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

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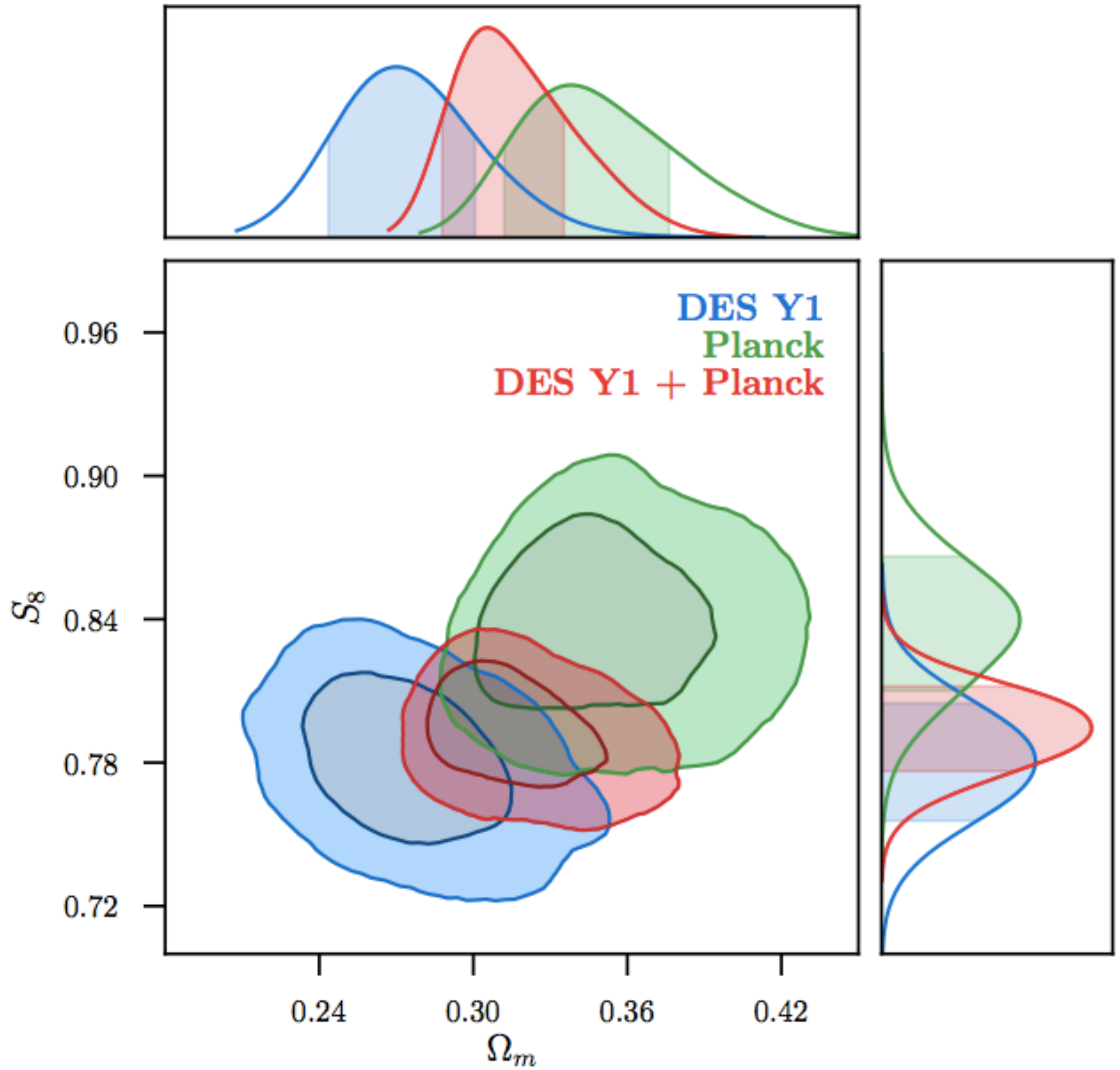
with Andres Salcedo, David Weinberg, Lehman Garrison, Douglas Ferrer, Jeremy Tinker, Daniel Eisenstein, Marc Metchnik, and Philip Pinto

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?

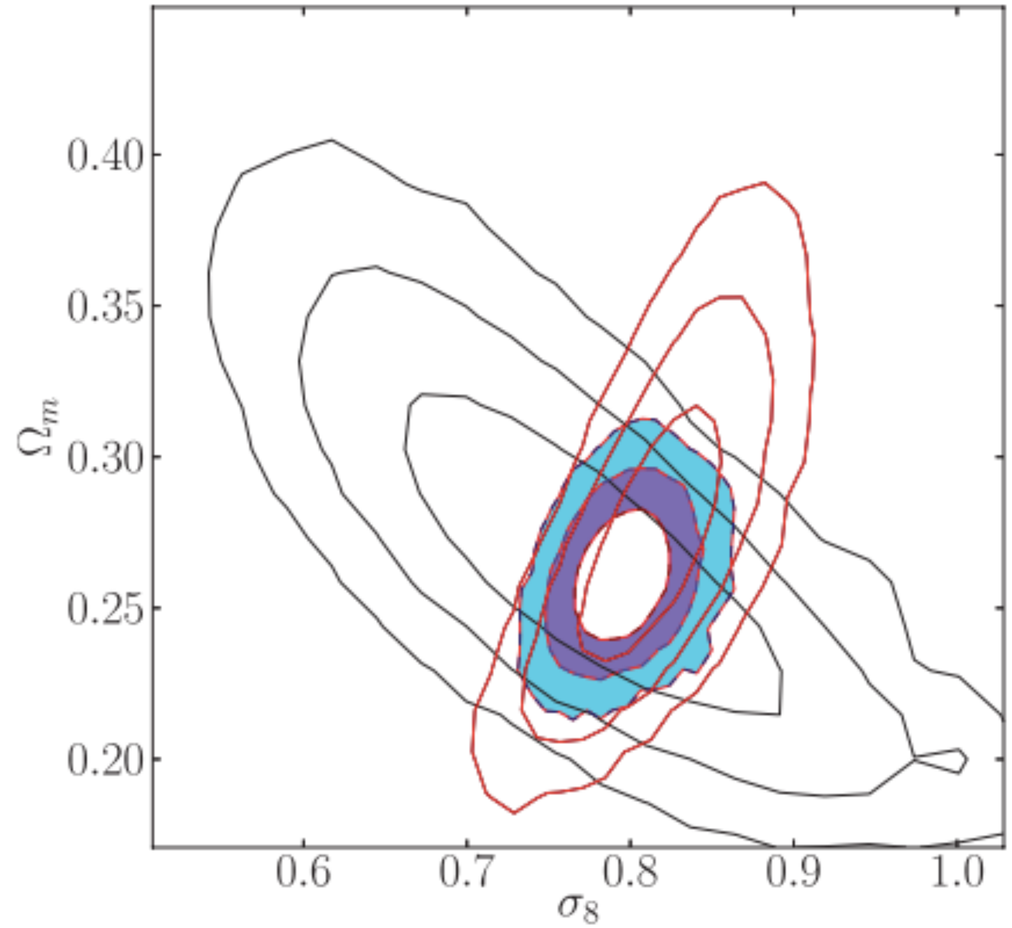


Figure: Mandelbaum+ 2013

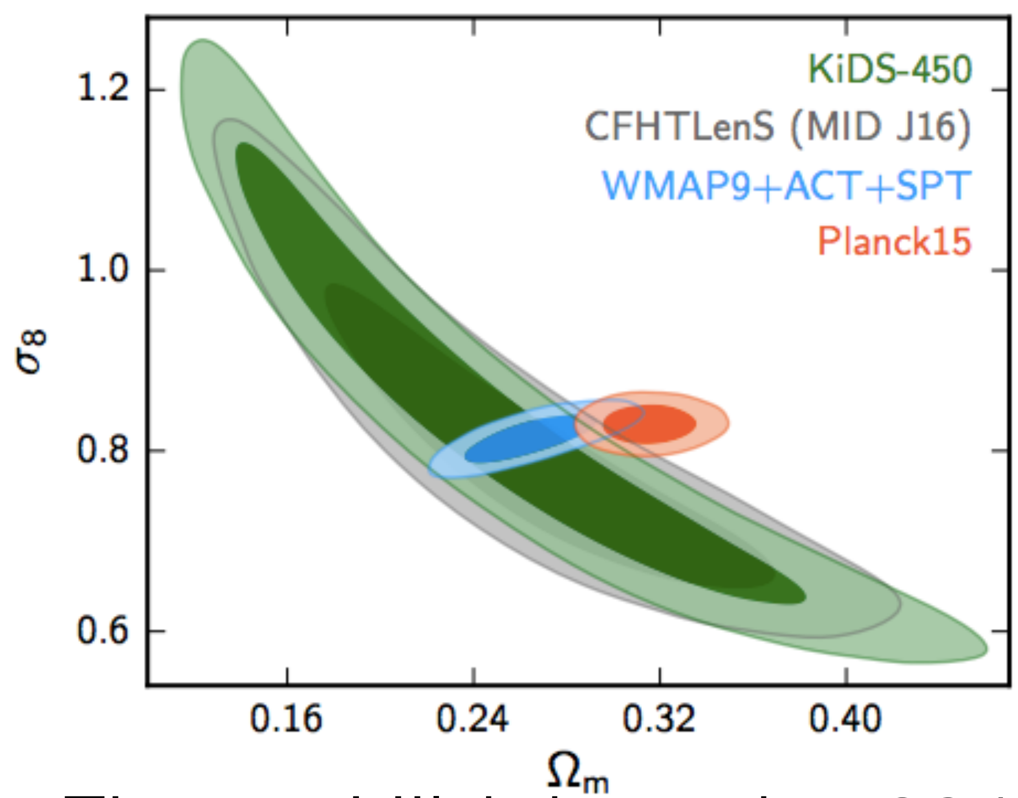


Figure: Hildebrandt+ 2016

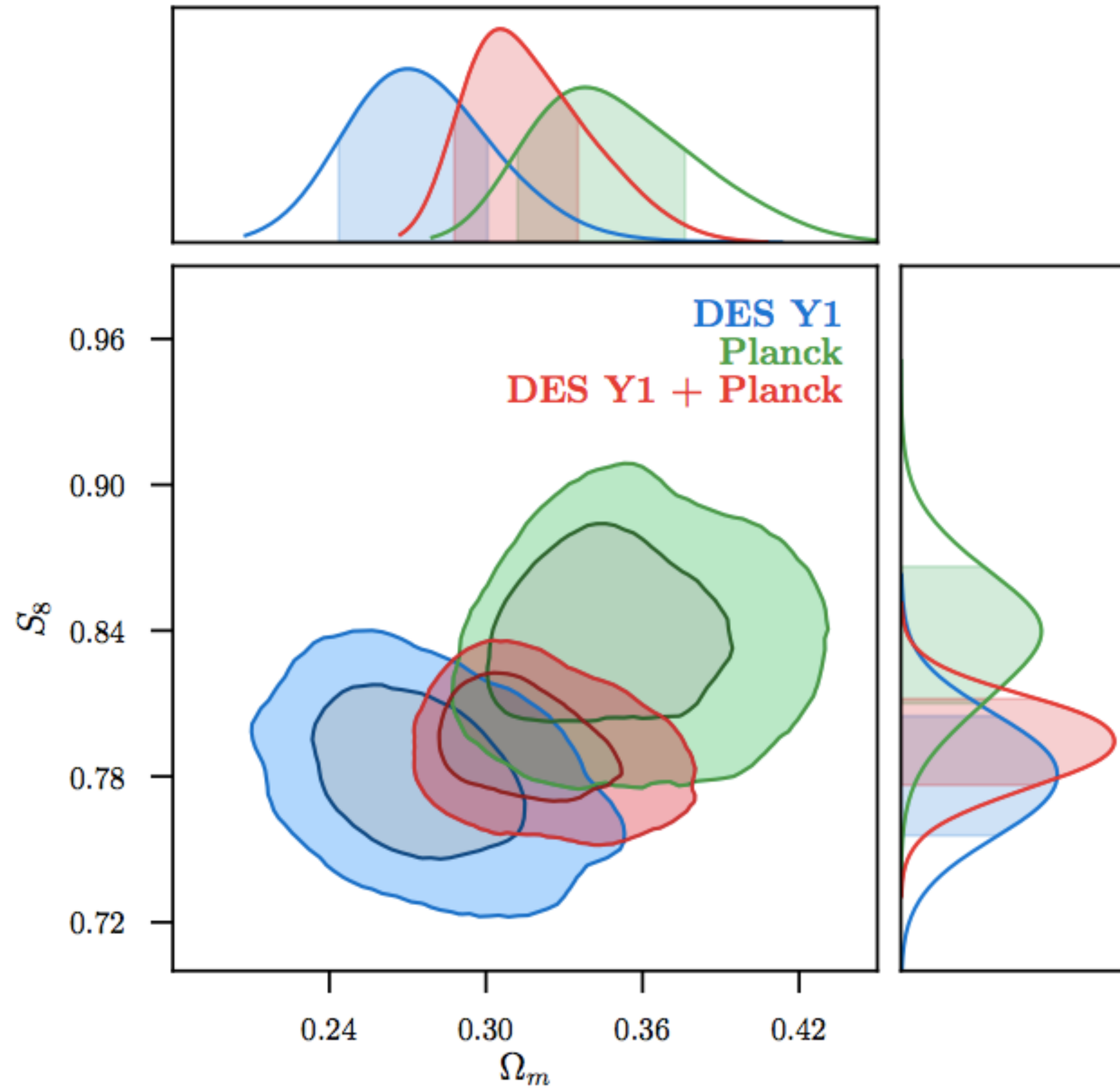
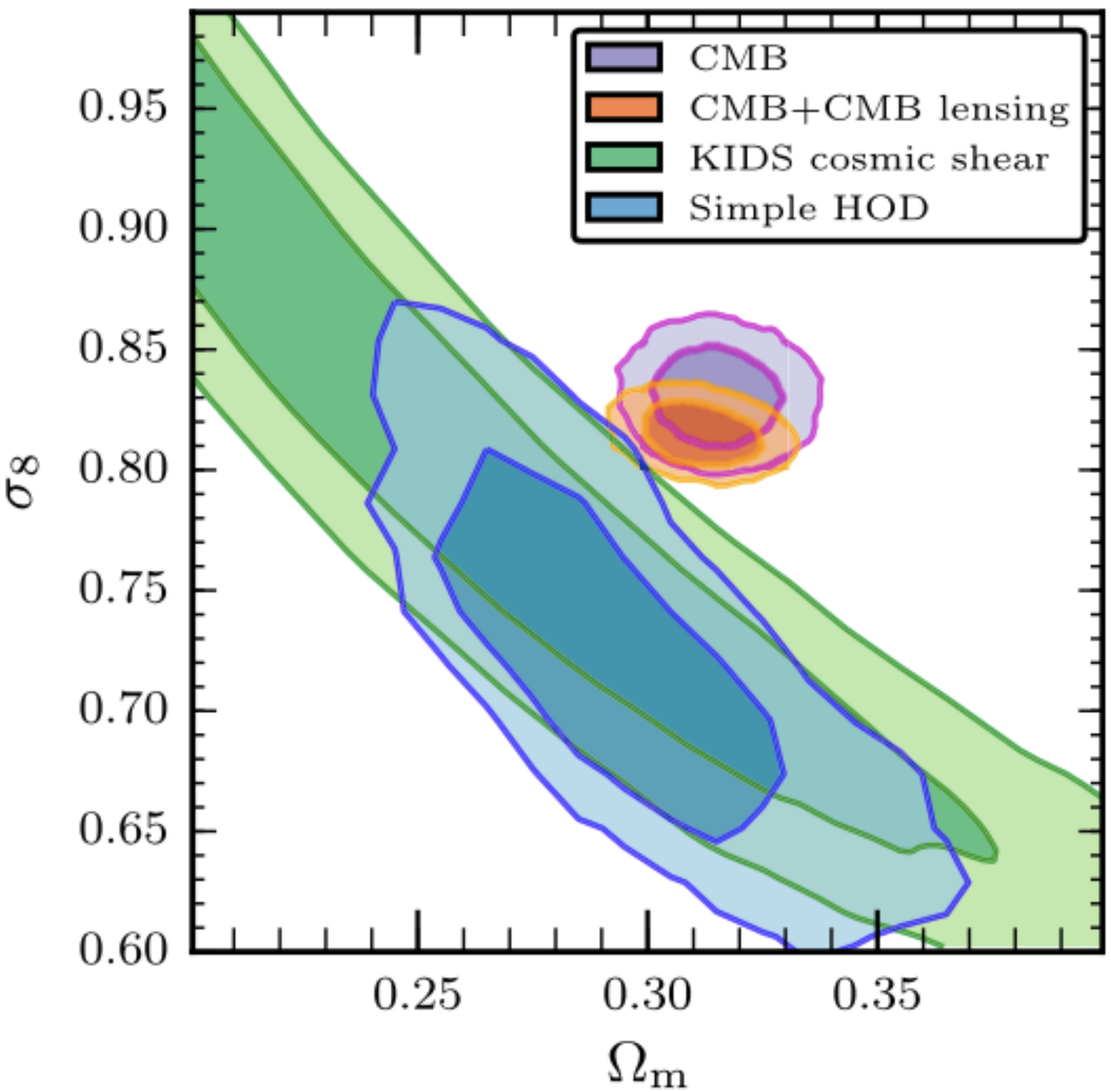
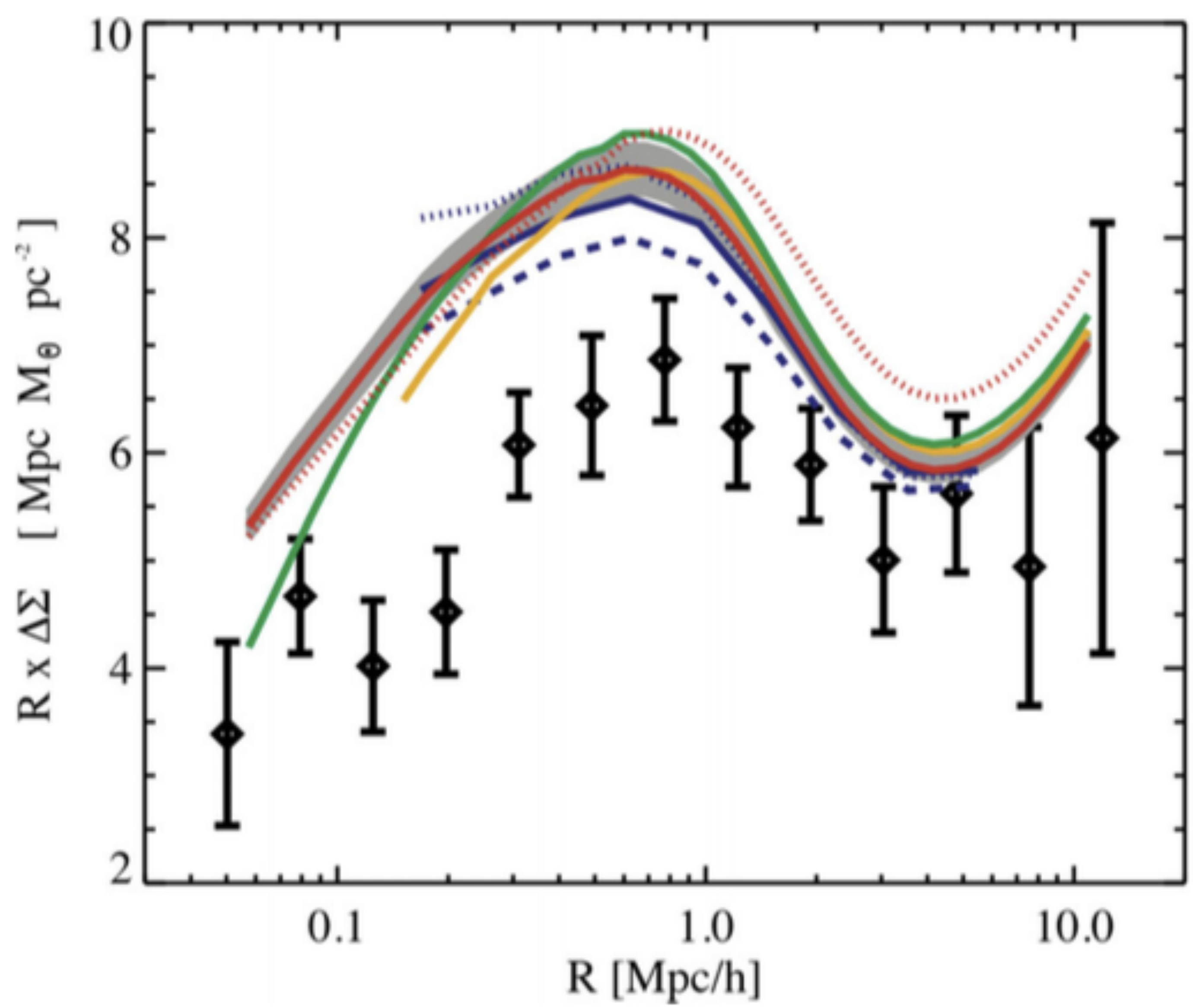


Figure: DES Collaboration 2017

Small scale systematics?



CMASS lens galaxies



Figures: Leauthaud+ 2017

Galaxy-galaxy lensing

Source plane

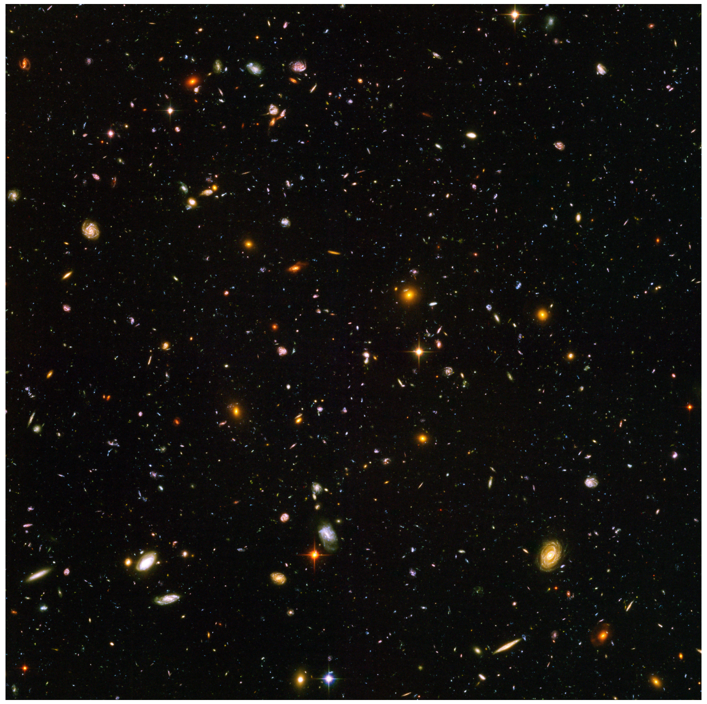


Image: Hubble Ultra Deep Field

Lens plane

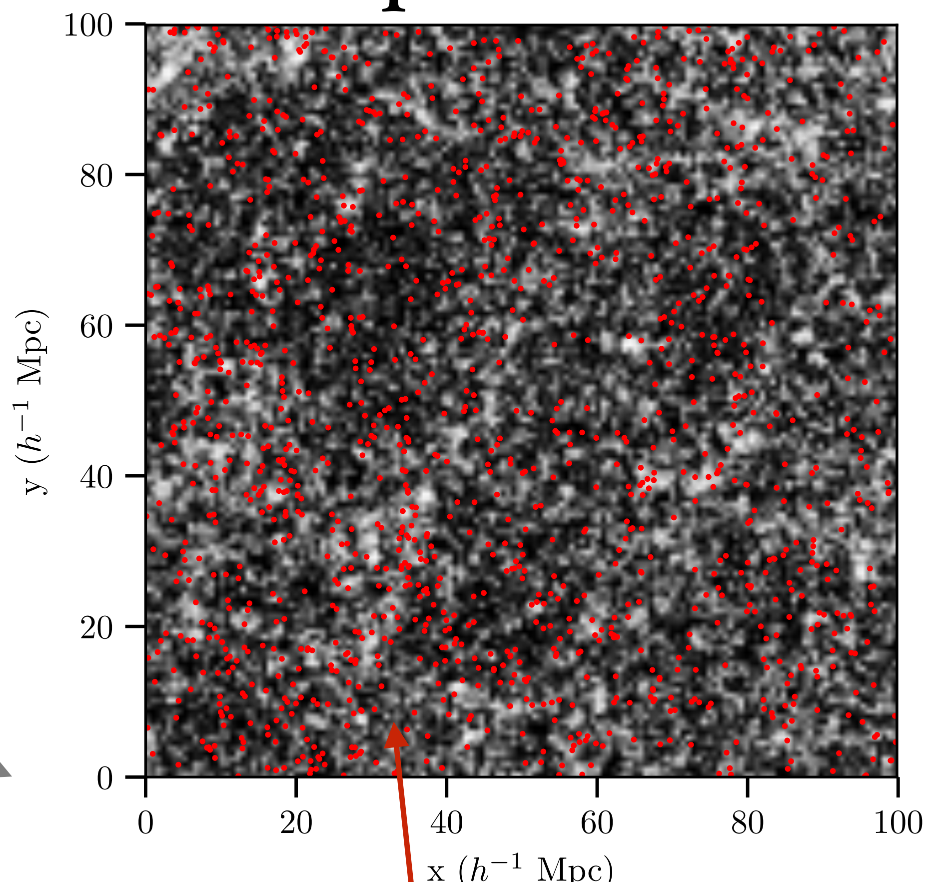
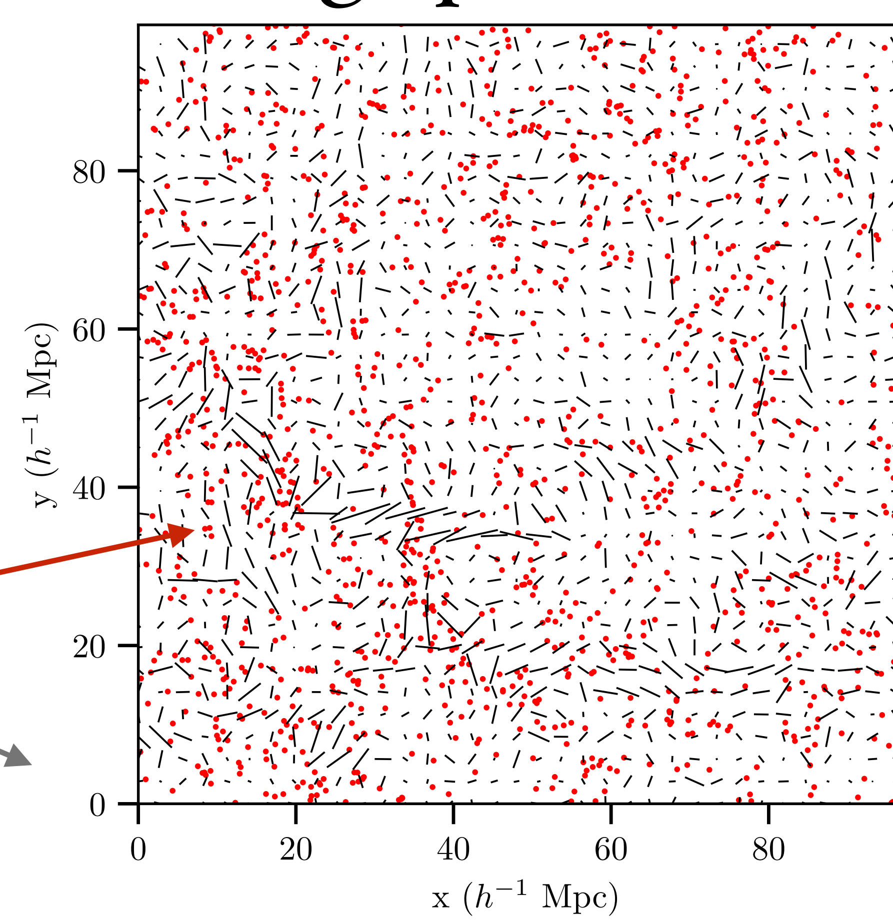


Image plane



lens galaxies

Model

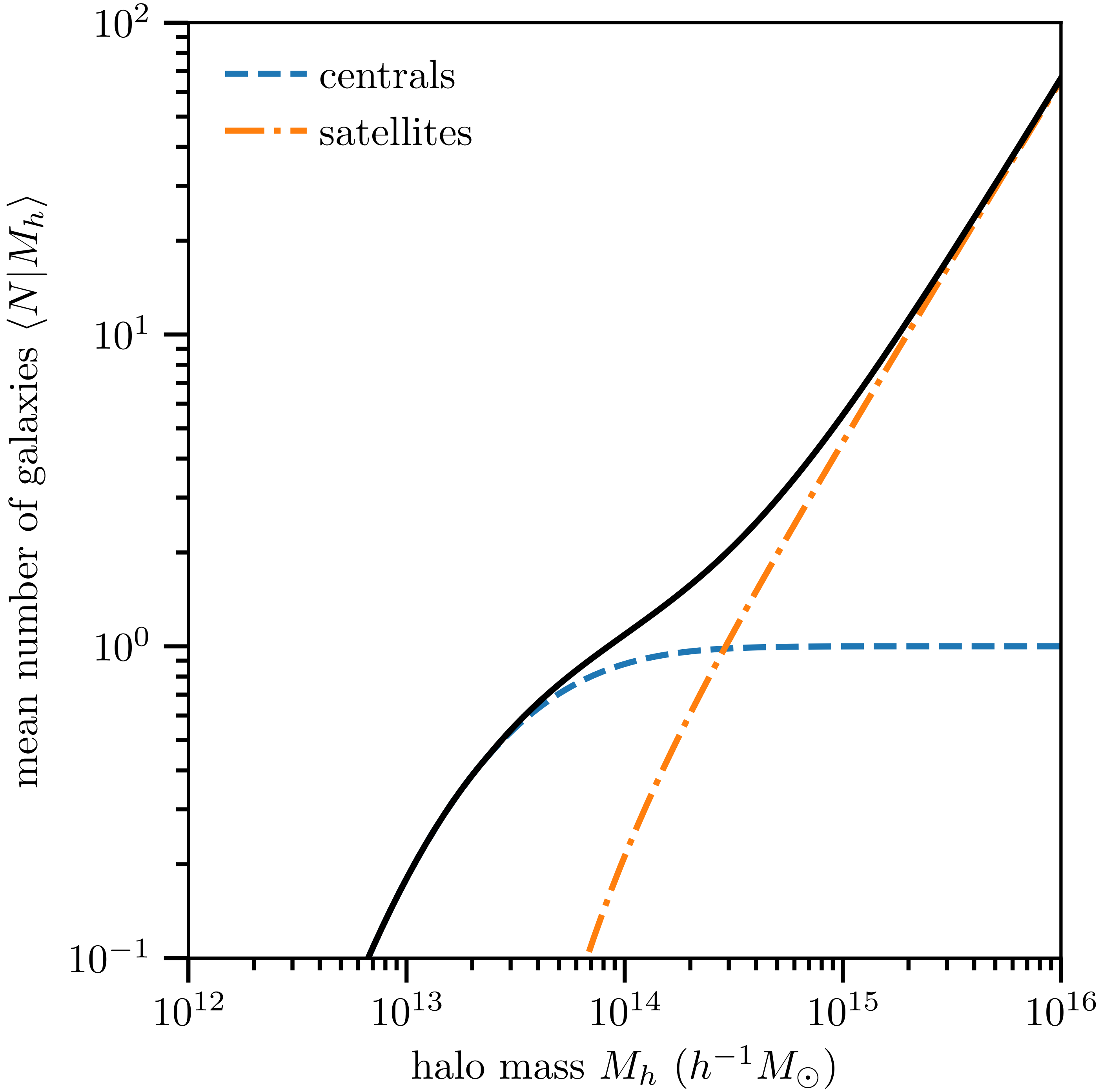
1. Galaxies live in dark matter halos
   (spherical overdensity of ~200)
2. One (or zero) galaxies live at the center of each halo
   (number determined by some function of halo mass)
3. Satellite galaxies live between the center and the halo radius, determined in the average by a spherically-symmetric 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

e.g. Berlind & Weinberg (2002)

Halo occupation distribution (HOD)

fiducial parameter values



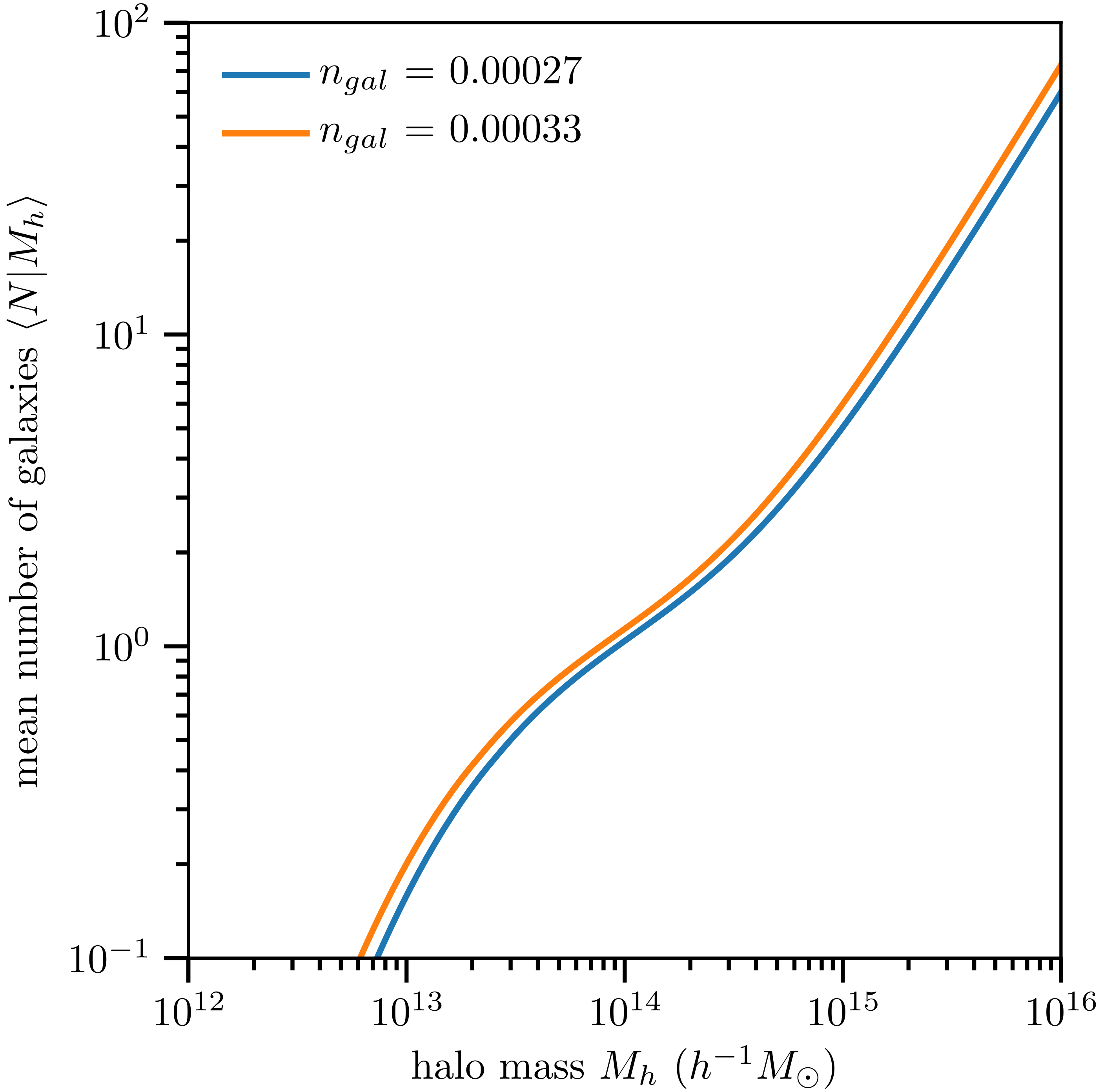
HOD specifies the conditional distribution: $<N|M_h>$

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)

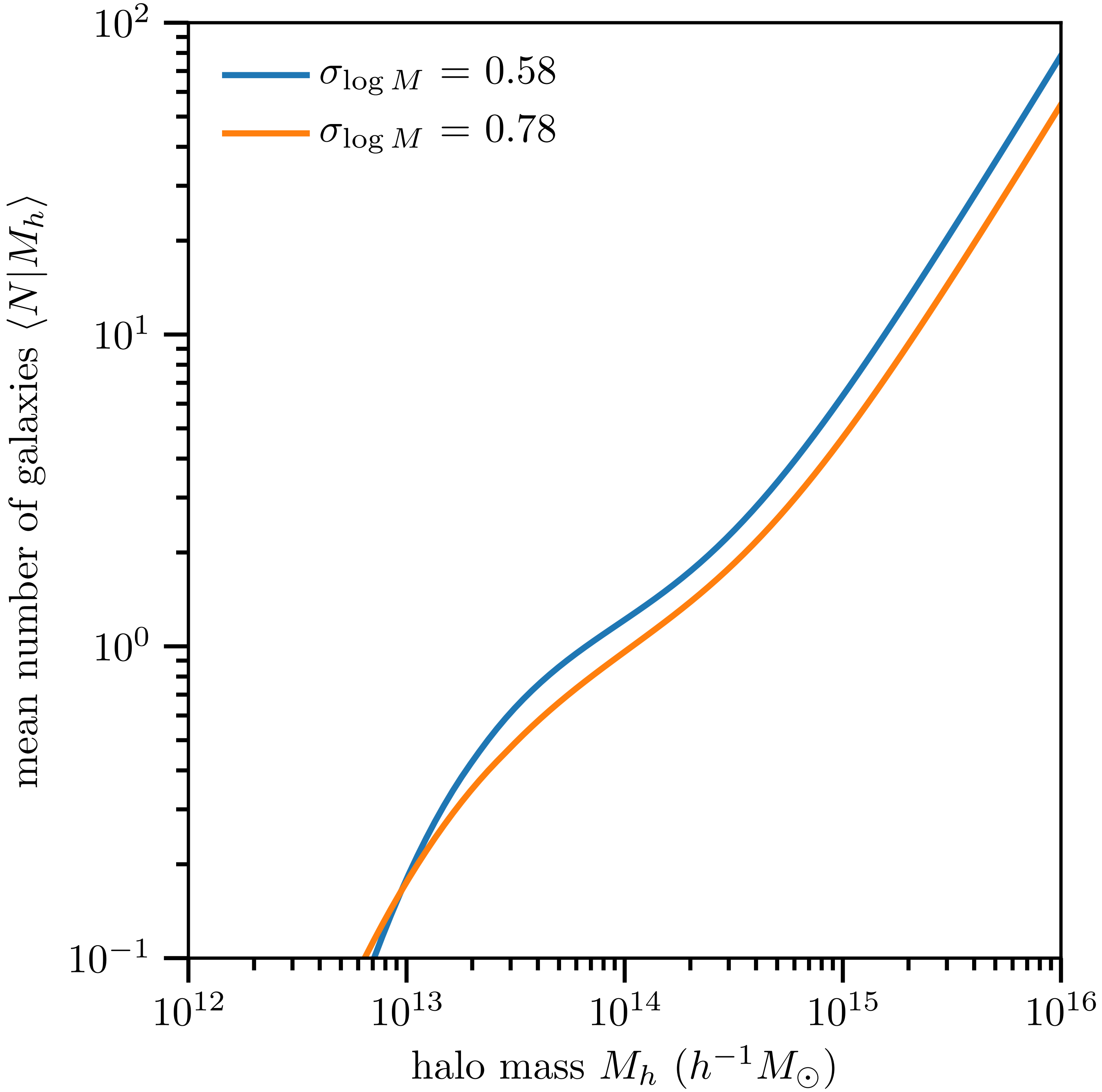
n_{gal}



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

Halo occupation distribution (HOD)

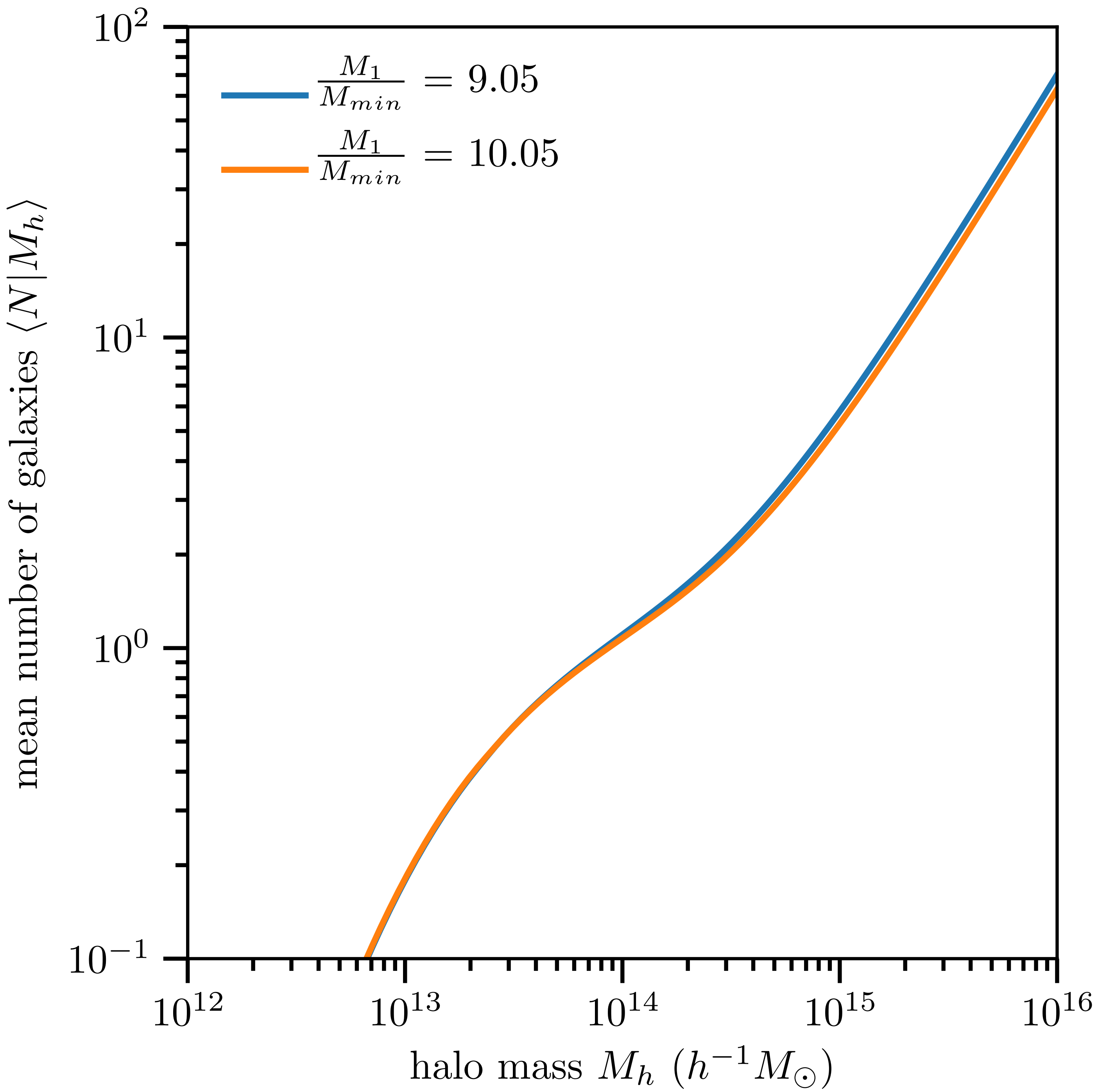
$\sigma_{\log M}$



Varying the scatter in halo mass to stellar mass

Halo occupation distribution (HOD)

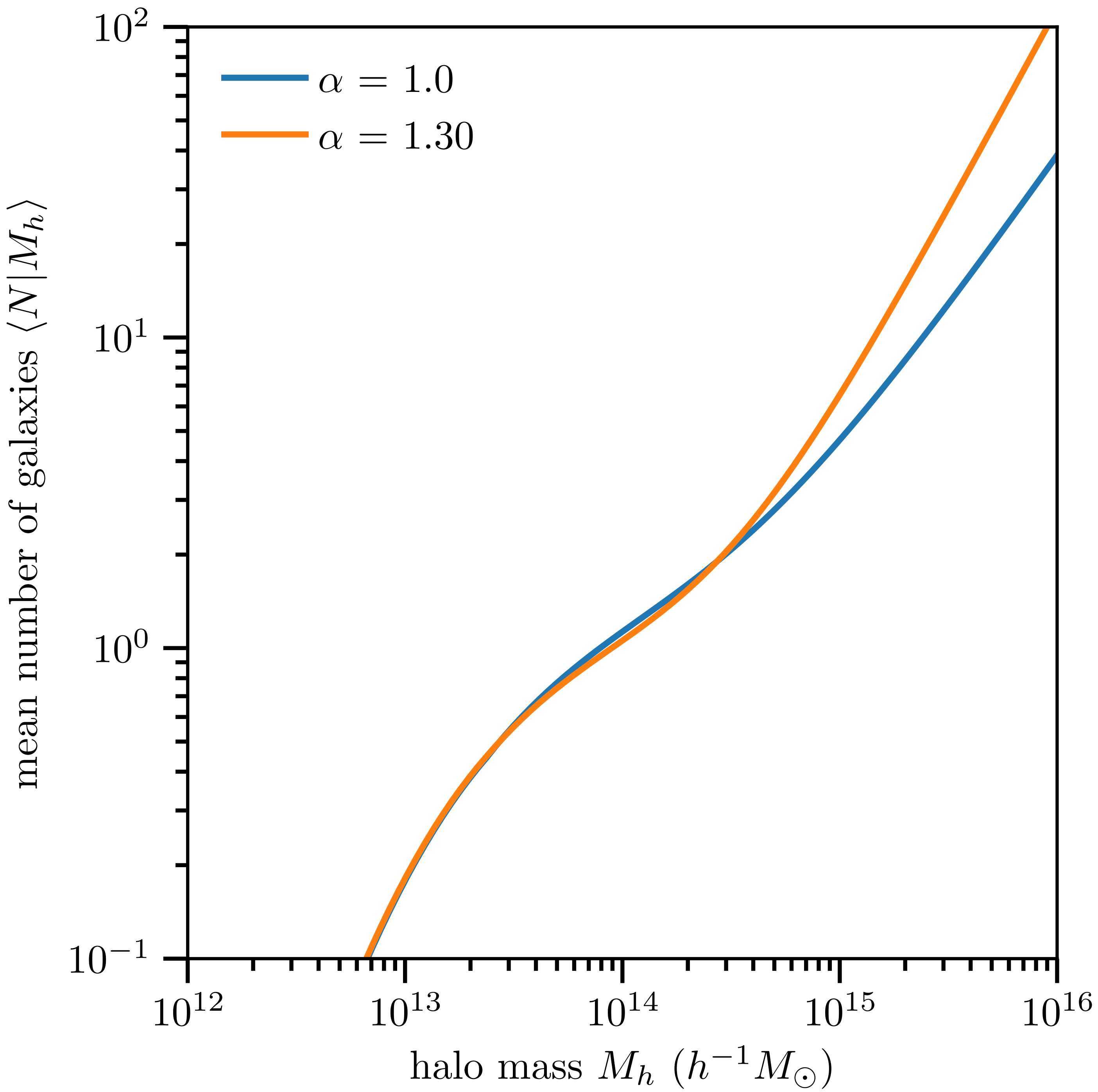
$M_1/M_{\min}$



Varying the halo mass at which there are satellite galaxies

Halo occupation distribution (HOD)

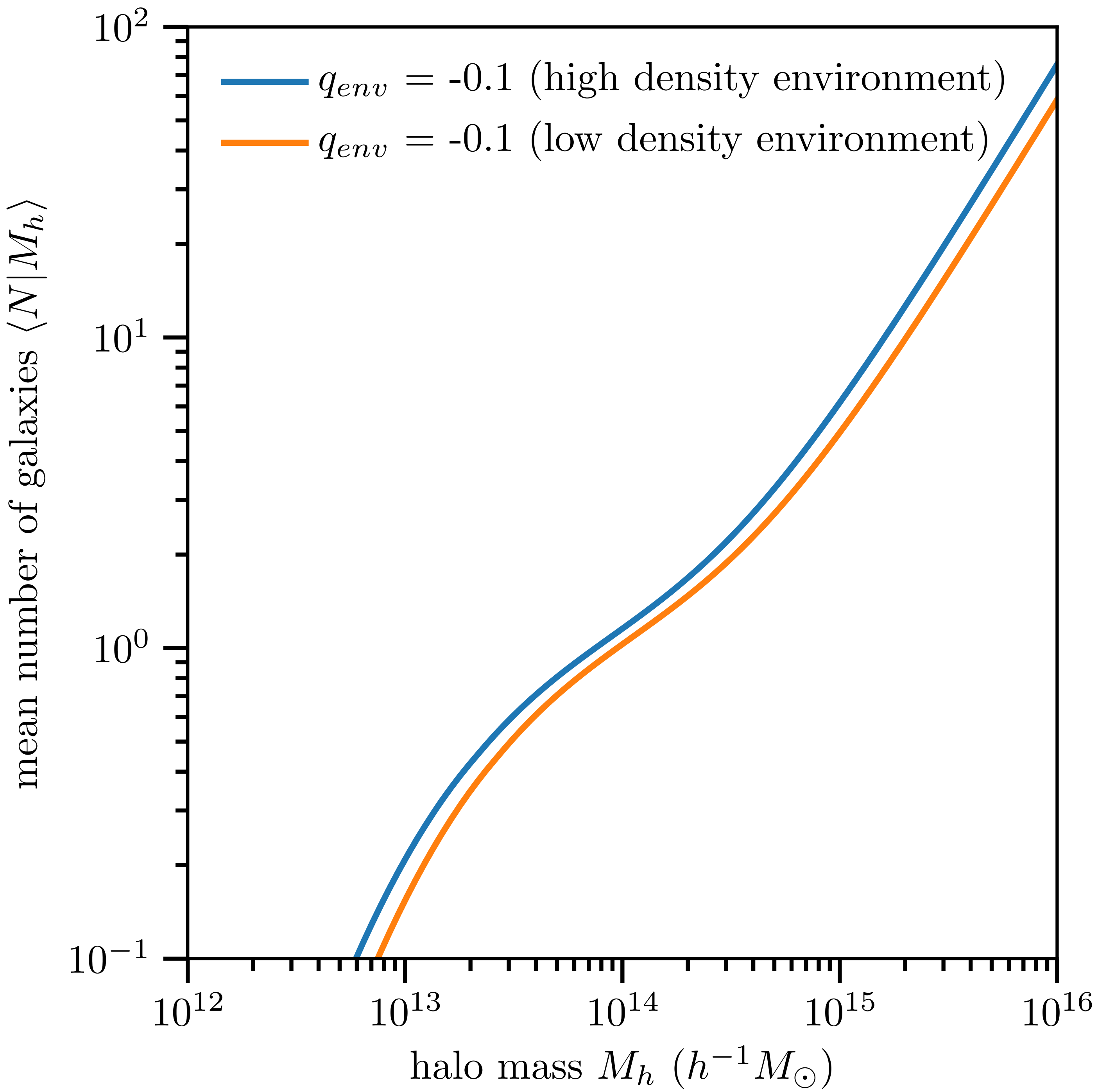
α



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

Emulator methodology

1. 40 N-body simulations within the Planck 2015 *w*CDM 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,

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

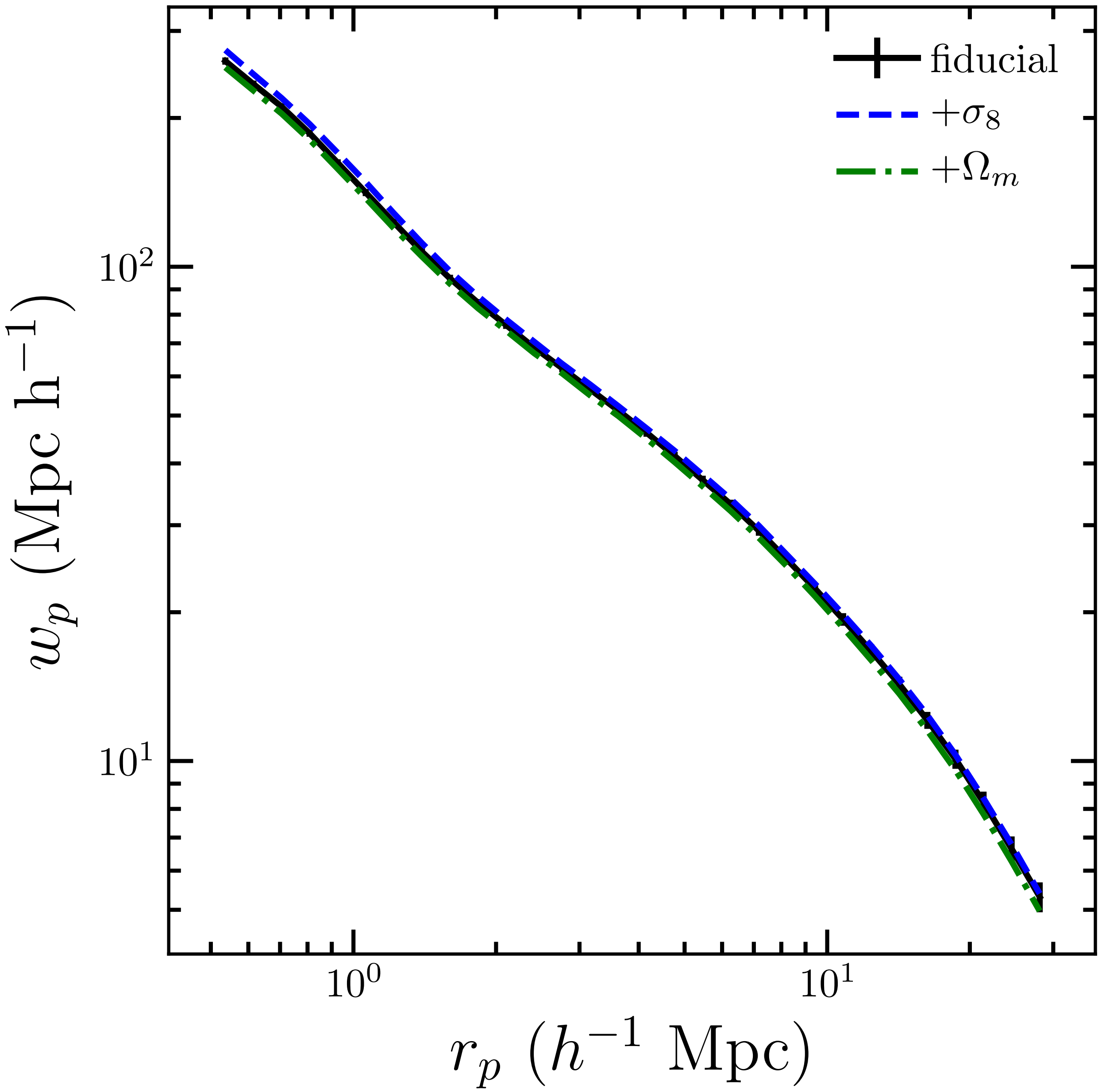
- scale-dependent correlation coefficient r_{gm},

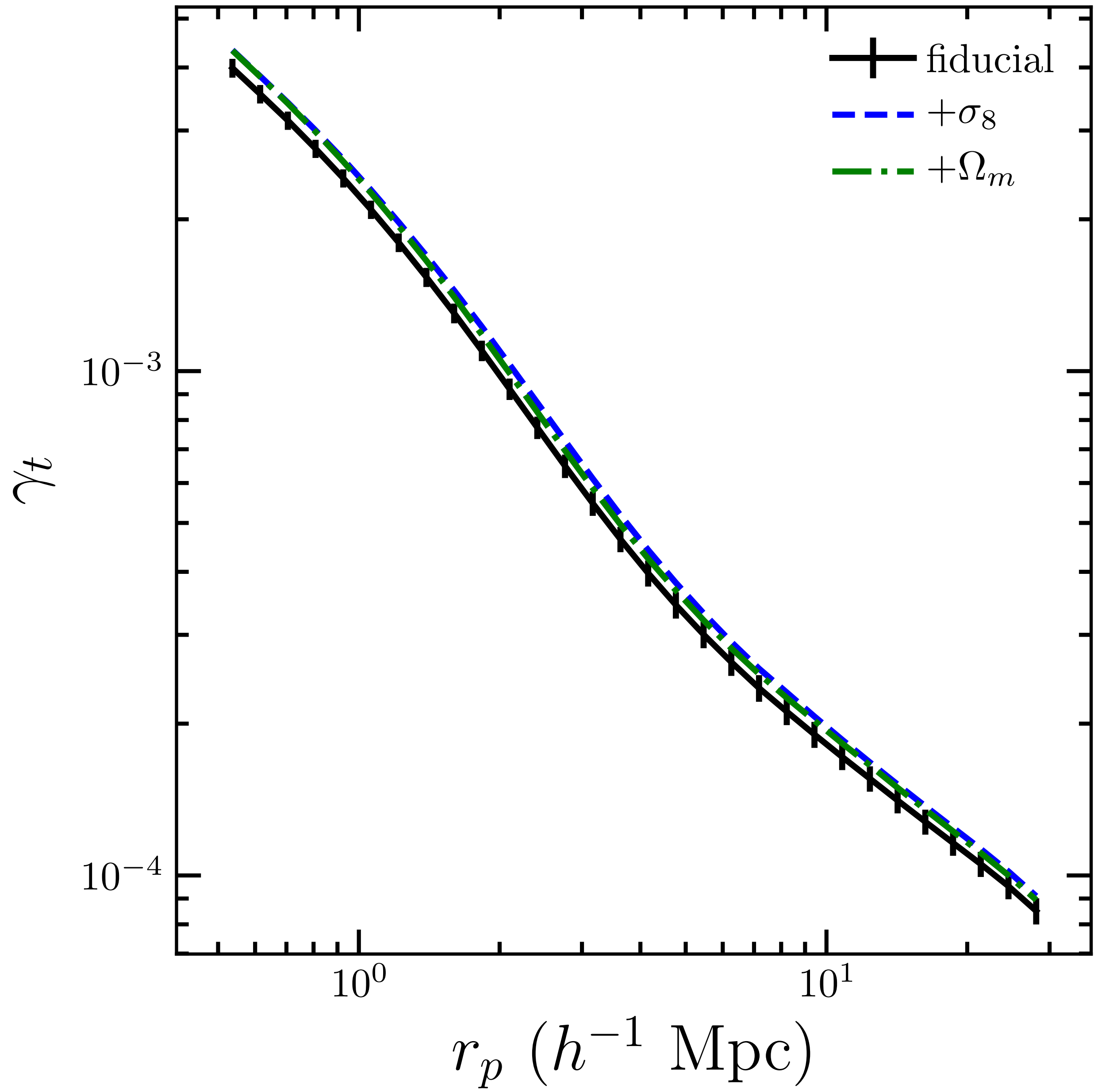
$$r_{\rm gm} = \left[\frac{\xi_{\rm gm}^2}{\xi_{\rm gg}\xi_{\rm mm}}\right]^{1/2}$$

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

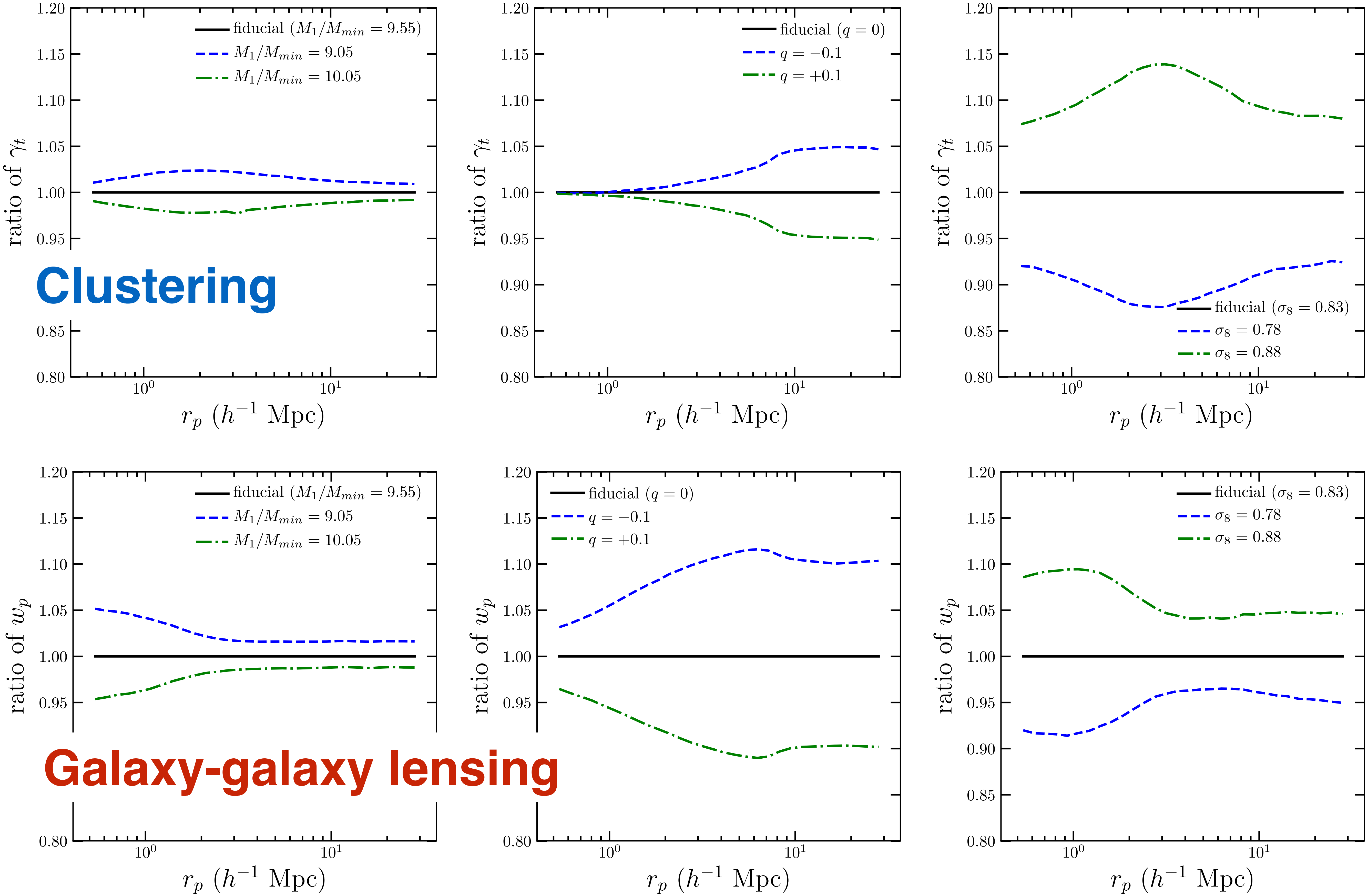
$$b_{\rm nl} = \left[\frac{\xi_{\rm mm}}{\xi_{\rm mm,lin}}\right]^{1/2}$$

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

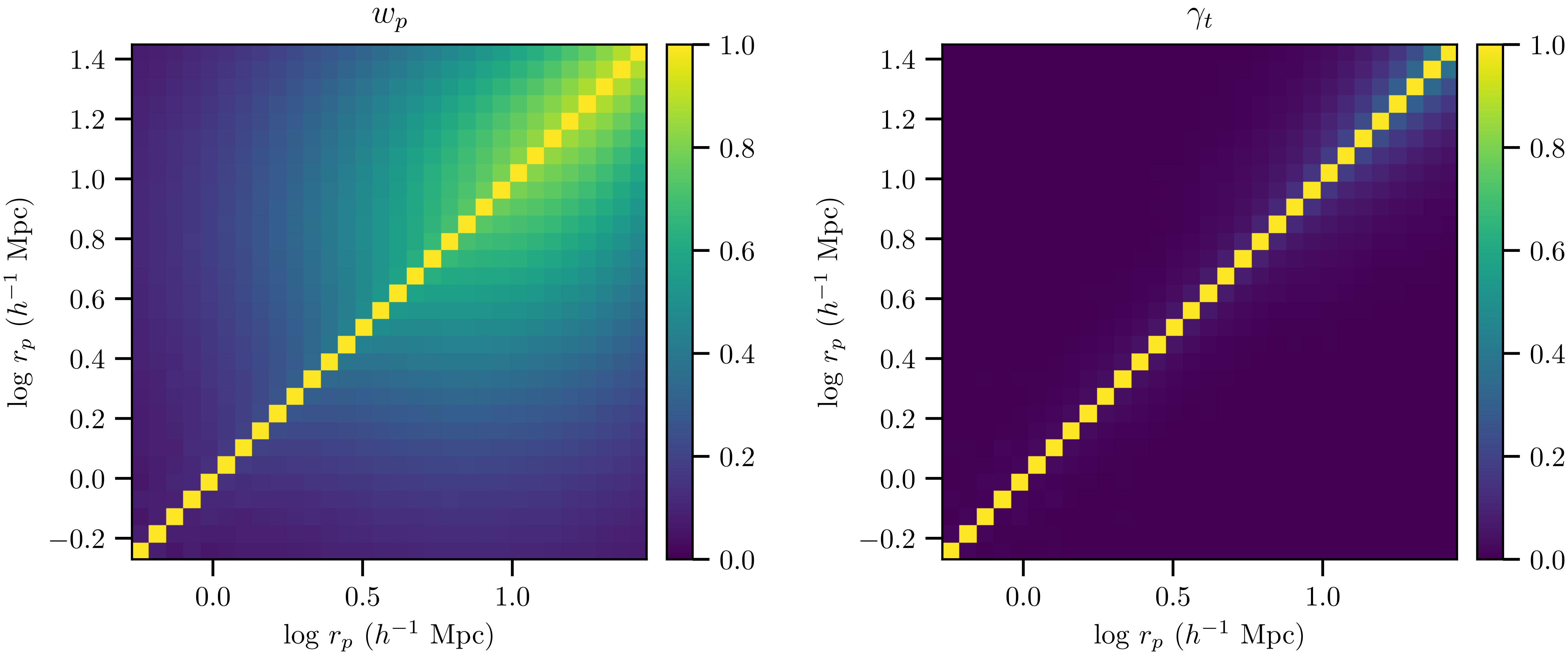




HOD (satellite M_{halo}) ‘Assembly bias’ Cosmology



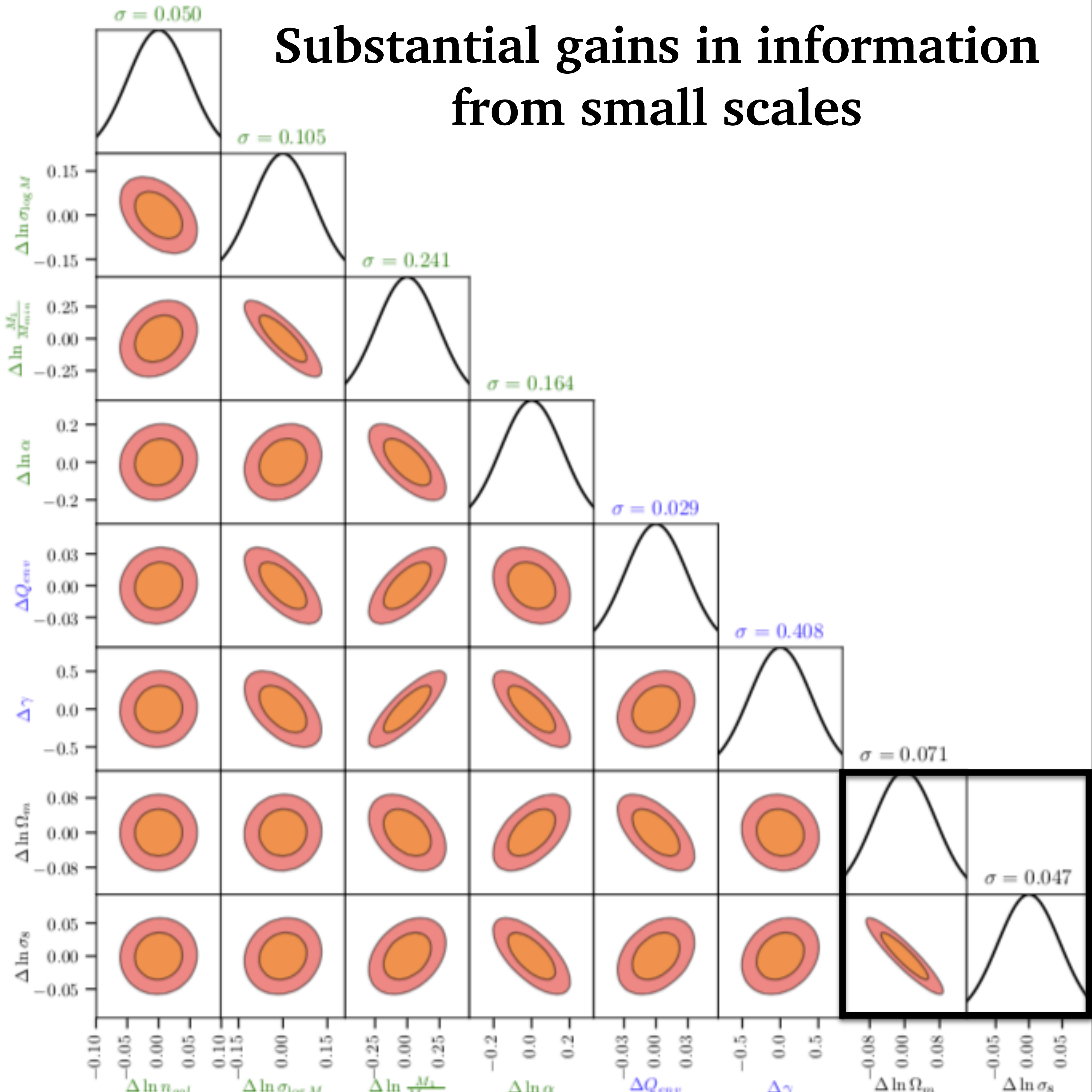
Covariance matrices and forecasting for LOWZ clustering and GGL



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

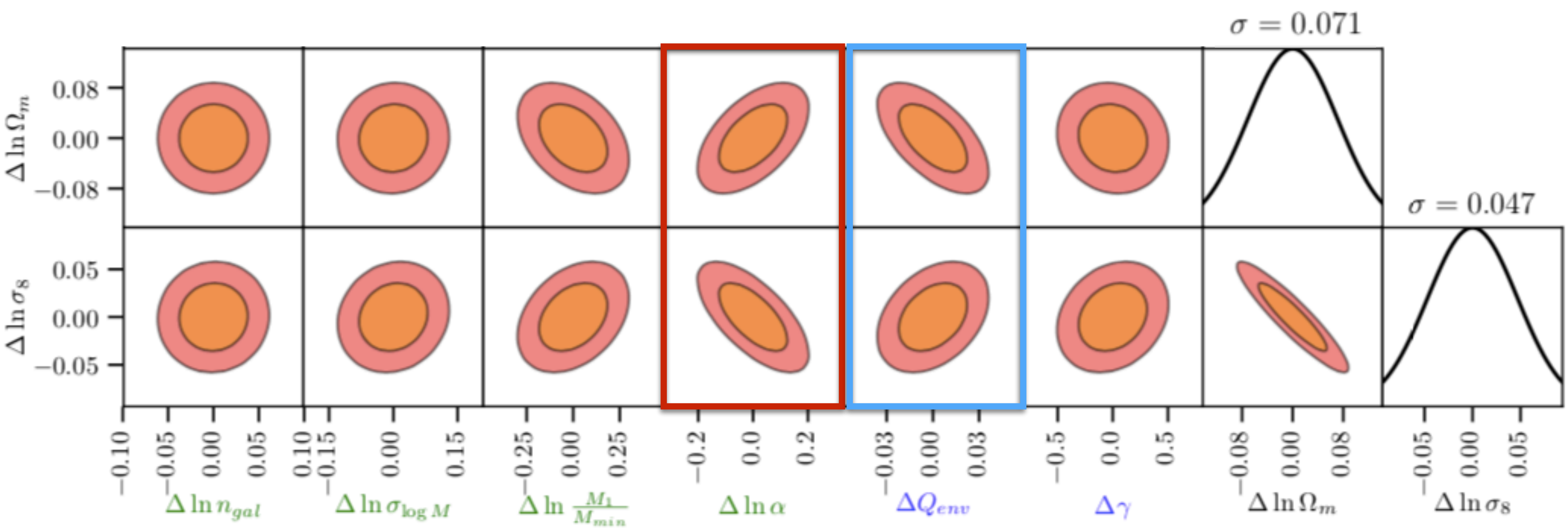
Substantial gains in information from small scales

- 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

Degeneracy with cosmological parameters

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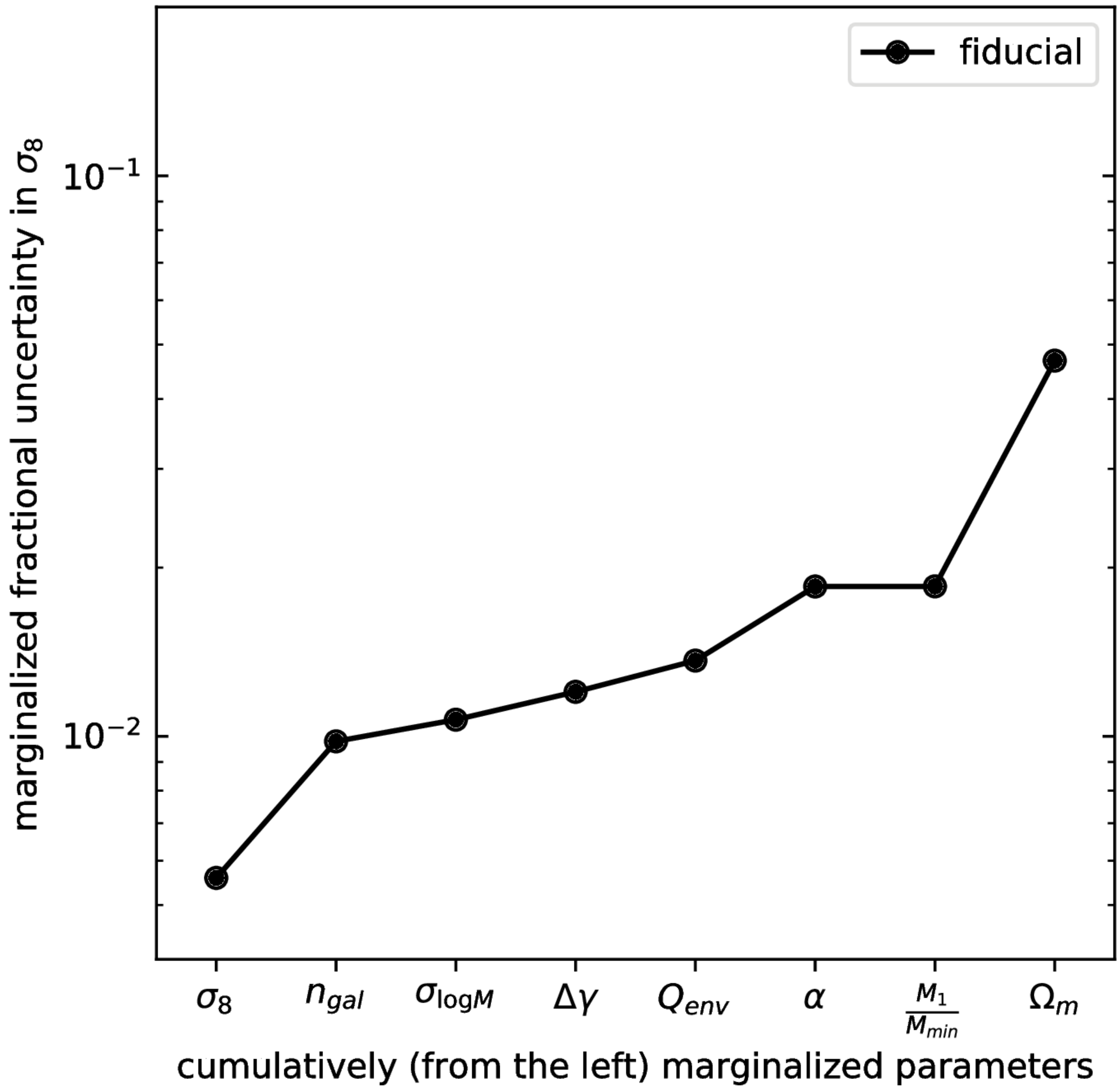
centrals only	0.589	$\boxed{0.014}$

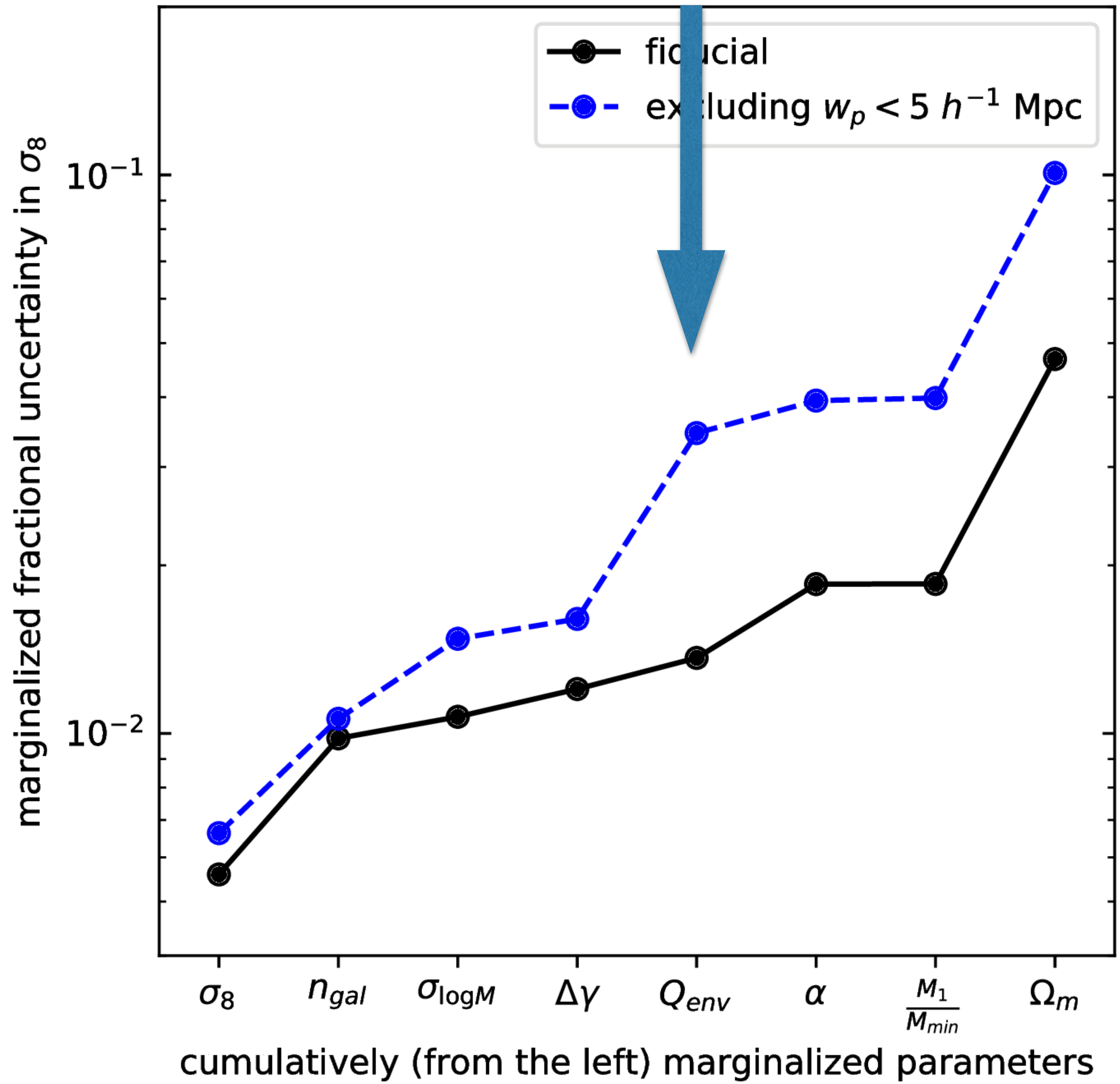
- Using yet smaller scales, we could constrain cosmology as well as a sample that (artificially) contained only central galaxies

What is the cost of marginalizing over galaxy formation uncertainties?

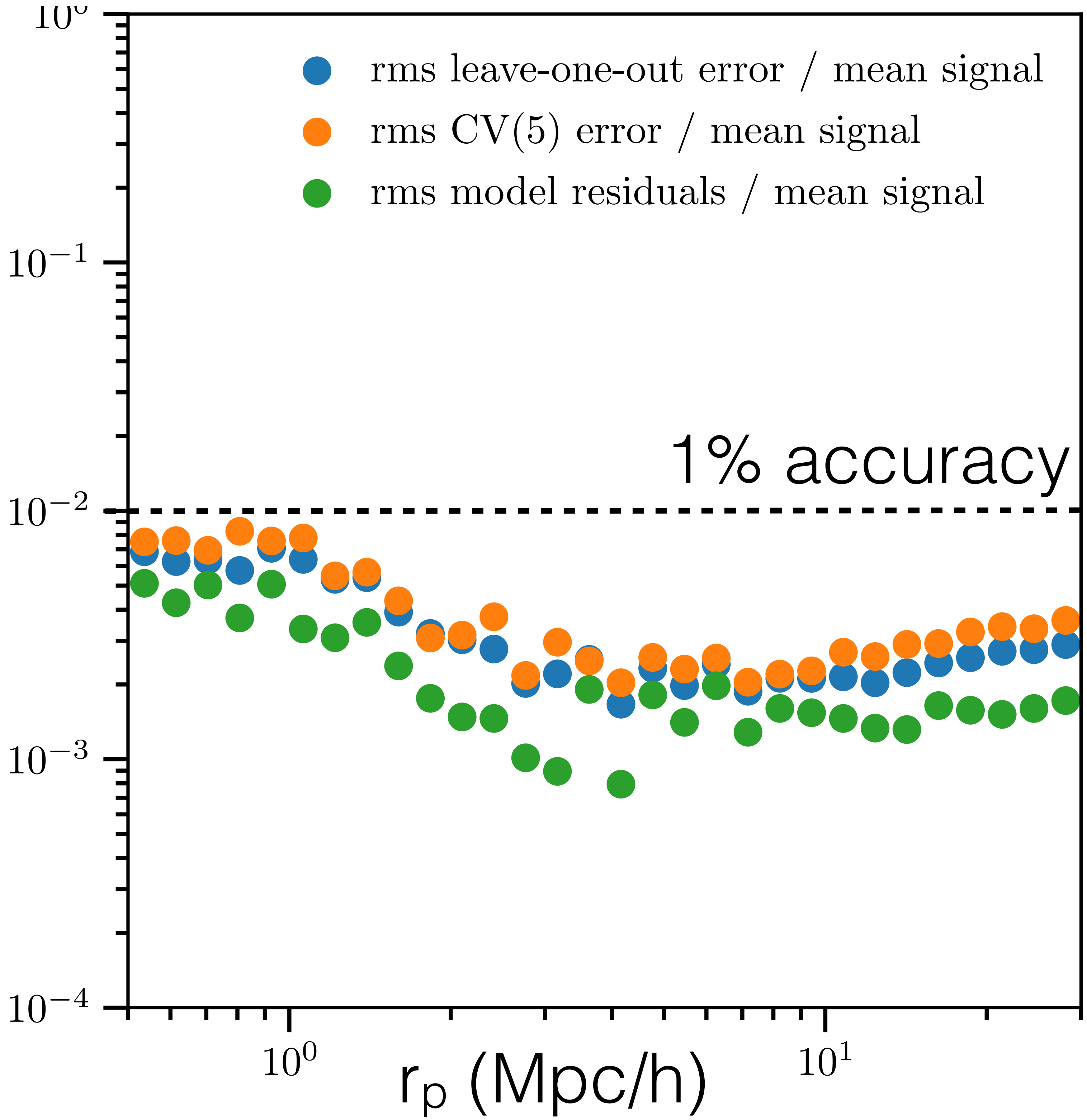


Effect of assembly bias without any small-scale clustering information

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 against other simulations 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

Part II: Galactic Winds and Dynamical Effects of Radiation Pressure on Dust

Collaborators: Todd Thompson (OSU), Mark Krumholz (ANU)

Published: MNRAS 477, 4665–4684 (2018)
doi:10.1093/mnras/sty907

Motivation for winds

- Feedback/outflows are necessary to prevent excessive star formation in simulations and semi-analytical galaxy formation models (e.g. Somerville+ 2008)
- Chemical evolution models of the Milky Way suggest strong outflows are needed (Weinberg 2017)
- Also winds are more or less directly observed:

Motivation for winds

- Also winds are more or less directly observed:

APOD 2013 July 4
Credit: Ken Crawford (Rancho Del Sol Obs.)

Motivation for radiation pressure on dust

- Supernova suffer 'overcooling' problem in simulations (Katz 1992; Katz, Weinberg & Hernquist 1996) unless cooling is a artificially prevented or delayed (e.g. Stinson+ 2006)

- New forms of feedback might be needed

- Radiation pressure on dust seems viable for driving turbulence and/or winds (Thompson, Quataert, Murray 2005)

Multiple-scattering radiation pressure

- TQM (+ others) mostly focused on multiple-scattering of IR photons on dust, because this leads to a energy-limited wind (i.e. all photon energy can be converted into kinetic energy of the wind)

- But this only applies for very high column densities (~1000 M☉/pc^2)

- Most galaxies are not optically thick to IR; column densities are ≪ 1000 M☉/pc^2

"Single-scattering" radiation pressure

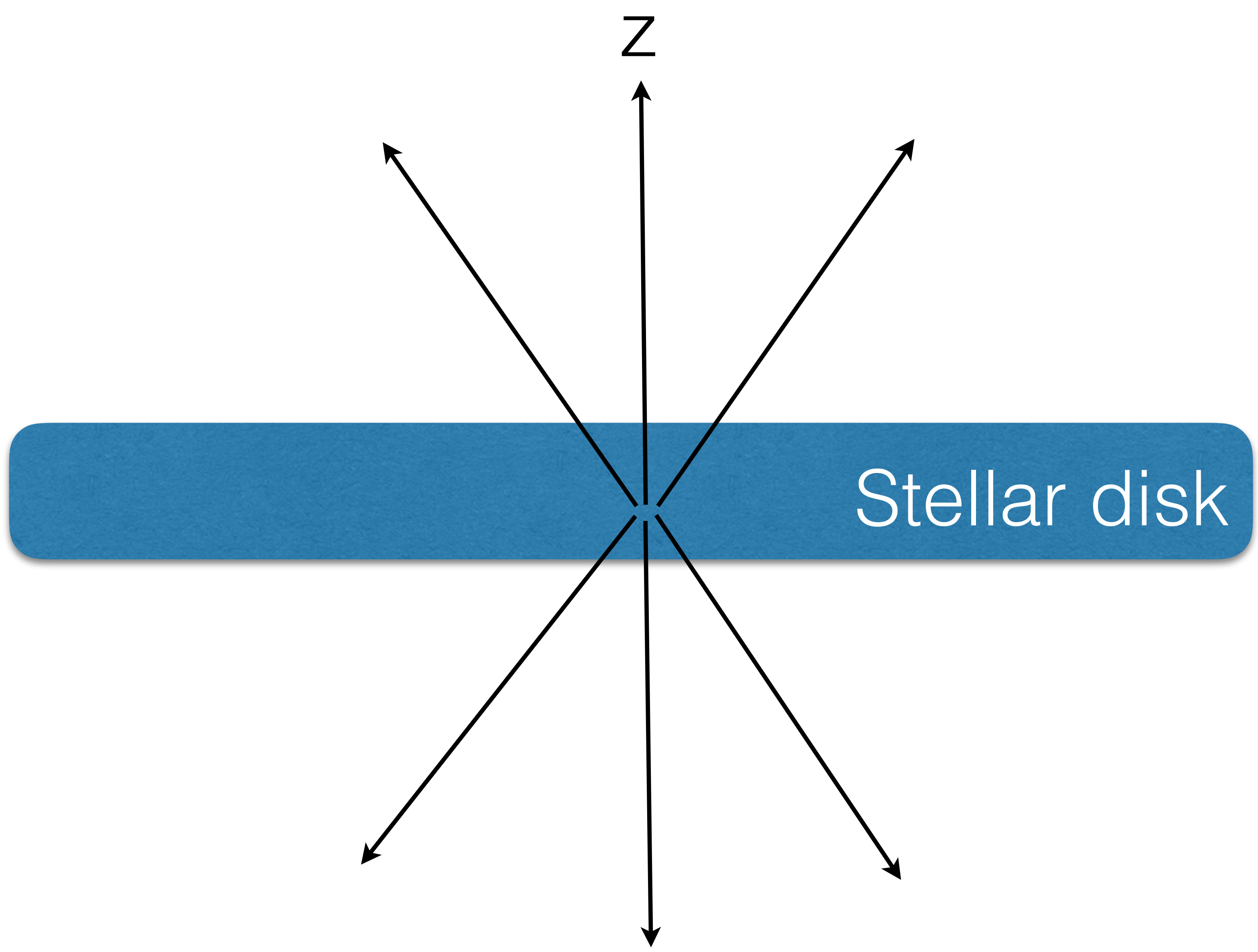
- Optically thick to direct UV/optical photons from young stellar populations, optically thin to IR photons

- The proposed dynamical effects come from each UV/optical photon being absorbed once by dust, momentum gained is thus **F/c** (as $\tau \rightarrow \infty$)

- The wind is therefore *momentum-limited*

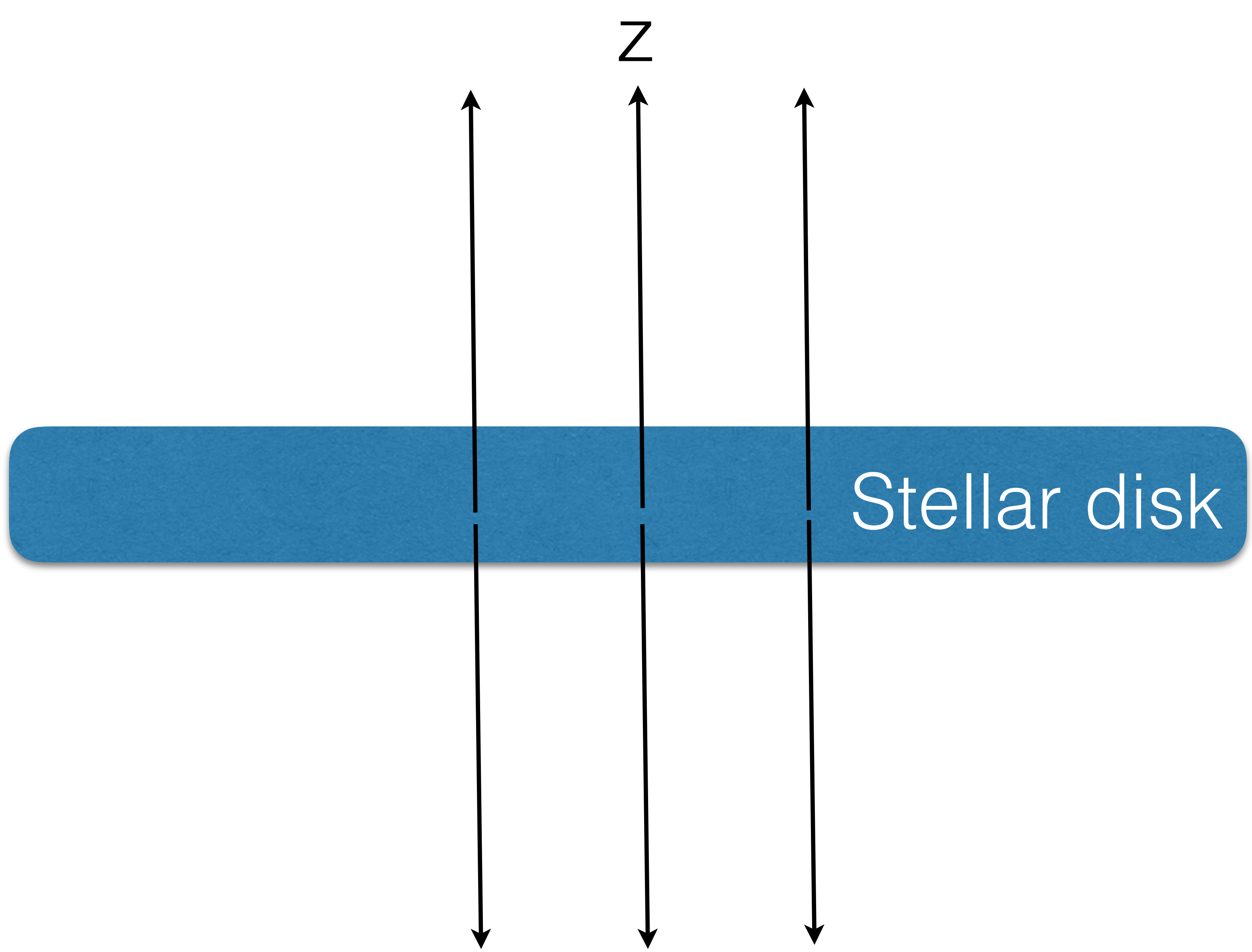
- *Question: Can single-scattering photon momentum either dynamically support galactic disks against collapse or drive galactic winds?*

Hydrostatic atmospheres supported by radiation pressure



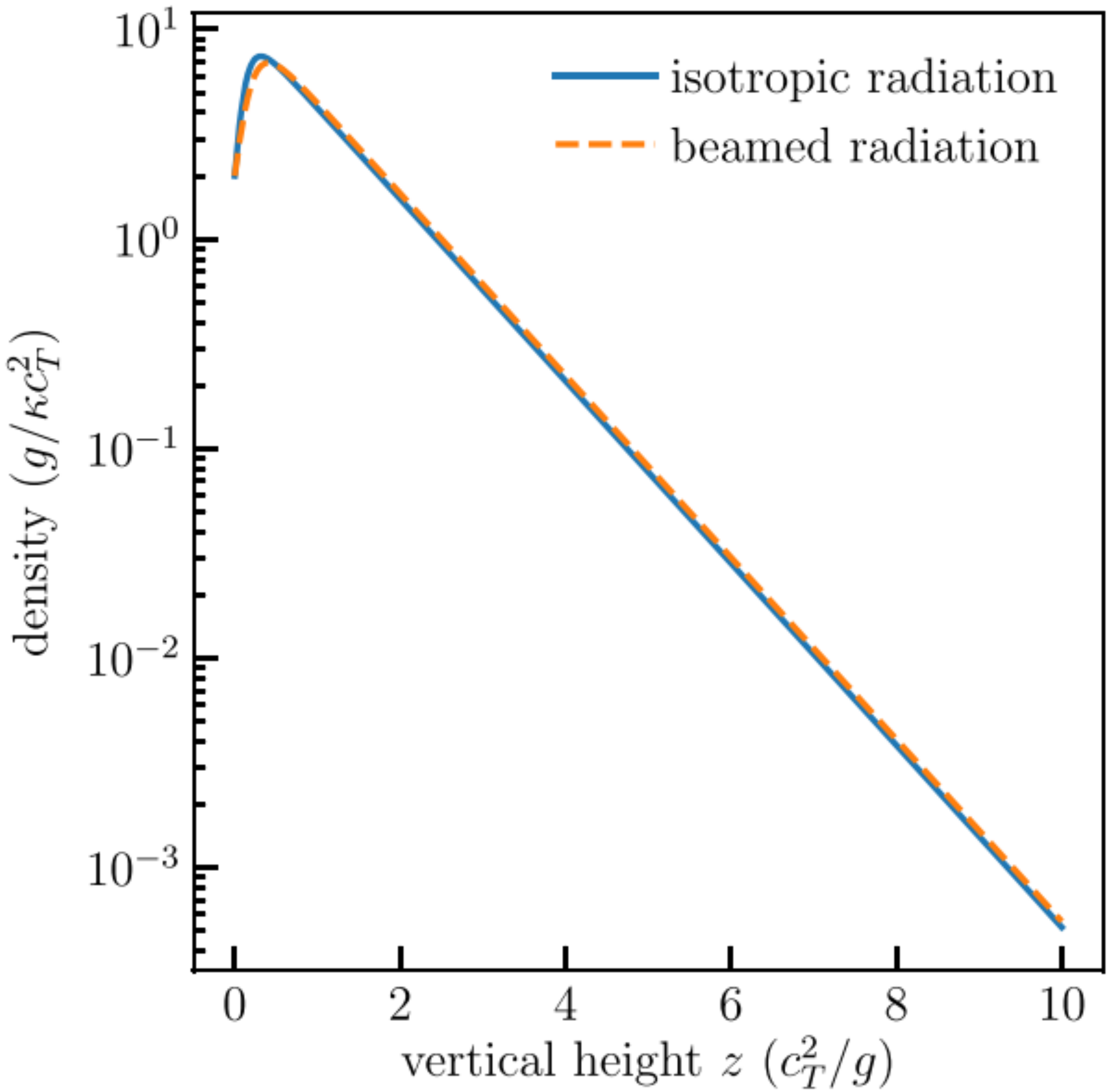
isotropic radiation pattern
(more realistic)

Hydrostatic atmospheres supported by radiation pressure



beamed radiation pattern
(easier to calculate)

Hydrostatic atmospheres supported by radiation pressure



Nonlocal linear stability analysis (beamed pattern)

$$\omega^2 = \left(k_x^2 + k_z^2\right) c_T^2 + i k_z g + \frac{\kappa}{c} F_0(z) \left[i k_z - \kappa \rho_0(z)\right], \tag{28}$$

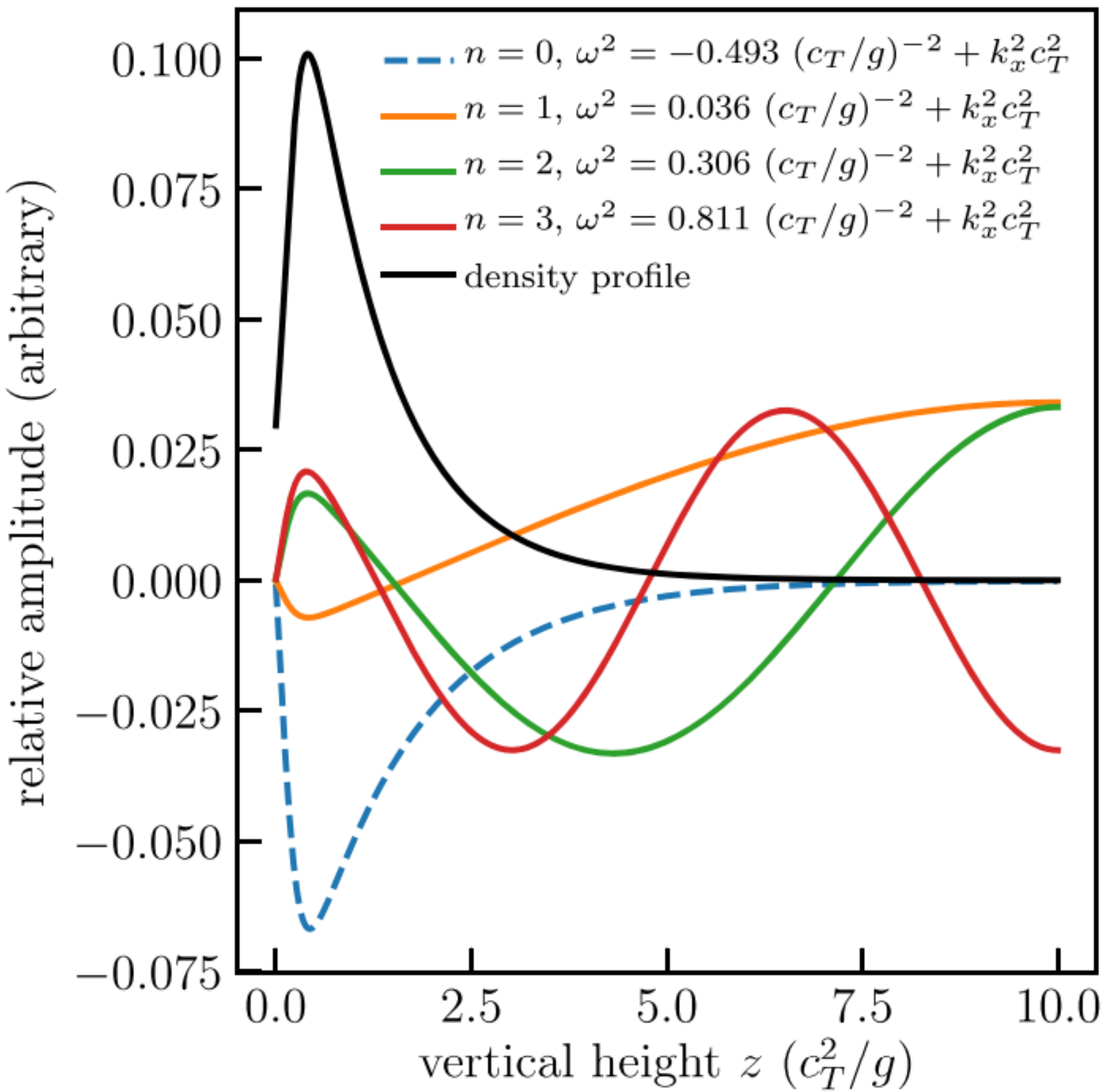
which is always stable for $k_z > 0$ and is unstable for $k_z = 0$, whenever the horizontal wavenumber k_x is less than a critical wavenumber

$$k_{x,\mathrm{c}} = c_T^{-1} \sqrt{\frac{\kappa}{c} F_0(z) \, \kappa \rho_0(z)}. \tag{29}$$

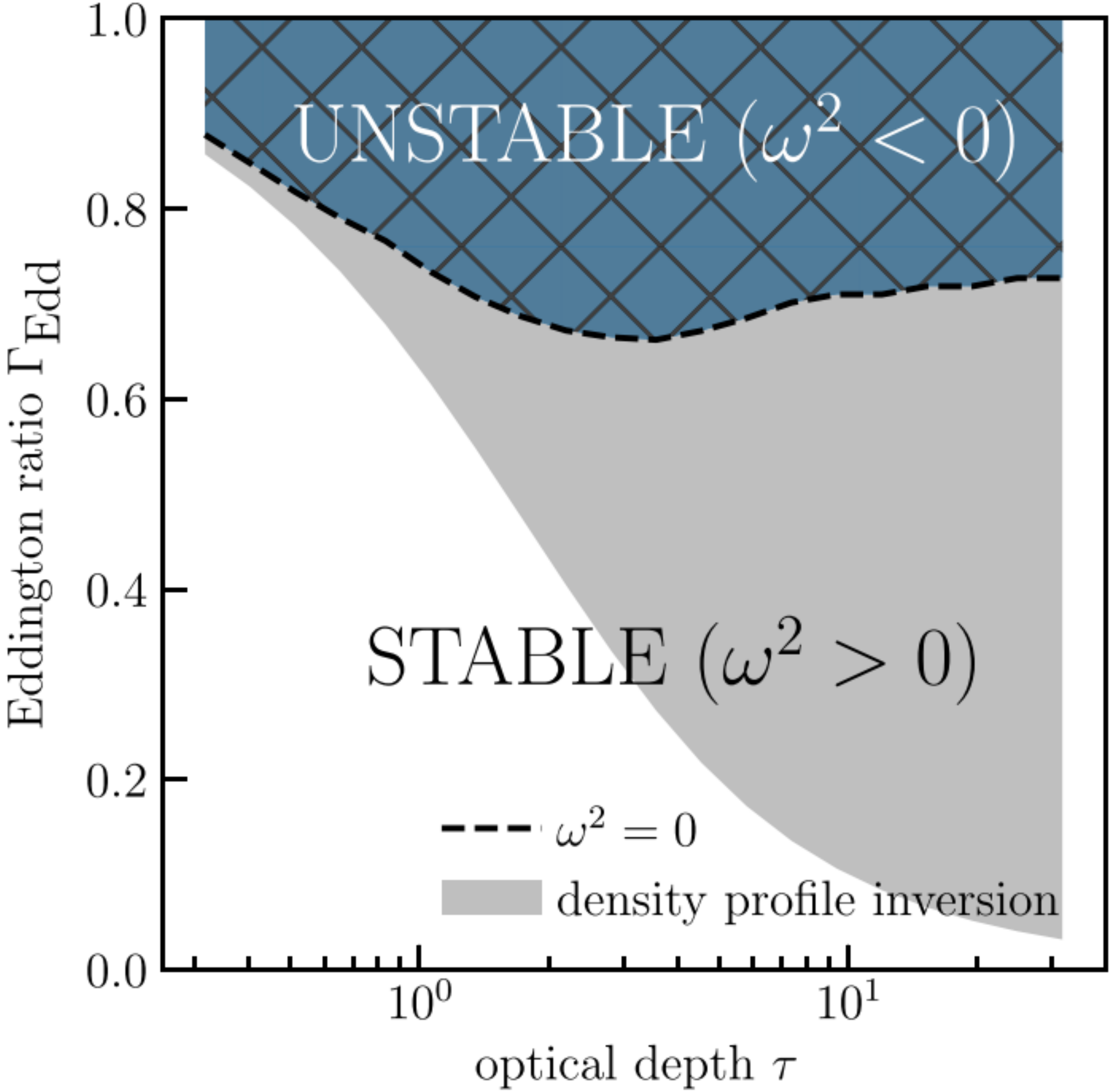
Therefore, radiation-supported atmospheres with beamed radiation are unstable to perturbations with a horizontal wavelength longer than

$$\lambda_\mathrm{c} = 2\pi / k_{x,\mathrm{c}} = 2\pi c_T \left(\tfrac{\kappa}{c} F_0(z) \, \kappa \rho_0(z)\right)^{-1/2} \tag{30}$$

$$= 4.8 \text{ pc} \left(\Gamma_\mathrm{Edd}^{-1/2} \tau^{-1}\right) \left(\frac{T}{300 \text{ K}}\right) \left(\frac{\Sigma}{100 \, \mathrm{M}_\odot \text{ pc}^{-2}}\right)^{-1}, \tag{31}$$



$n = 0,\ \omega^2 = -0.493\ (c_T/g)^{-2} + k_x^2 c_T^2$
$n = 1,\ \omega^2 = 0.036\ (c_T/g)^{-2} + k_x^2 c_T^2$
$n = 2,\ \omega^2 = 0.306\ (c_T/g)^{-2} + k_x^2 c_T^2$
$n = 3,\ \omega^2 = 0.811\ (c_T/g)^{-2} + k_x^2 c_T^2$
density profile
relative amplitude (arbitrary)
vertical height z (c_T^2/g)
0.100
0.075
0.050
0.025
0.000
−0.025
−0.050
−0.075
0.0
2.5
5.0
7.5
10.0



UNSTABLE ($\omega^2 < 0$)
STABLE ($\omega^2 > 0$)
$\omega^2 = 0$
density profile inversion
Eddington ratio $\Gamma_{\rm Edd}$
optical depth τ
1.0
0.8
0.6
0.4
0.2
0.0
10^0
10^1

Simulations (isotropic pattern)

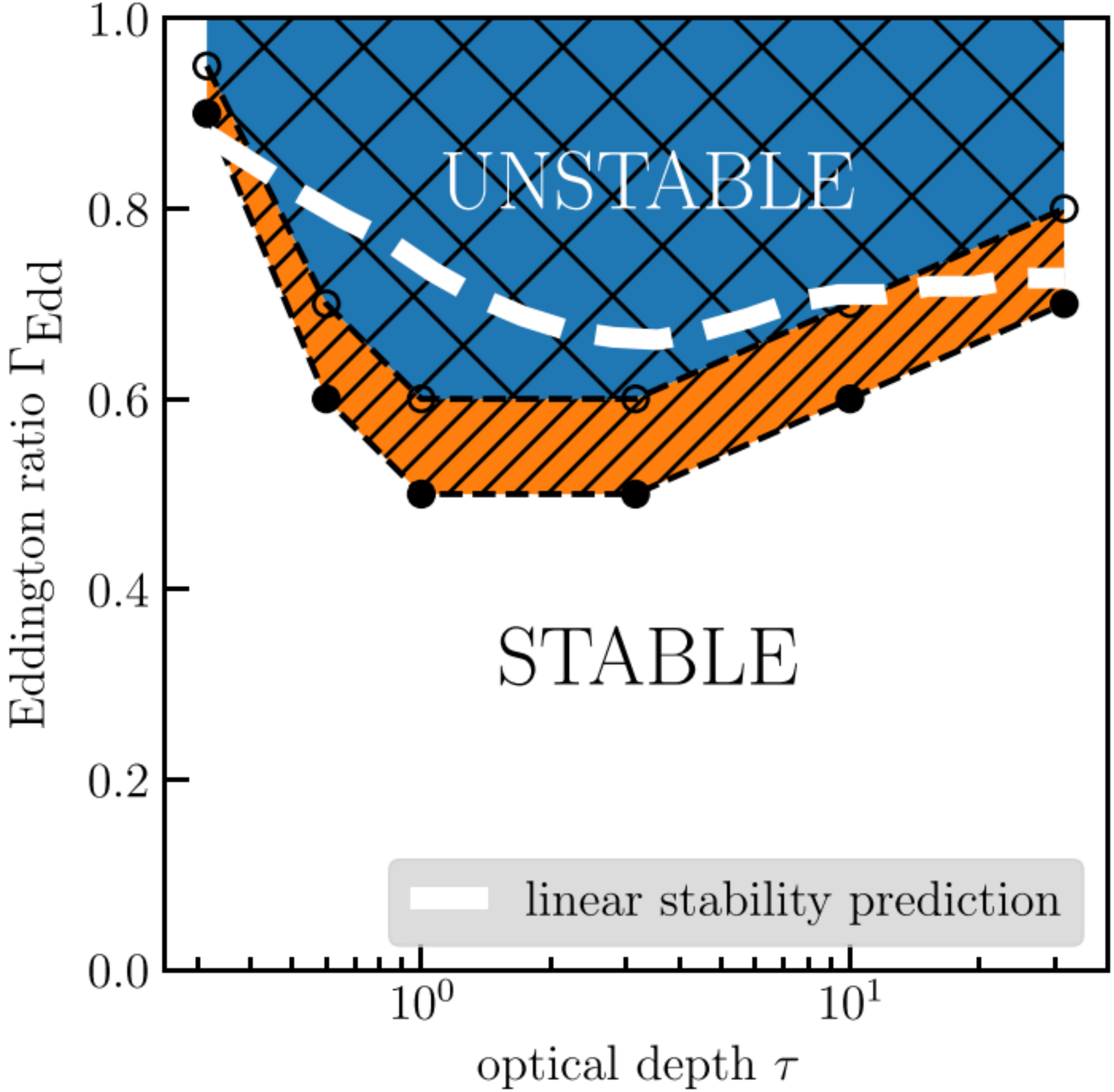
- New 2D radiation hydrodynamics code based on discontinuous Galerkin finite element discretization of the angle-dependent radiation transport equation [+hydrodynamics computed by ATHENA]
- Very efficient
  - Almost all simulations run on a single 8-core workstation
- See Appendix D of paper for details

Stable atmosphere

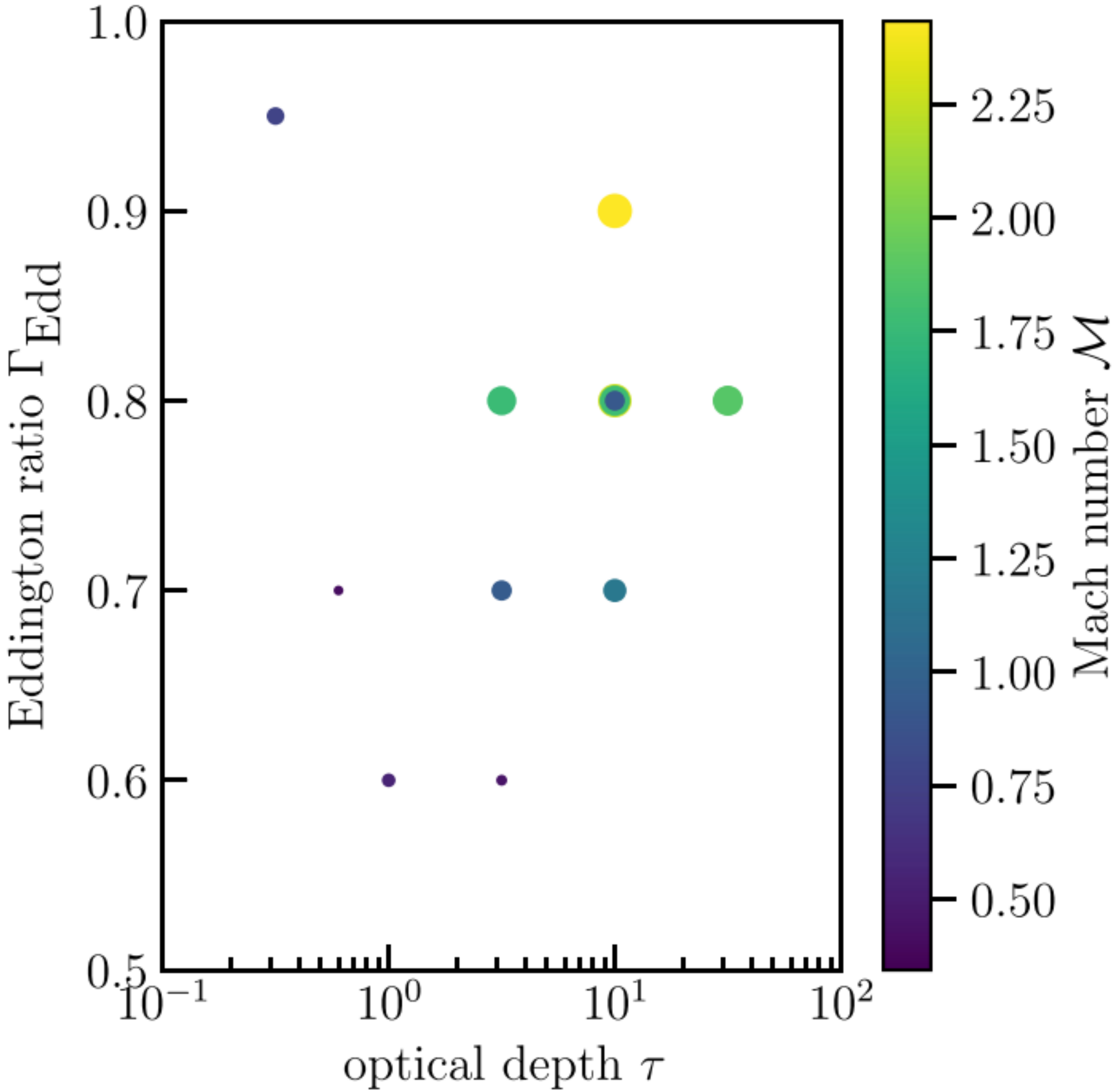
- [exit to play movie]

Unstable atmosphere

- [exit to play movie]



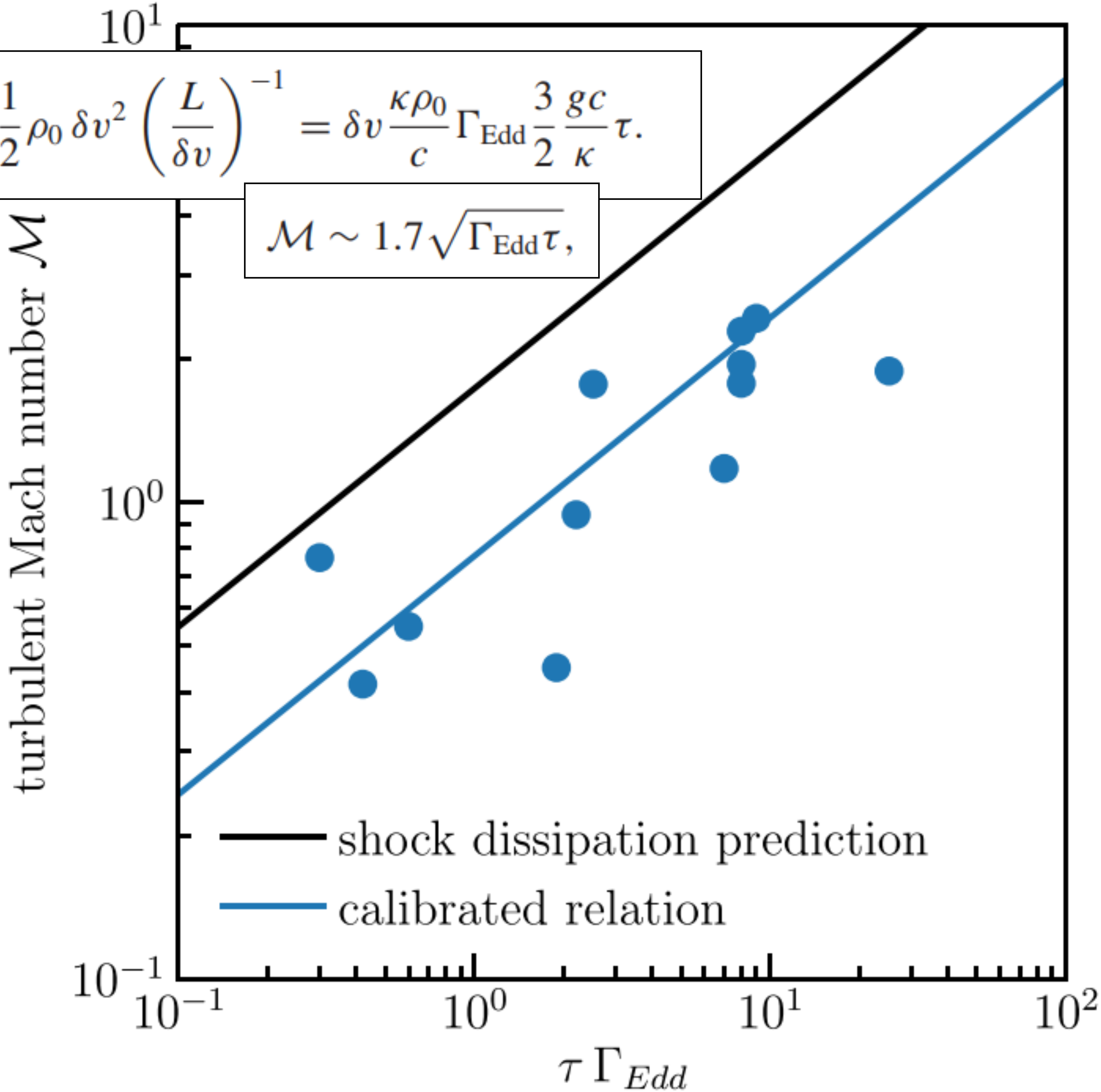
UNSTABLE
STABLE
linear stability prediction
Eddington ratio Γ_{Edd}
optical depth τ
1.0
0.8
0.6
0.4
0.2
0.0
10^0
10^1

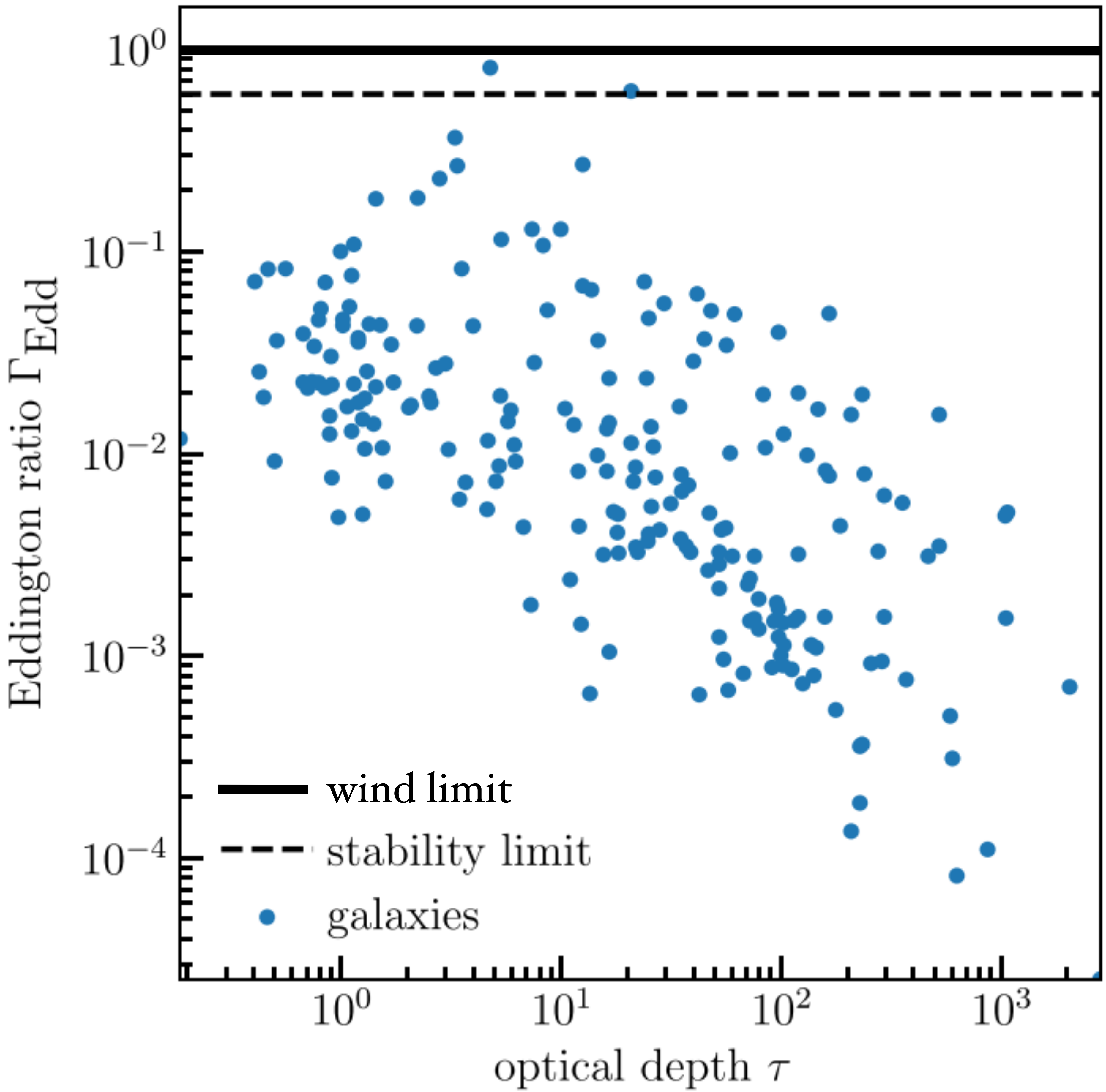


1.0
0.9
0.8
0.7
0.6
0.5
Eddington ratio Γ_{Edd}
10^{-1}
10^{0}
10^{1}
10^{2}
optical depth τ
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
Mach number $\mathcal{M}$

$$\frac{1}{2}\rho_0\,\delta v^2\left(\frac{L}{\delta v}\right)^{-1} = \delta v\,\frac{\kappa\rho_0}{c}\Gamma_{\rm Edd}\frac{3}{2}\frac{gc}{\kappa}\tau.$$

$$\mathcal{M} \sim 1.7\sqrt{\Gamma_{\rm Edd}\tau},$$





10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Eddington ratio $\Gamma_{\rm Edd}$
10^0
10^1
10^2
10^3
optical depth τ
wind limit
stability limit
galaxies

My conclusions

[does not necessarily represent views of collaborators]

- Single-scattering radiation pressure appears to be dynamically unimportant for galaxies in general
- But may contribute a small fraction of ISM turbulence in extreme radiation environments
- **Not** a plausible feedback process to invoke for subgrid models of galaxy formation (many papers in the literature have done this!)

Extra slides

Emulator flowchart

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

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

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

$$\downarrow$$

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

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

$$\downarrow$$

Emulator flowchart

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

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

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

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