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

Marion Dierickx for the BICEP/Keck Collaboration – APC, June 1st 2018

Photo credit: R. Schwarz

I. Inflation and the CMB

II. The BICEP/Keck experiment

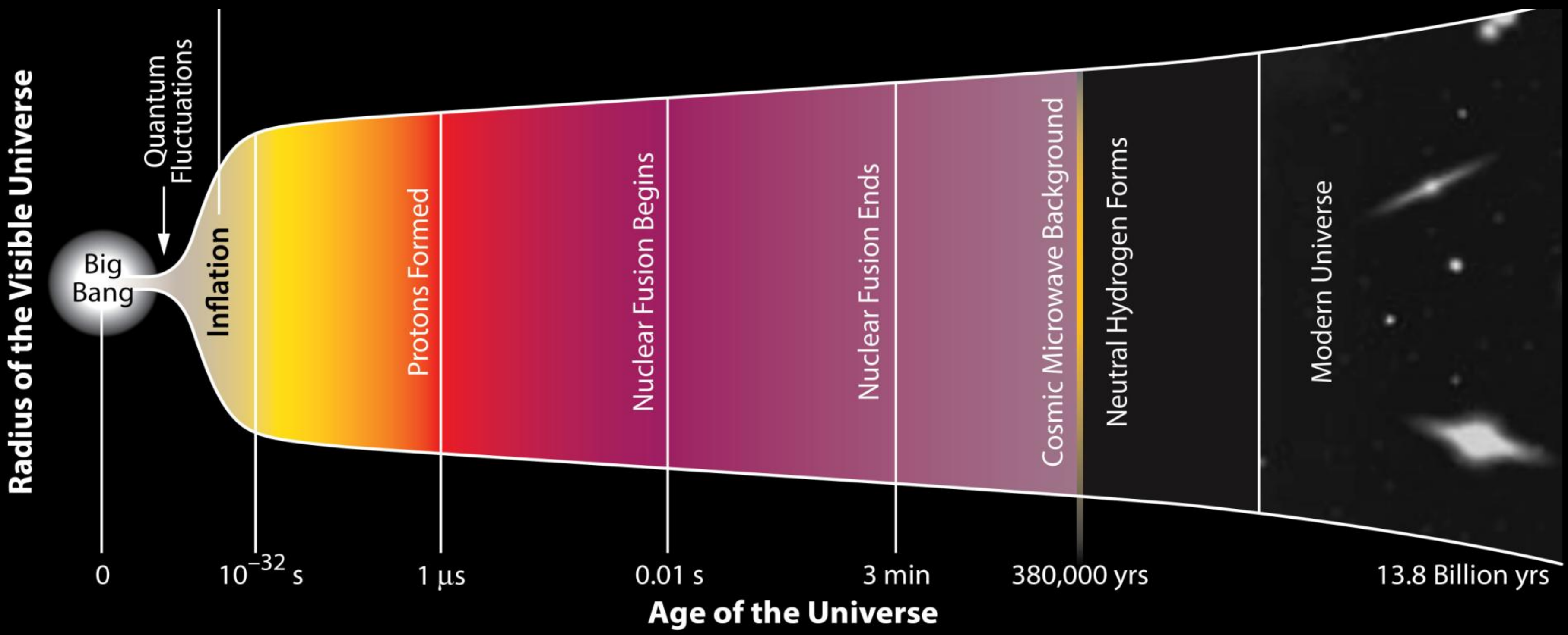
III. BK14, 15: Results with data up to 2015

IV. What’s next? BICEP3 and BICEP Array

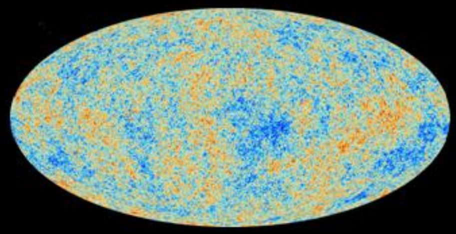
I.

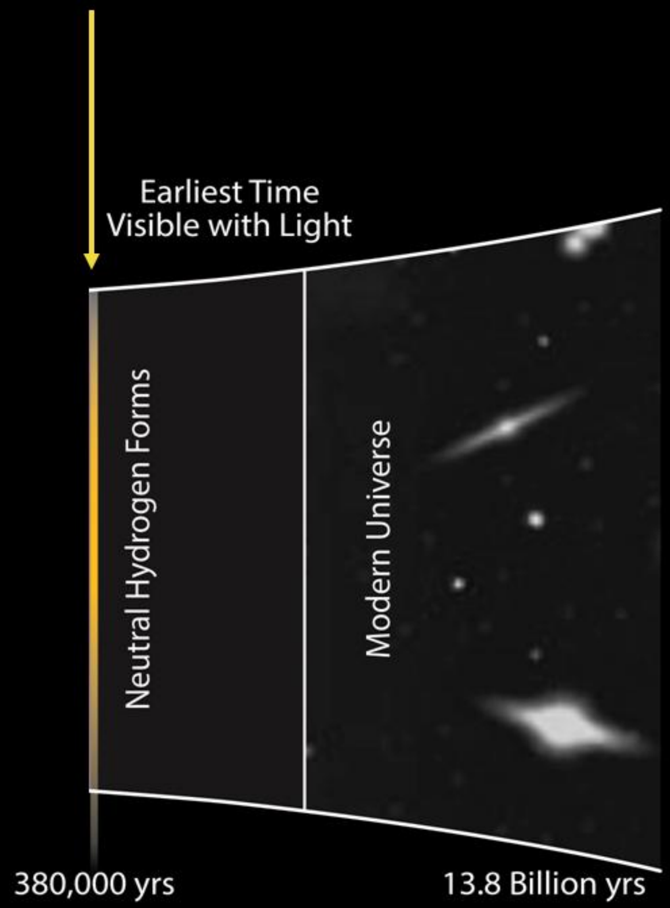
Inflation and the CMB

History of the Universe

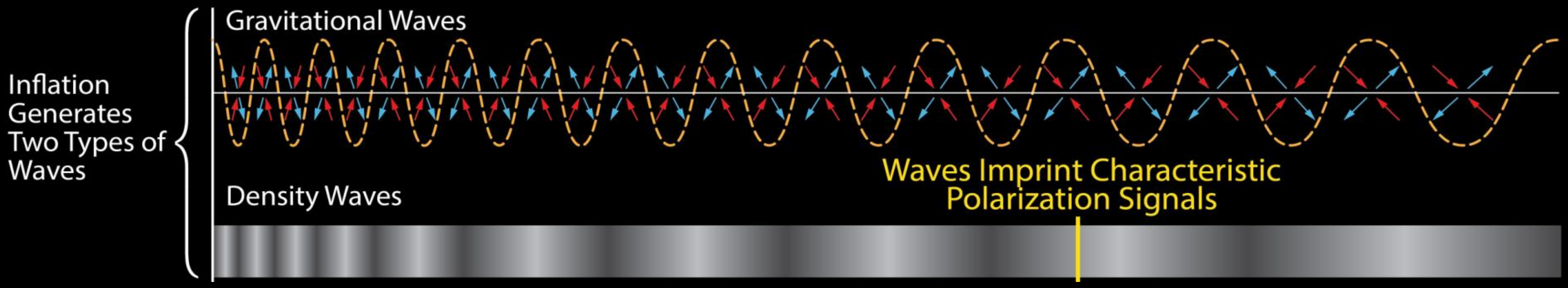


Photon decoupling

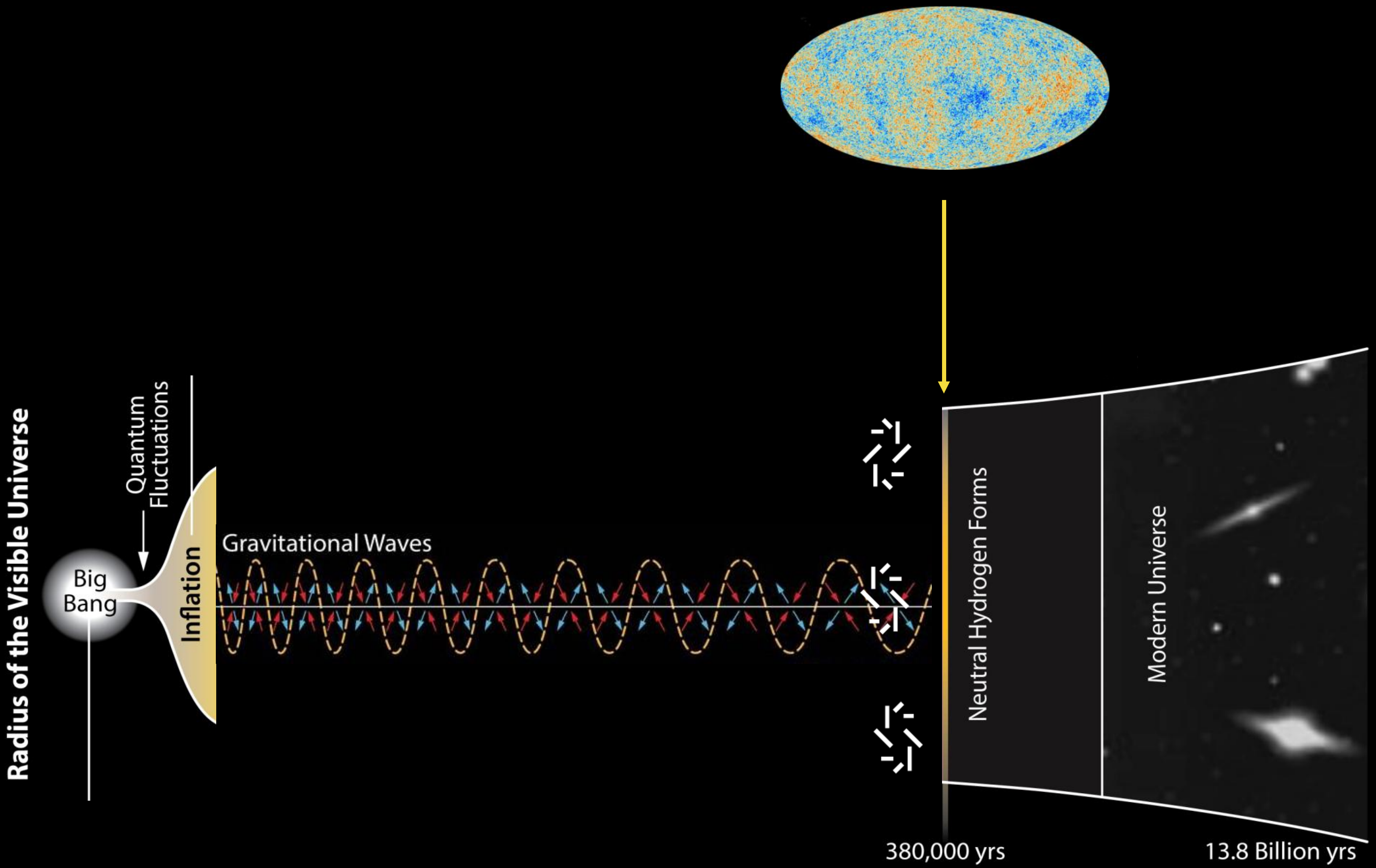




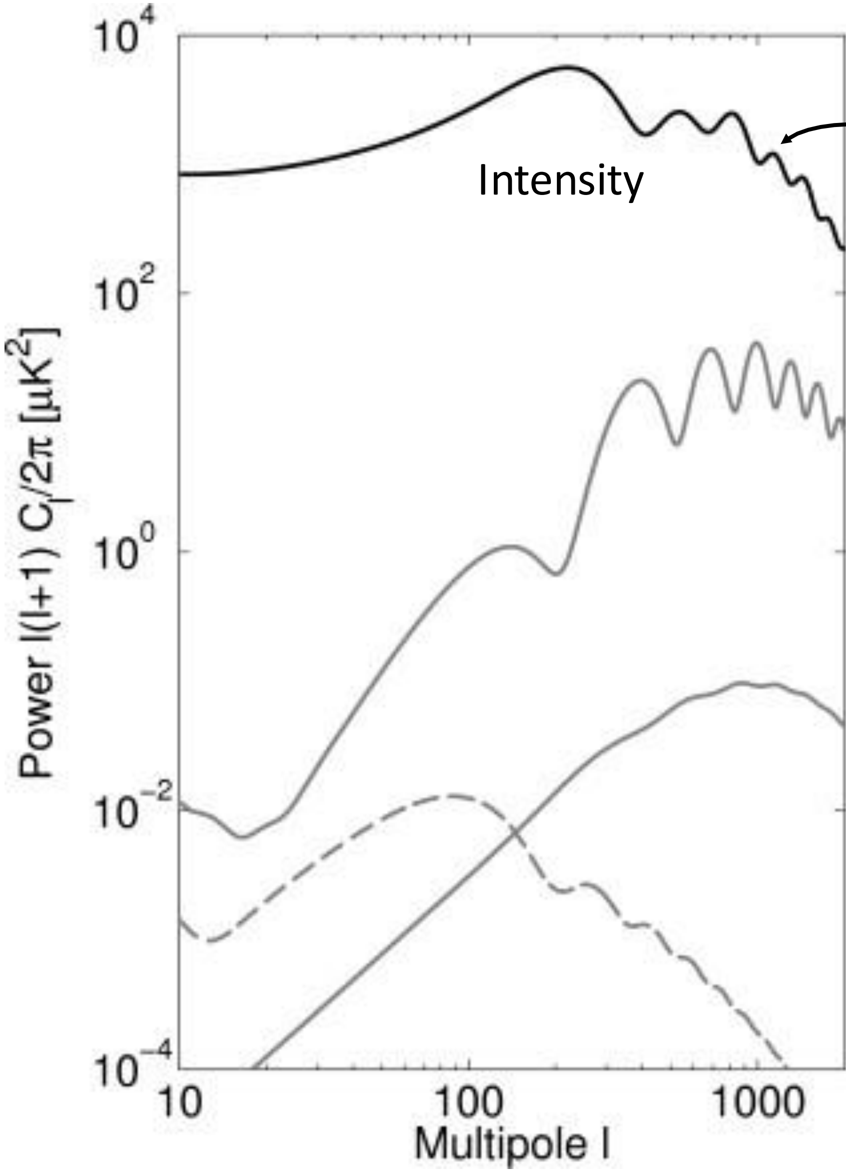
Inflation


Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals

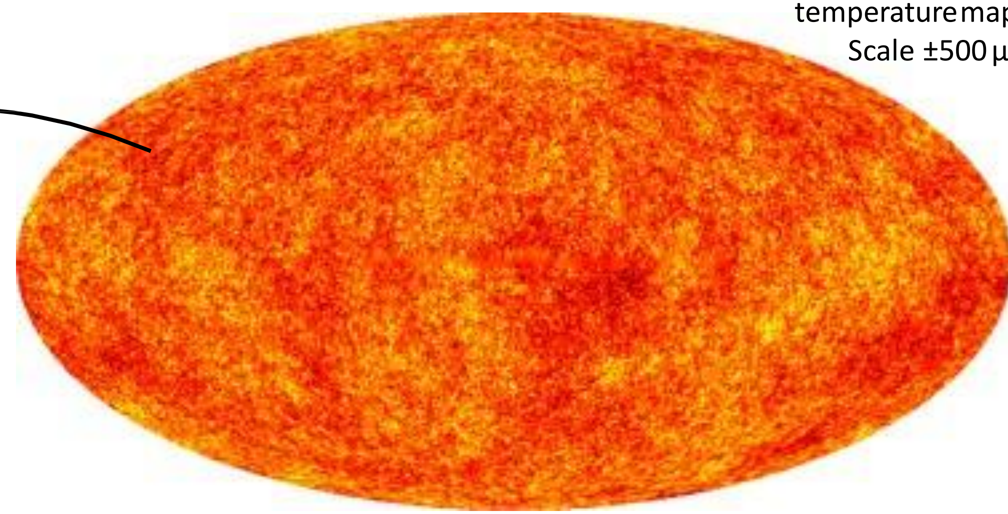
Imprint on the CMB



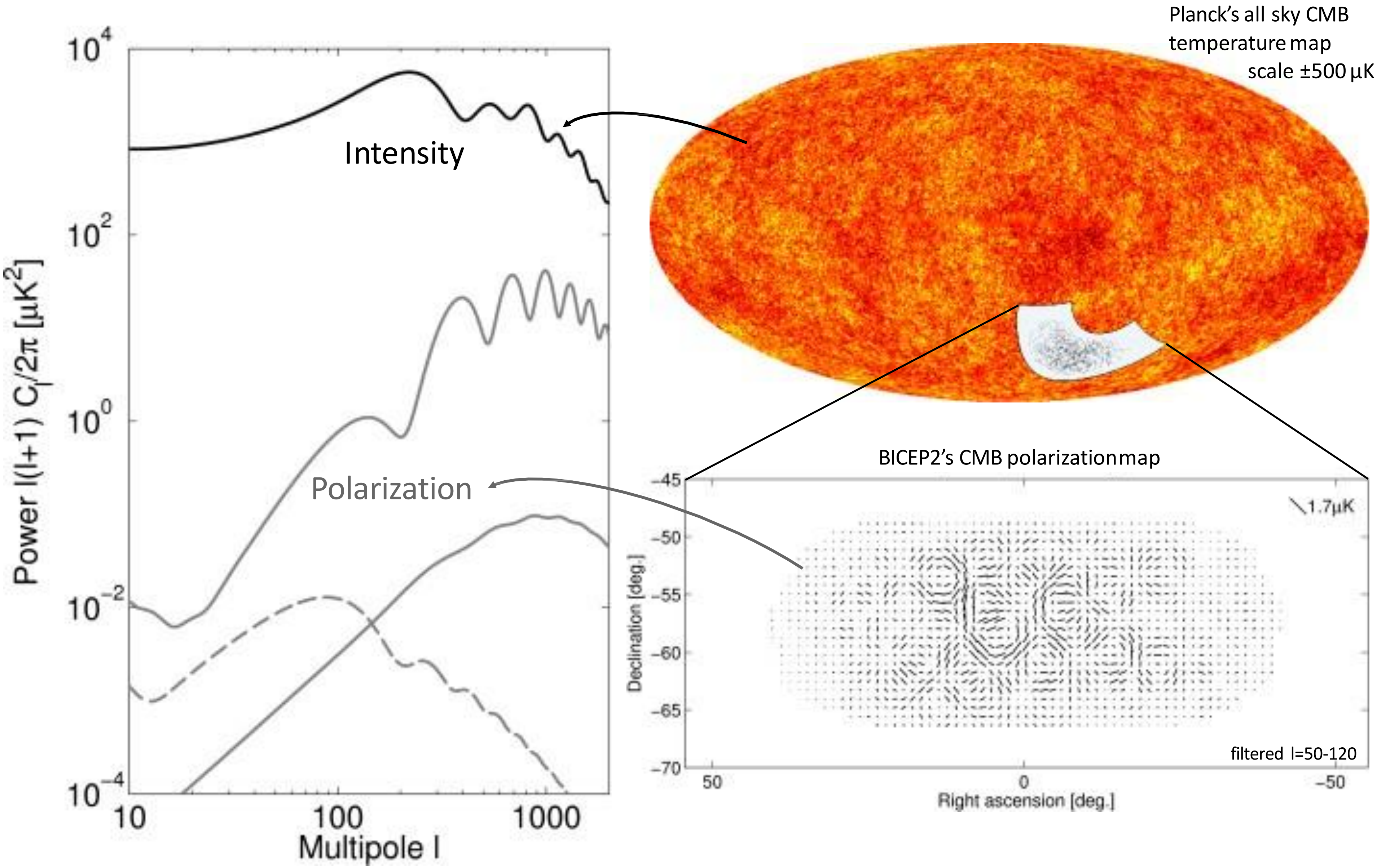
Cosmic Microwave Background



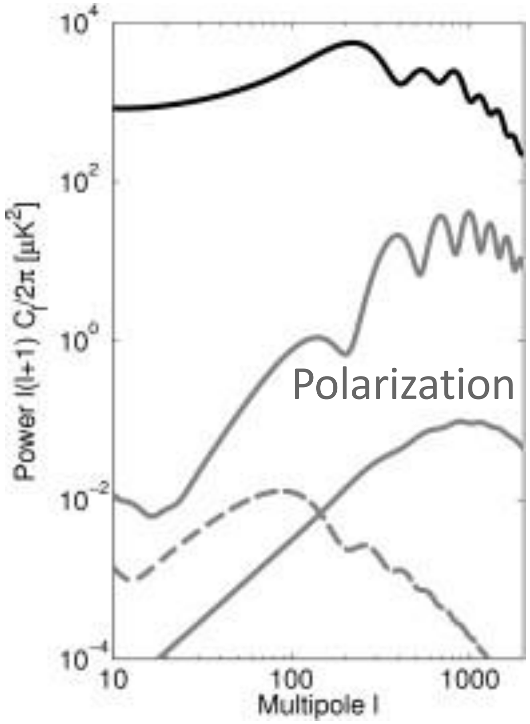
Planck's all sky CMB temperature map. Scale ±500 µK



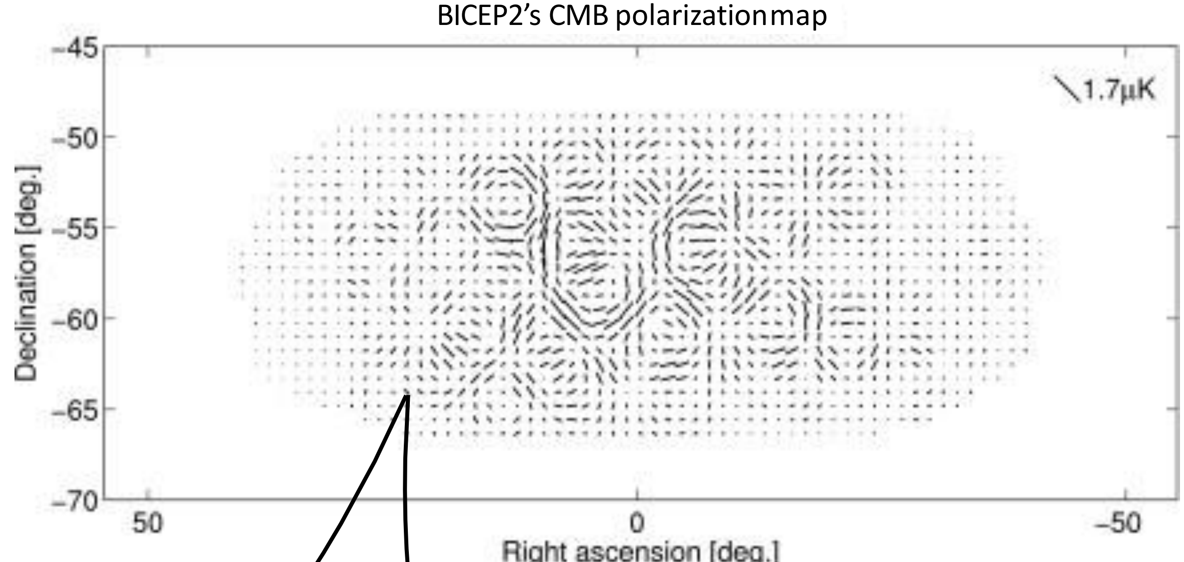
Cosmic Microwave Background



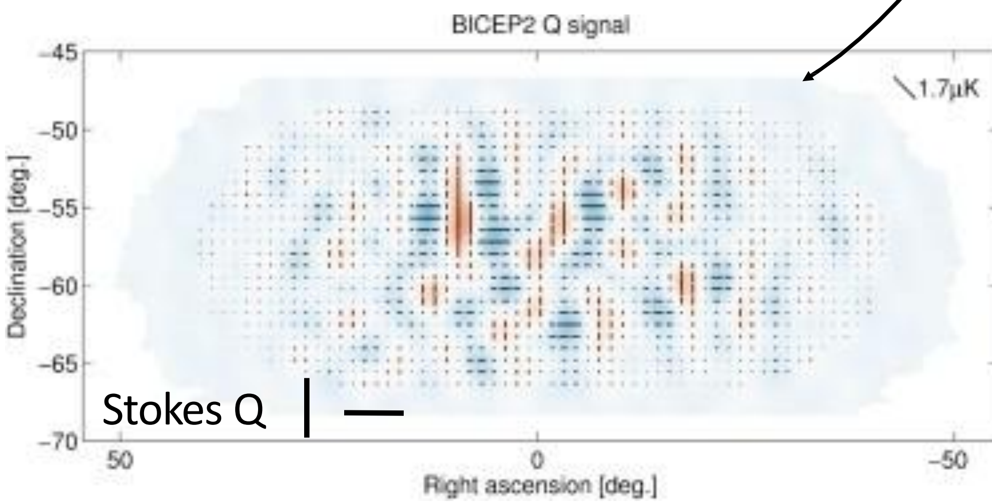
CMB Polarization

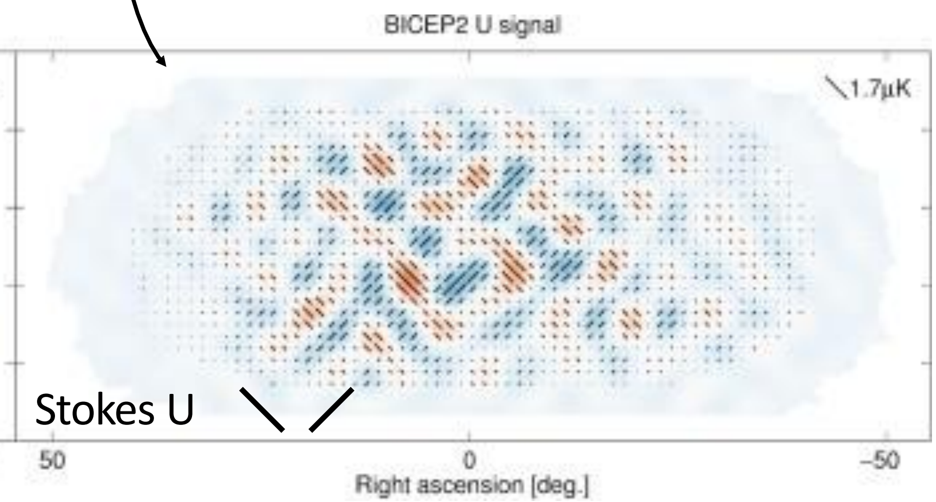


Need 2D basis to describe polarization map...

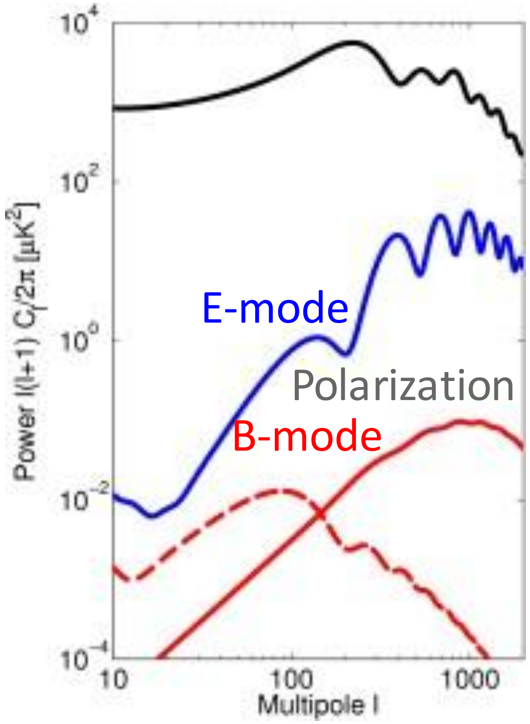


... familiar choice: Stokes Parameters Q&U





CMB Polarization



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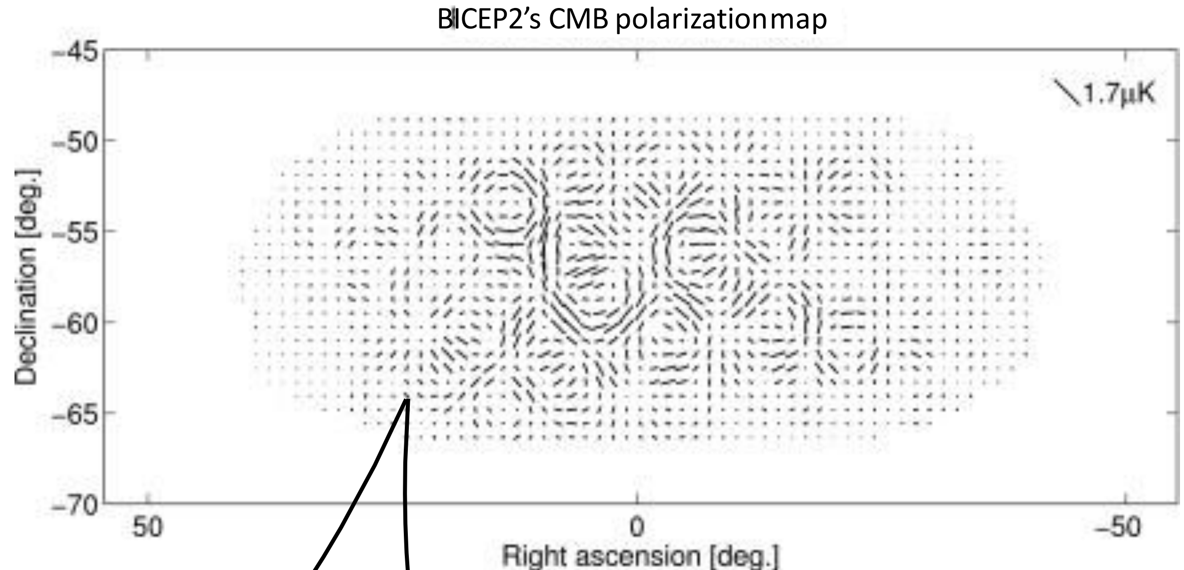
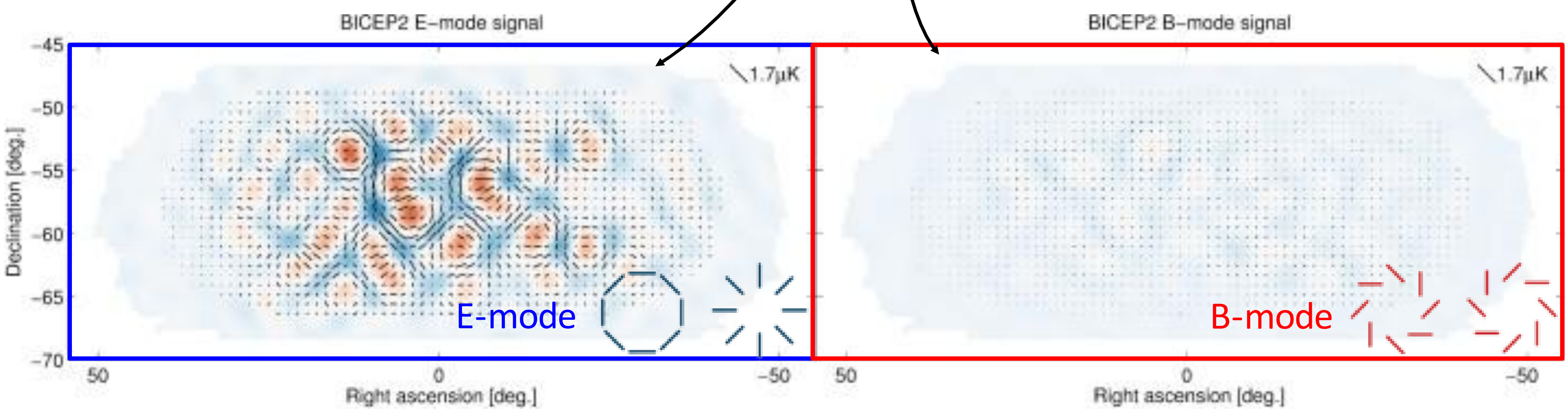
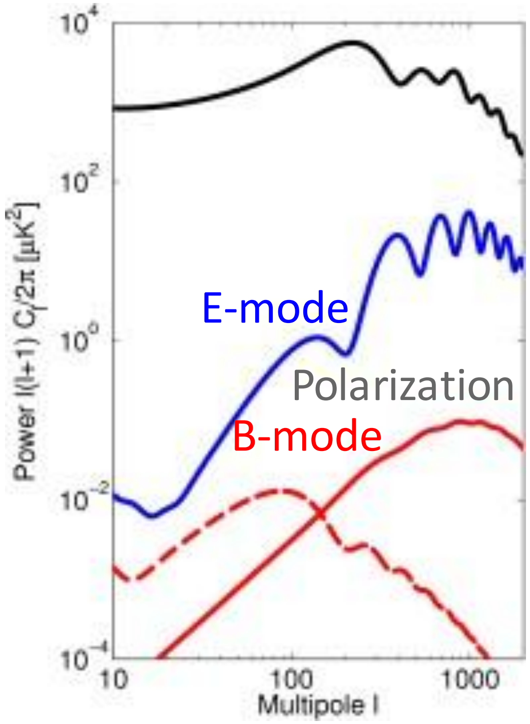


... clever choice for cosmology: E&B-modes



CMB Polarization



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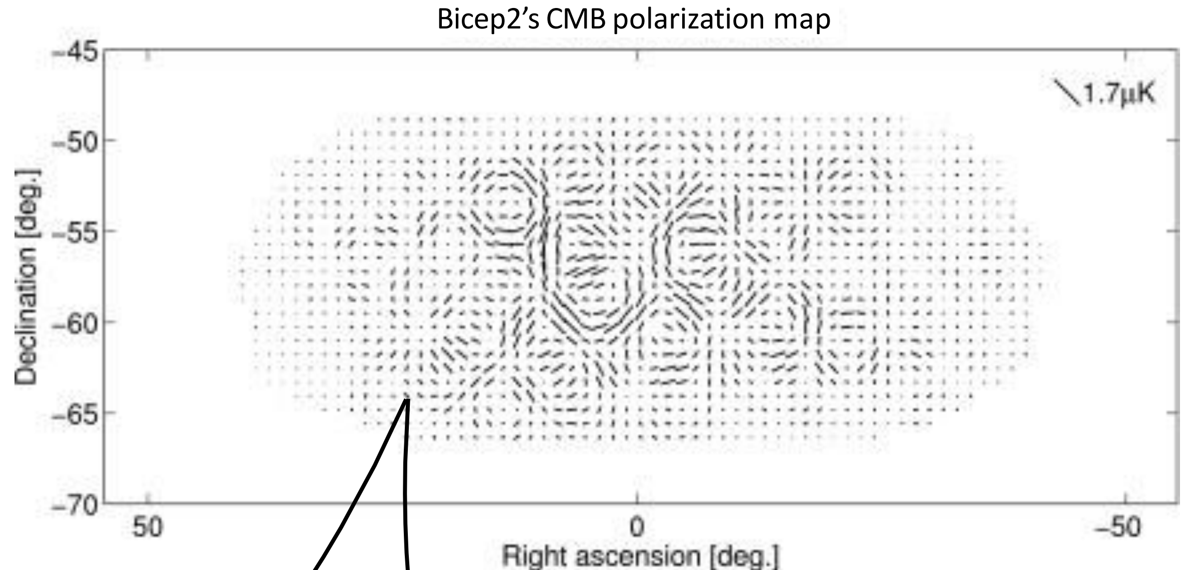

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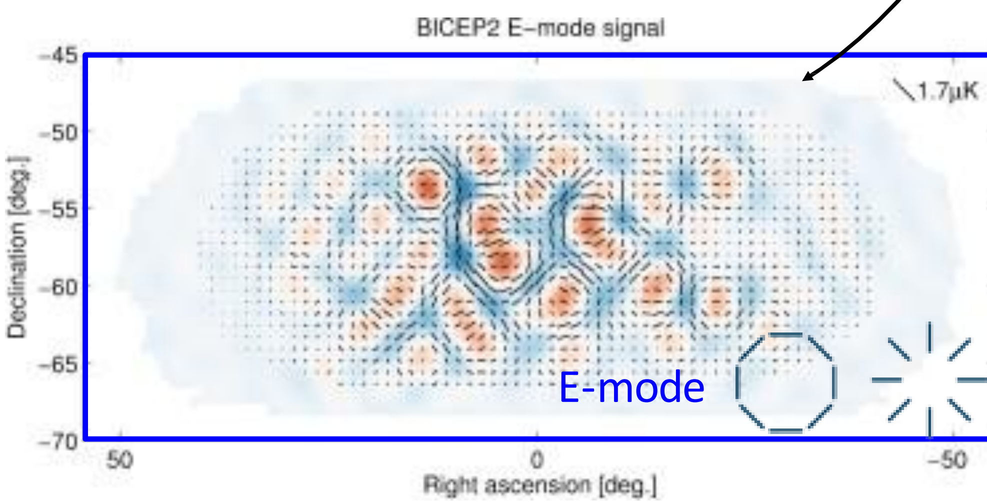
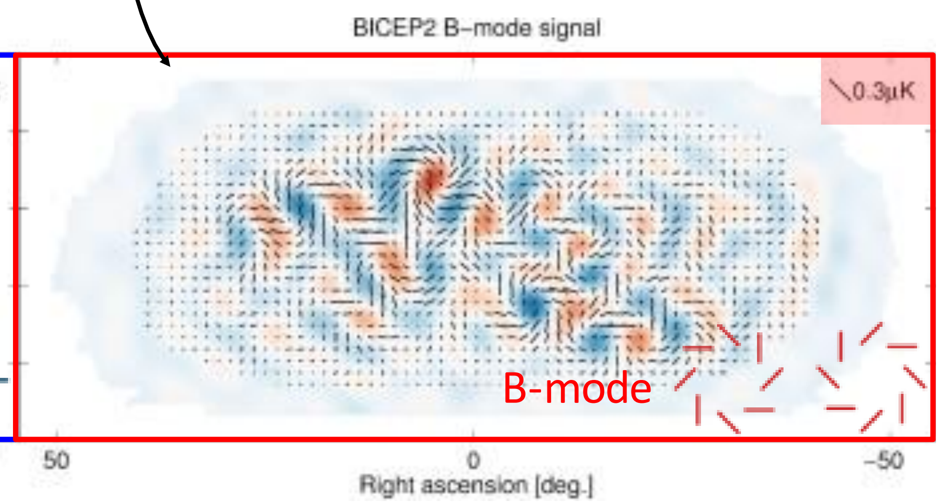
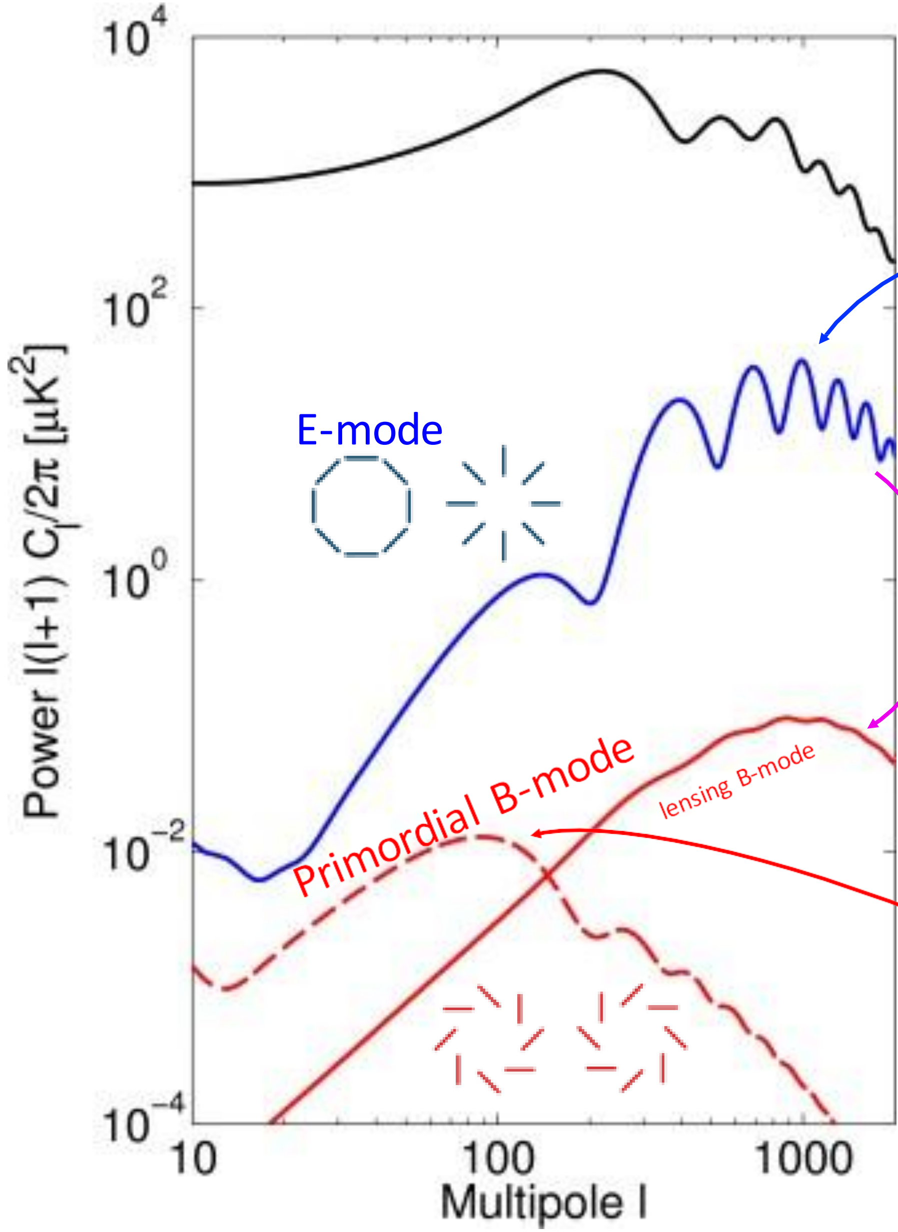
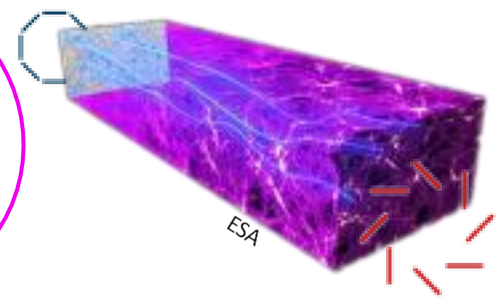




CMB Polarization



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



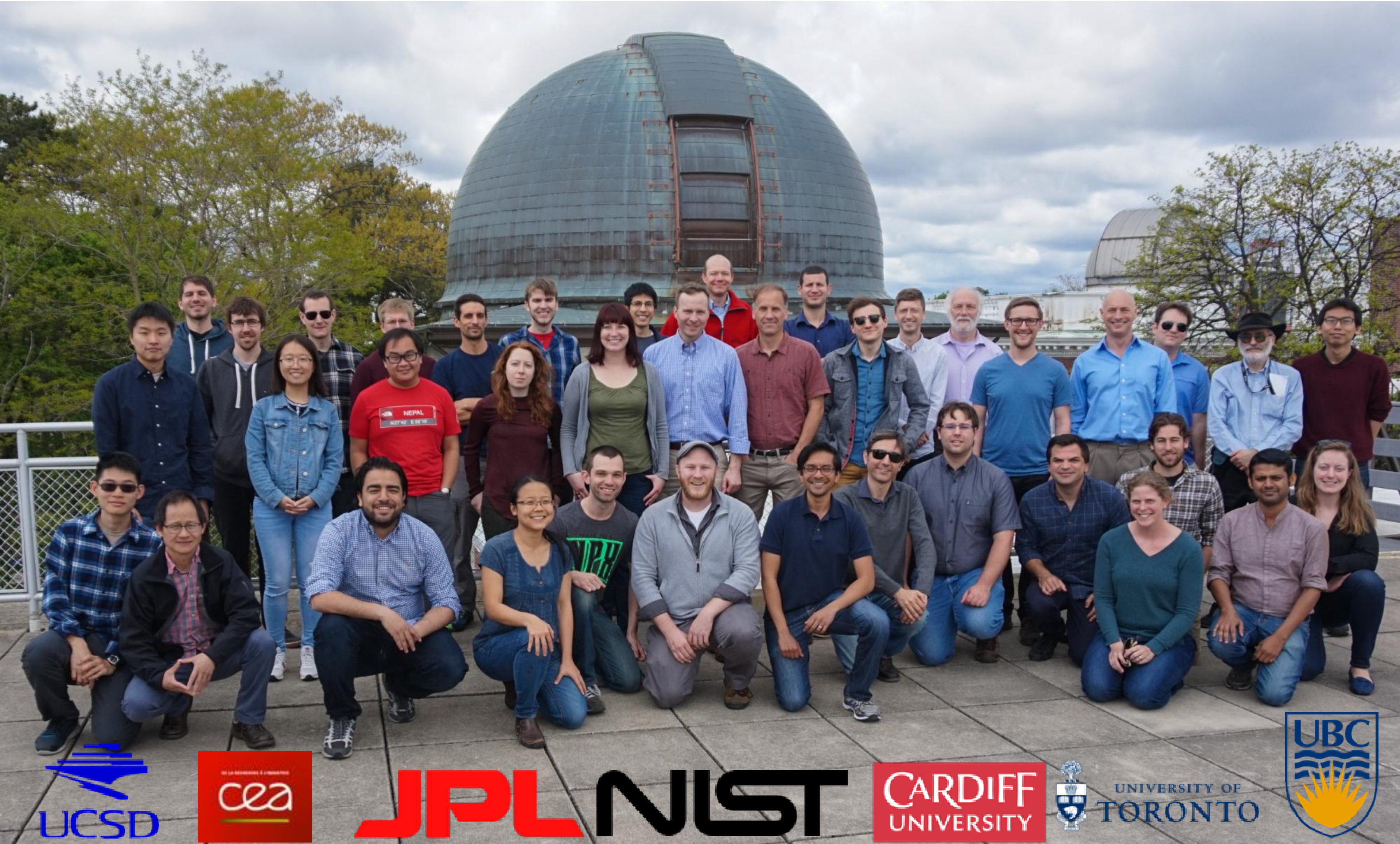
During propagation some of the E-modes are confused into B-modes by lensing

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

II.
The BICEP/Keck Experiment

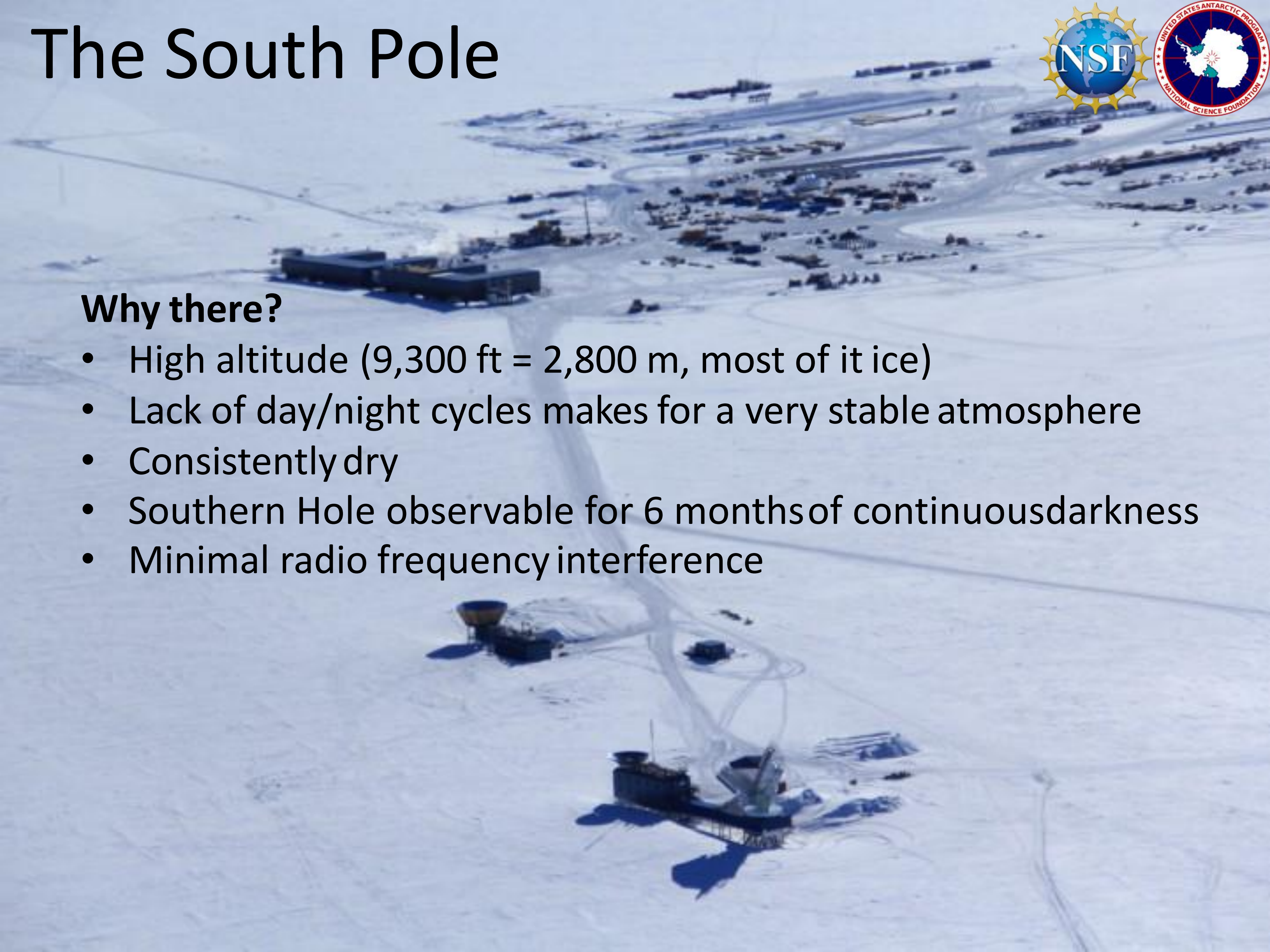
VE RI TAS
HARVARD

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891



The South Pole

The South Pole



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 Hole observable for 6 months of continuous darkness
- Minimal radio frequency interference

The Dark Sector

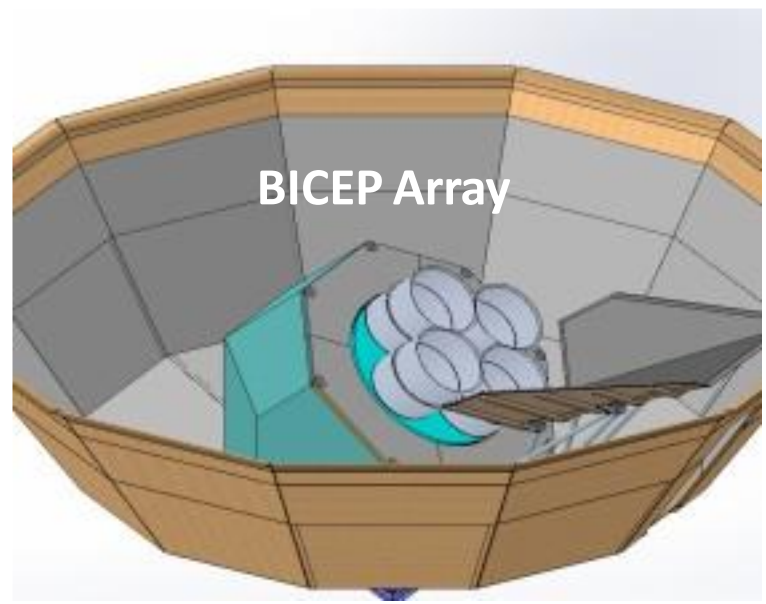
The Dark Sector

BICEP/Keck Experimental Strategy:

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

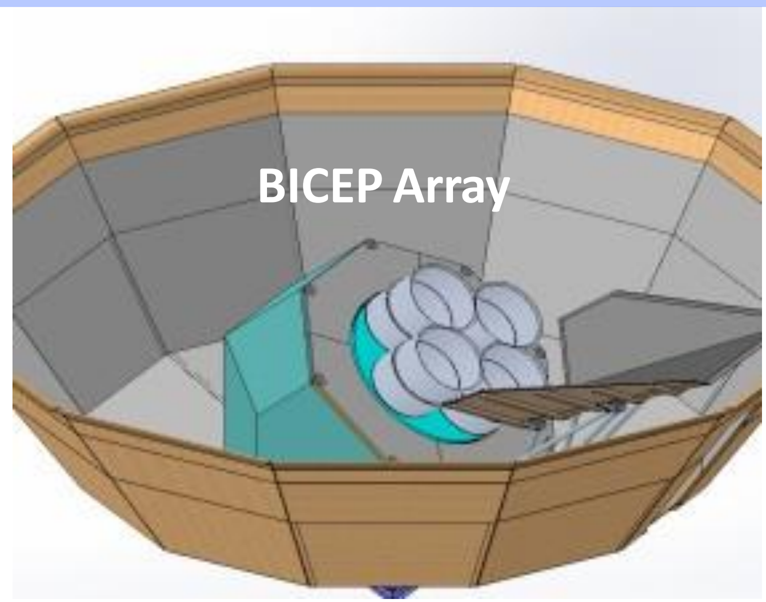
x 5 =

x 4 =



x 5 =

x 4 =



x 5 =

x 4 =

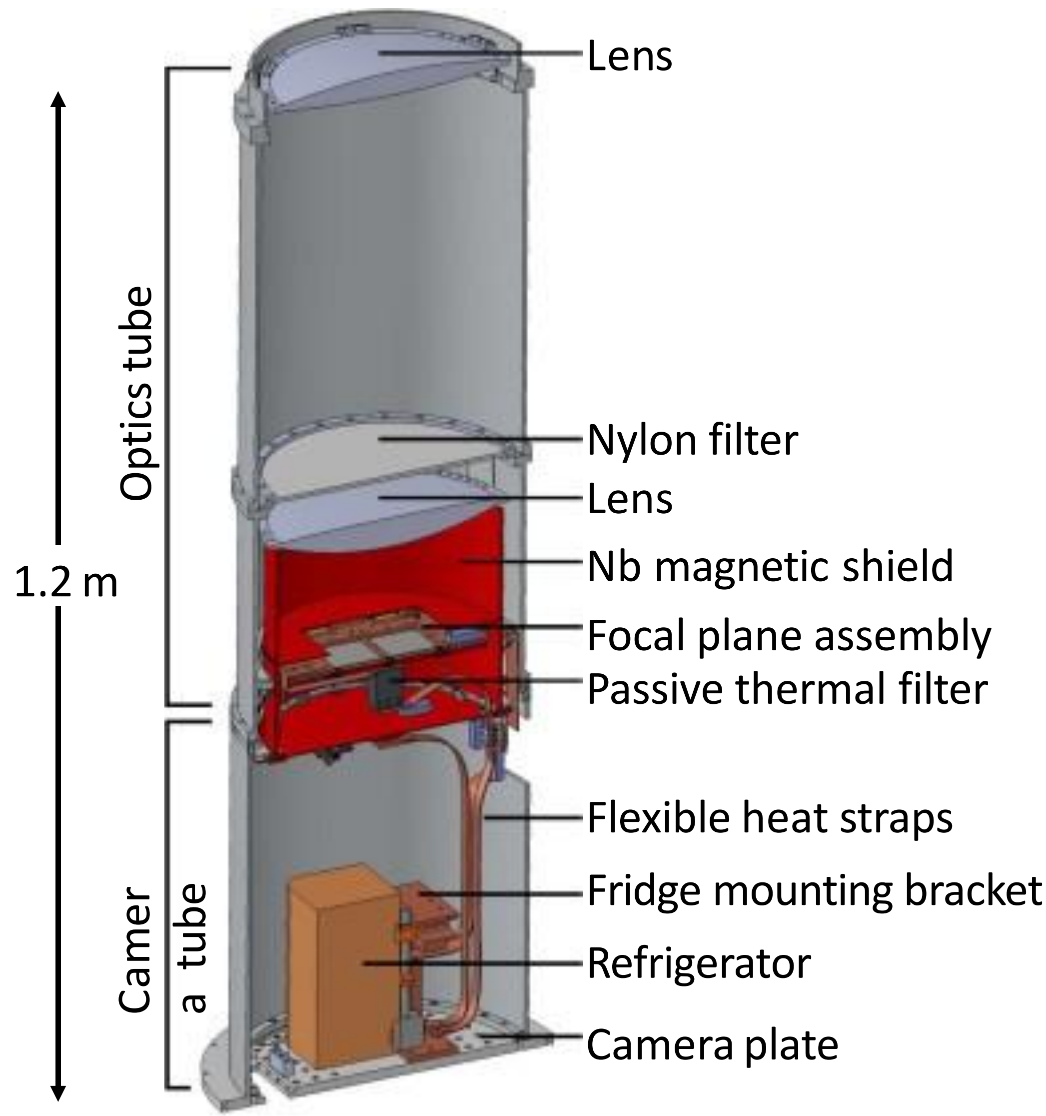
The BICEP2/Keck Telescopes

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.

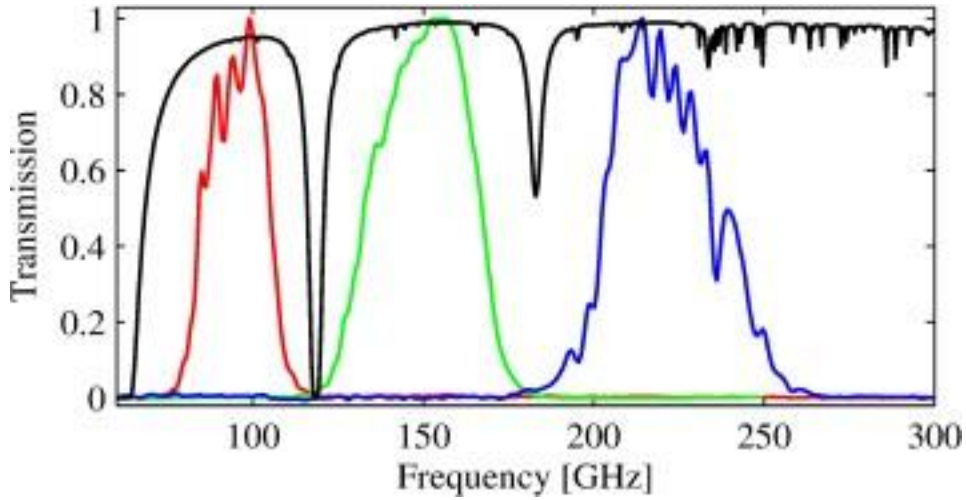
Pulse tube cryogenic cooler cools the optical elements to 4.2 K.

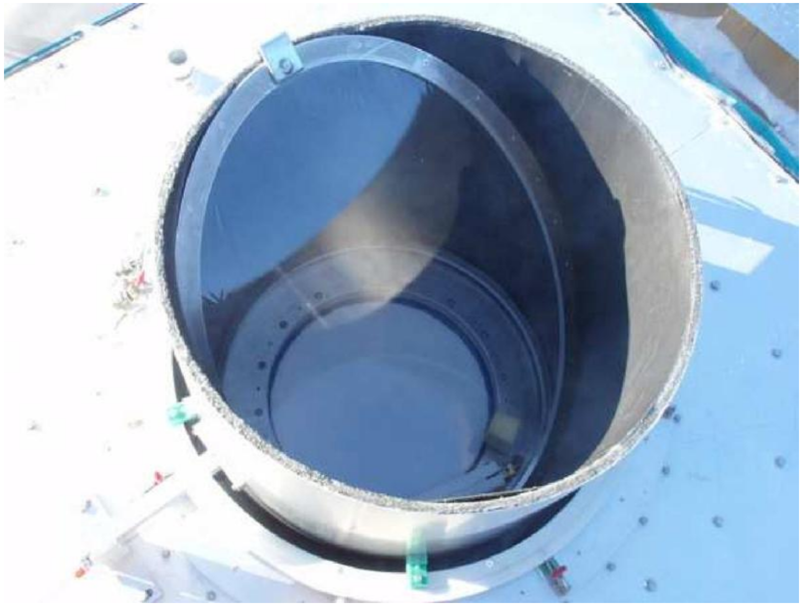
A 3-stage helium sorption refrigerator further cools the detectors to 0.27 K.

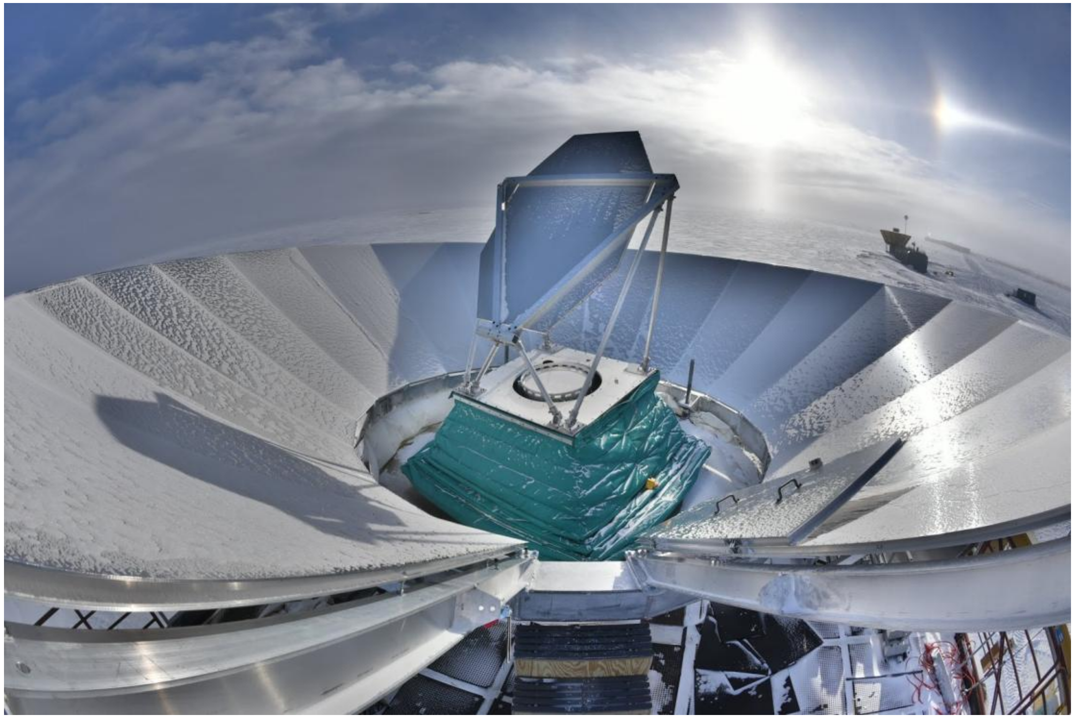


BICEP/Keck Calibrations

- Optical Efficiency
- Near-field Beam Mapping
- FTS
- Thick grill filter
- Forebaffle Loading
- Far sidelobe mapping
- Far-field beam mapping
- Polarization calibration
    - Rotating Polarized Source
    - Dielectric Sheet Calibrator

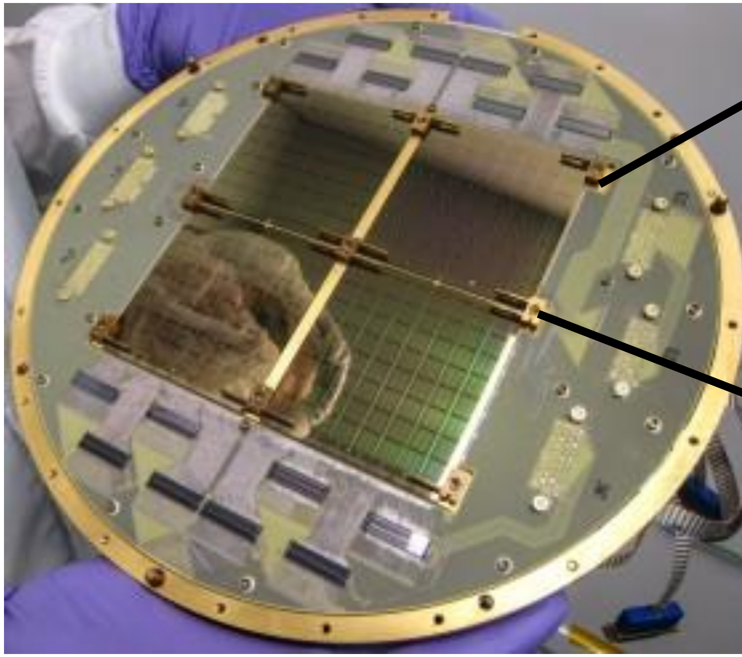




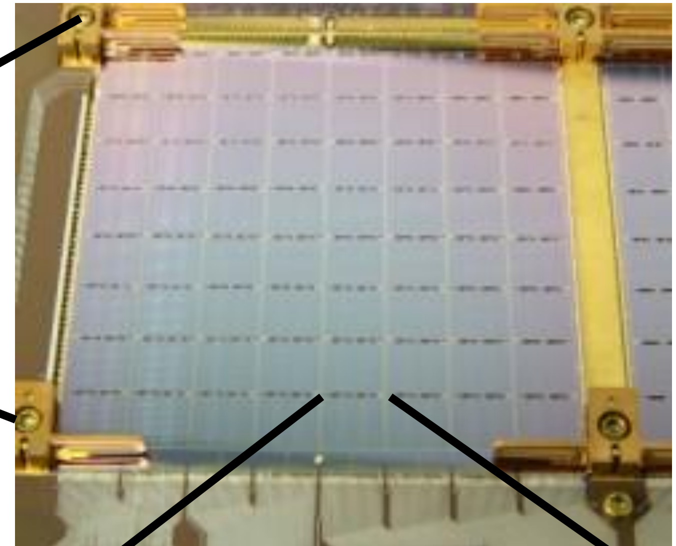


Detector Technology

Focal Plane



Planar Antenna Array



One pixel

Microstrip filters

Slot antennas

Transition Edge Sensor

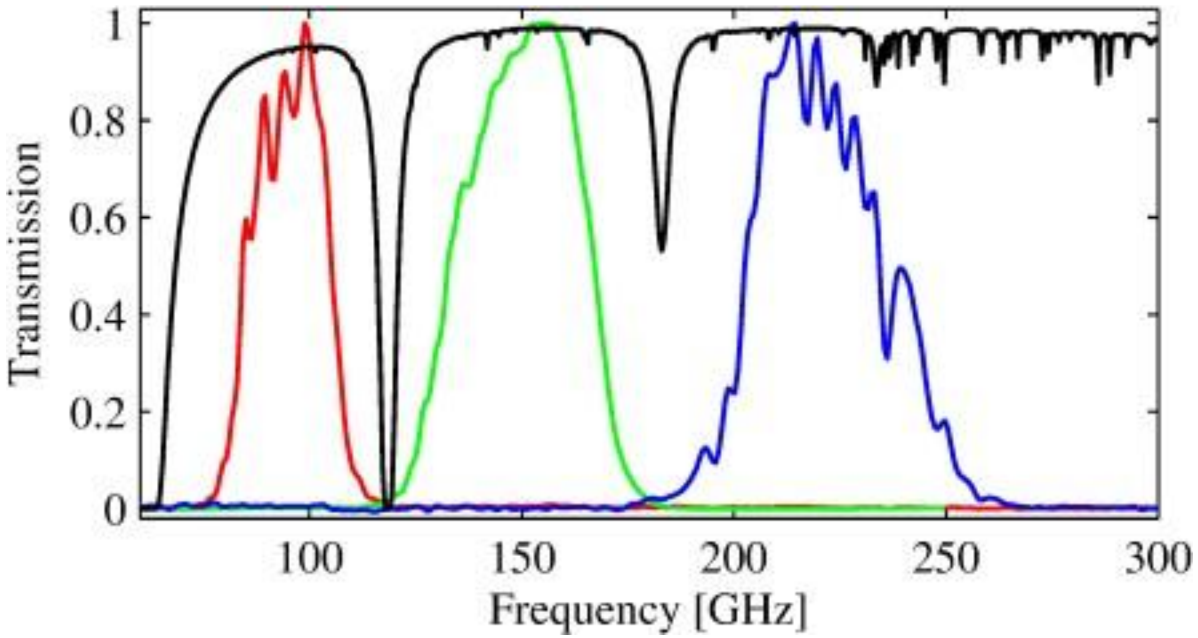
BICEP2/Keck Band Response

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

The ~25% fractional bandwidth fits within atmospheric transmission windows straddled by oxygen and water lines.

In these windows, the atmosphere is transparent to microwaves.

Typical South Pole atmospheric transmission



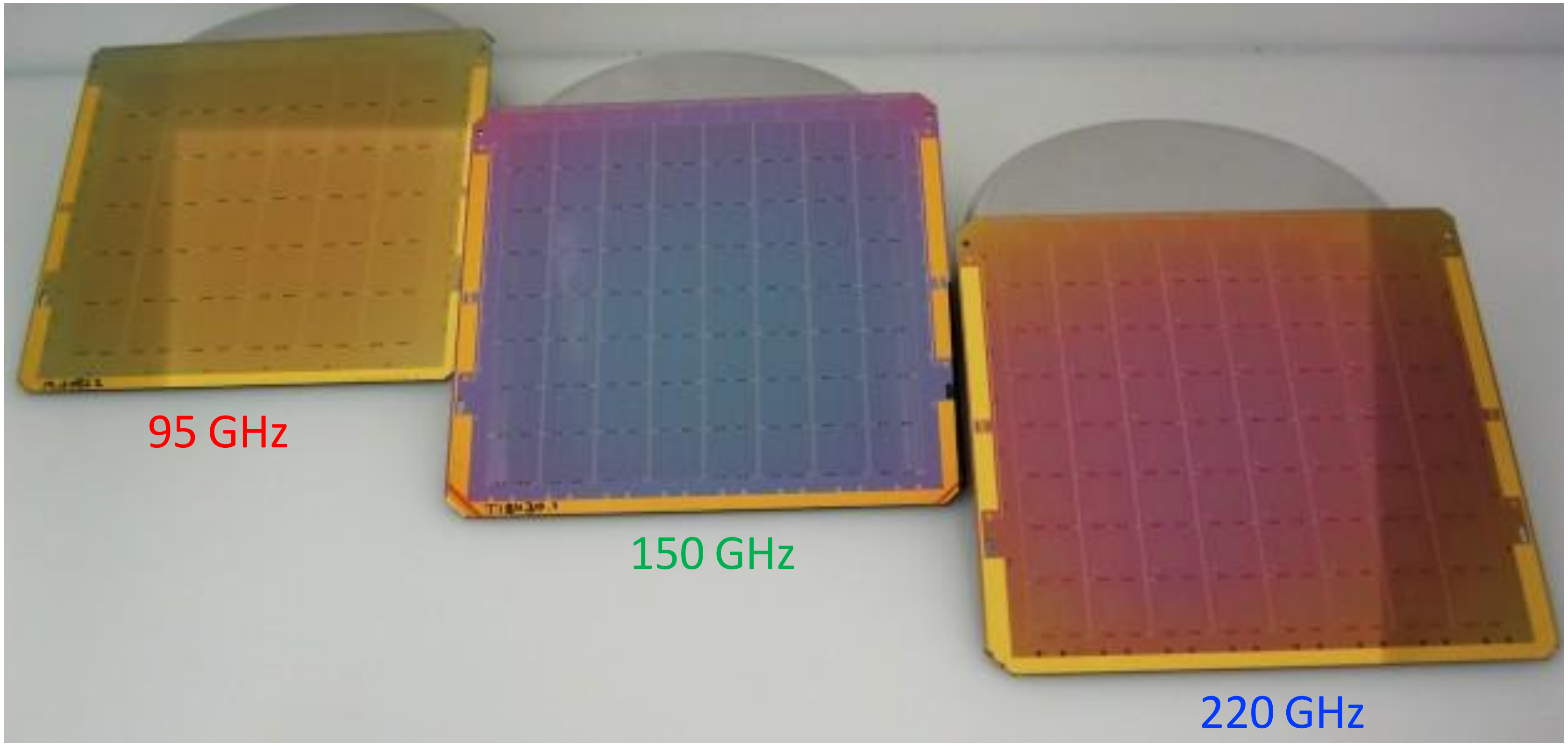
Choices of instrument response:

95 GHz

150 GHz

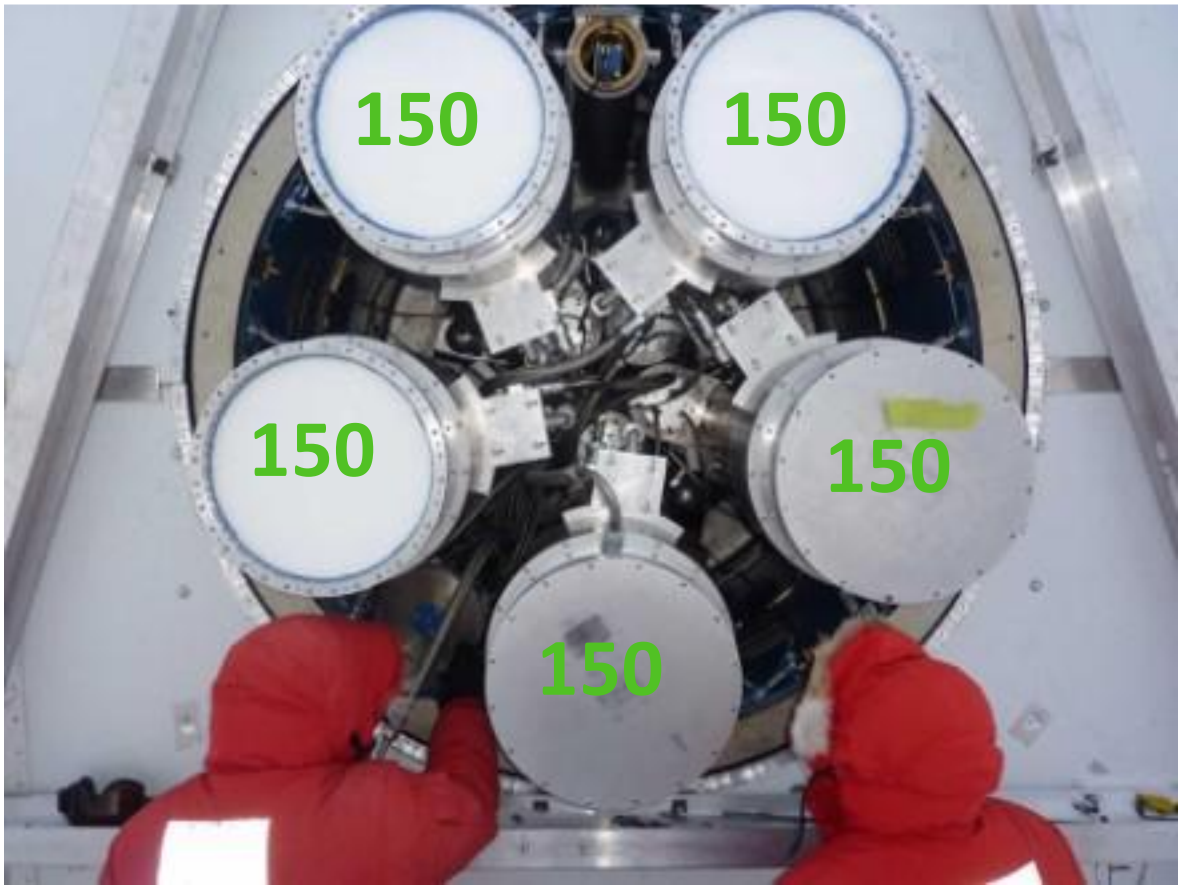
220 GHz

Detectors designed to scale in frequency



Up to 2013 – all 150 GHz
2014 – 95/150 GHz
2015 – 95/150/220 GHz
2017 – 220/270 GHz

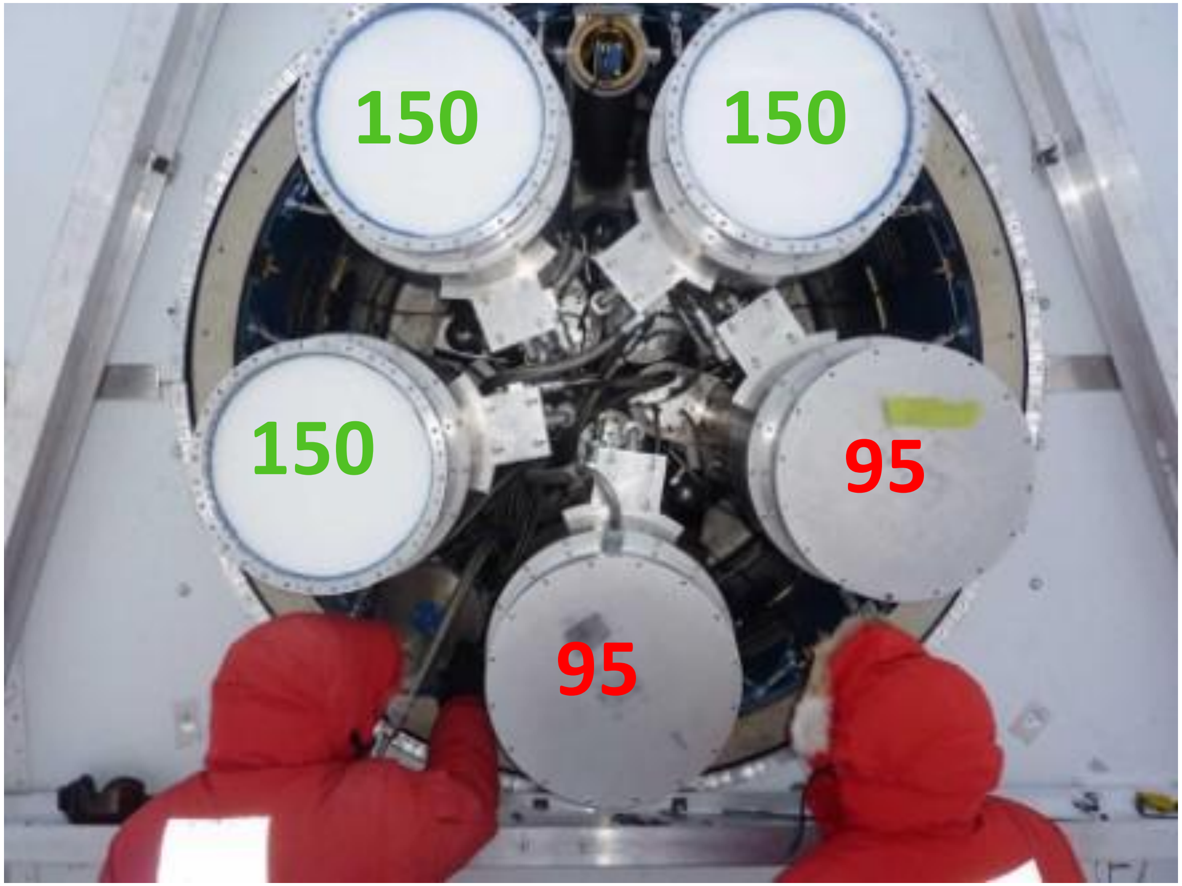
Keck Array Frequency Coverage



2012-2013

- 2012-2013: All Keck Array receivers at 150 GHz

Keck Array Frequency Coverage

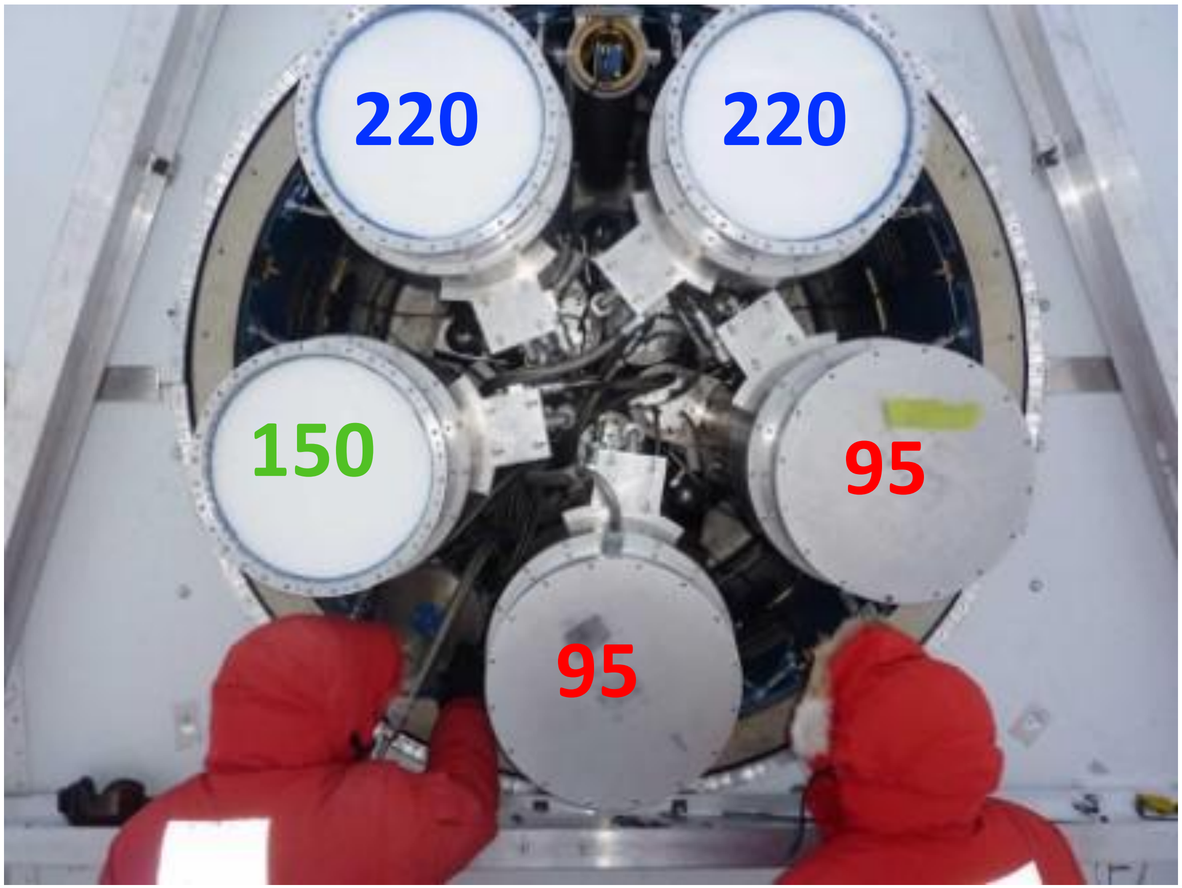


2014

- 2012-2013: All Keck Array receivers at 150 GHz
- 2014: Two 150 GHz receivers replaced with 95 GHz

BK14: The Keck Array and BICEP2 Collaborations, Phys. Rev. Lett. ***116****, 031302, 2015*

Keck Array Frequency Coverage



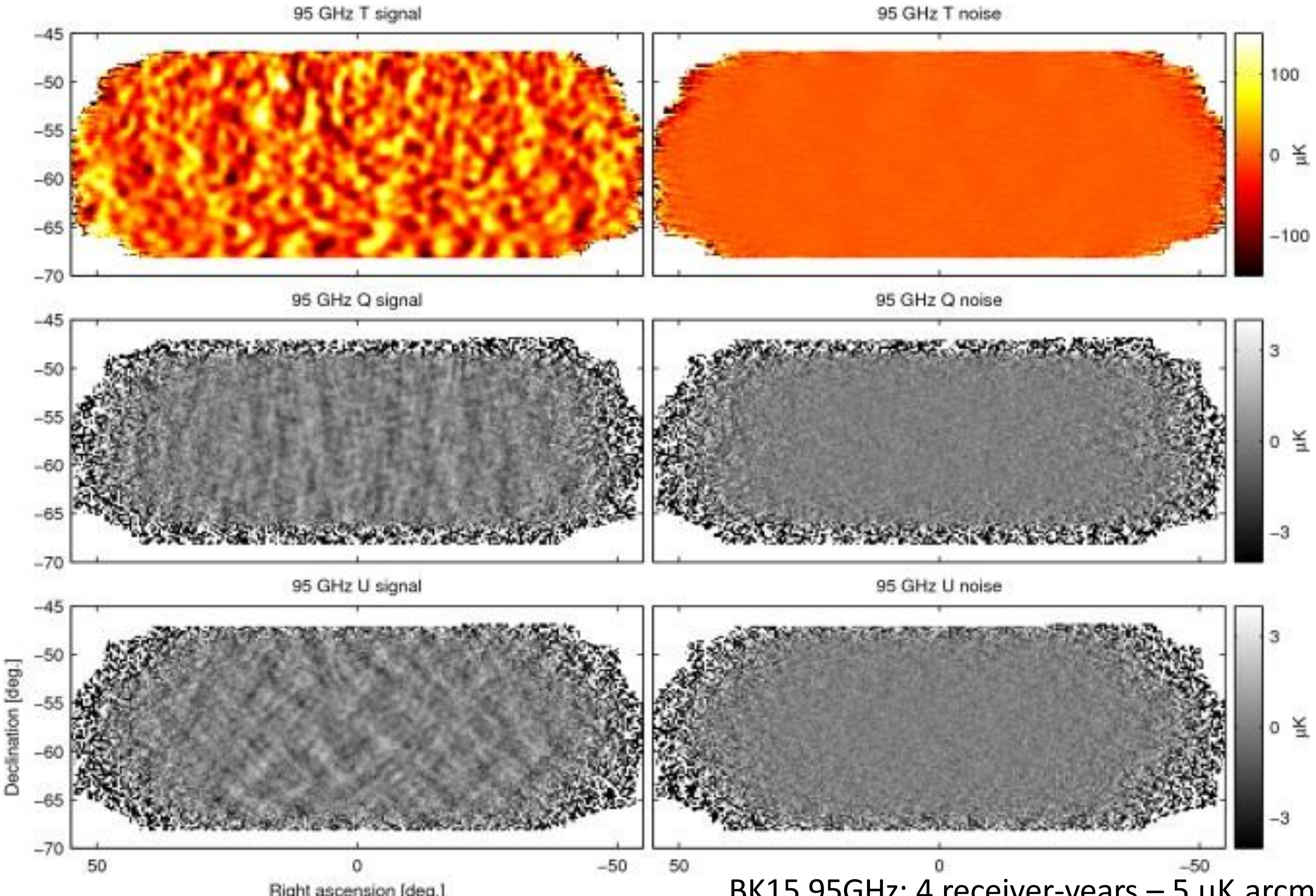
- 2012-2013: All Keck Array receivers at 150 GHz
- 2014: Two 150 GHz receivers replaced with 95 GHz
- 2015: Two additional 150s replaced with 220s

2015

BK15: Out soon!

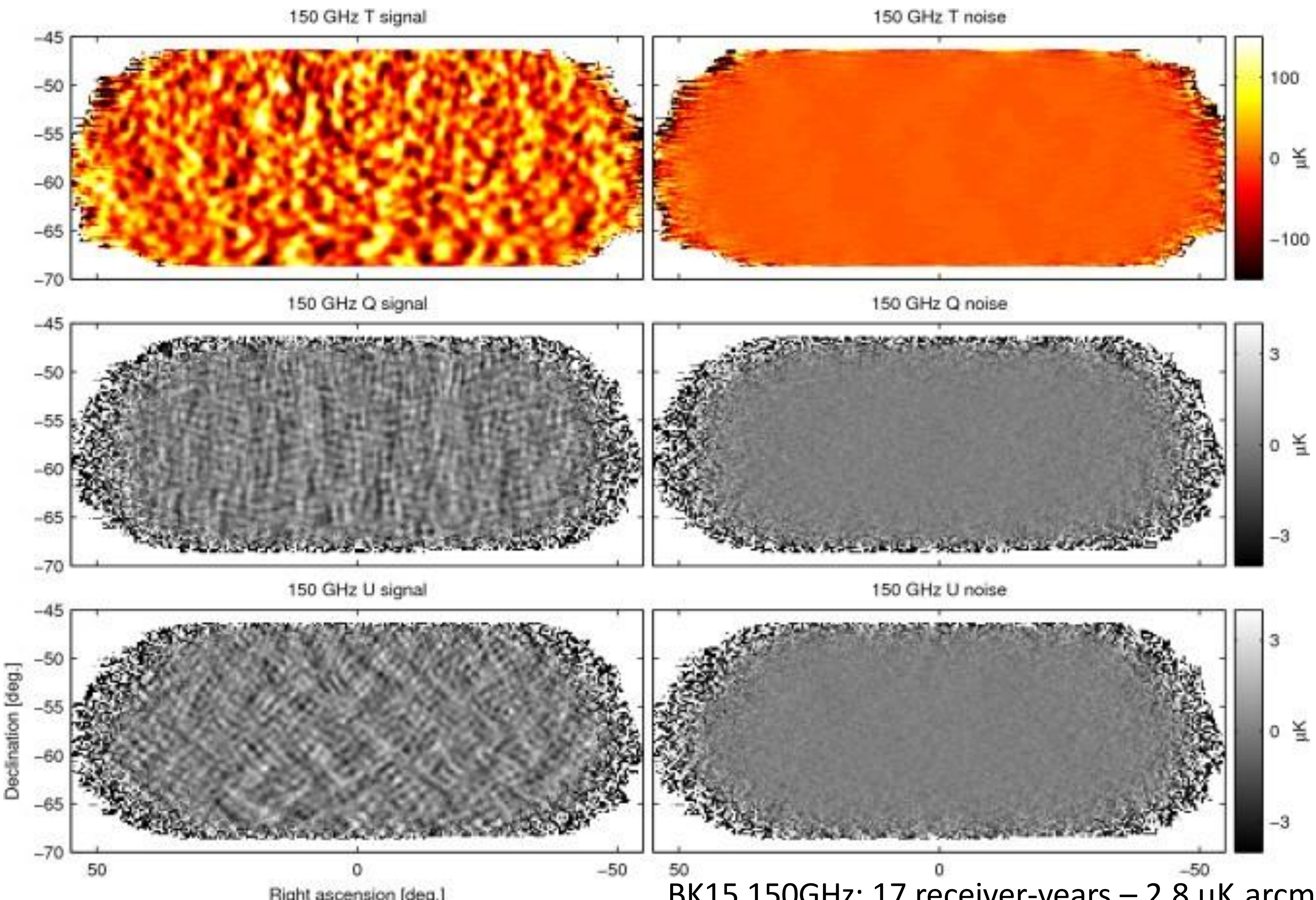
III.
Results with data up to 2015

Upcoming BK15 95GHz Maps



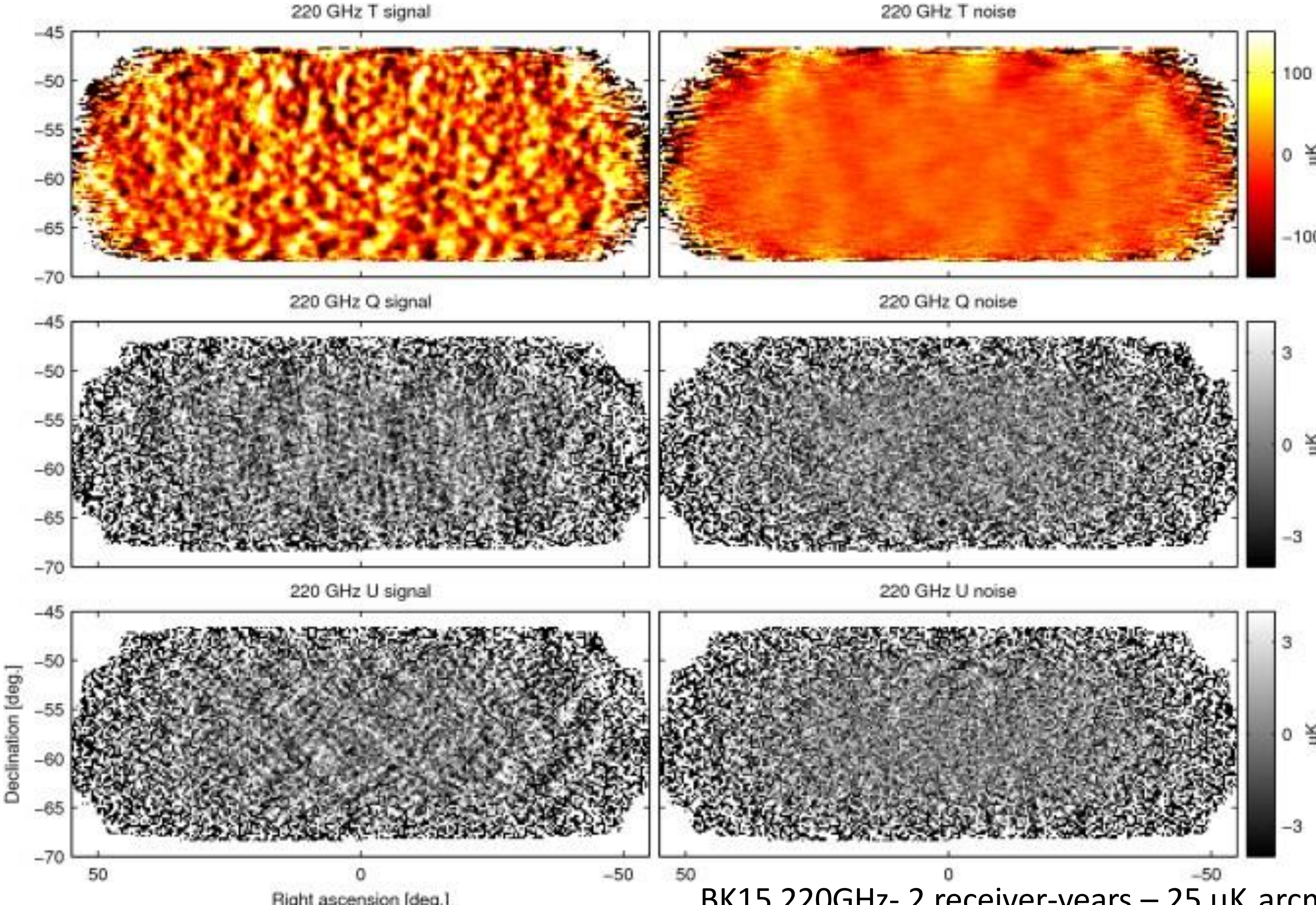
BK15 95GHz: 4 receiver-years – 5 μK arcmin

Upcoming BK15 150GHz Maps



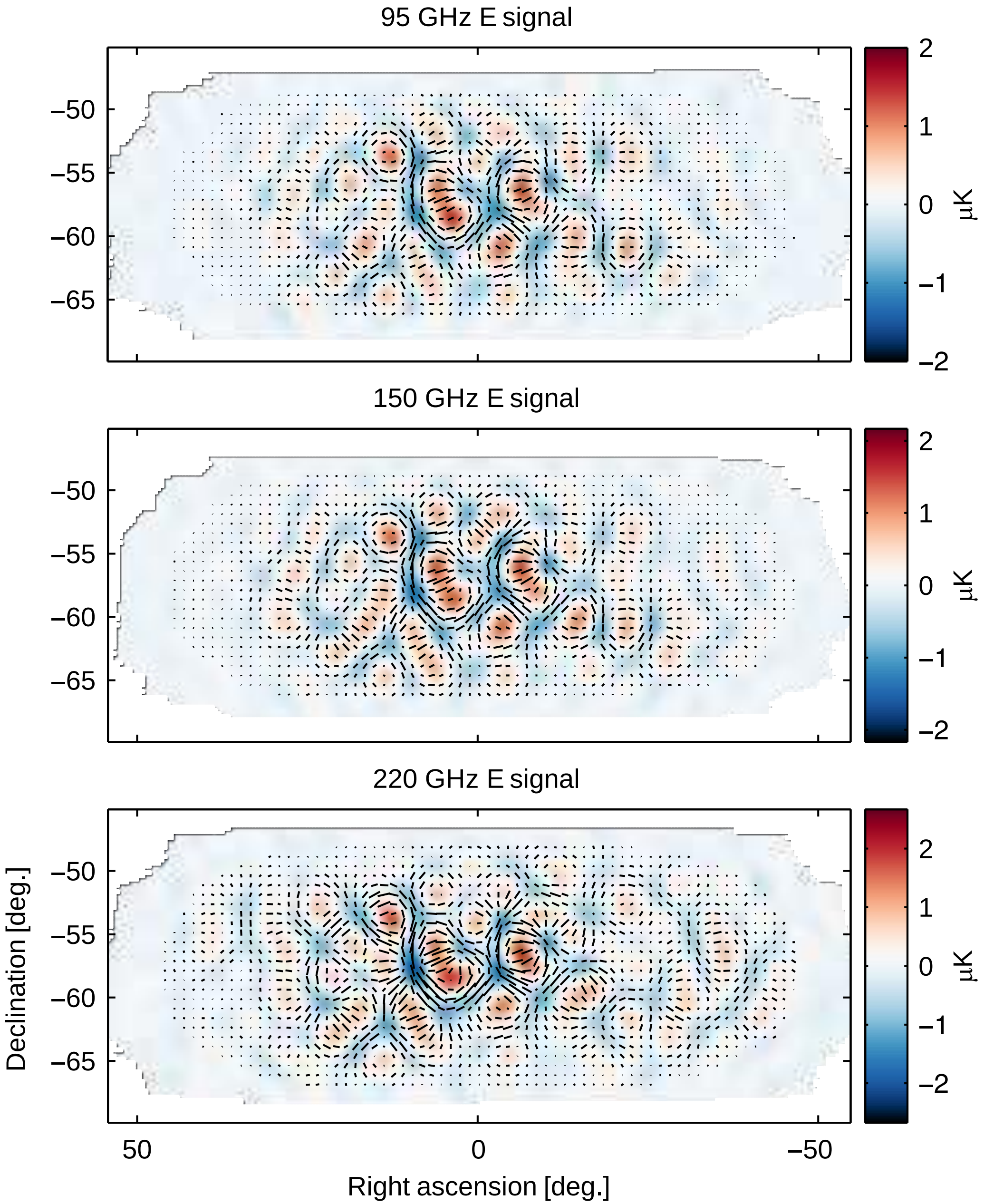
BK15 150GHz: 17 receiver-years – 2.8 μK arcmin

Upcoming BK15 220GHz Maps

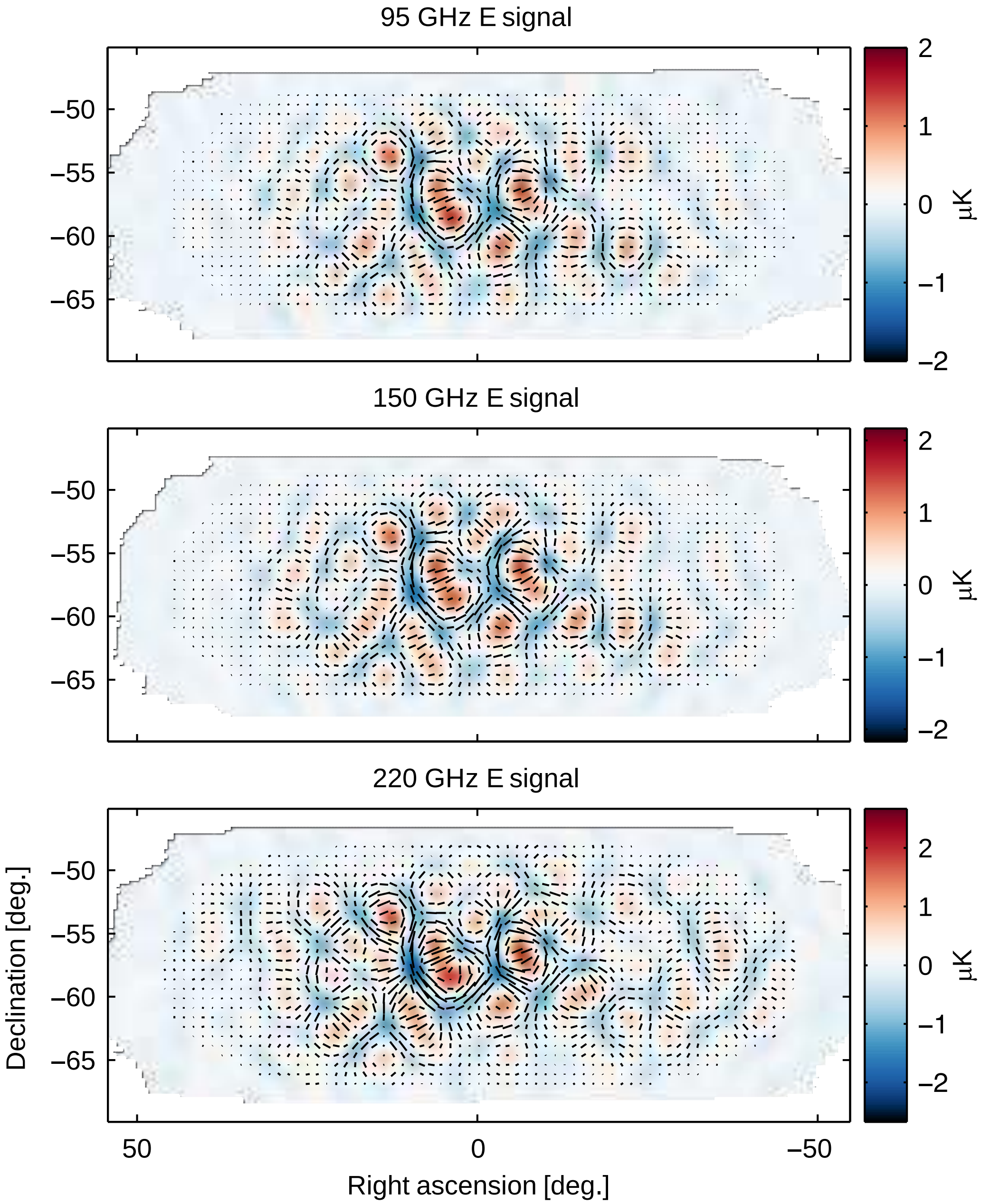


BK15 220GHz- 2 receiver-years – 25 μK arcmin

Upcoming Keck 2015-only E-mode Maps



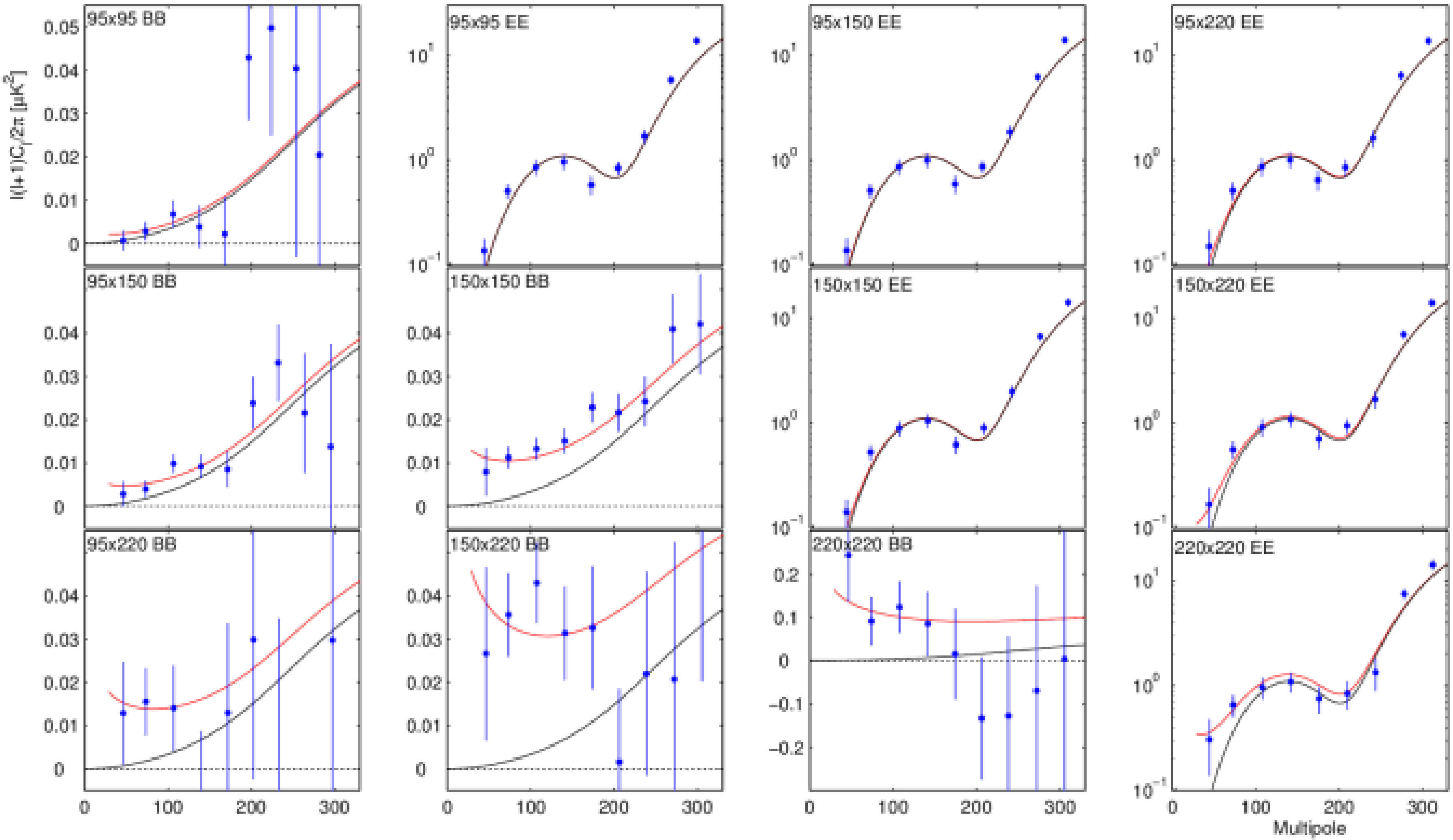
Upcoming Keck 2015-only E-mode Maps



New for BK15

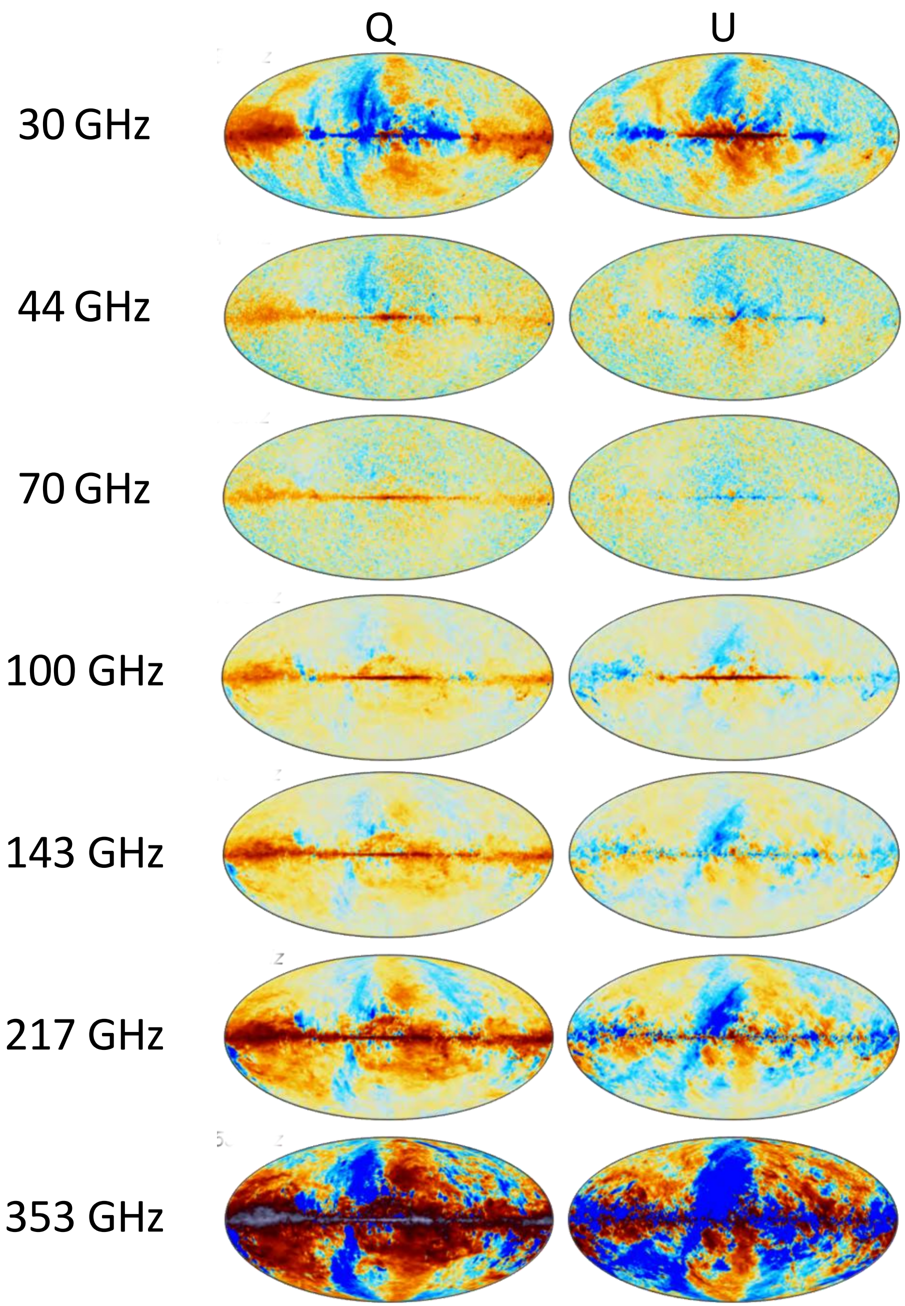
Already 3x deeper than Planck 217 GHz.

Upcoming BK15 spectra

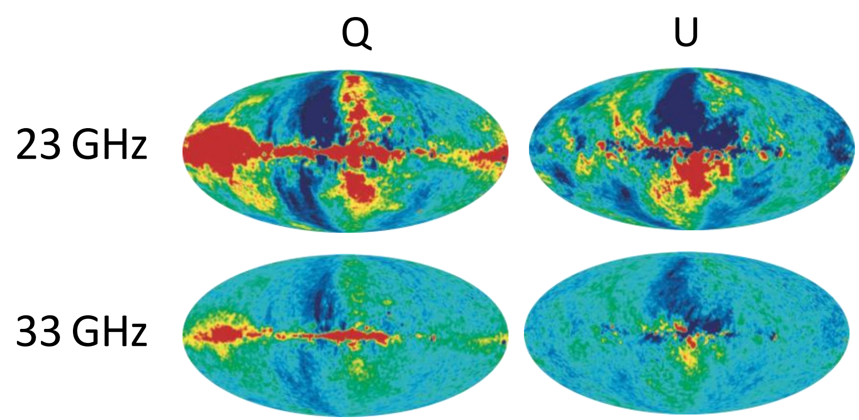


Spectra using all data up to and including 2015 – adding Keck 220 GHz for the first time.
Red line: BK14 baseline model (CMB+polarized dust model with r = 0)

Planck polarized maps at 7 frequencies + WMAP at 2 frequencies

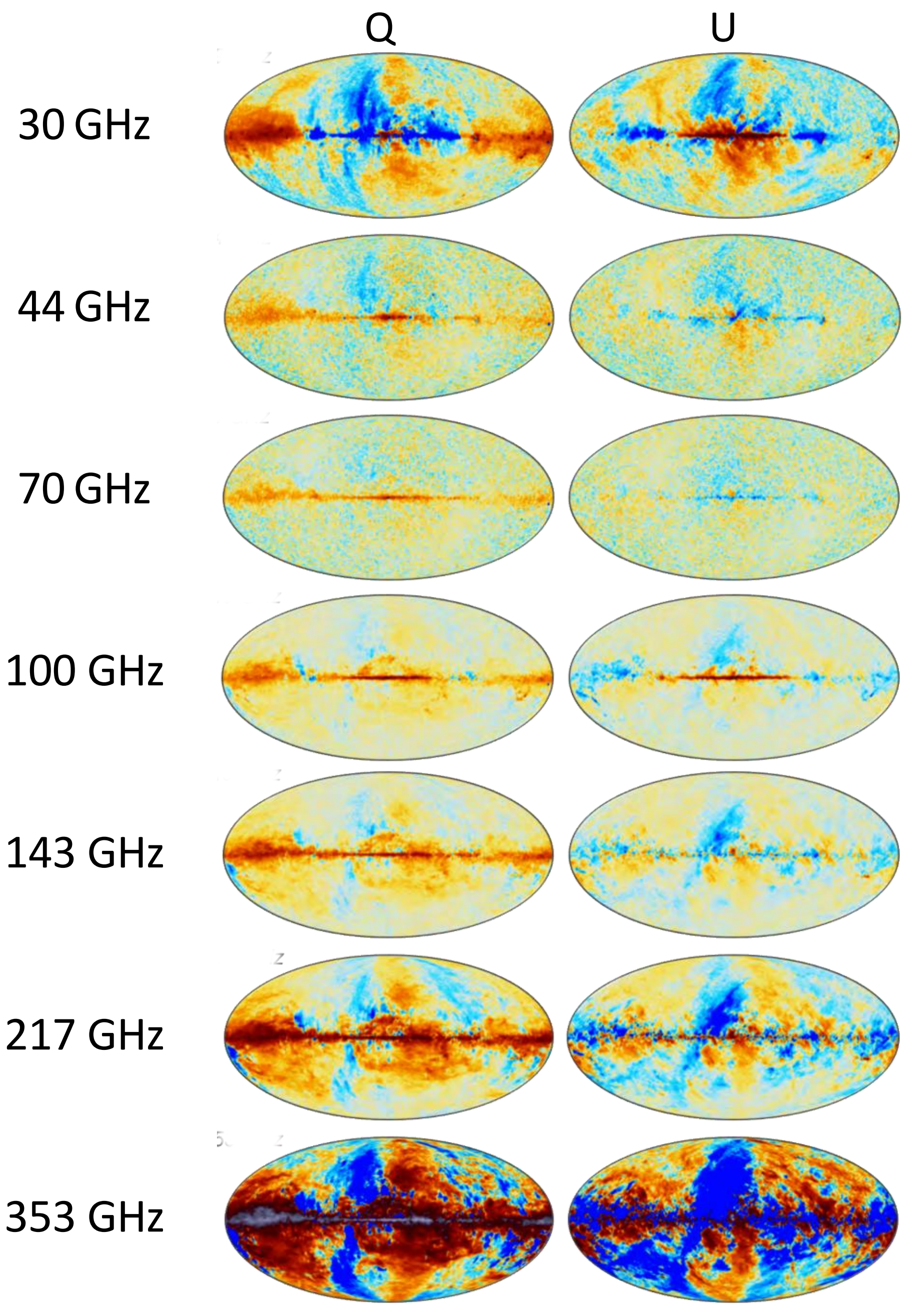


Fromarxiv 1502.01582



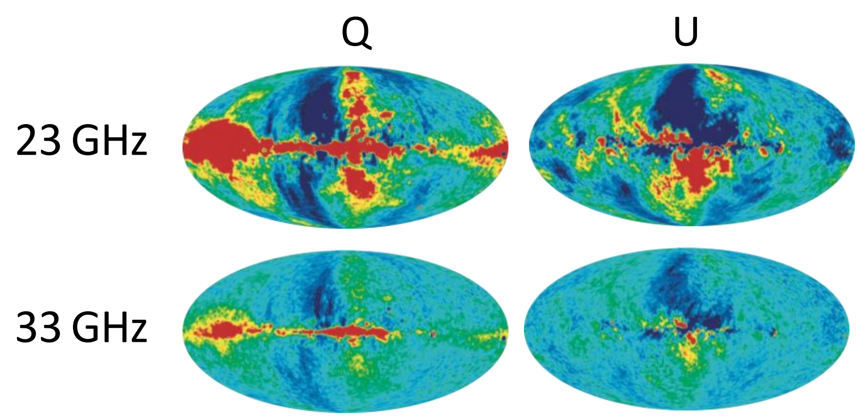
Fromarxiv 1212.5225

Planck polarized maps at 7 frequencies + WMAP at 2 frequencies



From arxiv 1502.01582

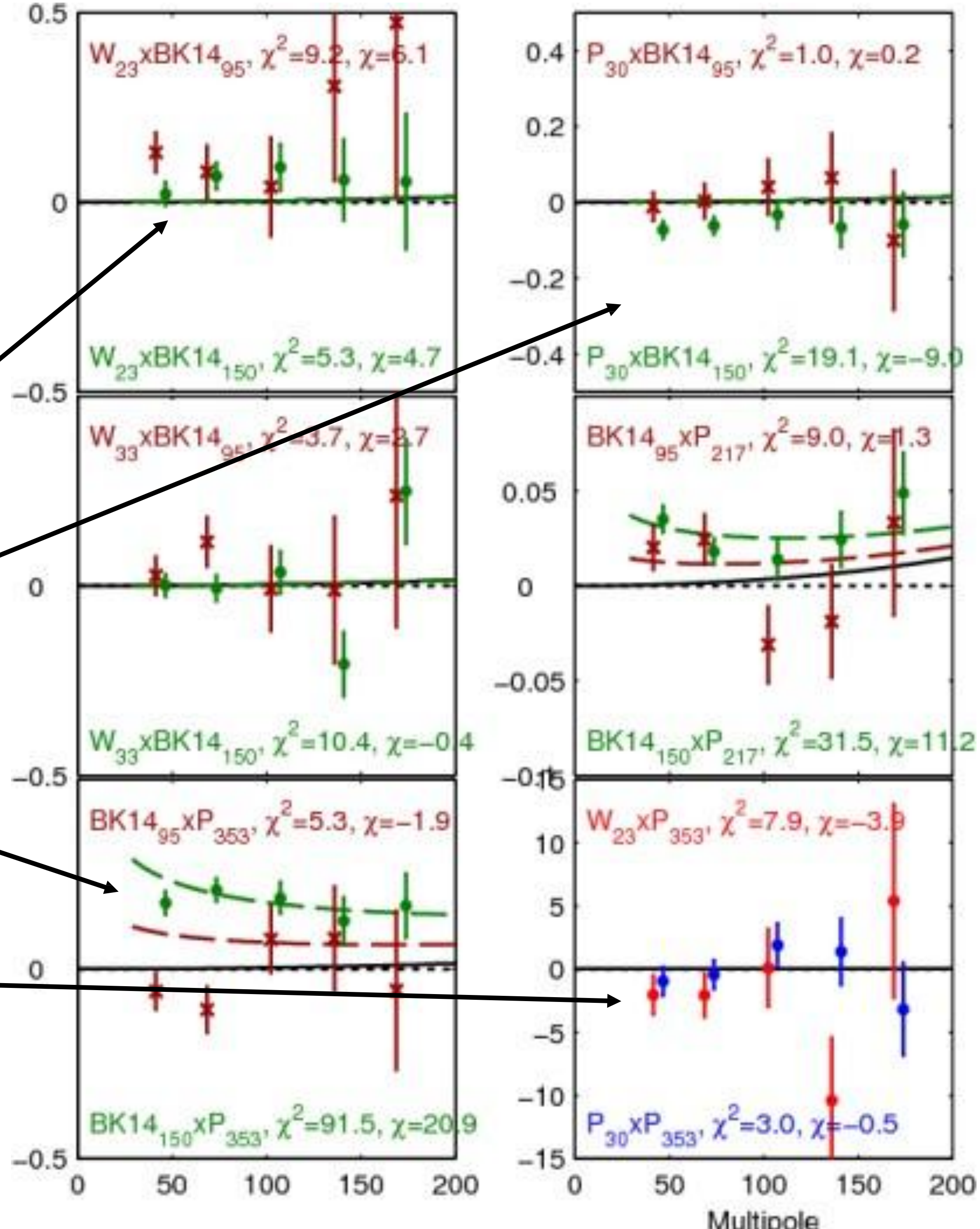
Polarized galactic synchrotron emission dominates at low frequencies.



From arxiv 1212.5225

Polarized thermal emission from galactic dust dominates at high frequencies.

A selected sample of cross spectra between BK and WMAP/Planck



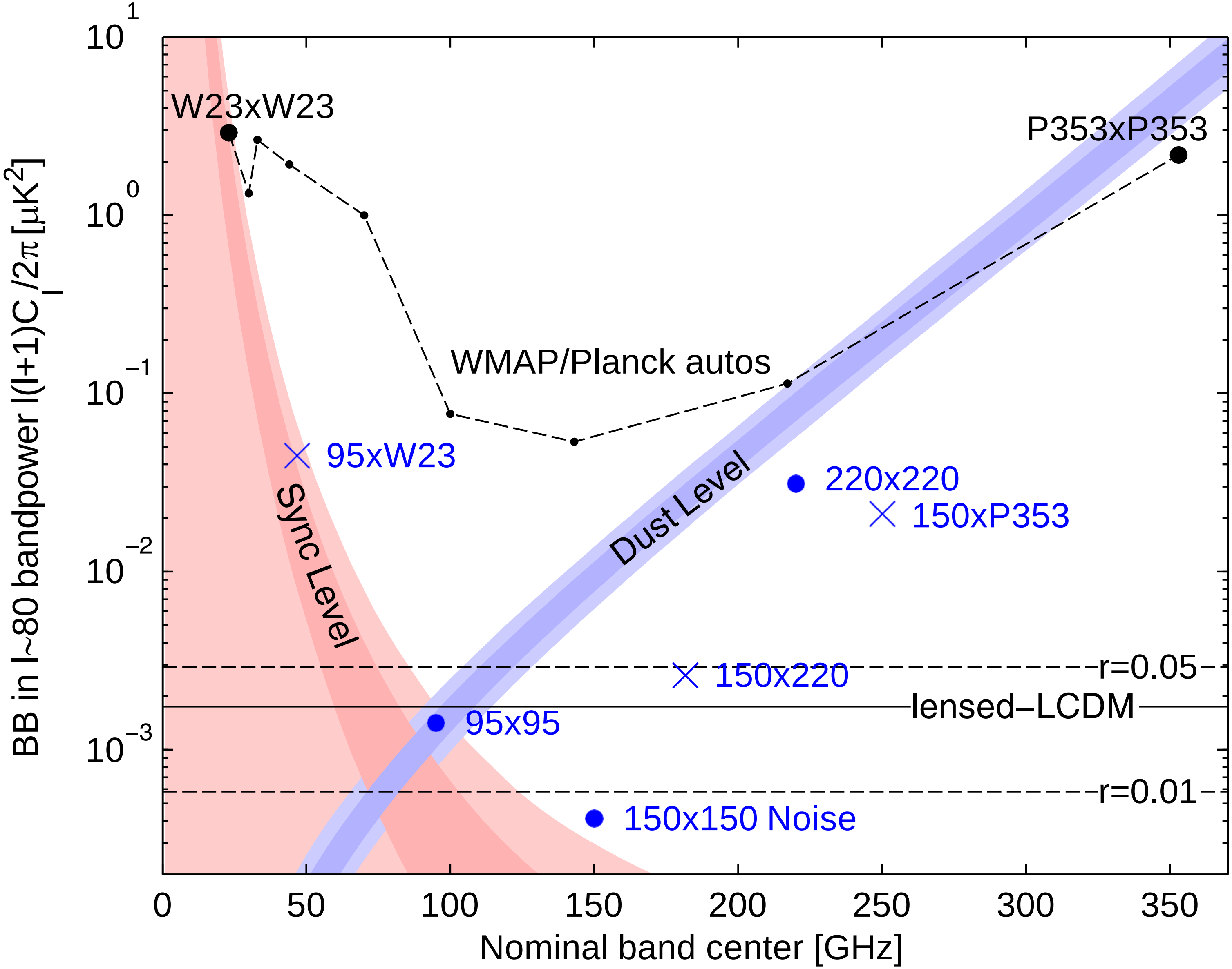
23x150 shows hint of synchrotron,

which don't appear in 30x150 .

Strong detection of dust in 150x353

No evidence for dust/sync correlation in 23x353.

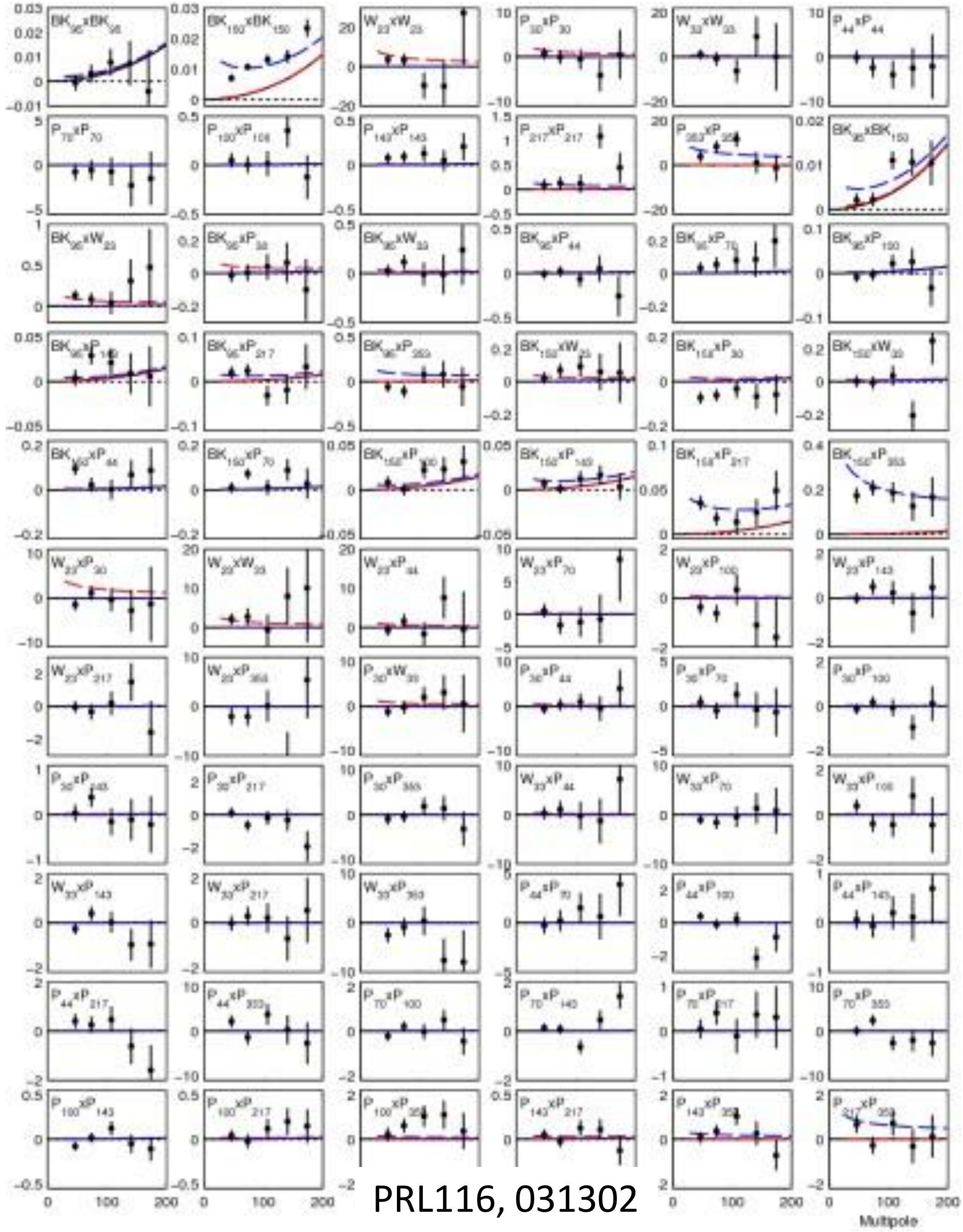
BK15 Band Sensitivity (at l=80)



BK14 Auto- and cross- spectra between BICEP/Keck, WMAP, and Planck bands

BK14: 66 spectra

BK15: add 220 GHz → 78 spectra



PRL116, 031302

Multicomponent likelihood analysis

Take the joint likelihood of all the spectra simultaneously, vs. model for BB:

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

Multicomponent likelihood analysis

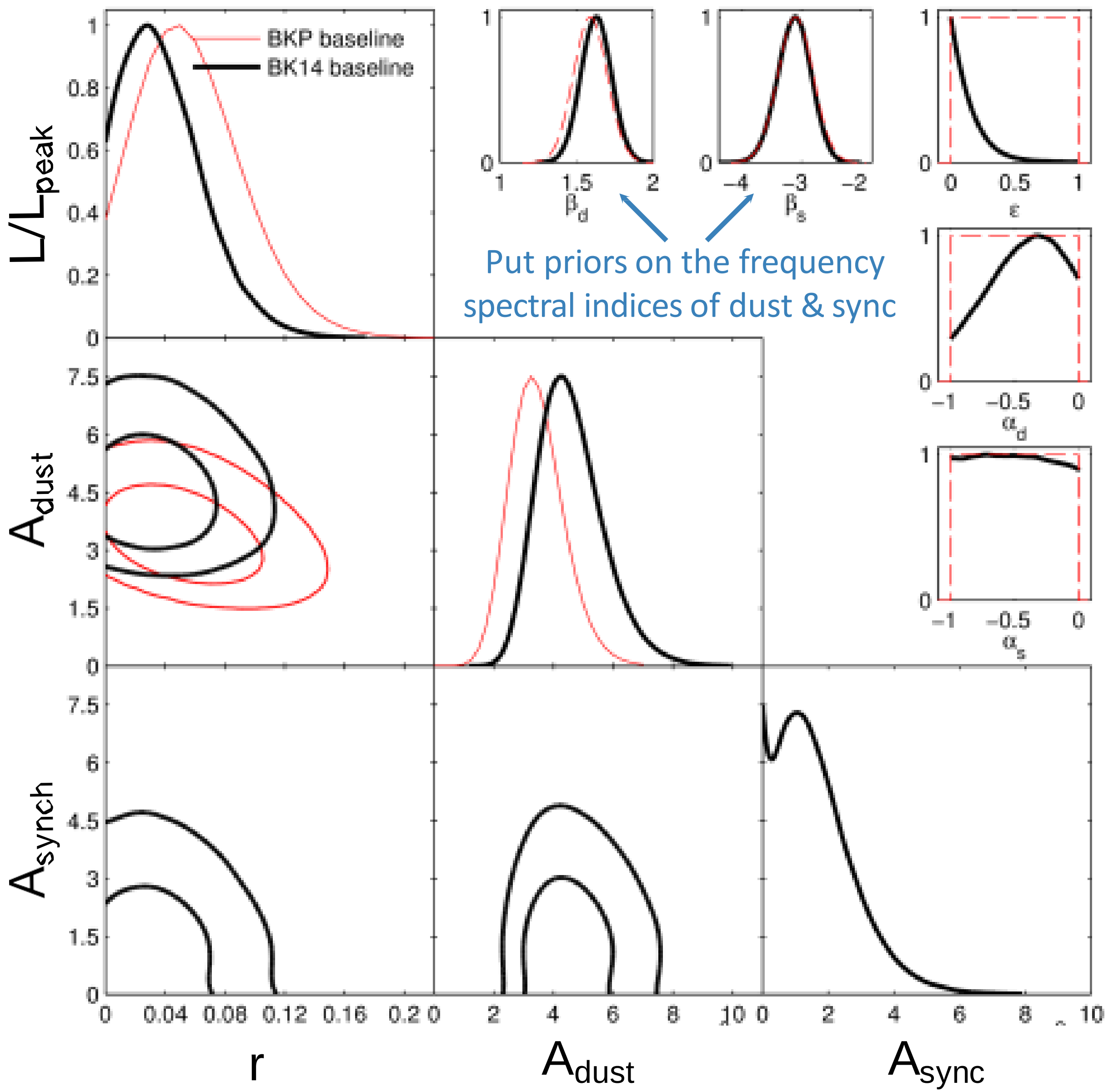
Take the joint likelihood of all the spectra simultaneously, vs. model for BB:

- 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/synch spatial correlation

BK14 Results



Allow dust/sync correlation

Put priors on the frequency spectral indices of dust & sync

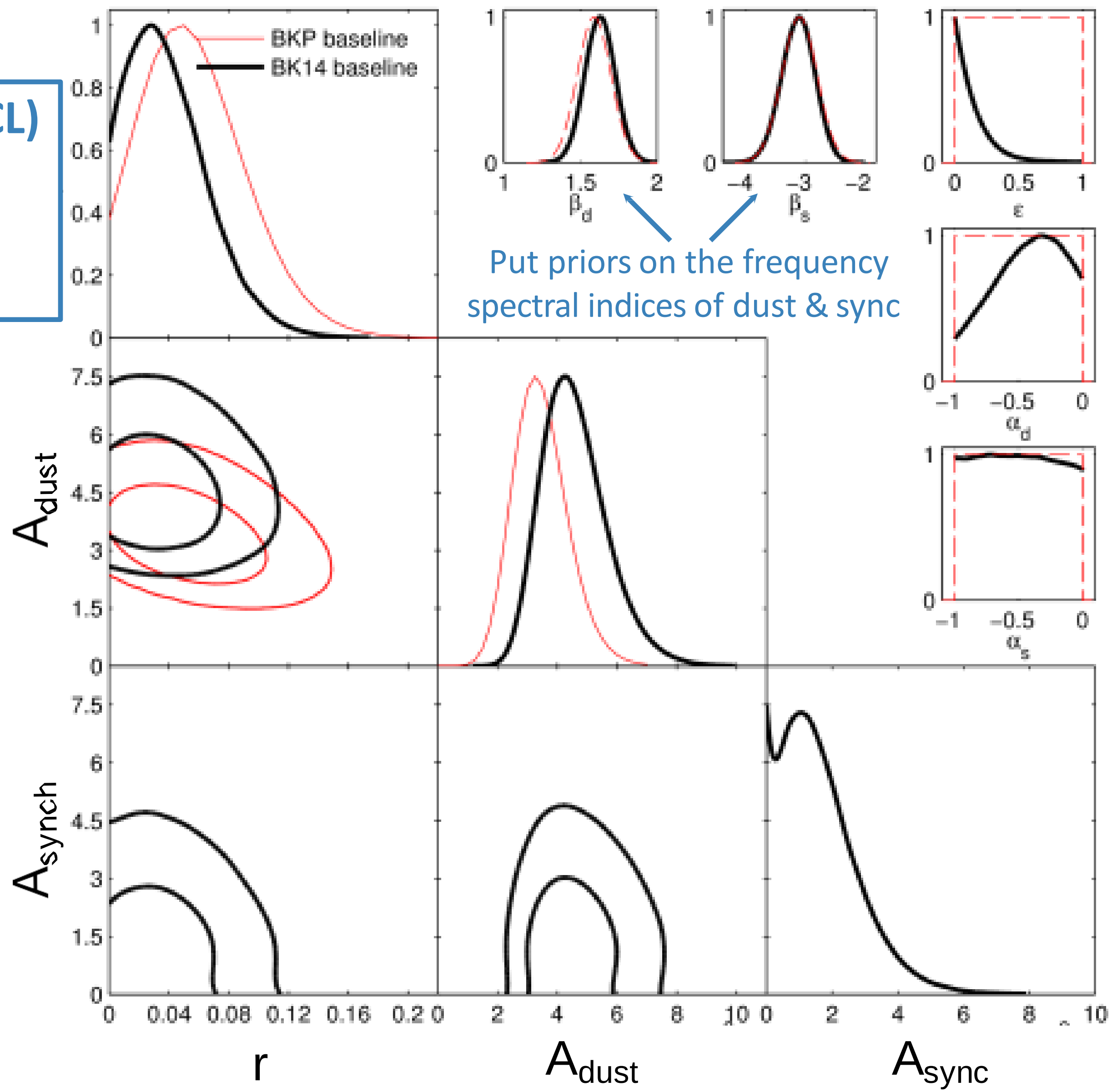
Marginalize over generous ranges in spatial spectral indices

Dust vs. r degeneracy lifted

BK14 Results

r < 0.009 (95% CL)
Now beats temperature constraints

Dust vs. r degeneracy lifted

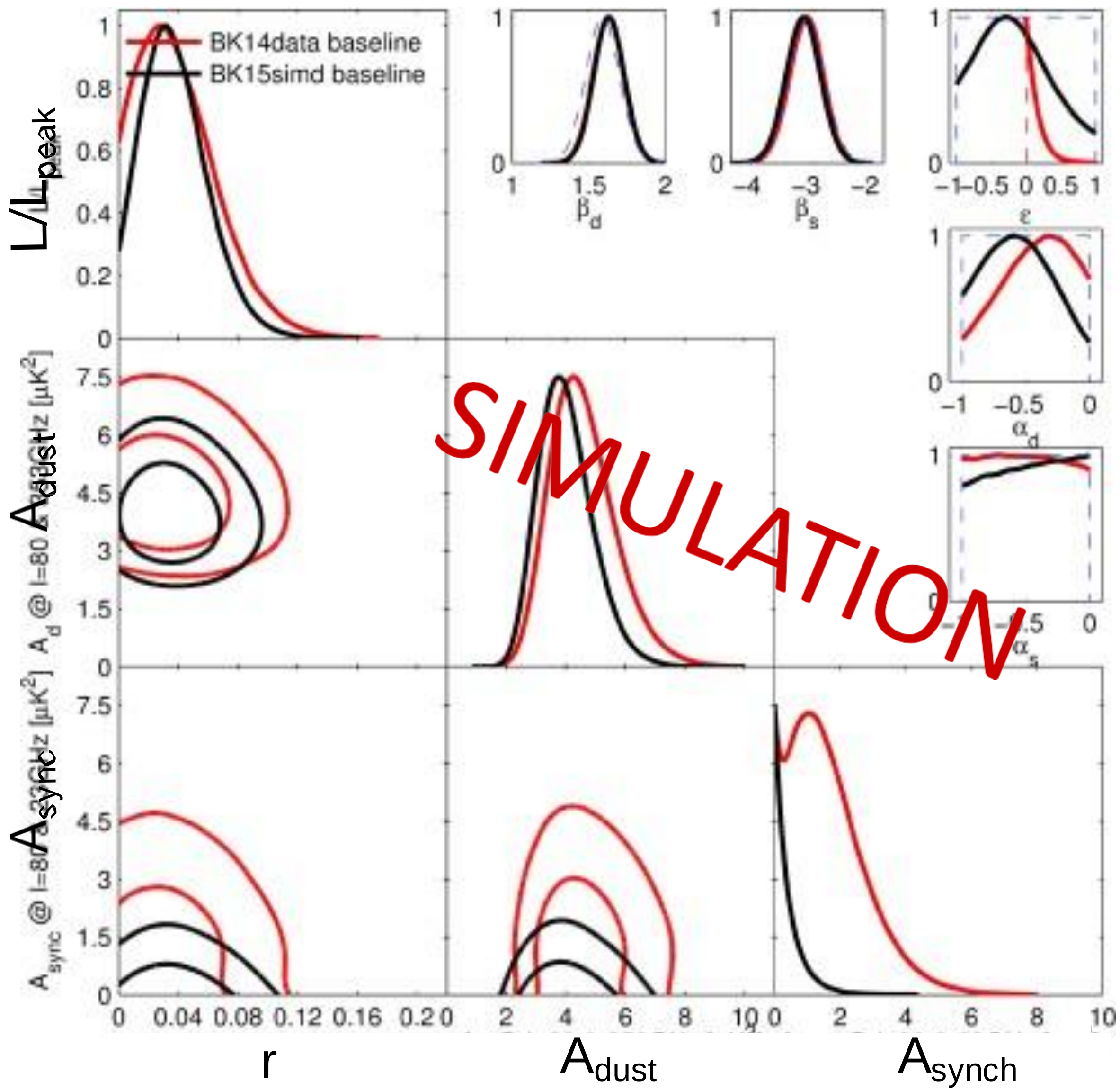


Allow dust/sync correlation

Put priors on the frequency spectral indices of dust & sync

Marginalize over generous ranges in spatial spectral indices

BK15 Simulated Results



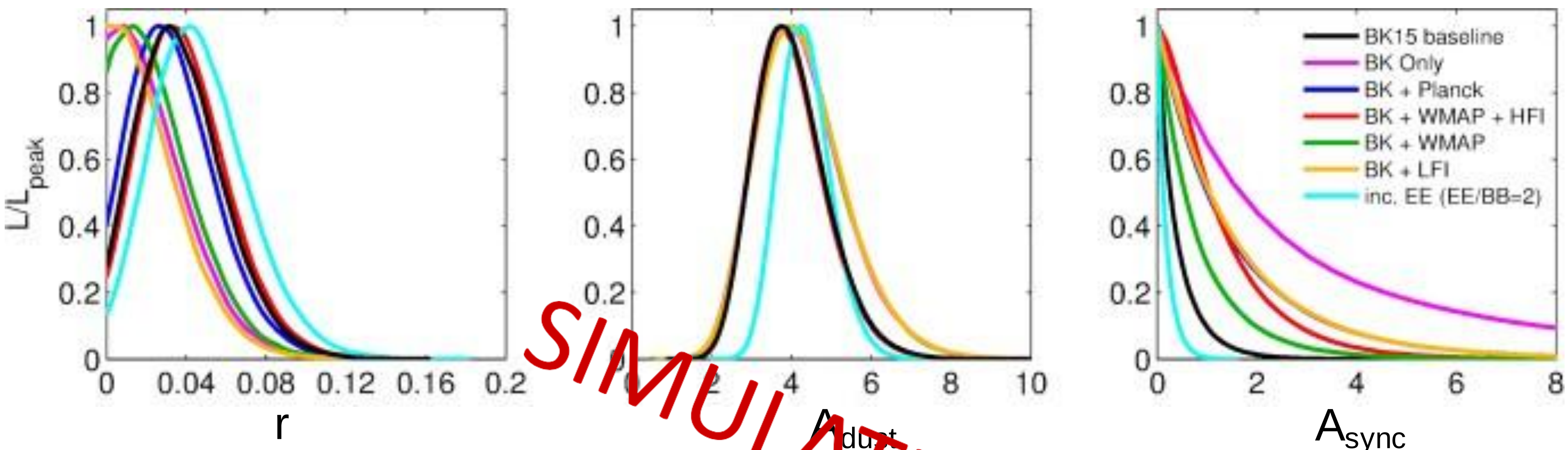
Allow dust/sync correlation, now [-1,1]

Plus many alternate analyses presented:

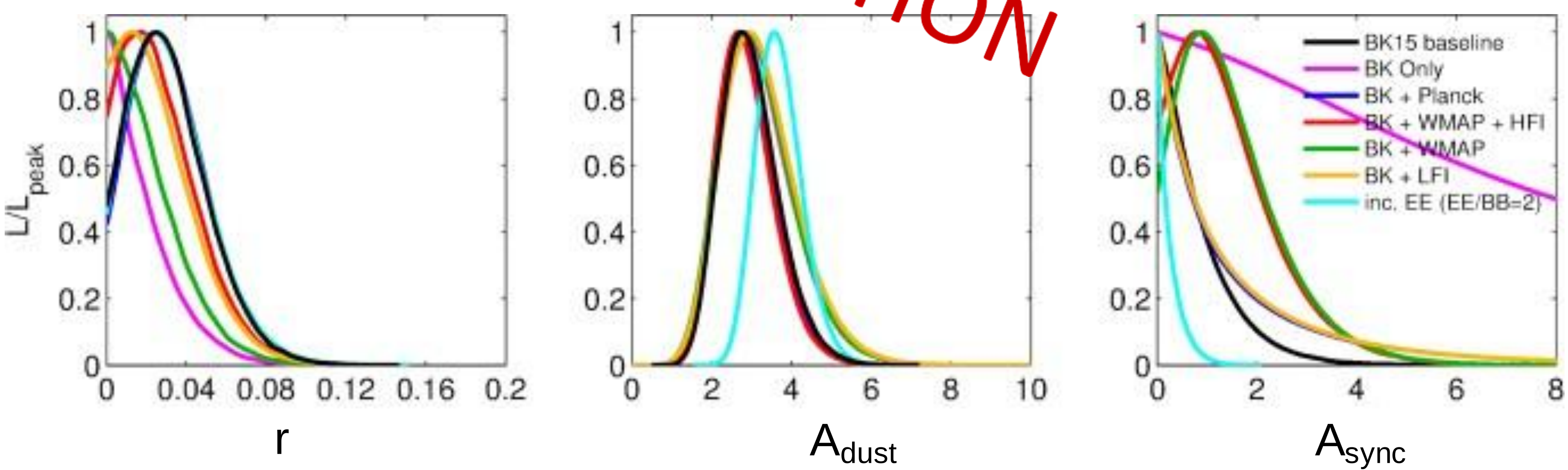
- Foreground priors
- Including EE
- WMAP/Planck data
- Dust decorrelation

BK15 Simulated Results: Variations with Data Selection

BK15 Sim119



BK15 Sim494



Dust Decorrelation?

Planck 2016

Planck intermediate results. L. Evidence for spatial variation of the polarized thermal dust spectral energy distribution and implications for CMB *B*-mode analysis

(Affiliations can be found after the references)

Preprint online version: June 24, 2016

ABSTRACT

Planck 2018

Planck intermediate results. LIV. Polarized dust foregrounds

(Affiliations can be found after the references)

Preprint online version: January 17, 2018

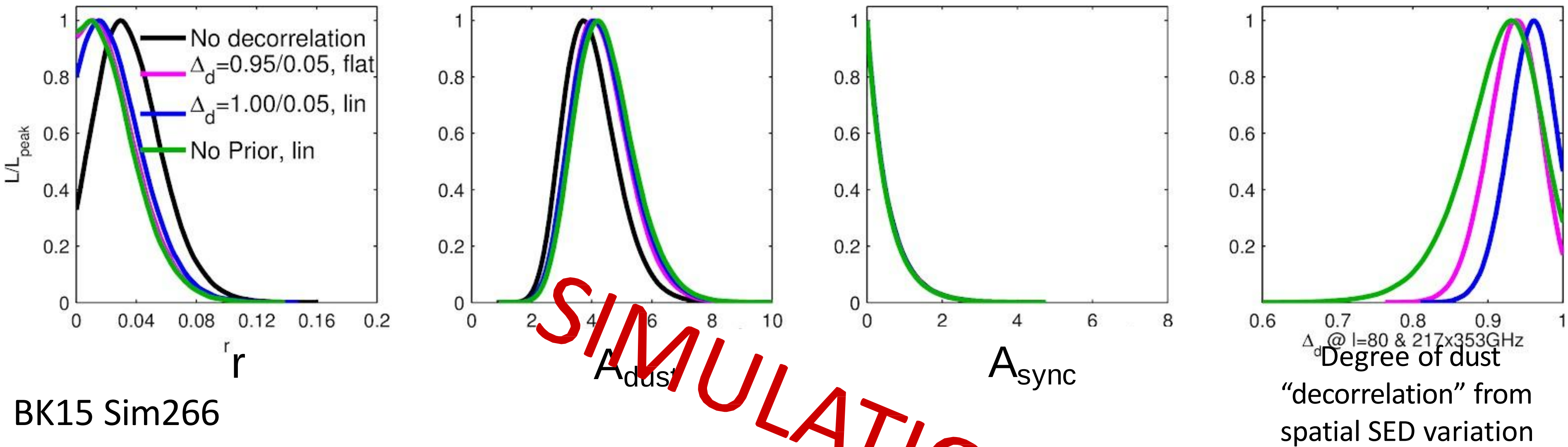
ABSTRACT

A departure of the correlation ratio from unity that cannot be attributed to a spurious decorrelation due to the cosmic microwave background, instrumental noise, or instrumental systematics… **detected at more than 99% confidence**

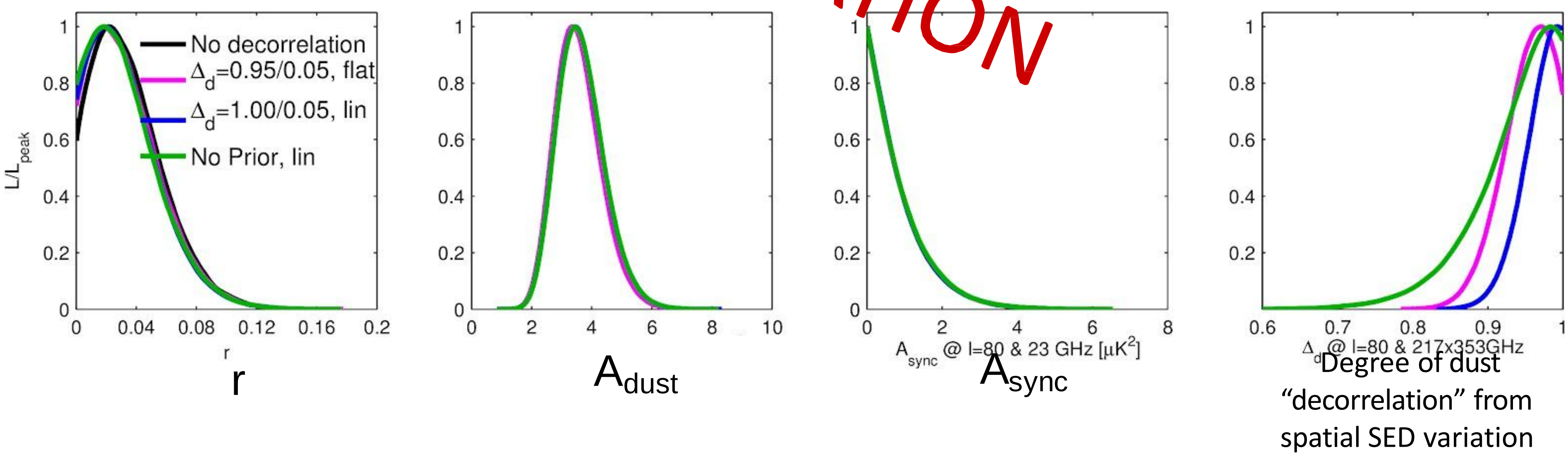
We find no evidence for a loss of correlation.
… might not be a problem for CMB experiments aiming at a primordial B-mode detection limit on the tensor-to-scalar ratio r ~ 0.01…

BK15 Simulated Results: Variations with Dust Modeling

BK15 Sim119



BK15 Sim266



IV.
What's Next?
BICEP3 and BICEP Array

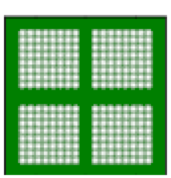
B3: Transition to 500mm-class receiver

Fully 95 GHz

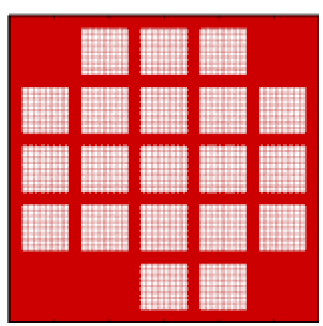
2560 detectors in modular focal plane.

Large-aperture optics and infrared filtering.

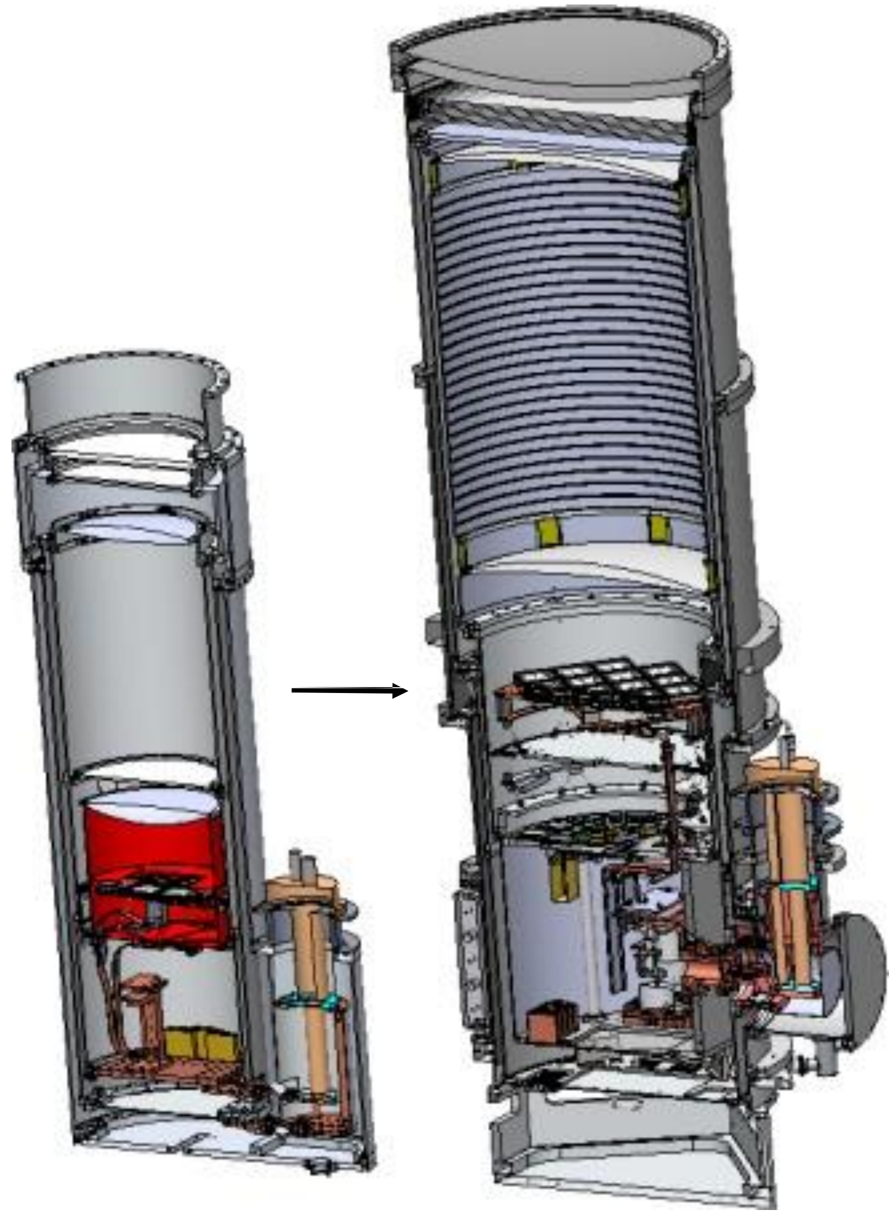
10x optical throughput of single BICEP2/Keck receiver.



BICEP2 FPU



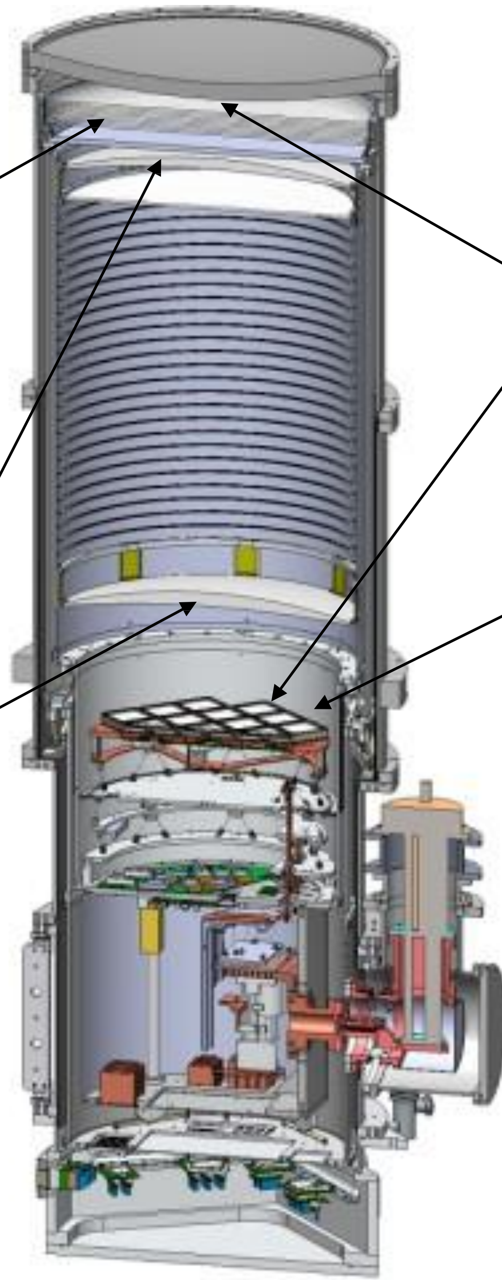
BICEP3

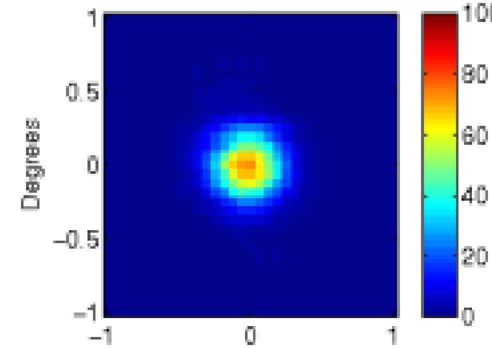


Keck receiver BICEP3

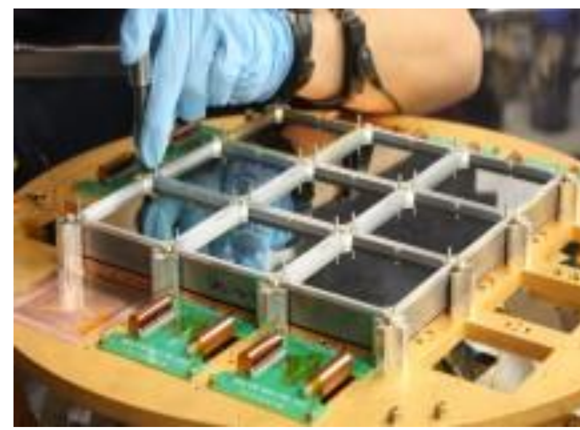
BICEP3 receiver

Zotefoam IR reflective filter stack





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



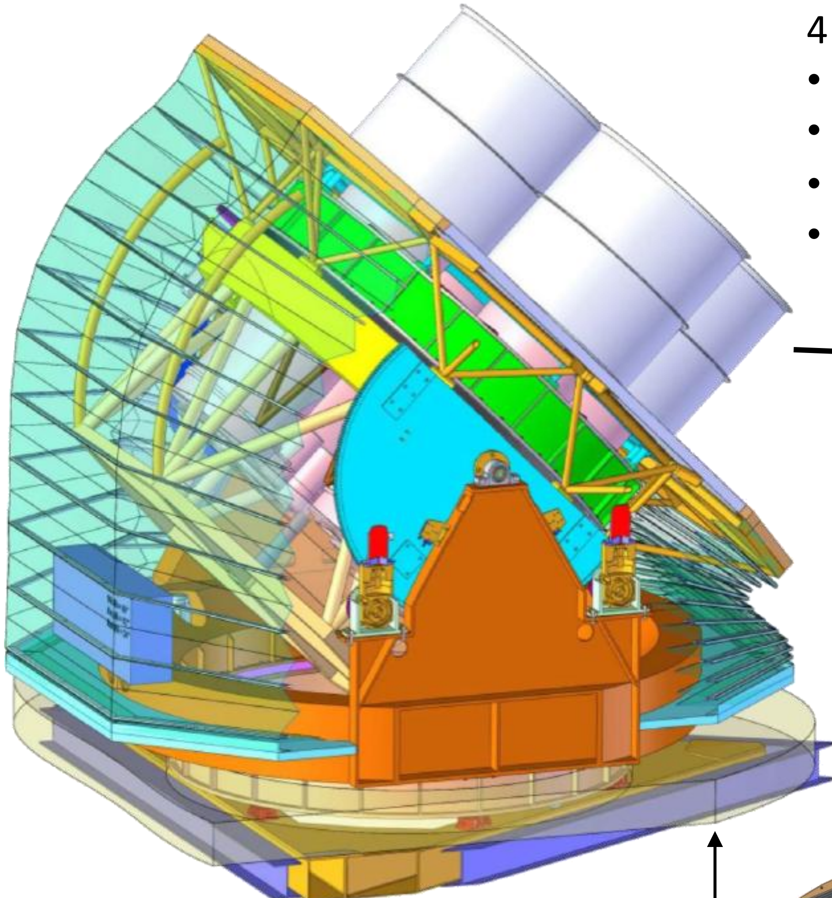
Plug & play detector modules each have 64 dual-pol 95 GHz camera pixels and contain cold multiplexing electronics.

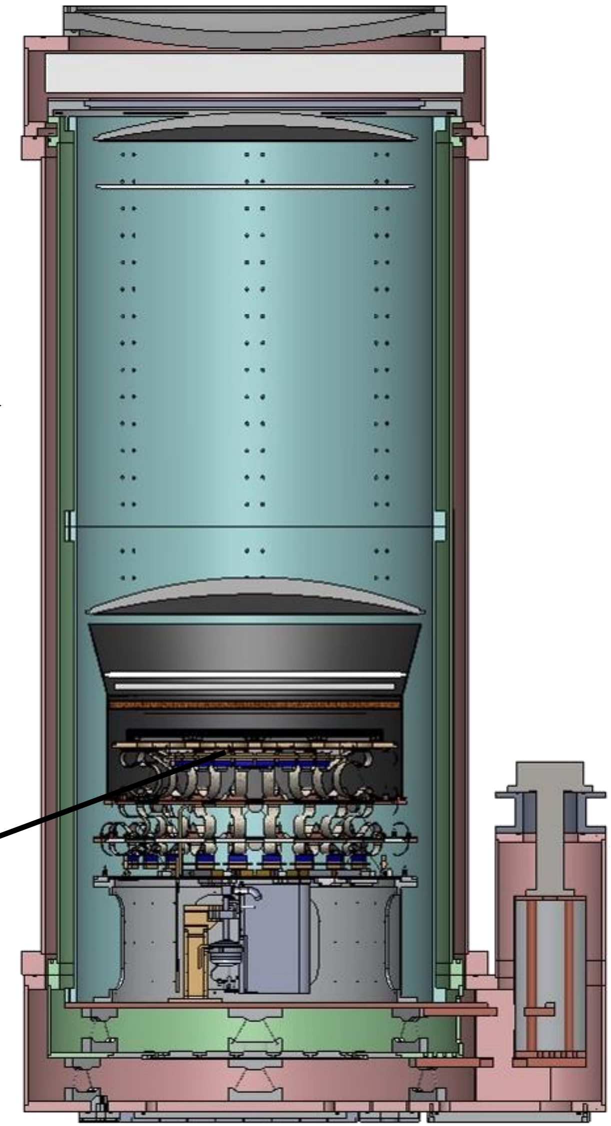
Thin, low loss, high thermal conductivity alumina filters and lenses with epoxy-based antireflection coating.

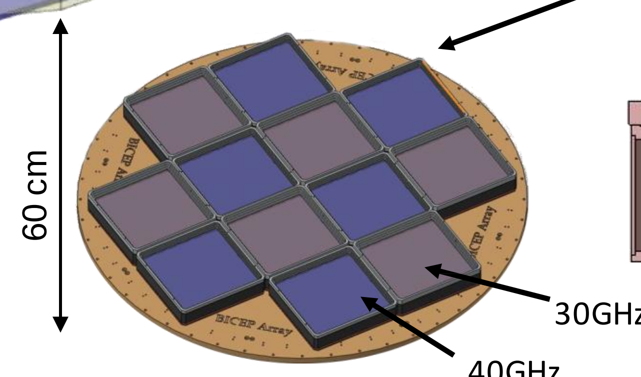
Building BICEP Array

4 wide-field receivers:

- 30/40 GHz
- 95 GHz
- 150 GHz
- 220/270 GHz





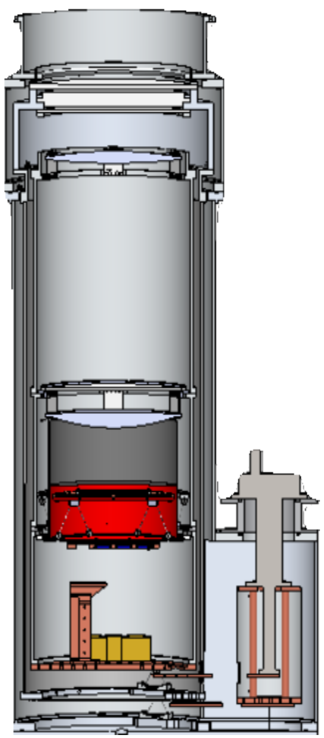


Focal plane layout

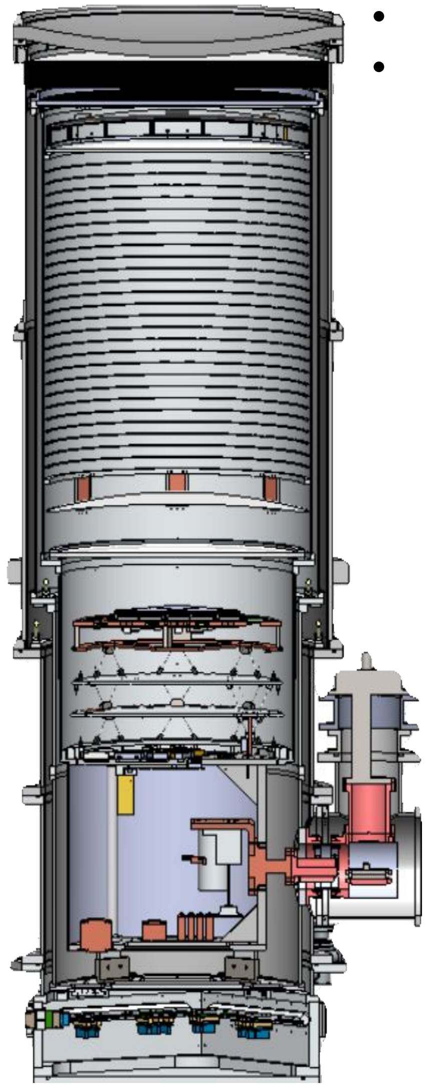
BICEP Array vs. predecessors

- 26cm aperture
- 15º FOV
- *f*/2.2 optics

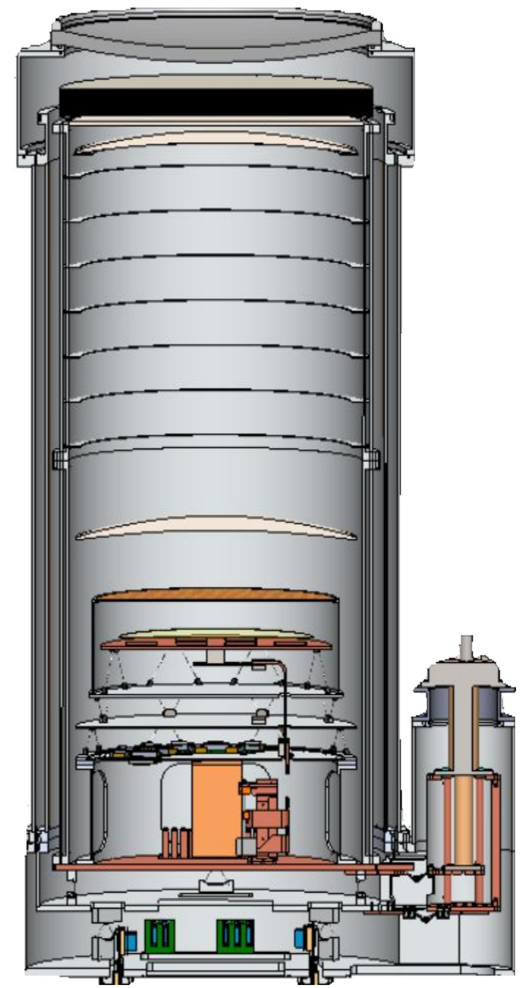
- 52cm aperture
- 28º FOV
- *f*/1.7 optics



Keck/BICEP2

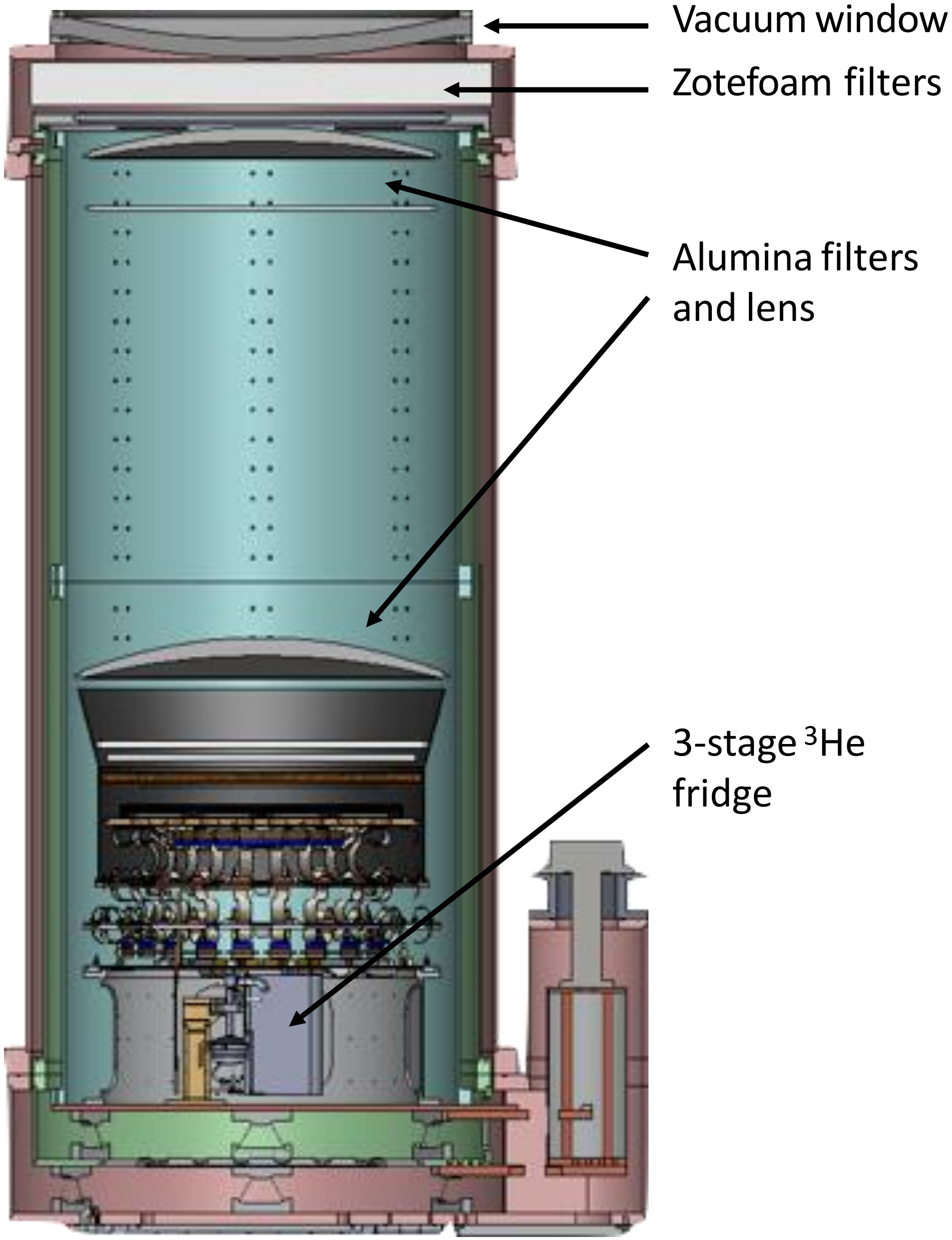


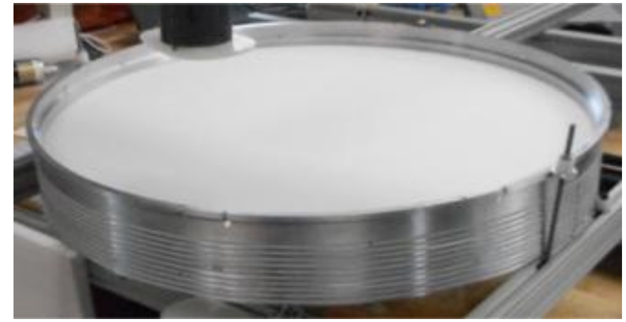
BICEP3



BICEP Array

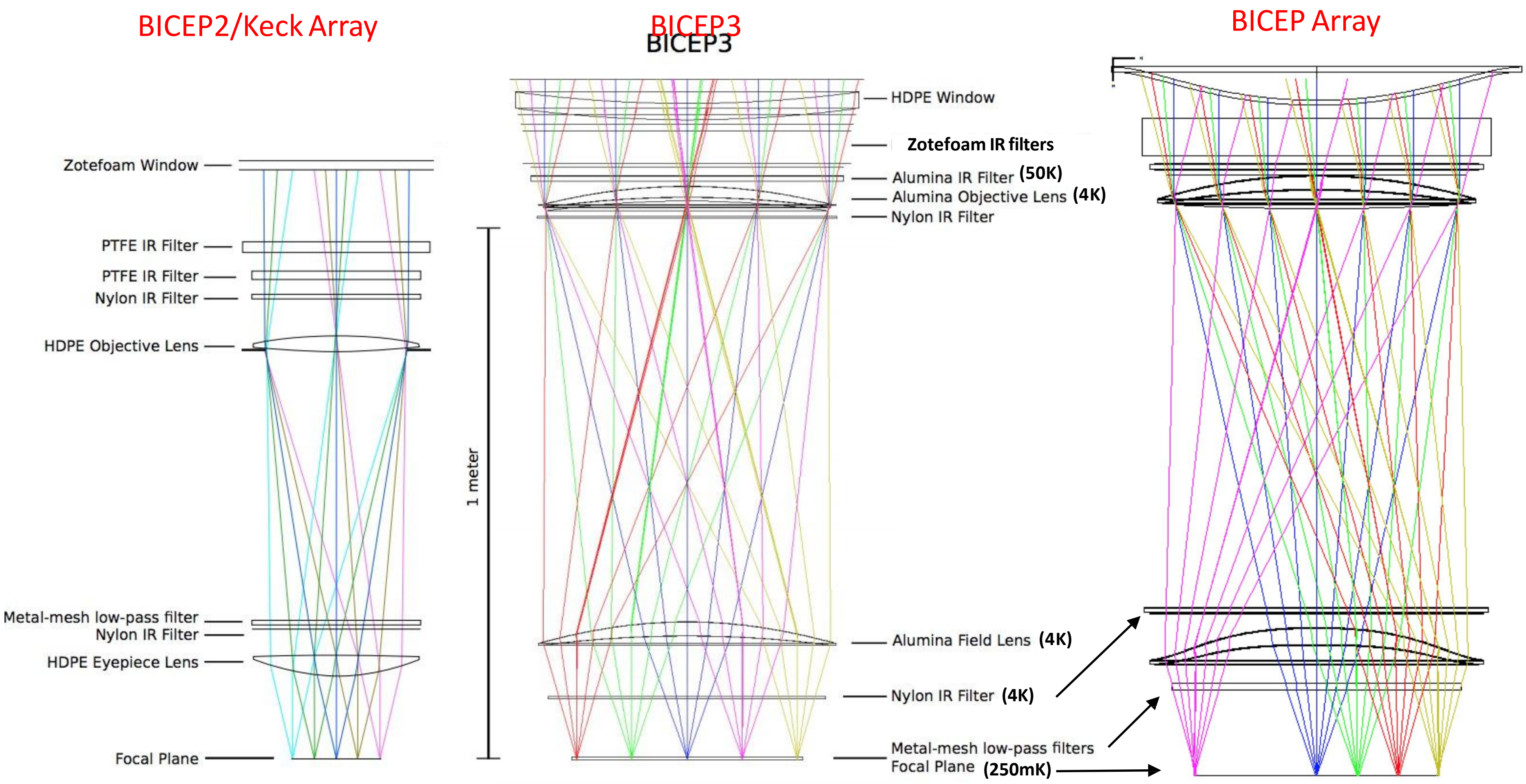
BA receiver


Vacuum window
Zotefoam filters
Alumina filters and lens
3-stage ^{3}He fridge

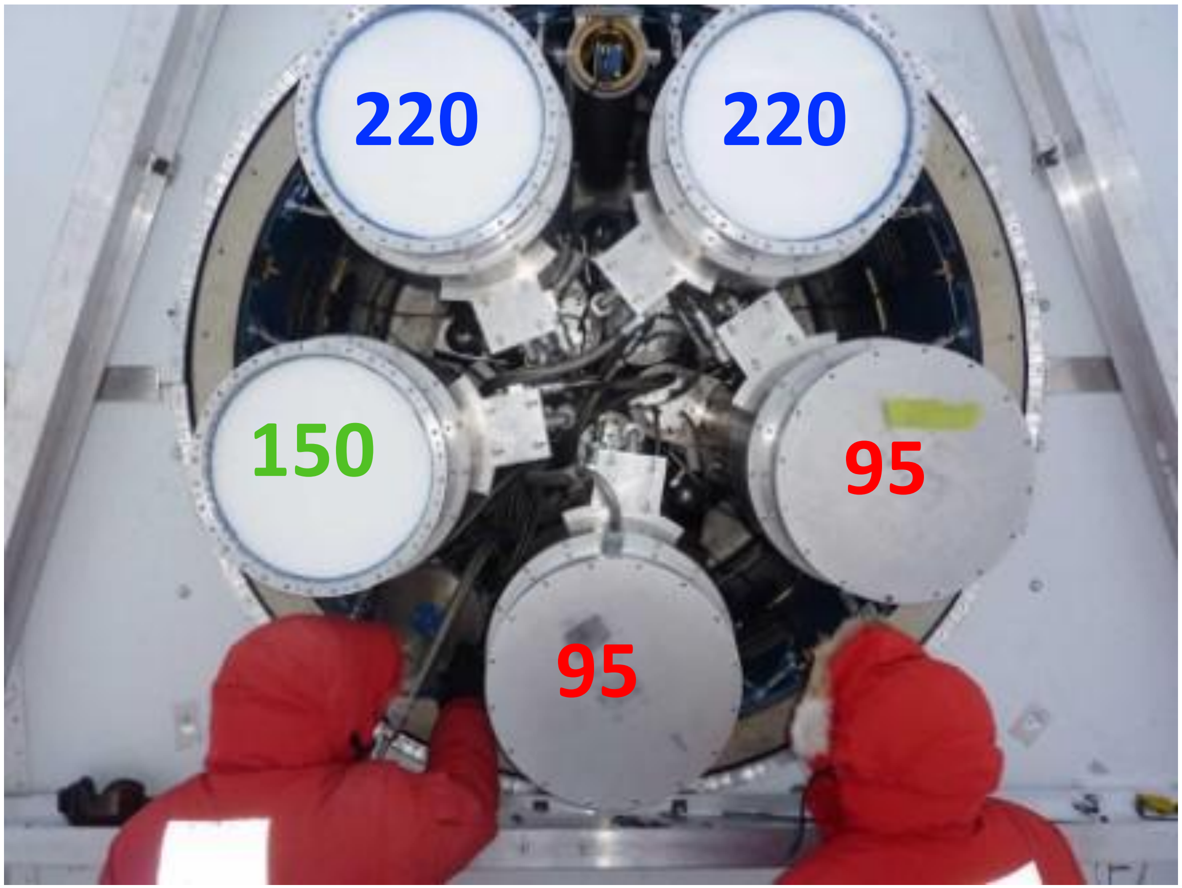


BICEP/Keck Optics

[Only approximately to scale]



Keck Array Frequency Coverage

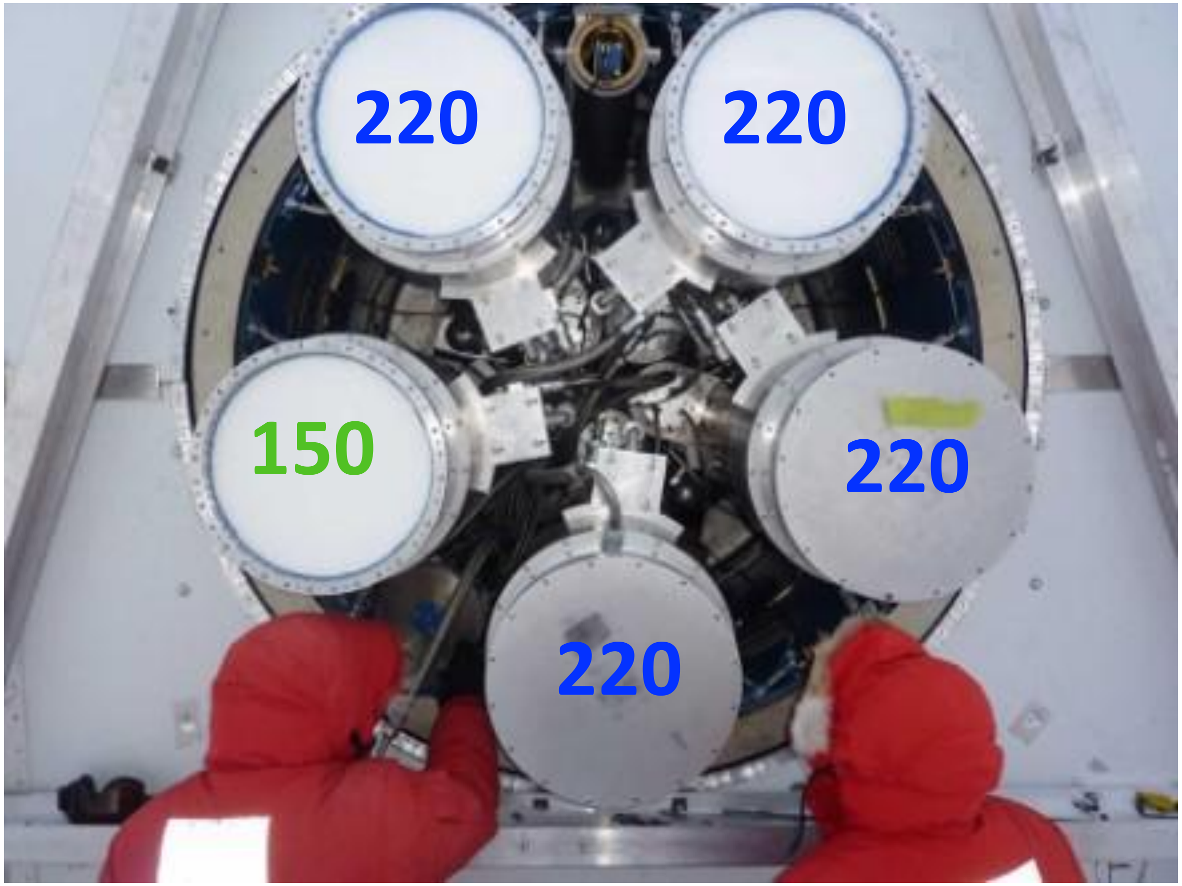


- 2012-2013: All Keck Array receivers at 150 GHz
- 2014: Two 150 GHz receivers replaced with 95 GHz
- 2015: Two additional 150s replaced with 220s

2015

BK15: Out soon!

Keck Array Frequency Coverage

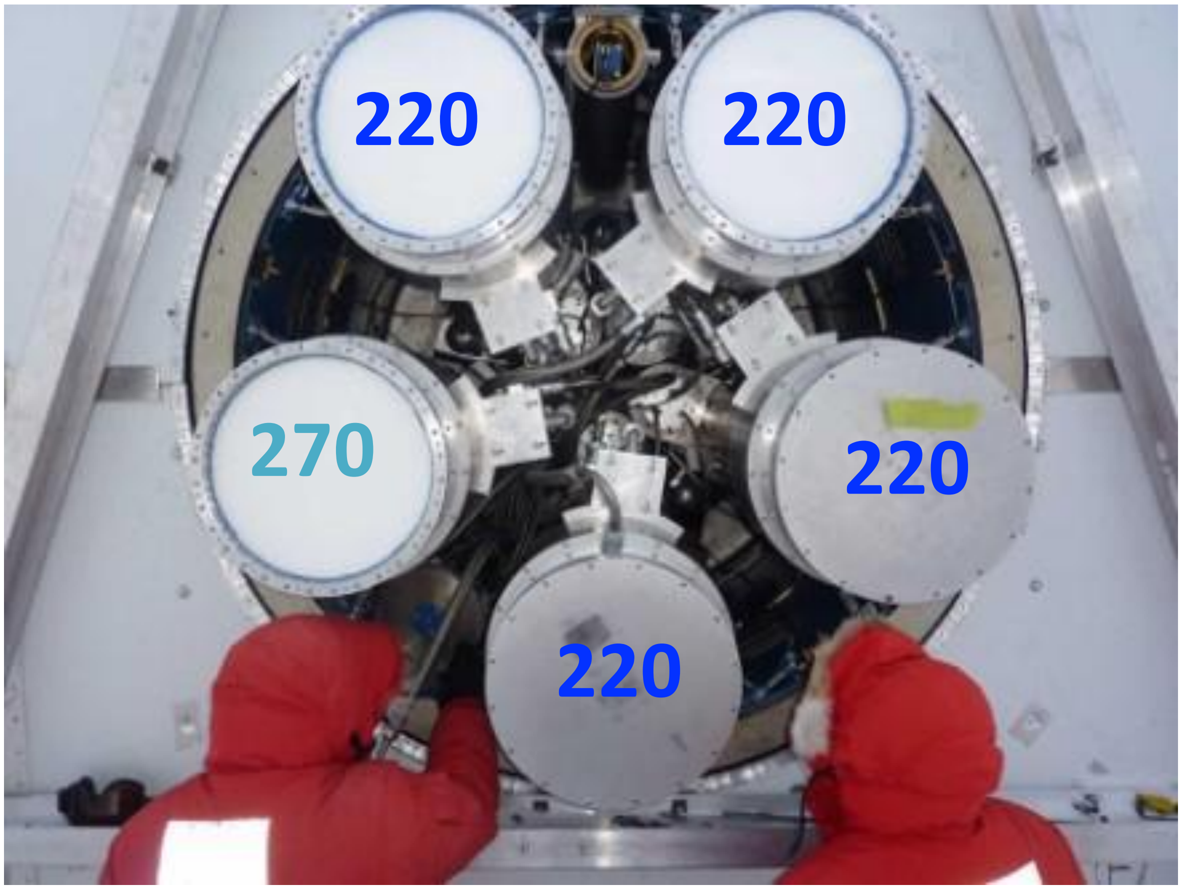


2016

Analysis ongoing

- 2012-2013: All Keck Array receivers at 150 GHz
- 2014: Two 150 GHz receivers replaced with 95 GHz
- 2015: Two additional 150s replaced with 220s
- 2016: Two 95 GHz receivers switched to 220 GHz (BICEP3 now observing at 95 GHz)

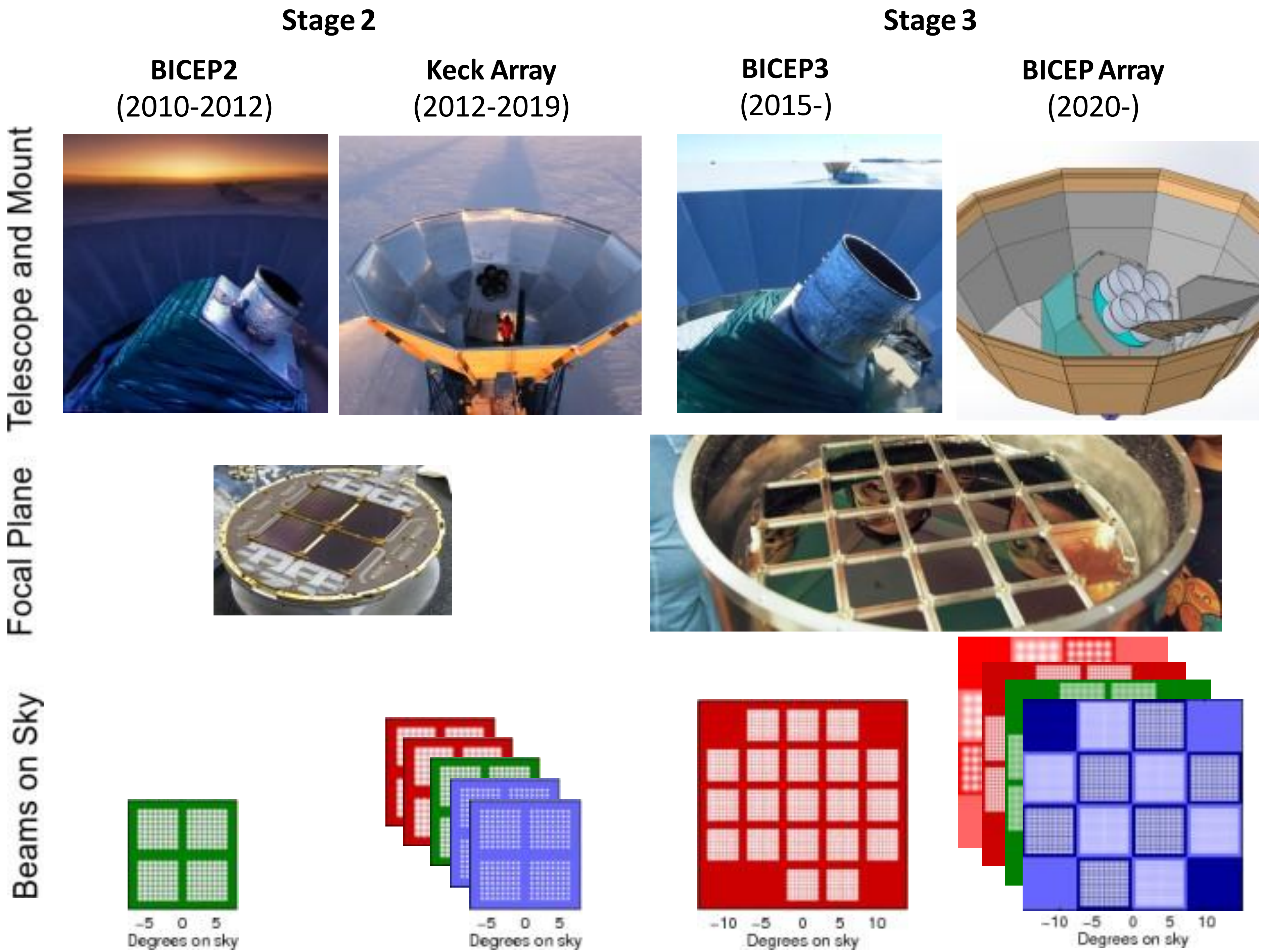
Keck Array Frequency Coverage



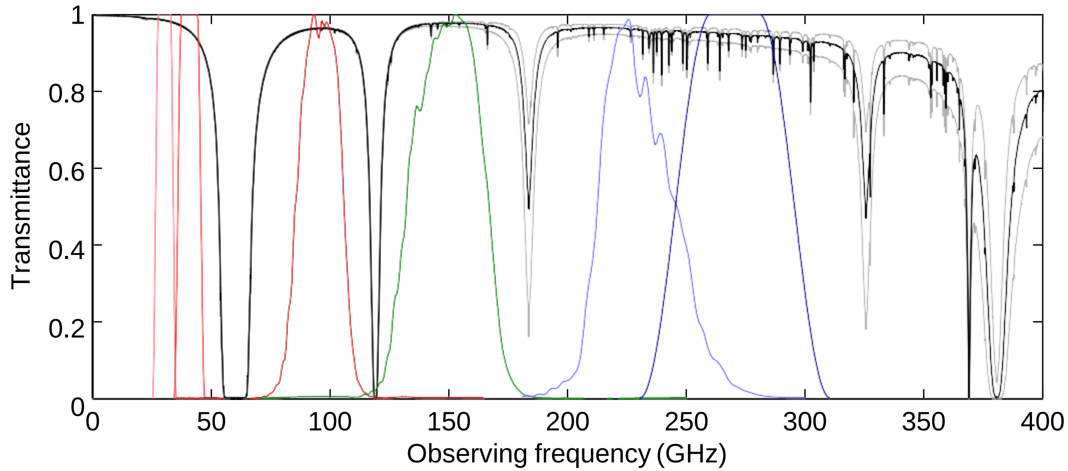
2017

Analysis ongoing

- 2012-2013: All Keck Array receivers at 150 GHz
- 2014: Two 150 GHz receivers replaced with 95 GHz
- 2015: Two additional 150s replaced with 220s
- 2016: Two 95 GHz receivers switched to 220 GHz (BICEP3 now observing at 95 GHz)
- 2017: Remaining 150 GHz receiver replaced with 270 GHz


Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2015-)
BICEP Array
(2020-)
Telescope and Mount
Focal Plane
Beams on Sky
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
−10 −5 0 5 10
Degrees on sky

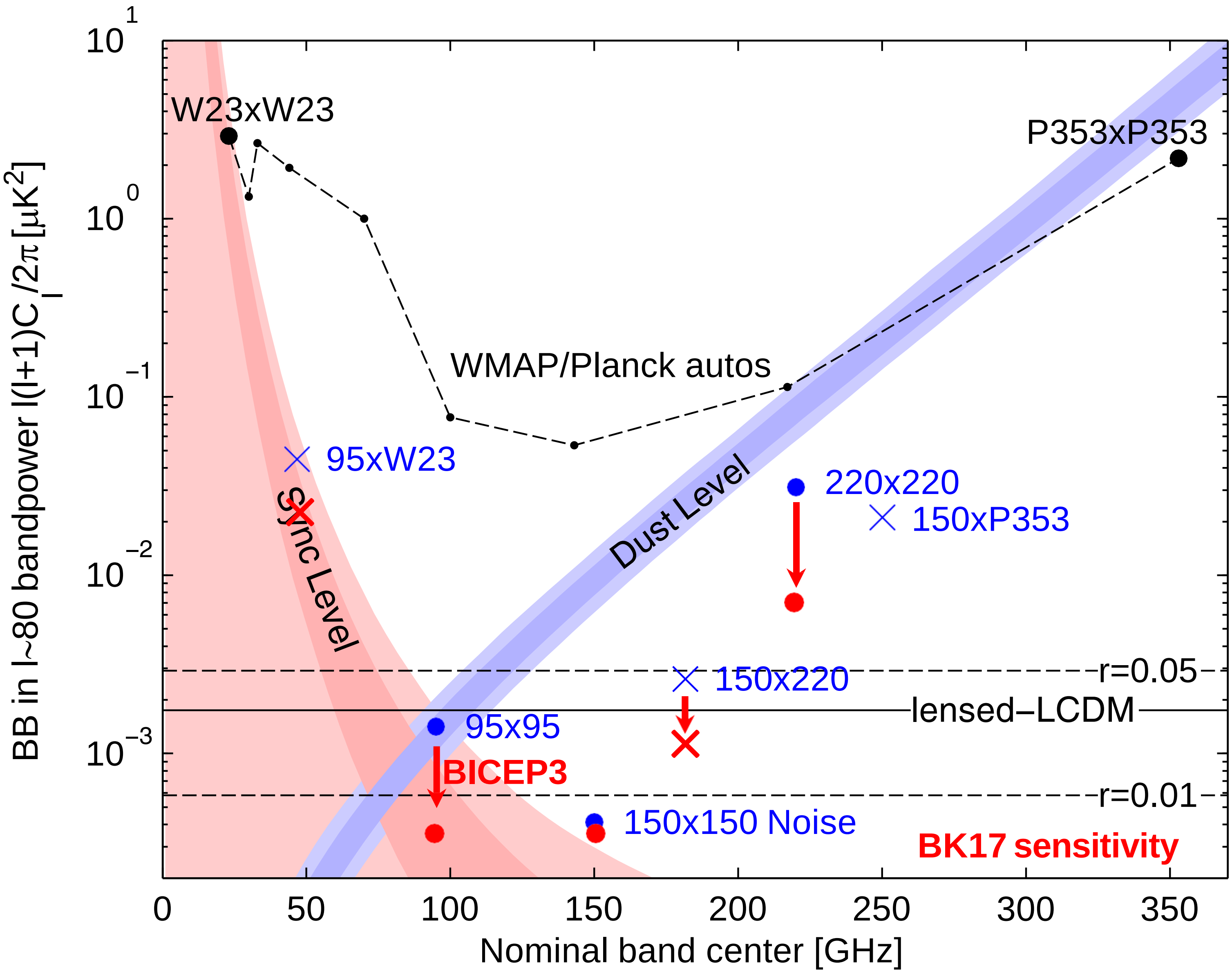
Future BICEP/Keck Frequency Coverage



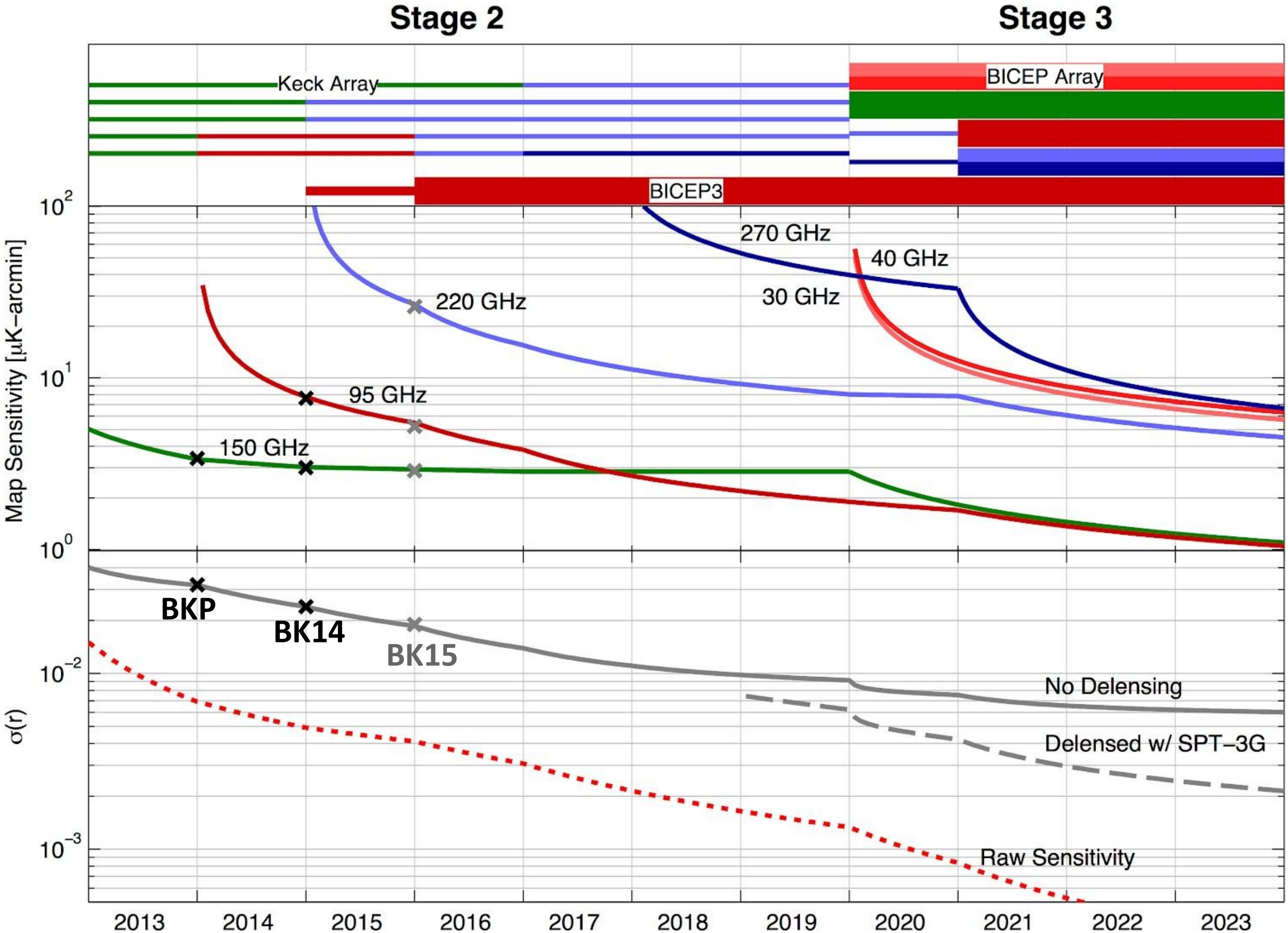
Receiver Observing Band (GHz)	Nominal Number of Detectors	Nominal Single Detector NET ($\mu K_{CMB}\sqrt{s}$)	Beam FWHM (arcmin)	Survey Weight Per Year $(\mu K_{CMB})^{-2}\ yr^{-1}$
Keck Array				
95	**288**	288	**43**	**24,000**
150	**512**	313	**30**	**30,000**
220	**512**	837	**21**	**2,000**
270	512	1310	17	800
BICEP3				
95	**2560**	288	**24**	213,000
BICEP Array				
⟨ 30	192	221	76	27,000
⟨ 40	300	301	57	21,000
95	3456	288	24	287,000
150	7776	313	15	453,000
⟨ 220	9408	837	11	37,000
⟨ 270	9408	1310	9	15,000

BK15 & BK17 Band Sensitivity (at l=80)

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

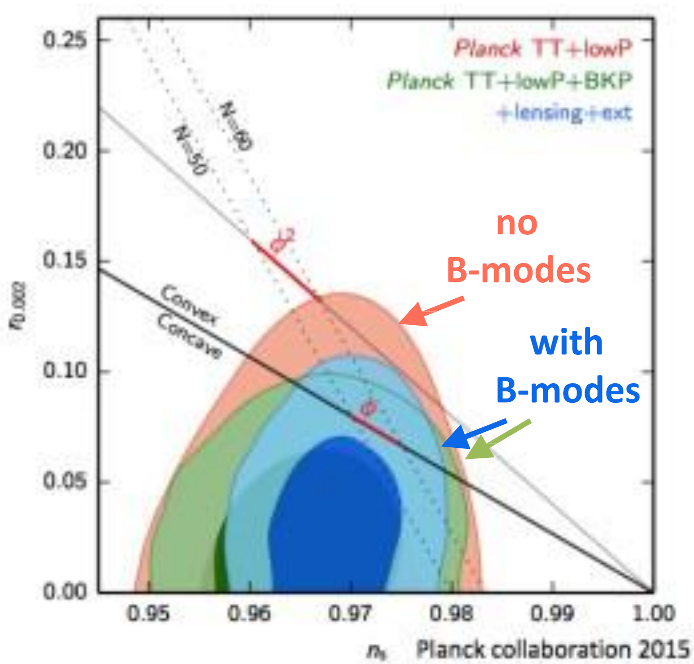


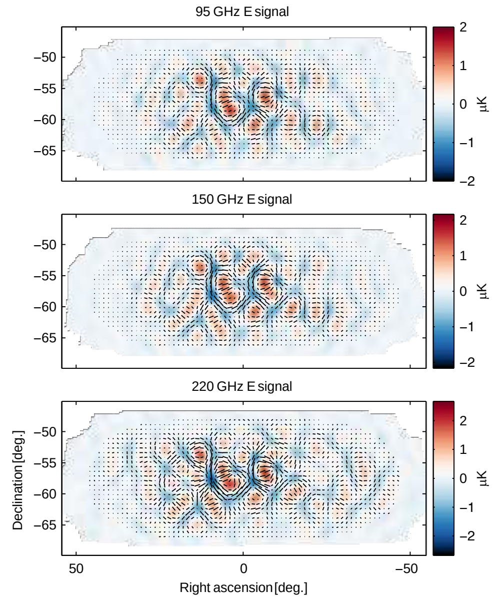
Summary



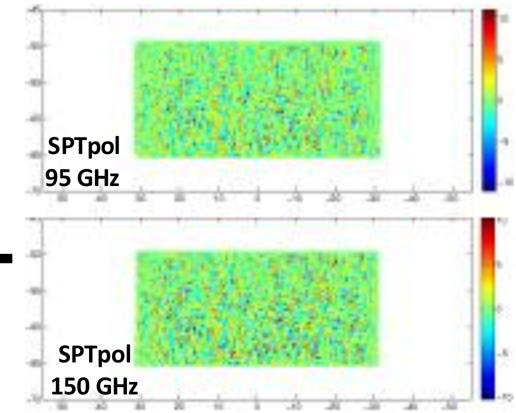
Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
Map Sensitivity [μK−arcmin]
10^2
10^1
10^0
BKP
BK14
BK15
No Delensing
Delensed w/ SPT−3G
Raw Sensitivity
σ(r)
10^{-2}
10^{-3}
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023

B-modes now drive progress on r





\+



Deep degree-scale maps:
Multiband for **foreground separation**

Deep high-resolution maps:
Precision delensing

- BICEP-Keck / Planck joint analysis (published Feb 2015): → **σ(*r*) = 0.034** (arXiv:1502.00612)
  Raw sensitivity with no foregrounds or lensing: σ(*r*) = 0.006
  It is now all about component separation!
- 2014 BICEP/Keck analysis adds deep 95 GHz → **σ(*r*) = 0.025** (arXiv:1510.09217)
- 2015 BICEP/Keck analysis adds deep 220 GHz → Expect **σ(*r*) = 0.019** (June 2018)
- 2017 BICEP/Keck + SPTpol delensing → Expect **σ(*r*) = 0.010** (Analysis ongoing)
- 2020-2022+ BICEP Array + SPT3G → Forecast **σ(*r*) ~ 0.003**

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 controlat degree angular scales

- BK14: Adding 2014 data including, for the first time, at 95GHz:
  - Modest improvement: $r_{0.05}<0.12$ goes to $r_{0.05}<0.09$
  - Important milestone: for the first time B-mode only constraint exceeds the sensitivity of TT-derived constraint ($r_{0.05}<0.12$)

- BK15: Adding 2015 data, which includes 220GHz:
  - Expected $\sigma(r)=0.019$
  - Now able to explore more data/modelvariations

- And we can go much further:
  - BICEP3 is online at 95 GHz
  - Delensing using SPT/SPT-3G
  - BICEP Array – $\sigma(r)=0.003$