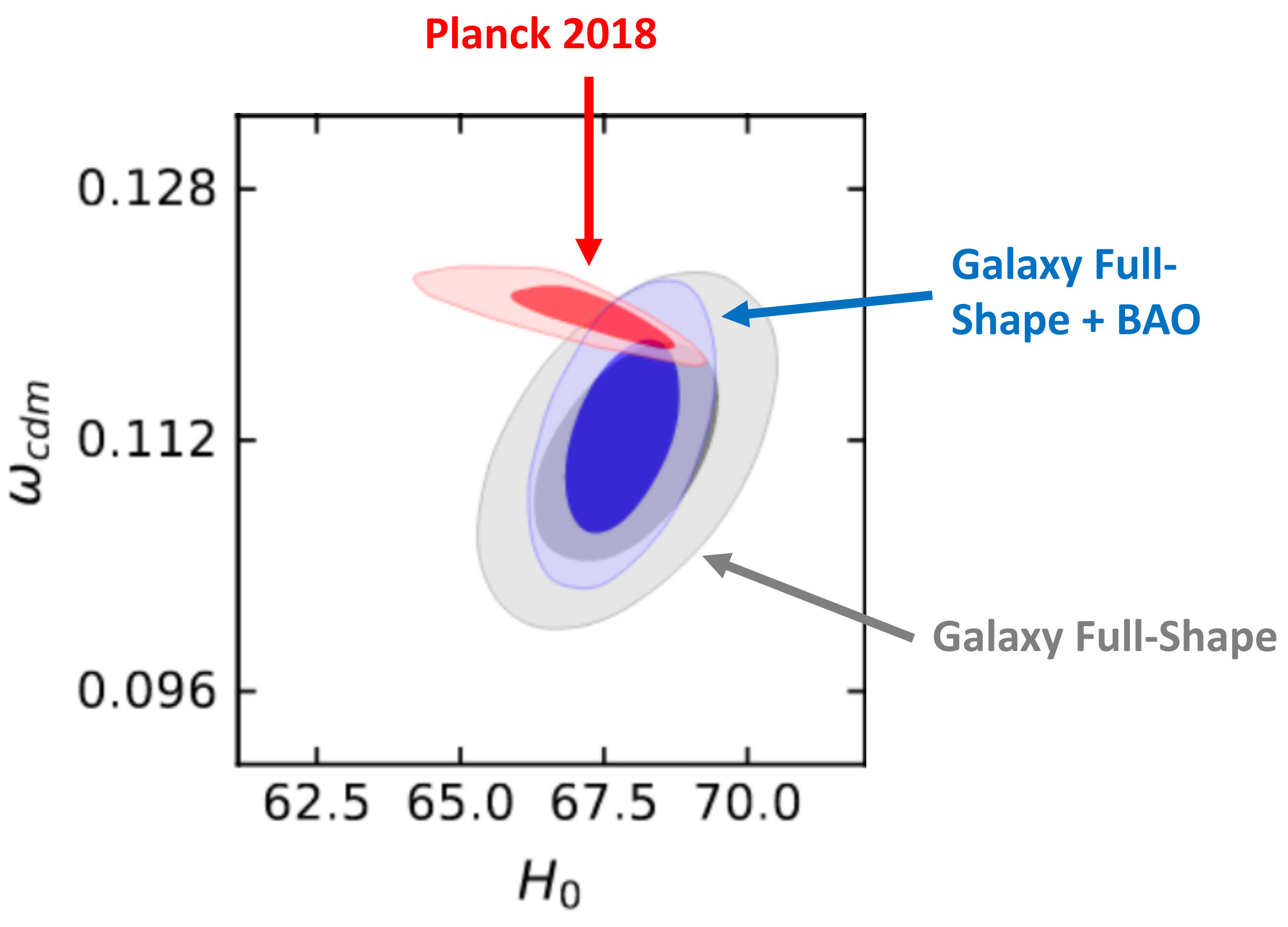


arXiv: 2002.04035

PRINCETON UNIVERSITY

Constraining Cosmology from Galaxy Surveys

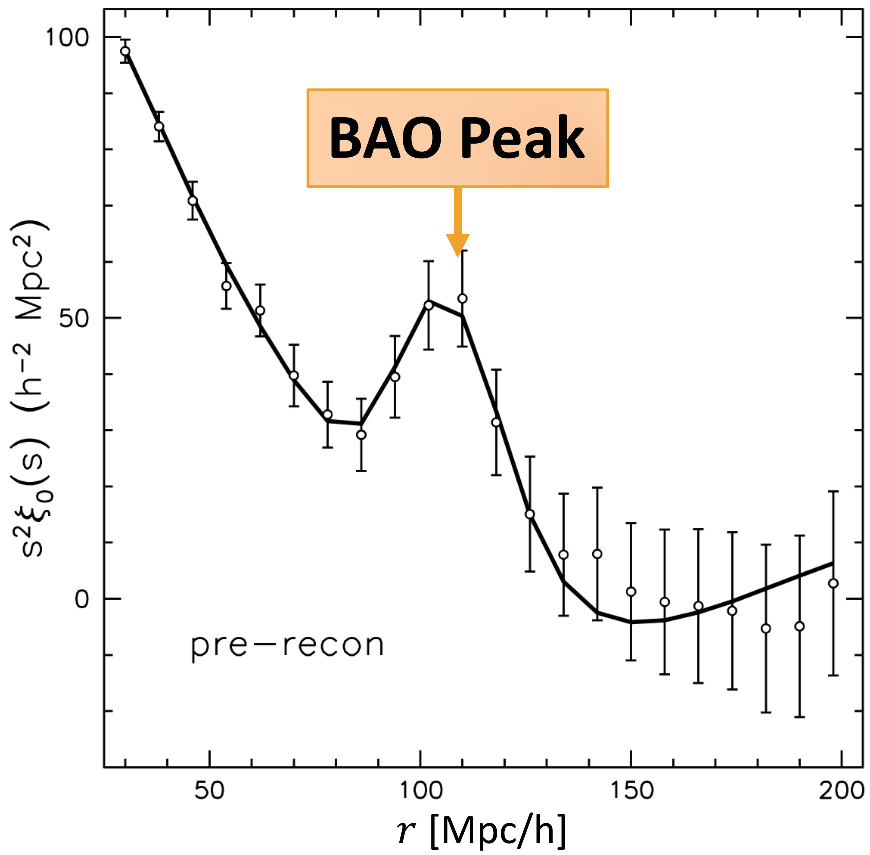
OLIVER PHILCOX (PRINCETON)

Collaborators:

- Misha Ivanov (NYU)
- Marko Simonović (CERN)
- Matias Zaldarriaga (IAS)

Mar 2, 2020

Cosmology from the BAO Peak



BOSS Correlation Function Monopole

- Measure the BAO peak **radially** and **tangentially** to constrain the **Alcock-Paczynski (AP)** parameters;

$$\xi(r_\parallel, r_\perp) \propto \xi^{\text{fid}}(r_\parallel \alpha_\parallel, r_\perp \alpha_\perp)$$

True correlation function

Fiducial correlation function

$$\alpha_\parallel = \frac{H^{\text{fid}}(z)\, r_s^{\text{fid}}(z_d)}{H(z) r_s(z_d)}$$

$$\alpha_\perp = \frac{D_A(z)\, r_s^{\text{fid}}(z_d)}{D_A^{\text{fid}}(z) r_s(z_d)}$$

Fiducial cosmology

True cosmology

Anderson+13

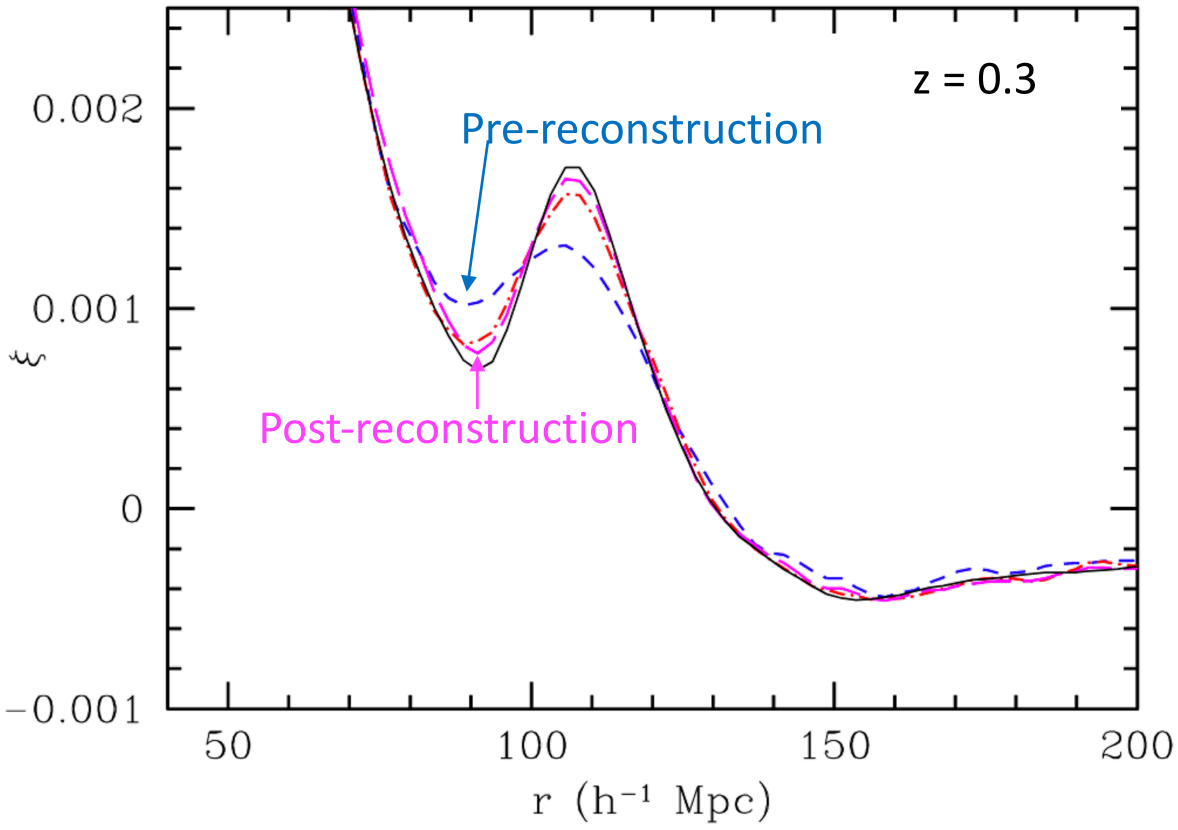
BAO Reconstruction

- Matter has moved since recombination!
  - - This **blurs** the BAO feature

- Can **underdo** long-wavelength motion by estimating the velocity field

$$\nabla \cdot \vec{v} \approx -\delta_{\mathrm{smoothed}}$$

- Return galaxies to their **Lagrangian** positions
  - Gives **sharper** BAO peak
  - Better constraints on cosmology



Eisenstein+06
Padamanbhan+12

Extracting $\{\alpha_\perp, \alpha_\parallel\}$

- Work in Fourier space with the power spectrum **monopole** and **quadrupole**

- Use linear theory model plus AP parameters

$$P^{\rm rec}_{\rm fid}(k,\mu) = \left[b + f\mu^2\left(1 - W(k)\right)\right]^2 P_{\rm nw}(k)\left[1 + \left(\mathcal{O}_{\rm lin}(k) - 1\right)e^{-k^2\Sigma^2(\mu)}\right]$$

Bias + smoothing   No-wiggle power   Suppressed wiggles

$$P^{\rm rec}_\ell(k) \sim \int_{-1}^{1} d\mu\, P^{\rm rec}_{\rm fid}\left(k'(k), \mu'(\mu)\right) L_\ell(\mu)$$

Multipole binning

AP parameters

- What about non-linear effects?

Philcox+20

Extracting $\{\alpha_\perp, \alpha_\parallel\}$

- Previously;
  - Add ~ 10 free polynomial parameters to account for the unknown power spectrum shape
- Now;
  - Use a **theoretical error covariance**

$$C^d \to C^d + C^e$$

Data Covariance

Error Covariance

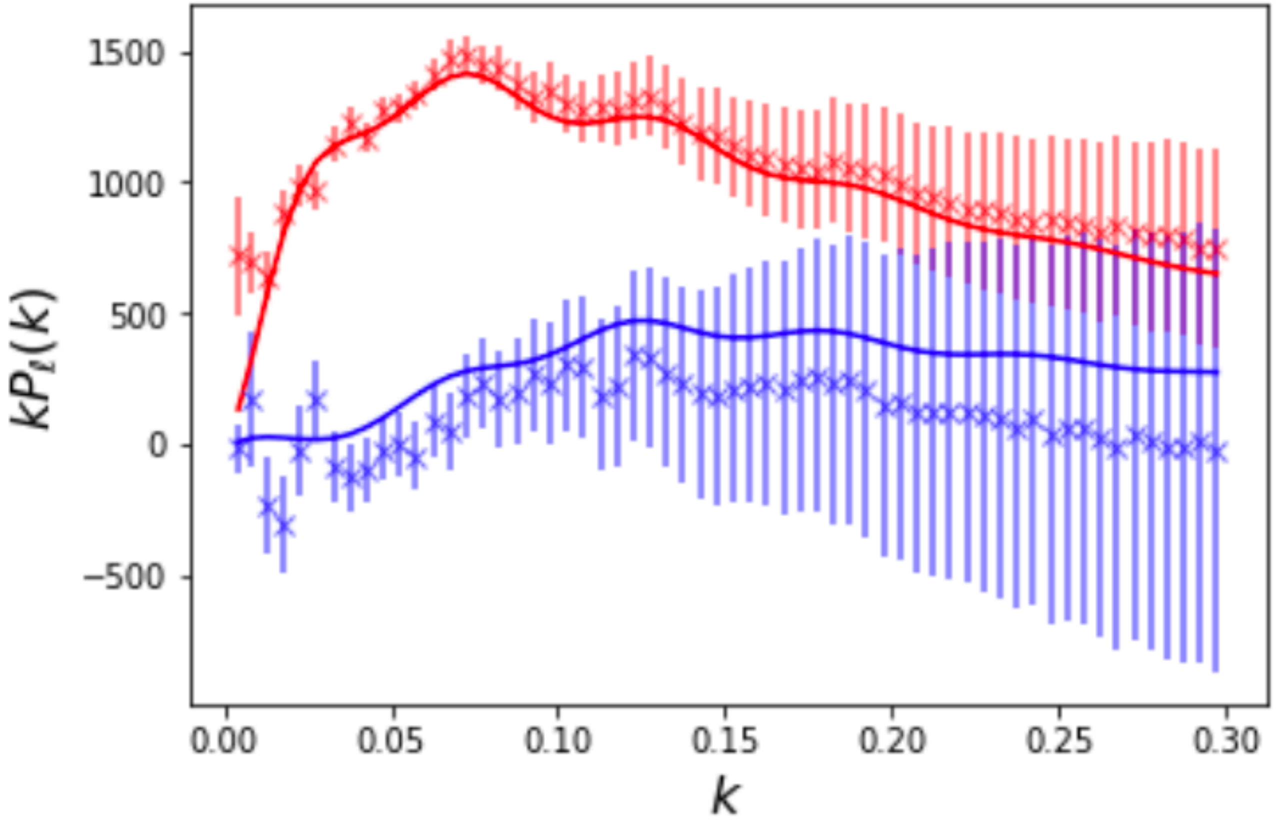
  - This has the amplitude of the non-linear corrections but is **correlated** -> can still measure BAO

Baldauf+16

Extracting $\{\alpha_\perp, \alpha_\parallel\}$

- This is **robust** and able to measure AP parameters into the **non-linear** regime

- Only **two** nuisance parameters; $\{b, \Sigma_{\rm NL}\}$



Reconstructed Monopole Power

Reconstructed Quadrupole Power

Philcox+20

Full-Shape (FS) Analysis

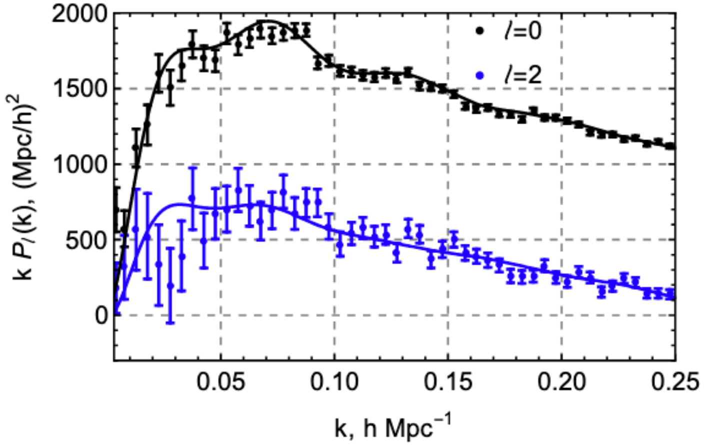
- Is there information in galaxy power spectra beyond the BAO peaks?

- Constrain cosmological parameters from the **full shape** of the **unreconstructed** spectrum

$$P_{g,\ell}(k) = P_{g,\ell}^{\mathrm{tree}}(k) + P_{g,\ell}^{1-\mathrm{loop}}(k) + P_{g,\ell}^{\mathrm{noise}}(k) + P_{g,\ell}^{\mathrm{ctr}}(k)$$

Linear Theory | 1-loop Perturbation Theory | Shot-noise | Counterterms

Spectra



MCMC →

Parameters

$$\{\omega_b, \omega_{cdm}, h, A_s, \sum m_\nu\}$$

Ivanov+19a
Ivanov+19b

Combining FS and BAO Analyses

- Full Shape analysis places **strong** constraints on cosmology

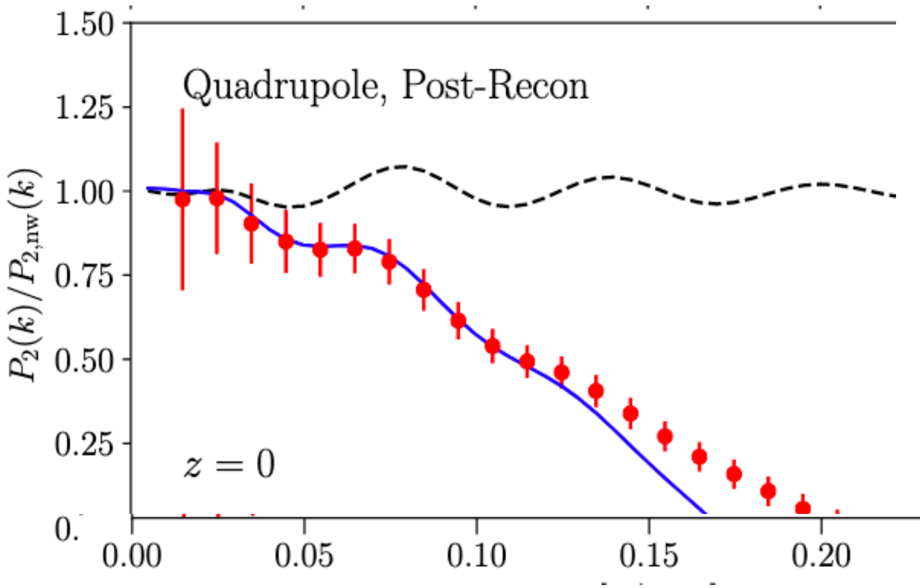
- Apply this to **reconstructed** power spectra?

However;

1. Reconstruction degrades the broadband power spectrum shape
2. Different reconstruction methods need different theory models!
3. Significant dependence on modeling assumptions (Sherwin+18)

Modeling reconstructed spectra is difficult

(Hikage+17,19, Chen+19)



Theory fails at $k \sim 0.1h/\mathrm{Mpc}$

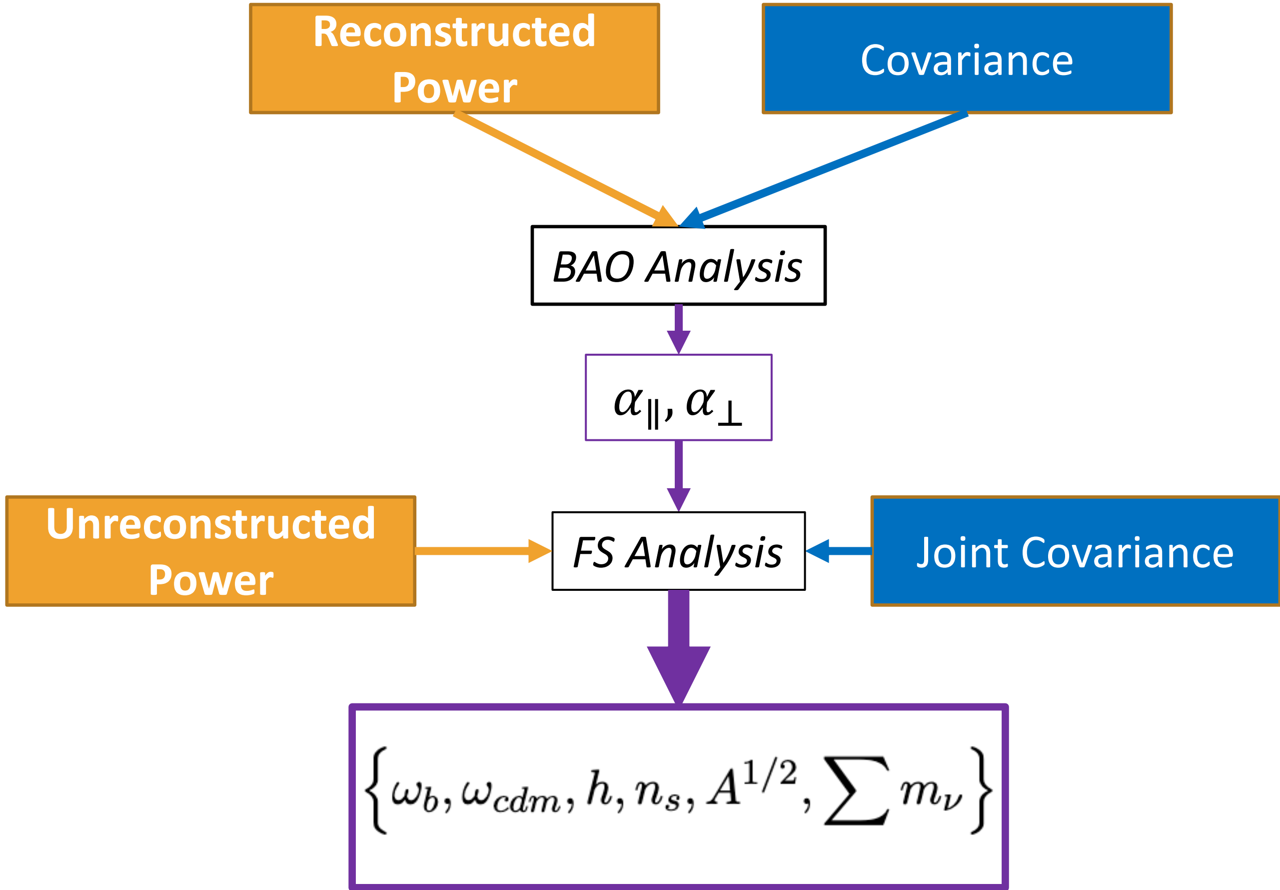
Hikage+19

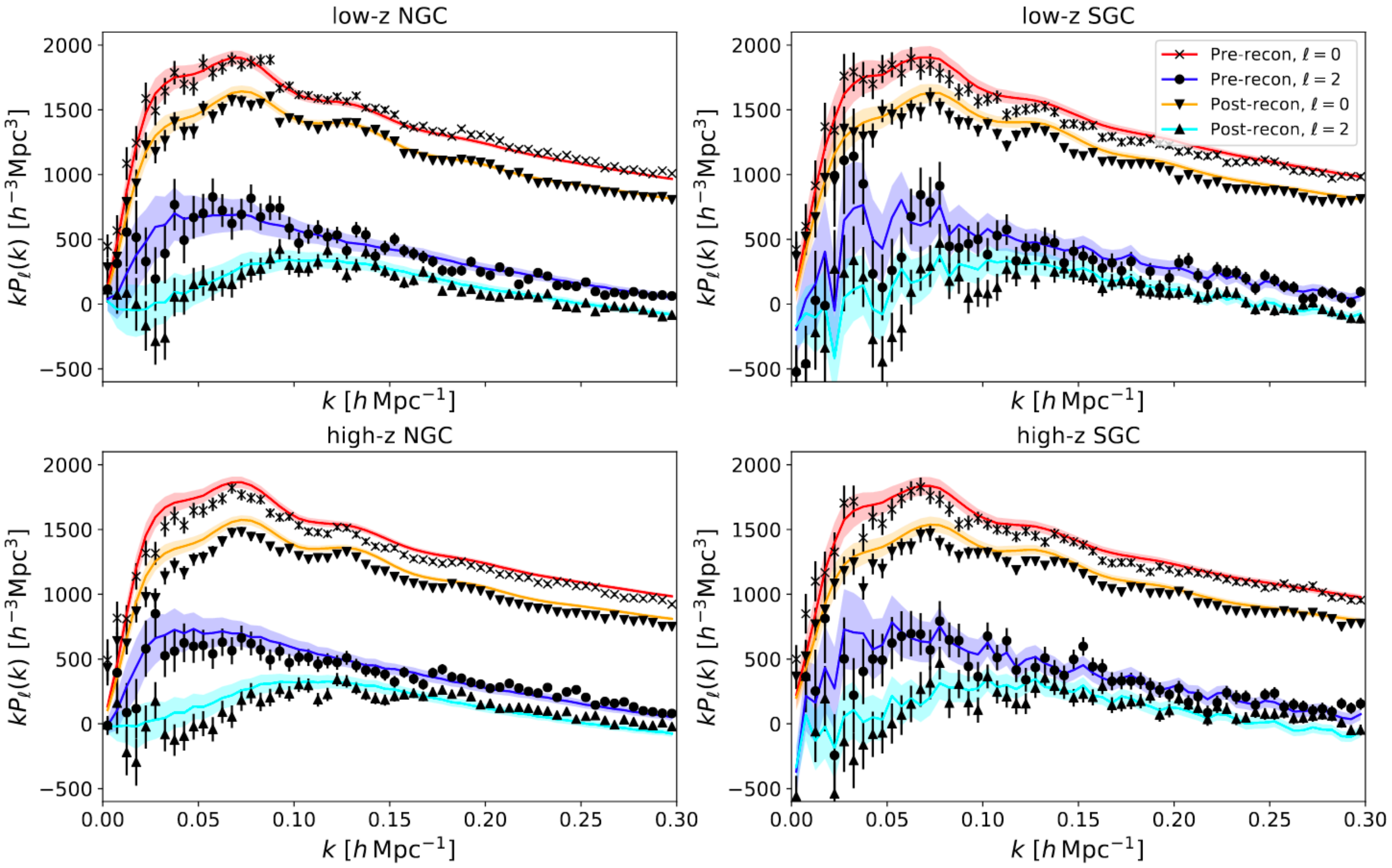
The Analysis Pipeline

1. Run **BAO analysis** on the **reconstructed data** to get **AP** parameters $\vec{\alpha}$

2. Generate **joint covariance** between **AP** parameters and $\boldsymbol{P_\ell^{\mathrm{unrec}}(k)}$

3. Run **FS analysis** on $\{\boldsymbol{P_\ell^{\mathrm{unrec}}(k)}, \vec{\boldsymbol{\alpha}}\}$





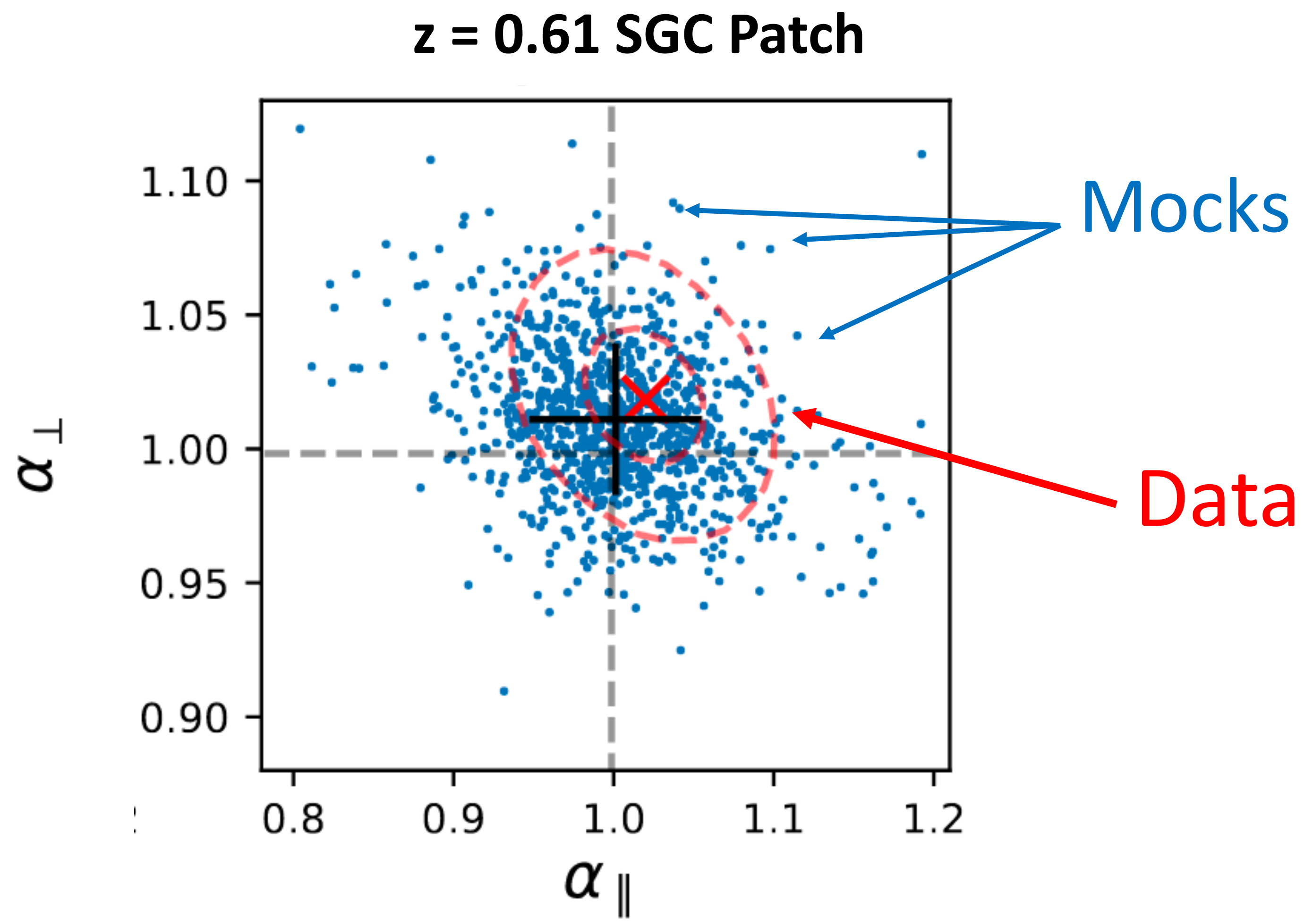
BOSS DR12

Two sky patches (NGC + SGC)

Two redshifts $z_{\rm eff} \in \{0.38, 0.61\}$

Total volume $V_{\rm eff} = 2.4\ (h^{-1}\mathrm{Gpc})^3$

All publicly available



Step 1: Measure AP Parameters

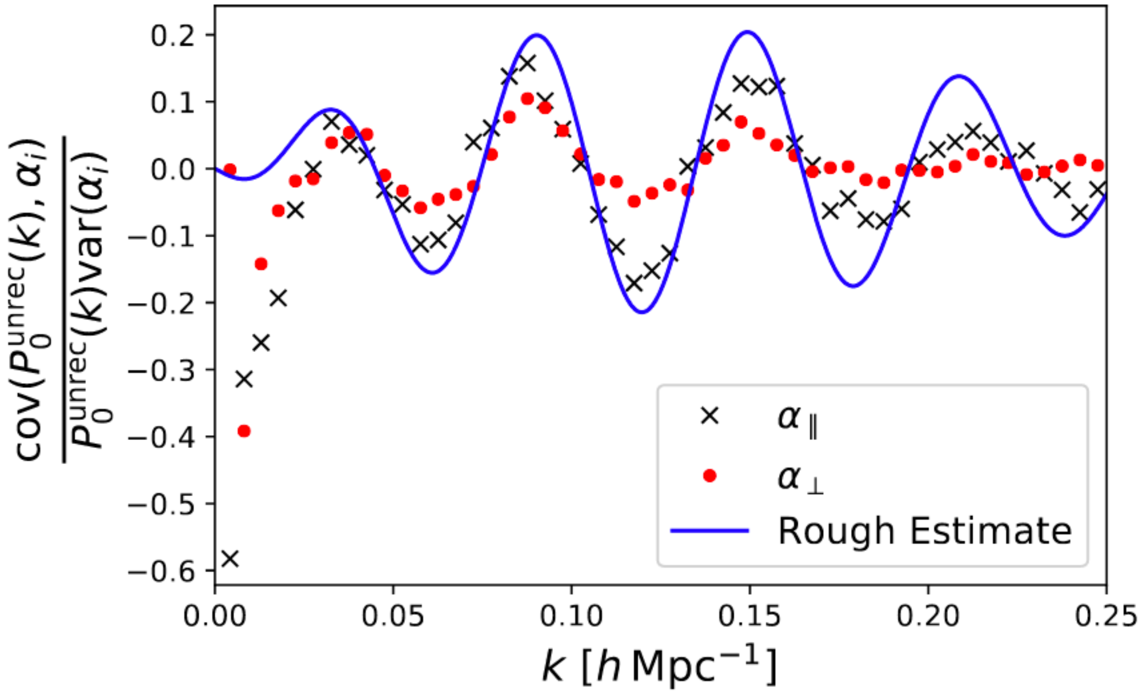
Use **linear + theoretical error** model

Constrain parameters via **MCMC** to get best-fit $\alpha_\perp, \alpha_\parallel$

Apply to Quick Particle Mesh mocks (Kitaura+15)

$$\mathrm{cov}\left(X_a, X_b\right) = \frac{1}{N_{\mathrm{mocks}} - 1} \sum_{n=1}^{N_{\mathrm{mocks}}} \left(X_a^{(n)} - \overline{X}_a\right)\left(X_b^{(n)} - \overline{X}_b\right)$$

for $X = \{P_0^{\mathrm{unrec}}(k), P_2^{\mathrm{unrec}}(k), \alpha_{\parallel}, \alpha_{\perp}\}$

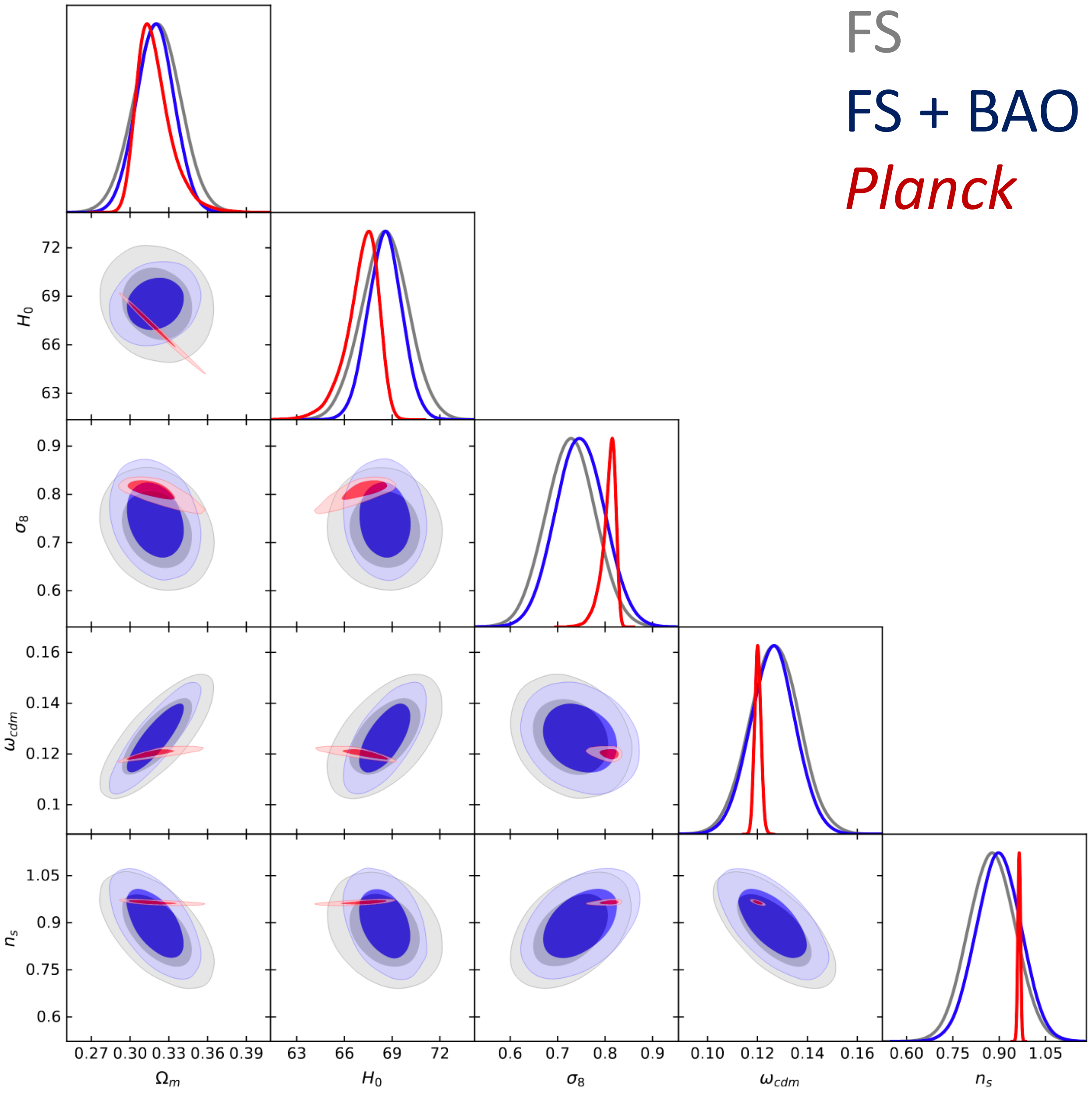


Step 2: Compute Covariances

Need a **joint covariance** of spectra and **AP** parameters

Measure from 999 mocks

Could also use basic **theory**



Step 3: FS Analysis

Use MCMC + **Full-Shape** likelihood in $\nu\Lambda$CDM

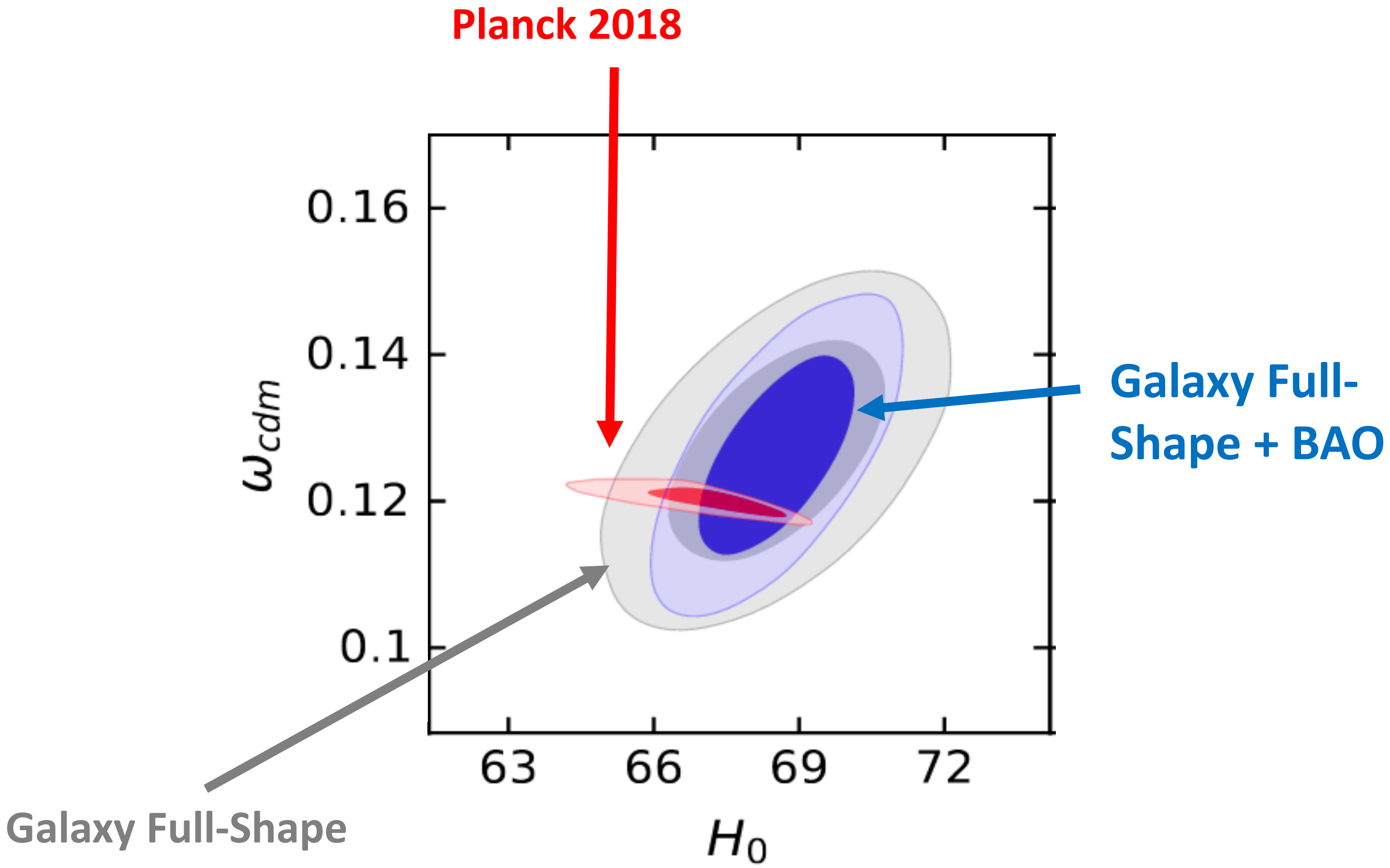
Nuisance parameters:

$$\{b_1, b_2, b_{\mathcal{G}_2}, P_{\text{shot}}, c_0, c_2, \tilde{c}\}$$

Cosmological parameters

$$\left\{\omega_b, \omega_{cdm}, h, n_s, A^{1/2}, \sum m_\nu\right\}$$

H_0	Full-Shape only	**Full-Shape + BAO**	Planck 2018
	68.55 ± 1.5	$\mathbf{67.9 \pm 1.1}$	$67.1^{+1.3}_{-0.72}$



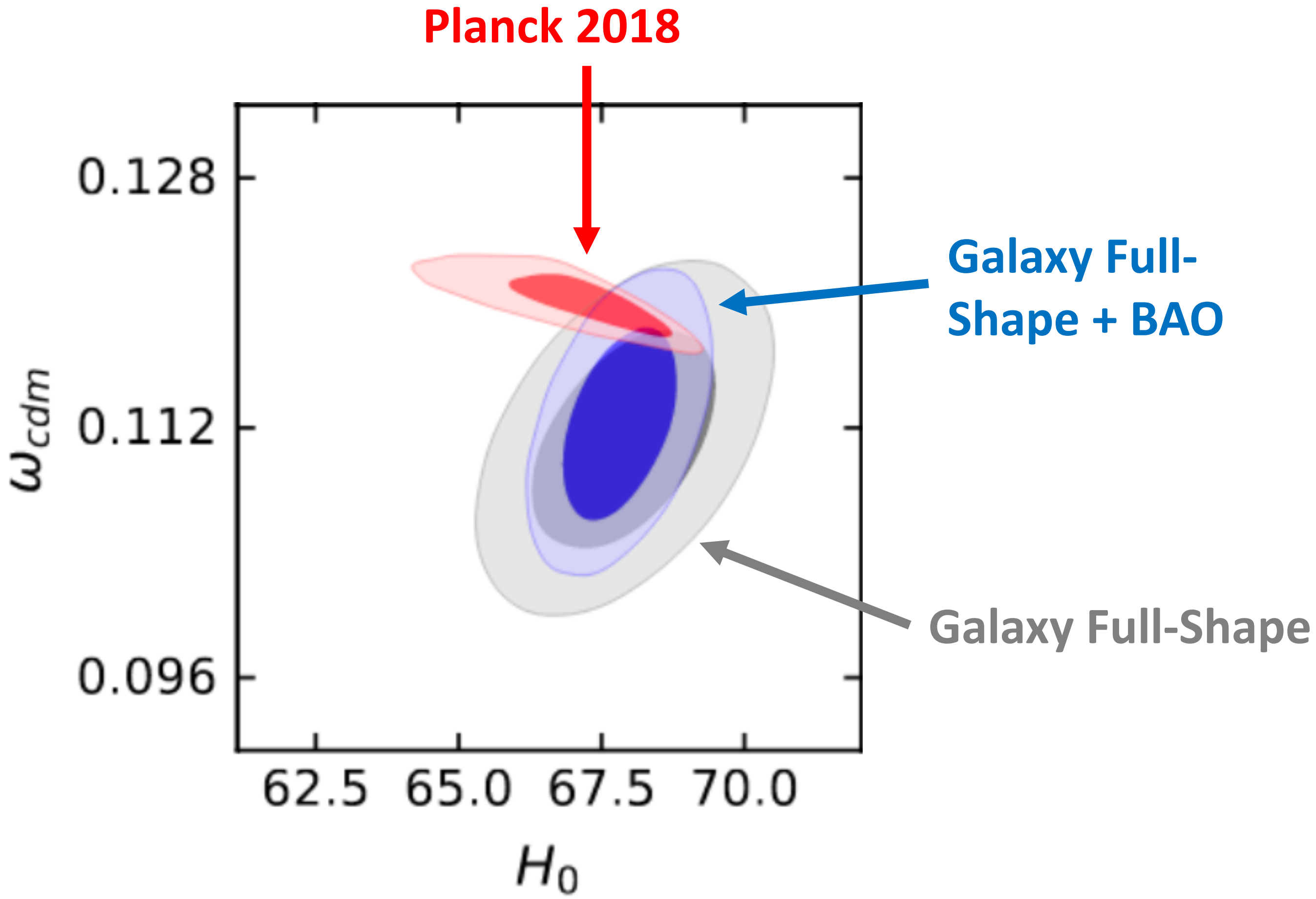
Free n_s

40% gain from including BAO information

Using **no** information from *Planck*

Just a BBN prior on ω_b

H_0	Full-Shape only	Full-Shape + BAO	Planck 2018
	67.90 ± 1.1	$\mathbf{67.8 \pm 0.7}$	$67.1^{+1.3}_{-0.72}$

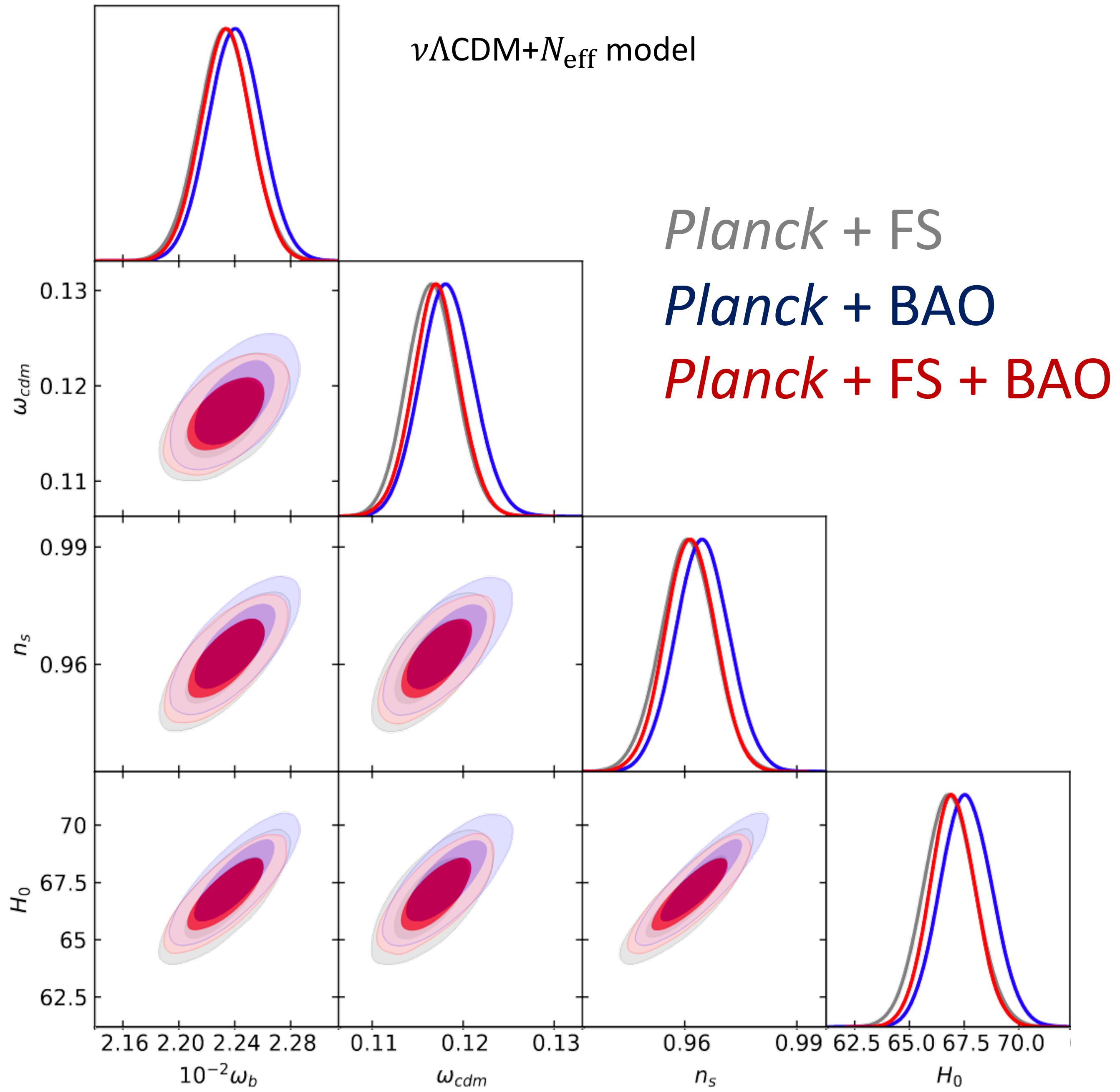


Fixed n_s

40% gain from including BAO information

Only using **spectral slope** from *Planck*

Stronger measurements than *Planck!*



Combination with *Planck*

BAO does **not** add extra information to *Planck*+FS analyses

Galaxy surveys **break** parameter **degeneracies**

Already broken by FS information!

BAO reconstruction will not be useful in the future

Conclusions

- Combining **Full-Shape** and **BAO** information gives **strong** constraints on cosmology from **galaxy surveys**

- Can **robustly** measure BAO via **theoretical error**, independent of reconstruction method

- Gives a 1.6% constraint on H_0 at $z \sim 0.5$ assuming ΛCDM, **independent** of the CMB

Extra Slides

Where is our Information Coming From?

Galaxy Surveys

- **Full shape** of galaxy power spectrum constrains ω_{cdm}, ω_b etc.
- This sets the **physical sound horizon** in ΛCDM
- Angular galaxy positions, especially the BAO scale, give H_0

CMB

- **Full shape** of CMB power spectrum constrains ω_{cdm}, ω_b etc.
- This sets the **physical sound horizon** in ΛCDM
- Angular CMB observations, especially the acoustic peaks, give H_0

`Early’ or `Late’ Measurements?

- Excluding the BBN prior, all our data comes from $z \sim 0.5$

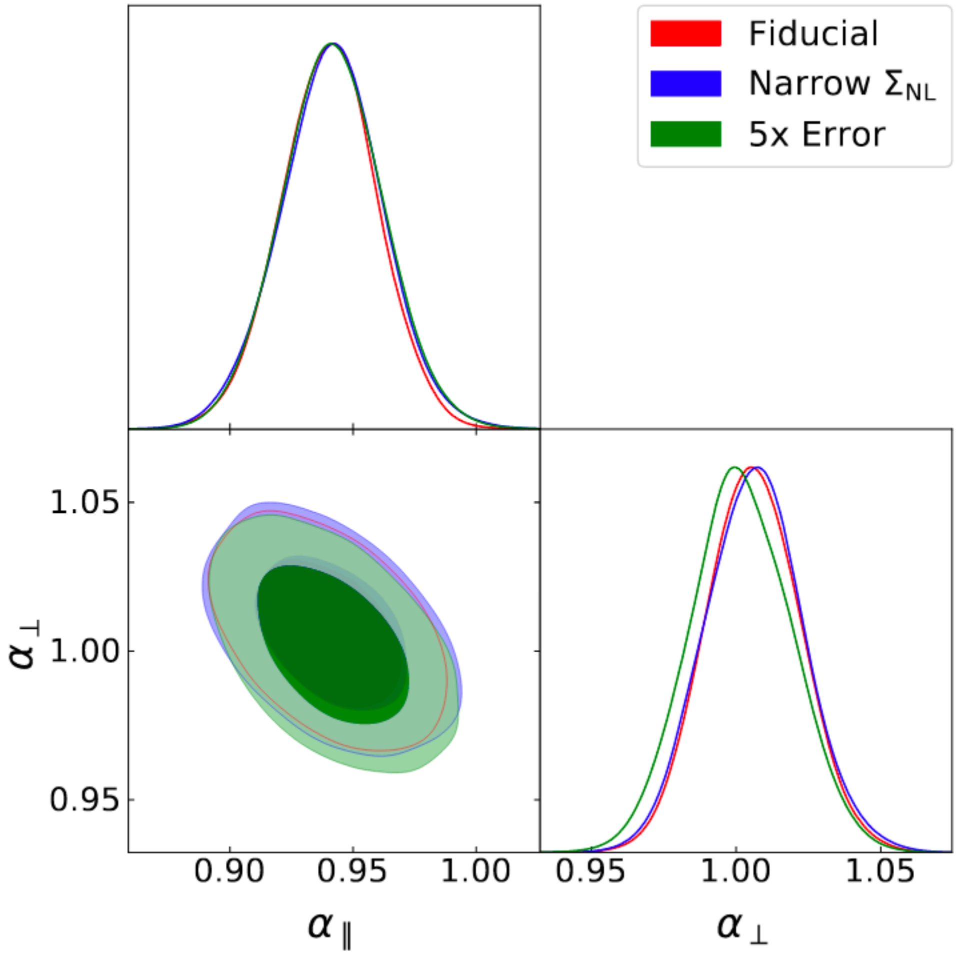
- But we use a cosmological model to generate $P_{lin}(k)$

- Our analysis encodes the **full** cosmological history since before **recombination**

- We are sensitive to new physics at $z > 0.5$

This is a measurement of H_0 at $z \sim 0.5$ within $\nu\Lambda$CDM

BAO Reconstruction Robustness

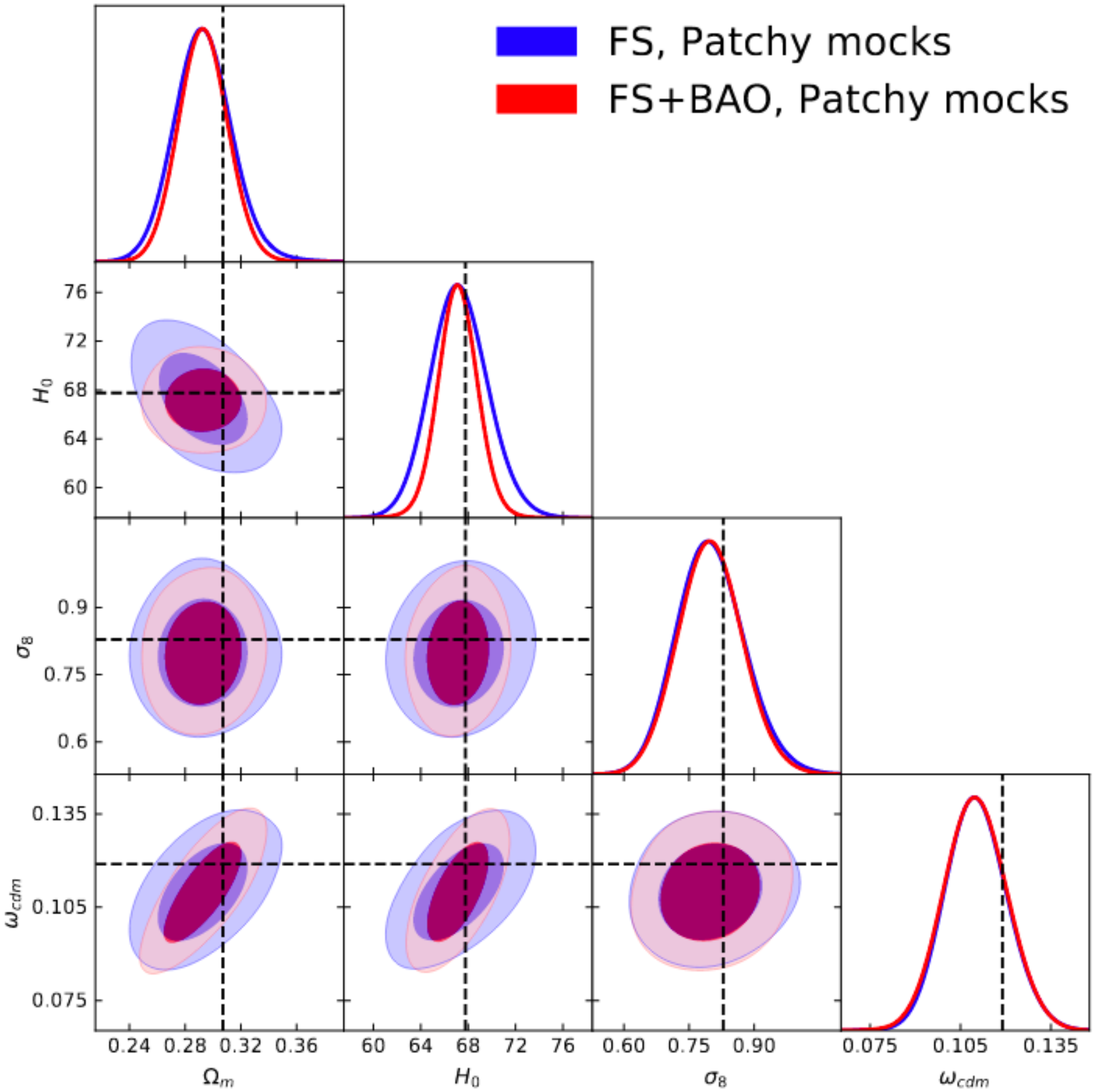


Test procedure by repeating with

1. A narrow prior on the non-linear damping scale Σ_{NL} (i.e. *fixed damping)*

2. Inflating the theoretical covariance error by 5^2

The analysis is robust

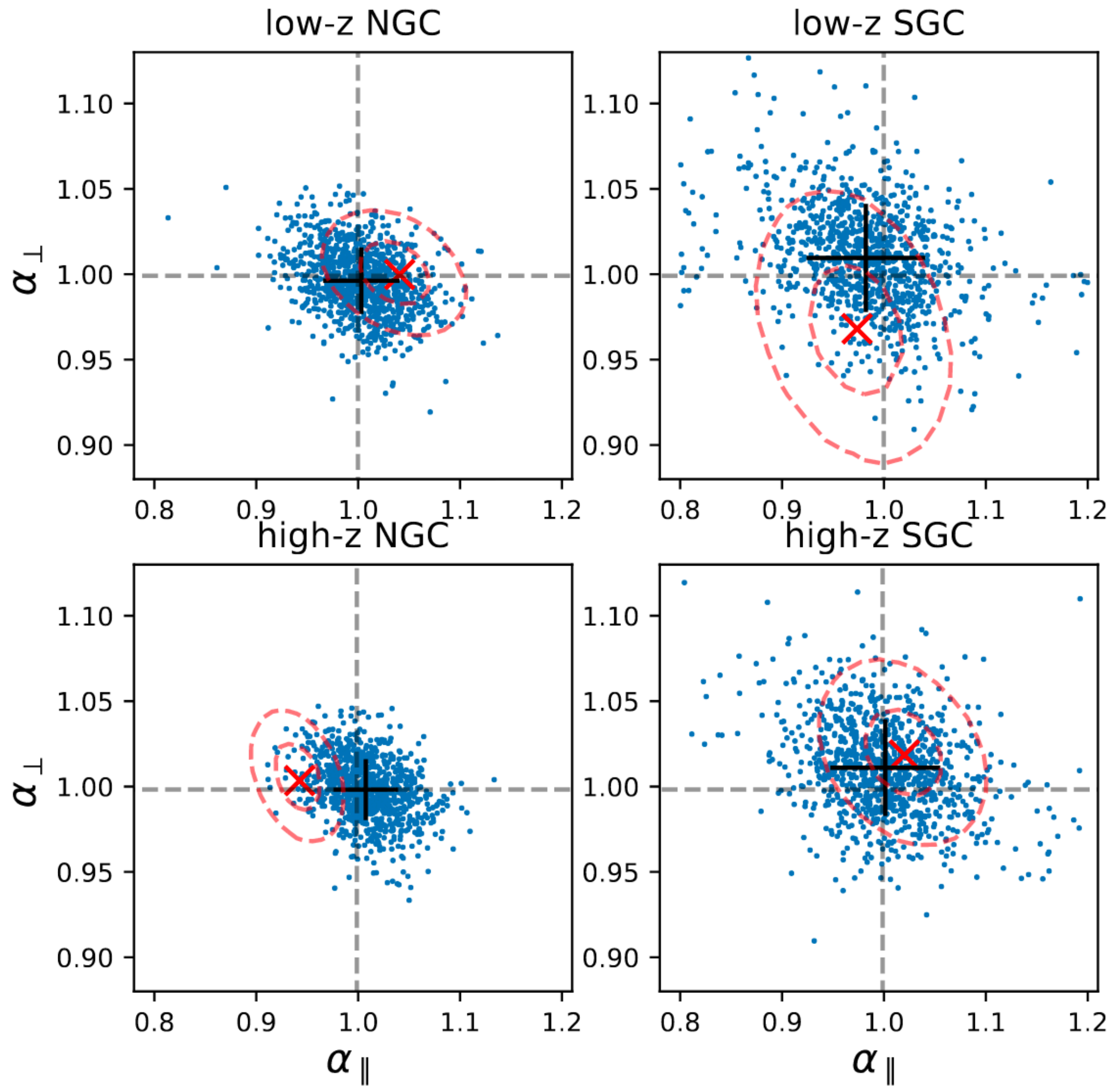


Tests on Mocks

- Run FS and FS+BAO analyses on the **mean** of QPM mocks

- Do not expect perfect agreement since mocks generated with approximate gravity solver and HOD model.

- Results are $< 1\sigma$ consistent



All AP Parameters

Approximate Joint Covariance

$$\mathrm{cov}\left(P^{\mathrm{unrec}}(k,\mu),\hat{\boldsymbol{\alpha}}\right) \equiv \langle \delta P^{\mathrm{unrec}}(k,\mu)\delta\hat{\boldsymbol{\alpha}}\rangle = \left\langle \left.\frac{\partial P^{\mathrm{unrec}}(k,\mu)}{\partial\boldsymbol{\alpha}}\right|_{\boldsymbol{\alpha}=\boldsymbol{\alpha}_0} \delta\hat{\boldsymbol{\alpha}}^T\delta\hat{\boldsymbol{\alpha}} \right\rangle$$

$$= \left.\frac{\partial P^{\mathrm{unrec}}(k,\mu)}{\partial\boldsymbol{\alpha}}\right|_{\boldsymbol{\alpha}=\boldsymbol{\alpha}_0} \cdot \mathrm{cov}(\hat{\boldsymbol{\alpha}}),$$

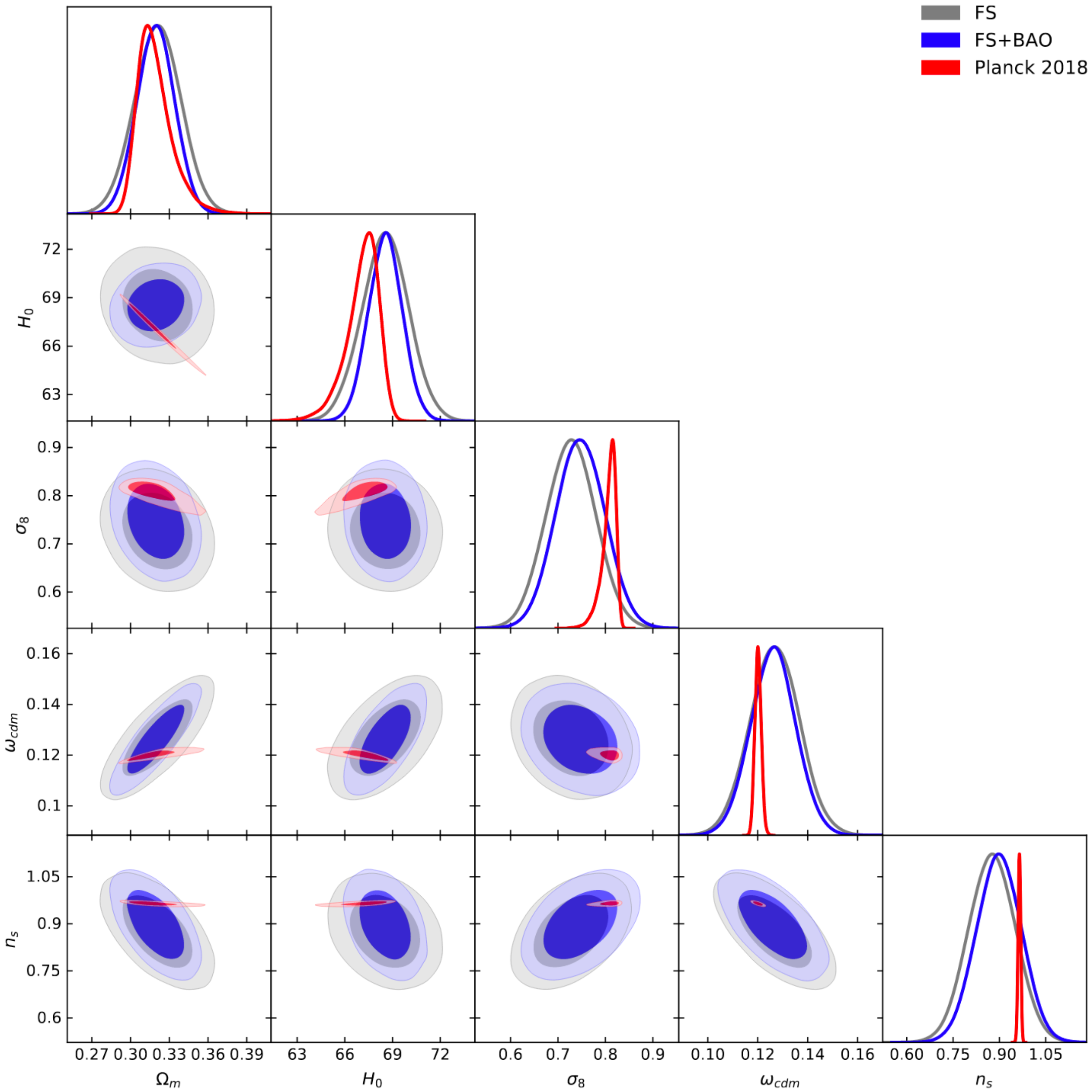
$$= \frac{\partial P^{\mathrm{unrec}}(k,\mu)}{\partial P^{\mathrm{rec}}(k,\mu)} \cdot \frac{\partial P_w^{\mathrm{rec}}(k,\mu)}{\partial\boldsymbol{\alpha}} \cdot \mathrm{cov}(\hat{\boldsymbol{\alpha}})$$

$$P_w(k;\alpha) \approx 0.05 P_{nw}(k)\sin\left(\frac{k\ell_{\mathrm{BAO}}}{\alpha}\right) e^{-k^2\left(\Sigma^2_{\mathrm{NL}}+\Sigma^2_{\mathrm{Silk}}\right)}$$

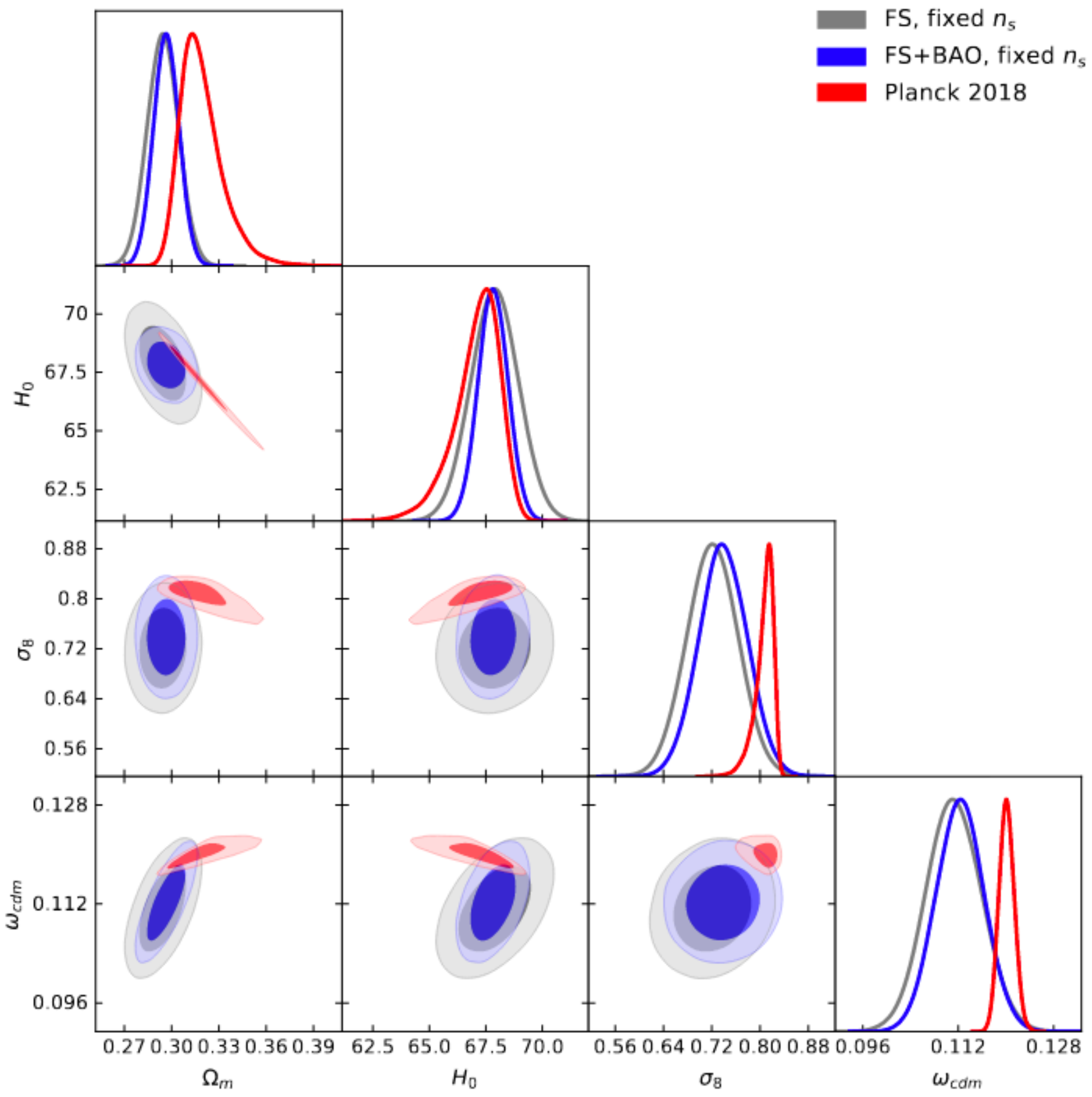
$$\frac{\mathrm{cov}(P^{\mathrm{unrec}}(k),\hat{\alpha})}{P^{\mathrm{unrec}}(k)\,\mathrm{var}(\hat{\alpha})} = \frac{\partial \log P^{\mathrm{unrec}}(k)}{\partial\alpha} \approx -0.05\frac{k\ell_{\mathrm{BAO}}}{\alpha^2}\cos\left(\frac{k\ell_{\mathrm{BAO}}}{\alpha}\right) e^{-k^2\left(\Sigma^2_{\mathrm{NL}}+\Sigma^2_{\mathrm{Silk}}\right)}$$

	base $\nu\Lambda$CDM		base $\nu\Lambda$CDM + fixed n_s	
Parameter	FS	FS+BAO	FS	FS+BAO
ω_{cdm}	$0.1265^{+0.01}_{-0.01}$	$0.1259^{+0.009}_{-0.0093}$	$0.1113^{+0.0047}_{-0.0048}$	$0.1121^{+0.0041}_{-0.0041}$
n_s	$0.8791^{+0.081}_{-0.076}$	$0.9003^{+0.076}_{-0.071}$	–	–
H_0	$68.55^{+1.5}_{-1.5}$	$68.55^{+1.1}_{-1.1}$	$67.90^{+1.1}_{-1.1}$	$67.81^{+0.68}_{-0.69}$
σ_8	$0.7285^{+0.055}_{-0.053}$	$0.7492^{+0.053}_{-0.052}$	$0.7215^{+0.044}_{-0.044}$	$0.7393^{+0.04}_{-0.041}$
Ω_m	$0.3203^{+0.018}_{-0.019}$	$0.3189^{+0.015}_{-0.015}$	$0.2945^{+0.01}_{-0.01}$	$0.2962^{+0.0082}_{-0.008}$

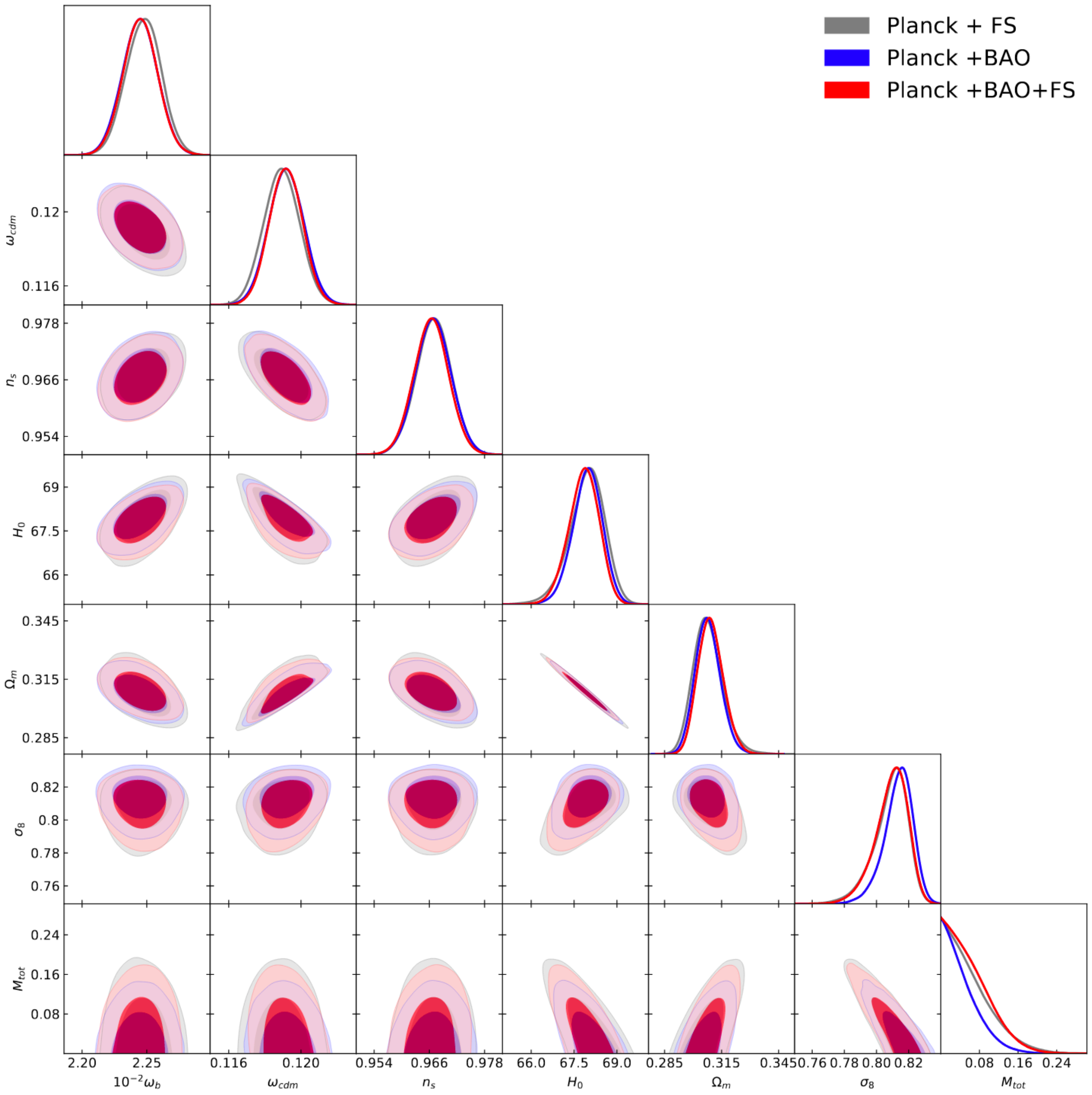
Full Constraints from Galaxy Surveys



Free n_s contours

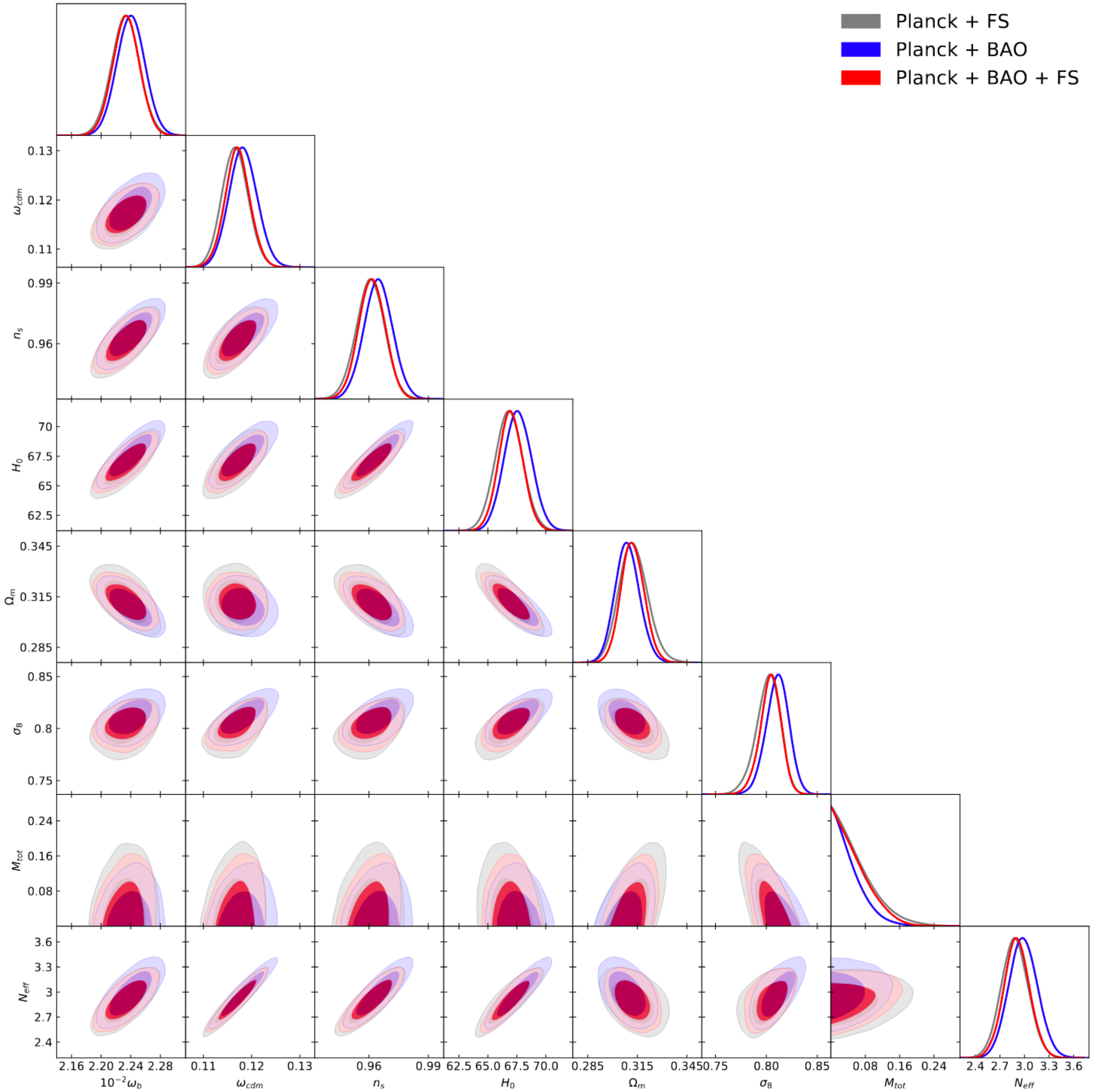


Fixed n_s contours



Planck+BOSS

$\nu\Lambda$CDM model



Planck+BOSS

$\nu\Lambda$CDM+N_{eff} model