Cosmology on small scales: Emulating galaxy clustering and galaxy-galaxy lensing into the deeply nonlinear regime

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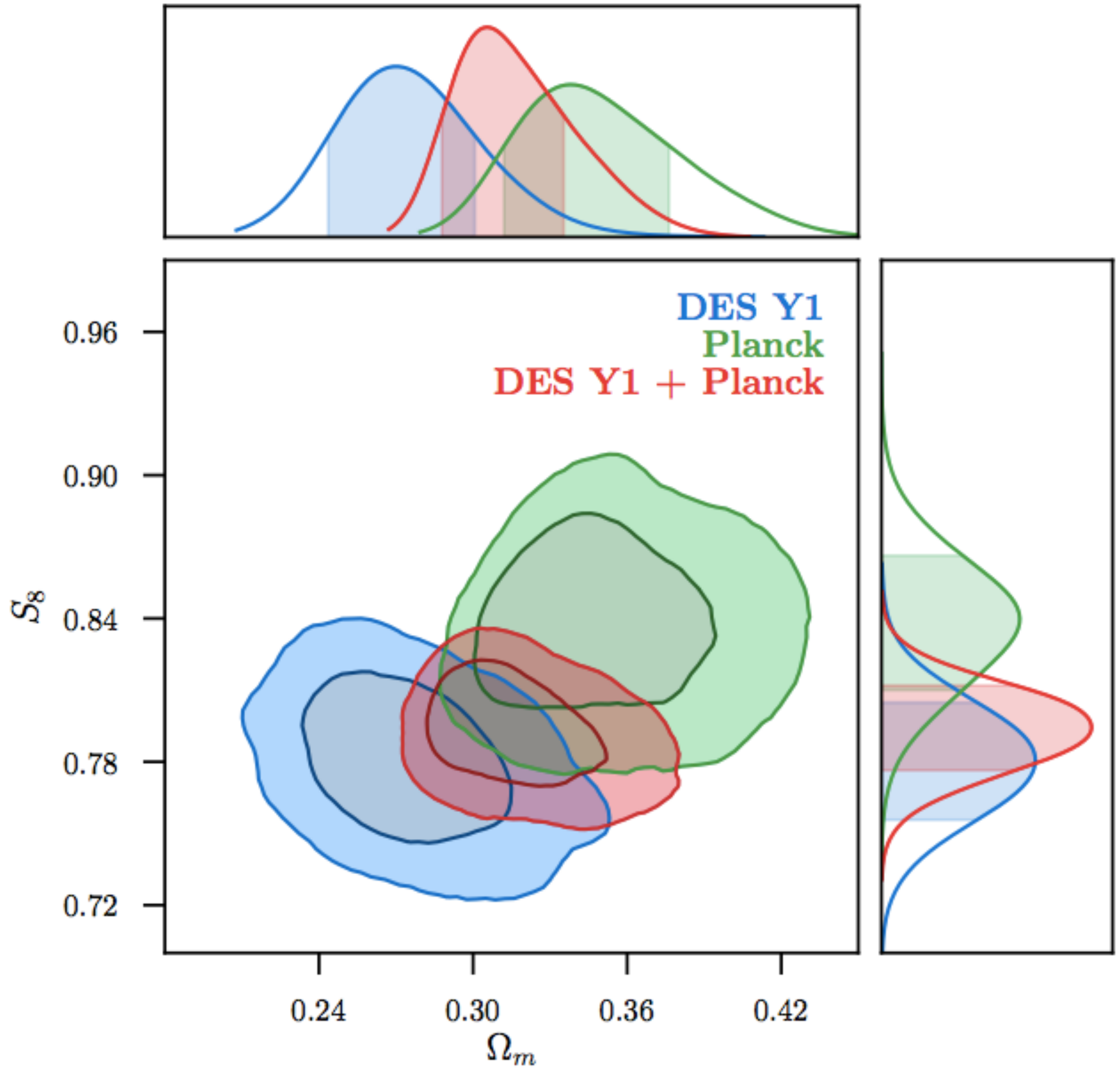
Why do we care?

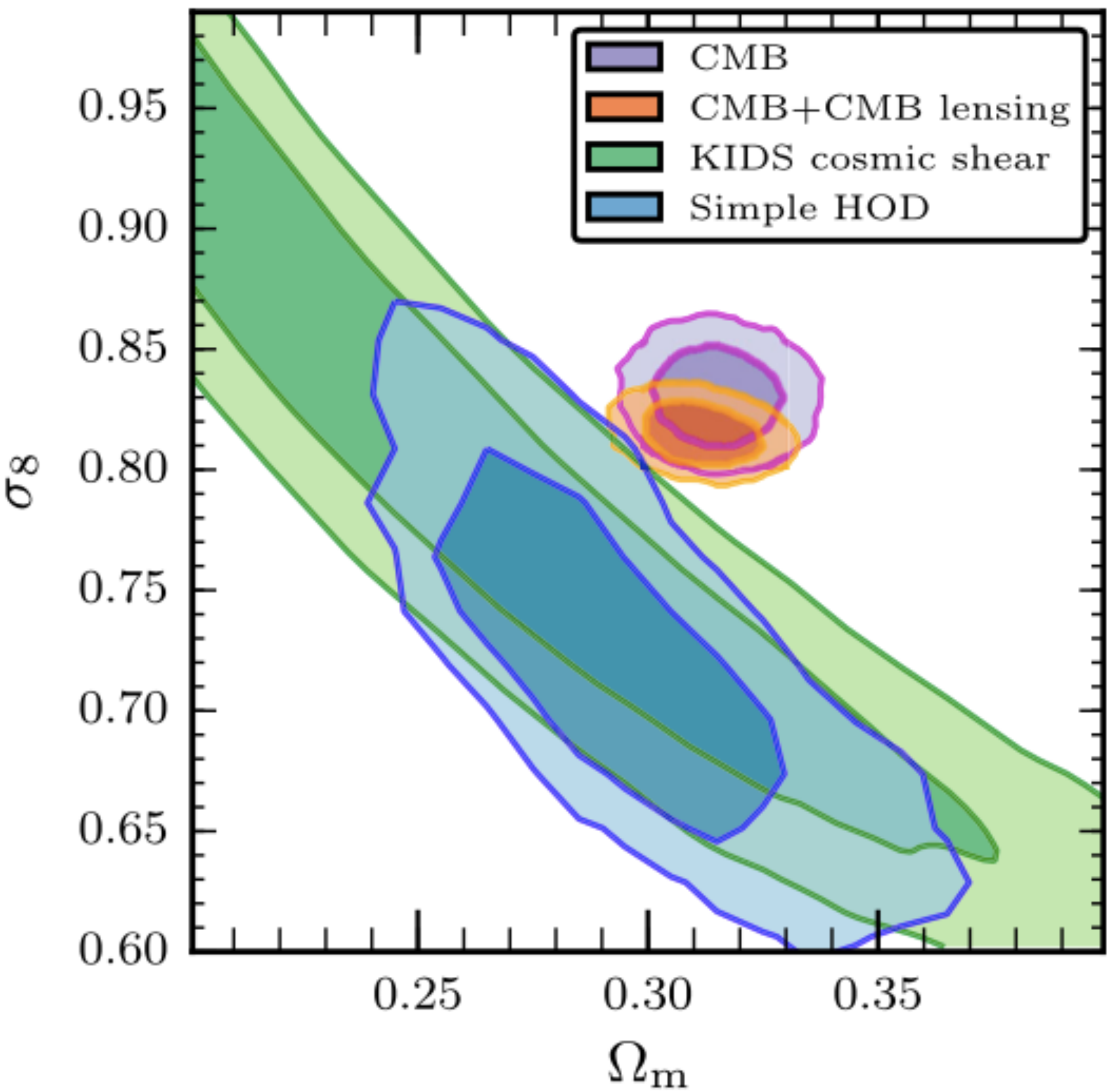
- Is there a discrepancy between high-redshift and low-redshift probes of cosmology?
  - Some weak lensing analyses (e.g., CFHTLens, KiDS) have favored a (significantly) lower amplitude of matter fluctuations relative to PLANCK
  - If found, tension is ~2σ, depending on the analysis



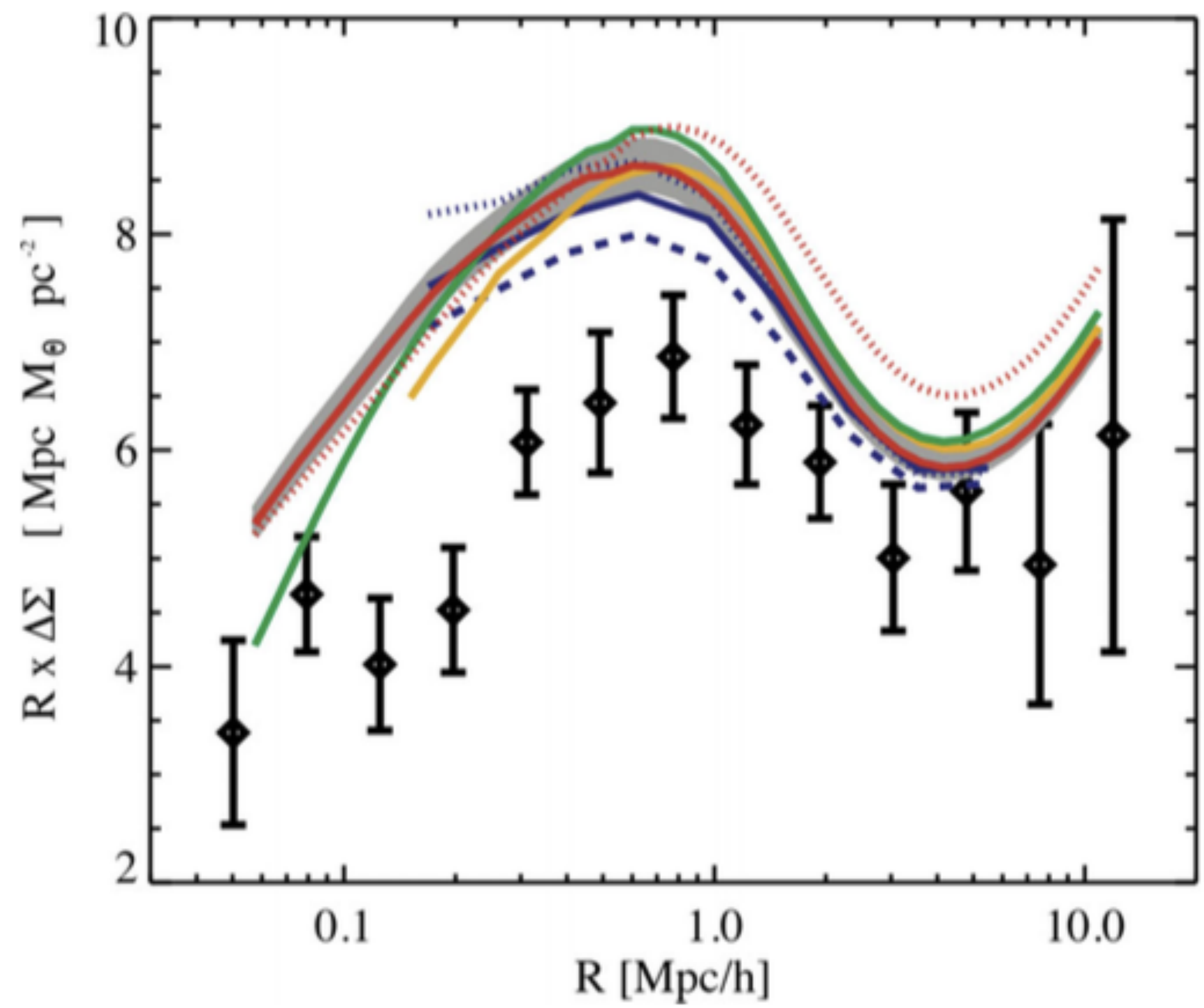
$(S_8 \propto \sigma_8 \Omega_m^{0.5})$

Figure: DES Collaboration

Small scale systematics?



CMASS lens galaxies

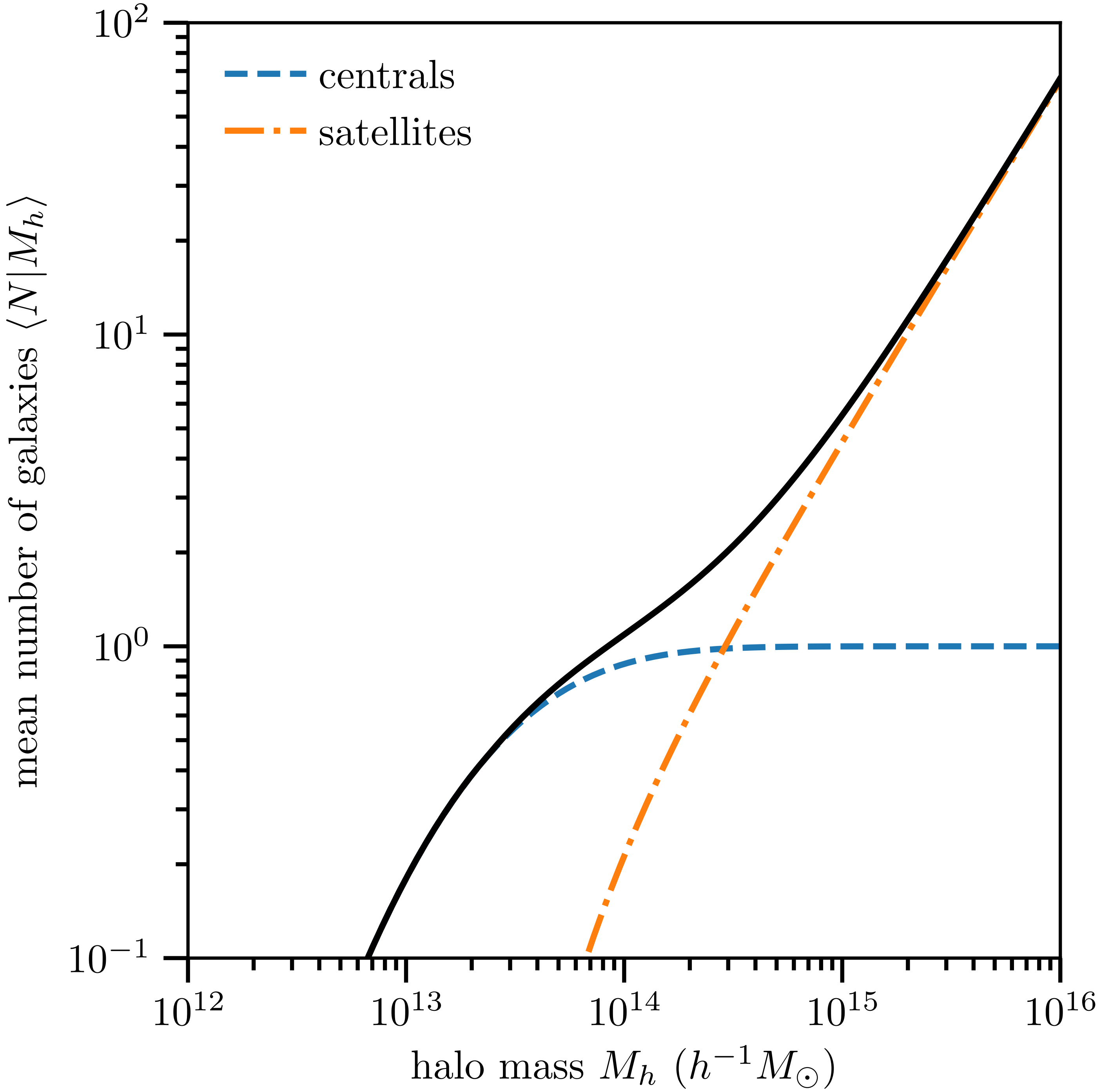


Figures: Leauthaud+ 2017

e.g. Berlind & Weinberg (2002)

Halo occupation distribution (HOD)

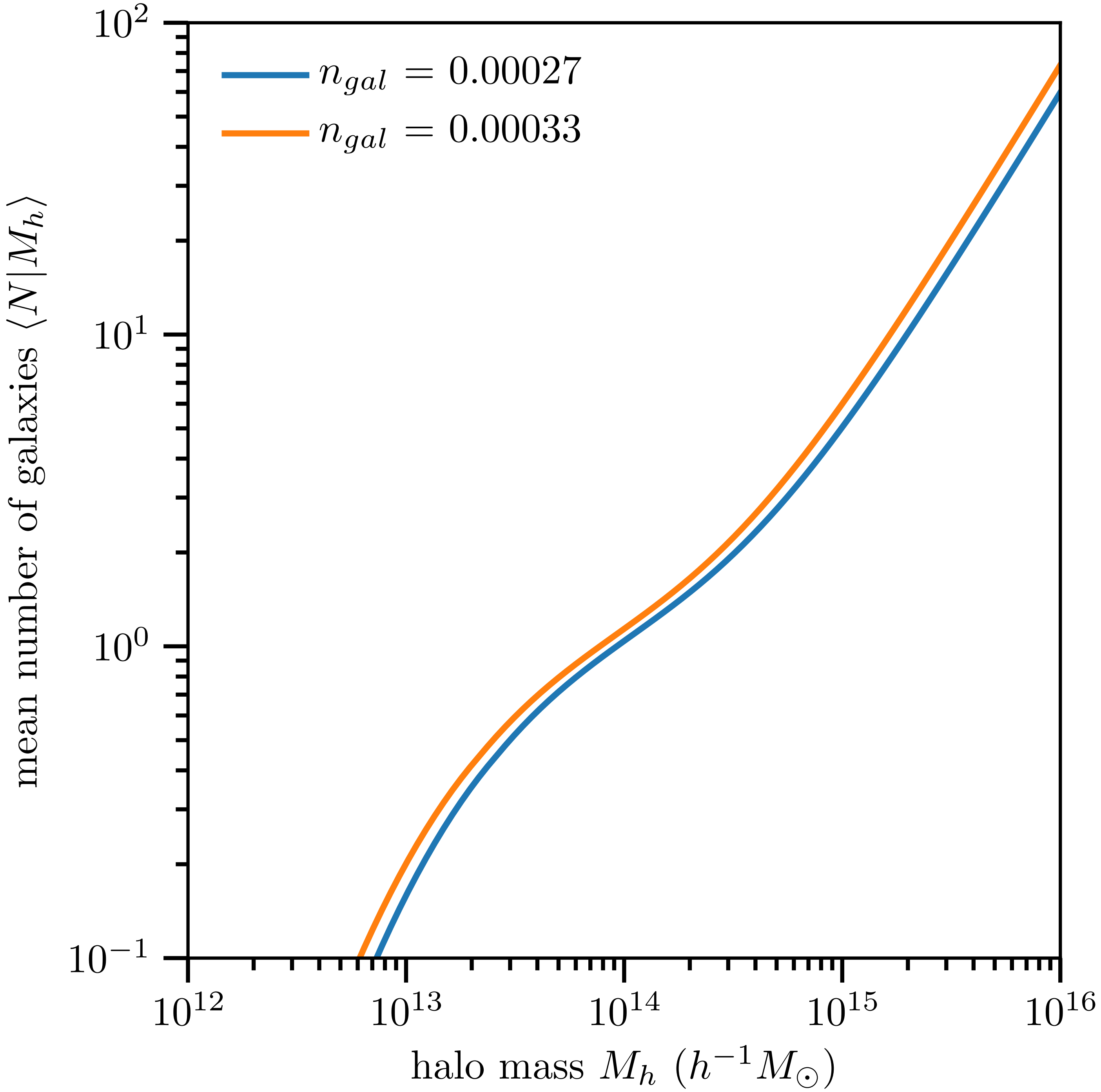
fiducial parameter values



HOD specifies the conditional distribution: $<N|M_h>$

Halo occupation distribution (HOD)

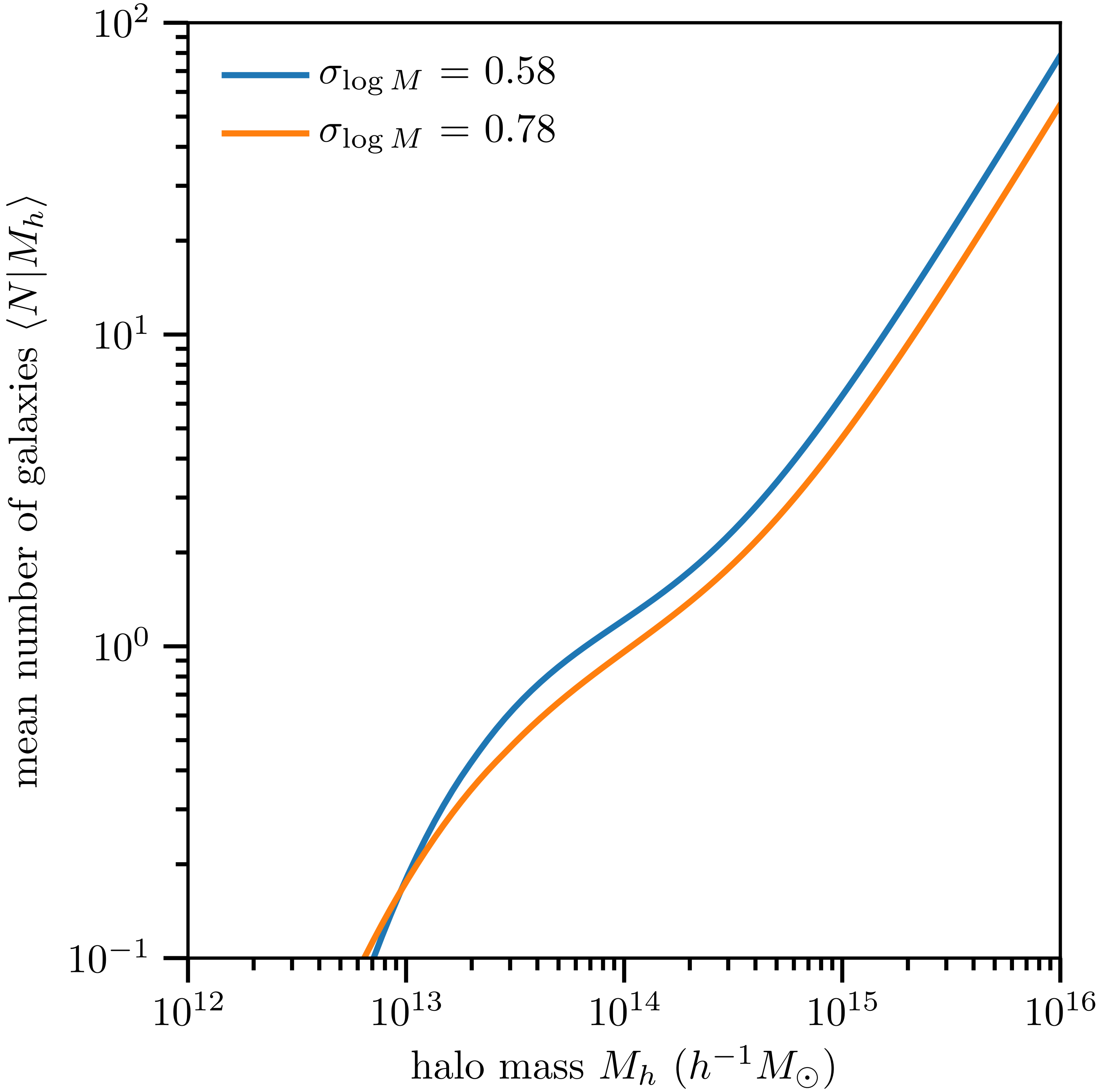
$n_{\rm gal}$



Effect on $\langle N|M_h\rangle$ due to varying galaxy number density

Halo occupation distribution (HOD)

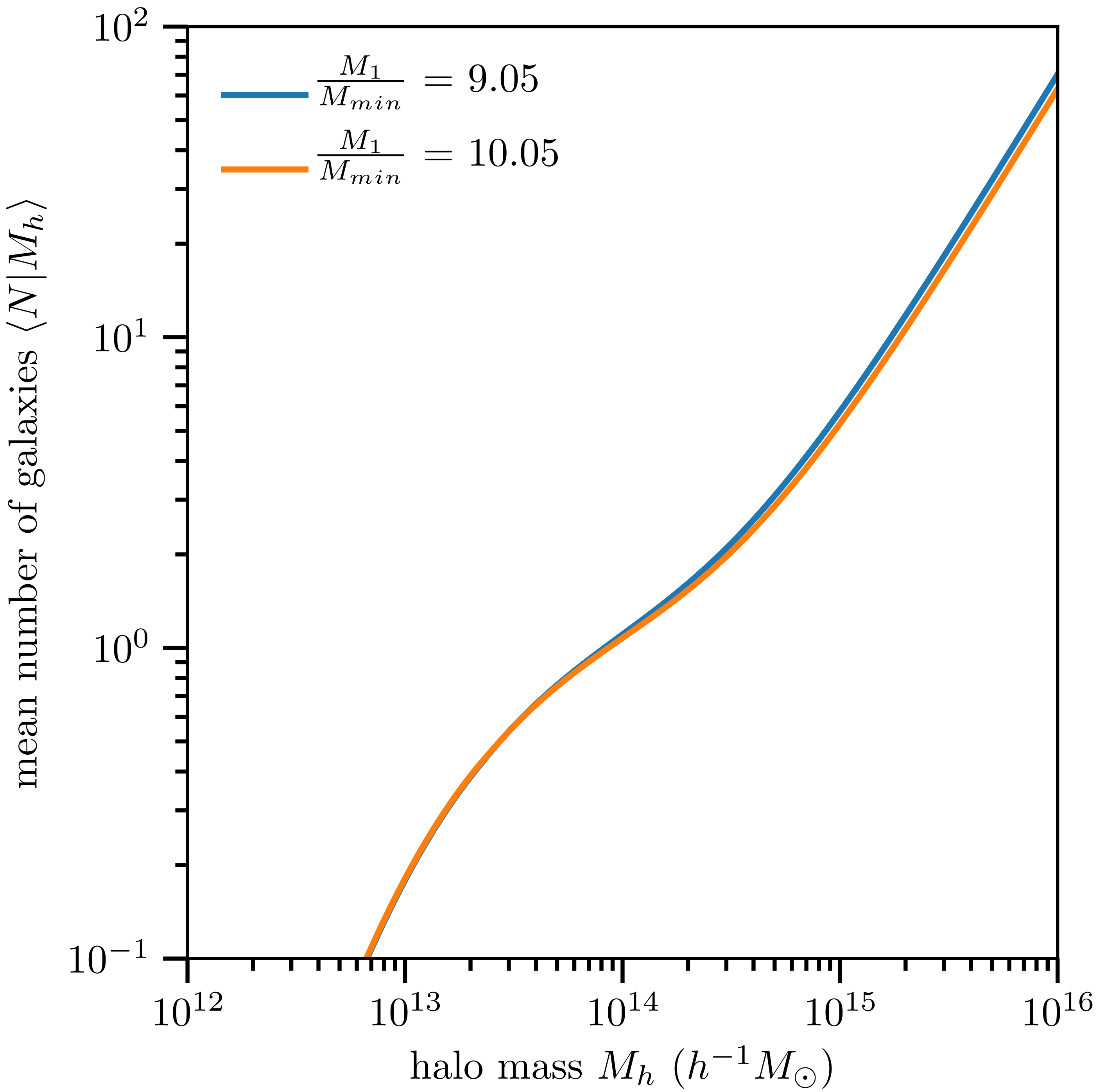
$\sigma_{\log M}$



Varying the scatter in halo mass to stellar mass

Halo occupation distribution (HOD)

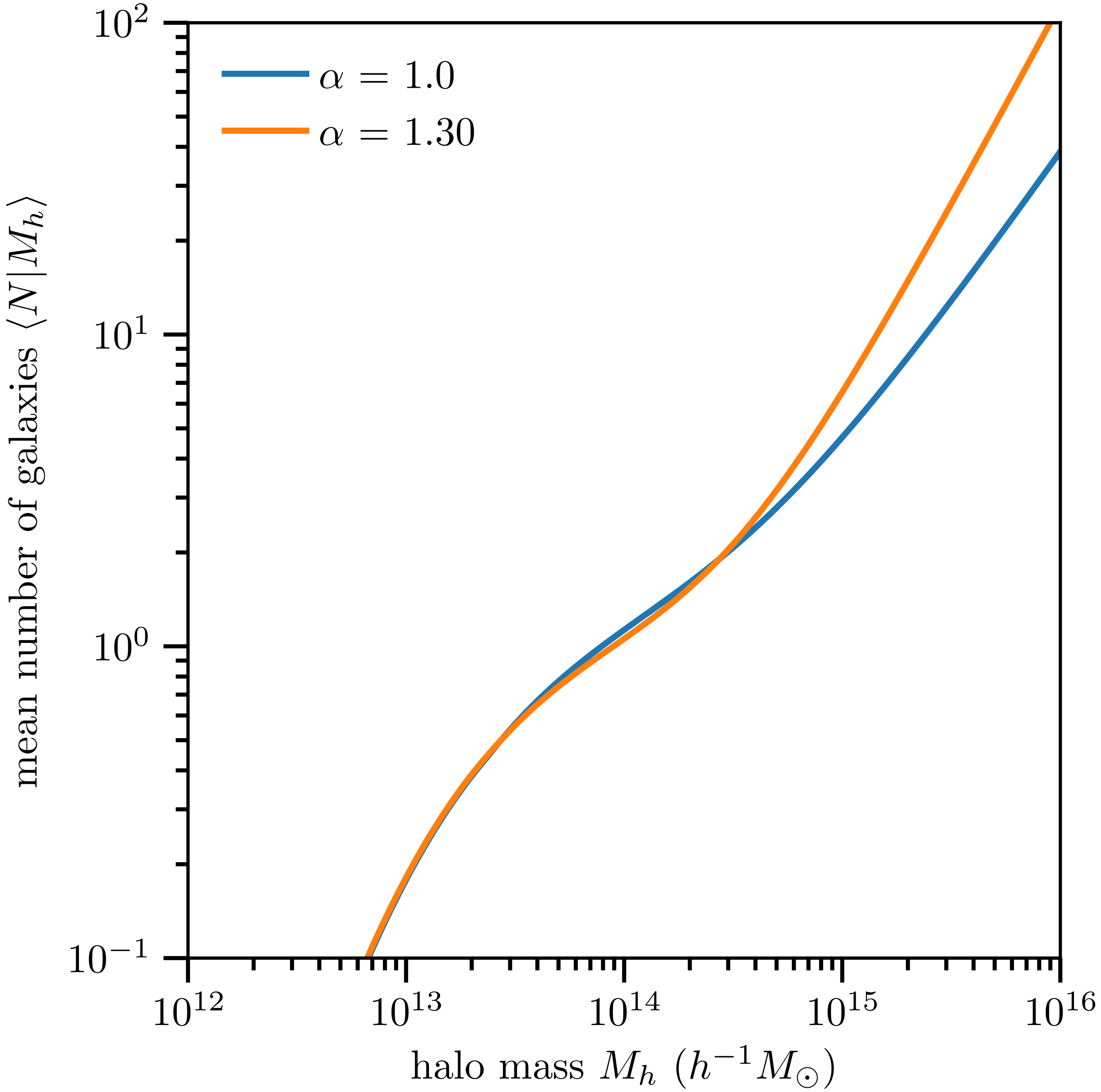
$M_1/M_{\rm min}$



Varying the halo mass at which there are satellite galaxies

Halo occupation distribution (HOD)

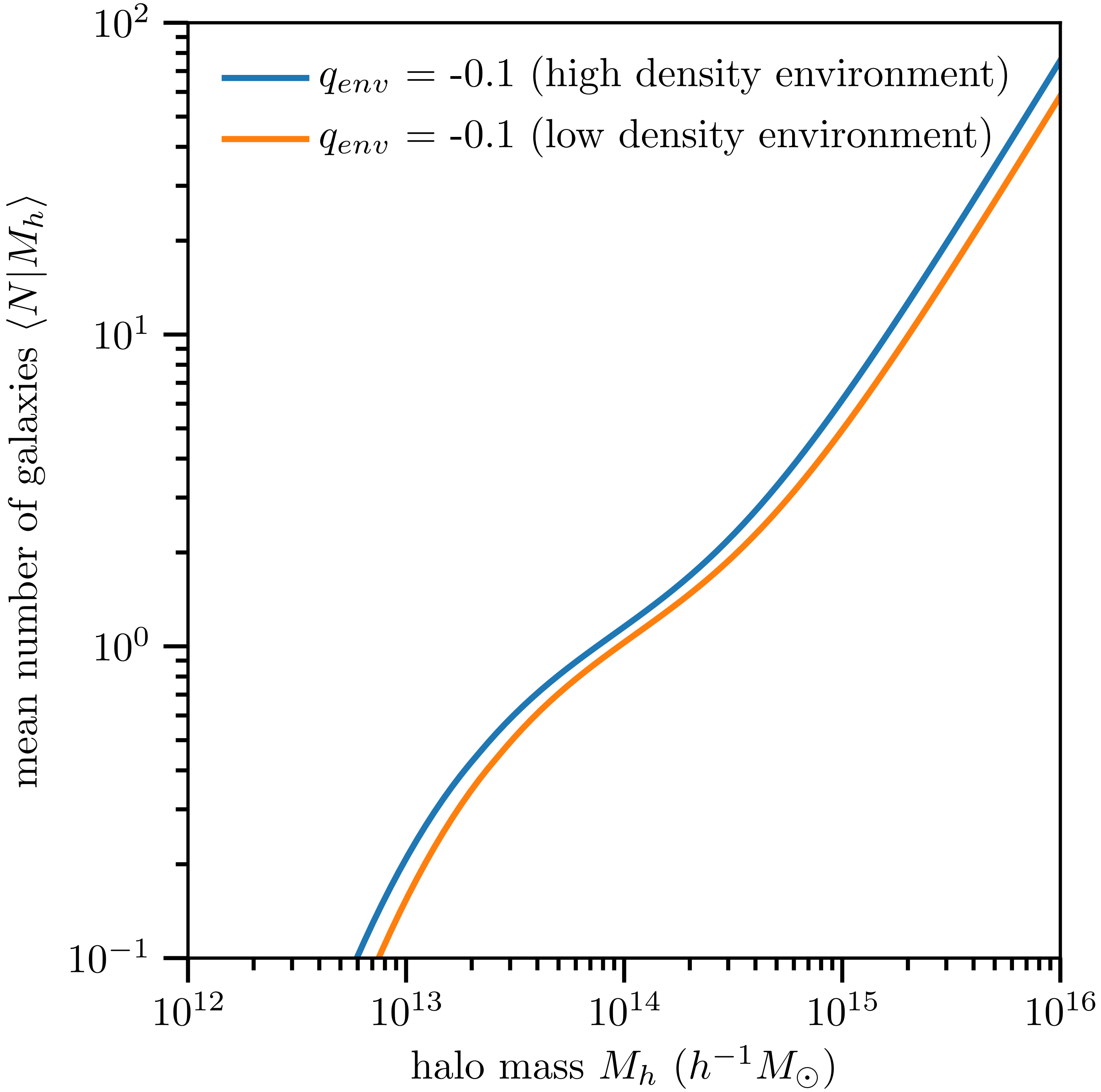
α



Varying the power-law slope of the high-mass HOD

Halo occupation distribution (HOD)

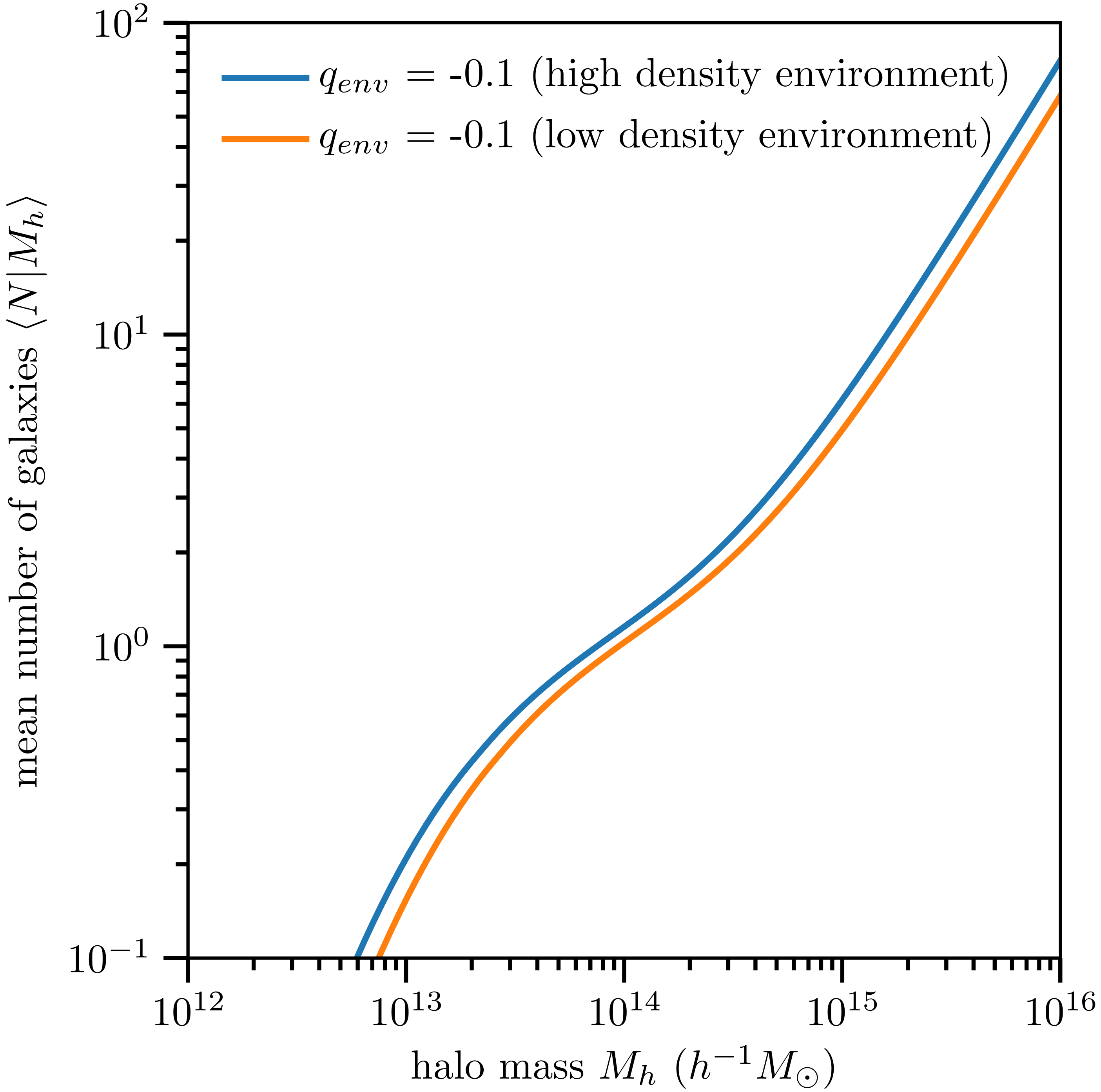
Q_{env}



Makes <$N|M_h$> a function of ~8 Mpc/h-scale overdensity

Halo occupation distribution (HOD) + assembly bias

Q_{env}



Makes $\langle N|M_h \rangle$ a function of ~8 Mpc/h-scale overdensity

Emulator methodology

1. 40 N-body simulations within the Planck 2015 wCDM allowed space
2. Populate dark matter halos with galaxies according to our extended HOD model
3. Compute the galaxy auto-correlation function and galaxy-matter cross-correlation function
4. Interpolate ('emulate') between models across the allowed parameter space
5. Compute projection integrals to obtain observables w_p and γ_t

Emulated quantities

- scale-dependent bias b_g,

$$b_{\mathrm{g}} = \left[\frac{\xi_{\mathrm{gg}}}{\xi_{\mathrm{mm}}} \right]^{1/2}$$

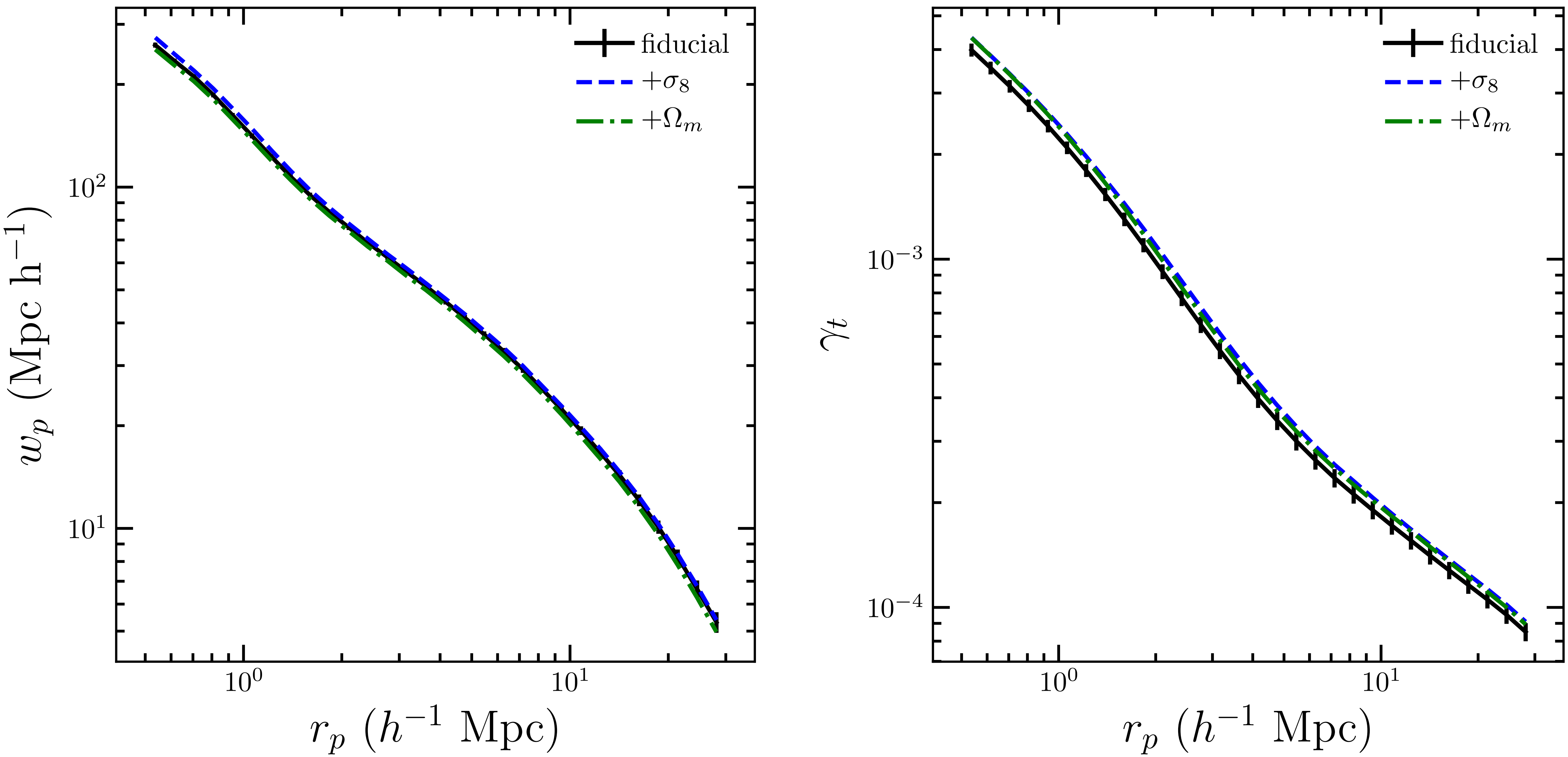
- scale-dependent correlation coefficient r_{gm},

$$r_{\mathrm{gm}} = \left[\frac{\xi_{\mathrm{gm}}^2}{\xi_{\mathrm{gg}} \xi_{\mathrm{mm}}} \right]^{1/2}$$

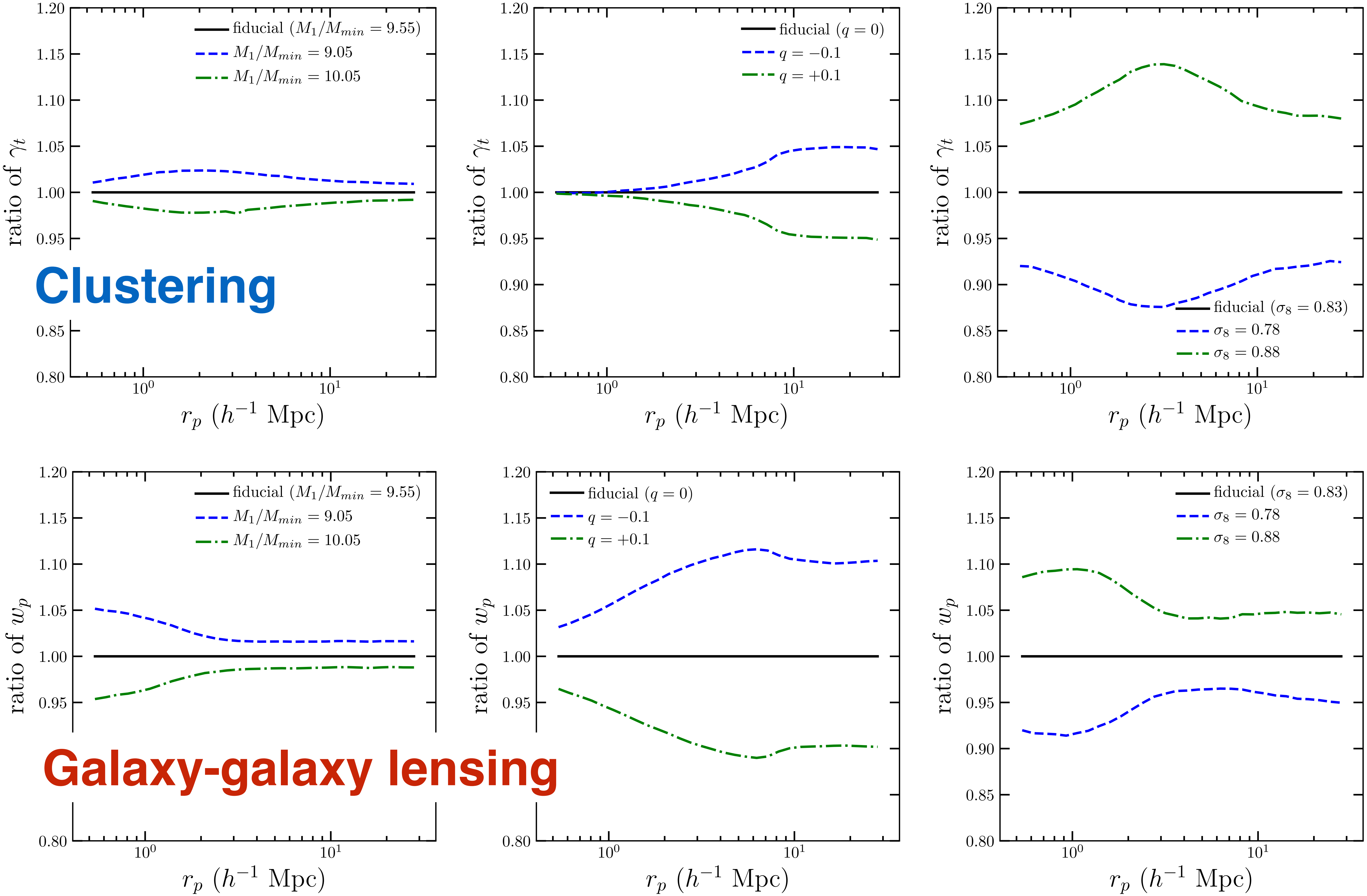
- scale-dependent ratio of the nonlinear-to-linear matter correlation function

$$b_{\mathrm{nl}} = \left[\frac{\xi_{\mathrm{mm}}}{\xi_{\mathrm{mm,lin}}} \right]^{1/2}$$

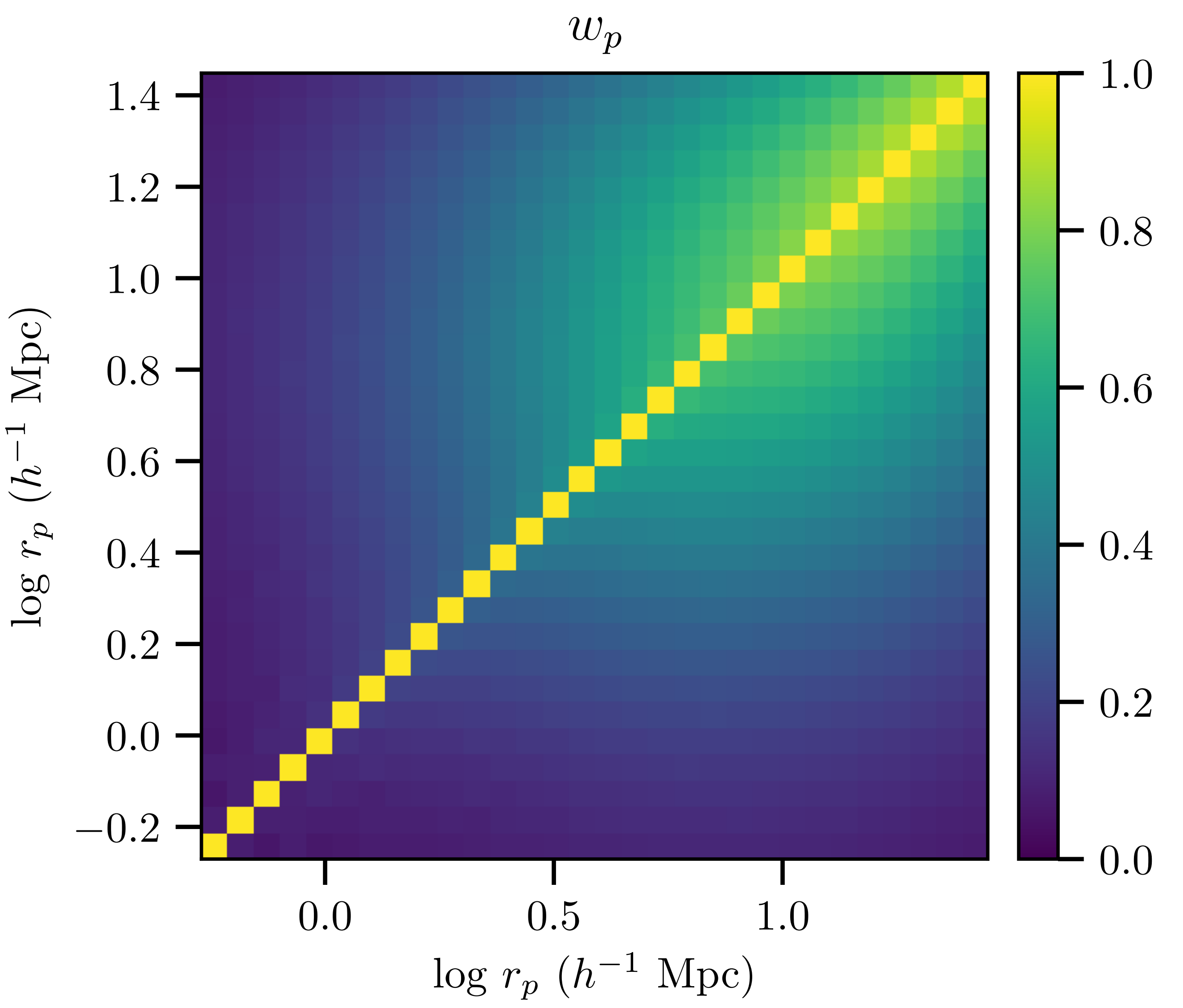
Galaxy-galaxy lensing and clustering signal on scales 0.5 < r_p < 30 Mpc/h



HOD (satellite M_{halo}) ‘Assembly bias’ Cosmology



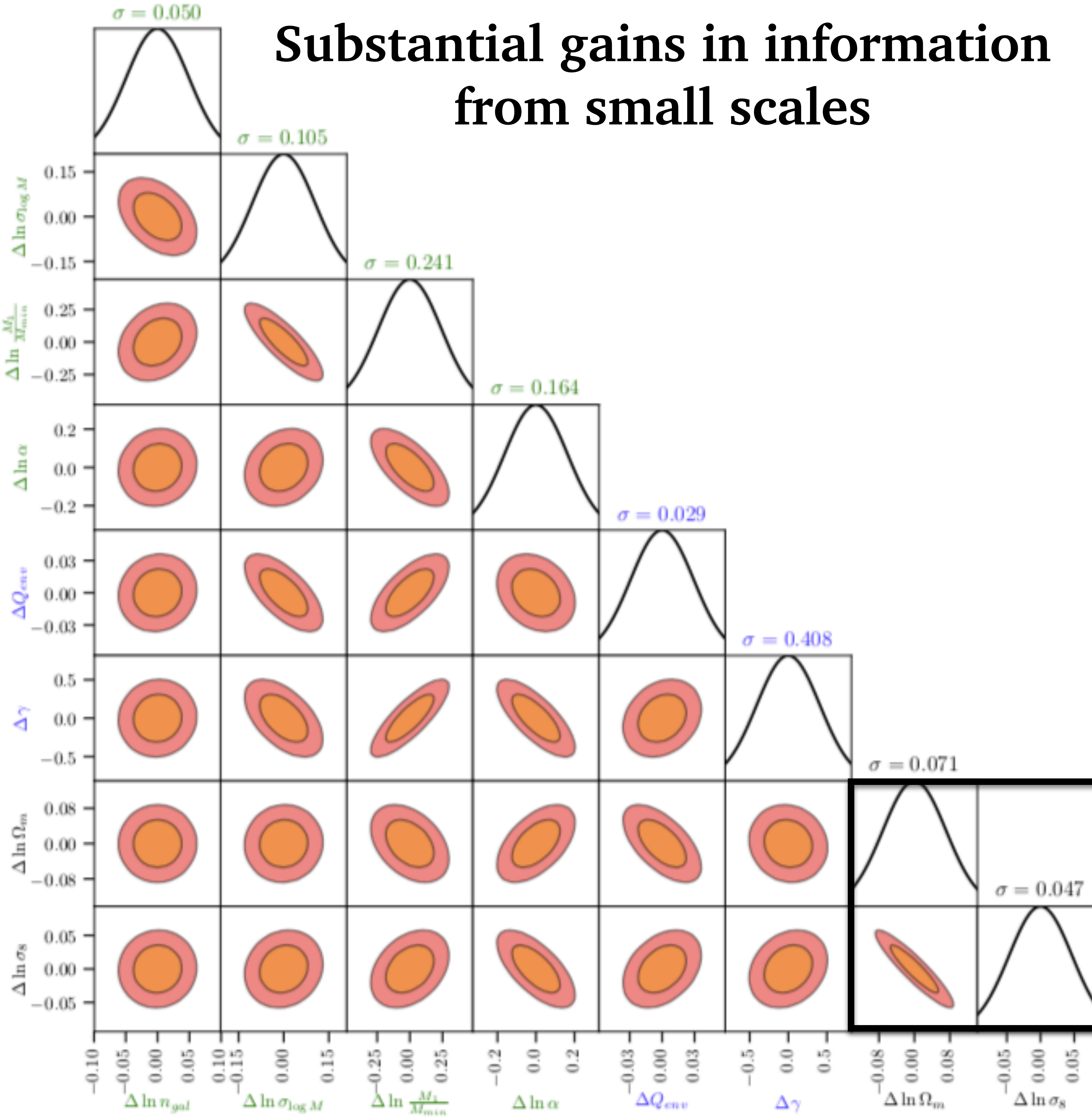
Covariance matrices and forecasting for LOWZ clustering and GGL



(n_{gal} = 3 x 10^{-4} h^3 Mpc^{-3}, ~1 galaxy arcmin^{-2})

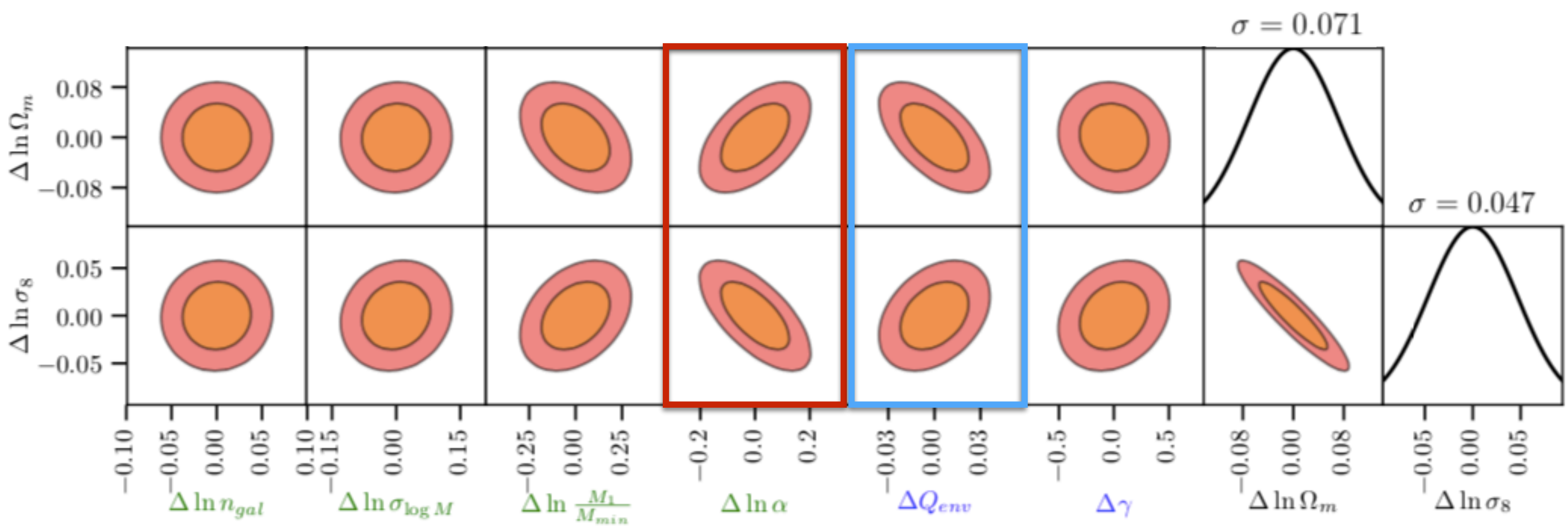
Substantial gains in information from small scales

- 2% uncertainty on $\sigma_8\Omega_m^{0.6}$
- Using only scales >2 Mpc/h (lensing) and >4 Mpc/h (clustering), the constraints degrade to 4%
- More precise constraints by a factor of >2, equivalent to >4x the survey area without small scales



Degeneracy with cosmological parameters

- Satellite galaxy parameters, assembly bias parameter are most degenerate with cosmological parameters Ω_m, σ_8



Degeneracy with cosmological parameters

- Satellite galaxy parameters, assembly bias parameter are most degenerate with cosmological parameters Ω_m, σ_8

	p	best-constrained $\sigma_8\Omega_m^p$
fiducial	0.605	0.019
$r_{\rm min} = 0.1\,h^{-1}$ Mpc	0.658	0.014
centrals only	0.589	0.014

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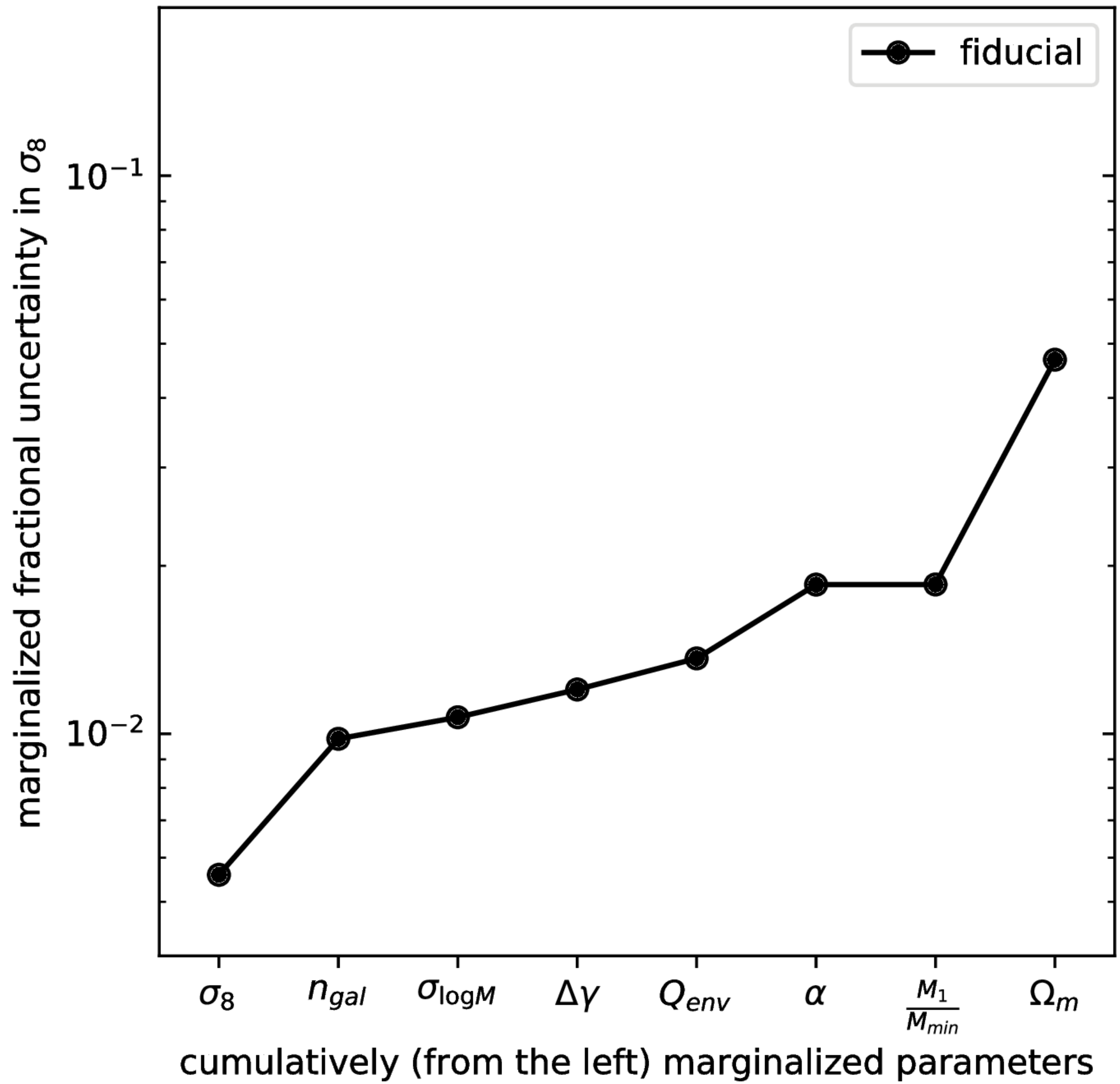
centrals only	0.589	$\boxed{0.014}$

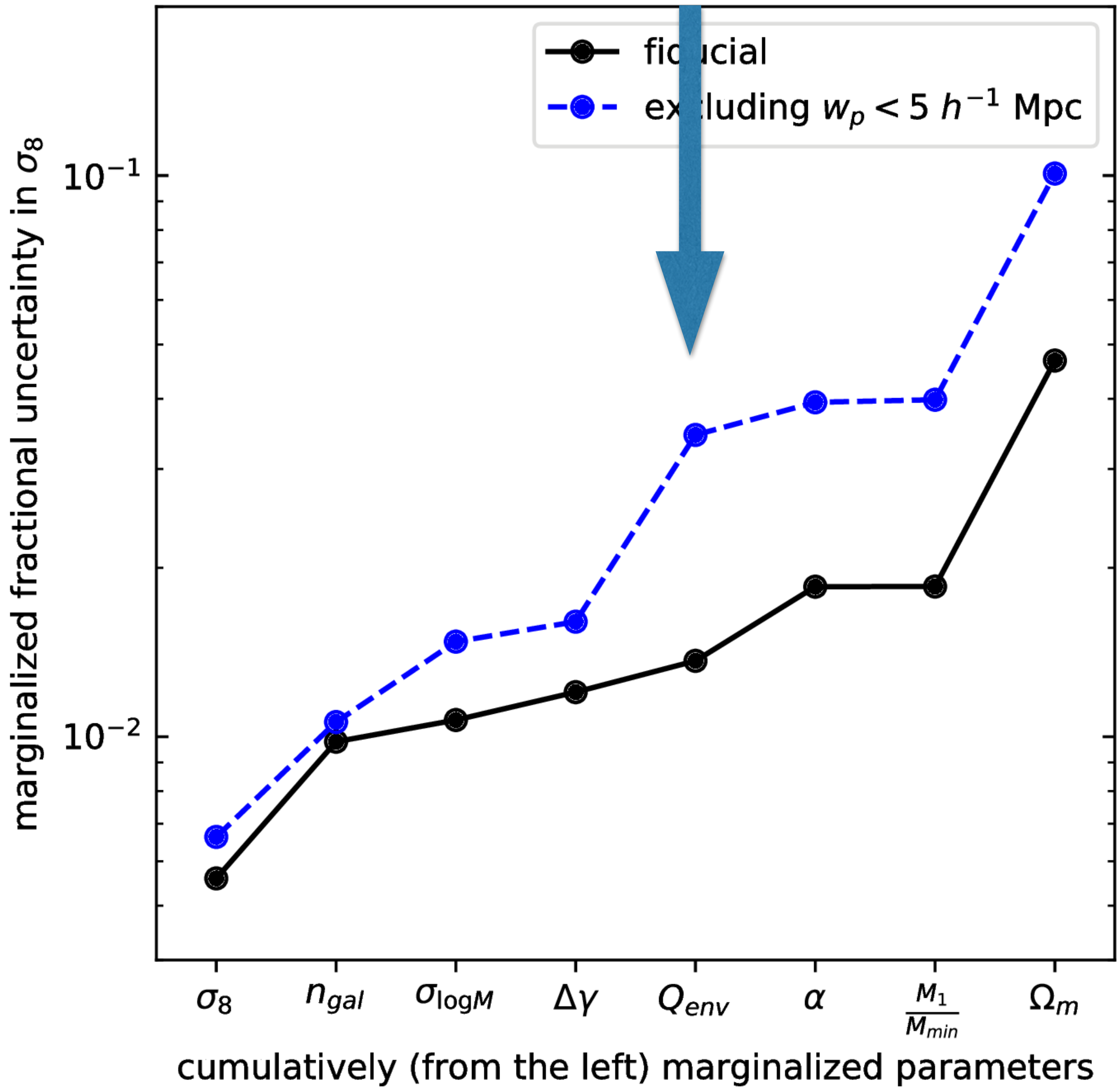
- Using yet smaller scales, we could constrain cosmology as well as a sample that (artificially) contained only central galaxies

What is the cost of marginalizing over galaxy formation uncertainties?

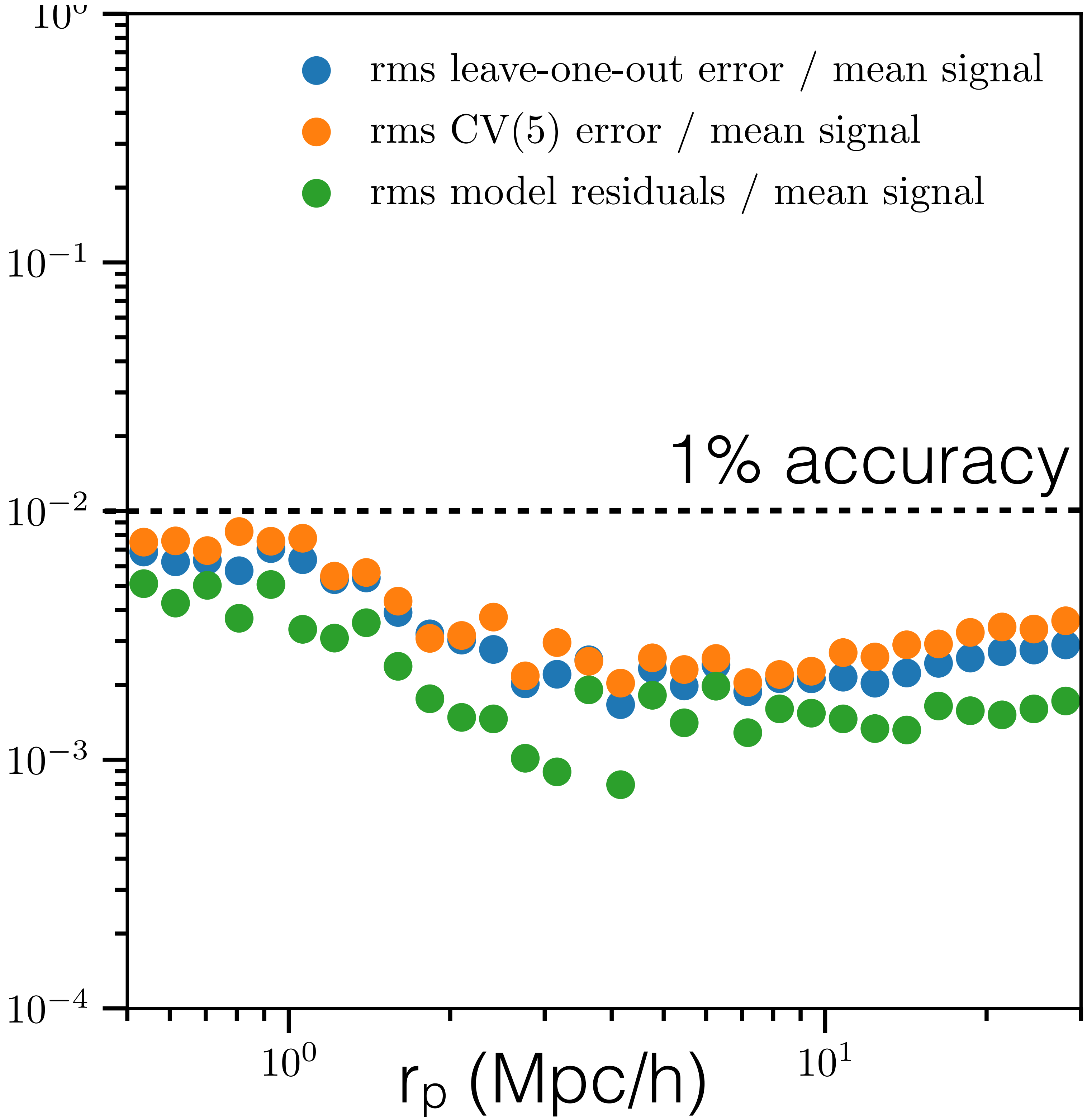


Effect of assembly bias without any small-scale clustering information

What is the cost of marginalizing over galaxy formation uncertainties?



The future: Emulating cosmology across wCDM parameter space



4th-order polynomial regression *(fixed HOD parameters)*

- Fractional accuracy of wp emulator
  - **Leave-one-out cross validation**

Conclusions

- Small scales have significant information within the framework of HOD galaxy bias models
- The future: emulating all wCDM cosmological parameters and HOD parameters using the full grid of 40 simulations, fitting to CMASS + DES lensing measurements
- Future progress on small scales will require testing to avoid bias in parameter inference due to baryonic effects, massive neutrinos
- We can test and rule out models of the galaxy-halo occupation jointly with cosmological models

Extra slides

Model

1. Galaxies live in dark matter halos
   (spherical overdensity of ~200)
2. One (or zero) galaxies live at the center of each halo
   (number determined by some function of halo mass)
3. Satellite galaxies live between the center and the halo radius, determined in the average by a spherically-symmetric profile
4. The number of satellites of a given halo is Poisson
   (mean determined by some function of halo mass)
5. The mass distribution on the scales of interest is entirely determined by gravitational collapse

<u>Result</u>: predict clustering and matter cross-correlation on all scales

Galaxy-galaxy lensing

Source plane

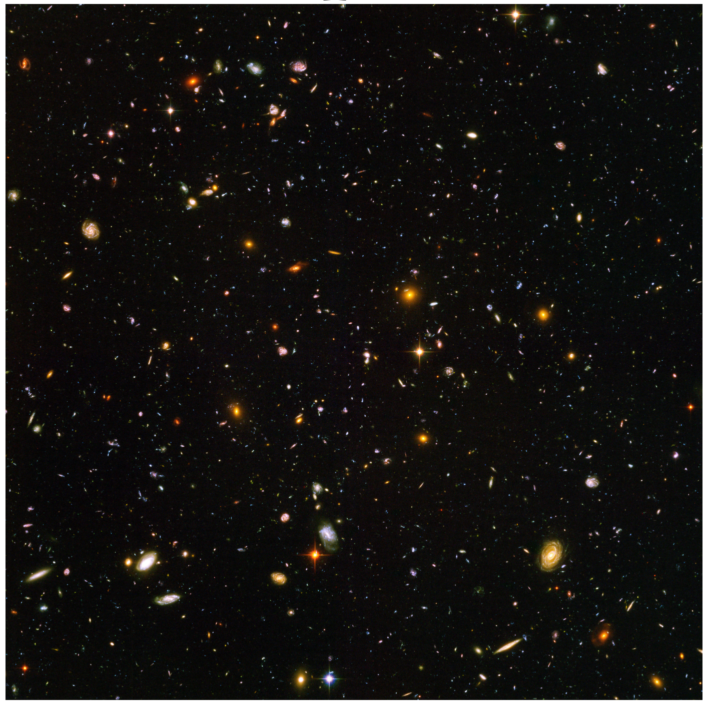


Image: Hubble Ultra Deep Field

Lens plane

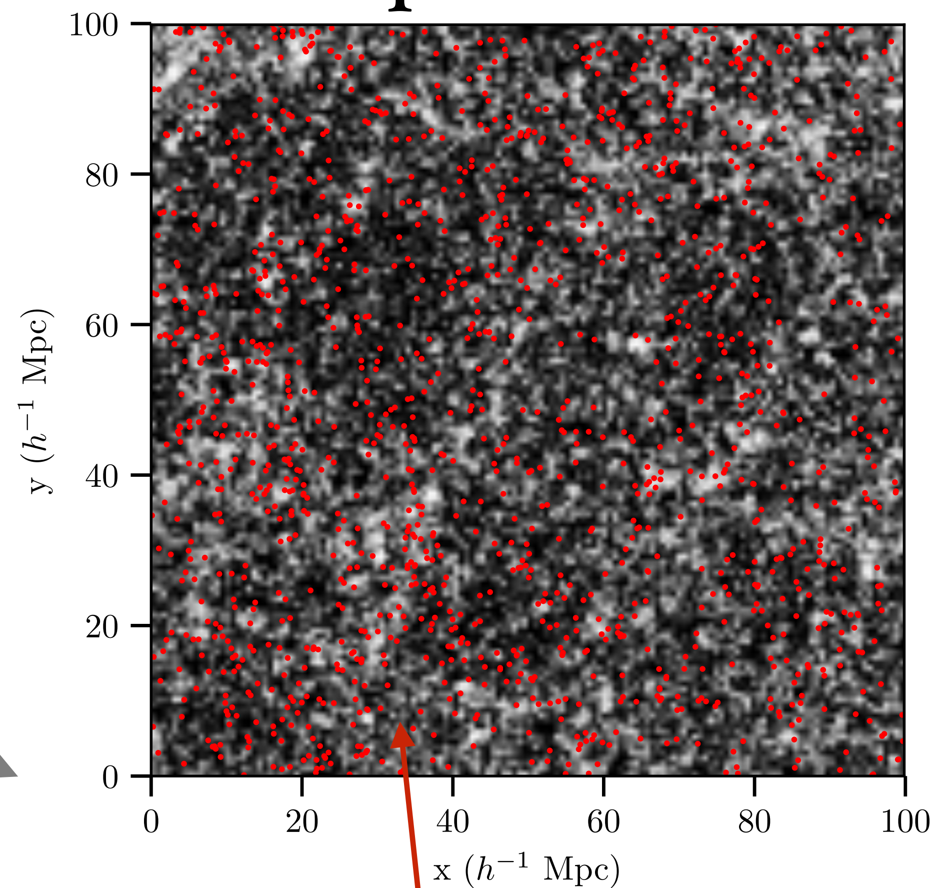
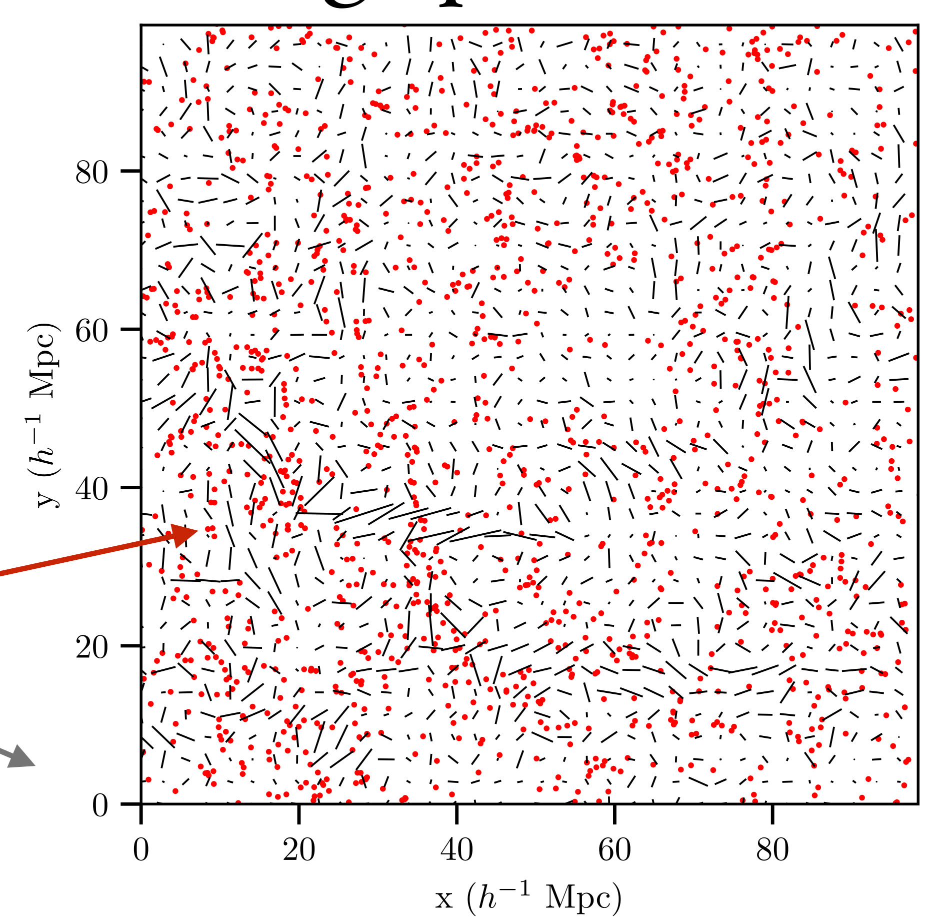


Image plane



lens galaxies

Model parameters

1. Number density of galaxies n_{gal}
2. Halo mass scatter at fixed stellar mass (how sharp is the transition from 0 to 1 galaxies?) $\sigma_{\log M}$
3. Ratio of characteristic halo mass for satellite galaxies to the minimum halo mass of the sample M_1/M_{min}
4. Power-law slope of satellite occupation α
5. Power-law slope of satellite galaxy profile w.r.t. NFW halo profile $\Delta\gamma$
6. Change in halo occupation due to environmental density on ~8 Mpc/h scales (in units of log halo mass) Q_{env}
7. *Cosmology:* Ω_{m}, σ_8

Why do we care?

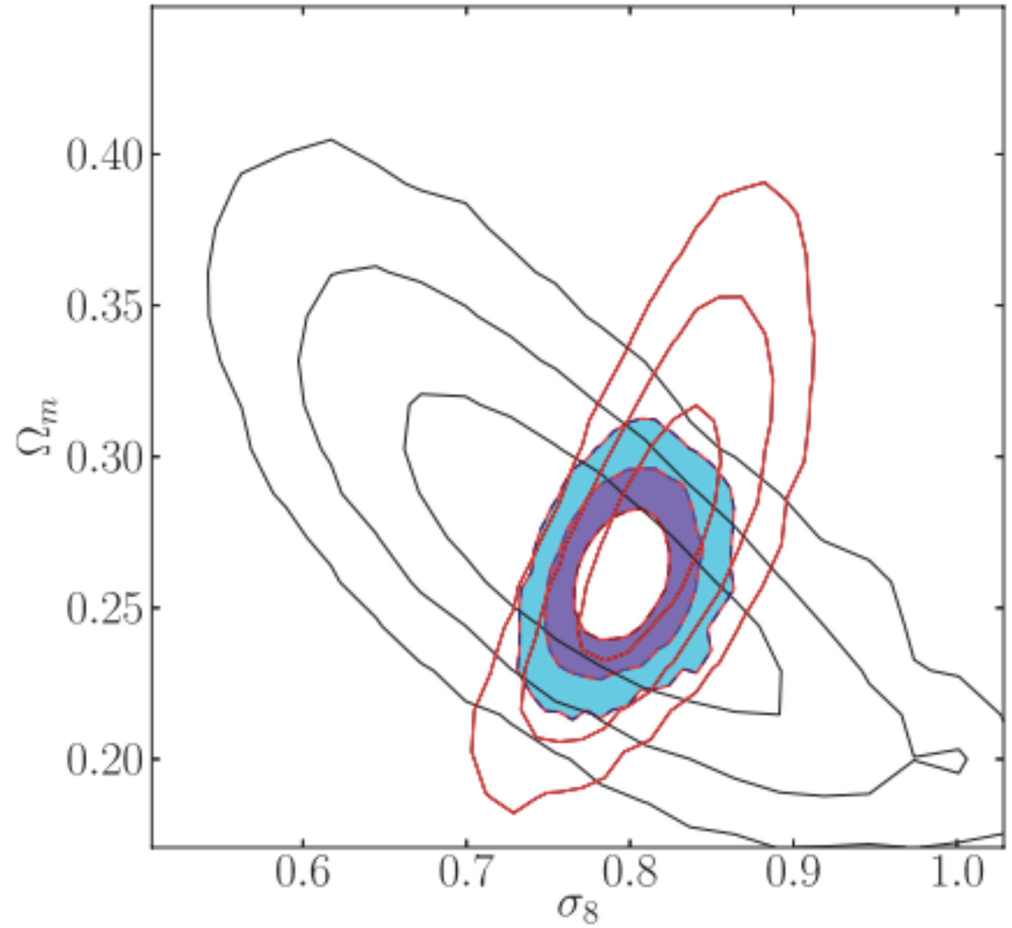


Figure: Mandelbaum+ 2013

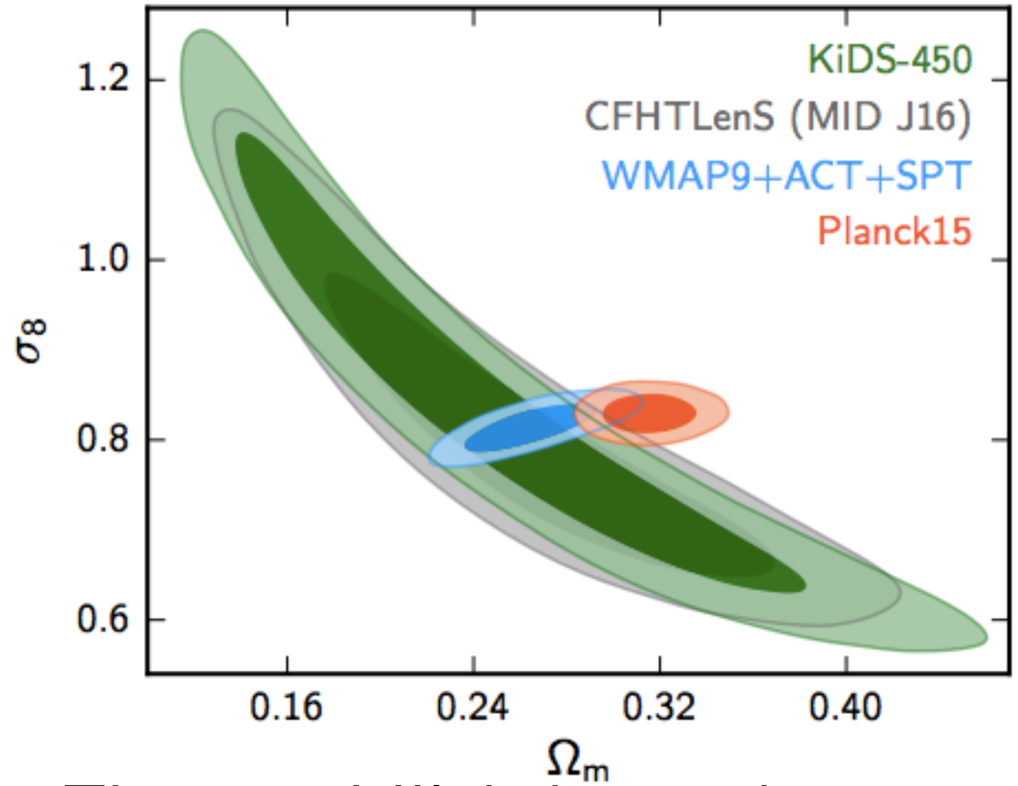


Figure: Hildebrandt+ 2016

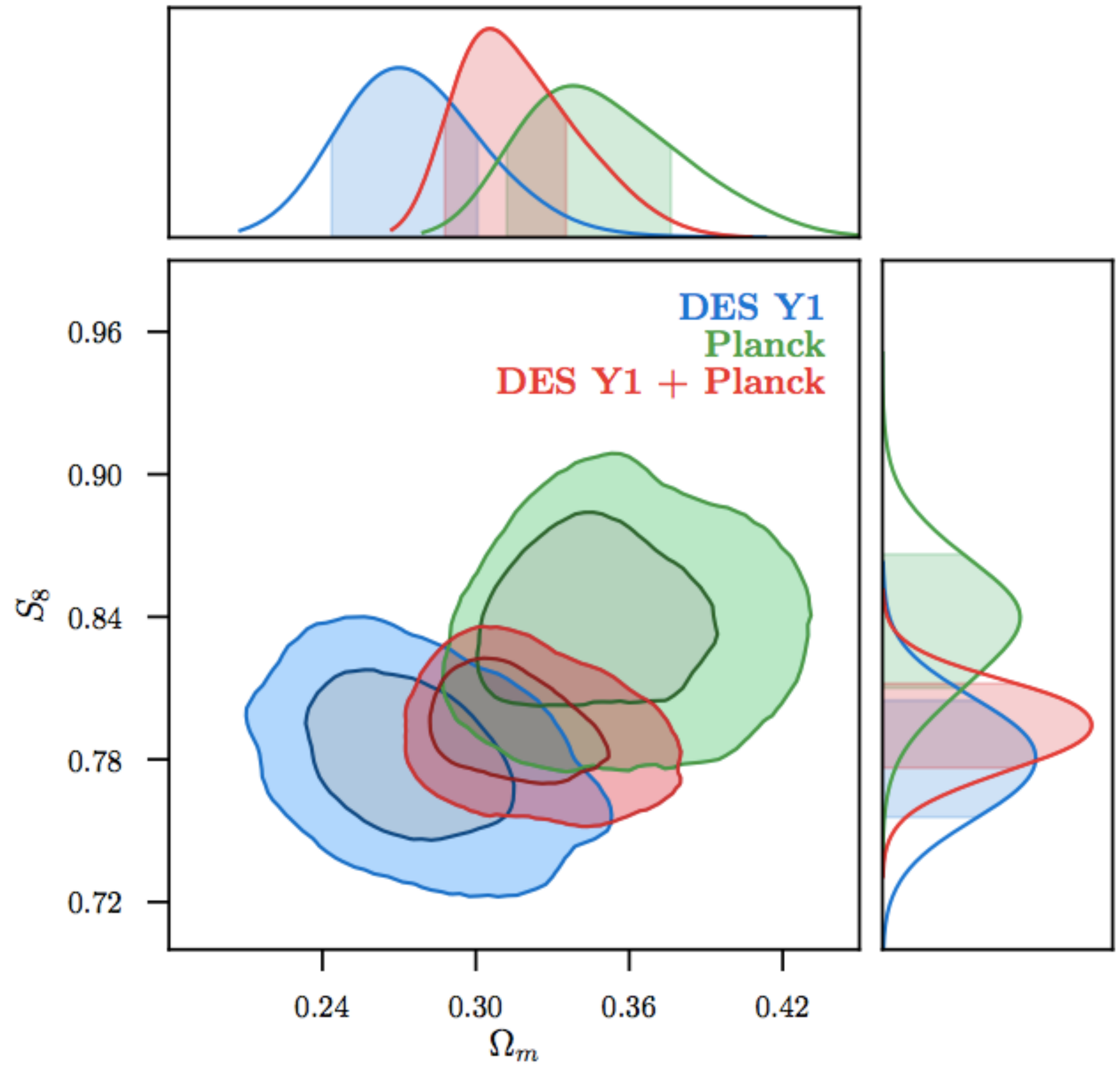


Figure: DES Collaboration 2017

Emulator flowchart

$$X(r) = X_{\rm fid}(r) + \sum_i \Delta p_i \frac{\partial X(r)}{\partial p_i}$$

$$X = \{\ln b_{\rm nl}(r), \ln b_g(r), \ln r_{\rm gm}(r)\}$$

$$p_i = \{\ln \sigma_8, \ln \Omega_m, \ln n_{\rm gal}, \ln \sigma_{\log M}, \ln M_1/M_{\rm min}, \ln \alpha, \Delta\gamma, Q_{\rm env}\}$$

$$\xi_{\rm gg} = b_g^2 (b_{\rm nl}^2 \xi_{\rm mm,lin})$$

$$\xi_{\rm gm} = r_{\rm gm}\, b_g (b_{\rm nl}^2 \xi_{\rm mm,lin})$$

Emulator flowchart

$$\xi_{\rm gg} = b_g^2 (b_{\rm nl}^2 \xi_{\rm mm,lin})$$

$$\xi_{\rm gm} = r_{\rm gm}\, b_g (b_{\rm nl}^2 \xi_{\rm mm,lin})$$

$$\Delta\Sigma(r_p) = \bar{\rho}\left[\frac{4}{r_p^2}\int_0^{r_p} r \int_0^{\infty} \xi_{\rm gm}\left(\sqrt{r^2+\pi^2}\right)\, d\pi\, dr - 2\int_0^{\infty} \xi_{\rm gm}\left(\sqrt{r_p^2+\pi^2}\right)\, d\pi\right]$$

$$w_p(r_p) = 2\int_0^{\pi_{\rm max}} \xi_{\rm gg}\left(\sqrt{r^2+\pi^2}\right)\, d\pi$$