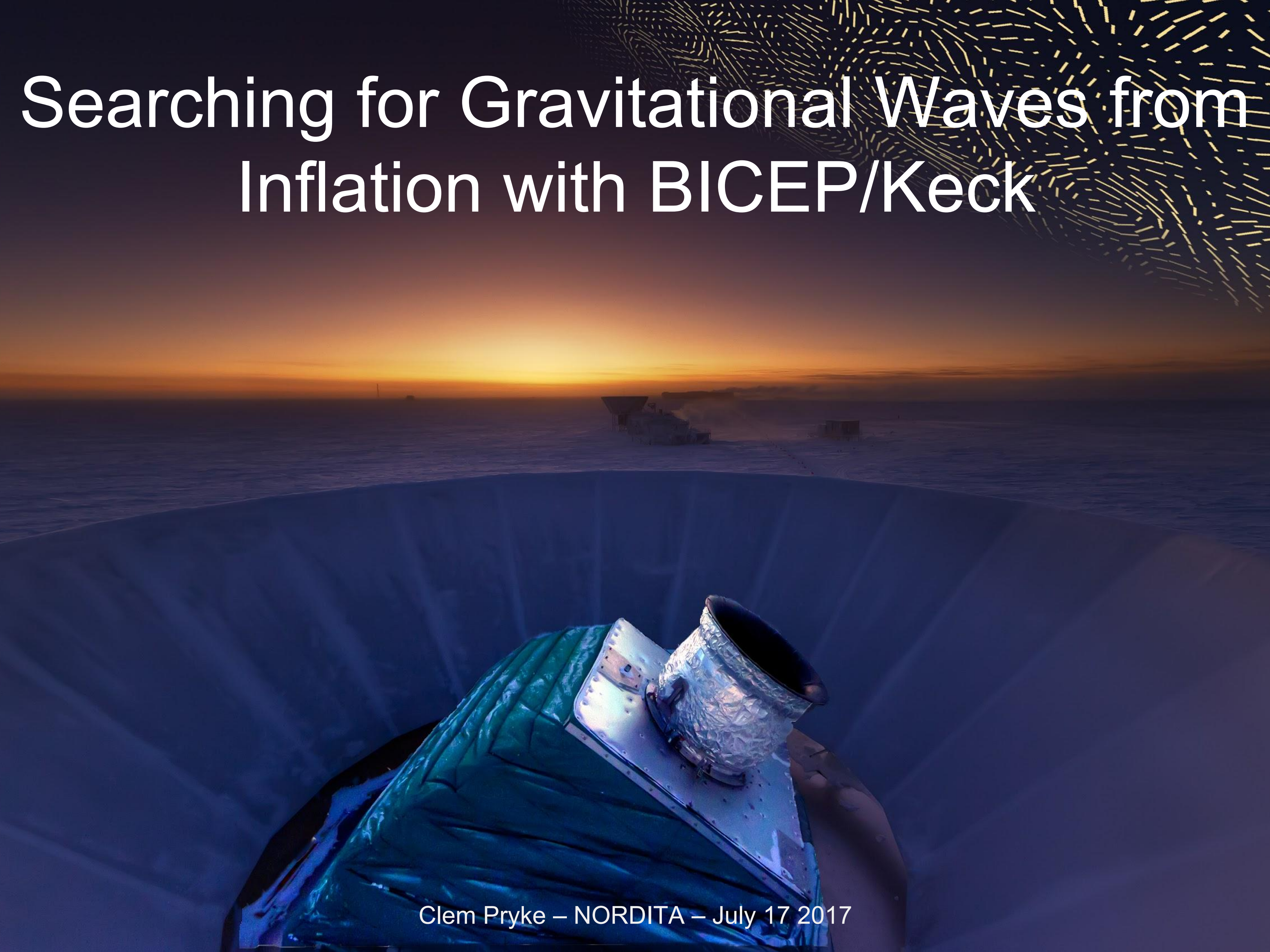
Searching for Gravitational Waves from Inflation with BICEP/Keck



Clem Pryke – NORDITA – July 17 2017

Cosmic Microwave Background (CMB)

The CMB traces the conditions of the universe at the time when atoms first began to form.

Consistent with the inflationary paradigm:

Inflation checklist:

✓ Flat geometry *(Ω_k < 0.005)*

✓ Superhorizon correlation

✓ Harmonic peaks (9+)

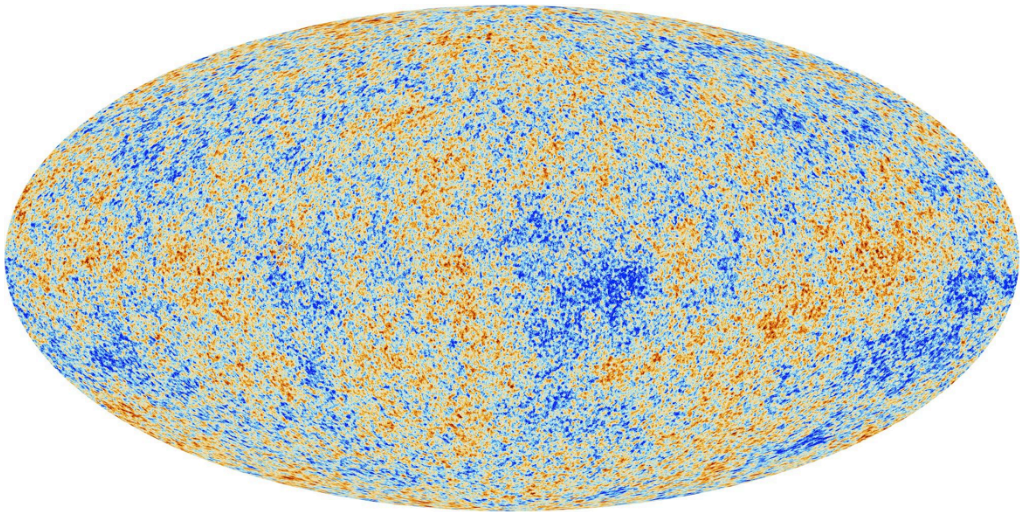
✓ Gaussian random fields

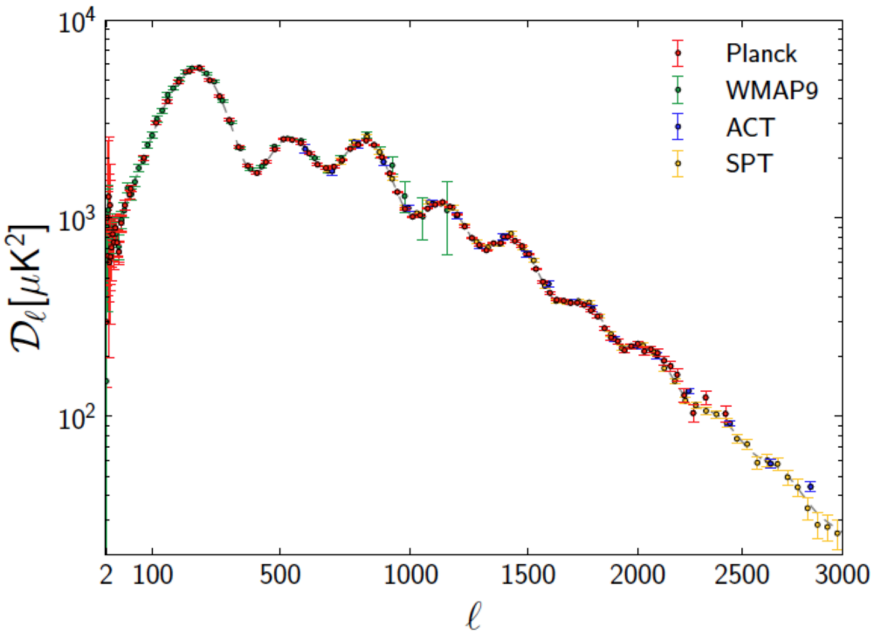
(fNL^{local} = 0.8 ± 5.0,
fNL^{equil} = −4 ± 43,
fNL^{ortho} = −26 ± 21)*

✓ Departure from scale invariance!

(n_s = 0.968 ± 0.006)

__ Inflationary gravitational waves (tensors) (r < 0.11)

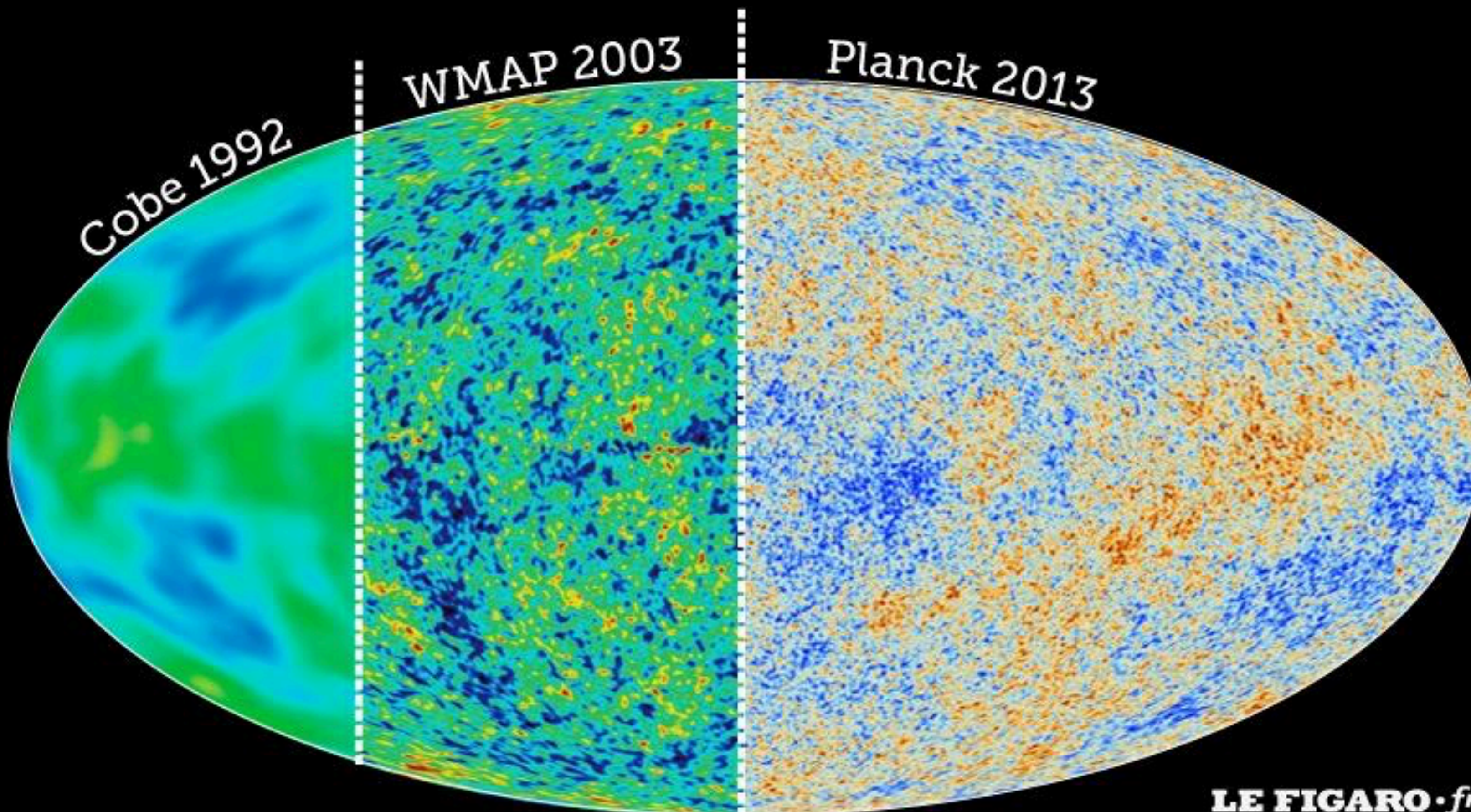




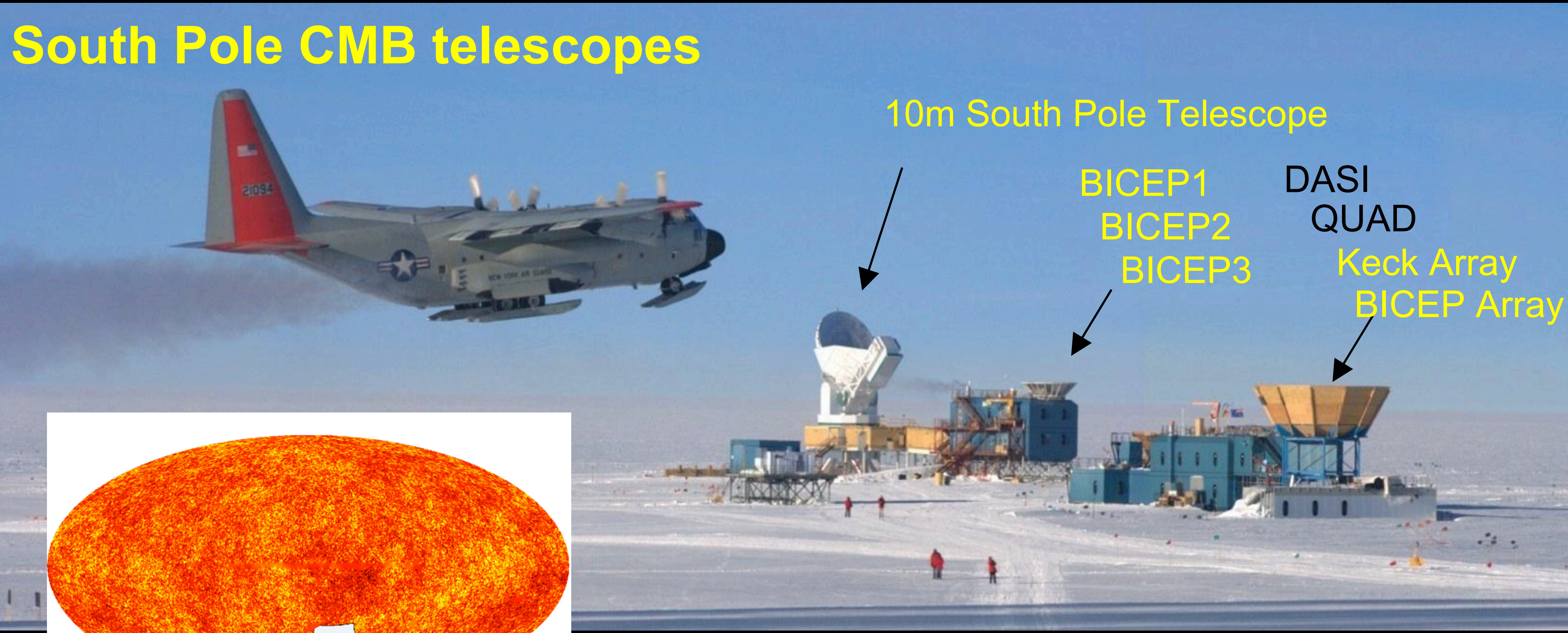
Planck Collaboration & ESA

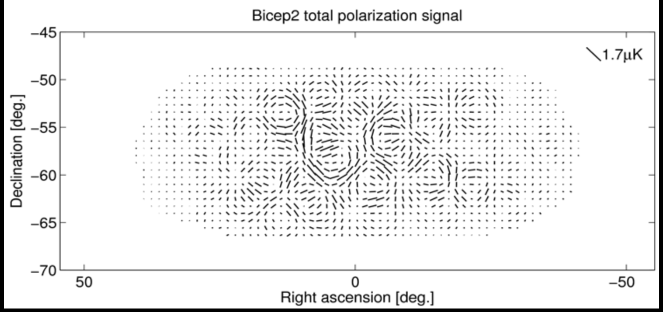
The BICEP/Keck Collaboration

Satellites map the full sky

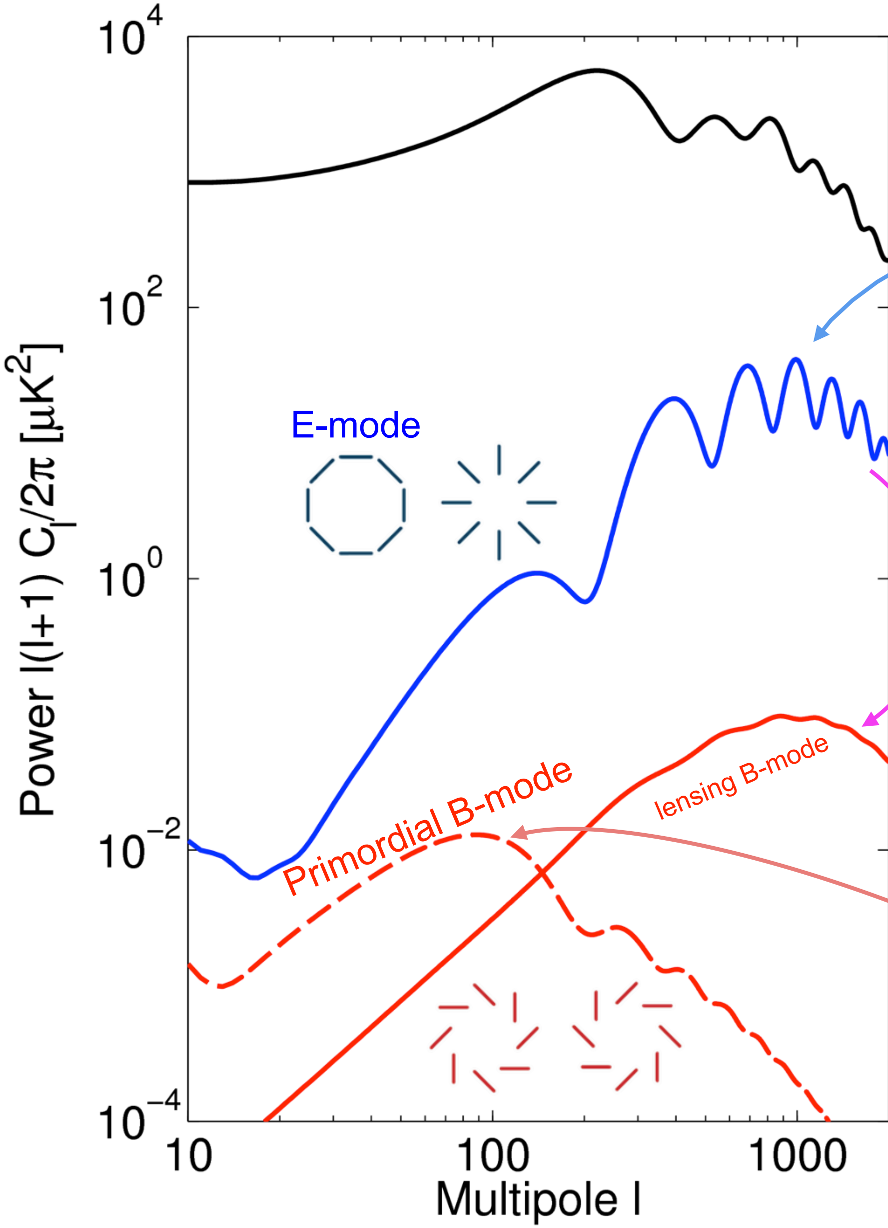


Ground based telescopes map part of the sky more deeply

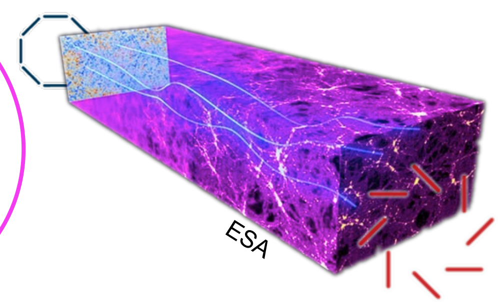




CMB Polarization power spectra



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

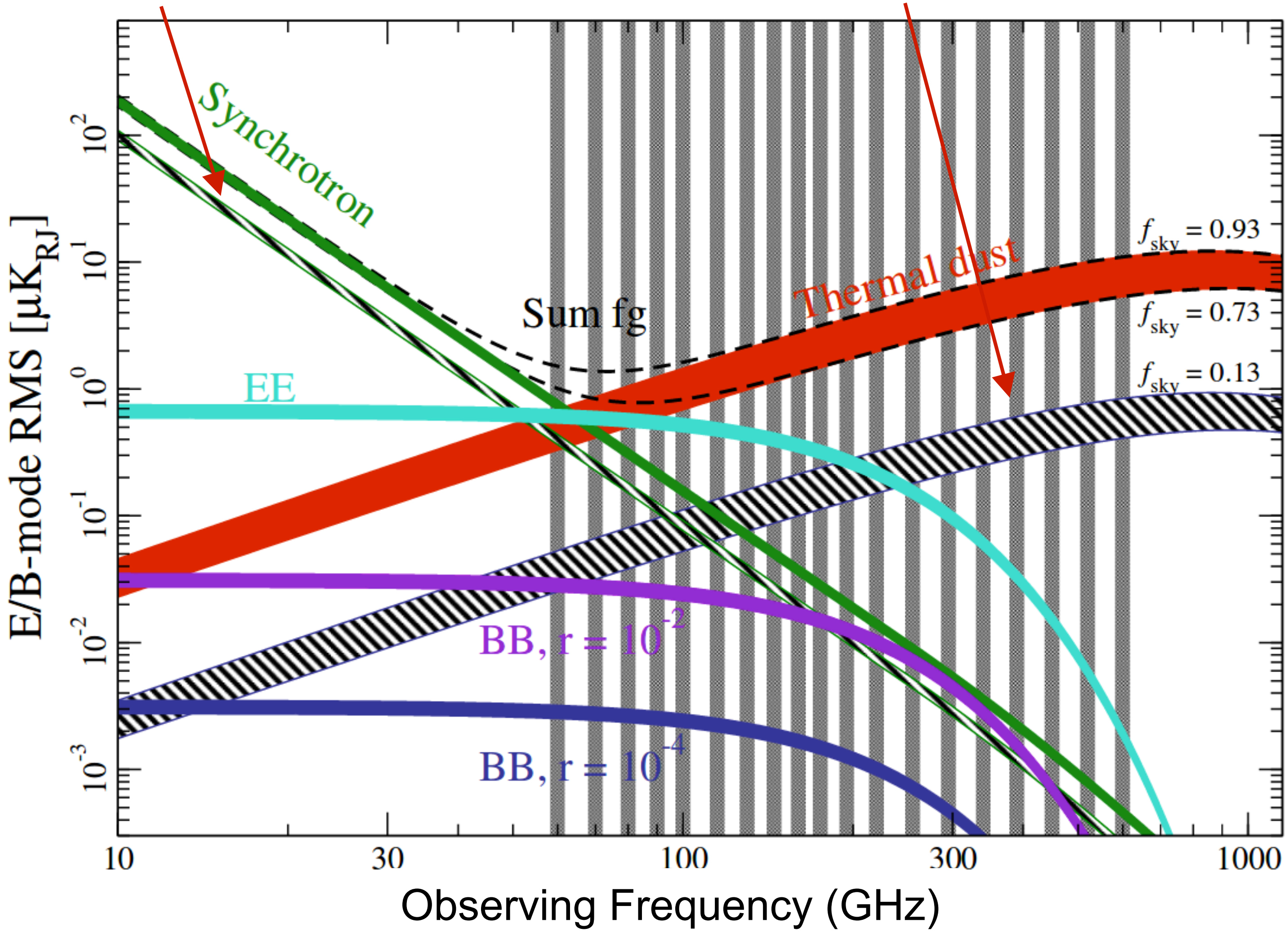
Inflationary gravitational waves are unique source of intrinsic B-modes
→ peaking at l≈80 : degree scales

The BICEP/Keck Collaboration

Polarized Foreground Contamination from Our Galaxy

At low frequency synchrotron contamination

At high frequency dust contamination



Big sky area

Cleanest small sky patch

From arxiv/ 1704.04501

This plot from recent CORE paper suggests foreground minimum in the cleanest patches around 100 GHz and equivalent to r~0.03 – consistent with what we are finding in the BICEP/Keck patch

VE RI TAS
HARVARD

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891

Experimental Strategy

→ Small aperture telescopes (cheap, fast, low systematics)
→ Target the 2 degree peak of the B-mode
→ Integrate continuously from South Pole
→ Observe 1% patch of sky

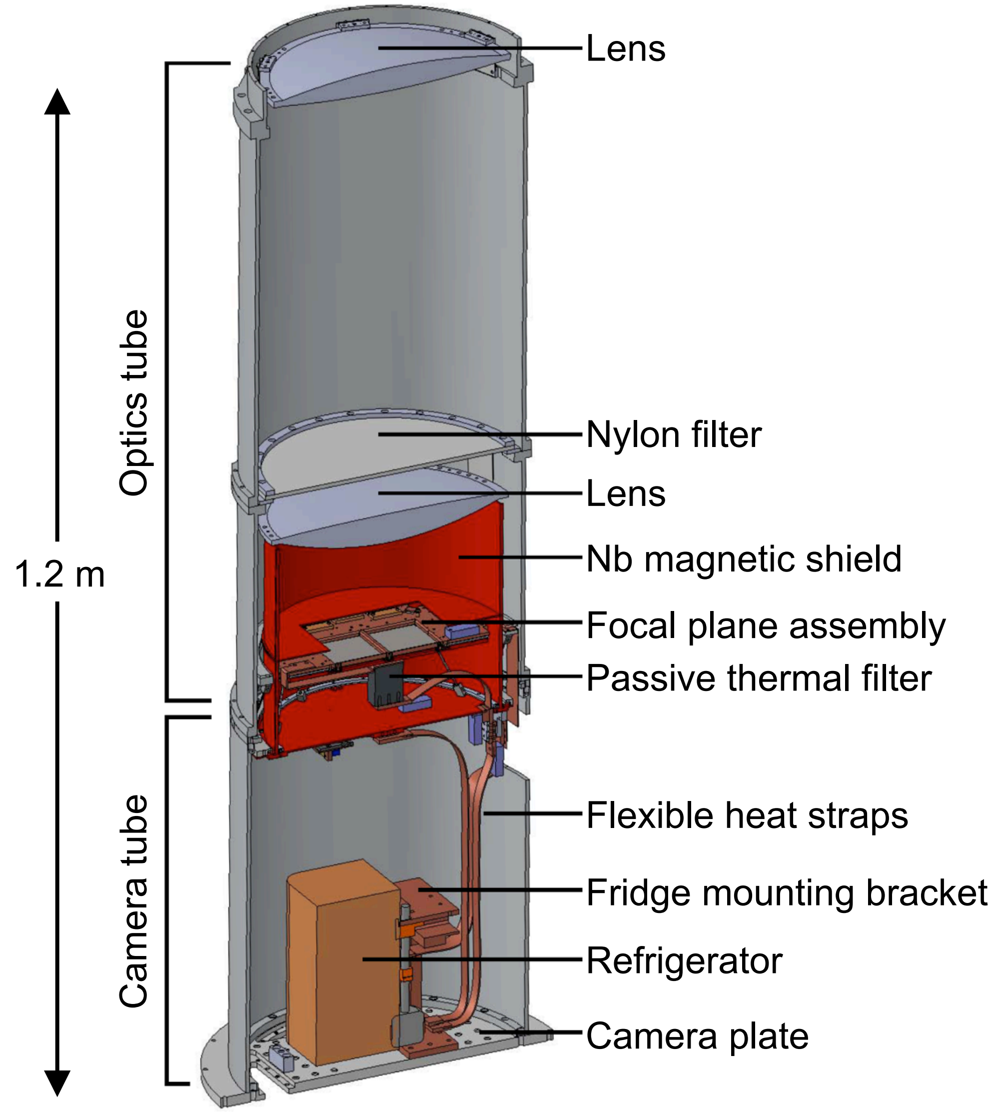
The BICEP/Keck Telescopes

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

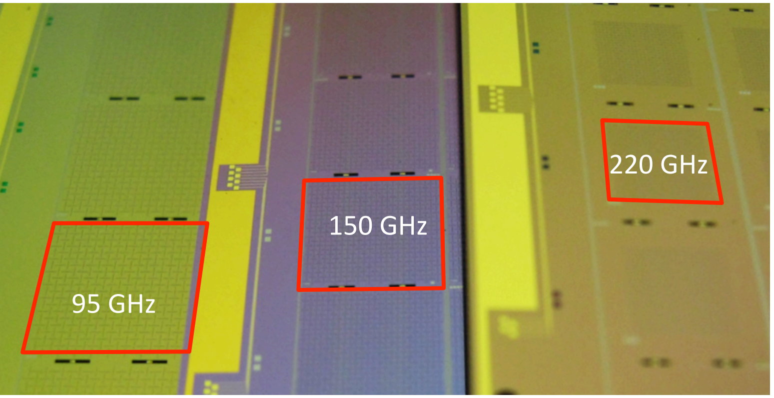
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation

Liquid helium/pulse tube cools the optical elements to 4 K

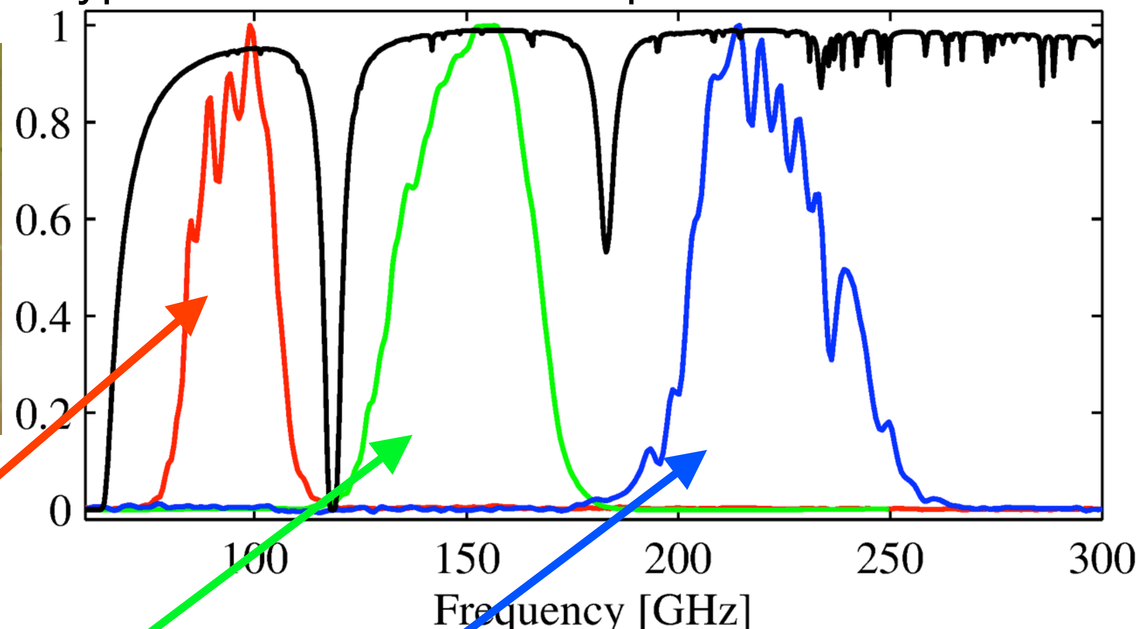
3-stage helium sorption refrigerator further cools the detectors to 0.27 K



The BICEP/Keck Collaboration

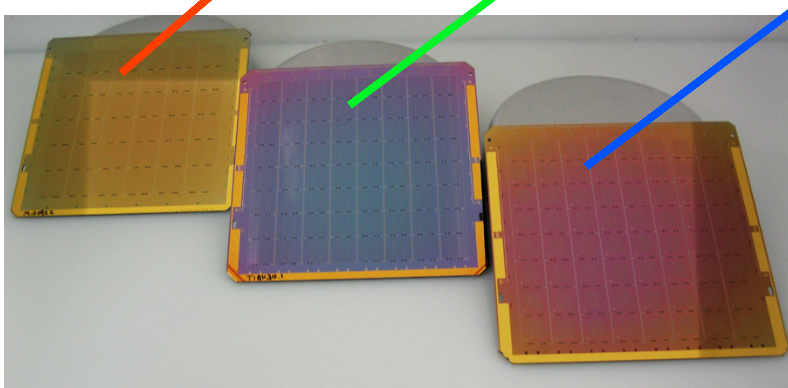


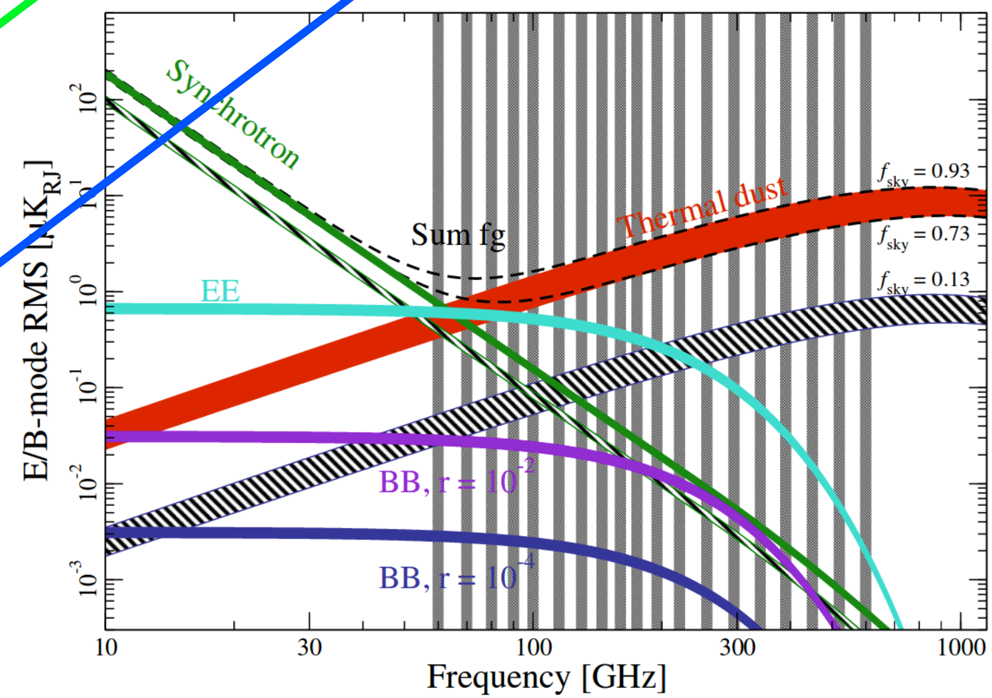
Typical South Pole atmospheric transmission



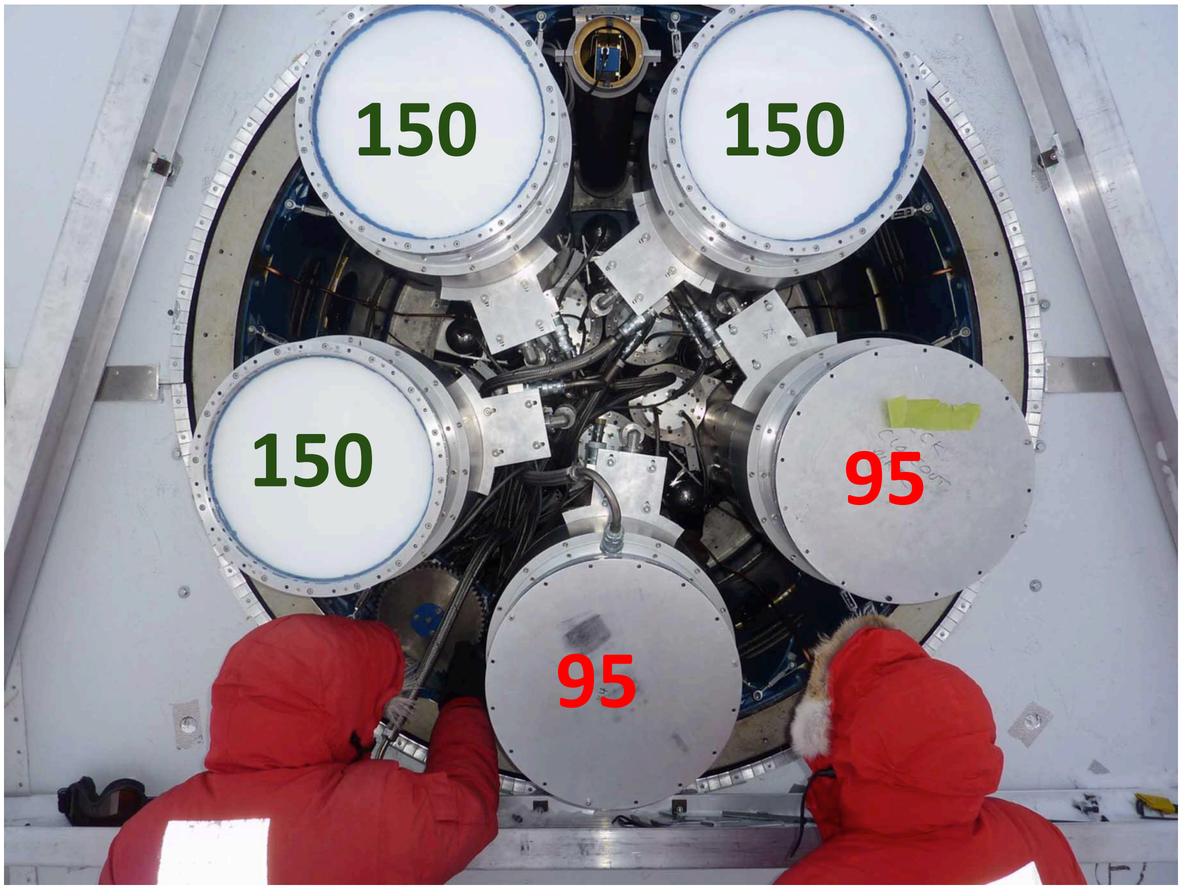
Planar detector arrays

…designed to scale in frequency





BK14 Dataset



BICEP2 2010-2012
150 GHz

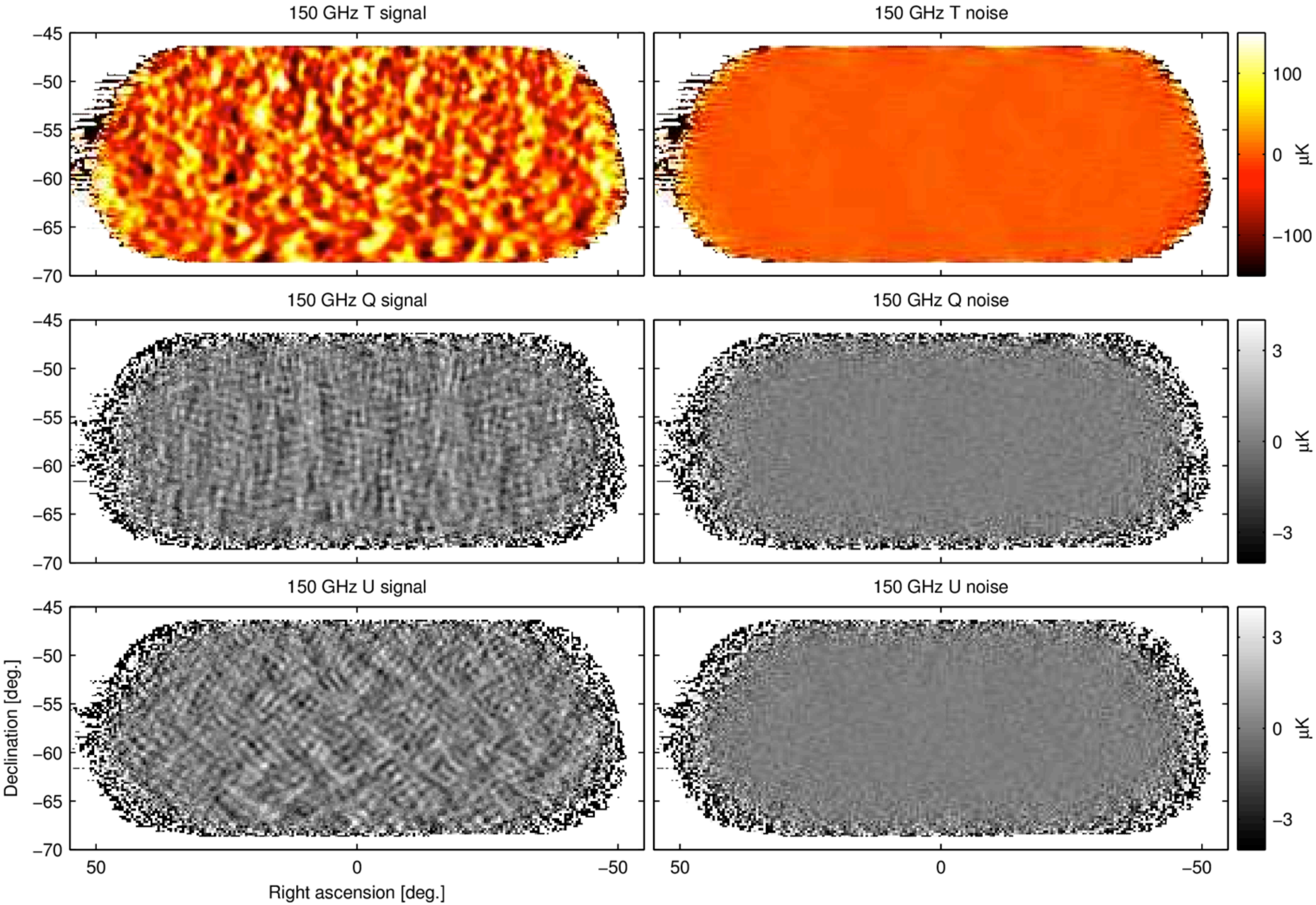
5x Keck 2012-2013
150 GHz

2x Keck 2014
95 GHz
3x Keck 2014
150 GHz

2014

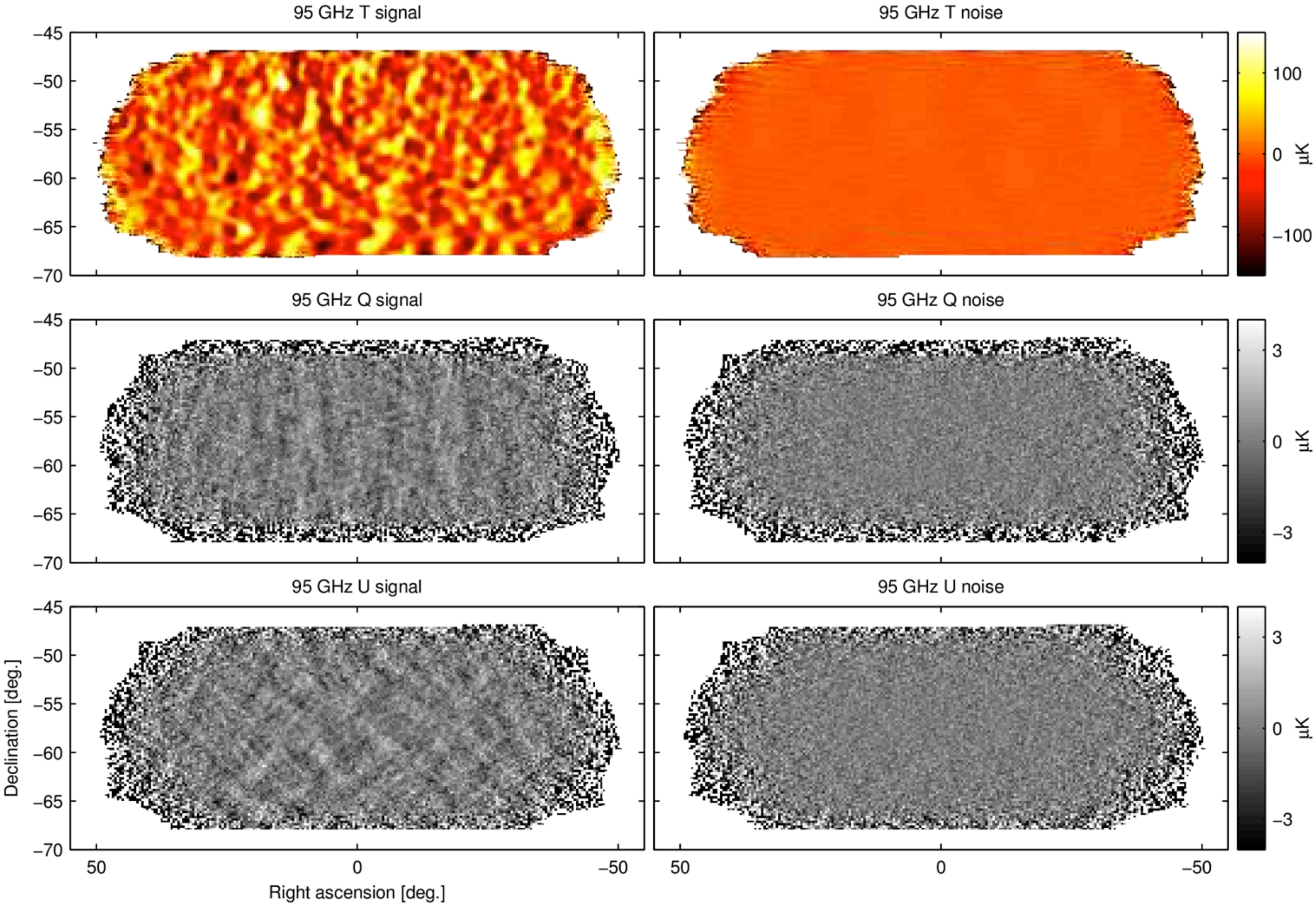
BK14 results published in PRL **116**, 031302, 2016
arXiv:1510.09217

150 GHz maps



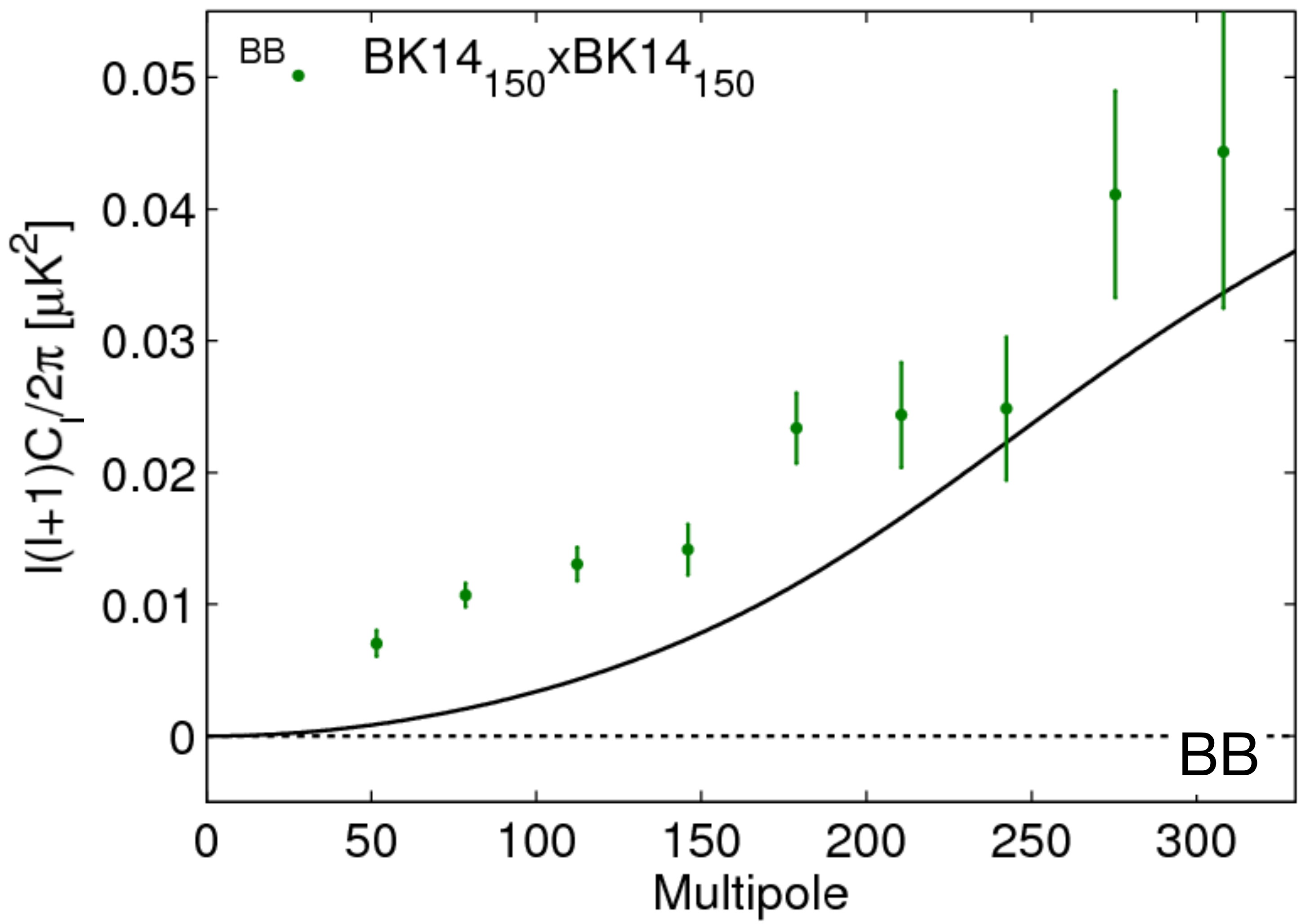
BK14 150GHz – 50 nK deg (3.0 μK arcmin)

95 GHz maps

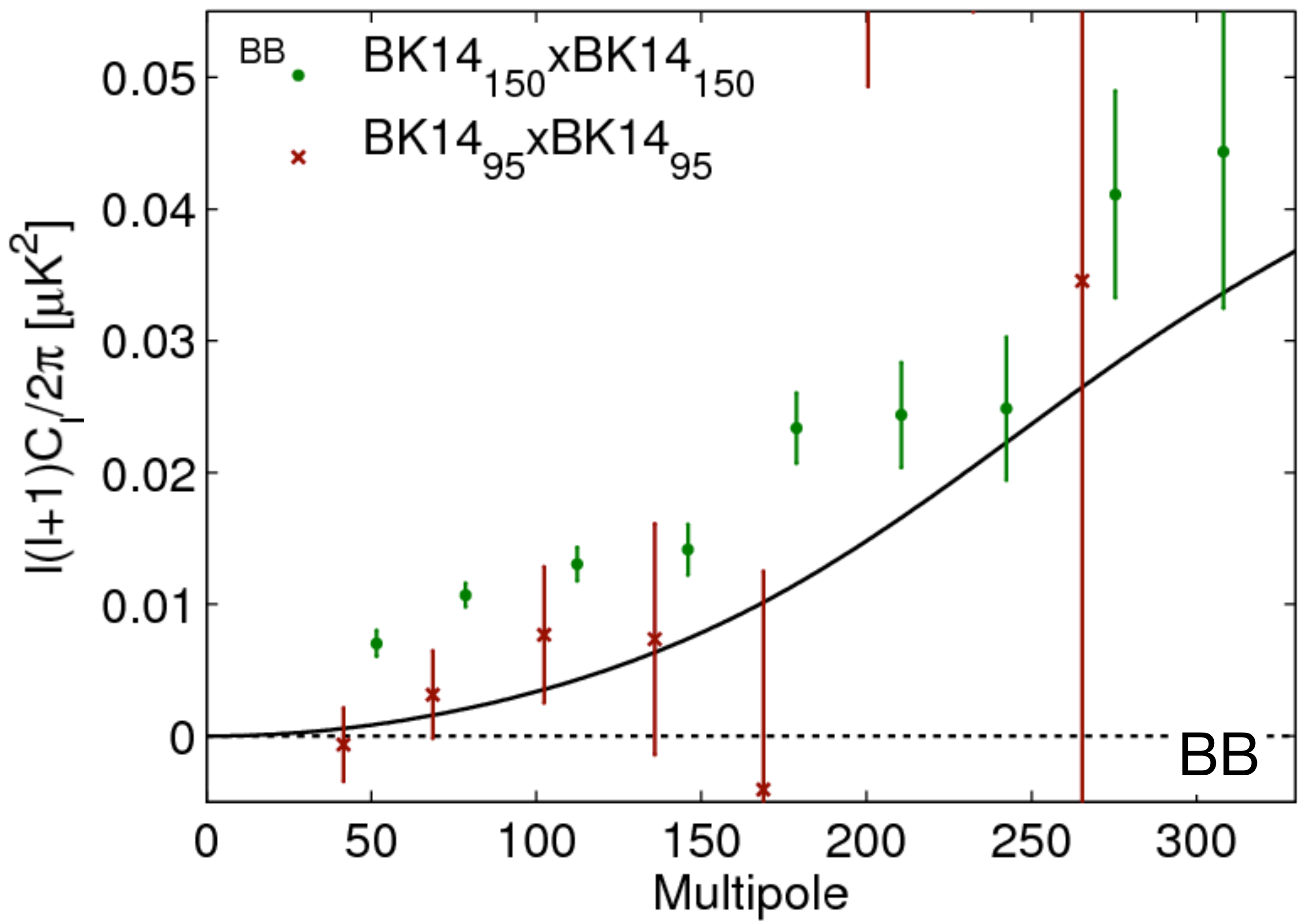


BK14 95GHz – 127 nK deg (7.6 μK arcmin)

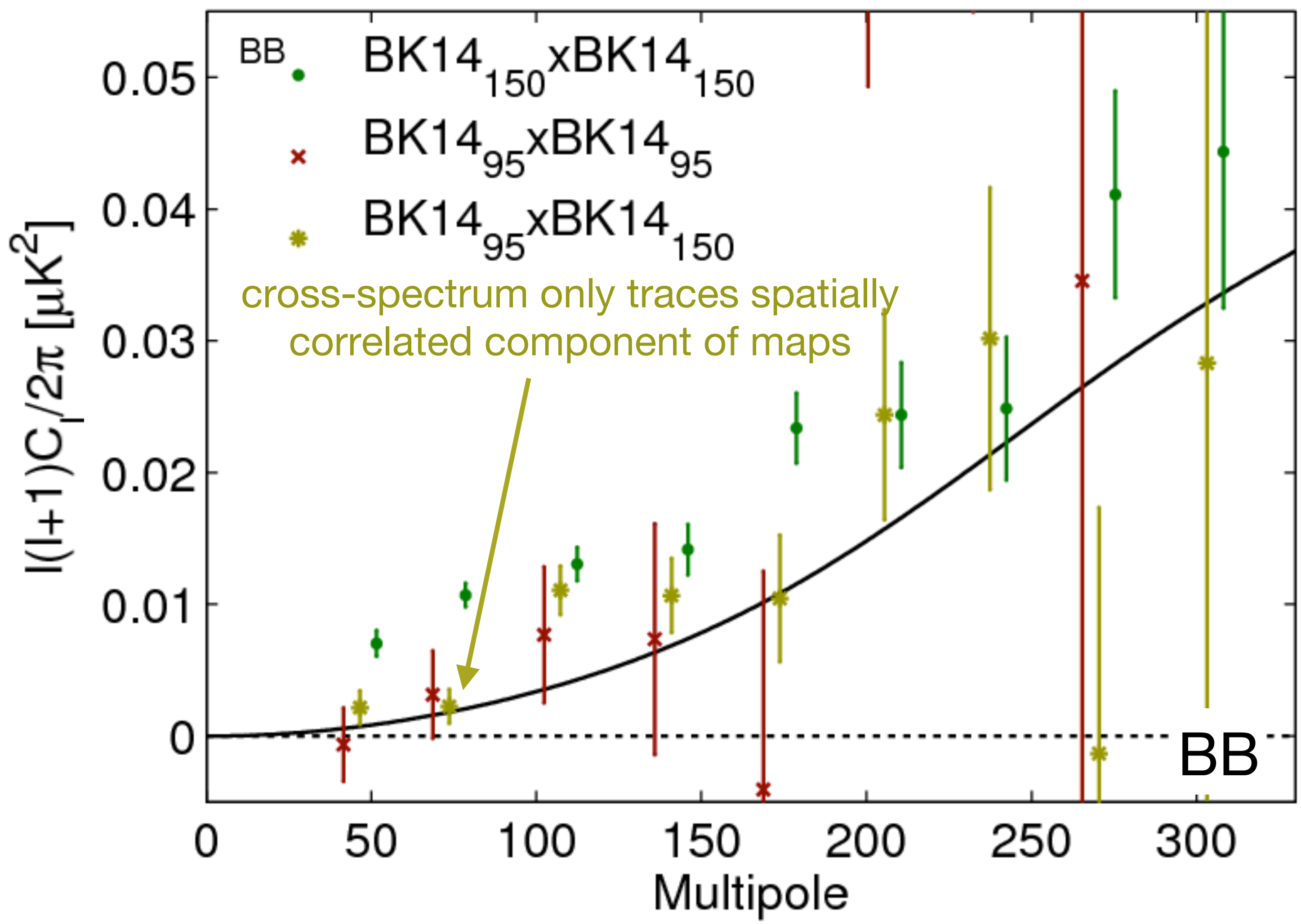
BICEP2 + Keck BB auto and cross-spectra



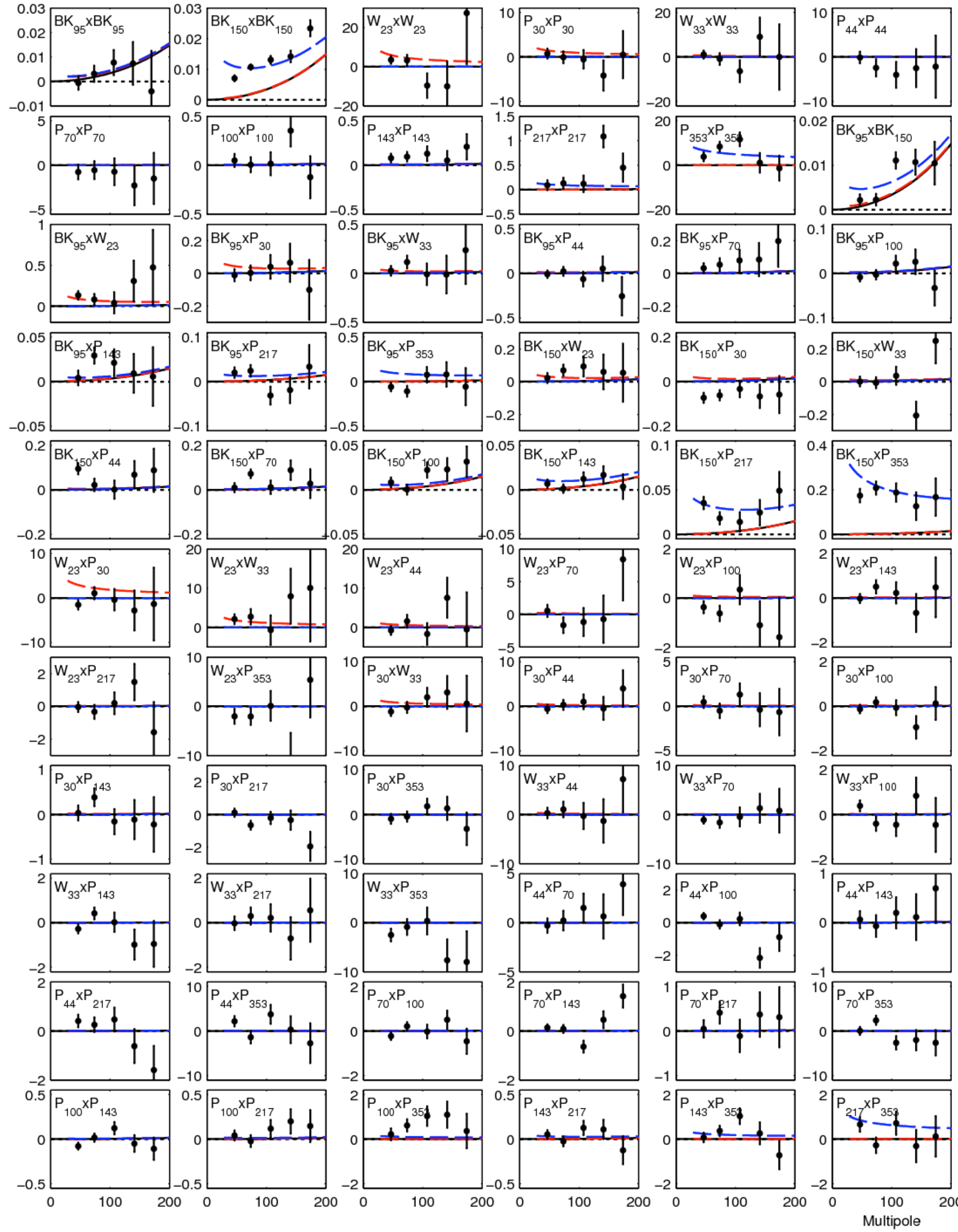
BICEP2 + Keck BB auto and cross-spectra



BICEP2 + Keck BB auto and cross-spectra



Take all possible auto- and cross spectra between BICEP/Keck, WMAP, and Planck bands (66 of them)



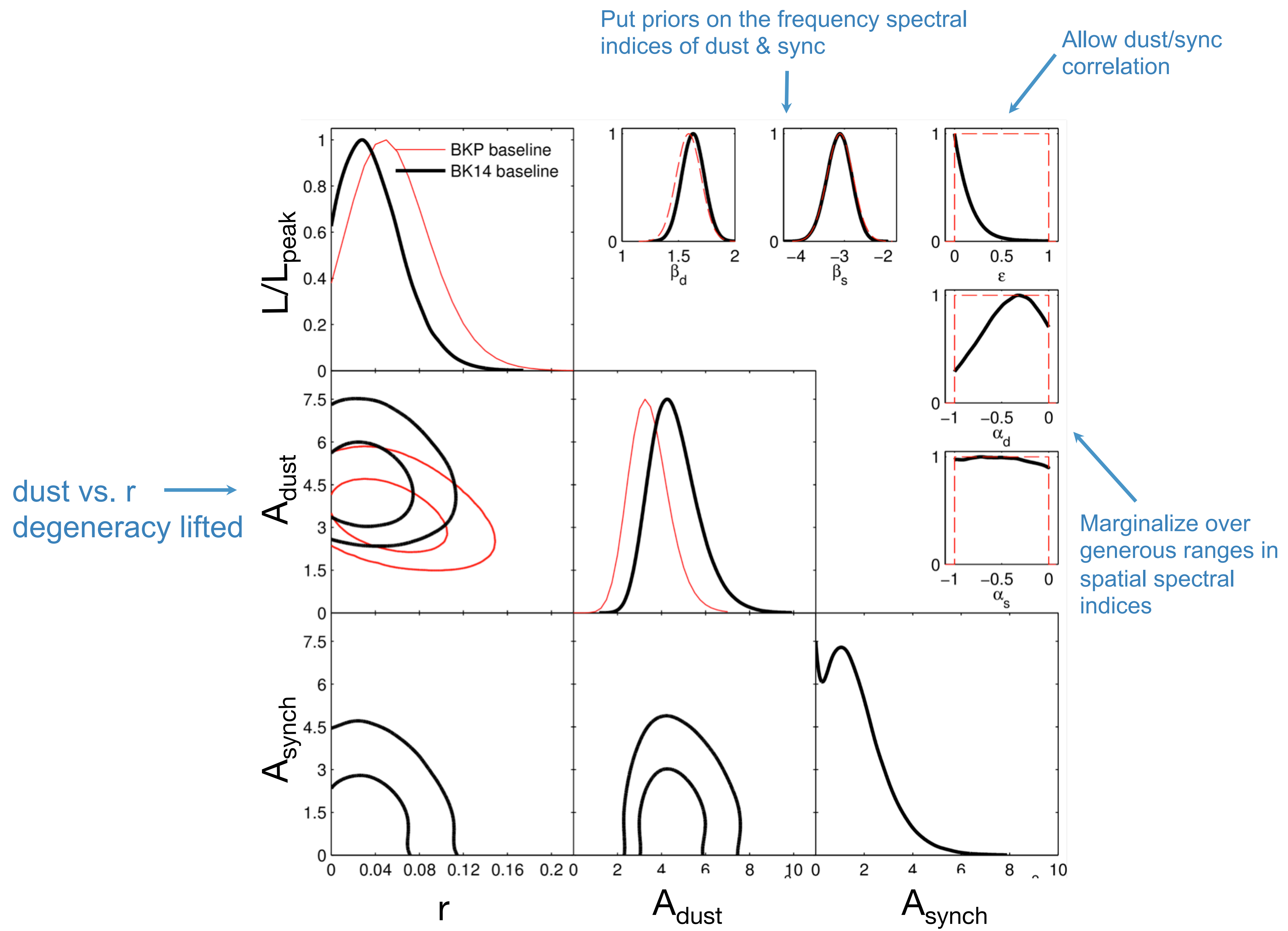
Multicomponent parametric likelihood analysis

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

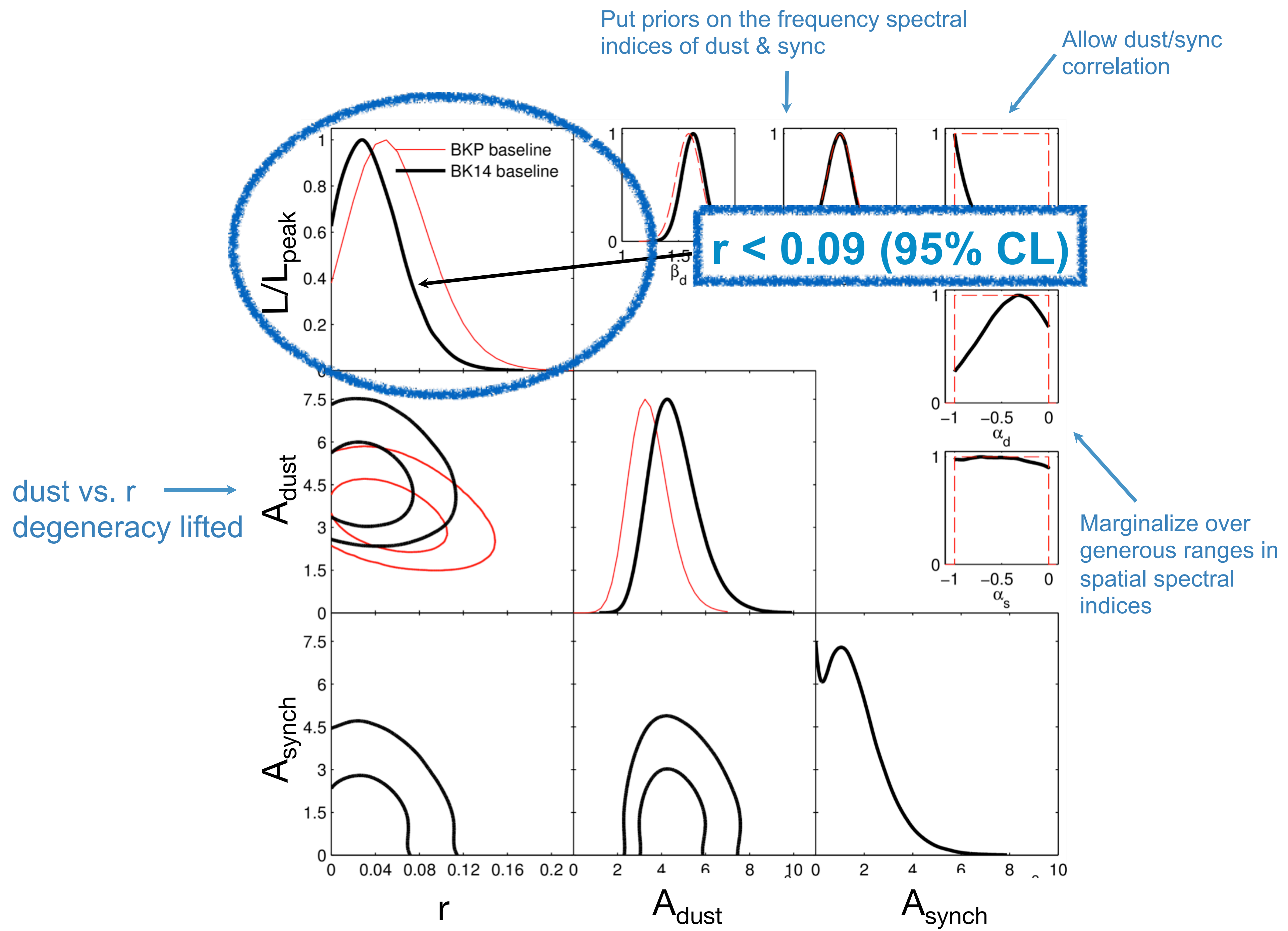
foreground model = dust + synchrotron

dust	synchrotron	
A_{dust}	A_{synch}	amplitudes @ l=80
β_{dust}	β_{synch}	frequency spectral indices
α_{dust}	α_{synch}	spatial spectral indices
ε		dust/synch spatial correlation

More on this technique this in Victor Buza talk this afternoon

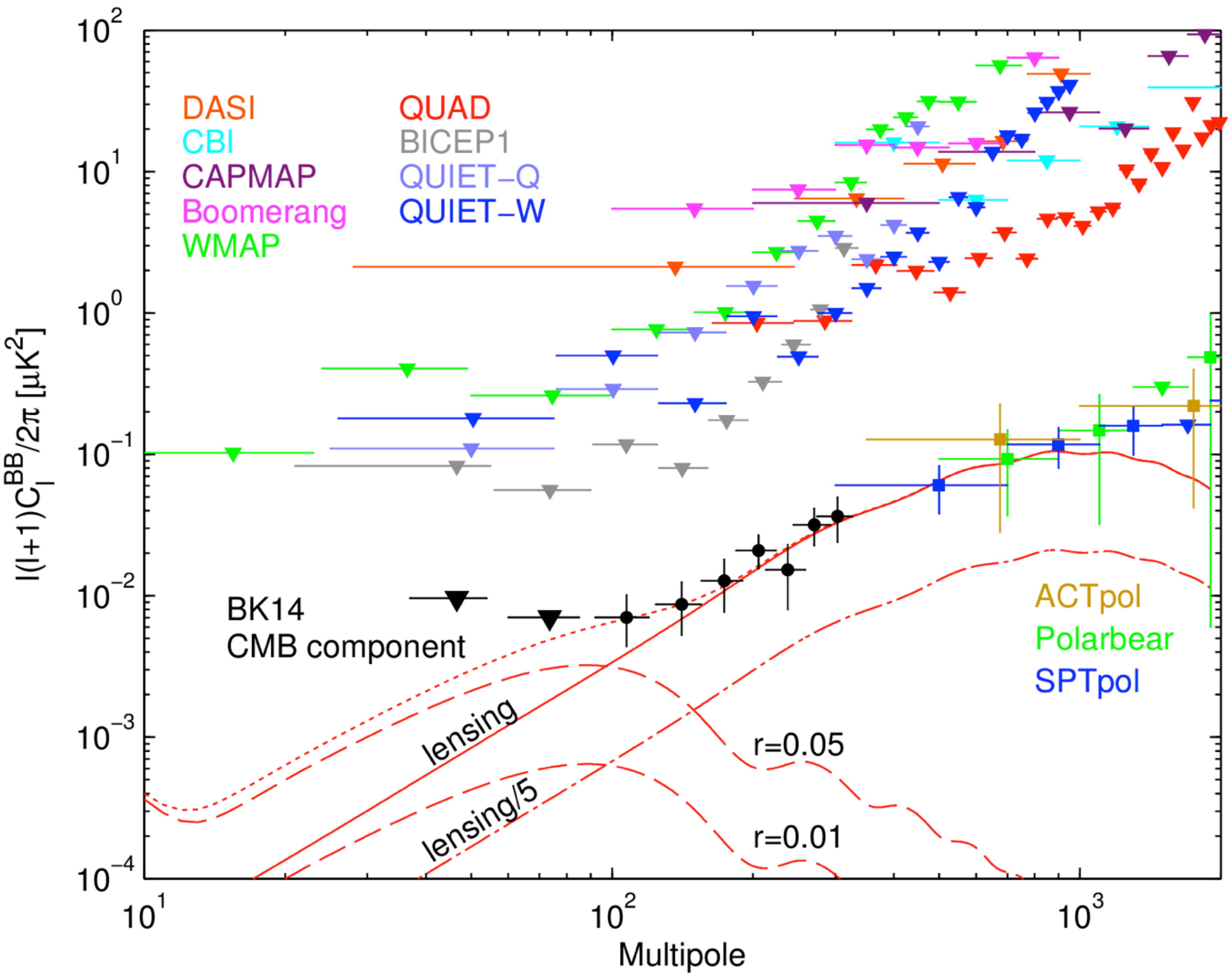


Put priors on the frequency spectral indices of dust & sync
Allow dust/sync correlation
Marginalize over generous ranges in spatial spectral indices
dust vs. r degeneracy lifted
BKP baseline
BK14 baseline
L/L_peak
A_dust
A_synch
r
β_d
β_s
ε
α_d
α_s



Put priors on the frequency spectral indices of dust & sync
Allow dust/sync correlation
r < 0.09 (95% CL)
BKP baseline
BK14 baseline
L/L_{peak}
β_d
α_d
α_s
dust vs. r degeneracy lifted
A_{dust}
A_{synch}
Marginalize over generous ranges in spatial spectral indices
r

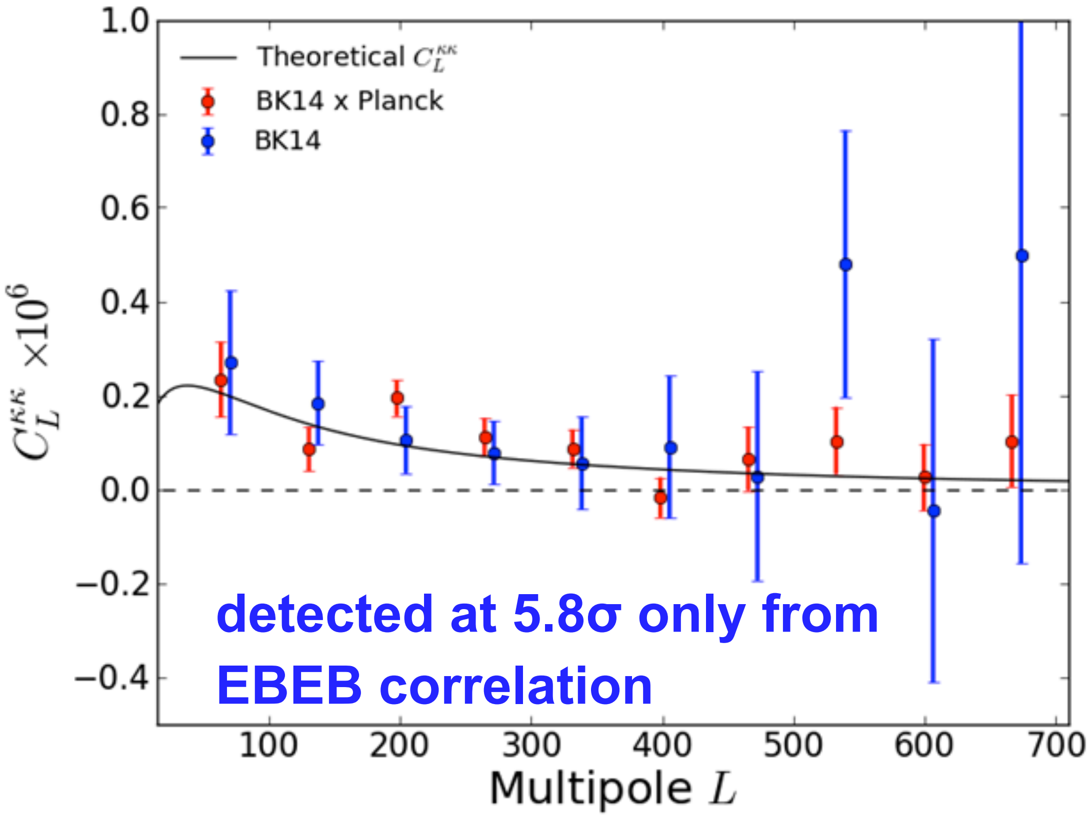
Published B-Mode Spectra



…as of July 2017

Uncertainties on *r* will shrink steadily as component separation improves with much *deeper multiband maps* currently being taken at Pole.

BK14 Gravitational Lensing



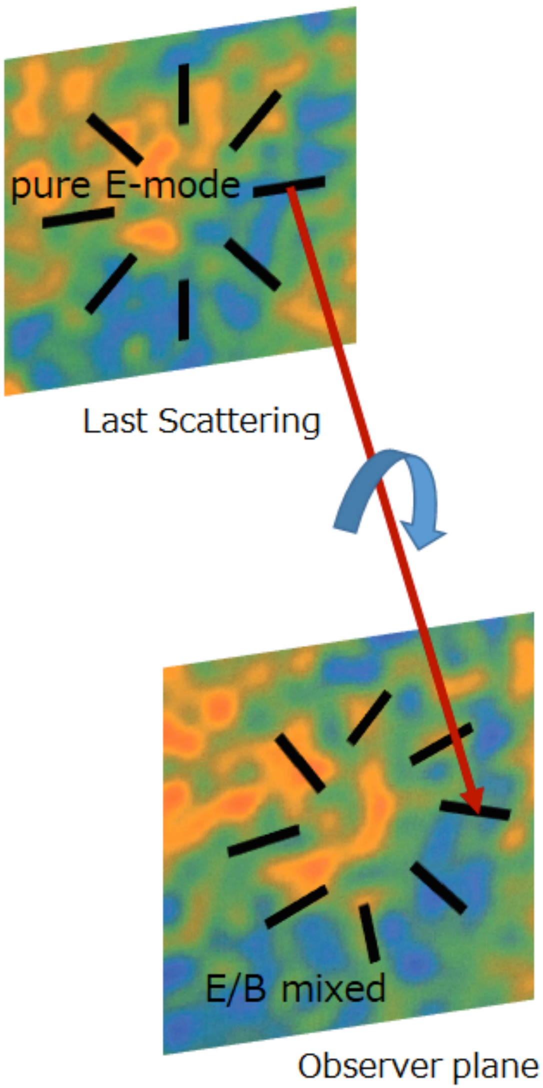
- ***κ*** **map is reconstructed from BK14 Q/U map at 150GHz**
- ***κ*** **map gives auto spectrum**
- **also correlated with Planck**
  → they are consistent

Measured amplitude is in good agreement with the BB results, and we can start to constrain alternative B-mode sources!

(cosmic string, magnetic field, axion, modified gravity,…)

ApJ **833** 228 2016. arXiv:1606.01968

BK14 Anisotropic Polarization Rotation



- **Axion-like particles…**

  …may arise in string theory with generic coupling to EM fields

  (e.g. Pospelov+'09, Caldwell+'11)

  $$\text{Lagrangian} \supset \frac{\phi}{2f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

  Coupling constant

  This leads to spatial variation of polarization angle rotation

  rotation angle

  $$\alpha(n) = \frac{\Delta\phi(n)}{f_a}$$

  Changes in phi during photon propagation

- **Primordial magnetic fields (PMF)…**

  …lead to polarization rotation by Faraday rotation

  (e.g. Kosowsky&Loeb'96, Harari+'97)

  Total rotation angle

  $$\alpha(n) = \frac{3c^2}{16\pi e^2}\nu^{-2}\int \dot{\tau}\, \vec{B} \cdot d\vec{l}$$

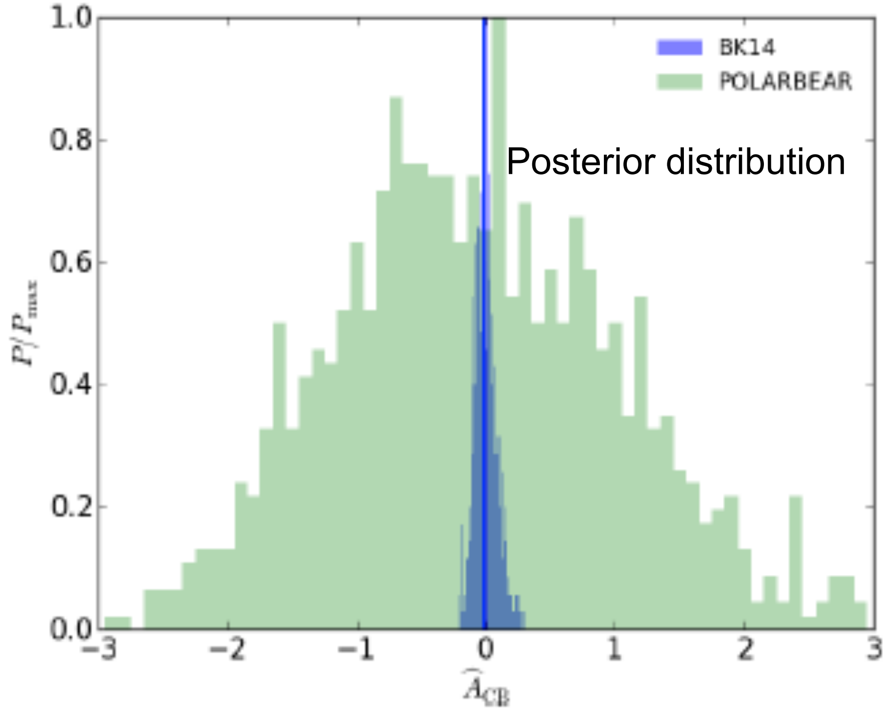
  Magnetic field

Unique probe of the early universe
w/ important implications for high energy physics

The BICEP/Keck Collaboration

arXiv:1705.02523

BK14 Anisotropic Polarization Rotation



If sources of the pol. rotation originated from inflation, expected rotation spectrum is scale-invariant:

$$\frac{L(L+1)}{2\pi} C_L^{\alpha\alpha} = A_{CB} \times 10^{-4}$$

Compared to previous measurements, BK14 improves constraints on this inflationary rotation spectrum by an **order of magnitude**.

$$A_{\rm CB} \leq 0.33 \ \text{at} \ 95\%$$

- **Implications**

  The above results lead to constraints on

  1) Coupling constant of the Chern-Simons term $\quad f_a \geq 1.7 \times 10^2 \frac{H_I}{2\pi}$

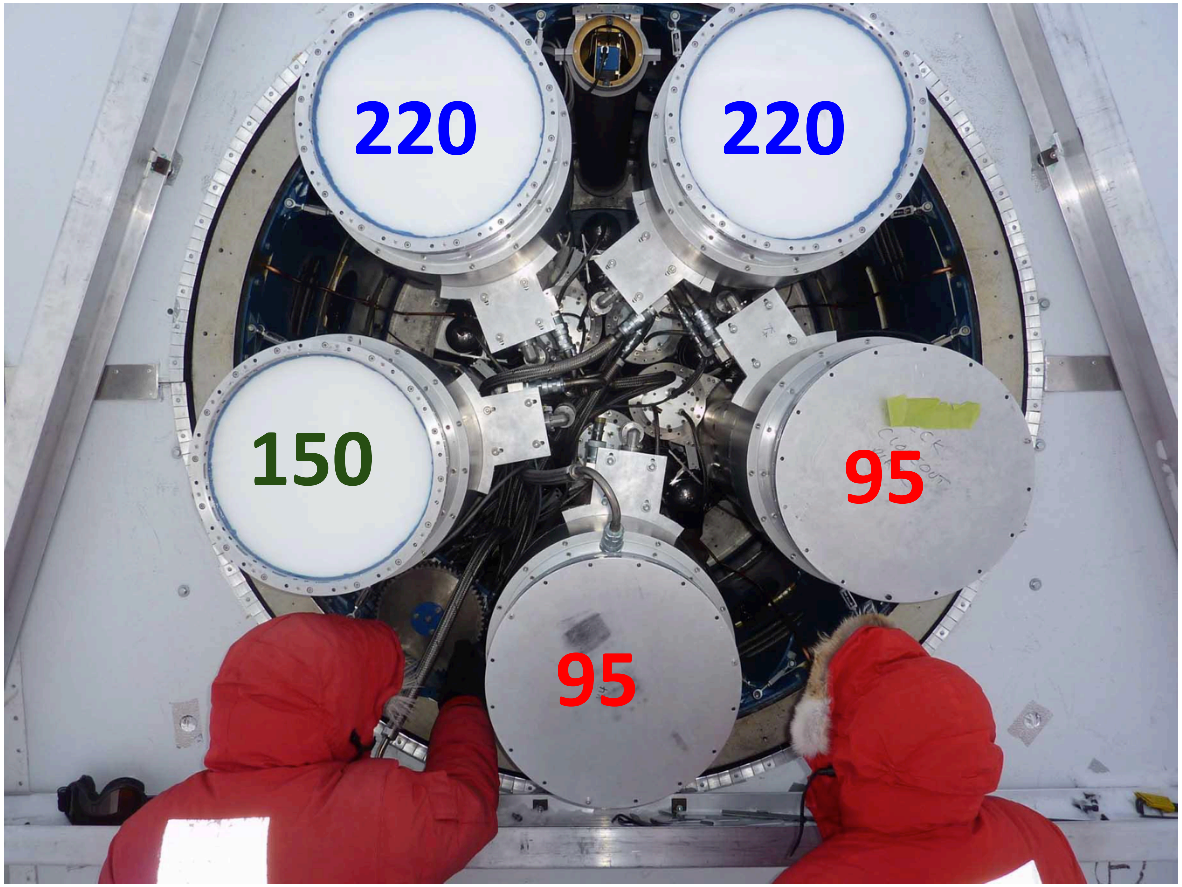
  2) Strength of the scale-invariant PMF smoothed over 1Mpc $\quad B_{1Mpc} \leq 30\text{nG}.$

The BICEP/Keck Collaboration

arXiv:1705.02523

BK15 Dataset

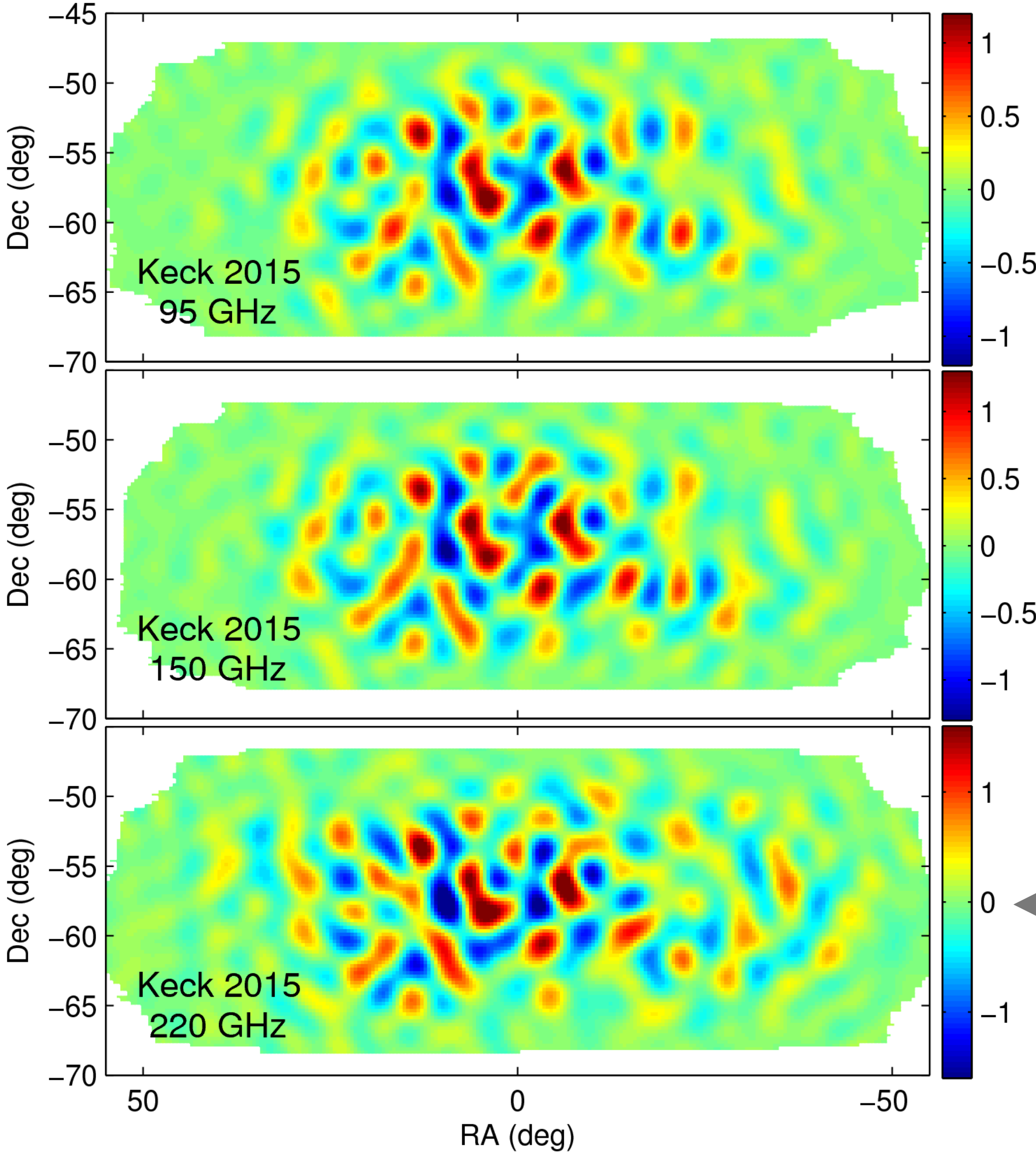
= BK14 +



2x Keck **95** GHz
1x Keck **150** GHz
2x Keck **220** GHz

2015

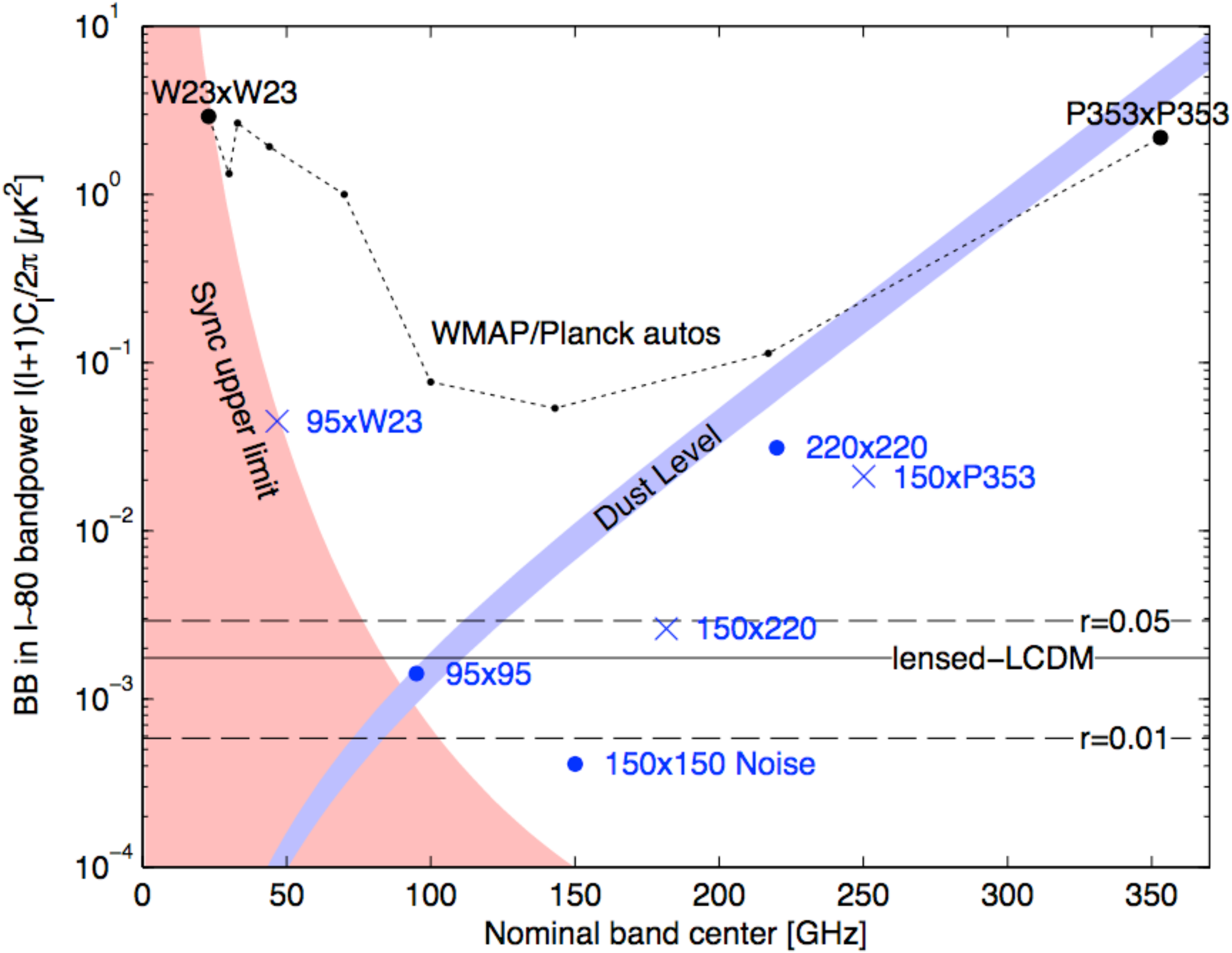
Keck 2015 single season E-mode maps



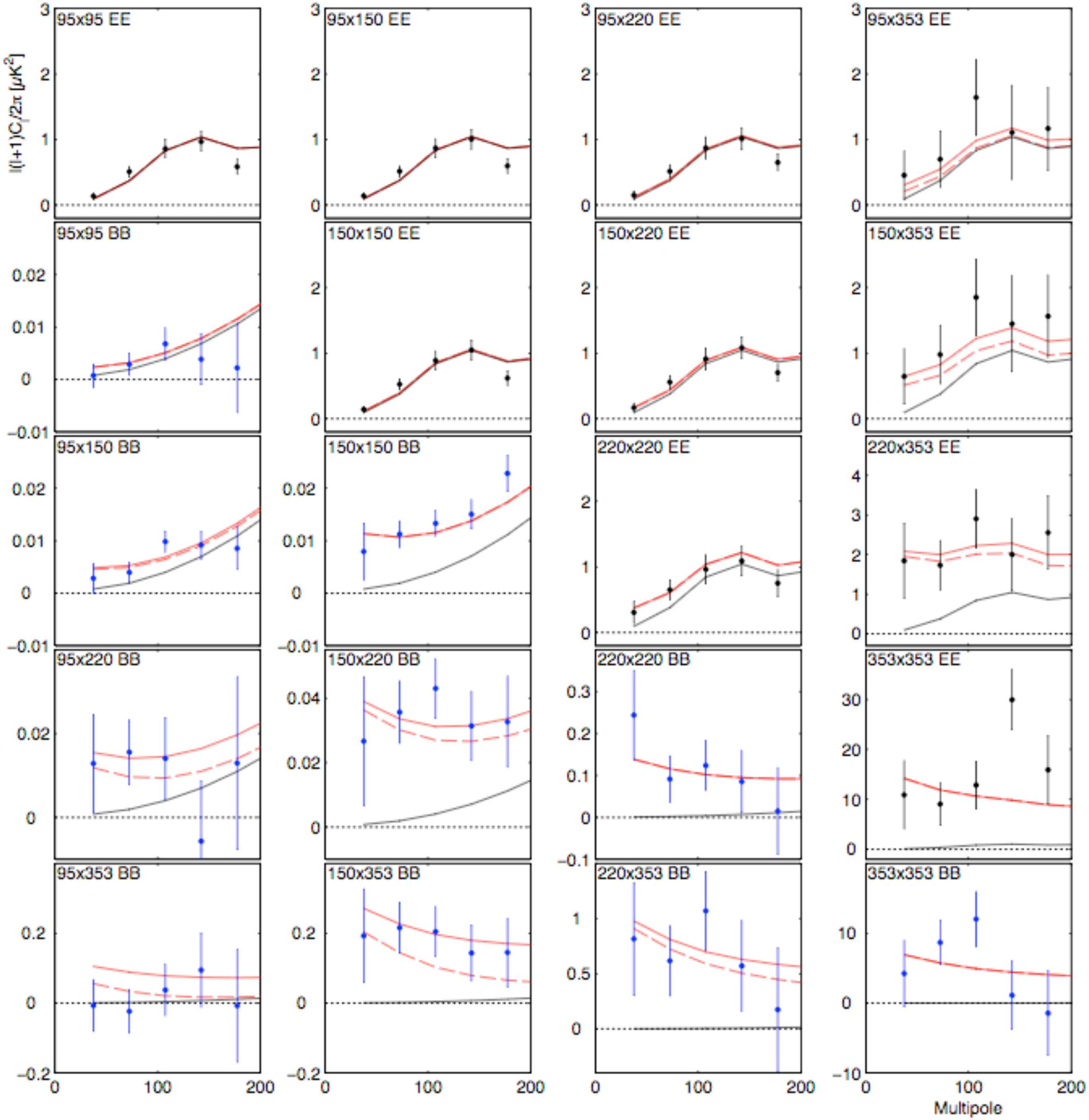
LCDM E-modes with high s/n at three frequencies in a single year!

Already deeper than Planck 217 GHz

Upcoming analysis: BK15 noise levels



Upcoming analysis: BK15 spectra



PIPL paper suggests the dust pattern decorrelates strongly between 217 and 353GHz

We can constrain the strength of decorrelation using BICEP/ Keck data

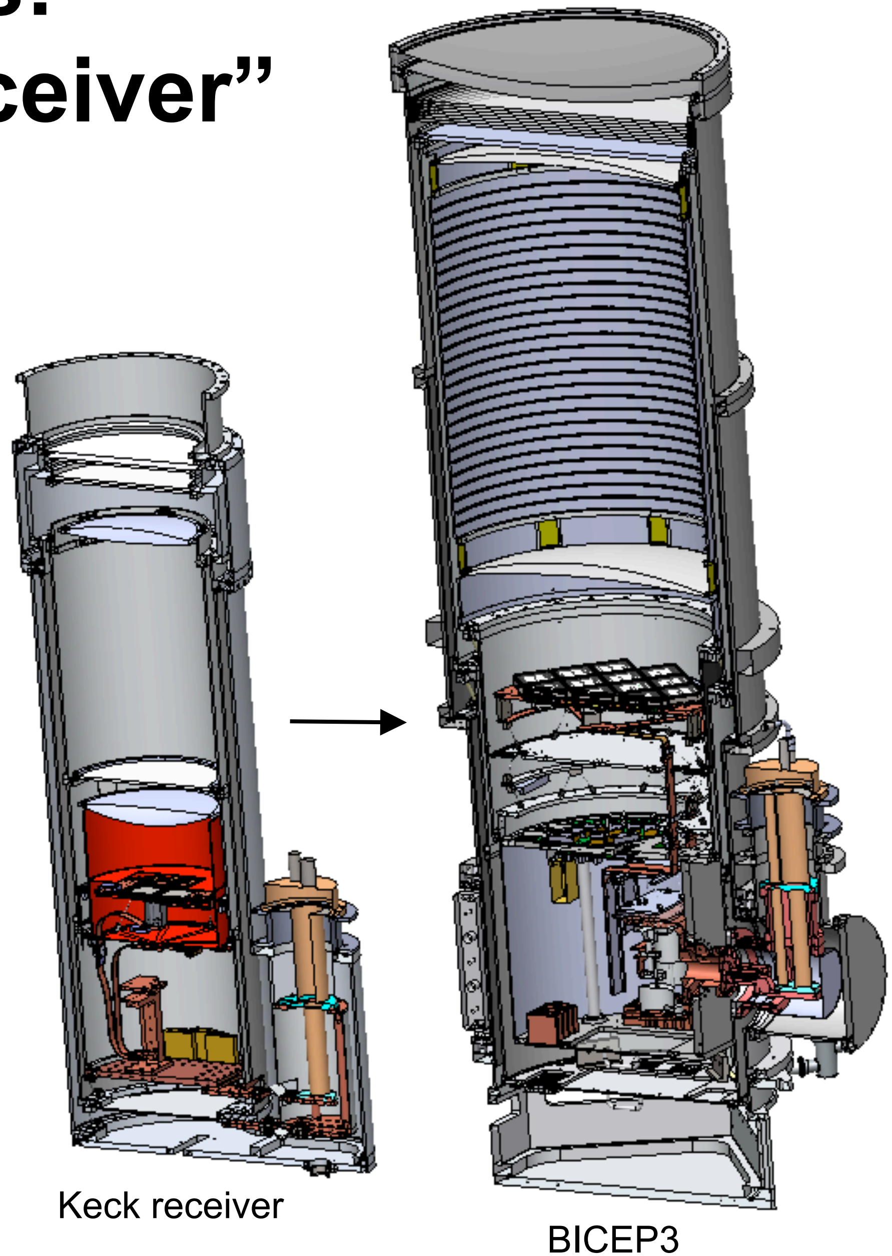
2016 onwards: BICEP3 “Super receiver”

All 95 GHz

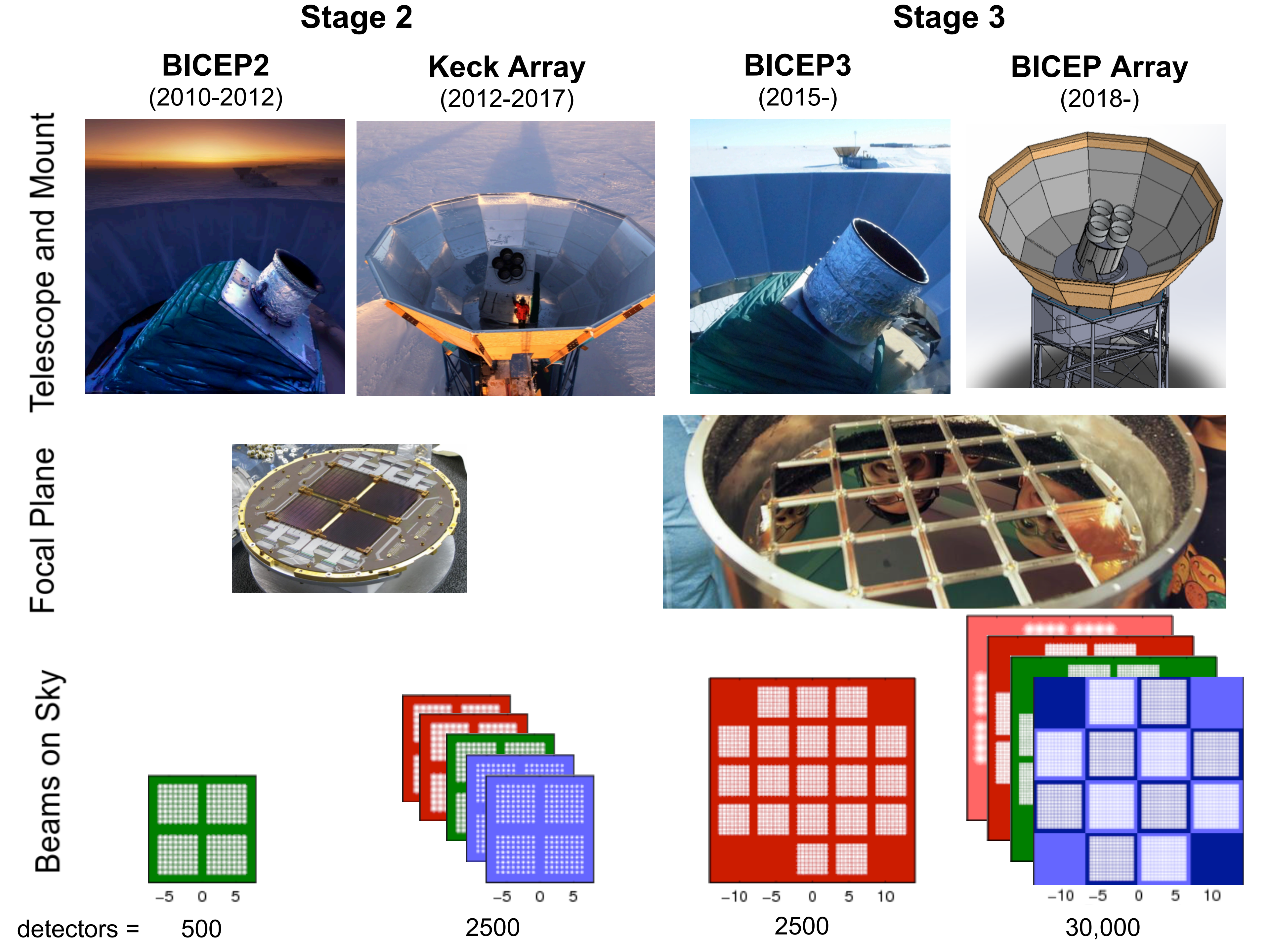
2560 detectors in modular focal plane

Large-aperture optics and infrared filtering

> 10x optical throughput of single BICEP2/Keck receiver

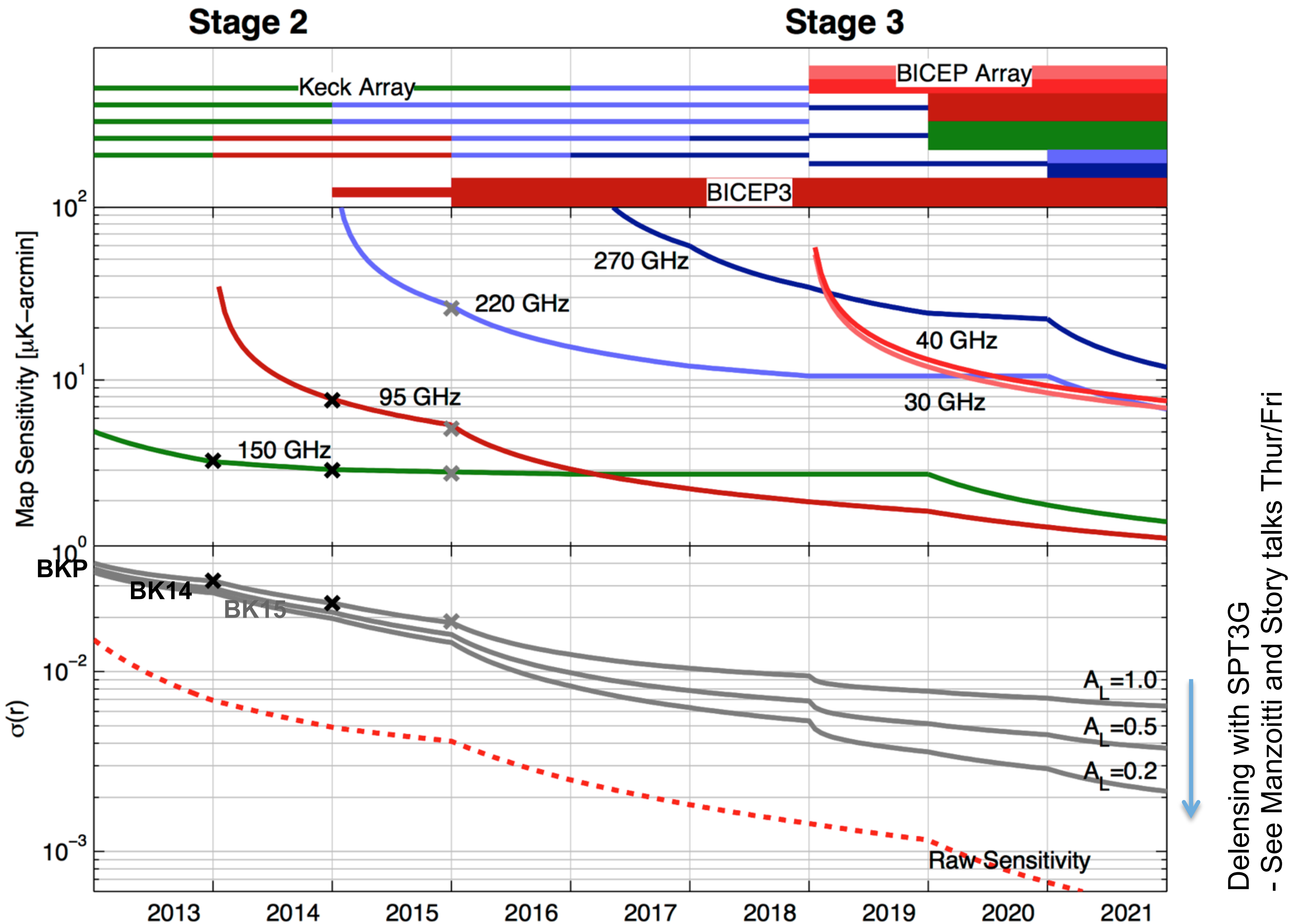


The BICEP/Keck Collaboration



Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2017)
BICEP3
(2015-)
BICEP Array
(2018-)
Telescope and Mount
Focal Plane
Beams on Sky
−5 0 5
−5 0 5
−10 −5 0 5 10
−10 −5 0 5 10
detectors = 500
2500
2500
30,000

BICEP Array + SPT3G as a Pathfinder for the CMB-S4 Deep Survey



- 6 band foreground control and σ(r)~0.003 by 2021
- Projections above are simple scaling from achieved published analyses (i.e. include all real-world performance hits) – see Victor Buza talk this afternoon

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

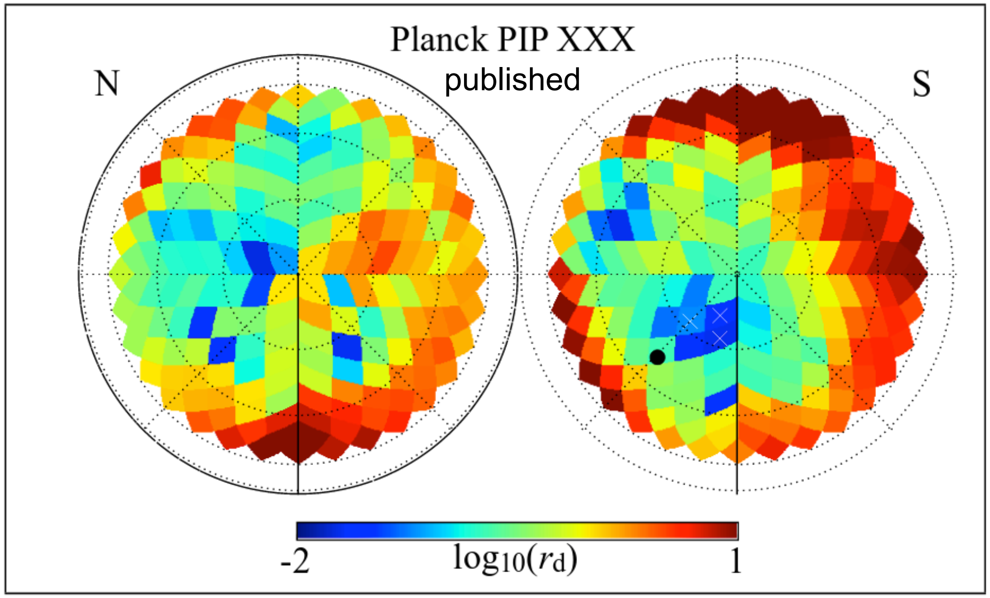
- Adding 2014 data including, for the first time 95GHz data:
- Results in modest improvement: $r_{0.05}<0.12$ goes to $r_{0.05}<0.09$
- However this is an important milestone: for the first time B-mode only constraint exceeds the sensitivity of (Planck) TT derived constraint ($r_{0.05}<0.12$)

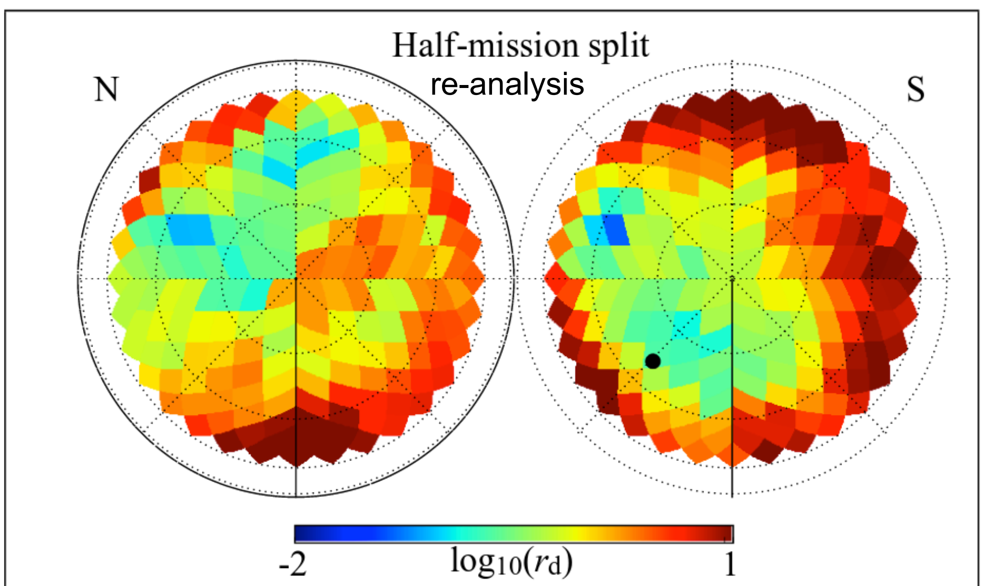
- And we can go much further:
- 2015 data also adds 220GHz - $\sigma(r)=0.019$
- And BICEP3 is now online at 95GHz
- …and we have BIG plans for the BICEP Array – $\sigma(r)<0.005$ in conjunction with SPT3G by 2021

- And beyond that is mega experiment CMB-S4…

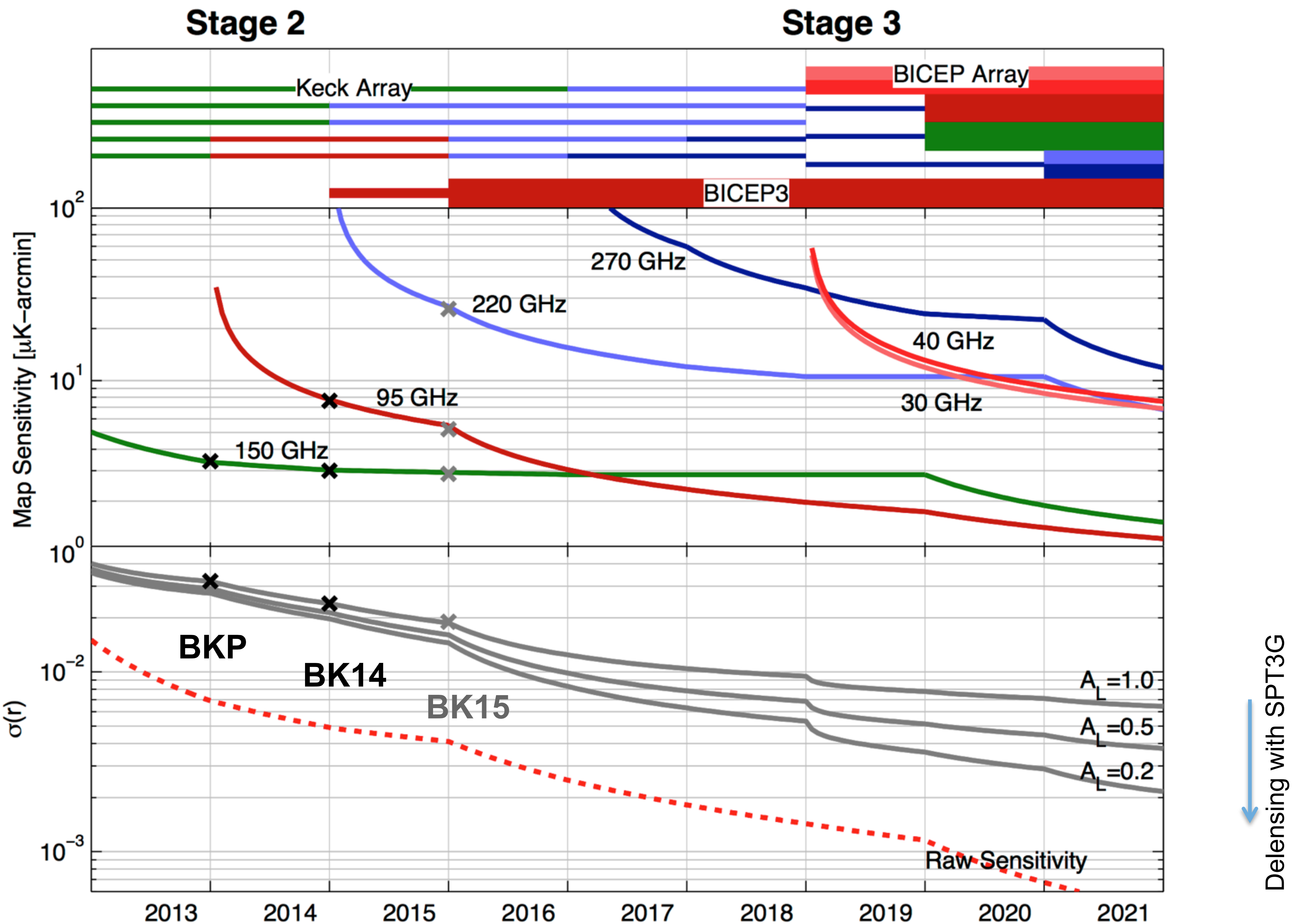
Backup Slides

Is there a cleaner small field than the BICEP/Keck field?

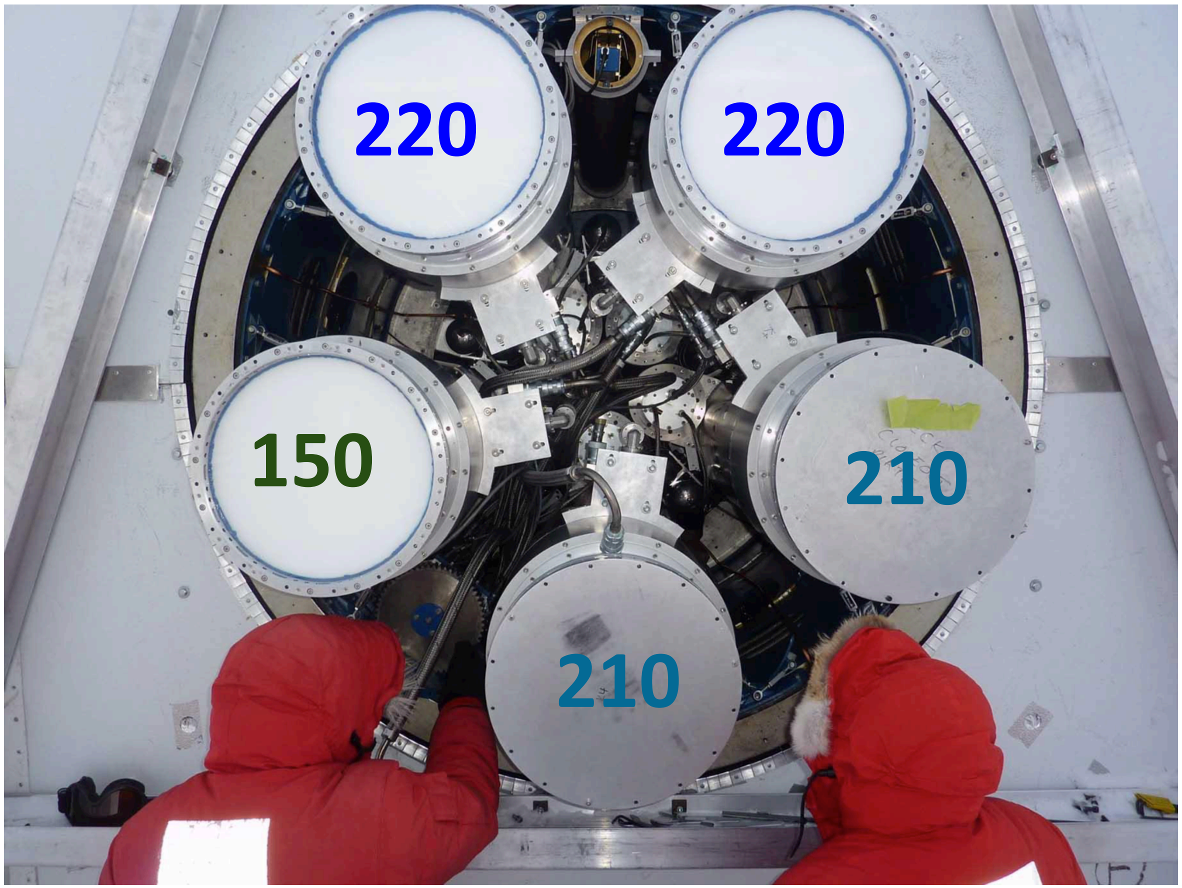




- The Planck 353GHz Q/U maps hit their noise floor in the cleanest regions
  - From this data it is not really possible to tell if there are cleaner small regions than the BICEP/ Keck field
- When we attempt to reproduce the Planck PIPXXX analysis we find that the apparent cleaner regions shift around depending on the data split selected
- The BK patch is currently the only low dust field where we actually know the dust level!


Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
Map Sensitivity [μK–arcmin]
270 GHz
220 GHz
40 GHz
95 GHz
30 GHz
150 GHz
σ(r)
BKP
BK14
BK15
A_L=1.0
A_L=0.5
A_L=0.2
Raw Sensitivity
Delensing with SPT3G
2013
2014
2015
2016
2017
2018
2019
2020
2021

BK16 Dataset = BK15 +



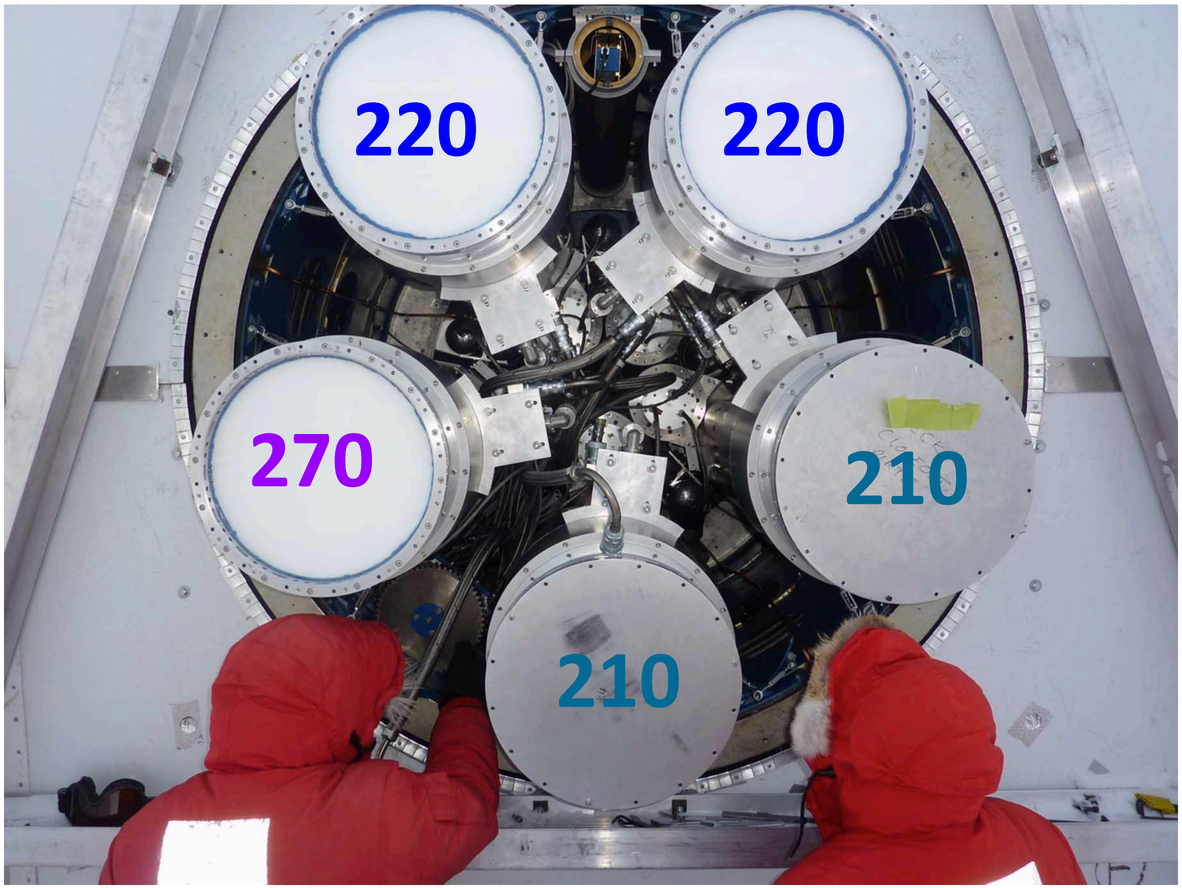
1x Keck **150** GHz
2x Keck **210** GHz
2x Keck **220** GHz

BICEP3 (3x Keck)
95 GHz

2016

BK17 Dataset

= BK16 +

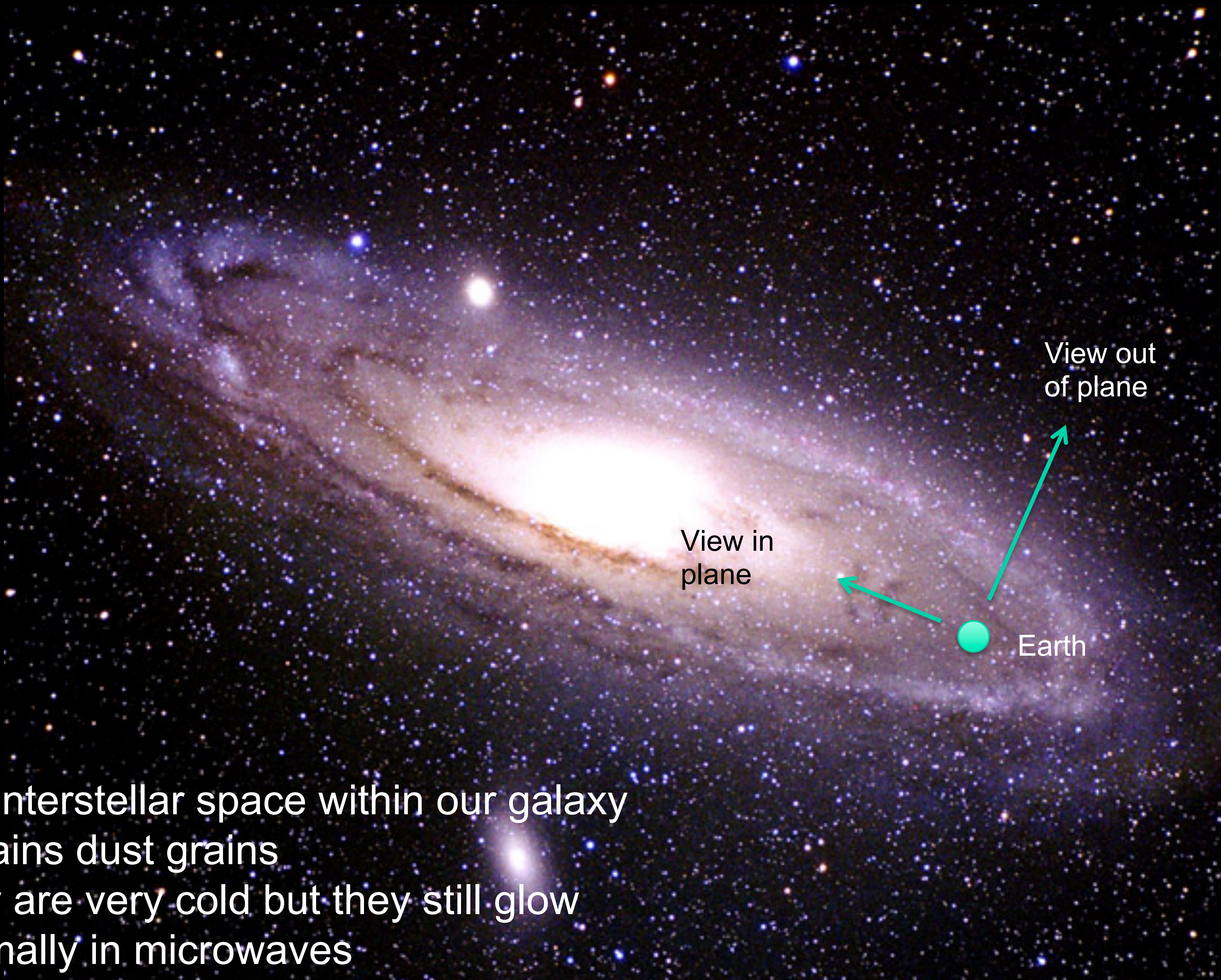


2x Keck **210** GHz
2x Keck **220** GHz
1x Keck **270** GHz

BICEP3 (5x Keck)
95 GHz

2017

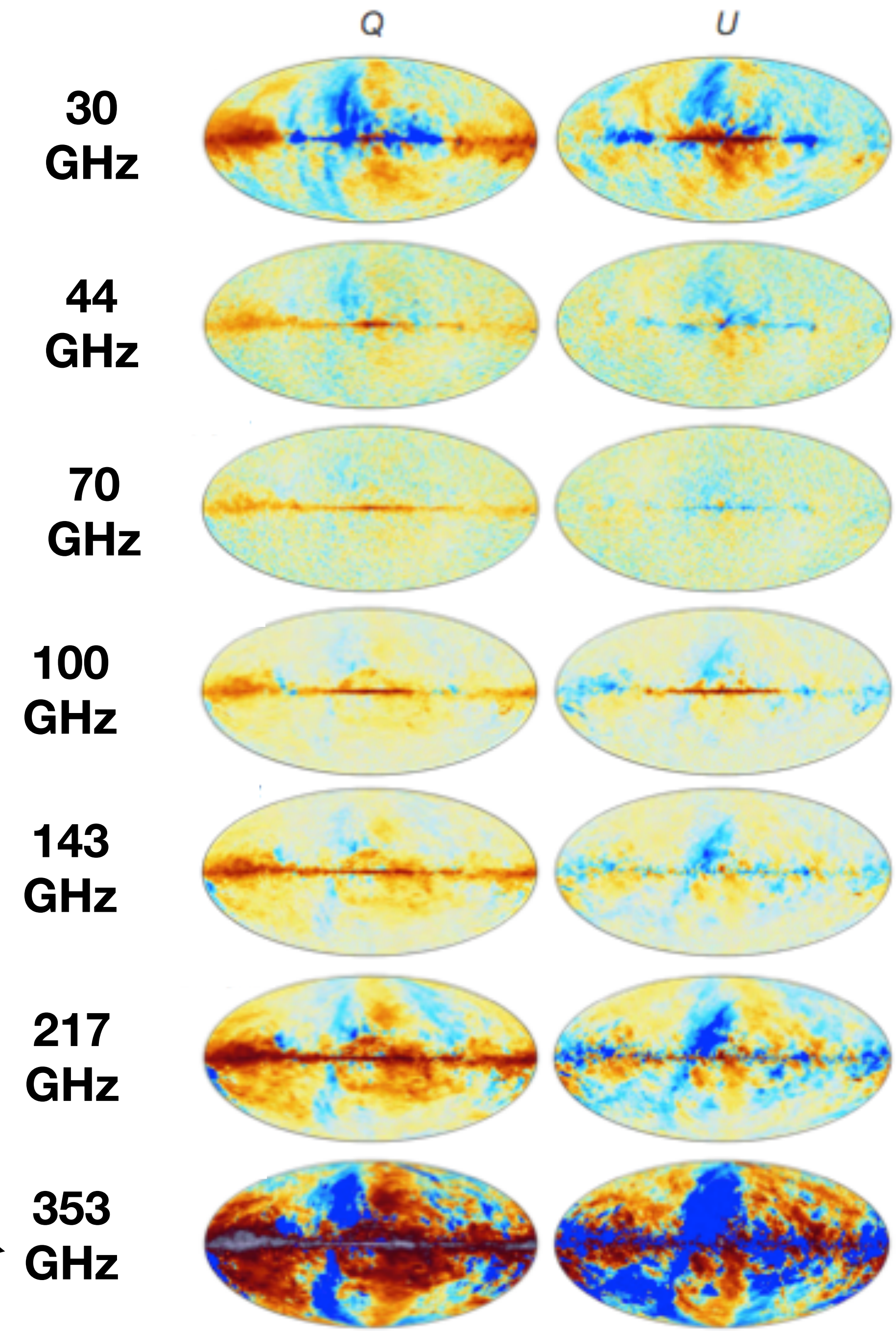
Unfortunately we are in a galaxy!



The interstellar space within our galaxy contains dust grains
They are very cold but they still glow thermally in microwaves

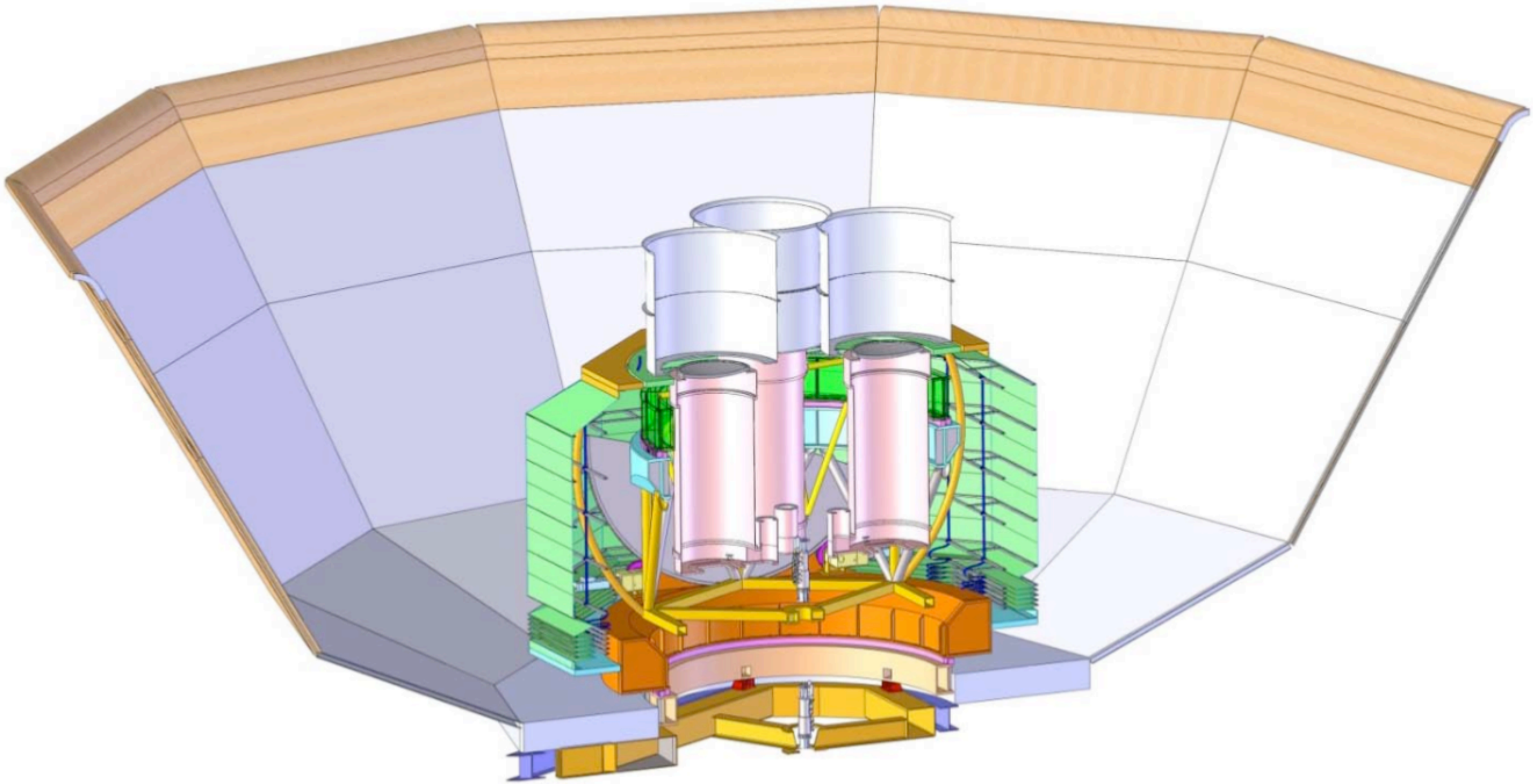
Planck and WMAP space missions have provided full sky polarized maps at 7+2 frequencies

353 GHz Planck map has limited signal-to-noise on dust in the BICEP/Keck field at few deg angular scales



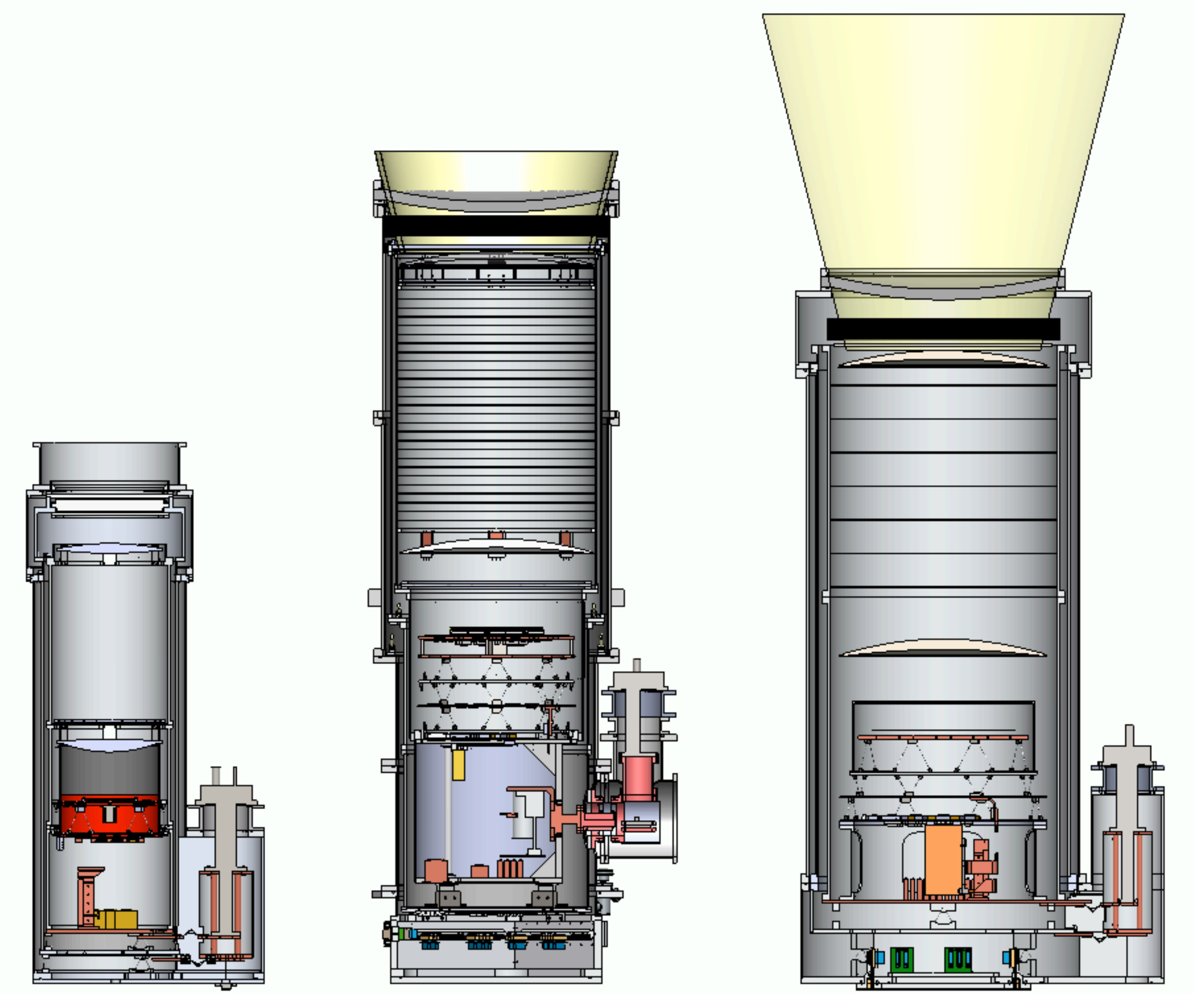
(Plot from arxiv/1502.01582)

Currently Designing BICEP Array Telescope Mount



This time next year this machine will be in the PAN high-bay for outfitting – then it will be shipped to South Pole for installation

Currently Designing BICEP Array Cryostat



Right now UMN grad student Mike Crumrine is designing the BICEP Array cryostat (right)