Probing solutions to the S8 tension with galaxy clustering

Pedro Carrilho

Based on **2207.13011, 2207.14784** and ongoing work
with
Alkistis Pourtsidou, Chiara Moretti, Maria Tsedrik

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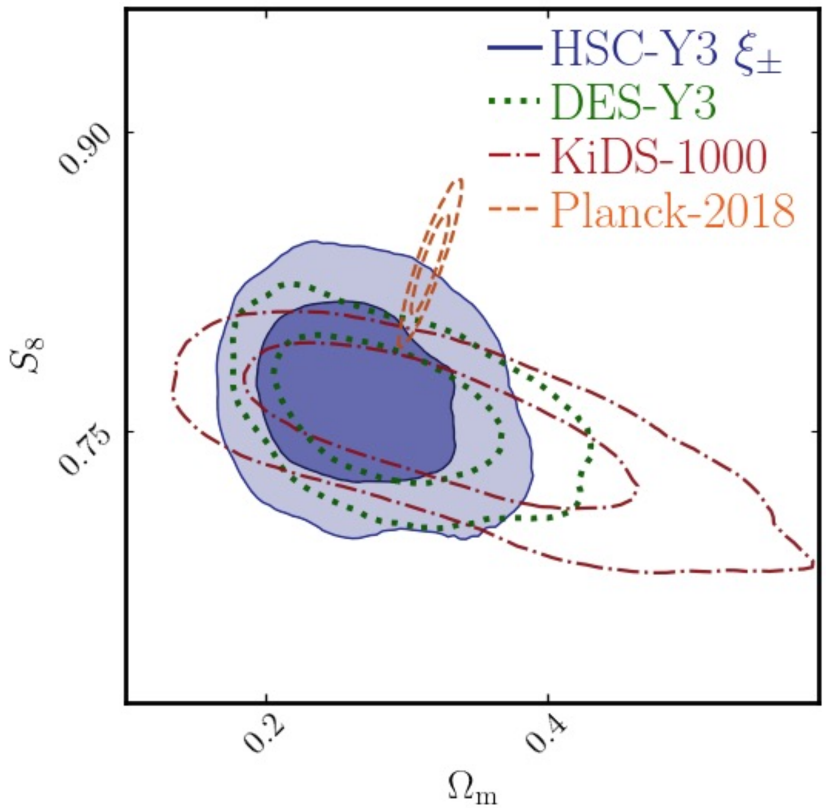
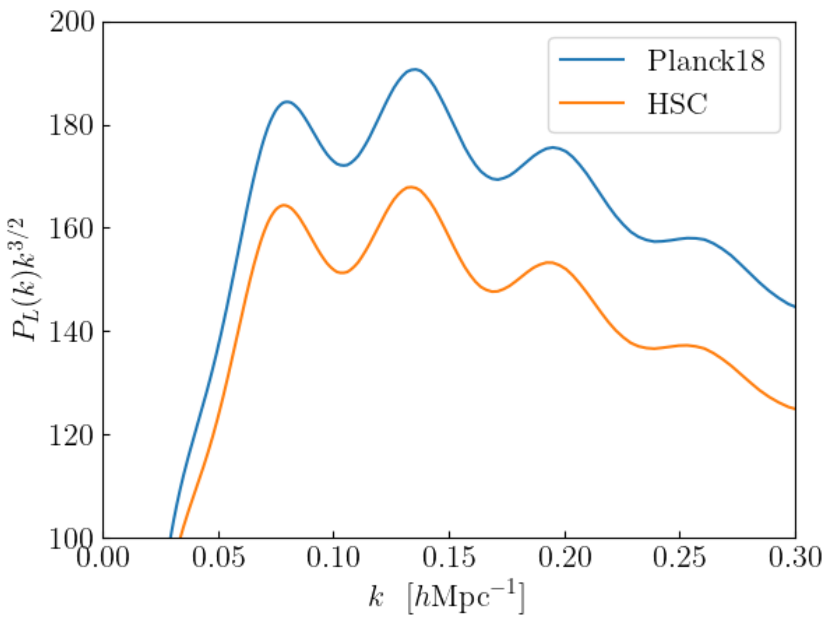
The troubles of the Universe

A possible crack in ΛCDM: $\boldsymbol{S_8}$ tension between WL and CMB

HSC Y3, Li et al 2023





$$S_8 = \sigma_8 \sqrt{\Omega_M/0.3} \qquad \sigma_8 \sim \int P_L(k)$$

- Do all probes of LSS see a low amplitude? Ex: spectroscopic clustering
- What could explain this tension?

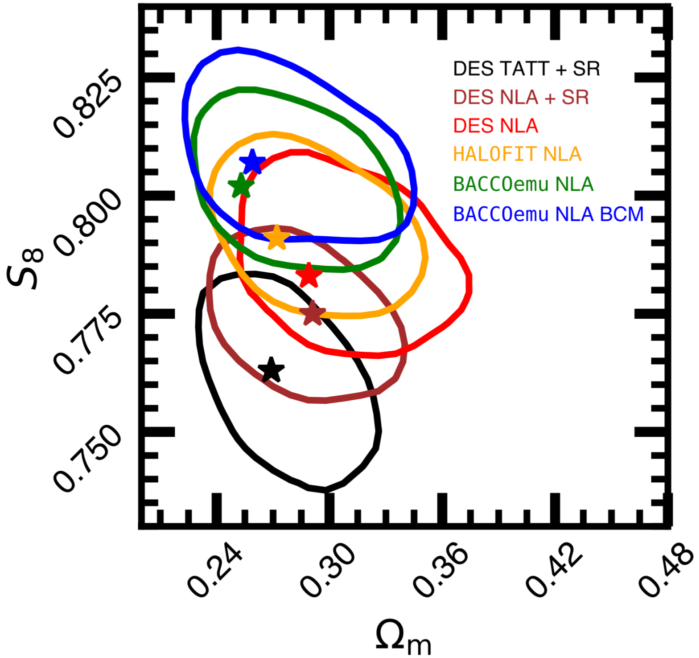
Solving the troubles

What can solve the S_8 tension?

More accurate data

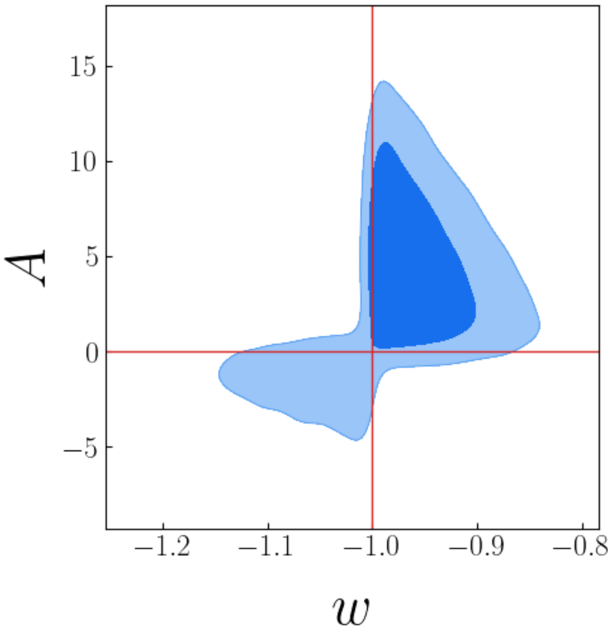
Euclid
(launching in July)

Alternative nonlinear modelling



[Aricò et al 2023]

New physics



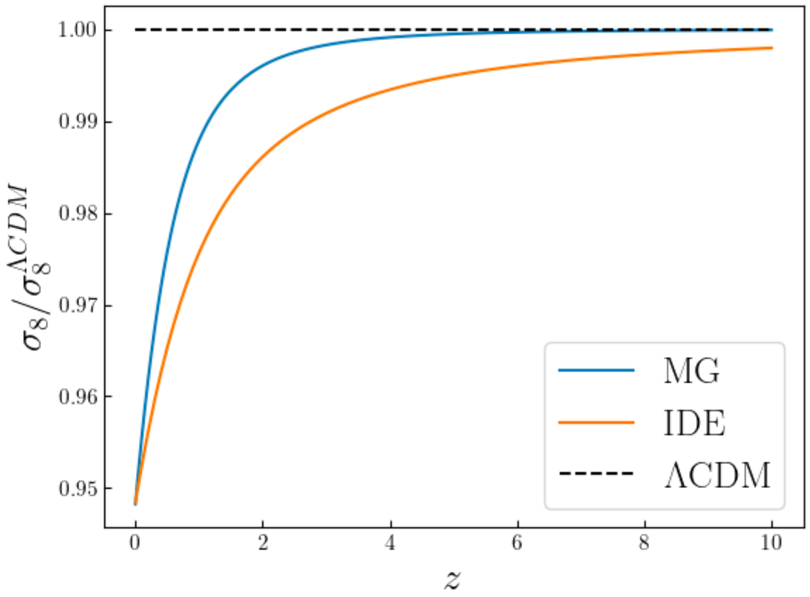
Solving the troubles

What new physics can solve the S_8 tension?

- Anything that suppresses lensing:
  - Modified gravity with η (or μ, Σ)

See talks by Camille Bonvin (Monday) and Agnès Ferté (Thursday)

- Anything that suppresses growth:
  - Friction from DM-DE interaction
  - Weaker gravity at late time



- How to test if these options work?
  - Use spectroscopic clustering and also measure the growth rate

$$f = \frac{d \log \sigma_8}{d \log a}$$

We use BOSS data!

Solving the troubles

Dark energy – dark matter momentum-exchange interaction

- We focus on the **Dark Scattering** model (wACDM): [Simpson 2010]

$$\theta \equiv \nabla \cdot \vec{v} \qquad \boxed{\theta_{\rm DM}' + (\mathcal{H} + \boldsymbol{A\, a\, \rho_{DE}})\theta_{\rm DM} + \nabla^2\phi = 0} \qquad A \equiv (1+w)\frac{\sigma_D}{m_{\rm DM}}$$

- Interaction acts as **additional friction**, generating **scale-indep. growth**

Modified Gravity

- General idea is to weaken gravity at late time

$$\nabla^2\phi = \frac{3}{2}\mathcal{H}^2\Omega_M\, \boldsymbol{\mu(z)}\, \delta$$

- We use the general gamma parametrisation: [Linder & Cahn 2007]

$$\boxed{f = {\Omega_M}^{\gamma}} \qquad \Lambda\text{CDM: } \gamma = 0.545$$

Our work

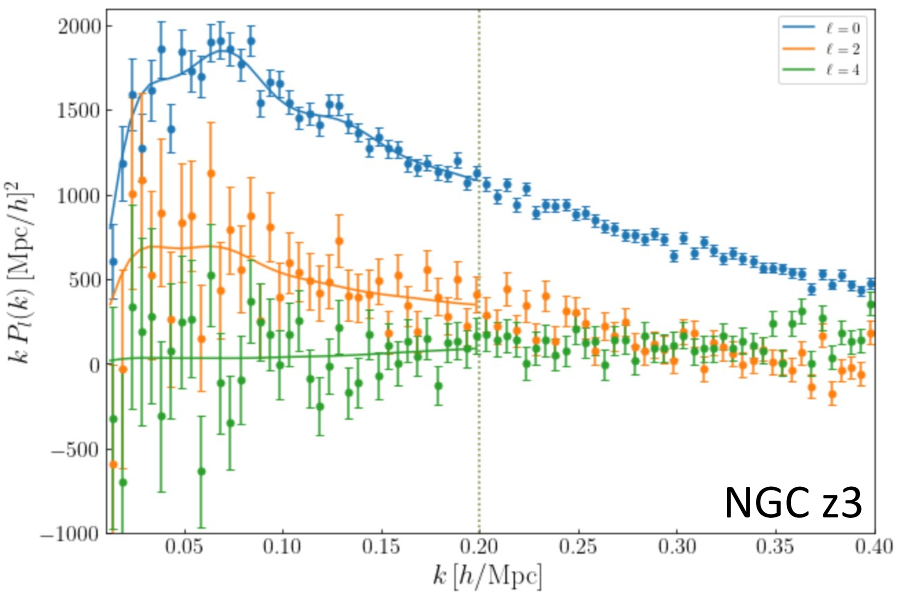
- We perform a full shape analysis of **BOSS DR12 power spectrum** data
- We use the most general **EFTofLSS** model for nonlinearities
- We show likelihood analyses for 3 different models
  - ΛCDM, Dark Scattering (wACDM) and gamma MG ($\gamma\Lambda$CDM) with massive νs
- We evaluate the importance of **priors** of nuisance parameters
- We perform forecasts for stage IV surveys

BOSS analysis - the data

- BOSS power spectrum multipoles:
  - Two redshift bins: $z_1 = 0.38$, $z_3 = 0.61$
  - Two skies: NGC and SGC
  - All multipoles up to $k_{max} = 0.2\ h/Mpc$

- BAO scale measurements:
  - Multiple redshifts:
    $z = (0.106, 0.15, 0.61, 2.334)$

- BBN prior on baryon density:
  - $100\omega_b = 2.268 \pm 0.038$



- Some cases have 3σ Planck prior:
  - $\log 10^{10} A_s = 3.044 \pm 0.042$
  - $n_s = 0.9649 \pm 0.012$

BOSS analysis - perturbative modelling

- For spectro. clustering, we use models based on perturbation theory
- Three ingredients for galaxy clustering:
  - Modelling the matter density and velocity fields: $\boldsymbol{\delta} = \frac{\delta\rho}{\rho}$, $\boldsymbol{\theta} = \nabla \cdot \vec{\boldsymbol{v}}$
  - Converting from real space to redshift space: $\boldsymbol{\delta_s}[\boldsymbol{\delta}, \boldsymbol{\theta}]$
  - Relating the galaxy field with the matter field: $\boldsymbol{\delta_g}[\boldsymbol{\delta_s}]$
- We use a 1-loop **EFTofLSS** model, the CLASS-PT model:

  [Ivanov et al 2020, Chudaykin et al 2020, Philcox & Ivanov 2022]
  - **4 bias + 3 stoch. params. + 4 counter-terms = 11 x 4 = 44 nuisance parameters**
  - Baseline priors set according to CLASS-PT prescription

BOSS analysis - ΛCDM results

- **CMB-free case**
  - Low amplitude

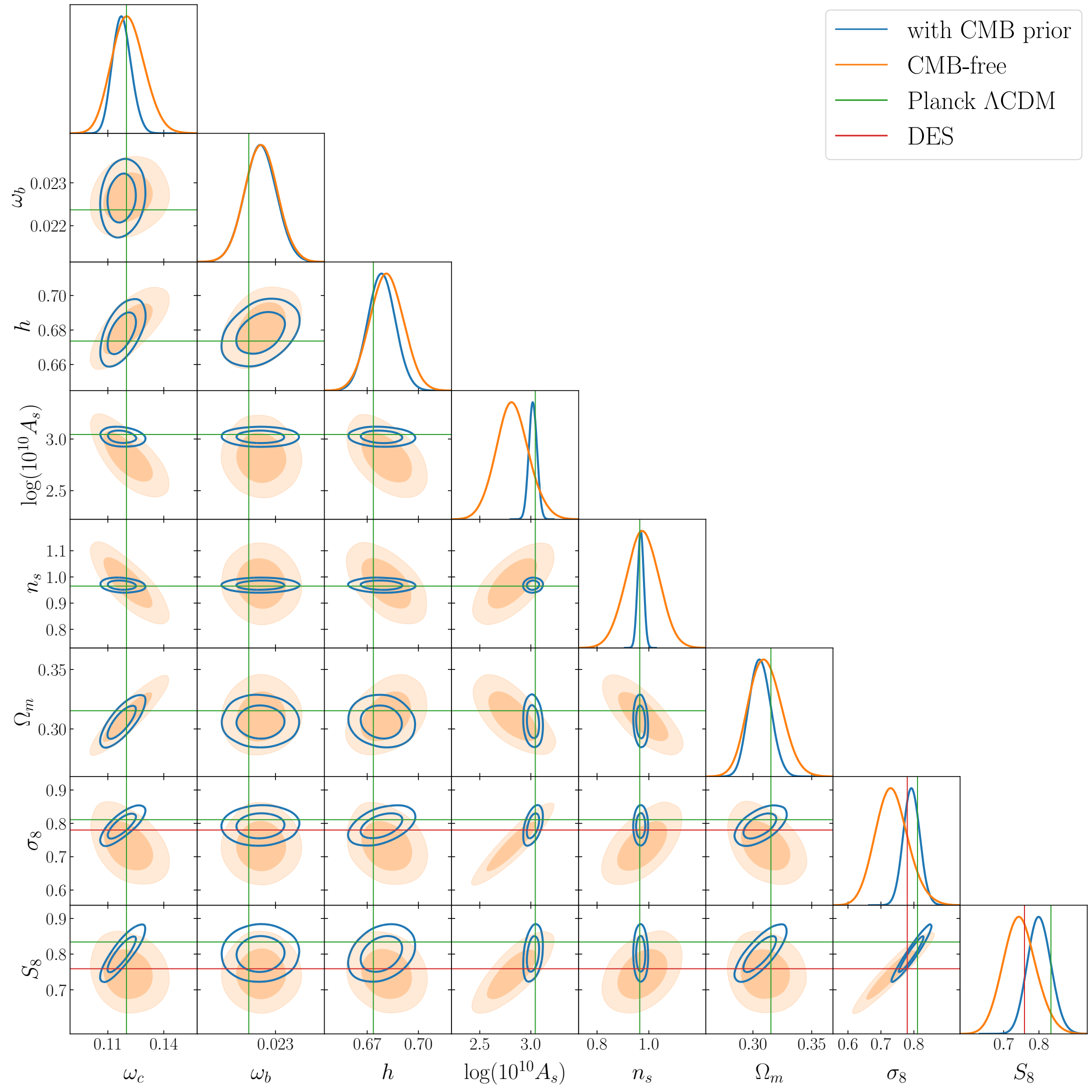
$$\log 10^{10} A_s = 2.821 \pm 0.158$$

$$S_8 = 0.746^{+0.044}_{-0.049}$$

  - Otherwise agrees with Planck

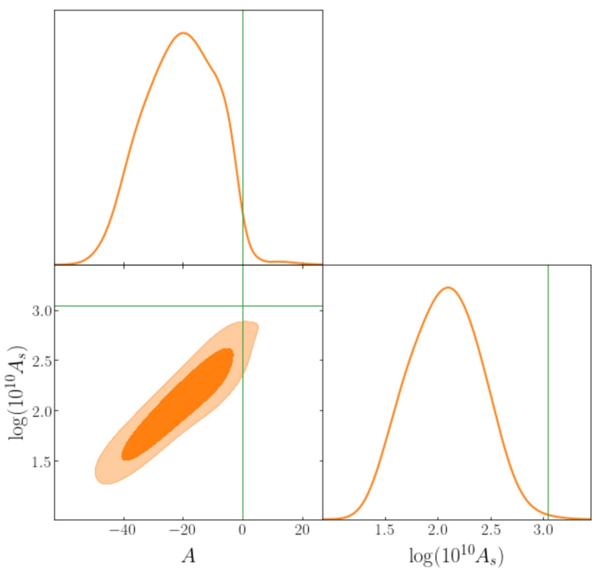
$$h = 0.681 \pm 0.010$$

- **CMB prior on A_s and n_s**
  - Agreement with Planck

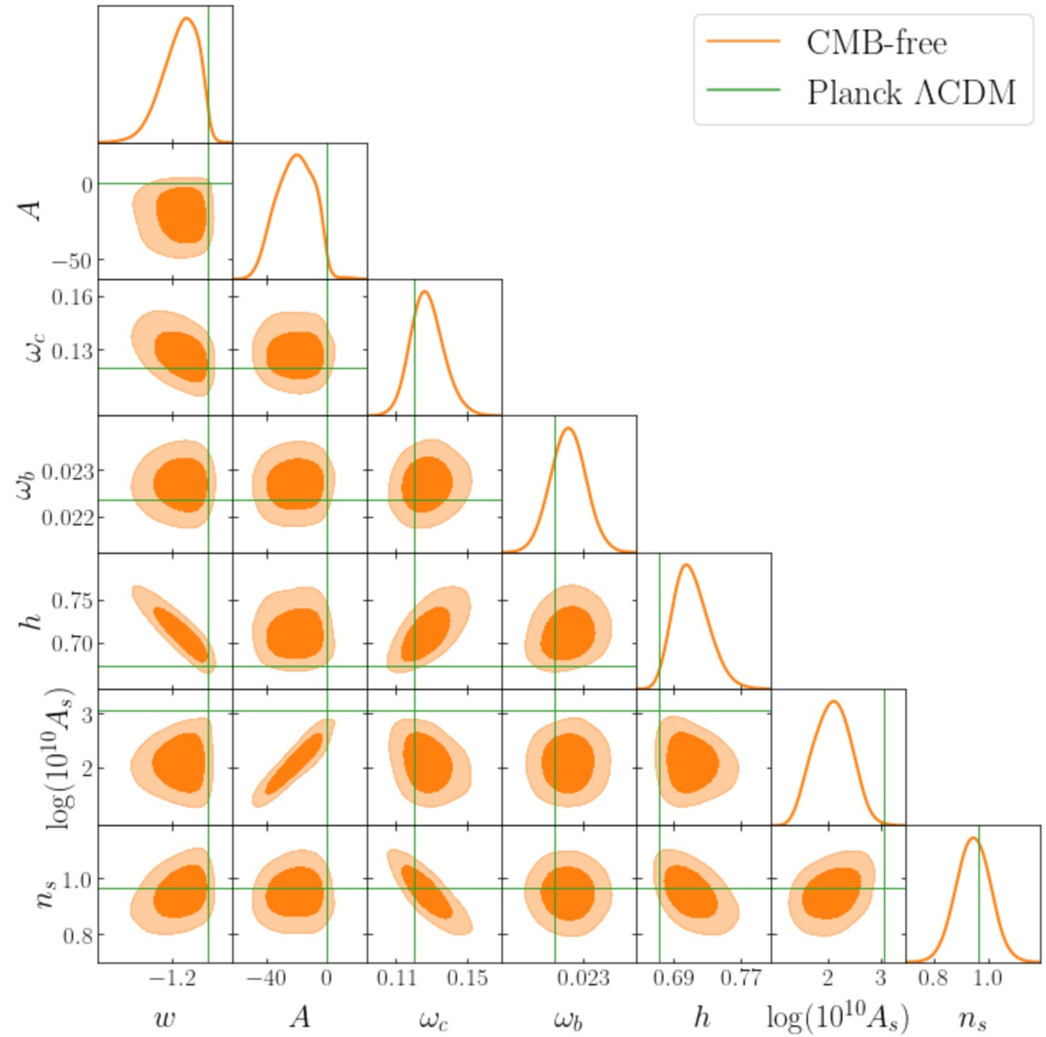


BOSS analysis - wACDM Results

- **CMB-free case**
  - Interaction brings degeneracies
  - Strong degeneracy in A_s, A, b_1



  - Cannot constrain interaction



BOSS analysis - wACDM Results

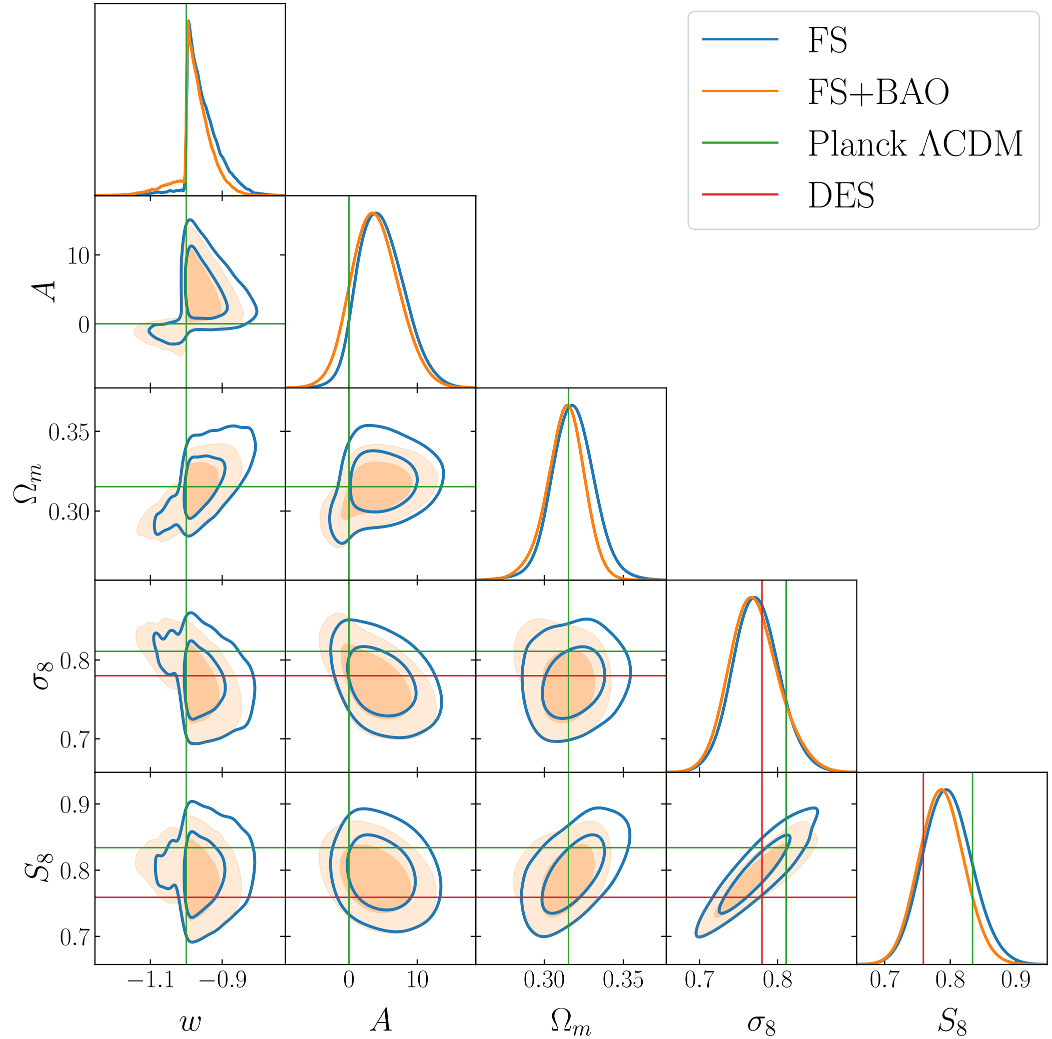
- **CMB prior on A_s and n_s**
  - Preference for $A > 0$ @ 1σ

    $$w = -0.972^{+0.036}_{-0.029}$$

    $$A = 3.9^{+3.2}_{-3.7}\ b/\mathrm{GeV}$$

    $$S_8 = 0.787 \pm 0.034$$

  - Agreement with Planck
  - Agreement with lensing σ_8
  - **Concordance restored!**



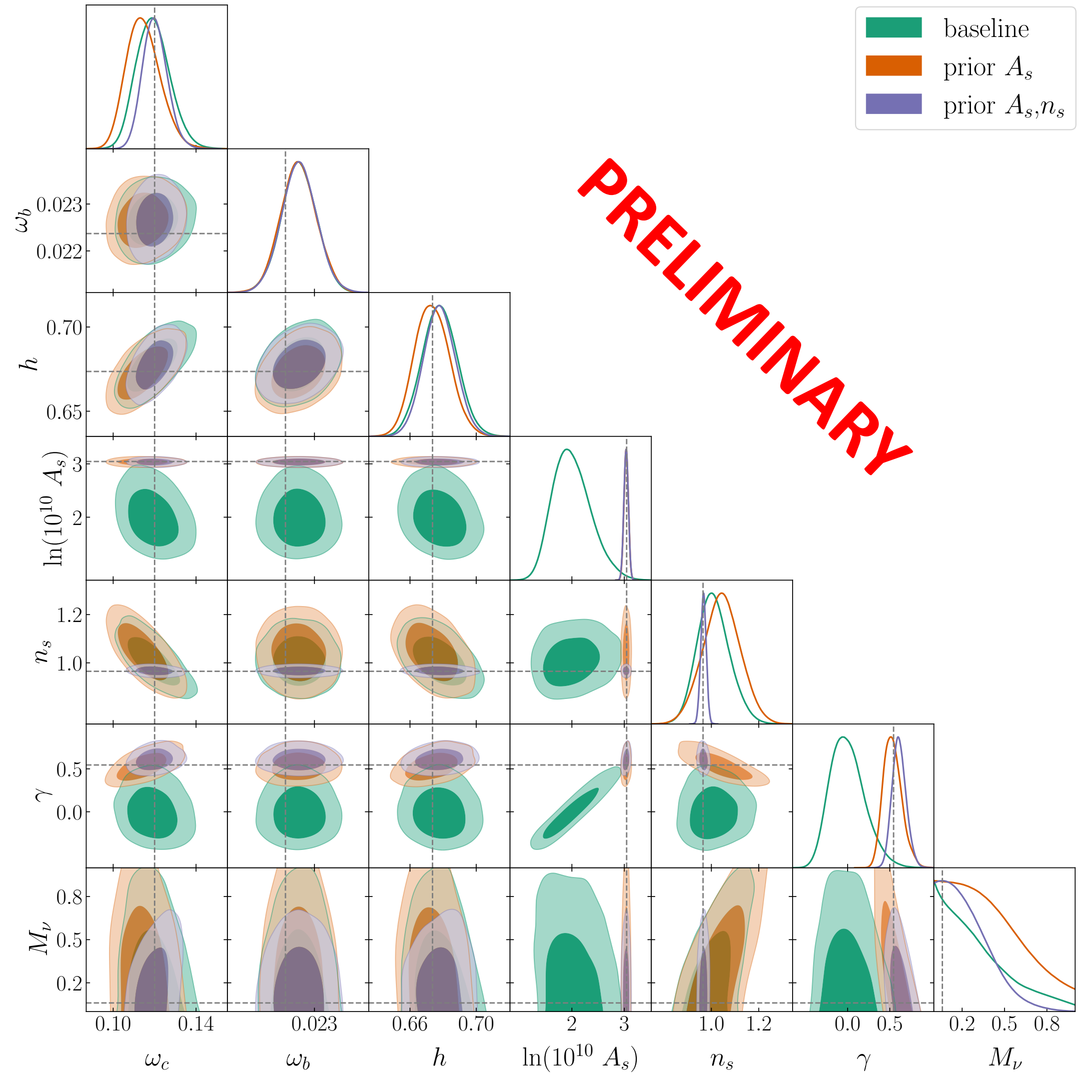
BOSS analysis - $\gamma\Lambda$CDM + massive ν Results

- **CMB-free case**
  - Same thing happens with γ
  - Reason is a **projection effect**
- **CMB prior on A_s and n_s**
  - Hint for high γ:

    $$\gamma = 0.612^{+0.75}_{-0.90}$$

  - Constraint on neutrino mass:

    $$\sum m_\nu < 0.3$$



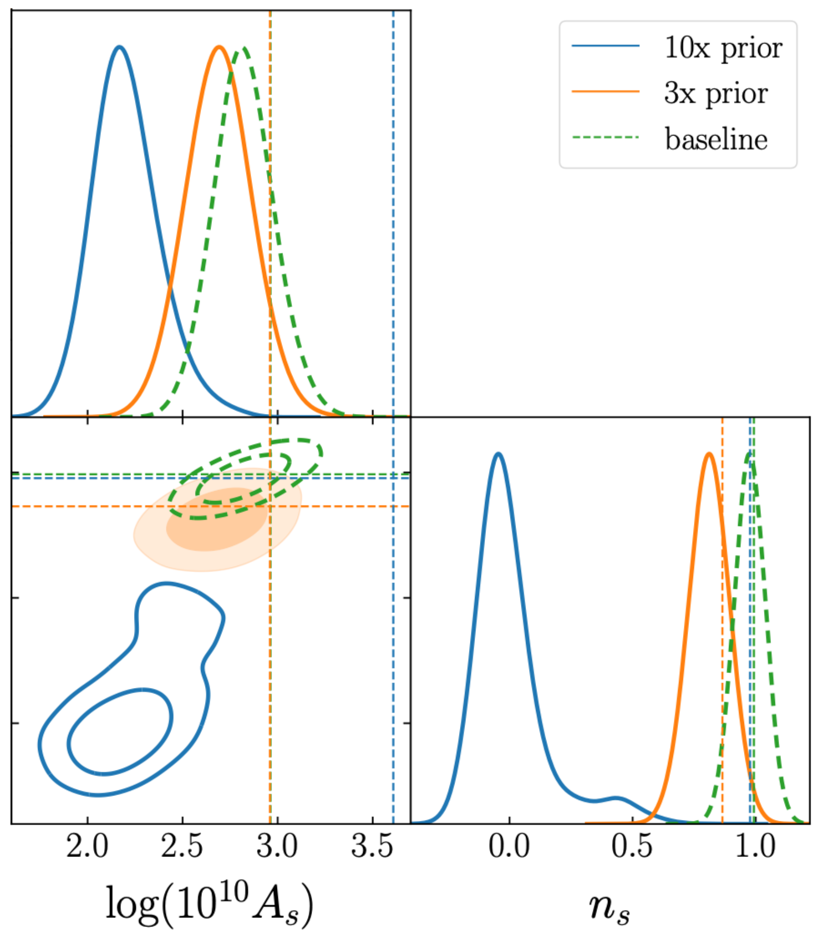
BOSS analysis - Dependence on priors

- But, there is a problem:
  - **Results depend on priors!**
- Why?
  - Huge non-Gaussianity of posteriors
- Large projection effect:

Max. of posterior
$\neq$
Mean

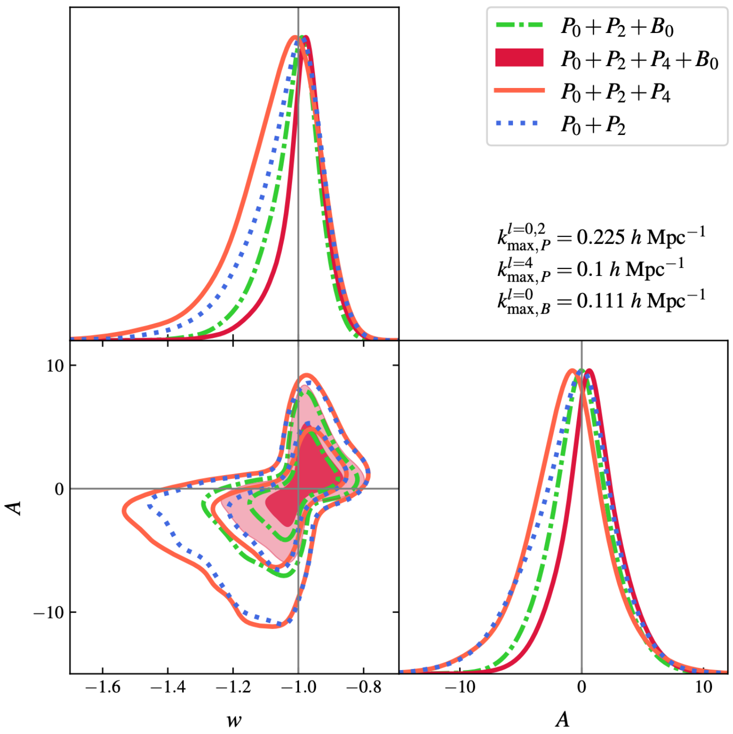
- But possibly not just projection

ΛCDM, CMB-free



Forecasts for stage IV

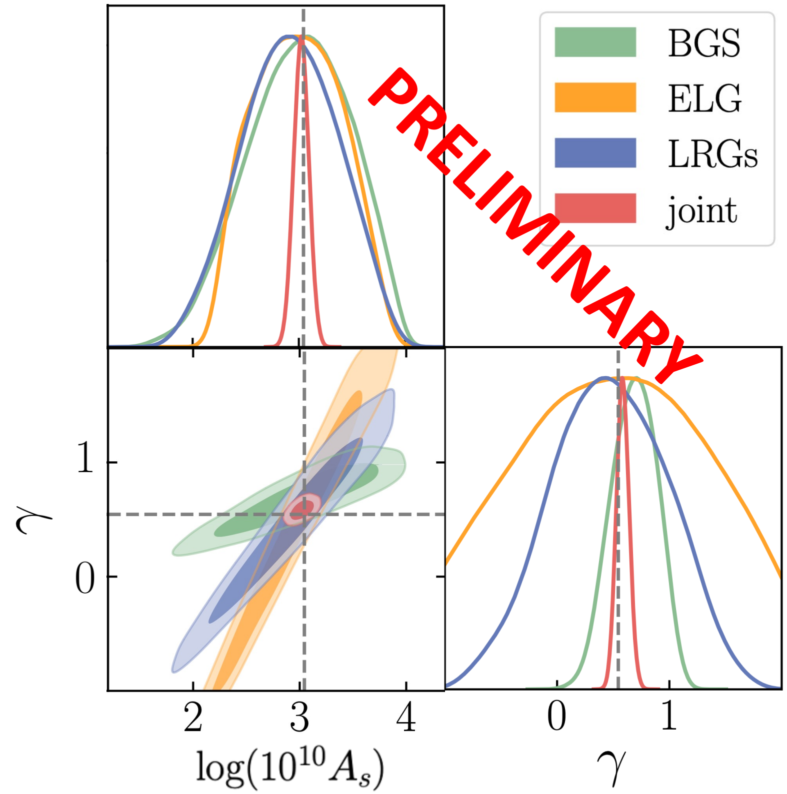
- Analysis with bispectrum



Work by Maria Tsedrik

30% better vs power spectrum only

- More redshifts break degeneracies:



$\boldsymbol{\sigma_\gamma = 0.06}$ without CMB info

- Stage IV will also improve prior effects, but more work needed!

Summary

- Several models can rectify S_8 tension
- The analyses of BOSS shows:
  - Concordance can be re-established within $w\Lambda$CDM or γCDM, and we find

$$w = -0.972^{+0.036}_{-0.029}\,, \qquad A = 3.9^{+3.2}_{-3.7}\, b/\mathrm{GeV}\,;$$

$$\gamma = 0.612^{+0.75}_{-0.90}$$

  - However, we see that **priors are informative** and change results!
- Stage IV forecasts show improvements with the bispectrum and with multi-z analyses.
- Future work:
  - Build emulator for analysis with lensing (with K. Carrion based on arxiv:2111.13598)
  - Perform further tests of the importance of priors, also for stage IV

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Extra slides

Interacting Dark energy

Unless some principle forbids it, dark energy could interact

$$\nabla_\mu T^{\mu\nu}_{\mathrm{DE}} = Q^\nu, \quad \nabla_\mu T^{\mu\nu}_{\mathrm{DM}} = -Q^\nu$$

- Here, we focus on **momentum-exchange** only:

$$\boldsymbol{Q^\nu \perp u^\nu}$$

- **Feature:** interaction only affects the perturbations.

- We work with the **Dark Scattering** model (wACDM) [Simpson 2010]

$\theta \equiv \nabla \cdot \vec{v}$

$$\theta_{\mathrm{DM}}' + (\mathcal{H} + \boldsymbol{A\, a\, \rho_{DE}})\theta_{\mathrm{DM}} + \nabla^2\phi = 0$$

$A \equiv (1+w)\dfrac{\sigma_D}{m_{\mathrm{DM}}}$

- Interaction acts as **additional friction**, generating **scale-indep. growth**

Power spectrum modelling

- We use a 1-loop EFTofLSS-based model: the so-called CLASS-PT model [Ivanov et al 2020, Chudaykin et al 2020]
  - Bias model

$$\delta_g = \boldsymbol{b_1}\delta_{cb} + \frac{\boldsymbol{b_2}}{2}\delta_{cb}^2 + \boldsymbol{b_{\mathcal{G}_2}}\mathcal{G}_2 + \boldsymbol{b_{\Gamma_3}}\Gamma_3 + \epsilon$$

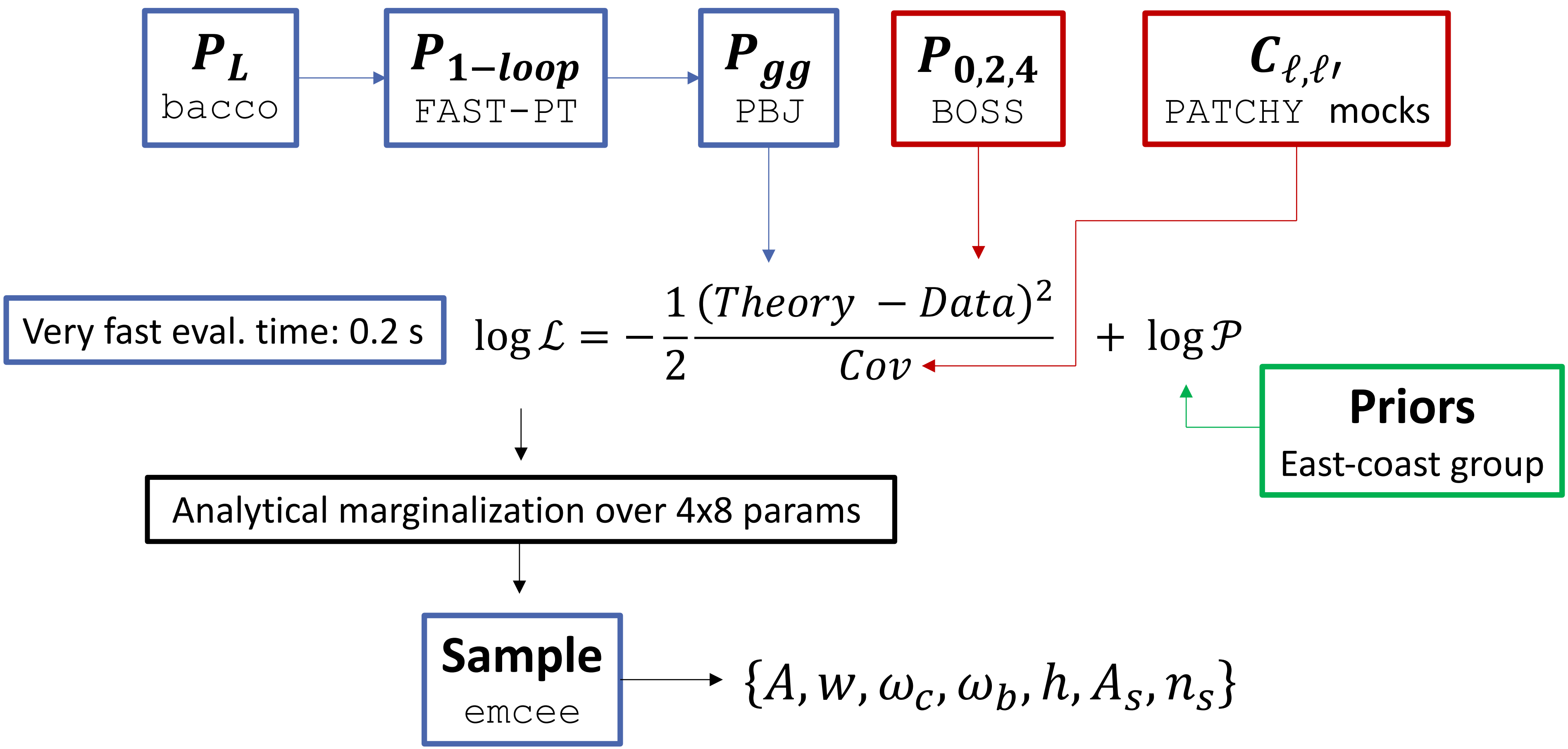
$$P_{\epsilon\epsilon} = \boldsymbol{N} + \boldsymbol{e_0}\, k^2 + \boldsymbol{e_2} k^2\mu^2$$

  - Counter-terms

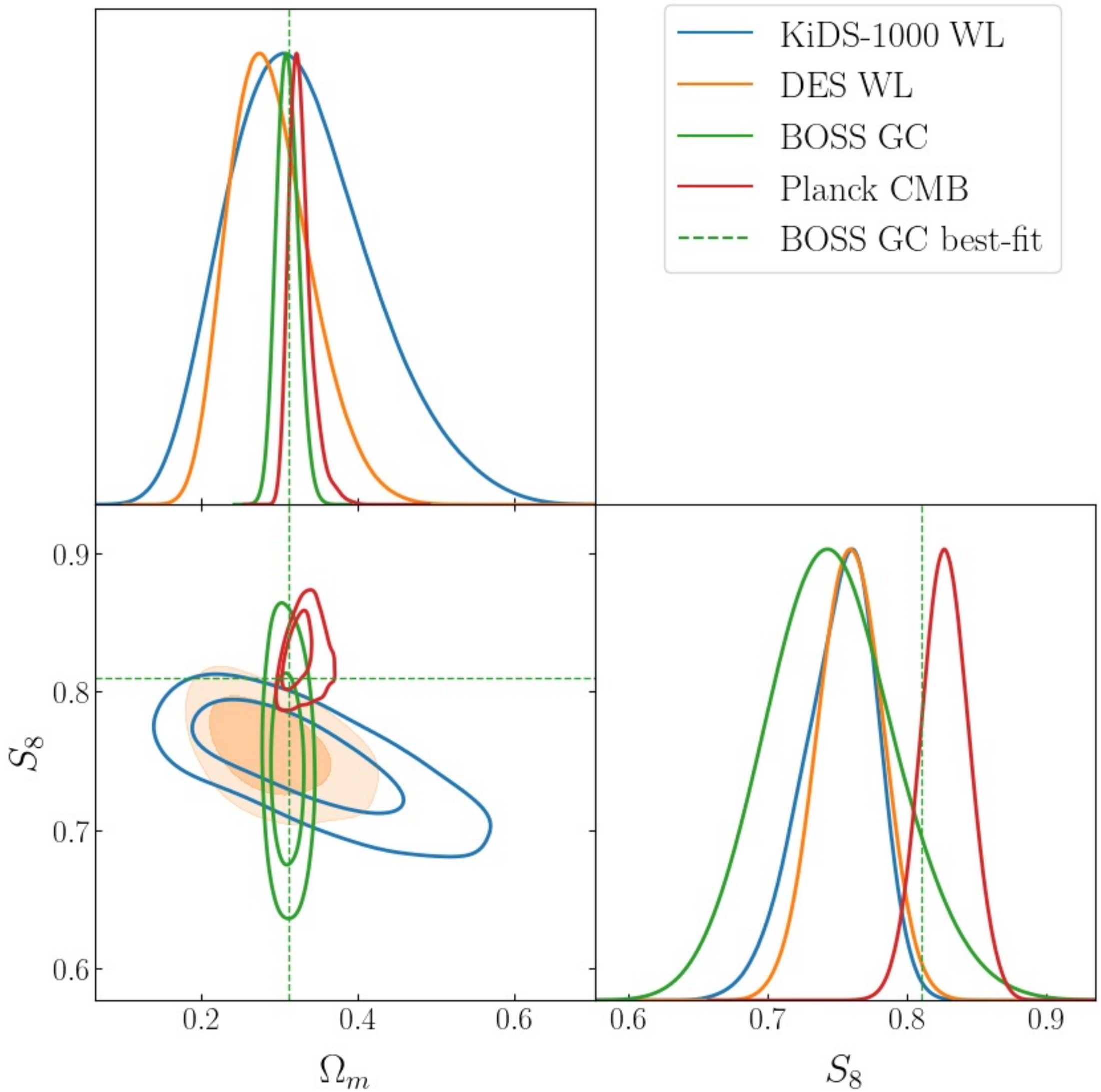
$$P_{\rm ctr}(k,\mu) = -2\, k^2 P_L(k)[\tilde{\boldsymbol{c}}_0 + \tilde{\boldsymbol{c}}_2\, f\mu^2 + \tilde{\boldsymbol{c}}_4\, f^2\mu^4] - \boldsymbol{c_{\nabla^4\delta}}\, f^4\, k^4\mu^4 P_{\rm Kais}(k,\mu)$$

  - Total of 11 nuisance parameters per redshift and sky cut (44 total)
  - **Priors** are set according to CLASS-PT/East Coast prescription

Analysis Set-up



Comparing BOSS vs WL

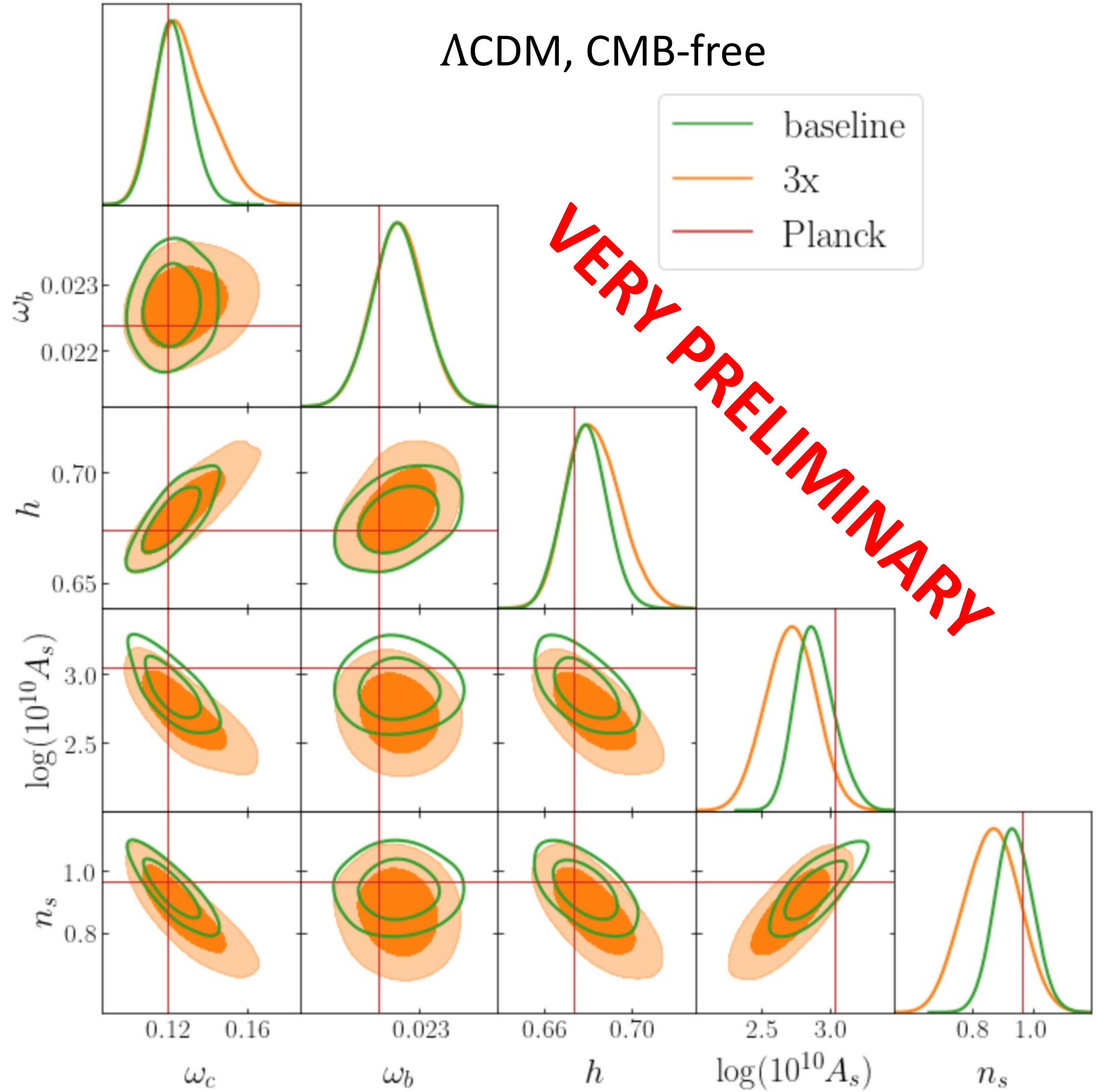


Dependence on priors – Solutions?

- Simulate everything better –> Get improved priors
- Use a simpler model –> ex: TNS or restricted EFTofLSS
- Wait for better data –> Euclid, DESI
- Use different statistics –> Profile posteriors
- Use additional probes –> ex: Bispectrum

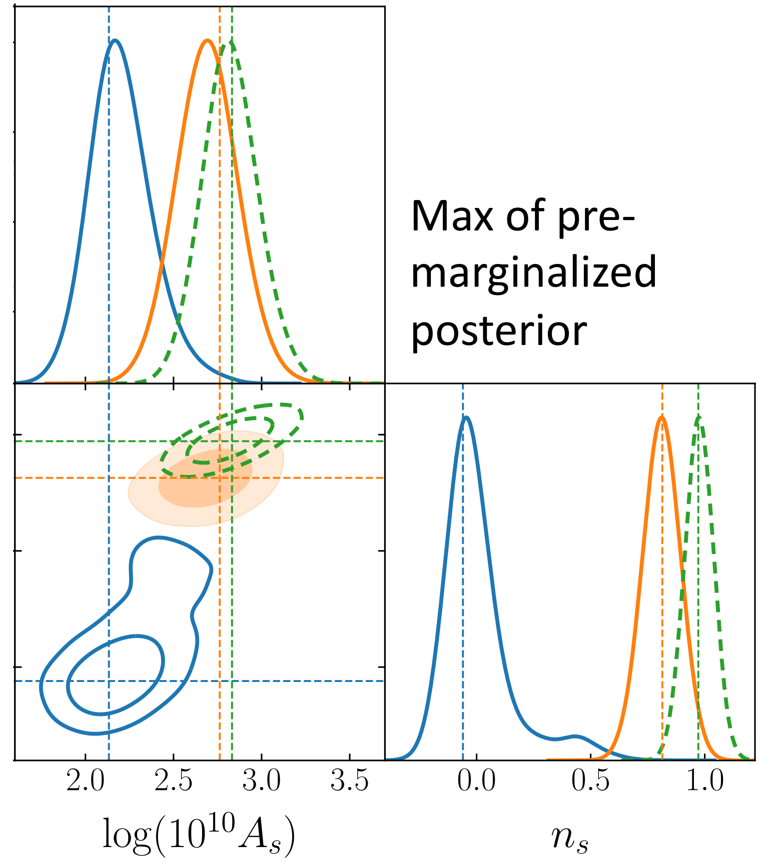
Dependence on priors - new tests

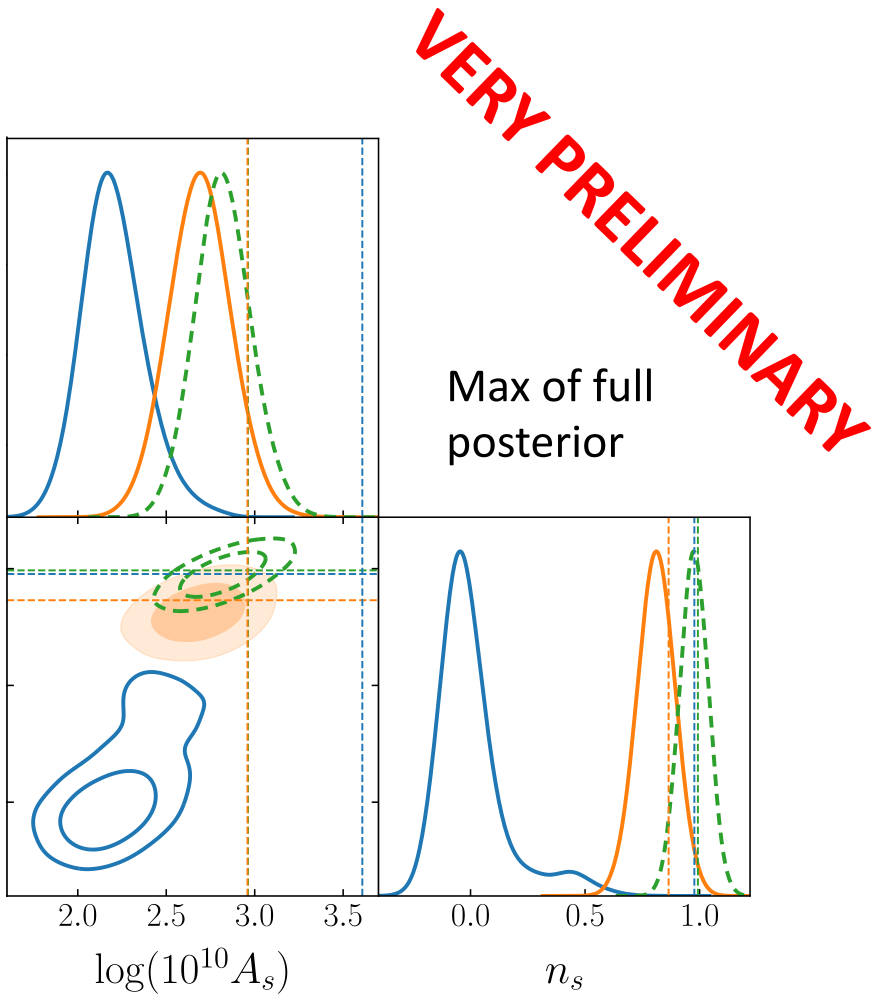
- Test with mock data vector
- Mock data generated with:
  - Planck cosmology
  - Most nuis. at centre of prior
- Similar deviations to real data



Dependence on priors - new tests

- Where is the projection?





- Probably most is from the 32 analytically marginalised parameters

Dependence on priors - new tests

- With and without c_{k^4}