

"The Analysis of the BOSS data from the EFTofLSS"

Based on several works with L. Senatore, P. Zhang, Y. Donath, M. Lewandowski, et al.

*1909.05271 (Λ CDM), 1909.07951 (v Λ CDM), 2003.07956 (PyBird code),
2003.08277 (PT challenge), 2006.12420 (EDE), 2012.07554 (clustering quintessence),
2110.00016 (RSD), 2110.07539 (correlation function),
2201.11518 (non-Gaussianity), 2206.08327 (1-loop bispectrum), 2211.xxxxx (EFT renormalization)*

<https://github.com/pierrexyz/pybird>

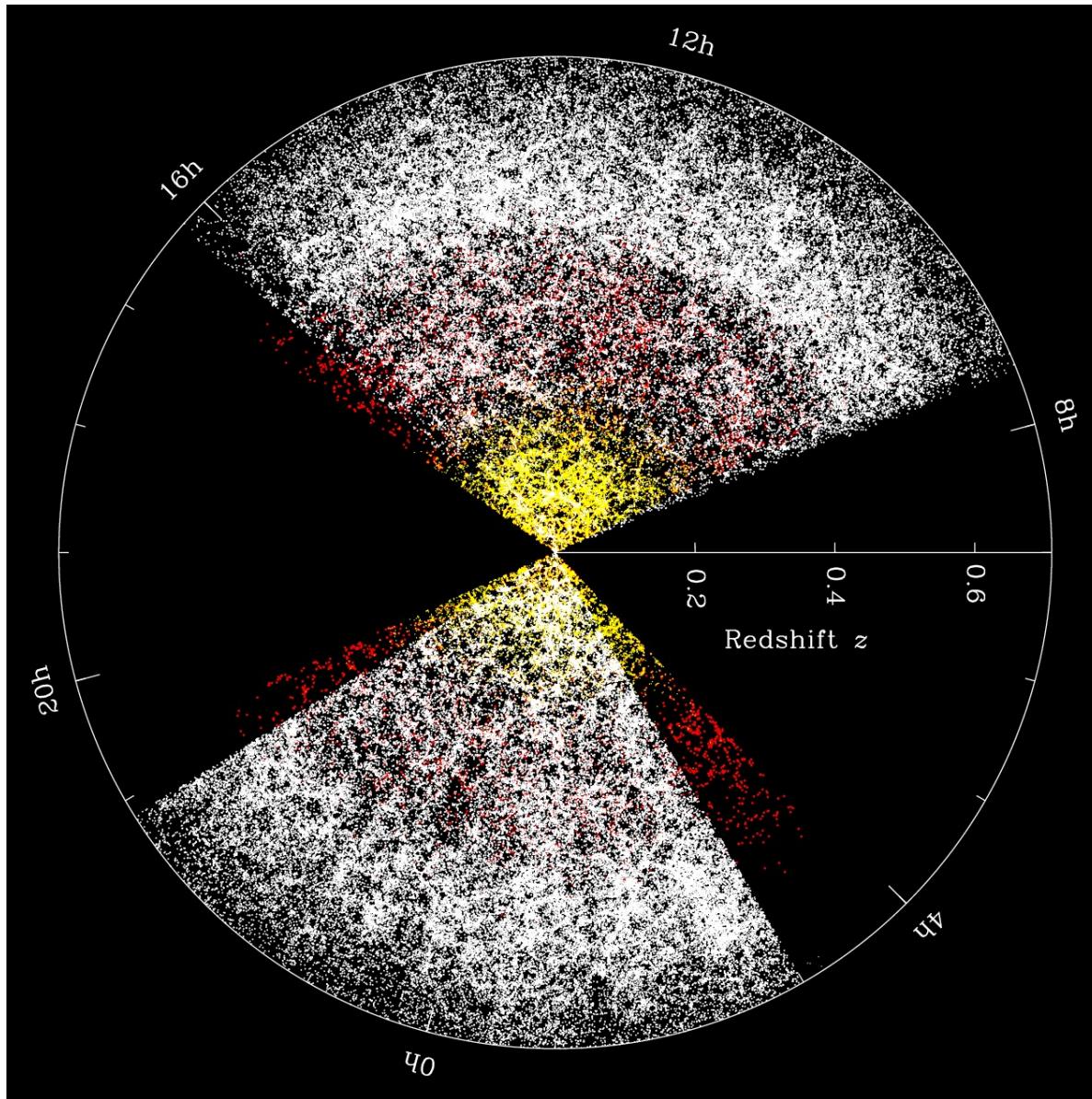
Cosmology and Fundamental Physics

- After WMAP and Planck, we now know quite a lot about the early Universe, and the late Universe as well
- How to continue getting *precise* and *accurate* information?
- And how to detect *signatures of new physics* (neutrino masses, PNG, dynamical DE, light mediators)?
- Large-Scale structure observations are there to be exploited, and we will get high-quality data in the next decade
- The problem is how to interpret these reliably.
Solution is the *EFTofLSS*

Complicated observables

- CMB is a 2d snapshot of perturbations still in the linear regime: only complication, well-understood plasma physics
- In LSS, we observe positions of galaxies in 3d, along the past lightcone
- Coordinates are distorted (redshift space)
- Galaxies are formed by really complicated physics...
- ... out of density perturbations that have grown by gravity

The BOSS Universe



The EFTofLSS

- Important observation: *on large scales*, dark matter (and baryons) behave like a homogeneous fluid with *small perturbations*
- So we do perturbation theory in δ_l , and expand in derivatives. We have to introduce renormalization to take into account the effects of unknown small-scale physics
- Galaxies on large scales are a **biased tracer** of underlying perturbations
- Redshift space: velocity-dependent coordinate change.
Opportunity: break rotational invariance, so can measure effects of velocity.
Complication: needs additional renormalization, PT breaks earlier

Organizing perturbative expansion

Biased tracer overdensity: non-local in time function of Galilean invariant fields

$$\delta_h(\vec{x}, t) = \int^t dt' H(t') f_h \left(\partial_i \partial_j \Phi(\vec{x}_{\text{fl}}, t'), \partial_i v^j(\vec{x}_{\text{fl}}, t'), \frac{\partial_{x_{\text{fl}}}}{k_M}, \epsilon(\vec{x}_{\text{fl}}, t'), t' \right) \Big|_{\vec{x}_{\text{fl}} = \vec{x}_{\text{fl}}(\vec{x}, t, t')}$$

$$\vec{x}_{\text{fl}} = \vec{x} + \int_t^{t'} \frac{dt''}{a(t'')} \vec{v}(\vec{x}_{\text{fl}}(\vec{x}, t, t''), t'')$$

Perturbative expansion gives the kernels

$$\delta_h^{(n)}(\vec{k}, a) = D(a)^n \int_{\vec{k}_1, \dots, \vec{k}_n}^{\vec{k}} K_n^h(\vec{k}_1, \dots, \vec{k}_n) \delta_{\vec{k}_1}^{(1)} \dots \delta_{\vec{k}_n}^{(1)}$$

MacDonald , Roy (2010)
Senatore (2014)
Desjacques, Jeong, Schmidt (2014)
Many others

Organizing perturbative expansion

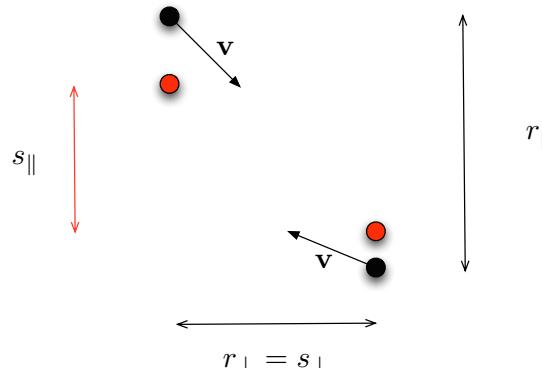
Finally, redshift space

$$\delta_{r,h}(\vec{k}, \hat{z}) = \delta_h(\vec{k}) + \int d^3x e^{-i\vec{k}\cdot\vec{x}} \left\{ \exp \left[-i \frac{(\hat{z} \cdot \vec{k})}{aH} (\hat{z} \cdot \vec{v}(\vec{x})) \right] - 1 \right\} (1 + \delta_h(\vec{x})) ,$$

$$\delta_{r,h}^{(n)}(\vec{k}, \hat{z}, a) = D(a)^n \int_{\vec{k}_1, \dots, \vec{k}_n}^{\vec{k}} K_n^{r,h}(\vec{k}_1, \dots, \vec{k}_n; \hat{z}) \delta_{\vec{k}_1}^{(1)} \dots \delta_{\vec{k}_n}^{(1)}$$

To this, we have to add counterterms and stochastic terms.

In Matt's talk there's all you want to know about them



Scoccimarro (2004)

Lewandowski, Senatore, Prada, Zhao, Chuang (2015)
Perko, Senatore, Jennings, Wechsler (2016)

IR resummation

- Perturbation theory is very slow to converge due to the effect of long-wavelength displacements
- Expansion parameters: motions of modes longer and smaller than k , and tides larger than k .
In our universe $\epsilon_{s<}$ is of order 1. In fact, large scale displacements move particles around.
- One can resum these displacements, improving the convergence.
We implement full Lagrangian resummation, no modifications when there are new physics scales

$$\epsilon_{s>} \sim k^2 \int_k^\infty d^3q \frac{P(q)}{q^2} \quad \epsilon_{s<} \sim k^2 \int_0^k d^3q \frac{P(q)}{q^2}$$

$$\epsilon_{\delta<} \sim \int_0^k d^3q P(q)$$

Senatore, Zaldarriaga (2014)
Baldauf, Mirbabayi, Simonovic, Zaldarriaga (2015)
Vlah, Seljak et al. (2015)
Ivanov, Sibiryakov (2016)
Lewandowski, Senatore (2018)
GDA, Senatore, Zhang (2019)

Observables: power spectrum

$$\langle \delta_{r,h}(\vec{k}_1, \hat{z}, a) \delta_{r,h}(\vec{k}_2, \hat{z}, a) \rangle = (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2) P^{r,h}(k_1, \hat{k}_1 \cdot \hat{z}, a)$$

$$P_{\text{1-loop tot.}}^{r,h}(k, \hat{k} \cdot \hat{z}, a) = D(a)^2 P_{11}^{r,h}(k, \hat{k} \cdot \hat{z}) + D(a)^4 (P_{22}^{r,h}(k, \hat{k} \cdot \hat{z}) + P_{13}^{r,h}(k, \hat{k} \cdot \hat{z}))$$

$$P_{11}^{r,h}(k, \hat{k} \cdot \hat{z}) = K_1^{r,h}(\vec{k}; \hat{z}) K_1^{r,h}(-\vec{k}; \hat{z}) P_{11}(k)$$

$$P_{22}^{r,h}(k, \hat{k} \cdot \hat{z}) = 2 \int_{\vec{q}} K_2^{r,h}(\vec{q}, \vec{k} - \vec{q}; \hat{z})^2 P_{11}(q) P_{11}(|\vec{k} - \vec{q}|)$$

$$P_{13}^{r,h}(k, \hat{k} \cdot \hat{z}) = 6 P_{11}(k) K_1^{r,h}(\vec{k}, \hat{z}) \int_{\vec{q}} K_3^{r,h}(\vec{q}, -\vec{q}, \vec{k}; \hat{z}) P_{11}(q)$$

$$P_{13}^{r,h,\text{ct}}(k, \hat{k} \cdot \hat{z}) = 2 K_1^{h,r}(\vec{k}; \hat{z}) P_{11}(k) \frac{k^2}{k_{\text{NL}}^2} \left(c_{\text{ct}} + c_{r,1} (\hat{k} \cdot \hat{z})^2 + c_{r,2} (\hat{k} \cdot \hat{z})^4 \right)$$

$$P_{22}^{r,h,\epsilon}(k, \hat{k} \cdot \hat{z}) = \frac{1}{\bar{n}} \left(c_1^{\text{St}} + c_2^{\text{St}} \frac{k^2}{k_{\text{NL}}^2} + c_3^{\text{St}} \frac{k^2}{k_{\text{NL}}^2} f(\hat{k} \cdot \hat{z})^2 \right)$$

Perko, Senatore, Jennings,
Wechsler (2016)
GDA, Gleyzes, Kokron, Markovic,
Senatore, Zhang et al. (2019)
Ivanov, Simonovic, Zaldarriaga
(2019)

Observables: bispectrum

$$\langle \delta_{r,h}(\vec{k}_1, \hat{z}, a) \delta_{r,h}(\vec{k}_2, \hat{z}, a) \delta_{r,h}(\vec{k}_3, \hat{z}, a) \rangle = (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) B^{r,h}(k_1, k_2, k_3, \hat{k}_1 \cdot \hat{z}, \hat{k}_2 \cdot \hat{z}, a)$$

$$B_{\text{1-loop tot.}}^{r,h} = D(a)^4 B_{211}^{r,h} + D(a)^6 \left(B_{222}^{r,h} + B_{321}^{r,h,(I)} + B_{321}^{r,h,(II)} + B_{411}^{r,h} \right)$$

$$B_{211}^{r,h} = 2K_1^{r,h}(\vec{k}_1; \hat{z}) K_1^{r,h}(\vec{k}_2; \hat{z}) K_2^{r,h}(\vec{k}_1, \vec{k}_2; \hat{z}) P_{11}(k_1) P_{11}(k_2) + \text{ 2 perms.}$$

$$\begin{aligned} B_{222}^{r,h} &= 8 \int_{\vec{q}} P_{11}(q) P_{11}(|\vec{k}_2 - \vec{q}|) P_{11}(|\vec{k}_1 + \vec{q}|) \\ &\quad \times K_2^{r,h}(-\vec{q}, \vec{k}_1 + \vec{q}; \hat{z}) K_2^{r,h}(\vec{k}_1 + \vec{q}, \vec{k}_2 - \vec{q}; \hat{z}) K_2^{r,h}(\vec{k}_2 - \vec{q}, \vec{q}; \hat{z}) \end{aligned}$$

$$\begin{aligned} B_{321}^{r,h,(I)} &= 6P_{11}(k_1) K_1^{r,h}(\vec{k}_1; \hat{z}) \int_{\vec{q}} P_{11}(q) P_{11}(|\vec{k}_2 - \vec{q}|) \\ &\quad \times K_3^{r,h}(-\vec{q}, -\vec{k}_2 + \vec{q}, -\vec{k}_1; \hat{z}) K_2^{r,h}(\vec{q}, \vec{k}_2 - \vec{q}; \hat{z}) + \text{ 5 perms.} \end{aligned}$$

$$B_{321}^{r,h,(II)} = 6P_{11}(k_1) P_{11}(k_2) K_1^{r,h}(\vec{k}_1; \hat{z}) K_2^{r,h}(\vec{k}_1, \vec{k}_2; \hat{z}) \int_{\vec{q}} P_{11}(q) K_3^{r,h}(\vec{k}_2, \vec{q}, -\vec{q}; \hat{z}) + \text{ 5 perms.}$$

$$B_{411}^{r,h} = 12P_{11}(k_1) P_{11}(k_2) K_1^{r,h}(\vec{k}_1; \hat{z}) K_1^{r,h}(\vec{k}_2; \hat{z}) \int_{\vec{q}} P_{11}(q) K_4^{r,h}(\vec{q}, -\vec{q}, -\vec{k}_1, -\vec{k}_2; \hat{z}) + \text{ 2 perms.}$$

A numerical workhorse: FFTLog

- Integrals over the PS are challenging and slow, and the PS changes at each cosmology... We FFTLog to separate cosmology dependence

$$P_{11}(k_n) = \sum_{m=-N_{\max}/2}^{N_{\max}/2} c_m k_n^{\nu+i\eta_m}$$
$$c_m = \frac{1}{N_{\max}} \sum_{l=0}^{N_{\max}-1} P_{11}(k_l) k_l^{-\nu} k_{\min}^{-i\eta_m} e^{-2iml/N} \quad \eta_m = \frac{2\pi m}{\log(k_{\max}/k_{\min})}$$

- Then **~everything** is a matrix multiplication of the coefficients

$$P_\sigma(k) = k^3 \sum_{m_1, m_2} c_{m_1} k^{-2\nu_1} M_\sigma(\nu_1, \nu_2) k^{-2\nu_2} c_{m_2}$$

Hamilton (1997)

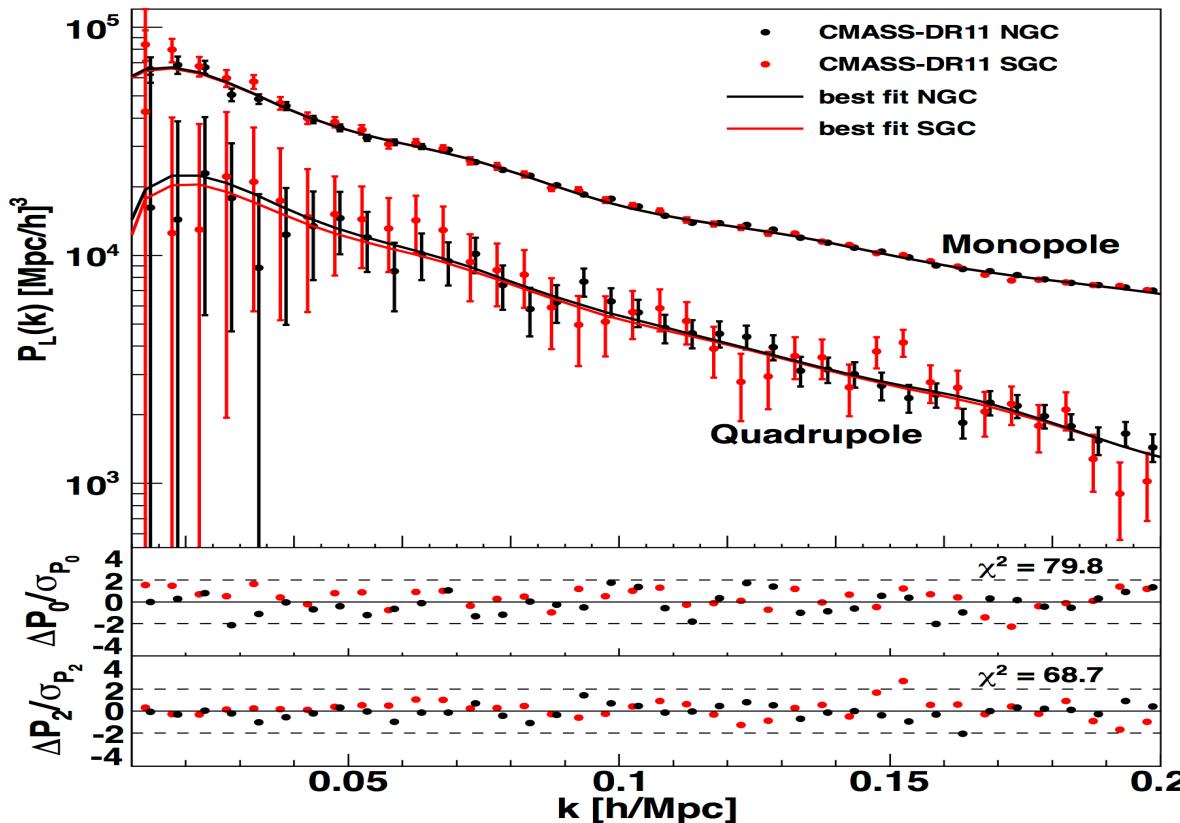
Simonovic, Baldauf, Zaldarriaga, Carrasco, Kollmeier (2017)
GDA, Senatore, Zhang (2020): PyBird

Towards data analysis: data

Standard data compression: we project angular dependence in Legendre polynomials, and bin in k-space.

Power spectrum: monopole, quadrupole, hexadecapole (already small and noisy)

Bispectrum: monopole and 3 quadrupoles



Towards data analysis: likelihood

- Bayesian parameter estimation using MCMC with physically motivated priors on cosmological and EFT parameters.
At each step (we need a lot of them!) one must evaluate the model
- 1-loop power spectrum: cosmological parameters + 10 EFT parameters.
Actually $c_{r,2}$ degenerate with $c_{r,1}$ when not using hexadecapole.
Then rotate $c_{2,4} = (b_2 \pm b_4)/\sqrt{2}$
For BOSS data, c_4 undetermined so fix it to 0
- Still, we are left with cosmo parameters (typically 4) plus 8 EFT...
PyBird gives fast evaluation (0.3-1s for PS), but we can reduce the dimensionality

Other codes:

CLASS-PT (Ivanov, Philcox et al.)

Velocileptors (Chen, Vlah, White)

Towards data analysis: efficient sampling

- Assume Gaussian likelihood with given covariance

$$-2 \ln \mathcal{P} = (T_i - D_i) C_{ij}^{-1} (T_j - D_j) - 2 \ln \mathcal{P}_{\text{pr}} = \\ g_\alpha F_{2,\alpha\beta} g_\beta - 2g_\alpha F_{1,\alpha} + F_0 \quad T_i = g_\alpha T_{G,i}^\alpha + T_{NG,i}$$

- Dependence on EFT parameters is *simple*.
All but 3 of them are linear in the PS, so we analytically marginalize over them.
Huge speedup, shift in best-fit negligible (and can be recovered)

$$-2 \ln \mathcal{P}_{\text{marg}} = -2 \ln \int d^n g \mathcal{P} = F_{1,\alpha} F_{2,\alpha\beta}^{-1} F_{1,\beta} + F_0 + \ln \det \frac{F_2}{2\pi}$$

Towards data analysis: a note on priors

- In Bayesian analysis, data update our belief on the model and its parameters. Must start from a probability measure on parameters. There is no “uninformative prior”.
- And what if data are not precise enough?

The status of LSS EFT analysis: two manifestly equivalent implementations of the manifestly correct theory on manifestly the same data produce manifestly different results. [#cosmology](#)

This seems a little strong. Ignoring bispectrum loops (which are quite preliminary), the main power spectrum results from the three groups are similar. This is true with / without windows (and with broad priors on eft parameters). But we should check for residual differences!

Priors on counterterms? The incarnation of the devil on Earth.



Towards data analysis: a note on priors

- “Typically”, data determine well cosmological parameters. We put a large uniform prior on them: akin to frequentist maximum likelihood approach.
- On the EFT parameters?
We know they have to be small, but not much more: except for a few, we center them at 0 with $\sigma=2$.
- Other choices are possible, as long as they cover the physically allowed region, but *EFT parametrization stays the same*.
“West Coast” and “East Coast” parameters are a *linear transformation of each other*.
Prior choice is, however, different.
- Now, best fits are unchanged, since both priors cover the allowed region.
1d projected posteriors are slightly different, due to different projection effects
(*Simon, Zhang et al. 2208.05929*)

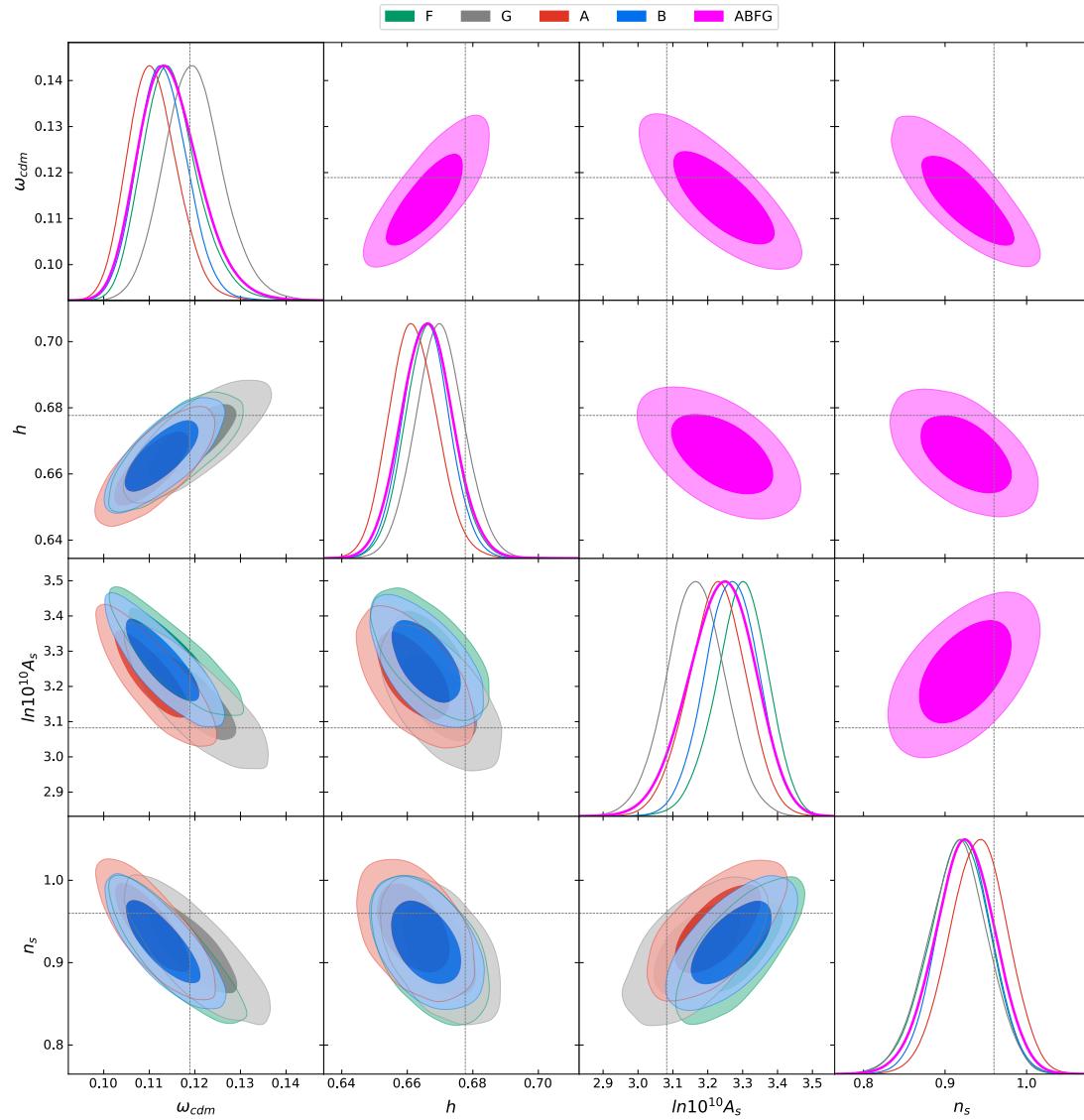
How do we measure parameters?

- Power spectrum has imprinted **BAO**
 - Amplitude depends on ω_b/ω_c , giving ω_c putting BBN prior on ω_b
 - Position depends on a scale: $\theta_{\text{LSS}} = (\theta_{\text{LSS},\perp}^2 \theta_{\text{LSS},\parallel})^{1/3}$ $\theta_{\text{LSS},\parallel} \simeq \frac{r_s}{cz_{\text{LSS}}/H(z_{\text{LSS}})}$ $\theta_{\text{LSS},\perp} \simeq \frac{r_s}{D_A(z_{\text{LSS}})}$
 - Multipoles allow measure of **both**, in Λ CDM this gives h
- Broadband shape
 - $P_{11,\ell=0} \sim b_1^2 A_s^{(k_{\text{max}})}$, $P_{11,\ell=2} \sim b_1 f A_s^{(k_{\text{max}})}$, $A_s^{(k_{\text{max}})} \sim A_s k_{\text{eq}}^2 \sim A_s \Omega_m h^2$
 - Deviation from scale invariance and suppression: n_s e $\sum m_\nu$
- Bispectrum
 - Adds lots of EFT parameters, but gives planar information:
improvements of 13% on Ωm , 18% on h , 30% on $\sigma 8$

Where do we stop?

- Very important issue: where to stop the fit?
Usual tradeoff between *accuracy* and *precision*: smaller scales have smaller errors, but perturbative approach starts to fail
- Two avenues: fits on simulations and/or adding NNLO estimate
- On simulations, we measure theoretical error as shift of 1σ region from the truth, after combining: we stop when we reach $\sim 0.3\sigma_{\text{data}}$
Why? If we combine in quadrature, then it means we shift the result by 5%
- NNLO estimate is an estimate of the largest neglected term: if it is detected, then we are not allowed to use those scales

Scale-cut with simulations



$$s_{\min} = 20 \text{ Mpc}/h$$

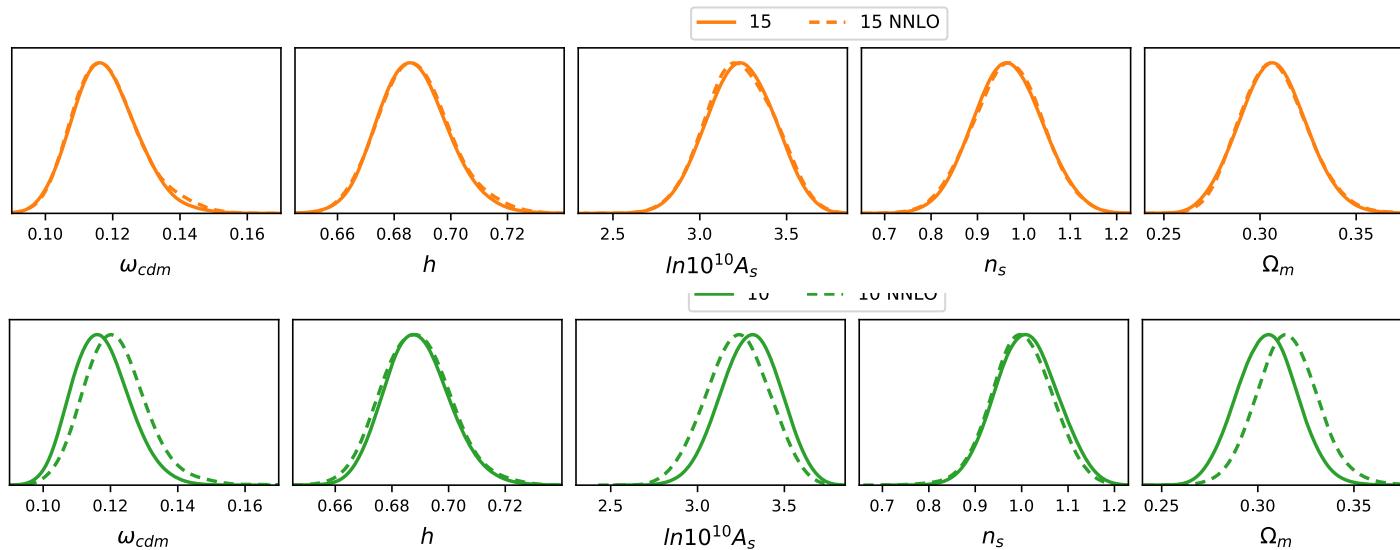
2-pt Correlation function
Zhang, GDA, Senatore, Zhao, Cai
2110.07539

Scale-cut without simulations

- Estimate the contribution of next-order effect, and estimate when they start to make a difference

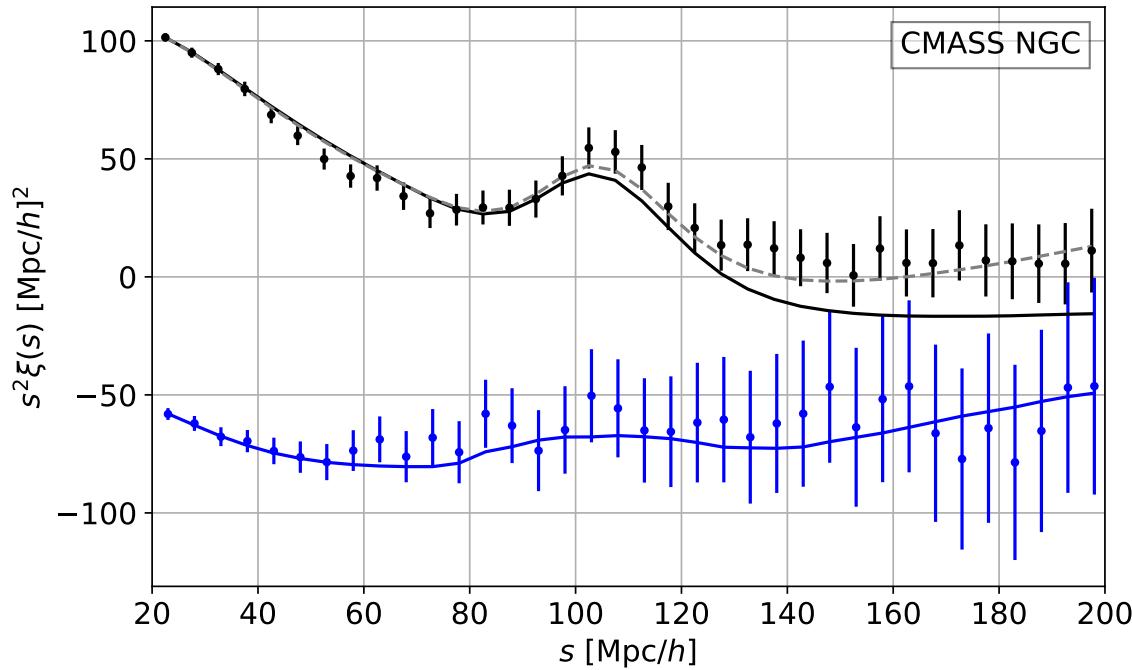
$$\xi_{\text{NNLO}}^\ell(s) = i^\ell \int \frac{dk}{2\pi^2} k^2 P_{\text{NNLO}}^\ell(k) j_\ell(ks)$$

$$P_{\text{NNLO}}^\ell(k) = b_{k^2 P_{\text{NLO}}}^\ell \frac{k^2}{k_M^2} P_{\text{NLO}}^\ell(k) + c_{r,4} b_1^2 \mu^4 \frac{k^4}{k_{M,R}^4} P_{11}(k) \Big|_\ell + c_{r,6} b_1 \mu^6 \frac{k^4}{k_{M,R}^4} P_{11}(k) \Big|_\ell$$

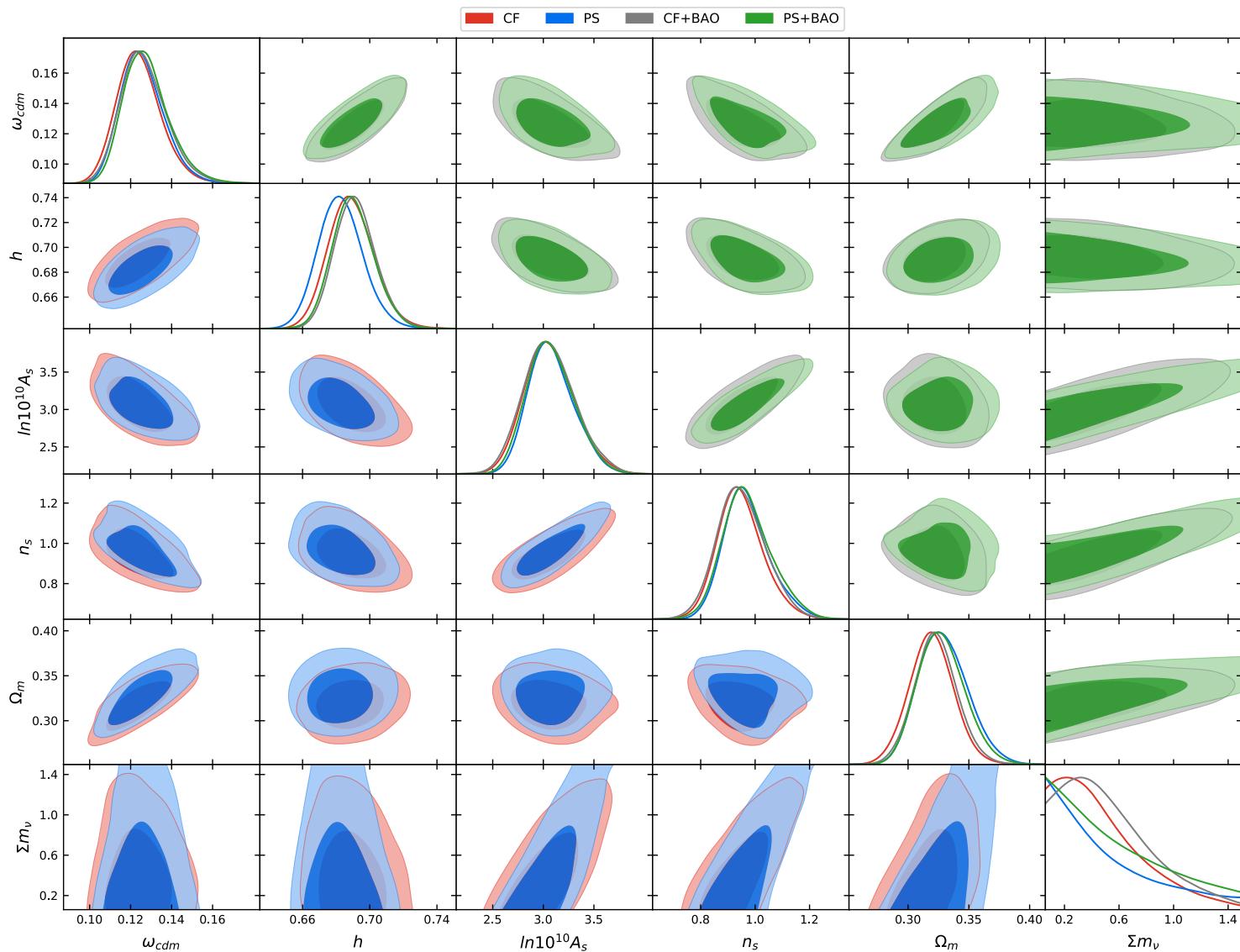


2pt function: real and Fourier space

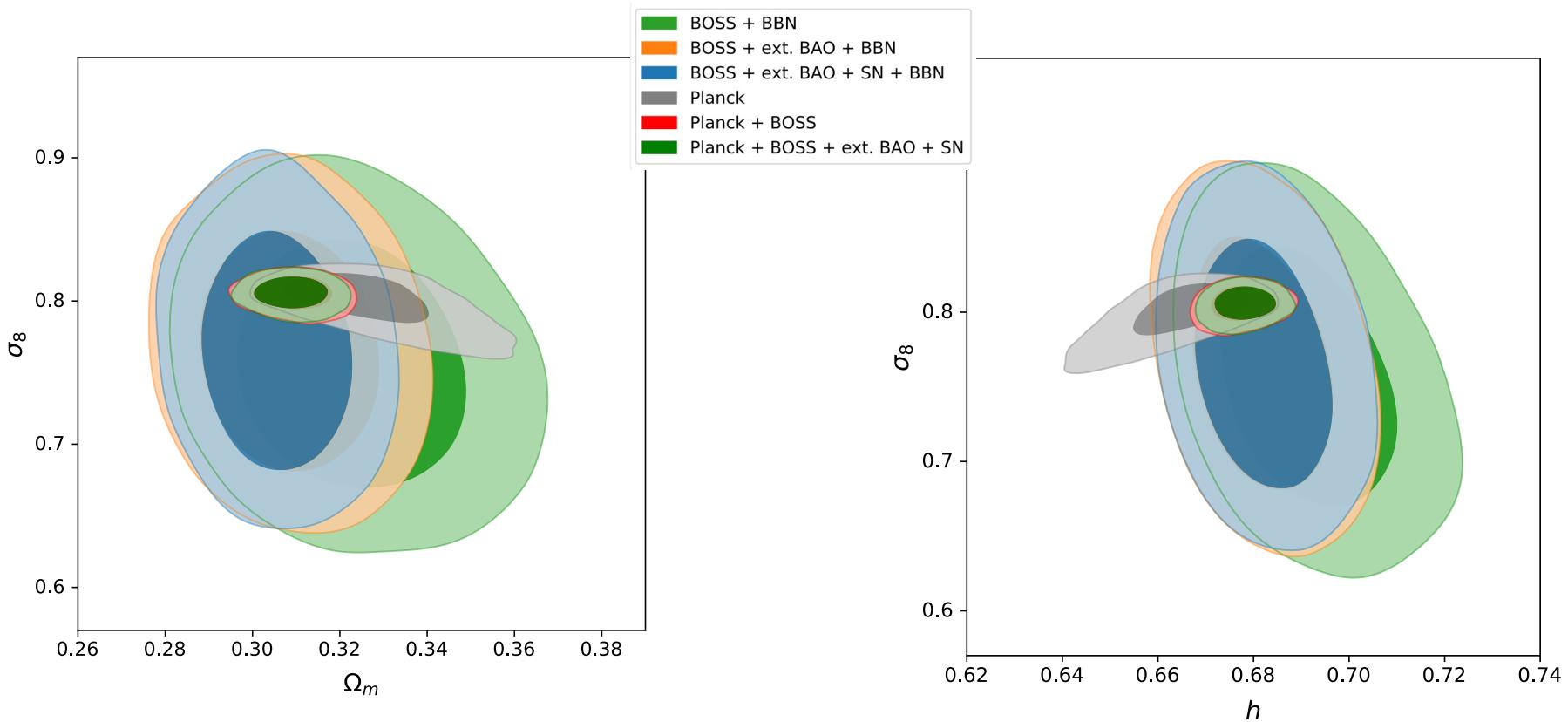
- Why analyze the same data in a different basis?
 - Easier to include BAO information
 - Useful check for systematics (both theory and data)



PS vs CF



Dataset consistency



- Tension in σ_8 was due to a systematics in the power spectrum estimator of BOSS

No tensions!

CF+BAO	best-fit	mean $\pm\sigma$
ω_{cdm}	0.1167	$0.1266^{+0.0098}_{-0.013}$
h	0.6817	$0.6915^{+0.011}_{-0.013}$
$\ln(10^{10} A_s)$	3.235	$3.062^{+0.24}_{-0.28}$
n_s	0.9743	$0.9503^{+0.082}_{-0.098}$
$\sum m_\nu$ [eV]	0.52	$< 1.15(2\sigma)$
Ω_m	0.3113	$0.323^{+0.017}_{-0.019}$
σ_8	0.7796	$0.7559^{+0.054}_{-0.062}$

Planck	best-fit	mean $\pm\sigma$
$100 \omega_b$	2.236	$2.233^{+0.015}_{-0.015}$
ω_{cdm}	0.1202	$0.1206^{+0.0013}_{-0.0013}$
$100 * \theta_s$	1.042	$1.042^{+0.00029}_{-0.0003}$
$\ln(10^{10} A_s)$	3.041	$3.05^{+0.015}_{-0.015}$
n_s	0.9654	$0.9643^{+0.0042}_{-0.0043}$
τ_{reio}	0.05238	$0.05597^{+0.0073}_{-0.0081}$
$\sum m_\nu$ [eV]	0.06	$< 0.26(2\sigma)$
h	0.6731	$0.6655^{+0.011}_{-0.0067}$
Ω_m	0.3162	$0.3262^{+0.0092}_{-0.015}$
σ_8	0.8101	$0.8004^{+0.016}_{-0.008}$

No tensions!

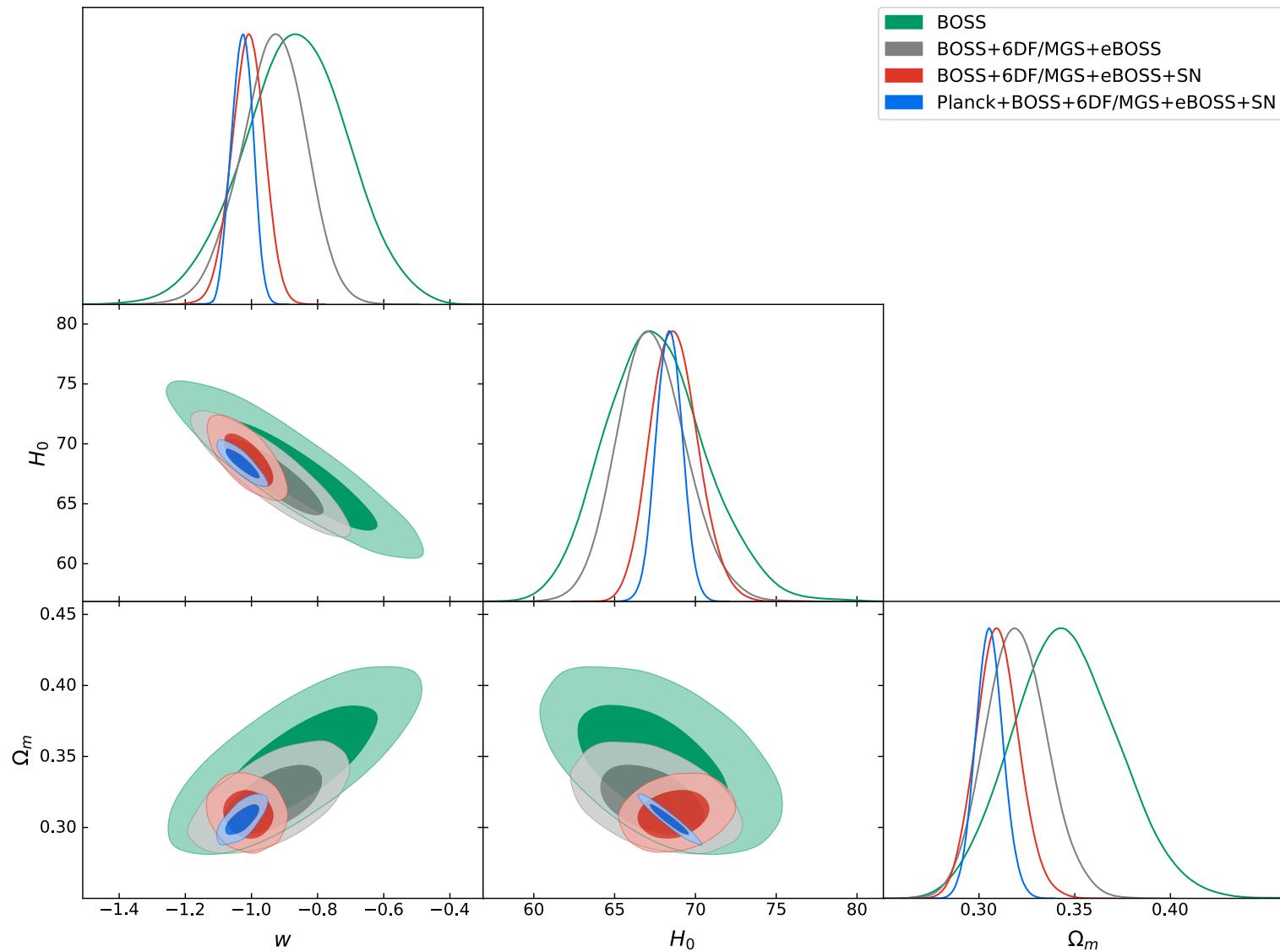
- This was $\nu\Lambda$ CDM. No tensions even putting tight constraint on ν mass < 0.25 eV
- BOSS (+BBN):
 $\sigma_8 = 0.733 \pm 0.053$, $S_8 = 0.750 \pm 0.052$
- BOSS +BAO (+BBN):
 $\sigma_8 = 0.748 \pm 0.051$, $S_8 = 0.752 \pm 0.050$
- Planck:
 $\sigma_8 = 0.800^{+0.016}_{-0.0072}$, $S_8 = 0.853 \pm 0.013$
- Consistency at 1σ , 1.6σ

Beyond Λ CDM: Clustering quintessence

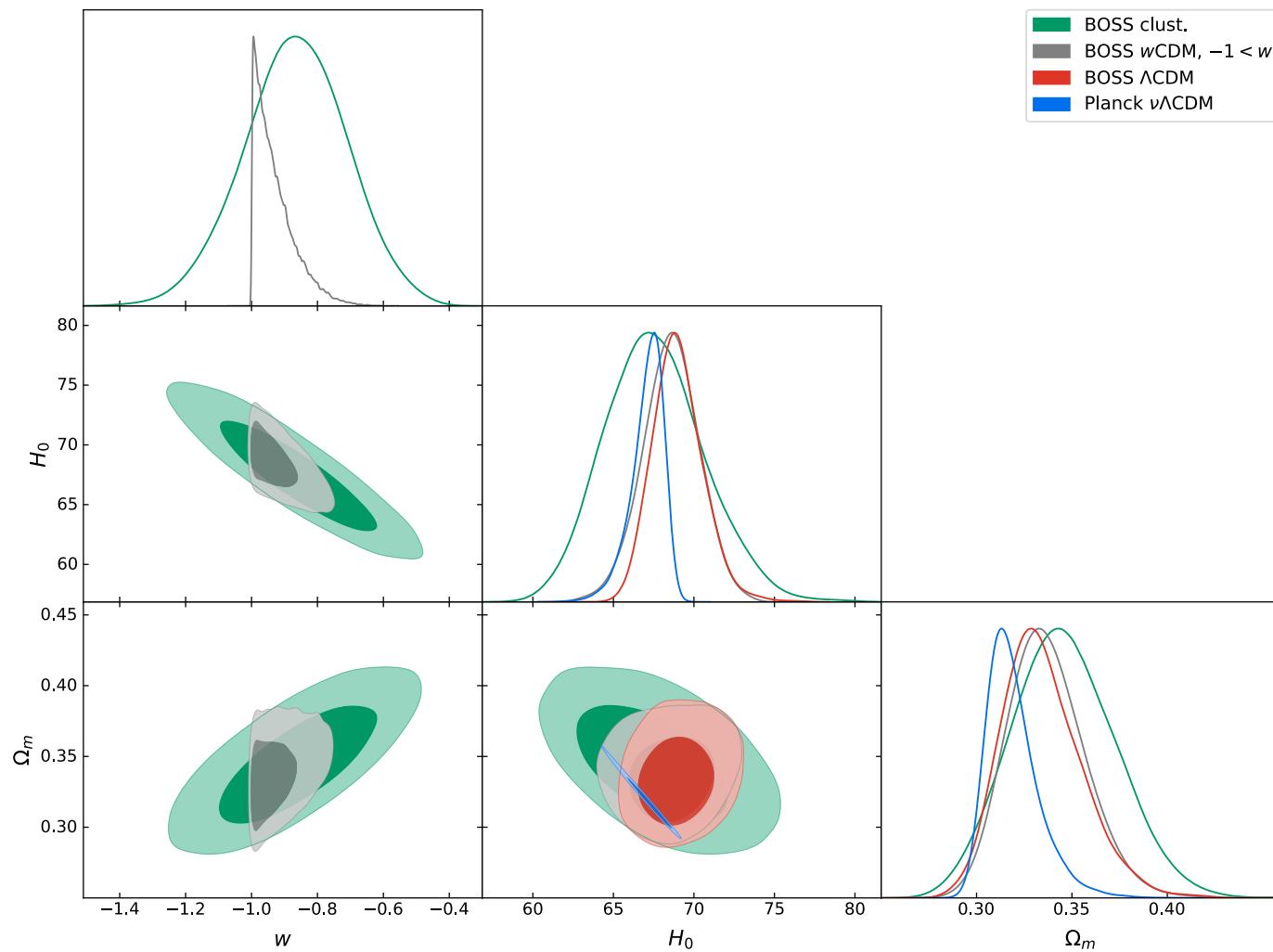
- Equation of state $w < -1$ is not allowed in single-field quintessence, unless the speed of sound is practically zero
- Equations require some modifications, and one must use exact time dependence (no separability of time and k)
- First LSS analysis for a theoretically consistent model with $w < -1$: the universe is suggesting a cosmological constant

Creminelli, GDA, Noreña, Vernizzi (2008)
Vernizzi, Sefusatti (2011)
Lewandowski, Maleknejad, Senatore (2016)
GDA, Donath, Senatore, Zhang (2020)

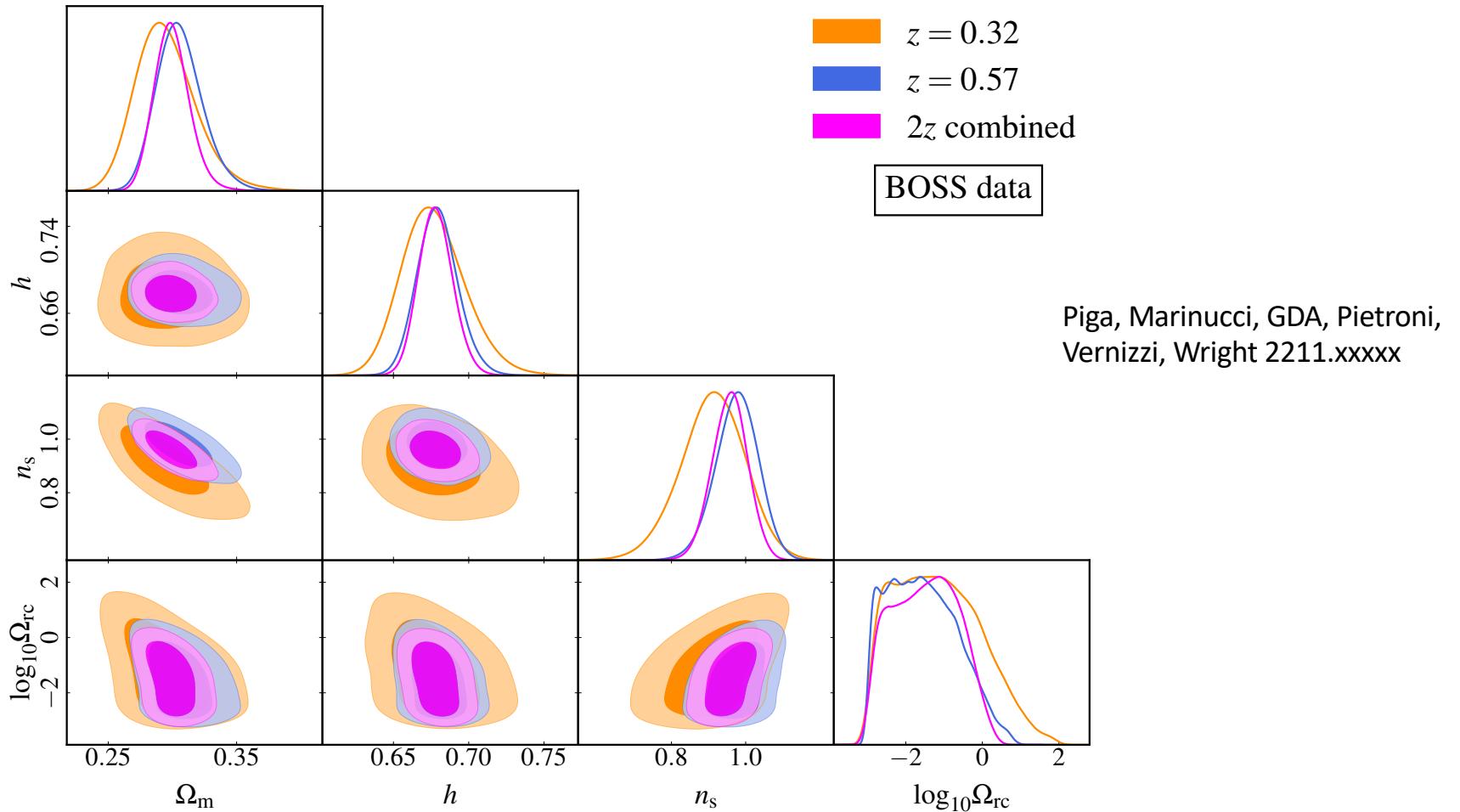
Clustering quintessence



Clustering vs smooth quintessence



Beyond Λ CDM: nDGP



- Actually an example of scale-independent models, which obey equivalence principle: bias parametrization dictated by symmetries
(GDA, Marinucci, Pietroni, Vernizzi 2021)

Beyond 2-pt: the 1-loop bispectrum in LSS

- Lots of work to develop the pipeline for 1-loop bispectrum in EFTofLSS
 - Biased tracers to 4th order in perturbations
 - Redshift distortions up to 4th order
 - Counterterms up to 2nd order
 - Efficient way of computing loop integrals
 - Generalization to non-Gaussian initial conditions

GDA, Lewandowski, Senatore, Zhang (2022)

GDA, Donath, Lewandowski, Senatore, Zhang (2022)

also Philcox, Ivanov, Cabass, Simonovic, Zaldarriaga (2022)

Theory Model

- Perturbation theory up to 4th order: 11 bias parameters

$$P_{11}^{r,h}[b_1], \quad P_{13}^{r,h}[b_1, b_3, b_8], \quad P_{22}^{r,h}[b_1, b_2, b_5], \quad B_{321}^{r,h,(I)}[b_1, b_2, b_3, b_5, b_6, b_8, b_{10}], \\ B_{211}^{r,h}[b_1, b_2, b_5], \quad B_{321}^{r,h,(II)}[b_1, b_2, b_3, b_5, b_8], \quad B_{411}^{r,h}[b_1, \dots, b_{11}], \quad B_{222}^{r,h}[b_1, b_2, b_5]$$

- Stochastic and counterterms up to 2nd order: 30 parameters

$$P_{13}^{r,h,ct}[b_1, c_1^h, c_1^\pi, c_1^{\pi v}, c_3^{\pi v}], \quad P_{22}^{r,h,\epsilon}[c_1^{\text{St}}, c_2^{\text{St}}, c_3^{\text{St}}], \\ B_{321}^{r,h,(II),ct}[b_1, b_2, b_5, c_1^h, c_1^\pi, c_1^{\pi v}, c_3^{\pi v}], \quad B_{321}^{r,h,(I),\epsilon}[b_1, c_1^{\text{St}}, c_2^{\text{St}}, \{c_i^{\text{St}}\}_{i=4,\dots,13}], \\ B_{411}^{r,h,ct}[b_1, \{c_i^h\}_{i=1,\dots,5}, c_1^\pi, c_5^\pi, \{c_j^{\pi v}\}_{j=1,\dots,7}], \quad B_{222}^{r,h,\epsilon}[c_1^{(222)}, c_2^{(222)}, c_5^{(222)}]$$

Theory Model

- IR-Resummation: for PS we do the correct Lagrangian resummation
- For bispectrum, we use the wiggle-no wiggle approximation
In linear term, substitute PS with

$$P_{\text{LO}}(k) = P_{\text{nw}}(k) + (1 + k^2 \Sigma_{\text{tot}}^2) e^{-\Sigma_{\text{tot}}^2} P_{\text{w}}(k)$$

- In loop terms, use on non-integrated PS

$$P_{\text{NLO}}(k) = P_{\text{nw}}(k) + e^{-\Sigma_{\text{tot}}^2} P_{\text{w}}(k) ,$$

Theory model

- **Window:** use approximation (on linear term) from Gil-Marin et al. (2014)

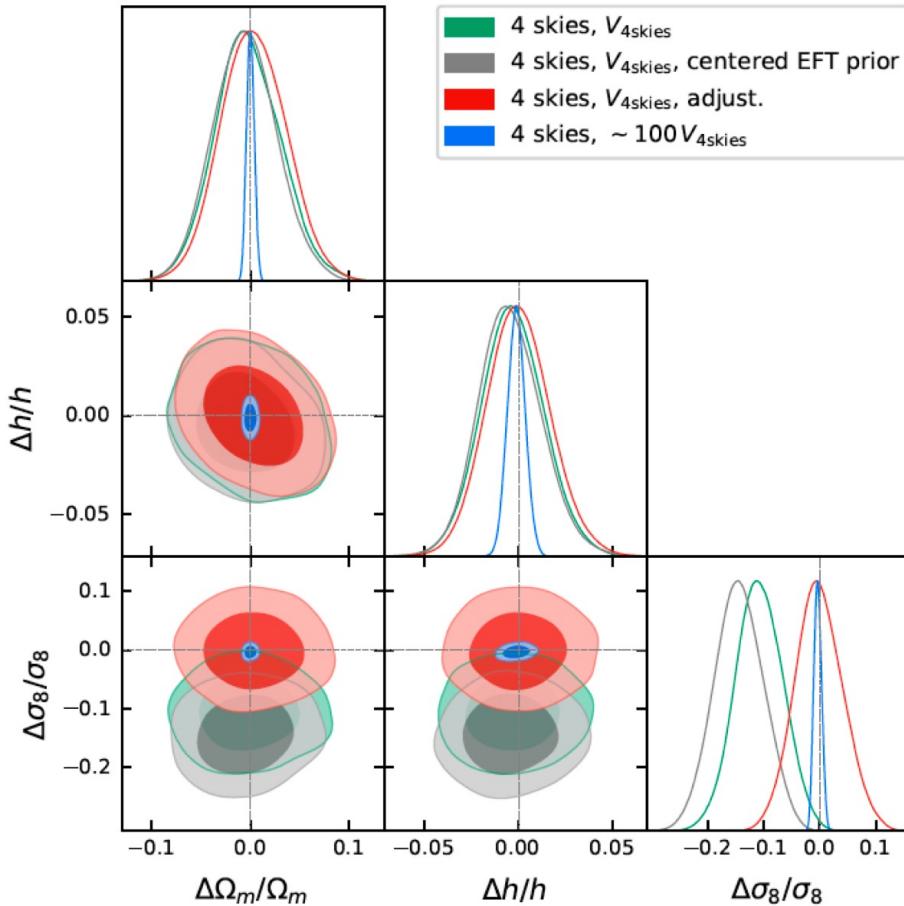
$$B_{211}^{r,h} = 2K_1^{r,h}(\vec{k}_1; \hat{z})K_1^{r,h}(\vec{k}_2; \hat{z})K_2^{r,h}(\vec{k}_1, \vec{k}_2; \hat{z})[W * P_{11}](\vec{k}_1)[W * P_{11}](\vec{k}_2) + \text{ 2 perms. ,}$$

$$[W * P_{11}](\vec{k}) = \int \frac{d^3 k'}{(2\pi)^3} W(\vec{k} - \vec{k}') P_{11}(\vec{k}')$$

- **Binning effect is important:** it is performed (together with AP) exactly on the linear part, loop terms are small
- Effect of approximations are small

$\Delta_{\text{shift}}/\sigma_{\text{stat}}$	Ω_m	h	σ_8
$P_\ell + B_0$: base - w/ NNLO	-0.03	-0.09	-0.03
$P_\ell + B_0$: base - w/o B_0 window	0.11	-0.05	0.01
$P_\ell + B_0 + B_2$: base - w/o B_0, B_2 window	0.51	0.09	0.02

A Bayesian problem



- On synthetic data, 1d truths are not recovered!
- Problem: too much phase space, due to projection of non-Gaussian multidimensional posterior
- What to do?

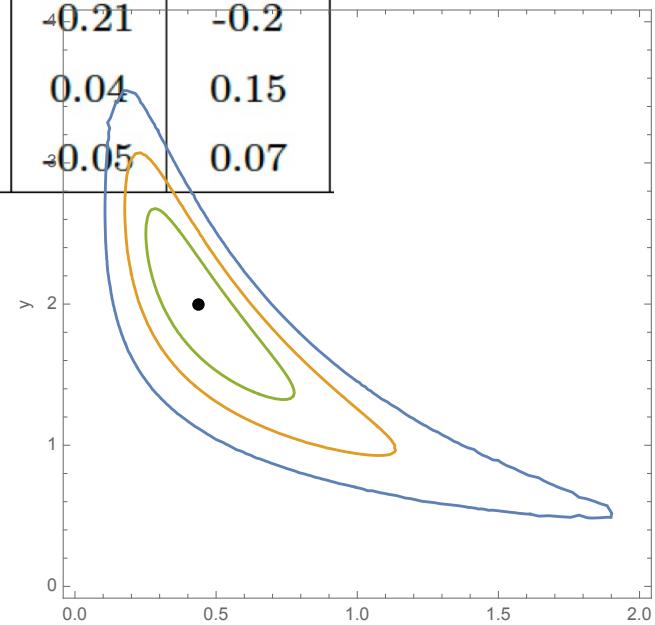
Taken at face value, crazy comparison of parameter measurements across experiments

Fixing phase space issues

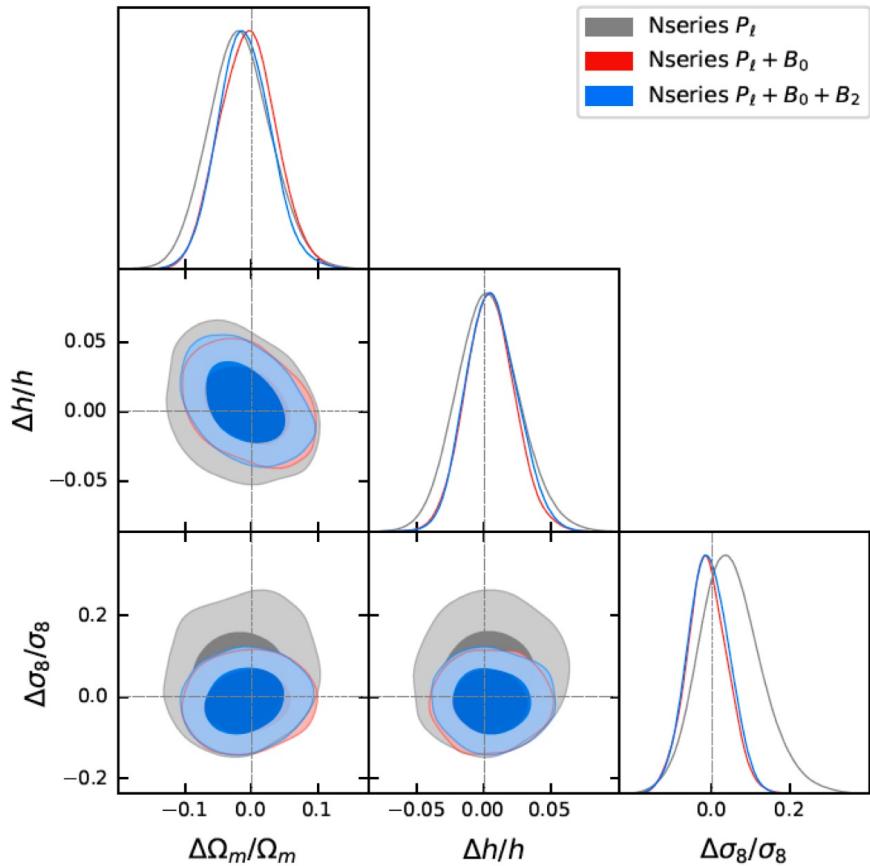
- Our solution: adjusting the prior, measuring the effect on synthetic data fit to our data

$$\ln \mathcal{P}_{\text{pr}}^{\text{ph. sp. 4sky}} = -48 \left(\frac{b_1}{2} \right) + 32 \left(\frac{\Omega_m}{0.31} \right) + 48 \left(\frac{h}{0.68} \right) ,$$

$\sigma_{\text{proj}}/\sigma_{\text{stat}}$	Ω_m	h	σ_8	ω_{cdm}
1 sky, $\sim 100 V_{1\text{sky}}$	-0.1	-0.14	-0.21	-0.2
1 sky, $V_{1\text{sky}}$, adjust.	0.13	0.06	0.04	0.15
4 skies, $V_{4\text{skies}}$, adjust.	0.1	0.	-0.05	0.07

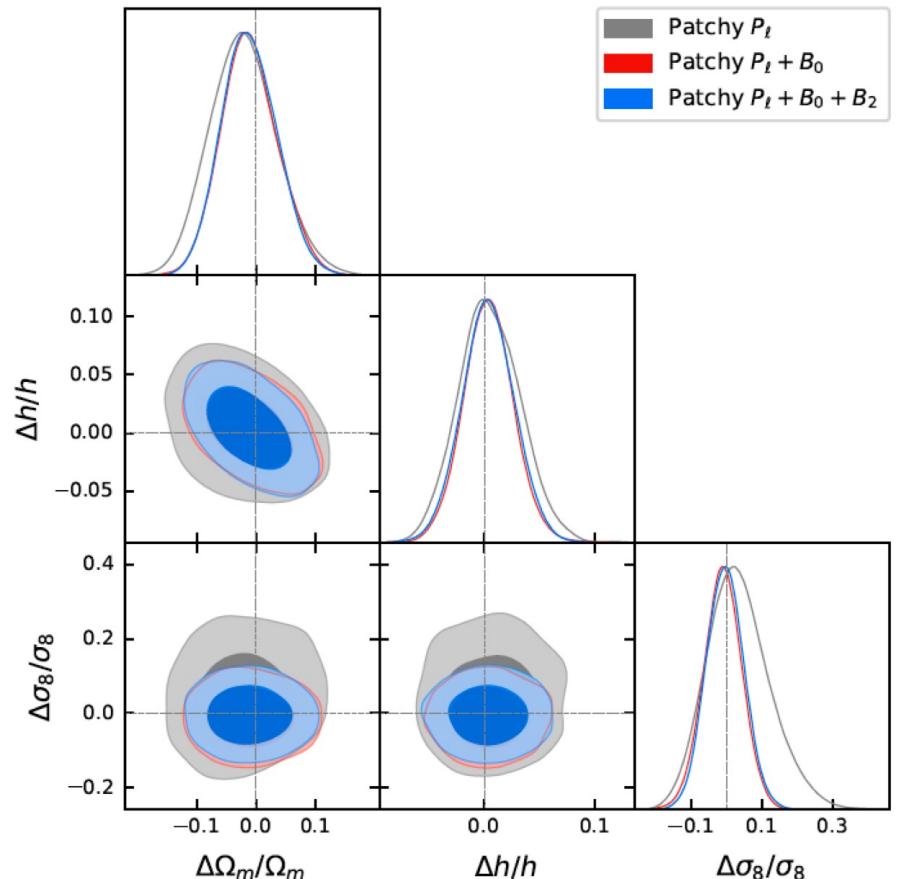


Theoretical error



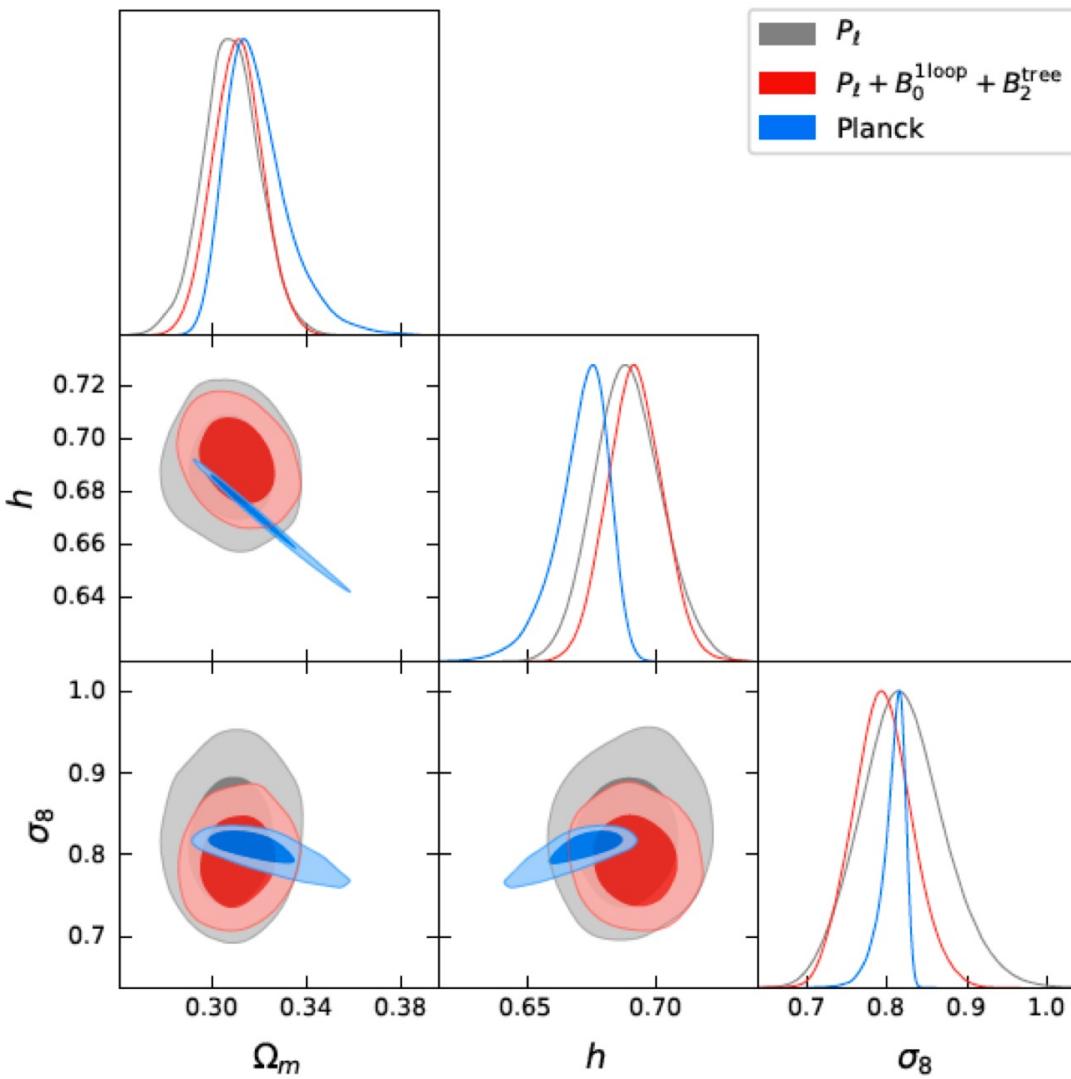
Nseries: 80 x BOSS volume

Safely within $\sigma_{\text{data}}/3$!



Patchy mocks: 2000 x BOSS volume

Results

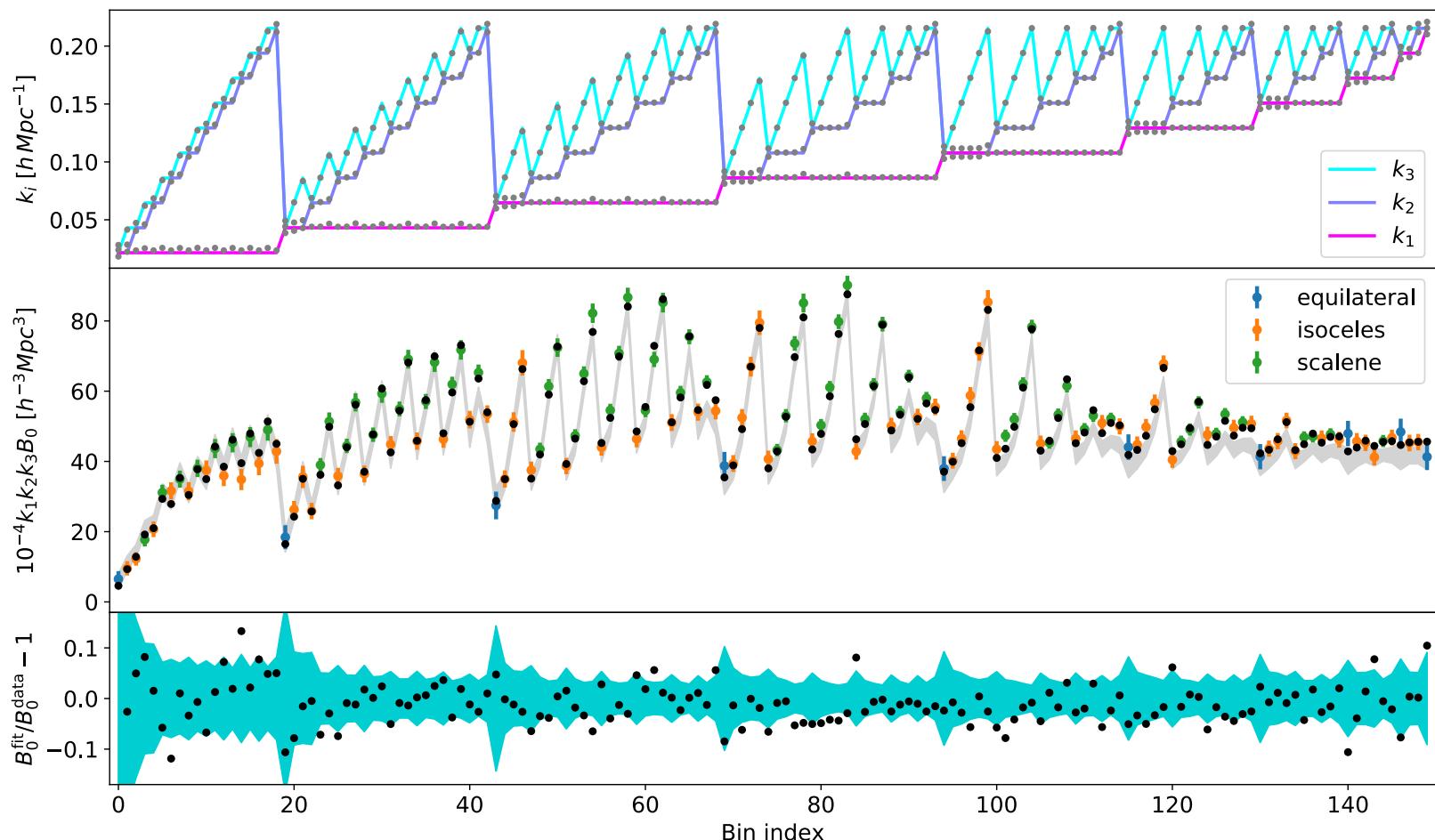


- Improvements of 13% on Ω_m , 18% on h , 30% on σ_8
- Consistency of observables
- Consistency with Planck: no tensions

Results

best-fit mean $\pm \sigma$	Ω_m	h	σ_8	ω_{cdm}	$\ln(10^{10} A_s)$	S_8
P_ℓ	0.2984	0.6763	0.8305	0.1143	3.123	0.8283
	0.308 ± 0.012	$0.689^{+0.012}_{-0.014}$	$0.819^{+0.049}_{-0.055}$	0.1232 ± 0.0075	3.02 ± 0.15	$0.830^{+0.051}_{-0.060}$
$P_\ell + B_0^{\text{tree}}$	0.3101	0.6907	0.8063	0.1248	2.98	0.8197
	0.309 ± 0.011	0.691 ± 0.012	0.804 ± 0.049	0.1246 ± 0.0058	2.97 ± 0.13	$0.816^{+0.050}_{-0.057}$
$P_\ell + B_0^{\text{1loop}}$	0.3210	0.6956	0.7882	0.1331	2.82	0.8153
	0.314 ± 0.011	0.693 ± 0.011	$0.790^{+0.033}_{-0.037}$	0.1278 ± 0.0061	2.90 ± 0.11	$0.807^{+0.037}_{-0.043}$
$P_\ell + B_0^{\text{1loop}} + B_2^{\text{tree}}$	0.3082	0.6928	0.7856	0.1258	2.88	0.7962
	0.311 ± 0.010	0.692 ± 0.011	0.794 ± 0.037	0.1255 ± 0.0057	2.94 ± 0.11	0.808 ± 0.041
Planck	$0.3191^{+0.0085}_{-0.016}$	$0.671^{+0.012}_{-0.0067}$	$0.807^{+0.018}_{-0.0079}$	0.1201 ± 0.0013	3.046 ± 0.015	0.832 ± 0.013

Best fit

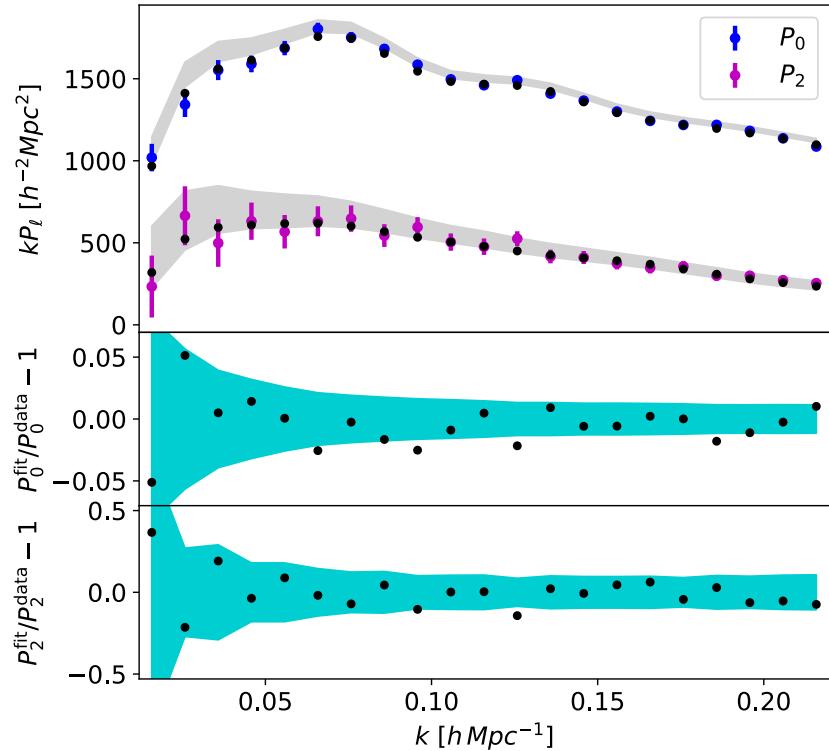
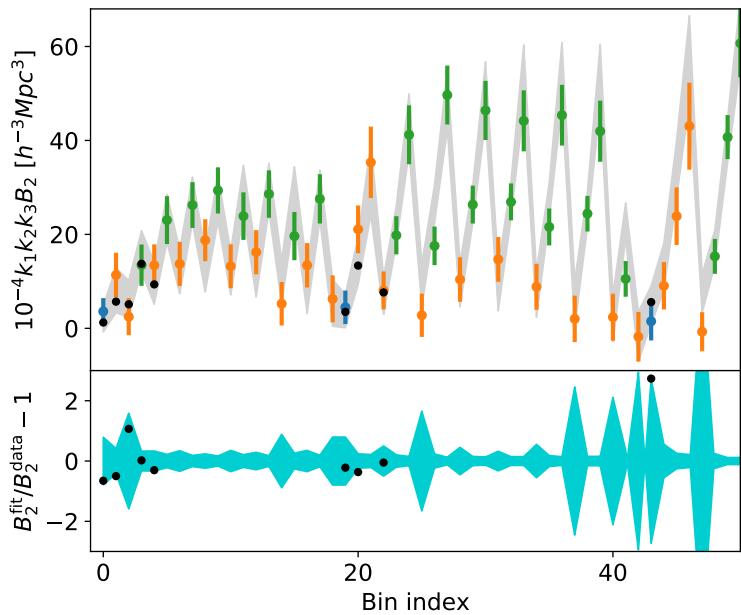


Bispectrum monopole, up to $k_{\max} = 0.23 h/\text{Mpc}$

Bispectrum quadrupole, tree-level, up to $k_{\max} = 0.08 h/\text{Mpc}$

Binned in triangles of $12 k_f \sim 0.02 h/\text{Mpc}$

Best fit



	$N_{\text{bin}} // \text{dof}$	$\min \chi^2$	$\min \chi^2 / \text{dof}$	$p\text{-value}$
CMASS NGC	$42 + 150 + 9 = 201$	159.5	0.79	0.99
CMASS SGC	$42 + 150 + 9 = 201$	188.7	0.94	0.72
LOWZ NGC	$36 + 62 + 9 = 107$	98.3	0.92	0.71
LOWZ SGC	$36 + 62 + 9 = 107$	106.4	0.99	0.50
Parameter Prior	$3 + 37(1 + 0.1 + 0.2 + 0.1 \cdot 0.2) \simeq 49$	8.9	-	-
Total	$616 - 49 = 567$	561.9	0.99	0.55

What next?

- From theory/computational side
 - Better (and not too slow) calculations of observational effects.
 - Emulators if much precision required (Bonici, GDA, Carbone, Bel, in progress)
 - Useful to restrict priors on bias/counterterms
 - Extended models
 - Robust covariance estimates
- From observational side
 - Address systematic errors... The analysis will detect them!
 - Measurements of EFT parameters in simulations
 - Accurate measurements of higher n-point functions

Summary

- Somewhat surprisingly, we can determine cosmological parameters from LSS, close to world record for some of them
- New discoveries/constraints around the corner: neutrino masses, new dark dof, dark energy, possible tensions with other datasets
- Many experiments around the corner: DESI, Euclid are 10x BOSS
- The era of precision cosmology will continue along this avenue