Caltech Observational Cosmology Group

Characterization of 260 GHz TES Bolometers for Detection of B-mode Polarization from the CMB

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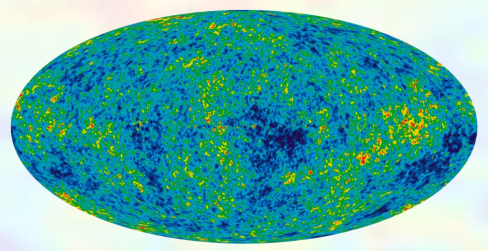
Background

Modern Cosmology tells us a great deal about the history of the universe:

- The universe has been expanding for approximately 13. 8 billion years.
- The Cosmic Microwave Background (CMB) was formed at the epoch of recombination (~380,000 years after the Big Bang), when protons, electrons, and neutrons combined to form neutral atomic gases.
- The early universe was extremely homogenous (as can be seen by the CMB temp. map), given by a configuration of very low entropy. This explains why the universe still has a large amount of order despite the 2nd law of thermodynamics.
- Stars and galaxies began to form during the epoch of reionization, and the light produced from these stars reionized the universe's neutral gas atoms.
- The universe is currently expanding at an accelerating rate due to Dark Energy

There is still much that is unknown about the universe however. For instance:

- **Flatness Problem:** How is the universe so homogenous when different regions seem too far away from each other to have ever interacted?
- **Horizon Problem:** The universe appears to be flat, which corresponds to an unstable equilibrium solution for the matter and energy density of the universe. Why is it that our universe's density is so close to this very specific value?
- **Magnetic Monopole Problem:** Why have magnetic monopoles never been observed?



Temperature Map of the CMB

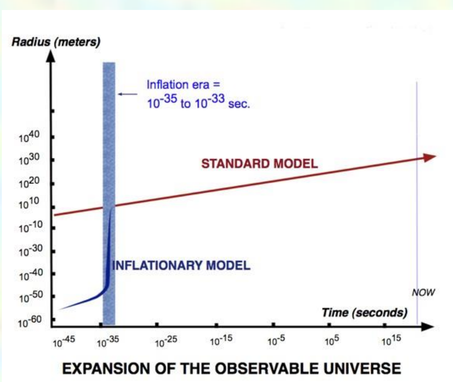
The CMB is largely uniform, but small fluctuations in temperature do exist. While the CMB temperature is ~2.723 K everywhere, the entire temperature range in this image is less than 400 μK.

Inflation

The three problems above can all be solved with Cosmic Inflation. Inflation is a model which attempts to explain the expansion of the universe as early as 10^{-35} seconds after the Big Bang. It is characterized by a period of rapid expansion caused by a second order phase transition, called Inflaton. Inflation is capable of explaining a large number of observed phenomena, making it an attractive theory, but there is currently very little evidence in direct support of inflation. Such evidence would add credibility to the theory and also provide estimates for characteristic model parameters.

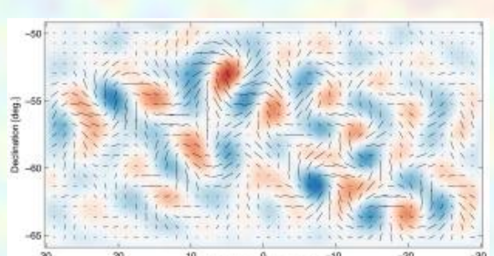
Unfortunately, the universe was opaque to electromagnetic waves prior to recombination, since photons were constantly being scattered by unpaired charged particles. As a result, we cannot see what the universe looked like at times earlier than 380,000 years after the Big Bang, because that information is simply not encoded in light. Gravitational waves only interact weakly with matter though, so primordial gravity waves should contain a history of the universe well before recombination. If Inflation did occur, then it theoretically would have generated gravitational waves that (in principle) we will be able to detect.

While we don't yet have the capability to search for this signal directly, we can instead look for evidence of such waves in the form of structures left behind in the Cosmic Microwave Background: The BICEP (Background Imaging of Cosmic Extragalactic Polarization) and Keck Array experiments aim to provide direct evidence supporting the theory of Inflation by using Transition Edge Sensor (TES) bolometers to detect B-mode polarization from the CMB.



Effect of Inflation on the Expansion Rate of the Universe

Because of the brief period of exponential expansion, Inflation would allow for the universe to be much more densely packed at 10^{-35}s. This could solve the Horizon Problem by giving different regions of the universe more time to interact and become homogenous.



BICEP2 Polarization Map

Polarization vector field constructed from BICEP2 data. The red and blue regions represent positive and negative B-modes, respectively. Unfortunately, it now appears that this signal was from foreground dust, and not the CMB.

B-Mode Polarization

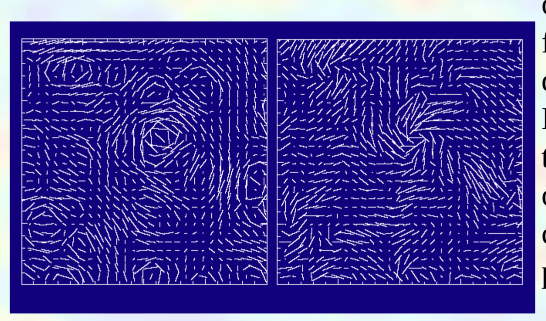
Photons from the CMB are detected by pairs of orthogonally polarized TES bolometers. The signal can be described by the Stokes parameters I, Q, U, and V:

$$I = \langle a_x^2\rangle + \langle a_y^2\rangle, \qquad Q = \langle a_x^2\rangle - \langle a_y^2\rangle$$

$$U = 2a_xa_y\cos(\theta_x - \theta_y), \qquad V = 2a_xa_y\cos(\theta_x - \theta_y)$$

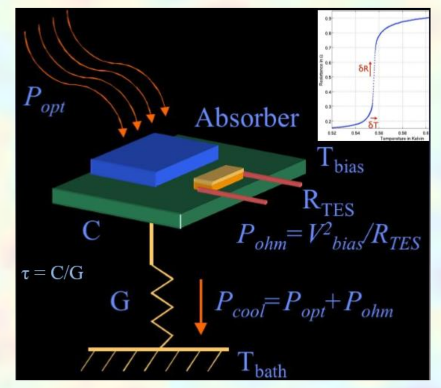
By recording these quantities over a region of the sky, it is possible to construct a vector field describing the CMB in that region (see BICEP2 Polarization Map). In order to search for large-scale structures on the surface, it is logical to describe this field in terms of its global properties. The polarization vector field is therefore described by linear combinations of the orthogonal basis formed from E-modes and B-modes (see E-Modes and B-Modes figure), which are non-local in nature. While these modes are actually computed by performing a spherical harmonics transform on the stokes parameter measurements, E-modes are analogous to the curl-free component of the vector field, and B-modes are analogous to the divergence-free portion.

Theoretical models of inflation predict that the generated gravitational waves will imprint the CMB with both E-modes and B-modes. In fact, E-modes from the CMB have already been detected by earlier experiments, since the E-mode signal is several orders of magnitude stronger. This is not sufficient evidence of inflation however, because there are other known causes of CMB E-modes, such as mass and energy density fluctuations in the early universe. Conversely, there are no other predicted causes for B-modes in the CMB, so detection of a non-zero B-mode component for the CMB polarization vector field would provide a strong argument in favor of Cosmic Inflation.



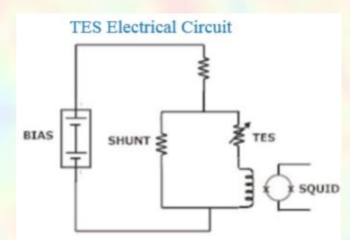
Example E-mode and B-mode Vector Fields

The left vector field is composed entirely from a superposition of E-modes. The right vector field is made with contributions only from B-modes.



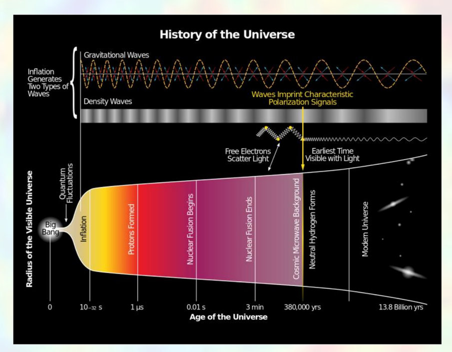
TES Diagram

Graph in upper left corner shows temperature dependence of a resistor around its phase change. Rest of diagram summarizes electrical and thermal connections to the sensor.



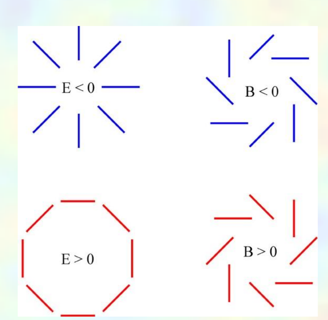
TES Circuit

Wiring schematic for a TES bolometer. Not shown is the entire chain of SQUIDs, which feedback on each other and keep the system in equilibrium.



Timeline of the Universe

Inflation would have caused a rapid expansion of the universe for the first 10^{-32} s after the big bang. The figure also shows primordial gravitational waves from Inflation, and how they would effect CMB polarization patterns.



E-Modes and B-Modes

Examples of fields composed of purely E-mode (left half), or purely B-mode. Though these modes are defined by a transformation of the Stokes parameters, E-modes can be viewed as curl-free, while B-modes are divergence-free.

Measuring Polarization with Transition Edge Sensors

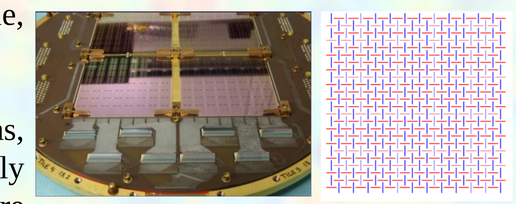
The B-mode polarization signal from the CMB — if present at all — will be very faint. As such, identifying B-modes requires instruments with a very high level of sensitivity.

Transition Edge Sensors meet this sensitivity requirement by taking advantage of a material's superconducting phase transition. At temperatures well below the critical temperature, the material is superconducting and has practically zero resistance. At temperatures well above the critical temperature, the material will have a more ordinary temperature dependence for its resistance. Within the transition range, however, the R vs. T curve is approximately a line of very large slope. By voltage biasing the TES such that its temperature lies within the transition range (see TES Diagram), we can determine the external power input to the detector by measuring its change in resistance.

The TES is placed in parallel with a shunt resistor. When the detector is heated, the TES resistance increases and its current decreases. This current drop is measured by a superconducting quantum interference device (SQUID) that is coupled to an inductor placed in series with the TES. (See TES Circuit)

BICEP and the Keck Array use TES bolometers made from Titanium and Aluminum in order to observe the CMB. Aluminum transitions at a higher temperature, so this is the curve used in lab to test various properties of the detectors. Titanium is used to collect actual polarization data at the south pole, because the lower transition temperature improves its sensitivity.

Each TES bolometer receives power by a beam-forming array of slot antennas, which collect light from the CMB. The TES bolometer is weakly thermally coupled to the 300mK thermal bath, and the sensitivity improves with the square root of the weakness of that thermal link. Detectors are arranged in an array of orthogonally polarized antenna pairs (see Detector Array), allowing for independent measurement of each direction of polarization.



Detector Array

Left: Picture of focal plane. The quadrants are made of a grid of slot array antennas, each of which is thermally coupled to its own TES.

Right: Pattern of slot array antenna orientation. Antennas are arranged like this to create co-centered, orthogonal detector pairs.

Obstacles

In 2014, BICEP2 announced that it had detected B-Mode polarization in the CMB. Unfortunately, further analysis suggested that the signal was actually due to polarized emission from galactic dust. While B-modes in the CMB can only be caused by gravitational waves from Inflation, there are a number of sources for B-mode polarization located within the foreground.

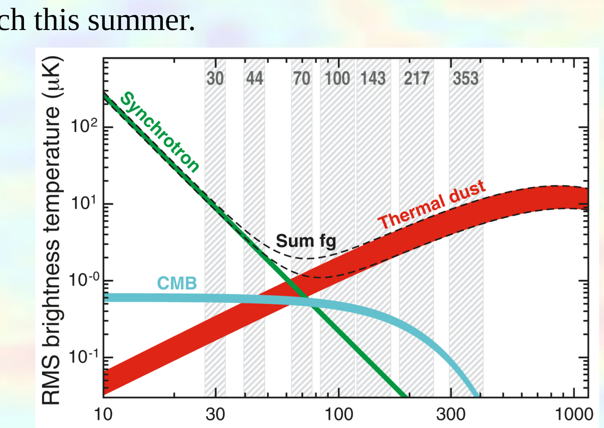
Galactic dust and Synchrotron emission are the two primary sources of B-mode noise within the foreground. Furthermore, the noise from these sources is larger than the signal we actually hope to measure. For frequencies below ~80 GHz, the B-modes produced by synchrotron emission are stronger than those from the CMB; for frequencies above ~60 GHz, B-modes produced by galactic dust are stronger than those from the CMB.

Solution

In order to avoid false positives from foreground sources such as dust and synchrotrons, future CMB polarization surveys will need to record polarization data for several different frequency ranges. Because the frequency dependence of the CMB is very different from that of dust or synchrotrons (see Frequency Dependence plot), sampling the aggregate signal at a variety of frequencies should make it possible to resolve the signal into its individual components and search for B-mode polarization from the CMB alone.

The frequency dependence for galactic dust and synchrotrons has already been thoroughly recorded by earlier experiments such as Planck. The only parameters that we need to estimate with a regression are the coefficients for these two functions. Once we have that, we can subtract both functions from our composite signal and see what remains.

The BICEP and Keck Arrays are currently probing the CMB with detectors designed to operate at 95, 150, and 230 GHz. New detectors with a frequency band centered at 260 GHz have already been designed and fabricated, but they must first be characterized in the lab before they can be sent to the South Pole for use in CMB polarization measurements. Characterizing this new array was one of the primary goals of my research this summer.



Frequency Dependence

Signal intensity as a function of frequency for the CMB, both sources of foreground error, and the composite signal. By sampling the total signal at enough frequencies, we hope to isolate the CMB B-mode intensity function from the noise.

Testing 260 GHz Detectors

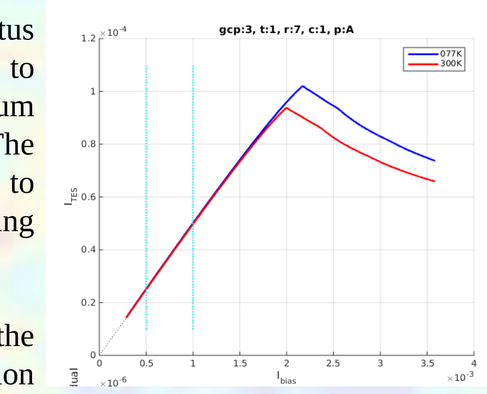
To fully characterize the 260 GHz detectors, we measured their optical efficiency, spectral response, and angular response. Data were collected for all these tests, but my analysis work has focused on the angular response. However, I will briefly describe the methodology for all tests, for reference.

Optical Efficiency

To measure the optical efficiency, a black body is placed above the apparatus window at room temperature (~300K), which causes each TES bolometer to receive an input power as described by the source's black body spectrum within the frequency range where the detectors are responsive. The voltagebias for each detector is slowly ramped up, causing the detectors to heat up until the Aluminum portion of the TES goes from superconducting into its transition phase.

Next, the source is cooled by filling it with liquid Nitrogen (~77K), and the voltage bias is once again ramped up until the TES's reach their transition phases. Because the source is cooler the second time, we expect a larger power bias to be necessary for the aluminum to begin transitioning (see TES Current Plot).

We can now use these measurements to compute an experimental value for dP/dT for each detector in the array. These estimates will then be compared to the theoretical value of dP/dT between the temperatures 300K and 77K, and we can use this to determine the optical efficiency of each detector as the percent of total photons in our frequency band that were detected by the bolometers. An average optical efficiency between 30 and 40 percent is generally considered sufficient. If this efficiency level is not reached, tuning the SQUID biasing may improve detector performance.



TES Current

Plot showing current through TES as a function of the bias current for a blackbody source at 300K (red), and at 77K (blue). Until the aluminum reaches its transition point, the TES current scales linearly with the bias current. Once it has been heated to this point, however, the TES resistance will increase, and so its current will fall. As seen in the plot, the detector requires a larger bias current to reach its transition phase at 77K.

Spectral Response

Spectral response is measured by operating a Martin-Puplett interferometer above the apparatus window. The Martin-Puplett interferometer has a small chamber filled with liquid Nitrogen, which acts as a black body source. The randomly polarized light from this source reaches a linear polarizer, which splits the beam into two orthogonally polarized columns. One beam is reflected at a fixed distance from the polarizer. The other beam is reflected by a motorized mirror, which travels at a constant velocity relative to the polarizer for the duration of the data acquisition run. Both beams are then reflected down to the focal plane, where they converge.

The interference between the two beams at the location of the detectors is determined by the instantaneous path length and the wavelength of the light rays that are interfering. The resulting time-stream of data is known as an interferogram. The interferogram for each bolometer is then transformed into a power vs. frequency spectrum in later analysis. These spectra will be used to compute the bandwidth for each sensor.

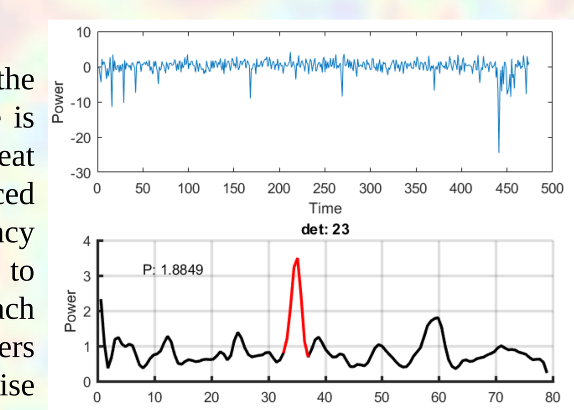
Martin Puplett Interferometer

Martin Puplett interferometer used to collect spectral response data for the 260 GHz detectors. Starting from the top left, light from the source is collimated, reflected towards the polarizing lens, and then split into two polarized beams. The beam that reflected off the polarizing lens is then reflected by the moving mirror. The other beam is reflected by the bottom stationary mirror.

Angular Response

Angular response describes the dependence of detector sensitivity on the angle that the source makes with the optical axis. Angular response is characterized with a process called near-field beam mapping. A heat source capable of being moved vertically and horizontally is placed above the array window. The heat source is given a signature frequency by optically chopping it (We set it to ~35 Hz). The source is moved to 1600 different positions on a 40 x 40 grid above the window. At each position, the source is held for 3 seconds while the TES bolometers record a time stream of the input power. There are many sources of noise that affect the power received by each detector, but the heat source signal can be identified by isolating the portion of the signal with the signature frequency (see Time Stream and Power Spectrum).

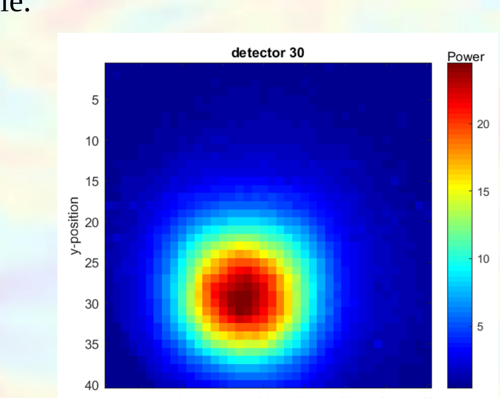
Once all 1600 runs are complete, we can construct a 40 x 40 pixel intensity map for each detector in the array (see Beam Map). For a well-behaved bolometer, the intensity is greatest when the source is directly above the detector, and then falls off radially as the off-axis angle is increased. Because the detectors are arranged in orthogonally polarized pairs, it is desirable for a pair of detectors to have very similar angular responses. If this is not the case, then it is possible for temperature to "leak" into a polarization measurement, since one polarization detector will be more sensitive than the other at specific angle.



Time Stream and Power Spectrum

The top plot shows the power recorded by detector 23 as a function of time (units are not seconds; they are related to the detector sampling rate). It is very difficult to determine identify the heat source in the time stream.

The bottom plot shows the same data after it was transformed into a power spectrum. Because we chopped the heater at ~35 Hz, we know that the red portion of the spectrum is from the source, so we estimate the integral of the corresponding range as the total power measured by the detector at the given source position.



Beam Map

By estimating the power for every source position, we can construct a 40x40 pixel intensity map for each detector. The map for detector 30 looks circular and very clean, which is promising, though we won't know how good it will be for measurement until we fit the map and compare its parameter estimates to those of the detector it's paired to.