May 2025 — Shanghai Jiao Tong University
Expanding the Boundaries of Dark Matter Halos

The infall region of galaxy clusters as a complementary probe to cluster abundance

Based on work in:
1. Mpetha el al. (2024), MNRAS, 532, 2, arxiv:2407.01661
2. Mpetha et al. (2025), arxiv:2501.09147

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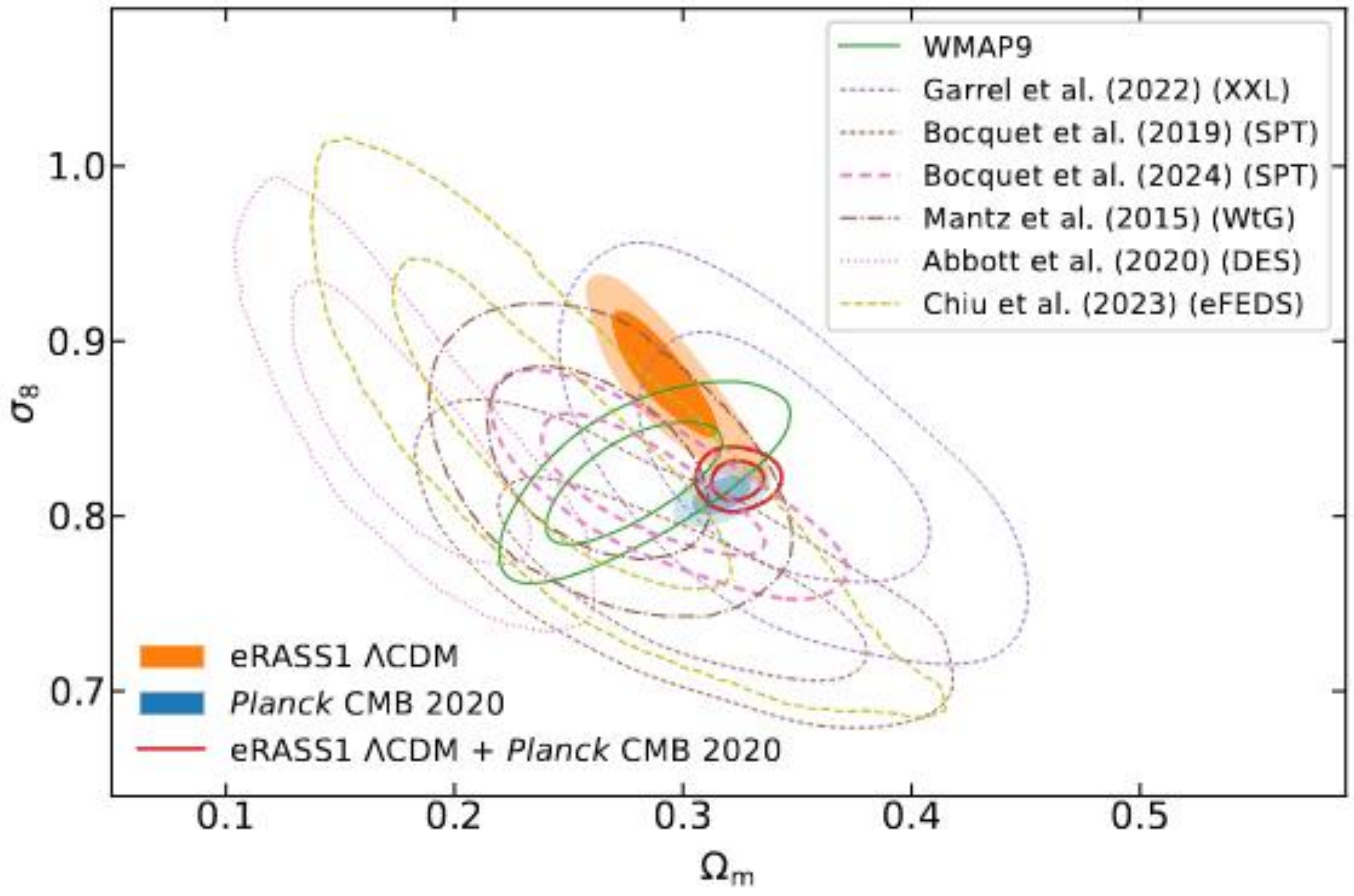
Motivation

- Galaxy clusters are an excellent test-bed for cosmology
- Their abundance constrains the amount of matter in the Universe, Ωm, and the amplitude of density fluctuations, σ8
- Can we use other cluster properties to do better

SRG/eROSITA All Sky Survey (eRASS) cosmological constraints

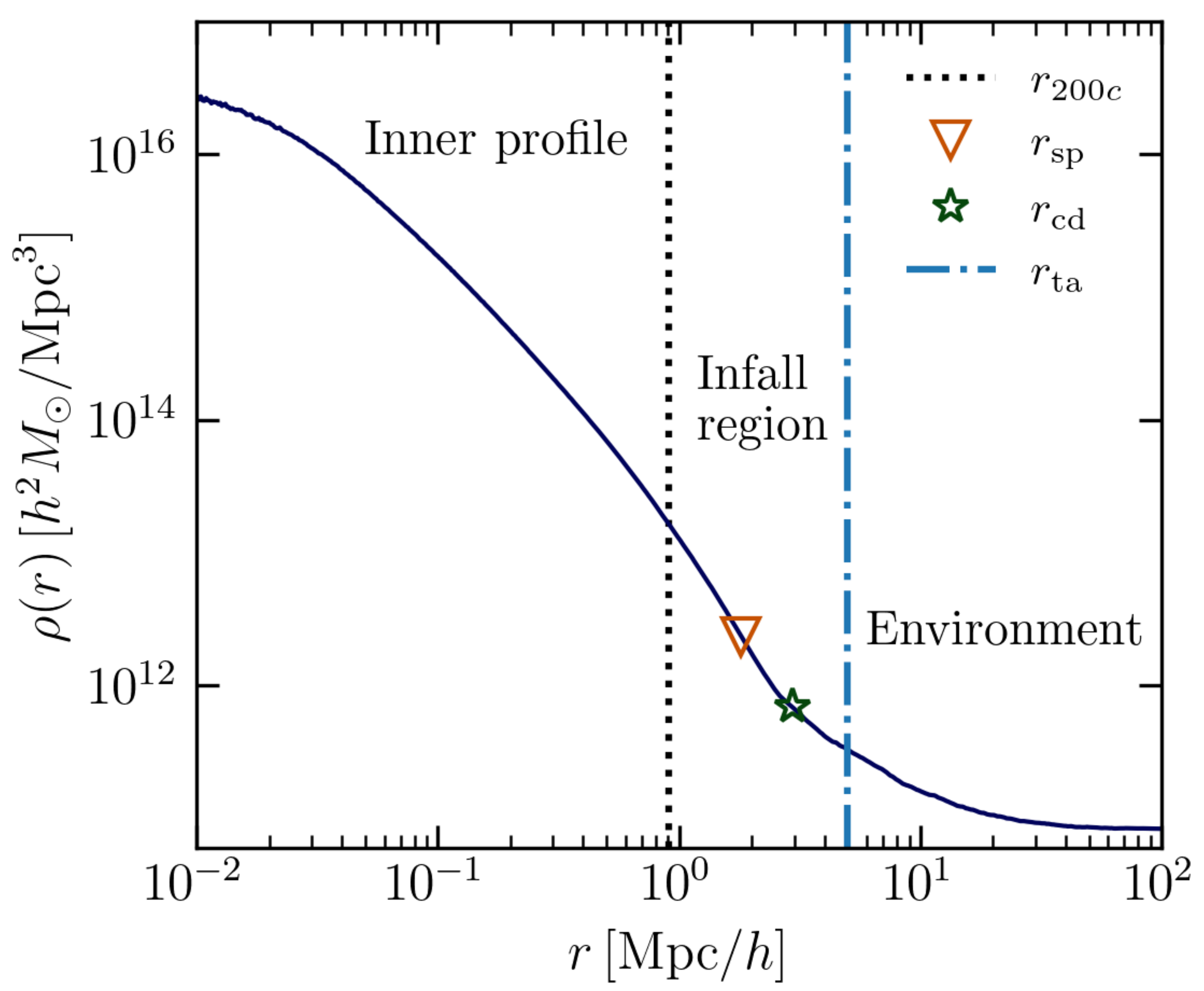


Ghirardini et al. 2024

Infall region

- Boundary between halo and environment
- Suite of 21 cosmological simulations with different Ω_m and σ_8 (Amoura et al. in prep)
- Shape of infall region depends on cosmology (Diemer et al 2017, Haggar et al 2024, Mpetha et al. 2024)

Density profile of (stacked) dark matter halo



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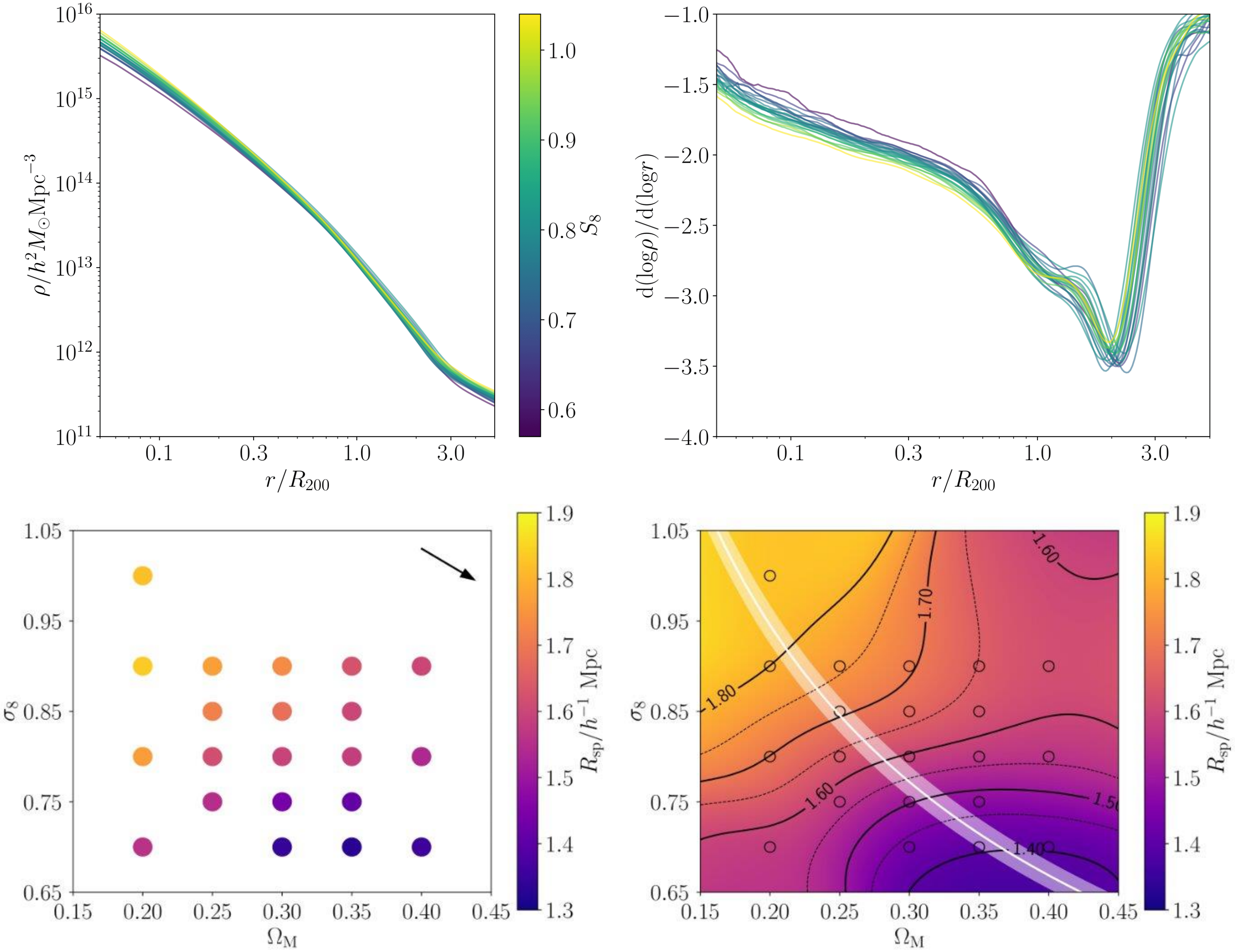


Haggar, Amoura, Mpetha et al. 2024

$$S_8 = \sigma_8\sqrt{\Omega_\mathrm{m}/0.3}$$

Weak lensing profiles of galaxy clusters

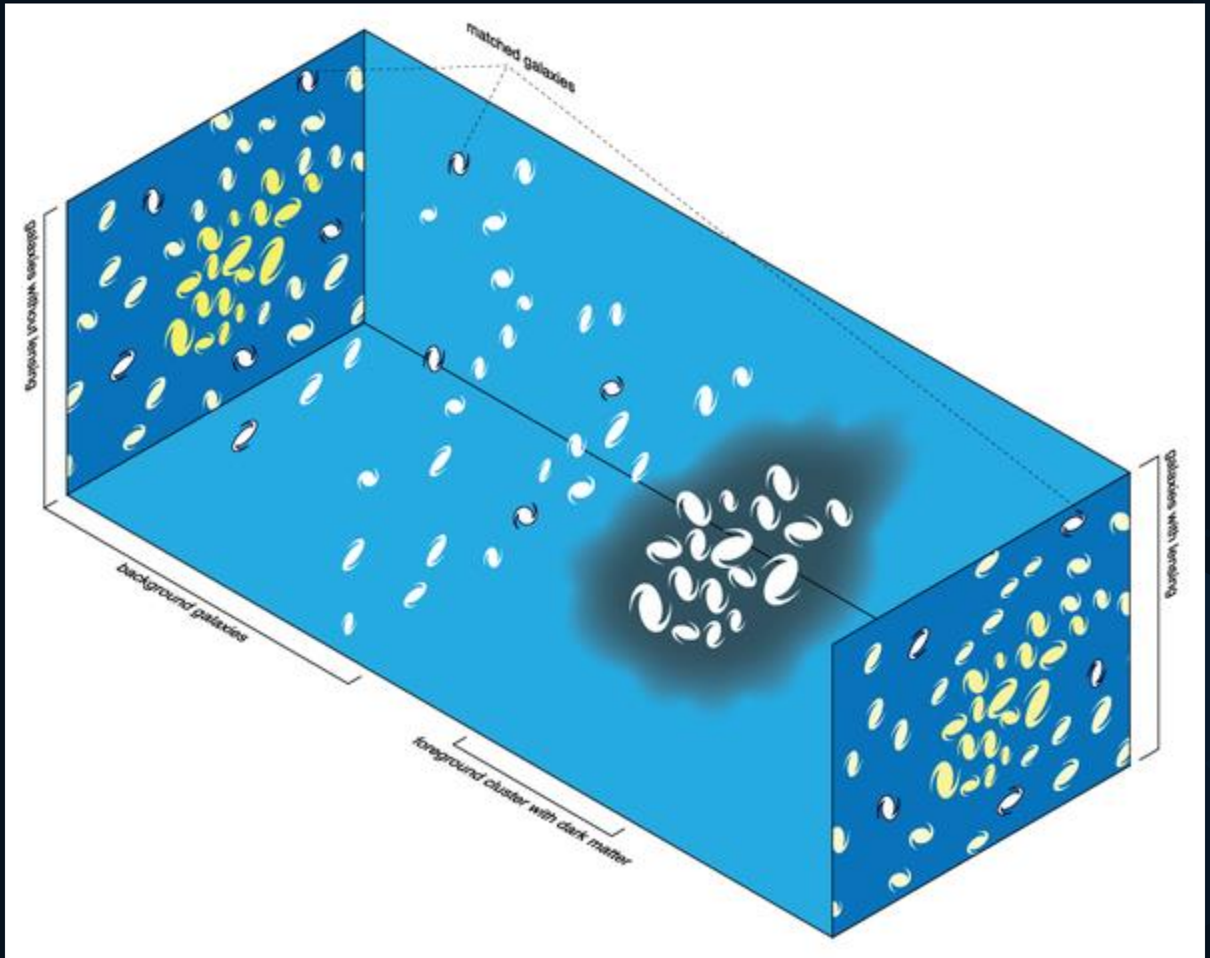
$$\Delta\Sigma(r) = \bar{\Sigma}(R) - \Sigma(R)$$

$$\Sigma(R) = 2\int_R^\infty \frac{\rho(r)r}{\sqrt{r^2 - R^2}}\,dr$$

- Measure distortion of shape of background galaxies: **radial lensing profile**

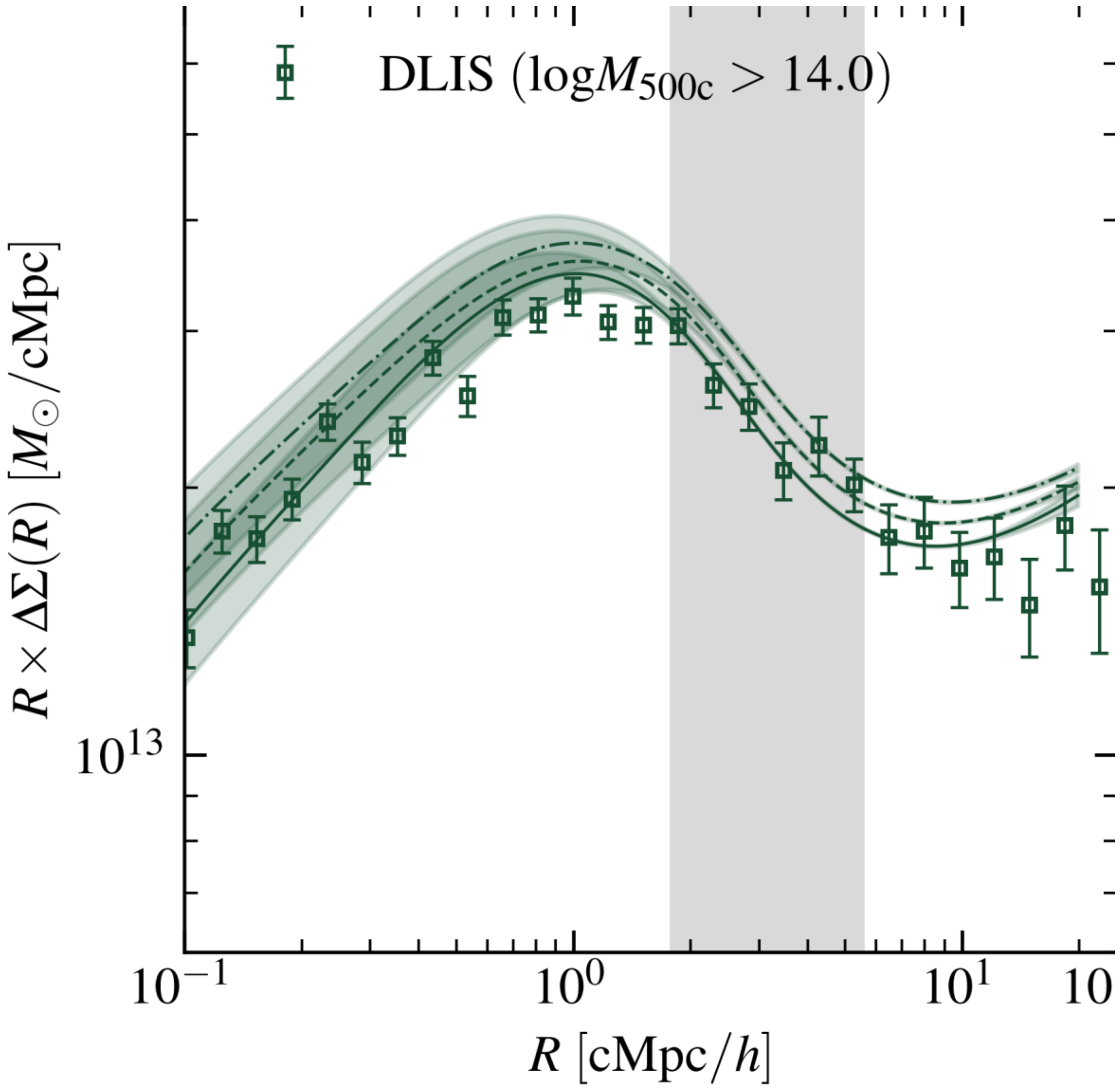
$$\Delta\Sigma(r) = \gamma_t(r)\Sigma_{\text{crit}}$$

- Better tracer of total mass distribution compared to galaxy number density – compare to DM simulations



Credit: Michael Sachs

Comparing Lensing Profiles to Simulations

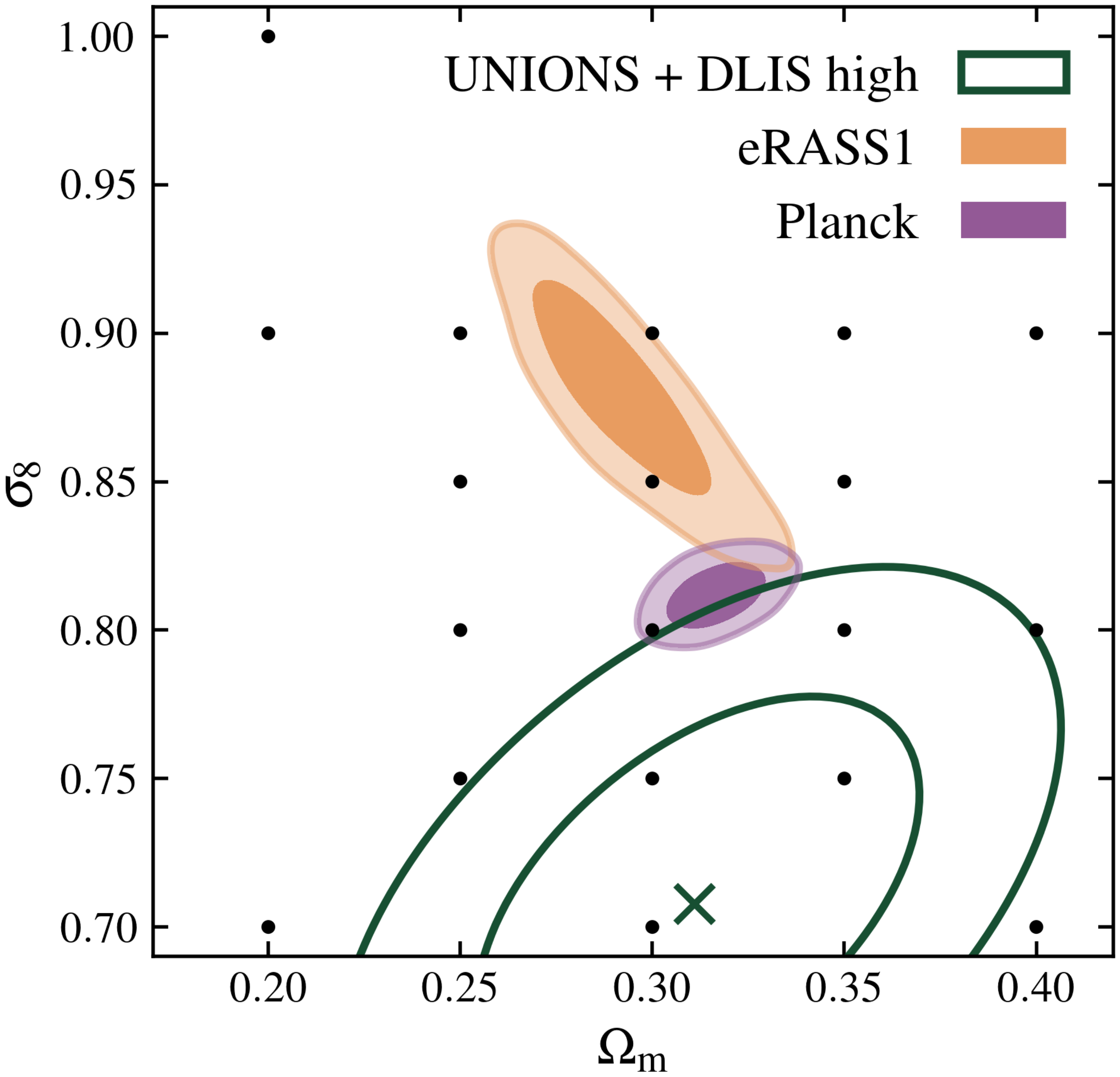


- UNIONS weak lensing catalogue v1.3 (unmasked, no photo-z's): 3,200 deg^2 with 8.5 sources deg^{-2} (Guinot et al. 2022)
- Publicly available lens catalogue: DESI Legacy Imaging Survey (DLIS, Wen & Han 2024)
- Figure compares simulation profiles (matched redshift range) to observed profiles (Ω_m=0.3) - Include observational effects in simulation profiles (mis-centering, Eddington bias)
- Which simulation best matches the data?

Mpetha et al. 2025

Results

- Compare DLIS profiles to simulations to find best-fitting cosmology
- Leads to Ω_m=0.31±0.04, σ_8=0.71±0.04
- Complementary degeneracy direction
- With improved lensing and cluster catalogues will be a competitive probe



Mpetha et al. 2025

Considerations

Key advantages to this approach include:

- Complementary degeneracy
- Compared to inner-region, less sensitive to baryons and mis-centering
- Extracting features also possible (and informative)

BUT complete and pure cluster catalogue is important to:

- Mitigate dynamical selection effects
- Provide accurate observed mass estimate for profile comparison

Conclusions + Future Work

- The infall region will help to break the large degeneracy in cluster abundance studies using only cluster information

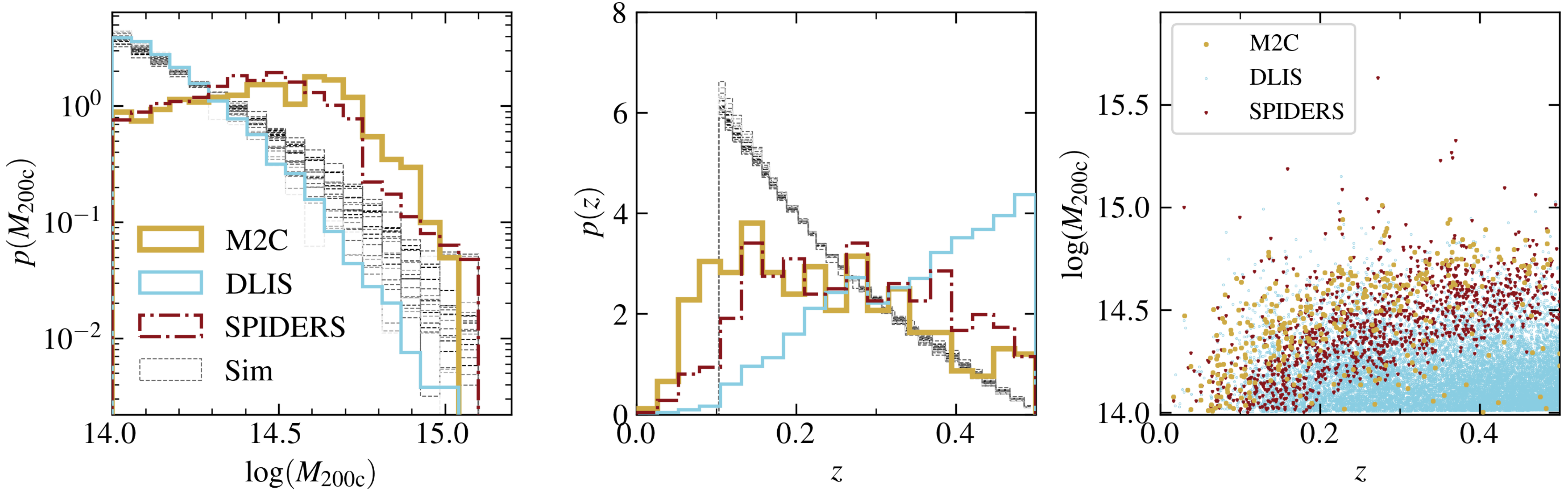
Next Steps:

- Use AbacusSummit (finer grid of cosmologies, more parameters, more halos)

- Use spec-z clusters (DESI) with new lensing surveys (UNIONS/Euclid/Roman)

Thanks for listening

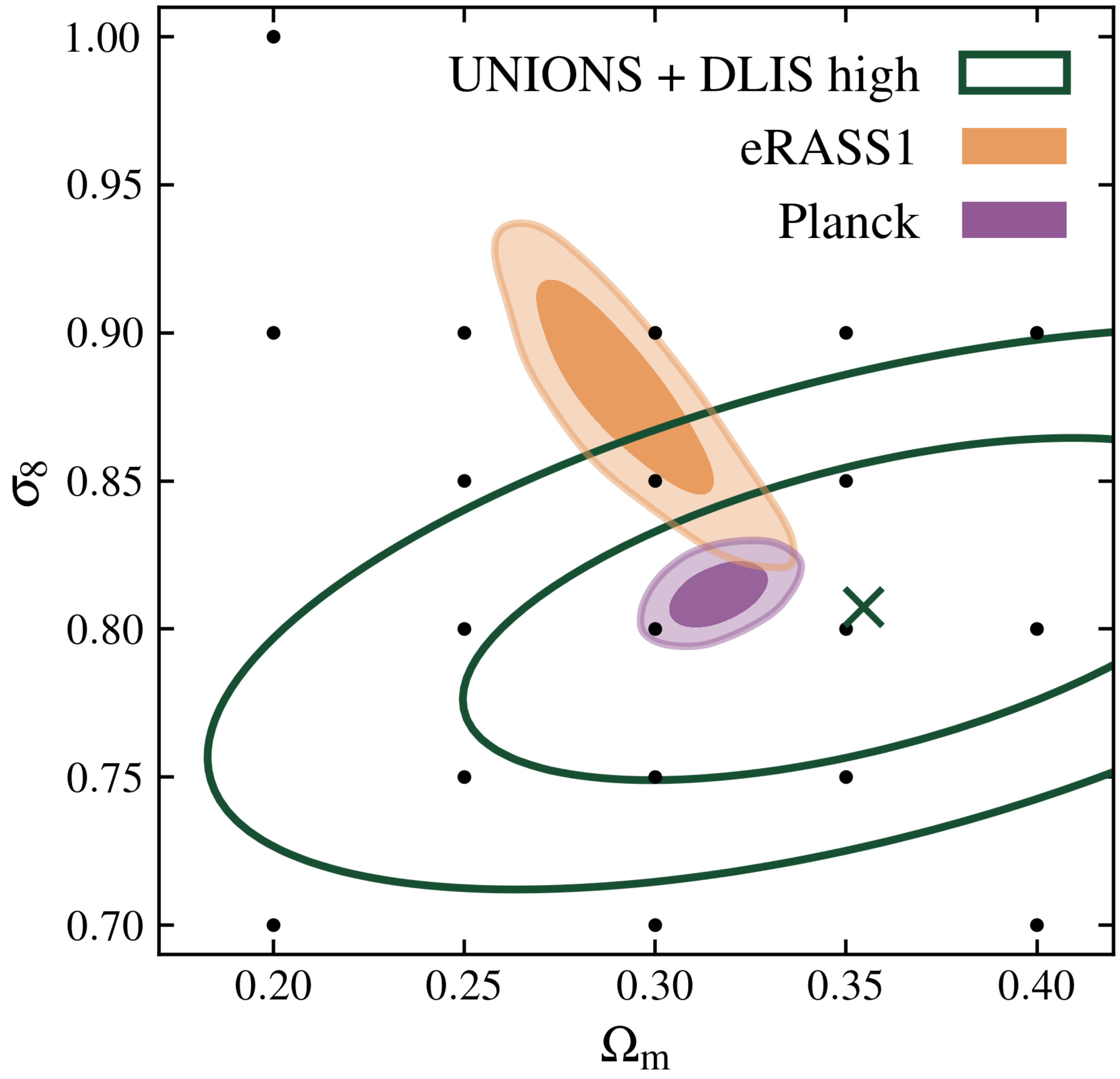
Backup Slides


M2C
DLIS
SPIDERS
Sim
$p(M_{200c})$
$\log(M_{200c})$
$p(z)$
z
$\log(M_{200c})$
z
M2C
DLIS
SPIDERS

Redshift weighting (in progress)

- Simulated and observed lenses have a different redshift distribution

- How do results change if we weight the stacking of simulation profiles based on the snapshot redshift, to represent the observed redshift distribution



Density Profile Model Fit

Diemer 2023 density profile model

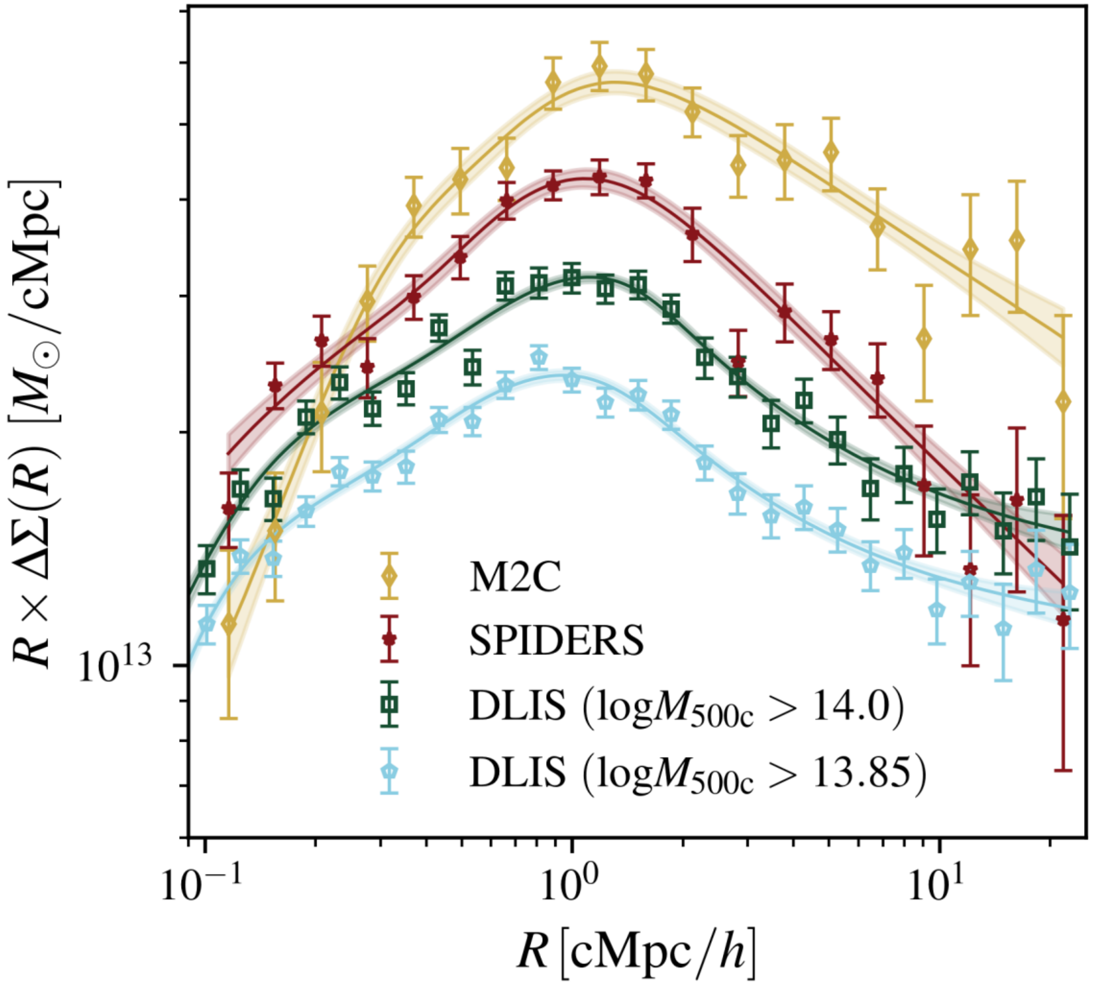
$$\rho(r) = \rho_{\text{orbit}} + \rho_{\text{infall}}$$

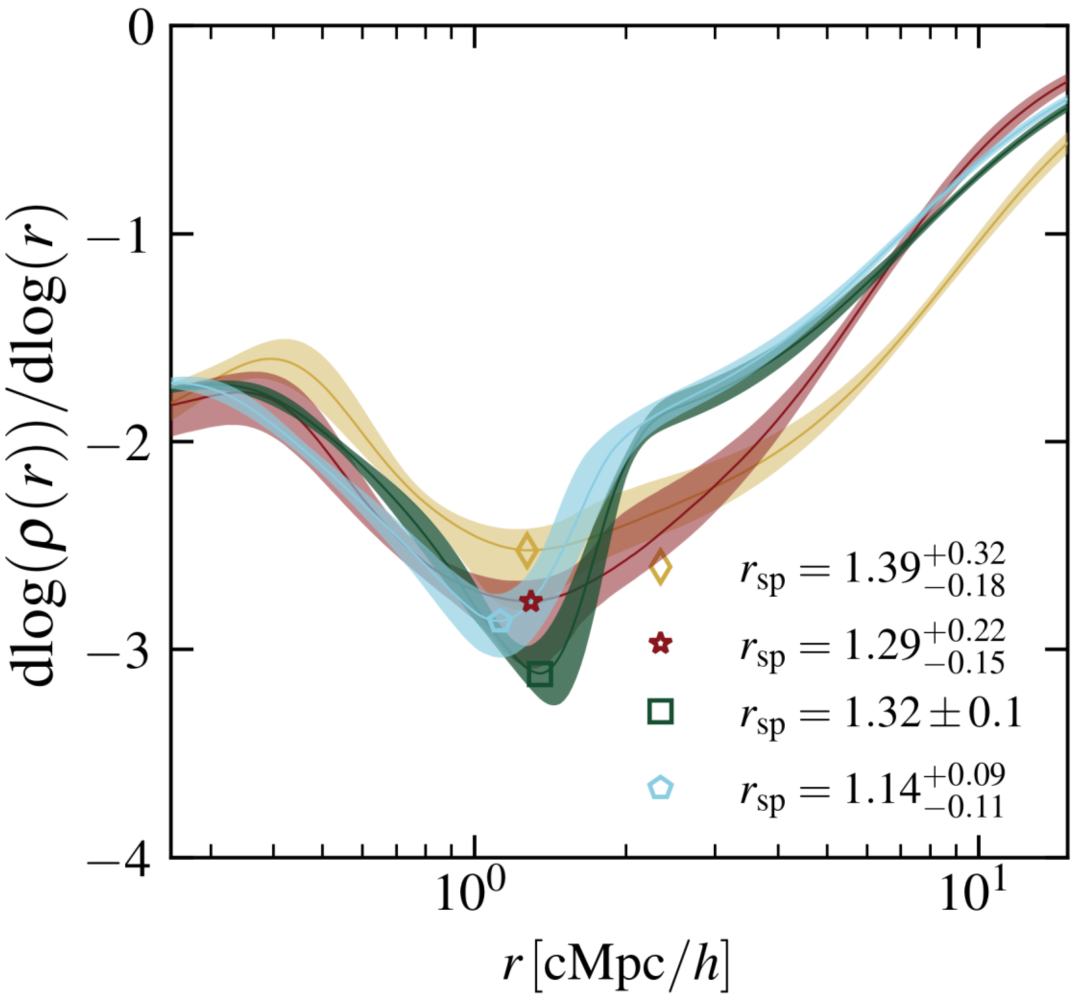
$$= \rho_s \exp\left(\left(-\frac{2}{\alpha}\right)\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right] - \left[\left(\frac{r}{r_t}\right)^{\beta} - \left(\frac{r_s}{r_t}\right)^{\beta}\right]\right) + \rho_m\left(1 + \frac{\delta_1}{\sqrt{(\delta_1/\delta_{\max})^2 + (r/r_{\text{pivot}})^{2s}}}\right)$$

Parameter	Fiducial value	Prior	Description	
$\log \rho_s$ / $[h^2 M_\odot/\text{cMpc}^3]$	$\log(10^3\, \rho_{\text{m}})$	$\log([10^1, 10^7]\, \rho_{\text{m}})$	Density at scale radius	Einasto
$\log r_s$ / $[\text{cMpc}/h]$	$\log(0.07\, r_{200\text{m}})$	$\log([0.01, 0.45]\, r_{200\text{m}})$	Scale radius	
$\log \alpha$	-1	$\log([0.03, 0.4])$	Slope of inner Einasto profile	
$\log r_t$ / $[\text{cMpc}/h]$	$\log(r_{200\text{m}})$	$\log([0.455, 3]\, r_{200\text{m}})$	Truncation radius for inner Einasto profile	Truncation
$\log \beta$	0	$[-1, 1.3]$	Sharpness of truncation	
$\log \delta_1$	1	$[0, 2]$	Overdensity at the pivot radius	Infalling
$\log \delta_{\max}$	2	$[0, 3 + \log(2)]$	Overdensity in the halo centre	
$\log s$	-1	$[-2, 2\log(2)]$	Slope of the infalling term	
$\log \sigma_{\text{off}}$ / $[\text{cMpc}/h]$	-0.5	$[-2, 0]$	Amplitude of offset distribution	Mis-centering
f_{off}	0.3	$[0, 1]$	Fraction of lenses with offset	

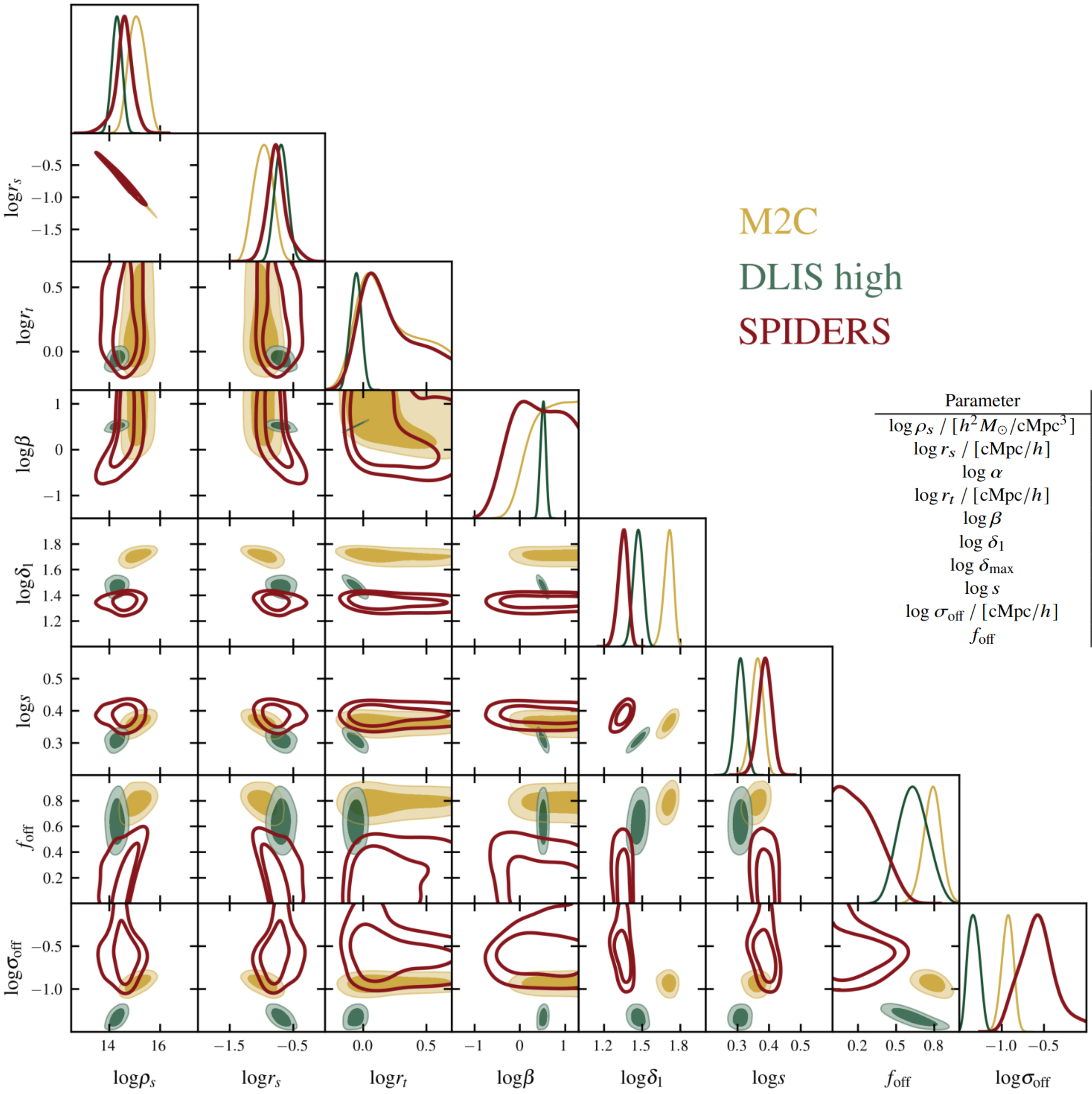
Results

- Fit profiles to find splashback radii
- Uncertainties too large for constraints





Mpetha et al. 2025 15



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