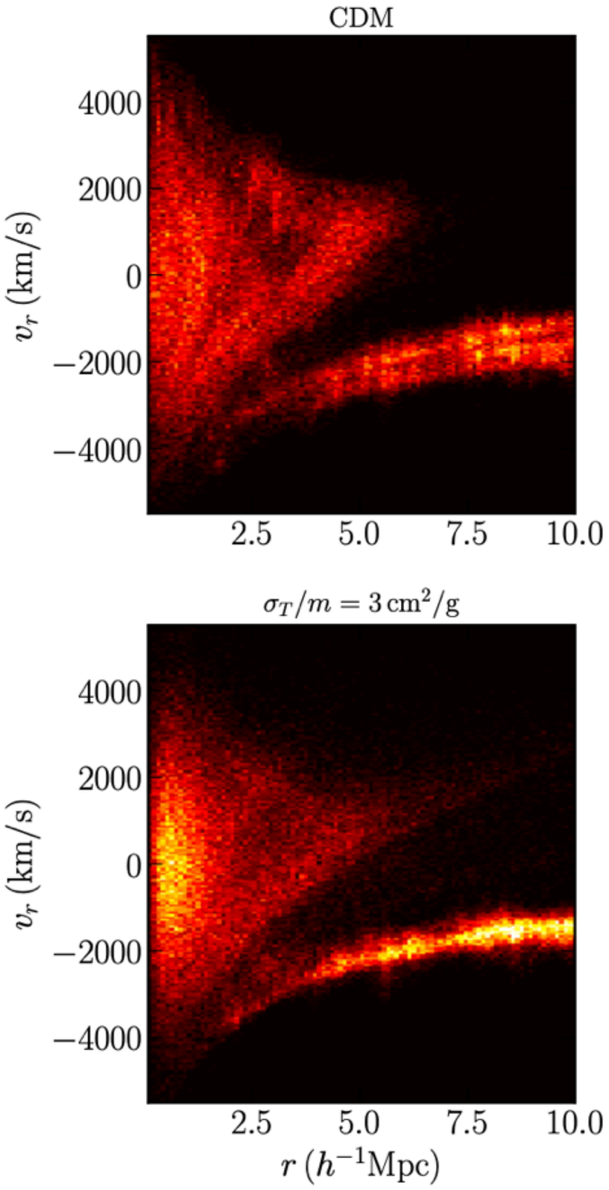
Adhikari et al 2014

Why the internal structure may be of interest?



Adhikari et al 2014

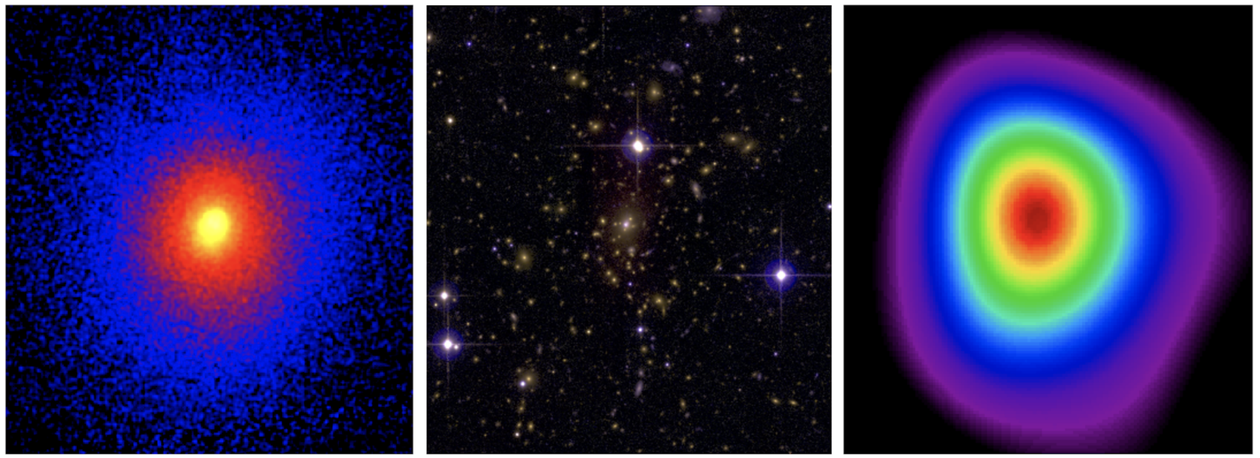
Encodes information of history



Properties of dark matter

Banerjee et al (incl. SA) 2019

Observing the mass and light distributions around galaxy clusters



X-ray Optical tSZ

Allen et al 2011

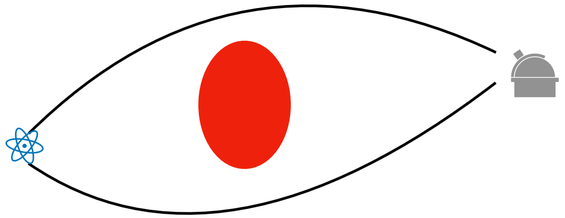
Observations of Galaxy clusters

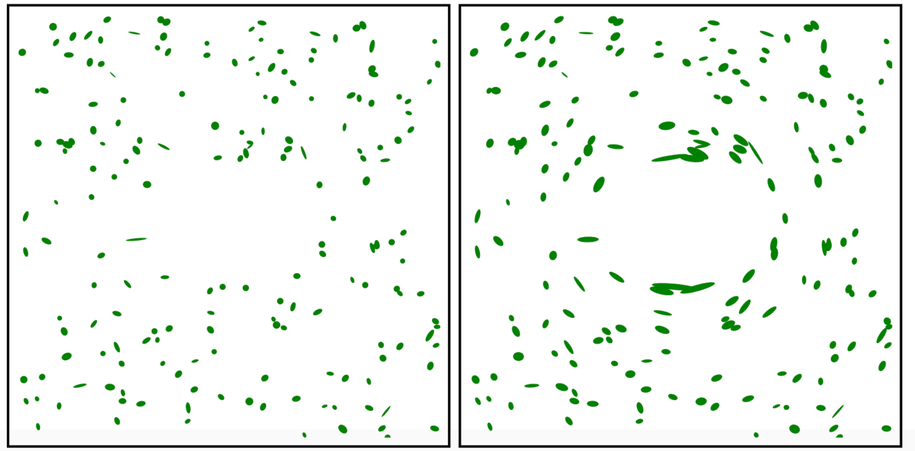
Distribution of Galaxies

Abell 2218

Study the distribution of galaxies that trace the potential of the parent dark matter halos

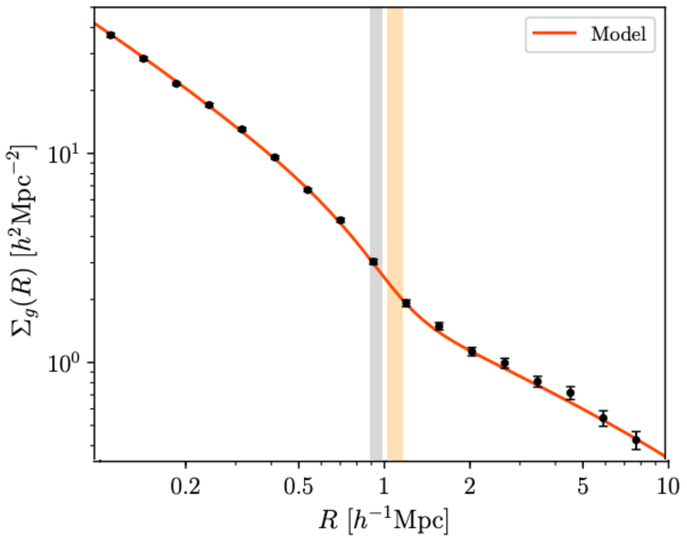
Lensing of background galaxies





Study the distortion of background galaxies due to massive halo in the line of sight

How do we model the distributions (galaxy distribute or lensing)?



Chang et al. (incl. SA) 2017

$$
\begin{aligned}
\rho(r) &= \rho^{\rm coll}(r) + \rho^{\rm infall}(r), \\
\rho^{\rm coll}(r) &= \rho^{\rm Ein}(r) f_{\rm trans}(r) \\
\rho^{\rm Ein}(r) &= \rho_s \exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right) \\
f_{\rm trans}(r) &= \left[1 + \left(\frac{r}{r_t}\right)^{\beta}\right]^{-\gamma/\beta}, \\
\rho^{\rm infall}(r) &= \rho_0 \left(\frac{r}{r_0}\right)^{-s_e},
\end{aligned}
$$

Diemer & Kravtsov 2014

$$\Sigma_g(R) = \int_{-h_{\rm max}}^{h_{\rm max}} dh\, \rho_g(\sqrt{R^2 + h^2})$$

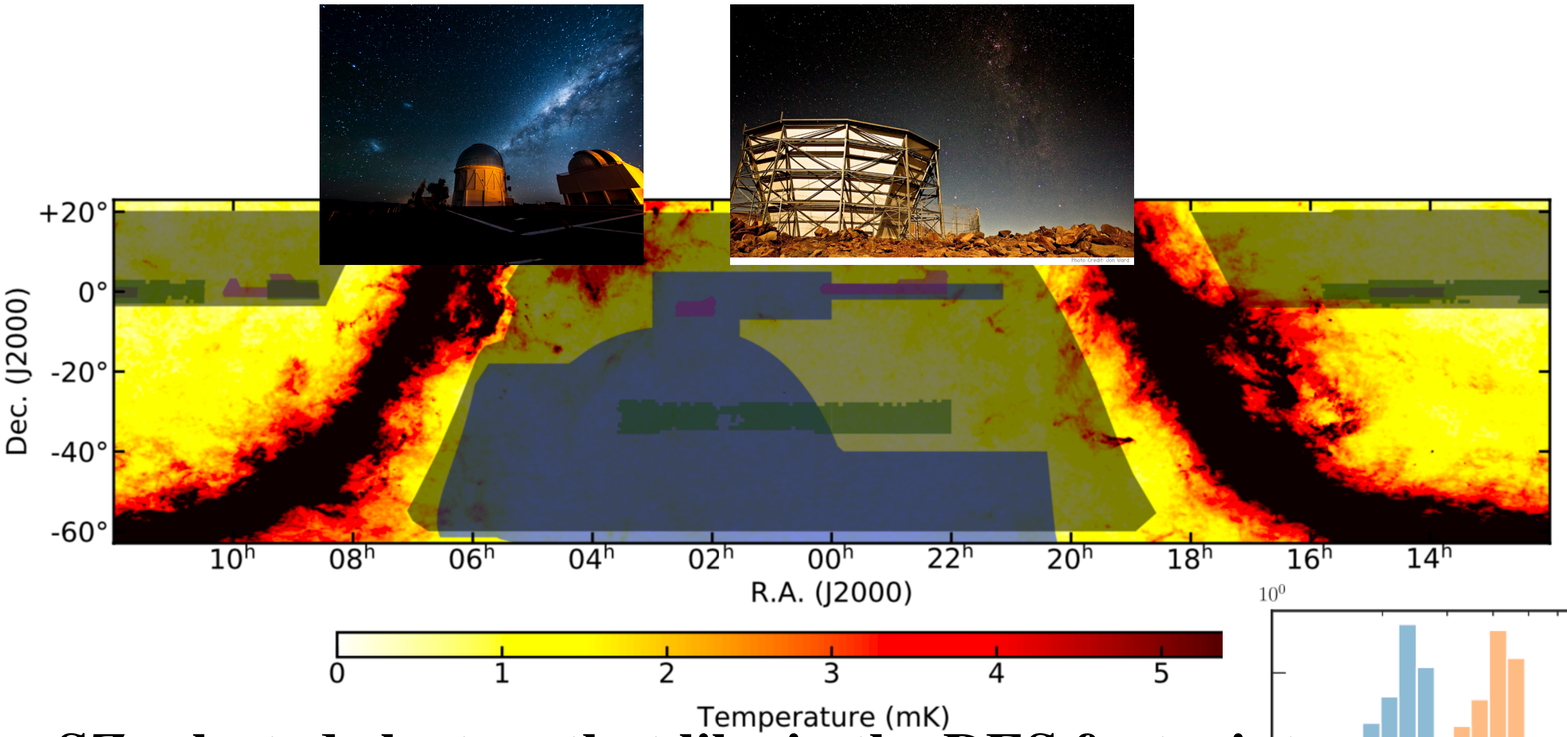
Projected galaxy density

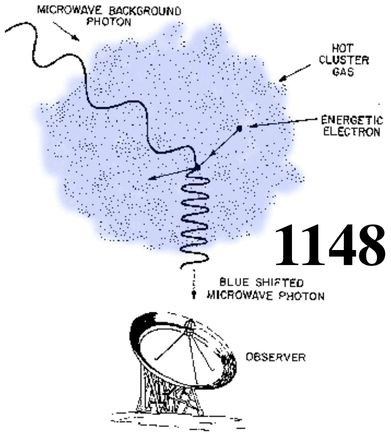
$$\Delta\Sigma = \Sigma(<R) - \Sigma(R)$$

Lensing signal- excess surface density

Observing the mass and light distributions around galaxy clusters

Shin et al. 2021



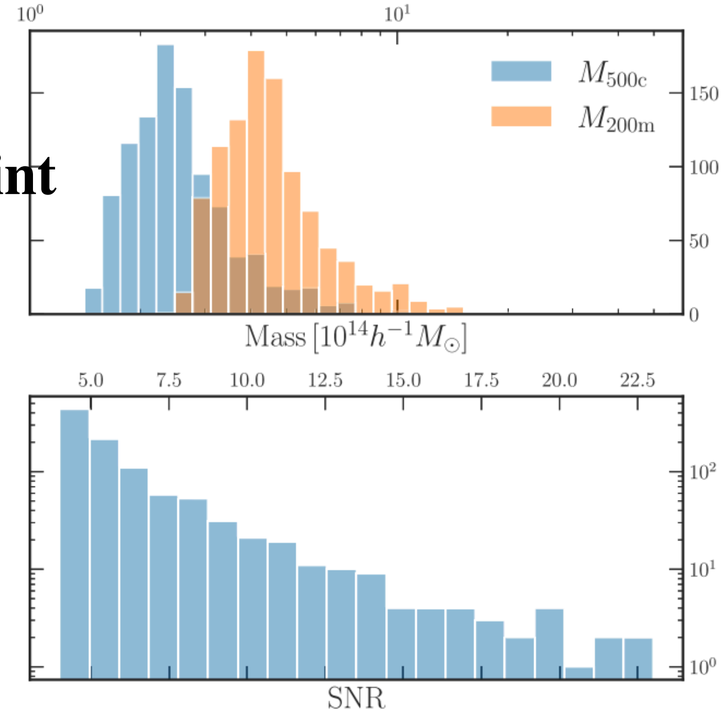


1148 clusters SZ selected clusters that like in the DES footprint

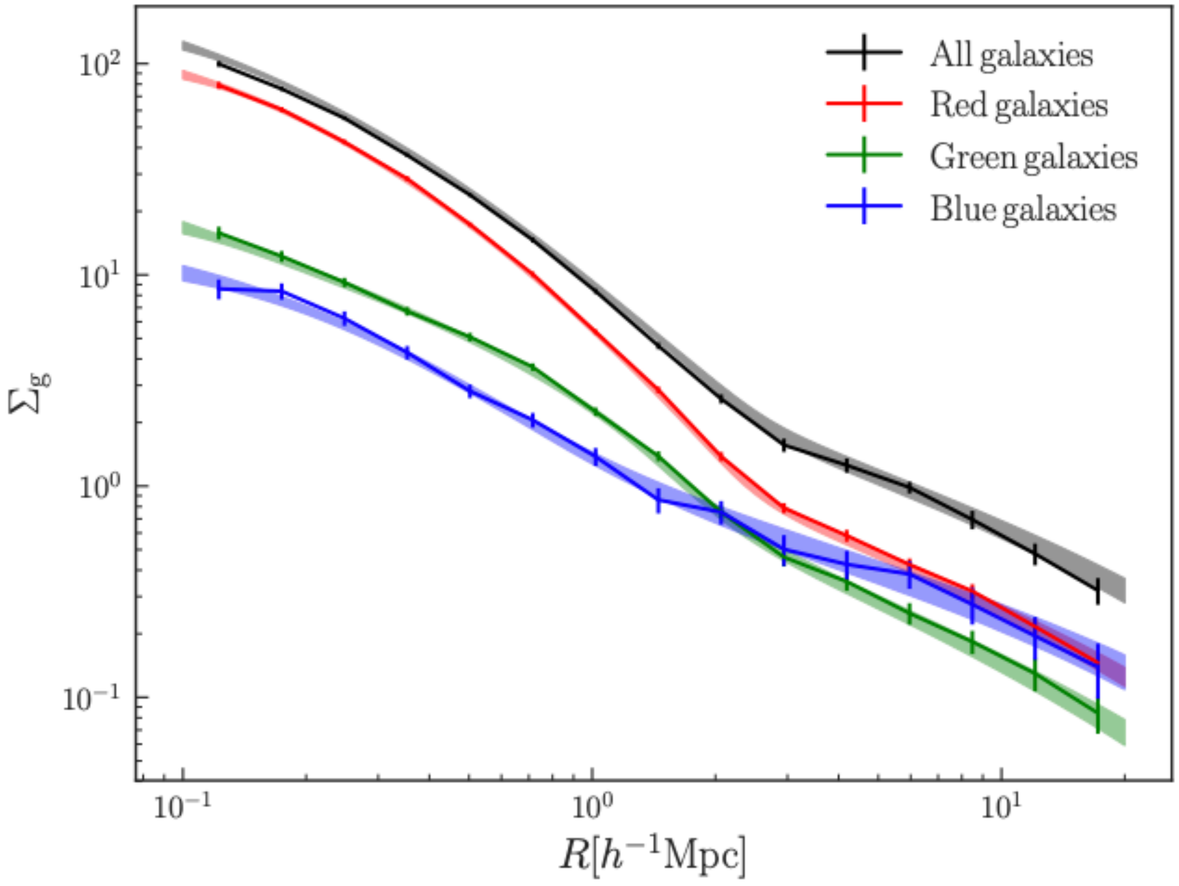
SNR > 4

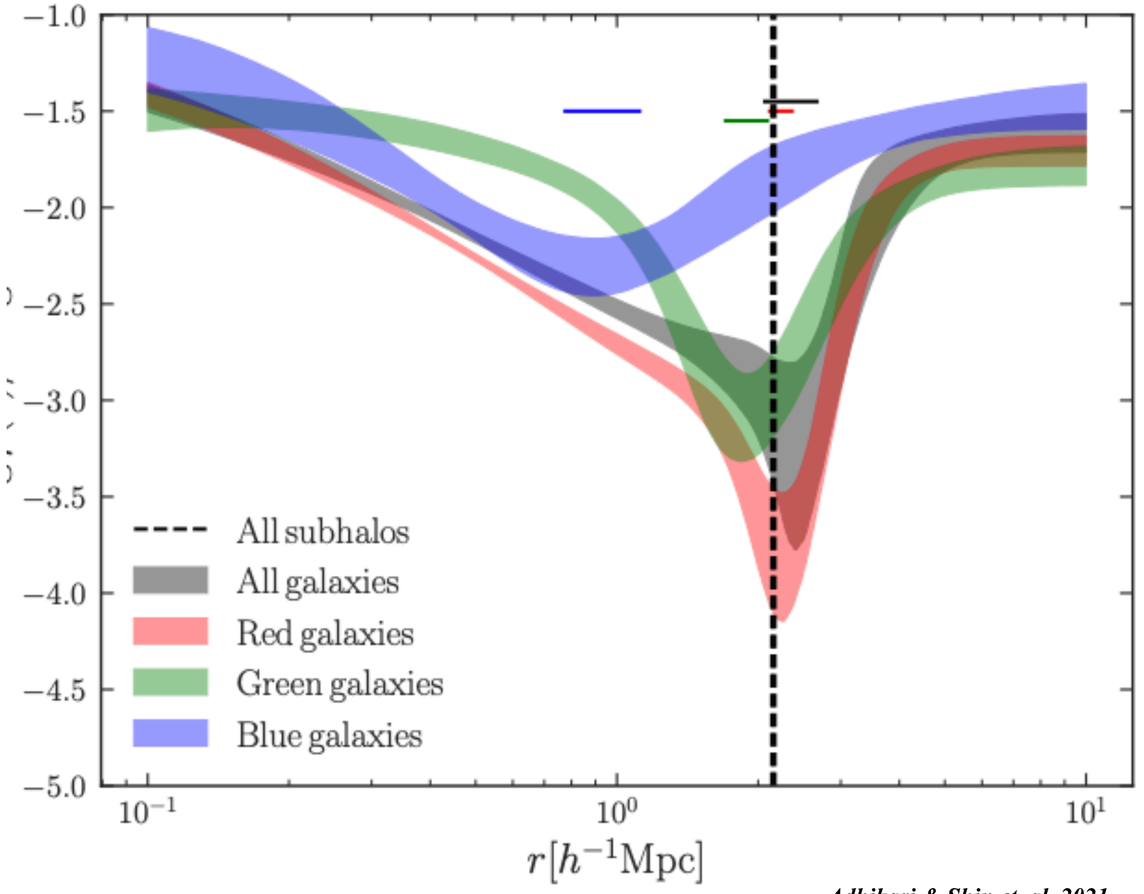
$0.15 < z < 0.7$

$\langle M_{500c} \rangle > 2.72 \times 10^{14} M_{\odot}/h$



The Distribution of galaxies inside galaxy clusters



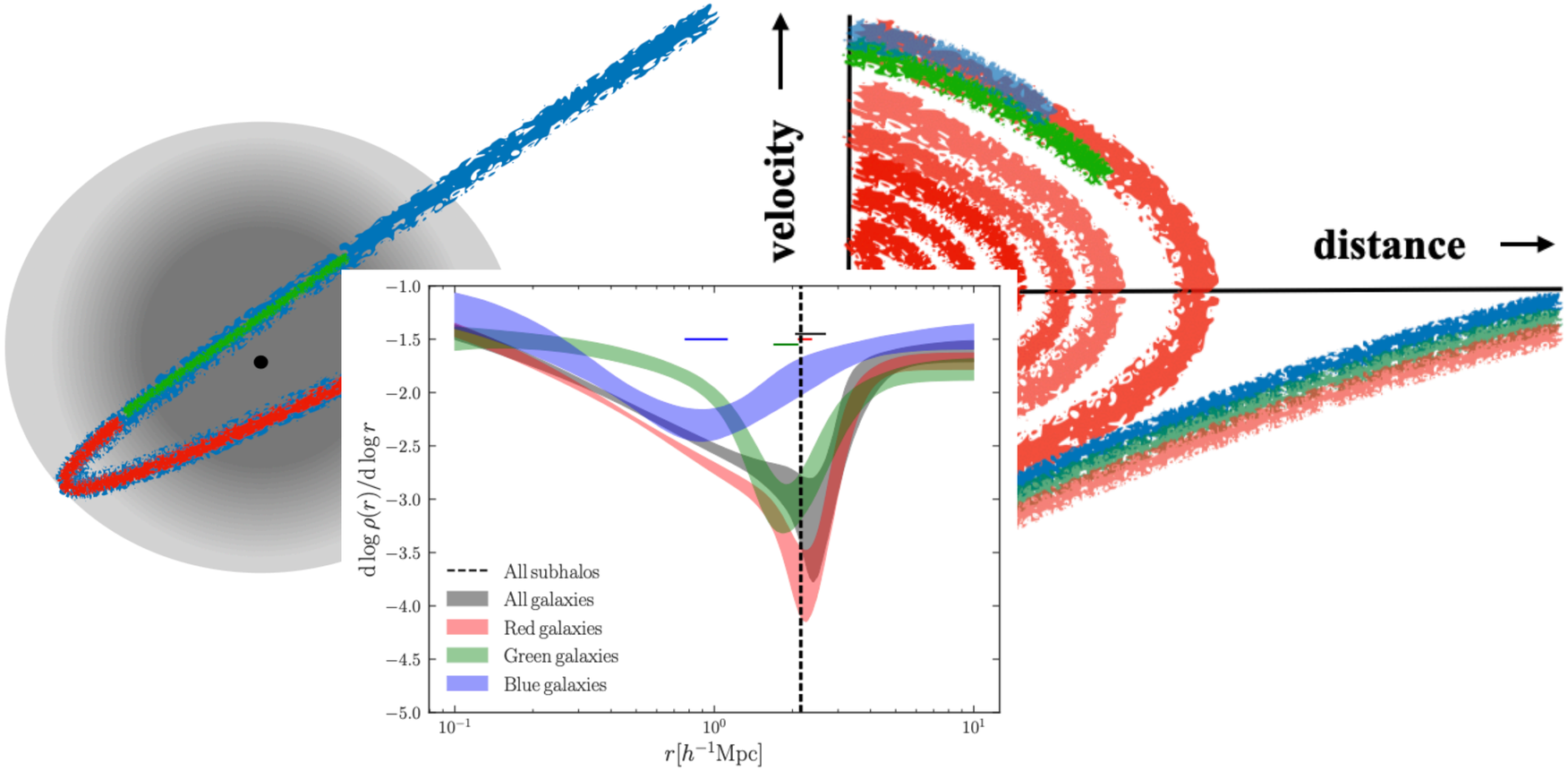


Adhikari & Shin et. al. 2021

The splashback radius as a clock in the halo

Galaxies stop forming stars with time as they fall into a halo

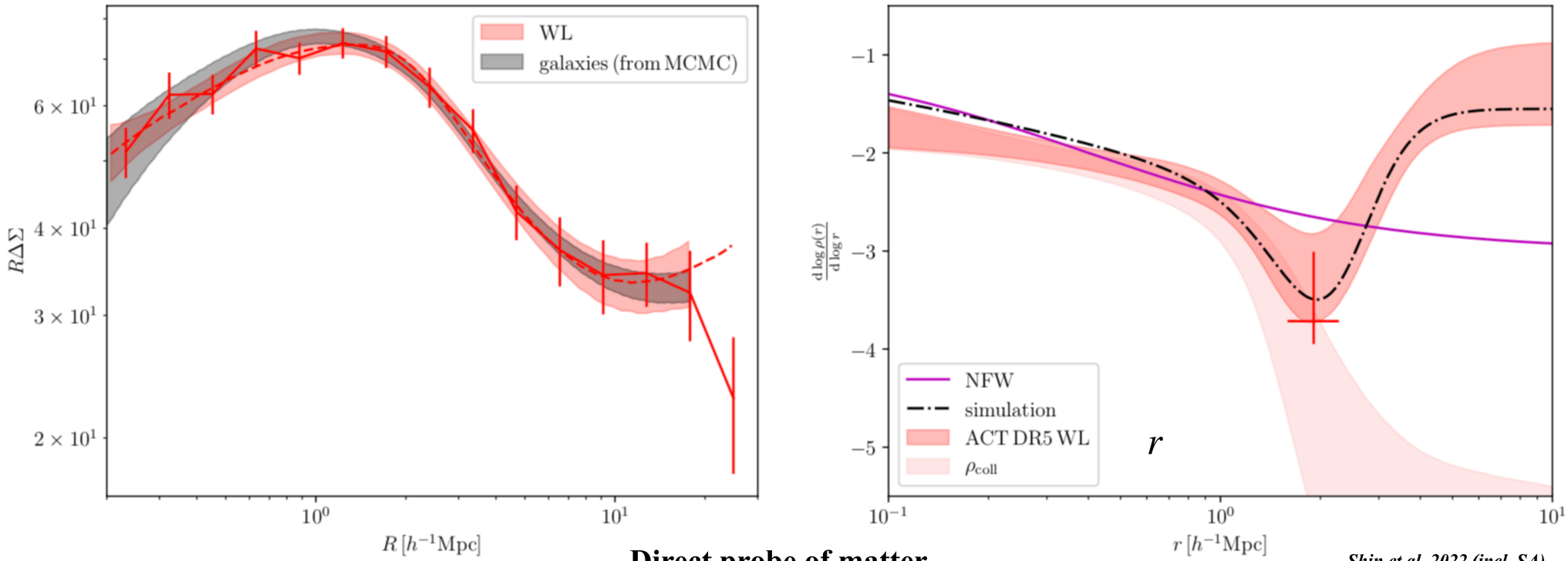
Blue star-forming galaxies turn into red and dead galaxies



Minimum traces the time spent in the cluster by a population of galaxies

Halo profile from weak Gravitational Lensing

Distribution of Dark Matter in galaxy clusters



Direct probe of matter

Shin et al. 2022 (incl. SA)

Lensing observable

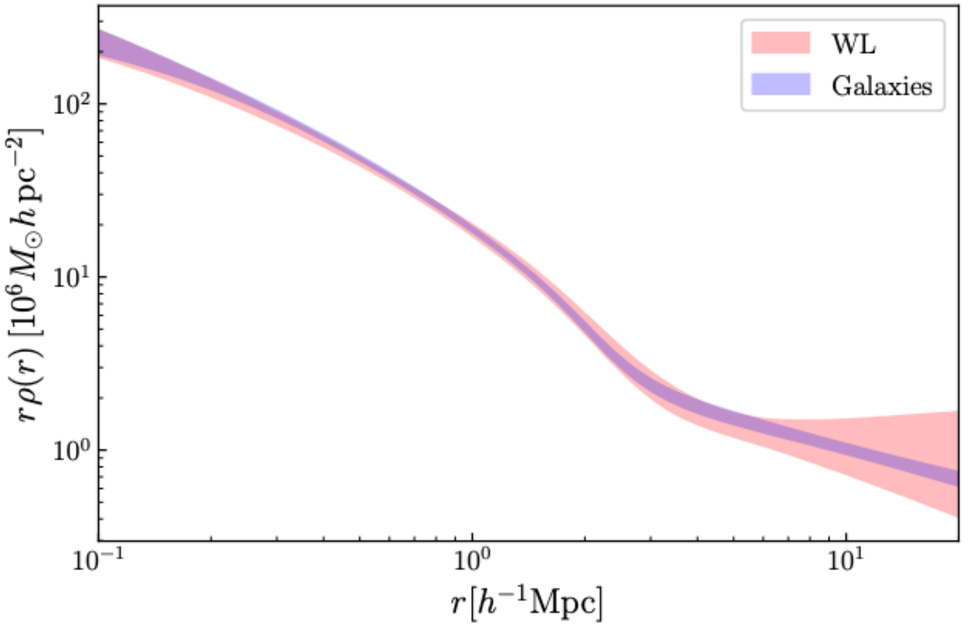
$$\Delta\Sigma(R) = \overline{\gamma_t}(R)\,\Sigma_{\mathrm{crit}}(z_\mathrm{l}, z_\mathrm{s}),$$

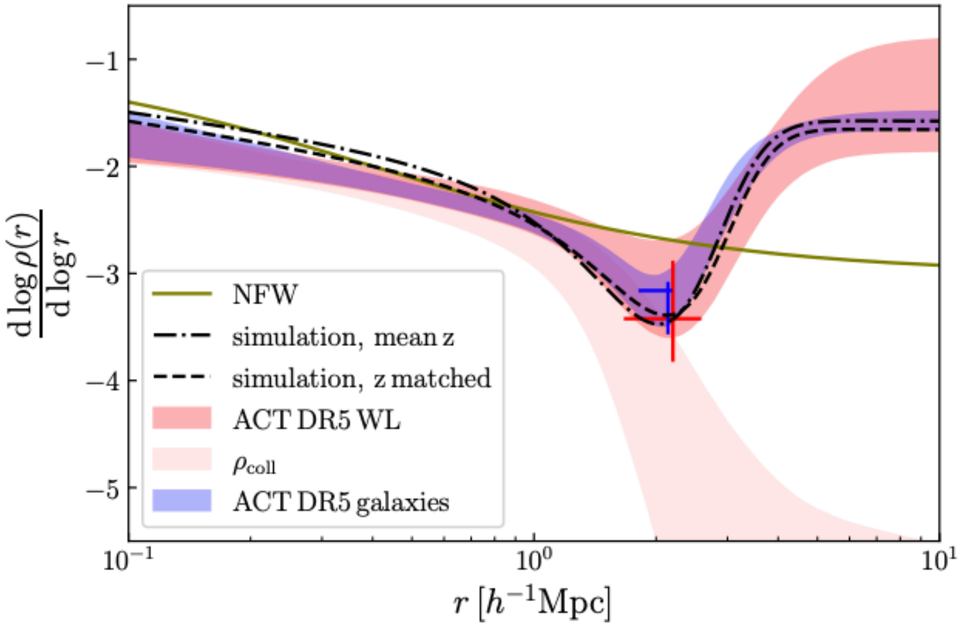
Tangential shear

$$\Delta\Sigma = \Sigma(<R) - \Sigma(R)$$

$$\Sigma(R) = 2\int_R^\infty \frac{\rho(R')R'}{\sqrt{R'^2 - R^2}}\mathrm{d}R'$$

The distribution of Dark Matter and Galaxies in clusters

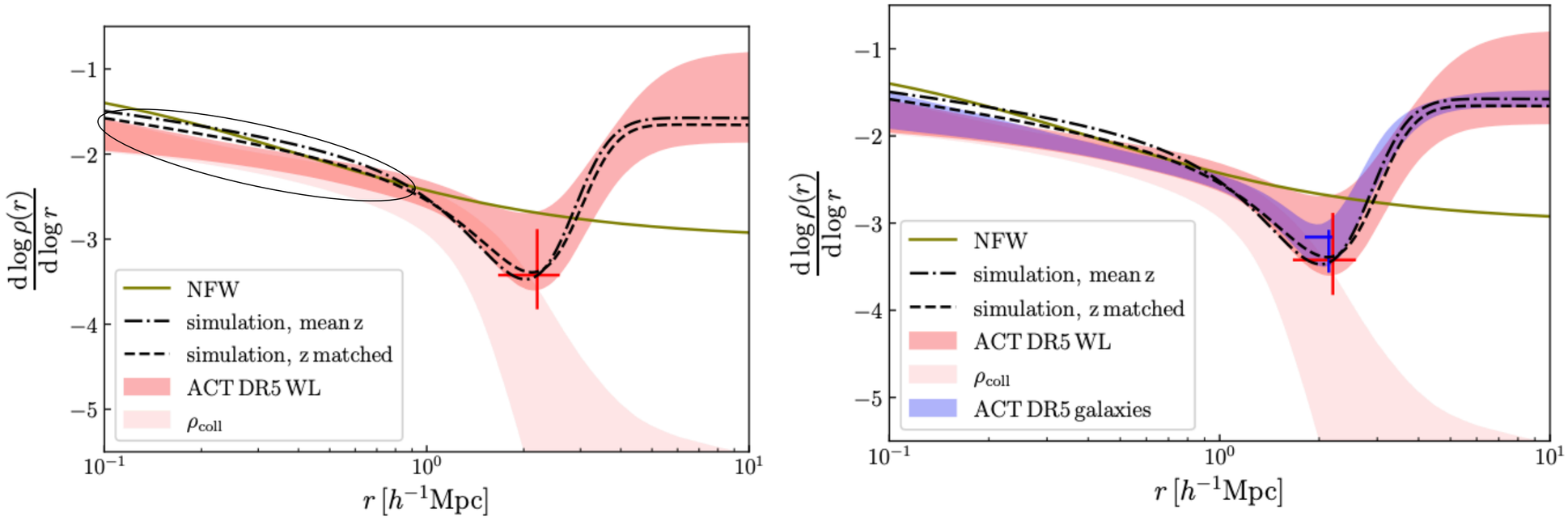




Shin et al. 2022 (+ SA)

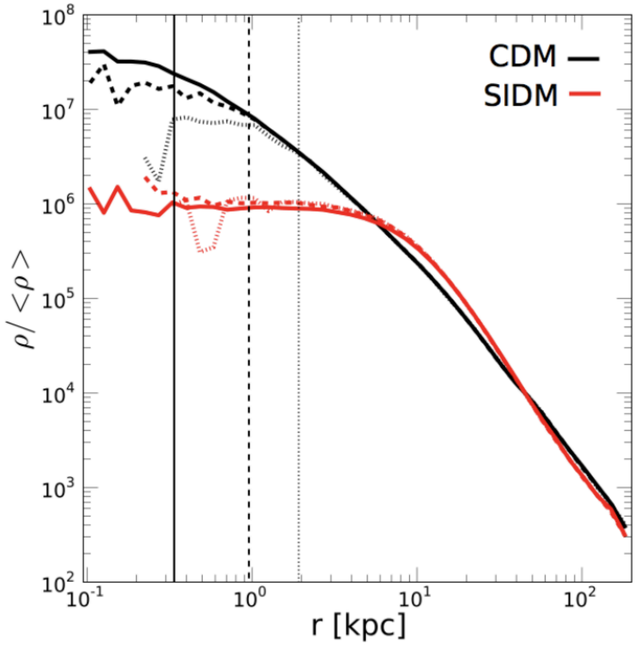
Galaxies and Dark Matter follow each other!

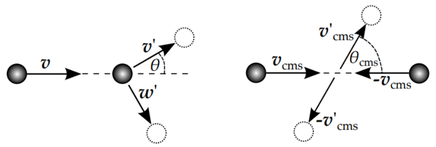
What does this tell us about dark matter?



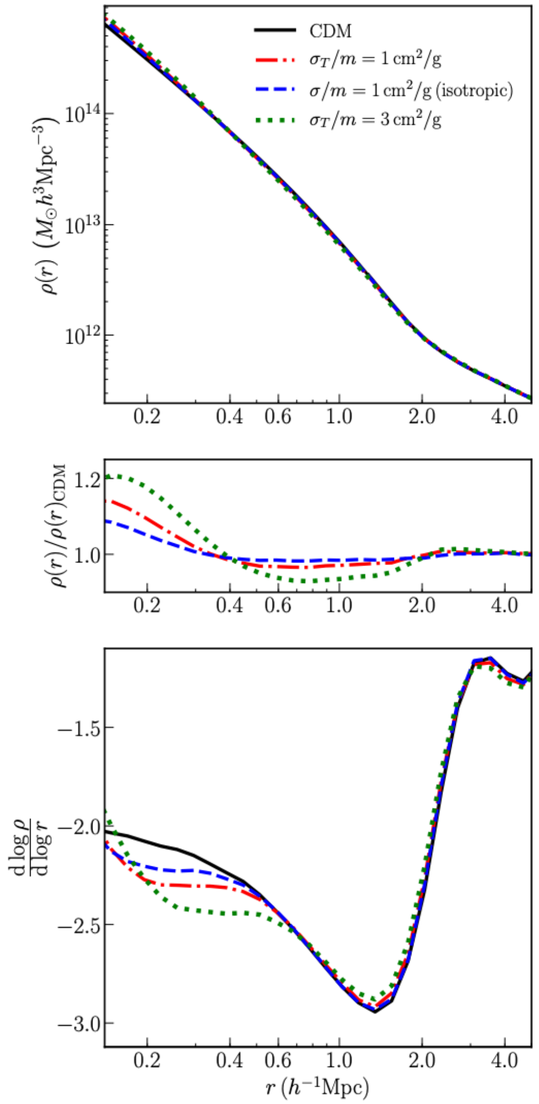
Shin et al. 2022 (incl. SA)

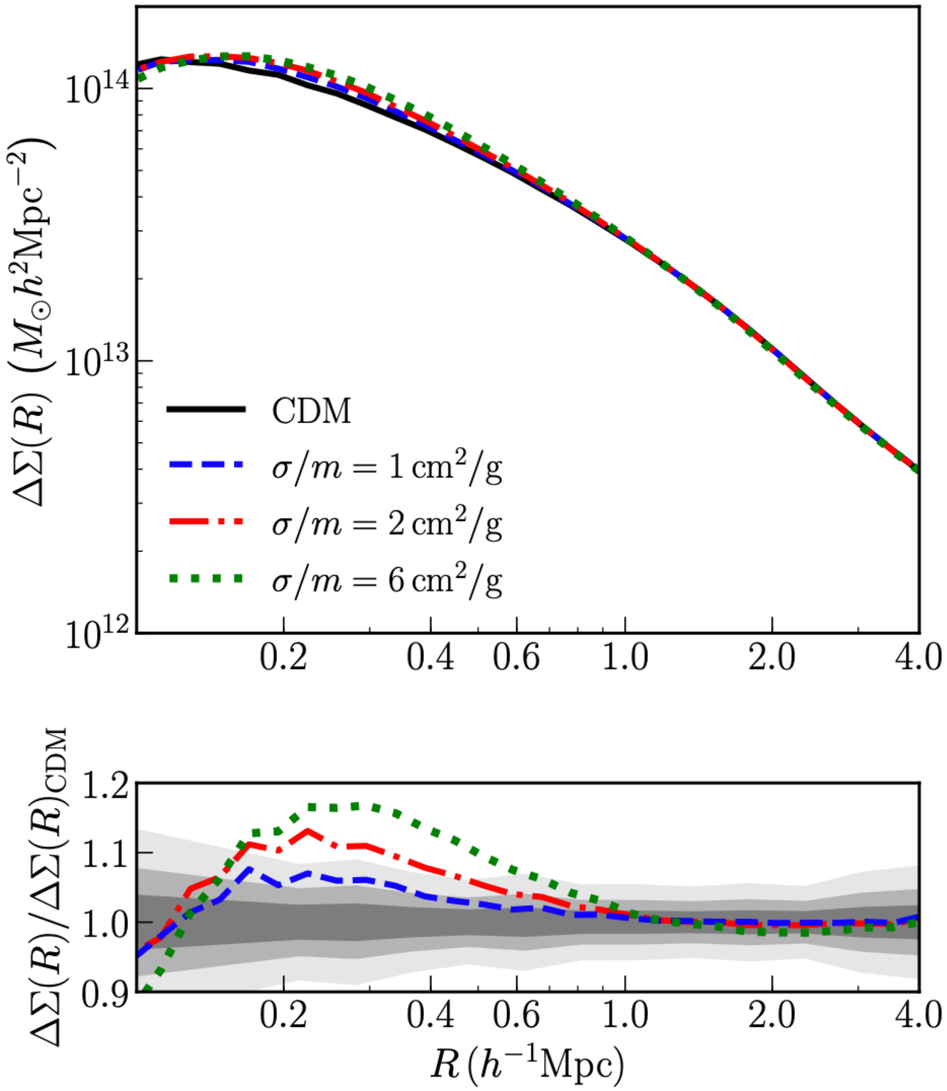
Can we use cluster profiles to constrain dark matter models?





Vogelsberger et al 2012



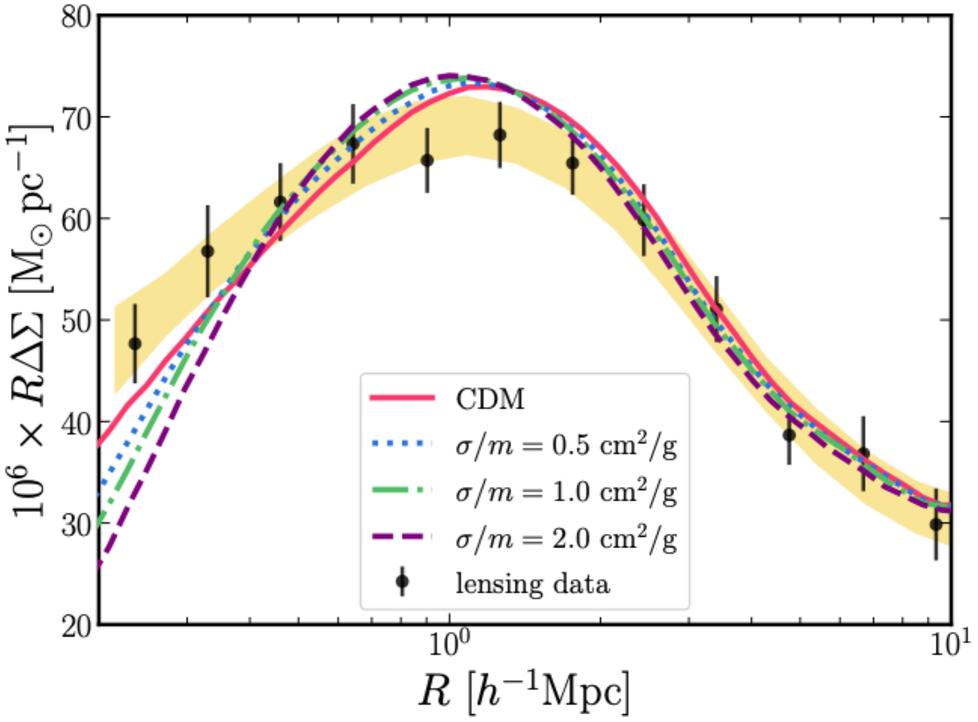


Banerjee et al. 2019 (incl. SA)

Constraining dark matter models with weak lensing profiles

With **Yiming Zhong**, Tae Hyeon-Shin, Arka Banerjee, Bhuvnesh Jain

Models with elastic scattering of self-interacting dark matter

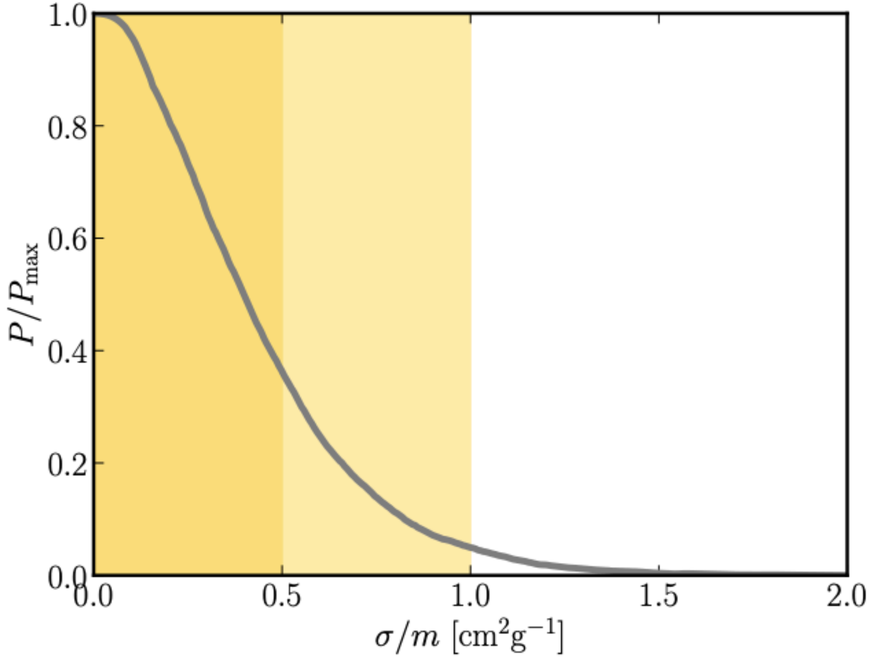


Adhikari, Zhong et al. 2023

Comparison of observed shape of the profile with different dark matter models

Current constraints on dark matter models

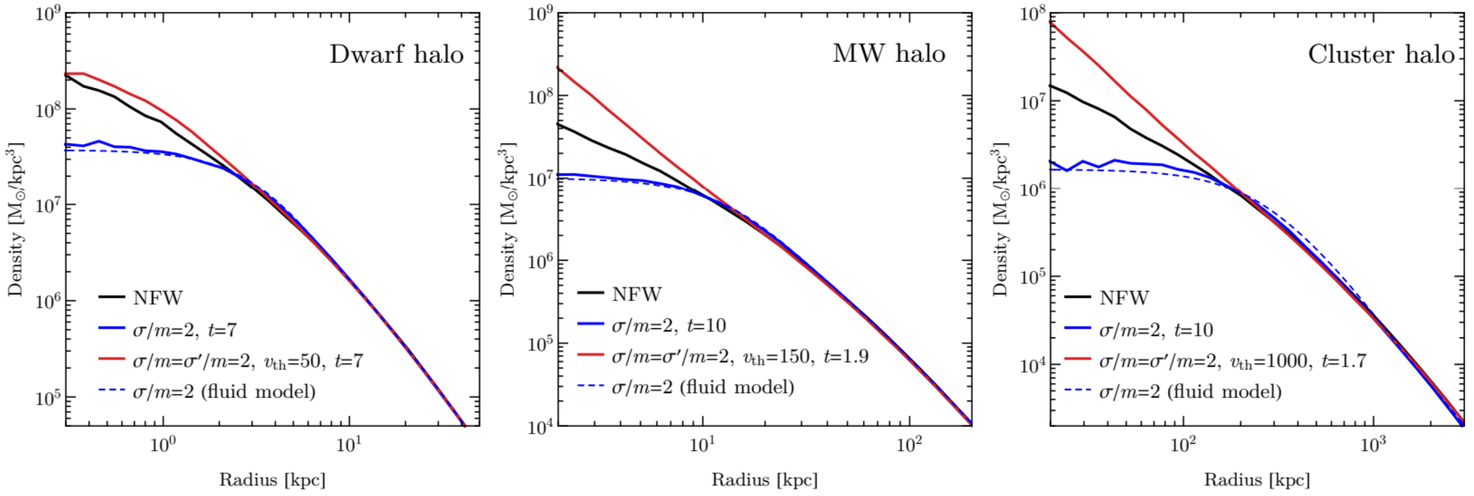
In the pure elastic scattering case the constraints from weak leansing are consistent with the Bullet cluster constraints



$$\sigma/m < 0.5\ (1.0)\ \mathrm{cm}^2/\mathrm{g}$$

At 68% (95 %)confidence

The evolution of halos in Dissipative dark matter models



Huo et al. 2020

σ/m Elastic cross-section

σ'/m Dissipative cross-section

loss or $E_{\rm loss}$ Energy loss per scattering

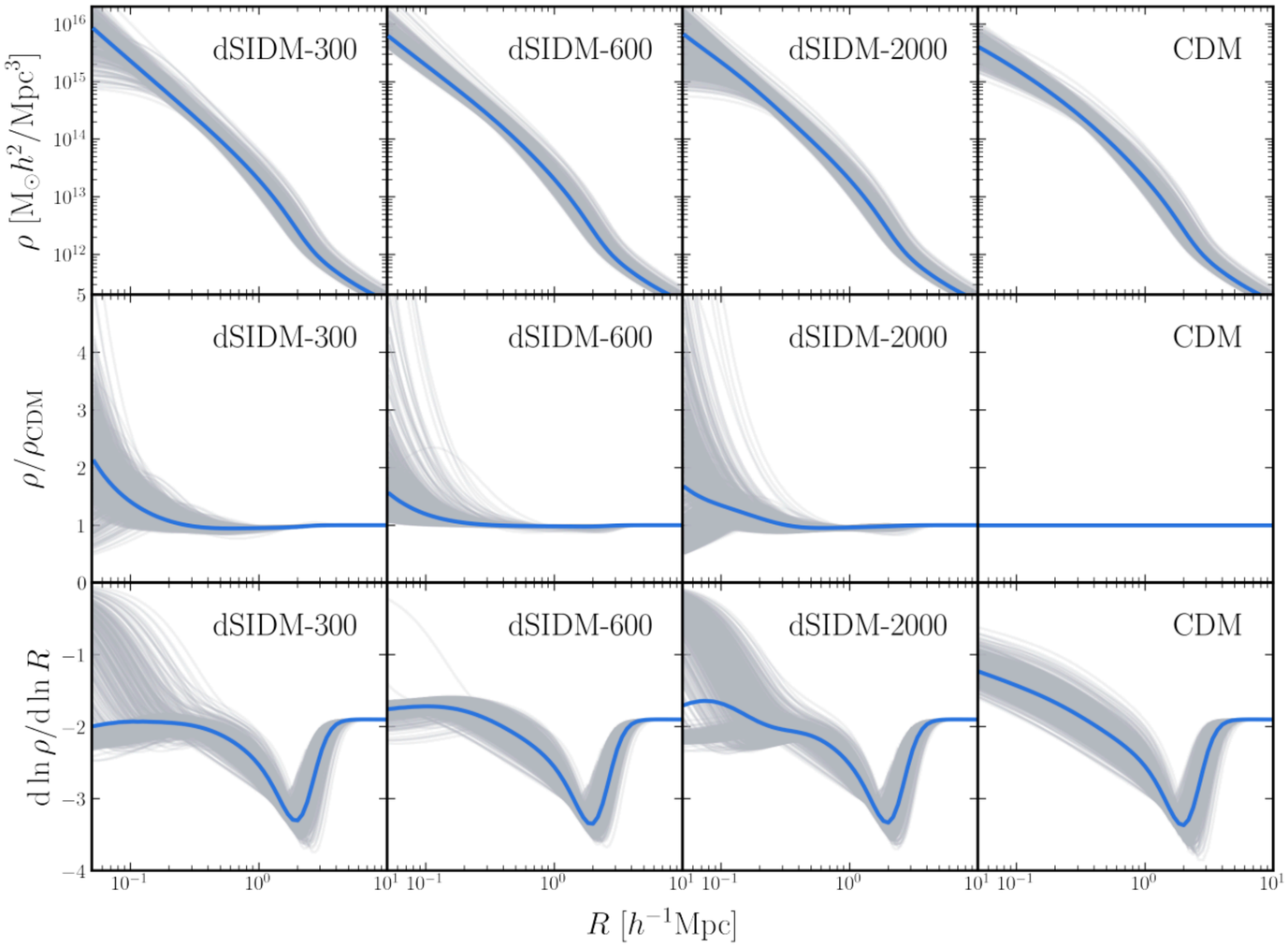
$\chi\chi \rightarrow \chi\chi$ $\chi\chi \rightarrow \chi'\chi'$

χ and χ' have a small mass splitting

Core collapse on cluster scales?

Net bulk cooling that leads to collapsed cores

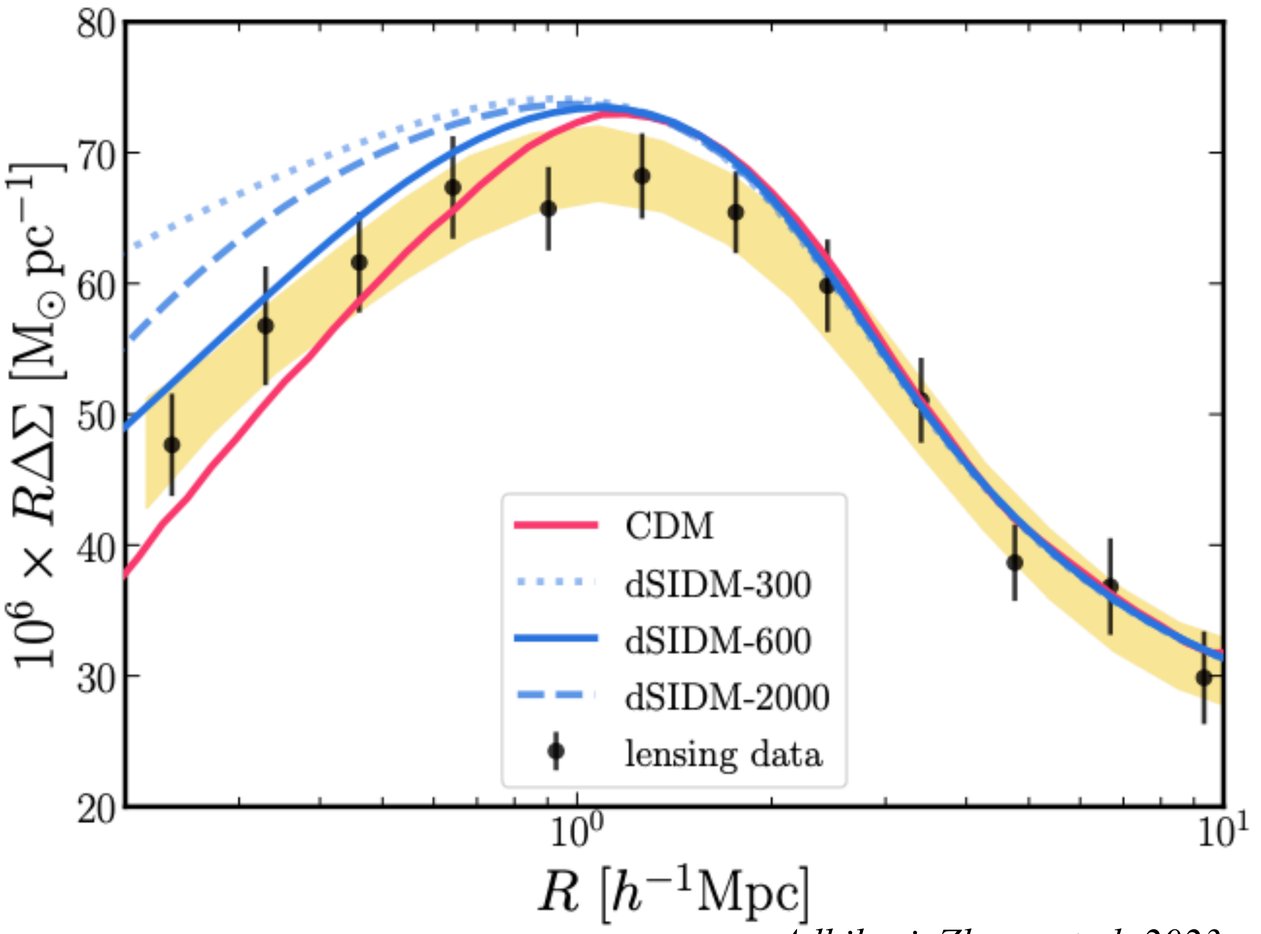
Comparison to observation



Adhikari, Zhong et al. 2023

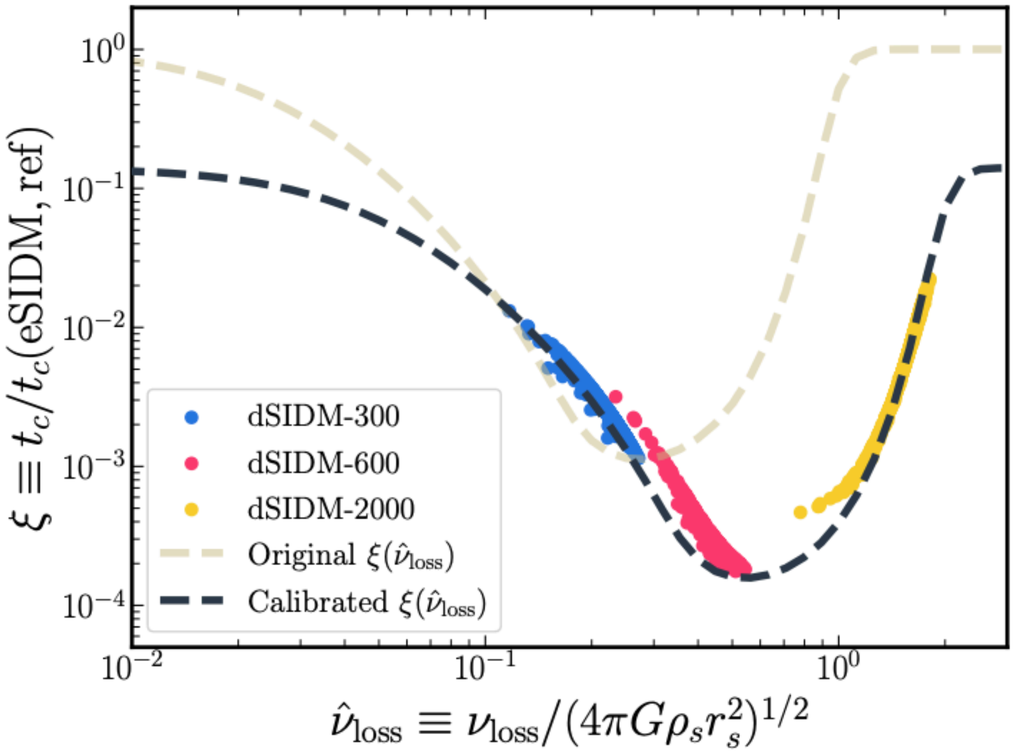
- Forward model mass distribution
- Pick concentration distribution
- Pick DK14 profiles for concentration distribution
- Evolve the inner halo term that is ‘orbiting’/‘virialized’ (ignore infall)

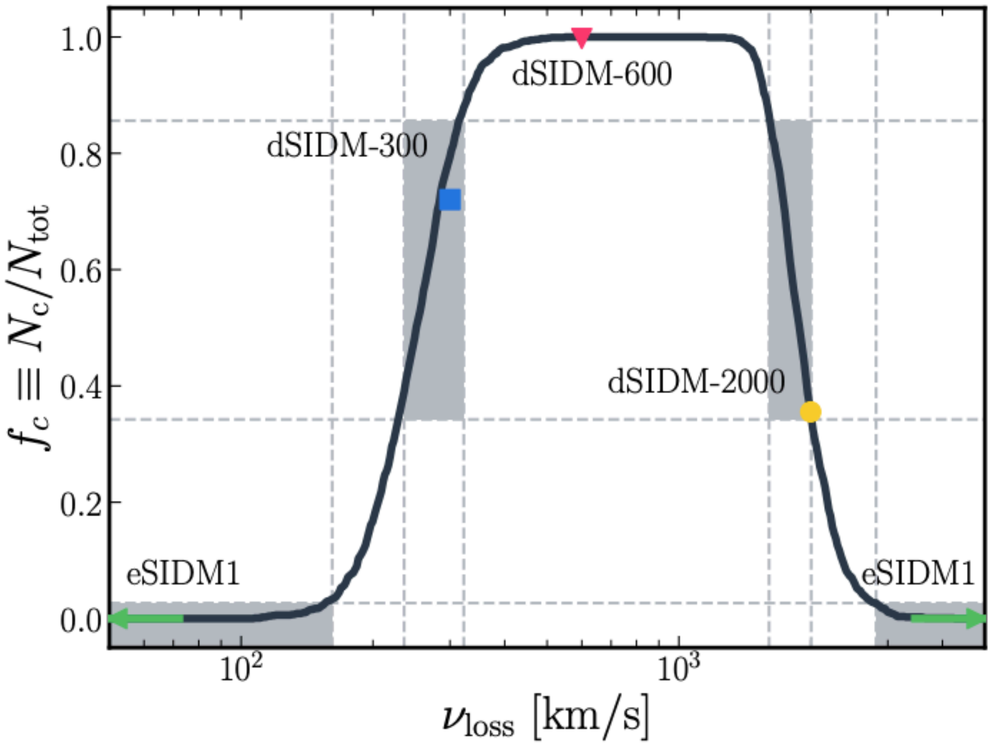
Constraining dark matter models with weak lensing profiles



Adhikari, Zhong et al. 2023

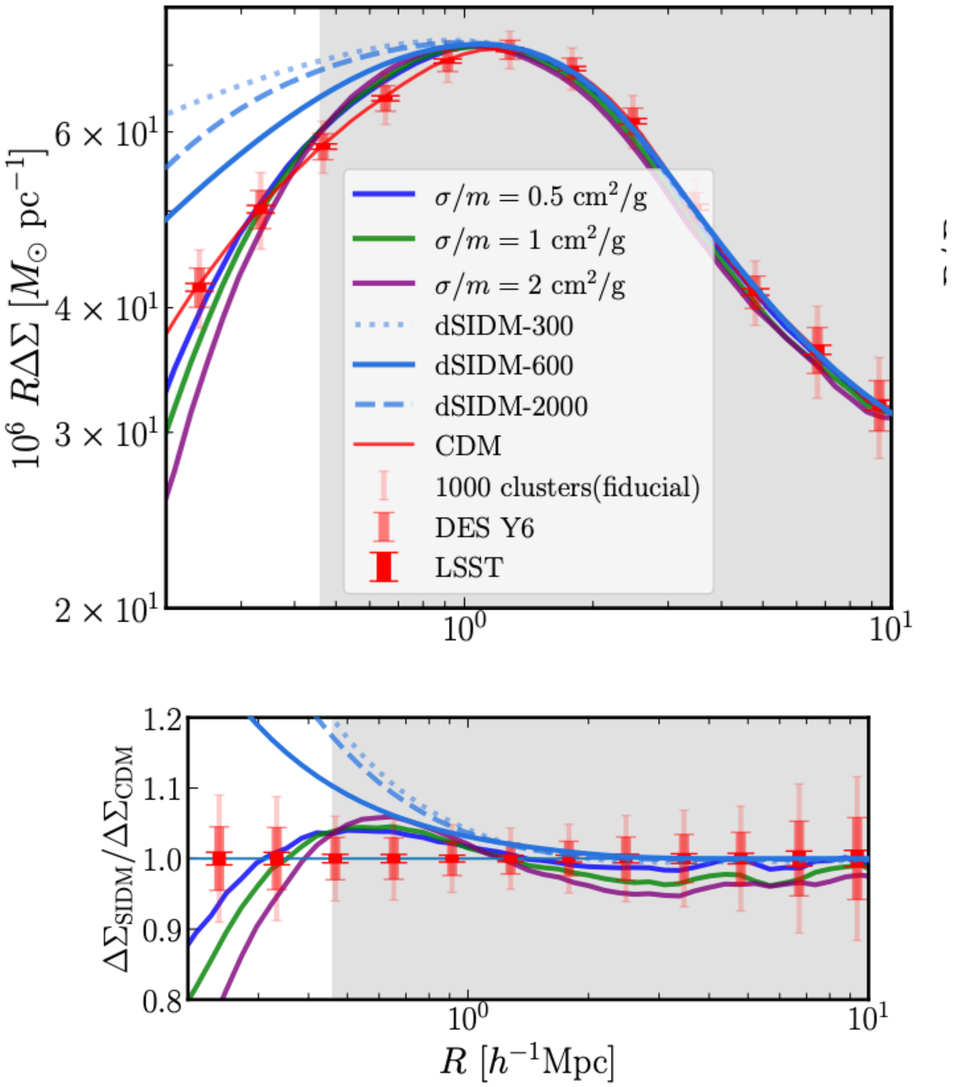
Current constraints on dark matter models



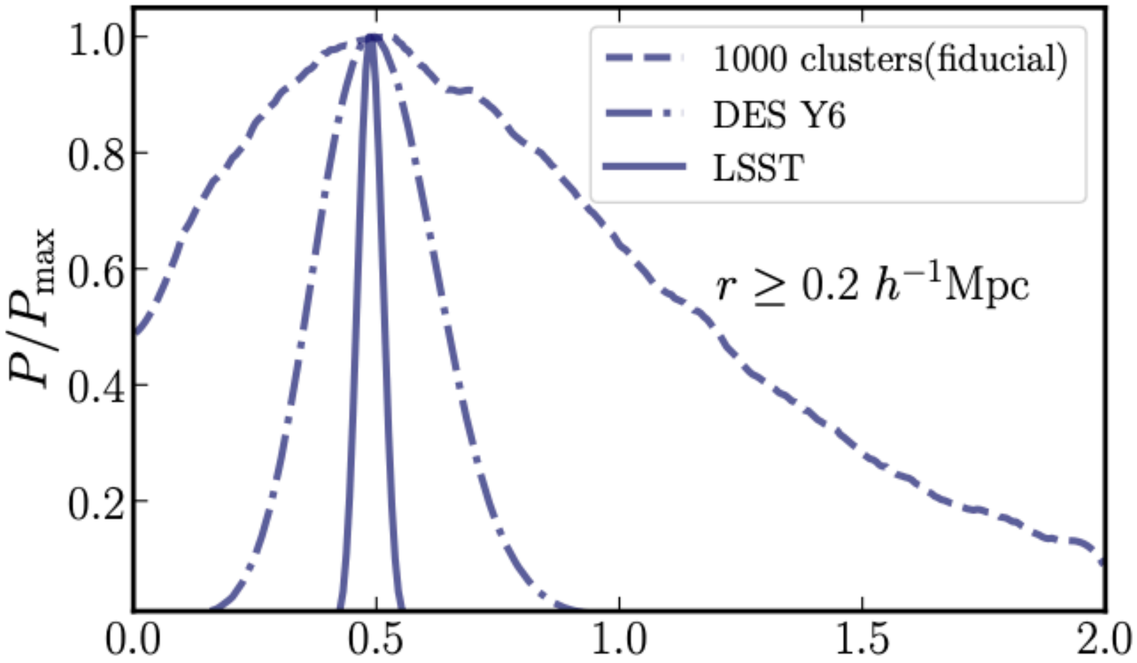


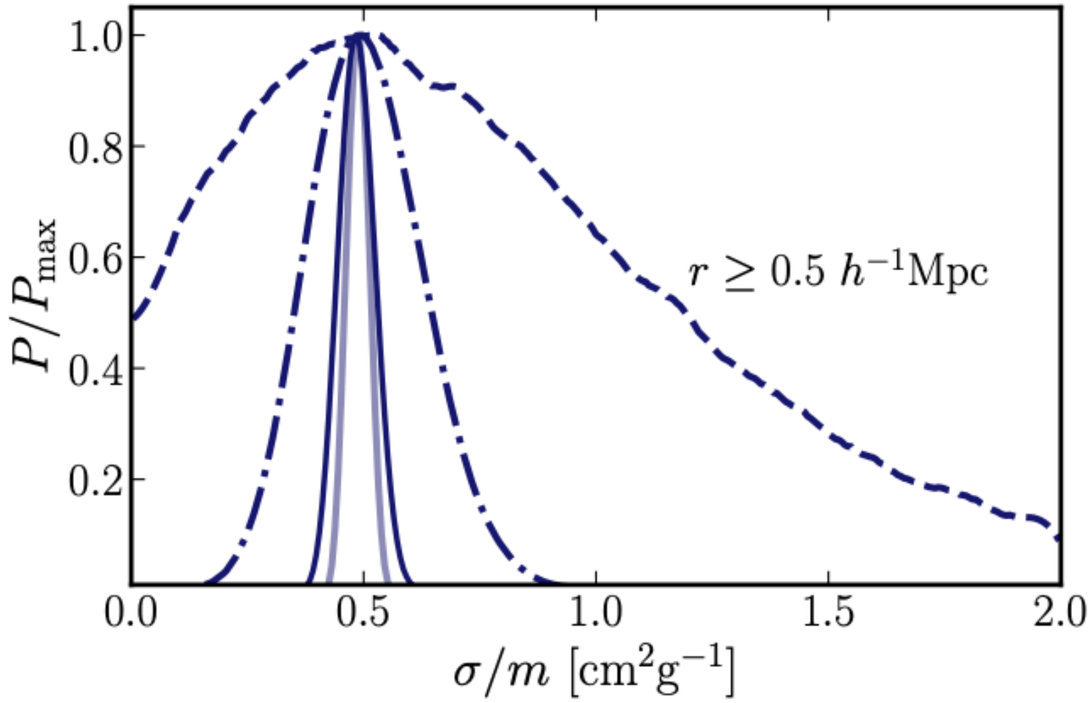
Adhikari, Zhong et al. 2023

Constraints from an LSST-like survey



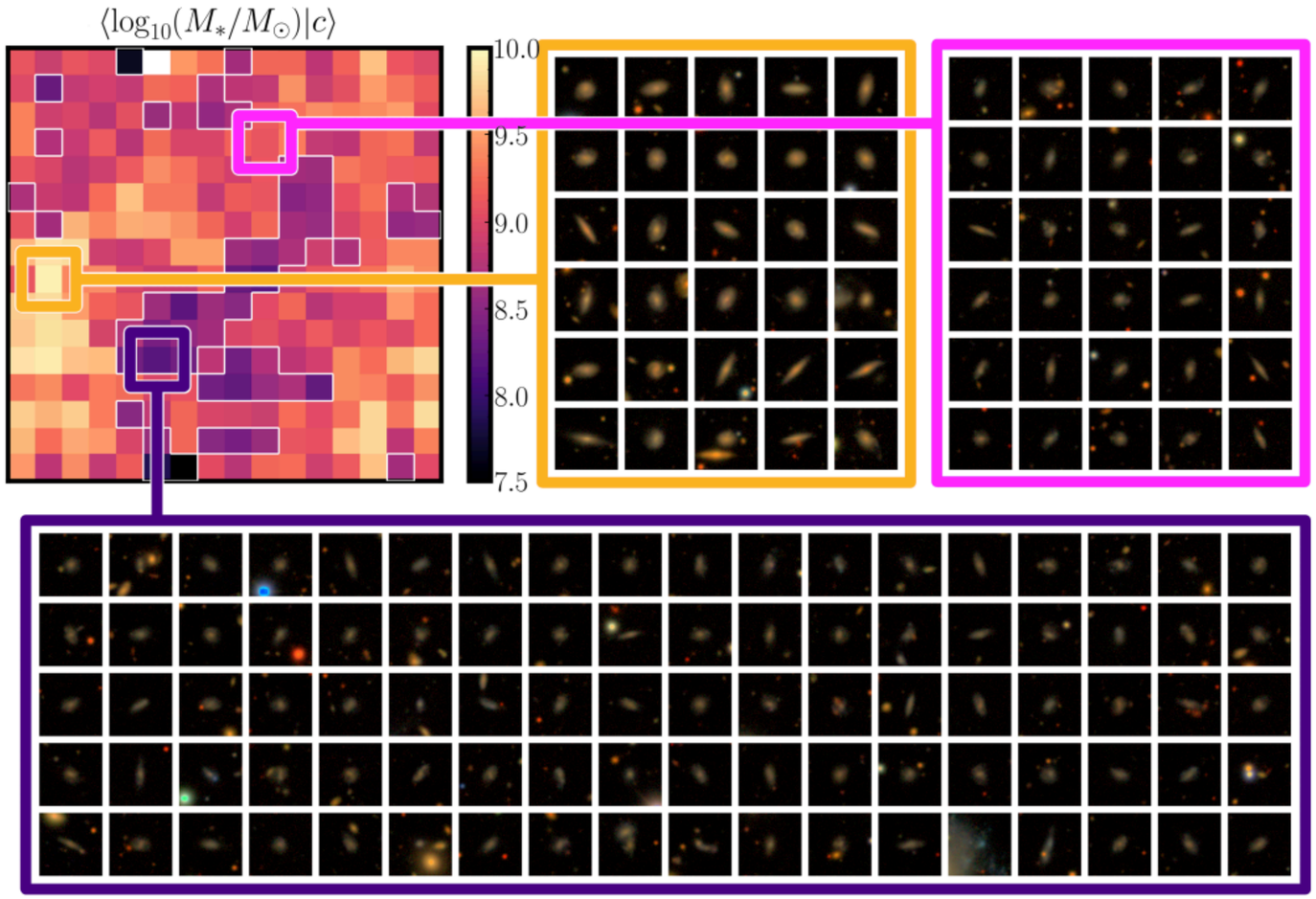
Constraints from an LSST-like survey





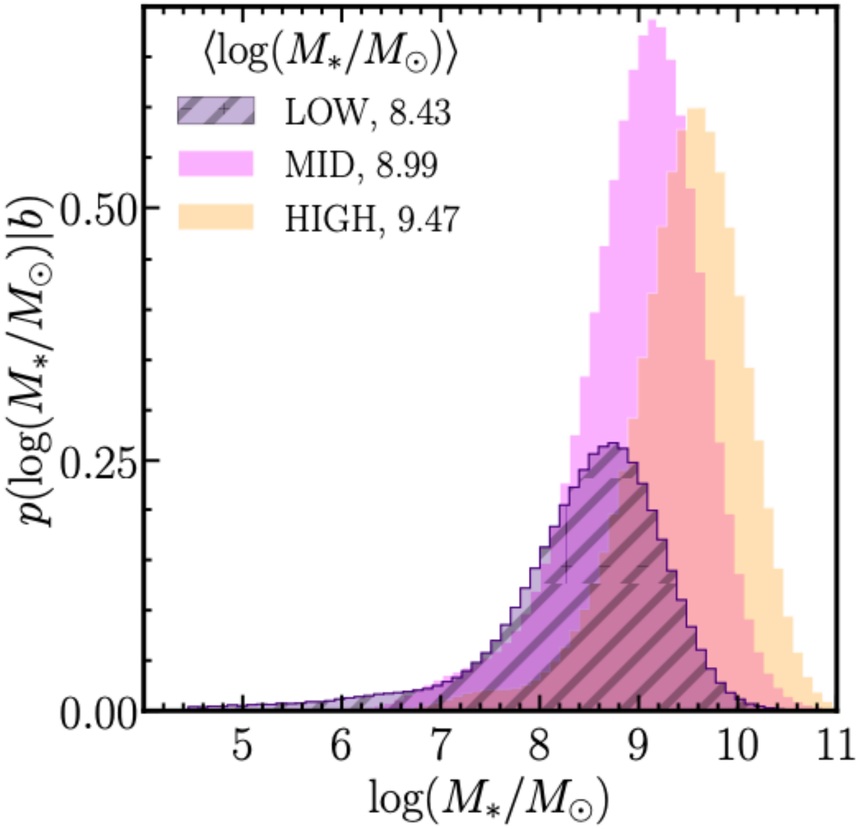
The faint galaxy regime in observations

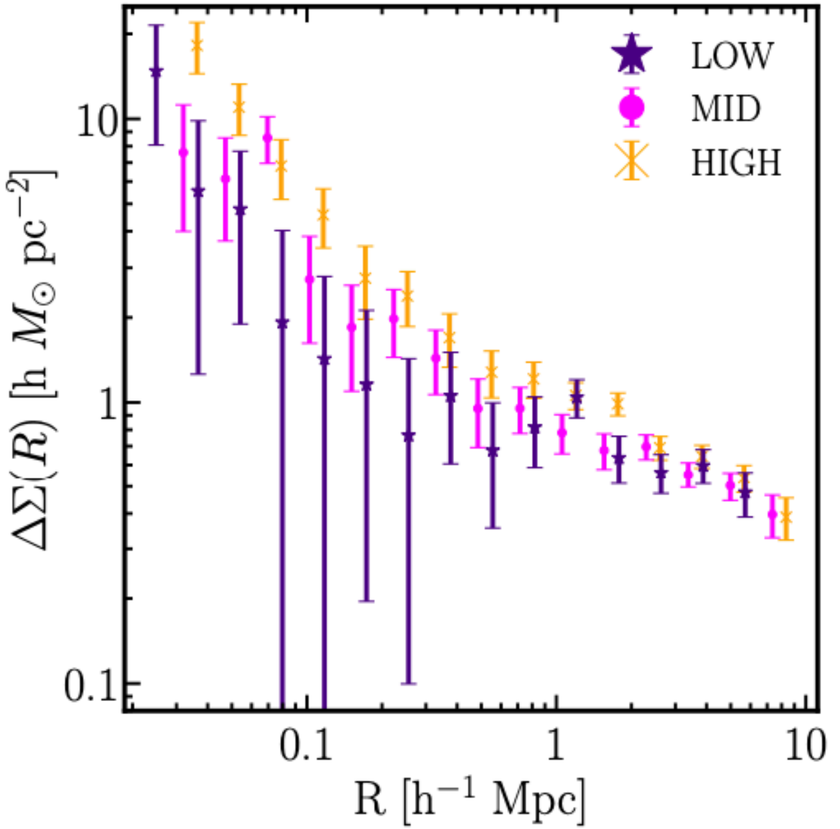
With Joseph Thornton, Alexandra Amon, Risa Wechsler and Yao yuan Moao



Thornton et al. 2023 (incl. Adhikari)

Weak Lensing profile of dwarf galaxies

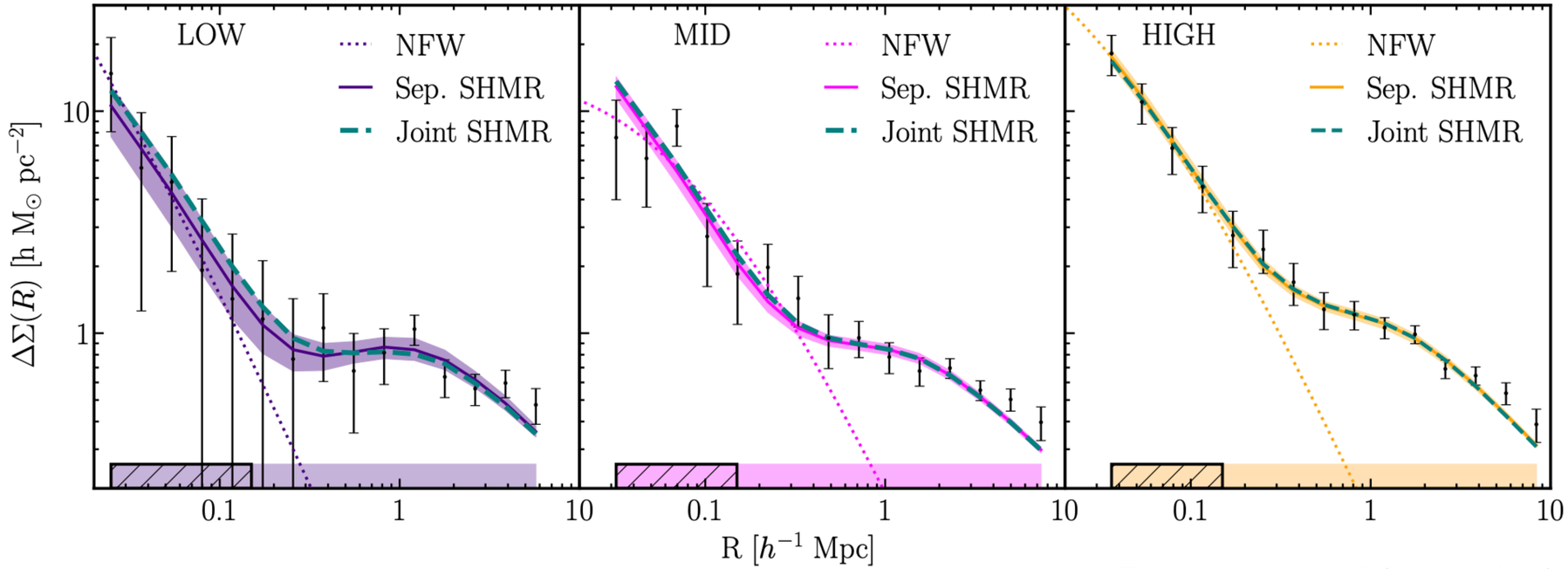




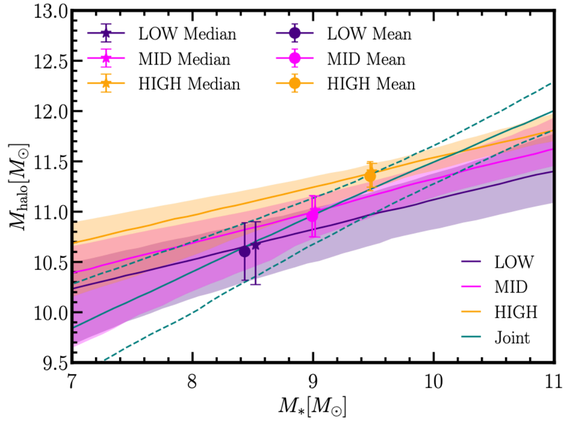
Thornton et al. 2023 (incl. Adhikari)

Thornton et al. 2023 (incl. Adhikari)

The faint galaxy regime in observations



Thornton et al. 2023 (incl. Adhikari)



Conclusions and Outlook

- **Dark Matter self-interactions can leave diverse signatures across the entire viral region of a dark matter halo.**
- **The natural evolution of dark matter halos in SIDM will lead to core-expansion followed by core-collapse.**

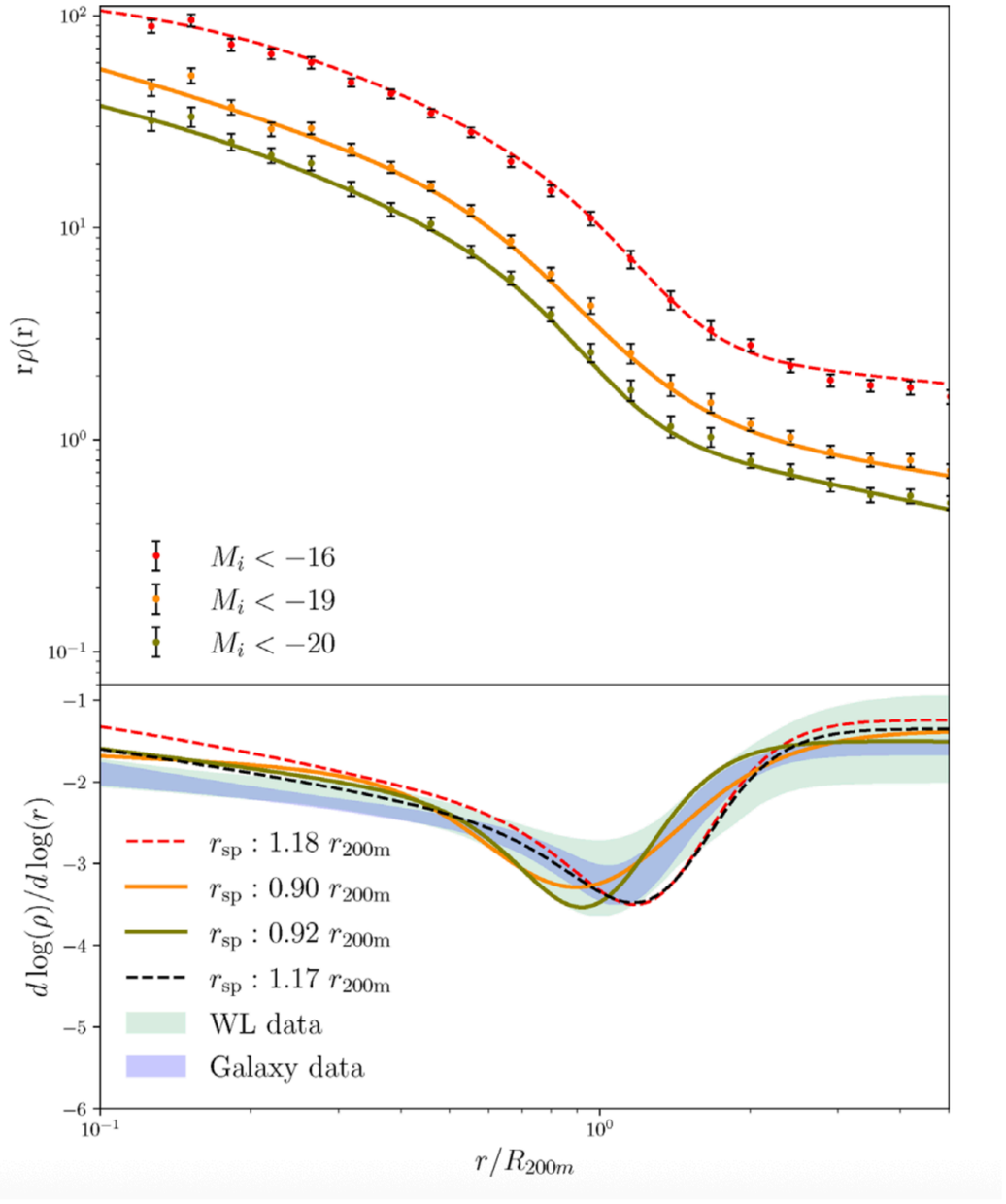
Observations

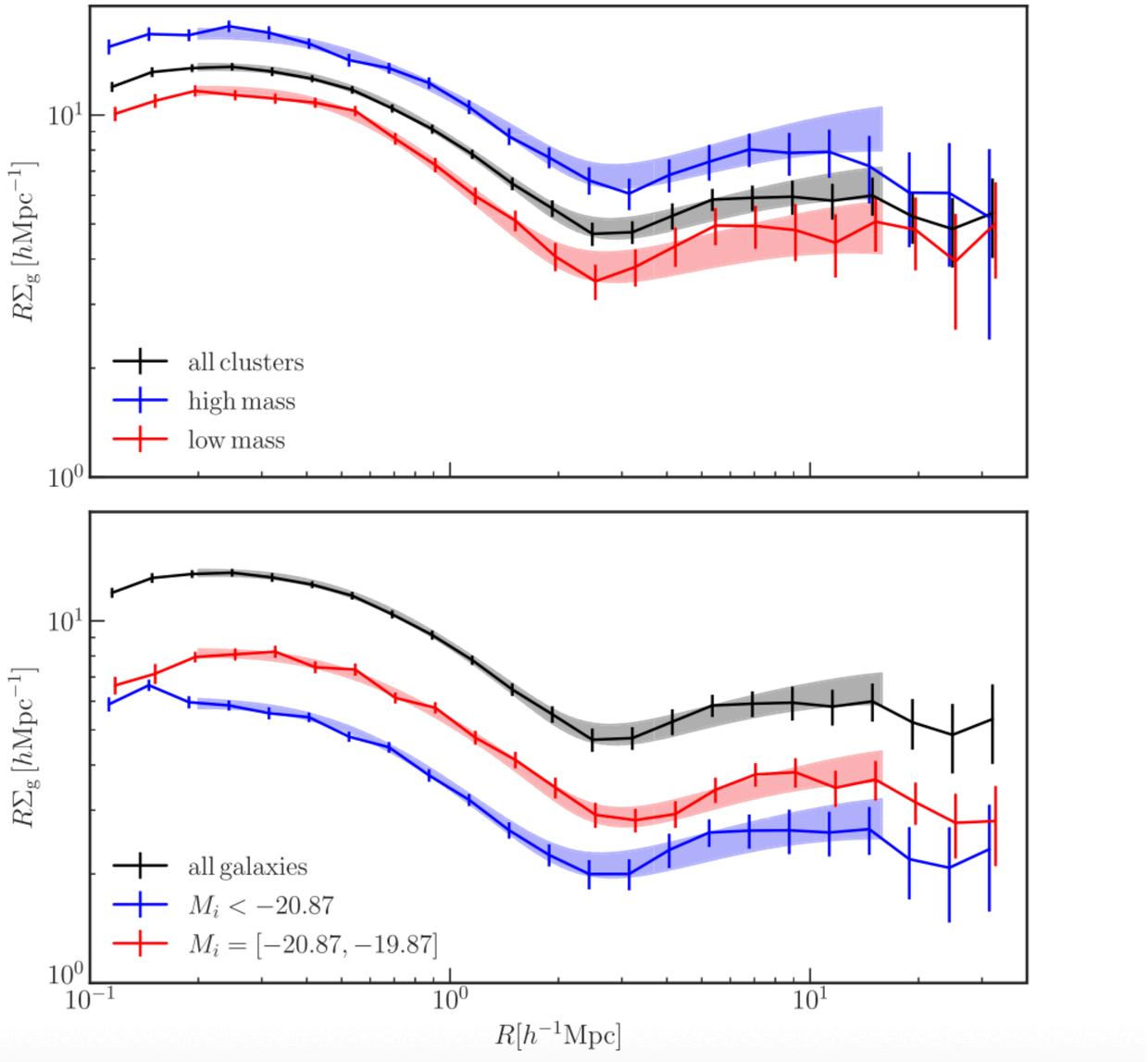
- **Massive cluster provide a laboratory to probe dark matter self interactions across a wide range of scales**
- **Currently largely consistent with CDM but in future it will prove to be a competitive, independent probe for SIDM and ther models of dark matter.**

Current bounds from DES Y3 lensing are consistent with bullet cluster constraints at 95% confidence level, and is used as a novel probe to rule out parts of dissipative dark matter parameter space.

- **Push to smaller scales - Group mass - RedMagic galaxies**
- **Galaxy mass**
- **Dwarf scales**

Comparison with hydrodynamic simulations - Illustris TNG-300





Cluster mass variation

Galaxy mass variation