Characterization of Dust Polarization In Planck 353 Ghz Maps

Sushmita Walve
Mentor : Dr. Colin Bischoff
Physics Department, University of Cincinnati
Department Advisor : Dr. Richard Gass

Abstract

Planck is a European Space Agency satellite mission that mapped the whole sky in seven polarization-sensitive frequency bands. The highest polarization-sensitive band is 353 GHz, which is dominated by dust signal. The goals of this project is to make a statistical characterization of B mode polarization of dust in clean regions at a scale of 2 to 3 degrees (multipoles of 80) by using the Planck 353 ghz maps. By analyzing B mode angular spectrum power spectrum and temperature power spectrum we can determine the scalar-to-tensor ratio r, r is defined by the ratio of amplitude of primordial tensor and scalar perturbation. The polarized maps will need to be analyzed to characterize the amplitude of dust. We can analyze angular power spectra by squaring it since r contributes to the power in the function of angular spectra. By understanding the low dust regions in the sky at high galactic latitude we can better understand the uncertainty from instrumental noise

Using Cross spectrum analysis done through exploring these split maps, an improved version of the Planck map by characterizing the b mode amplitude from the dust in the galactic regions was produced and is shown in this paper. It is important to note that the data points in the maps are highly correlated so it was important to account the co related data points in the overlapped regions. Current and future attempts to measure tensor-to-scalar ratio will target low-foreground regions of the sky. Choices of the cleanest areas of the polarized sky cannot be made from using Planck's total intensity maps alone because polarization fraction can vary significantly in low dust regions.

1. Introduction

The Cosmic Microwave Background (CMB) is the residual thermal radiation from the Big Bang. It is the oldest light in the universe. In the past several decades, CMB has been fundamental to observational cosmology. The characterization of the temperature and polarization anisotropies of the CMB has helped to establish and measure the parameters of the standard cosmological model (ΛCDM). The ΛCDM (Lambda cold dark matter) model provides us with the framework to explain the observed properties of the cosmos, such as expansion history of the universe.

Cosmic inflation is a theory which predicts the exponential expansion of space at the beginning of the universe. Inflation is necessary to explain the initial conditions of the LCDM, since the model does not otherwise provide an explanation for it. Inflation predicts the large-scale geometry and structure of the universe, which has been important in mapping CMB across the sky. Inflation also predicts the existence of a background of gravitational wave perturbations also known as tensor mode perturbations.

The gravitational waves produced by inflation can be observed because of their effect of the temperature and polarization fields of the CMB. CMB B-mode polarization is the most promising method for detection of this gravitational wave background. The amplitude of tensors is parameterized by r, which is the tensor-to-scalar ratio [1]. The theoretical predictions of r from models of inflation span a wide range of values. If the polarization is parallel or perpendicular to this direction, it is called an E-mode polarization. If it is crossed at 45 degree angles, it is called a B-mode polarization. Density perturbations just generate parallel polarization and so generate only E-mode polarization.Gravitational waves generate both and so have a component of B-mode polarization [7].

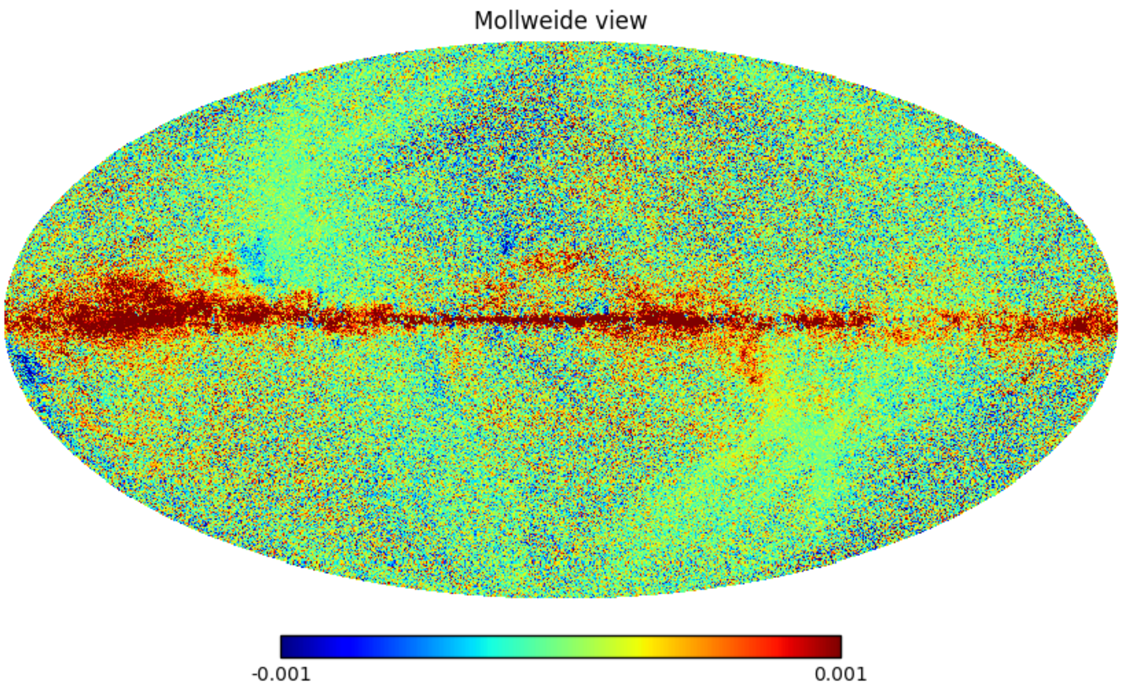
To have better an understanding of level of dust b mode polarizations across the sky so we used the data about the polarizations in the sky in form of maps and separated the *E*- and *B*-mode contributions for all possible wave vectors. Gravitational waves from inflation can source *B*-mode polarization, so a *B*-mode search allows us to target the signal of inflation at very high sensitivity without being swamped by the larger *E*-modes [6].

The dust in our Galaxy acts as foreground contamination for measurements of the CMB.The brightness of the thermal emission produced by the interstellar dust grains increases rapidly from the 100–150 GHz frequencies used for CMB observations, and dominates at higher frequencies. The dust brightness varies significantly over the sky and some lines of sight are much cleaner than others. The dust grains align with the Galactic magnetic field to produce emission with a degree of linear polarization. The observed degree of polarization depends on the structure of the Galactic magnetic field along the line of sight, as well as the properties of the dust grains. This polarized dust emission results in both E-mode and B-mode. We distinguish between dust and CMB by using multi-frequency data set.

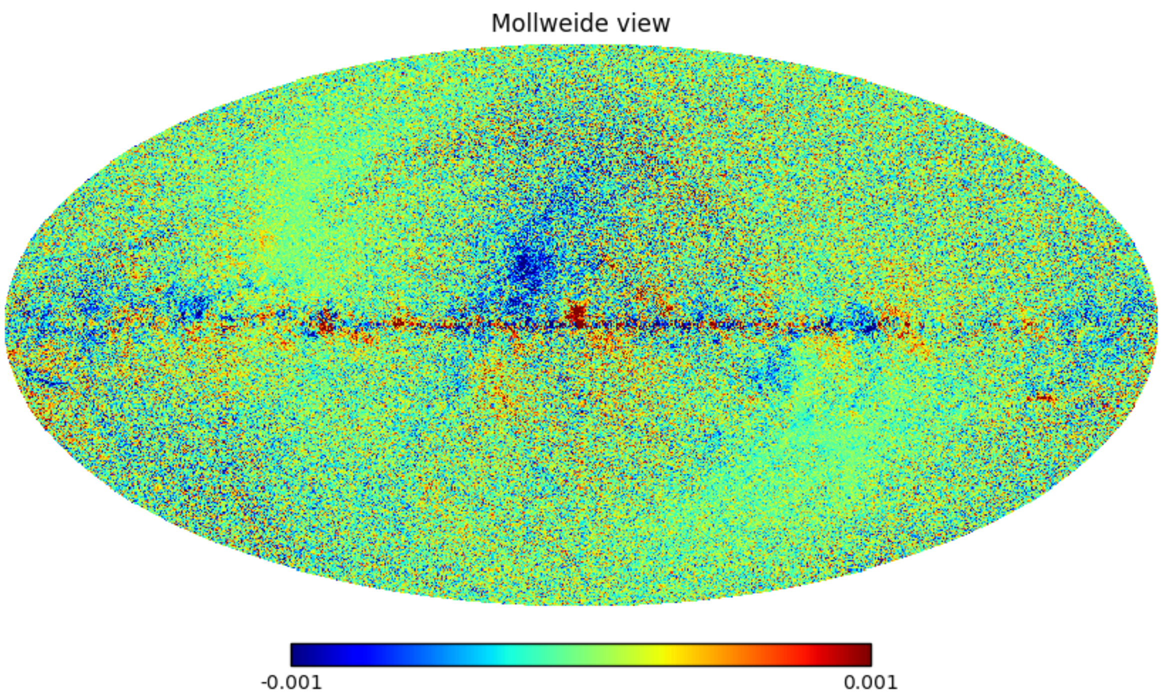
2. Data

Current attempts to measure tensor-to-scalar ratio (like BICEP2 and Keck Array, [2]) focus on the power spectrum of B-mode polarization at angular scales of a few degrees but galactic foregrounds (especially dust) will bias attempts to measure r. Foregrounds can be distinguished from the CMB based on their electromagnetic spectrum since dust is brighter at high frequencies, so multi-frequency data sets are needed to determine the source of observed B-mode signals [1].
Planck mapped the whole sky in seven polarization-sensitive frequency bands. The highest polarization-sensitive band is 353 GHz, which is dominated by dust signal. They investigated dust polarization in sky patches at high Galactic latitude with sizes comparable to those surveyed by ground based CMB experiments [3]. They also derived statistical properties of dust polarization from the angular power spectrum, characterizing the shape of the spectra and their amplitude with respect to both the observing frequency and the sky region over which they are computed. Planck results show that subtraction of polarized dust emission will be essential for detecting primordial B-modes at a level of $r = 0.1$ or below. The current best constraint on r is $r < 0.09$ at 95% confidence from reference [2] and this result uses Planck data for dust subtraction.

The Planck 353 GHz polarization maps help provide information about these regions. Using these maps we can classify which regions are the cleanest and what level of foreground contamination to expect. We consider three data split maps: (i) detector-set maps, where the detectors at a given frequency are divided into two groups, (ii) yearly maps, where the data from the first and second years of observations are used for the two maps, and (iii) half-ring maps, where the data from each pointing period is divided in halves. Planck results show that the accuracy of our current understanding of the polarized dust is limited by noise in the Planck 353 GHz maps.



These figures use a Mollweide projection to depict the entire sky (surface of a 2-sphere) as a flat two-dimensional image. This map shows the Q polarization for detector split 1 from [5]



This map shows the U polarization in detector split 1

We used three data split maps
(i) detector-set maps, where the detectors at a given frequency are divided into two groups,
(ii) yearly maps, where the data from the first and second years of observations are used for the two maps, and
(iii) half-ring maps, where the data from each pointing period is divided in halves.

We then classified which regions are the cleanest and what level of foreground contamination to expect. These have the same signal, so every time we split the data we will get different noises.

3. Analysis

Cross spectrum analysis

Our analysis is an extension of what was done in Ref [3] (The data points from the Ref [3] dust amplitude map are correlated due to selection of overlapping fields. By studying how the map depends on patch shape and patch selection, we did an auto spectrum analysis using Planck noise simulations to de-bias the result. We assessed the correlation and dependence on path shape and selection and produce an improved version of the Planck map of dust polarization amplitude shown in Figure 8 of Ref [3] by characterizing the b mode amplitude from the dust in the galactic regions.

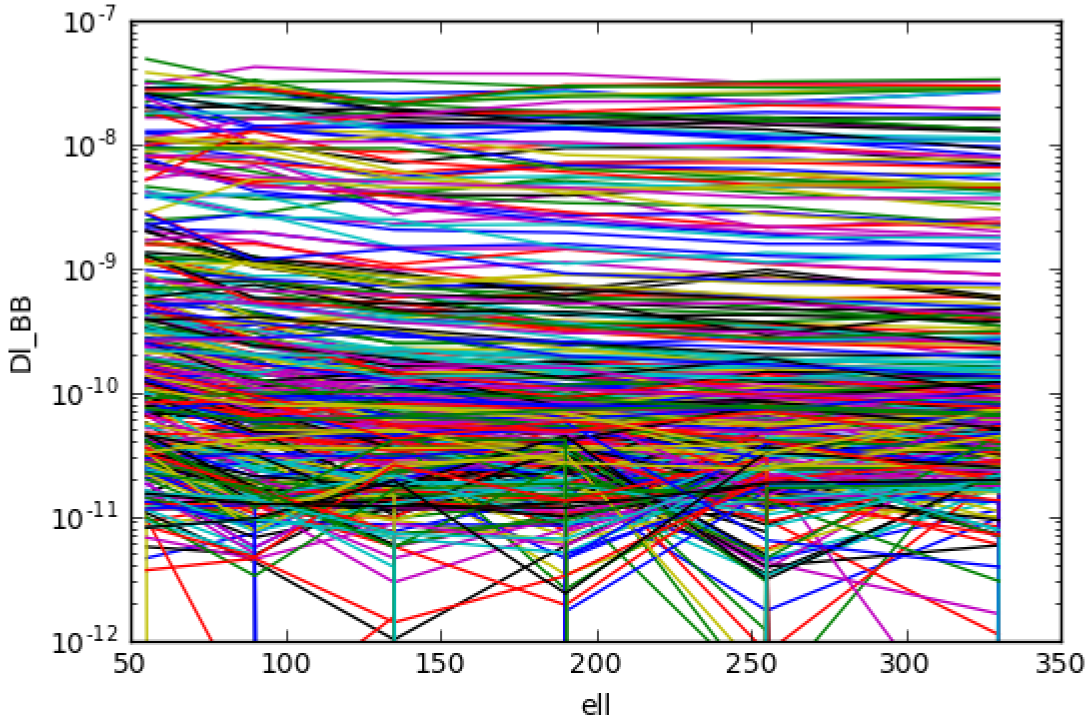


Figure 2. This the raw data of the power spectra on a log scale.

We calculated the mean and Standard deviation for these power spectra. Here we can see all the signal from dust clearly. Using python to create these maps and calculated uncertainty using 3 different data splits. Everytime we split the data, we produced different noise but the signal is the same since they are correlated. Our goal was to be able to include a better understanding of this uncertainty from instrumental noise in the new map.
This equation shows how we completely remove the noise from the equation.

Let's say we have m1 and m2, m1 = Bs + Bn1 and m2 = Bs + Bn2

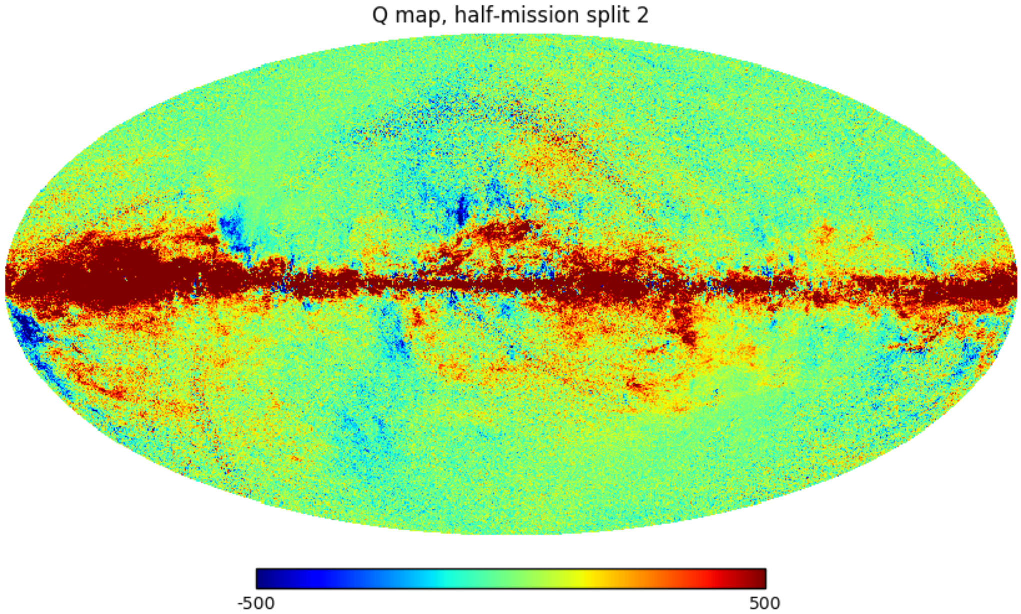
<m1 X m2> where l belongs to B

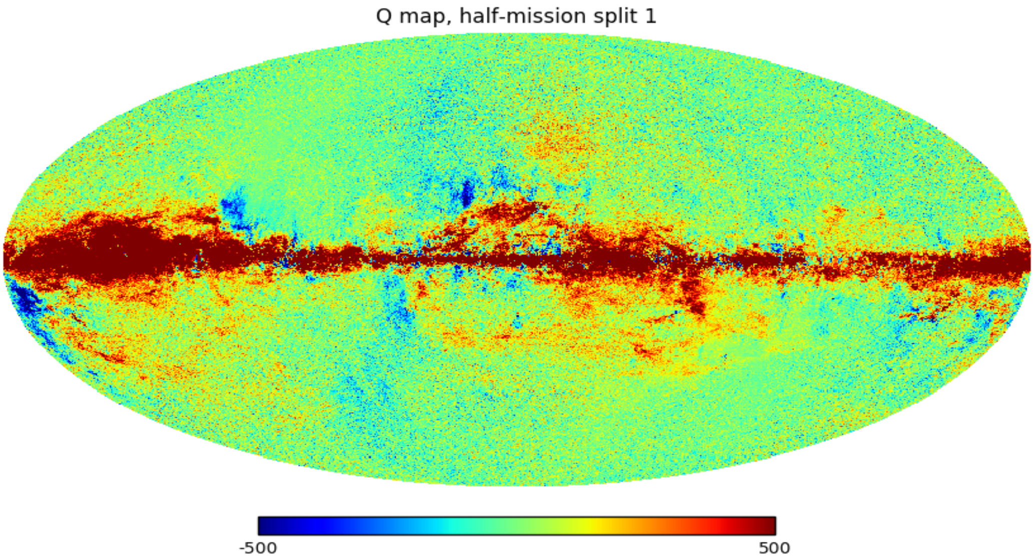
= <Bs x Bs> + <Bs X Bn2> + <Bn1 X Bs> + <Bn1 X Bn2>

= < Bs X Bs>

Planck measures Q/U intensities for linear polarization and the Cross spectrum analysis tells us the b-mode power in the little fields. By analyzing the B mode angular power spectrum, we determined the equivalent tensor-to- scalar ratio r due to dust. R is the dust power in terms of amplitude of gravitational waves. We did not choose the regions near the galactic plane since it is high in dust.

Q map, half-mission split 2





These are Q polarization maps from detector split 1 and 2 which we analyzed for b modes.

The Planck 353 GHz maps, were downloaded from the Planck Legacy Archive [5].We calculated the simple dust estimator by summing the first three ell bins. Three data splits give three different versions of this estimator. The mean vs standard deviation of the dust estimators, fit this to the model we were using. Once we had this model for the standard deviation of the dust estimator, we can use it to assign an uncertainty to the dust estimate that scales with the mean level of the dust. This model allowed us to calculate, for each patch, the probability that the dust level is above a given threshold. Ell bins represent different ranges of angular scales. The first ell bin ranges from ell=40, which is approximately 5 degrees, to ell=70, which is approximately 3 degrees. Second ell bin ranges from ell=70 to ell=100, which is about 2 degrees. The angular scale in degrees is approximately 180/ell

Weighted combination

We had a theoretical spectrum available, which had B modes in gravitational waves. This particular file is for a theory with tensor-to-scalar ratio r = 0.1. This means that the initial conditions of the universe, immediately after inflation, had 10 times as much power in scalar fluctuations (density perturbations) as in tensor fluctuations (gravitational waves). The average level of spectra in each ell bins (different ranges of angular scales) was calculated and used the values of Nb in the formula Wb = CB/ NB^2 and then calculated the weighted average, for all of the 350 spectra.

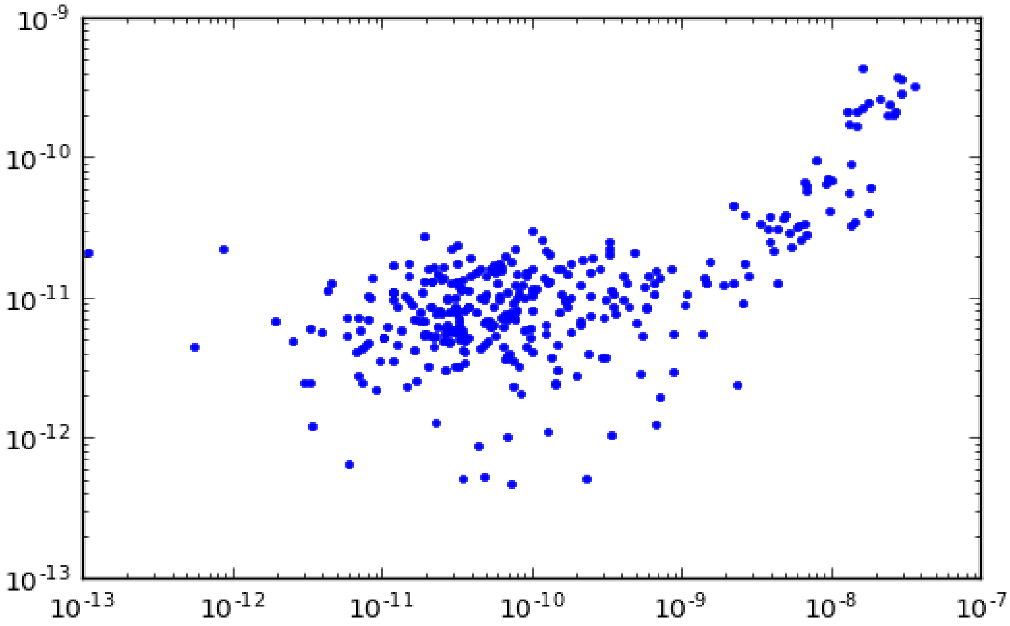
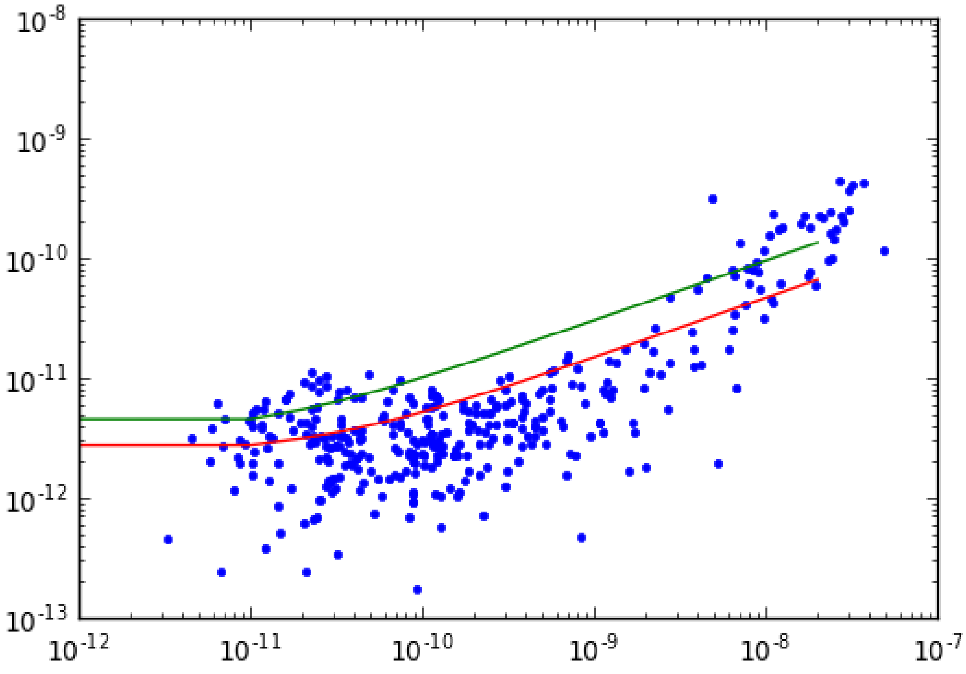


Figure: Mean Vs Standard deviation plot.

X axis is the mean for all 350 fields. Y axis is the standard deviations, it tells us how well the estimates agreed. The values that are at high means have higher dust so we picked the regions with low means and low standard deviations for our observation. We determined the noise levels in each ell bin by averaging over fields with very low dust signal.

C. Error analysis

We calculated chi^2 distribution for each ell bin and used a model to fit the data. We made sure to keep out of the negative regions. We set up a minimization algorithm to find the best fit for each bins.



This is the best fit model for bin 0, which is the first bin.

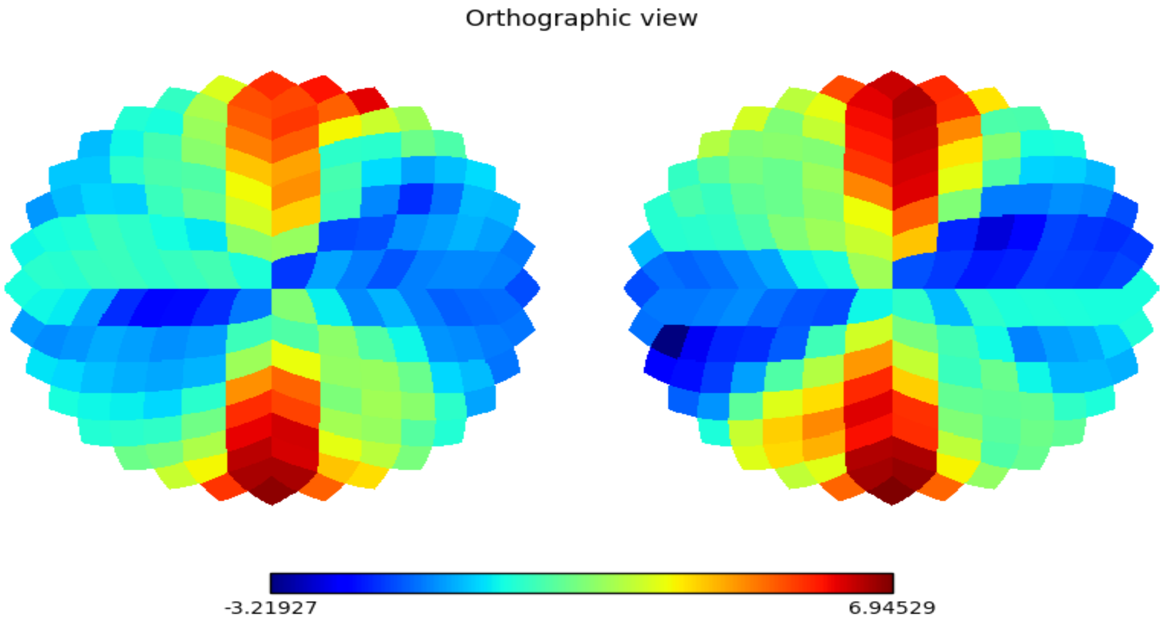
Since we were primarily interested in the low-dust / noise-dominated regions, we simply select those fields based on their mean bandpower value by making a cut on the mean signal level and then taking the average of the standard deviations for that sample. This gave us an error estimate for each ell bin that can be used to combine the six ell bins into a single estimator of the dust level. The values for uncertainty for each elle bin are noted in the table below.

Bin 0	3.4977225187739937e-12
Bin 1	4.2093370481025045e-12
Bin 2	6.5144949381683176e-12
Bin 3	9.0002568596458025e-12
Bin 4	1.3407661266252822e-11
Bin 5	1.6968310878412529e-11

R is the dust power in terms of amplitude of gravitational waves. After calculating the average level of spectra in each ell bins, which go from 40-70 , 70-100, 100-130, 130-170,170-200, 200-230 respectively. We use the values of Nb that were found and use in the formula Wb = CB/ NB^2 that is a weighted sum of the band powers. We calculated equivalent dust power by using a weighted combination of bandpowers for all 350 spectra.

4. Results

We rescaled our dust map from 353 GHz to 150 GHz (BICEP2 observing frequency), by multiplying it by a factor of 0.001557. This is because the dust is much less bright at 150 GHz, which is very helpful for our observation.



This is the final produced map. Orthographic view is the view of the north and south poles. The calculated dust power at 150 GHz is in terms of "r", which is the amplitude of a gravitational wave signal in the CMB. There is a large contrast between the brightest and faintest regions of this map.

For example, on the scale the dark blue pixel has log(dust power) = -3.219 which means that it corresponds to r ~ 0.04. And the dark red pixels on the end of the scale have log(dust power) = +6.9, which means that they correspond to r ~ 1000.

References

[1] BICEP2 / Keck / Planck joint analysis paper The BICEP2/Keck and Planck Collaborations, 2015, Phys. Rev. Lett., 114, 101301

[2] BICEP2 / Keck 2014 results (our most recent results paper) The Keck Array and BICEP2 Collaborations, 2016, Phys. Rev. Lett., 116, 031302\

[3] Planck intermediate results 30 (PIP XXX) Planck Collaboration, 2016, Astron. Astrophys., 586, A133

[4] Planck Collaboration, “Planck 2015 results. VIII. High Frequency Instrument data processing: Calibration and maps”, Astron. Astrophys., 594, A8 (2016).

[5] Planck Legacy Archive, http://www.cosmos.esa.int/web/planck/pla

[6] CMB Polarization.” *CMB Polarization*, Colin Bischoff, www.cfa.harvard.edu/~cbischoff/cmb/.

[7]“B-Modes.” *CMB Introduction*, W. Hu, background.uchicago.edu/~whu/intermediate/Polarization/polar5.html.