BICEP/Keck Array: B-Mode Polarization Results and Future Plans

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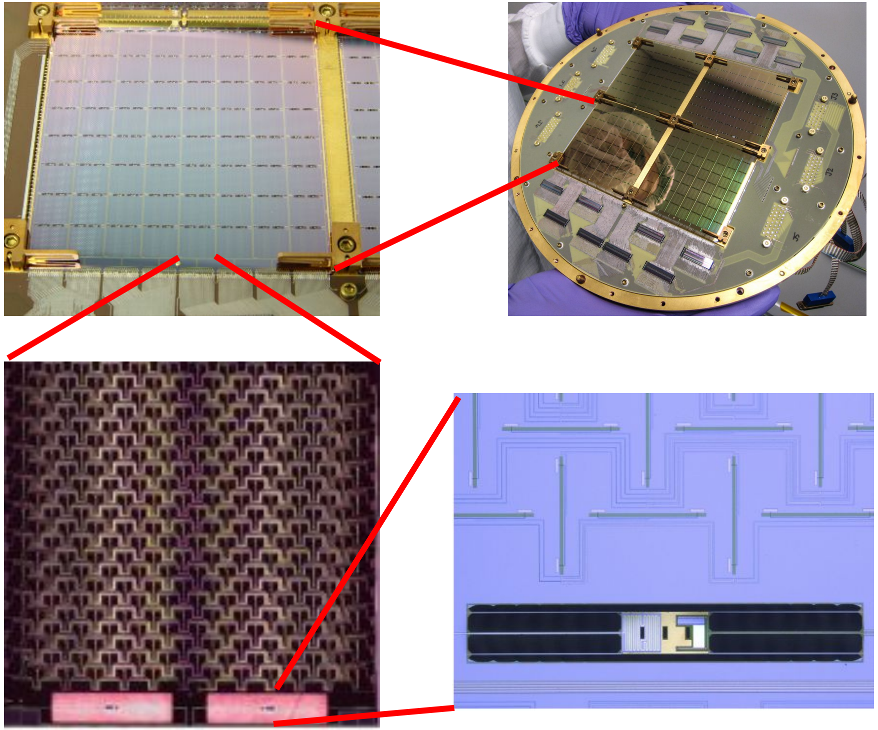
NSF/Schramm Fellow @ University of Chicago/Fermilab
From Planck to the Future of CMB, 2022-05-26

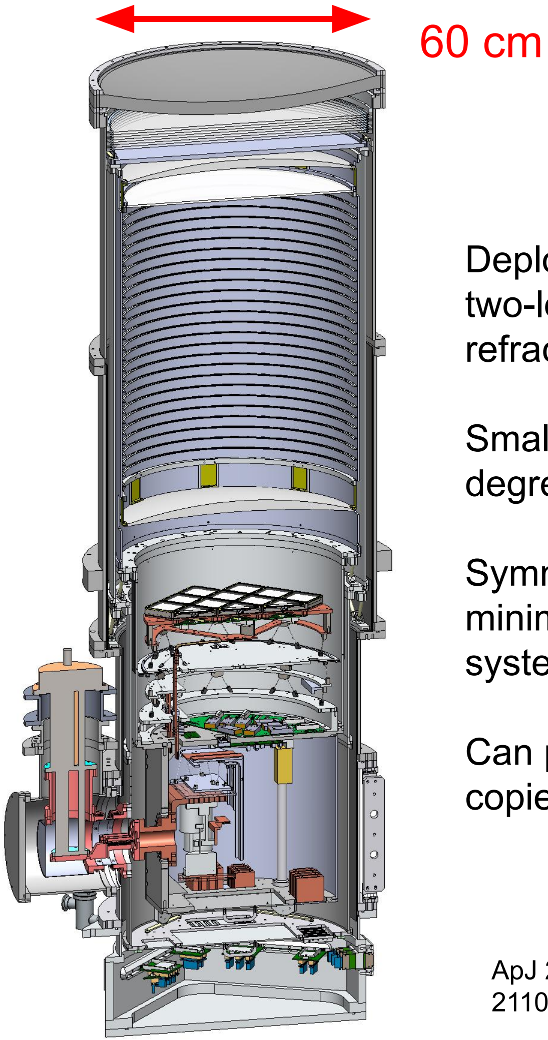
The BICEP/Keck Array Collaboration

May 2022

The BICEP/Keck Strategy



Mass-produce large-format arrays of background limited transition edge sensor bolometers



Deploy them in simple, two-lens on-axis refracting telescopes:

Small apertures tuned for degree angular scales

Symmetric design minimizes polarization systematics

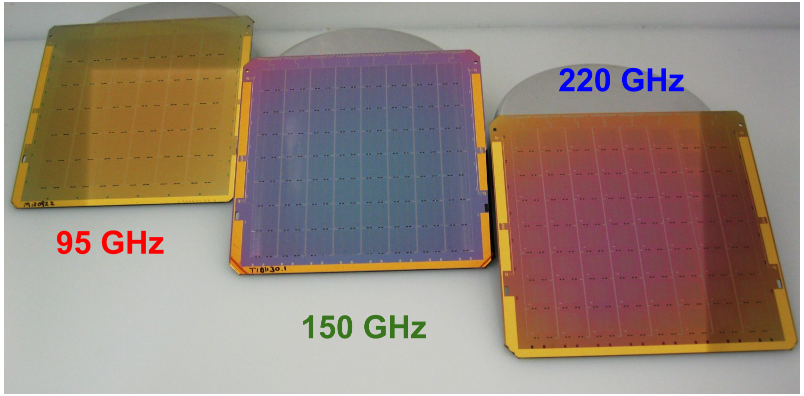
Can produce many copies

ApJ 2022
2110.00482

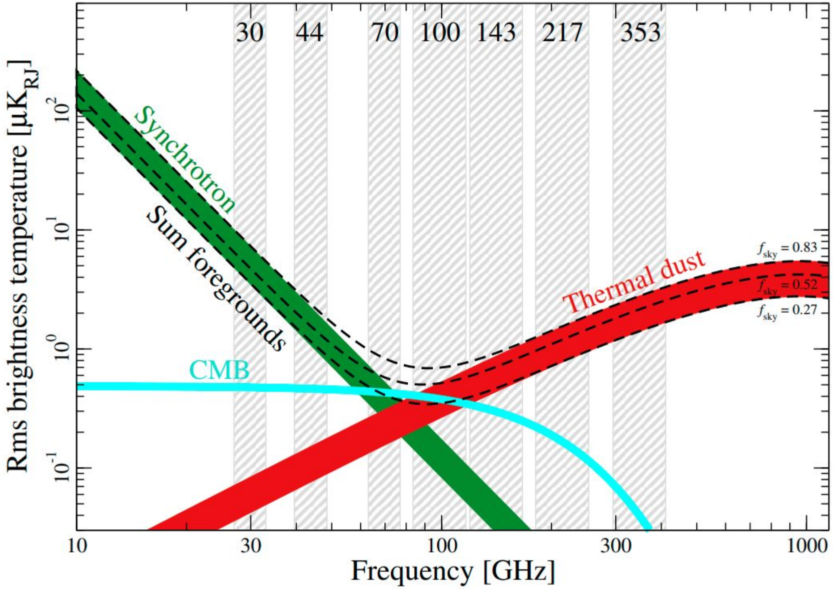
The BICEP/Keck Strategy

Observe over a wide frequency range to characterize Galactic foregrounds

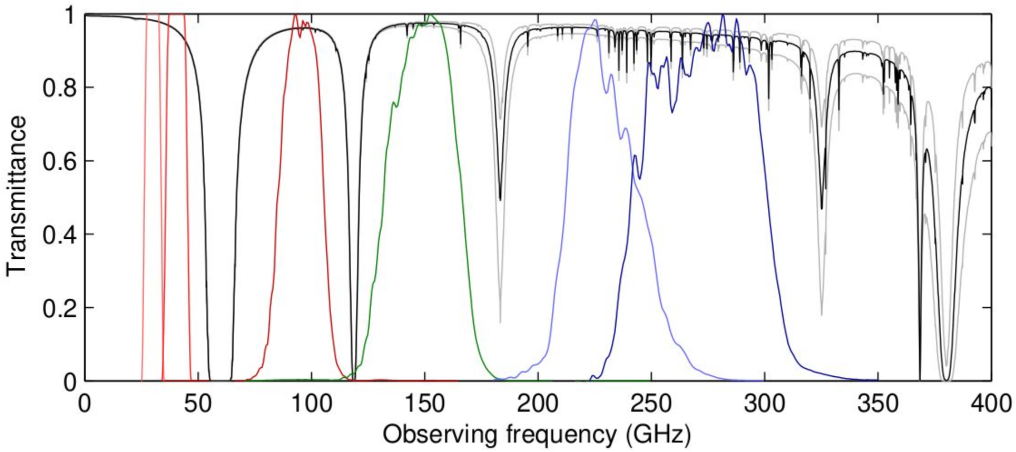
Detectors designed to scale in frequency



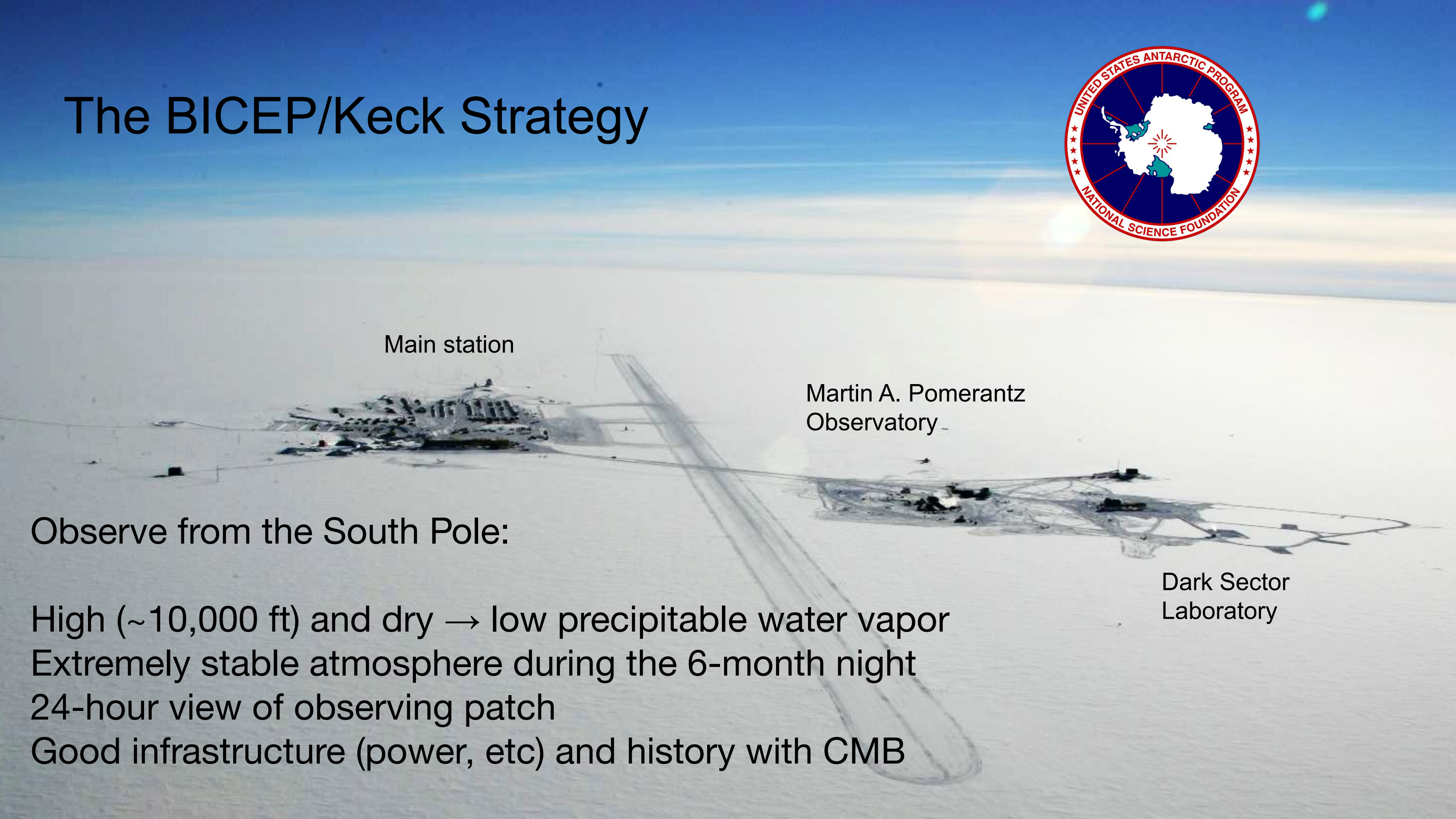
Optics simplified by monochromatic design



Planck
1807.06205



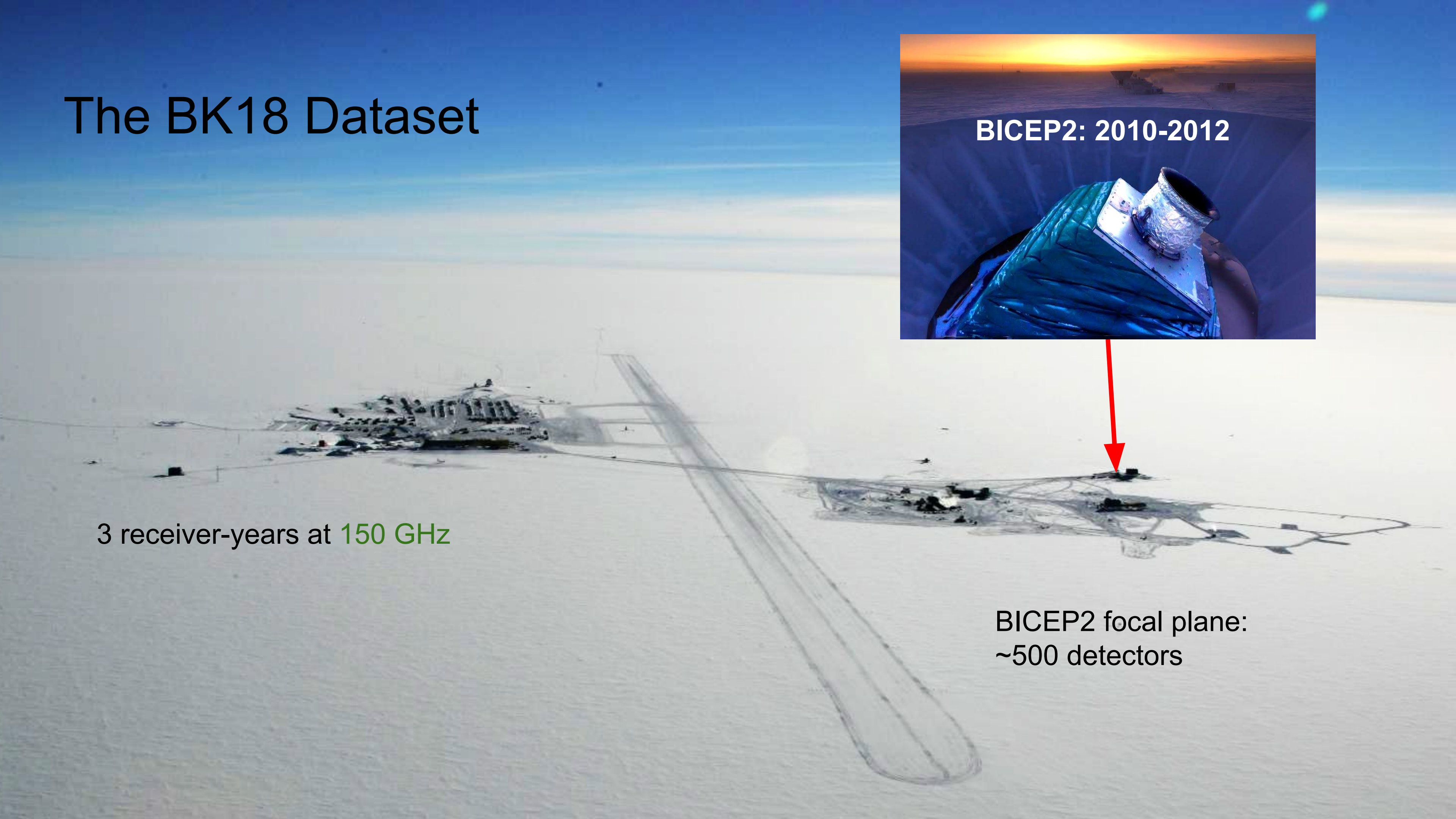
The BICEP/Keck Strategy



Observe from the South Pole:

High (~10,000 ft) and dry → low precipitable water vapor
Extremely stable atmosphere during the 6-month night
24-hour view of observing patch
Good infrastructure (power, etc) and history with CMB

The BK18 Dataset



3 receiver-years at 150 GHz

BICEP2 focal plane:
~500 detectors

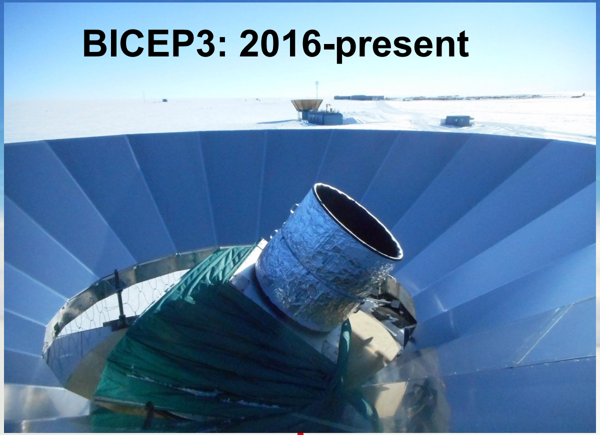
The BK18 Dataset

Keck Array: 2012-2019

3 receiver-years at 150 GHz +
4 receiver-years at 95 GHz +
15 receiver-years at 150 GHz +
14 receiver-years at 220 GHz

5x BICEP2-class receivers in a single mount (changed frequencies several times)

The BK18 Dataset



3 receiver-years at 150 GHz +
4 receiver-years at 95 GHz +
15 receiver-years at 150 GHz +
14 receiver-years at 220 GHz +
24 receiver-years at 95 GHz

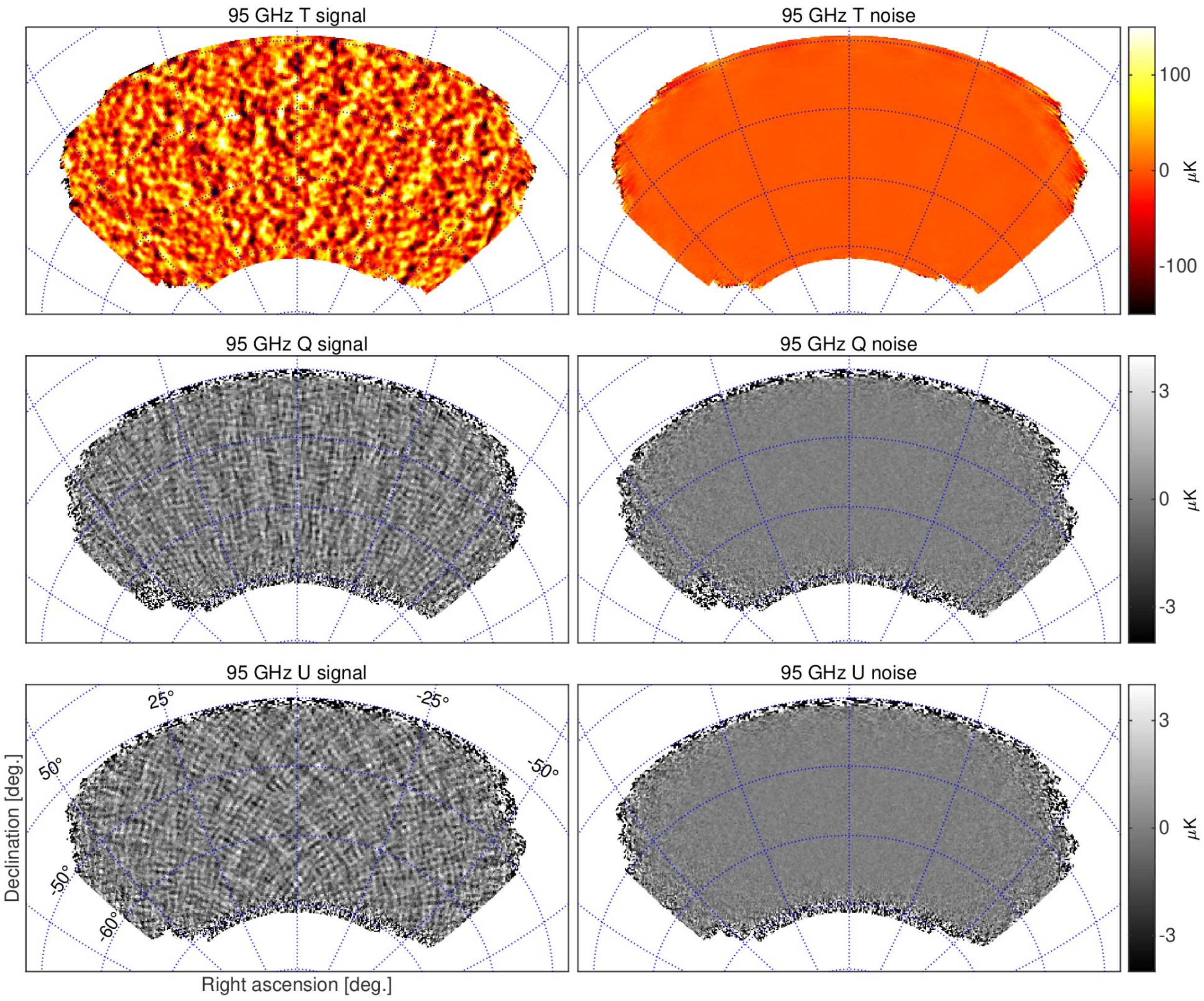
Keck Array detector count in a single receiver


Photo: Keith Vanderlinde

BK18 Maps

95 GHz:

2.8 μK-arcmin over ~600 deg^2



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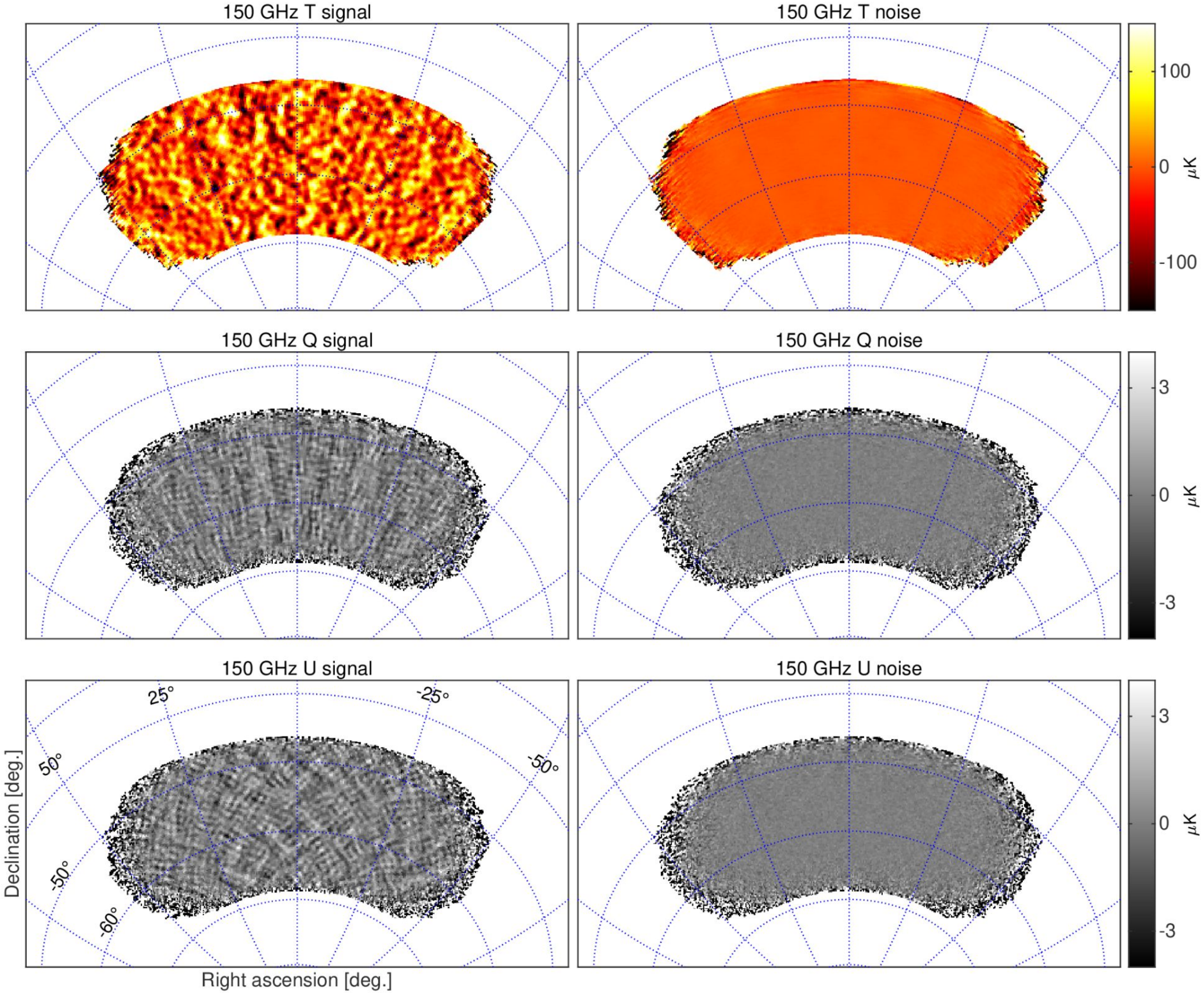
2110.00483

BK18 Maps

150 GHz:

2.8 μK-arcmin over ~400 deg^2



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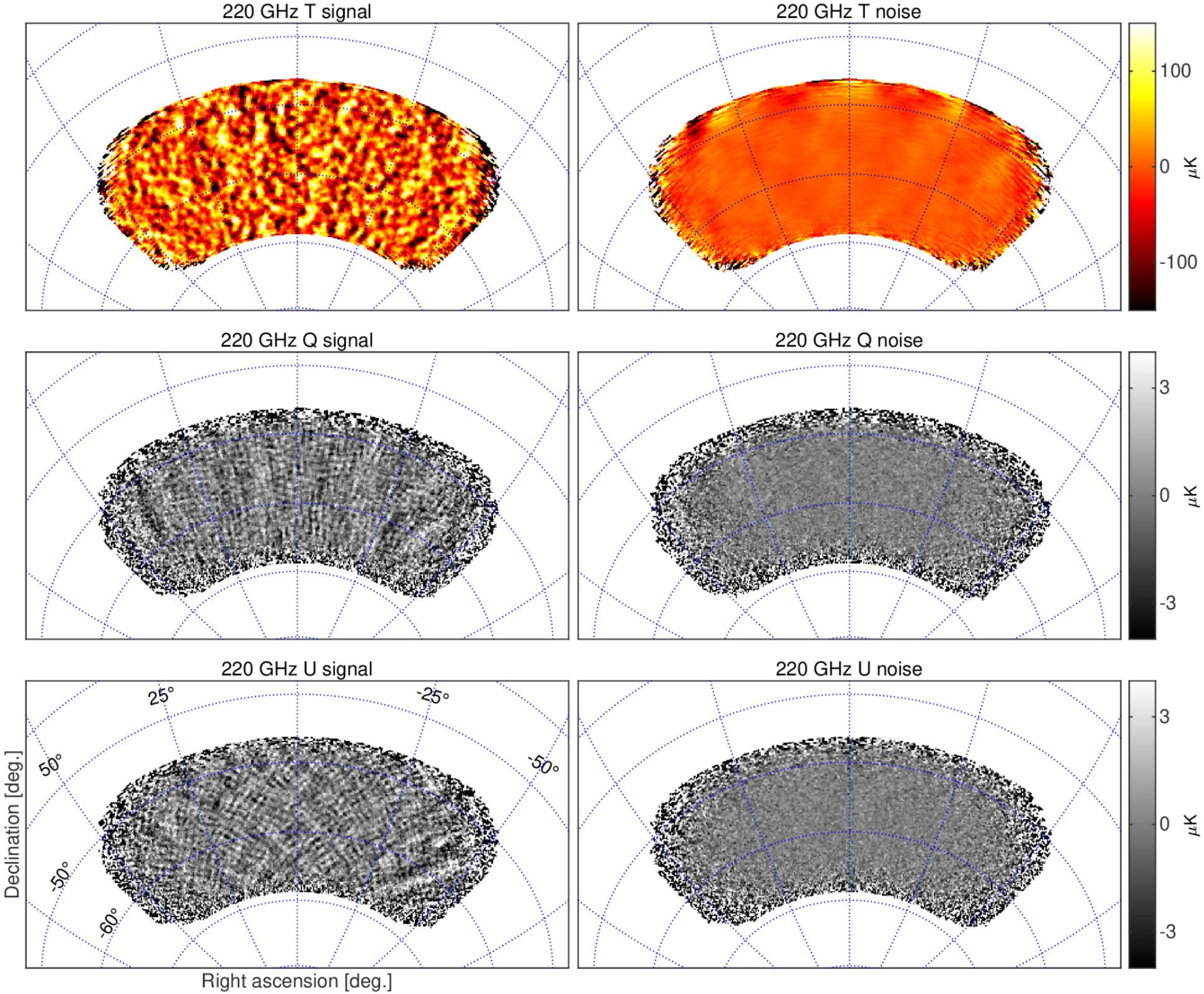
BK18 Maps

220 GHz:

8.8 μK-arcmin over ~400 deg^2



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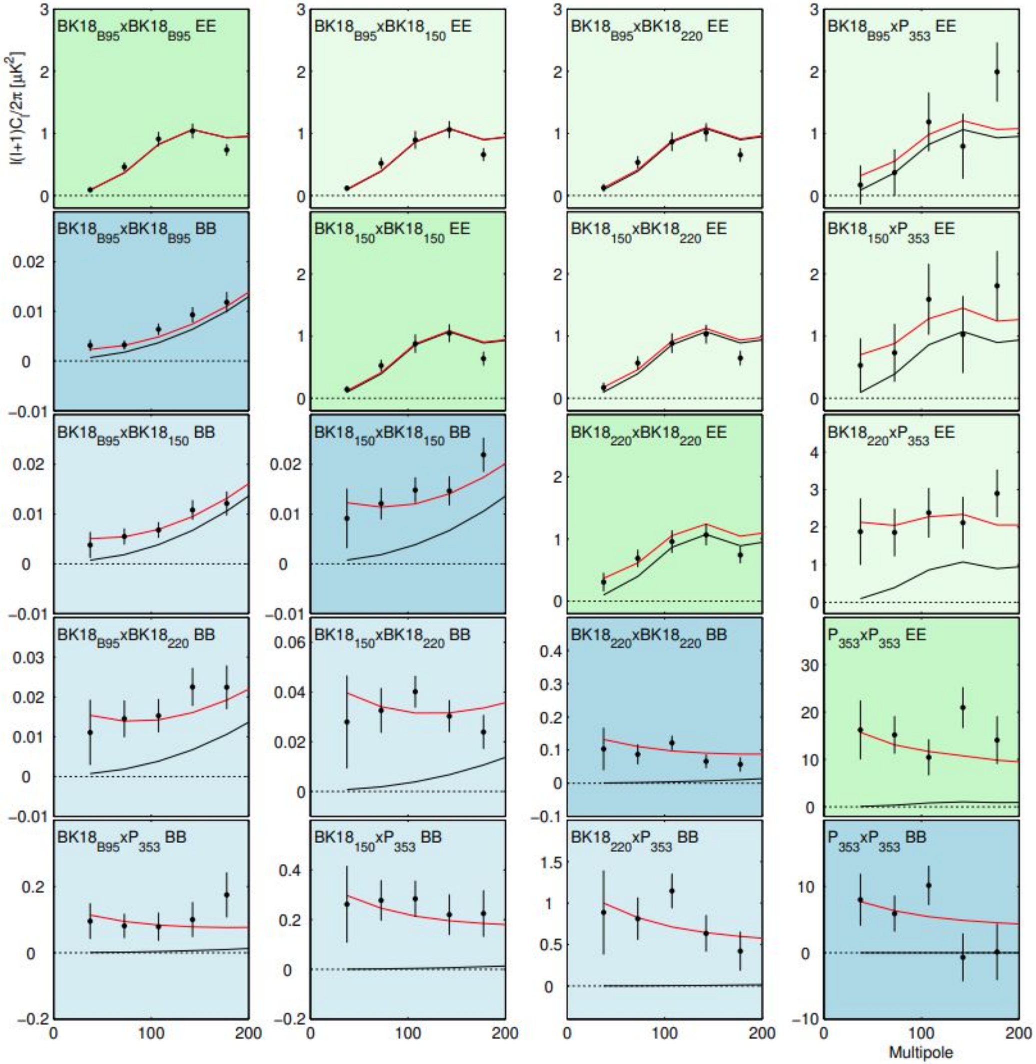
BK18 Spectra

Auto/cross spectra between:
BICEP3 95 GHz
BICEP2/Keck 150 GHz
Keck 220 GHz
Planck 353 GHz

Black lines are LCDM
Red lines are LCDM + foreground

Blue panels are BB spectra



Green panels are EE spectra

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Likelihood Analysis

Joint likelihood of all 66 BB spectra + cross-spectra (incl. Planck + WMAP)

7-parameter model: Lensed LCDM + *r* + dust/synch foregrounds

- Amplitudes
- Spatial spectral indices
- Frequency spectral indices
- Dust/synch spatial correlation

Keck 220 GHz now exceeds Planck 353 SNR on dust - β_d prior no longer needed!

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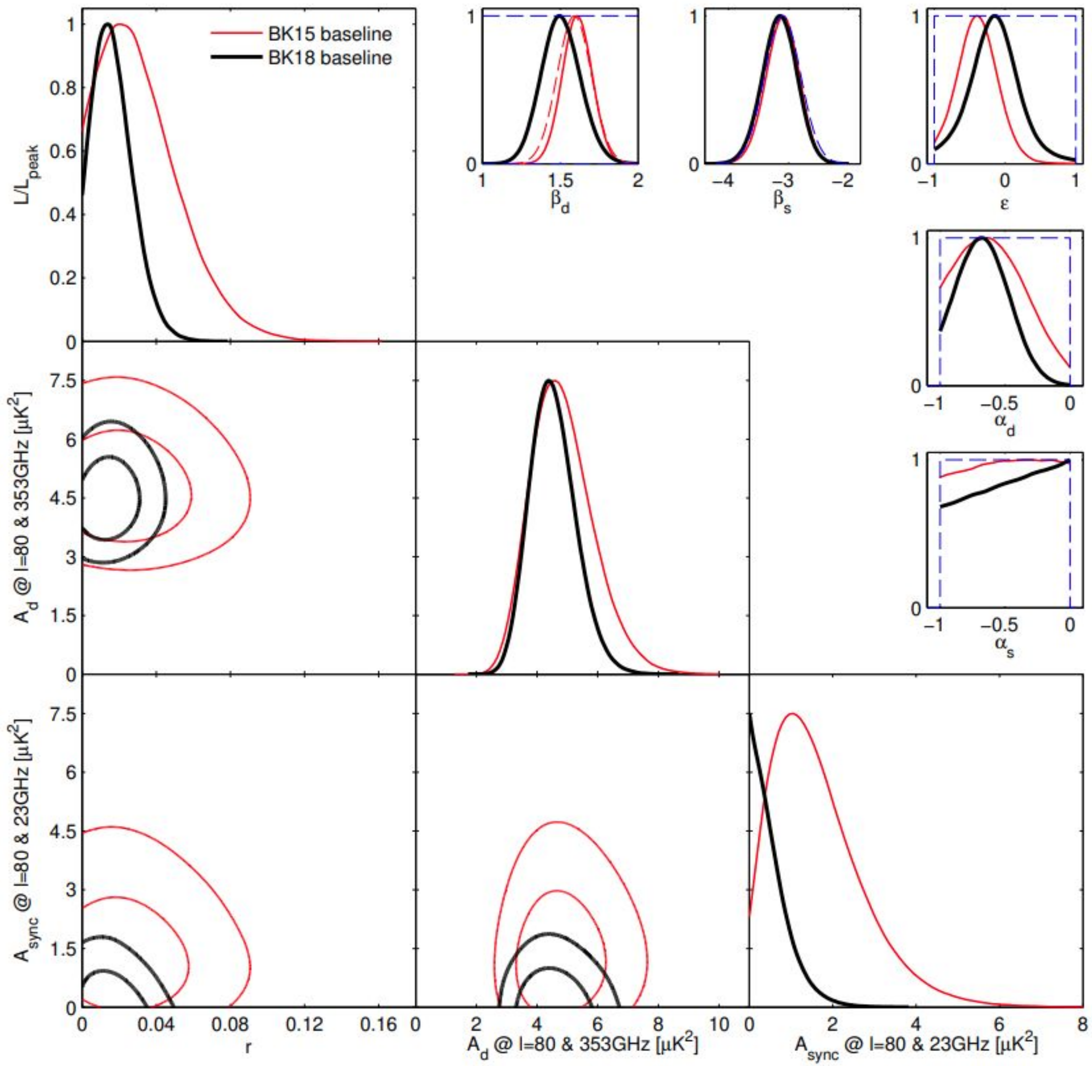
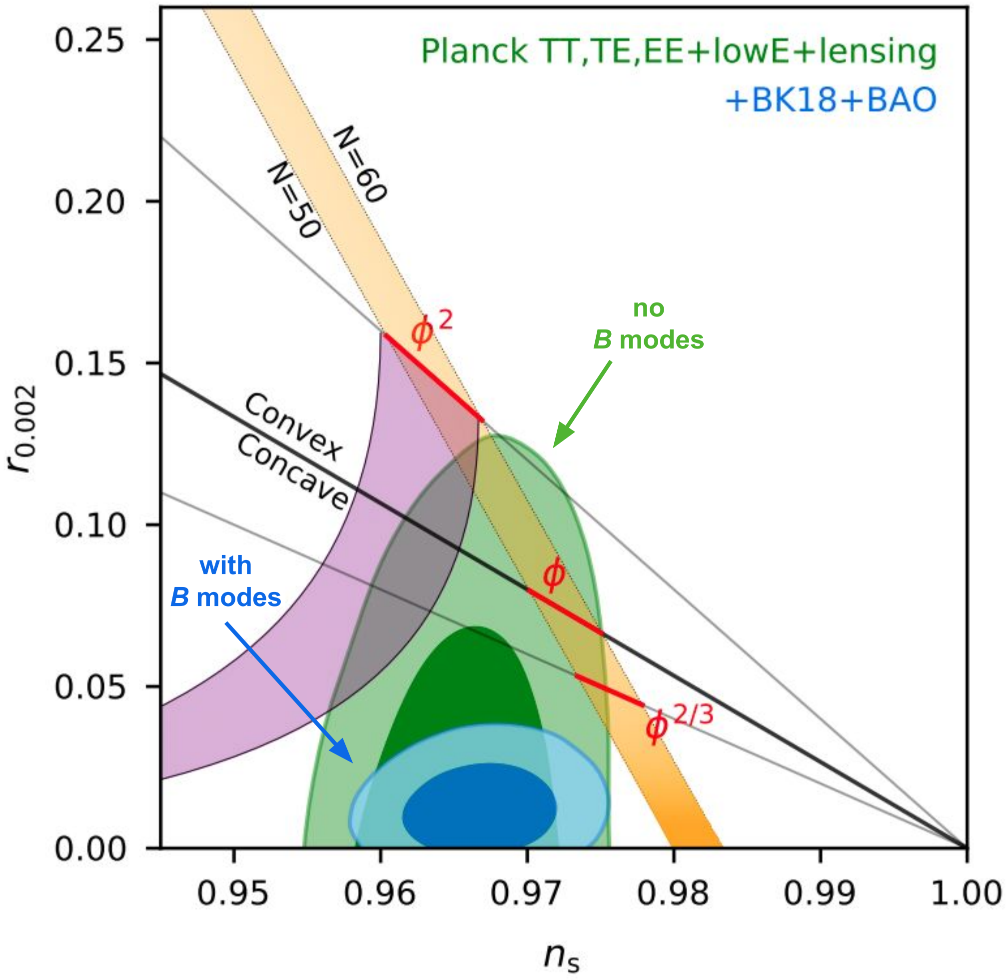


Inflationary Constraints

BKP (1502.00612)	$r_{0.05} < 0.09$
BK14 (1510.09217)	$r_{0.05} < 0.07$
BK15 (1810.05216)	$r_{0.05} < 0.06$
BK18 (2110.00483)	$r_{0.05} < 0.036$

B modes are now excluding popular inflationary models (monomial, natural inflation…)



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Spectral Decomposition

Bandpower-by-bandpower fit to a **CMB** + **dust** + **synch** model (Planck β_d prior imposed)

Additional evidence that polarized dust follows a power law

Synchrotron tightly limited

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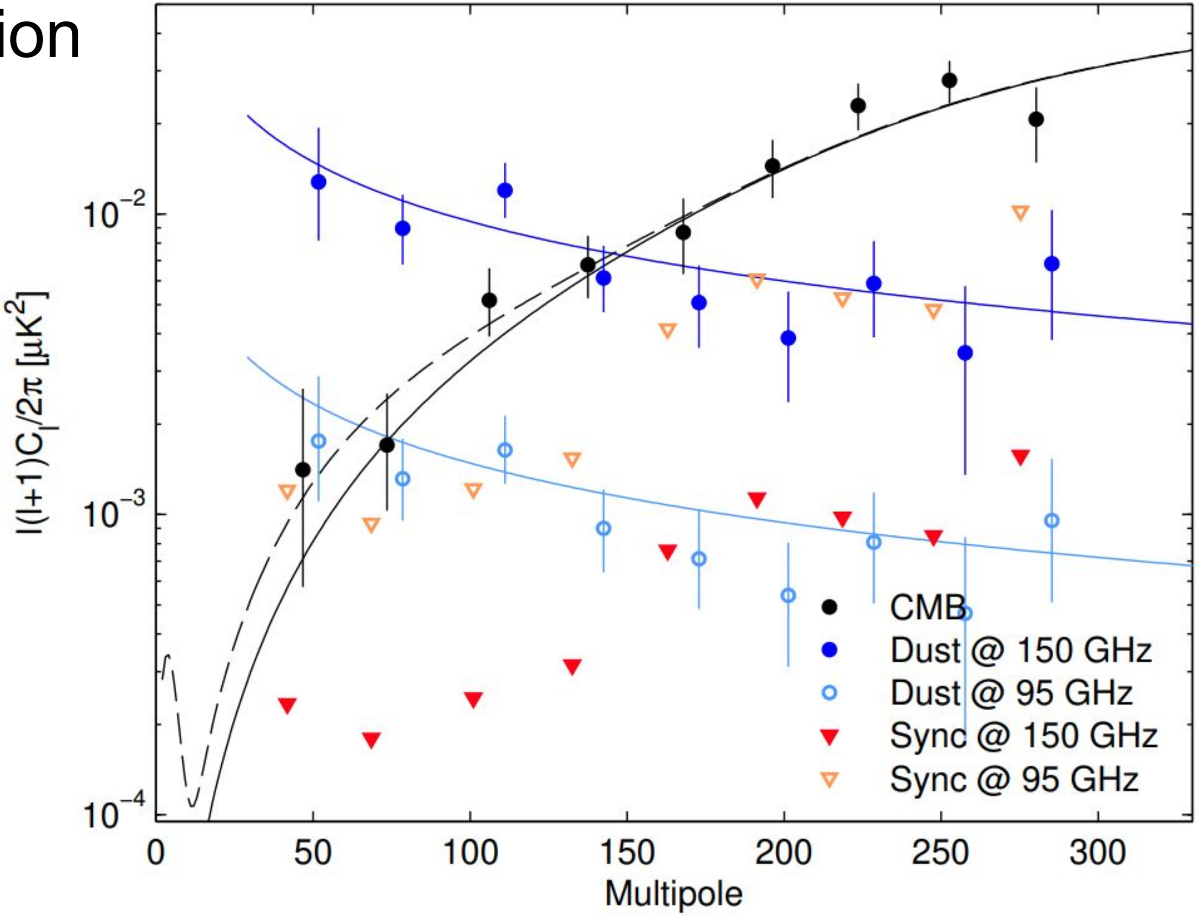

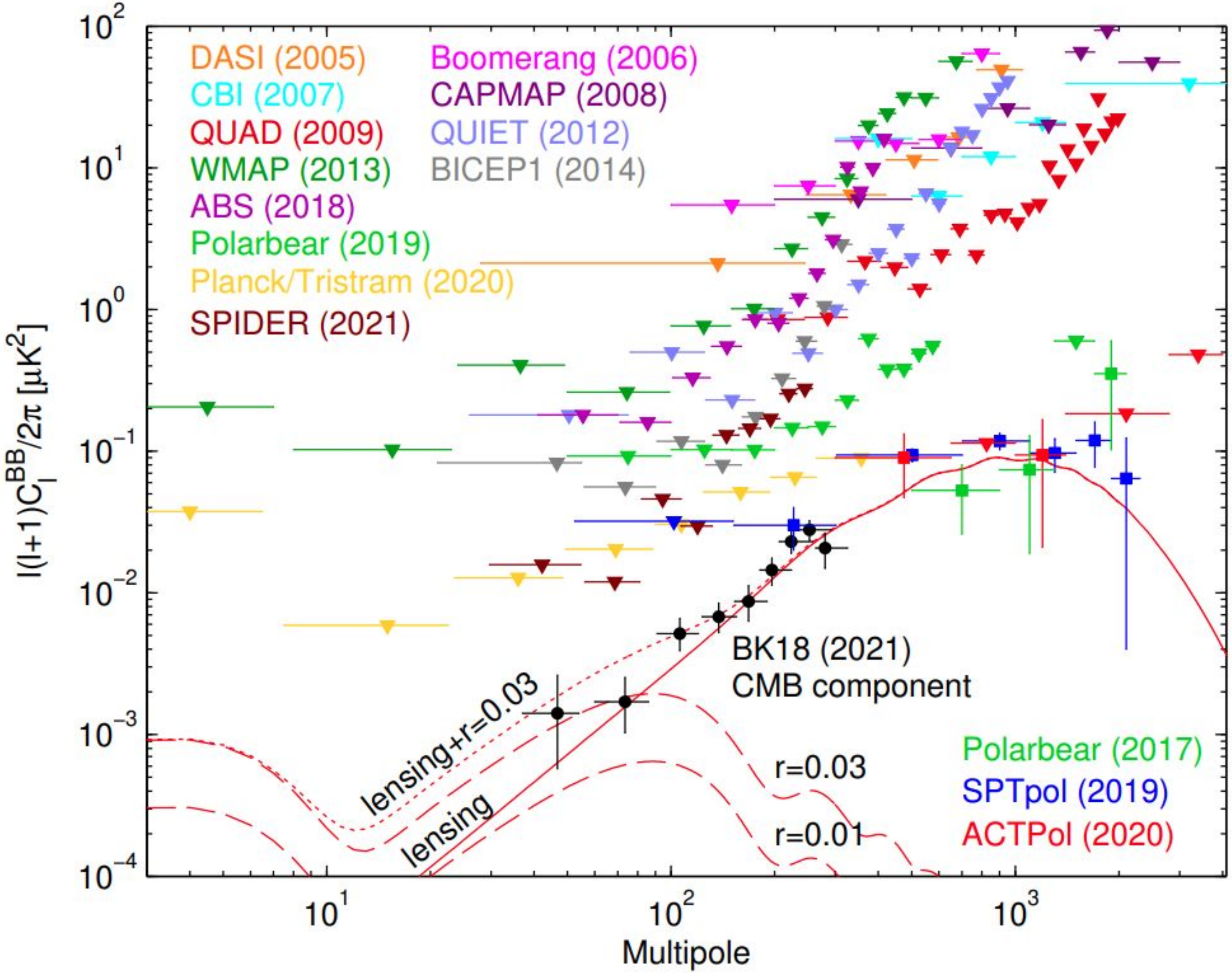

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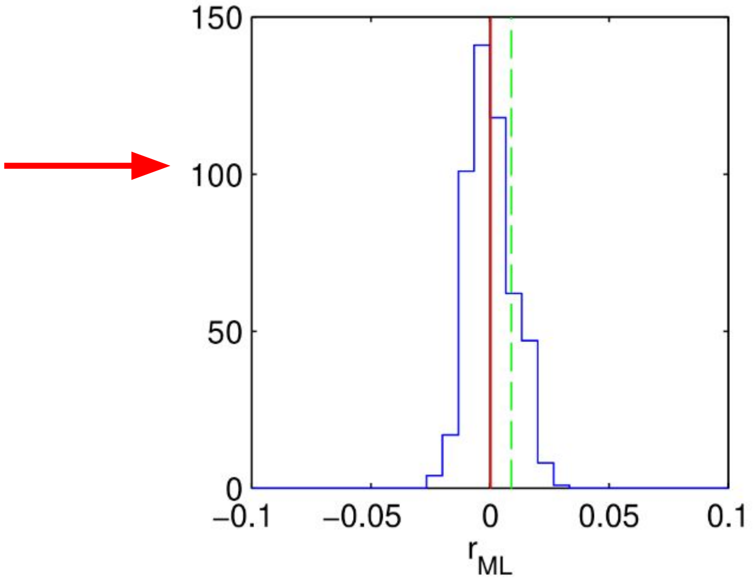
What Limits BK18?

Sims with dust + lensing (standard)	σ(r) = 0.009
Sims without foregrounds	σ(r) = 0.007
Sims without lensing	σ(r) = 0.004
Sims without foregrounds or lensing	σ(r) = 0.002



Delensing with high-resolution SPT-3G data is critical going forward!

(and of course more deep, multifrequency degree-scale data)

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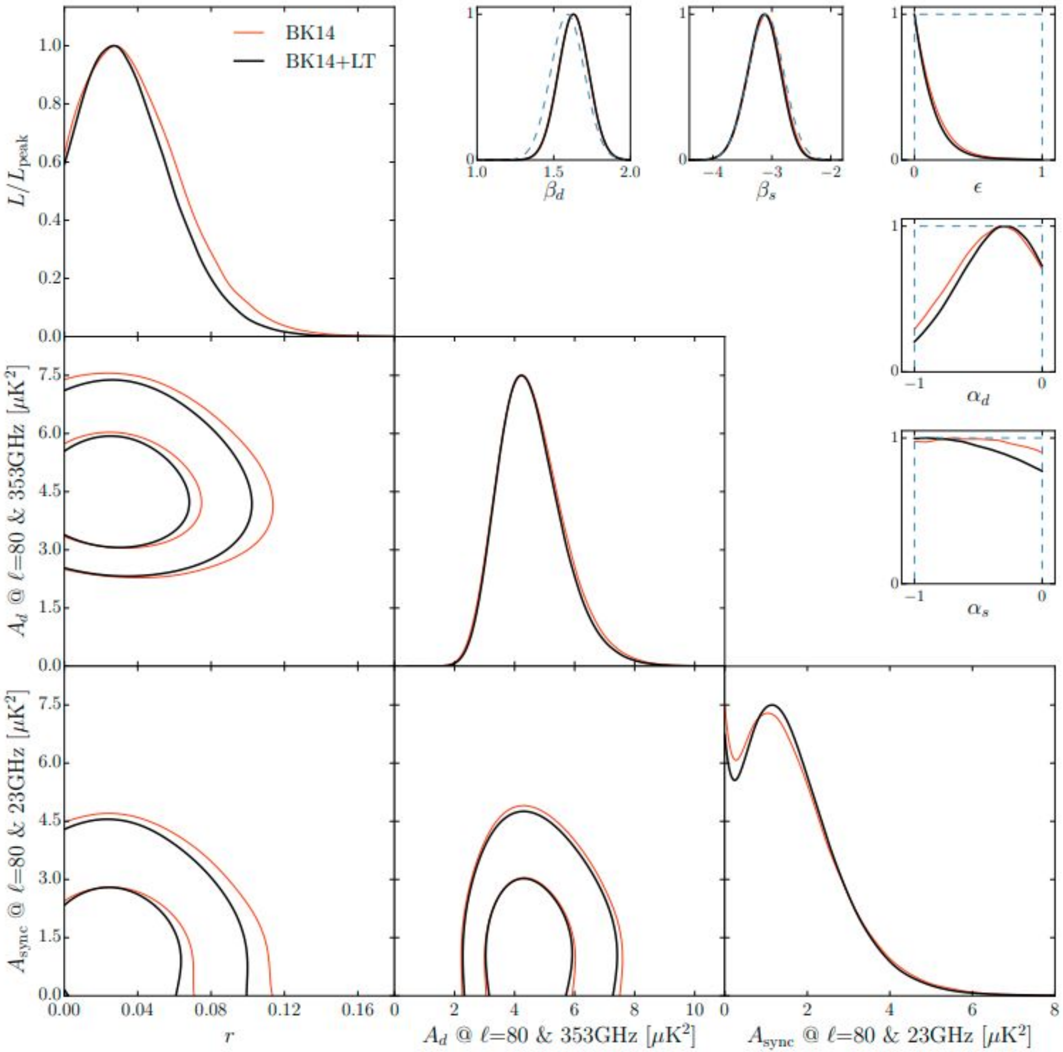
Delensing Demo

Create a “lensing template” using SPTpol (E modes) and Planck (CIB map as phi tracer)

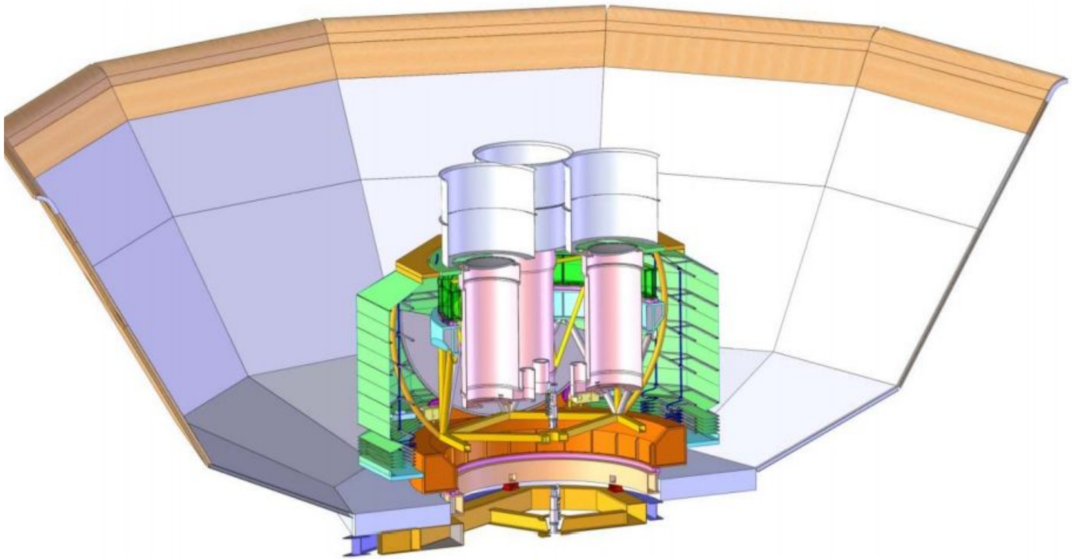
Add lensing template to BK14 analysis: *r* limit reduced by ~10%, in line with simulations

Impact for future datasets will be much greater - eventually move to “internal” phi estimates

PRD 2021
2011.08163



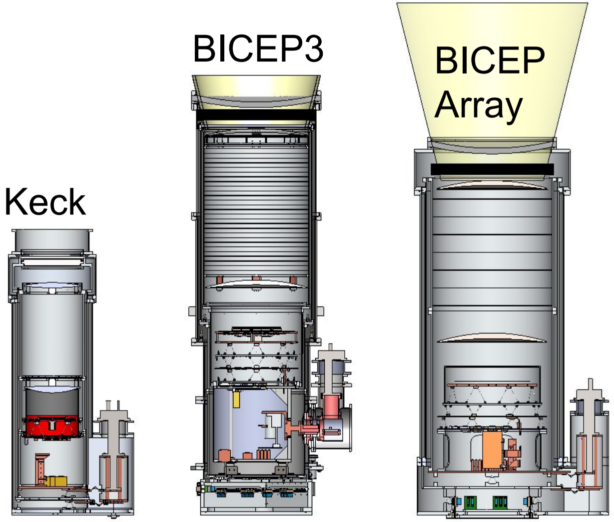
BICEP Array is under construction



Replace Keck Array with 4x BICEP3-class receivers on a new mount

Nominal detector counts:

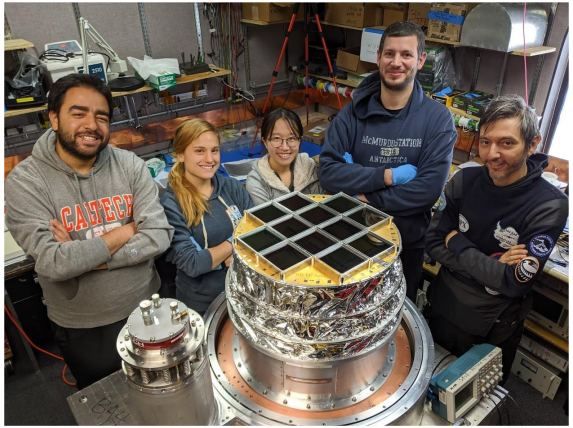
192 @ 30 GHz
300 @ 40 GHz
4056 @ 95 GHz
7776 @ 150 GHz
8112 @ 220 GHz
12288 @ 270 GHz



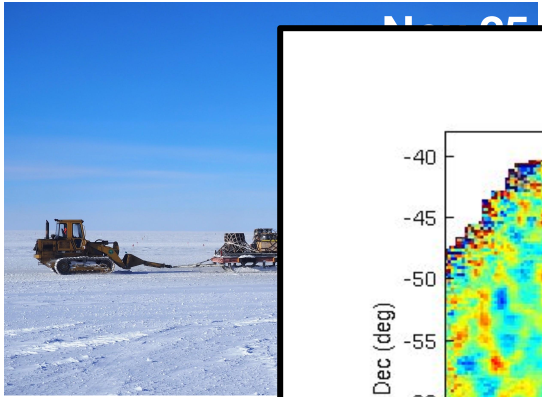
2019-2020 Deployment

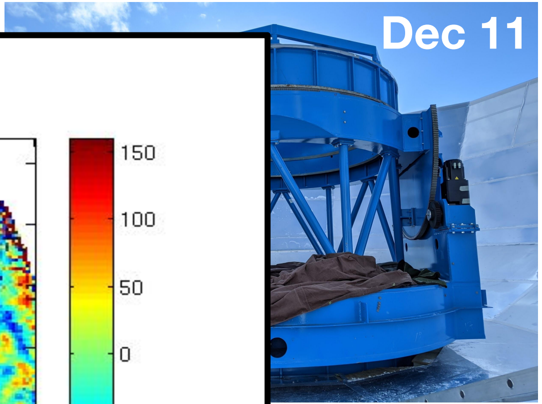
Three-month window during the Antarctic summer to perform:

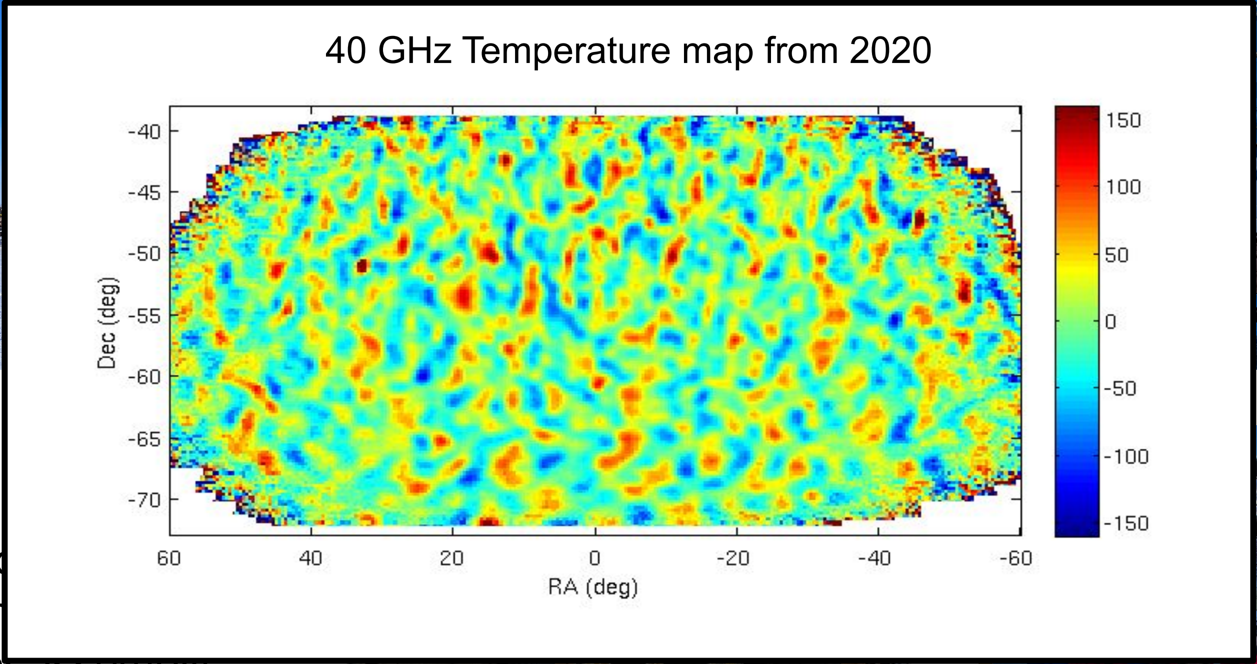
- Keck Array demolition
- BA mount installation
- BA1 receiver assembly
- Full system integration



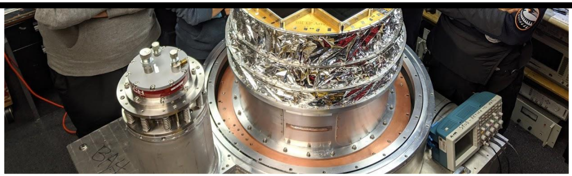
2019-2020 Deployment

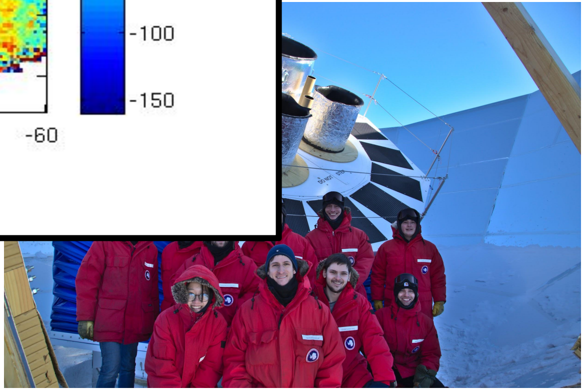






Three-month wi
Antarctic summ
- Keck Array d
- BA mount in
- BA1 receiver assembly
- Full system integration

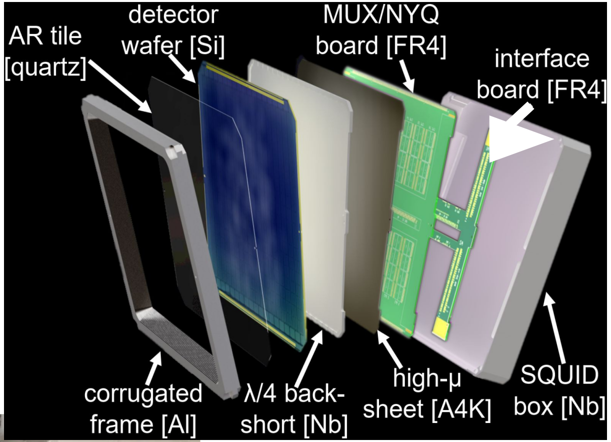


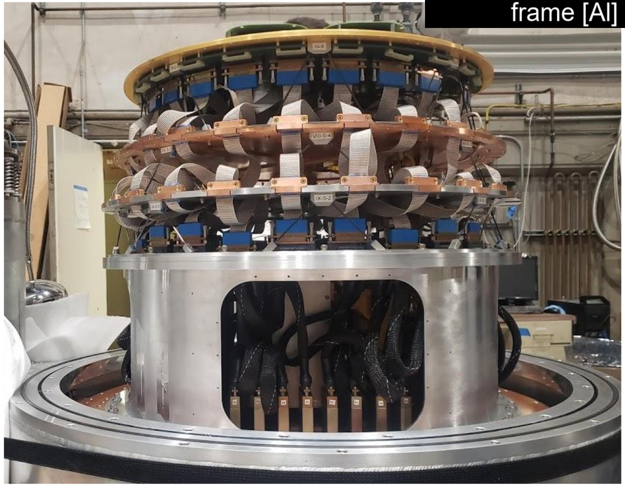


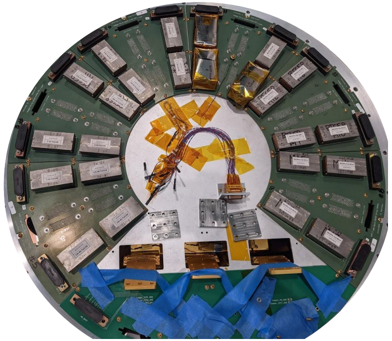
BA2 - 150 GHz Receiver

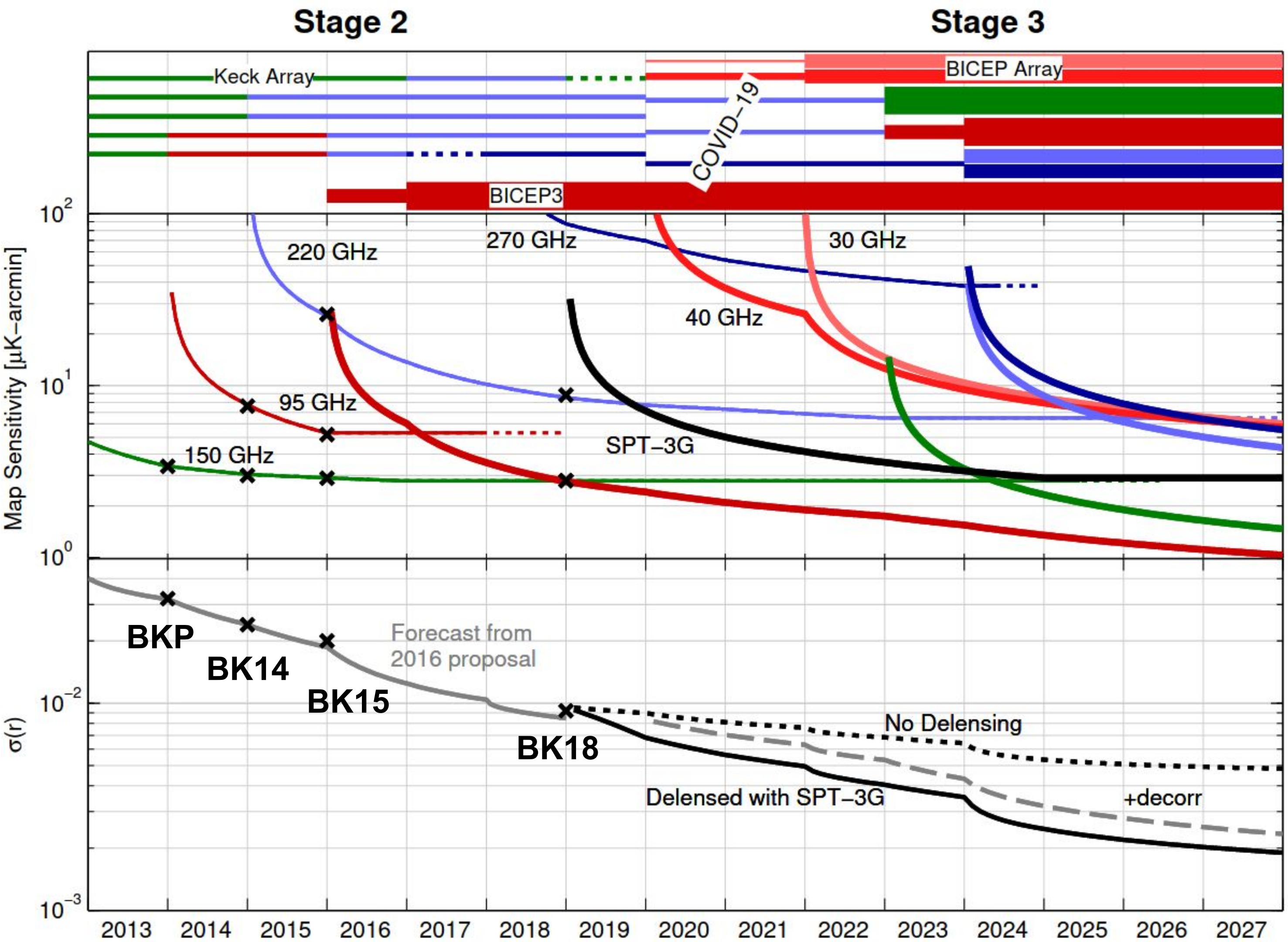
12 modules for 7778 detectors

Required a new high-density readout PCB









Stage 2
Stage 3
Keck Array
BICEP Array
COVID–19
BICEP3
Map Sensitivity [μK–arcmin]
220 GHz
270 GHz
30 GHz
40 GHz
95 GHz
150 GHz
SPT–3G
σ(r)
BKP
BK14
BK15
Forecast from
2016 proposal
BK18
No Delensing
Delensed with SPT–3G
+decorr
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027

Summary

BICEP/Keck has produced the deepest degree-scale CMB polarization maps to date, and the tightest limits on primordial gravitational waves.

Adding 2016-2018 data improves the constraint from $r < 0.07$ to $r < 0.036$.

For the first time, we do not require priors from other parts of the sky.

BICEP3 continues to take data and BICEP Array has accumulated 2 years of low-frequency maps - more BA receivers to deploy soon! Delensing with SPT-3G will improve r constraints significantly. Anticipate $\sigma(r) \sim 0.003$.

BA + SPT-3G serves as a pathfinder for the CMB-S4 inflation survey.

Backup

BA-2 150GHz Receiver

BA-2 is in its Integration and Calibration Phase ahead of its Deployment (2021-2022?):

Some BA2 facts:

- 12x Detector Modules for 7778 TES Detectors at 150GHz
- Using a 41 Row Select multiplexing (4x Mux11 chips per Column) this requires 32 x 6 = 192 Columns.
- 6x Multi Channel Electronic Crates are required. Each of them reads 2x Detector Modules
- Detector Module needed a new High Density Readout PCB to accommodate such large number of Detectors