Probing Features in the Primordial Power Spectrum

Arman Shafieloo

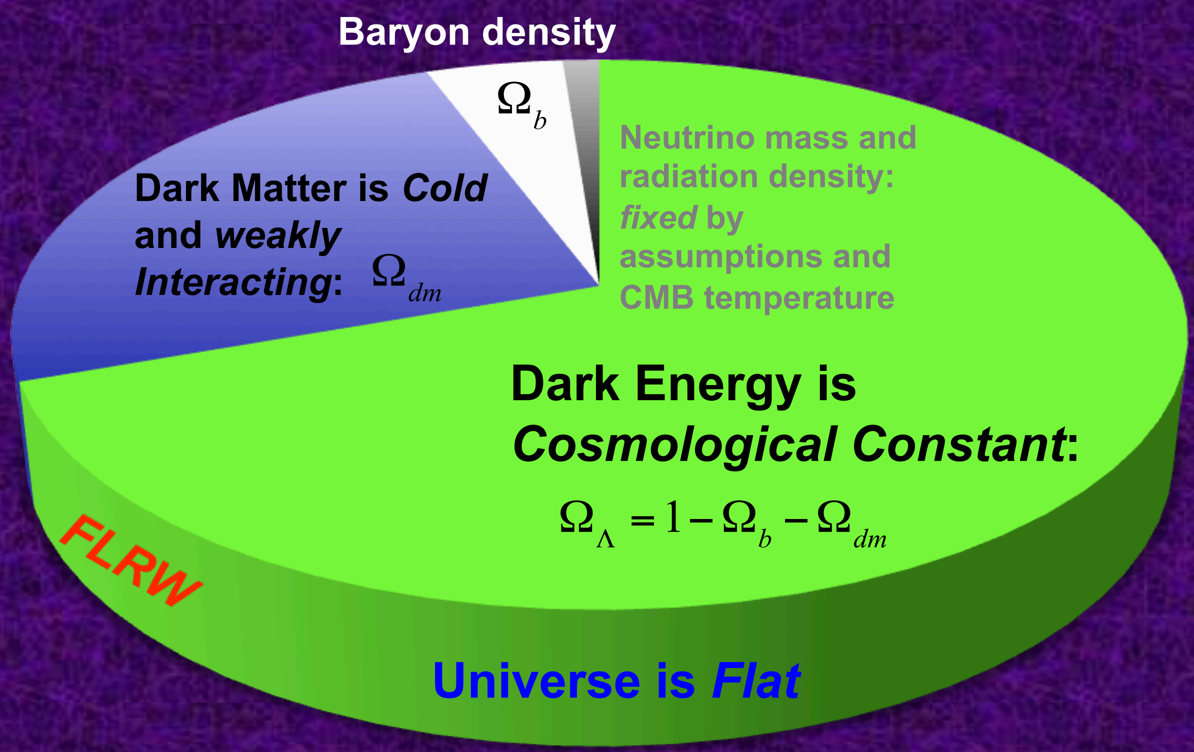
Korea Astronomy and Space Science Institute (KASI)

& University of Science and Technology (UST)

General Relativity - The Next Generation
February 19 - 23, 2018
YITP, Kyoto University

Standard Model of Cosmology

Using measurements and statistical techniques to place sharp constraints on parameters of the standard cosmological model.



Initial Conditions:
Form of the Primordial Spectrum is *Power-law*

n_s, A_s

Epoch of reionization

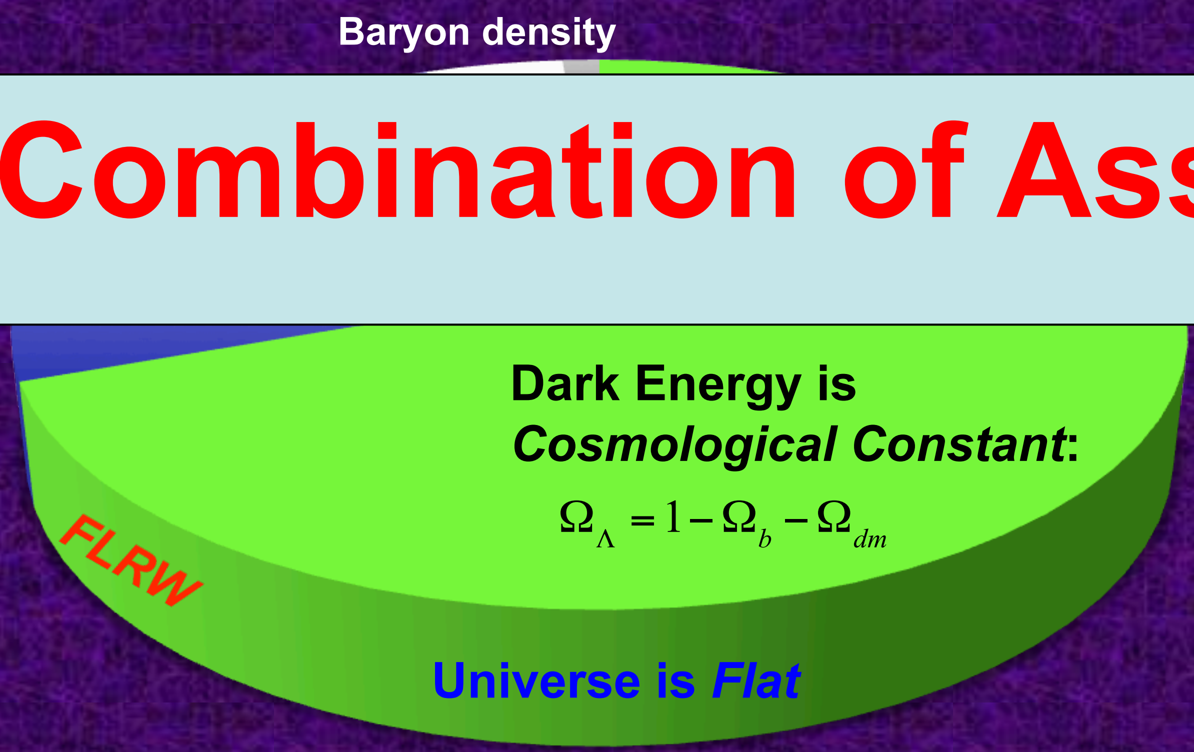
τ

Hubble Parameter and the Rate of Expan

H_0

Standard Model of Cosmology

Using measurements and statistical techniques to place sharp constraints on parameters of the standard cosmological model.



Combination of Assumptions

Epoch of reionization

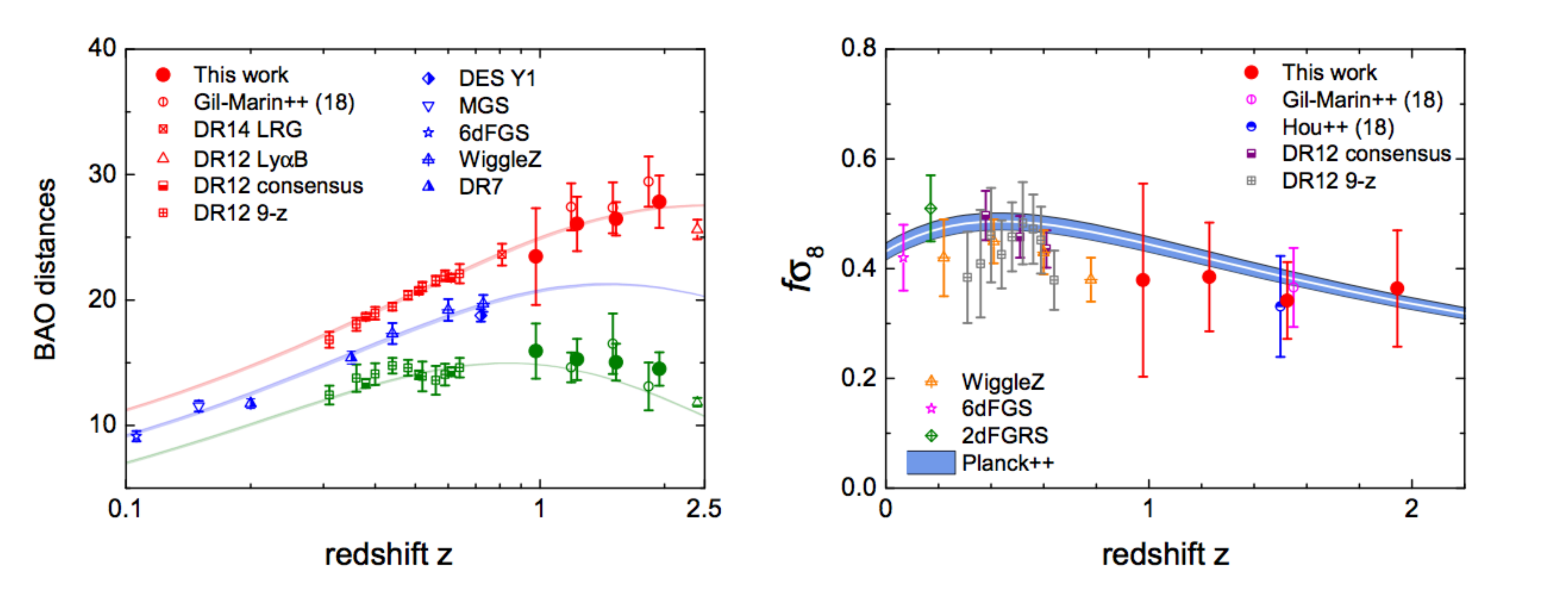
τ

Hubble Parameter
and the Rate of
Expan

H_0

Standard Model of Cosmology

combination of *reasonable* assumptions!



Zhao et al, [eBOSS collaboration] arXiv:1801.03043

But there can be always a but.....

Beyond the Standard Model of Cosmology

- The universe might be more complicated than its current standard model (Vanilla Model).
- There might be some extensions to the standard model in defining the cosmological quantities.
- This needs proper investigation, using advanced statistical methods, high performance computational facilities and high quality observational data.

How to go Beyond the Standard Model of Cosmology?

- Finding features in the data beyond the flexibility of the standard model (using non-parametric reconstructions or using hyper-functions).
- Introducing theoretical/phenomenological models that can explain the data better (statistically significant) with respect to the standard model.
- Finding tension among different independent data assuming the standard model (making sure there is no systematic).

Implementing well cooked statistical approaches to get the most out of the data is essential!

Testing deviations from an assumed model

(without comparing different models)

Gaussian Processes:

Modeling of the data around a mean function searching for features by looking at the likelihood space of the hyperparameters.

Bayesian Interpretation of Crossing Statistic:

Comparing a model with its own possible variations considering a hyperfunction.

Gaussian Process

➔Efficient in statistical modeling of stochastic variables
➔Derivatives of Gaussian Processes are Gaussian Processes
➔Provides us with all covariance matrices

Shafieloo, Kim & Linder, PRD 2012
Shafieloo, Kim & Linder, PRD 2013

Data

Mean Function

$$\begin{bmatrix} \mathbf{y} \\ \mathbf{f} \\ \mathbf{f}' \\ \mathbf{f}'' \end{bmatrix} \sim \mathcal{N}\left(\begin{bmatrix} \mathbf{m}(\mathbf{Z}) \\ \mathbf{m}(\mathbf{Z_1}) \\ \mathbf{m}'(\mathbf{Z_1}) \\ \mathbf{m}''(\mathbf{Z_1}) \end{bmatrix}, \begin{bmatrix} \Sigma_{00}(Z,Z) & \Sigma_{00}(Z,Z_1) & \Sigma_{01}(Z,Z_1) & \Sigma_{02}(Z,Z_1) \\ \Sigma_{00}(Z_1,Z) & \Sigma_{00}(Z_1,Z_1) & \Sigma_{01}(Z_1,Z_1) & \Sigma_{02}(Z_1,Z_1) \\ \Sigma_{10}(Z_1,Z) & \Sigma_{10}(Z_1,Z_1) & \Sigma_{11}(Z_1,Z_1) & \Sigma_{12}(Z_1,Z_1) \\ \Sigma_{20}(Z_1,Z) & \Sigma_{20}(Z_1,Z_1) & \Sigma_{21}(Z_1,Z_1) & \Sigma_{22}(Z_1,Z_1) \end{bmatrix} \right),$$

$$\Sigma_{\alpha\beta} = \frac{d^{(\alpha+\beta)}K}{dz_i^{\alpha} dz_j^{\beta}},$$

$$\begin{bmatrix} \overline{\mathbf{f}} \\ \overline{\mathbf{f}'} \\ \overline{\mathbf{f}''} \end{bmatrix} = \begin{bmatrix} \mathbf{m}(\mathbf{Z_1}) \\ \mathbf{m}'(\mathbf{Z_1}) \\ \mathbf{m}''(\mathbf{Z_1}) \end{bmatrix} + \begin{bmatrix} \Sigma_{00}(Z_1,Z) \\ \Sigma_{10}(Z_1,Z) \\ \Sigma_{20}(Z_1,Z) \end{bmatrix} \Sigma_{00}^{-1}(Z,Z)\,\mathbf{y}$$

Kernel

$$k(z,z') = \sigma_f^2 \exp\left(-\frac{|z-z'|^2}{2l^2}\right),$$

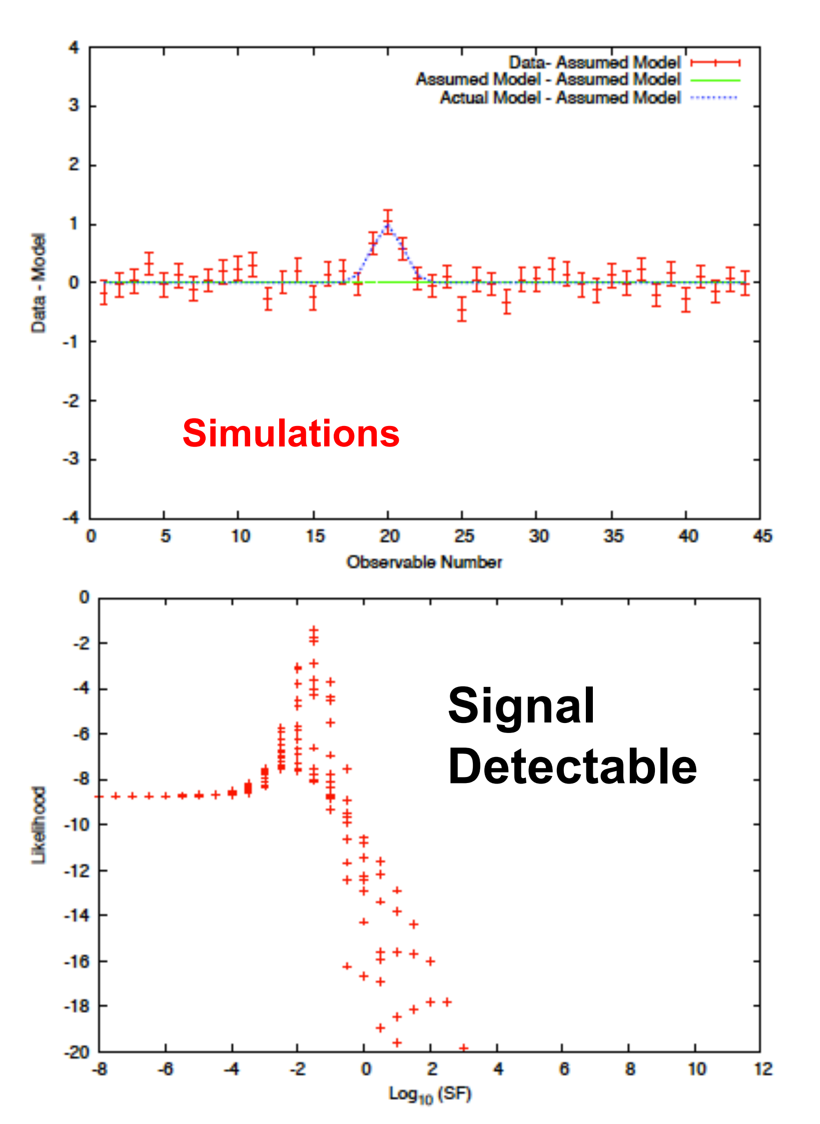
GP Hyper-parameters

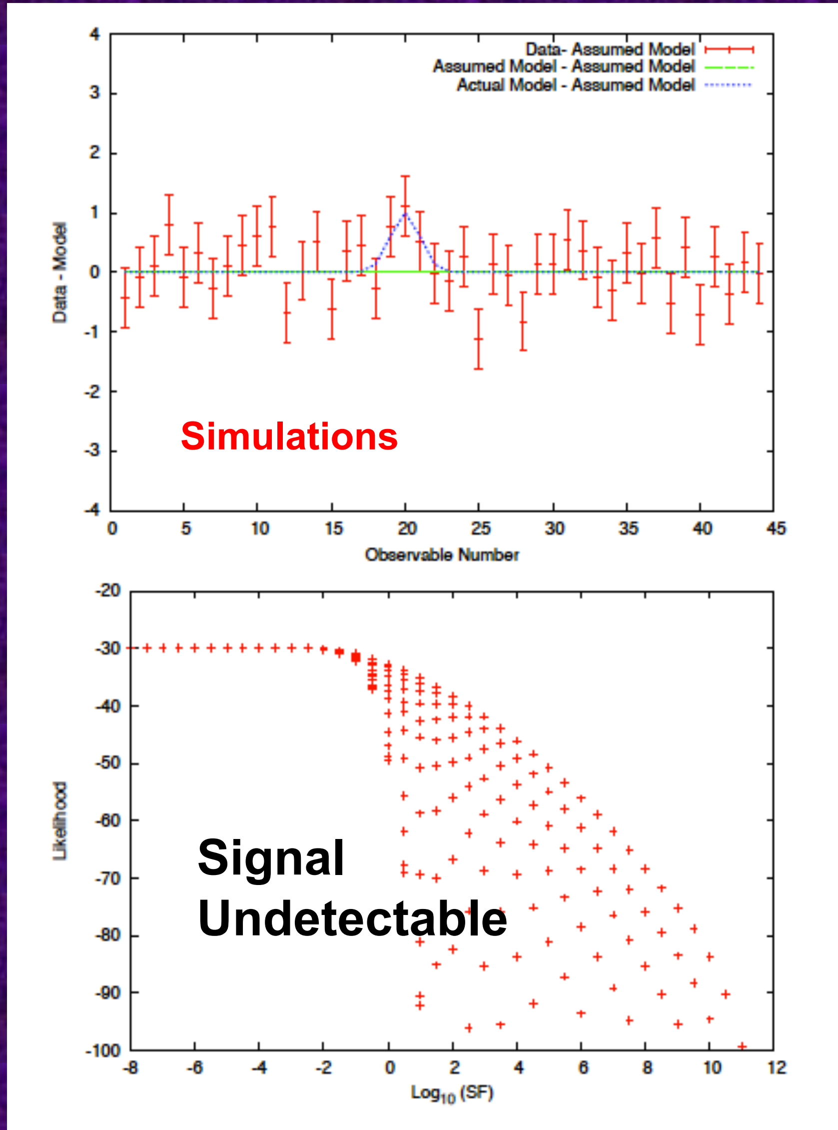
$$\mathrm{Cov}\left(\begin{bmatrix} \mathbf{f} \\ \mathbf{f}' \\ \mathbf{f}'' \end{bmatrix}\right) = \begin{bmatrix} \Sigma_{00}(Z_1,Z_1) & \Sigma_{01}(Z_1,Z_1) & \Sigma_{02}(Z_1,Z_1) \\ \Sigma_{10}(Z_1,Z_1) & \Sigma_{11}(Z_1,Z_1) & \Sigma_{12}(Z_1,Z_1) \\ \Sigma_{20}(Z_1,Z_1) & \Sigma_{21}(Z_1,Z_1) & \Sigma_{22}(Z_1,Z_1) \end{bmatrix} - \begin{bmatrix} \Sigma_{00}(Z_1,Z) \\ \Sigma_{10}(Z_1,Z) \\ \Sigma_{20}(Z_1,Z) \end{bmatrix} \Sigma_{00}^{-1}(Z,Z)\left[\Sigma_{00}(Z,Z_1), \Sigma_{01}(Z,Z_1), \Sigma_{02}(Z,Z_1)\right].$$

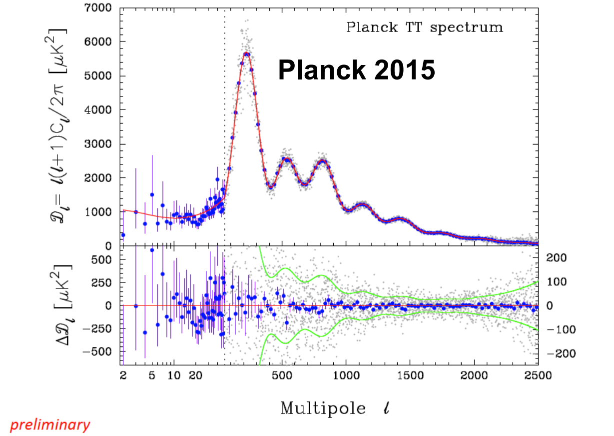
$$2\ln p(y|f) = -y^T \Sigma_{00}(Z,Z)^{-1} y - \ln\det \Sigma_{00}(Z,Z) - n\ln(2\pi),$$

GP Likelihood

Detection of the features in the residuals

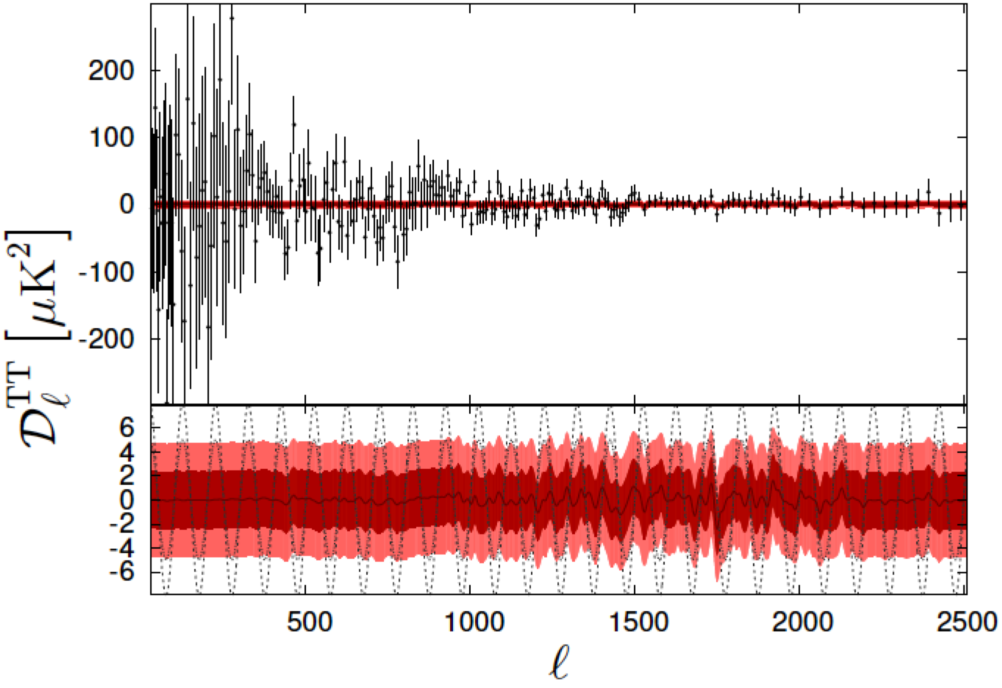


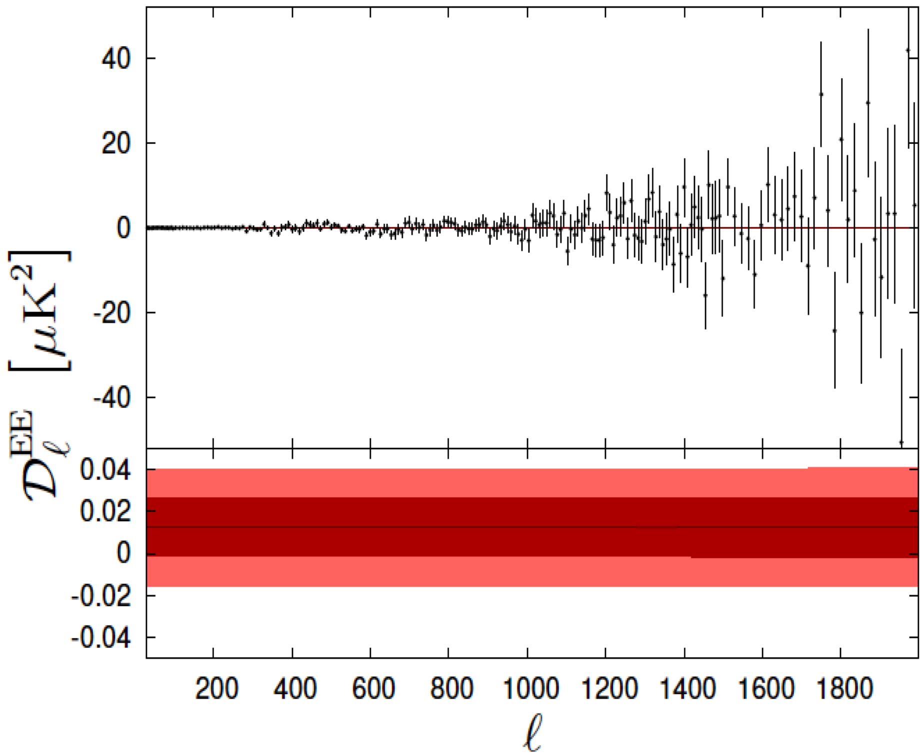


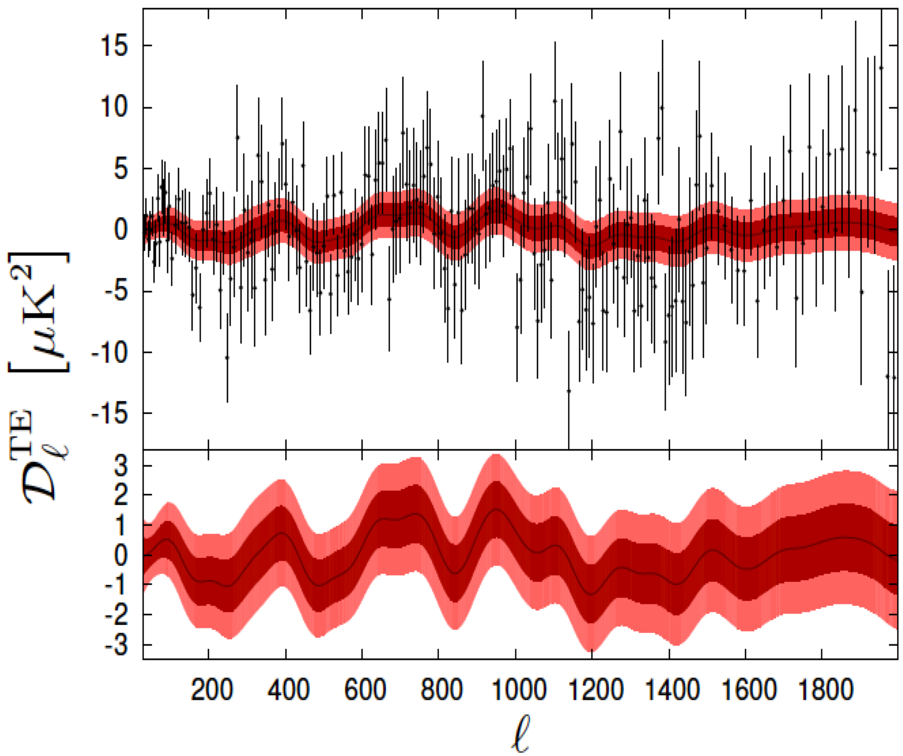


GP Reconstruction of Planck TT, TE, EE spectra

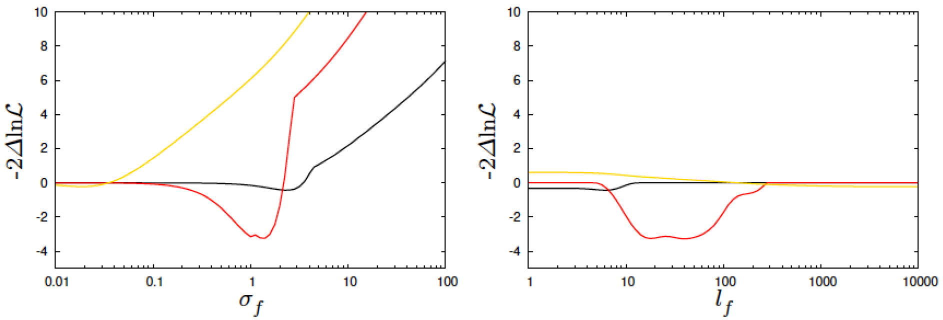
Aghamousa, Hamann & Shafieloo, JCAP 2017

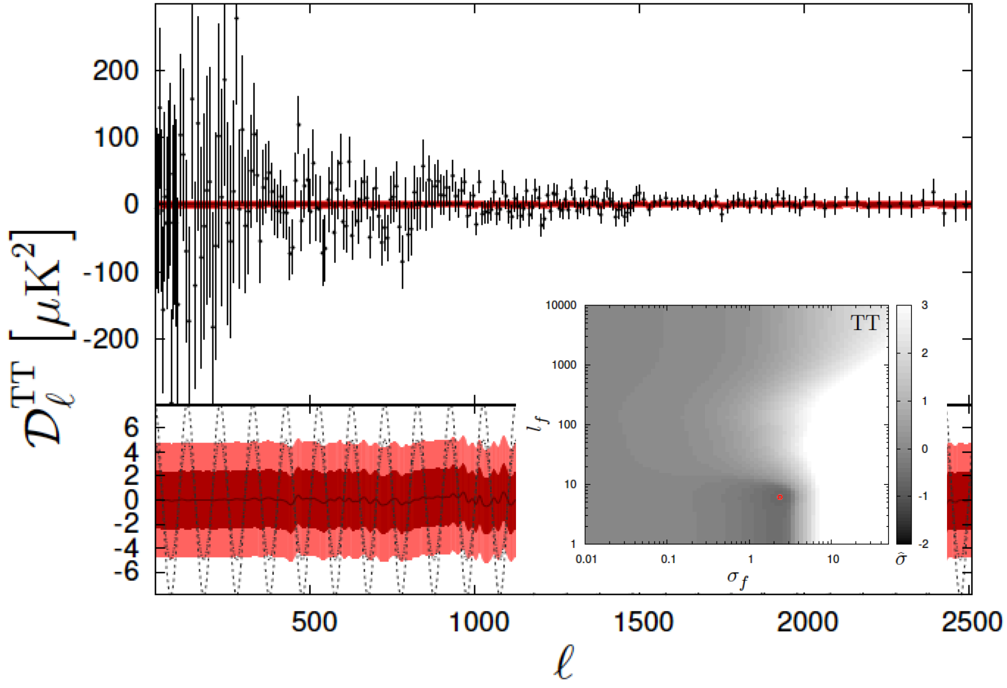






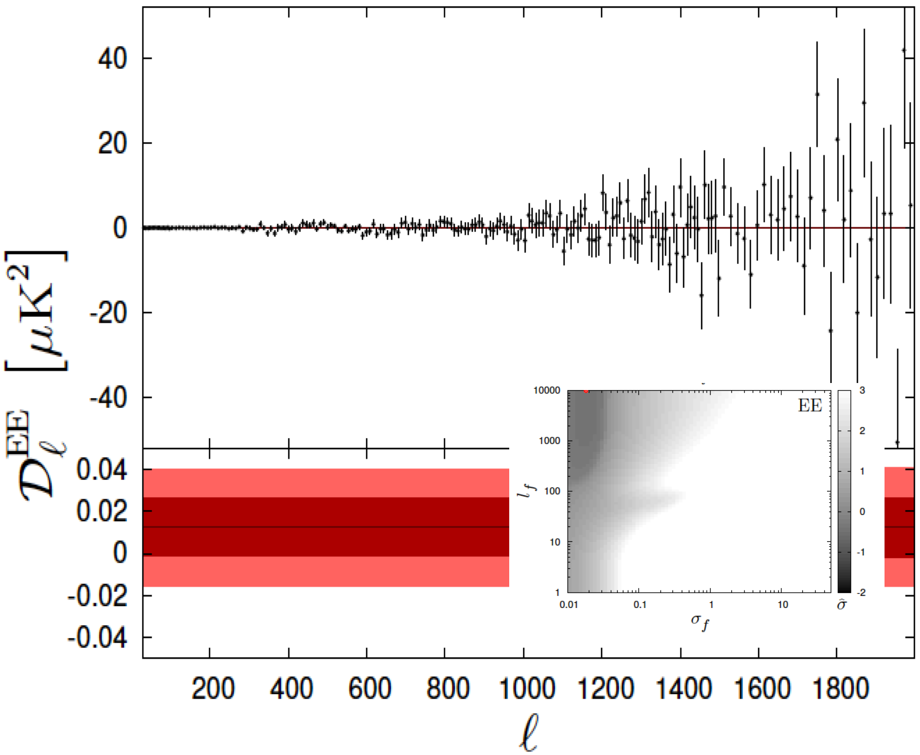
Excellent agreement between Planck & the best-fit LCDM

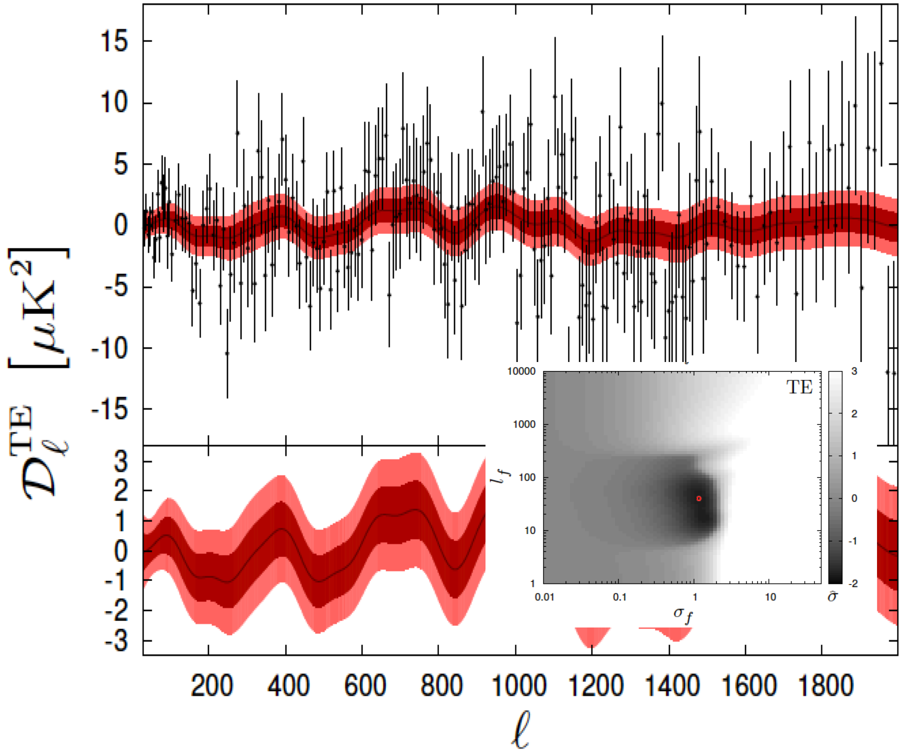




GP Reconstruction of Planck TT, TE, EE spectra

Aghamousa, Hamann & Shafieloo, JCAP 2017





Bayesian Interpretation of Crossing Statistics

- To deal with unknown uncertainties/ systematics in the data.
- To go beyond averaging nature of Chi square statistic (as a core metric in most statistical analysis) extracting more information from the data.

Theoretical Model **Crossing Function**

$$\mathcal{C}_\ell^{\rm TT}\Big|^{N}_{\rm modified} = \mathcal{C}_\ell^{\rm TT}\Big|_{\Omega_{\rm b},\Omega_{\rm CDM},{\rm H_0},\tau,{\rm A_s},{\rm n_s}} \times T_N(C_0, C_1, C_2, ..., C_N, \ell).$$

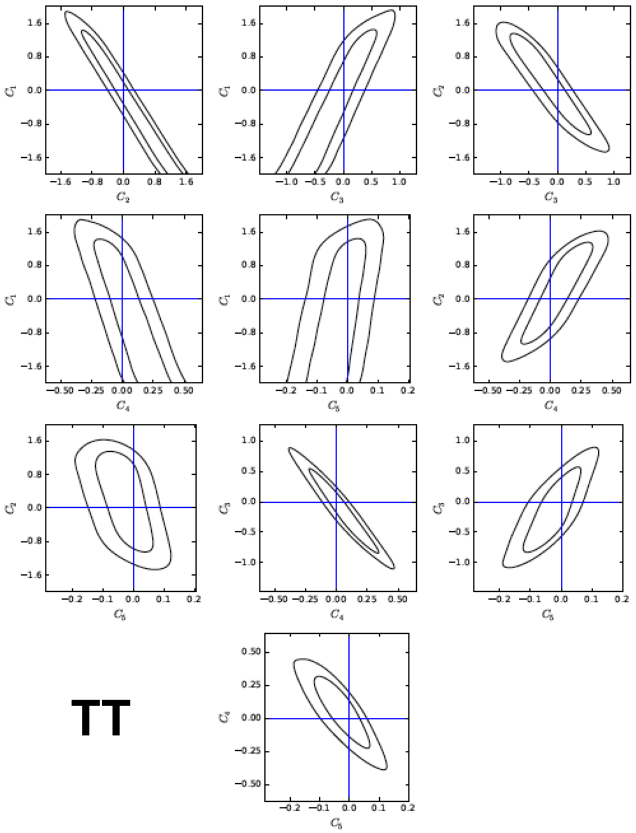
$$\begin{aligned}
T_0(C_0,x) &= C_0\\
T_{\rm I}(C_0,C_1,x) &= T_0(C_0,x) + C_1\ x\\
T_{\rm II}(C_0,C_1,C_2,x) &= T_{\rm I}(C_0,C_1,x) + C_2(2x^2-1)\\
T_{\rm III}(C_0,C_1,C_2,C_3,x) &= T_{\rm II}(C_0,C_1,C_2,x) + C_3(4x^3-3x)\\
T_{\rm IV}(C_0,C_1,C_2,C_3,C_4,x) &= T_{\rm III}(C_0,C_1,C_2,C_3,x) + C_4(8x^4-8x^2+1)\\
T_{\rm V}(C_0,C_1,C_2,C_3,C_4,C_5,x) &= T_{\rm IV}(C_0,C_1,C_2,C_3,C_4,x) + C_5(16x^5-20x^3+5x).
\end{aligned}$$

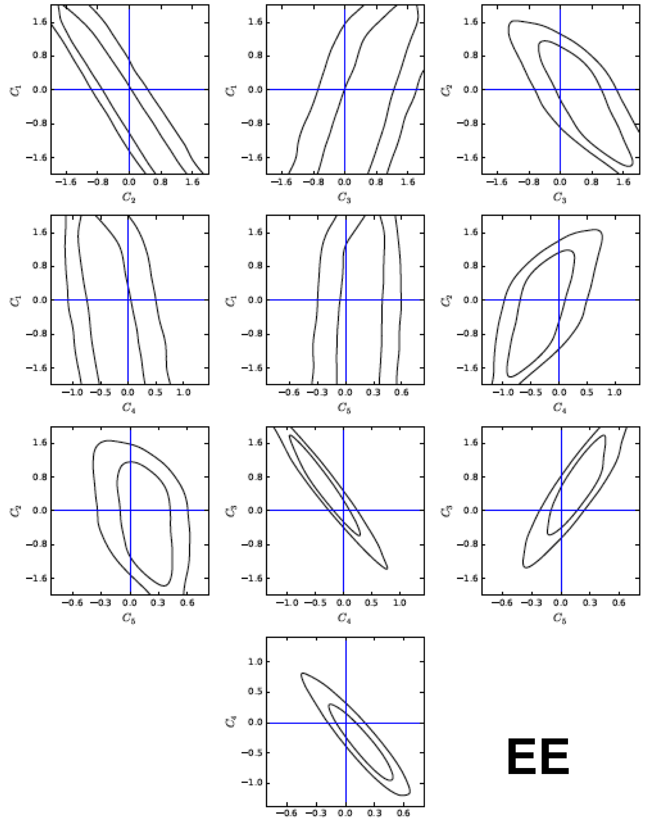
$$x = \ell/\ell_{\rm max} \qquad \ell_{\rm max} = 2500.$$

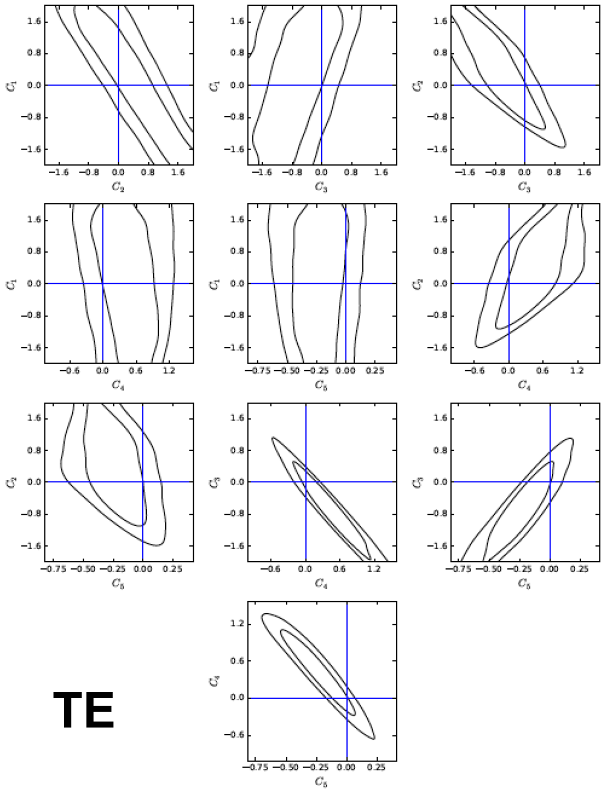
Shafieloo et al JCAP 2011
Shafieloo, JCAP 2012a
Shafieloo, JCAP 2012b

Chebychev polynomials **have the properties of orthogonality and convergence within the limited range of -1 < x < 1.**

Test of consistency between LCDM model and Planck 2015 data







Crossing parameters marginalized over cosmological parameters fitting TT data

Crossing Statistic (Bayesian Interpretation)

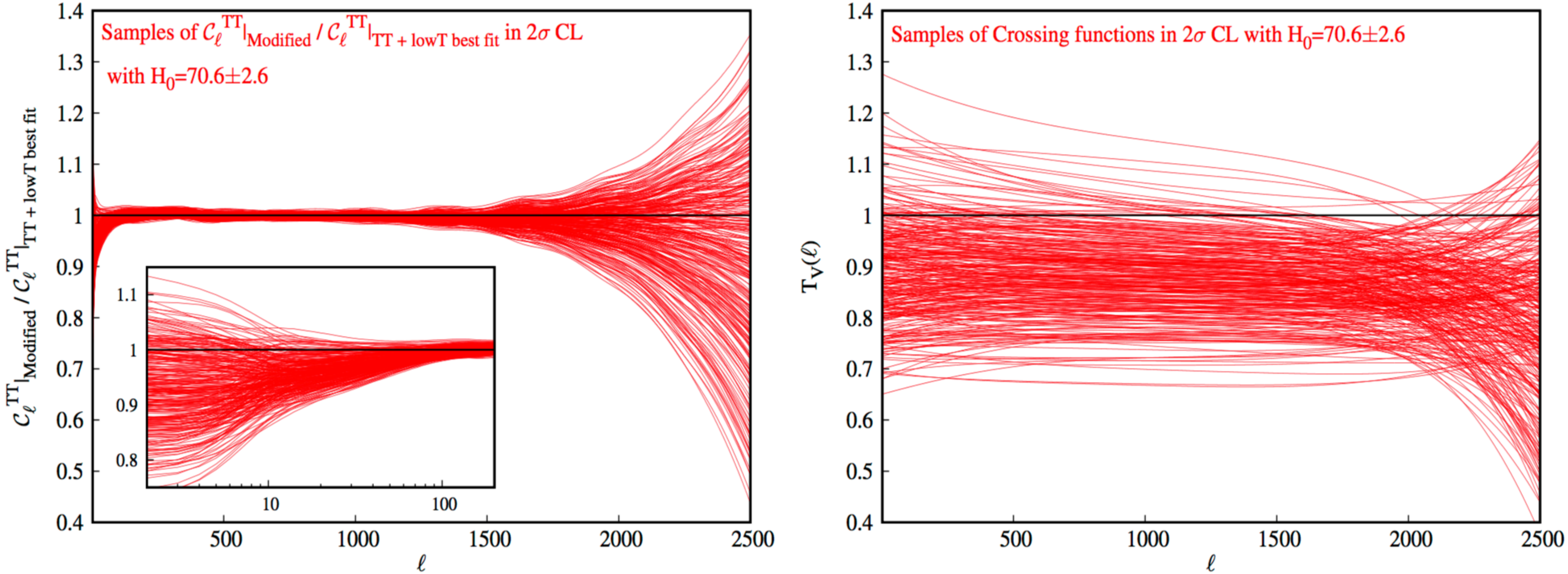
Theoretical model **Crossing function**

$$\mathcal{C}_\ell^{\rm TT}\,|^N_{\rm modified} = \mathcal{C}_\ell^{\rm TT}\,|_{\Omega_{\rm b},\Omega_{\rm CDM},{\rm H}_0,\tau,{\rm A_S},{\rm n_S},\ell} \;\times\; T_i(C_0, C_1, C_2, ..., C_N, \ell).$$

Confronting the concordance model of cosmology with *Planck 2015* data

Shafieloo and Hazra, JCAP 2017

Completely Consistent



Why to go beyond Power-Law PPS if data consistent to the standard model (and single field inflation) ?

1. PL is consistent to the data, but there might be other interesting forms of PPS also consistent to the current data. This can have important theoretical implications to consider more complicated inflationary scenarios or alternative models.

2. Non-PL forms of the PPS possibly result to different background parameters fitting the same data. Crucial for cosmological parameter estimation and studying late universe.

3. Might help (or may not) resolving tensions between different cosmological observations within the framework of the LCDM model.

4. Power-law PPS (and standard model in general) is boring.

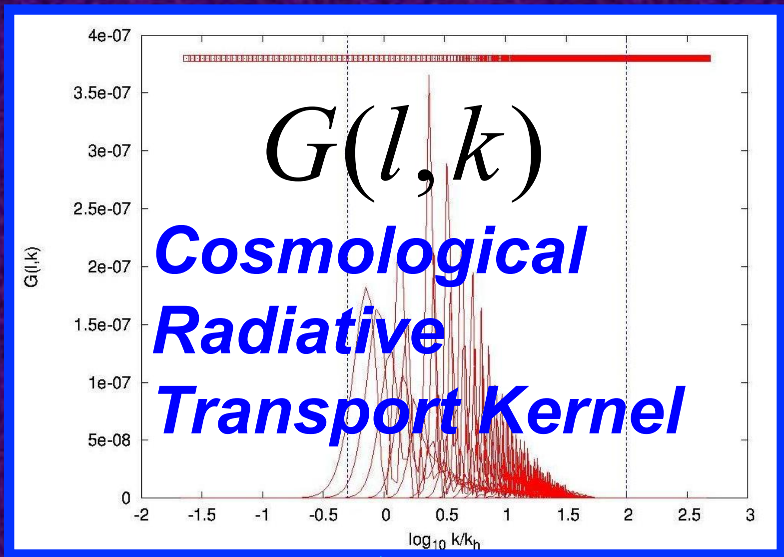
$$P(k)$$

Primordial Power Spectrum

?

Suggested by Model of Inflation and the early universe

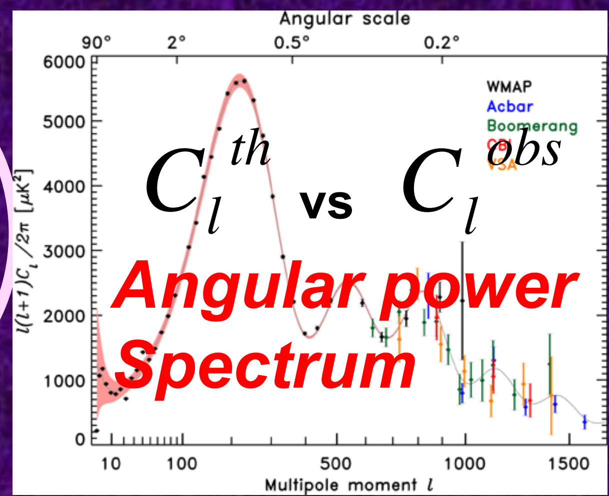
$$C_l = \sum G(l,k)P(k)$$



$$G(l,k)$$

Cosmological Radiative Transport Kernel

Determined by background model and cosmological parameters



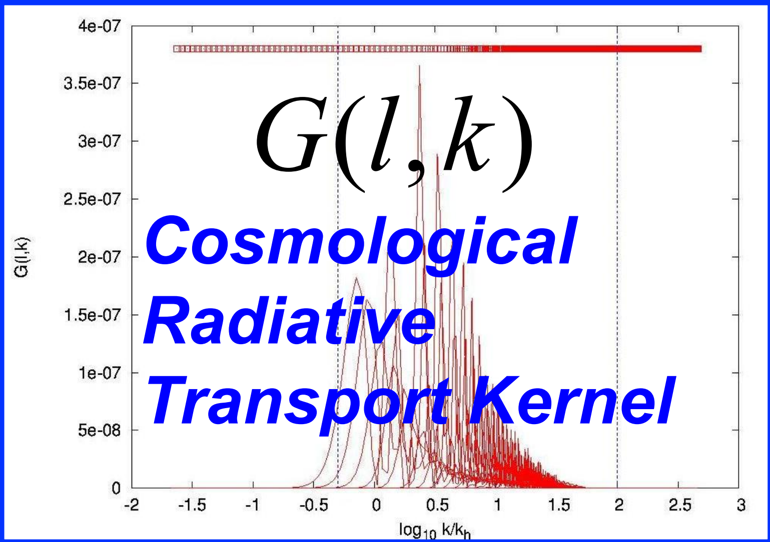
C_l^{th} vs C_l^{obs}

Angular power Spectrum

Detected by observation

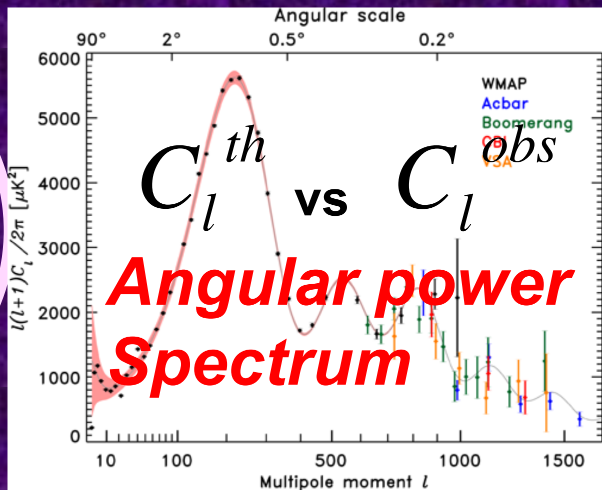
We cannot anticipate the unexpected !!

$$C_l = \sum G(l,k)P(k)$$



Determined by background model and cosmological parameters

Detected by observation



DIRECT TOP DOWN APPROACH

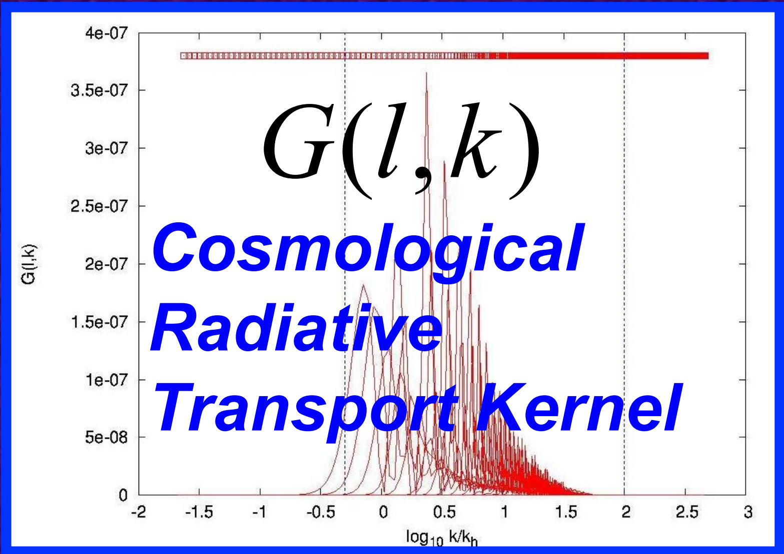
$P(k)$

Primordial Power Spectrum

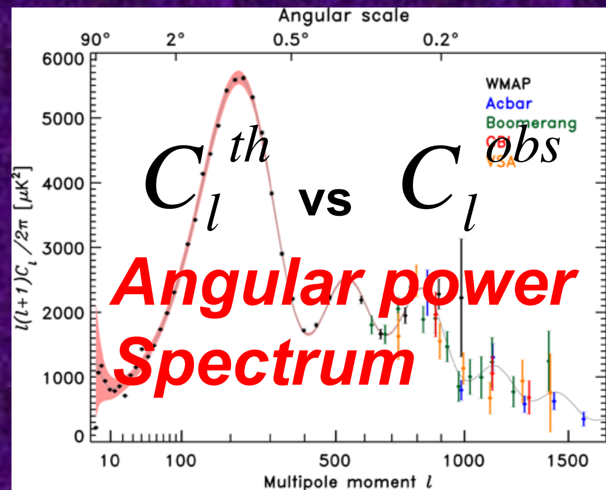
?

Reconstructed by Observations

$$C_l = \sum G(l,k)P(k)$$



Determined by background model and cosmological parameters



Detected by observation

Model Independent Estimation of Primordial Spectrum

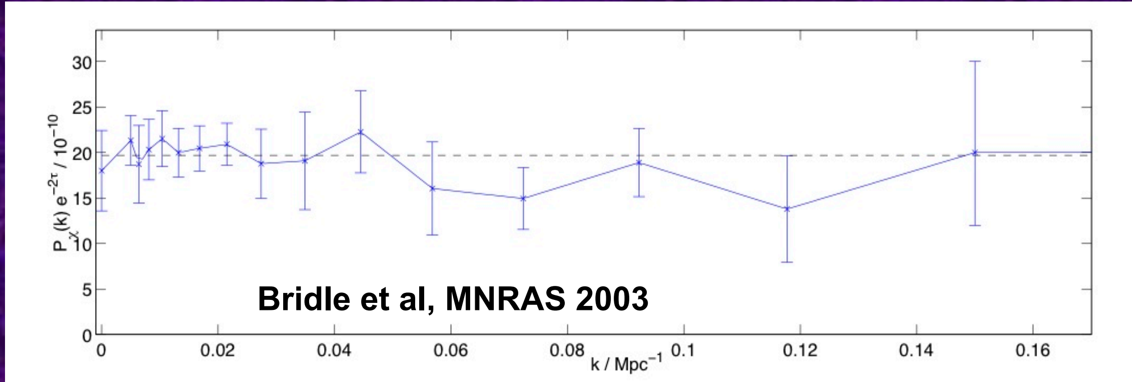
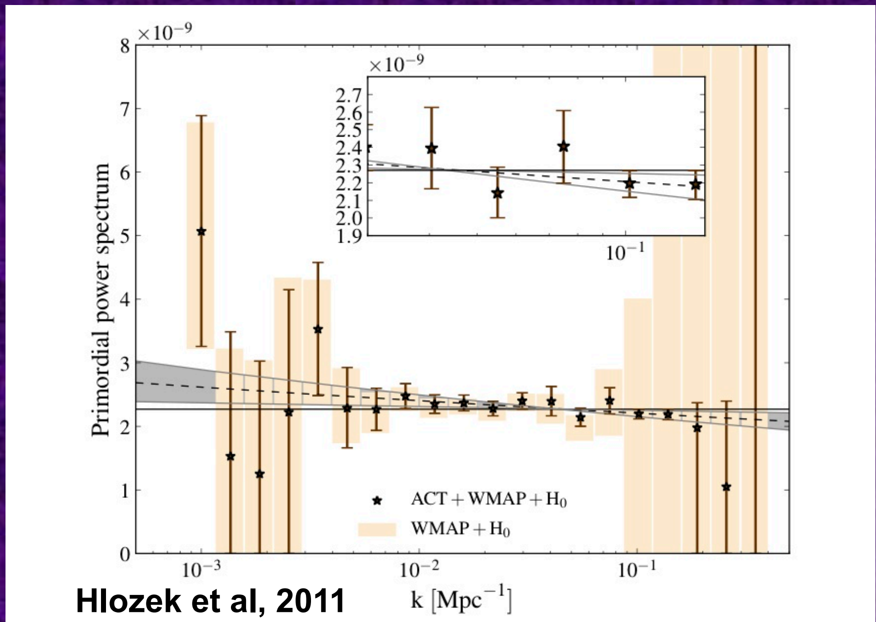
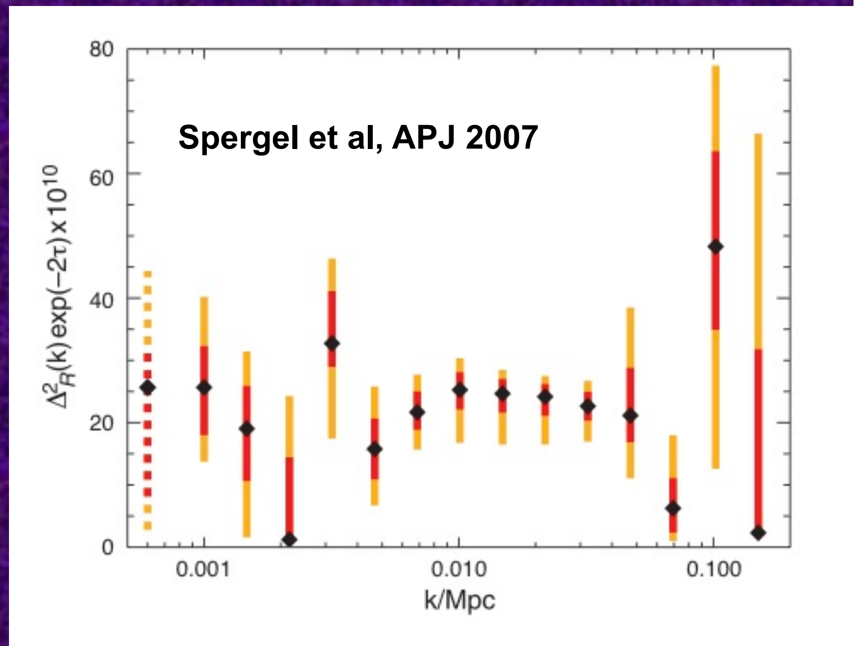


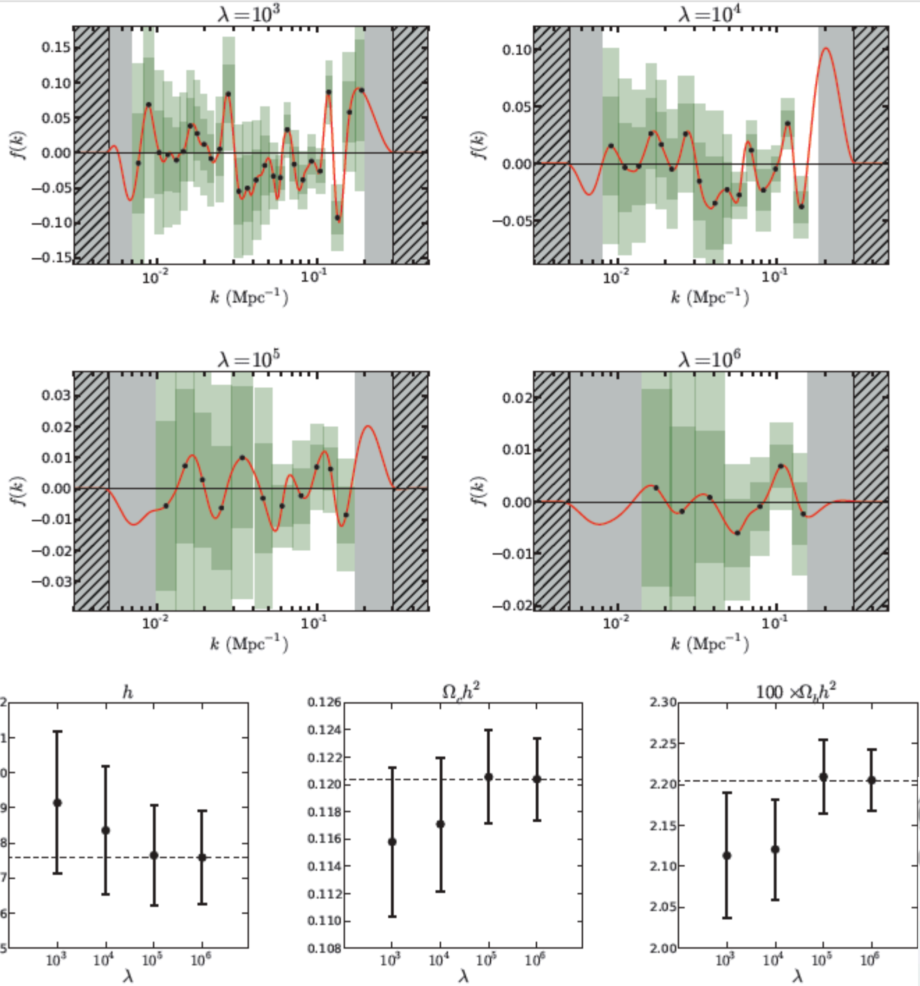
Figure 4. Reconstruction of the shape of the primordial power spectrum in 16 bands after marginalising over the Hubble constant, baryon and dark matter densities, and the redshift of reionization.

What is usually done: Binning Primordial Spectrum





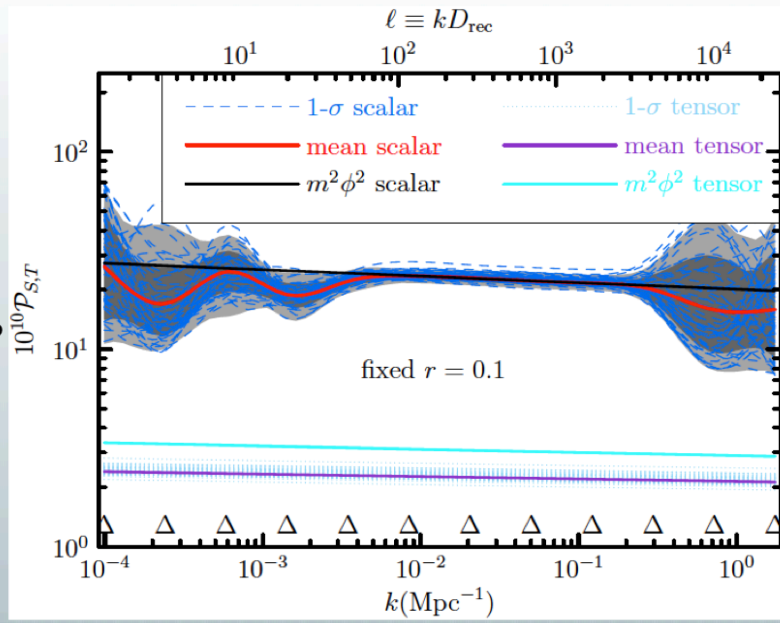
Planck 2013



Planck 2015

Power spectra reconstruction

2015
TT+lowP
+BAO+JLA
+Hlow



12-knots power spectra

(actually used 3 different methods, all with similar results)

Modified Richardson-Lucy Deconvolution

$$C_\ell = \sum_i G_{\ell k_i} P_{k_i}$$

- ➔Iterative algorithm.
- ➔Not sensitive to the initial guess.
- ➔Enforce positivity of P(k).

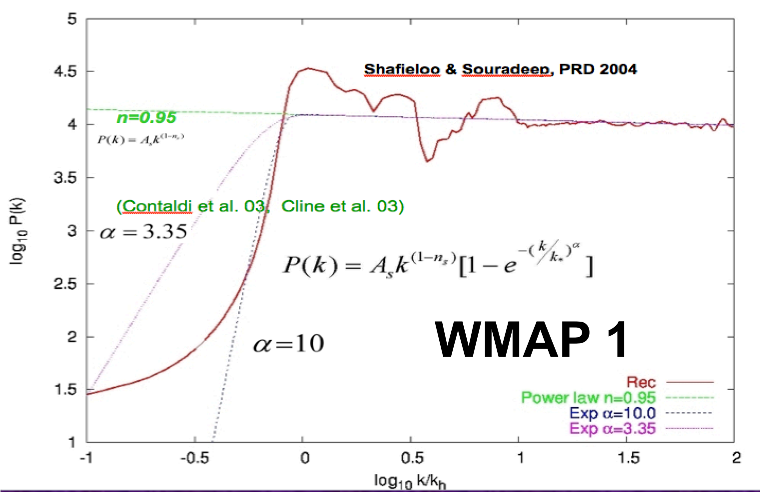
[$G(l,k)$ is positive definite and C_l is positive]

$$P_k^{(i+1)} - P_k^{(i)} = P_k^{(i)} \times \left[\sum_{\ell=2}^{\ell=900} \tilde{G}_{\ell k}^{\rm un-binned} \left\{ \left(\frac{C_\ell^{\rm D} - C_\ell^{\rm T(i)}}{C_\ell^{\rm T(i)}} \right) \tanh^2 \left[Q_\ell (C_\ell^{\rm D} - C_\ell^{\rm T(i)}) \right] \right\}_{\rm un-binned} + \sum_{\ell_{\rm binned} > 900} \tilde{G}_{\ell k}^{\rm binned} \left\{ \left(\frac{C_\ell^{\rm D} - C_\ell^{\rm T(i)}}{C_\ell^{\rm T(i)}} \right) \tanh^2 \left[\frac{C_\ell^{\rm D} - C_\ell^{\rm T(i)}}{\sigma_\ell^{\rm D}} \right]^2 \right\}_{\rm binned} \right], \quad (1)$$

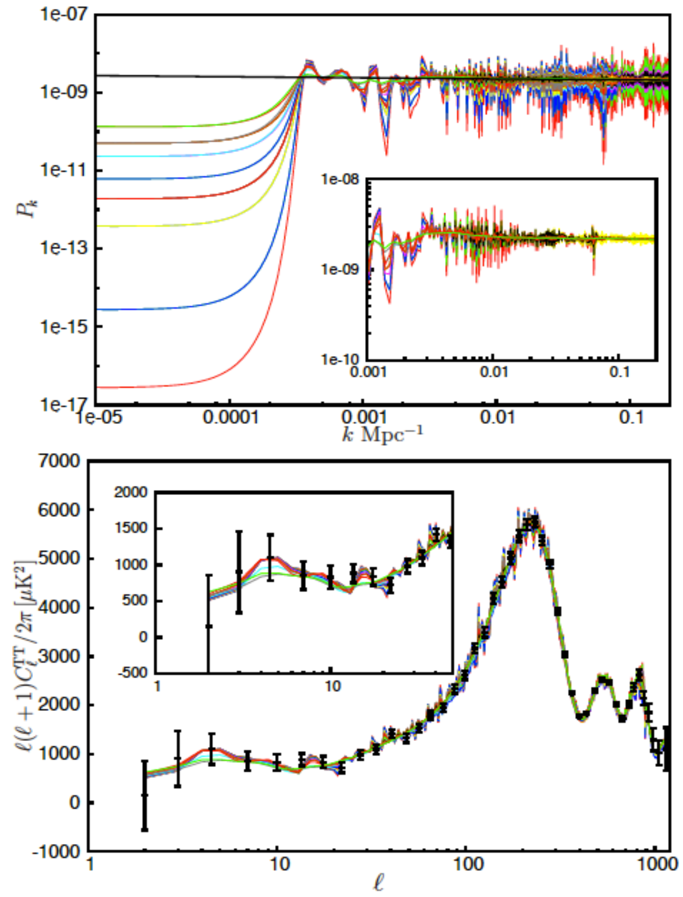
$$Q_\ell = \sum_{\ell'} (C_{\ell'}^{\rm D} - C_{\ell'}^{\rm T(i)}) COV^{-1}(\ell, \ell'),$$

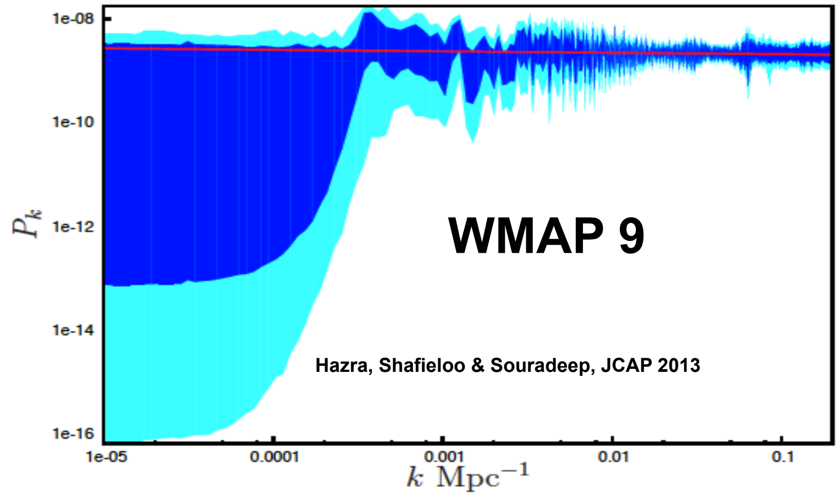
Shafieloo & Souradeep PRD 2004 ;
Shafieloo et al, PRD 2007;
Shafieloo & Souradeep, PRD 2008;
Nicholson & Contaldi JCAP 2009
Hamann, Shafieloo & Souradeep JCAP 2010
Hazra, Shafieloo & Souradeep PRD 2013
Hazra, Shafieloo & Souradeep JCAP 2013
Hazra, Shafieloo & Souradeep JCAP 2014
Hazra, Shafieloo & Souradeep JCAP 2015

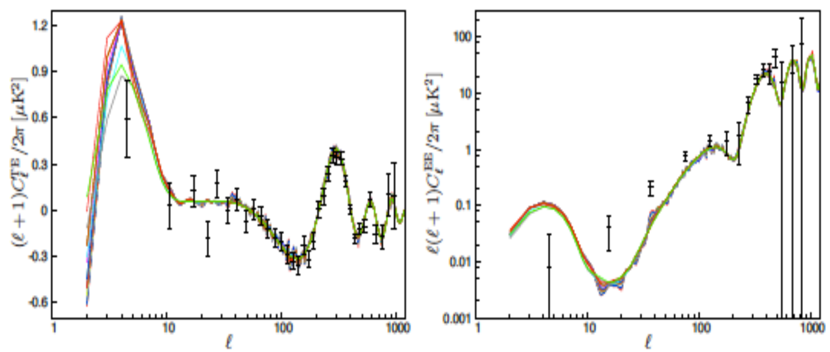
Hazra, Shafieloo, Souradeep, in prep 2018



Primordial Power Spectrum from WMAP



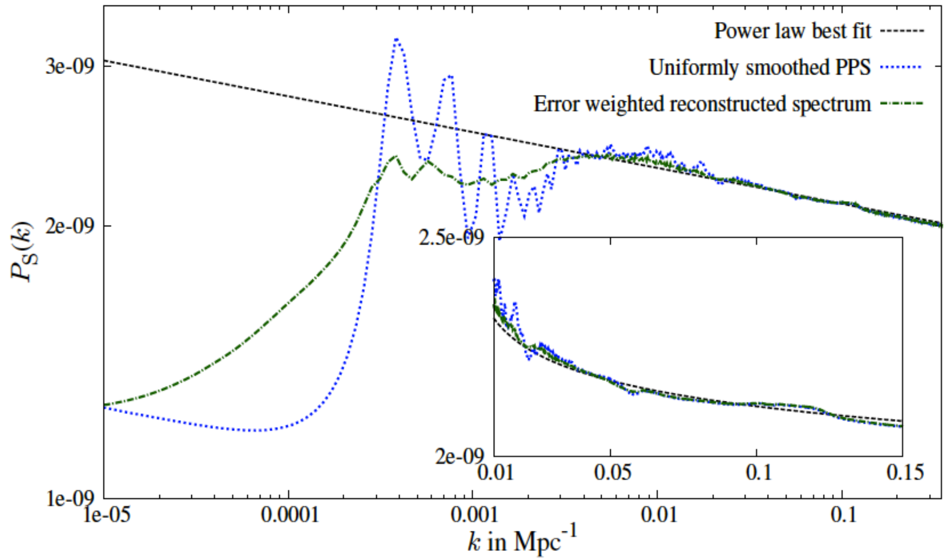


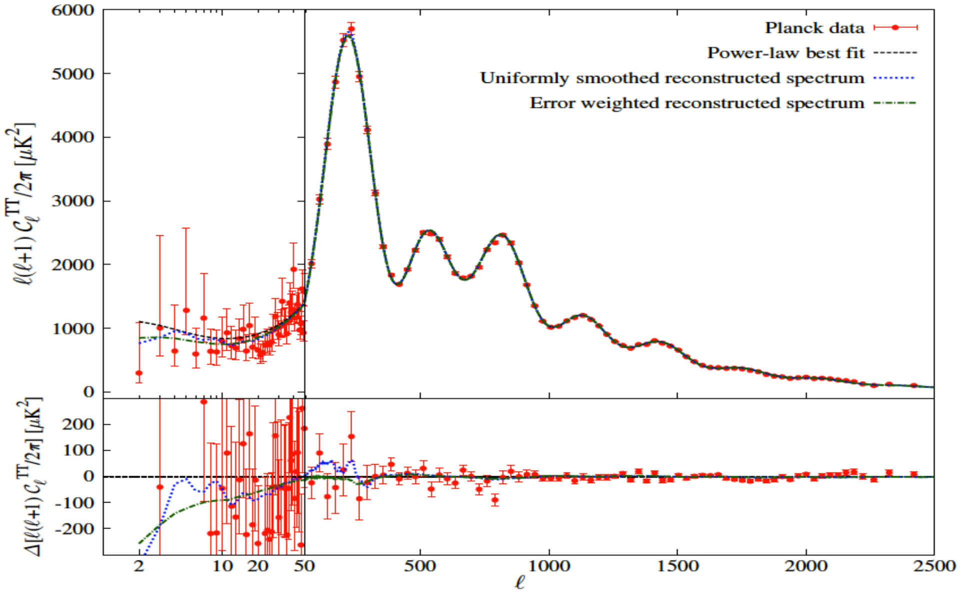


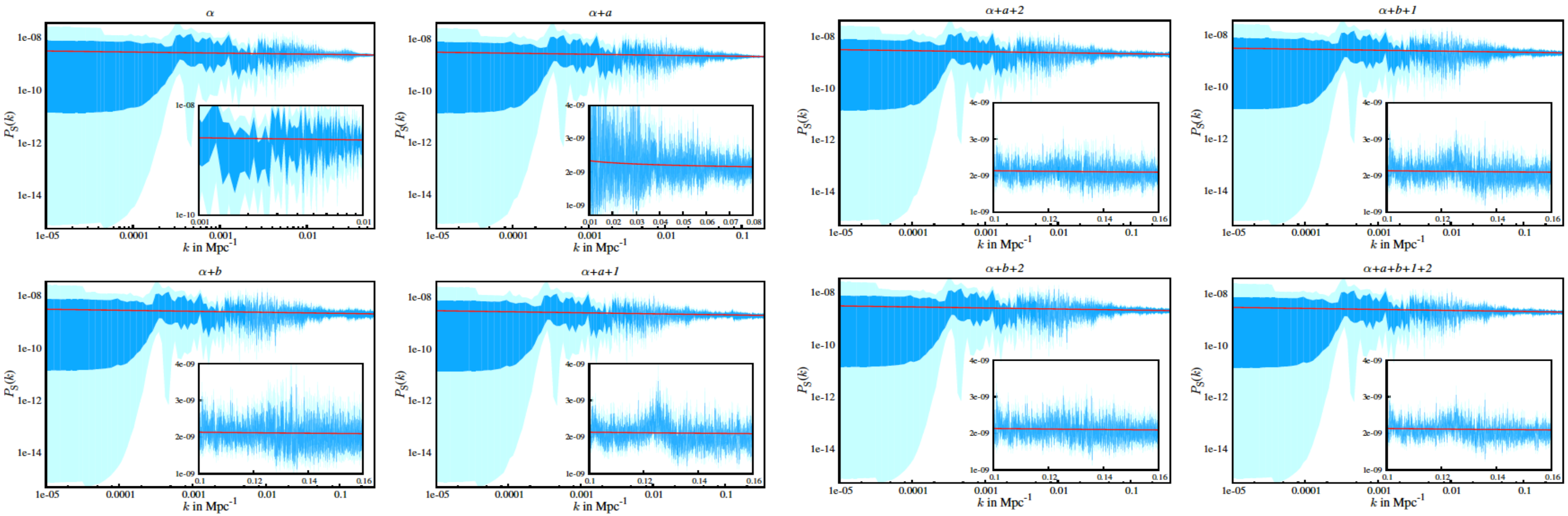
Our symbol	Spectra	Multipoles(ℓ)	Scales
α	low-ℓ	2-49	Largest scales
a	100 GHz × 100 GHz	50-1200	Intermediate scales
b	143 GHz × 143 GHz	50-2000	Intermediate scales
1	217 GHz × 217 GHz	500-2500	Small scales
2	143 GHz × 217 GHz	500-2500	Small scales

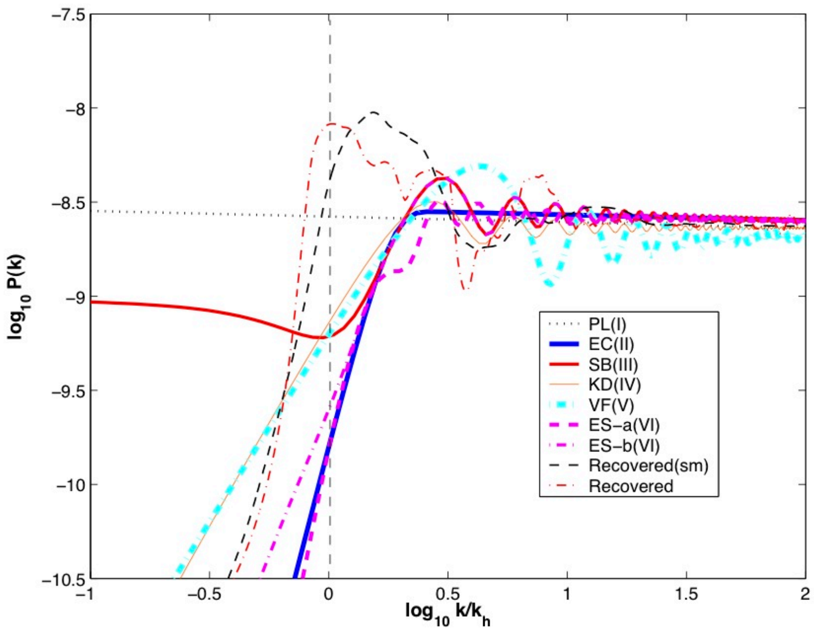
Primordial Power Spectrum from Planck

Hazra, Shafieloo & Souradeep, JCAP 2014









Starobinsky (1992)

Kink in the potential

Vilenkin and Ford (1982)

Pre-inflationary radiation dominated era

Contaldi et al, (2003)

Pre-inflationary kinetic dominated era

Cline et al, (2003)

Exponential cut off

Shafieloo & Souradeep (2004)

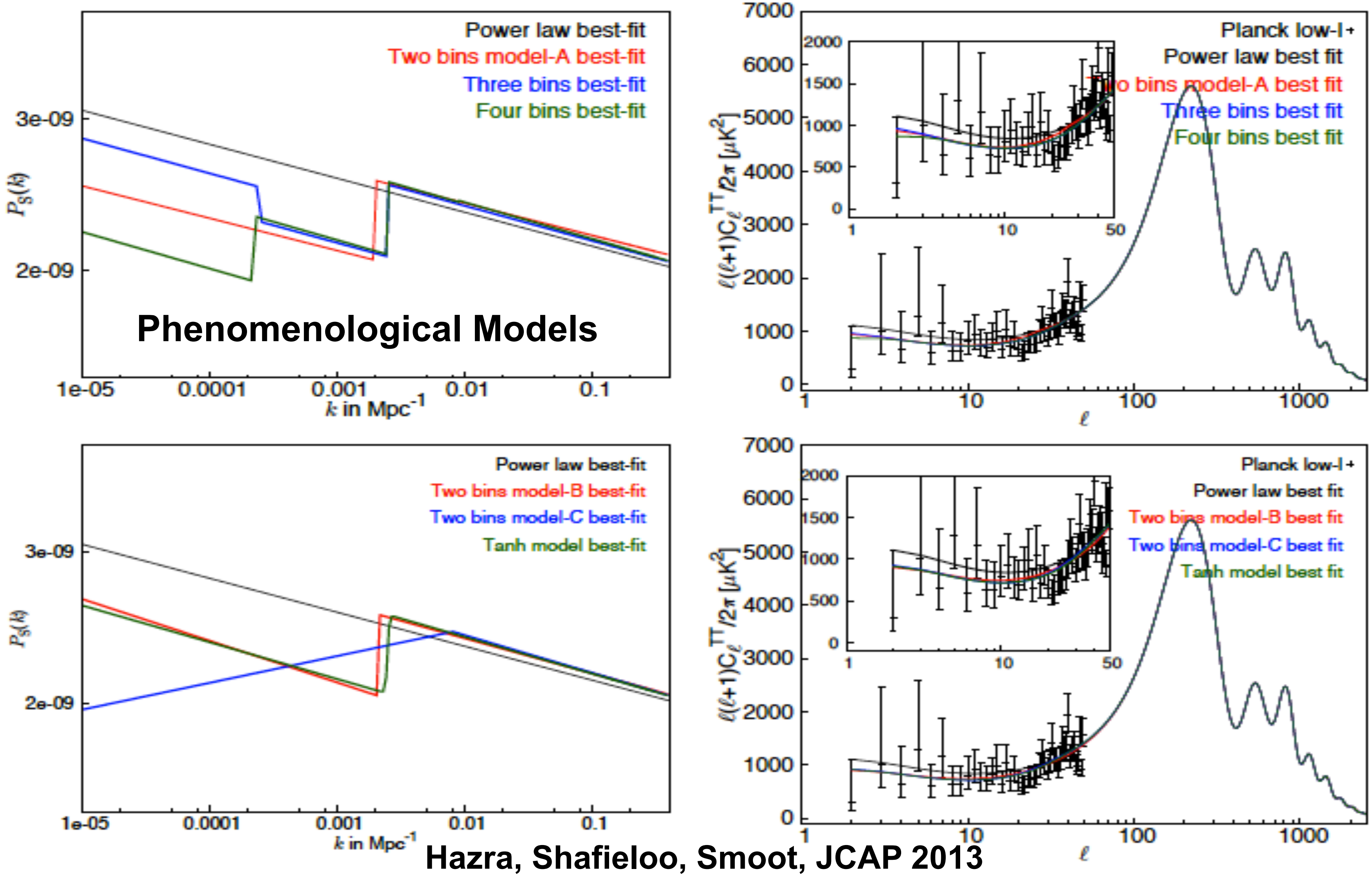
Direct Reconstruction

Theoretical Implication: Importance of the Features in the primordial spectrum

TABLE II: Best fit values of parameters specifying the initial power spectrum (k_*, α, R_*, n_s) and other relevant cosmological parameters for a class of model power spectra with a infrared cutoff (dataset used: WMAP TT data).

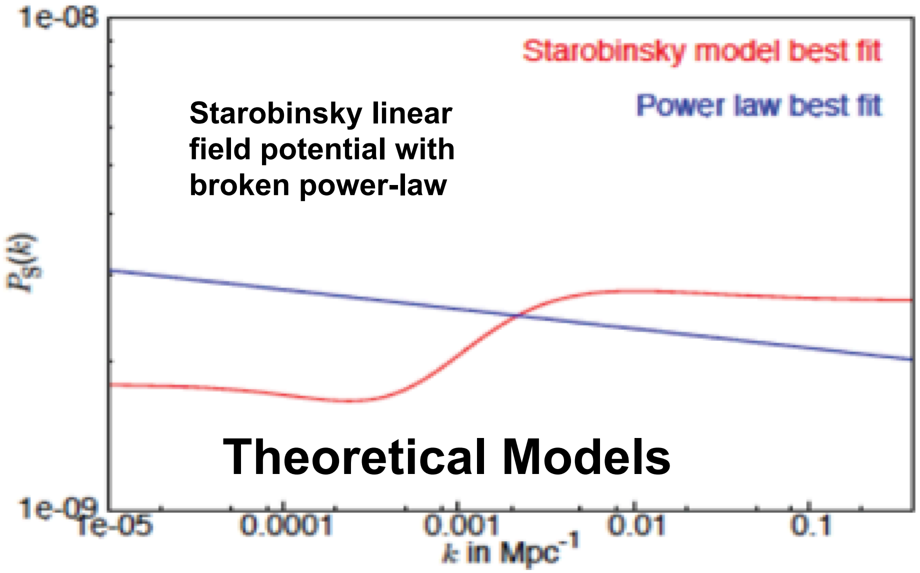
Parameter	Expo-cutoff EC(II)	Starobinsky SB(III)	Kin. Dom. KD(IV)	VF VF(V)	**Expo-staro(a)**[†] ES-a(VI)	Expo-staro(b)[‡] ES-b(VI)	Power Law PL(I)
$k_*(\times 10^{-4})\text{Mpc}^{-1}$	$3.0^{+4.8}_{-2.9}$	$3.1^{+5.8}_{-2.8}$	$3.5^{+3.0}_{-3.3}$	$0.4^{+0.7}_{-0.3}$	$\mathbf{3.0^{+0.5}_{-2.0}}$	$3.1^{+5.8}_{-2.1}$	–
α	$9.6^{+0.3}_{-8.6}$	–	–	–	$\mathbf{0.58^{+4.6}_{-0.43}}$	$0.72^{+9.1}_{-0.55}$	–
R_*	–	$0.73^{+0.25}_{-0.14}$	–	–	$\mathbf{0.17^{+0.80}_{-0.15}}$	$0.35^{+0.63}_{-0.20}$	–
n_s	$0.95^{+0.16}_{-0.03}$	$0.98^{+0.14}_{-0.07}$	$1.4^{+0.09}_{-0.90}$	$1.0^{+0.04}_{-0.15}$	$\mathbf{0.96^{+0.15}_{-0.08}}$	$0.99^{+0.08}_{-0.12}$	$0.96^{+0.30}_{-0.05}$
τ	$0.014^{+0.37}_{-0.004}$	$0.15^{+0.25}_{-0.14}$	$0.17^{+0.09}_{-0.15}$	$0.01^{+0.35}_{-0.001}$	$\mathbf{0.26^{+0.15}_{-0.08}}$	$0.28^{+0.12}_{-0.27}$	$0.014^{+0.500}_{-0.004}$
$z_{re}{}^a$	$3.2^{+21.7}_{-0.7}$	$16.3^{+11.5}_{-13.9}$	$17.8^{+4.9}_{-15.2}$	$2.7^{+23.5}_{-0.22}$	$\mathbf{23.8^{+5.9}_{-5.0}}$	$23.5^{+3.9}_{-21.0}$	$3.2^{+26.6}_{-0.83}$
Ω_Λ	$0.70^{+0.16}_{-0.18}$	$0.71^{+0.17}_{+0.24}$	$0.70^{+0.13}_{-0.21}$	$0.71^{+0.12}_{-0.20}$	$\mathbf{0.74^{+0.13}_{-0.10}}$	$0.75^{+0.12}_{-0.23}$	$0.65^{+0.24}_{-0.23}$
$\Omega_b h^2$	$0.022^{+0.006}_{-0.001}$	$0.023^{+0.005}_{-0.004}$	$0.024^{+0.001}_{-0.002}$	$0.023^{+0.005}_{-0.002}$	$\mathbf{0.023^{+0.004}_{-0.003}}$	$0.025^{+0.002}_{-0.005}$	$0.023^{+0.009}_{-0.002}$
$-\ln \mathcal{L}$	484.89	484.89	485.18	486.46	**483.44**	484.45	486.28
$\chi^2_{\text{eff}} \equiv -2\ln \mathcal{L}$	969.78	969.78	970.36	972.92	**966.88**	968.90	972.56
d.o.f.	891	891	892	892	**890**	890	893

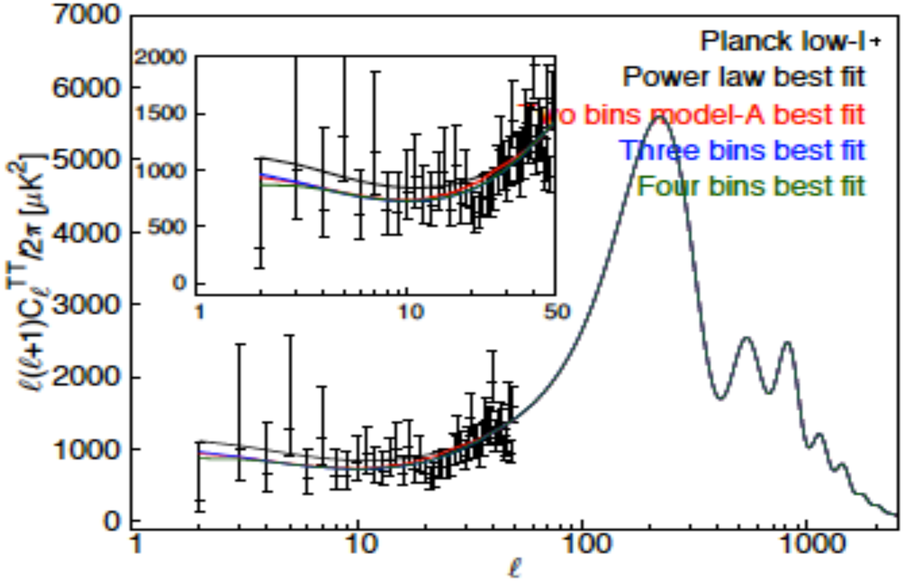
Beyond Power-Law: there are some other models consistent to the data.

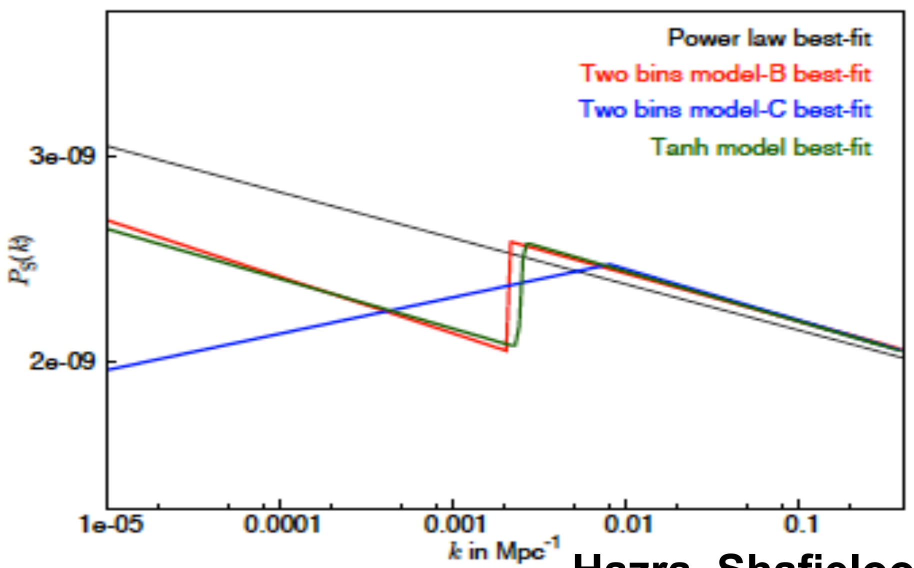


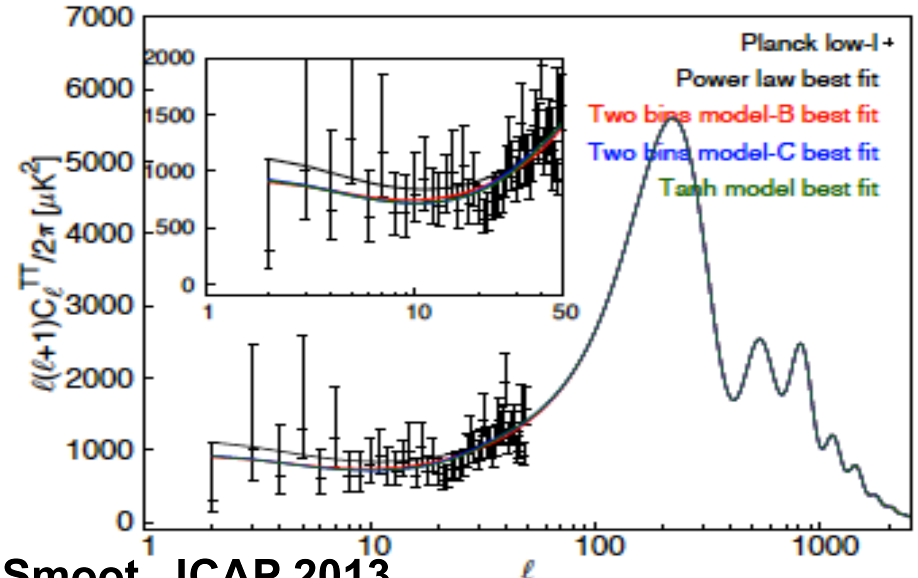
Hazra, Shafieloo, Smoot, JCAP 2013

Beyond Power-Law: there are some other models consistent to the data.









Hazra, Shafieloo, Smoot, JCAP 2013

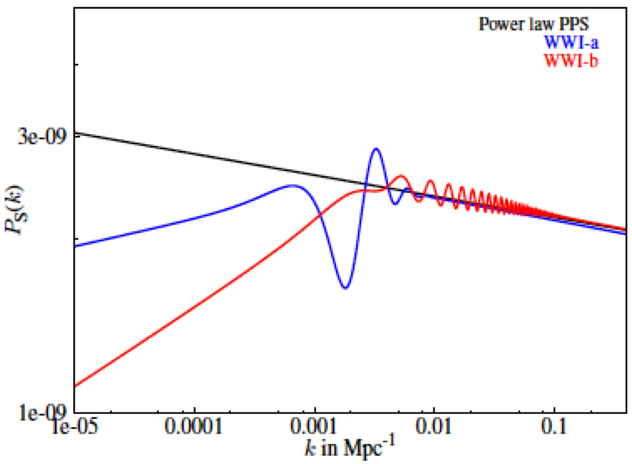
Individual likelihoods comparison						
Individual likelihood	Baseline	WWI-a $\Delta_{DOF} = 4$	WWI-b $\Delta_{DOF} = 4$	WWI-c $\Delta_{DOF} = 4$	WWI-d $\Delta_{DOF} = 4$	WWI′ $\Delta_{DOF} = 2$
TT	761.1	762	761.9	762.8	762.8	762.4
lowT	15.4	8.2	13.4	12.1	13	10.2
Total	778.1	772.1 (-6)	777 (-1.1)	777 (-1.1)	778.4 (0.3)	775 (-3.1)
EE	751.2	748.8	747.2	748.6	750.2	746.8
lowTEB	10493.6	10490	10495.6	10492.4	10495.7	10492.2
Total	11248.8	11241.8 (-7)	11246.2 (-2.6)	11244.5 (-4.3)	11249.3 (0.5)	11242.3 (-6.5)
TTTEEE	2431.7	2432.7	2422.6	2427.8	2421.7	2426.5
lowTEB	10497	10490.8	10495.1	10493.4	10495.3	10492.7
Total	12935.6	12929.5 (-6.1)	12924.2 (-11.4)	12927.6 (-8)	12923.4 (-12.2)	12925.2 (-10.4)
TT	764.5	763.6	762.2	764.4	762.9	762.8
EE	753.9	754.8	750.5	750.8	750.8	751
TE	932	933.4	928.7	929.2	927	928.8
lowTEB	10498.4	10490.4	10495.8	10493.7	10495.6	10492.4
BKP	41.6	42	42	42.6	41.8	42.9
Total	12997	12991 (-6)	12985.9 (-11.1)	12987.2 (-9.8)	12985 (-12)	12985.1 (-11.9)
TTTEEE	2431.7	2432.8	2421.4	2426.7	2421	2425.7
lowTEB	10498.5	10490.5	10495.5	10493.6	10495.8	10492.6
BKP	41.6	42	42.7	42	41.9	42.5
Total	12978.3	12971.3 (-7)	12967.3 (-11)	12968.6 (-9.7)	12965 (-13.3)	12968.6 (-9.7)
TT (bin1)	8402.1	8404.1	8403.9	8405.2	8402.1	8401.9
lowT	15.4	8.3	13.3	11.9	13.2	10.3
Total	8419.6	8414.7 (-4.9)	8419.5 (-0.1)	8419.8 (0.2)	8418.1 (-1.5)	8414.4 (-5.2)
TTTEEE (bin1)	24158.2	24158.6	24149	24155	24148.4	24151.5
lowTEB	10497.6	10490.3	10493.4	10493.6	10495.3	10492.7
Total	34661.9	34655.3 (-6.6)	34650.5 (-11.4)	34654.4 (-7.5)	34649.5 (-12.4)	34650.6 (-11.3)

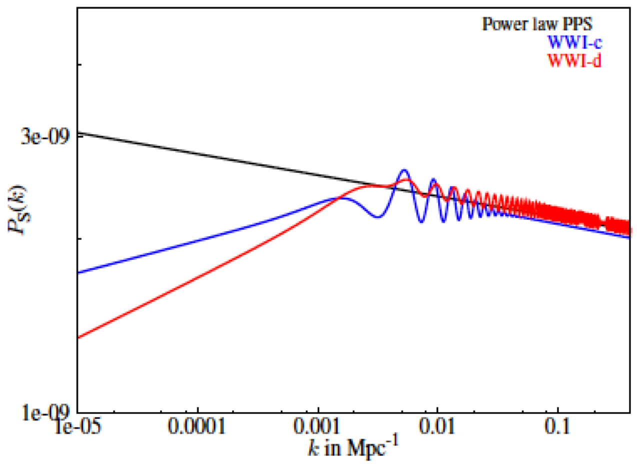
Beyond Power-Law:

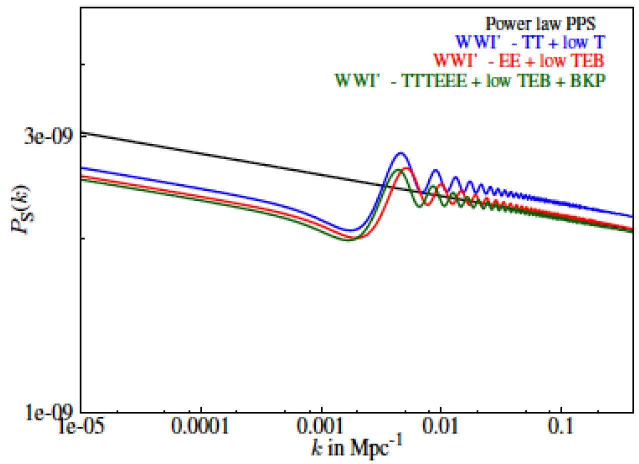
there are some other models consistent to the data.

Wiggly Whipped Inflation

Hazra, Shafieloo, Smoot, JCAP 2013
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2014A
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2014B
Hazra, Shafieloo, Smoot, Starobinsky, PRL 2014
Hazra, Shafieloo, Smoot, Starobinsky, JCAP 2016







Forms of PPS and Effects on the Background Cosmology

- Flat Lambda Cold Dark Matter Universe (LCDM) with power–law form of the primordial spectrum
- It has 6 main parameters.

Ω_b, Ω_m, H_0, τ → 1 → G(l,k) → 2

$$C_l = \sum G(l,k)P(k)$$

3 ↕

$$C_l^{obs}$$

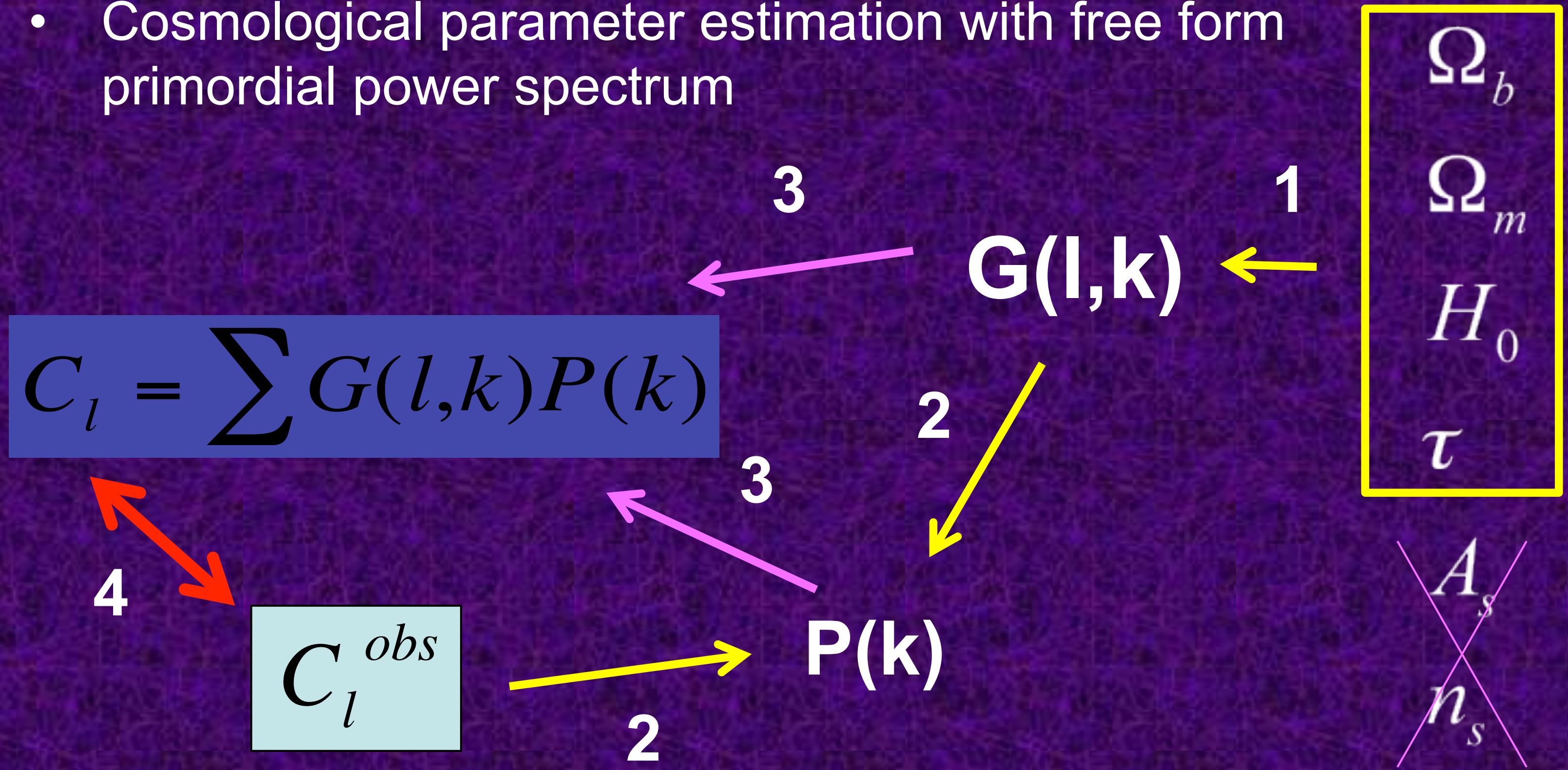
A_s, n_s → 1 →

$$P(k) = A_s[\frac{k}{k_*}]^{n_s-1}$$

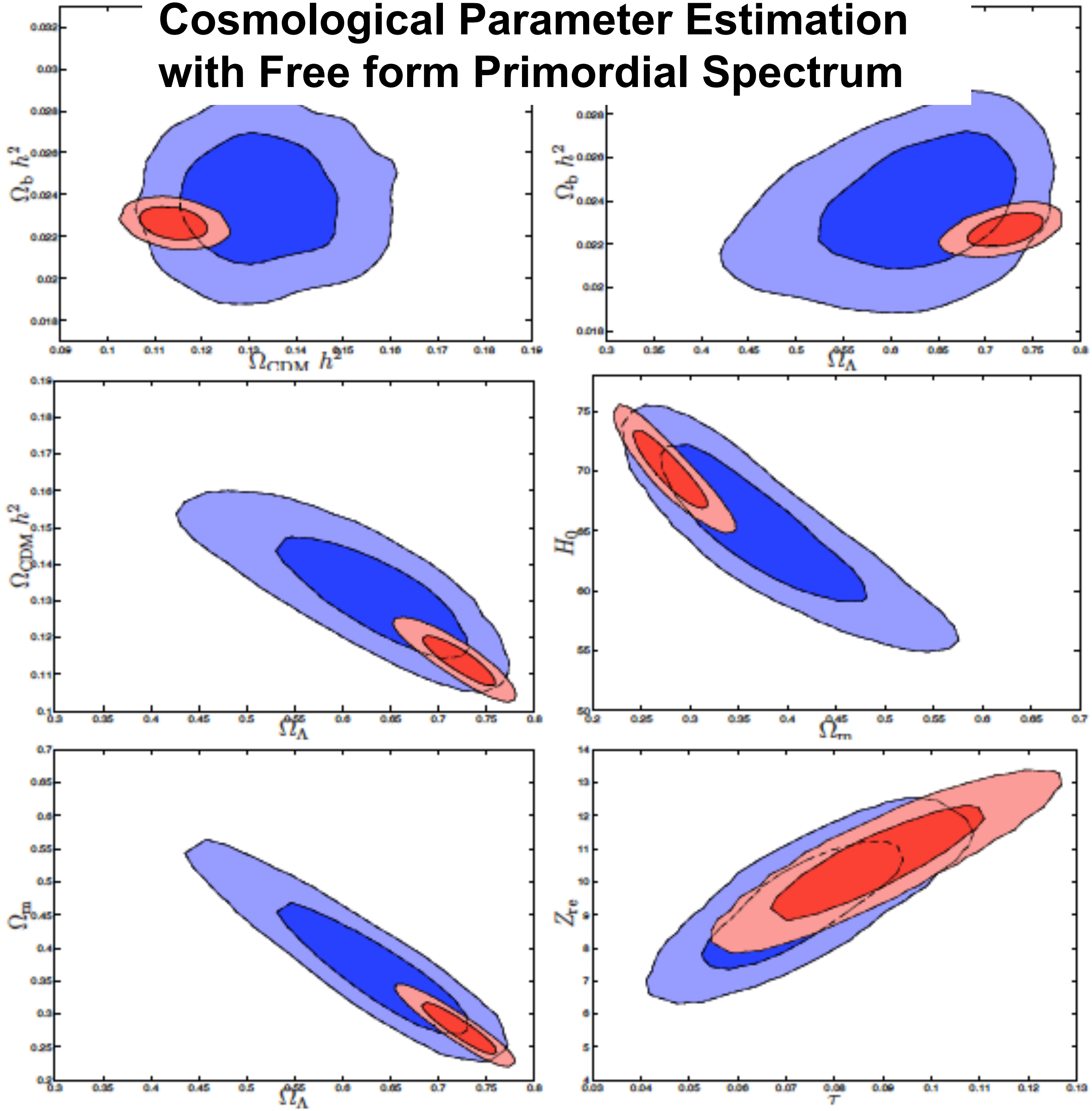
→ 2

Forms of PPS and Effects on the Background Cosmology

- Cosmological parameter estimation with free form primordial power spectrum



Cosmological Parameter Estimation with Free form Primordial Spectrum



WMAP9 Data

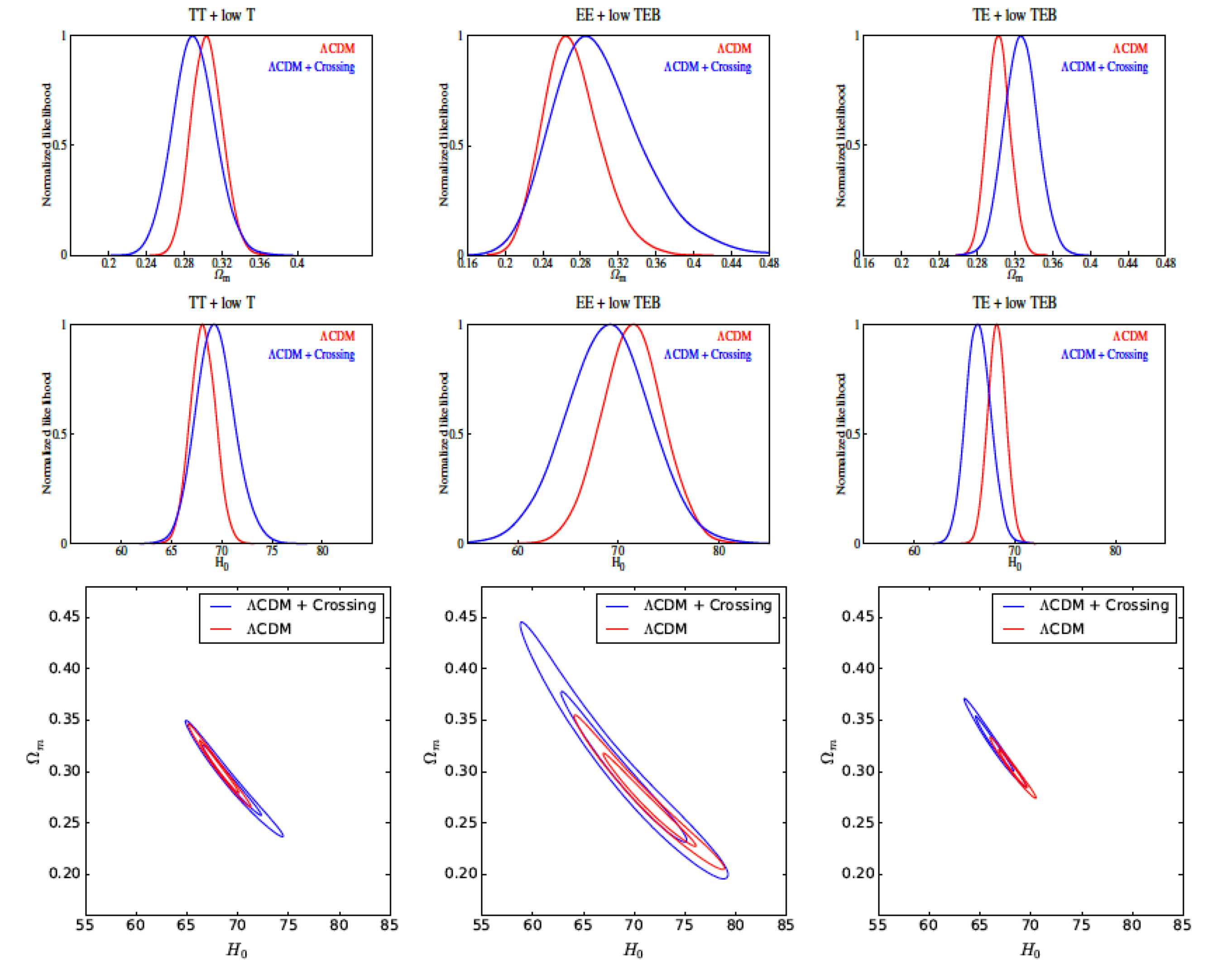
Red Contours: Power Law PPS

Blue Contours: Free Form PPS

Hazra, Shafieloo & Souradeep, PRD 2013

Planck 2015

Considering Crossing hyperfunctions and effect on background parameters.



Shafieloo & Hazra, JCAP 2017

Planck 2015

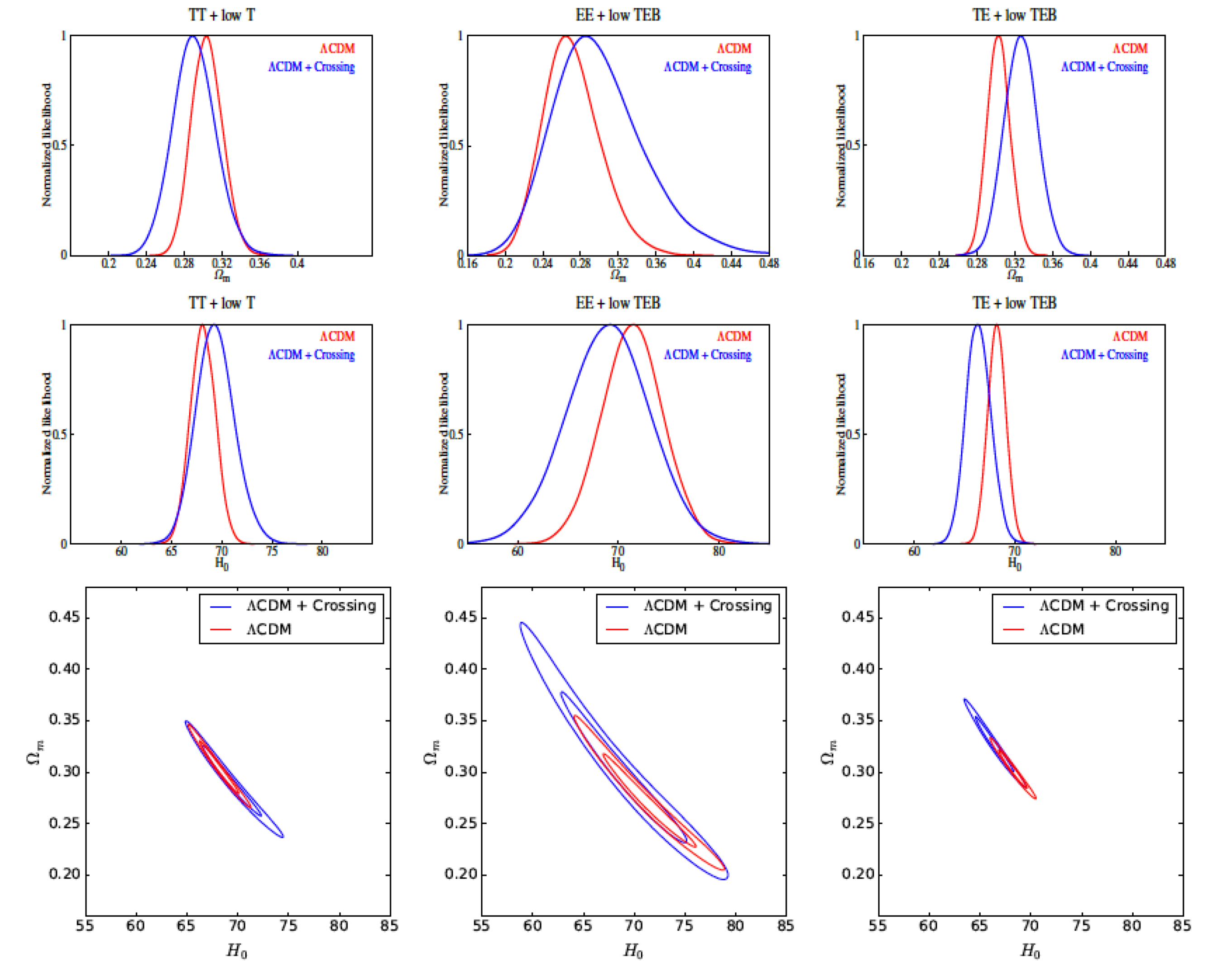
Considering Crossing hyperfunctions and effect on background parameters.

Planck polarization data and local H0 measurements seems having irresolvable tension. **Maybe either or both have systematics? If not, new physics might be the answer.**

Notice:

Planck was designed to be a full sky temperature anisotropy probe.

Shafieloo & Hazra, JCAP 2017



Complete reconstruction analysis with Planck polarization data

Works to do soon! (near future)

Full picture

$$C_\ell^{TT} = \int \frac{dk}{k} P(k) \quad G_\ell^{TT}(k)$$

$$C_\ell^{EE} = \int \frac{dk}{k} P(k) \quad G_\ell^{EE}(k)$$

$$C_\ell^{BB} = \int \frac{dk}{k} P_t(k) \quad G_\ell^{BB}(k)$$

$$C_\ell^{TE} = \int \frac{dk}{k} P(k) \quad G_\ell^{TE}(k)$$

Searching for correlations!

$$P_S(k), P_T(k), P_{iso}(k)$$

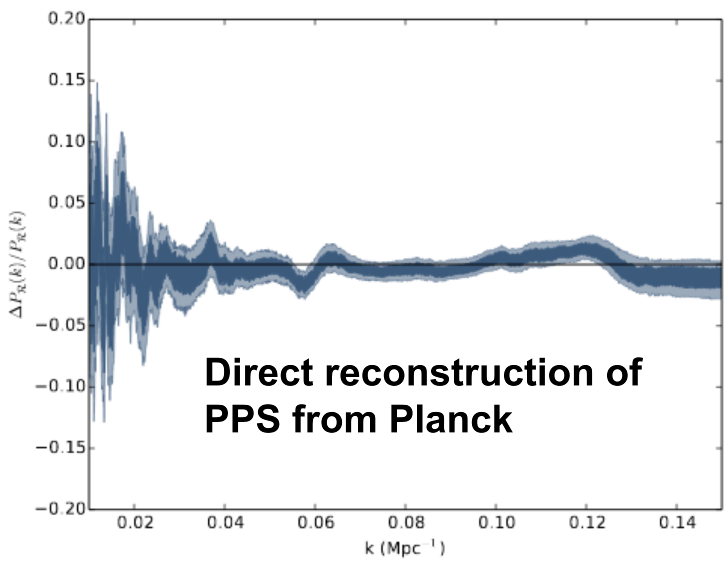
Primordial power spectra from Early universe

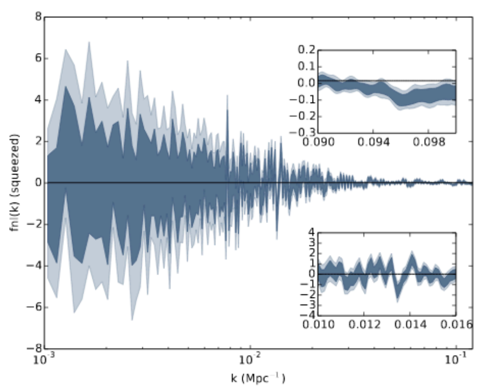
$$G_\ell^{TT}(k), G_\ell^{EE}(k), G_\ell^{BB}(k), G_\ell^{TE}(k)$$

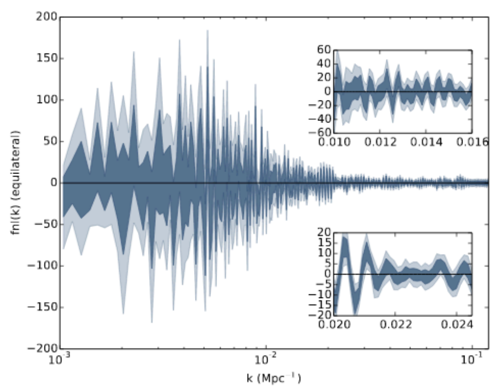
Post recombination Radiative transport kernels in a **given** cosmology

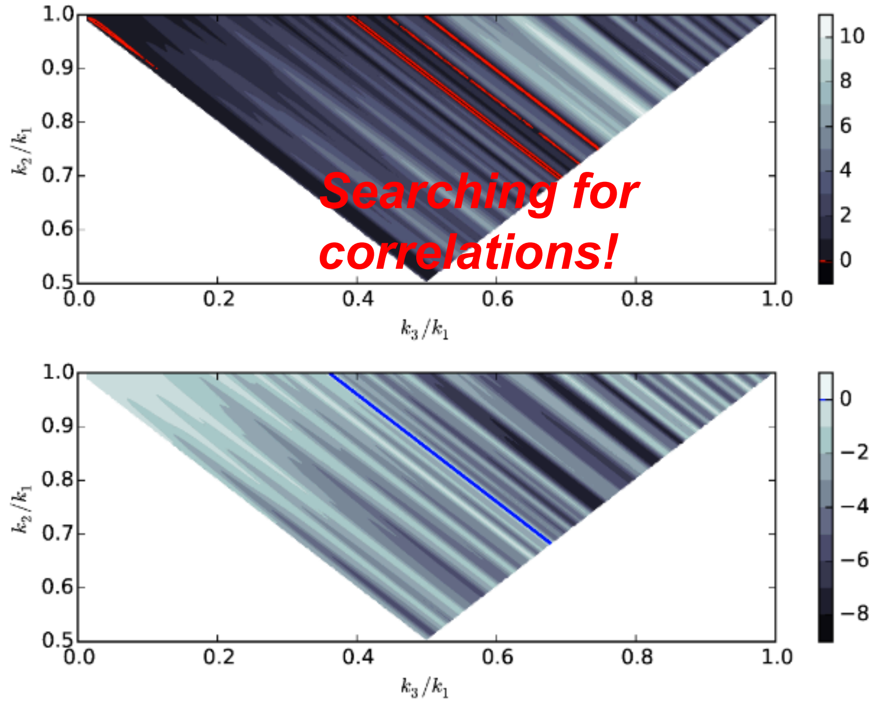
Works to do soon! (maybe near future)

Joint constraint on inflationary features using the two and three-point correlations of temperature and polarization anisotropies





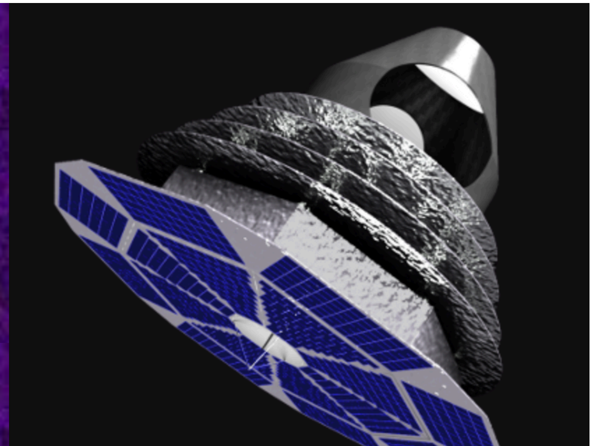




Bispectrum in terms of the reconstructed power spectrum and its first two derivatives

Appleby, Gong, Hazra, Shafieloo, Sypsas, PLB 2015

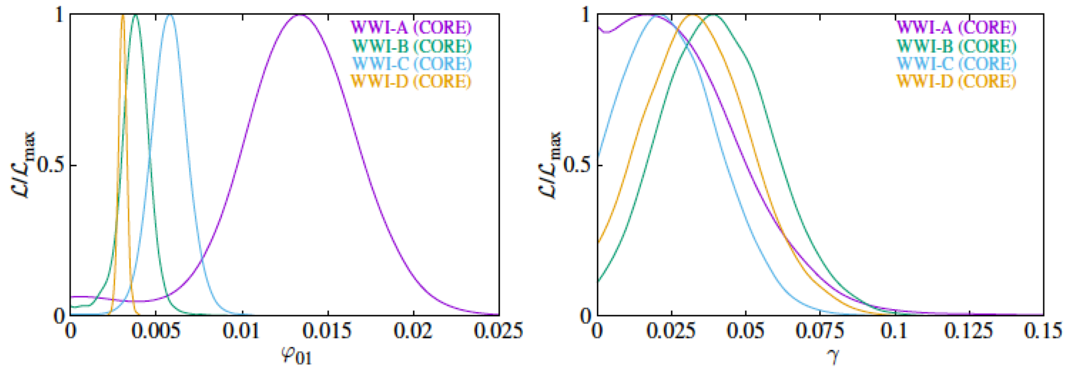
Features with Future of CMB



Di Valentino et al,
arXiv:1612.00021

With Cosmic Origins Explorer (CORE)-like survey specification

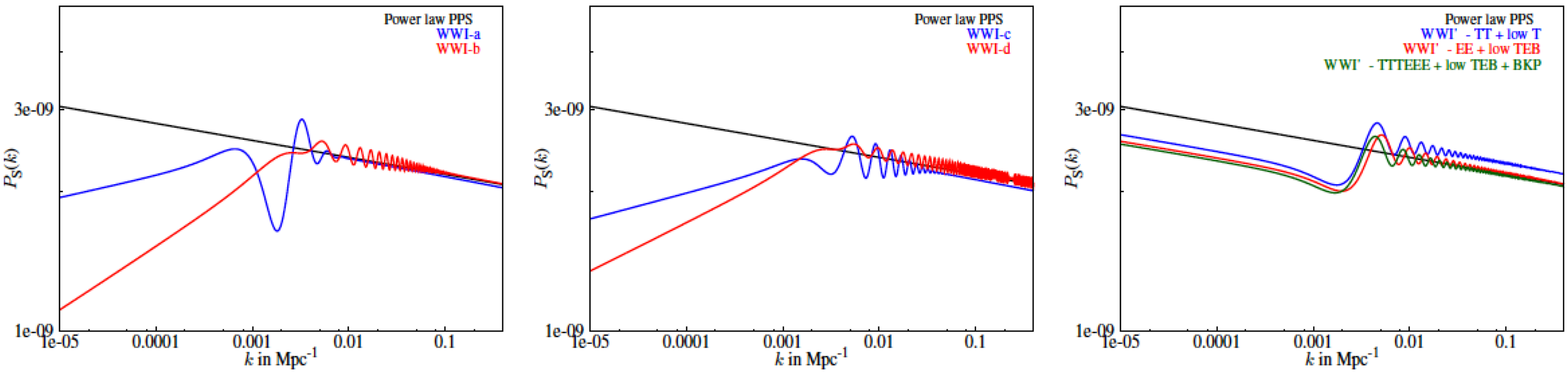
Wiggles **Suppression**



Wiggly Whipped Inflation

Hazra, Paoletti, Ballardini, Finelli,
Shafieloo, Smoot, Starobinsky,
JCAP 2018

- Large scale suppressions can not be detected with high significance
- Some of the intermediate and small scale oscillations can be detected, if present



From 2D to 3D

Using LSS data to test early universe scenarios

Key issues:

1. We need to estimate matter power spectrum but we observe galaxies. Hence we have to model the bias and estimate its parameters accurately and precisely to connect the observables to theory. Bias modeling would be different for different surveys and susceptible to systematics.

2. Does power spectrum (or bi-spectrum, etc) necessarily contains all the information in 3D data of LSS? Can’t reducing dimensionality of the data wash out some information?

From 2D to 3D

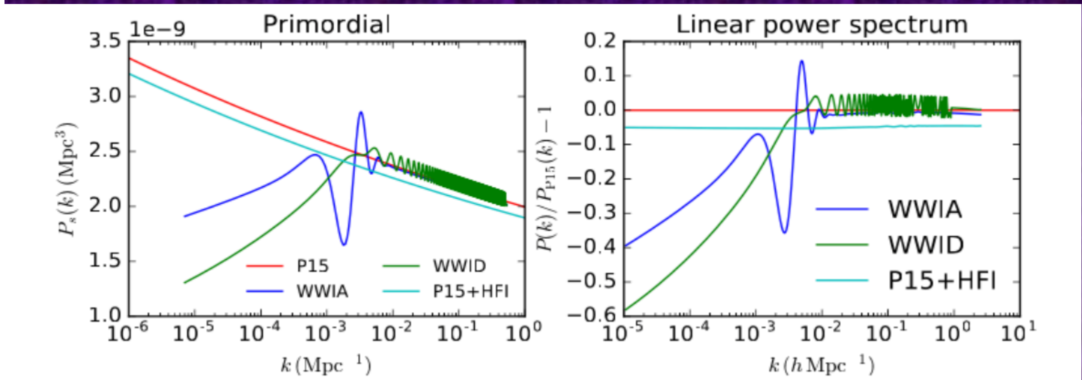
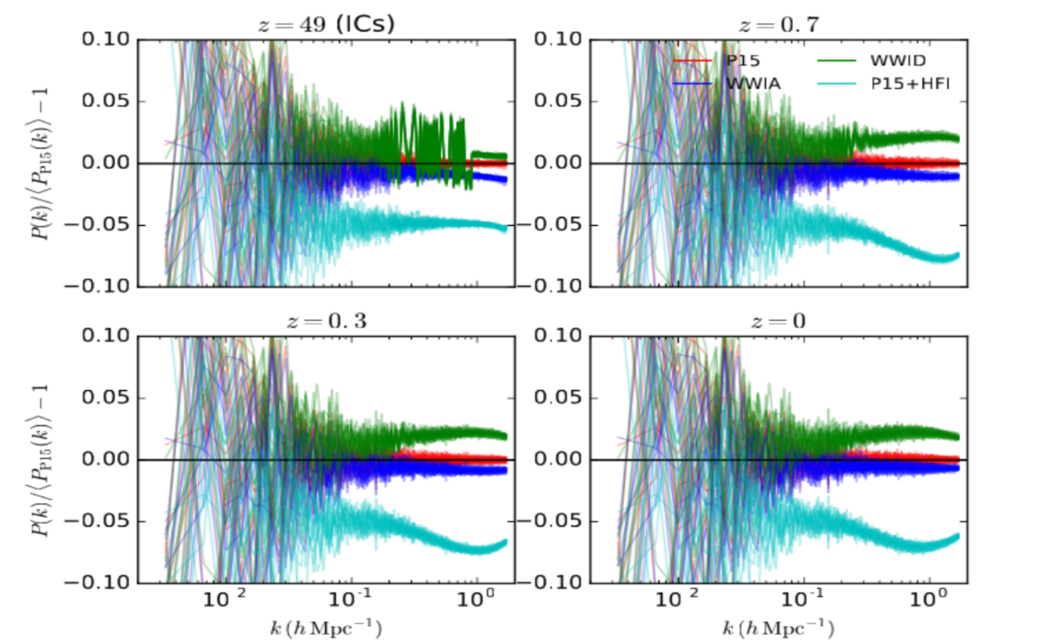


Table 2: Cosmological parameters of models

Model	Ω_m	H_0 ($\mathrm{km\,s^{-1}\,Mpc^{-1}}$)	σ_8	n_s
P15	0.319	66.93	0.8156	0.9625
WWIA	0.320	66.86	0.8340	NA
WWID	0.318	67.01	0.8419	NA
P15+HFI	0.319	66.93	0.8156	0.9619



N-Body Simulation (DESI like)

L'Huillier, Shafieloo, Hazra, Smoot, Starobinsky
arXiv:1710.10987

To distinguish degenerate models that cannot be distinguished using CMB data or LSS matter power spectrum.

From 2D to 3D

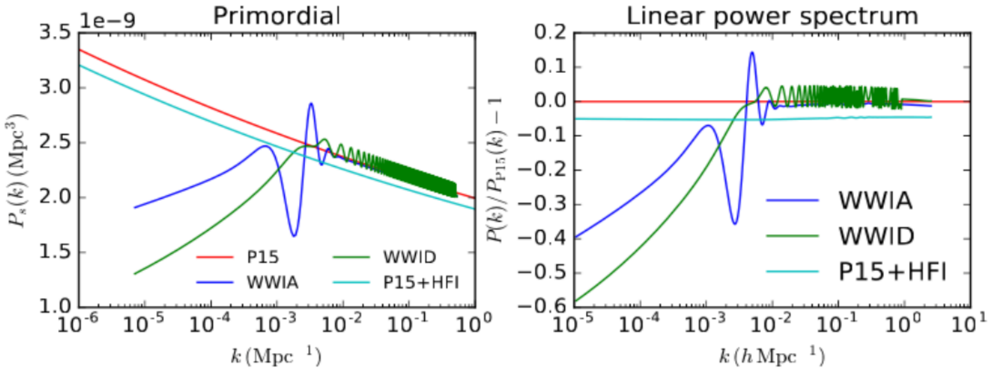


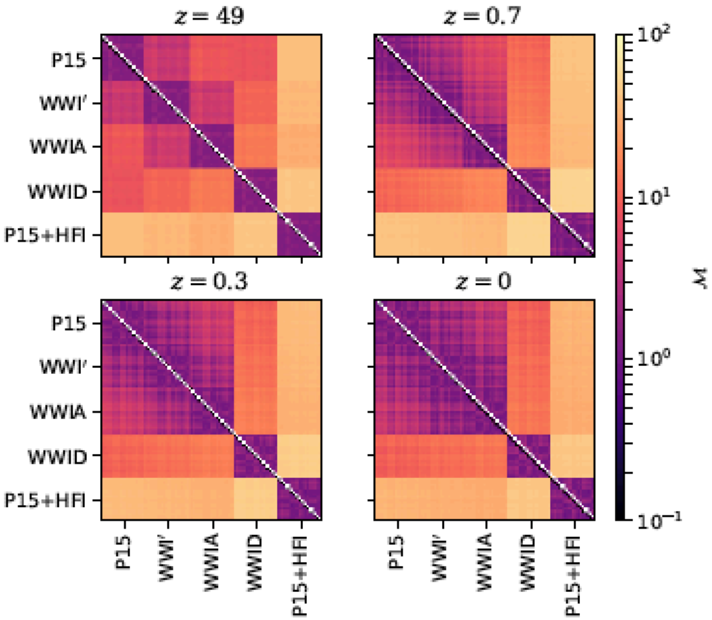
Table 2: Cosmological parameters of models

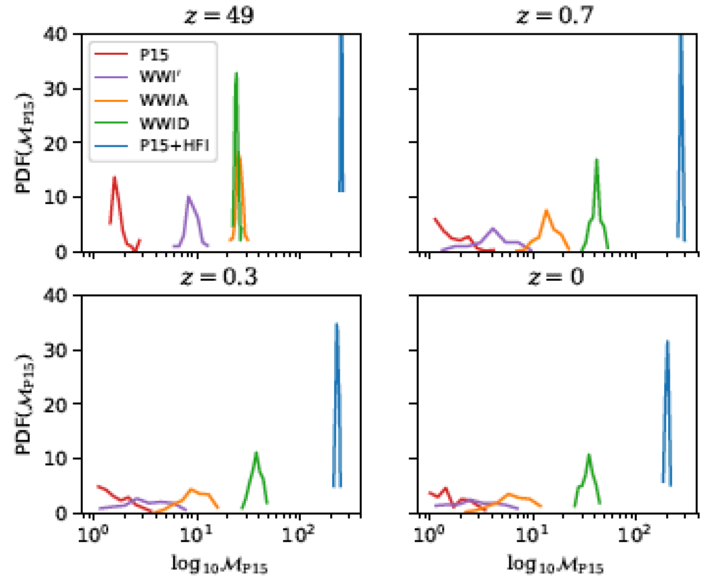
Model	Ω_m	H_0 (km s^{-1} Mpc^{-1})	σ_8	n_s
P15	0.319	66.93	0.8156	0.9625
WWIA	0.320	66.86	0.8340	NA
WWID	0.318	67.01	0.8419	NA
P15+HFI	0.319	66.93	0.8156	0.9619

N-Body Simulation (DESI like)

L'Huillier, Shafieloo, Hazra, Smoot, Starobinsky
arXiv:1710.10987

2 point correlation functions and power spectrum unable to distinguish between the models





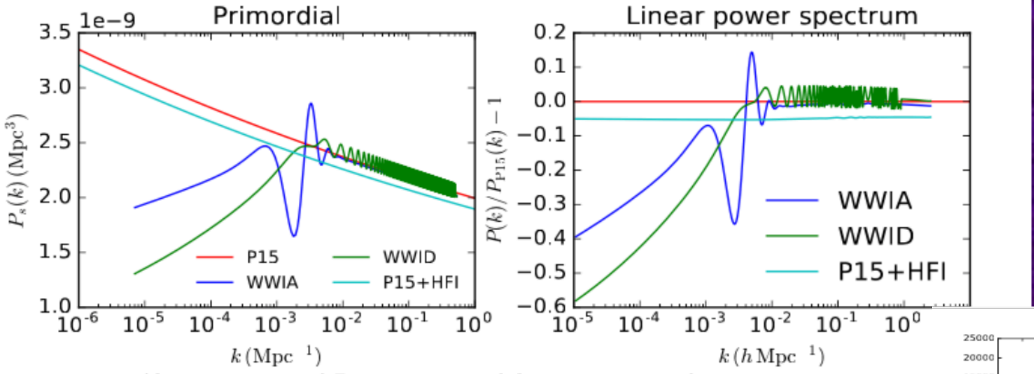
$$\Xi_{P_i}(k) = \frac{P_i(k) - \langle P_{P15}(k)\rangle}{\sigma_{P_{P15}}(k)}, \qquad M_{\mathrm{mod}_i^m,\mathrm{mod}_j^n} = \sqrt{\frac{1}{N_k}\sum_k \left(\Xi_{P_{\mathrm{mod}_i^m}}(k) - \Xi_{P_{\mathrm{mod}_j^n}}(k)\right)^2},$$

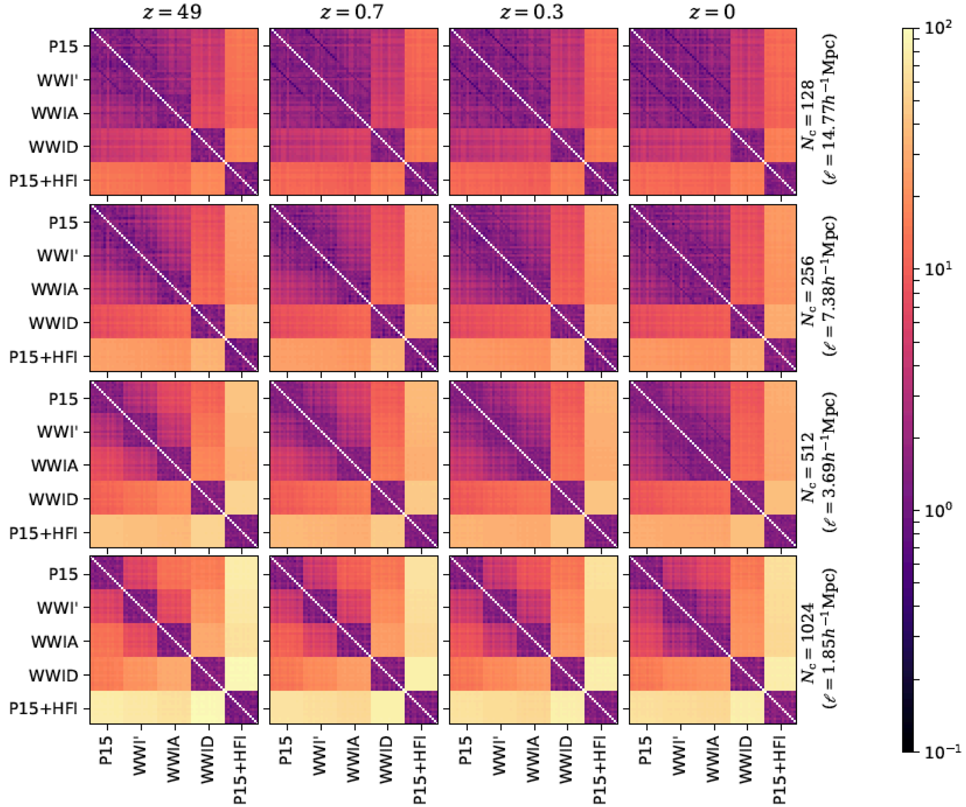
Going beyond power spectrum

From 2D to 3D

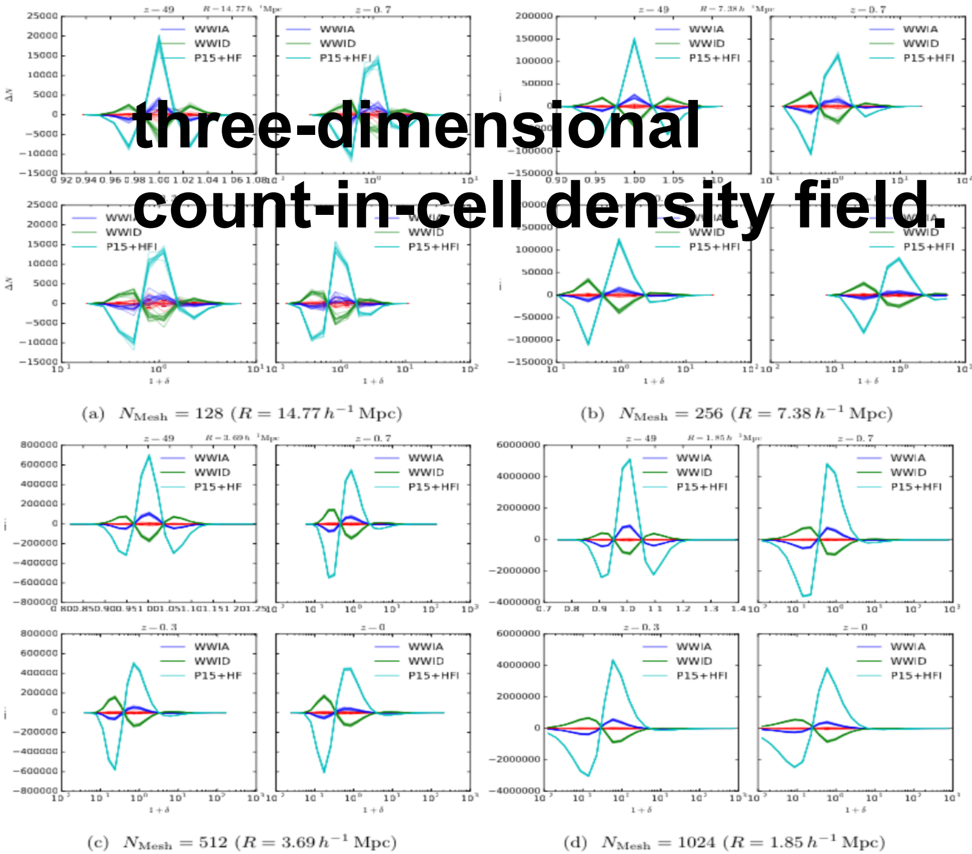
N-Body Simulation (DESI like)

L'Huillier, Shafieloo, Hazra, Smoot, Starobinsky
arXiv:1710.10987

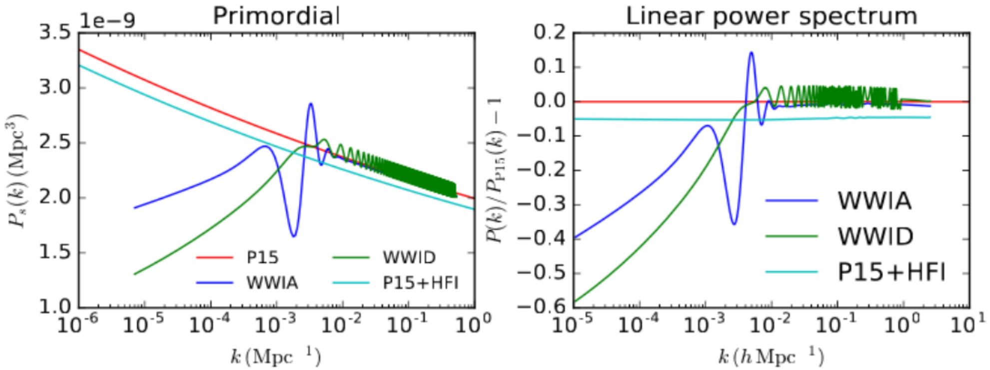




three-dimensional count-in-cell density field.

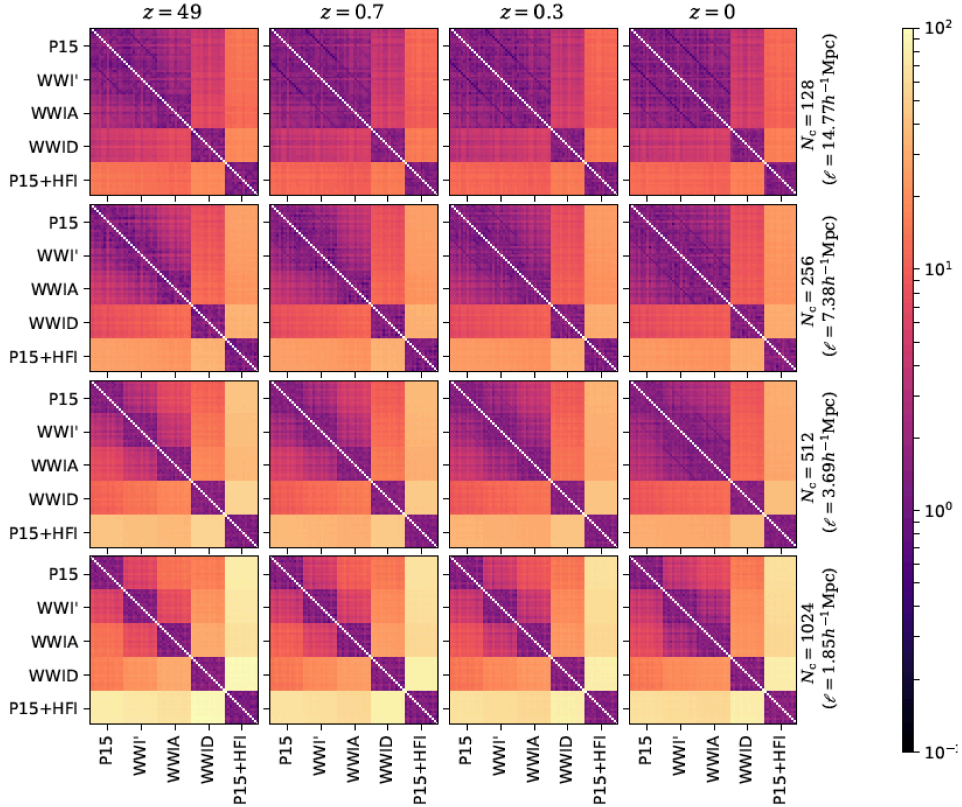


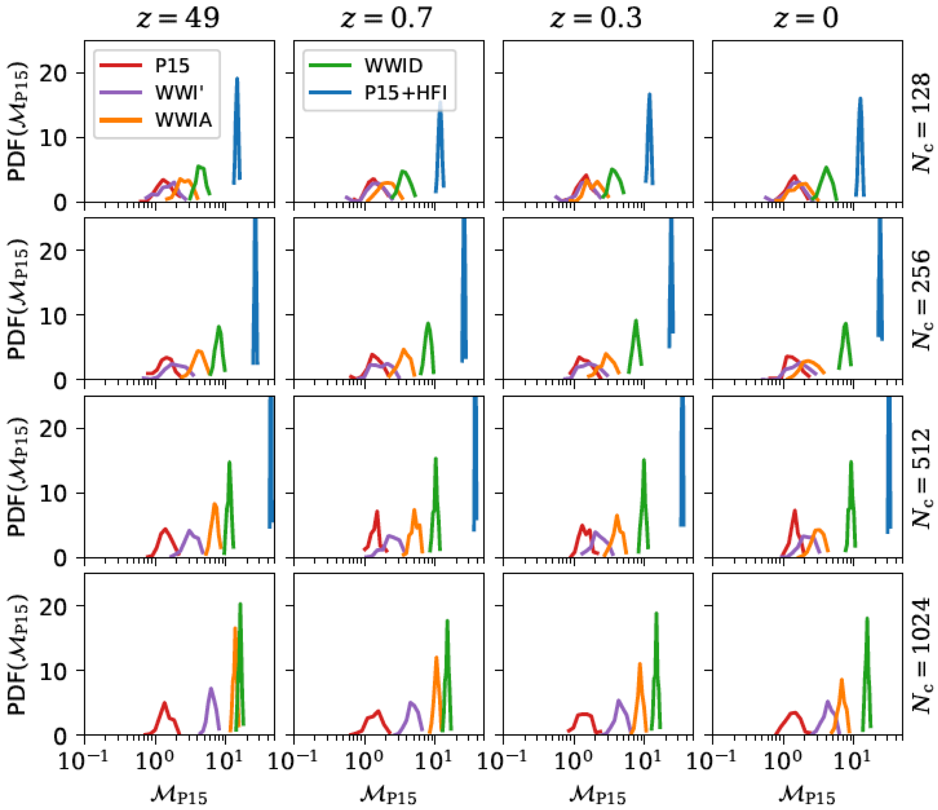
From 2D to 3D



N-Body Simulation (DESI like)

L'Huillier, Shafieloo, Hazra, Smoot, Starobinsky
arXiv:1710.10987





Going beyond power spectrum

From 2D to 3D

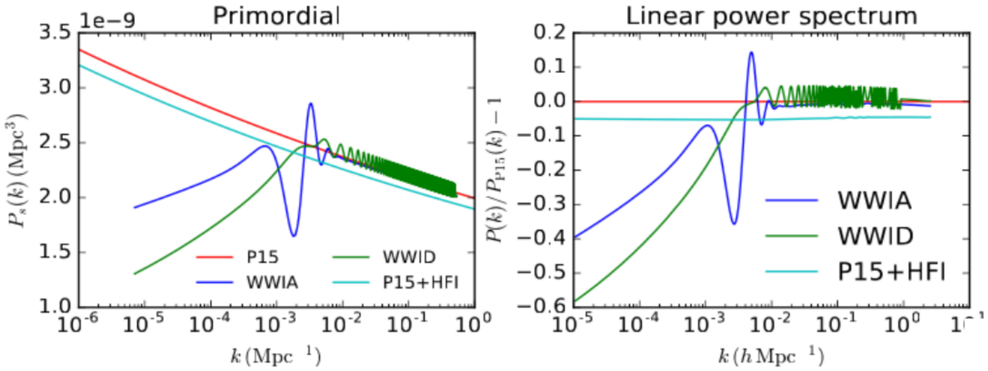


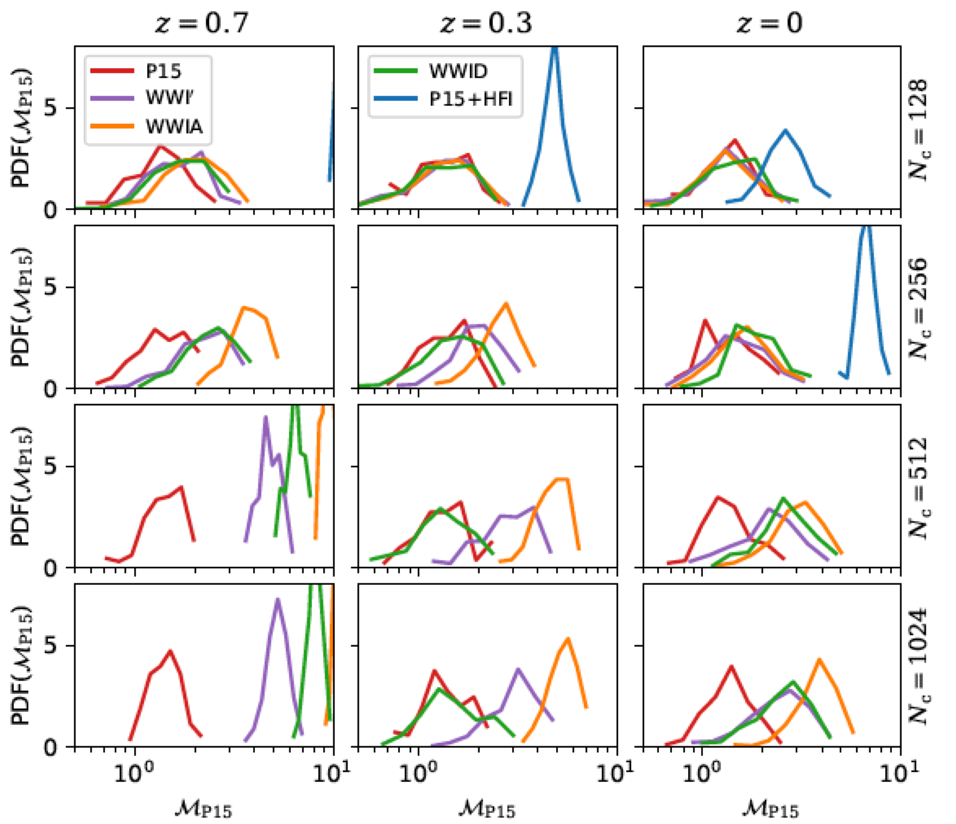
Table 2: Cosmological parameters of models

Model	Ω_m	H_0 ($\mathrm{km\,s^{-1}\,Mpc^{-1}}$)	σ_8	n_s
P15	0.319	66.93	0.8156	0.9625
WWIA	0.320	66.86	0.8340	NA
WWID	0.318	67.01	0.8419	NA
P15+HFI	0.319	66.93	0.8156	0.9619

N-Body Simulation (DESI like)

L'Huillier, Shafieloo, Hazra, Smoot, Starobinsky
arXiv:1710.10987

Using mass-weighted halo density



Summary

- Standard power-law form of the primordial spectrum explains the current data well.
- Many models with features can be still consistent to the data. It is not only about getting closer to the actual inflation model but also the effect on late universe.
- Finding approaches to use efficiently large scale structure data to break the degeneracies between early universe scenarios is an important challenge.
- Using all power of the data is important. Probably we have to go beyond power-spectrum, bispectrum or conventional analysis.