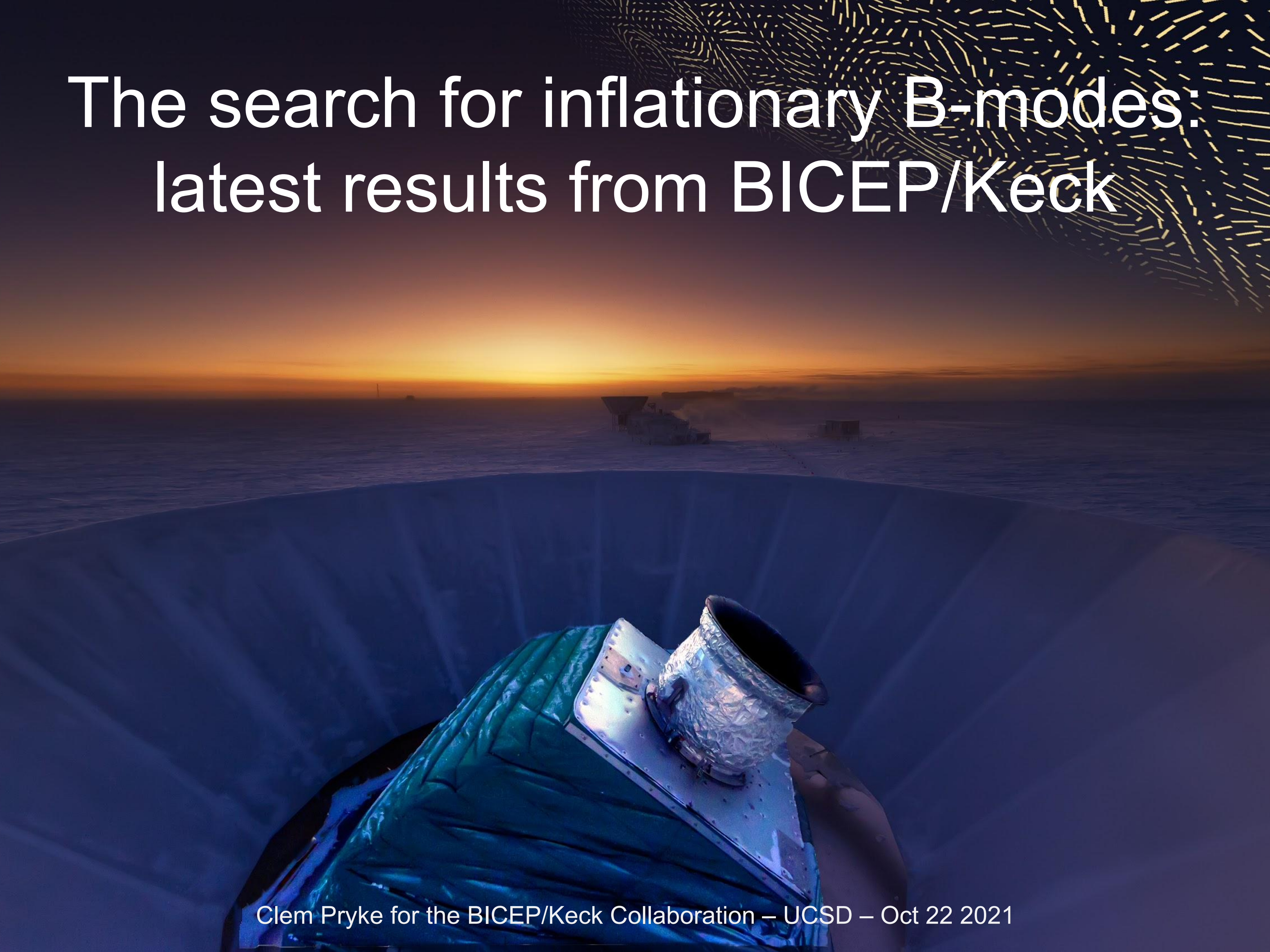
The search for inflationary B-modes: latest results from BICEP/Keck



Clem Pryke for the BICEP/Keck Collaboration – UCSD – Oct 22 2021

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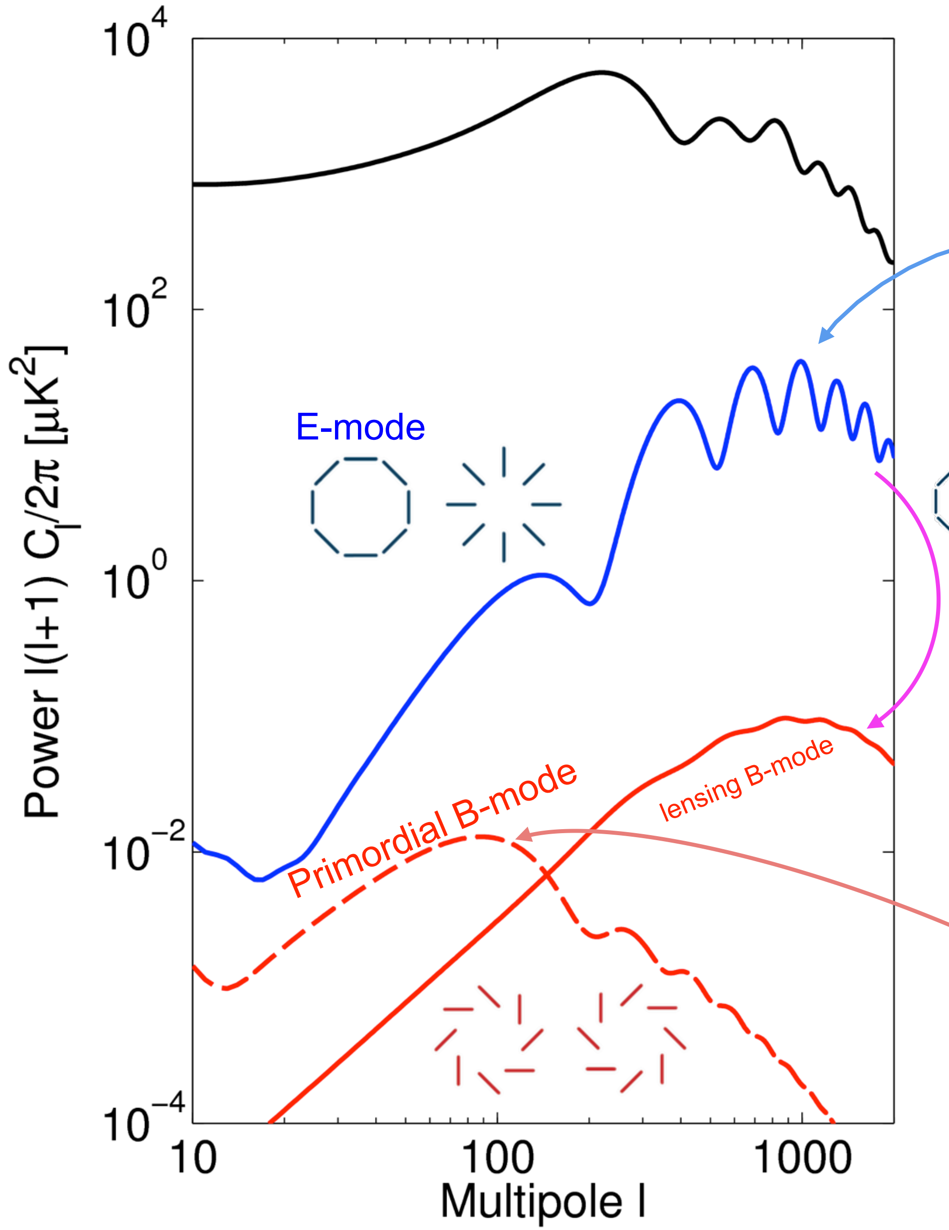
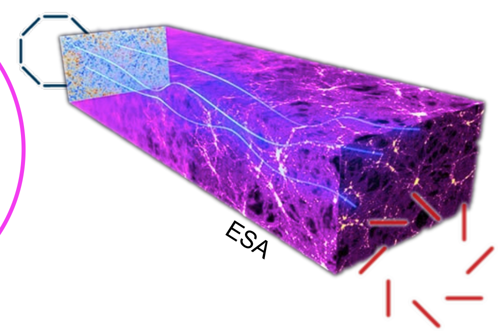
Motivation/Background

- Using the CMB and other data the LCDM cosmological paradigm has been developed – it works great and allows us to understand the development of the universe all the way back to a high energy state.
- However, LCDM leaves many unanswered questions such as the “horizon problem” and how the empirically simple conditions at the start of the plasma phase were set up.
- Theory of “Inflation” added on the beginning of LCDM to explain.
- If it happened Inflation will have made a background of gravitational waves which will have imprinted a B-mode (curl) into the polarization pattern of the CMB.
- We may be able to detect these if we can make a sensitive enough telescope – a wide range of inflation models exist – the simplest are already ruled out – more complex ones can produce r which is undetectably small…

CMB power spectra



In standard ΛCDM only E-modes are present at last scattering



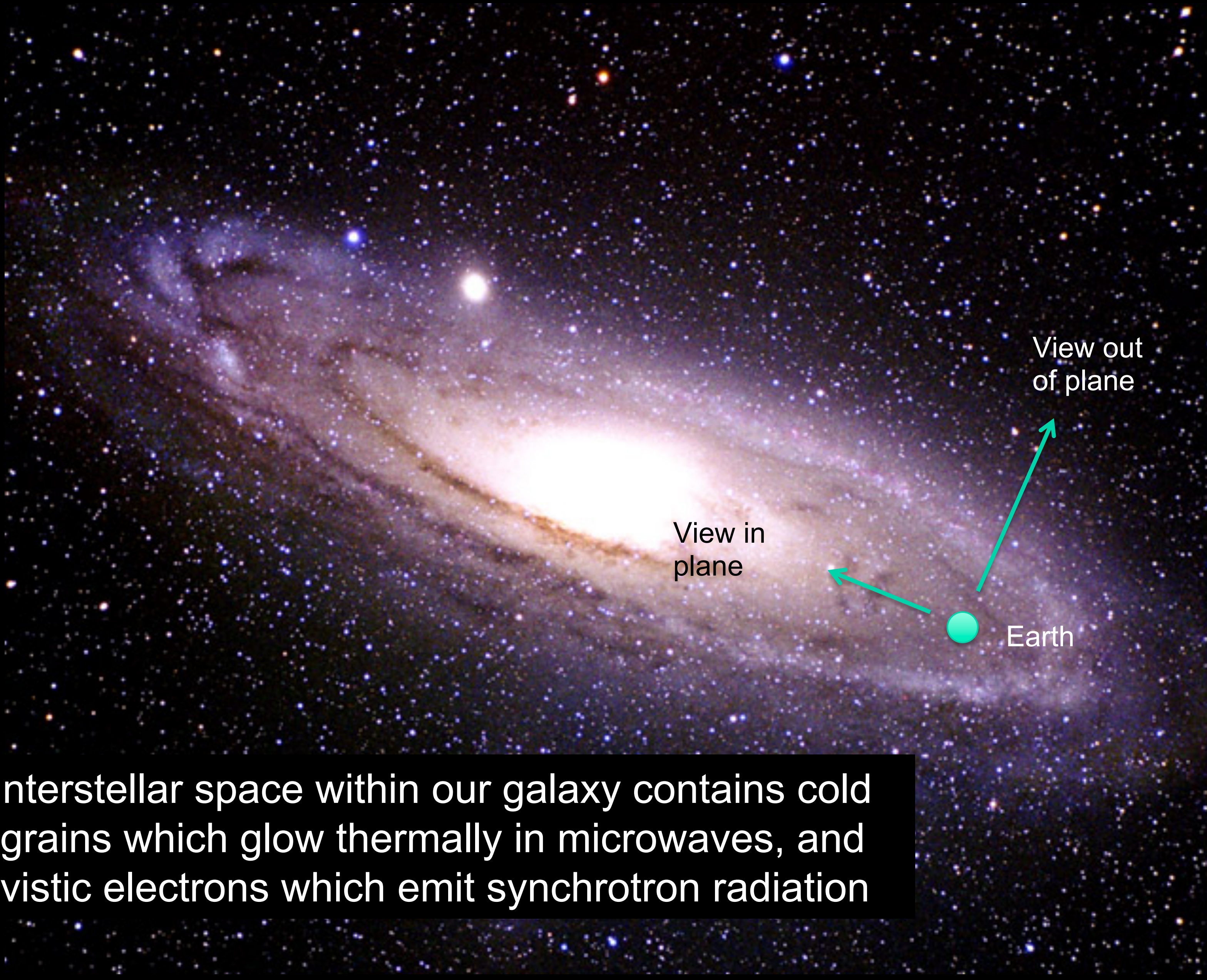
During propagation some of the E-modes are confused into B-modes by lensing

Inflationary gravitational waves are unique source of intrinsic B-modes
→ peaking at l≈80 : few degree scales

BICEP/Keck Basic Experimental Strategy

→ Small aperture telescopes (cheap, fast, low systematics)
→ Target the 2 degree peak of the PGW B-mode
→ Integrate continuously from South Pole
→ Observe 1% patch of sky (smaller is actually better!)
→ Scan and pair difference modulation

Foreground emission from our galaxy



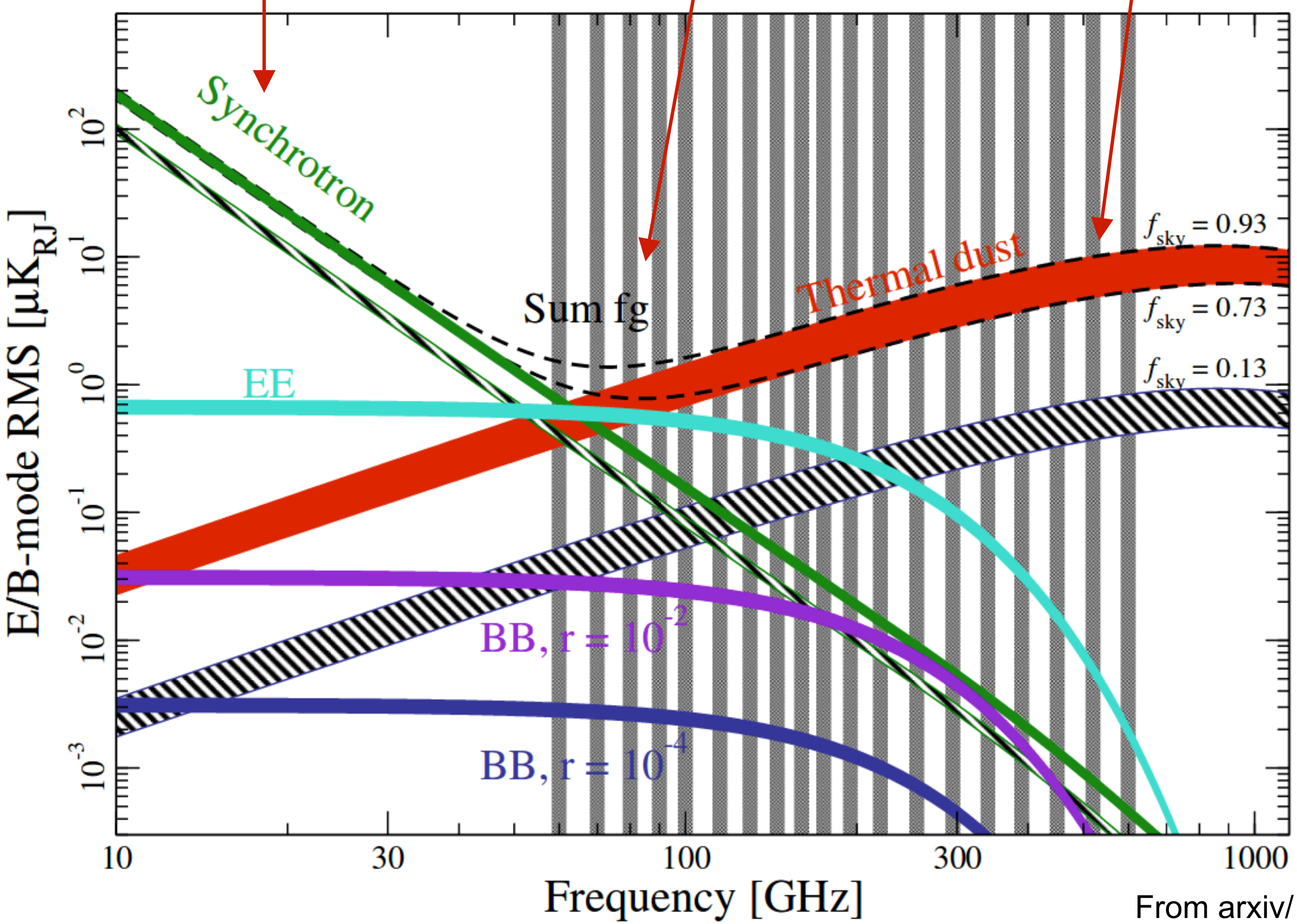
The interstellar space within our galaxy contains cold dust grains which glow thermally in microwaves, and relativistic electrons which emit synchrotron radiation

Overcoming Polarized Foreground Contamination

At low frequency synchrotron contamination

Mid frequencies minimum contamination

At high frequency dust contamination



Going to smaller/ cleaner sky patch

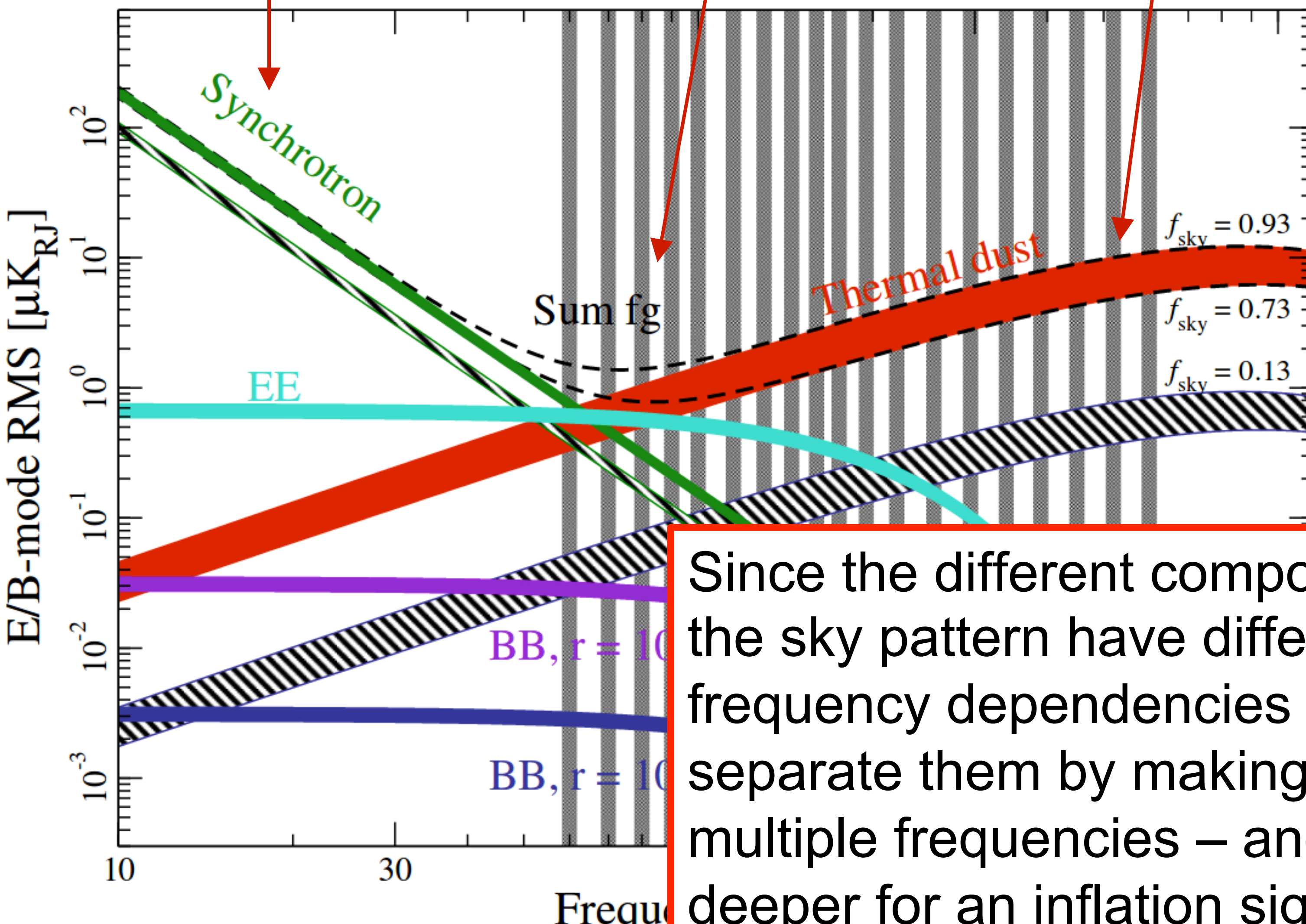
From arxiv/1704.04501

Overcoming Polarized Foreground Contamination

At low frequency synchrotron contamination

Mid frequencies minimum contamination

At high frequency dust contamination



Going to smaller/ cleaner sky patch

Since the different components of the sky pattern have different frequency dependencies one can separate them by making maps at multiple frequencies – and probe deeper for an inflation signal

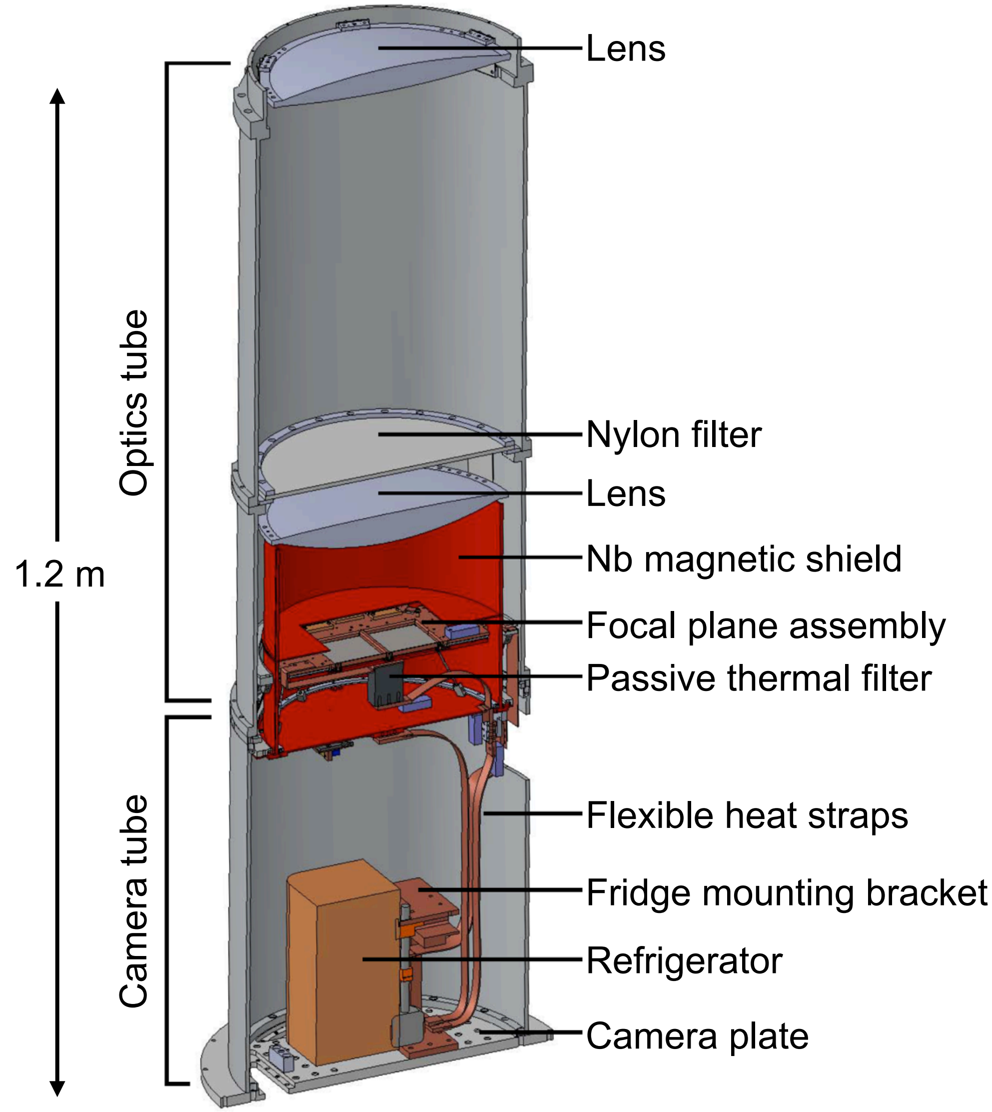
The BICEP/Keck Telescopes

Telescope as compact as possible while still having the angular resolution to observe degree-scale features.

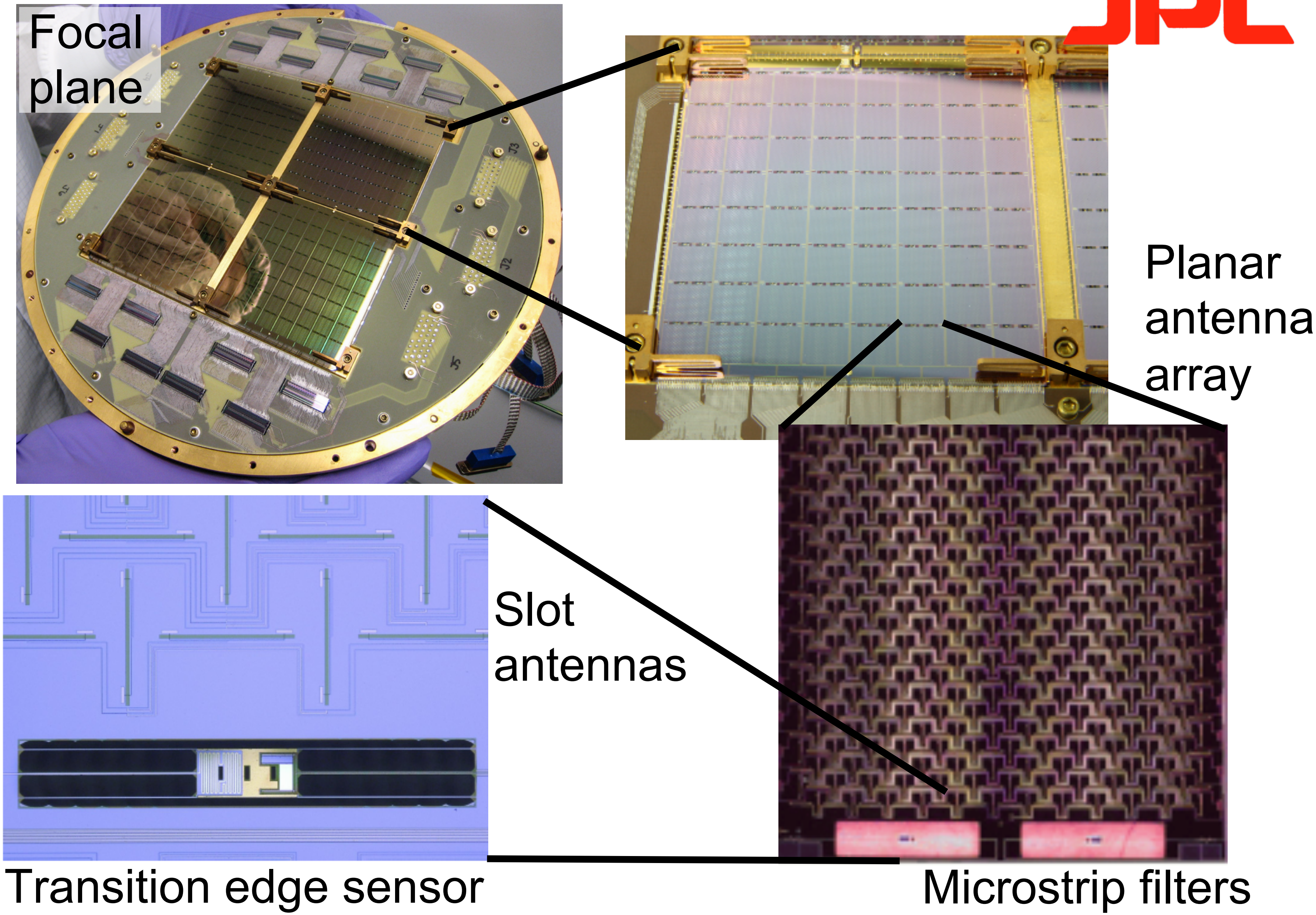
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

Pulse tube cooler cools the optical elements to 4.2 K.

A 3-stage helium sorption refrigerator further cools the detectors to 0.27 K.



Mass-produced Superconducting Detectors



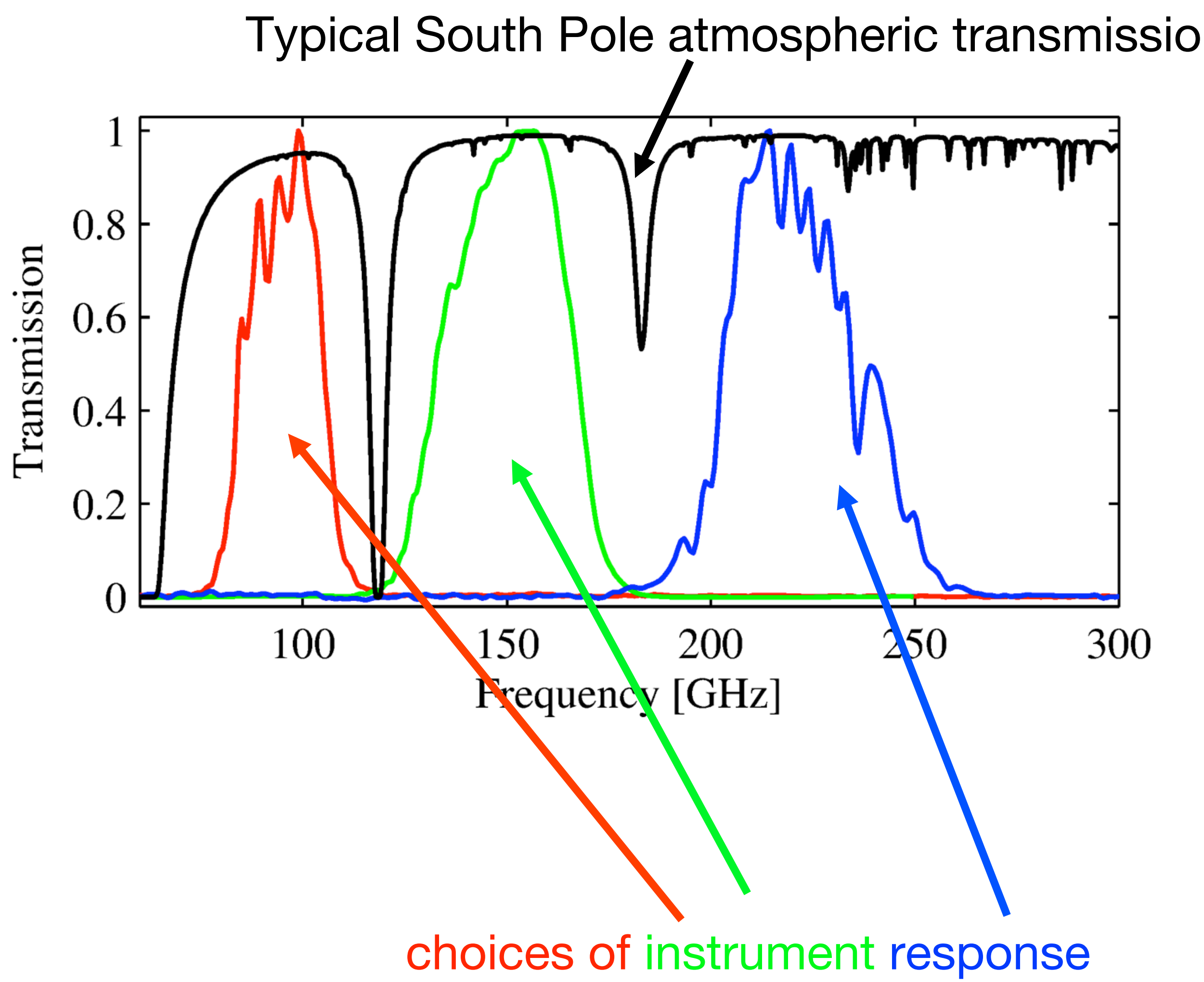
BICEP/Keck Band Passes

The dry South Pole atmosphere provides excellent observing conditions most of the year.

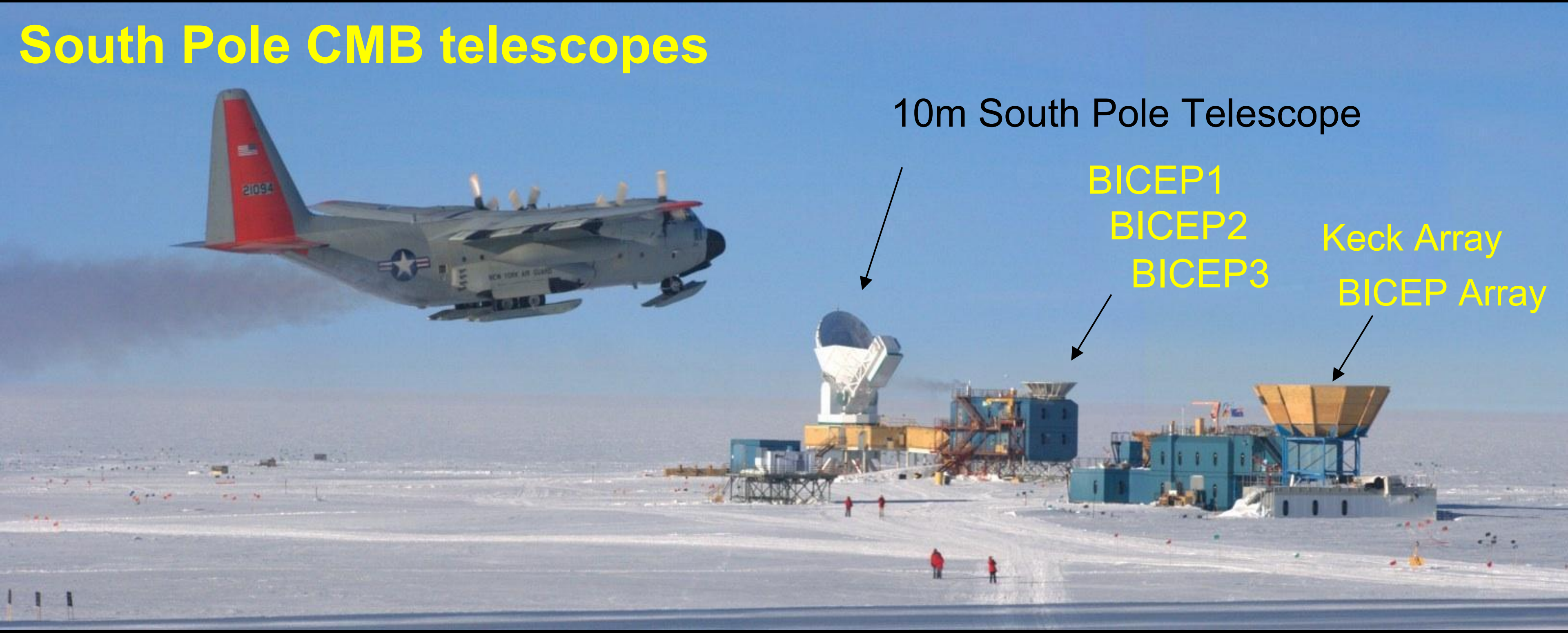
The approx. 30% fractional bandpasses fit within atmospheric transmission windows straddled by oxygen and water lines.

In these windows, the atmosphere is quite transparent to microwaves.

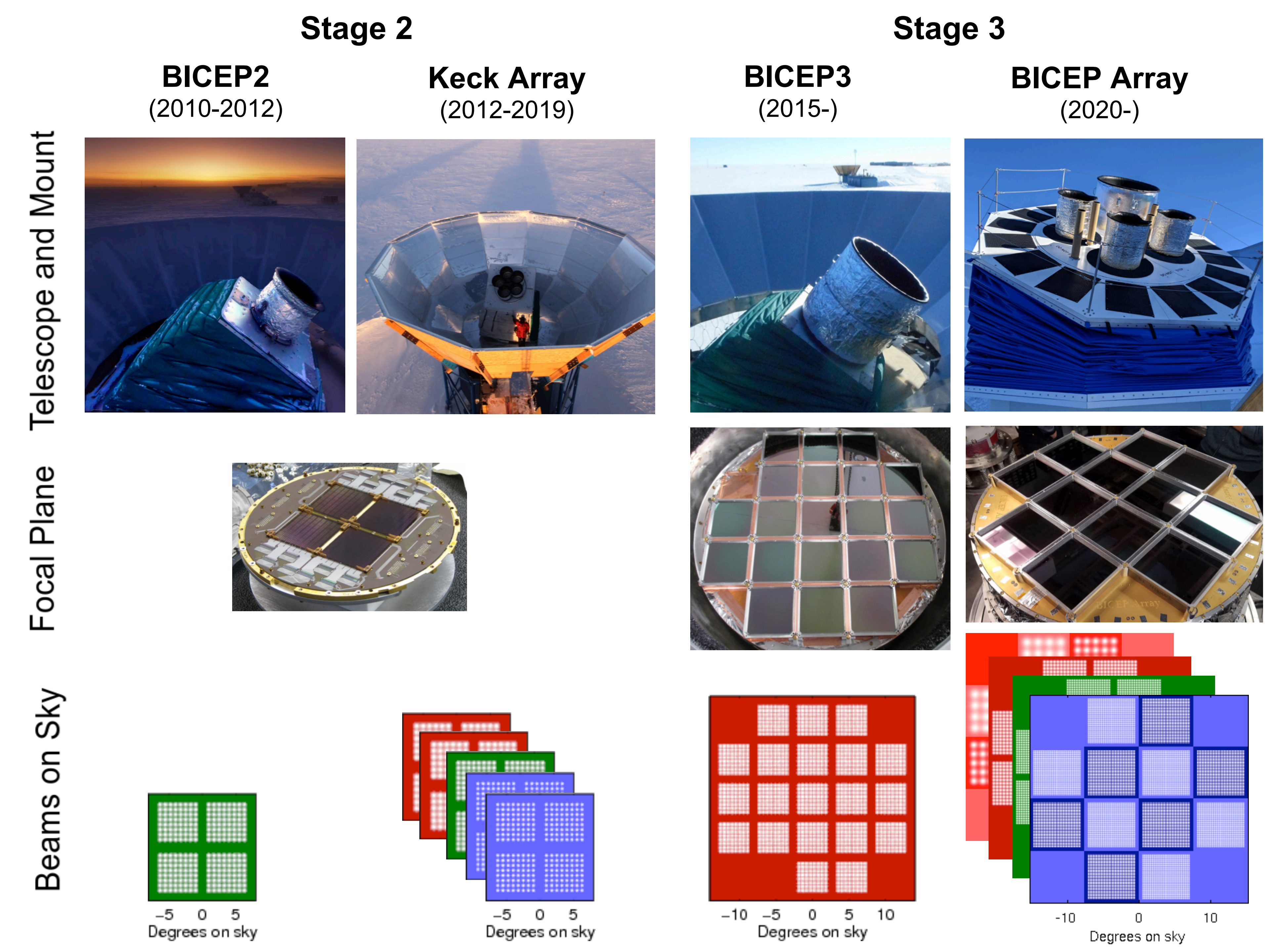
The detector passbands are defined by a filter printed directly onto the focal plane wafers.



Why do this at the Pole?



- High and *dry* – see out into space
- On Earth's rotational axis - One day/night cycle per year
  - Long night makes for great quality data
- Good support infrastructure – power, cargo, data comm
- Food and accommodation provided
- Even Tuesday night bingo…



Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2015-)
BICEP Array
(2020-)
Telescope and Mount
Focal Plane
Beams on Sky
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
-10 0 10
Degrees on sky

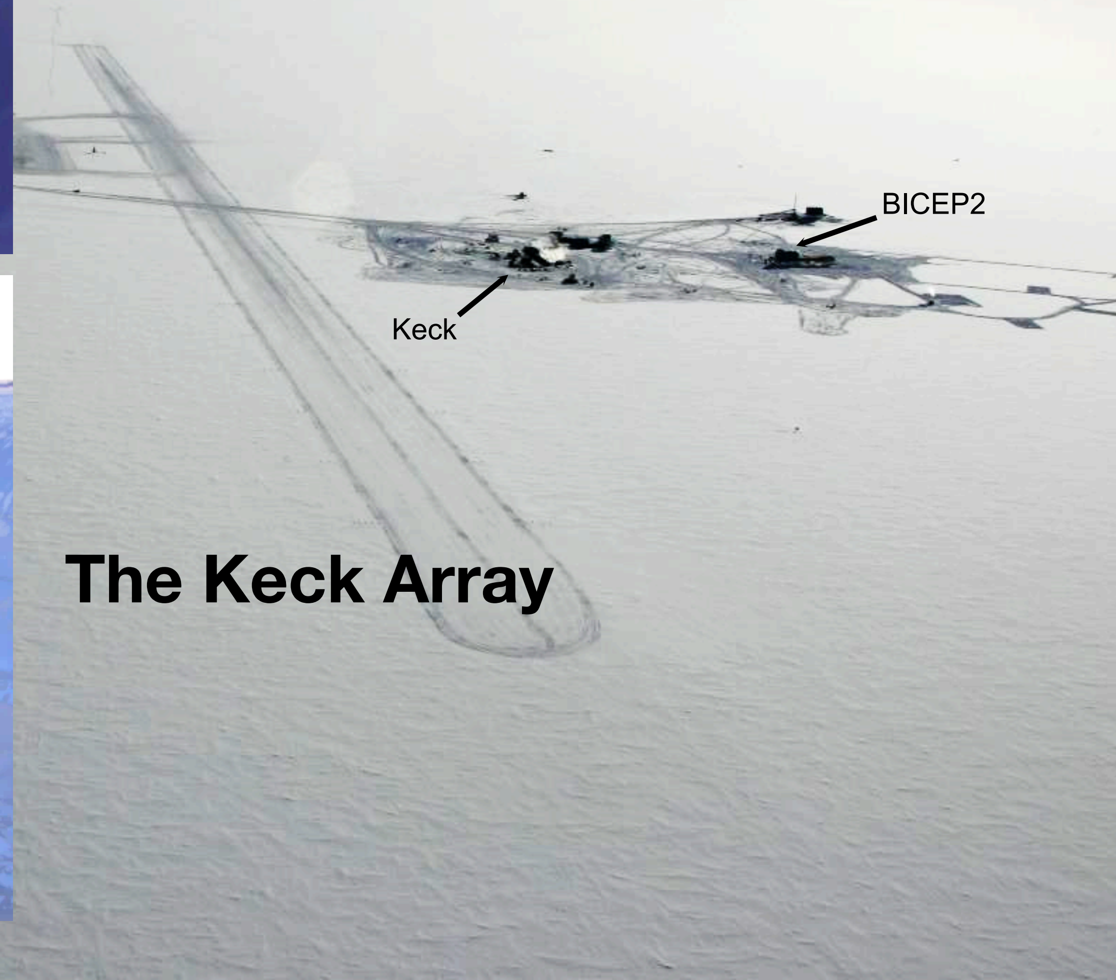
South Pole Site

BICEP2 and Keck Array

BICEP2 2009-2011

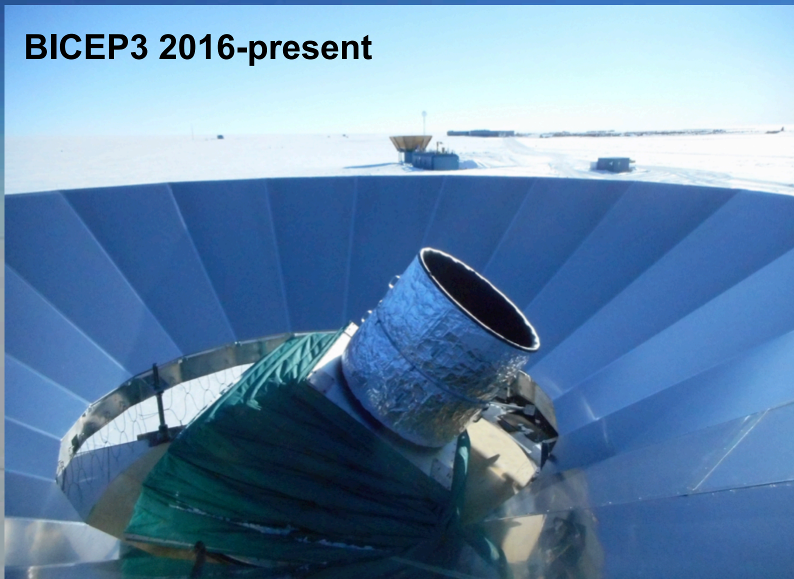
Keck Array 2011-2019

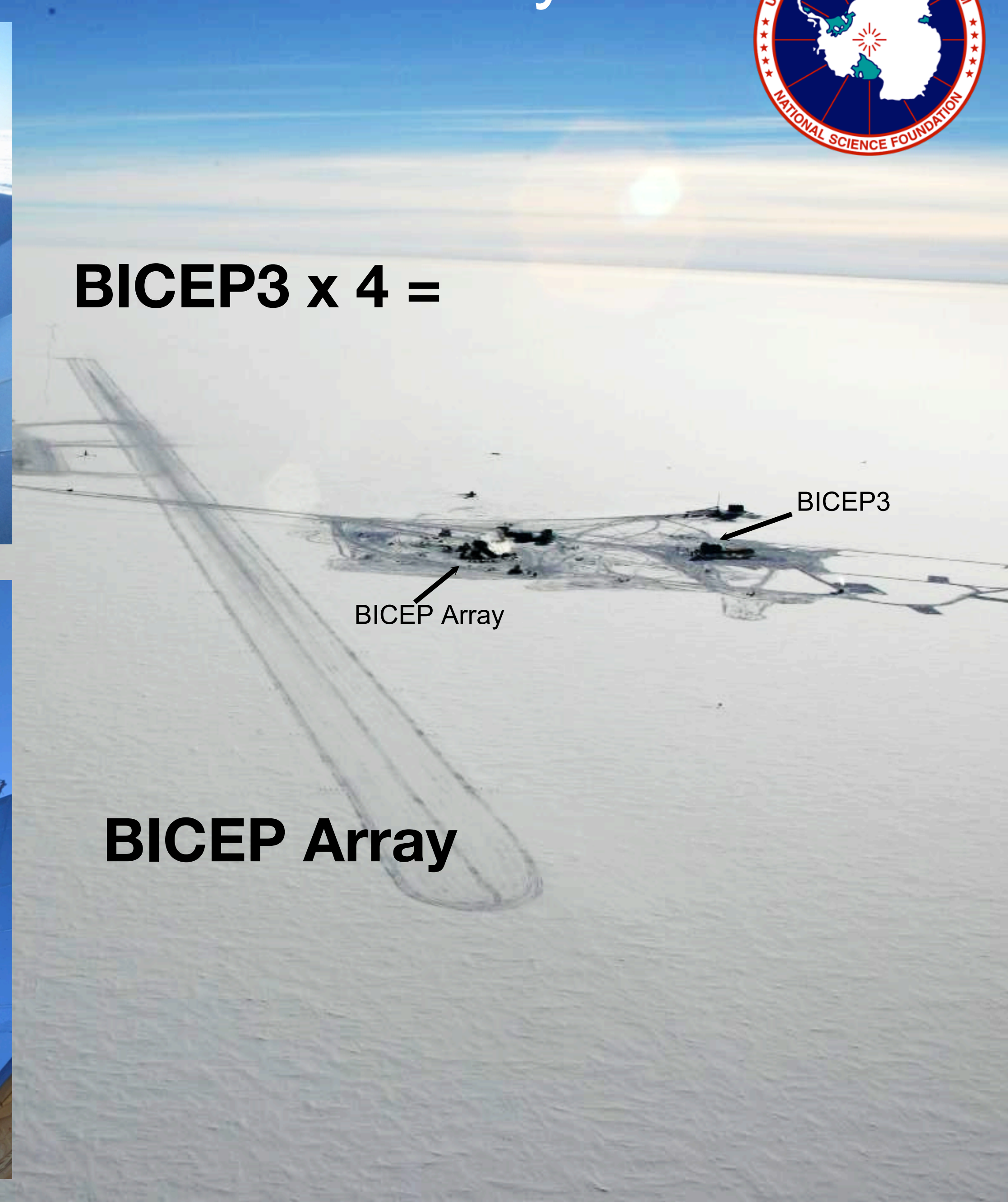
BICEP2 x 5 =



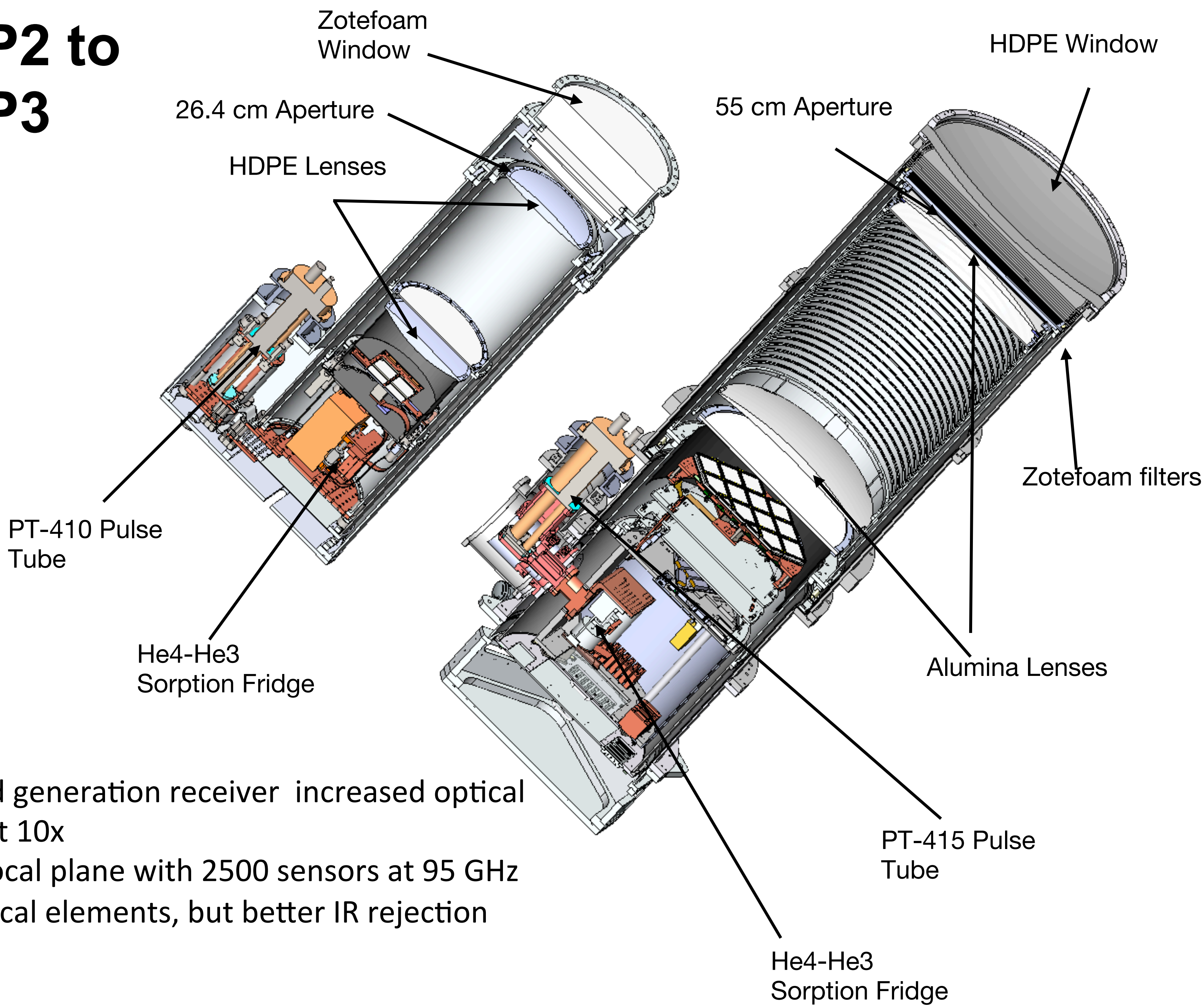
The Keck Array

BICEP3 and BICEP Array

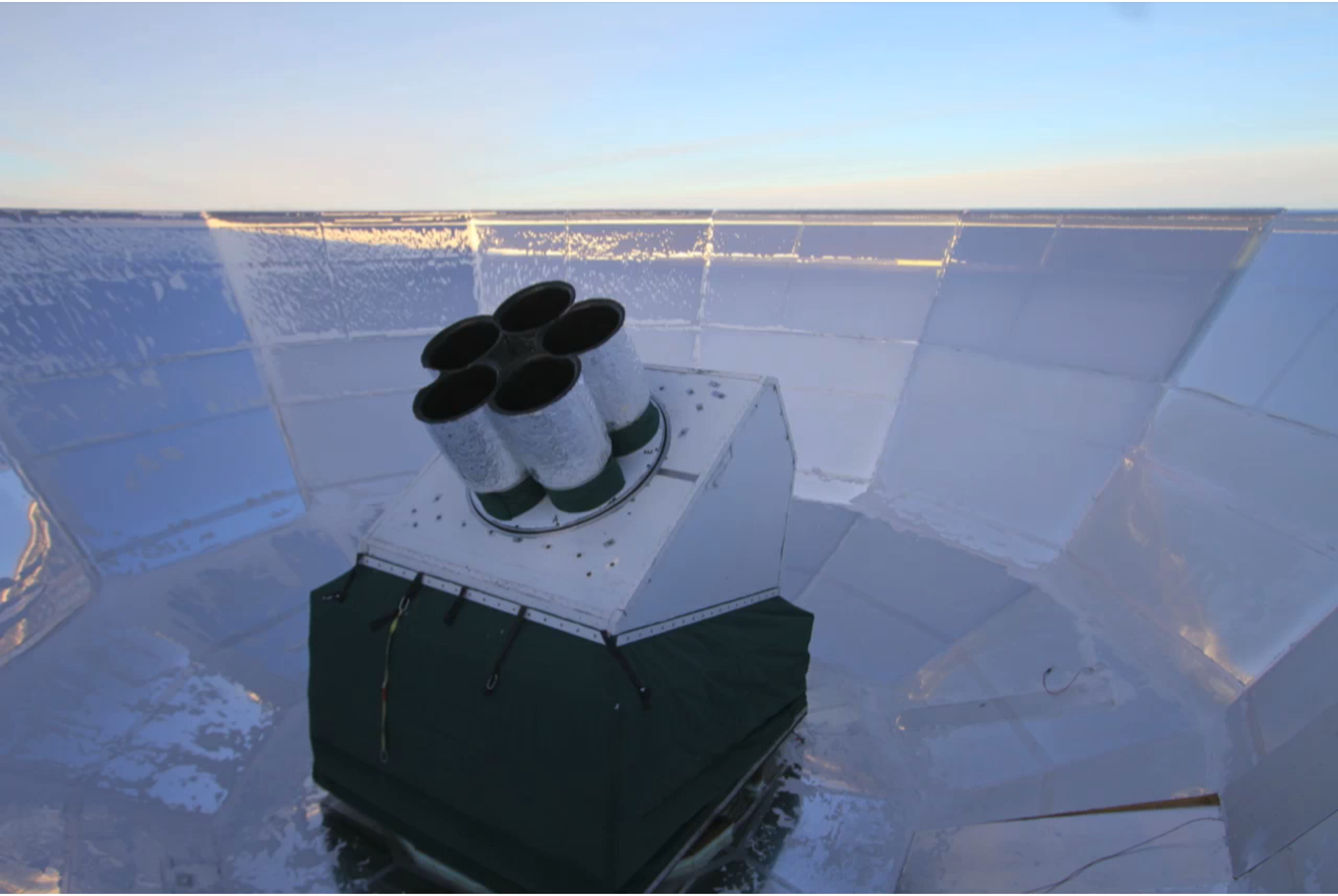




BICEP2 to BICEP3

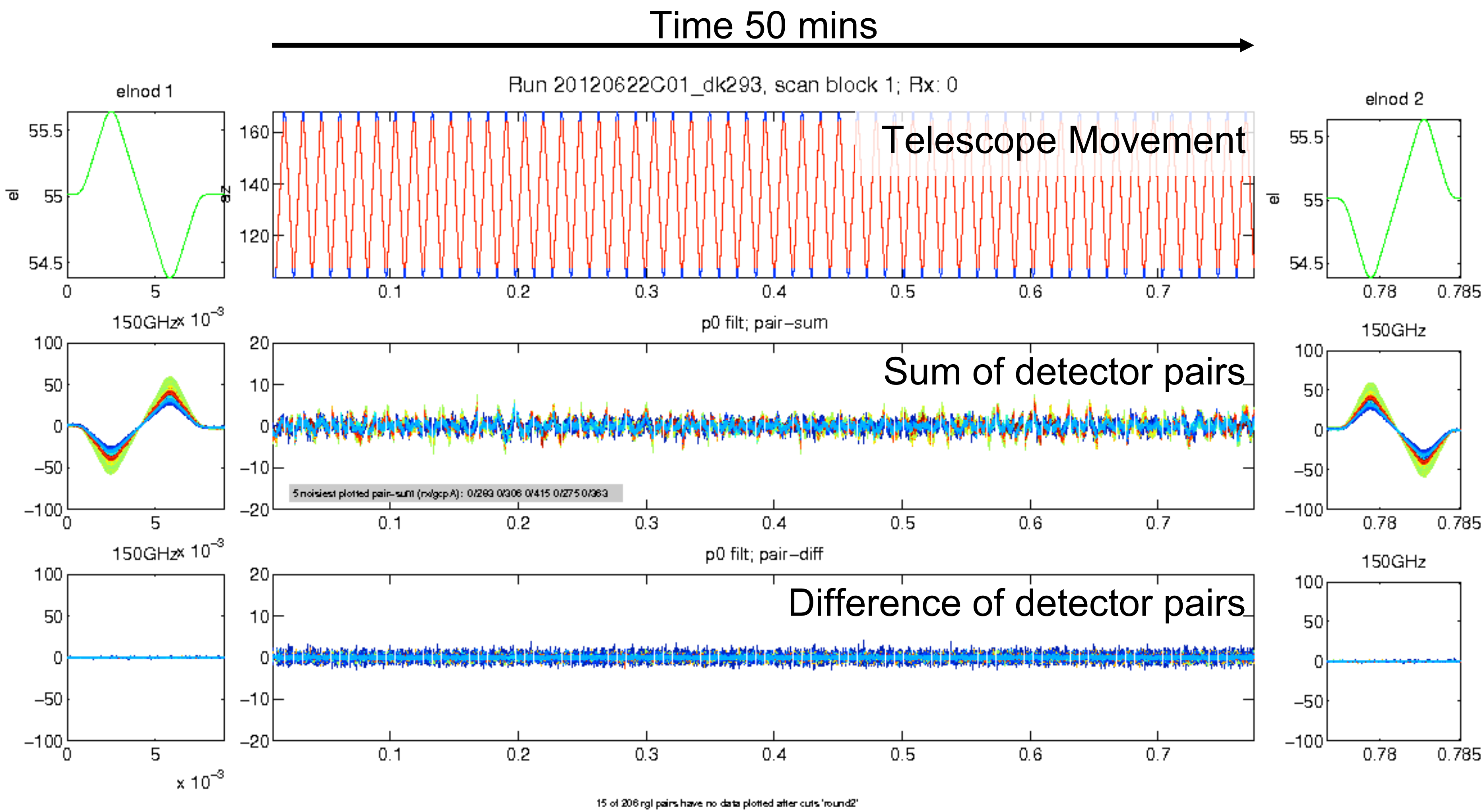


- BICEP's 3rd generation receiver increased optical throughput 10x
- Modular focal plane with 2500 sensors at 95 GHz
- Larger optical elements, but better IR rejection



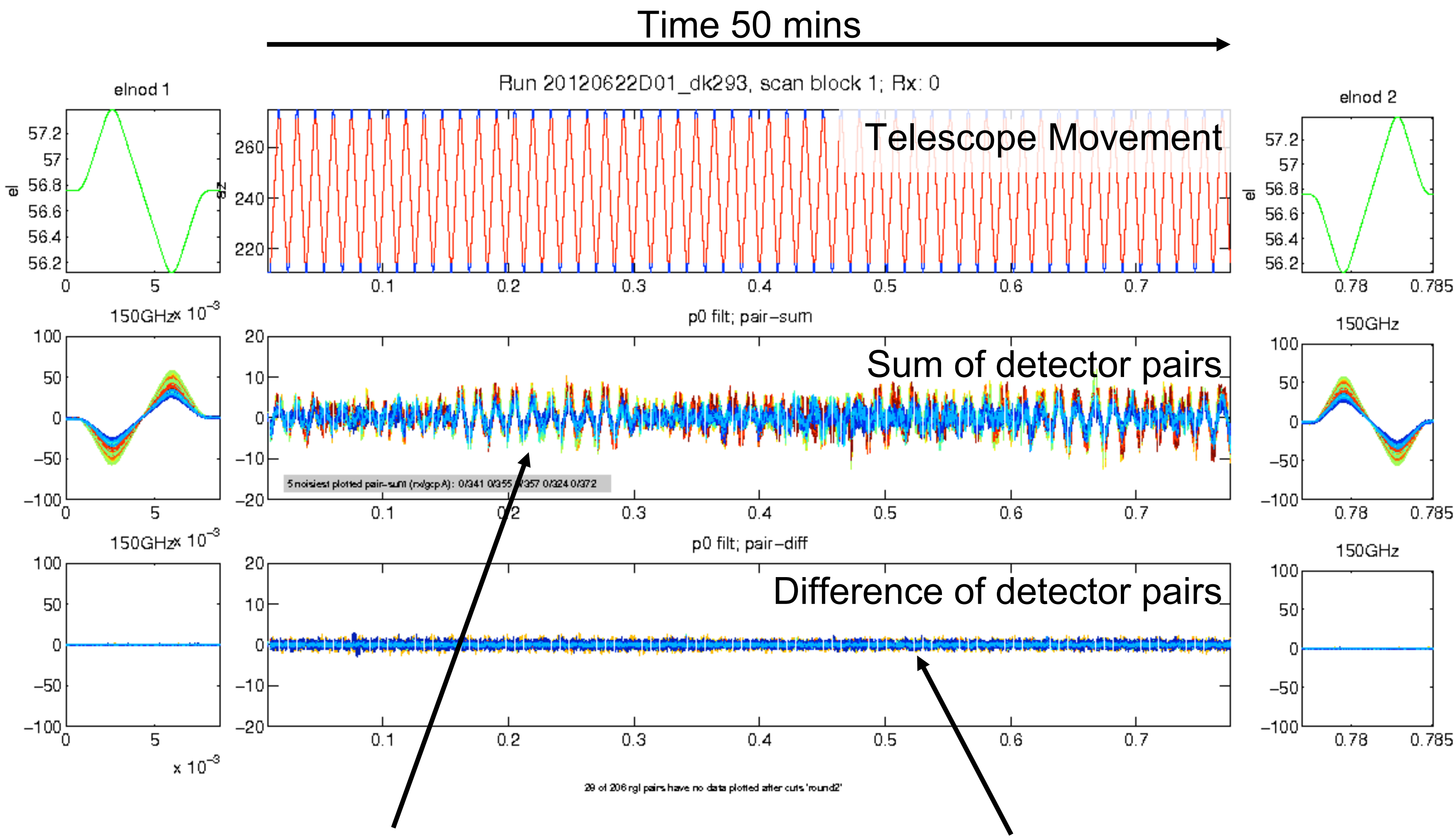
Clem Pryke for The Bicep2 Collaboration

Raw Data - Perfect Weather



- Cover the whole field in 60 such scansets then start over at new boresight rotation
- Scanning modulates the CMB signal to freqs < 4 Hz

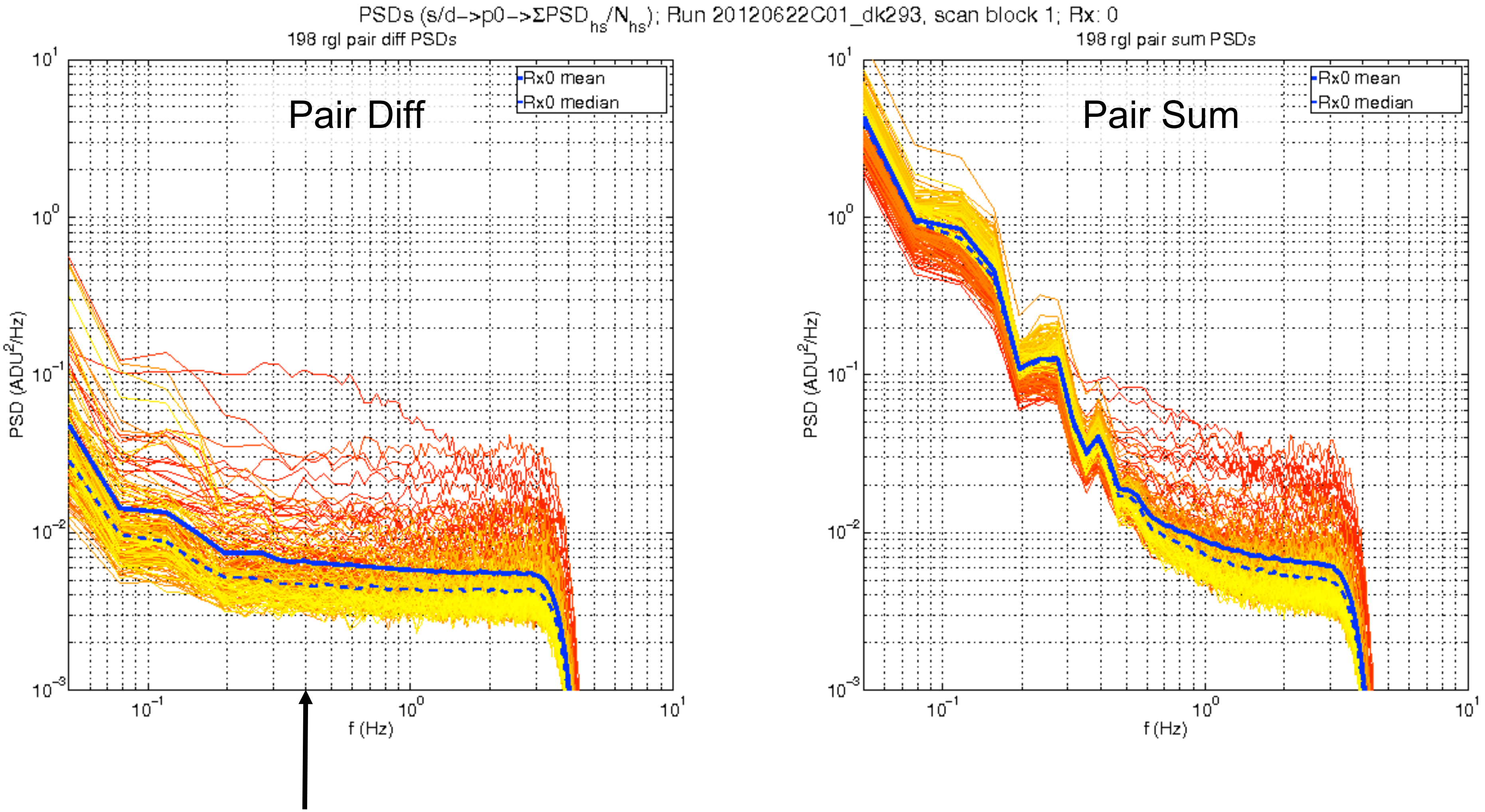
Raw Data - Worse Weather



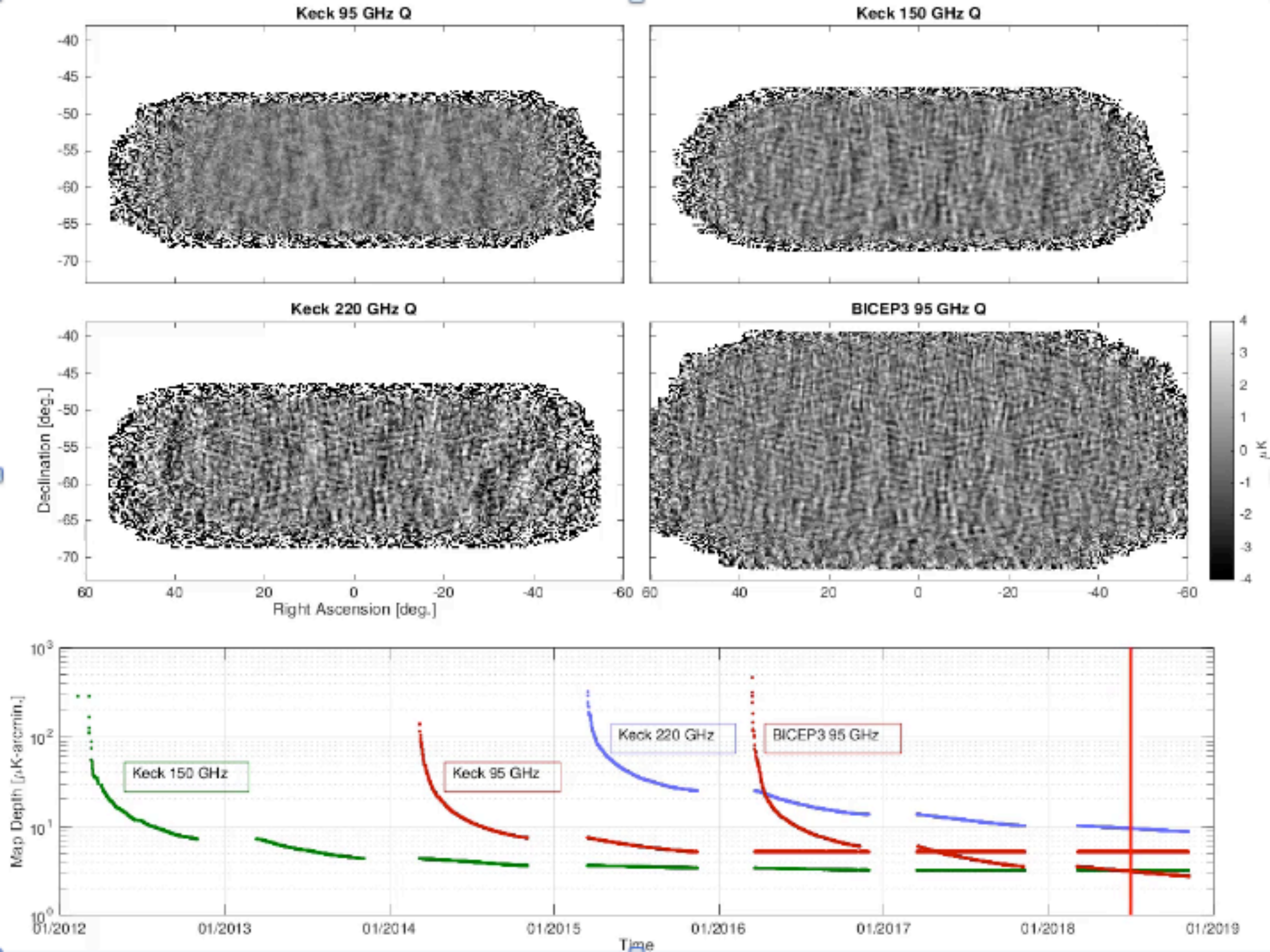
- ➢ Scanning over lumpy atmosphere → "clouds"
- ➢ Pair difference still clean → atmosphere is unpolarized

The BICEP/Keck Collaboration

Timestream PSDs

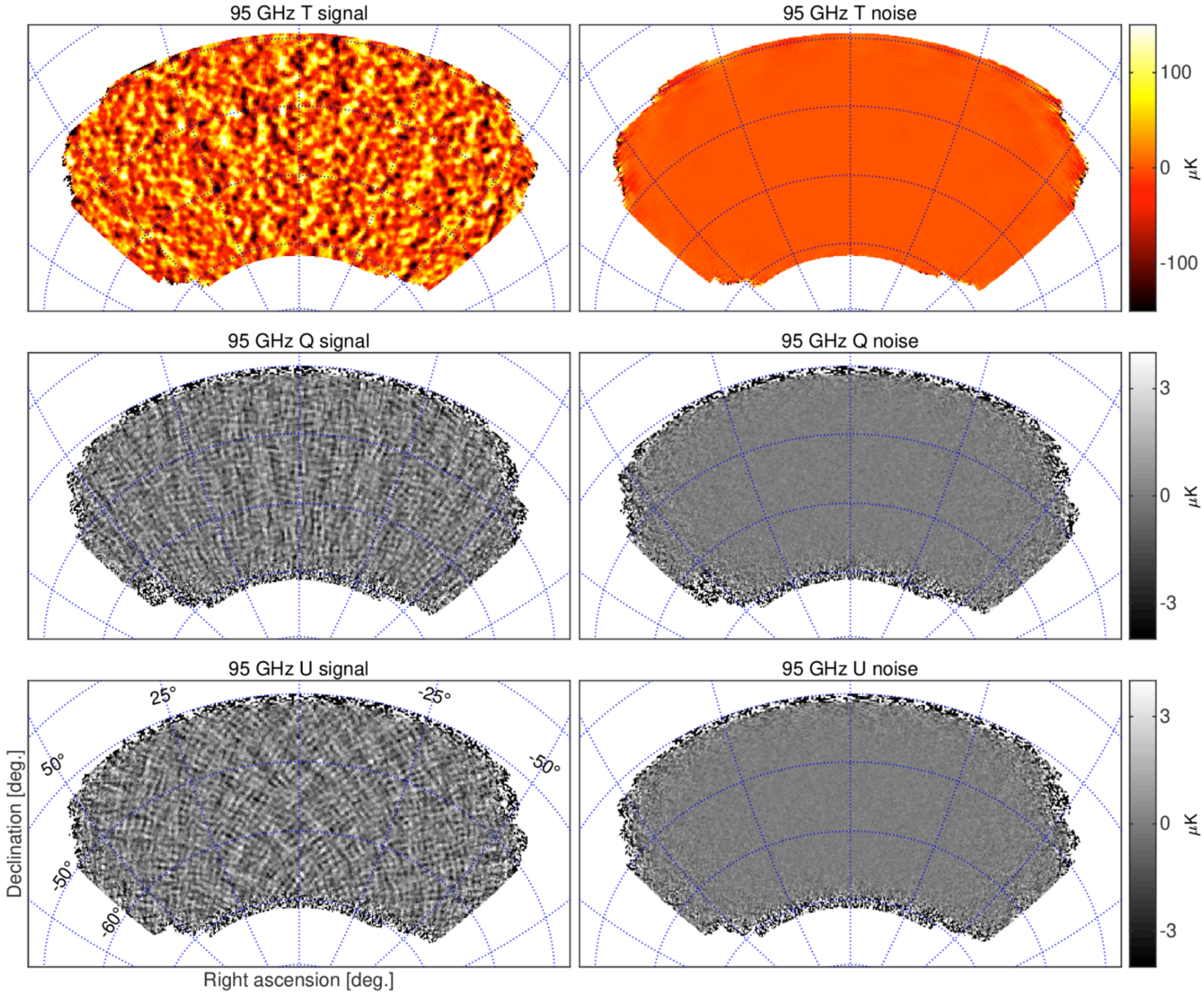


➢ Multipole 100 at 0.4Hz

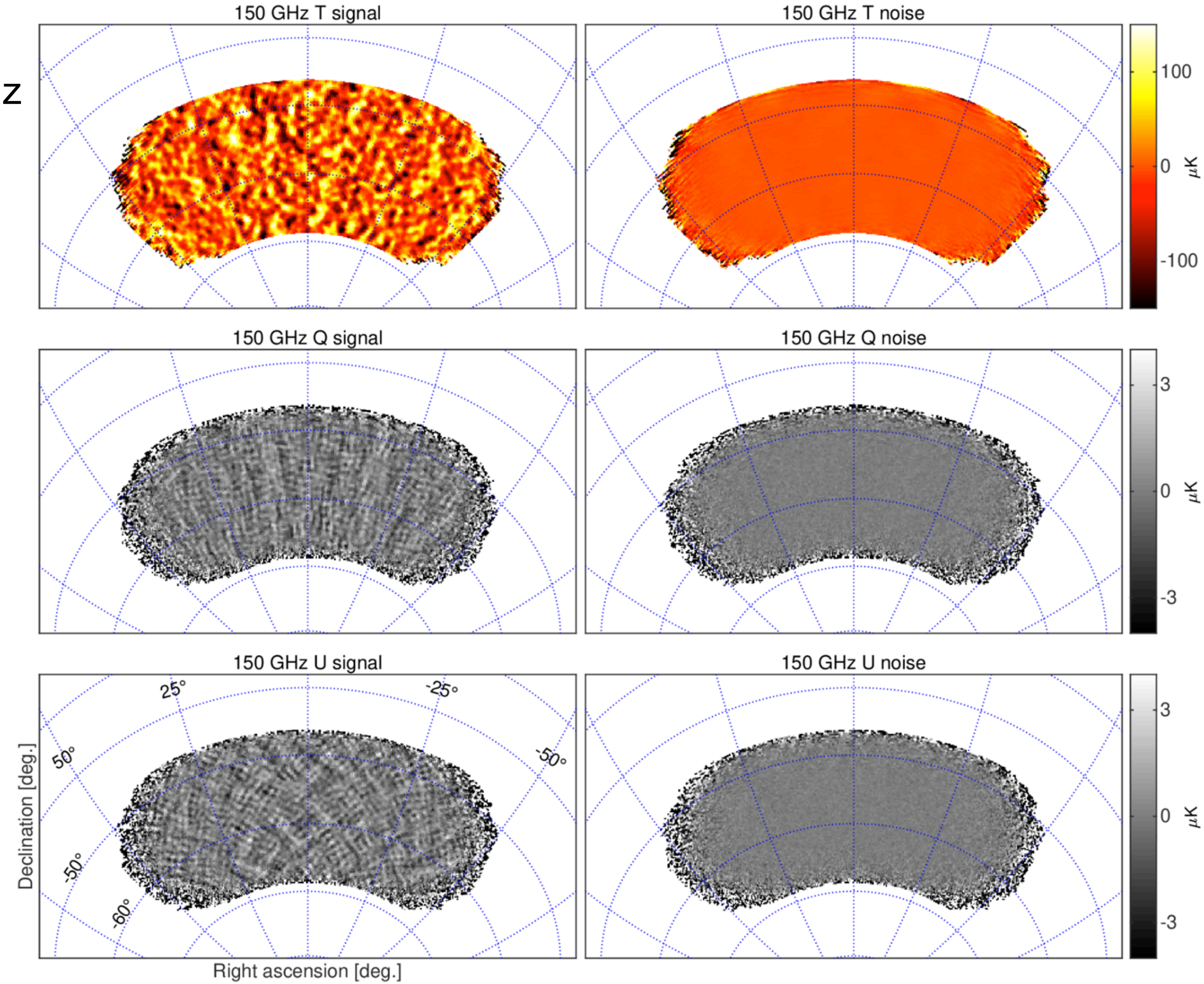


Keck 95 GHz Q
Keck 150 GHz Q
Keck 220 GHz Q
BICEP3 95 GHz Q
Declination [deg.]
Right Ascension [deg.]
μK
Map Depth [μK-arcmin.]
Time
Keck 150 GHz
Keck 95 GHz
Keck 220 GHz
BICEP3 95 GHz

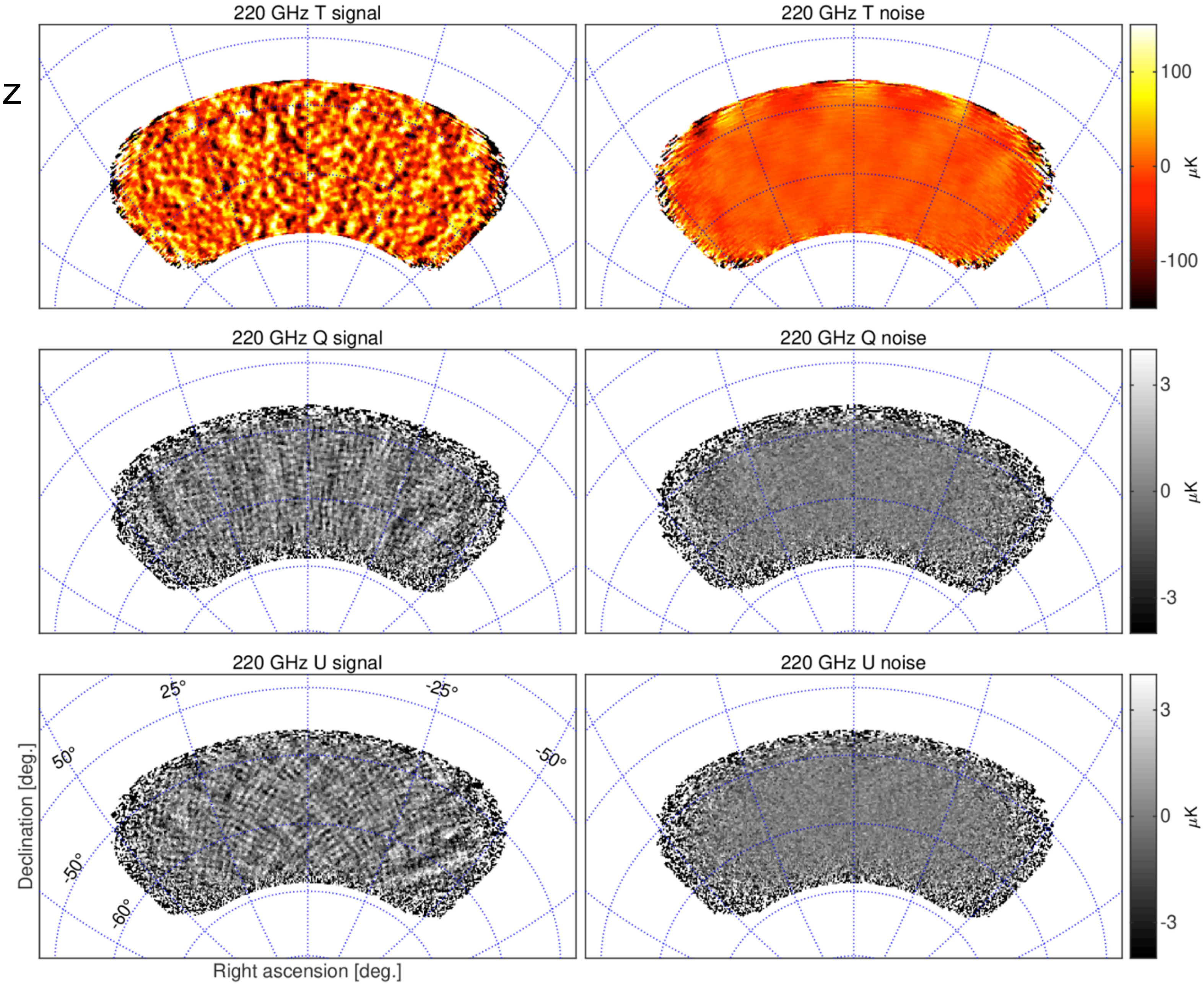
BK18
95GHz
Maps



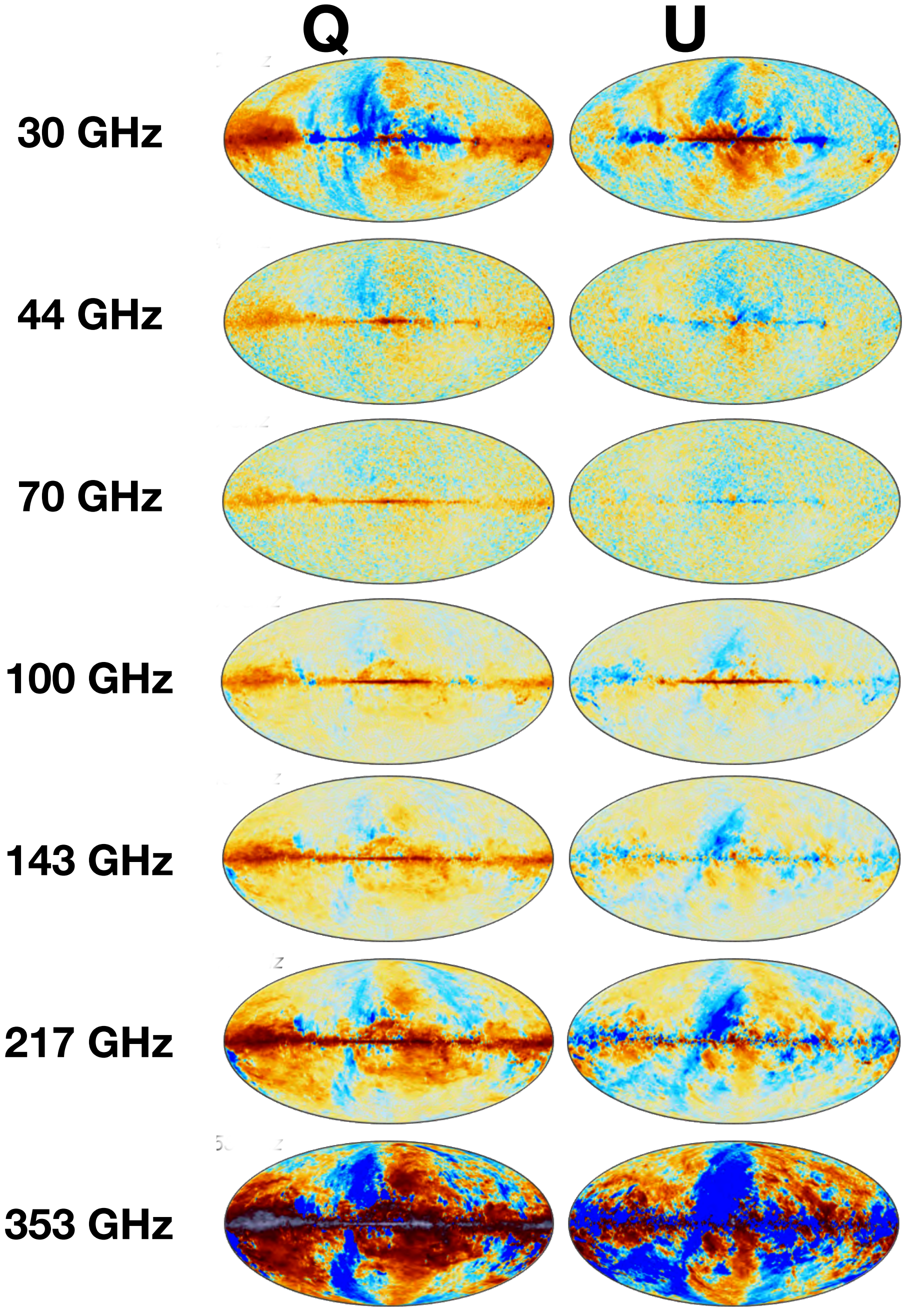
BK18
150GHz
Maps



BK18
220GHz
Maps

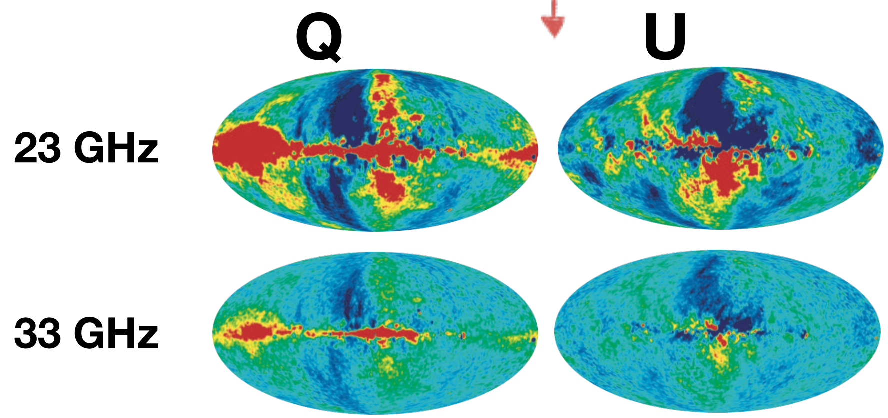


Add to the mix: Planck at 7 frequencies and WMAP at 2 frequencies



From arxiv 1502.01582

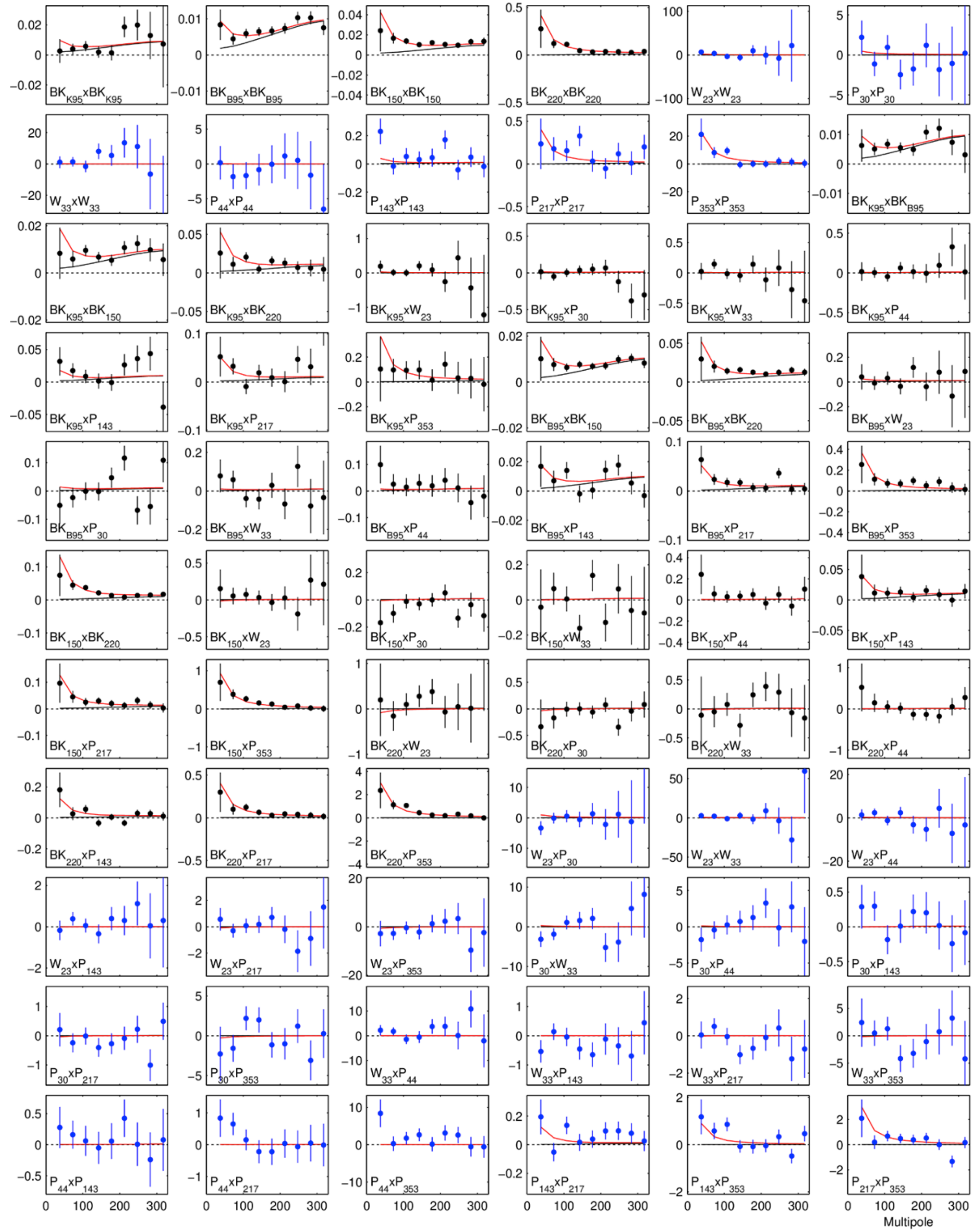
Polarized galactic **synchrotron** dominates at low frequencies



From arxiv 1212.5225

Polarized thermal emission (~20K) from galactic **dust** aligned in magnetic fields dominates at high frequencies

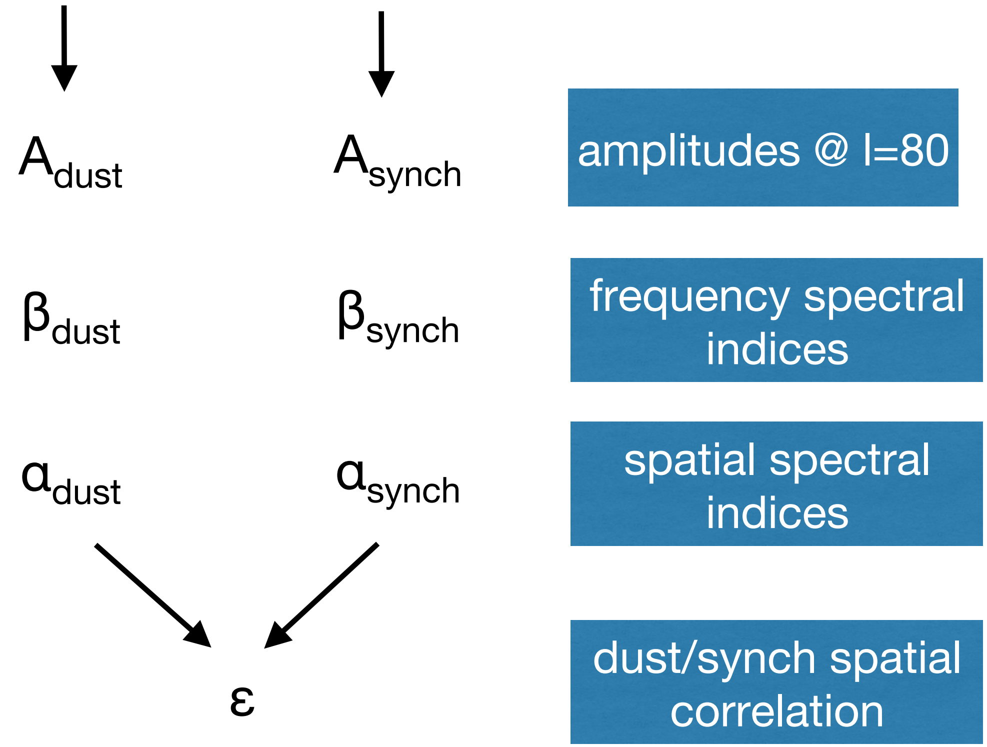
Analysis Technique: Take all possible auto- and cross spectra between the BICEP/Keck, WMAP, and Planck bands (66 of them) and compare to model of CMB +foregrounds



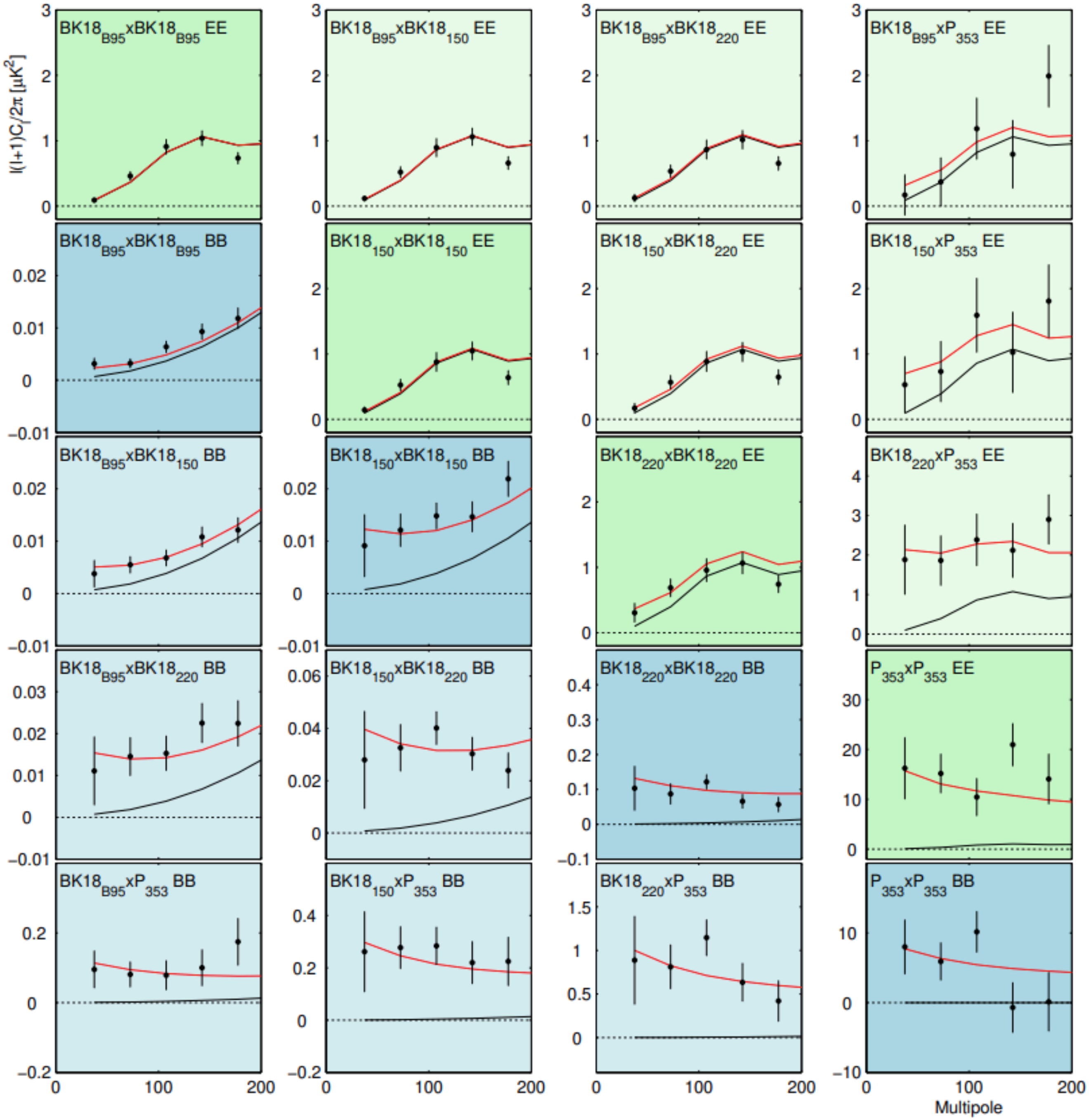
Multicomponent parametric likelihood analysis

Take the joint likelihood of all the spectra simultaneously vs. model for BB that is the ΛCDM lensing expectation + 7 parameter foreground model + r

foreground model = dust + synchrotron



BK18 auto/cross spectra between: BICEP3 95GHz, BICEP2/Keck 150GHz, Keck 220GHz, and Planck 353GHz



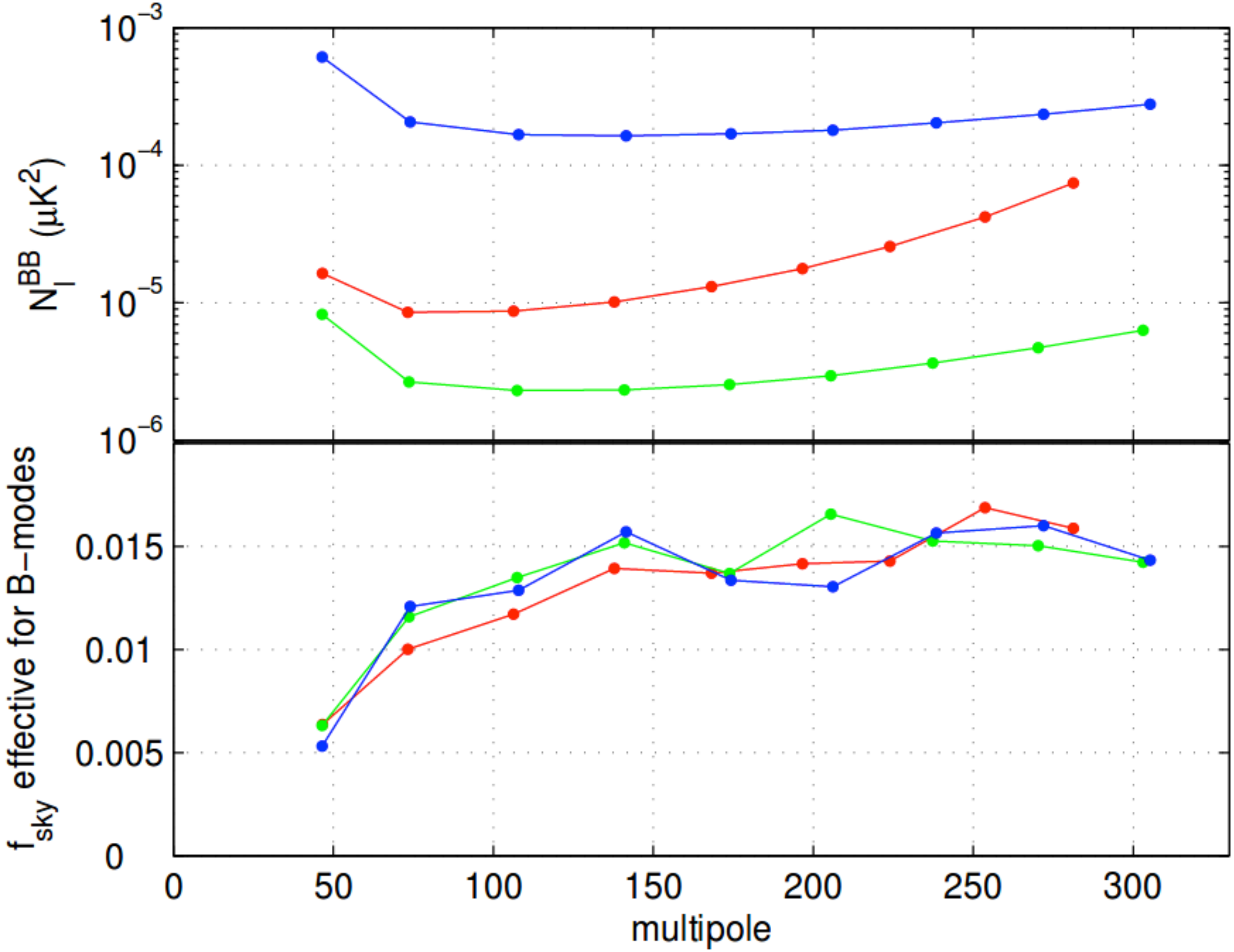
Green panels are EE spectra

Black lines are LCDM

Red lines are LCDM+foreground

Blue panels are BB spectra

BK15 Noise Spectra and f_{sky} Effective



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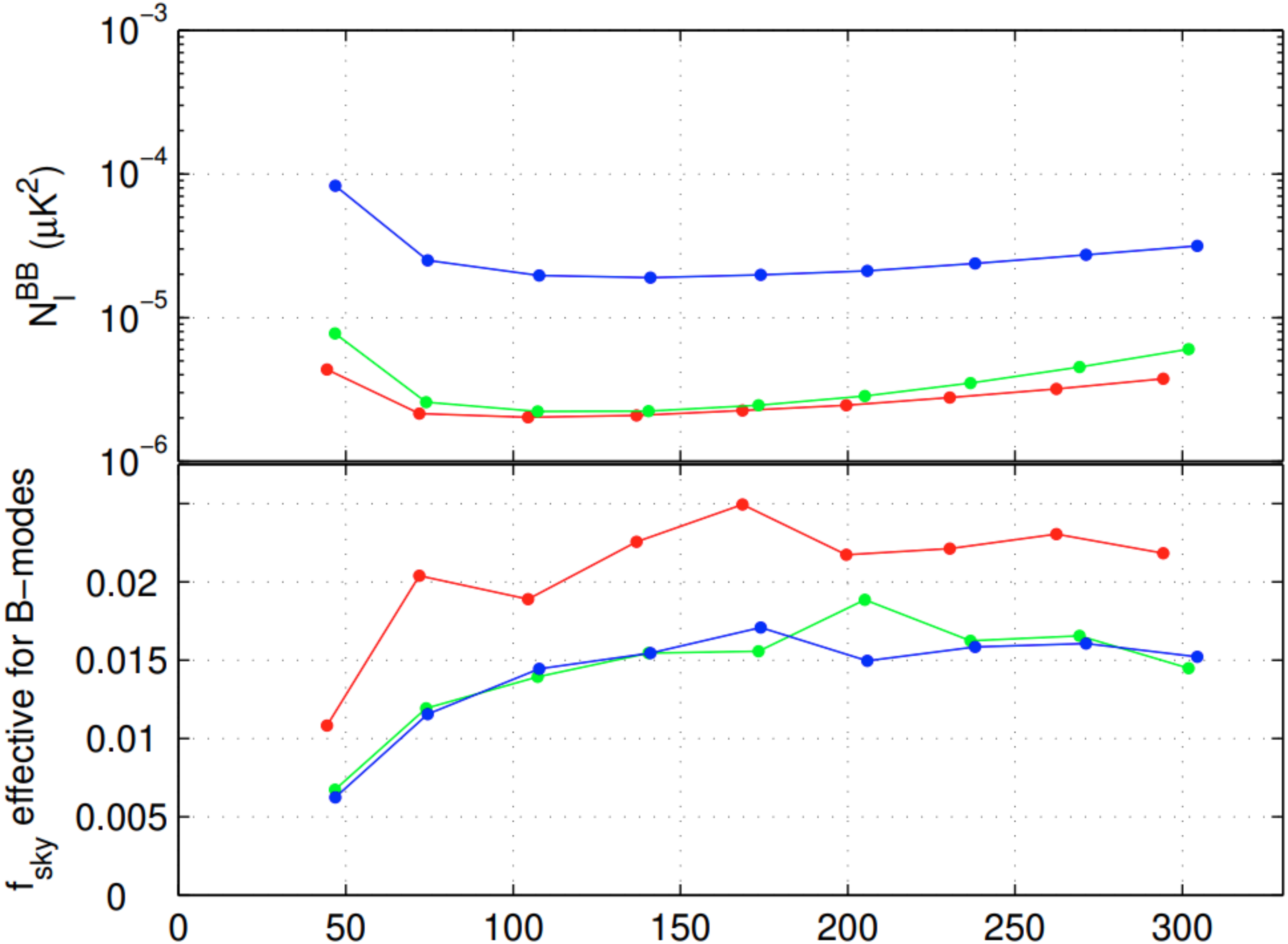
BK18 Noise Spectra and f_{sky} Effective



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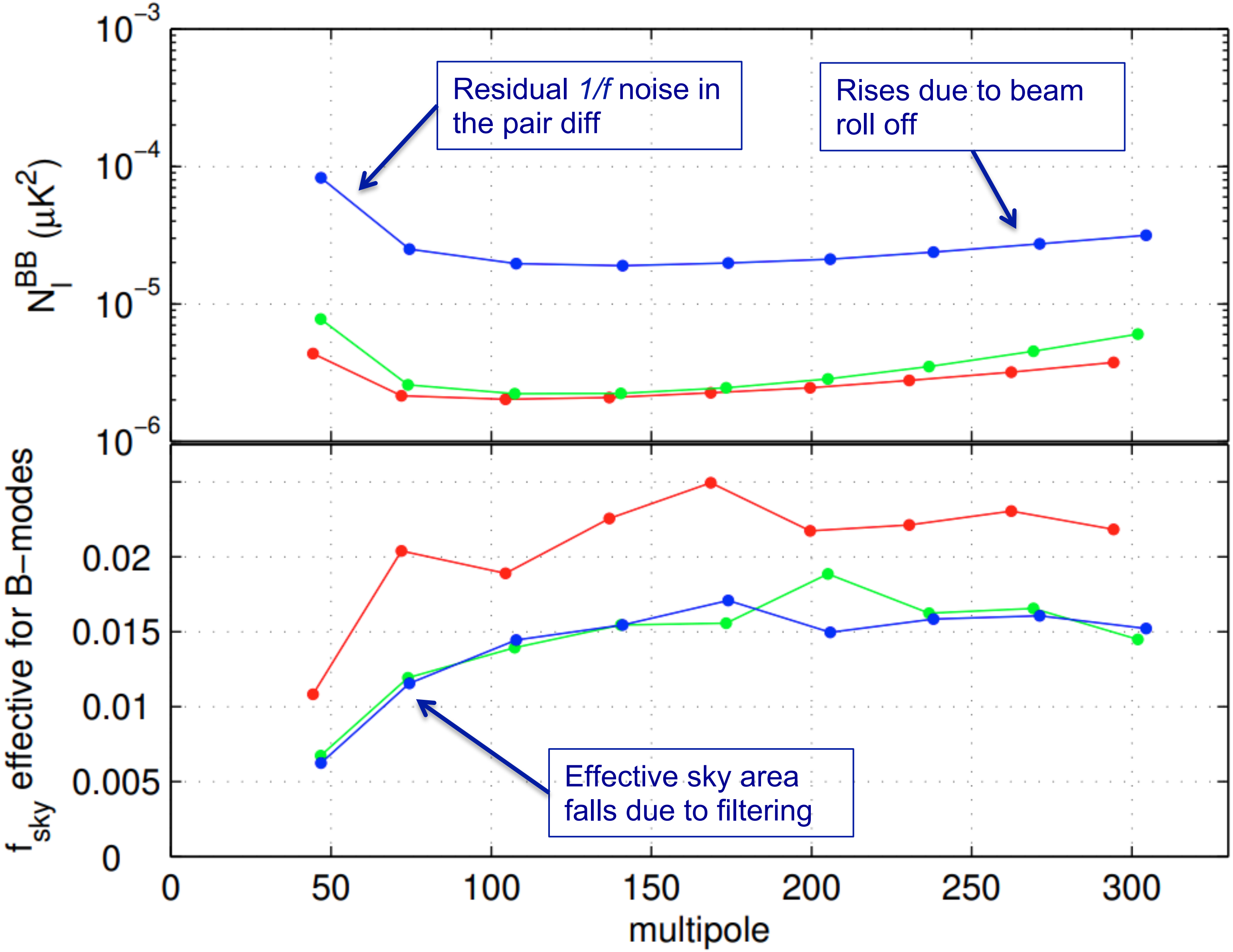
BK18 Noise Spectra and f_{sky} Effective



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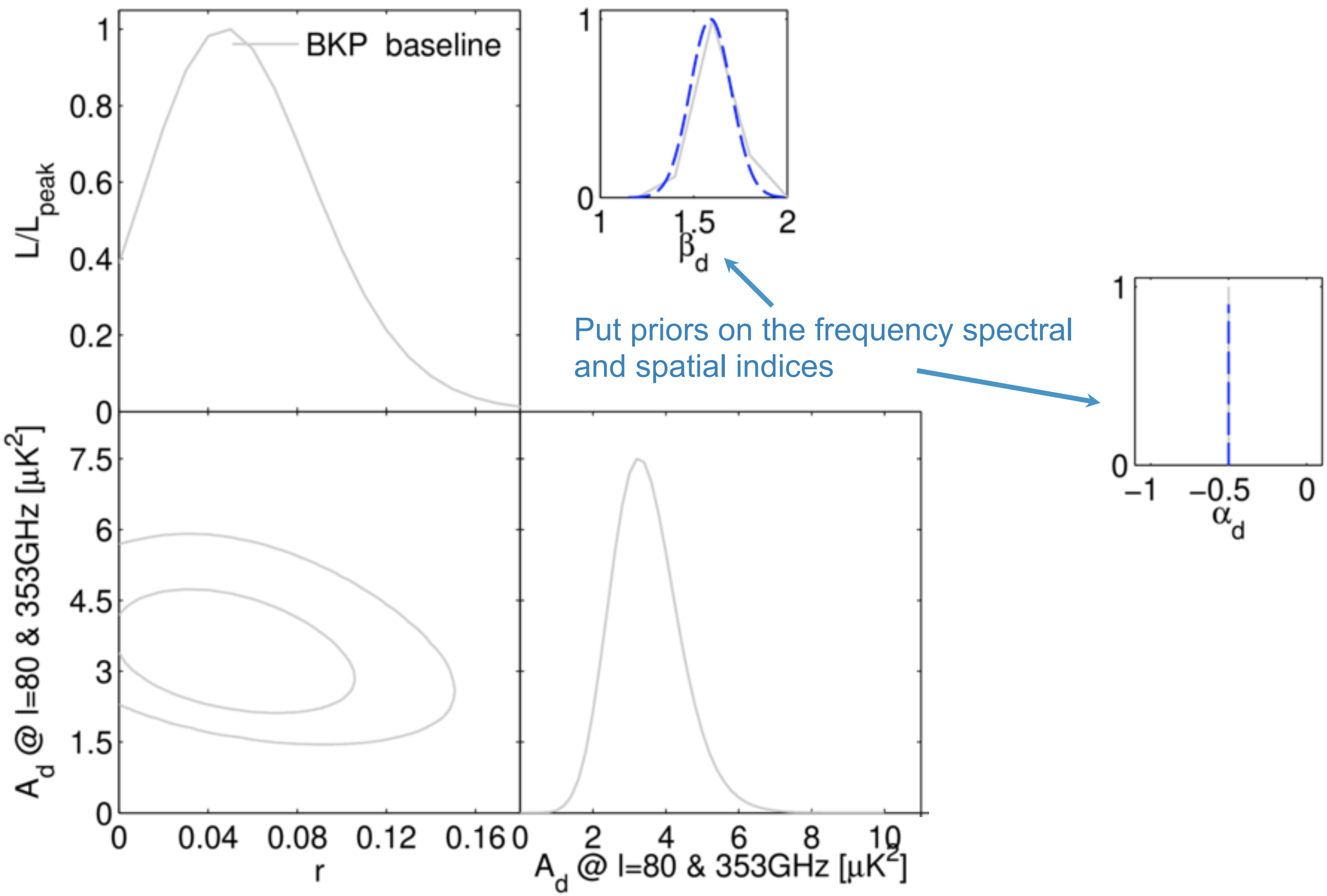
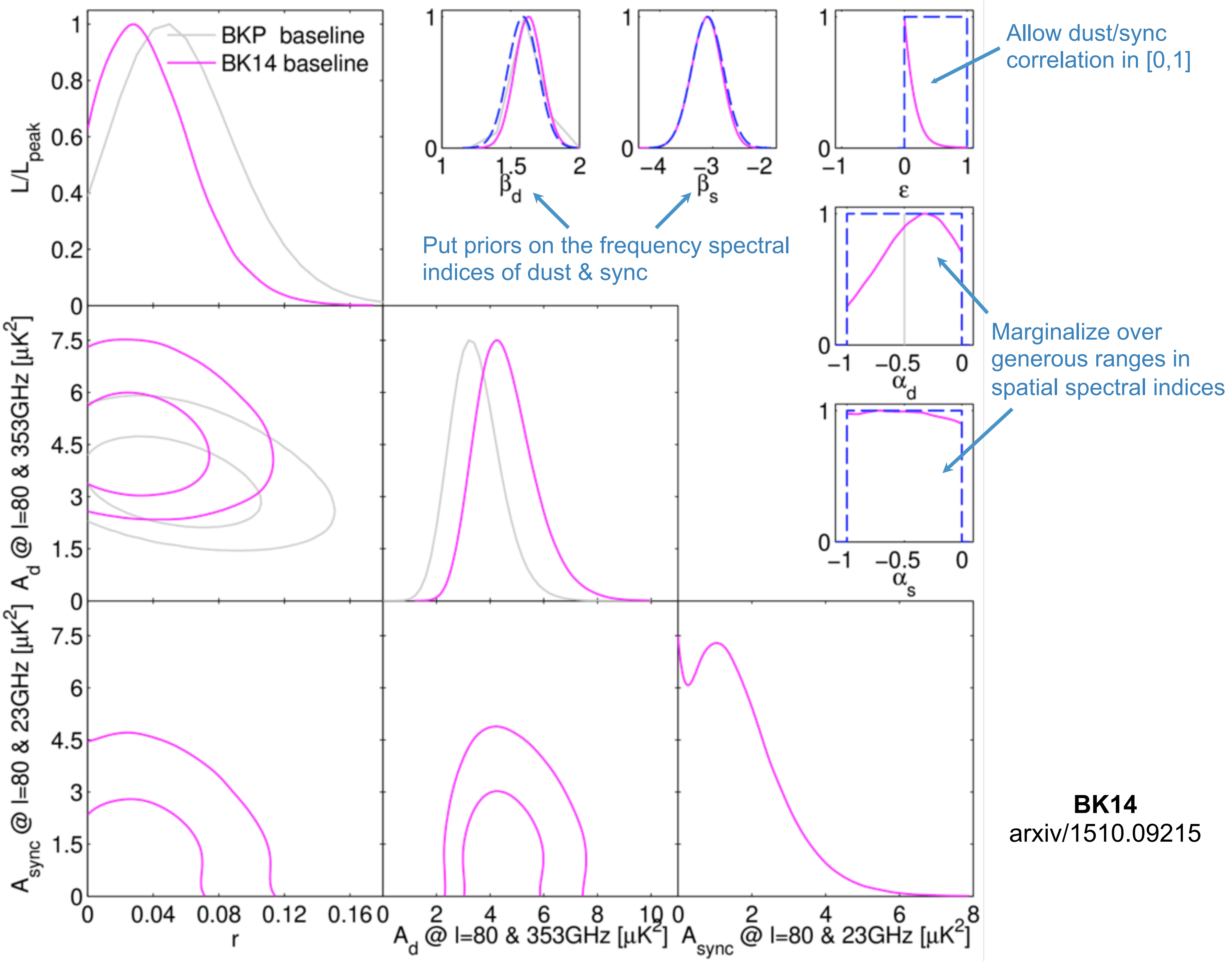
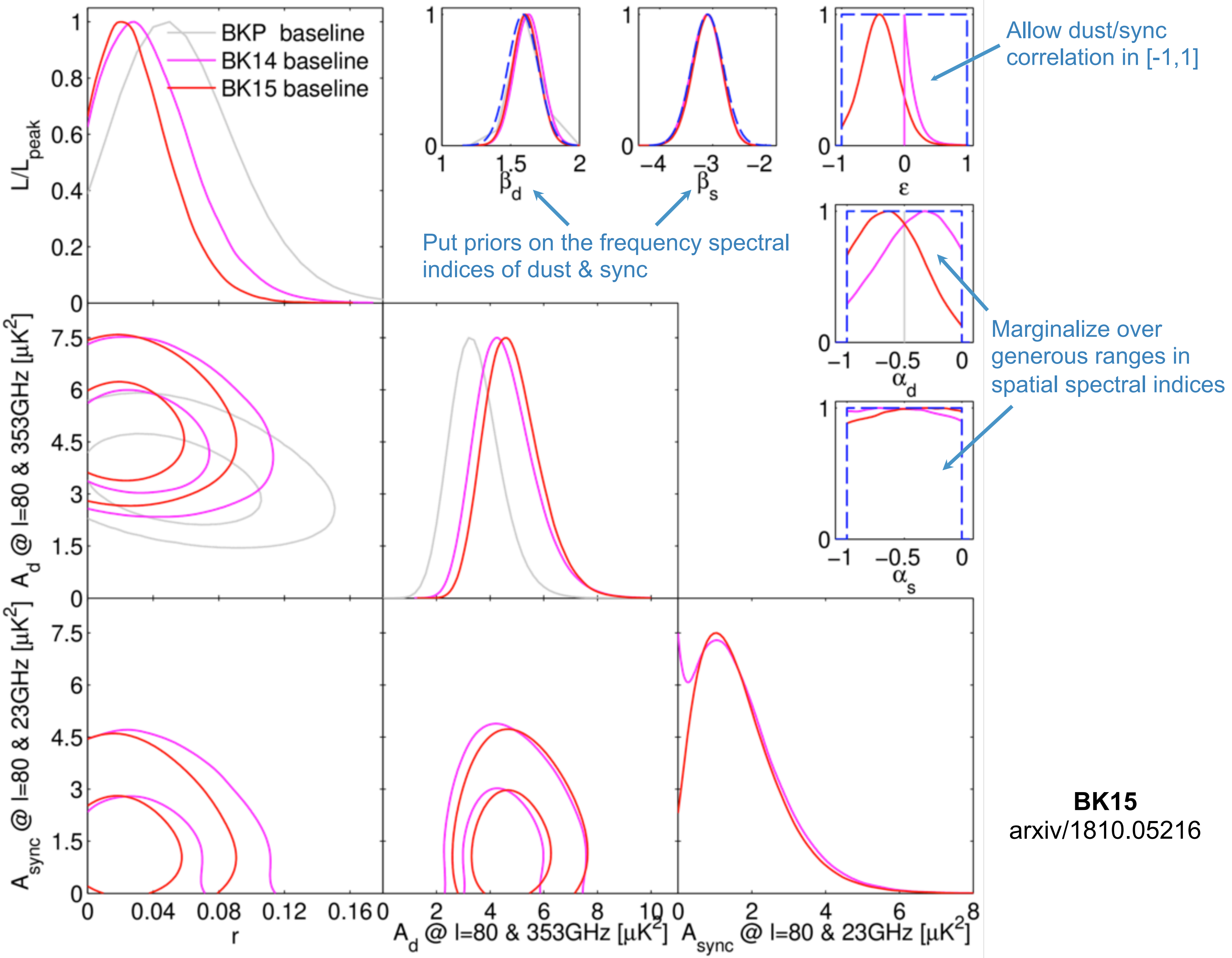


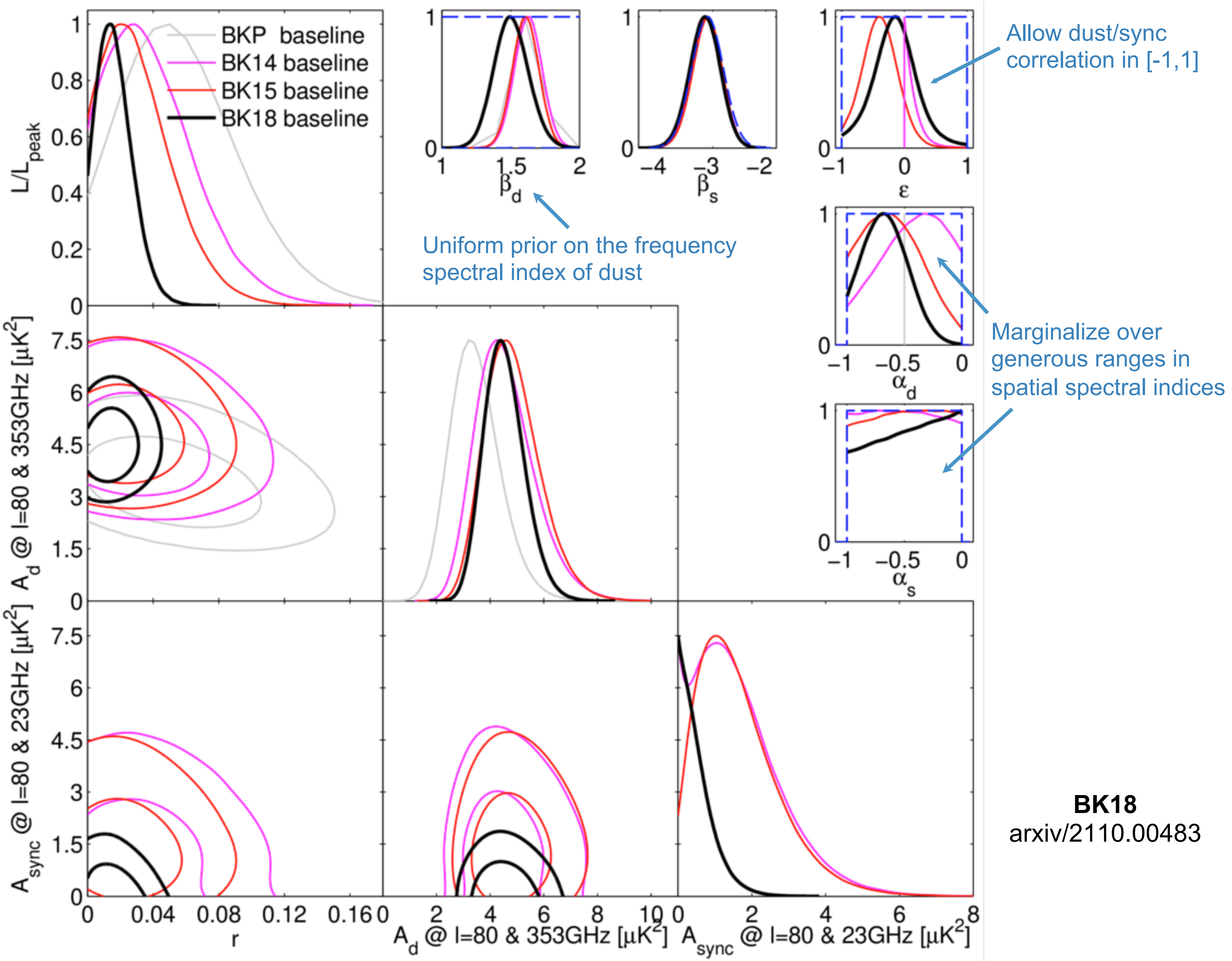
BKP
arxiv/1502.00612



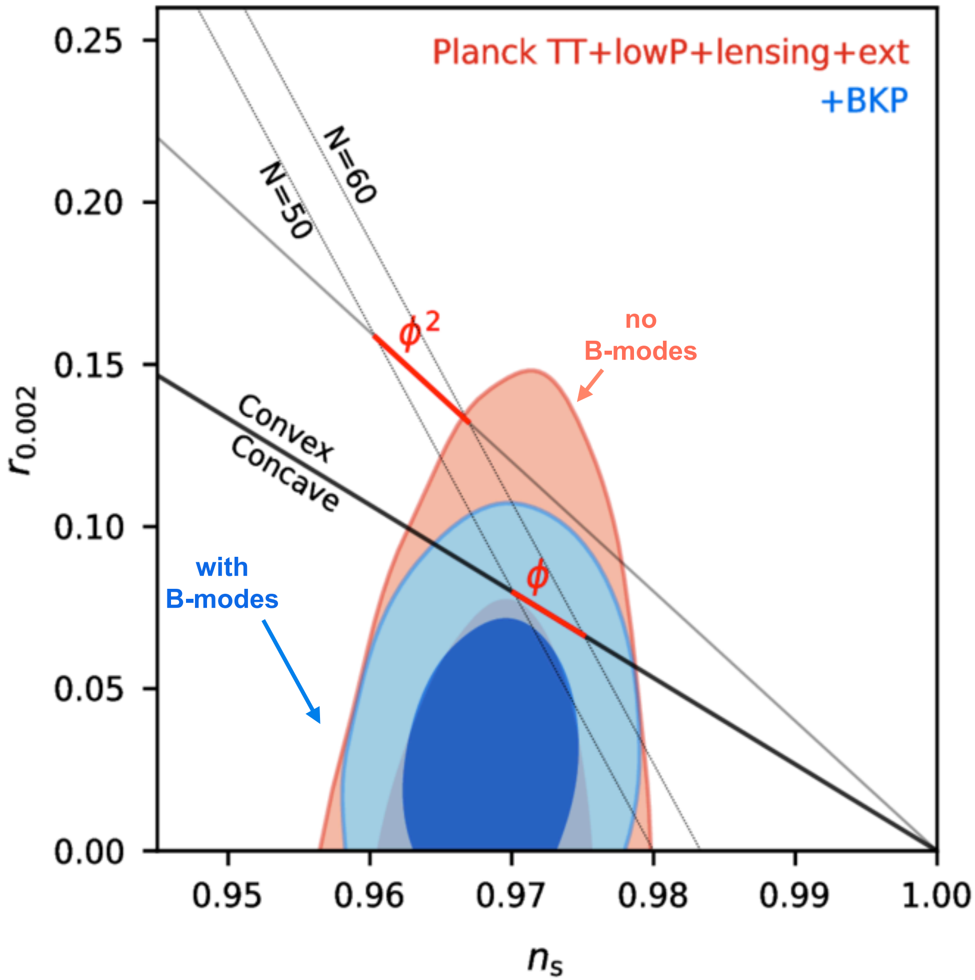
BK14
arxiv/1510.09215



BK15
arxiv/1810.05216



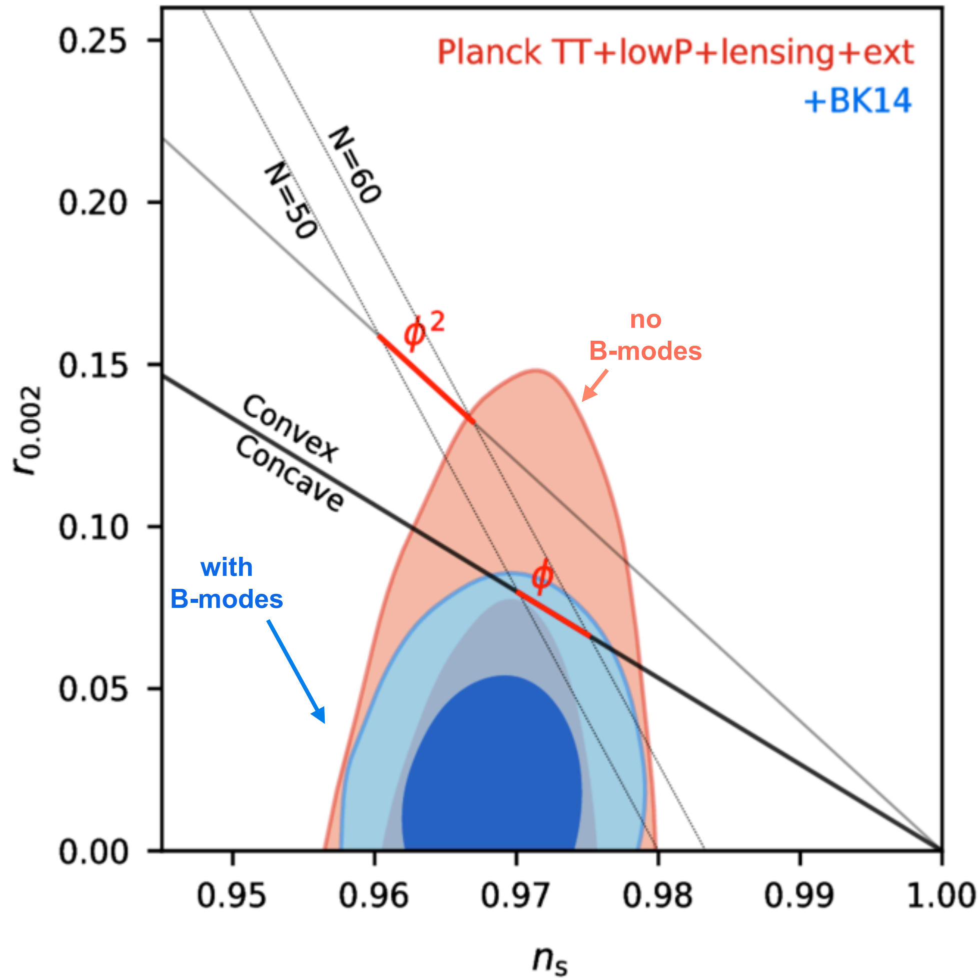
BK18
arxiv/2110.00483



$r_{.05} < 0.09$

BKP

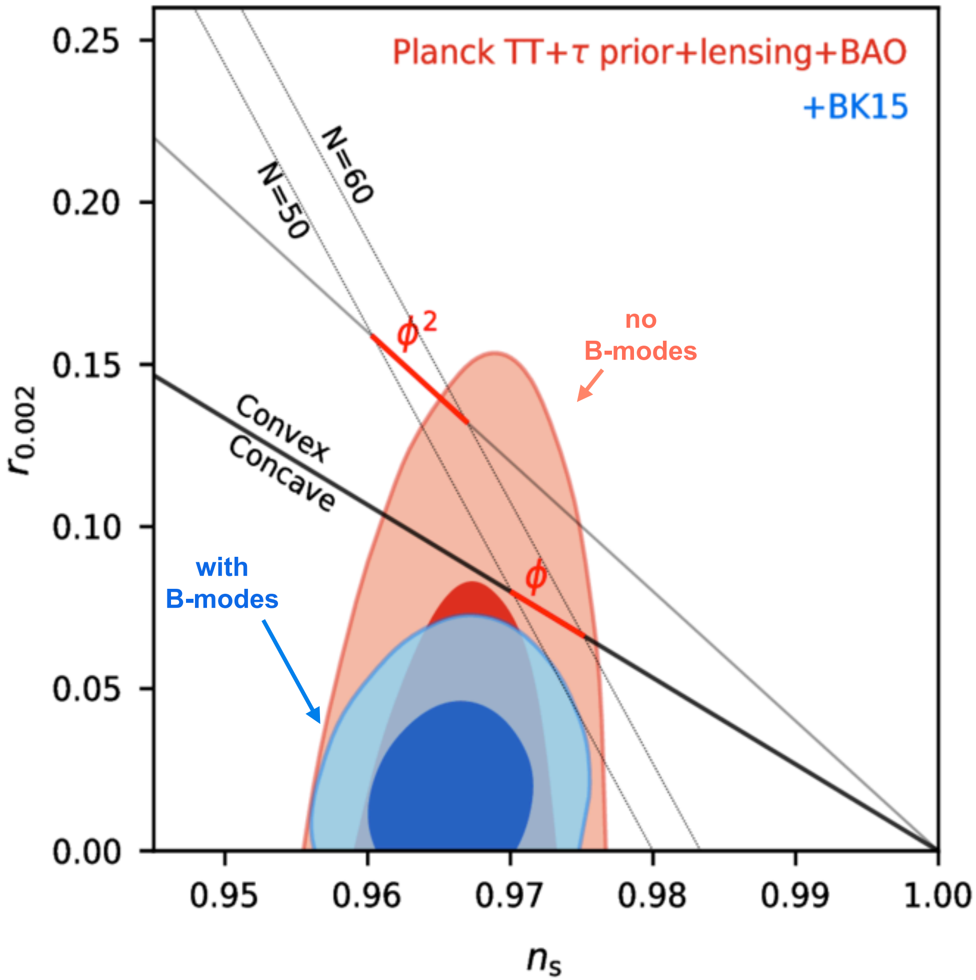
arxiv/1502.00612



$r_{.05} < 0.07$

BK14

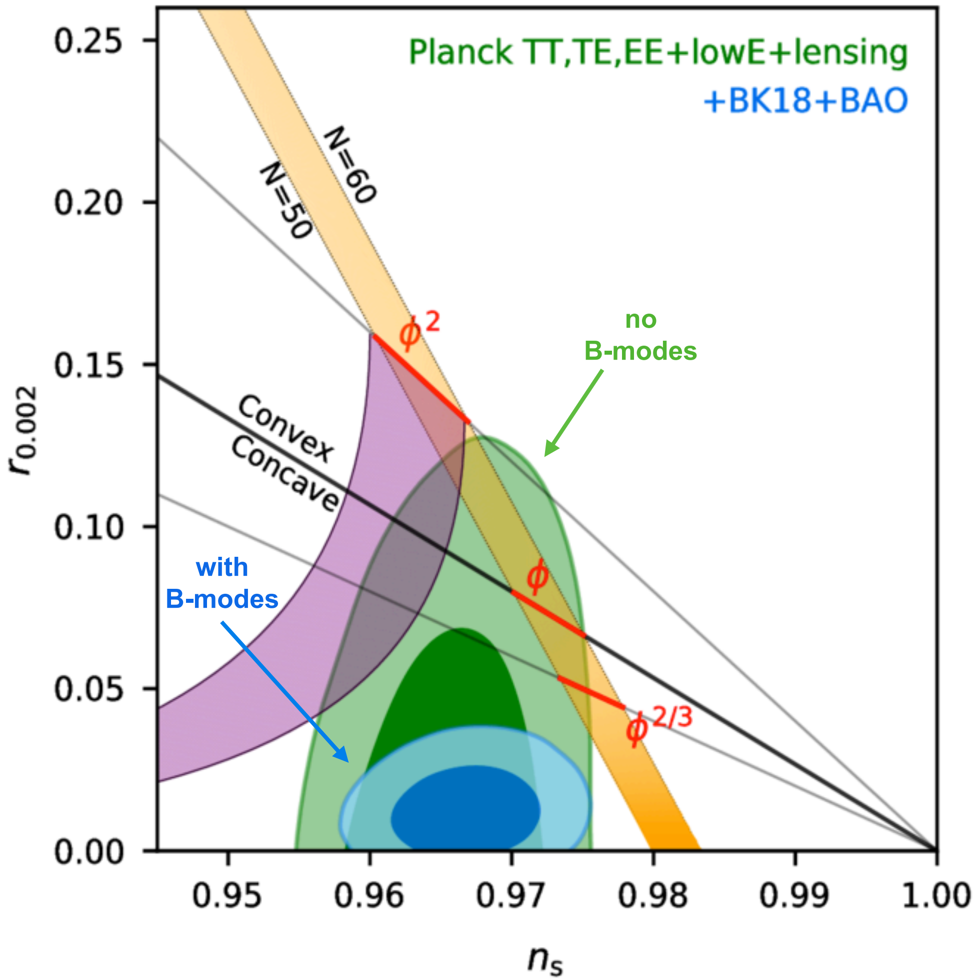
arxiv/1510.09217



$r_{.05} < 0.06$

BK15

arxiv/1810.05216

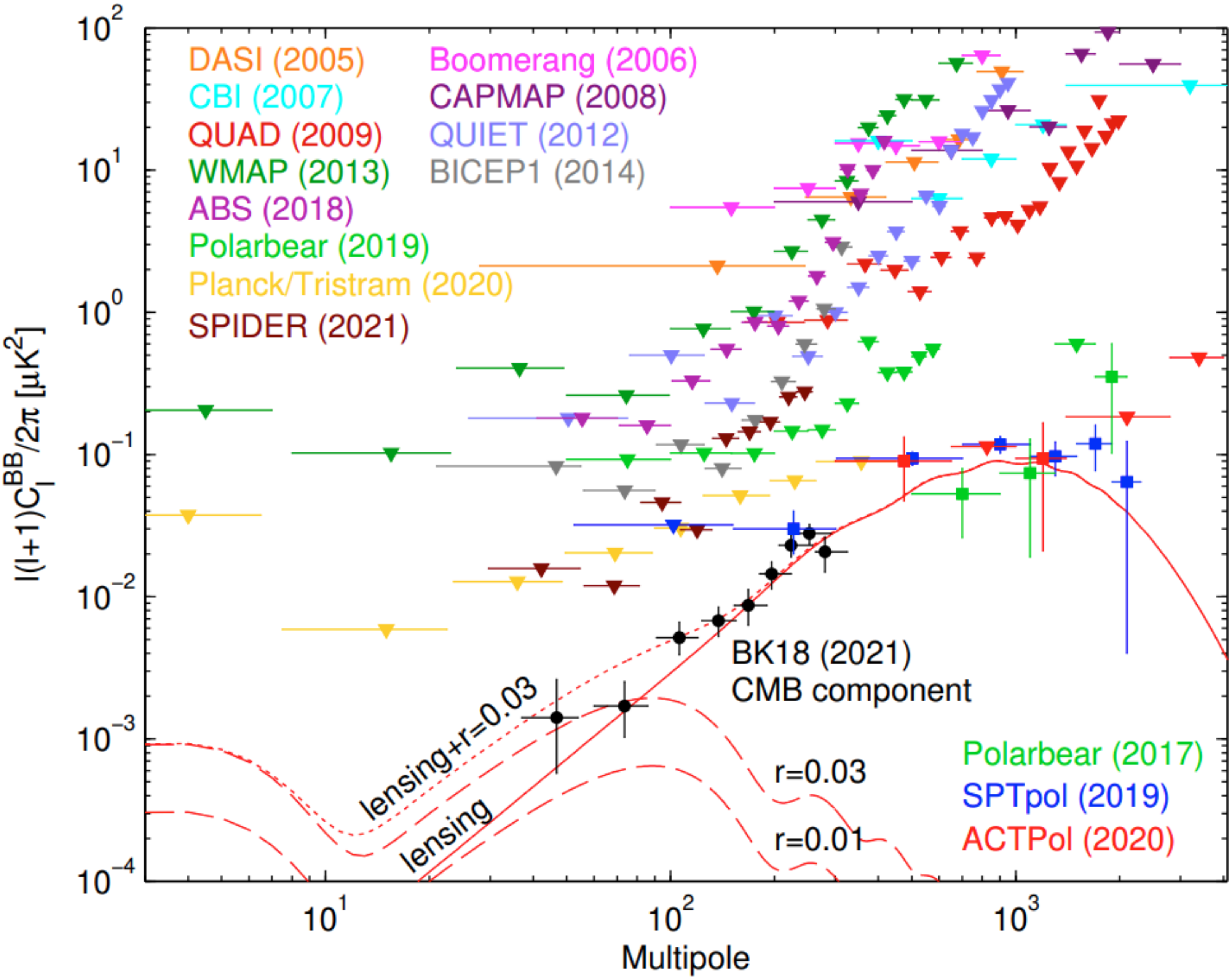


$r_{.05} < 0.035$

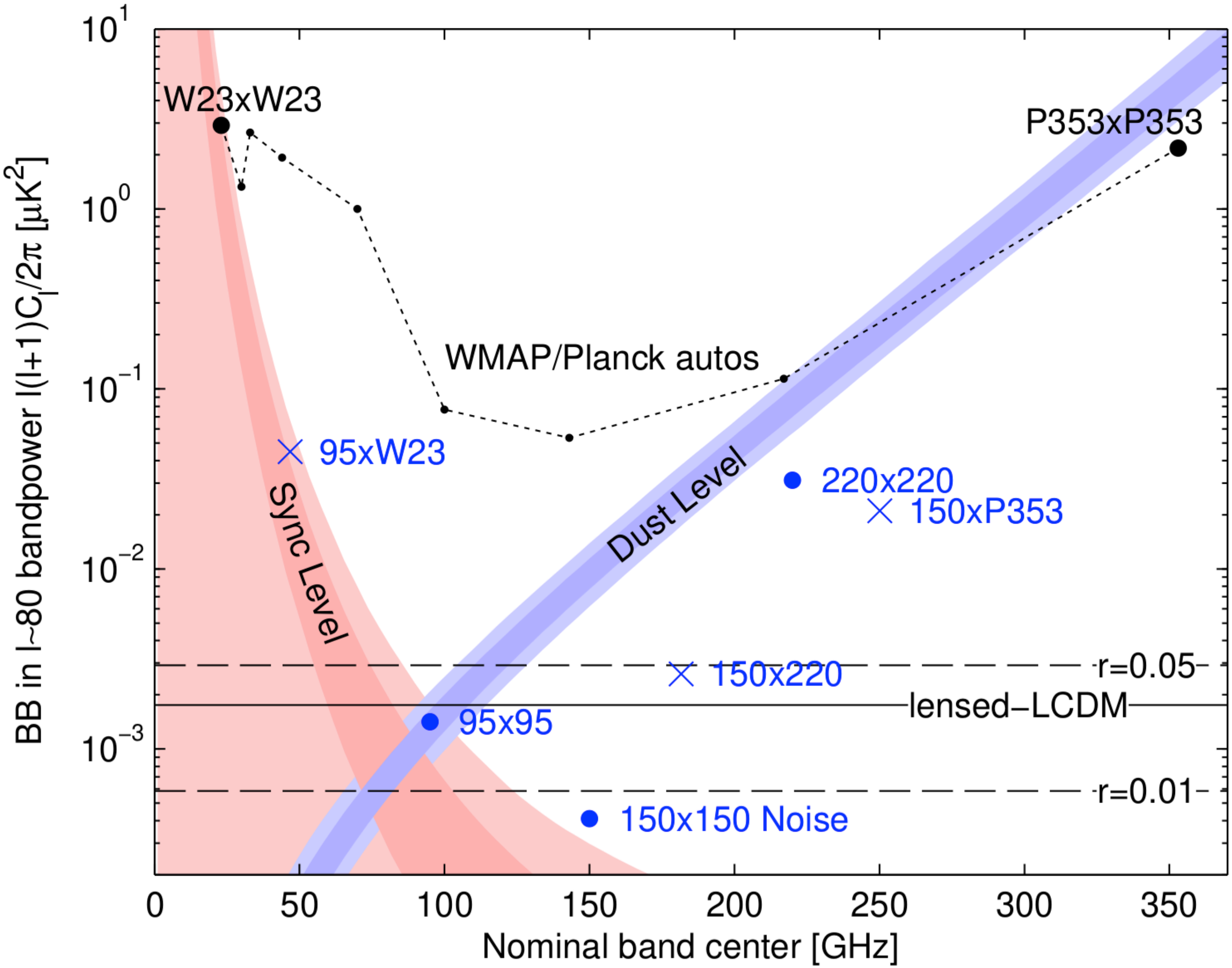
BK18

arxiv/2110.00483

Per bandpower CMB component extraction



BK15 ell=80 bandpower noise/signal



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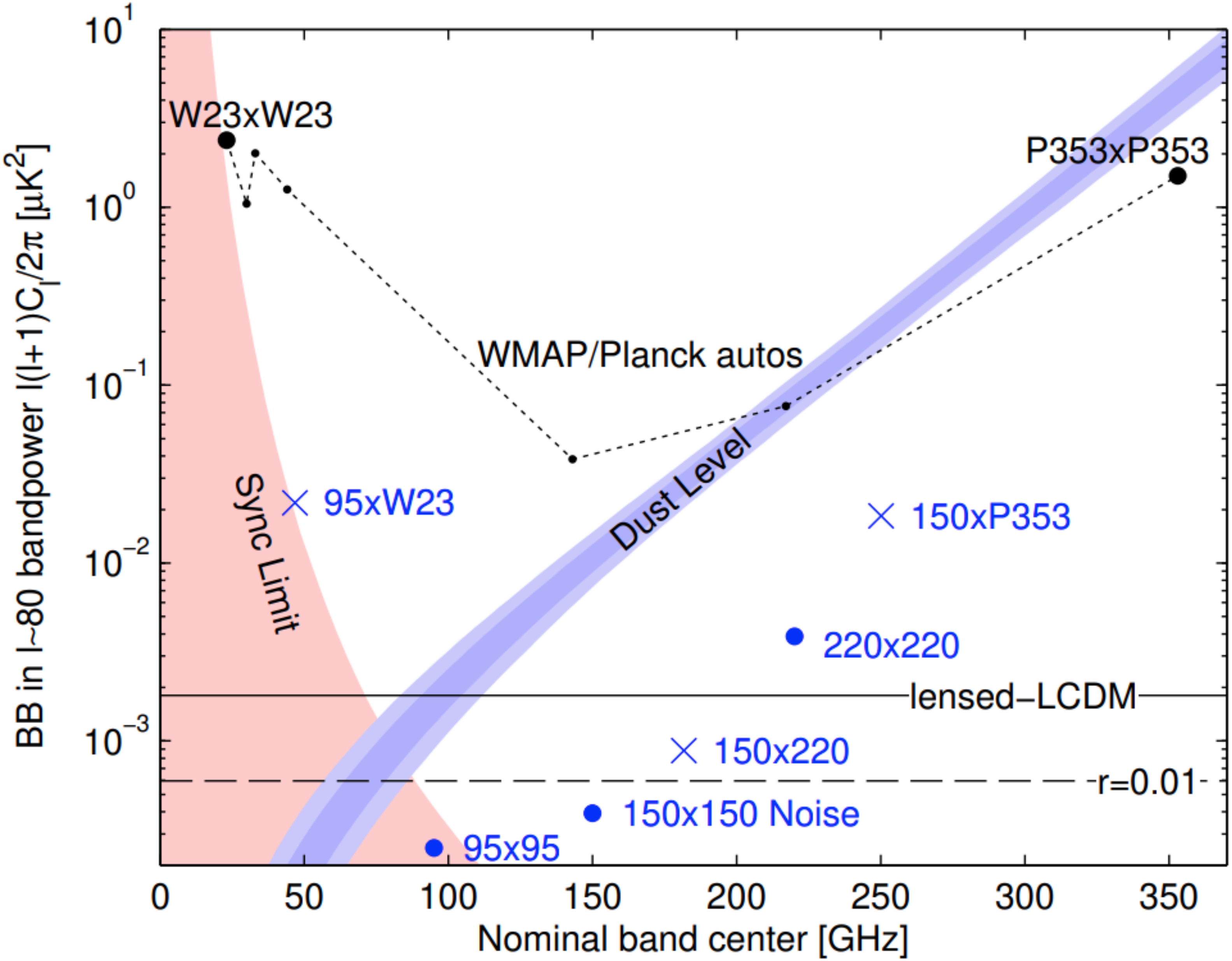
BK18 ell=80 bandpower noise/signal

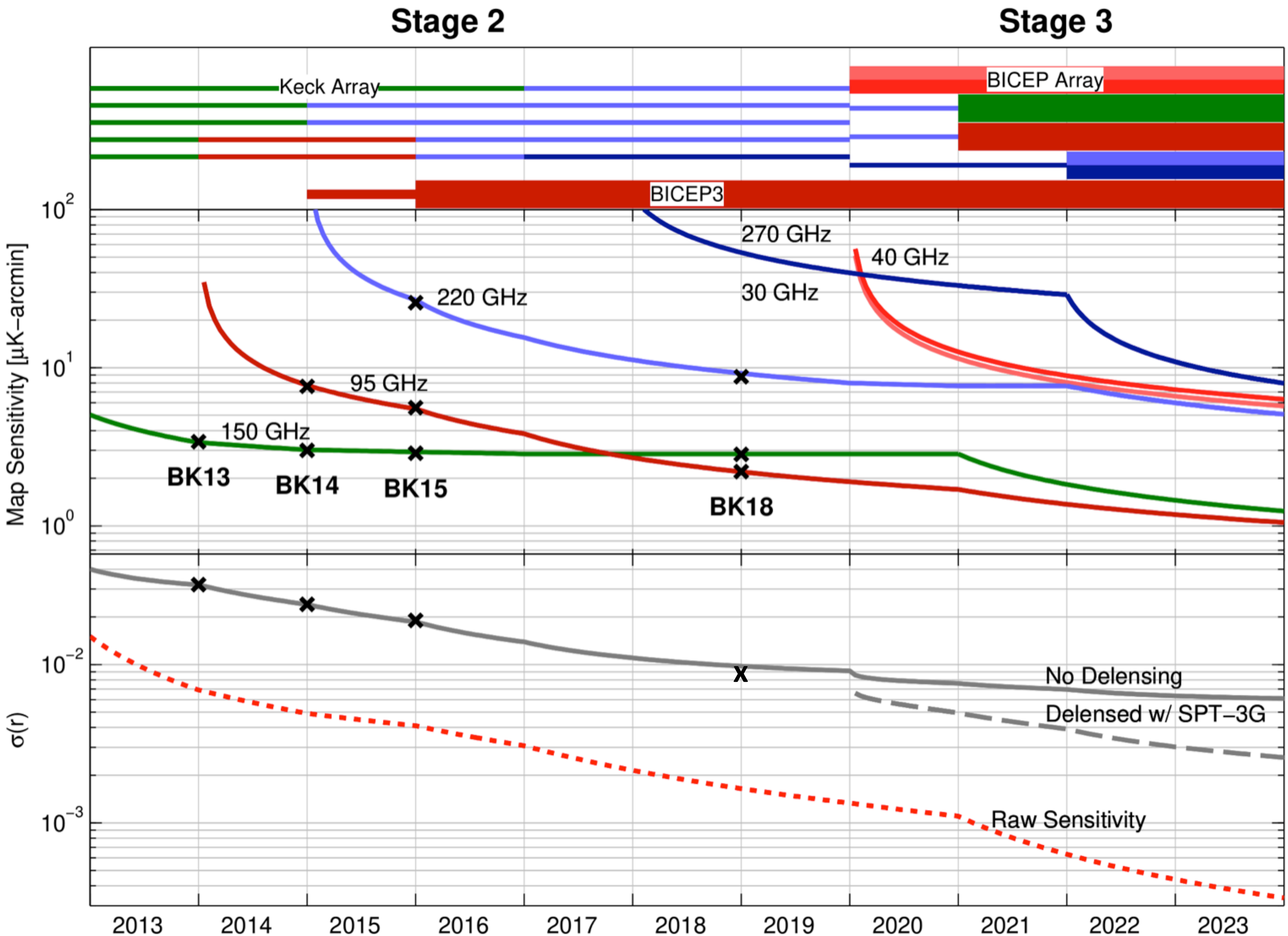


The BICEP/Keck Collaboration

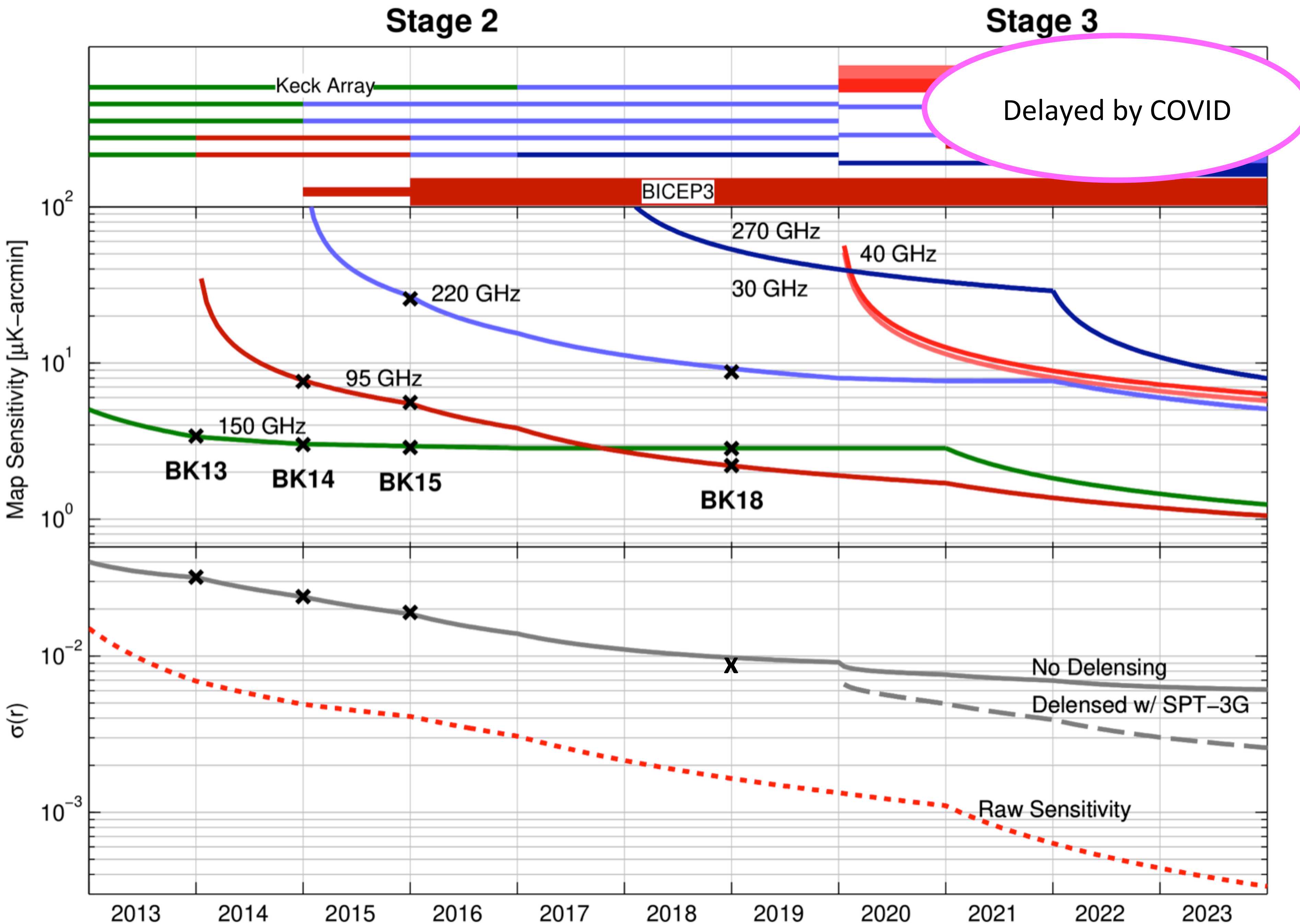
What limits BK18?

- BK18 mainline simulations with dust and lensing give $\sigma(r)=0.009$
- Running on simulations which contain no lensing gives $\sigma(r)=0.004$
- Running without foreground parameters on simulations where the dust amplitude is set to zero gives $\sigma(r)=0.007$
- Running without foreground parameters on simulations which have neither dust or lensing gives $\sigma(r)=0.002$

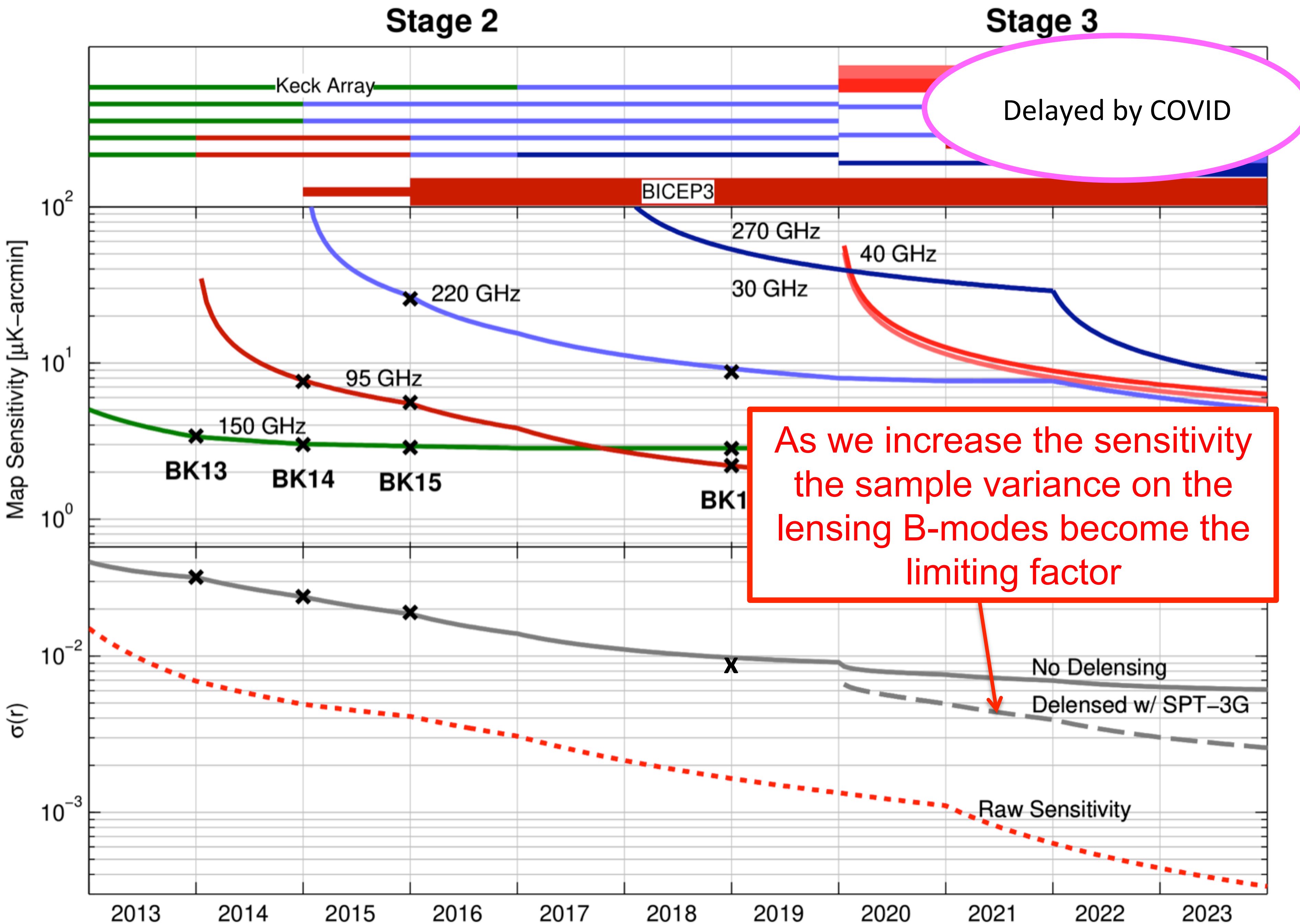
Bottom line: BK is already heavily lensing limited

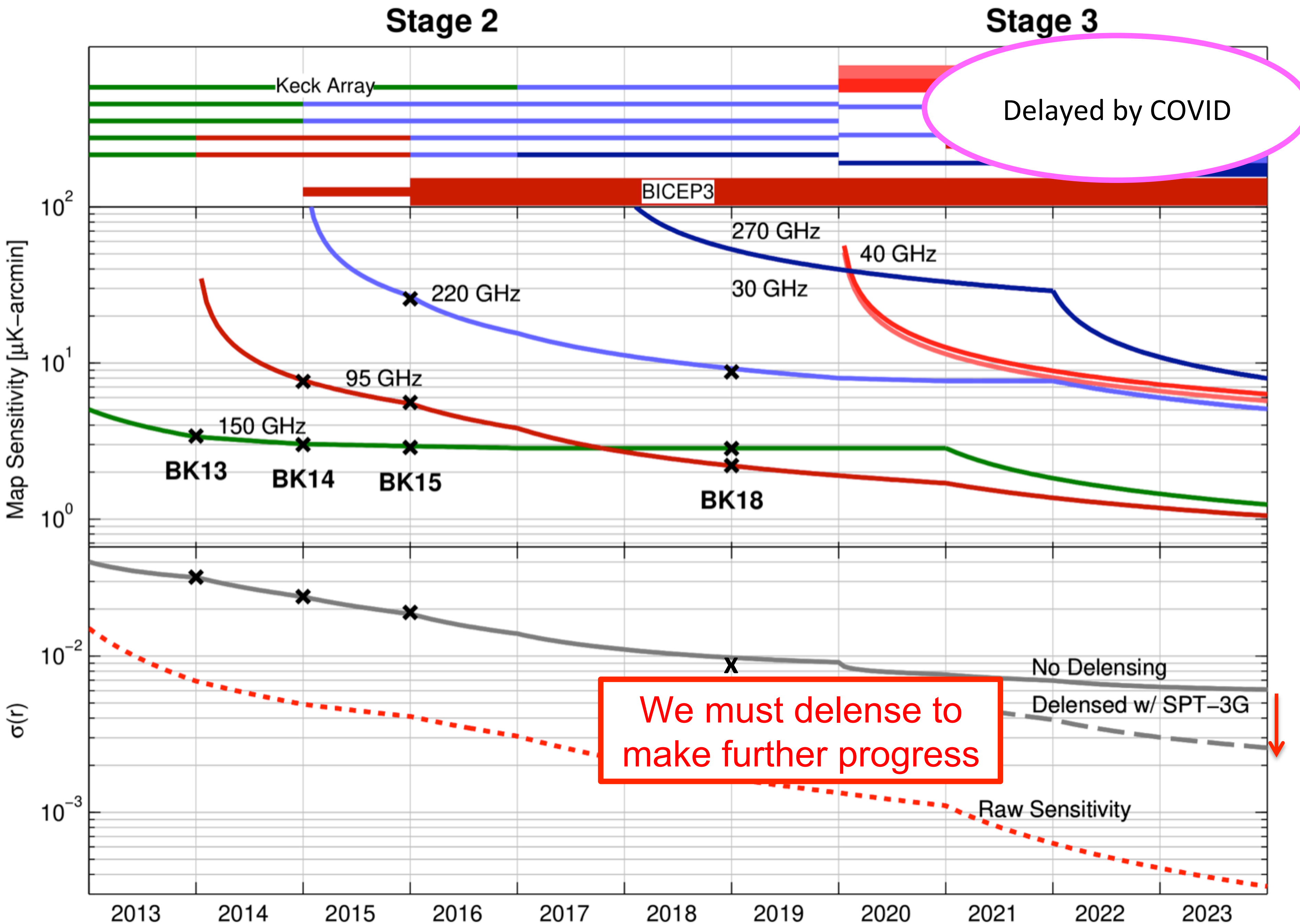


Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
BK13
BK14
BK15
BK18
Map Sensitivity [μK−arcmin]
σ(r)
No Delensing
Delensed w/ SPT−3G
Raw Sensitivity
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023



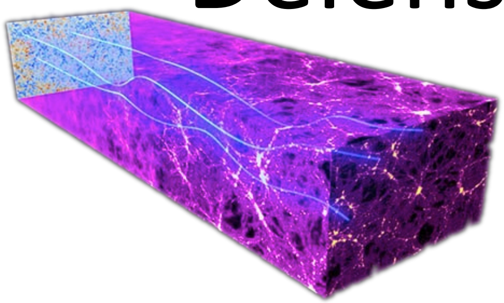
Stage 2
Stage 3
Keck Array
Delayed by COVID
BICEP3
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
BK13
BK14
BK15
BK18
Map Sensitivity [μK−arcmin]
10^2
10^1
10^0
σ(r)
10^{-2}
10^{-3}
No Delensing
Delensed w/ SPT−3G
Raw Sensitivity
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023

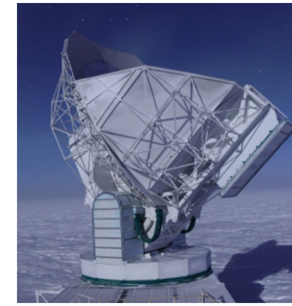

Stage 2
Stage 3
Keck Array
BICEP3
Delayed by COVID
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
BK13
BK14
BK15
BK1
Map Sensitivity [μK−arcmin]
σ(r)
As we increase the sensitivity the sample variance on the lensing B-modes become the limiting factor
No Delensing
Delensed w/ SPT−3G
Raw Sensitivity
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023



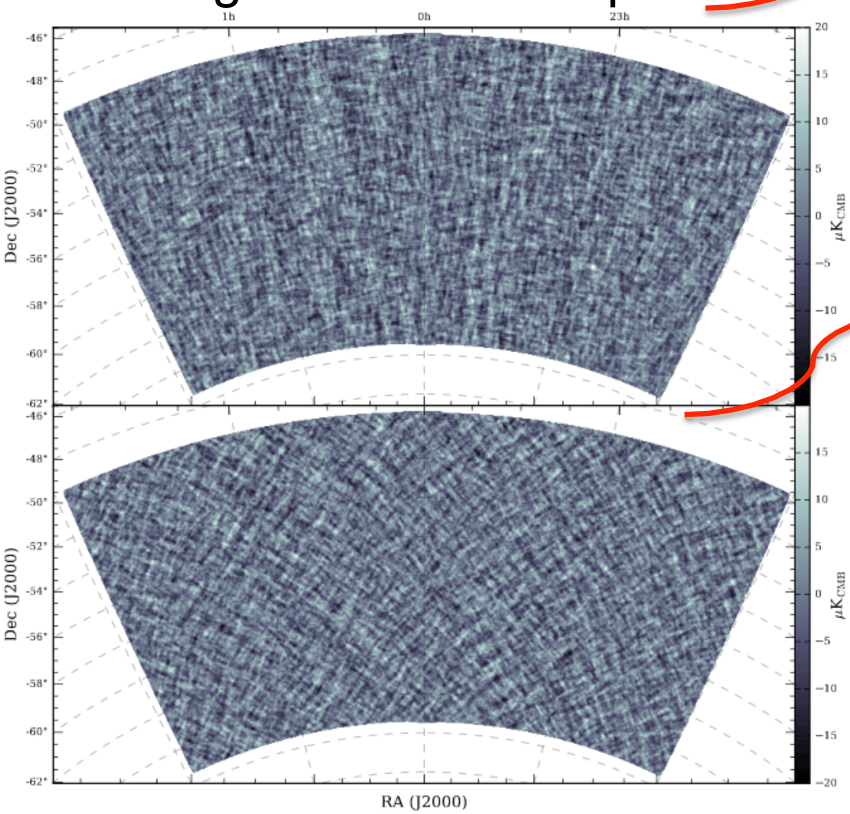
Stage 2
Stage 3
Keck Array
Delayed by COVID
BICEP3
Map Sensitivity [μK–arcmin]
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
BK13
BK14
BK15
BK18
σ(r)
No Delensing
Delensed w/ SPT–3G
We must delense to make further progress
Raw Sensitivity
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023

Delensing with SPT-3G data

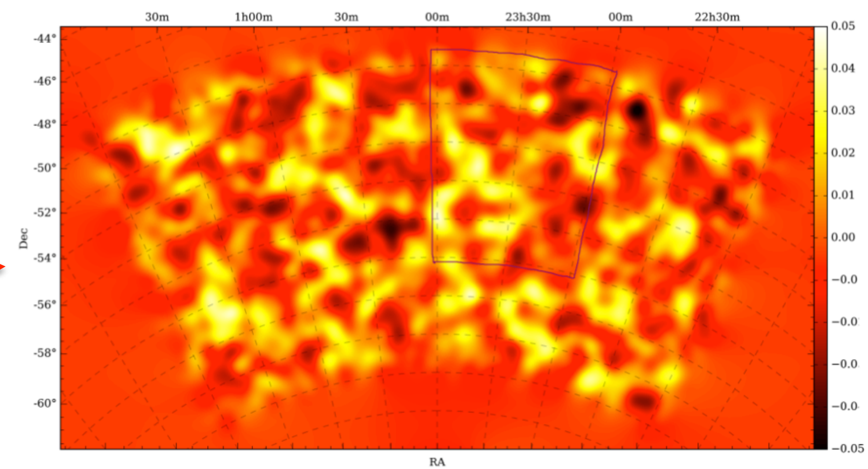




High resolution maps



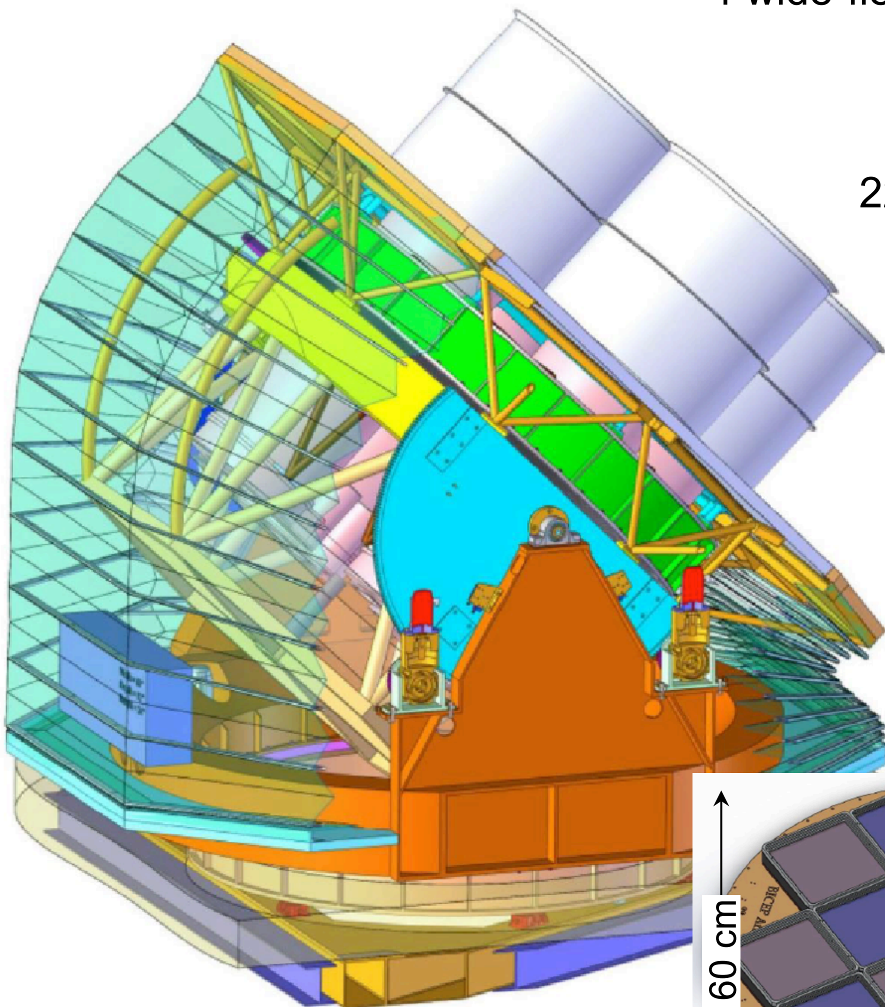
Can be used to reconstruct the lensing deflection map…



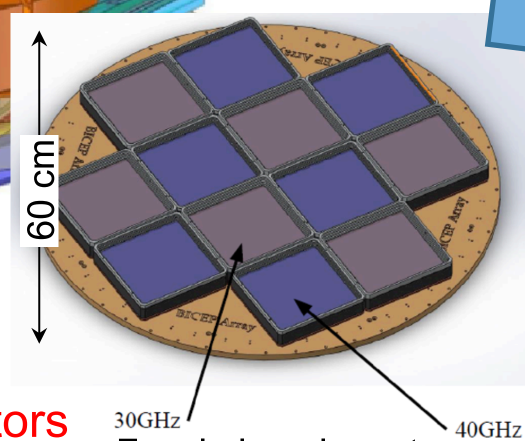
…which can then be used to calculate and the lensing signal enabling a deeper search for inflationary gravitational waves

BICEP Array Under Construction

4 wide-field receivers
30/40 GHz
95 GHz
150 GHz
220/270 GHz

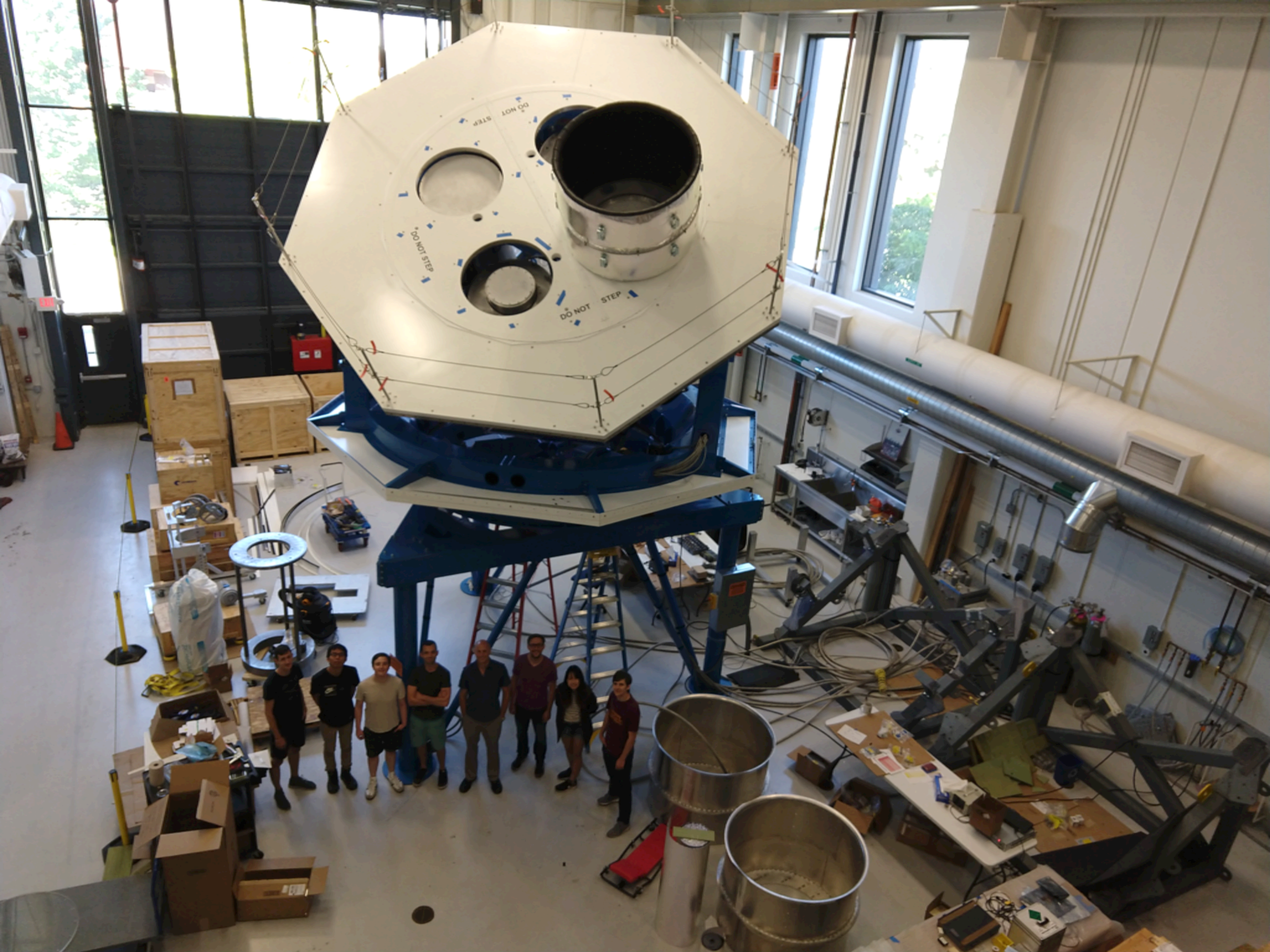


Wide-field cryogenic receiver



Focal plane layout

When complete >30,000 detectors


DO NOT STEP
DO NOT STEP
DO NOT STEP

BICEP Array 2019-20 initial deployment

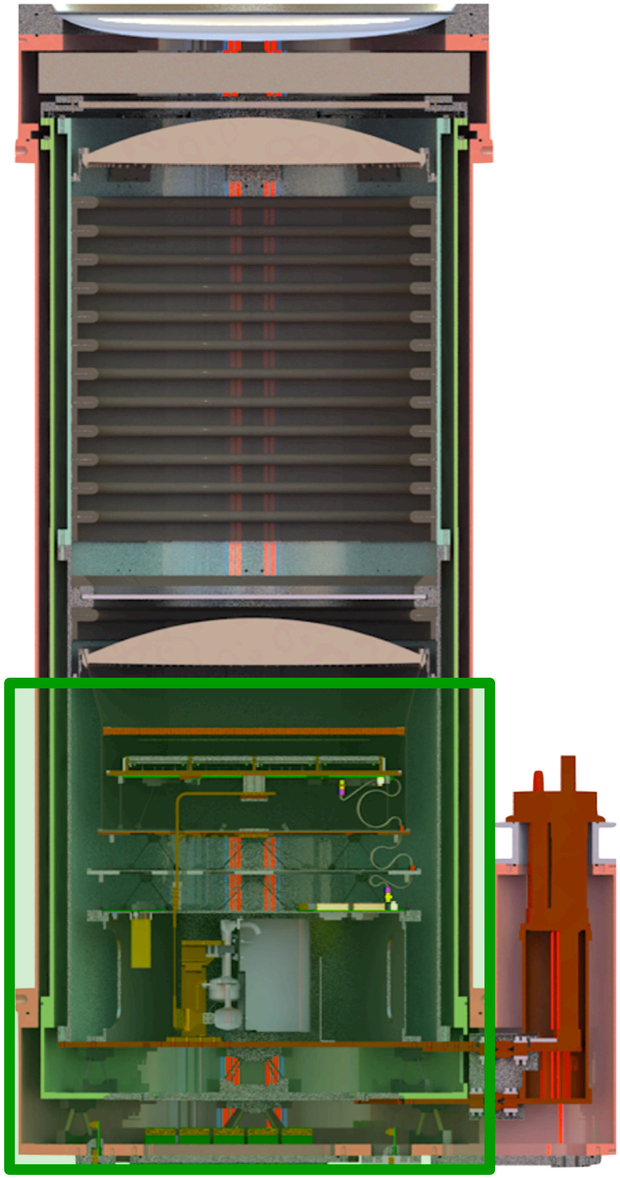
Three-month window during the Antarctic summer to perform:

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

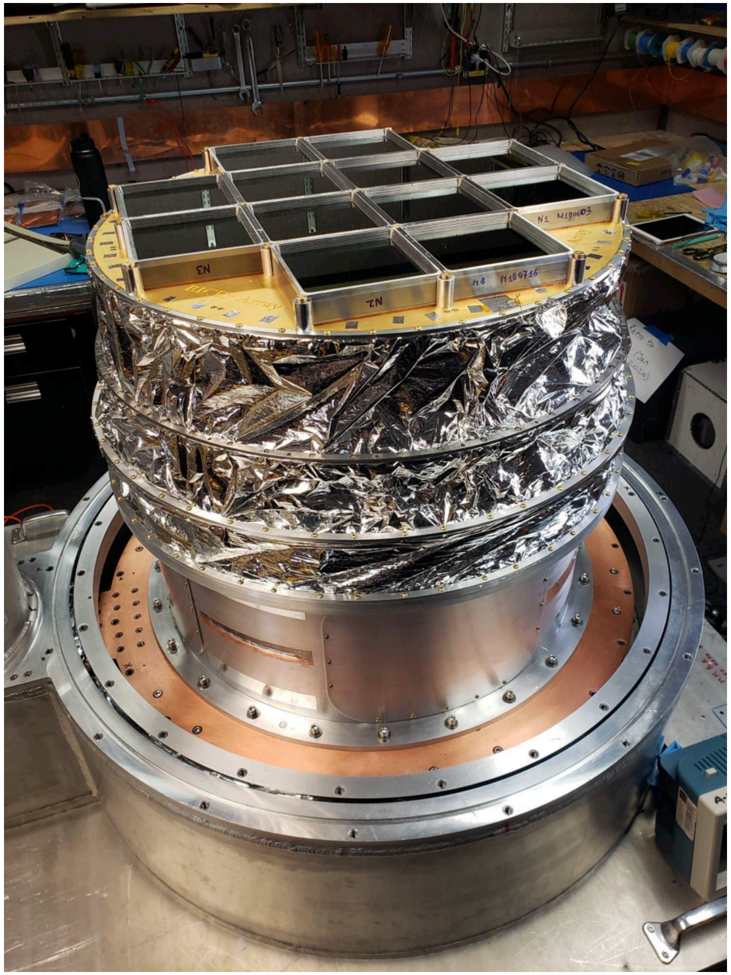
60,000 lbs of cargo, equivalent to 3 dedicated LC-130 Hercules flights to the South Pole.

30+ personnel:
- 2/3 scientists
- 1/3 contractors

BA1 instrumental highlights



Camera insert



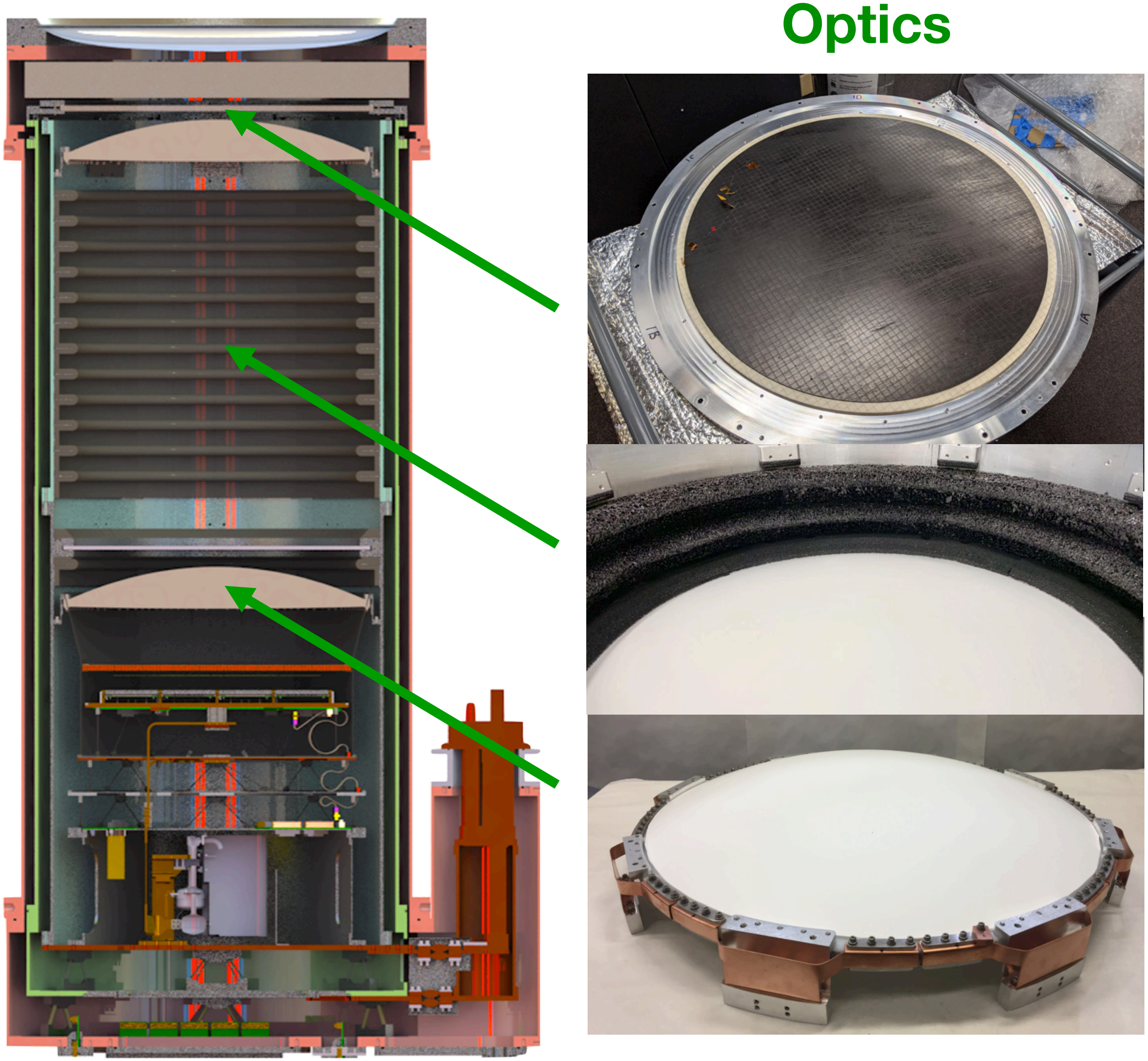
192/300 TES detectors at 30/40 GHz.

Integrated in 12 shielded modules, each with a low-pass mesh filters.

Time-Domain multiplexed readout.

BA1 instrumental highlights

Optics



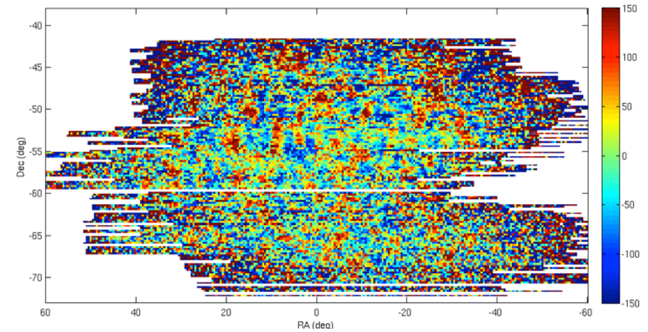
Alumina absorptive IR filter, AR-coated with laser-diced epoxy.

Internal absorptive baffling for scattering control.

Polyethylene lenses, AR-coated with expanded Teflon.
550mm clear aperture.

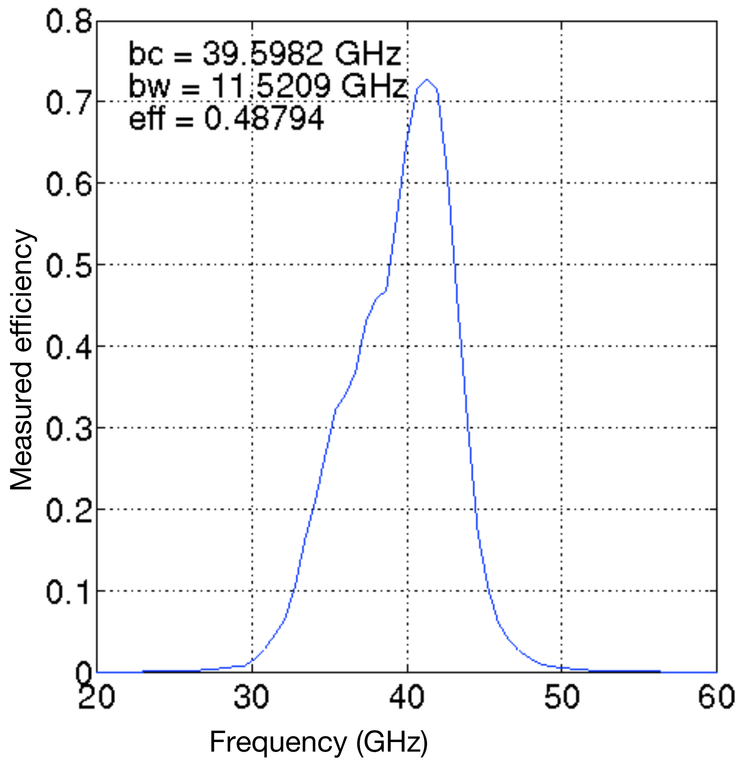
BA1 (30/40 GHz) installation

- The receiver reached baseline temperatures on Dec 30 2019. Excellent cryogenic performance.
- Small yield loss due to untested detector modules.
- Ran calibration campaign (Far-Field Beam Mapping, Far-Sidelobe Mapping).

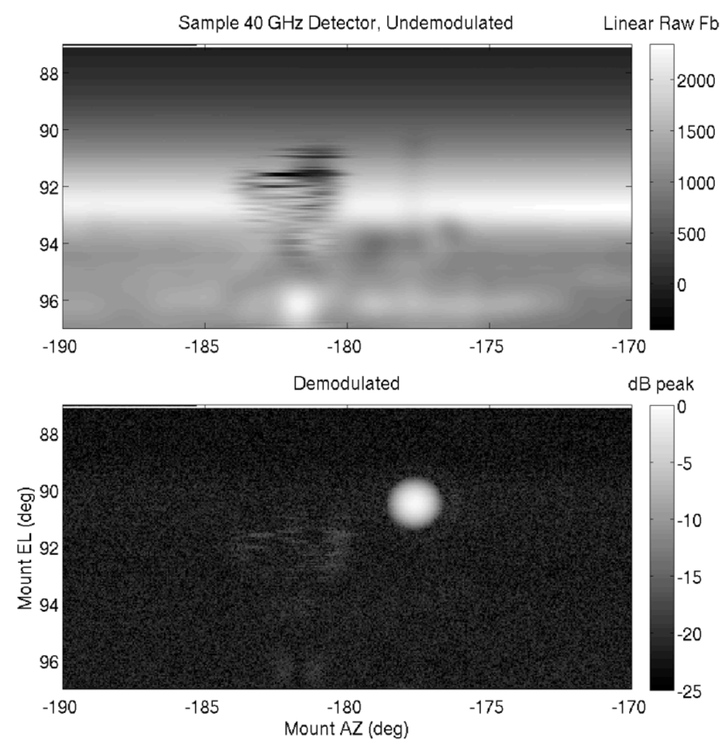


First light!

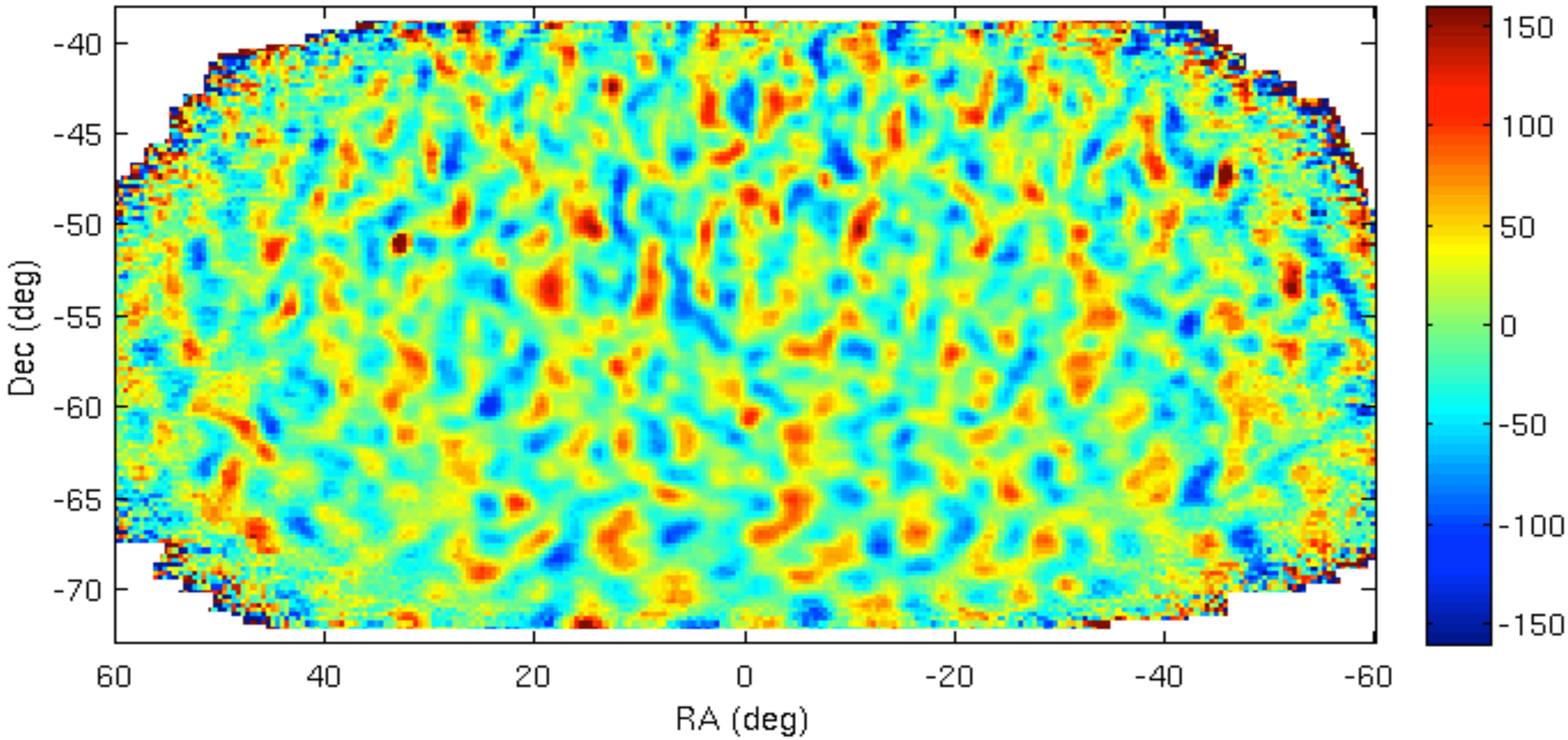
Spectral response of an example 40 GHz detector



Beam mapping

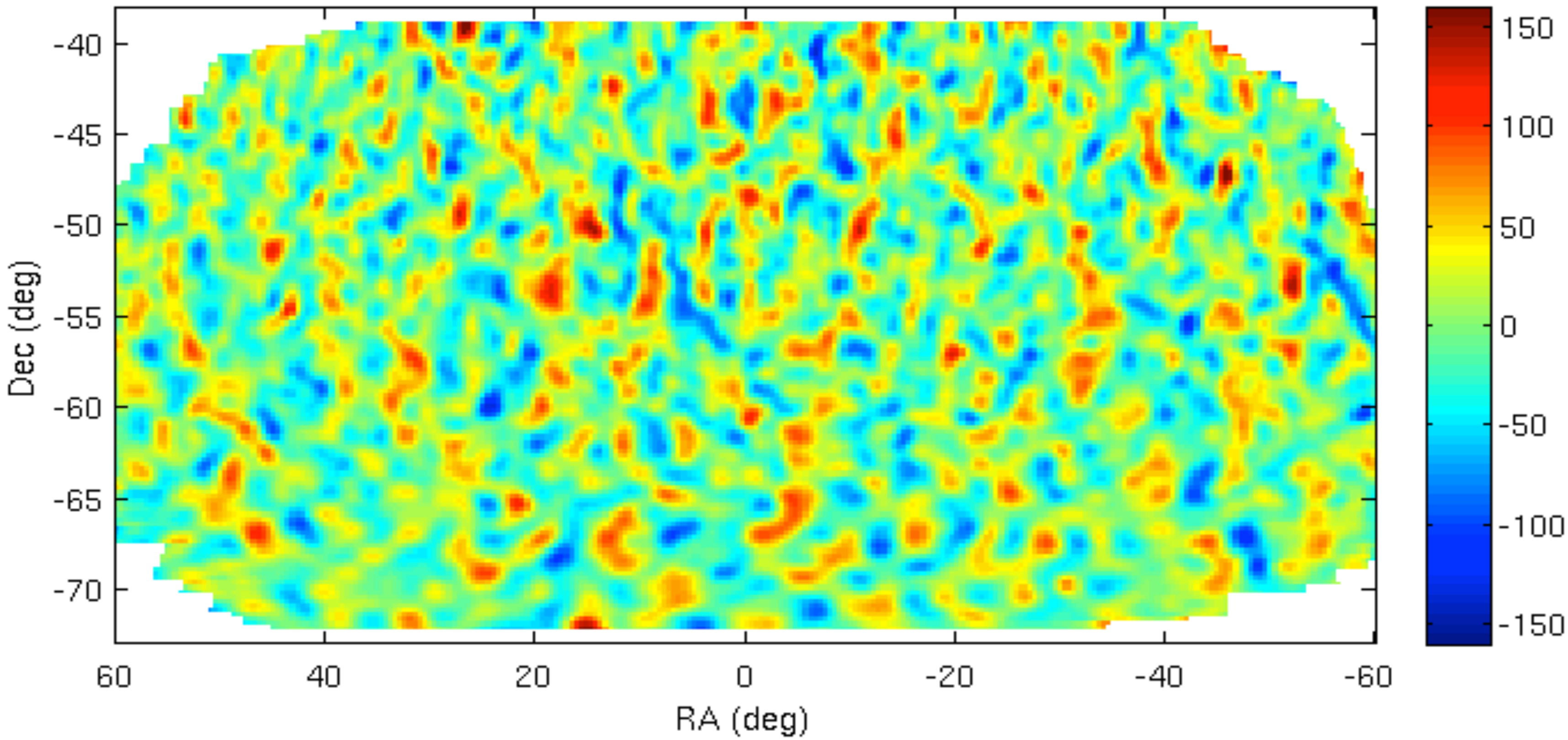


First year BA1 40GHz temperature map



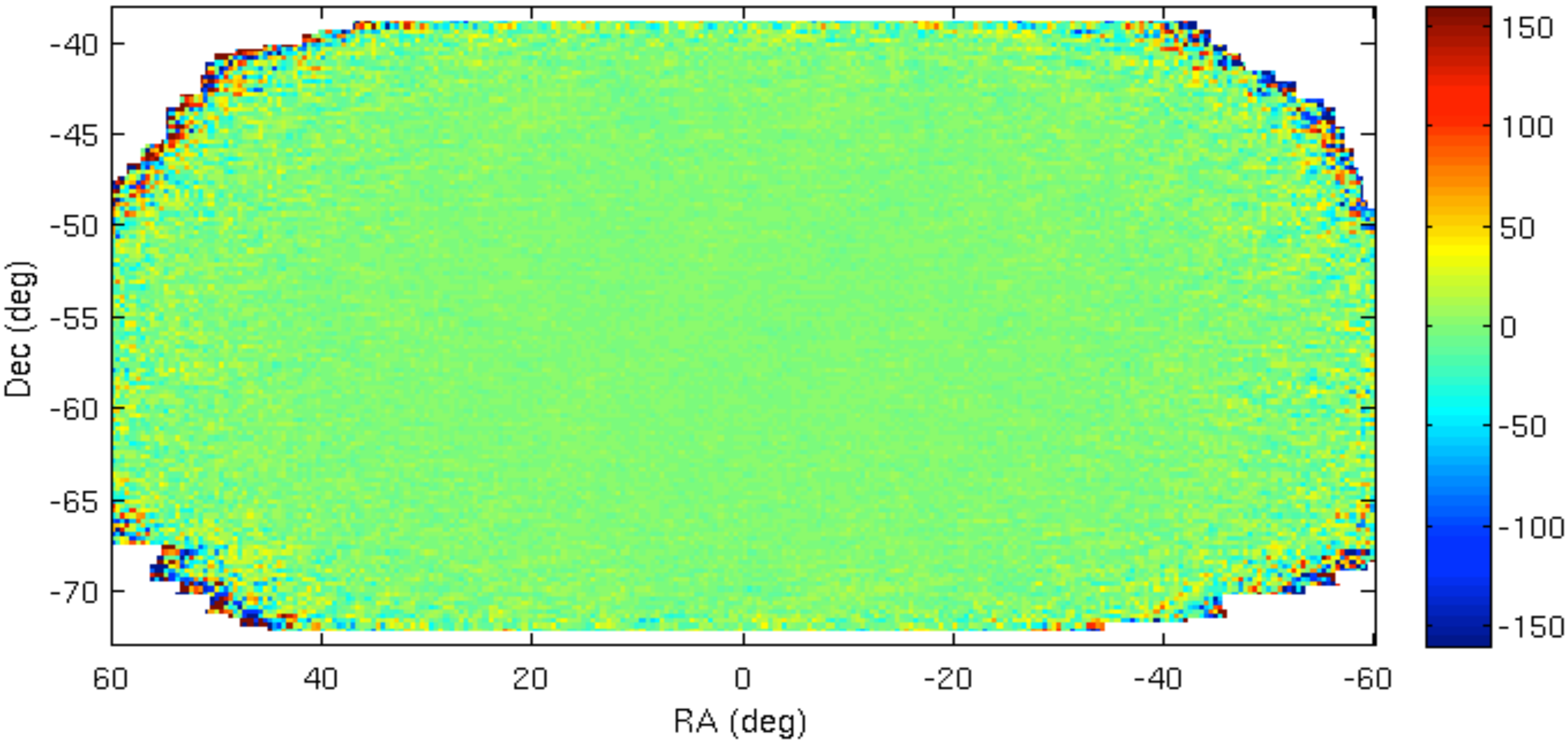
CMB temperature anisotropies from first year of observation

Re-observed Planck 44GHz



CMB temperature anisotropies from Planck LFI 4-year

First year BA1 40GHz temperature map



Scan-direction jackknife implies high S/N detection

Conclusions

- BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:
- Best published sensitivity to date
- Best proven systematic control at degree angular scales

- Adding 2016-18 data (from BK15 to BK18):
- Goes from $r_{0.05}<0.07$ to $r_{0.05}<0.036$
- For the first time no priors from other regions of sky

- And we can keep going:
- BICEP Array mount and first receiver running
- Delensing in conjunction with SPT3G

- Other things I can talk about:
- Delensing technique (lensing template)
- E/B separation (matrix purification)
- Beam systematics and deprojection thereof
- Detailed beam measurements to predict undeprojected residual