Features in Inflation and Generalized Slow Roll

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BICEP Exercise
Year of the B-Mode

- Gravitational lensing B-modes (SPTPol, Polarbear...) detected
- Gravitational wave B-modes (BICEP2) measured
Tensor Tension

- In ΛCDM with power law scalar power spectra, Planck temperature power spectrum in tension with BICEP2 polarization detection
Tensor Temperature Excess

- $r=0.2$ and fixed acoustic peaks produces an excess in temperature power spectrum that is not observed (limits $r<0.11$ 95% CL)
- Exacerbates a preexisting 2-3σ tension in $\Lambda$CDM at $r=0$
Running of the Tilt

- Introducing scale by running tilt changes inferences from temperature spectrum, weakening upper limit on \( r \)

- \( r=0.2 \) requires a large running of order the tilt, not compatible with scale-free potentials, more indicative of transient feature

\[ \frac{dn_s}{d\ln k} = -0.02 \]

Suppresses scalar spectrum above recombination horizon
Inflationary Features and Generalized Slow Roll
Ordinary Slow-Roll Approximation

- Curvature power spectrum given by

\[ \Delta^2_{R}(k) = \left. \frac{H^2}{8\pi^2 M_{pl}^2 \epsilon_H c_s} \right|_{k=1/s} \]

where \( s = \int dN c_s / (aH) \) is the inflationary sound horizon and

\[ \epsilon_H = -\frac{d \ln H}{dN} \ll 1 \]

- The tensor-scalar ratio \( r = 16\epsilon_H c_s \)

- Scalars can be suppressed by making \( r \) evolve strongly with scale

- Evolution of slow-roll parameters violates the ordinary slow roll approximation but does not interrupt inflation if \( \epsilon_H \ll 1 \)

- Not sufficient to introduce features directly into \( \Delta^2_R \)
Generalized Slow-Roll Approximation

- Transient evolution in $\epsilon_H c_s$ preserves approximate de Sitter background

- Solve the Mukhanov-Sasaki equation iteratively with Green function technique using deviations from de Sitter as external source (Stewart 2002; Choe, Gong, Stewart 2004)

- Single source function $G'$ captures power spectrum deviations up to order unity with percent level accuracy (Dvorkin & Hu 2010)

- Valid for any $P(X, \phi)$ or inflation EFT described by $(g_{00} + 1)^n$ operators (Hu 2011)

- Bispectrum for all terms including leading order modefunction correction terms for $c_s^{-2}$ enhanced operators (Adshead, Hu, Miranda 2013)
GSR and the Potential

- GSR source function $G'$ vs potential combination $3(V'/V)^2 - 2V''/V$

Dvorkin & Hu (2009)
Featuring the BICEP
Tensor Temperature Excess

- Prefers sharper change than running, suppression over 1efold (excess exists even without tensors)
- Steps in power from steps in tensor scalar ratio $\epsilon_H c_s$
Freezeout of Curvature

- **Source** function $G'$ deviations from de Sitter
- $G' = 1 - n_s$ is tilt in slow roll
Freezeout of Curvature

- De Sitter mode functions give $W$, linear transfer to \textit{curvature} power.
- For \textit{sharp features}, curvature power\textit{ oscillates} or rings.
Freezeout of Curvature

- De Sitter mode functions give $W$, linear transfer to curvature power
- For sharp features, curvature power oscillates or rings
Transfer to Anisotropy

- Radiation transfer projects to temperature, E-polarization anisotropy
- Projection is sharp in the acoustic temperature regime, everywhere in E-polarization
Transfer to Anisotropy

- Radiation transfer projects to temperature, E-polarization anisotropy
- Projection is **sharp** in the **acoustic temperature** regime, everywhere in E-polarization

\[ l(l+1)C_l/2\pi (\mu K^2) = \Delta C_l/C_l \]

- Power law \( r=0 \)
- Step \( r=0.2 \)

Beyond slow roll

Miranda, Hu, Adshead (2014)
Polarization Predictions

- Matching tensor excess in E-mode polarization
- If scalars are suppressed by feature, E-modes compensated as well (as opposed to TT statistical fluke)

![Graph showing polarization predictions](Miranda, Hu, Adshead (2014))
Reconstructing the Source
Inverse Problem

- Source function completely describes observable scalar properties
- Invert directly from observables to inflationary source
- Use transfer functions of a precomputed basis for rapid MCMC
WMAP Basis

- Complete **principal component** basis for any observable feature with $\Delta N > 1/4$
- **Cosmic variance** and WMAP beam limit number to 20 components
- Maximum likelihood $2\Delta \ln L = 17$

Dvorkin & Hu (2011)
Functional Constraints on Source

- 20 PC filter on source function from WMAP data
- Suppression at $s > 1000\text{Mpc}$ consistent with and Planck (in progress)
- BICEP2 changes preference for oscillation as tensors absorb and modify TT features

Dvorkin & Hu (2011)
If features are due to single field inflation (GSR) there must be corresponding ones in polarization

Dvorkin & Hu (2011)
**Bispectrum Features**

- Predicts features in the bispectrum
- Efficiently calculated through generalized slow-roll
- Bispectrum features related to the $l \sim 20-40$ glitch are large but confined to too small a range to be observed

Adshead, Hu, Dvorkin, Peiris (2011)

Chen et al (2007)
Sharp Steps
Oscillations in Planck Data

- Sharp step preferred in fits at $\Delta \chi^2 = 11-15$
- Chance noise realizations can produce spurious fits, matching E-polarization is key test
Oscillatory high $k$ power represents the Fourier transform of sharp correlation function feature with mild log divergence.
Sharp Step

- Oscillatory high $k$ power damped by finite width of feature
- For theoretical maximum $k^2$ to $k_{eq}s_s \sim 100$; $S/N \sim$ power spectrum

Adshead & Hu (2012;2014)
Summary

- **Planck-BICEP2 tension** between TT and BB may indicate features in inflationary spectrum
- **Step** in tensor scalar ratio $r \propto \epsilon H c_s$ significantly favored in $\Lambda$CDM
- Relatively sharp features preferred, beyond scope of ordinary slow roll approximation
- **Ringing** in spectrum highly constrained in acoustic regime, matching E-polarization predicted, testable
- **Generalized slow roll** technique accurately computes power spectrum and bispectrum
- Extremely sharp step separately preferred but can be mimicked by noise
- **Conclusive tests** in polarization and bispectrum