Inflation Signatures

“To B or not to B”

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Creating Polarization in the CMB

- Quadrupole Anisotropy
- Thomson Scattering
- Linear Polarization
Nomenclature

\[(Q \pm iU)(\hat{n}) = \sum_{\ell,m} a_{\pm 2,\ell m} \pm 2 Y_{\ell m}(\hat{n})\]

\[a_{E,\ell m} \equiv -\frac{1}{2} (a_{2,\ell m} + a_{-2,\ell m})\]

\[a_{B,\ell m} \equiv -\frac{1}{2i} (a_{2,\ell m} - a_{-2,\ell m})\]
E and B Modes

E < 0

E > 0

B < 0

B > 0
Power Spectra

\[ C_{\ell}^{XY} \equiv \frac{1}{2\ell + 1} \sum_m \langle a_{X,\ell m}^* a_{Y,\ell m} \rangle, \quad X, Y = T, E, B \]

\[ a_{X,\ell m} = 4\pi (-i)^\ell \int \frac{d^3 k}{(2\pi)^3} \Delta_{X\ell}(k) \{ \zeta_{\vec{k}}, h_{\vec{k}} \} Y_{\ell m}(\hat{k}) \]

\[ C_{\ell}^{BB} = (4\pi)^2 \int k^2 dk \underbrace{P_h(k) \Delta_{B\ell}^2(k)}_{\text{Inflation}} \]
What do we learn

• No other known mechanism produces super horizon tensor fluctuation

• Inflation potential

\[ V^{1/4} \sim \left( \frac{r}{0.01} \right)^{1/4} \times 10^{16} \text{ GeV} \]

• Super Planckian field variation

\[ \frac{\Delta \phi}{M_{\text{pl}}} = \mathcal{O}(1) \times \left( \frac{r}{0.01} \right)^{1/2} \]
BiCEP 2 March 17 Results

• Claim detection of $r=0.2 +0.07, -0.05$
• $r=0$ rejected at 7 sigma
BiCEP B mode measurements

- Measure Tx and Ty with two orthogonal bolometers cooled to 270 mK – He3
- Optics are refractive - ~ 0.5 deg beam – cover ~ 1% sky
- One freq channel in BiCEP 2 – 150 Ghz – atmospheric window
- Measure Q and U linear polarization states
- \( Q = \frac{1}{2}(Tx-Ty) \) – rotate 45 deg to get U
- V (circular pol) not measured
- Tx, Ty include instrument (few K), atmosphere (10K), gal (small in I, not in Q,U), CMB (~0.5K - Ta)
- 256 pairs of crossed bolo - ~ 300 micro K in 1 sec
- Integrate to get ~ 100 nK per 1 deg pixel
- MUST suppress/ understand all above (~10+K to \( 10^{-7} \) K level) this is \( 10^8 \) rejection
- BiCEP is not a differential polarimeter - neither is Planck
- Systematic refection of all the above is critical
Planck Mission

- Planck mission data collecting 2009-2013 has ended
- Planck T (intensity) for about ½ mission released 2013
- Planck Q,U NOT released yet – 2014, 2015
- $r \sim 0.05$ (2 sigma) sensitivity possible at low $l$
- 30-1000 GHz freq coverage
- Full sky
TT Power Spectra – 7 peaks resolved
Error bars include SV and CV
Note low quadrupole
Marginalized $n_s$ and $r$ (1,2σ)

$n_s$ does not equal 1

$r < 0.11$ (2 σ) from T alone

Energy scale for “standard inflation” $< 1.9 \times 10^{16}$ Gev (2 σ)

Planck polarization this year
Selected parameters
Lensing Potential Measured
High Significance (25 sigma)
Mode by mode SNR ~ 0.7 at L=30

\[ \phi_{WF}(\hat{n}) \]

Galactic North

Galactic South
Planck polarization at Extrema T and Q

Left – cold spots , Right – hot spots
Top - data, bottom - Best fit model prediction
Aberration of the CMB

Our motion shifts amplitude and angles
Expected effect is $10^{-3}$ of $10^{-5} = 10$ ppb!

• Left show exaggerated effect - 700x increase in our speed to 85% c.

• Our real speed relative to CMB is $\sim 0.12\%$ c

• We use this to look for the effect

• We know the direction and speed from CMB dipole

• Effects both amplitude and angles ($\sim 4'$)

• Angular effect is not trivial compared to lensing

$$\delta T (n^\wedge) = T_0 n^\wedge \cdot \beta + \delta T 1(n^\wedge - \nabla(n^\wedge \cdot \beta))(1 + n^\wedge \cdot \beta)$$
Concerns

- $r=0.2$ is larger than recent Planck upper limit ($r<0.11$) BUT this assumed no running (no scale dependence) of spectral index
- BiCEP has less than 1% sky coverage
- BiCEP really has only 1 freq – 150 GHz
- Internal systematic concerns
- Foregrounds are a major worry in all B mode experiments – no good polarized dust model yet
- Planck will “weigh in” soon