Detecting Fingerprints of Inflation in the CMB

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PhD Seminar on Inflation

Thomson Scattering

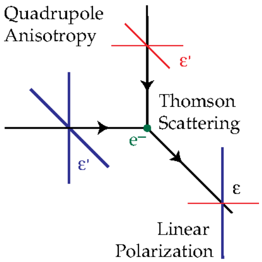
Nice tutorial about Polarization of CMB Anisotropies in
`http://background.uchicago.edu/~whu/polar/webversion/polar.html`

- CMB photons scattered via Thomson scattering
- Thomson scattering depends on polarization and is anisotropic

Thomson Scattering

$$\frac{d\sigma_T}{d\Omega} \propto |\hat{e} \cdot \hat{e'}| \tag{1}$$

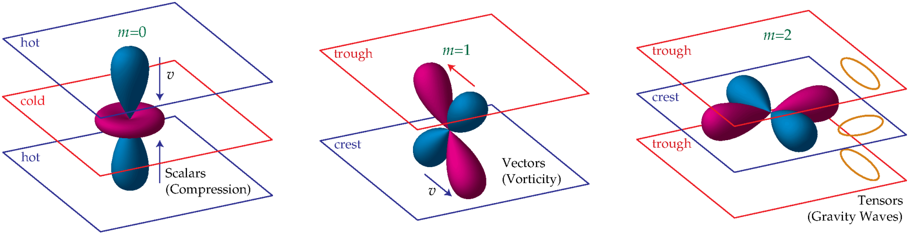
- If incoming radiation is isotropic orthogonal polarization states cancel out and the scattered radiation is unpolarized
- We need a **quadrupole anisotropy in the intensity or temperature** to produce linear polarization
  $\rightarrow$ incident radiation from perpendicular directions has different intensities



Quadrupolar Anisotropies in Temperature

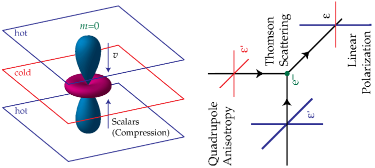
Three types of perturbations:

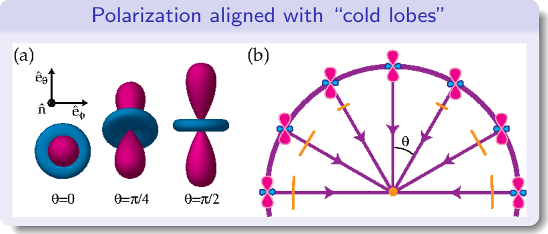
- **Scalar**:
  Fluctuations in (energy) density of the plasma result in a flow from hotter to colder regions
- **Vector**:
  Vorticity in the plasma cause Doppler shifts. Contribution expected to be negligible and left out in the following
- **Tensor**:
  Gravitational waves stretch and squeeze space in orthogonal directions

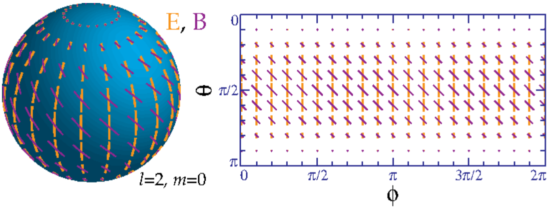


Scalar Perturbations

- Gradient of temperature create flows from hot to cold temperatures



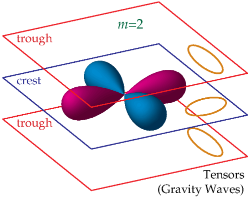


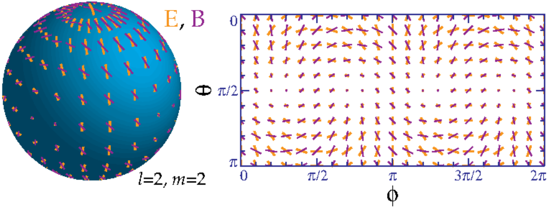


- Pattern is highly symmetrical.
- Polarization North-South (up-down) direction and is independent of longitude

Tensor Perturbations

- Gravitational waves create a quadrupolar stretching of space $\rightarrow$ quadrupolar stretching of wavelength of the incident photons produces a quadrupolar temperature variation
- Quadrupolar temperature variation with Thomson scattering produces polarization
- Polarization pattern depends on orientation of quadrupole moment with respect to scattering direction (analogue to scalar perturbations)





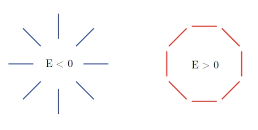
- Pattern not symmetric
- Pattern has Northeast-Southwest and Northwest-Southeast components

E- and B-Modes

- Polarization pattern can be decomposed into two components: **E- and B-modes**

E-Modes

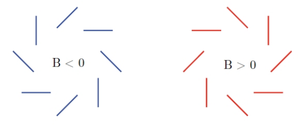
- In analogy to E-field
- *Curl-free*
- Radial around cold spots and tangent around hot spots



- Created by scalar and tensor perturbations

B-Modes

- In analogy to B-field
- *Divergence-free*
- Handedness, B-Mode pattern changes sign under parity transformation



- **Created by tensor (gravitational wave) perturbations only**

Describing the CMB Anisotropies in Power Spectra

- Question: How to present the information contained in the millions of pixels of the CMB map more compact?
- Power spectrum characterizes the size of the fluctuations as a function of the angular scale
- The fluctuations can be written in terms of spherical harmonics Y_l^m
- E.g the temperature fluctuations

$$\Delta T(\theta, \phi) = \sum_{l,m} a_{lm} Y_l^m(\theta) \tag{2}$$

- Combine multipole moments a_{lm} to power spectrum

$$C_l^T = \frac{1}{2l+1} \sum_m \langle a_{lm}^* a_{lm} \rangle \tag{3}$$

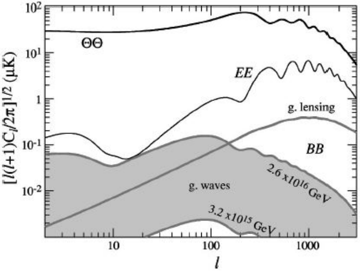
- $C_l \propto \langle \Delta T(\hat{n}) \cdot \Delta T(\hat{n}') \rangle$, the statistical mean of the product of two temperature differences observed in two different directions
- Define angular power spectra for E- and B-modes the same

$$C_l^{XY} \equiv \frac{1}{2l+1} \sum_m \left\langle a *_{X,lm} a_{Y,lm} \right\rangle \text{with} X, Y = T, E, B \tag{4}$$

Anatomy of Power Spectrum of CMB Anisotropy

How strong do we expect the polarization power spectrum to be?

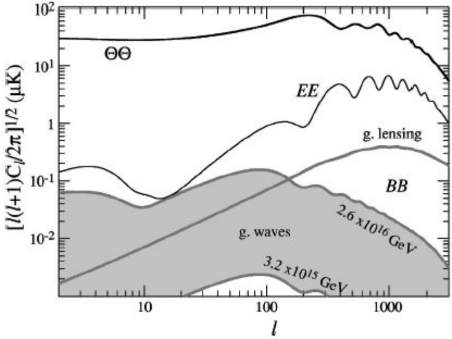
- Polarization only at final stage of recombination when
  - still free electrons for photons to scatter at
  - but mean free path of photons is high enough to preserve quadrupole anisotropy in temperature
- Expect only about 10% of CMB radiation polarized
- Amplitude of polarization power spectrum highly suppressed, of order 10^{-6} K



E-Modes

- Polarized signal suppressed
- At large scales re-ionization peak
- EE (velocity maxima) and TT (density maxima) peaks out of phase

B-Modes in the CMB Power Spectrum



B-Modes

- E-modes produce B-modes by gravitational lensing
- At high l high contribution from gravitational lensing
- Most B-modes from gravity waves on large scales $l < 300$
- BB peaks at horizon scale around $l = 100$
- Additional bump at small l from re-ionization
- Amplitude of BB depends on energy scale of inflation

Studying B-Modes of the CMB Polarization

- The polarization power spectrum isolates the gravitational wave spectrum: **B-Modes are produced only by tensor perturbations**
- Amplitude of B-mode power spectrum is linked to energy scale of inflation
- Polarization is very small

Foregrounds: An Experimental Challenge

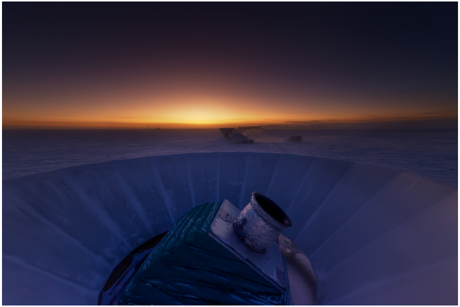
- Microwave emission from the Milky Way
  - Warm dust in the plane
  - Synchrotron radiation from electrons in Galactic magnet field
  - Bremsstrahlung from ionized H
  - Line emission from molecules
- High redshift galaxies
- Planets, asteroids and comets in the Solar System

- The **B**ackground **I**maging of **C**osmic **E**xtragalactic **P**olarization (BICEP) was specially designed to measure the B-modes of the CMB polarization

The BICEP2 Experiment

Experimental Requirements

- CMB peaks at 150 GHz
- B-mode maximum expected around $l \approx 100$
- Amplitude expected very low ($r < 0.22$ at 95% CL form WMAP)
  - Need high sensitivity
  - low systematics



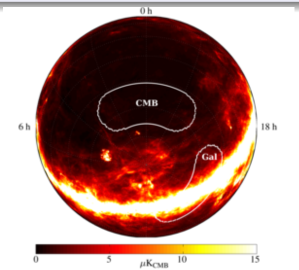
BICEP2

- Successor of BICEP1
- Observed from the South Pole from 2010-2012

The BICEP2 Location

The Admundsen-Scott South Pole Station

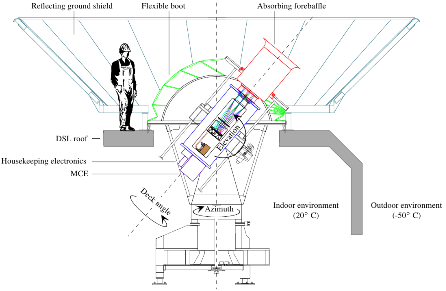
- Good infrastructure available
- Lower humidity reduces atmospheric noise due to absorption and emission of water
- 6 month of continuous night:
  - stable observing conditions
  - 24-hour visibility of same part of sky

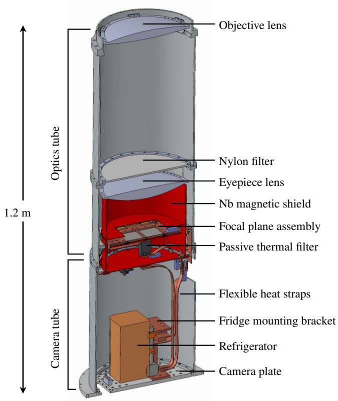


The Southern Hole

- Primary observation field is the *Southern Hole*
- Well away from Galactic plane
- Very low level of Galactic dust emission
- Expected low level of polarized foregrounds

The BICEP2 Instrument





BICEP2 Telescope

- Used same mount as for BICEP1
- Optics kept simple, avoiding reflecting components that might add instrumental polarization
- Optics cooled to 4 K
- Telescope shielded from stray light from ground

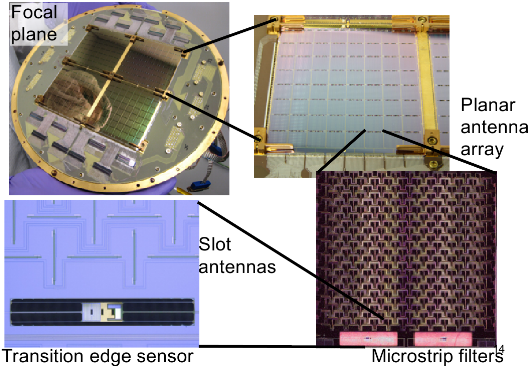
The BICEP2 Detectors

Detection Principle

- Measure optical power of orthogonal linear polarization
- Sum gives the temperature
- Difference gives the polarization

The Polarimeter Unit

- Orthogonal slot antennas → sensitive to polarization
- Signal read out by transition edge sensor (TES) bolometers
- In total 256 pixels



from http://astro.uchicago.edu/depot/talks/bicep2bmodes_kicp.pdf

Results from BICEP2

Selected for a Viewpoint in *Physics*

PRL **112**, 241101 (2014) PHYSICAL REVIEW LETTERS week ending 20 JUNE 2014

Detection of *B*-Mode Polarization at Degree Angular Scales by BICEP2

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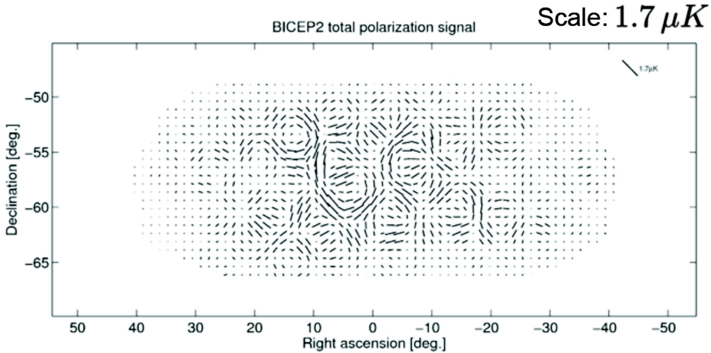
We report results from the BICEP2 experiment, a cosmic microwave background (CMB) polarimeter specifically designed to search for the signal of inflationary gravitational waves in the *B*-mode power spectrum around $\ell \sim 80$. The telescope comprised a 26 cm aperture all-cold refracting optical system equipped with a focal plane of 512 antenna coupled transition edge sensor 150 GHz bolometers each with temperature sensitivity of $\approx 300\ \mu K_{CMB}\sqrt{s}$. BICEP2 observed from the South Pole for three seasons from 2010 to 2012. A low-foreground region of sky with an effective area of 380 square deg was observed to a depth of 87 nK deg in Stokes Q and U. In this paper we describe the observations, data reduction, maps, simulations, and results. We find an excess of *B*-mode power over the base lensed-ΛCDM expectation in the range $30 < \ell < 150$, inconsistent with the null hypothesis at a significance of $> 5\sigma$. Through jackknife tests and simulations based on detailed calibration measurements we show that systematic contamination is much smaller than the observed excess. Cross correlating against WMAP 23 GHz maps we find that Galactic synchrotron makes a negligible contribution to the observed signal. We also examine a number of available models of polarized dust emission and find that at their default parameter values they predict power $\sim(5\text{–}10)\times$ smaller than the observed excess signal (with no significant cross-correlation with our maps). However, these models are not sufficiently constrained by external public data to exclude the possibility of dust emission bright enough to explain the entire excess signal. Cross correlating BICEP2 against 100 GHz maps from the BICEP1 experiment, the excess signal is confirmed with 3σ significance and its spectral index is found to be consistent with that of the CMB, disfavoring dust at 1.7σ.

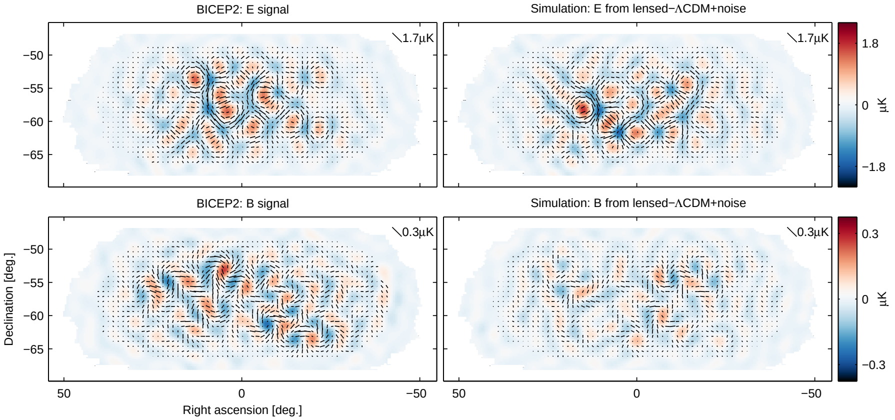
Polarization Map



from http://astro.uchicago.edu/depot/talks/bicep2bmodes_kicp.pdf

- Polarization map looks as expected if E-modes are dominant
- B-mode contribution small
- e.g. for r=0.1 the contribution is 10 times smaller at $l = 100$
- Decompose polarization map into E- and B-maps

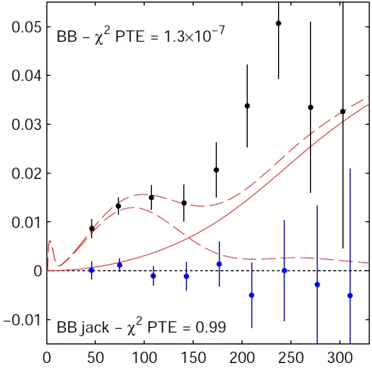
E- and B-Maps



B-Mode Signal

- Detection of B-modes with high signal-to-noise ratio
- Signal seems evenly distributed over observed field → cosmological signal

BB- Power Spectrum



BB Excess

- Range $2 < l < 340$
- High l: consistent with lensed-ΛCDM (solid red line)
- Low l: excess over the lensed-ΛCDM
- Jackknife (blue points): The differ maps from different data sets do not see an excess

BB Excess Significance

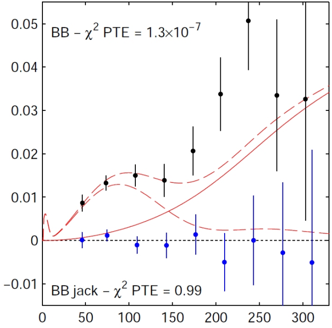
- How likely is it that the observed difference from the expected (here lensed-ΛCDM) arises by chance?
- Probability of excess (PTE) is 1.3×10^{-7}
- Significance of 5.3σ

Systematics

- Can the observed excess of the BB-signal be explained by
  1. instrumental artifacts or
  2. Galactic or extragalactic foregrounds?

Instrumental Artifacts

- Studied intensively e.g. with Jackknife spectra
- Here the difference of maps from different time periods, detectors, etc is taken to derive the power spectrum
- Correlated components like sky signal fully cancel out
- Uncorrelated contributions like noise are constant
- An amplitude present only in one data set will stay



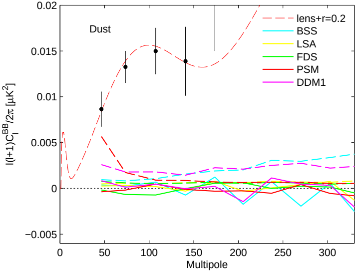
- Jackknife spectrum does not show the excess

Foregrounds to CMB

- Can the observed excess of the BB-signal be explained by
  1. instrumental artifacts or
  2. Galactic or extragalactic foregrounds?

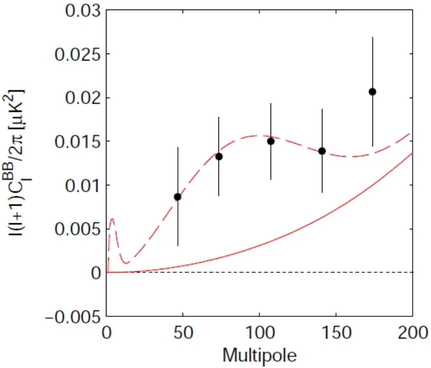
Foregrounds

- Dominant foreground is
  1. Galactic synchrotron emission and
  2. dust emission
- Polarized synchrotron emission estimated from WMAP data to be negligible
- Compare existing models and new model based on Planck data for polarized dust
- For the Planck data based model (DDM1) a 5% polarization of the sky is assumed
- To be comparable with the observed excess signal the polarization fraction should be 13%



- Spectra from dust models are well below the observed signal

Constraints on Tensor-to-Scalar Ratio

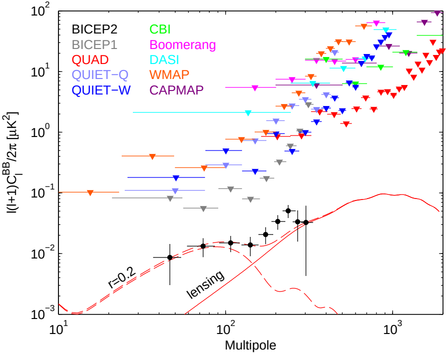


- Black points: Data points from BICEP2
- Red dashed curve: maximum likelihood lensed-ΛCDM + r = 0.20 model
- Red solid line: lensed-ΛCDM

Tensor-to-Scalar Ratio

- Tensor-to-scalar ration $r = 0.20^{+0.07}_{-0.05}$
- r=0 ruled out at 7σ

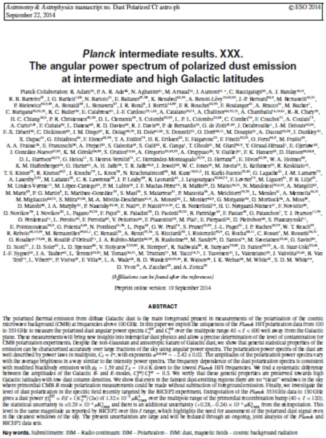
Summary of BICEP2 Results



- Former experiments report only upper limits on BB spectra
- However, BICEP2 measures only at 150 GHz, thus is less sensitive to polarized dust emission
- They report an excess of B-modes and r=0.20 **without foreground subtraction**
- BICEP2 result are in tension with indirect limits on r from Planck: $r < 0.11$

New Planck Results on Polarized Dust Emission

Question: How big would be a B-signal generated by Galactic Dust?



Astronomy & Astrophysics manuscript no. Dust Polarized Cl astro-ph © ESO 2014
September 22, 2014

arXiv:1409.5738v1 [astro-ph.CO] 19 Sep 2014

Planck intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes

Planck Collaboration: R. Adam, P. A. R. Ade, N. Aghanim, M. Arnaud, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, N. Bartolo, E. Battaner, K. Benabed, A. Benoît-Lévy, J.-P. Bernard, M. Bersanelli, P. Bielewicz, A. Bonaldi, L. Bonavera, J. R. Bond, J. Borrill, F. R. Bouchet, F. Boulanger, A. Bracco, M. Bucher, C. Burigana, R. C. Butler, E. Calabrese, J.-F. Cardoso, A. Catalano, A. Challinor, A. Chamballu, R.-R. Chary, H. C. Chiang, P. R. Christensen, D. L. Clements, S. Colombi, L. P. L. Colombo, C. Combet, F. Couchot, A. Coulais, … G. Roudier, B. Rouillé d'Orfeuil, J. A. Rubiño-Martín, B. Rusholme, M. Sandri, D. Santos, M. Savelainen, G. Savini, D. Scott, J. D. Soler, L. D. Spencer, V. Stolyarov, R. Stompor, R. Sudiwala, R. Sunyaev, D. Sutton, A.-S. Suur-Uski, J.-F. Sygnet, J. A. Tauber, L. Terenzi, M. Tomasi, M. Tristram, M. Tucci, J. Tuovinen, L. Valenziano, J. Valiviita, B. Van Tent, L. Vibert, P. Vielva, F. Villa, L. A. Wade, B. D. Wandelt, R. Watson, I. K. Wehus, M. White, S. D. M. White, D. Yvon, A. Zacchei, and A. Zonca

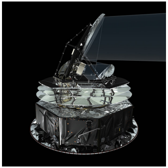
(Affiliations can be found after the references)

Preprint online version: 19 September 2014

ABSTRACT

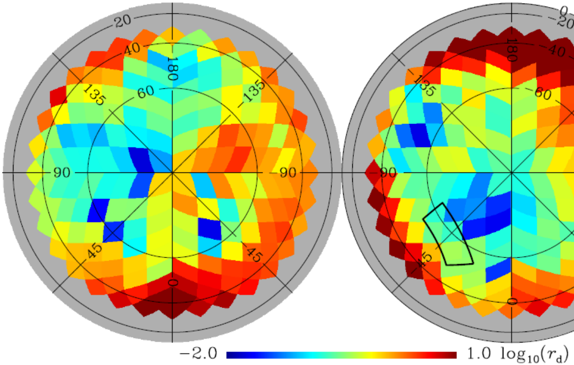
The polarized thermal emission from diffuse Galactic dust is the main foreground present in measurements of the polarization of the cosmic microwave background (CMB) at frequencies above 100 GHz. In this paper we exploit the uniqueness of the *Planck* HFI polarization data from 100 to 353 GHz to measure the polarized dust angular power spectra C_ℓ^{EE} and C_ℓ^{BB} over the multipole range $40 < \ell < 600$ well away from the Galactic plane. These measurements will bring new insights into interstellar dust physics and allow a precise determination of the level of contamination for CMB polarization experiments. Despite the non-Gaussian and anisotropic nature of Galactic dust, we show that general statistical properties of the emission can be characterized accurately over large fractions of the sky using angular power spectra. The polarization power spectra of the dust are well described by power laws in multipole, $C_\ell \propto \ell^{\alpha}$, with exponents $\alpha^{EE,BB} = -2.42 \pm 0.02$. The amplitudes of the polarization power spectra vary with the average brightness in a way similar to the intensity power spectra. The frequency dependence of the dust polarization spectra is consistent with modified blackbody emission with $\beta_d = 1.59$ and $T_d = 19.6$ K down to the lowest *Planck* HFI frequencies. We find a systematic difference between the amplitudes of the Galactic B- and E-modes, $C_\ell^{BB}/C_\ell^{EE} = 0.5$. We verify that these general properties are preserved towards high Galactic latitudes with low dust column densities. We show that even in the faintest dust-emitting regions there are no "clean" windows in the sky where primordial CMB B-mode polarization measurements could be made without subtraction of foreground emission. Finally, we investigate the level of dust polarization in the specific field recently targeted by the BICEP2 experiment. Extrapolation of the *Planck* 353 GHz data to 150 GHz gives a dust power $\mathcal{D}_\ell^{BB} \equiv \ell(\ell+1)C_\ell^{BB}/(2\pi)$ of $1.32 \times 10^{-2}\,\mu K^2_{CMB}$ over the multipole range of the primordial recombination bump ($40 < \ell < 120$); the statistical uncertainty is $\pm 0.29 \times 10^{-2}\,\mu K^2_{CMB}$ and there is an additional uncertainty $(+0.28, -0.24) \times 10^{-2}\,\mu K^2_{CMB}$ from the extrapolation. This level is the same magnitude as reported by BICEP2 over this ℓ range, which highlights the need for assessment of the polarized dust signal even in the cleanest windows of the sky. The present uncertainties are large and will be reduced through an ongoing, joint analysis of the *Planck* and BICEP2 data sets.

Key words. Submillimetre: ISM – Radio continuum: ISM – Polarization – ISM: dust, magnetic fields – cosmic background radiation



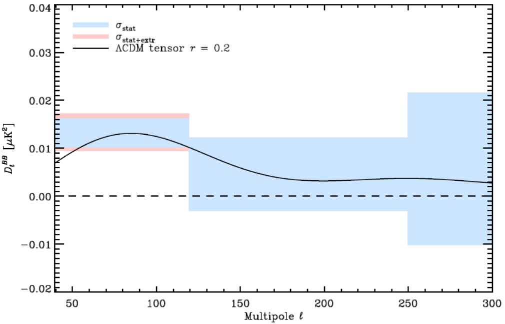
- The Planck high frequency instrument (HFI) measures linear polarization at 100, 143, 217 and 353 GHz
- Planck measured the all-sky dust polarization at 353 GHz where dust emission dominates over other polarized signals
- In the publication they calculate the polarization angular spectrum from the 353 GHz maps
- Finally the 353 GHz are extrapolated to 150 GHz (BICEP2 frequency) to estimate the amplitude in the BB-spectrum of BICEP2

B-mode Polarization Generated by Dust



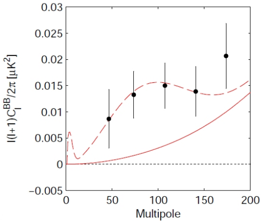
- No *clear* area for primordial B-mode search
- r_d is ratio of amplitude normalized to $6.71 \times 10^{-2}\ \mu K^2$, the extrapolated estimation of the amplitude of tensor CMB for r=1 at l=80
- $r_d = 0.207$ in approximated BICEP2 field (black box) $\rightarrow$ expected level of dust polarization $\mathcal{D}_l^{BB}$ is $1.39 \times 10^{-2}\ \mu K^2$

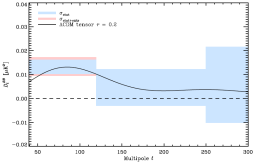
BB Angular Spectrum



- Expected level of dust polarized $\mathcal{D}_l^{BB}$ is 1.32×10^{-2} μK^2
- Statistical error from simulation: $\pm 0.29 \times 10^{-2}$ μK^2
- Additional uncertainty from extrapolation (+0.28,-0.24) 10^{-2} μK^2
- **BICEP2 signal is well explained by dust**

Conclusion from Planck on B-Modes Signal from BICEP2





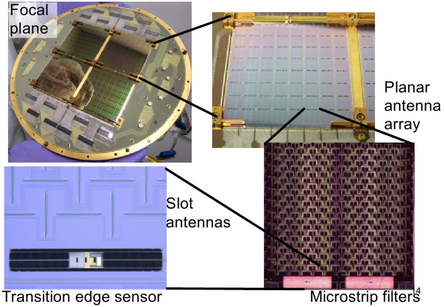
- The B-mode signal observed by BICEP2 can be explained by polarized dust emission
- Even if BICEP2 sees dust contamination there might still be contribution of B-modes from gravitational waves

- For the search of primordial B-mode there is no observation window where the foreground emission can be neglected
- Planck has identified possible regions of low dust polarization amplitude
- If BICEP2 signal explained by dust only this quantifies challenges for future polarized CMB experiments

- Keep in mind that Planck extrapolates from 353 to 150 GHz
- Let's wait for a dedicated joint analysis of Planck and BICEP2 – e.g. cross-correlation of Planck and BICEP2 maps

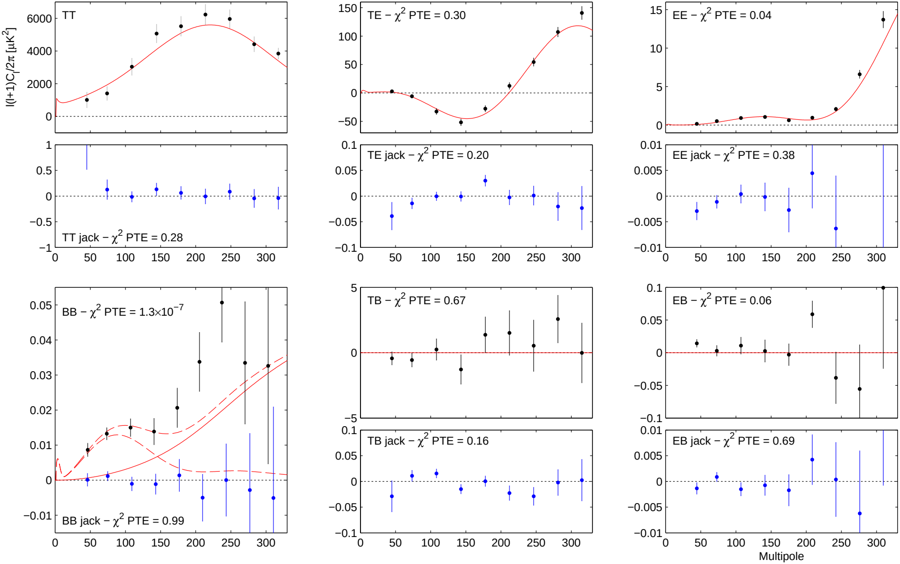
Bonus Slides

Details to BICEP2 Focal Plane



- Slot antennas are polarization sensitive since microwave radiation excites electric fields across the slot
- The currents induced around the slots couple to microstrips
- Orthogonal slots are read out by two independent microstrip networks
- Bandpass filter in between → Defined frequency band centered around 150 GHz
- Signals from the sub antennas are summed and transmitted to independent bolometer island and read out with TES
- TES's explore the high temperature dependence of superconducting phase transition → change in temperature results in residence change, thus change of flowing current

Power Spectra



How to get from Measured Data to B-Maps?

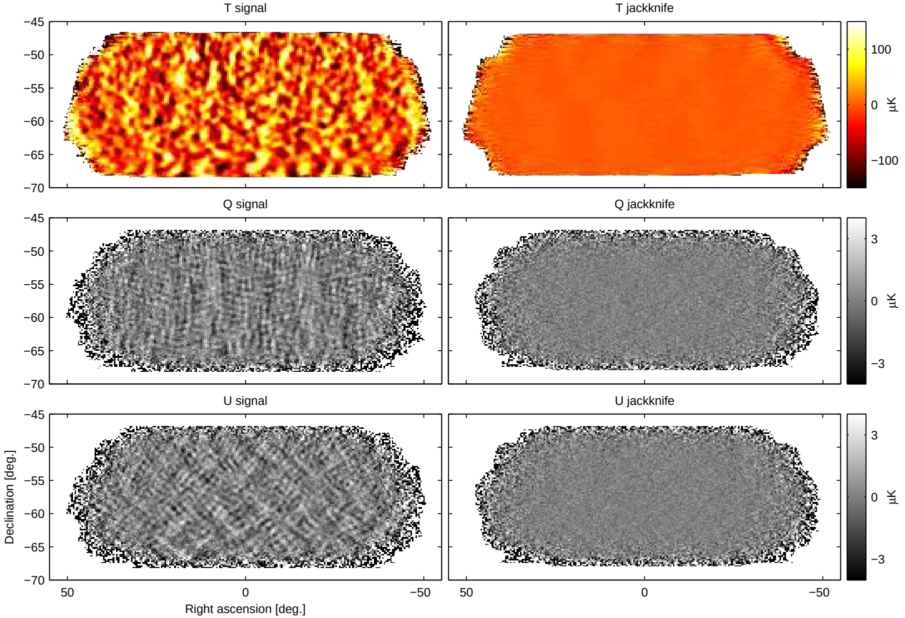
Reminder

- One detector pair measures optical power of orthogonal polarizations
- The sum gives the temperature
- The difference gives the polarization

Stokes Parameters

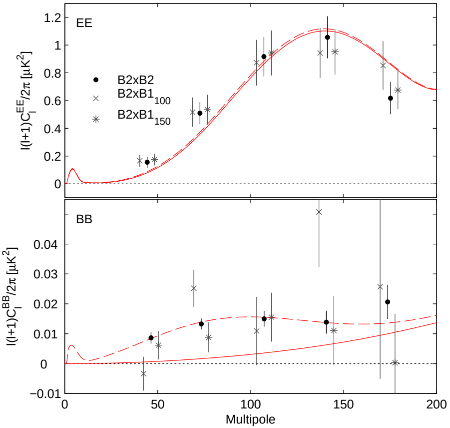
- Polarization state described by Stokes Parameters
  $Q = P_{0^\circ} - P_{90^\circ} = \langle E_x^2 - E_y^2 \rangle$
  $U = P_{45^\circ} - P_{135^\circ} = \langle 2E_x E_y \cos\delta \rangle$
- Q $\rightarrow$ vertical stripes pattern
- U $\rightarrow$ diagonal stripes pattern

T, Q and U Maps



T signal
T jackknife
Q signal
Q jackknife
U signal
U jackknife
−45
−50
−55
−60
−65
−70
Declination [deg.]
50
0
−50
Right ascension [deg.]
100
0
−100
μK
3
0
−3
μK
3
0
−3
μK

Cross Correlation with BICEP1



- BICEP1:
  - different technology $\rightarrow$ control of systematics
  - additional observation at 100 GHz $\rightarrow$ sensitive to different foregrounds
- For dust domination: expect little cross correlation between BICEP2 $\times$ BICEP1$_{100}$
- for synchrotron domination: expect cross correlation higher than BB
- Correlation shows that the B-signal seems to be cosmological rather than foreground

The Planck Analysis

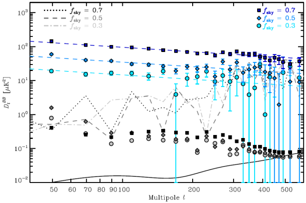
- Planck divides the 353 GHz maps into six large regions covering different percentages of the sky (0.3 - 0.8)
- Analyzing these six regions of the sky Planck finds
  - A power dependence of the amplitude $\mathcal{D}_l$

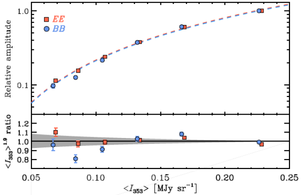
$$\mathcal{D}_l^{EE,BB} \propto l^{-2.42} \qquad (5)$$

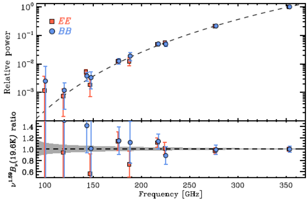
  - A dependence of the amplitude on the mean dust intensity $\langle I_{353} \rangle$

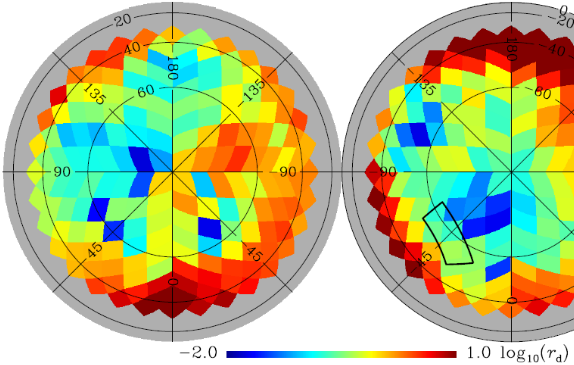
$$A^{EE,BB}(\langle I_{353} \rangle) \propto \langle I_{353} \rangle^{1.9} \qquad (6)$$

- They find a frequency dependence of the angular power spectrum in agreement with a modified black body spectrum with $\beta_d = 1.59$ and $T_d = 19.6$ K



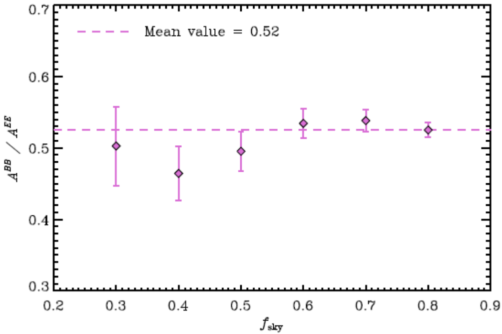






- Determine amplitude $A^{EE,BB}_{l=80}$ with power law
- Empirical law $A^{EE,BB} \propto \langle I_{353} \rangle^{1.9}$ holds for small regions in sky as well
- Use modified blackbody spectrum to extrapolate from 353 GHz to 150 GHz

Amplitude of BB Relative to EE



- Planck observes in all regions more power in the EE dust spectrum than in the BB
- Planck finds

$$\frac{A^{BB}}{A^{BB}} = 0.52 \pm 0.03 \tag{7}$$

- This differs significantly from unity, which is assumed in existing models of polarized dust