Primordial power spectrum from Planck

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This talk is based on :

- D. K. Hazra, A. Shafieloo and T. Souradeep, **Primordial power spectrum from Planck**, *arXiv:1406.4827*.

- D. K. Hazra, A. Shafieloo and G. F. Smoot, **Reconstruction of broad features in the primordial spectrum and inflaton potential from Planck**, JCAP **1312**, 035 (2013).
- D. K. Hazra, A. Shafieloo, G. F. Smoot, A. A. Starobinsky, **Ruling out the power-law form of the scalar primordial spectrum**, JCAP **1406** (2014) 061.
- D. K. Hazra, A. Shafieloo, G. F. Smoot, A. A. Starobinsky, **Whipped Inflation**, *Phys. Rev. Lett.* **113**, *071301 (2014)*
- D. K. Hazra, A. Shafieloo, G. F. Smoot, A. A. Starobinsky, **Wiggly Whipped Inflation**, *arXiv:1405.2012, To appear in JCAP.*

A brief roadmap of this talk

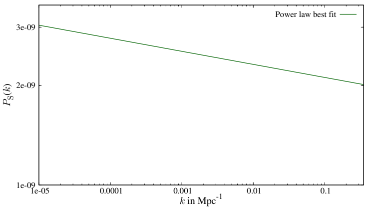
- **Origin and evolution of Richardson-Lucy algorithm for reconstruction**
- **Planck angular power spectrum**
- **Applications : consistency with WMAP-9, degeneracies with lensing, features and their importance**

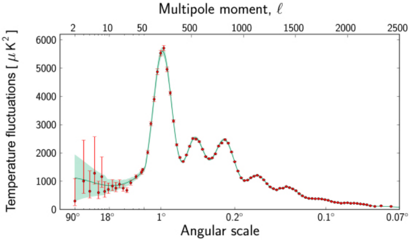
- **Primordial power spectrum from Planck and BICEP2**

Primordial power spectrum (P_k) $\Longrightarrow$ Angular power spectrum (C_ℓ^{T})

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

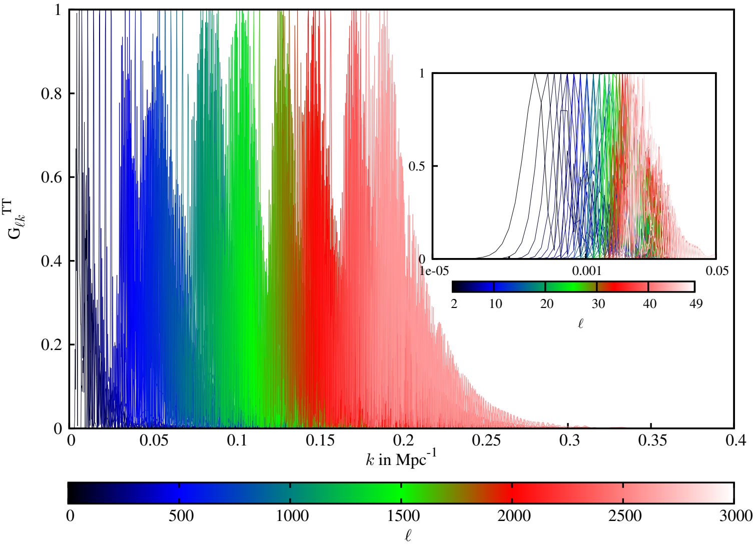
Here $G_{\ell k}$ is the radiative transport kernel and connects the Primordial Power Spectrum (PPS) to the angular power spectrum.





Planck 2013

Transport kernel $(G_{\ell k})$:



Hazra, Shafieloo and Souradeep, 2014

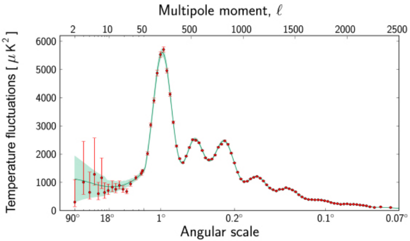
The Richardson-Lucy algorithm : Origin

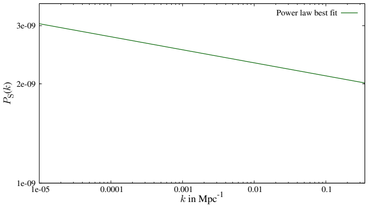
This deconvolution iteratively solves for the PPS [1]:

Richardson (1972) and Lucy (1974)

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

PPS at $i+1$'th iteration is obtained as a correction factor to the i'th PPS through the deconvolution





[1]Initial applications : Baugh and Efstathiou, MNRAS, 1993, 1994

The Richardson-Lucy algorithm : Evolution

Improved Richardson-Lucy (IRL) algorithm makes it CMB error sensitive:

[See, A. Shafieloo and T. Souradeep, Phys. Rev. D **70** (2004) 043523; A. Shafieloo, T. Souradeep, P. Manimaran, P. K. Panigrahi and R. Rangarajan, Phys. Rev. D **75** (2007) 123502 ; A. Shafieloo and T. Souradeep, Phys. Rev. D **78** (2008) 023511.]

$$P_k^{(i+1)} - P_k^{(i)} = P_k^{(i)} \times \left[\sum_\ell \widetilde{G}_{\ell k} \left(\frac{C_\ell^{\mathrm{D}} - C_\ell^{\mathrm{T}(i)}}{C_\ell^{\mathrm{T}(i)}} \right) \tanh^2 \left[\frac{C_\ell^{\mathrm{D}} - C_\ell^{\mathrm{T}(i)}}{\sigma_\ell^{\mathrm{D}}} \right]^2 \right]$$

- The method error weighs each multipole
- For similar error, it provides preference to the multipole where C_ℓ^{T} is further away from C_ℓ^{D}
- Designed to work with uncorrelated binned data

The Richardson-Lucy algorithm : Evolution

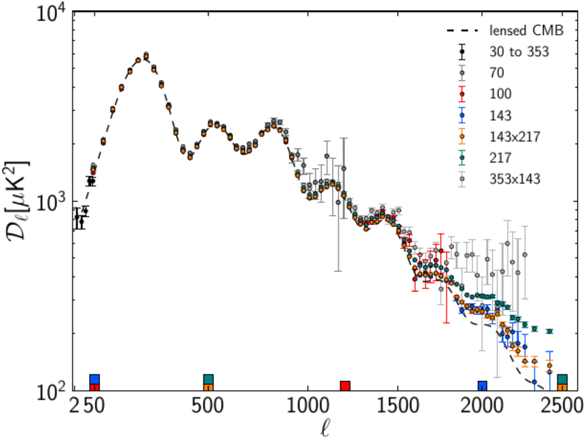
Modified Richardson-Lucy (MRL) algorithm for correlated data: [See, D. K. Hazra, A. Shafieloo and T. Souradeep, JCAP **1307**, 031 (2013); D. K. Hazra, A. Shafieloo, T. Souradeep, Phys. Rev. D **87** (2013) 123528.]

$$P_k^{(i+1)} - P_k^{(i)} = P_k^{(i)} \times \left[\sum_{\ell=2}^{\ell=900} \widetilde{G}_{\ell k}^{\text{unbinned}} \left\{ \left(\frac{C_\ell^{\mathrm{D}} - C_\ell^{\mathrm{T}(i)}}{C_\ell^{\mathrm{T}(i)}} \right) \tanh^2 \left[Q_\ell (C_\ell^{\mathrm{D}} - C_\ell^{\mathrm{T}(i)}) \right] \right\}_{\text{unbinned}} \right.$$
$$\left. + \sum_{\ell_{\text{binned}} > 900} \widetilde{G}_{\ell k}^{\text{binned}} \left\{ \left(\frac{C_\ell^{\mathrm{D}} - C_\ell^{\mathrm{T}(i)}}{C_\ell^{\mathrm{T}(i)}} \right) \tanh^2 \left[\frac{C_\ell^{\mathrm{D}} - C_\ell^{\mathrm{T}(i)}}{\sigma_\ell^{\mathrm{D}}} \right]^2 \right\}_{\text{binned}} \right]$$

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

- Provides analysis with unbinned angular power spectrum
- Switches to binned reconstruction where SNR becomes < 1.

Issues with Planck



Planck 2013

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

The Richardson-Lucy algorithm : As of today

Modified Richardson-Lucy (MRL) algorithm for correlated data: [See, D. K. Hazra, A. Shafieloo and T. Souradeep, arXiv:1406.4827[astro-ph.CO].]

$$P_k^{(i+1)} - P_k^{(i)} = P_k^{(i)} \times \sum_{\nu} \left[\sum_{\ell=\ell^{\nu}_{\rm min}}^{\ell^{\nu}_{\rm max}(\leq 1900)} \frac{1}{g_{\nu}(\ell)} \widetilde{G}_{\ell k} \left\{ \left(\frac{C_\ell^{{\rm D}'_\nu} - C_\ell^{{\rm T}(i)}}{C_\ell^{{\rm T}(i)}} \right) \tanh^2 \left[Q_\ell (C_\ell^{{\rm D}'_\nu} - C_\ell^{{\rm T}(i)}) \right] \right\}_{\rm unbinned} \right.$$

$$\left. + \sum_{\ell=\ell^{\nu}_{\rm min}(>1900)}^{\ell^{\nu}_{\rm max}} \frac{1}{g'_{\nu}(\ell)} \widetilde{G'}_{\ell k} \left\{ \left(\frac{C_\ell^{{\rm D}'_\nu} - C_\ell^{{\rm T}(i)}}{C_\ell^{{\rm T}(i)}} \right) \tanh^2 \left[\frac{C_\ell^{{\rm D}'_\nu} - C_\ell^{{\rm T}(i)}}{\sigma_\ell^{{\rm D}_\nu}} \right]^2 \right\}_{\rm binned} \right]$$

$C_\ell^{{\rm D}'_\nu} \equiv$ " clean" angular power spectrum (*i.e.* the data) from the spectrum ν after calibrating and subtracting the foreground power spectrum from each of the *raw* angular power spectrum, $C_\ell^{{\rm D}_\nu}$ provided by Planck.

- Designed to work with Planck
- Combines different spectra from Planck and provides effective PPS from set of combinations
- Foreground effects, calibration and lensing are considered

Planck data : Nomenclature

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

Reference to the individual Planck spectra

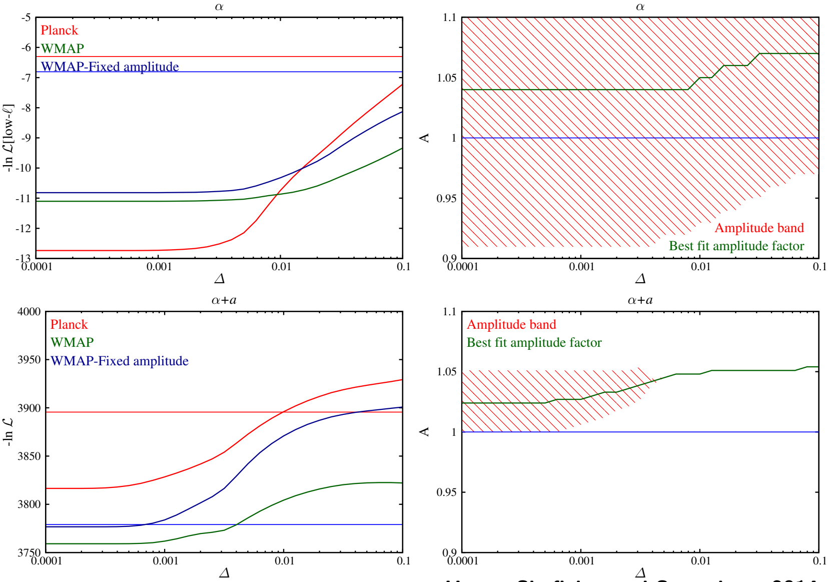
Application I : Consistency check with WMAP-9

After reconstruction, we smooth the data with a smoothing width Δ as,

$$P_k^{\rm Smooth} = \frac{\sum_{\tilde{k}={\rm k_{min}}}^{\rm k_{max}} P_{\tilde{k}}^{\rm Raw} \times \exp\left[-\left(\frac{\log\tilde{k}-\log k}{\Delta}\right)^2\right]}{\sum_{\tilde{k}={\rm k_{min}}}^{\rm k_{max}} \exp\left[-\left(\frac{\log\tilde{k}-\log k}{\Delta}\right)^2\right]}$$

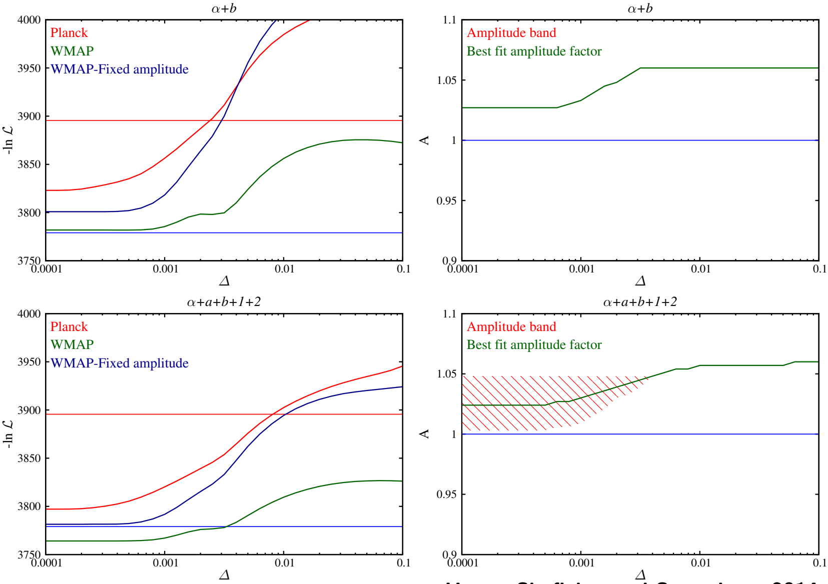
- Fit the smooth reconstructed PPS to WMAP-9 data
- We allow an overall amplitude shift
- Locate the possible region in amplitude where the PPS fits WMAP-9 better than power law PPS
- Compare different spectra from Planck and WMAP-9

Application I : Consistency check with WMAP-9



Hazra, Shafieloo and Souradeep, 2014

Application I : Consistency check with WMAP-9



Hazra, Shafieloo and Souradeep, 2014

Application I : Consistency check with WMAP-9

- **Low-ℓ and $100~\mathrm{GHz} \times 100~\mathrm{GHz}$ is most consistent with WMAP-9**

- **4% and 2.5% amplitude shift for reconstructed PPS from low-ℓ and $100~\mathrm{GHz} \times 100~\mathrm{GHz}$ provides best fit to WMAP-9**

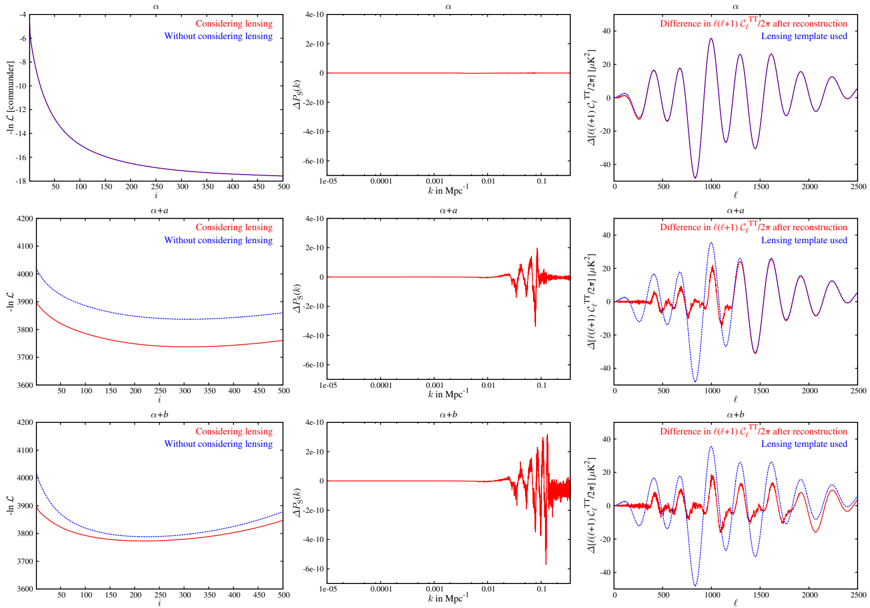
- **PPS reconstructed from combined spectrum indicates Planck is in agreement with WMAP-9 provided an amplitude shift of 2.5%.**

[Note that we found it before through other analysis, D. K. Hazra and A. Shafieloo, Phys. Rev. D 89, 043004 (2014)]

Application II : Degeneracies with lensing

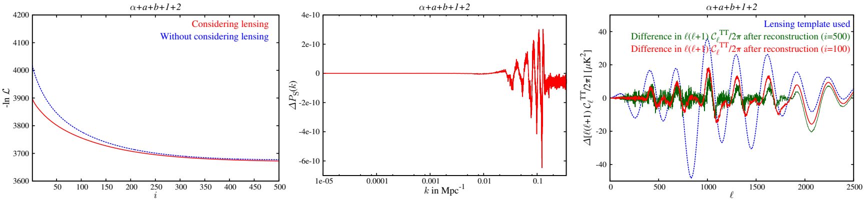
- Using the MRL reconstruct 2 PPS.
  First one reconstructed assuming lensing $\Longrightarrow C_\ell^{\mathrm{D}'_\nu}$ is obtained subtracting lensing template, $C_\ell^{\mathrm{Lens-template}} = C_\ell^{\mathrm{Lensed}} - C_\ell^{\mathrm{un-lensed}}$
  For second one assume no lensing.
- Define the difference in the reconstructed PPS :
  $\Delta P_k \equiv P_k^{\mathrm{Lens}} - P_k^{\mathrm{No-Lens}}$.
- Obtain 2 reconstructed C_ℓ^{T} from both the PPS.
  Add the lensing template back to the first C_ℓ^{T} obtained only.
- Define the difference in the angular power spectra as,
  $\Delta C_\ell^{\mathrm{TT}} \equiv C_\ell^{\mathrm{Lens}} - C_\ell^{\mathrm{No-Lens}}$.
- Examine the $-\ln\mathcal{L}$ as a function of MRL iterations for $i \leq 500$ in different combinations of Planck spectra.

Application II : Degeneracies with lensing



Hazra, Shafieloo and Souradeep, 2014

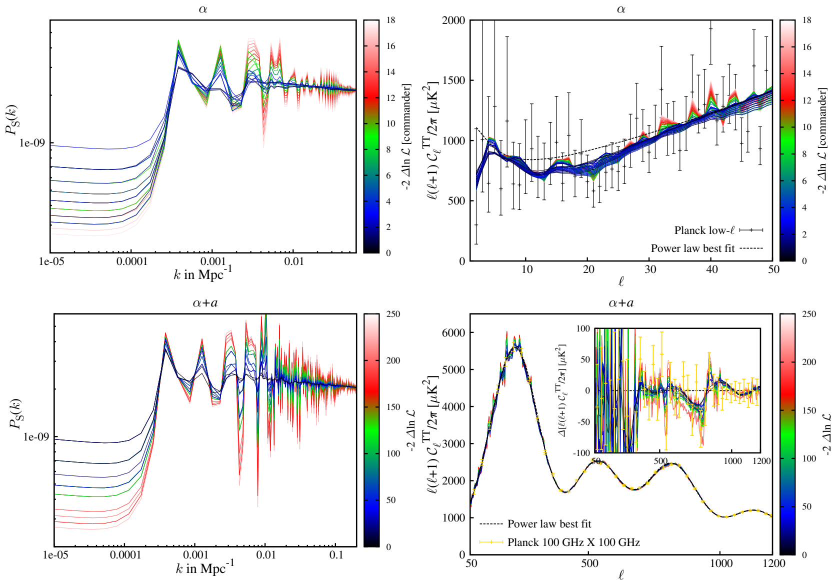
Application II : Degeneracies with lensing



Hazra, Shafieloo and Souradeep, 2014

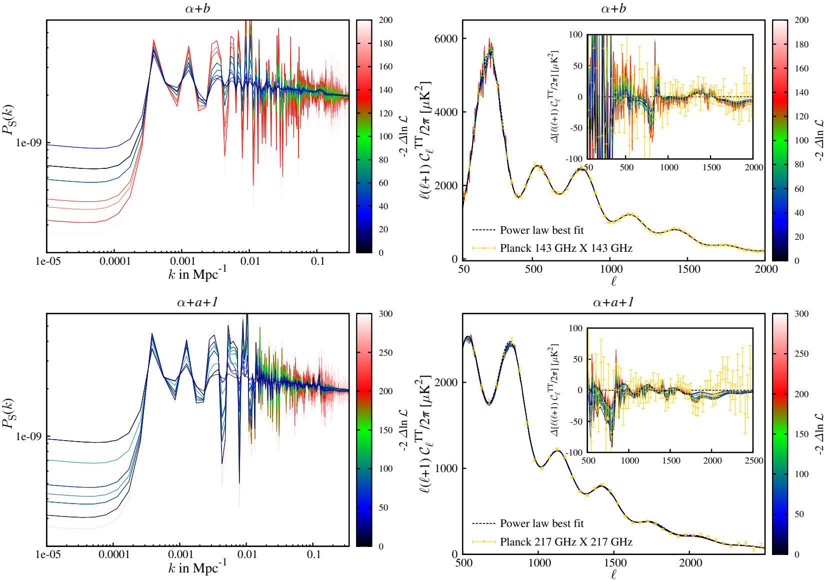
- **At large scales there is no lensing**
- **Reconstruction with and without lensing $\Longrightarrow$ indicates evidence of lensing in the angular power spectrum**
- **Reconstruction is highly degenerate with lensing effect and one must take care of lensing before reconstruction such that lensing is not imprinted as features**

Application III : Features



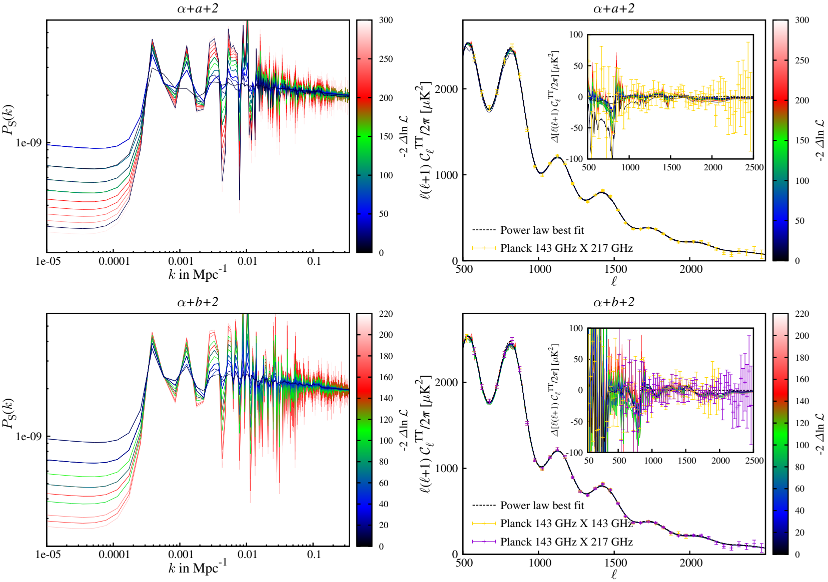
Hazra, Shafieloo and Souradeep, 2014

Application III : Features



Hazra, Shafieloo and Souradeep, 2014

Application III : Features



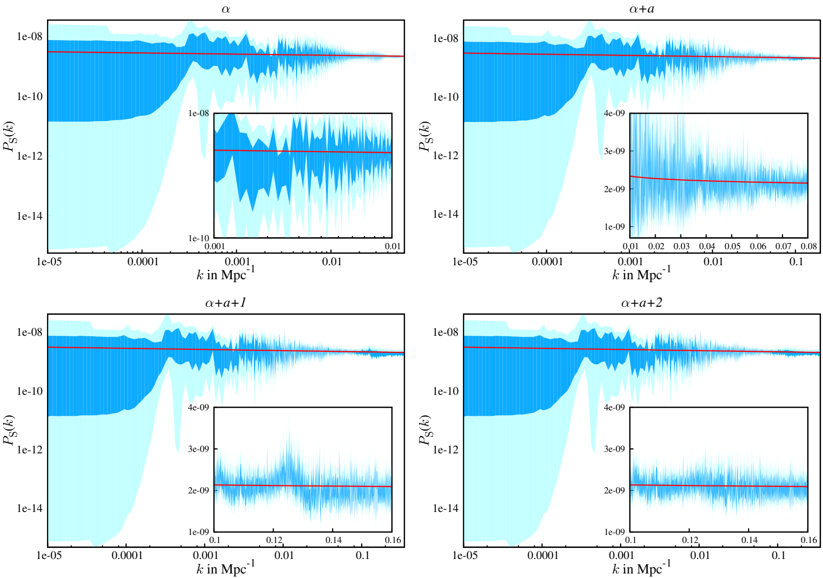
Hazra, Shafieloo and Souradeep, 2014

Features and error estimation

- **Based on the original spectrum simulate 1000 mock spectra**
- **From each spectra reconstruct 1000 PPS**
- **Locate the mostly dense region containing 68.3% and 95.5% spectra**
- **Overplot and check the consistency of best for power law PPS**

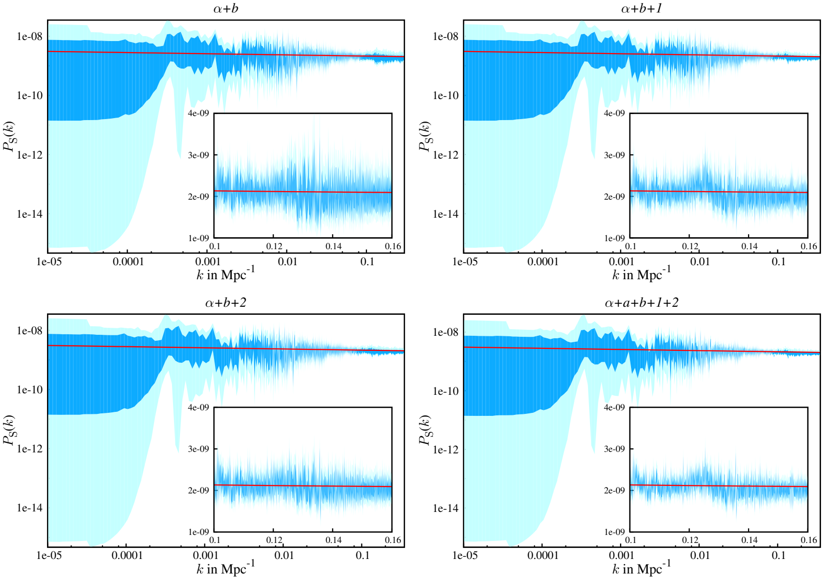
For another analysis of falsification of power law PPS, see Hamann, Shafieloo, Souradeep, JCAP 04 (2010) 010

Features and error estimation



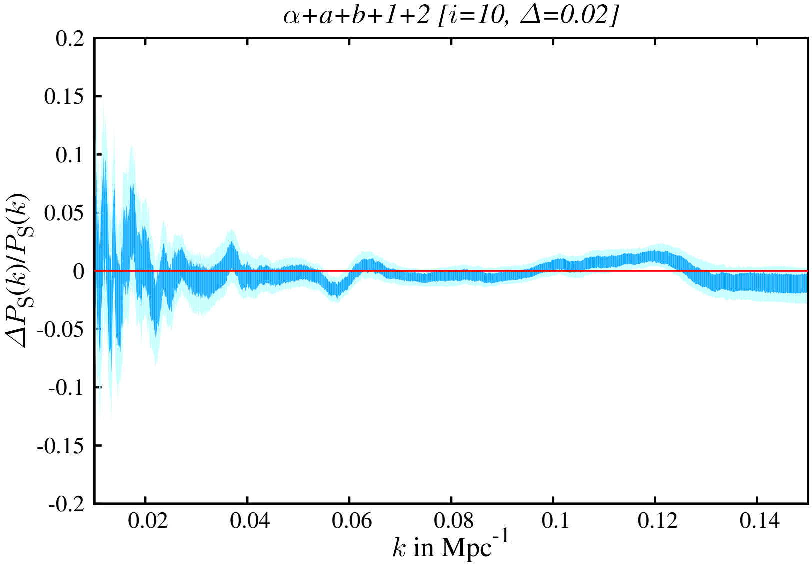
Hazra, Shafieloo and Souradeep, 2014

Features and error estimation



Hazra, Shafieloo and Souradeep, 2014

Features and error estimation



Hazra, Shafieloo and Souradeep, 2014

Features and error estimation

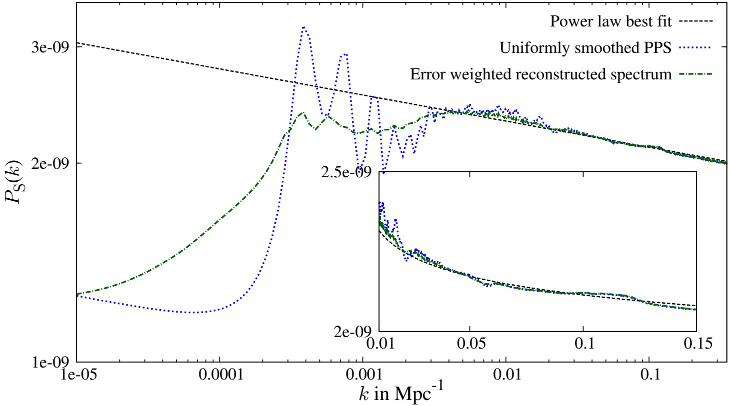
- $k \simeq 0.002\ \mathrm{Mpc}^{-1}$ $(\ell \simeq 22)$ **has more than** 1σ **significance**

- $k \simeq 0.02\ \mathrm{Mpc}^{-1}$ $(\ell \simeq 250 - 300)$ **has more than** 1σ **significance while** $k \sim 0.055 - 0.065\ \mathrm{Mpc}^{-1}$ $(\ell \simeq 750 - 850)$ **feature is more than** 2σ **away from power law**

- $k \sim 0.12 - 0.14\ \mathrm{Mpc}^{-1}$ $(\ell \sim 1800 - 2000)$ **feature is more than** 2σ **significant but not present in** $143\ \mathrm{GHz} \times 217\ \mathrm{GHz}$ **cross correlation which indicates this to be systematic effect** [2]

[2] Planck also reported this feature appearing due to small systematics

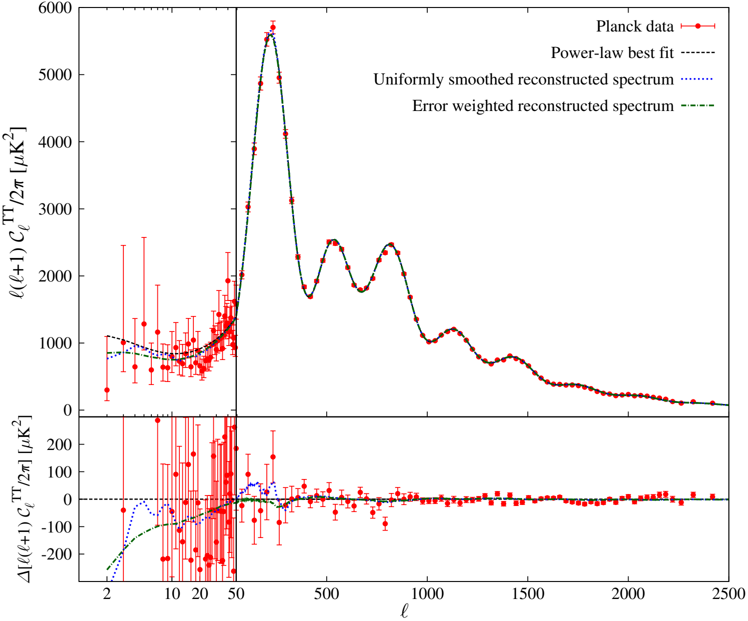
Towards a smooth PPS



Hazra, Shafieloo and Souradeep, 2014

Need a suppression in scalar power at large scales. [also shown in a previous paper **D. K. Hazra, A. Shafieloo and G. F. Smoot, JCAP 1312, 035 (2013)**]

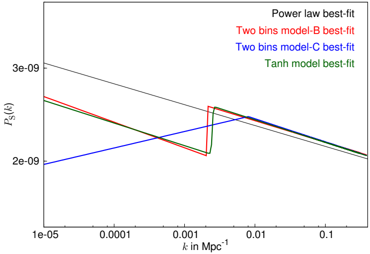
Towards a smooth PPS

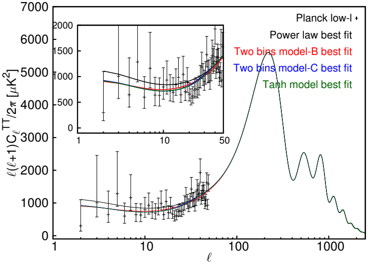


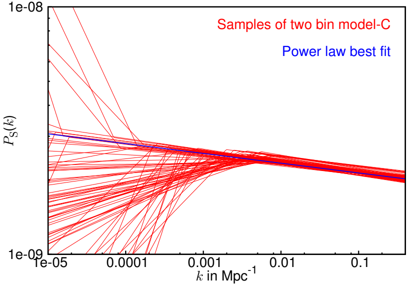
Hazra, Shafieloo and Souradeep, 2014

Optimized binning of primordial power spectra

D. K. Hazra, A. Shafieloo and G. F. Smoot, **JCAP 1312, 035 (2013)**



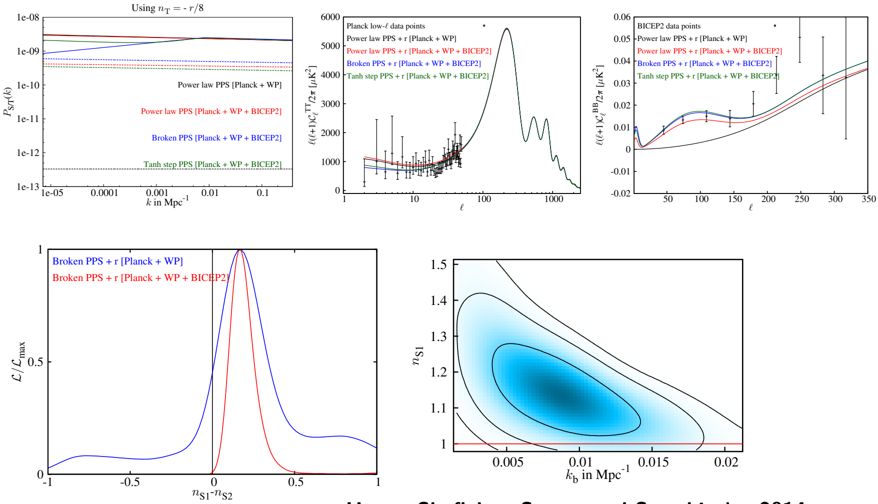




Hazra, Shafieloo and Smoot, 2013

BICEP2 era : a phenomenological approach

D. K. Hazra, A. Shafieloo, G. F. Smoot, A. A. Starobinsky, *Ruling out the power-law form of the scalar primordial spectrum*, **JCAP 1406 (2014) 061.**



Hazra, Shafieloo, Smoot and Starobinsky, 2014a

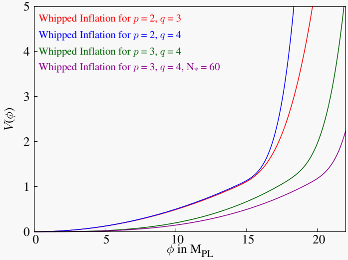
BICEP2 era : Towards a theory - Whipped Inflation

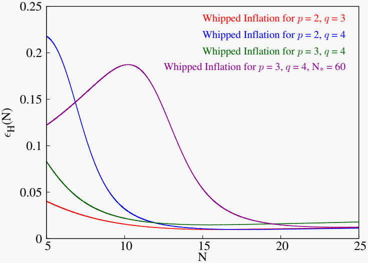
D. K. Hazra, A. Shafieloo, G. F. Smoot, A. A. Starobinsky, *Whipped Inflation*, **Phys. Rev. Lett. 113, 071301 (2014) [Editor's suggestion].**

Whipped Inflation potential

$$V(\phi) = \gamma\phi^p + \lambda(\phi - \phi_0)^q \; \Theta(\phi - \phi_0),$$

Moderate fast-roll $\Longrightarrow$ strict slow-roll

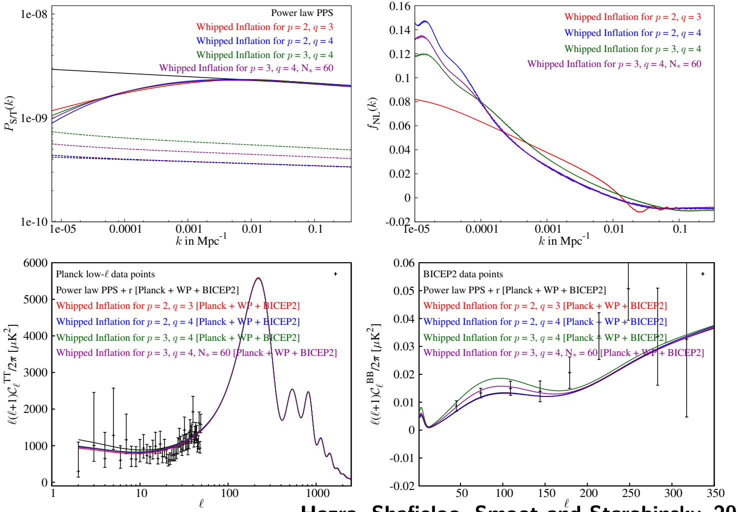




Hazra, Shafieloo, Smoot and Starobinsky, 2014b

BICEP2 era : Whipped Inflation

Using **BINGO : BI-Spectra and Non-Gaussianity Operator**, D. K. Hazra, L. Sriramkumar and J. Martin, JCAP **1305**, 026 (2013), we calculated the PPS and the Bispectra of the Whipped Inflation.



Hazra, Shafieloo, Smoot and Starobinsky, 2014b

BINGO : BI-Spectra and Non-Gaussianity Operator, D. K. Hazra, L. Sriramkumar and J. Martin, JCAP **1305**, 026 (2013),

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BINGO - BI-spectra and Non-Gaussianity Operator

The BI-spectra and Non-Gaussianity Operator or, simply, BINGO, is a Fortran 90 code that numerically evaluates the scalar bi-spectrum and the non-Gaussianity parameter f_{NL} in single field inflationary models involving the canonical scalar field. The code is based on the Maldacena formalism to evaluate the bi-spectrum [1] and early efforts towards applying the formalism to situations involving deviations from slow roll as well as certain procedures developed to numerically investigate such scenarios [2,3].

BINGO can evaluate all the contributions to the scalar bi-spectrum and the non-Gaussianity parameter f_{NL} for an arbitrary triangular configuration of the wavenumbers. We are making a particular version of the code publicly available here.

A few words on the methods and procedures adopted by BINGO

Computing the bi-spectrum involves first having to evaluate the background as well as the perturbations, and then carrying out integrals consisting of

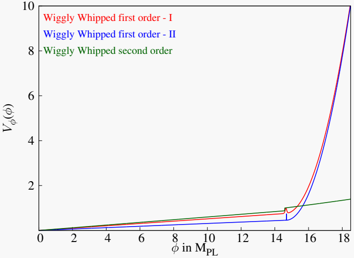
BICEP2 era : Whipped Inflation and beyond

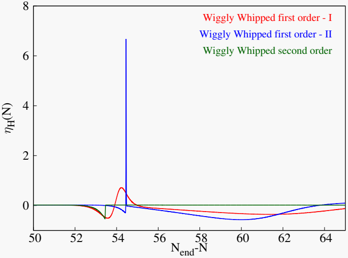
D. K. Hazra, A. Shafieloo, G. F. Smoot, A. A. Starobinsky, *Wiggly Whipped Inflation*, To appear in **JCAP**.

Wiggly Whipped Inflation potentials

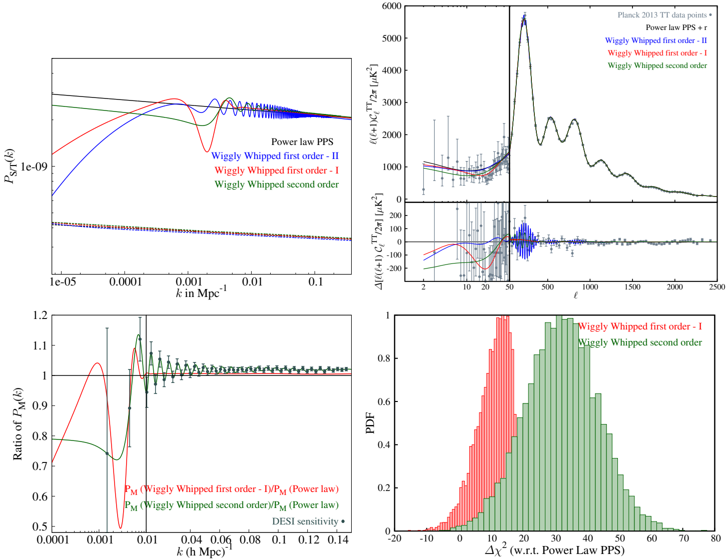
$$V(\phi) = \gamma\phi^p + \lambda\left[(\phi-\phi_0)^q + \phi_{01}^q\right]\,\Theta(\phi-\phi_0) : \texttt{WWI} - \texttt{type I}$$
$$V(\phi) = \gamma\phi^p + \lambda\phi^p\,(\phi-\phi_0)\,\Theta(\phi-\phi_0) : \texttt{WWI} - \texttt{type II}$$

Moderate fast-roll $\Longrightarrow$ temporary sharp departure $\Longrightarrow$ strict slow-roll





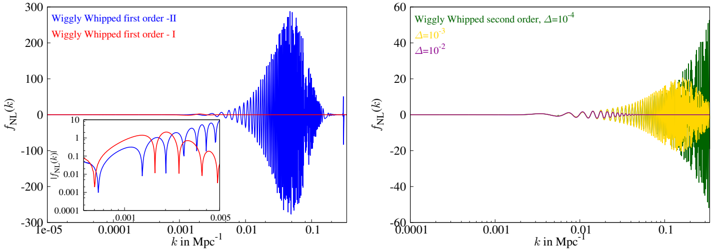
BICEP2 era : Wiggly Whipped Inflation



Hazra, Shafieloo, Smoot and Starobinsky, 2014c

BICEP2 era : WWI $\Longrightarrow$ The Bispectra

Smoothing the discontinuity in the potential leads to suppression in bispectra [J. Martin, L. Sriramkumar, D. K. Hazra, *Sharp inflaton potentials and bi-spectra: Effects of smoothening the discontinuity*, **arXiv:1404.6093 [astro-ph.CO]**.]. Hence same PPS can generate different $f_{\rm NL}$. Wiggly Whipped Inflation generates $f_{\rm NL}$ depending on the modelling of the discontinuity.



Hazra, Shafieloo, Smoot and Starobinsky, 2014c

Thank you