CERN

Tensions in cosmology - new physics vs. systematics

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403 x 404

Standard model of cosmology

1. Einstein's theory of gravity
2. Metric: homogeneous and isotropic at large scales
3. Constituents: baryons, 'cold' dark matter (CDM), a dark energy described by cosmological constant (Λ)
4. Initial condition: 'complete slow roll' inflation with power law form of primordial power spectrum

BASELINE: ΛCDM + power law primordial spectrum

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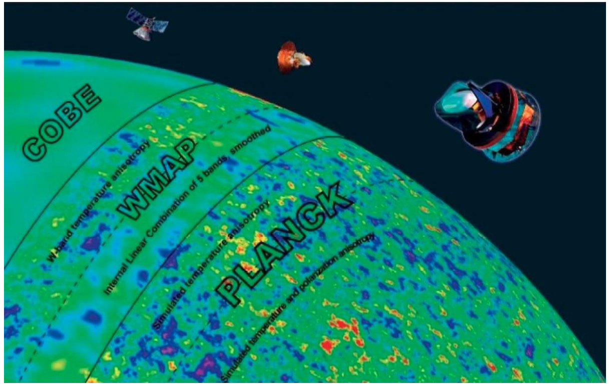
How do we determine the standard model parameters ?

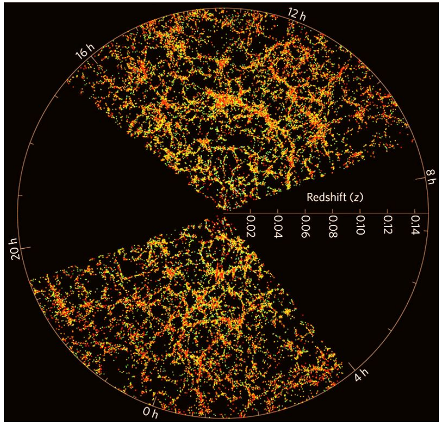
Cosmological observations

High redshift: Cosmic Microwave Background

Low redshifts: Supernovae, galaxy clustering lensing ++

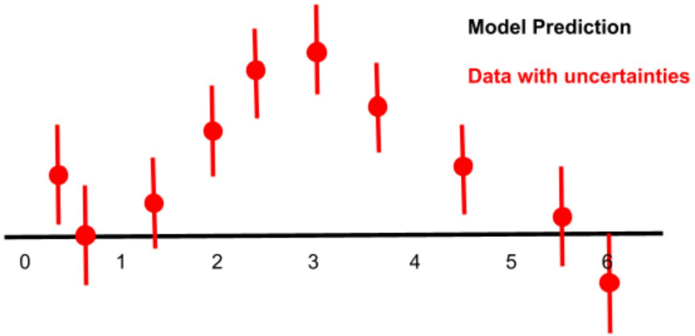


NASA/ESA



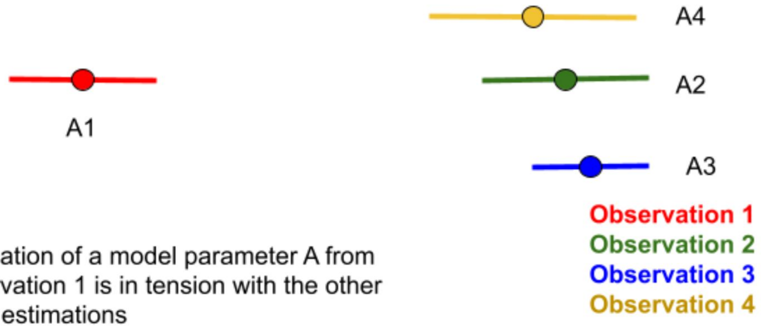
SDSS

Anomalies



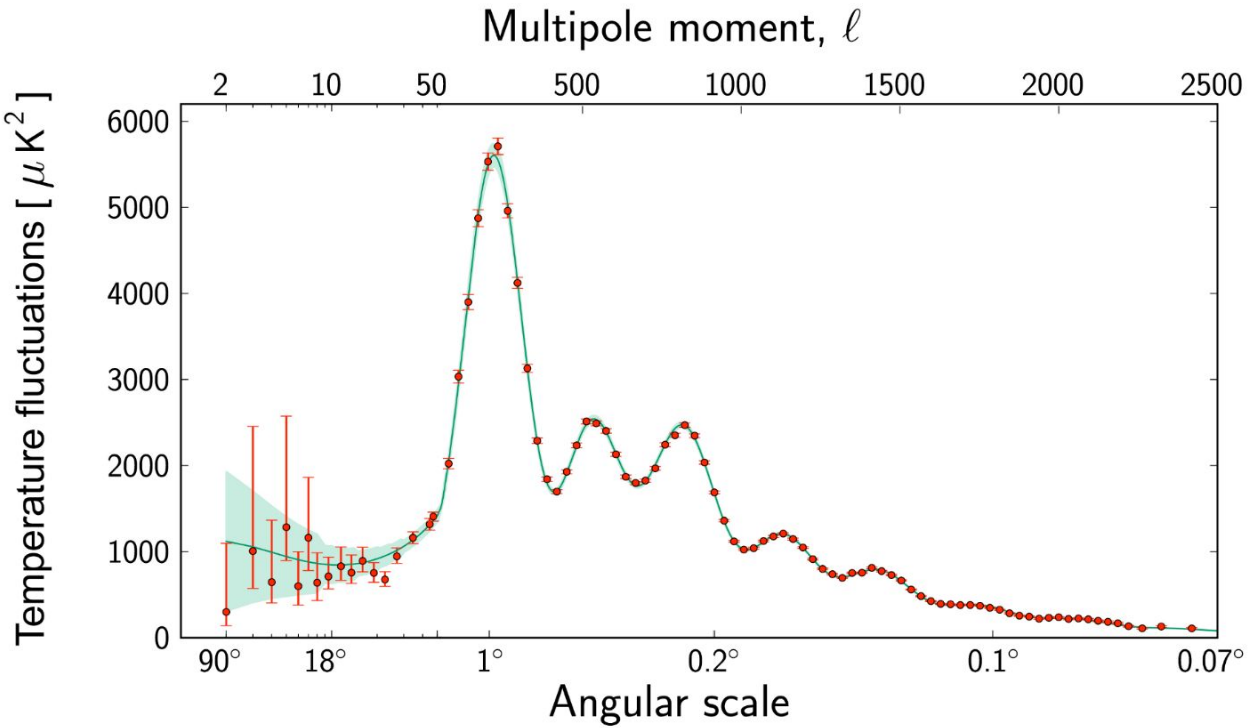
An example of anomaly in data w.r.t. the model prediction around the horizontal coordinates 2-4

Tensions

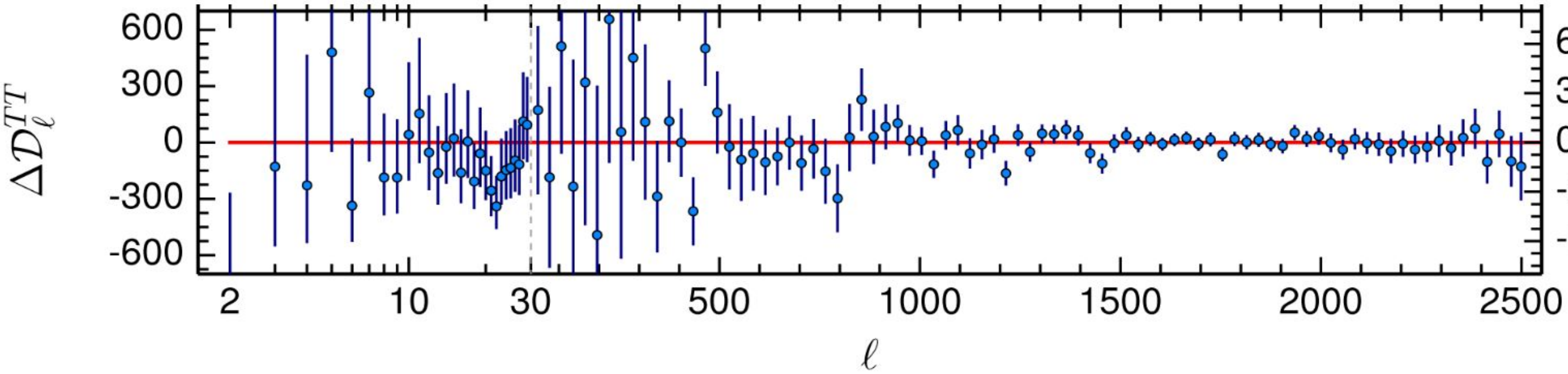


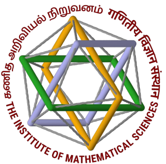
Estimation of a model parameter A from observation 1 is in tension with the other three estimations

Planck data


Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK²]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale

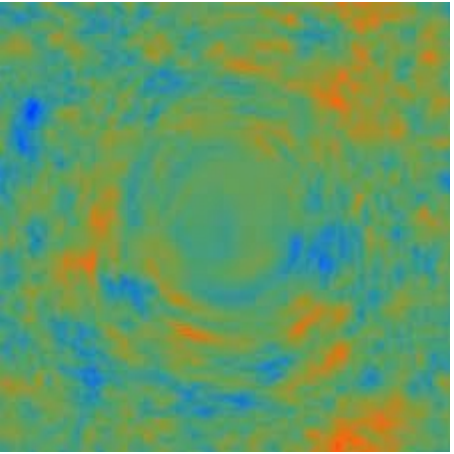
Planck anomalies

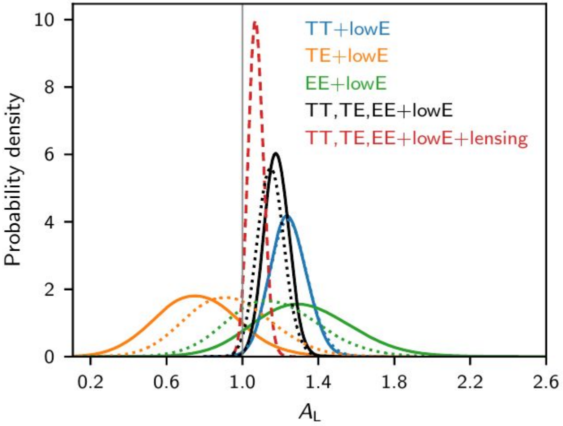




Anomalies (lensing)

Acoustic peaks in the CMB appear smoother

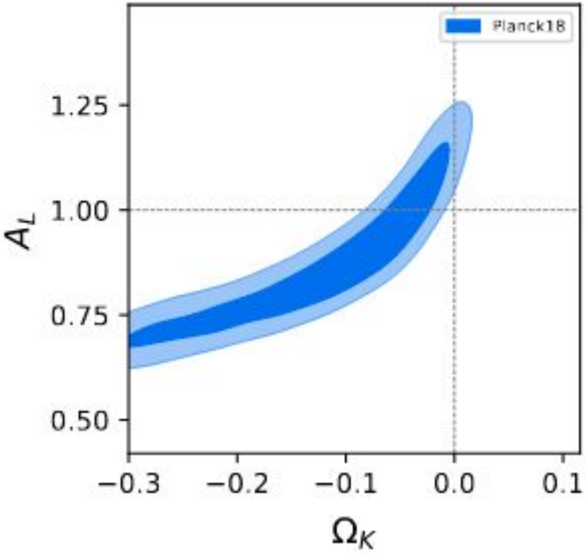




Planck 2018

Solution

Closed Universe: a spatial curvature

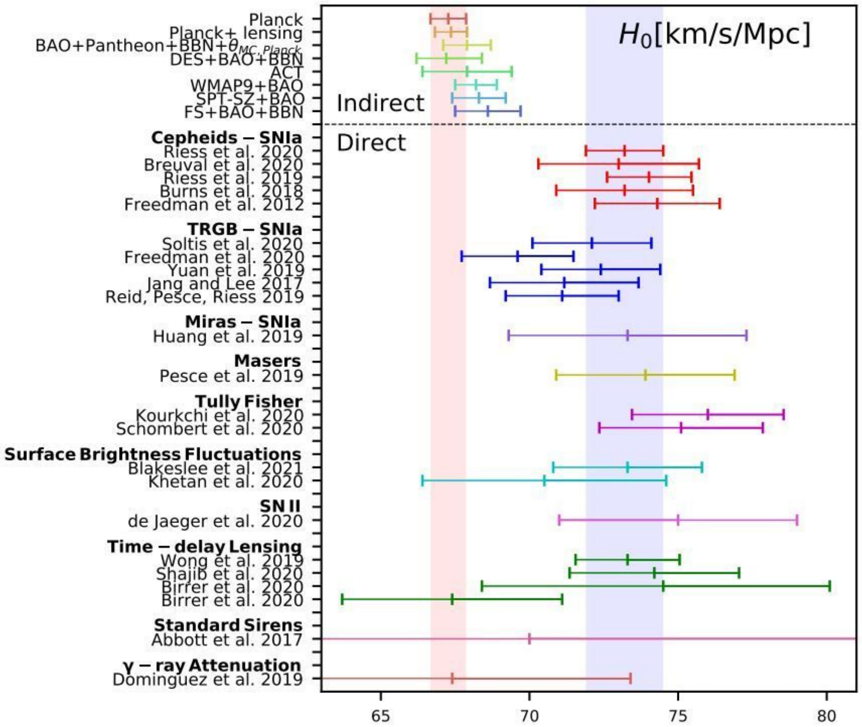


Planck 18, Di Valentino, 2019

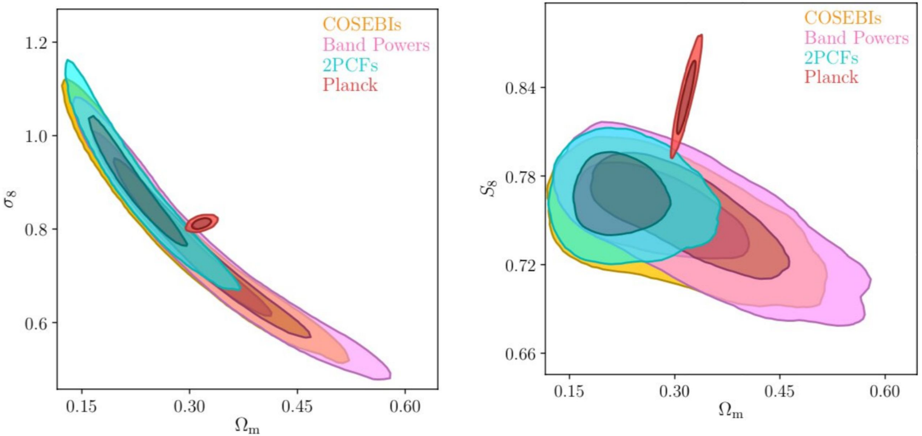
Tensions

H0 tension

Di Valentino 2020

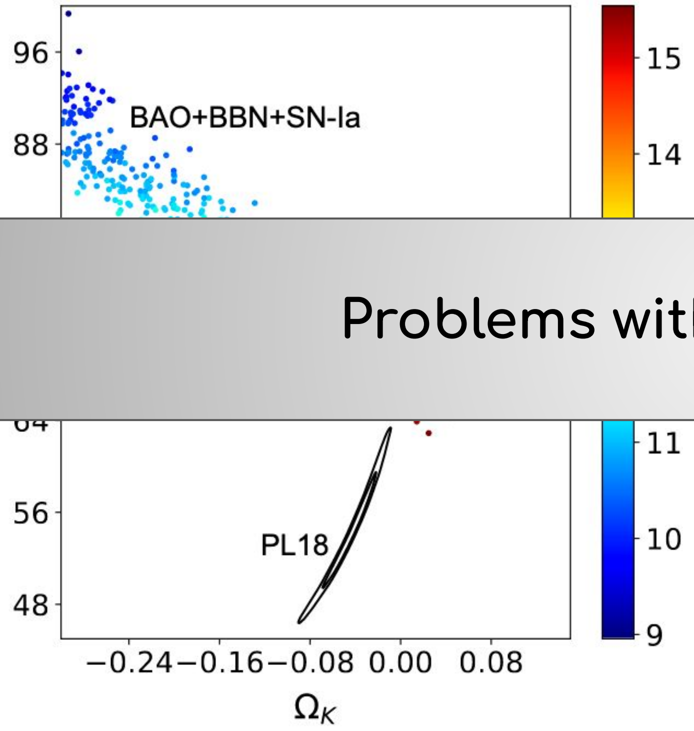


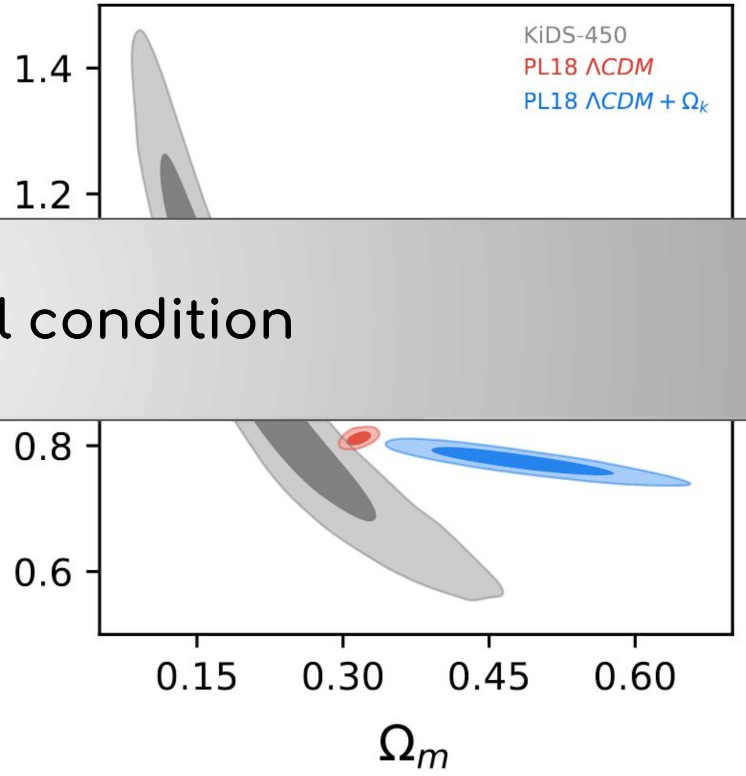
S8 tension



KiDS1000: Asgari 2020

Closed Universe aggravates tensions





Problems with initial condition

Di Valentino, 2019

Solutions to H0 tensions

1. Early dark energy – Poulin+ 2018, +++
2. Emergent dark energy (late time solution) – Li, Shafieloo, 2019, +++
3. Negative Λ – Sen + 2021, ++
4. Scalar-tensor theory, Rossi + 2019 , +++
5. Early modified gravity, Braglia + 2020, +++
6. Other extensions to standard model – +++
7. Systematics in the H0 measurements – +++
8. Systematics in the Planck CMB data – +++

A common solution: let's explore the primordial physics

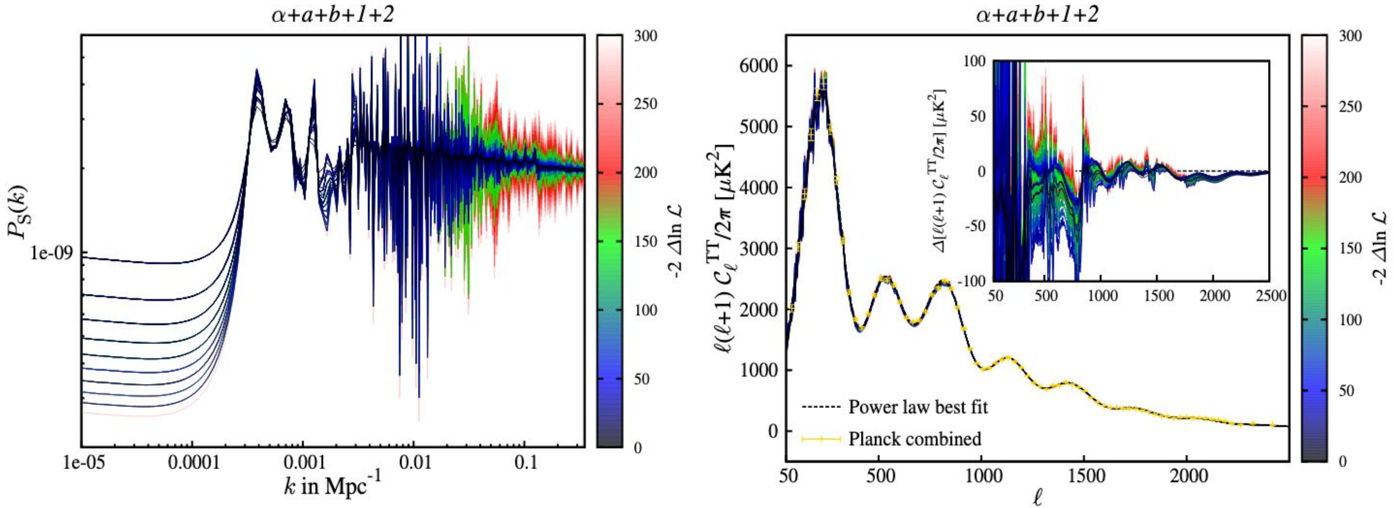
Let us reconstruct the primordial power spectrum

- A spectrum that mimics lensing
- A spectrum that prefers flat Universe
- A spectrum that prefers higher H0 than baseline
- A spectrum that prefers lower S8 than baseline

Let's rewind (reconstruction: top down approach)

Reconstruction: primordial power spectrum from Planck

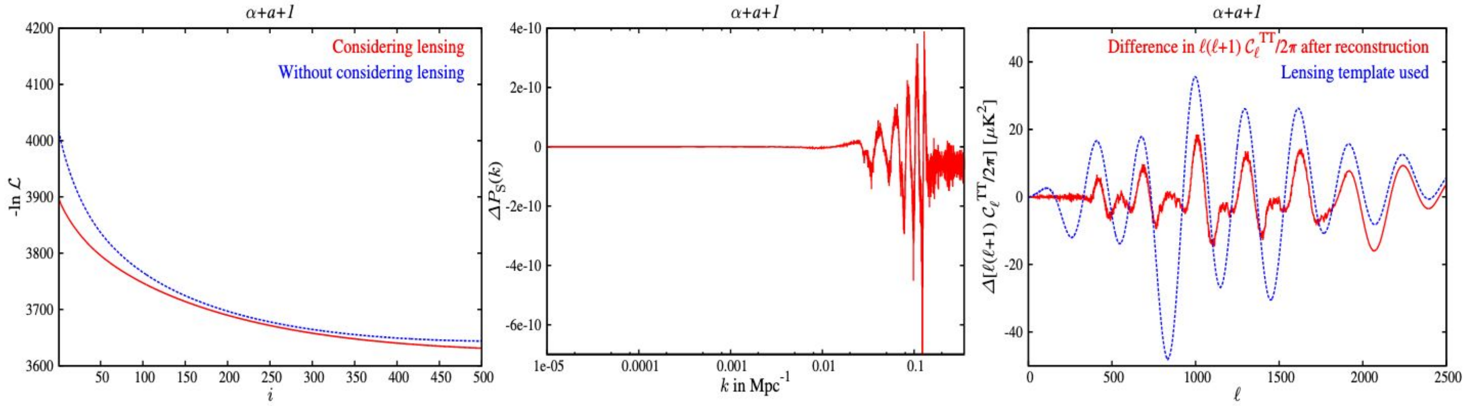
Given the transfer function, Modified Richardson Lucy can reconstruct the primordial power spectrum from angular power spectrum data iteratively



Hazra, Shafieloo, Souradeep JCAP 2014

Let's rewind

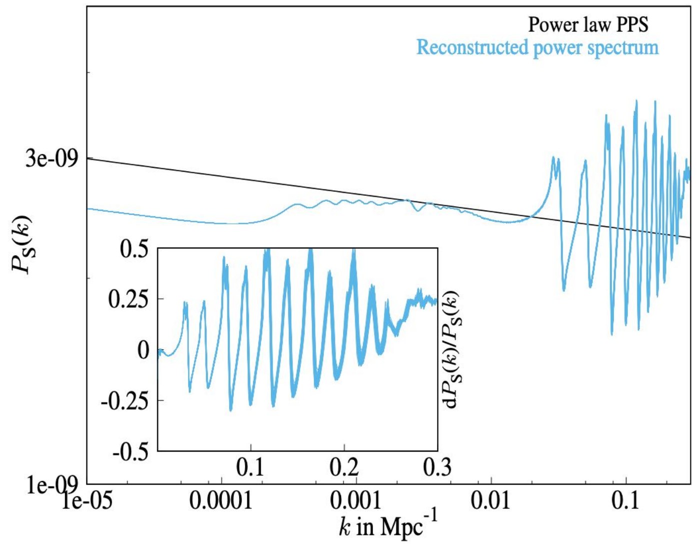
Primordial features can mimic the lensing effects with oscillations at small scales

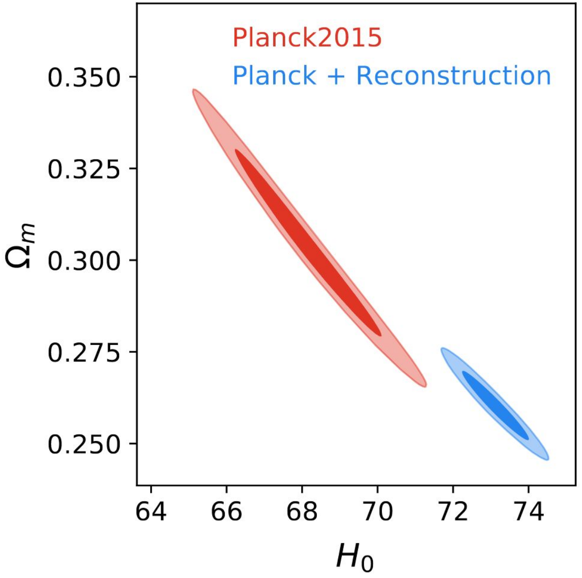


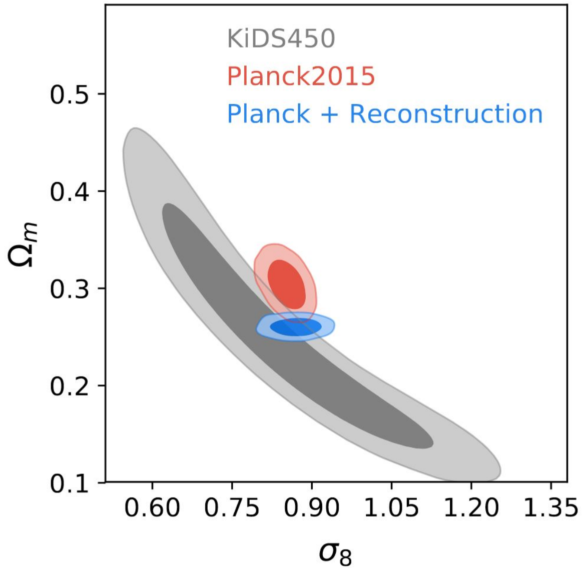
Hazra, Shafieloo, Souradeep JCAP 2014

Let's rewind

Can primordial features solve H0 and S8 tension ?







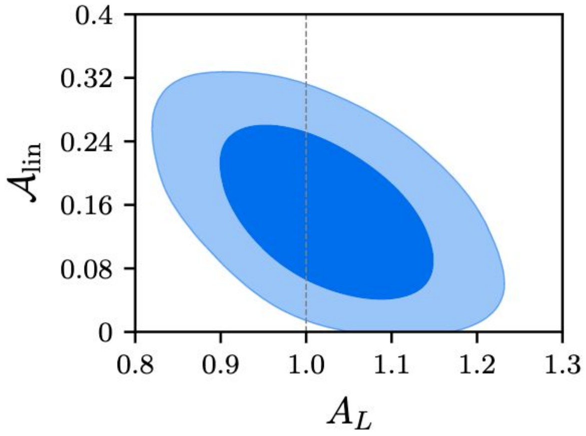
Hazra, Shafieloo, Souradeep JCAP 2019

Let's rewind: Planck 2018 paper V2

The following spectra was proposed as a solution to Alens problem:

$$\mathcal{P}_{\mathcal{R}}^{0}(k)\left[1+\mathcal{A}_{\rm lin}\,\exp(-(k-\mu_{\rm env})^2/2\sigma_{\rm env}^2)\,\cos\left(\omega_{\rm lin}k/k_*+\varphi_{\rm lin}\right)\right]$$

This is similar to our reconstruction (2014)
demonstrating sinusoidal oscillations
at small scales:



Planck 2018 V2

One Spectrum: the idea

Assume the excess lensing effect is actually a primordial signal

Treat the best fit baseline+Alens best fit to the Planck TT data as the input spectrum for reconstruction

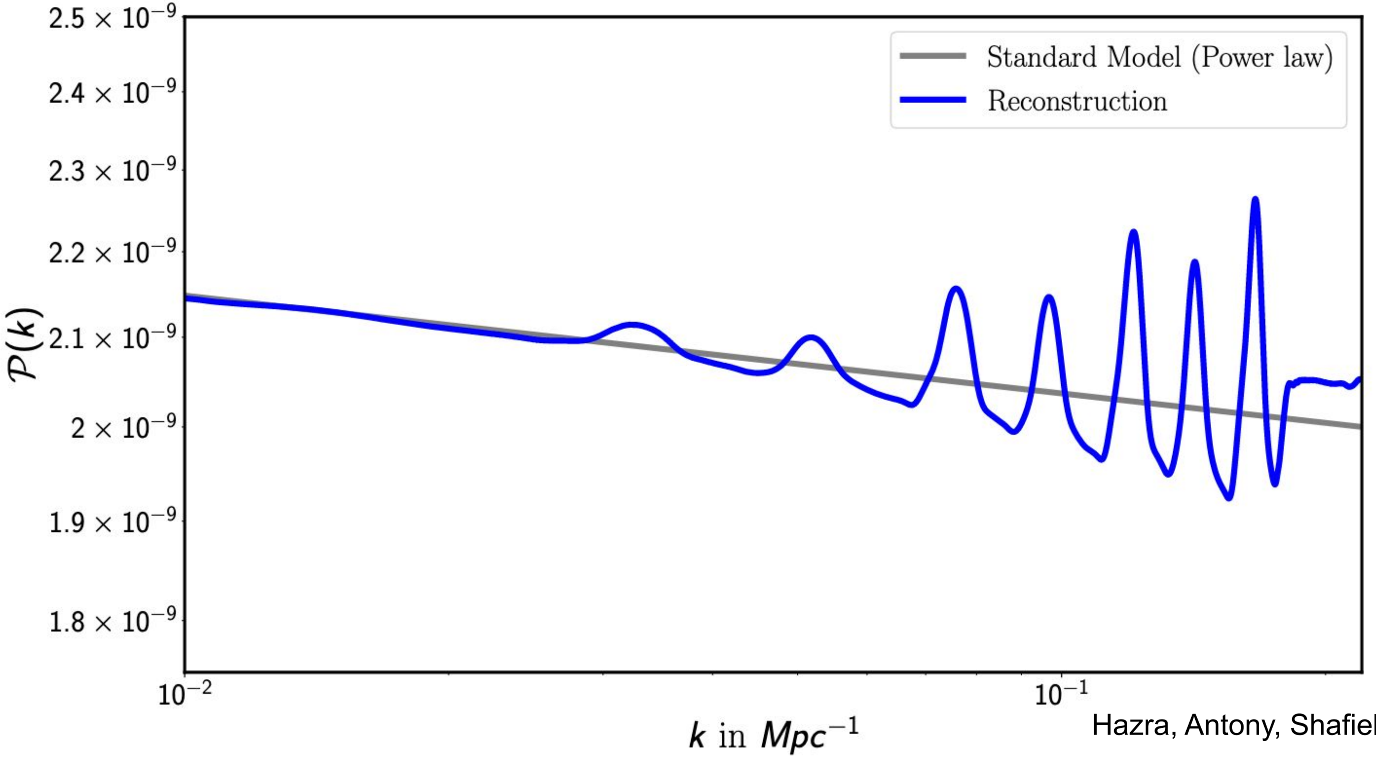
Subtract the lensing effect corresponding to Alens=1

What remains is the residual excess smoothing corresponding to 10% excess lensing

A reconstruction is expected to capture the primordial features that can mimic the effect

Hazra, Antony, Shafieloo, JCAP 2022

One Spectrum



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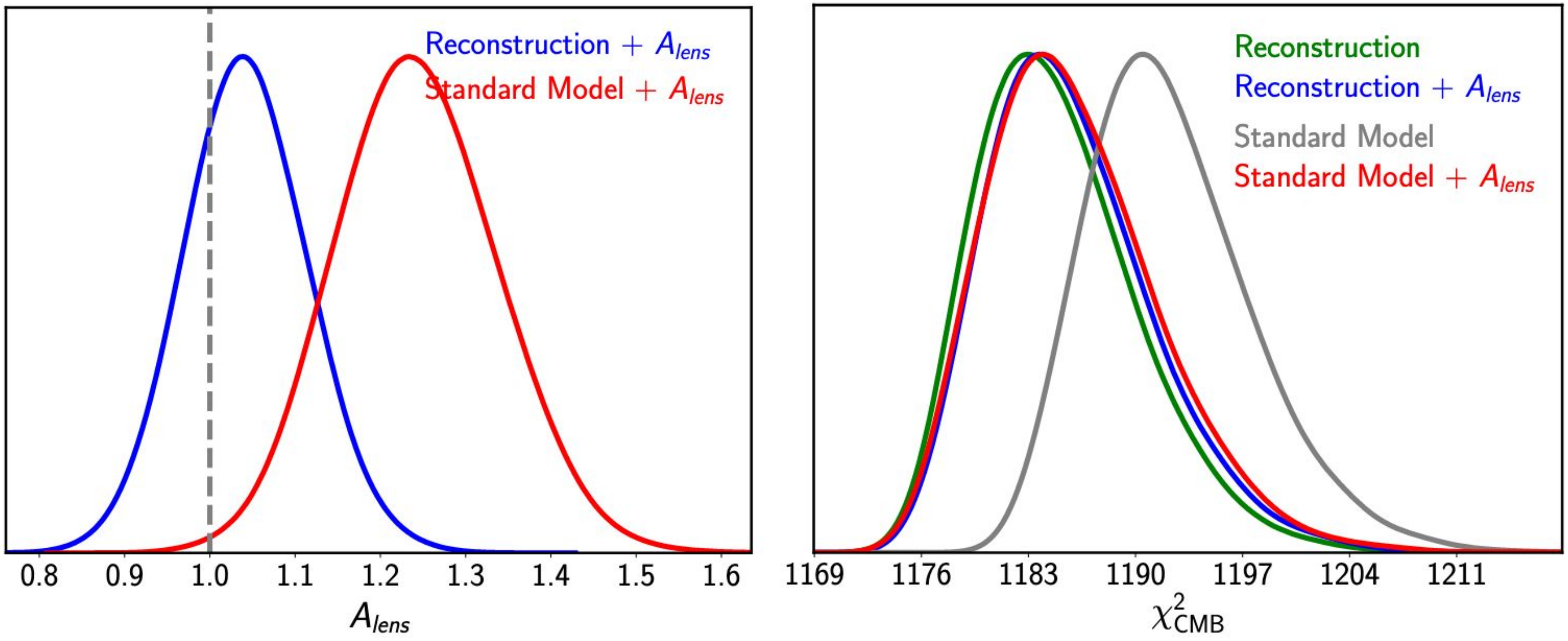
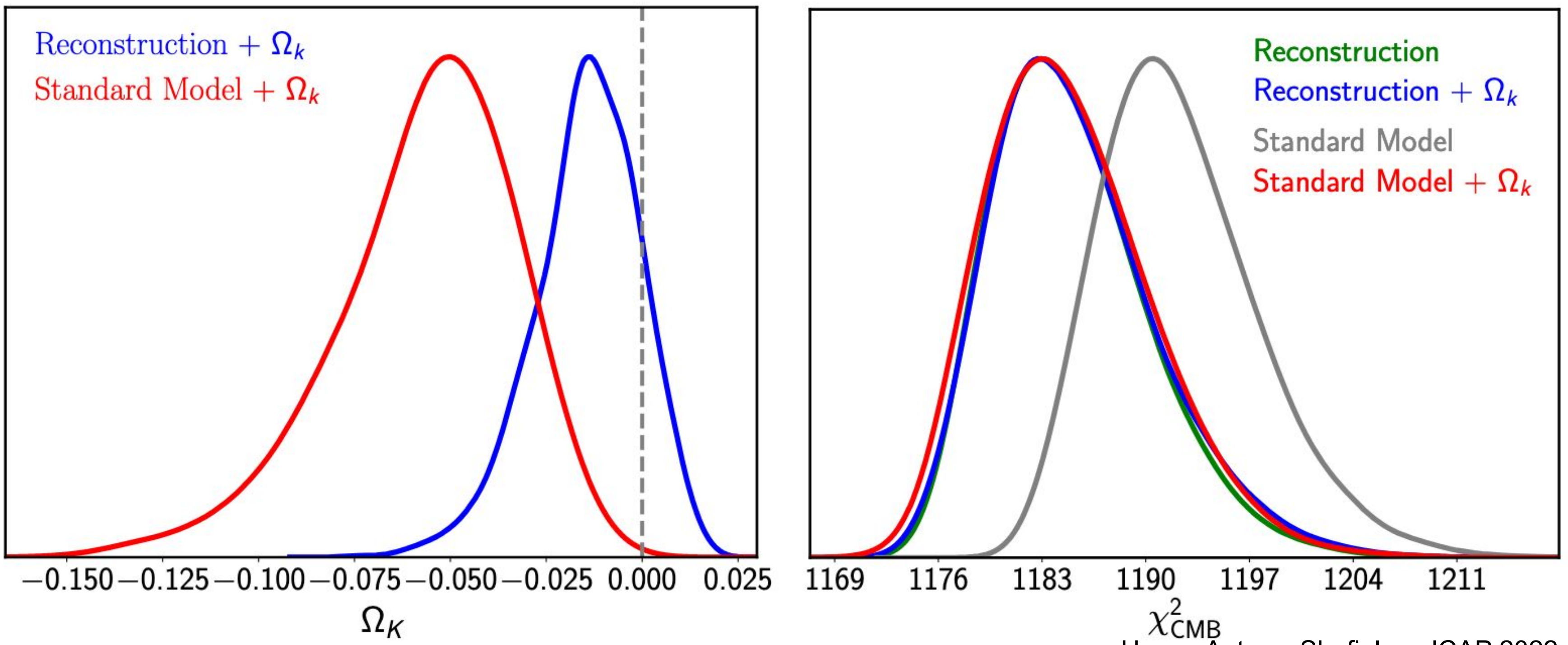
Mimics excess lensing



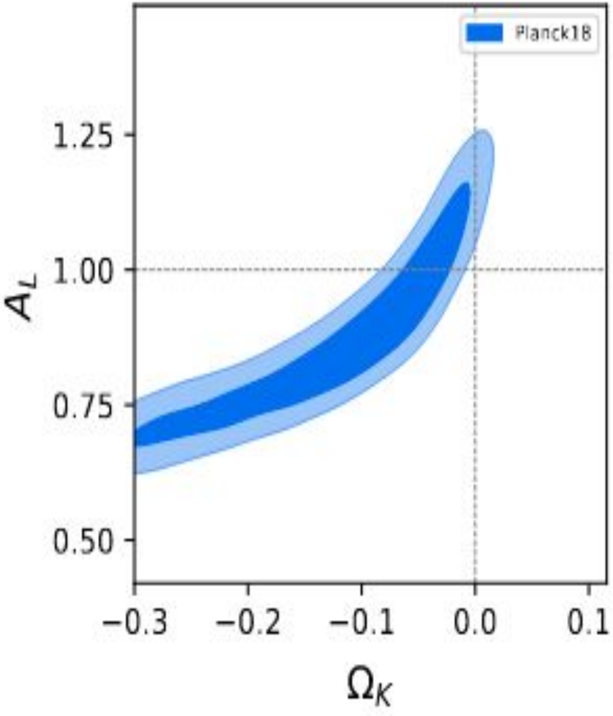
Hazra, Antony, Shafieloo, JCAP 2022

Prefers flat Universe



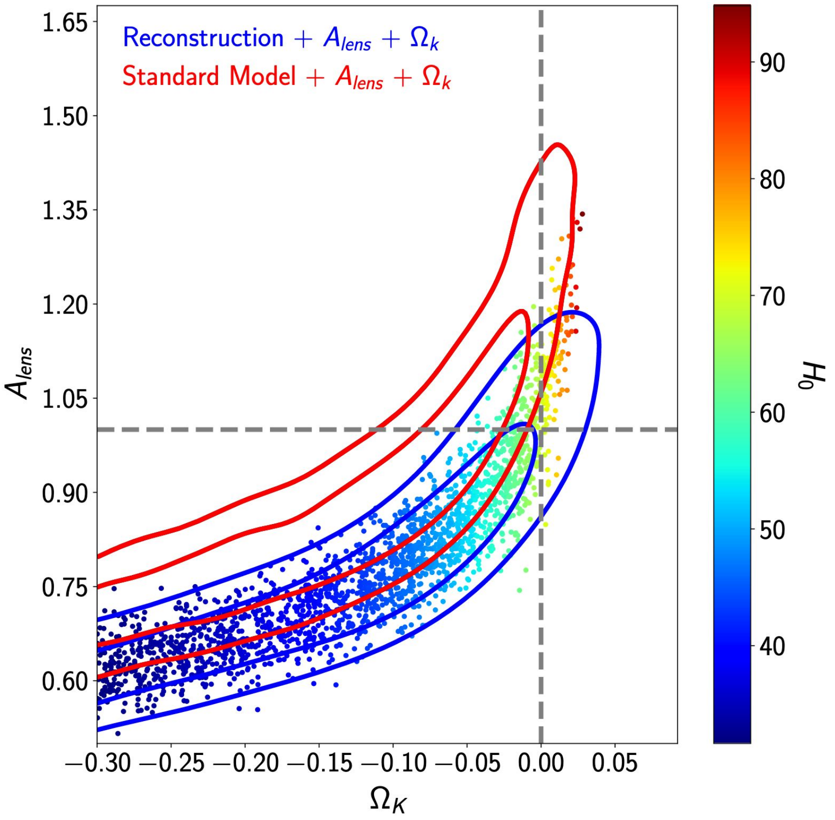
Hazra, Antony, Shafieloo, JCAP 2022

Brings back cosmic concordance

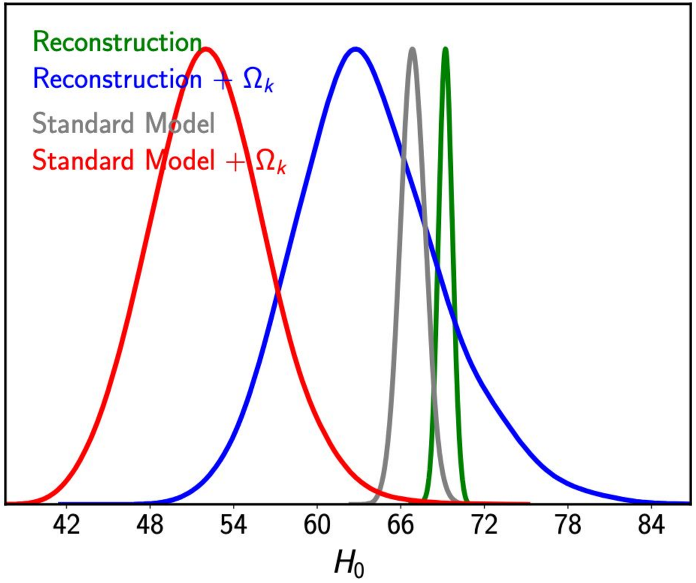


Di Valentino, 2019

Brings back cosmic concordance



Reduces H0 tension



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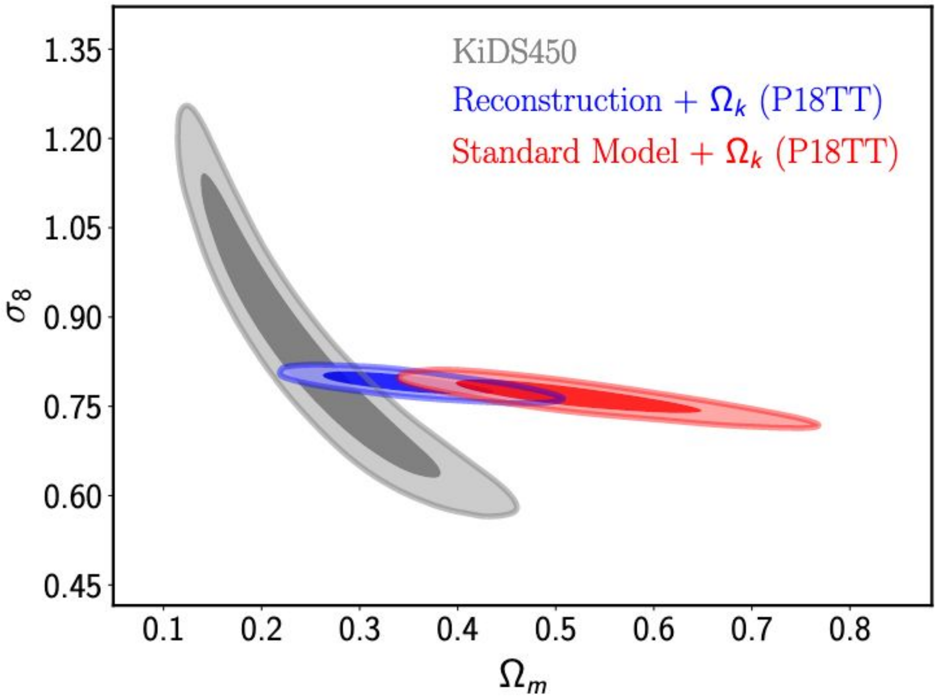
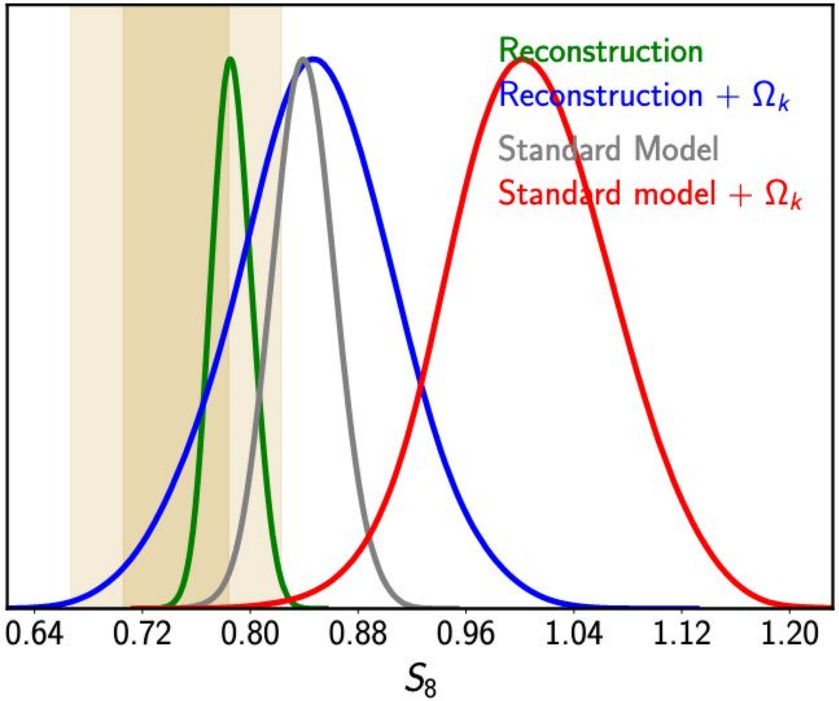
Solves S8 problem





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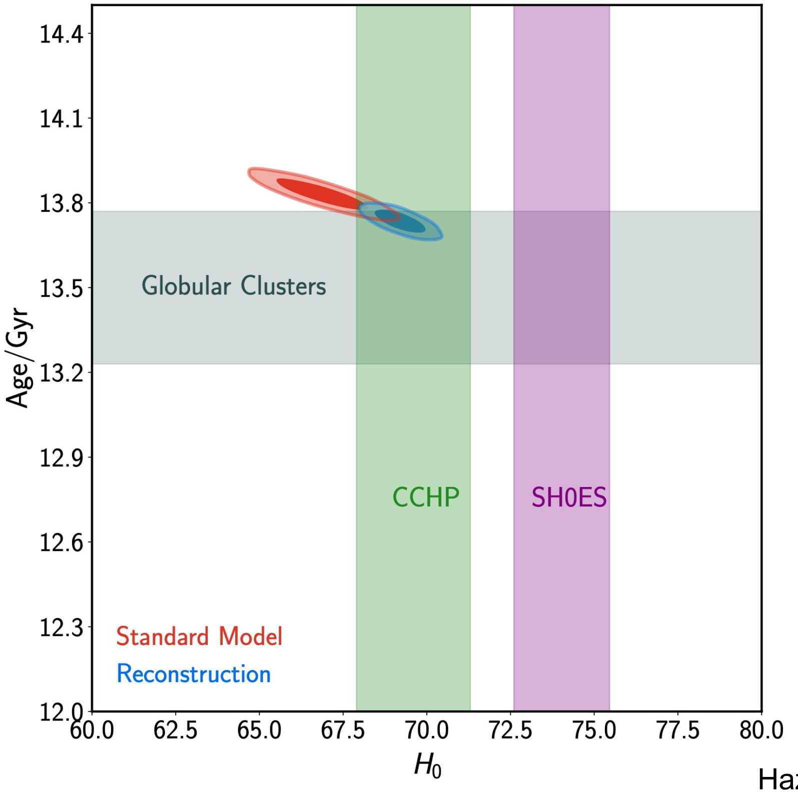
Age of the Universe



Hazra, Antony, Shafieloo, JCAP 2022

One Spectrum

Therefore, we find:

- ***One Spectrum*** mimics lensing
- ***One Spectrum*** prefers flat Universe
- ***One Spectrum*** prefers higher H0 than baseline
- ***One Spectrum*** prefers lower S8 than baseline

Can we parametrize such spectrum?

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

Models/Data	P18TT	P18TT + HST
New spectrum	-1.14 $\pm$ 0.53	2.67 $\pm$ 0.53
Restricted spectrum	-0.58 $\pm$ 0.52	3.4 $\pm$ 0.53

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

10^{-2} 10^{-1}

k in Mpc^{-1}

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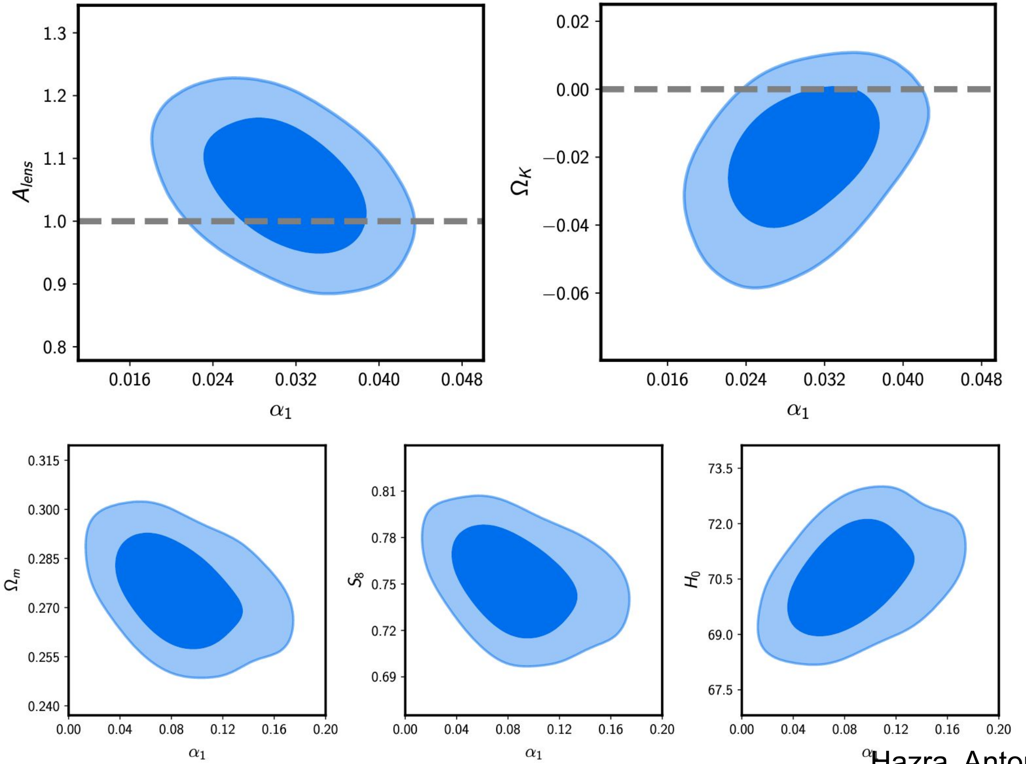
Positive correlations of solutions



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Best fit and evidence

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%

10 10

k in Mpc^{-1}

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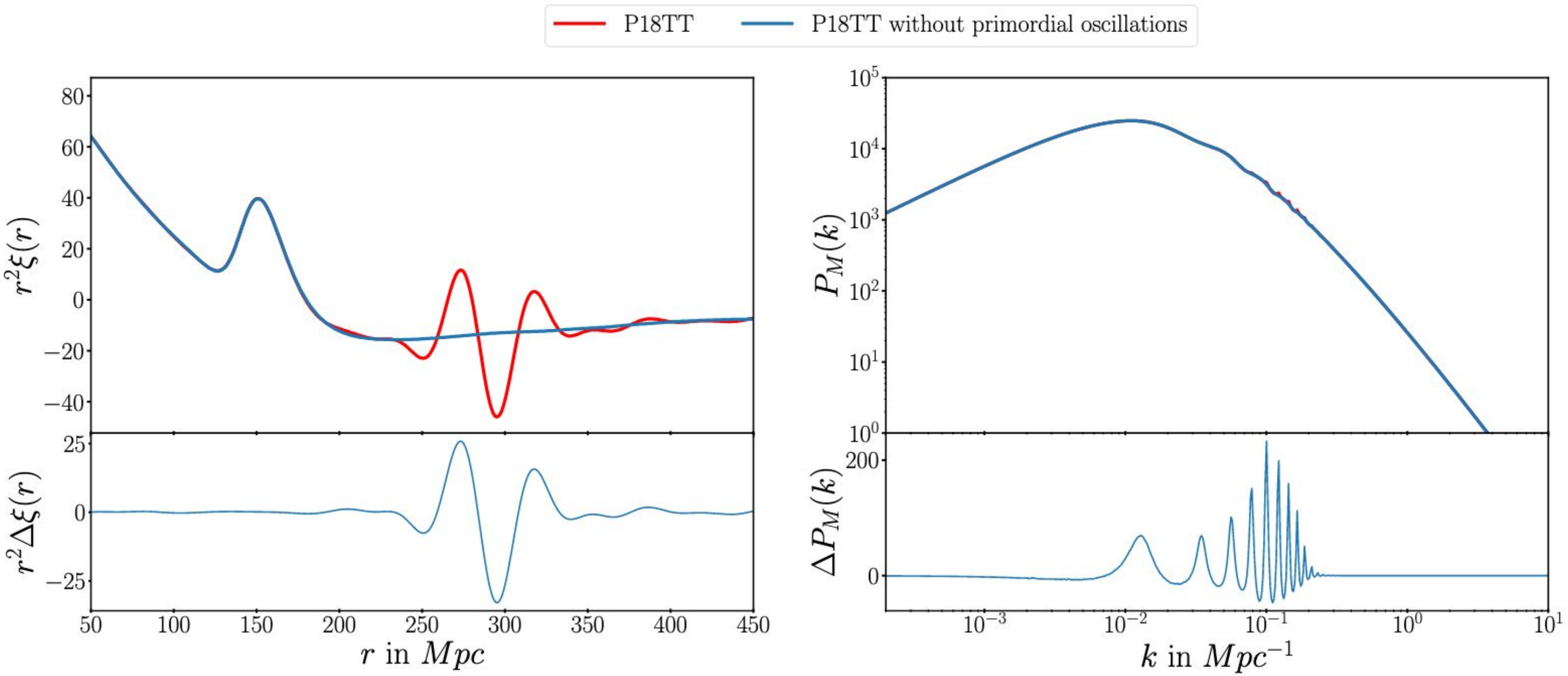
Implications for the large scale structure



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Theoretical explanation: An inflationary trajectory

An intermediate fast roll phase in the scalar field dynamics. We parametrize the Hubble flow function

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

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Why Hubble flow functions and not potential ?

Usually potential parameters restricts the prior space of spectral tilt. Exploration of this degeneracy demands a wide prior on the spectral tilt

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

The baseline parametrization of the Hubble flow function allows us to have wide priors on scalar spectral amplitude, tilt, and tensor-to-scalar ratio

This one parametrization allows us to marginalize over all minimal slow roll potentials

The free parameters are $H^2_{\ i}/\epsilon_1$, ϵ_1 and ϵ_2

Why Hubble flow functions and not potential ?

Here: $$n_s = 1 - 2\epsilon_1 - \epsilon_2$$

$$r = 16\epsilon_1$$

The spectral amplitude is proportional to $\frac{H_i^2}{\epsilon_1}$

Given these parameters, we solve the Hubble flow function numerically to obtain the evolution of the Hubble radius during inflation

Using Bunch-Davies vacuum initial condition, we solve the Mukhanov-Sasaki equations to get the primordial scalar and tensor power spectra

NOTE: No assumption on the potential goes in here. We work with canonical Lagrangian

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Datasets

We consider the temperature data separately (P18TT) and including polarization (P18TP) and lensing (P18TPL). Also P18TTEE was considered.

1. P18TT + BK18
2. P18TT + BK18 + S21
3. P18TEEE + BK18
4. P18TEEE + BK18 + S21
5. P18TP + BK18
6. P18TP + BK18 + S21
7. P18TPL + BK18
8. P18TPL + BK18 + S21

In all combinations we use BICEP-Keck 2018 data (BK18). It provides an upper bound on the tensors and therefore on ϵ_1

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Reasons for including SH0ES21 (S21)

When two datasets are in tension w.r.t. a model, an analysis combining the datasets would provide an unrealistic posterior on parameters. In such a case the drag on the parameters from both data degrades the fit to both datasets.

Here, on the other hand compared to the baseline parametrization, without using S21, we find posteriors on H0 shifts to higher value (1σ shift) with 8-11 improvements in χ^2

When S21 is used – the best fit to the joint data provides ~20 improvement in fit. Breakdown in χ^2 shows $\chi^2{}_{\rm CMB}$ for the best fit to the joint dataset is nearly 3 χ^2 better than the baseline best fit to CMB only data.

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Shifts in parameters

Data	$\Delta\chi^2$ Total	$\Delta\chi^2$ CMB	$\Delta\chi^2$ SH0ES	C.L.	$1-2\epsilon_1-\epsilon_2$ ($\simeq n_s$)	$16\epsilon_1$ ($\simeq r$)	H_0	S_8	Ω_m
P18TT+BK18	-8.3	-8.3	-	82.7	0.963±0.005	<0.036	66.86±0.86	0.840±0.022	0.321±0.012
					0.971±0.007	<0.040	68.06±1.14	0.814±0.027	0.306±0.015
P18TEEE+BK18	-2.7	-2.7	-	< 68	0.969±0.009	<0.041	67.91±0.77	0.814±0.020	0.308±0.010
					0.968±0.009	<0.041	67.63±0.86	0.819±0.022	0.311±0.012
P18TP+BK18	-10.7	-10.7	-	72.5	0.965±0.004	<0.036	67.26±0.59	0.835±0.015	0.317±0.008
					0.969±0.005	<0.037	67.71±0.66	0.826±0.017	0.311±0.009
P18TPL+BK18	-8.4	-8.4	-	70	0.965±0.004	<0.035	67.35±0.53	0.832±0.012	0.315±0.007
					0.968±0.004	<0.037	67.63±0.57	0.829±0.013	0.312±0.008
P18TT+BK18+S21	-19.5	-10.9	-8.6	> 99.9	0.976±0.005	<0.040	69.41±0.68	0.781±0.017	0.287±0.008
					0.986±0.007	<0.047	70.85±0.78	0.754±0.018	0.273±0.008
P18TEEE+BK18+S21	-1.2	-1.0	-0.2	< 68	0.981±0.008	<0.046	69.76±0.63	0.772±0.016	0.284±0.007
					0.979±0.009	<0.040	69.77±0.67	0.771±0.017	0.284±0.008
P18TP+BK18+S21	-19.3	-9.7	-9.6	98.6	0.973±0.004	<0.039	68.71±0.53	0.802±0.014	0.297±0.007
					0.978±0.004	<0.041	69.27±0.58	0.791±0.014	0.291±0.007
P18TPL+BK18+S21	-11.5	-10.4	-1.1	92.1	0.972±0.004	<0.038	68.56±0.48	0.808±0.011	0.299±0.006
					0.975±0.004	<0.041	68.90±0.51	0.804±0.011	0.296±0.006

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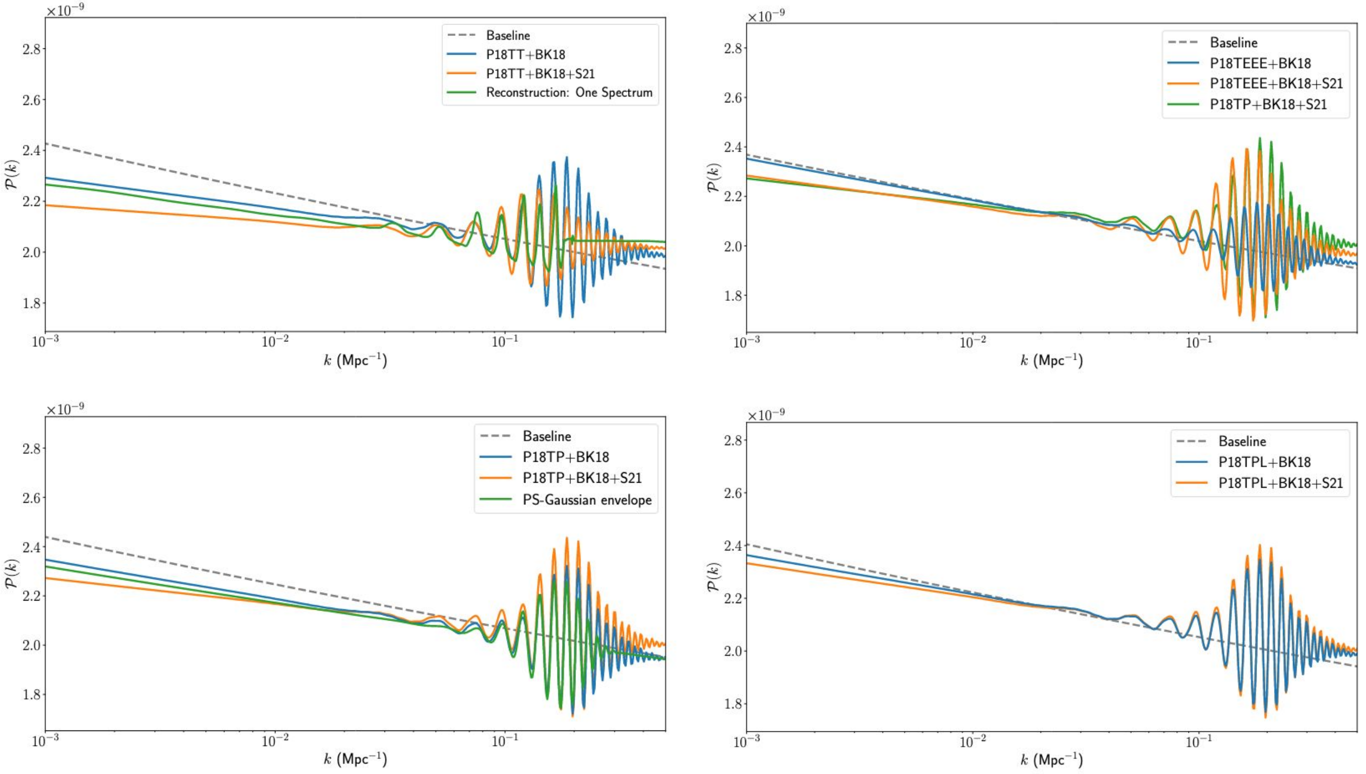
Best fit spectra



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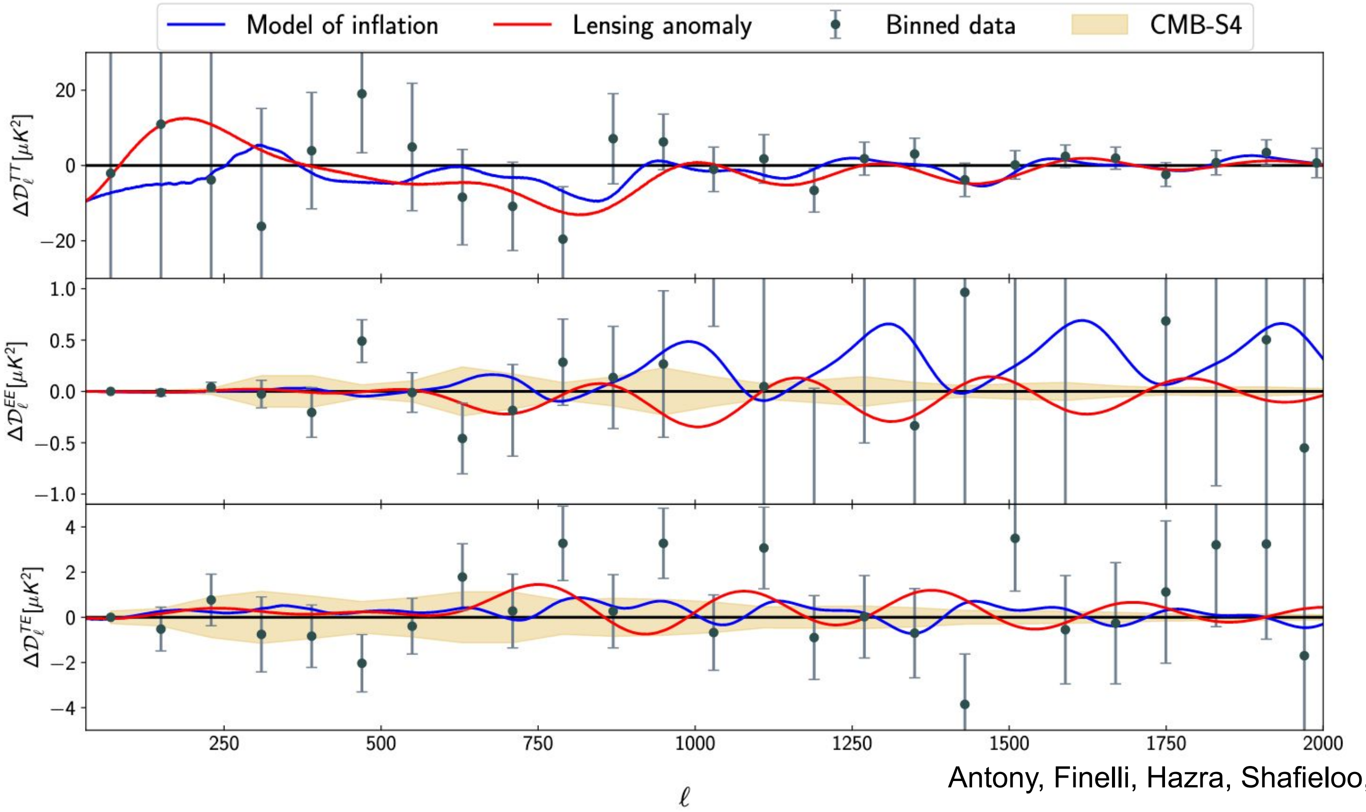
Breaking the degeneracy



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Reverse engineering to find the potential

The potential can be obtained with reverse engineering:

$$V(\phi[N]) = 3M_{\mathrm{Pl}}^2 H[N]^2(1-\epsilon_H[N]/3)$$

The reconstructed potential can be expressed with the following template:

$$\frac{\Delta V(\phi)}{V_{\mathrm{baseline}}(\phi)} = \frac{\alpha\cos[\omega(\phi-\phi_0)]}{1+\beta(\phi-\phi_0)^2}$$

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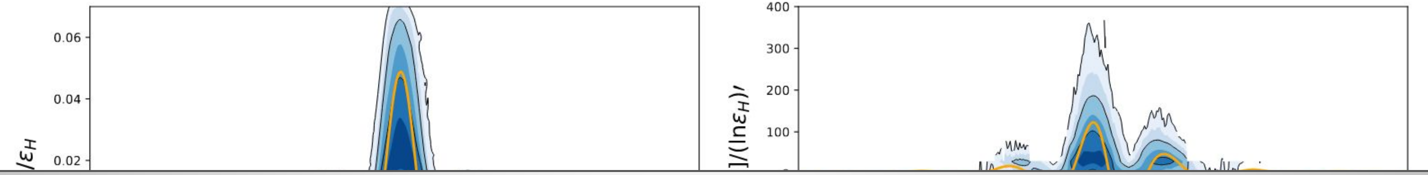
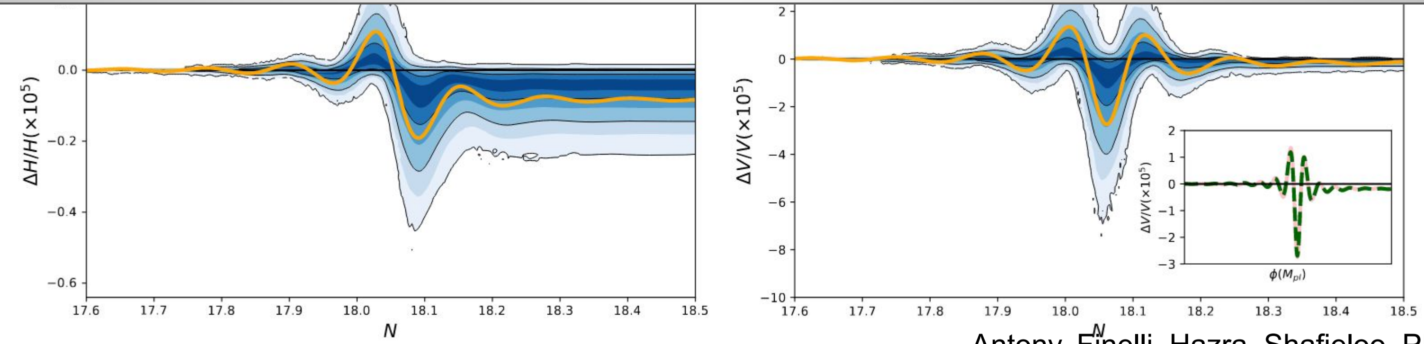
New physics of scalar field evolution



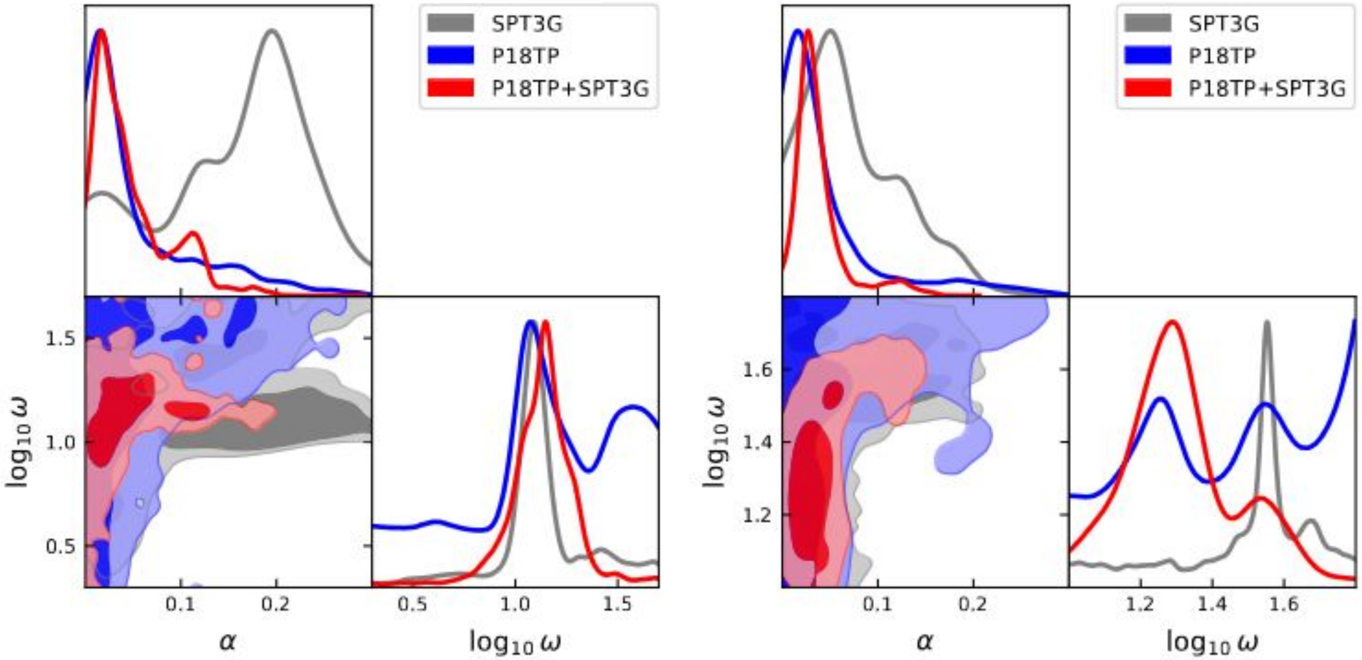
Strong support for an intermediate fast roll for 0.5 e-folds during inflation



Antony, Finelli, Hazra, Shafieloo, PRL 2023

Small Scale CMB data

$$P_{\rm local}^{\rm lin}(k) = P_0(k)\left[1+\alpha\cos\left(\omega\,\frac{k}{k_*}+\phi\right)e^{-\frac{\beta^2(k-\mu)^2}{2k_*^2}}\right] \qquad P_{\rm local}^{\rm log}(k) = P_0(k)\left[1+\alpha\cos\left(\omega\ln\frac{k}{k_*}+\phi\right)e^{-\frac{\beta^2(k-\mu)^2}{2k_*^2}}\right]$$



Antony, Finelli, Hazra, Paoletti, Shafieloo 2024

In summary

1. Anomalies and tensions within and between cosmological observations are correlated

2. ***One Spectrum*** provides a common solution

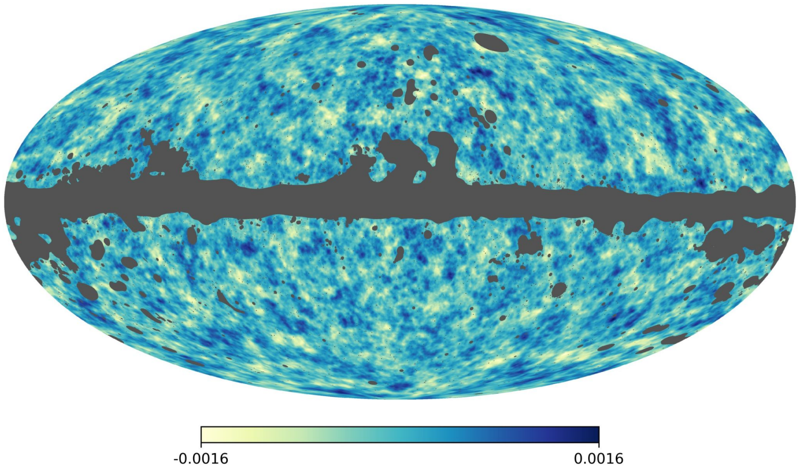
3. We find statistically significant preference for an intermediate fast roll during inflation as a candidate for new physics

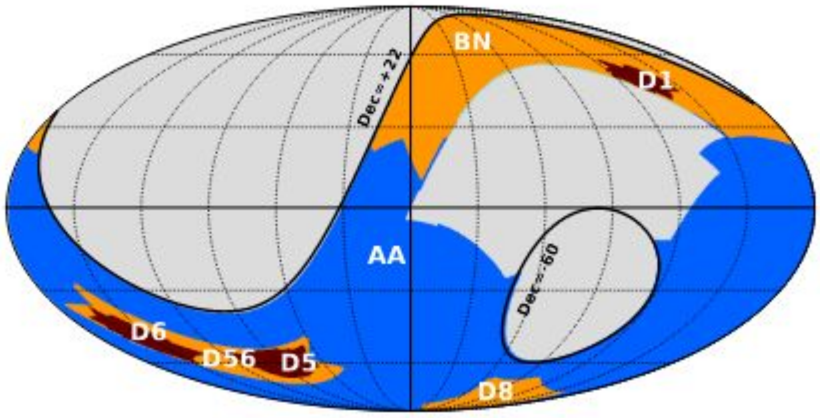
4. The candidate has strong signatures in CMB polarization and large scale structures at particular scales, that can be tested soon with upcoming data

5. Certain supports arise from small scale CMB data and the bispectrum too

When tension can be systematics ?

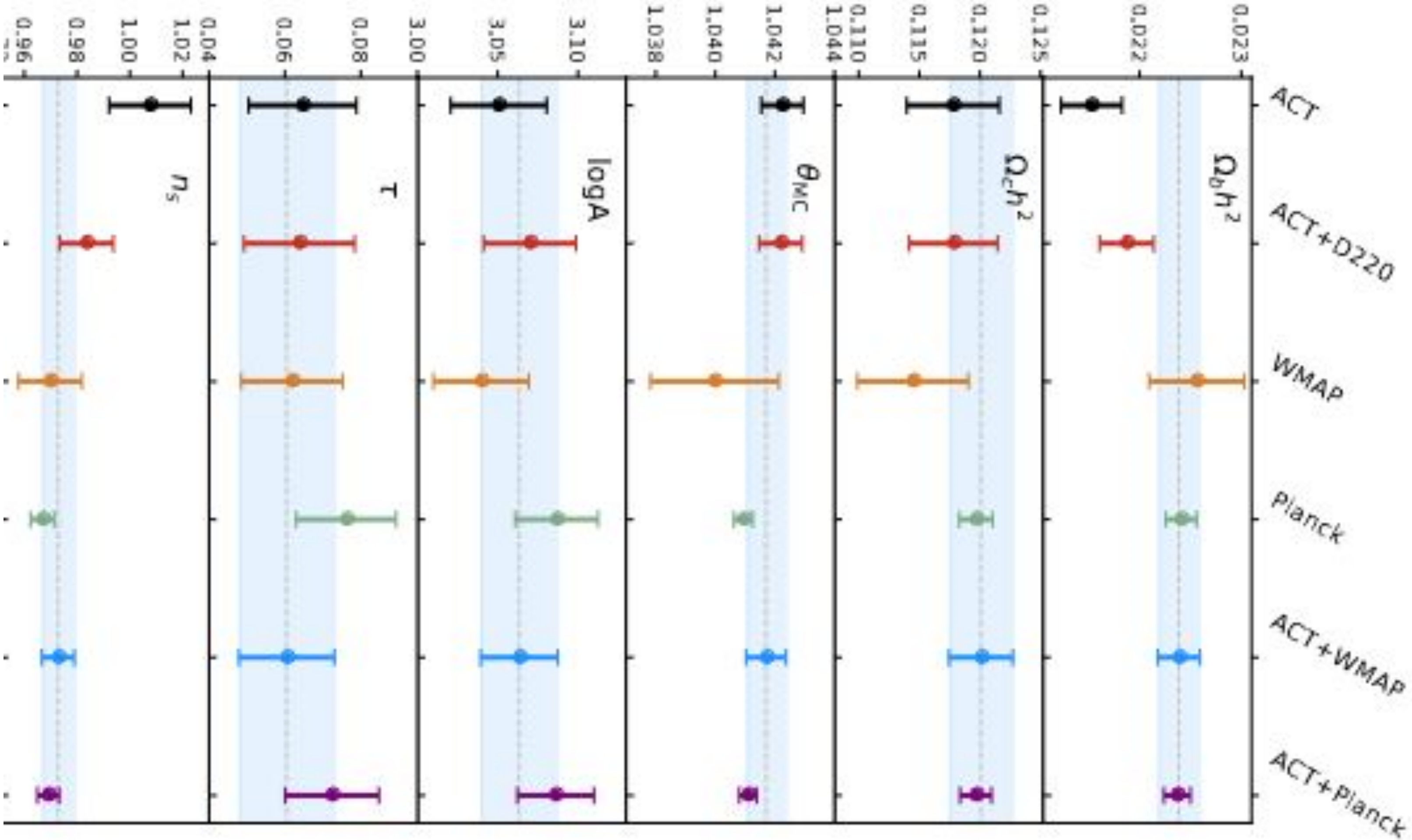
Planck PR3 and ACT DR4





Planck PR3

ACT DR4


ACT
ACT+D220
WMAP
Planck
ACT+WMAP
ACT+Planck
$\Omega_b h^2$
$\Omega_c h^2$
θ_{MC}
logA
τ
n_s

AcT DR4

Exploring the discrepancy between Planck PR3 and ACT DR4

Parametric test:

Instead of power law:

$$\mathcal{P}_S(k) = A_s(k/k_0)^{n_s-1}$$

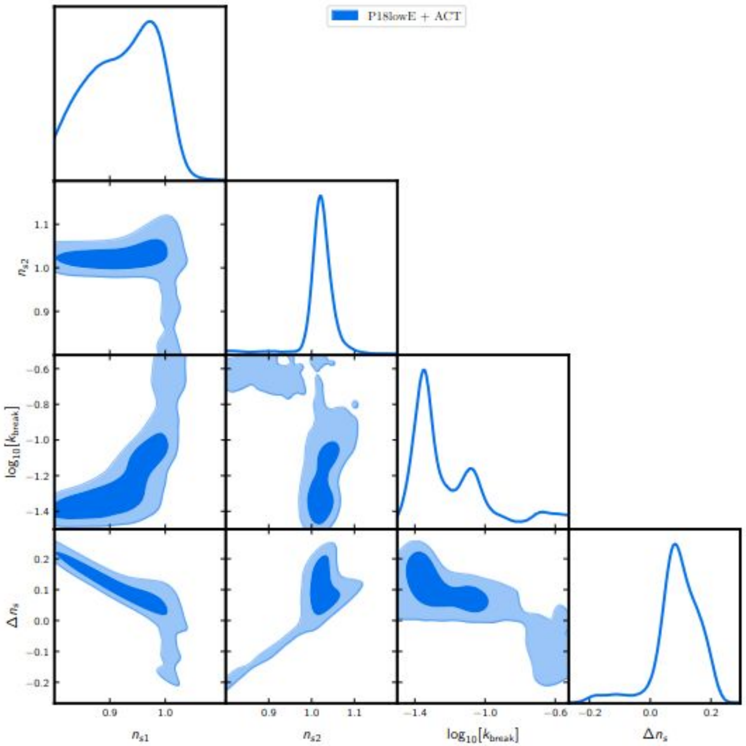
We use a simple extension with a transition in tilt:

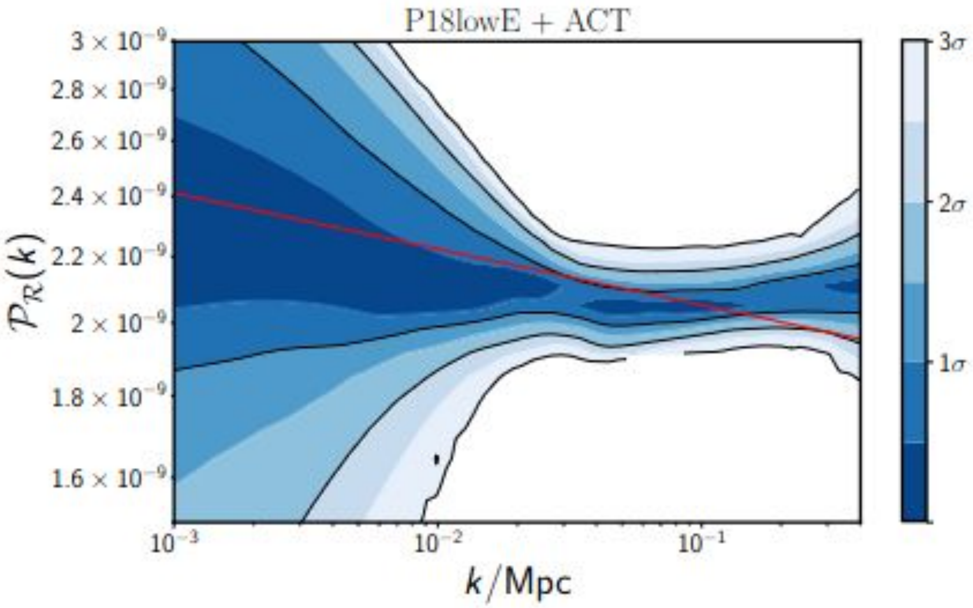
$$\mathcal{P}_S^{\text{broken}}(k) = A_s(k = k_{\text{break}}) \times \begin{cases} (k/k_{\text{break}})^{n_{s1}-1}, & \text{if } k \leq k_{\text{break}} \\ (k/k_{\text{break}})^{n_{s2}-1}, & \text{if } k \geq k_{\text{break}} \end{cases}$$

Difference in tilt will be the parameter of interest.

Hazra, Beringue, Errard, Shafieloo, Smoot (to appear soon)

Exploring the discrepancy between Planck PR3 and ACT DR4





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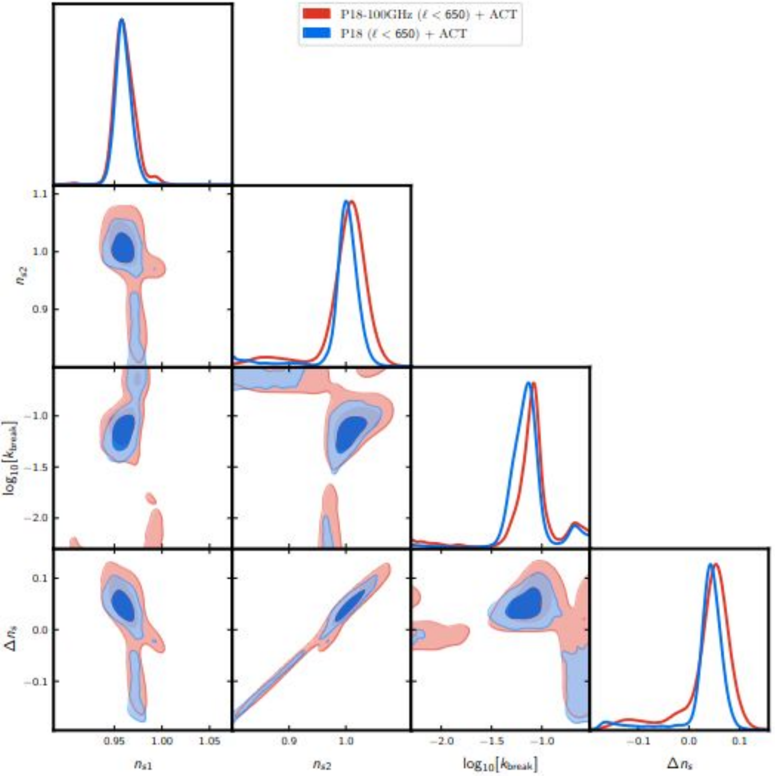

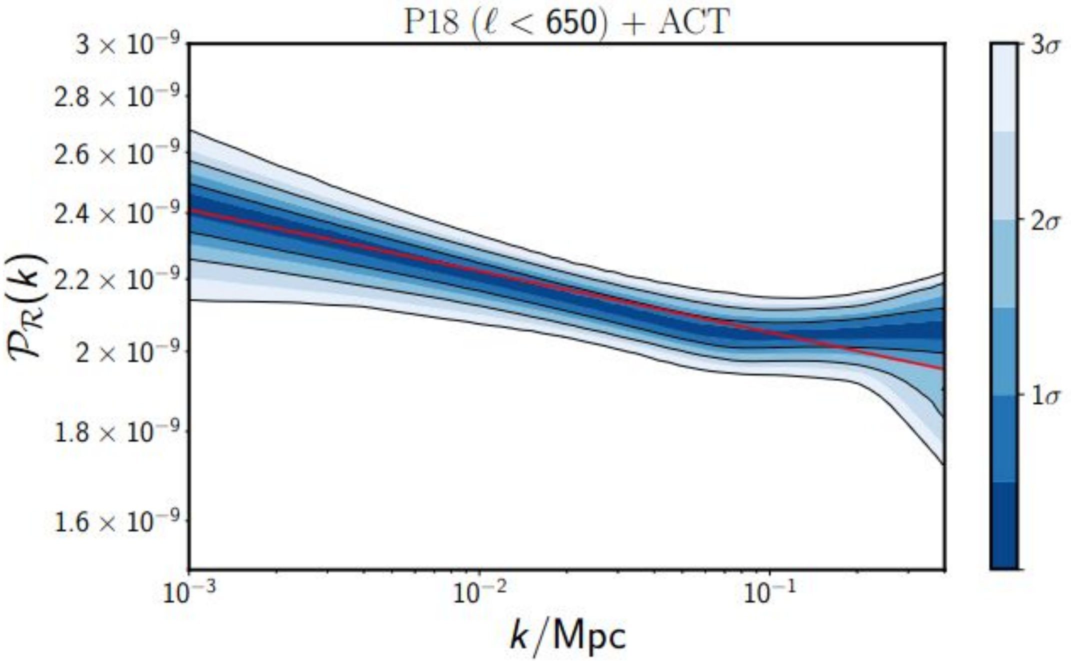

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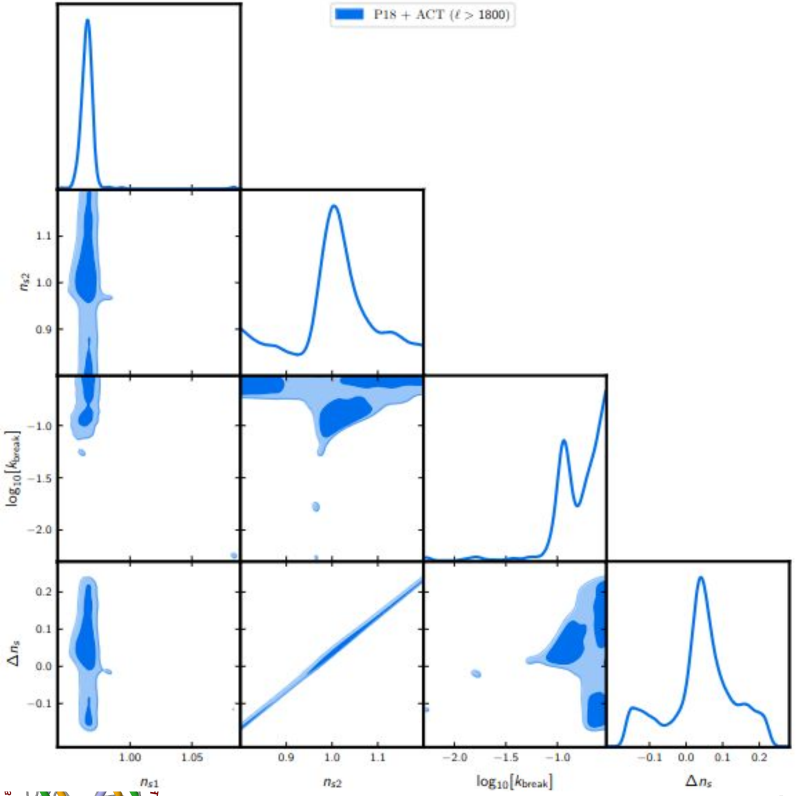
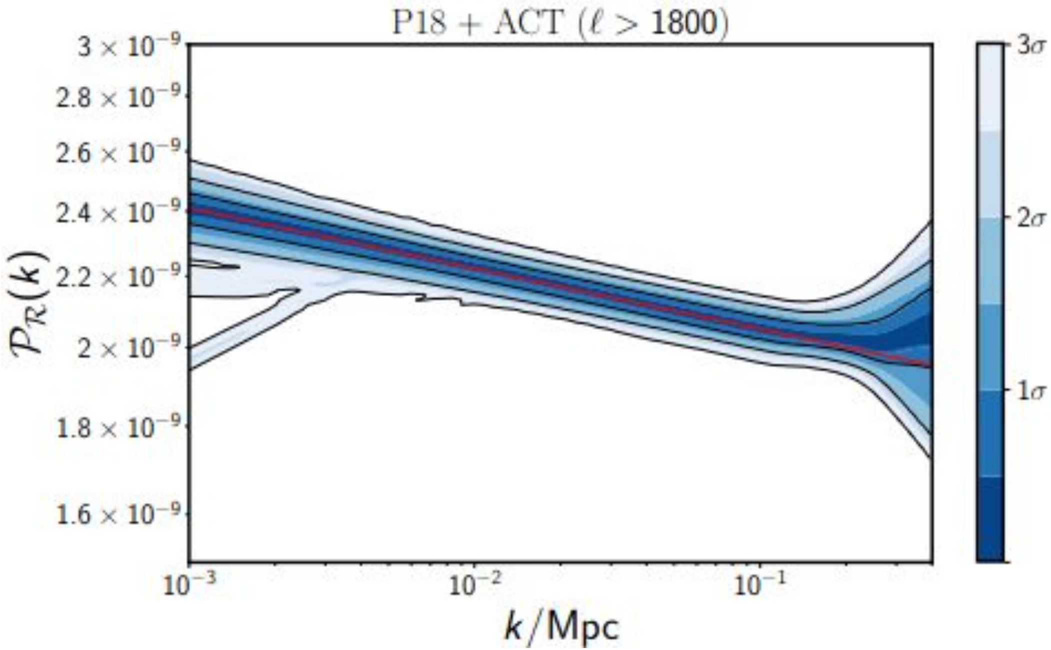




Hazra, Beringue, Errard, Shafieloo, Smoot (to appear soon)

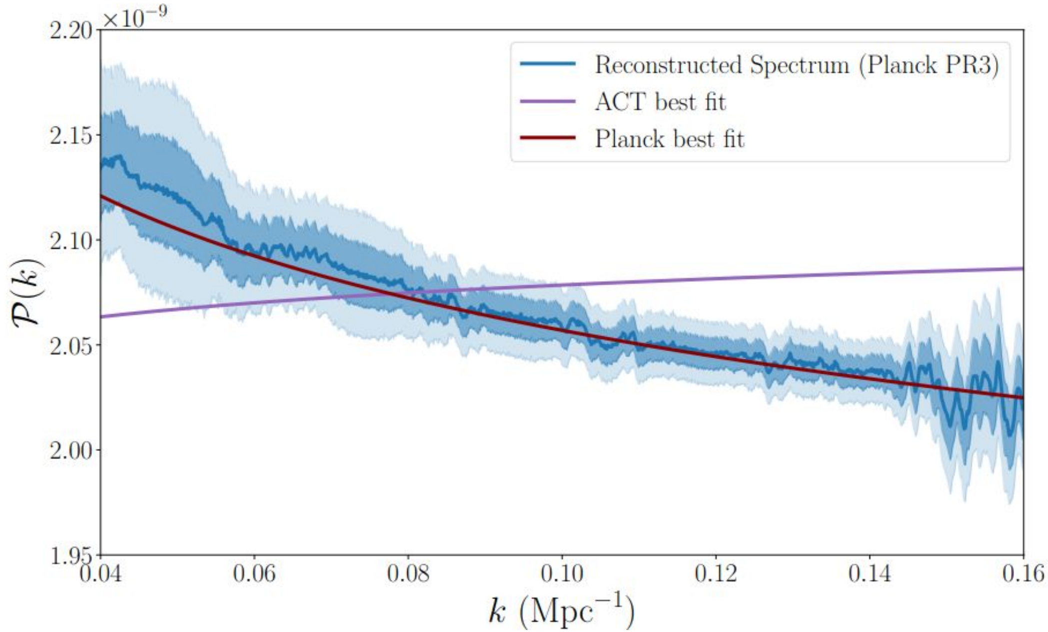
Exploring the discrepancy between Planck PR3 and ACT DR4

Datasets	$\Delta\chi^2_{\mathrm{eff}}$	$\ln B$
P18+ACT ($\ell > 1800$)	-2.4	-0.3
P18lowE+ACT	-6.8	0.7
P18-100GHz ($\ell < 650$)+ACT	-8.1	0.3
P18 ($\ell < 650$)+ACT	-7.1	1.2
P18-143-217GHz+ACT ($\ell > 1800$)	-0.7	-1.1
P18EE+ACT	-9.7	1.8
P18TEEE+ACT	-6	0.9

Hazra, Beringue, Errard, Shafieloo, Smoot (to appear soon)

Exploring the discrepancy between Planck PR3 and ACT DR4

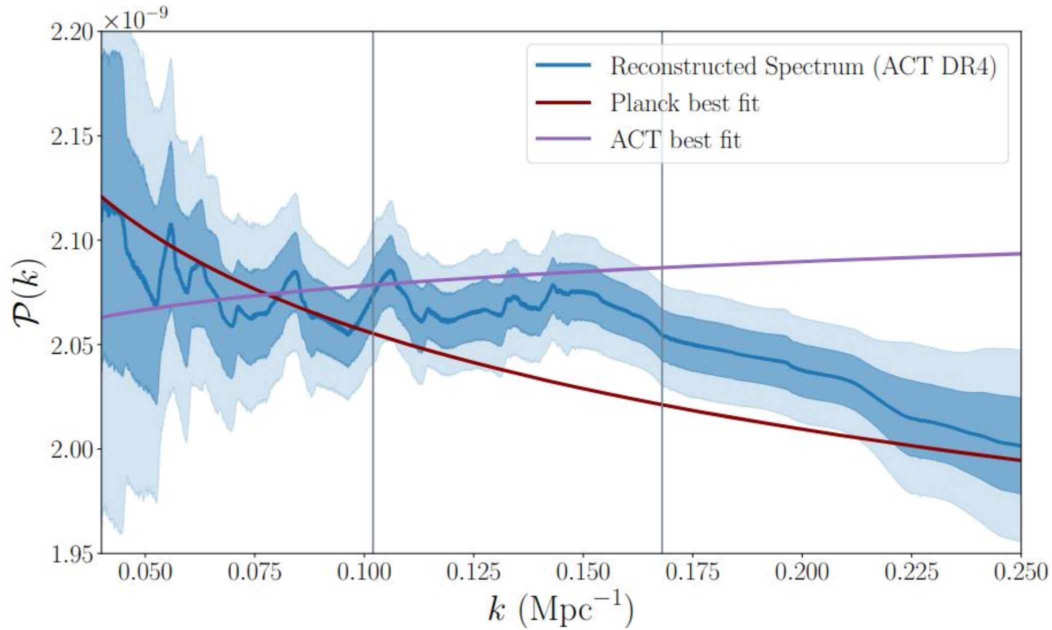
Non-parametric approach: Reconstruction



Hazra, Beringue, Errard, Shafieloo, Smoot (to appear soon)

Exploring the discrepancy between Planck PR3 and ACT DR4

Non-parametric approach: Reconstruction



Hazra, Beringue, Errard, Shafieloo, Smoot (to appear soon)

In summary

1. The discrepancy is there within ACT data itself at 2σ

2. Preference for a break in power increases if truncated Planck data is used jointly with ACT

3. The blue tilt from ACT is preferred at k ~ 0.08 – 0.16/Mpc (ℓ ~ 1100 – 2200)

4. When data are combined respecting the signal to noise ratios, the significance of the transition goes away

5. In such cases, the tension seems to not arising from any new physics

New physics or systematics

Hubble tension, S8 tension and lensing anomalies seem to be correlated. Therefore it is possible for new physics to emerge from there

Tensions between Planck and ACT seem to be coming from systematics. Statistical significance to the new physics candidates are originating from data selection effect in the joint analysis

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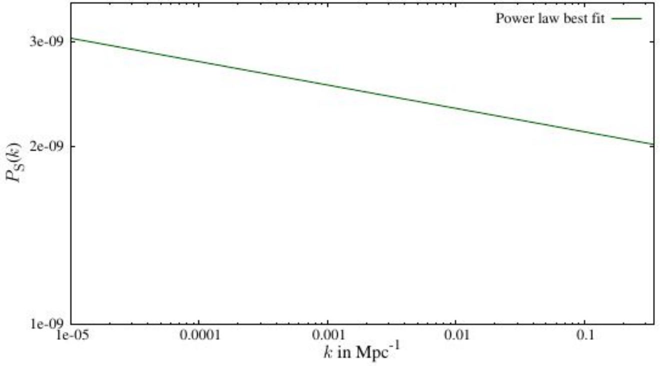
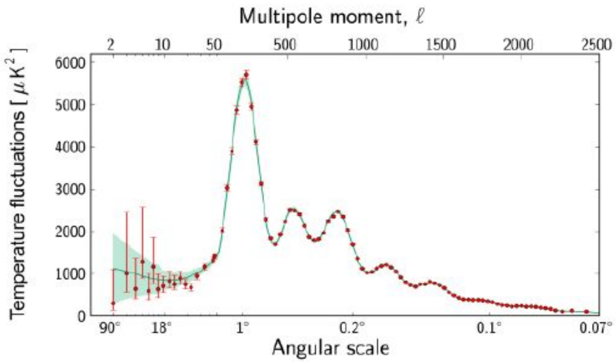
Thank you

Reconstruction of localized features

Primordial power spectrum



Angular power spectrum (Planck)



$$C_\ell^{\mathrm{T}} = \sum_i G_{\ell k_i} P_{k_i}$$

$G_{\ell k}$ is the radiative transport kernel

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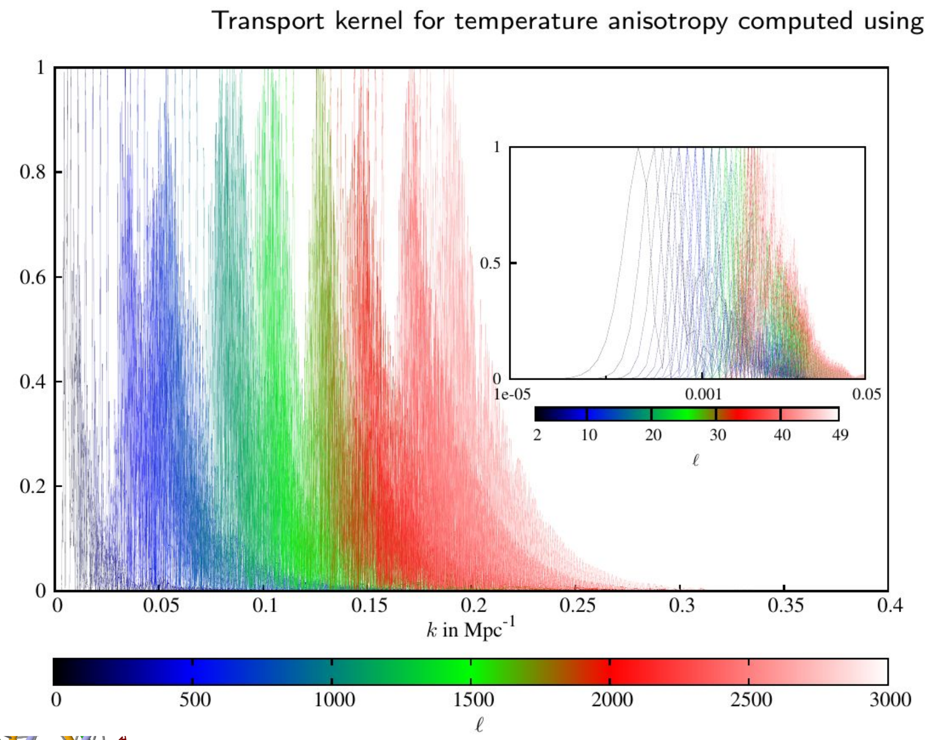
Reconstruction of localized features



The transport kernel depends on background cosmology

Using a baseline cosmology we attempt to reconstruct the primordial power spectrum from the CMB angular power spectrum data

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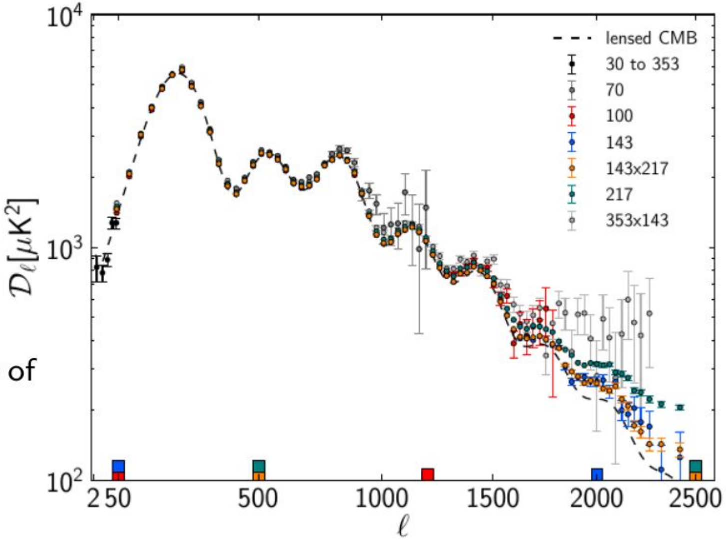
Reconstruction (Richardson-Lucy algorithm)

Richardson (1972) and Lucy (1974)

$$P_k^{(i+1)} - P_k^{(i)} = P_k^{(i)} \times \left[\sum_{\ell} \widetilde{G}_{\ell k} \left(\frac{C_\ell^{\mathrm{D}} - C_\ell^{\mathrm{T}(i)}}{C_\ell^{\mathrm{T}(i)}} \right) \right]$$

- 5 different spectra for parameter estimation, calculated from combinations of maps in different frequency channels
- Foreground and calibration effects
- Substantial lensing

Angular power spectra (in different Planck frequencies)



Planck 2013

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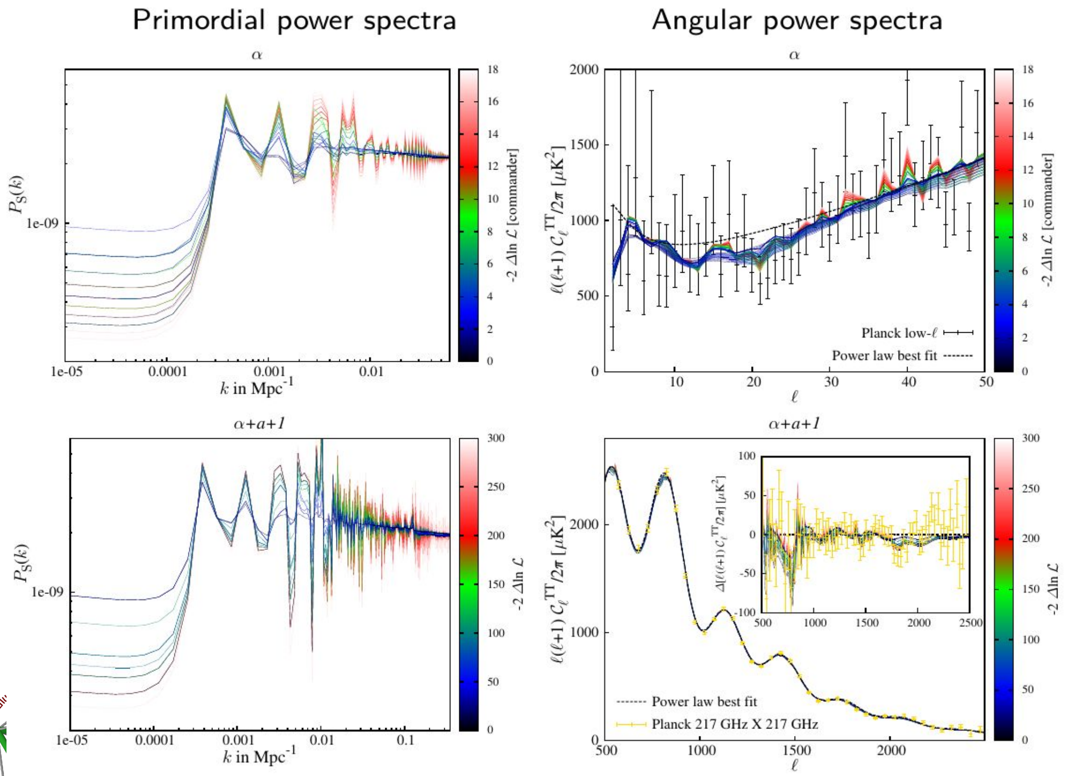
Reconstruction (Modified Richardson-Lucy)



MRL reconstructs the free-form primordial power spectrum from different combinations of frequency channels

Helps to identify features present in all frequencies

Also helps to check consistencies between frequencies

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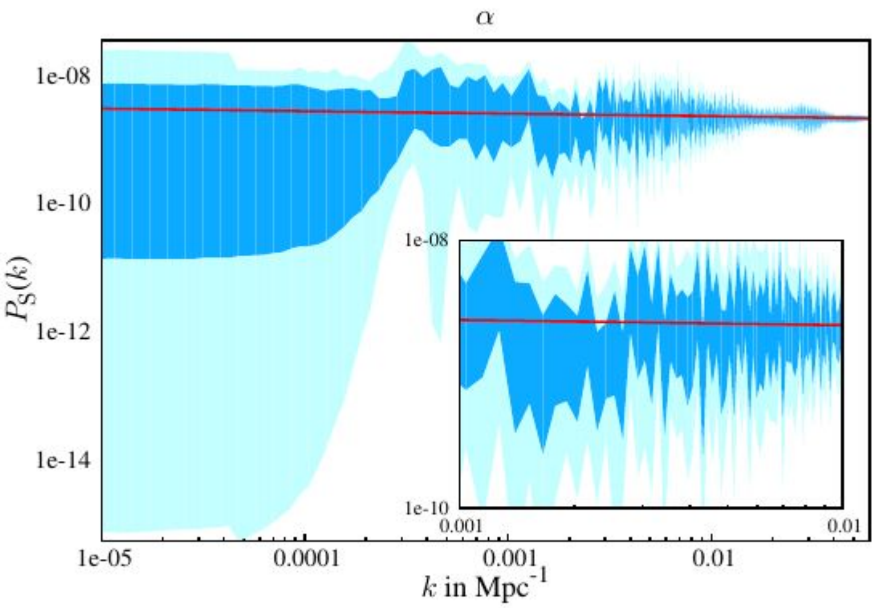
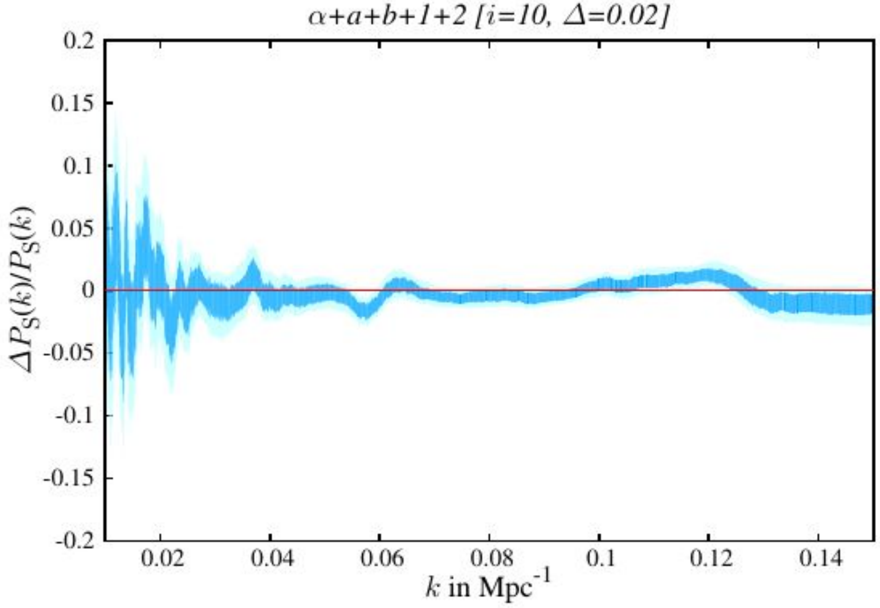
Features that seem '*important*'





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