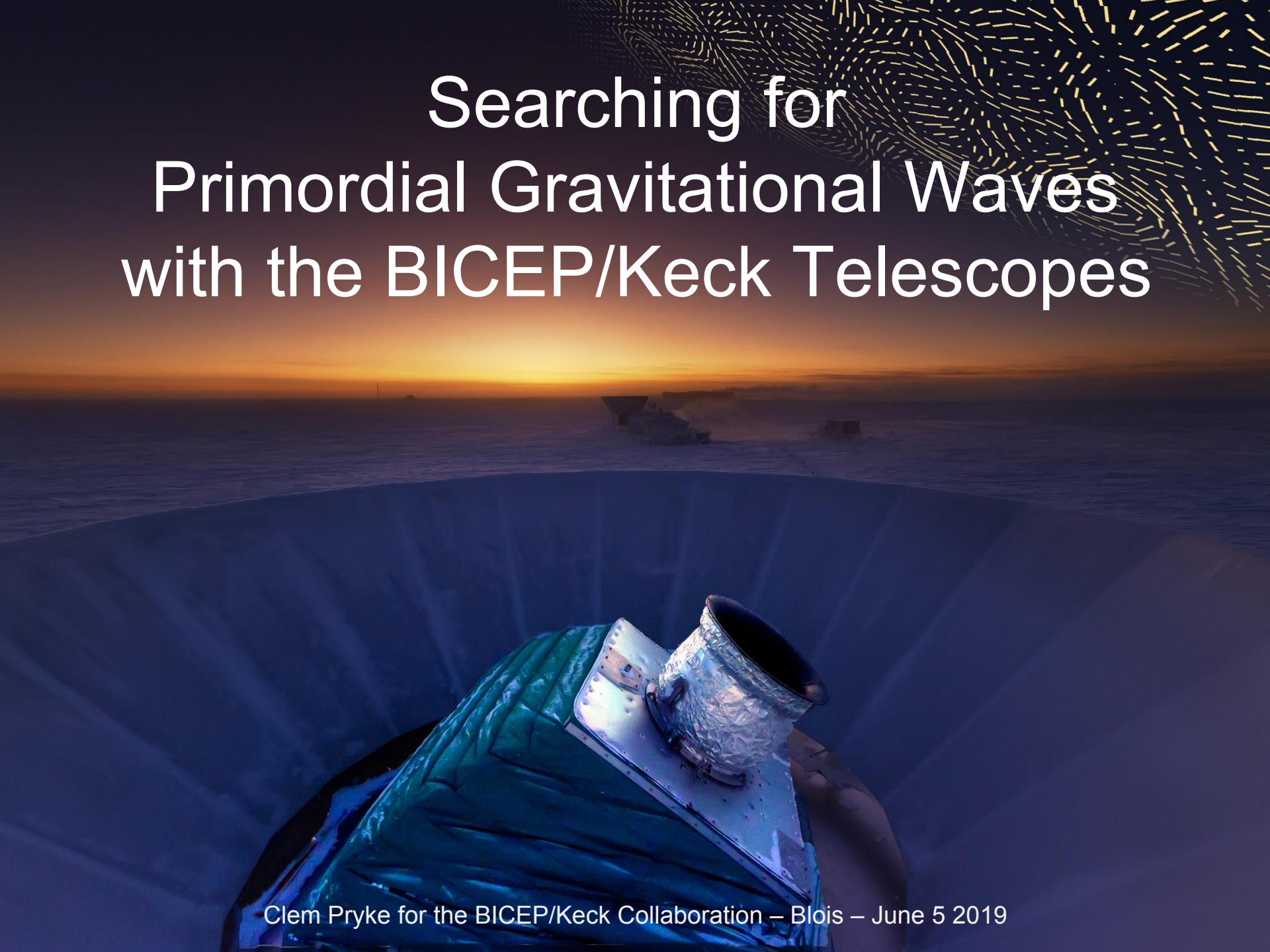
Searching for Primordial Gravitational Waves with the BICEP/Keck Telescopes

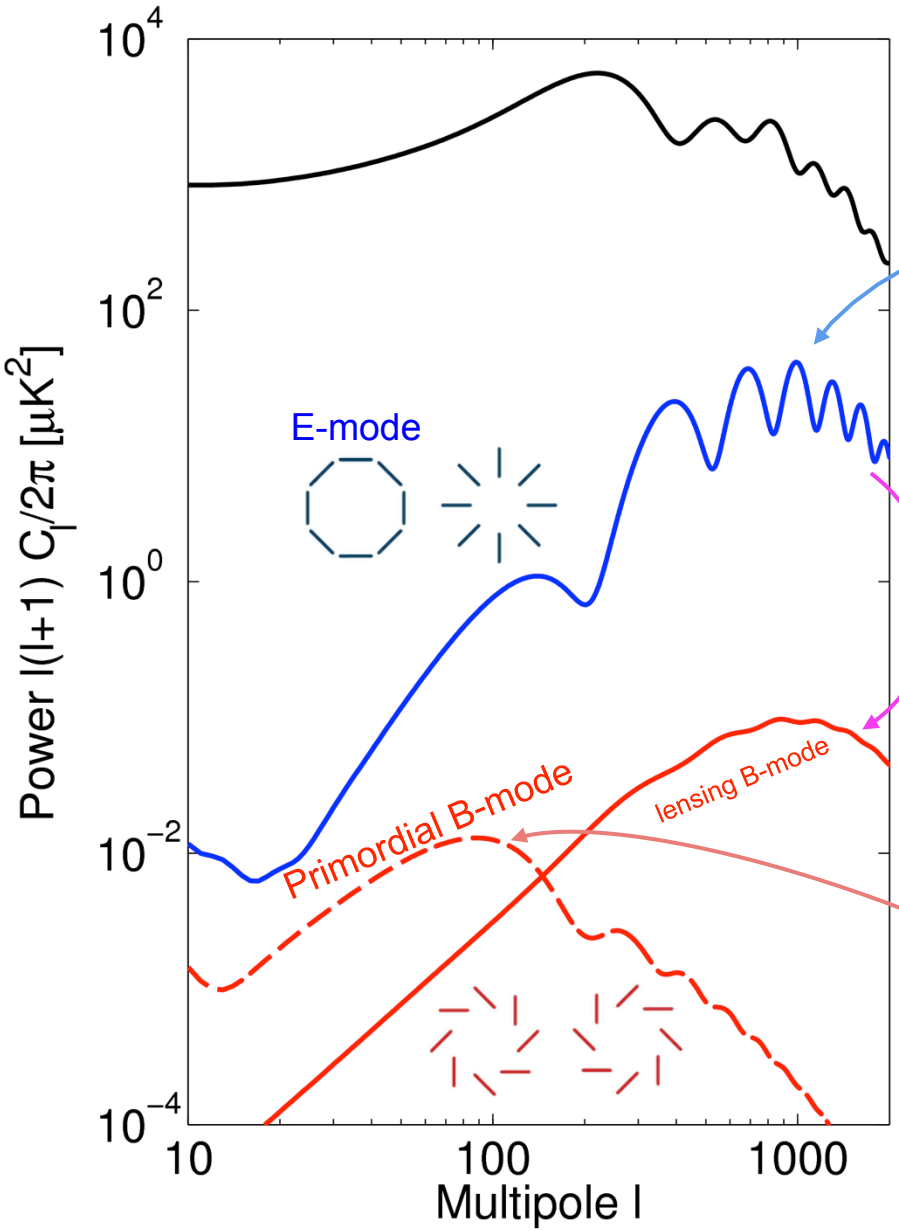


Clem Pryke for the BICEP/Keck Collaboration – Blois – June 5 2019

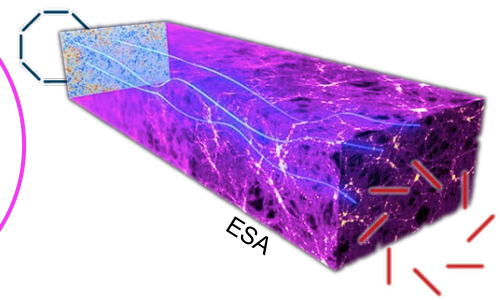
Motivation/Background

- The Universe is expanding/cooling – in the past it was hotter/denser
- The cosmic microwave background (CMB) comes to us from “last scattering” when the universe made the plasma to neutral gas transition – during the plasma phase the physics was simple
- Using the CMB and other data the LCDM cosmological paradigm has been developed – it works great and allows us to understand the development of the universe all the way back to a high energy state
- However, LCDM leaves many unanswered questions such as the “horizon problem” and how the (simple!) initial conditions were set up
- Theory of “Inflation” added to LCDM to explain – says our entire observable Universe came from a sub-atomic speck in a hyper expansion lasting a tiny fraction of a second
- Inflation will have made a background of gravitational waves which will have imprinted a B-mode (curl) into the polarization pattern of the CMB
- We may be able to detect these if we can make a sensitive enough telescope – a wide range of inflation models exist – the simplest are already ruled out – more complex ones can produce *r* which is undetectably small…

CMB 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 : few degree scales

Stage 2

Stage 3

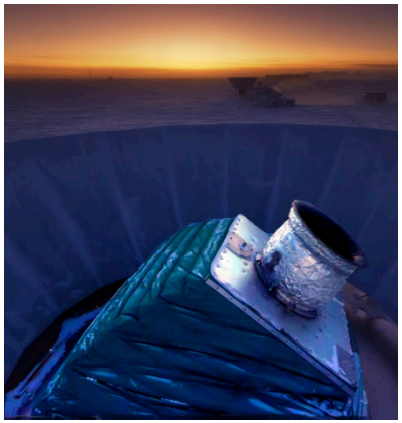
BICEP2
(2010-2012)

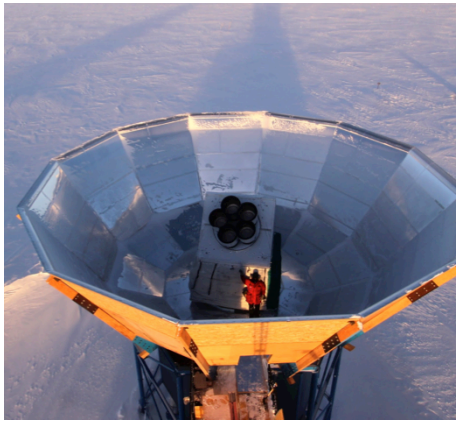
Keck Array
(2012-2019)

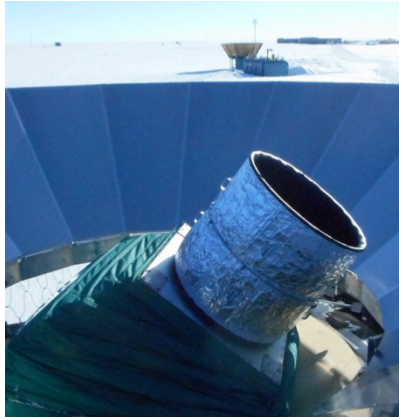
BICEP3
(2016-)

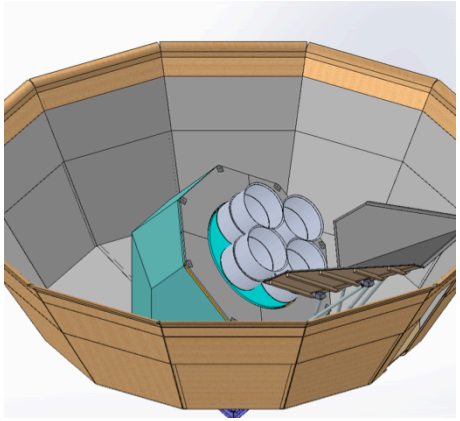
BICEP Array
(2020-)

Telescope and Mount

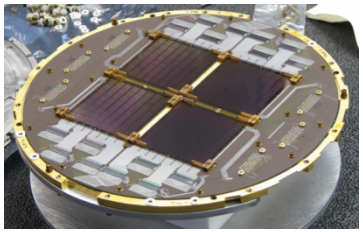


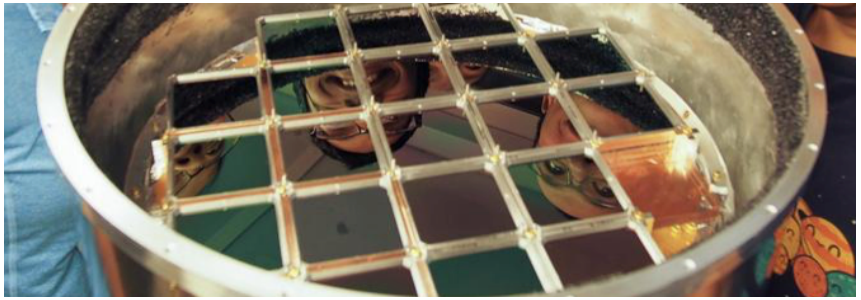




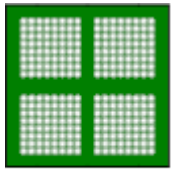


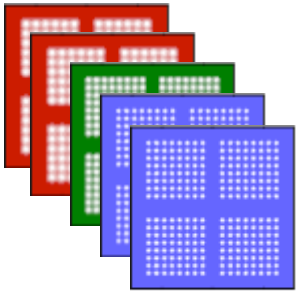
Focal Plane

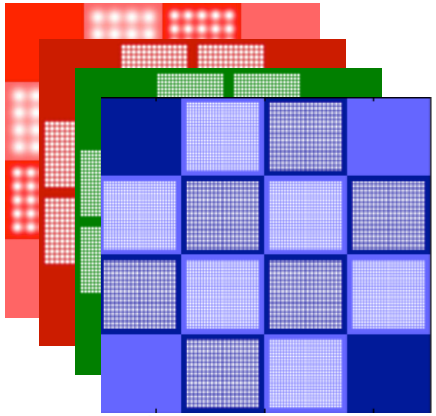




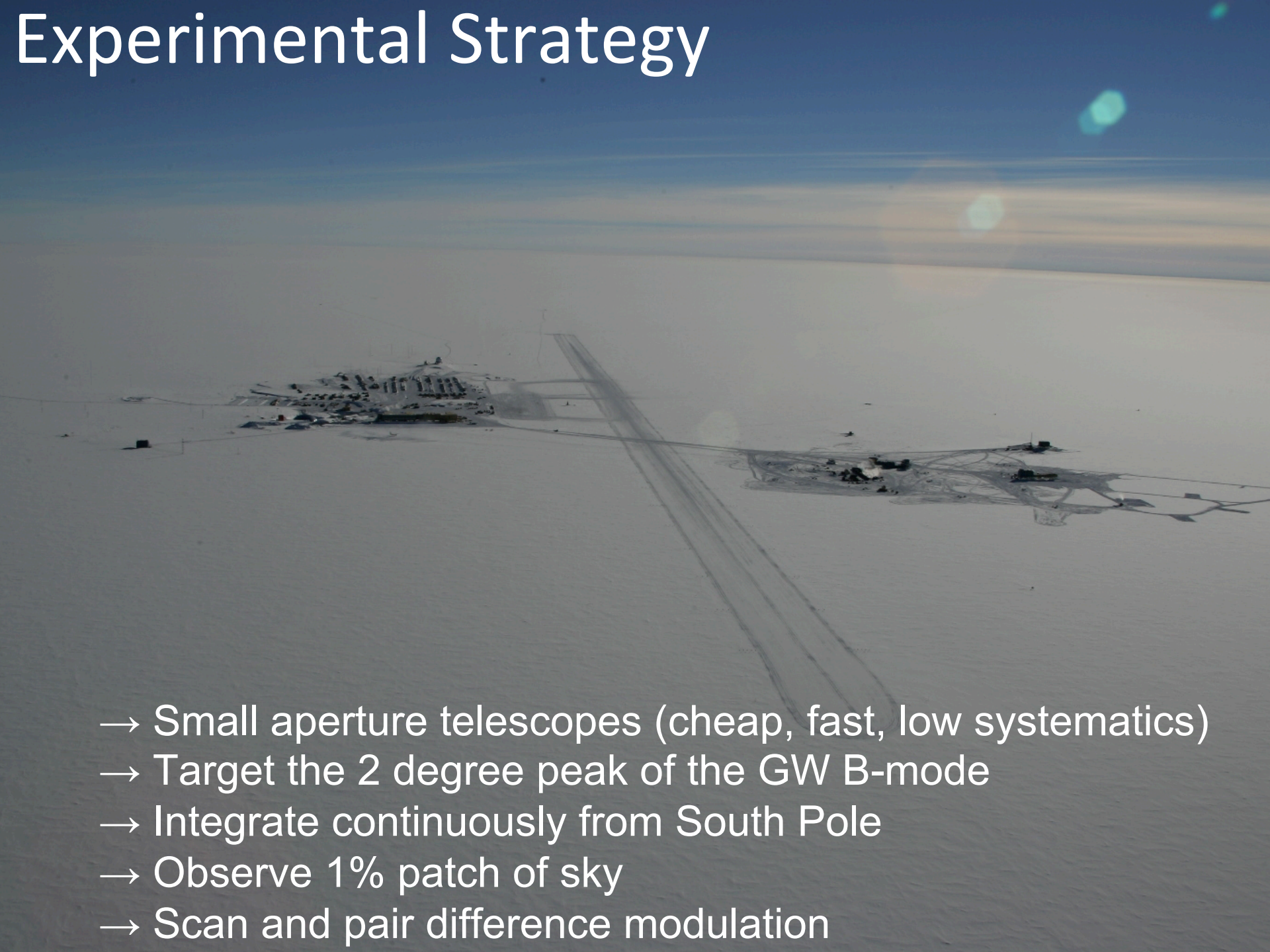
Beams on Sky







Experimental Strategy



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

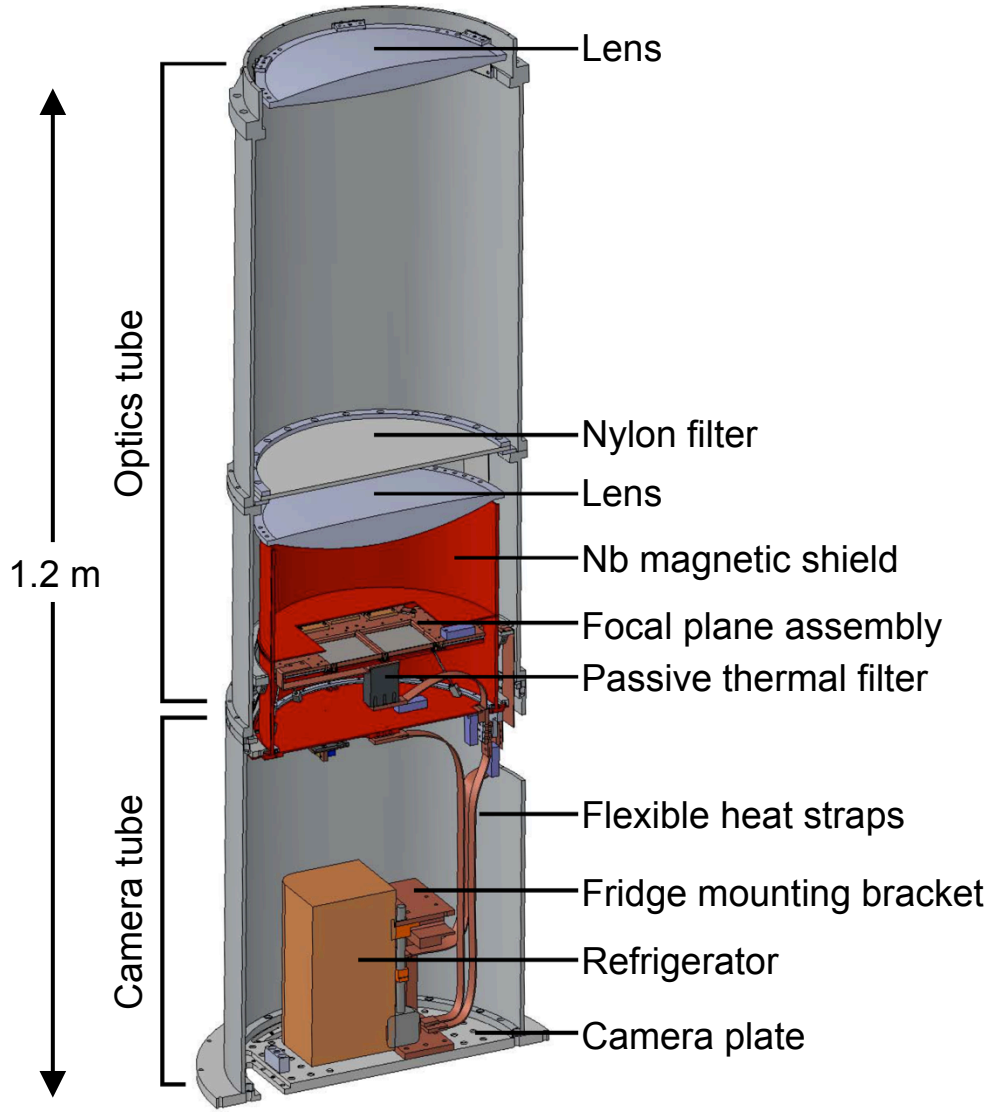
The BICEP2/Keck Telescopes

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

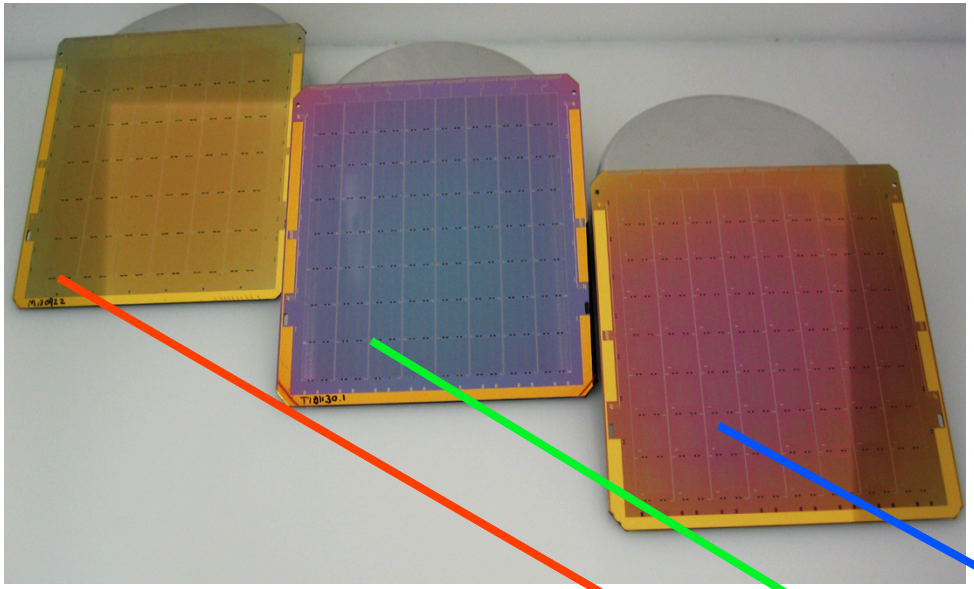
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation

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

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

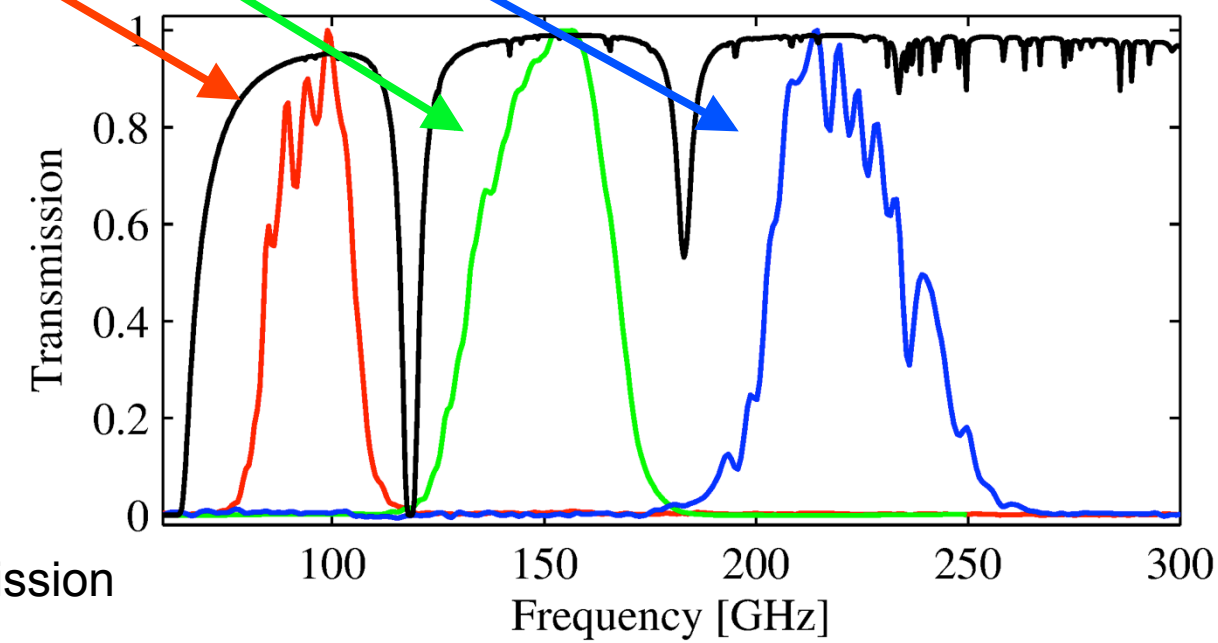


Planar superconducting detector arrays



…designed to scale
in frequency

Up to 2013 – all 150GHz
2014 – 2x95 3x150GHz
2015 – 2x95 1x150 2x220GHz
2016 – B3 1x150 4x220GHz
2017 – B3 4x220 1x270GHz
2018 – B3 4x220 1x270GHz



Typical South Pole
atmospheric transmission

BK15 Results Came Out Last Fall

BICEP2 / *Keck Array* X: Constraints on Primordial Gravitational Waves using *Planck*, WMAP, and New BICEP2/*Keck* Observations through the 2015 Season

Keck Array and BICEP2 Collaborations: P. A. R. Ade,[1] Z. Ahmed,[2] R. W. Aikin,[3] K. D. Alexander,[4] D. Barkats,[4] S. J. Benton,[5] C. A. Bischoff,[6] J. J. Bock,[3,7] R. Bowens-Rubin,[4] J. A. Brevik,[3] I. Buder,[4] E. Bullock,[8] V. Buza,[4,9] J. Connors,[4] J. Cornelison,[4] B. P. Crill,[7] M. Crumrine,[10] M. Dierickx,[4] L. Duband,[11] C. Dvorkin,[9] J. P. Filippini,[12,13] S. Fliescher,[10] J. Grayson,[14] G. Hall,[10] M. Halpern,[15] S. Harrison,[4] S. R. Hildebrandt,[3,7] G. C. Hilton,[16] H. Hui,[3] K. D. Irwin,[14,2,16] J. Kang,[14] K. S. Karkare,[4,17] E. Karpel,[14] J. P. Kaufman,[18] B. G. Keating,[18] S. Kefeli,[3] S. A. Kernasovskiy,[14] J. M. Kovac,[4,9] C. L. Kuo,[14,2] N. A. Larsen,[17] K. Lau,[10] E. M. Leitch,[17] M. Lueker,[3] K. G. Megerian,[7] L. Moncelsi,[3] T. Namikawa,[19] C. B. Netterfield,[20,21] H. T. Nguyen,[7] R. O'Brient,[3,7] R. W. Ogburn IV,[14,2] S. Palladino,[6] C. Pryke,[10,8,*] B. Racine,[4] S. Richter,[4] A. Schillaci,[3] R. Schwarz,[10] C. D. Sheehy,[22] A. Soliman,[3] T. St. Germaine,[4] Z. K. Staniszewski,[3,7] B. Steinbach,[3] R. V. Sudiwala,[1] G. P. Teply,[3,18] K. L. Thompson,[14,2] J. E. Tolan,[14] C. Tucker,[1] A. D. Turner,[7] C. Umiltà,[6] A. G. Vieregg,[23,17] A. Wandui,[3] A. C. Weber,[7] D. V. Wiebe,[15] J. Willmert,[10] C. L. Wong,[4,9] W. L. K. Wu,[17] H. Yang,[14] K. W. Yoon,[14,2] and C. Zhang[3]

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(Draft As accepted by PRL)

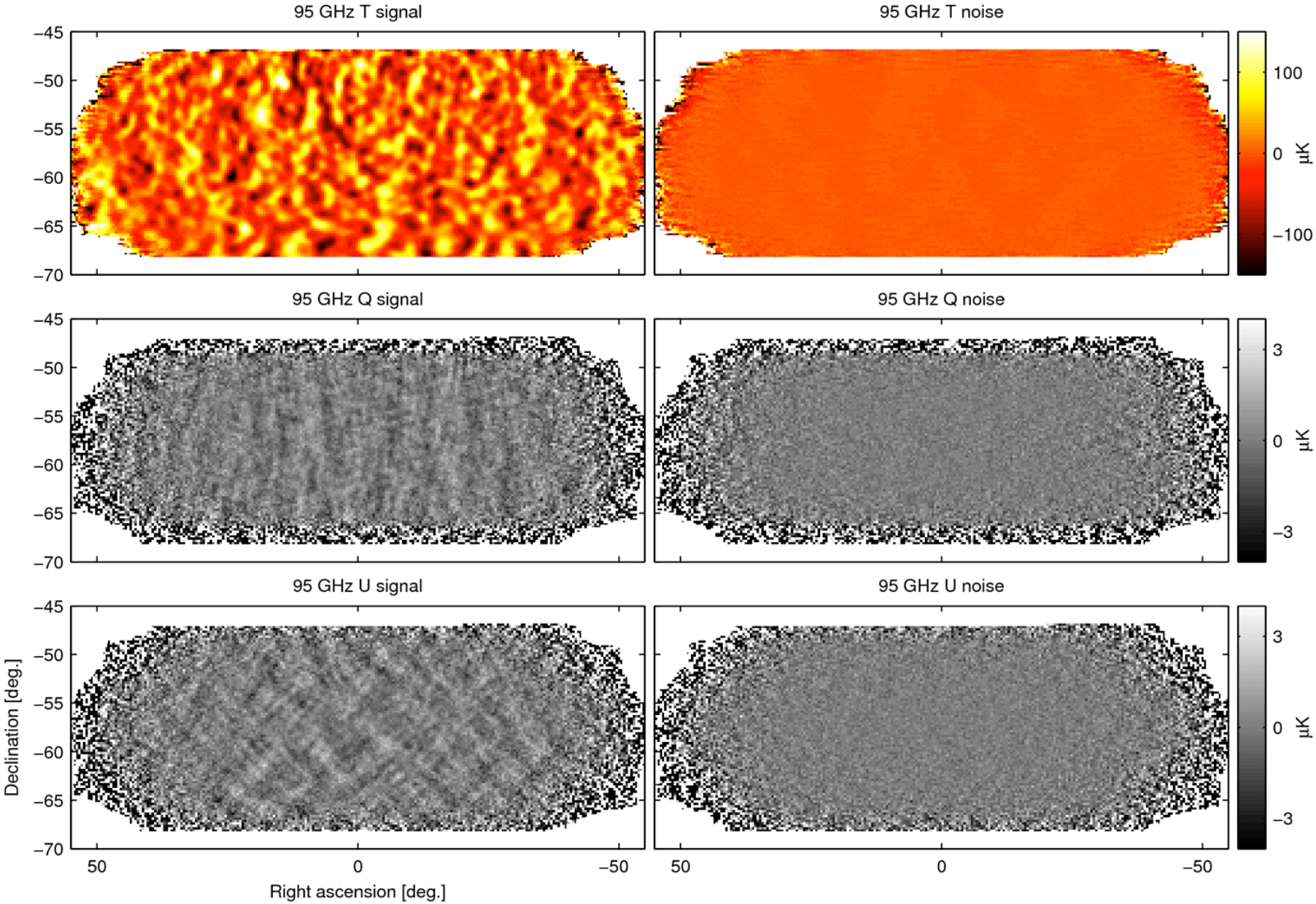
We present results from an analysis of all data taken by the BICEP2/*Keck* CMB polarization experiments up to and including the 2015 observing season. This includes the first *Keck Array* observations at 220 GHz and additional observations at 95 & 150 GHz. The Q/U maps reach depths of 5.2, 2.9 and 26 μK_{cmb} arcmin at 95, 150 and 220 GHz respectively over an effective area of ≈ 400 square degrees. The 220 GHz maps achieve a signal-to-noise on polarized dust emission approximately equal to that of *Planck* at 353 GHz. We take auto- and cross-spectra between these maps and publicly available WMAP and *Planck* maps at frequencies from 23 to 353 GHz. We evaluate the joint likelihood of the spectra versus a multicomponent model of lensed-ΛCDM+r+dust+synchrotron+noise. The foreground model has seven parameters, and we impose priors on some of these using external information from *Planck* and WMAP derived from larger regions of sky. The model is shown to be an adequate description of the data at the current noise levels. The likelihood analysis yields the constraint $r_{0.05} < 0.07$ at 95% confidence, which tightens to $r_{0.05} < 0.06$ in conjunction with *Planck* temperature measurements and other data. The lensing signal is detected at 8.8σ significance. Running maximum likelihood search on simulations we obtain unbiased results and find that $\sigma(r) = 0.020$. These are the strongest constraints to date on primordial gravitational waves.

arxiv/1810.05216

BK15 = includes all data taken up to, and including, 2015 season

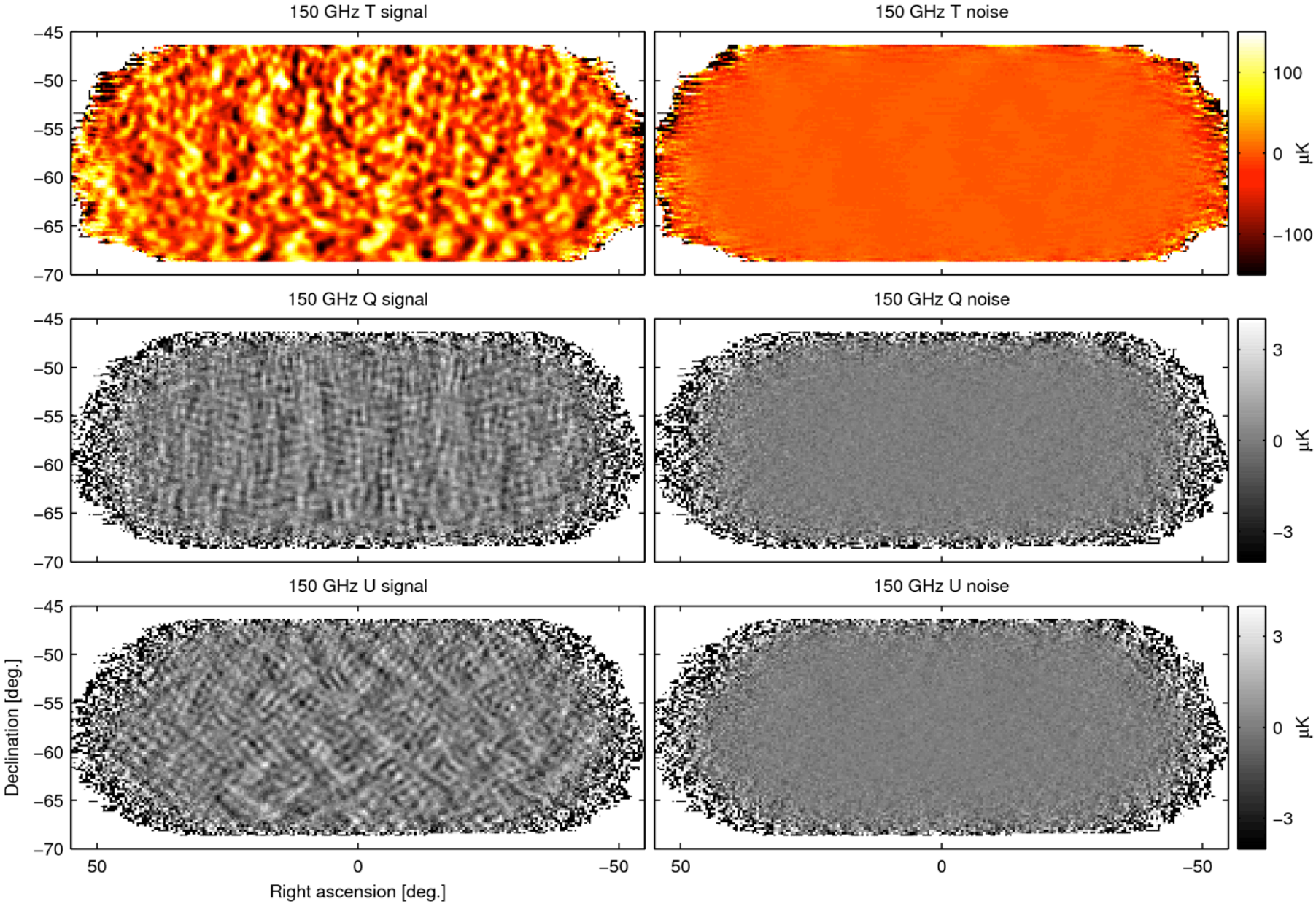
Three years since BK14 – Sorry for the delay!

BK15 95GHz Maps



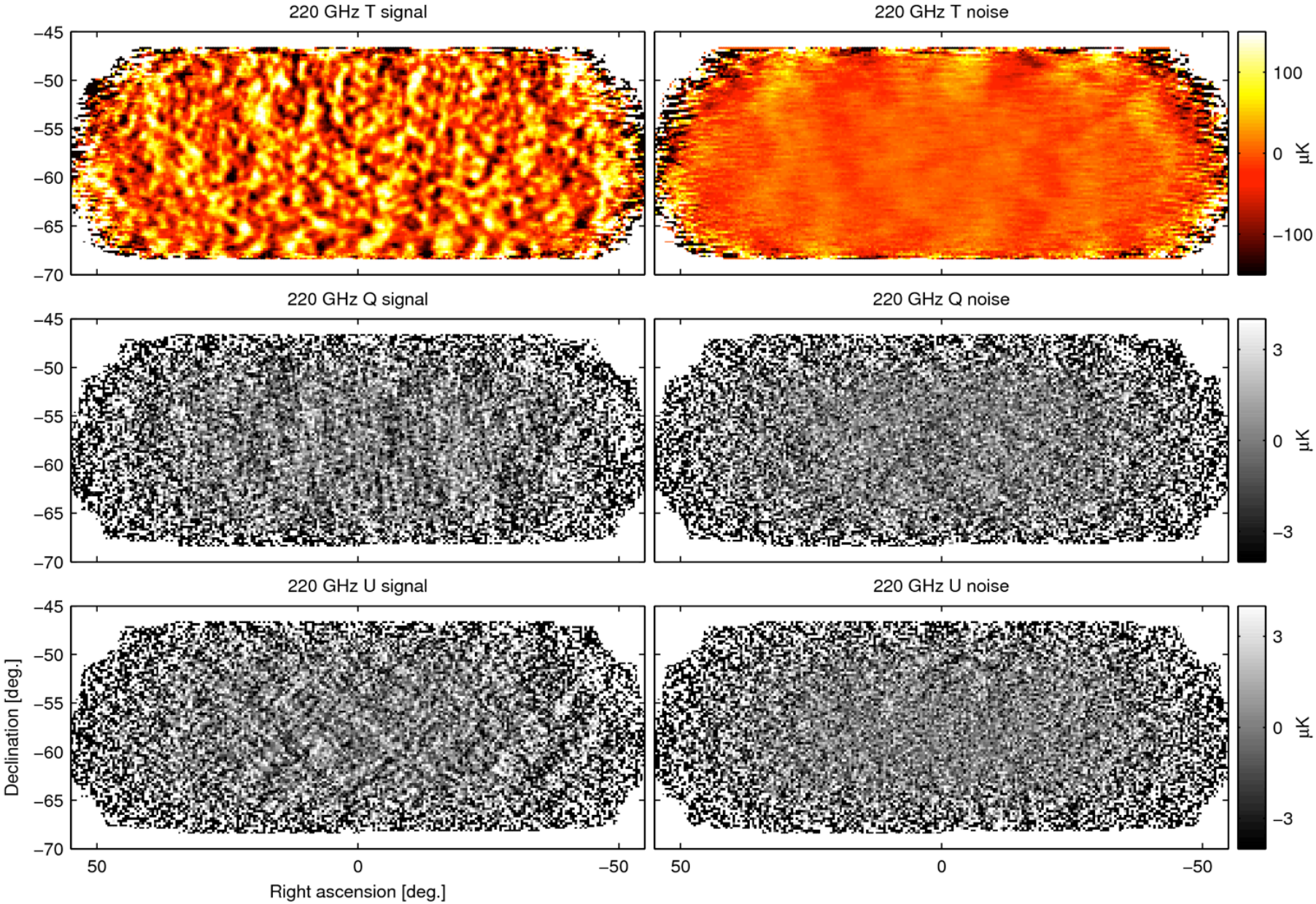
BK15 95GHz – 5 μK arcmin

BK15 150GHz Maps



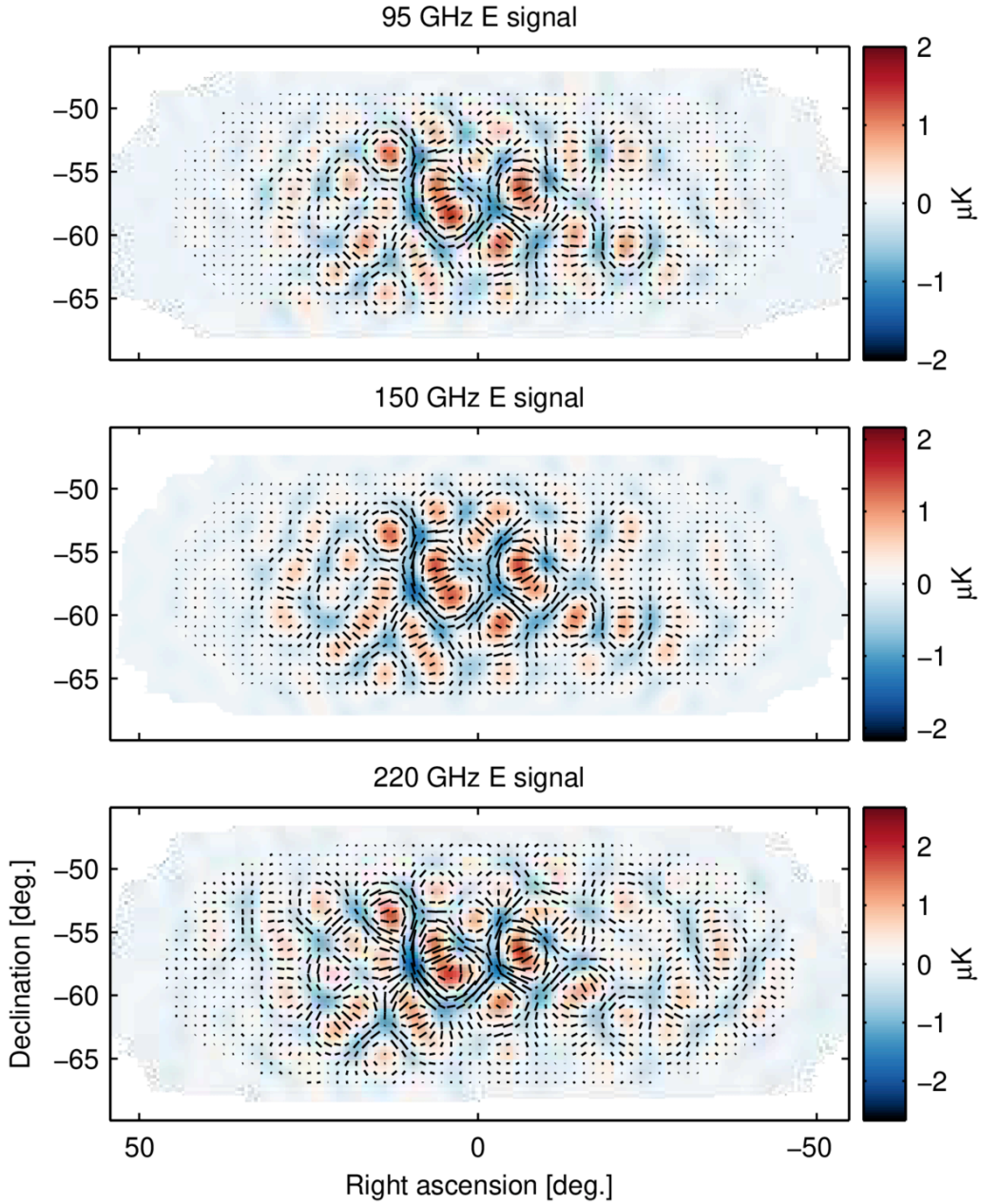
BK15 150GHz – 2.8 μK arcmin

BK15 220GHz Maps



BK15 220GHz – 25 μK arcmin

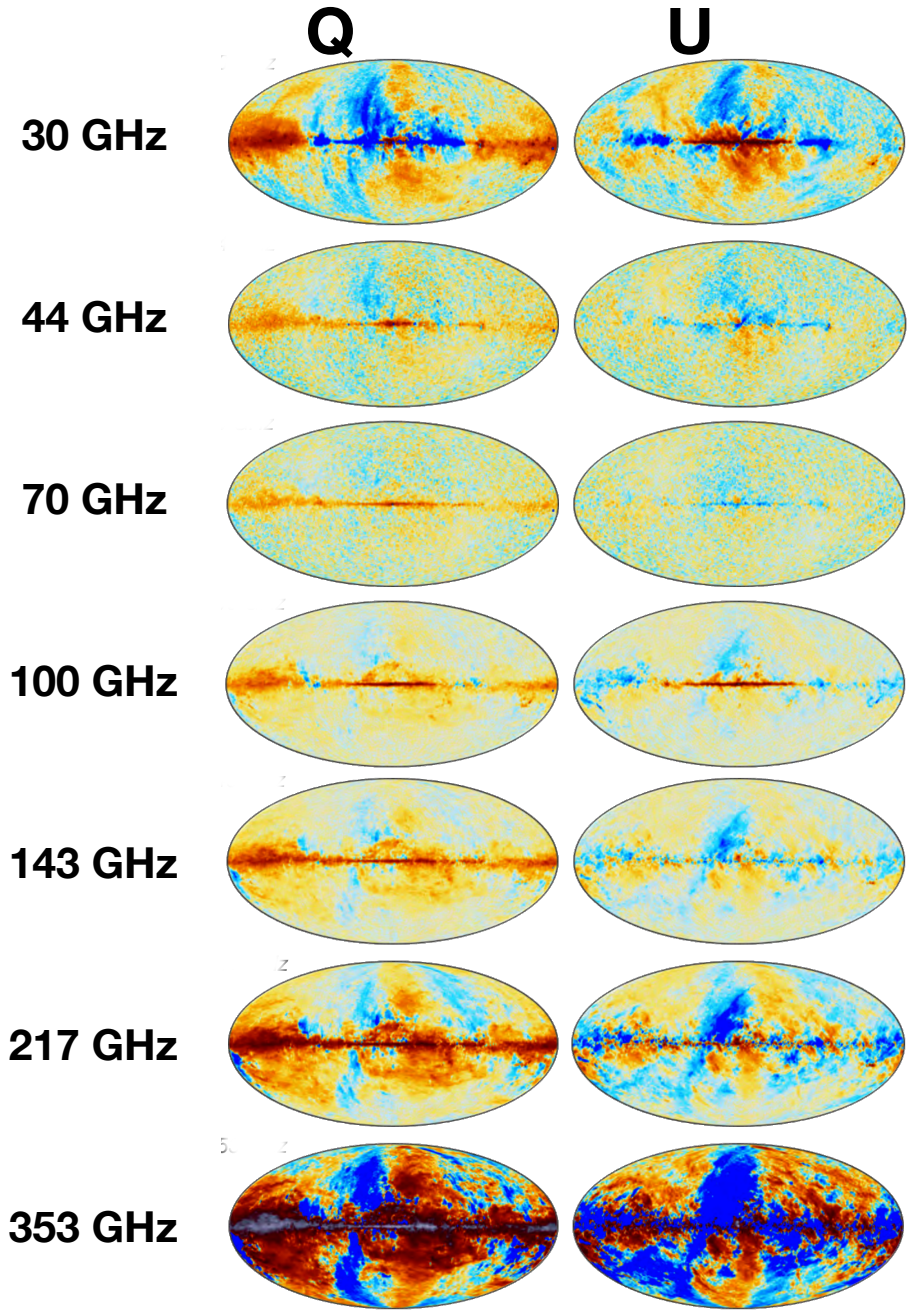
Just for fun: Keck 2015 single season E-mode maps



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

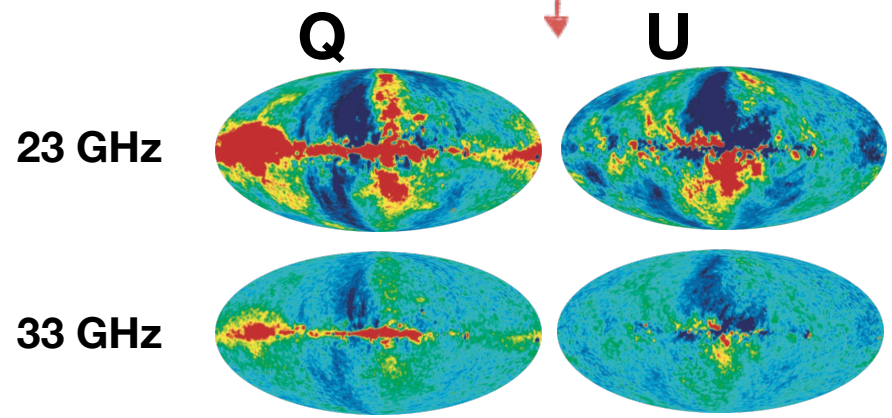
Already deeper than Planck 217 GHz

Add to the mix: Planck at 7 frequencies and WMAP at 2 frequencies



From arxiv 1502.01582

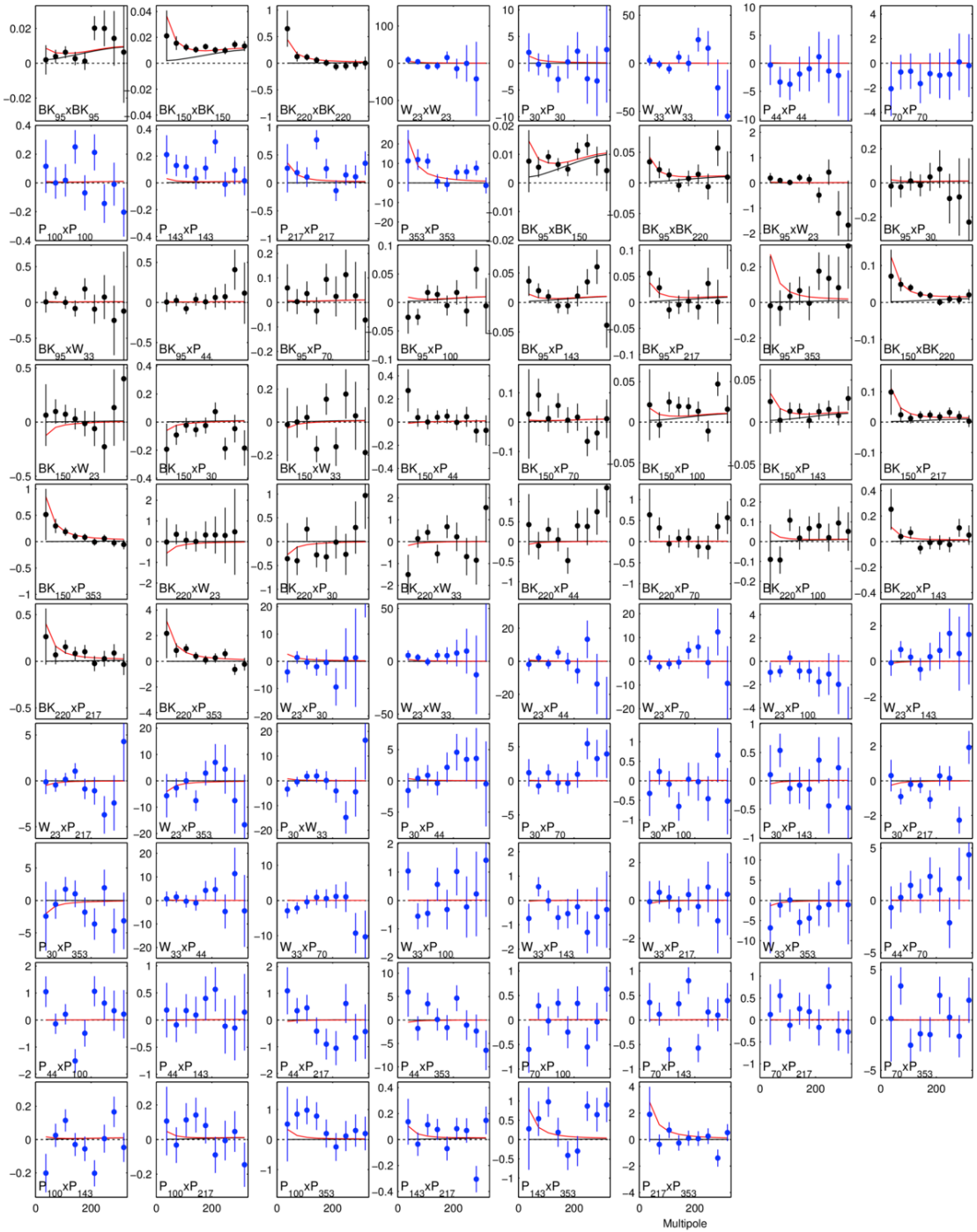
Polarized galactic **synchrotron** dominates at low frequencies



From arxiv 1212.5225

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

Take all possible auto- and cross spectra between the BICEP/Keck, WMAP, and Planck bands (78 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

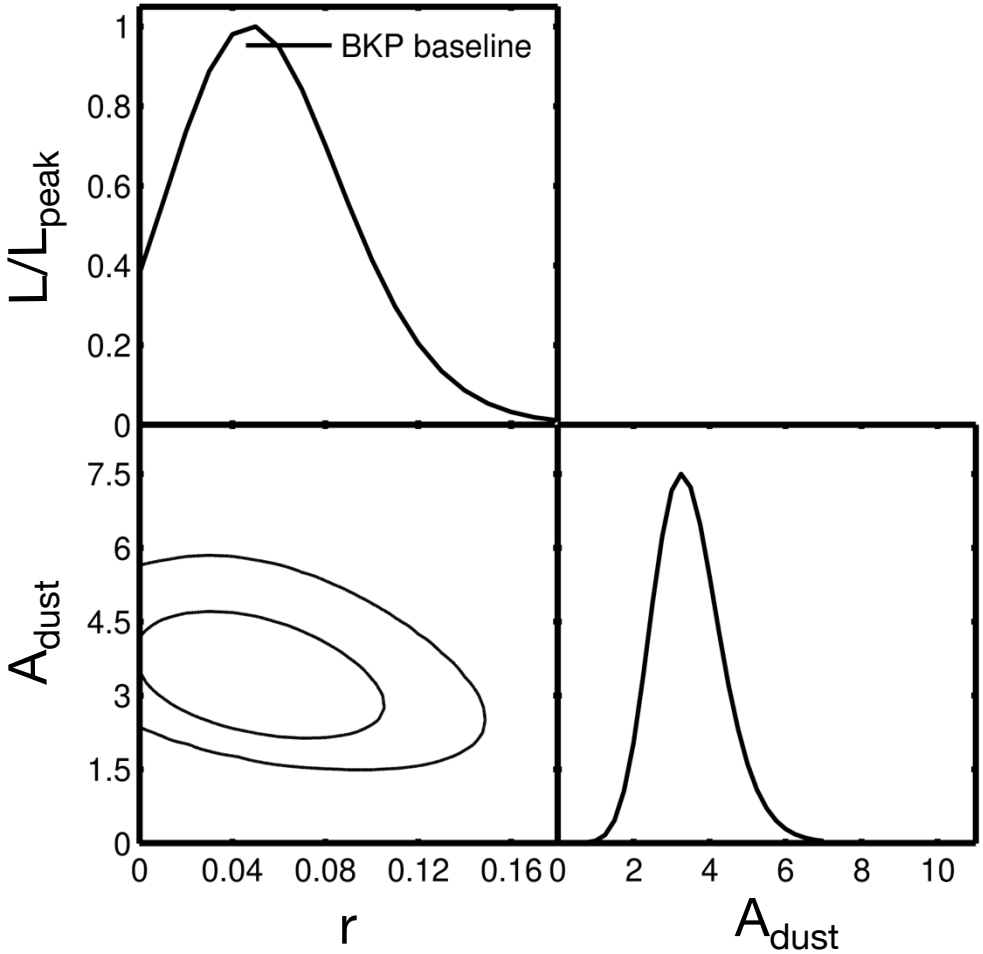
foreground model = dust + synchrotron

A_{dust} A_{synch} — amplitudes @ l=80

β_{dust} β_{synch} — frequency spectral indices

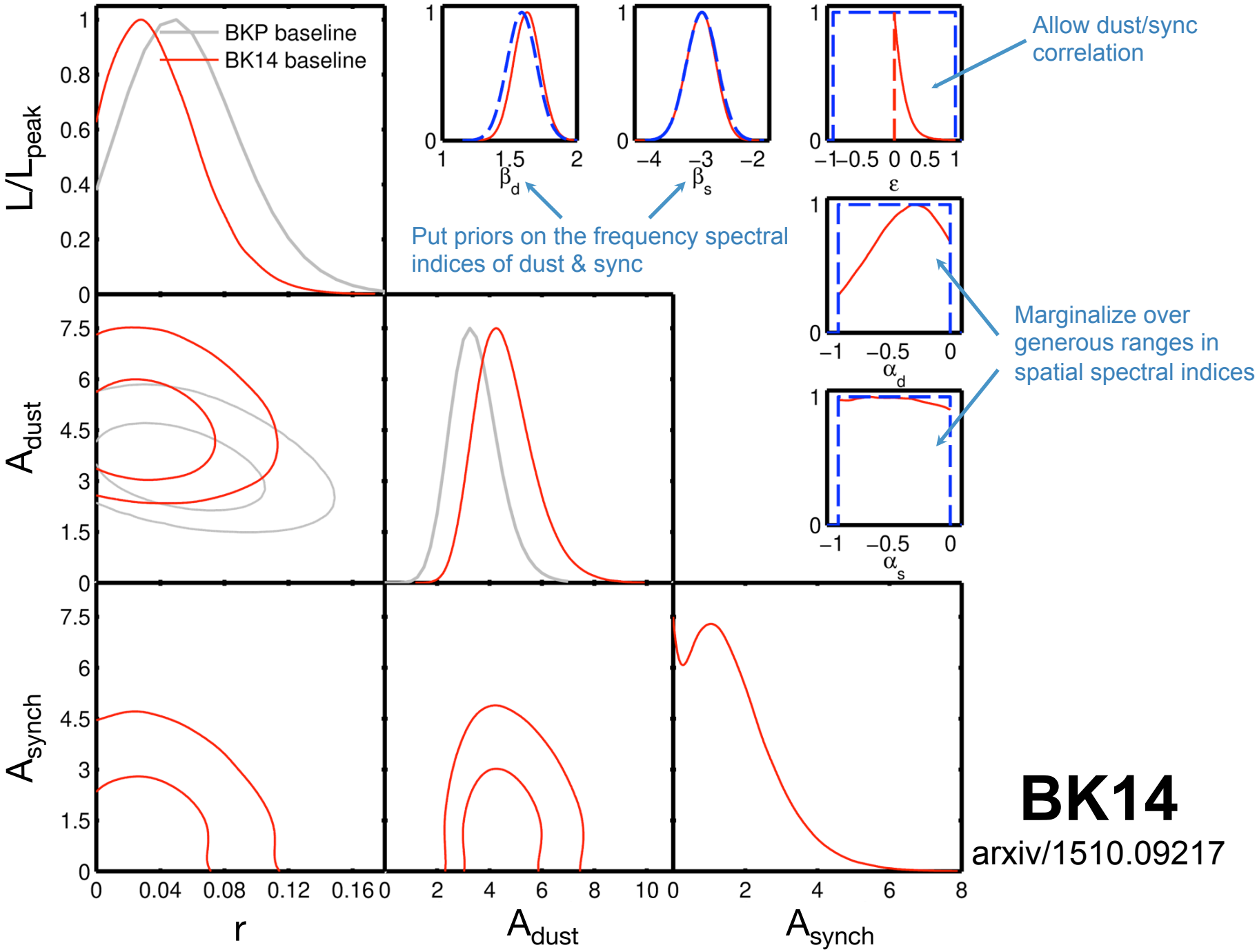
α_{dust} α_{synch} — spatial spectral indices

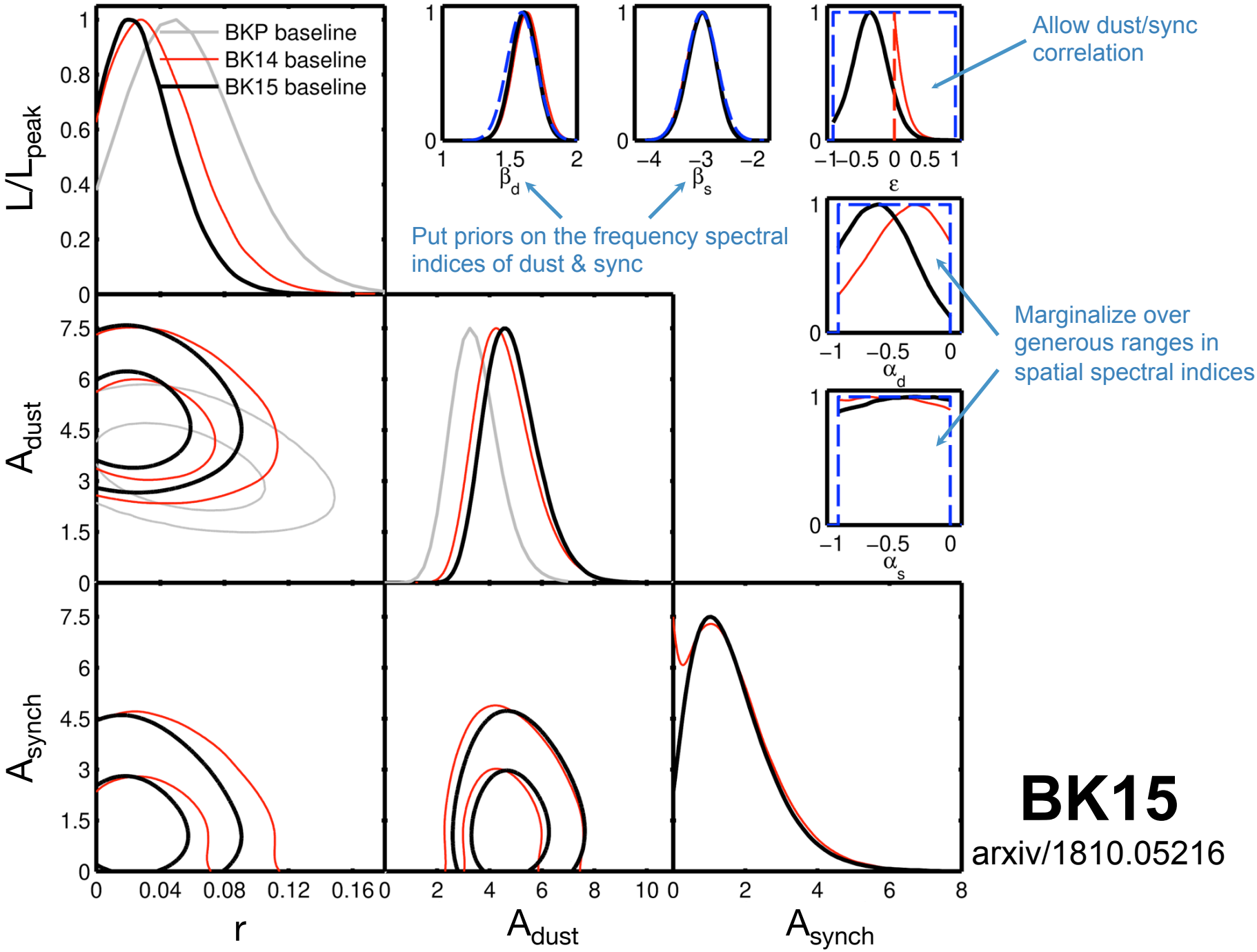
ε — dust/synch spatial correlation

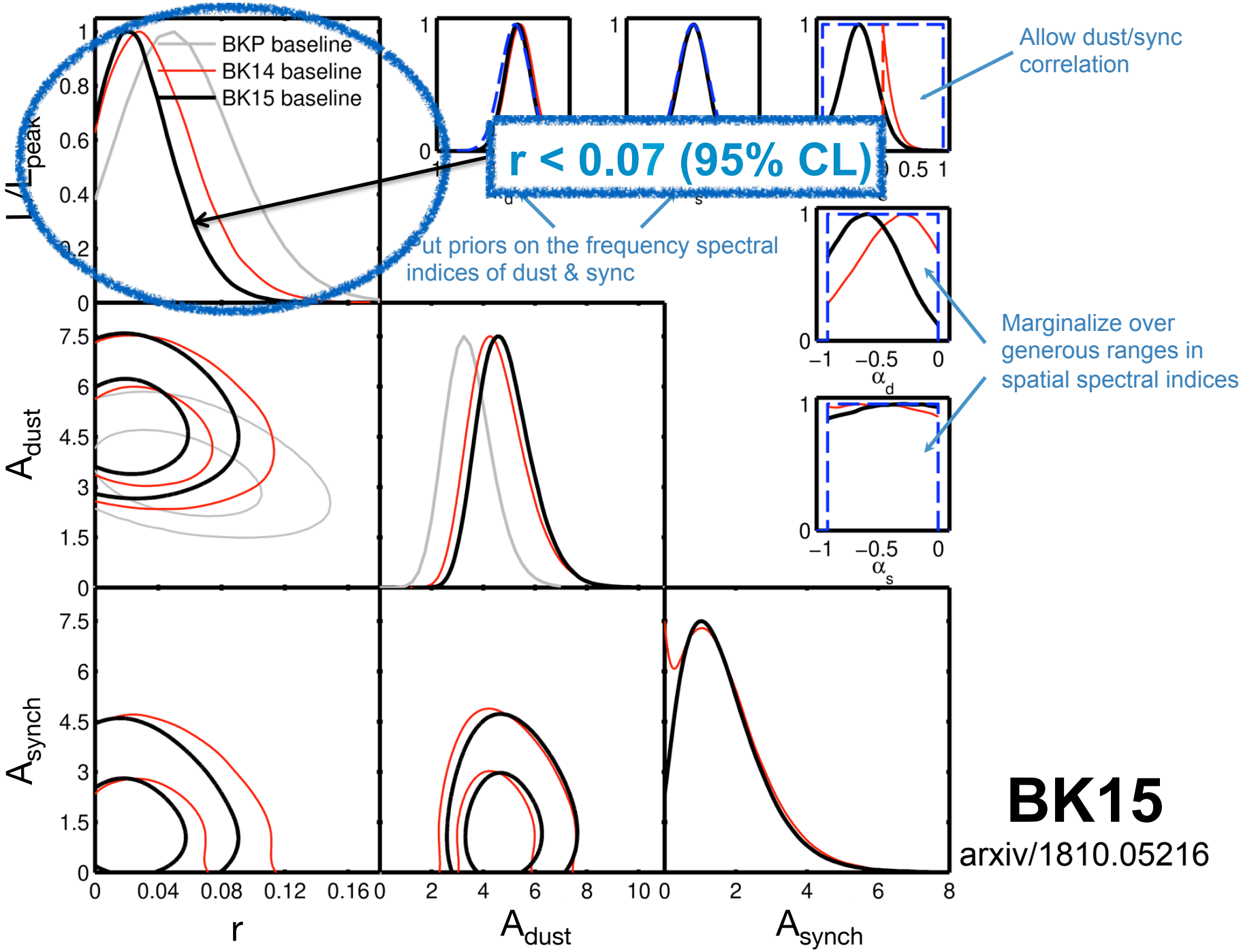


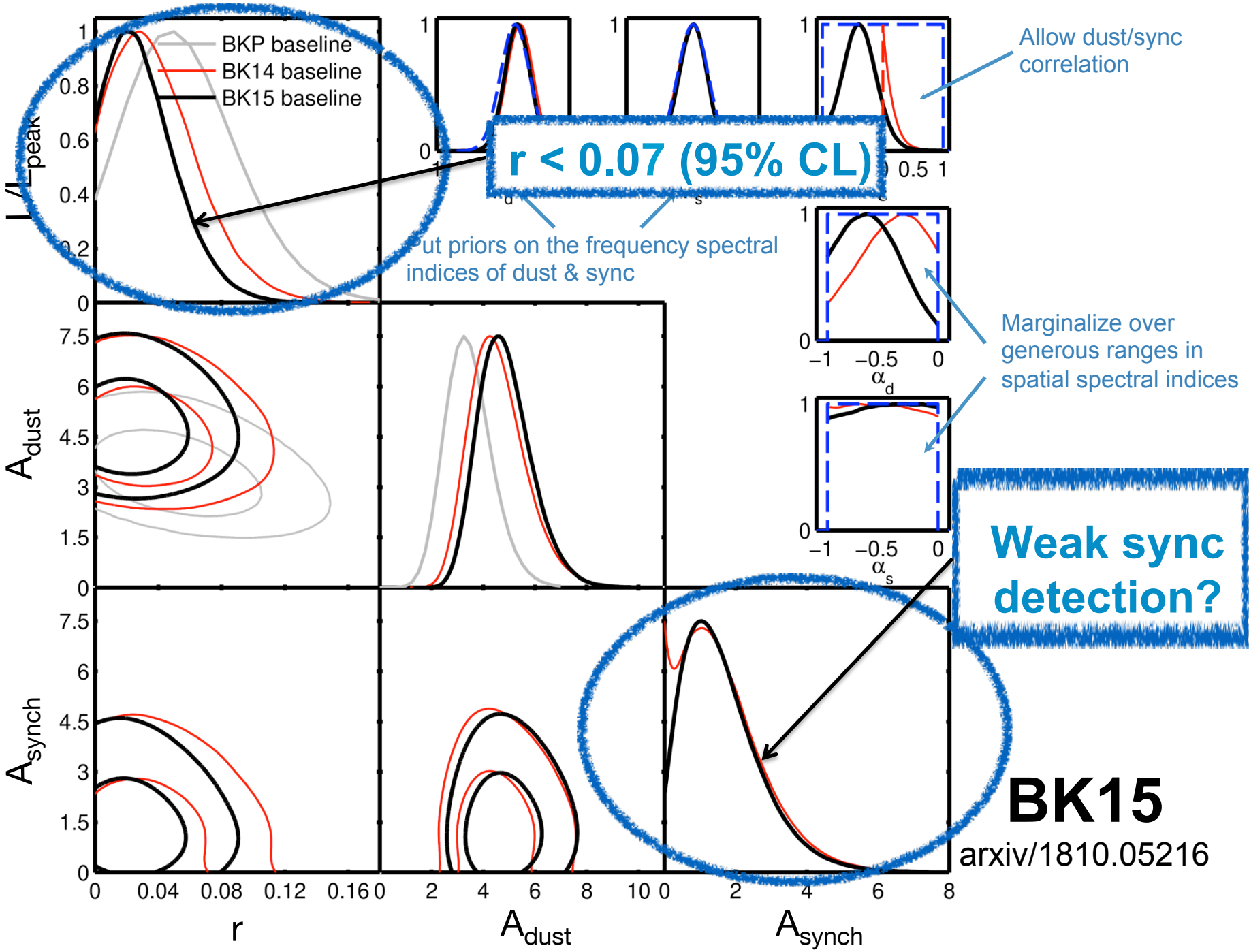
BKP

arxiv/1502.00612

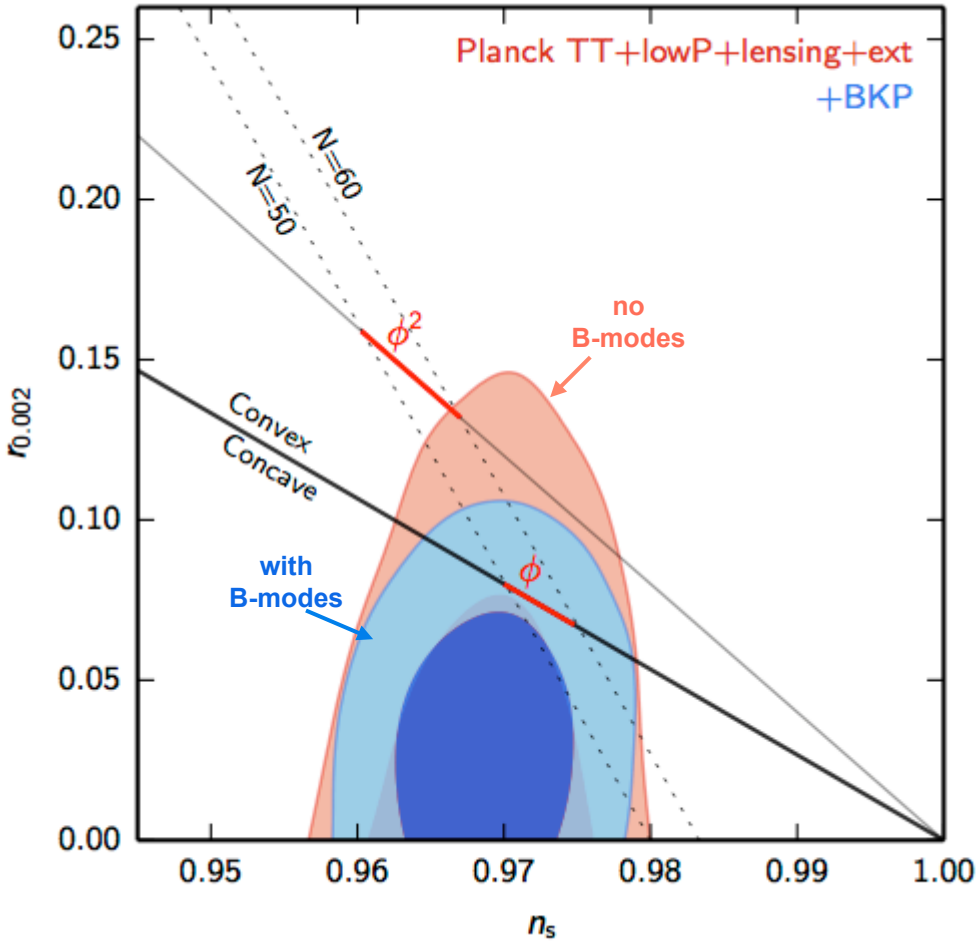

BKP baseline
BK14 baseline
L/L_peak
A_dust
A_synch
r
A_dust
A_synch
β_d
β_s
ε
α_d
α_s
Allow dust/sync correlation
Put priors on the frequency spectral indices of dust & sync
Marginalize over generous ranges in spatial spectral indices
BK14
arxiv/1510.09217


BKP baseline
BK14 baseline
BK15 baseline
L/L_peak
A_dust
A_synch
r
β_d
β_s
ε
α_d
α_s
Allow dust/sync correlation
Put priors on the frequency spectral indices of dust & sync
Marginalize over generous ranges in spatial spectral indices
BK15
arxiv/1810.05216


BKP baseline
BK14 baseline
BK15 baseline
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
L/L_{peak}
A_{dust}
A_{synch}
r
α_d
α_s
BK15
arxiv/1810.05216


BKP baseline
BK14 baseline
BK15 baseline
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
Weak sync detection?
BK15
arxiv/1810.05216
r
A_dust
A_synch
α_d
α_s

Adding in temperature

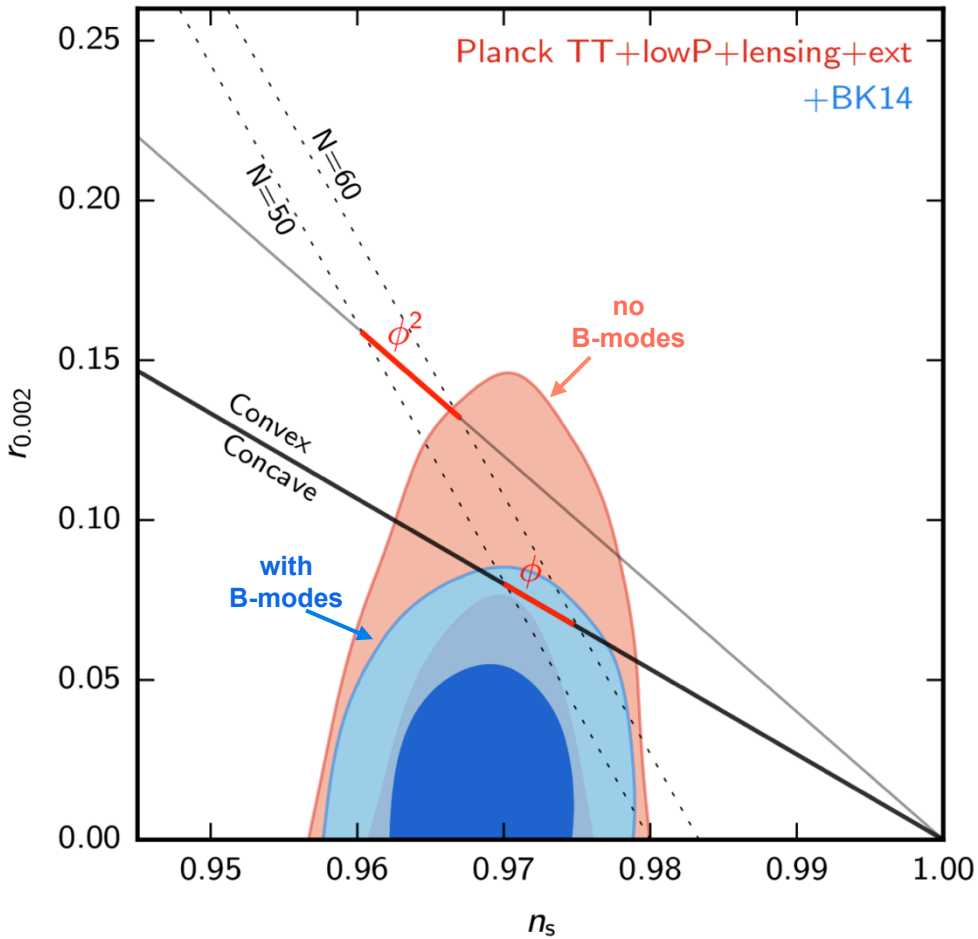


r < 0.09

BKP

arxiv/1502.00612

Adding in temperature

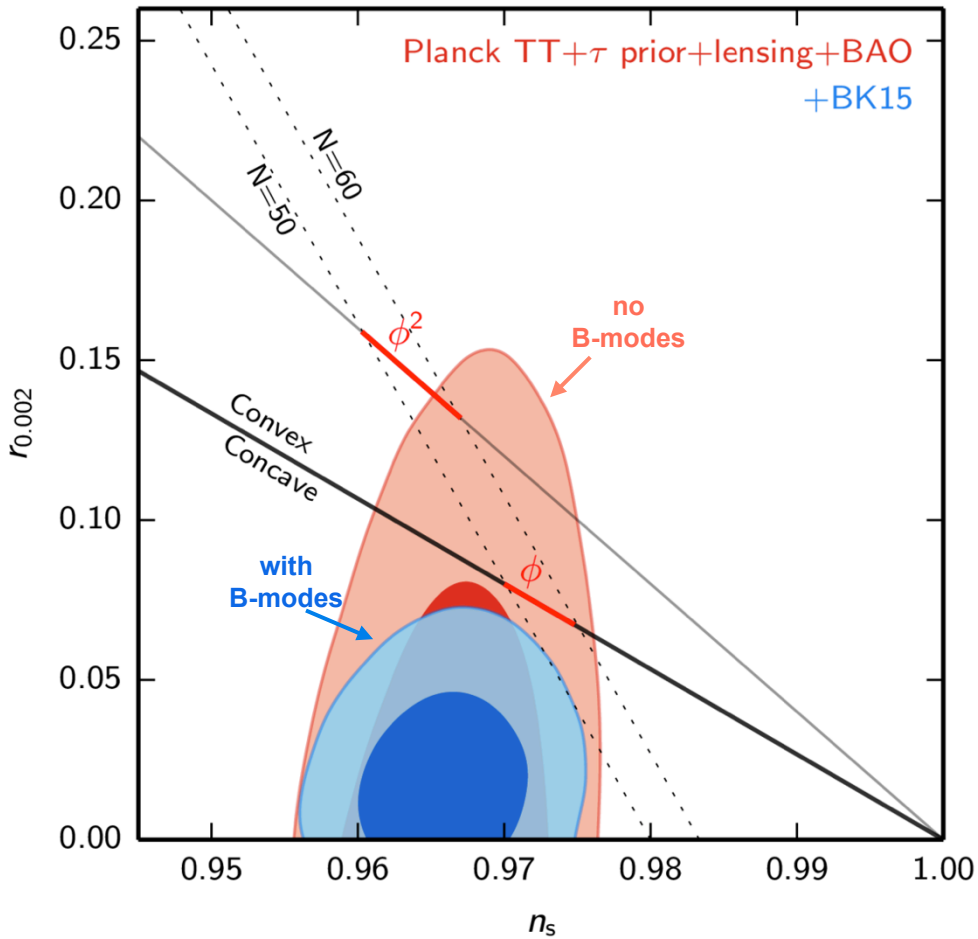


$r_{.05} < 0.07$

BK14

arxiv/1510.09217

Adding in temperature

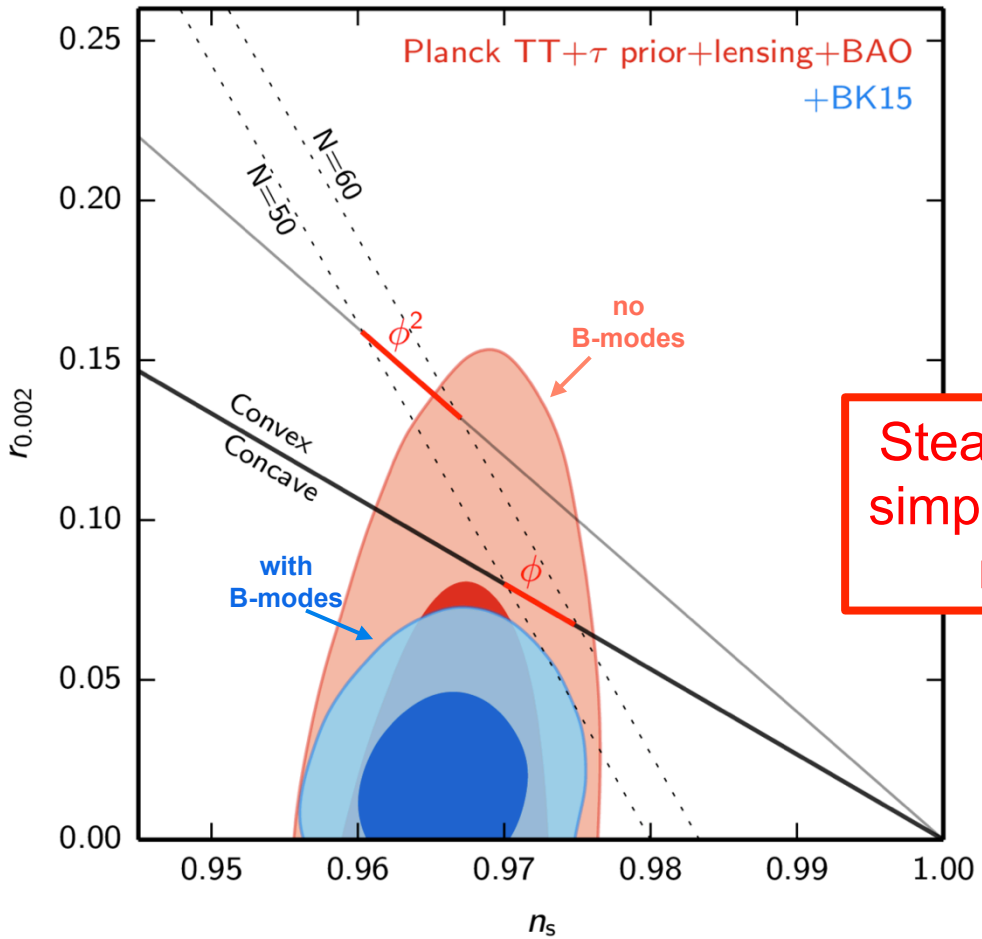


$r_{.05} < 0.06$

BK15

arxiv/1810.05216

Adding in temperature



Steadily ruling out simpler inflationary models…

$r_{.05} < 0.06$

BK15

arxiv/1810.05216

2016 onwards: BICEP3 "Super receiver"

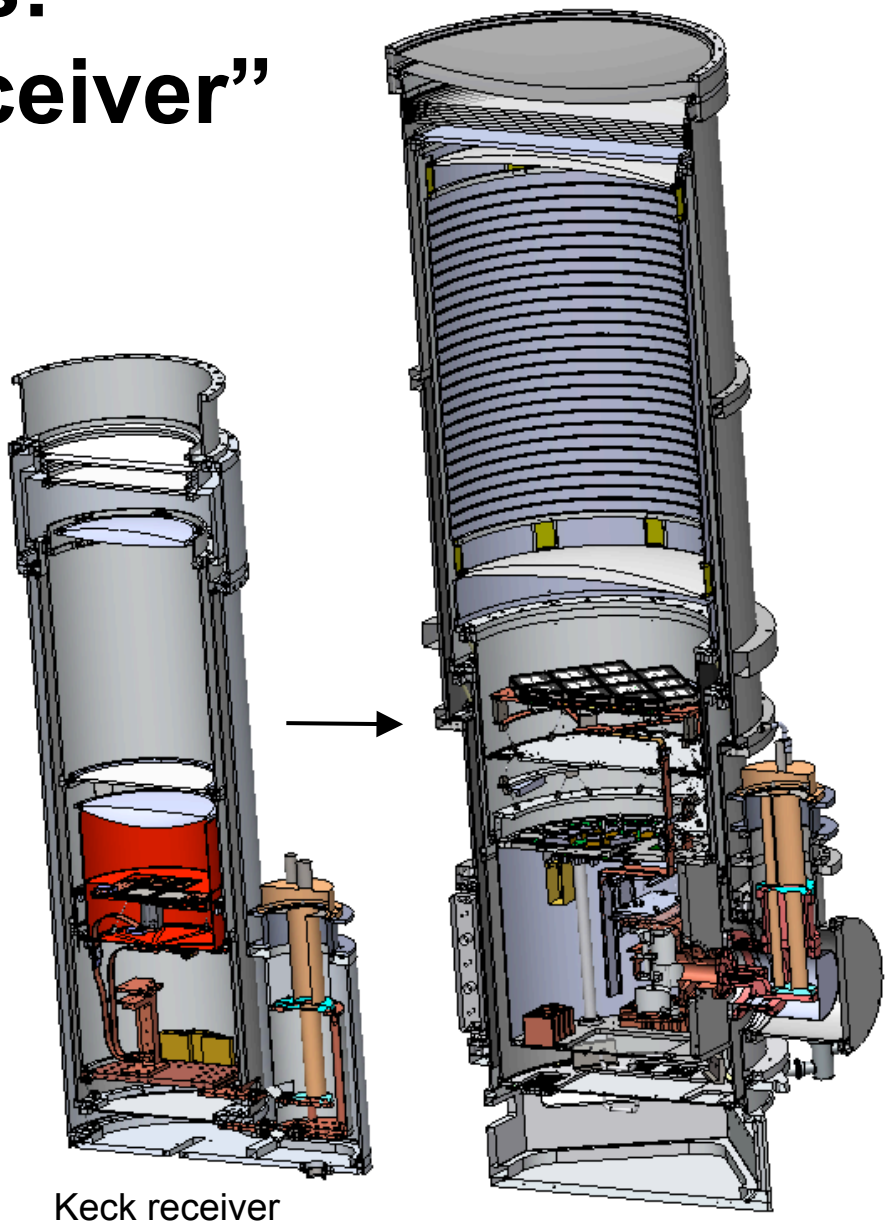
All 95 GHz

2560 detectors in modular focal plane

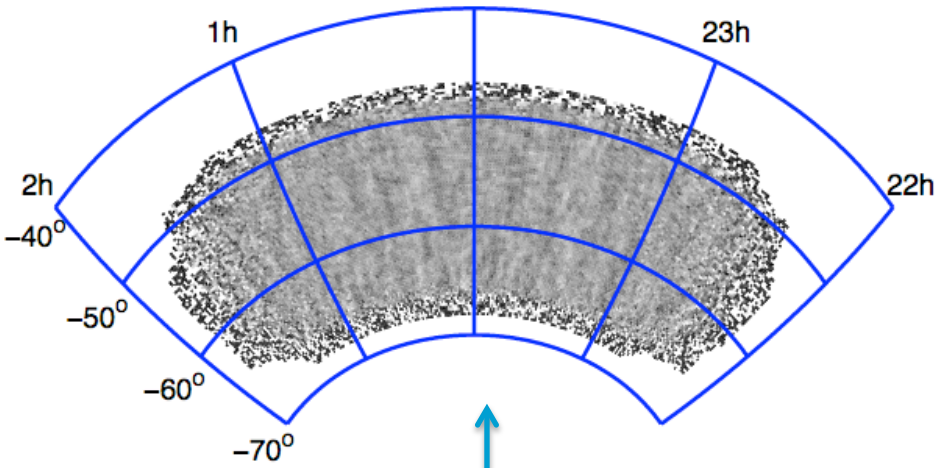
Larger-aperture optics

> 10x optical throughput of single BICEP2/Keck receiver

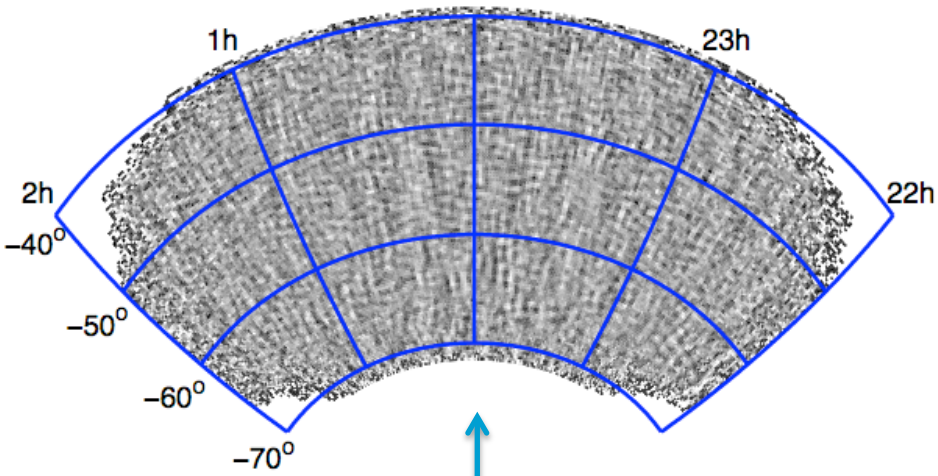
Means larger field of view and lower noise faster



Larger receiver = more sky area

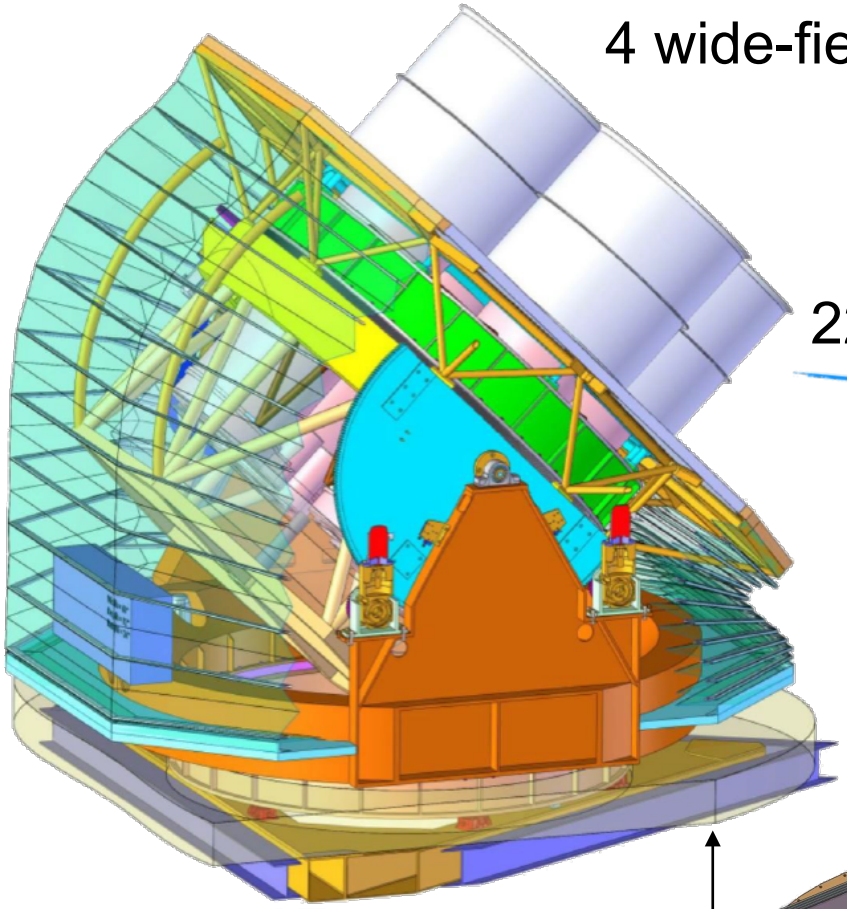


Keck 95 GHz *Q* map after 4 receiver years

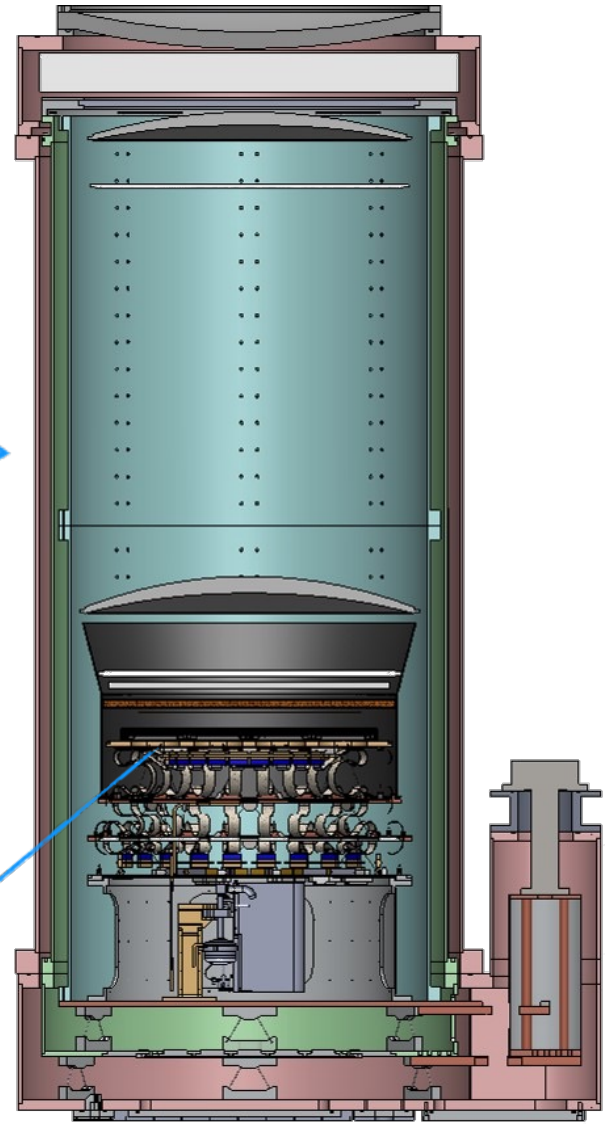


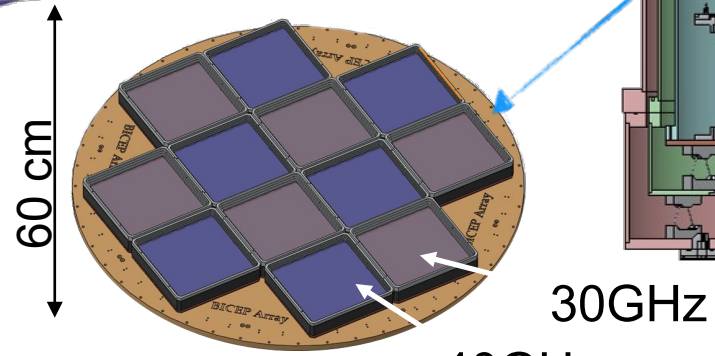
BICEP3 95 GHz *Q* map after 1 receiver year (2017) (Increased area, angular-resolution and sensitivity)

Next Gen Experiment BICEP Array Under Construction



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

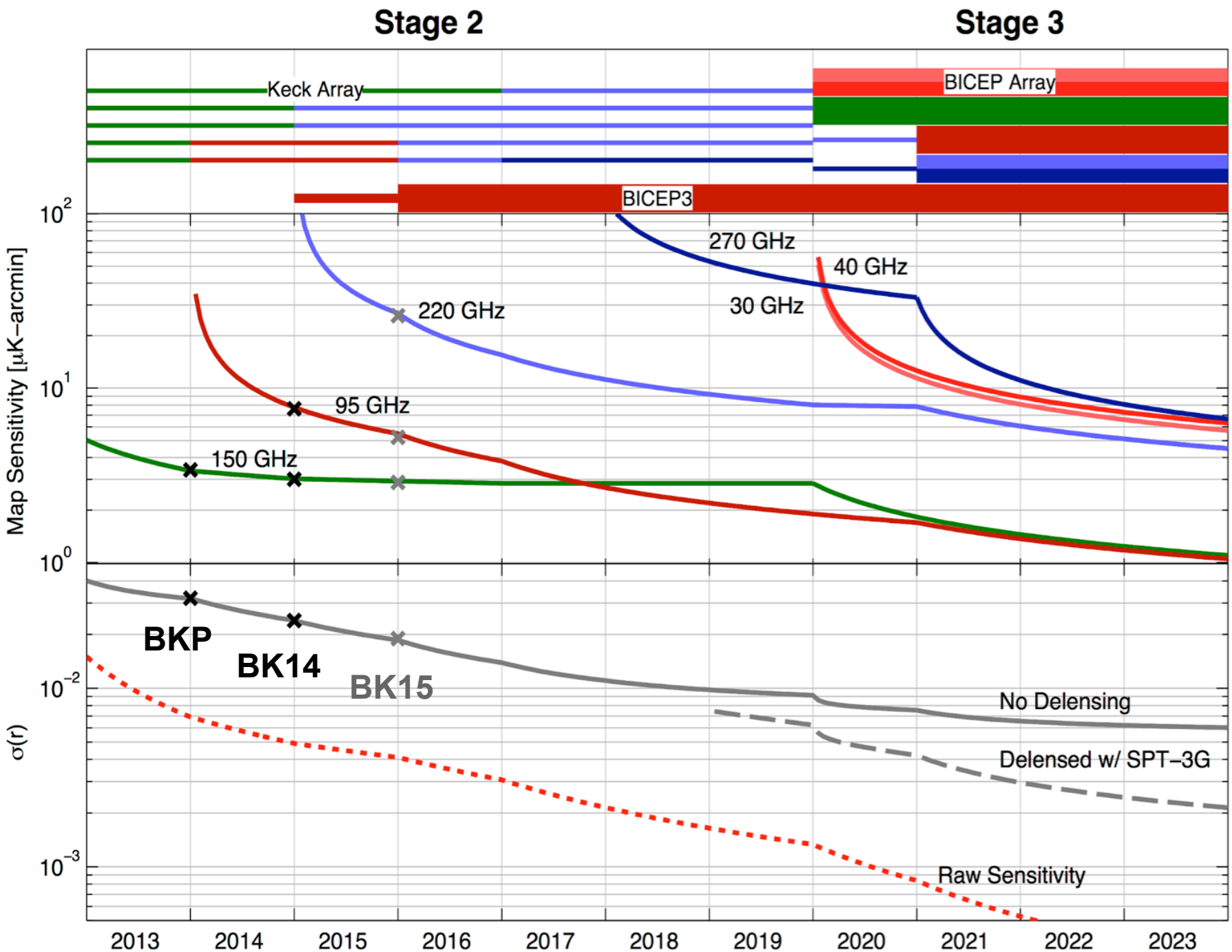




Focal plane layout

Right Now Assembling New Telescope at UMN

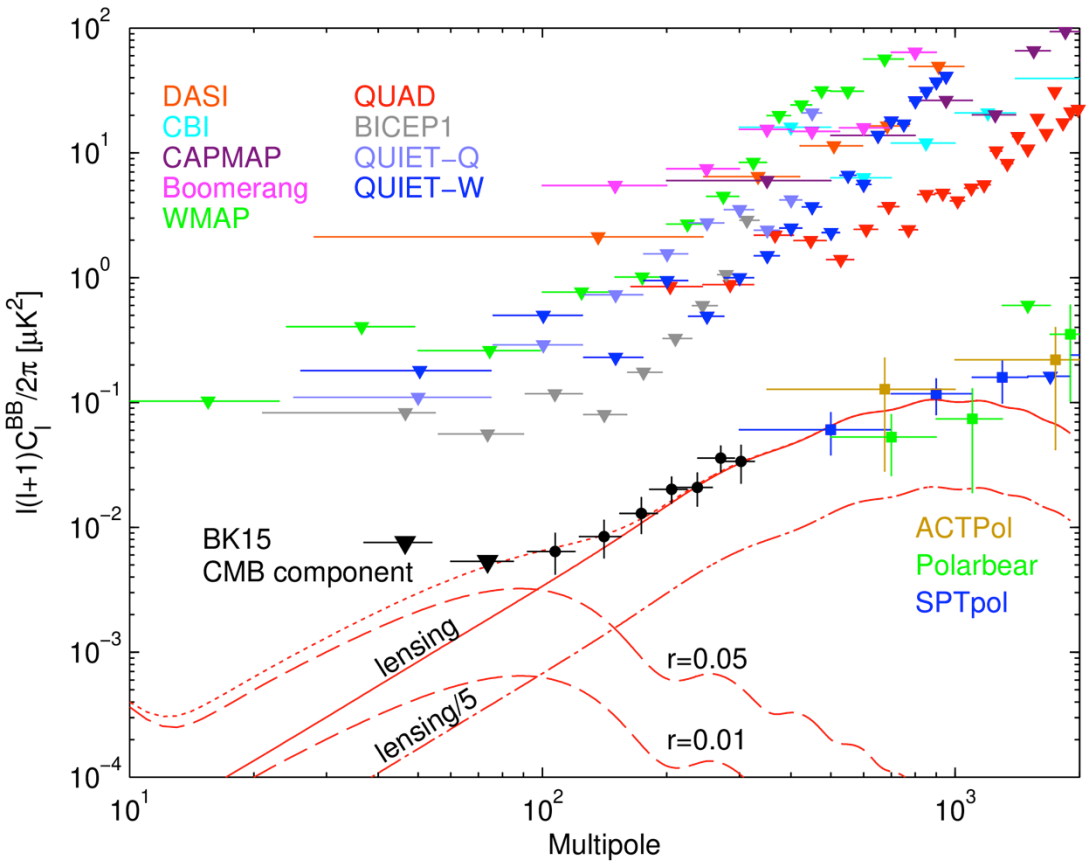
New Telescope Moving

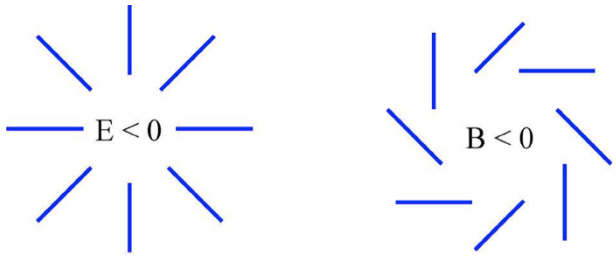

Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
Map Sensitivity [μK−arcmin]
10^2
10^1
10^0
BKP
BK14
BK15
No Delensing
Delensed w/ SPT−3G
Raw Sensitivity
σ(r)
10^{-2}
10^{-3}
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023

BICEP/Keck Constraints on Inflation to Date

r = tensor to scalar ratio, i.e. amplitude of inflationary gravitational-wave background

State of B-mode polarization power spectra in 2018





Published B-Mode Sensitivity to r			
Experiment	**Year**	**Bands [GHz]**	**σ(r)**
DASI	2004	26…36	7.5
BICEP1 2yr	2009	100, 150	0.28
WMAP 7yr	2010	30…60	1.1
QUIET-Q	2010	43	0.97
QUIET-W	2012	95	0.85
BICEP1 3yr	2013	100, 150	0.25
BICEP2	2014	150	0.10
BK + Planck	2015	150 + Planck	0.034
BK14	2015	95, 150 + P	0.024
ABS	2018	150	0.7
Planck	2018	30...353	~0.2
BK15	2018	95,150,220 + P	0.020
BK18	2020?	95,150,220 + P	0.010 (est)

Conclusions

- BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:
- BK15 result sets $r_{0.05}<0.07$ and $\sigma(r)=0.020$

- BICEP3 is running since 2016 with high sensitivity at 95GHz, and Keck Array continues to run at 220GHz, plus new 270GHz band
- We intend to go straight to BK18 analysis which will approach $\sigma(r)=0.010$

- BICEP Array is under construction and will go much further
- Next gen. receivers in five bands
- Delensing in conjunction with SPT3G is under development
- Project BK23 $\sigma(r)<0.003$

- And beyond that is mega experiment CMB-S4…

- Foreground complexity is and will remain a serious issue – the hope is that we can measure it *and* constrain *r* simultaneously without a large loss of sensitivity.