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BERKELEY COSMOLOGY SEMINAR

2022-10-25

ISOLATING THE LINEAR SIGNAL IN SMALL SCALE RSD

WHY ARE WE TALKING ABOUT THIS?

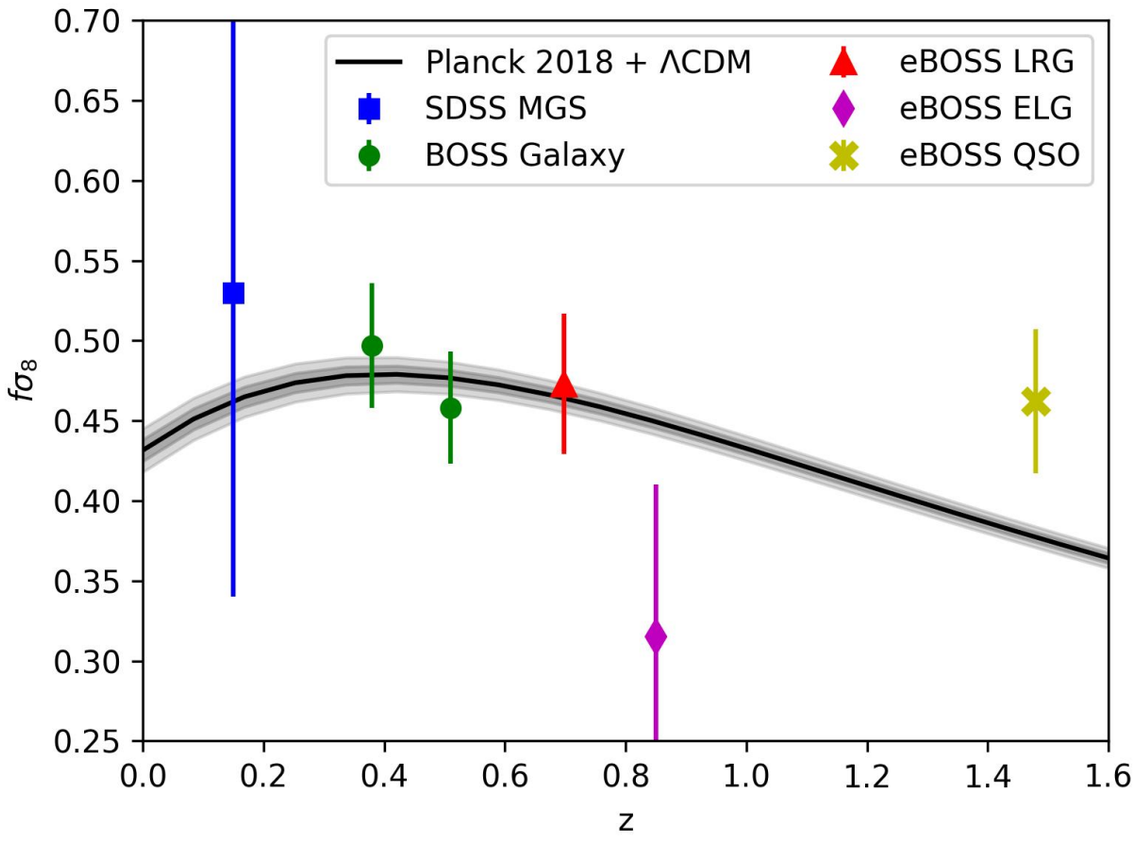
BACKGROUND

BIG PICTURE

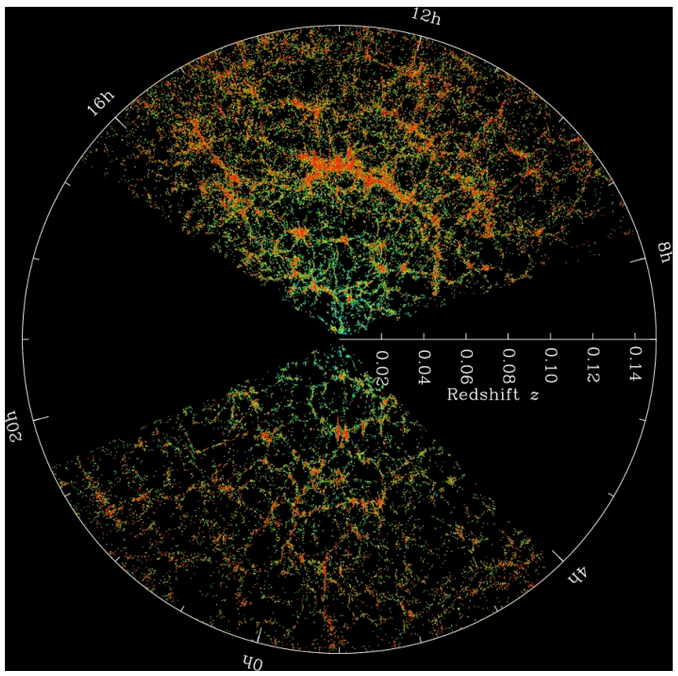
- Accelerated expansion of the Universe behaves like a cosmological constant, but lacks an underlying explanation
- Theories of dark energy or modified gravity affect the growth of structure, parameterized by $f\sigma_8$, and can be tested with galaxy clustering
- f is the logarithmic growth rate of density fluctuations

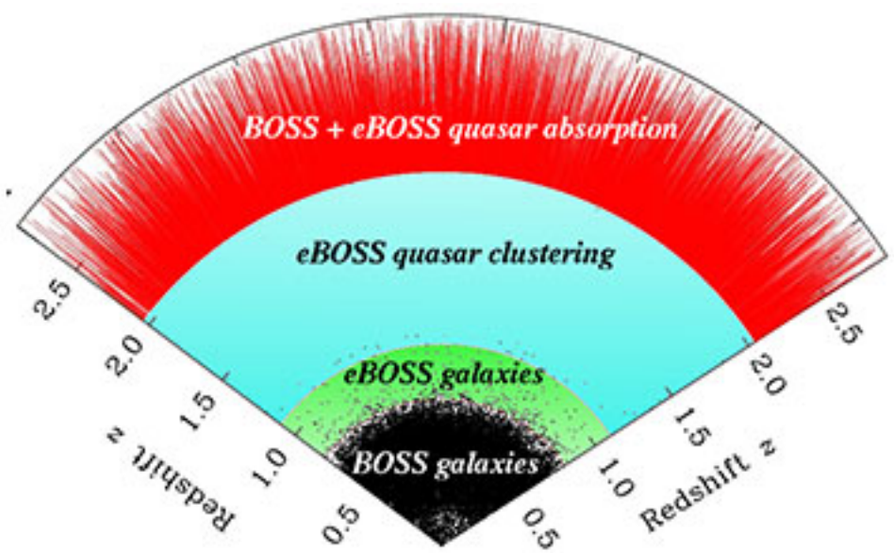
$$f(\Omega_m) = \frac{dlnD}{dlna} \quad ; \quad D \propto \delta_+$$

- σ_8 is the rms variance of density fluctuations in a sphere of radius $8h^{-1}Mpc$



GALAXY SPECTROSCOPIC SURVEYS





- Convert redshifts to distances assuming the Hubble flow
- The eBOSS observed 300 000 high redshift ($0.6<z<1.0$) LRGs, as well as ELG and QSO
- Fibre collisions corrected by pairwise-inverse-probability weights, giving unbiased clustering at all scales

CORRELATION FUNCTION

- Excess probability of finding another galaxy at a given separation relative to if they followed a Poissonian distribution

$$\xi(r_\parallel, r_\perp) = \frac{DD(r_\parallel, r_\perp) - 2DR(r_\parallel, r_\perp)}{RR(r_\parallel, r_\perp)} + 1$$

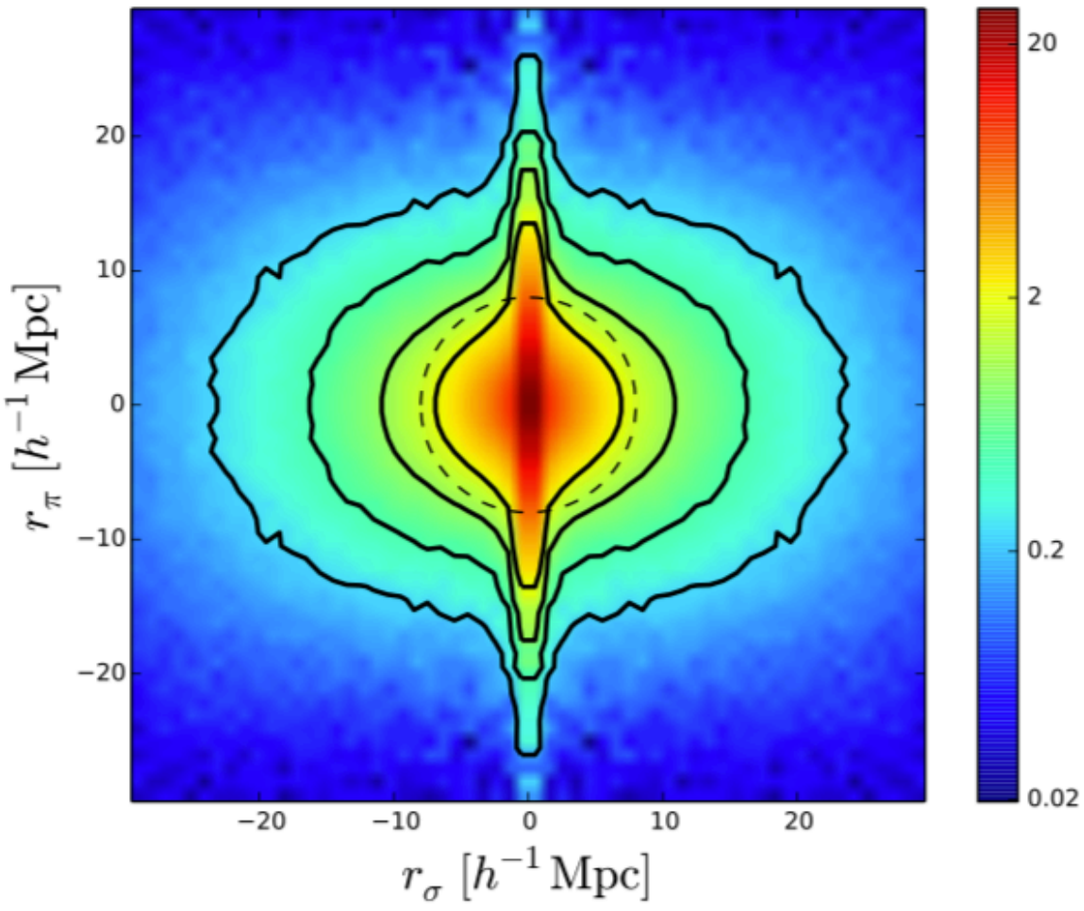
$$w_p(r_\perp) = 2\int_0^{r_{\parallel,max}} dr_\parallel \xi(r_\parallel, r_\perp)$$

- Use ξ_0, ξ_2, and w_p in analysis

$$\xi_l(s) = \frac{2l+1}{2}\int d\mu_s \xi(s, \mu_s) L_l(\mu_s)$$

REDSHIFT SPACE DISTORTIONS

- Peculiar velocities shift the position of galaxies in redshift space
- In the linear regime (>40 h^{-1} Mpc) gives a direct constraint on $f\sigma_8$
- Better signal-to-noise below 40 h^{-1}Mpc, but extracting linear information is non-trivial



2D correlation function in separation parallel (y-axis) and perpendicular (x-axis) to the line of sight. (Reid et al. 2014, 1404.3742)

WHAT DID YOU DO?

ANALYSIS METHODS

COSMOLOGICAL EMULATOR

- Gaussian process based machine learning trained on Aemulus simulation suite to predict galaxy correlation functions
- 16 parameter model; 7 wCDM, 8 HOD, and velocity scaling parameter

wCDM: $\Omega_m, \Omega_b, \sigma_8, h, n_s, N_{eff}, w$

HOD: $\log M_{sat}, \alpha, \log M_{cut}, \sigma_{\log M}, f_{max}, v_{bc}, v_{bs}, c_{vir}$

Velocity Scaling: γ_f

- Keep N_{eff}, w fixed for a total of 14 free parameters

VELOCITY SCALING

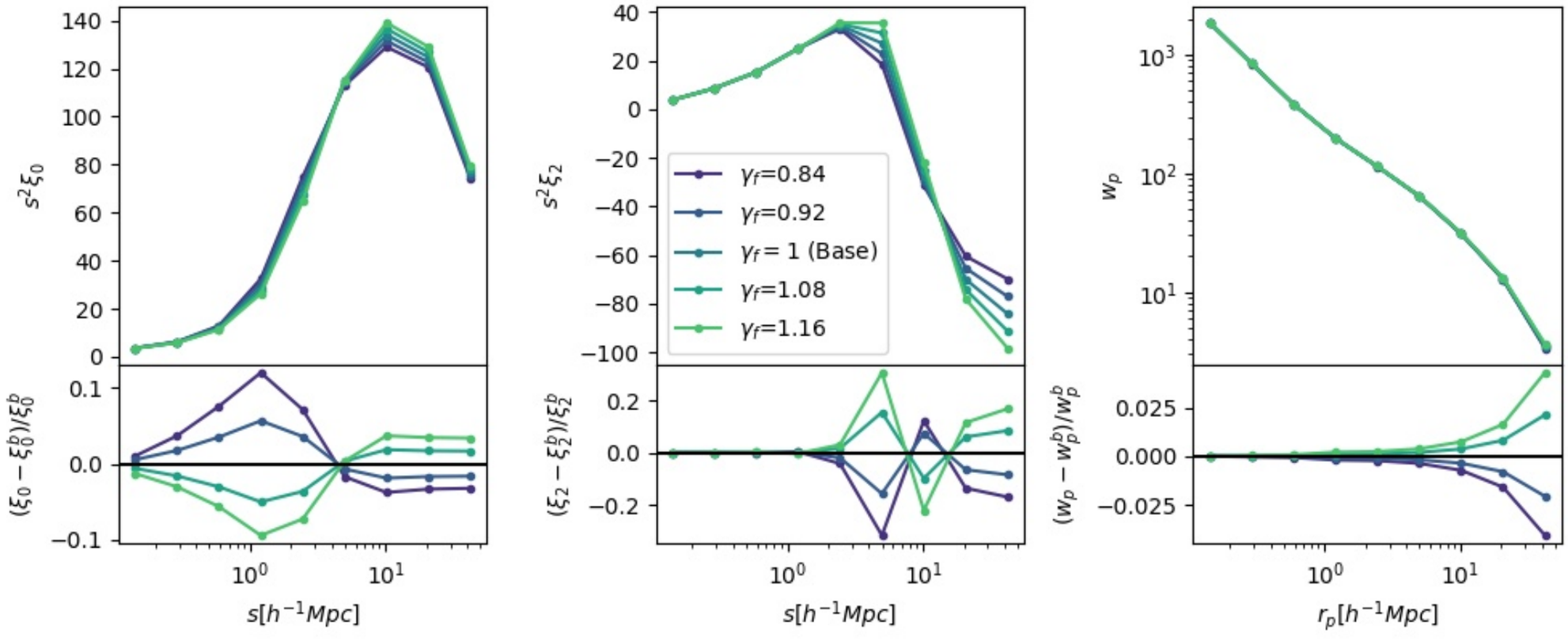
- γ_f rescales all bulk halo velocities in the simulation
- In the linear regime the amplitude of the velocity field is directly proportional to $f\sigma_8$

$$\boldsymbol{v_k} = \frac{i\boldsymbol{k}}{k^2} Ha\delta_{\boldsymbol{k}} f$$

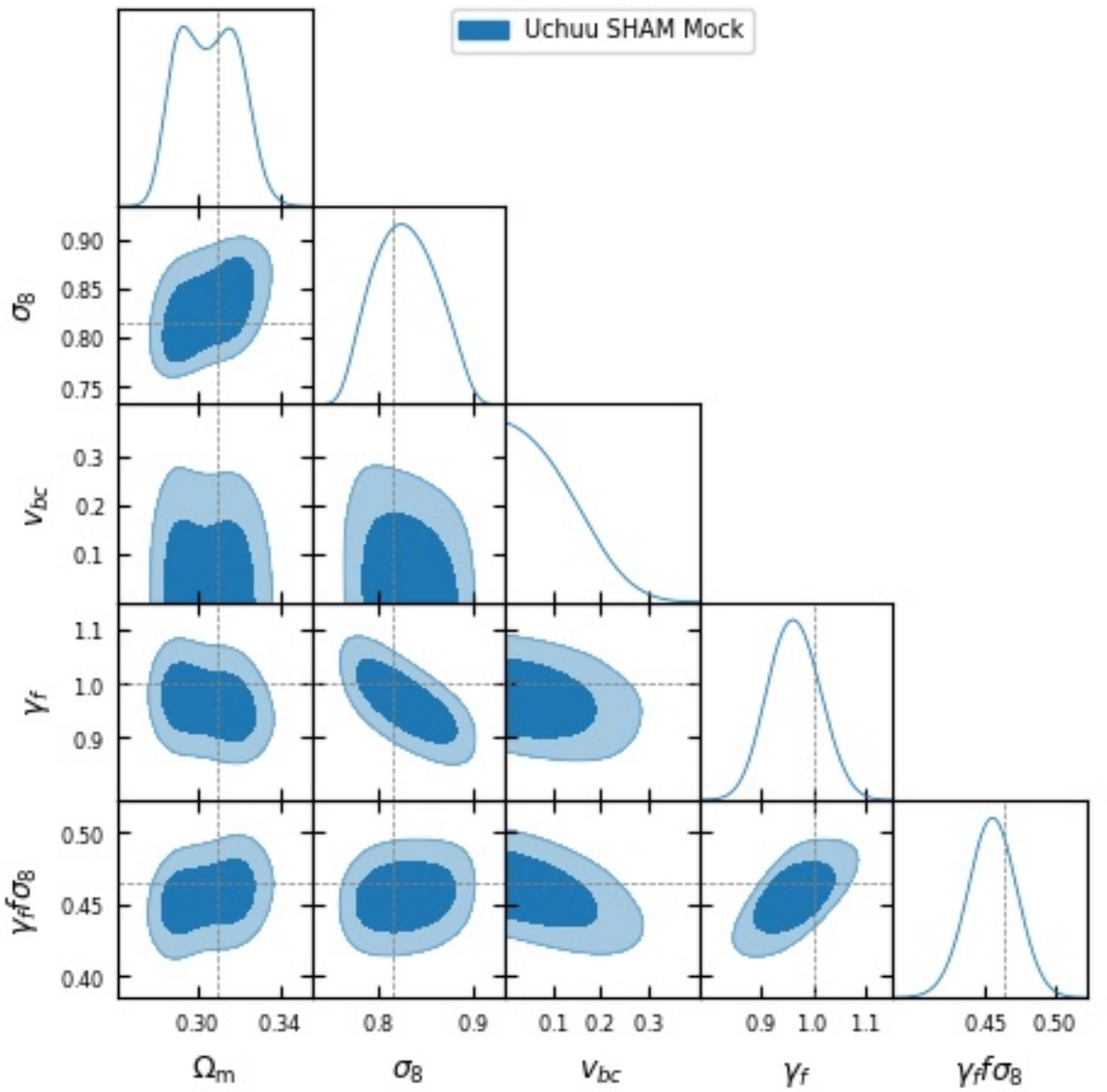
- A fractional change in γ_f is equal to a fractional change in the linear growth rate, so $f_{meas} = \gamma_f f_{wCDM}$
- Parameterizes deviations from expected growth within a ΛCDM framework, assessing tension in the growth of structure specifically

NON-LINEAR VELOCITIES

- On linear scales a change in γ_f corresponds to a change in the growth rate, but not necessarily true on non-linear scales
- Identify $7\,h^{-1}\mathrm{Mpc}$ as the transition, so use $7 < r < 60\,h^{-1}\mathrm{Mpc}$ to constrain $f\sigma_8$, and γ_f as a test of $\Lambda\mathrm{CDM}$ using $0.1 < r < 60\,h^{-1}\mathrm{Mpc}$



MOCK TESTING



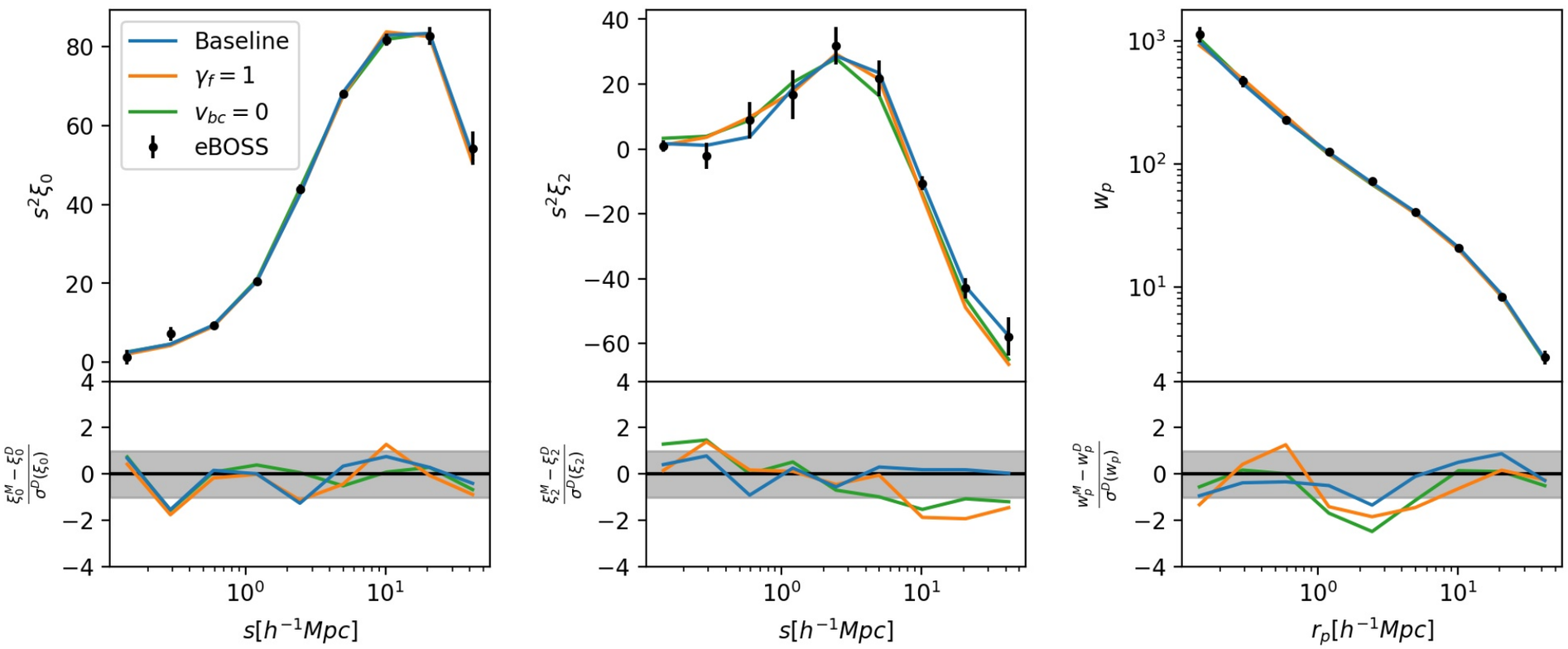
- Tested full pipeline with a SHAM mock from the Uchuu simulation
- Using a different galaxy-halo connection model shows that the HOD parameterization is robust
- Recovered the expected cosmology and γ_f

FINALLY THE GOOD PART…

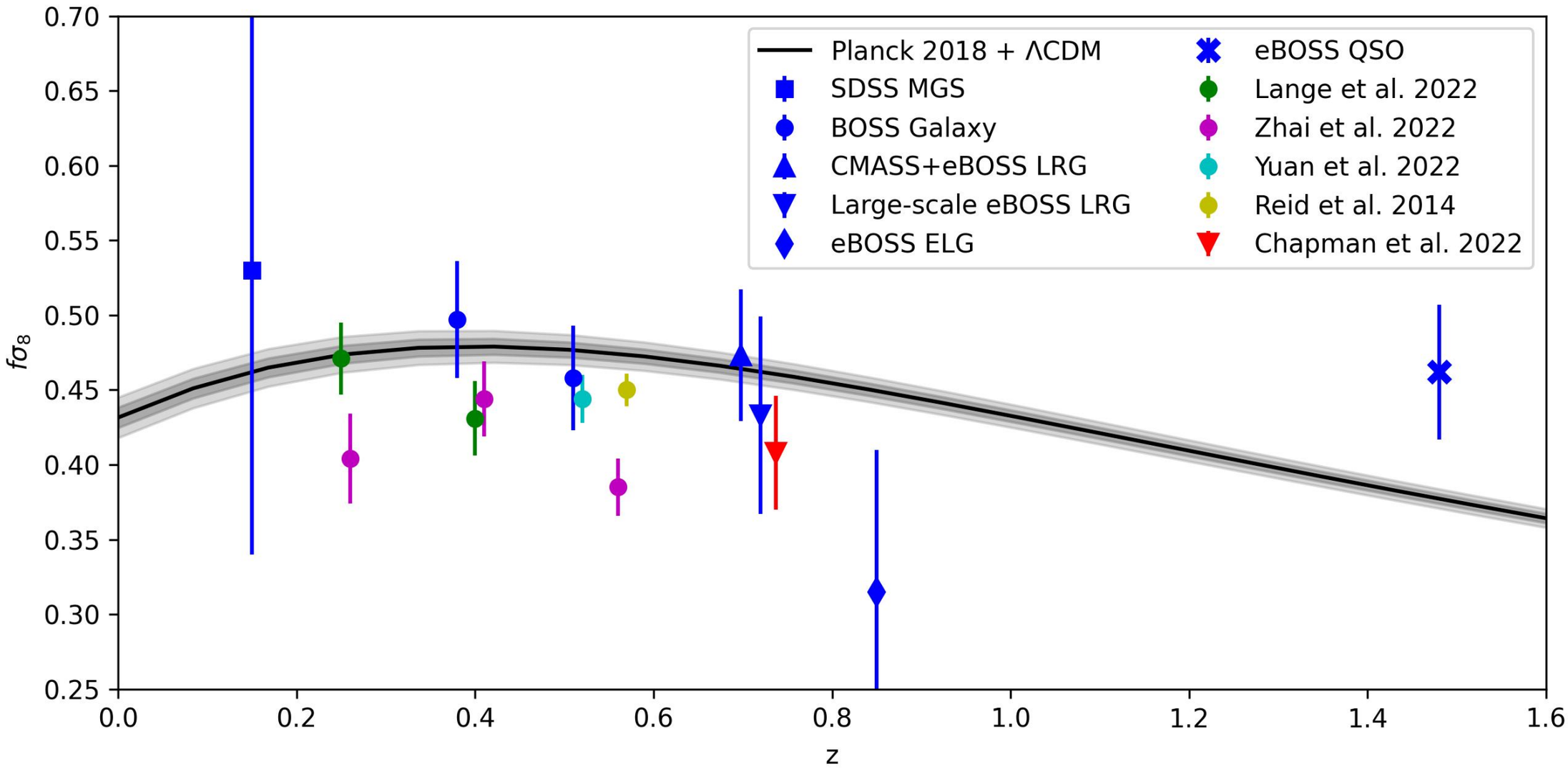
PUBLISHED RESULTS

HEADLINE RESULTS

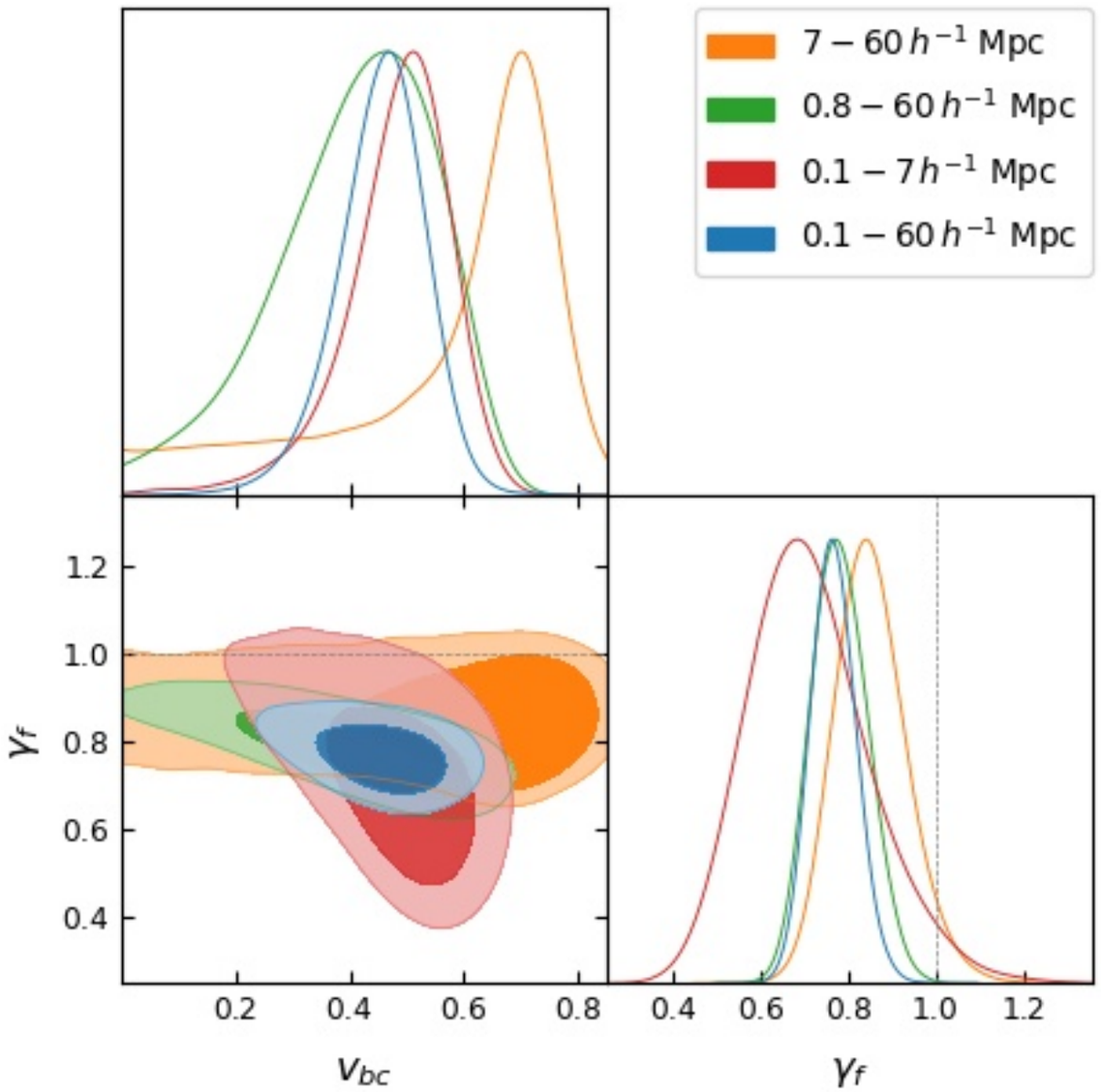
- Using $7 < r < 60\,h^{-1}\mathrm{Mpc}$ measure $f\sigma_8(z = 0.737) = 0.408 \pm 0.038$, 1.4σ below the Planck2018 expectation and a factor of 1.7 better than the large scales
- Using $0.1 < r < 60\,h^{-1}\mathrm{Mpc}$ measure $\gamma_f = 0.767 \pm 0.052$, 4.5σ below the value for ΛCDM



COMPARISON TO OTHER SDSS RESULTS



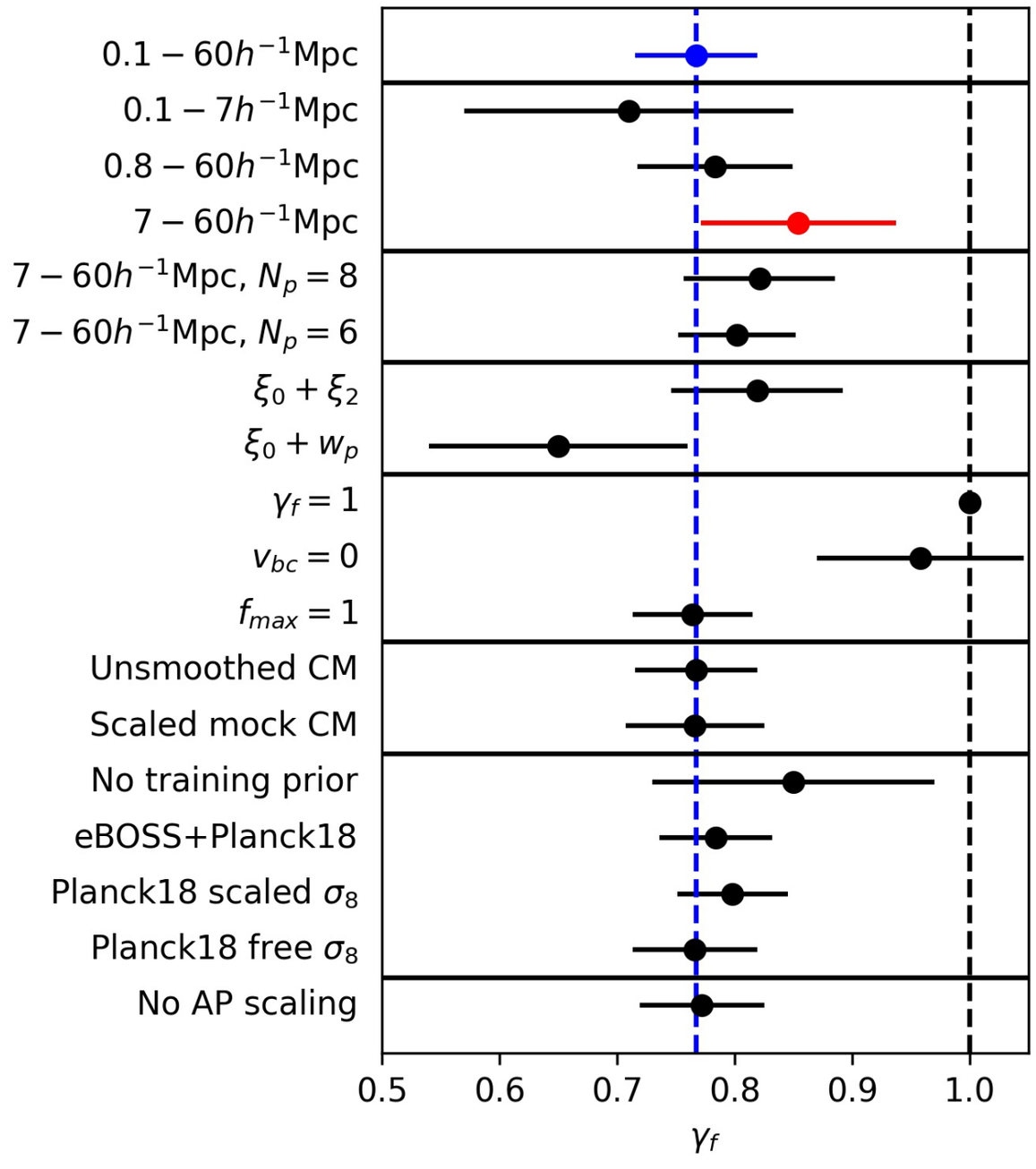
SCALE DEPENDENCE



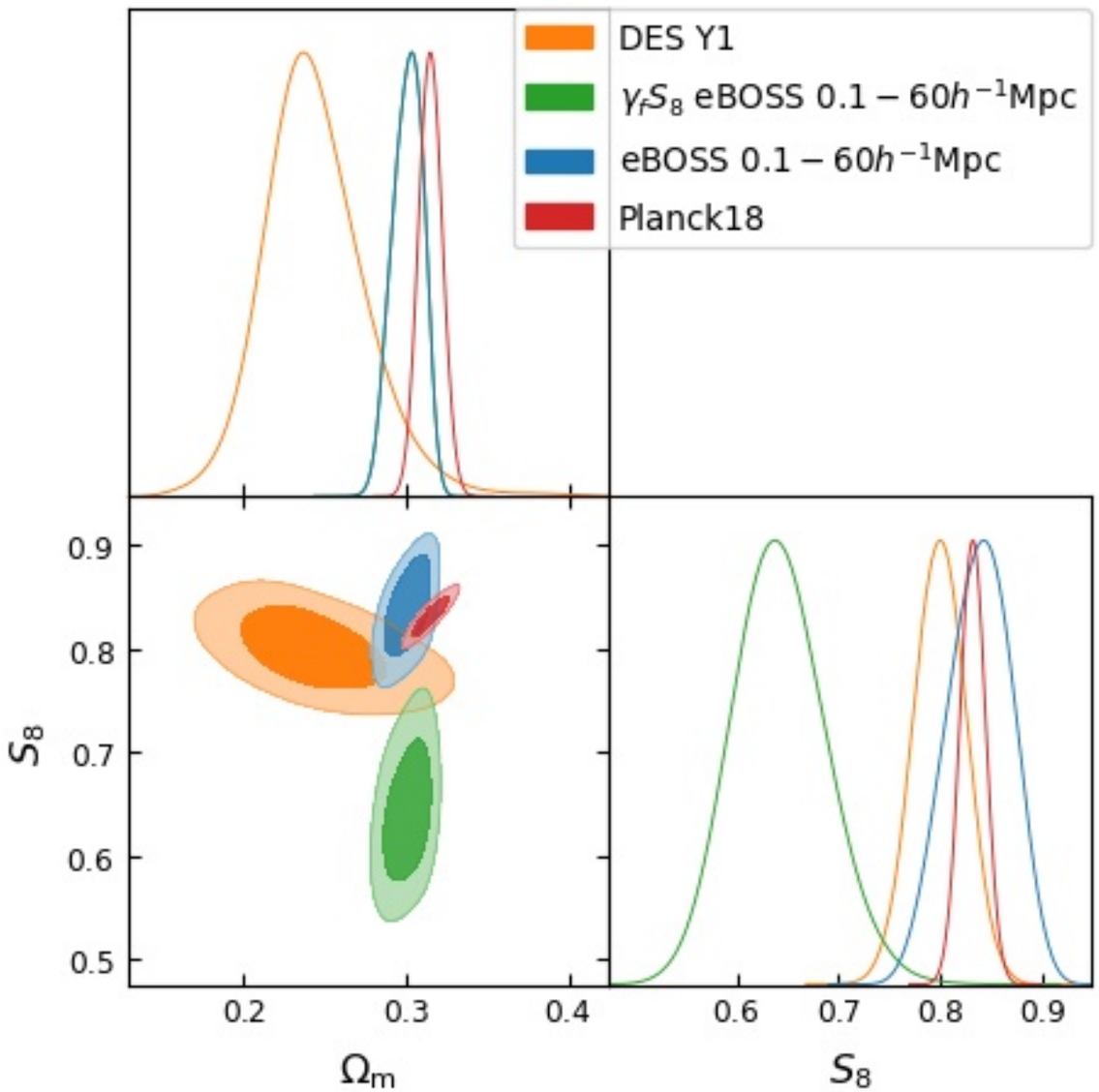
- Small scales prefer a low value of γ_f and non-zero $v_{\rm bc}$
- Large scales prefer a larger value of γ_f and no degeneracy with $v_{\rm bc}$
- The non-linear scales drive the stronger tension from all scales

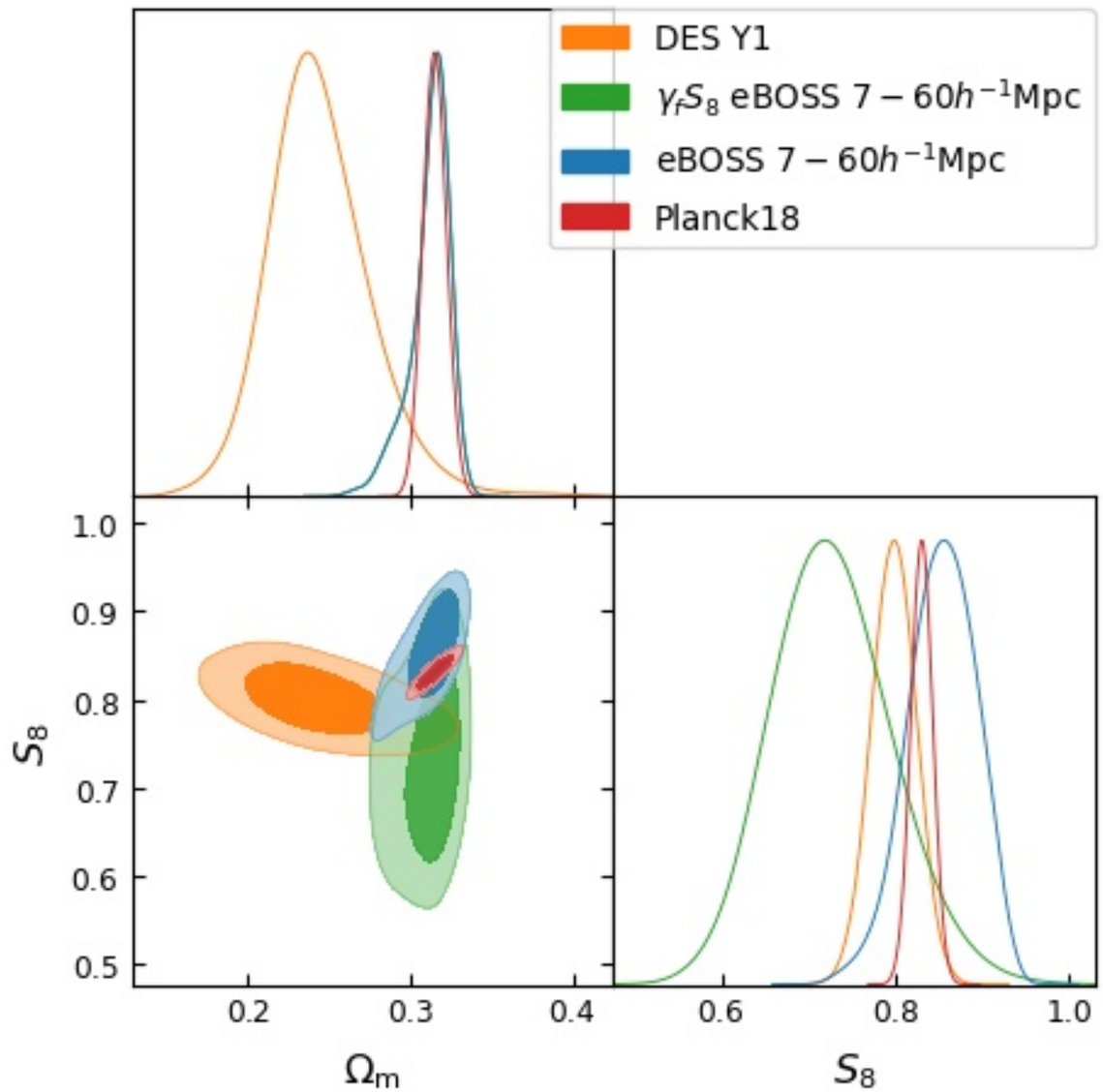
ALL FITS

Run	γ_f	N_P	N_D	χ^2
$0.1 - 60\,h^{-1}$Mpc	0.767 ± 0.052	14	27	14.1
$0.1 - 7\,h^{-1}$Mpc	0.71 ± 0.14	14	18	7.8
$0.8 - 60\,h^{-1}$Mpc	0.783 ± 0.066	14	18	4.2
$7 - 60\,h^{-1}$Mpc	0.854 ± 0.083	14	9	0.36
$7 - 60\,h^{-1}$Mpc, 8 parameters	0.821 ± 0.064	8	9	0.74
$7 - 60\,h^{-1}$Mpc, 6 parameters	0.802 ± 0.050	6	9	1.8
$\xi_0 + \xi_2$	0.819 ± 0.073	14	18	5.0
$\xi_0 + w_p$	0.65 ± 0.11	14	18	5.4
$\gamma_f = 1$	1	13	27	28.0
$v_{\rm bc} = 0$	0.958 ± 0.088	13	27	22.5
$f_{\rm max} = 1$	0.764 ± 0.051	13	27	16.6
Unsmoothed covariance matrix	0.767 ± 0.052	14	27	14.3
Scaled mock covariance matrix	0.766 ± 0.059	14	27	12.0
No training prior	0.85 ± 0.12	14	27	12.1
eBOSS+Planck18	0.784 ± 0.048	14*	27	18.5
eBOSS+Planck18 scaled σ_8	0.798 ± 0.047	14*	27	19.1
eBOSS+Planck18 free σ_8	0.766 ± 0.053	14*	27	18.0
No AP scaling	0.772 ± 0.053	14	27	14.5



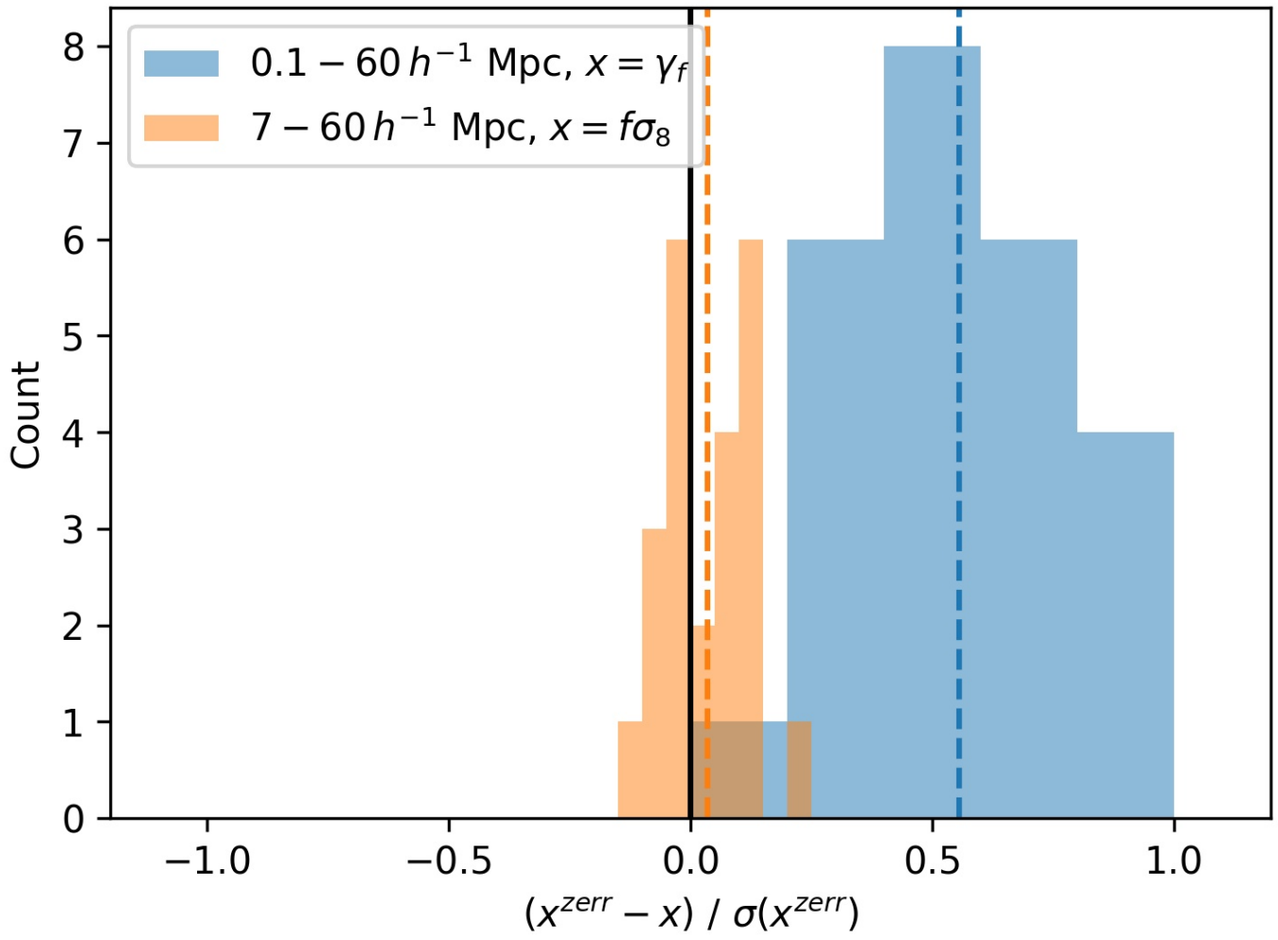
COMPARISON TO LENSING





REDSHIFT UNCERTAINTY

- The eBOSS sample has a redshift uncertainty well fit by a Gaussian of width $\sigma = 91.8\,\mathrm{km/s}$, giving a mean offset of $65.6\,\mathrm{km/s}$
- On non-linear scales the redshift uncertainty is similar to the halo velocities, giving a degeneracy with γ_f
- Correcting this bias would shift our measurement to lower values of $f\sigma_8$



NEW RESULTS

ISOLATING THE LINEAR SIGNAL

LINEAR SIGNAL

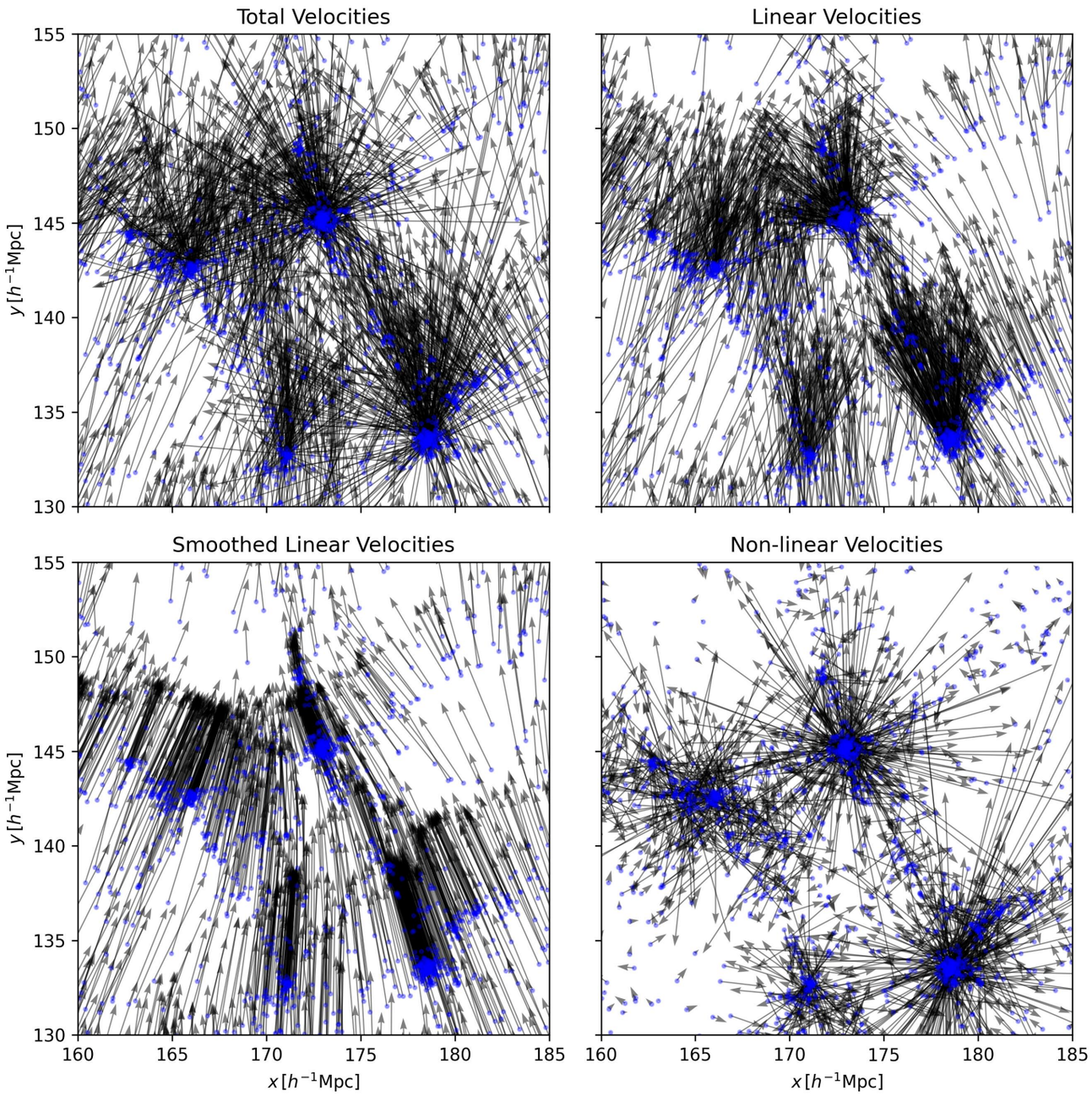
- Split the scaling parameter into two independent scalings: γ_l for the linear component of the velocity, and γ_n for the non-linear
- Use the initial conditions code to calculate the linear velocity of each particle and evolve to low redshift assuming linear growth

$$\boldsymbol{v}(z_2) = \frac{Haf\sigma_8(z_2)}{Haf\sigma_8(z_1)}\boldsymbol{v}(z_1)$$

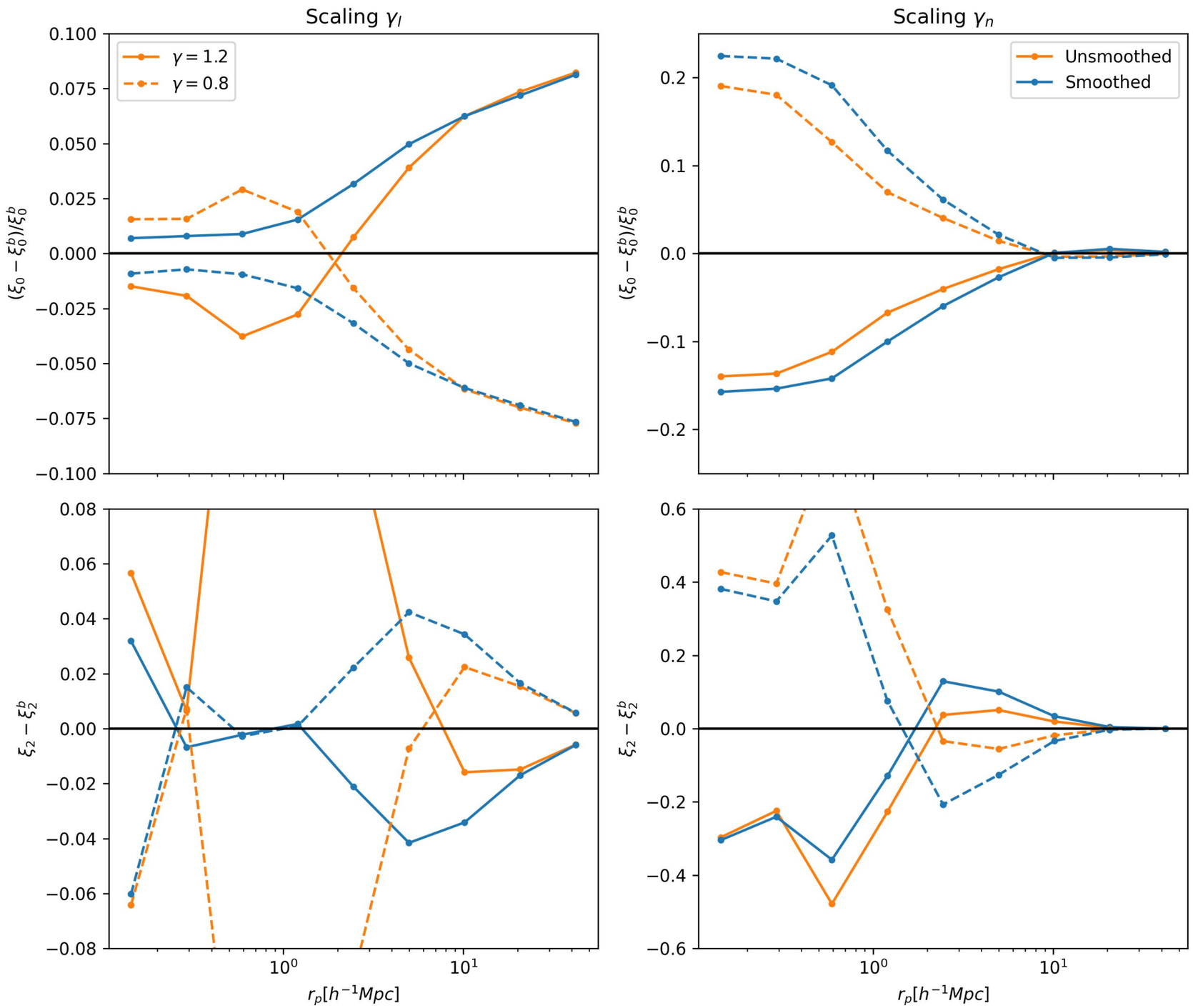
- Non-linear velocities defined as the remainder between the total and linear velocity: $\boldsymbol{v}_{nl} = \boldsymbol{v}_{tot} - \boldsymbol{v}_{lin}$

SMOOTHING THE VELOCITY FIELD

- Initially assigned halos the mean linear velocity of their particles
- To better align linear velocity smoothed using a tophat kernel with radius 5 $h^{-1}\mathrm{Mpc}$ on a grid with cell length 1 $h^{-1}\mathrm{Mpc}$
- Maintains the large scale growth while ensuring already collapsed objects are comoving



LINEAR SIGNAL

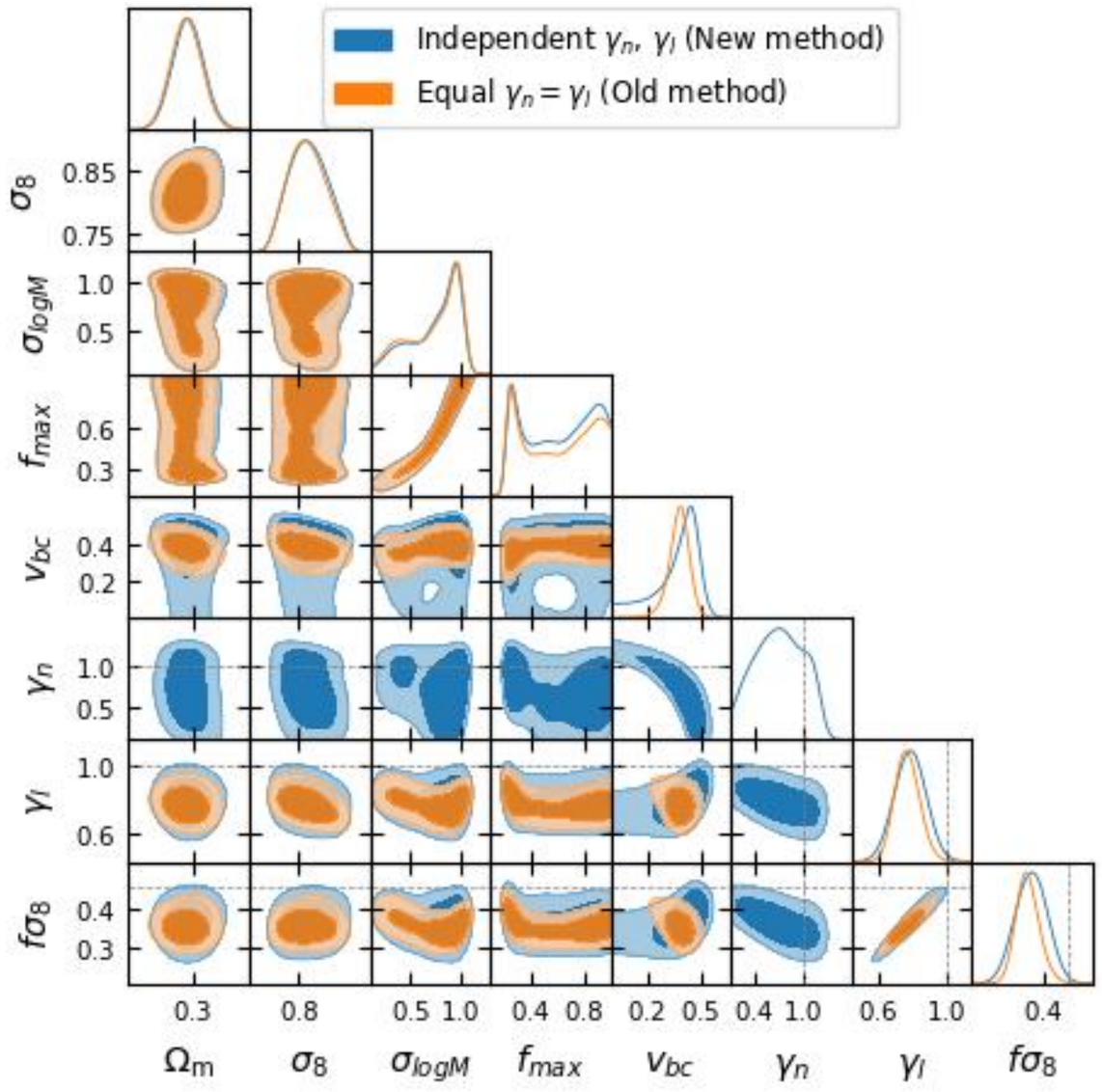


BUILDING A NEW EMULATOR

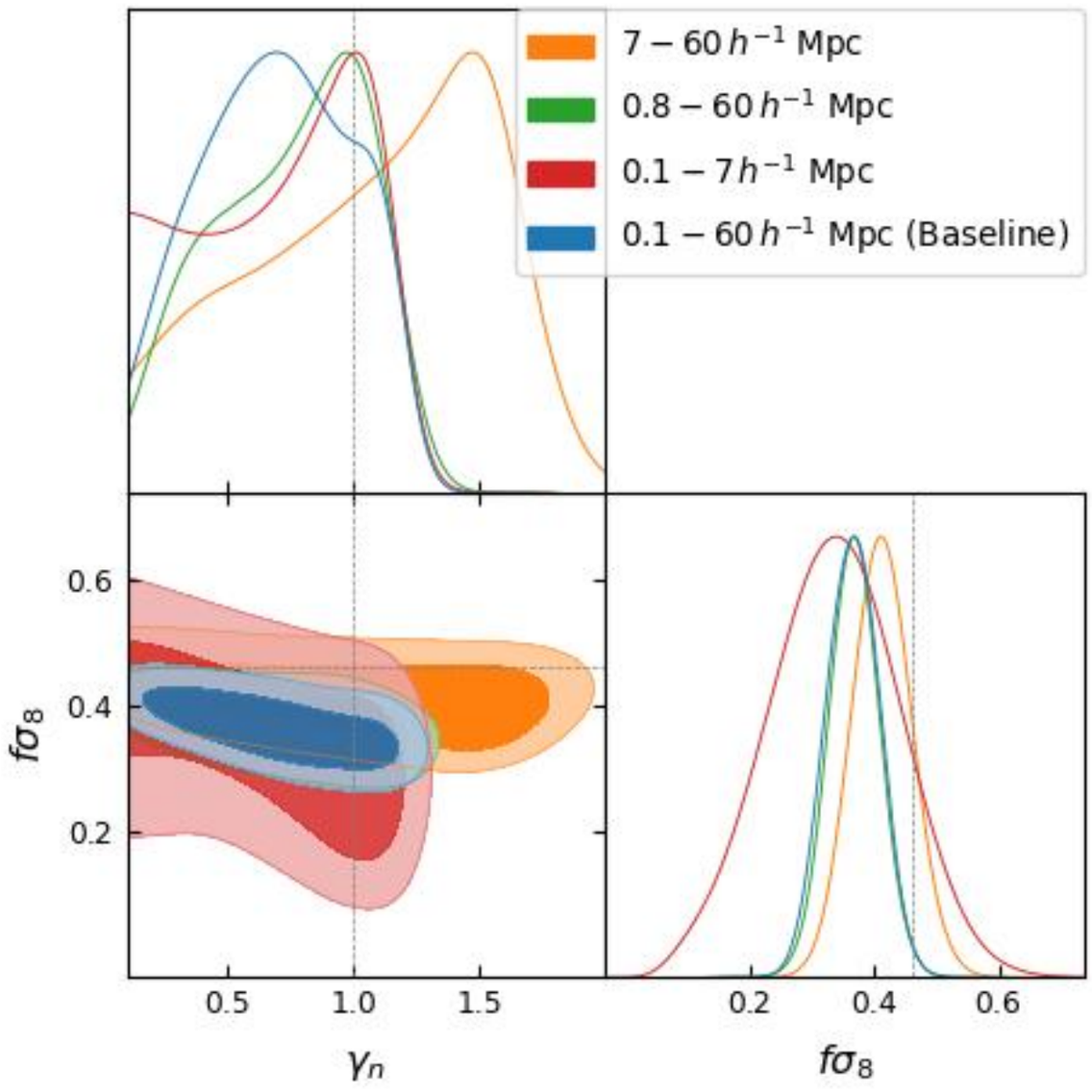
- Change from Aemulus simulation suite to Abacus Suite because of the publicly available IC code zeldovich-PLT
- Abacus consists of 40 simulation boxes sampled over a range of cosmologies, with box length 1100 $h^{-1}\mathrm{Mpc}$ and 1440^3 particles
- Rebuilt emulator using new parameters γ_l and γ_n
- Fit to eBOSS LRG sample from Chapman et al. 2022 over full $0.1 - 60\,h^{-1}\mathrm{Mpc}$

NEW EMULATOR RESULTS

- γ_l constraints remain similar to combined scaling in previous emulator, resulting in increased tension
- Low value of γ_n preferred by fit, but generally poorly constrained



REDUCED SCALE DEPENDENCE



- Splitting the scaling parameter into γ_l and γ_n reduces the tension between the small and large scale measurements
- An offset of $\sim 1\sigma$ still exists between the large and intermediate scales

STATE OF THE FIELD

	Chapman et al. In Prep.	Chapman et al. 2022	Lange et al. 2022	Zhai et al. 2022	Yuan et al. 2022
Data	eBOSS LRG	eBOSS LRG	BOSS LOWZ	BOSS LOWZ+CMASS	BOSS CMASS
Simulations	Abacus	Aemulus	Aemulus	Aemulus	AbacusSummit
Model	Emulator+γ_l, γ_n	Emulator+γ_f	Cosmological Evidence Modelling	Emulator+γ_f	Constrained HOD Emulator

- Four research groups, using a variety of data, simulations, and models have found consistently low values of $f\sigma_8$
- Extensive tests have been performed on contamination of non-linear signal, galaxy-halo connection model, and observational systematics
- Common threads are the cosmological model, dark matter only simulations, and HOD

FUTURE DIRECTIONS

- Retrain emulator using AbacusSummit for larger volume, more cosmologies, and higher resolution
- Refine velocity split model and extend to quasi-linear evolution
- Test modelling using recovery tests on hydrodynamical simulations, extended HOD models
- Investigate redshift uncertainty modelling dependence on redshift, halo mass, observational characteristics
- Measure small-scale RSD in DESI LRG and ELG samples

SUMMARY

- Measured $f\sigma_8(z = 0.737) = 0.408 \pm 0.038$ from small-scale RSD in eBOSS LRGs, 1.4σ below the Planck2018 expectation and a factor of 1.7 better than the large scales
- Improved model using velocity split model, finding increased tension with Planck2018 + ΛCDM expectation
- Small-scale RSD give consistently low values of $f\sigma_8$ across changes in data, simulations, and modelling
- Results point to HOD breakdown, deviation in small-scale CDM simulations, or tension with ΛCDM
- Contact me at **mj3chapm@uwaterloo.ca** with additional comments and questions!