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

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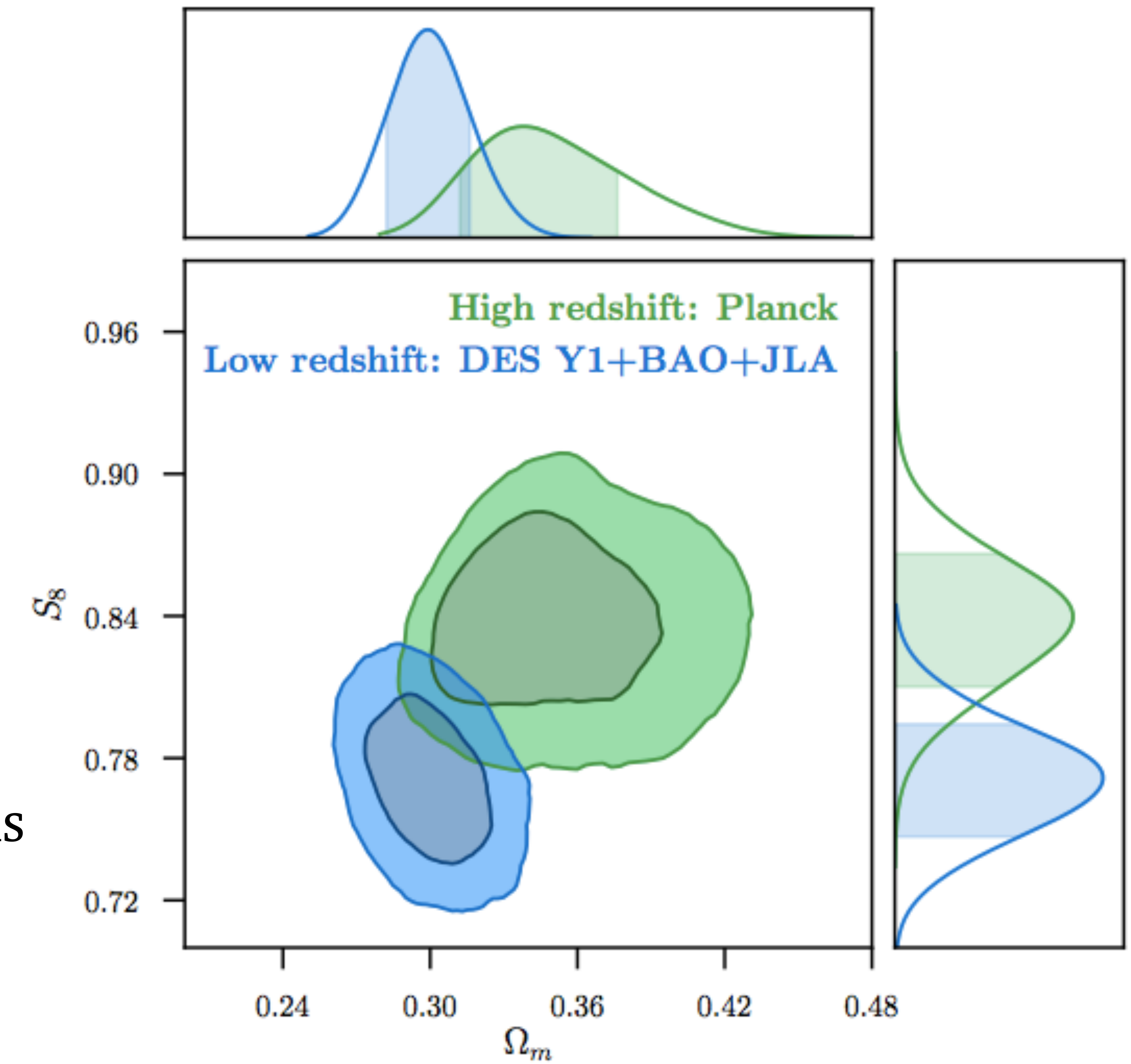
Why do we care?

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



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

Figure: DES Collaboration

Galaxy-galaxy lensing

Source plane

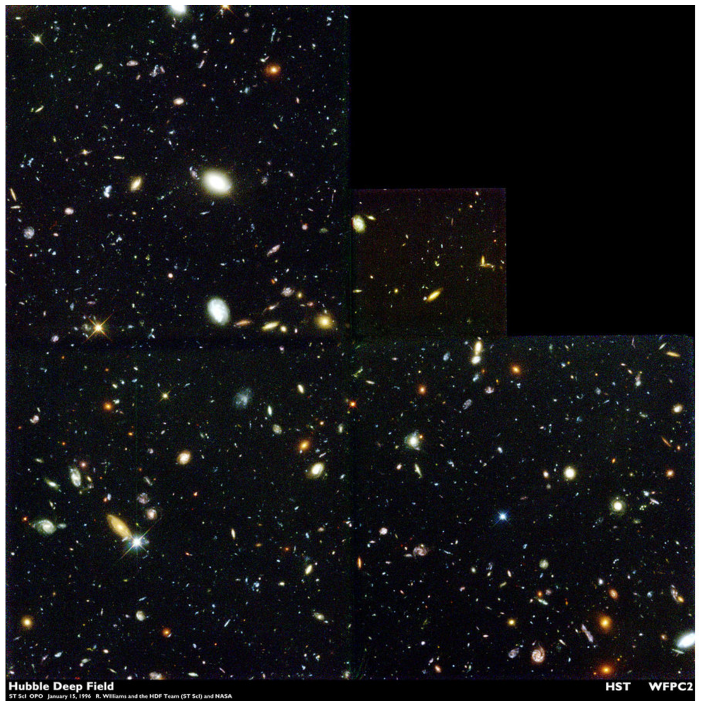


Image: Hubble Deep Field
(for illustrative purposes only)

Lensing plane

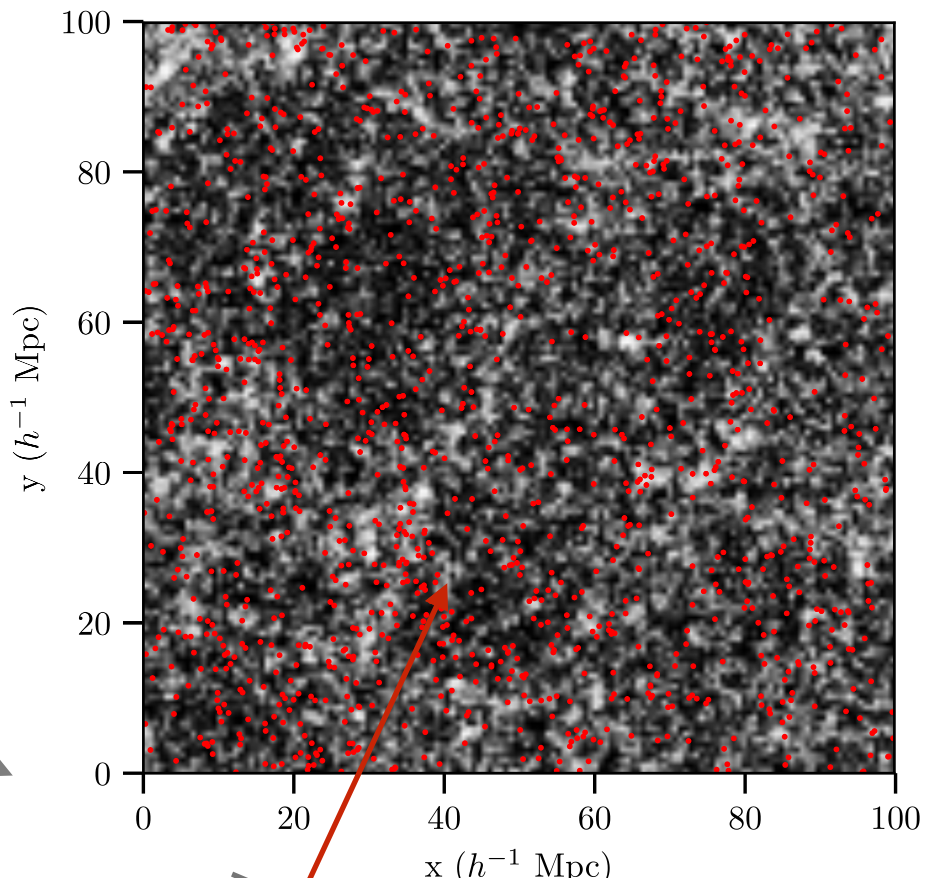
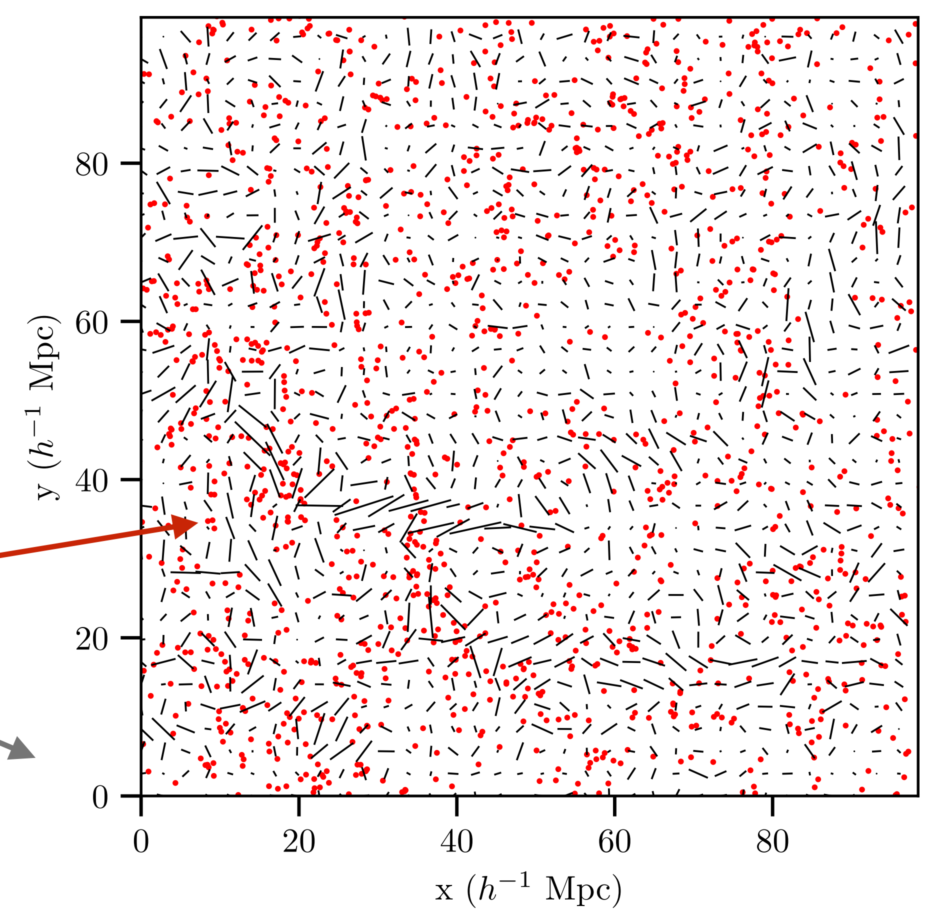
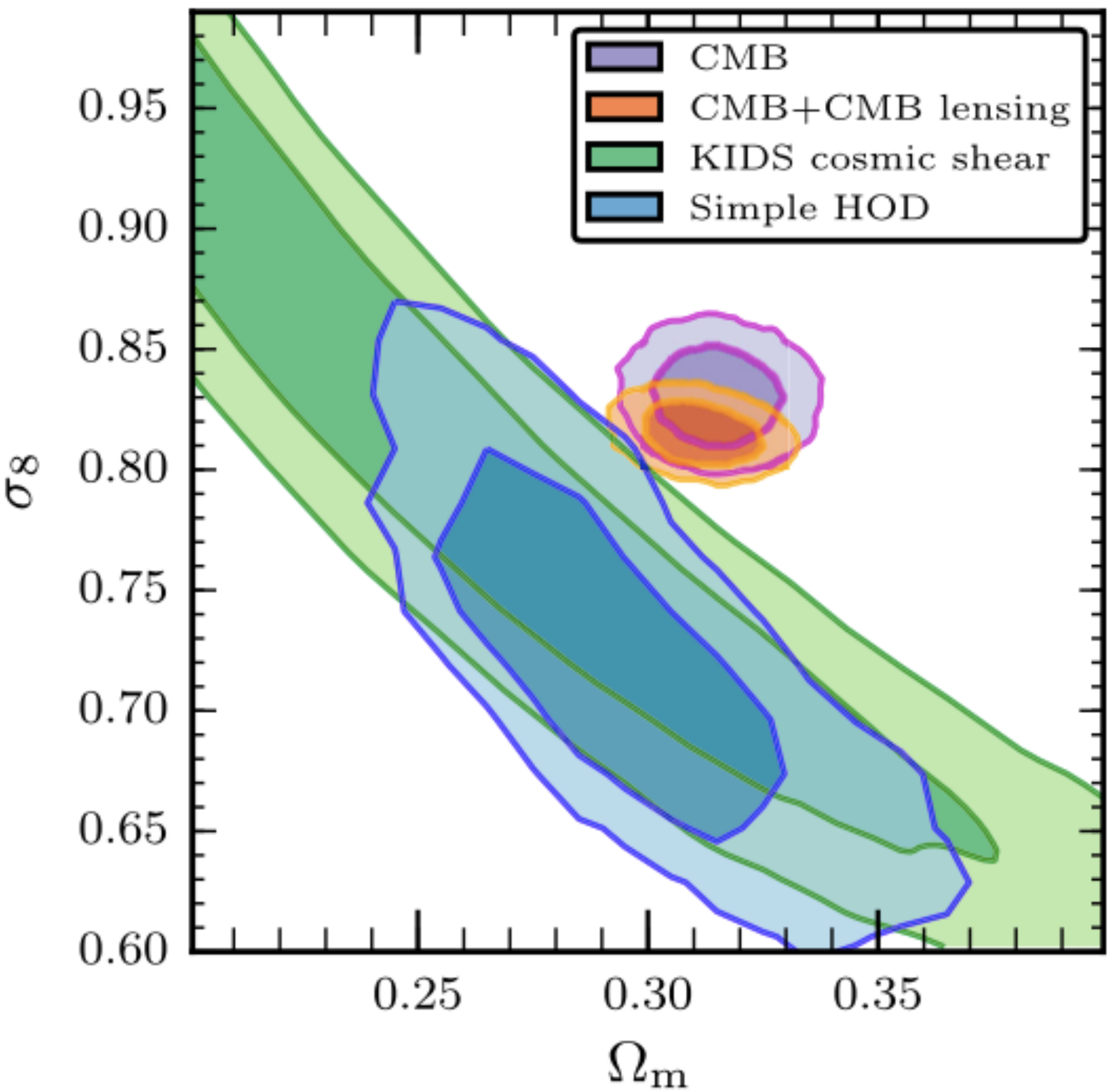


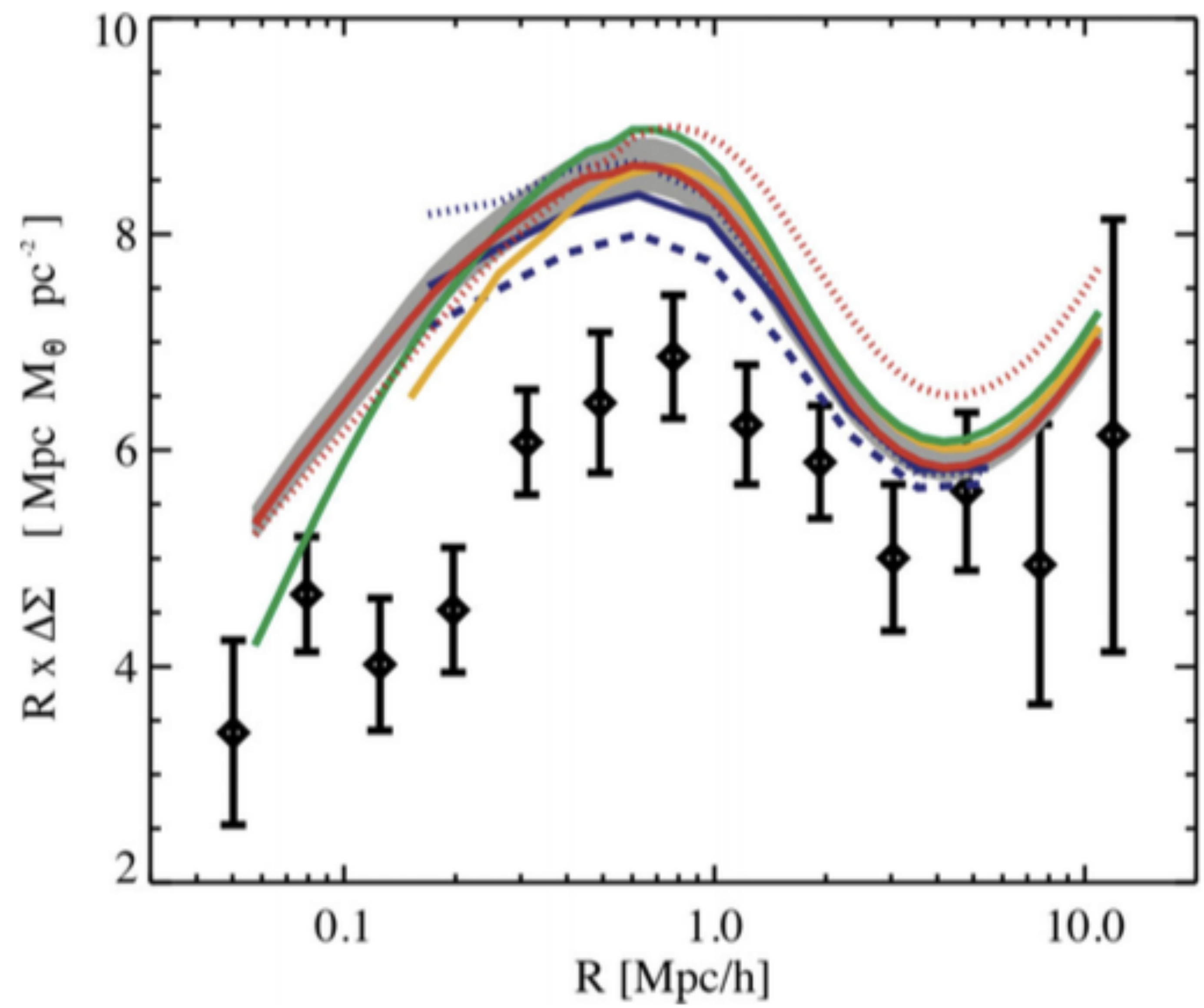
Image plane



'lens' galaxies

Small scale systematics?

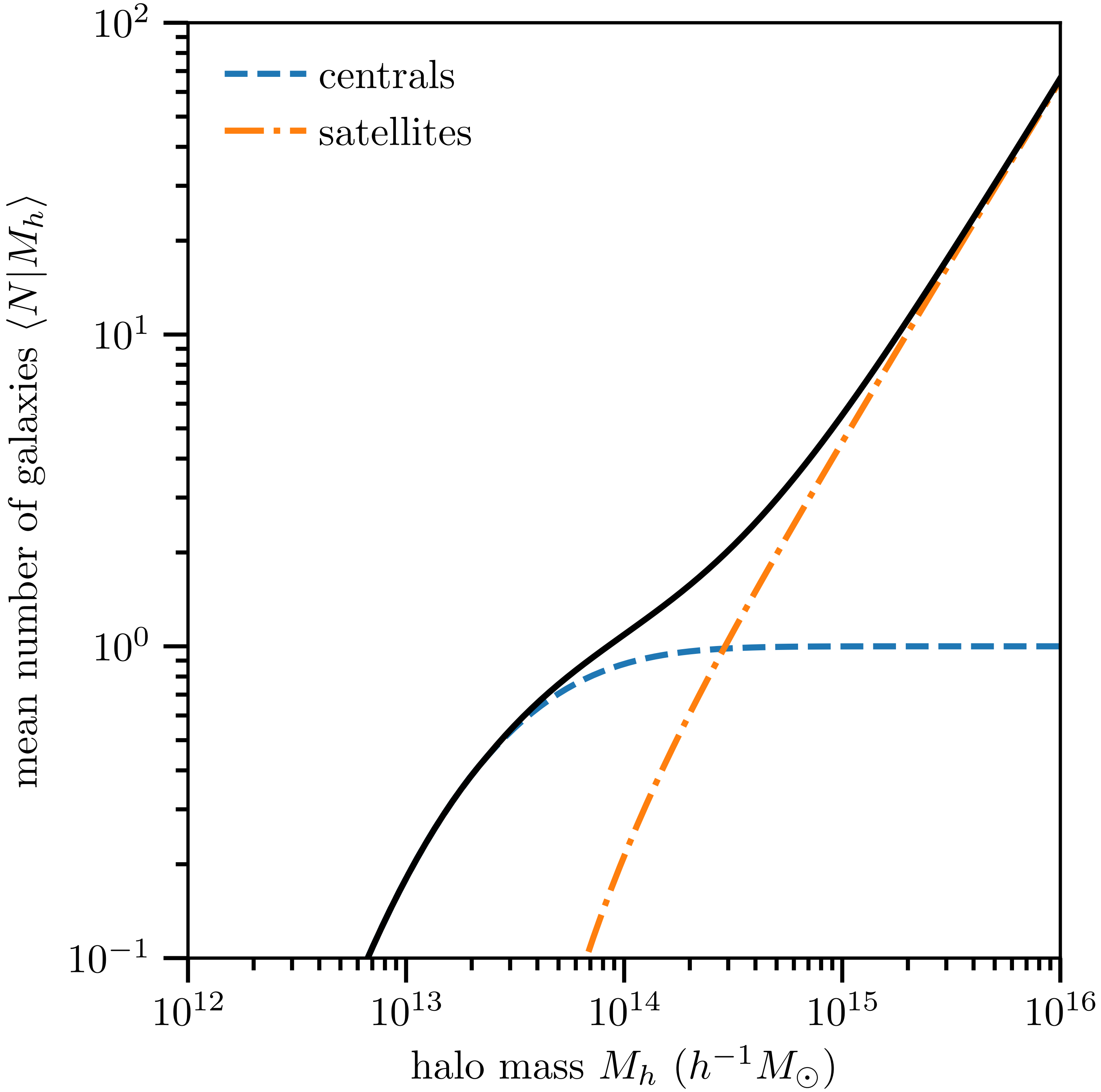




Figures: Leauthaud+ 2017

Halo occupation distribution (HOD)

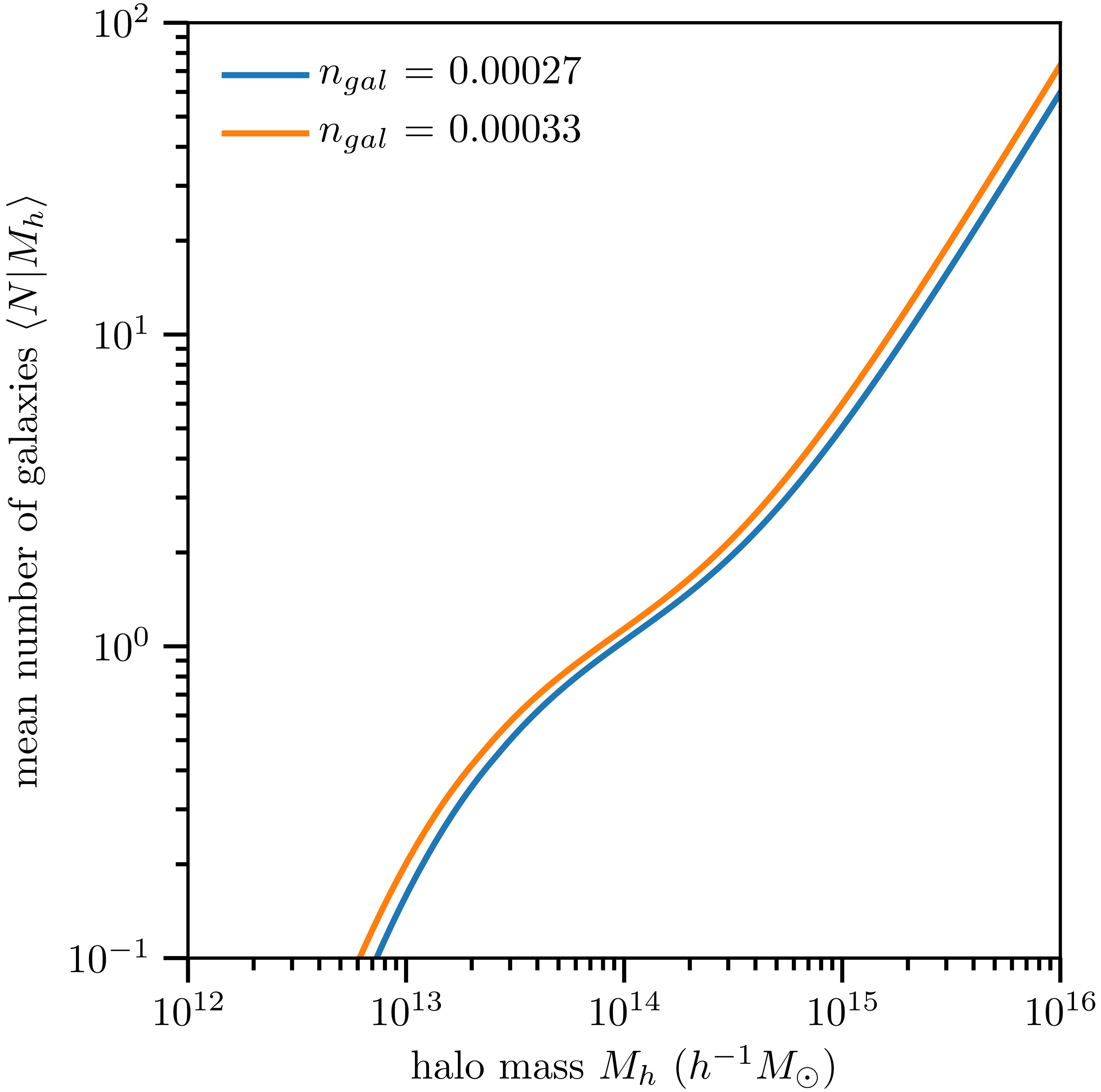
fiducial model



e.g. Berlind & Weinberg (2002)

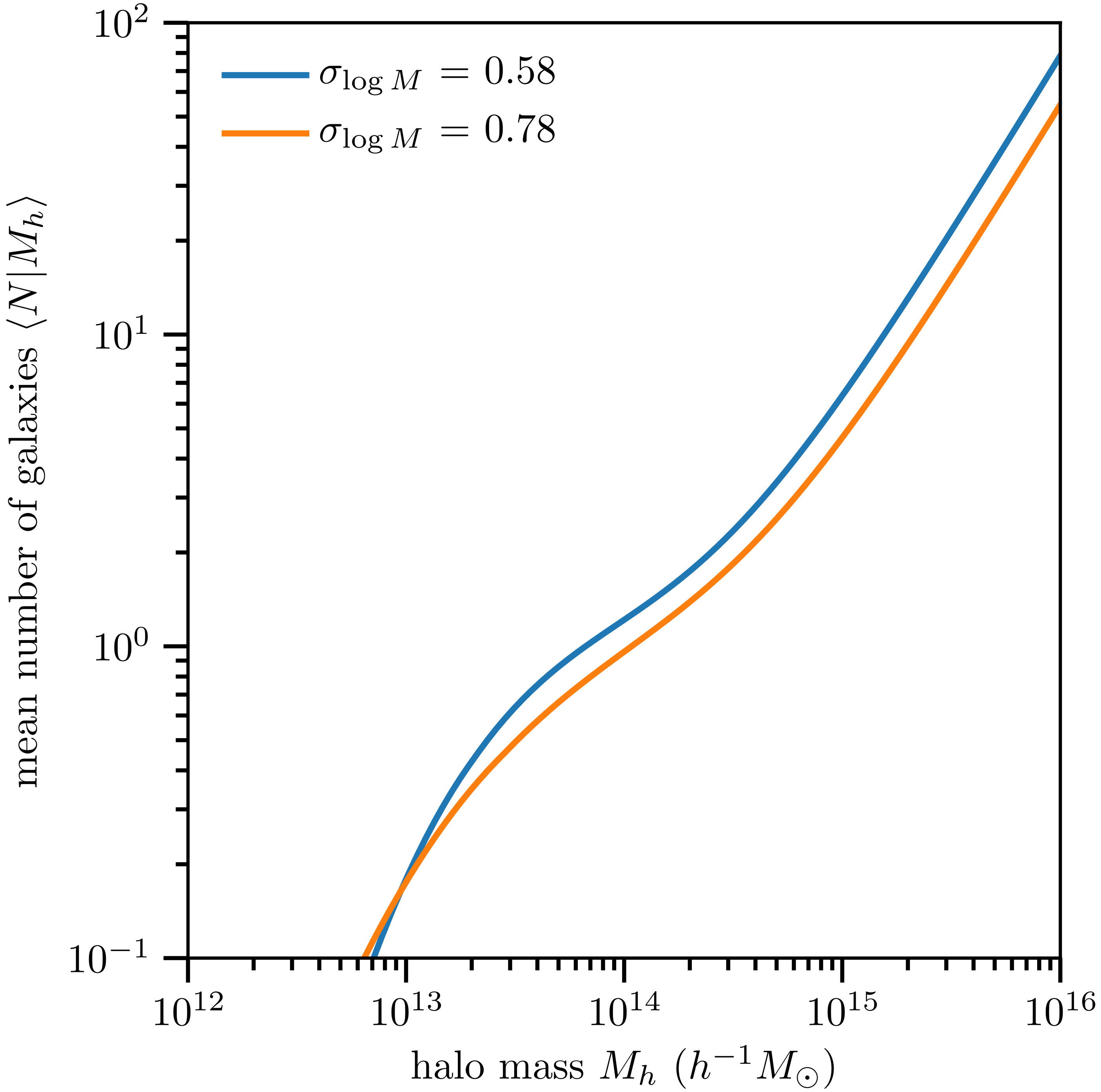
Halo occupation distribution (HOD)

$n_{\rm gal}$



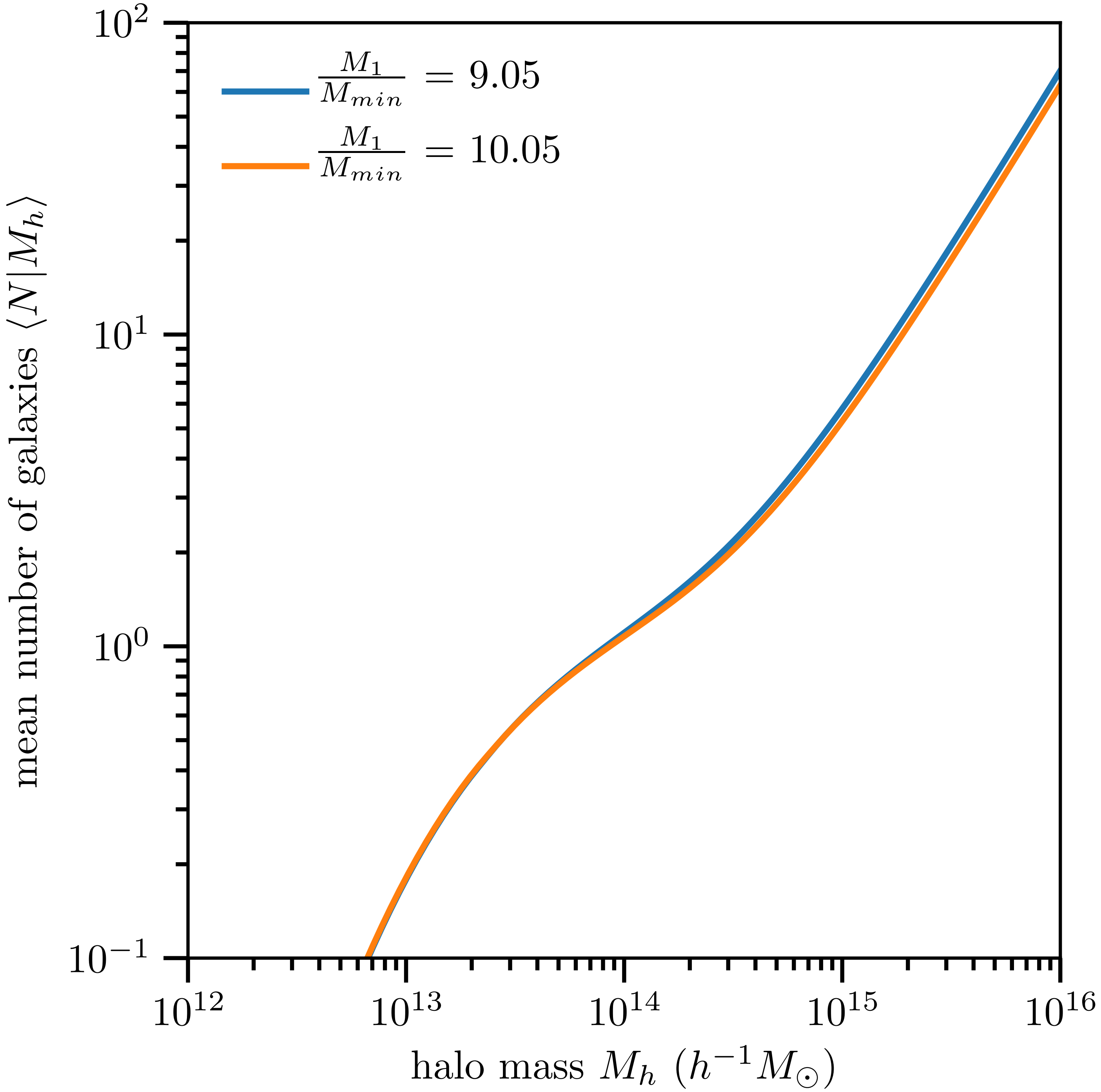
Halo occupation distribution (HOD)

$\sigma_{\log M}$



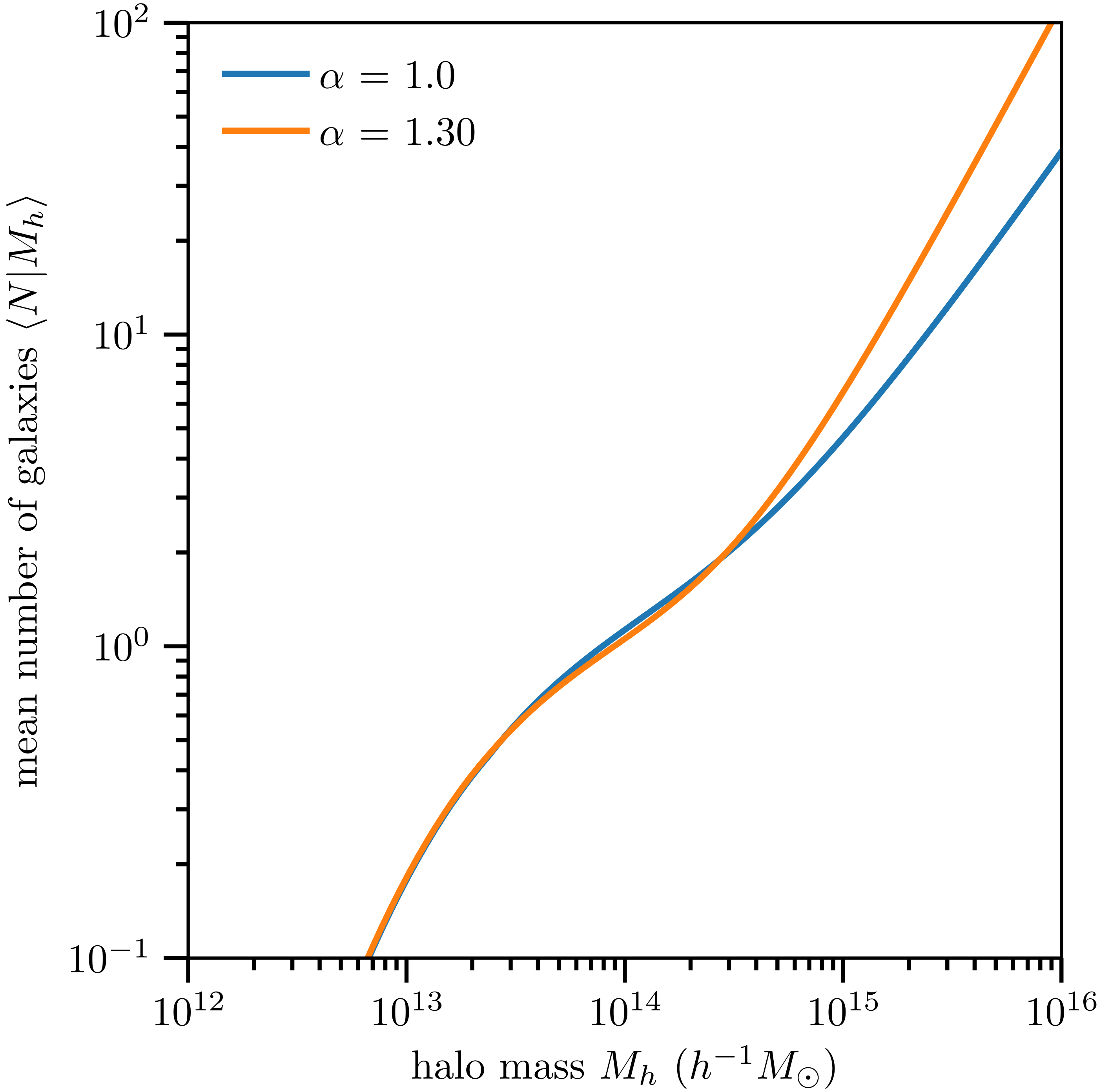
Halo occupation distribution (HOD)

M_1/M_{min}



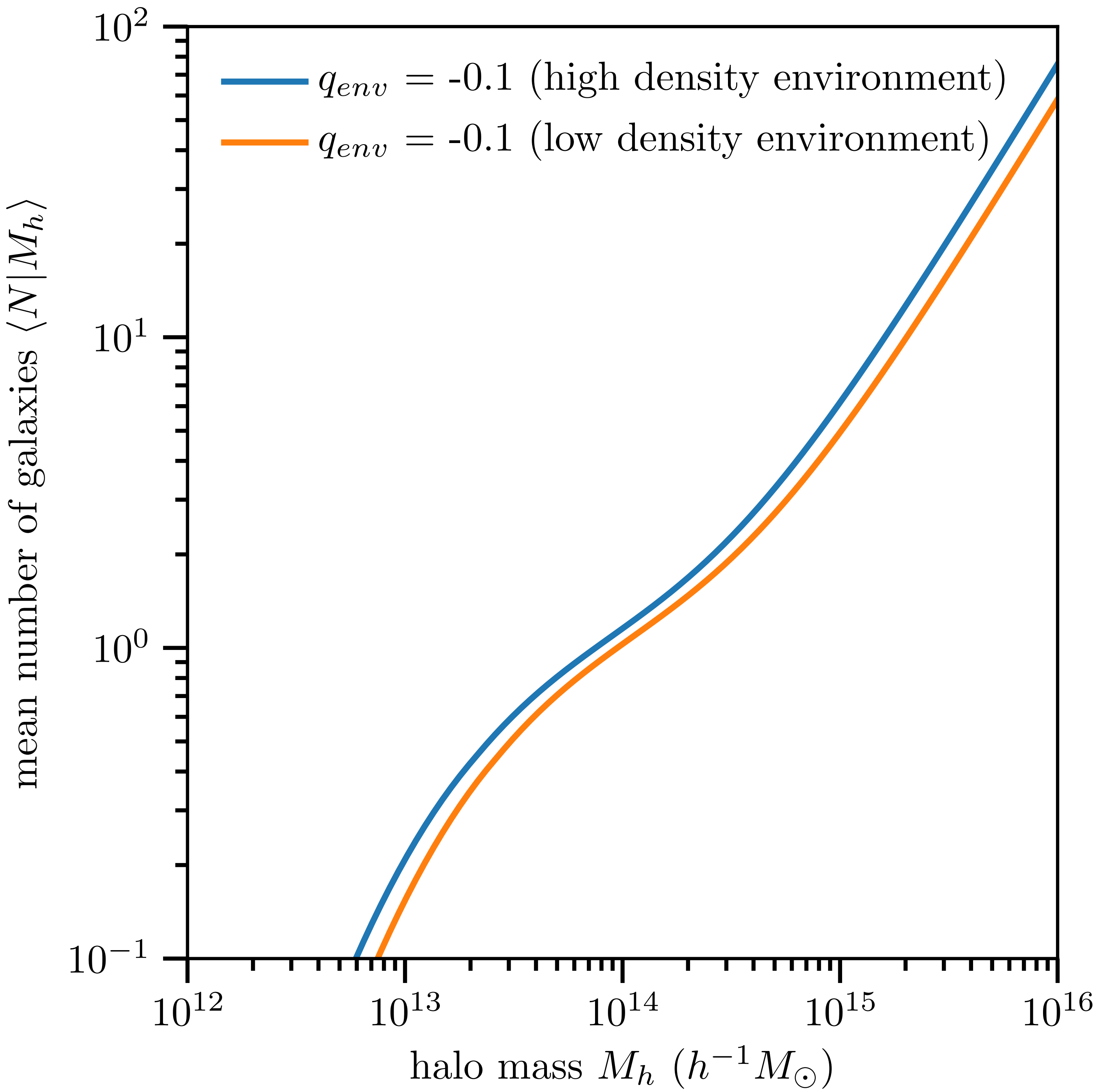
Halo occupation distribution (HOD)

α



Halo occupation distribution (HOD)

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 *(currently only a subset involving 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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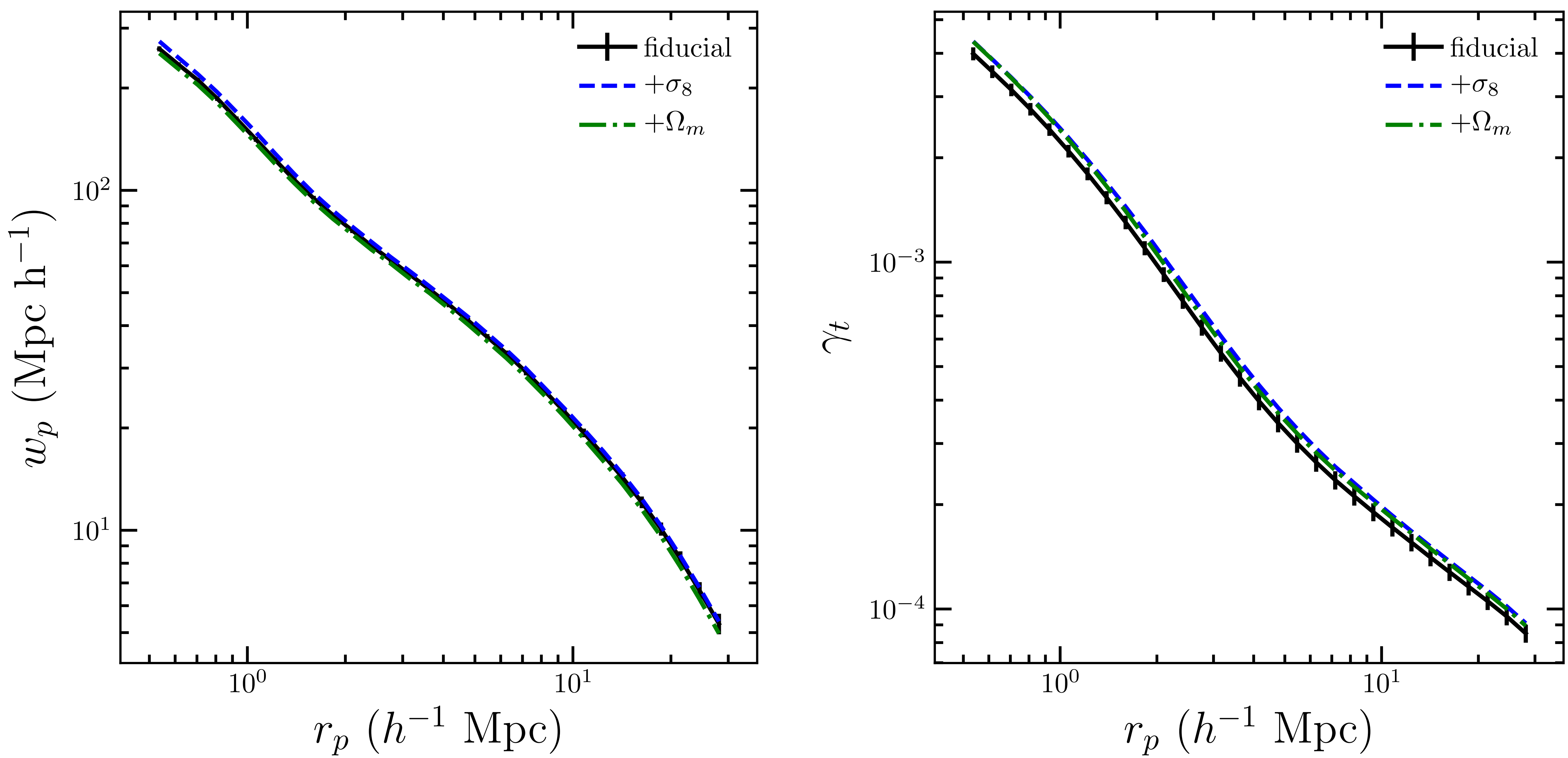
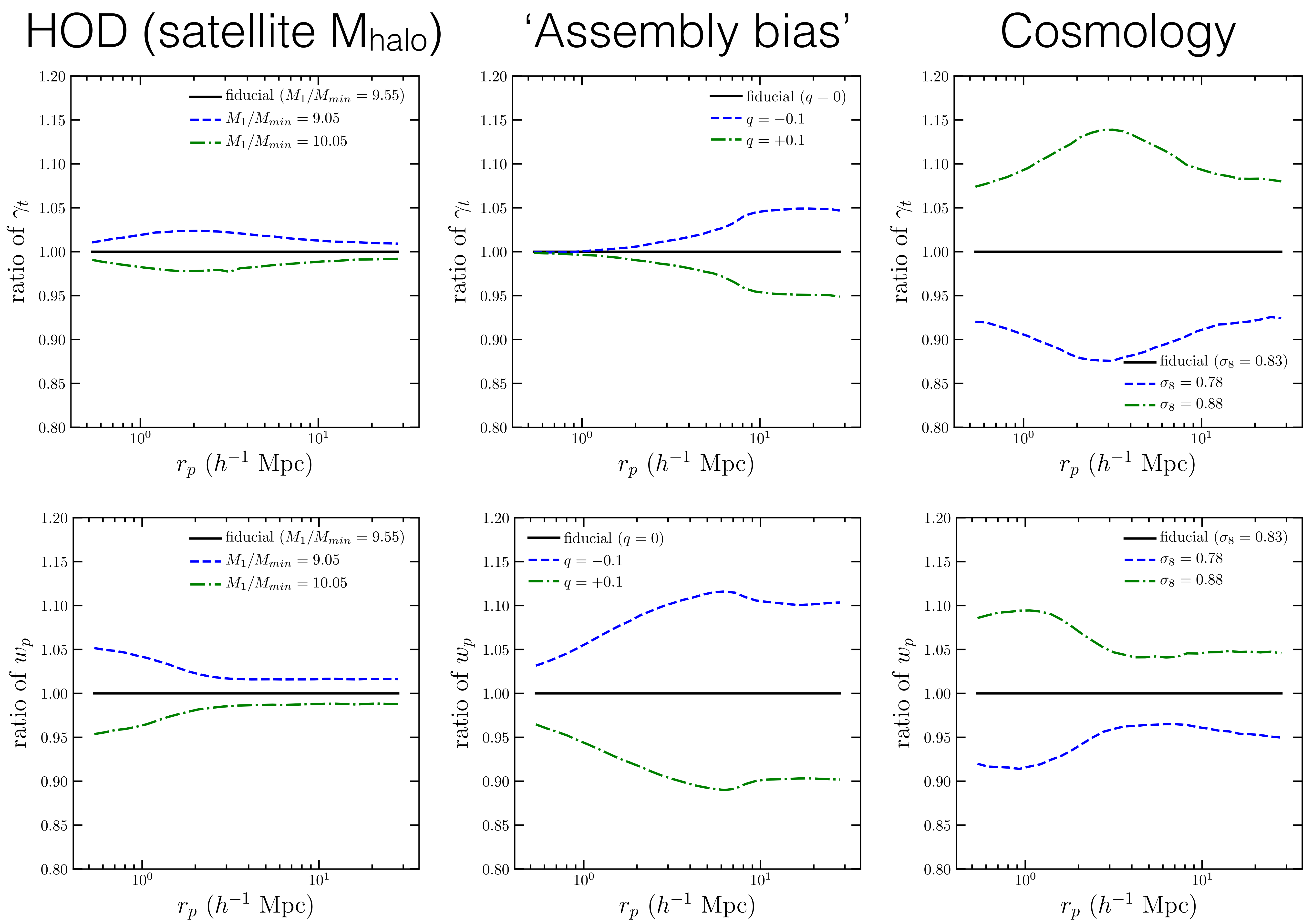
Emulator methodology

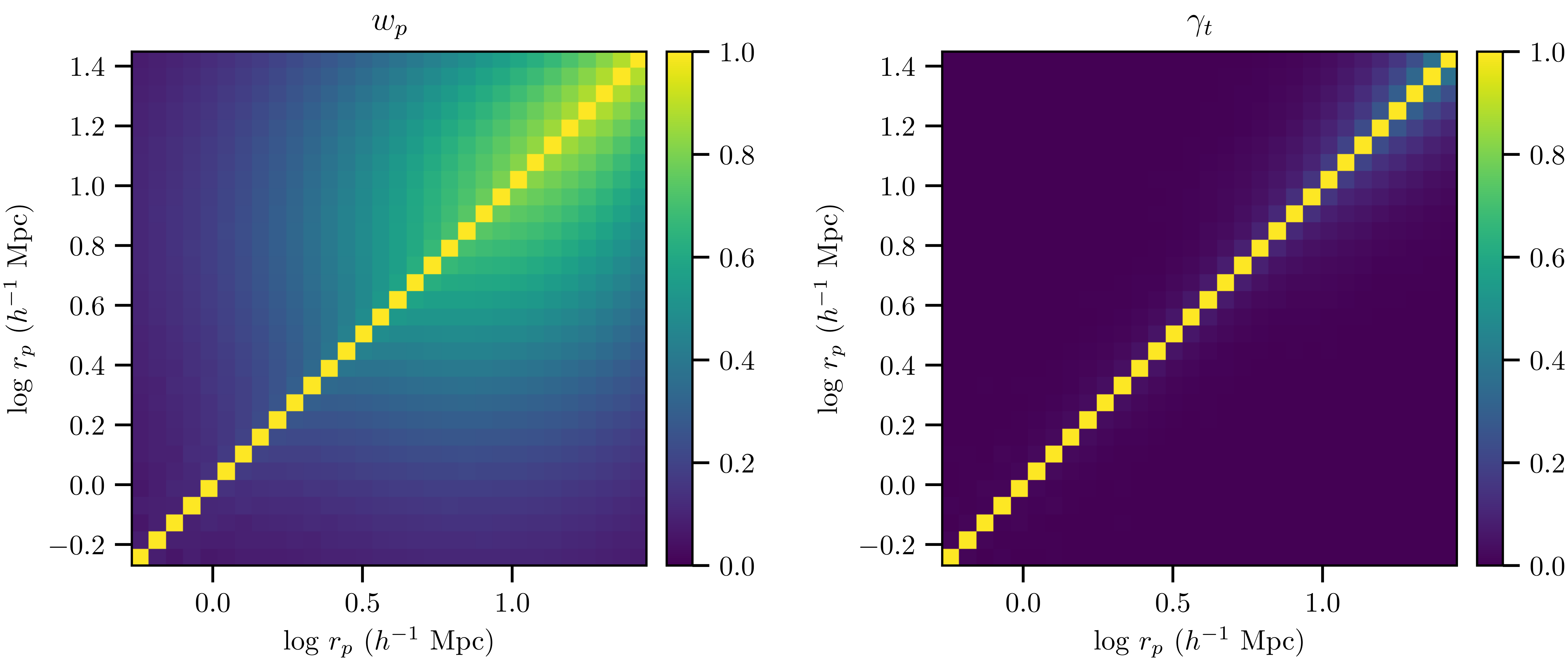
- Interpolating between models — this can be nontrivial:
  - Introduced to cosmology by the ‘CosmicEmu’ Gaussian process interpolation of the nonlinear power spectrum obtained from simulations (Heitmann+ 2009)
  - We instead interpolate various scale-dependent quantities using a (1st- or 2nd-order) Taylor expansion (similar to methodology of Mandelbaum+ 2013):
    - scale-dependent bias b_g,
    - (scale-dependent) correlation coefficient r_{gm}, and
    - (scale-dependent) ratio of the nonlinear-to-linear matter correlation function (we denote this b_{nl})

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)
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
10^0
10^1

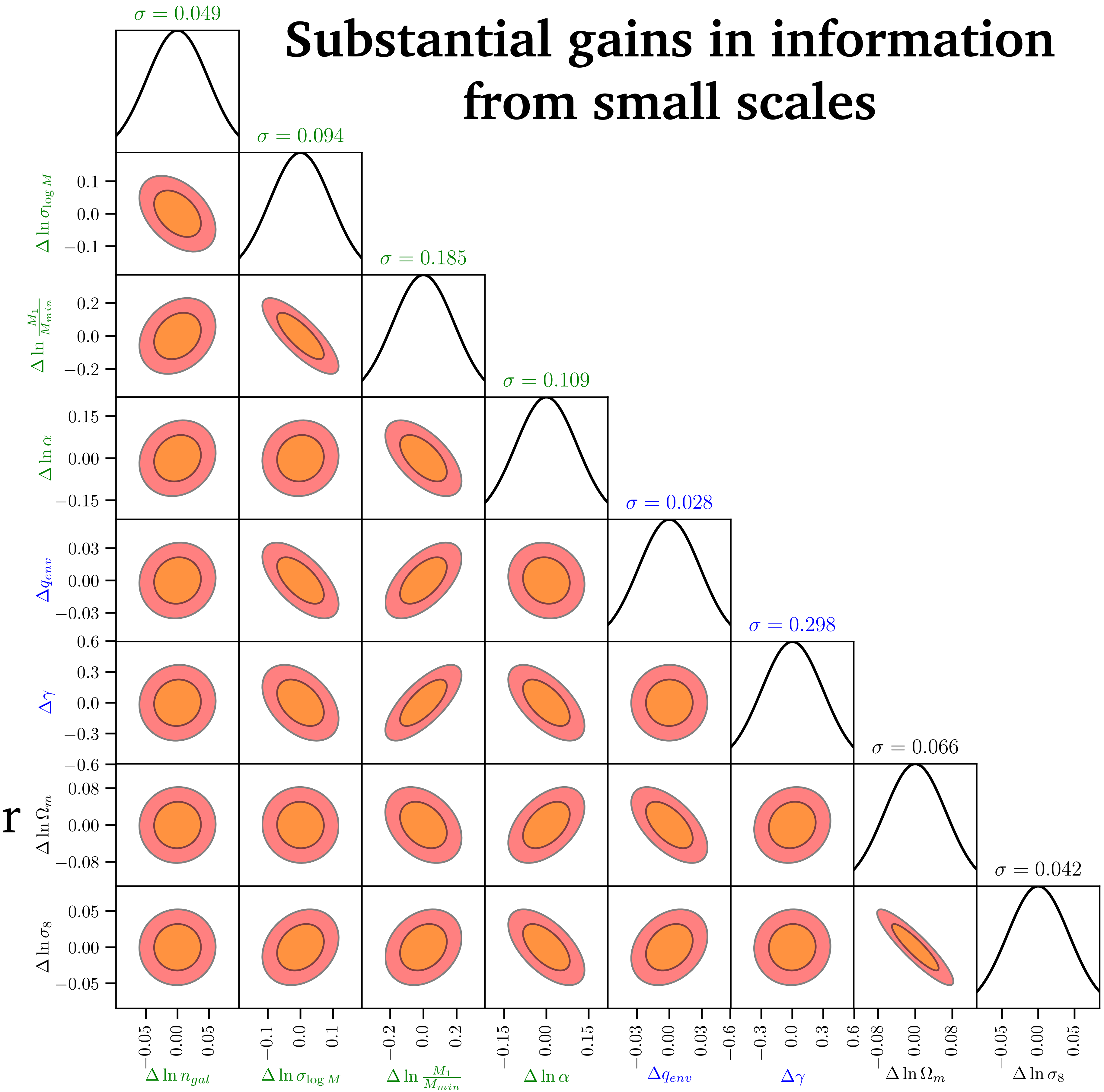
Covariance matrices and forecasting for LOWZ GGL with SDSS imaging



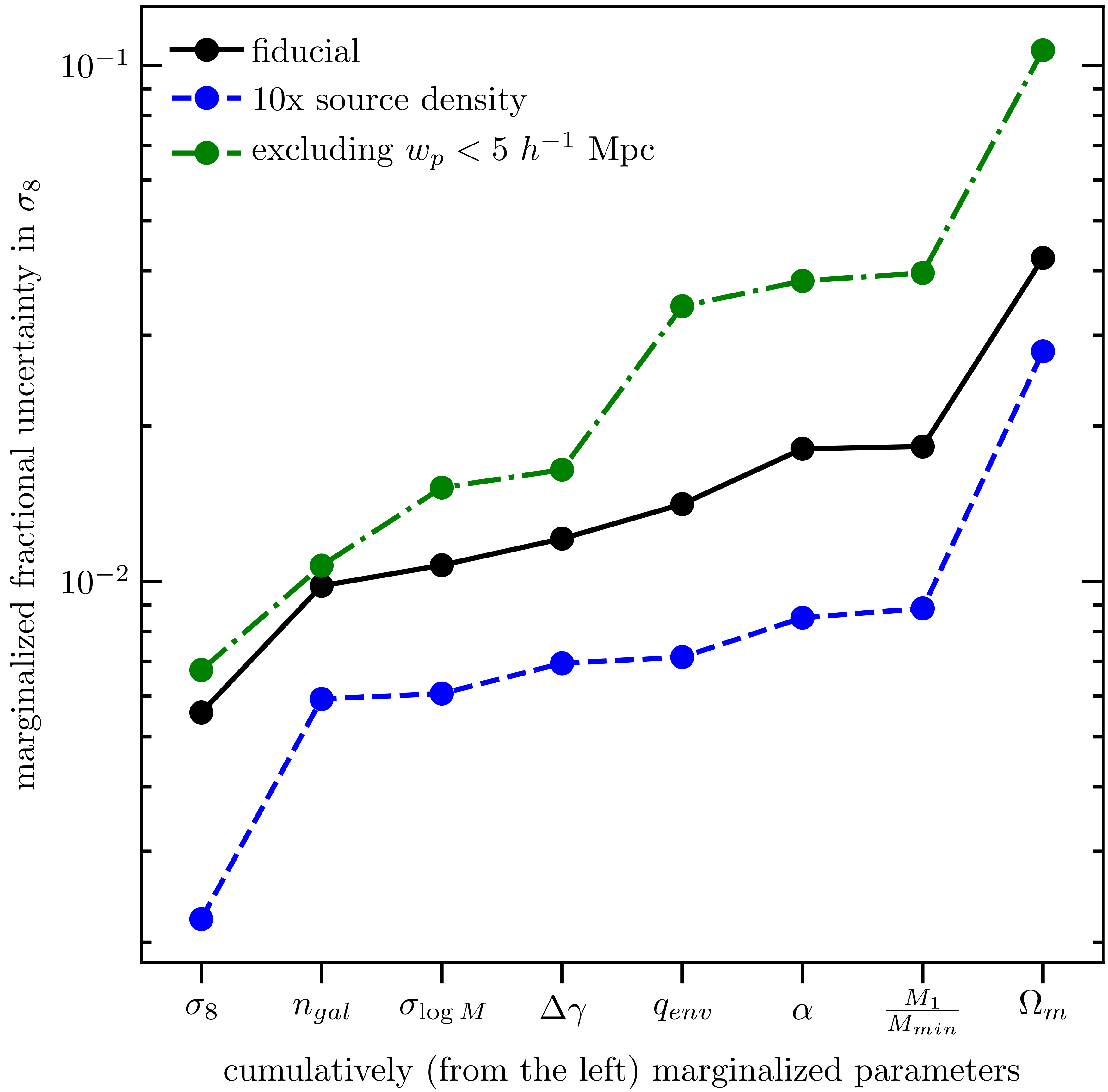
(n_{gal} = 3 x 10^{-4} h^3 Mpc^{-3}, ~1 galaxy $arcmin^{-2}$)

Substantial gains in information from small scales

- Cosmological constraints forecasted: 1.8% uncertainty on $\sigma_8\Omega_m^{0.58}$
- Using only scales >2 Mpc/h (lensing) and >4 Mpc/h (clustering), the constraints degrade to 3.8%
- More precise constraints by a factor of >2, equivalent to >4x the survey area without small scales



What is the cost of marginalizing over galaxy formation uncertainties?



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: considering additional cosmological parameters using the full grid of simulations, fitting to CMASS + DES lensing measurements

Questions?