Just enough inflation: power spectrum modifications on large scales

Francisco Gil Pedro

in collaboration with:
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Outline:

- Observational hints
- The standard inflationary picture
- The spectrum of slow-roll inflation
- Pre-inflation and the power spectrum
- Degeneracy in power loss
- Summary
Observational hints

Francisco Gil Pedro, Trieste, 8 July 2014

Abstract

This paper presents the Planck likelihood, a complete statistical description of the two-point correlation function of the CMB temperature fluctuations that accounts for all known relevant uncertainties, both instrumental and astrophysical in nature. We use this likelihood to derive two best estimates of the CMB angular power spectrum, Planck and Planck X, covering 2 ≤ ℓ ≤ 2000. The main source of error at ℓ ≤ 2000 is cosmic variance. Uncertainties are small-scale foreground model and instrumental noise dominate the error budget at higher ℓ. For ℓ < 50, our likelihood exploits all Planck frequency channels from 30 to 550 GHz, separating the cosmological CMB signal from dust Galactic foregrounds through a physically motivated Bayesian component separation technique. At ℓ ≥ 50, we employ a simple Gaussian likelihood approximation based on a few-parameters model of CMB component derived from multiple detector combinations between the 100, 143, and 217 GHz frequency channels, together with power spectrum foreground templates. We validate this likelihood against an extensive suite of consistency tests, and assess the impact of residual foreground and instrumental uncertainties on the final cosmological parameters. We find good internal consistency among the high-ℓ cross-spectra with results that are consistent with the independent calibration. We compare our results with foreground-cleaned CMB maps derived from all Planck frequencies, as well as with cross-spectra derived from the 90 GHz Planck data, and find broad agreement in terms of spectrum residuals and cosmological parameters. More work is needed to improve the agreement with the Planck likelihood at lower ℓ. In this paper, we present the final version of the Planck likelihood, including all Planck data release information, as well as a comprehensive list of references and a detailed description of the likelihood. The Planck likelihood is available for download from the Planck Collaboration website.

Key words. Cosmology: cosmic microwave background — Surveys: Methodic data analysis

Preprint online version: 26th March 2013


DESY
This paper presents the Planck likelihood, a complete statistical description of the two-point correlation function of the CMB temperature fluctuations that accounts for all known relevant uncertainties, both instrumental and astrophysical in nature. We use this likelihood to derive our best estimate of the CMB angular power spectrum from Planck over three decades in multipole moment, $\ell$, covering $2 \leq \ell \leq 2500$. The main source of error at $\ell \leq 1500$ is cosmic variance. Uncertainties in small-scale foreground modelling and instrumental noise dominate the error budget at higher $\ell$s. For $\ell < 50$, our likelihood exploits all Planck frequency channels from 30 to 353 GHz, separating the cosmological CMB signal from diffuse Galactic foregrounds through a physically motivated Bayesian component separation technique. At $\ell \geq 50$, we employ a correlated Gaussian likelihood approximation based on a fine-grained set of angular cross-spectra derived from multiple detector combinations between the 100, 143, and 217 GHz frequency channels, marginalizing over power spectrum foreground templates. We validate our likelihood through an extensive suite of consistency tests, and assess the impact of residual foreground and instrumental uncertainties on the final cosmological parameters. We find good internal agreement among the high-$\ell$ cross-spectra with residuals below a few $\mu$K$^2$ at $\ell \geq 1000$, in agreement with estimated calibration uncertainties. We compare our results with foreground-cleaned CMB maps derived from all Planck frequencies, as well as with cross-spectra derived from the 70 GHz Planck map, and find broad agreement in terms of spectrum residuals and cosmological parameters. We further show that the best-fit LCDM cosmology is in excellent agreement with preliminary Planck $E$E and $T$E polarisation spectra. We find that the standard LCDM cosmology is well constrained by Planck from the measurements at $\ell \leq 1500$. One specific example is the spectral index of scalar perturbations, for which we report a 5.4 $\sigma$ deviation from scale invariance, $n_s \neq 1$. Increasing the multipole range beyond $\ell \approx 1500$ does not increase our accuracy for the LCDM parameters, but instead allows us to study extensions beyond the standard model. We find no indication of significant departures from the LCDM framework. Finally, we report a tension between the Planck best-fit LCDM model and the low-$\ell$ spectrum in the form of a power deficit of 5–10% at $\ell \leq 40$, with a statistical significance of 2.5–3 $\sigma$. Without a theoretically motivated model for this power deficit, we do not elaborate further on its cosmological implications, but note that this is our most puzzling finding in an otherwise remarkably consistent dataset.

Key words: Cosmology, cosmic background radiation — surveys — Methodic data analysis
Observational hints

\[ \mathcal{P}_R(k) = \mathcal{P}_0(k) \left\{ 1 - \exp \left[ -\left( \frac{k}{k_c} \right)^{\lambda_c} \right] \right\}. \]

<table>
<thead>
<tr>
<th>Model</th>
<th>(-2\Delta \ln \mathcal{L}_{\text{max}})</th>
<th>(\ln B_{0X})</th>
<th>Parameter</th>
<th>Best fit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wiggles</td>
<td>-9.0</td>
<td>1.5</td>
<td>(\alpha_w)</td>
<td>0.0294</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\omega)</td>
<td>28.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\varphi)</td>
<td>0.075 (\pi)</td>
</tr>
<tr>
<td>Step-inflation</td>
<td>-11.7</td>
<td>0.3</td>
<td>(A_r)</td>
<td>0.102</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\ln (\eta_\text{Pl/Mpc}))</td>
<td>8.214</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\ln x_{\text{d}})</td>
<td>4.47</td>
</tr>
<tr>
<td>Cutoff</td>
<td>-2.9</td>
<td>0.3</td>
<td>(\ln \left( k_c / \text{Mpc}^{-1} \right) )</td>
<td>-8.493</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\lambda_c)</td>
<td>0.474</td>
</tr>
</tbody>
</table>

**Figure 39.** Power spectrum amplitude, \(q\), relative to the best-fit Planck model as a function of \(\ell_{\text{max}}\), as measured by the low-\(\ell\) Planck and WMAP temperature likelihoods, respectively. Error bars indicate 68 and 95% confidence regions.

**Table 11.** Improvement in fit and logarithm of the Bayes factor with respect to power law ΛCDM and best fit parameter values for the wiggles, step-inflation, and cutoff models. The larger \(\ln B_{0X}\), the greater the preference for a featureless power law spectrum.
Tensor modes contribute to TT spectrum on large scales

large $r$ increases:
- significance of power loss
- level of power loss

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Cosmic variance

We only have one sky

Measurements on largest scales are statistically limited

Cosmic variance

CV is the simplest explanation for low-\( \ell \) anomaly

CV can be decreased using LSS data

[1309.4060]

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Figure 37. The 2013 Planck CMB temperature angular power spectrum. The error bars include cosmic variance, whose magnitude is indicated by the green shaded area around the best fit model. The low-\( \ell \) values are plotted at 2, 3, 4, 5, 6, 7, 8, 9.5, 11.5, 13.5, 16, 19, 22.5, 27, 34.5, and 44.5.
The standard picture

\[ \ln aH \]

- 60 e-folds of slow-roll: \[ \ln aH \sim +N_e \]
- Radiation era: \[ \ln aH \sim -N_e \]
- Matter era: \[ \ln aH \sim -\frac{1}{2}N_e \]

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The standard picture

\[ \ln aH \]

60 e-folds of slow-roll:
\[ \ln aH \sim +N_e \]

radiation era:
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matter era:
\[ \ln aH \sim -\frac{1}{2}N_e \]

\[ t_{60} \quad t_e \]

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The standard picture

60 e-folds of slow-roll: $\ln aH \sim +N_e$

radiation era: $\ln aH \sim -N_e$

matter era: $\ln aH \sim -\frac{1}{2}N_e$

$t_{60}$
$t_e$

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The standard picture

ln $aH$

60 e-folds of slow-roll: $\ln aH \sim +N_e$

eradiation era: $\ln aH \sim -N_e$

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$\zeta$ decays $\zeta$ freezes

$t_{60}$ $t_e$

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The standard picture

\[ \ln aH \]

60 e-folds of slow-roll:
\[ \ln aH \sim +N_e \]

radiation era:
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matter era:
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\[ \zeta \text{ decays} \]

\[ \zeta \text{ freezes} \]

\[ \zeta \text{ decays} \]

\[ N_e \]

\[ t_{60} \quad t_e \]

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The Mukhanov-Sasaki Equation

curvature perturbation: \( \zeta \quad u \equiv \zeta \ z \quad \text{with} \quad z \equiv a\sqrt{2\epsilon_H} \)

\[ u'' + \left( k^2 - \frac{z''}{z} \right) u = 0 \]

Useful to use efolds as ‘time’ coordinate

Assume background of the form: \( aH \sim e^{\xi N} \)

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The Mukhanov-Sasaki Equation

curvature perturbation:  \[ \zeta \quad u \equiv \zeta z \quad \text{with} \quad z \equiv a\sqrt{2\epsilon_H} \]

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Useful to use efolds as 'time' coordinate

Assume background of the form:  \[ aH \sim e^{\xi N} \quad \text{inflation:} \quad \xi = 1 + \mathcal{O}(\epsilon_H, \eta_H) \]

Francisco Gil Pedro, Trieste, 8 July 2014
The Mukhanov-Sasaki Equation

curvature perturbation: \( u \equiv \zeta z \) with \( z \equiv a \sqrt{2 \epsilon_H} \)

\[
\ddot{u} + \left( k^2 - \frac{z''}{z} \right) u = 0
\]

Useful to use e-folds as 'time' coordinate

Assume background of the form: \( aH \sim e^{\xi N} \)

inflation:
\[
\xi = 1 + \mathcal{O}(\epsilon_H, \eta_H)
\]

\[
u_{\alpha\alpha} + \xi u_\alpha + \left\{ \left( \frac{k}{aH} \right)^2 - (1 + \xi) \right\} u = 0
\]

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The Mukhanov-Sasaki Equation

The behaviour of curvature perturbations depends on $L_{\text{hor}} \equiv H^{-1}$ during inflation:

- $k > aH \iff \lambda_{\text{phys}} < H^{-1}$ \textbf{inside} horizon, $\zeta$ **decays**
- $k < aH \iff \lambda_{\text{phys}} > H^{-1}$ \textbf{outside} horizon, $\zeta$ **freezes**

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The Mukhanov-Sasaki Equation

Behaviour of curvature pert. depends on $L_{\text{hor}} \equiv H^{-1}$ during inflation:

\[ k > aH \leftrightarrow \lambda_{\text{phys}} < H^{-1} \quad \text{inside horizon, } \zeta \text{ decays} \]

\[ k < aH \leftrightarrow \lambda_{\text{phys}} > H^{-1} \quad \text{outside horizon, } \zeta \text{ freezes} \]

\[ u = C^{(1)} \frac{1}{\sqrt{\xi aH}} H_{\nu}^{(1)} \left( \frac{k}{\xi aH} \right) + C^{(2)} \frac{1}{\sqrt{\xi aH}} H_{\nu}^{(2)} \left( \frac{k}{\xi aH} \right) \]

$C^{(1)}, C^{(2)}$ set by ics

\[ \nu = \left| \frac{2 + \xi}{2\xi} \right| \]

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The spectrum of slow-roll inflation

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The spectrum of slow-roll inflation

deep inside horizon $\lambda_{phys} \ll H^{-1}$ modes do not feel curvature

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The spectrum of slow-roll inflation

deep inside horizon \( \lambda_{phys} \ll H^{-1} \) modes do not feel curvature

flat space mode functions

\[ C^{(1)} = \sqrt{\frac{\pi}{2}} \]
\[ C^{(2)} = 0 \]

\[ u = \frac{\sqrt{\pi/2}}{\sqrt{aH}} H^{(1)}_\nu \left( \frac{k}{aH} \right) \]
\[ \nu = \frac{3}{2} + \epsilon_H + \frac{1}{2} \eta_H \]
\[ \xi = 1 + \mathcal{O}(\epsilon_H, \eta_H) \]

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The spectrum of slow-roll inflation

deep inside horizon $\lambda_{phys} \ll H^{-1}$ modes do not feel curvature

flat space mode functions

$C^{(1)} = \sqrt{\pi/2}$

$C^{(2)} = 0$

$$u = \frac{\sqrt{\pi/2}}{\sqrt{aH}} H_{\nu}^{(1)} \left( \frac{k}{aH} \right)$$

$$\nu = \frac{3}{2} + \epsilon_H + \frac{1}{2} \eta_H$$

$$\xi = 1 + \mathcal{O}(\epsilon_H, \eta_H)$$

$$P_k \equiv k^3 \left| \frac{u}{z} \right|^2 \sim \frac{H^2}{\epsilon_H} k^{3-2\nu}$$

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The spectrum of slow-roll inflation

\[ P_\zeta = A_s \left( \frac{k}{k_*} \right)^{n_s - 1} \]

Planck XXII:

\[ n_s = 0.9603 \pm 0.0073 \]

\[ \ln(10^{10} A_s) = 3.089^{+0.024}_{-0.027} \]

\[ k_* = 0.002 \text{ Mpc}^{-1} \]

Scale invariance is excluded by more than 5 \( \sigma \)

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Pre-inflation and the power spectrum

?? What if inflation was short ??
Pre-inflation and the power spectrum

What if inflation was short??

theoretically well motivated:

\[ P(N_e) \sim \left( \frac{1}{N_e} \right)^\alpha \]

\[ \alpha > 0 \]

Freivogel et al. 2007
McAllister et al. 2013
Pre-inflation and the power spectrum

?? What if inflation was short ??

theoretically well motivated: \[ P(N_e) \sim \left( \frac{1}{N_e} \right)^\alpha \quad \alpha > 0 \]

Can this leave an imprint on the power spectrum?

Modifies large scale part of spectrum
Pre-inflation and the power spectrum

$\ln aH$  

Pre-inflation  

Slow-roll inflation

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Pre-inflation and the power spectrum

\[ \ln aH \]

pre-inflation

slow-roll inflation

\[ k \gg a_0 H_0 \]

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Pre-inflation and the power spectrum

\[
\ln aH \\
\begin{array}{c}
\text{pre-inflation} \\
? \\
\text{slow-roll inflation}
\end{array}
\]

\[
k \gg a_0 H_0
\]

\[
k \sim a_0 H_0
\]

Francisco Gil Pedro, Trieste, 8 July 2014
## What pre-inflation?

<table>
<thead>
<tr>
<th>Type</th>
<th>$\xi$</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Fast-roll</td>
<td>$\xi = -2$</td>
<td>Contaldi et al. 2003</td>
</tr>
<tr>
<td>Super inflation</td>
<td>$\xi = 2$</td>
<td>Liu et al. 2013</td>
</tr>
<tr>
<td>Climbing scalars</td>
<td></td>
<td>Sagnotti et al. 2012/14</td>
</tr>
<tr>
<td>Radiation domination</td>
<td>$\xi = -1$</td>
<td>Nicholson&amp;Contaldi 2007</td>
</tr>
<tr>
<td>Matter domination</td>
<td>$\xi = -1/2$</td>
<td>Kinney&amp;Powell 2008</td>
</tr>
<tr>
<td>Curvature domination</td>
<td>$\xi = 0$</td>
<td>Linde et al. 1998,…,2011</td>
</tr>
<tr>
<td>Pre-inflation Mechanism</td>
<td>Formula $\xi$</td>
<td>References</td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>---------------</td>
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<td>Linde et al. 1998,…,2011</td>
</tr>
</tbody>
</table>

What similarities and what differences?

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What pre-inflation?

\[ aH \sim e^{\xi N} \]

\[ \xi < -\frac{1}{2} \]
\[ w > 0 \]

\[ -\frac{1}{2} < \xi < 0 \]
\[ -\frac{1}{3} < w < 0 \]

\[ 0 < \xi < 1 \]
\[ -1 < w < -\frac{1}{3} \]

\[ \xi > 1 \]
\[ w < -1 \]

\[ \omega \approx -1 \]
\[ \xi \approx 1 \]

\[ \omega = -\frac{1 + 2 \xi}{3} \]

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What pre-inflation?

\[ aH \sim e^{\xi N} \]

\[ \omega = -\frac{1 + 2\xi}{3} \]

\[ \xi > 1 \]
\[ w < -1 \]

\[ \xi < -1/2 \]
\[ w > 0 \]

\[ \omega \approx -1 \]
\[ \xi \approx 1 \]
Type I backgrounds

Decelerated expansion: $H$ decreases

Large scale spectrum from superhorizon modes

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Type I backgrounds

Decelerated expansion: $H$ decreases

Large scale spectrum from superhorizon modes

large scales set by pre-inflationary vacuum

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Type I backgrounds

Decelerated expansion: $H$ decreases

Large scale spectrum from superhorizon modes

$k \gg aH \big|_0 \quad \rightarrow \quad P_k \sim \frac{H_{\text{inf}}^2}{\epsilon_H}$

$k \sim aH \big|_0$

$k \ll aH \big|_0$

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Type I backgrounds

Decelerated expansion: $H$ decreases

Large scale spectrum from superhorizon modes

\[ k \gg aH|_0 \rightarrow P_k \sim \frac{H_{inf}^2}{\epsilon_H} \]

\[ k \sim aH|_0 \]

\[ k \ll aH|_0 \]

\[ \xi < -1/2 \]

\[ \nu < 3/2 \]

\[ \xi \sim 1 \]

\[ \nu \sim 3/2 \]

large scales set by pre-inflationary vacuum

frozen: $\xi < -2$

decaying: $-2 < \xi < 0$

with $n_s \geq 1$

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Type I backgrounds

Decelerated expansion: $H$ decreases

Large scale spectrum from superhorizon modes

$\xi < -1/2, \nu < 3/2$

$k \gg aH|_0 \rightarrow P_k \sim \frac{H_{\text{inf}}^2}{\epsilon_H}$

$k \sim aH|_0$

$k \ll aH|_0$

Frozen: $\xi < -2$

Decaying: $-2 < \xi < 0$

with $n_s \geq 1$

large scales set by pre-inflationary vacuum

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Type I backgrounds

Decelerated expansion: $H$ decreases

Large scale spectrum from superhorizon modes

$k \gg aH \mid_0 \rightarrow P_k \sim \frac{H_{\text{inf}}^2}{\epsilon_H}$

$k \sim aH \mid_0$

$k \ll aH \mid_0 \rightarrow P_k \sim H^2 \times \left( \frac{k}{aH} \right)^{n_s-1}$

deep IR behaviour determined by $n_s$:

large scales set by pre-inflationary vacuum

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Type I backgrounds

Decelerated expansion: $H$ decreases

Large scale spectrum from superhorizon modes

$\xi < -1/2$
$v < 3/2$
$\xi \sim 1$
$v \sim 3/2$

$k \gg aH|_0 \rightarrow P_k \sim \frac{H_{inf}^2}{\epsilon_H}$

$k \sim aH|_0$

$k \ll aH|_0 \rightarrow P_k \sim H^2 \times \left(\frac{k}{aH}\right)^{n_s-1}$

deep IR behaviour determined by $n_s$:

IR power suppression

large scales set by pre-inflationary vacuum

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We see what we put in: choice of ICs determines power on large scales.
Type IV backgrounds

Accelerated expansion: $H$ is growing $H \propto e^{(\xi - 1)N_e}$

Large scale spectrum from pre-inf. subhorizon modes

$k \gg aH|_0$

$k \sim aH|_0$

$k \ll aH|_0$

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Type IV backgrounds

Accelerated expansion: $H$ is growing $\quad H \propto e^{(\xi-1)N_e}$

Large scale spectrum from pre-inf. subhorizon modes

$$k \gg aH|_0 \quad \rightarrow \quad P_k \sim \frac{H_{\text{inf}}^2}{\epsilon_H}$$

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Type IV backgrounds

Accelerated expansion: $H$ is growing $H \propto e^{(\xi-1)N_e}$

Large scale spectrum from pre-inf. subhorizon modes

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Type IV backgrounds

Accelerated expansion: $H$ is growing $H \propto e^{(\xi-1)N_e}$

Large scale spectrum from pre-inf. subhorizon modes

$k \gg aH|_0 \rightarrow P_k \sim \frac{H_{inf}^2}{\epsilon_H}$

$k \sim aH|_0$

$k \ll aH|_0$

Frozen with $n_s > 1$

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Type IV backgrounds

Accelerated expansion: \( H \) is growing \( H \propto e^{(\xi-1)N_e} \)

Large scale spectrum from pre-inf. subhorizon modes

\[
\begin{align*}
\ln aH & \quad \xi \sim 1 \\
N_e & \quad \nu \sim 3/2 \\
\frac{1}{2} < \nu < \frac{3}{2}
\end{align*}
\]

\[
\begin{align*}
k \gg aH|_0 & \quad \rightarrow P_k \sim \frac{H_{\text{inf}}^2}{\epsilon_H} \\
\frac{1}{2} < \nu < \frac{3}{2}
\end{align*}
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\begin{align*}
k \sim aH|_0 & \quad \rightarrow P_k \sim H^2 \times \left(\frac{k}{aH}\right)^{n_s-1} \\
\frac{1}{2} < \nu < \frac{3}{2}
\end{align*}
\]

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Type IV backgrounds

Accelerated expansion: $H$ is growing $\quad H \propto e^{(\xi - 1)N_e}$
Large scale spectrum from pre-inf. subhorizon modes

$P_k \propto \frac{H_{\text{inf}}^2}{\epsilon_H}$

$k \gg aH|_0 \quad \rightarrow \quad P_k \sim \frac{H_{\text{inf}}^2}{\epsilon_H}$

$k \sim aH|_0$

$k \ll aH|_0 \quad \rightarrow \quad P_k \sim H_{\text{inf}}^2 \times \left( \frac{k}{aH} \right)^{n_s - 1}$

Low power on large scales

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Type IV backgrounds

background:
red $\xi = \frac{3}{2}$
green $\xi = 2$
blue $\xi = \frac{5}{2}$

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Type IV backgrounds

- **background:**
  - red $\xi = 3/2$
  - green $\xi = 2$
  - blue $\xi = 5/2$

- Same broad features
  - Different peak amplitude
  - Different low-k fall-off

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Type IV backgrounds

- **background:**
  - red: $\xi = 3/2$
  - green: $\xi = 2$
  - blue: $\xi = 5/2$

- Same broad features
- Different peak amplitude
- Different low-k fall-off

More robust than Type I:
- Insensitive to choice of ICs

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Pre-inflation and power loss

Degeneracy: one-parameter family of primordial spectra

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Pre-inflation and power loss

Degeneracy: one-parameter family of primordial spectra

Interesting hints: [1311.1599] & [1402.1418] claim these spectra are better fits than simpler monotonic parametrization

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Persistent hints from COBE / WMAP / PLANCK

Short inflation modifies large scale/low- $\ell$ power spectrum

Different ways to reduce power

Degeneracy/universality in power loss

Better understanding requires fit to the data

We might be seeing pre-inflationary phase
Thank you