An Update from BICEP/*Keck*

CMB-S4 Collaboration Meeting

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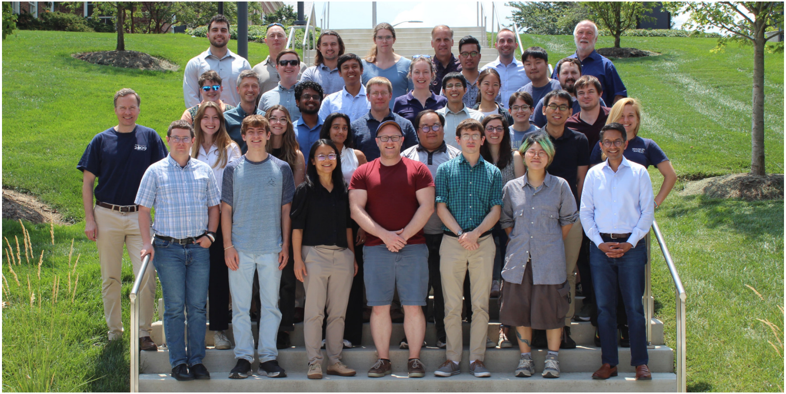
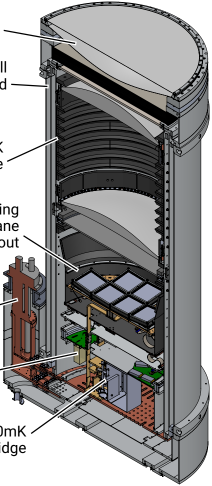
2024-07-31

The BICEP/*Keck* Collaboration



BICEP/*Keck* Experimental Strategy

- Deep observations of a low-foreground patch from the South Pole.
- TES detectors coupled to phased-array antennas.
- Small-aperture cryogenic refracting optics with extensive baffling.
- Pair-differencing, boresight rotation.
- Relentless effort to evaluate and improve instrument performance.

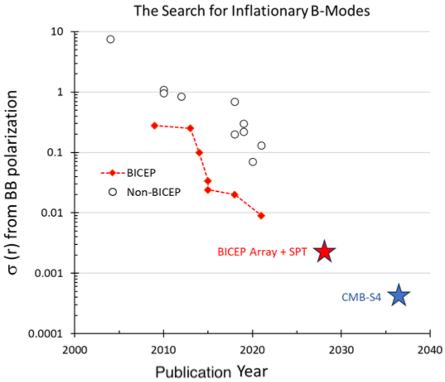


The South Pole, a Unique Window to the CMB

There is longstanding recognition across the field of CMB that the South Pole is a uniquely well-suited observing site:

- High altitude (∼10,000 ft).
- Extremely dry, stable atmosphere.
- Featureless, thermally-stable terrain. Minimal diurnal variation.
- Continuous observing (24/7, year-round access to the southern sky).

Constraints on Inflation from B-modes to Date



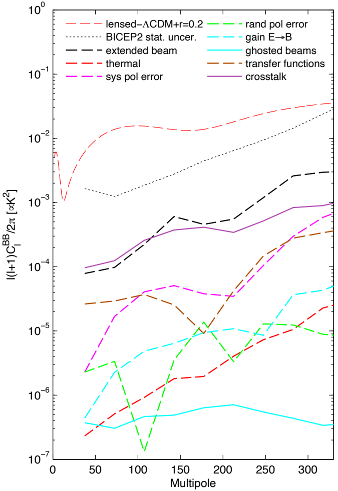
B-mode sensitivity to r published by BICEP/*Keck* (red) and other space- and ground-based experiments. (A table summary of these published results is appended at the end of this presentation.)

In Oct 2021 we published the results of our most recent multicomponent multispectral likelihood analysis, which included BICEP/*Keck*, WMAP and *Planck* data up to 2018:

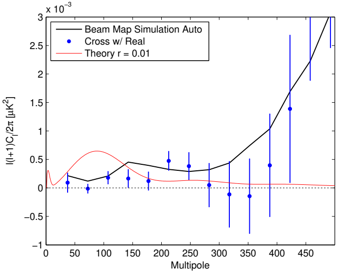
$$r < 0.036,\ \sigma(r) = 0.009$$

It is only in the course of pushing down toward $r \sim 0.01$ that we have learned the factors that affect these deep measurements.

Continual Improvements to Systematics Control



Estimated levels of systematics in BICEP2 as compared to a lensed-ΛCDM+$r = 0.2$ spectrum. (BK-III, ApJ 814, 110, 2015.)



BB power spectra corresponding to $T \to P$ leakage in BICEP3 (BK-XIII, Phys. Rev. Lett. 127, 151301, 2021).

- Systematics are continually reevaluated for each round of increase in sensitivity. In the most recent result, the bias on r from $T \to P$ leakage was estimated at $1.5 \pm 1.1 \times 10^{-3}$. Further improvements are needed for CMB-S4.
- **Overlap with the BA survey offers a means of systematics validation that could strengthen the CMB-S4 inflation case.**

Next: BICEP Array High-Frequency Receiver Deployment

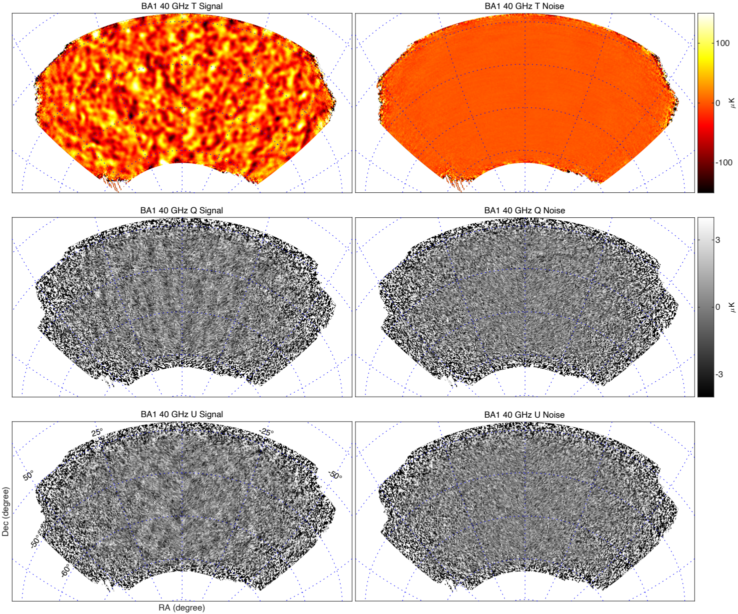
The B3/BA survey will soon reach full frequency coverage:

- BA 30/40 GHz since 2020
- B3 95 GHz since 2016
- BA 150 GHz since 2023
- BA 220/270 GHz to deploy in October 2024.

A single BA 150, 220 or 270 GHz module has 25% more detectors than an entire *Keck Array* receiver. (Each BA FPU has 12 detector modules.)

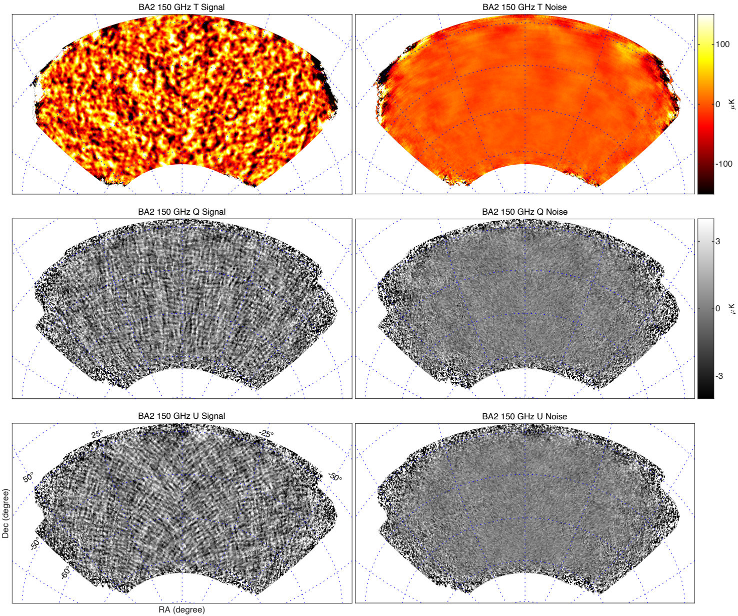
BA 220/270 GHz receiver, currently at Stanford.

BICEP Array 40 GHz 3-year Maps



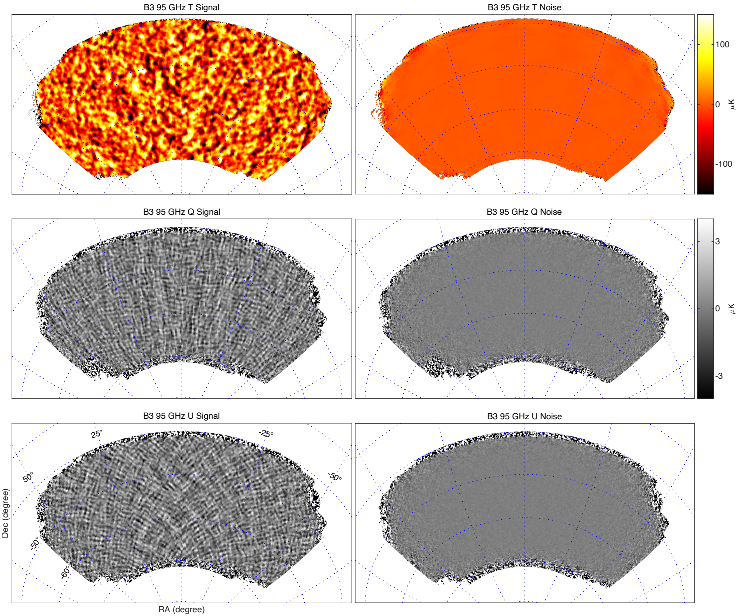
As of 2024, the low-frequency receiver has 7 detector modules at 40 GHz, 4 modules at 30 GHz, and one dichroic module.

BICEP Array 150 GHz First-Year Maps (FPU only 40% populated)



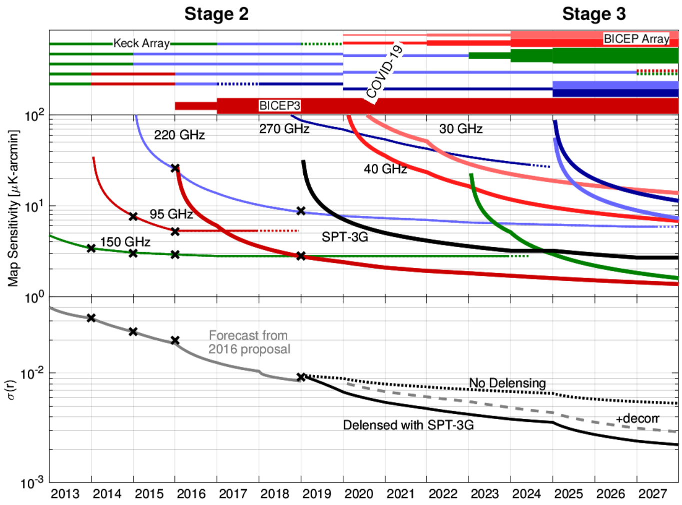
Five additional 150 GHz detector modules were installed during the 2023–24 austral summer, bringing the current total to 10 modules (3240 pairs).

BICEP3 95 GHz 8-year Maps (up to 2023)



These are the deepest CMB polarization maps ever made. (The noise power is ~ 3 times better than in the previously published 3-year maps from BICEP3.)

Performance-Based Forecasts



Achieved survey weight tracks with projections based on past performance.
In this frequency-optimized experiment, the limiting factor for $\sigma(r)$ is now lensing.

The Next Leap in r Will Come From Delensing with SPT-3G

- A proof-of-concept analysis of BICEP/*Keck* 2014 + SPTpol datasets demonstrated a $\sim$10% improvement in $\sigma(r)$. (Phys. Rev. D 103, 022004, 2021)
- Work is ongoing to reconstruct the lensing potential from high-res SPT-3G 2019-20 data. Validation of the resulting lensing map is in progress.
- Forecasts for BK+SPT data *already on disk* give $\sigma(r) \sim 0.004$.
- Both experiments are continuing to acquire more data and to optimize overlapping surveys, offering a clear path to $\sigma(r) < 0.002$.

Paving the Way for Next-Generation Experiments - I

Survey strategy and data quality:

BICEP/*Keck* data contain a wealth of information on survey design, achieved performance and environmental impacts.

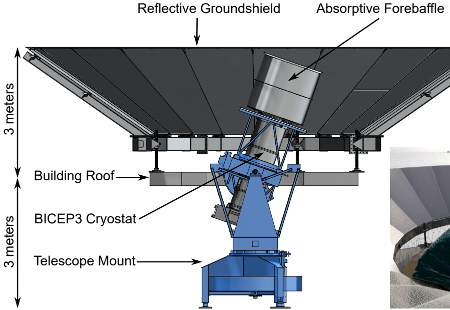
As an example, long-baseline data from Pole are being used to characterize and mitigate atmospheric effects:

- Analysis by Baibhav Singari identified noise scaling penalties in BICEP/*Keck* data caused by atmospheric polarization. See also this afternoon's talk by Anna Coerver for effects on SPT data.
- Using maps from the water vapor radiometer in continuous operation at Pole since 2018, Sofia Fatigoni's thesis developed a new method to cross-correlate BICEP/*Keck* data and noise from variable PWV. (Paper in preparation.)

See Thu afternoon's session "Chile SAT Design and Considerations," convened by John Kovac and Jeff McMahon.

Understanding instrumental systematics, sidelobe control and shielding performance:

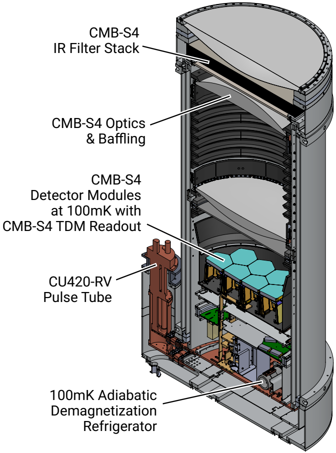
- Overlap in observing region with the BA survey and direct data comparison would provide a cross-check for CMB-S4 systematics studies.
- Shielding requirements are a major design driver for CMB-S4 SATs. Using BICEP3, our best-understood polarimeter, we can test the shielding factor and geometries of the groundshield and forebaffle in-situ.



Paving the Way for Next-Generation Experiments - III

PreSAT, the Precursor SAT CMB Polarimeter:

- By incorporating candidate CMB-S4 SAT technologies in an existing BA receiver, PreSAT will enable full-stack laboratory testing and early risk retirement for new CMB-S4 designs.
- The PreSAT testbed is intended to be a 90 GHz / 150 GHz dichroic receiver, compatible with use of CMB-S4 SAT MF detector modules.
- Field testing is envisioned to validate the results of lab campaigns.



Credit: Matthew Petroff

The Road Ahead

- 2024+:
  - Analysis well underway for the BICEP/*Keck* 2023 dataset.
  - Deploy high-frequency BICEP Array receiver (220/270 GHz).
  - Continue to add detectors and tune sensitivity of the array.
- 2025+:
  - Initiation of the BICEP Array Replacement Tower project, building toward a more efficient use of resources at the Pole.
  - Results of first joint delensing analysis with SPT-3G data.
- "NSF is committed to CMB science and will continue to support current CMB activities at the South Pole" (May 2024 statement)

Questions?

CMB S4

Backup Slides

2024-07-31

Constraints on Inflation from B-modes to Date

Experiment	arxiv post	Bands [GHz]	σ(r)
DASI	0409357	26…36	7.5
BICEP1 2yr	0906.1181	100, 150	0.28
WMAP 7yr	1001.4538	30…60	1.1
QUIET-Q	1012.3191	43	0.97
QUIET-W	1207.5034	95	0.85
BICEP1 3yr	1310.1422	100, 150	0.25
BICEP2	1403.3985	150	0.10
BK13 + Planck	1502.00612	150 + Planck	0.034
BK14 + WP	1510.09217	95, 150 + WP	0.024
ABS	1801.01218	150	0.7
Planck	1807.06209	30...353	~0.2
BK15 + WP	1810.05216	95,150,220+WP	0.020
Polarbear	1910.02608	150 + P	0.3
SPTpol	1910.05748	95 + 150	0.22
Planck/Tristram	2010.01139	30...353	0.07
SPIDER	2103.13334	95 + 150	0.13
BK18 + WP	2110.00483	95,150,220+WP	0.009
Polarbear	2203.02495	150 + P	~0.16

B-mode sensitivity to r published by BICEP/*Keck* (green) compared to other experiments.