B-mode Polarization Results from BICEP/Keck Array

Kirit Karkare for the BICEP/Keck Array Collaborations
Rencontres du Vietnam
2015-08-17

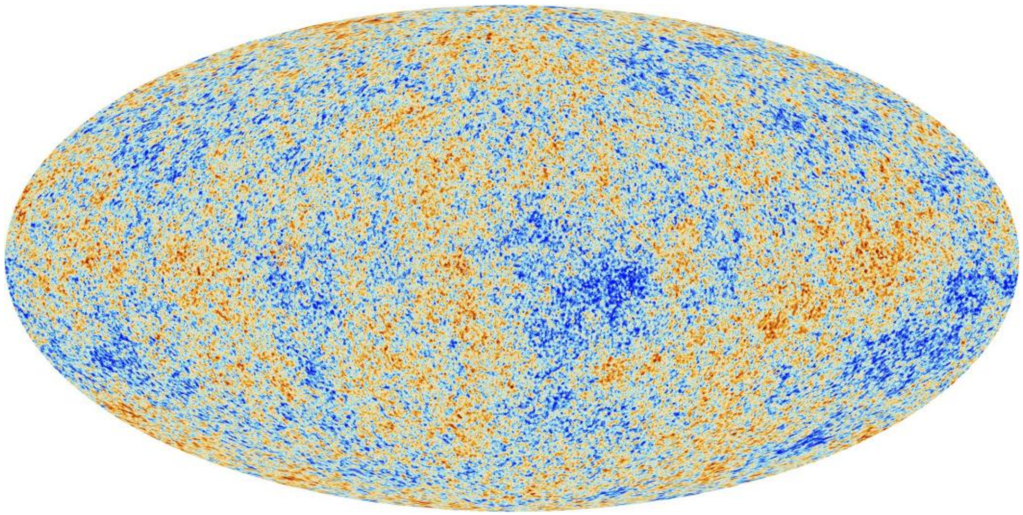

VE RI TAS
HARVARD
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
cea
UCSD
JPL
NIST
CARDIFF UNIVERSITY
UNIVERSITY OF TORONTO
UBC

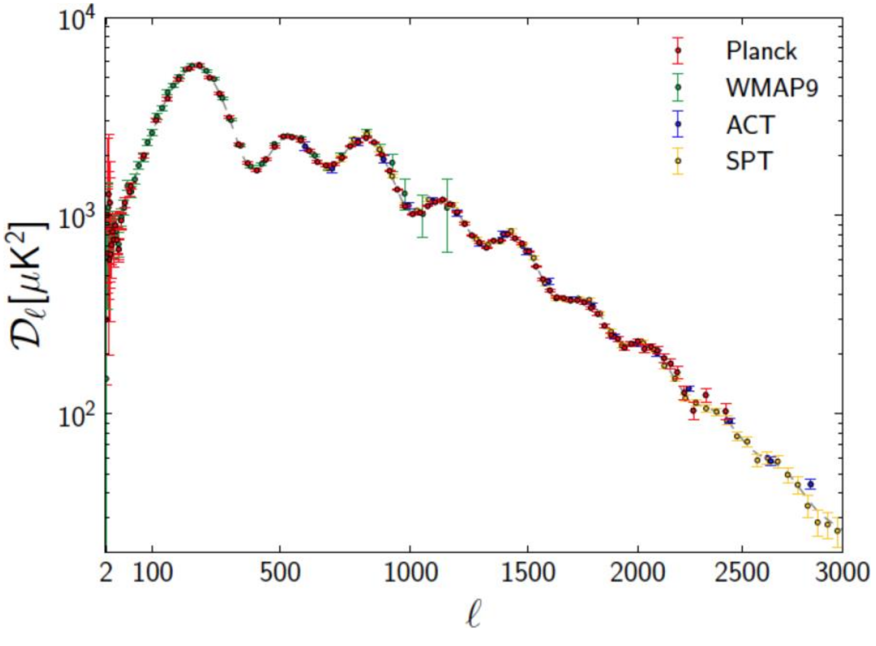
CMB Temperature Measurements / Inflation

CMB temperature anisotropy now measured over full range of angular scales

Consistent with ΛCDM and constrains its parameters to sub-percent accuracy

Inflation "invented" in 1980s to explain facts about the Universe which were known or suspected





Planck Collaboration & ESA

Why Inflation?

Solves the **horizon problem**: Why is the CMB nearly uniform? How do apparently causally disconnected regions of space get set to the same temperature?

→ A volume much larger than our entire observable universe today was once a causally connected subatomic speck

Solves the **flatness problem**: Why is the net spatial curvature close to zero?

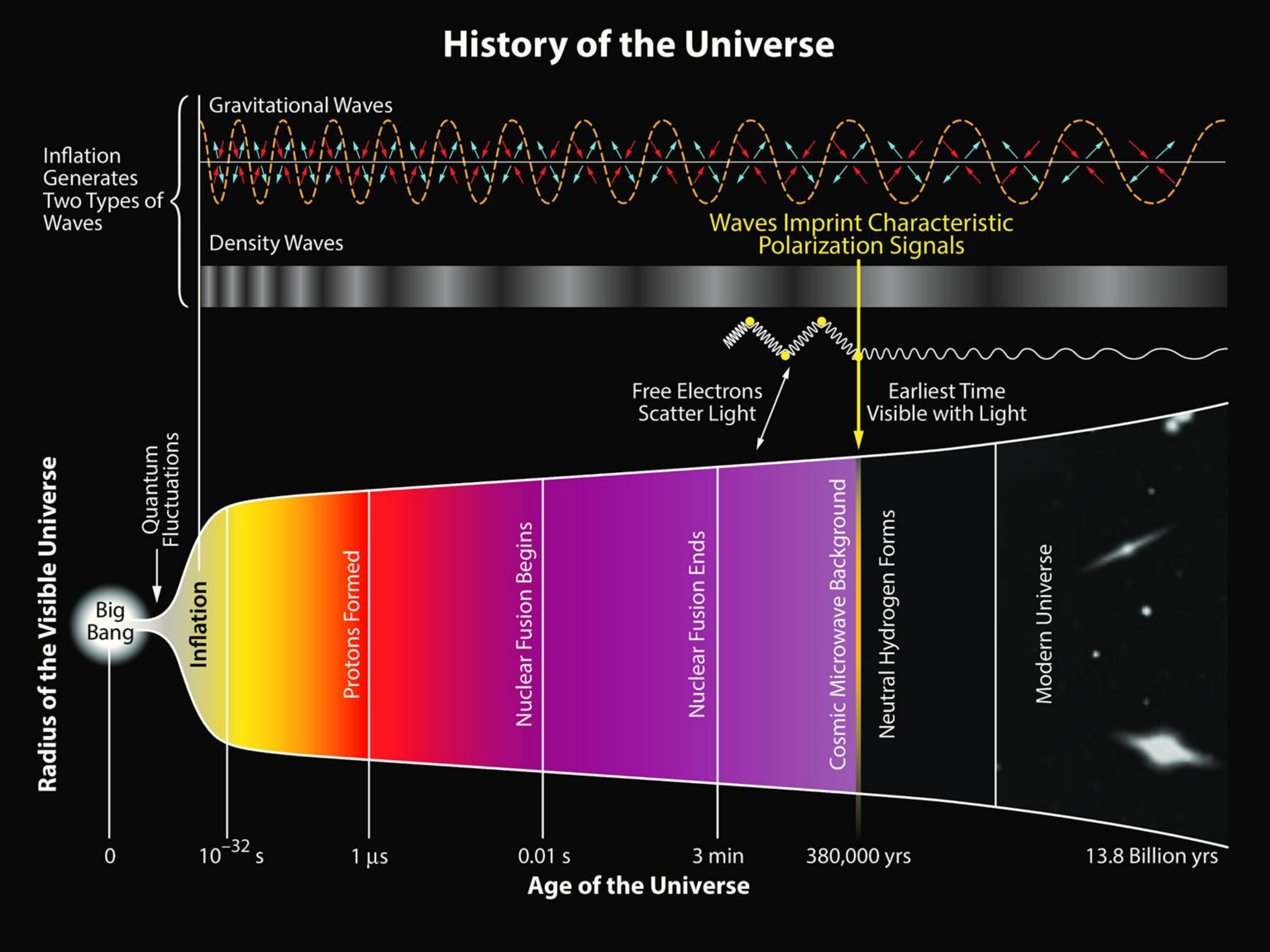
→ Any initial spatial curvature is diluted away to undetectabilty by the exponential expansion

Explains the **initial perturbation spectrum**: Why was it close to flat power law?

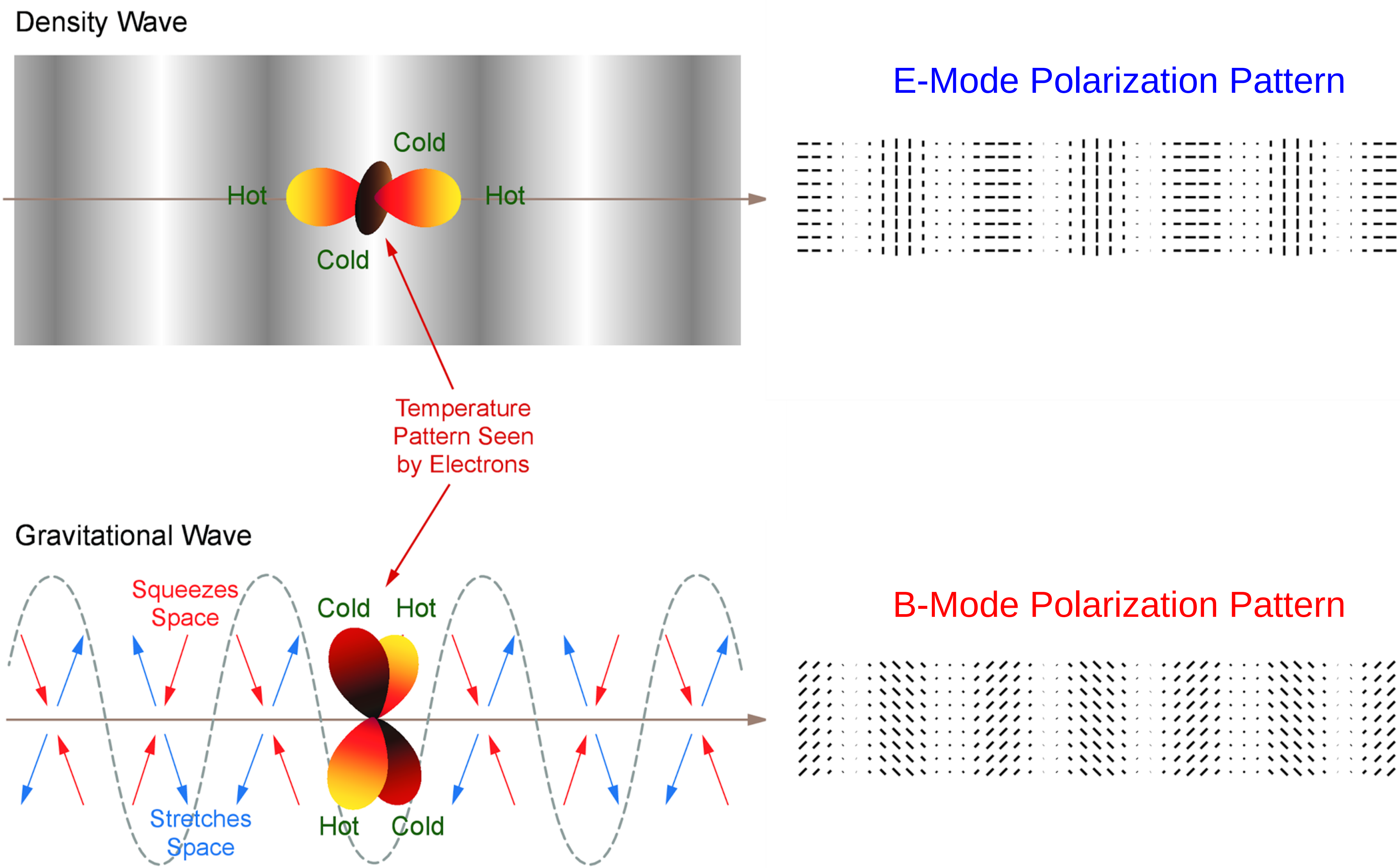
→ Equal amount of perturbations are injected at each step in the exponential expansion

Solves the **monopole problem**: Why do we not observe magnetic monopoles in the Universe today?

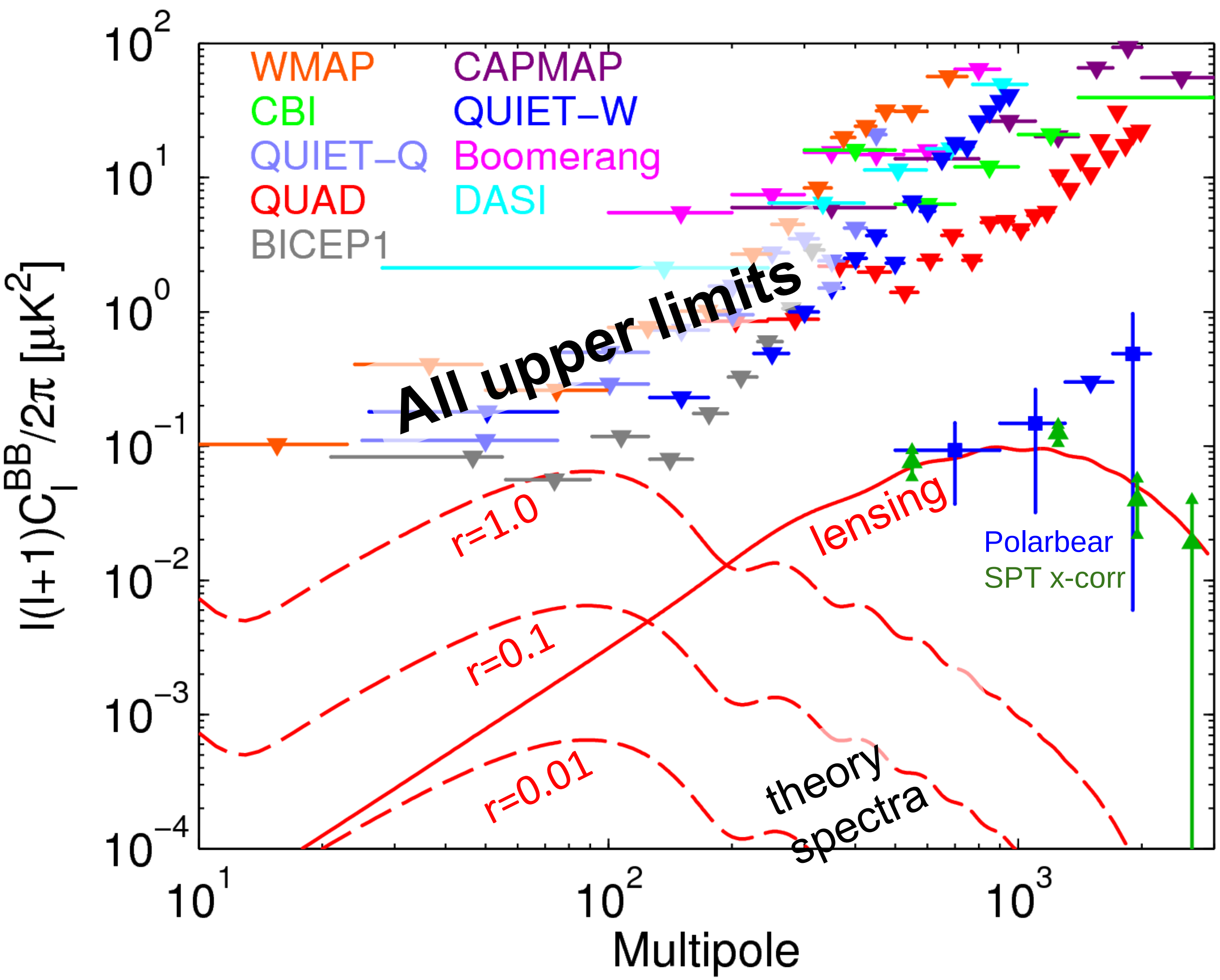
→ Monopoles are diluted away to undetectability


History of the Universe
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10^{-32} s
1 µs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

CMB Polarization



The State of B-mode Measurements last March



In simple inflationary gravitational wave models the

tensor-to-scalar ratio r

is the only parameter to the B-mode spectrum.

Before BICEP2: only upper limits from searches for Inflationary B-modes

BICEP1 limits translated to:

r < 0.7 (95% CL)

At high multipoles lensing B-mode dominant

SPT x-corr: lower limits on lensing B-mode from cross correlation using the CIB

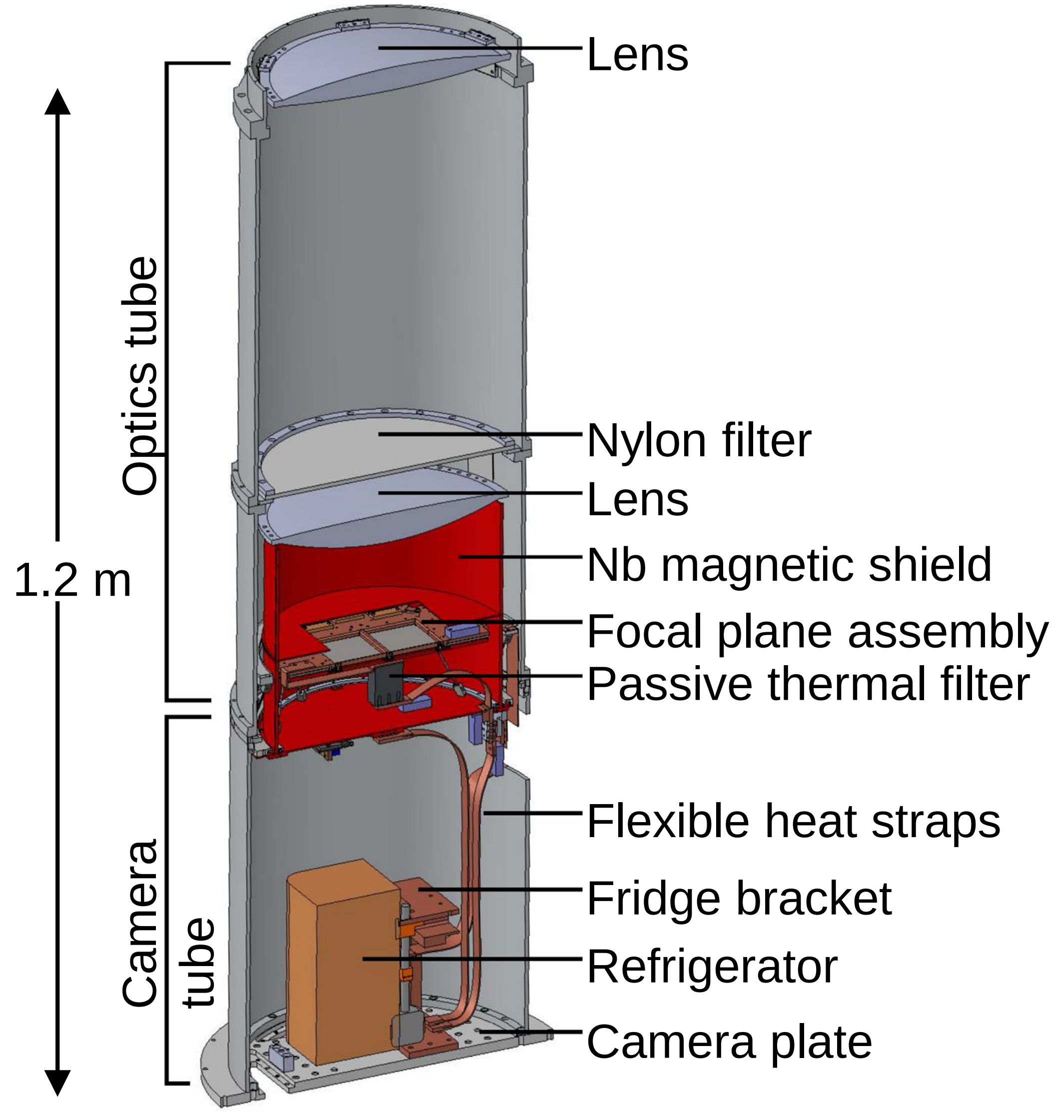
The BICEP2/Keck Telescopes

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

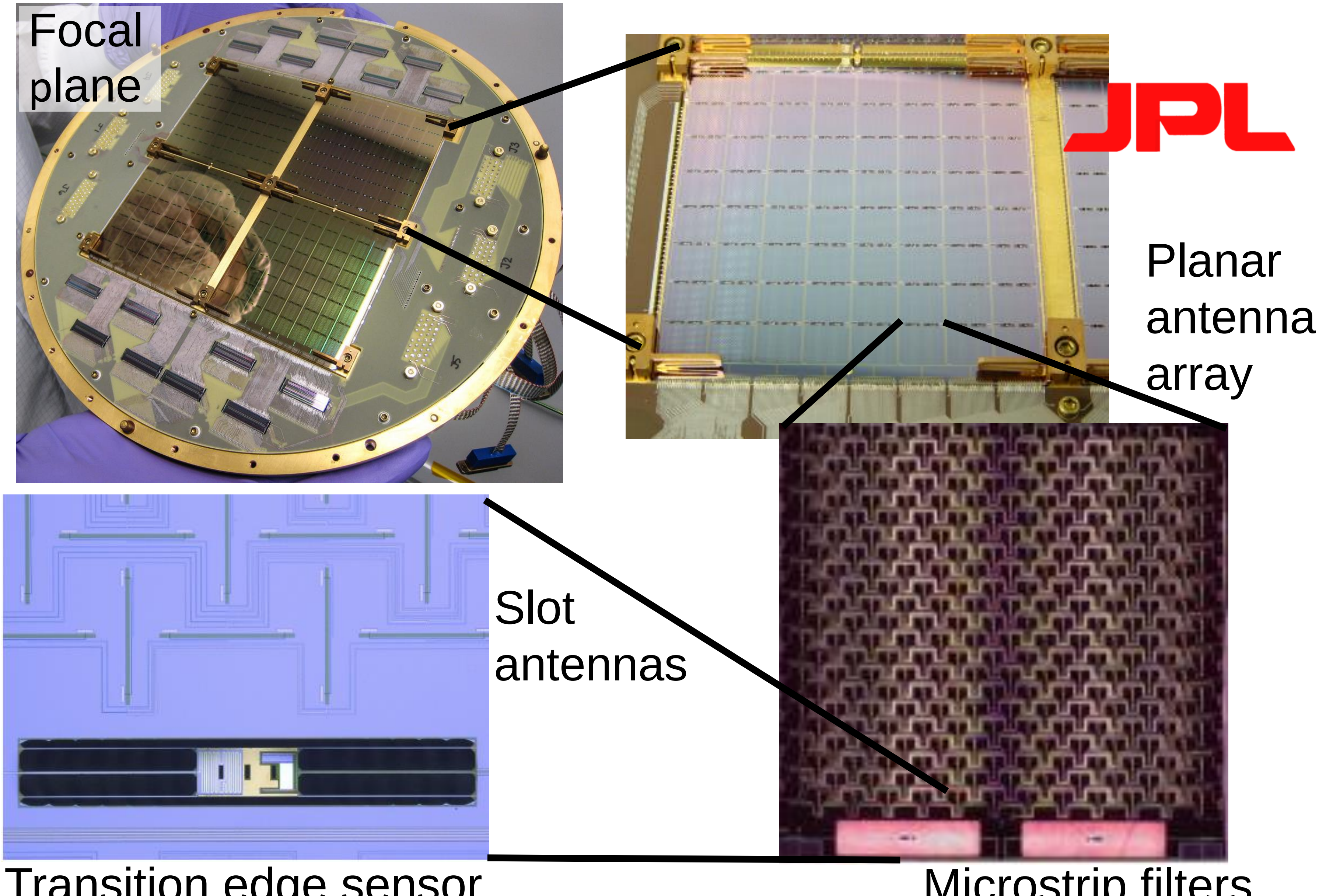
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation

Liquid helium 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

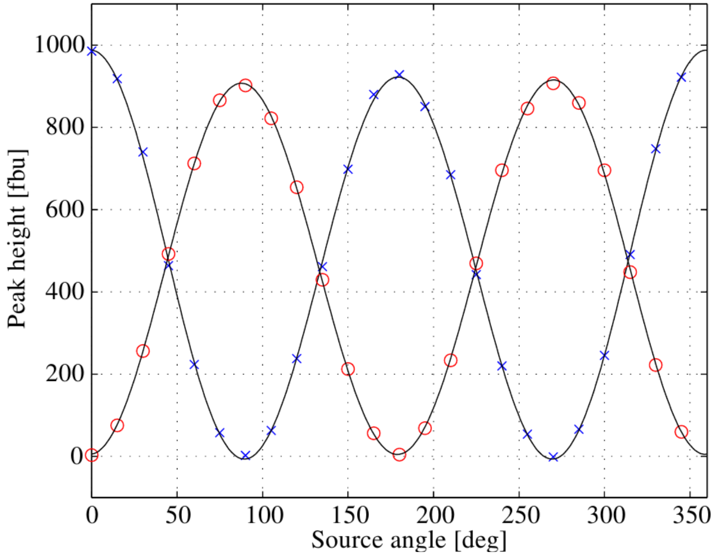


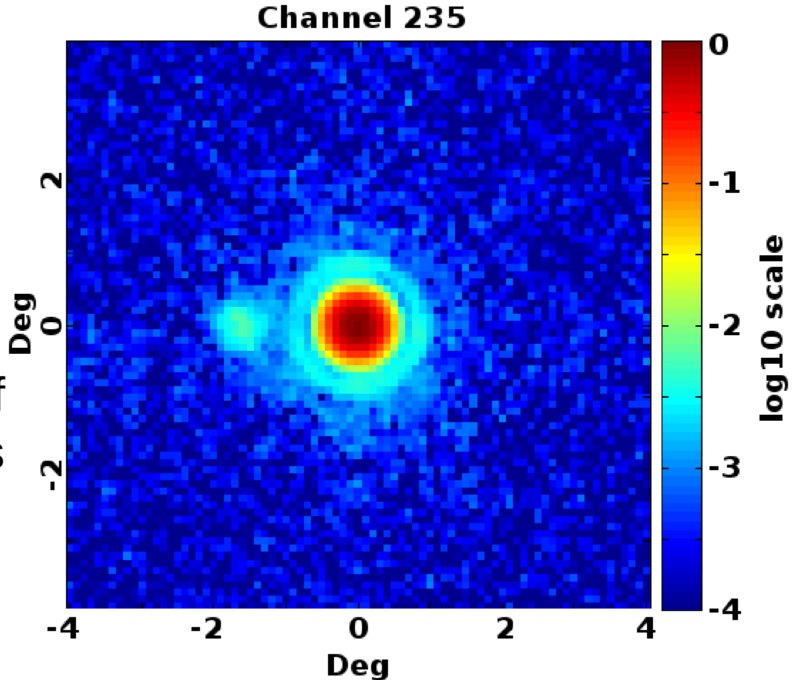
Calibration Measurements

For instance...

Far field beam mapping

Detector Polarization Calibration





Hi-Fi beam maps of individual detectors

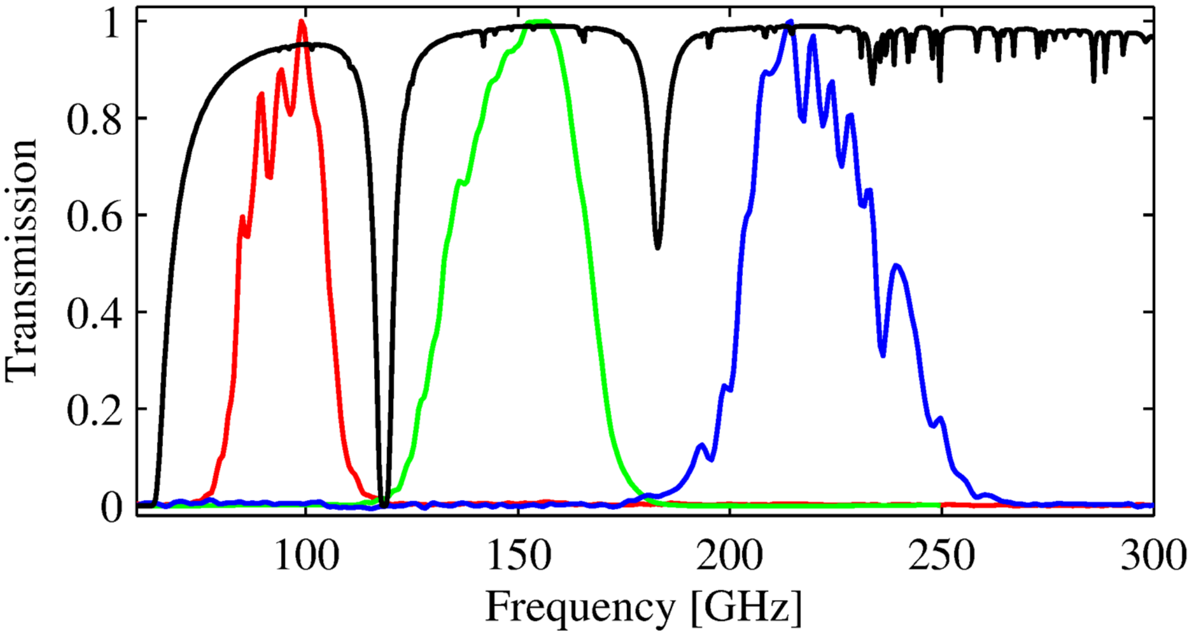
Detailed description in Instrument and Beams papers arxiv/1403.4302 and 1502.00596

BICEP2/Keck Band Response

28% fractional bandwidth fits within an atmospheric transmission window straddled by oxygen and water lines

In this window, the atmosphere is transparent to microwaves

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



Detailed description in Detectors paper arxiv/1502.00619

BICEP2 and Keck Array at South Pole

BICEP2 and Keck Array at South Pole

BICEP2, 2010–2012

Keck Array, 2011–

BICEP2 and Keck Array at South Pole

BICEP2, 2010–2012

Keck Array, 2011–

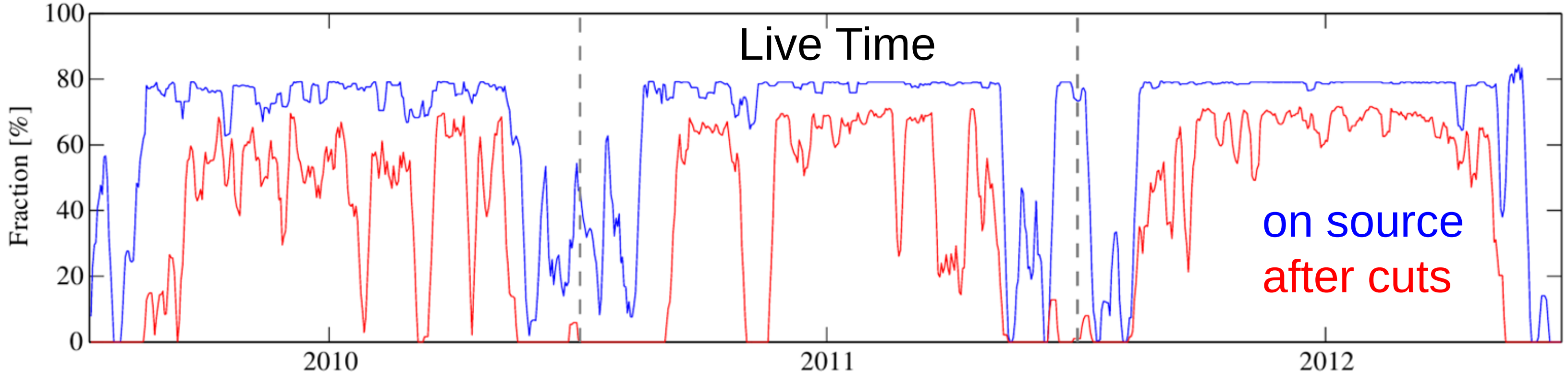
Relentless observation from Amundsen-Scott South Pole Station

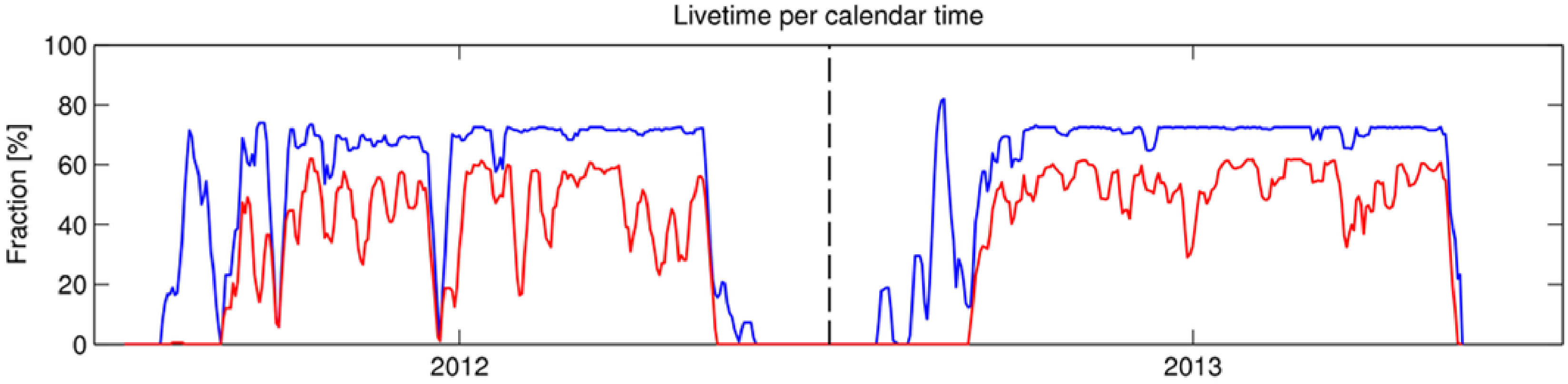
Dry, stable atmosphere, high altitude, 24 hour coverage of the Southern Sky

Observations focus on a ~400 square degree patch, chosen for low foreground emission

Experimental strategy is to dig deep at 150 GHz until detecting a signal

BICEP2/Keck Array Data Quality/Cuts



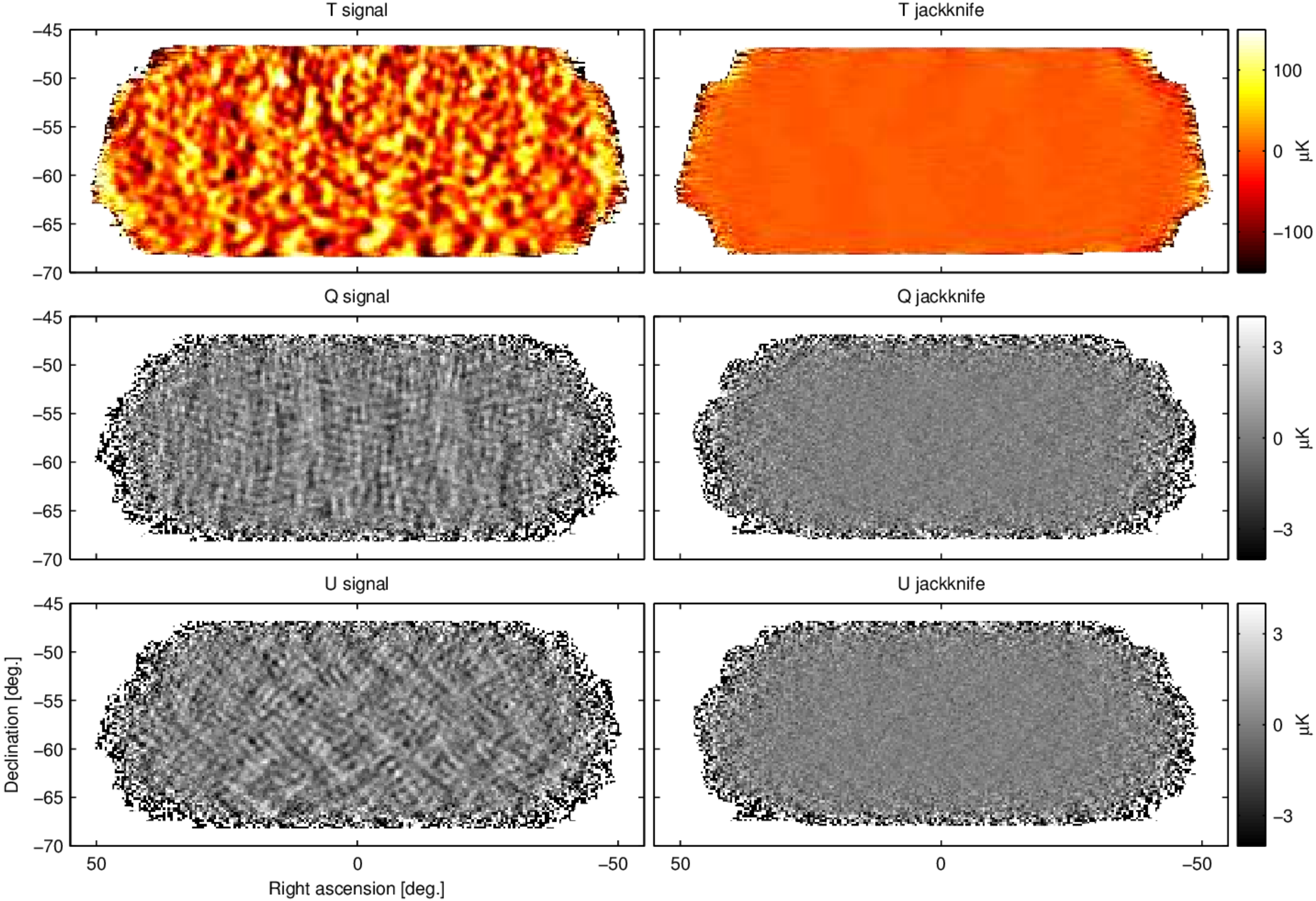


Multistage data cut procedure: Ensures that all data used in map making is taken when the experiment is operating properly and has stationary, well-behaved noise

Many cuts identify periods of exceptionally bad weather and are redundant

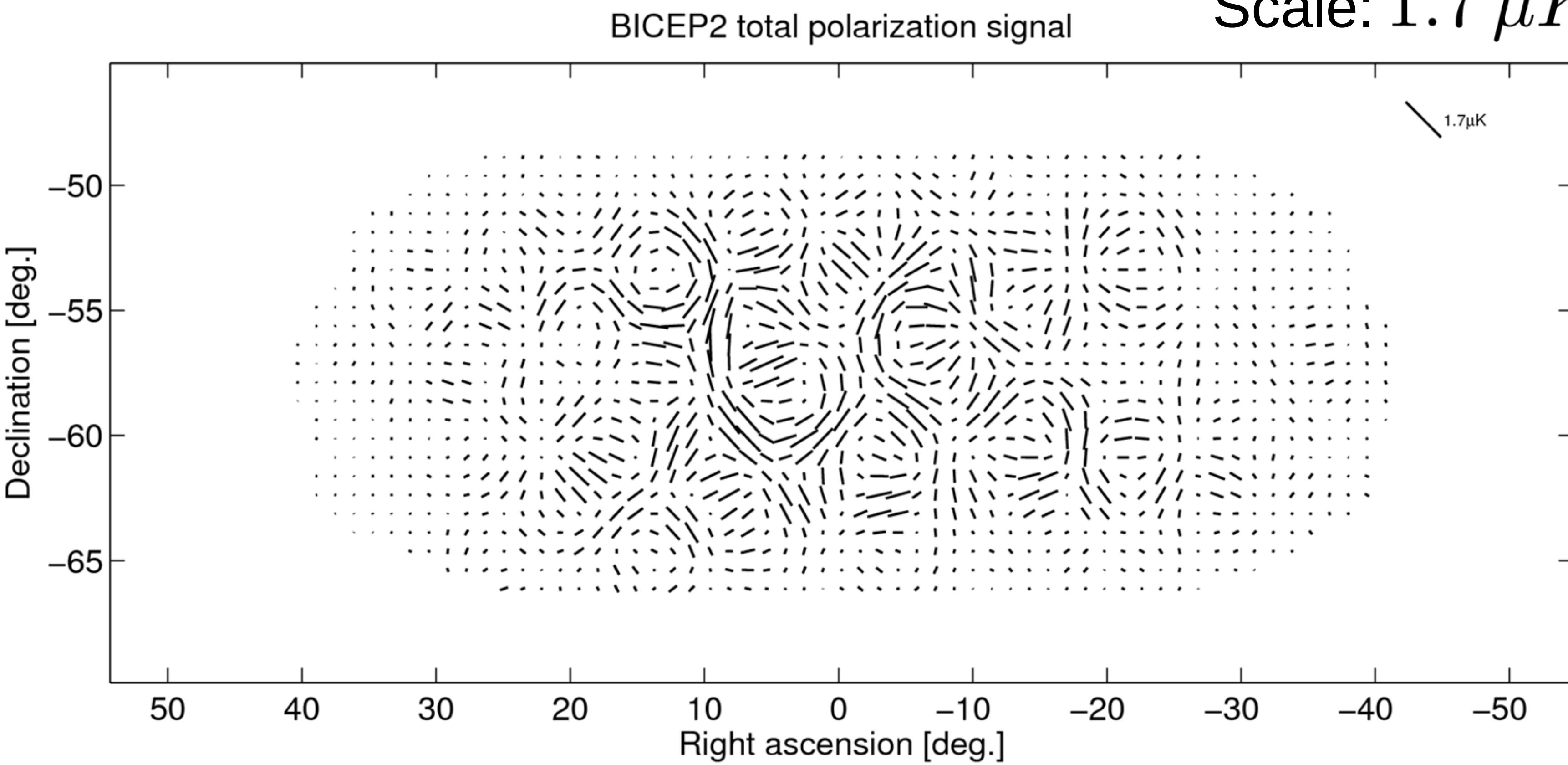
BICEP2 data very well-behaved: pass fraction = 63%

BICEP2 T and Stokes Q/U Maps



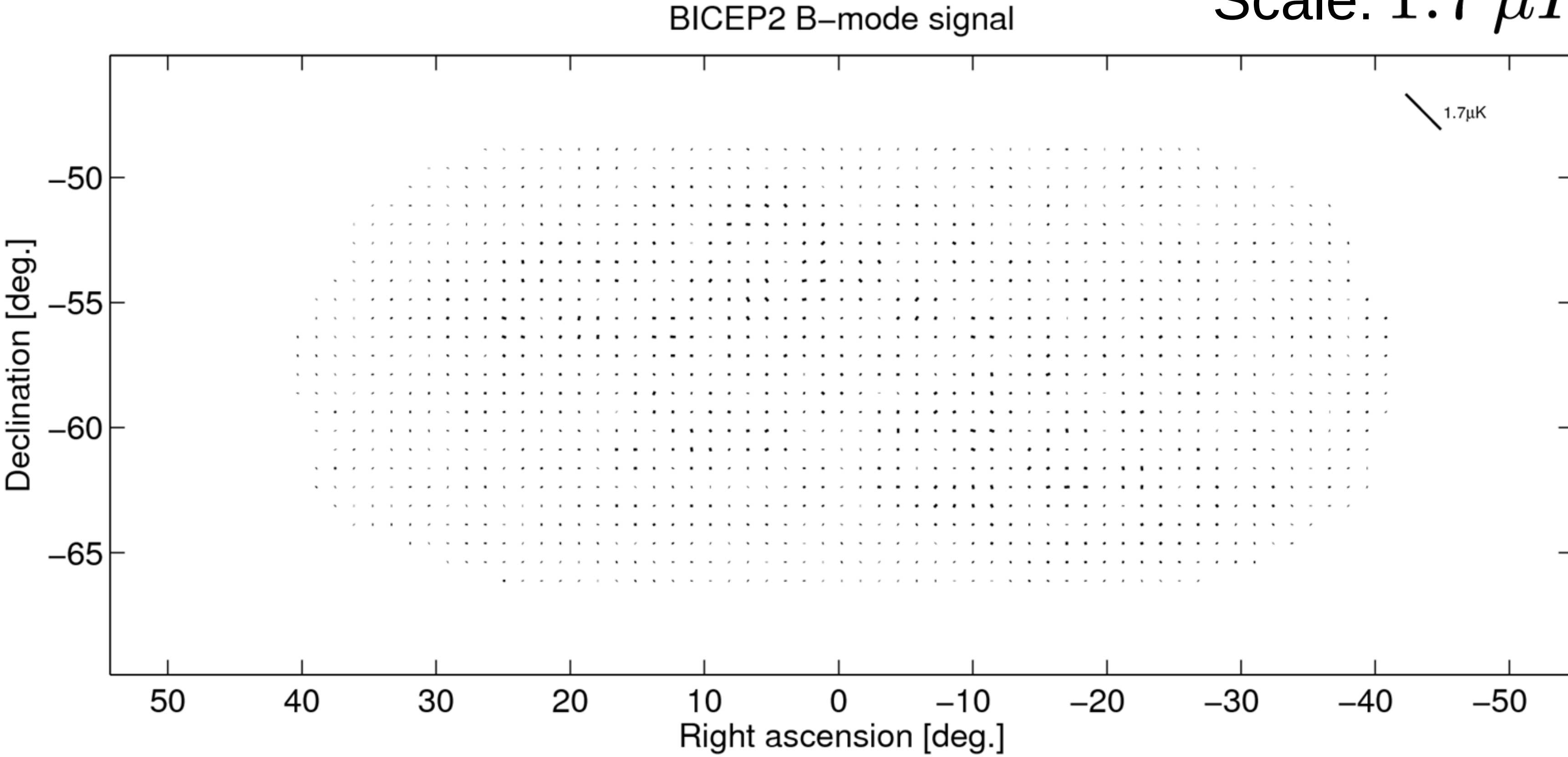
Total Polarization

Scale: $1.7\,\mu K$



B-mode Contribution

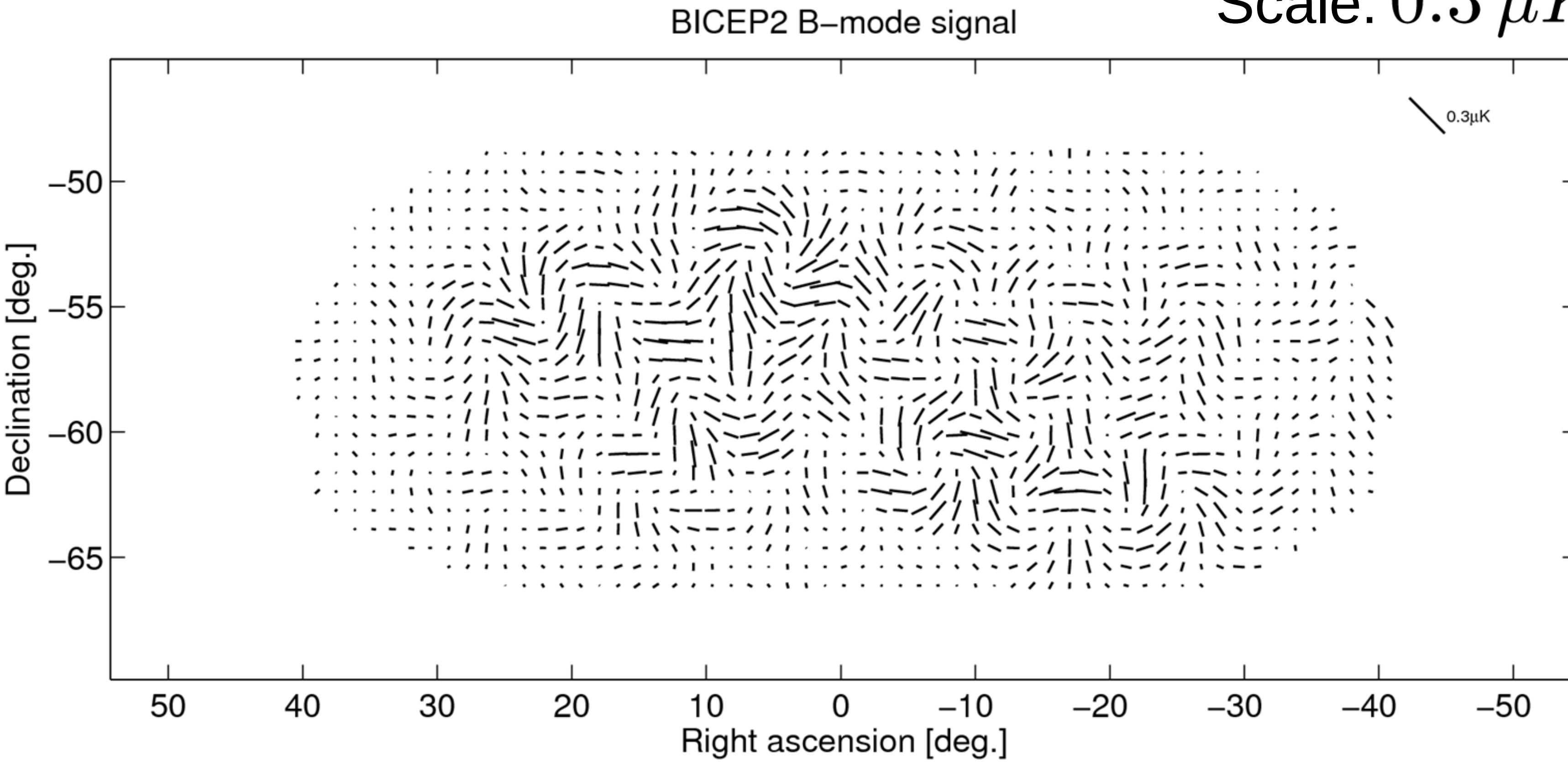
Scale: $1.7\,\mu K$



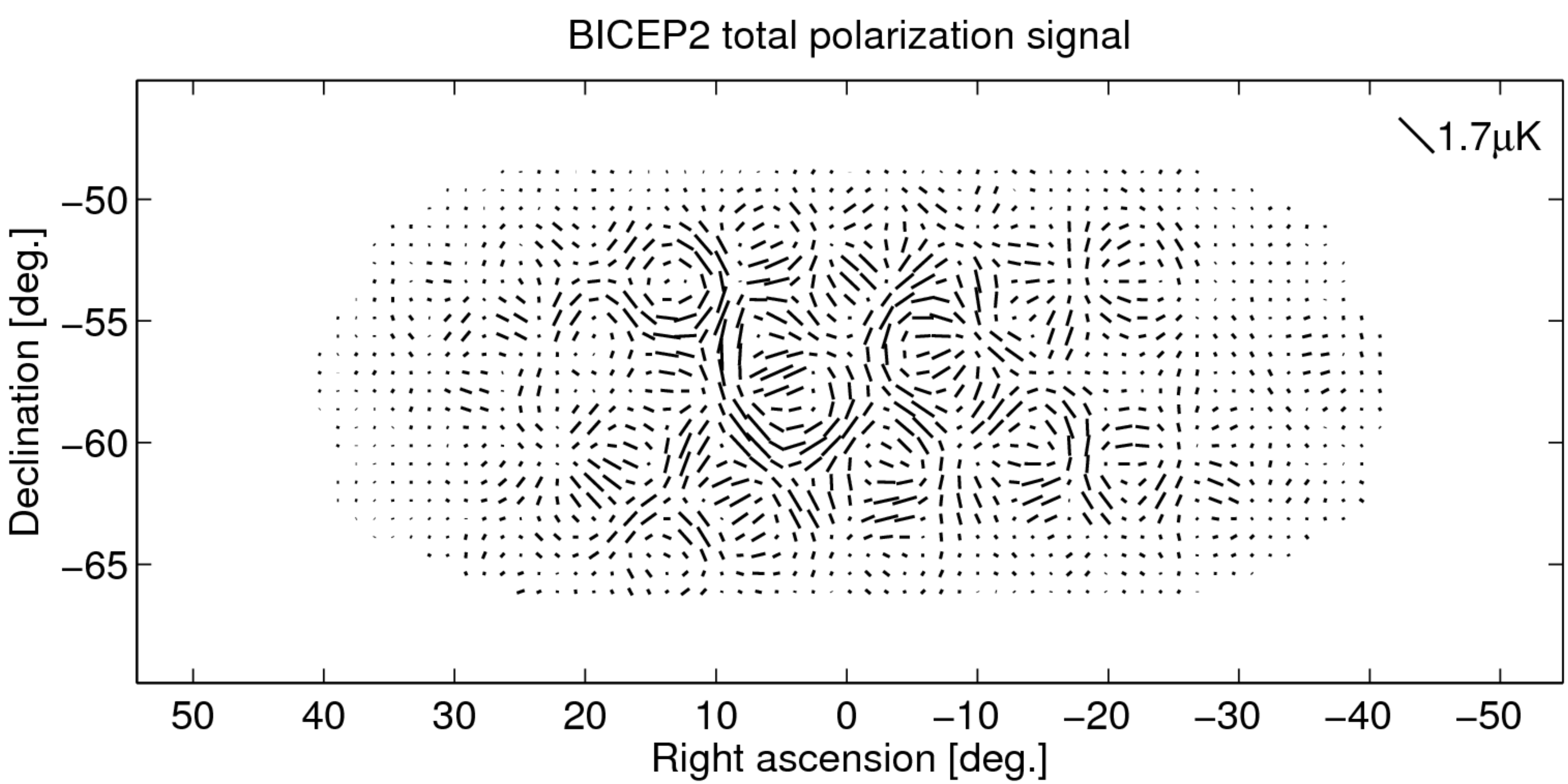
B-modes of r=0.1 contribute ~1/10 of the total polarization amplitude at l=100

B-mode Contribution

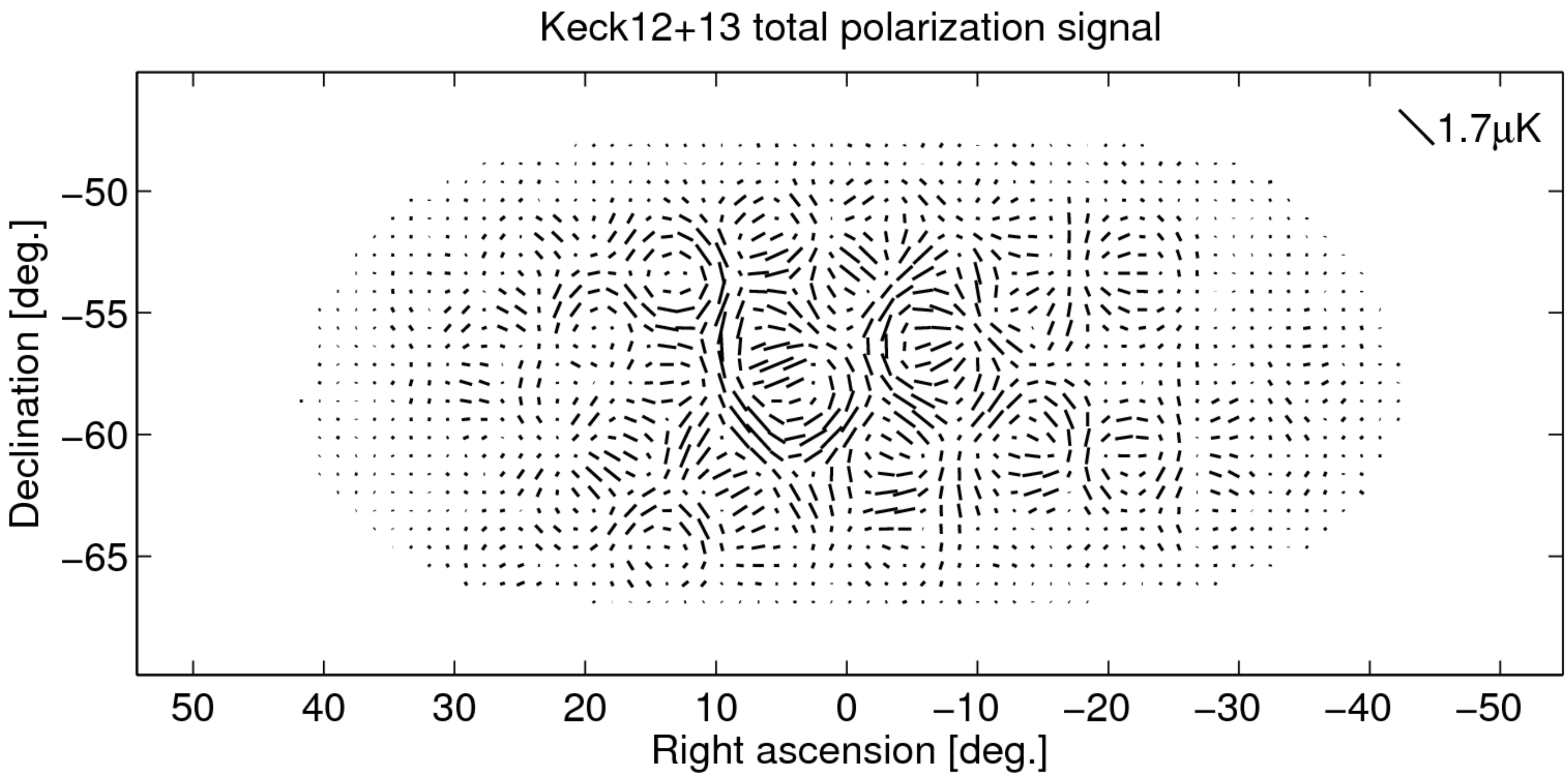
Scale: $0.3\,\mu K$



B-modes of r=0.1 contribute ~1/10 of the total polarization amplitude at l=100

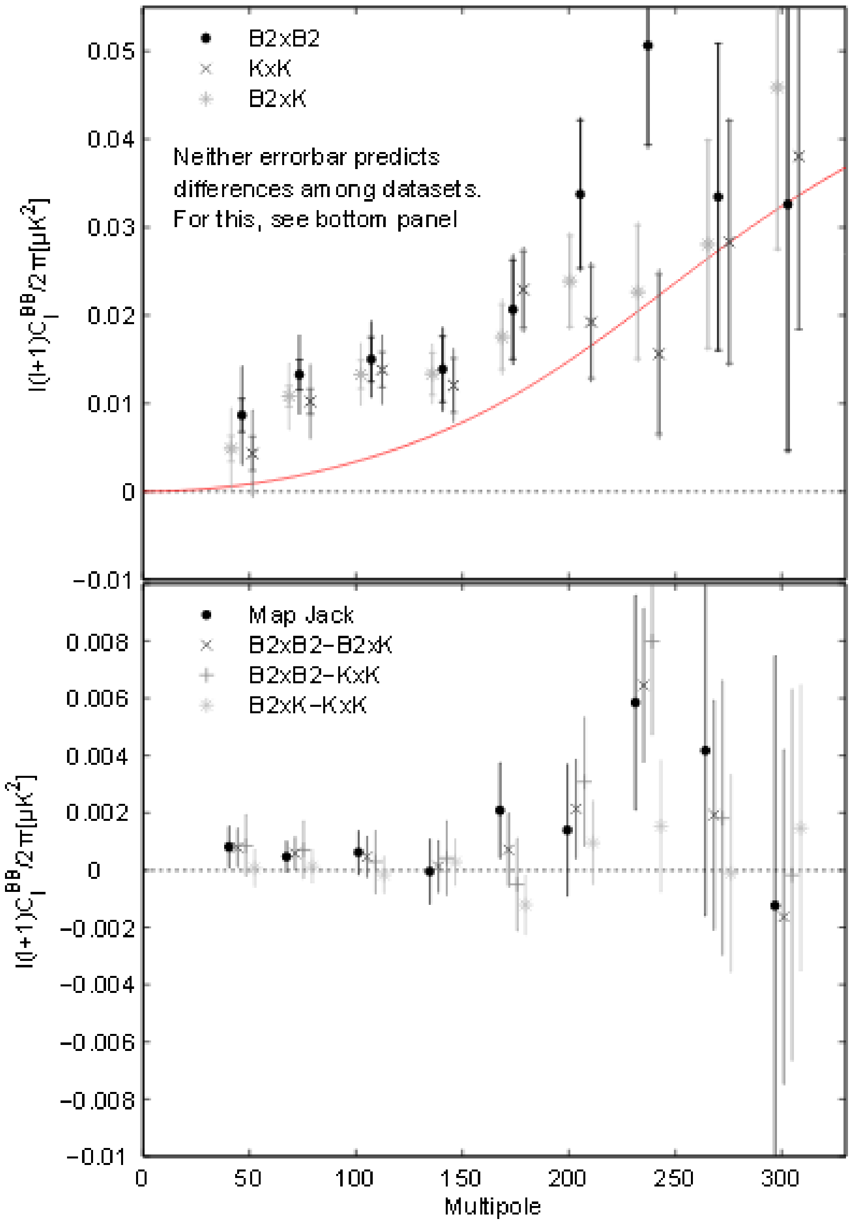


BICEP2 total polarization signal
1.7μK
−50
−55
−60
−65
Declination [deg.]
50
40
30
20
10
0
−10
−20
−30
−40
−50
Right ascension [deg.]



Keck12+13 total polarization signal
1.7μK
Declination [deg.]
−50
−55
−60
−65
Right ascension [deg.]
50
40
30
20
10
0
−10
−20
−30
−40
−50

BB Spectra from BICEP2/Keck



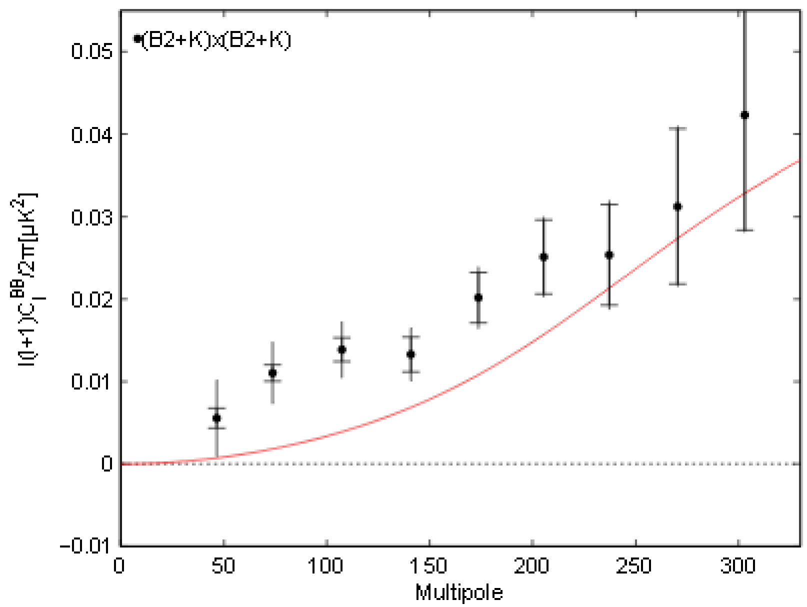
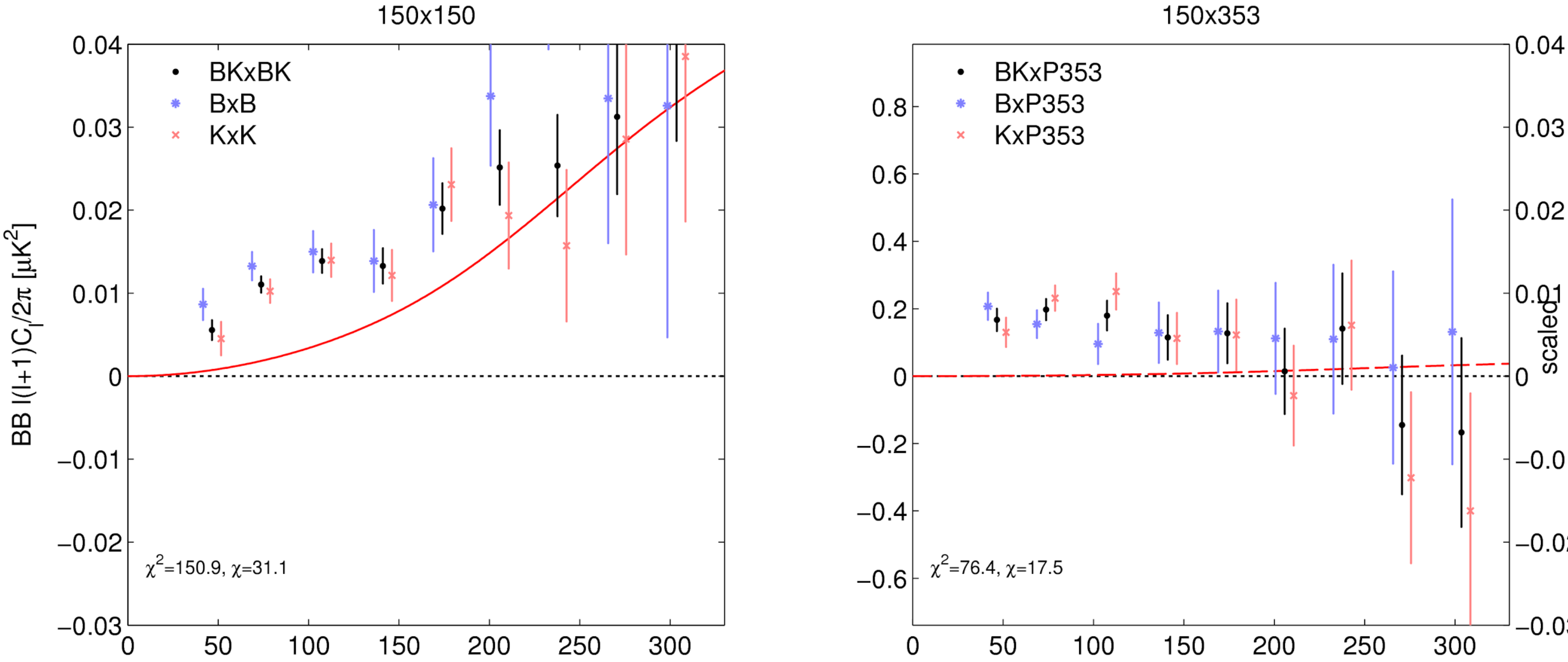


FIG. 9.— The *BB* power spectrum of combined BICEP2 and *Keck Array* maps. The inner error bars are the standard deviation of the lensed-ΛCDM+noise simulations, while the outer error bars also contain excess power at low-ℓ.

Keck Array Paper: arXiv/1502.00643

BB Spectra from BICEP2 x Keck x Planck 353 GHz



Correlation of 150 GHz and 353 GHz B-modes detected at high significance

Scaling the frequency cross-spectrum by the expected brightness ratio (~25) of dust indicates that dust contribution is comparable in magnitude to BK excess over LCDM

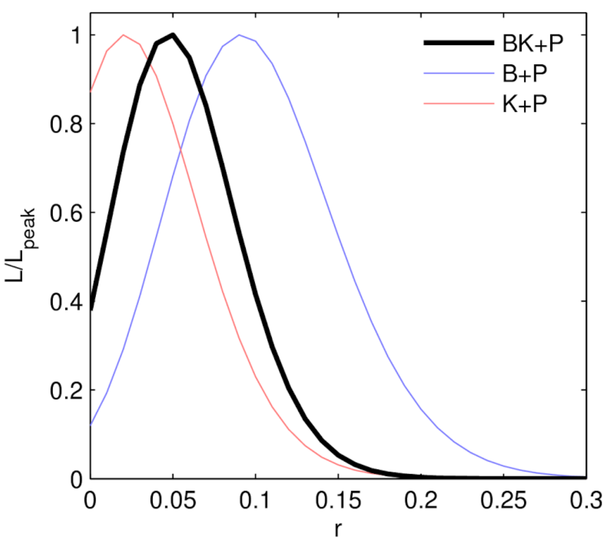
Phys. Rev. Lett. 114, 101301 (2015)

Multi-component, Multi-spectral Likelihood Analysis

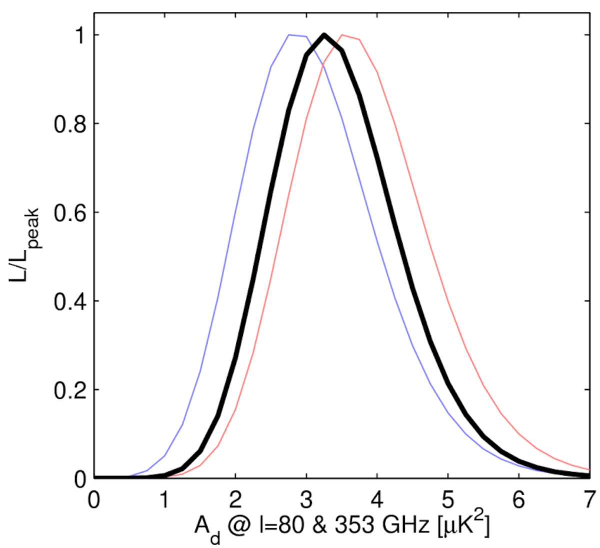
Fiducial analysis uses BICEP2+Keck 150 GHz, Planck 217 and 353 GHz

Calculate likelihood for r vs A_d (dust power at 353 GHz, ℓ=80)

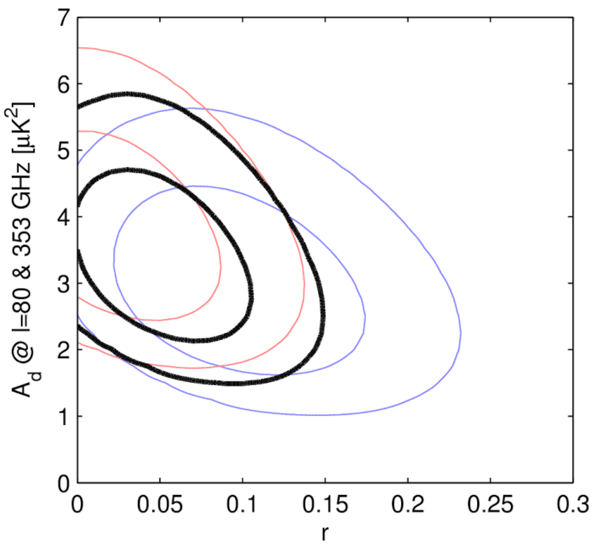
Marginalize over uncertainty in dust spectral index with prior $\beta_{dust} = 1.59 \pm 0.11$ based on Planck observations over large sky fraction



r constraint consistent with zero: L_0/L_{peak} is 0.4 (8% of the time in a dust only model)



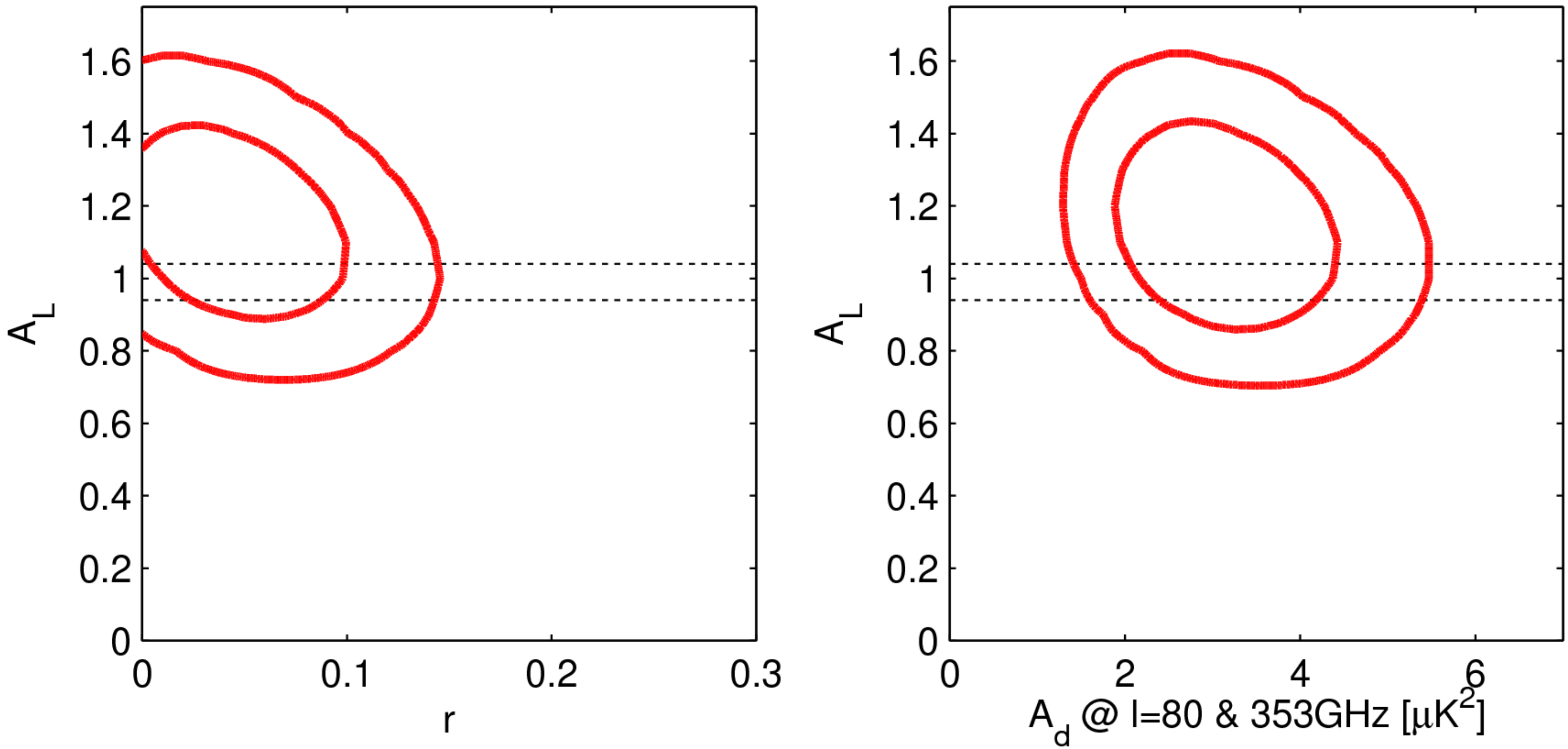
Dust is detected with 5.1 σ significance



As expected dust and r are anti-correlated

Phys. Rev. Lett. 114, 101301 (2015)

Constraints on Lensing B-modes



Using bandpowers up to ℓ~330, lensing is detected at 7.0 σ significance

Lensing and dust are distinct in angular scale, can be cleanly separated.

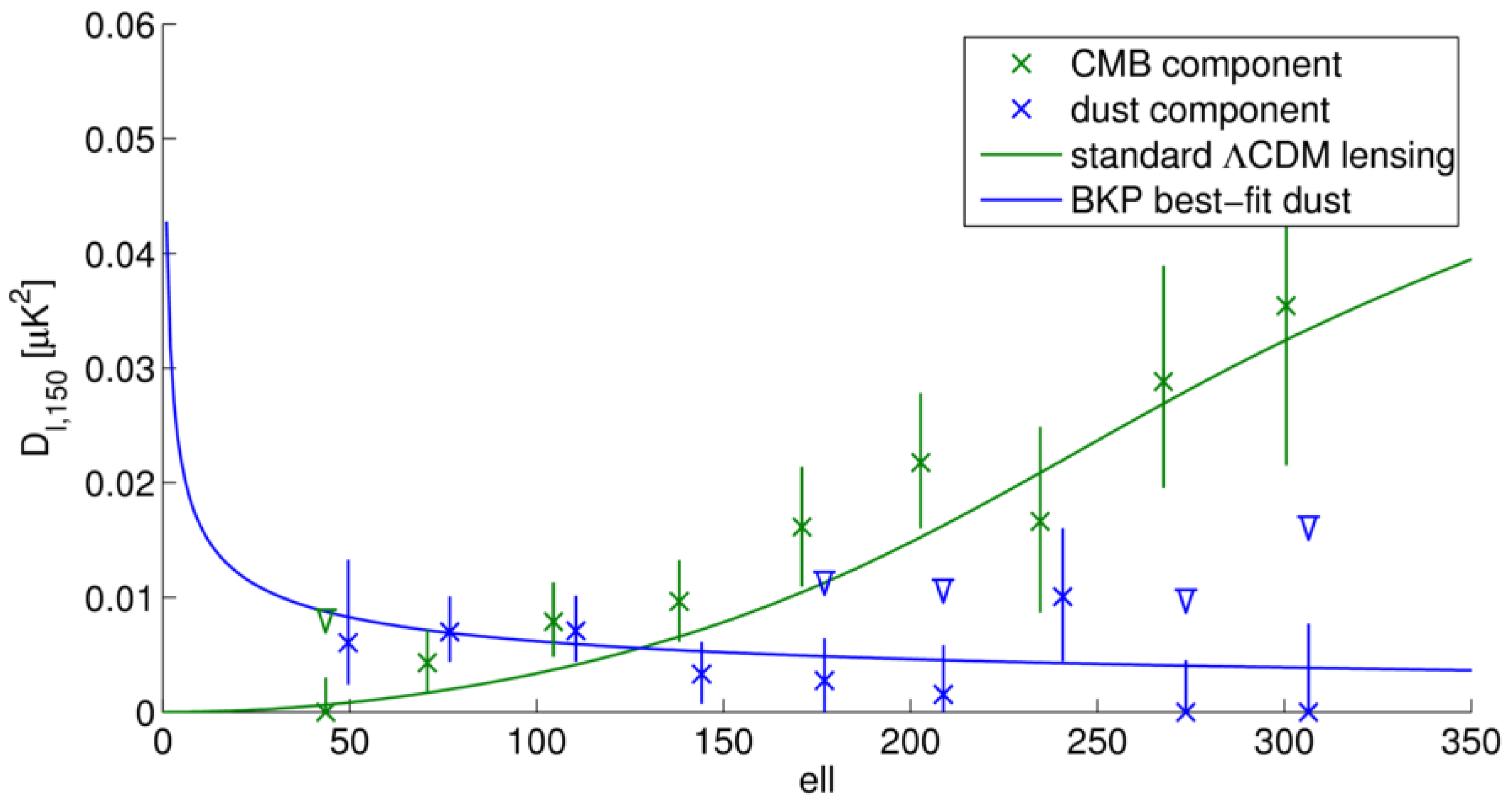
Phys. Rev. Lett. 114, 101301 (2015)

CMB/Dust Separation Per-Bandpower

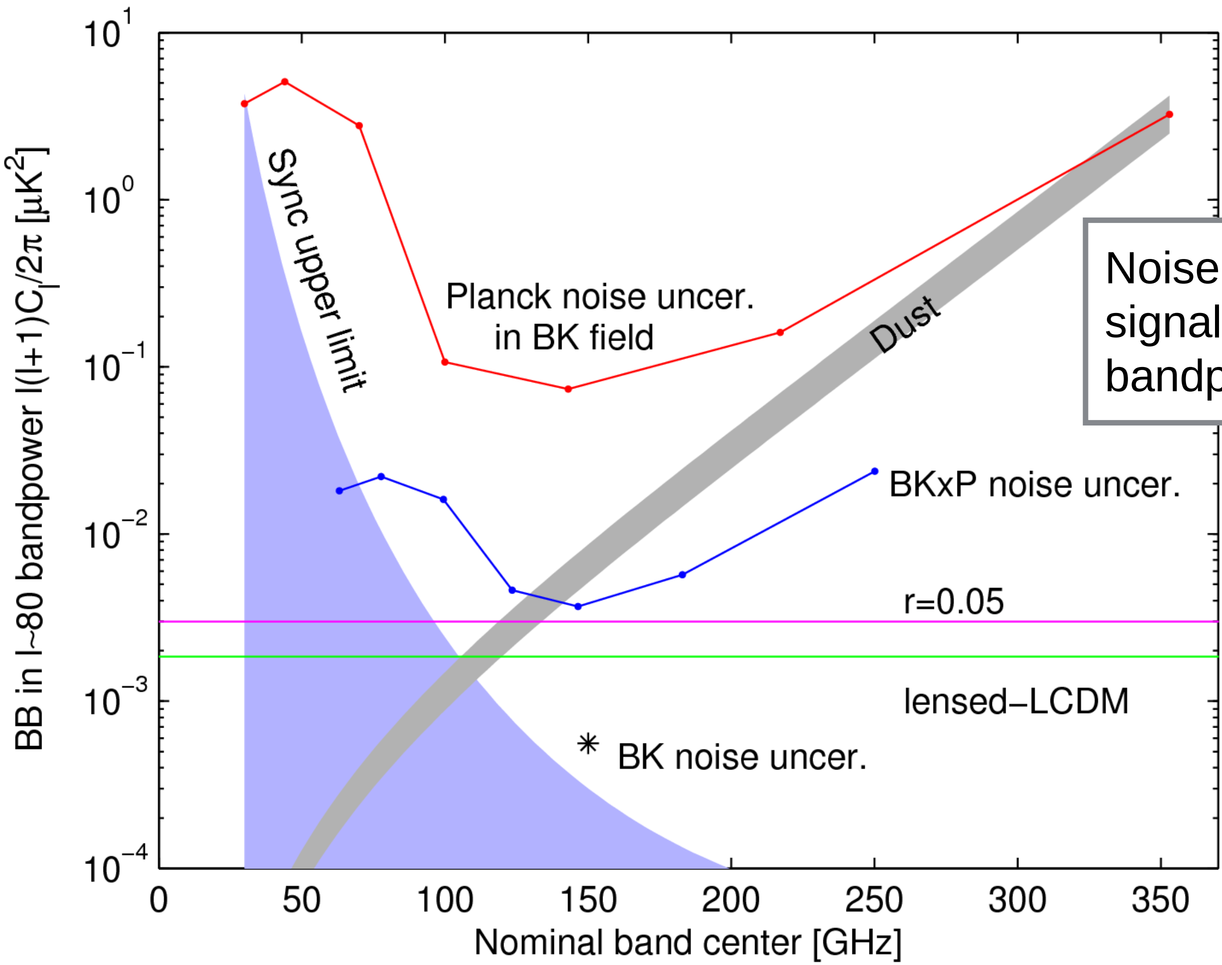
Uses multicomponent analysis framework to constrain CMB and dust contribution to each band at 150 GHz (no assumption about spectral shape in ℓ)

Using BICEP2+Keck, Planck 217, and Planck 353 GHz, as in fiducial analysis

Error bars are 68% credible intervals derived from marginalized 1D posteriors.



Comparison of signal levels and noise uncertainty

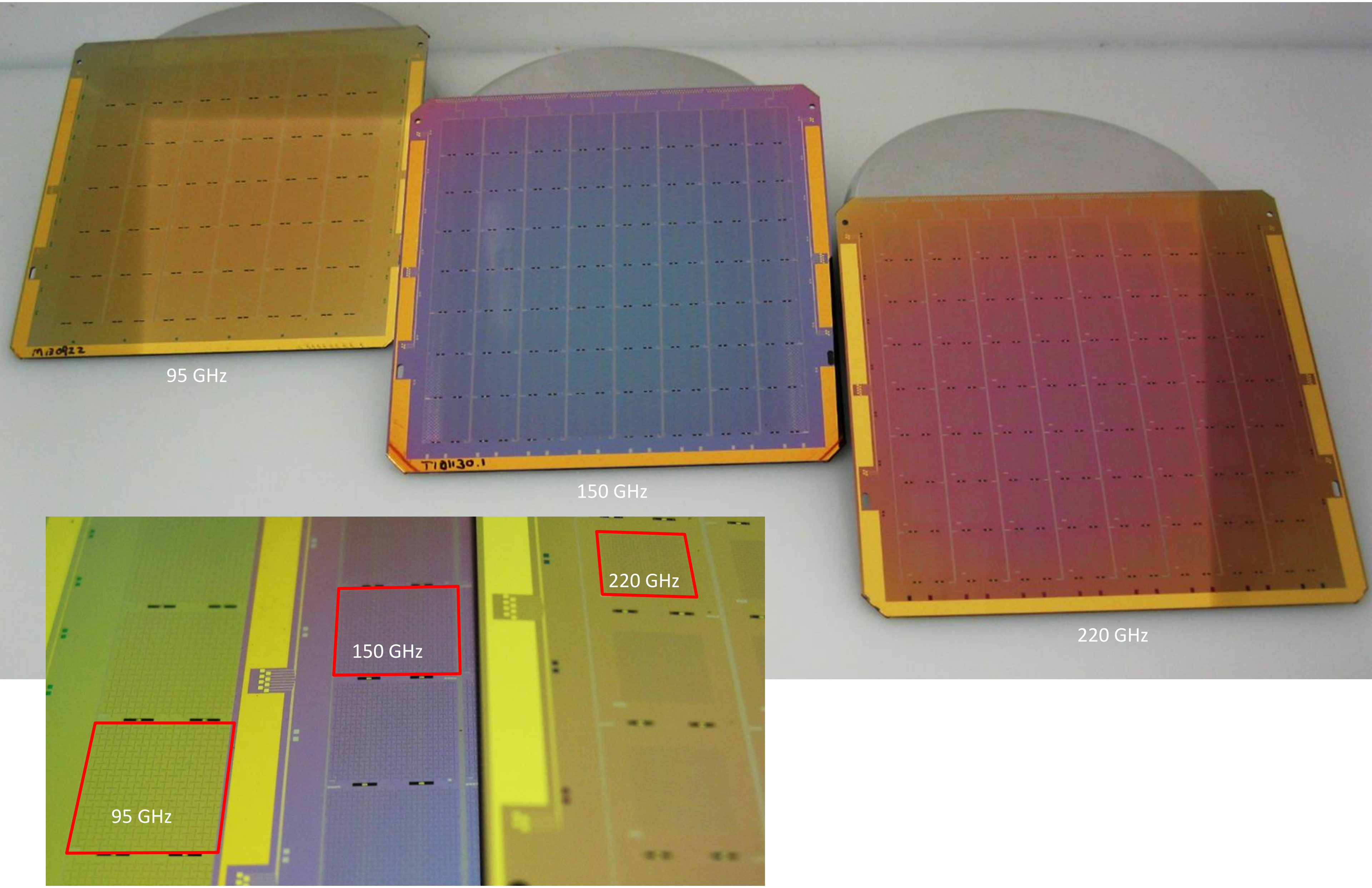


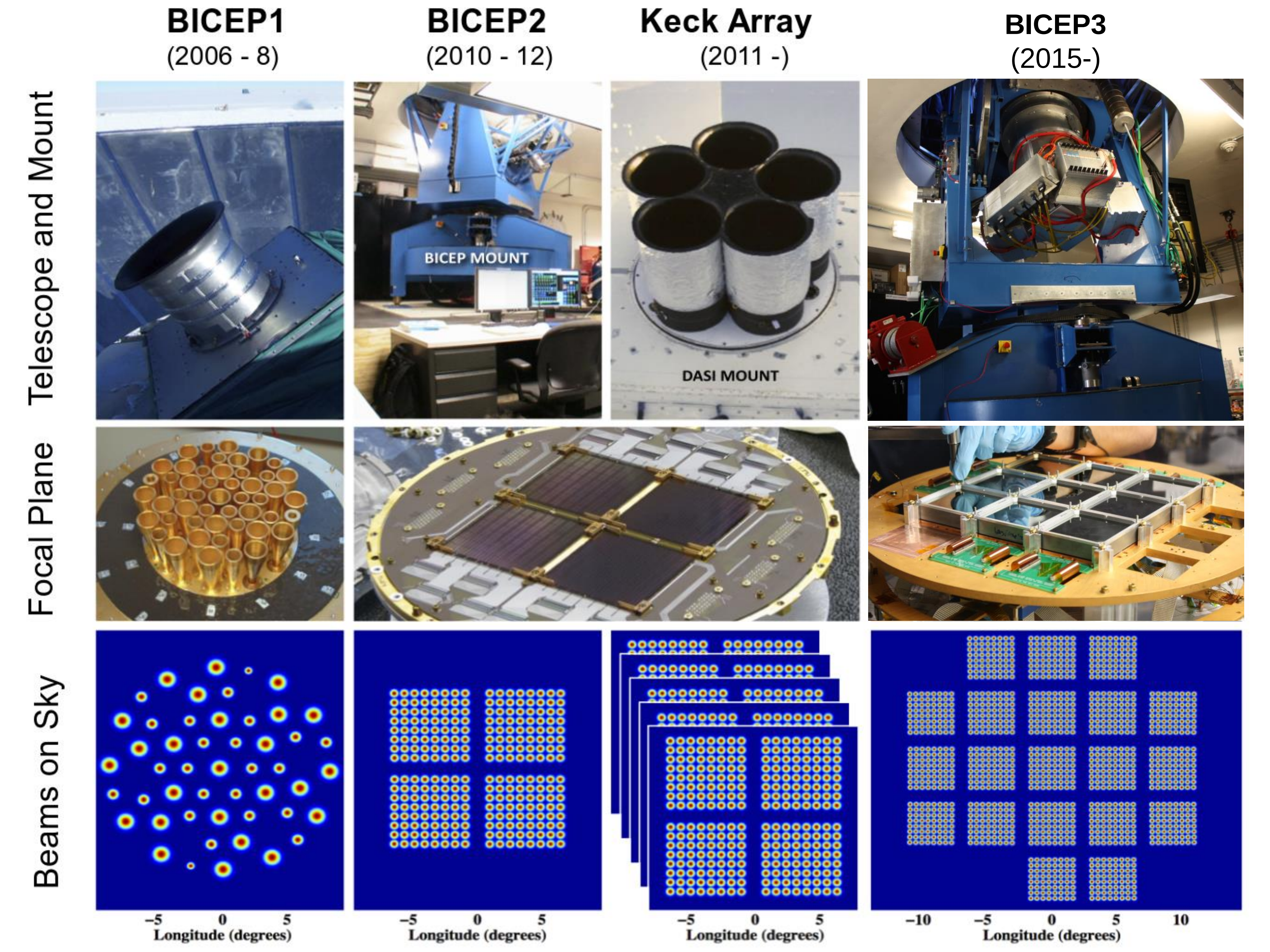
Noise uncertainty and signal levels in ℓ=80 bandpower

Noise uncertainty in P353 is the current limiting factor – to make further progress we need deep maps at frequencies other than 150 GHz.

Phys. Rev. Lett. 114, 101301 (2015)

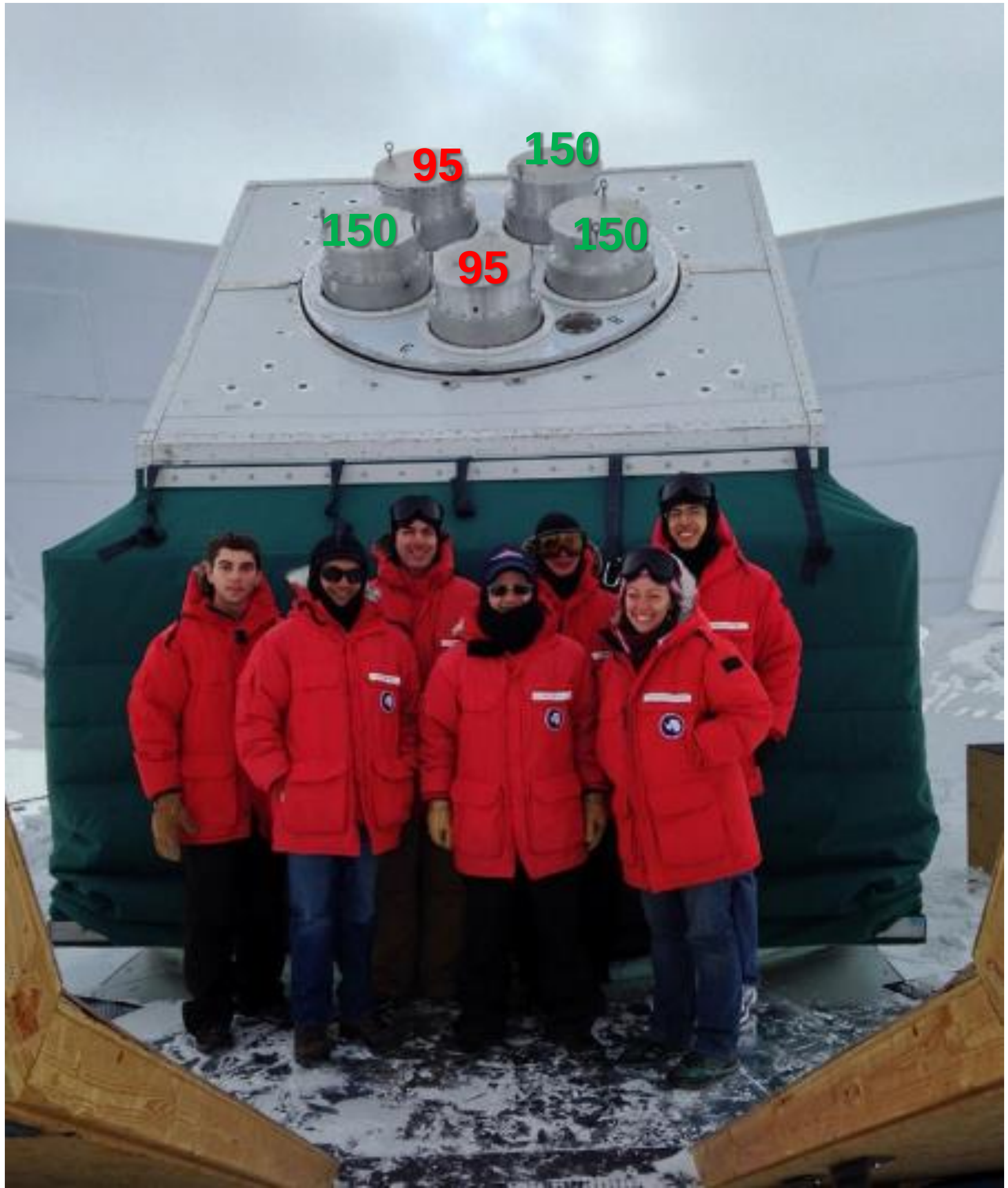
Detectors Designed to Scale in Frequency



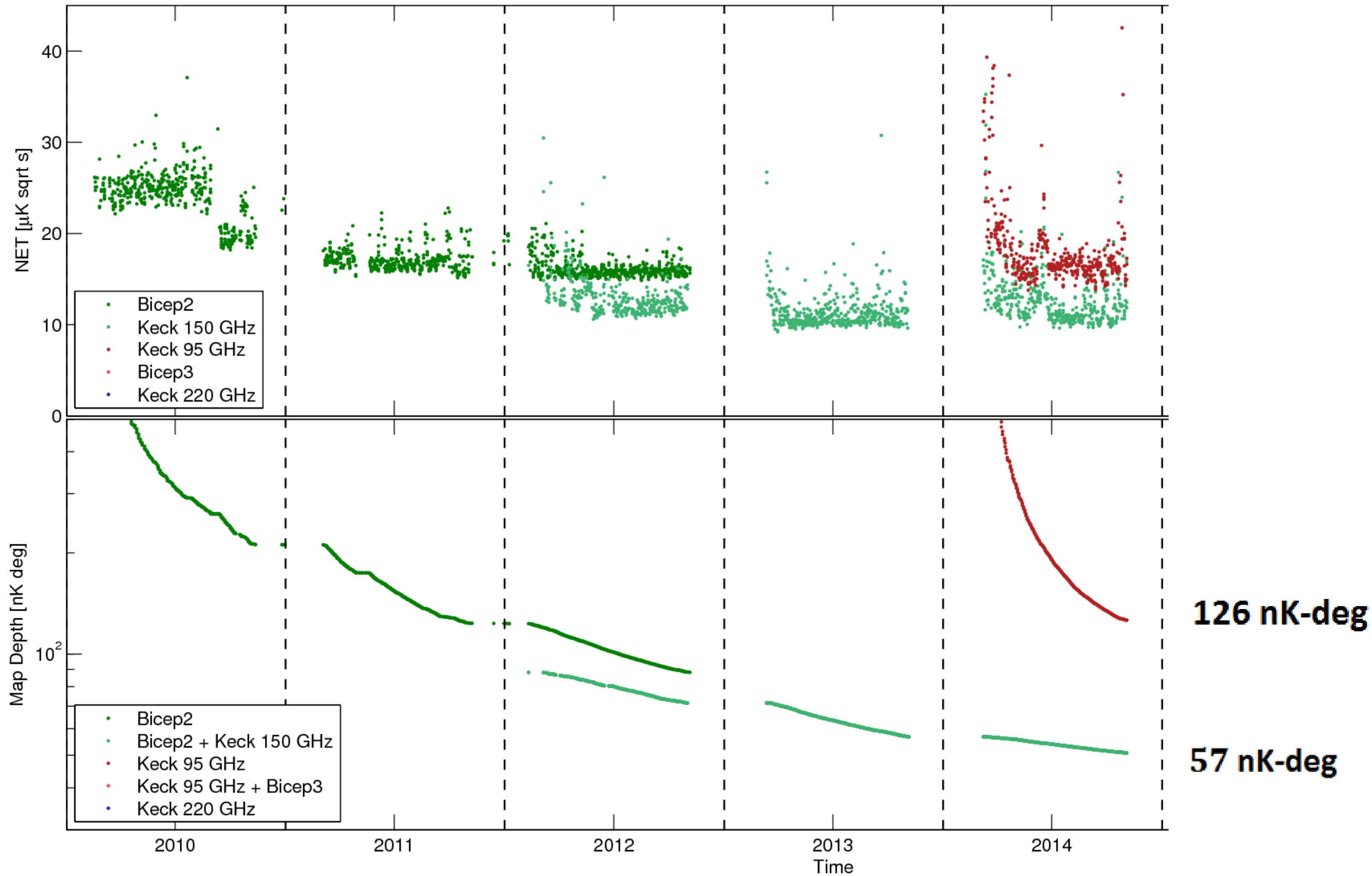


BICEP1
(2006 - 8)
BICEP2
(2010 - 12)
Keck Array
(2011 -)
BICEP3
(2015-)
Telescope and Mount
Focal Plane
Beams on Sky
BICEP MOUNT
DASI MOUNT
−5
0
5
Longitude (degrees)
−10
10

December 2013: Keck at two frequencies!

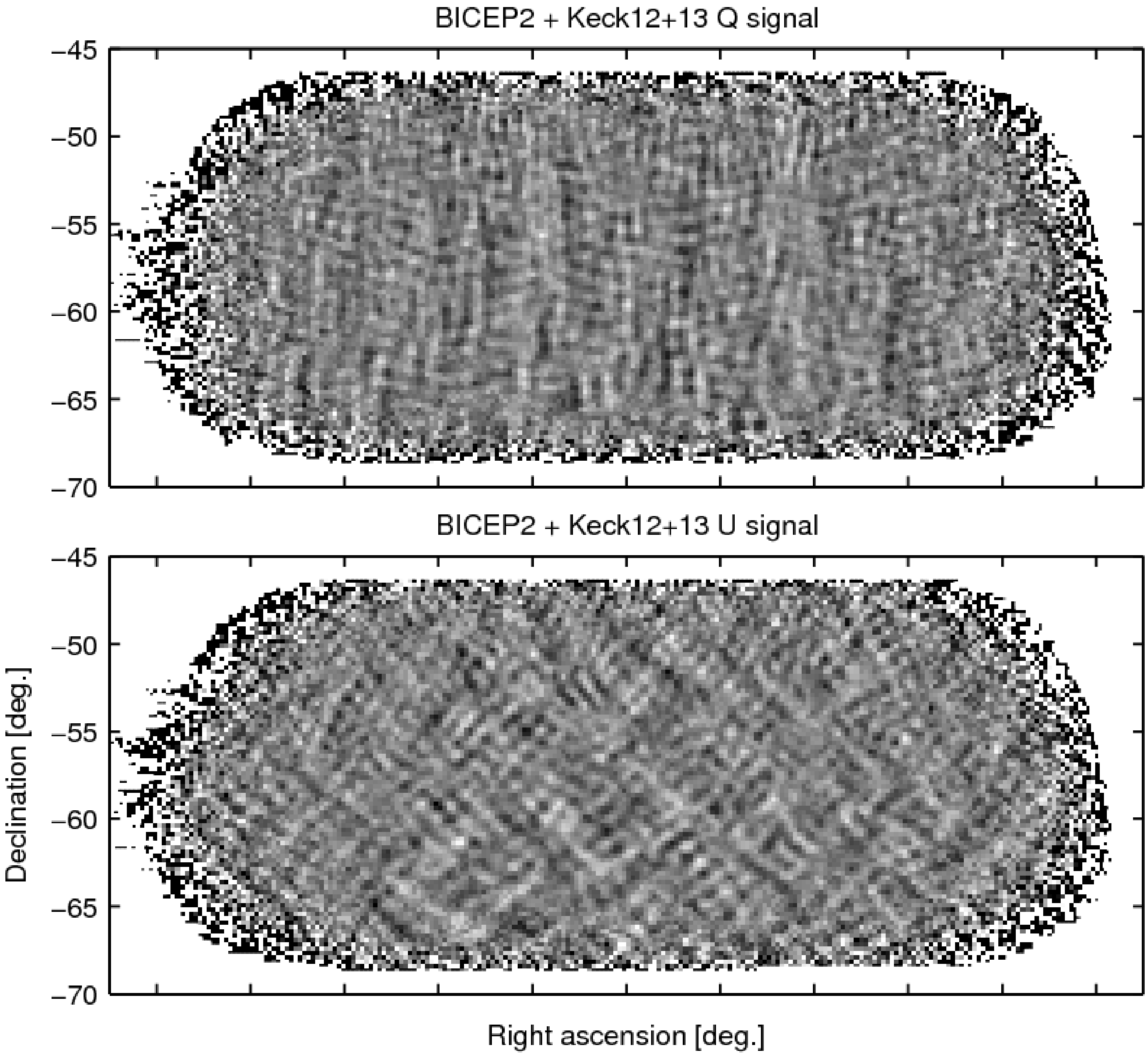


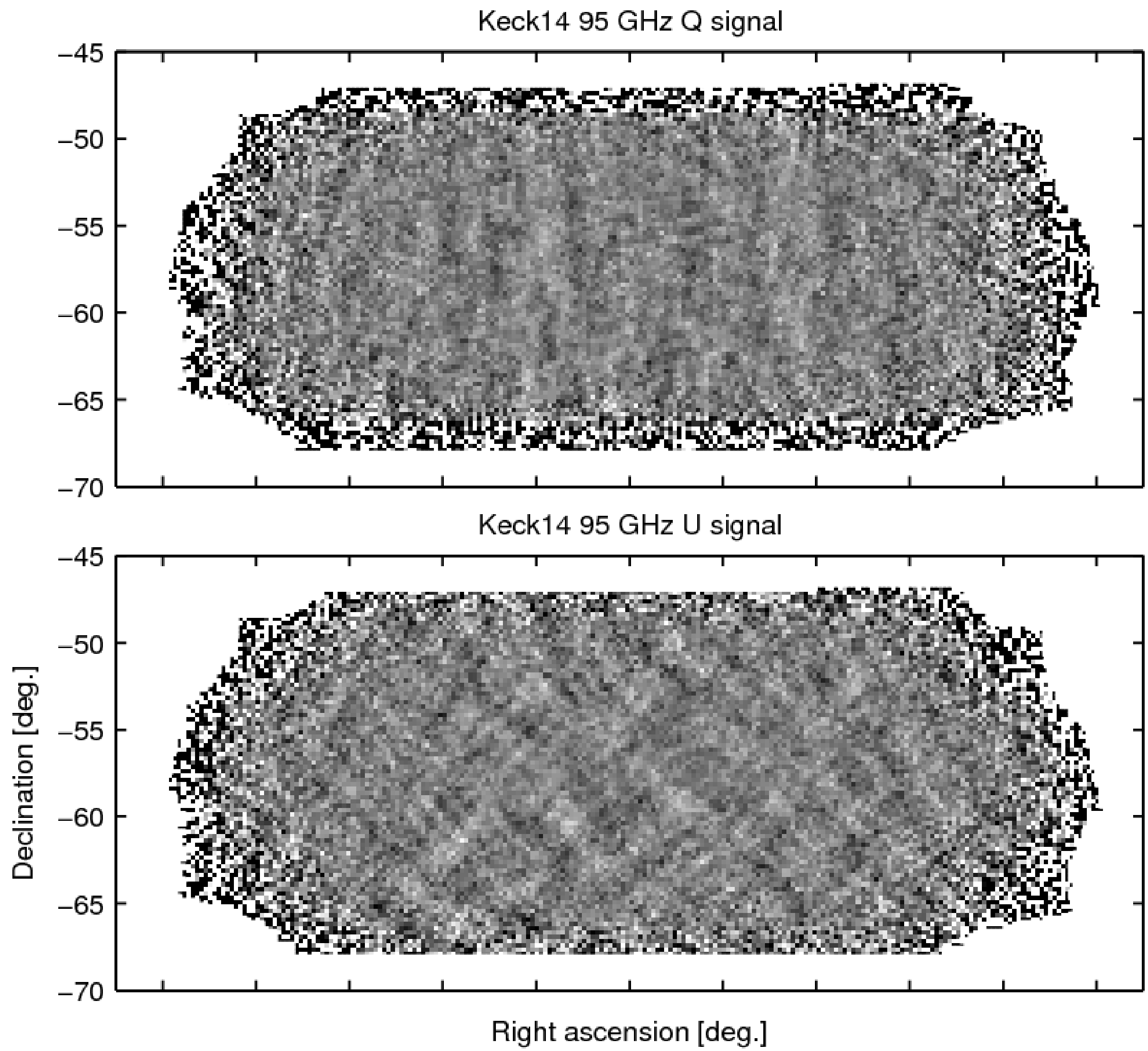
BK Sensitivity through 2014



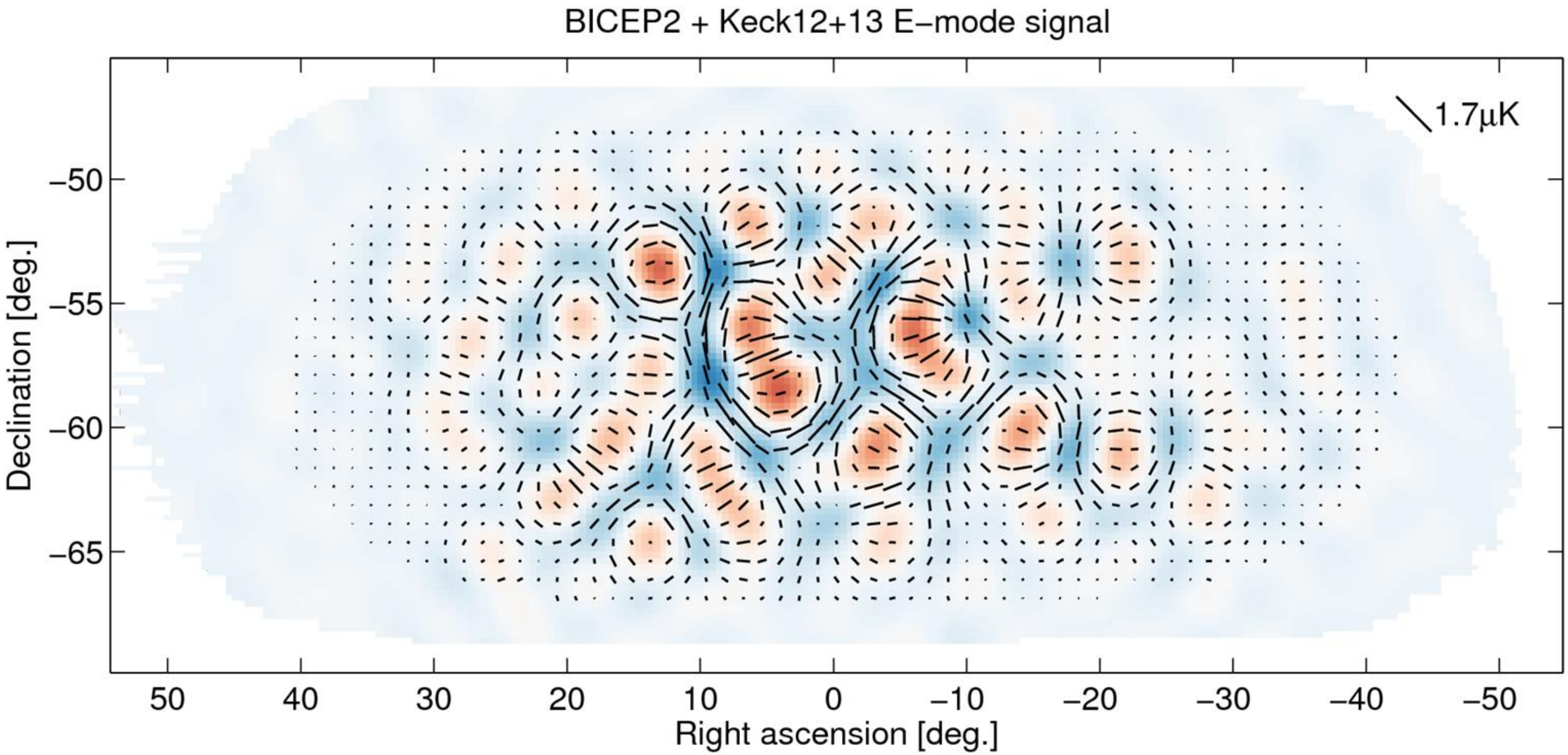
BK Sensitivity

	Q,U Map rms noise N [nk-deg] (μK-arcmin)	Survey effective area A [deg^2]	Total Q+U Survey Weight $W = 2A/N^2$ [μK^{-2}]
BICEP2	87 (5.2)	380	101,000
BICEP2 + Keck12+13	57 (3.4)	400	248,000
Keck14 95 GHz	126 (7.6)	375	47,000

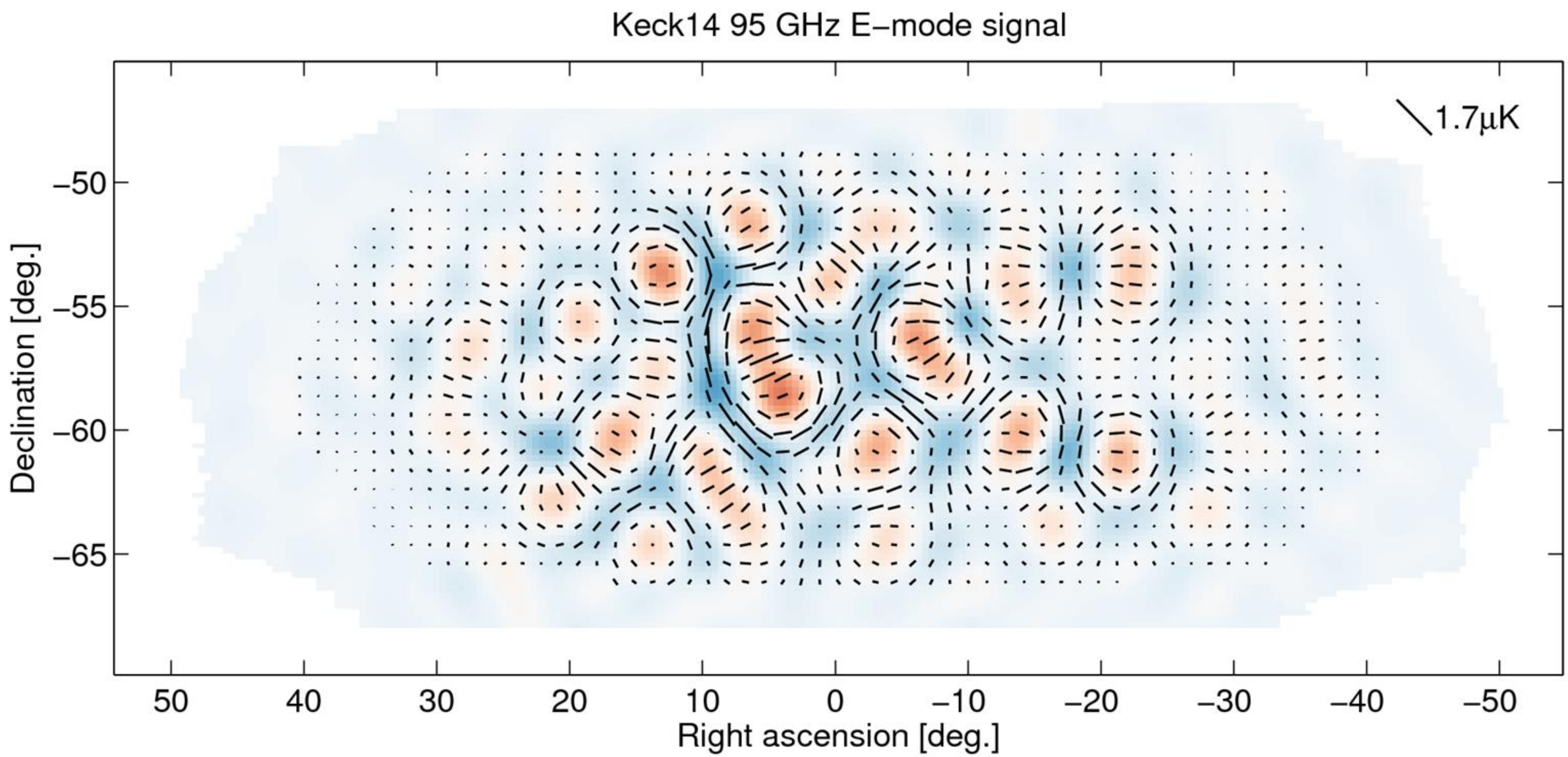

BICEP2 + Keck12+13 Q signal
BICEP2 + Keck12+13 U signal
−45
−50
−55
−60
−65
−70
Declination [deg.]
Right ascension [deg.]



Keck14 95 GHz Q signal
Keck14 95 GHz U signal
−45
−50
−55
−60
−65
−70
Declination [deg.]
Right ascension [deg.]

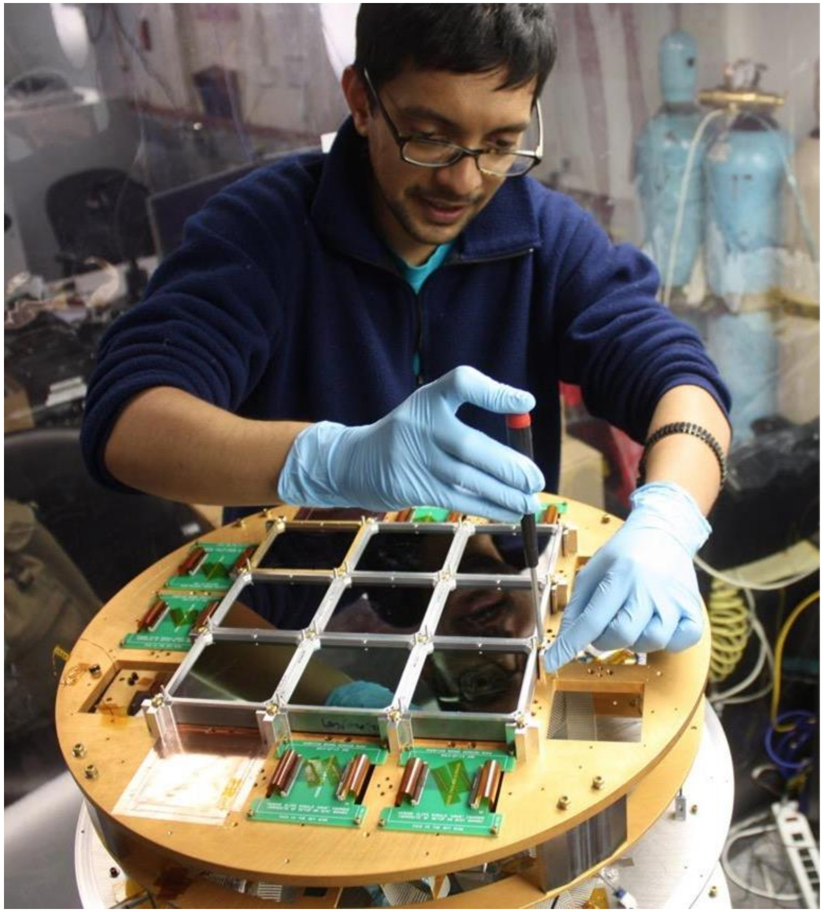


BICEP2 + Keck12+13 E−mode signal
1.7μK
−50
−55
−60
−65
Declination [deg.]
50
40
30
20
10
0
−10
−20
−30
−40
−50
Right ascension [deg.]



Reduction in amplitude with respect to 150 GHz due to increased beam size (which is uncorrected in these map plots)

New for 2015 – BICEP3 and Keck 220



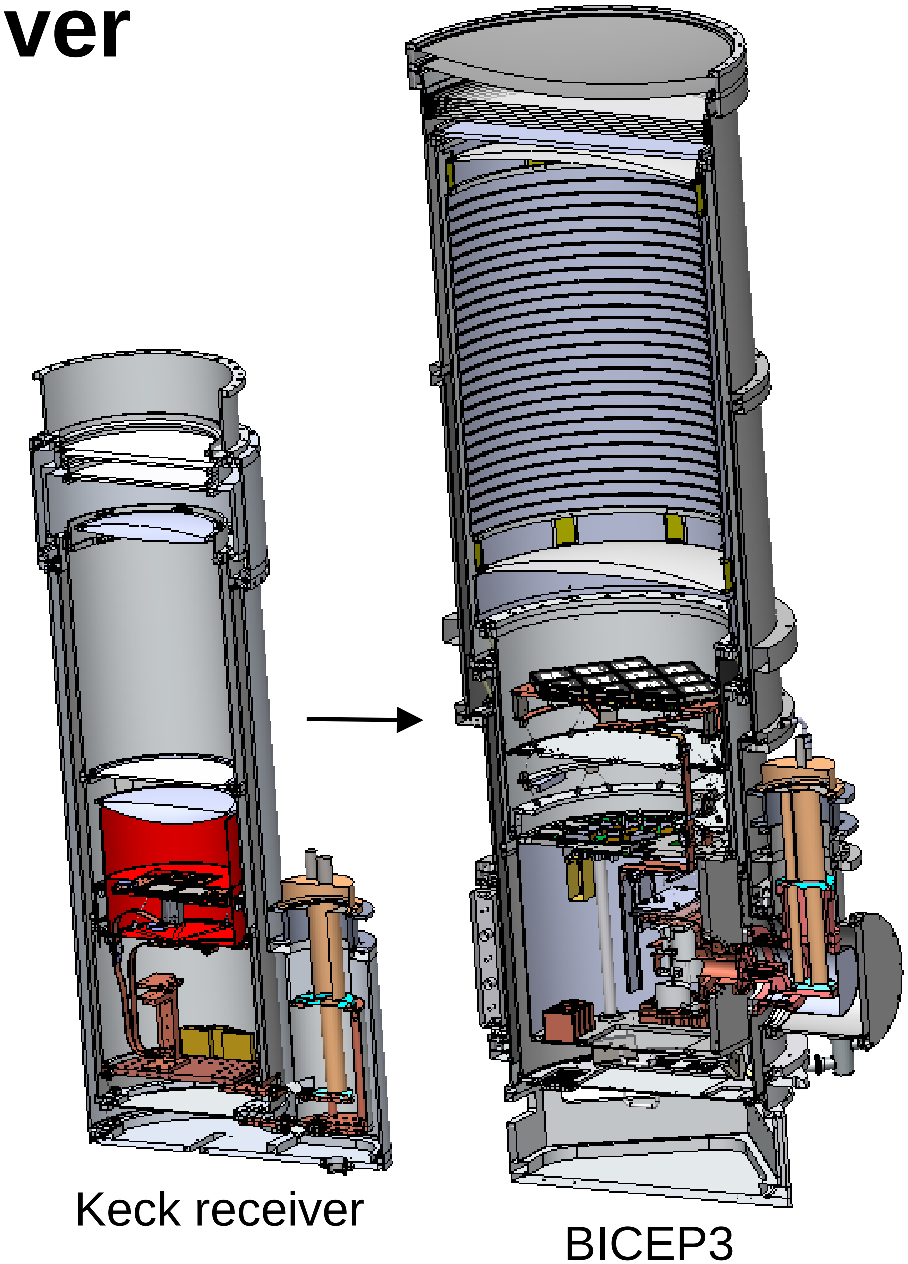
BICEP3: Super receiver

All 95 GHz

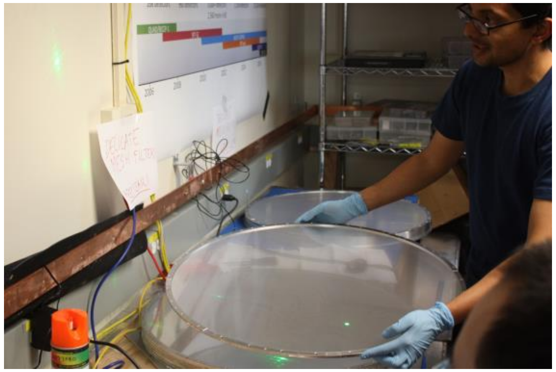
2560 detectors in modular focal plane
(45% populated in 2015)

Large-aperture optics and infrared filtering

10x optical throughput of single BICEP2/Keck receiver

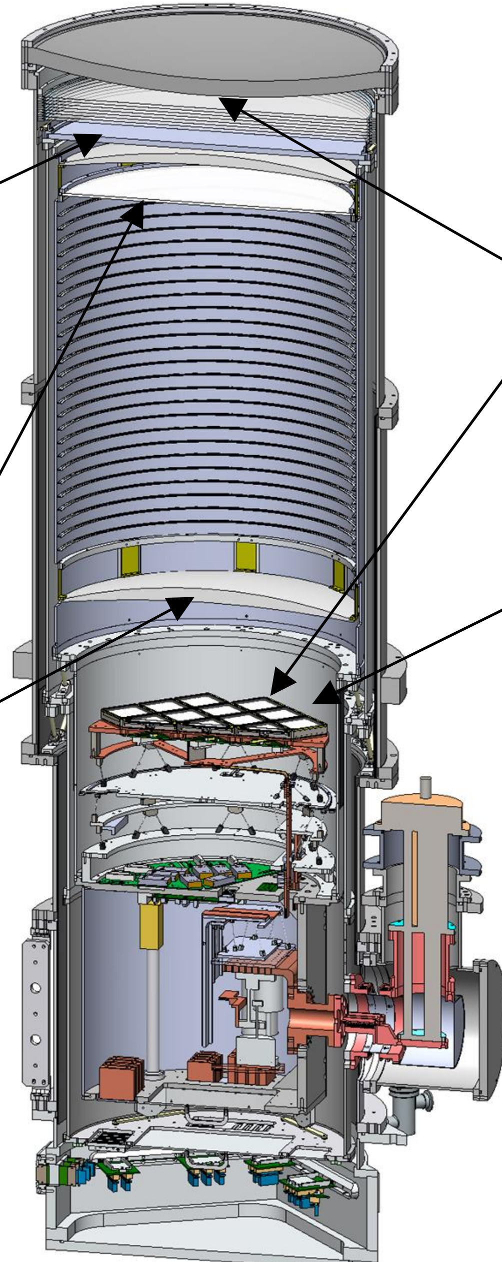


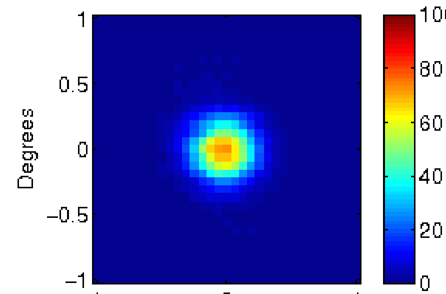
BICEP3 technology



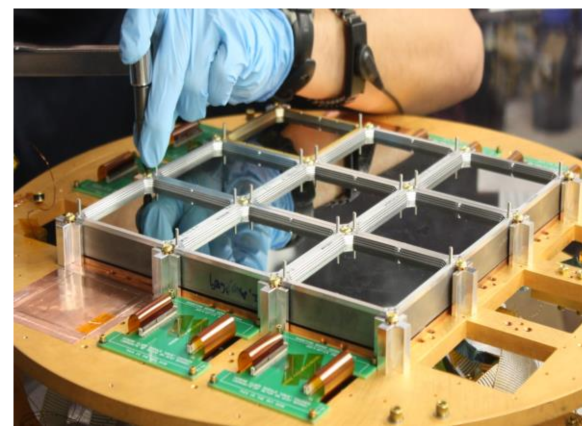
Large area Infrared shaders with ~O(10) micron aluminum features on mylar

Thin, low loss, high thermal conductivity alumina filters and lenses with epoxy-based antireflection coating





680-mm clear aperture window,
fast optics (f/1.6), FOV ~28°
95 GHz beam FWHM ~0.35°

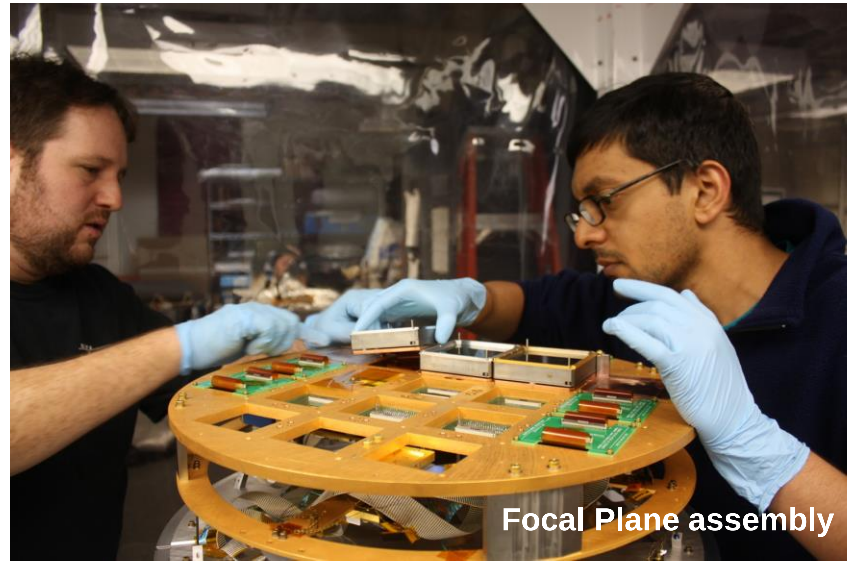


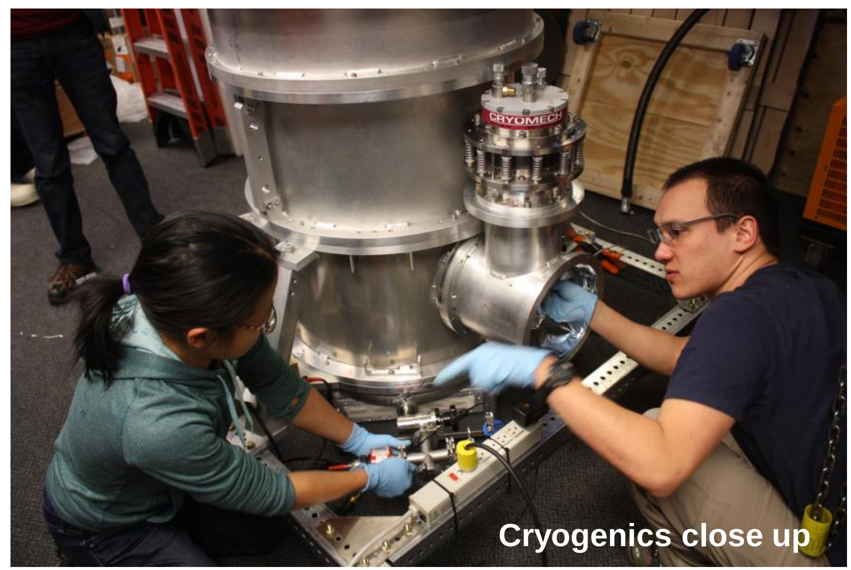
Plug & play detector modules each have 64 dual-pol 95 GHz camera pixels and contain cold multiplexing electronics.

BICEP3 in Harvard lab: October 2014

December 2015: BICEP3 assembly at South Pole

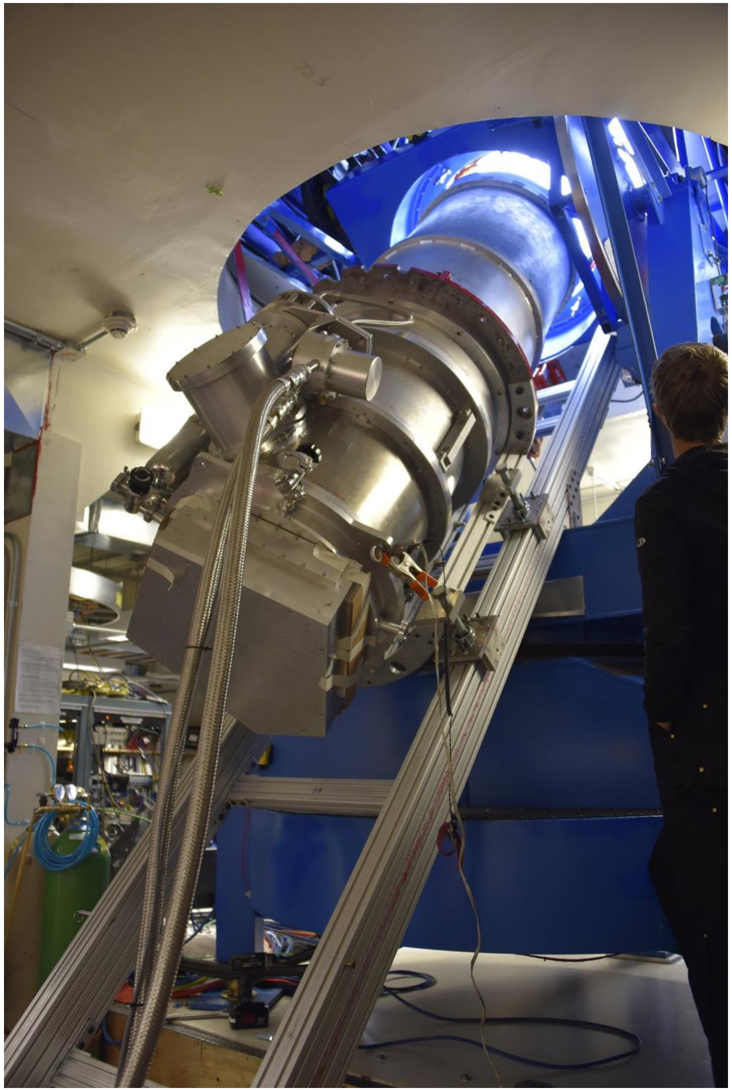

Optics tube installation


Focal Plane assembly



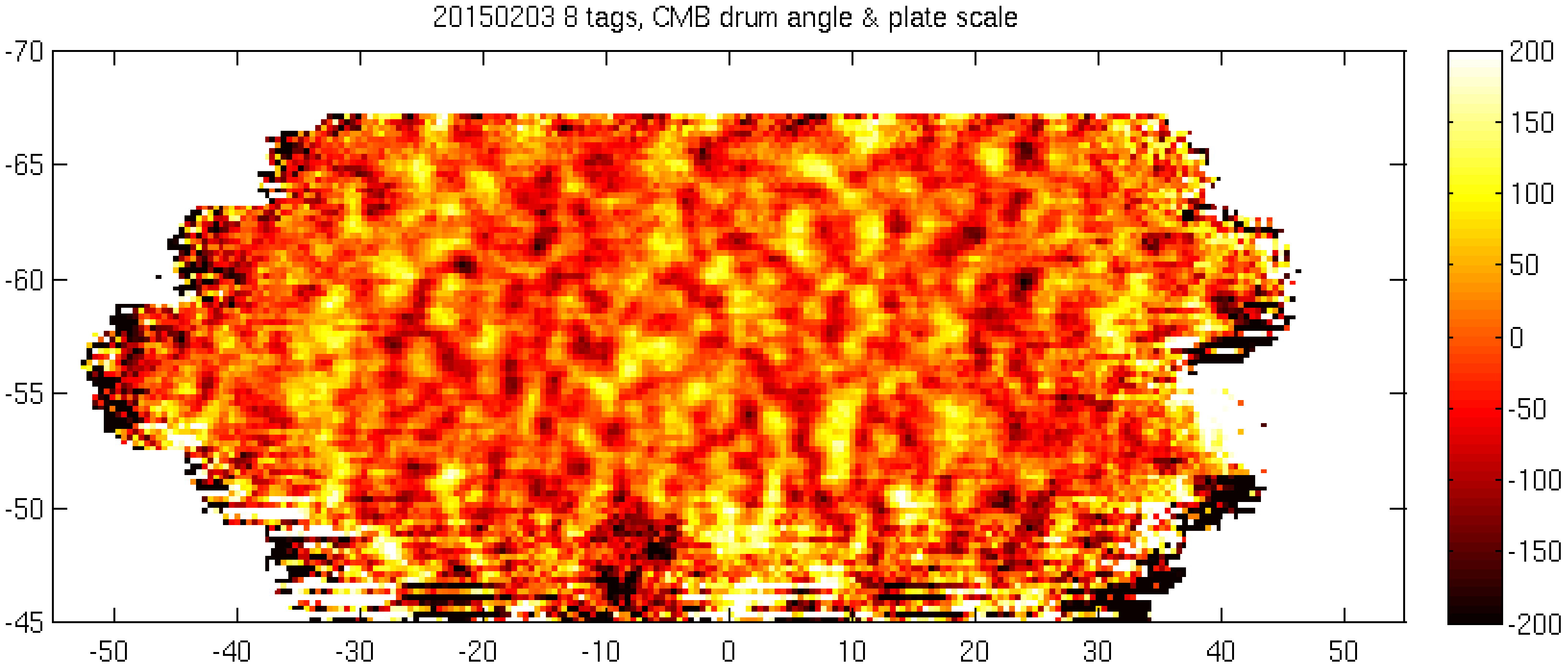
Cryogenics close up

January 2015: Installed in BICEP mount



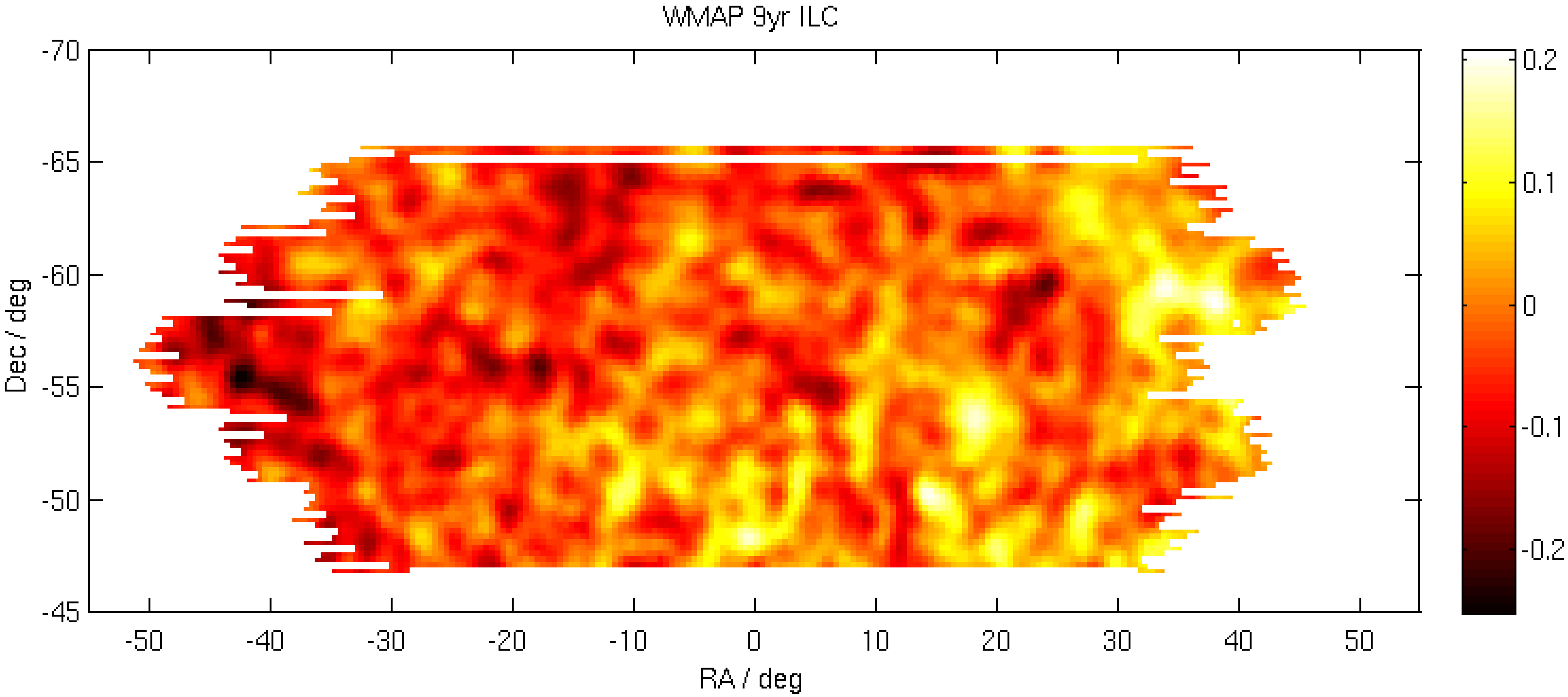
Replaces BICEP2 in Dark Sector Lab at South Pole

First light: See CMB T features in 6 hours!



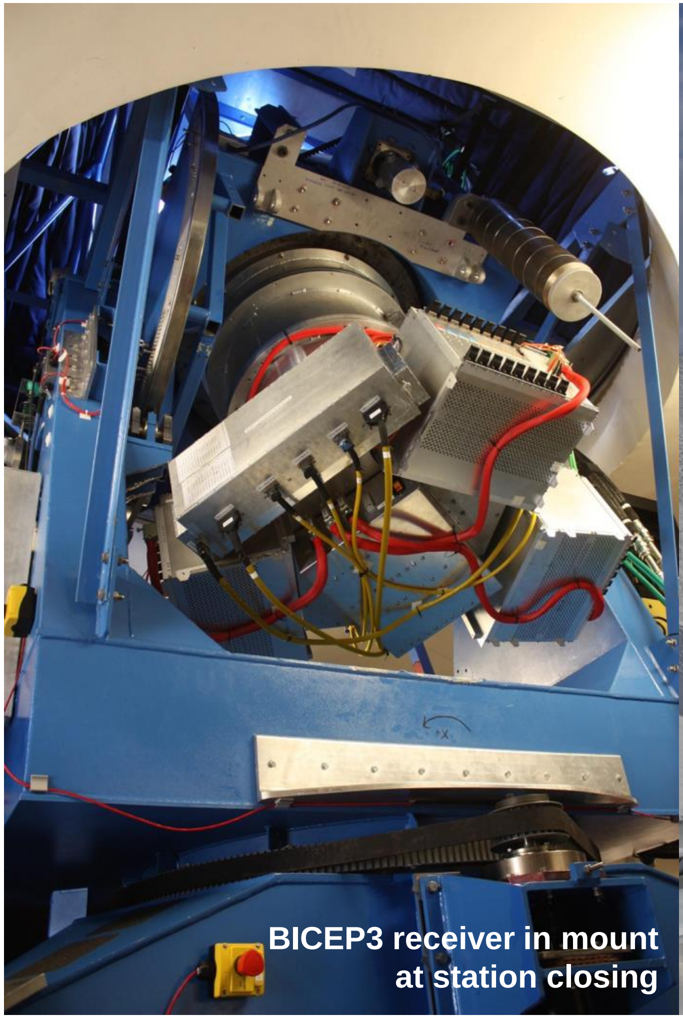
BICEP3 first six hours of test CMB scans,
no filtering, approximate noise weighting and calibration

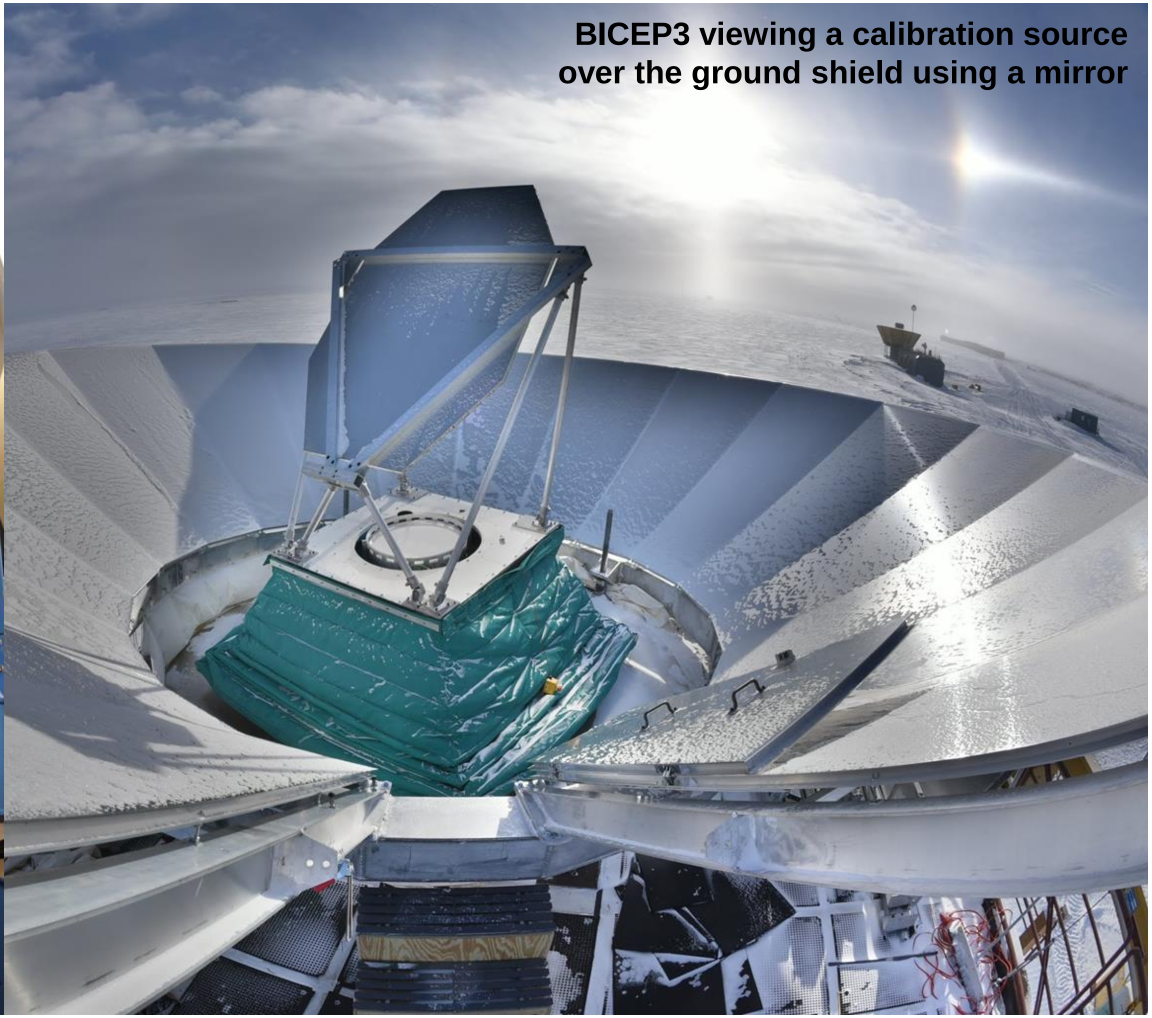
First light: Compare with WMAP 9 yr



WMAP 9yr T anisotropies as seen in BICEP field

Feb - Mar 2015: Winter prep and calibration before CMB observation



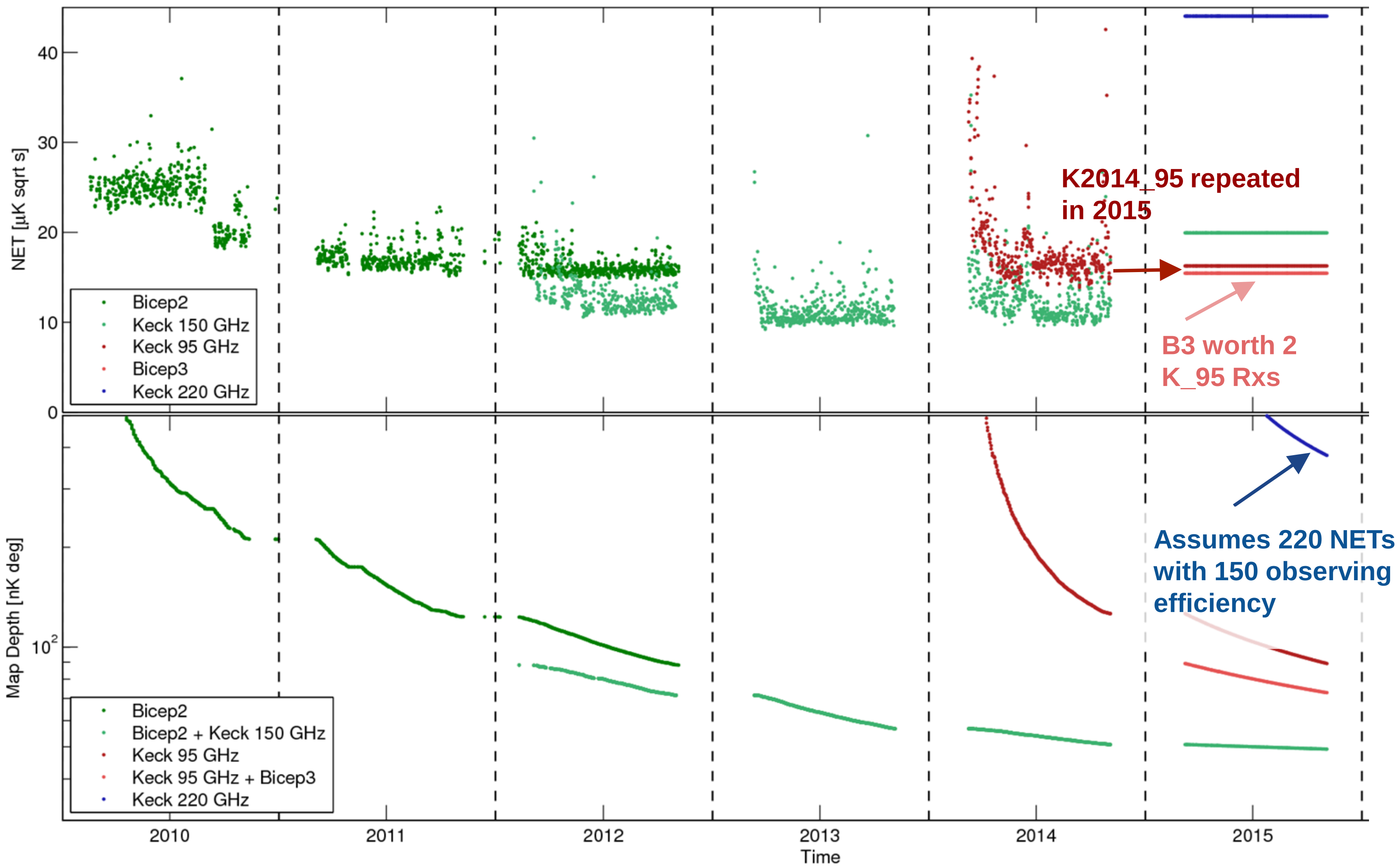


Also now installed: Keck Array 220 GHz

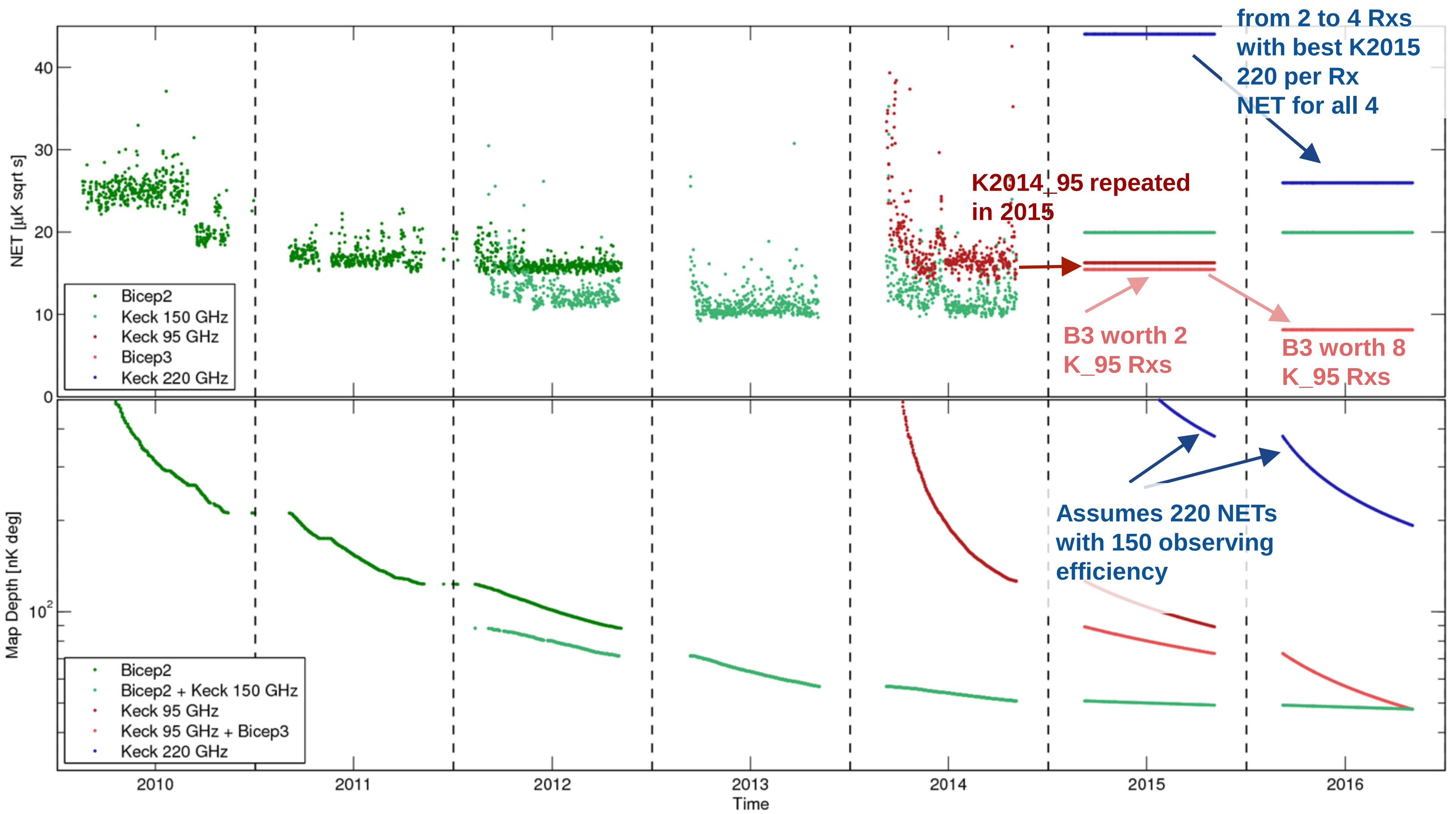
January 2015: Tri-color Keck!

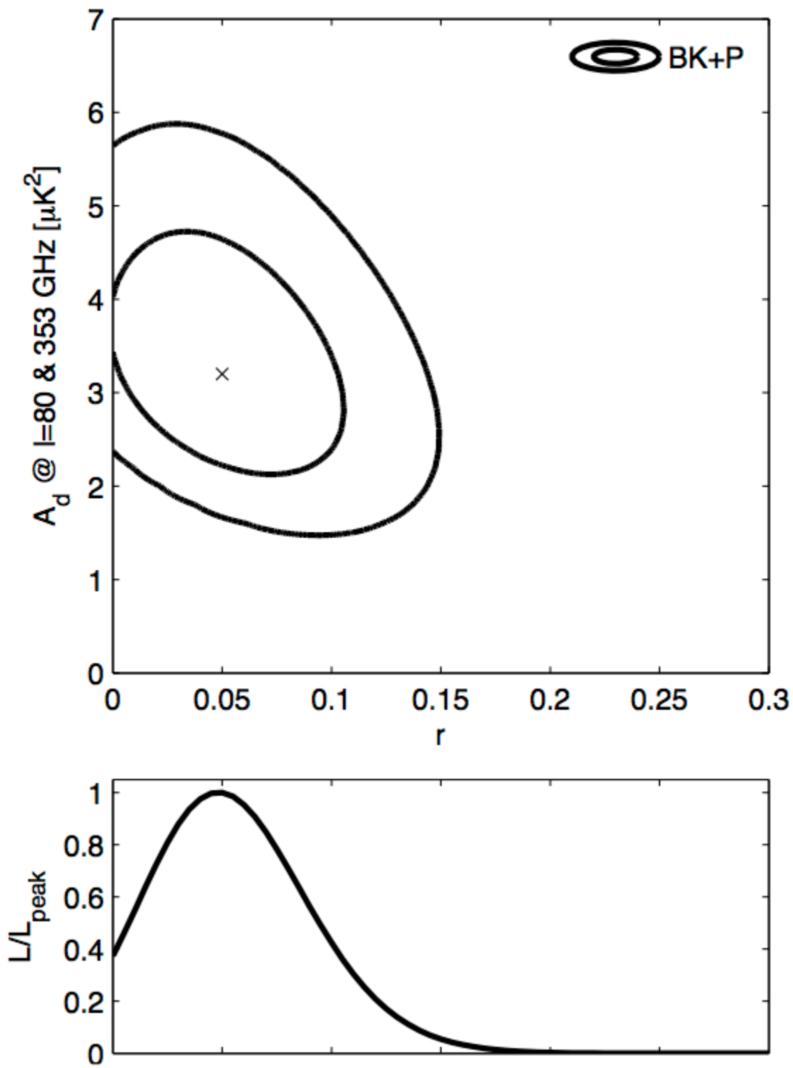
Keck receivers in 2015:
2 x 95 GHz, 1 x 150 GHz, 2 x 220 GHz

BK Sensitivity Projection: 2015



BK Sensitivity Projection: 2016





Data Included:

- BK150 (2013)
- Planck, 217 and 353 GHz

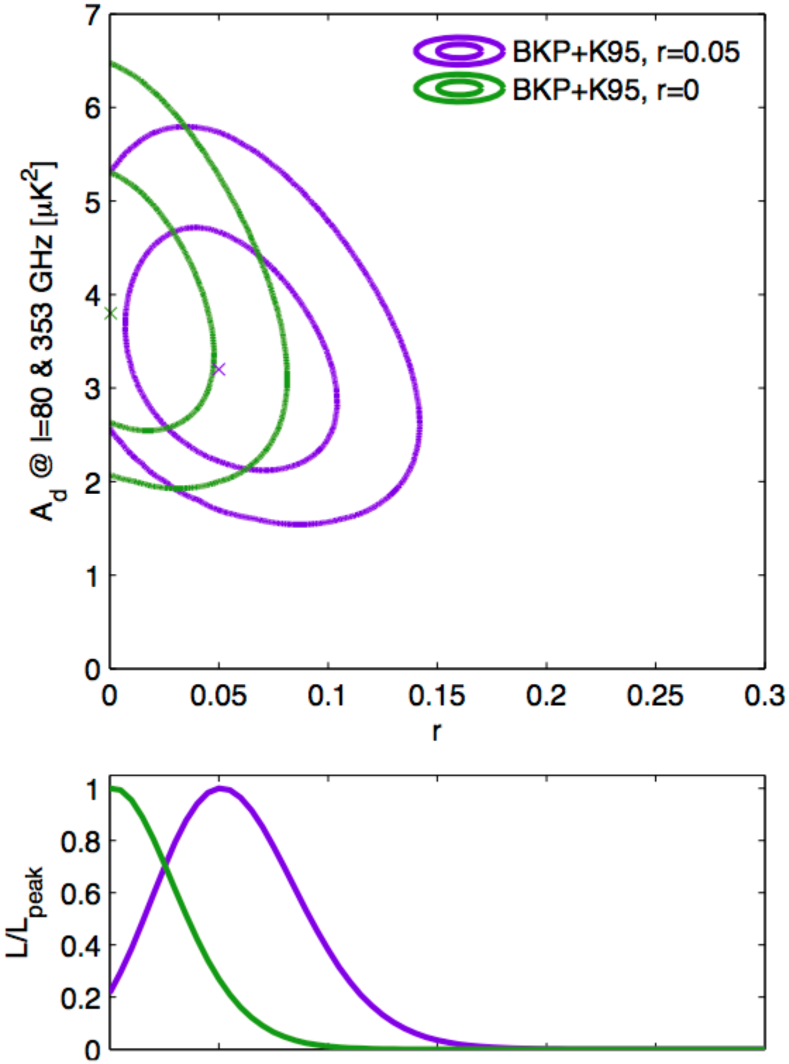
Likelihood results from a basic lensed-ΛCDM+r+dust model, fitting the 5 lowest bandpowers of the BB auto- and cross-spectra taken between maps at the above frequencies

The Maximum likelihood on the grid has:
$r = 0.05$, $A_d = 3.3\ \mu K^2_{CMB}$ (BKP ML point)

For dust SED use modified blackbody model and marginalize over range $\beta_d = 1.59 \pm 0.11$

We assume no synchrotron contribution

Foregrounds only PTE = 8.0%



Data Included:

- BK150 (2013)
- Planck, 30 - 353 GHz
- Keck (2014), 95 GHz

Contours are projected likelihood contours centered on different expectation values:

$r = 0.05$, $A_d = 3.3\ \mu K^2_{CMB}$ (BKP ML point)

$r = 0$, $A_d = 3.8\ \mu K^2_{CMB}$

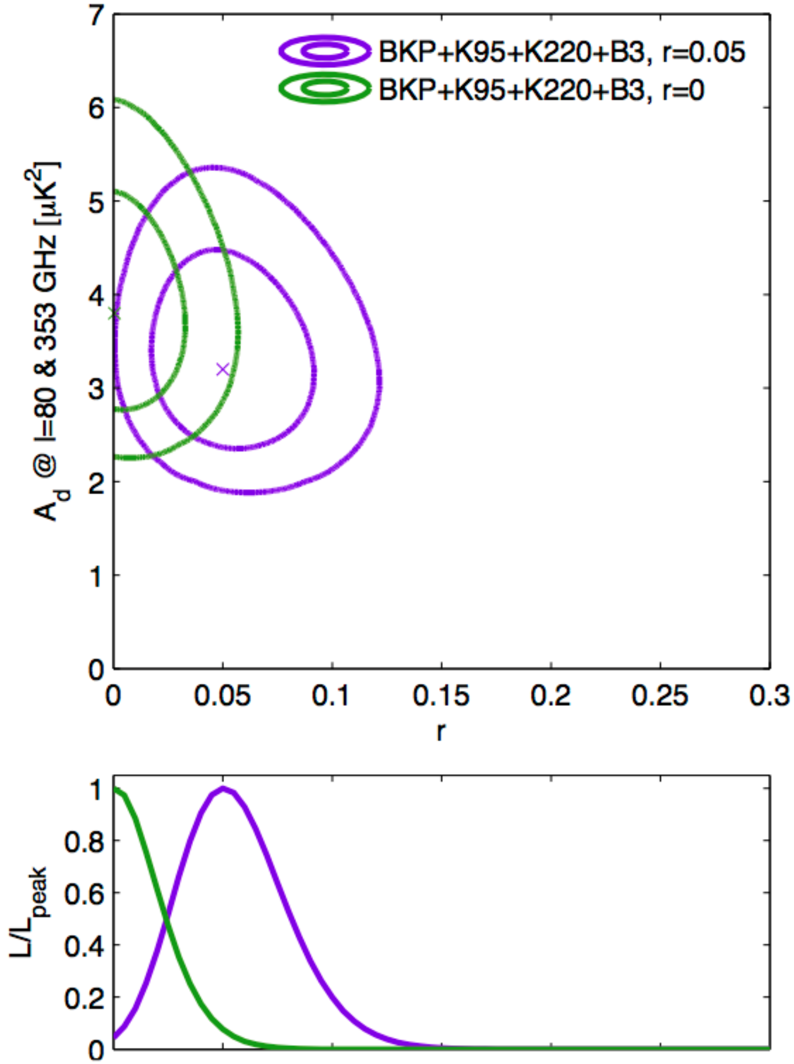
Of course we can't predict how the actual data will shift

Both cases here assume synchrotron contribution, β_s=-3.3 and A_{sync} = 3e-4 μK^2_{CMB} (current BKP 95% upper limit)

$r < 0.060$ (95%) [0.062 if β_s=-3.0]

— or —

Foregrounds only PTE = 4.0% [4.3% if β_s=-3.0]



Data Included:

- BK150 (2013)
- Planck, 30 - 353 GHz
- Keck (2014 + 2015), 95 GHz
- Keck (2015), 220 GHz
- BICEP3 (2015), 95 GHz

Contours are projected likelihood contours centered on different expectation values:

$r = 0.05$, $A_d = 3.3\ \mu K^2_{CMB}$ (BKP ML point)

$r = 0$, $A_d = 3.8\ \mu K^2_{CMB}$

Of course we can't predict how the actual data will shift

Both cases here assume synchrotron contribution, β_s=-3.3 and A_{sync} = 3e-4 μK^2_{CMB} (current BKP 95% upper limit)

r < 0.041 (95%) [0.043 if β_s=-3.0]

— or —

Foregrounds only PTE = 0.6% [0.9% if β_s=-3.0]

Conclusions – Right Now

Last March BICEP2 reported a detection of B-mode polarization in the CMB at 150GHz well in excess of the standard model expectation

- This signal is confirmed by new data from Keck Array

We have done a joint analysis with Planck - The fundamental conclusion is that dust is detected at high significance, and $r < 0.12$ at 95% confidence.

- Multi-component likelihood gives $\sigma(r) \sim 0.035$ -- This is a very direct constraint on tensors!
- No significant evidence for $r > 0$. Currently $r = 0$ and $r = 0.1$ are at equal likelihood
- There may yet be a gravitational wave signal, but if there is it must be considerably smaller than the full signal.

Additionally, lensing B-modes are detected at 7.0 σ significance

Noise in P353 is the current limiting factor

- To make further progress, we need better data at frequencies other than 150 GHz

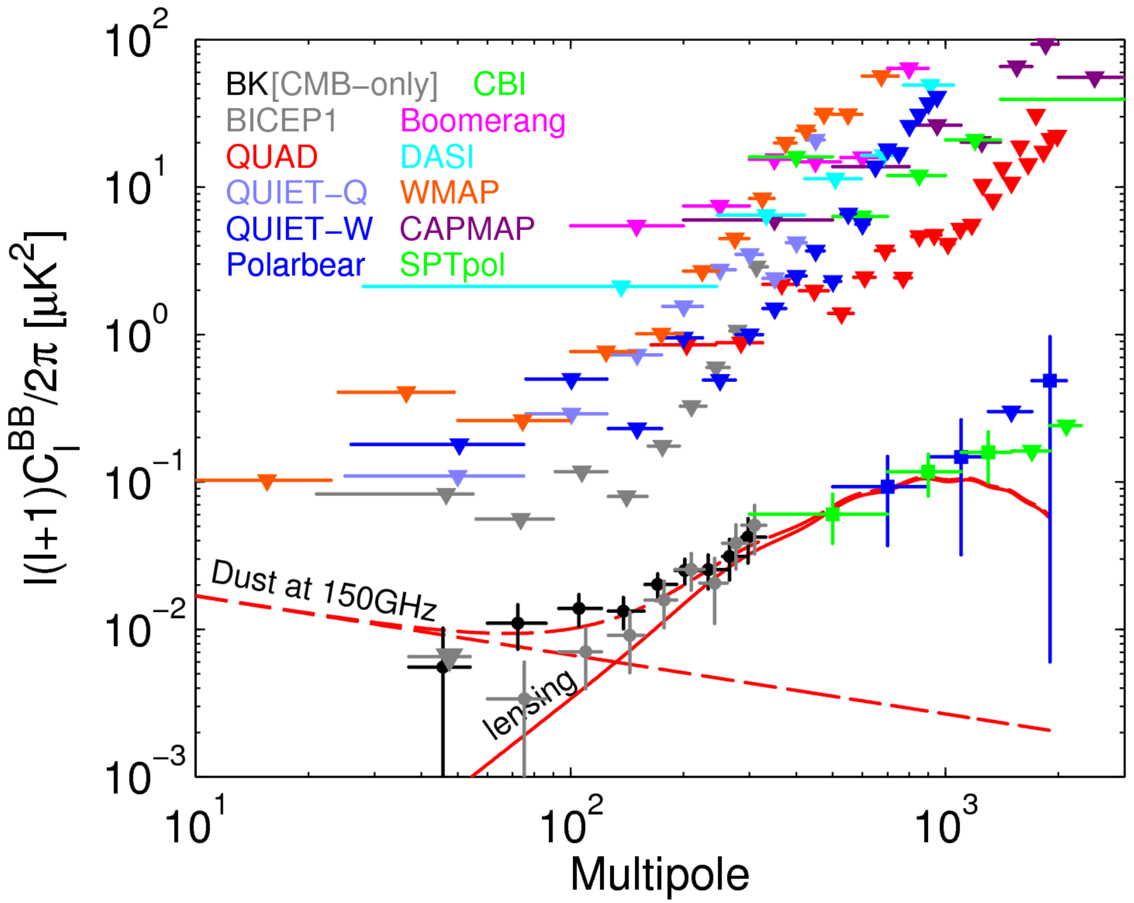
Conclusions – Coming Soon

Keck 95 GHz ~ next few months

- Maps are already nearing B2 sensitivity, 5x lower dust

BICEP3 + Keck 220 GHz ~ by end of 2015

- Deep maps at 220 GHz coming
- 95 GHz (BICEP3 + Keck) will soon surpass 150 GHz
- At this ultra-deep level, we can expect to learn a lot quickly about FG discrimination



More joint analyses to come: SPTpol, others soon?


Stay tuned !