Fujikawa & Oguri 2026 OJAp, arXiv:2512.09342
Fujikawa & Oguri in prep

The stellar and dark matter distributions in early-type galaxies measured by weak and strong gravitational lensing

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4 August 2026 Precision Cosmology with Strong Lensing Time Delays

Introduction

Cold Dark Matter (CDM)

- interactions other than gravity ×
- collisionless damping ×

→ large-scale structure ✅
small-scale observations ☐
→ **Small-Scale Challenges**

e.g. cusp-core problem

In the central region of the halo,

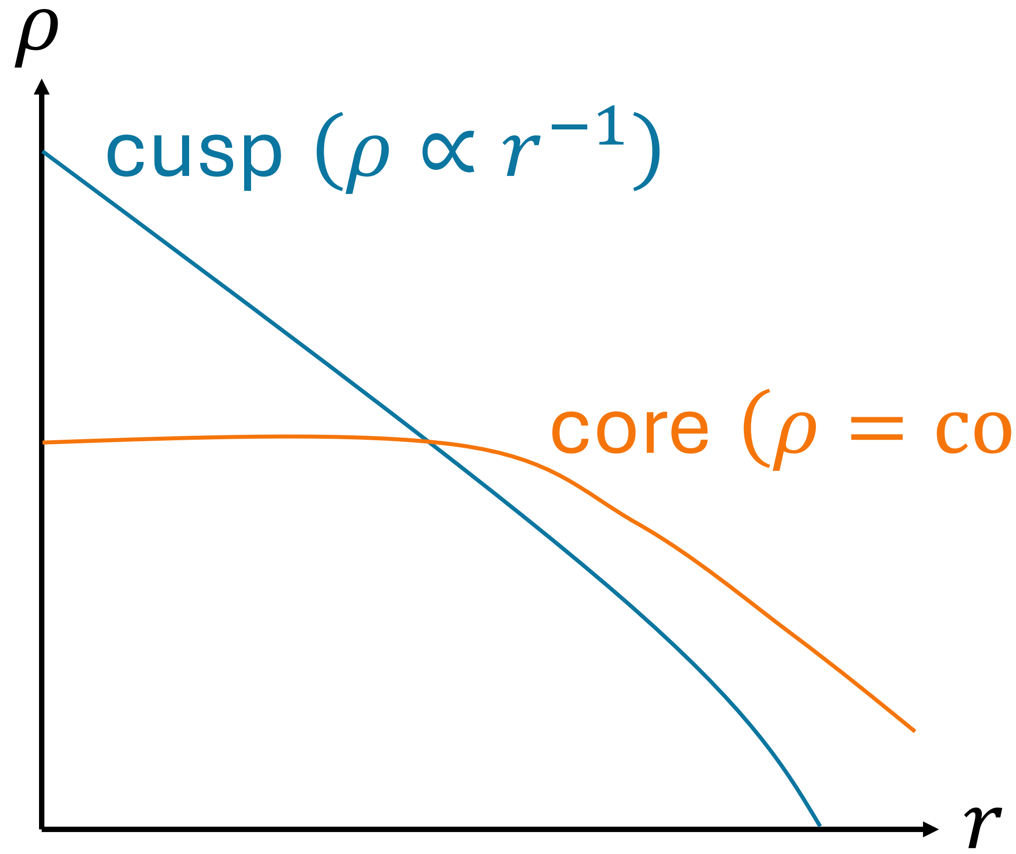
- CDM

  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



Motivation

- **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

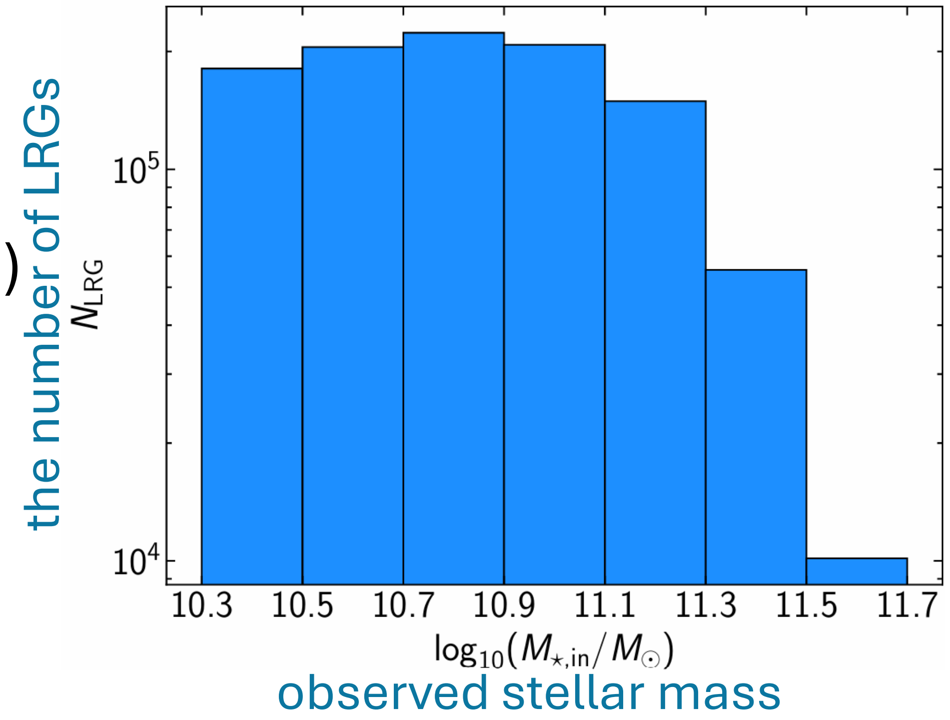
- **Advances in observational techniques**
  ➡ possibility of probing central density distributions of galaxies through weak gravitational lensing

Weak Lensing Analysis

Data

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

- source galaxy
  - 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)
  - $0.4 < z < 0.6$



Method

measured tangential shear of source galaxy γ_t

→ differential surface mass density of lens galaxy

$$\Delta\Sigma(r) = \gamma_t \times \Sigma_{\mathrm{cr}}$$
$$= \bar{\Sigma}(< r) - \Sigma(r)$$

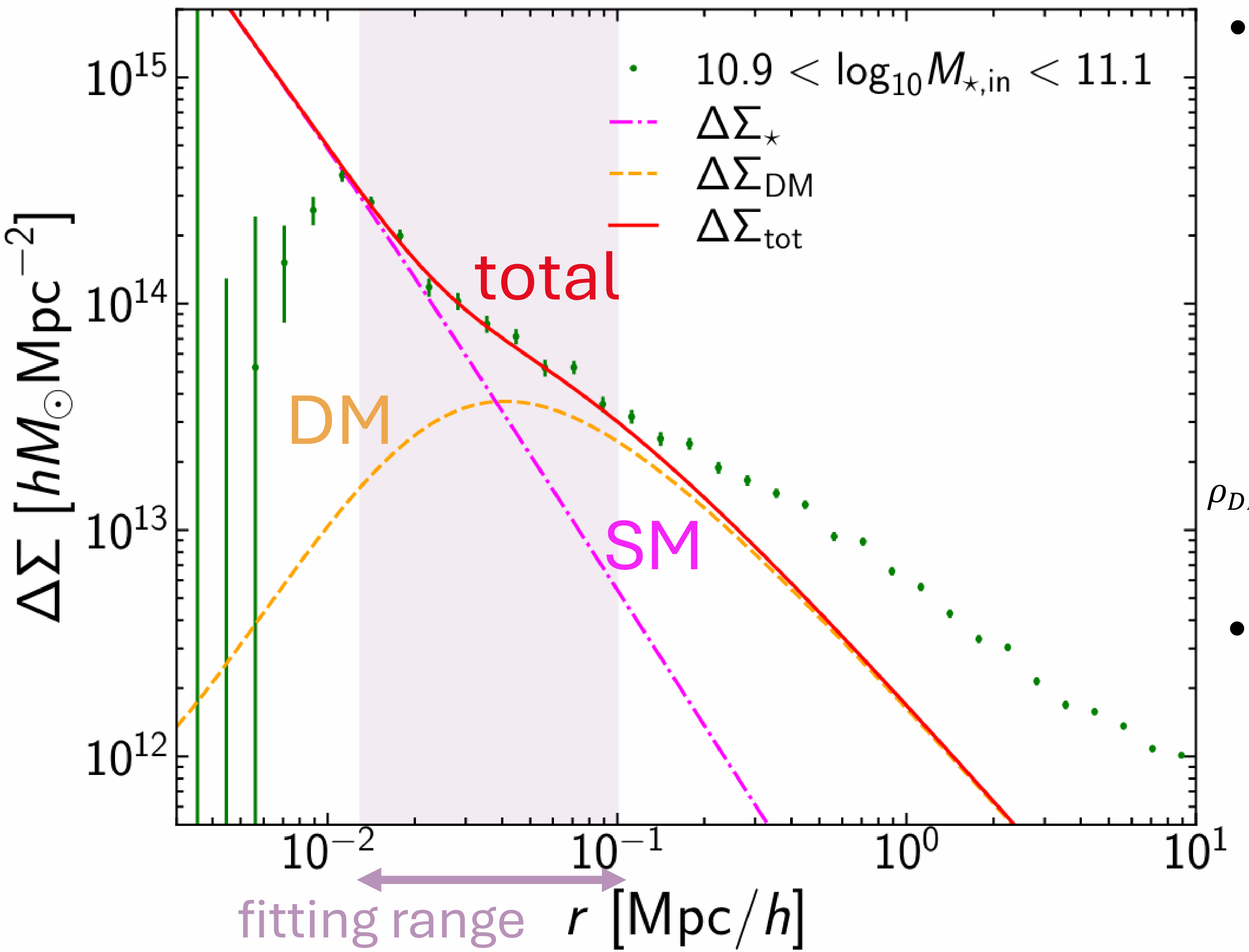
Σ_{cr} : critical surface mass density

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

Individual lensing signal is too small

→ stacking a large number of lens galaxies

Inner Profile Fitting



- Model
  stellar matter (SM)
  ➡ Hernquist

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

  dark matter (DM)
  ➡ cored power-law

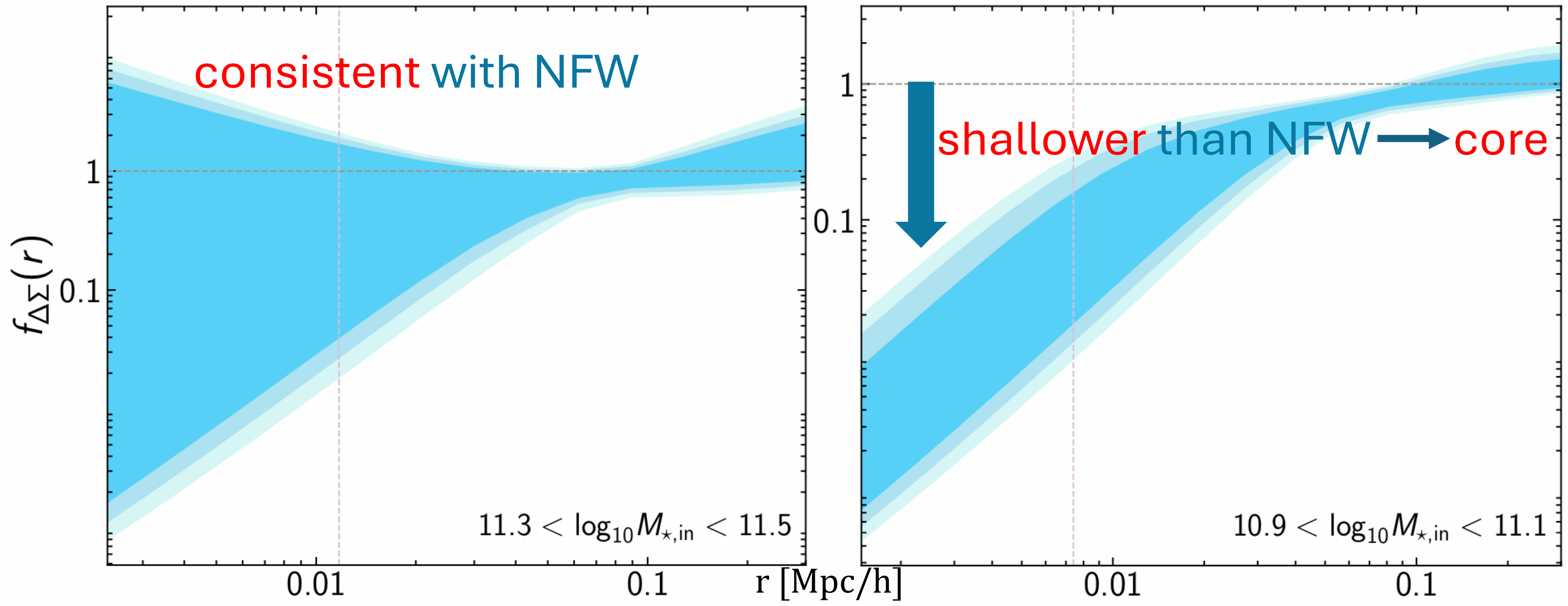
$$\rho_{DM}(r) = M_\star \frac{3+\gamma}{2\pi^{\frac{3}{2}} {r_e}^3} \frac{\Gamma\left(-\frac{\gamma}{2}\right)}{\Gamma\left(-\frac{1+\gamma}{2}\right)} A \left(\frac{r^2 + {r_c}^2}{{r_e}^2}\right)^{\frac{\gamma}{2}}$$

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

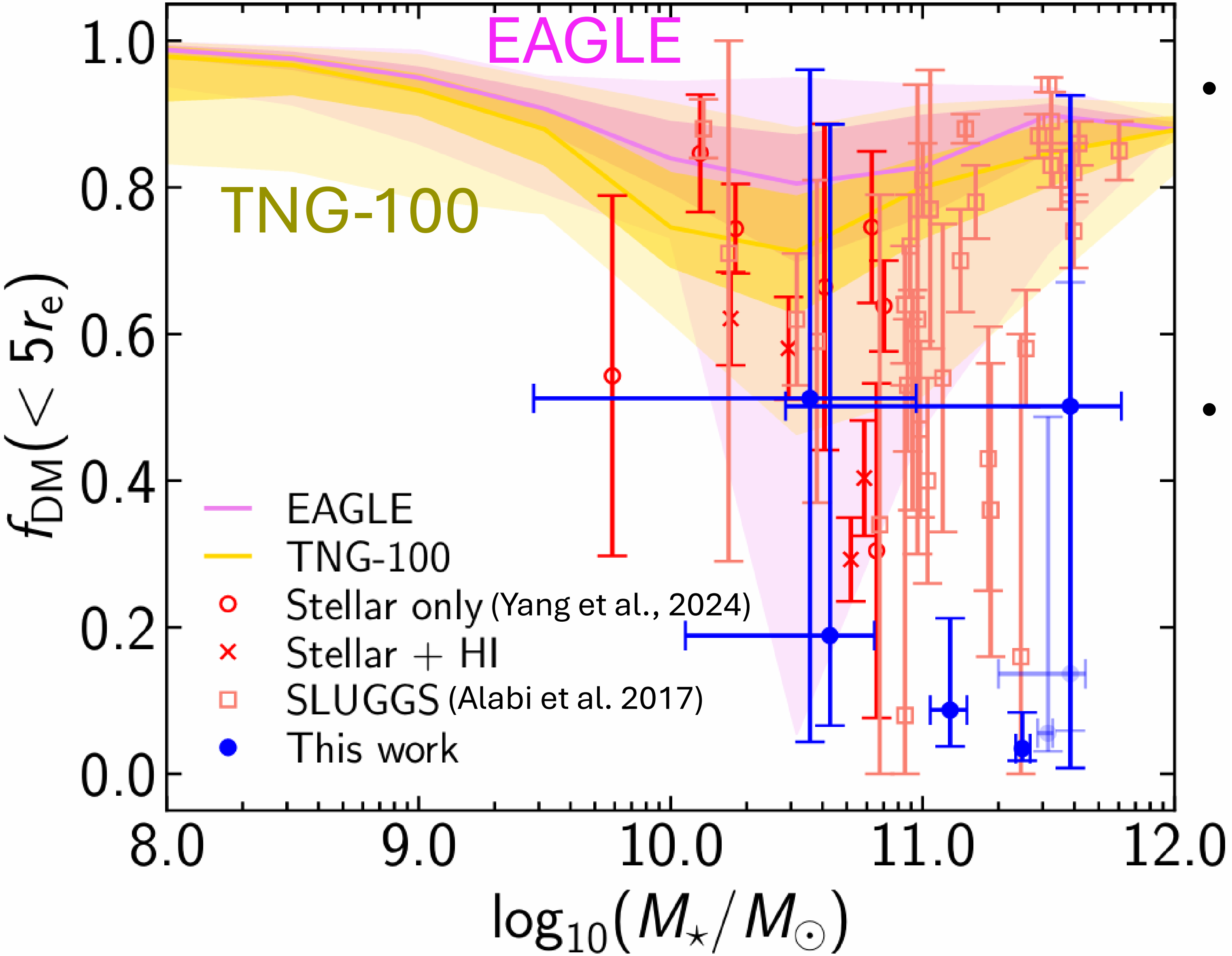
Comparison with NFW

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

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



Comparison with simulations



- dark matter fraction

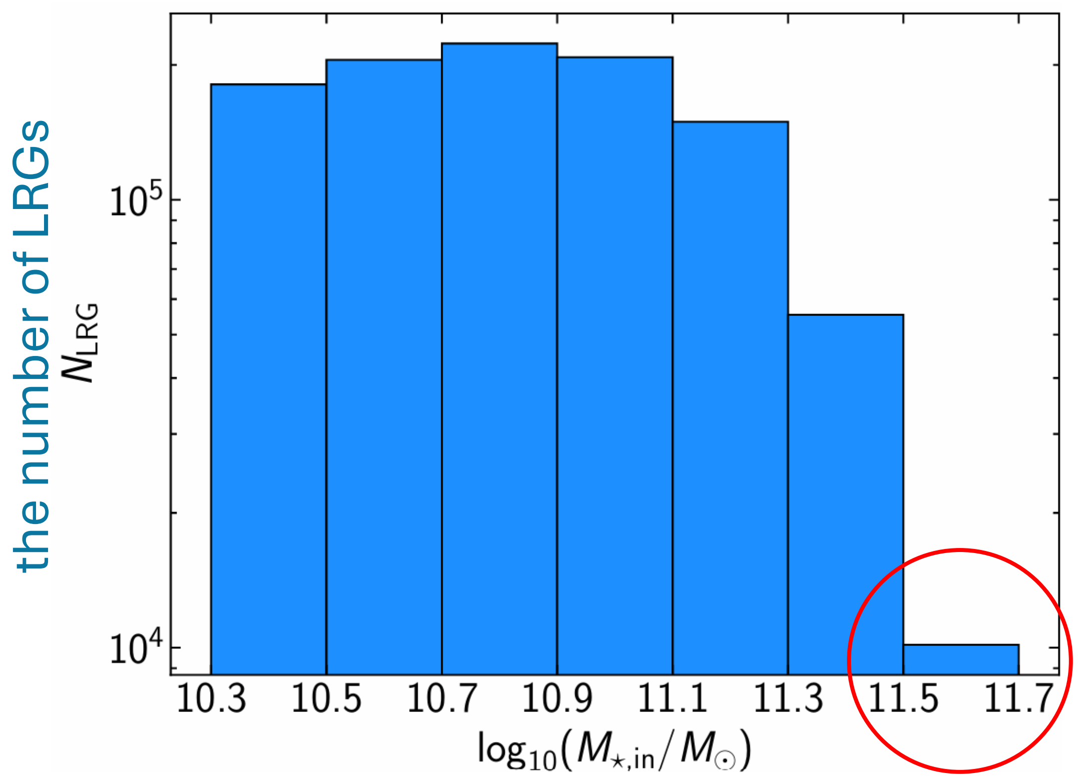
$$f_{DM}(< 5r_e) = \frac{M_{\rm DM}(r<5r_e)}{M_\star(r<5r_e)+M_{\rm DM}(r<5r_e)}$$

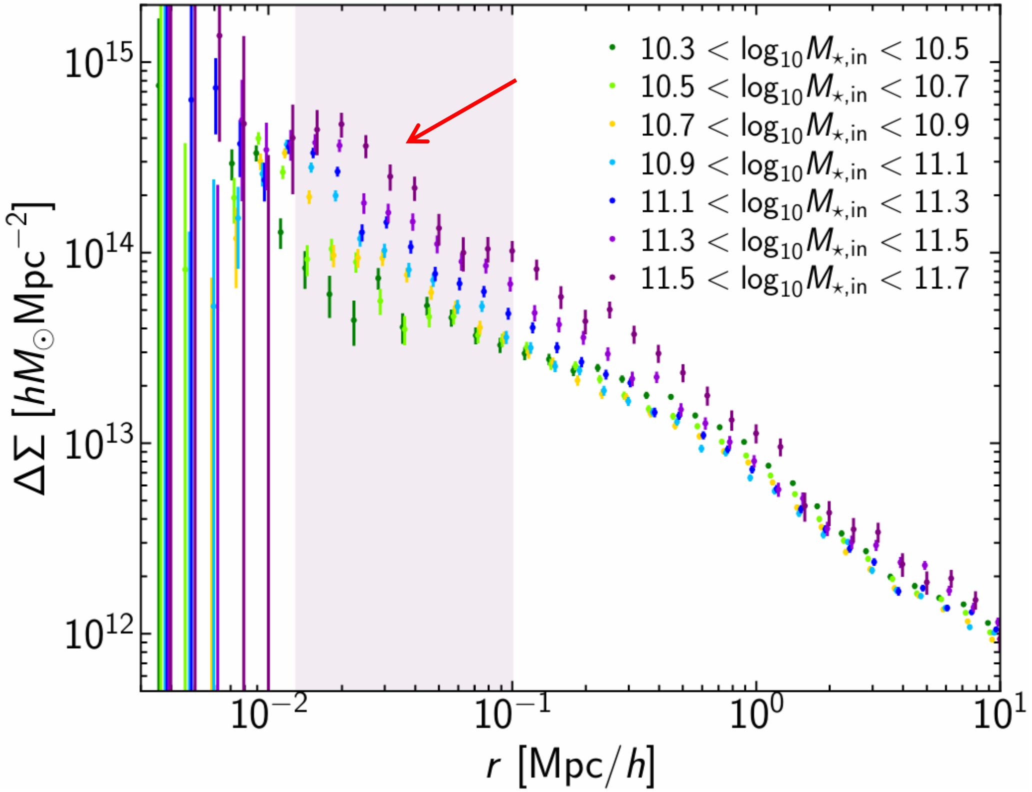
(r_e: the half-light radius)

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

actual feedback effect may be stronger

Limitation of Weak Lensing Analysis





For the highest stellar mass bin,
small number of lens galaxies → large statistical uncertainty
(intrinsic shape noise)

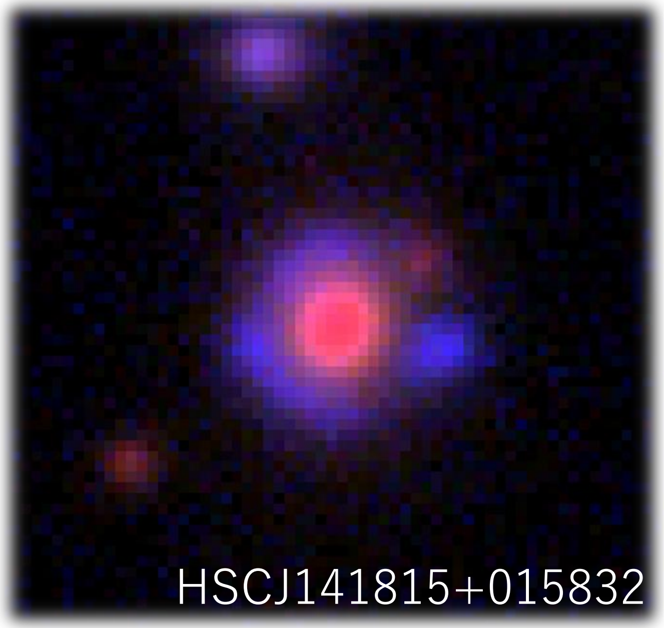
combining weak and strong lensing
to obtain tighter constraints in the highest stellar mass bin

Strong Lensing Analysis

Data

14 strong lens systems with spec-z from

- Survey of Gravitationally-lensed Objects in HSC Imaging (SuGOHI; Sonnenfeld et al. 2019; Gawade et al. 2025)
- Strong Lensing Legacy Survey (SL2S; Gavazzi et al. 2012; Tan et al. 2024)
- BOSS Emission-Line Lens Survey (BELLS; Brownstein et al. 2011; Tan et al. 2024)



Method

- Einstein radius θ_{Ein}
- spec-z of lens and source galaxy

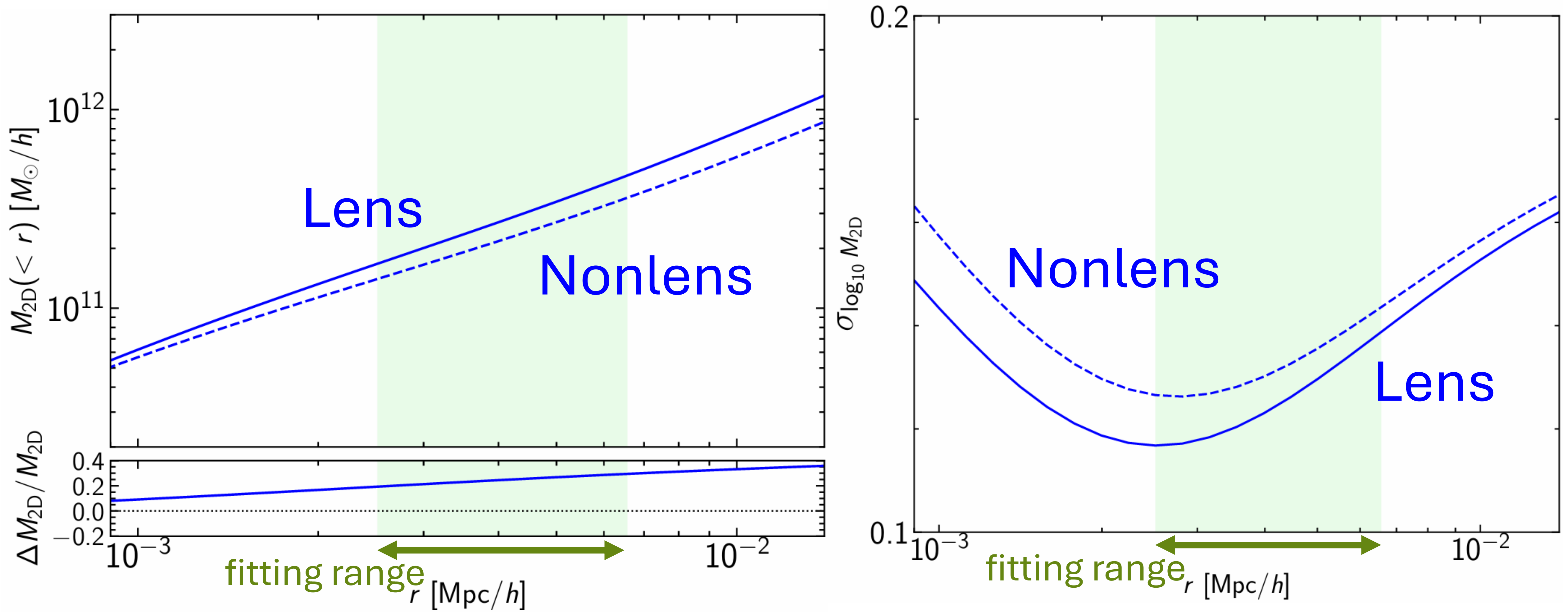
→ $$\mathrm{M_{2D}}(< \theta_{\mathrm{Ein}}) = \pi \mathrm{D_{ol}}^2 \theta_{\mathrm{Ein}}^2 \Sigma_{\mathrm{cr}}$$

$\mathrm{D_{ol}}$: angular diameter distance between the observer and the lens galaxy

Σ_{cr} : critical surface mass density

applying to multiple lens galaxies → average $\mathrm{M_{2D}}(< \mathrm{r})$

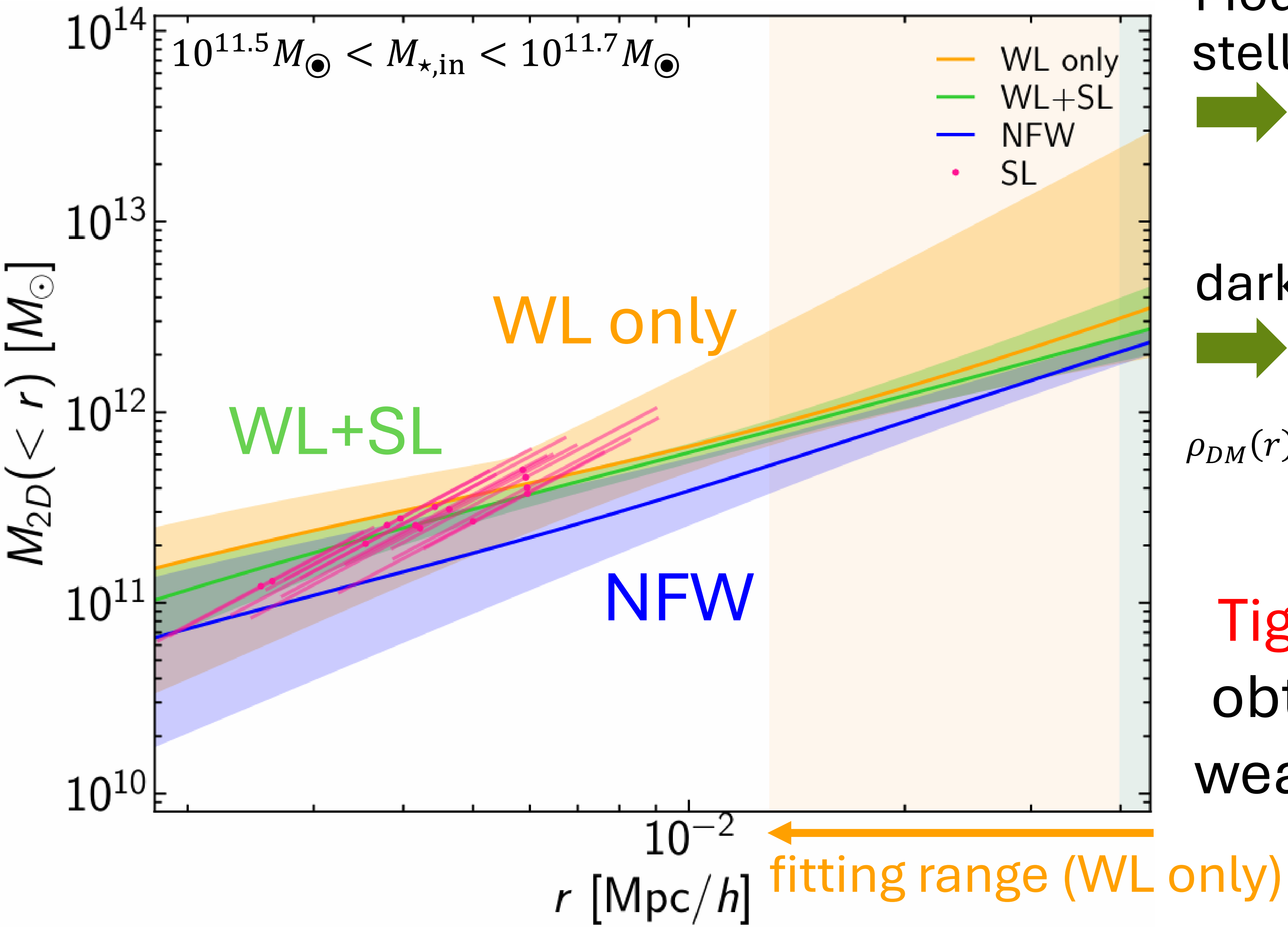
Strong-lensing selection bias and intrinsic scatter



- correcting for strong-lensing selection bias using a mock catalog (Abe et al. 2025)
- intrinsic scatter from mock

$$\sigma_{\log_{10}\mathrm{M_{2D}}}\sim 0.14$$

Inner Profile Fitting (WL+SL)



- Model

stellar matter (SM)

→ Hernquist

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

dark matter (DM)

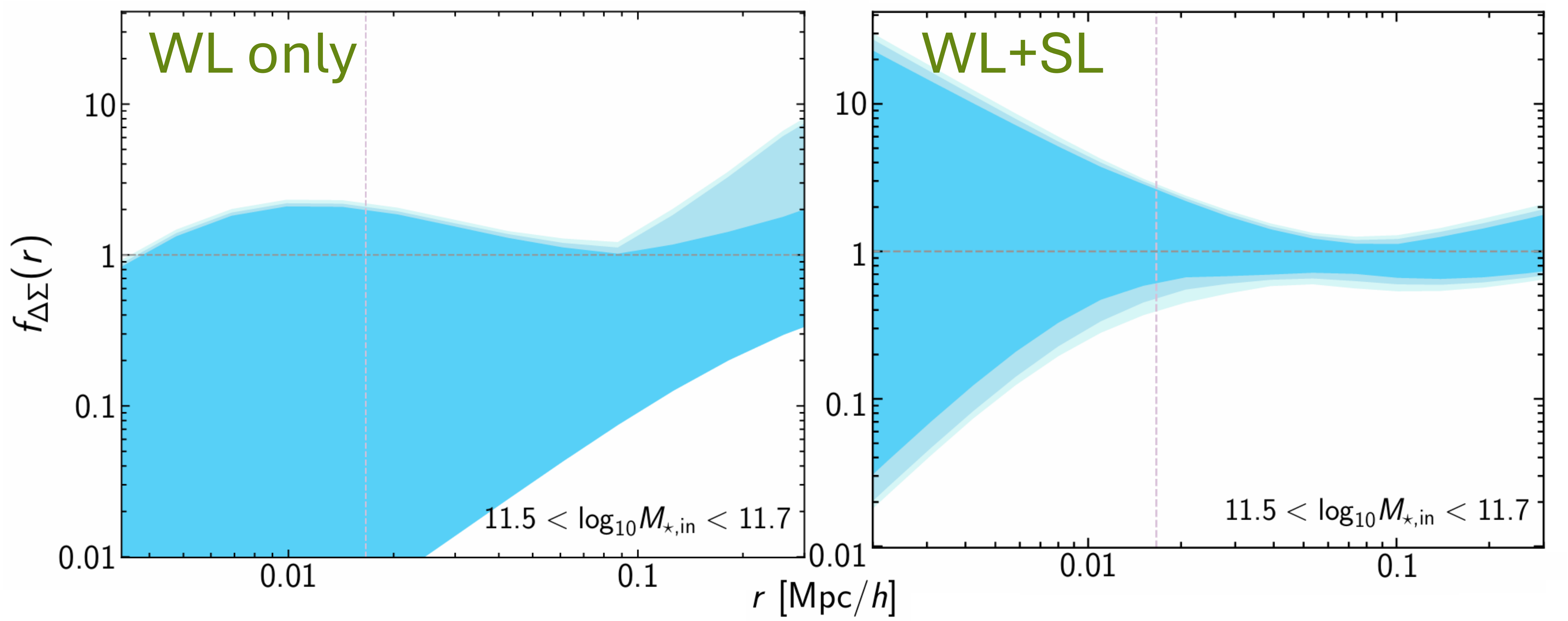
→ cored power-law

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

Tighter constraints are obtained by combining weak and strong lensing

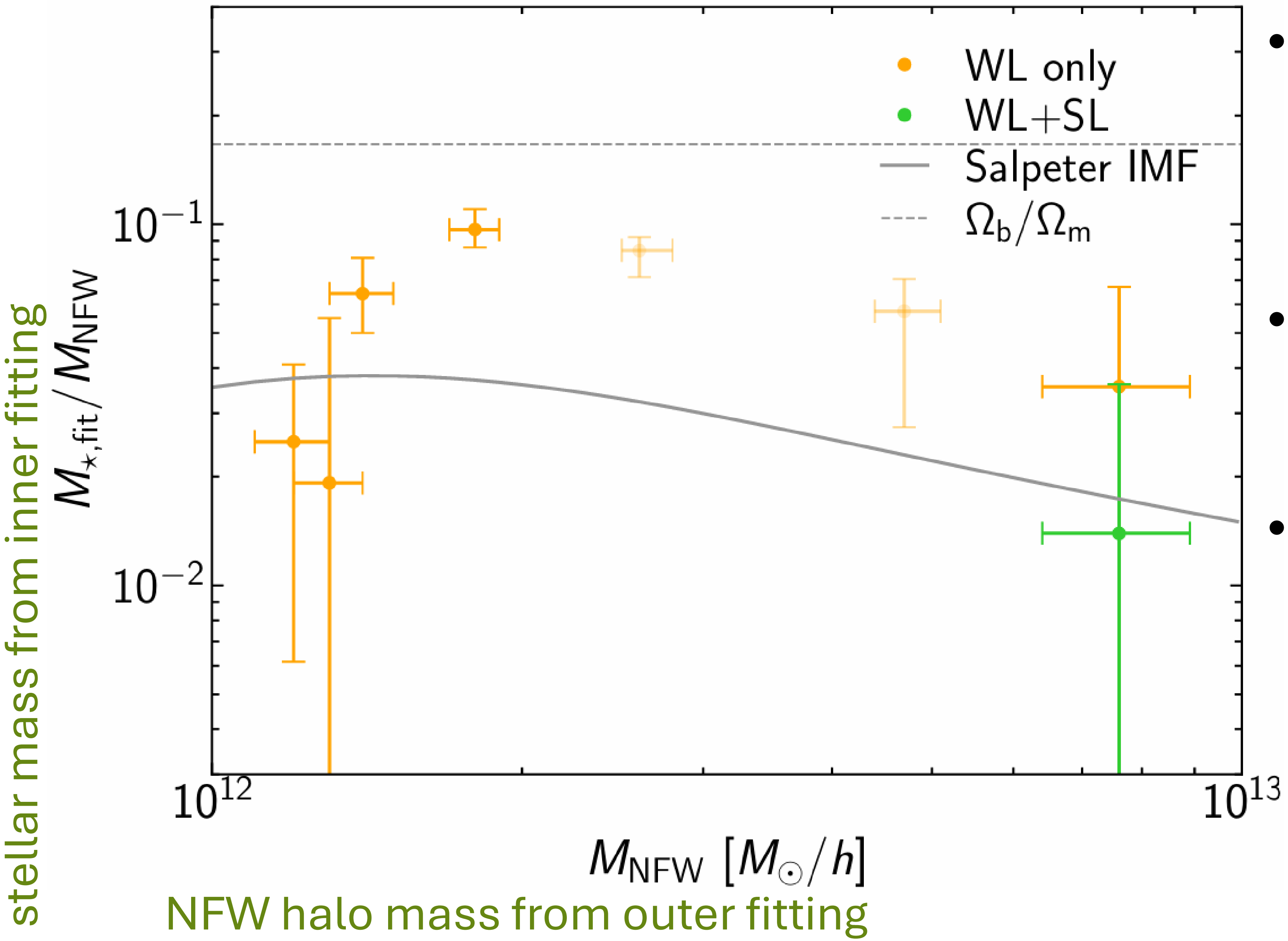
Comparison with NFW (WL+SL)

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



More tightly consistent with NFW

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



- constraining SHMR **without** relying on $M_\star/L$ or IMF assumption
- For the highest mass bin, consistent w/ Salpeter IMF
- For lower mass bins, higher $M_\star$ than expected from Salpeter IMF
  ➡ possibility of **more bottom-heavy IMF**

Summary

✓ We investigate central dark matter distributions of early-type galaxies by combining weak and strong lensing analysis

✓ We provide new constraints on

- central dark matter profiles

  → cored distributions are favored in intermediate mass bins
- the SHMR
- the stellar IMF

  → more bottom-heavy than Salpeter IMF in intermediate mass bins

Future Work

➢ considering more flexible dark matter profile model

➢ investigating the redshift dependence

➢ researching total mass profile

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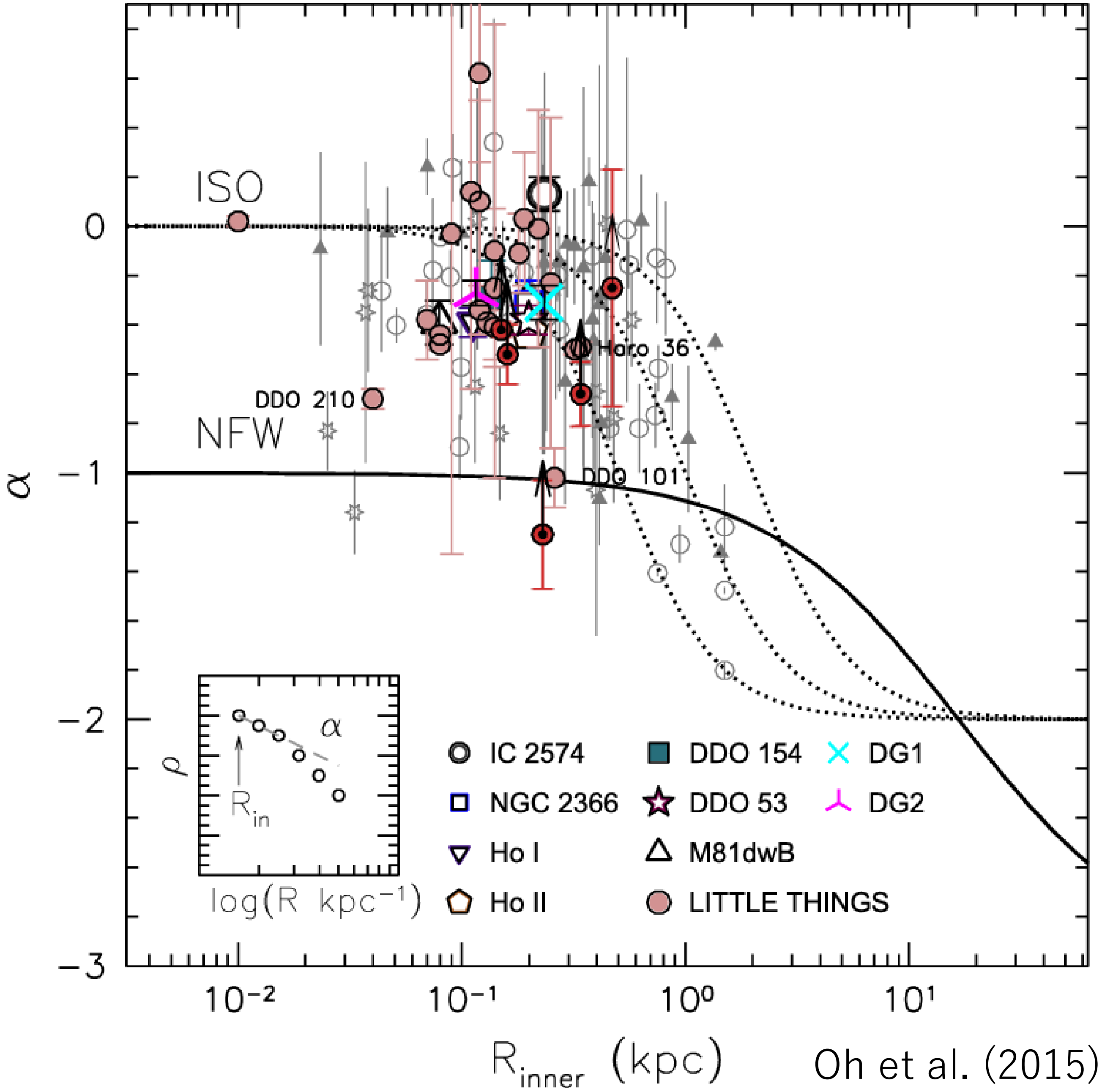
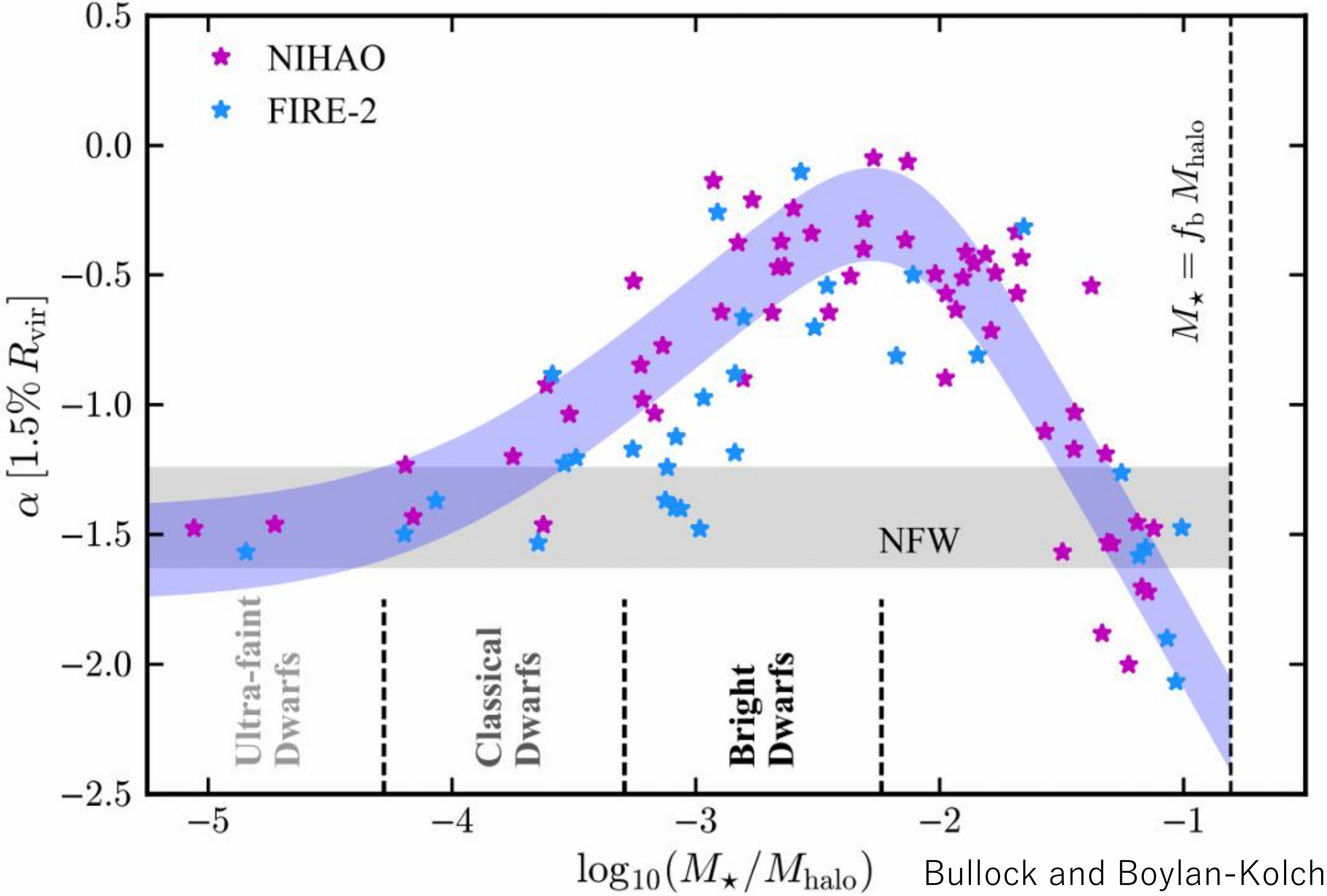
Backup Slides

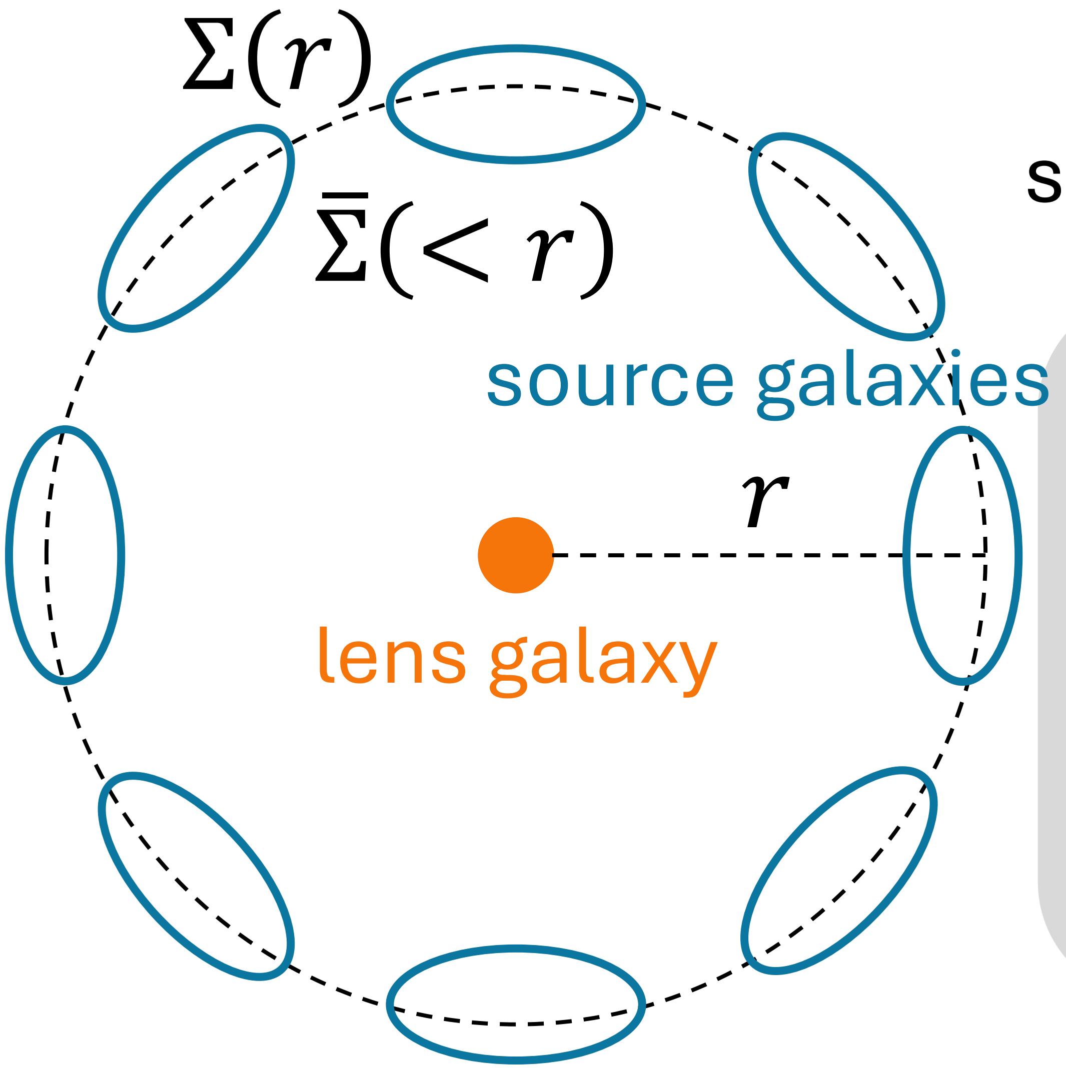

ISO
NFW
DDO 210
Haro 36
DDO 101
0
−1
−2
−3
α
10^{-2}
10^{-1}
10^{0}
10^{1}
R_{inner} (kpc)
ρ
R_{in}
$\log(R\ kpc^{-1})$
IC 2574
NGC 2366
Ho I
Ho II
DDO 154
DDO 53
M81dwB
LITTLE THINGS
DG1
DG2

Oh et al. (2015)



Bullock and Boylan-Kolchin (2017)

Weak Gravitational Lensing



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

measuring tangential shear γ_{t}

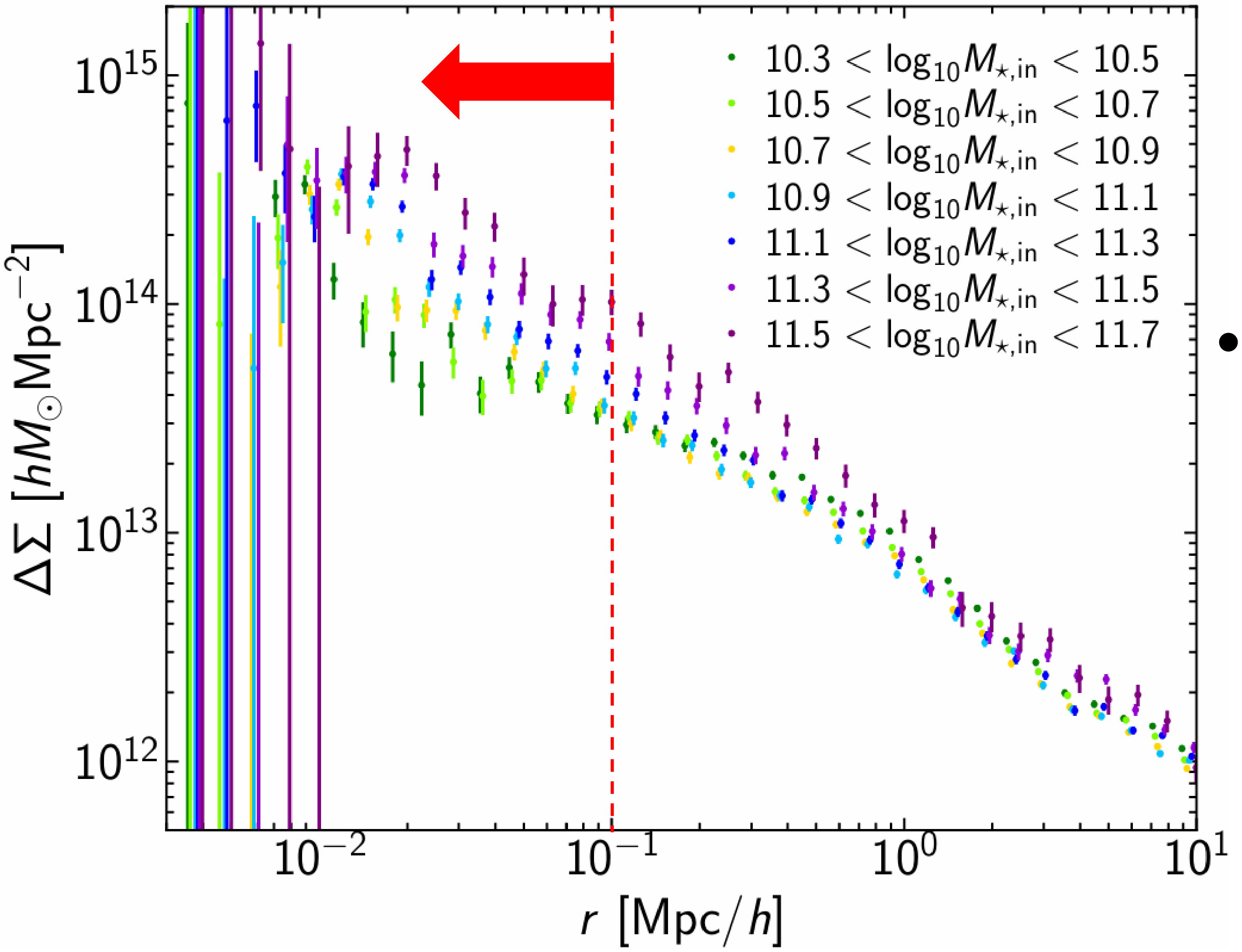
differential surface mass density

$$\Delta\Sigma(r) = \gamma_{\mathrm{t}} \times \Sigma_{\mathrm{cr}}$$
$$= \bar{\Sigma}(< r) - \Sigma(r)$$

(Σ_{cr} : critical surface mass density)

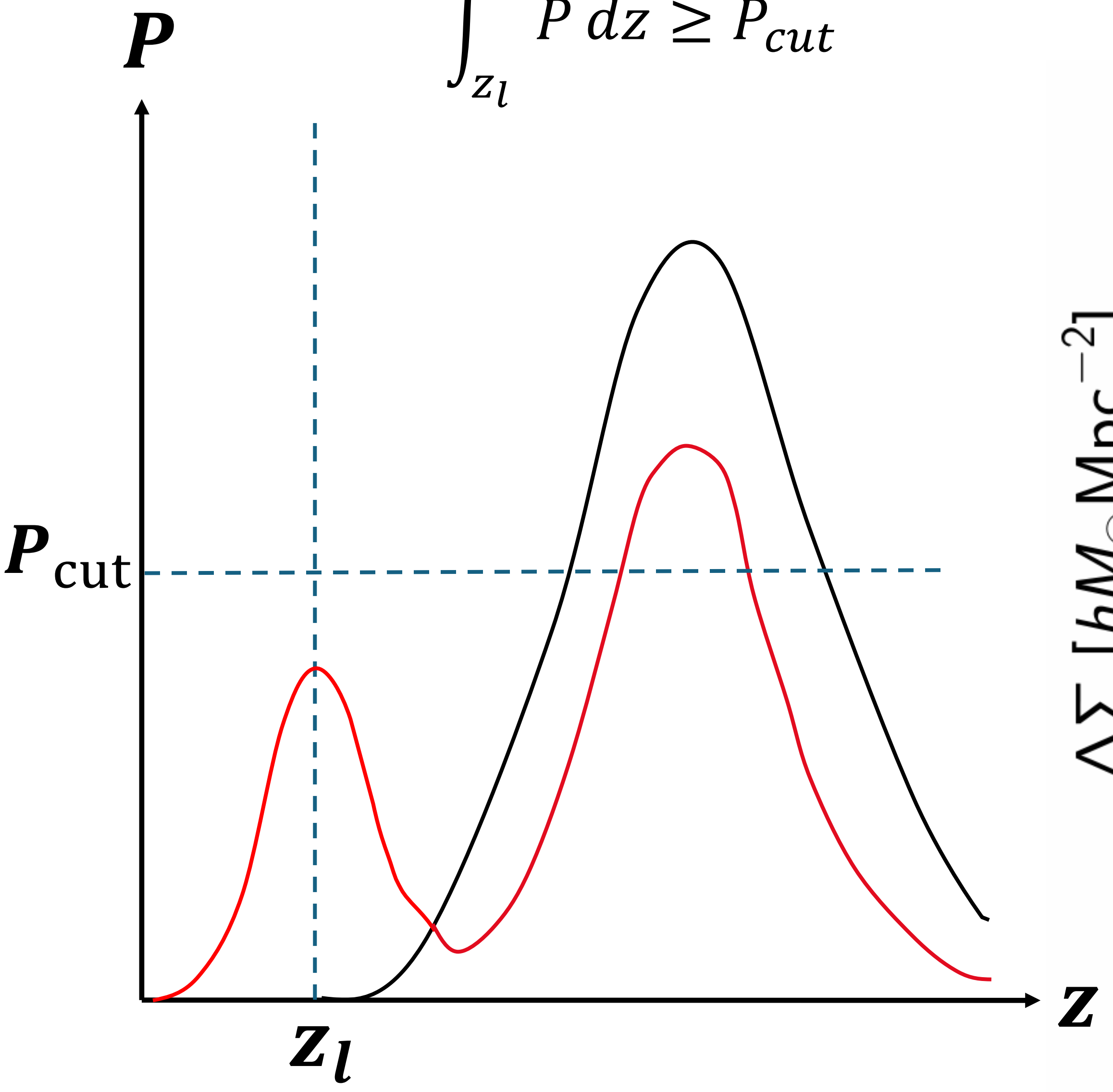
Individual lensing signal is too small → stacking a large number of lens galaxies

Measurement

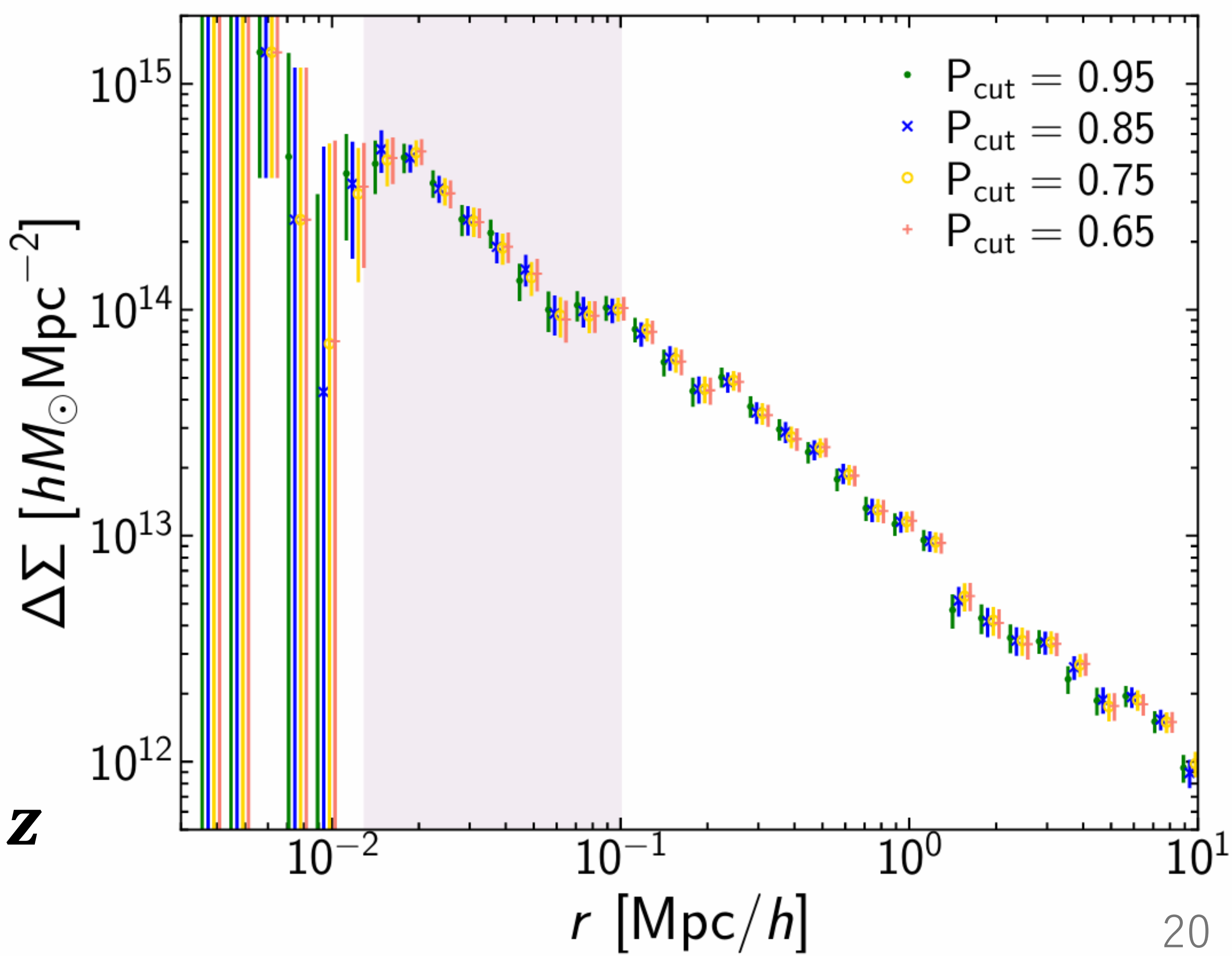


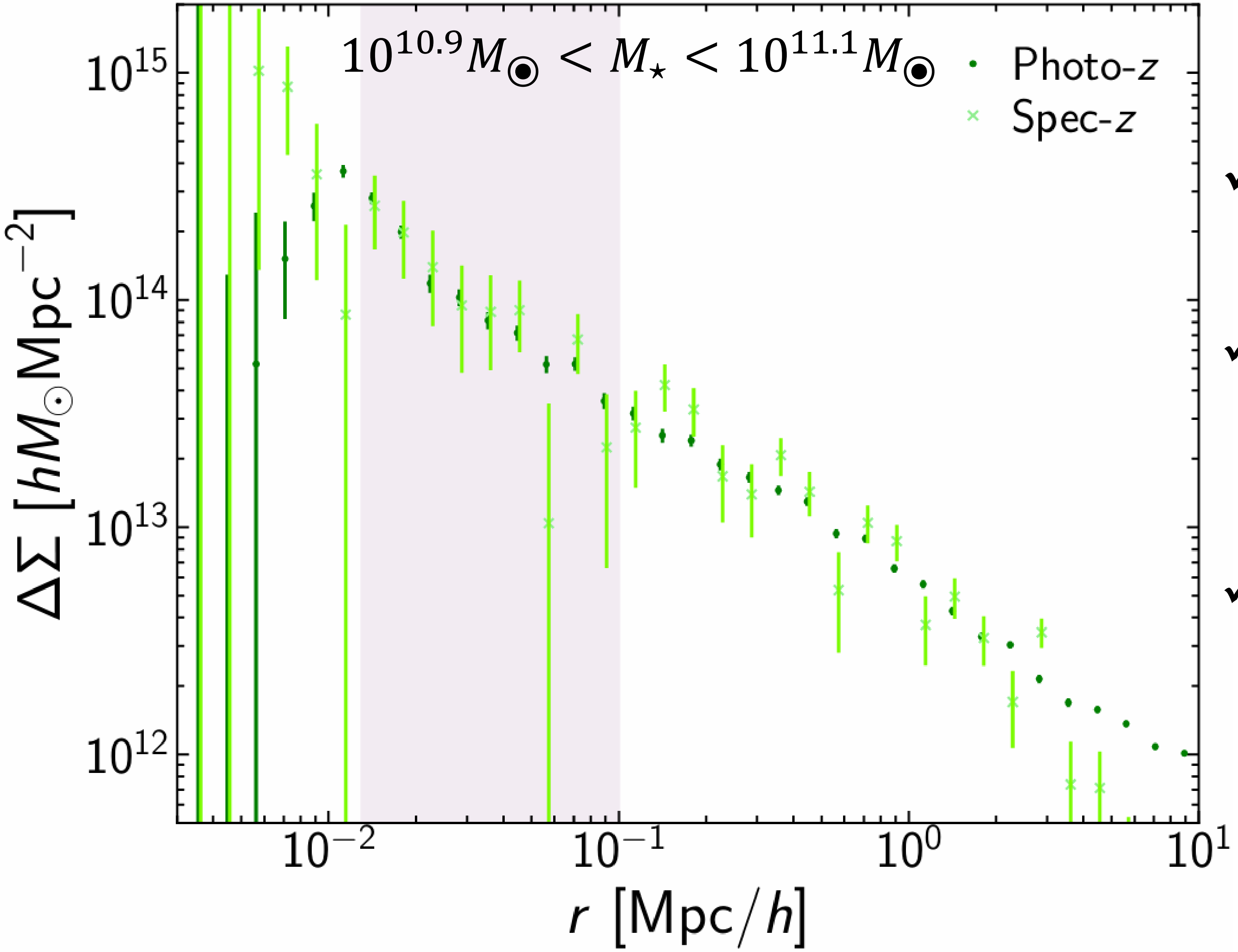
- we want to know the central dark matter distribution

$$\int_{z_l}^{\infty} P\,dz \geq P_{cut}$$



$10^{11.5}M_\odot < M_\star < 10^{11.7}M_\odot$

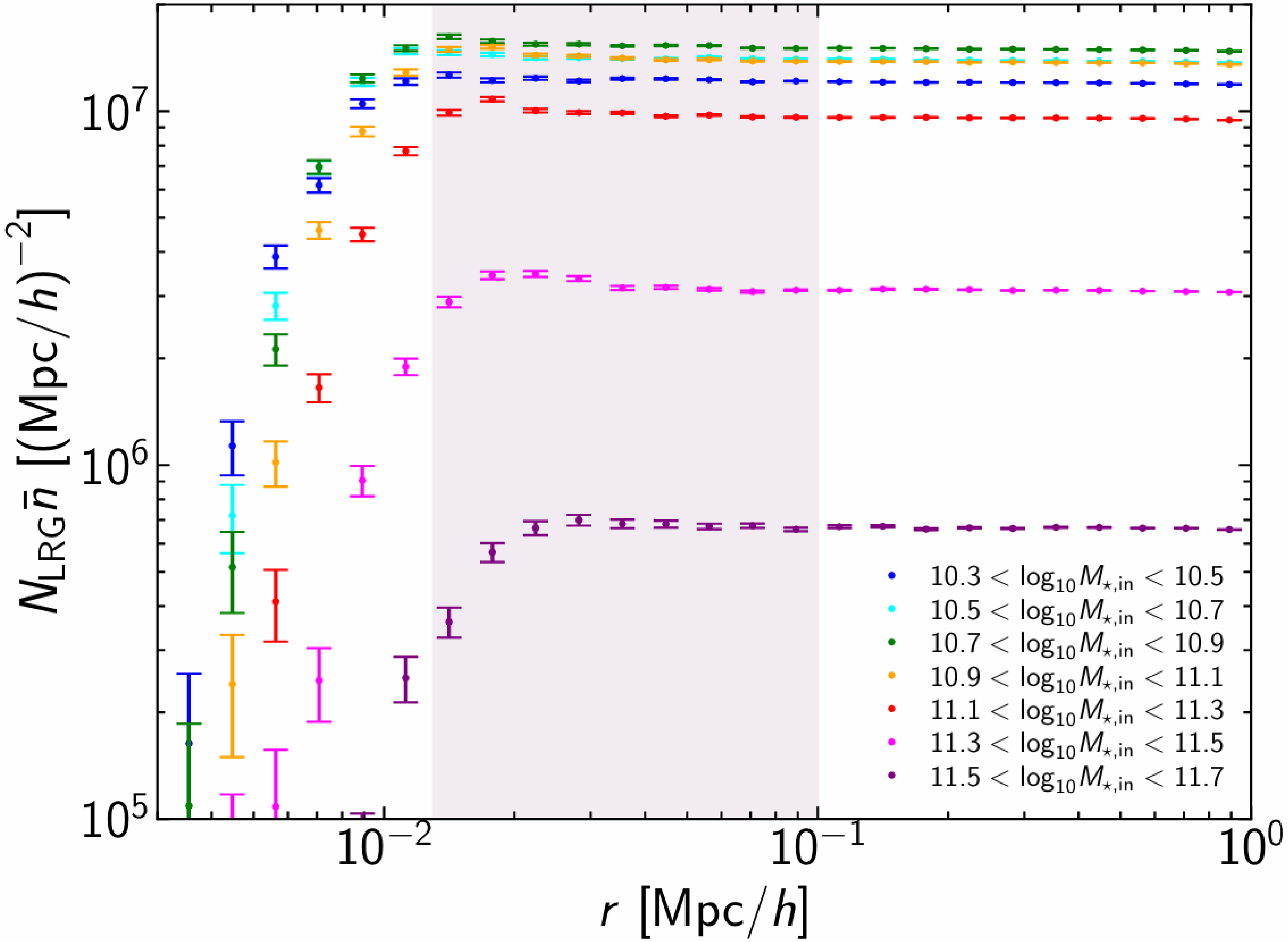




✓$\chi^2 = \sum \frac{(\Delta\Sigma_{spec} - \Delta\Sigma_{photo})^2}{\sigma_{spec}^2 + \sigma_{photo}^2}$

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

✓For the other mass bins, χ^2 is within the 95% confidence interval



$N_{\rm LRG}\bar{n}$ [(Mpc/h)$^{-2}$]
10^7
10^6
10^5
10^{-2}
10^{-1}
10^0
r [Mpc/h]
$10.3 < \log_{10} M_{\star,\rm in} < 10.5$
$10.5 < \log_{10} M_{\star,\rm in} < 10.7$
$10.7 < \log_{10} M_{\star,\rm in} < 10.9$
$10.9 < \log_{10} M_{\star,\rm in} < 11.1$
$11.1 < \log_{10} M_{\star,\rm in} < 11.3$
$11.3 < \log_{10} M_{\star,\rm in} < 11.5$
$11.5 < \log_{10} M_{\star,\rm in} < 11.7$

✓stellar matter (SM) component → Hernquist (parameters $M_\star, r_e$)

✓dark matter (DM) component → cored power-law

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

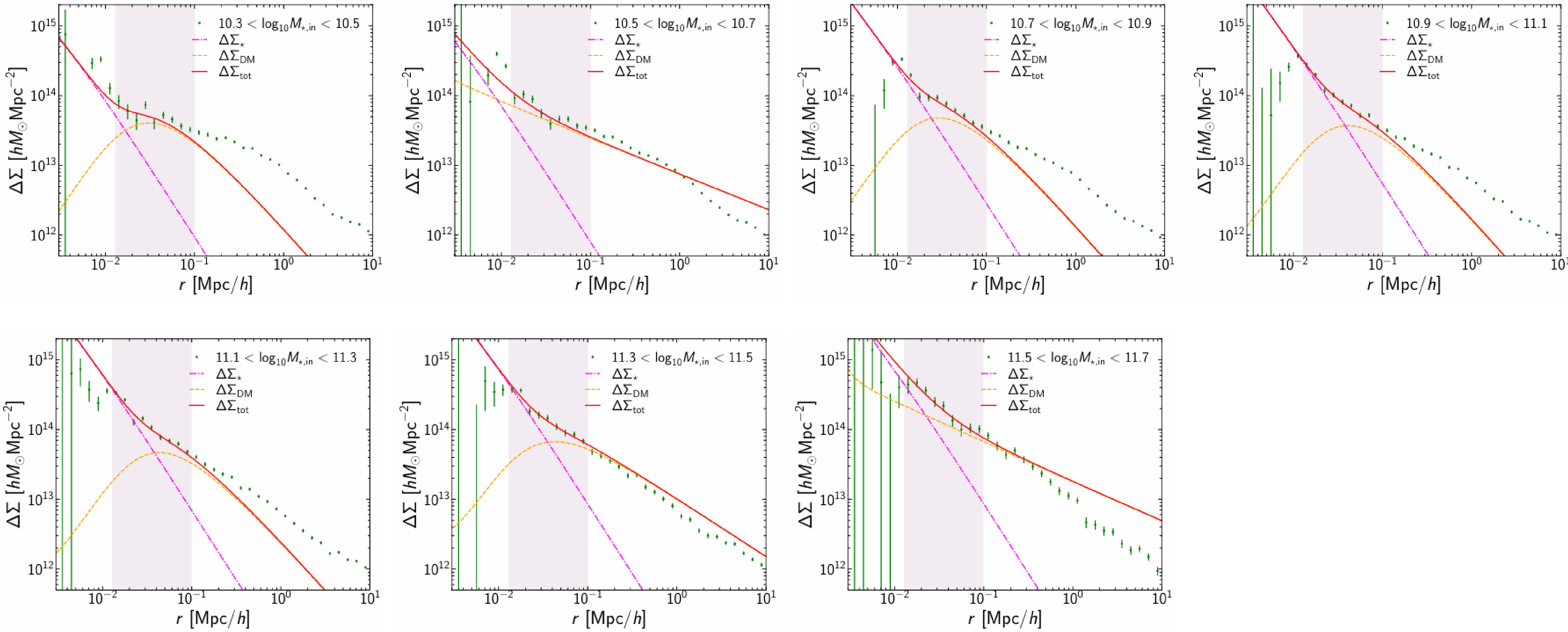
$$\Sigma_{DM}(r) = \int_{-\infty}^{\infty} \rho_{DM}\left(\sqrt{r^2 + Z^2}\right) dZ$$

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

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

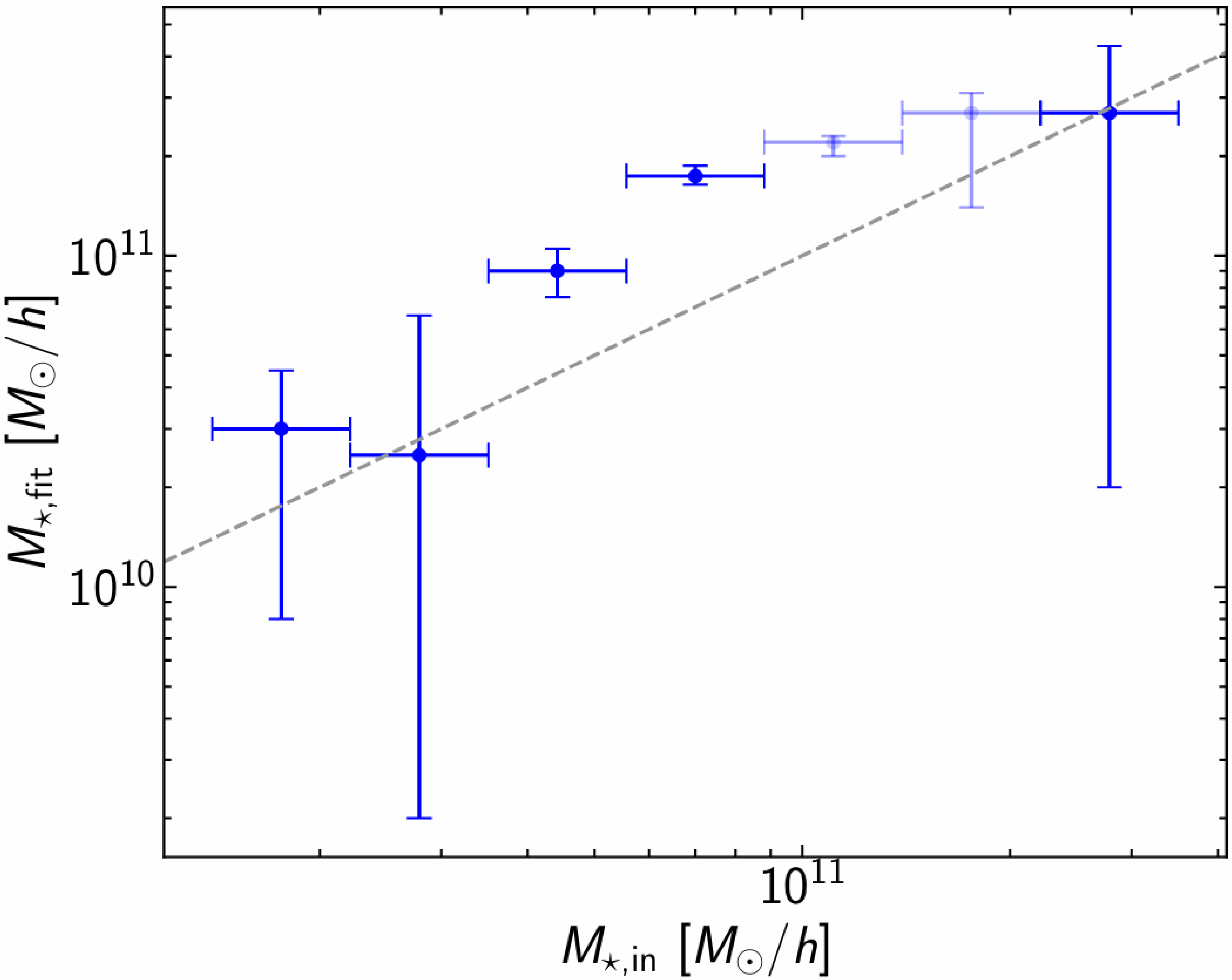
→ $\Delta\Sigma_{DM} = \bar{\Sigma}_{DM}(<r) - \Sigma_{DM}(r)$

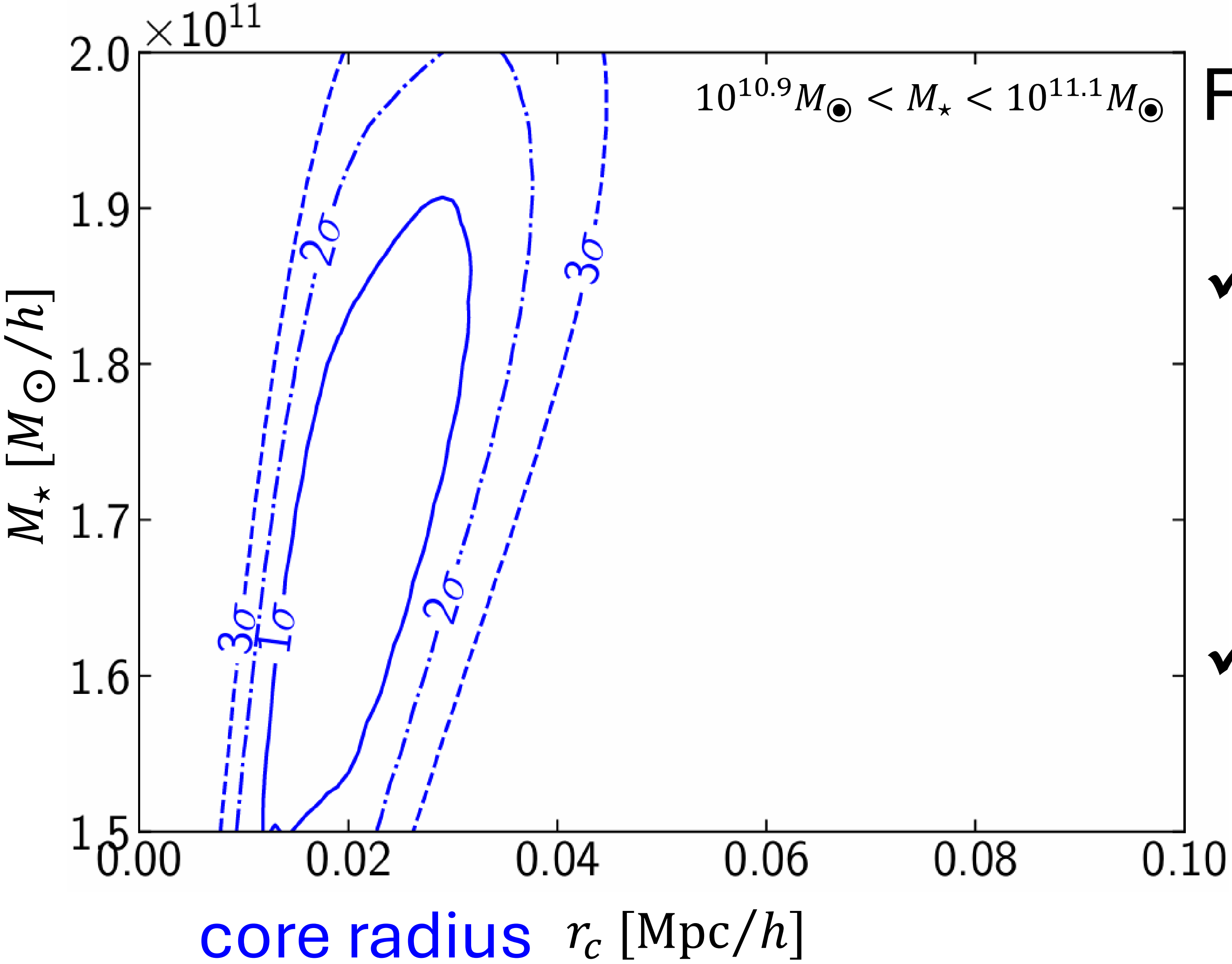
→ total mass $\Delta\Sigma_{tot} = \Delta\Sigma_{SM} + \Delta\Sigma_{DM}$



10.3 < log$_{10}M_{\star,\rm in}$ < 10.5
10.5 < log$_{10}M_{\star,\rm in}$ < 10.7
10.7 < log$_{10}M_{\star,\rm in}$ < 10.9
10.9 < log$_{10}M_{\star,\rm in}$ < 11.1
11.1 < log$_{10}M_{\star,\rm in}$ < 11.3
11.3 < log$_{10}M_{\star,\rm in}$ < 11.5
11.5 < log$_{10}M_{\star,\rm in}$ < 11.7
$\Delta\Sigma_\star$
$\Delta\Sigma_{\rm DM}$
$\Delta\Sigma_{\rm tot}$
$\Delta\Sigma$ [$hM_\odot$Mpc^{-2}]
r [Mpc/h]
10^{12}
10^{13}
10^{14}
10^{15}
10^{-2}
10^{-1}
10^{0}
10^{1}

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

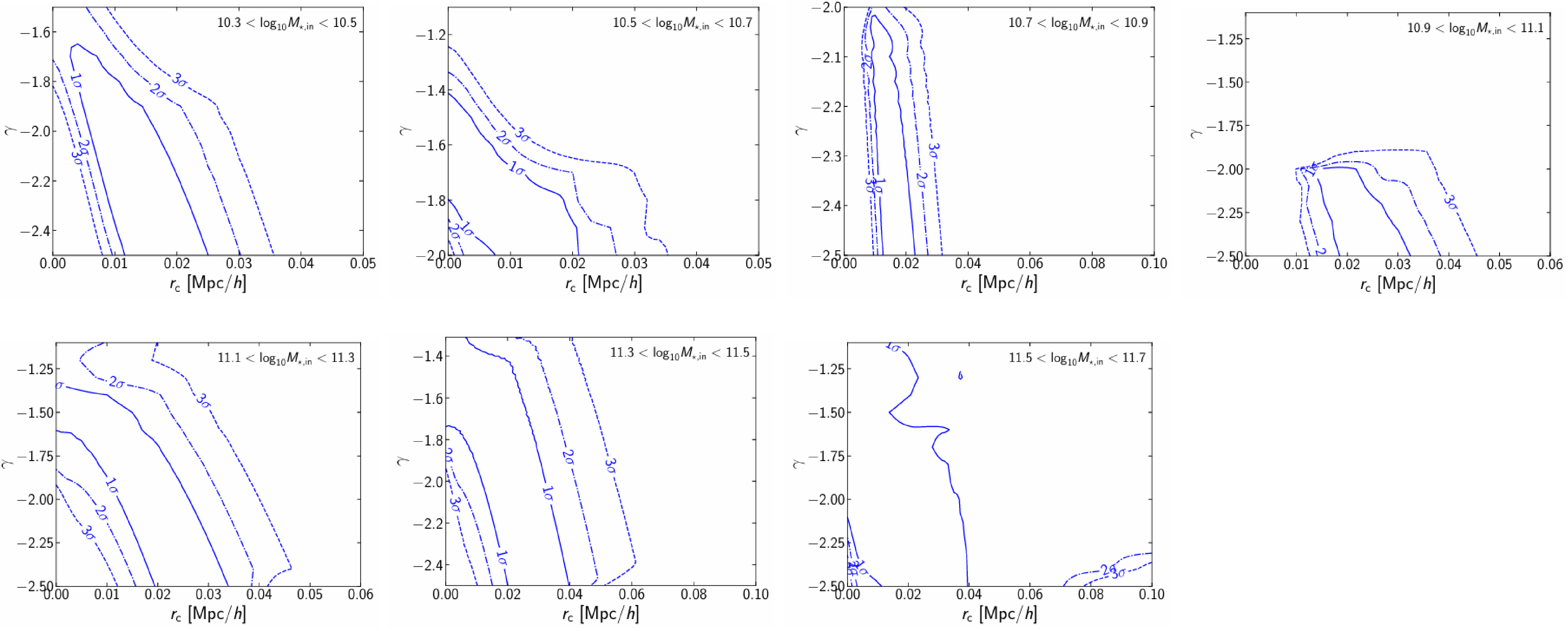

10^{11}
10^{10}
$M_{\star,\rm fit}\ [M_\odot/h]$
10^{11}
$M_{\star,\rm in}\ [M_\odot/h]$



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

✓ r_c is inconsistent with zero within 3σ
→ cored profile

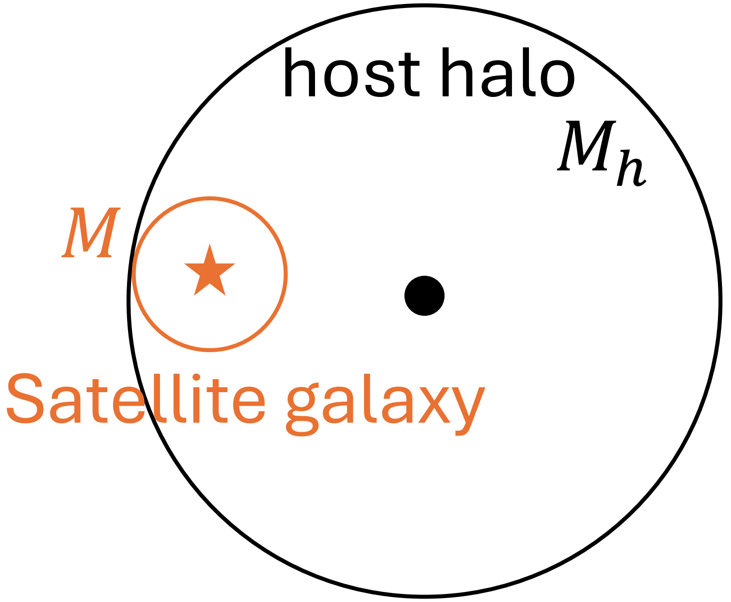
✓ Because of the baryon feedback?

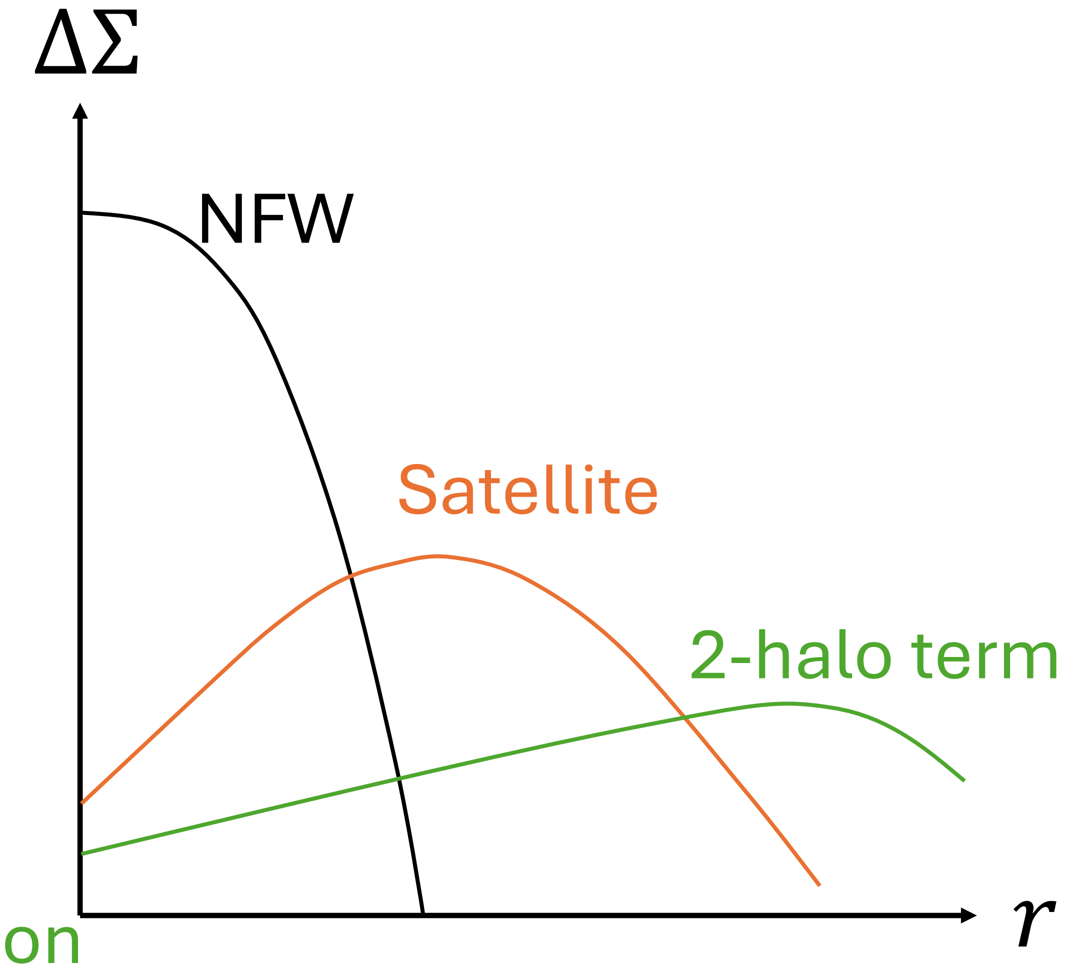


10.3 < log10M⋆,in < 10.5
10.5 < log10M⋆,in < 10.7
10.7 < log10M⋆,in < 10.9
10.9 < log10M⋆,in < 11.1
11.1 < log10M⋆,in < 11.3
11.3 < log10M⋆,in < 11.5
11.5 < log10M⋆,in < 11.7
γ
rc [Mpc/h]
1σ
2σ
3σ

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

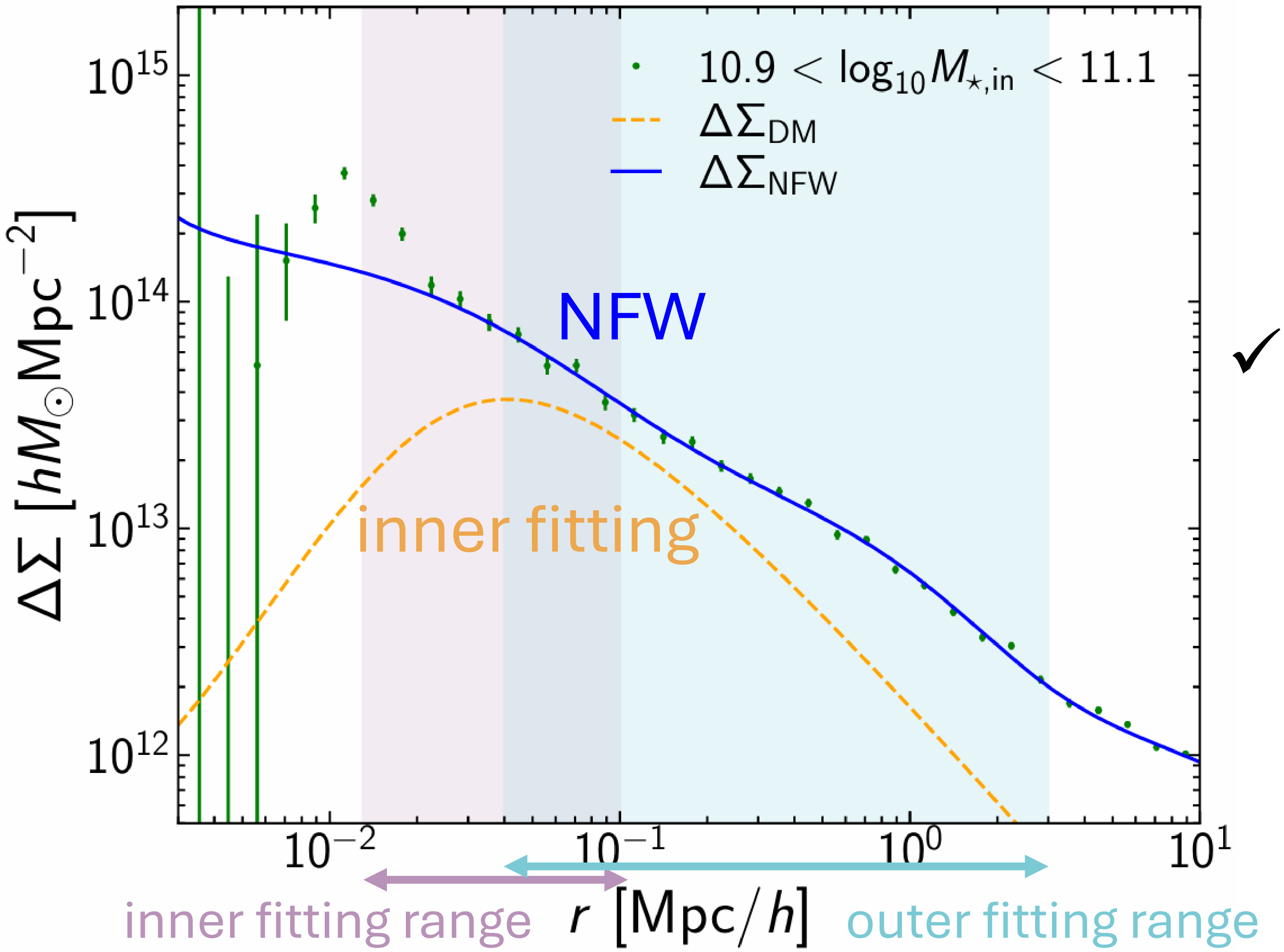
✓ Satellite galaxy





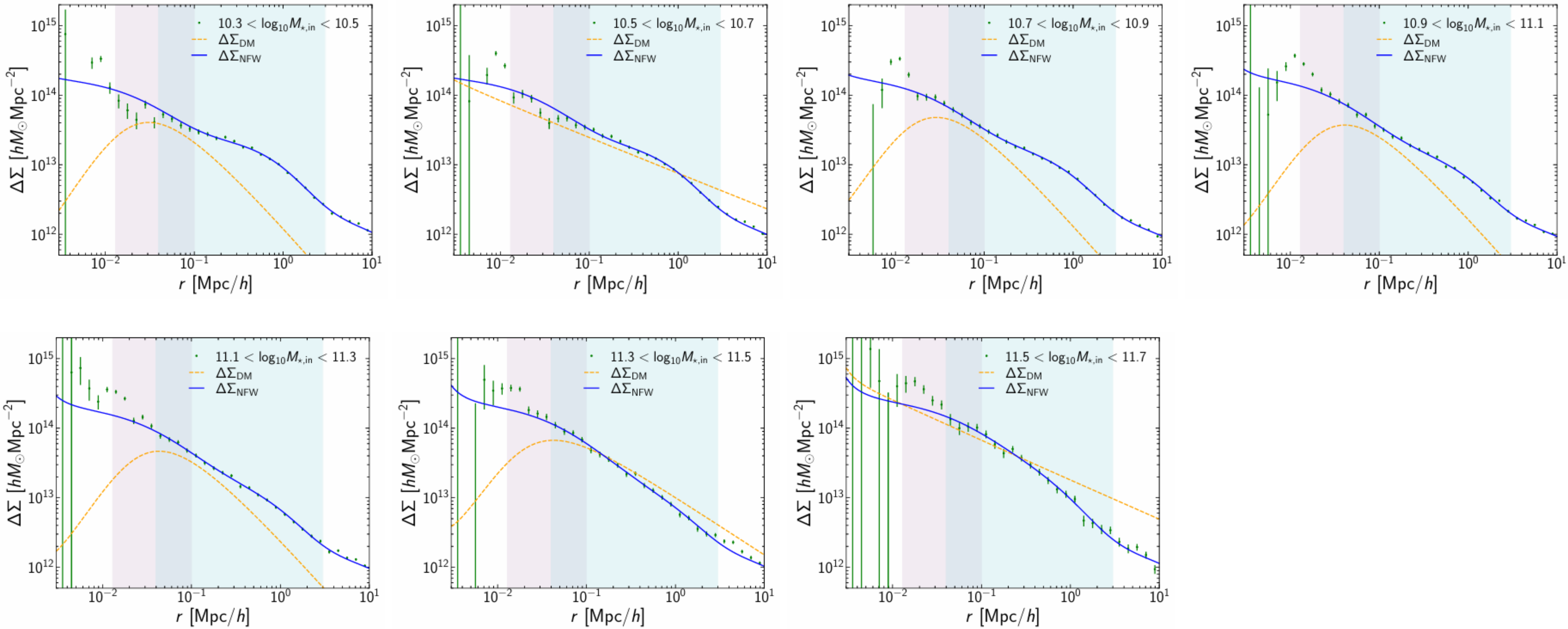
✓ 2-halo term

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

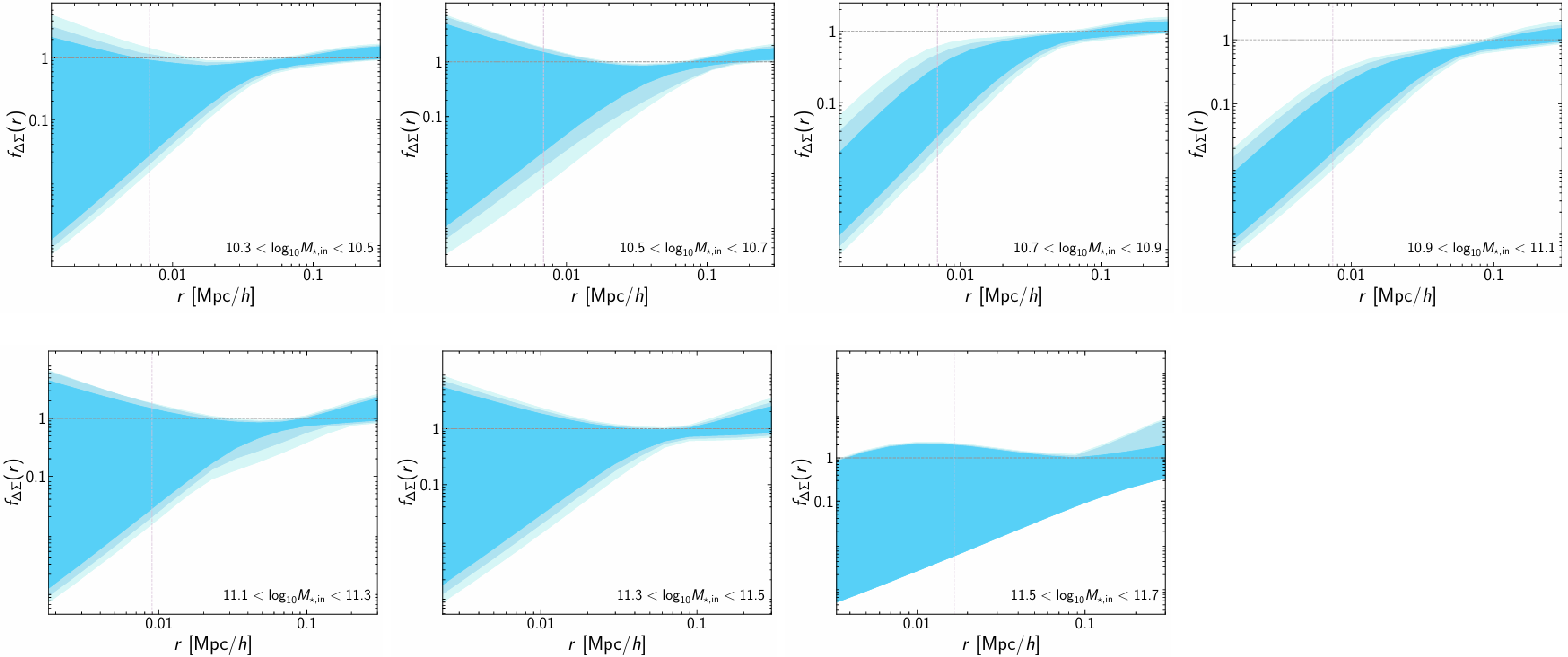


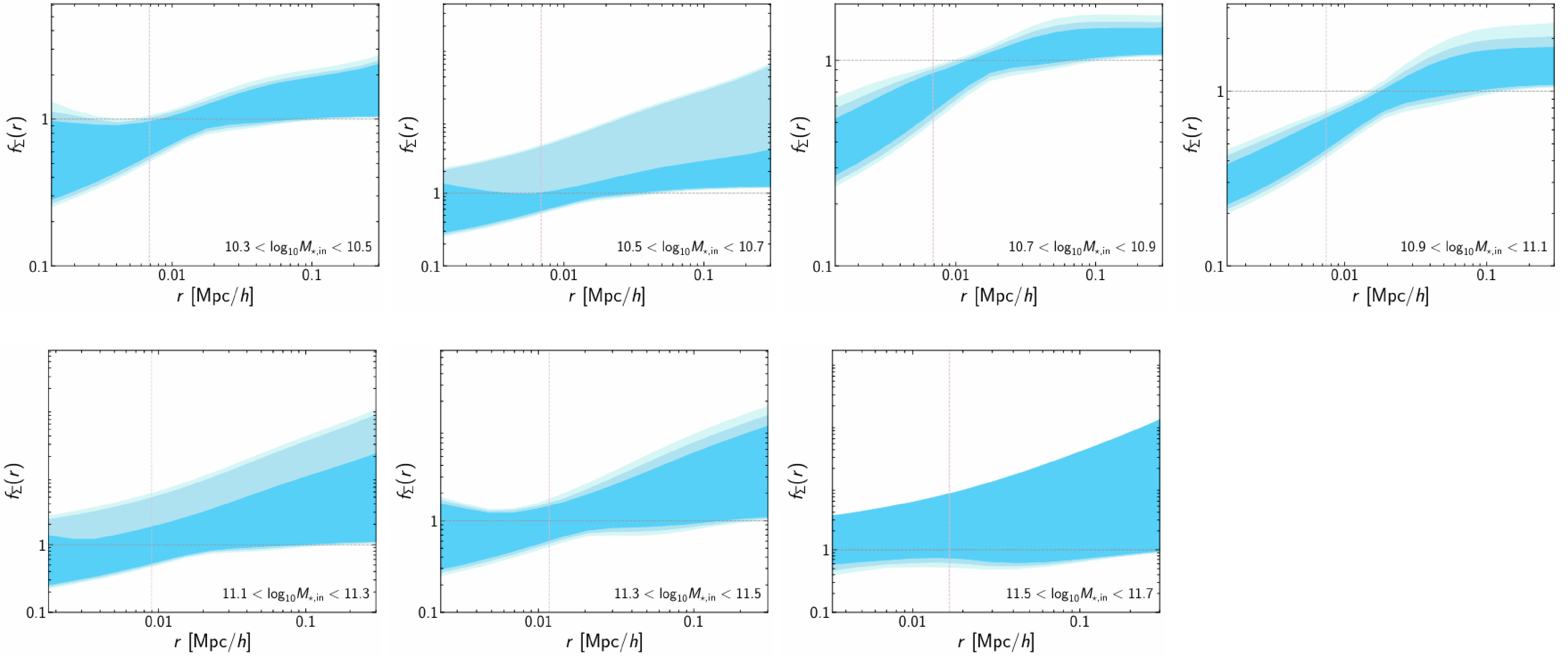
✓evaluating with

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

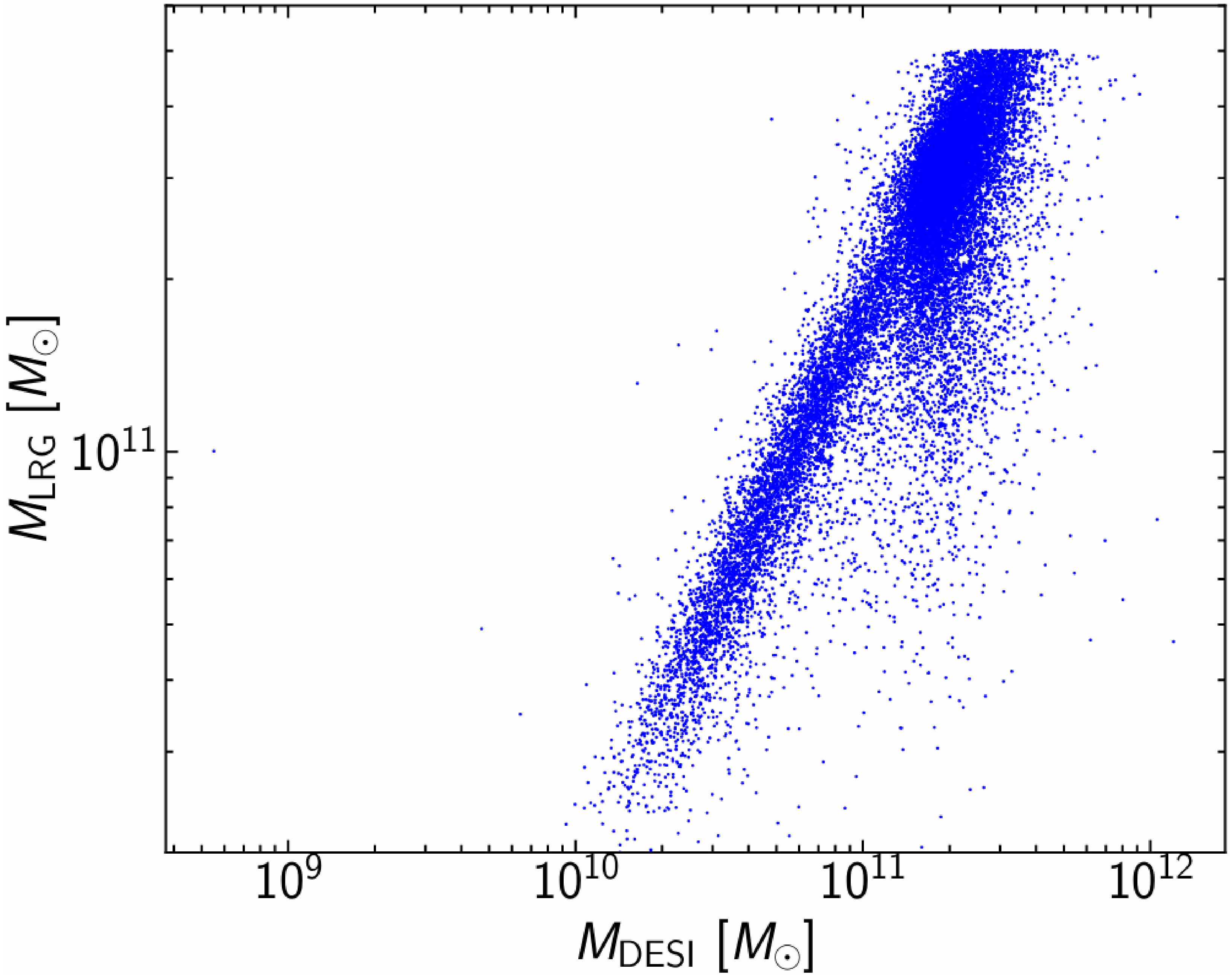

$10.3 < \log_{10} M_{\star,\rm in} < 10.5$
$10.5 < \log_{10} M_{\star,\rm in} < 10.7$
$10.7 < \log_{10} M_{\star,\rm in} < 10.9$
$10.9 < \log_{10} M_{\star,\rm in} < 11.1$
$11.1 < \log_{10} M_{\star,\rm in} < 11.3$
$11.3 < \log_{10} M_{\star,\rm in} < 11.5$
$11.5 < \log_{10} M_{\star,\rm in} < 11.7$
$\Delta\Sigma_{\rm DM}$
$\Delta\Sigma_{\rm NFW}$
$\Delta\Sigma\ [hM_\odot \mathrm{Mpc}^{-2}]$
$r\ [\mathrm{Mpc}/h]$
10^{12} 10^{13} 10^{14} 10^{15}
10^{-2} 10^{-1} 10^{0} 10^{1}

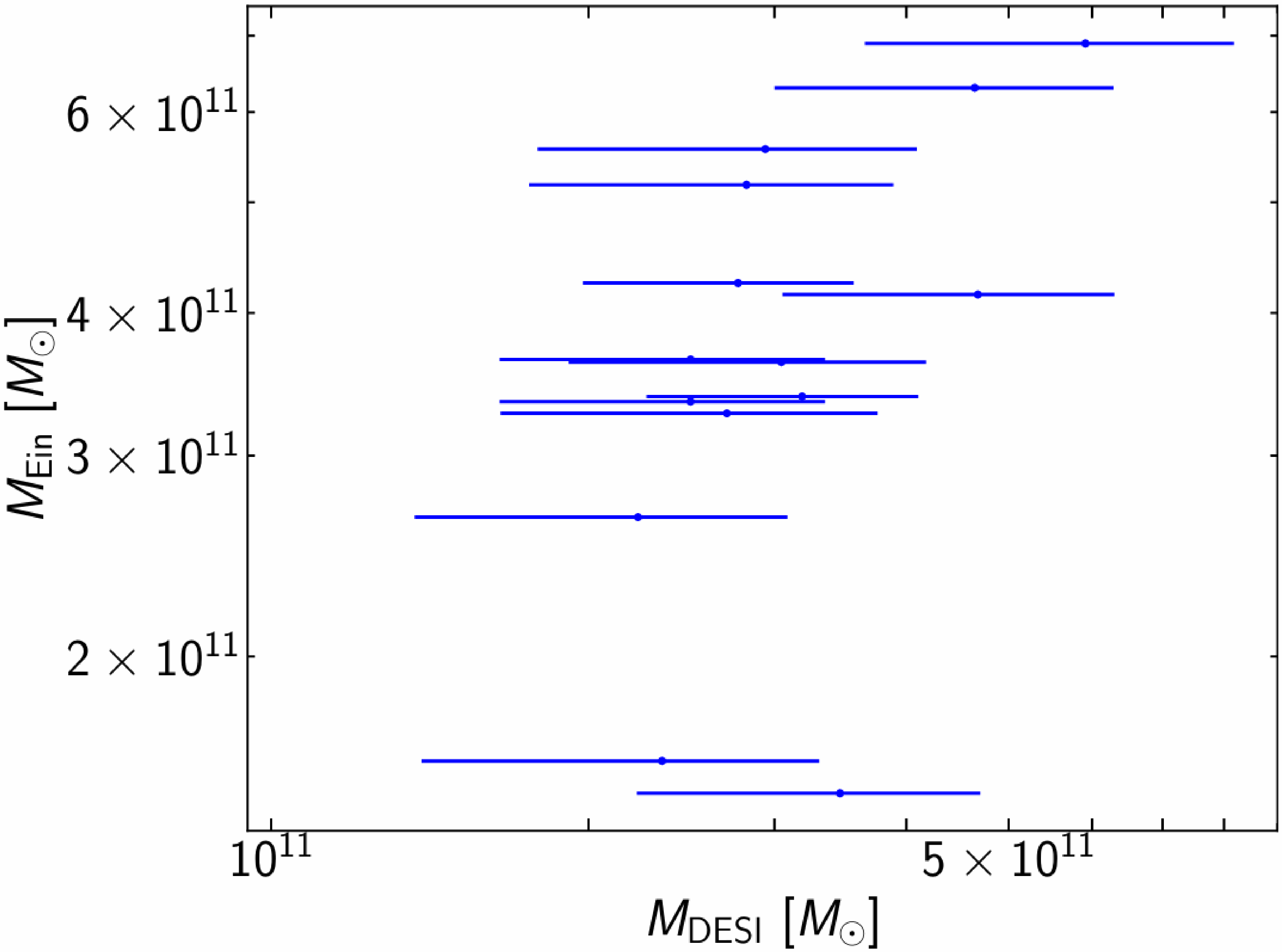
$\log_{10}(M_{\star,\mathrm{in}}[M_\odot])$	$M_{\mathrm{NFW}}\ [M_\odot/h]$	$M_{\mathrm{h}}\ [M_\odot/h]$	f_{sat}	$\chi^2_{\mathrm{out}}/\mathrm{dof}$
10.3–10.5	$1.2^{+0.1}_{-0.1} \times 10^{12}$	$5.1^{+0.1}_{-0.1} \times 10^{13}$	$0.40^{+0.00}_{-0.01}$	19.3/16
10.5–10.7	$1.3^{+0.1}_{-0.1} \times 10^{12}$	$5.4^{+0.5}_{-0.4} \times 10^{13}$	$0.32^{+0.02}_{-0.02}$	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

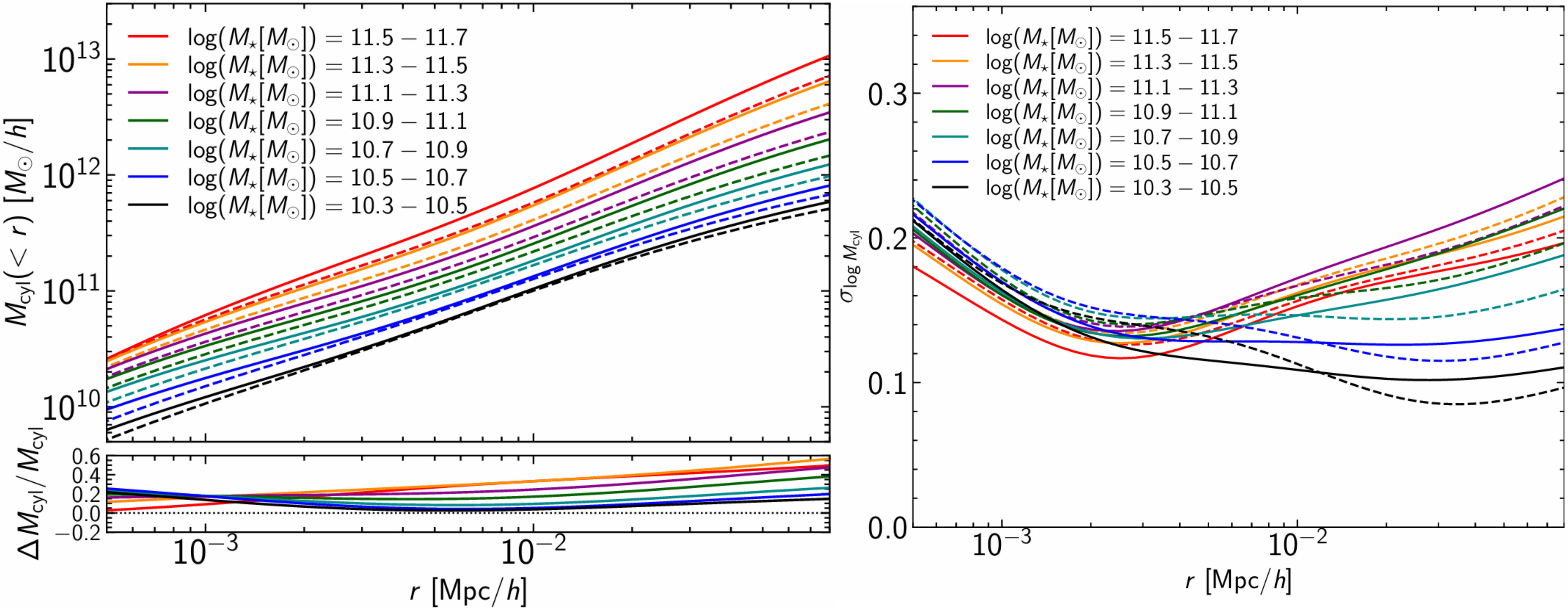

$f_{\Delta\Sigma}(r)$
r [Mpc/h]
1
0.1
0.01
$10.3 < \log_{10} M_{\star,\mathrm{in}} < 10.5$
$10.5 < \log_{10} M_{\star,\mathrm{in}} < 10.7$
$10.7 < \log_{10} M_{\star,\mathrm{in}} < 10.9$
$10.9 < \log_{10} M_{\star,\mathrm{in}} < 11.1$
$11.1 < \log_{10} M_{\star,\mathrm{in}} < 11.3$
$11.3 < \log_{10} M_{\star,\mathrm{in}} < 11.5$
$11.5 < \log_{10} M_{\star,\mathrm{in}} < 11.7$


$f_\Sigma(r)$
r [Mpc/h]
$10.3 < \log_{10} M_{\star,\mathrm{in}} < 10.5$
$10.5 < \log_{10} M_{\star,\mathrm{in}} < 10.7$
$10.7 < \log_{10} M_{\star,\mathrm{in}} < 10.9$
$10.9 < \log_{10} M_{\star,\mathrm{in}} < 11.1$
$11.1 < \log_{10} M_{\star,\mathrm{in}} < 11.3$
$11.3 < \log_{10} M_{\star,\mathrm{in}} < 11.5$
$11.5 < \log_{10} M_{\star,\mathrm{in}} < 11.7$

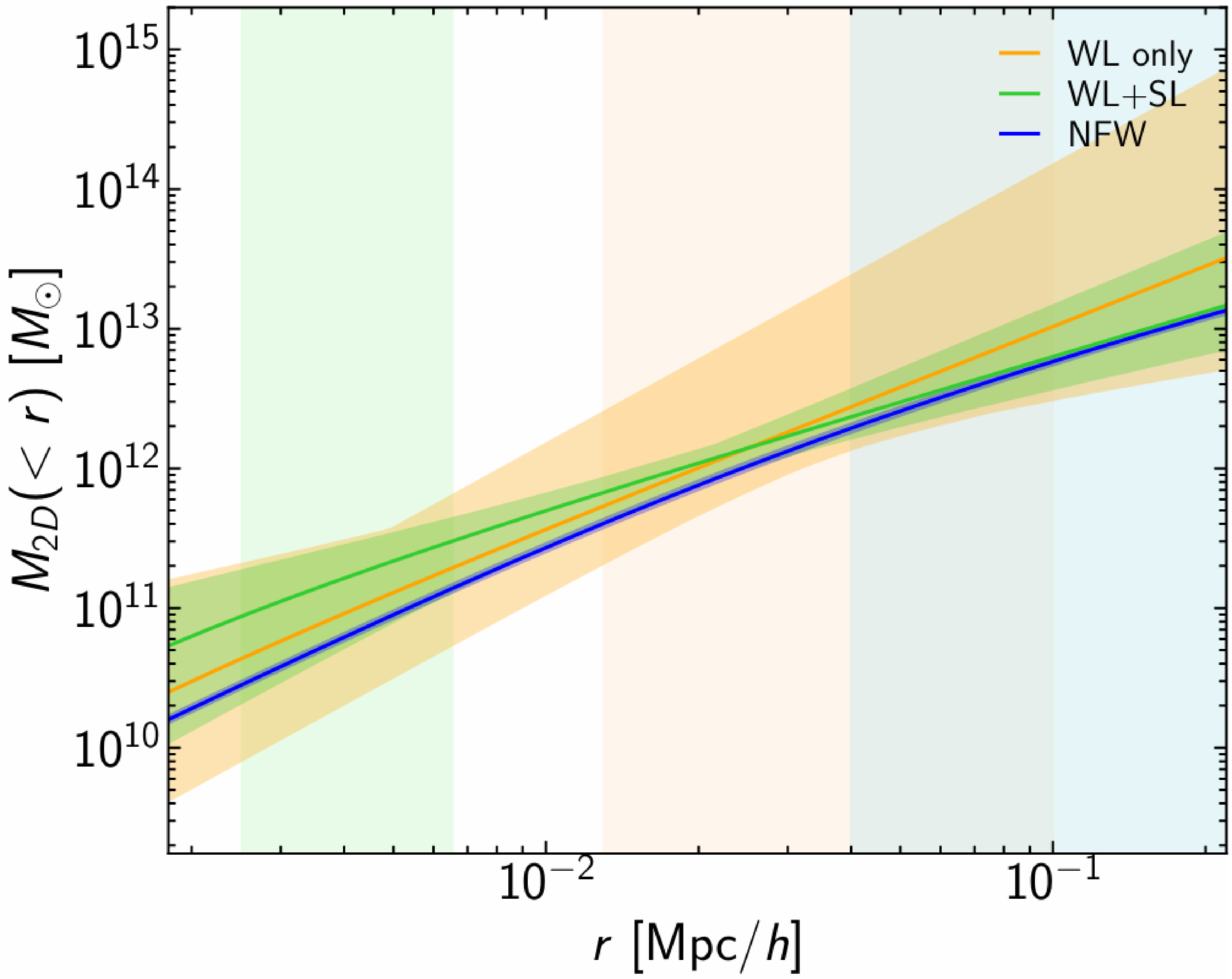
$\log_{10}(M_{\star,\mathrm{in}}[M_\odot])$	$f_{\mathrm{DM}}(< 5r_{\mathrm{e}})$
10.3–10.5	$0.19^{+0.70}_{-0.12}$
10.5–10.7	$0.51^{+0.45}_{-0.47}$
10.7–10.9	$0.087^{+0.125}_{-0.050}$
10.9–11.1	$0.035^{+0.050}_{-0.017}$
11.1–11.3	$0.056^{+0.431}_{-0.025}$
11.3–11.5	$0.14^{+0.53}_{-0.08}$
11.5–11.7	$0.50^{+0.42}_{-0.49}$


$M_{\mathrm{LRG}}\ [M_\odot]$
10^{11}
10^9 10^{10} 10^{11} 10^{12}
$M_{\mathrm{DESI}}\ [M_\odot]$

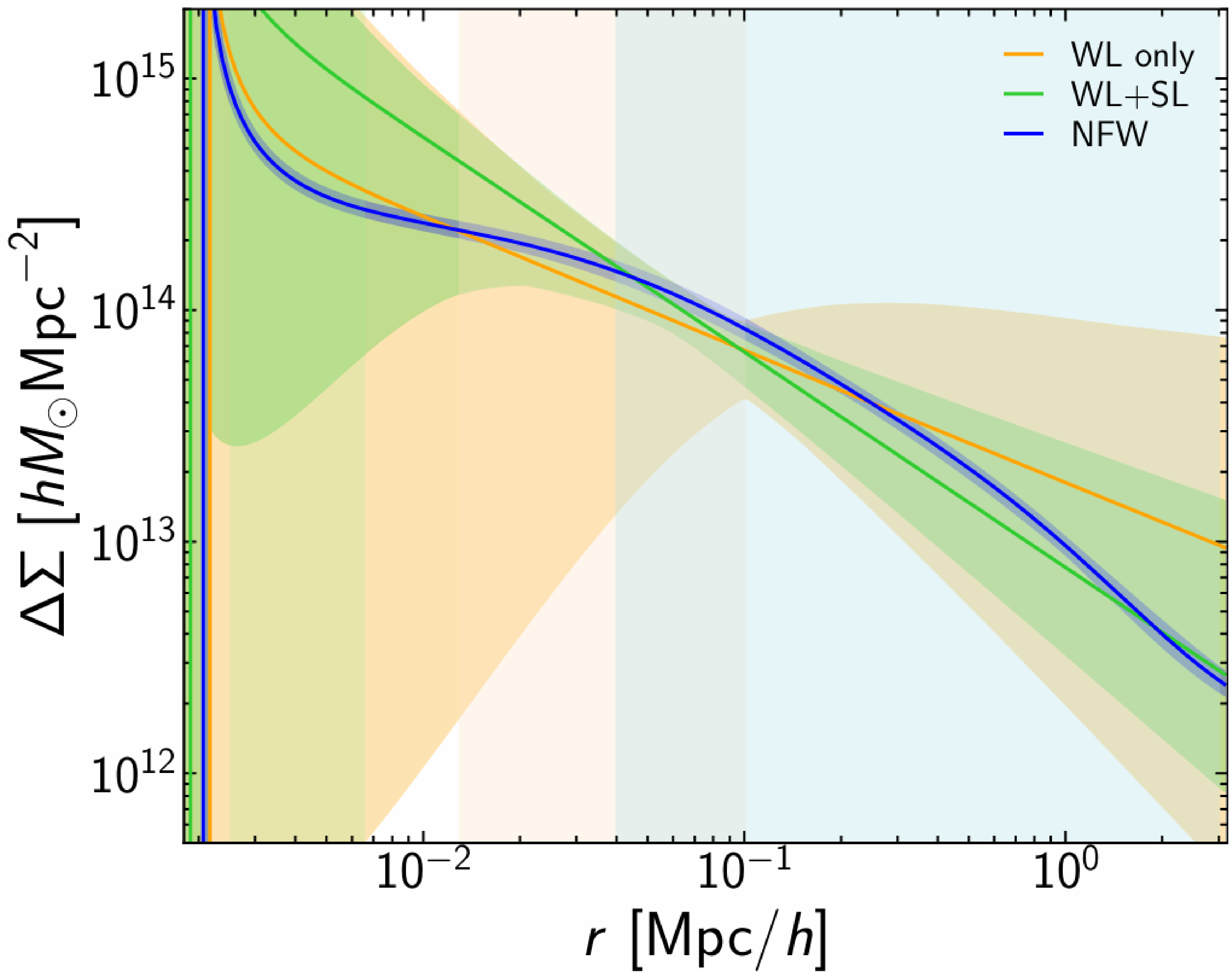

6×10^{11}
4×10^{11}
3×10^{11}
2×10^{11}
$M_{\rm Ein}$ [$M_\odot$]
10^{11}
5×10^{11}
$M_{\rm DESI}$ [$M_\odot$]

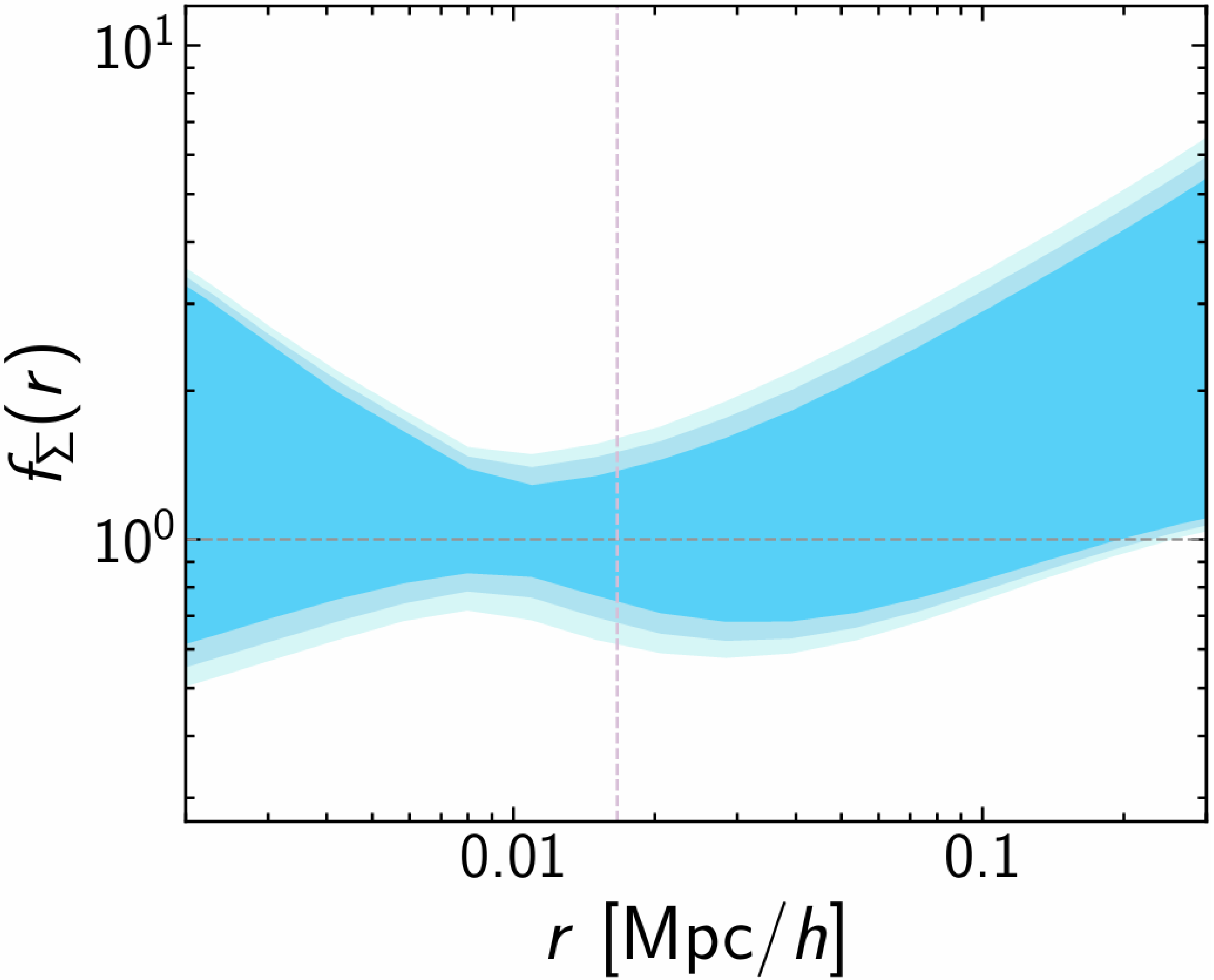


$\log(M_\star[M_\odot]) = 11.5 - 11.7$
$\log(M_\star[M_\odot]) = 11.3 - 11.5$
$\log(M_\star[M_\odot]) = 11.1 - 11.3$
$\log(M_\star[M_\odot]) = 10.9 - 11.1$
$\log(M_\star[M_\odot]) = 10.7 - 10.9$
$\log(M_\star[M_\odot]) = 10.5 - 10.7$
$\log(M_\star[M_\odot]) = 10.3 - 10.5$
$M_{\rm cyl}(<r)\ [M_\odot/h]$
$\Delta M_{\rm cyl}/M_{\rm cyl}$
$\sigma_{\log M_{\rm cyl}}$
r [Mpc/h]



WL only
WL+SL
NFW
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
$M_{2D}(< r)$ $[M_\odot]$
10^{-2}
10^{-1}
r [Mpc/h]


WL only
WL+SL
NFW
10^{15}
10^{14}
10^{13}
10^{12}
$\Delta\Sigma\ [hM_\odot \mathrm{Mpc}^{-2}]$
10^{-2}
10^{-1}
10^{0}
$r\ [\mathrm{Mpc}/h]$



10^1
10^0
$f_\Sigma(r)$
0.01
0.1
r [Mpc/h]