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GCCL SEMINAR

2021-07-30

MEASURING THE GROWTH RATE USING SMALL-SCALE CLUSTERING IN EBOSS

WHAT DO YOU MEAN “SMALL-SCALE”?

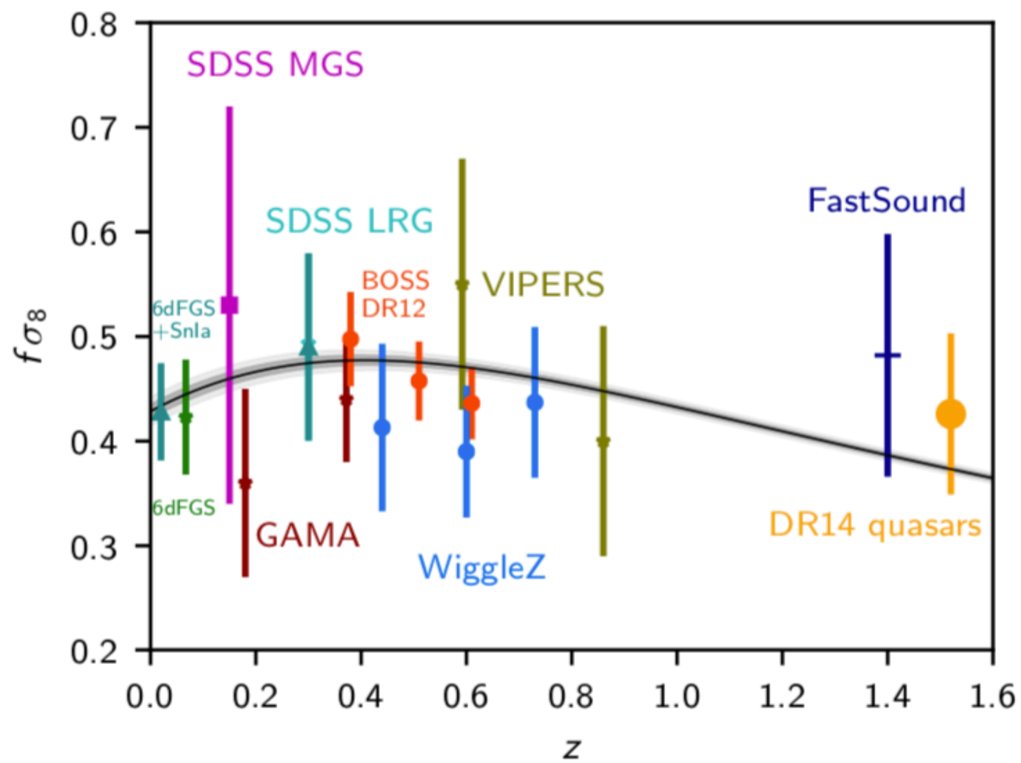
INTRODUCTION

THE GROWTH RATE

- Theories of dark energy or modified gravity affect the growth of structure, parameterized by $f\sigma_8$
- 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 8 $h^{-1}Mpc$



Constraints on the growth rate from various galaxy redshift surveys. Planck TT,TE,EE+lowE+lensing shown in black with 68% and 95% confidence ranges. (Planck Collaboration et al. 2018)

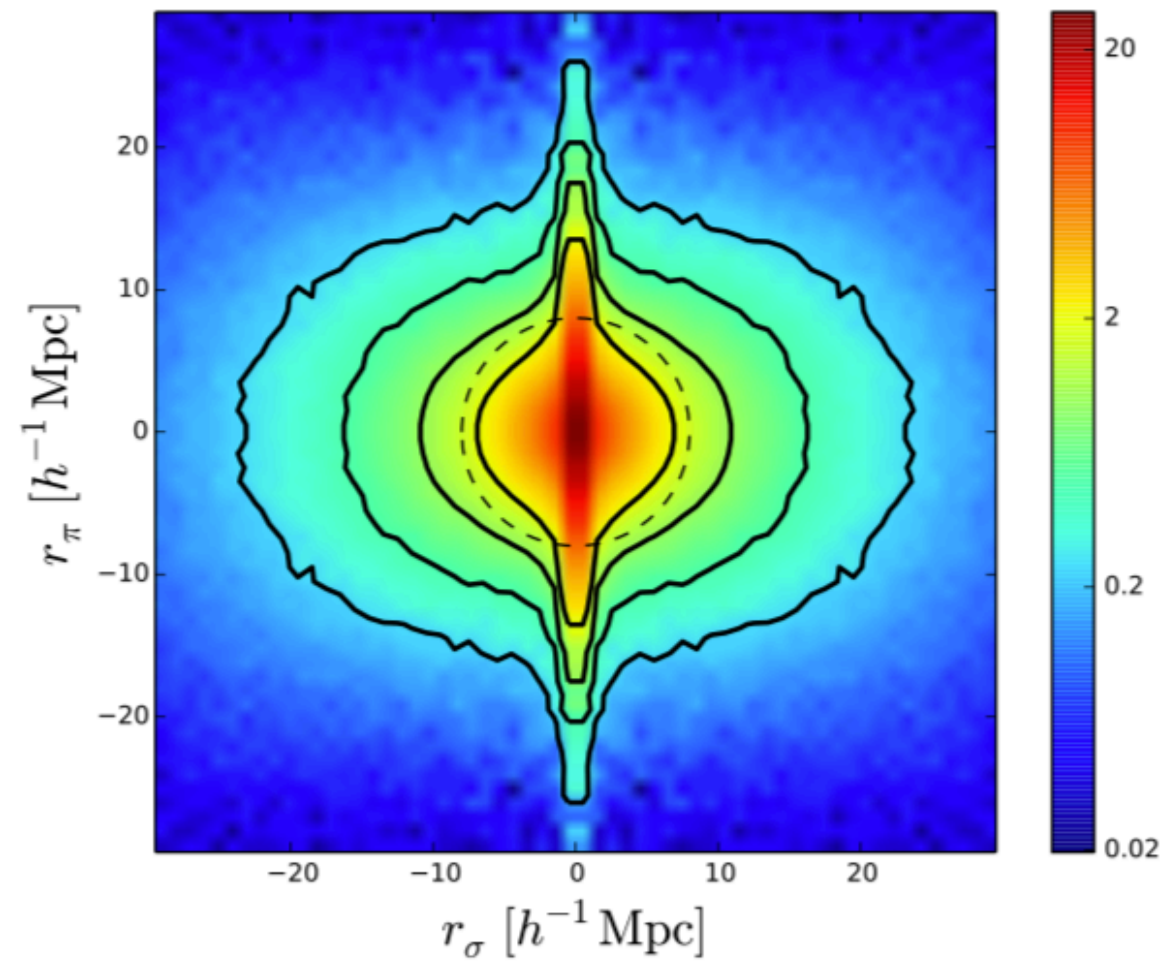
REDSHIFT SPACE DISTORTIONS

- Peculiar velocities shift the position of galaxies in redshift space:

$$\nabla \cdot \mathrm{v}_p = -aHf\delta_m$$

$$\delta_g^s(\mathrm{k}) = (b + f\mu^2)\delta_m^r(\mathrm{k})$$

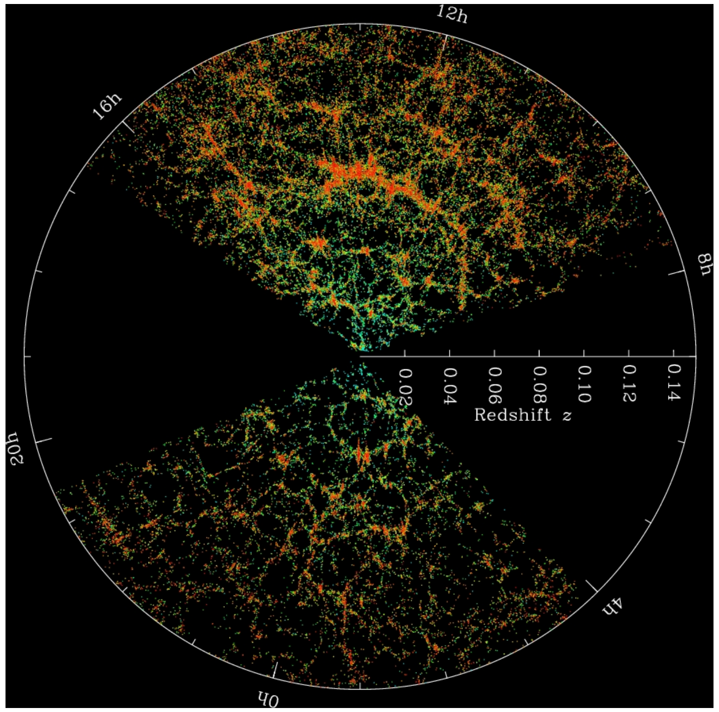
- In the linear regime (>40 h^{-1}Mpc) gives a direct constraint on $f\sigma_8$
- Below ~40 h^{-1}Mpc need to model non-linearities using N-body simulations

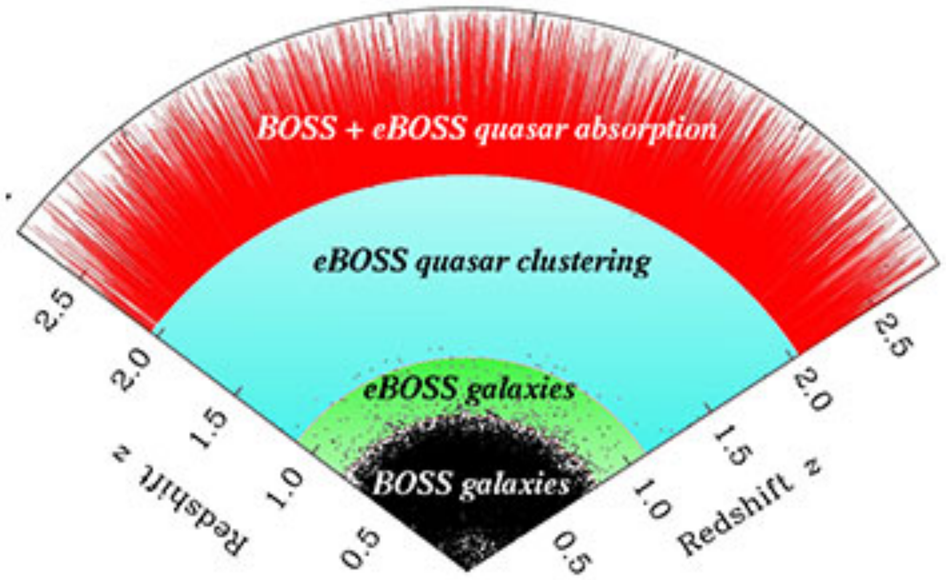


2D correlation function in separation parallel (y-axis) and perpendicular (x-axis) to the line of sight. (Reid et al. 2014, 1404.3742)

EXTENDED BARYON OSCILLATION SPECTROSCOPIC SURVEY (EBOSS)

- Spectroscopic surveys convert redshifts to distances assuming the Hubble flow
- The Baryon Oscillation Spectroscopic Survey (BOSS) observed 1.5 million Luminous Red Galaxies (LRG) in the redshift range (0.1<z<0.7)
- The extended BOSS (eBOSS) observed an additional 300 000 high redshift (0.6<z<1.0) LRGs, as well as ELG and QSO





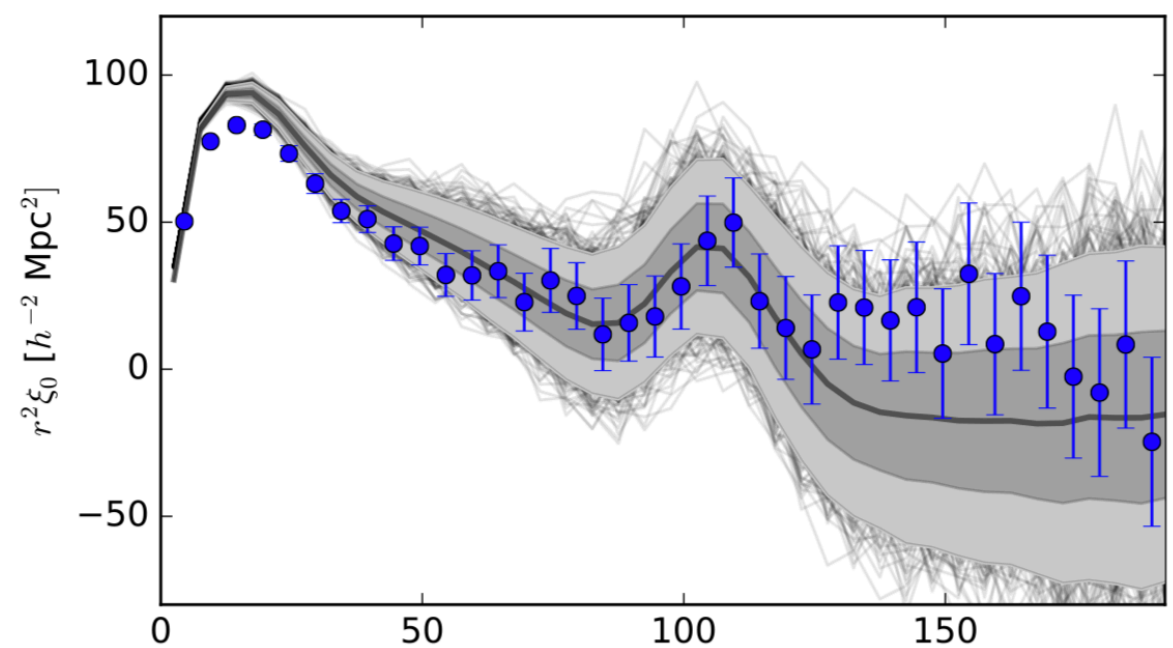
CORRELATION FUNCTION

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

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

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

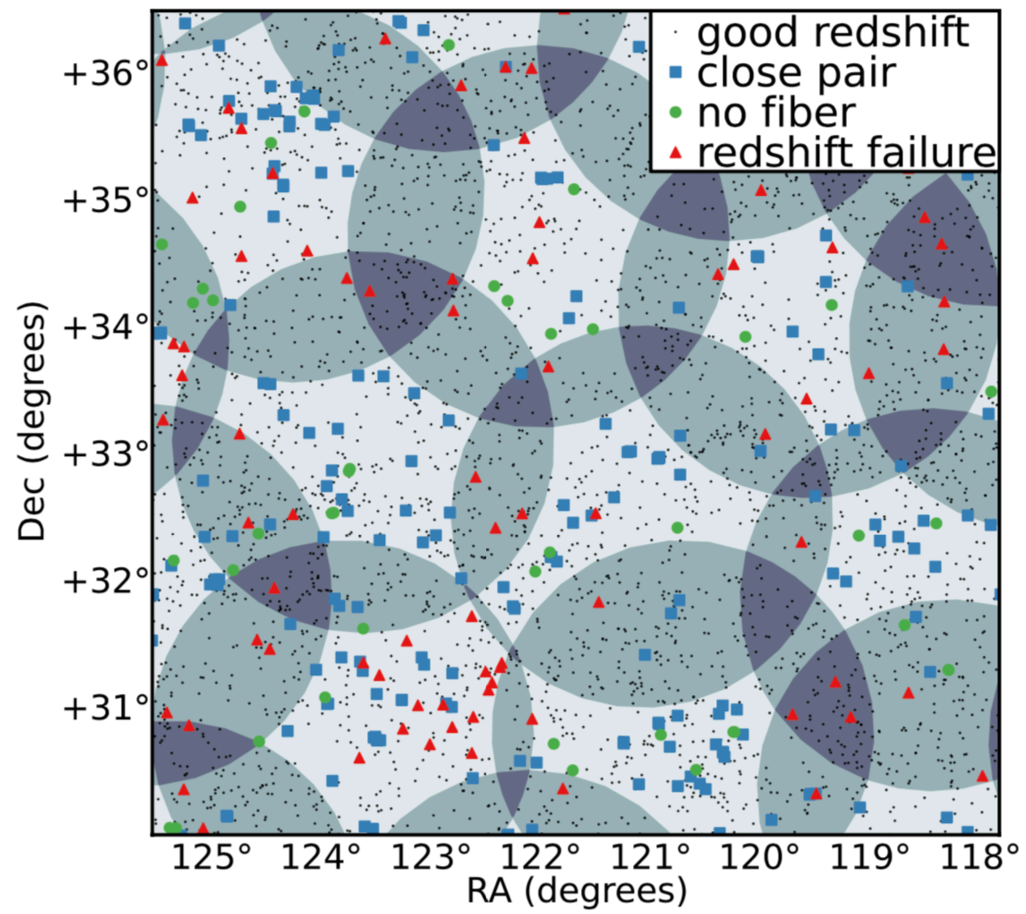
$$\xi_l(s) = \frac{2l+1}{2}\int d\mu_s \xi(s, \mu_s) L_l(\mu_s)$$



Correlation function monopole of the combined BOSS CMASS + eBOSS DR14 (Bautista et al. 2017)

FIBRE-COLLISION

- Physical size of fibre prevents targeting two objects within 62″
- Separation on the sky is correlated with radial separation, leading to a biased sample
- Commonly corrected using nearest-neighbour weights, which approximately correct issue but perform worse on smaller scales



Result of fibre assignment, Ross et al. 2012

REID ET AL. 2014 (1404.3742)

A 2.5% measurement of the growth rate from small-scale redshift space clustering of SDSS-III CMASS galaxies

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2 August 2018

ABSTRACT

We perform the first fit to the anisotropic clustering of SDSS-III CMASS DR10 galaxies on scales of $\sim 0.8 - 32\, h^{-1}$ Mpc. A standard halo occupation distribution model evaluated near the best fit Planck ΛCDM cosmology provides a good fit to the observed anisotropic clustering, and implies a normalization for the peculiar velocity field of $M \sim 2 \times 10^{13}\, h^{-1}\, M_{\odot}$ halos of $f\sigma_8(z = 0.57) = 0.450 \pm 0.011$. Since this constraint includes both quasi-linear and non-linear scales, it should severely constrain modified gravity models that enhance pairwise infall velocities on these scales. Though model dependent, our measurement represents a factor of 2.5 improvement in precision over the analysis of DR11 on large scales, $f\sigma_8(z = 0.57) = 0.447 \pm 0.028$, and is the tightest single constraint on the growth rate of cosmic structure to date. Our measurement is consistent with the Planck ΛCDM prediction of 0.480 ± 0.010 at the $\sim 1.9\sigma$ level. Assuming a halo mass function evaluated at the best fit Planck cosmology, we also find that 10% of CMASS galaxies are satellites in halos of mass $M \sim 6 \times 10^{13}$ $h^{-1}\, M_{\odot}$. While none of our tests and model generalizations indicate systematic errors due to an insufficiently detailed model of the galaxy-halo connection, the precision of these first results warrant further investigation into the modeling uncertainties and degeneracies with cosmological parameters.

Key words: cosmology: large-scale structure of Universe, cosmological parameters, galaxies: haloes, statistics

- Reid et al. 2014 made a 2.5% measurement of $f\sigma_8$ using small-scale clustering within the BOSS CMASS sample
- Found factor of 2.5 improvement in statistical error over large scales
- Systematics dominated by fixed cosmology modelling and fibre collision effect

WHAT DO YOU DO BETTER?

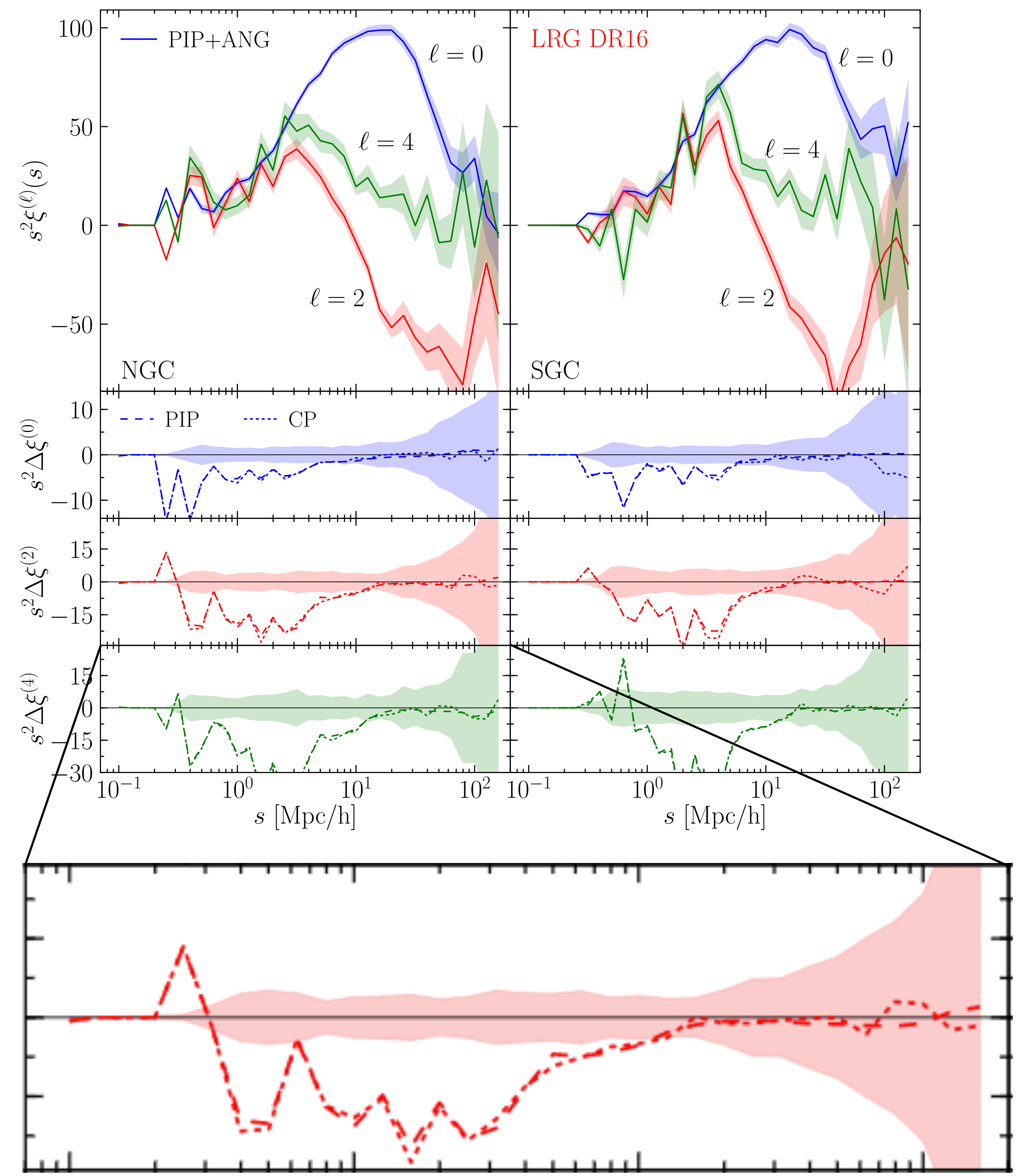
METHODS

PAIRWISE-INVERSE-PROBABILITY WEIGHTING (PIP)

- Inversely weight pairs by the probability of the pair being observed
- Combined with angular upweighting (ANG) to correct single-pass regions

$$DD(\vec{s}) = \sum \mathrm{w}^{\mathrm{PIP}}_{mn} w^{\mathrm{tot}}_{m} w^{\mathrm{tot}}_{n} \times \frac{DD_{\mathrm{par}}(\theta)}{DD^{\mathrm{PIP}}_{\mathrm{fib}}(\theta)}$$

- See Mohammad et al. 2020 (2007.09005) for details



HALO OCCUPATION DISTRIBUTION (HOD)

- Probability distribution $P(N|M)$ that a halo of mass M contains N galaxies
- Our model separates the occupation of centrals and satellites, and depends on 5 free parameters

$$N_{cen}(M) = \frac{f_{max}}{2}\left[1 + \text{erf}\left(\frac{\log_{10} M - \log_{10} M_{min}}{\sigma_{\log M}}\right)\right]$$

$$N_{sat}(M) = \left(\frac{M}{M_{sat}}\right)^{\alpha} \exp\left(-\frac{M_{cut}}{M}\right) \frac{N_{cen}(M)}{f_{max}}$$

AEMULUS COSMOLOGICAL EMULATOR

- Gaussian process based machine learning from N-body simulations to predict galaxy correlation functions to <1% without the need to run additional simulations each step
- 16 parameter model; 7 wCDM parameters and 9 HOD parameters

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

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

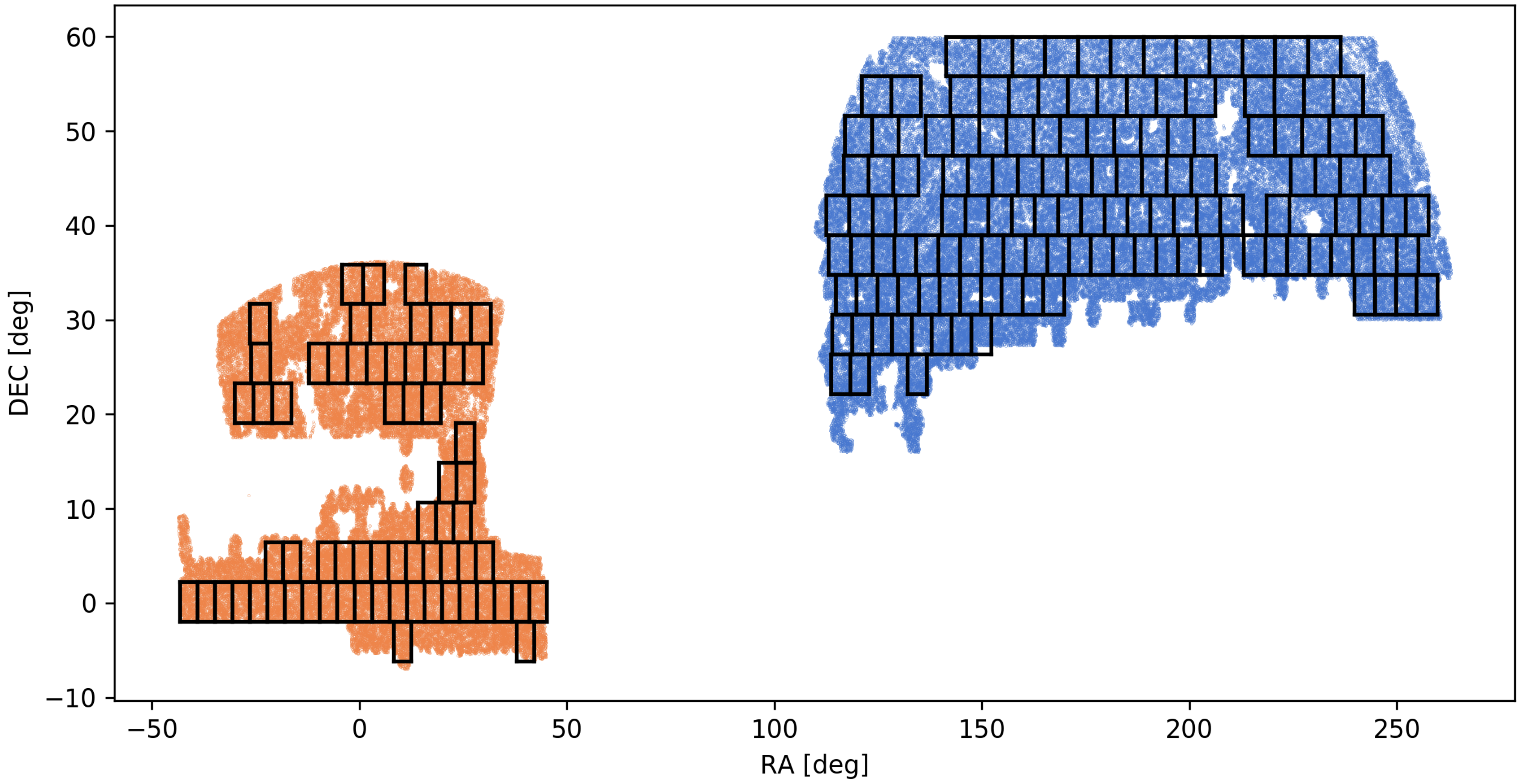
- In the linear regime a fractional change in γ_f is equal to a fractional change in the linear growth rate, $f = \gamma_f f_{wCDM}$
- We keep N_{eff}, w fixed for a total of 14 free parameters

JACKKNIFE COVARIANCE MATRIX

- Divide survey into equal area regions, and remove regions with low occupation to ensure all regions contribute approximately equally and are not affected by geometry

$$C_{i,j} = \frac{n-1}{n} \sum_{k}^{n} (\xi_{i,k} - \bar{\xi}_i)(\xi_{j,k} - \bar{\xi}_j)$$

- Rescale covariance matrix by the ratio of $R_{assigned}/R_{full}$ to match effective volume of full sample

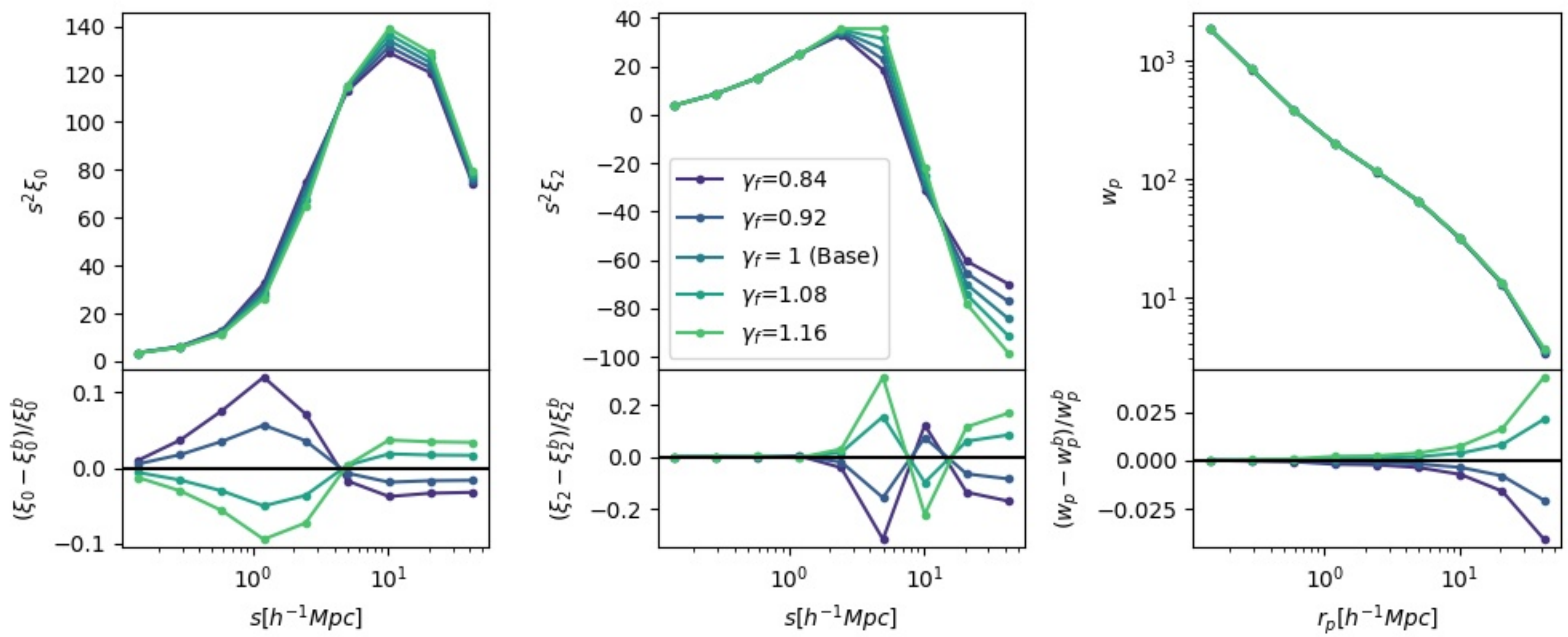


GREAT. DOES IT WORK THOUGH?

ROBUSTNESS CHECKS

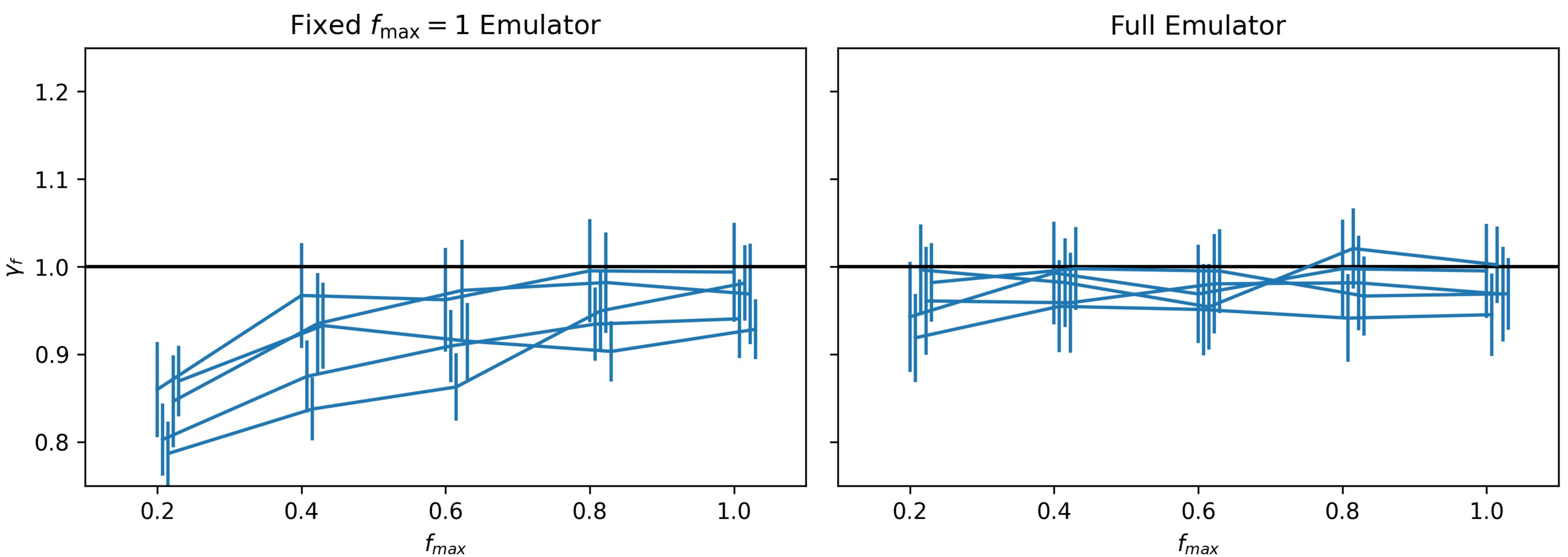
NON-LINEAR VELOCITIES

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



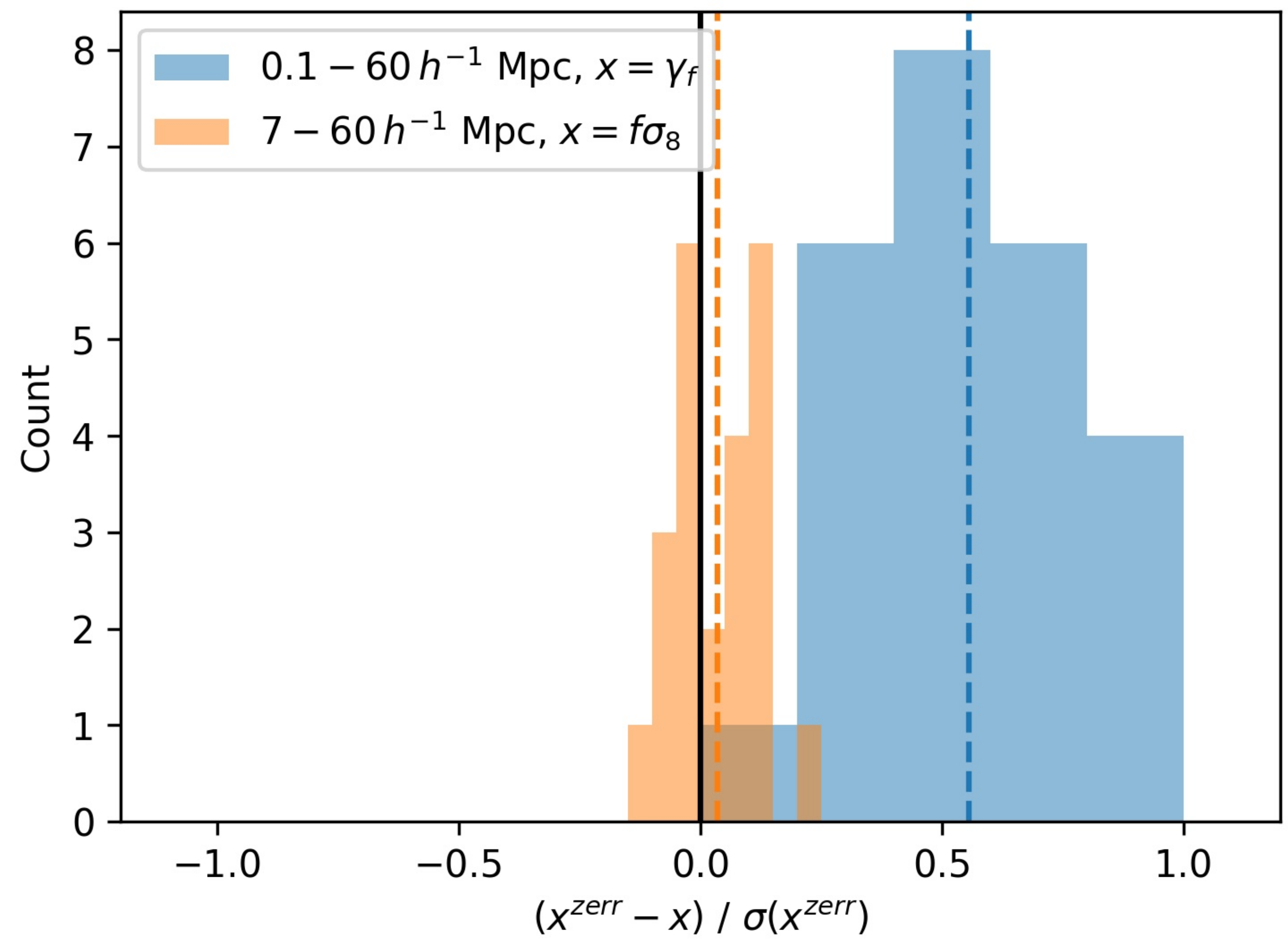
GALAXY SELECTION

- eBOSS is targeted using magnitude cuts, so some bright galaxies are excluded
- Without f_{max} the HOD model assumes all high mass halos contain a central galaxy, so that the model sample is more highly biased than the data sample

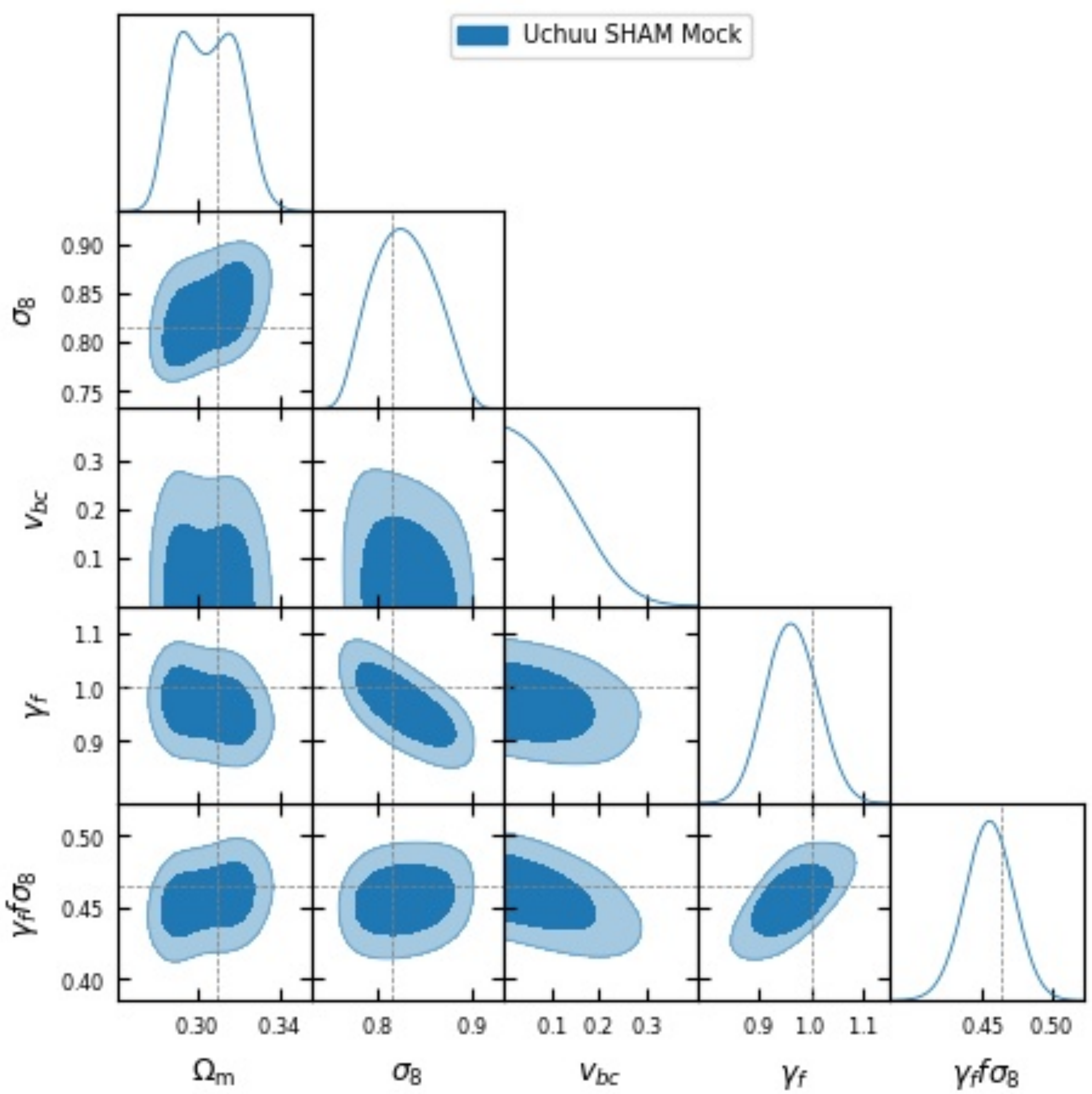


REDSHIFT UNCERTAINTY

- 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 increase our tension with ΛCDM



MOCK TESTING



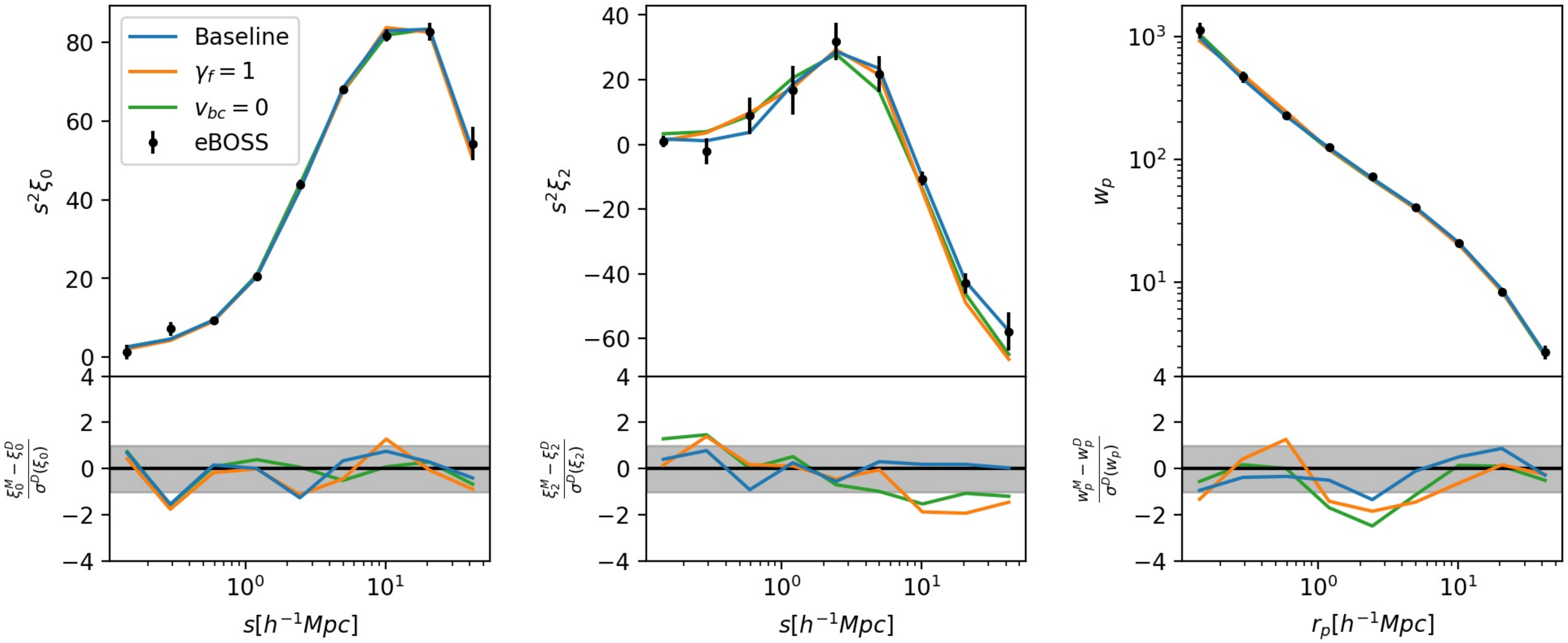
- Tested full pipeline using a SHAM mock
- Using a different galaxy-halo connection model shows that the HOD parameterization is robust
- Recovered the expected value of γ_f

GET TO THE INTERESTING PART ALREADY!

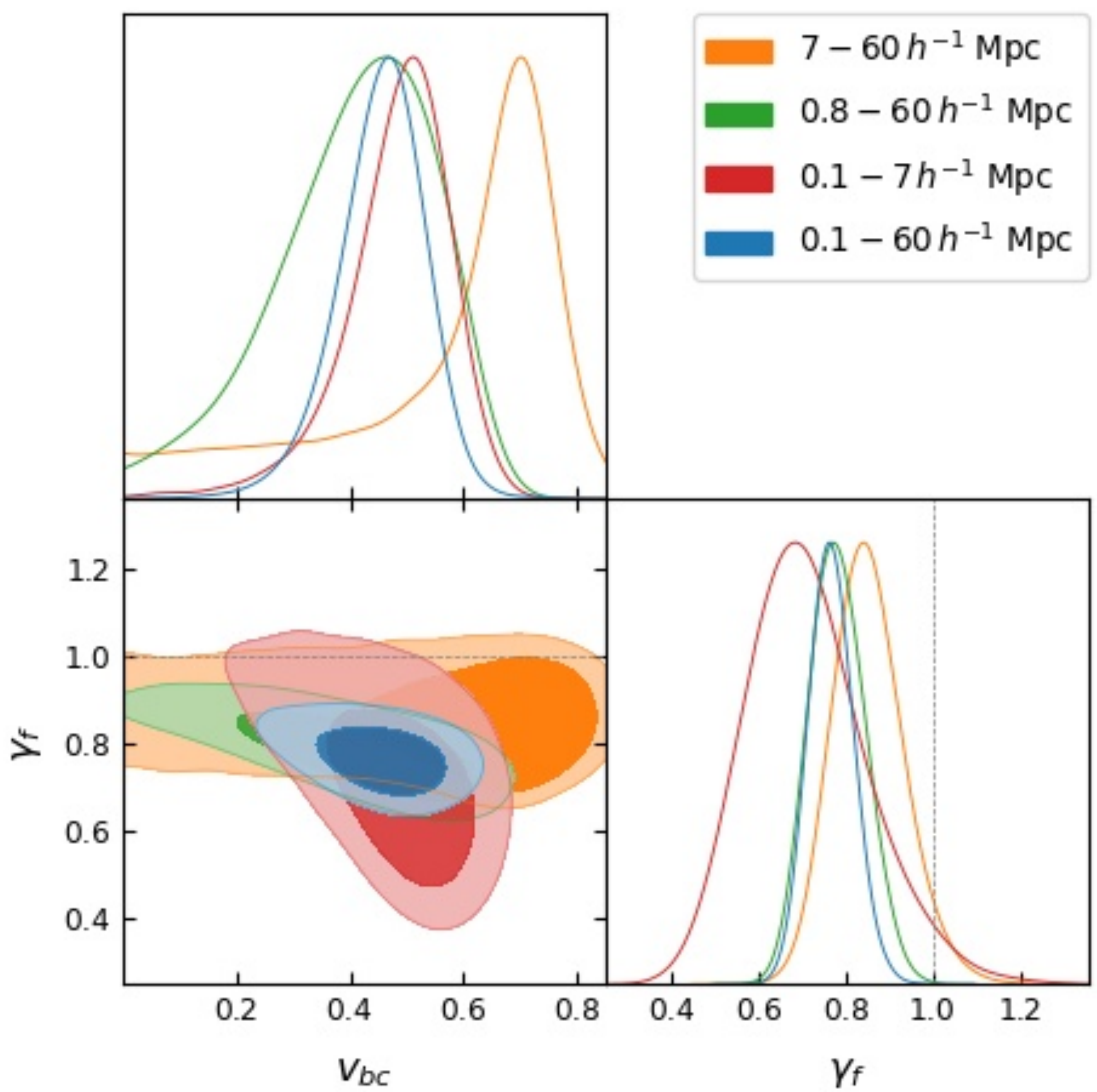
RESULTS

HEADLINE RESULTS

- Using $7 < r < 60\,\mathrm{km/s}$ 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 $0.1 < r < 60\,\mathrm{km/s}$ measure $\gamma_f = 0.767 \pm 0.052$, 4.5σ below the value for ΛCDM



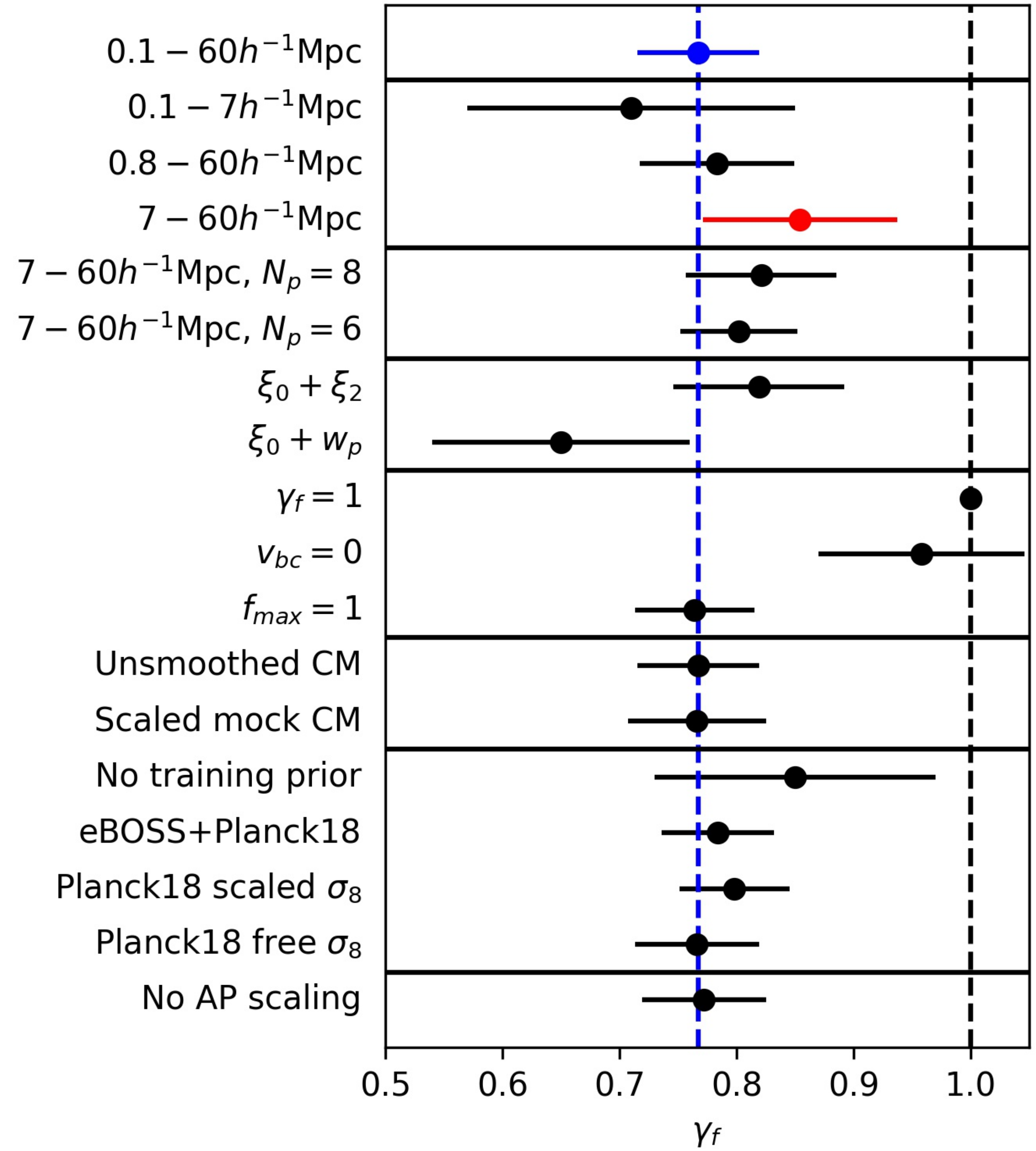
SCALE DEPENDENCE



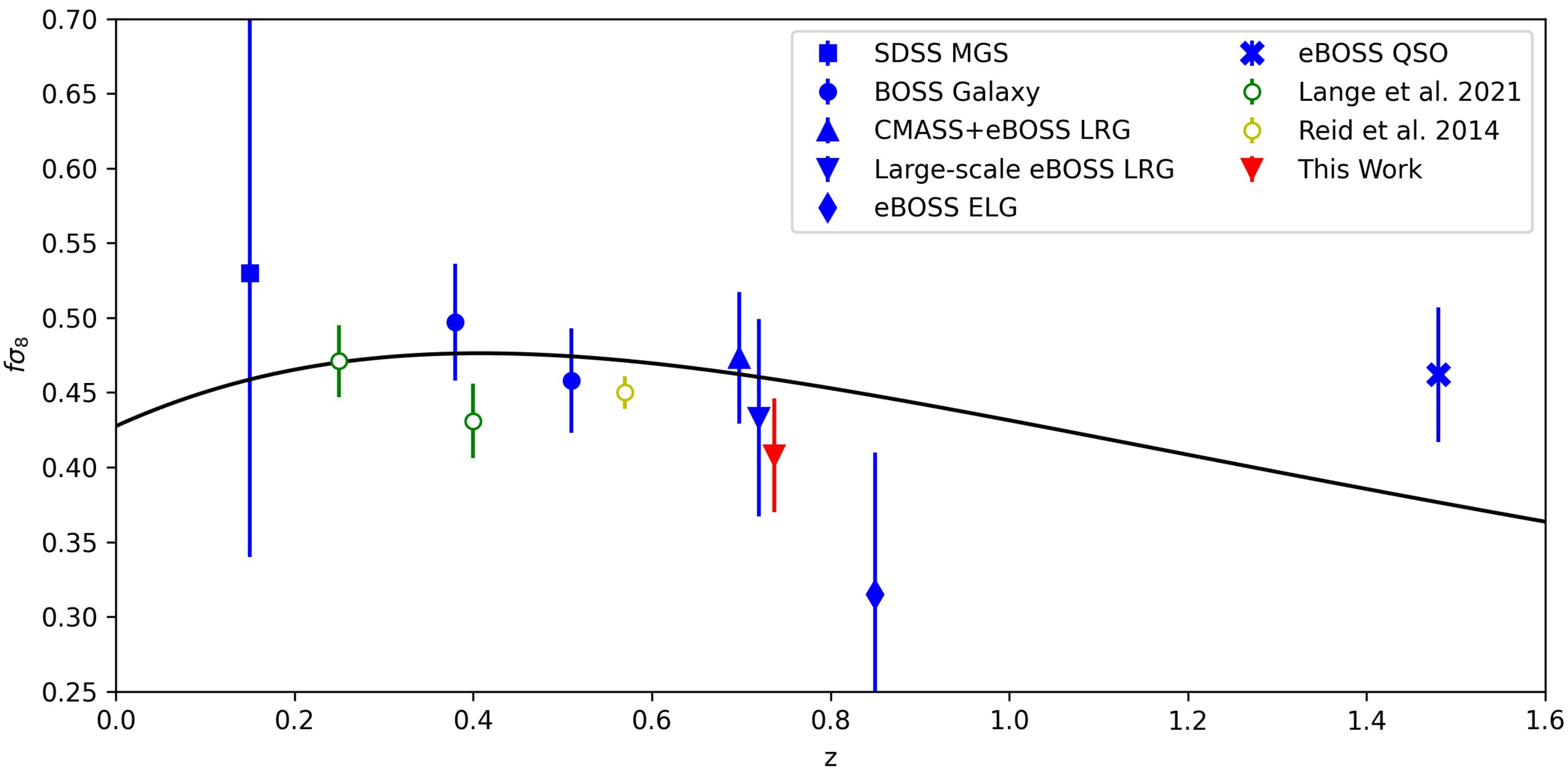
- Small scales prefer a low value of γ_f and non-zero $v_{\rm bc}$
- Large scales prefer a larger value of γ_f and no degeneracy with $v_{\rm bc}$
- The non-linear scales drive the stronger tension from all scales

ALL FITS

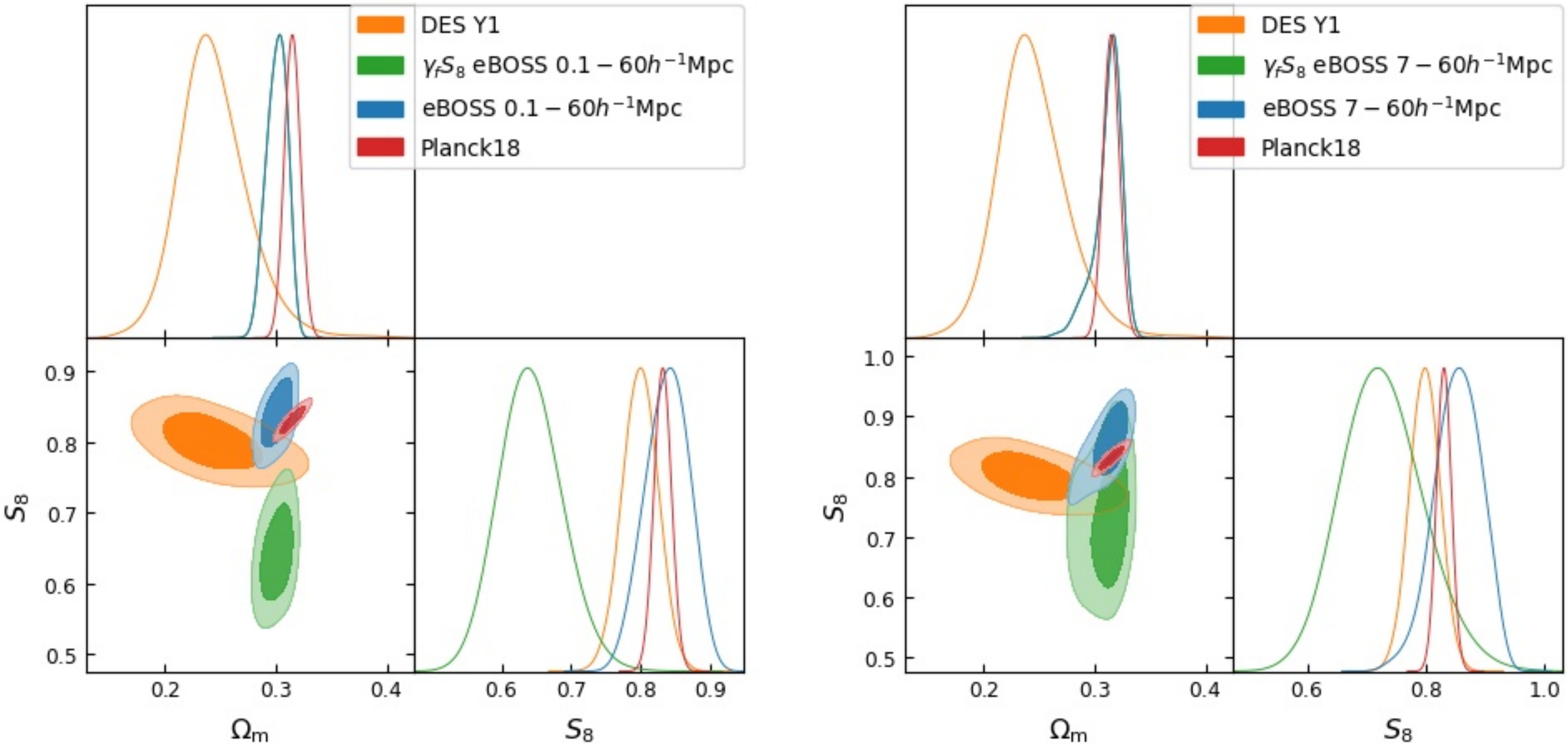
Run	γ_f	N_P	N_D	χ^2
$0.1-60\,h^{-1}$Mpc	0.767 ± 0.052	14	27	14.1
$0.1-7\,h^{-1}$Mpc	0.71 ± 0.14	14	18	7.8
$0.8-60\,h^{-1}$Mpc	0.783 ± 0.066	14	18	4.2
$7-60\,h^{-1}$Mpc	0.854 ± 0.083	14	9	0.36
$7-60\,h^{-1}$Mpc, 8 parameters	0.821 ± 0.064	8	9	0.74
$7-60\,h^{-1}$Mpc, 6 parameters	0.802 ± 0.050	6	9	1.8
$\xi_0 + \xi_2$	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
$v_{bc} = 0$	0.958 ± 0.088	13	27	22.5
$f_{max} = 1$	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



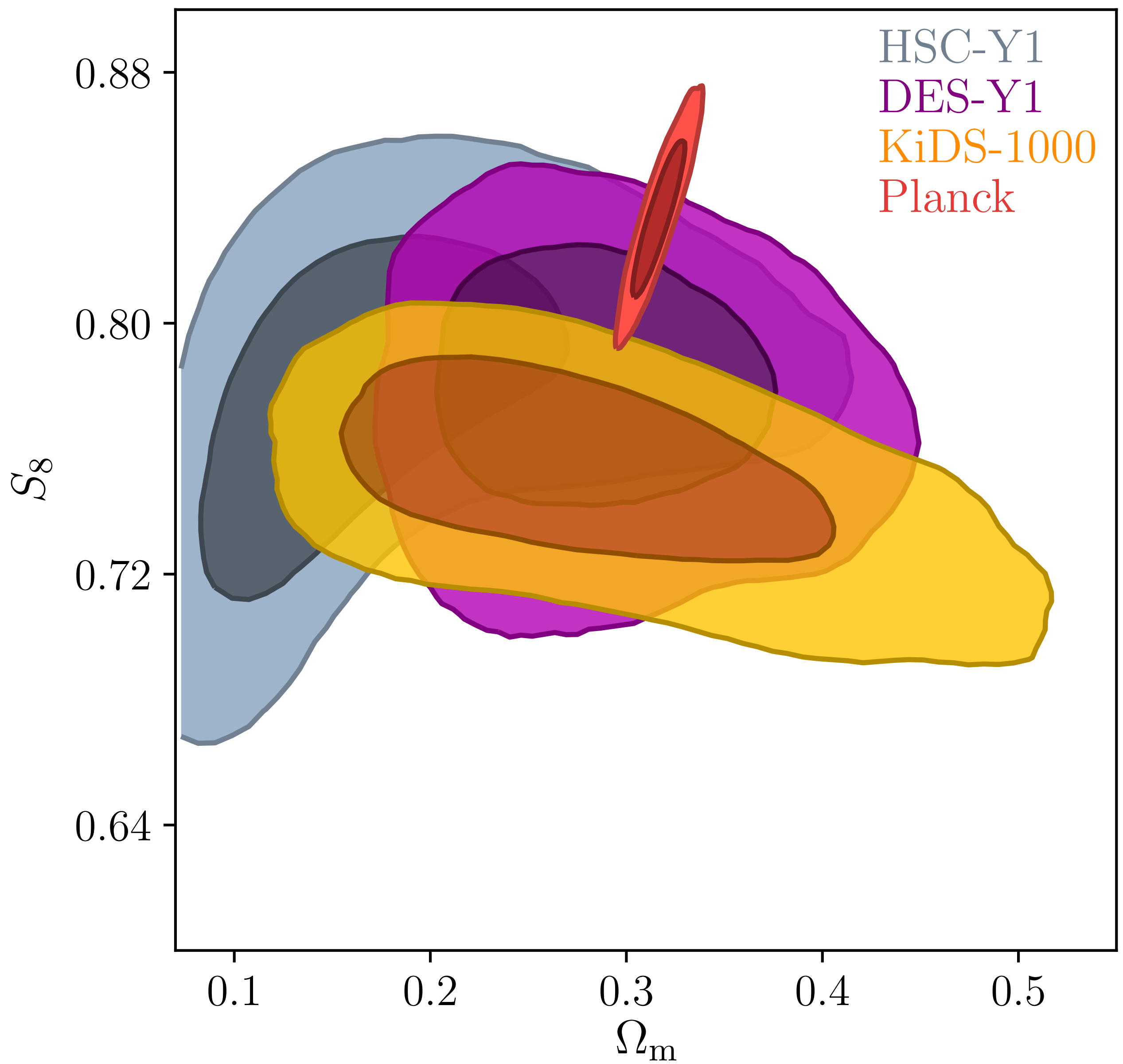
COMPARISON TO OTHER SDSS RESULTS

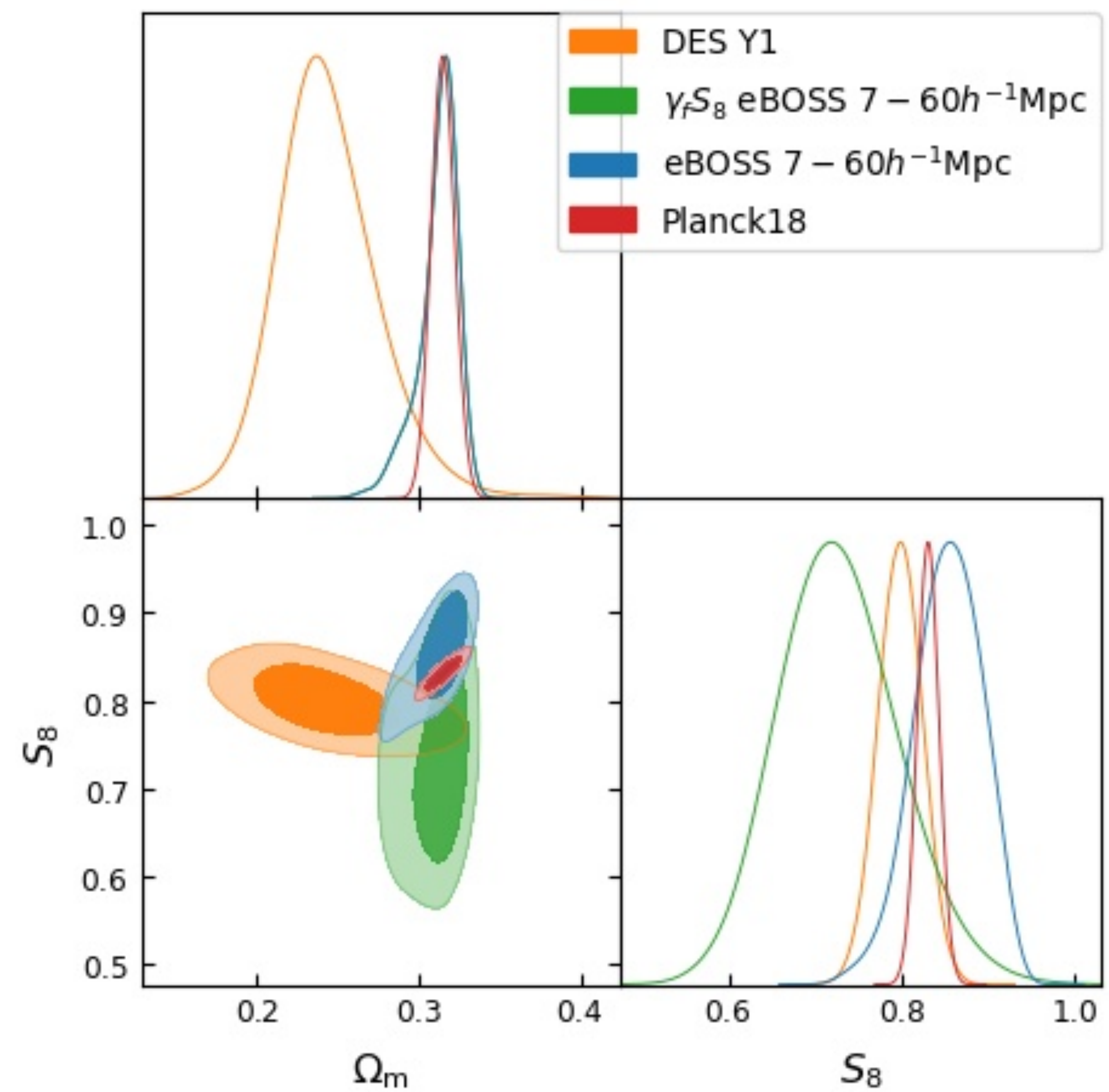


COMPARISON TO LENSING

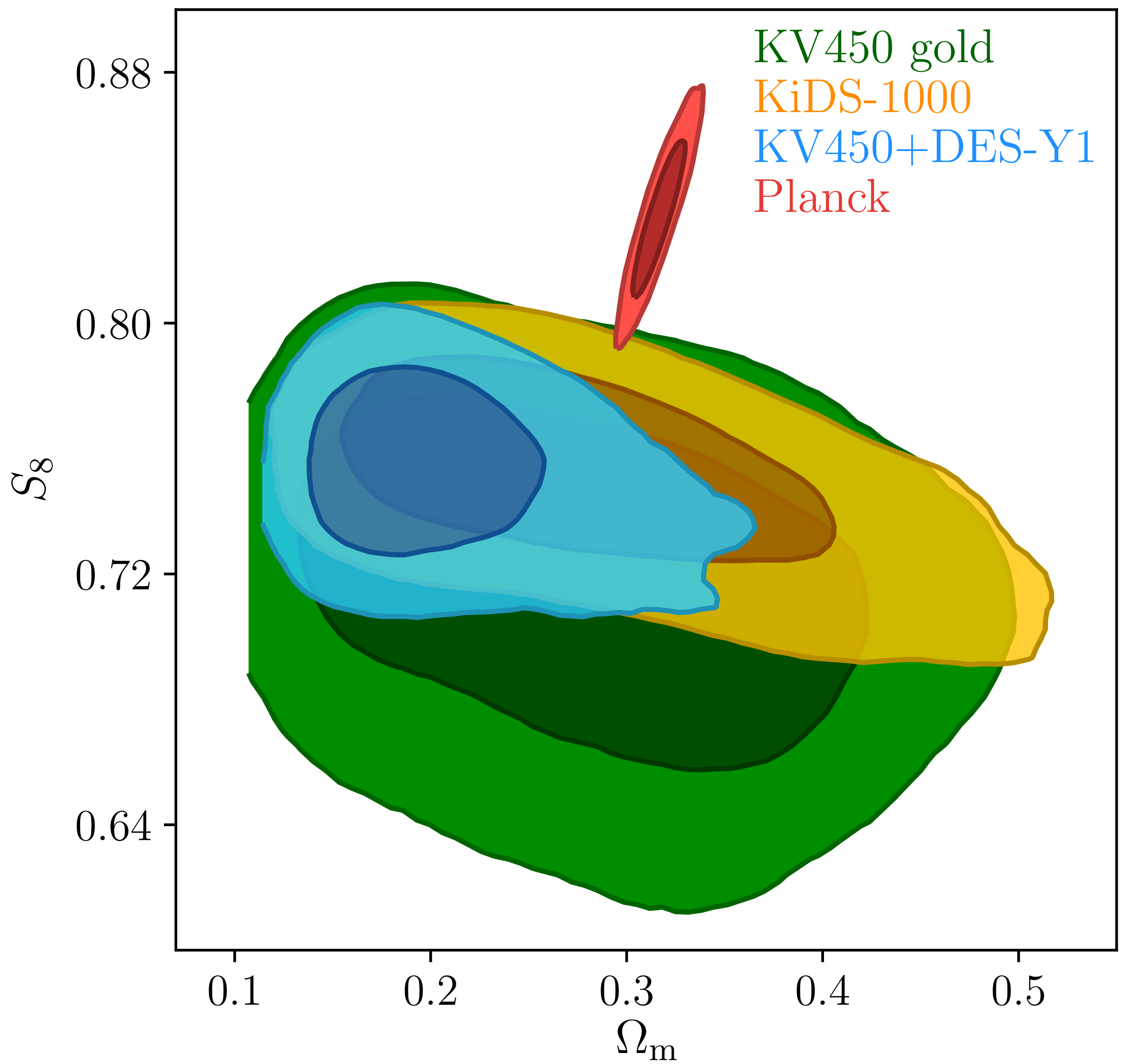


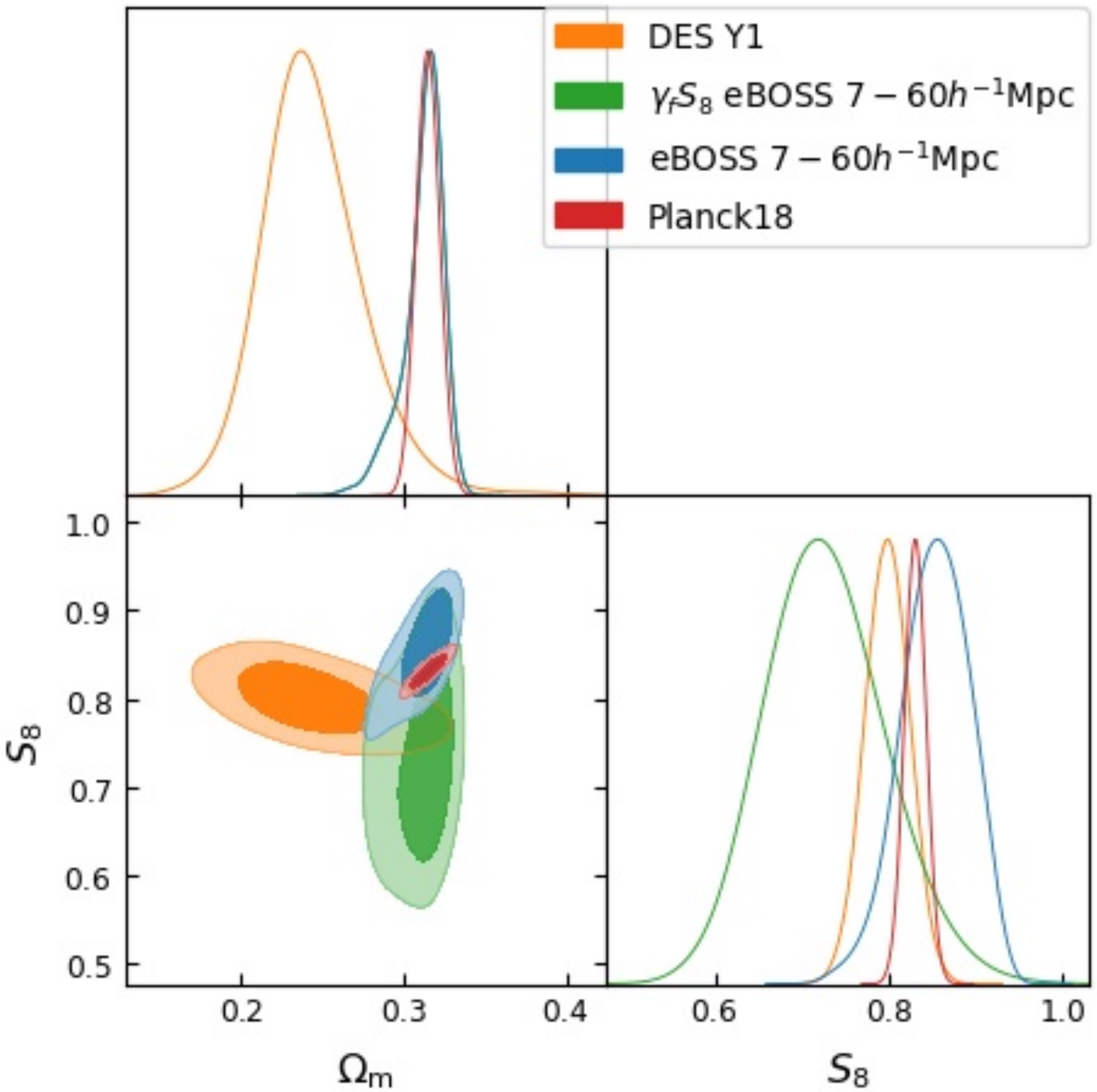
COMPARISON TO LENSING





COMPARISON TO LENSING





POTENTIAL IMPROVEMENTS

- Redshift uncertainty is a significant source of systematic uncertainty, especially at higher redshifts (DESI, Euclid)
- The uncertainty is limited by the emulator error in many measurement bins
- We make a conservative separation cut to isolate the linear information, but additional information could be extracted from non-linear scales
- The source of the tension from non-linear scales is unknown (baryonic physics, HOD model breakdown, new physics?)

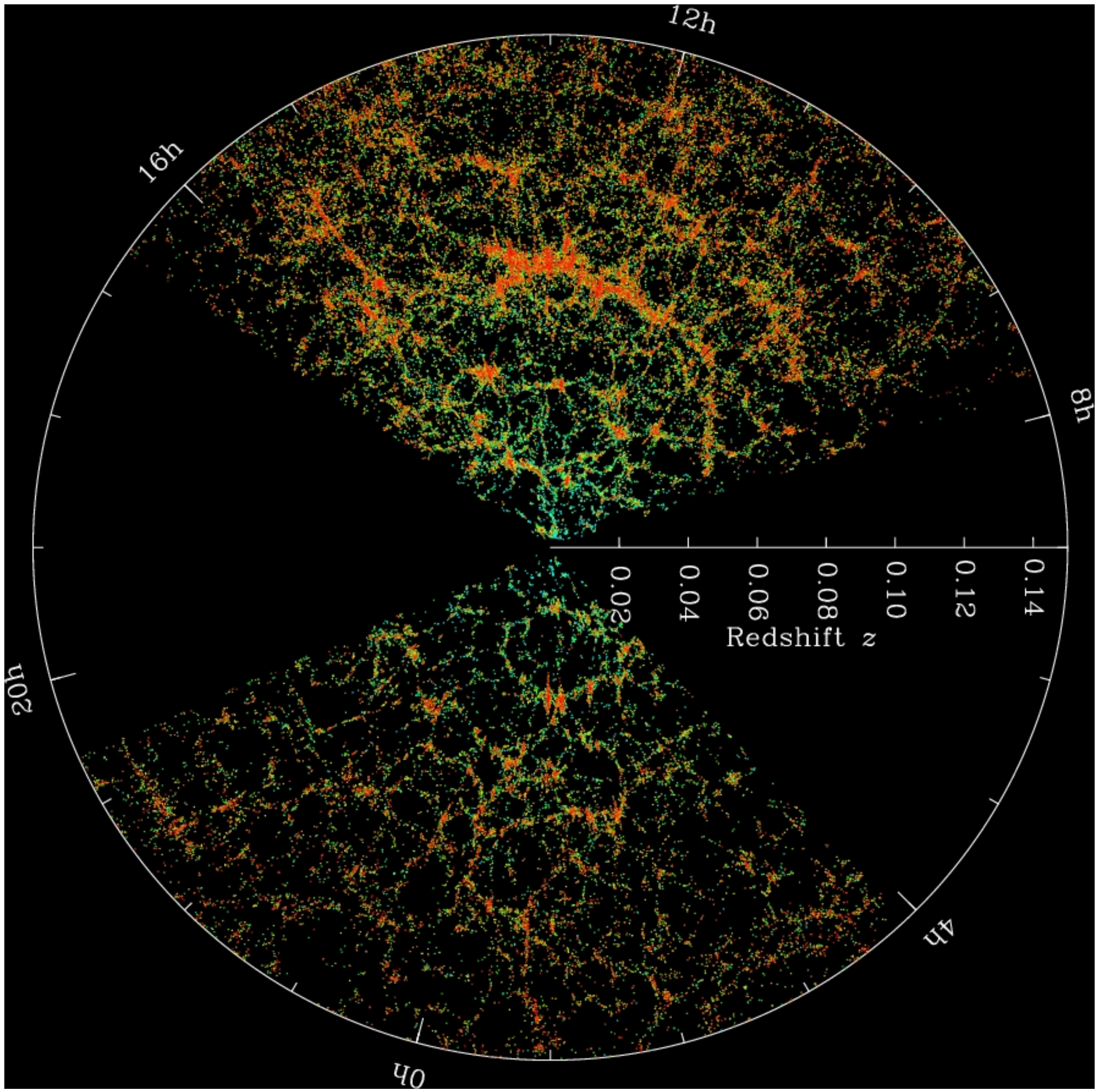
SUMMARY

- We use PIP+ANG weights and Aemulus emulator remove the major systematics of previous analyses
- 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 $0.1 < r < 60\,\mathrm{km/s}$ find 4.5σ tension with ΛCDM
- Redshift uncertainty, impact of non-linear velocities, and breakdown of HOD model important for future analyses
- Contact me at **mj3chapm@uwaterloo.ca** with additional comments and questions!

BUT WHAT ABOUT…?

EXTRA SLIDES

SPECTROSCOPIC GALAXY SURVEYS

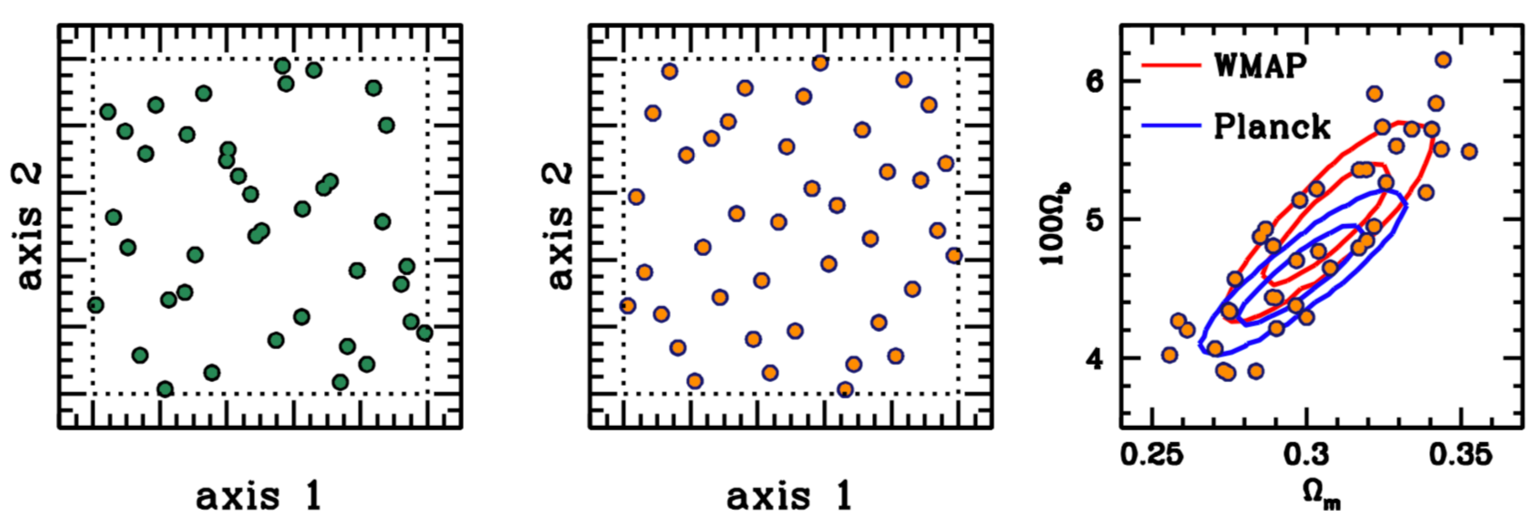


- Determine redshift from spectra of distant galaxies
- Redshifts are converted to distances assuming the recession is caused by the expansion of the Universe

$$d_C(z) = c\int_0^z \frac{dz'}{H(z')}$$

AEMULUS COSMOLOGICAL EMULATOR

- Gaussian process based machine learning from N-body simulations to predict galaxy correlation functions
- Latin hypercube efficiently samples cosmological parameter space
- Results accurate to <1% without the need to run additional simulations each step



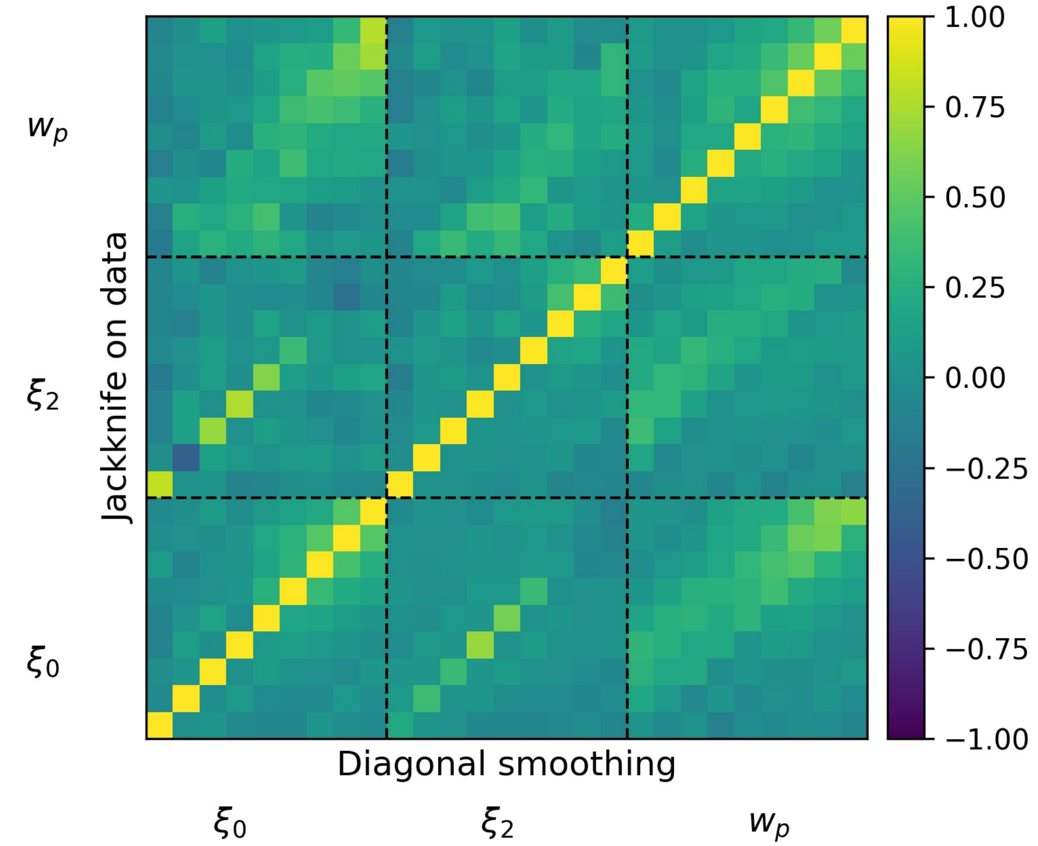
2D Projection of 7D parameter space, DeRose et al. 2018 (1804.05865)

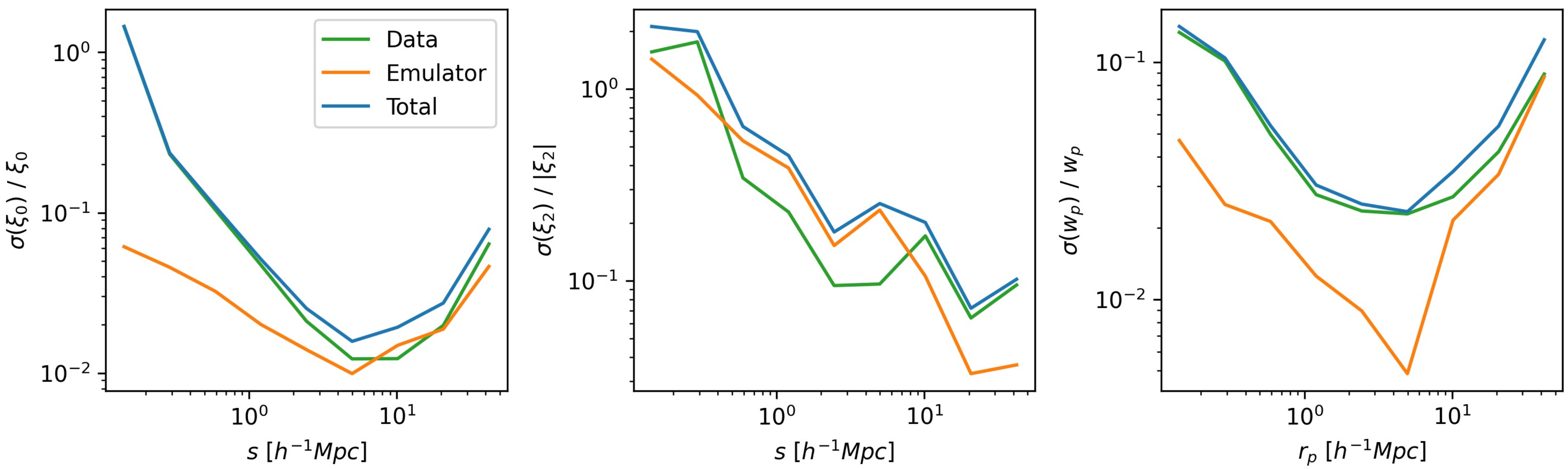
JACKKNIFE COVARIANCE MATRIX

1. Choose occupation threshold, N_t, desired number of regions, N_R, and estimated region size, l
2. Cover eBOSS footprint with equal area square regions of side length l
3. Remove all regions below occupation threshold ($N < N_t$)
4. If number of remaining regions, N_r, is greater than N_R proceed to Step 5, otherwise reduce l and repeat Steps 2-4
5. Remove lowest occupation regions until $N_r = N_R$

JACKKNIFE COVARIANCE MATRIX

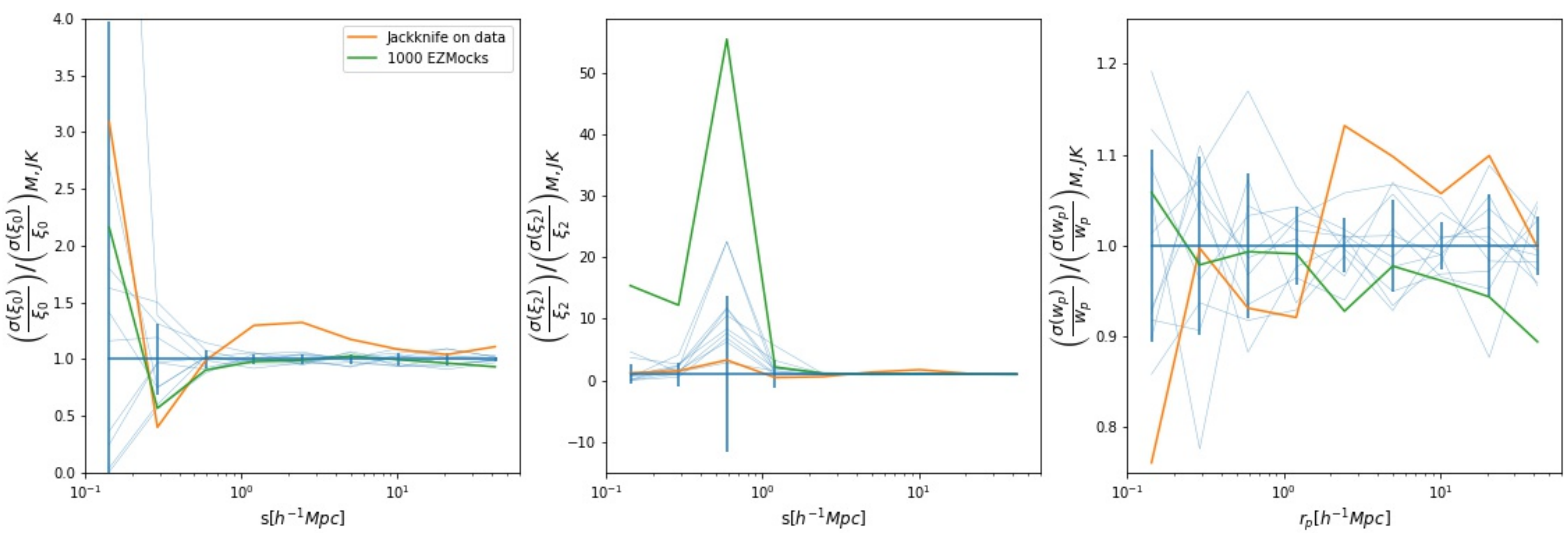
- Correlation matrix is highly diagonal so we smooth along the diagonals
- Combine with emulator error and apply Hartlap factor for final covariance matrix





JACKKNIFE COVARIANCE MATRIX

- Comparing diagonal elements using relative error and find agreement between data JK, 1000 mocks, and JK on mocks



AP SCALING

- Corrects for difference between the true cosmology and the cosmology assumed for distance calculations

$$a_\perp = \frac{D_M(z_{\rm eff})}{D_M^{\rm fid}(z_{\rm eff})} \quad , \quad a_\parallel = \frac{D_H(z_{\rm eff})}{D_H^{\rm fid}(z_{\rm eff})}$$

$$\xi_0^{\rm fid}(r^{\rm fid}) = \xi_0(\alpha r) + \frac{2}{5}\epsilon\left[3\xi_2(\alpha r) + \frac{d\xi_2(\alpha r)}{d\ln(r)}\right]$$

$$\xi_2^{\rm fid}(r^{\rm fid}) = (1 + \frac{6}{7}\epsilon)\xi_2(\alpha r) + 2\epsilon\frac{d\xi_0(\alpha r)}{d\ln(r)} + \frac{4}{7}\epsilon\frac{d\xi_2(\alpha r)}{d\ln(r)}$$

$$w_p^{\rm fid}(r_p^{\rm fid}) = w_p(a_\perp r_p)$$

EXPLORING THE LIKELIHOOD

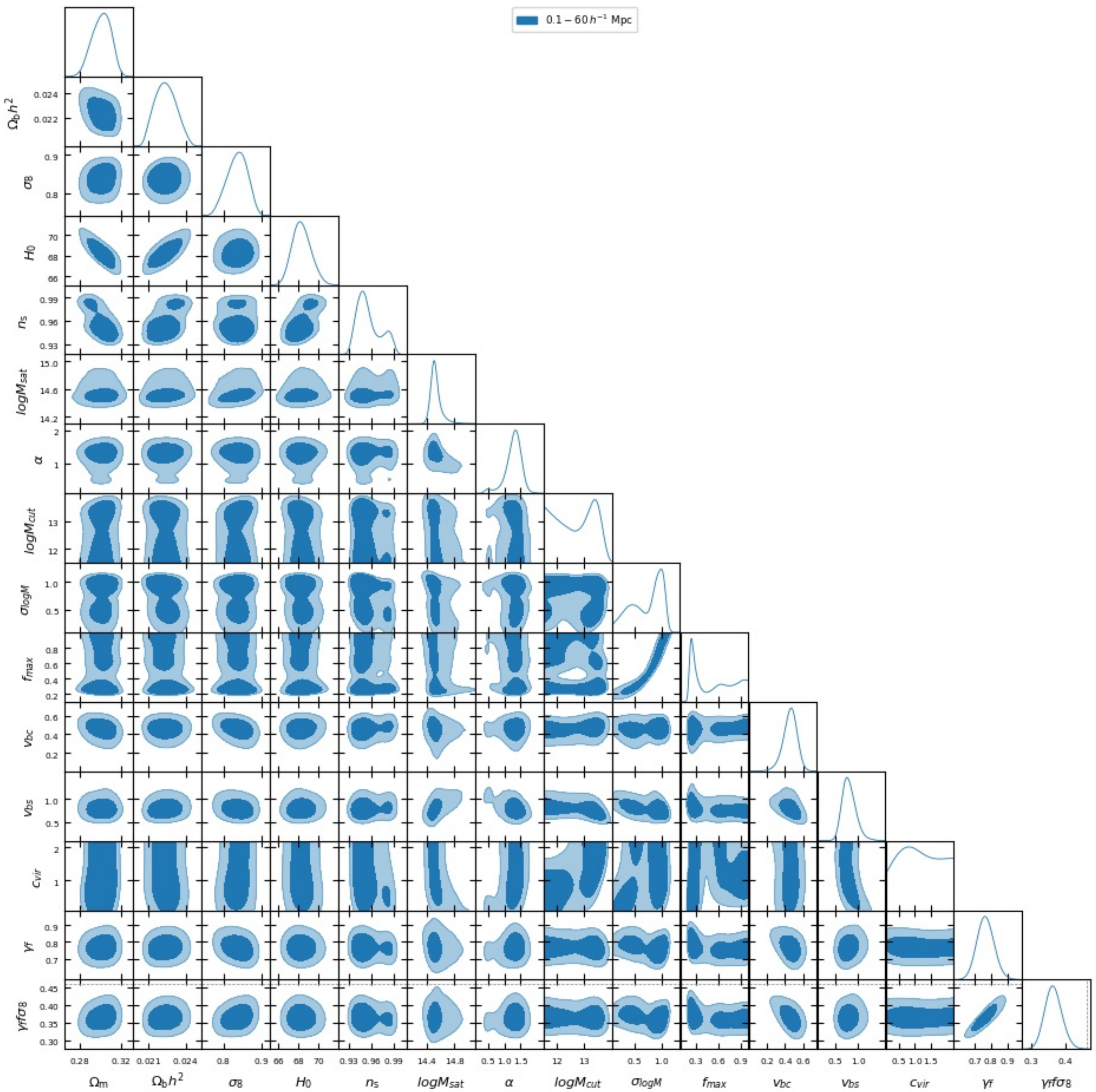
- Use Cobaya MCMC sampler to explore the likelihood
- Use priors slightly larger than training range to detect poorly constrained parameters
- Test additional cosmological priors restricting parameters using a distance threshold from the training points and Planck2018 constraints

Parameter	Training Range	Prior Range
Ω_m	[0.255, 0.353]	[0.225, 0.375]
$\Omega_b h^2$	[0.039, 0.062]	[0.005, 0.1]
σ_8	[0.575, 0.964]	[0.5, 1]
h	[0.612, 0.748]	[0.58, 0.78]
n_s	[0.928, 0.997]	[0.8, 1.2]
$N_{\rm eff}$	[2.62, 4.28]	3.046
w	[-1.40, -0.57]	-1
$\log M_{\rm sat}$	[14.0, 16.0]	[13.8, 16.2]
α	[0.2, 2.0]	[0.1, 2.2]
$\log M_{\rm cut}$	[10.0, 13.7]	[11.5, 14]
$\sigma_{\log M}$	[0.1, 1.6]	[0.08, 1.7]
$v_{\rm bc}$	[0, 0.7]	[0, 0.85]
$v_{\rm bs}$	[0.2, 2.0]	[0.1, 2.2]
$c_{\rm vir}$	[0.2, 2.0]	[0.1, 2.2]
γ_f	[0.5, 1.5]	[0.25, 1.75]
$f_{\rm max}$	[0.1, 1]	[0.1, 1]

UCHUU

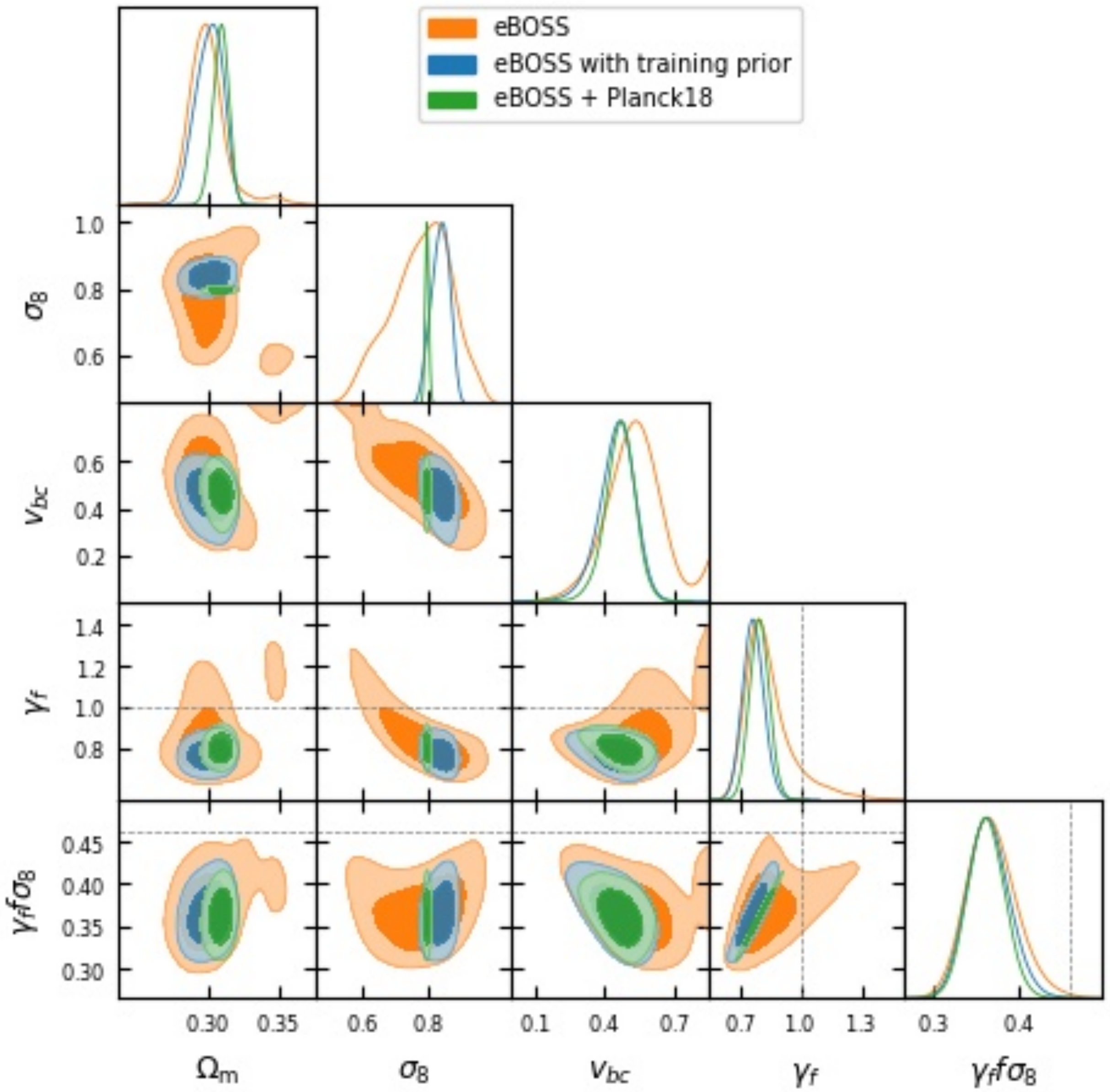
- Large, high resolution simulation with Rockstar halos
- $L_{box} = 2000\ Mpc/h$, 12800^3 particles, $3.27 \times 10^8 M_{\odot}/h$
- Created HOD and SHAM mocks for robustness checks

HEADLINE RESULTS



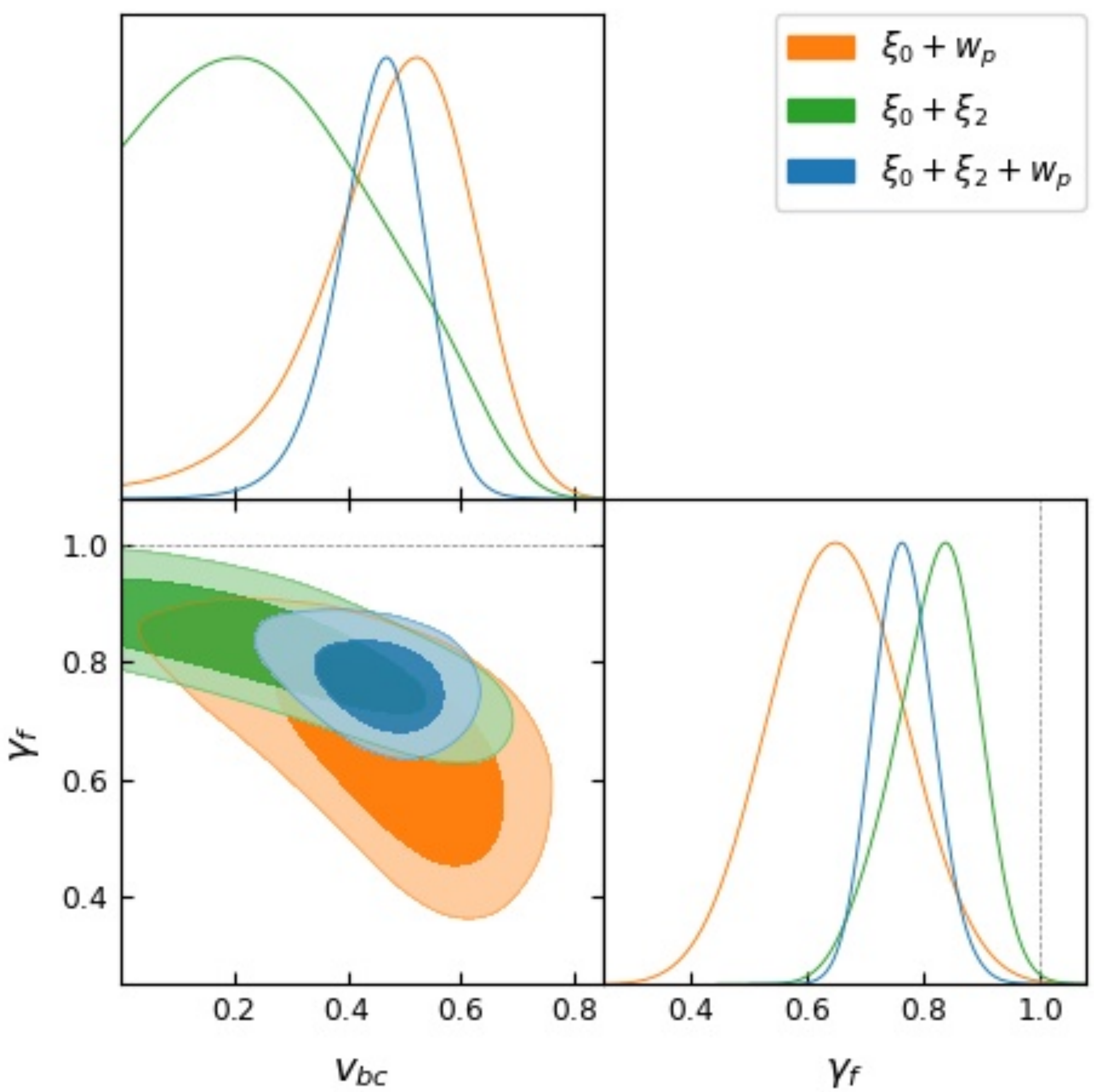
- All well-constrained parameters are within the training range
- All cosmological parameters consistent with Planck2018
- Close to Gaussian constraints on parameters of interest

TESTING COSMOLOGICAL PRIORS



- Aemulus training prior restricts cosmological parameters to well trained region
- Tested combined fit with Planck2018 TT+EE+TE+lensing likelihoods
- Find consistent constraints in all cases

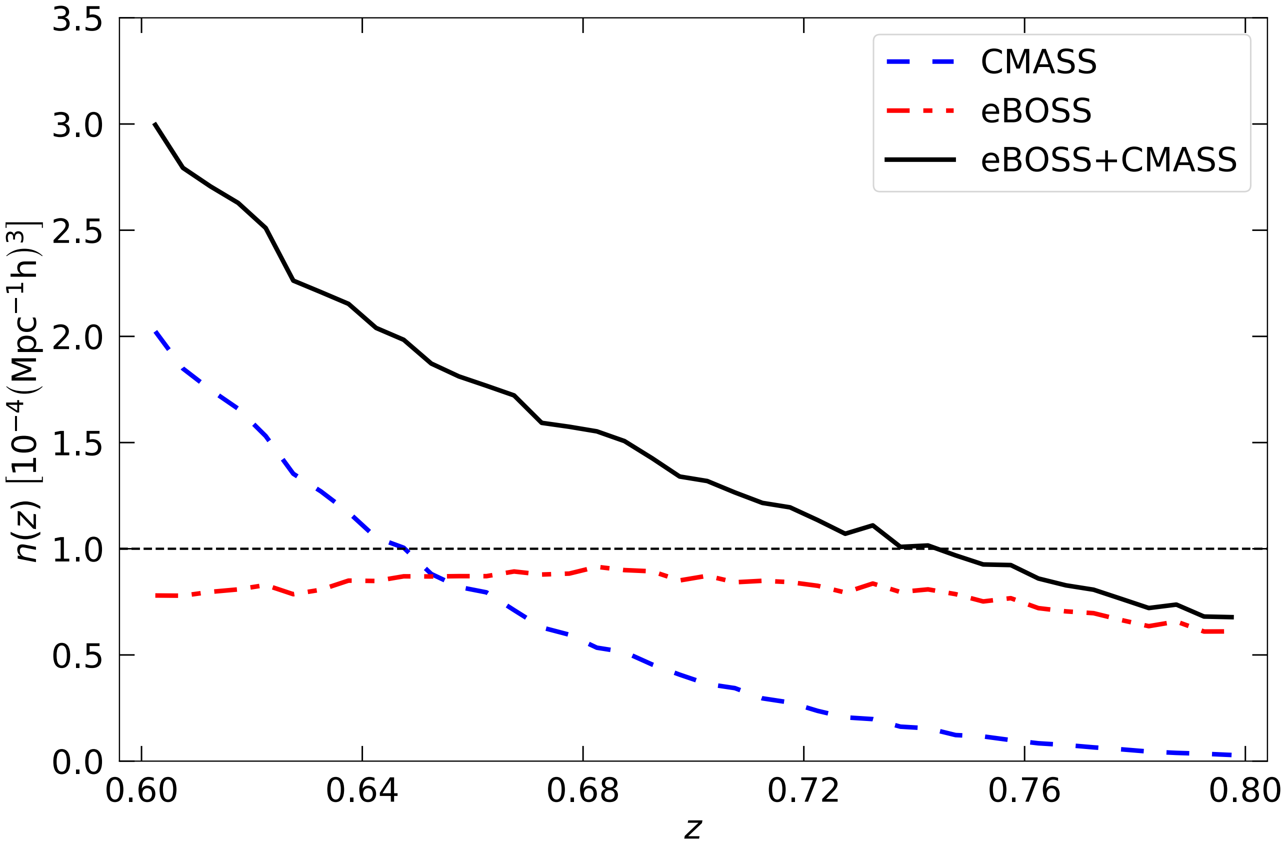
MEASUREMENT DEPENDENCE



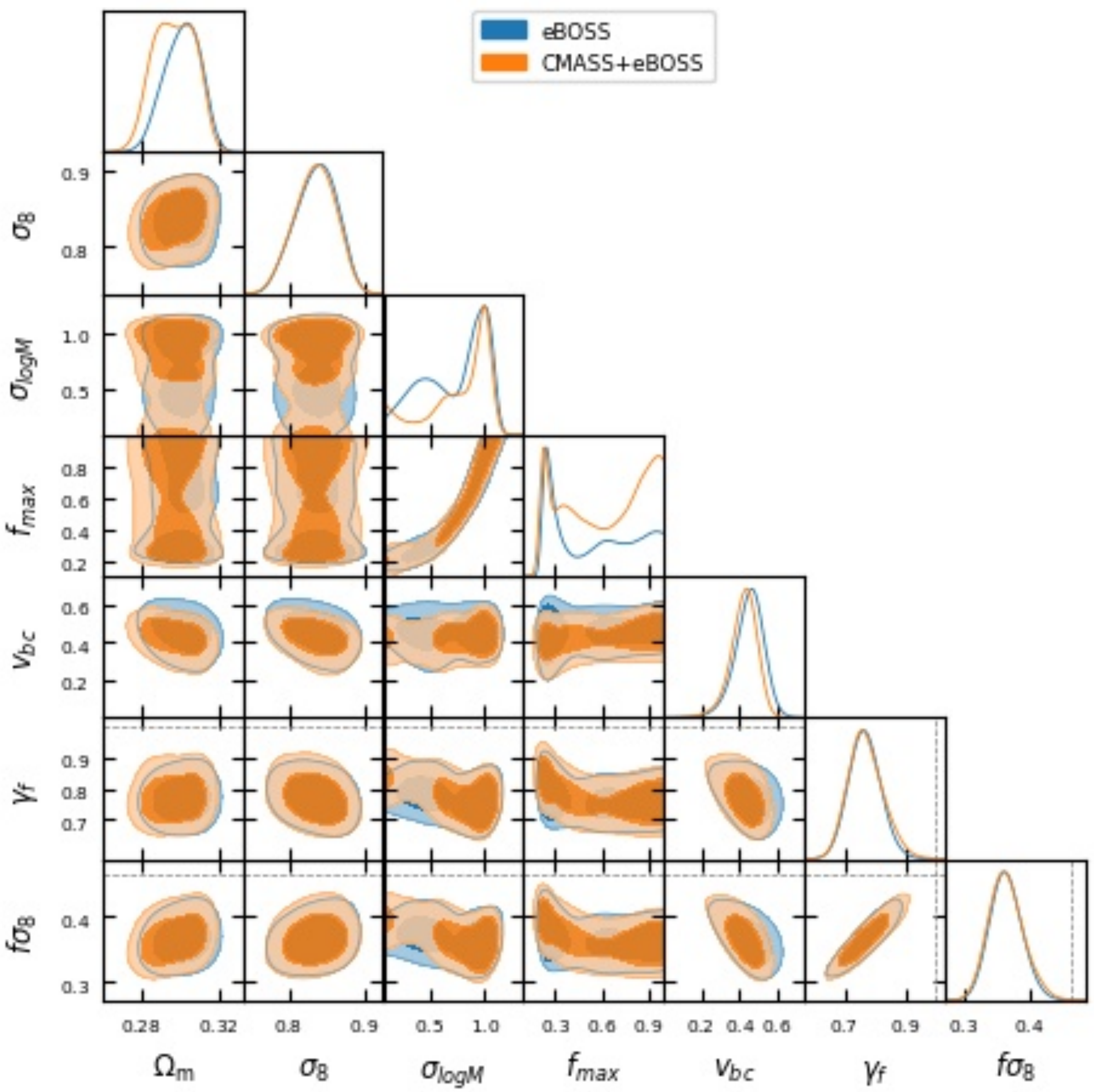
- Monopole and projected correlation function more strongly prefer non-zero $v_{\rm bc}$ and low γ_f
- Multipoles prefer larger γ_f along degeneracy with $v_{\rm bc}$
- Combined fit occupies the overlap region

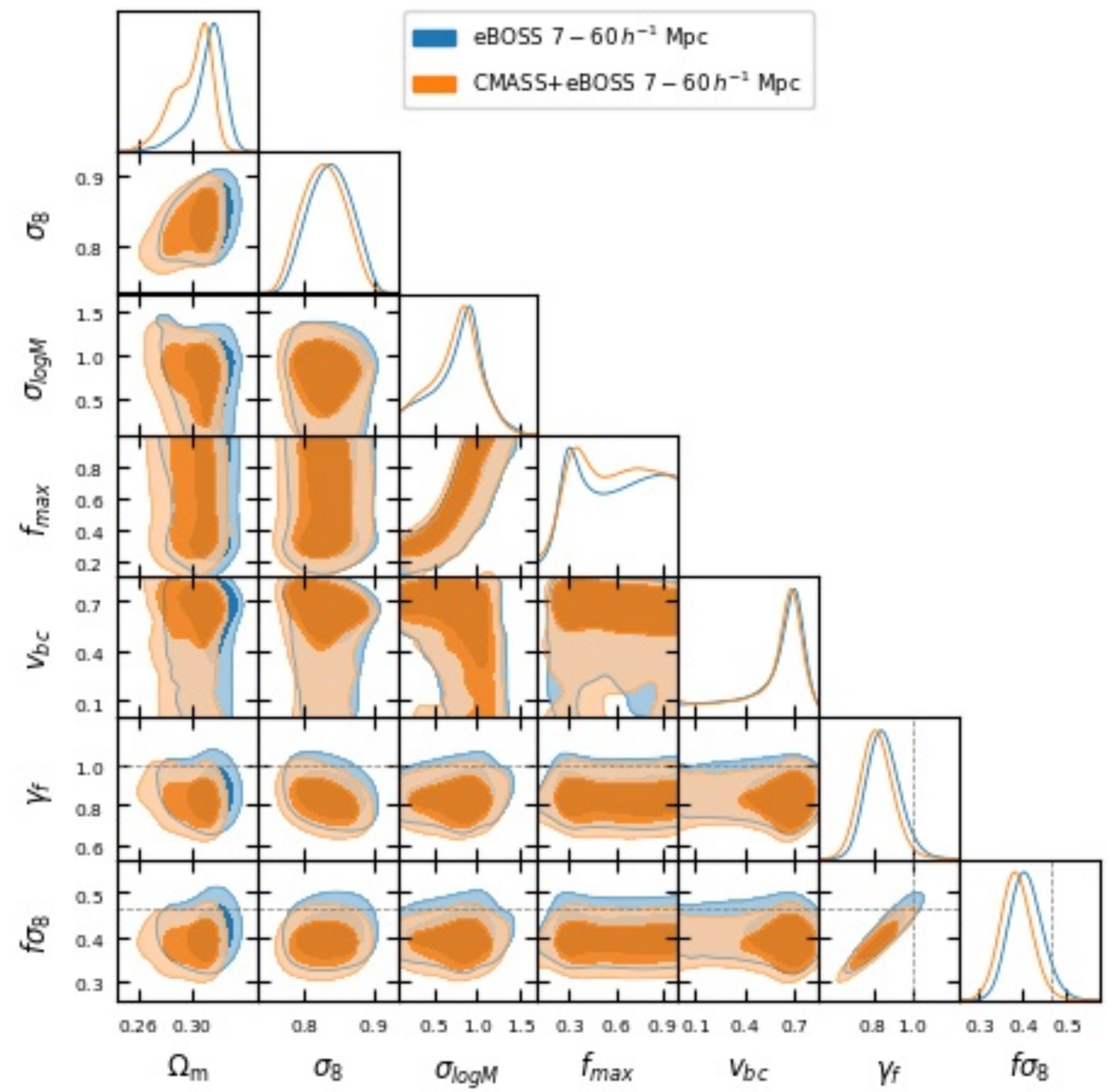
CMASS+EBOSS

- Additionally fit to a combined BOSS CMASS+eBOSS sample between $0.6 < z < 0.8$
- Adding CMASS increases the number of objects and completeness, but skews $n(z)$
- HOD formalism assumes single population for entire sample



CMASS+EBOSS


eBOSS
CMASS+eBOSS
Ω_m
σ_8
σ_{logM}
f_{max}
v_{bc}
γ_f
$f\sigma_8$


eBOSS $7-60\,h^{-1}$ Mpc
CMASS+eBOSS $7-60\,h^{-1}$ Mpc
Ω_m
σ_8
σ_{logM}
f_{max}
v_{bc}
γ_f
$f\sigma_8$