Constraining Inflation with the BICEP/*Keck* CMB Polarization Experiments

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The BICEP/*Keck* (BK) series of cosmic microwave background (CMB) polarization experiments has, over the past decade and a half, produced a series of field-leading constraints on cosmic inflation via measurements of the "B-mode" polarization of the CMB. Primordial B modes are directly tied to the amplitude of primordial gravitational waves (PGW), thier strength parameterized by the tensor-to-scalar ratio, r, and thus the energy scale of inflation. Having set the most sensitive constraints to-date on r, $\sigma(r) = 0.009$ ($r_{0.05} < 0.036, 95\%$ C.L.) using data through the 2018 observing season ("BK18"), the BICEP/*Keck* program has continued to improve its dataset in the years since. We give a brief overview of the BK program and the "BK18" result before discussing the program's ongoing efforts, including the deployment and performance of the *Keck Array*'s successor instrument, BICEP Array, improvements to data processing and internal consistency testing, new techniques such as delensing, and how those will ultimately serve to allow BK reach $\sigma(r) \lesssim 0.003$ using data through the 2027 observing season.

1 Introduction

Our Universe is well-described by a hot Big Bang model, with the bulk of its energy density made up by a cold dark matter (CDM) component and a dominant cosmological constant component Λ [1]. This "ΛCDM" model has seen extensive success in matching observations of both the low- and high-redshift universes, but, on its own, possesses a few noteworthy deficiencies. It does not provide a mechanism for the generation of the primordial perturbations which seeded further structure growth, nor does it explain the thermalization of the CMB on acausal scales (the "horizon problem") or the apparent fine-tuning of the cosmological spatial flatness parameter (the "flatness problem"). These deficiencies can be addressed through the inclusion of a period of rapid accelerating expansion, "inflation", at very early times. This generic paradigm has seen a wealth of indirect evidence, with the lowest-order predicitions of Gaussianity, adiabaticity, and near scale-invariance of the primoridal perturbation spectrum all confirmed to exquisite precision [2]. However, inflation also predicts a background of PGW [3], as-yet undetected. If these PGW could be measured, this would serve as direct evidence — a "smoking gun" — for the inflationary scenario.

Such a background of PGW would induce a particular odd-parity "B-mode" pattern in the polarization of the CMB [4,5], which may be detectable. ΛCDM (scalar) fluctuations are only capable of generating even-parity "E modes", thus a detection of primordial B modes would be tantamount to a detection of PGW, and a direct probe of the inflationary potential. Temperature-based probes of inflation have become limited by cosmic variance in the past decade [2], thus B-mode polarization is currently the most promising avenue by which to search for direct evidence of inflation.

Practical challenges to measuring primordial B-mode polarization are manyfold. Due to the weak nature of any potential primordial B-mode signal, temperature-to-polarization leakage introduced by the instrument and E-to-B leakage introduced by the experiment design and analysis may be major concerns, and weak instrumental systematics may become critically important. There are also significant astrophysical challenges, in the form of foreground emission (primarily from galactic dust, but potentially also due to mechanisms such as galactic synchrotron radiation) and gravitational lensing of the CMB by large-scale structure along the line-of-sight, which mixes E and B and must be carefully accounted for (see subsection 5.3 and references therein).

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Herein, we proceed by briefly reviewing the experimental strategy and history of the BICEP/*Keck* program to-date in section 2, briefly noting the current cosmological constraints in section 3, and then in section 4 discussing the progress of the BICEP/*Keck* program since the previous publication. Finally, we review the future directions of the project in section 5.

2 The BICEP/*Keck* Experiments

The BICEP/*Keck* telescopes search for B-mode polarization by employing small-aperture refracting polarimeters at the geographic South Pole to observe a small patch of sky continuously throughout the Polar winter. Utilizing small-aperture telescopes enables rigorous control of instrumental systematic effects, ease of maintenance and upgradability, and facilitates boresight rotation. BK receivers utilize superconducting transition edge sensor (TES) bolometer arrays [6] and all-cold refractive optics, and have significant internal and external baffling/shielding to mitigate off-axis coupling of the receiver to terrestrial sources of radiation.

BICEP/*Keck* telescopes scan a constant throw in azimuth, periodically (once every ~ 2 hours) updating the Right Ascension to center on the observing field. Allowing the observing field to drift with the rotation of the Earth over the set of scans allows for robust removal of azimuth-fixed signals by removing the common signal in azimuth across all scans. After a fixed period of scans and integrated calibration measurements, the helium sorption refrigerator cooling the focal plane is cycled and any routine maintenance is performed, before beginning a new set of scans. This process is repeated constantly throughout the Austral winter and ultimately over multiple years (observing seasons).

BICEP2 observed from 2010–2012 at 150 GHz. *Keck Array* was an array of five BICEP2-class receivers operating from 2012–2019, later observing at multiple frequencies from 95 to 270 GHz to discriminate foregrounds (dust, for example, being brighter at higher frequencies). BICEP3 began science observations in 2016 at 95 GHz, featuring an instantaneous sensitivity comparable to the entire *Keck Array*. BICEP Array, an array of BICEP3-class receivers succeeding *Keck*, began operations along with its first receiver in 2020.

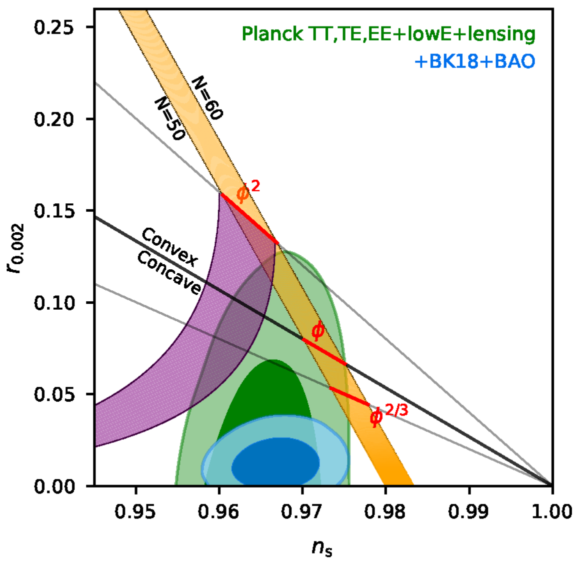

Figure 1 – Constraints in the $r - n_s$ plane with the inclusion of BICEP/*Keck* and BAO data. Note that BAO data primarily results in the shrinking in the n_s-direction; the improvement in r is driven almost entirely by BICEP/*Keck*. Adapted from Figure 5 of BK18 [7].

3 BK18 Cosmological Constraints

BICEP/*Keck*'s latest published "BK18" constraints [7] are based on data up-to and including the 2018 observing season, in addition to external data from *Planck* and WMAP, and are the first published constraints to include data taken by BICEP3. BK18 set the limit $r_{0.05} < 0.036$ (95% C. L.), with a sensitivity $\sigma(r) = 0.009$. The constraint on the $r - n_s$ plane is shown in figure 1. These remain the most sensitive published constraints on primordial gravitational waves from CMB B-mode polarization. BK18's sensitivity is dominated by only three seasons of BICEP3 data, and lensing sample variance is now the dominant contribution to BK18's $\sigma(r)$, rather than the uncertainty on foreground emission as in prior releases. These last two facts serve to underscore the importance of BK's ongoing efforts, described in the subsequent sections.

BK18 employs BK's historical standard analysis procedure of constructing an equidistant cylindrical projection map, estimating the angular power spectra based on the mean in annuli of the 2-D Fourier transforms of those maps, and evaluating the joint likelihood of all resulting auto- and cross-spectra against a multicomponent model consisting of lensed-ΛCDM, foregrounds, and r. Extensive suites of simulations were constructed to both estimate fluctuation and significance levels and against which to compare various data splits to probe for systematics.

4 Data Collected Since 2018

Since 2018, BICEP3 and its companion instrument — *Keck Array*, succeeded by BICEP Array — have continued to observe the CMB during each year's Austral winter season. This represents a significant increase in survey weight at 95 GHz, and the extension of the BICEP/*Keck* program's frequency coverage to both higher and lower observing frequencies. The next BICEP/*Keck* map set is currently planned to be "BK23", containing data up to and including 2023. We briefly describe the progress and show preliminary BK23 coadded maps for a noteworthy subset of frequency bands.

4.1 BICEP3

BICEP3 was deployed during the 2014–2015 Austral summer season, beginning science observations during the 2016 Austral winter season. BICEP3 was improved significantly between the 2016 and 2017 seasons with the installation of better-performing detector tiles and the replacement of some optical filtering elements. BICEP3 and the three-year dataset are described in detail in *BICEP/Keck Collaboration et al.* (2022) [8]. During the 2022-2023 Austral summer, the computer systems for BICEP3, inherited from BICEP2 and nearing 15 years of age, were replaced, and the same season an experimental ultra-thin high modulus polyethylene (HMPE) vacuum window [9] was installed to improve loading and overall sensitivity. Otherwise, BICEP3 has operated in a configuration identical to that described in the BICEP3 instrument paper [8].

We designate the BICEP3 95 GHz map as "L95", in reference to the larger field-of-view/coverage area (with respect to a *Keck*-class receiver) and the 95 GHz observing frequency. "BK23 L95" represents 5 additional seasons (2019–2023) of winter CMB data as compared with the 3 seasons in BK18 L95, ultimately producing a map $\sqrt{\frac{3}{8.8}}$ times less noisy (8.8 rather than 8 owing to the suboptimal performance of BICEP3 in 2016). The BK23 L95 (BICEP3 95 GHz 8-year) map is shown in figure 3. We caution that this map should still be considered preliminary, though note that we anticipate ultimate sensitivity levels better than that which would be inferred solely from the fraction of additional data, owing to improvements to data processing and analysis described in section 5.2.

4.2 BICEP Array

The 30/40 GHz "BA1" receiver was deployed during the 2019–2020 Austral summer as well as the new BICEP Array telescope mount. At the same time, three *Keck* receivers, two observing at 220 GHz and one at 270 GHz, were moved from the old mount, having been installed in adapters to mimic the mass and center-of-gravity of BICEP Array-class receivers. BA1's focal plane is comprised of 12 detector module units, with modules operating at either 30 or 40 GHz arranged in a checkerboard pattern. The exact proportion and arrangement of modules has changed over the first few years of operation. The 40 GHz modules consist of a 5×5 grid of detector pairs, while 30 GHz modules have a 4×4 arrangement owing to the larger antenna size. BA1's design and initial performance are described in further detail in Schillaci *et al.* (2020) [10]. BA1 represents the first extension of BICEP/*Keck*'s frequency coverage below 95 GHz; the low-

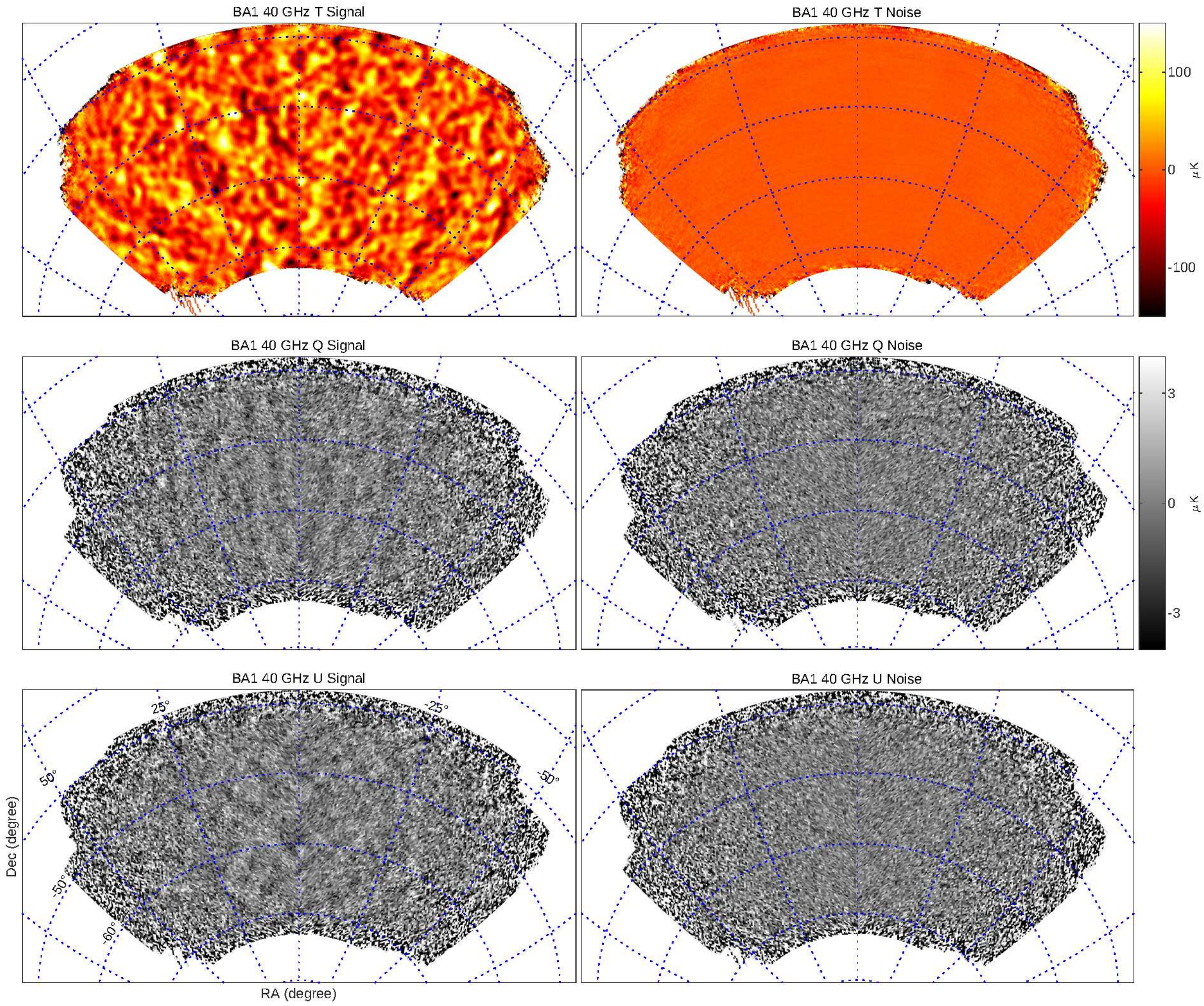

Figure 2 – Preliminary BICEP Array 40 GHz 4-year ("BK23 L40") temperature and polarization maps. From the top, the rows show temperature, Stokes Q, and Stokes U maps. The left-hand column shows the signal maps, while the right-hand column shows a single realization of noise. The "plus" pattern in Q and "cross" pattern in U is easily visible by-eye in the signal maps, and is characteristic of an E-mode-dominated sky.

frequency channels are intended to aid in characterizing the emission of galactic synchrotron which increases towards lower frequencies.

The restriction of Antarctic operations during the 2020–2021 Austral summer caused by the COVID-19 pandemic resulted in BICEP Array operating in the same configuration in 2021 as it did in 2020. During the 2021–2022 Austral summer, a small team was able to deploy to install new detector tiles in BA1, and to install new optical filtering elements to eliminate unexpected out-of-band coupling [11]. The detector module upgrades represented a shift towards a higher proportion of 30 GHz detector modules, intended to improve sensitivity to the synchrotron foreground, and the installation of some experimental dichroic modules [12].

Poor performance of the tiles installed in the 2021–2022 summer led to further focal plane upgrades to BA1 during the 2022–2023 and 2023–2024 summers. The 2022 30 GHz modules were replaced with better-performing ones, and the 2022 dichroic tiles were replaced with with known-well-functioning 40 GHz modules. As of the 2024 observing season, BA1 is comprised of 7 modules (175 pairs/350 TES detectors) at 40 GHz, 4 modules (64 pairs/128 TES detectors) at 30 GHz, and a single remaining dichroic module (16 each of 30 GHz and 40 GHz pairs). The BK23 L40 maps are shown in figure 2.

During the 2022–2023 Austral summer season, one of the 220 GHz *Keck*-class receivers was decomissioned and replaced by the second BICEP Array-class receiver, "BA2", observing at 150

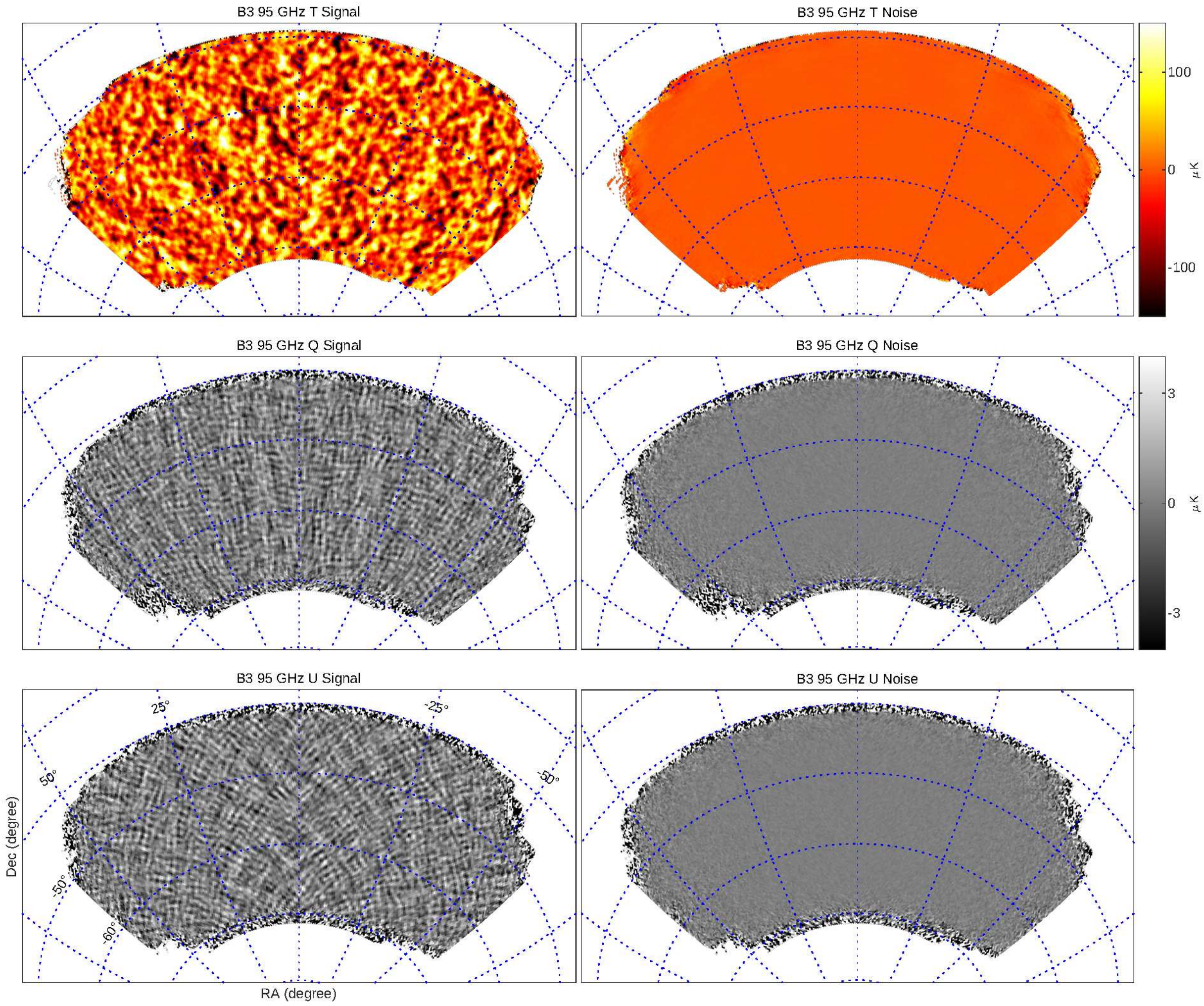

Figure 3 – Preliminary BICEP3 95 GHz 8-year ("BK23 L95") temperature and polarization maps.

GHz. For this initial observing season, only 5 of the 12 detector modules were installed due to fabrication and testing throughput limitations. These modules were arranged on the focal plane such that the overall map coverage was similar to BICEP3/BA1, while maintaining good redundancy of coverage over differing boresight angles. BA2 also employed an ultra-thin HMPE vacuum window as was installed in BICEP3 for the 2023 season, which should be even more beneficial at the higher observing frequency.

BA2 detector tiles consist of 18x18 grids of detector pairs, *i.e.* 324 pairs (648 individual TES detectors) per wafer – 25% more than in an entire *Keck* 150 GHz receiver. BA2 will ultimately observe with 12 of these tiles for a total of 3888 pairs (7776 TES detectors). The design and development of the 150 GHz modules for BA2 is described in Schillaci *et al.* (2023) [13].

The five tiles installed in BA2 in 2023 have a total of 1620 optically coupled detector pairs, already a 25% increase in detector count over BICEP3. In figure 4, we show the preliminary BA2 first-year ("BK23 L150") temperature and polarization maps. Five additional modules were installed in BA2 during the 2023–2024 Austral summer, bringing the current total to 10 modules/3240 detector pairs (6480 TES detectors).

In addition to the introduction of BA1 and BA2, BK23 will contain 10 additional *Keck* receiver-years of 220 GHz data taken in 2019 and with the *Keck* receivers installed in BICEP Array (representing a $\sim 50\%$ increase over BK18), and the first data (6 *Keck* receiver-years) at 270 GHz. This high-frequency data will aid significantly in the discrimination of the galactic dust foreground emission. However, owing to the smaller instantaneous field of view, the maps produced

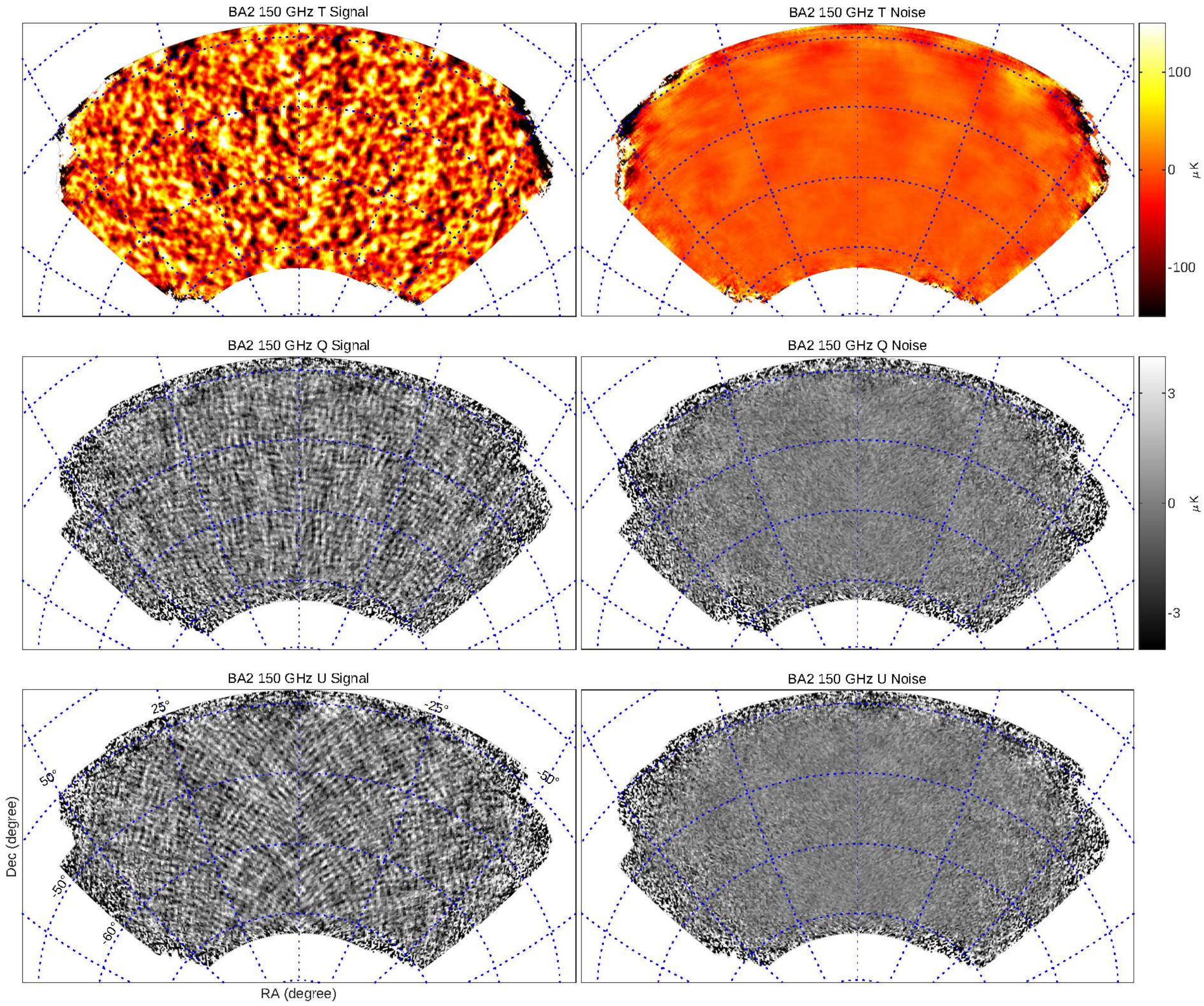

Figure 4 – Preliminary BICEP Array 150 GHz 1-year ("BK23 L150") temperature and polarization maps.

by these *Keck*-class receivers will not provide information on foregrounds for the additional sky area covered by BICEP3/BA-class receivers. This capability, as well as a significant increase in detector count, will be provided by the deployment of the 220/270 GHz "BA4" receiver, described further in subsection 5.1.

5 Future Outlook

5.1 BA4

The third BICEP Array-class receiver to be deployed is designated "BA4". BA4 will observe at 220 and 270 GHz, again employing monochromatic (220 or 270 GHz) detector modules, 6 at each band, arranged in a checkerboard pattern. BA4 will be time division-multiplexed with the same architecture as is used in BA2, and will therefore have an identical density and number of detectors (324 detector pairs per module $\times$ 12 modules). BA4, through its larger field-of-view and vastly increased detector count, will significantly improve measurements of the galactic dust foreground, and its increased resolution and sensitivity may even enable more sophisticated studies of the distribution of polarized dust in the galactic plane. BA4 is currently being integrated and undergoing in-lab calibration measurements at Stanford University, and is planned to deploy to the South Pole this coming 2024–2025 Austral summer.

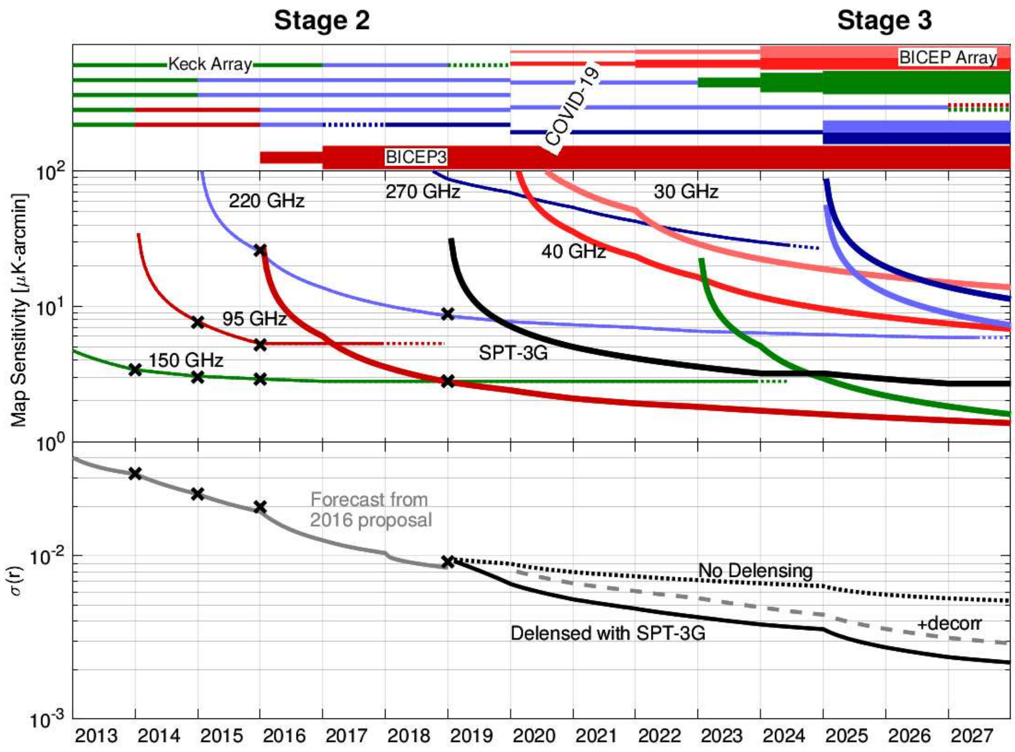

Figure 5 – Achieved and projected sensitivity of the BICEP/*Keck* experiment and its constituent observing bands. The top subfigure shows a schematic of the observing configuration during a given season, with line color being a proxy for observing frequency and width for detector count. The middle subfigure shows the progression of raw sensitivity in each BK observing band, and that of SPT-3G (solid black) used for delensing. The bottom subfigure shows the progression of the primary figure-of-merit for the experiment, $\sigma(r)$, as a function of time; the solid line denotes the sensitivity when delensing in conjunction with SPT-3G (removing about 70% of the lensing signal at full sensitivity), while the dotted represents the progression of sensitivity with no delensing — note the much earlier level-off of $\sigma(r)$ if delensing is not performed. The gray dashed line is the result of freeing a parameter used to model first-order decorrelation of foregrounds as a function of frequency. Black "×" denote published values.

5.2 Reanalysis

A key feature of the upcoming BK23 map set will be the from-scratch reanalysis of all archival data dating back to BICEP2's 2010 observing season. Previously, new seasons of data were analyzed and validated independently, before being coadded to the previous dataset's maps, thus locking-in choices, techniques, and software initially chosen over a decade ago. A key philosophy behind the implementation of this reanalysis project was optimizing performance, scalability, and compatibility, to enable easier collaboration with external groups (such as adopting the widely-used HEALPix [14] pixelization) and more rapid iteration of analysis choices.

Low-level changes implemented for the reanalysis include optimizations to: readout transfer function deconvolution, the removal of timestream glitches, timestream filtering, timestream weighting, and data quality cuts, among others. Timestream polynomial filtering has been moved to a Legendre polynomial basis to better orthogonalize the removed modes, scan-synchronous subtraction has been moved to a longer timescale, and timestream weighting has been optimized to prioritize the low-frequency regime of interest for constraining r.

Alongside low-level processing changes, a new automated data reduction pipeline and suite of automatically generated diagnostics has been constructed. This reduction pipeline emphasizes transparency, robustness, and ease-of-use, while the diagnostics represent significant improvements in information density and accessibility. The ability to accurately assess increasingly large volumes of incoming data is critically important to overall observing efficiency, and will only become more so as new experiments with even larger detector counts come online.

One more notable area of improvement in the reanalysis is the overhauling of internal consistency testing and map validation. This includes varying and in many cases extending the amount of data used in various data splits used to probe for systematic effects, and constructing more robust statistical tools to assess the outcomes of those tests.

5.3 Delensing

Figure 5 shows the achieved and projected reach of the BICEP/*Keck* experiment over time. A noteworthy feature of the $\sigma(r)$ plot is that sensitivity rapidly levels-off despite increasing per-band map depths if there is no delensing. In BICEP's relatively small patch, the number of lensing modes is limited, and thus the effective sample variance on lensing is large; indeed, as mentioned it is already the dominant contribution to BK18's $\sigma(r)$, rather than uncertainty on foreground emission. With detailed high-resolution polarization maps and knowledge of the integrated lensing potential provided via BICEP's collaboration with the South Pole Telescope (SPT) — constituting the South Pole Observatory (SPO) — the specific lensing modes can be subtracted, enabling much deeper r constraints even on a small patch. This delensing approach has already been demonstrated successfully on older BK, SPT, and *Planck* data [15], and new techniques [16] promise even further improvements. BICEP's current results and the sensitivity levels of newly collected data all affirm the necessity of delensing to achieve competitive limits on r going forward.

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