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

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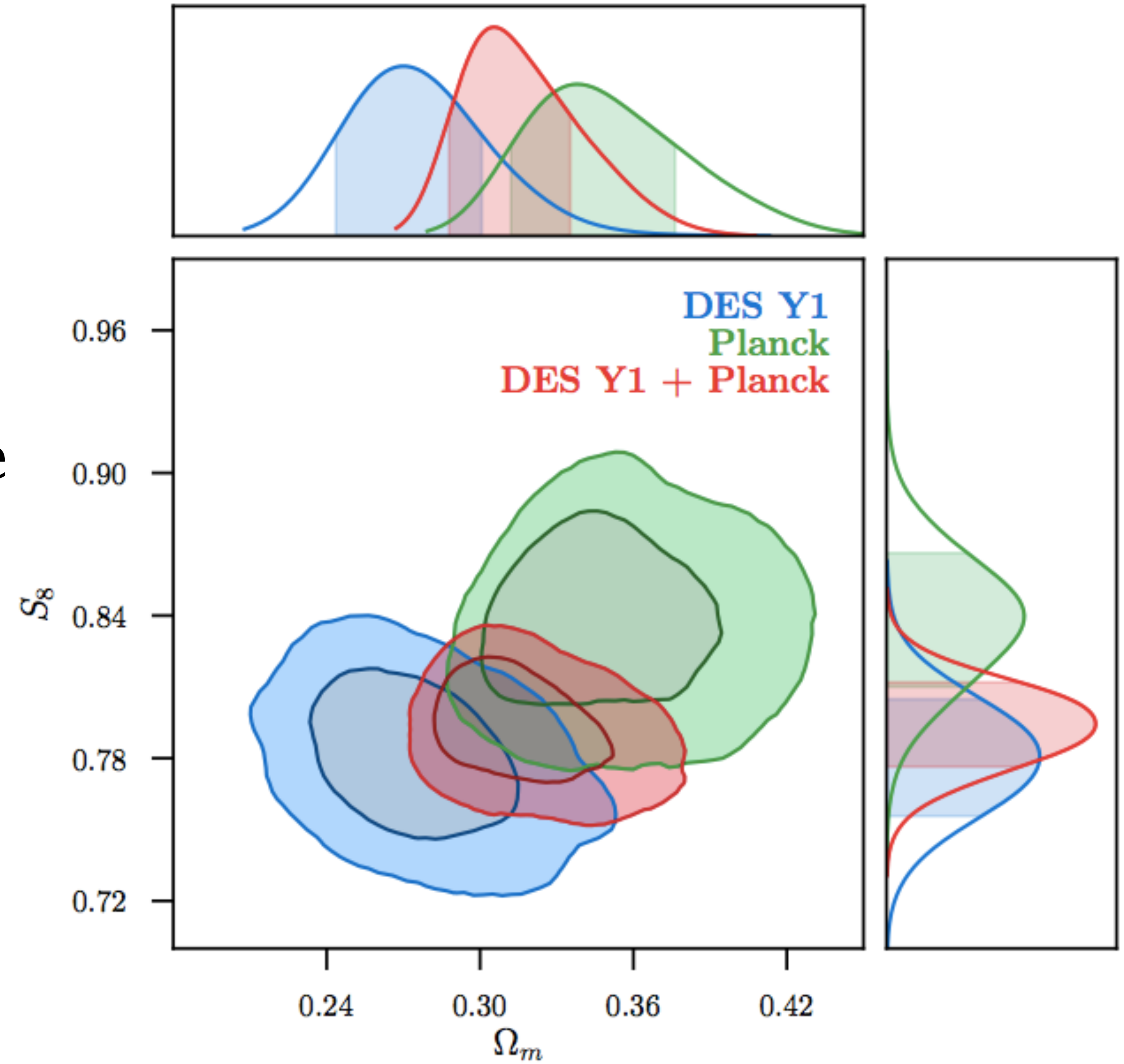
Why do we care?

- 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

Why do we care?

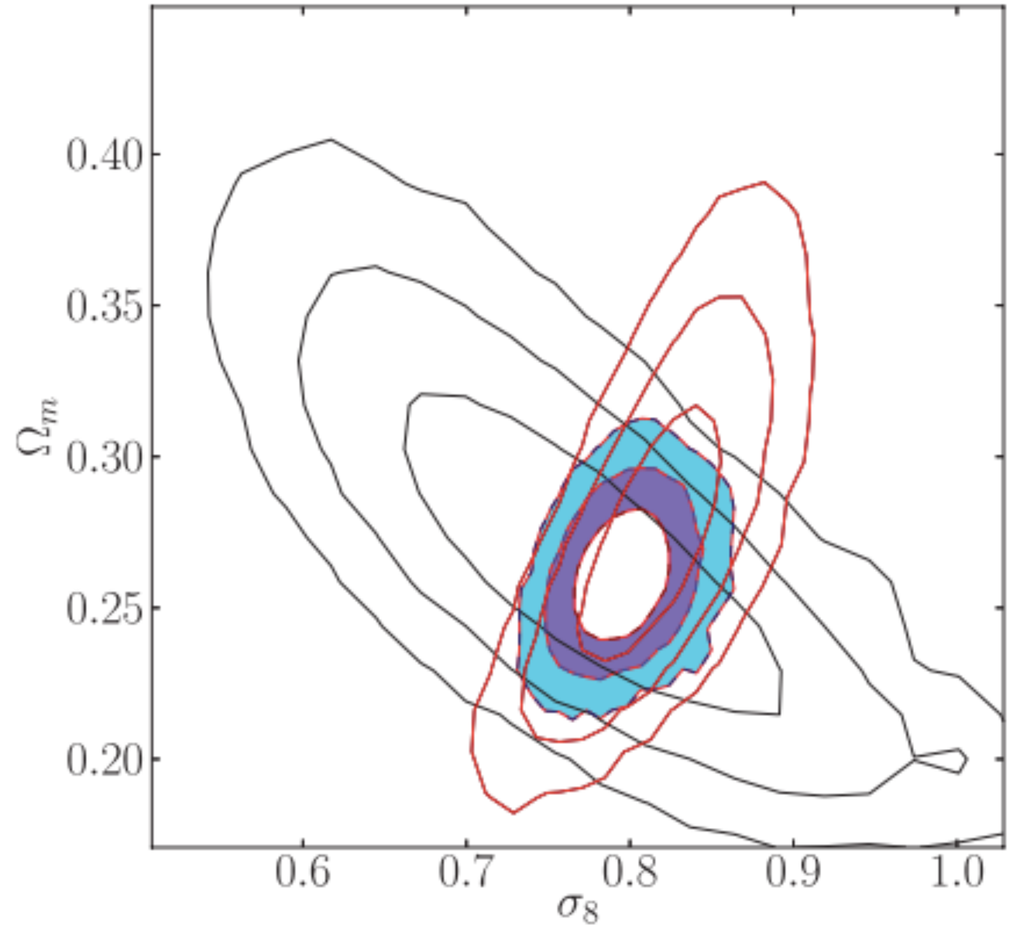


Figure: Mandelbaum+ 2013

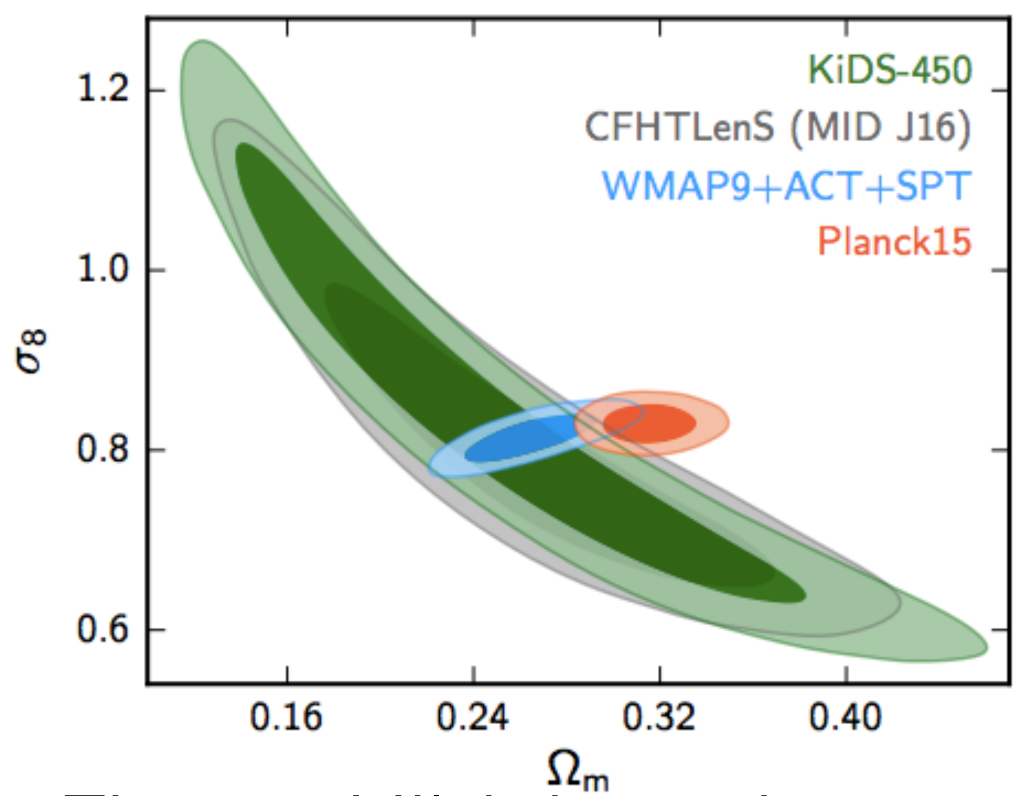


Figure: Hildebrandt+ 2016

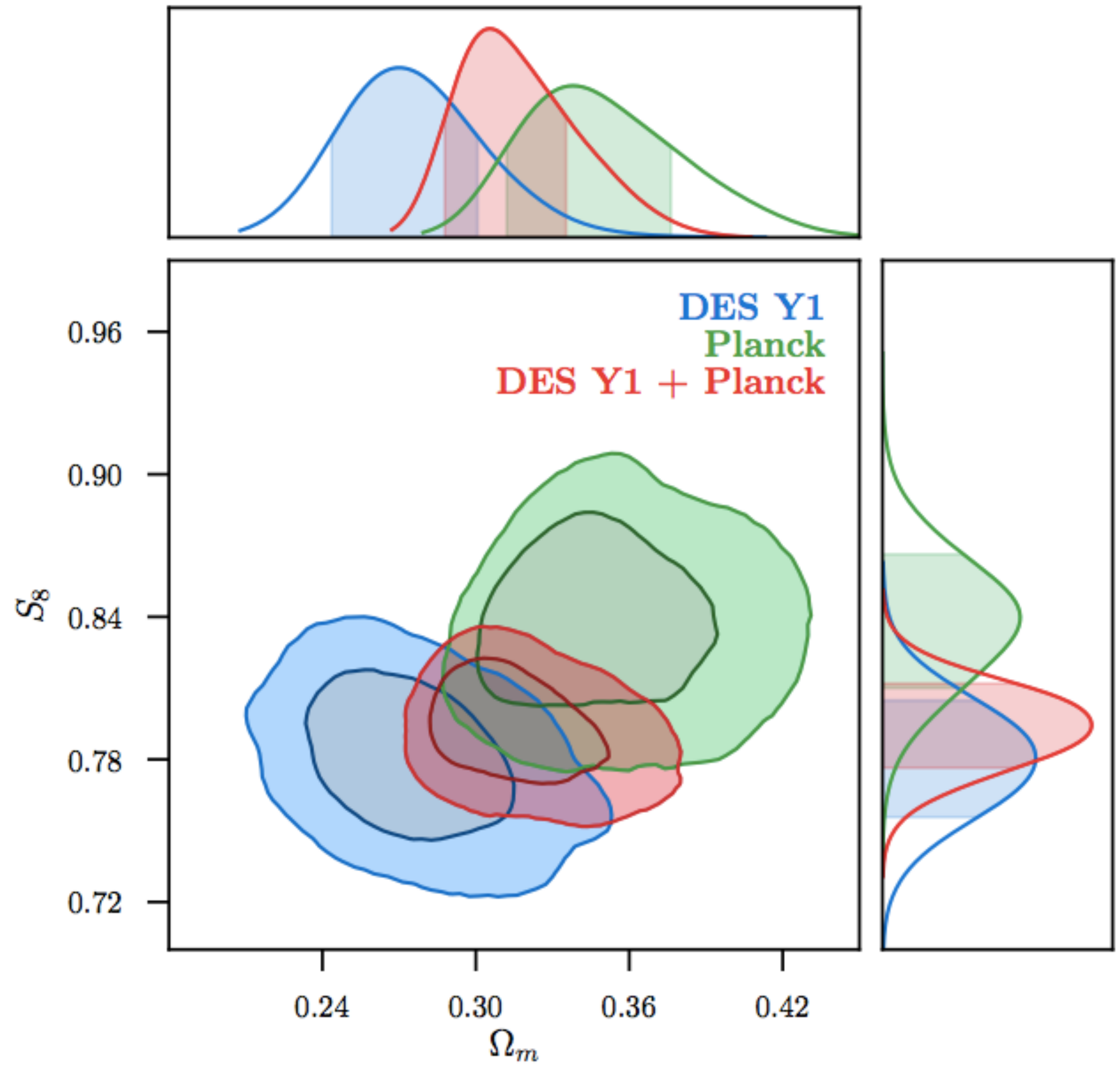
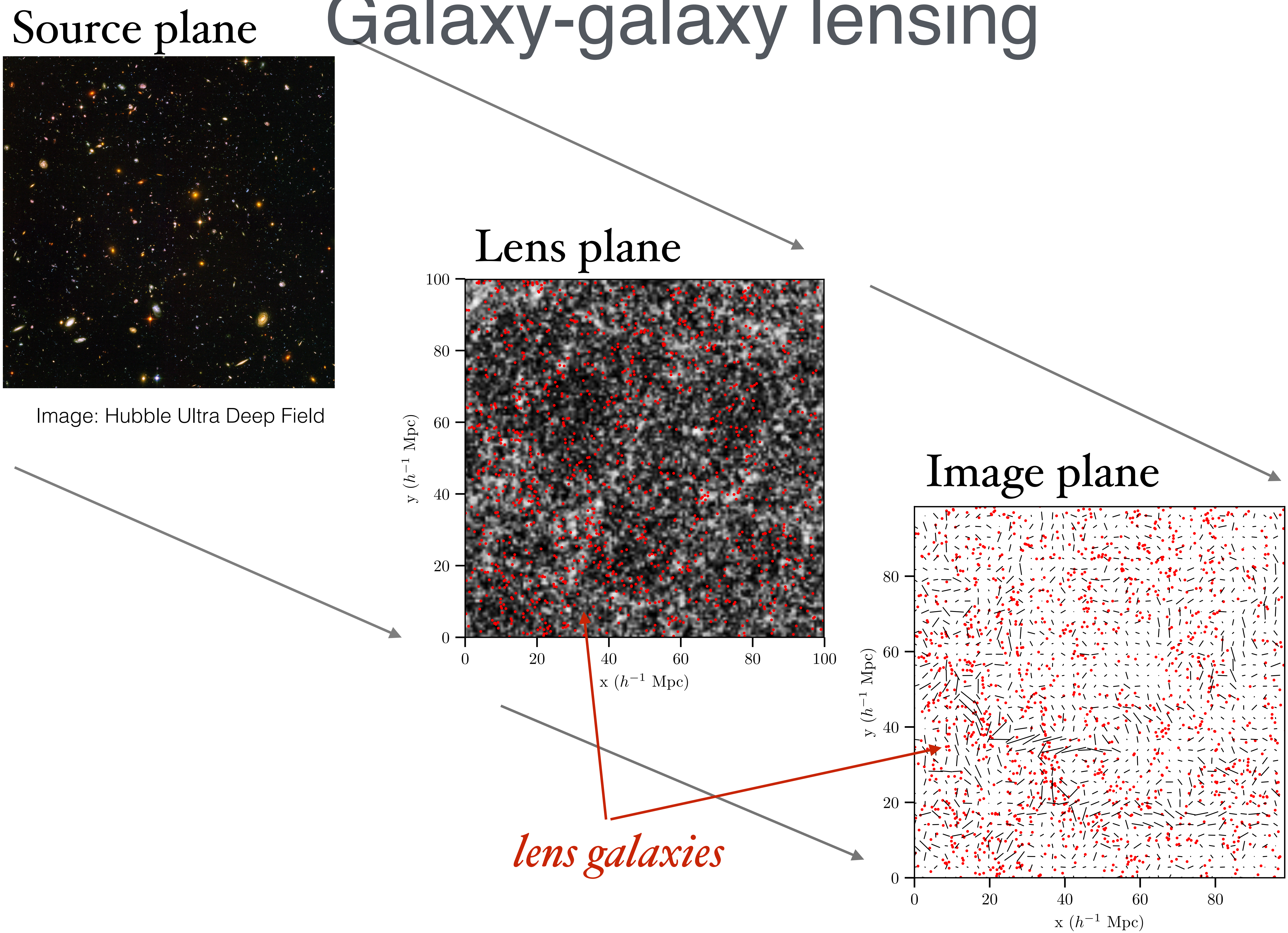
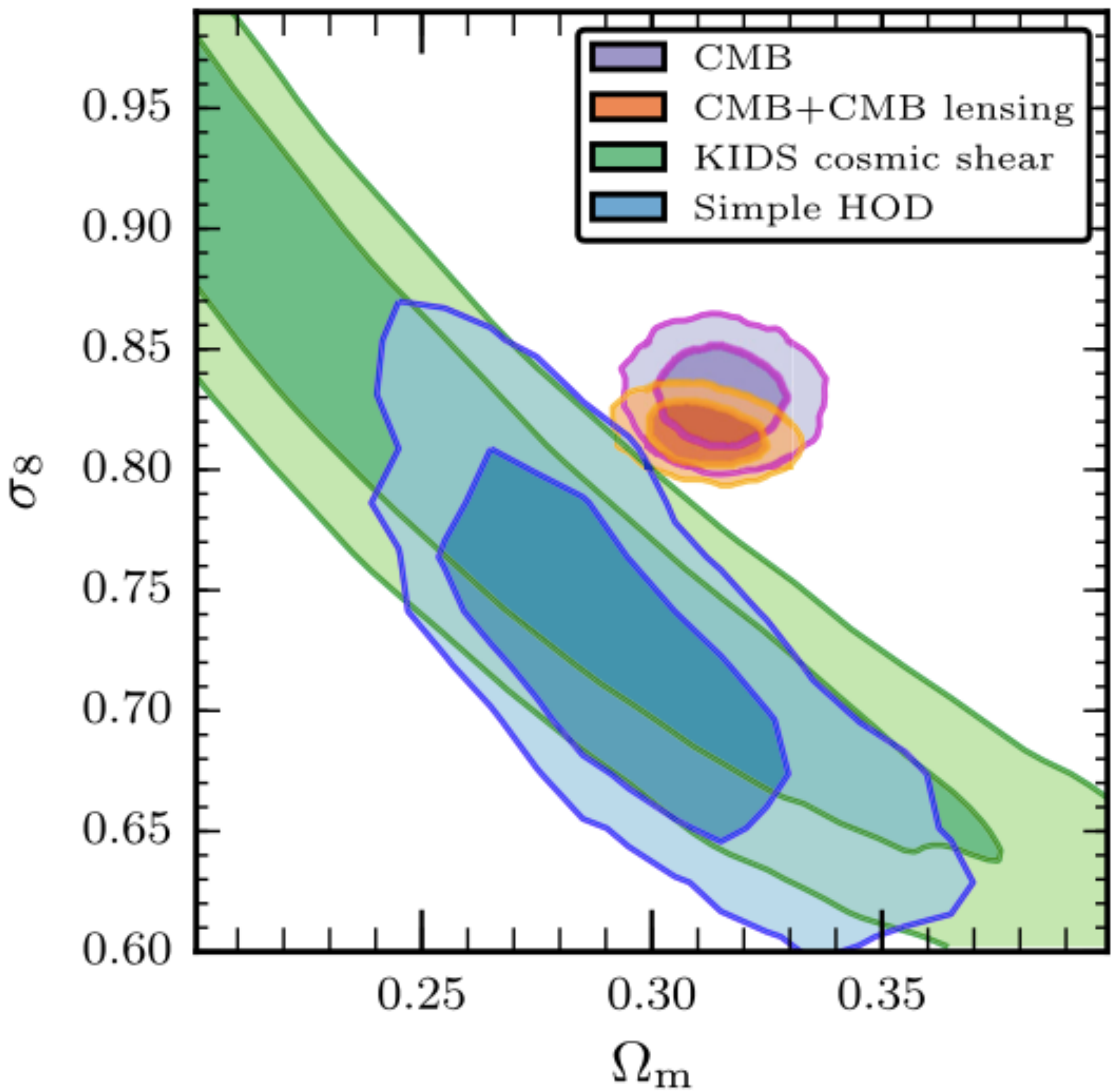


Figure: DES Collaboration 2017

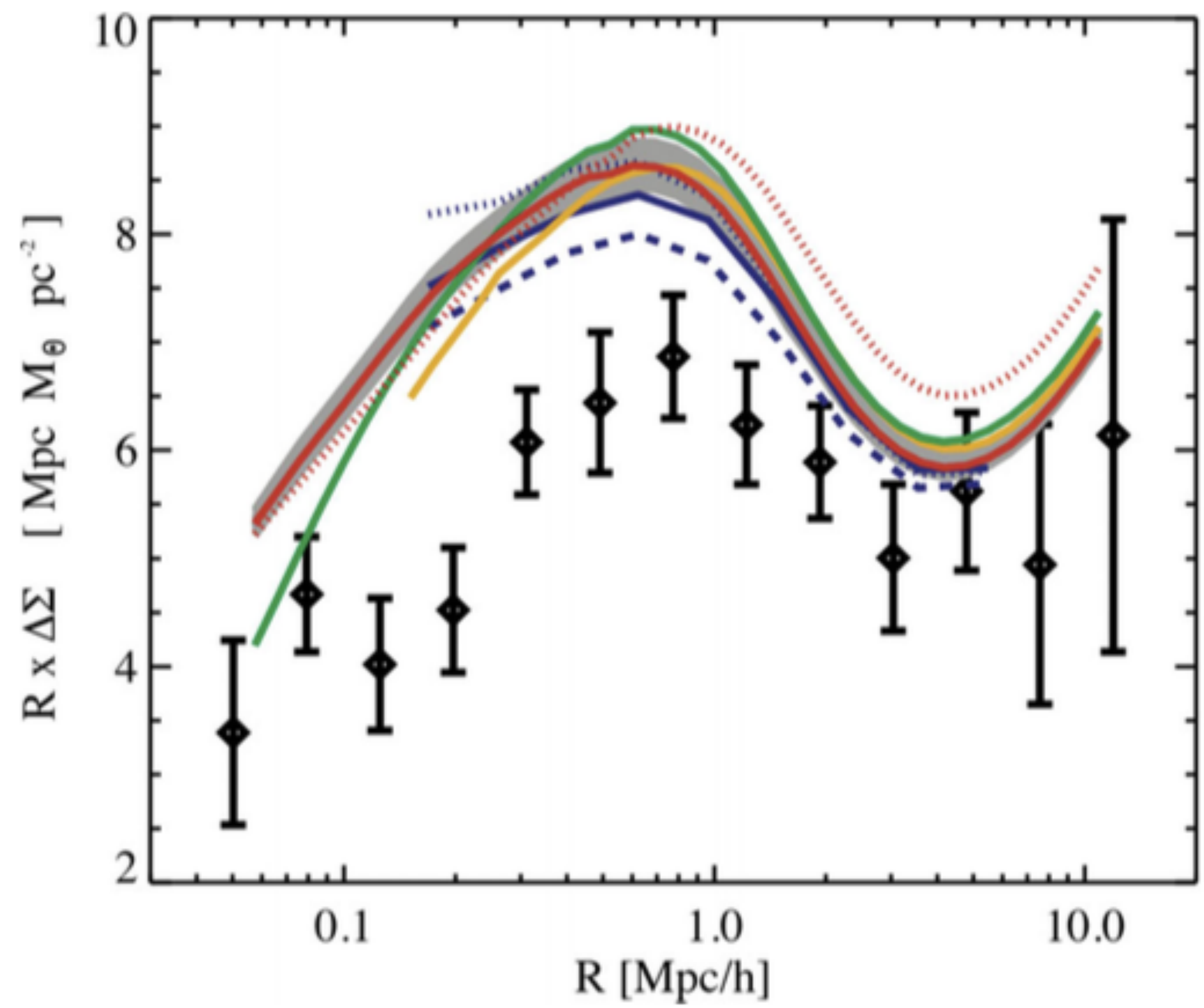
Galaxy-galaxy lensing



Small scale systematics?



CMASS lens galaxies



Figures: Leauthaud+ 2017

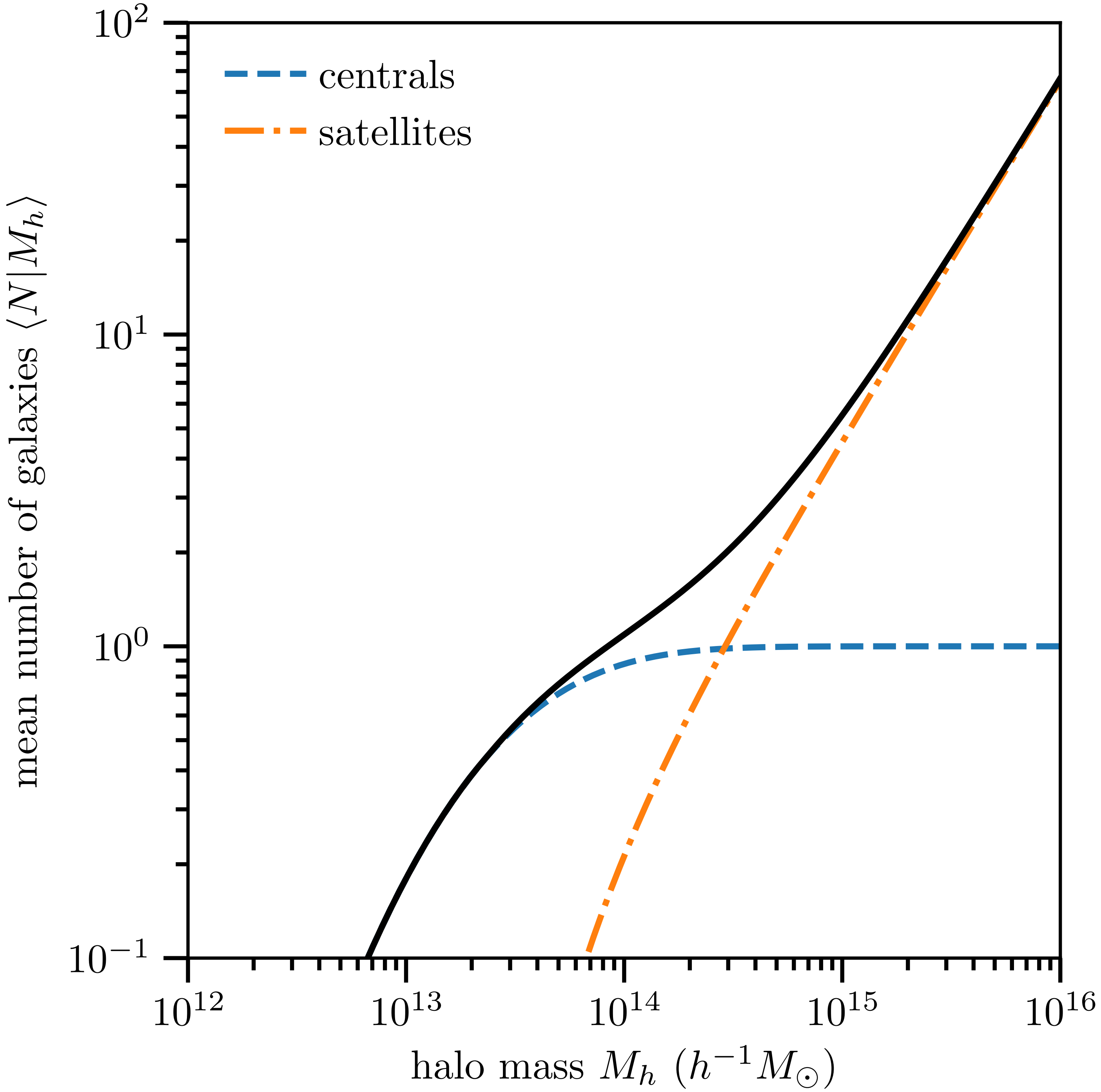
Model

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

Result: predict clustering and matter cross-correlation on all scales e.g. Berlind & Weinberg (2002)

Halo occupation distribution (HOD)

fiducial parameter values



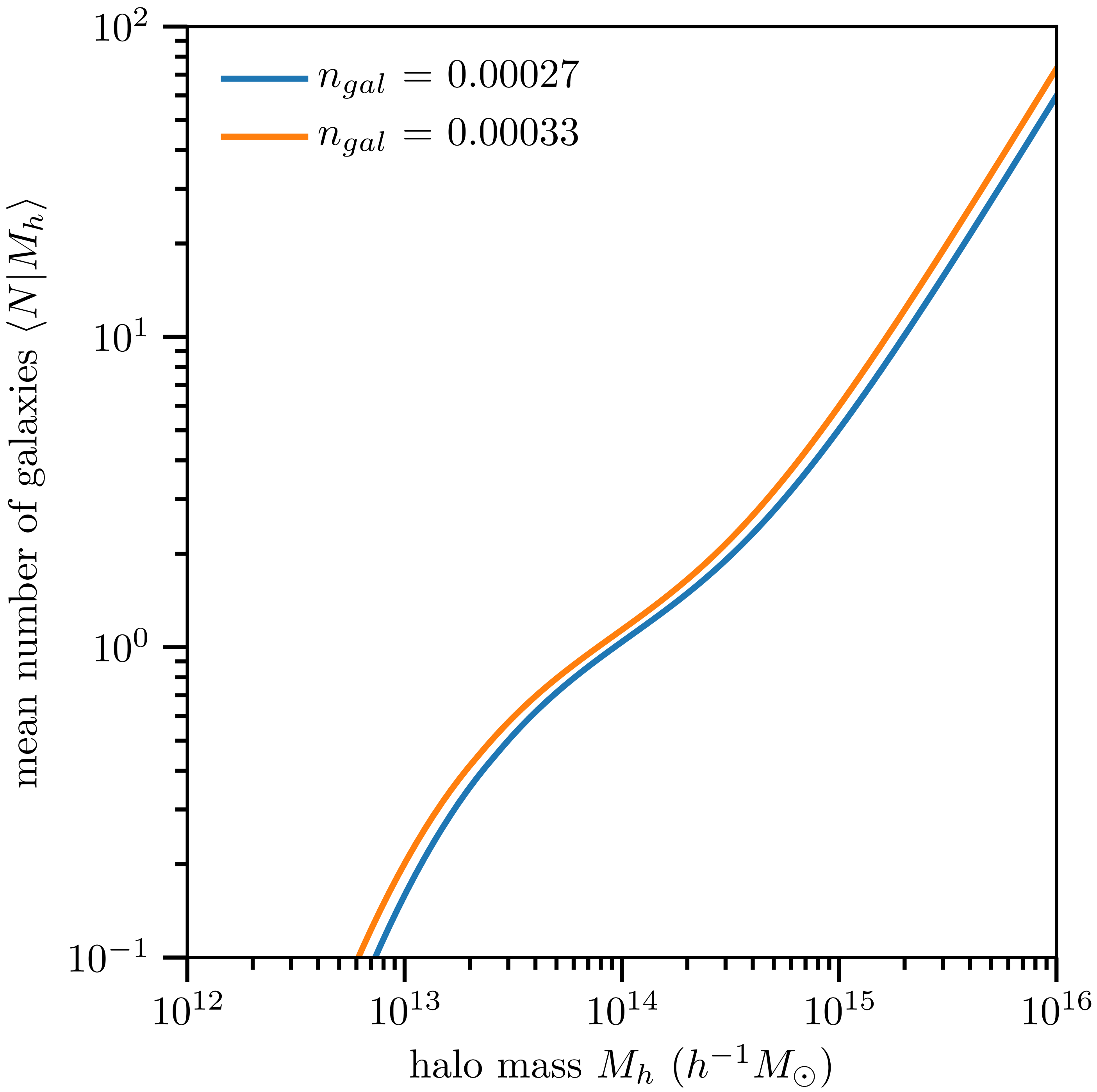
HOD specifies the conditional distribution: $\langle N|M_h \rangle$

Model parameters

1. Number density of galaxies $n_{\rm gal}$
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 $M_1/M_{\rm min}$
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) $Q_{\rm env}$
7. *Cosmology:* $\Omega_{\rm m}$, σ_8

Halo occupation distribution (HOD)

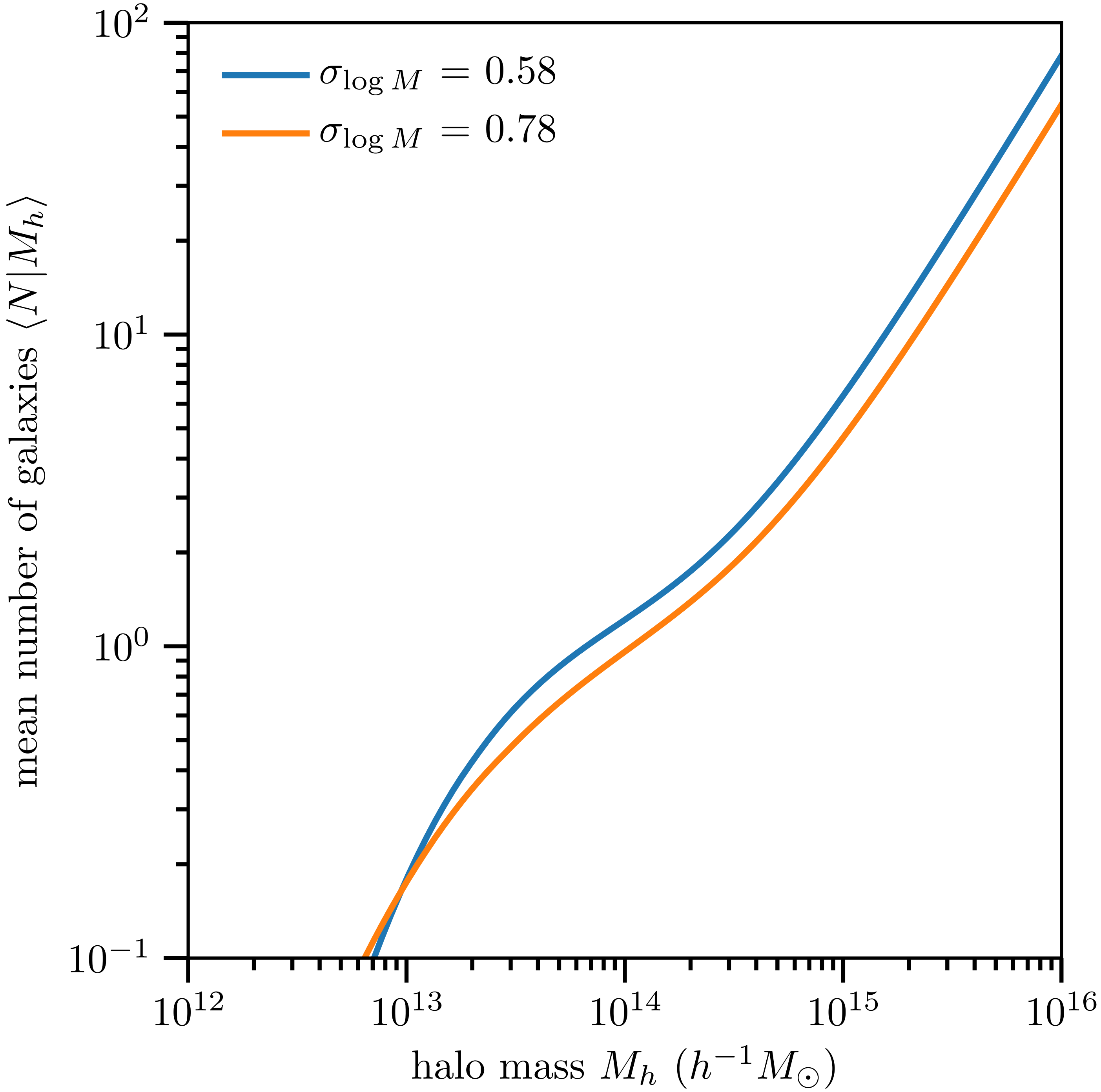
n_{gal}



Effect on $<N|M_h>$ due to varying galaxy number density

Halo occupation distribution (HOD)

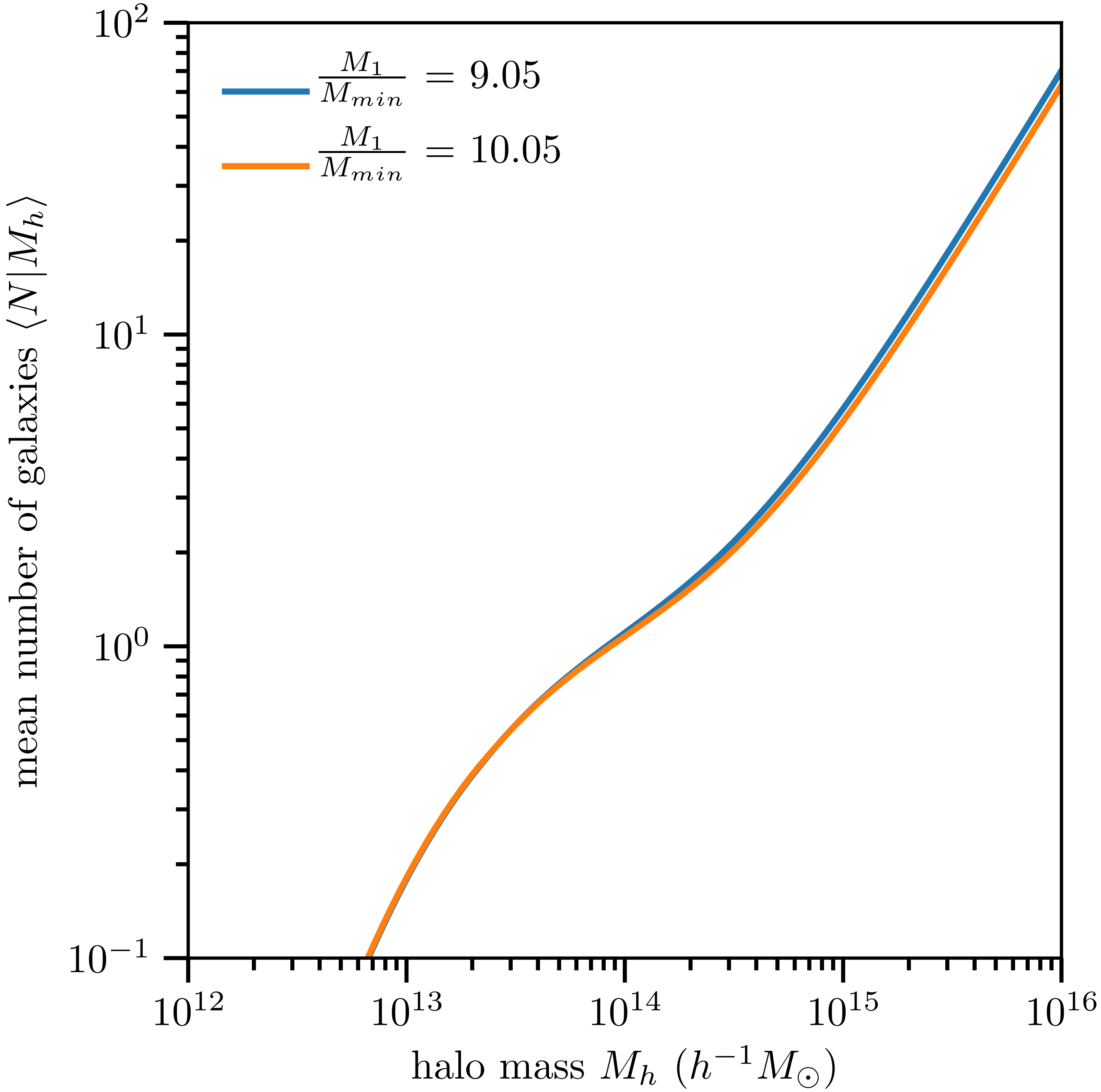
$\sigma_{\log M}$



Varying the scatter in halo mass to stellar mass

Halo occupation distribution (HOD)

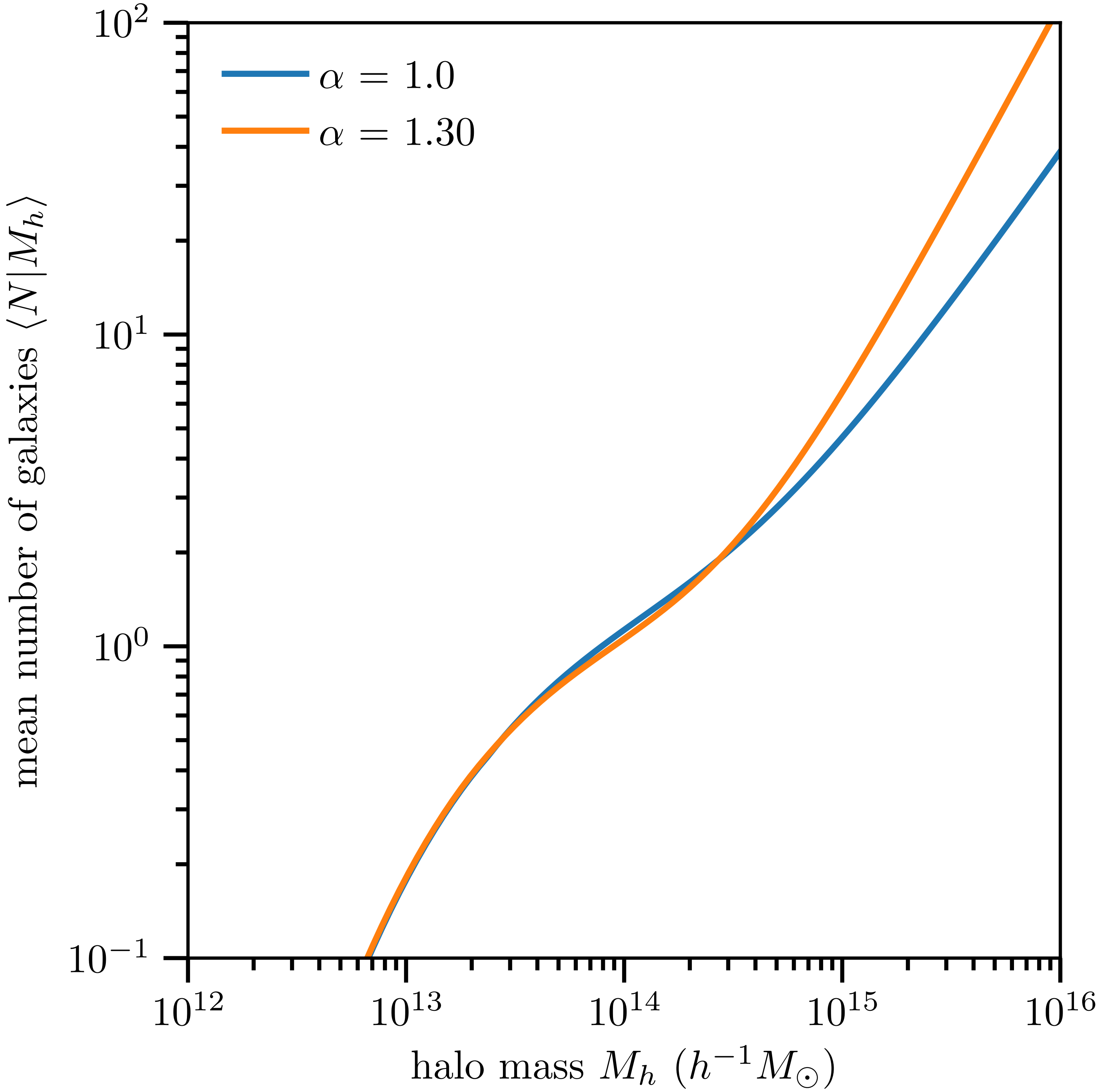
$M_1/M_{\rm min}$



Varying the halo mass at which there are satellite galaxies

Halo occupation distribution (HOD)

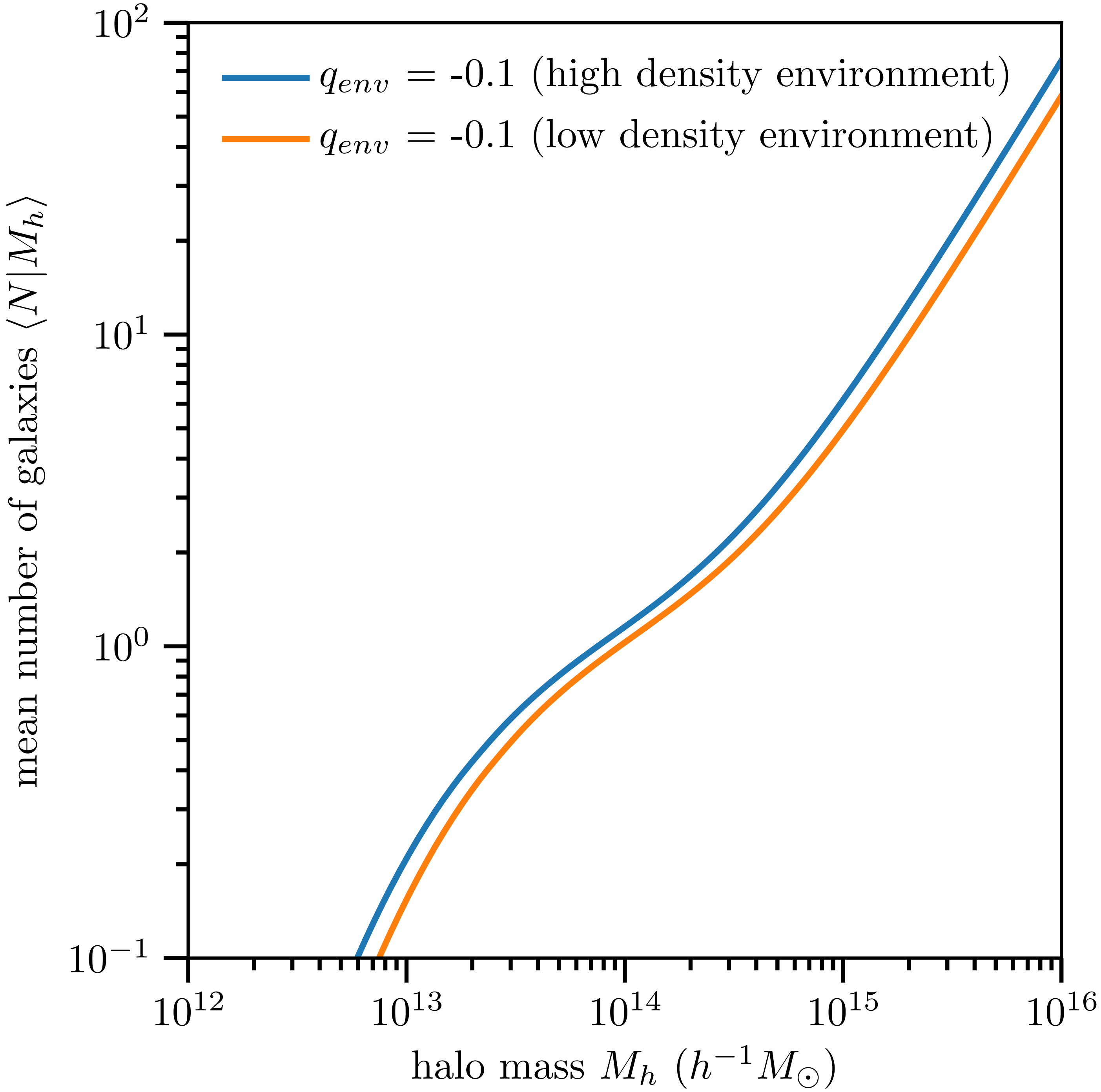
α



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

Halo occupation distribution (HOD)

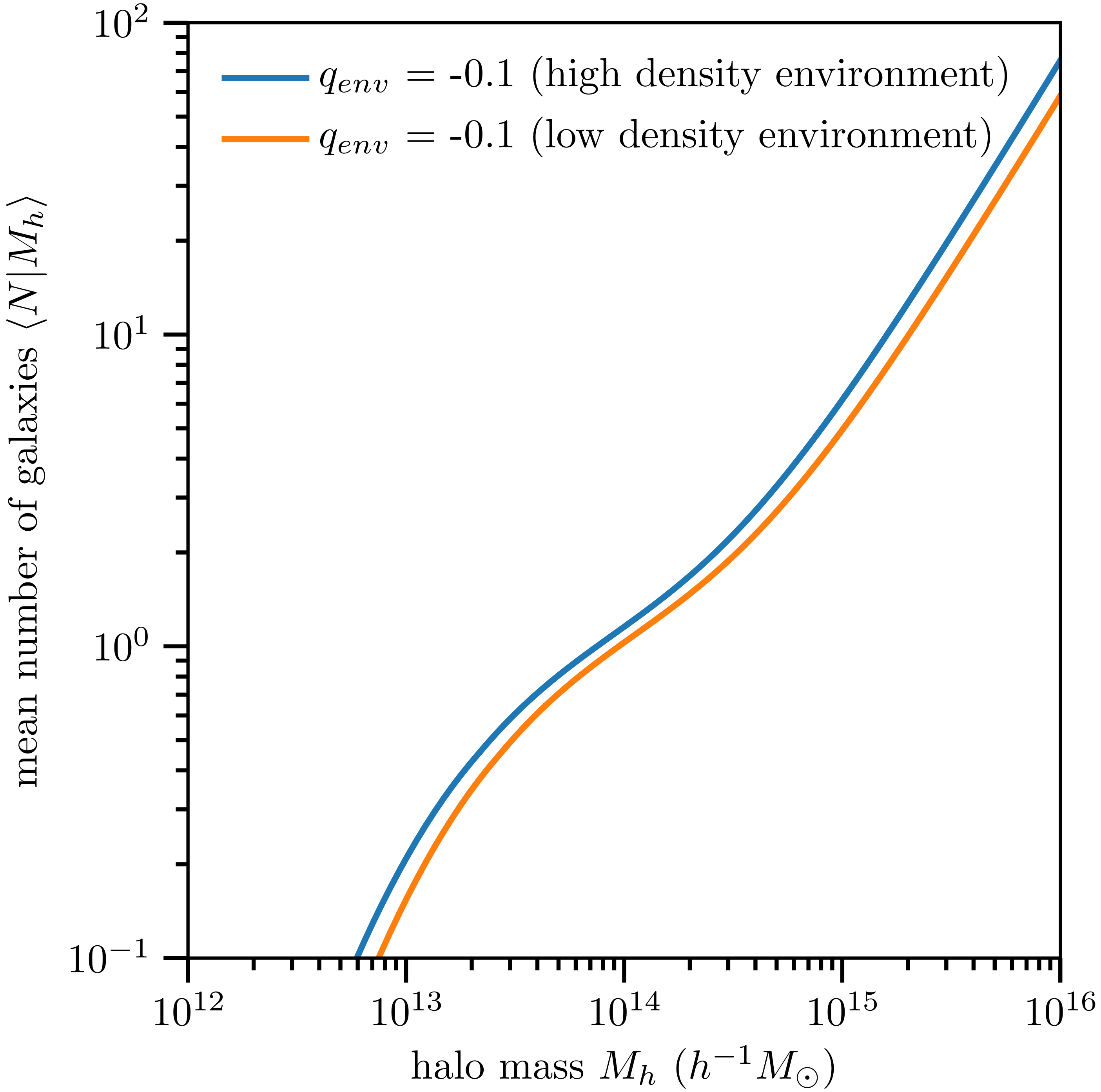
Q_{env}



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

Halo occupation distribution (HOD) + assembly bias

Q_{env}



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

Emulator methodology

1. Run 40 N-body simulations with different cosmological parameters chosen from within the Planck 2015 *w*CDM allowed space *(for this paper, a subset involving only σ_8, Ω_M)*
2. Populate dark matter halos with galaxies according to a phenomenological model of galaxy counts as a function of halo mass *and* environmental density (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

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Emulator methodology

- Interpolating between models — this can be nontrivial:
  - Introduced to cosmology by the 'CosmicEmu' Gaussian Process interpolation of the nonlinear power spectrum obtained from simulations (Heitmann+ 2009)
  - We instead interpolate various scale-dependent quantities using a Taylor expansion (similar to methodology of Mandelbaum+ 2013)

Emulator methodology

- (scale-dependent) bias b_g,

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

- (scale-dependent) correlation coefficient r_{gm},

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

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

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

Emulator methodology

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

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

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

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

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

Emulator methodology

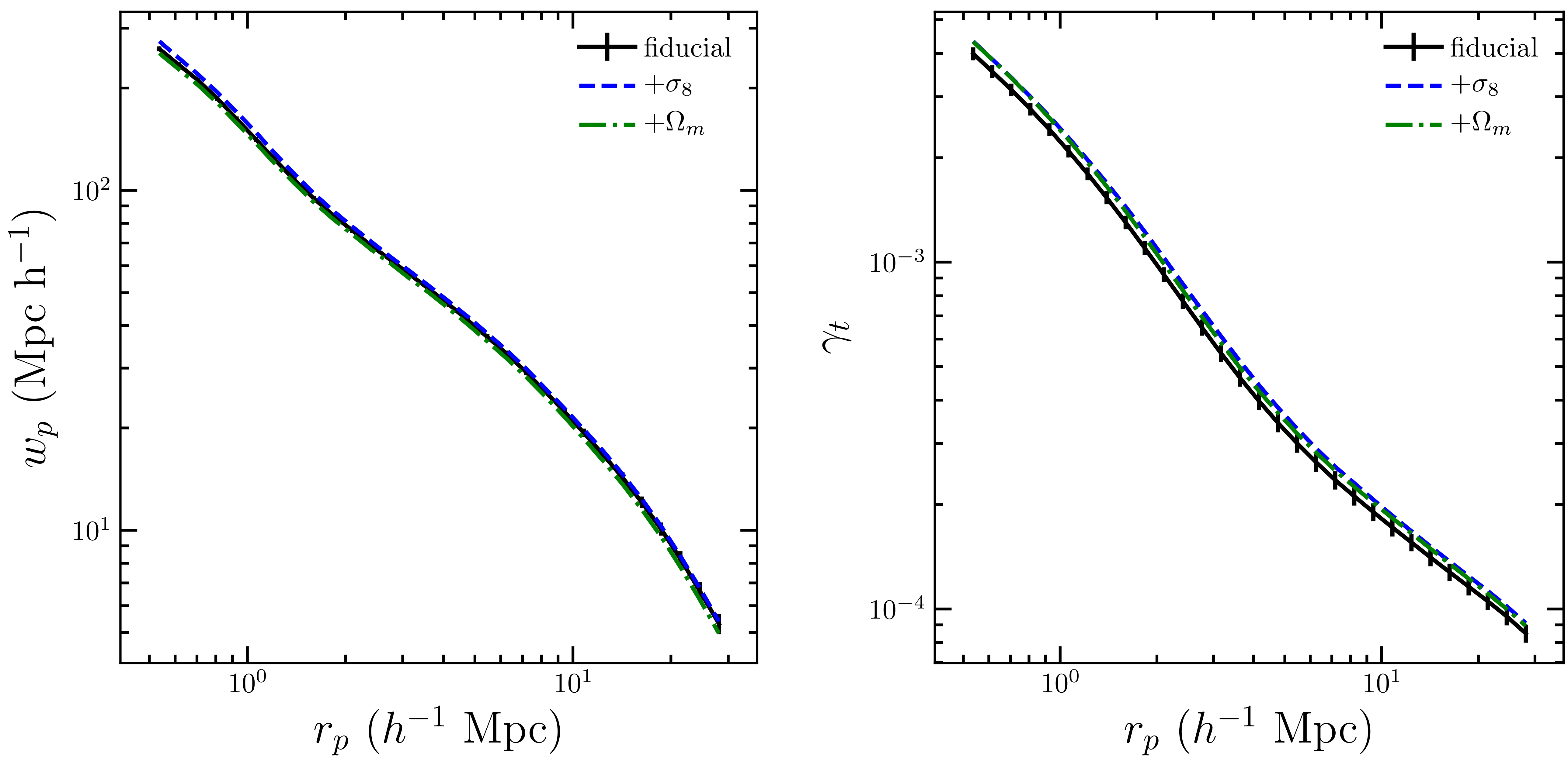
$$\xi_{\mathrm{gg}} = b_g^2 (b_{\mathrm{nl}}^2 \xi_{\mathrm{mm,lin}})$$

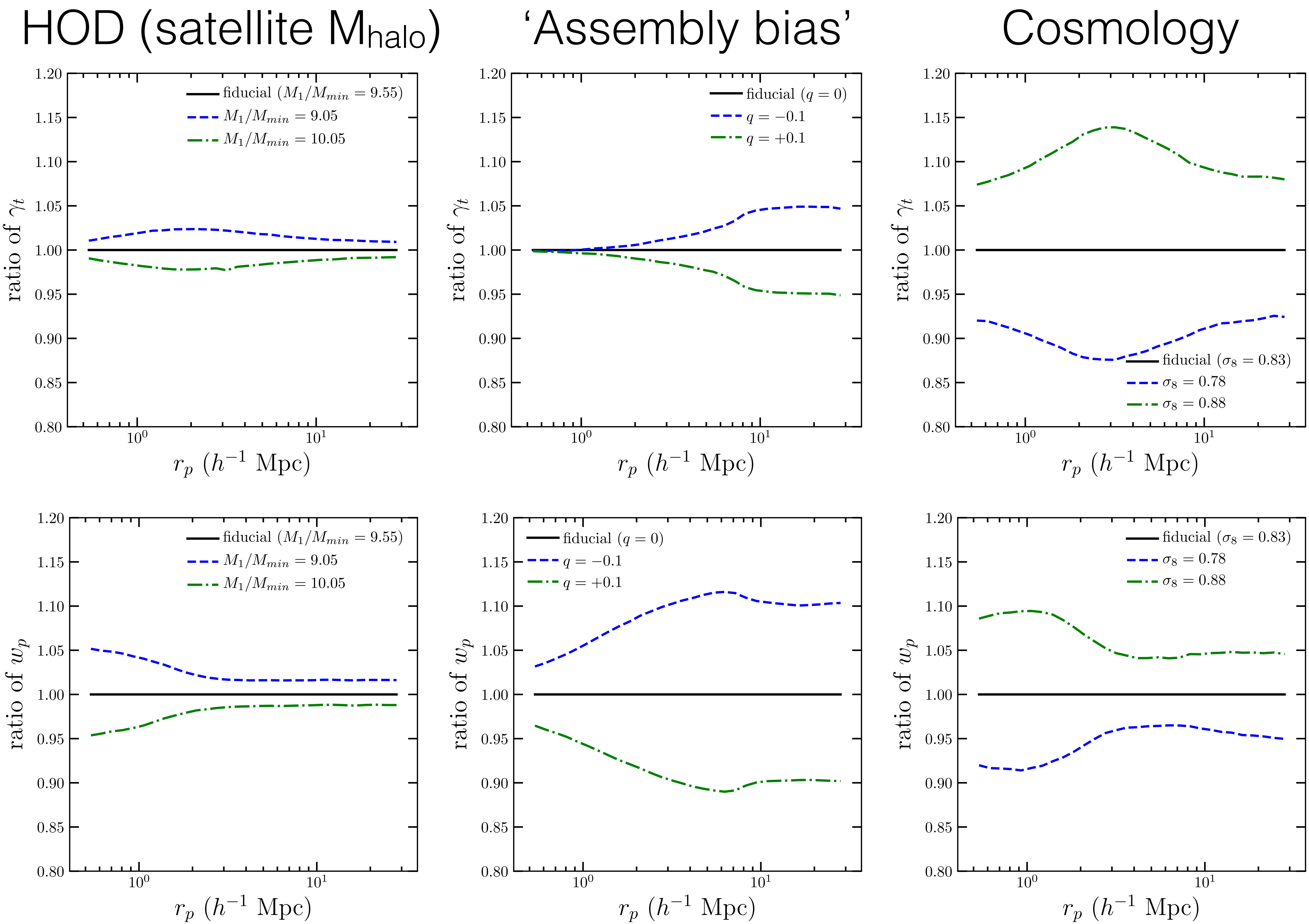
$$\xi_{\mathrm{gm}} = r_{\mathrm{gm}}\, b_g (b_{\mathrm{nl}}^2 \xi_{\mathrm{mm,lin}})$$

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

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

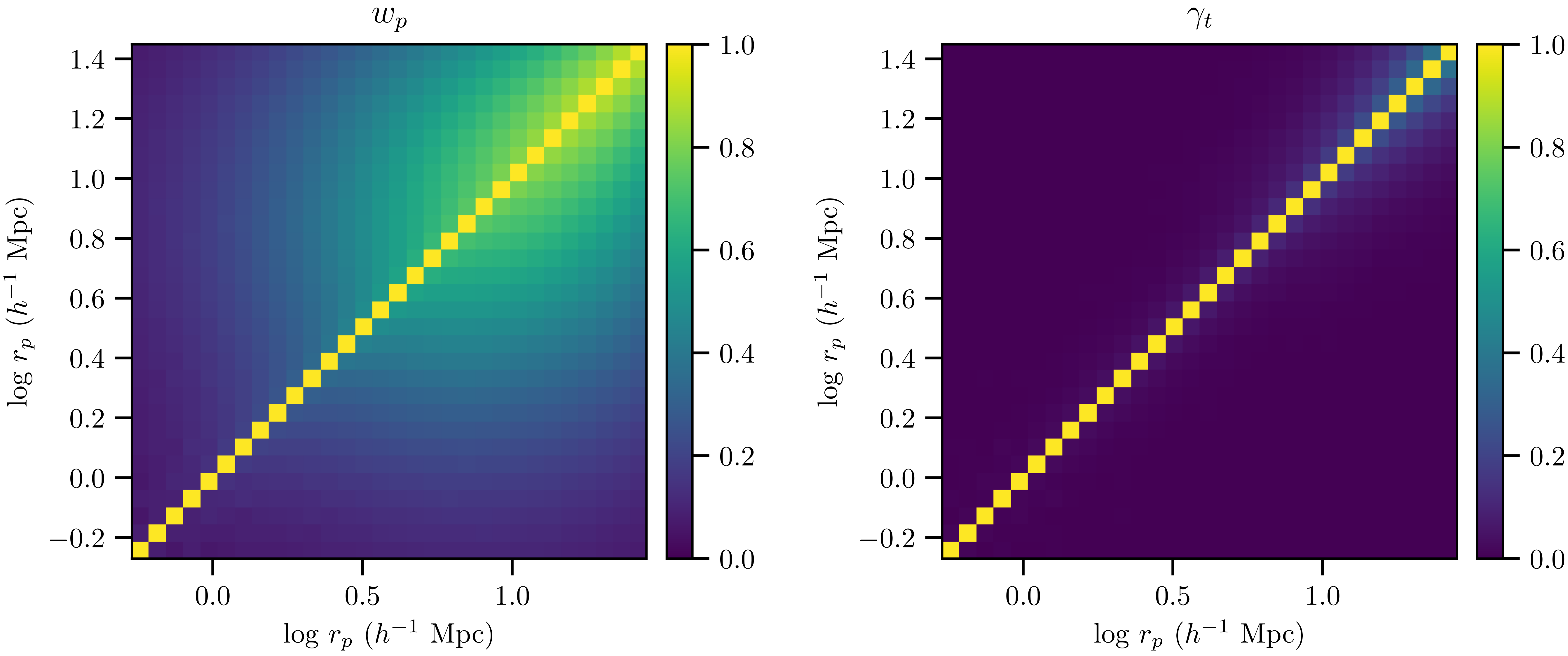
Galaxy-galaxy lensing and clustering signal on scales $0.5 < r_p < 30$ Mpc/h





HOD (satellite M$_{halo}$)
'Assembly bias'
Cosmology
fiducial ($M_1/M_{min} = 9.55$)
$M_1/M_{min} = 9.05$
$M_1/M_{min} = 10.05$
fiducial ($q = 0$)
$q = -0.1$
$q = +0.1$
fiducial ($\sigma_8 = 0.83$)
$\sigma_8 = 0.78$
$\sigma_8 = 0.88$
ratio of γ_t
ratio of w_p
r_p (h^{-1} Mpc)

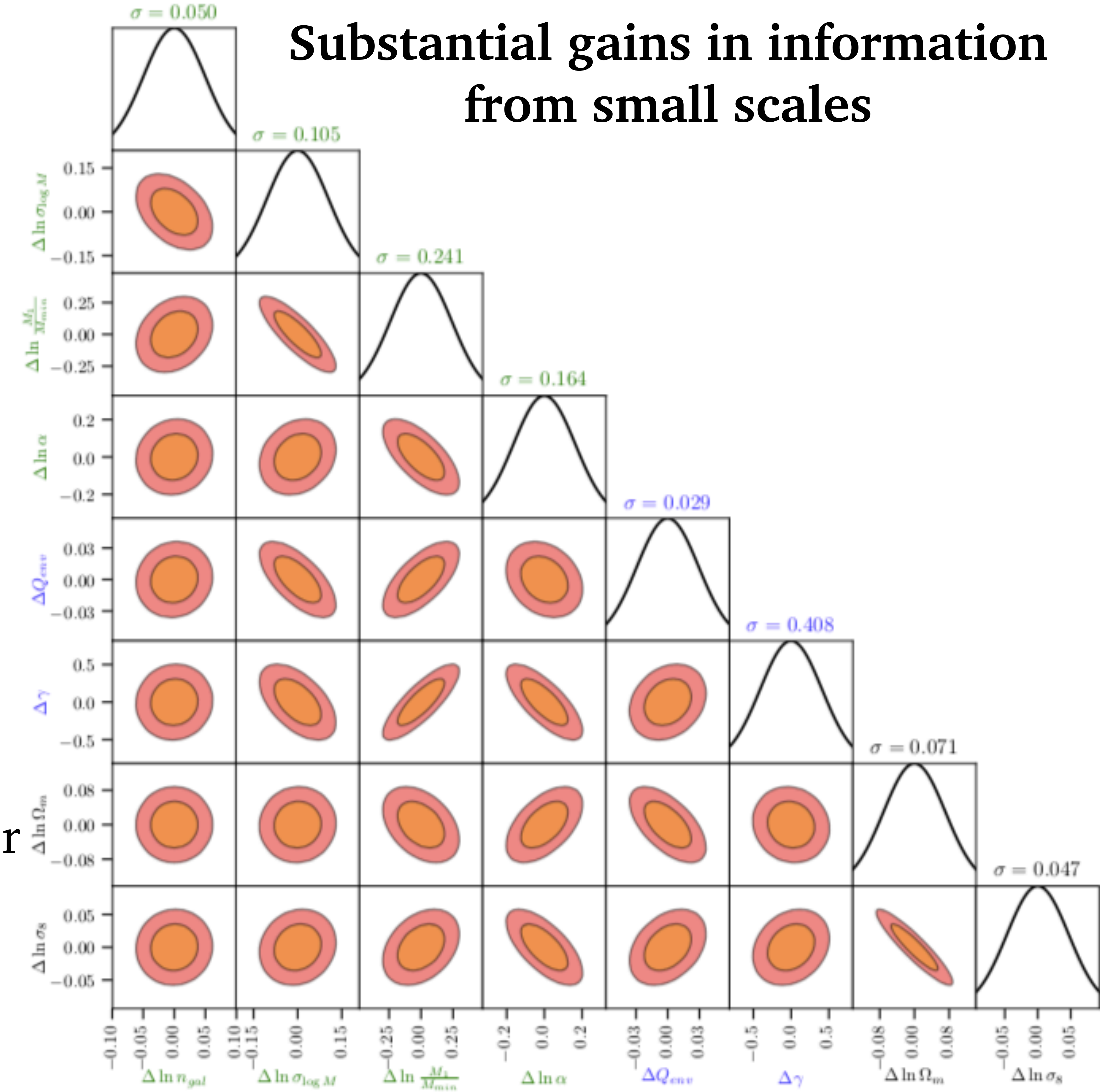
Covariance matrices and forecasting for LOWZ GGL with SDSS imaging



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

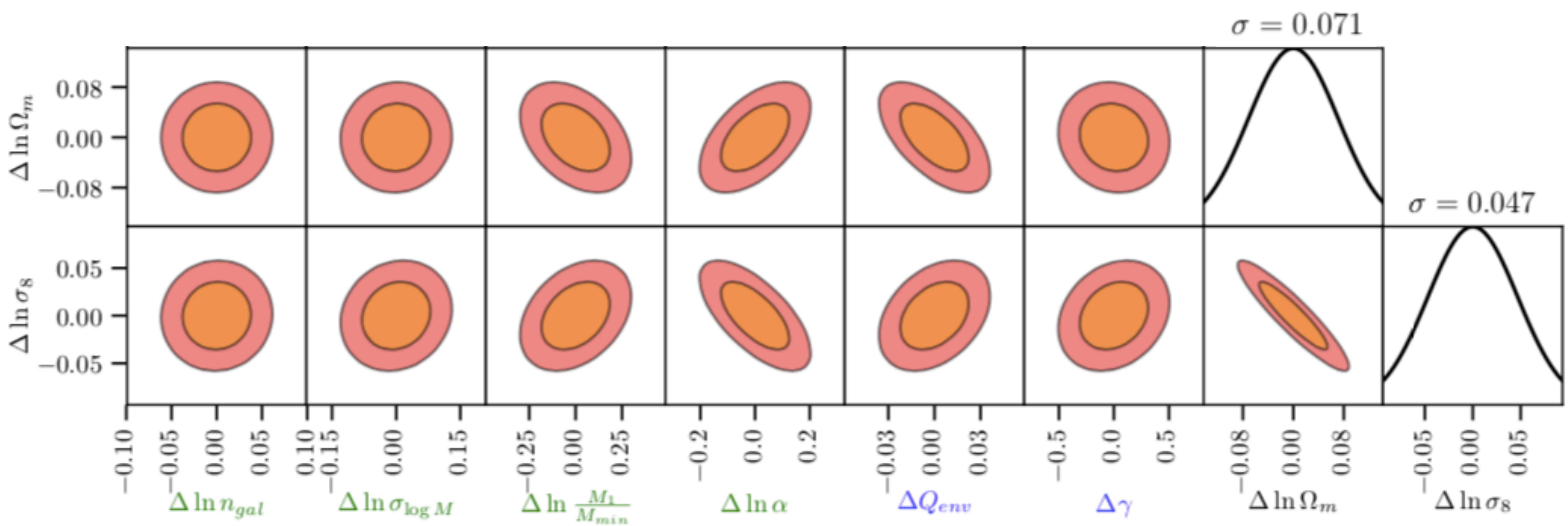
Substantial gains in information from small scales

- Cosmological constraints forecasted: 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

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

Degeneracy with cosmological parameters

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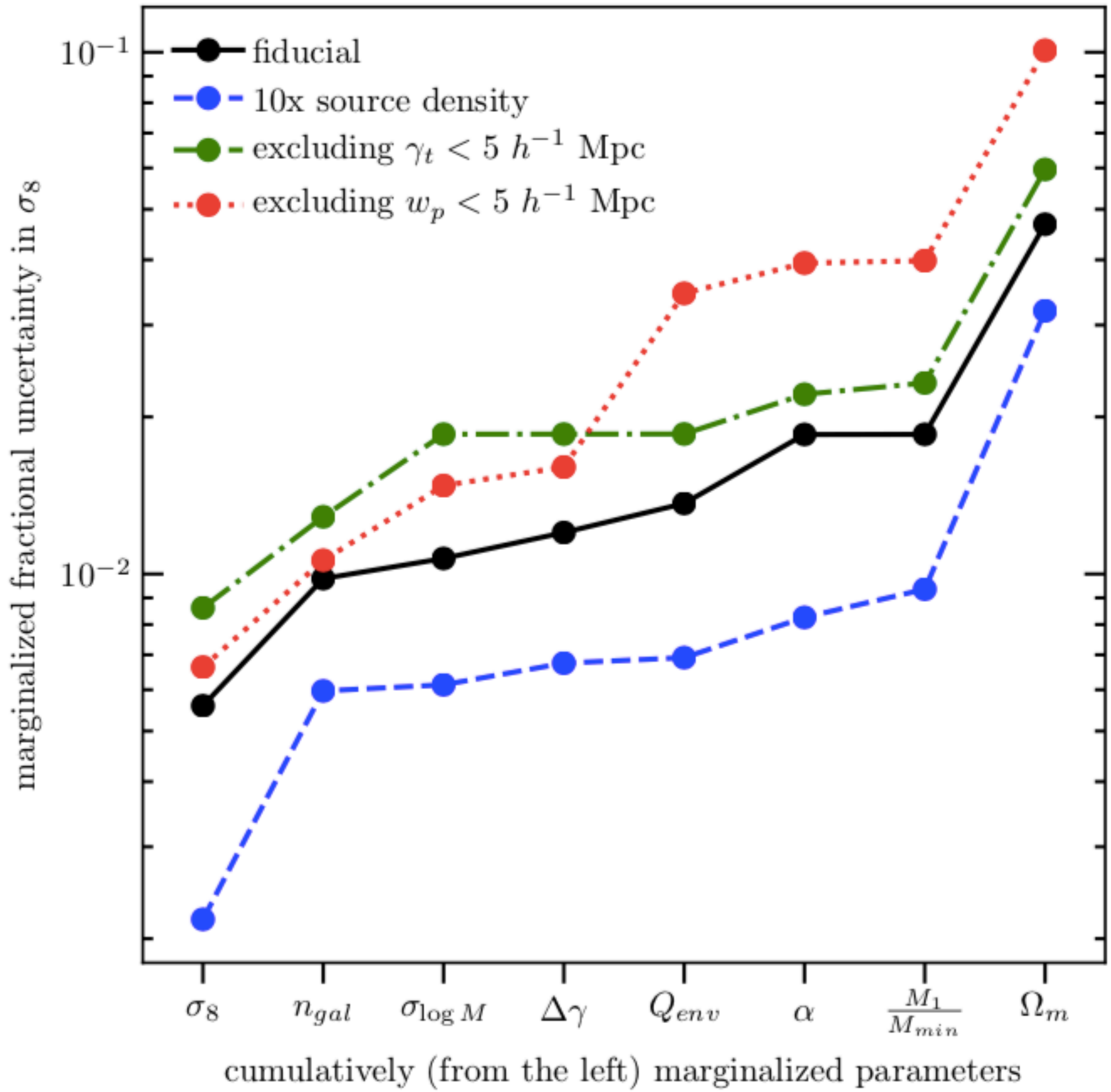
fiducial	0.605	0.019
$r_{\min} = 0.1\,h^{-1}$ Mpc	0.658	$\boxed{0.014}$
centrals only	0.589	$\boxed{0.014}$

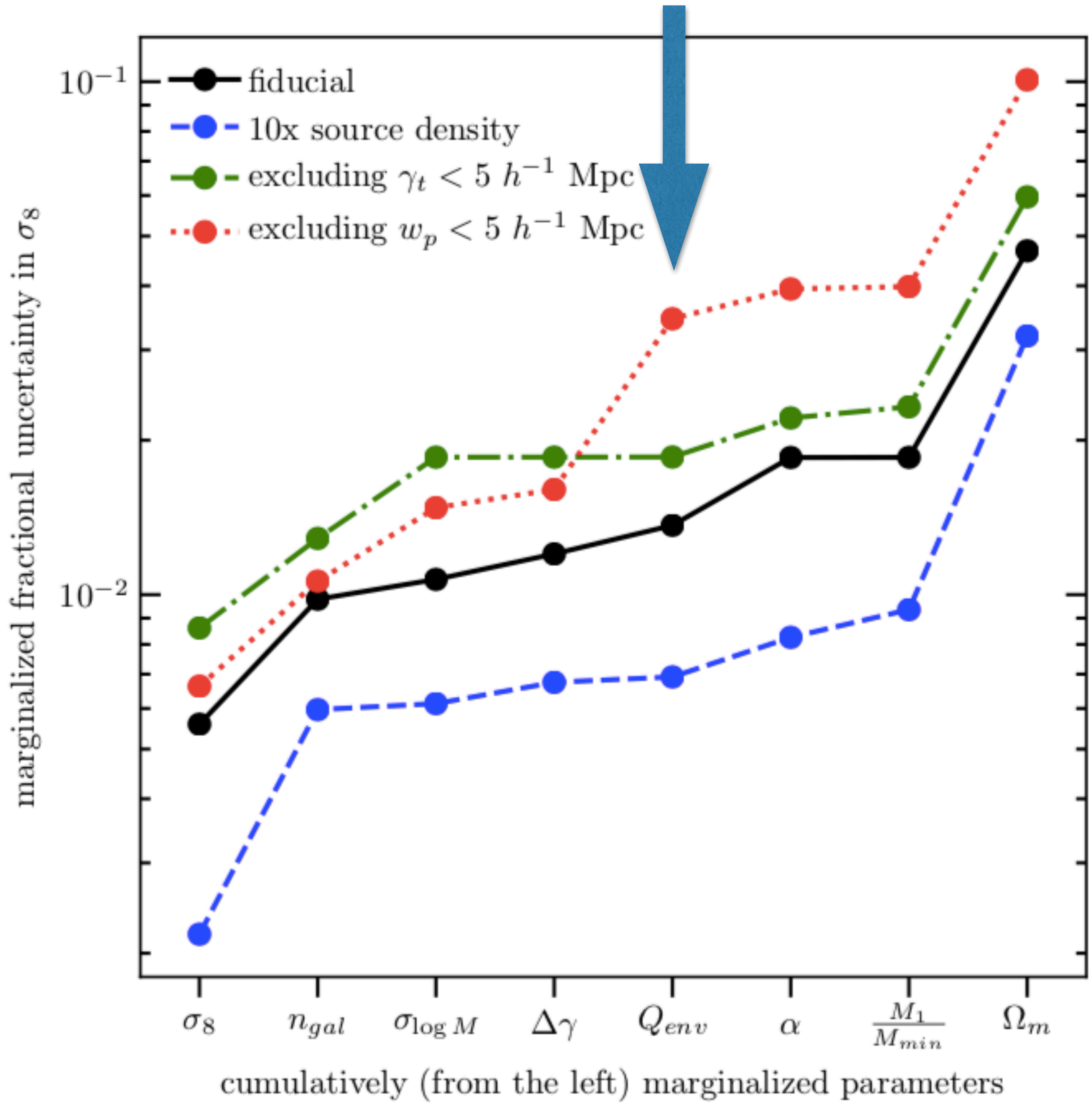
- Using yet smaller scales, we could constrain cosmology as well as a sample that (artificially) contained only central galaxies

What is the cost of marginalizing over galaxy formation uncertainties?

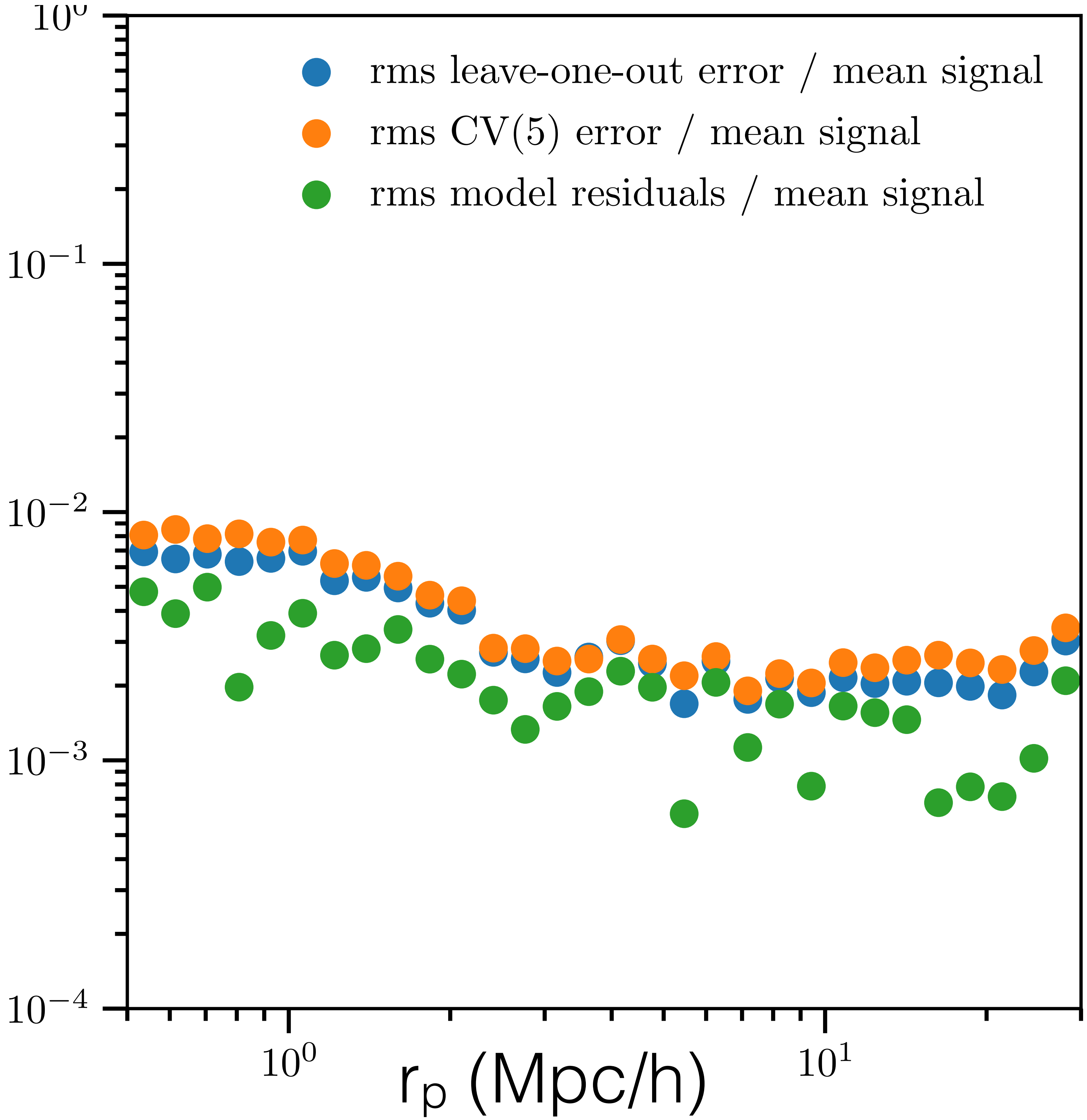


Effect of assembly bias without any small-scale clustering information

What is the cost of marginalizing over galaxy formation uncertainties?



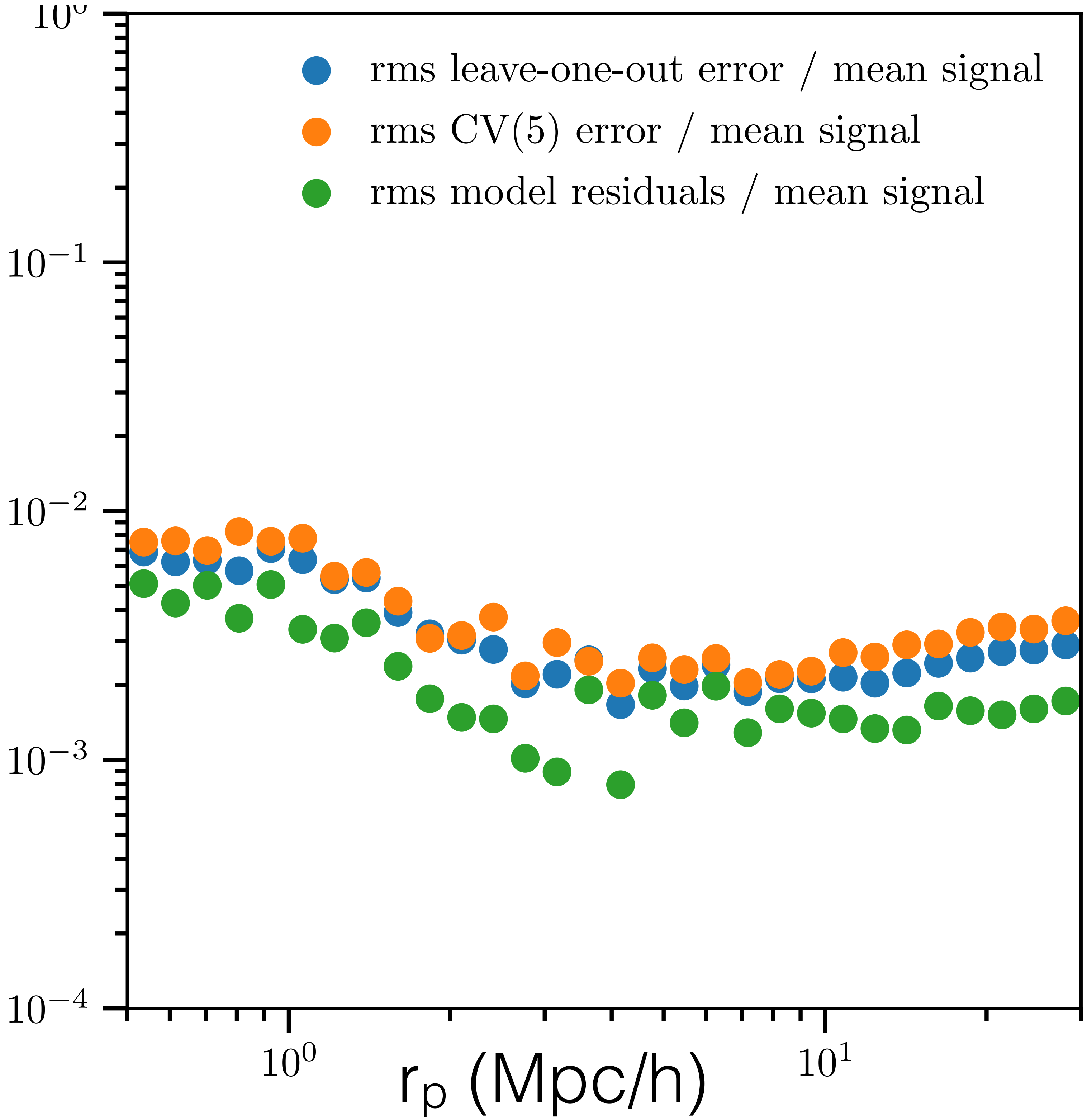
The future: Emulating cosmology across wCDM parameter space



Gaussian process regression with Matérn kernel

(fixed HOD parameters)

The future: Emulating cosmology across wCDM parameter space



4th-order polynomial kernel regression

(fixed HOD parameters)

- Polynomial regression works just as well as 'standard' Gaussian process regression!
- At least with fixed HOD parameters…

Conclusions

- Cosmology on small scales is promising, but will depend on control of astrophysical systematics
- We can verify that our recovery of cosmology is unbiased with mock cosmological analysis of hydrodynamic simulations, other models of galaxy formation that are completely different
- We can test and rule out models of the galaxy-halo occupation jointly with cosmological models
- The future: emulating all wCDM cosmological parameters using the full grid of simulations, fitting to CMASS + DES lensing measurements