

Inflationary Cosmology Post-Planck 2015

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GRANDMA,
PHYSICISTS
HAVE DISCOVERED
DEFINITIVE EVIDENCE
OF **INFLATION!**

REALLY?
DID THOSE SCIENTISTS
FINALLY BUY THEIR
GROCERIES?



■ Inflation

- * The ABC of Inflation
- * CMB à la WMAP9 and Planck 2015
- * Test of inflationary predictions
- * Status of inflationary models

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■ New Avenues...

- * Hemispherical asymmetry
- * Delensing techniques
- * Primordial non-Gaussianity
- * CMB spectral distortions
- *

Puzzles of standard Big Bang Cosmology

- Horizon
- Flatness
- Monopole
- Structure formation...

The ABC of Inflation

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Wayout

Super-fast accelerated expansion at the beginning \implies Inflation

Dynamics? \longrightarrow Scalar field

EM tensor components $\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$; $p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$

Governing Equations

$$H^2 = \frac{1}{3M_P^2} \left[\frac{1}{2}\dot{\phi}^2 + V(\phi) \right]$$

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

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Employ slow roll condition

$$\dot{\phi}^2 \ll V(\phi) \quad ; \quad |\ddot{\phi}| \ll 3H|\dot{\phi}|, V'(\phi)$$

Slow roll parameters $\epsilon_V = \frac{M_P^2}{2} \left[\frac{V'}{V} \right]^2 \ll 1$

$$\eta_V = M_P^2 \left[\frac{V''}{V} \right] \ll 1$$

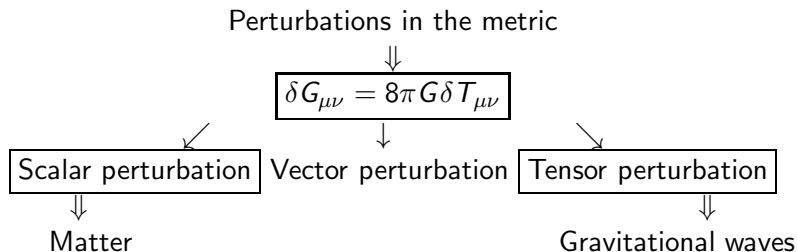
For sufficient inflation $N = \ln \frac{a_f}{a_i} \approx -\frac{1}{M_P^2} \int_{\phi_i}^{\phi_f} \frac{d\phi}{\sqrt{2\epsilon_V}} \approx 56 - 70$

Solves first 3 puzzles at a single go.

Structure formation? \longrightarrow Perturbations

Quantum fluctuations of inflaton exit horizon and get frozen.
Appear as classical perturbations after horizon re-entry.

Inflation provides seeds of perturbations.

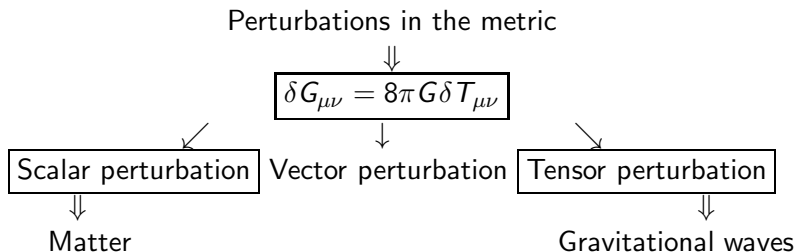


Solves Puzzle No.4

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Solves Puzzle No.4

First impression: Too good to be true!!

Inflationary predictions

Observable parameters	Scalar modes	Tensor modes
Power spectrum	$P_R(k) = \frac{k^3}{2\pi^2} \frac{ v ^2}{z^2} \Big _*$	$P_T(k) = 2 \times \frac{k^3}{2\pi^2} \frac{2}{M_P^2} \frac{ u ^2}{a^2} \Big _*$
Tensor to scalar ratio		$r = \frac{P_T _*}{P_R _*}$
Spectral index	$n_S = 1 + \frac{d \ln P_R(k)}{d \ln k} \Big _*$	$n_T = \frac{d \ln P_T(k)}{d \ln k} \Big _*$
Running of S.I.	$\alpha_S = \frac{dn_S}{d \ln k} \Big _*$	$\alpha_T = \frac{dn_T}{d \ln k} \Big _*$

* $\Rightarrow k = aH$

+ Consistency relation $r = -8n_T$

more or less generic for

- slow roll
- single scalar, canonical, minimally coupled
- $c_s \approx 1$

Inflationary predictions

- Universe is mostly homogeneous and isotropic

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- Spatially flat universe $\Rightarrow \Omega_{\text{tot}} \approx 1 \pm 10^{-4}$
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- Scalar modes dominant. $P_R(k) \simeq P_R(k_*) \left(\frac{k}{k_*}\right)^{n_s-1}$
 $P_R(k_*) \propto \frac{V(\phi)}{24\pi^2 \epsilon_V} \Rightarrow$ **small initial fluctuations**

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If $(n_s - 1) \neq 0 \Rightarrow$ **perturbations originated from dynamics of scalar field**

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If $(n_s - 1) \neq 0 \Rightarrow$ **perturbations originated from dynamics of scalar field**
- Generic spectrum $P_R(k) \simeq P_R(k_*) \left(\frac{k}{k_*}\right)^{n_s-1+n'_s \ln(k/k_*)}$
If $n'_s \neq 0 \Rightarrow$ **deviation from power law**

Inflationary predictions

- Tensor modes would be small but bear strong physical significance.
A small fraction of CMB photons get polarized due to quadrupole anisotropies. \Rightarrow 2 polarization modes (E & B)

B modes \rightarrow Gravitational waves

+ NG + Lensing + Magnetic field...

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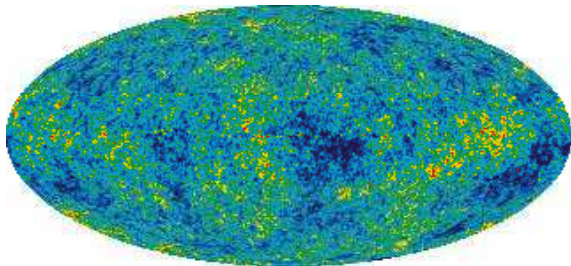
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Caution :

A good fraction of the above predictions can be violated with more complicated models

The CMB sky



Background temperature $T_0 = 2.725K$ at all directions
⇒ The Universe is homogeneous and isotropic at largest scale

All about CMB temperature

Background : $T_0 = 2.725K \rightarrow$ Blackbody spectrum

Fluctuations : $-200\mu K < \Delta T < 200\mu K$

$$\Delta T_{rms} \sim 70\mu K$$

$$\Delta T_{pE} \sim 5\mu K$$

$$\Delta T_{pB} \sim 10 - 100nK$$

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How to decode information?

$\Delta T(n) = \sum a_{\ell m} Y_{\ell m}(n) \rightarrow$ spherical harmonics

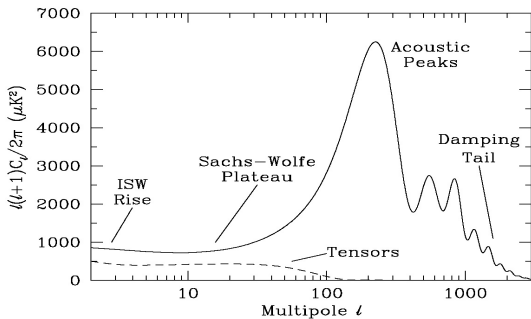
\Rightarrow 2-point correlation function $C_\ell = \frac{1}{2\ell+1} \sum |a_{\ell m}|^2$

$$C_\ell = \int \frac{dk}{k} P_R(k) T_\ell^2(k)$$

- Temperature anisotropy T + two polarization modes E & B

\Rightarrow Four CMB spectra: $C_\ell^{TT}, C_\ell^{EE}, C_\ell^{BB}, C_\ell^{TE}$

- Parity violation/systematics \Rightarrow Two more spectra: C_ℓ^{TB}, C_ℓ^{EB}



Peak positions, heights and ratios give cosmological parameters \Rightarrow imprints of both early universe and late universe

Fundamental/ fit parameters

$\Omega_b h^2$ = baryonic matter density

$\Omega_c h^2$ = dark matter density

Ω_χ = dark energy density

A_s = amplitude of scalar power spectrum

n_s = scalar spectral index

τ = optical depth

r = tensor-to-scalar ratio

Altogether 6 (or 7 if $r \neq 0$)

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Derived parameters

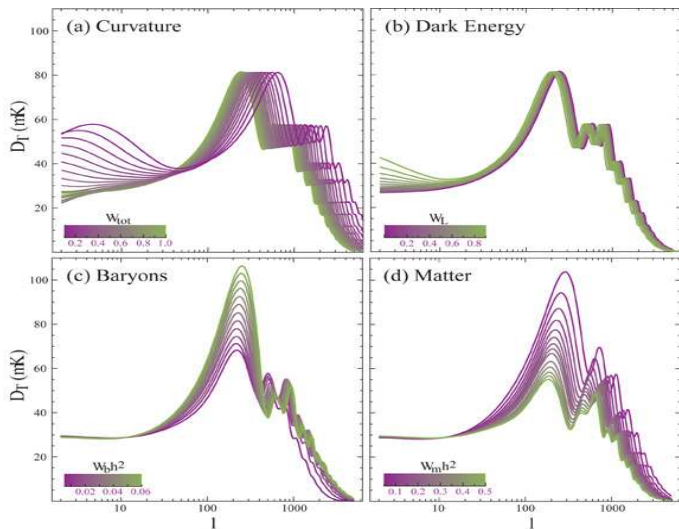
$t_0, H_0, \Omega_b, \Omega_c, \Omega_m, \Omega_k, \Omega_{\text{tot}}, \sigma_8, z_{\text{eq}}, z_{\text{reion}} \dots$

WMAP9 vis-à-vis Planck

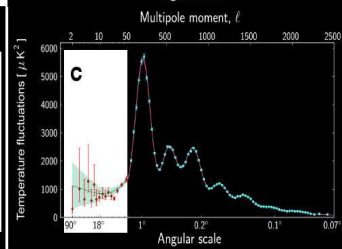
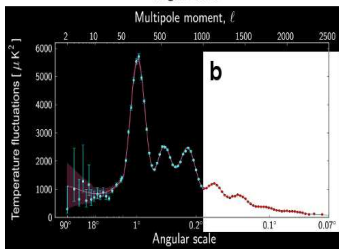
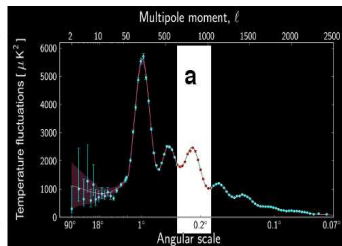
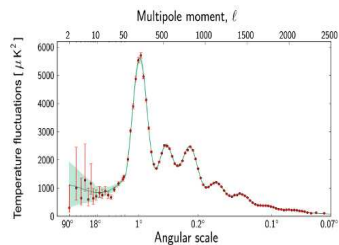
Parameters	WMAP 9	Planck 2013
A_s	$(2.464 \pm 0.072) \times 10^{-9}$	$(2.196^{+0.051}_{-0.060}) \times 10^{-9}$
n_s	0.9606 ± 0.008	0.9603 ± 0.0073
n'_s	-0.023 ± 0.001	-0.013 ± 0.009
r	< 0.13	< 0.11
$\Omega_b h^2$	0.02264 ± 0.0005	0.022007 ± 0.00033
$\Omega_c h^2$	0.1138 ± 0.0045	0.1196 ± 0.0031
Ω_χ	$0.7135^{+0.0095}_{-0.0096}$	$0.685^{+0.018}_{-0.016}$
τ	0.088 ± 0.015	$0.089^{+0.012}_{-0.014}$
H_0	69.32 ± 0.80 km/s/Mpc	67.3 ± 1.2 km/s/Mpc
t_0	13.772 ± 0.059 Gyr	13.817 ± 0.048 Gyr

WMAP9 and Planck give consistent results

How sensitive to parameters the CMB TT plot is?



Planck 2015 highlights



Planck 2015 highlights

Ade et.al., 1502.01589; 1502.01590; 1502.01592; 1502.00612

Parameters	Planck2015 TT+low P	Planck2015 TT,TE,EE+low P
$\Omega_b h^2$	0.02222 ± 0.00023	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1198 ± 0.0015
Ω_M	0.315 ± 0.013	0.3156 ± 0.0091
$\ln(10^{10} A_S)$	3.089 ± 0.036	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.9645 ± 0.0049
τ	0.078 ± 0.019	0.079 ± 0.017
H_0	67.31 ± 0.96	67.27 ± 0.66
σ_8	0.829 ± 0.014	0.831 ± 0.013
r	< 0.11	< 0.07 (+BICEP2 Keck)

NG Parameters	Planck2015 TT	Planck2015 TT+low P
f_{NL}^{loc}	2.5 ± 5.7	0.8 ± 5.0
f_{NL}^{eq}	-16 ± 70	-4 ± 43
f_{NL}^{ortho}	-34 ± 33	-26 ± 21

Test of predictions post-Planck 2015

Boring universe, 6 parameters suffice

More matter, less energy (slightly altered from Planck 2013)

Little bit **older universe** (13.771 Gyr WMAP9 \rightarrow 13.817 Gyr)

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Outliners are still there \Rightarrow physical origin?

Large scale **anomalies** : hemispherical asymmetry?

Big **cold spot** \Rightarrow superstructure?

Primordial gravity waves (PGW) revisited

- March 2013: Planck: $r < 0.11 \Rightarrow$ GW yet undetected
- Feb 2014: BICEP2: $r \approx 0.2 \Rightarrow$ **Primordial GW detected??**
- Feb 2015: Joint analysis of Planck + BICEP2 Keck array:
 $r < 0.07 \Rightarrow$ GW yet undetected but even better constrained
- Feb 2015: LIGO: **GW detected from blackhole mergers!!**

Hunt for primordial gravity waves is still on \rightarrow PIXIE, PRISM...

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Caution: Sources of contamination in r

- Lensing in TT spectrum (due to intervening medium)
- Non-gaussianities
- Primordial magnetic field (Faraday rotation \Rightarrow E-B mixing)
- Lensing in Polarized B-modes

Intrinsic, delensed, polarized B-modes will confirm proper PGW

Have we “seen” inflation in the sky?

No, not yet!!

Can be claimed only when we detect

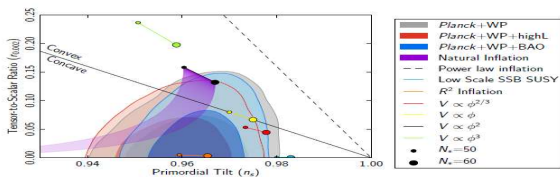
- r conclusively
- n_T independently and verify consistency relation $r = -8n_T$ for
 - * slow roll
 - * single field, canonical, minimally coupled
 - * $c_s \approx 1$
- α_T (or confirm it is zero)
- f_{NL} for single field vs multi field debate

... but of course we are zeroing in!

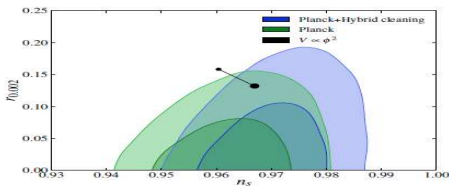
What can we say about the inflationary models?

Chaotic + minimal coupling

P.A.R.Ade et.al., 1303.5082



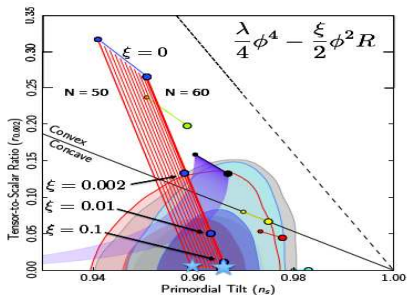
Tightly constrained. Different cleaning: Spergel et.al., PRD:2015



ϕ^2 marginally consistent,

Chaotic + non-minimal coupling

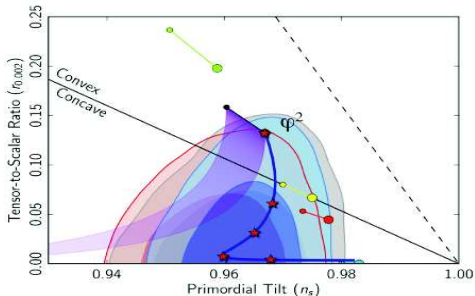
Bezrukov et.al., JHEP:2013



Allowed, even ϕ^4 for $\xi/2 > 10^{-3}$

but issues, e.g. candidate inflaton? Higgs?

$$V(\phi) = \frac{m^2 \phi^2}{2} (1 - a\phi + a^2 b \phi^2)^2$$



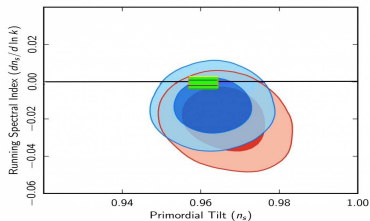
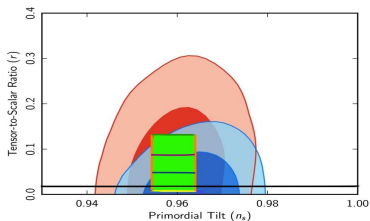
Allowed, with $b = 0.34, a = 0, 0.03, 0.05, 0.1, 0.13$

but issues, e.g. SUGRA origin is debatable

MSSM(inflexion point)

Choudhury, Majumdar, SP, JCAP:2013

$$V(\phi) = \alpha + \beta(\phi - \phi_0) + \gamma(\phi - \phi_0)^3 + \kappa(\phi - \phi_0)^4 + \dots$$



Planck+WP9+BAO: Blue: Λ CDM+ $r(\alpha_S)$, Red: Λ CDM+ $r + \alpha_S$

Allowed, better fit for low l

Starobinsky model

Starobinsky, Sov. Astron. Lett: 1983

$$L = \sqrt{-g} \left(\frac{R}{2} + \frac{R^2}{12M^2} \right), \quad M \ll M_p$$

can be reduced to canonical gravity + scalar field by field redefinition and metric transformation

$$N \sim 60 \Rightarrow n_S \sim 0.967, r \sim 0.003$$

$$N \sim 60 \Rightarrow n_S \sim 0.964, r \sim 0.004.$$

Allowed

Many models, except a few with very high r , are still allowed.

Two open questions

- All models lead to same predictions matching with Planck.
Can they be incorporated into a common platform?
Superconformal theory??
Universal attractor??

Linde, 1402.0526

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- All models lead to same predictions matching with Planck.
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Superconformal theory??
Universal attractor?? Linde, 1402.0526

- Among all **allowed** models, which ones are **more probable**?

Most probable models

Model selection algorithm

Liddle et.al., astro-ph/0608184

Consider 2 models

- \mathcal{M}_1 with one model parameter θ
- \mathcal{M}_2 with two model parameters α and β

How do they fair against some data D ? \Rightarrow maximum likelihood

$$\mathcal{L}_1 = \mathcal{L}_{1,\max} \exp^{-\chi^2(\theta)/2} \quad ; \quad \mathcal{L}_2 = \mathcal{L}_{2,\max} \exp^{-\chi^2(\alpha,\beta)/2}$$

But this does not distinguish between “complexity” of the models.

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Occam's razor : penalize complex models.

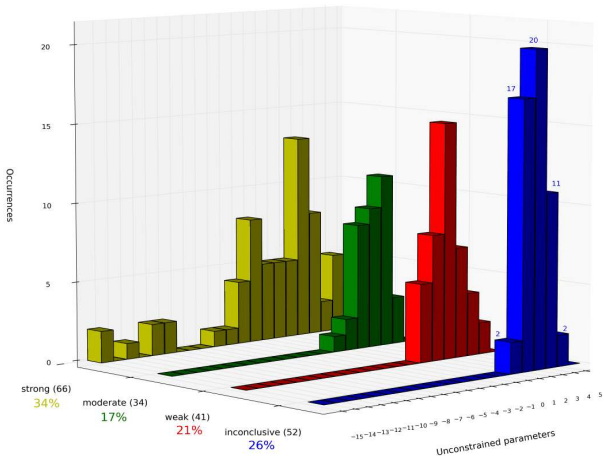
Best models are those who can make best compromise between simplicity and quality of fits

Calculate Bayesian evidence

$$\mathcal{E}_1 = \int \mathcal{L}_1(D/\theta)\pi(\theta)d\theta \quad ; \quad \mathcal{E}_2 = \int \mathcal{L}_2(D/\alpha,\beta)\pi(\alpha,\beta)d\alpha d\beta$$

Prior distributions satisfy $\int \pi(\theta)d\theta = 1$; $\int \pi(\alpha,\beta)d\alpha d\beta = 1$

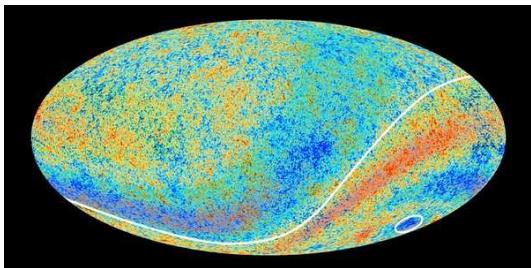
Lower evidence \Rightarrow More probable : Jeffrey's scale

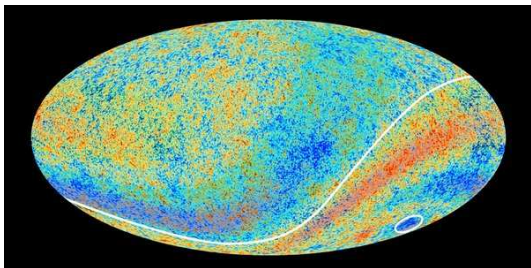


~ 26% models are most probable. J.Martin et al., JCAP:2014
 + Bayesian complexity \Rightarrow ~ 9%. Preferred potential: pleatue type.
 But it all depends on how reliable Bayesian evidence calculation is!

- Hemispherical asymmetry
- Delensing techniques
- Primordial non-Gaussianity
- CMB spectral distortions
-

Hemispherical asymmetry





- Modifications to inflation? (Carroll, PRD:2008; Qureshi, 1610.05776)
- Earlier universe preceding Big Bang? (Efstathiou,)
- Undiscovered source in solar system? (Yoho, PRD:2011)
- Intrinsic anisotropy? (Souradeep et. al., JCAP:2016)

A nice review by Huterer, 1004.5602

Effects of lensing

- Broadening of peaks
- Non-Gaussianity

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Why delensing?

- Better estimate of parameters
- B-modes: can remove degeneracy

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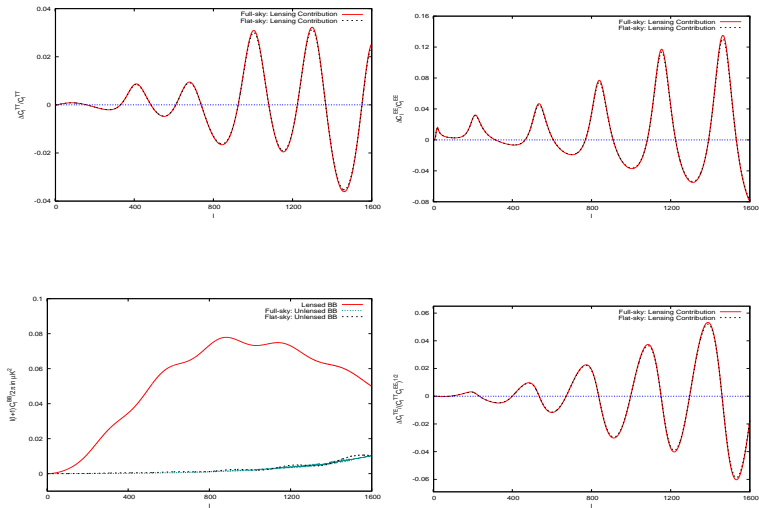
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To do

- Propose delensing techniques
- Check if better result than CAMB
- Estimate unlensed parameters afresh

Delensing using matrix inversion technique

Pal, Padmanabhan, SP, MNRAS:2014



Fractional difference between lensed and unlensed power spectra

Non-Gaussianity

Perturbations mostly Gaussian, described by 2-PCF

If (small) non-Gaussianities are present \rightarrow reflected via B modes

3- and 4-PCF \Rightarrow bispectrum f_{NL} & trispectrum g_{NL}, τ_{NL}

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Why important?

- Maldacena limit \Rightarrow single field ($|f_{NL}| < 1$) vs multifield ($|f_{NL}| > 5$)
- B modes = GW + NG + lensing \Rightarrow Need to separate out NG for correct estimate of GW
- Suyama-Yamaguchi consistency relation between f_{NL} & τ_{NL}

Non-Gaussianity

Perturbations mostly Gaussian, described by 2-PCF

If (small) non-Gaussianities are present \rightarrow reflected via B modes

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Planck 2015 bounds

NG Parameters	Planck2015 TT	Planck2015 TT+low P
f_{NL}^{loc}	2.5 ± 5.7	0.8 ± 5.0
f_{NL}^{eq}	-16 ± 70	-4 ± 43
f_{NL}^{ortho}	-34 ± 33	-26 ± 21

Take-home message

Have we “seen” inflation in the sky?

No, not yet!!

... but of course we are zeroing in!

The point is not to pocket the truth but to chase it. – Elio Vittorini