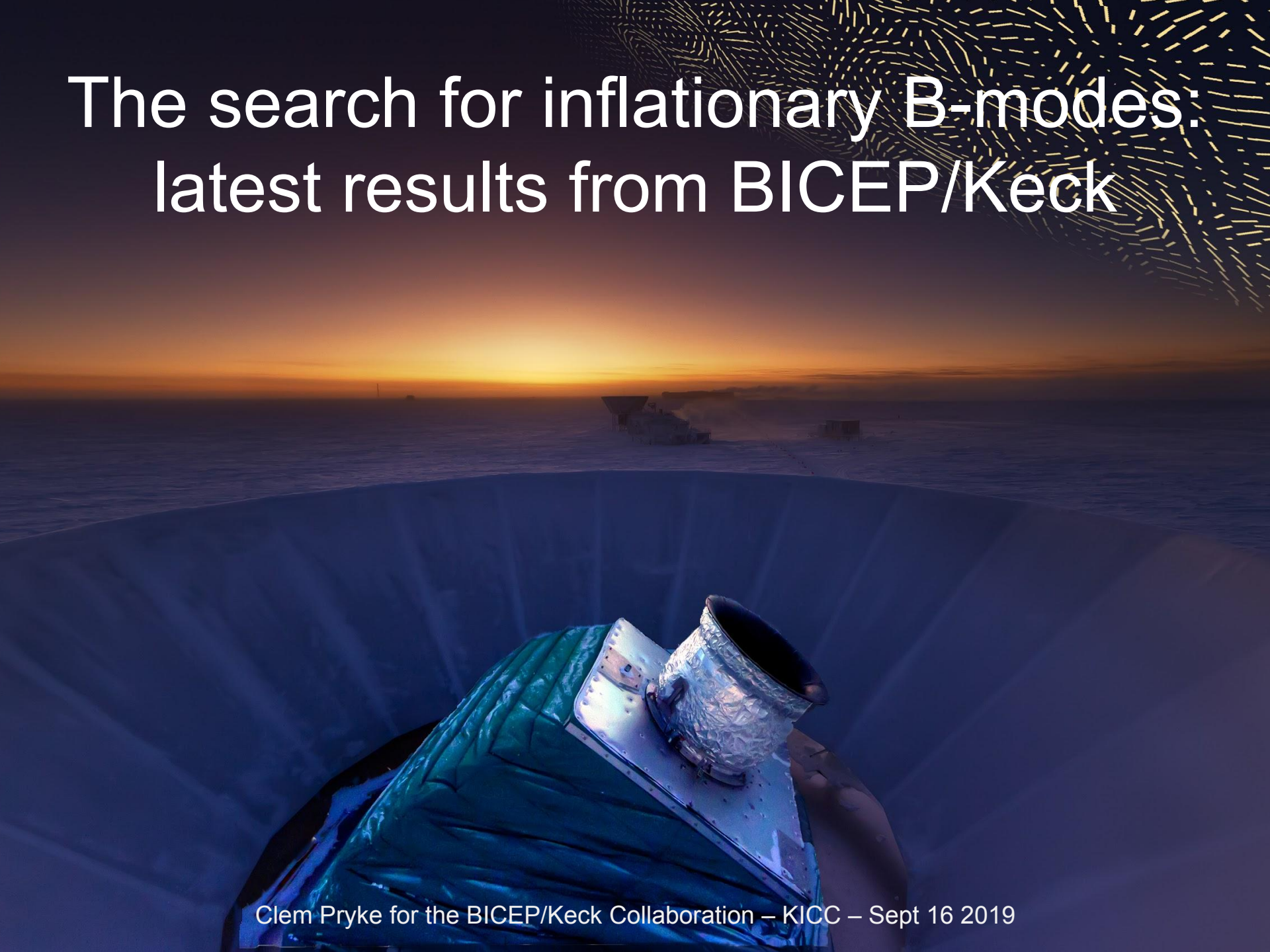
The search for inflationary B-modes: latest results from BICEP/Keck

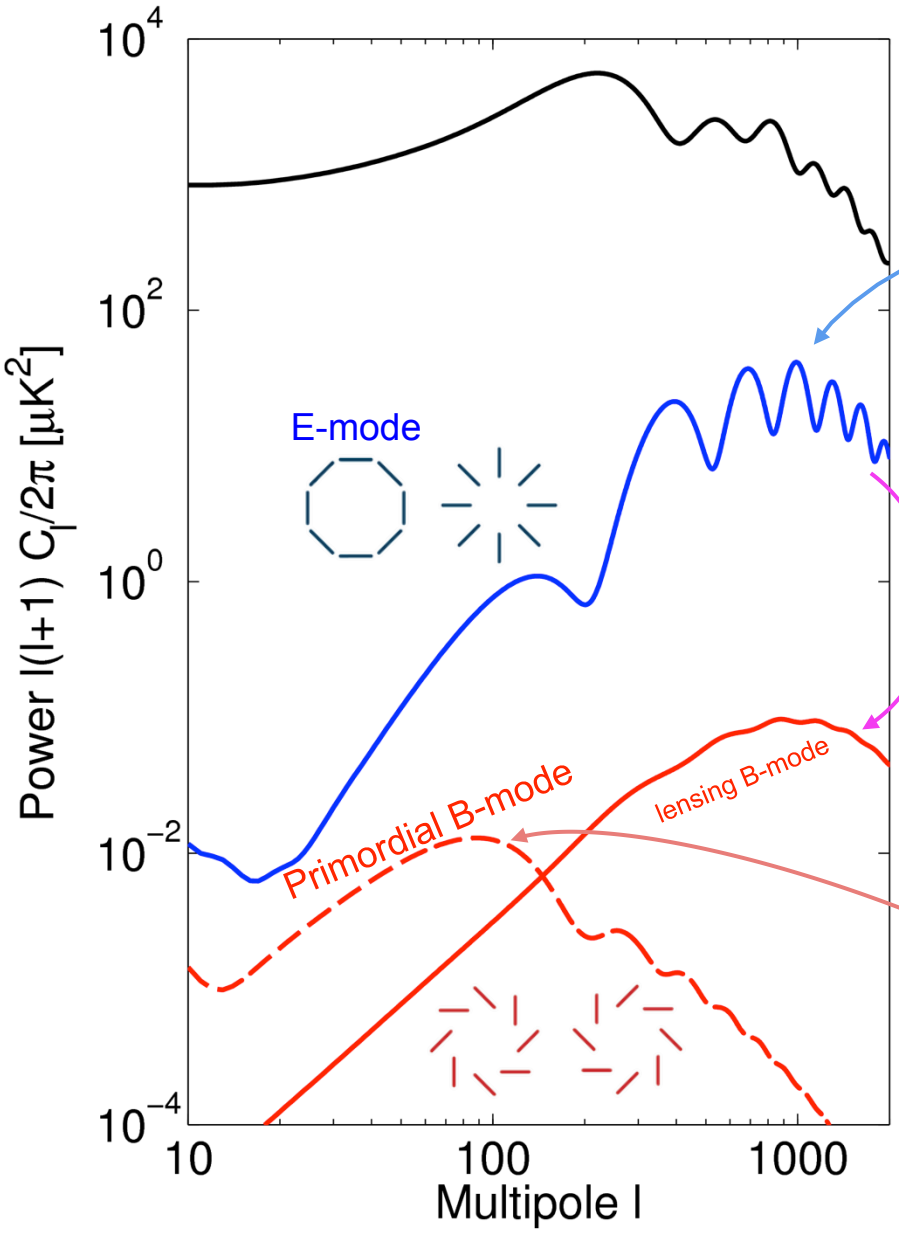


Clem Pryke for the BICEP/Keck Collaboration – KICC – Sept 16 2019

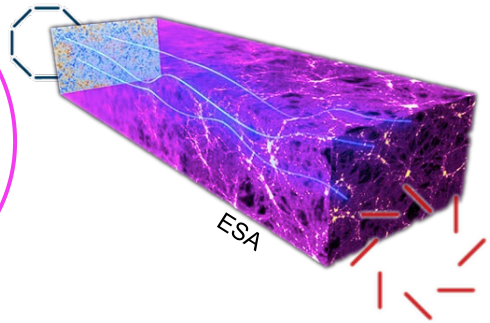
Motivation/Background

- 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



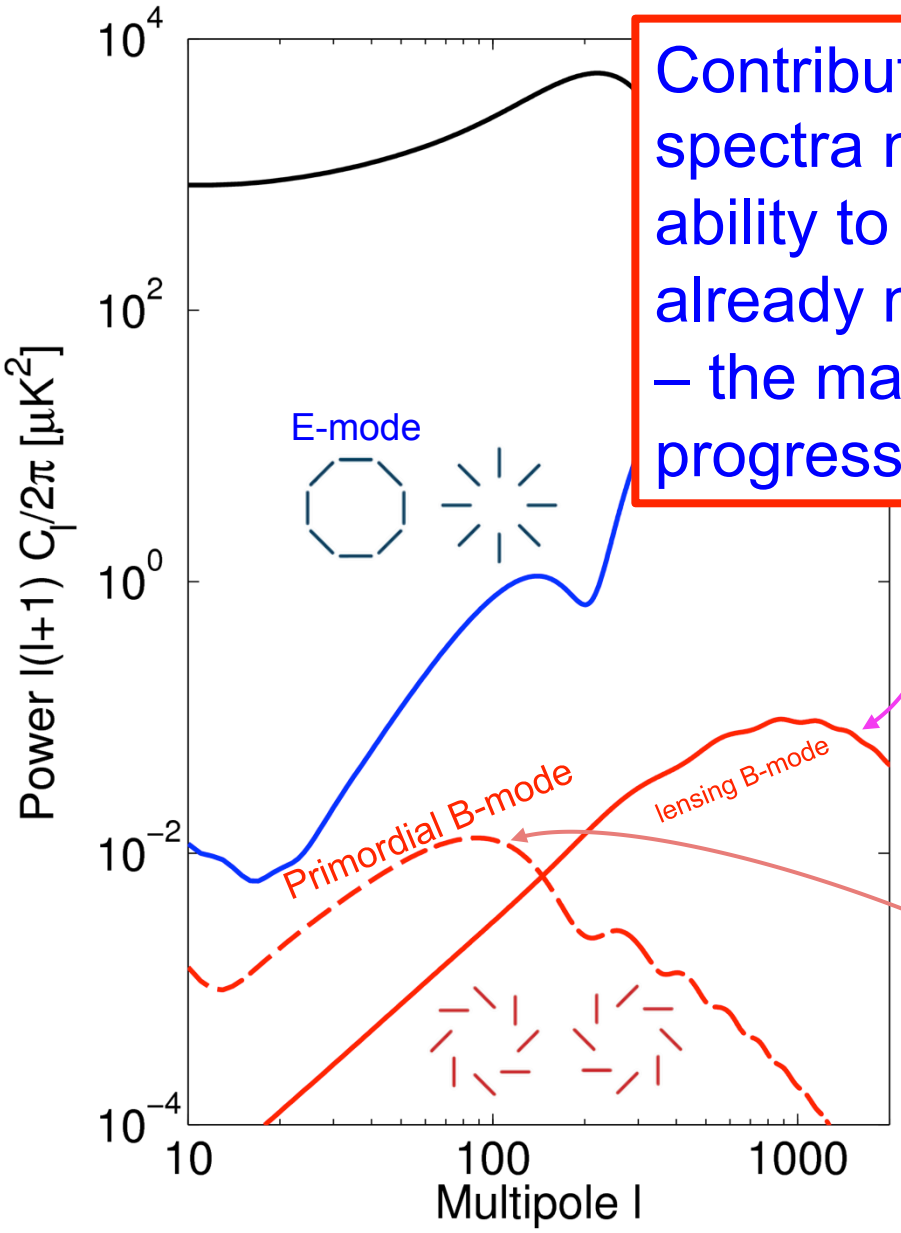
In standard ΛCDM only E-modes are present at last scattering



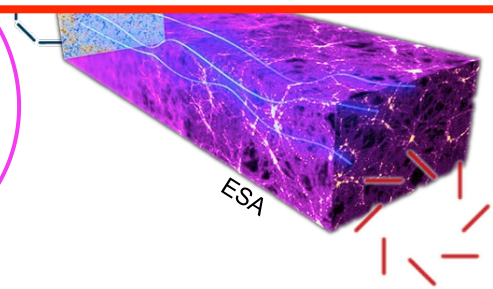
During propagation some of the E-modes are confused into B-modes by lensing

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

CMB power spectra



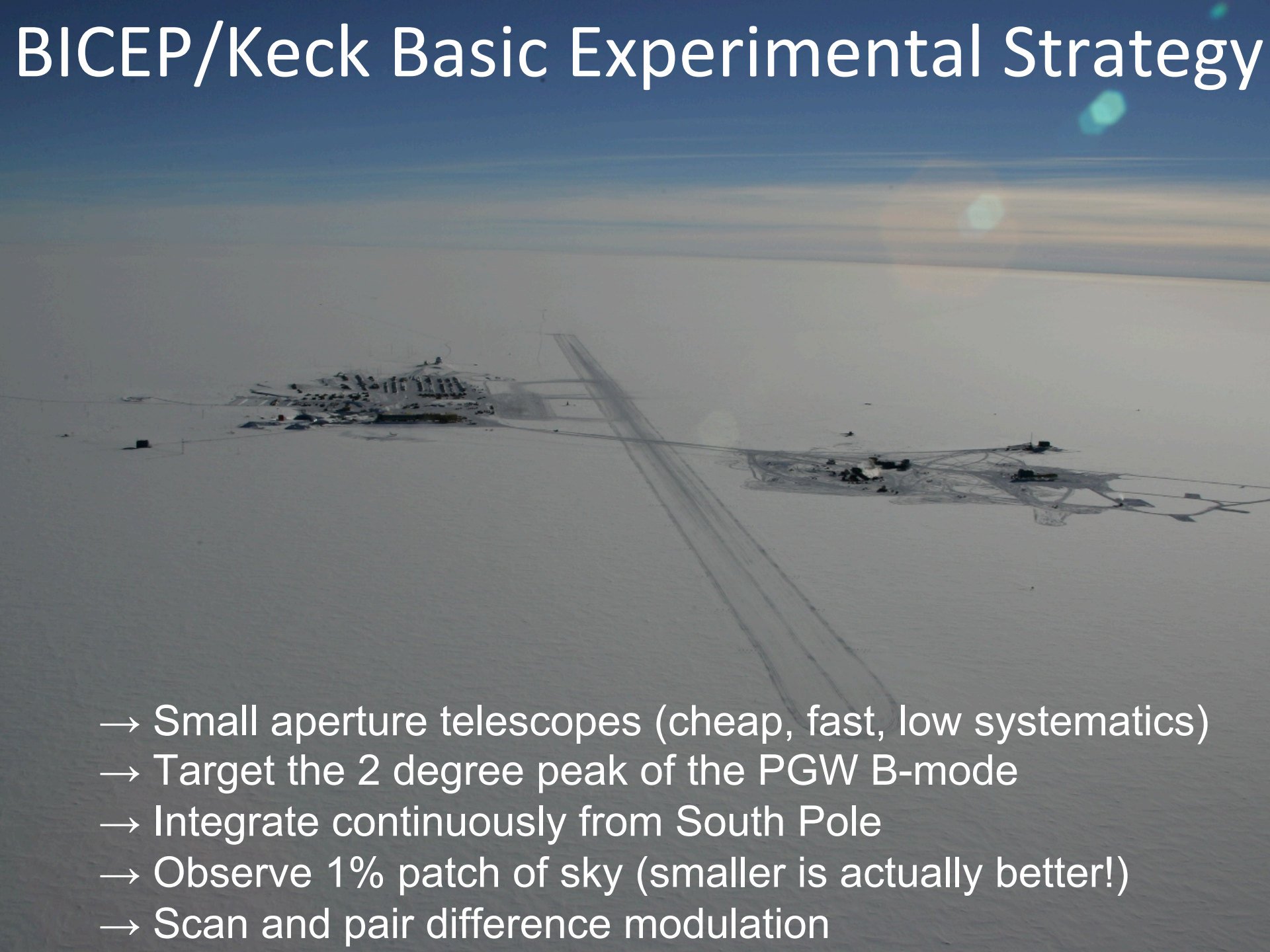
Contributions from PGW to T and E-spectra not shown here – However, ability to constrain *r* from these already maxed out at cosmic variance – the main way to make further progress is using B-modes…



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

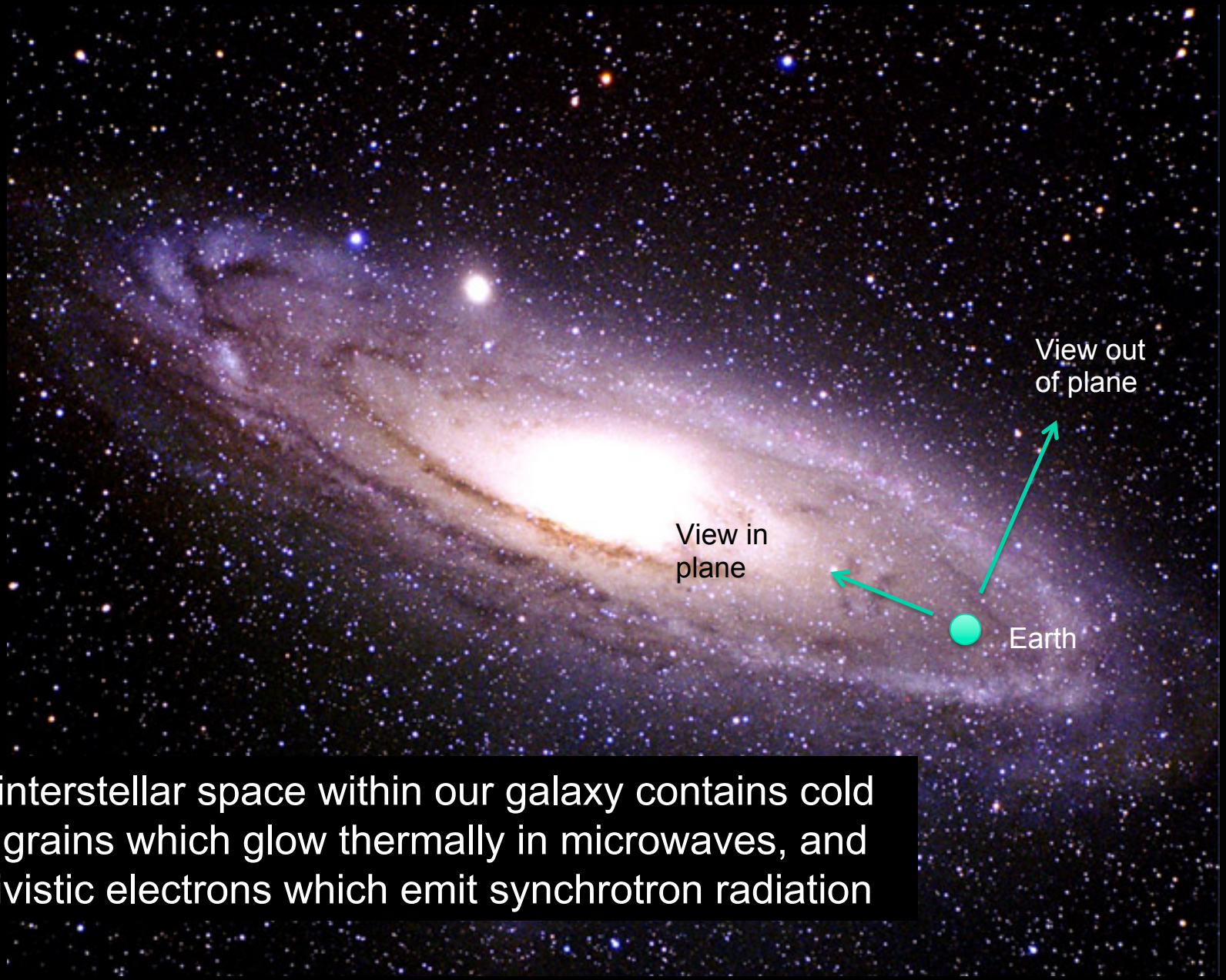
Inflationary gravitational waves are unique source of intrinsic B-modes
→ peaking at l≈80 : few degree scales

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



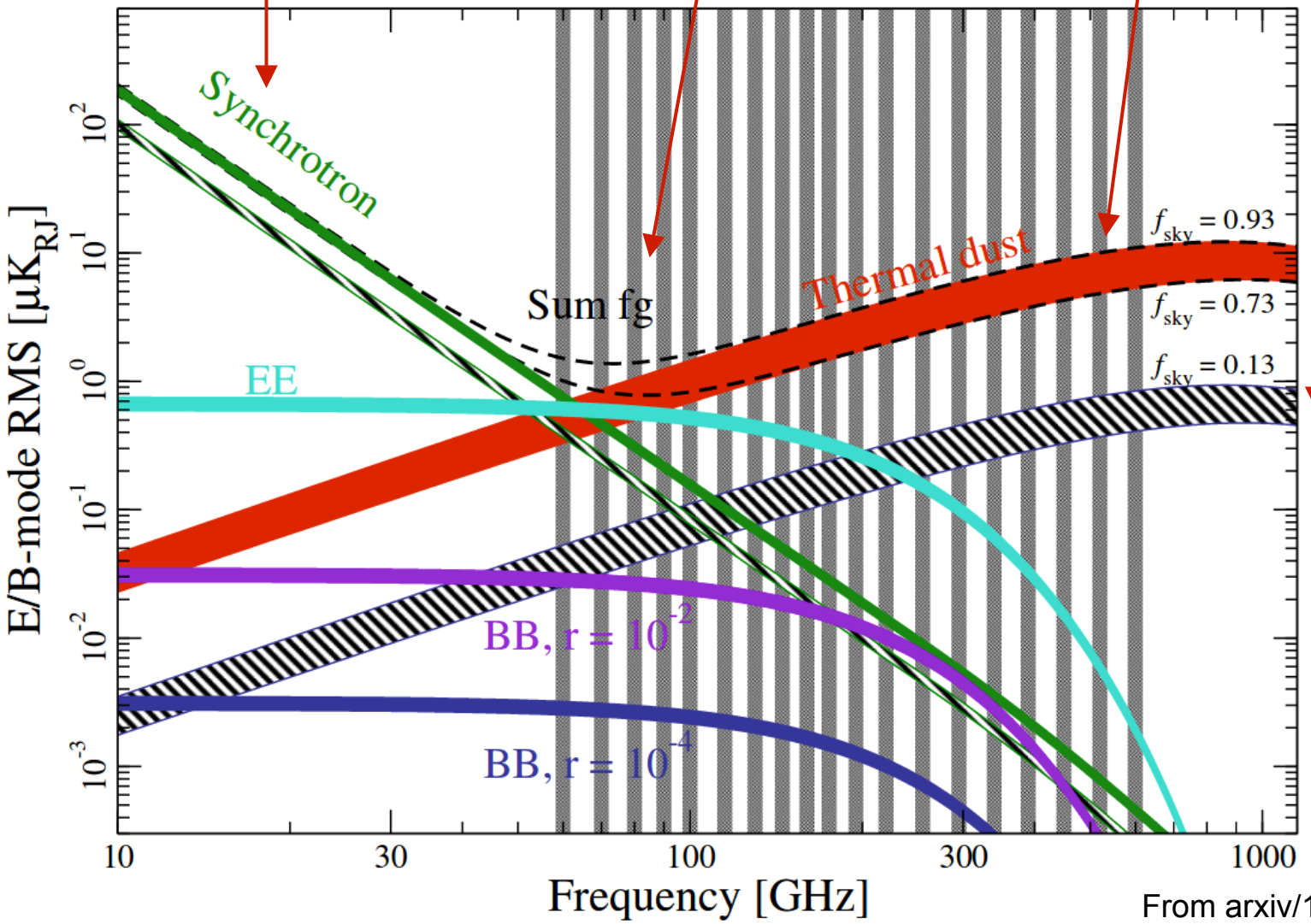
The interstellar space within our galaxy contains cold dust grains which glow thermally in microwaves, and relativistic electrons which emit synchrotron radiation

Overcoming Polarized Foreground Contamination

At low frequency synchrotron contamination

Mid frequencies minimum contamination

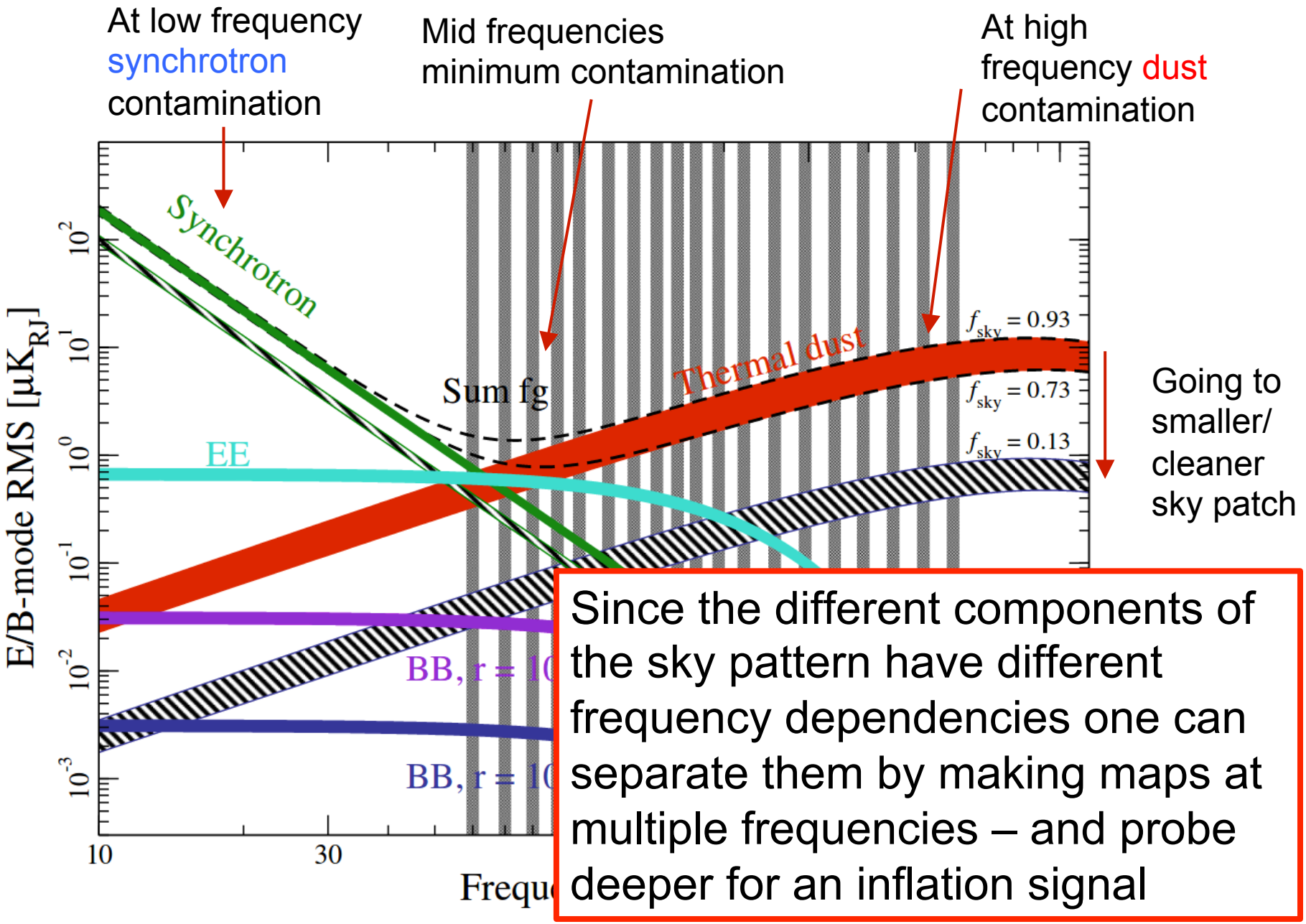
At high frequency dust contamination



Going to smaller/ cleaner sky patch

From arxiv/1704.04501

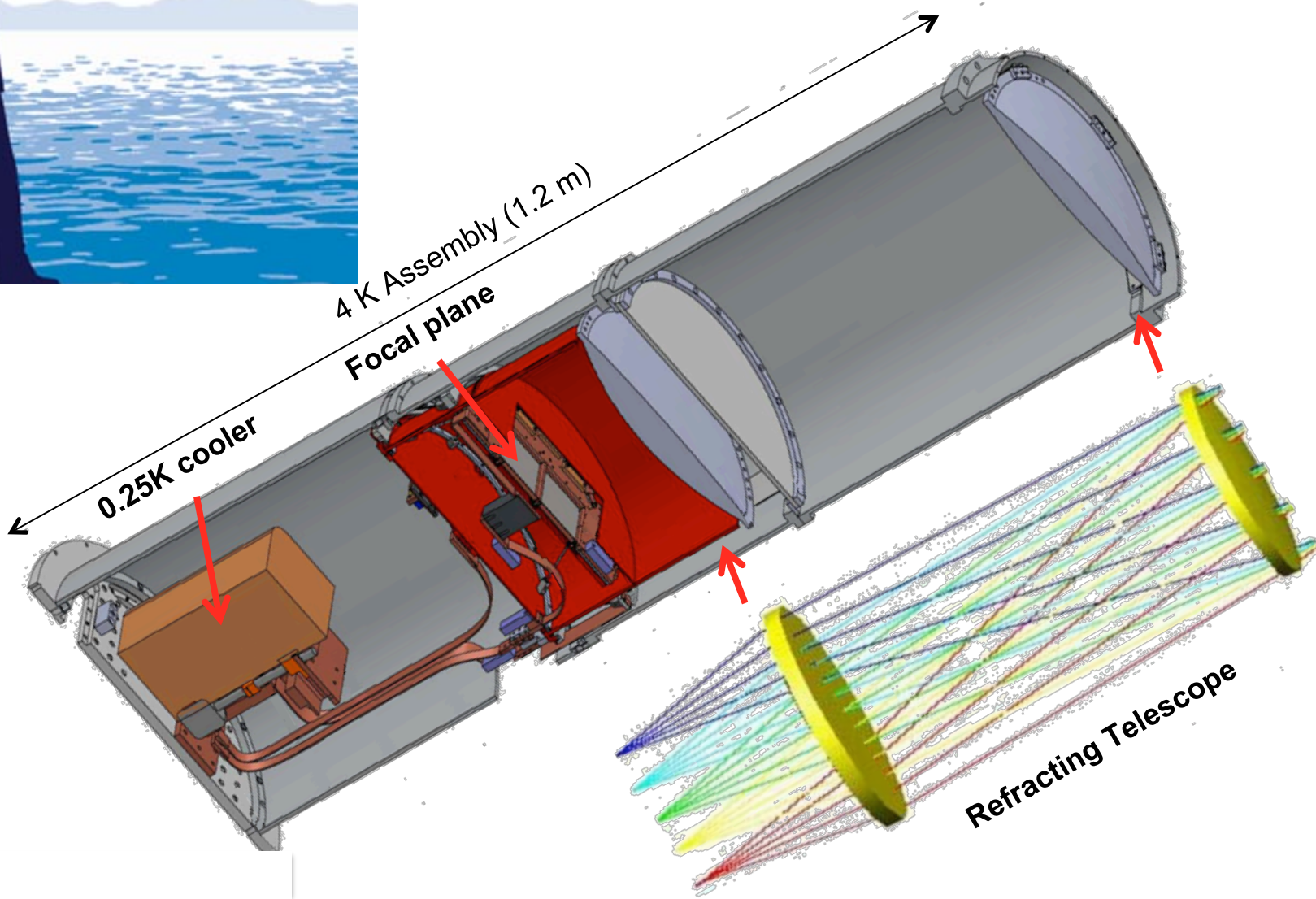
Overcoming Polarized Foreground Contamination



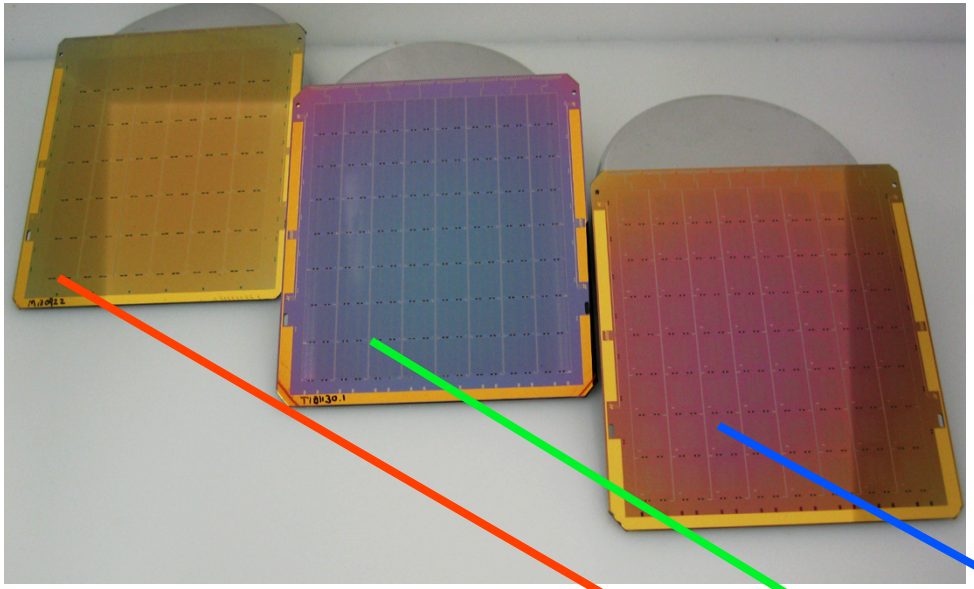
Since the different components of the sky pattern have different frequency dependencies one can separate them by making maps at multiple frequencies – and probe deeper for an inflation signal

BICEP/Keck Experimental Concept

- Small aperture
- Wide field of view
- Cold refractor

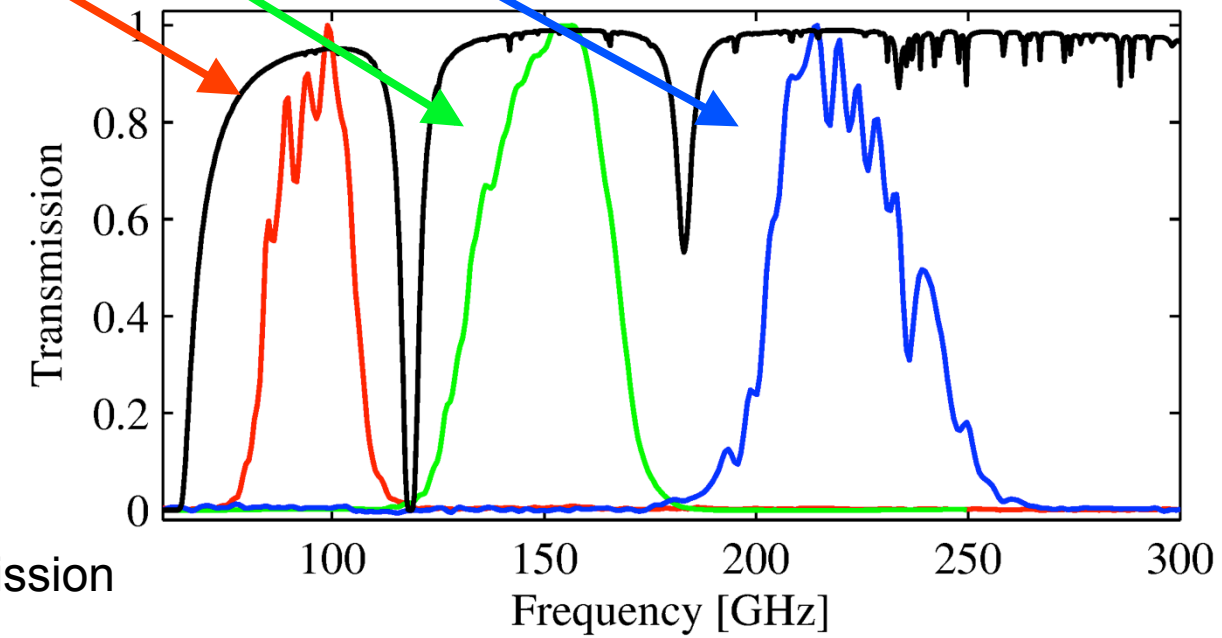


Planar superconducting detector arrays



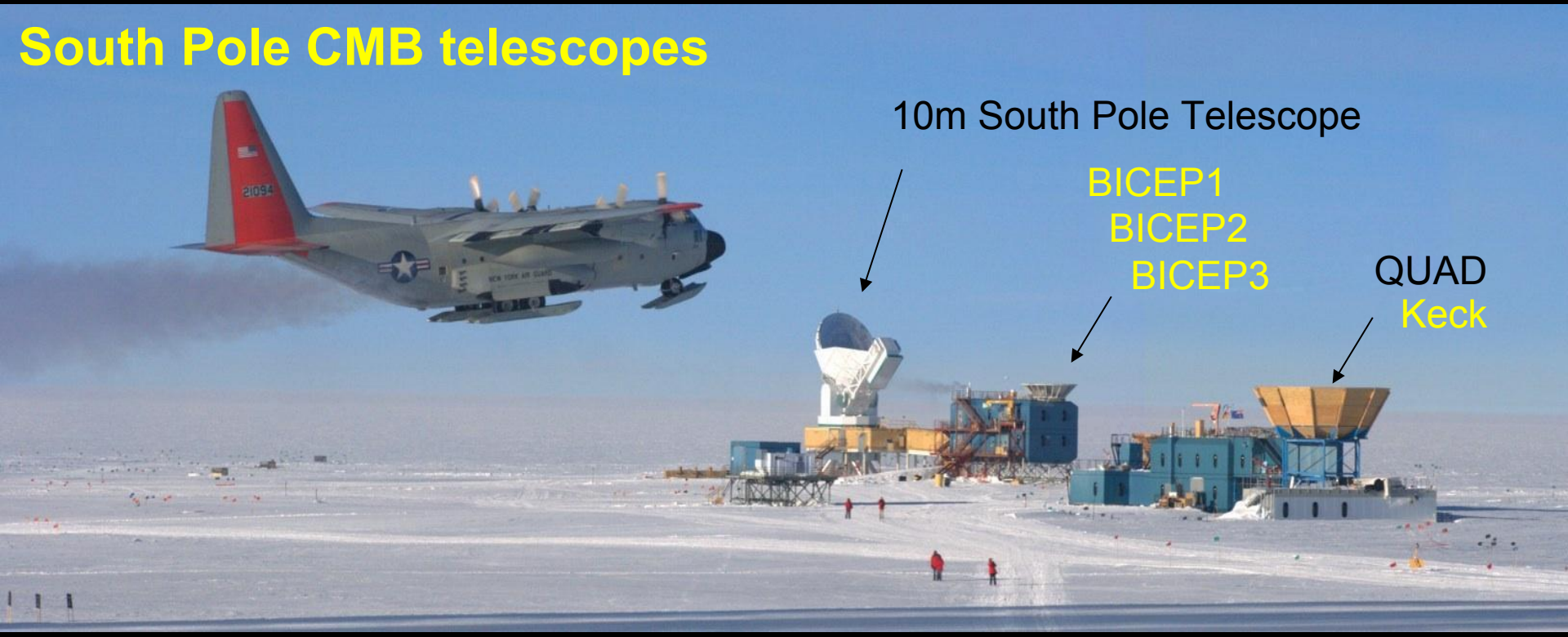
…designed to scale
in frequency

Up to 2013 – all 150GHz
2014 – 2x95 3x150GHz
2015 – 2x95 1x150 2x220GHz
2016 – B3 1x150 4x220GHz
2017 – B3 4x220 1x270GHz
2018 – B3 4x220 1x270GHz

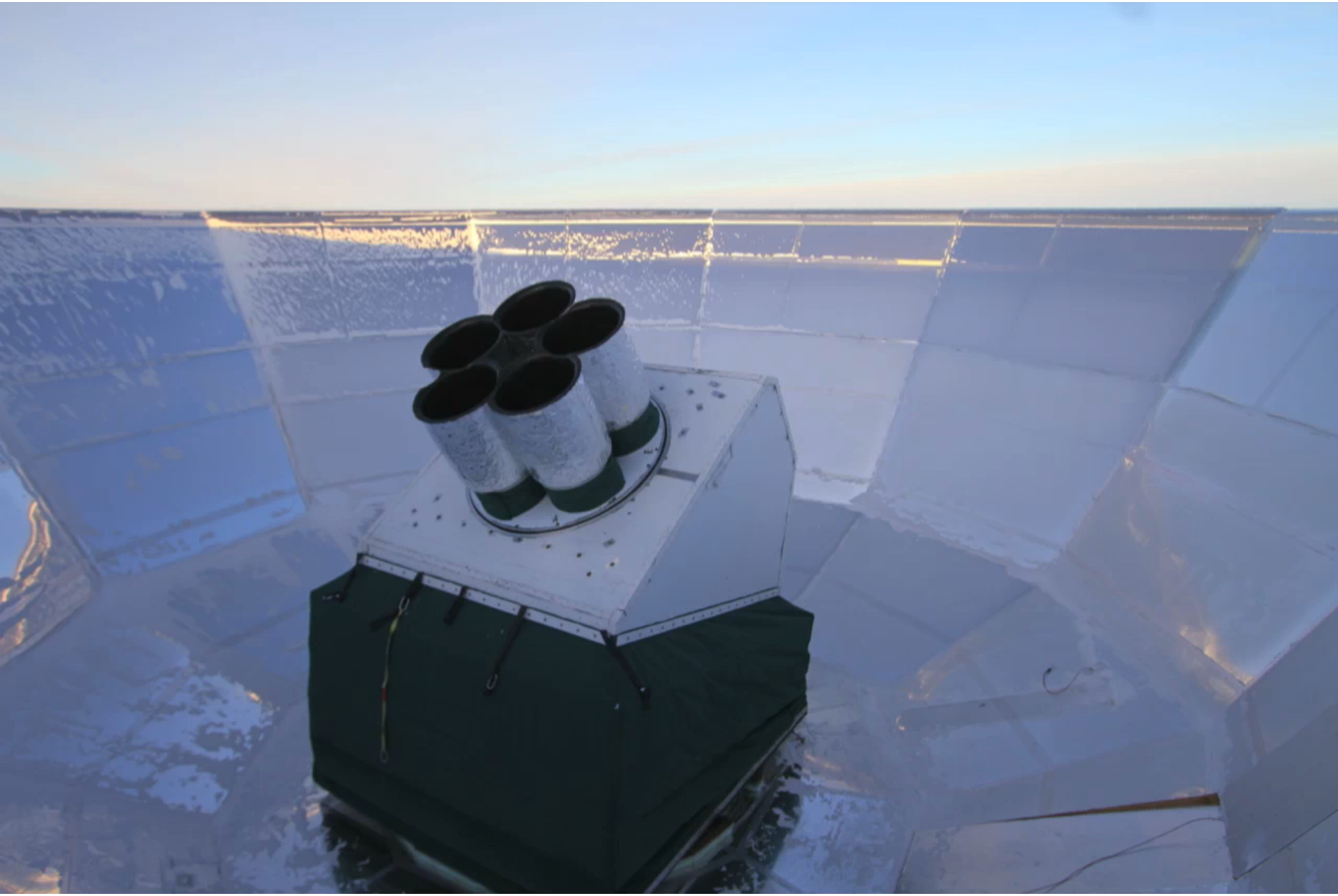


Typical South Pole
atmospheric transmission

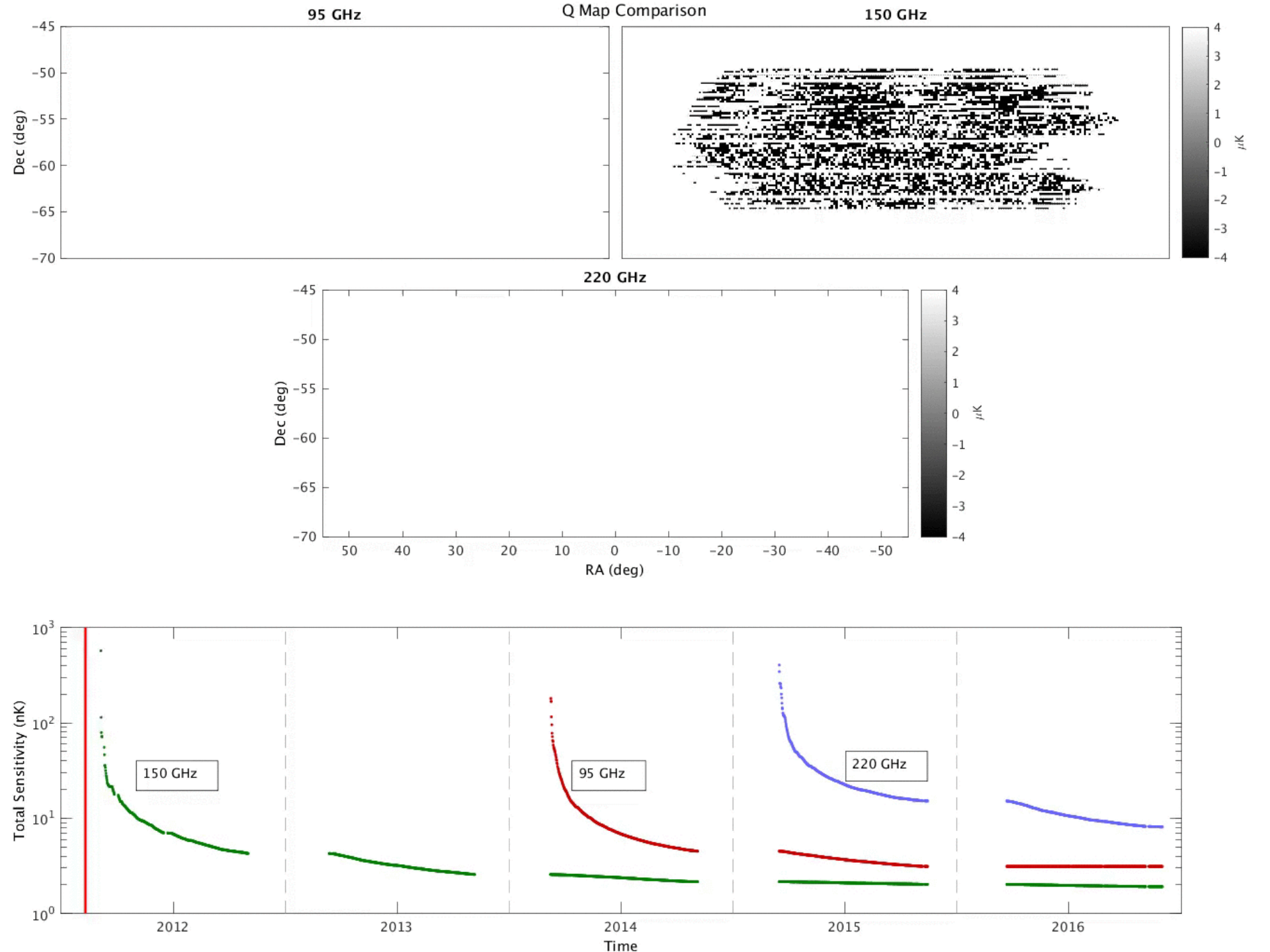
Why do this at the Pole?



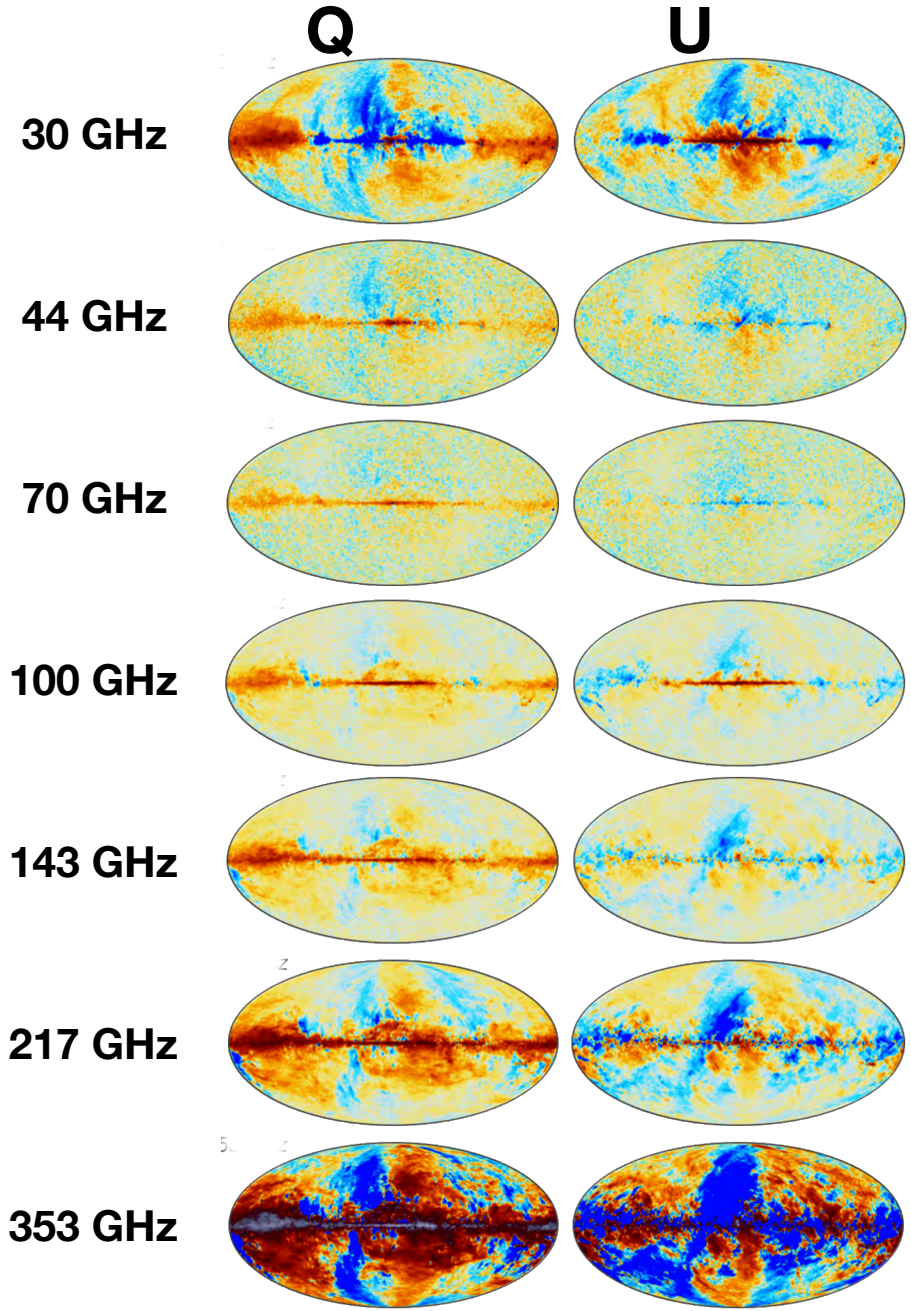
- High and *dry* – see out into space
- On Earth's rotational axis - One day/night cycle per year
  - Long night makes for great quality data
- Good support infrastructure – power, cargo, data comm
- Food and accommodation provided
- Even Tuesday night bingo…



Clem Pryke for The Bicep2 Collaboration

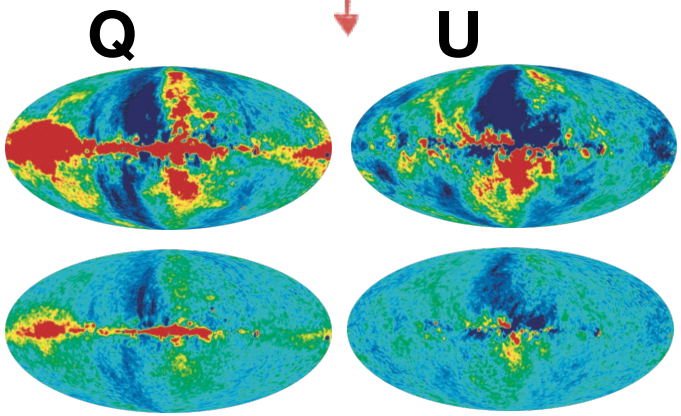

Q Map Comparison
95 GHz
150 GHz
220 GHz
Dec (deg)
RA (deg)
μK
Total Sensitivity (nK)
Time
150 GHz
95 GHz
220 GHz
2012
2013
2014
2015
2016

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



From arxiv 1502.01582

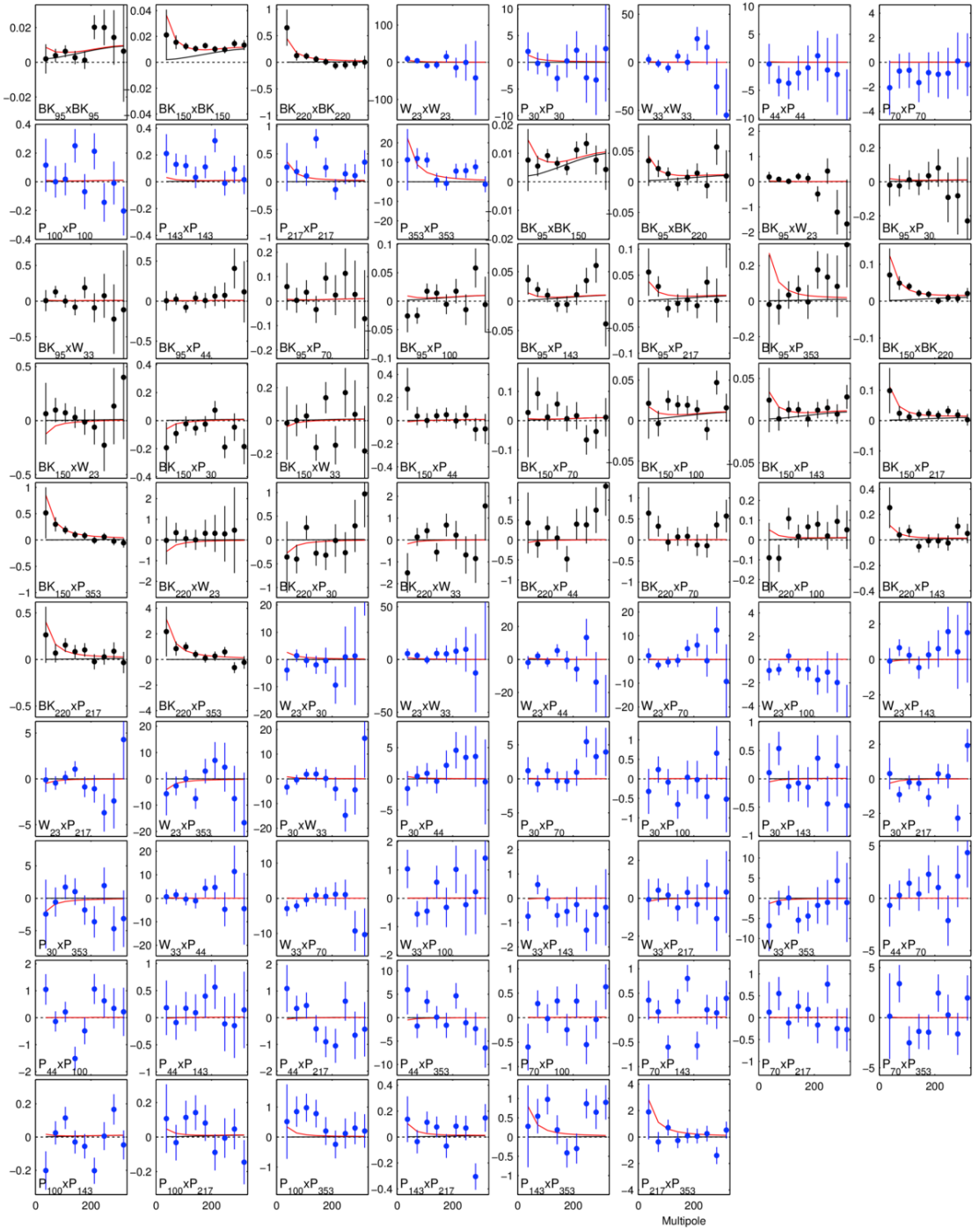
Polarized galactic **synchrotron** dominates at low frequencies



From arxiv 1212.5225

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

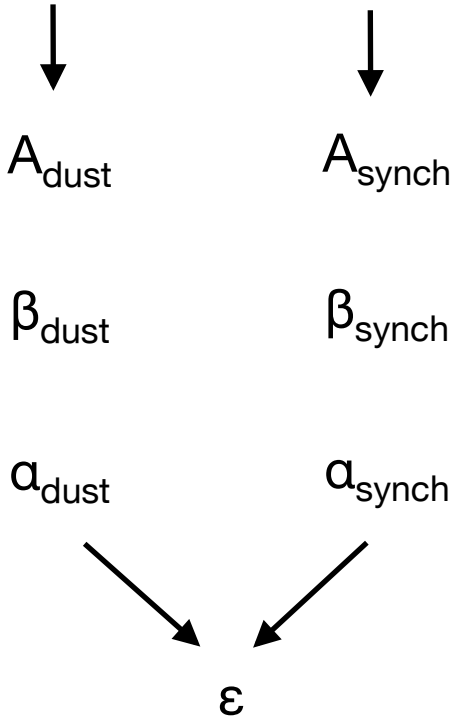
Analysis Technique: Take all possible auto- and cross spectra between the BICEP/Keck, WMAP, and Planck bands (78 of them) and compare to model of CMB +foregrounds



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

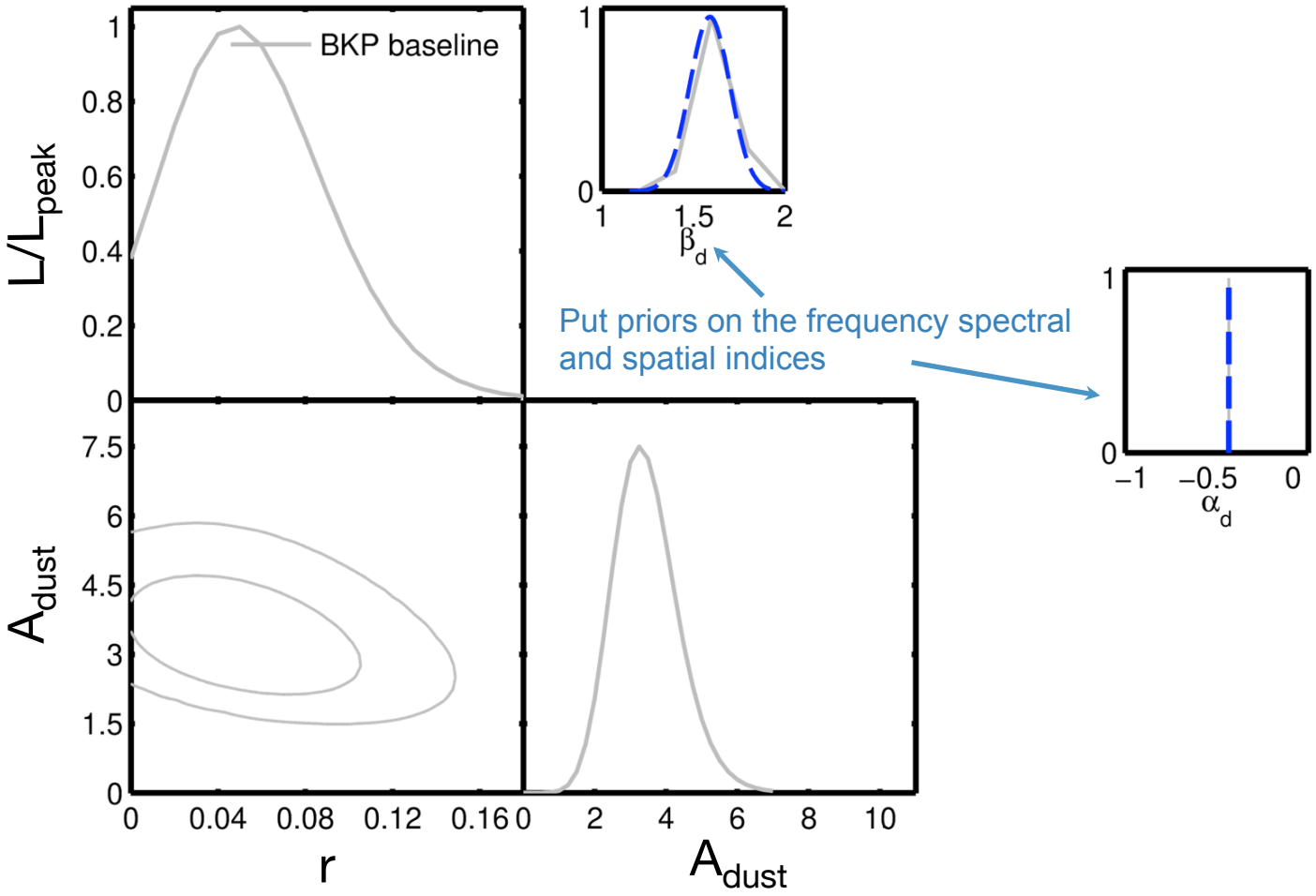


amplitudes @ l=80

frequency spectral indices

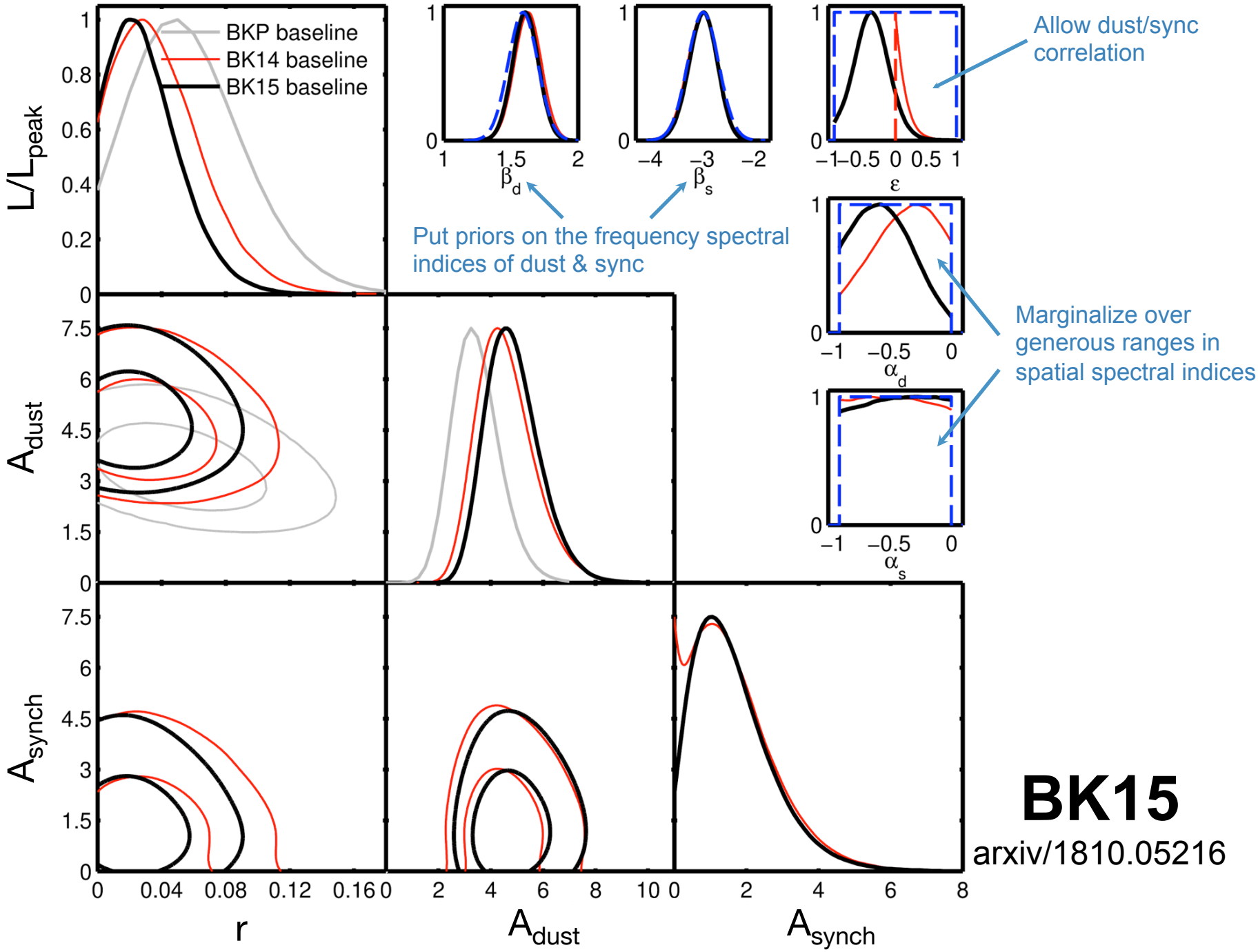
spatial spectral indices

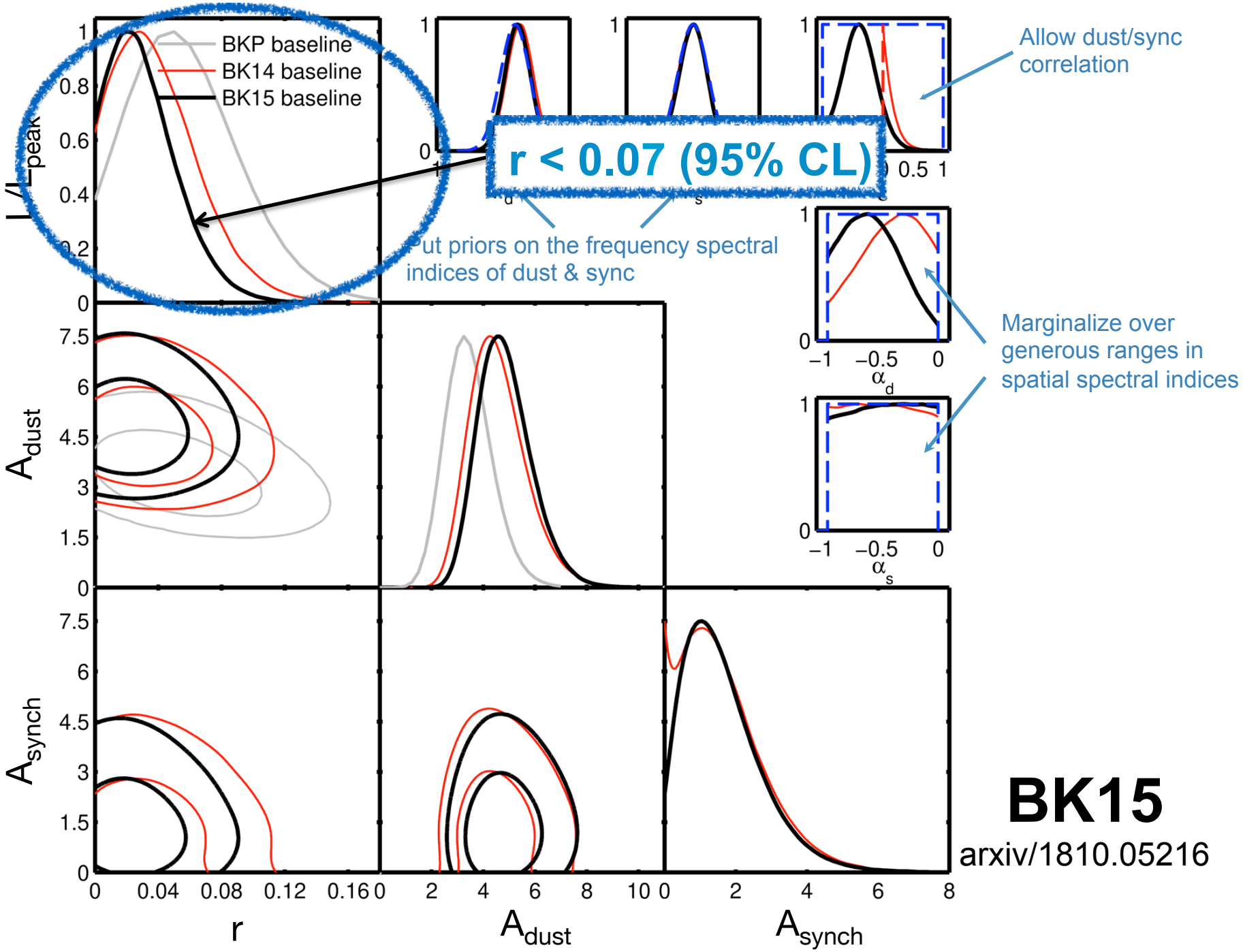
dust/synch spatial correlation



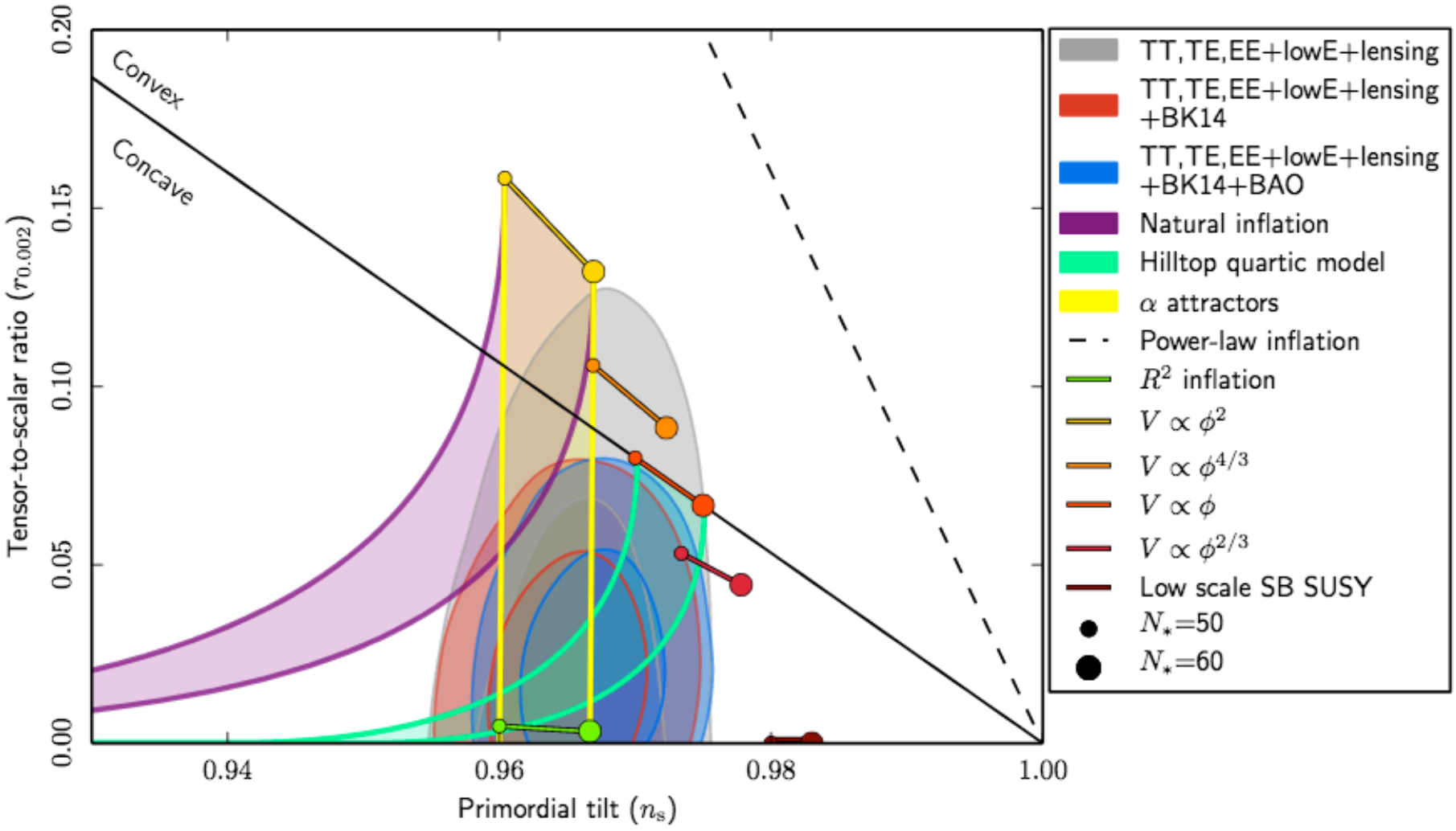
BKP

arxiv/1502.00612

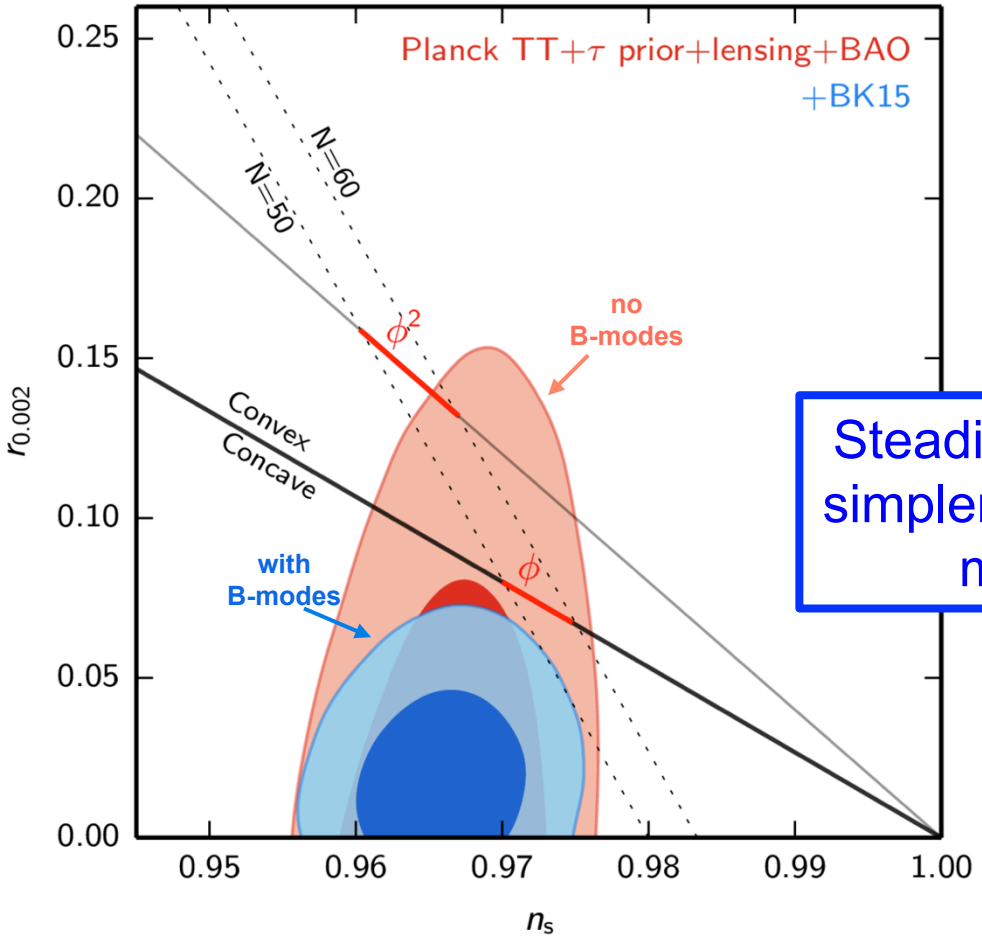

BKP baseline
BK14 baseline
BK15 baseline
L/L_peak
A_dust
A_synch
r
A_dust
A_synch
β_d
β_s
ε
α_d
α_s
Allow dust/sync correlation
Put priors on the frequency spectral indices of dust & sync
Marginalize over generous ranges in spatial spectral indices
BK15
arxiv/1810.05216


BKP baseline
BK14 baseline
BK15 baseline
L/L_peak
r < 0.07 (95% CL)
Allow dust/sync correlation
Put priors on the frequency spectral indices of dust & sync
Marginalize over generous ranges in spatial spectral indices
A_dust
A_synch
r
α_d
α_s
BK15
arxiv/1810.05216

Combining with Planck (Planck 2018 results include BK14 data)



BK15 Squeezes down a little more in on *r*



Steadily ruling out simpler inflationary models

BK15

arxiv/1810.05216

r < 0.06

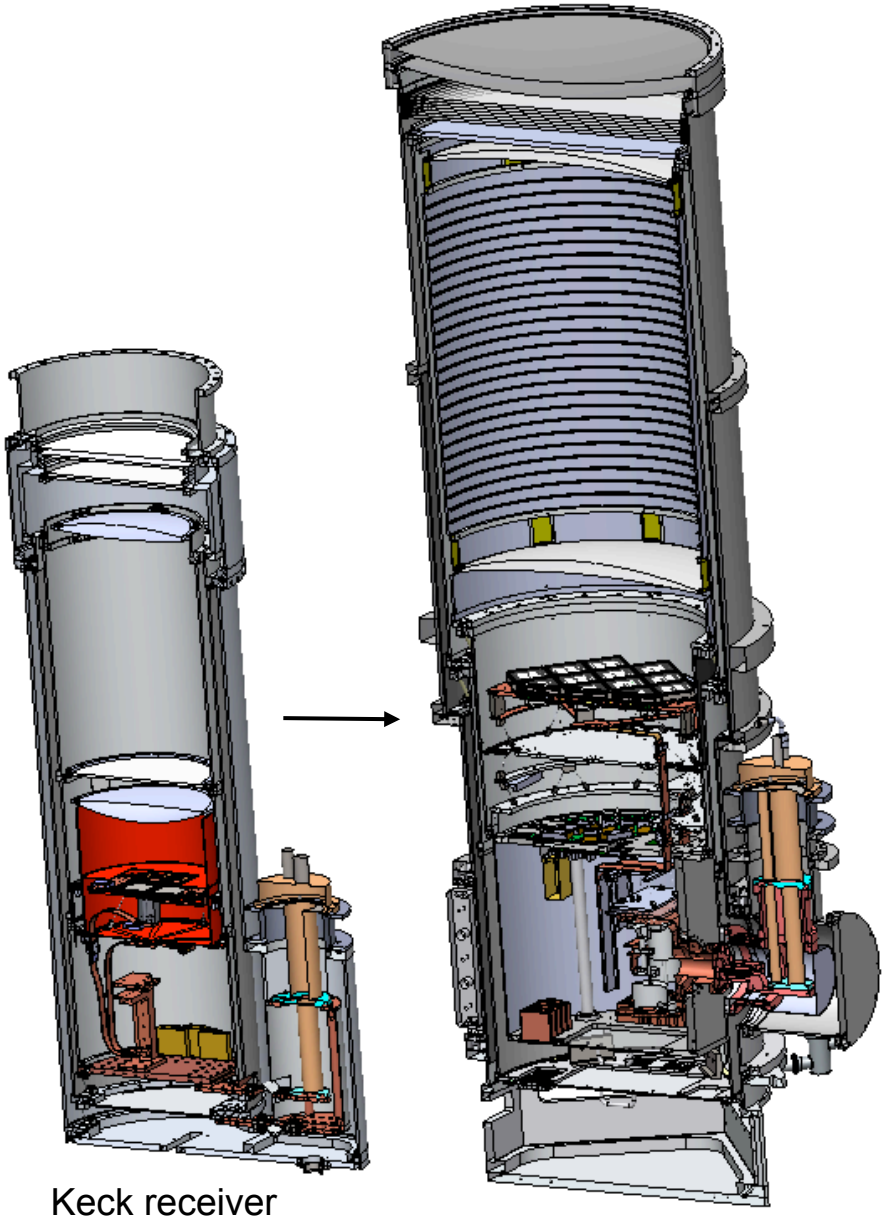
BICEP3: Next Generation Receiver

All 95 GHz

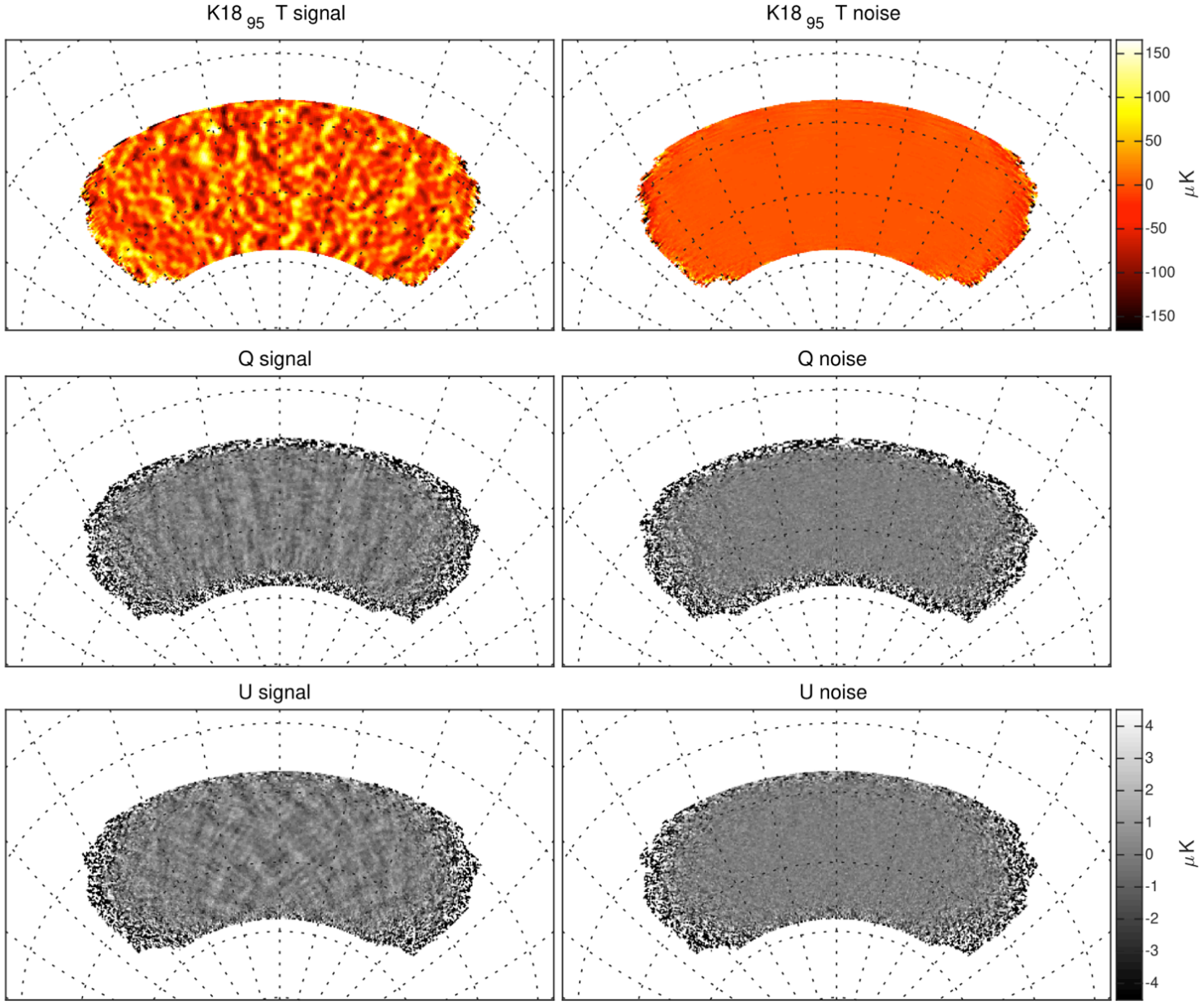
2500 detectors in modular focal plane

Large-aperture optics and infrared filtering

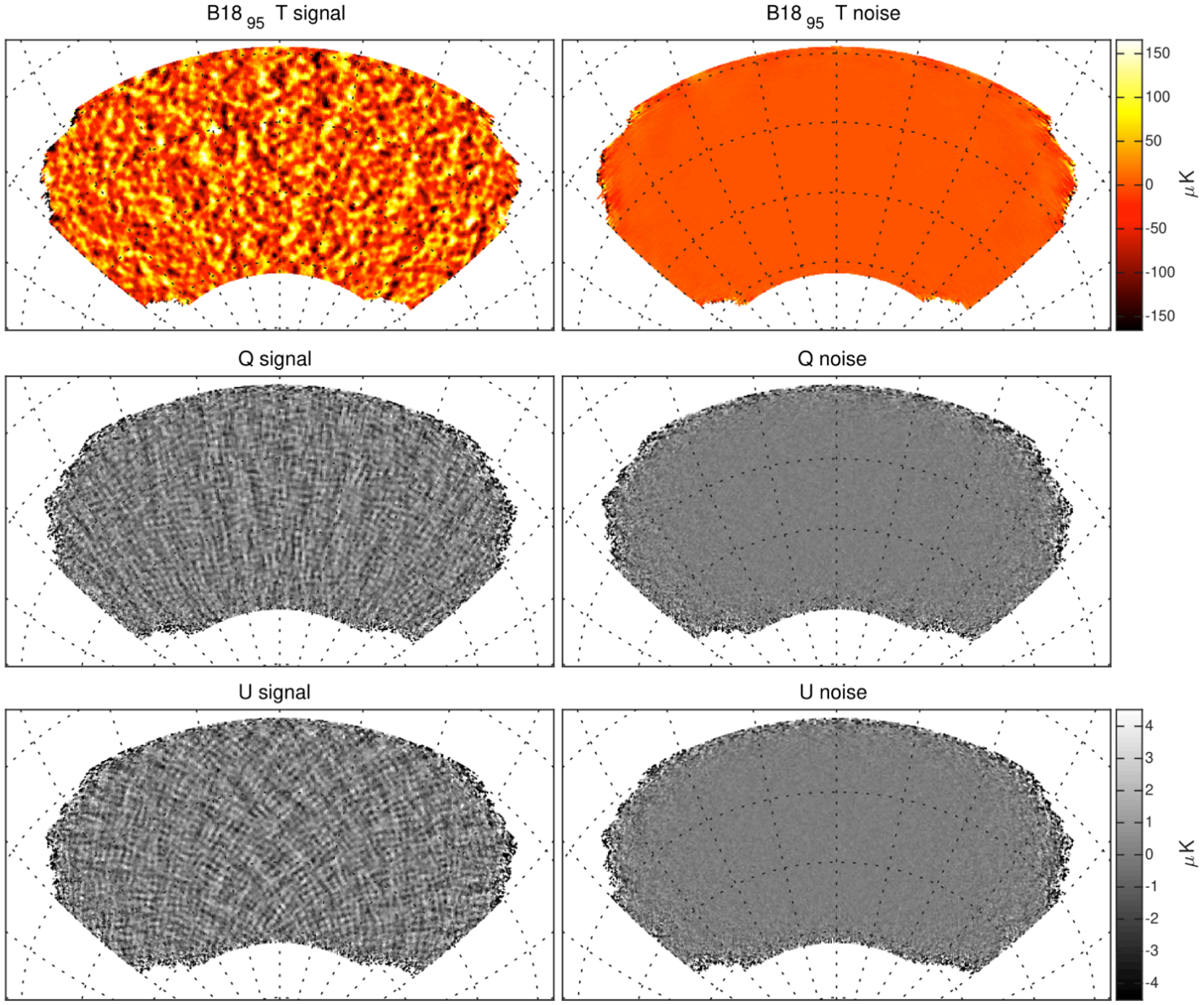
> 10x optical throughput of BICEP2/Keck receivers



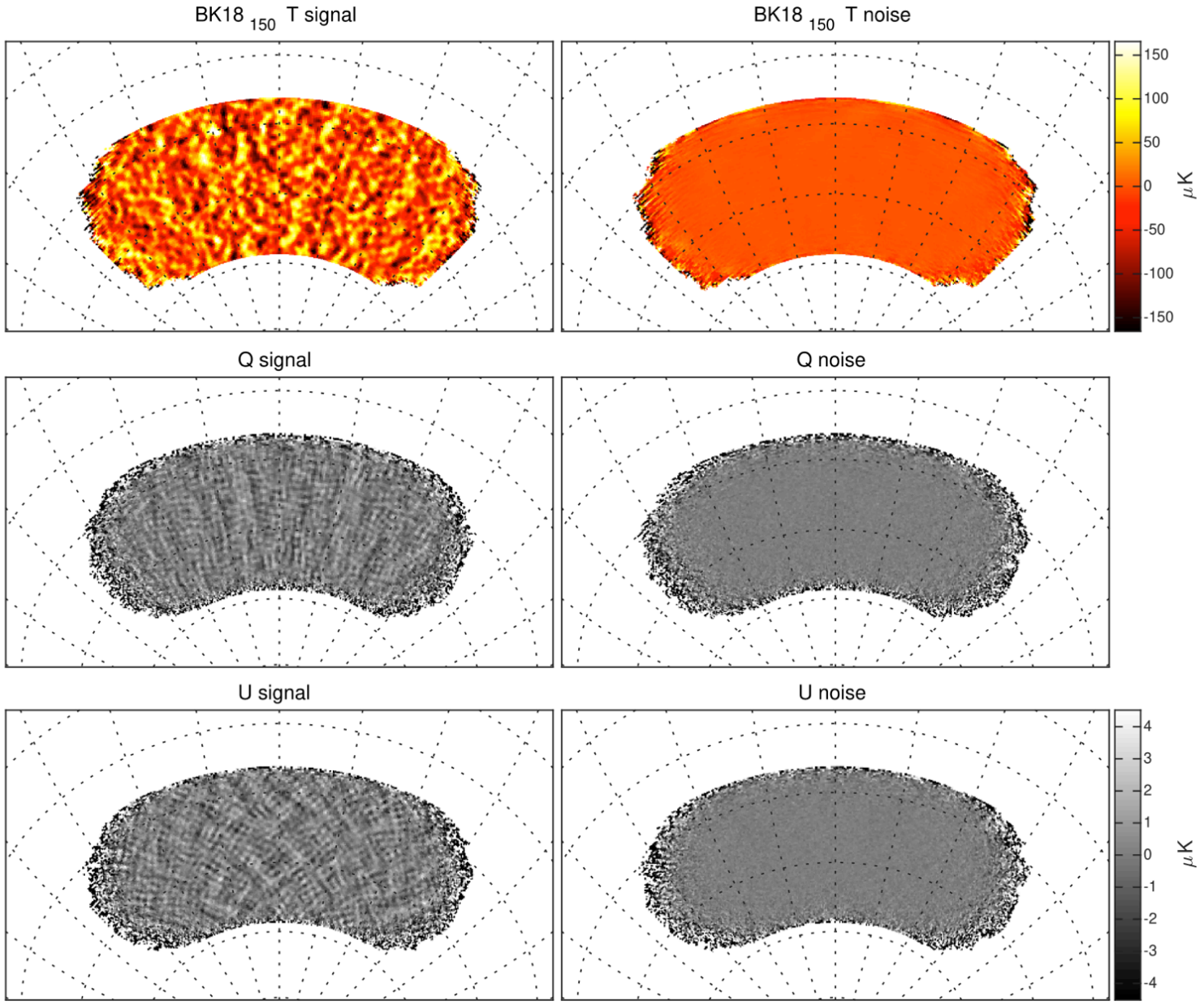
BK18 95GHz Map (*Keck*)



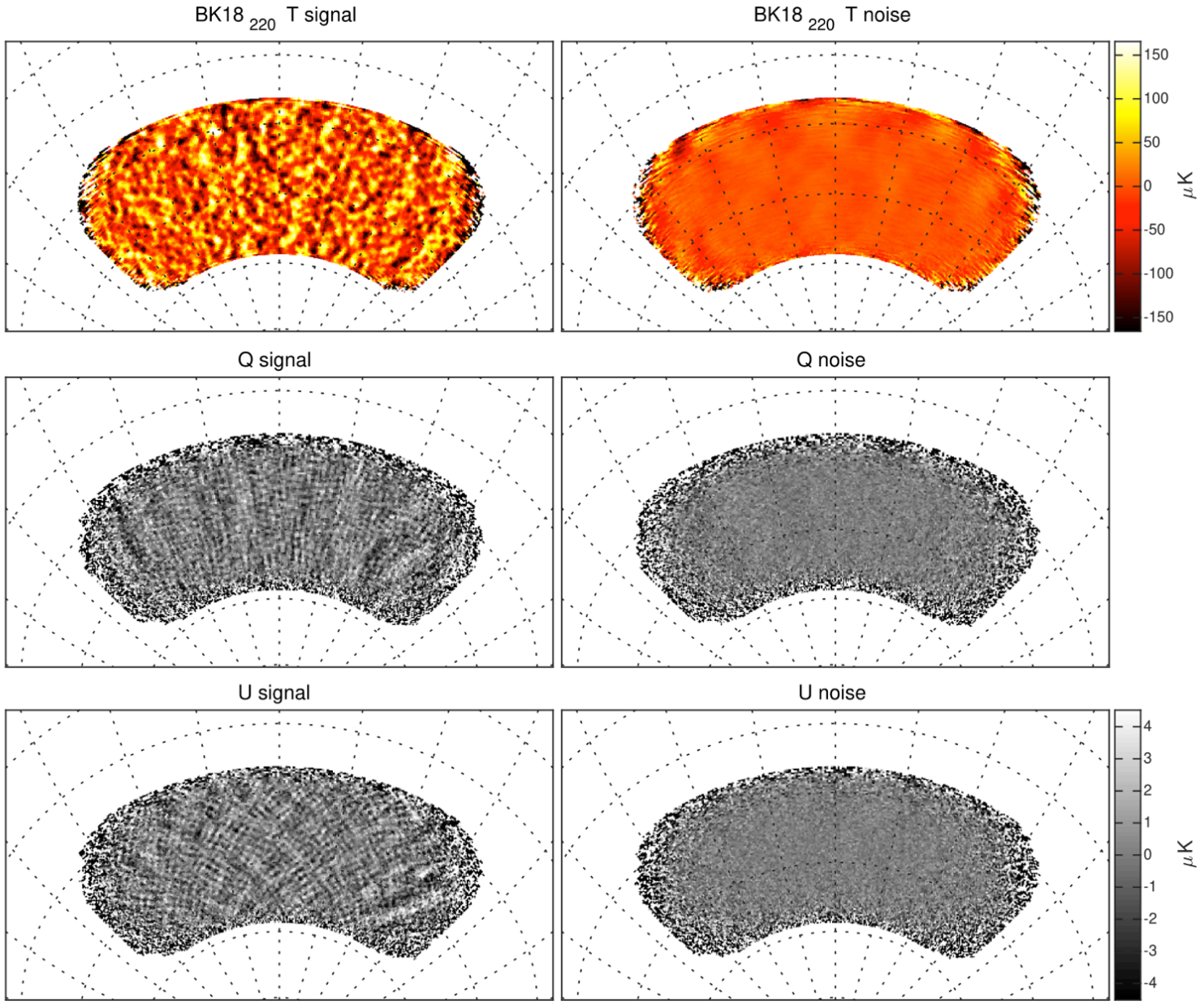
BK18 95GHz Map (BICEP3)



BK18 150GHz Map (BICEP2+*Keck*)



BK18 220GHz Map (*Keck*)



Stage 2

Stage 3

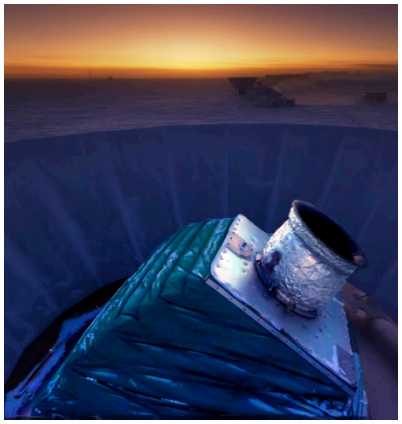
BICEP2
(2010-2012)

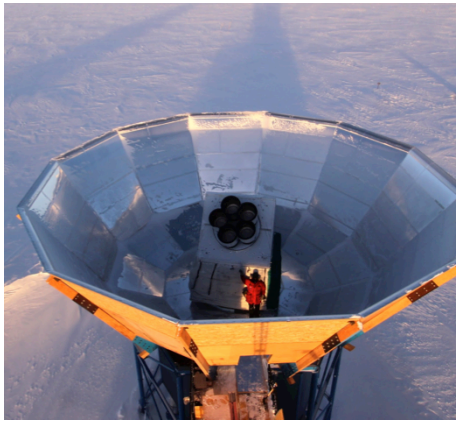
Keck Array
(2012-2019)

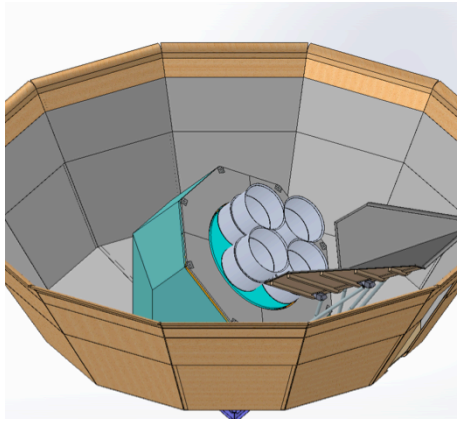
BICEP3
(2016-)

BICEP Array
(2020-)

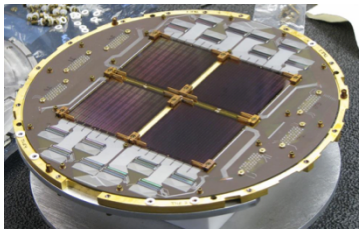
Telescope and Mount

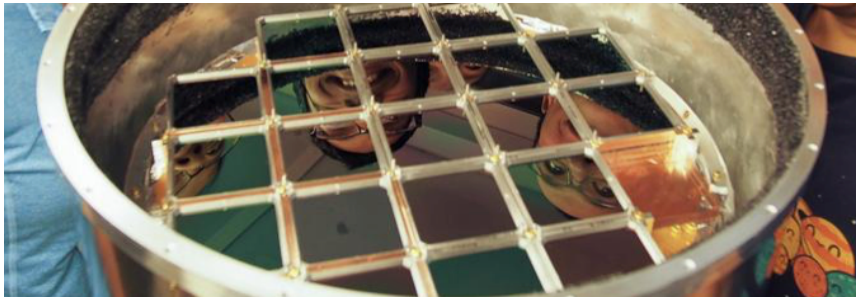




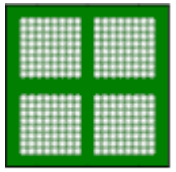


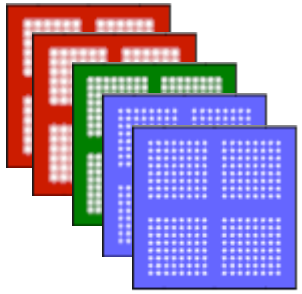
Focal Plane

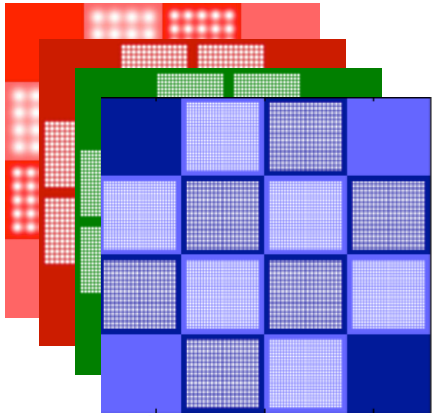




Beams on Sky

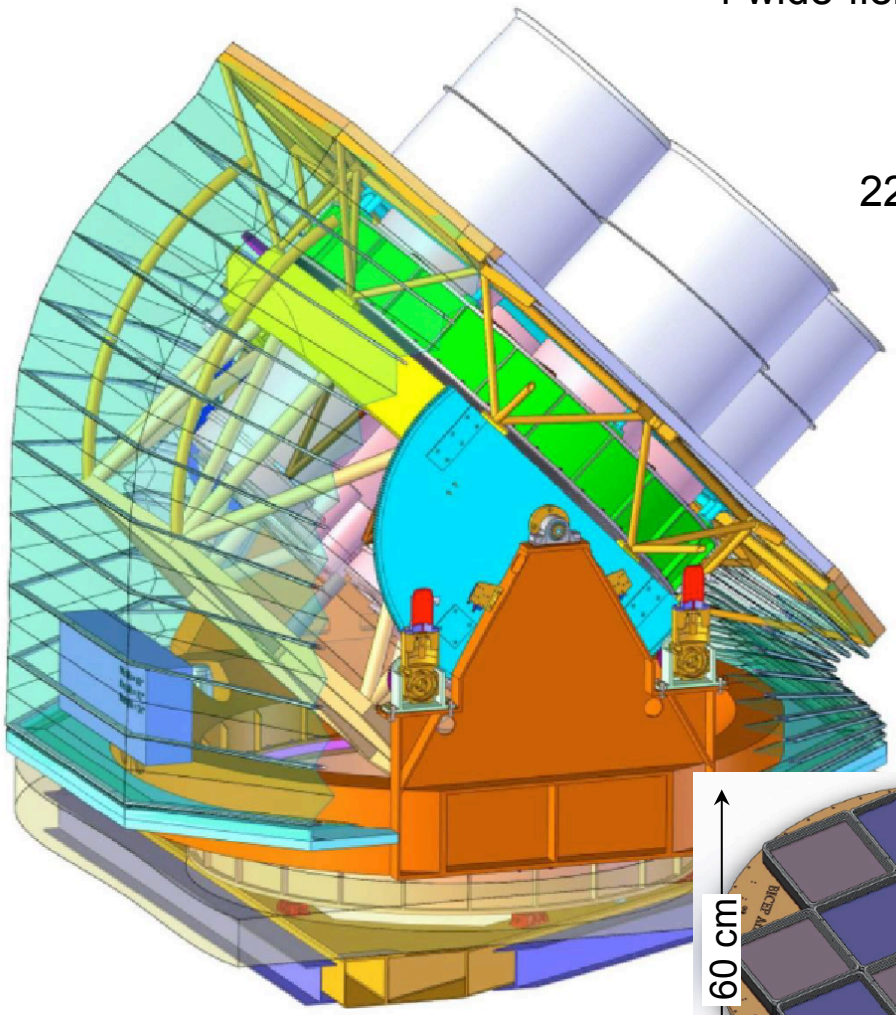




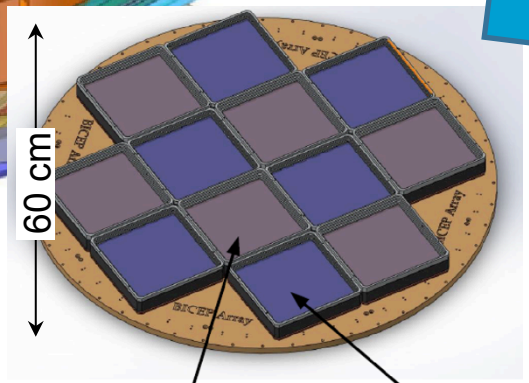


BICEP Array Under Construction

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

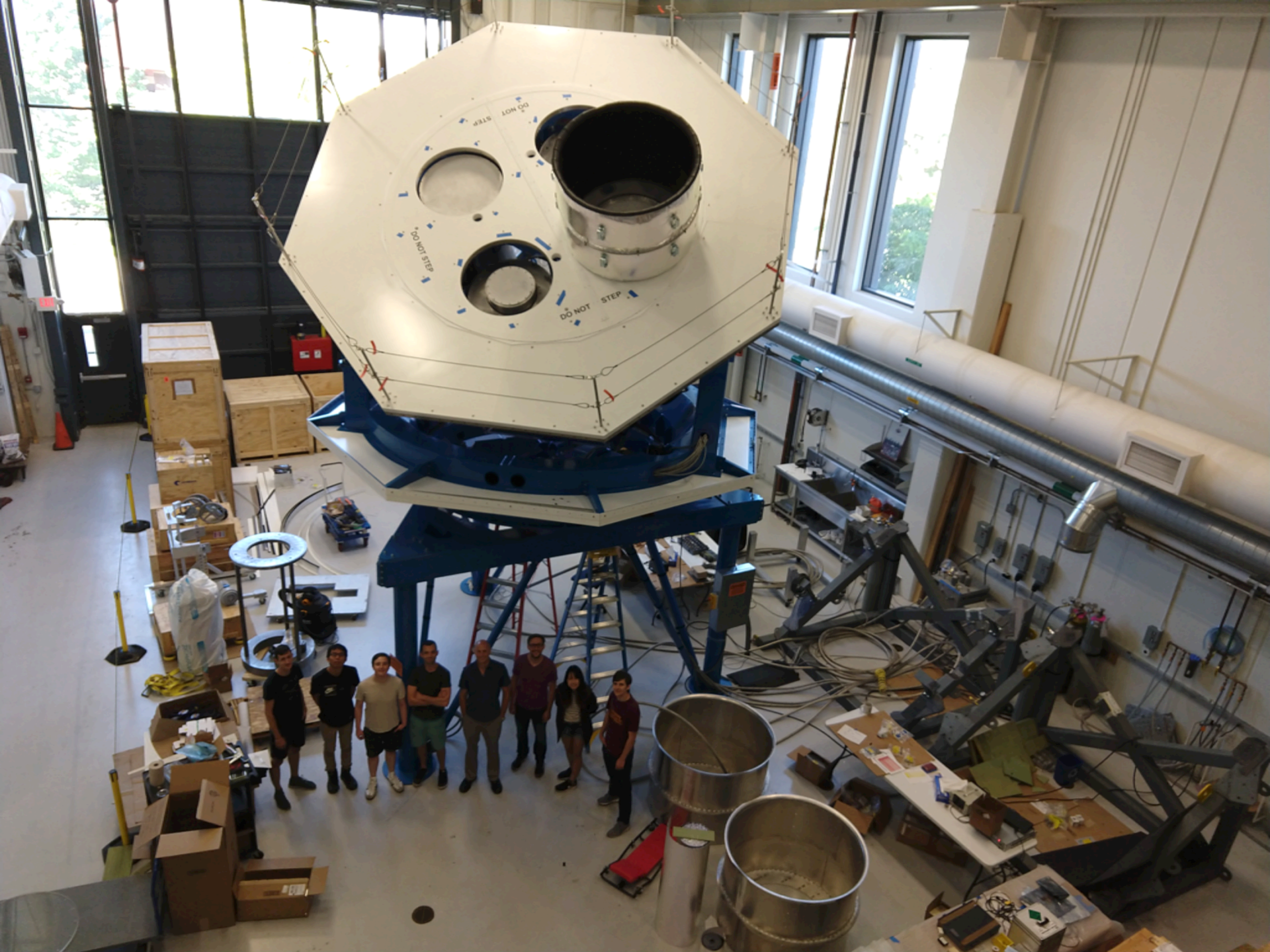


Wide-field cryogenic receiver



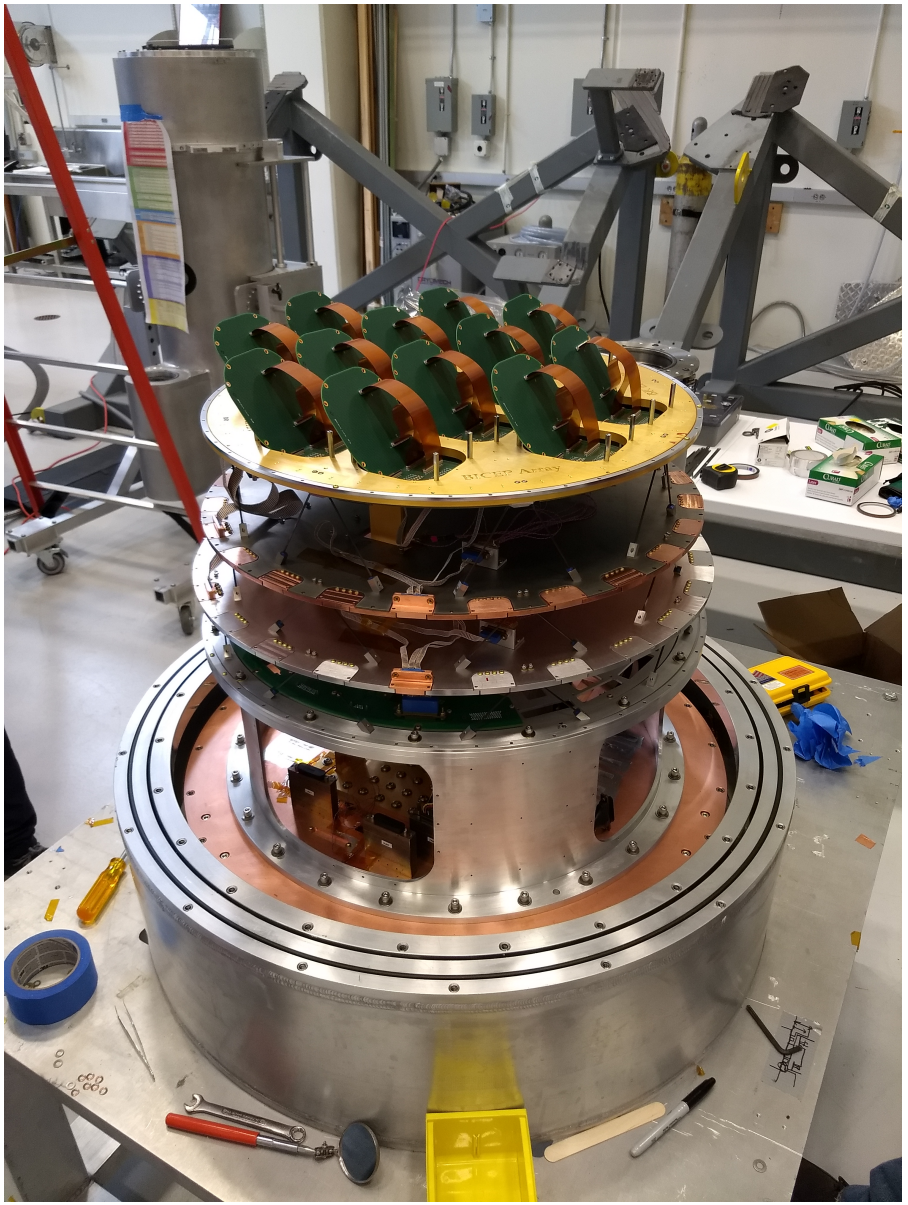
Focal plane layout

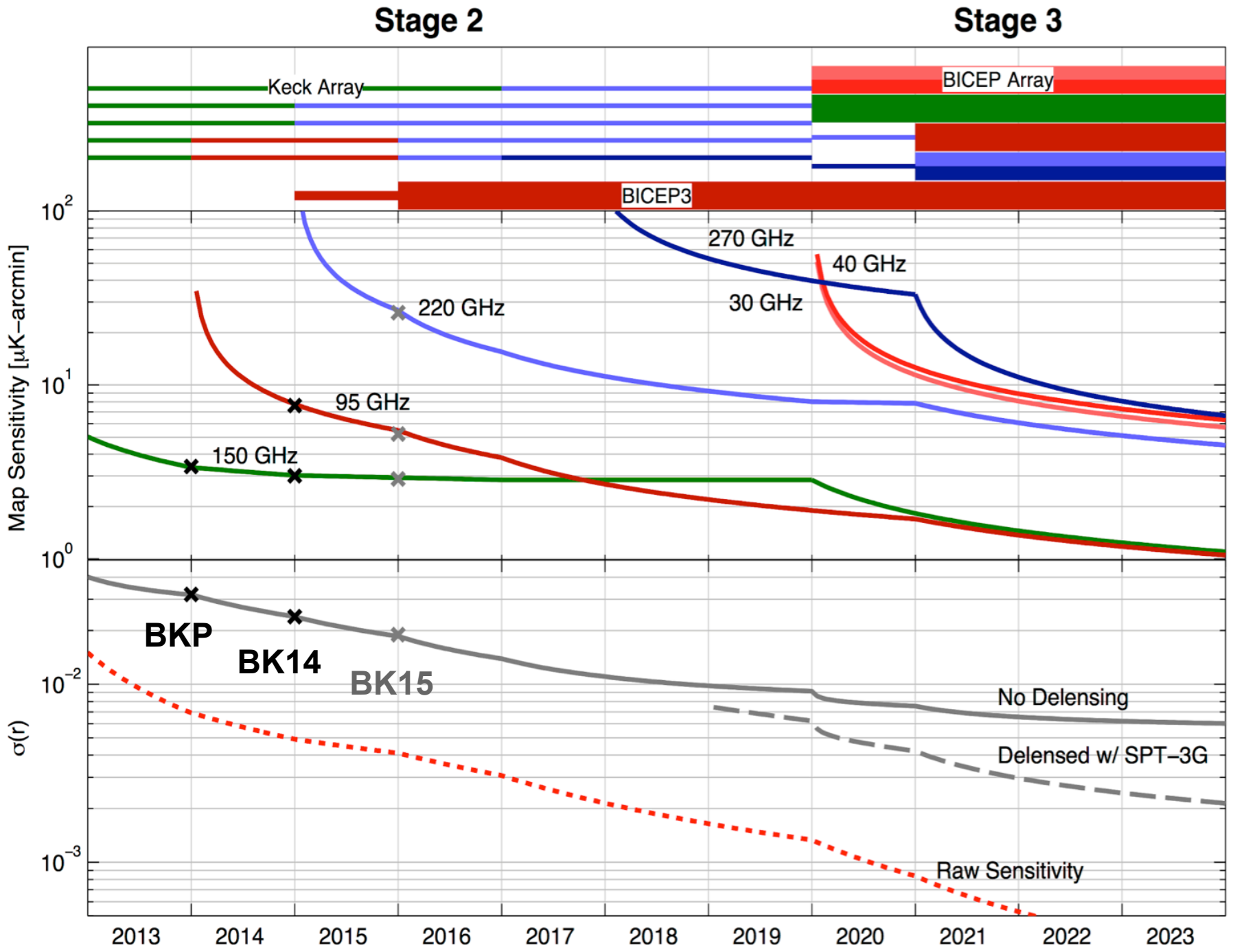
When complete >30,000 detectors

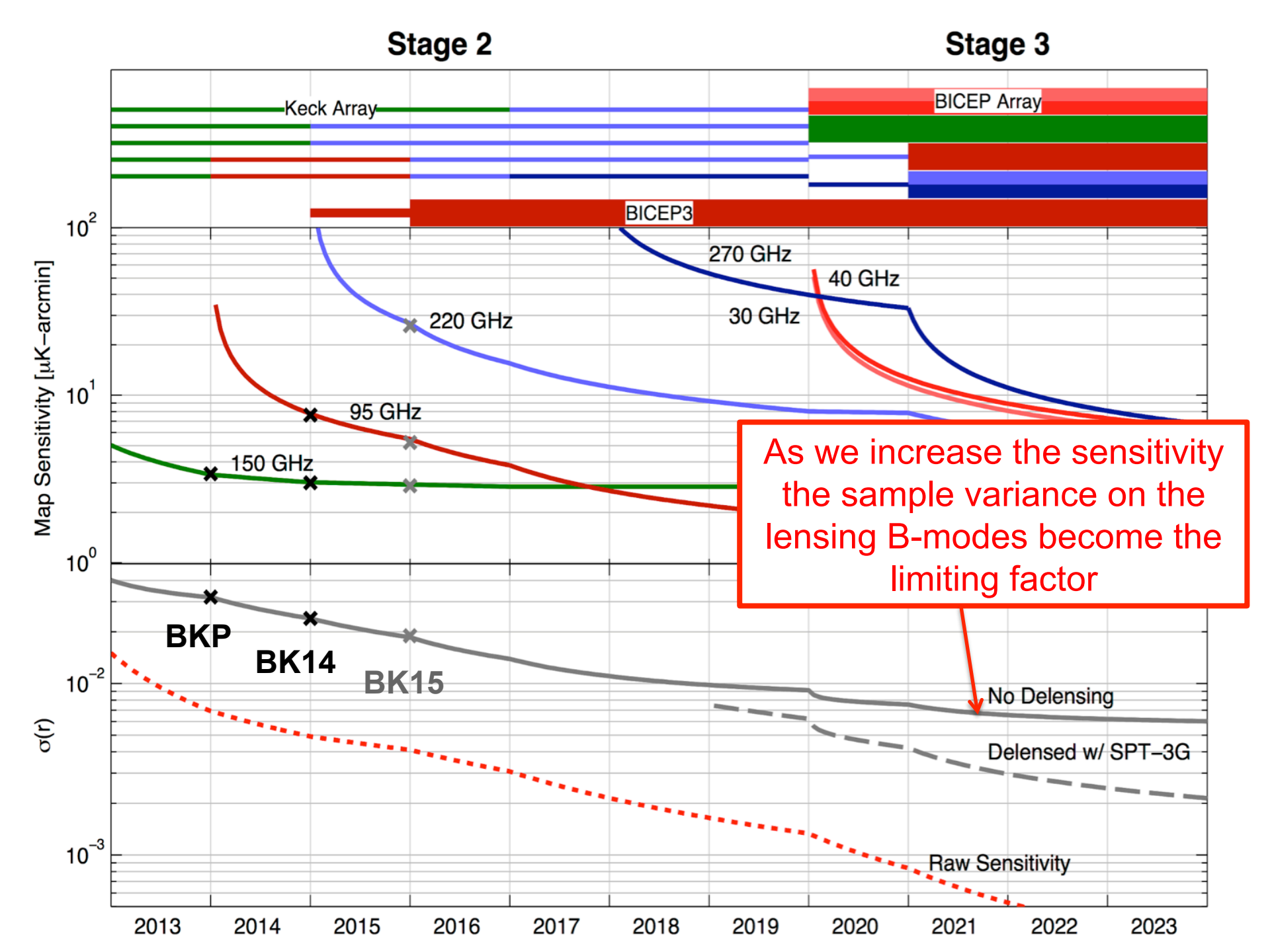

DO NOT STEP
DO NOT STEP
DO NOT STEP

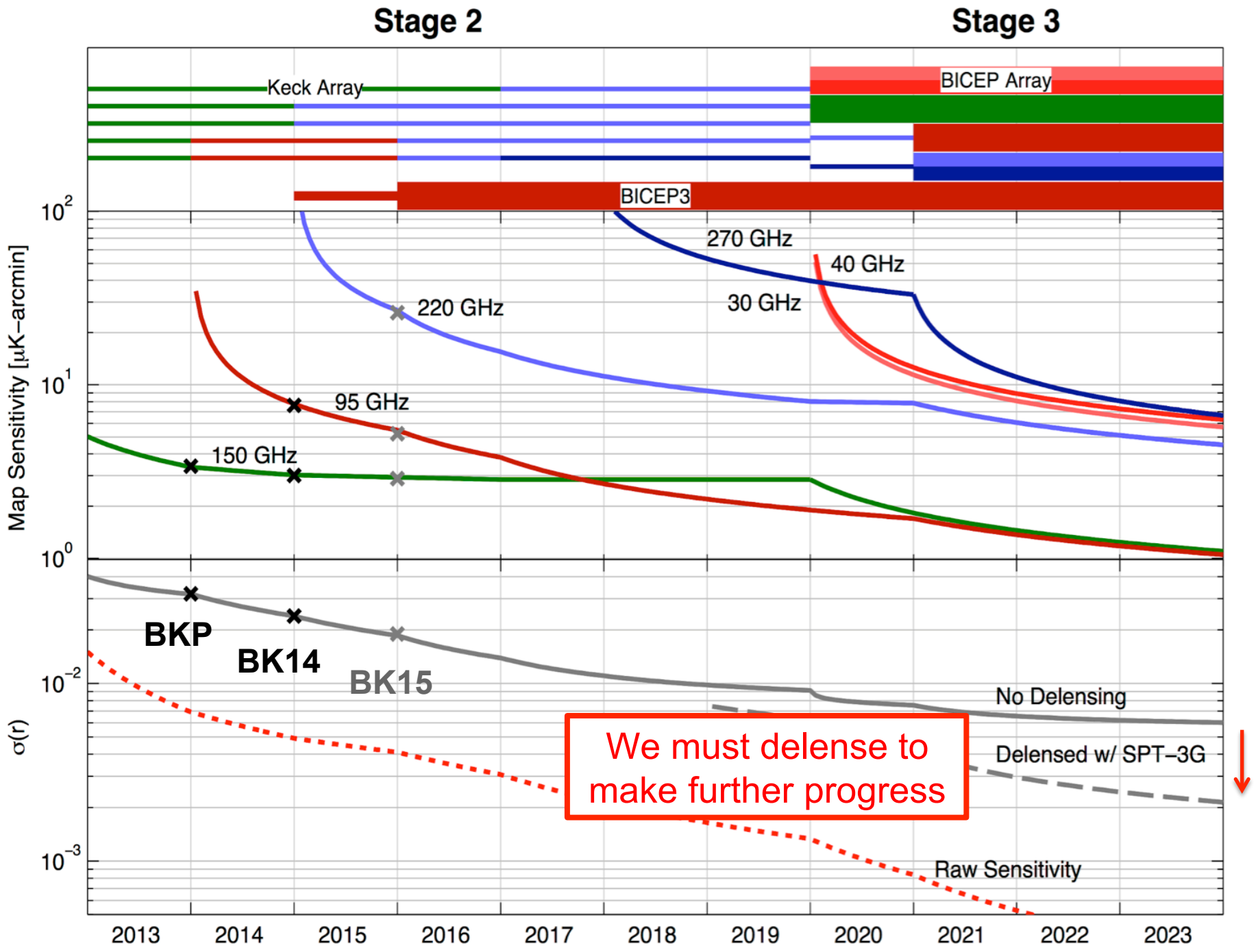
New mount about to ship from UMN to Pole

Lots of new hardware

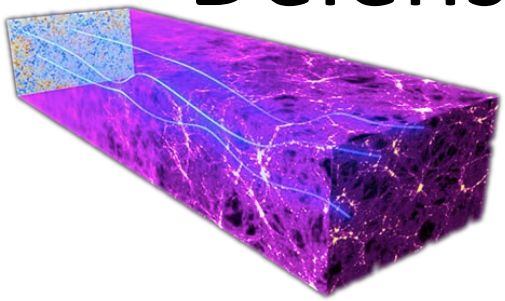


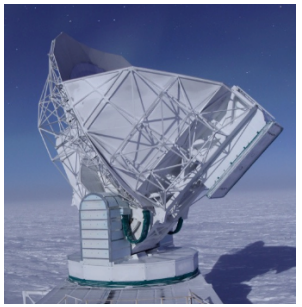

Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
Map Sensitivity [μK–arcmin]
10^2
10^1
10^0
BKP
BK14
BK15
No Delensing
Delensed w/ SPT–3G
Raw Sensitivity
σ(r)
10^{-2}
10^{-3}
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023


Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
Map Sensitivity [μK–arcmin]
10^2
10^1
10^0
BKP
BK14
BK15
10^{-2}
10^{-3}
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

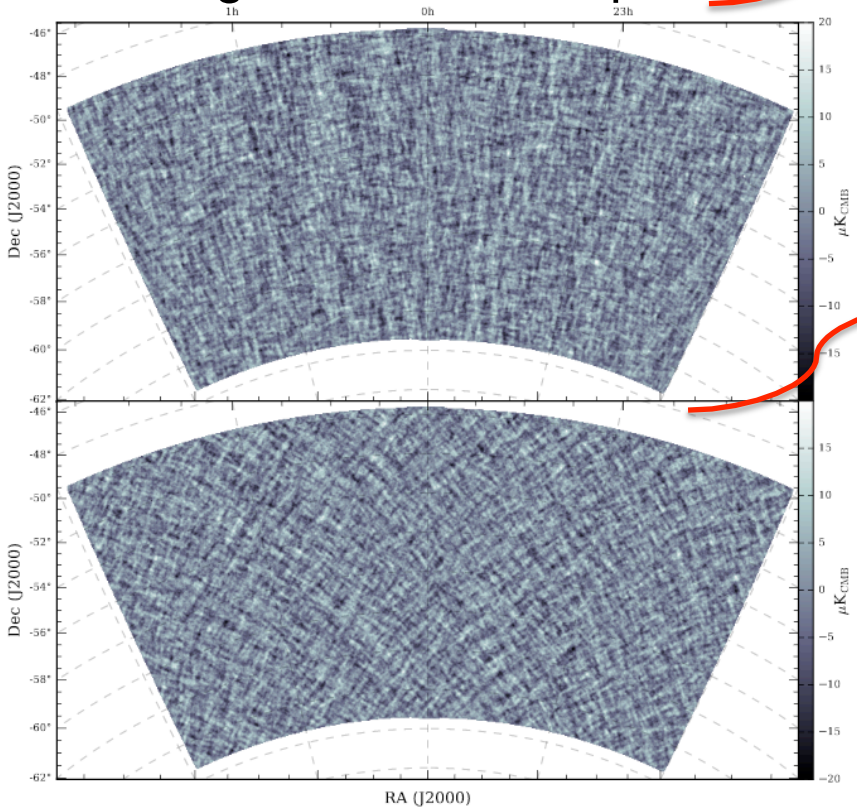

Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
Map Sensitivity [μK–arcmin]
10^2
10^1
10^0
BKP
BK14
BK15
No Delensing
Delensed w/ SPT–3G
Raw Sensitivity
σ(r)
10^{-2}
10^{-3}
We must delense to make further progress
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023

Delensing with SPT-3G data

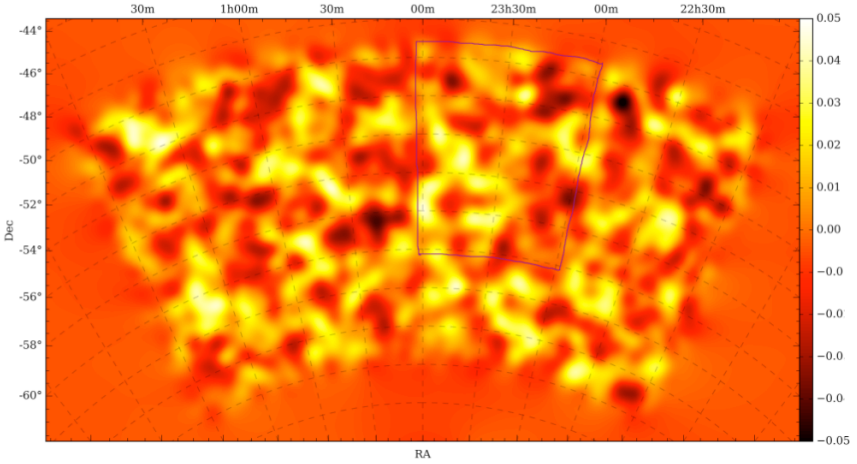




High resolution maps



Can be used to reconstruct the lensing deflection map…



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

Conclusions

- BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:
- BK15 result sets $r_{0.05}<0.06$ and $\sigma(r)=0.020$

- BICEP3 is running since 2016 with high sensitivity at 95GHz, and Keck Array continues to run at 220GHz, plus new 270GHz band
- We intend to go straight to BK18 analysis which will approach $\sigma(r)=0.010$

- BICEP Array is under construction and will go much further:
- Next gen. receivers in five bands
- Delensing in conjunction with SPT3G under development
- Projecting BK23 $\sigma(r)<0.003$

- And beyond that is mega experiment CMB-S4…

- Foreground complexity is and will remain a serious issue – the hope is that we can measure it *and* constrain *r* simultaneously without a large loss of sensitivity. Time will tell.