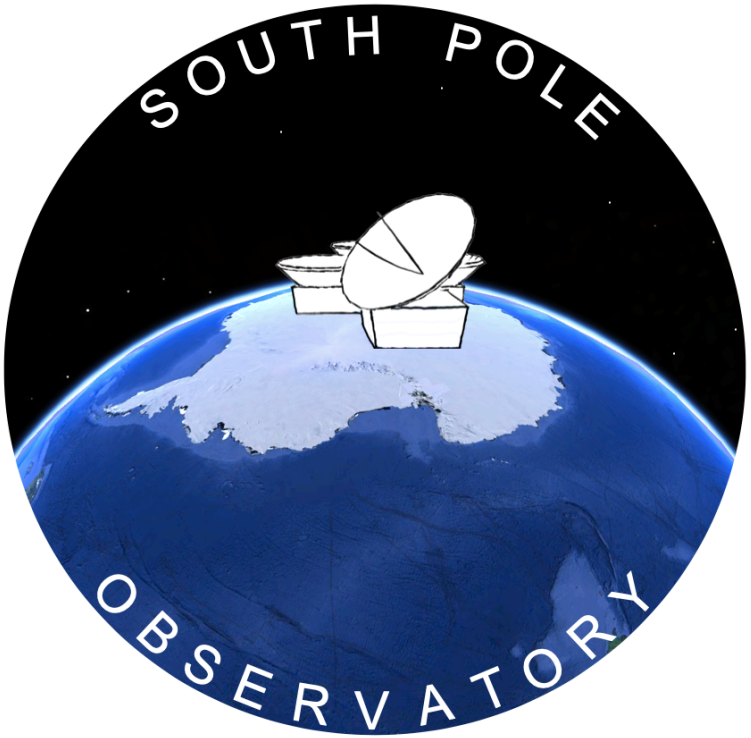
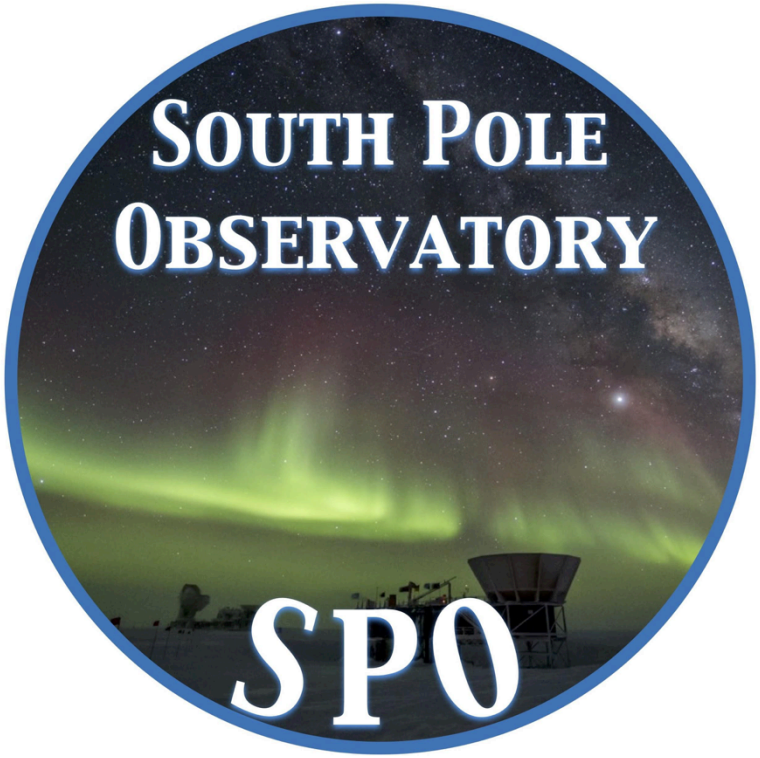
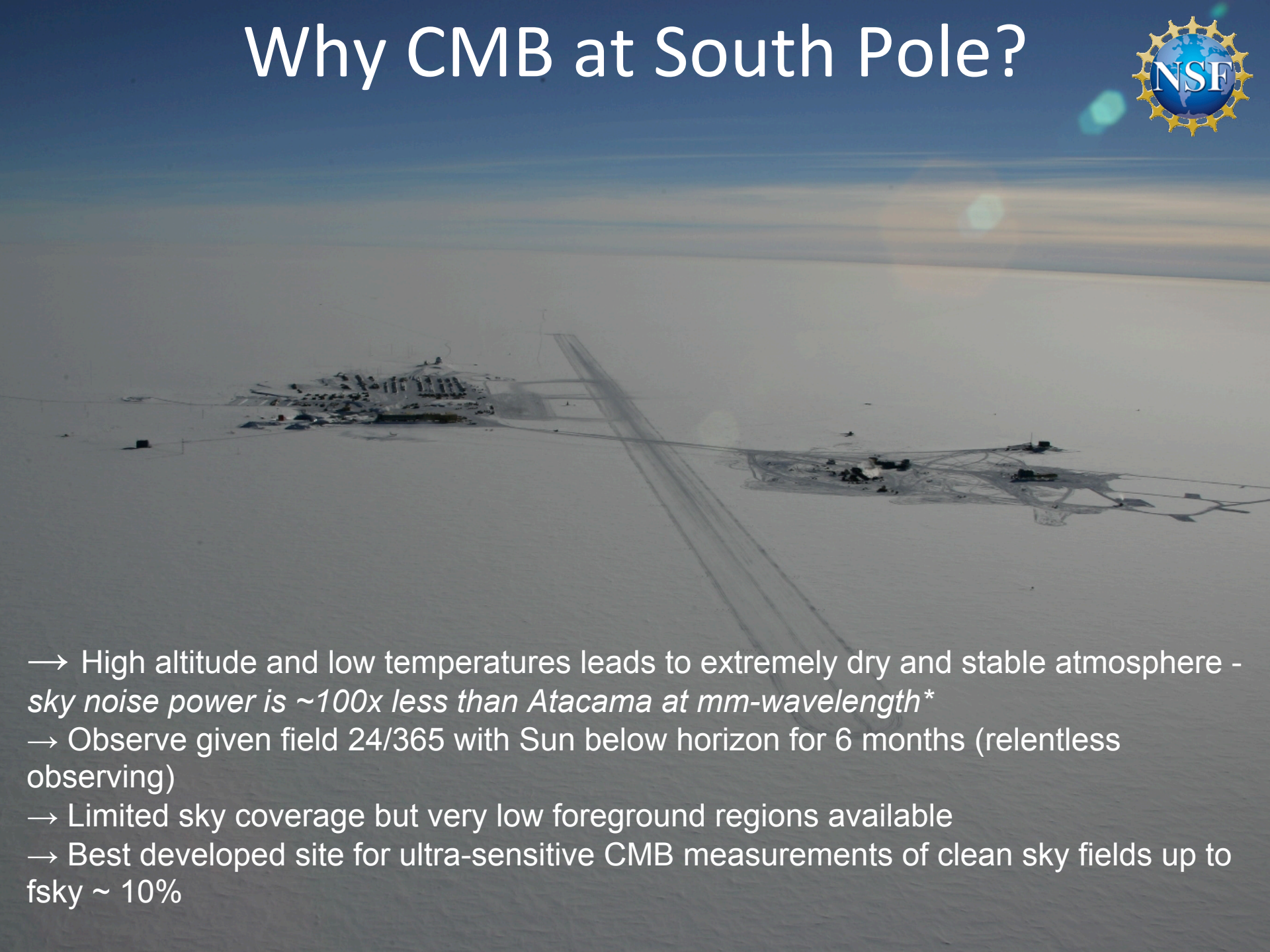

SOUTH POLE
OBSERVATORY

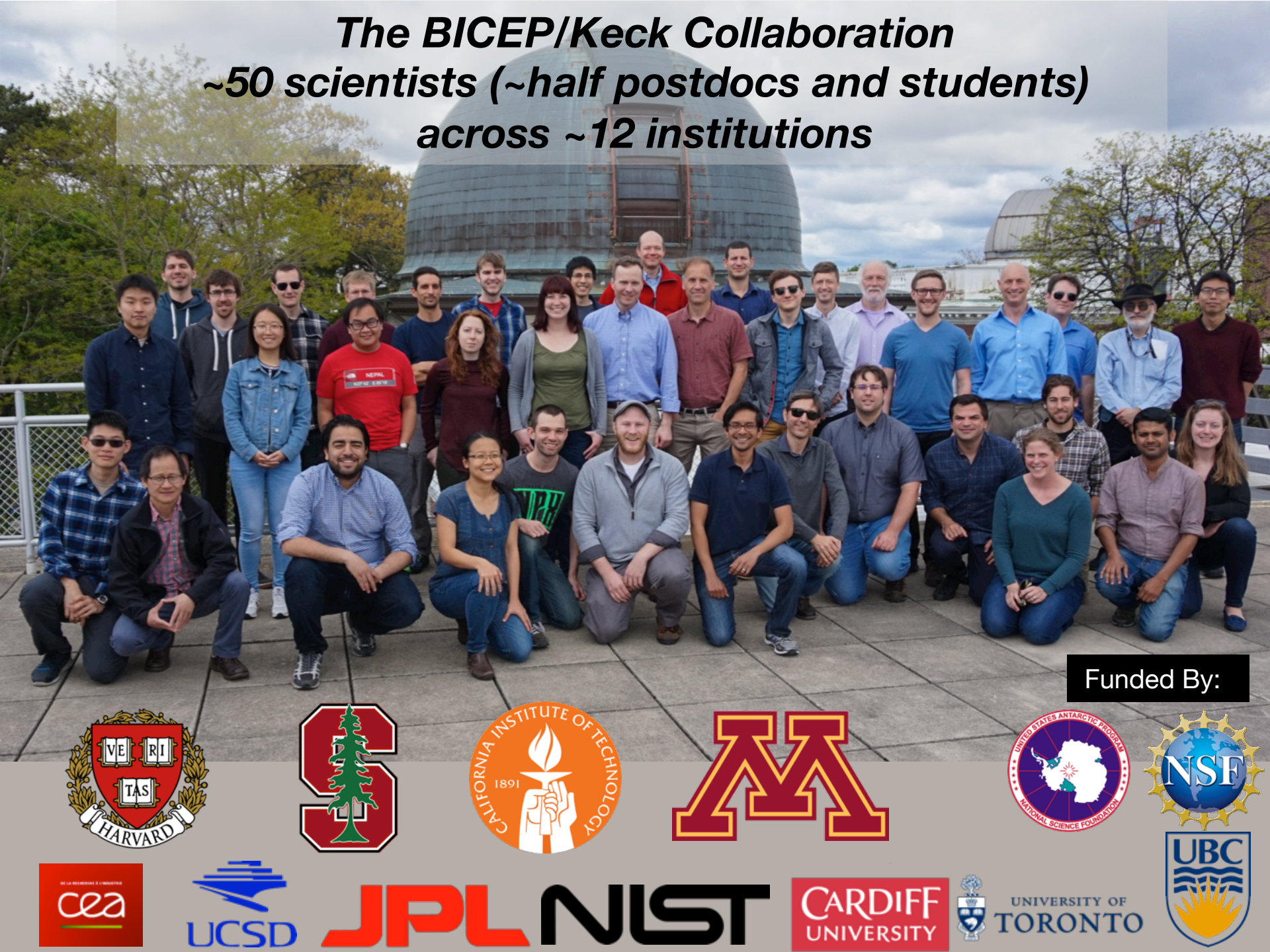

SOUTH POLE
OBSERVATORY


SOUTH POLE
OBSERVATORY
SPO

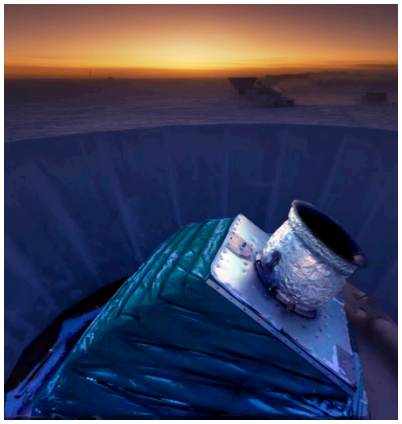
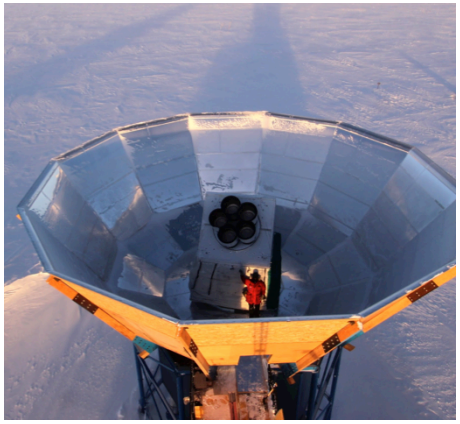
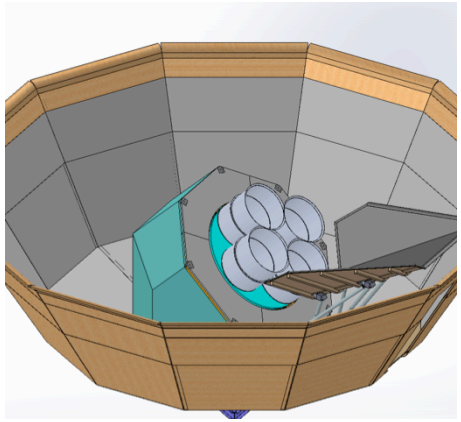
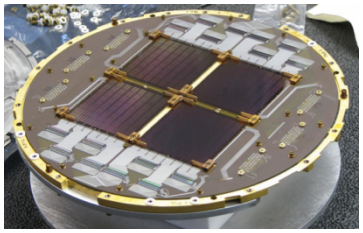
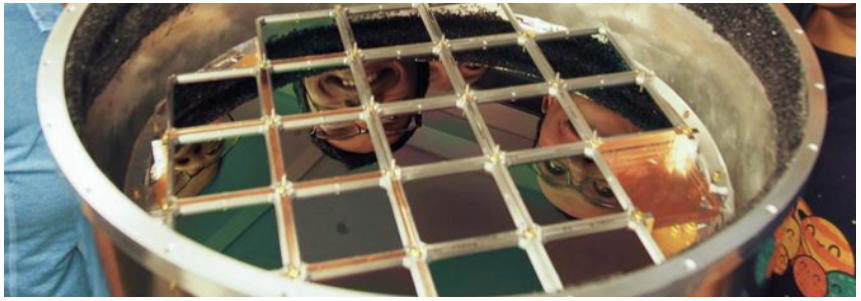
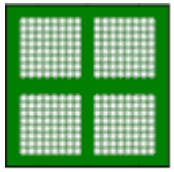
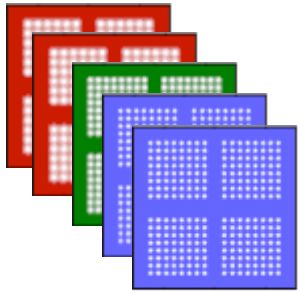
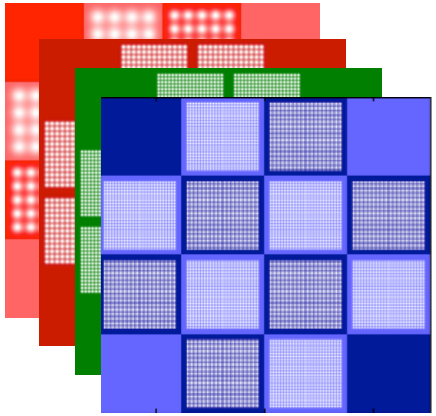
Why CMB at South Pole?



→ High altitude and low temperatures leads to extremely dry and stable atmosphere - *sky noise power is ~100x less than Atacama at mm-wavelength**
→ Observe given field 24/365 with Sun below horizon for 6 months (relentless observing)
→ Limited sky coverage but very low foreground regions available
→ Best developed site for ultra-sensitive CMB measurements of clean sky fields up to fsky ~ 10%


The BICEP/Keck Collaboration
~50 scientists (~half postdocs and students)
across ~12 institutions
Funded By:
HARVARD
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
UNITED STATES ANTARCTIC PROGRAM
NATIONAL SCIENCE FOUNDATION
NSF
cea
UCSD
JPL
NIST
CARDIFF UNIVERSITY
UNIVERSITY OF TORONTO
UBC

The Ongoing BICEP/Keck Program

	BICEP2 (2010-2012)	Keck Array (2012-2019)	BICEP3 (2015-)	BICEP Array (2020-)
Telescope and Mount				
Focal Plane				
Beams on Sky				

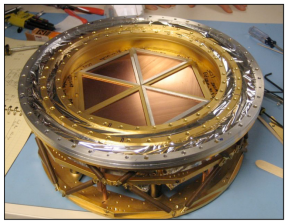

The SPT-3G Collaboration (July 2018)
~70 scientists (~half postdocs and students)
across ~20 institutions
Funded By:
Argonne NATIONAL LABORATORY
BERKELEY LAB
NIST
Fermilab
NSF
KICP
Kavli Institute for Cosmological Physics AT THE UNIVERSITY OF CHICAGO
Berkeley University of California
Case
CASE WESTERN RESERVE UNIVERSITY
McGill
Colorado
University of Colorado at Boulder
CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD
UCDAVIS
UNIVERSITY OF CALIFORNIA
THE UNIVERSITY OF CHICAGO
LMU
LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
Harvard-Smithsonian Center for Astrophysics
SLAC
U.S. DEPARTMENT OF ENERGY

The South Pole Telescope (SPT)

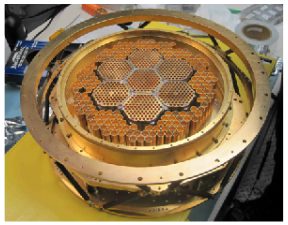
10-meter
submm-quality telescope

100 **150** **220** GHz and
1.6 **1.2** **1.0** arcmin resolution

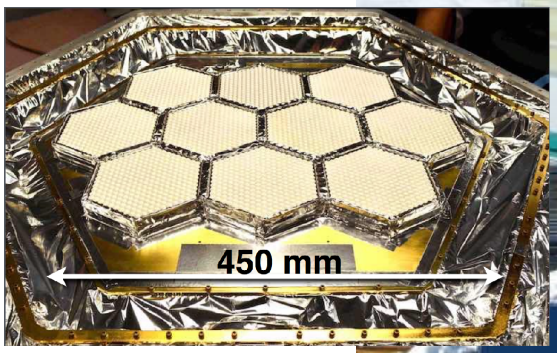
2007: SPT-SZ
960 detectors
100,150,220 GHz

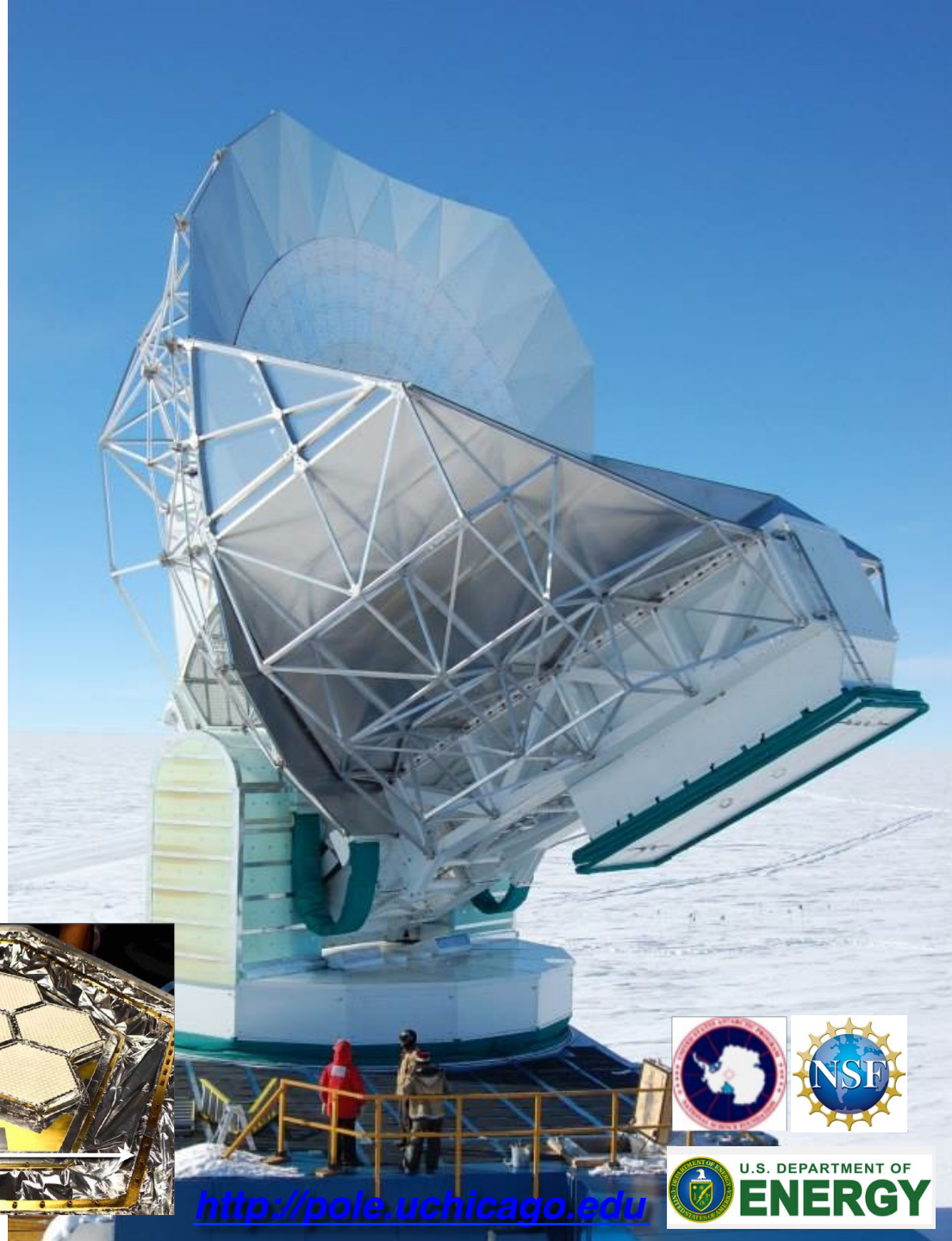


2012: SPTpol
1600 detectors
100,150 GHz
+Polarization



2017: SPT-3G
16,000 detectors
100,150, 220 GHz
+Polarization



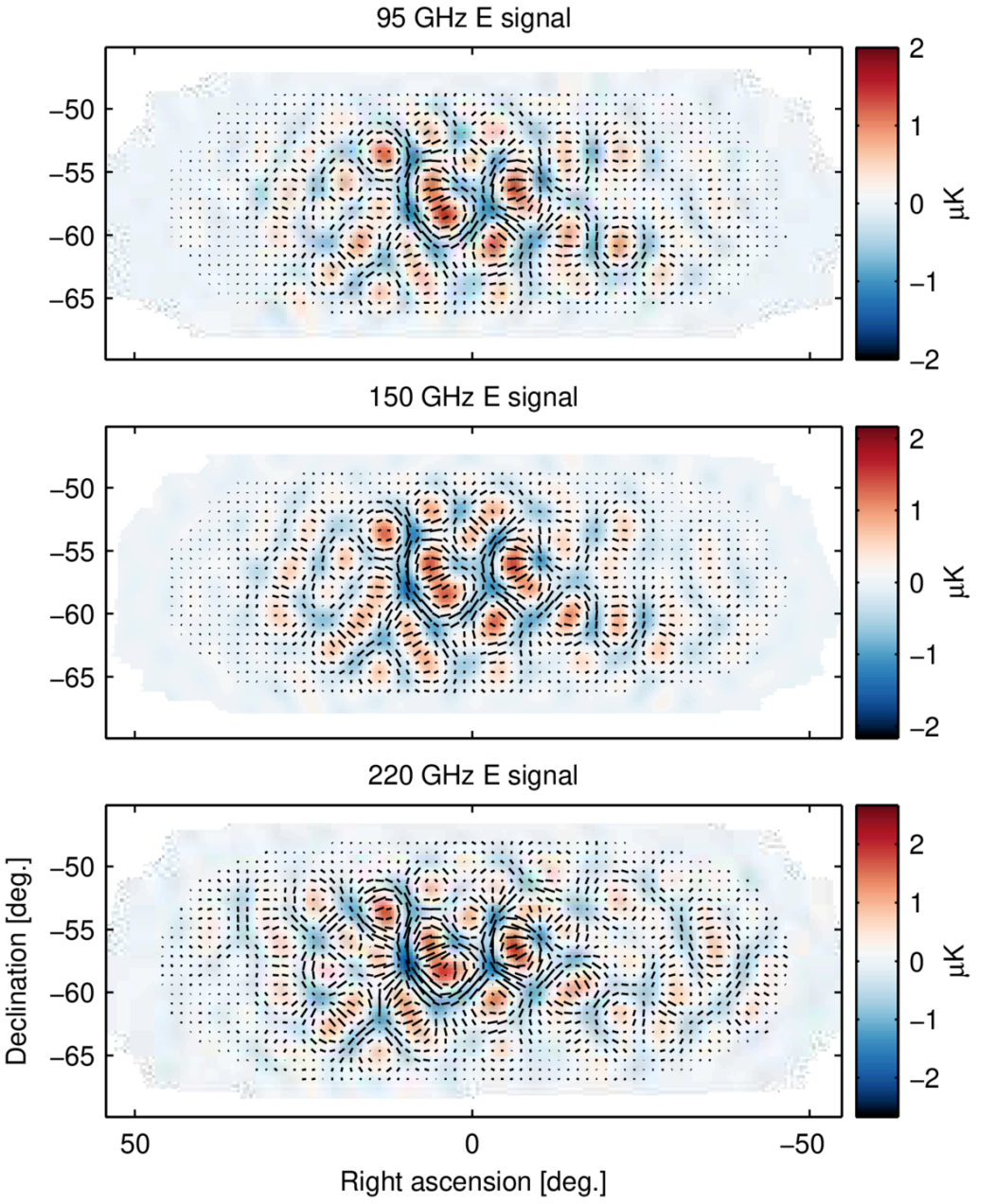


http://pole.uchicago.edu

U.S. DEPARTMENT OF ENERGY

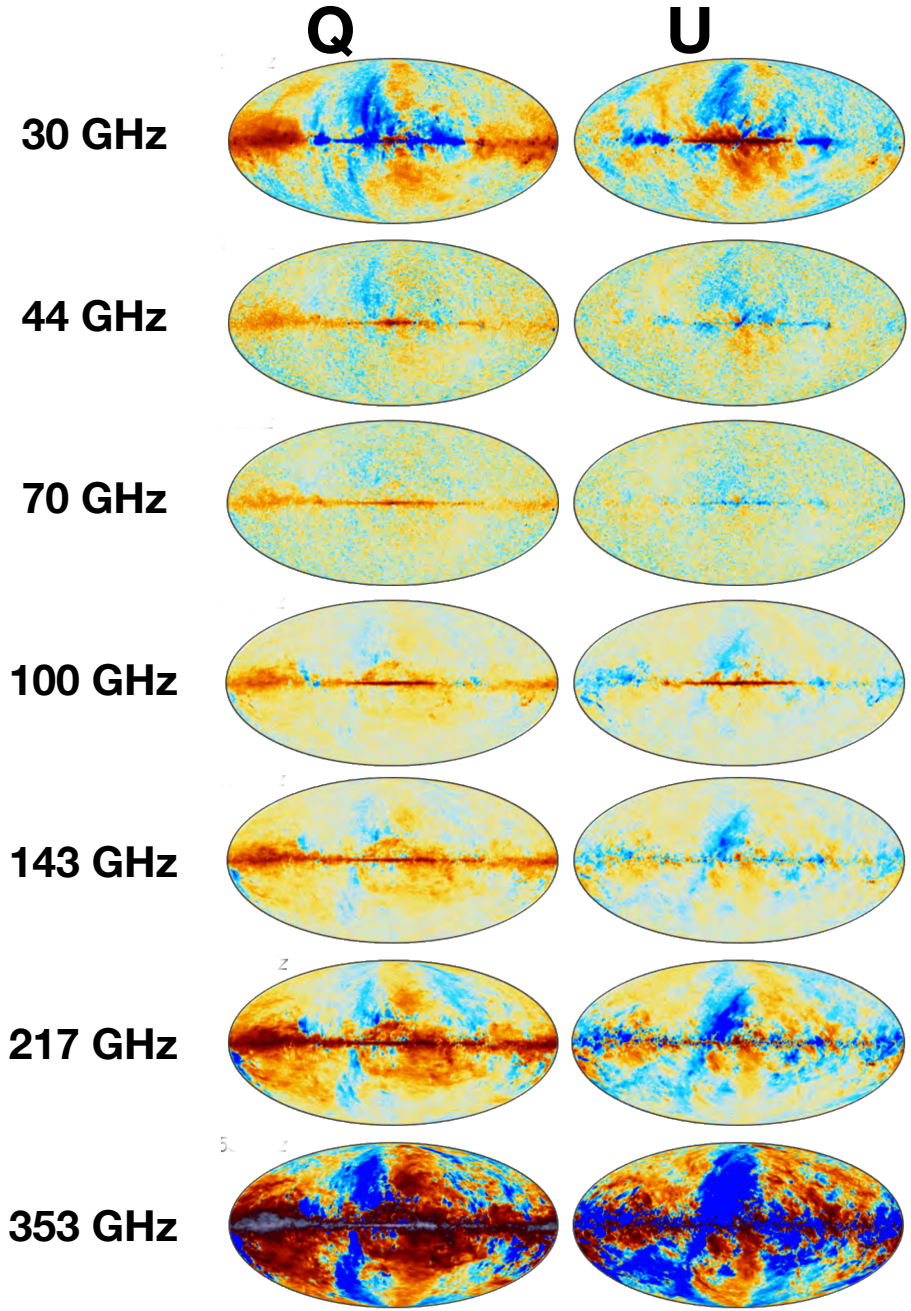
BICEP/Keck Current Results and New BICEP Array Upgrade

Just for fun: Keck 2015 single season E-mode maps



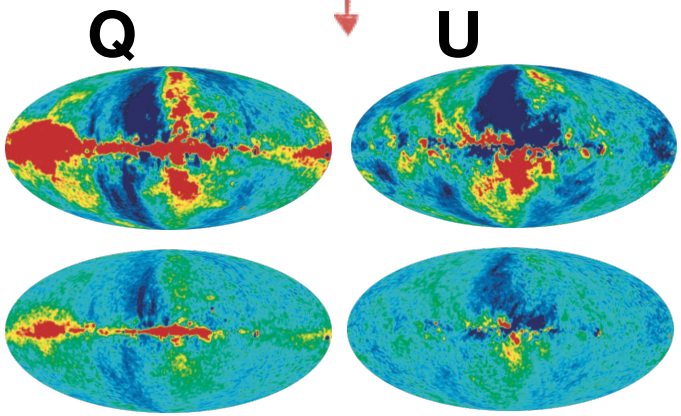
This plot shows LCDM E-modes with high s/n at three frequencies from data taken in a single season!

Add to BK data: Planck at 7 frequencies and WMAP at 2 frequencies



From arxiv 1502.01582

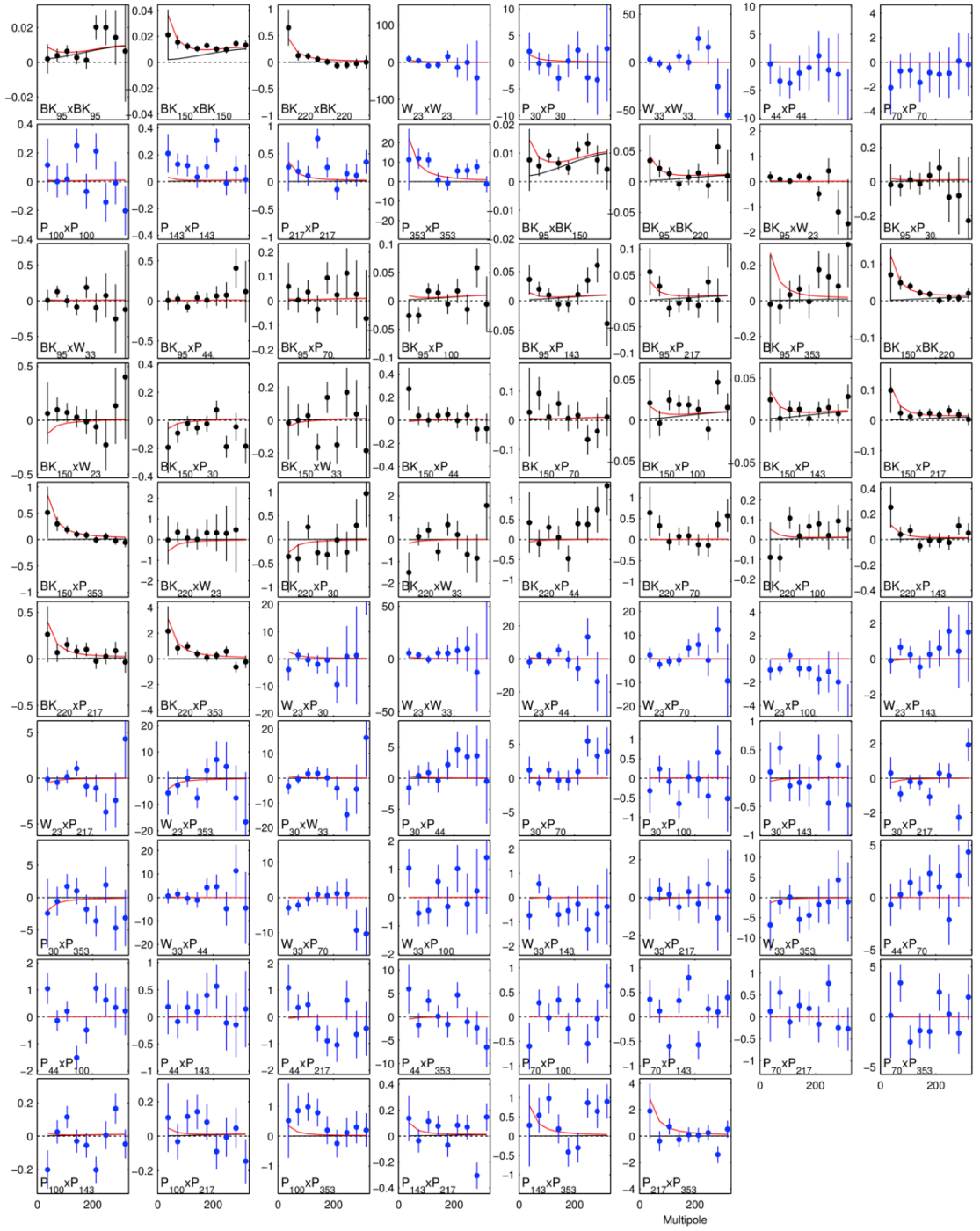
Polarized galactic **synchrotron** dominates at low frequencies



From arxiv 1212.5225

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

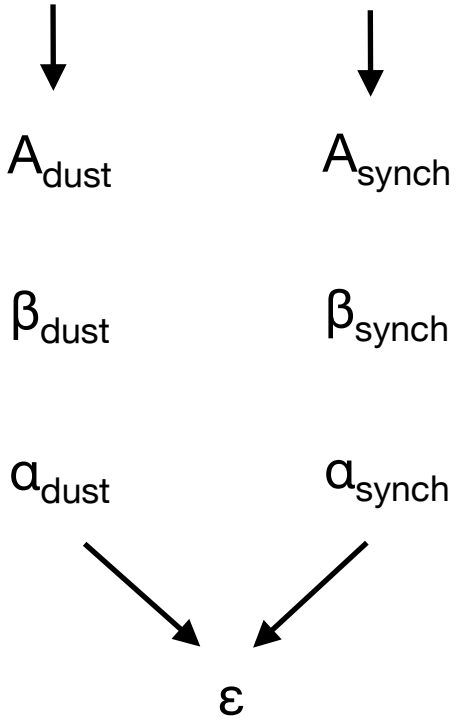
Current BK Analysis Technique: Take all possible auto- and cross spectra between the BICEP/Keck, WMAP, and Planck bands (78 of them) and compare to parametric model of CMB +foregrounds



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

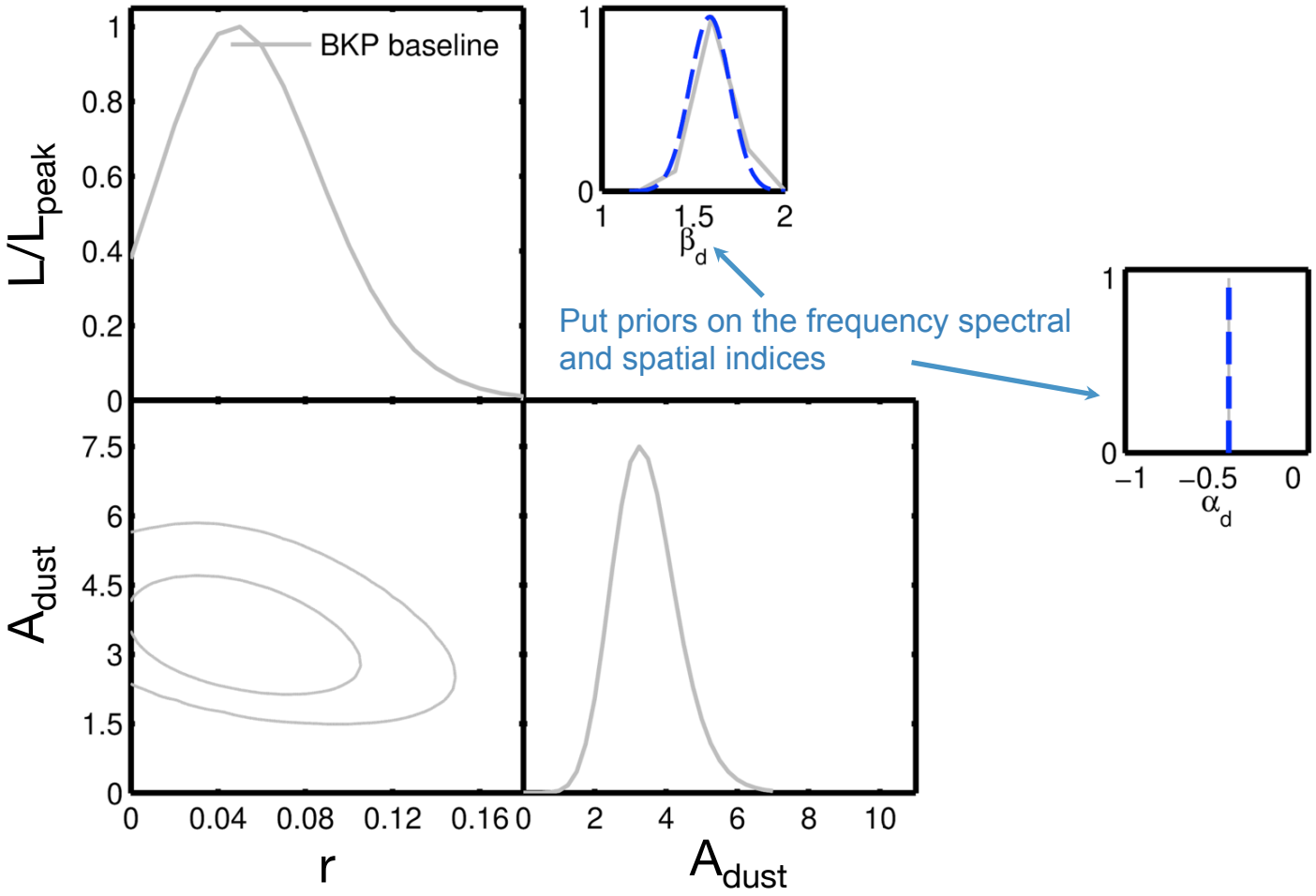


amplitudes @ l=80

frequency spectral indices

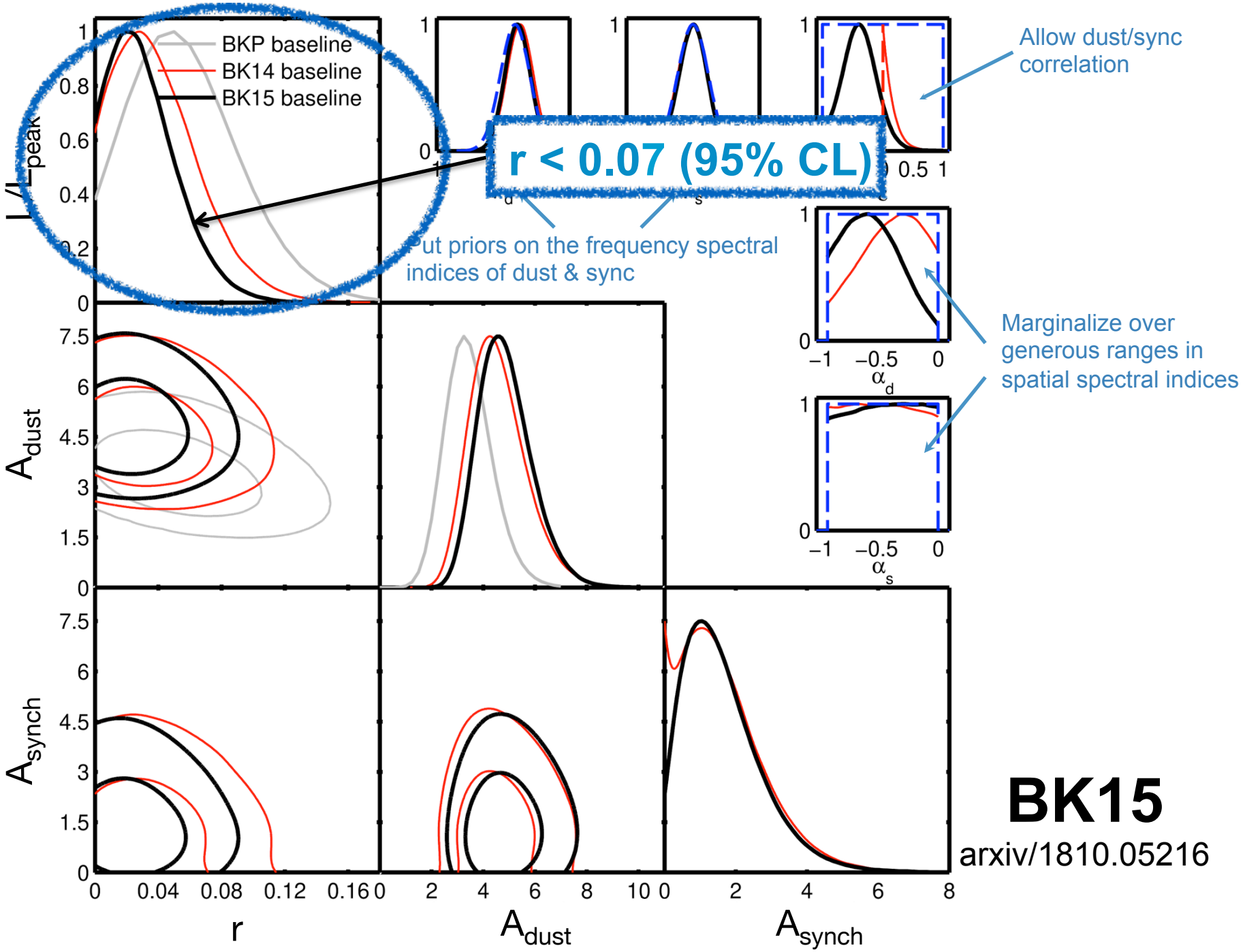
spatial spectral indices

dust/synch spatial correlation

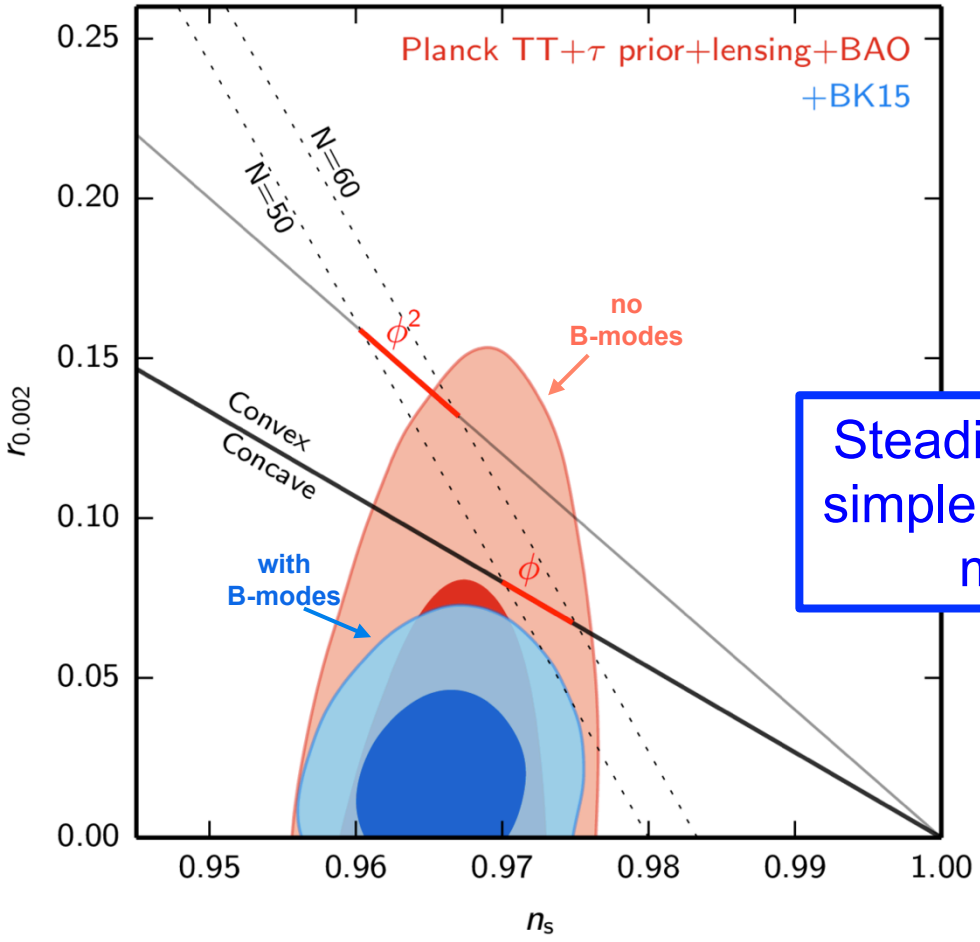


BKP

arxiv/1502.00612


BKP baseline
BK14 baseline
BK15 baseline
L/L_peak
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

Adding in Planck temperature data



Steadily ruling out simpler inflationary models

BK15

arxiv/1810.05216

r < 0.06

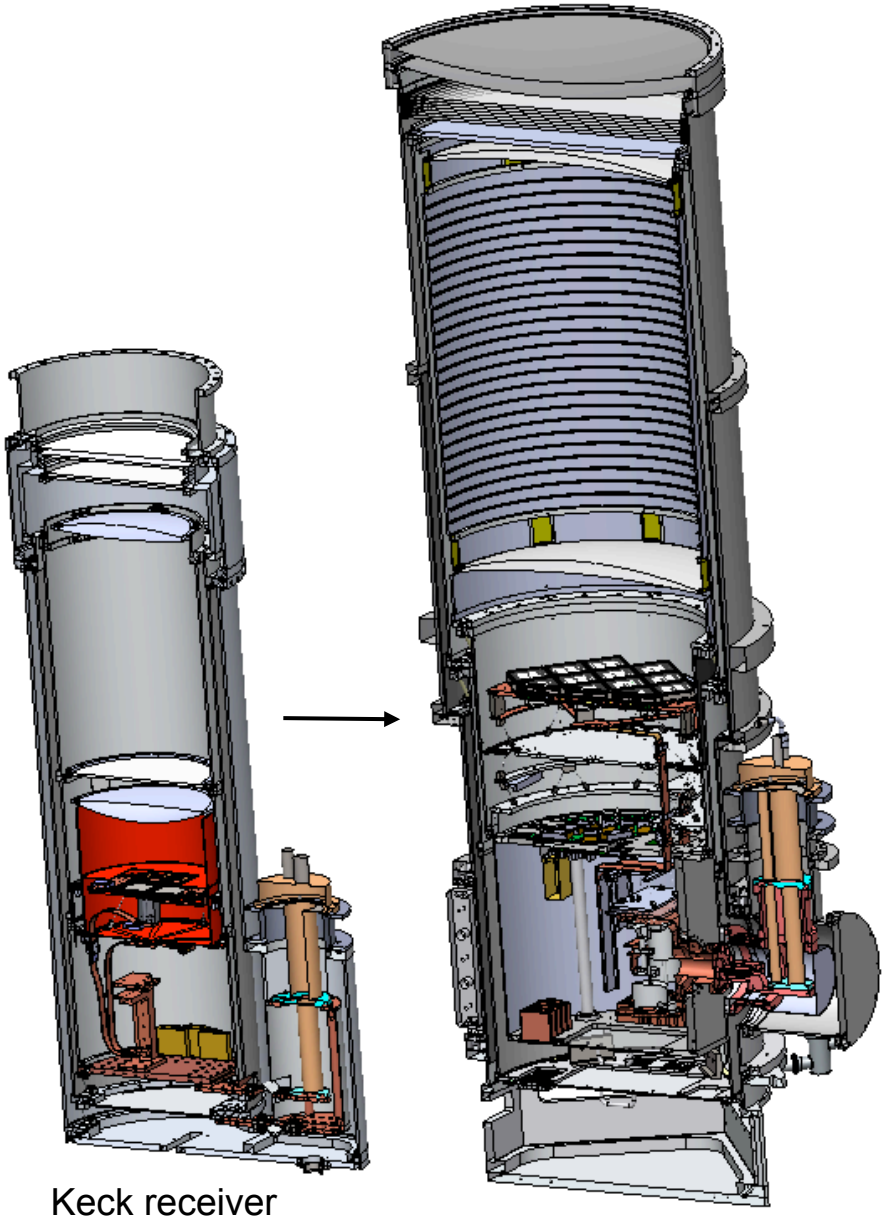
BICEP3: Next Generation Receiver

All 95 GHz

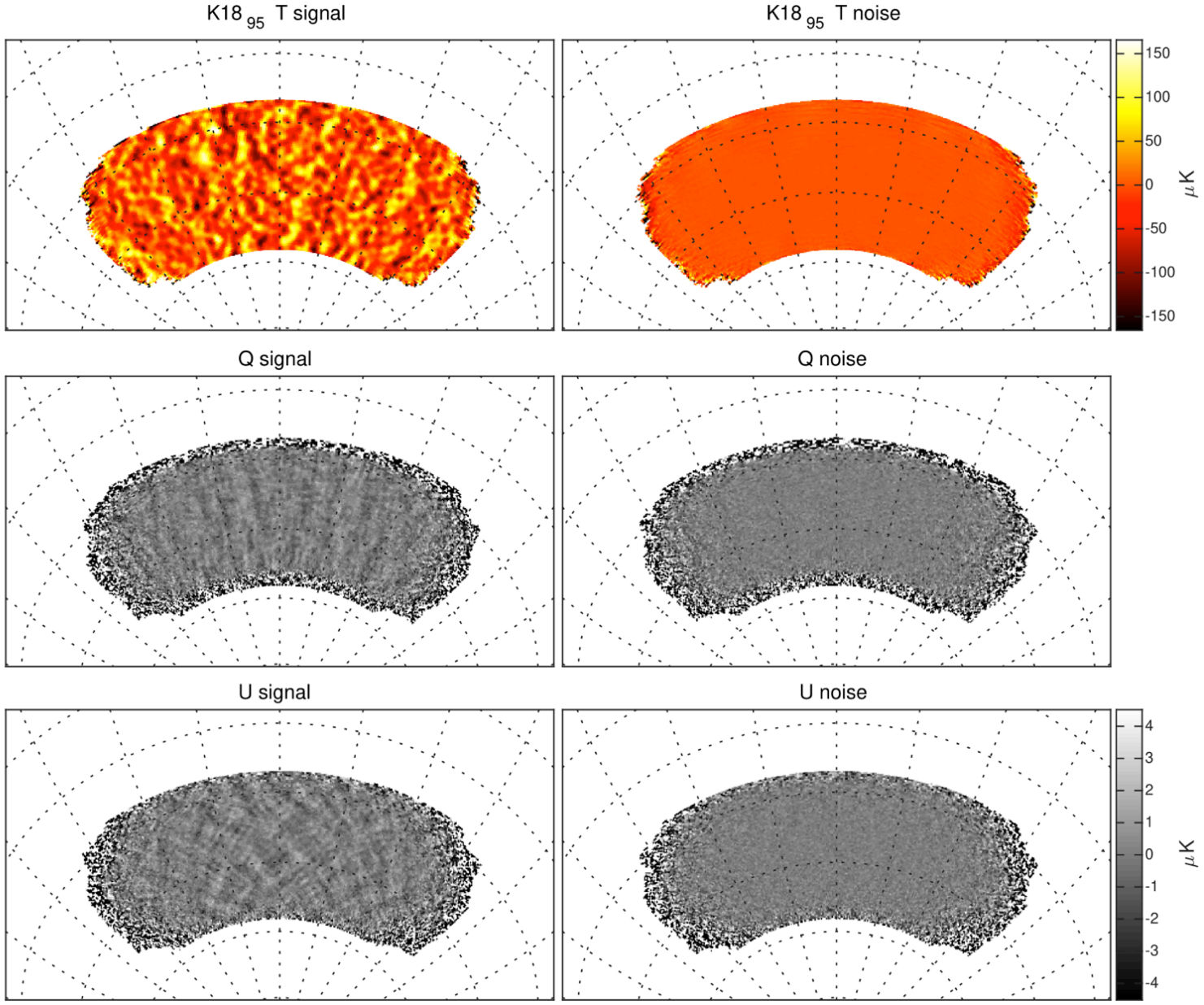
2500 detectors in modular focal plane

Large-aperture optics and infrared filtering

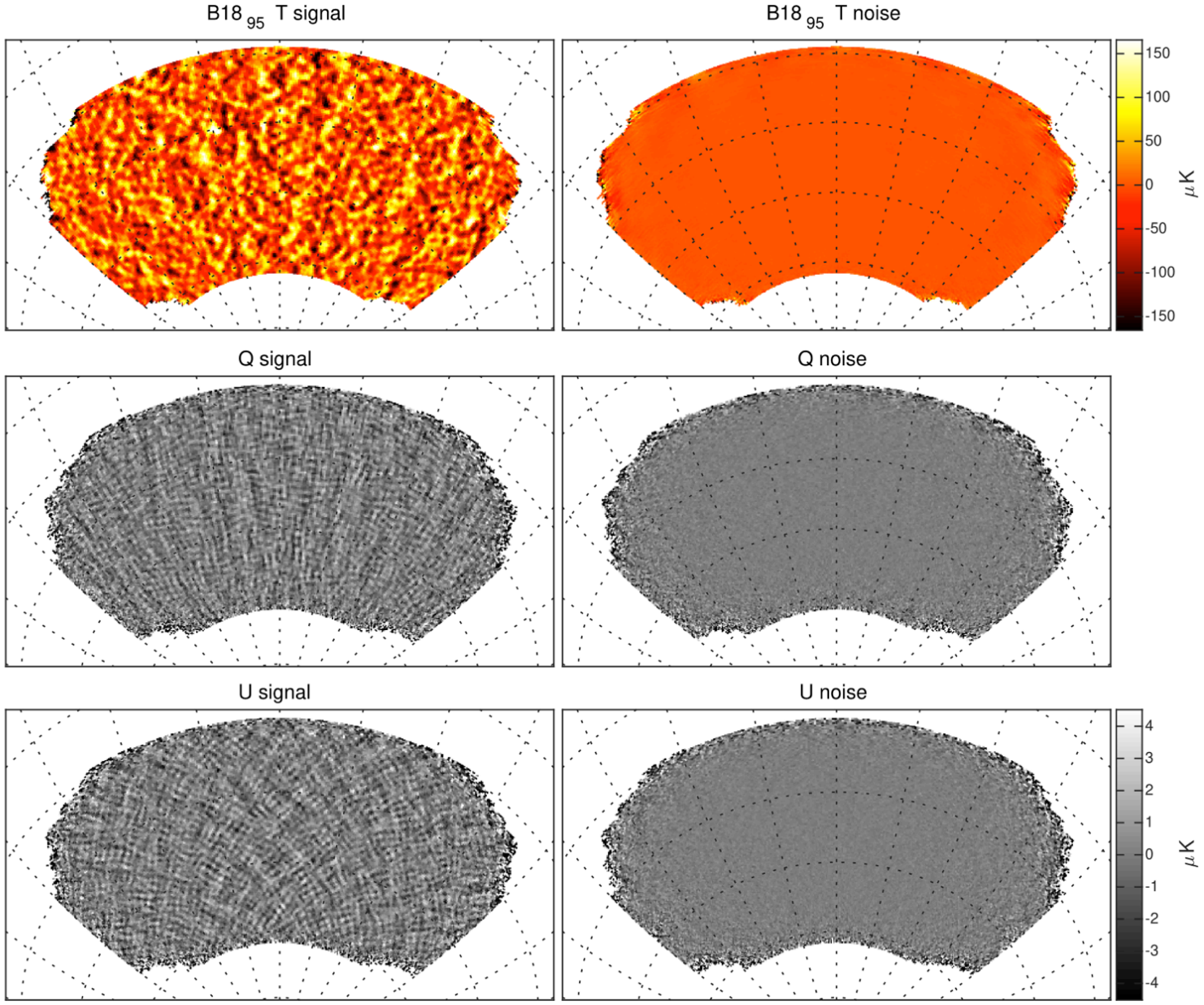
> 10x optical throughput of BICEP2/Keck receivers



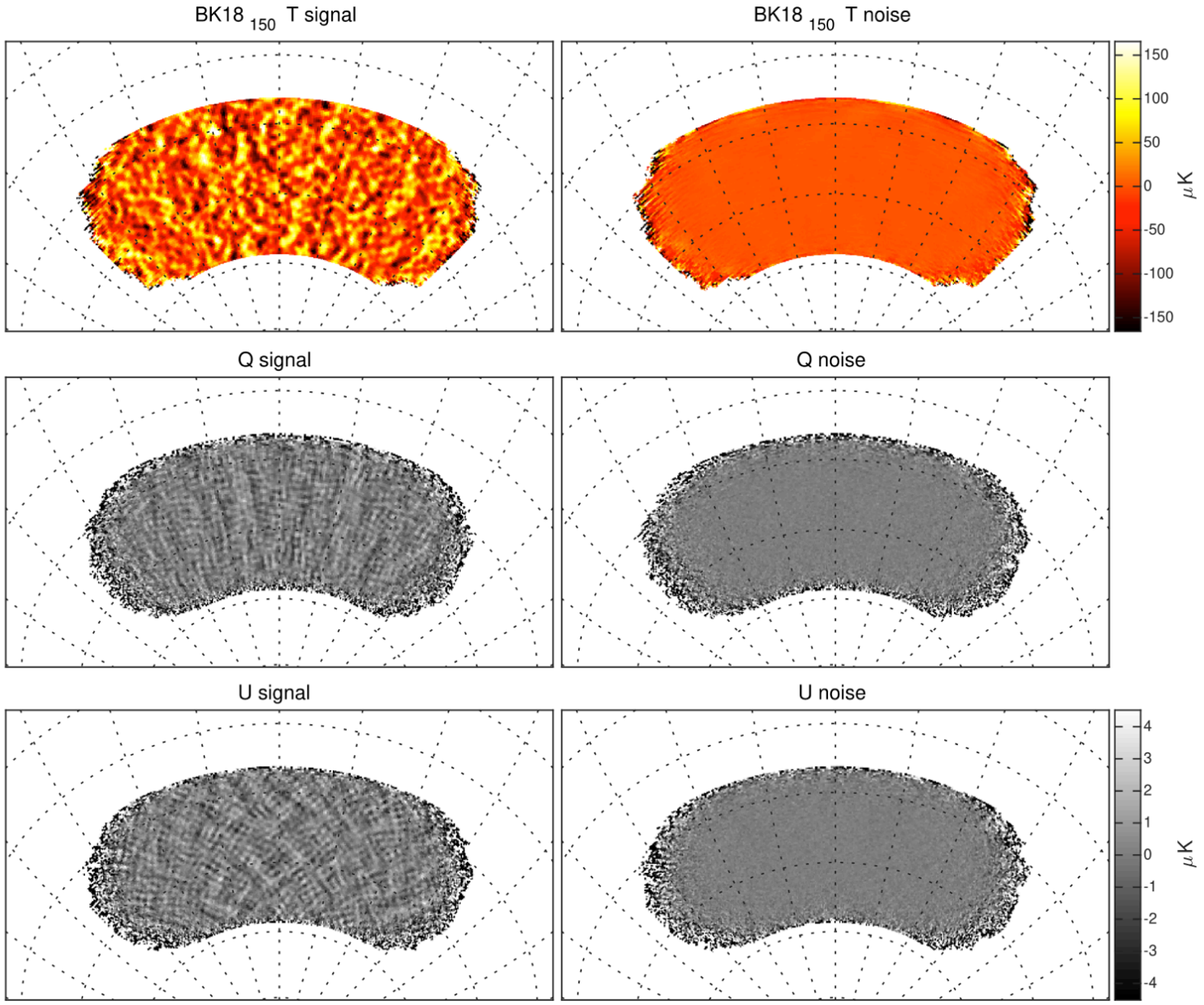
BK18 95GHz Map (*Keck*)



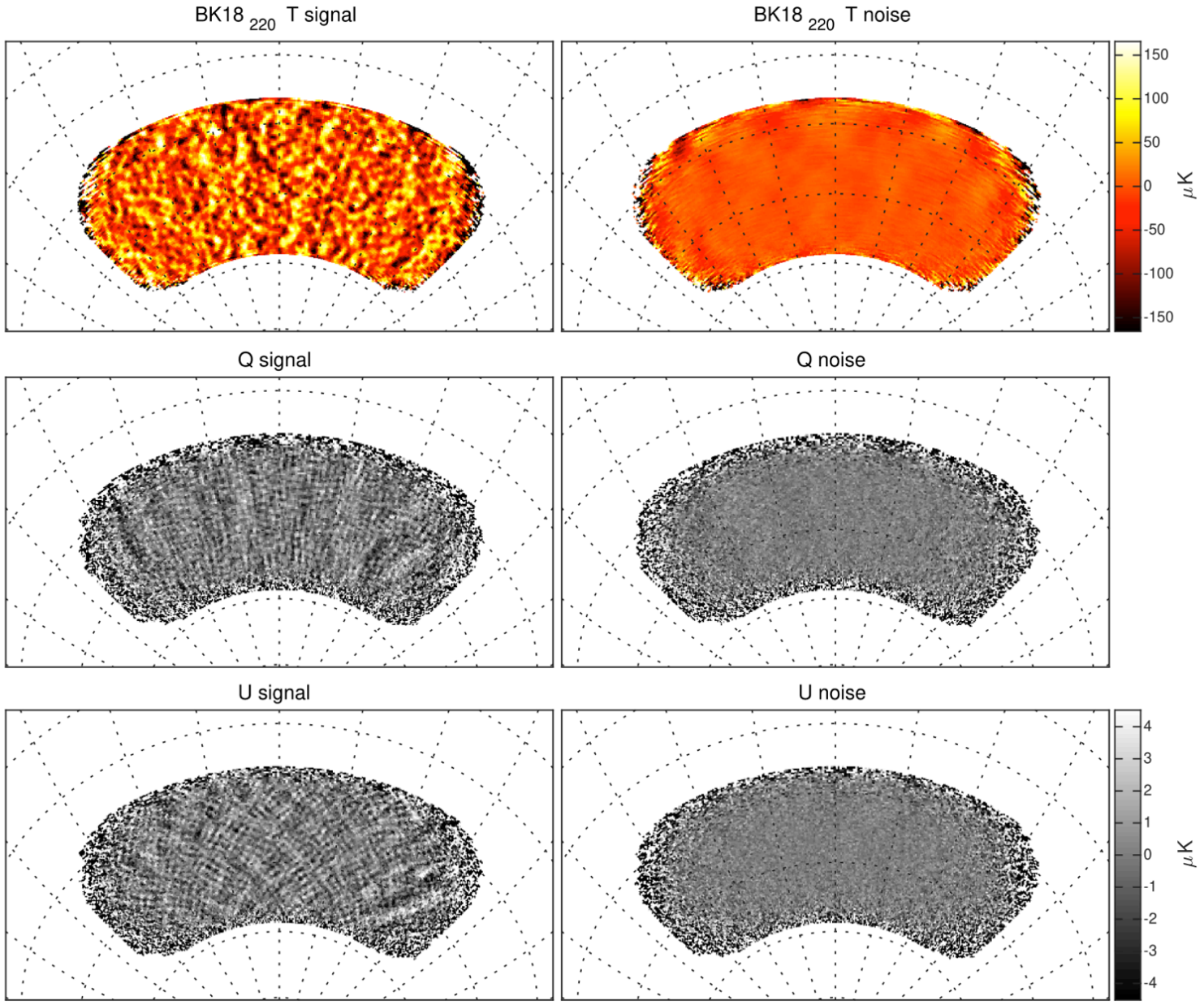
BK18 95GHz Map (BICEP3)



BK18 150GHz Map (BICEP2+*Keck*)

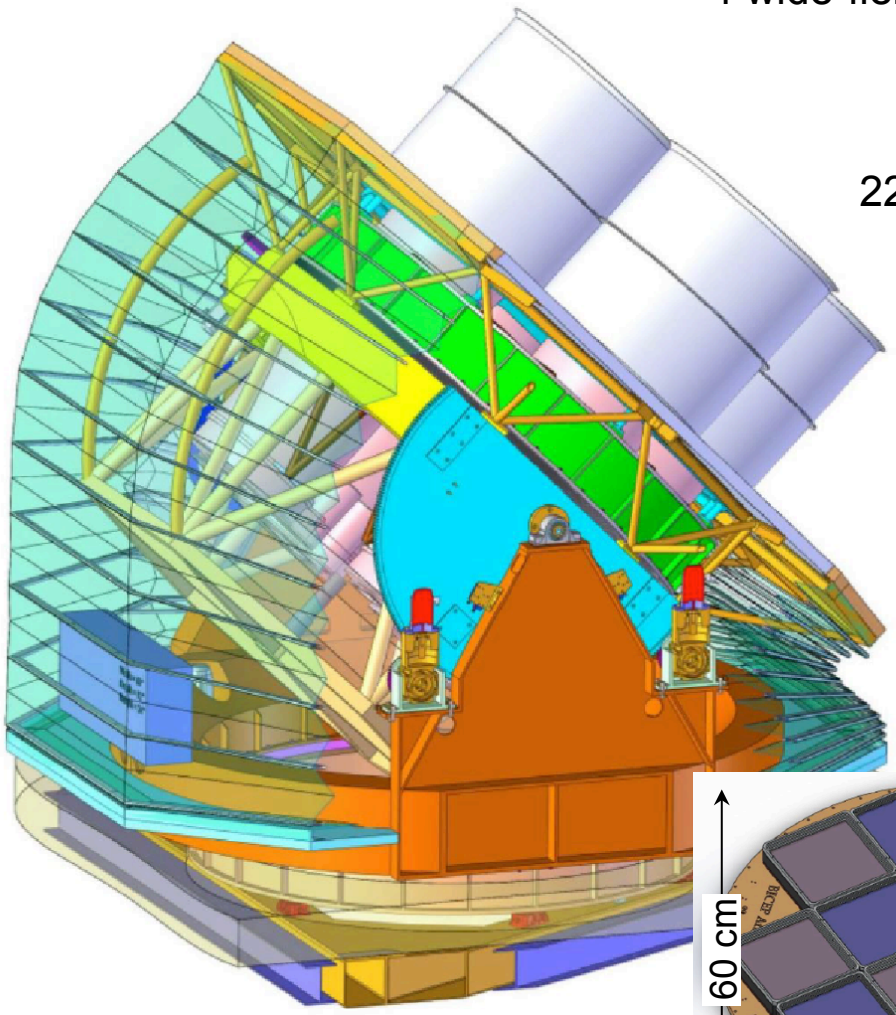


BK18 220GHz Map (*Keck*)

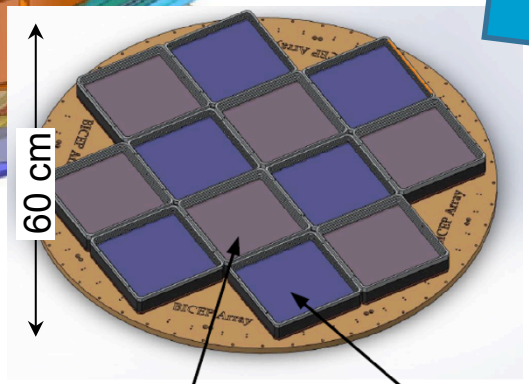


BICEP Array Under Construction

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

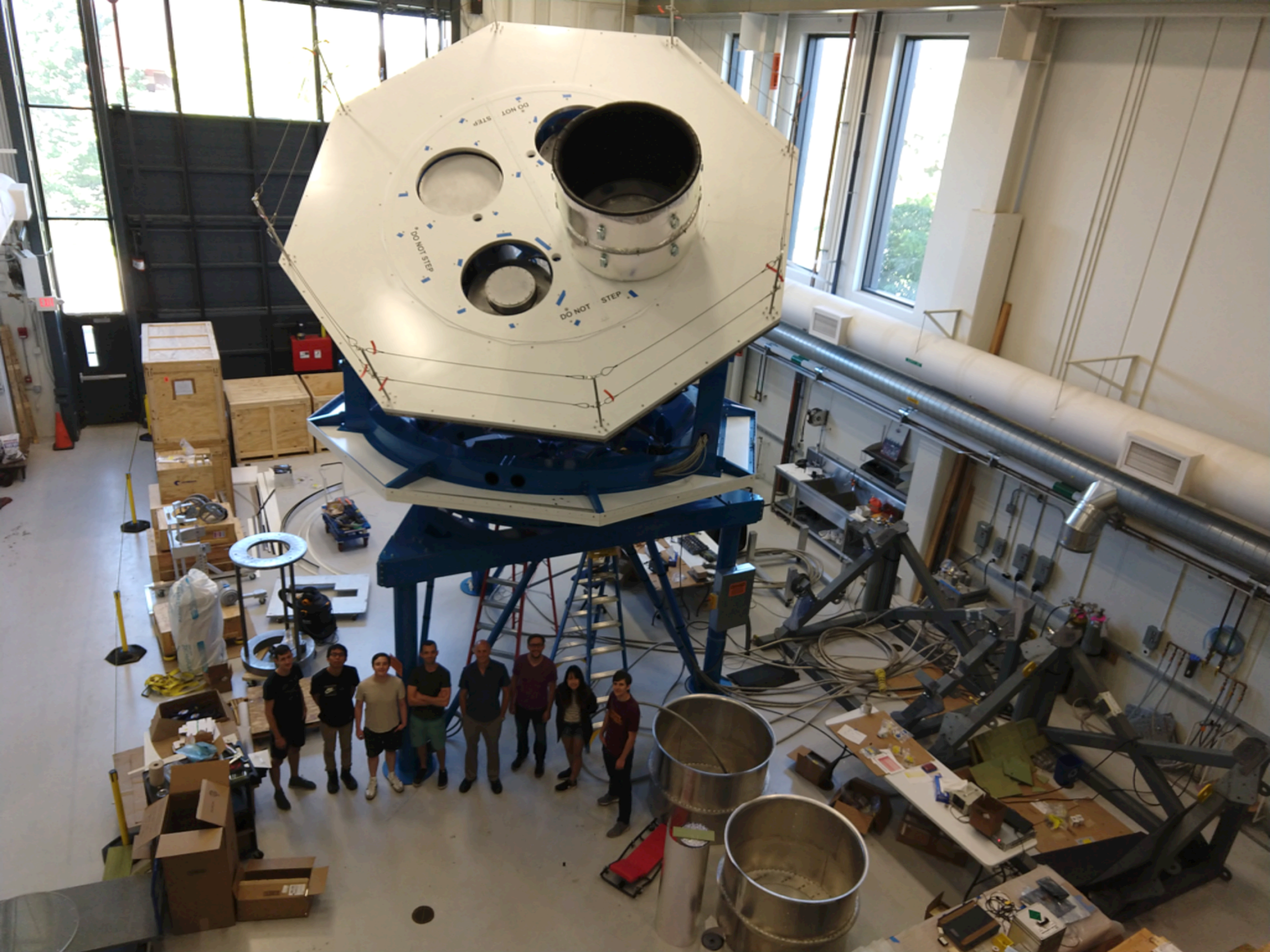


Wide-field cryogenic receiver



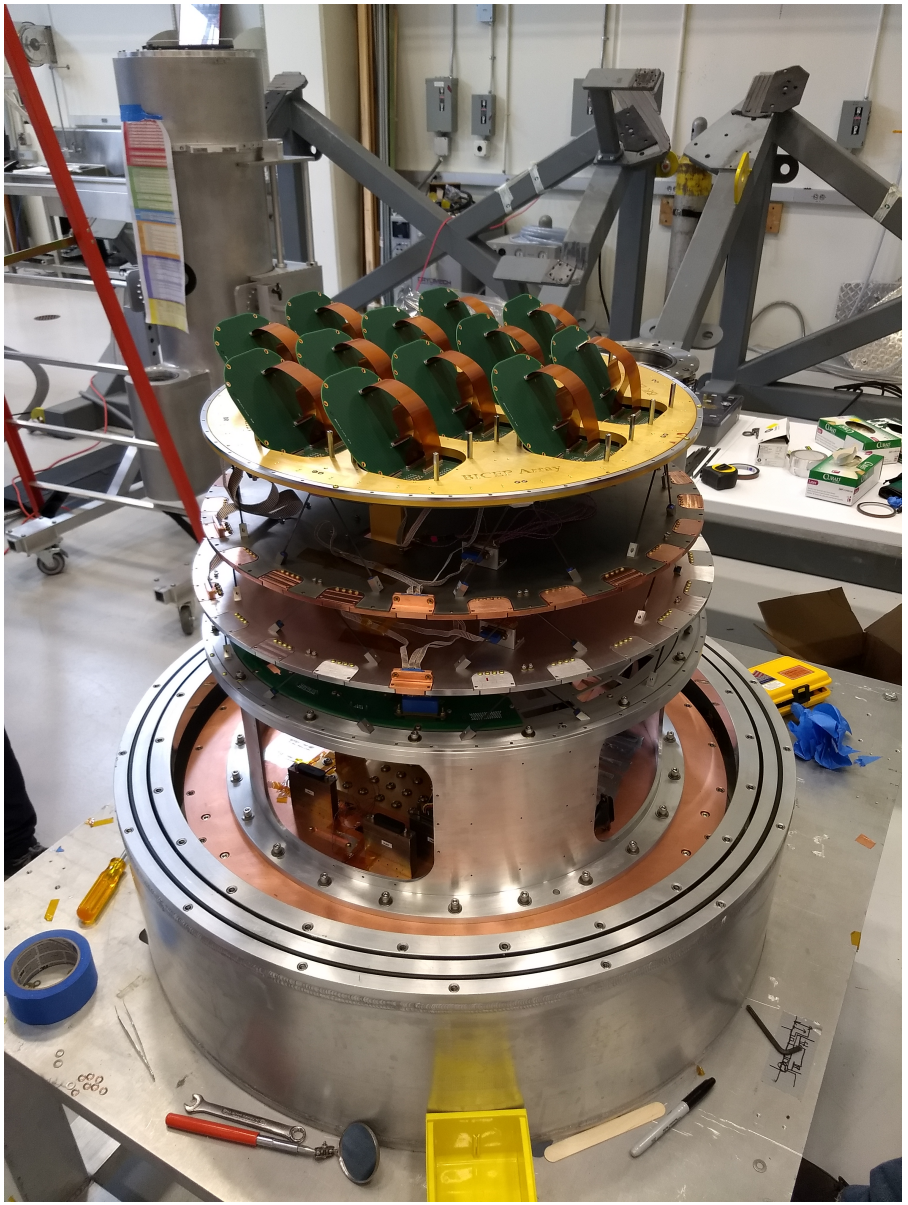
Focal plane layout

When complete >30,000 detectors

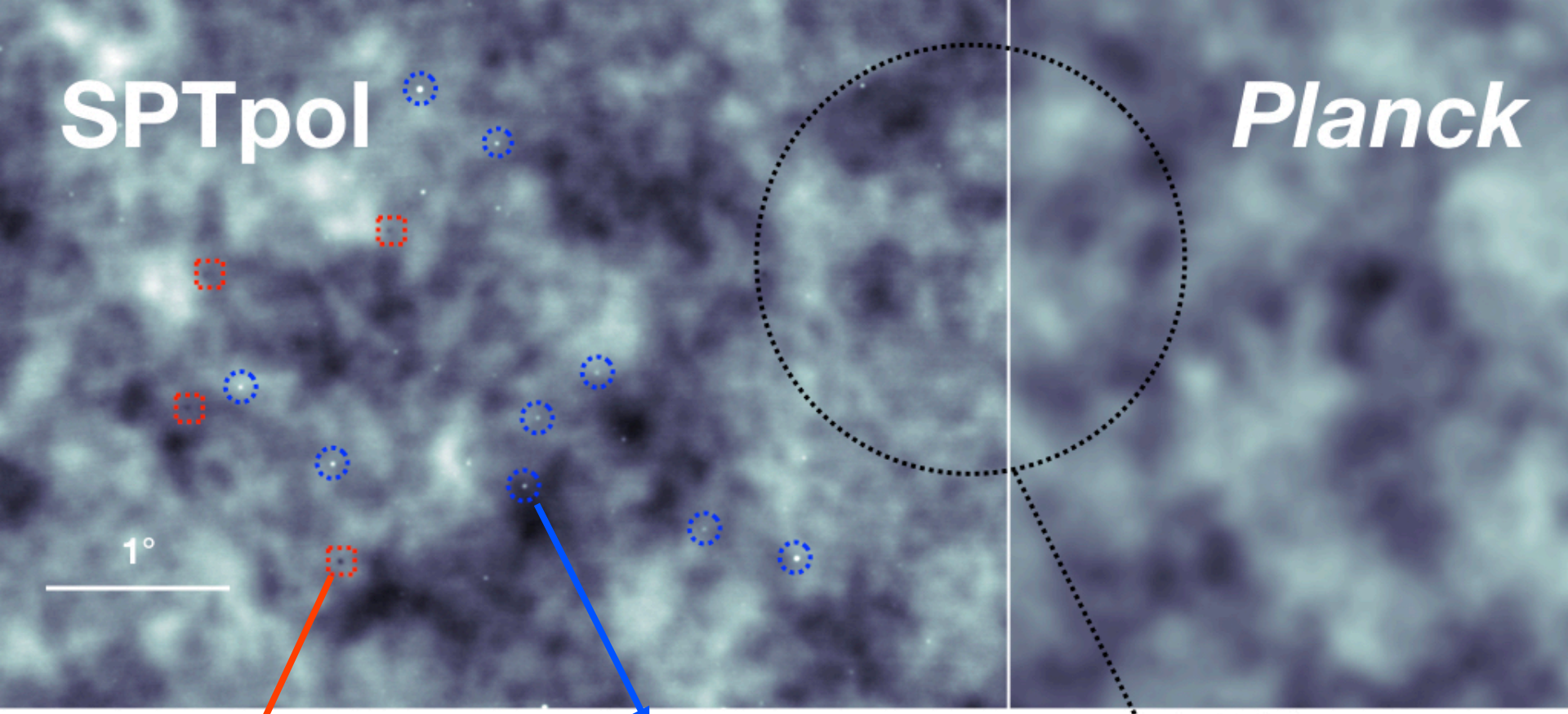

DO NOT STEP
DO NOT STEP
DO NOT STEP

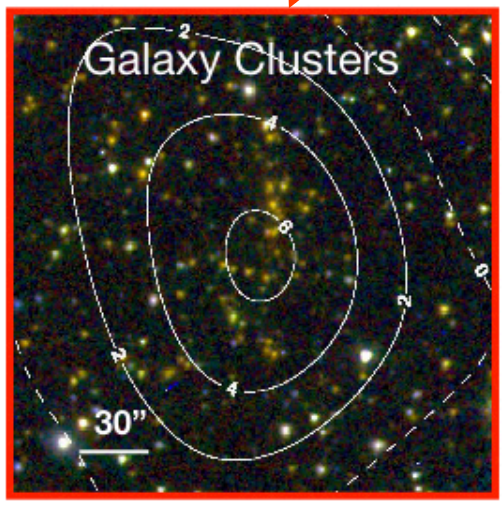
New mount about to ship from UMN to Pole

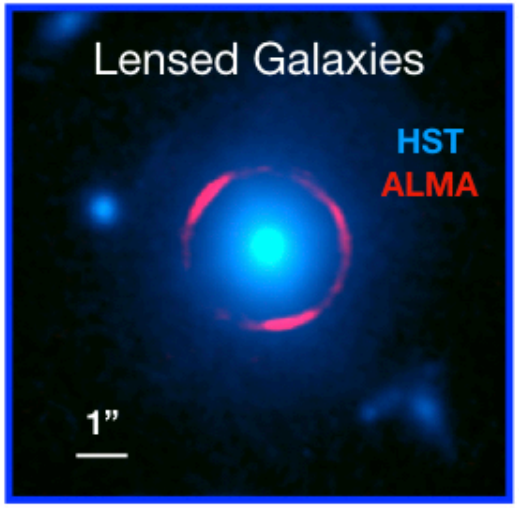
Lots of new hardware

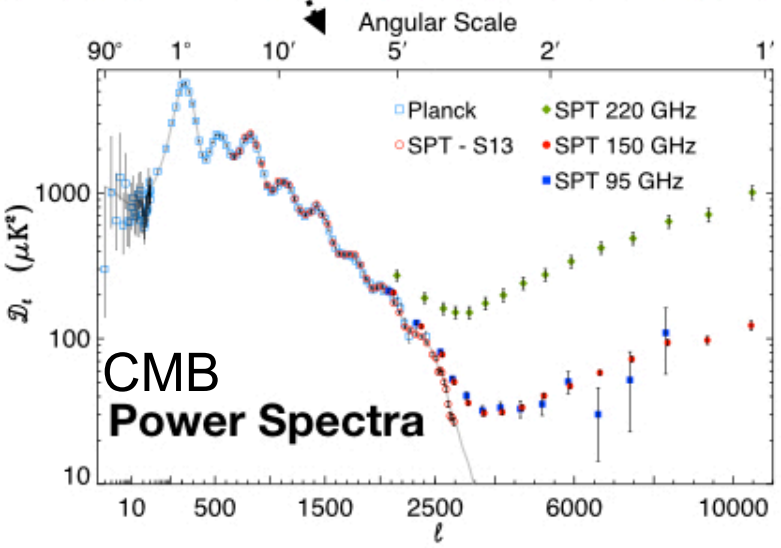


SPT Existing Results and Ongoing SPT-3G Observations

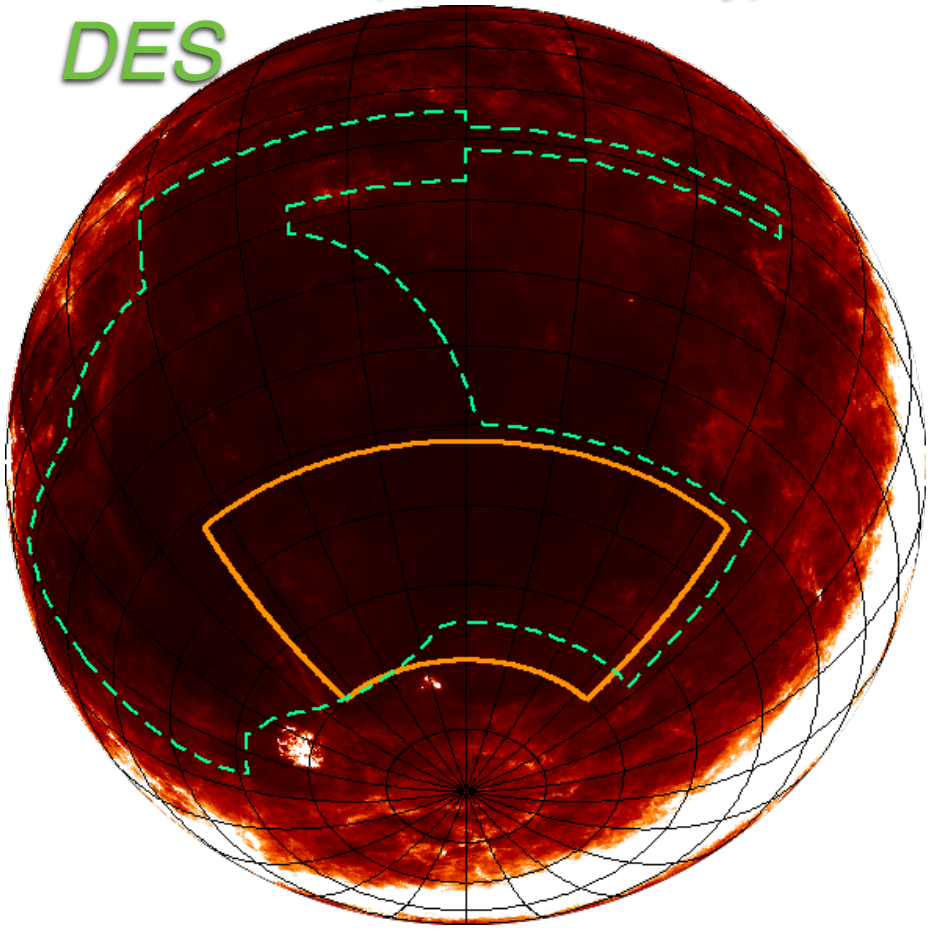

SPTpol
Planck
1°


Galaxy Clusters
30”


Lensed Galaxies
HST
ALMA
1”

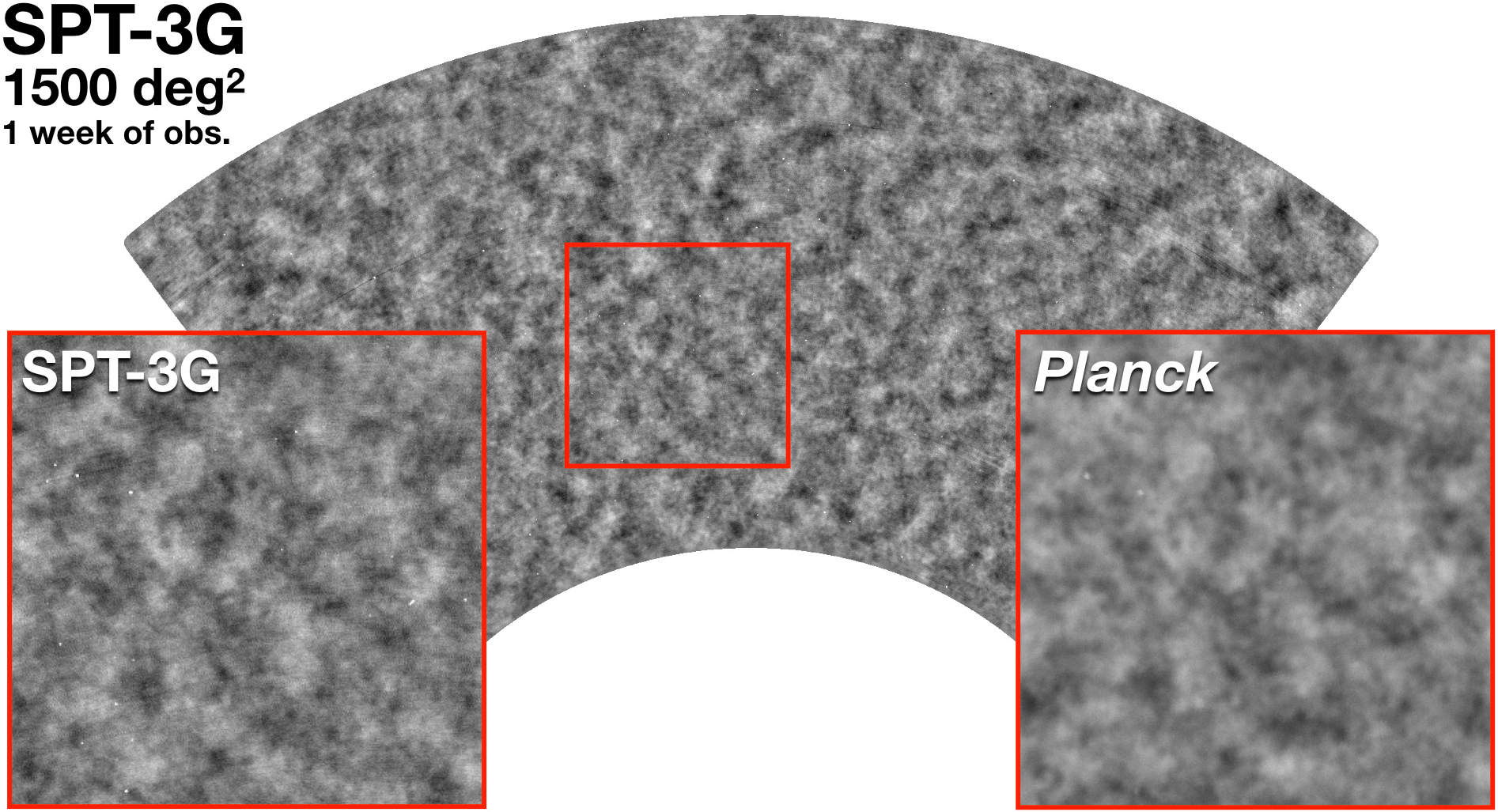

Angular Scale
90°
1°
10′
5′
2′
1′
Planck
SPT - S13
SPT 220 GHz
SPT 150 GHz
SPT 95 GHz
1000
100
10
$\mathcal{D}_\ell$ (μK^2)
CMB
Power Spectra
10
500
1500
2500
6000
10000
ℓ

The SPT-3G 1500 deg^2 Survey



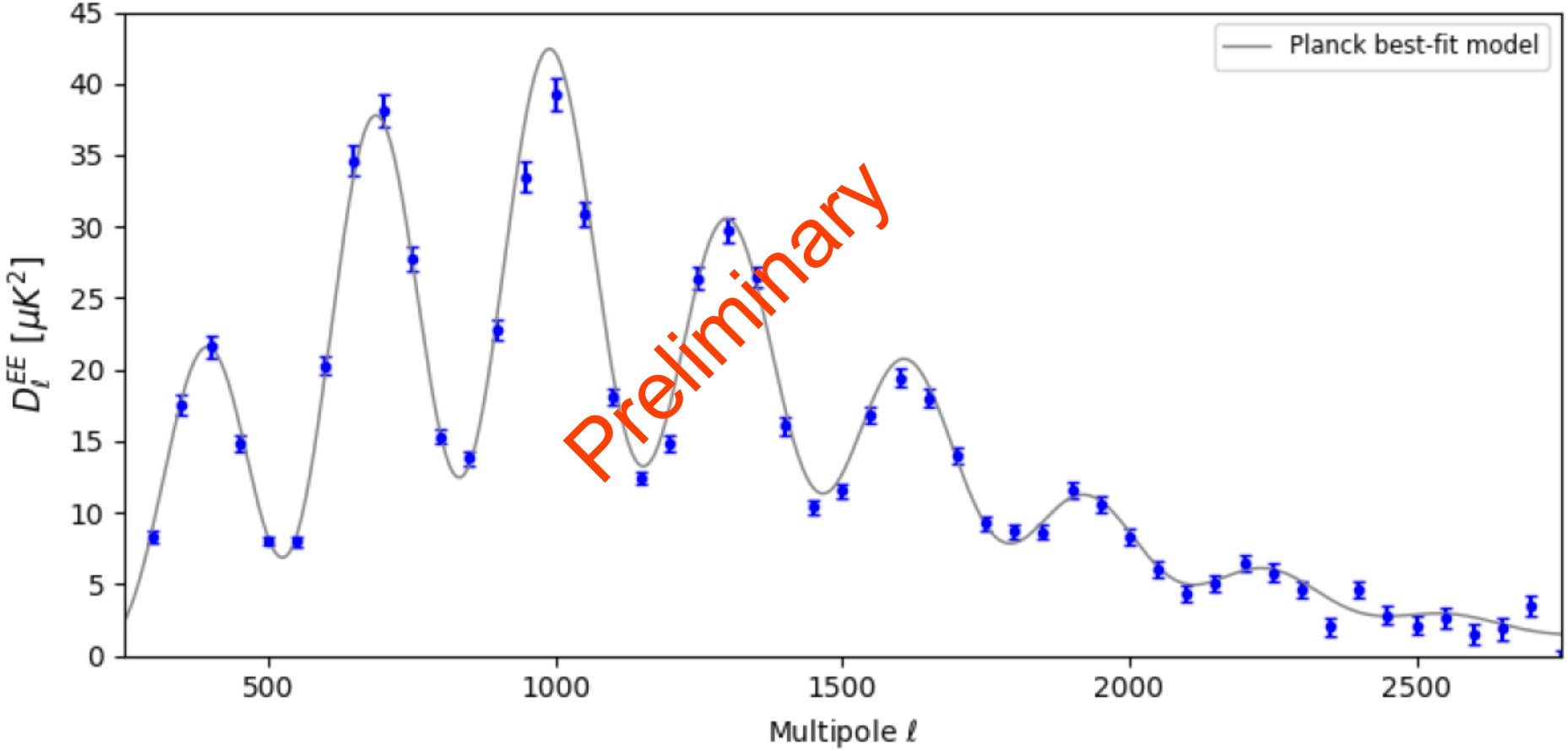
- *SPT-3G 1500 deg2 survey will be ~10x deeper than SPT-SZ*
- *Overlaps with BICEP-array to optimize Inflation/r constraint using CMB-de-lensing*

	Obs. Years	Area (deg^2)	95 GHz (uK-arcmin)	150 (uK-arcmin)	220 (uK-arcmin)
SPT-SZ	2007-11	2500	40	17	80
SPTpol-500d	2012-16	500	13	5	-
SPTpol-100d	2012-16	100	10	4	-
SPTpol-2700d	2012-16	2700	47	28	-
SPT-3G (projected)	*2018-23*	*1500*	*3.0*	*2.2*	*8.8*



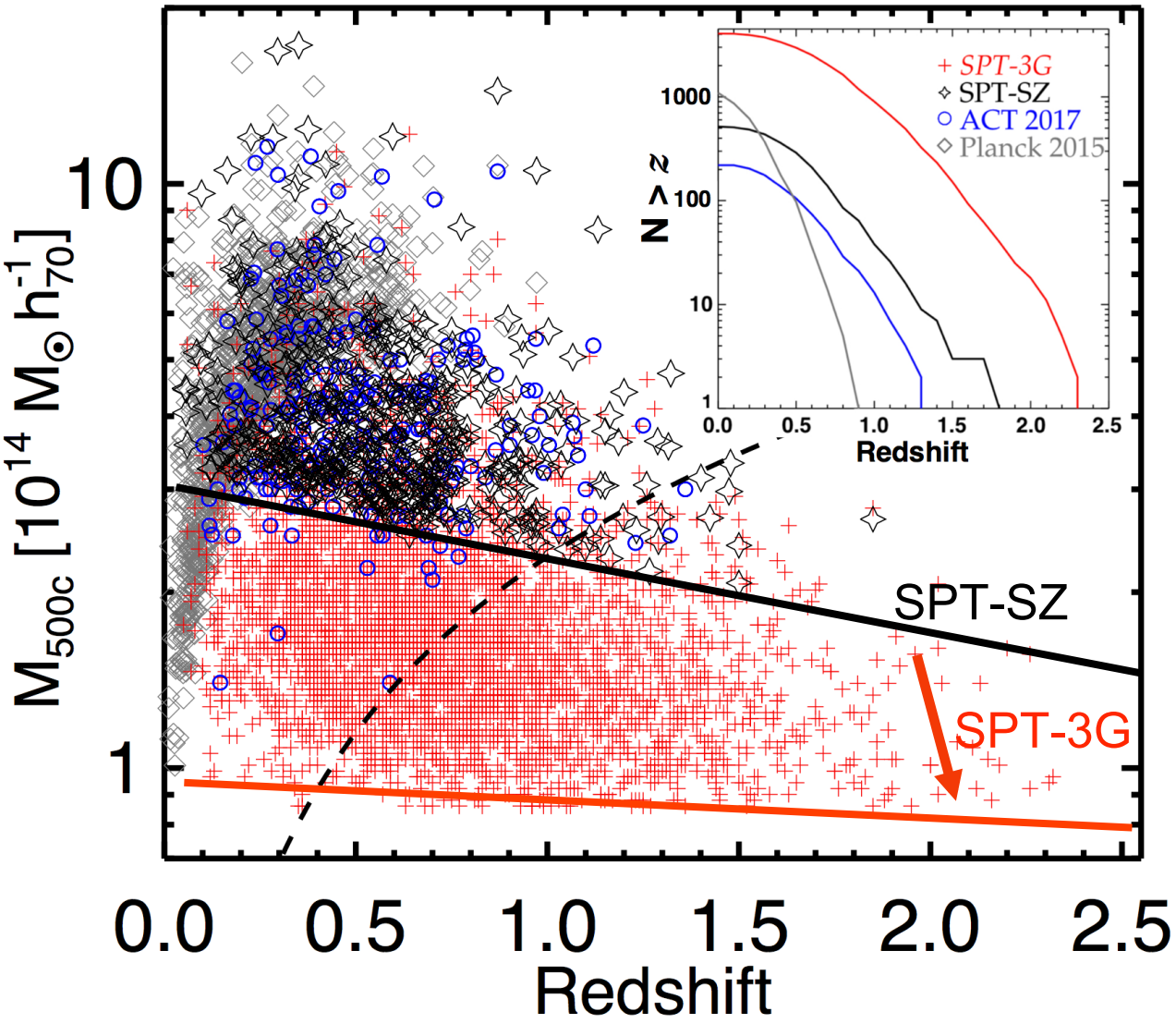
- ***SPT-3G data gets to ~Planck depth on 1500d field with a ~week of data.***
- ***Observe 1500d field every ~2 days for 6 years***

SPT-3G: 2018 EE Power Spectrum



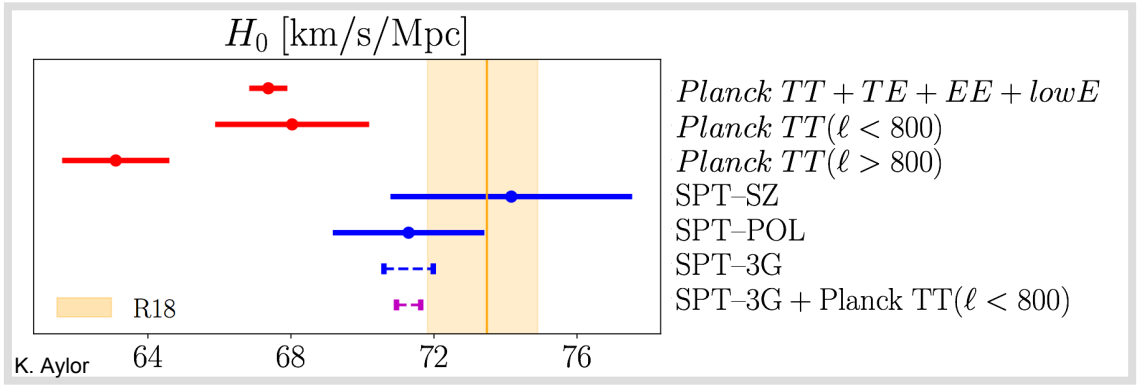
- ***Using 2018 150 GHz data, SPT-3G is the most sensitive measurement of the CMB EE polarization spectrum from 700 < ℓ < 1700***

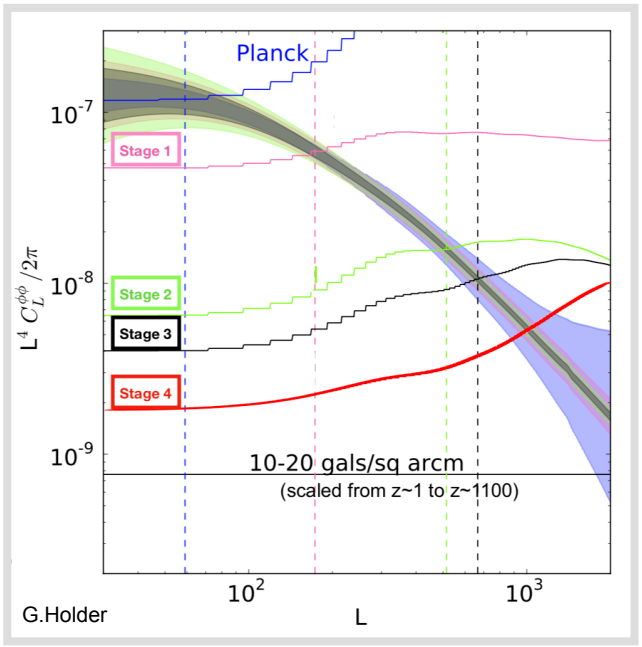
SPT-3G (Forecast): Cluster

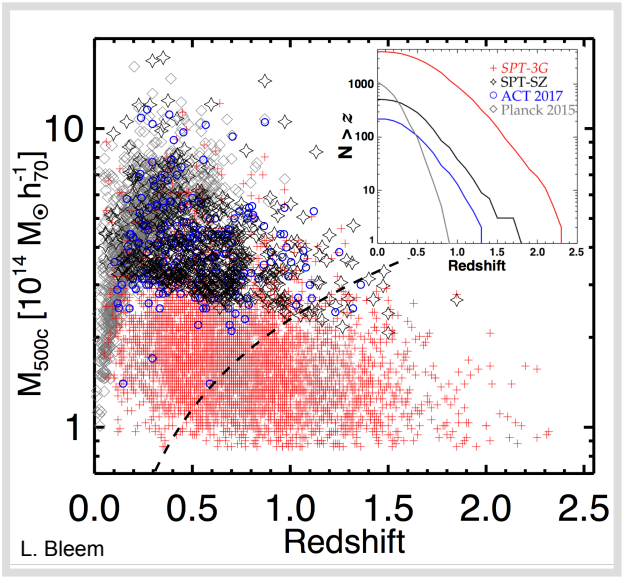


- SPT-3G mass limit will be ~10^{14} M_{sun}
  - ~3x lower than SPT-SZ survey
  - Deep 3-band data enables check of astrophysical confusion
- ***At z > 1: Nearly 1000 clusters!***
  - At z > 2: ~10s of clusters?

SPT-3G: Cosmology & Astrophysics





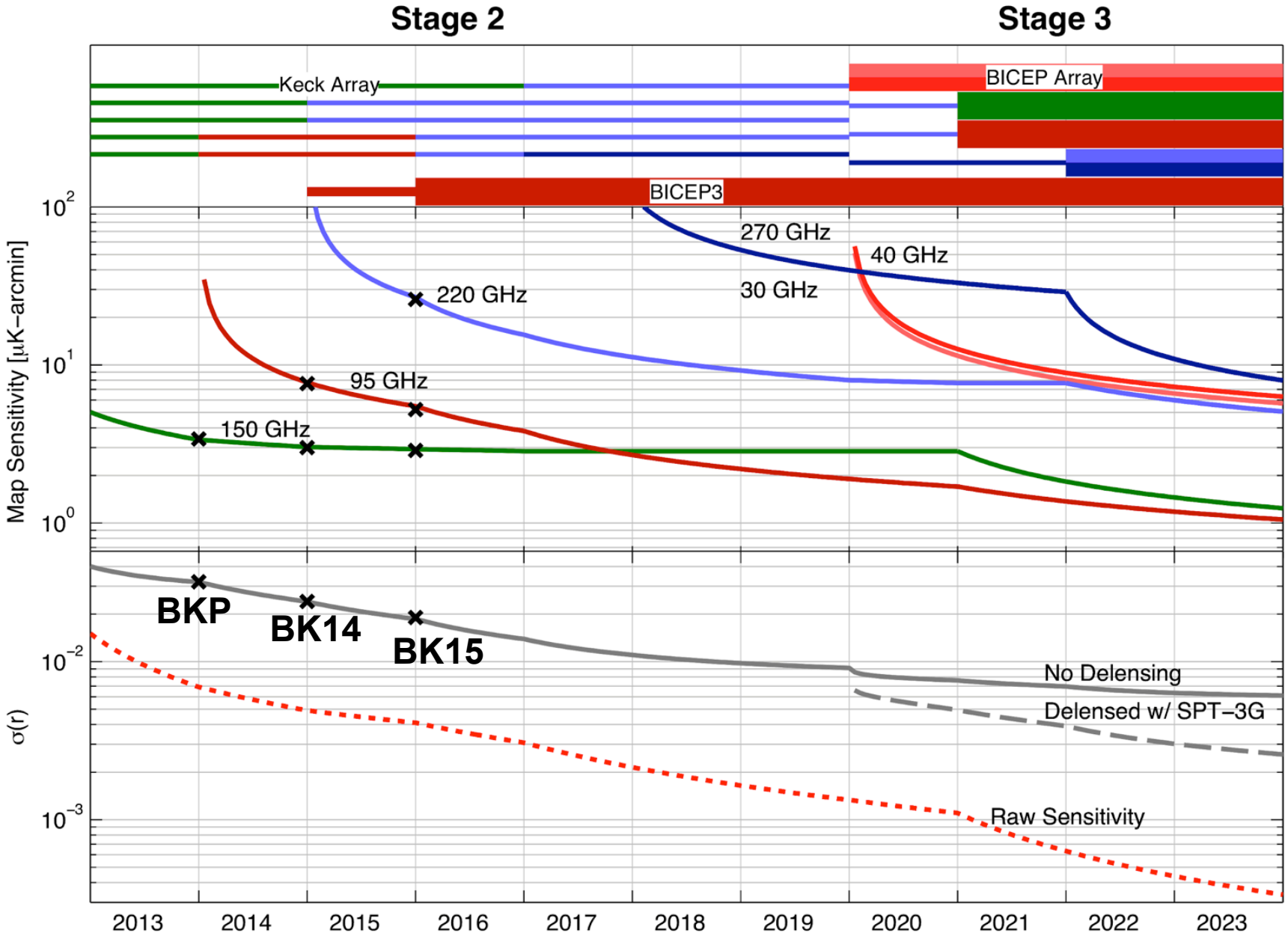


Deep survey complements measurements from a wide survey. For SPT-3G:

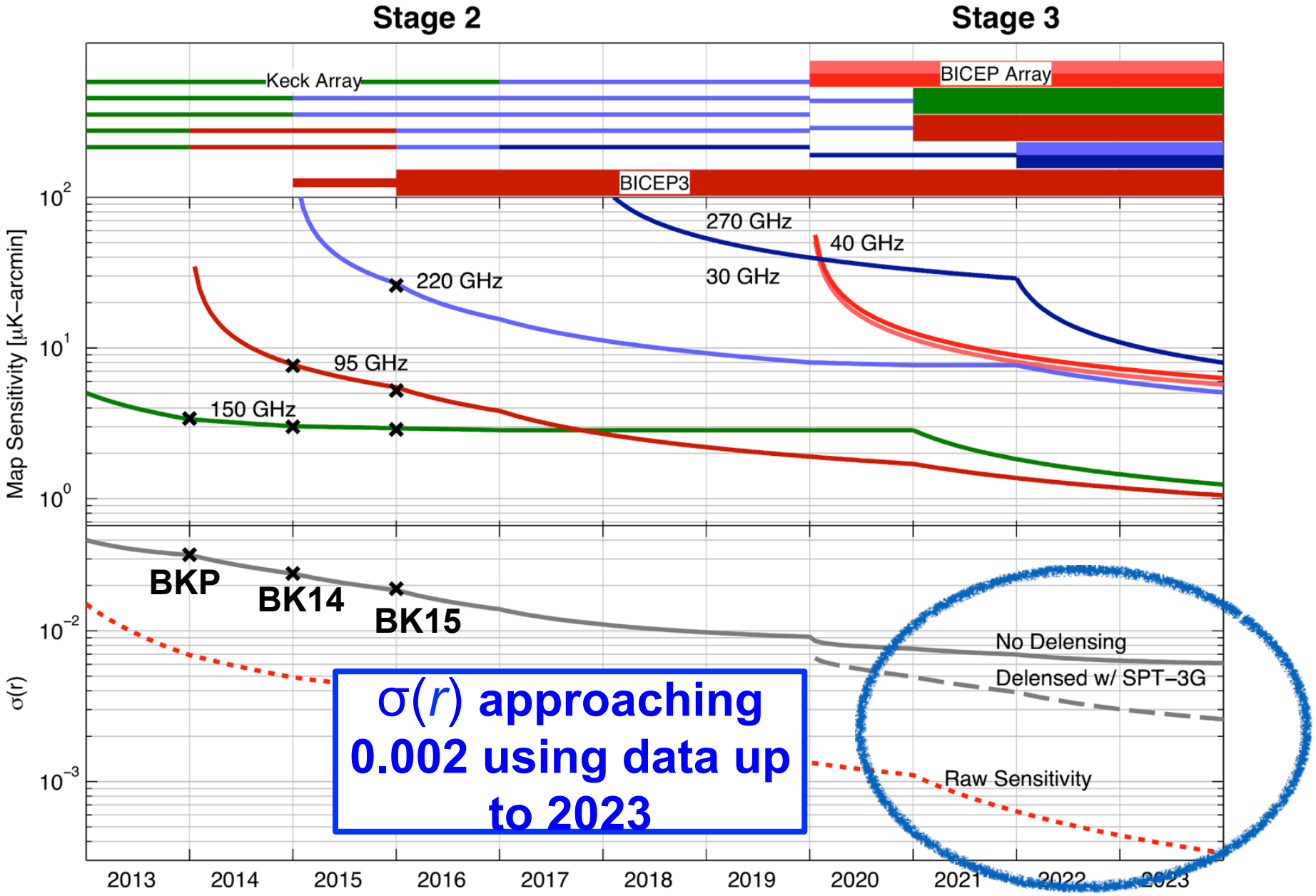
- ***Damping Tail Physics:*** *Improve S/N of CMB power spectra by factors of > ~10 at ℓ>2500 versus current measurements*
- ***CMB lensing:*** *Maps have similar S/N to LSST in broad tomographic bins*
- ***Clusters:*** *More efficient at finding high-z clusters, discovering clusters at z > 2, proto-clusters out to z > 4*
- ***Transients:*** *Daily observations of 1500 deg^2 field provide new window into mm-wave transients (e.g., GRBs, FRBs), and mJy-level monitoring of 1000s of blazars*
- ***and more!***

Breaking through the lensing floor – The need to jointly analyze BK and SPT

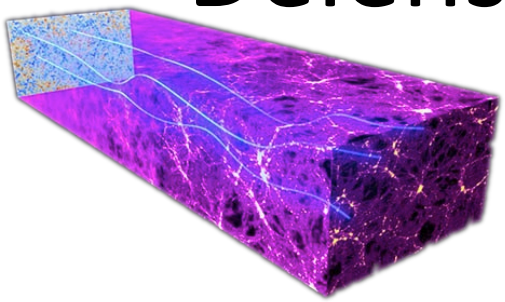
BICEP/Keck/SPT-3G Projections

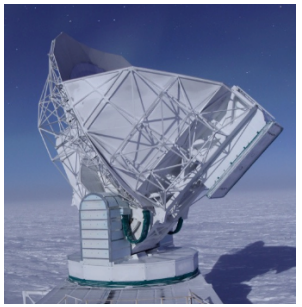


BICEP/Keck/SPT-3G Projections

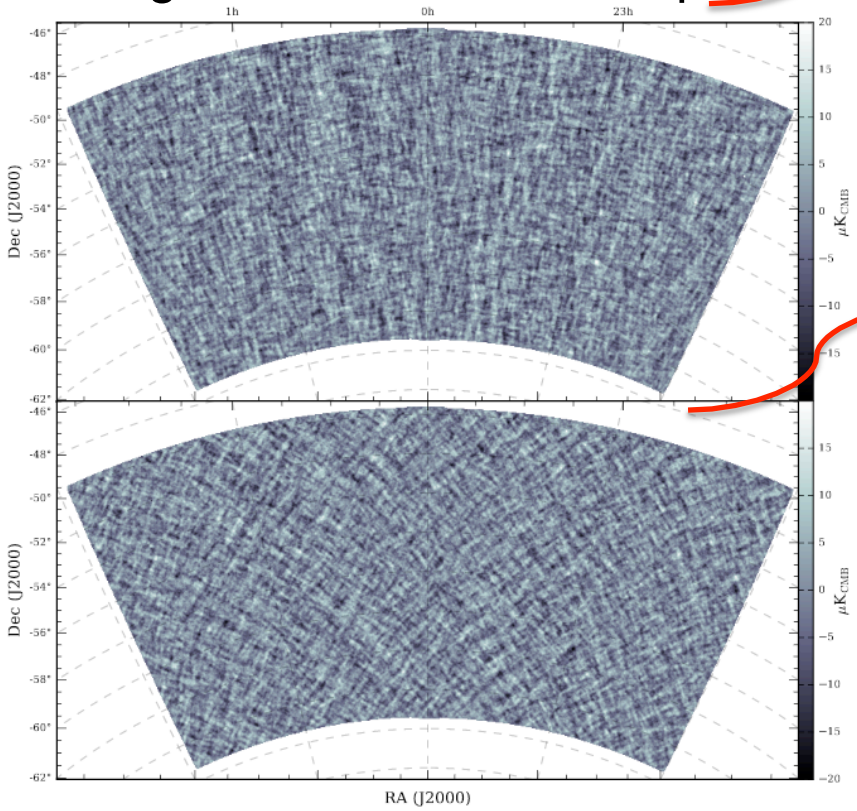


Delensing with SPT-3G data

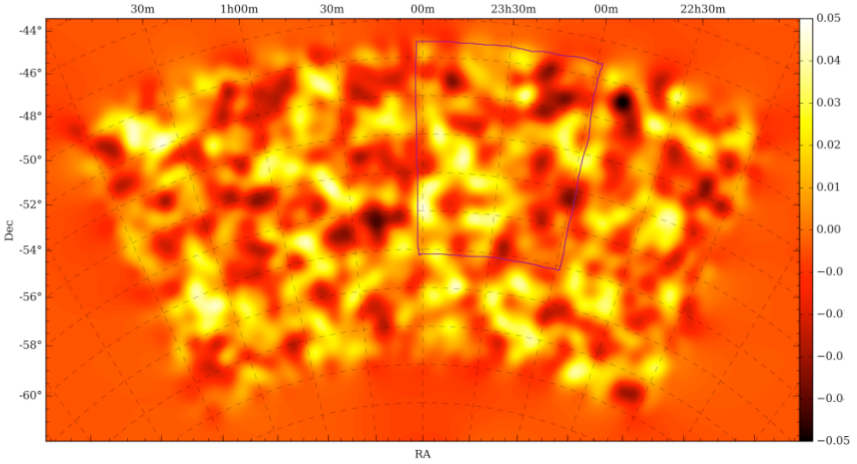




High resolution CMB maps



Can be used to reconstruct the lensing deflection field…



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

BKSPT Delensing

- BICEP/Keck will soon hit the “lensing wall”
- Joint analysis with SPT3G can break through this – the *r* science demands joint analysis
- Preliminary BK14+SPTpol+CIB analysis has been developed and is nearly ready for publication
- Recent MSIP includes funding to develop BK+SPT3G analysis

The SPO

Convergent science prompts us to form the South Pole Observatory:

- SPO is a new entity to guide the development of the combined South Pole CMB program to produce the highest possible science return.
- SPO builds on existing collaboration between the BICEP/Keck and SPT programs, increasing coordination of their Stage 3 activities.
- SPO serves as an umbrella organization, coordinating ongoing projects and leading new initiatives for infrastructure and science.
- SPO and the SPT and BICEP/Keck South Pole CMB projects are committed to support CMB-S4 by freely sharing the data and lessons learned from ongoing and new Stage 3 observations needed for S4's design, and by continuing to develop the infrastructure and methods CMB-S4 will need.

Opportunities for additional collaboration within SPO may include:

- Contributions to infrastructure at Pole - towers/telescopes etc. (see e.g. JC's talk next)
- Involvement with analysis work including joint projects
- Talk to us!

Backup Slides

What is SPO?

From an LOI to the CMB-S4 leadership:

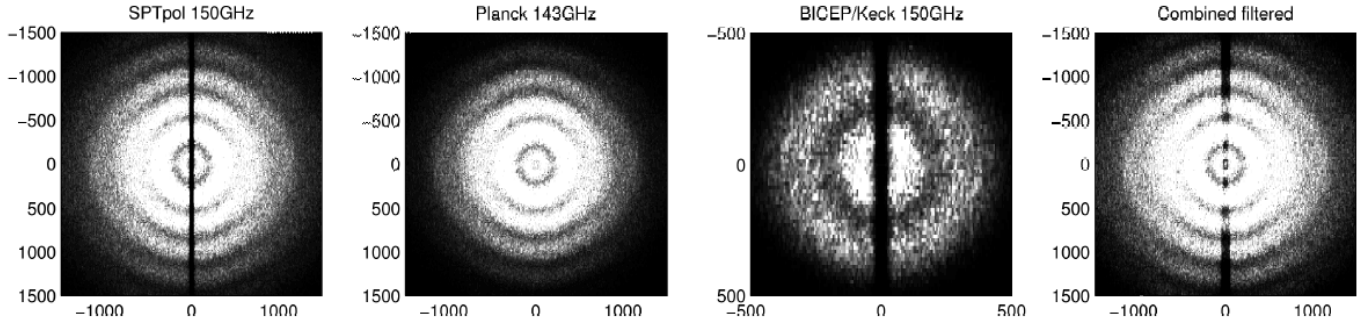
“We are increasing the coordination of the South Pole CMB program through the formation of a South Pole Observatory (SPO), which will serve as an umbrella organization for the continuing South Pole Stage 3 experiments into the next decade. The SPO will build upon the current MOU between the BICEP/Keck and SPT programs by establishing a formal entity to guide the development of the combined South Pole CMB program for producing the highest science return. These developments and the observational results will continue to benefit CMB-S4.”

Opportunities for involvement may include:

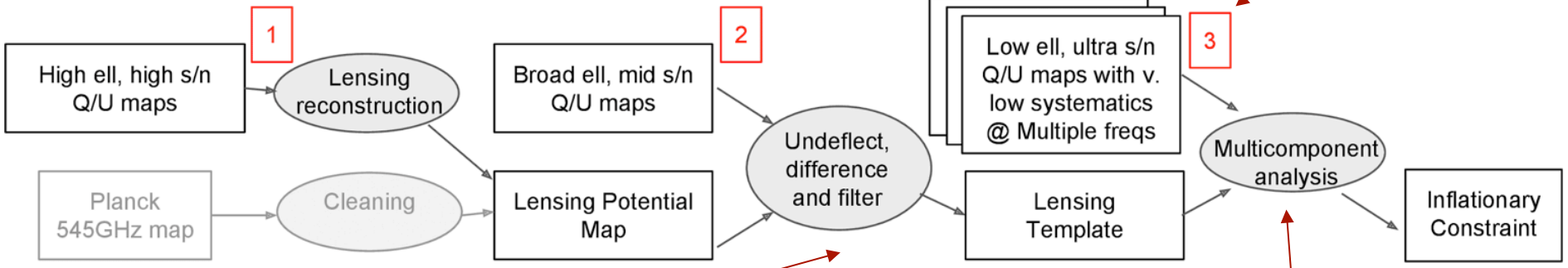
Contributions to infrastructure at Pole (see JC’s talk next)

Lensing template approach:

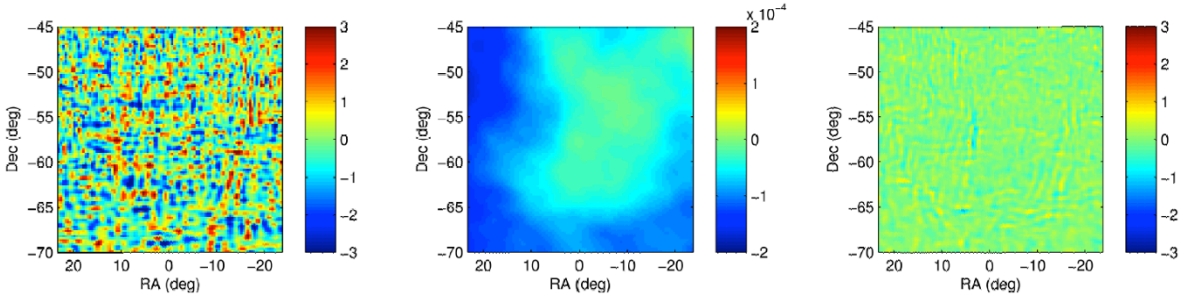
Combine SPT/Planck/BK Q/U maps



The usual BK maps

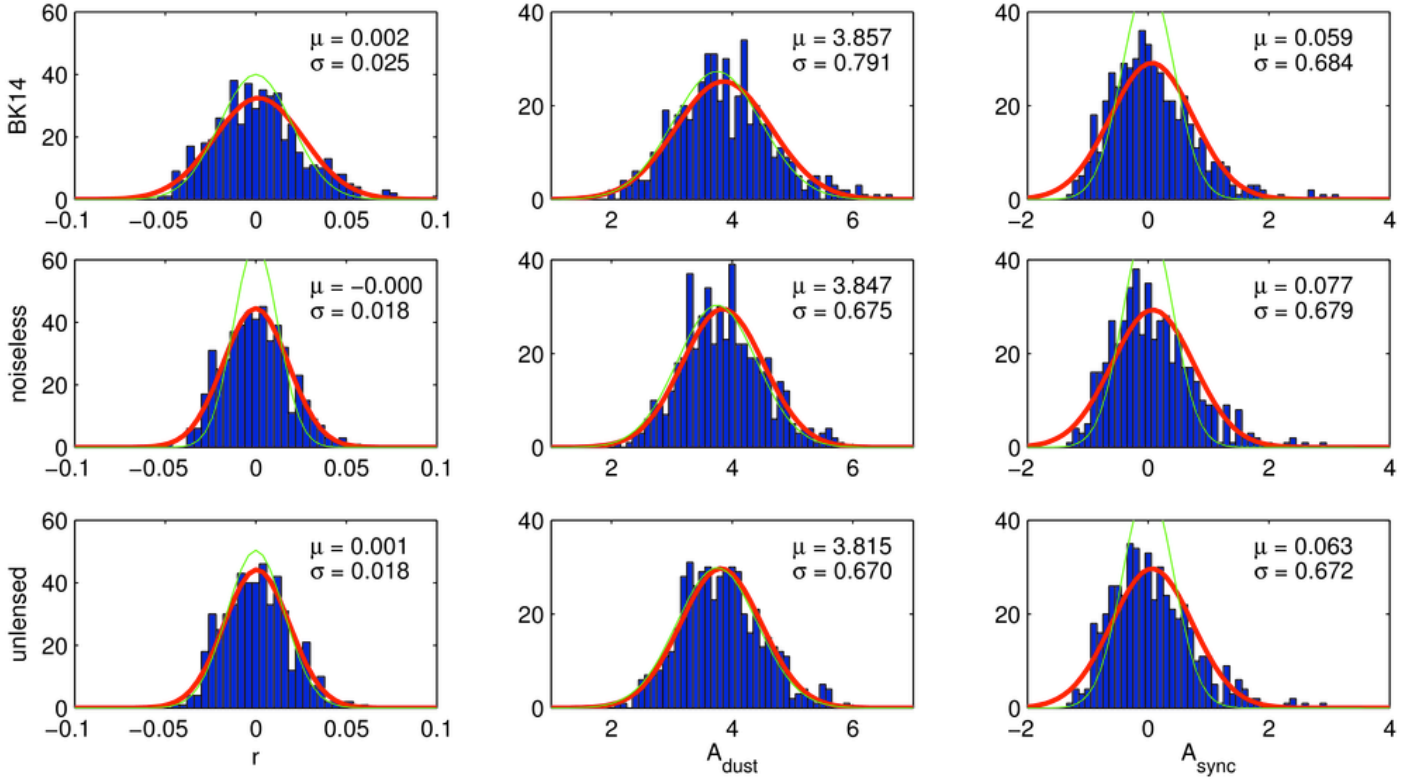


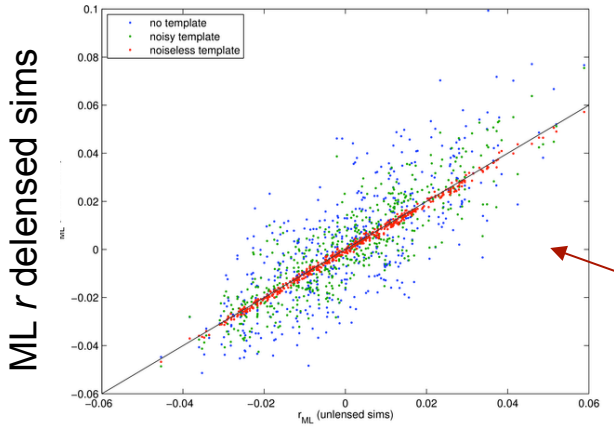
At the moment doing *map space* un-deflect operation



Natural extension: don't "delens" maps and take spectra - instead add a "lensing template" virtual band to the stack of multi-frequency input maps. So long as we can calculate expectation values for the auto and cross spectra it fits right in.

Perfect lensing template in multicomponent analysis matches performance from sims that do not include CMB lensing, σ(r) ~ 0.018 for BK14.





If we have a perfect lensing template then "delensing" works perfectly - the ML *r* values are identical between unlensed and delensed sims on a *realization-by-realization* basis. (red points)