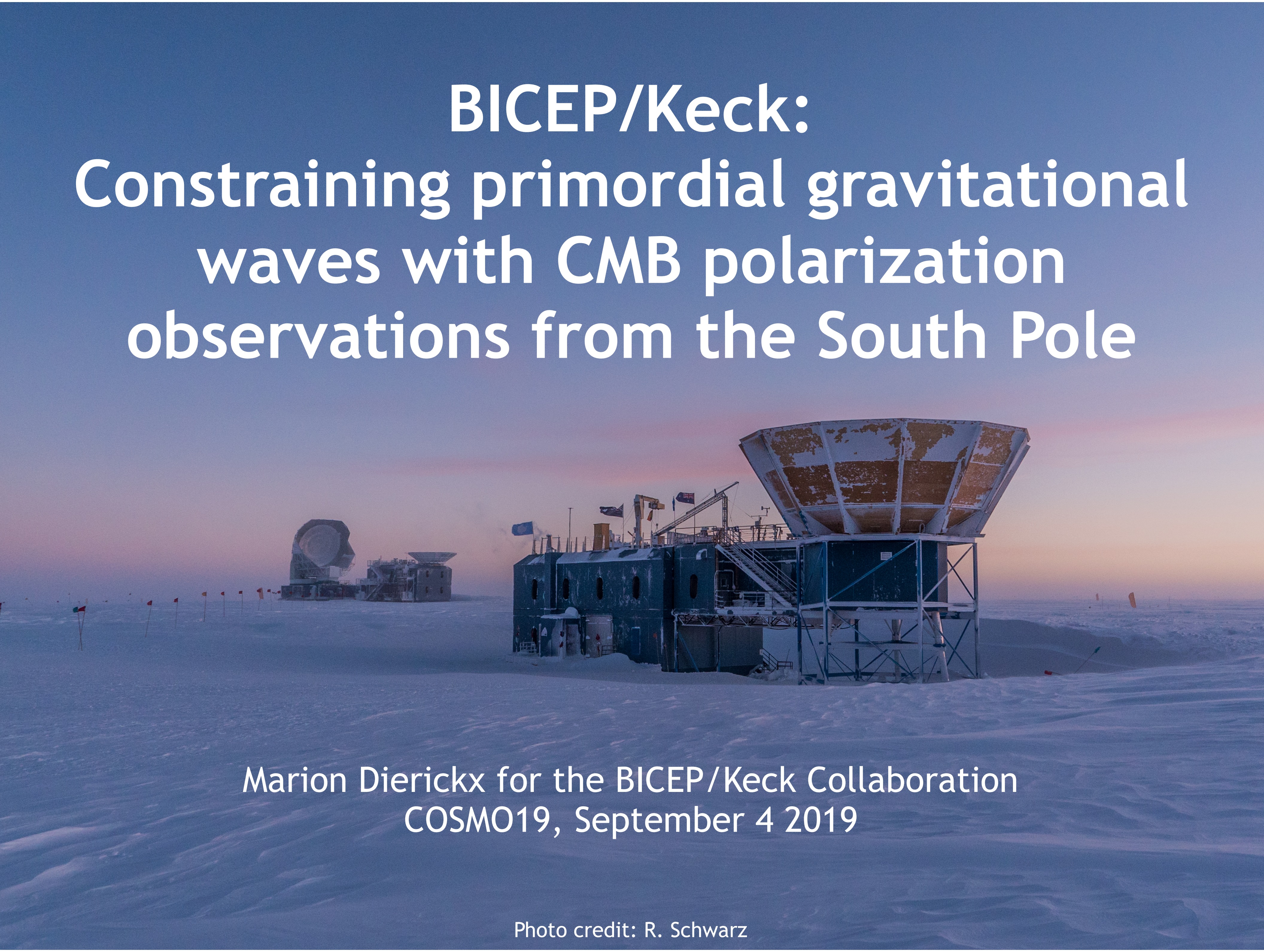
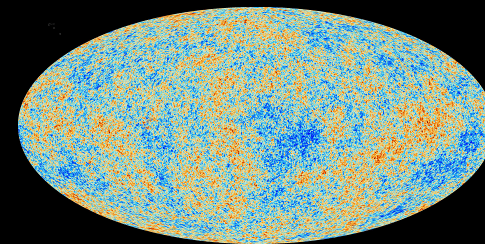
BICEP/Keck: Constraining primordial gravitational waves with CMB polarization observations from the South Pole

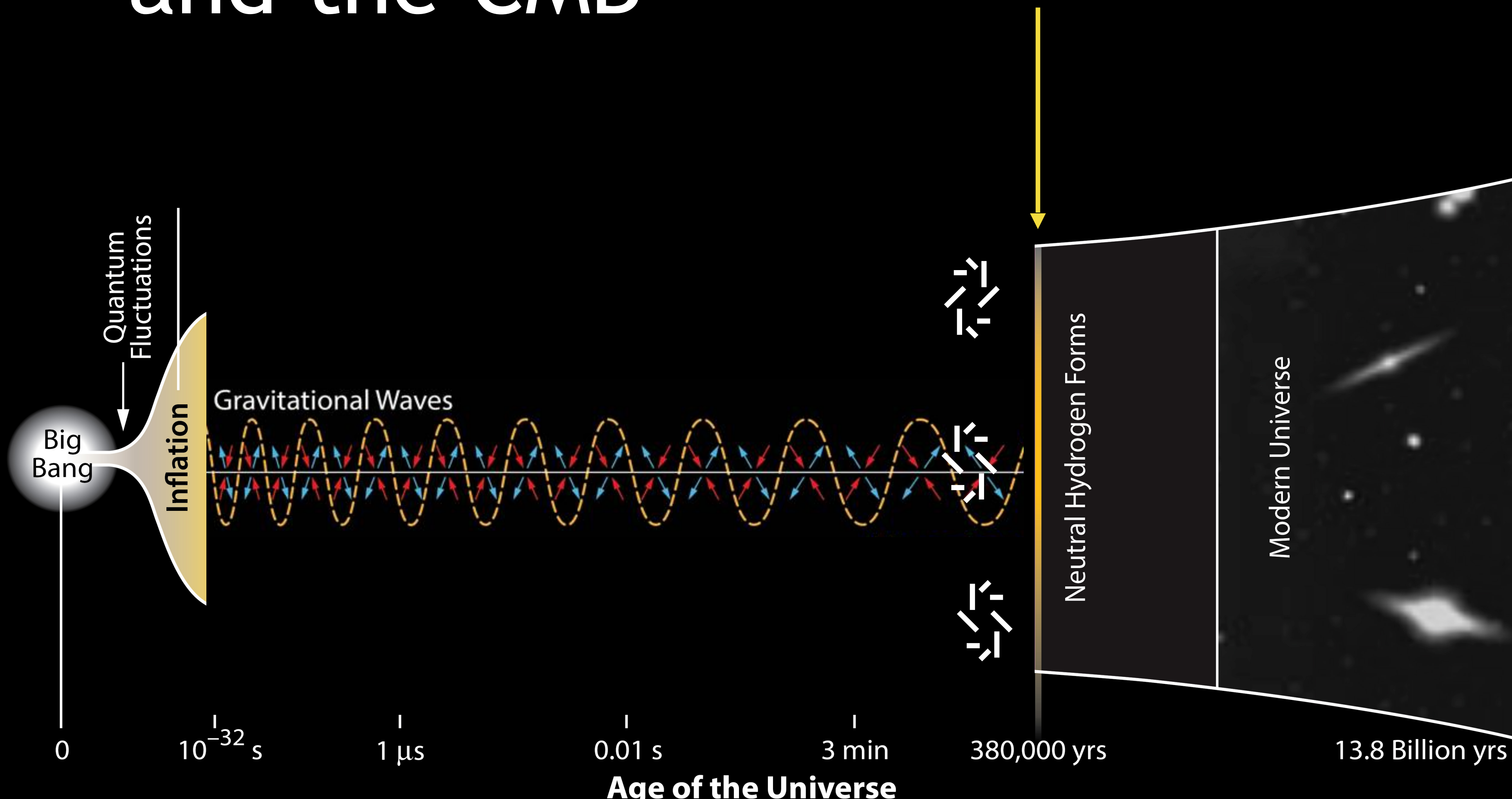


Marion Dierickx for the BICEP/Keck Collaboration
COSMO19, September 4 2019

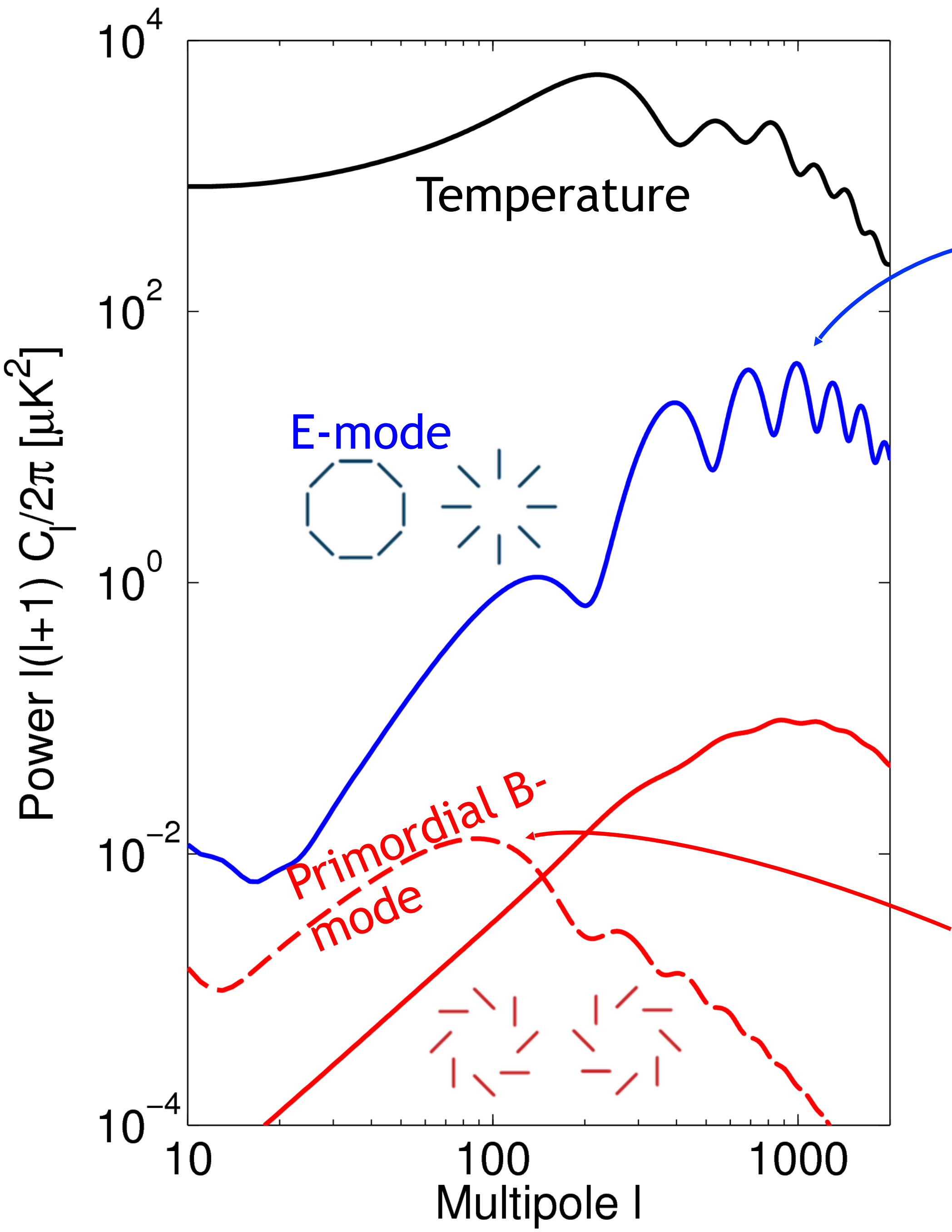
Photo credit: R. Schwarz

Primordial Gravitational Waves and the CMB





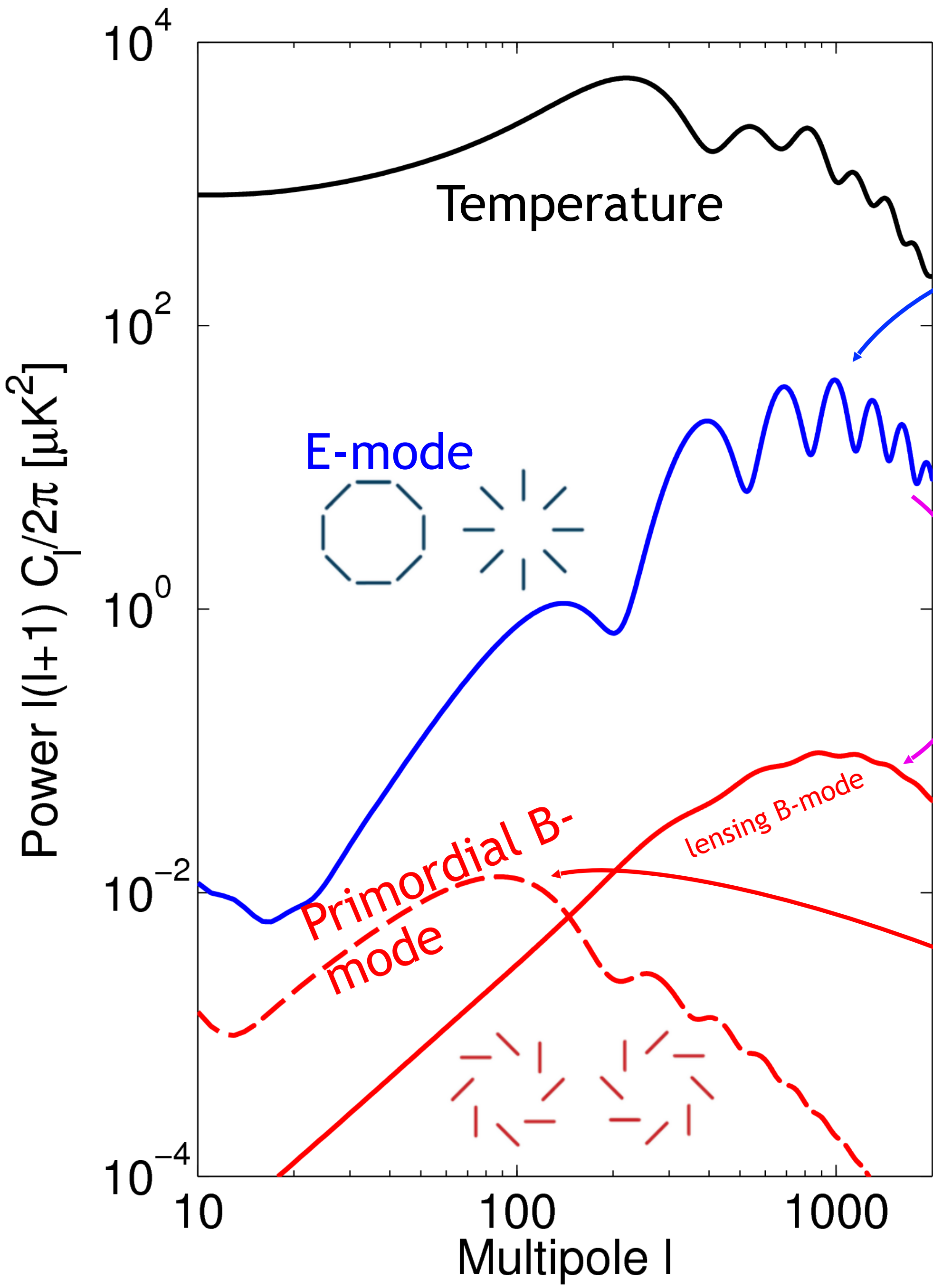
CMB Polarization



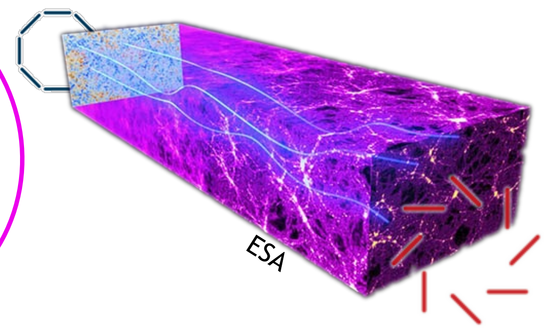
In standard ΛCDM only E-modes are present at last scattering

Inflationary gravitational waves are the unique source of B-modes
→ peaking at l≈100 : degree scales

CMB Polarization



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



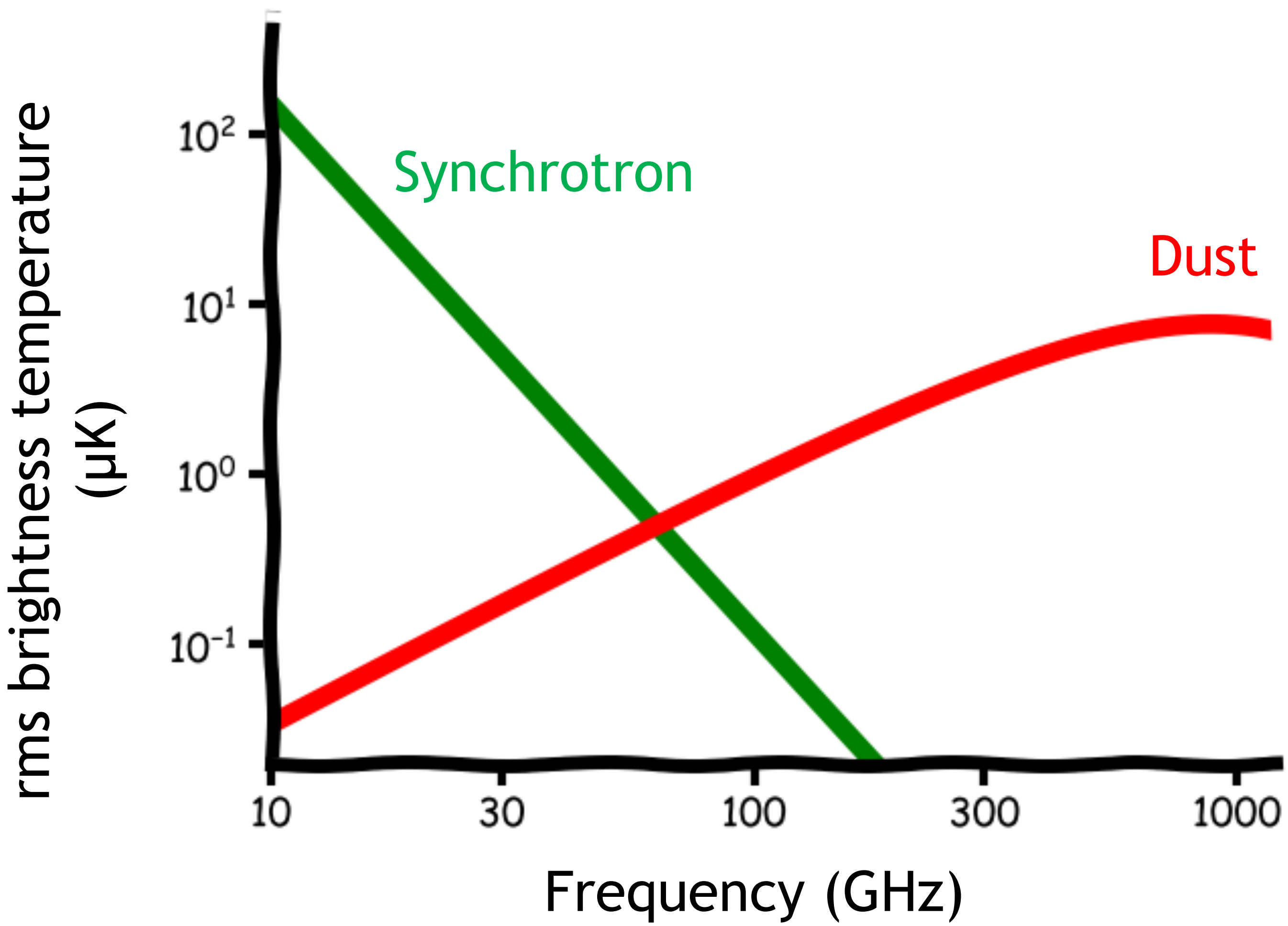
During propagation some of the E-modes are transformed into B-modes by lensing

Inflationary gravitational waves are the unique source of B-modes
→ peaking at l≈100 : degree scales

Galactic Foregrounds

Mitigation strategy for additional "foreground" E- and B-mode signals:

- Observe at high galactic latitudes
- Expand frequency range in order to perform component separation



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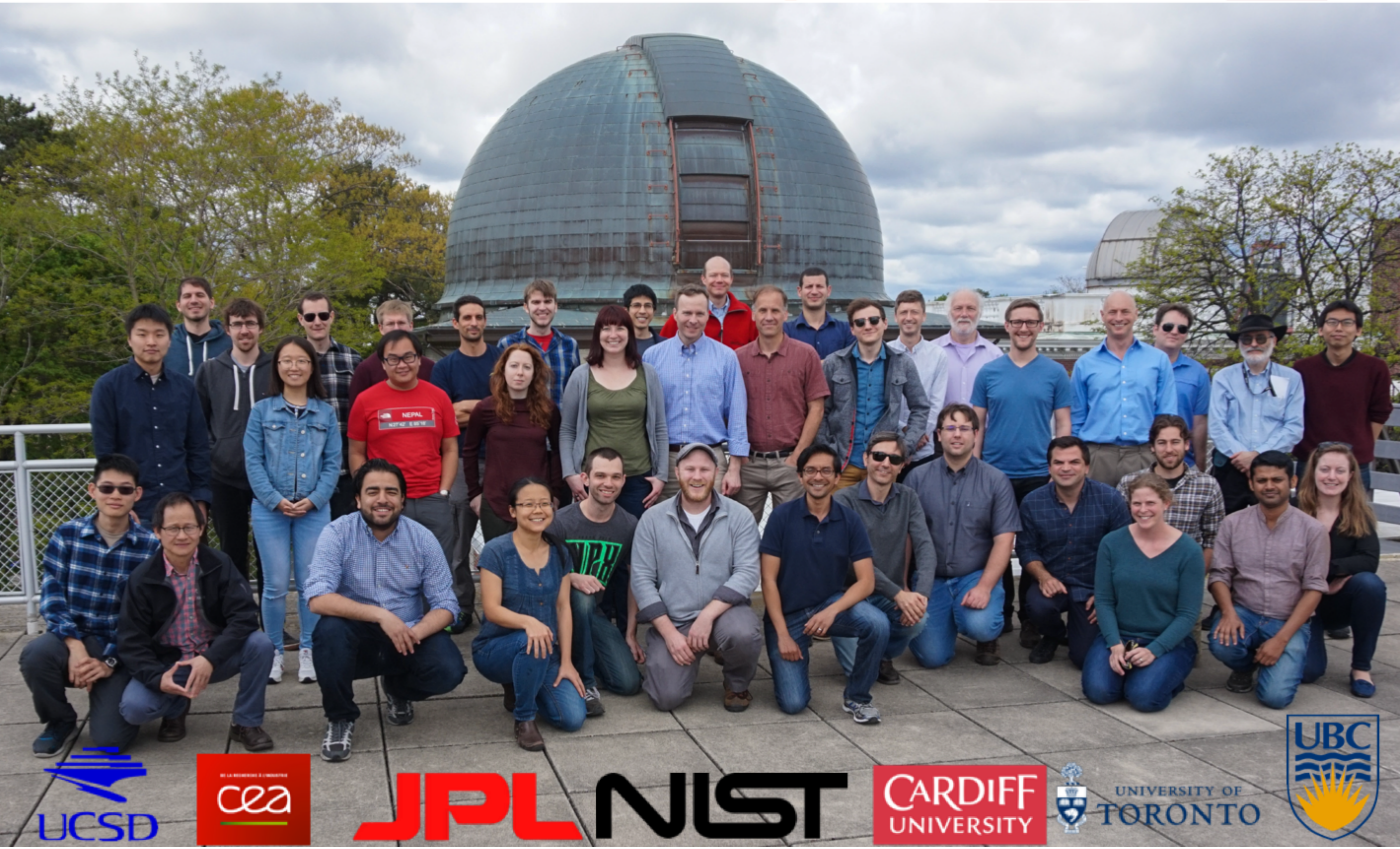
HARVARD

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891

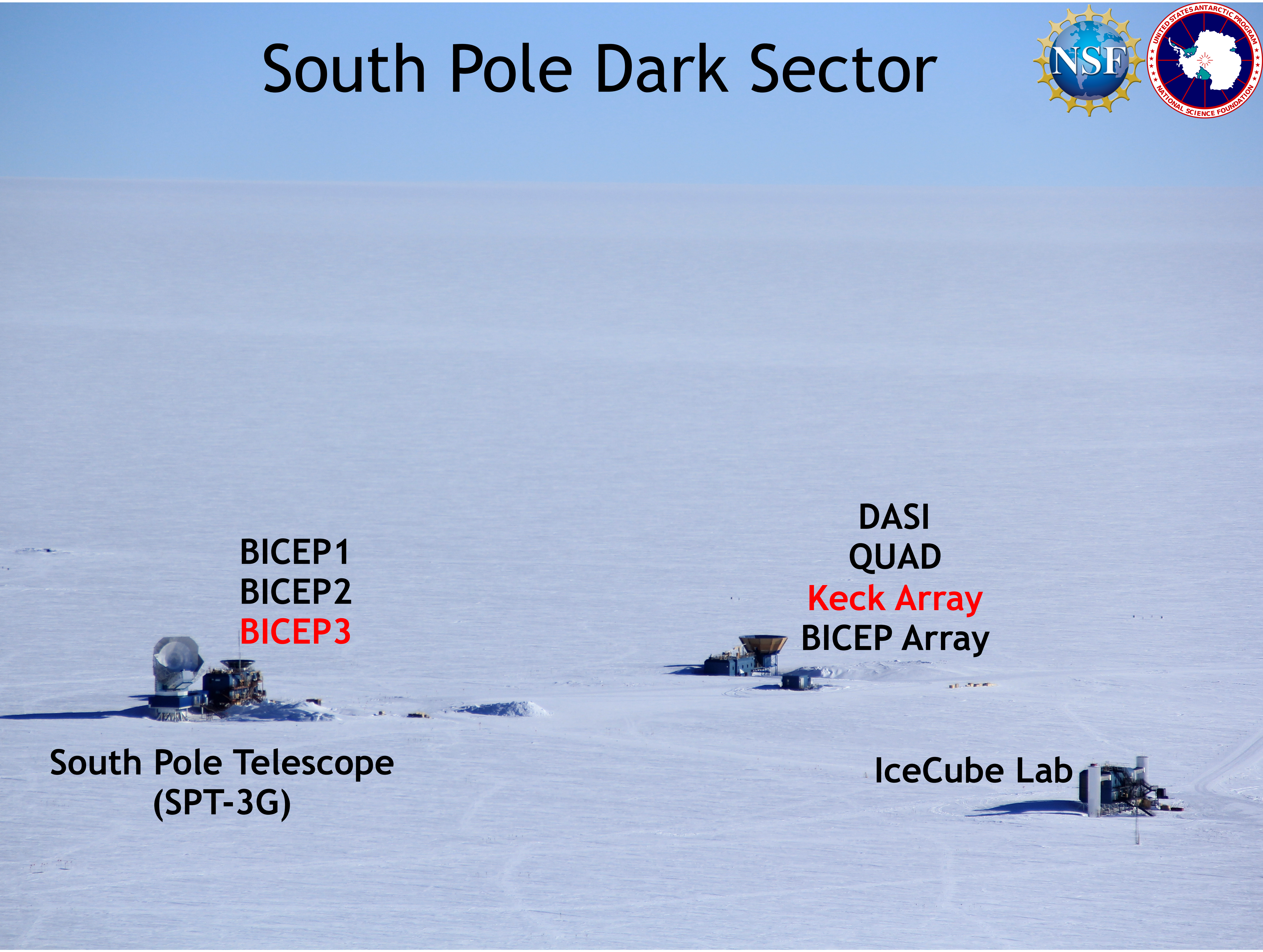


South Pole Dark Sector

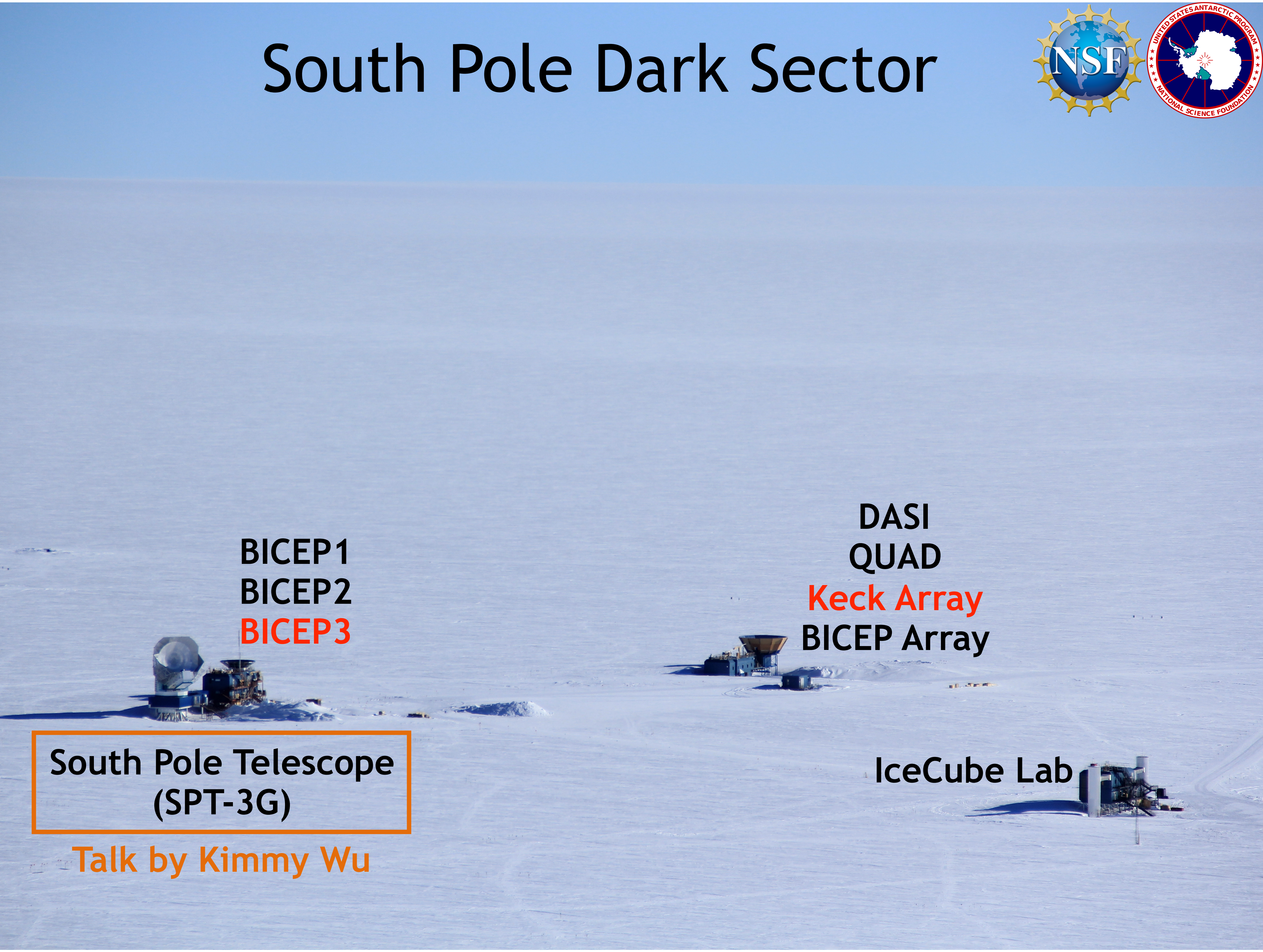
Why there?

- High altitude (9,300 ft = 2,800 m, most of it ice)
- Lack of day/night cycles makes for a very stable atmosphere
- Consistently dry
- Southern sky observable for 6 months of continuous darkness
- Minimal radio frequency interference

South Pole Dark Sector



South Pole Dark Sector



South Pole Dark Sector

BICEP/Keck Experimental Strategy:

- Target 2-degree peak of B-mode power spectrum
- Target the same 1% patch of sky since 2006
- Small-aperture refractive optics (cheap, low systematics)
- Initial effort at 150 GHz, now multi-frequency observations

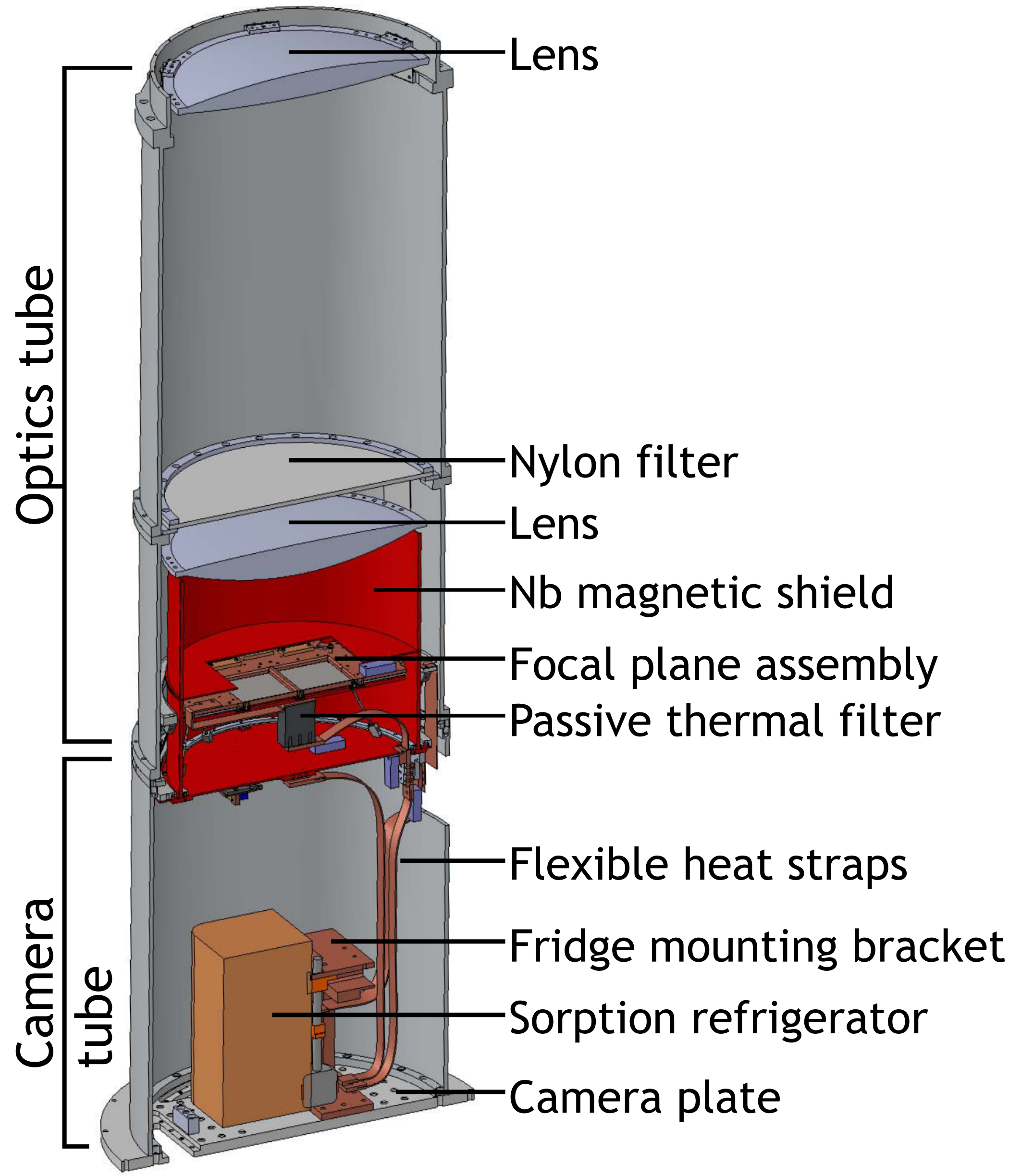
BICEP/Keck instrument overview

Telescope as compact as possible while allowing angular resolution to observe degree-scale features.

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

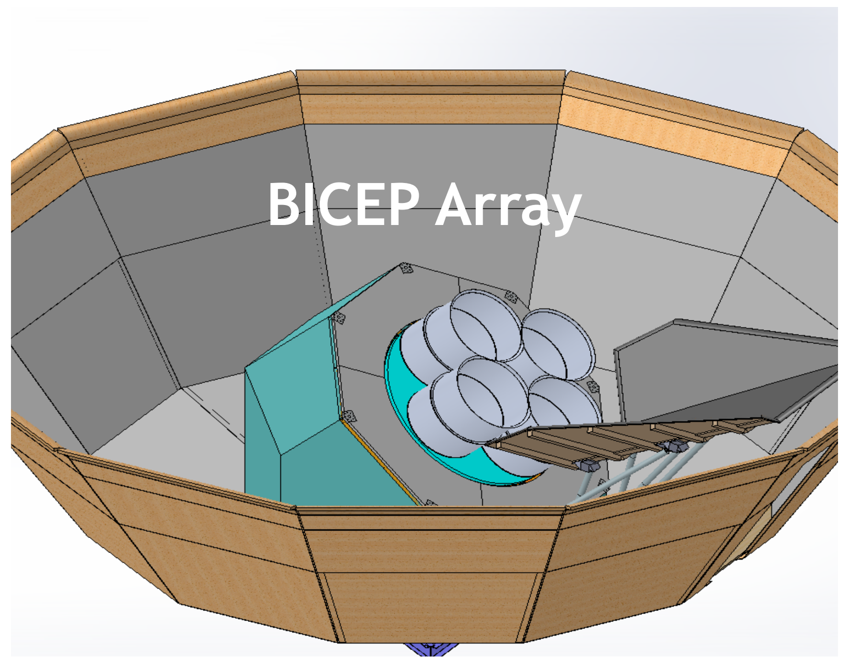
A pulse tube cryogenic cooler cools the optical elements to 4.2K.

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



x 5 =

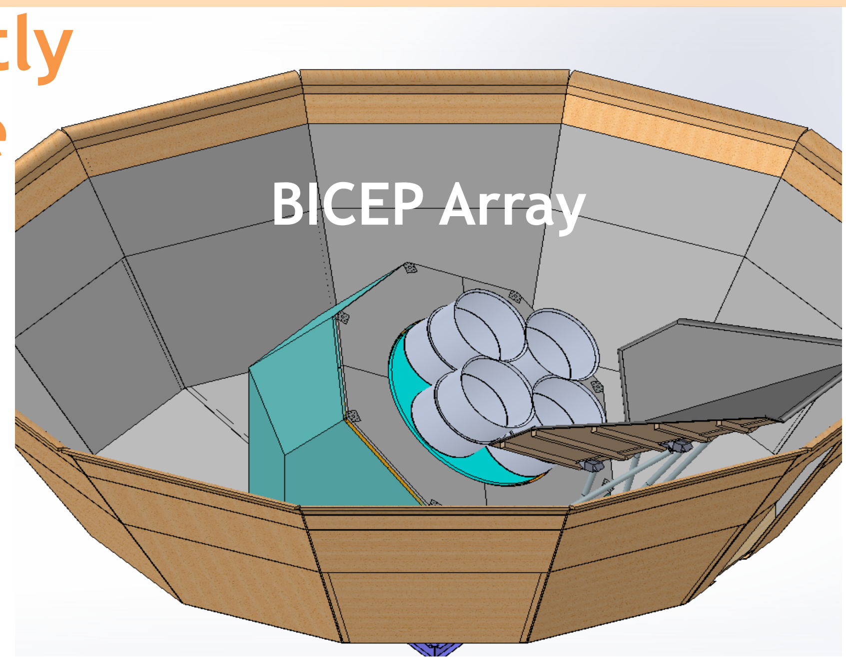
x 4 =



x 5 =

Currently in the field

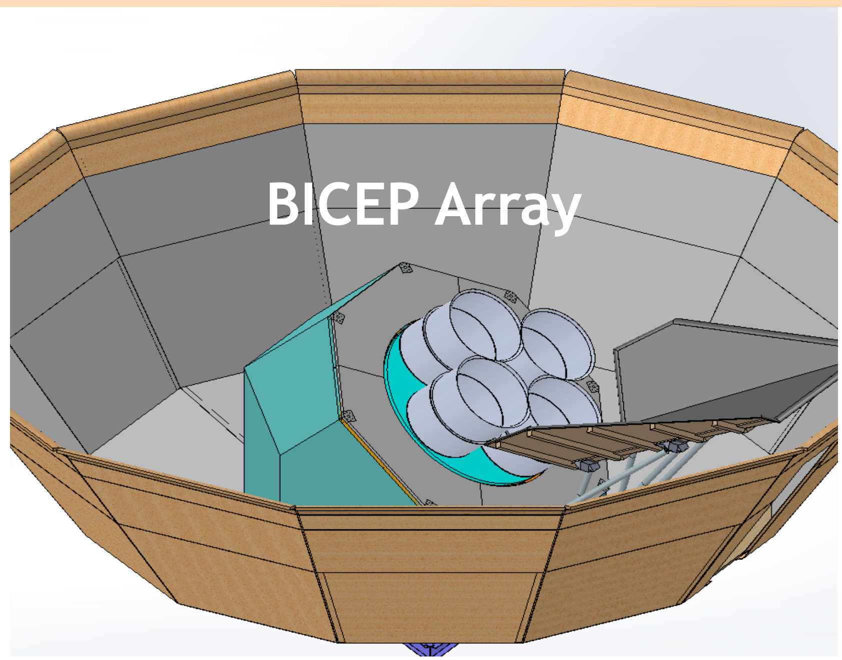
x 4 =



Latest published analysis: BK15

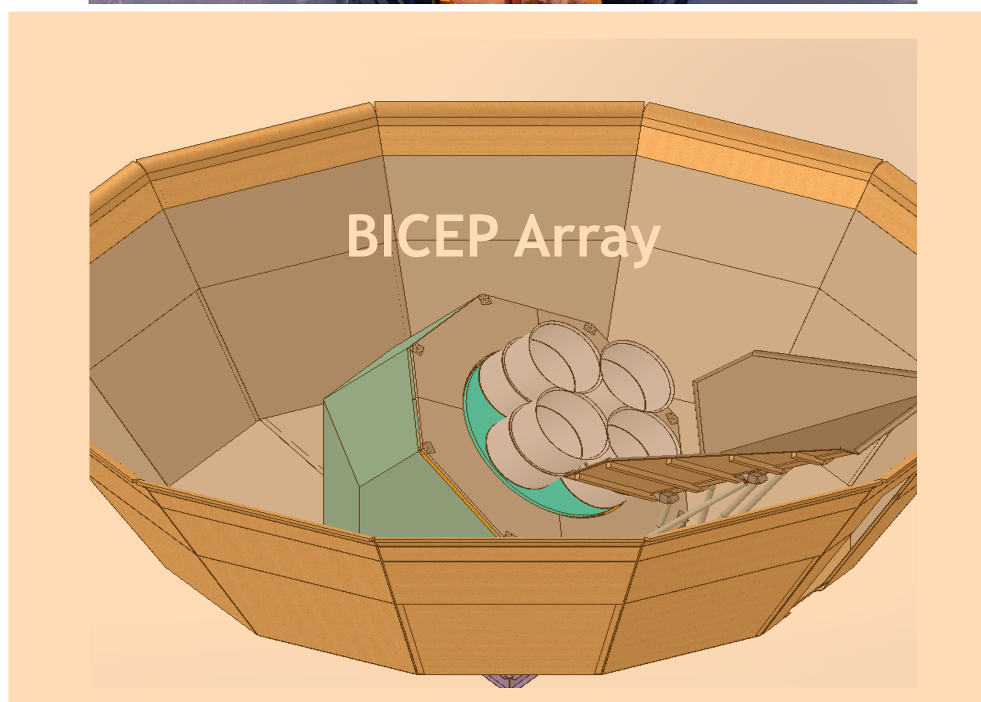
x 5 =

x 4 =



x 5 =

x 4 =



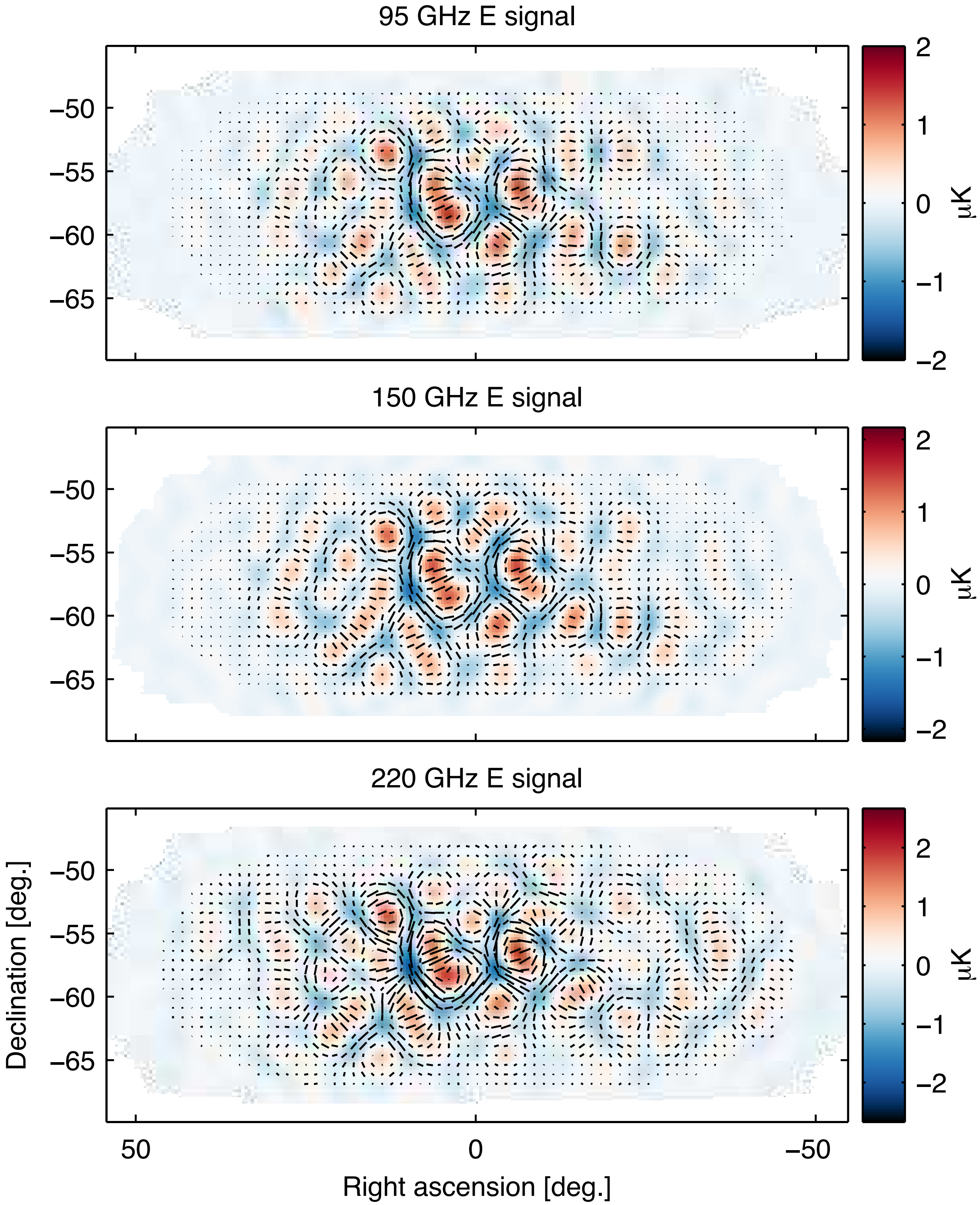
Currently building

Keck Array 2012-13

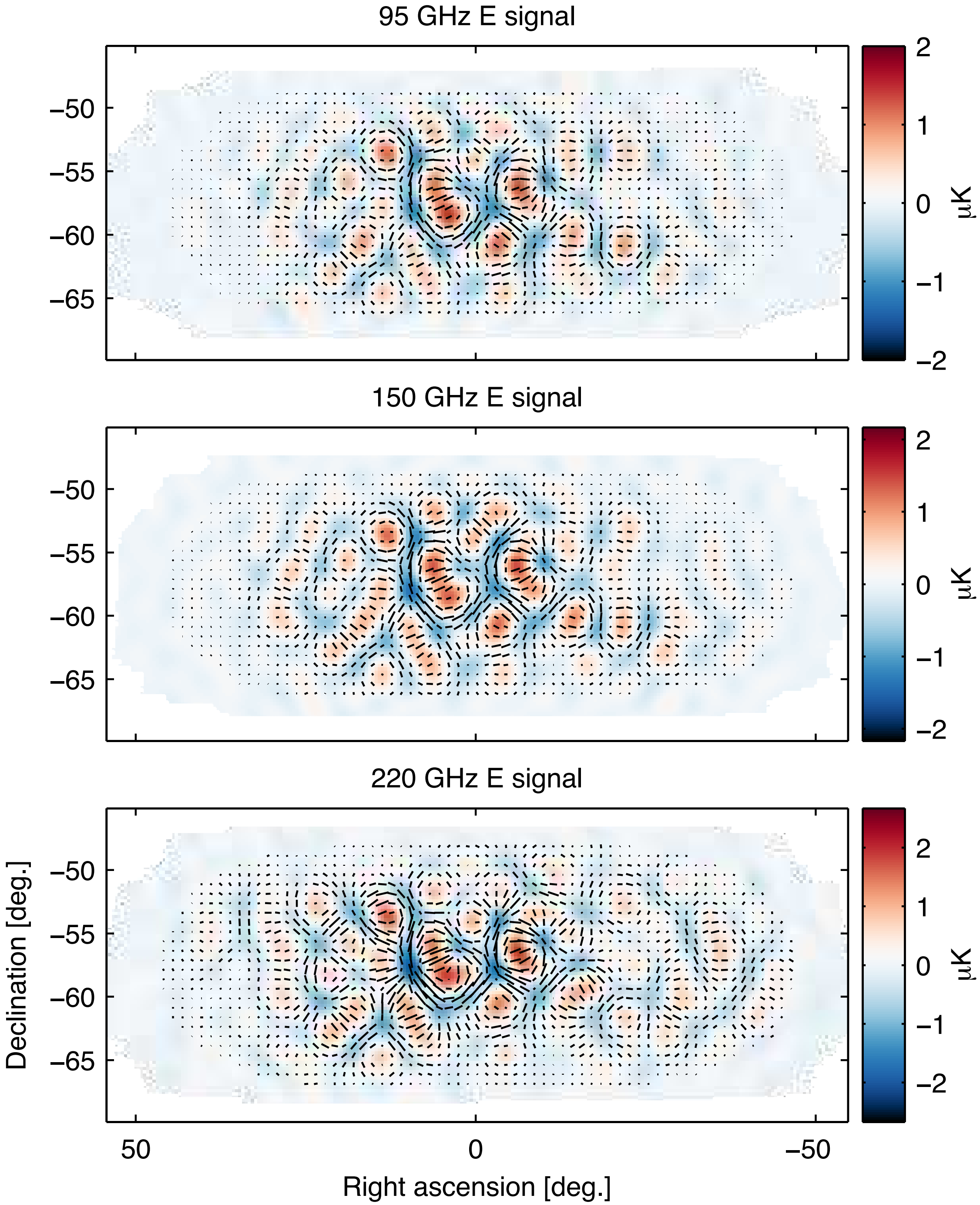
Keck Array 2014

Keck Array 2015

Keck 2015 season-only E-mode Maps



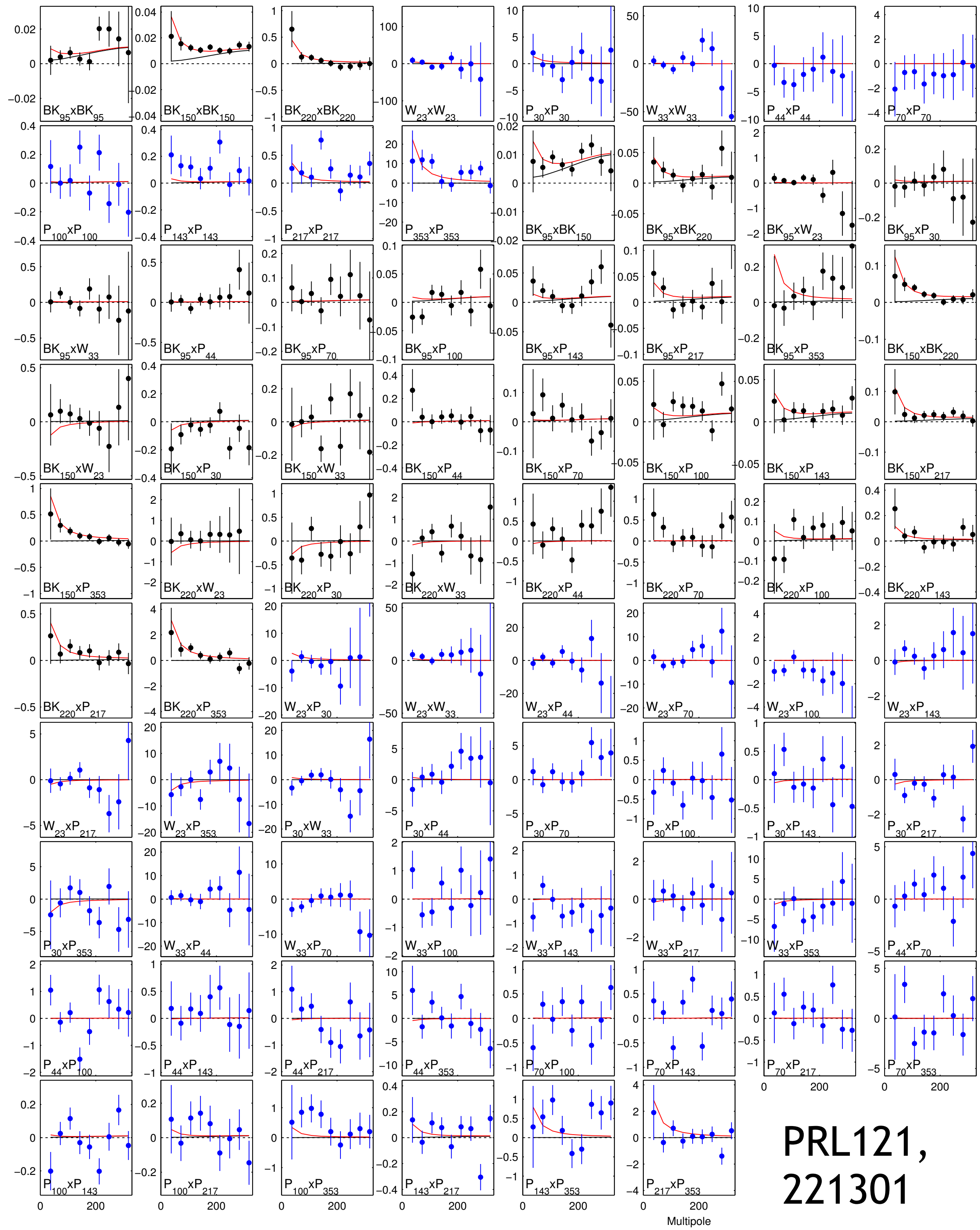
Keck 2015 season-only E-mode Maps



In one year of observations, the 220 GHz map is already 3x deeper than Planck's 217 GHz.

BK15 Auto- and cross- spectra between BICEP/Keck, WMAP, and Planck bands

For the BK15 release we included our new 220 GHz channel, yielding 78 spectra.



PRL121, 221301

Multicomponent Likelihood Analysis

Take the joint likelihood of all the spectra simultaneously, compare to a model for BB:

- Expectation for ΛCDM and lensing
- **7-parameter foreground model**
- ***r***

Multicomponent Likelihood Analysis

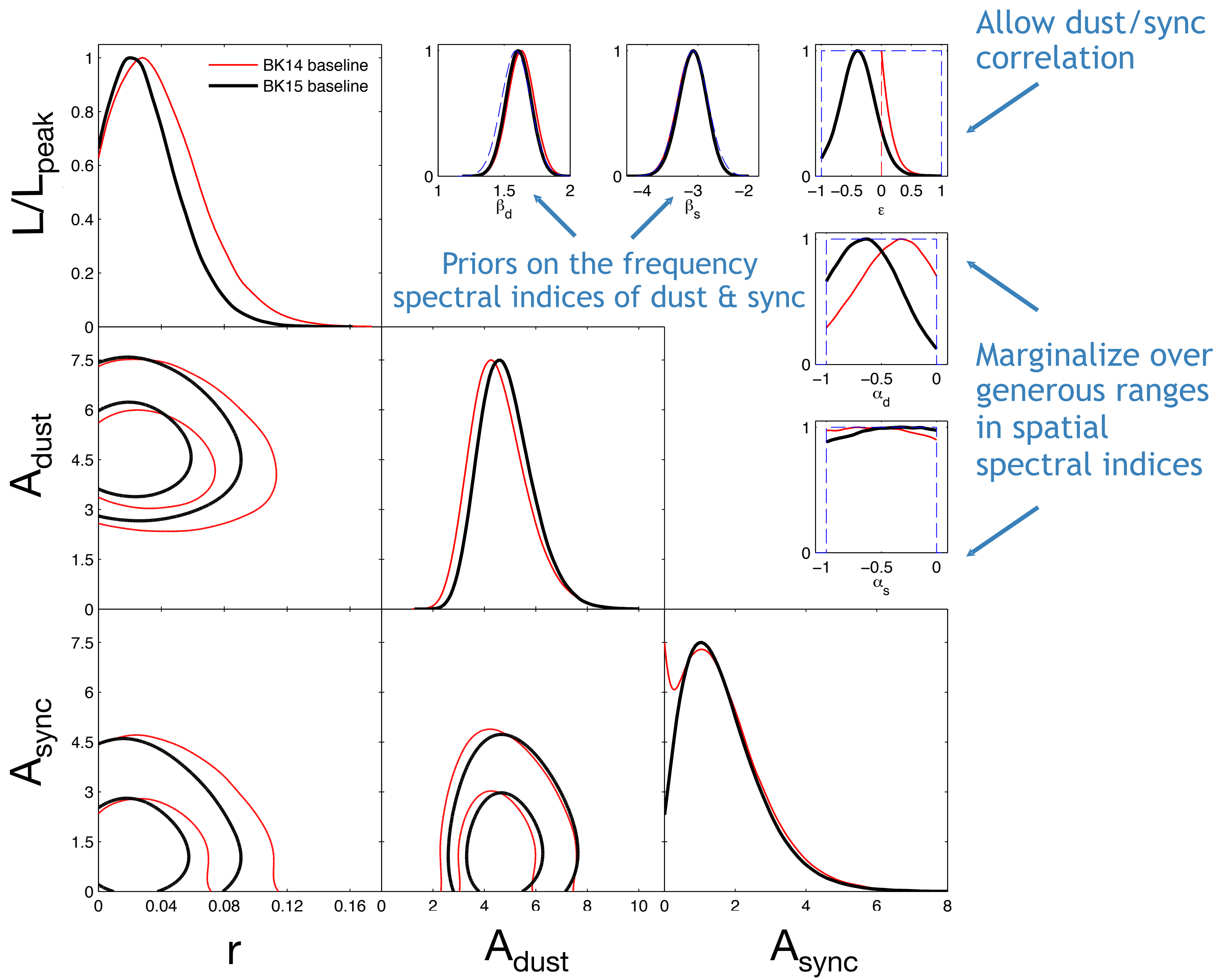
Take the joint likelihood of all the spectra simultaneously, compare to a model for BB:

- Expectation for ΛCDM and lensing
- **7-parameter foreground model**
- ***r***

Foreground model = dust + synchrotron

A_{dust}	A_{sync}	Amplitudes @ l=80
β_{dust}	β_{sync}	Frequency spectral indices
α_{dust}	α_{sync}	Spatial spectral indices
ε		Dust/sync spatial correlation

BK15 Results

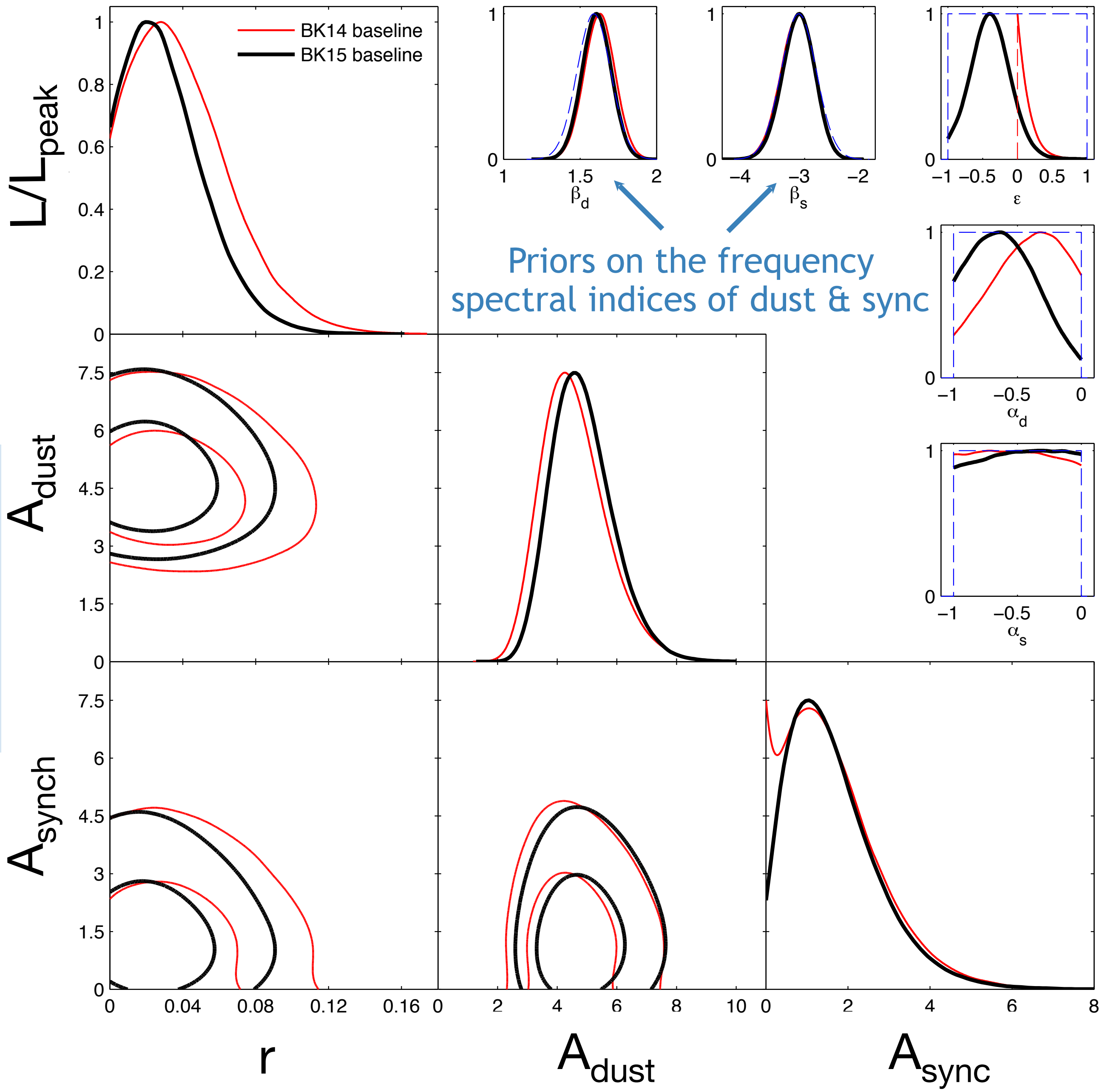


BK15 Results

r < 0.07
(95% CL)

Plus many alternate analyses presented:

- Foreground priors
- Including EE
- WMAP/Planck data
- Dust decorrelation



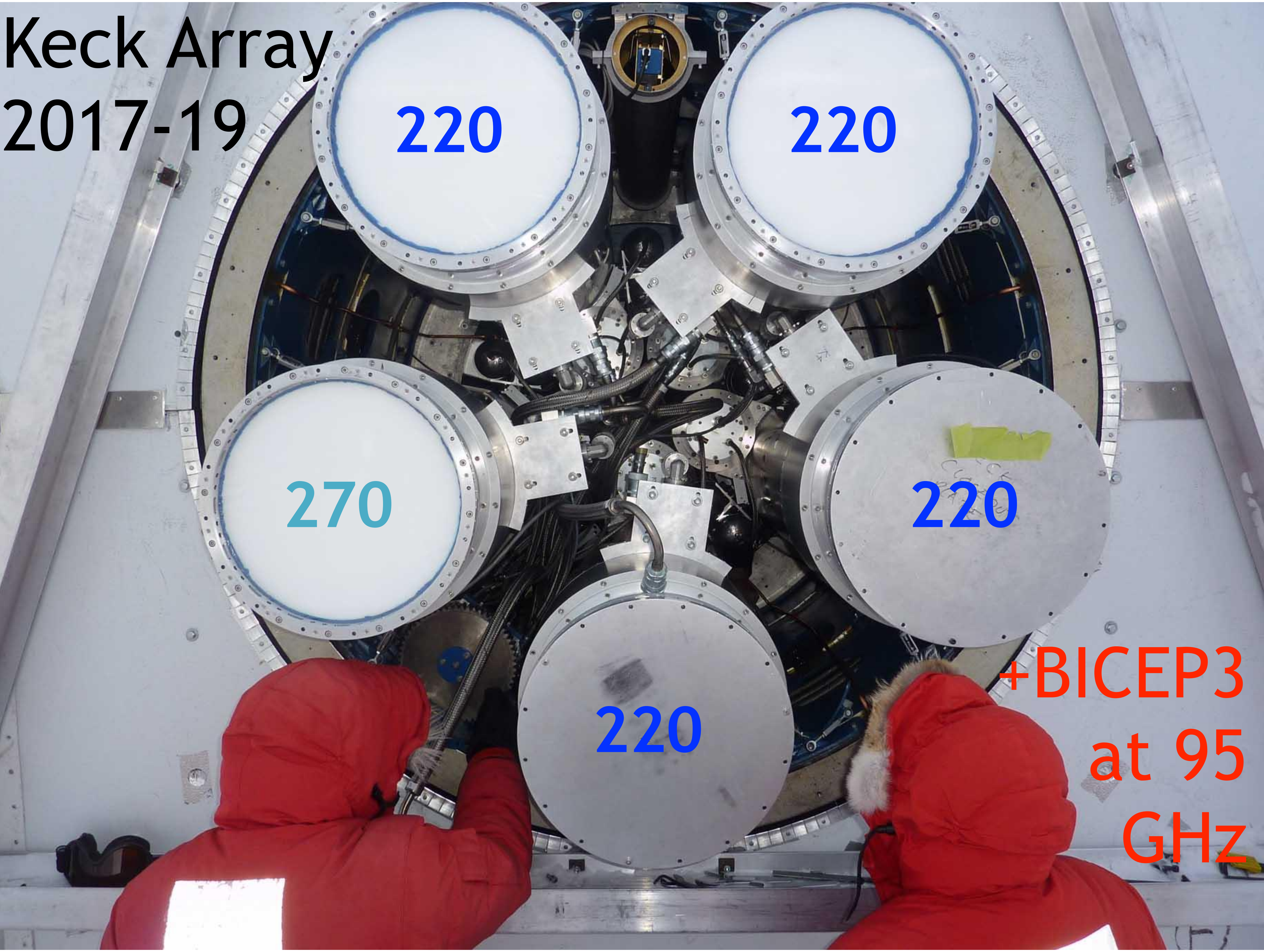
Allow dust/sync correlation

Priors on the frequency spectral indices of dust & sync

Marginalize over generous ranges in spatial spectral indices

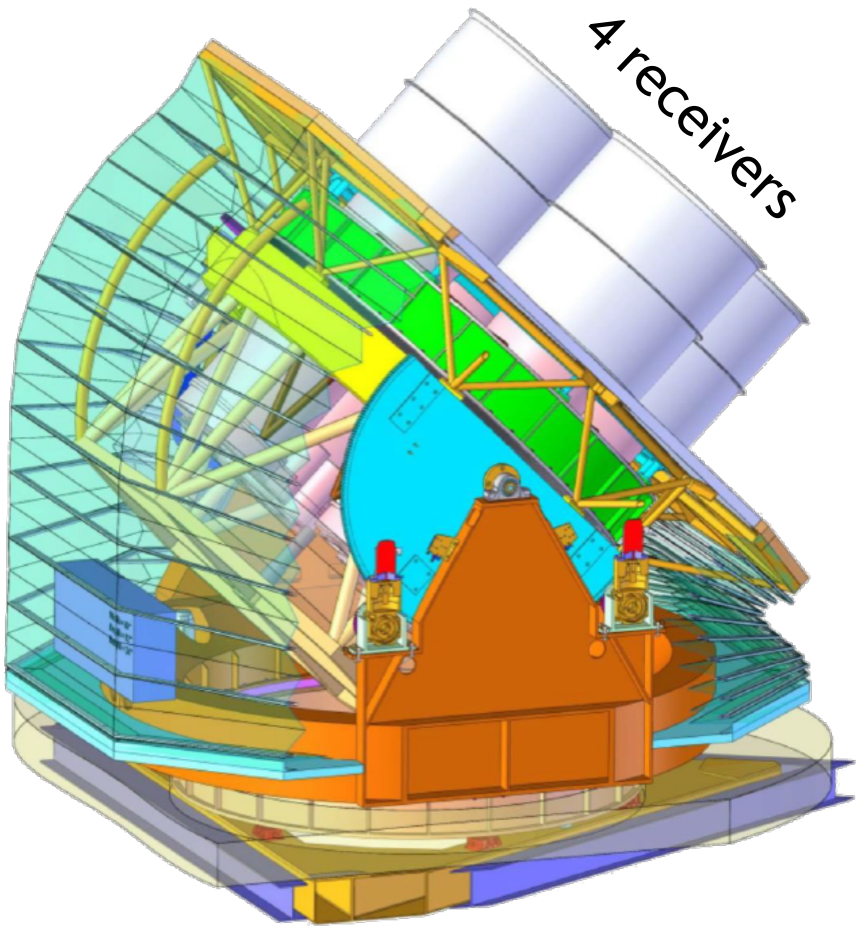

Keck Array
2015
220
220
150
95
95

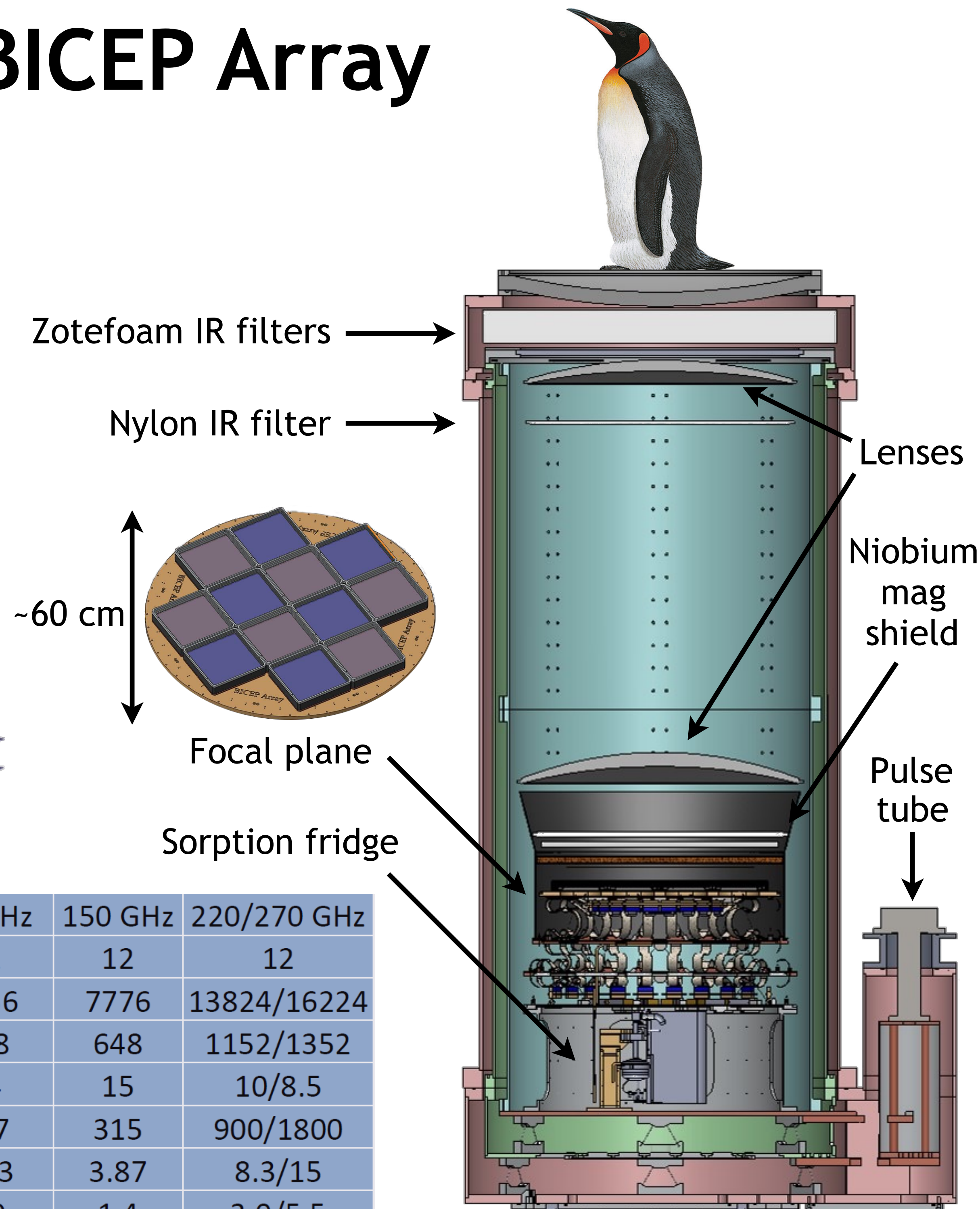

Keck Array
2016
220
220
150
220
220
+BICEP3
at 95
GHz



Keck Array
2017-19
220
220
270
220
220
+BICEP3
at 95
GHz

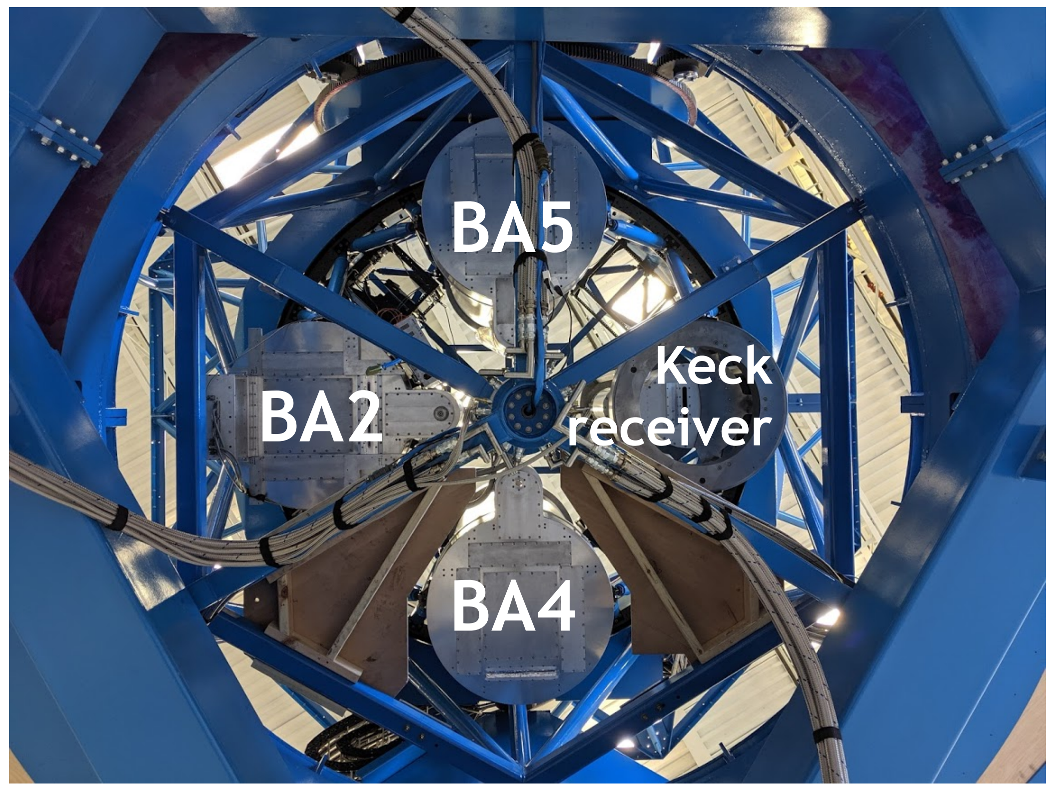
2019 onwards: BICEP Array





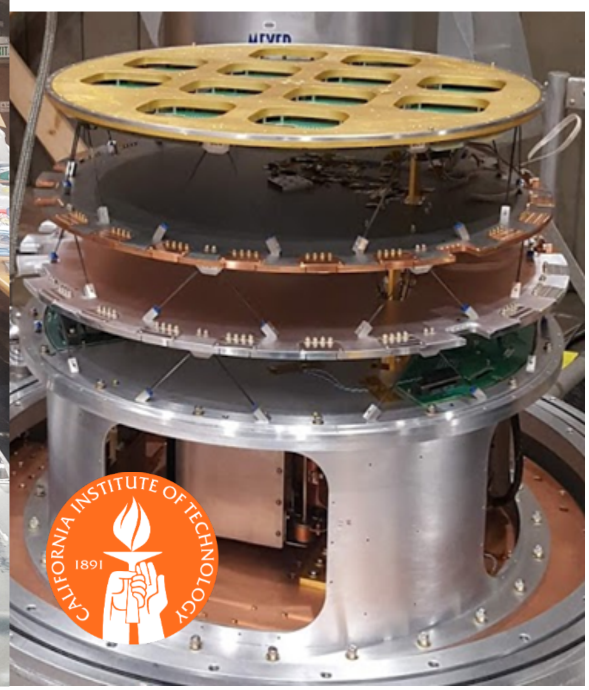
Frequency	30/40 GHz	95 GHz	150 GHz	220/270 GHz
Tiles	12	12	12	12
# Detectors	192/300	3456	7776	13824/16224
# Det/ Tile	32/50	288	648	1152/1352
Beam FWHM (arcmin)	76/57	24	15	10/8.5
NET per det (uK-rts)	268/334	267	315	900/1800
Instr. NET (uK-rts)	21/21	4.93	3.87	8.3/15
3-yr map depth (uK-arcmin)	7.5/7.5	1.9	1.4	3.0/5.5

BICEP Array mount at U. Minnesota

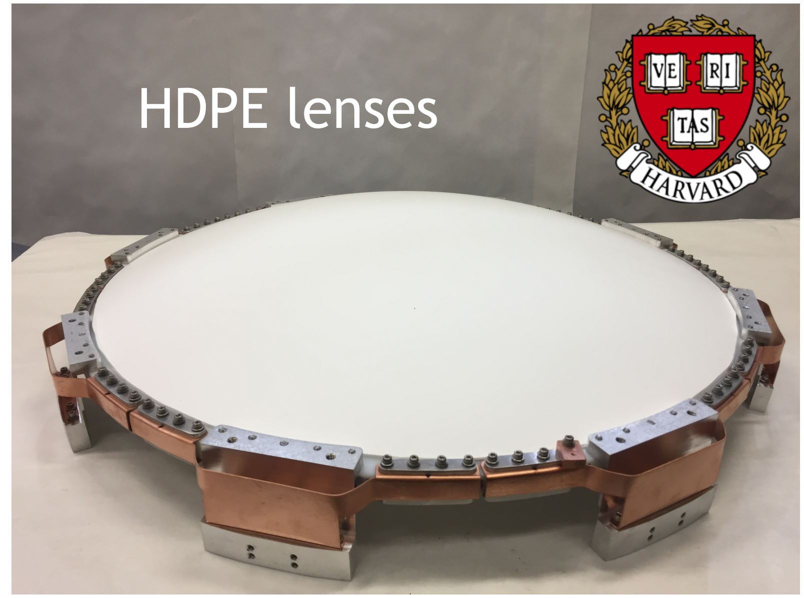


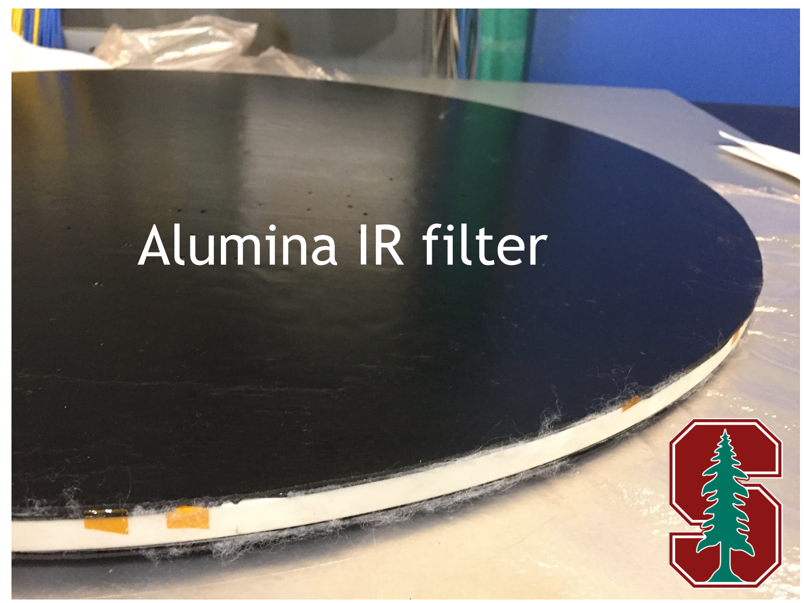
BA1 (30/40 GHz) integration

Receiver performance

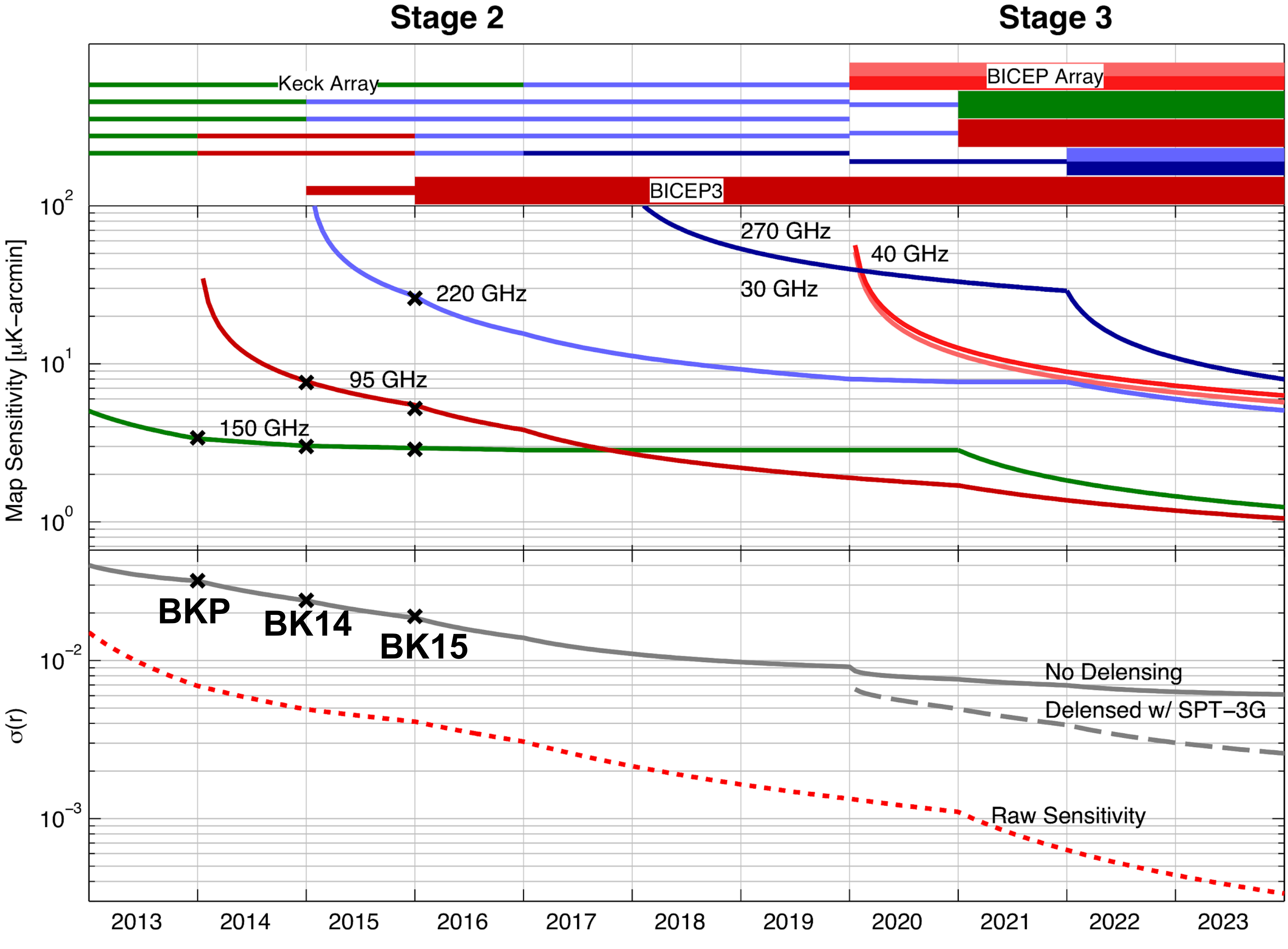


Optics





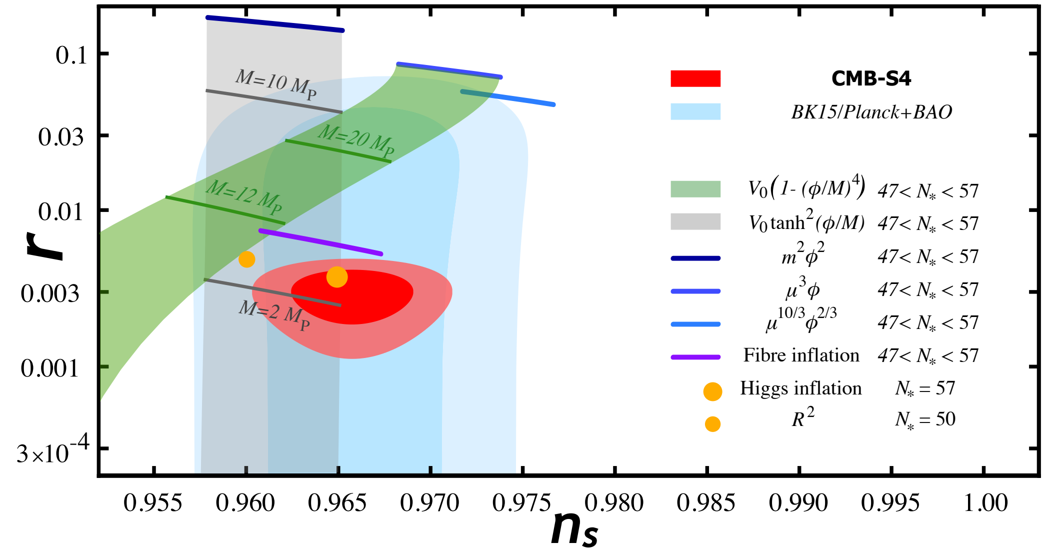
Summary



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

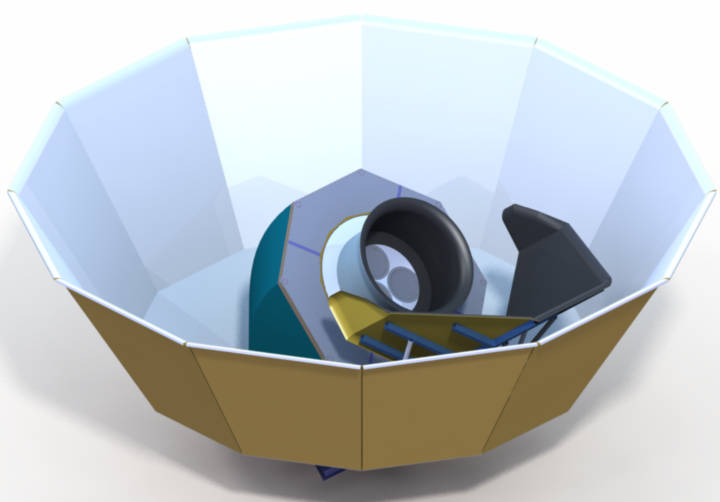
CMB-S4 Measurement of *r*

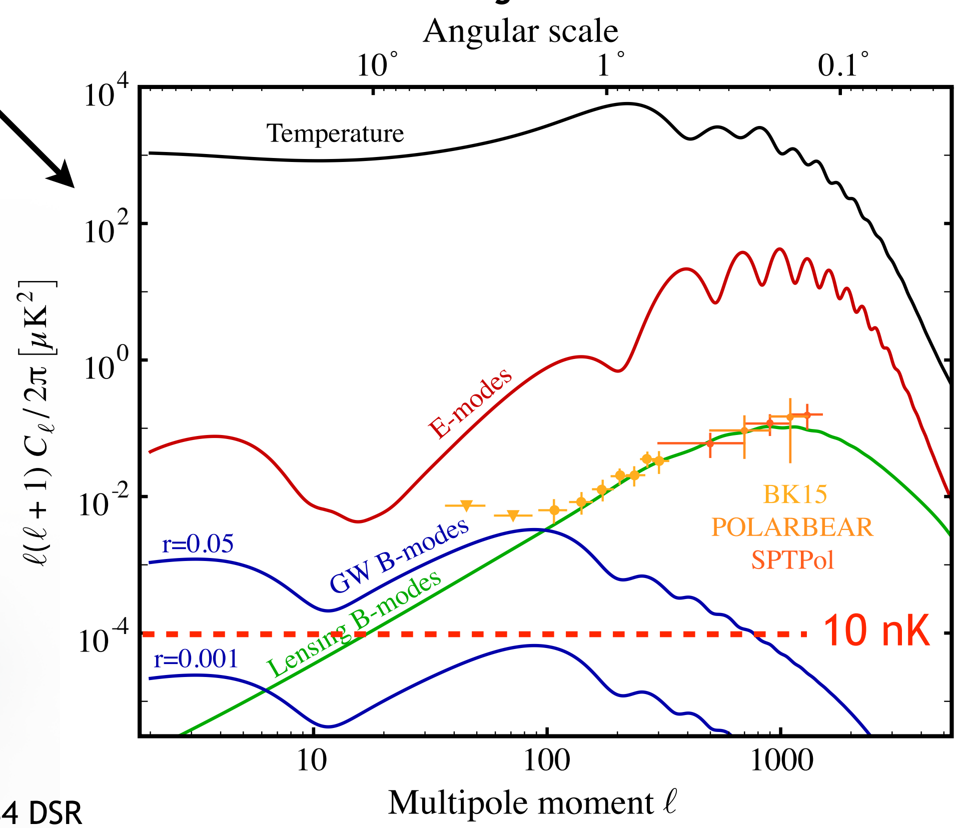
Goal: r < 0.001 at 95%, or detect r = 0.003 at high confidence →



This means < 10 nK uncertainties at degree scales. Requires:

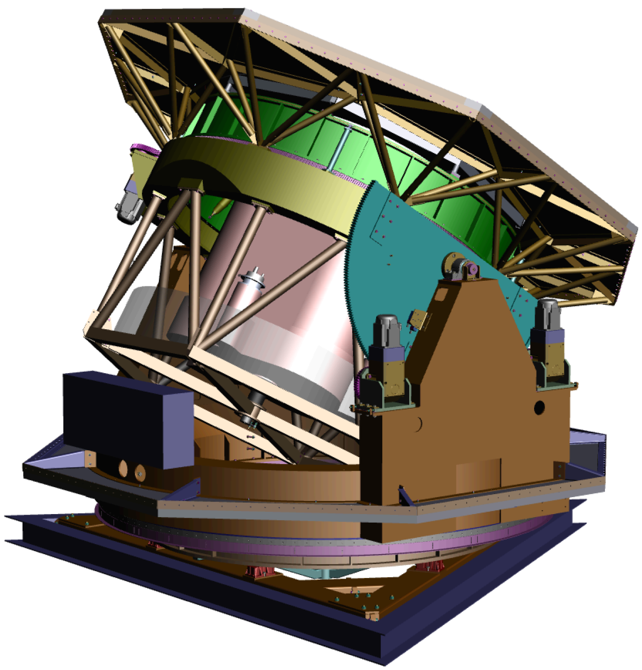
- Raw sensitivity
- Systematics control
- Foreground separation





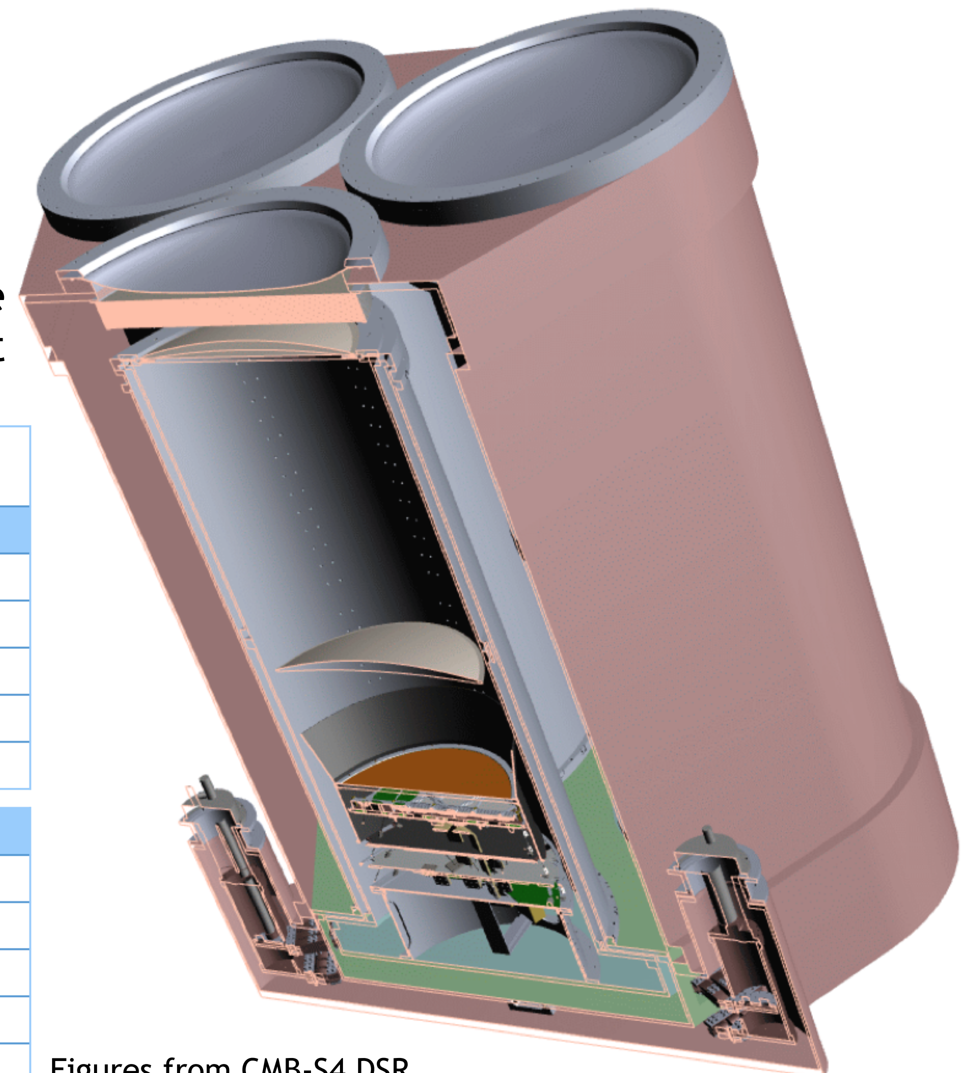
Figures from CMB-S4 DSR

CMB-S4 Small Aperture Telescopes



The S4 reference design for the SAT mounts, optics and shielding is modeled after Stage-3 BICEP3 and BICEP Array.

3 optics tubes inside a single cryostat



bands	lenses	field of view	min edge taper	modulation	detectors/ tube	tubes
SATs at South Pole, 12 tubes						
30 / 40	2x 55cm Al	29^0	-9.3 dB	scan	576	1
85 / 145	2x 55cm Al	29^0	-6.2 dB	scan	7056	4
95 / 155	2x 55cm Al	29^0	-8.4 dB	scan	7056	4
220 / 270	2x 44cm Si	29^0	-12.5 dB	scan	16884	3
				subtotals	107,676 detectors	
SATs in Chile, 6 tubes						
30 / 40	3x 55cm Al	35^0	-6.8 dB	scan	684	1
85 / 145	3x 44cm Si	35^0	-5.7 dB	HWP	6084	2
95 / 155	3x 44cm Si	35^0	-8.0 dB	HWP	6084	2
220 / 270	3x 44cm Si	35^0	-13.4 dB	HWP	16884	1
				subtotals	41,904 detectors	

Figures from CMB-S4 DSR

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

- BK15: Adding 2015 data including, for the first time, at 220 GHz:
  - Incremental improvement wrt BK14: from $r_{0.05}<0.09$ to $r_{0.05}<0.07$
  - Plank 15 + BK15 $r_{0.05}<0.06$ [$r_{0.002}<0.055$] (arXiv 1810.05216)
  - Beam systematics constrained to 0.1 $\sigma(r)$ (arXiv 1904.01640)

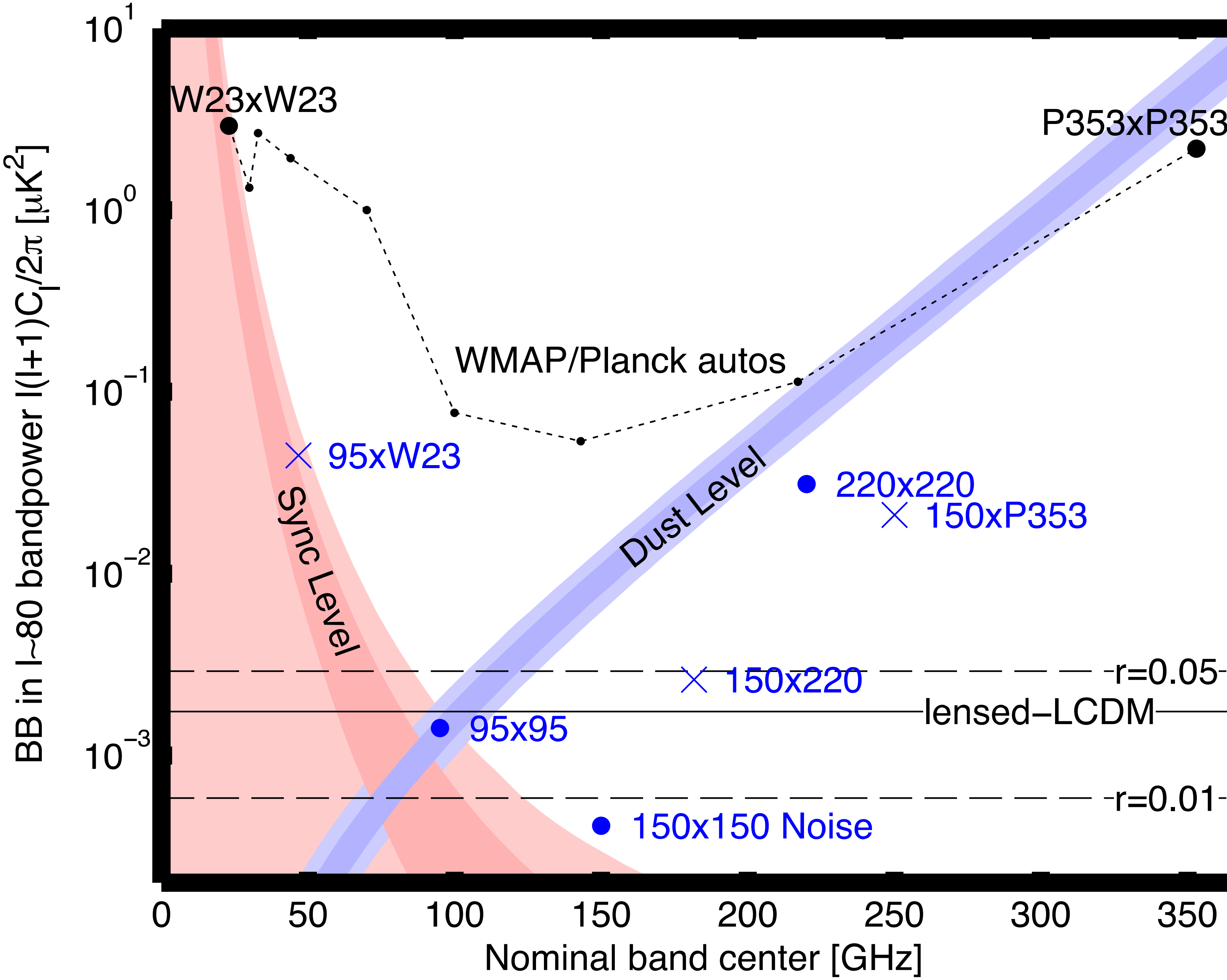
- Currently analyzing 3 years (2016-18) of 95 GHz data from BICEP3 and 2 years of 270 GHz data from Keck: BK18 data analysis
  - Pushing multiband observations & component separation

- And we can go much further:
  - BICEP Array begins observing in 2020 – expect $\sigma(r) \sim 0.003$
  - Delensing using SPT/SPT-3G data
  - Next Generation CMB Experiment: CMB Stage-4


Thank you!

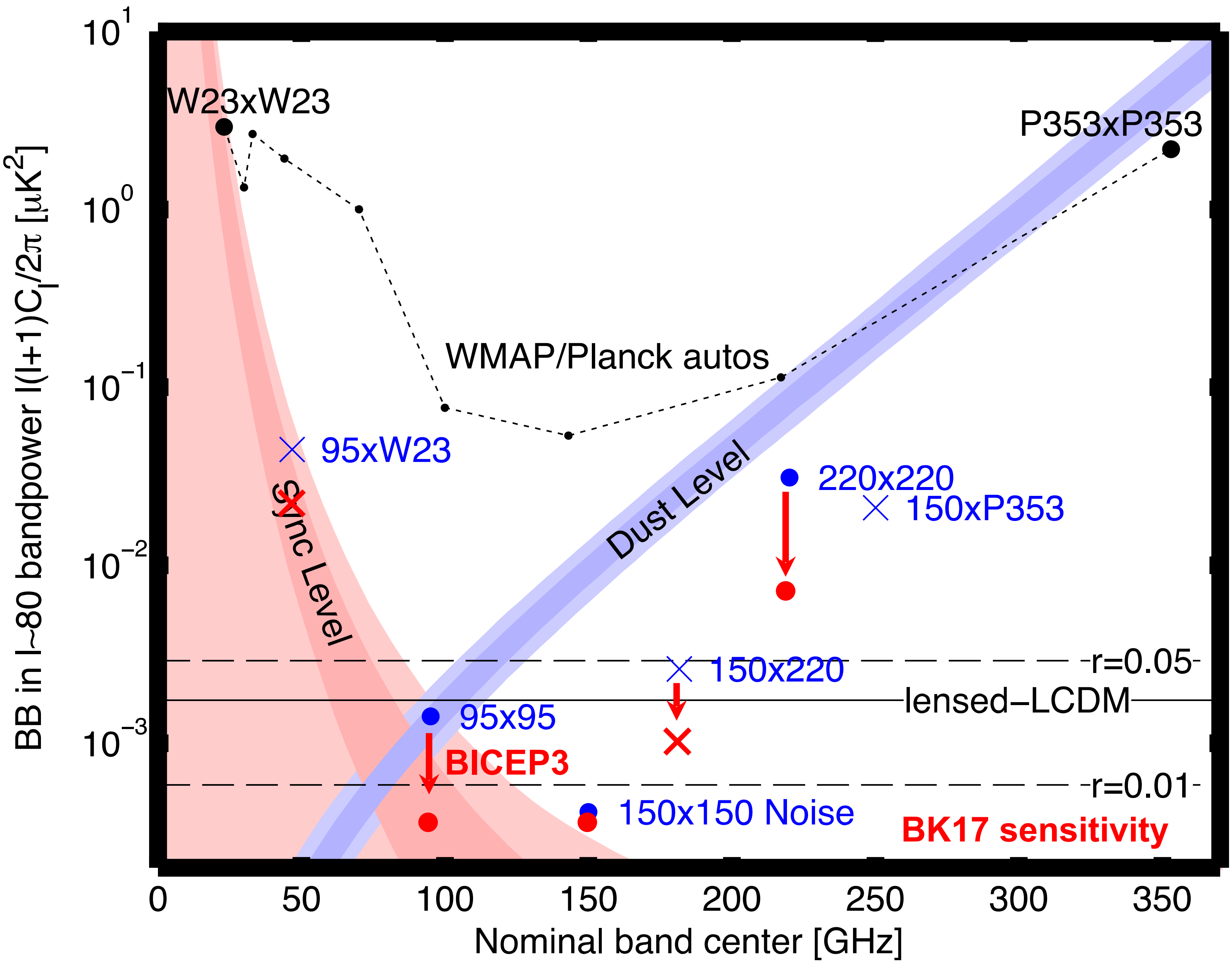
Extra slides

BK15: Current Band Sensitivity (at l=80)

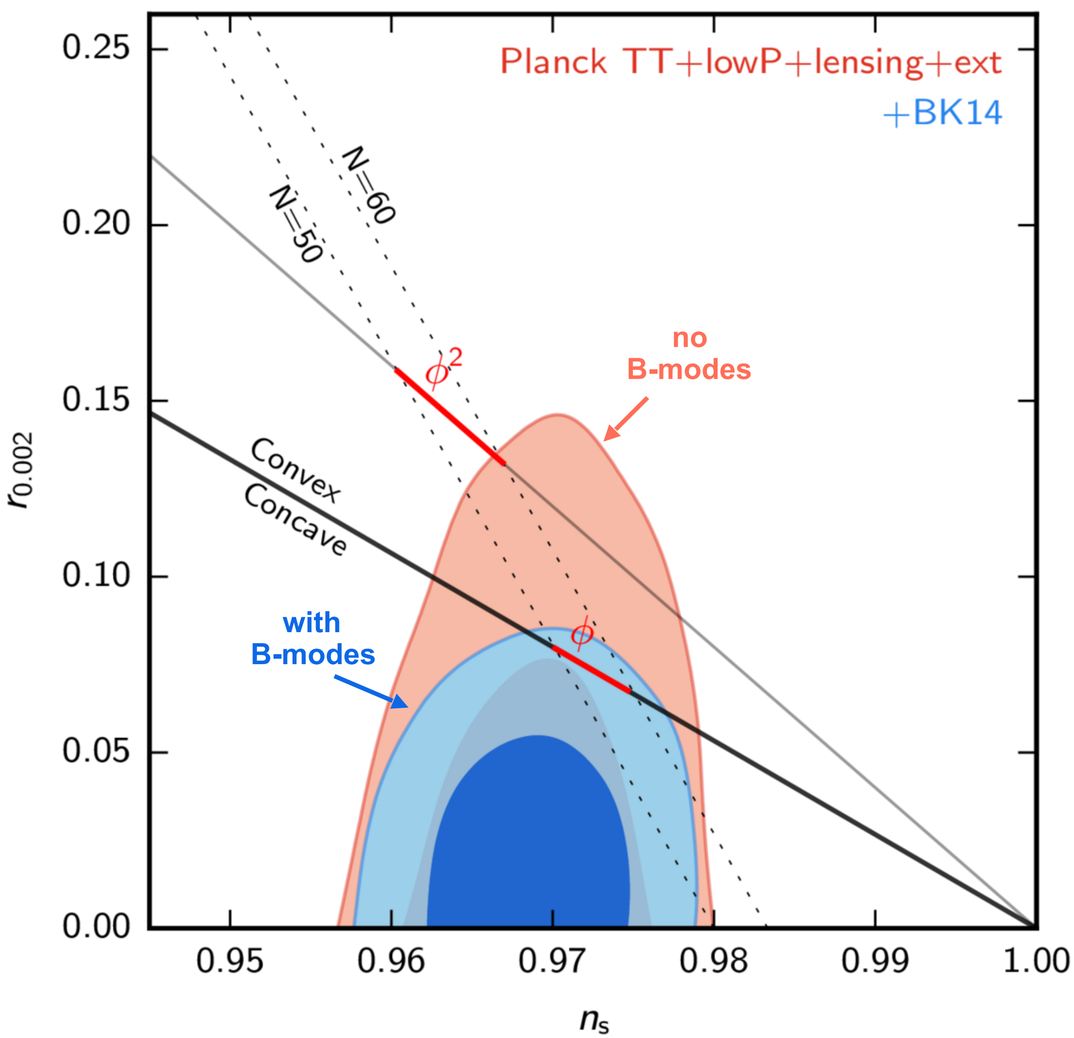


BK17: Expected Band Sensitivity (at l=80)

BK17 errors on *r* will be dominated by synchrotron sensitivity.

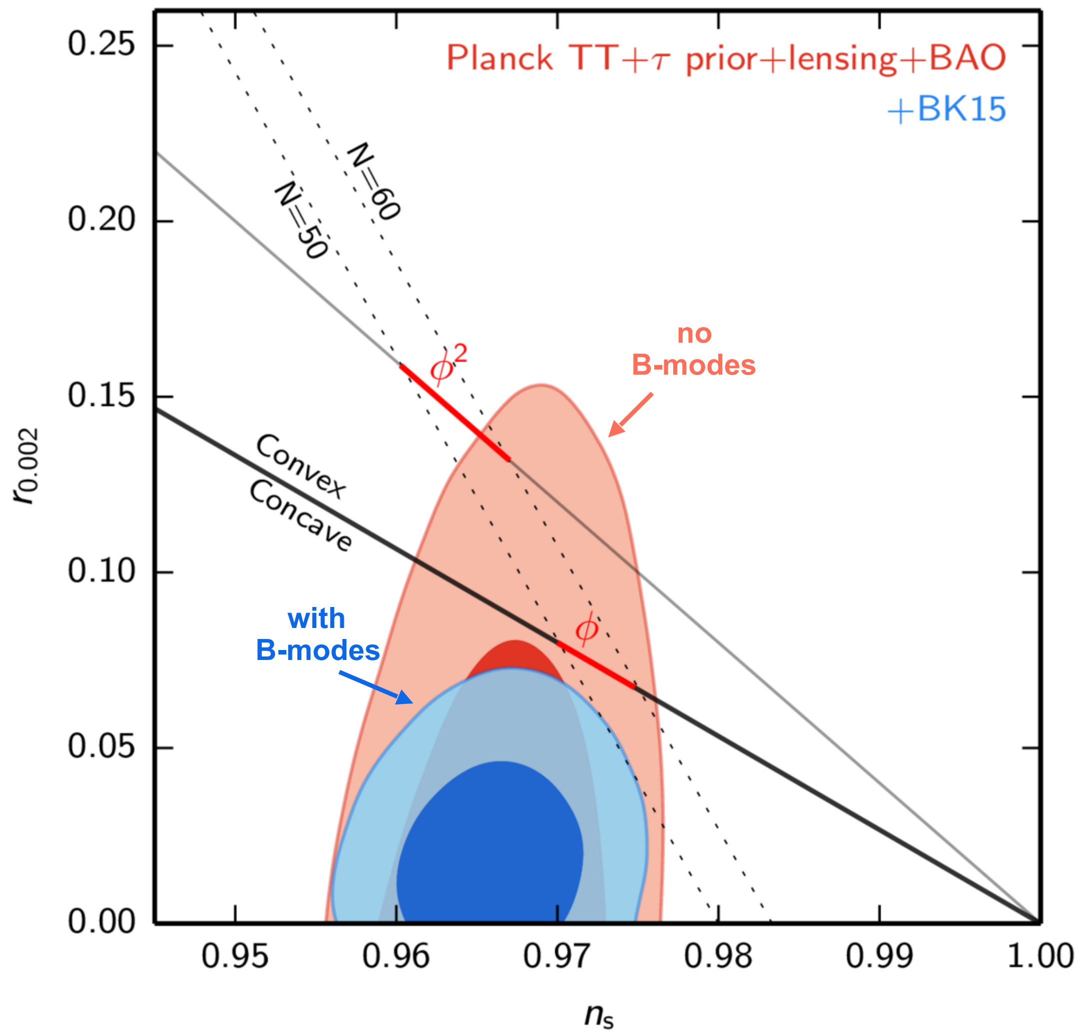


Adding in temperature



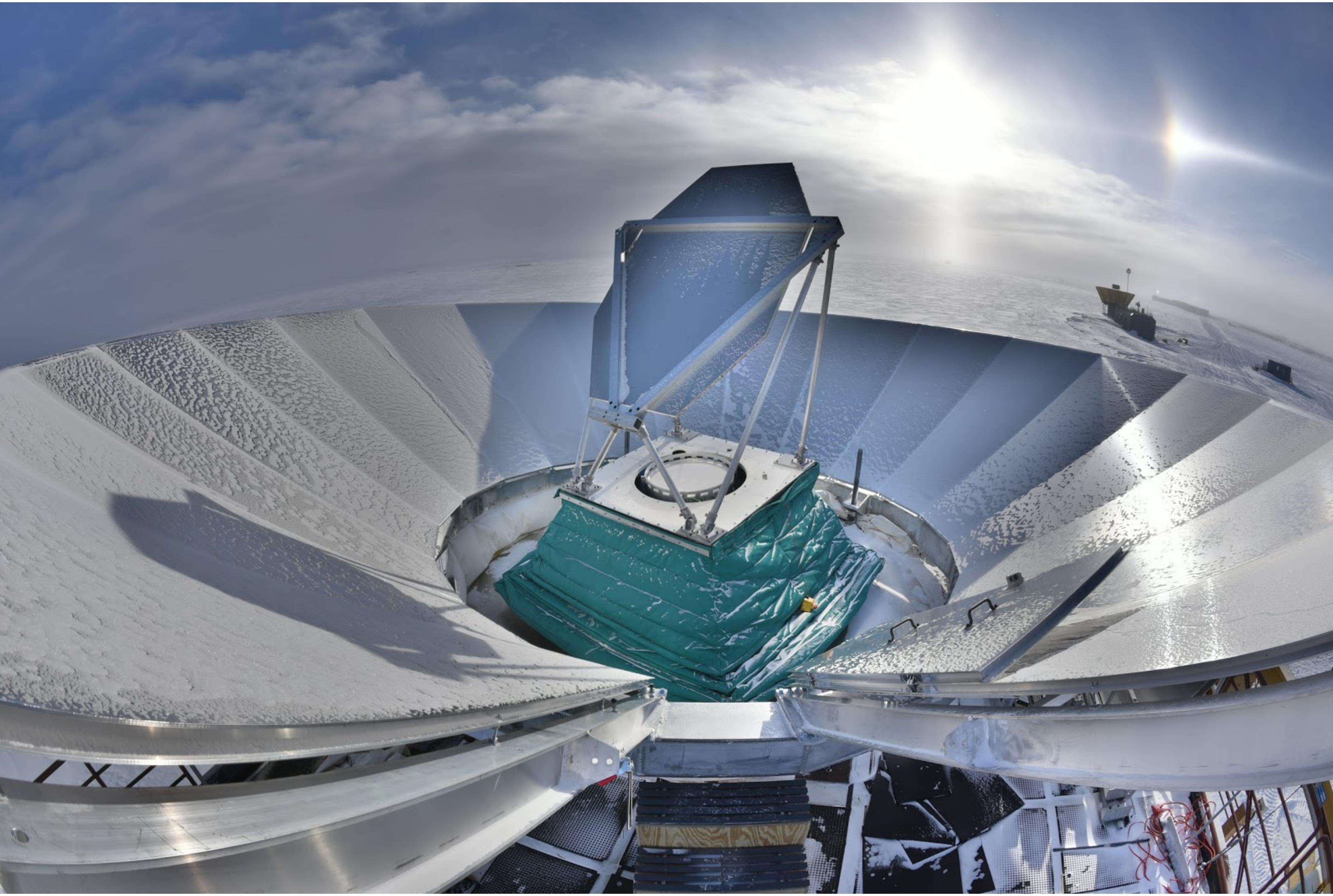
$r_{.05} < 0.07$

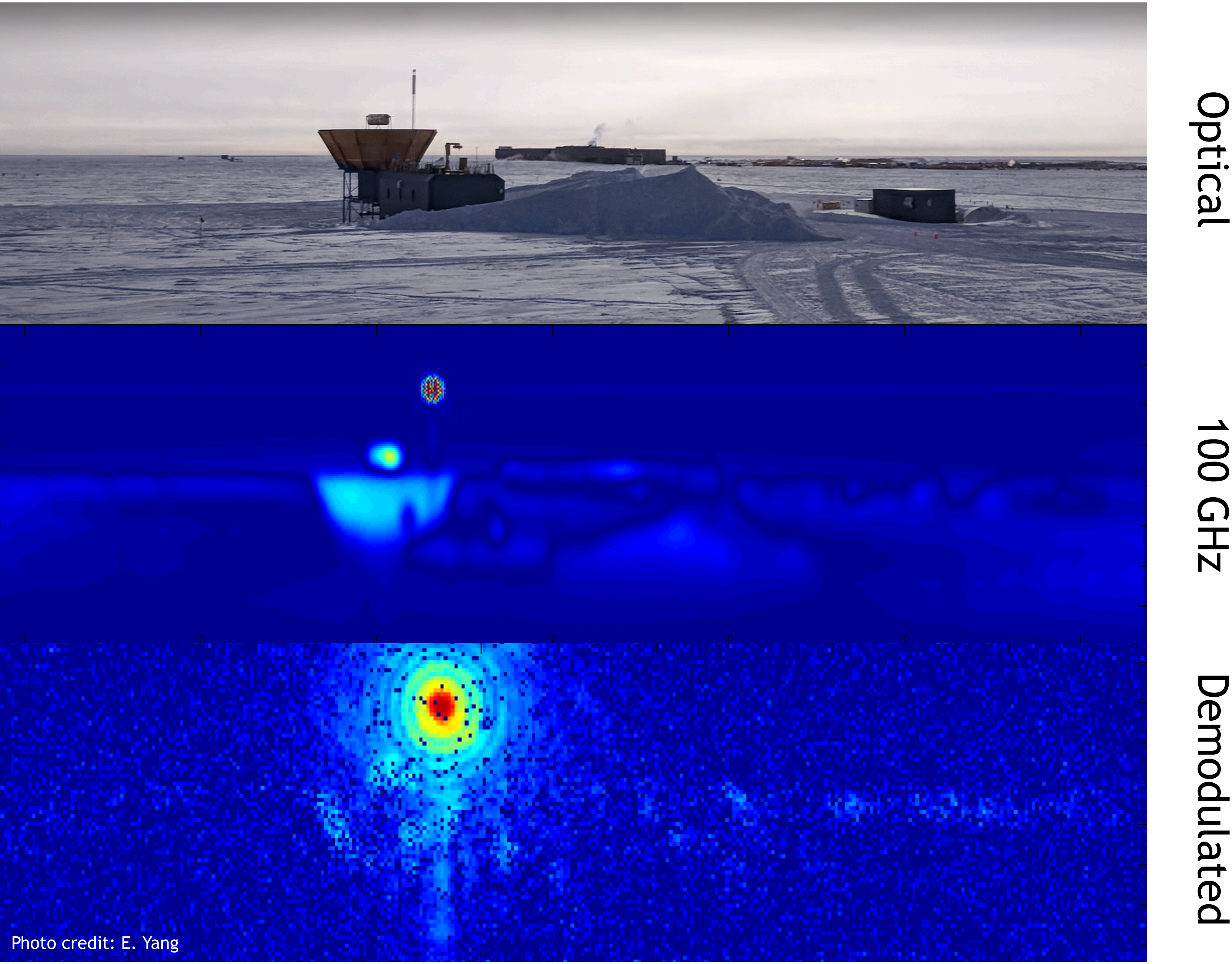
Adding in temperature



$r_{.05} < 0.06$

Far-Field Beam Mapping




Optical
100 GHz
Demodulated
Photo credit: E. Yang