# Joint Analysis of CMB Datasets in the Era of BICEP2, the Keck Array, and Planck


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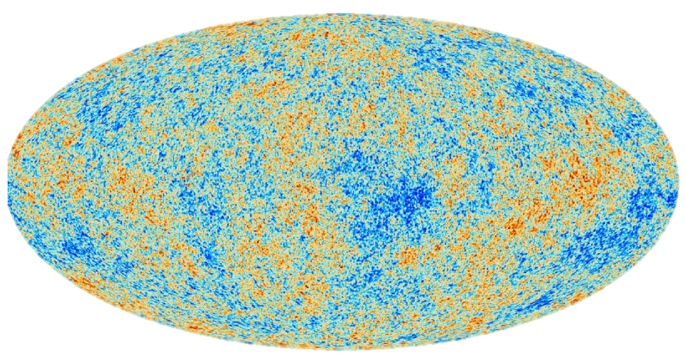
## STATUS OF THE FIELD: A WIDE VARIETY OF CMB EXPERIMENTS

In the past two decades, the study of the cosmic microwave background (CMB) has provided astonishing insights into the Universe and has helped establish the standard cosmological model. The sensitivity of CMB experiments has increased by orders of magnitude and E-mode polarization has been conclusively detected. The detection of B-mode polarization from galactic foregrounds, gravitational lensing of E-mode polarization, or gravitational waves generated by inflation is an ongoing endeavor. A wide range of experiments, from ground-based instruments like BICEP2 and the Keck Array to space satellites like Planck continue to add to our store of knowledge about the CMB.



**ABOVE:** All sky map produced by Planck, with foregrounds removed. Image courtesy of ESA and the Planck Collaboration.

With so many CMB experiments measuring overlapping regions of the sky, the ability to carry out rigorous joint analysis of these datasets is becoming increasingly important. Using data from multiple surveys allows progress on a number of fronts, including:

- comparison analyses to verify signals "on the sky" and quantify the instrumental noise
- foreground separation
- optimal combined BB power spectrum or parameter constraints
- lensing / delensing

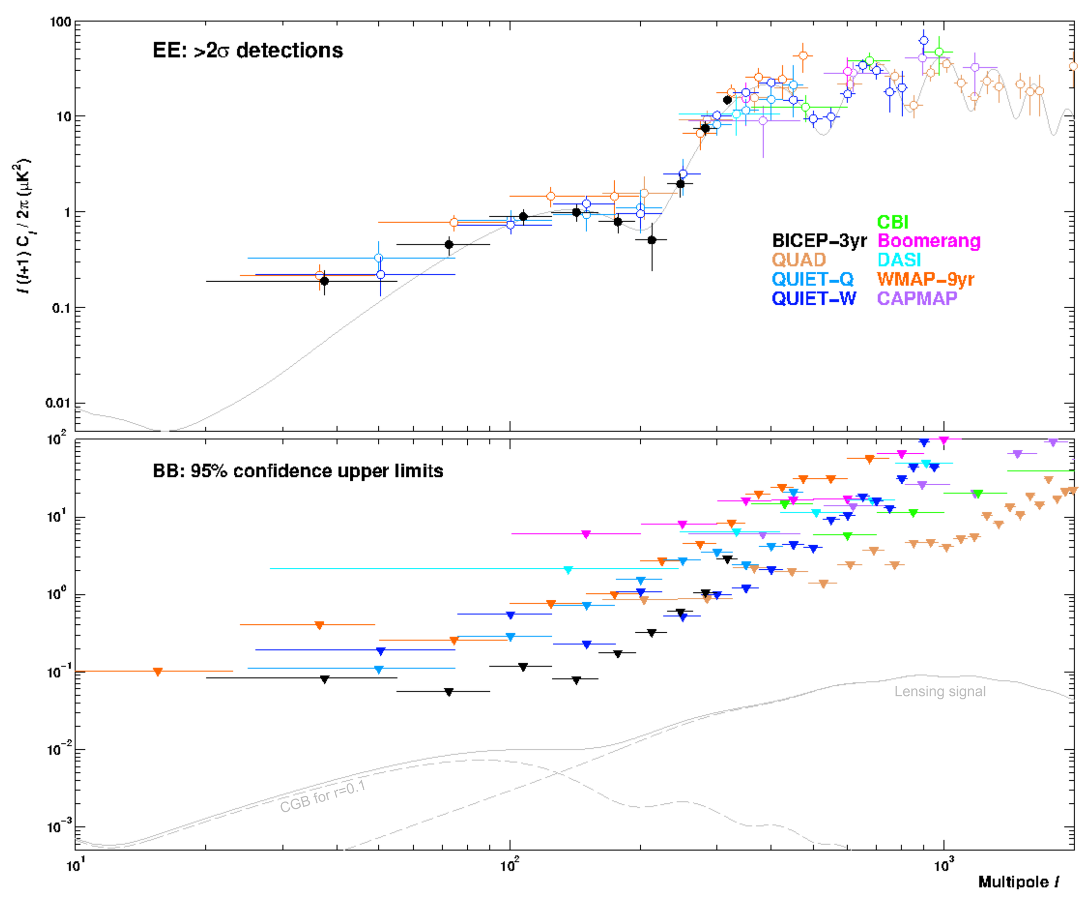
I am currently working to implement better ways to combine data from multiple CMB experiments in order to attack these problems.

## BICEP2/KECK ARRAY SCIENCE: OPTIMIZED FOR B-MODE

**BICEP2** and the **KECK ARRAY** are a series of ground-based CMB polarization experiments designed to detect primordial B-mode polarization originating from an inflationary gravitational-wave background. BICEP2 operated from 2009-2012 and the Keck Array began operations with three receivers in late 2010 and added an additional two in late 2011. It is currently in its third year of data collection. Both experiments are located at the South Pole Station, Antarctica.

**SCIENCE GOALS:**

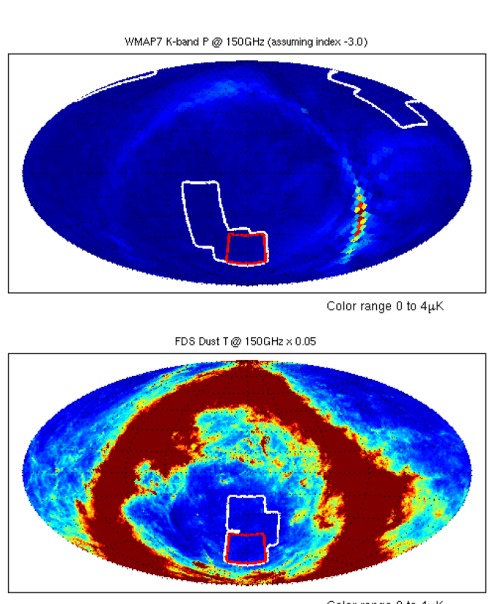
- Detect B-modes for r > 0.02 with 95% confidence
- Characterize the Galactic foregrounds in the cleanest field on the sky
- Detect gravitational lensing of CMB polarization on degree scales

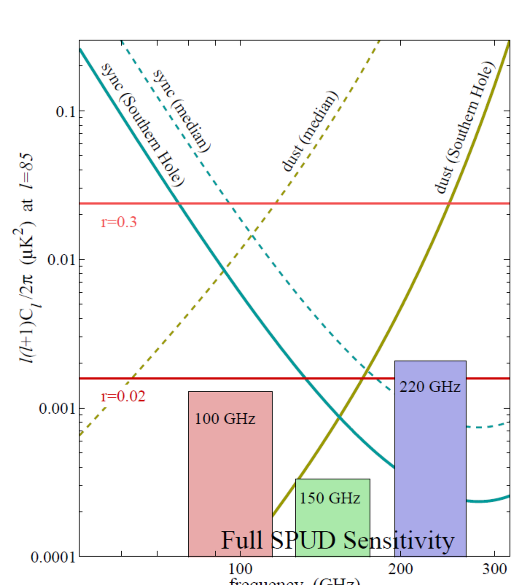



**RIGHT:** The expected power spectrum of the E-mode and B-mode polarization of the CMB (solid lines), for a Cosmic Gravitational-Wave Background (CGB) with a tensor to scalar ratio of r=0.1. Measurements (round dots) and upper limits (triangles) from pre-Keck Array experiments are also shown. Only upper limits have been set on the B-mode polarization spectrum, with the best limits coming from the BICEP and QUAD telescopes at the South Pole.

## SOUTH POLE, ANTARCTICA

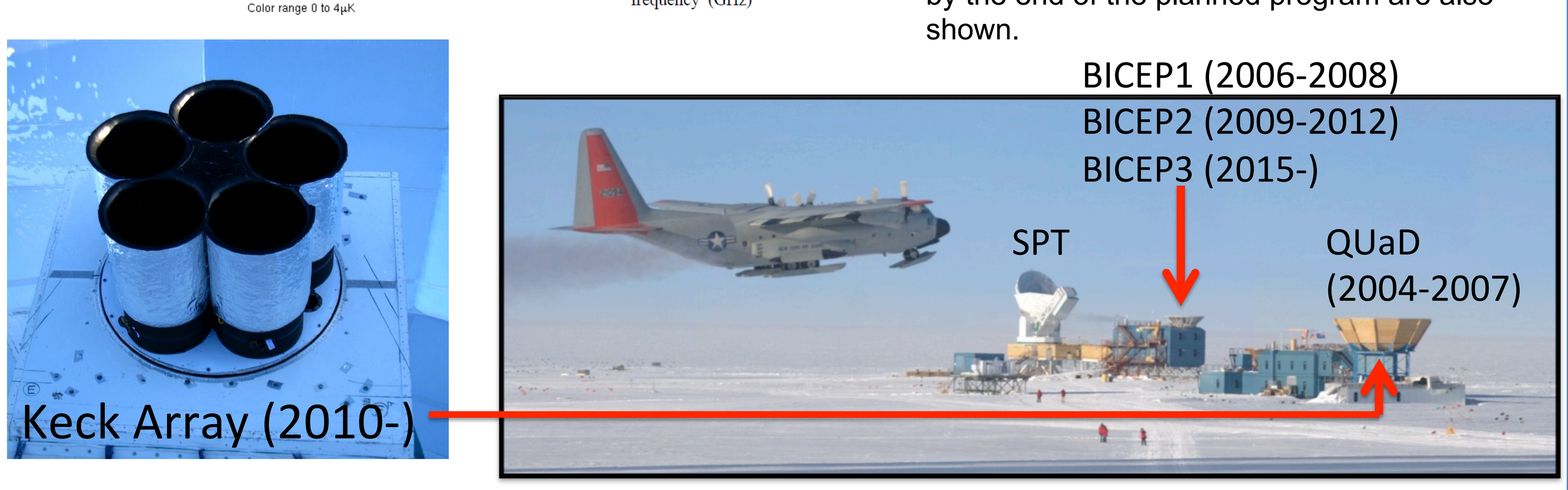
- Extremely stable, dry atmosphere at high altitude (9,300 feet above sea level)
- 24hr visibility of target field for deep integration
- Minimize foregrounds in Southern Hole



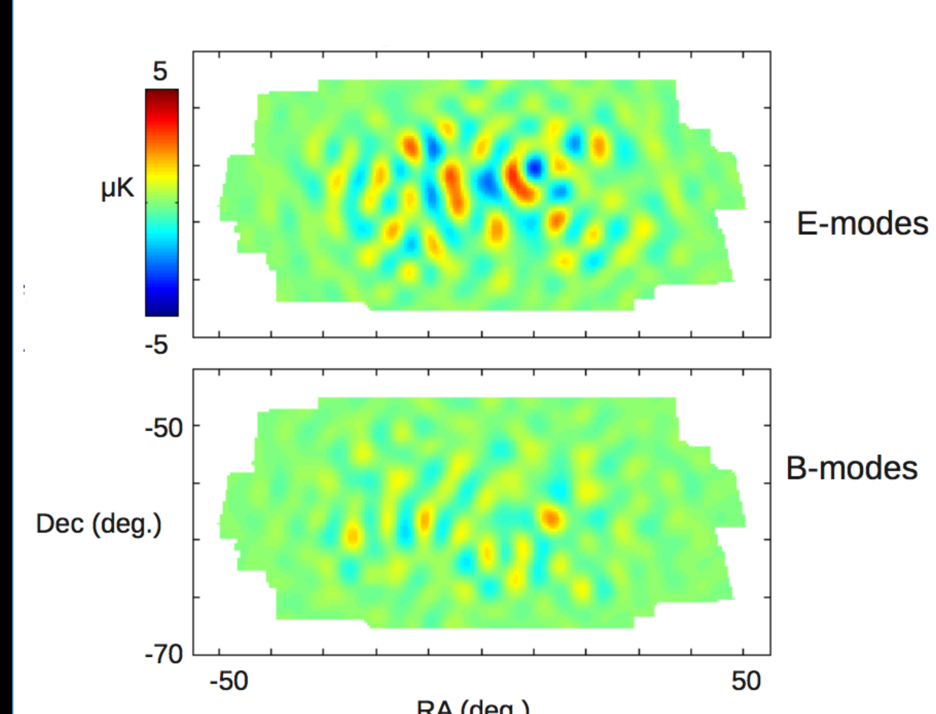


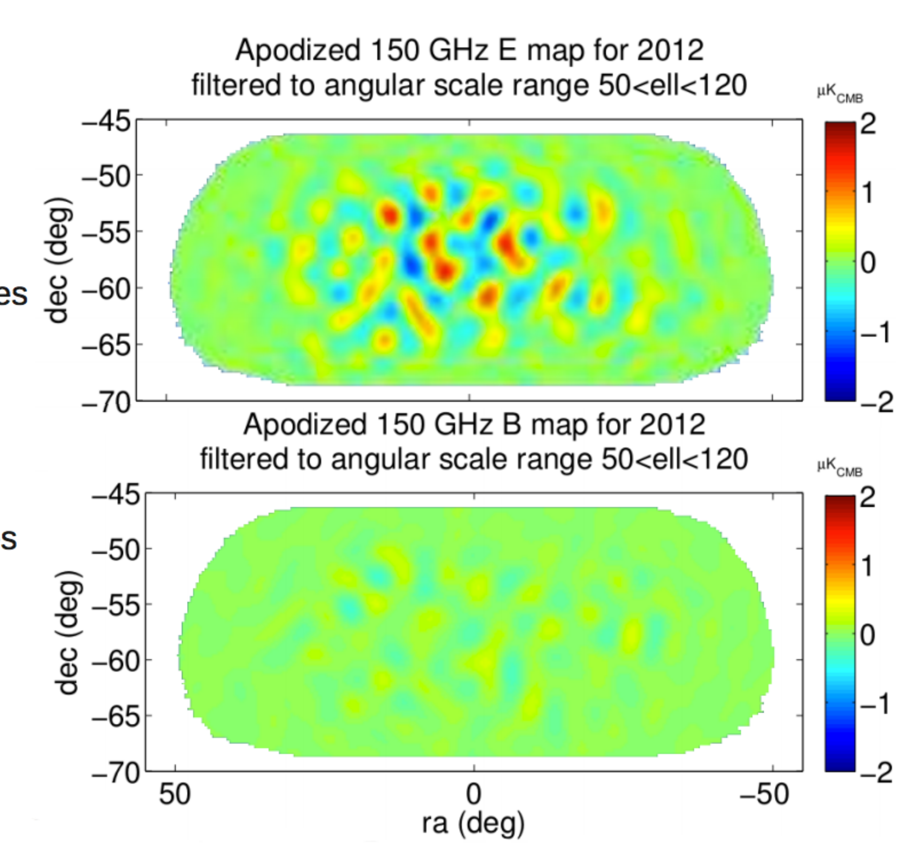

**FAR LEFT:** All-sky maps of the expected levels of polarized foregrounds at 150GHz. The upper figure is a map of the WMAP K-band polarized intensity map extrapolated to 150GHz assuming a spectral index of -3. The lower figure shows the FDS brightness model multiplied by an assumed dust polarization fraction of 5%. The SPUD/Keck Array field is outlined in red. The white outline is the aggregate boundary of all trial fields found to be as good, or better.

**LEFT:** Estimates of the frequency spectrum of the dominant Galactic foregrounds. The dust and synchrotron emission in the Southern Hole (solid lines) is much less than the median foreground emission over the sky (dashed lines). The sensitivity levels that will be reached by the end of the planned program are also shown.




## BICEP/KECK ARRAY POLARIZATION MAPS




**LEFT:** BICEP1 3-year 150-GHz polarization sensitivity maps: 500 nK-deg. for an effective area of 203 square degrees. The B-mode signal is consistent with noise and sets a limit of r < 0.7 with 95% confidence. Maps generated by Colin Bischoff.

**RIGHT:** Keck Array 1-year 150-GHz polarization sensitivity maps: 170 nK-deg. for an effective area of 397 square degrees. These 1-year Keck maps have already reached the same sensitivity as maps generated from 2 years of BICEP2 data. Maps generated by Sarah Kernasovskiy.

## MATRIX-BASED DATASET COMPARISONS

Given the significance of a B-mode detection and the intense interest and competition in this field, any claim (limit or detection) needs to be subject to verification by reanalysis and repeated observation. The BICEP/Keck Array collaboration uses a full suite of statistical tools to check the consistency of the datasets from these instruments, including jackknives and noise simulations. Another approach is to encode the noise and instrumental properties of any experiment in a matrix, so that the observations collected by the experiment are a product of this matrix and the true sky. This methodology has been rigorously studied by Knox et al. (1998) and Tegmark (1999), among others. In contrast to complete sets of simulations, whose large size makes sharing difficult, these matrices could easily form part of a public data release of the BICEP2/Keck array sky maps, allowing other groups to make use of our data and independently confirm or refute our results.

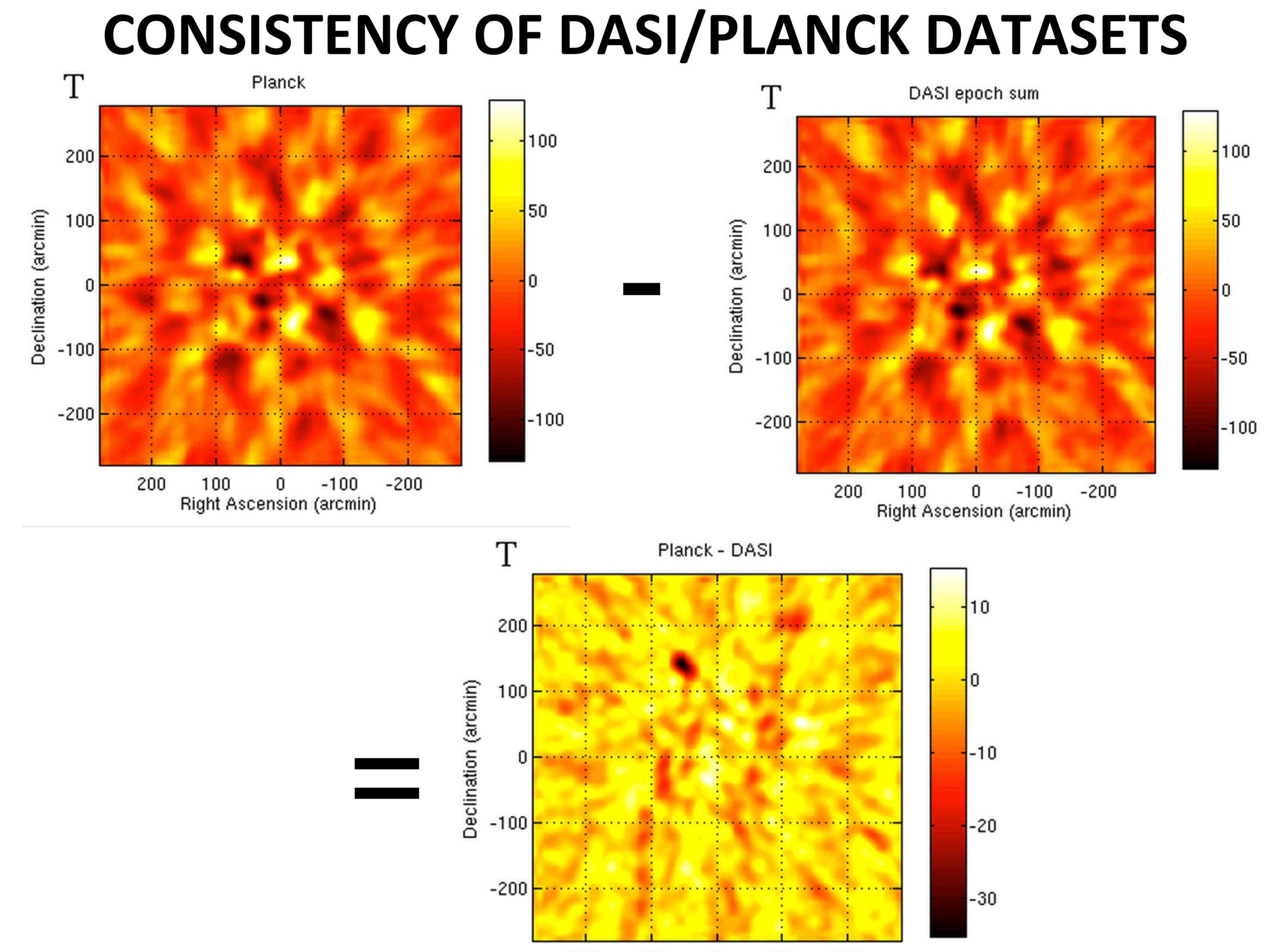
**BENEFITS OF THE MATRIX-BASED APPROACH:**

- Can combine data from maps with different resolution, beam size, and sky sampling strategies with no loss of information
- Allows complete modeling of complicated noise and filtering/masking
- Manageable file sizes (for our ground-based experiments), with $N_{pix} < 10^5$ – easy to share publically, allowing other groups to recreate our analysis

**CURRENT STATUS OF PROJECT:**

My long-term goal is to implement matrix-based techniques to combine data from our group's experiments with data from other CMB experiments, such as DASI, WMAP, and Planck. As an initial step, I have done some simple statistical tests to quantify the agreement between the sky as seen by DASI, a ground-based interferometer, and Planck. These tests allow me to check for calibration and pointing offsets in DASI, check whether the level of noise in the data is consistent with the reported noise for each experiment, and constrain the foregrounds.

## CONSISTENCY OF DASI/PLANCK DATASETS




**Above:** The 26 GHz sky as seen by DASI (above right) and the Planck 143 GHz sky resampled to a DASI-like sky using the known properties of the DASI experiment (above left). We expect the residuals to be consistent with the reported noise of the two experiments (and any unknown systematic effects not accounted for by our matrix encoding the properties of DASI).

**Below:** The difference between the skies observed by the two experiments. The residuals are a small fraction of the original signal. The negative feature at (50, 150) corresponds to a pair of point sources reported by the Planck collaboration.