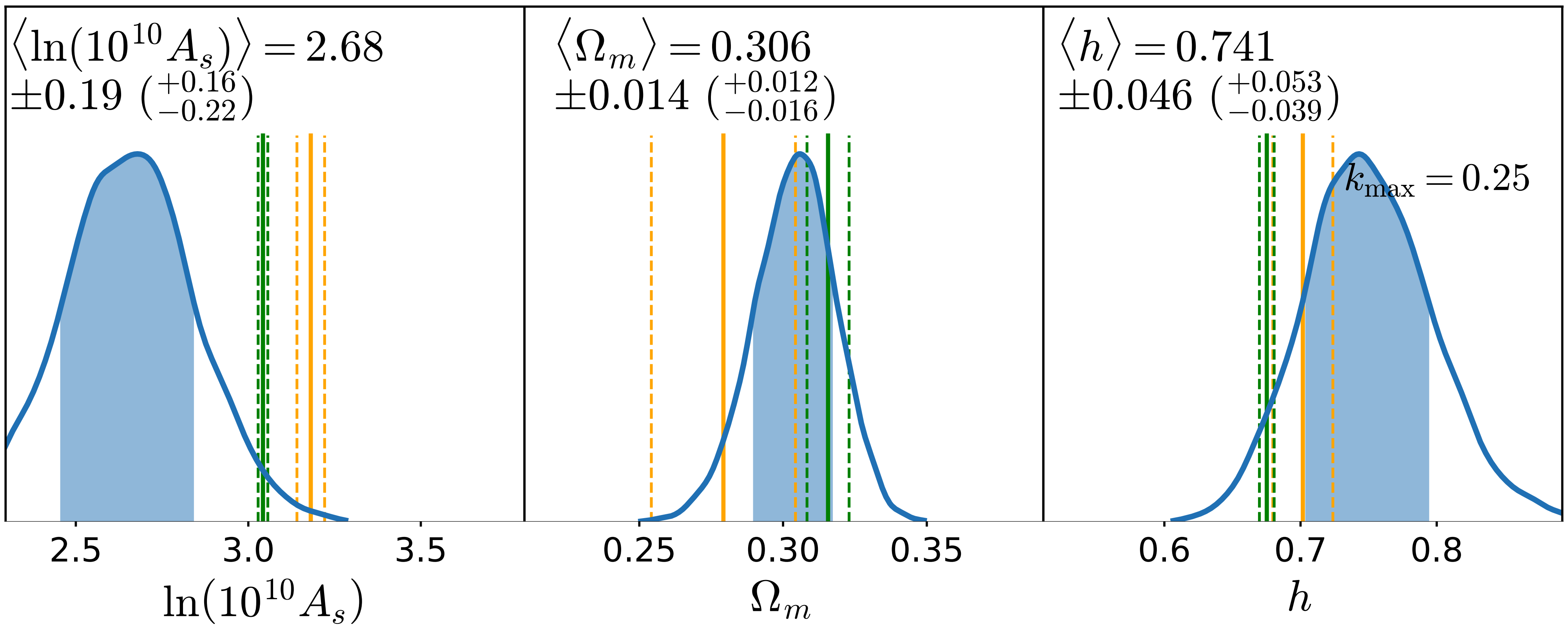
Leonardo Senatore (Stanford)

The Effective Field Theory of Large-Scale Structure applied to SDSS/BOSS Data

Analysis of the SDSS/BOSS data

– *Preliminary* results of the power spectrum analysis of the CMASS NGC sample



- We assume flat $\Lambda\mathrm{CDM}$ and Planck's n_s & Ω_b/Ω_m
- and measure $A_s,\ \Omega_m,\ H_0,\ b_1 \quad \leftrightarrow \quad f,\ \sigma_8,\ H_0,\ b_1$
- These *preliminary* results, if confirmed, tell us that there is the potentiality of much improving the whole *legacy* of SDSS.

Purpose of the talk

– I am not a specialist of LSS data analysis, which is probably more delicate than CMB. Hopefully this talk makes the professionals excited enough that they jump on this.

The end of a long journey

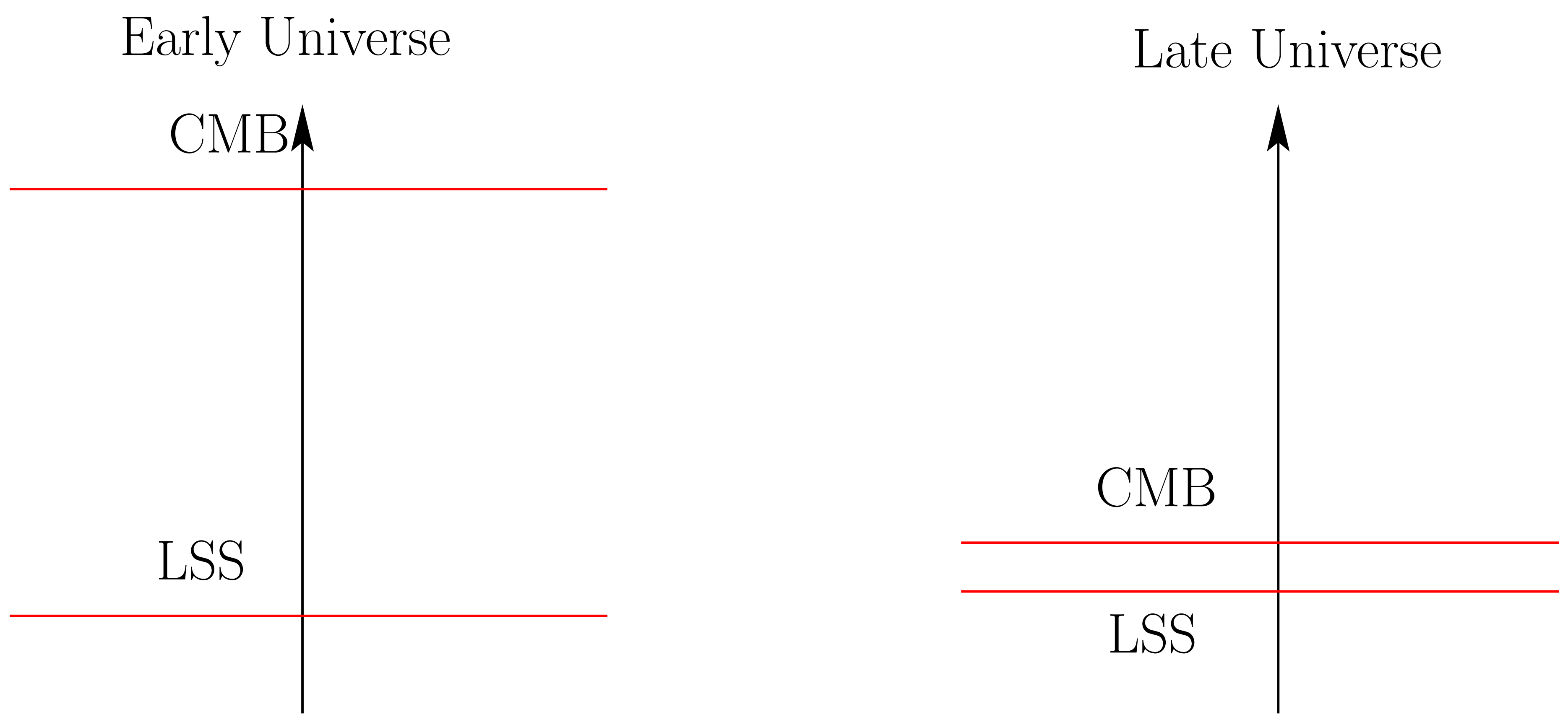
The Gathering Storm

The Gathering Storm

– After the completion of the Planck satellite, no guaranteed very large improvement is expected from measurements of the primordial CMB

– How to we continue to explore the beginning of the universe?

– LSS (directly or through CMB) will be the leading next probe. But where do we stand:



– If we are interested in the physics of the late time universe, such as dark energy or astrophysics, we are fine: a small jump is enough.

The Gathering Storm

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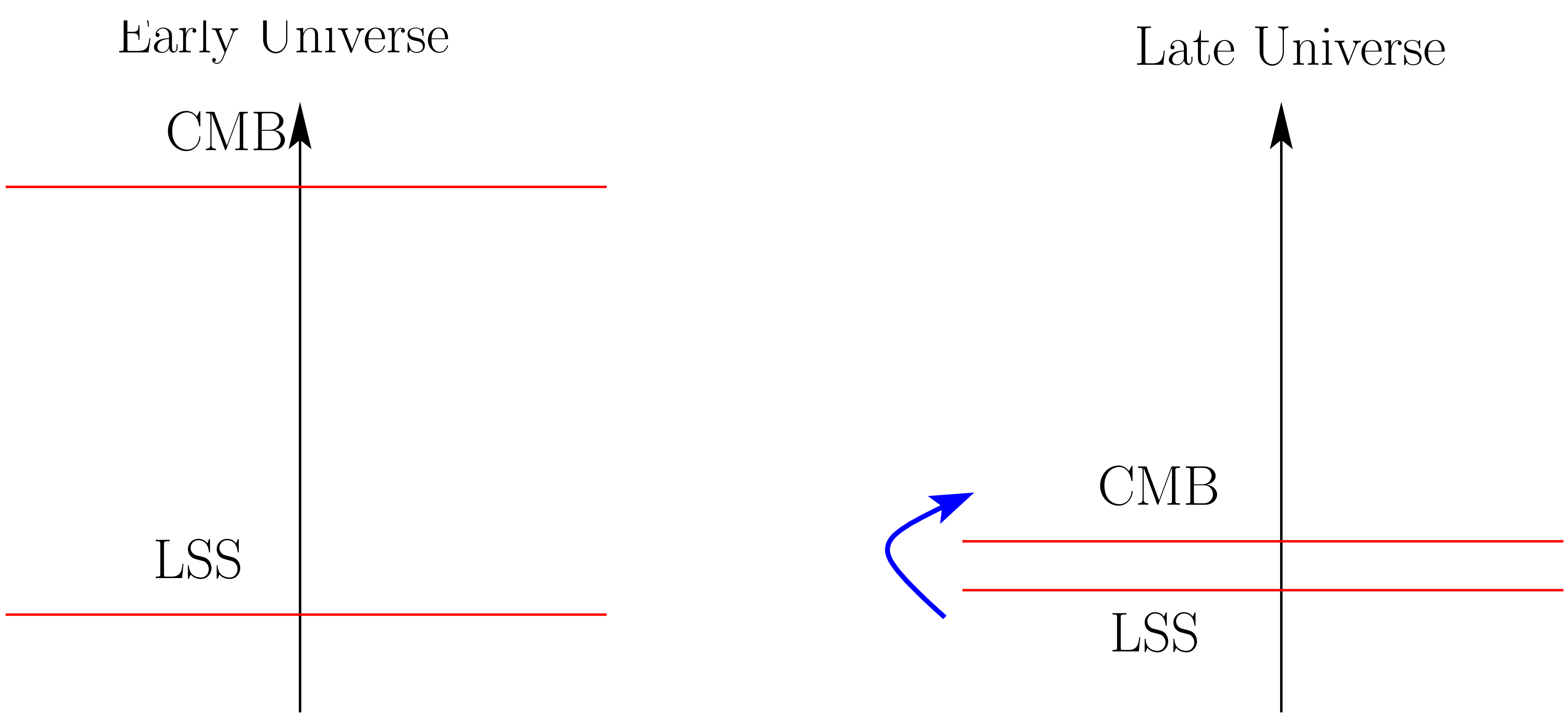
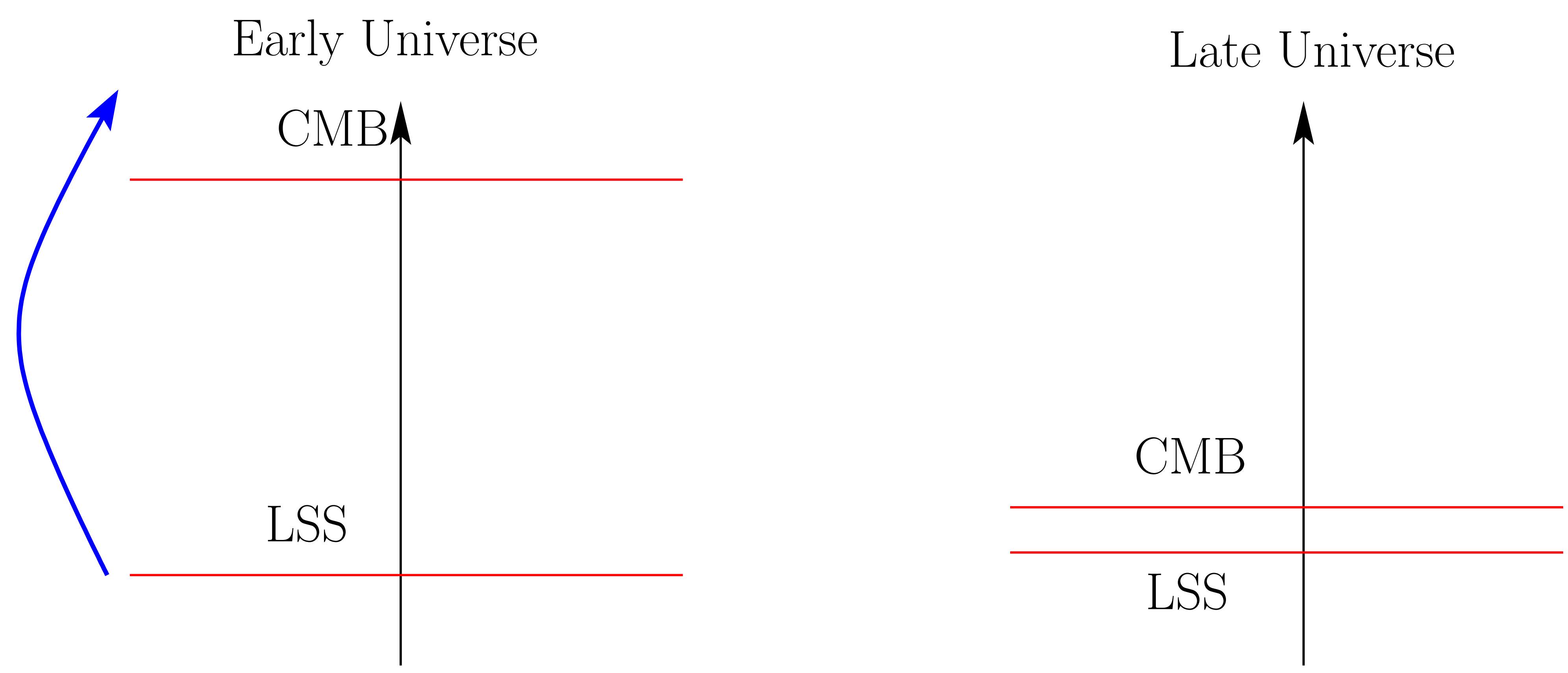


– If we are interested in the physics of the late time universe, such as dark energy or astrophysics, we are fine: a small jump is enough.

The Gathering Storm

– But the precision of the CMB and the heroes such as the WMAP and Planck teams, have allowed Cosmology to be part not just of *astrophysics*, but also of the so-called *fundamental physics*, such as quantum gravity, BSM, etc..

– If we want that to continue to belong also to this group, we need to make this happen:



– For the primordial universe, a large jump is required

– We have to do it, either with sims or analytics. I will present an analytic approach.

CMB vs LSS

- The route if very hard and grievous.
- But think to the heroes of the CMB! (or of the very first LSS ones, as in fact at the beginning cosmology started with LSS, and LSS dominated CMB for a long time)
- In the middle 90's, after the discovery of the CMB anisotropies by COBE, it aroused the promise that the CMB could make Cosmology a high-precision science
  - that allowed us to firmly seat at the table of Fundamental Physics, not only of Astrophysics.
  - Notwithstanding widespread skepticism, the promise was remarkably fulfilled
- Now, in order to continue this journey, we need make the same for LSS
  - Will the promise be fulfilled?
  - This is a challenge of the utmost importance

The EFTofLSS applied to data: the Complete Story

A long, long journey

– Dark Matter & Baryons

– Galaxies

– Redshift space

– IR-resummation

– Of course, none of this would have been possible without the precedent work of people like Bernardeau, Bond, Kaiser, Matsubara, MacDonald, Peebles, Refregier, Scheth, Scoccimarro, Seljak, Takada, White, and *Zeldovich*…

– But the EFTofLSS provides the first (and only) rigorous, convergent formalism to the true answer for $k \ll k_{\rm NL}$

– With it, we are not trying to answer only *Astrophysics* questions (for which the astro-models might be enough and we should keep using them, but the EFTofLSS has also to say on this). Our purpose is also to continue the journey that allowed us to make *Fundamental Physics* out of cosmology

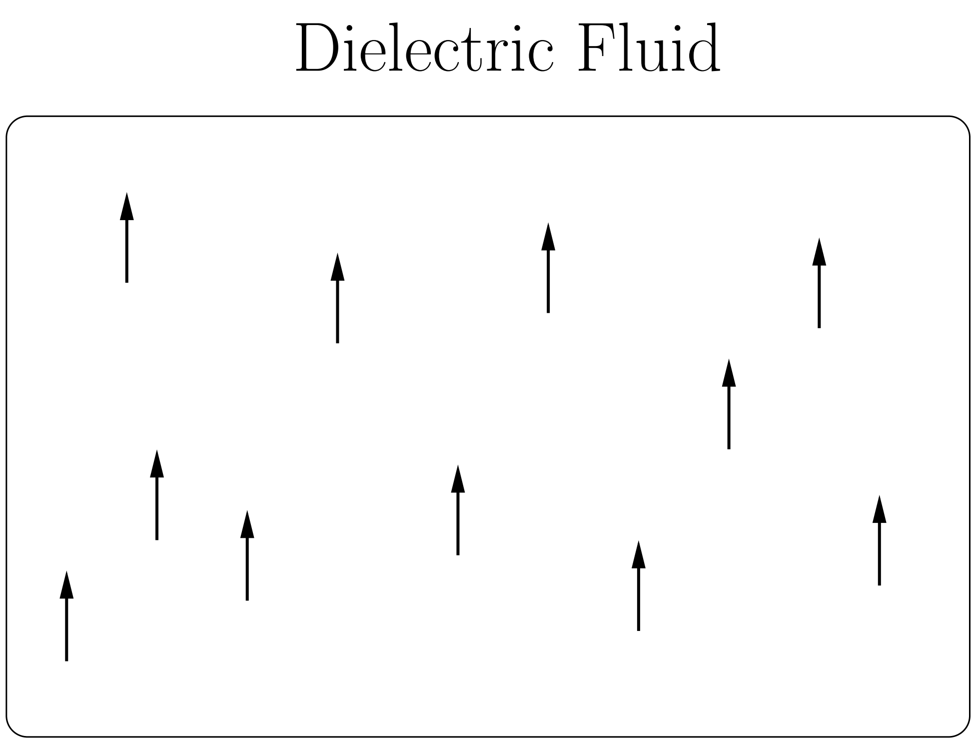
  - because of this, we have to be very rigorous, i.e. accurate.

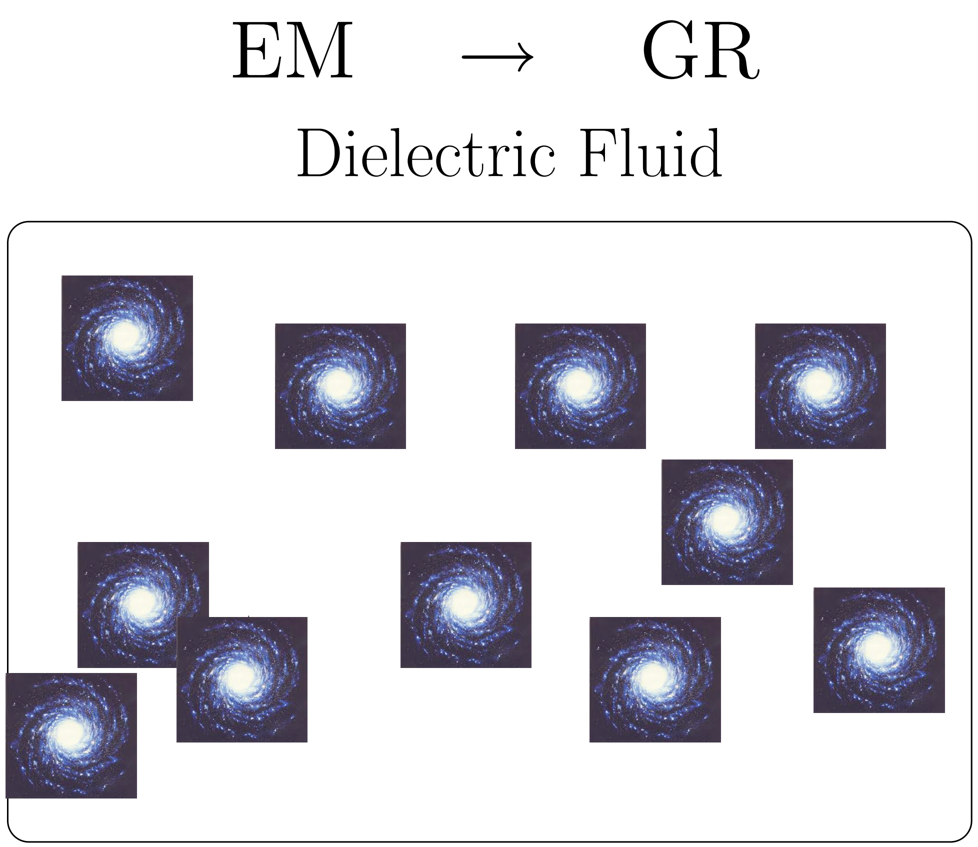
The EFTofLSS and Dieletric Materials

– The theory of dielectric materials is the theory of a massless spin-one object (light) interacting with composite objects (atoms)

– Very similarly, the EFTofLSS is the theory of massless spin-two object (gravity), interacting with composite objects (galaxies)

- so it is conceptually quite easy





Dark Matter and Baryons

The Effective ~Fluid

– In history of universe Dark Matter moves about $1/k_{\rm NL} \sim 10\,{\rm Mpc}$

– it is an effective fluid-like system with mean free path ~ $1/k_{\rm NL} \sim 10\,{\rm Mpc}$

– it interacts with gravity so matter and momentum are conserved

• Skipping many subtleties, the resulting equations are equivalent to fluid-like equations

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

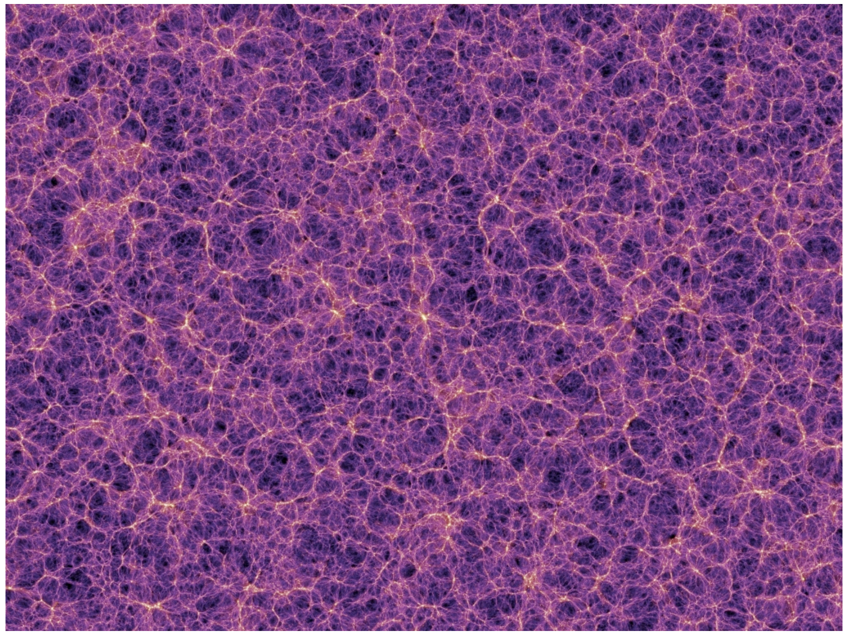
$$\partial_t\rho_l + H\rho_l + \partial_i\left(\rho_l v_l^i\right) = 0$$

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

with Baumann, Nicolis and Zaldarriaga **JCAP 2012**
with Carrasco and Hertzberg **JHEP 2012**
with Porto and Zaldarriaga **JCAP 2014**

– short distance physics appears as a non trivial stress tensor for the long-distance fluid

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



Dealing with the Effective Stress Tensor

- For dealing with long dist., expectation value over short modes (integrate them out)

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

- At long-wavelengths, the only fluctuating fields have small fluctuations: Taylor expand

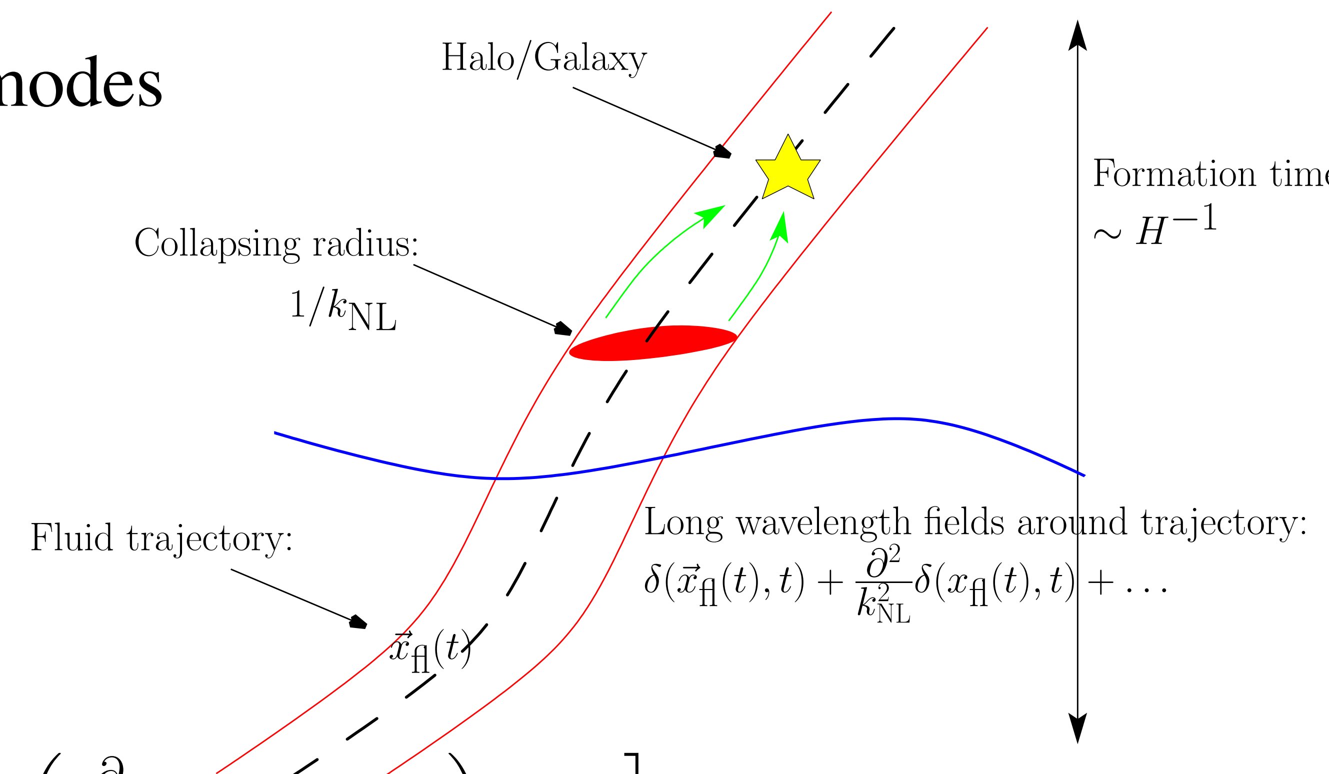
$$\Rightarrow \quad \langle \tau_{ij}(\vec{x},t)\rangle_{\text{long fixed}} = \int^{t} dt'\; K_1(t,t')\,\frac{\delta\rho}{\rho}(x_{\text{fl}},t') + \mathcal{O}\left((\delta\rho/\rho)^2\right)$$

- We obtain equations containing only long-modes

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

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

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



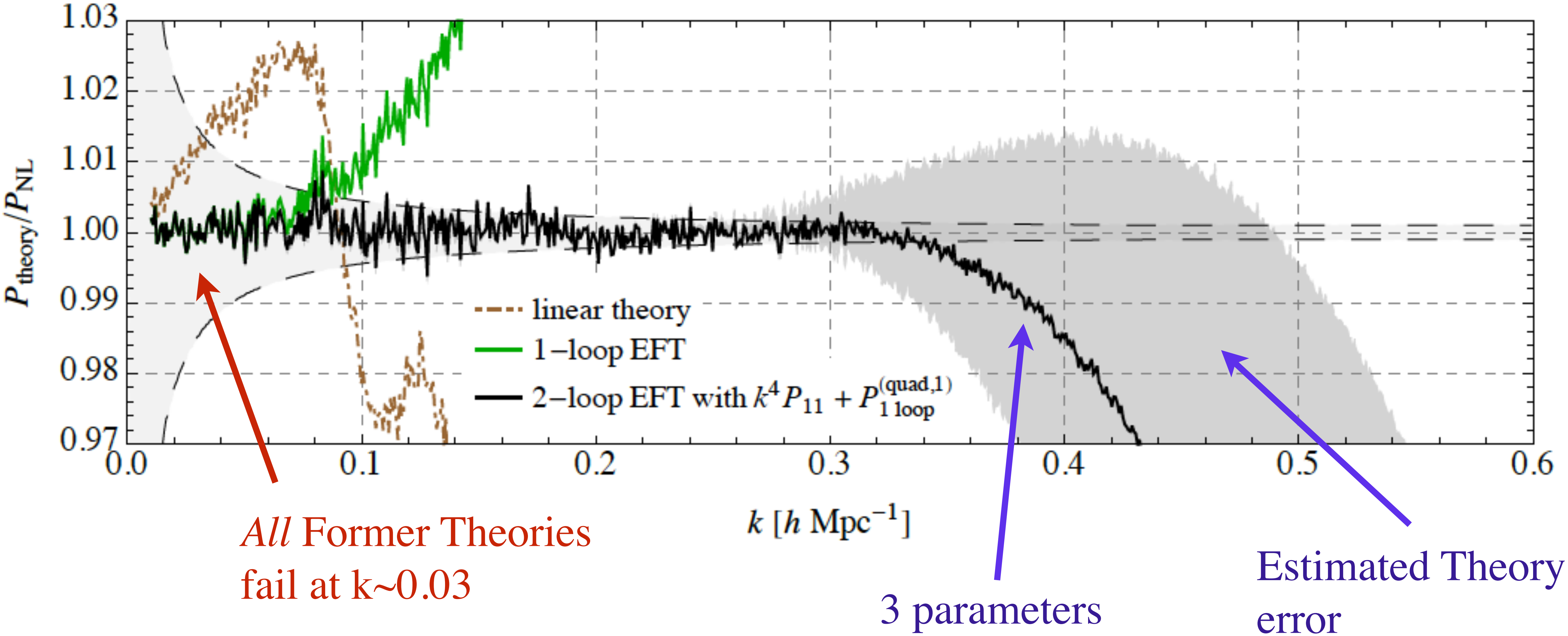
$$\langle \tau_{ij}\rangle_{\text{long-fixed}} \sim \delta_{ij}\left[p_0 + c_s\,\delta\rho_l + \mathcal{O}\left(\frac{\partial}{k_{\text{NL}}},\partial_i v_l^i,\delta\rho_l^2,\ldots\right) + \Delta\tau\right]$$

every term allowed by symmetries

- How many terms to keep?

  –each term contributes as an extra factor of $\quad \dfrac{\delta\rho_l}{\rho} \sim \dfrac{k}{k_{\text{NL}}} \ll 1$

EFT of Large Scale Structures at Two Loops



with Carrasco, Foreman and Green **JCAP1407**
with Zaldarriaga **JCAP1502**
with Foreman and Perrier **1507**
see also Baldauf, Shaan, Mercolli and Zaldarriaga **1507, 1507**

- Order by order improvement $\left(\frac{k}{k_{\rm NL}}\right)^L$
- Theory error estimated
- k-reach pushed to $k \sim 0.34\, h\, \text{Mpc}^{-1}$
- Huge gain wrt former theories

EFT of Large-Scale Structure

- Extended to
  - baryons

    with Lewandowski and Perko **JCAP1502**

  - neutrinos

    with Zaldarriaga **1707**

  - dark energy

    with Lewandowsky and Maleknejad **JCAP 1705**

  - non-gaussianities

    with Angulo, Fasiello, Vlah **1503**
    Assassi et al **1506,** Assassi et al **1509,**
    with Lewandowsky *et al* **1512**

Galaxy Statistics

senatore **1406**
with Lewandowsky *et al* **1512**
with Perko, et al. **1610**

Galaxies in the EFTofLSS

Senatore **1406**

- On bias, there was a long history before, summarized by McDonald Roy **2010** and this builds up on that. However, Senatore **1406** provided the first complete parametrization.
- The nature of Galaxies is very complicated. If we change the electron mass, the number density of galaxies changes (galaxies are UV sensitive objects).
- So practically impossible to predict

$$n_{\rm gal}(\vec x, t) = f_{\text{very complicated}}\left[\{H(t'), \Omega_{\rm dm}(t'), \ldots, \rho_{\rm dm}(x', t'), \rho_b(x', t'), \ldots, m_e, m_p, g_{ew}, \ldots\}|_{\text{on past light cone}}\right]$$

- However, if we are interested only on *long-wavelength* properties of $n_{\rm gal}(t)_k$, we realize that the only objects carrying non trivial space dependence are the fluctuating fields, which, *at long-wavelengths*, are small $\Longrightarrow$ we can Taylor expand $f_{\text{very complicated}}$

Galaxies in the EFTofLSS

Senatore **1406**

- Therefore

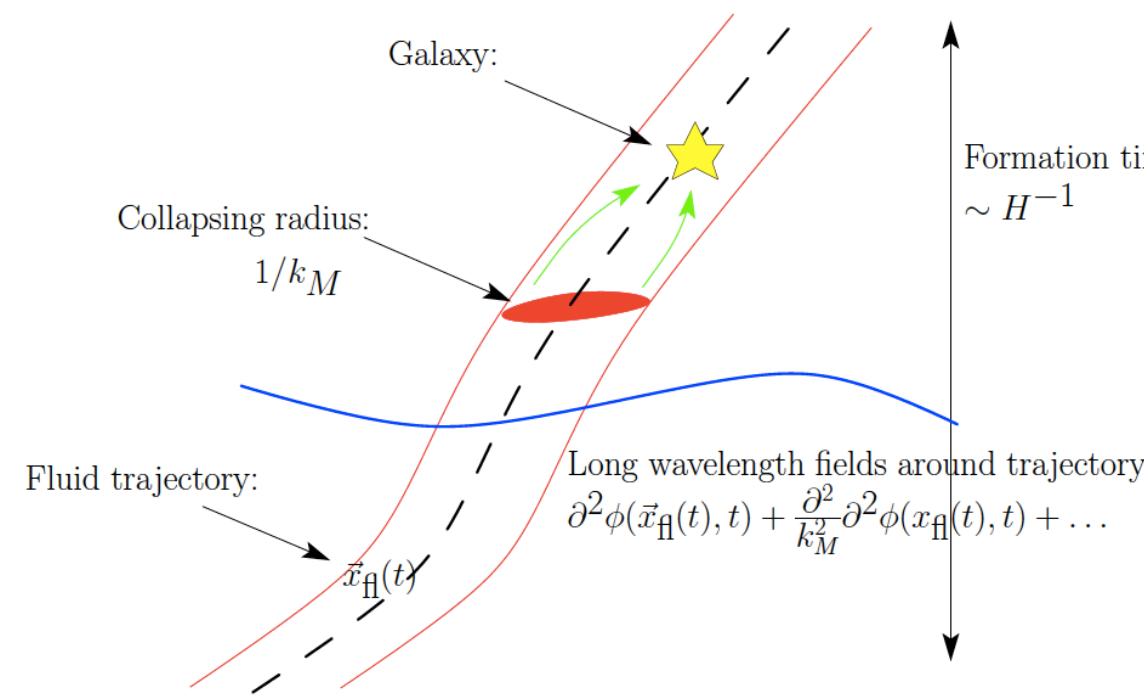
$$n_{\rm gal}(\vec x,t)=f_{\text{very complicated}}\left[\left\{H(t'),\Omega_{\rm dm}(t'),\ldots,\rho_{\rm dm}(x',t'),\rho_b(x',t'),\ldots,m_e,m_p,g_{ew},\ldots\right\}\Big|_{\text{on past light cone}}\right]$$

$$\Downarrow \quad \text{Taylor Expansion}$$

$$\delta_M(\vec x,t)\simeq\int^t dt'\;H(t')\;\left[\bar c_{\partial^2\phi}(t,t')\,\frac{\partial^2\phi(\vec x_{\rm fl},t')}{H(t')^2}\right.$$
$$+\bar c_{\partial_i v^i}(t,t')\,\frac{\partial_i v^i(\vec x_{\rm fl},t')}{H(t')}+\bar c_{\partial_i\partial_j\phi\partial^i\partial^j\phi}(t,t')\,\frac{\partial_i\partial_j\phi(\vec x_{\rm fl},t')}{H(t')^2}\frac{\partial^i\partial^j\phi(\vec x_{\rm fl},t')}{H(t')^2}+\ldots$$
$$+\bar c_\epsilon(t,t')\;\epsilon(\vec x_{\rm fl},t')+\bar c_{\epsilon\partial^2\phi}(t,t')\;\epsilon(\vec x_{\rm fl},t')\frac{\partial^2\phi(\vec x_{\rm fl},t')}{H(t')^2}+\ldots$$
$$\left.+\bar c_{\partial^4\phi}(t,t')\,\frac{\partial^2_{x_{\rm fl}}}{{k_{\rm M}}^2}\frac{\partial^2\phi(\vec x_{\rm fl},t')}{H(t')^2}+\ldots\right].$$

- all terms allowed by symmetries are present
- all physical effects are included
- extended to non-gaussianities and baryons

with Angulo, Fasiello, Vlah **1503**
Assassi et al **1506,** Assassi et al **1509,**
with Lewandowsky *et al* **1512**



Redshift space

with Zaldarriaga **1409**
with Lewandowsky *et al* **1512**

Counterterms

with Zaldarriaga **1409**
with Lewandowsky *et al* **1512**

- Redshift space is a field-dependent local change of coordinates:

$$\rho_r(\vec{x}_r)\; d^3x_r = \rho(\vec{x})\; d^3x\ , \quad \Rightarrow \qquad \delta_r(\vec{x}_r) = \left[1+\delta\left(\vec{x}(\vec{x}_r)\right)\right]\left|\frac{\partial \vec{x}_r}{\partial \vec{x}}\right|^{-1}_{\vec{x}(\vec{x}_r)} - 1\ .$$

- Need for counterterms (expectation value on short modes)

$$\delta_{\ell,g,r}(\vec{k},t) = \delta_{\ell,g}(\vec{k},t) - i\frac{k_z}{aH}v^z_{\ell,g}(\vec{k},t) + \frac{i^2}{2}\left(\frac{k_z}{aH}\right)^2 [v^z_{\ell,g}(\vec{x},t)^2]_{\vec{k}} \quad + \ldots$$

fields at same location: add counterterms

$$[v_z^2]_{R,\vec{k}} = [v_z^2]_{\vec{k}} + \left(\frac{aH}{k^r_{\rm NL}}\right)^2\left[c_{11}\delta^{(3)}_D(\vec{k}) + \left(c_{12}+c_{13}\mu^2\right)\delta(\vec{k})\right]$$

expectation value

response

- Baryons, Primordial NG included

with Lewandowski et al **1512**

- Now, all pieces ingredients are prepared.

IR-Resummation

with Zaldarriaga **1404**

IR-resummation and the BAO peak

- As has been know for some time (I knew it from *Scoccimarro*), perturbation theory is extremely slow to converge due to the effect of IR-displacements. They affect the feature in real space named BAO peak
- Observers try to address this in several ways (see for example BAO reconstruction).
- The first, and in a sense unique, consistent way to resum the IR-displacements was obtained in with Zaldarriaga **1404**

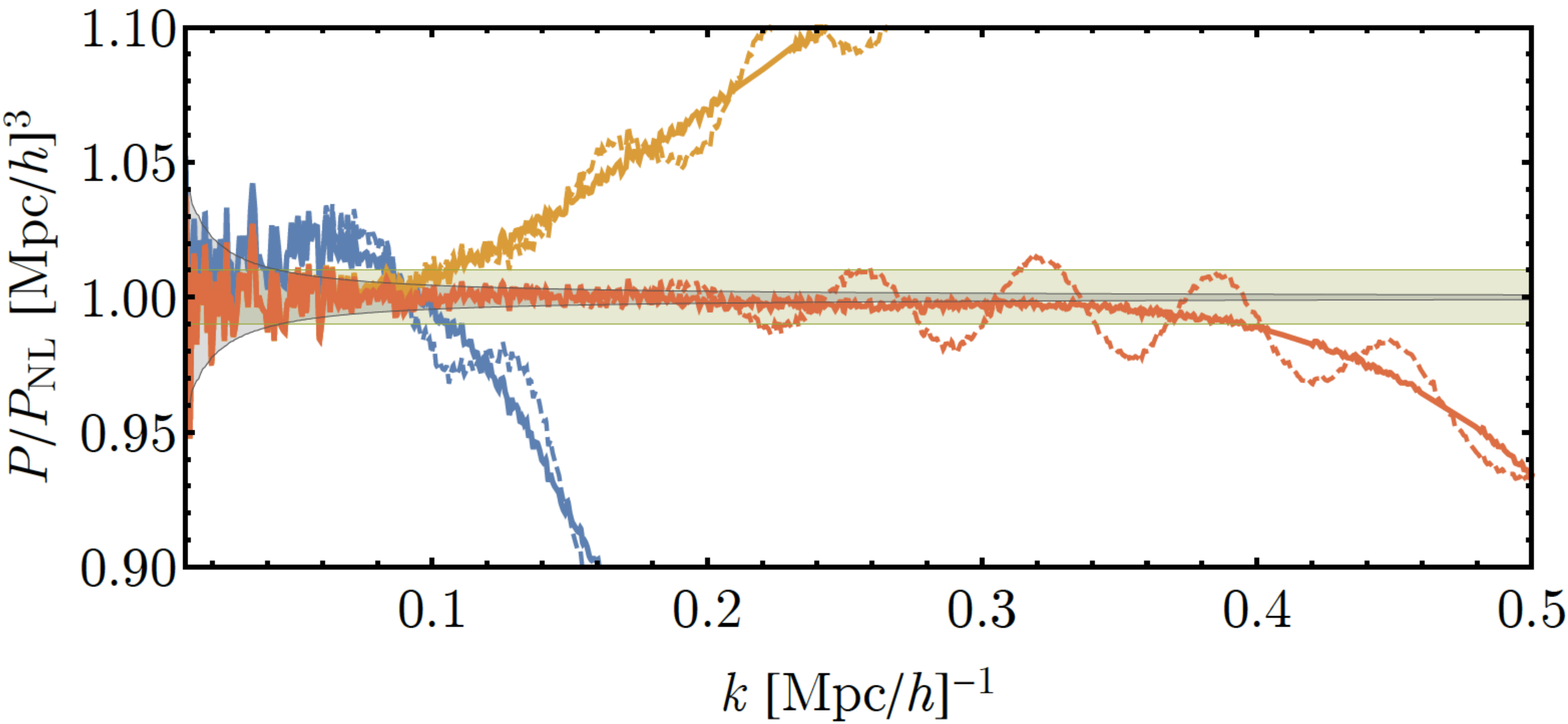
$$P_{\rm IR-resummed}(k) \sim \int dq\; M(k,q)\cdot P_{\rm non-resummed}(q)$$

- One can do several approximation to this formula, due to a trick developed in with Zaldarriaga **1404** such that as we go to higher orders in perturbations, the exact result is kept.
- The exact IR-resummation has been applied to redshift space in with Lewandowski et al **1512**

IR-resummation and the BAO peak

- It works very well

with Zaldarriaga **1404**
with Trevisan **JCAP1805**



- Similarly well in redshift space with Lewandowski et al **1512**

Galaxies in Redshift Space

with Perko, Jennings, Wechsler **1610**

Pipeline to Observables

- Correlations of Galaxy density in Redshfit space

$$\Uparrow$$

- In terms of Correlations of Galaxy density and velocity in real space + EFT parameters

$$\Uparrow$$

- In terms of Correlation of dark matter and tidal tensors, etc. + EFT parameters

$$\Uparrow$$

- Dark matter correlations from fluid equations + EFT parameters

- $\Rightarrow$ IR-resummation

Relevant equations

Galaxies in Redshift space in the EFTofLSS

- Halo-Halo power spectrum in redshift space

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

- where the counterterm contribution is given

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

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

All codes in
EFTofLSS public repository

Galaxies in Redshift space in the EFTofLSS

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- where the counterterm contribution is given

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

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

All codes in
EFTofLSS public repository

Galaxies in Redshift space in the EFTofLSS

- and the kernels in redshift space are just functions of the kernels for density and velocity in real space

$$
\begin{aligned}
K^{(1)}_{h,r}(\vec{q}_1) &= K^{(1)}_{\delta_h}(\vec{q}_1) + f\mu^2 K^{(1)}_{\theta_h}(\vec{q}_1) = b_1 + f\mu^2 \\
K^{(2)}_{h,r}(\vec{q}_1,\vec{q}_2) &= K^{(2)}_{\delta_h}(\vec{q}_1,\vec{q}_2) + f\mu^2 K^{(2)}_{\theta_h}(\vec{q}_1,\vec{q}_2) \\
&\quad + \frac{1}{2}\mu f \left(\frac{k q_{2z}}{q_2^2} + \frac{k q_{1z}}{q_1^2}\right) K^{(1)}_{\theta_h}(\vec{q}_1) K^{(1)}_{\delta_h}(\vec{q}_2) + \frac{1}{2}\mu^2 f^2 \frac{k^2 q_{1z} q_{2z}}{q_1^2 q_2^2} K^{(1)}_{\theta_h}(\vec{q}_1) K^{(1)}_{\theta_h}(\vec{q}_2)
\end{aligned}
$$

- which depend on 4 bias coefficients, using the physically-natural base of descendents

Senatore **1406**

$$
\begin{aligned}
b_1 &= \tilde{c}_{\delta,1} \\
b_2 &= \tilde{c}_{\delta,2(2)} \\
b_3 &= \tilde{c}_{\delta,3} + 15\tilde{c}_{s^2,2} \\
b_4 &= \tilde{c}_{\delta^2,1(2)} \,.
\end{aligned}
$$

- So, summary:
- 4 bias coefficients+ 3 non-stochastic counterterms+ 3 stochastic counterterm
    - *=10 `bias' parameters or `EFT' parameters*

Analysis of the BOSS/SDSS data

Guido d'Amico, Jerome Gleyzes, Nickolas Kockron, Dida Markovic, Leonardo Senatore, Matias Zaldarriaga, Pierre Zhang,
Florian Beutler, Hector Gill-Marin

in completion

Analysis of the BOSS/SDSS data

- We are now ready to analyze the data.

- We have 10 `EFT parameters'+ 3 cosmological parameters
  - dependence on 10 `EFT parameters' is analytic
  - dependence on cosmological parameters is not. So, we run a grid for `3' cosmological parameters (easy improvements are possible)
- Then we run an MCMC with 13 parameters, giving ample physically-motivated priors to the coefficients. At every MCMC step, we re-evaluate the model.
- We need to know our $k_{\rm max}$: we determine this, as well as the reach of the theory, comparing our results with simulations, using all the simulations that SDSS uses.

- on sims, 2 bias coefficients seem not to play a role (2 stoch. biases): dropped for the moment $\Rightarrow$ MCMC with 11 parameters

Exact Marginalization

- The dependence on the bias coefficients is quasi-linear: lots of tricks to do:
- For 5 biases, *linear* dependence:

$$P_{\ell,\,\mathrm{EFTofLSS}}(k,\vec{b}) = \sum_i f_i(\vec{b}) P_{\ell,\,\mathrm{EFTofLSS},\,i}(k) =$$

$$= \sum_i b_{\mathrm{G},i} P_{\mathrm{lin},\,\ell,\,\mathrm{EFTofLSS},\,i}\left(k,\vec{b}_{\mathrm{NG}}\right) + P_{\mathrm{indep},\,\ell,\,\mathrm{EFTofLSS}}\left(k,\vec{b}_{\mathrm{NG}}\right)$$

- Since we do not care of their numerical value, we can exactly marginalize over them:

$$\mathcal{L}(\vec{b}) = e^{-\frac{1}{2}\sum_{\ell,k}\left(P_{\ell,\,\mathrm{EFTofLSS}}(k,\vec{b})-P_{\ell,\,\mathrm{Data}}(k)\right)\cdot C^{-1}_{\ell,\ell'}(k,k')\cdot\left(P_{\ell',\,\mathrm{EFTofLSS}}(k',\vec{b})-P_{\ell,\,\mathrm{Data}}(k')\right)}$$

$$\Rightarrow \quad \mathcal{L}_{\mathrm{marg}}(\vec{b}_{\mathrm{NG}}) = \int d^5 b_{\mathrm{G}}\; \mathcal{L}(\vec{b}_{\mathrm{G}},\vec{b}_{\mathrm{NG}}) =$$

$$= \int d^5 b_{\mathrm{G}}\; e^{-\sum_{ij} b_{G,i}\,\cdot M_{\mathrm{quad},ij}(P_{EFT},P_{\mathrm{data}},\vec{b}_{\mathrm{NG}})\cdot\, b_{G,j}+\sum_i M_{\mathrm{lin},i}\cdot\, b_{G,j}+M_{\mathrm{indep.}}} = \frac{1}{\det\left(M_{\mathrm{quad}}\right)} e^{-\frac{1}{2}M_{\mathrm{lin},i}\cdot M^{-1}_{\mathrm{quad}}{}_{ij}\cdot M_{\mathrm{lin},j}+\dots}$$

$$= f_{\mathrm{unction}}(\Omega,\vec{b}_{\mathrm{NG}},\mathrm{data})$$

- We obtain a likelihood function only of 6 parameters (but slower to evaluate).
    - so we use both likelihoods and compare

Window function

- Contrary to former astro-inspired models, the EFTofLSS is arbitrary accurate at low k's, but when it fails, it fails *big time*.
- This creates difficulties in applying the survey window-function. It is also waste of time
- Normally

$$P_\ell(k) \overset{\text{FFTlog}}{\longrightarrow} \xi_\ell(r) \quad \rightarrow \quad \xi_\ell^{(W)}(r) = Q_{\ell,\ell'}(r) \cdot \xi_\ell(r) \overset{\text{FFTlog}}{\longrightarrow} P_\ell^{(W)}(k)$$

- Since we have difficulties in doing FFTlog due to bad UV-behavior of EFT, we do directly in Fourier space:

$$P_\ell^{(W)}(k) = \int dk'\, W(k,k')_{\ell,\ell'} \cdot P_{\ell'}(k') \quad \text{with} \quad W(k,k')_{\ell,\ell'} = \int ds\, j_\ell(ks)\, Q_{\ell,\ell'}(s) \cdot j_\ell(k's)$$

  - computationally doable: one FFTlog for each k

- Substitute in Likelihood and define the new masked Covariance (once forever):

$$\log\left(\mathcal{L}(\vec{b})\right) = \sum P^{(W)}_{\text{EFTofLSS}} \cdot C^{-1} \cdot P^{(W)}_{\text{EFTofLSS}} = \sum P_{\text{EFTofLSS}}\, W^{Tr} \cdot C^{-1} \cdot W \cdot P_{\text{EFTofLSS}}$$

- So, we can evaluate the *full model* at each MCMC step.

Power Spectrum in Simulations

Challenge Boxes

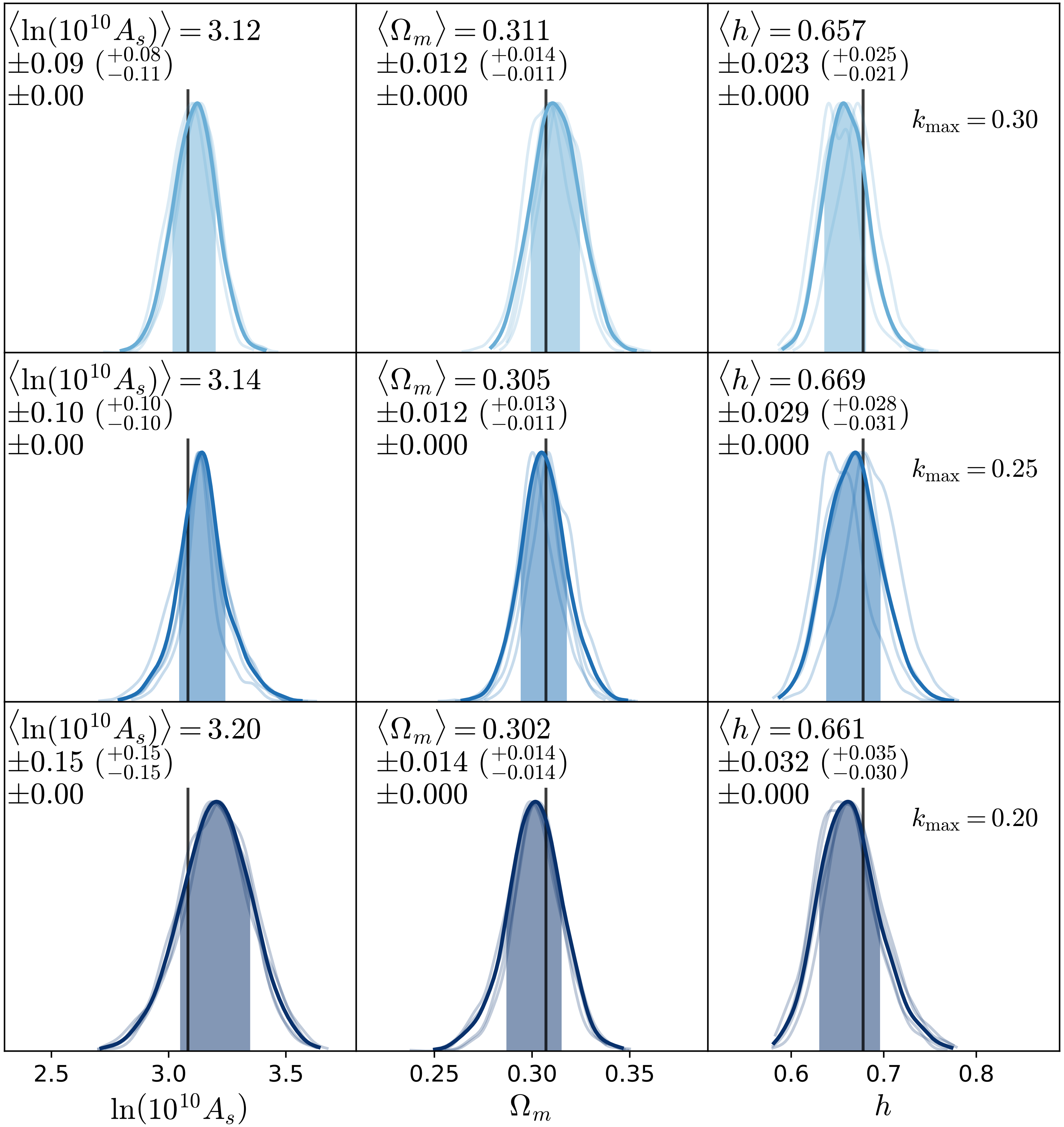
- Challenge boxes are good-quality N-body simulations of BOSS volume, populated with 4 HOD's, 4-times SDSS volume
- Fit three multipoles
- We measure $A_s,\ \Omega_m,\ H_0,\ b_1$
- Theory systematic error (bias):
    - unmeasurably small
        - assuming simulations
    - Important test passed
- Errors decrease like

$$\Delta A_s \sim k_{\rm max}^{-1.4}$$

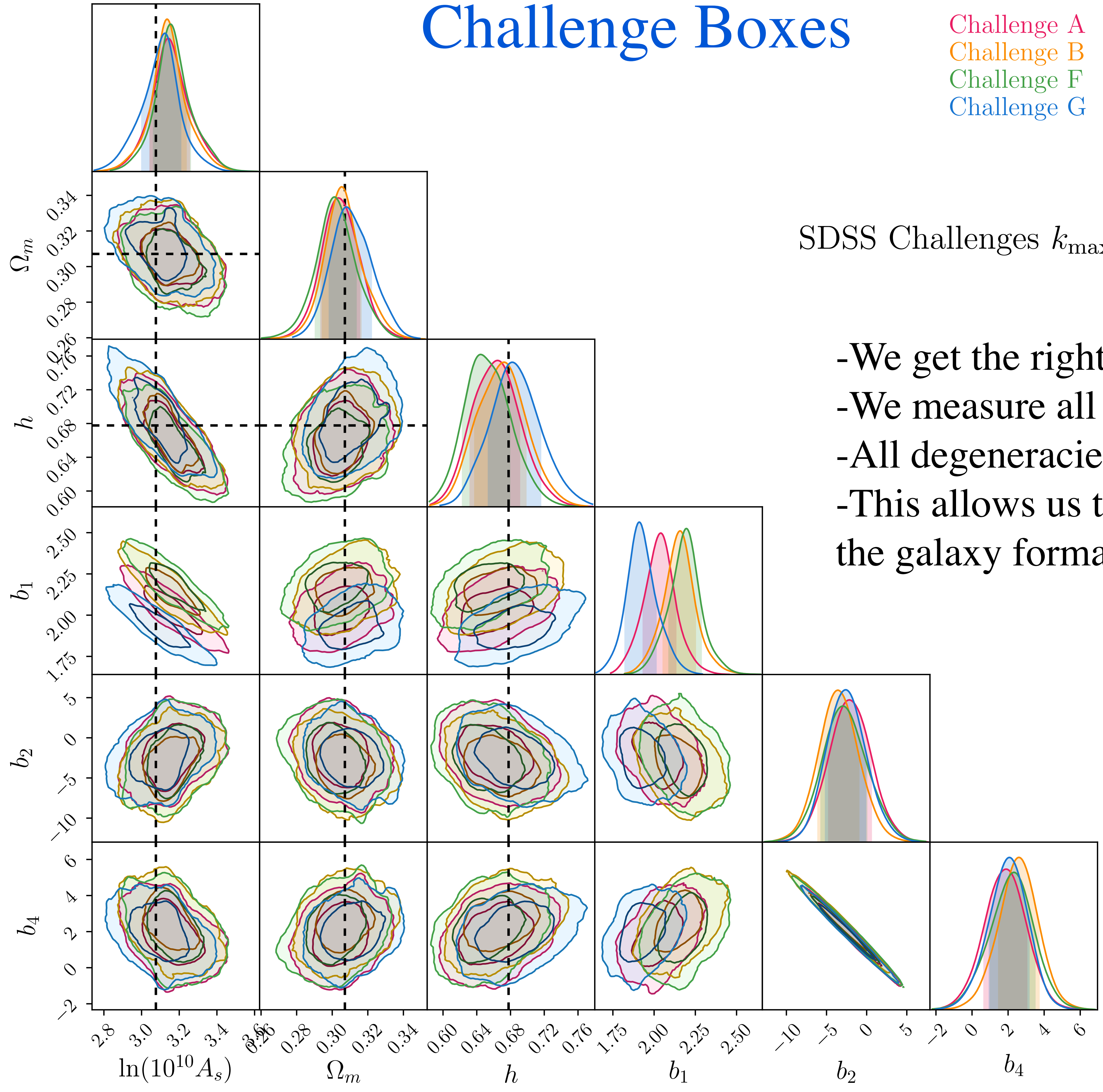
$$\Delta \Omega_n \sim k_{\rm max}^{-0.4}$$

$$\Delta H_0 \sim k_{\rm max}^{-0.8}$$

- same results with non-marg likl.



Challenge Boxes



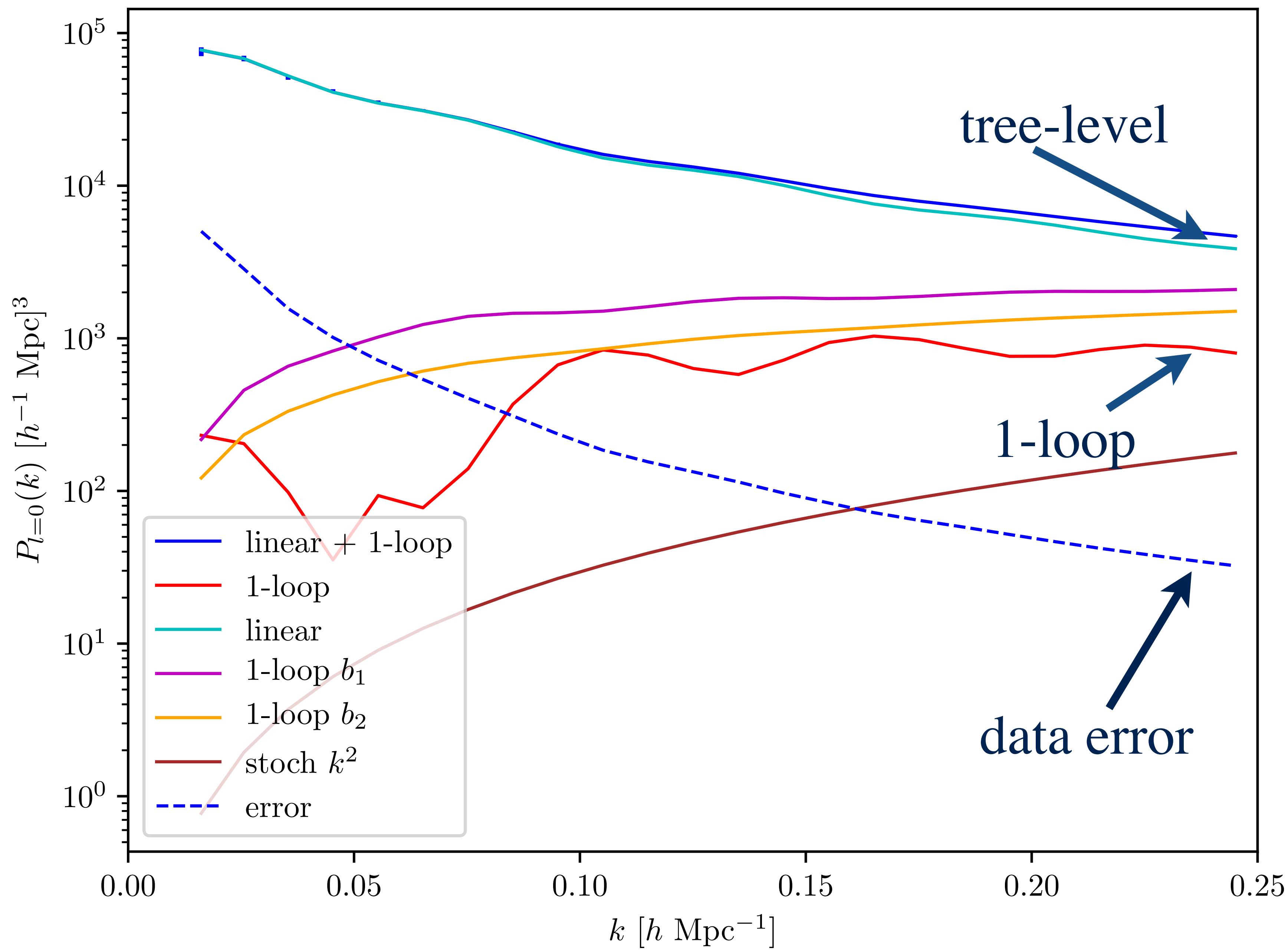
SDSS Challenges $k_{\max} = 0.25$

- -We get the right cosmology
- -We measure all the biases
- -All degeneracies are broken
- -This allows us to help infer the galaxy formation mechanism

Theoretical Consistency: Challenge Boxes

- Best fit model:

	b_1	b_2	b_3	b_4	$c_{\rm ct}$	$c_{r,1}$	$c_{r,2}$	$10 \times c_{\epsilon,1}$
Challenge A	2.1	-2.8	-1.5	4.4	-1.4	-13.9	-0.5	-0.3



- Theoretical Consistency
  - parameters $\sim\ \mathcal{O}(2)$
    - exc. is shot noise
  - $\dfrac{P_{1-\mathrm{loop}}}{P_{11}} \sim 10\%$

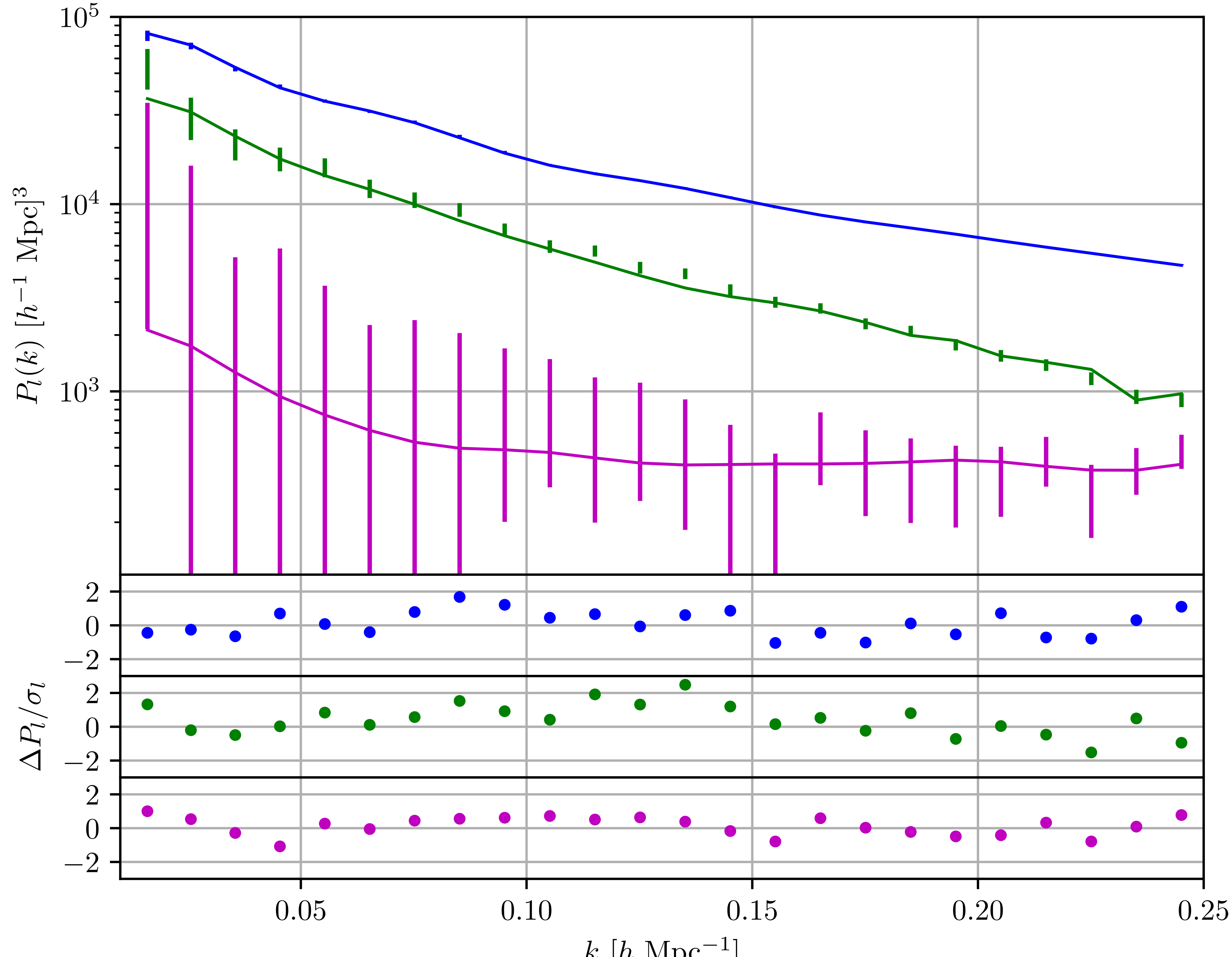
$$\Rightarrow \quad \frac{P_{2-\mathrm{loop}}}{P_{11}} \sim 1\% \sim \sigma_{\rm data}(k_{\rm max} = 0.25\, h\, \mathrm{Mpc}^{-1}\ )$$

Challenge Boxes

- Best fit model:

	$\ln(10^{10}A_s)$	Ω_m	h	min χ^2/d.o.f.	p-value
Challenge A	3.12	0.298	0.661	42/(72-11)	0.97

- Data Consistency
    - good p-value
    - nothing major



Physical Considerations

- We measure $A_s,\ \Omega_m,\ H_0,\ b_1$, without any significant prior from CMB. How is this possible?

- Notice that we analyze the full spectrum, no splitting osc.+smooth. But, in order to understand, we can split the smooth and the oscillating signal.

- BAO-scale (sound horizon) and relative amplitude $\sim\ \Omega_m h^{-4}\ \&\ \Omega_m h^2$

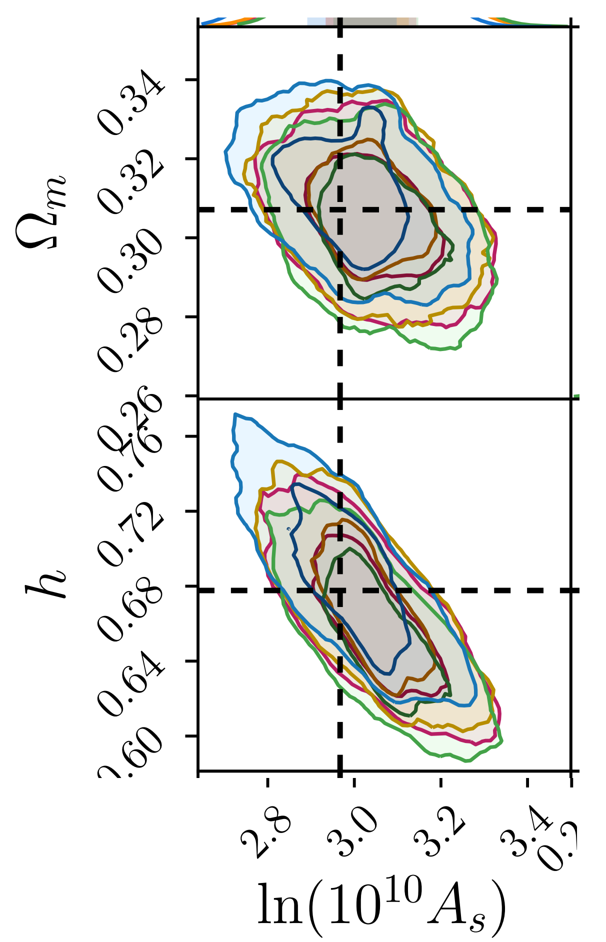
- Linear monopole and quadrupole

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

- So, this allows us to solve for all the four variables: $A_s,\ \Omega_m,\ H_0,\ b_1$

- In particular $\quad P_{11,\ell=0} \sim b_1^2 A_s^{(k_{\rm max})} \sim b_1^2 A_s k_{\rm eq}^2 \propto b_1^2 A_s \Omega_m h^2$

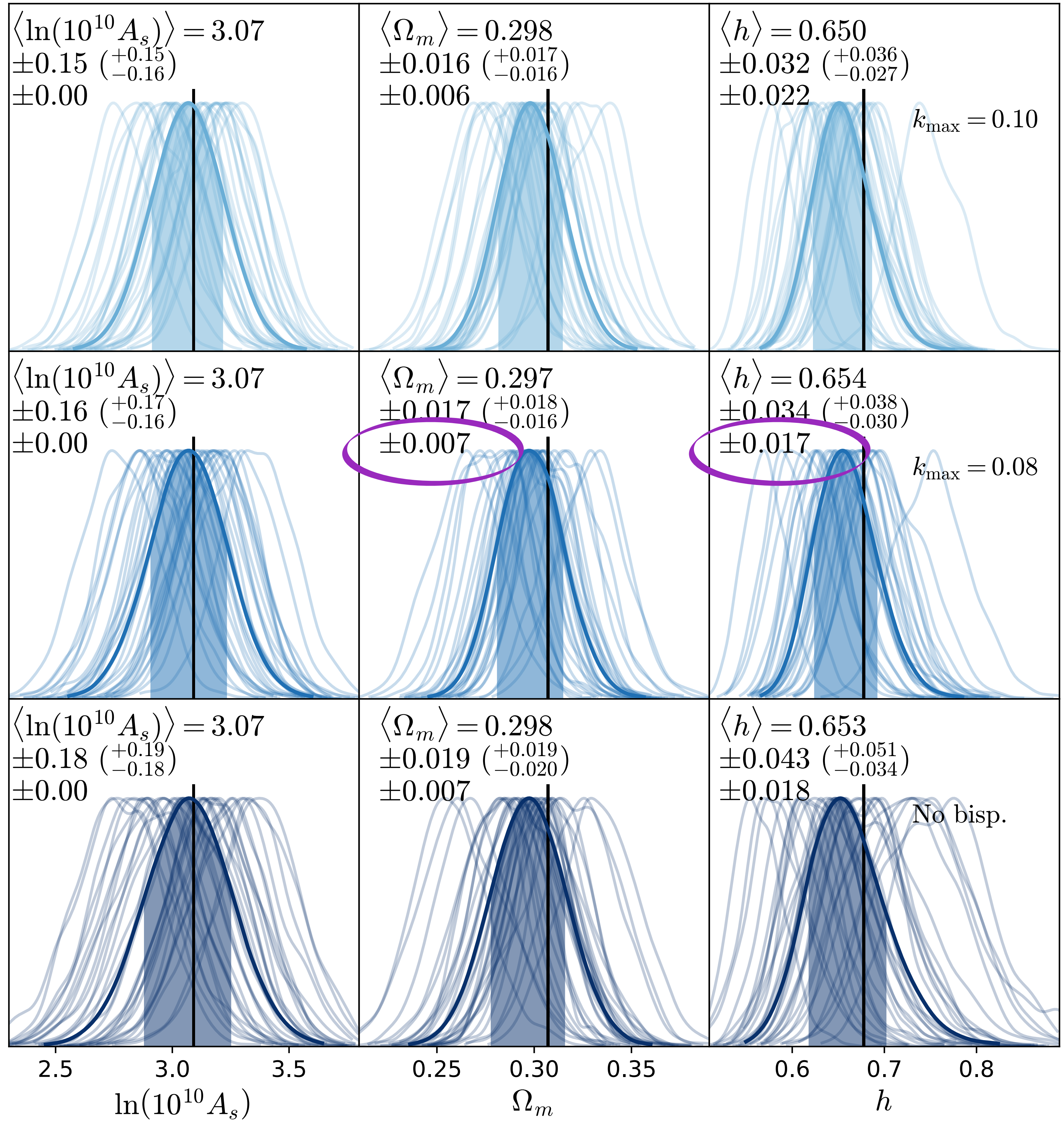
$$\Rightarrow \quad \text{anticorrelation of} \quad (A_s \,\&\, b_1),\ (A_s \,\&\, h),\ (\Omega_m \,\&\, h)$$



- Additional information comes further from exaducaple, non-linear terms and overall shape, which depends on $k_{\rm eq}$

Pachy Mocks

- Low-quality model-simulations
  - with good redshift modeling
  - good window function
  - SDSS volume
- Error bars similar to SDSS
- Systematic error computed combining 30 boxes
  - very small on $\Omega_m, \ h$
  - entirely due to quality of Patchy mocks
- Test passed.



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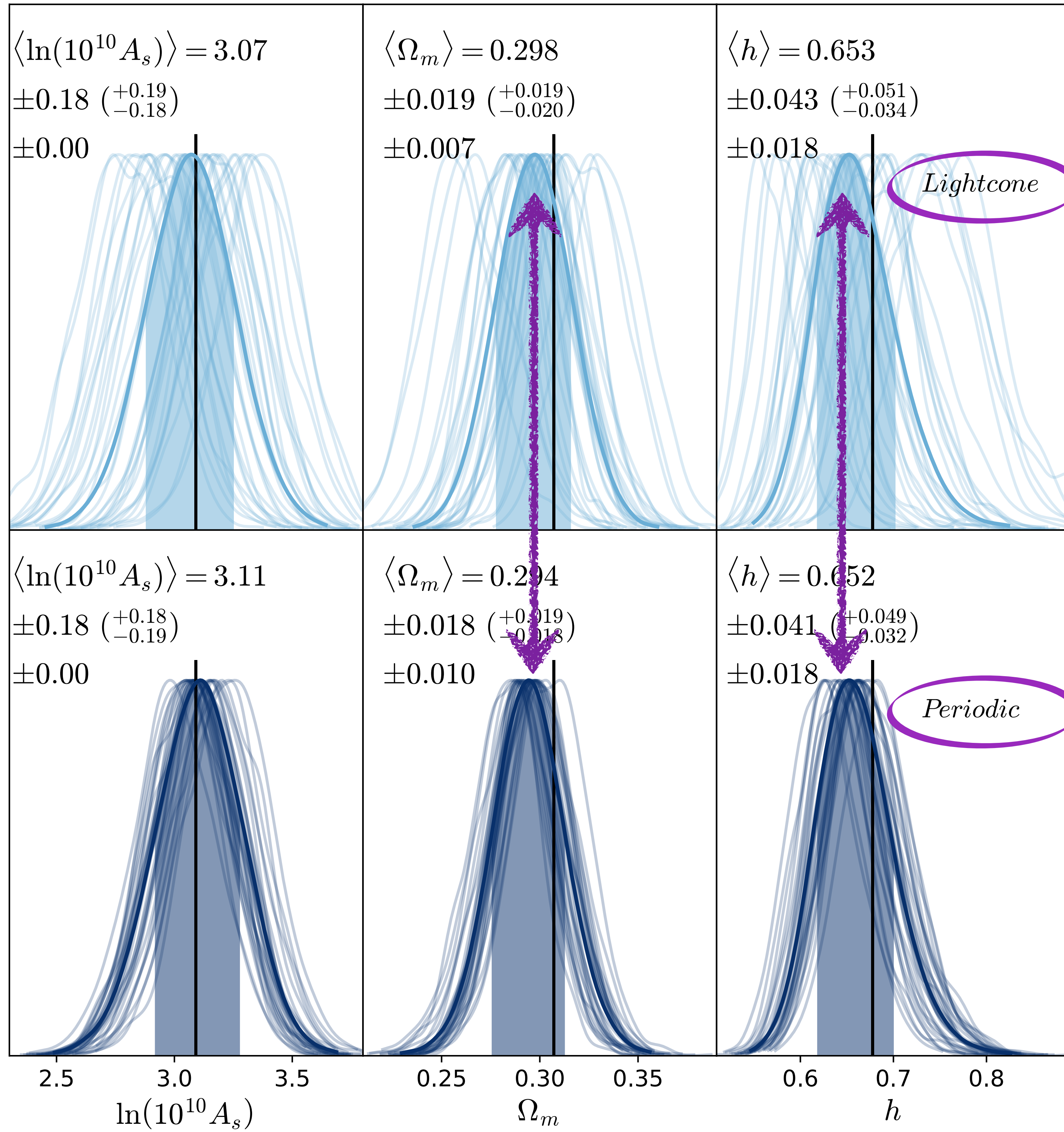

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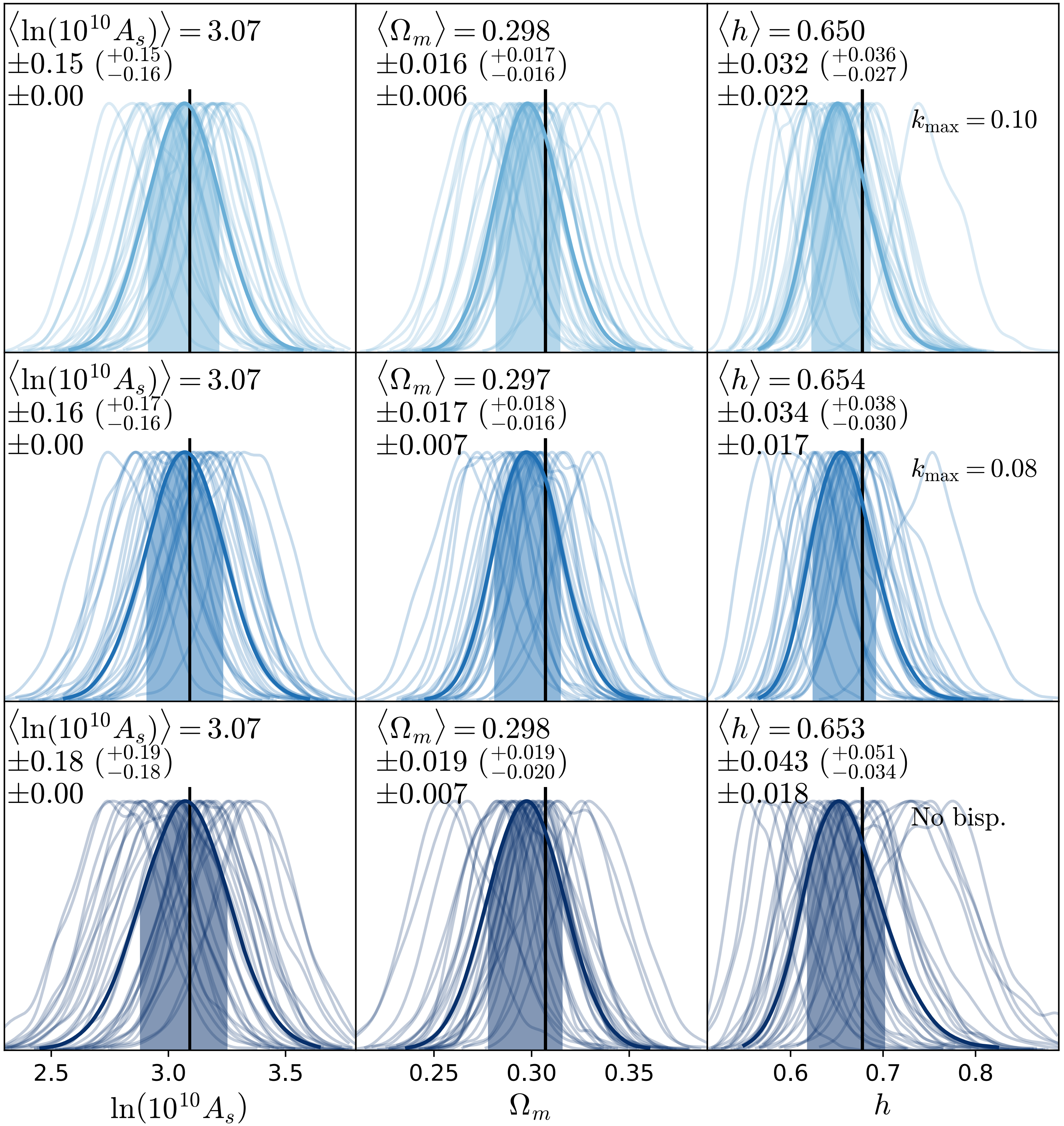
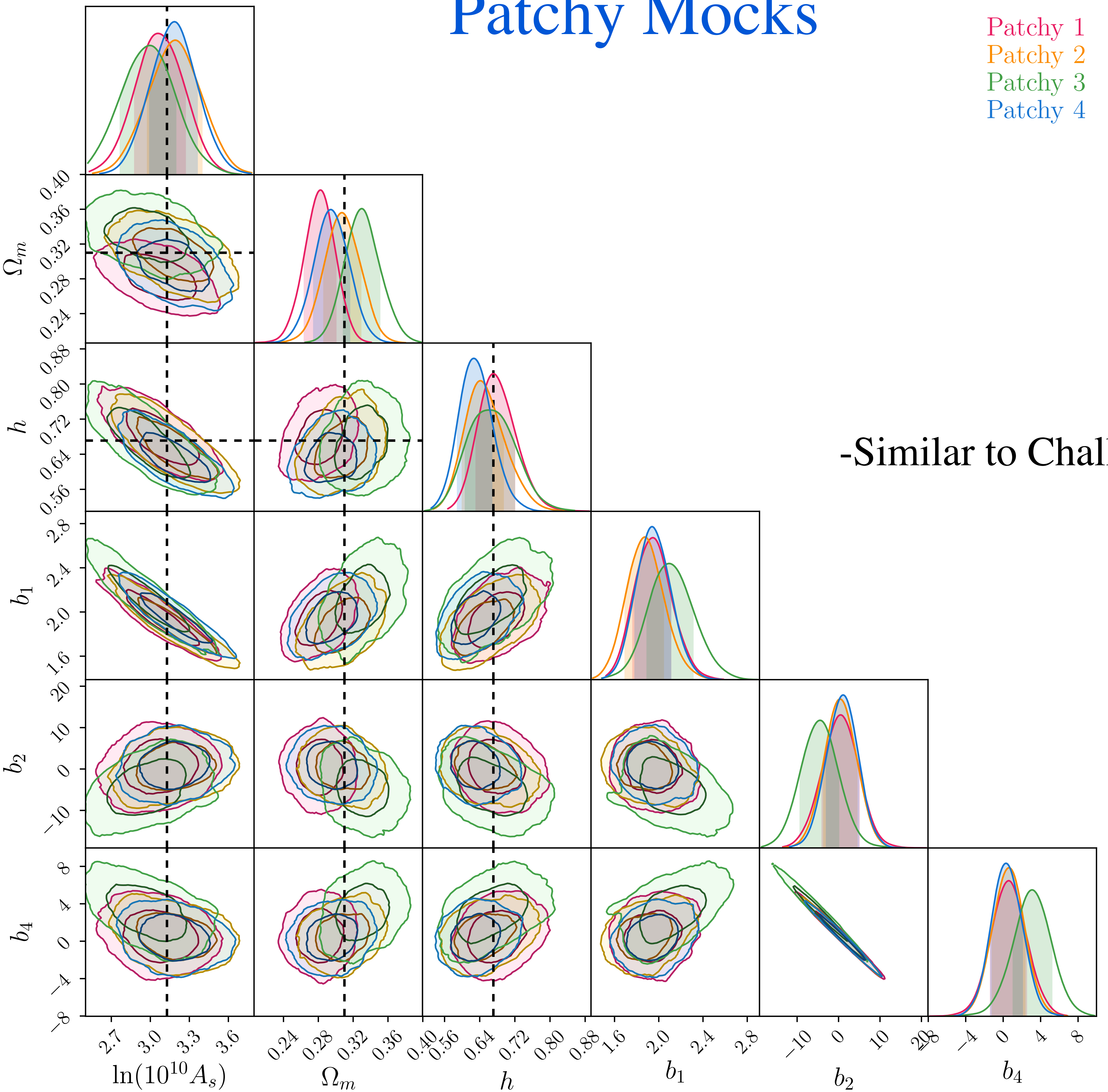


Patchy Mocks

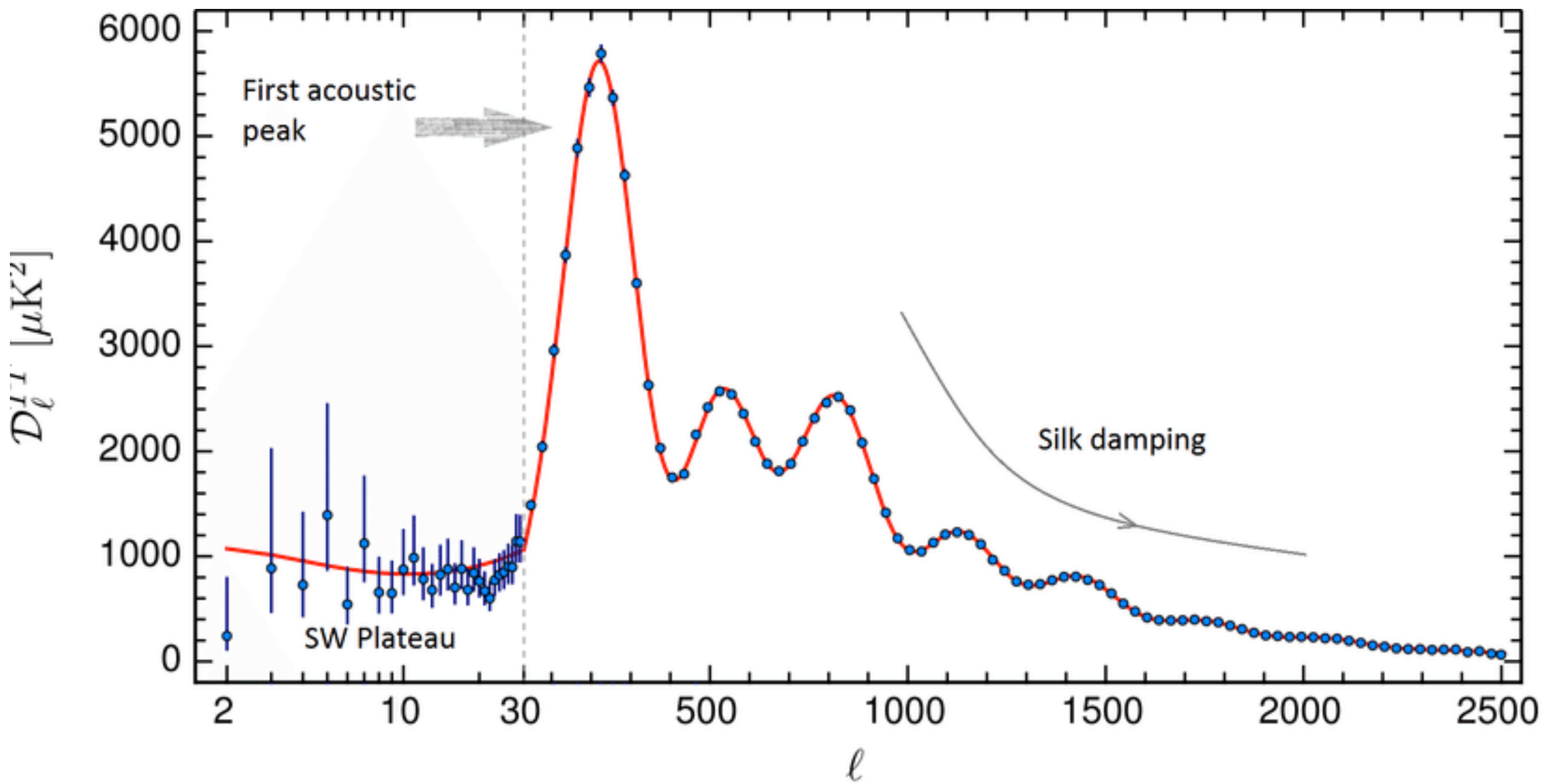


-Similar to Challenge

Adding Planck’s sound-horizon prior

Apply prior on Planck's horizon at decoupling

- Planck measures sound's horizon at decoupling very well.
- For $\Lambda\mathrm{CDM}$, highly insensitive to late universe physics.
- This is normally used as `BAO calibration': we do not need it, but we can use it.



Challenge Boxes with Planck's horizon

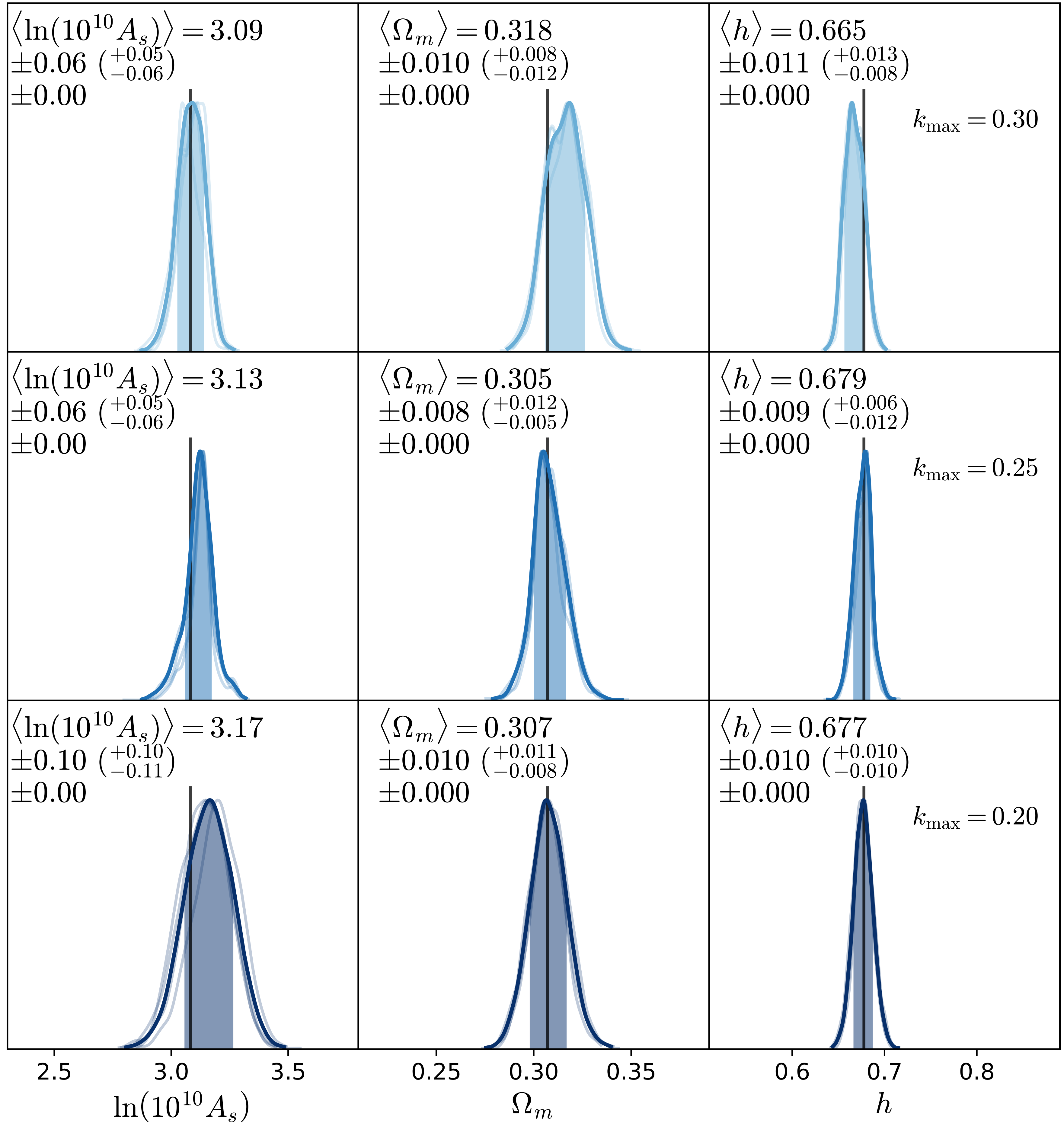
- Error bar reduction

$$\Delta A_s \sim 35\%$$

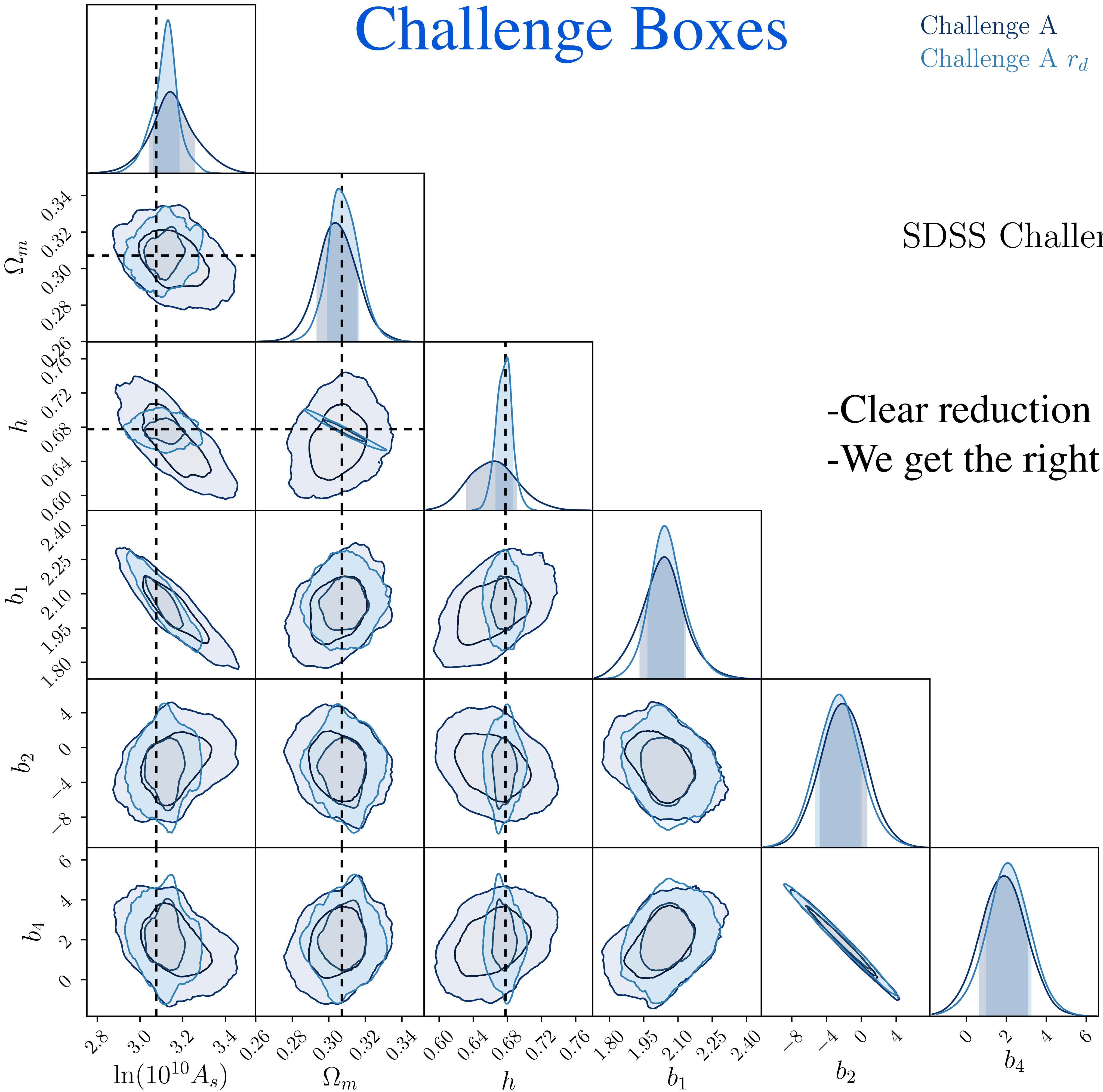
$$\Delta \Omega_n \sim 15\%$$

$$\Delta H_0 \sim 60\%$$

- No systematic error detected



Challenge Boxes



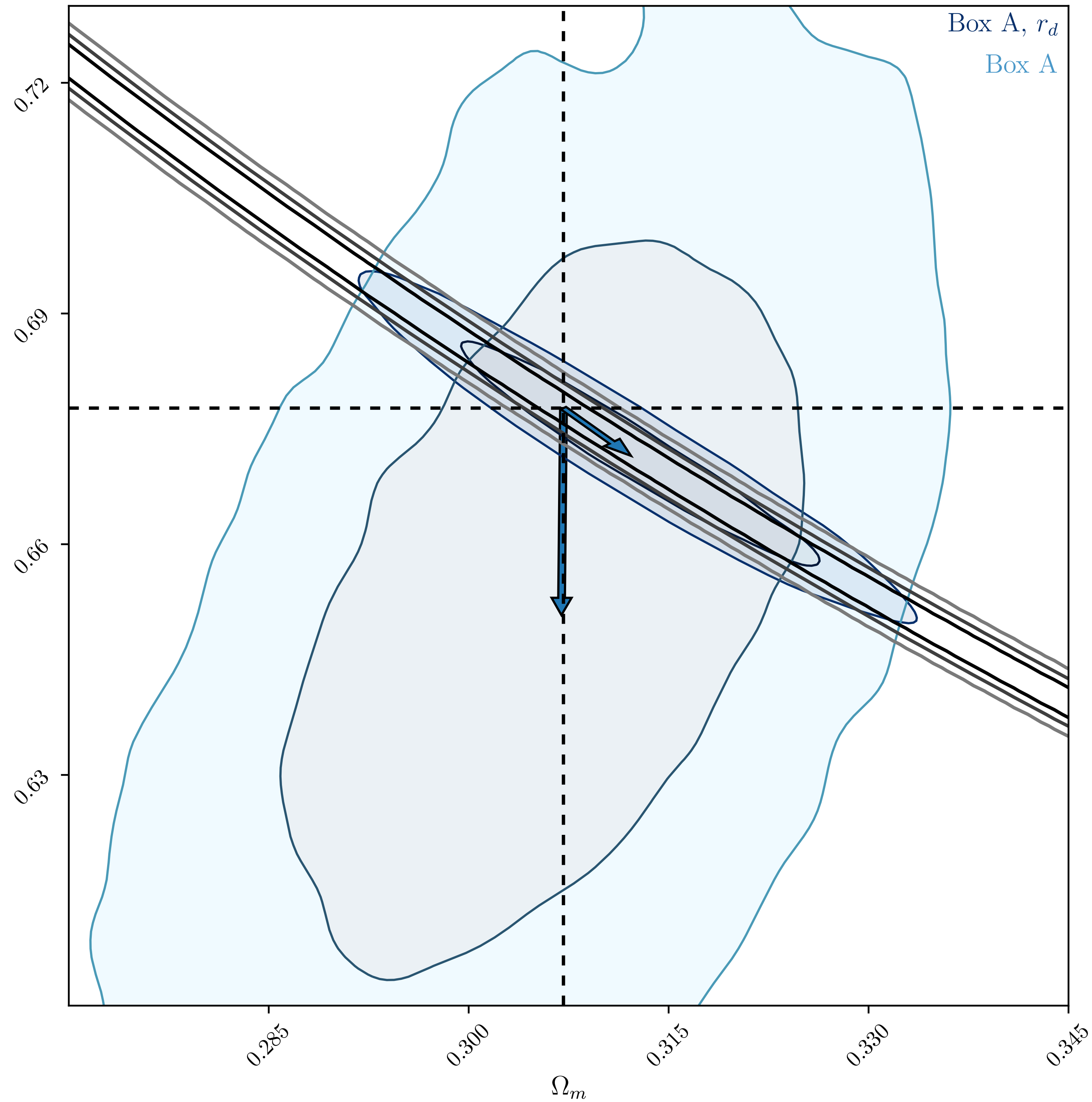
SDSS Challenges $k_{\max} = 0.25$

-Clear reduction in the contours

-We get the right cosmology

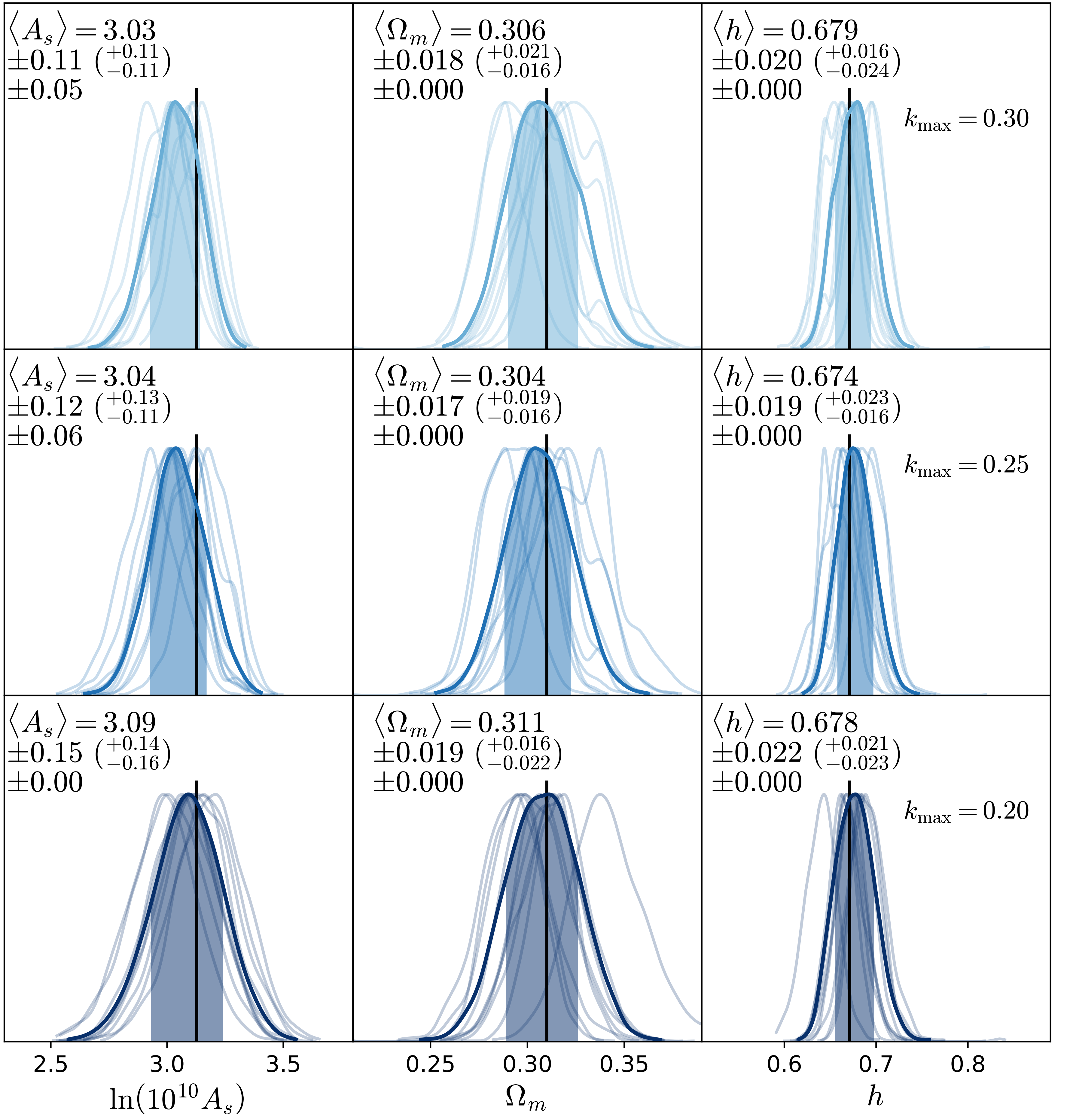
Reduction of systematic

- The theory error is reduced.



Pachy Mocks

- ~same as Challenge



Adding Bispectrum Monopole

Bispectrum

- In the EFTofLSS, the bispectrum at tree level is *predicted* by the same parameters that enter in the one-loop power spectrum.
- $\Longrightarrow$ We can analyze it
    - (we could also analyze the trispectrum with roughly the same parameters)

- Unfortunately, SDSS does not have an collaboration measurement of the bispectrum
    - (nor of the trispectrum).

- The Bispectrum monopole has been measured by Gill Marin *et al*. **2016**

Challenge Boxes with Bispectrum monopole

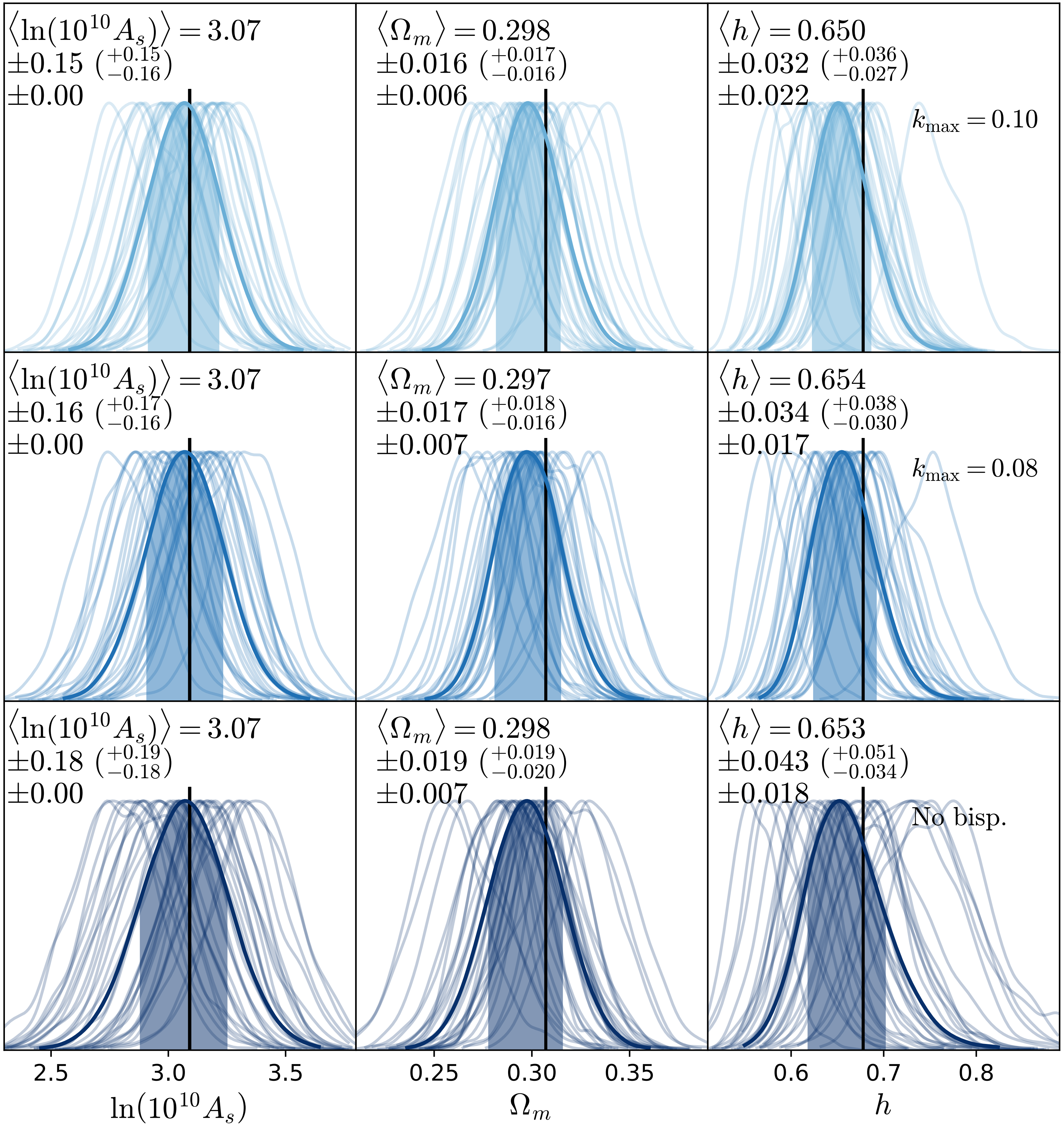
- Error bar reduction

$\Delta \ln(10^{10} A_s) \sim 8\%,$

$\Delta\Omega_m \sim 12\%$,

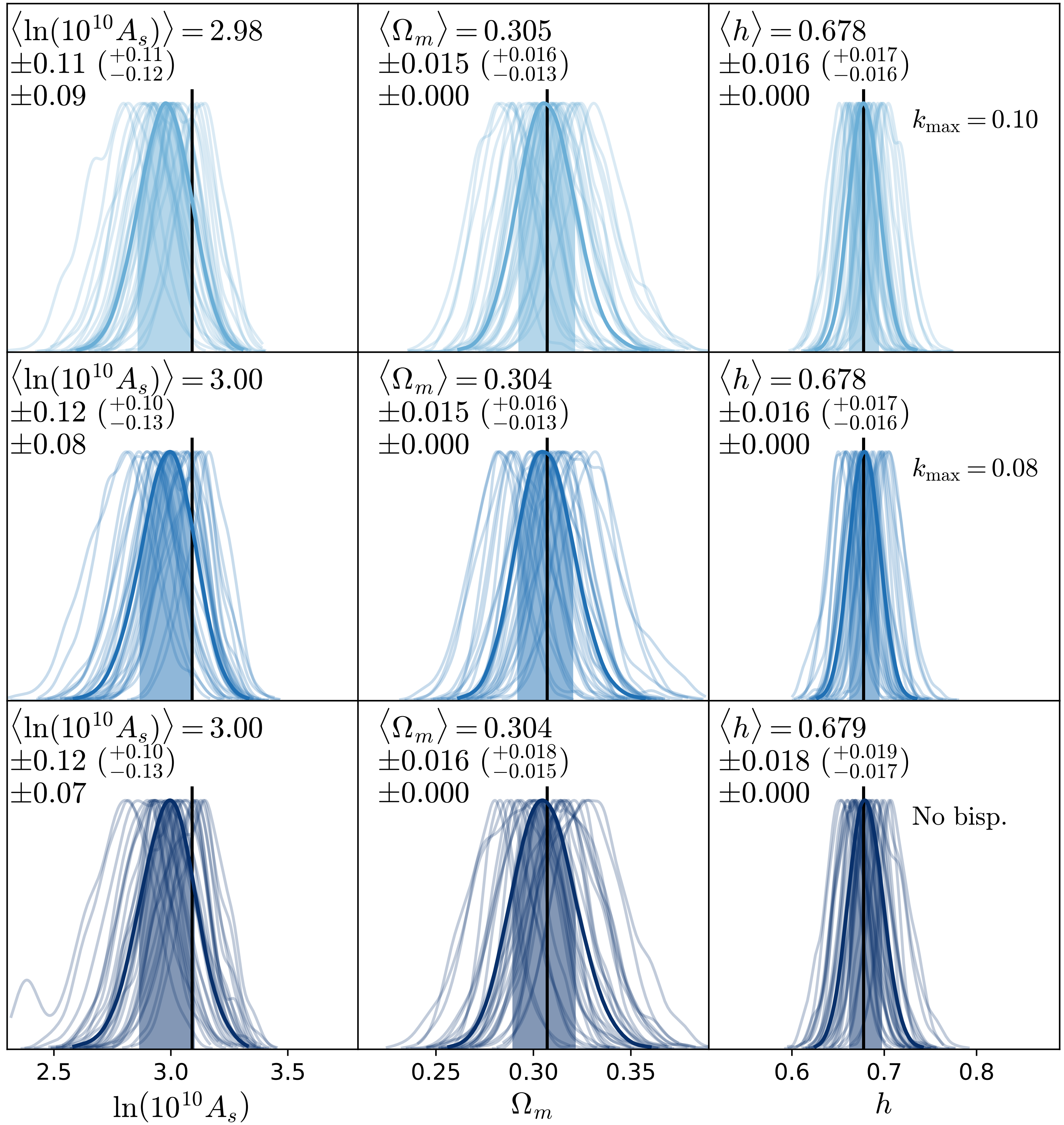
$\Delta h \sim 16\%.$

- No systematic error detected

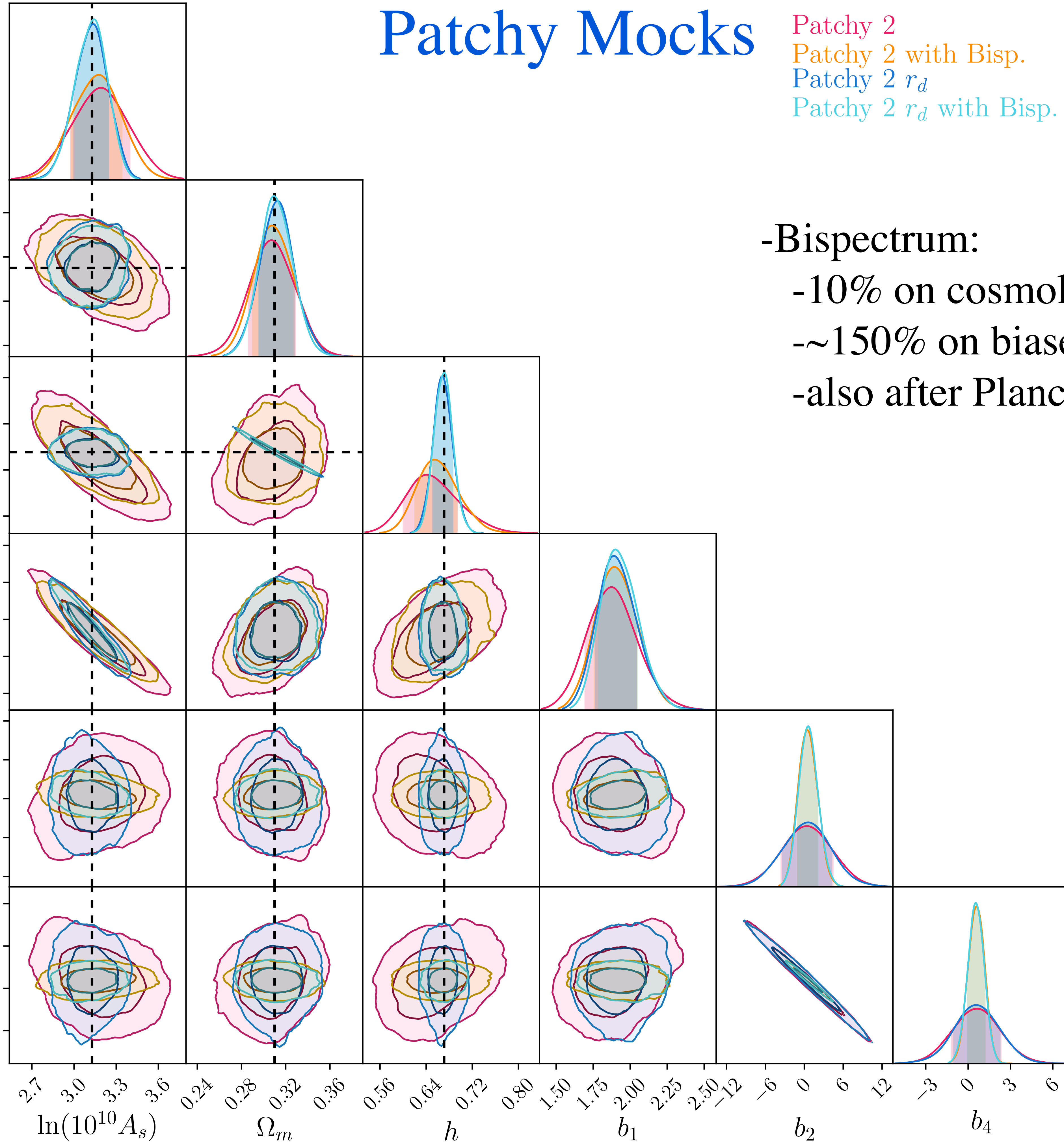


Challenge Box +Bispectrum monopole+Plank's horizon

- ~same story
- slight systematic in A_s
- but due to quality of Mocks



Patchy Mocks



-Bispectrum:
- -10% on cosmological parameter
- -~150% on biases (galaxy formation)
- -also after Planck's horizon prior

Summary of Simulations

- ~Small error bars, breaking of degeneracies, no evidence of systematic error up to $k_{\max} = 0.3\, h\,\mathrm{Mpc}^{-1}$

- Theoretically and data consistent

	$\ln(10^{10}A_s)$		Ω_m		h	
	σ_{stat}	σ_{sys}	σ_{stat}	σ_{sys}	σ_{stat}	σ_{sys}
Challenge	0.10	0.00	0.012	0.000	0.029	0.000
Challenge with r_d	0.06	0.00	0.008	0.000	0.009	0.000
Patchy NGC	0.18	0.00	0.019	0.007	0.043	0.018
Patchy NGC with r_d	0.12	0.07	0.016	0.000	0.018	0.000
Patchy NGC with Bisp.	0.15	0.00	0.016	0.006	0.032	0.022
Patchy NGC with Bisp. with r_d	0.11	0.09	0.015	0.000	0.016	0.000

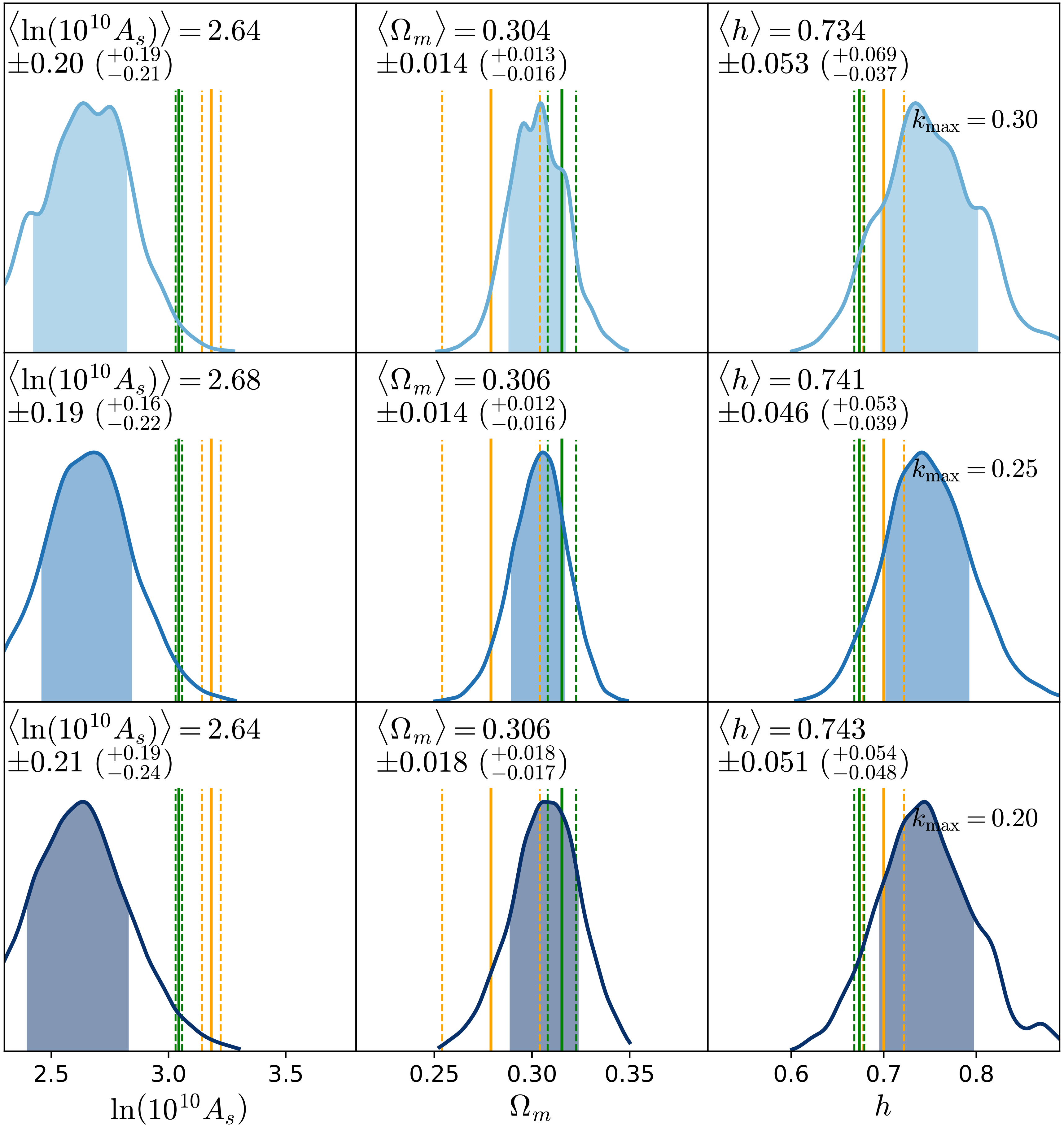
DATA!

BOSS/CMASS NGC sample

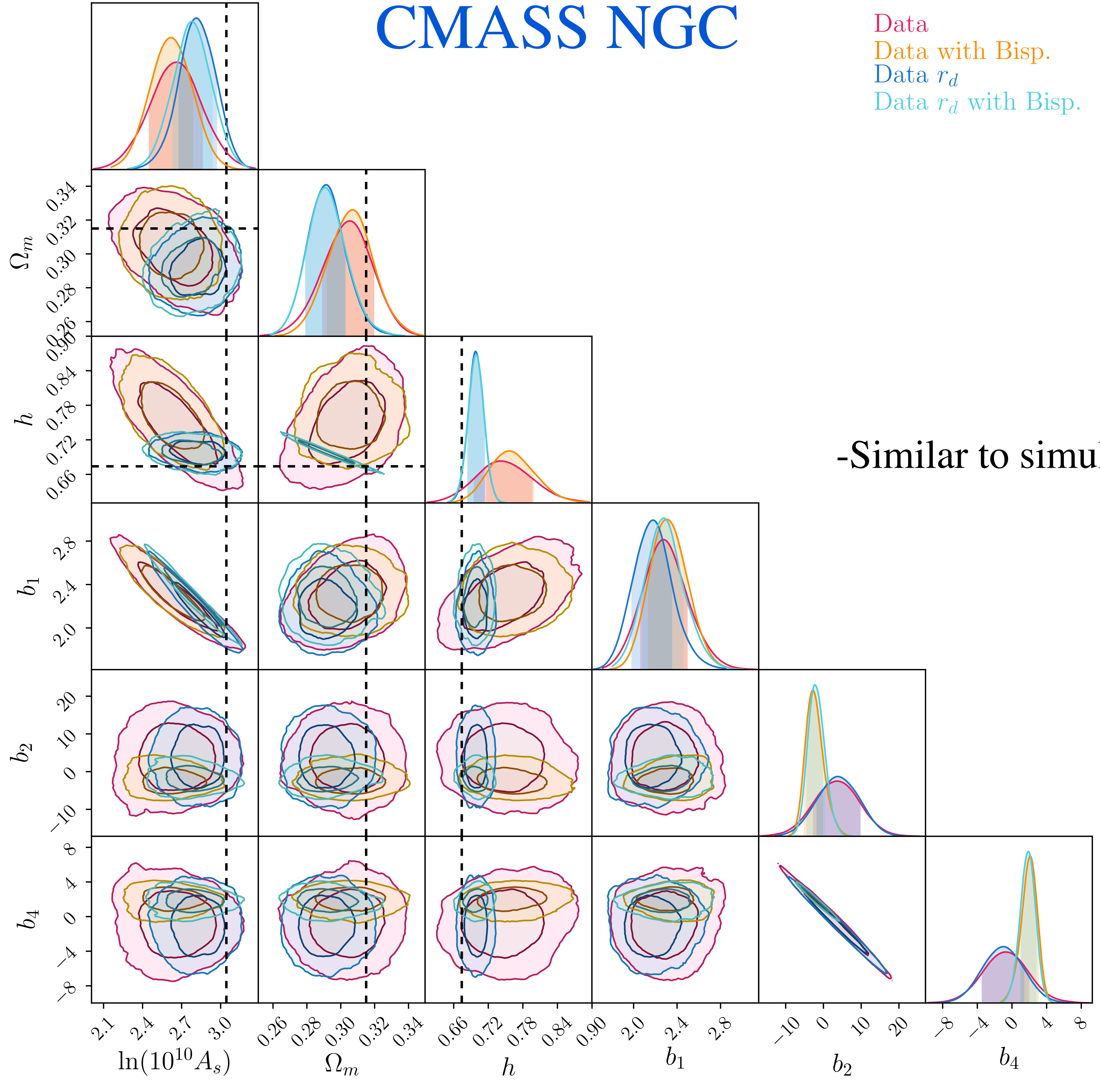
- We measure

$$A_s,\ \Omega_m,\ H_0,\ b_1$$
$$(\leftrightarrow \quad \sigma_8,\ f,\ H_0, b_1)$$

- $k_{\max} = 0.3\, h\,\mathrm{Mpc}^{-1}$ appears a bit problematic on data, we focus on $k_{\max} = 0.25\, h\,\mathrm{Mpc}^{-1}$
- to $19\%, 5\%, 6\%$
- Adding bispectrum improves by ~10%
- from SDSS alone



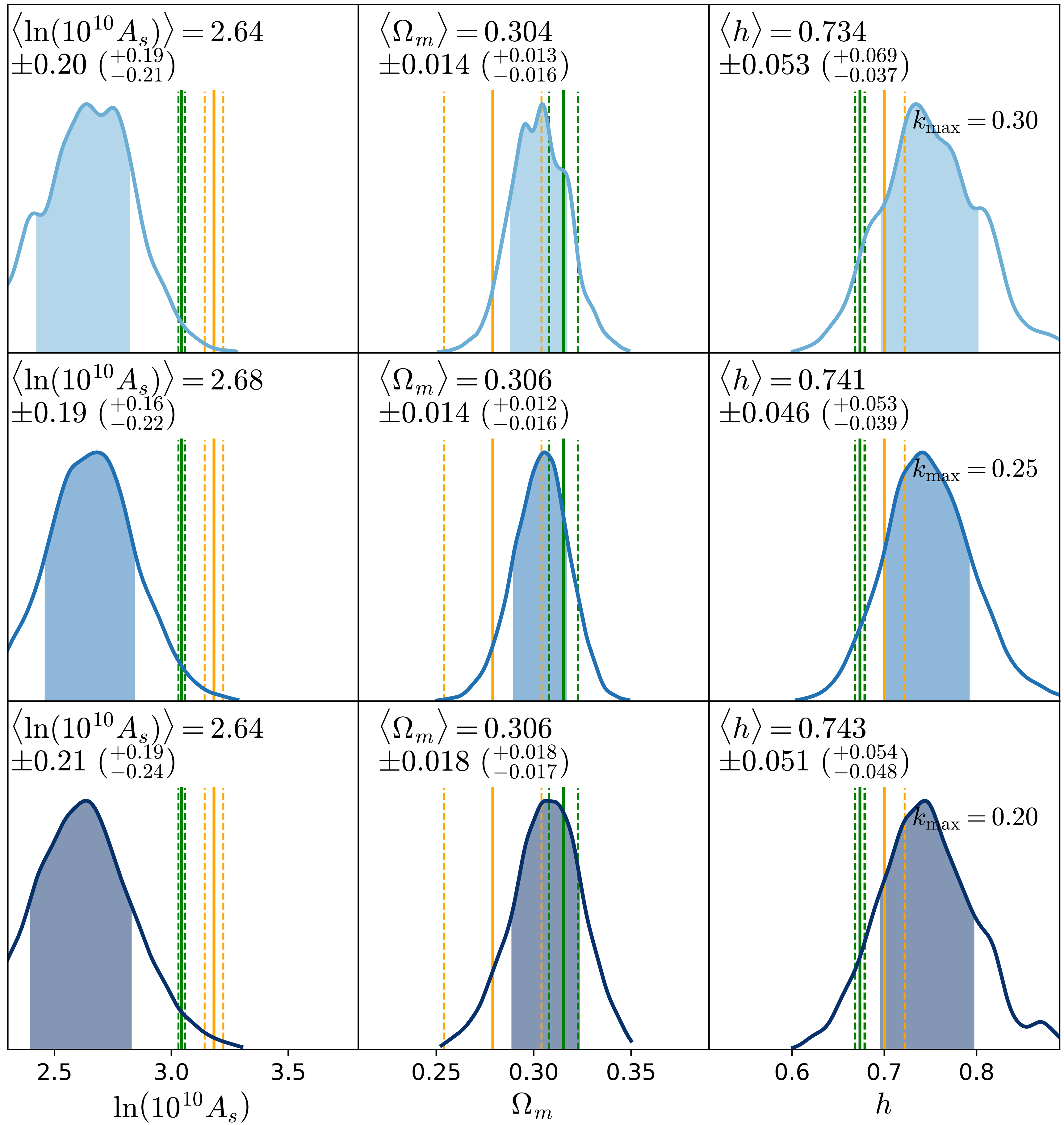
CMASS NGC



-Similar to simulations

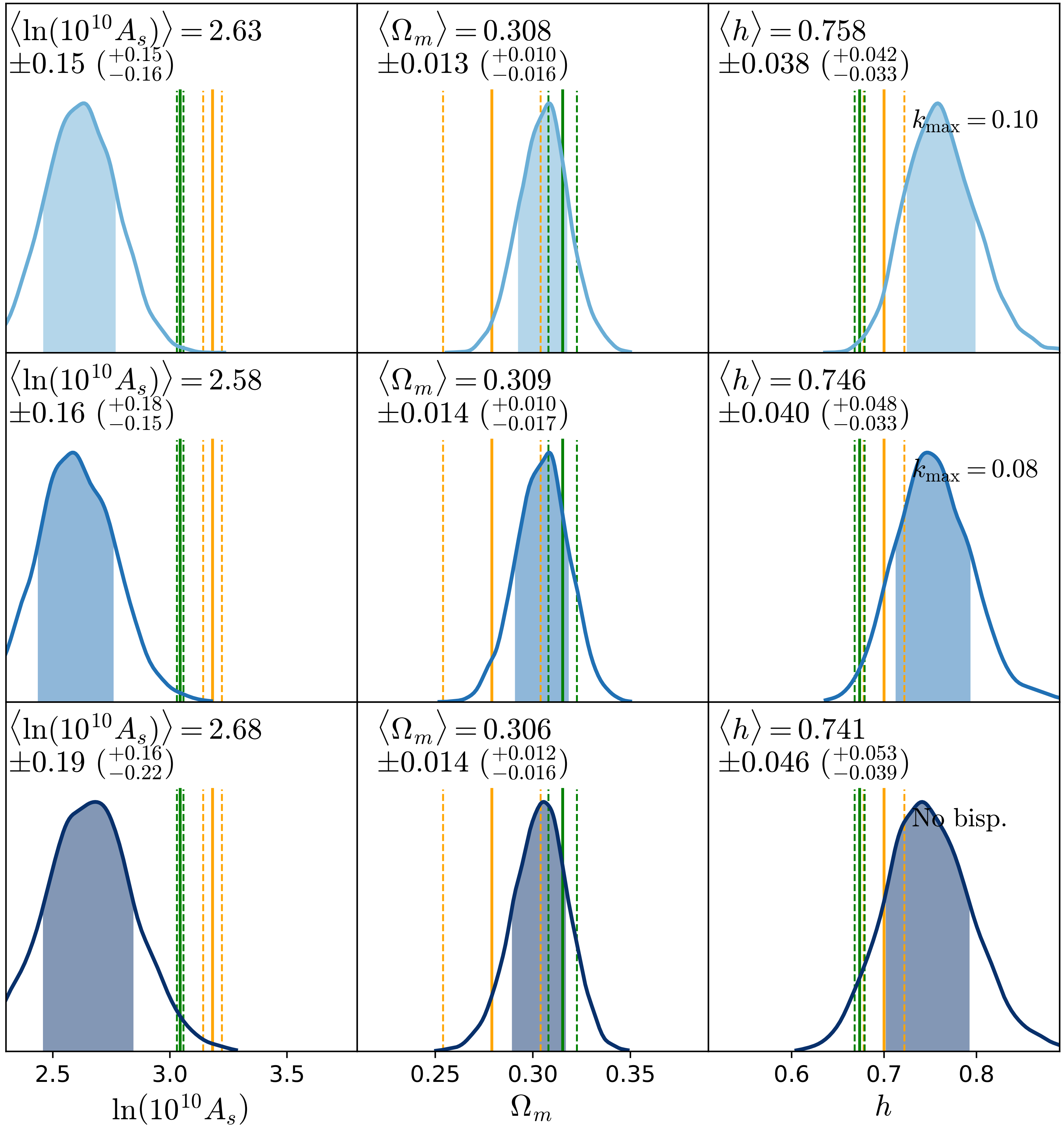
BOSS/CMASS NGC sample

- Green is Planck2018
- Yellow is WMAP9yr
- Inferior to Planck2018, but not so much to Planck2013
- Compared to WMAP9yr, we are better in Ω_m and comparable in h !
- This analysis could have been done long time ago
- LSS can be very powerful



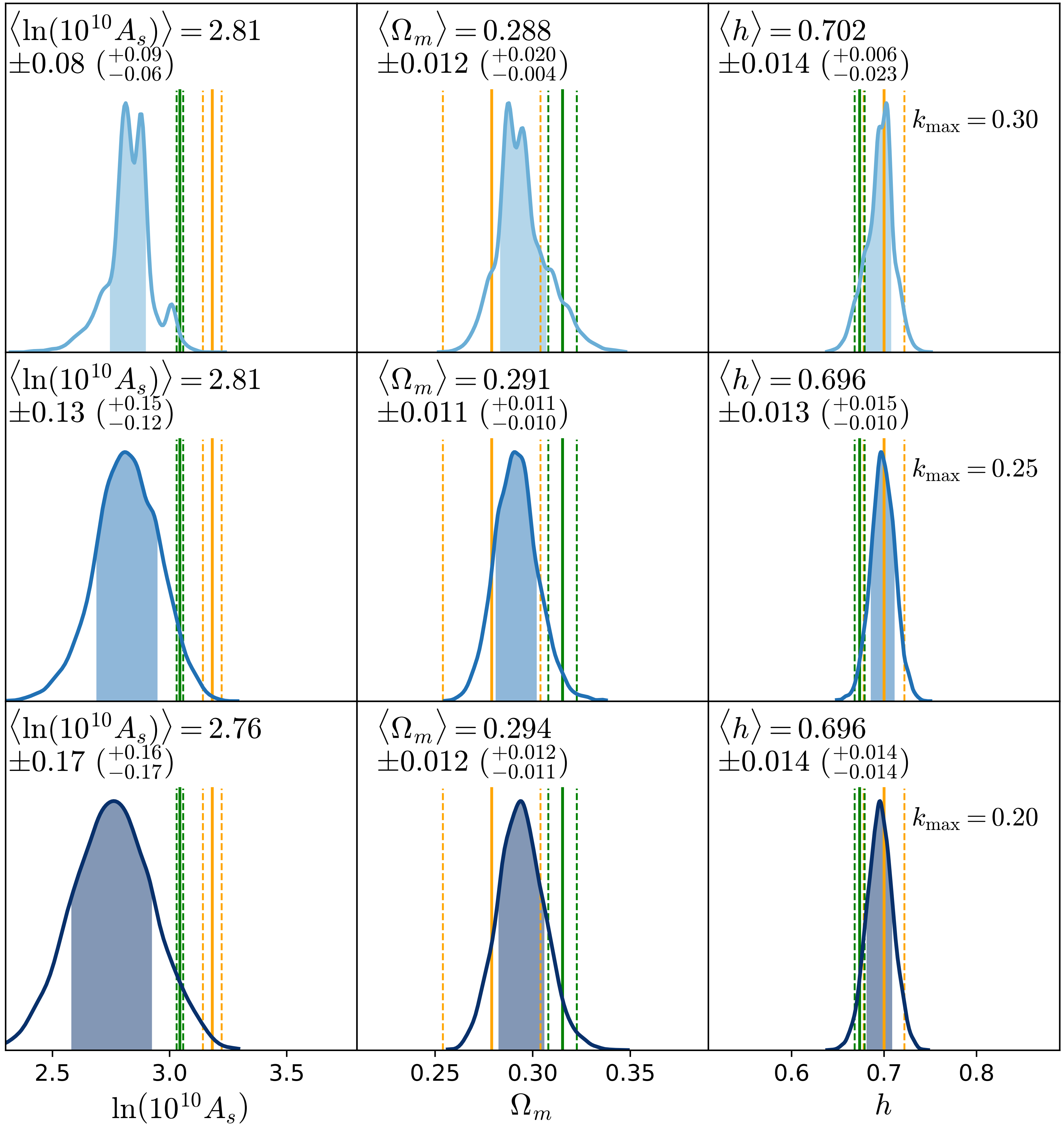
CMASS NGC + Bispectrum Mon

- quite as in sims



CMASS NGC + Planck's horizon

- quite as in sims



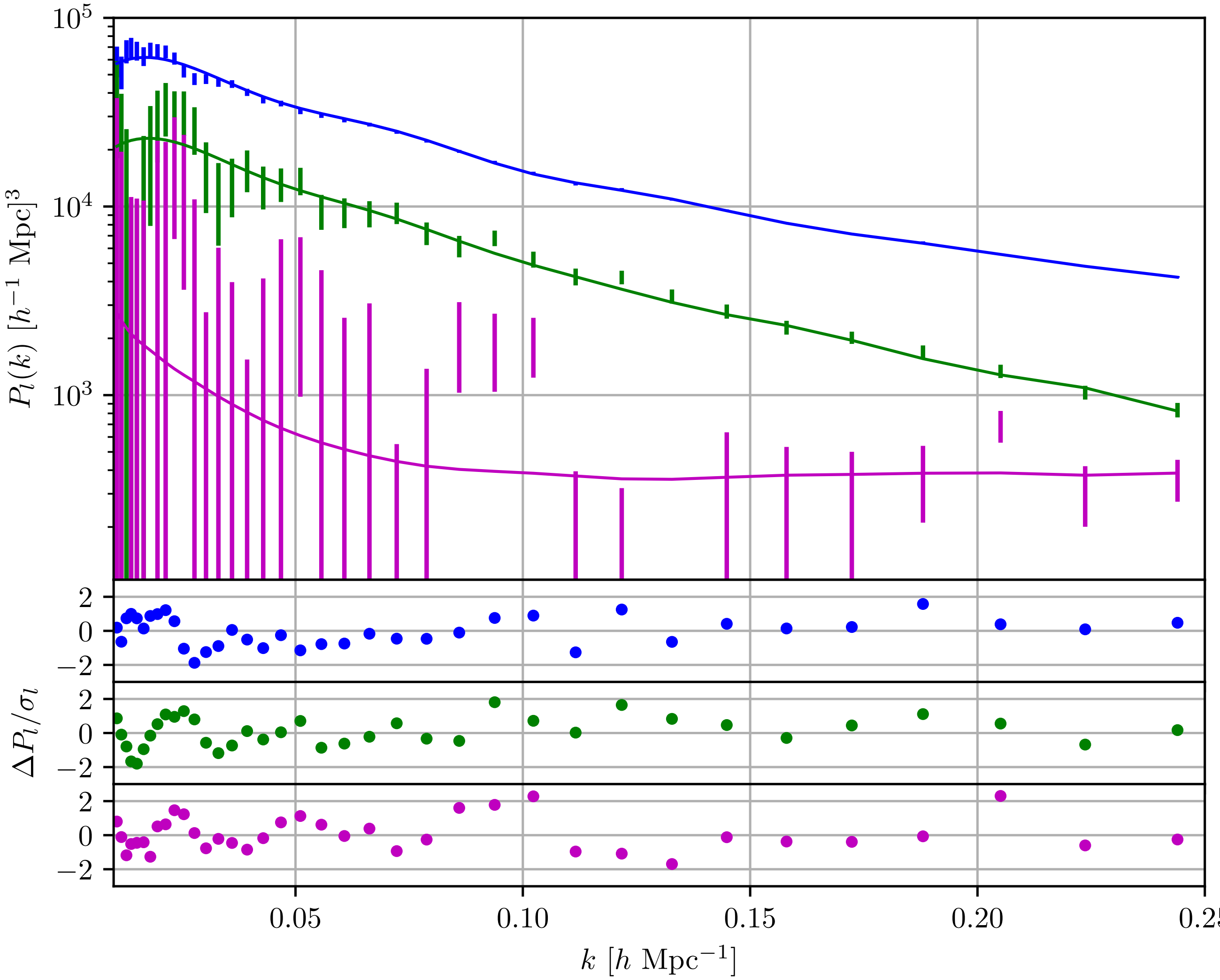
Data Best Fit

- Best fit model:

	$\ln(10^{10}A_s)$	Ω_m	h	min χ^2/d.o.f.	p-value
CMASS NGC	2.70	0.308	0.742	106/(111-11)	0.32
CMASS NGC + Bisp.	2.68	0.309	0.747	133/(111+34-12)	0.48

	b_1	b_2	b_3	b_4	$c_{\rm ct}$	$c_{r,1}$	$c_{r,2}$	$10 \times c_{\epsilon,1}$	$10 \times c_{\epsilon,4}$
CMASS NGC	2.3	3.1	3.2	-1.0	0.0	-9.2	0.5	0.0	-
CMASS NGC + Bisp.	2.3	-2.8	5.3	4.3	1.0	-12.2	0.7	0.0	0.9

- Data Consistency
    - good p-value
    - nothing major
    - similar to Patchy

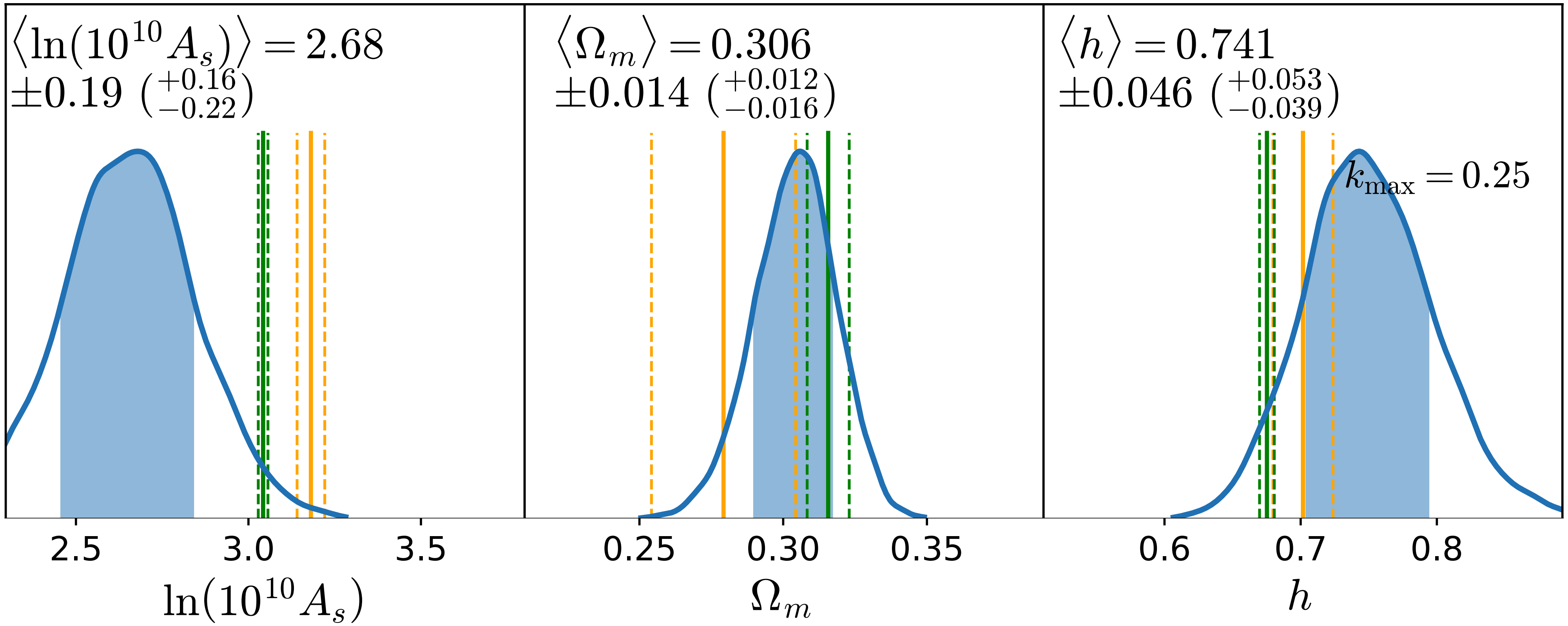


Summary of Error bars

	$\ln(10^{10}A_s)$	Ω_m	h
CMASS NGC	$2.68 \pm 0.19\,\left(^{+0.16}_{-0.22}\right)$	$0.306 \pm 0.014\,\left(^{+0.012}_{-0.016}\right)$	$0.741 \pm 0.046\,\left(^{+0.053}_{-0.039}\right)$
CMASS NGC with r_d	$2.81 \pm 0.13\,\left(^{+0.15}_{-0.12}\right)$	$0.291 \pm 0.011\,\left(^{+0.011}_{-0.010}\right)$	$0.696 \pm 0.013\,\left(^{+0.015}_{-0.010}\right)$
CMASS NGC with Bisp.	$2.58 \pm 0.16\,\left(^{+0.18}_{-0.15}\right)$	$0.309 \pm 0.014\,\left(^{+0.010}_{-0.017}\right)$	$0.746 \pm 0.040\,\left(^{+0.048}_{-0.033}\right)$
CMASS NGC with Bisp. with r_d	$2.74 \pm 0.14\,\left(^{+0.15}_{-0.13}\right)$	$0.291 \pm 0.011\,\left(^{+0.011}_{-0.010}\right)$	$0.699 \pm 0.013\,\left(^{+0.012}_{-0.013}\right)$

- all data sets consistent and good (also as we change $k_{\rm max}$).
- $f\sigma_8 = 0.42\,\left(^{+0.033}_{-0.021}\right)$ is about 36% better than the SDSS collaboration Beutler *et al*. **2016**
    - but we did not use the SGC, so, just counting volume, we expect to be 50% better
    - plus, we measure all parameters

Tension with Planck



• Mild tension with Planck, ameliorated by inclusion of Plank's sound's horizon

	p-value of Planck 1σ value			effective σ-deviation of Planck 1σ value		
	$\ln(10^{10}A_s)$	Ω_m	h	$\ln(10^{10}A_s)$	Ω_m	h
CMASS NGC	0.12	0.84	0.20	1.6	0.2	1.3
CMASS NGC with r_d	0.11	0.11	0.20	1.6	1.6	1.3
CMASS NGC with Bisp.	0.01	0.95	0.04	2.6	0.1	2.1
CMASS NGC with Bisp. with r_d	0.06	0.16	0.13	1.9	1.4	1.5

• Of course, community should re-check the observational systematics.

Linear Theory

- It is highly biased even at $k_{\max} = 0.1 h/\mathrm{Mpc}$
- It has much larger error bars
- Does not break degeneracies

What is next?

- These results suggest we can extract much more cosmological and galactic information from LSS
- For the EFTofLSS community:
  - Use some priors from sims on our parameters.
  - Higher order calculations.
  - of course, extend analyses to beyond $\Lambda\mathrm{CDM}$
- From community:
  - Very important: measure higher $n-\mathrm{point}$ functions.
  - Get trustable priors from numerical simulations
  - Go back to observational systematic errors.
  - Hopefully we can team up with specialists, and do it for all experiments (eBOSS, DES, DESI, Euclid,LSST, ...)

Summary

- After a long theoretical development, the EFTofLSS is being applied to LSS data, in this case the SDSS.
- It seems that there can be a major qualitative and quantitive improvement on the way we use LSS data.
- To me, the opportunity is great, the importance of doing this is utmost, and there is lots of work to do for lots of people