UNIVERSITÀ DI PARMA

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"The Analysis of the SDSS/BOSS data from the EFTofLSS"

Based on

GDA, Gleyzes, Kokron, Markovic, Senatore, Zhang et al. 1909.05271

Colas, GDA, Senatore, Zhang, Beutler 1909.07951

https://github.com/pierrexyz/cbird

IAS program ``High Energy Physics''
20/1/2020

Cosmology and Fundamental Physics

- After WMAP and Planck, we now know quite a lot about the early Universe, and the late Universe as well

- Problem: how to continue getting precise and accurate information?

- We should go back to the first play tool of cosmologists, the analysis of Large Scale Structure

Some complications

- CMB can be understood easily: a weakly perturbed plasma, linear physics is enough
- A 6-parameter model fits 1500 data points: impressive!
- LSS has potentially much more information, but difficult to understand: observe messy astrophysical objects, moreover in distorted coordinates (aka redshift space)
- Let's start naïve and humble and do perturbation theory... Is that useful at all?

An effective fluid on large scales

- In the history of the Universe, Dark Matter moves only $\frac{1}{k_{NL}} \sim 10 \text{ Mpc}$

- Vlasov hierarchy can be truncated, giving an effective fluid-like system with mean free path $\frac{1}{k_{NL}} \sim 10 \text{ Mpc}$

- Interactions with gravity conserve mass and momentum

The equations for Dark Matter

- We get the fluid-like equations

$$\nabla^2 \Phi_l = H^2 \frac{\delta \rho_l}{\rho}$$

$$\partial_t \rho_l + H \rho_l + \partial_i \left(\rho_l v_l^i \right) = 0$$

$$\dot{v}_l^i + H v_l^i + v_l^j \partial_j v_l^i = \frac{1}{\rho} \partial_j \tau_{ij}$$

- Short distance physics appears as an effective stress tensor for the long-distance physics

$$\tau_{ij} \sim \delta_{ij} \, \rho_{\rm short} \, \left(v_{\rm short}^2 + \Phi_{\rm short} \right)$$

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

Dealing with short distances

Expectation values over short distance modes, in the presence of long ones

$$\langle \tau_{ij}(\vec{x},t)\rangle_{\text{long fixed}} = f_{\text{very complicated}}\left[\{H(t'),\Omega_{\text{dm}}(t'),\ldots,\rho_{\text{dm}}(x',t'),\ldots,m_{\text{dm}},\ldots\}|_{\text{on past light cone}}\right]$$

Large scales are perturbative! So we expand

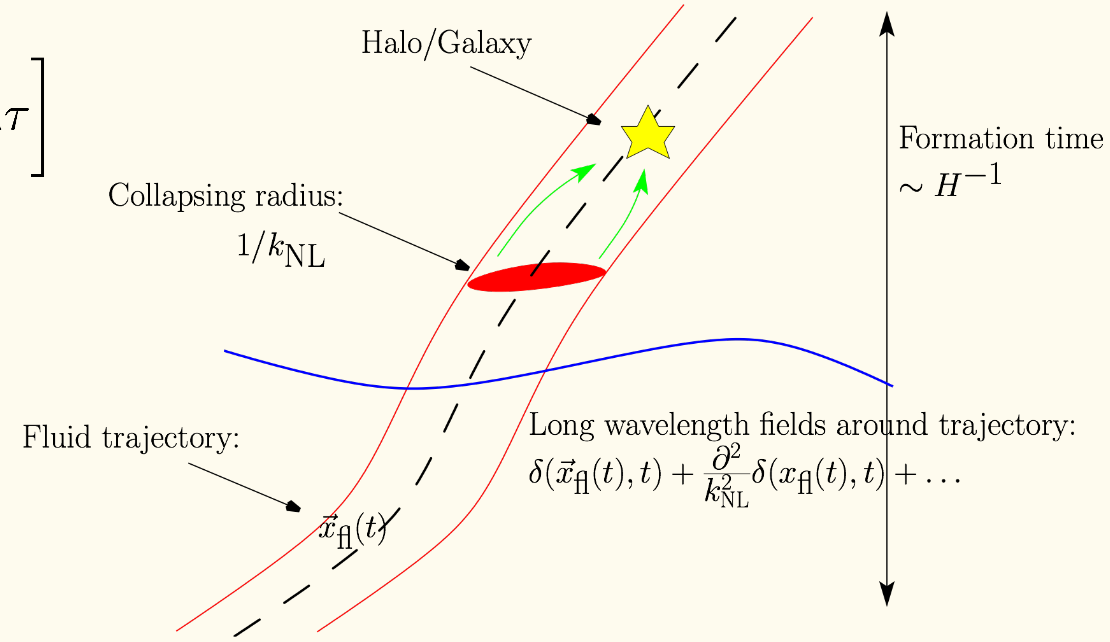
$$\Rightarrow \quad \langle \tau_{ij}(\vec{x},t)\rangle_{\text{long fixed}} = \int^t dt'\; K_1(t,t')\,\frac{\delta\rho}{\rho}(x_{\text{fl}},t') + \mathcal{O}\left((\delta\rho/\rho)^2\right)$$

$$\langle \tau_{ij}\rangle_{\text{long-fixed}} \sim \delta_{ij}\left[p_0 + c_s\,\delta\rho_l + \mathcal{O}\left(\frac{\partial}{k_{\text{NL}}},\partial_i v_l^i,\delta\rho_l^2,\ldots\right) + \Delta\tau\right]$$

How many terms to keep?

Roughly $\delta\rho_l/\rho_l \sim k/k_{NL}$

We keep as many as needed



From CDM to galaxies

- Baryons. EFT with 2 fluids, similar non-linear scale

- Galaxies. Complicated physics, but long modes of $n_{\rm gal}(t,\vec{x})$ can only depend on large-wavelength fluctuations of DM and baryon fields. We have to include all terms allowed by symmetries, getting a bunch of bias coefficients: important to have a complete basis!

- Redshift space. A field-dependent change of coordinates, brings up counterterms from product of fields at the same point

Lewandowski, Perko, Senatore (2015)

Senatore (2014)
Desjaques, Jeong, Schmidt (2014)
Angulo, Fasiello, Senatore, Vlah (2015)
Schmidt (2016)

Senatore, Zaldarriaga (2014)
Lewandowski, Senatore et al. (2015)

IR resummation

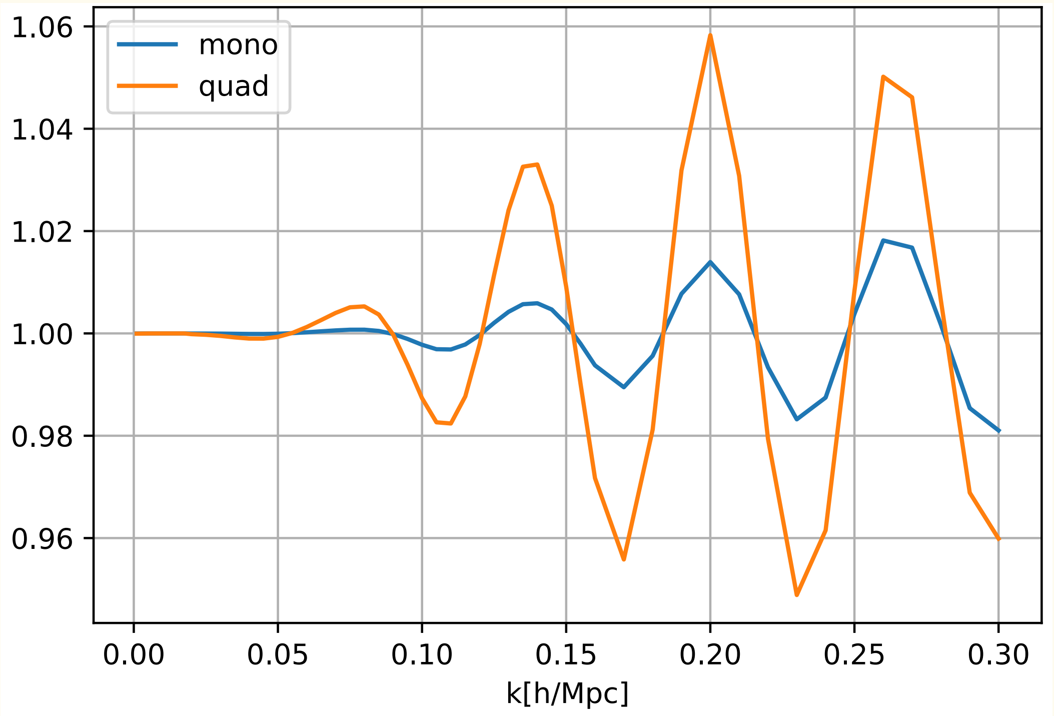
- Perturbation theory is very slow to converge due to the effect of IR displacements

- In particular, they affect the BAO peak in real space

- We can resum them, leading to

$$P_{\mathrm{IR-res}}(k) \sim \int \mathrm{d}s\, Q(k,s) \cdot \xi_{\mathrm{non-res}}(s)$$

- This is numerically subtle, and the time bottleneck.
  Several approximations have been made, but we choose to implement the full formula.



Senatore, Zaldarriaga (2014)
Baldauf, Mirbabayi, Simonovic, Zaldarriaga (2015)
Vlah, Seljak et al. (2015)
Ivanov, Sibiryakov (2016)

Putting it all together

- Halo-halo power spectrum in redshift space

$$\begin{aligned}\langle\delta_{h,r}(\vec{k})\delta_{h,r}(\vec{k})\rangle &= \langle\delta^{(1)}_{h,r}\delta^{(1)}_{h,r}\rangle + \langle\delta^{(2)}_{h,r}\delta^{(2)}_{h,r}\rangle + 2\langle\delta^{(1)}_{h,r}\delta^{(3)}_{h,r}\rangle + \langle\delta_{h,r}\delta_{h,r}\rangle_{\rm ct} + \langle\delta_{h,r}\delta_{h,r}\rangle_{\epsilon} \\ &= (K^{(1)}_{h,r})^2 P_{11}(k) + 2\int d^3\vec{q}\,\left(K^{(2)}_{h,r}(\vec{q},\vec{k}-\vec{q})_{\rm sym}\right)^2 P_{11}(|\vec{k}-\vec{q}|)P_{11}(q) \\ &\quad +6\int d^3\vec{q}\,K^{(3)}_{h,r}(\vec{q},-\vec{q},\vec{k})_{\rm sym}K^{(1)}_{h,r}P_{11}(q)P_{11}(k) + \langle\delta_{h,r}\delta_{h,r}\rangle_{\rm ct} + \langle\delta_{h,r}\delta_{h,r}\rangle_{\epsilon}\end{aligned}$$

$$\langle\delta_{h,r}(\vec{k})\delta_{h,r}(\vec{k})\rangle_{\rm ct} = 2P_{11}(k)(b_1+f\mu^2)\left(\mu^2\left(\frac{k}{k_{\rm M}}\right)^2\tilde{c}_{r,1} + \mu^4\left(\frac{k}{k_{\rm M}}\right)^2\tilde{c}_{r,2} + c^{(\delta_h)}_{\rm ct}\left(\frac{k}{k_{\rm NL}}\right)^2\right)$$

$$\langle\delta_{h,r}\delta_{h,r}\rangle_{\epsilon} = \frac{1}{\bar{n}_W}\left(c_{\epsilon,1} + c_{\epsilon,2}\left(\frac{k}{k_{\rm M}}\right)^2 + c_{\epsilon,3}f\mu^2\left(\frac{k}{k_{\rm M}}\right)^2\right)$$

Perko, Senatore, Jennings, Wechsler (2016)

Towards data analysis

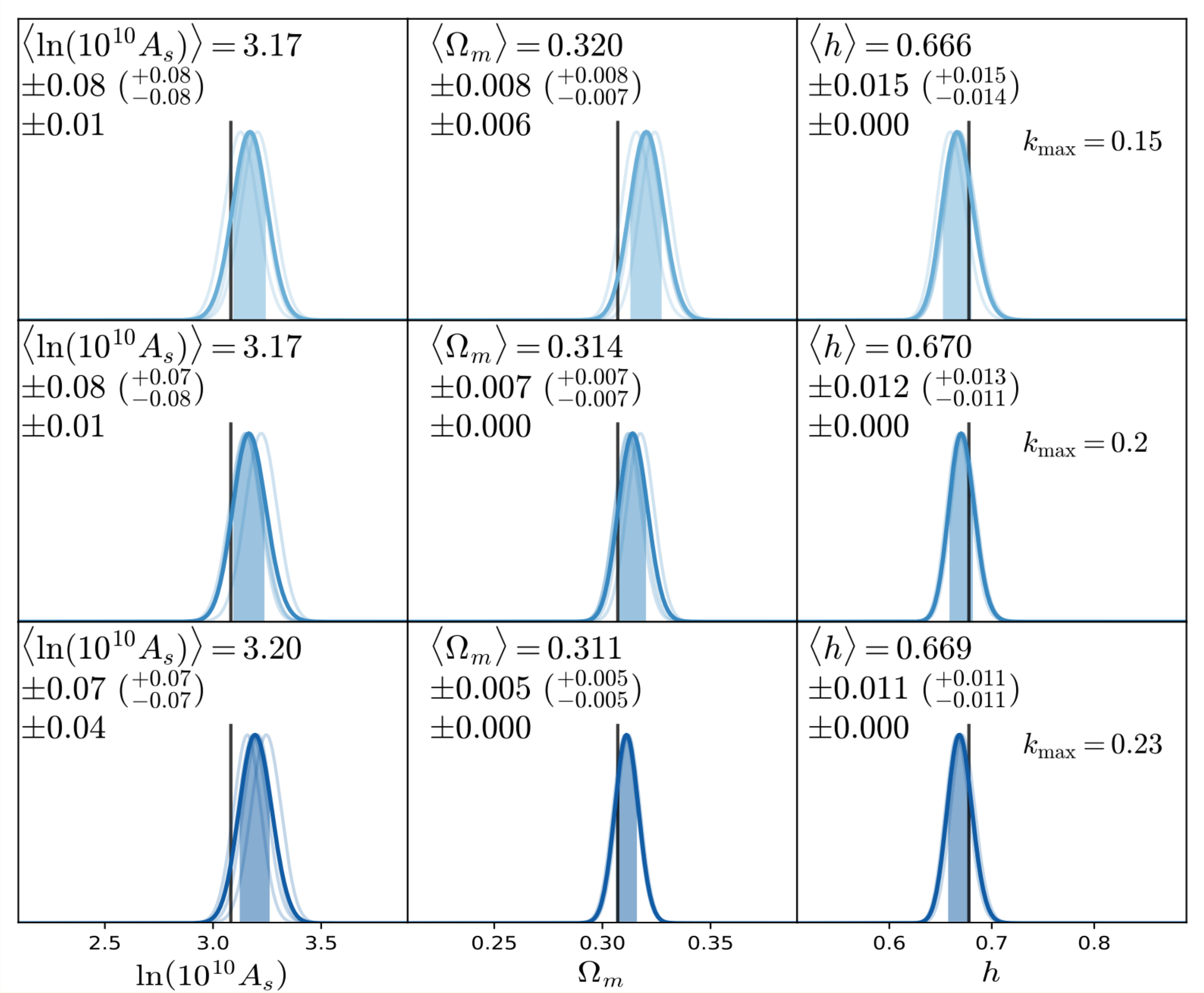
- Power spectrum up to one loop: 10 EFT parameters + cosmological parameters

- Strategy: dependence on EFT parameters is analytic (and we can analytically marginalize 5) but we have to numerically calculate the nonlinear IR-resummed power spectrum for each cosmology

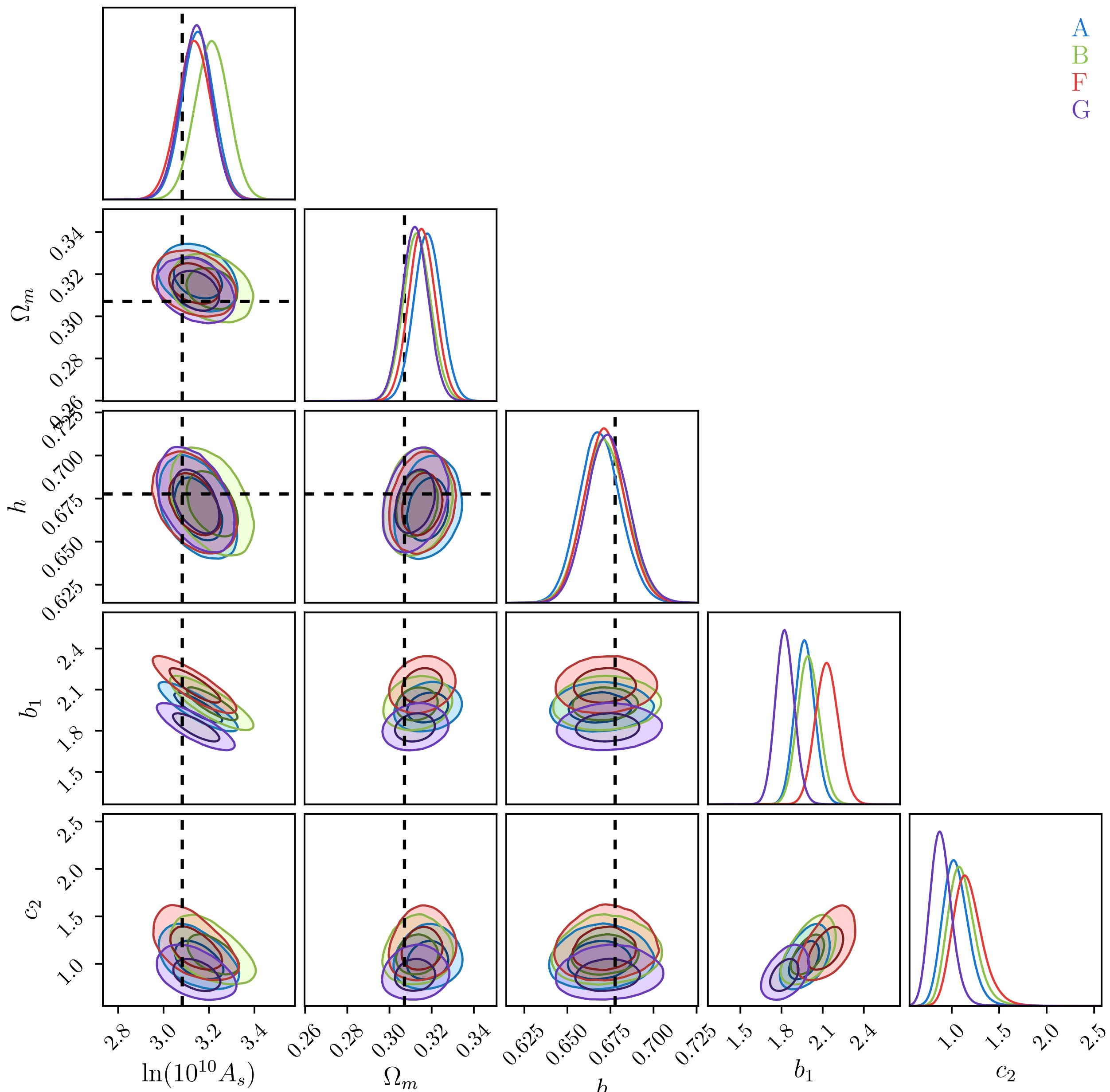
- Bayesian analysis (through MCMC) with several physically motivated priors.
  First paper: interpolate from a 3-parameter grid ($\ln(A_s), \Omega_m, h$)
  Second paper: use Taylor expansion to explore 6 parameters ($\ln(A_s), \Omega_m, h, \omega_b, n_s, \sum m_\nu$)

Simulations: Challenge boxes ABFG

- Challenge boxes are good-quality N-body simulations, populated with 4 different HOD's, 16 times the SDSS volume
- Study the $k_{\rm max}$ to which we can trust our theory
- Check validity of the model: 3 parameters do not play a role, dropped for the moment
- Theory systematic error: very small up to $0.20\ h/{\rm Mpc}$



Simulations: Challenge boxes



- We get the right cosmology
- We measure the biases, and check that HODs are different
- Degeneracies are broken

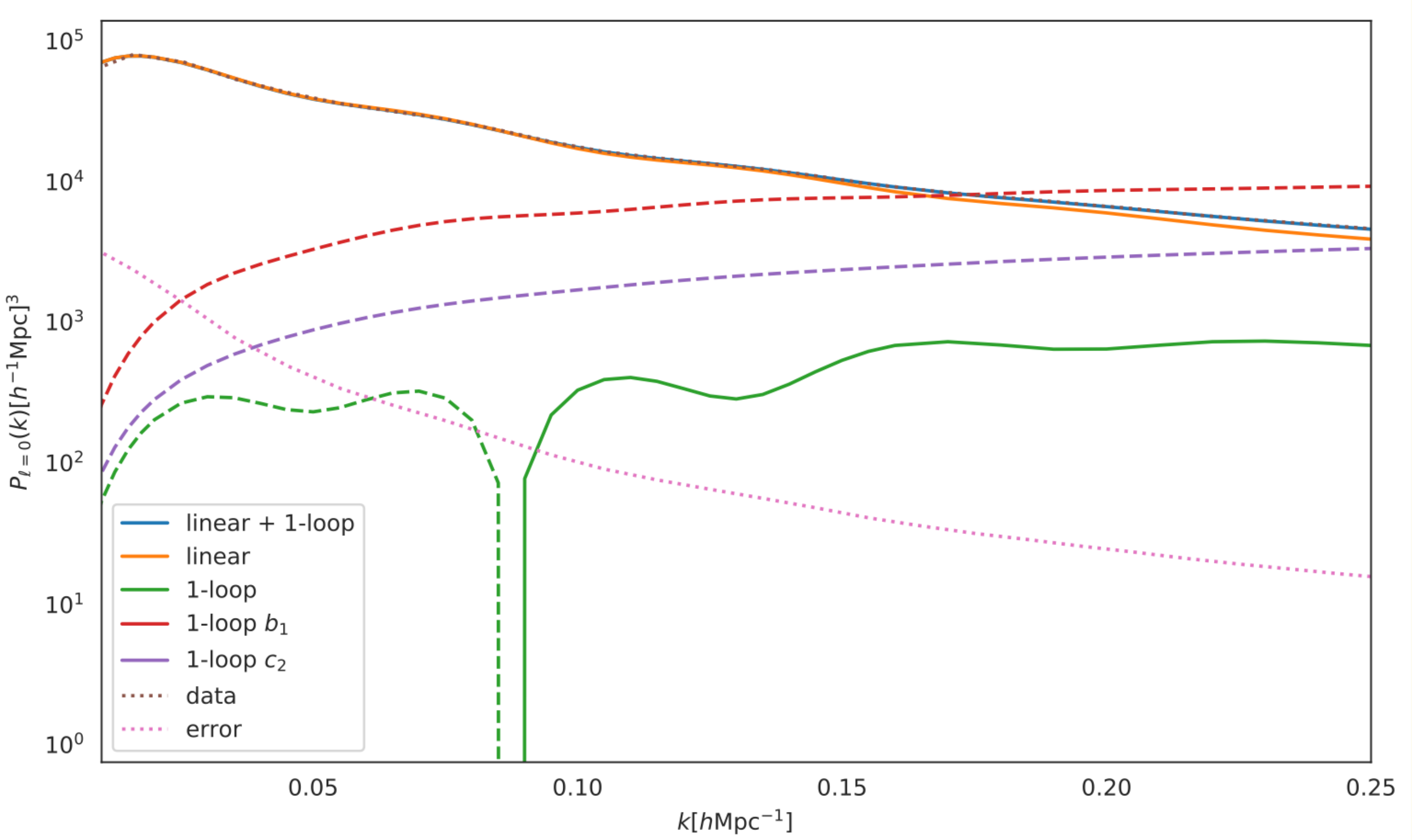
Best fit and consistency

Best fits

	$\ln(10^{10}A_s)$	Ω_m	h	b_1	min χ^2/d.o.f.	p-value
Challenge A	3.18	0.317	0.668	1.94	50/(38-9)	0.007
	c_2/c_4	b_3	$c_{\rm ct}$	$c_{r,1}$ $(+c_{r,2})$	$c_{\epsilon,1}/\bar{n}_g$	$c_{\epsilon,\rm quad}$
Challenge A	1.0	-1.6	-0.7	-6.9	-	-4.1

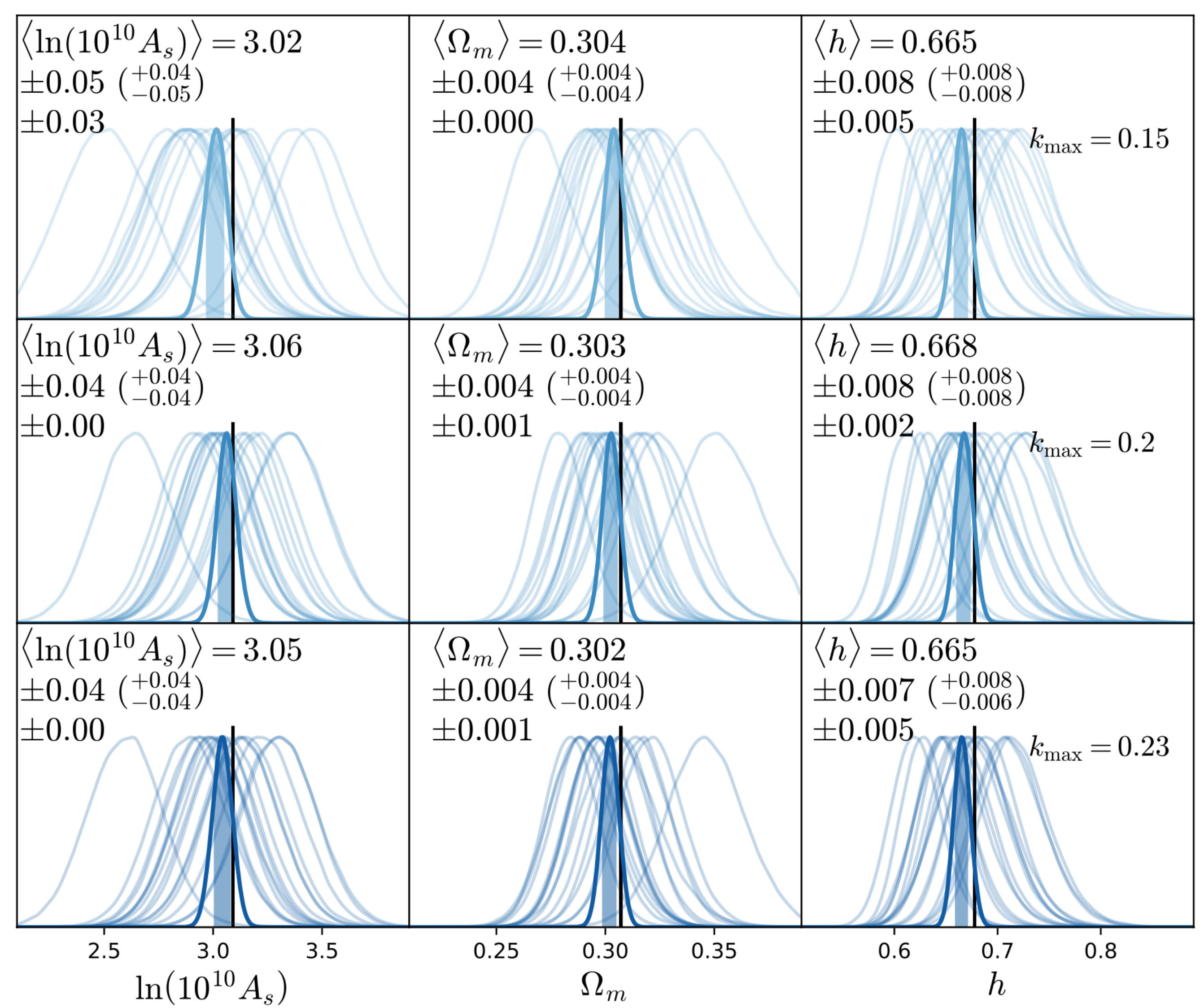
$$\frac{P_{1-\rm loop}}{P_{11}} \sim 10\%$$

$$\Rightarrow \quad \frac{P_{2-\rm loop}}{P_{11}} \sim 1\% \sim \sigma_{\rm data}(k_{\rm max} = 0.25\, h\,{\rm Mpc}^{-1})$$



Simulations: Patchy boxes

- Dynamics: approximate gravity solver
- Observational effects
  - window function
  - redshift selection
  - fiber collisions
- Negligible systematic error



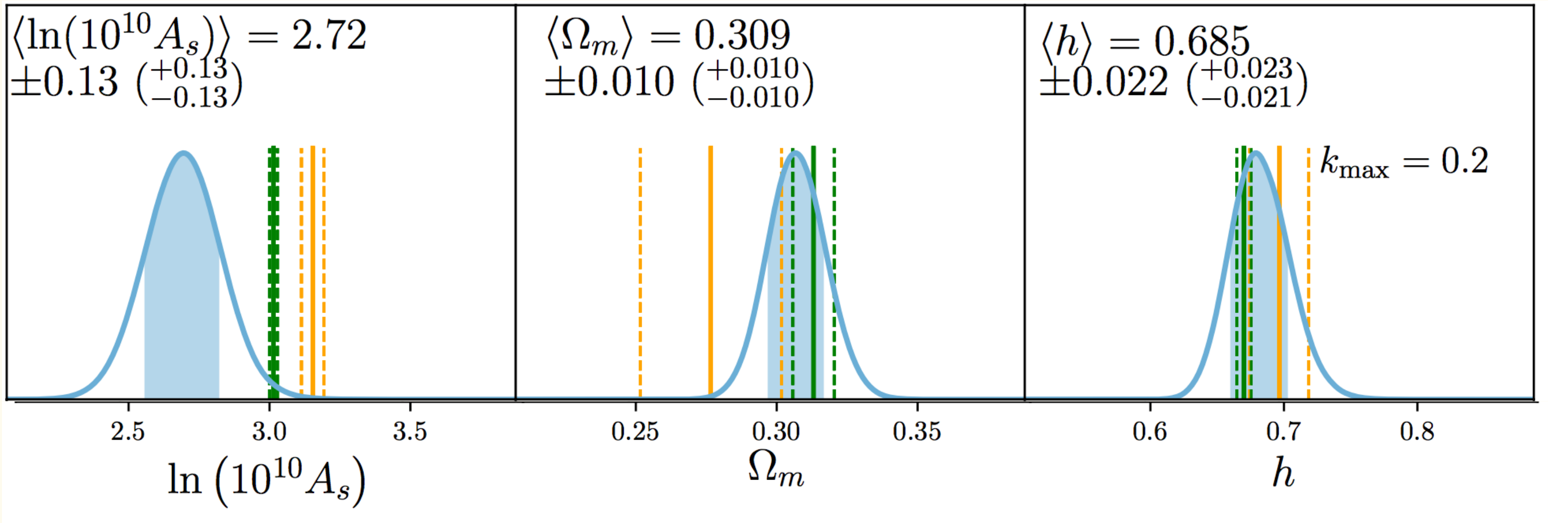
Physical considerations

- We measure A_s, Ω_m, h without any significant prior from CMB. How is this possible?
- BAO scale $\sim \Omega_m h^{-4}$ and BAO amplitude $\sim \Omega_m h^2$ (fixed $f_{\rm bc}$)
- Linear monopole and quadrupole

$$b_1^2 A_s^{(k_{\rm max})} \ \& \ b_1 f A_s^{(k_{\rm max})} \sim b_1 \Omega_m^{4/7} A_s^{(k_{\rm max})} \quad \text{where} \quad A_s^{(k_{\rm max})} \equiv A_s \left(\frac{k_{\rm eq}}{k_{\rm max}}\right)^2 \ \text{and} \ k_{\rm eq} \sim \Omega_m h^2$$

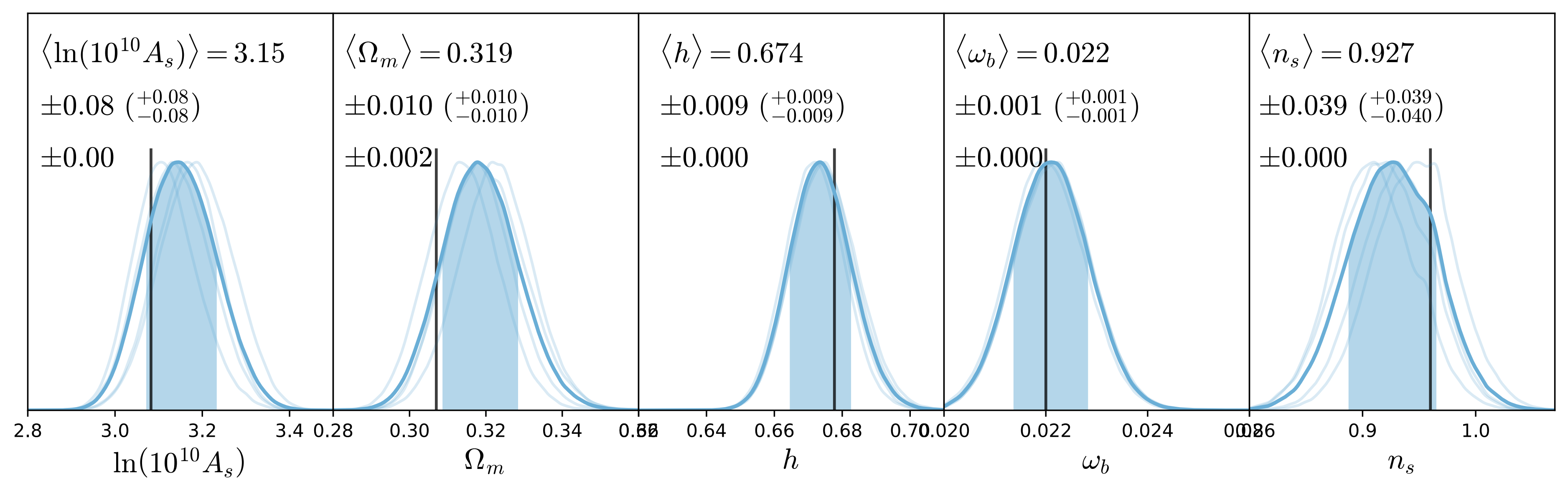
- We can solve for all the four variables A_s, Ω_m, h, b_1
- In particular $P_{11,\ell=0} \sim b_1^2 A_s^{(k_{\rm max})} \sim b_1^2 A_s k_{\rm eq}^2 \propto b_1^2 A_s \Omega_m h^2$
- Anticorrelations between $(A_s, b_1), (A_s, h)$, not in (Ω_m, h)

Data: BOSS CMASS x LOWZ

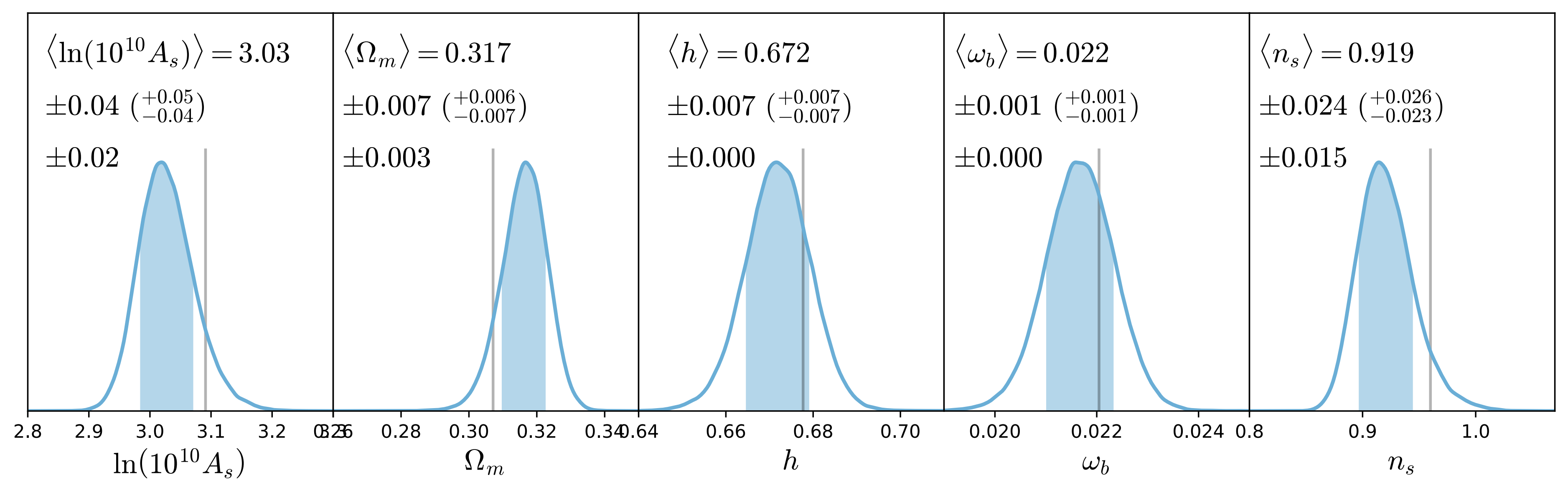


- Green is Planck2018, yellow is WMAP9yr
- Ω_m as good as Planck!
- H_0 as good as supernovae (and can do better)
- Slight tension on A_s, 2.3σ

$\nu\Lambda$CDM: Tests on simulations



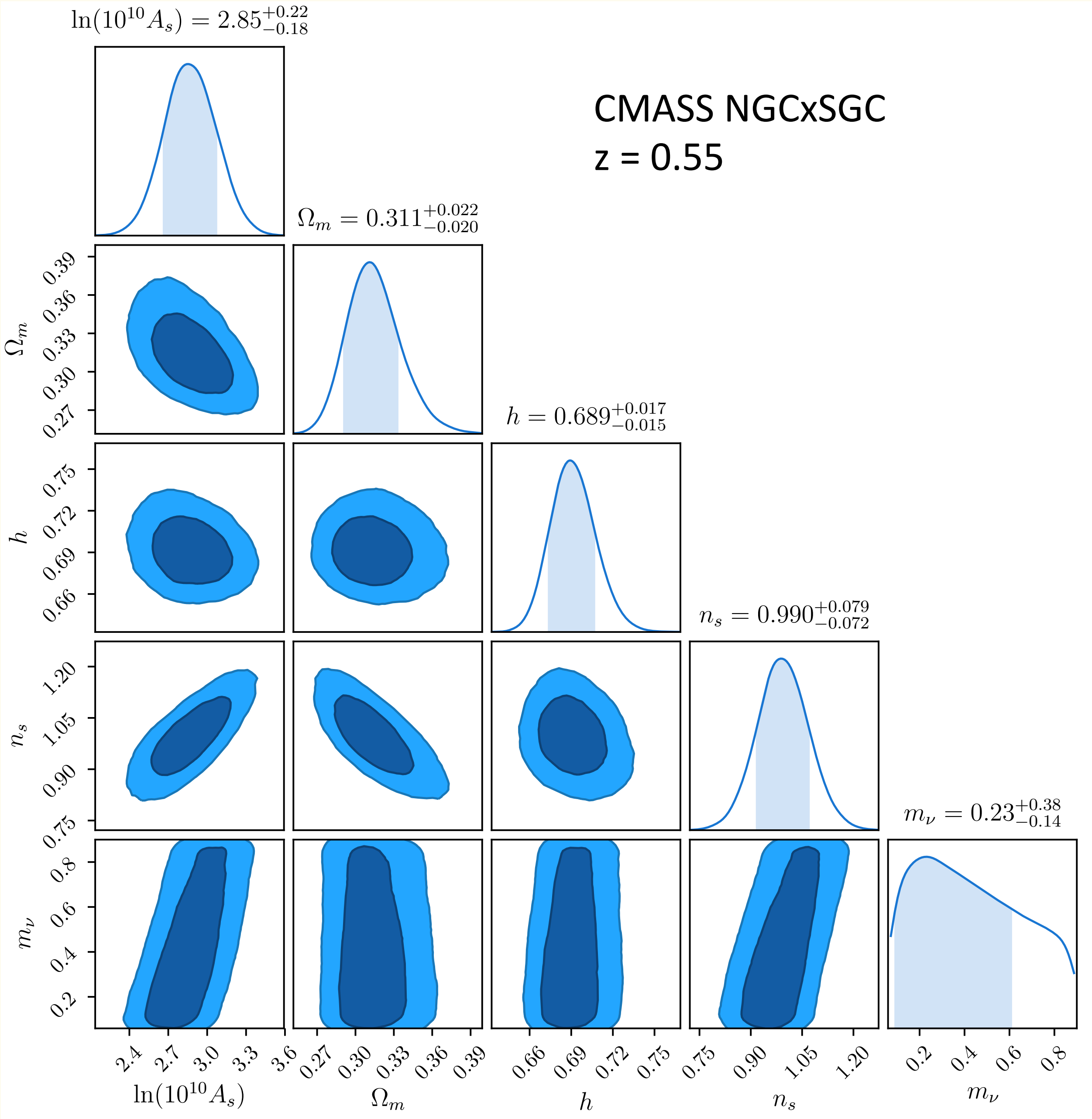
Challenges ABFG,
wide ω_b prior,
$k_{\max} = 0.23\ h/\mathrm{Mpc}$



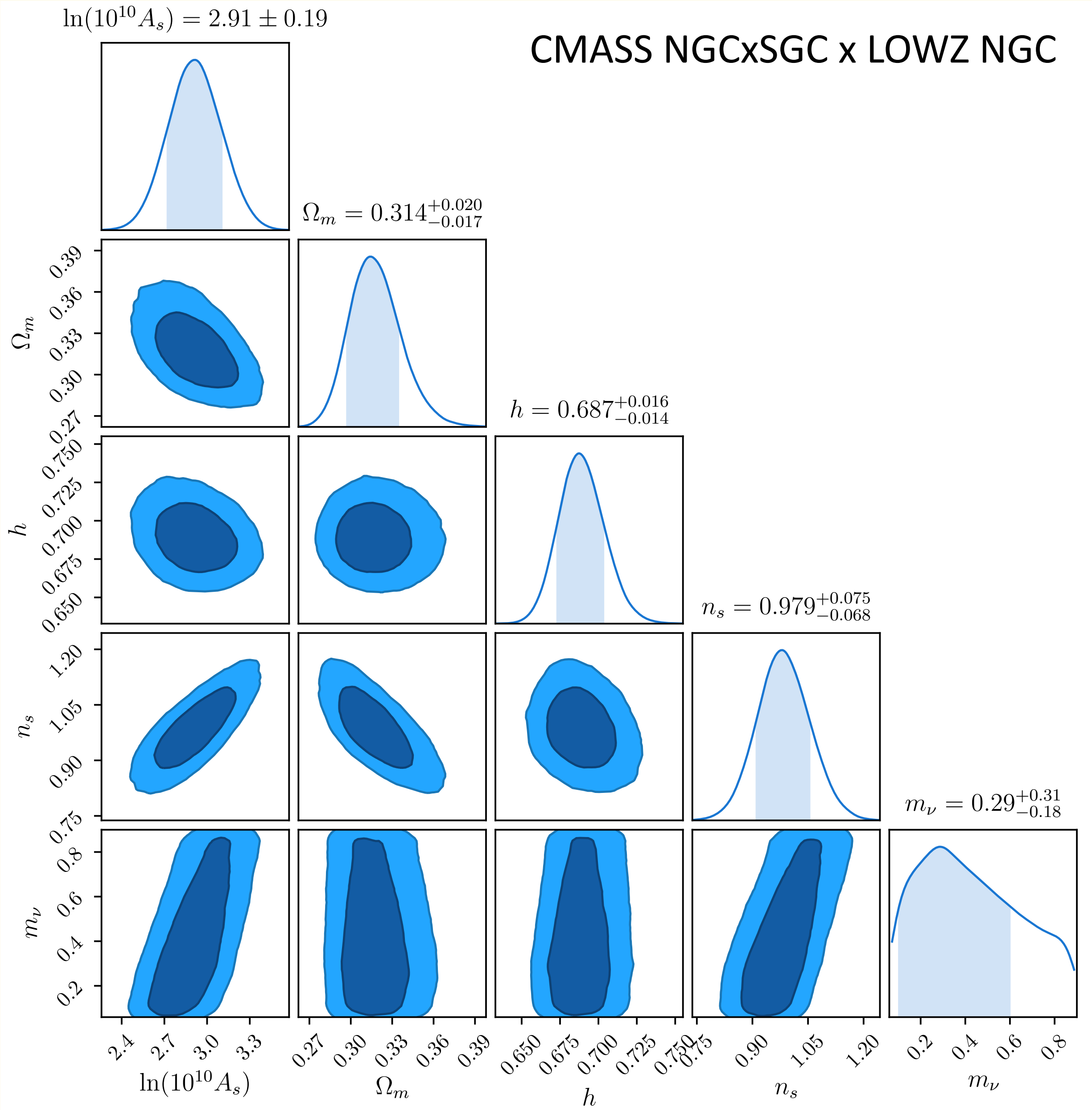
16 Patchy mocks,
wide ω_b prior,
$k_{\max} = 0.23\ h/\mathrm{Mpc}$

$\nu\Lambda CDM$

- Amazingly, we can do without CMB information
- Wide prior on n_s, $[0.7{,}1.25]_{\mathrm{flat}}$
- BBN prior on ω_b
- Great results!
  Small error on h,
  determination of n_s to 5%,
  still wide interval for $\sum m_\nu$



$\nu\Lambda CDM$



Our H_0 measurement

- We got a new, independent measurement of H_0 with 2% precision: 68.7±1.5 km/s/Mpc

- This comes from a global fit combining the CMASS NGC and SGC samples at $z{\sim}0.55$ and the LOWZ NGC sample at $z{\sim}0.32$

- Larger error if we put a prior on $f_{bc} = \Omega_b/\Omega_c$ instead of ω_b (at the cost of increasing error in Ω_m)

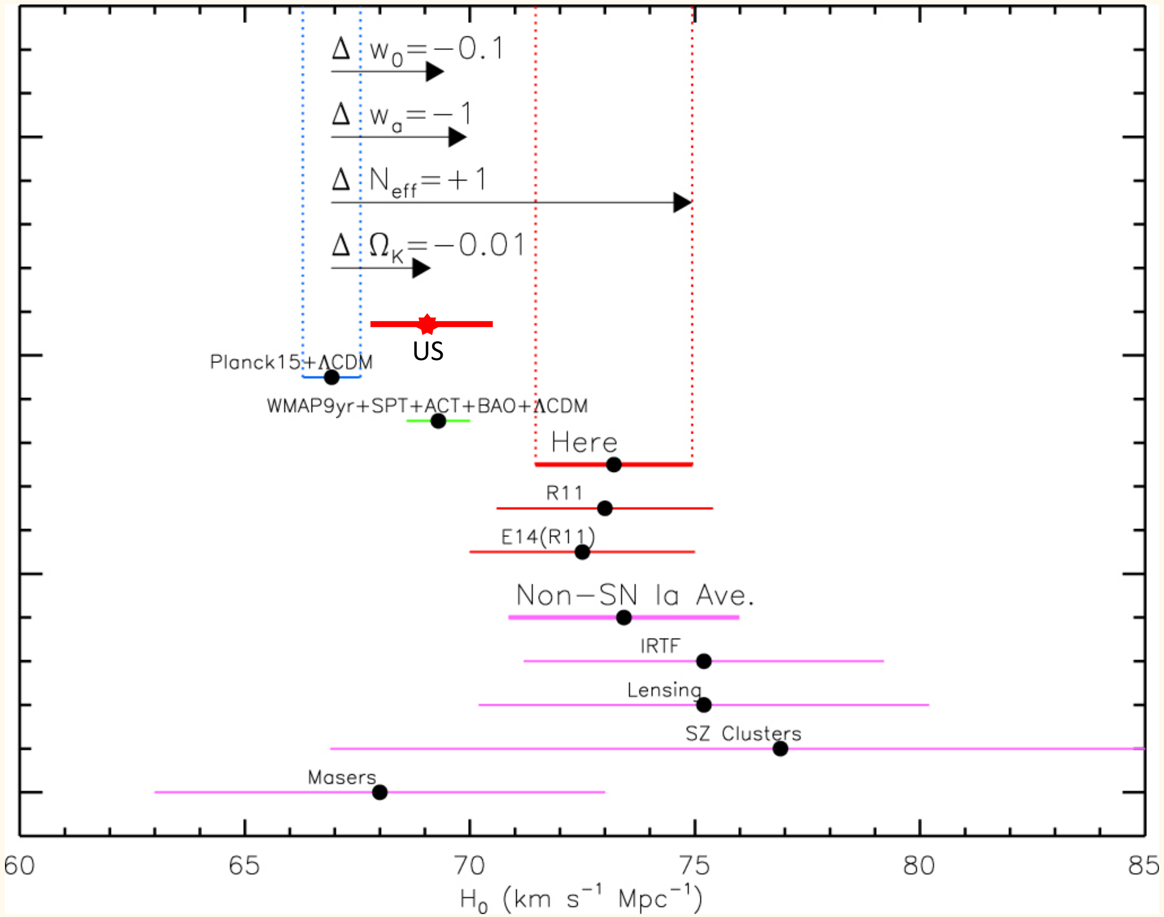
The H_0 controversy

- Several other methods to measure H_0
  - Local cosmic distance ladder (SH0ES and other probles)
  - Time-delay distances from strong lensing (H0LICOW)
  - Sound horizon (Planck, BAO)
- It looks like the local probes (and the lenses) give a consistently higher value that Planck/LSS
- What's going on? How to reconcile?

New Physics?

- Early Universe H_0 comes from a precisely determined *angular* scale, which is the ratio of 2 very different *linear* scales: the sound horizon in the early universe (depending on densities ω_b, ω_m), and the angular diameter distance from us to the CMB (depending on H_0)

- Challenge: leave the angular size fixed, while playing with new physics parameters, respecting constraints from the late Universe



What next?

- From theory side
  - Use simulations to understand better the parameters
  - Calculations at higher order
  - Extend beyond $\nu\Lambda$CDM
- From observational side
  - Accurate measurements of higher n-point functions
  - Get measurements of EFT parameters from simulations
  - Address observational systematic errors

Summary

- Somewhat surprisingly, first determination of actual $\nu\Lambda$CDM parameters from LSS
- We can get a major qualitative and quantitative improvement: good accuracy and precision
- New discoveries/constraints around the corner: neutrino masses, new dark dof, dark energy, sharpening tensions with other datasets
- Hopefully, the era of precision cosmology will continue along this avenue

Thank you!