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"EFT of the Large-Scale Structure"

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

1909.05271 (ΛCDM), 1909.07951 ($\nu\Lambda$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), 2211.17130 (EFT renormalization)

https://github.com/pierrexyz/pybird

PONT 2023

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, inflation)?
- 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.
  Our solution is the *EFTofLSS*

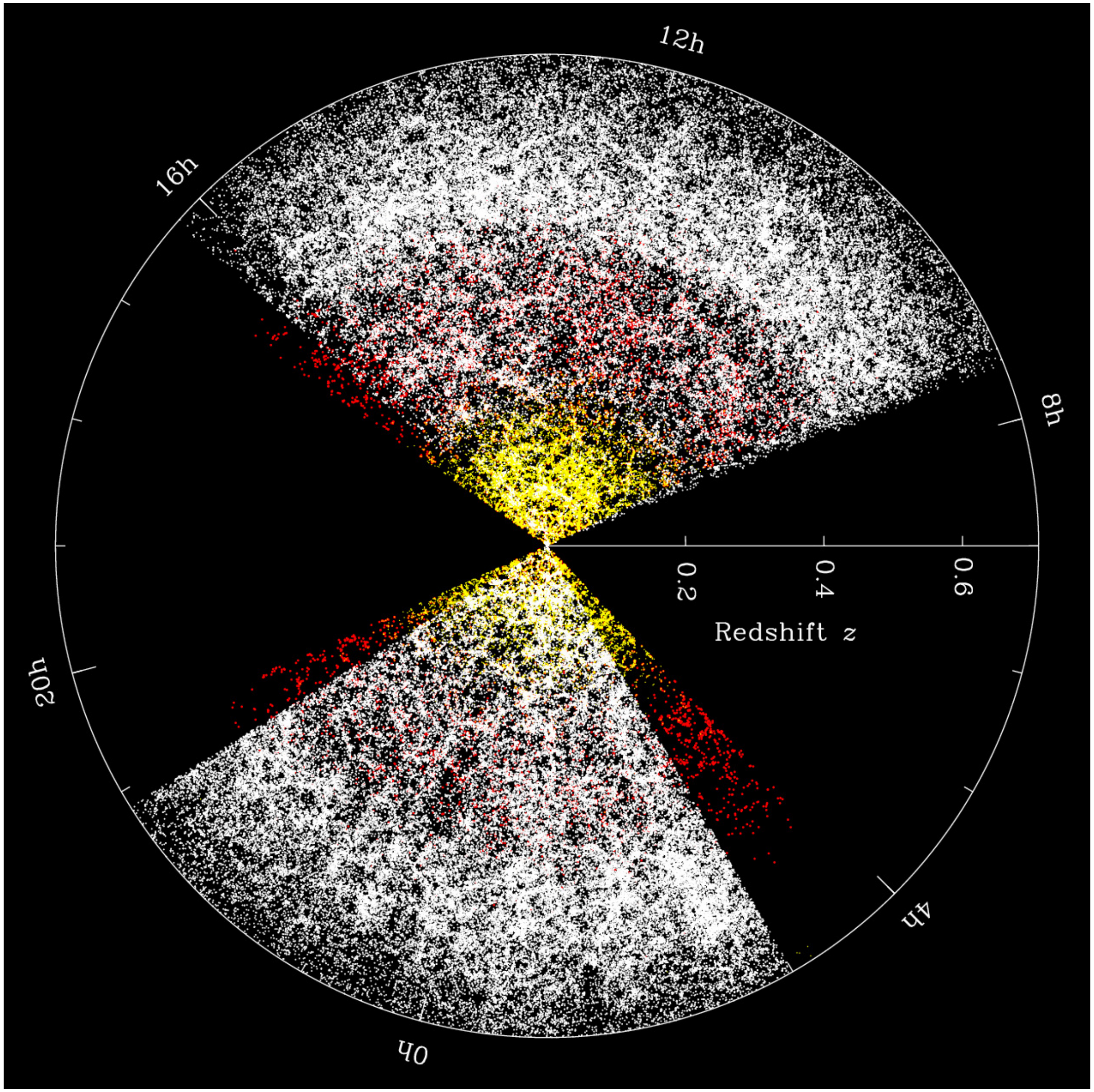
Baumann, Nicolis, Senatore, Zaldarriaga (2012)
Carrasco, Hertzberg, Senatore (2012)

Complicated observables

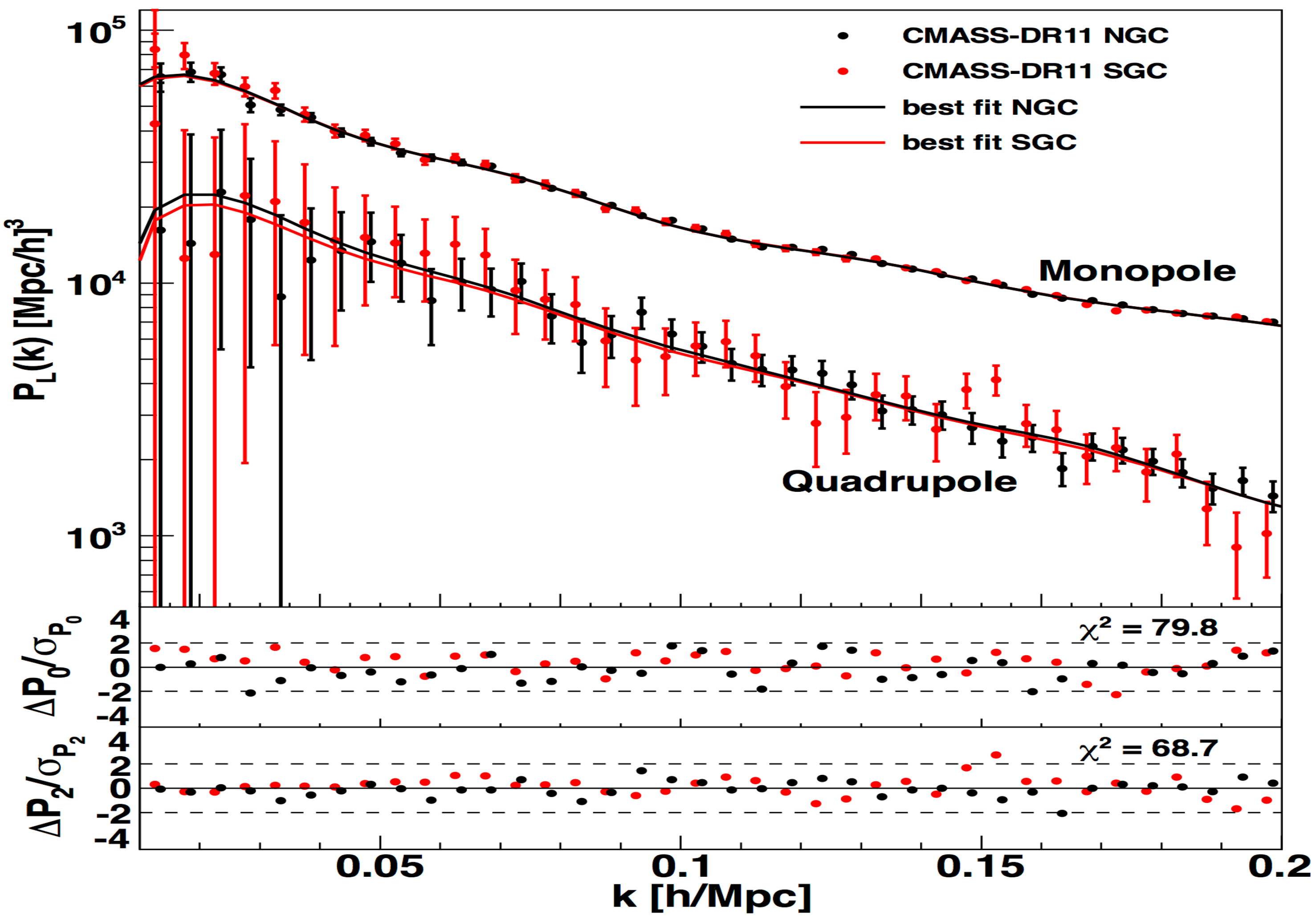
- CMB is a 2d snapshot of perturbations still in the linear regime: only complication, well-understood plasma physics

- 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 BOSS power spectrum



The EFTofLSS

- Important observation: *on large scales*, dark matter (and baryons) behave like a homogeneous fluid with *small perturbations*

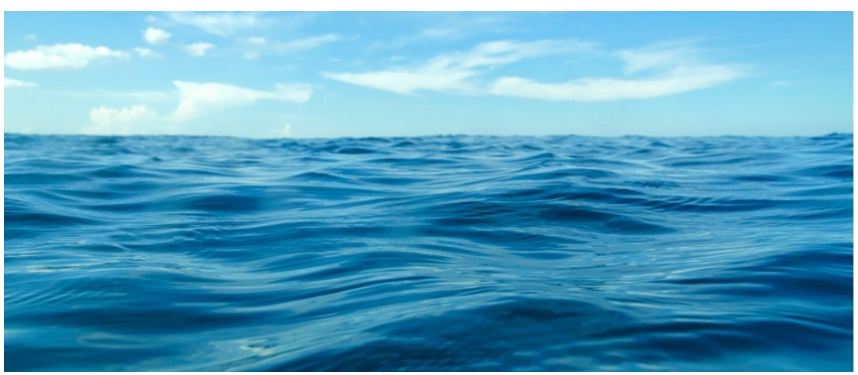
- So we do perturbation theory in δ_l, and expand in derivatives. We have to introduce renormalization to take into account the effects of unknowkn small-scale physics

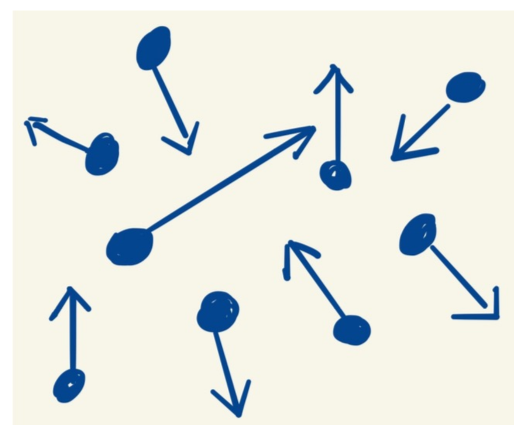
- Galaxies on large scales are a biased tracer of underlying perturbations

- Redshift space: velocity-dependent coordinate change.
  Opportunity: break rotational invariance, so can measure effects of velocity.
  Complication: needs additional renormalization, PT breaks earlier

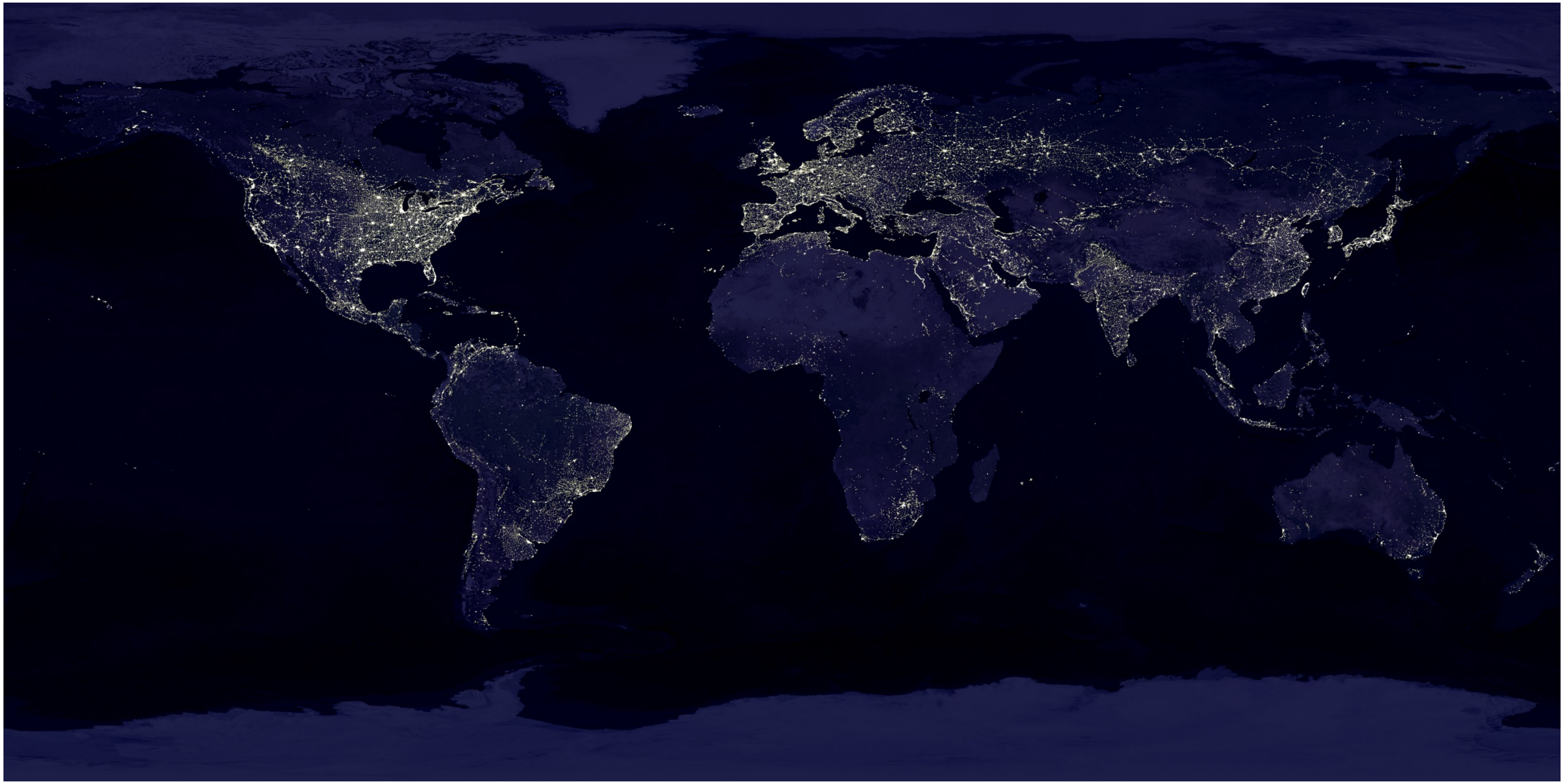
An effective fluid on large scales

- We would like to see the gravitational perturbations: they are traced by dark matter
- In the history of the Universe, cold dark matter moves only $k_{NL}^{-1} \sim 10$ Mpc
- Vlasov hierarchy can be truncated, giving an effective fluid-like system with mean free path k_{NL}^{-1}
- DM does not interact like molecules of a fluid, but behaves like a 'gravitational fluid'





Bias

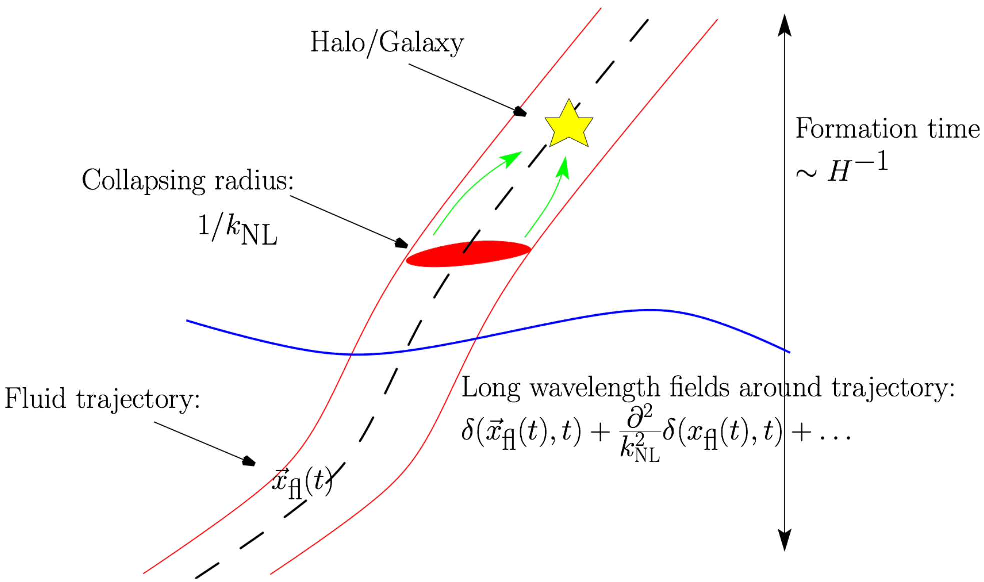


From CDM to galaxies

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

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

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



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

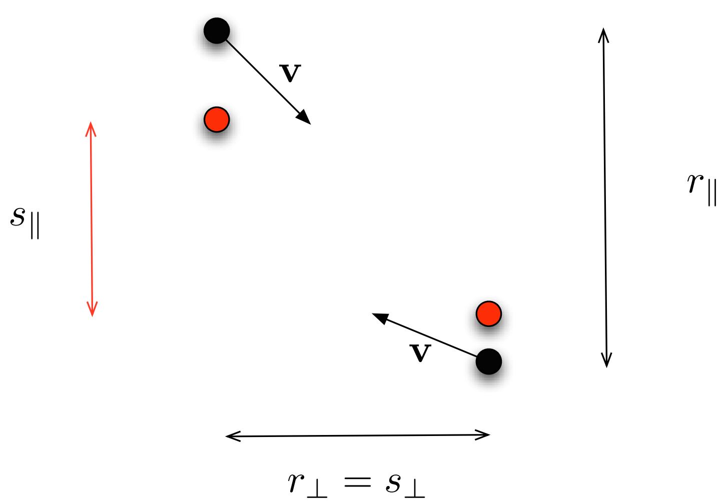
From real to redshift space

Finally, redshift space

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

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

To this (i.e. bias expansion in redshift space), we have to add *counterterms* (proportional to large-scale fields) and *stochastic terms* (e.g. shot-noise).



Scoccimarro (2004)
Lewandowski, Senatore, Prada, Zhao, Chuang (2015)
Perko, Senatore, Jennings, Wechsler (2016)

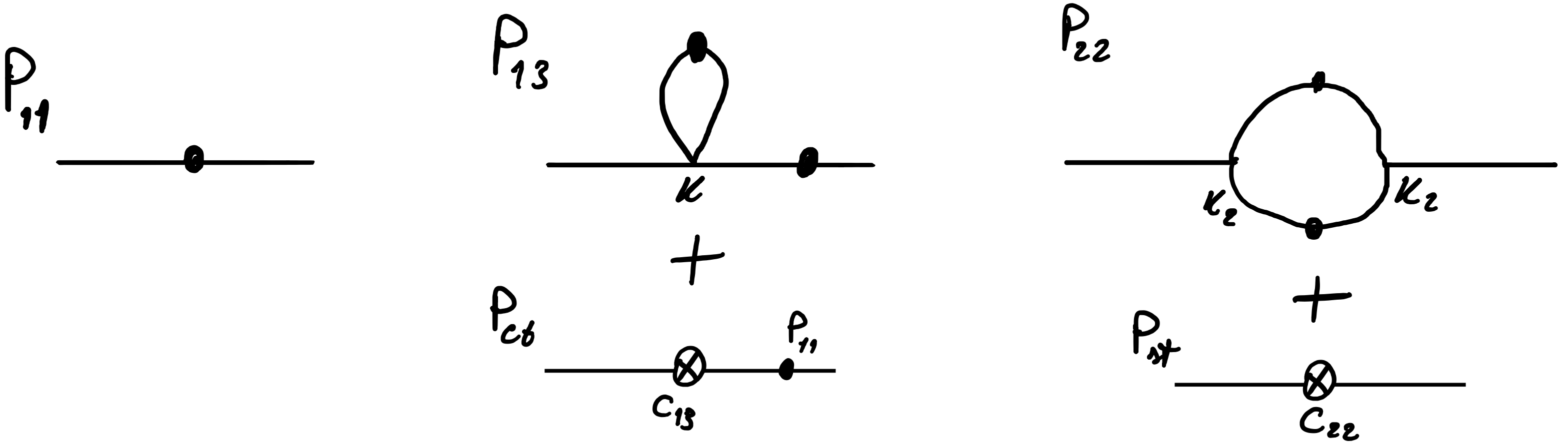
Observables: power spectrum

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

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

$$P^{r,h\text{ct}}_{13}(k, \hat{k}\cdot\hat{z}) = 2K^{h,r}_1(\vec{k};\hat{z})P_{11}(k)\frac{k^2}{k^2_{\text{NL}}}\left(c_{\text{ct}} + c_{r,1}(\hat{k}\cdot\hat{z})^2 + c_{r,2}(\hat{k}\cdot\hat{z})^4\right)$$

$$P^{r,h,\epsilon}_{22}(k, \hat{k}\cdot\hat{z}) = \frac{1}{\bar{n}}\left(c^{\text{St}}_1 + c^{\text{St}}_2\frac{k^2}{k^2_{\text{NL}}} + c^{\text{St}}_3\frac{k^2}{k^2_{\text{NL}}}f(\hat{k}\cdot\hat{z})^2\right)$$

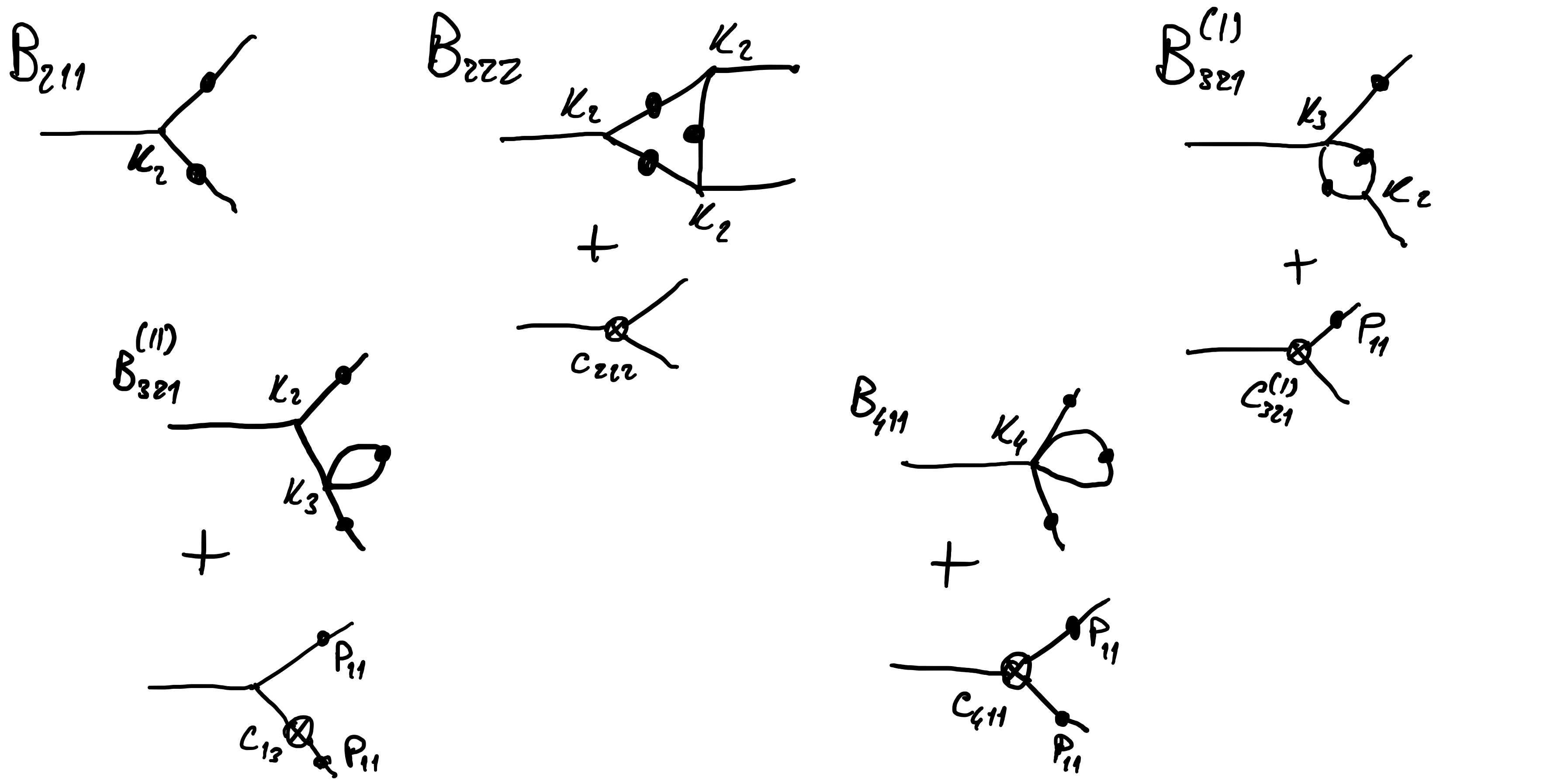


Perko, Senatore, Jennings, Wechsler (2016)
GDA, Gleyzes, Kokron, Markovic, Senatore, Zhang et al. (2019)
Ivanov, Simonovic, Zaldarriaga (2019)

Observables: bispectrum

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

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



Full theory model, up to 4th order

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

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

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

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

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: $\theta_{\rm LSS} = \left(\theta^2_{\rm LSS,\perp}\theta_{\rm LSS,\parallel}\right)^{1/3}$ $\theta_{\rm LSS,\parallel} \simeq \frac{r_s}{cz_{\rm LSS}/H(z_{\rm LSS})}$ $\theta_{\rm LSS,\perp} \simeq \frac{r_s}{D_A(z_{\rm LSS})}$
  - Multipoles allow measure of both, in ΛCDM this gives h

- Broadband shape
  - $P_{11,\ell=0} \sim b_1^2 A_s^{(k_{\rm max})}$, $P_{11,\ell=2} \sim b_1 f A_s^{(k_{\rm max})}$, $A_s^{(k_{\rm max})} \sim A_s k_{\rm eq}^2 \sim A_s \Omega_m h^2$
  - 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 *σ8*

Towards data analysis: data

Main observables for us: galaxy clustering correlation functions

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

- Bispectrum: monopole and 3 quadrupoles (1 gives already most of the info)

Possible to use data in other ways: real-space correlation function, wedges, principal component compression

Can apply formalism to other biased tracers too

Towards data analysis: likelihood

- Bayesian parameter estimation using MCMC with physically motivated priors on cosmological and EFT parameters.
  At each one must evaluate the model, and we need a lot of steps!

- First problem: numerical efficiency.
  Complicated (and slow) loop integrals are done expanding initial power spectrum in basis functions, to isolate cosmology-independent part: FFTLog for P(k), fewer 'complex propagators' for bispectrum.
  Developed Pybird: 0.3-1s for P(k), few sec for bispectrum

- Second problem: efficient sampling.
  We want to sample cosmological parameters (3-5 or more). We have also EFT parameters (7-10 for power spectrum, up to 37 for bispectrum!).
  Most of them appear linearly, can marginalize analytically.

Other codes:
CLASS-PT (Ivanov, Philcox et al.)
Velocileptors (Chen, Vlah, White)

Towards data analysis: efficient sampling

- Assume Gaussian likelihood with given covariance

$$-2\ln\mathcal{P} = (T_i - D_i)C^{-1}_{ij}(T_j - D_j) - 2\ln\mathcal{P}_{\rm pr} =$$

$$g_\alpha F_{2,\alpha\beta} g_\beta - 2 g_\alpha F_{1,\alpha} + F_0 \qquad T_i = g_\alpha T^\alpha_{G,i} + T_{NG,i}$$

- 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)

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

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?

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, Poulin, Smith (2022)
also Carrilho, Moretti, Pourtsidou (2022)

Where do we stop?

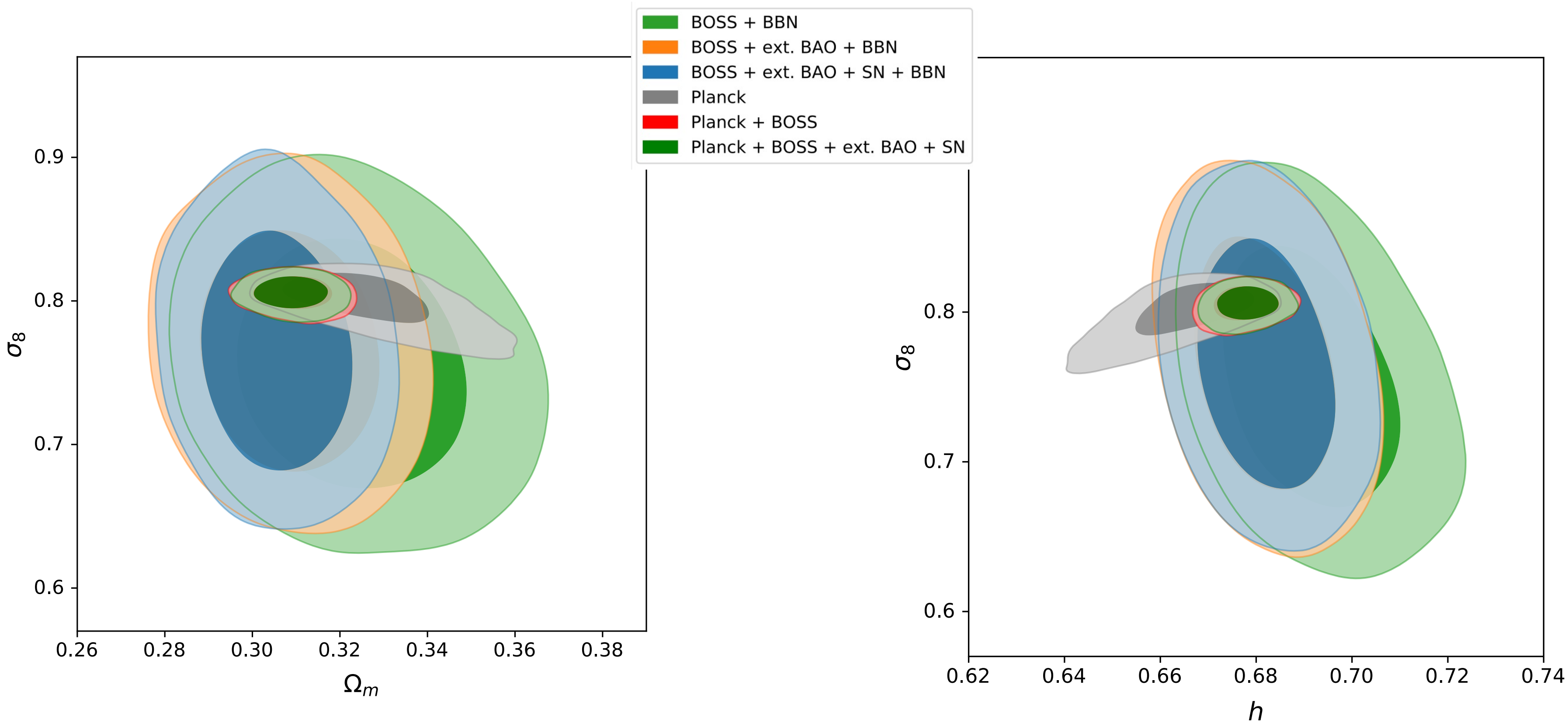
- Very important issue: where to stop the fit?
  Usual tradeoff between *accuracy* and *precision*: smaller scales have smaller errors, but perturbative approach starts to fail

- 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 $\sim 0.3\sigma_{\rm data}$
  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

2-pt function: dataset consistency



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

Chen, Vlah, White 2021
Beutler, Macdonald 2021

No tensions with Planck

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	$0.7559^{+0.054}_{-0.062}$

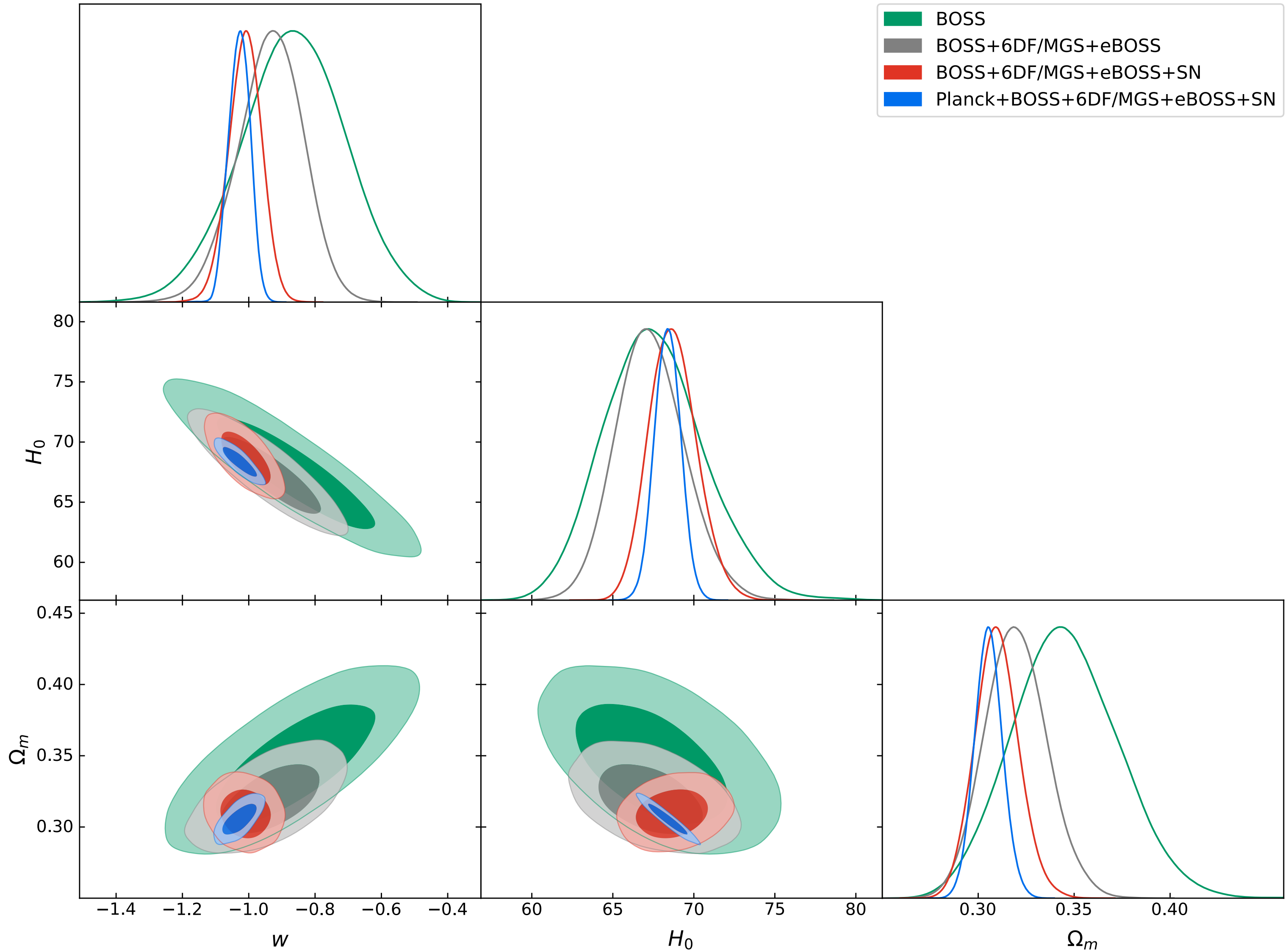
Planck	best-fit	mean$\pm\sigma$
$100\ \omega_b$	2.236	$2.233^{+0.015}_{-0.015}$
ω_{cdm}	0.1202	$0.1206^{+0.0013}_{-0.0013}$
$100 * \theta_s$	1.042	$1.042^{+0.00029}_{-0.0003}$
$\ln(10^{10}A_s)$	3.041	$3.05^{+0.015}_{-0.015}$
n_s	0.9654	$0.9643^{+0.0042}_{-0.0043}$
τ_{reio}	0.05238	$0.05597^{+0.0073}_{-0.0081}$
$\sum m_\nu$ [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	$0.8004^{+0.016}_{-0.008}$

Beyond ΛCDM: Clustering quintessence

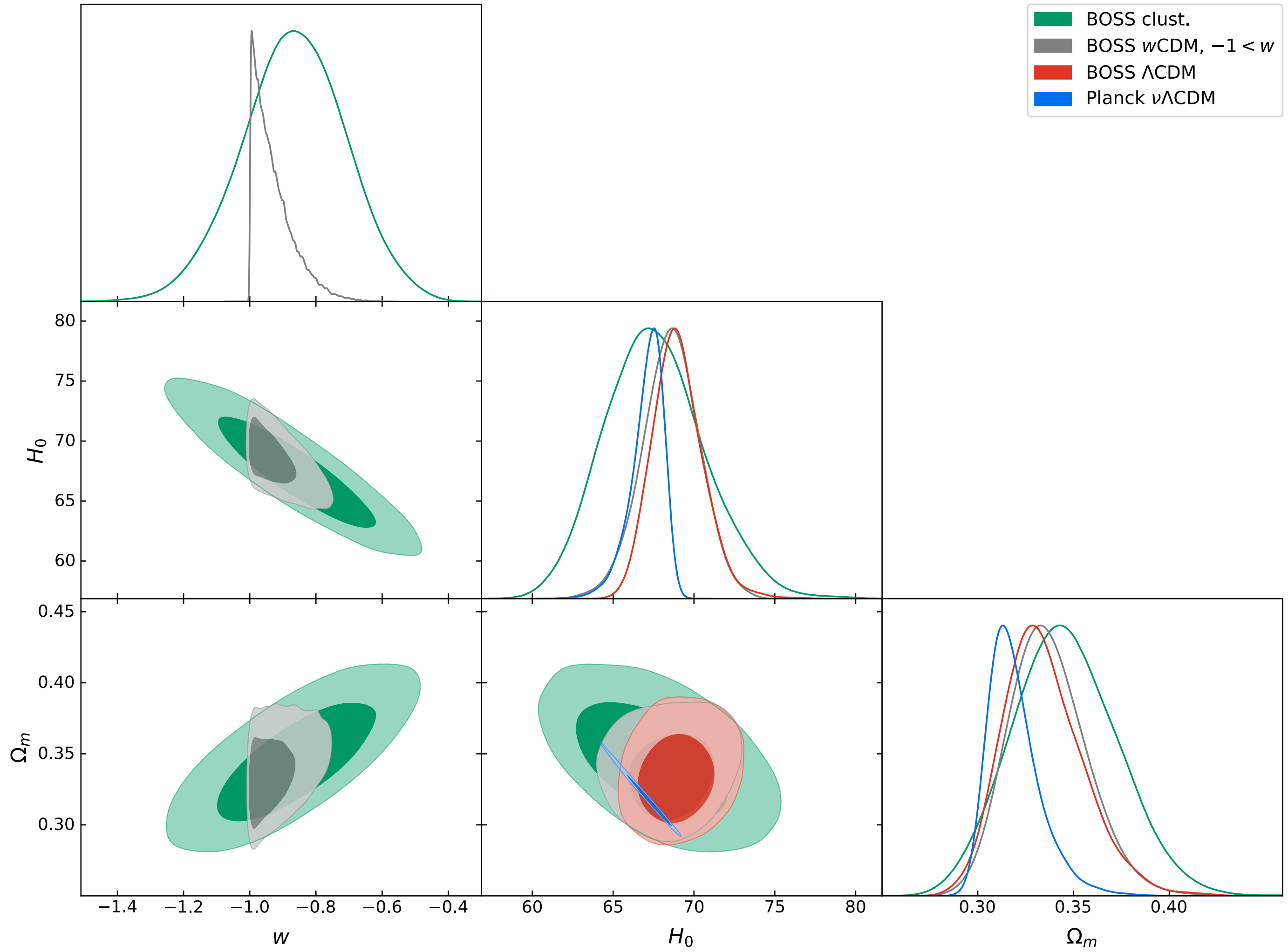
- Equation of state w<-1 is not allowed in single-field quintessence, unless the speed of sound is practically zero
- Equations require some modifications, and one must use exact time dependence (no separability of time and k)
- First LSS analysis for a theoretically consistent model with w<-1: the universe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

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

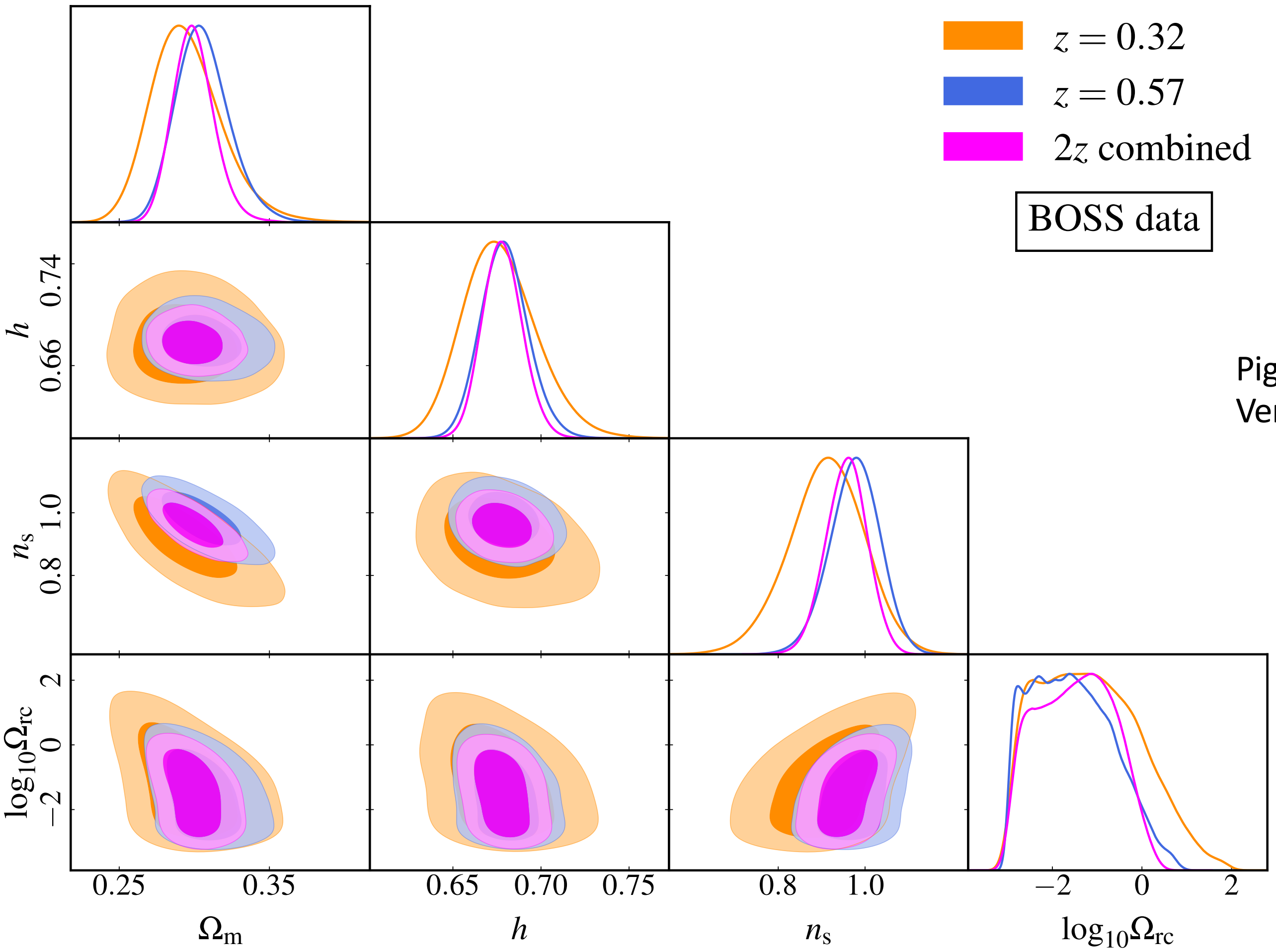
Clustering quintessence



Clustering vs smooth quintessence



Beyond ΛCDM: nDGP



Piga, Marinucci, GDA, Pietroni, Vernizzi, Wright 2211.12523

- Actually an example of scale-independent models, which obey equivalence principle: bias parametrization dictated by symmetries

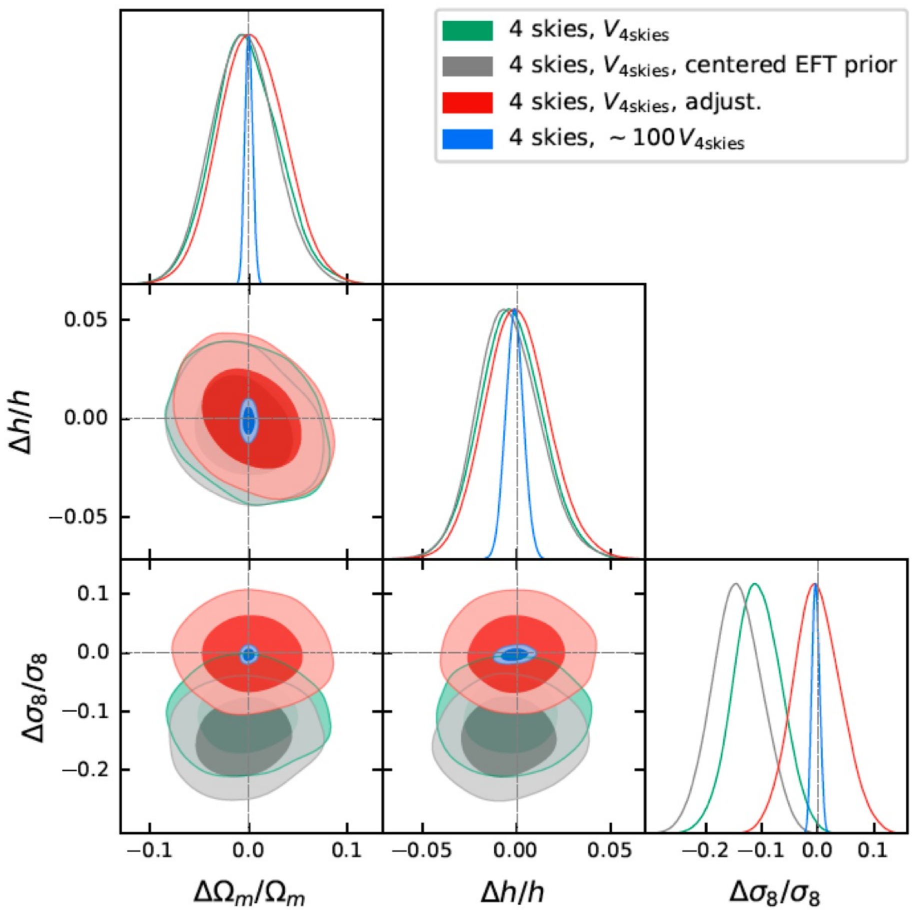
(GDA, Marinucci, Pietroni, Vernizzi 2021)

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 4^{th} order in perturbations
  - Redshift distortions up to 4^{th} order
  - Counterterms up to 2^{nd} order
  - Efficient way of computing loop integrals
  - Generalization to non-Gaussian initial conditions
- Some observational effects are still treated approximately: it works for BOSS data, some more work to do for next-generation surveys

GDA, Lewandowski, Senatore, Zhang (2022)
GDA, Donath, Lewandowski, Senatore, Zhang (2022)
also Philcox, Ivanov, Cabass, Simonovic, Zaldarriaga (2022)

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

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

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

So, about tensions...

- Data errors are presently not so small

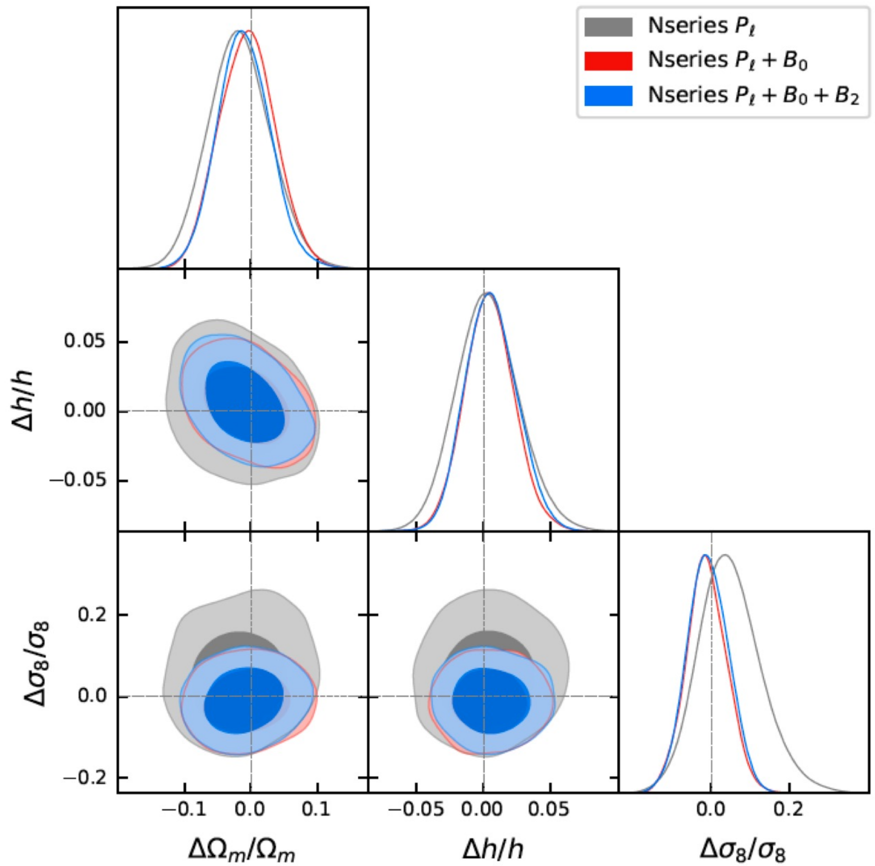
- The theory model has many parameters (not only EFTofLSS)

- And we are interested in few physics parameters (as opposed to a machine analyzing the ~10 dimensional posterior)

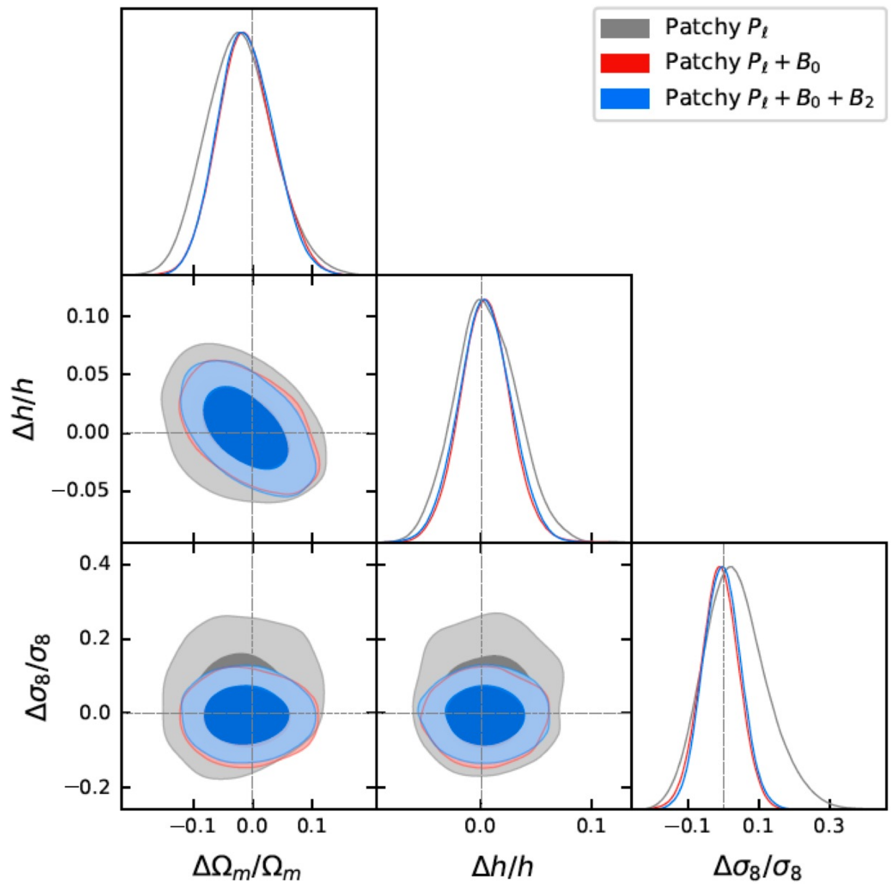
- With Bayesian methods, we have to integrate over a lot of parameter space to reach 1d or 2d constraints that we humans understand

- Error probably well estimated, but what about central value?

Theoretical error



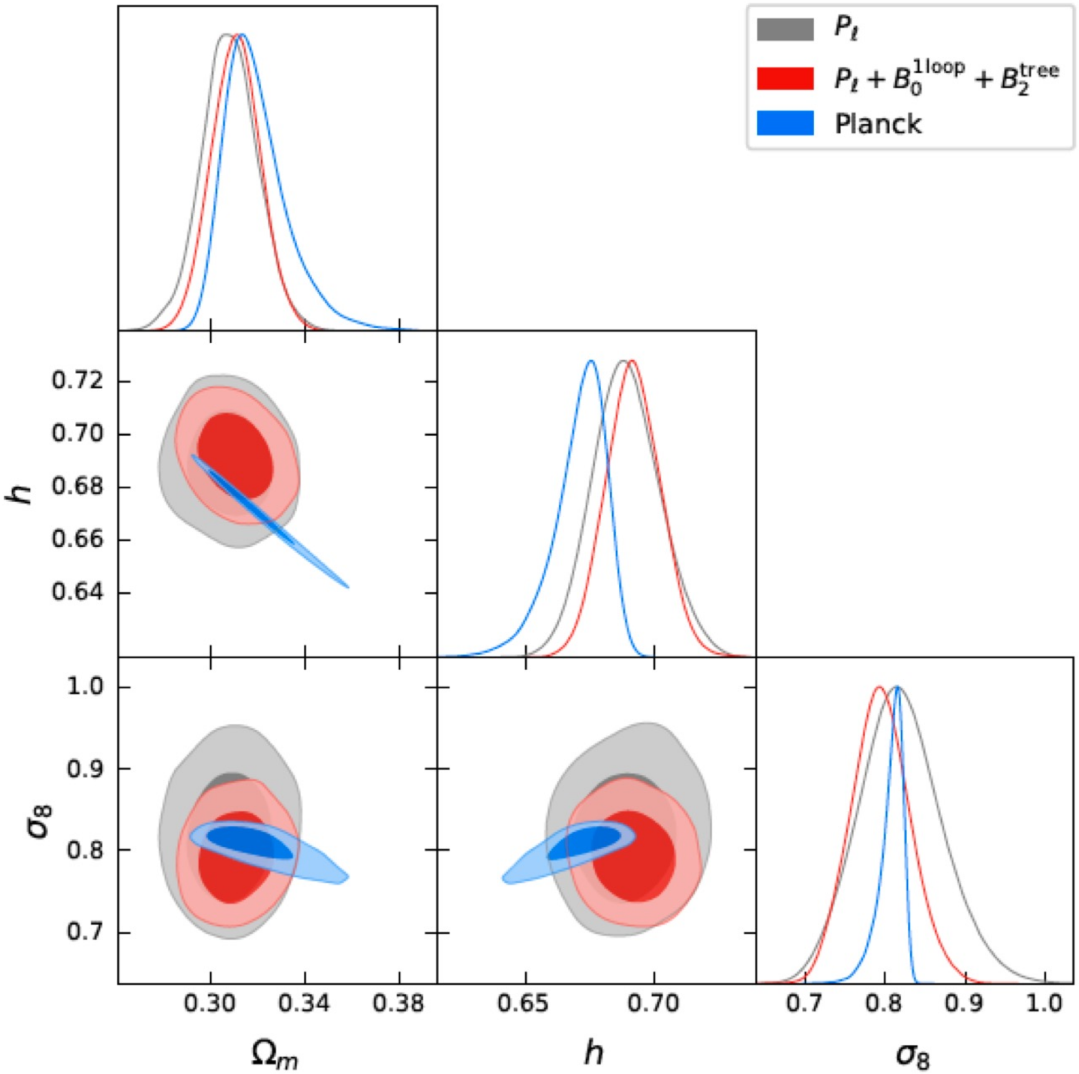
Nseries: 80 x BOSS volume



Patchy mocks: 2000 x BOSS volume

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

Results



- Improvements of *13%* on *Ωm, 18%* on *h, 30%* on *σ8*
- 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 0.308 ± 0.012	0.6763 $0.689^{+0.012}_{-0.014}$	0.8305 $0.819^{+0.049}_{-0.055}$	0.1143 0.1232 ± 0.0075	3.123 3.02 ± 0.15	0.8283 $0.830^{+0.051}_{-0.060}$
$P_\ell + B_0^{\rm tree}$	0.3101 0.309 ± 0.011	0.6907 0.691 ± 0.012	0.8063 0.804 ± 0.049	0.1248 0.1246 ± 0.0058	2.98 2.97 ± 0.13	0.8197 $0.816^{+0.050}_{-0.057}$
$P_\ell + B_0^{\rm 1loop}$	0.3210 0.314 ± 0.011	0.6956 0.693 ± 0.011	0.7882 $0.790^{+0.033}_{-0.037}$	0.1331 0.1278 ± 0.0061	2.82 2.90 ± 0.11	0.8153 $0.807^{+0.037}_{-0.043}$
$P_\ell + B_0^{\rm 1loop} + B_2^{\rm tree}$	0.3082 0.311 ± 0.010	0.6928 0.692 ± 0.011	0.7856 0.794 ± 0.037	0.1258 0.1255 ± 0.0057	2.88 2.94 ± 0.11	0.7962 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

What next?

- From theory/computational side
  - Better (and not too slow) calculations of observational effects.
  - Differentiable emulators (Bonici, GDA, Carbone, Bel, in progress)
  - Useful to restrict priors on bias/counterterms
  - Predictions for extended models
  - Robust covariance estimates
  - Other observables: field level?
- From observational side
  - Address systematic errors… The analysis will detect them!
  - Measurements of EFT parameters in simulations
  - Accurate measurements of higher n-point functions

Interesting physics?

- Neutrino masses (some people may not be interested much since they actually exist)
- Light dark matter/mediators
- Relics
- Properties of dark energy
- Definitely a shot at primordial non-Gaussianity
- With higher redshifts and smaller scales (e.g. intensity mapping), probe more of inflation?

  (could be not smooth, GDA, Kaloper, 2011.09489, also w/ Westphal 2101.05861; 2112.13861)

Summary

- Somewhat surprisingly, we can determine cosmological parameters from LSS, close to world record for some of them

- New discoveries/constraints around the corner

- Precise way to pinpoint possible tensions with other datasets, but let's be careful

- Many experiments around the corner: DESI, Euclid are 10x BOSS

- The era of precision cosmology will continue along this avenue

Merci