



# The stellar and dark matter distributions in early-type galaxies measured by stacked weak gravitational lensing from the HSC-SSP data

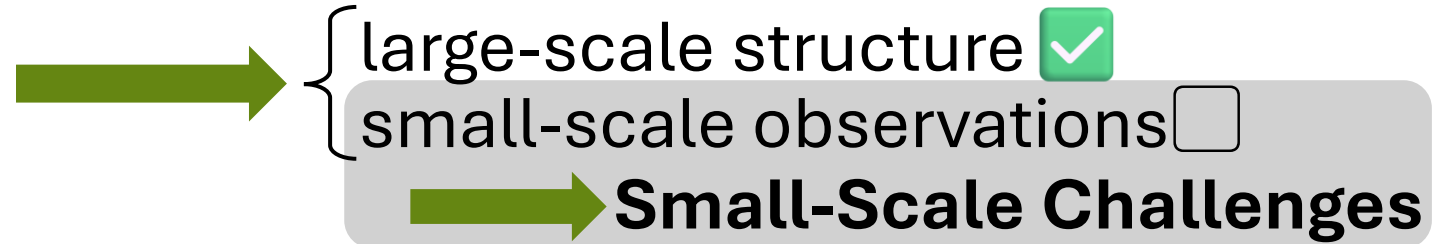
Chiba University

Momoka Fujikawa Masamune Oguri

# Introduction

## Cold Dark Matter (CDM)

- interactions other than gravity ✗
- collisionless damping ✗



e.g. cusp-core problem

In the central region of the halo,

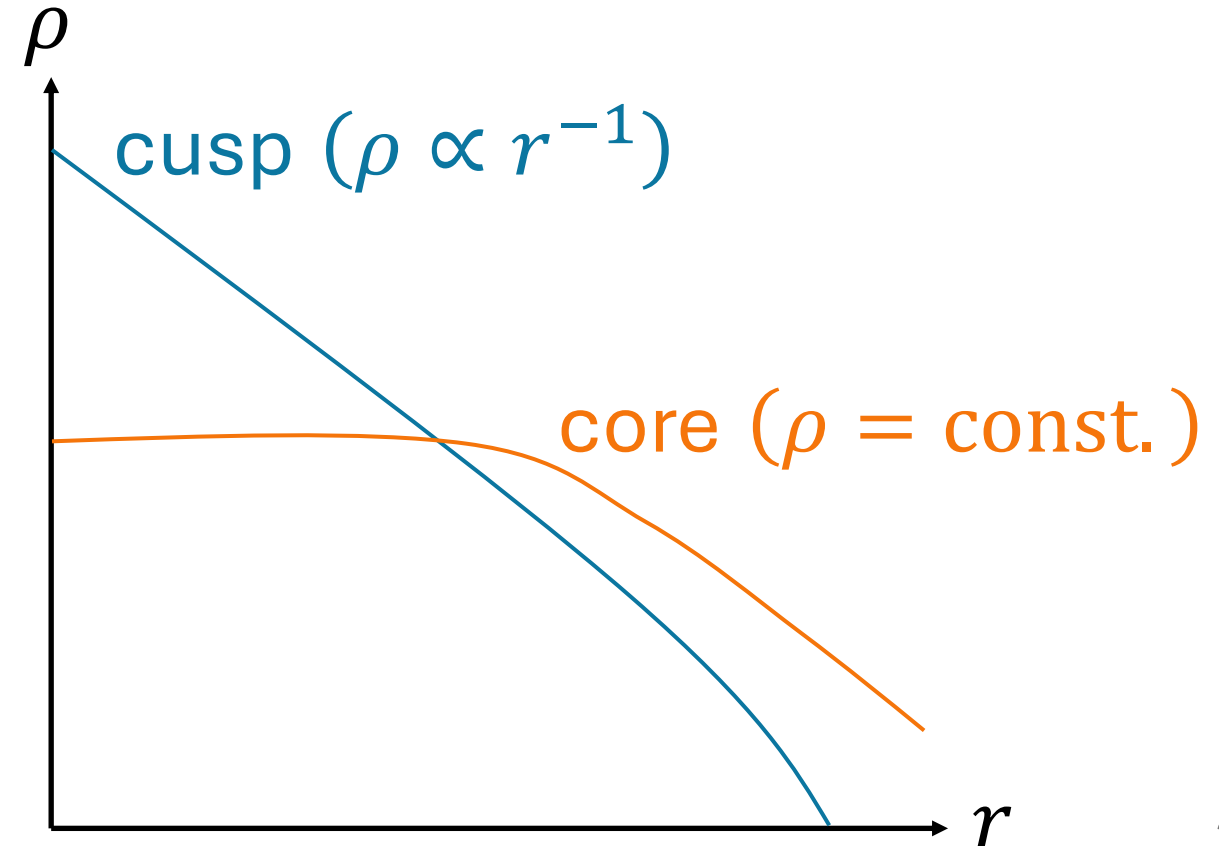
- **CDM**

Navarro-Frenk-White (NFW)

$$\rho(r) = \frac{\rho_s}{\frac{r}{r_s} \left(1 + \frac{r}{r_s}\right)^2}$$

- **some observations**

e.g. rotation curves of dwarf galaxies



- **Previous researches**


velocity dispersion (Cappellari et al., 2012)

strong gravitational lensing (Treu, 2010 ; Oguri et al., 2014)

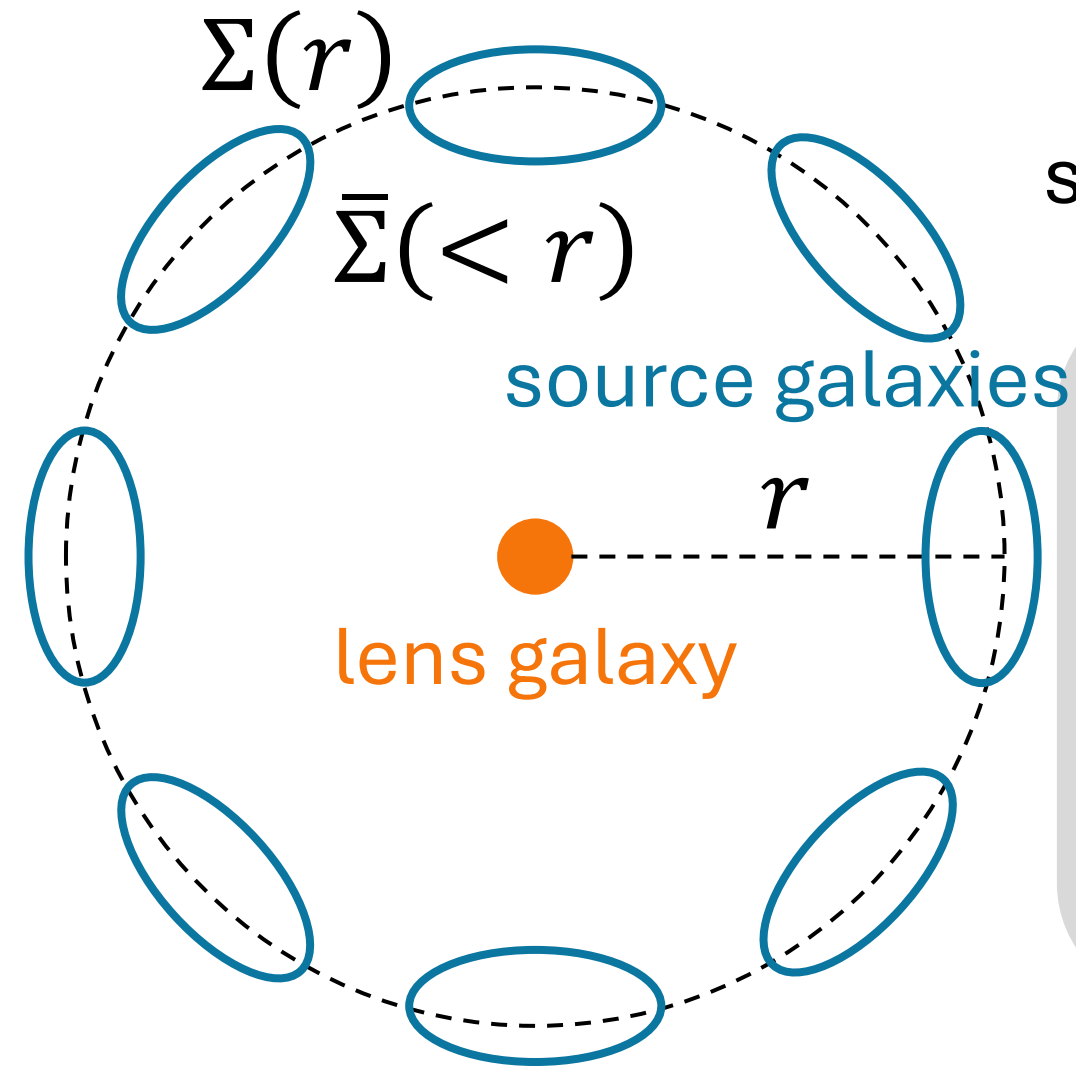
 the central density profiles of early-type galaxies

- **Advances in observational techniques**

e.g. Subaru Telescope

 possibility of proving central density distributions of galaxies through weak gravitational lensing

# Weak Gravitational Lensing



surface mass density  $\Sigma(r) = \int_{-\infty}^{\infty} \rho(\mathbf{r}) dZ$

measuring tangential shear  $\gamma_t$



differential surface mass density

$$\begin{aligned}\Delta\Sigma(r) &= \gamma_t \times \Sigma_{cr} \\ &= \bar{\Sigma}(< r) - \Sigma(r)\end{aligned}$$

(  $\Sigma_{cr}$  : critical surface mass density )

Individual lensing signal  
is too small



stacking a large number of lens galaxies

# Data

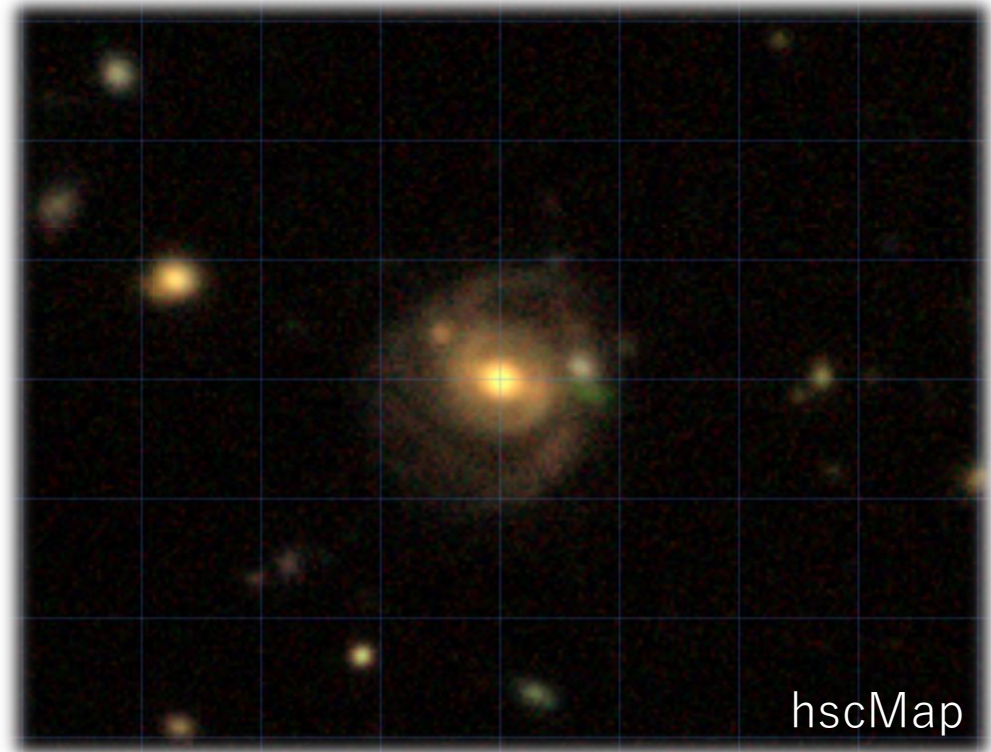
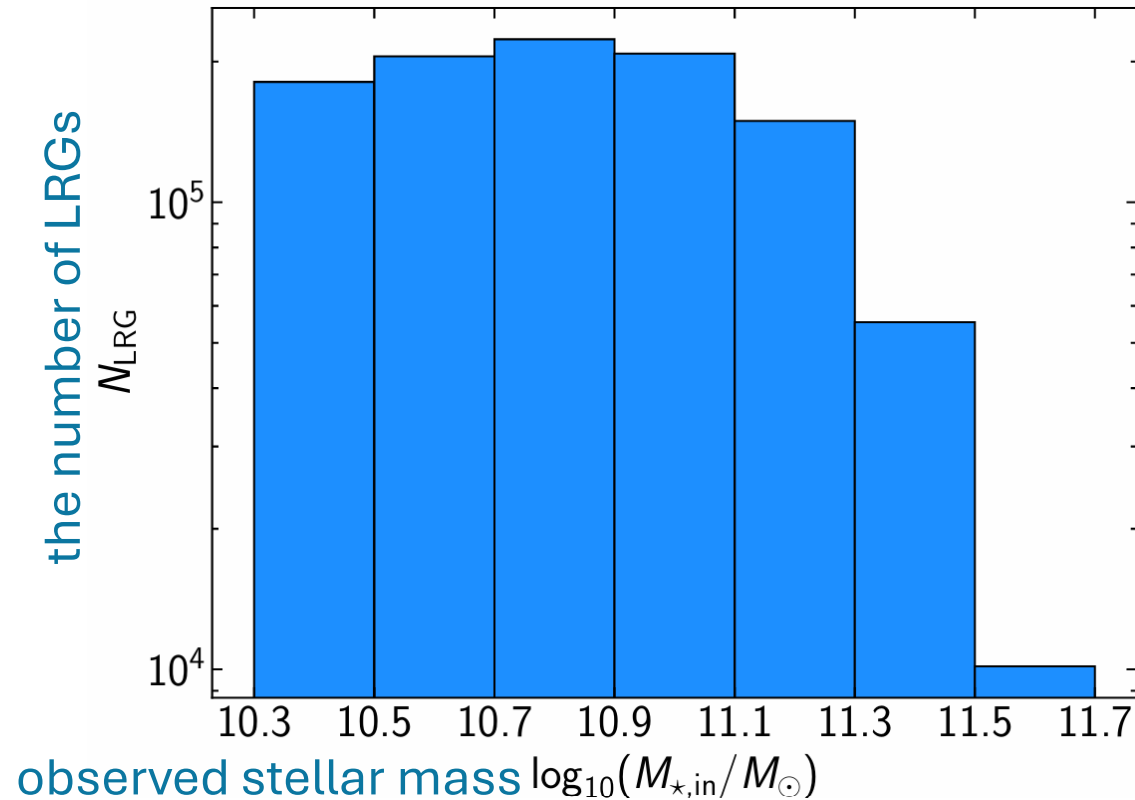
## Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP)

- **galaxy shape sample**

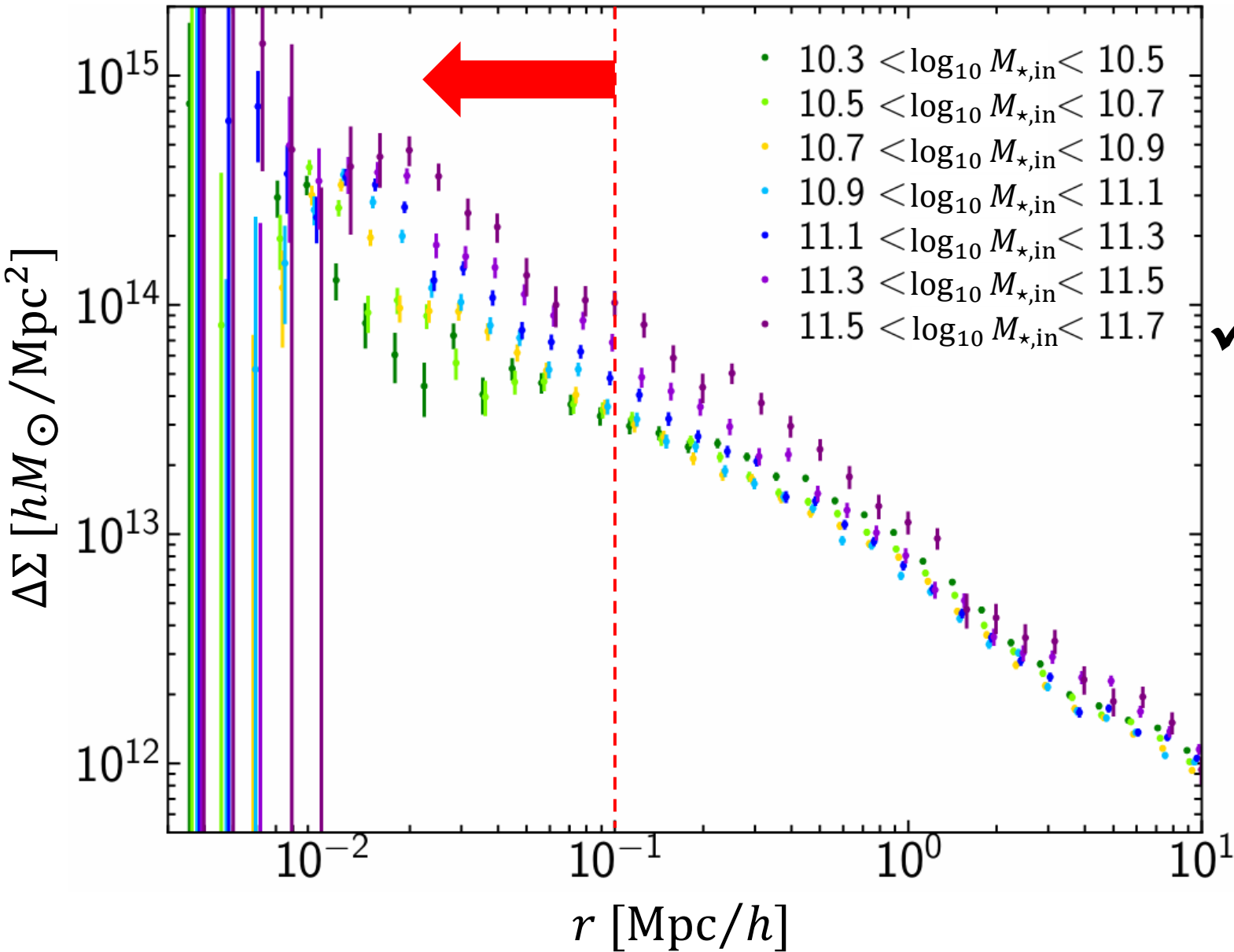
- public three-year shape galaxy catalog (Li et al., 2022)
- 36 million galaxies

- **lens galaxy**

- final-year photometric Luminous Red Galaxies sample (Oguri et al., 2026)
- $0.4 < z < 0.6$

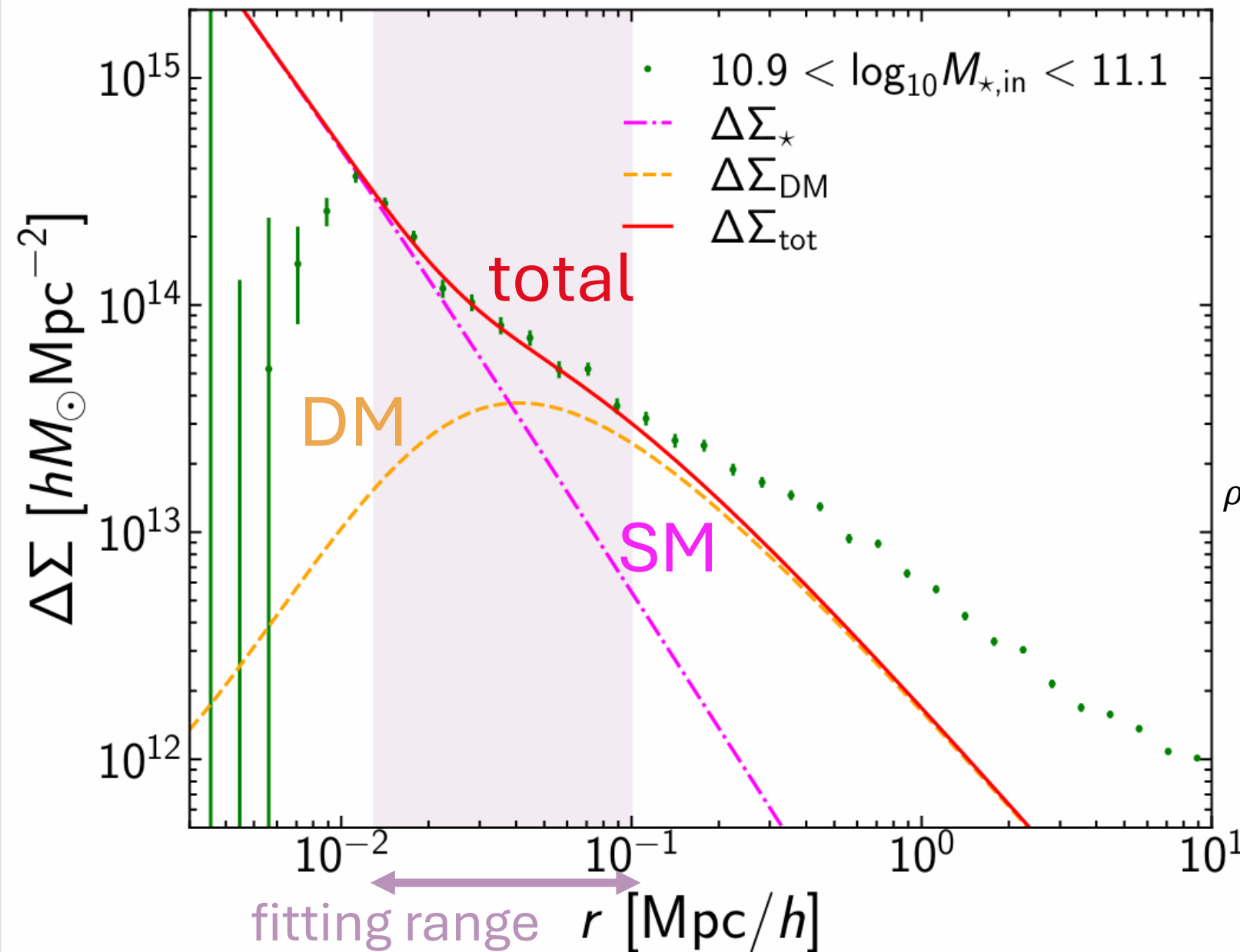


# Measurement



✓ we want to know  
the **central** dark matter  
distribution

# Inner Profile Fitting



- Model stellar matter (SM)   
➔ Hernquist

$$\rho_{SM}(r) = \frac{M_{\star} a}{2\pi r} \frac{1}{(r+a)^3}$$

- dark matter (DM)   
➔ cored power-law

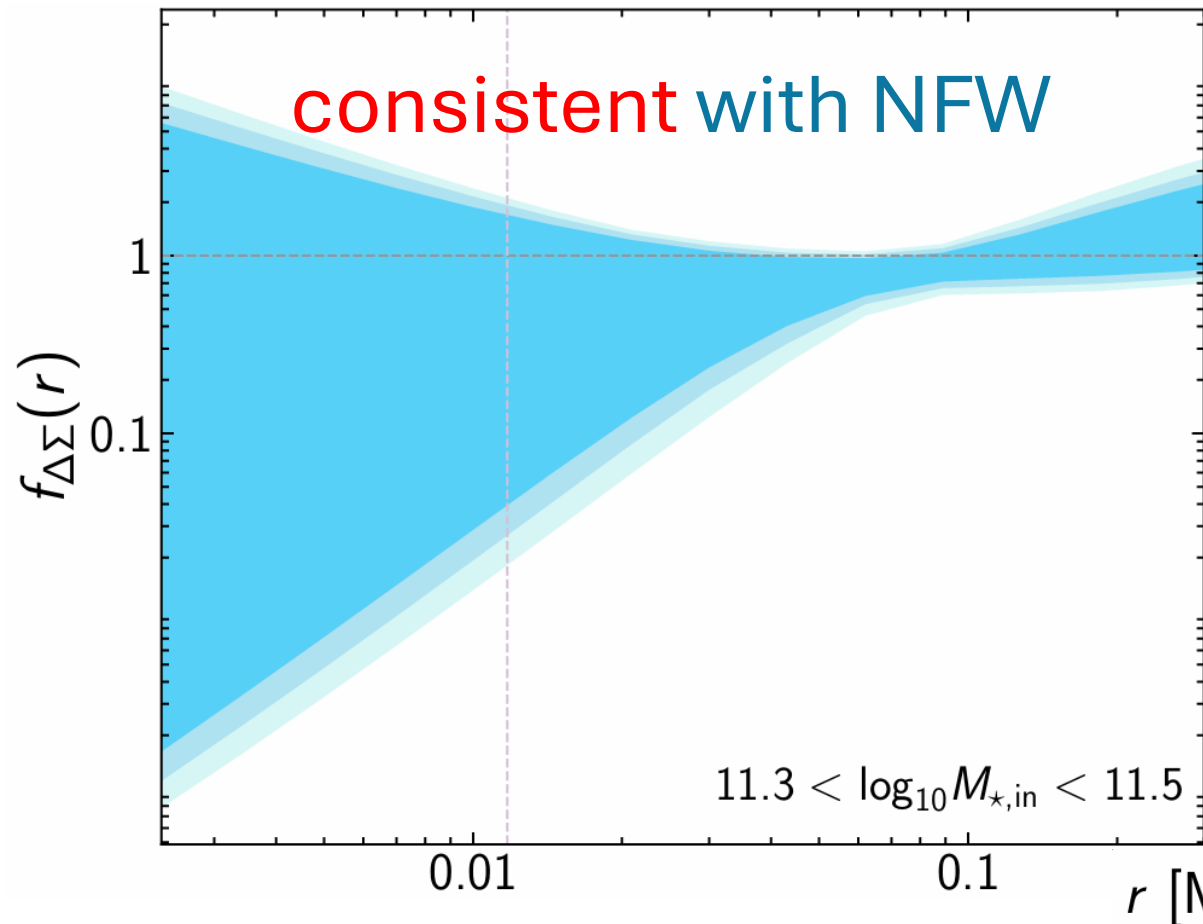
$$\rho_{DM}(r) = M_{\star} \frac{3+\gamma}{2\pi^{\frac{3}{2}} r_e^3} \frac{\Gamma(-\frac{\gamma}{2})}{\Gamma(-\frac{1+\gamma}{2})} A \left( \frac{r^2 + r_c^2}{r_e^2} \right)^{\frac{\gamma}{2}}$$

- investigating from observation data   
without assuming a specific dark matter model

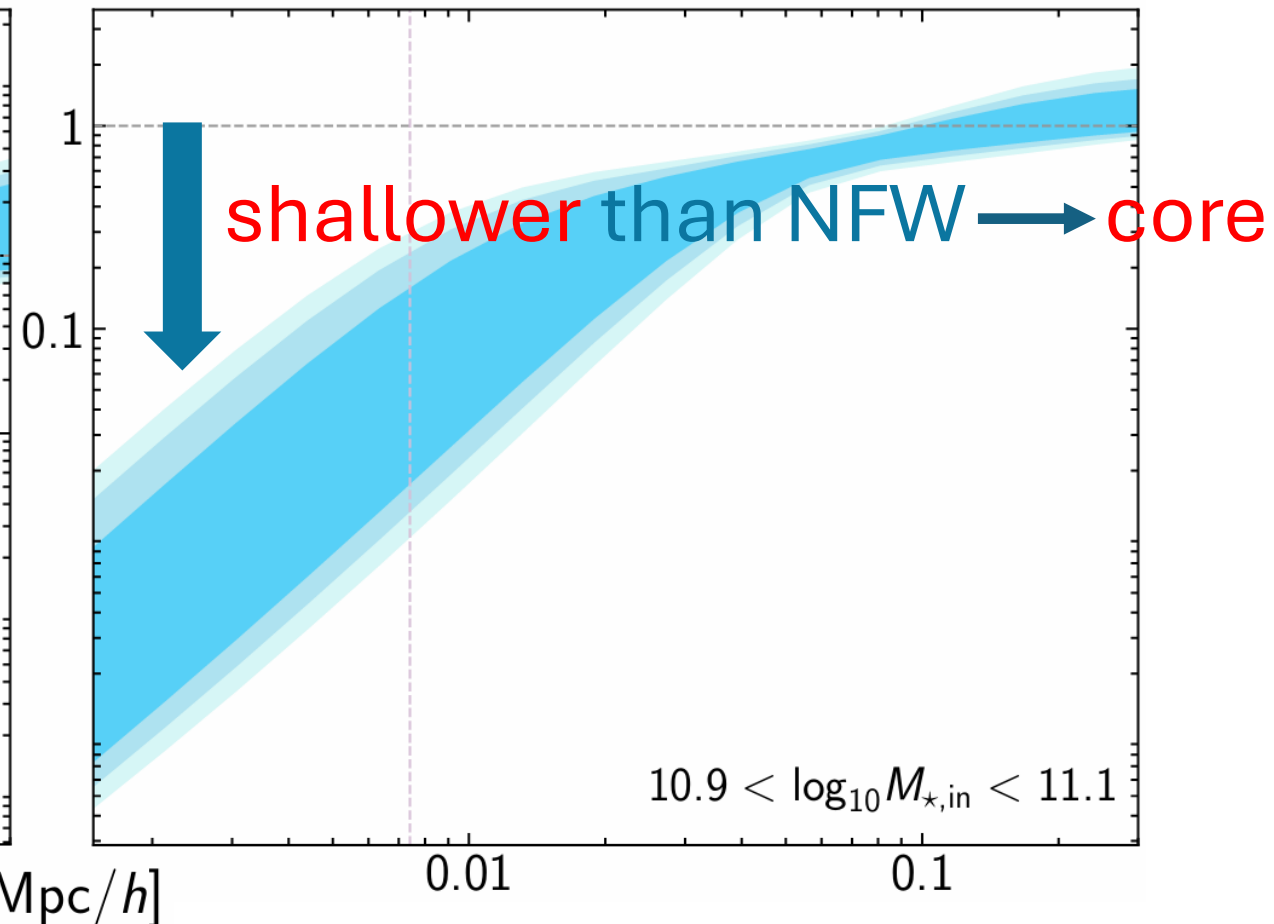
# Comparison with NFW

- $f_{\Delta\Sigma}(r) = \frac{\Delta\Sigma_{\text{DM}}(r)}{\Delta\Sigma_{\text{NFW}}(r)}$  ← obtained from the outer fitting

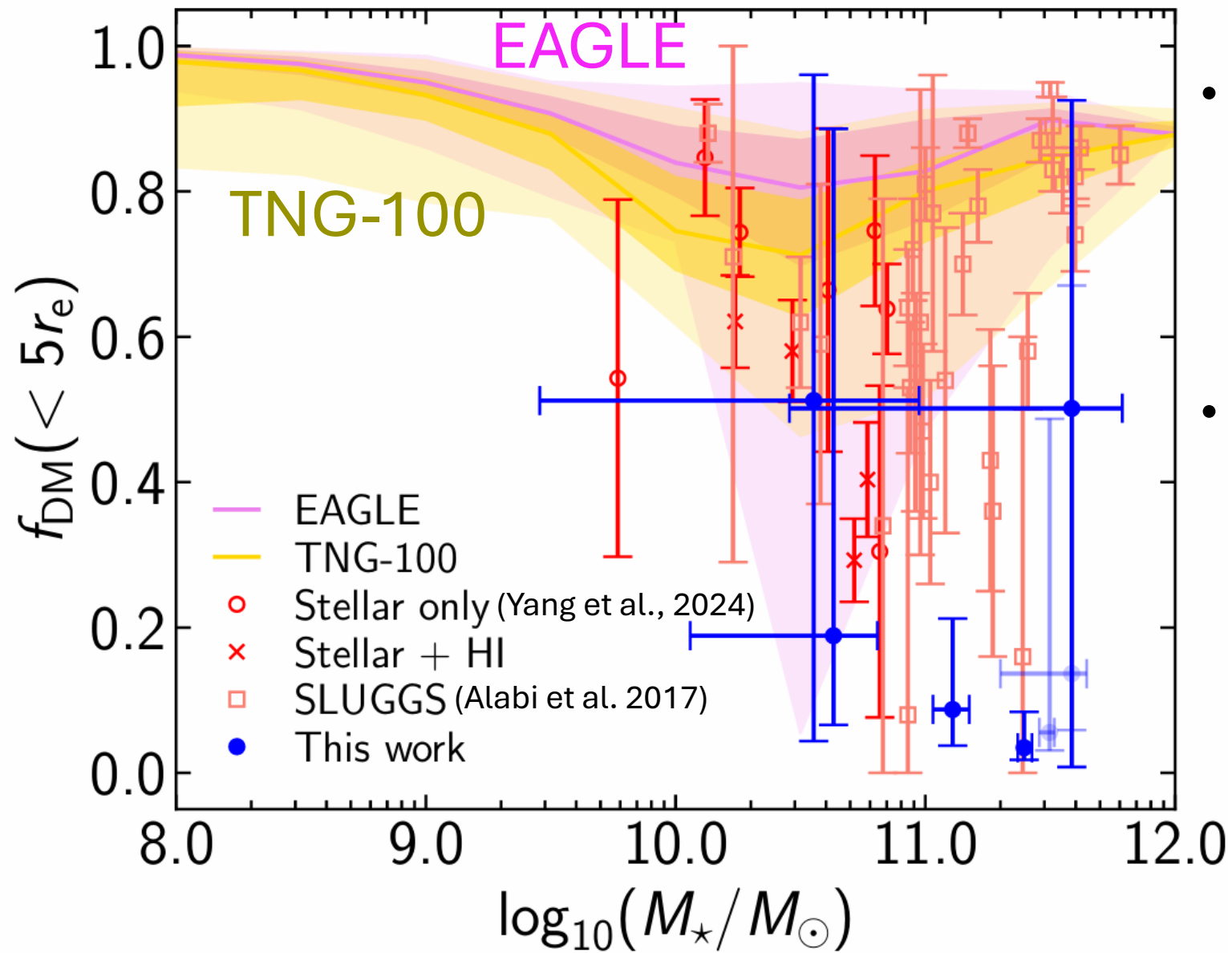
$M_{\star,\text{in}} < 10^{10.7} M_{\odot}, 10^{11.1} M_{\odot} < M_{\star,\text{in}}$



$10^{10.7} M_{\odot} < M_{\star,\text{in}} < 10^{11.1} M_{\odot}$



# Comparison with simulations



- dark matter fraction

$$f_{DM}(< 5r_e) = \frac{M_{DM}(r < 5r_e)}{M_*(r < 5r_e) + M_{DM}(r < 5r_e)}$$

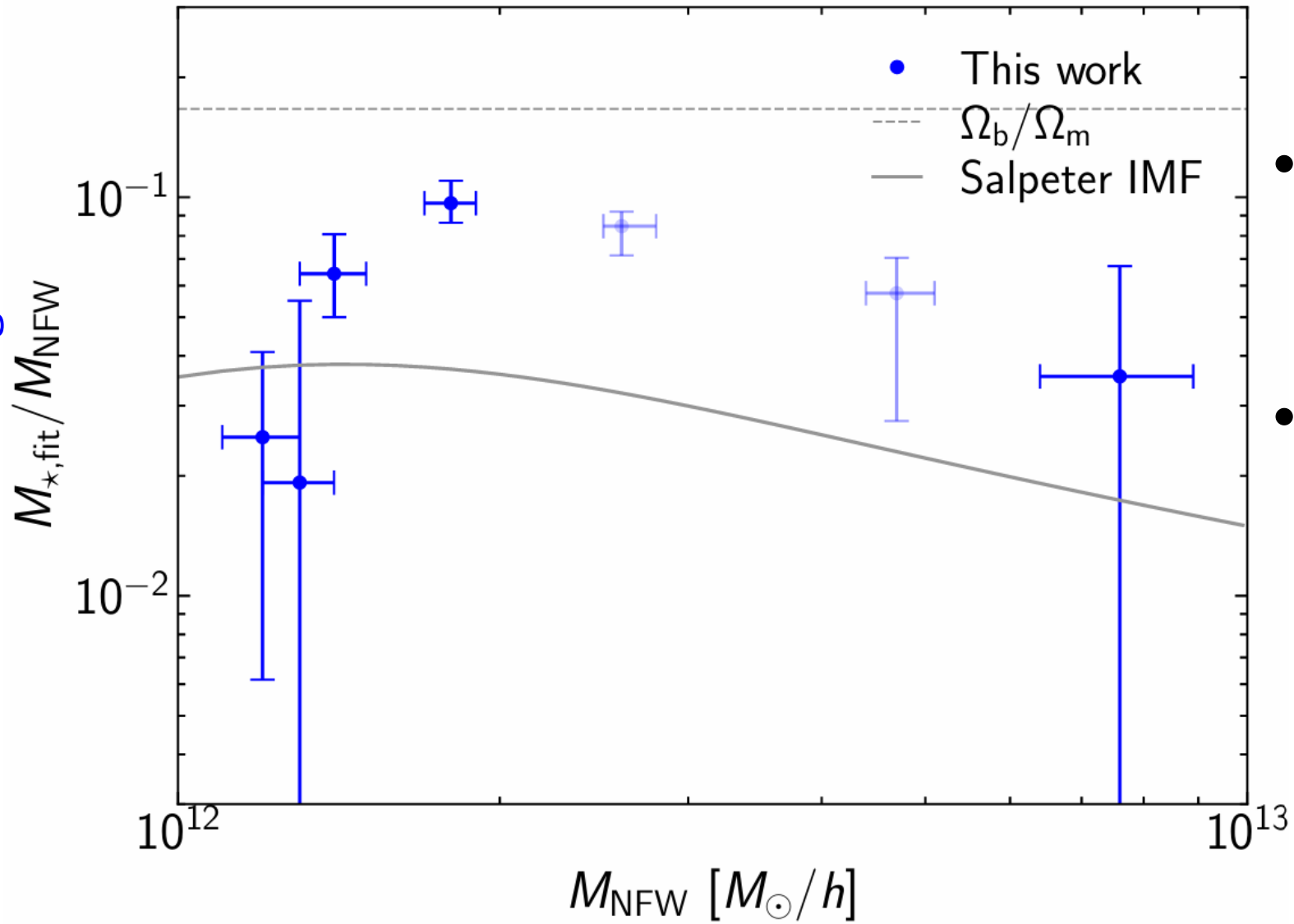
( $r_e$ : the half-light radius)

- For  $10^{10.7} M_\odot < M_{*,in} < 10^{11.1} M_\odot$ ,  
lower than the values predicted from hydrodynamical simulations

➔ actual feedback effect may be **stronger**

# Constraint on Stellar-to-halo Mass Relation (SHMR)

stellar mass from inner fitting



NFW halo mass from outer fitting

- constraining SHMR using only weak lensing
  - larger  $M_{\star}$  than expected from Salpeter IMF
- ➔ possibility of more bottom-heavy IMF



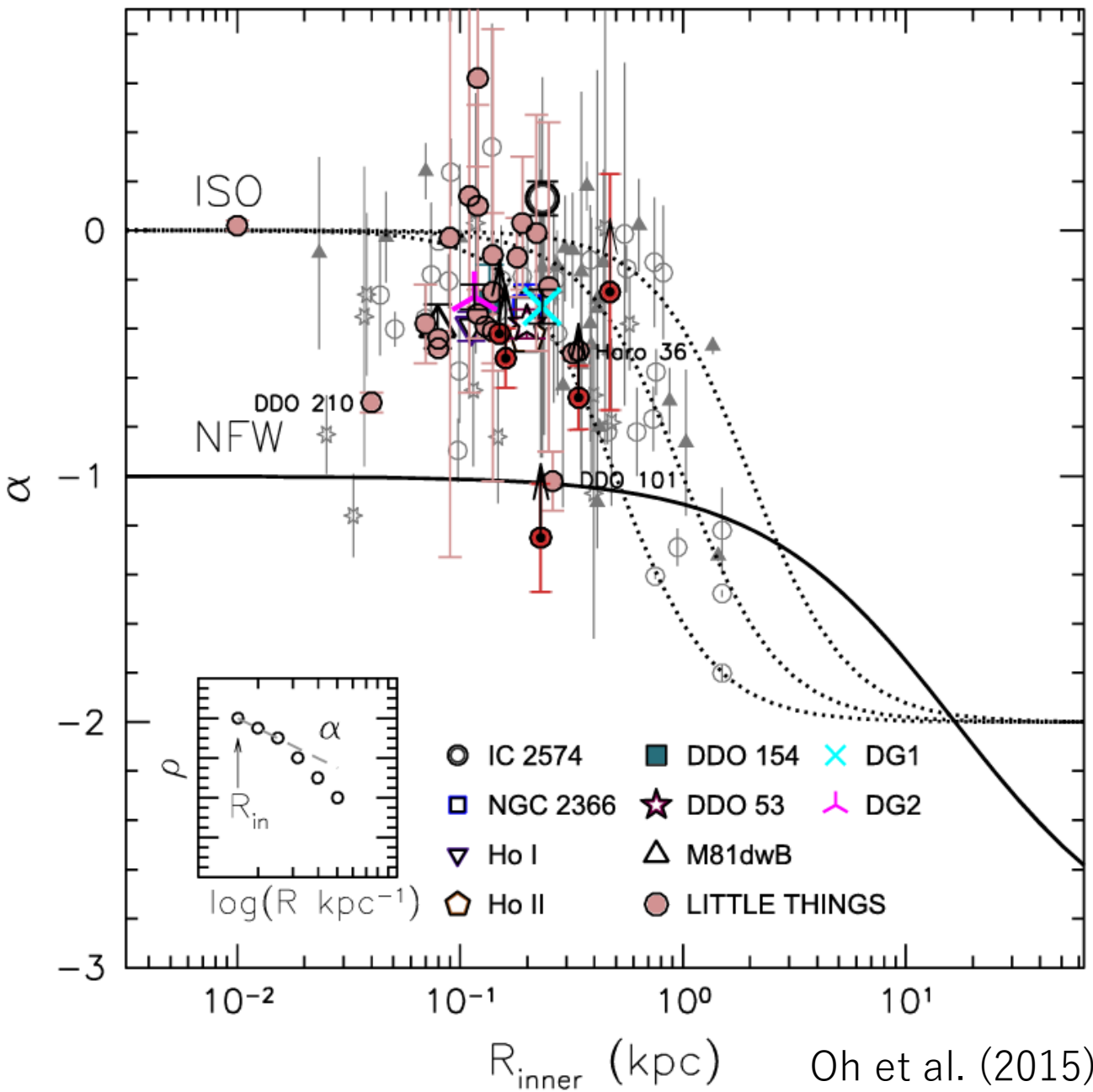
- ✓ Our results from **the HSC-SSP data** have demonstrated that **stacked weak lensing** is a viable tool for studying central density distributions of galaxies.
- ✓ We provide new constraints on
  - central dark matter profiles
    - **cored** distributions are favored in several mass bins
  - the SHMR
  - the stellar IMF
    - more **bottom-heavy** than Salpeter IMF

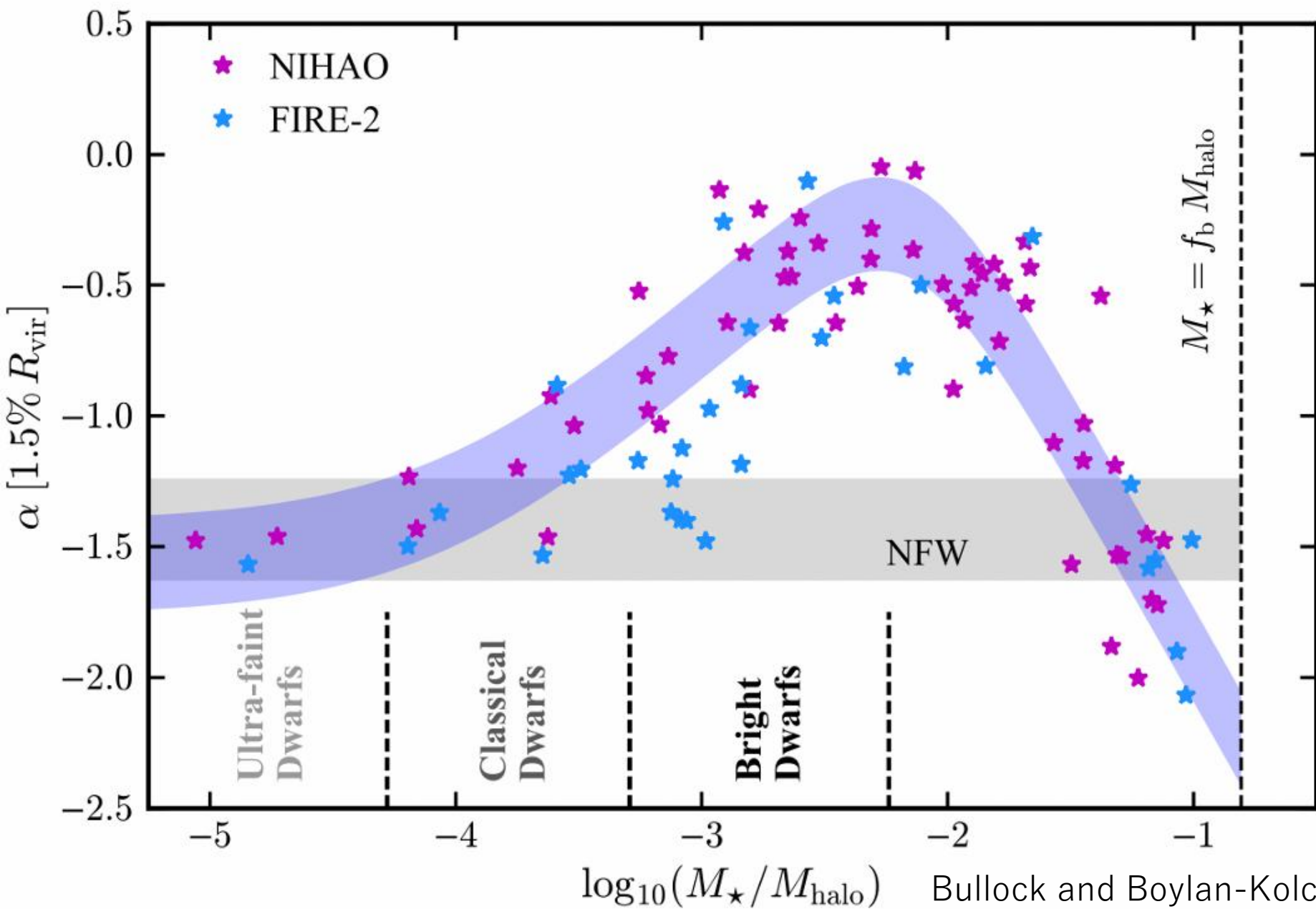
## Future Work

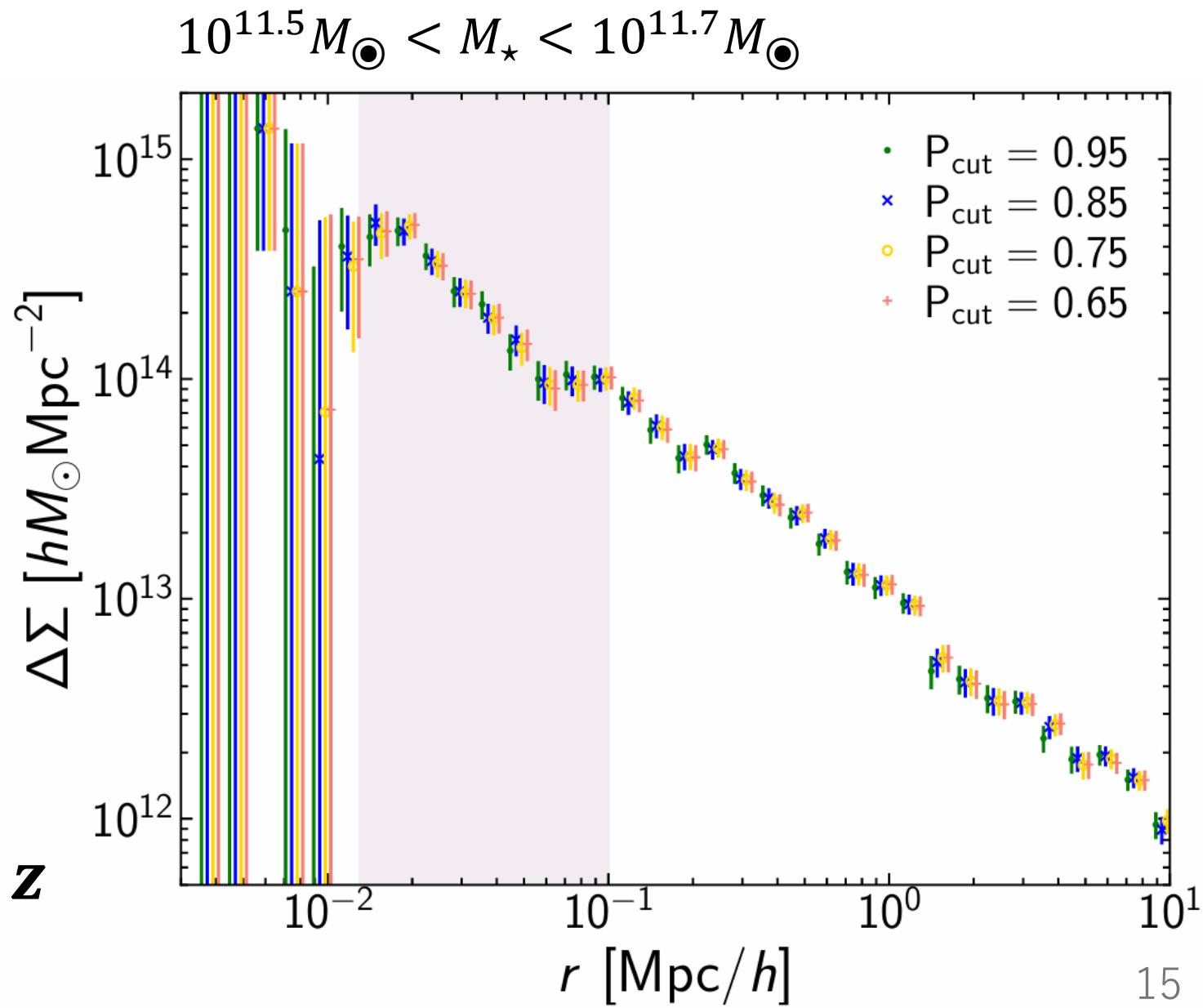
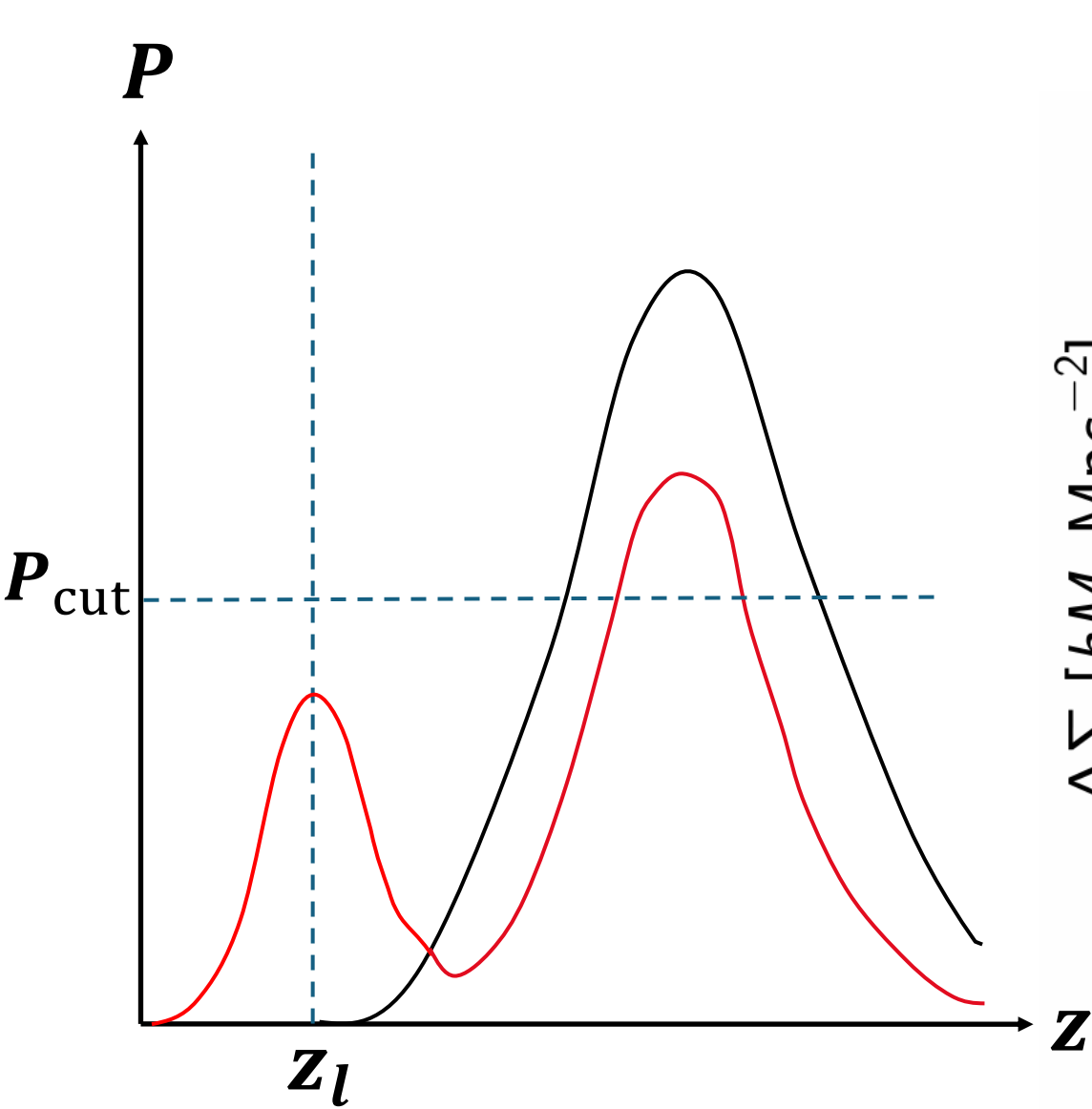
- considering **more flexible** dark matter profile model
- combining the constraints with those from **strong gravitational lensing**

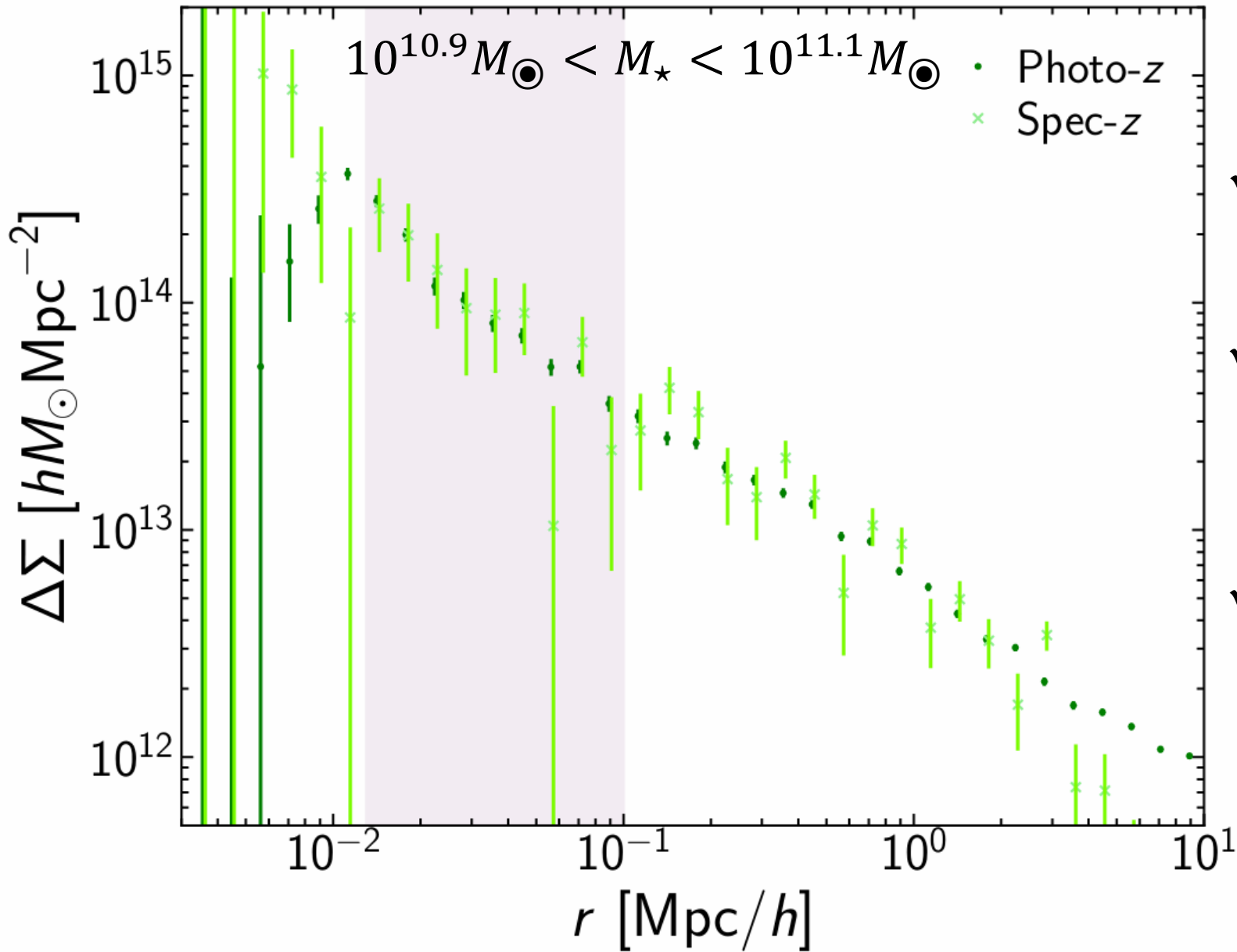
---

# Backup Slides





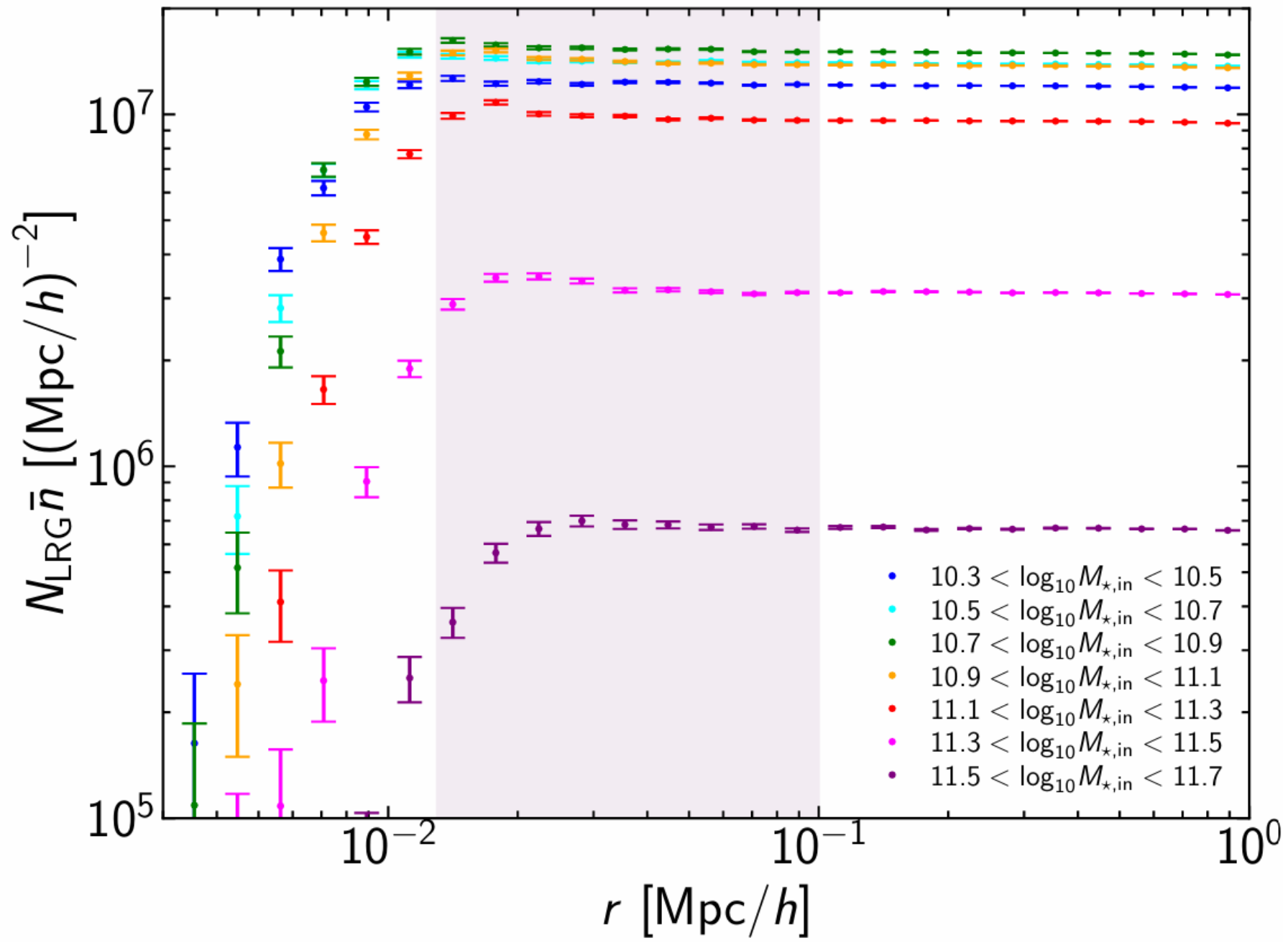




$$\sqrt{\chi^2} = \sum \frac{(\Delta\Sigma_{spec} - \Delta\Sigma_{photo})^2}{\sigma_{spec}^2 + \sigma_{photo}^2}$$

✓ For  $10^{11.3} M_{\odot} < M_{\star} < 10^{11.5} M_{\odot}$ ,  $\chi^2$  falls outside the 95% confidence interval ( $2.7 \lesssim \chi^2 \lesssim 19.0$ )

✓ For the other mass bins,  $\chi^2$  is within the 95% confidence interval



- ✓ stellar matter (SM) component → Hernquist (parameters  $M_*$ ,  $r_e$ )
- ✓ dark matter (DM) component → **cored power-law**

$$\rho_{DM}(r) = M_* \frac{3 + \gamma}{2\pi^{\frac{3}{2}} r_e^3} \frac{\Gamma\left(-\frac{\gamma}{2}\right)}{\Gamma\left(-\frac{1 + \gamma}{2}\right)} A \left(\frac{r^2 + r_c^2}{r_e^2}\right)^{\frac{\gamma}{2}}$$

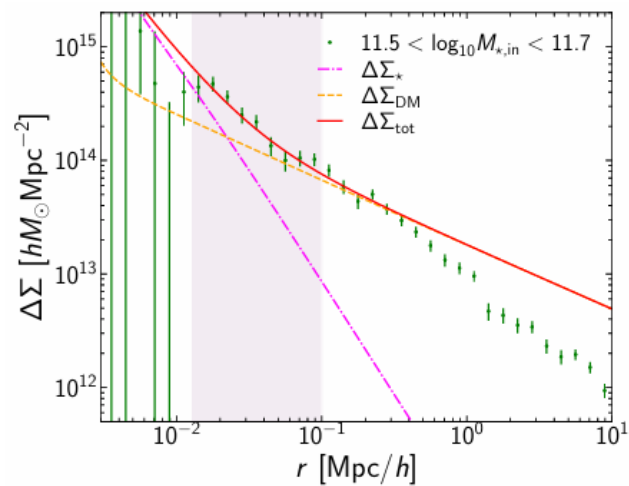
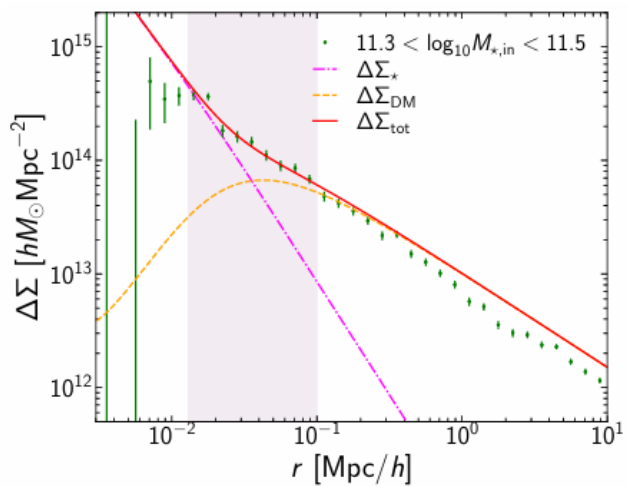
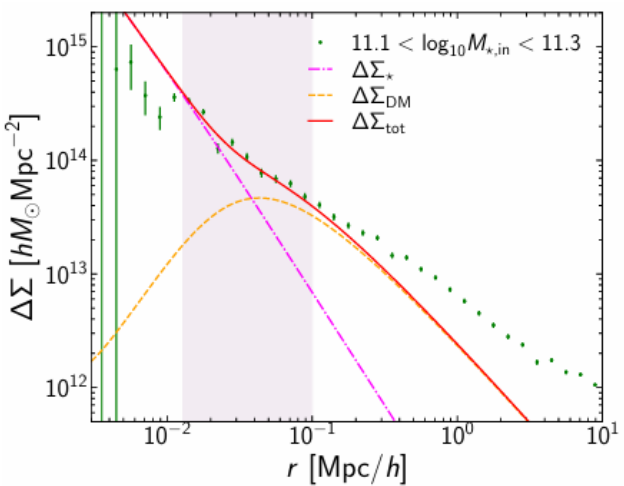
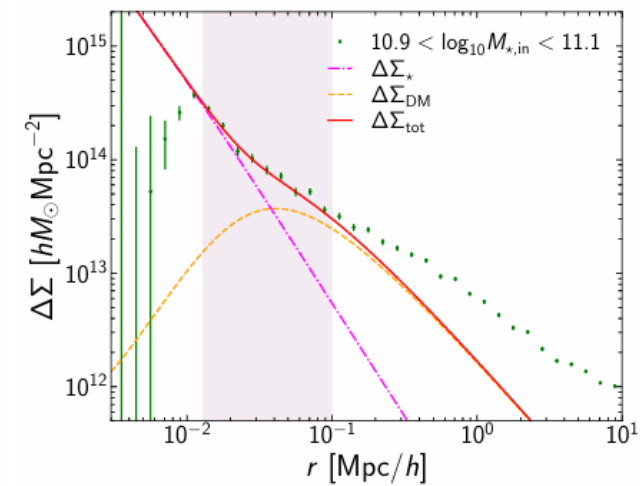
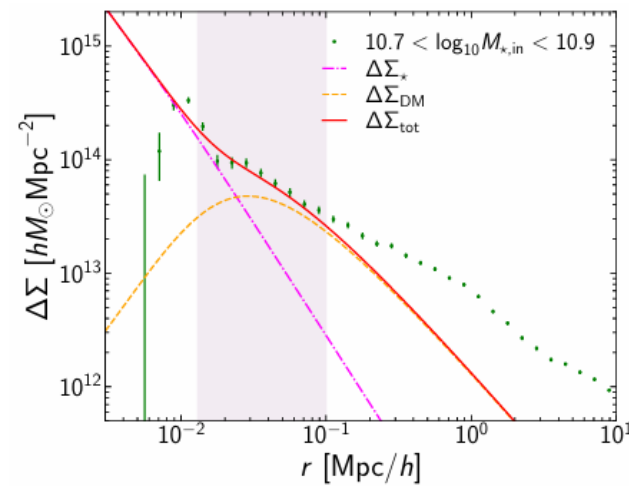
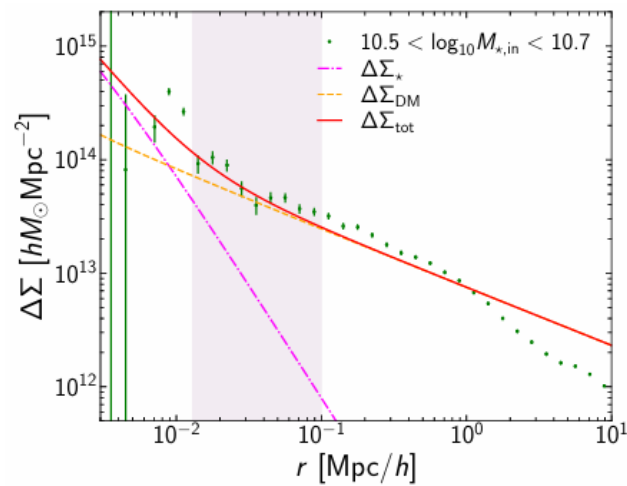
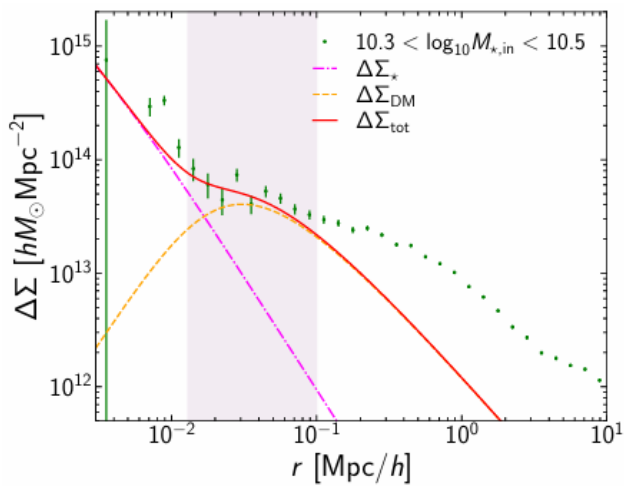
$$\Sigma_{DM}(r) = \int_{-\infty}^{\infty} \rho_{DM}\left(\sqrt{r^2 + Z^2}\right) dZ$$

$$M_{2D}(< r) = \int_0^r 2\pi r \Sigma_{DM}(r) dr$$

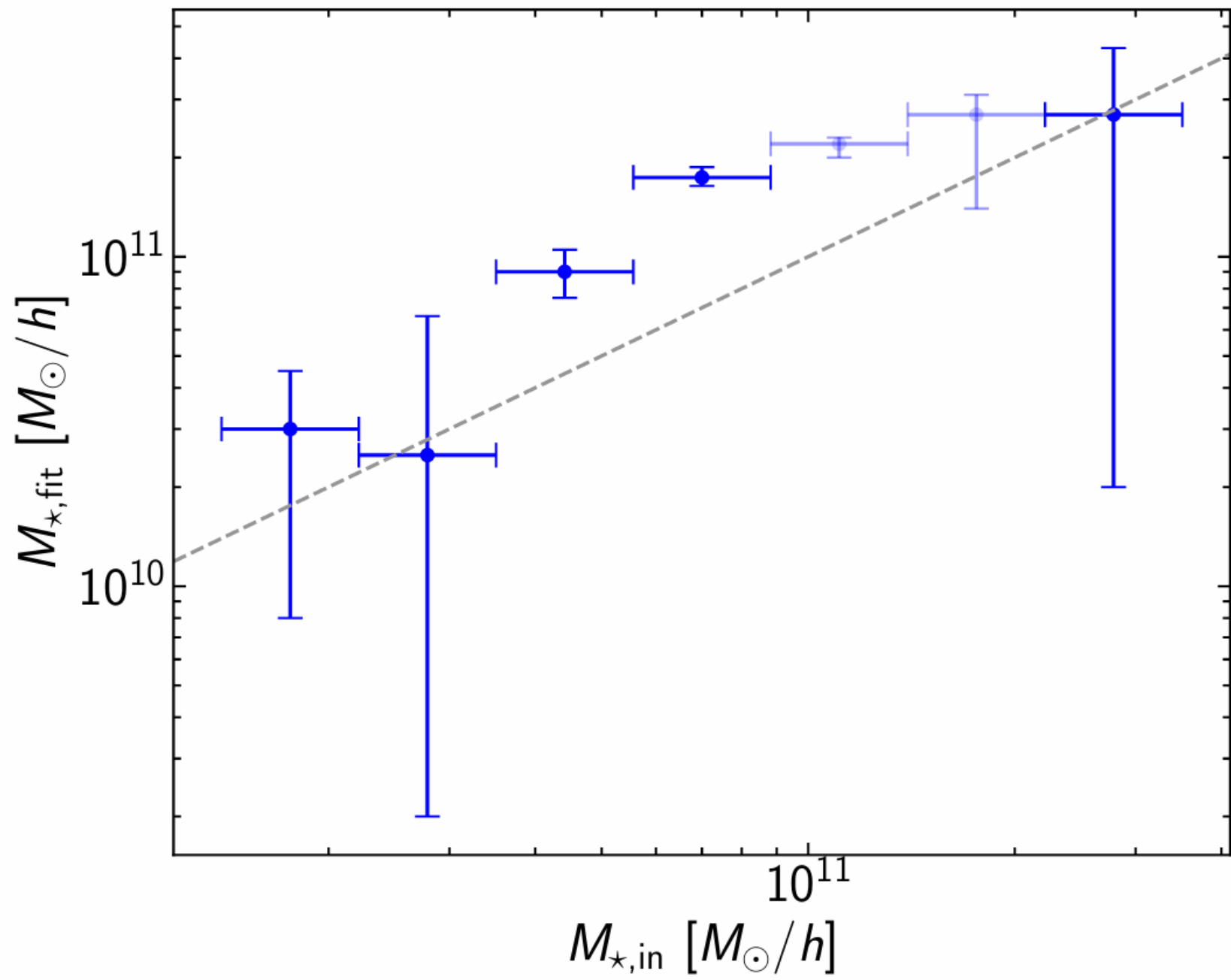
$$\bar{\Sigma}_{DM}(< r) = \frac{M_{2D}(< r)}{\pi r^2}$$

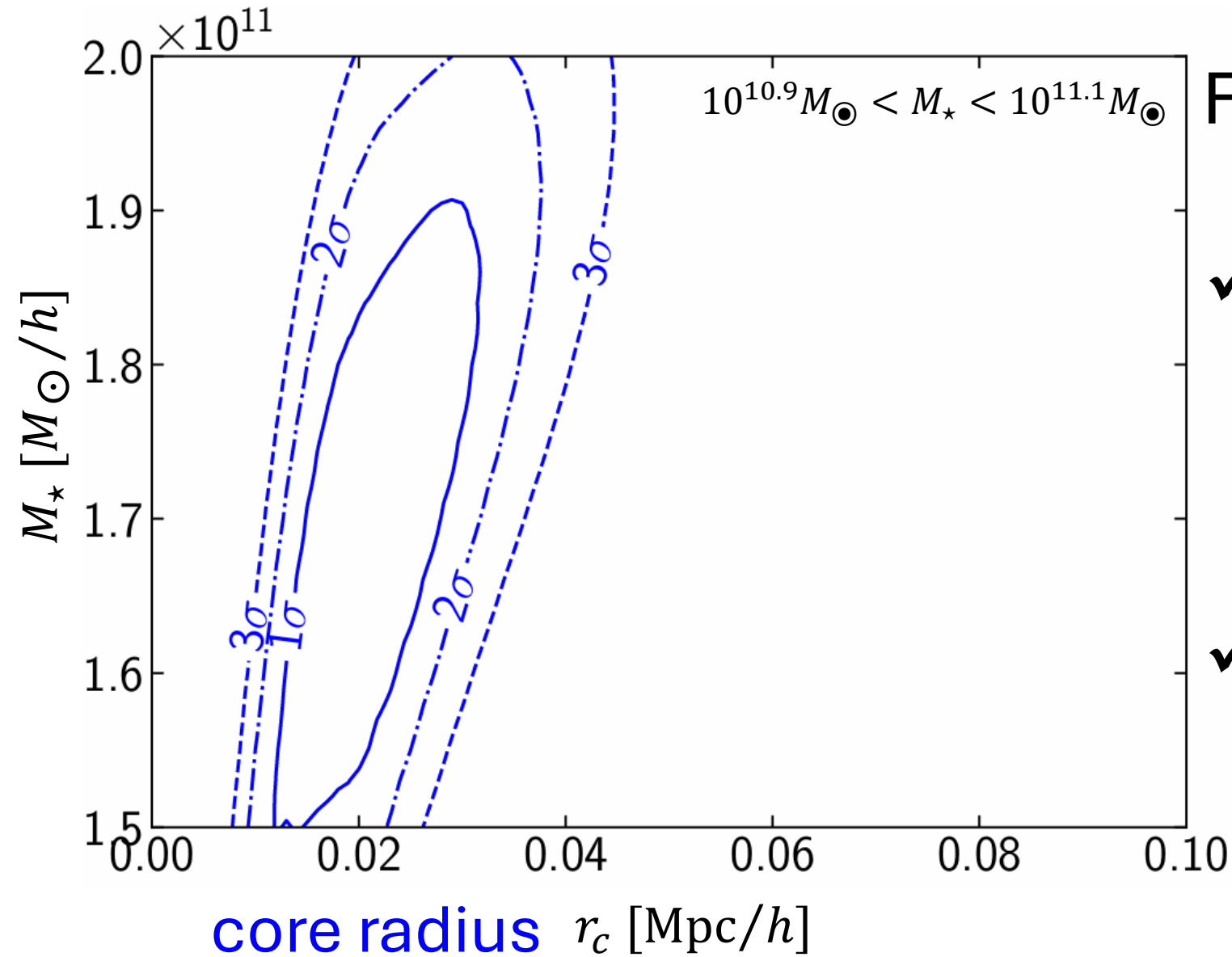
$$\Delta\Sigma_{DM} = \bar{\Sigma}_{DM}(< r) - \Sigma_{DM}(r)$$

→ total mass  $\Delta\Sigma_{tot} = \Delta\Sigma_{SM} + \Delta\Sigma_{DM}$



$\log_{10}(M_{\star,\text{in}}[M_{\odot}])$	$N_{\text{LRG}}$	$r_e$ [Mpc/ $h$ ]	$A$	$\gamma$	$r_c$ [Mpc/ $h$ ]	$M_{\star,\text{fit}} [M_{\odot}/h]$	$\chi_{\text{in}}^2/\text{dof}$
10.3–10.5	$1.81 \times 10^5$	$1.4 \times 10^{-3}$	$7.5_{-6.0}^{+12.0}$	$-2.50_{-0.00}^{+0.50}$	$1.8_{-0.9}^{+0.4} \times 10^{-2}$	$3.0_{-2.2}^{+1.5} \times 10^{10}$	9.4/5
10.5–10.7	$2.05 \times 10^5$	$1.4 \times 10^{-3}$	$0.2_{-0.0}^{+4.0}$	$-1.51_{-0.29}^{+0.06}$	$0.0_{-0.0}^{+1.5} \times 10^{-2}$	$2.5_{-2.3}^{+4.1} \times 10^{10}$	10.2/5
10.7–10.9	$2.23 \times 10^5$	$1.4 \times 10^{-3}$	$2.7_{-2.1}^{+0.4}$	$-2.50_{-0.00}^{+0.33}$	$1.7_{-0.4}^{+0.3} \times 10^{-2}$	$9.0_{-1.5}^{+1.5} \times 10^{10}$	11.8/5
10.9–11.1	$2.08 \times 10^5$	$1.5 \times 10^{-3}$	$1.9_{-1.6}^{+0.3}$	$-2.50_{-0.00}^{+0.41}$	$2.4_{-0.6}^{+0.5} \times 10^{-2}$	$1.7_{-0.1}^{+0.2} \times 10^{11}$	8.8/5
11.1–11.3	$1.49 \times 10^5$	$1.8 \times 10^{-3}$	$1.9_{-1.8}^{+0.7}$	$-2.46_{-0.04}^{+0.76}$	$2.5_{-1.3}^{+0.5} \times 10^{-2}$	$2.2_{-0.2}^{+0.1} \times 10^{11}$	19.2/5
11.3–11.5	$5.54 \times 10^4$	$2.3 \times 10^{-3}$	$0.2_{-0.1}^{+3.9}$	$-1.83_{-0.67}^{+0.52}$	$1.8_{-1.8}^{+1.7} \times 10^{-2}$	$2.7_{-1.3}^{+0.4} \times 10^{11}$	11.1/5
11.5–11.7	$1.02 \times 10^4$	$3.3 \times 10^{-3}$	$0.2_{-0.1}^{+8.0}$	$-1.56_{-0.52}^{+0.55}$	$1_{-1}^{+16} \times 10^{-3}$	$2.7_{-2.5}^{+1.6} \times 10^{11}$	6.4/5

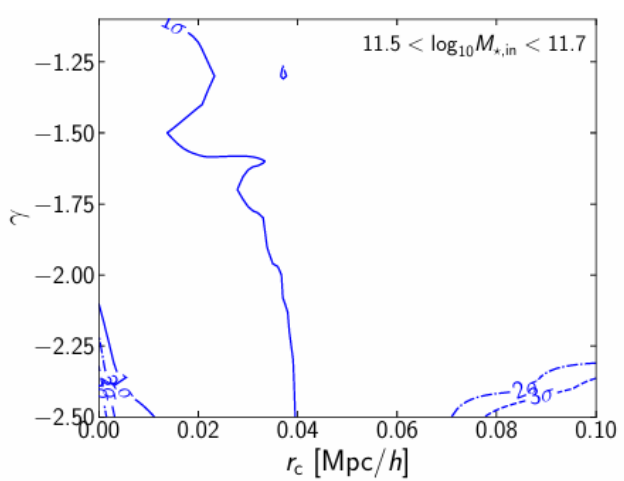
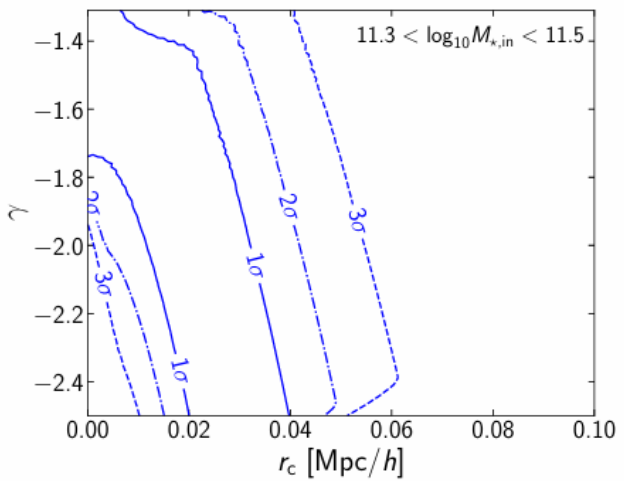
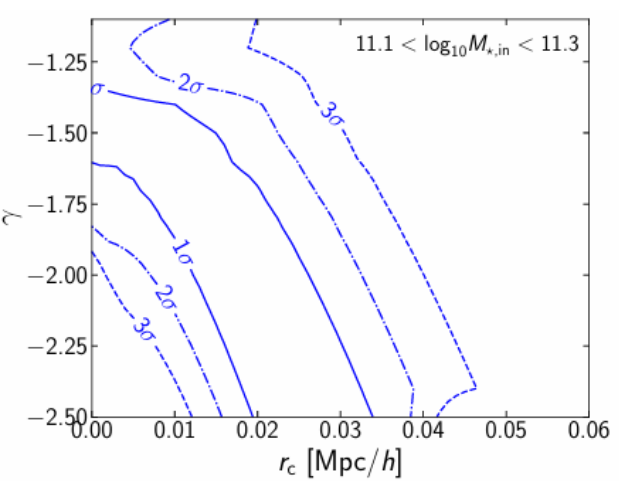
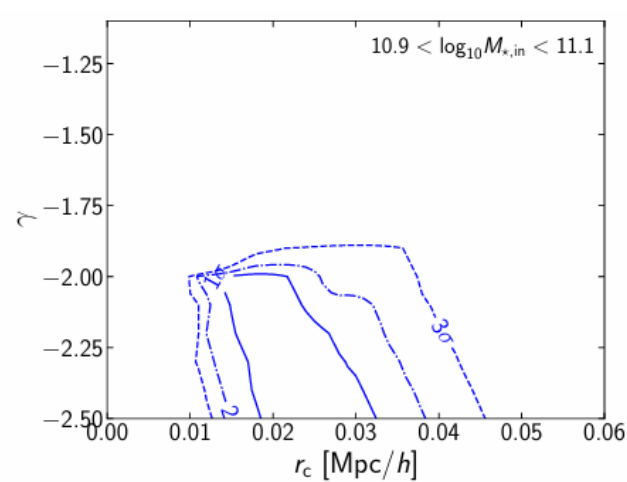
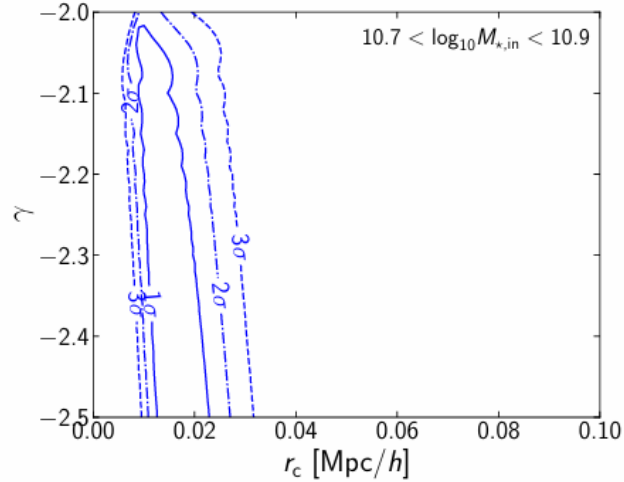
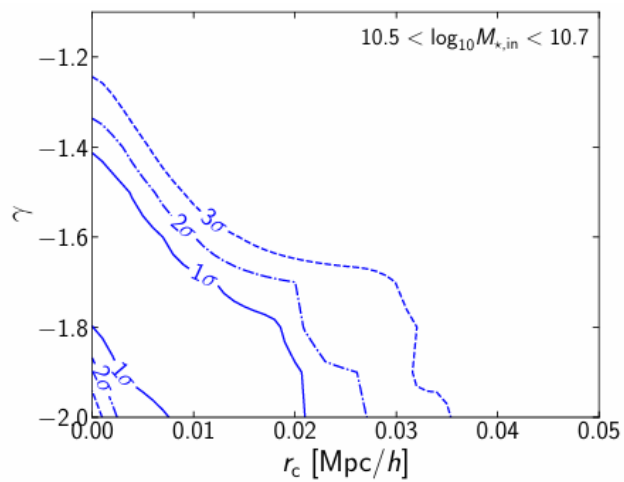
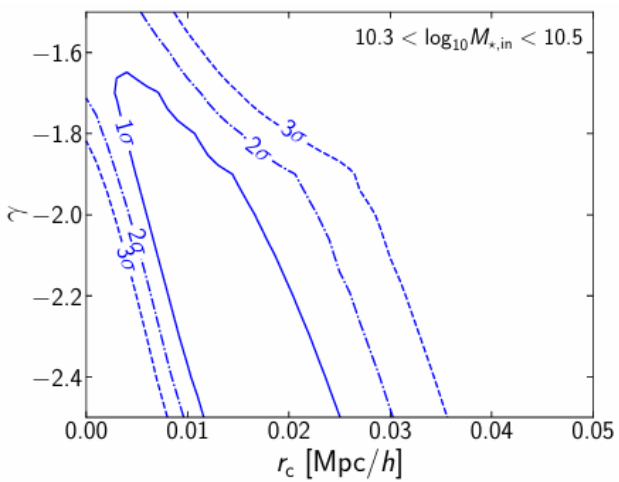




For  $10^{10.7} M_{\odot} < M_{\star} < 10^{11.1} M_{\odot}$ ,

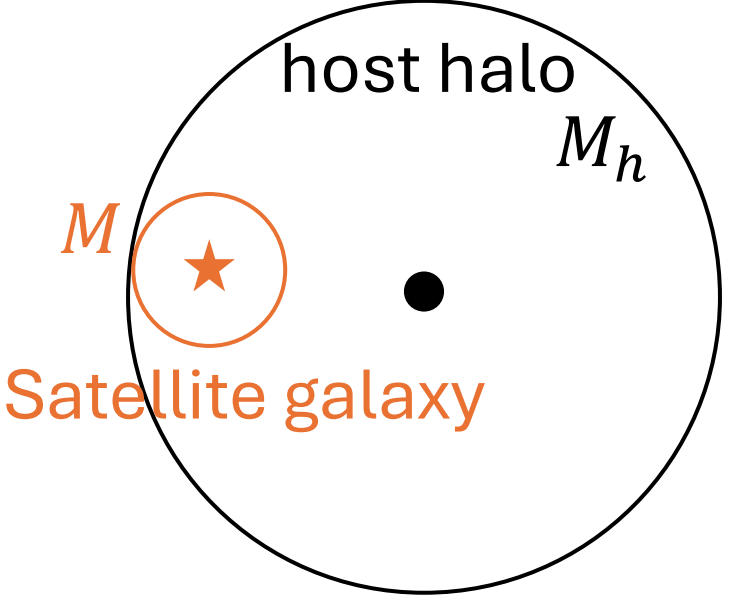
✓  $r_c$  is **inconsistent**  
with zero within  $3\sigma$   
➔ cored profile

✓ Because of the  
baryon feedback?



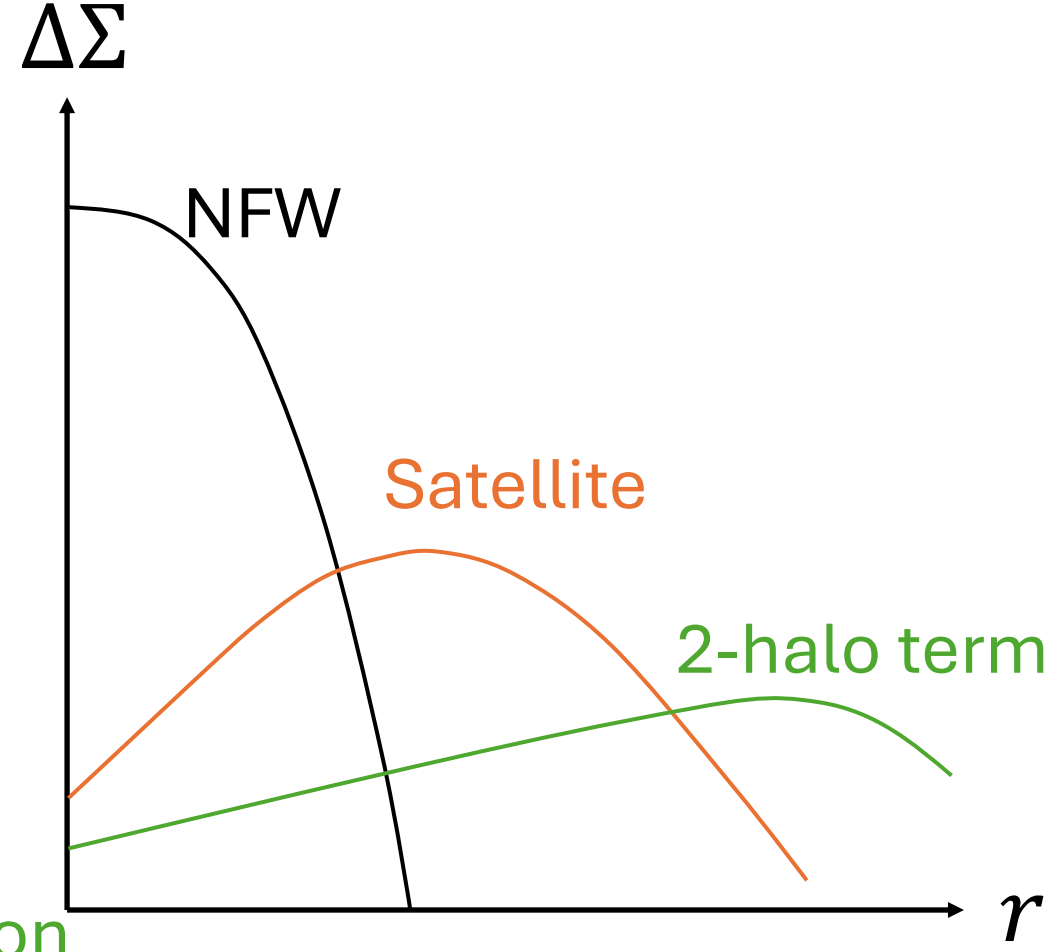
✓  $\Delta\Sigma(r) = \Delta\Sigma_{NFW}(M) + f_{sat}\Delta\Sigma_h(M_h) + \Delta\Sigma_{2h}(M, M_h)$

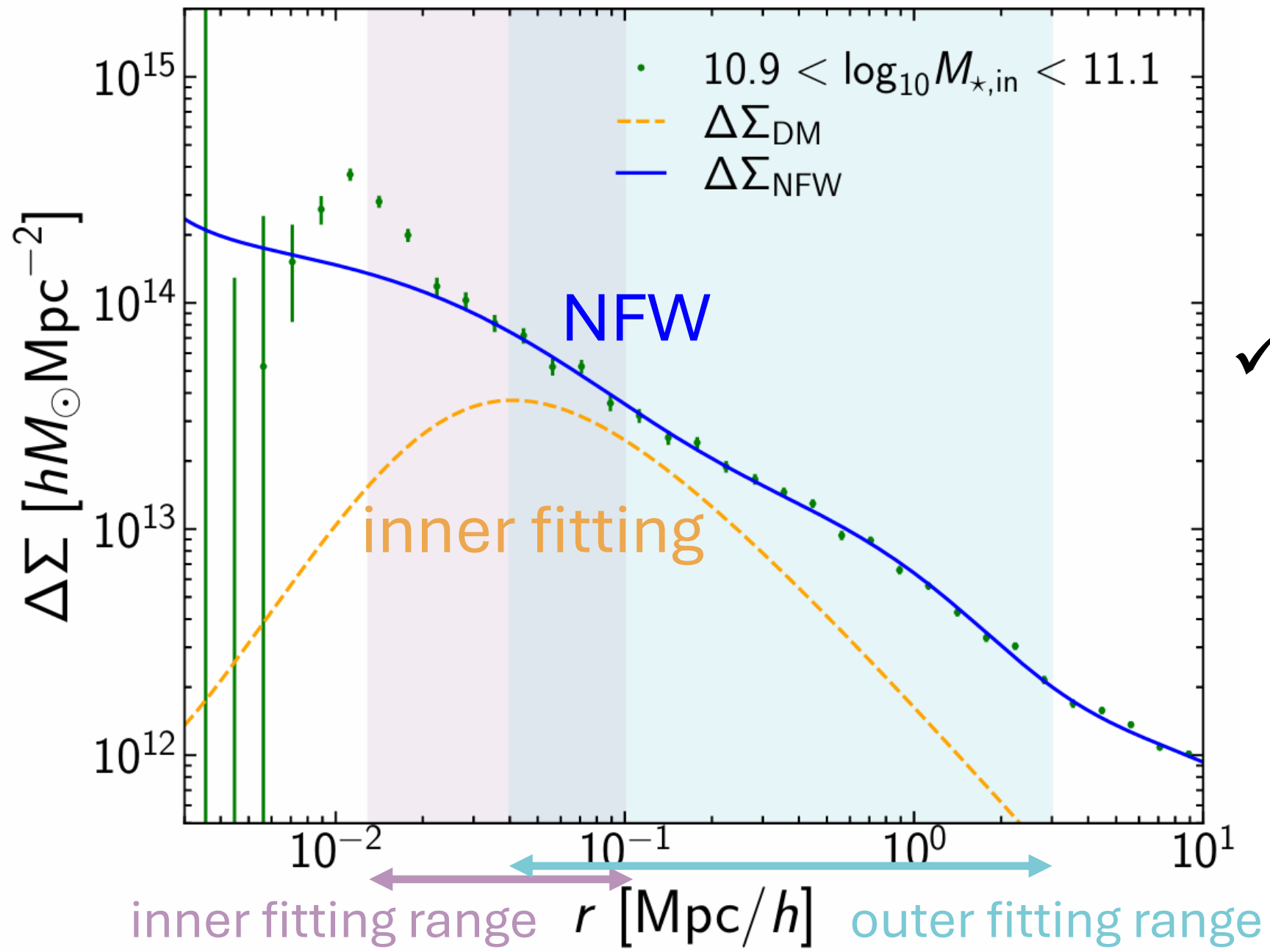
✓ Satellite galaxy



✓ 2-halo term

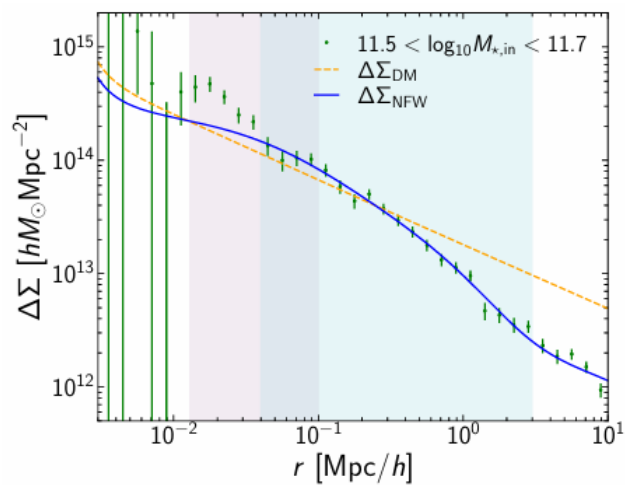
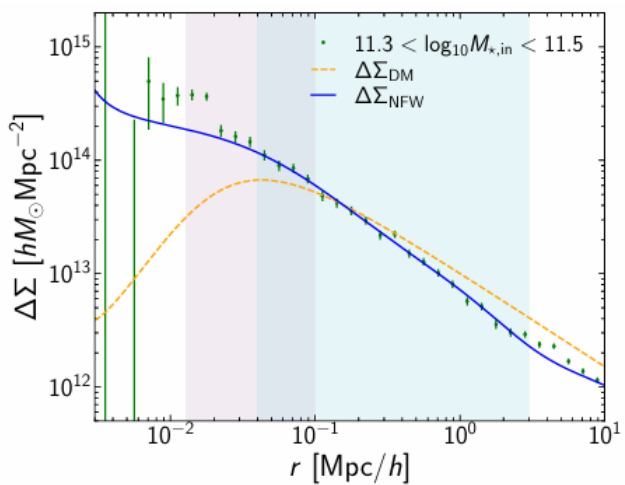
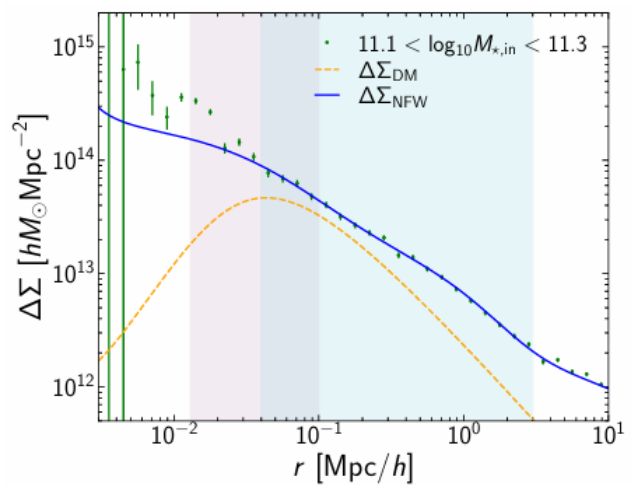
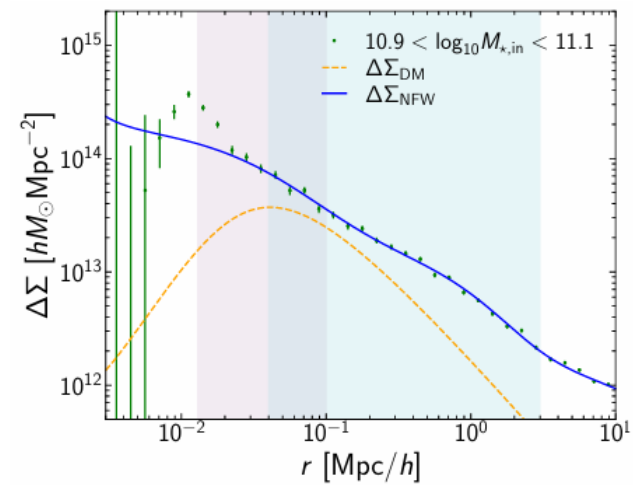
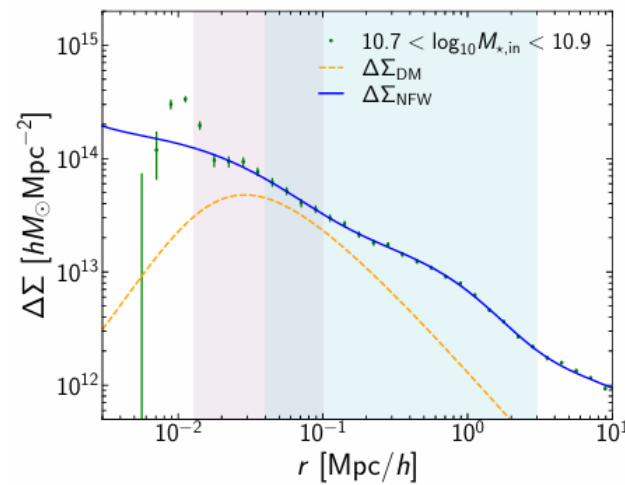
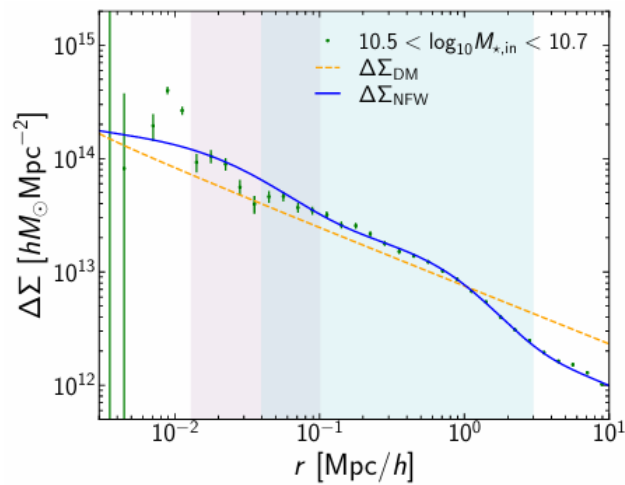
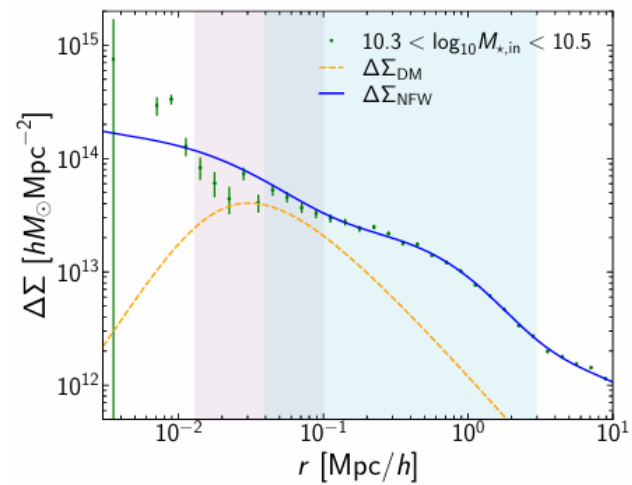
$\Delta\Sigma_{2h}(M, M_h) \propto \underbrace{b(M, M_h)}_{\text{halo bias}} \times \underbrace{\xi_m}_{\text{correlation function}}$



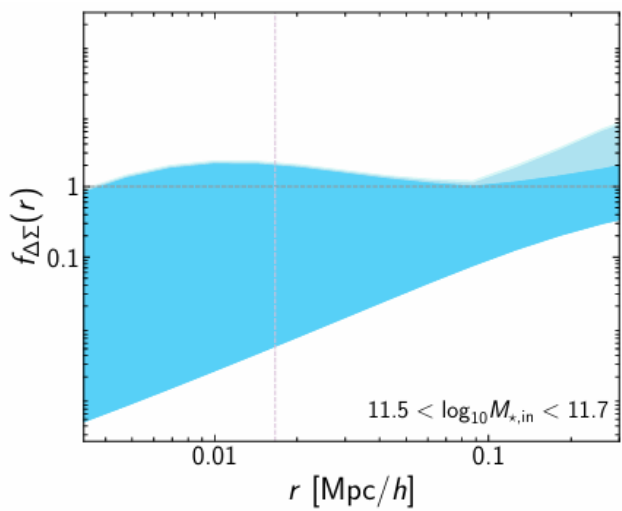
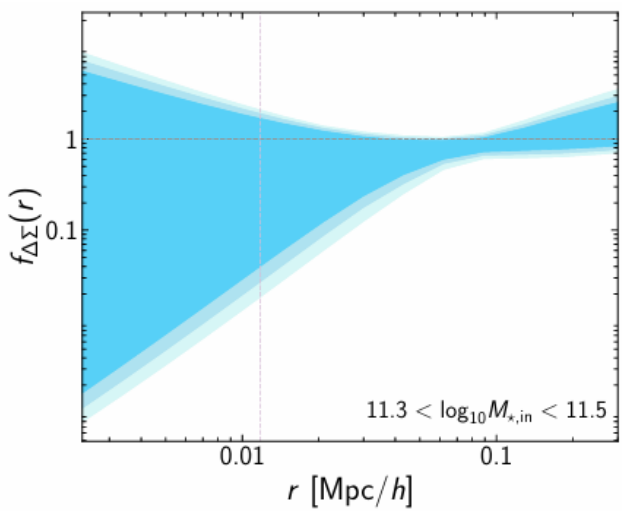
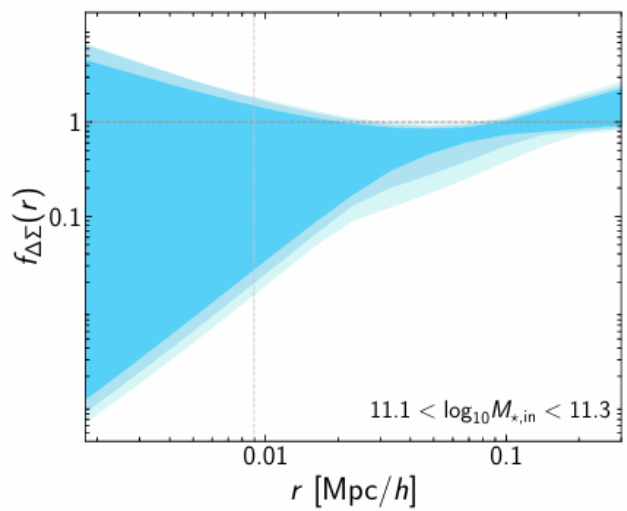
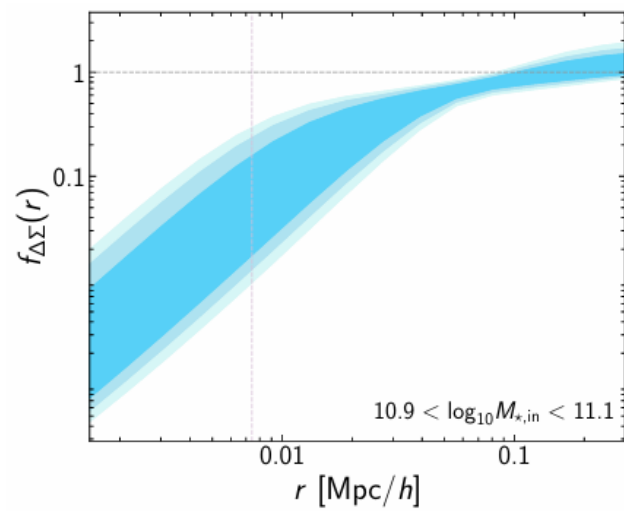
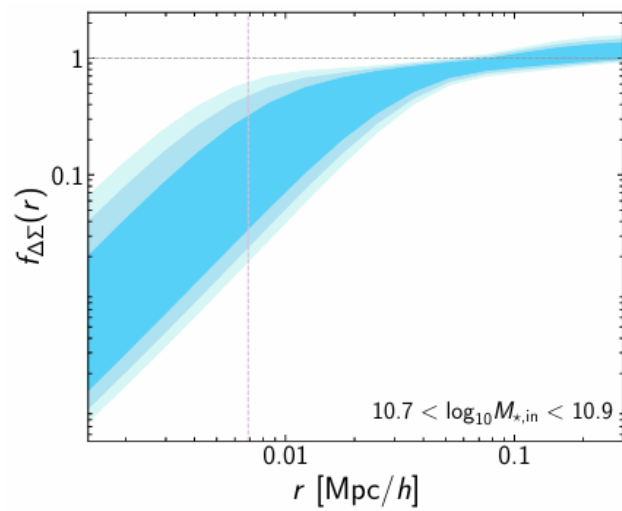
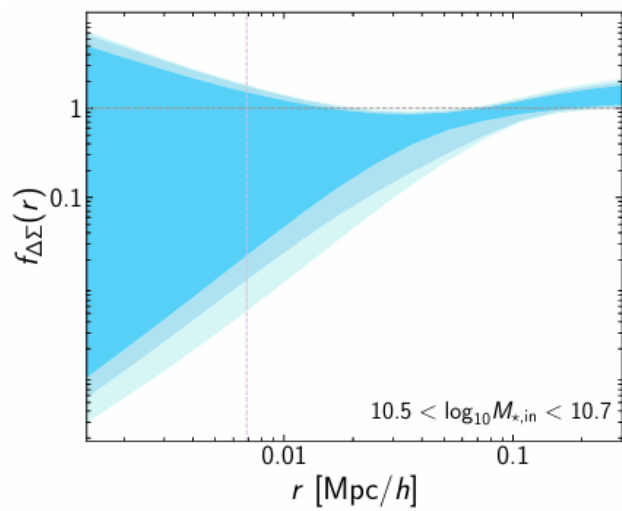
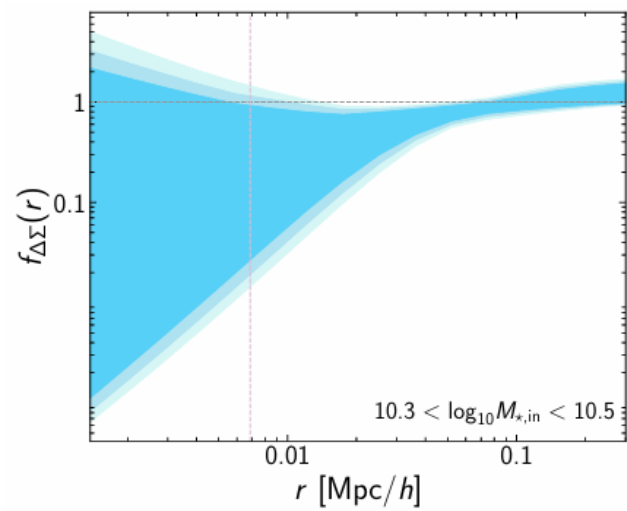


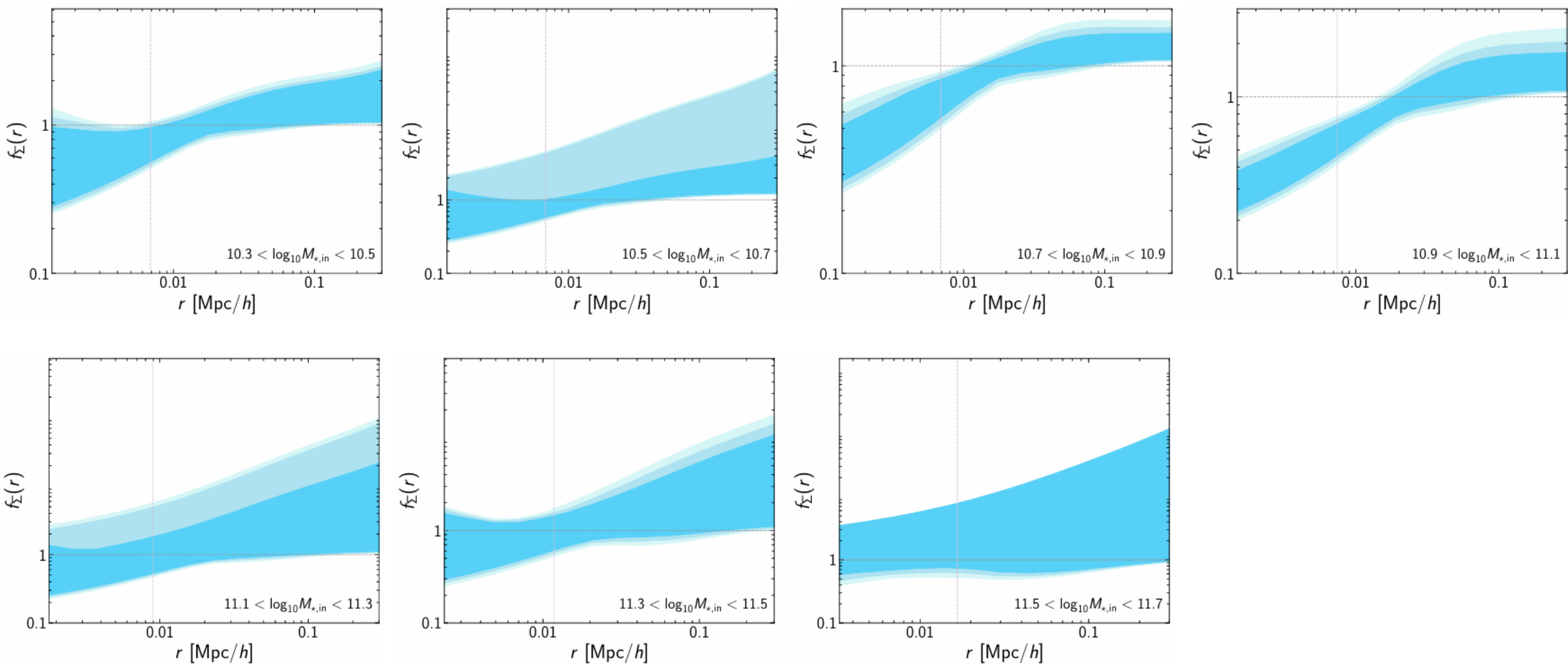
✓ evaluating with

$$f_{\Delta\Sigma}(r) = \frac{\Delta\Sigma_{\text{DM}}(r)}{\Delta\Sigma_{\text{NFW}}(r)}$$



$\log_{10}(M_{\star,\text{in}}[M_{\odot}])$	$M_{\text{NFW}} [M_{\odot}/h]$	$M_{\text{h}} [M_{\odot}/h]$	$f_{\text{sat}}$	$\chi_{\text{out}}^2/\text{dof}$
10.3–10.5	$1.2^{+0.1}_{-0.1} \times 10^{12}$	$5.1^{+0.1}_{-0.1} \times 10^{13}$	$0.40^{+0.00}_{-0.01}$	19.3/16
10.5–10.7	$1.3^{+0.1}_{-0.1} \times 10^{12}$	$5.4^{+0.5}_{-0.4} \times 10^{13}$	$0.32^{+0.02}_{-0.02}$	20.9/16
10.7–10.9	$1.4^{+0.1}_{-0.1} \times 10^{12}$	$5.5^{+0.6}_{-0.1} \times 10^{13}$	$0.27^{+0.02}_{-0.02}$	19.3/16
10.9–11.1	$1.8^{+0.1}_{-0.1} \times 10^{12}$	$6.8^{+0.9}_{-0.7} \times 10^{13}$	$0.21^{+0.02}_{-0.02}$	31.4/16
11.1–11.3	$2.6^{+0.2}_{-0.1} \times 10^{12}$	$6.7^{+1.1}_{-0.6} \times 10^{13}$	$0.21^{+0.02}_{-0.03}$	13.31/16
11.3–11.5	$4.7^{+0.4}_{-0.3} \times 10^{12}$	$1.1^{+0.4}_{-0.3} \times 10^{14}$	$0.14^{+0.03}_{-0.03}$	19.2/16
11.5–11.7	$7.6^{+1.3}_{-1.2} \times 10^{12}$	$4.9^{+4.1}_{-1.6} \times 10^{13}$	$0.30^{+0.10}_{-0.10}$	16.0/16





$\log_{10}(M_{\star,\text{in}}[M_{\odot}])$	$f_{\text{DM}}(< 5r_e)$
10.3–10.5	$0.19^{+0.70}_{-0.12}$
10.5–10.7	$0.51^{+0.45}_{-0.47}$
10.7–10.9	$0.087^{+0.125}_{-0.050}$
10.9–11.1	$0.035^{+0.050}_{-0.017}$
11.1–11.3	$0.056^{+0.431}_{-0.025}$
11.3–11.5	$0.14^{+0.53}_{-0.08}$
11.5–11.7	$0.50^{+0.42}_{-0.49}$