A Primordial Solution to Tensions in Cosmology

Akhil Antony

Discordances in cosmology and the violation of slow-roll inflationary dynamics.

Akhil Antony, Fabio Finelli, Dhiraj Kumar Hazra, Arman Shafieloo

https://arxiv.org/abs/2202.14028

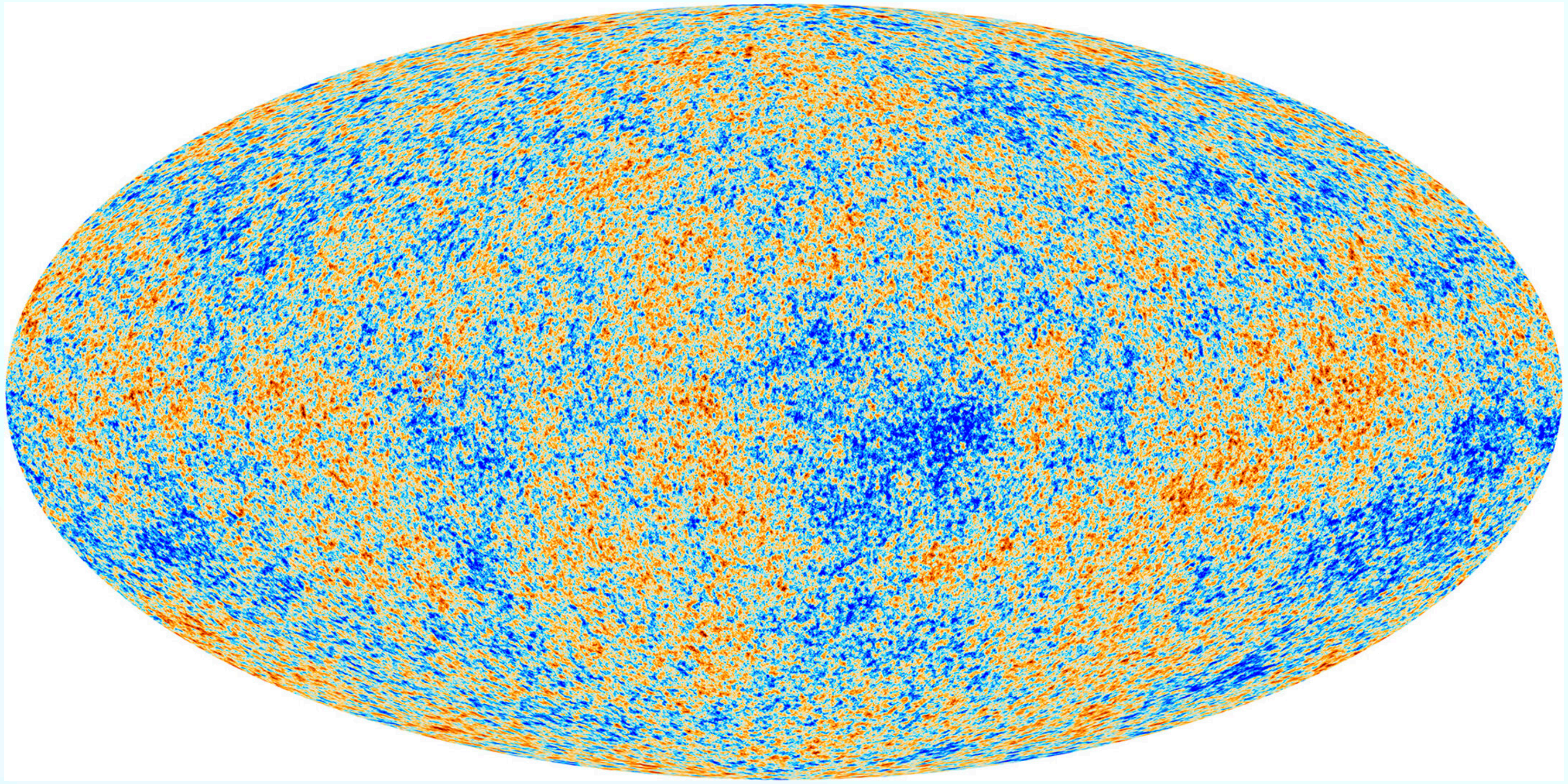
One spectrum to cure them all: Signature from early Universe solves major anomalies and tensions in cosmology.

Dhiraj Kumar Hazra, **Akhil Antony**, Arman Shafieloo

JCAP 08(2022) 063 (https://arxiv.org/abs/2201.12000).

Cosmic Microwave Background

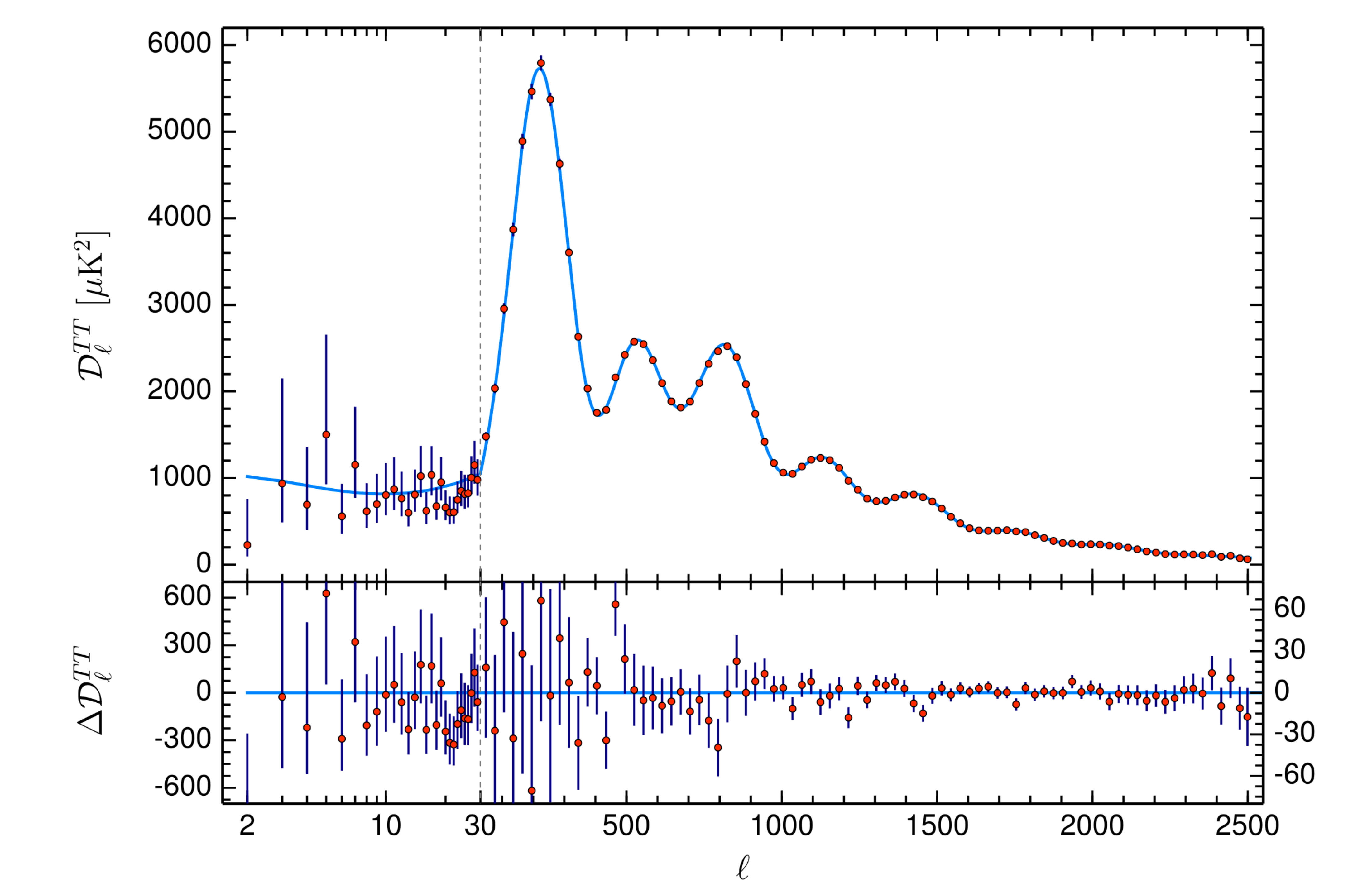
CMB



- Remnant radiation from the big bang epoch.
- Uniform temperature of 2.726K with tiny fluctuations
- Image of the Universe at the decoupling epoch.
- CMB Probes- COBE, WMAP, Planck (space probes); ACT, SPT (ground based)

Cosmic Microwave Background

CMB

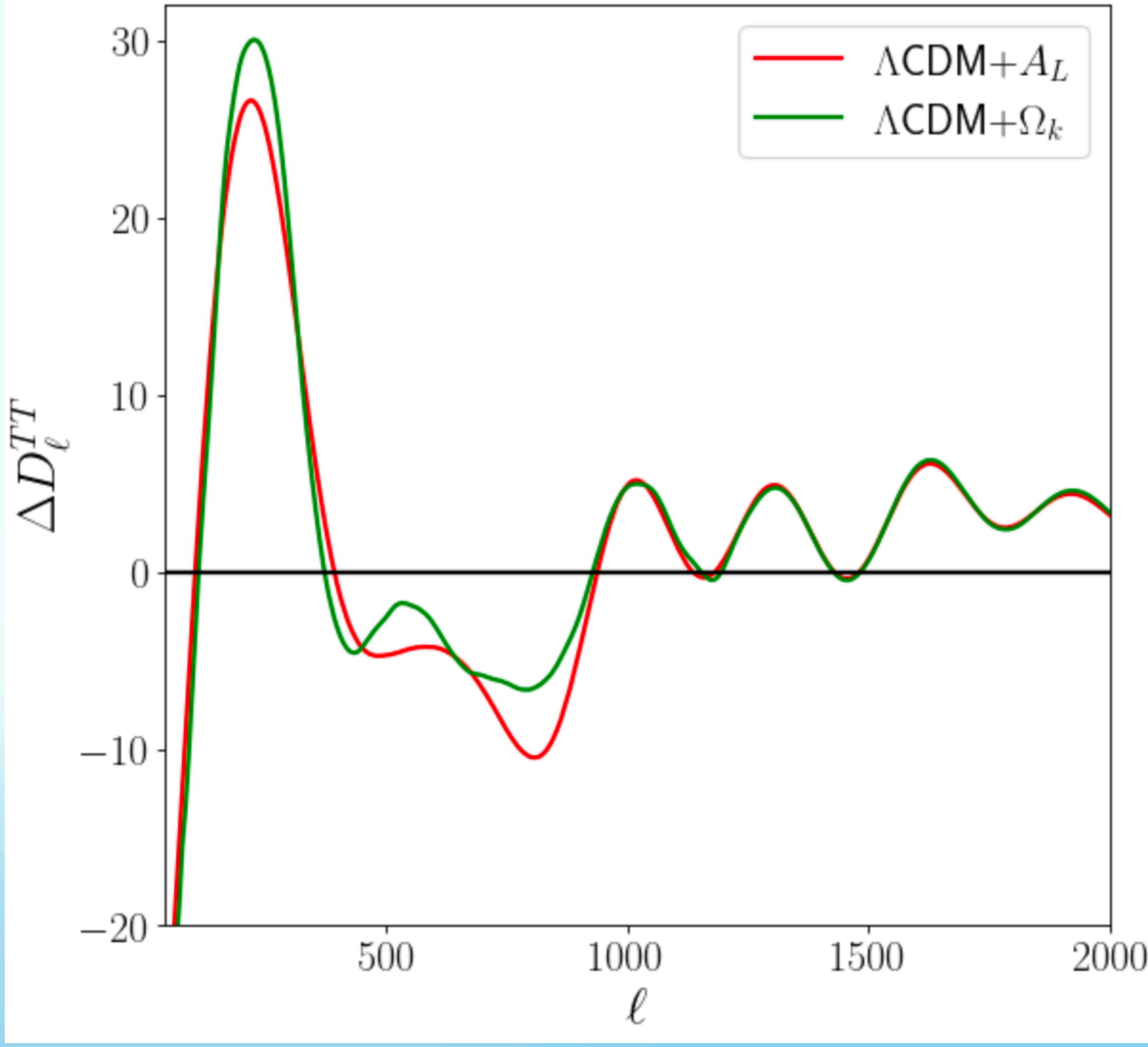


Cosmic Microwave Background

Excess damping acoustic peaks

$$\Delta D = D_{extension} - D_{\Lambda CDM}$$

- Indicate extra smoothing of acoustic peaks at multipoles higher than 800
- Low amplitude at multipoles lower than 40.



Tensions in Cosmology

Observation A

$X = x_a \pm \sigma_a$

Observation B

$X = x_b \pm \sigma_b$

- Observation A is in tension with observation B when

$$|x_a - x_b| > 2\sqrt{\sigma_a^2 + \sigma_b^2}$$

Tensions in Cosmology

Alens Anomaly

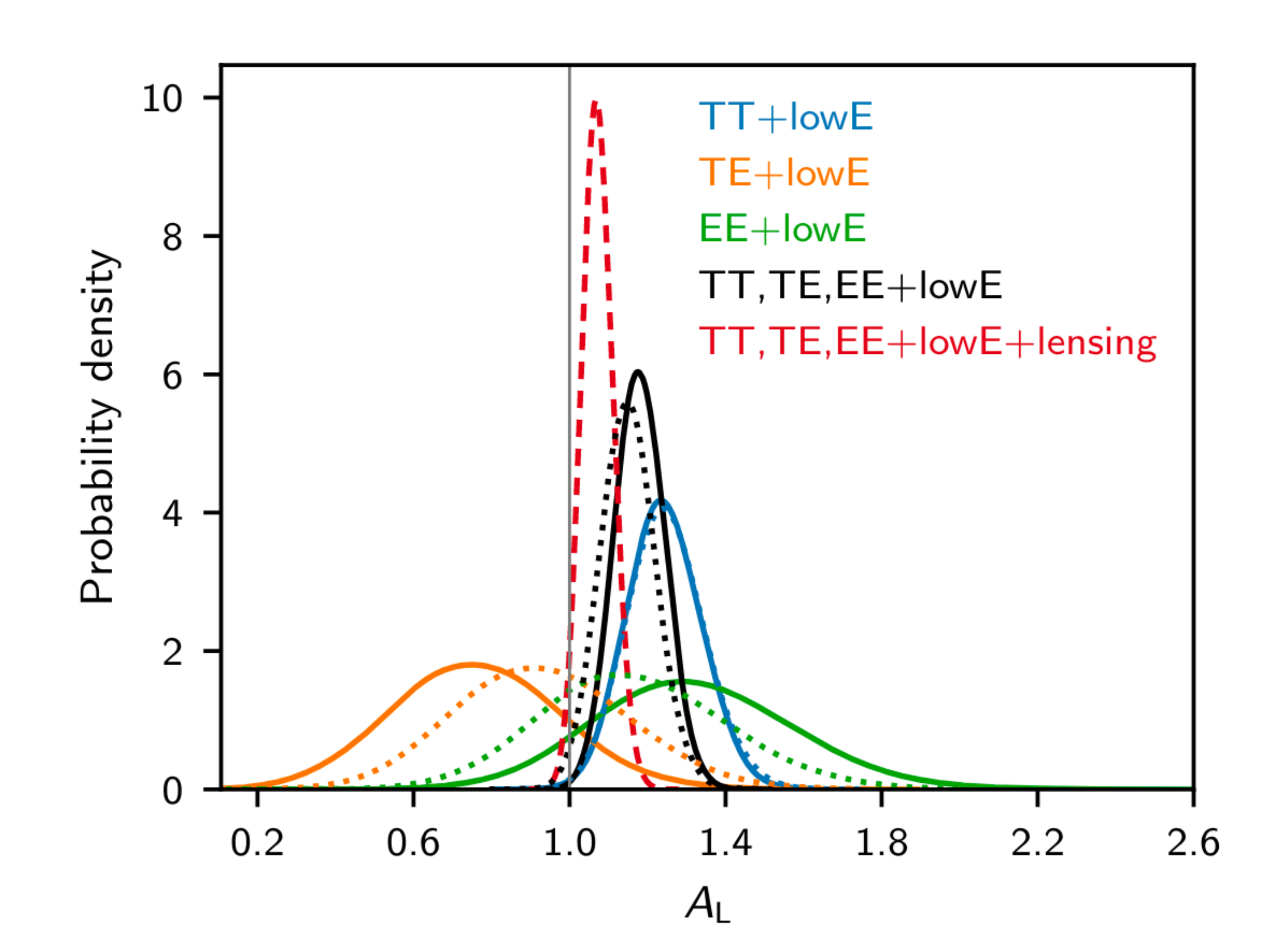
- A_L is a consistency parameter
- Planck prefer $A_L > 1$

1. $A_L = 1.243 \pm 0.096$

   (P18 TT + lowE, $\Delta\chi^2 = 8.7$)

2. $A_L = 1.180 \pm 0.065$

   (P18 TTTEEE + lowE, $\Delta\chi^2 = 9.7$)



Tensions in Cosmology

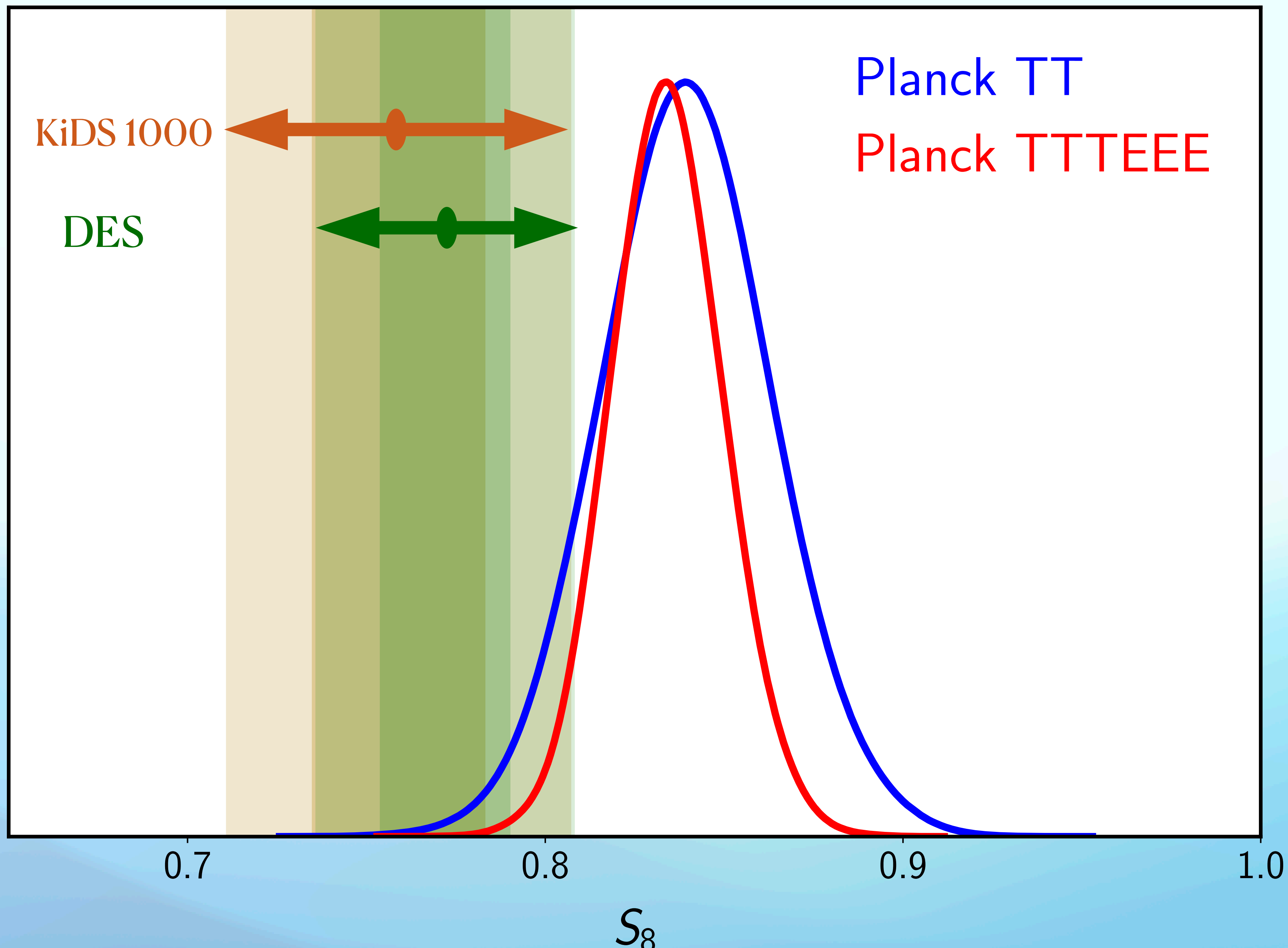
S_8 tension

- $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$
- DES survey provides $S_8 = 0.772^{+0.018}_{-0.017}$
- KiDS 1000 provide $S_8 = 0.759^{+0.024}_{-0.021}$
- Planck TT+lowl+lowE : $S_8 = 0.840 \pm 0.024$

  Planck TTTEEE+lowl+lowE : $S_8 = 0.834 \pm 0.016$

Tensions in Cosmology

S_8 tension



Tensions in Cosmology

H_0 tension

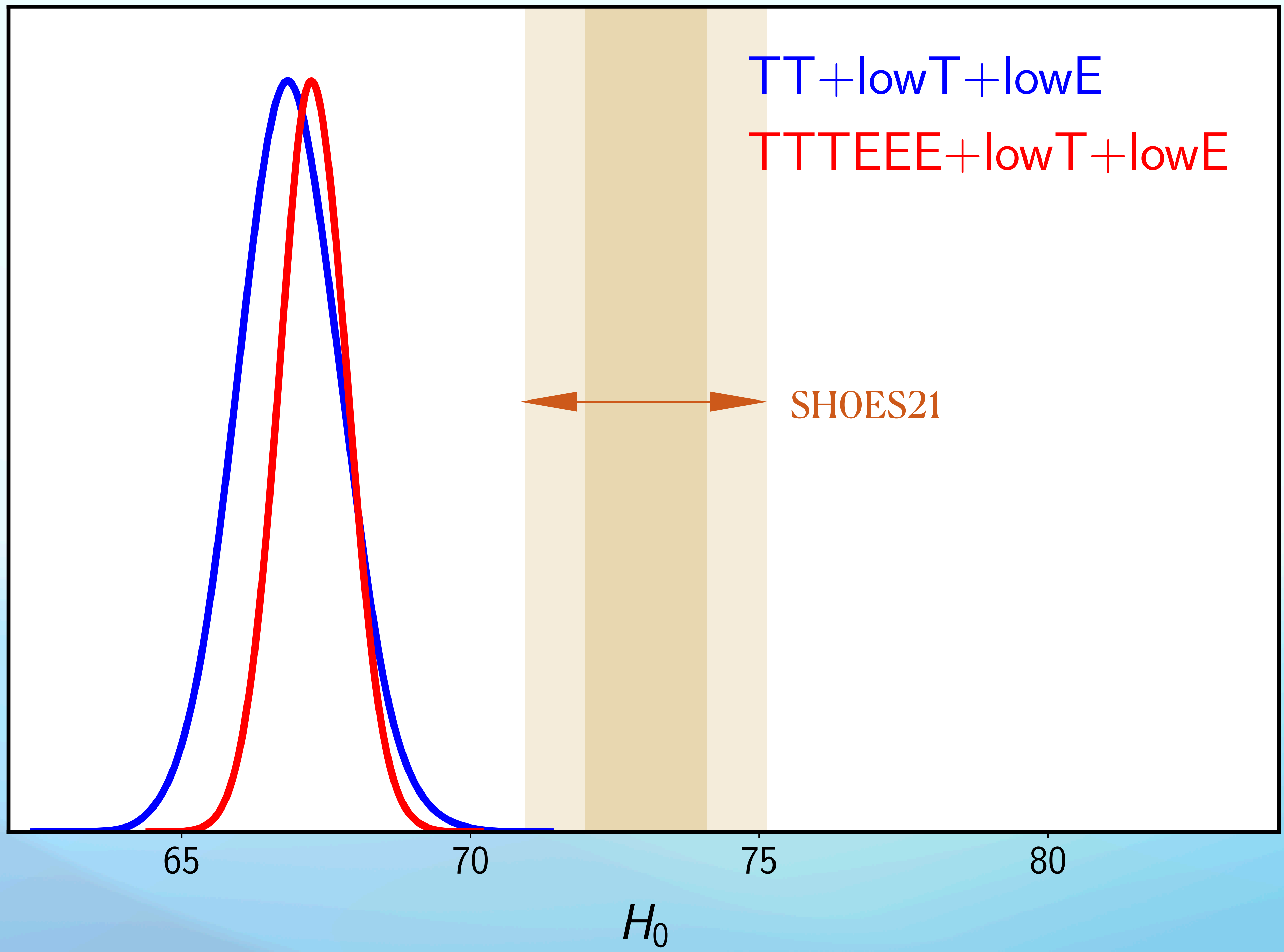
- Planck TT+lowl+lowE : $H_0 = 66.88 \pm 0.92$

  TTTEEE+lowl+lowE : $H_0 = 67.27 \pm 0.60$

- SH_0ES measurement : $H_0 = 73.04 \pm 1.04$
- Time delay cosmography of the lensed quasars and calibration of the Tip of Red Giant Branch (TRGB) indicates to a higher Hubble constant.

Tensions in Cosmology

H_0 tension



Tensions in Cosmology

Curvature problem

- ΛCDM prefers curved space over flat space
  - $\Omega_K = -0.056^{+0.028}_{-0.018}$ (P18 TT + lowE)
  - $\Omega_K = -0.044^{+0.018}_{-0.015}$ (P18 TTTEEE + lowE)

Tensions in Cosmology

Curvature problem

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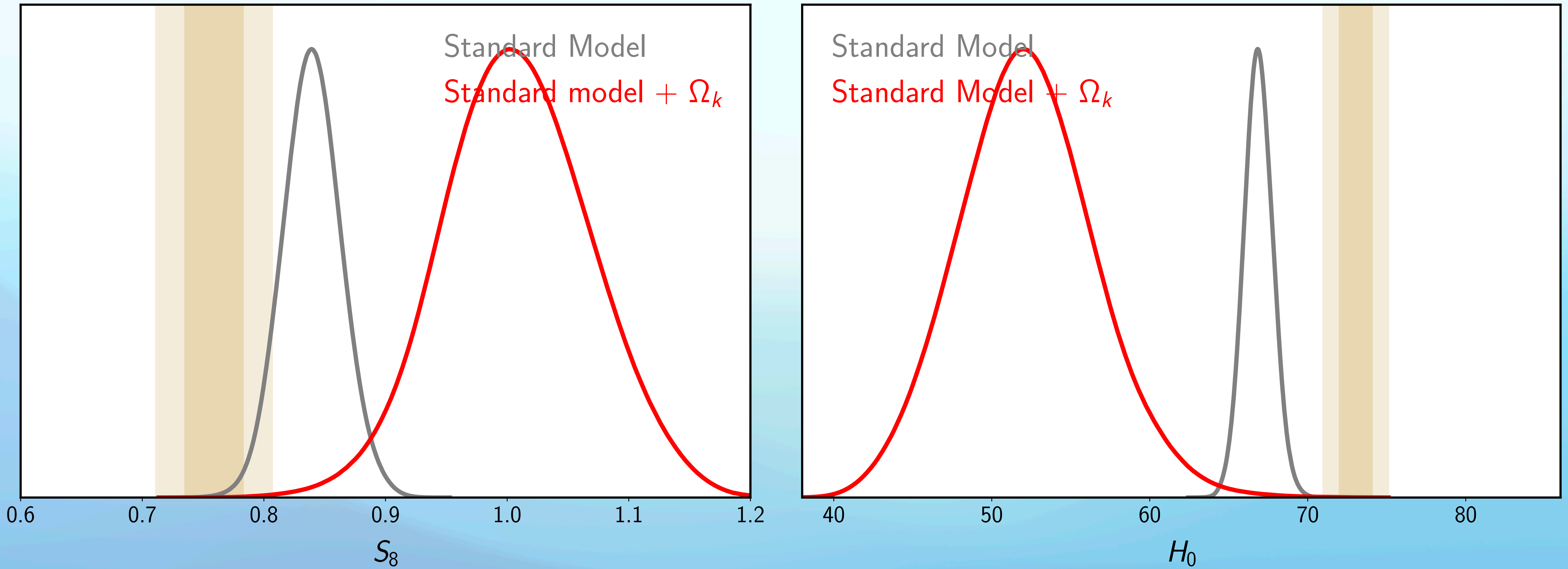


Tensions in Cosmology

Anomalies and tensions

	Planck TT	Planck TP	Theoretical/ Other observations
A_L	1.243 ± 0.096	1.180 ± 0.065	1.0
Ω_k	-0.056 ± 0.024	-0.042 ± 0.017	0.0
S_8	0.840 ± 0.024	0.834 ± 0.016	$0.759^{+0.024}_{-0.021}$
H_0	66.88 ± 0.92	67.27 ± 0.60	73.05 ± 1.04

Can primordial features reproduce the extra lensing effect?

Methodology

Modified Richardson Lucy

- $$\mathscr{C}_\ell^{theory} = \sum_{k=k_{min}}^{k_{max}} G_{\ell k} \mathscr{P}_k$$
- $$\mathscr{P}_k^{i+1} - \mathscr{P}_k^{i} = \mathscr{P}_k^{i} \times \sum_{\ell=\ell_{min}}^{\ell_{max}} \tilde{G}_{\ell k} \left(\frac{\mathscr{C}_\ell^{data} - \mathscr{C}_\ell^{theory(i)}}{\mathscr{C}_\ell^{theory(i)}} \right)$$
- Requires unlensed CMB spectrum

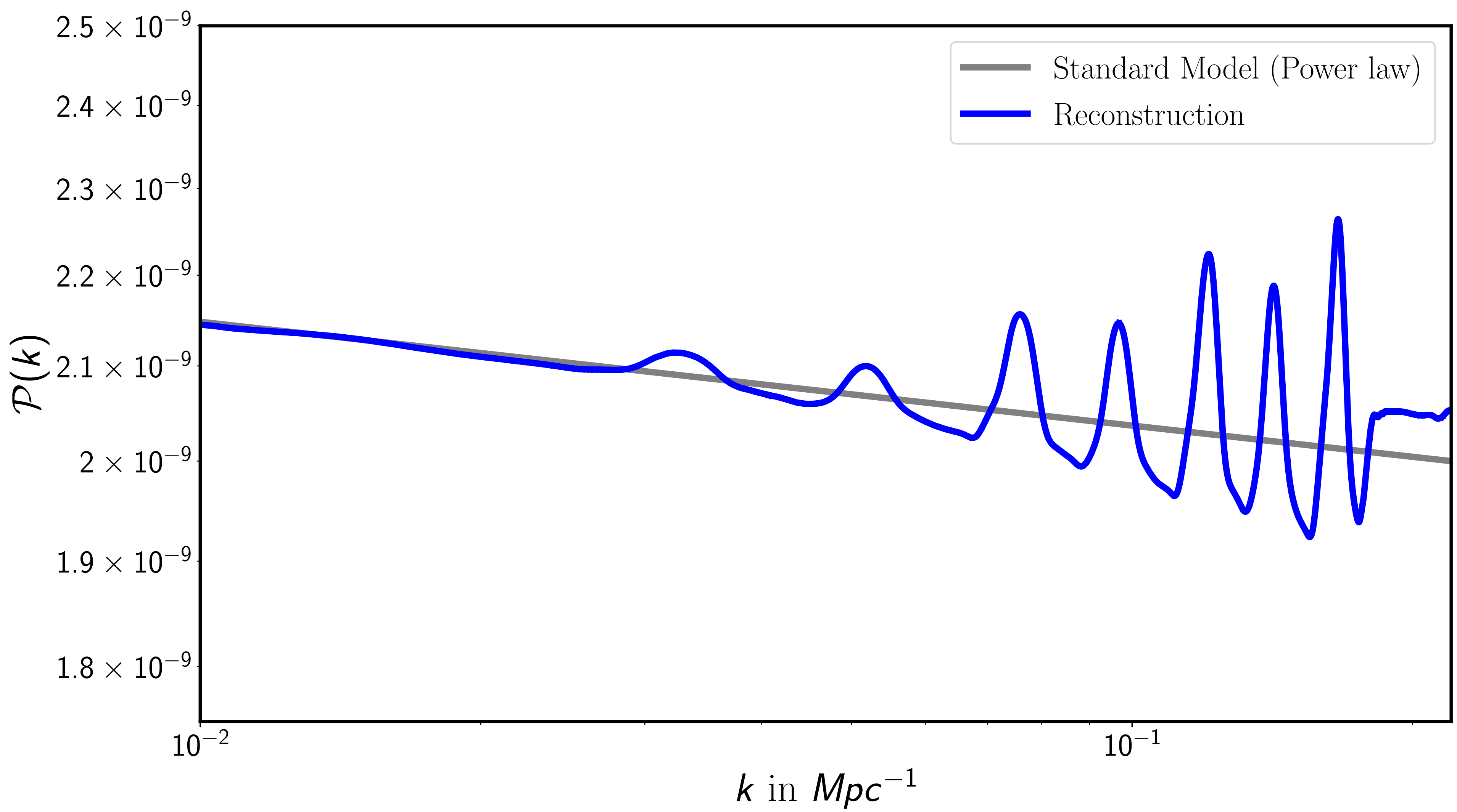
Reconstruction

Methodology

- Reconstruct the primordial power spectrum that mimics the extra lensing
- Here C_ℓ^{data} is the difference between Standard model + A_{lens} best fit lensed angular power spectrum and the spectrum for same set of parameter but A_{lens} (= 1 here).
- Above unlensed spectrum contains excess lensing signature due to $A_{lens} > 1$

Reconstruction

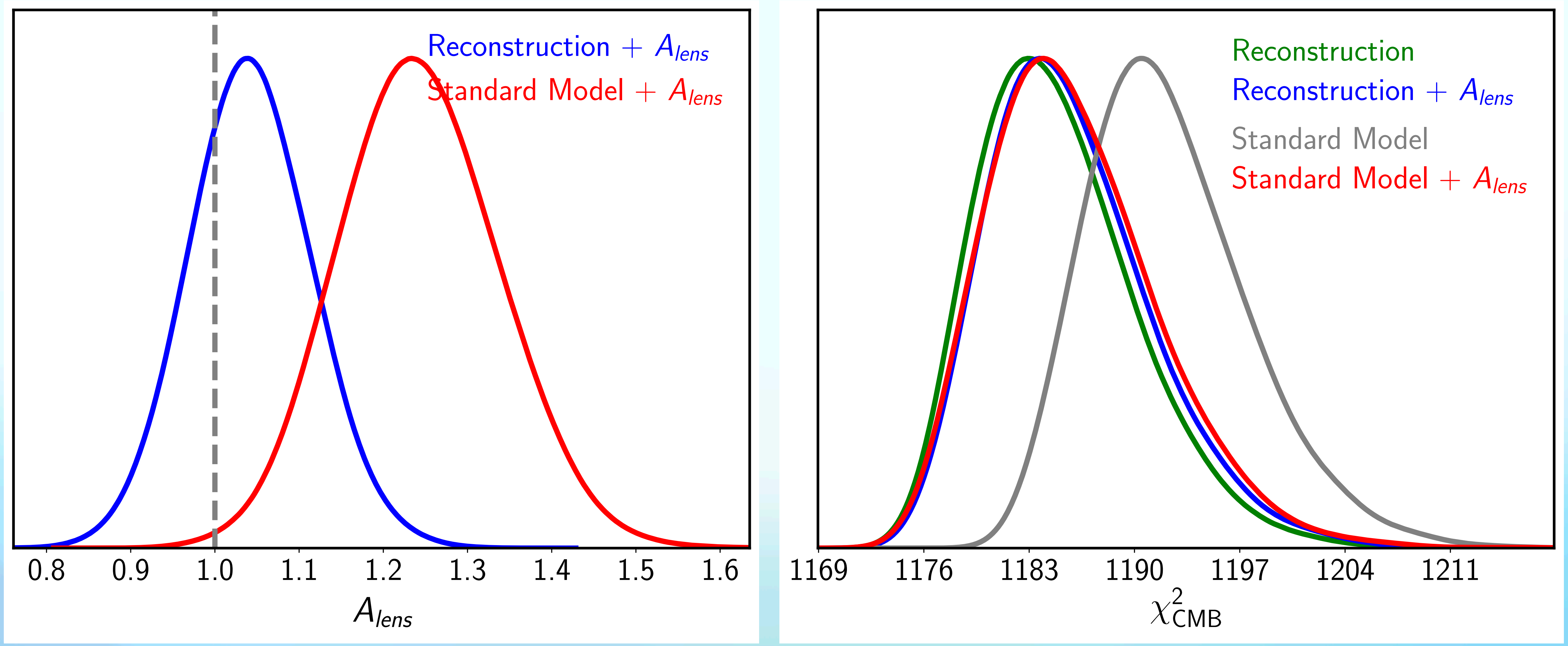
Methodology



Reconstructed spectrum that brings back cosmological concordance.

Reconstruction

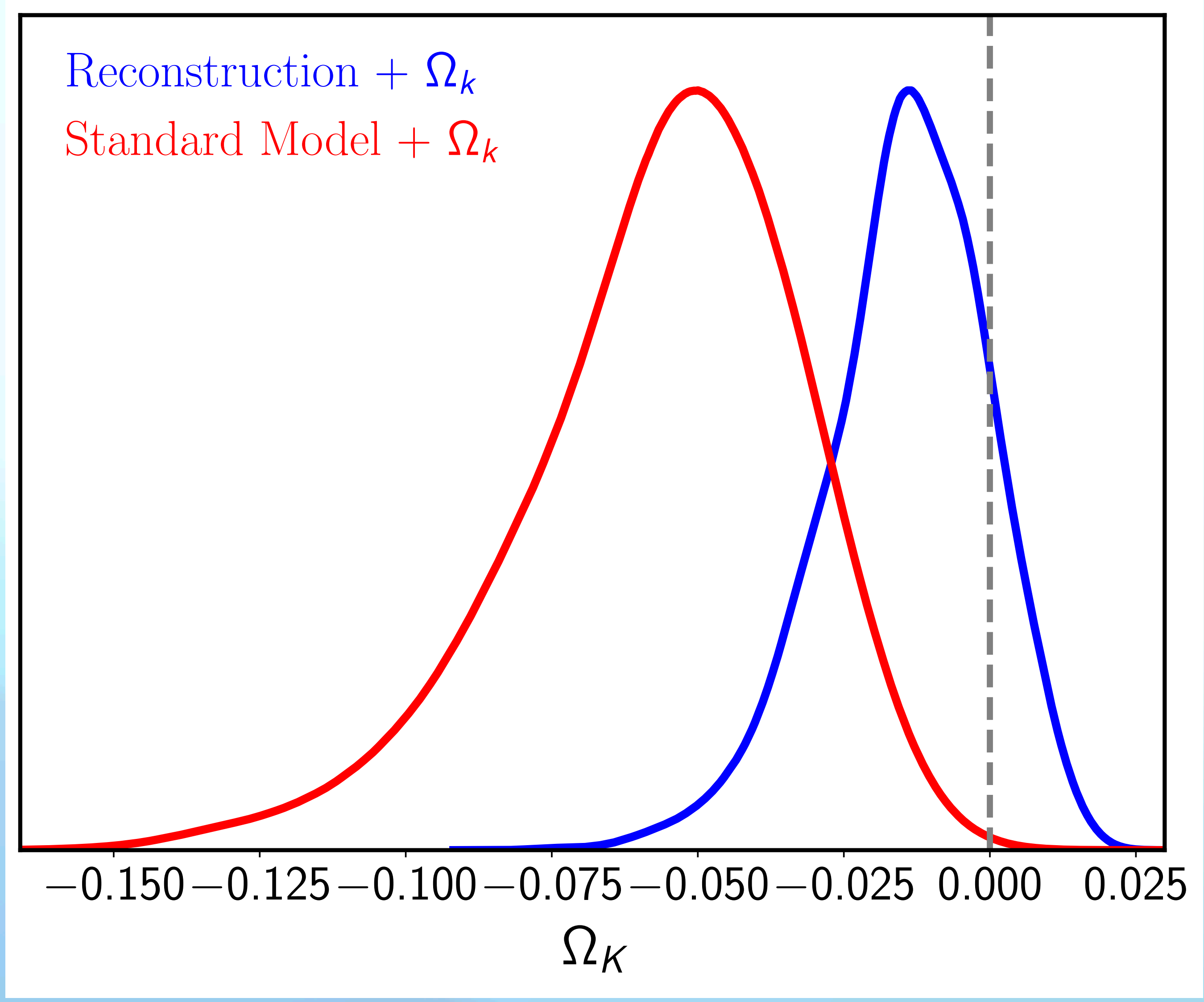
A_{lens} Anomaly

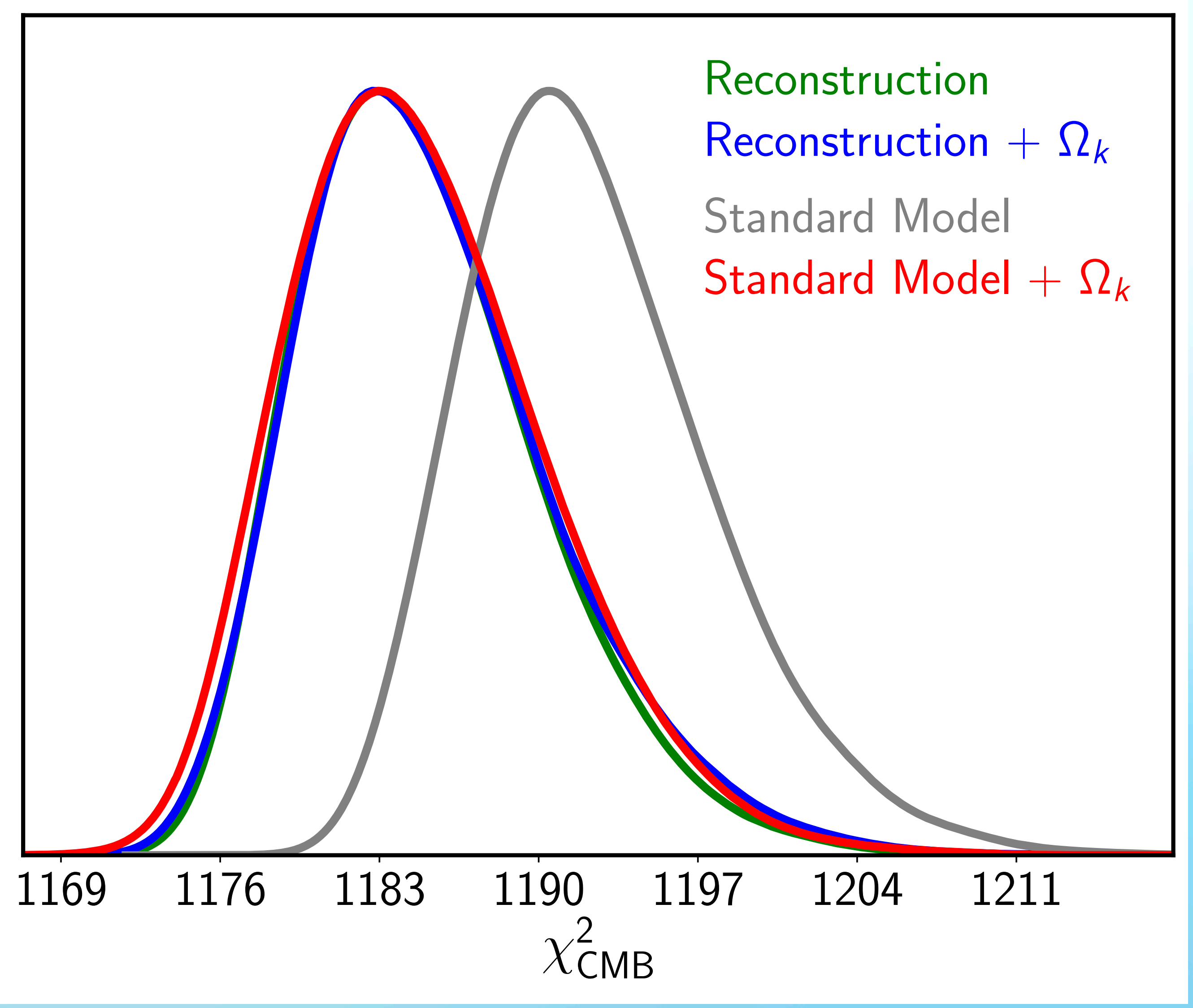


[Left] Marginalized posteriors of lensing amplitude (A_{lens}) obtained in the Standard Model and when reconstructed spectrum is used.
[Right] Marginalized posteriors of χ^2 from CMB in these two analyses compared with the Standard Model where lensing amplitude is fixed to 1.

Reconstruction

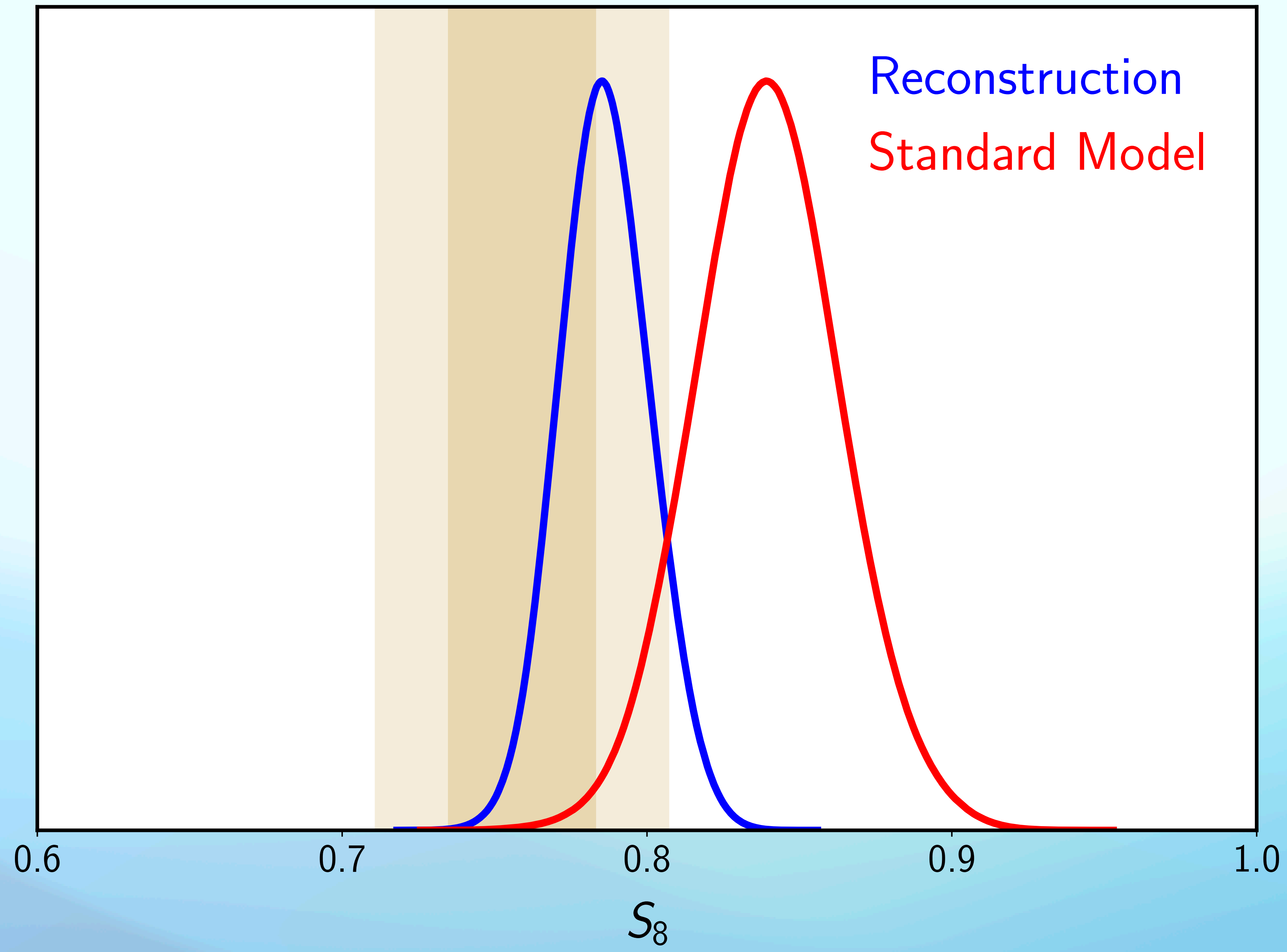
Curvature (Ω_k) problem





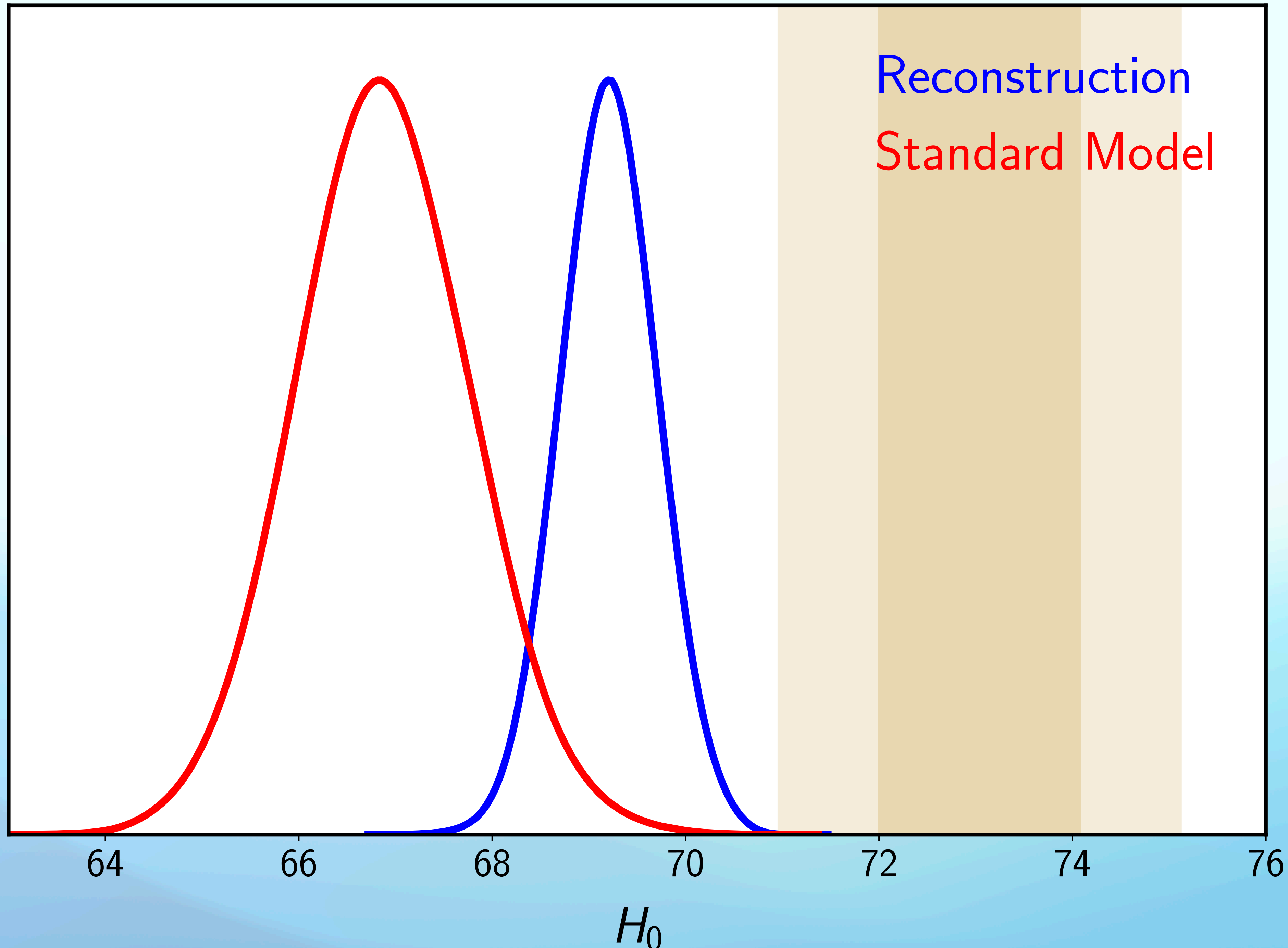
Reconstruction

S_8 tension



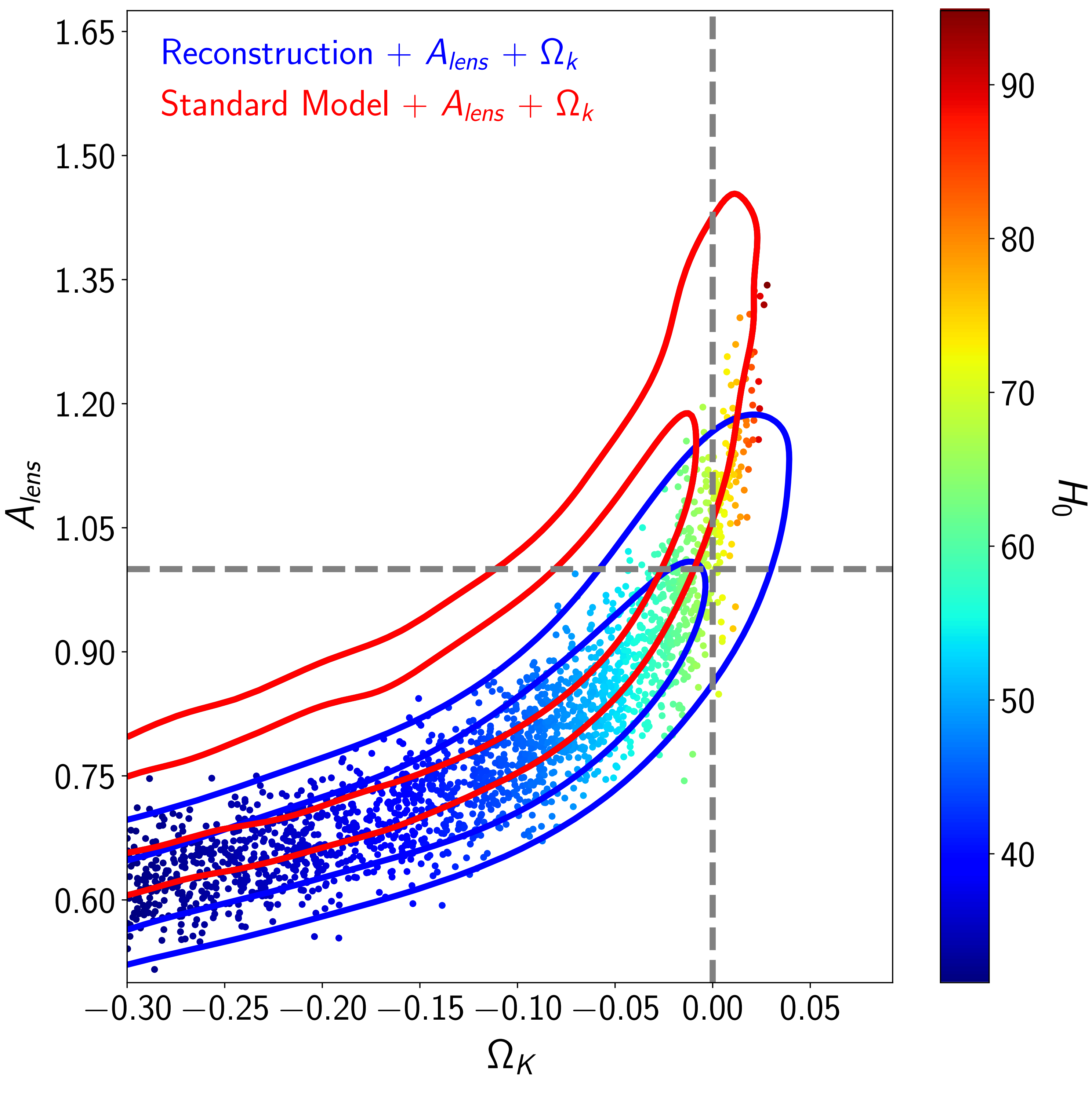
Reconstruction

H_0 tension



Reconstruction

$A_{lens} + \Omega_k$



An analytical template that mimics Reconstruction

Power spectrum template

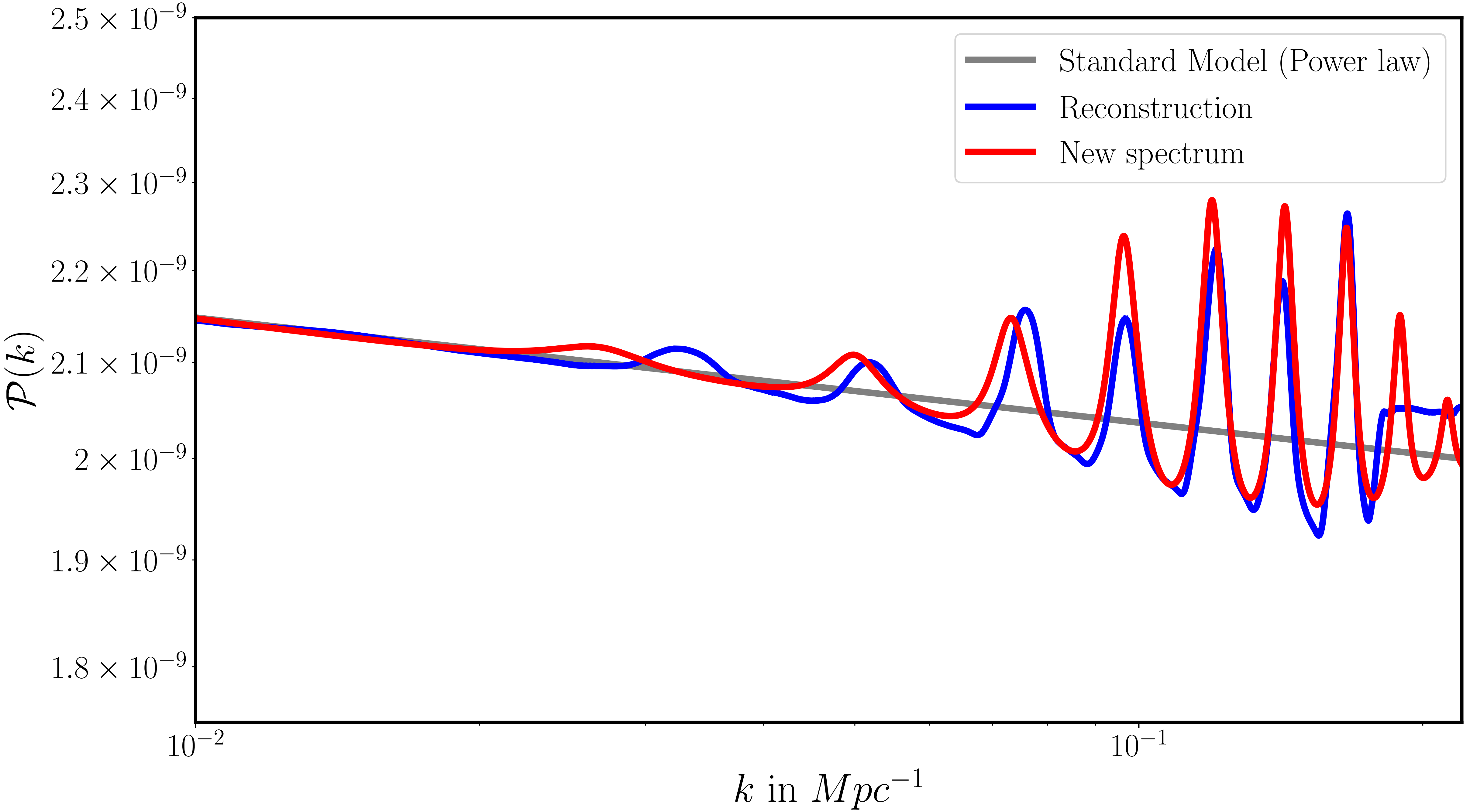
Functional form

- Reconstructed power spectrum has the following characteristic
  - Oscillations in the spectrum are nearly linear in k
  - Oscillations decay towards large scales
  - Peaks are more pronounced than the trough

$$\mathscr{P}_{New}(k) = \mathscr{P}_{Power\ Law}(k)\left[1 + \frac{\alpha_1 \sin\big(\omega(k-k_0)\big)}{\Big(1-\alpha_2 \sin\big(\omega(k-k_0)\big)\Big)\Big(1+\beta(k-k_0)^4\Big)}\right]$$

Power spectrum template

Results



Power spectrum template

Restricted spectrum

$$\mathscr{P}_{Restricted}(k) = \mathscr{P}_{Power\ Law}(k)\left[1 + \frac{\alpha_1 \sin\big(\omega(k-k_0)\big)}{1+\beta(k-k_0)^4}\right]$$

Model/Data	P18 TT	P18 TT + HST
New spectrum	-1.14 ± 0.53	2.67 ± 0.53
Restricted spectrum	-0.58 ± 0.52	3.4 ± 0.53

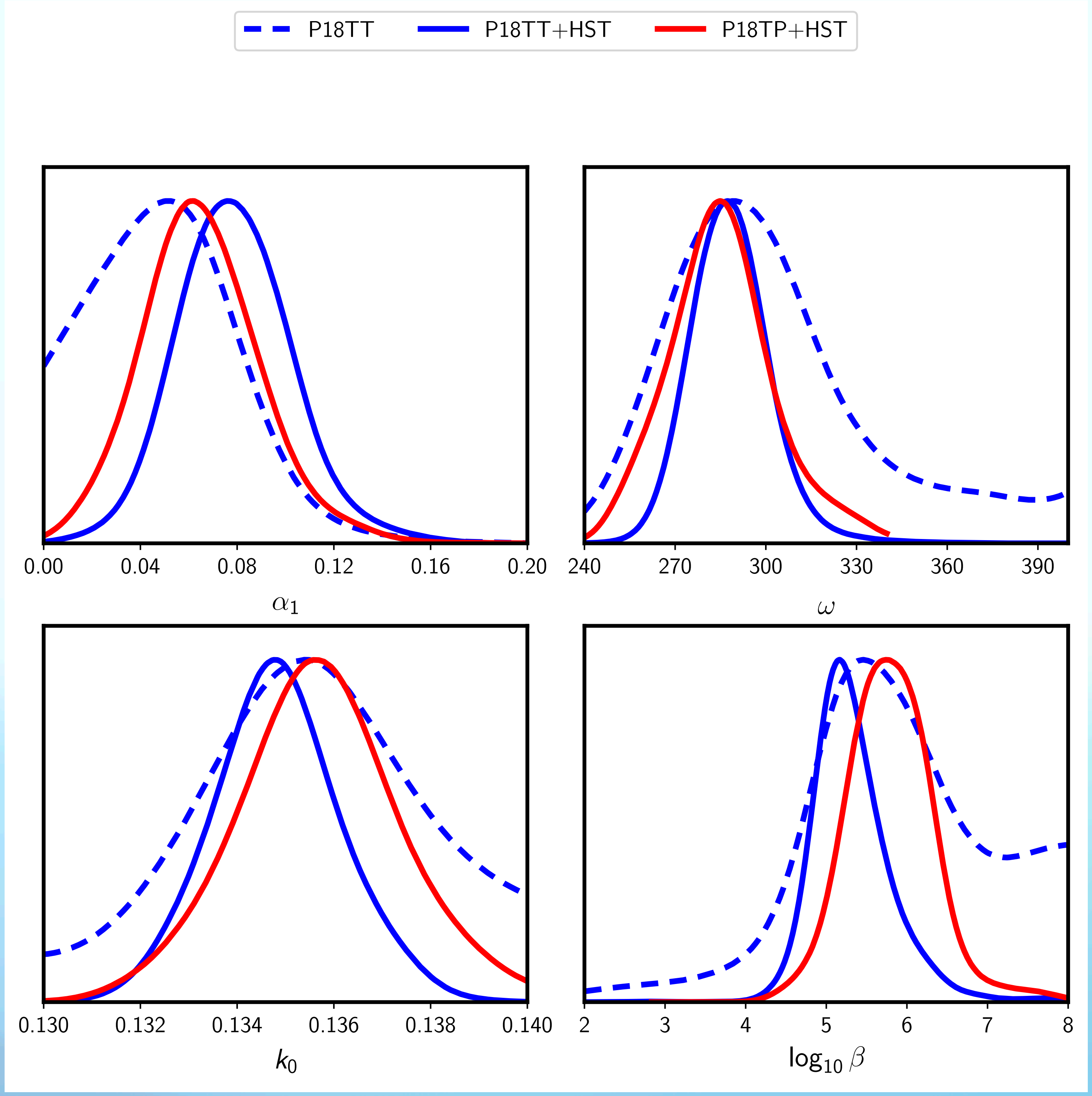
Power spectrum template

Restricted spectrum

Data	ln[Bayes factor]	C.L.
P18TP	-0.01 ± 0.54	95%
P18TP + HST	1.46 ± 0.55	99.5%
P18TT + ACT + DES + HST	2.28 ± 0.65	99.6%
P18TP + ACT + DES + HST	1.94 ± 0.66	98.7%
P18TP + DES + HST	2.32 ± 0.64	99.5%
P18TP + ACT + DES + BAO + SN + HST	−0.34 ± 0.66	98.5%
P18TP + ACT + DES	−0.85 ± 0.66	99.5%

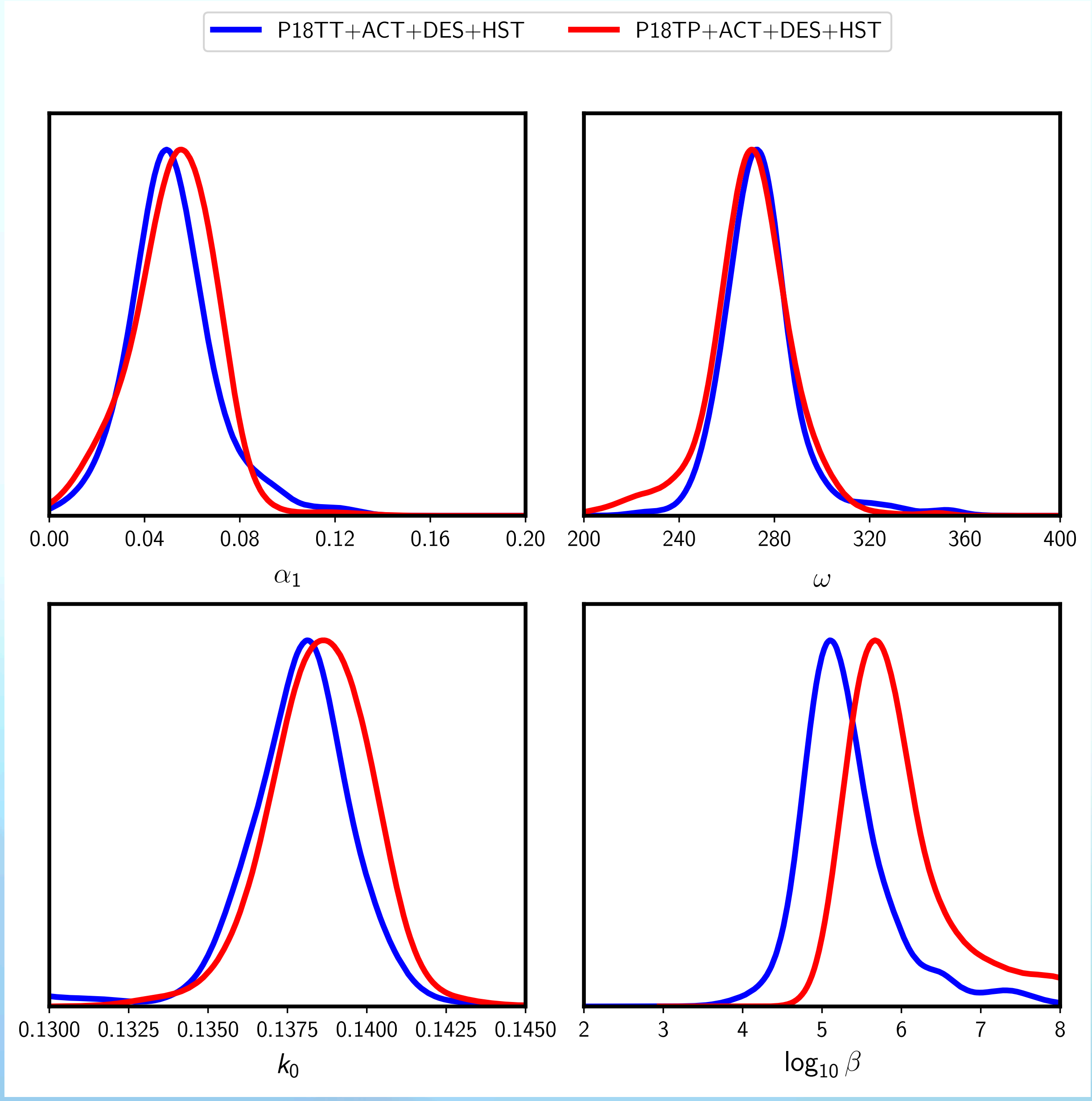
Power spectrum template

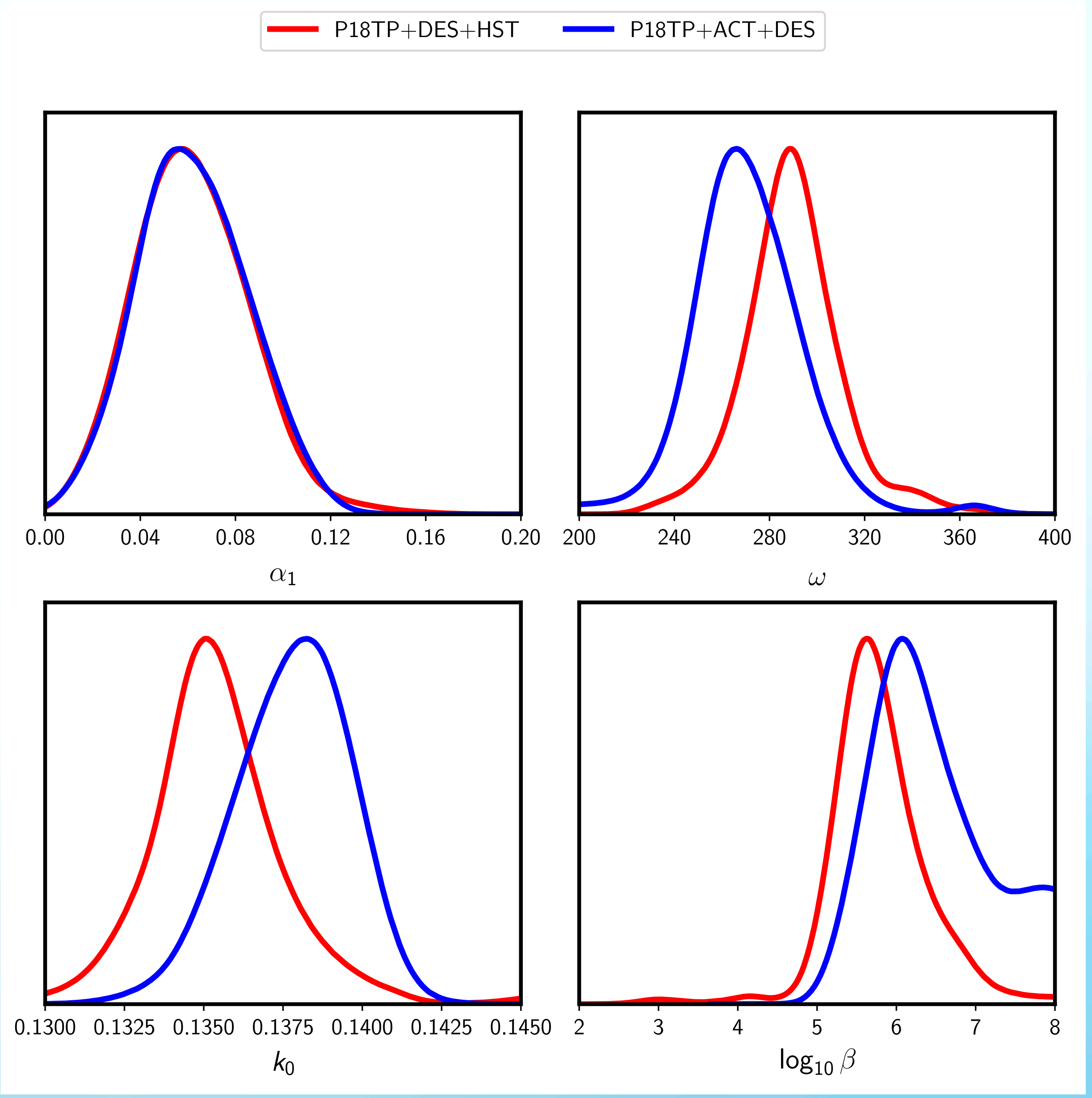
Posterior distribution of parameters



Power spectrum template

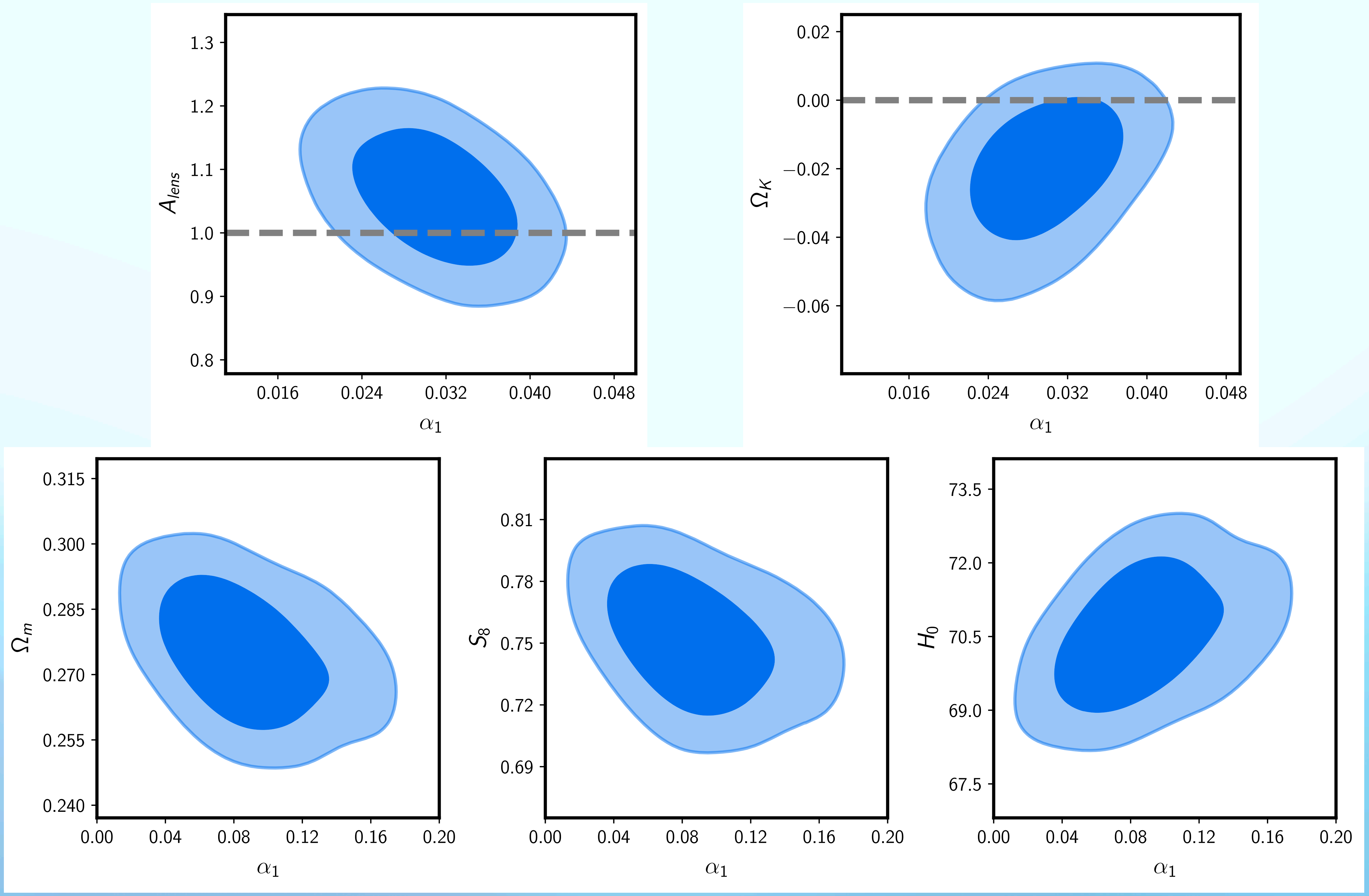
Posterior distribution of parameters





Power spectrum template

Correlations



An intermediate fast roll phase in inflation that solves the tension.

Hubble Slow-roll Parameter

Inflationary model

- A model that mimics the above power spectrum
- We work with Hubble slow roll parameter instead of a potential
- The baseline function

$$\epsilon_H^b(N) = \epsilon_1 \exp\left[\epsilon_2(N - N_*)\right]$$

- N is the no of e-folds of expansion happened to scalar factor a
- $r \simeq 16\epsilon_1 \quad \text{and} \quad n_s = 1 - 2\epsilon_1 - \epsilon_2$

Hubble slow parameter

Inflationary model

- The full feature form

$$\epsilon_H(N) = \epsilon_H^b(N)\left(1 + \frac{\alpha\cos\left[\omega(N-N_0)\right]}{1+\beta(N-N_0)^2}\right)$$

- Generates resonant features ($\beta \to 0$) and sharp features ($\omega \to 0$)
- This creates an envelope of sin + sin log + sin oscillation.

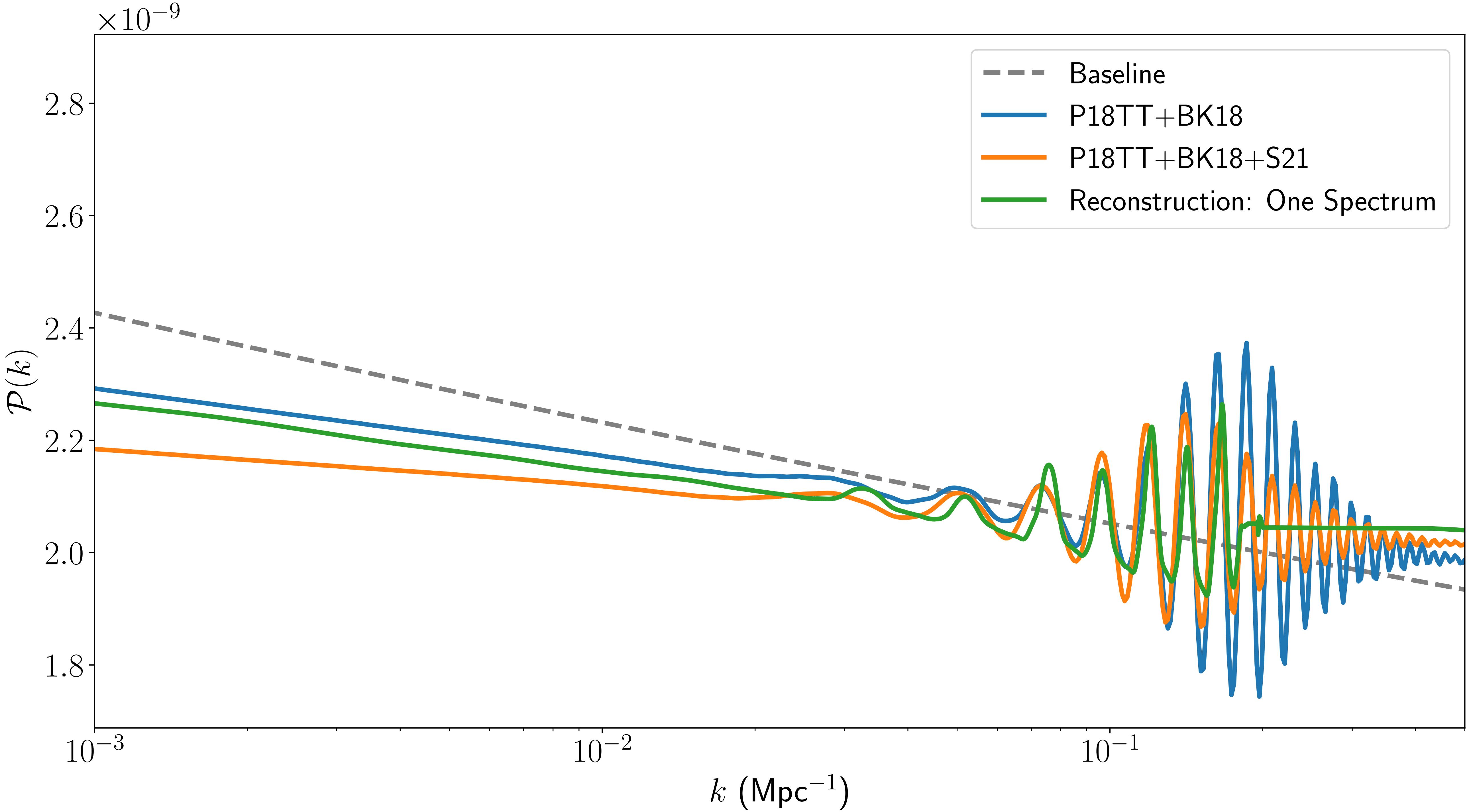
Datasets analysed

Inflationary model

- The dataset we studied are the following:
    1. TT lowl lowE BK18 - P18TT+BK18
    2. TTTEEE lowl lowE BK18 - P18TP+BK18
    3. TTTEEE lowl lowE BK18 lensing - P18TPL+BK18
    4. TEEE lowl lowE BK18 - P18TEEE+BK18
- We use H_0 latest release along with above datasets - S21.

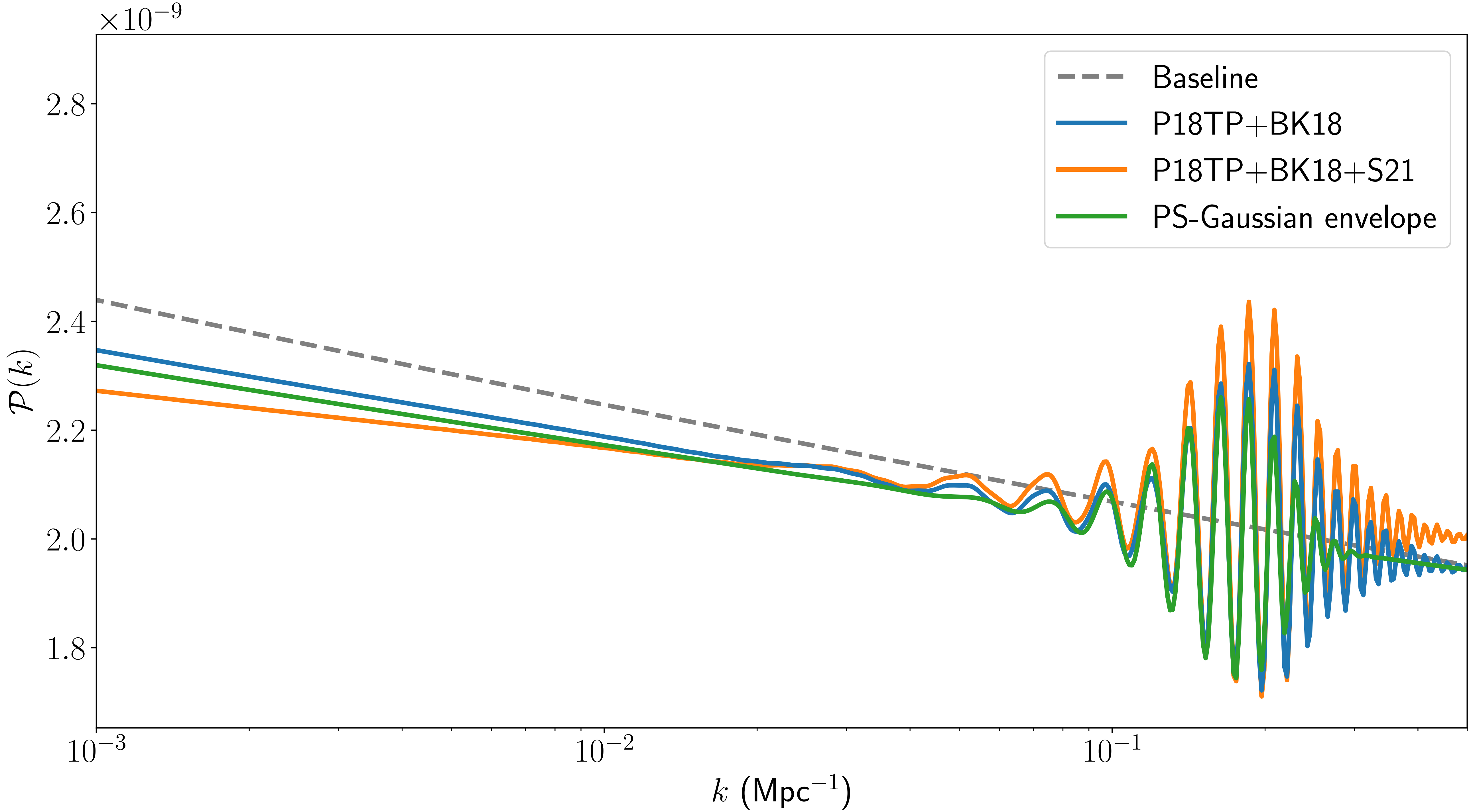
Results - Power spectrum

Inflationary model



Results - Power spectrum

Inflationary model



Results

Inflationary model

DATA	$\Delta\chi^2$	H_0	S_8
P18TT+BK18	-8.3	66.86 ± 0.86	0.840 ± 0.022
		68.06 ± 1.14	0.814 ± 0.027
P18TP+BK18	-10.7	67.26 ± 0.59	0.835 ± 0.015
		67.71 ± 0.66	0.826 ± 0.017
P18TPL+BK18	-8.4	67.35 ± 0.53	0.832 ± 0.012
		67.63 ± 0.57	0.829 ± 0.013
P18TEEE+BK18	-2.7	67.91 ± 0.77	0.814 ± 0.020
		67.63 ± 0.86	0.819 ± 0.022

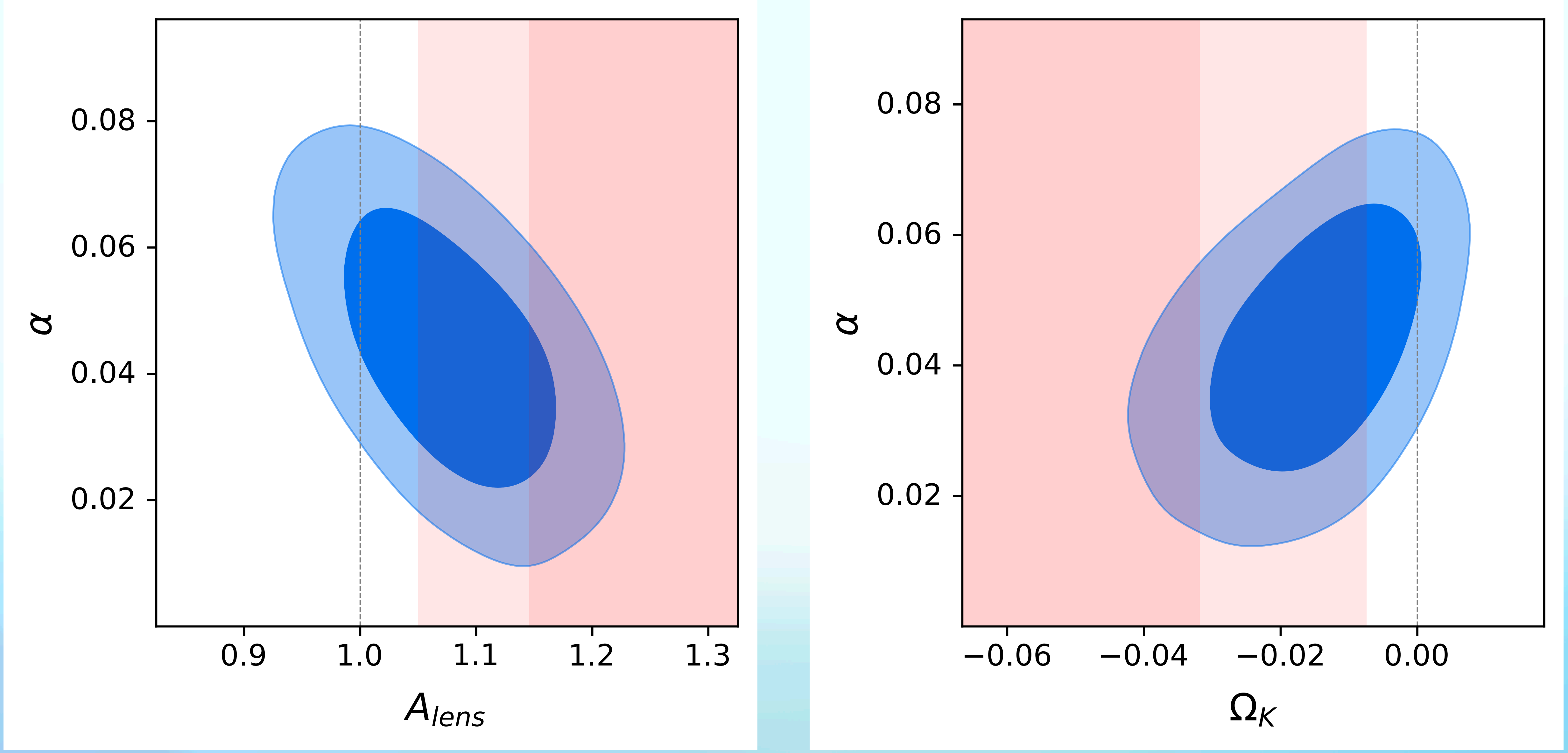
Results- With Riess21

Inflationary model

DATA	$\Delta\chi^2$	H_0	S_8
P18TT+BK18+S21	-19.5	69.41 ± 0.68	0.781 ± 0.017
		70.85 ± 0.78	0.754 ± 0.018
P18TP+BK18+S21	-19.3	68.71 ± 0.53	0.802 ± 0.014
		69.27 ± 0.58	0.791 ± 0.014
P18TPL+BK18+S21	-11.5	68.56 ± 0.48	0.832 ± 0.012
		68.90 ± 0.51	0.829 ± 0.013
P18TEEE+BK18+S21	-1.2	69.76 ± 0.63	0.808 ± 0.011
		69.77 ± 0.67	0.804 ± 0.011

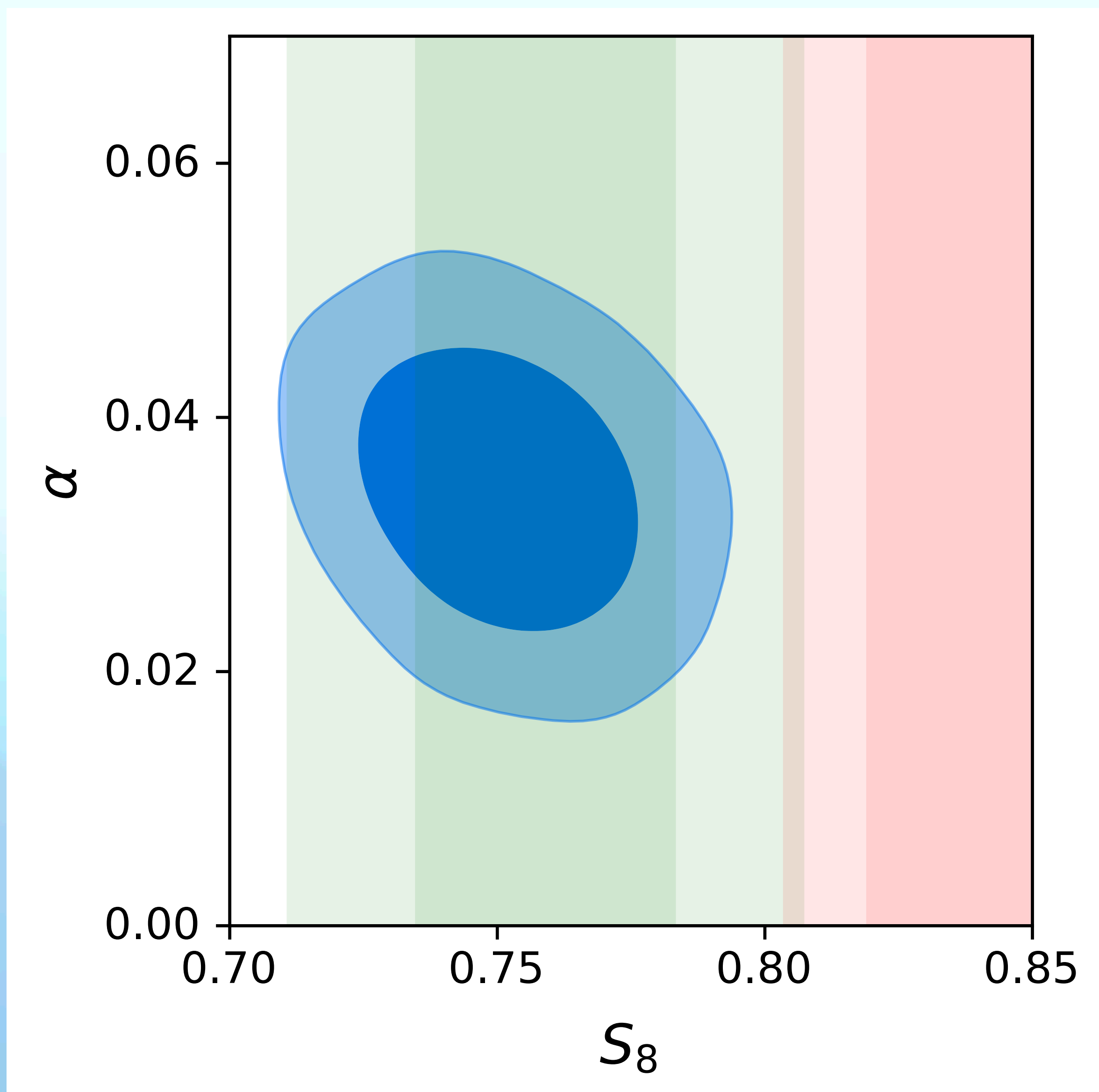
Results- Correlation

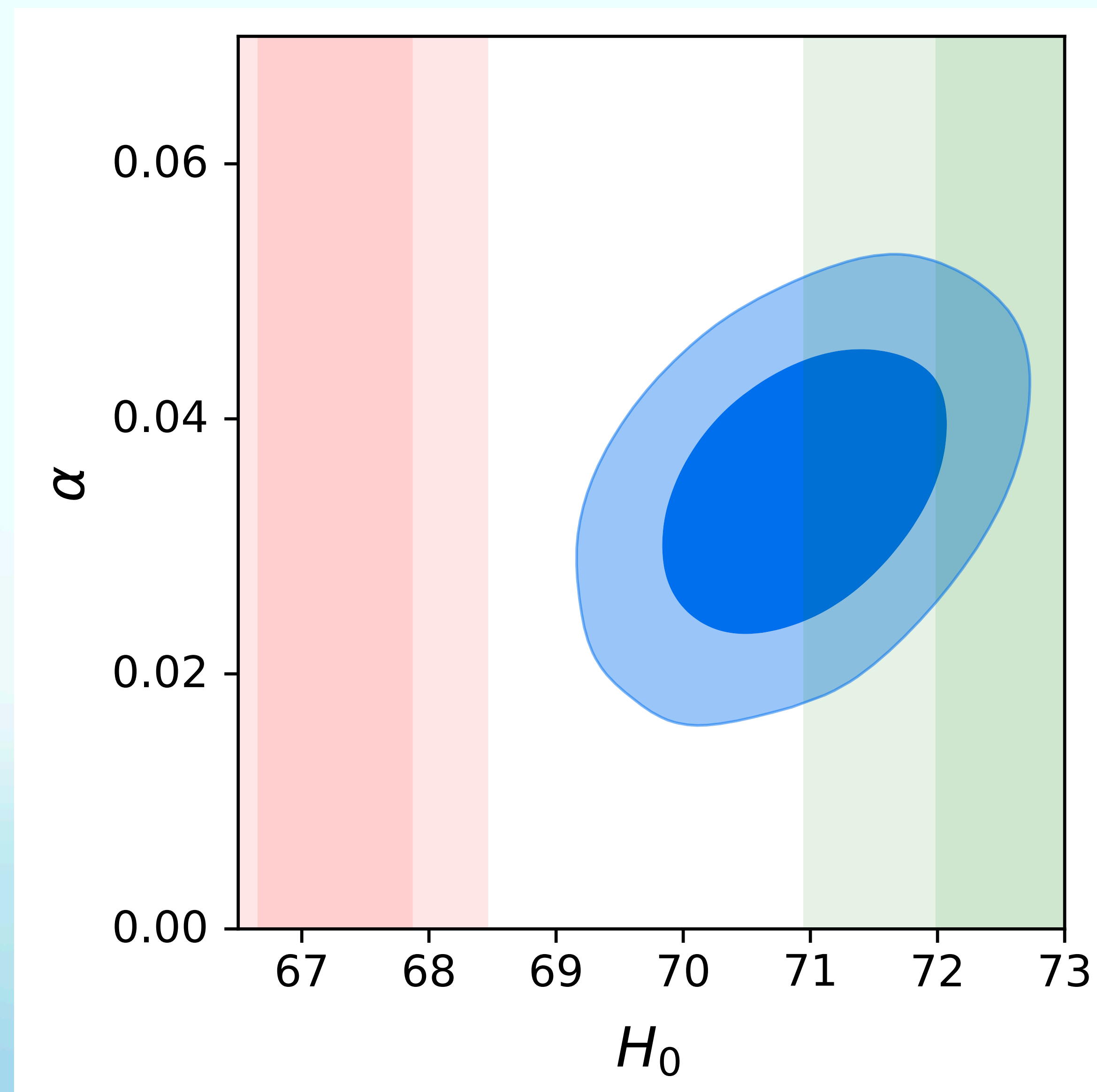
Inflationary model



Results

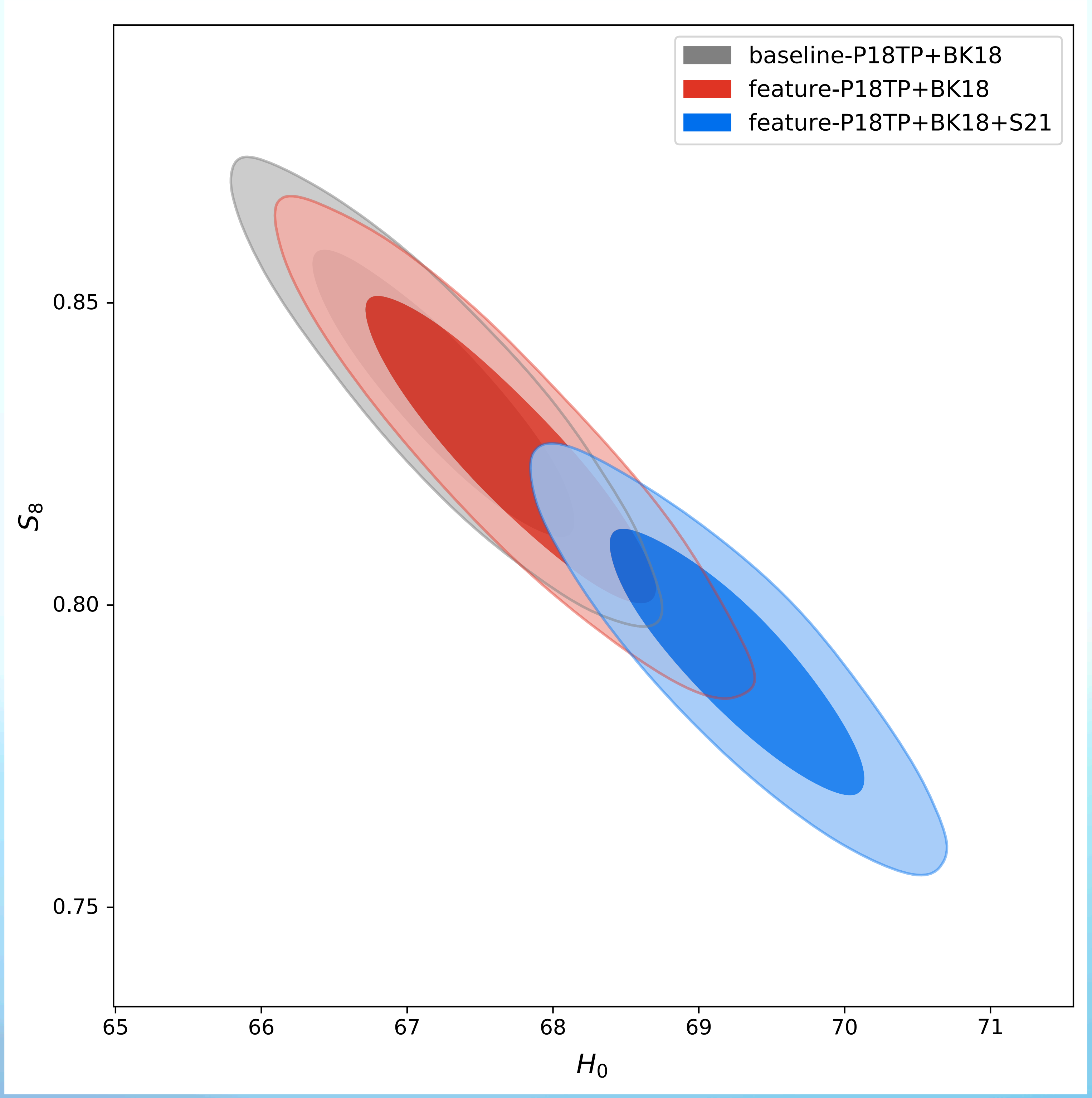
Inflationary model





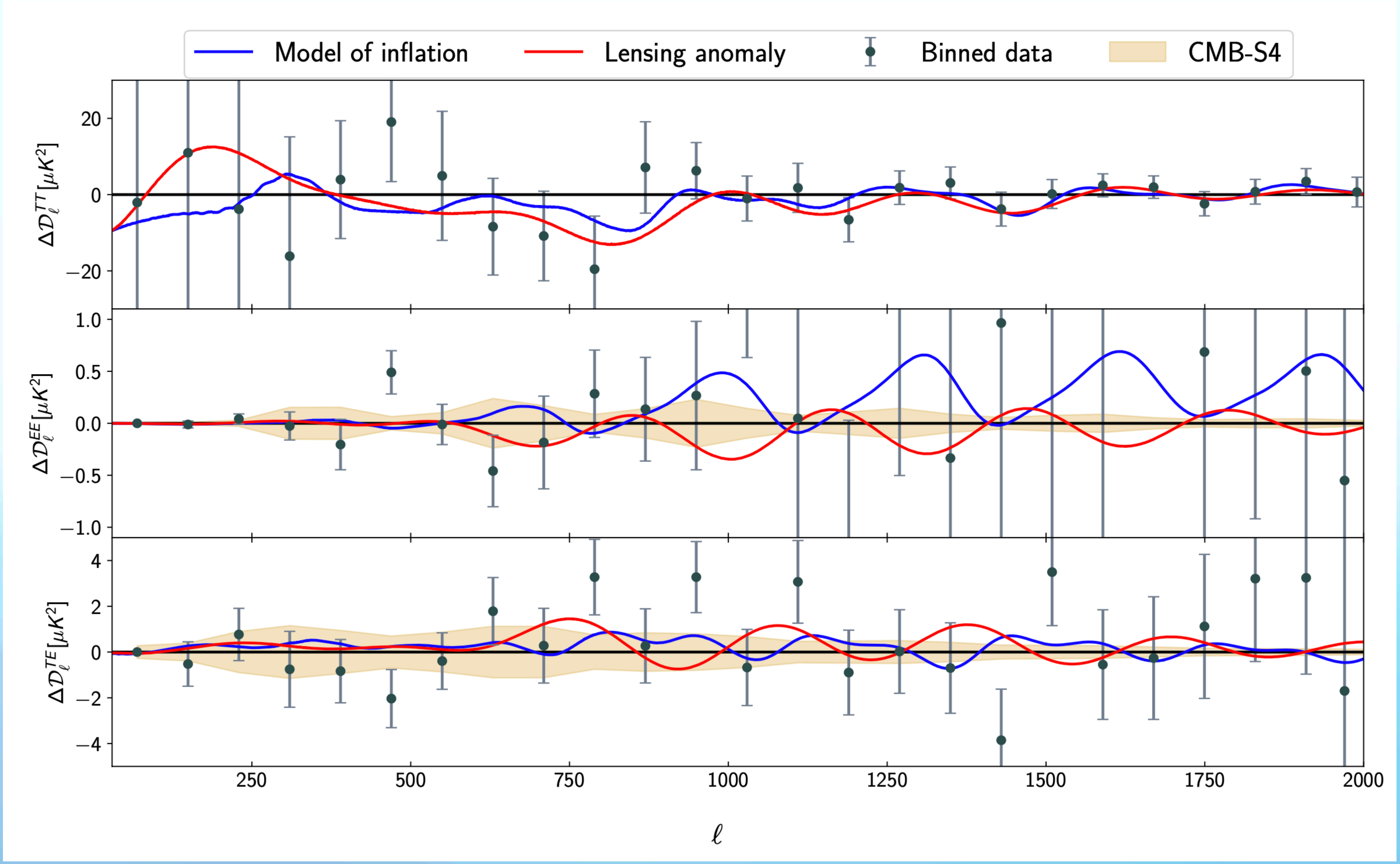
Results

Inflationary model



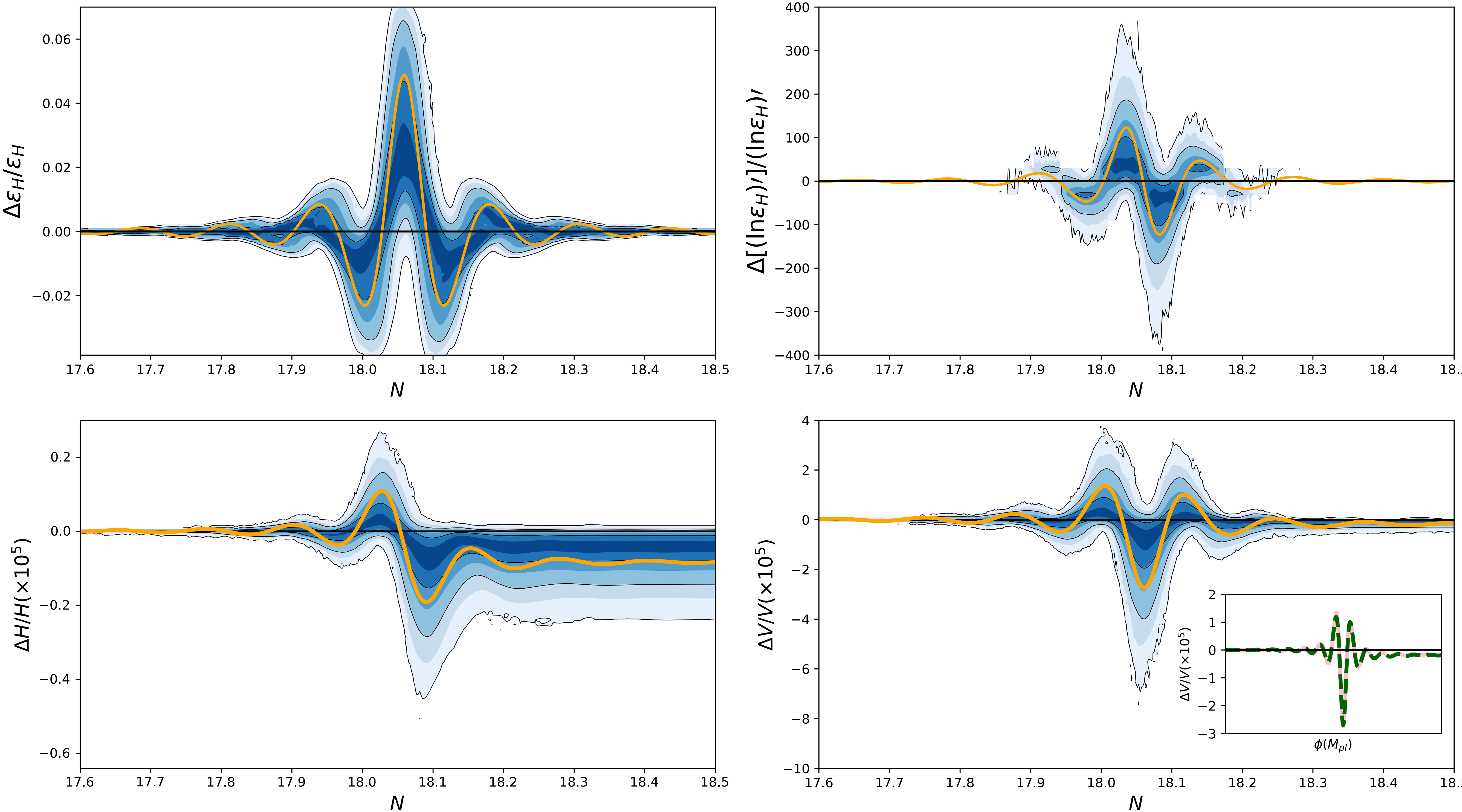
Results - Residuals

Inflationary model



Results - Reconstructed Potential

Inflationary model



Conclusions

- An intermediate fast roll in inflationary dynamics for a period of 0.5 e-folds solves the lensing anomaly in a flat Universe.
- This has a completely different signature in the polarisation anisotropy spectrum compared to A_L.
- Simultaneously prefers a lower value of S_8 and higher value of H_0.
- When priors on H_0 introduces, it gives 20 improvement in χ^2 with better agreement to SH0ES data.
- Reconstruction of potential points towards damped oscillatory features in baseline slow roll potential.