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

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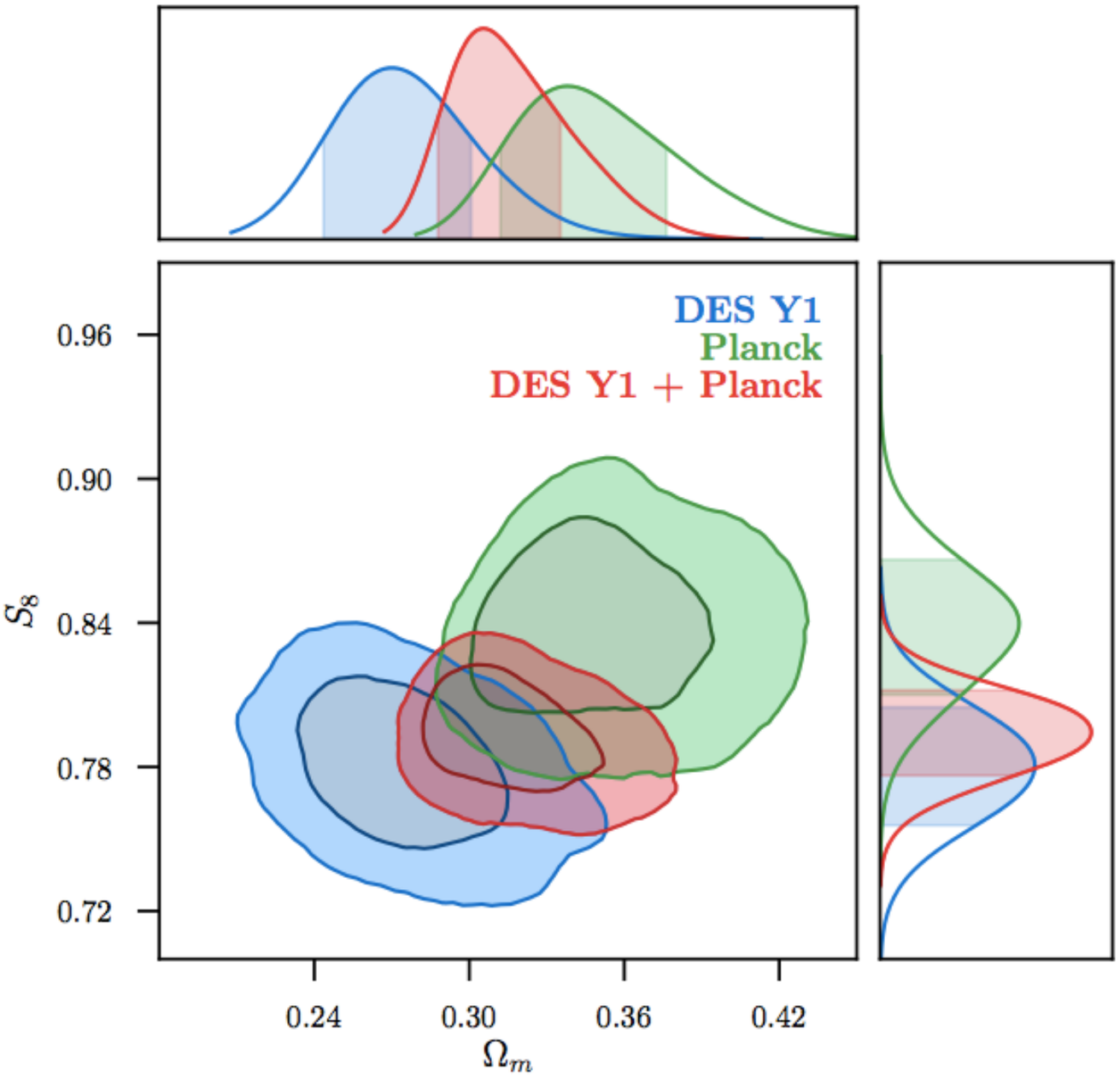
# Why do we care?

- 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

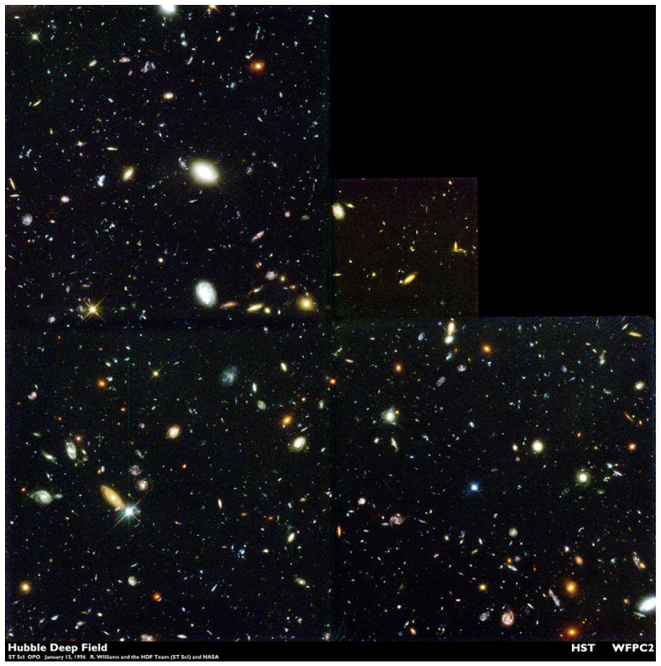
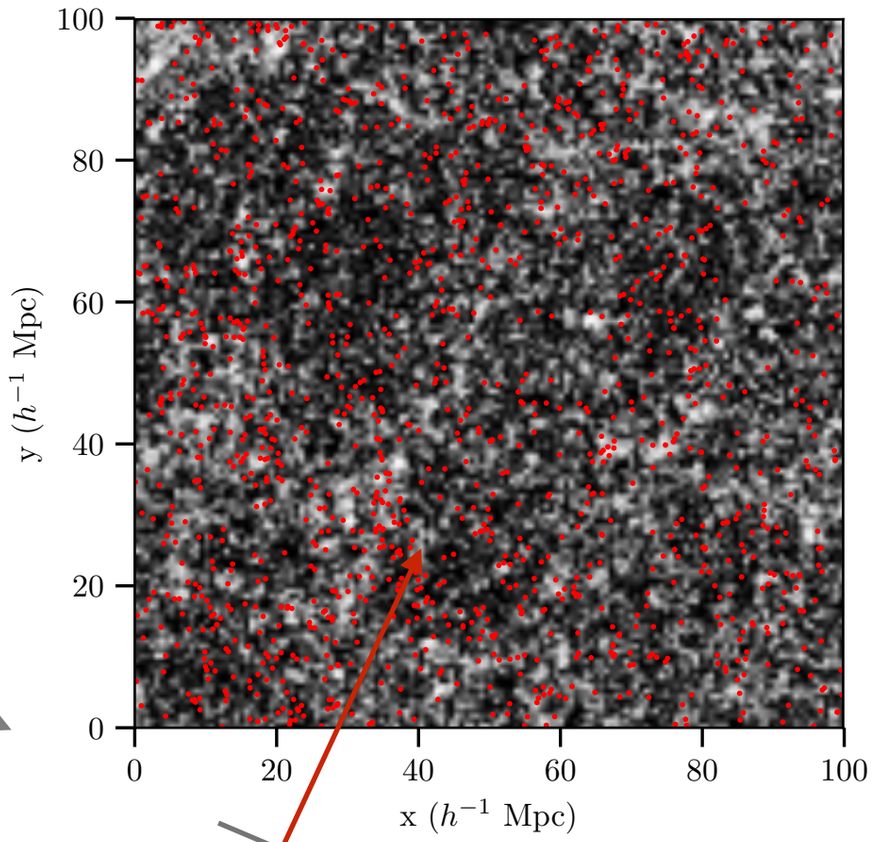
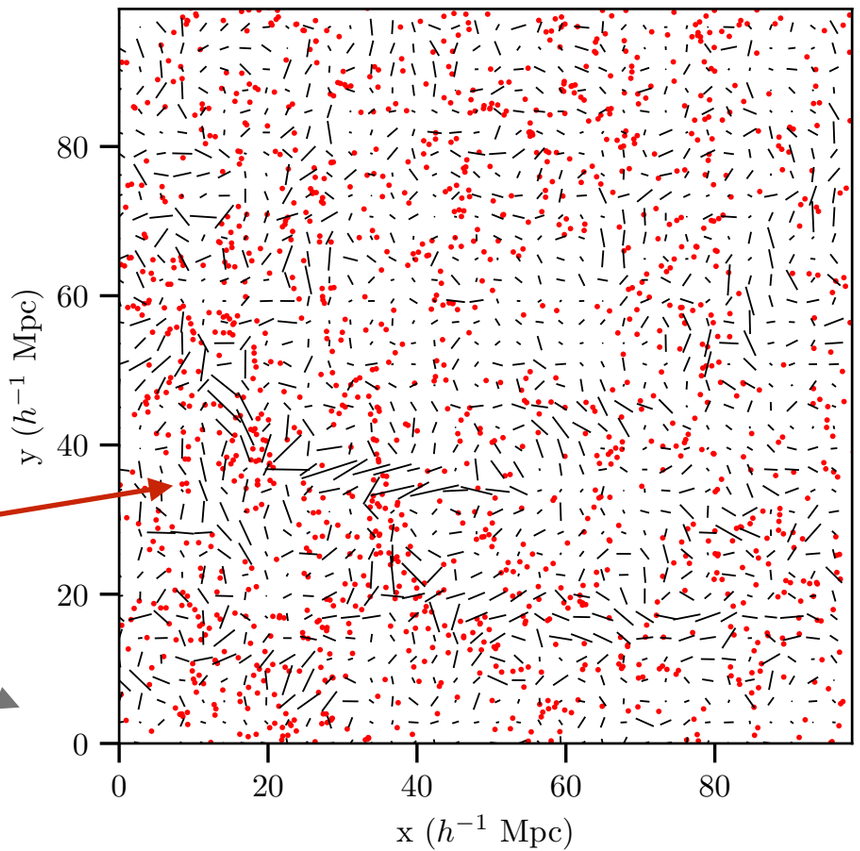



Image: Hubble Deep Field
(for illustrative purposes only)

## Lensing plane

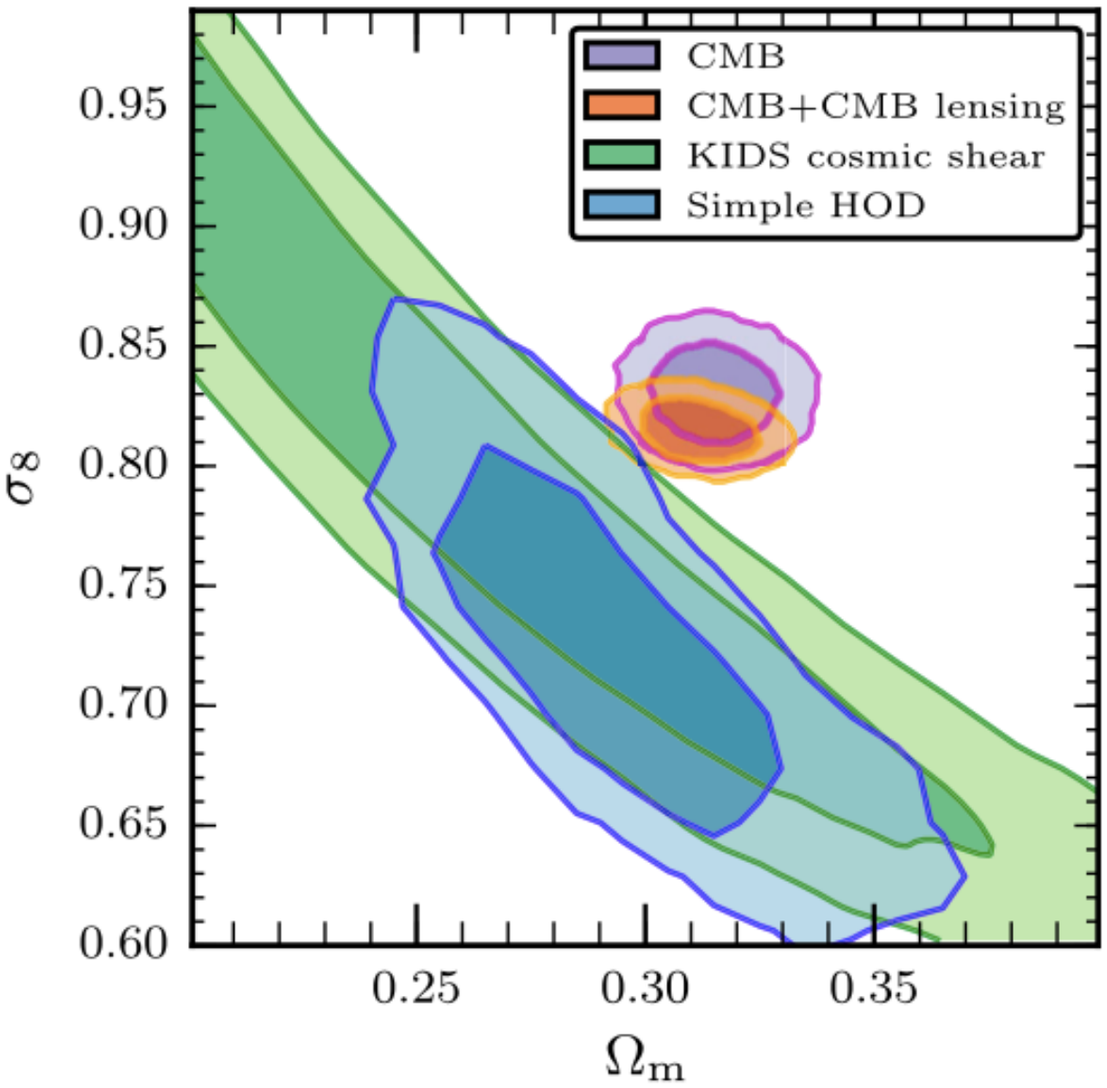


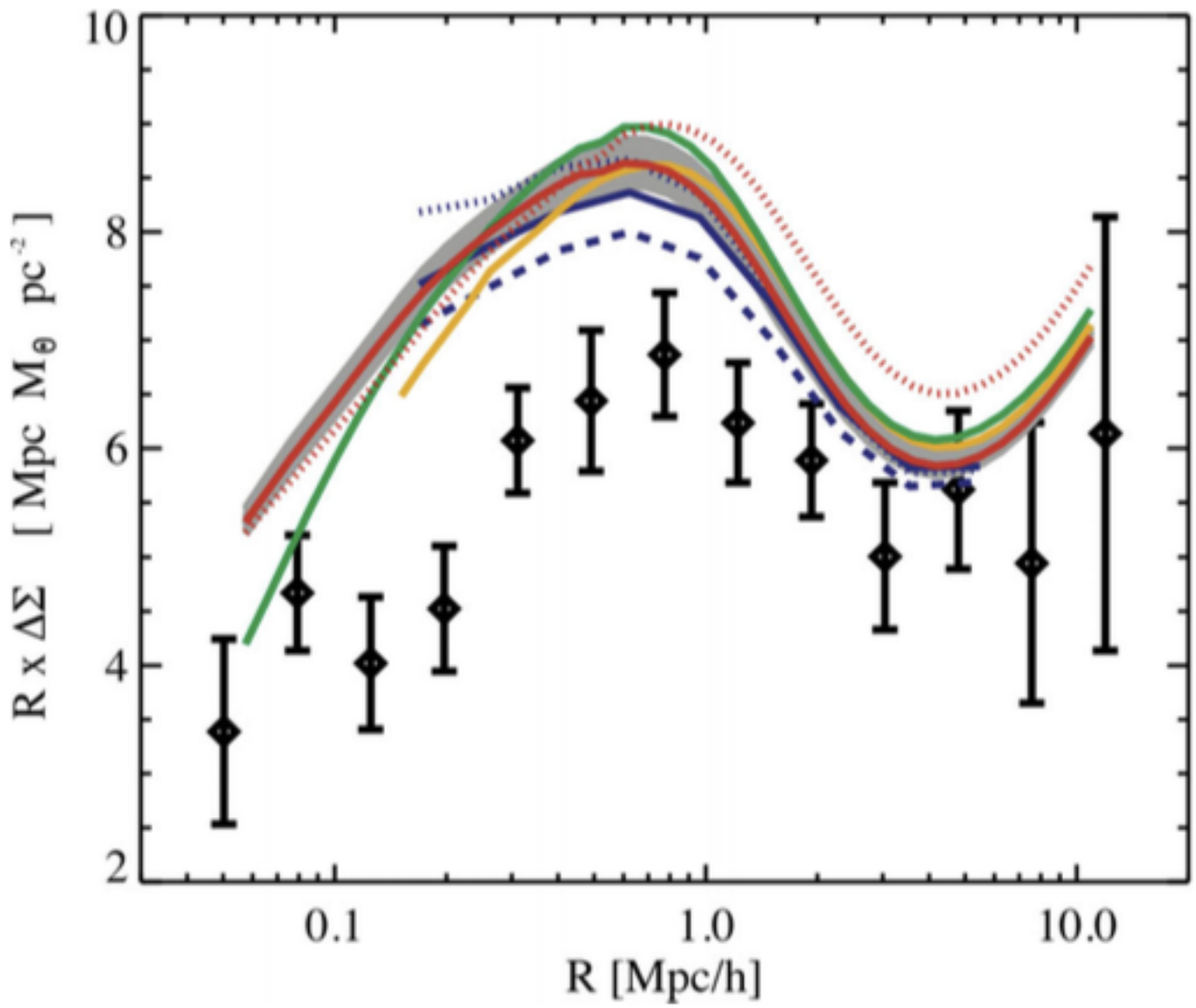

## Image plane




*'lens' galaxies*

# Small scale systematics?



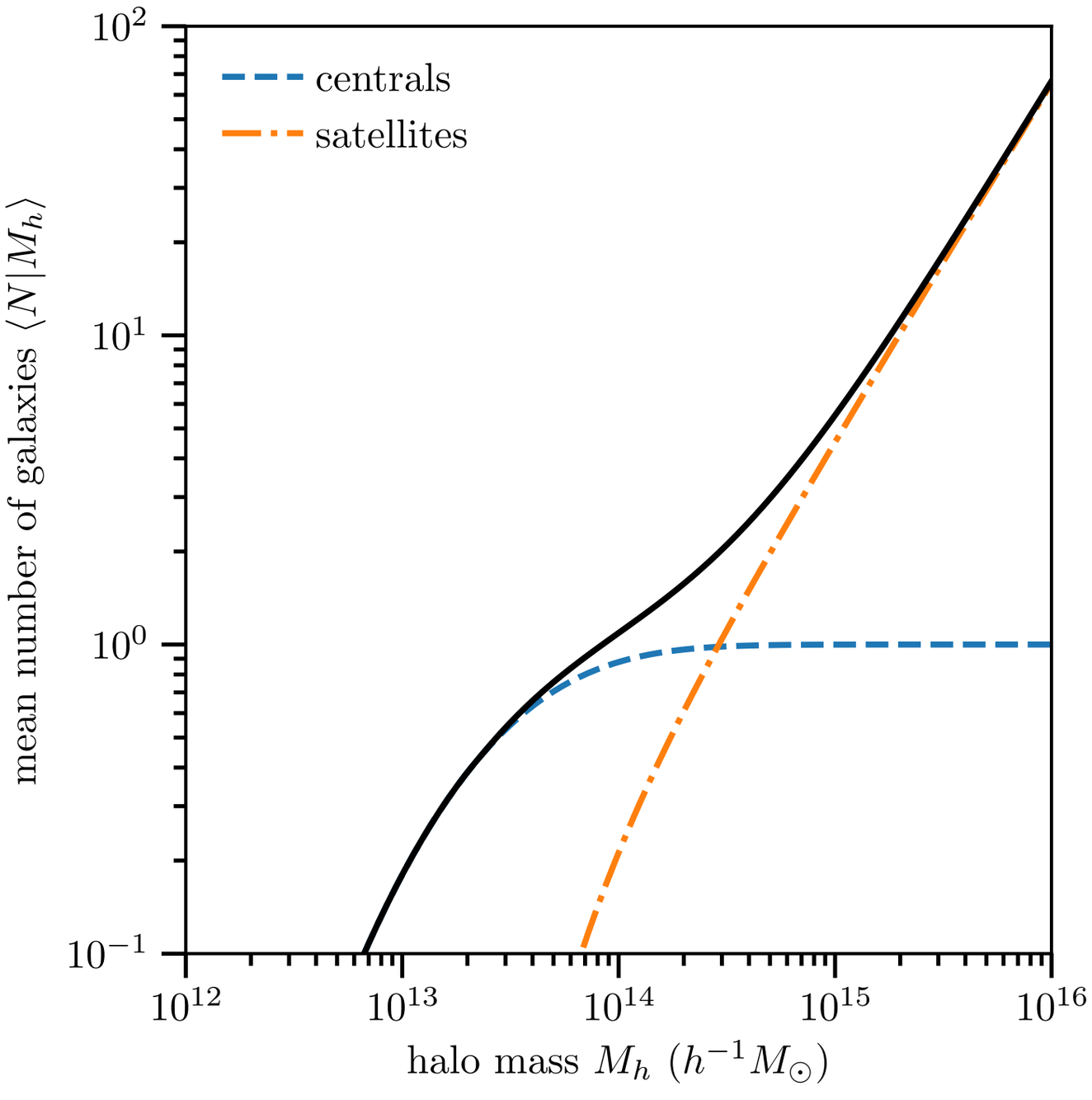




Figures: Leauthaud+ 2017

e.g. Berlind & Weinberg (2002)

# Halo occupation distribution (HOD)

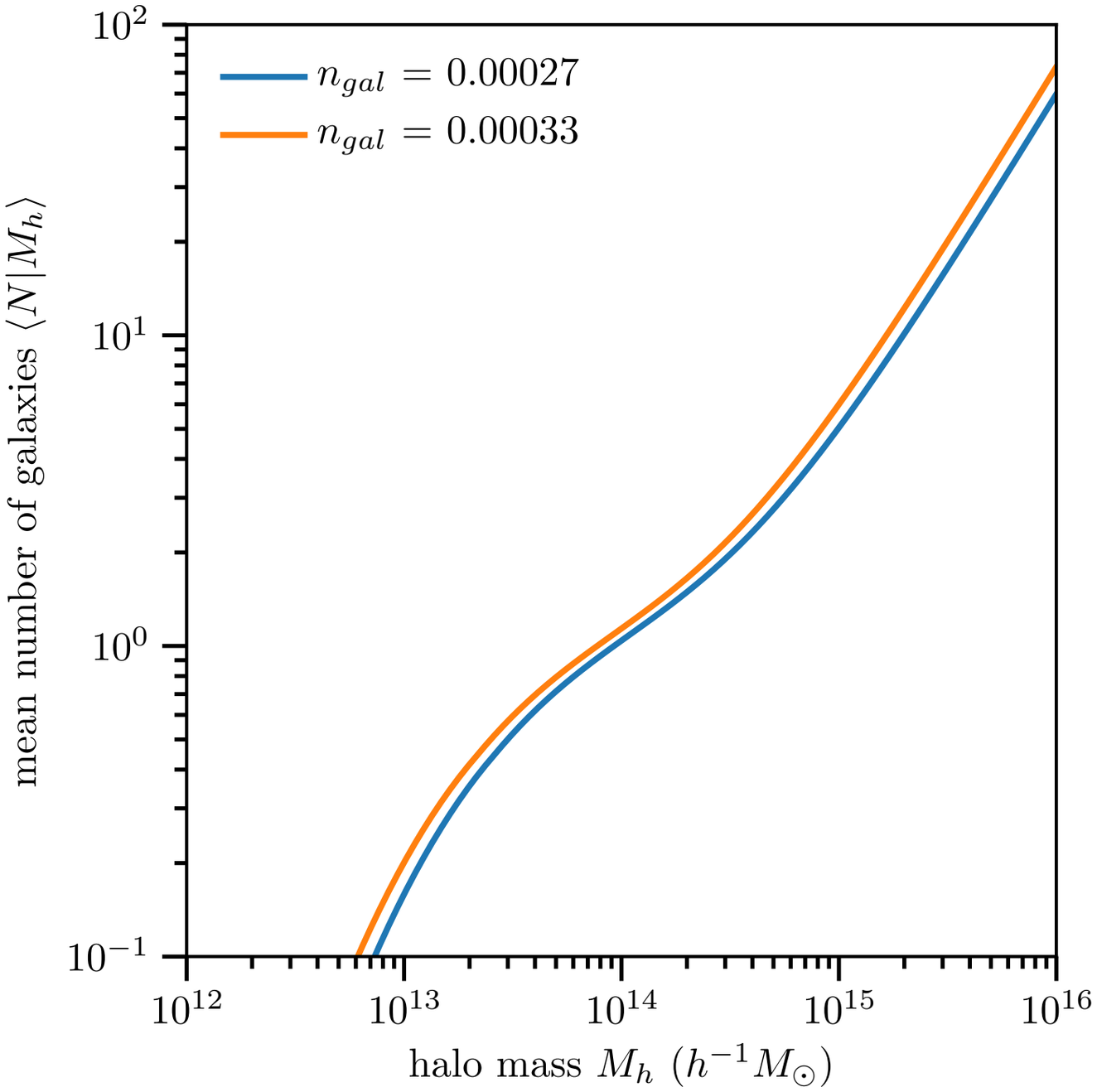
fiducial parameter values




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

# Halo occupation distribution (HOD)

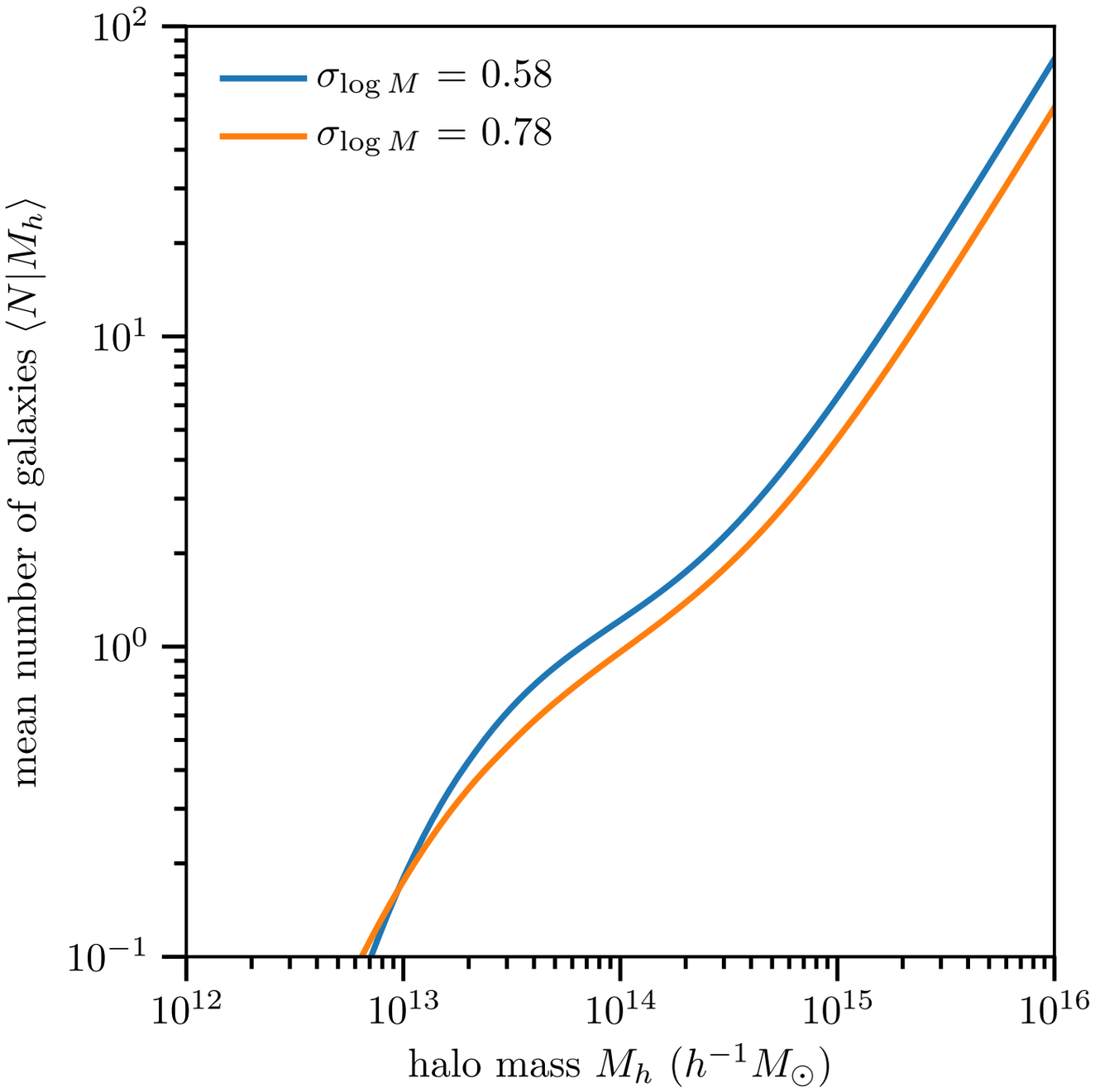
$n_{\mathrm{gal}}$




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

# Halo occupation distribution (HOD)

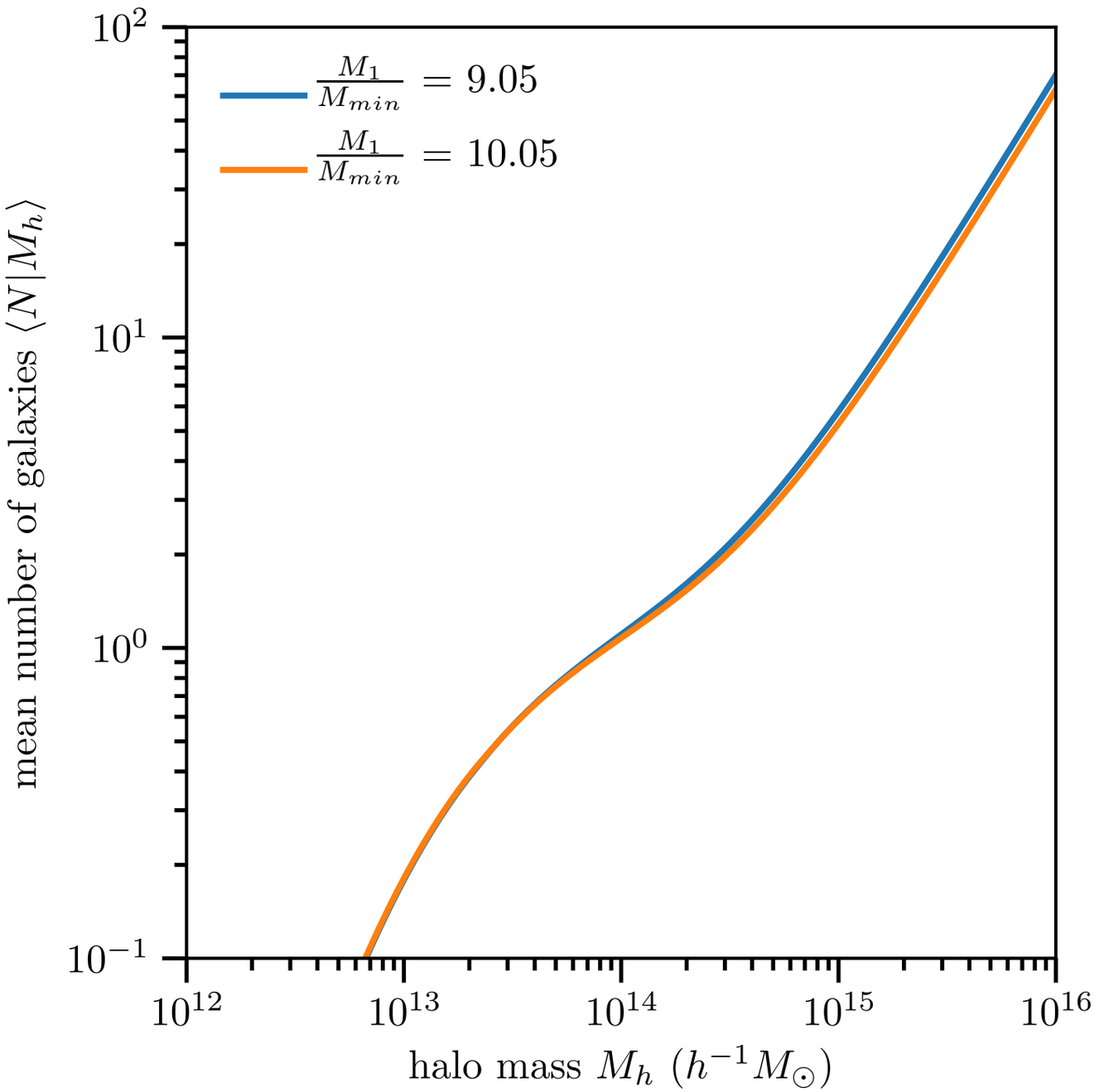
$\sigma_{\log M}$




Varying the scatter in halo mass to stellar mass

# Halo occupation distribution (HOD)

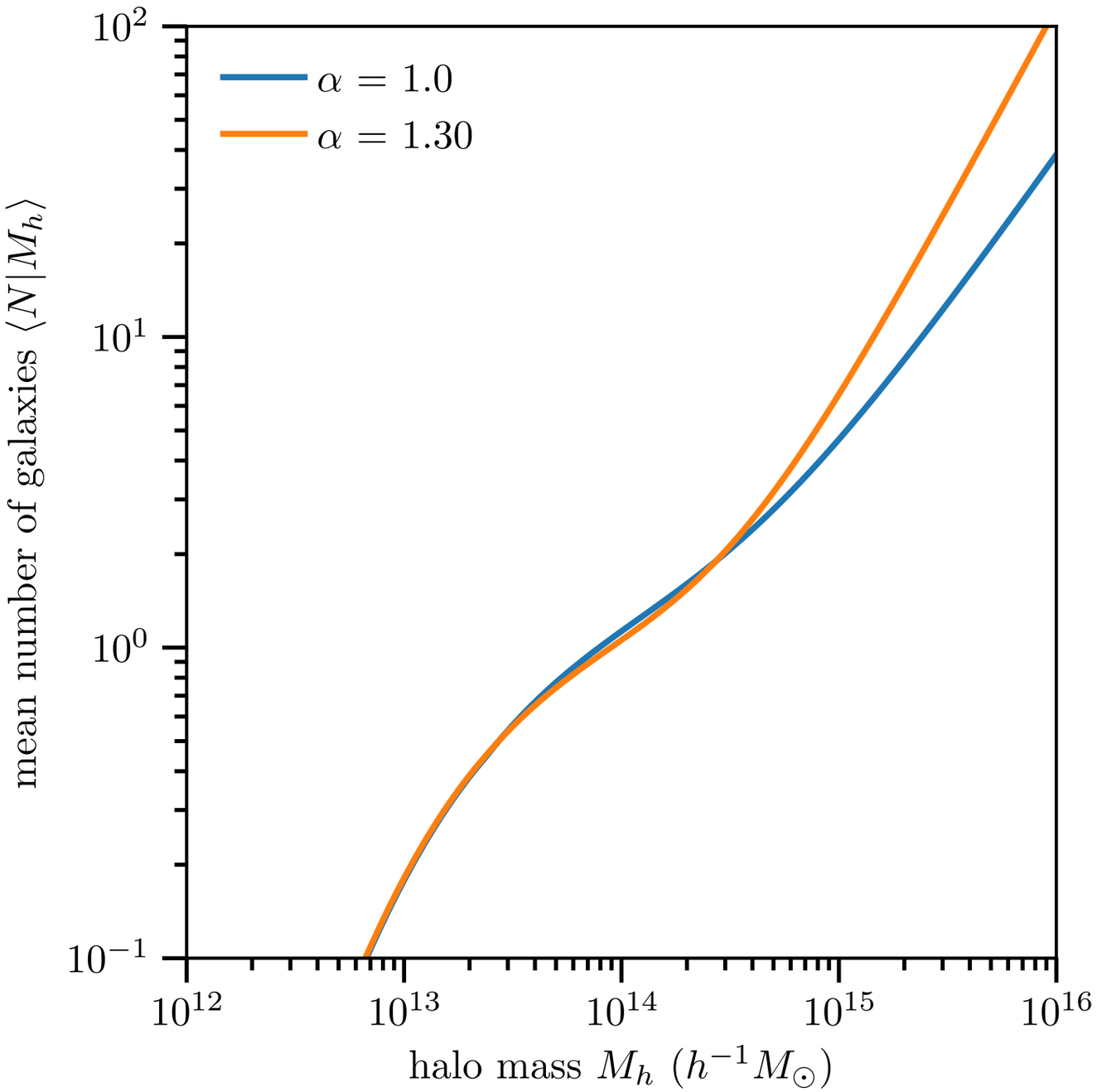
$M_1/M_{\rm min}$




Varying the halo mass at which there are satellite galaxies

# Halo occupation distribution (HOD)

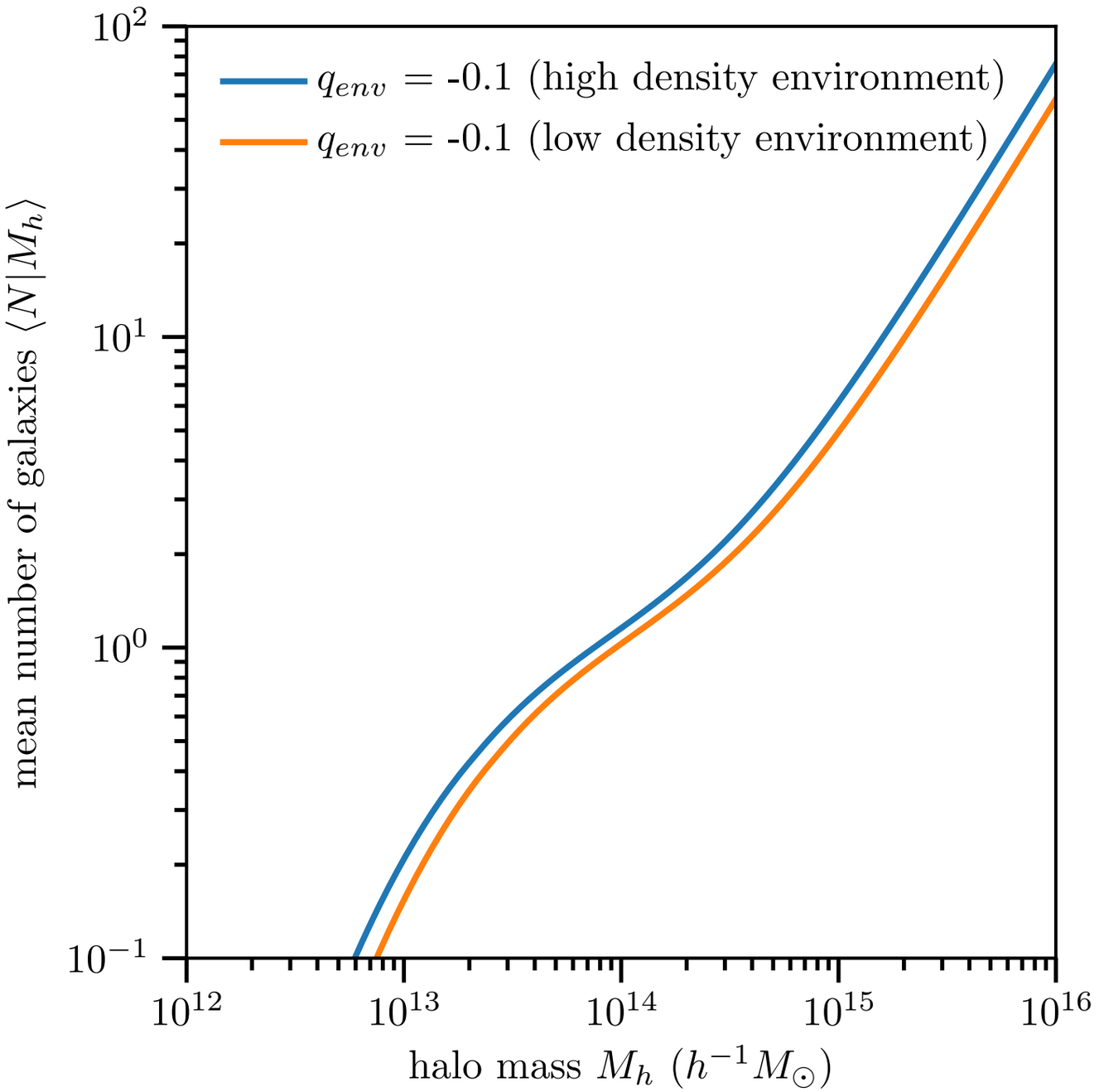
$\alpha$




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

# Halo occupation distribution (HOD)

$Q_{\rm env}$




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 $\sigma_8, \Omega_M$)*
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 $\gamma_t$

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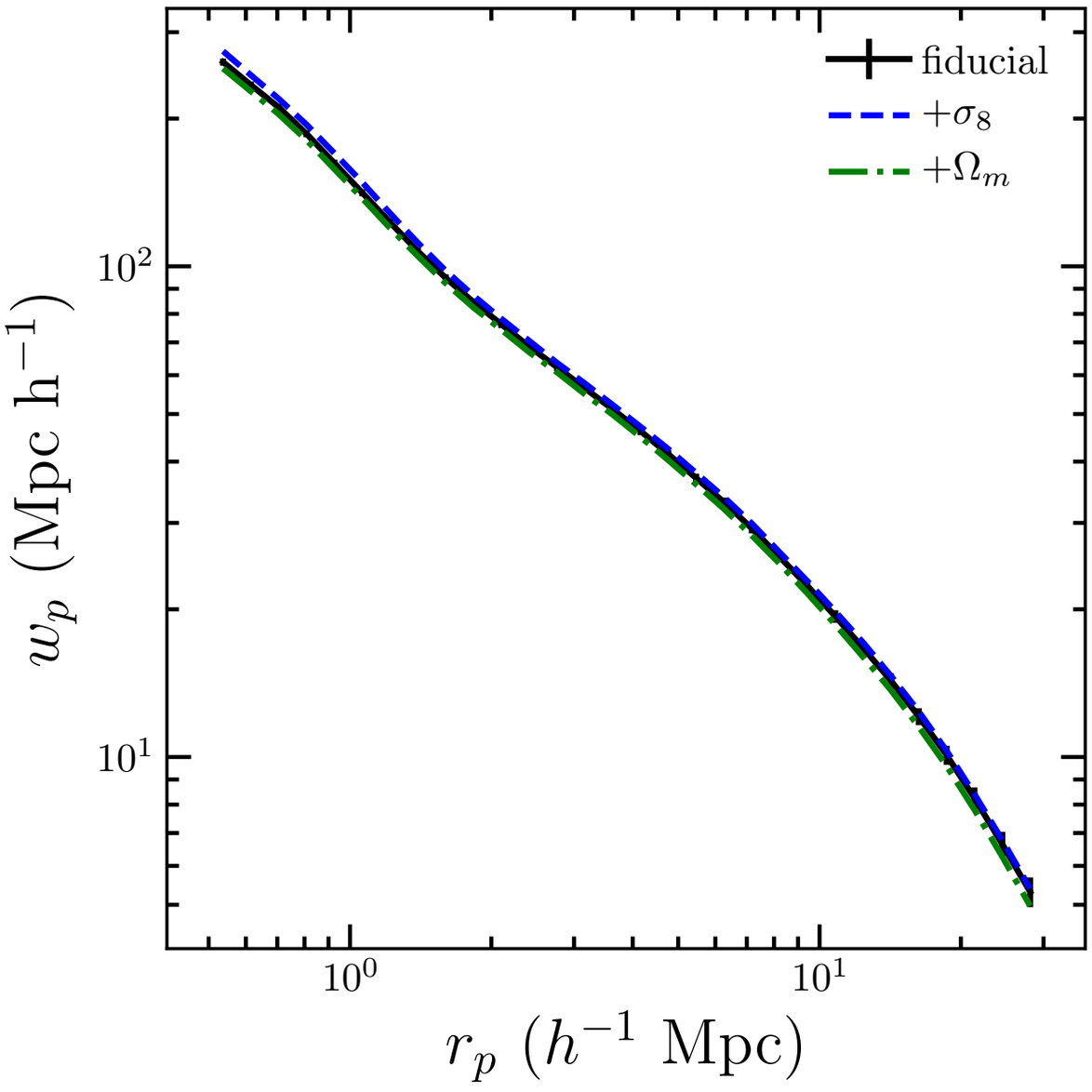
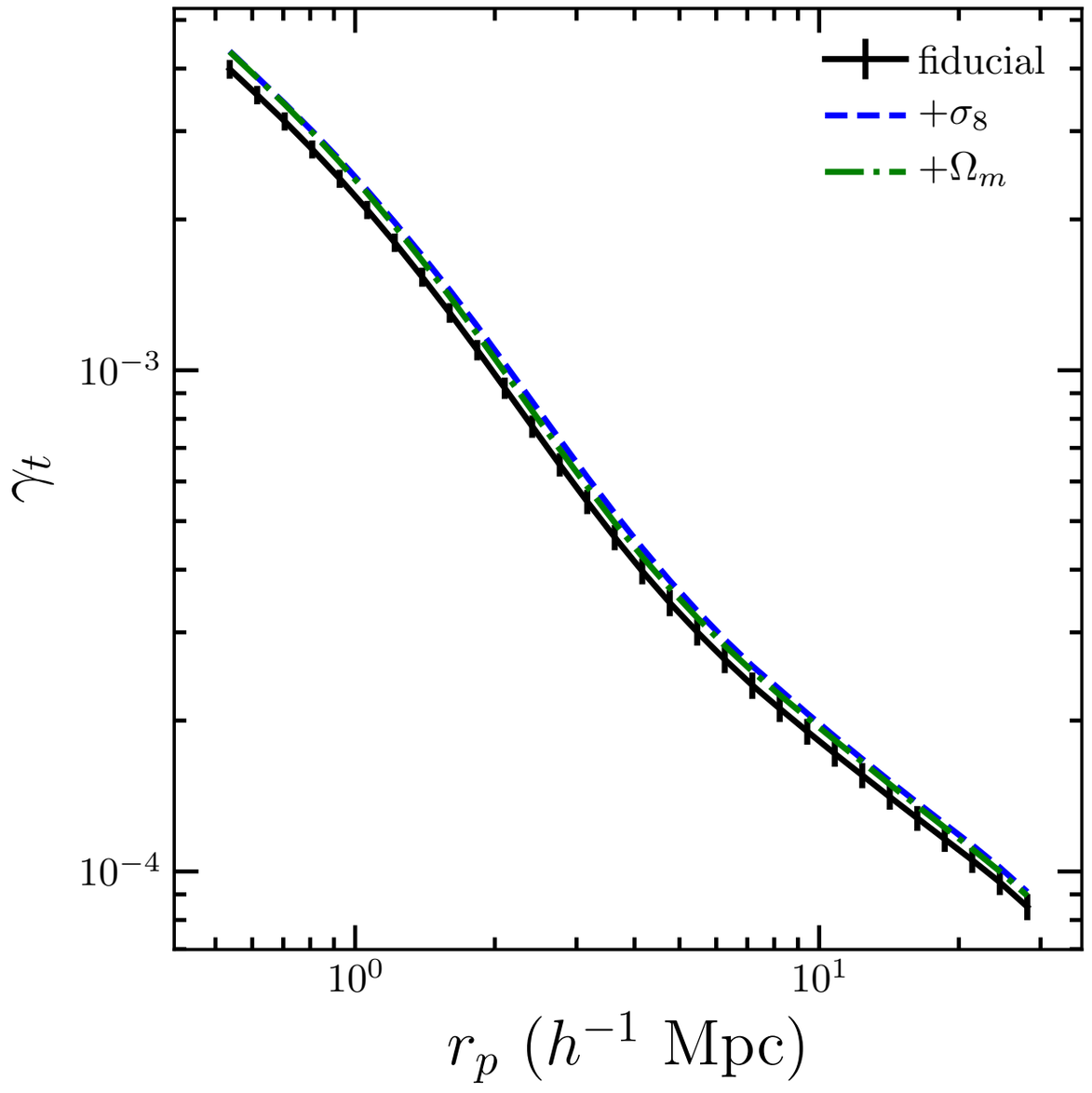
# Emulator methodology

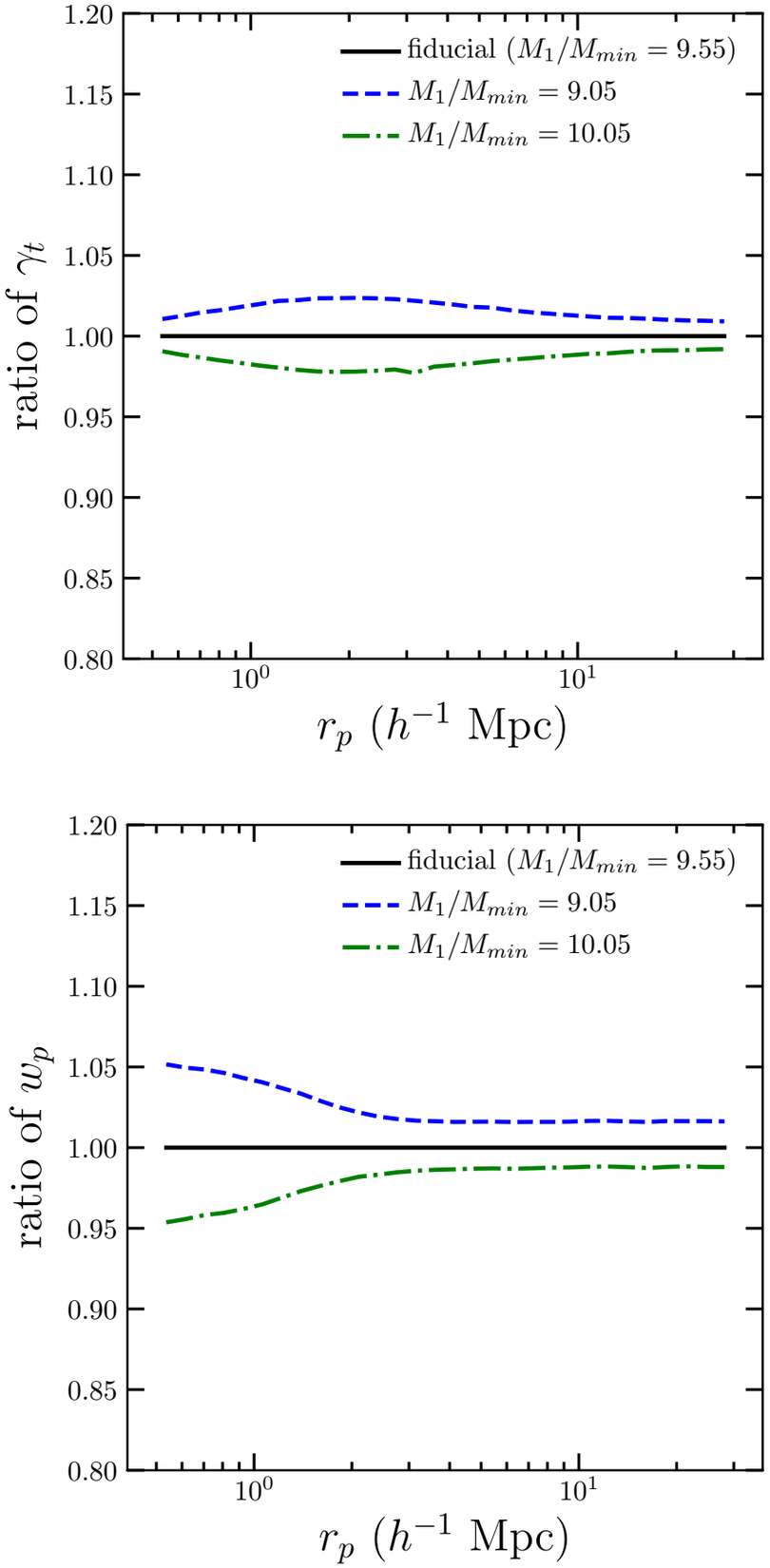
- Interpolating between models — this can be nontrivial:
  - Introduced to cosmology by the 'CosmicEmu' Gaussian process interpolation of the nonlinear power spectrum obtained from simulations (Heitmann+ 2009)
  - We instead interpolate various scale-dependent quantities using a (1st- or 2nd-order) Taylor 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/$h$

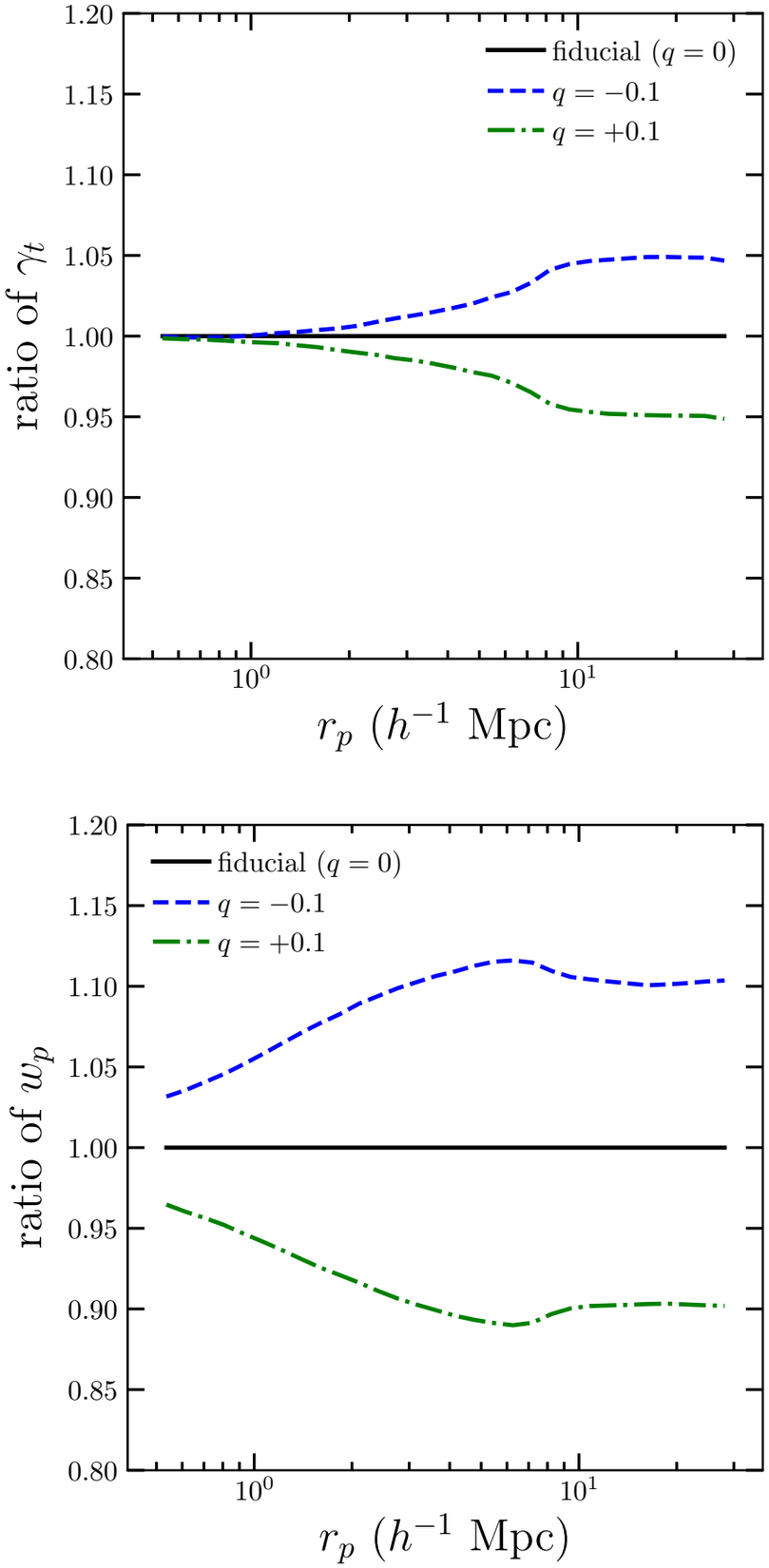


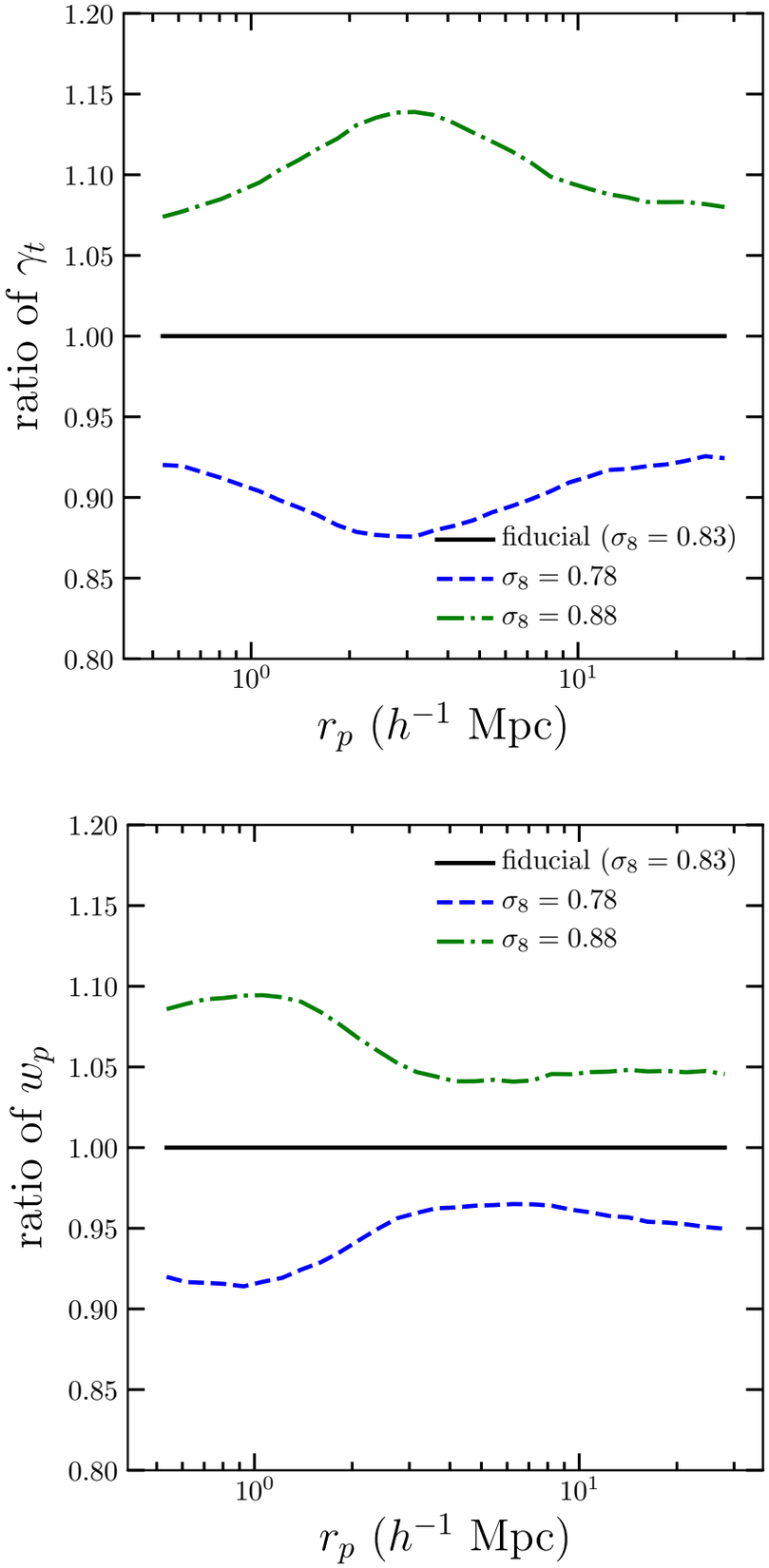
# HOD (satellite $M_{halo}$)



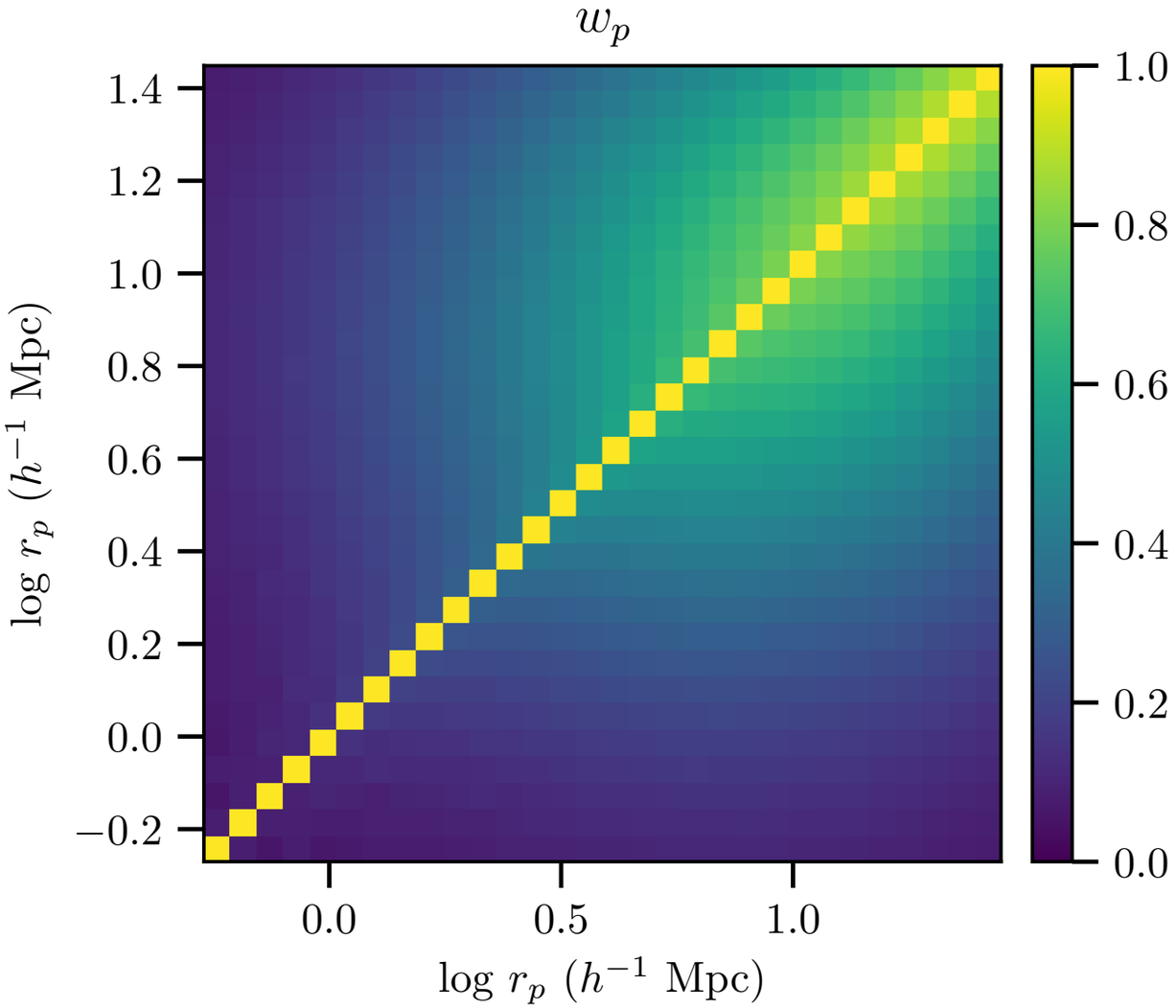

# 'Assembly bias'

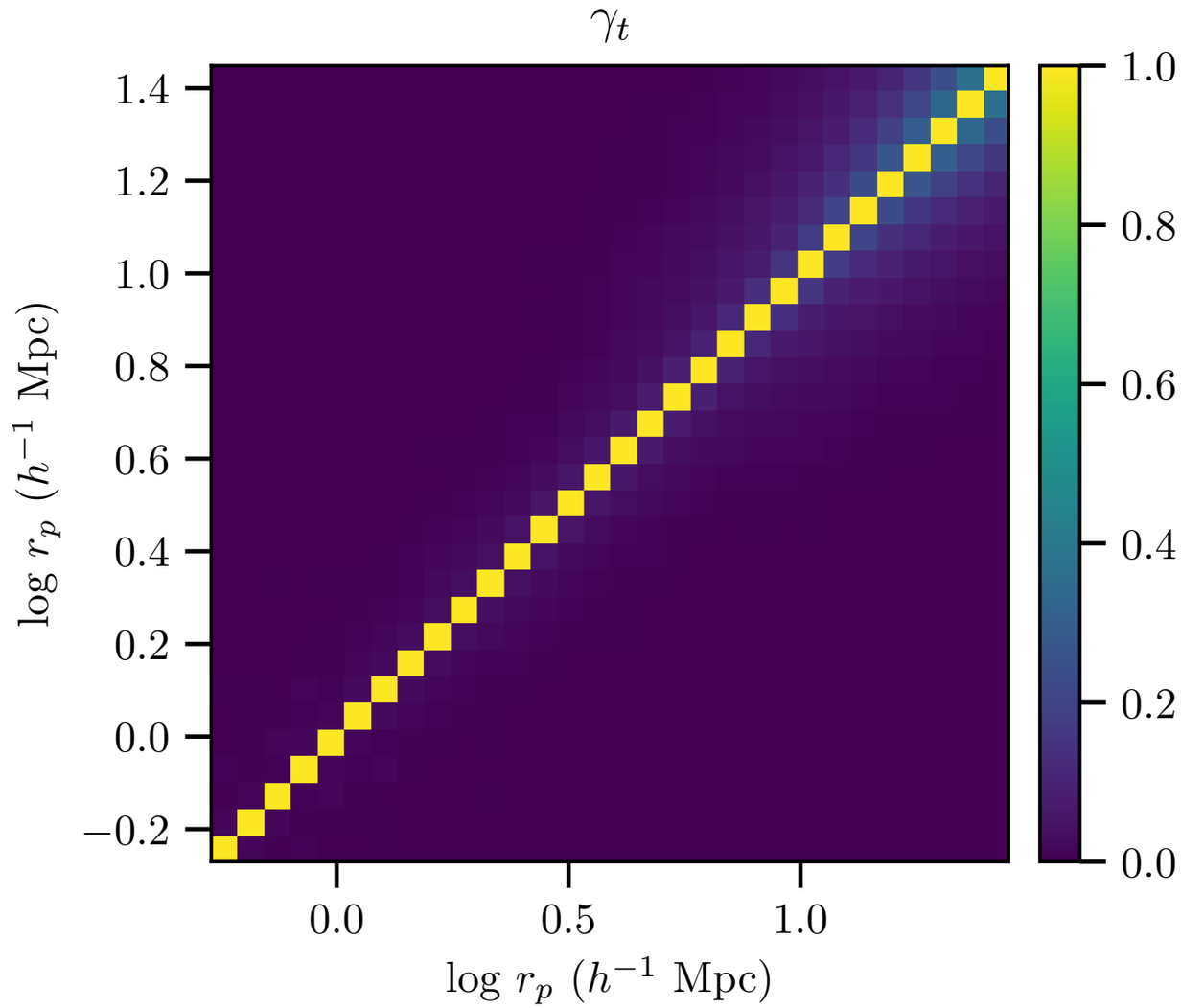



# Cosmology



# Covariance matrices and forecasting for LOWZ GGL with SDSS imaging

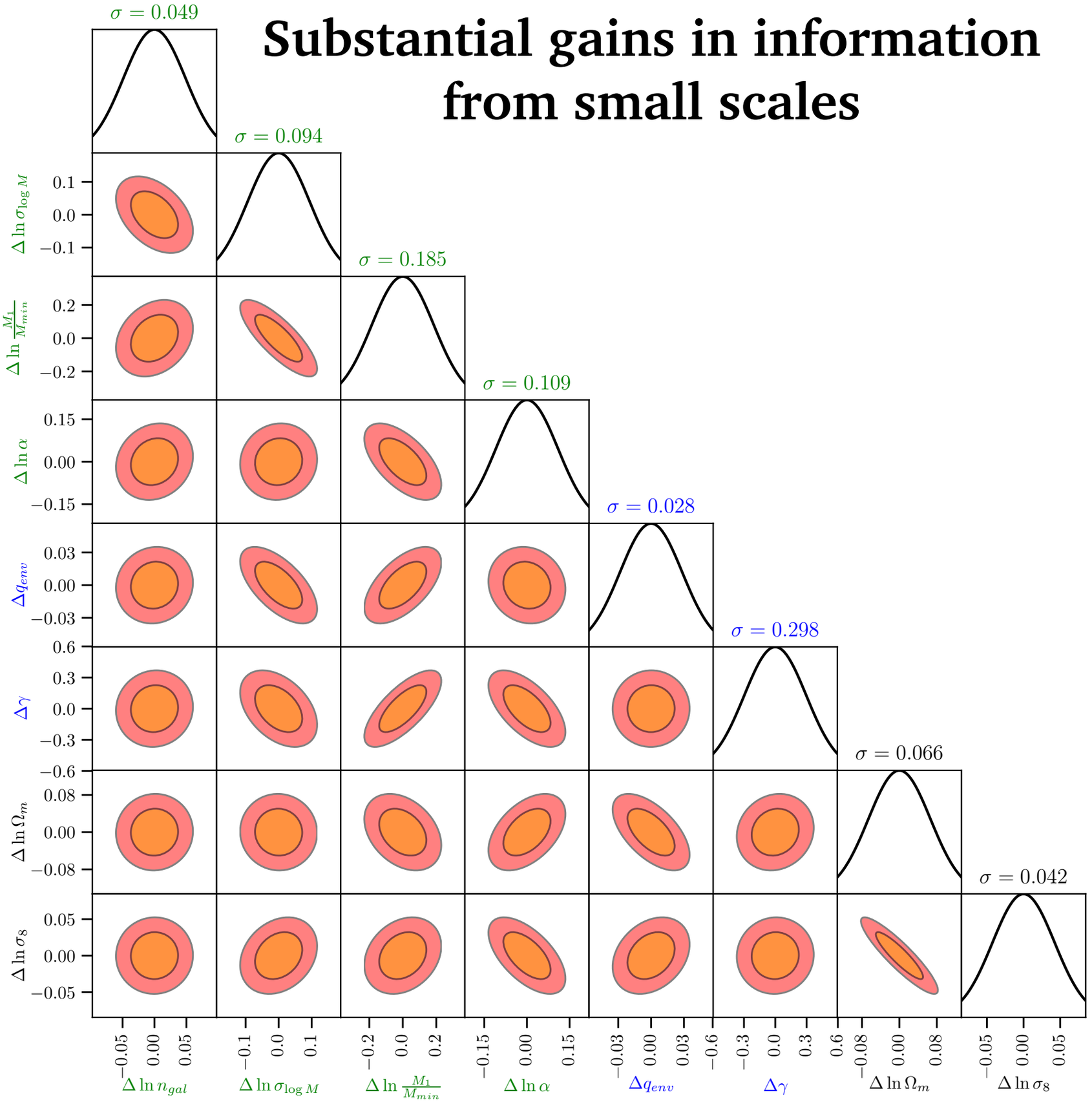


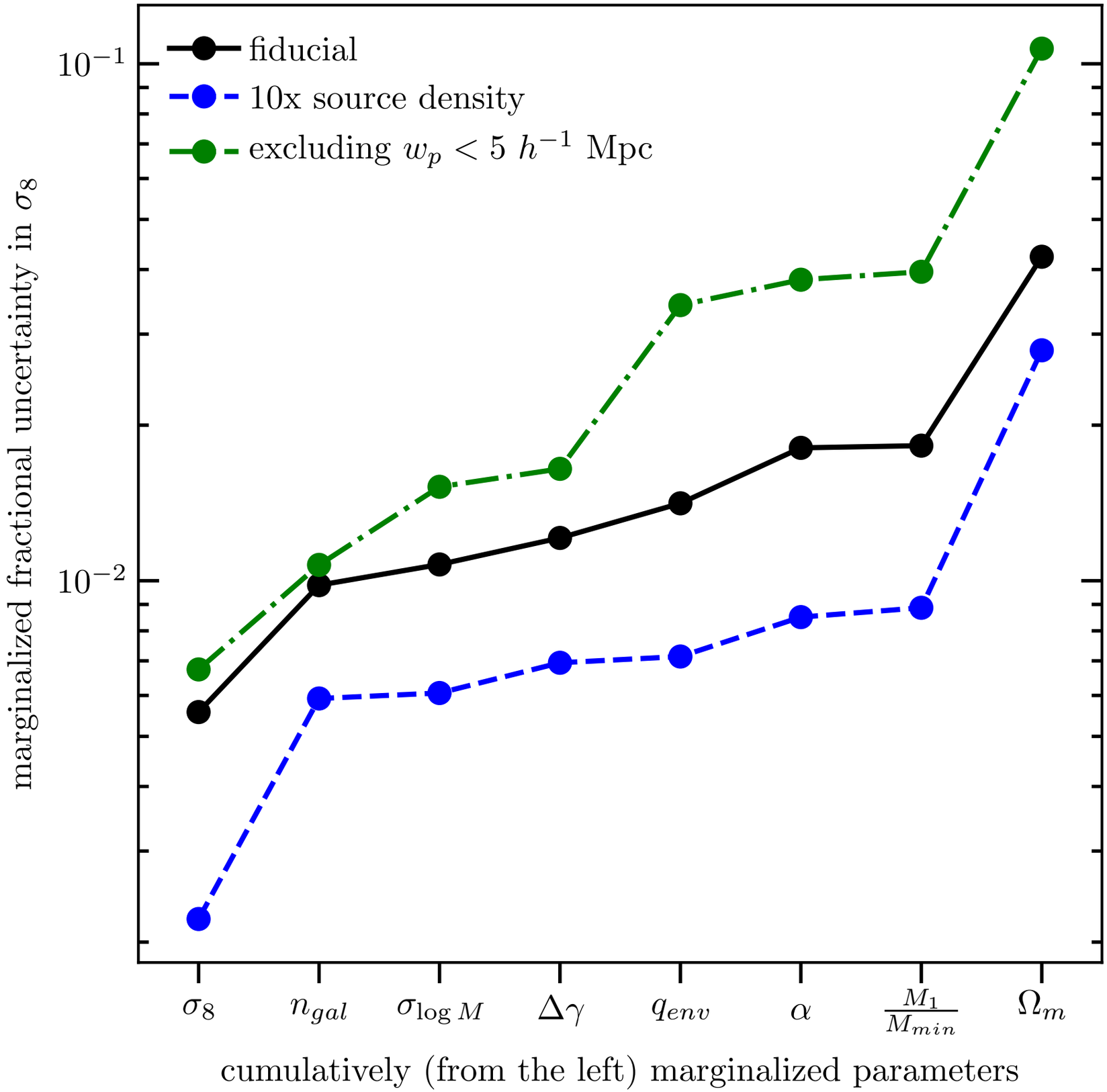

($n_{gal}$ = 3 x $10^{-4}$ $h^3$ Mpc$^{-3}$, ~1 galaxy arcmin$^{-2}$)

# 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?