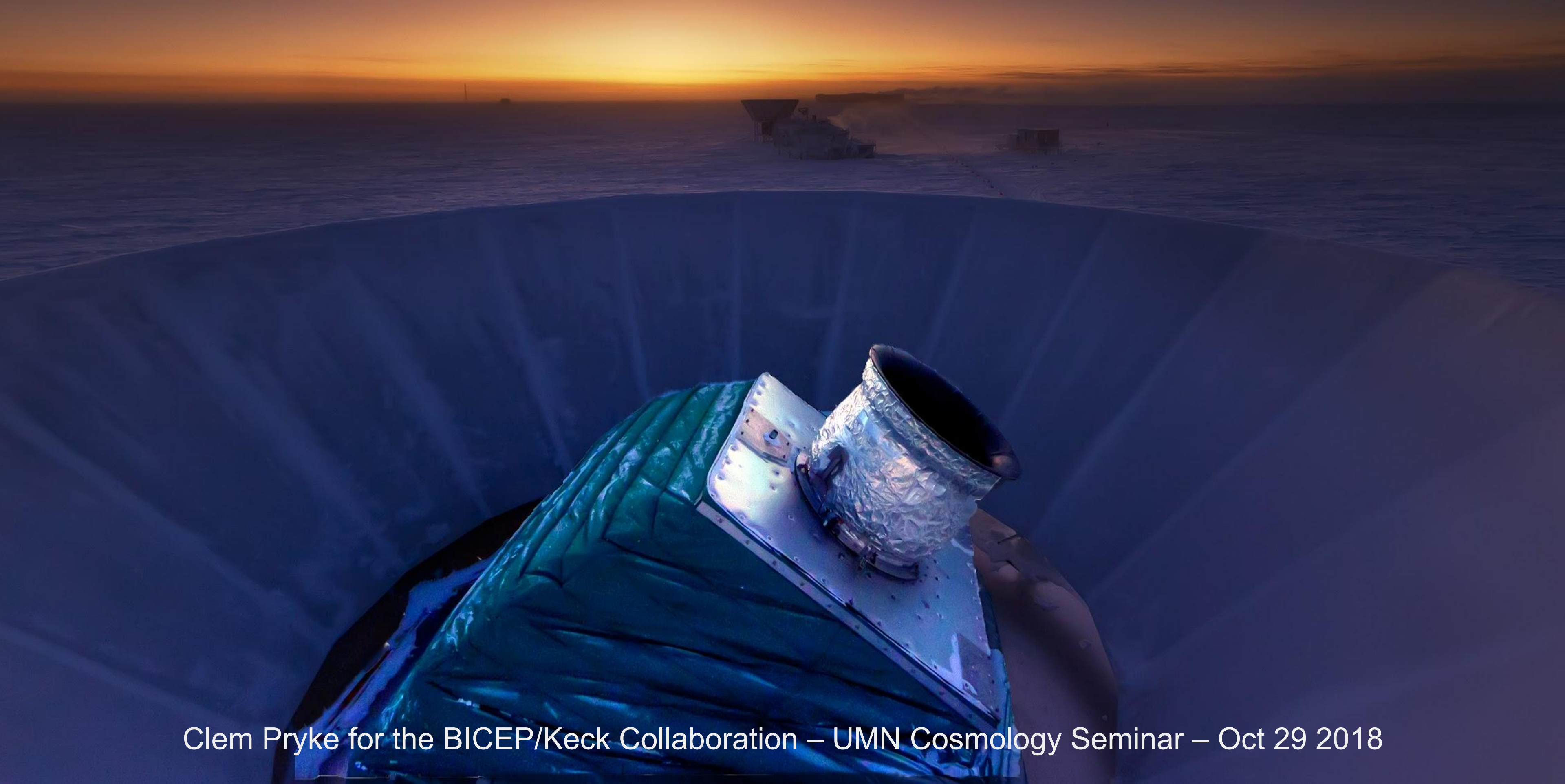
Searching for Primordial Gravitational Waves with the BICEP/Keck Telescopes



Clem Pryke for the BICEP/Keck Collaboration – UMN Cosmology Seminar – Oct 29 2018

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+)

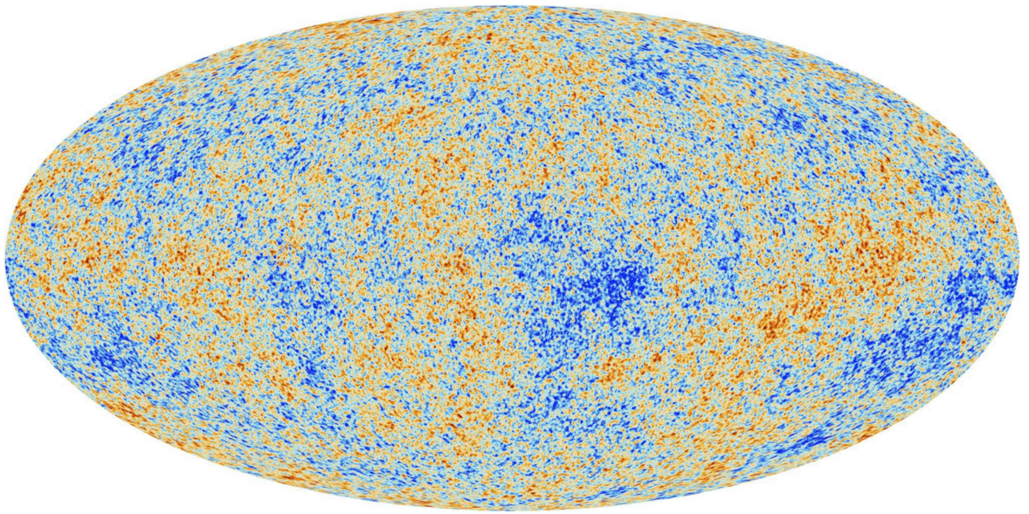
✓ Gaussian random fields

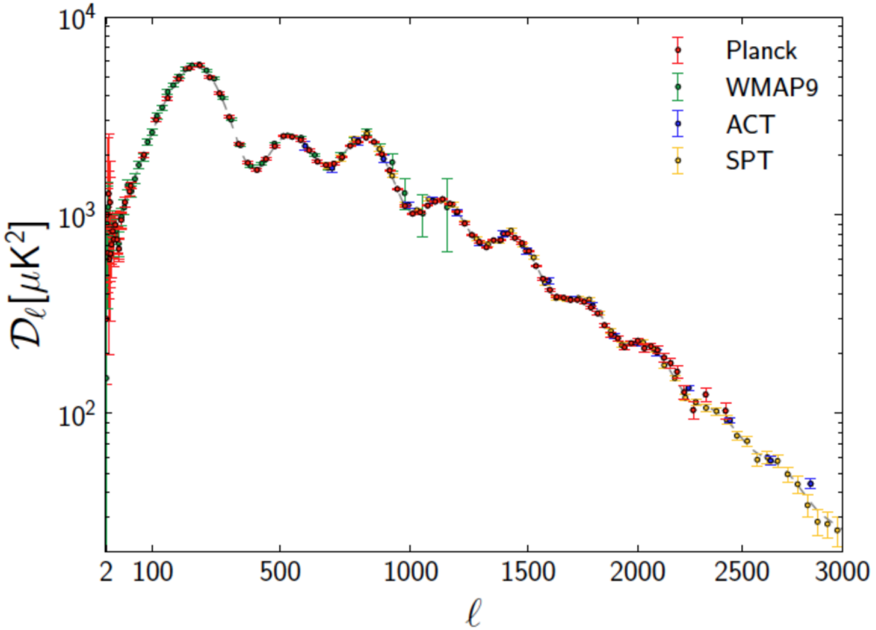
(f_{NL}^{local} = 0.8 ± 5.0,
f_{NL}^{equil} = −4 ± 43,
f_{NL}^{ortho} = −26 ± 21)*

✓ Departure from scale invariance!

(n_s = 0.968 ± 0.006)

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

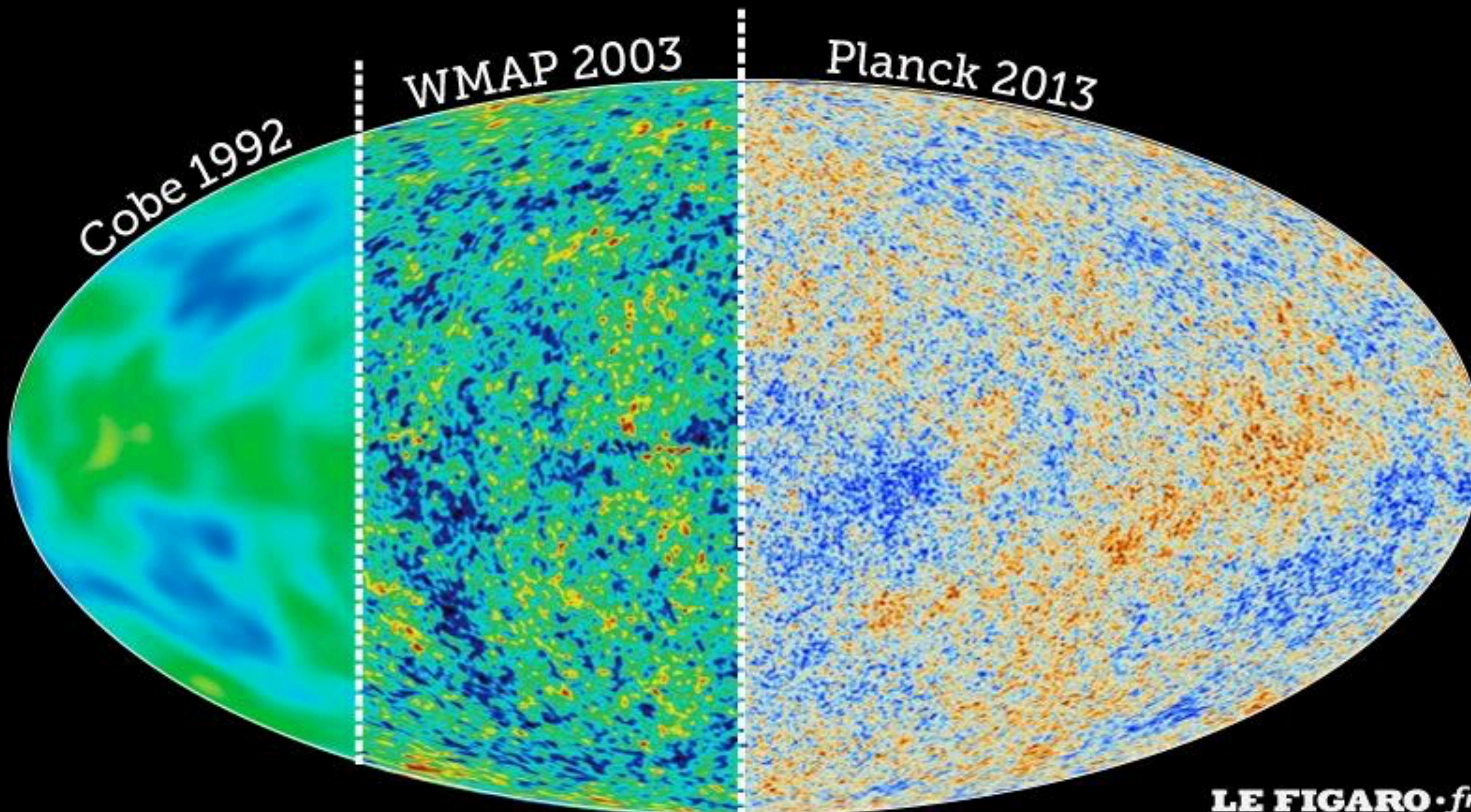




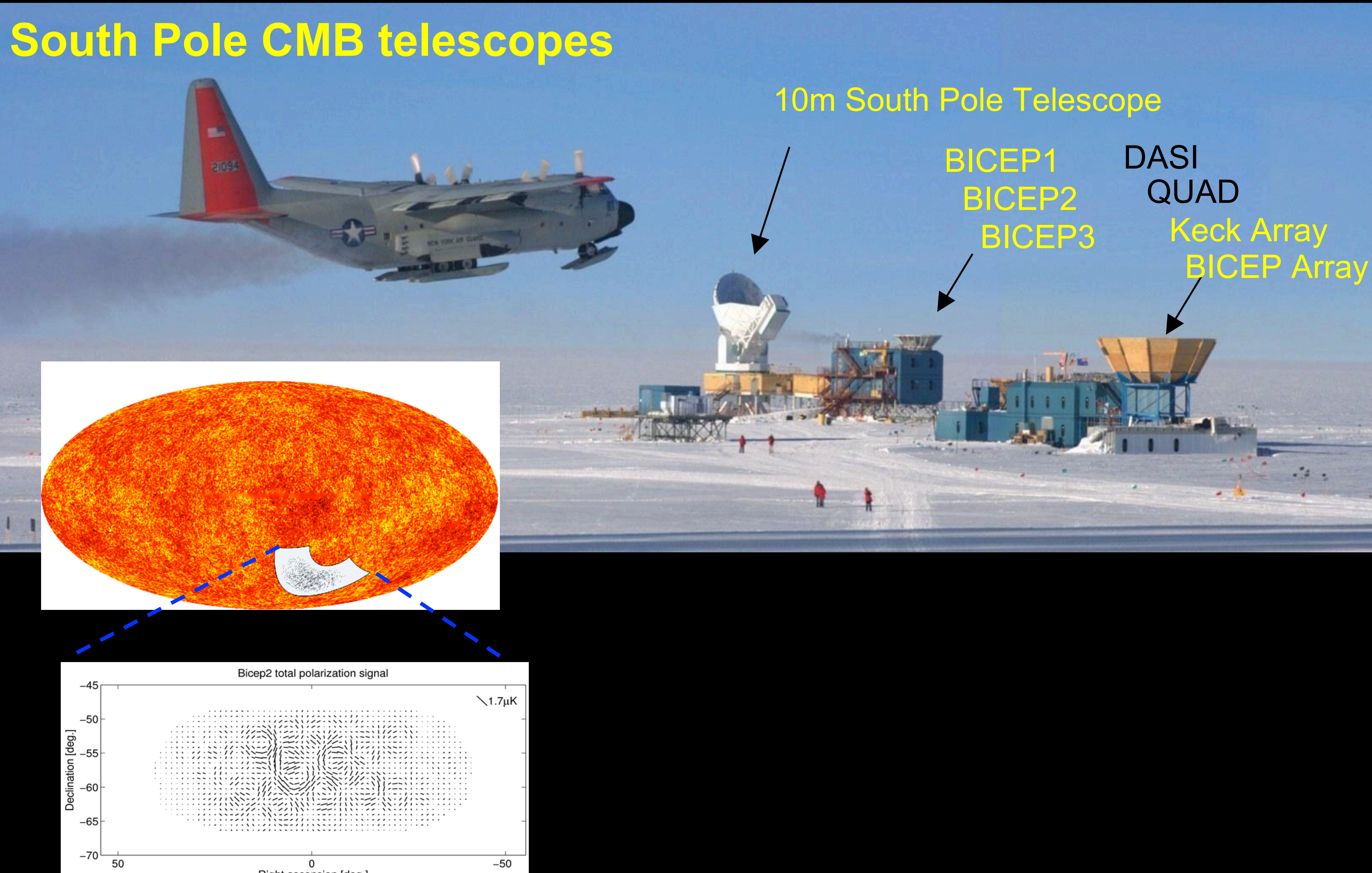
Planck Collaboration & ESA

The BICEP/Keck Collaboration

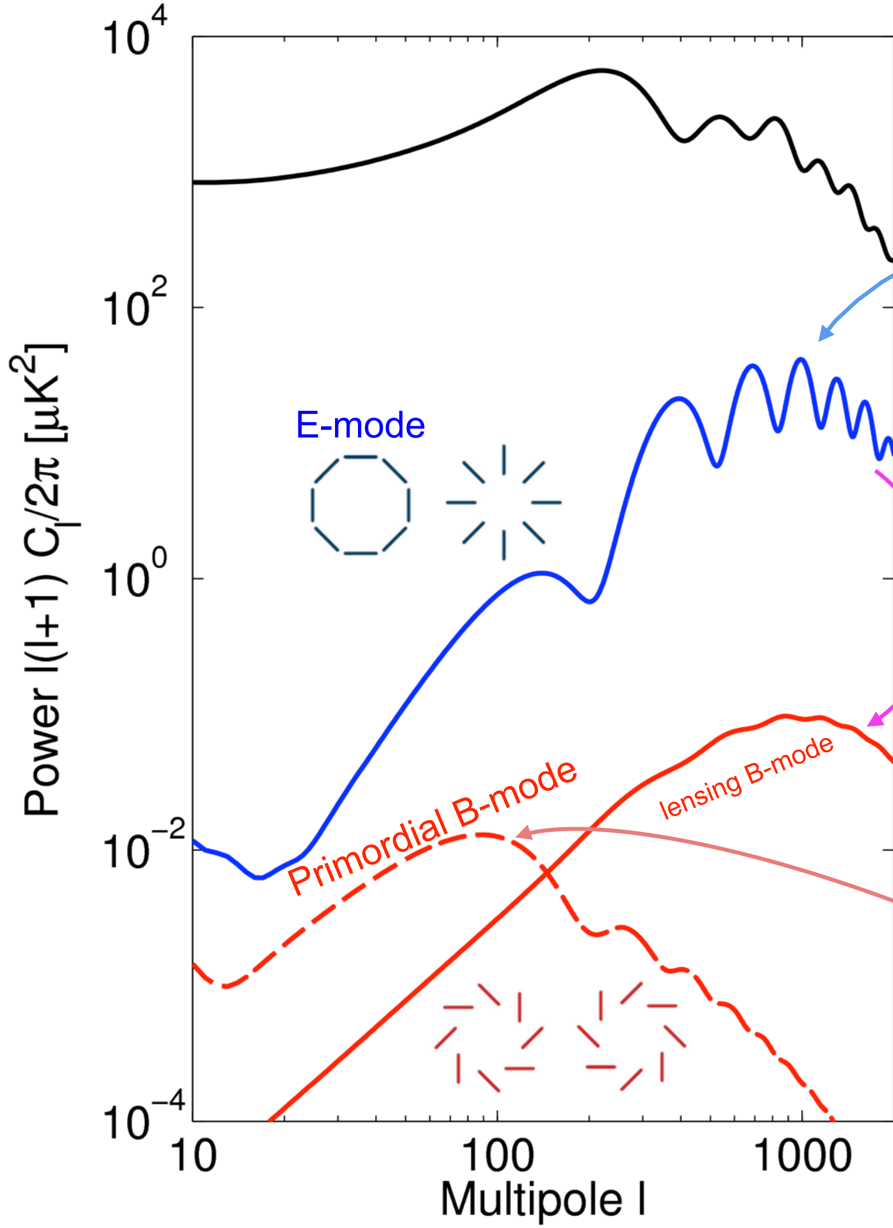
Satellites map the full sky



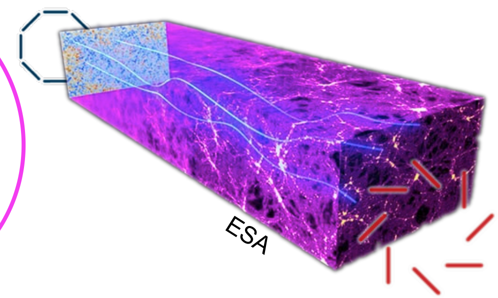
Ground based telescopes map part of the sky more deeply



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

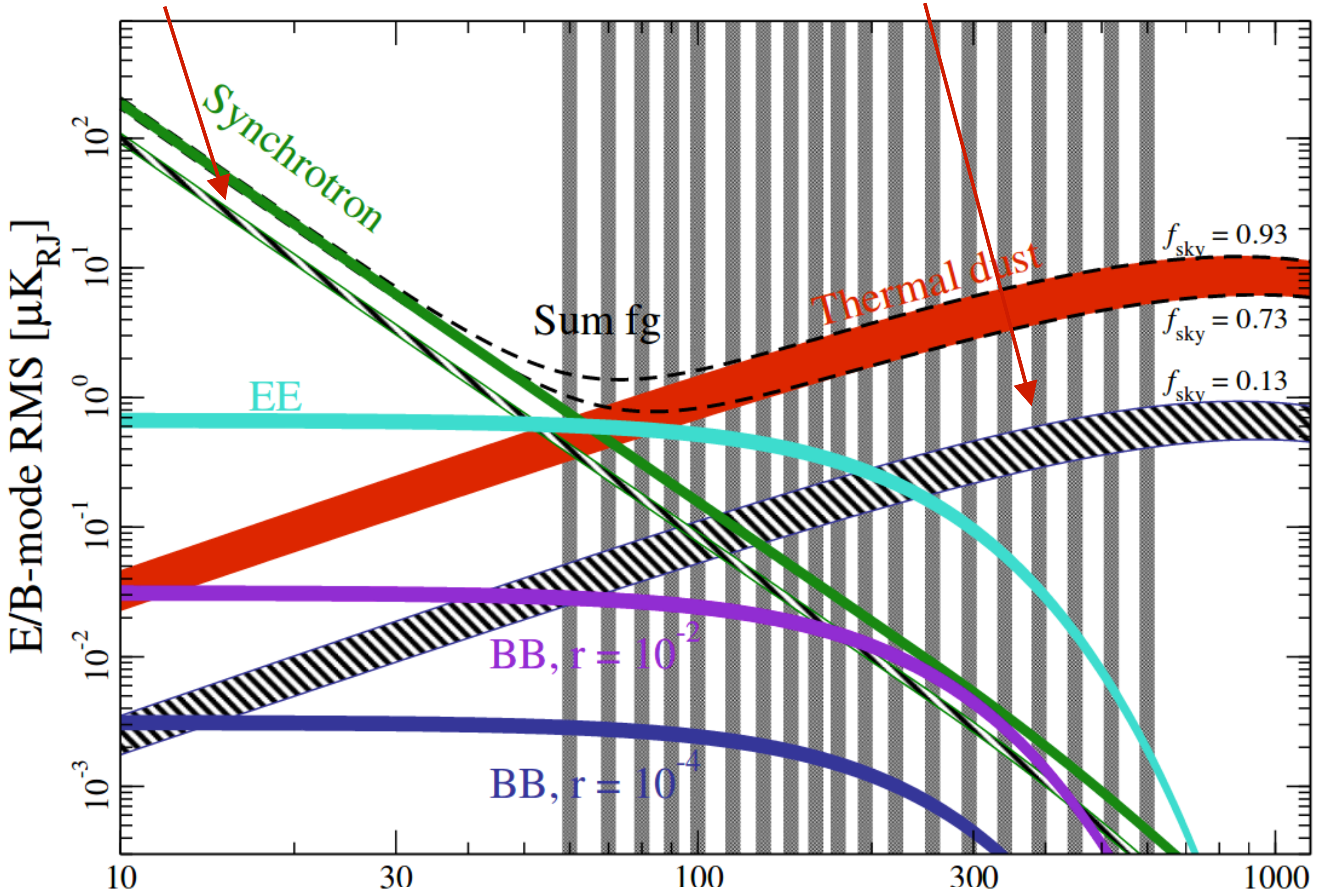
Inflationary gravitational waves are unique source of intrinsic B-modes
→ peaking at l≈80 : degree scales

The BICEP/Keck Collaboration

Polarized Foreground Contamination from Our Galaxy

At low frequency synchrotron contamination

At high frequency dust contamination

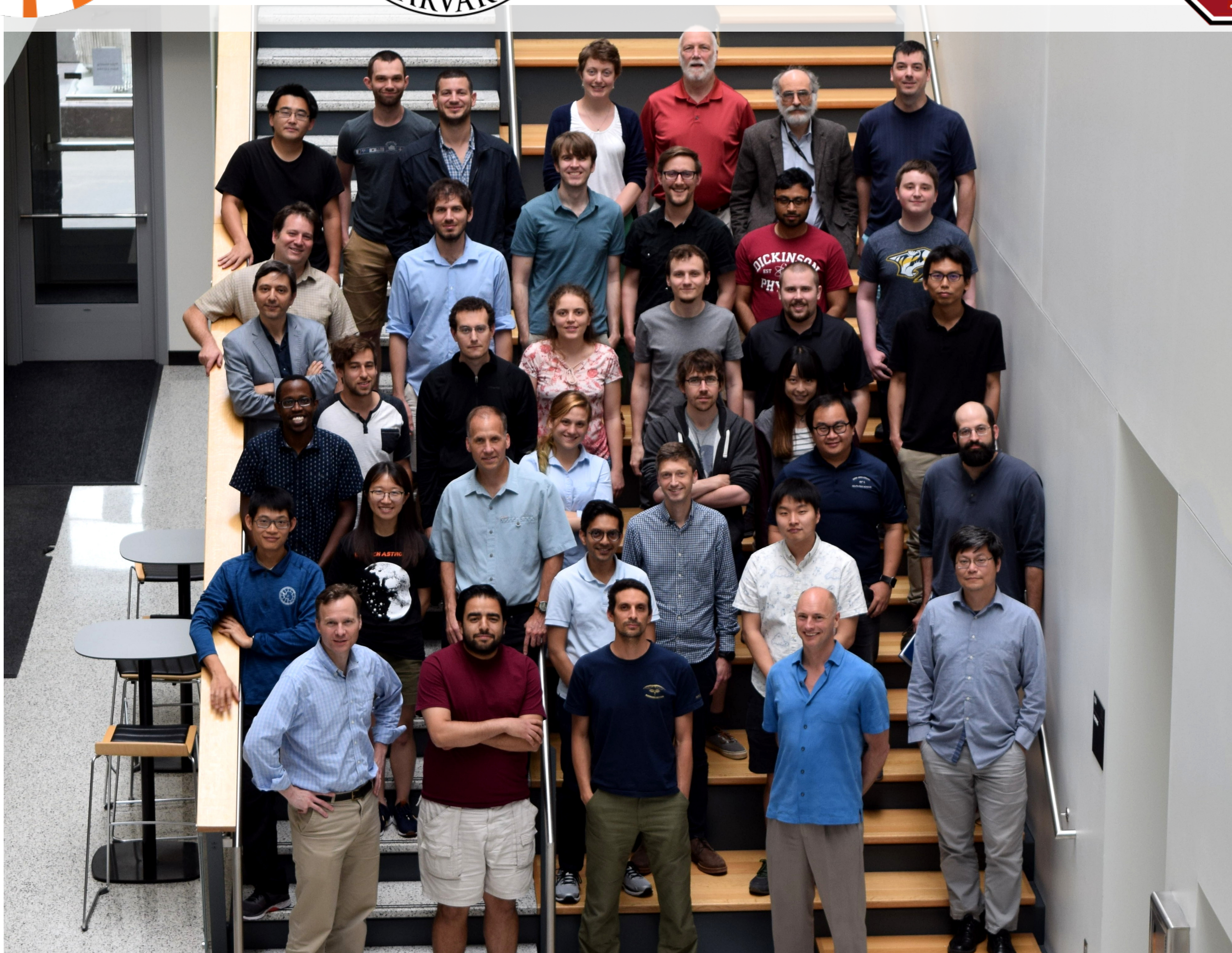


From arxiv/1704.04501

This plot from 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

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

VE RI TAS HARVARD



cea

UCSD

JPL

NIST

CARDIFF UNIVERSITY

UNIVERSITY OF TORONTO

UBC

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
→ Scan and pair difference modulation

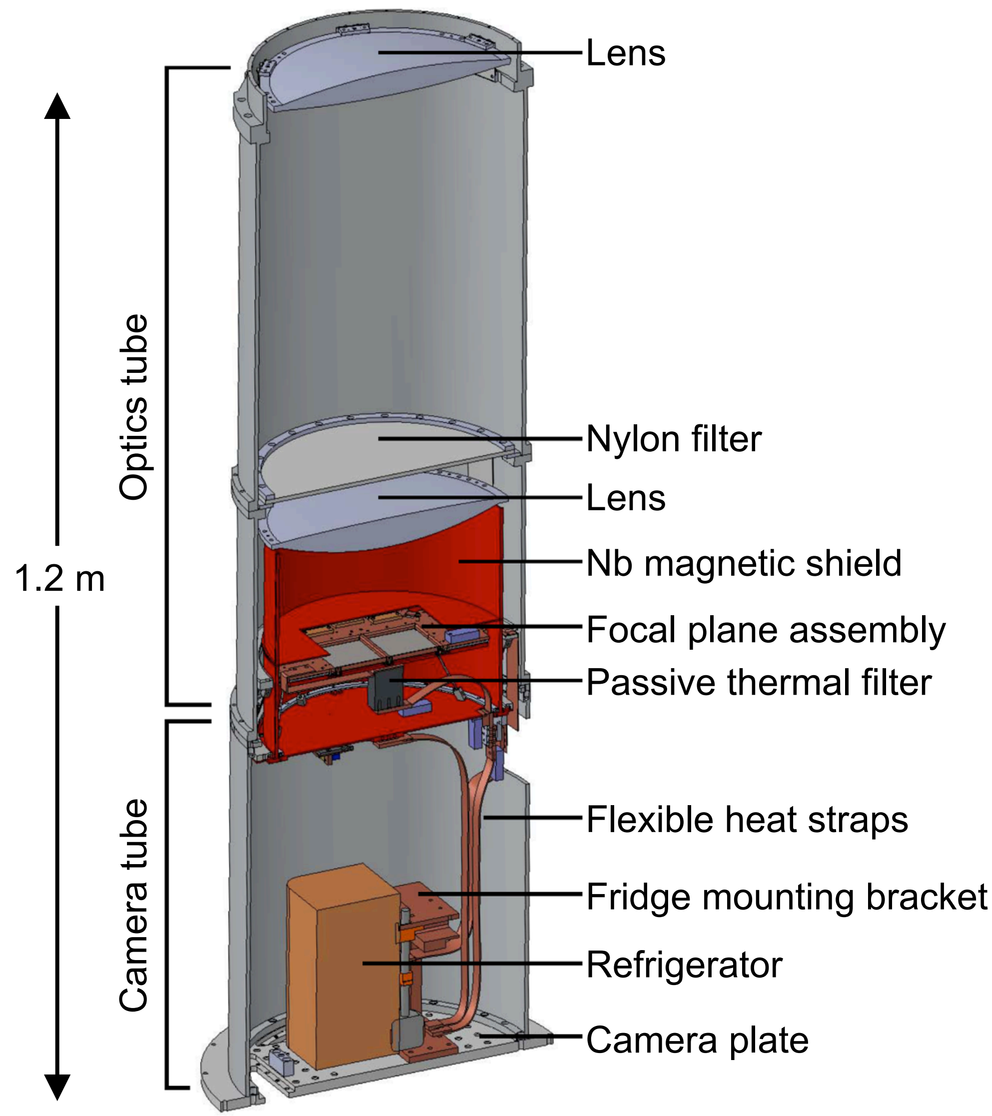
The BICEP2/Keck Telescopes

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

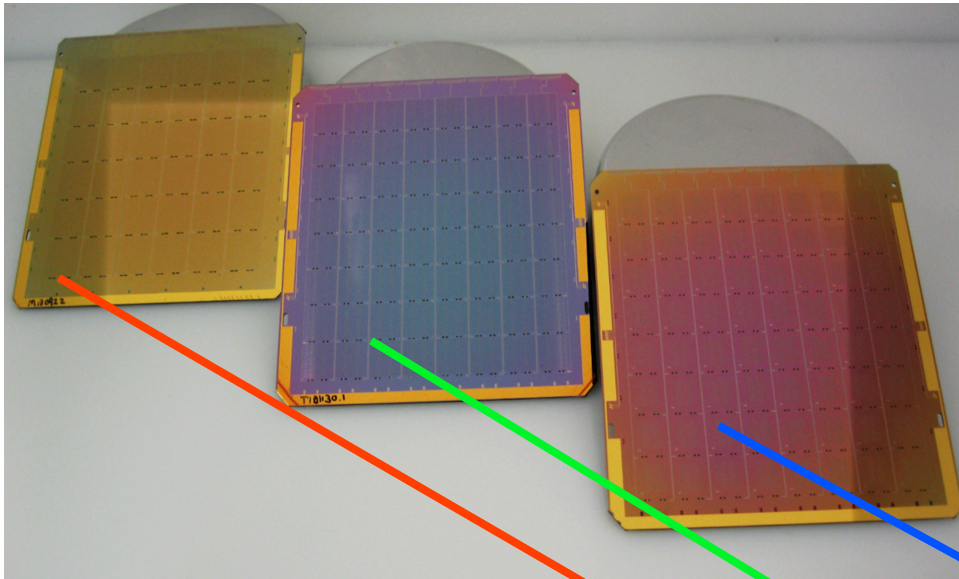
3-stage helium sorption refrigerator further cools the detectors to 0.27 K

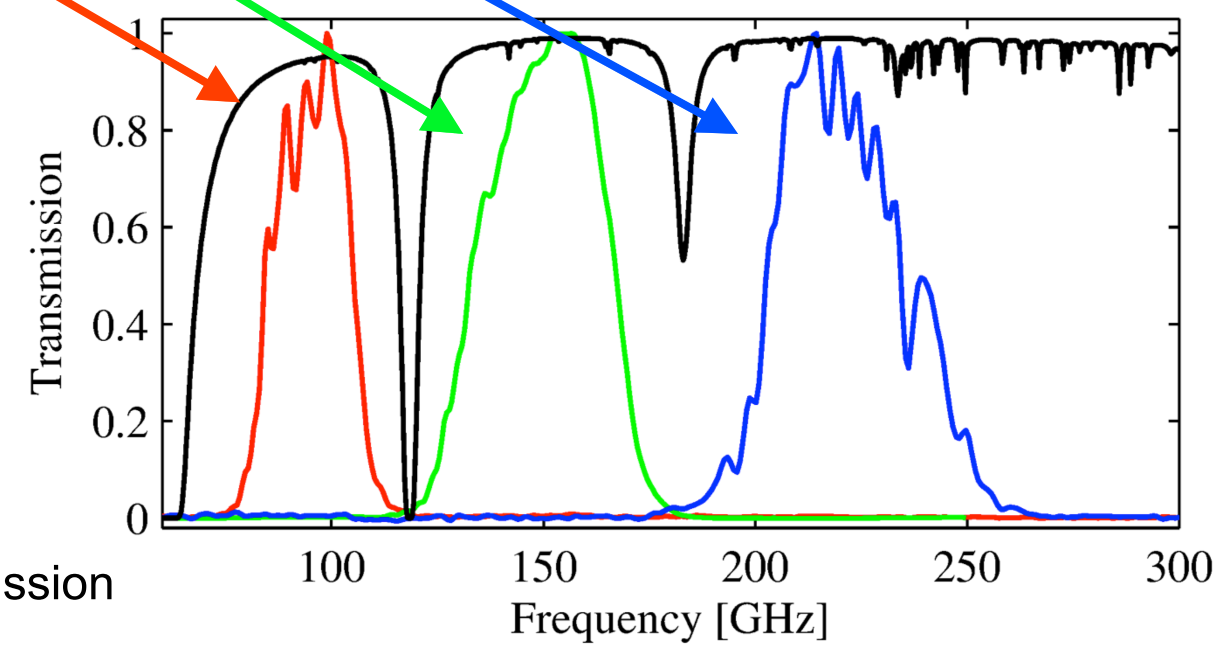


Planar superconducting detector arrays

…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

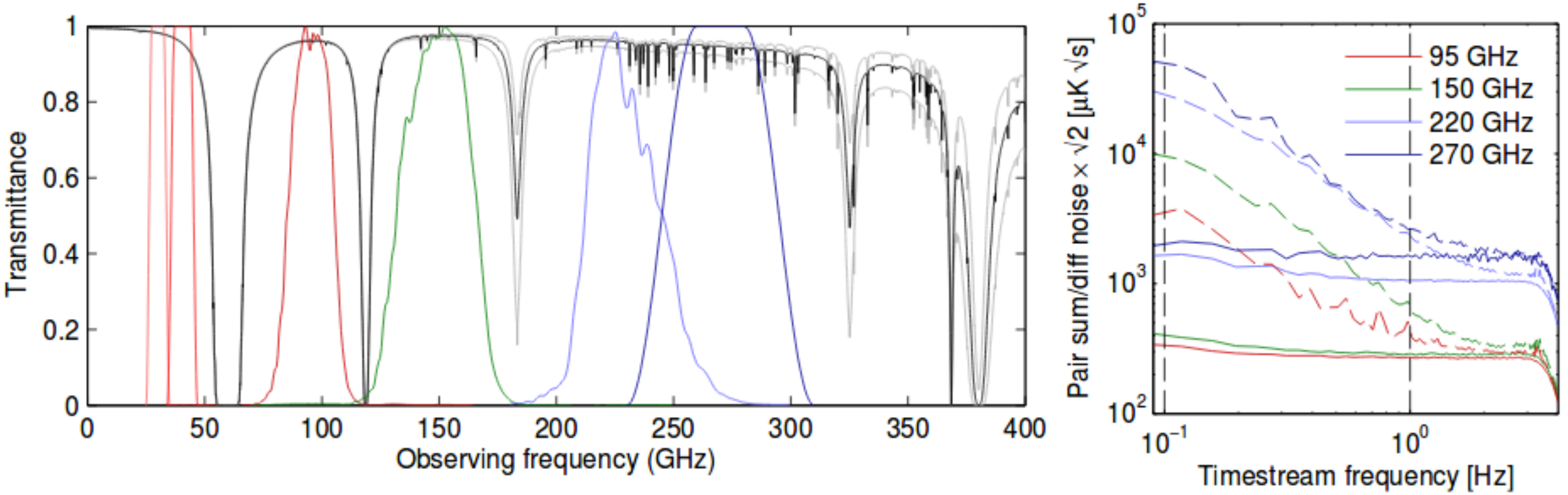




Typical South Pole
atmospheric transmission

Pair Differencing Can Work at Pole

No need for additional polarization modulation



Pair-differenced TES bolometers are stable to 0.1 Hz with no additional modulation

- demonstrated up to 270 GHz
- DC biased, time-domain SQUID readouts

However, using pair differencing means we have to worry a lot about the differential beam

- So we expend a lot of effort to measure it

Adding a modulator is no silver bullet - they often carry a noise penalty and have their own systematics issues

BK15 Results Appeared on arxiv 2 Weeks Ago

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

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(Draft As accepted by PRL)

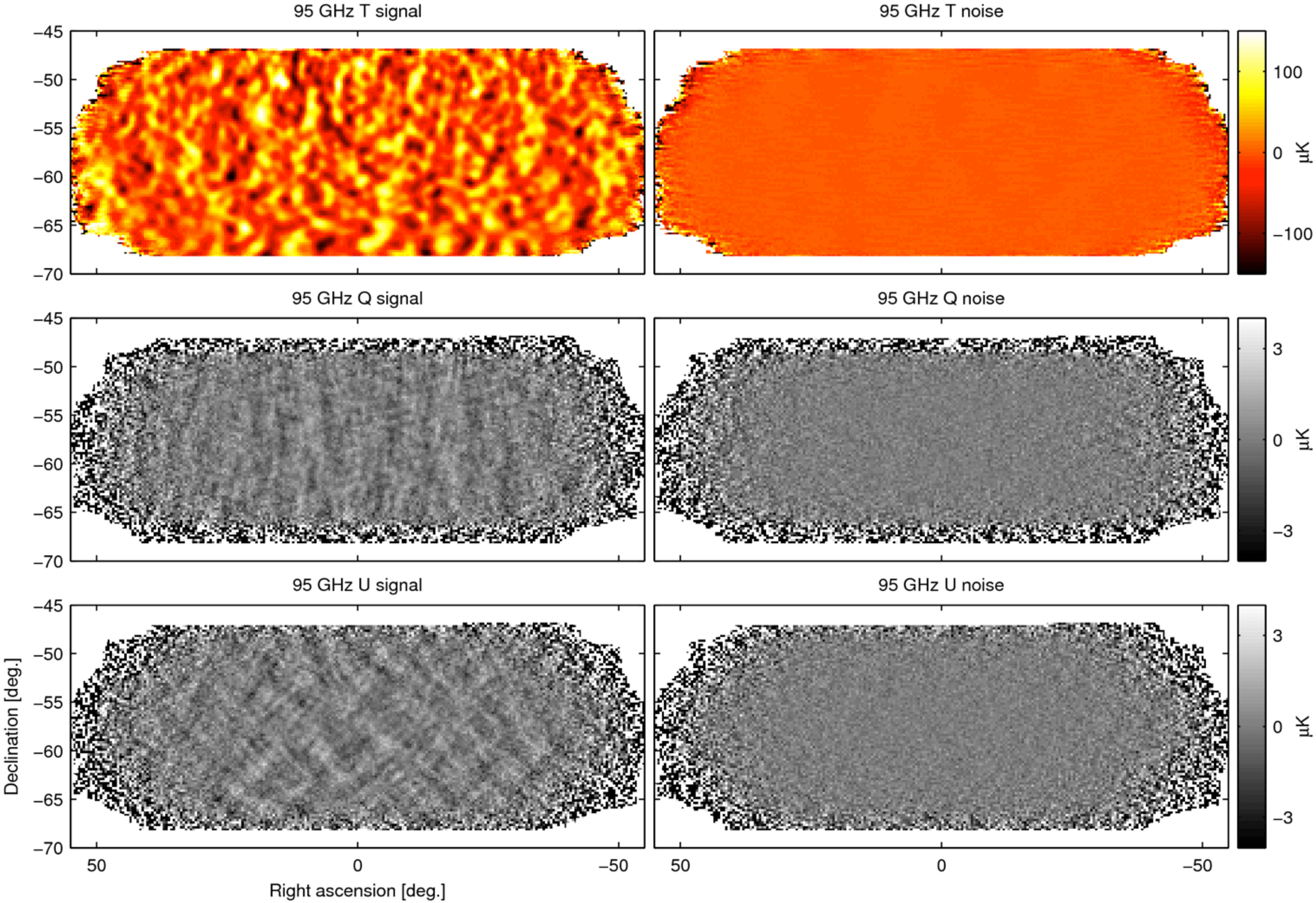
We present results from an analysis of all data taken by the BICEP2/*Keck* CMB polarization experiments up to and including the 2015 observing season. This includes the first *Keck Array* observations at 220 GHz and additional observations at 95 & 150 GHz. The Q/U maps reach depths of 5.2, 2.9 and 26 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 – Accepted by PRL

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

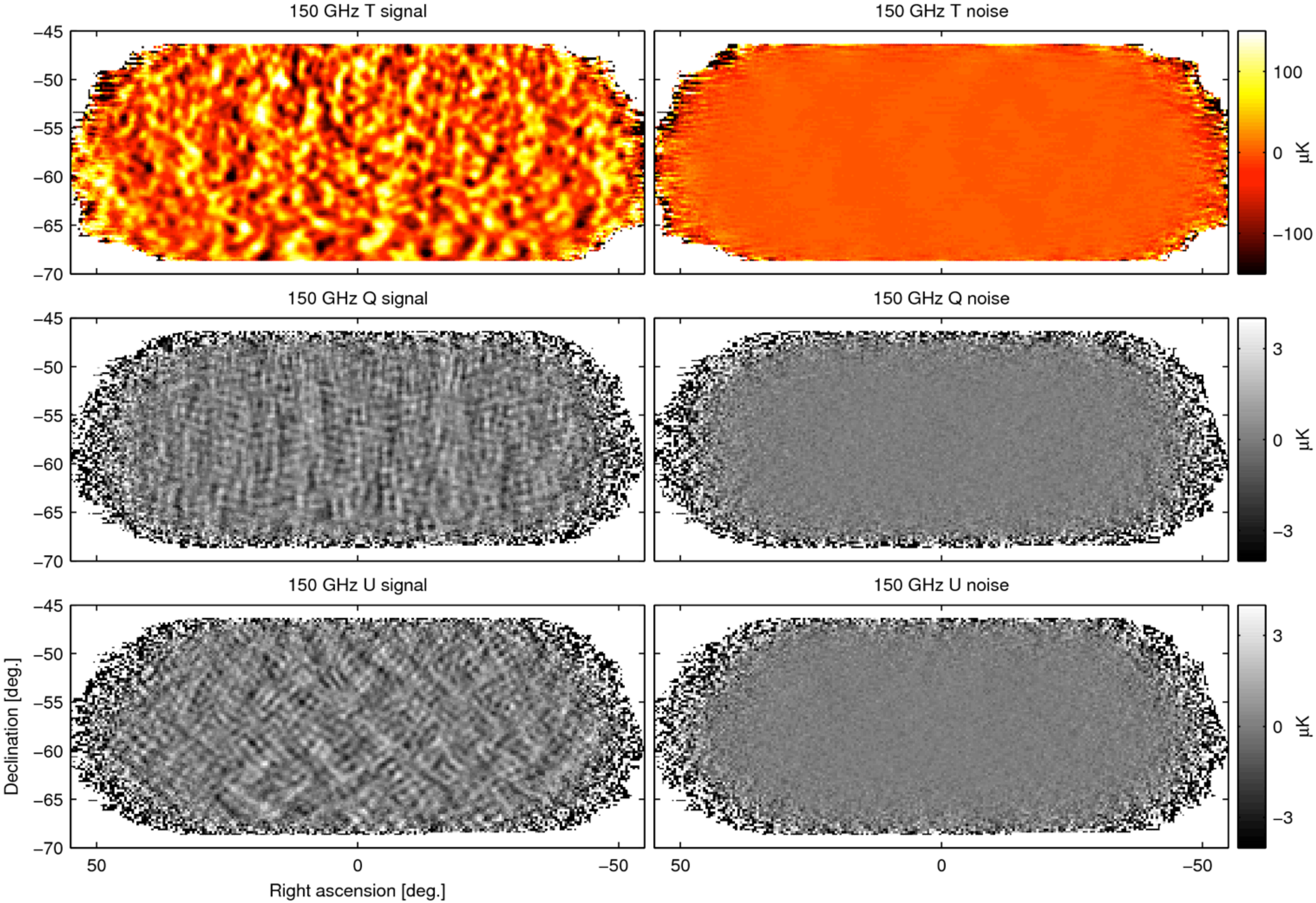
Three years since BK14 – Sorry for the delay! I will try to explain why it took so long…

BK15 95GHz Maps



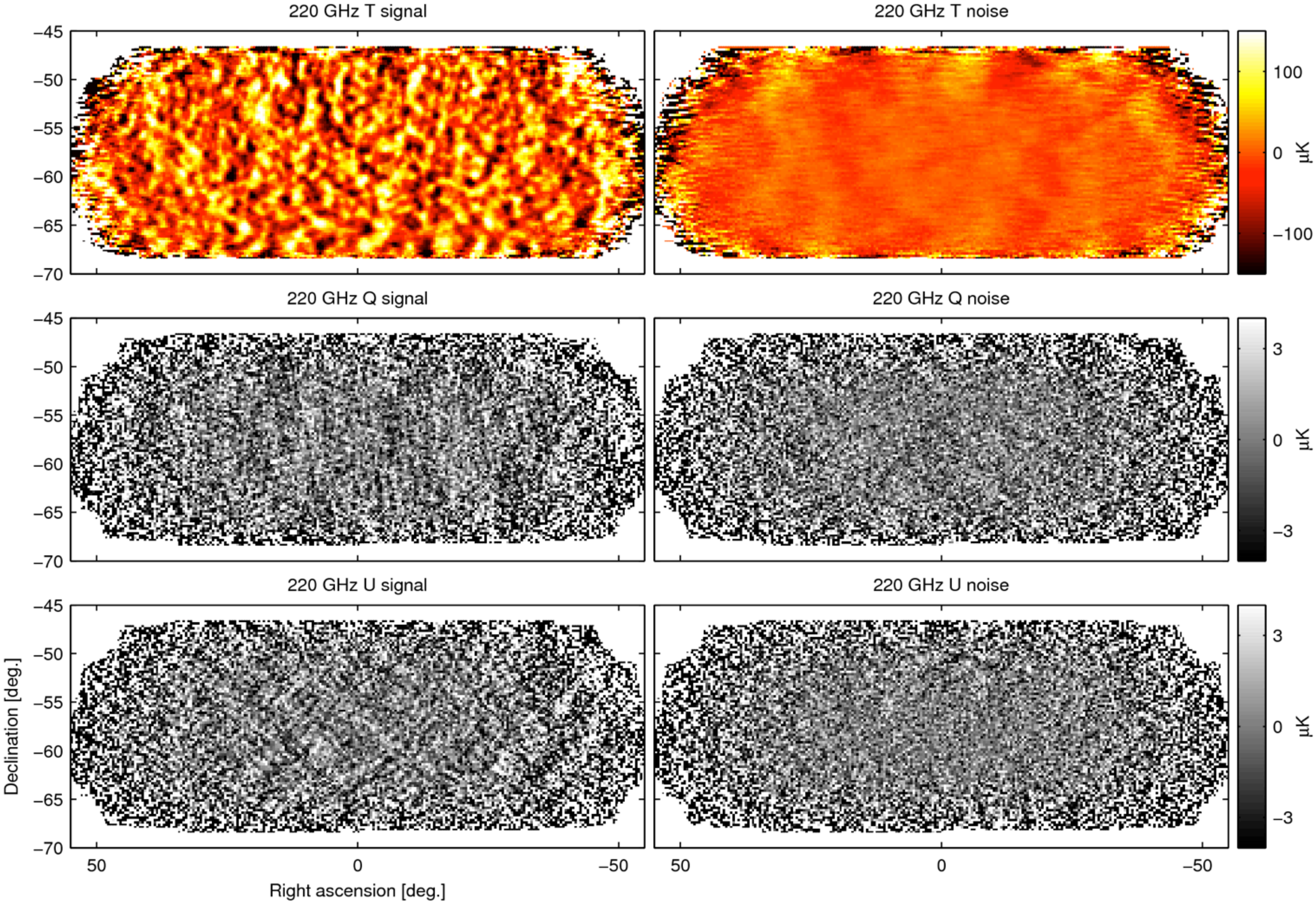
BK15 95GHz – 5 μK arcmin

BK15 150GHz Maps



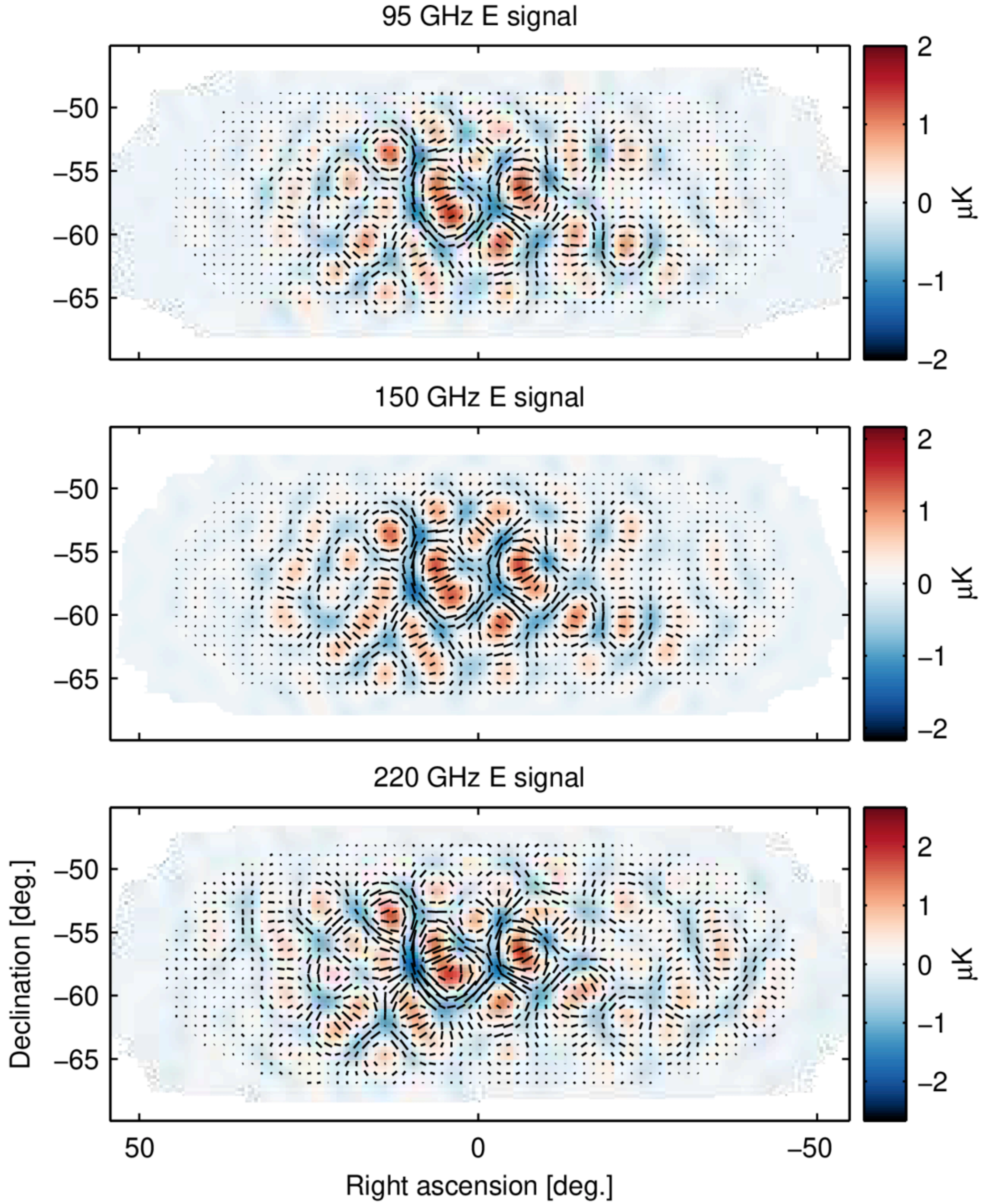
BK15 150GHz – 2.8 μK arcmin

BK15 220GHz Maps



BK15 220GHz – 25 μK arcmin

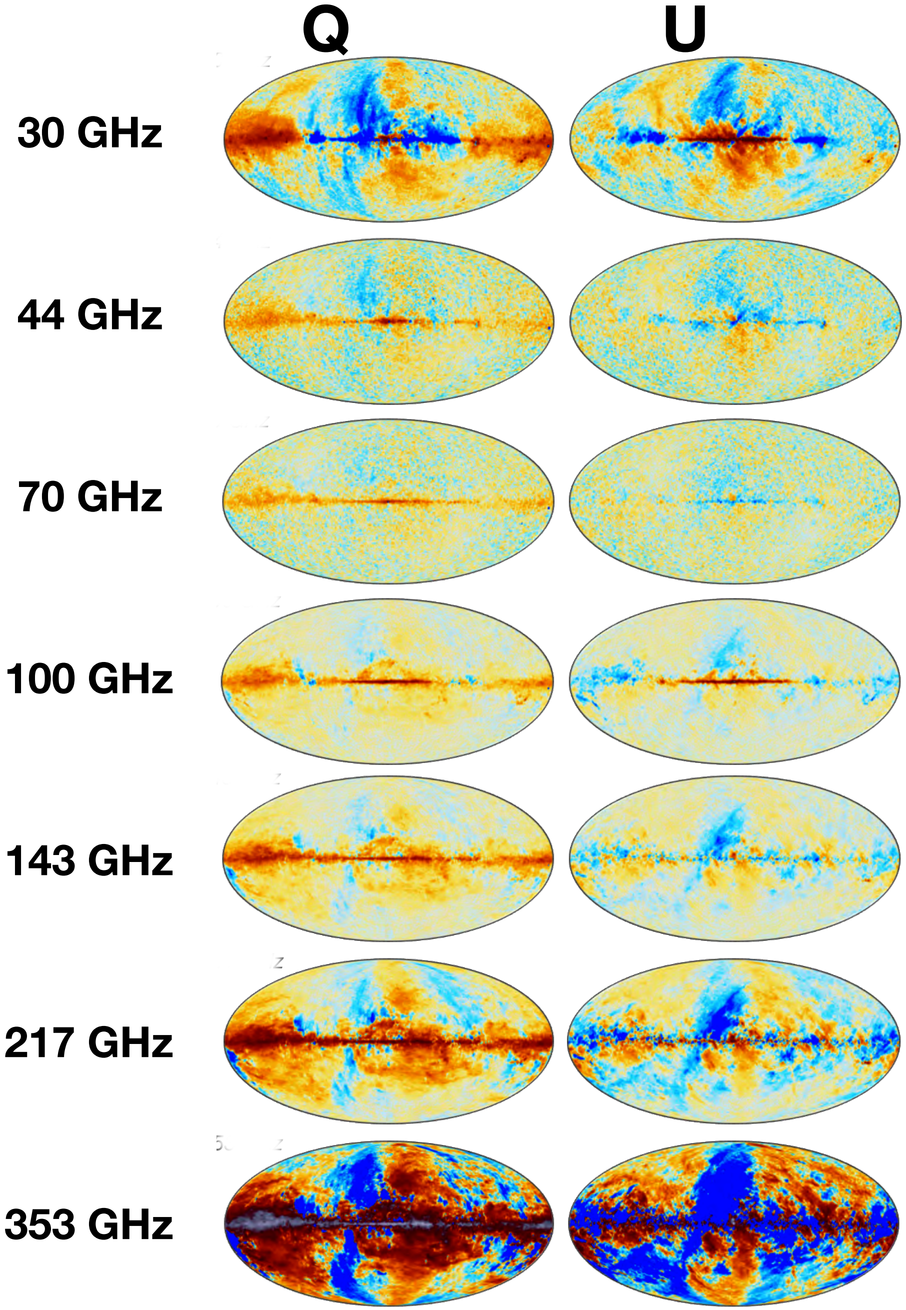
Just for fun: Keck 2015 single season E-mode maps



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

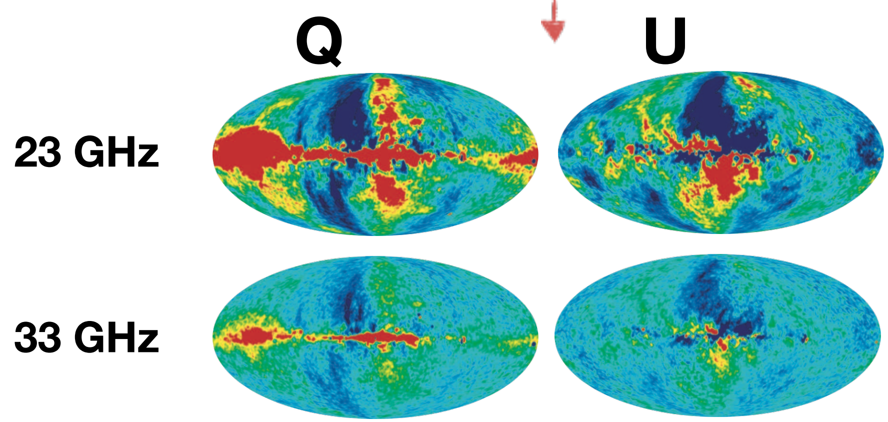
Already deeper than Planck 217 GHz

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



From arxiv 1502.01582

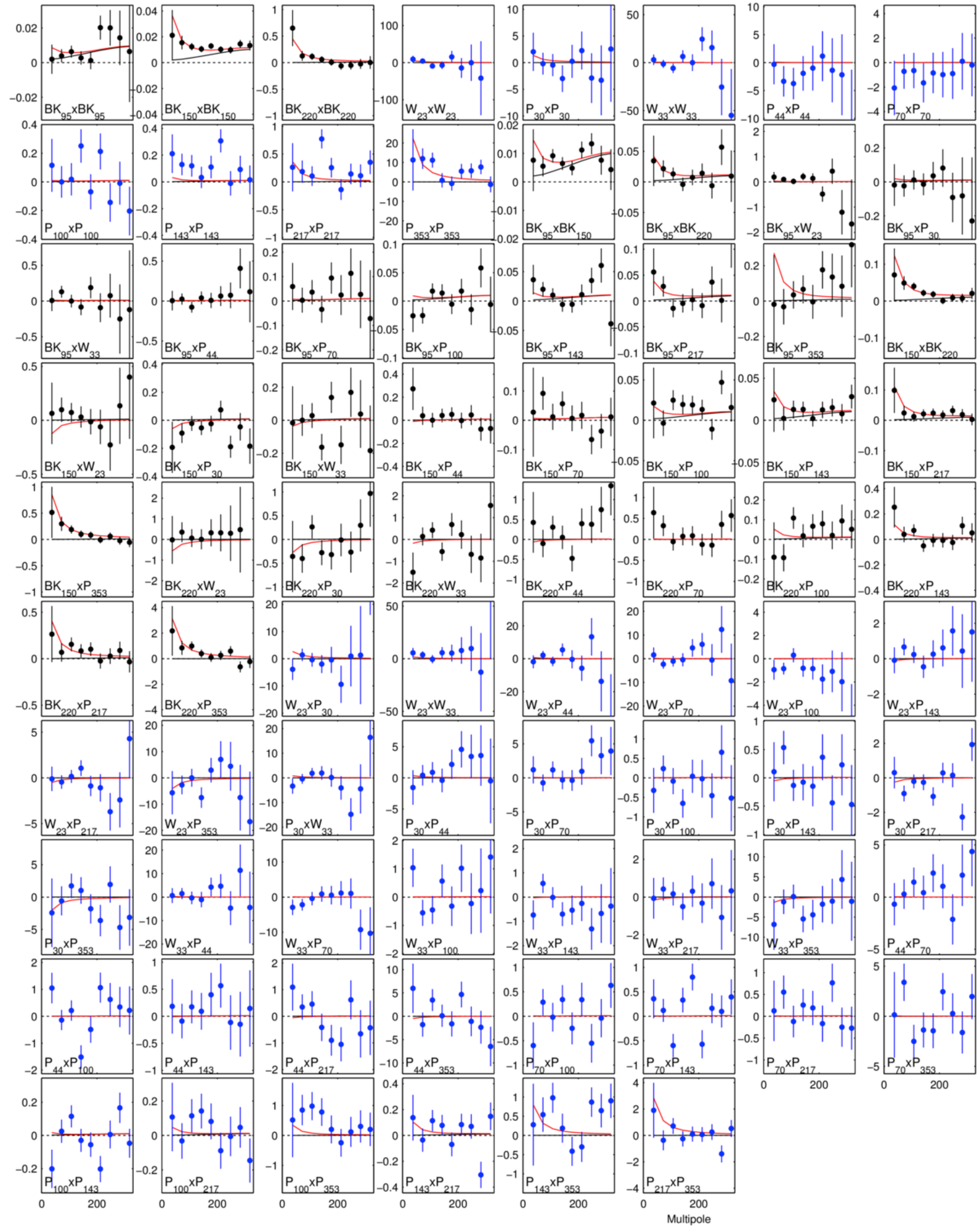
Polarized galactic **synchrotron** dominates at low frequencies



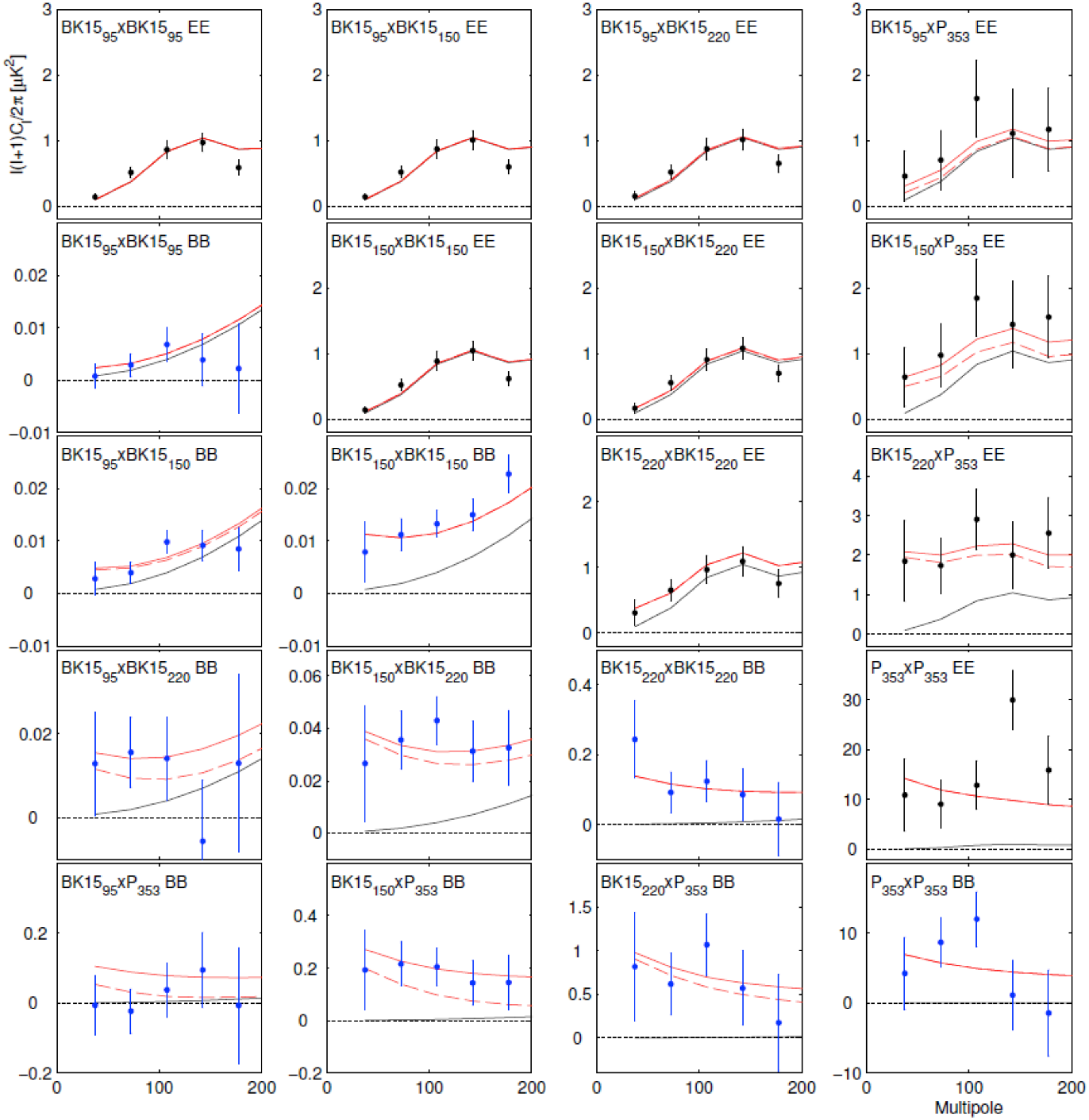
From arxiv 1212.5225

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)



BK15+P353 Spectra



Upper/right plots are EE (black points)

Lower/left plots are BB (blue points)

220GHz auto/ cross spectra are all new

Red solid line is best fit multicomponent model from previous (BK14) analysis - It fits all the spectra

Chi-squared is OK – no evidence yet for non-Gaussianity of the dust pattern

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

Dust/Sync Spatial Power Laws?

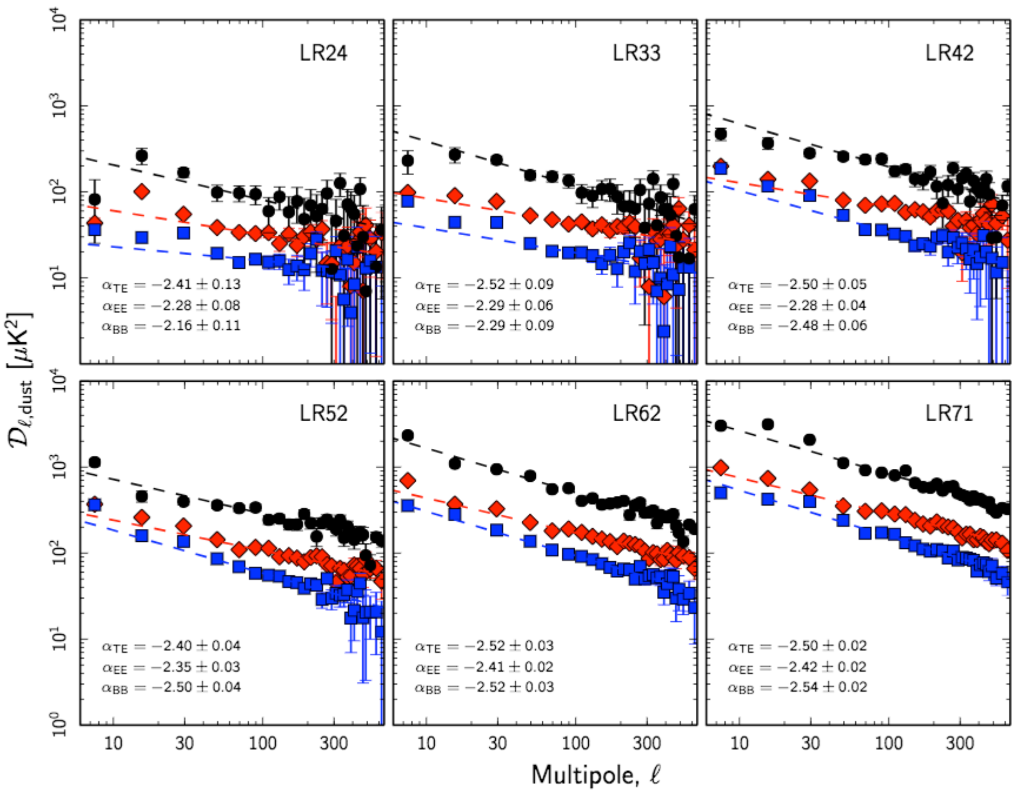


Fig 2 of arxiv/1801.04945 – Planck dust analysis

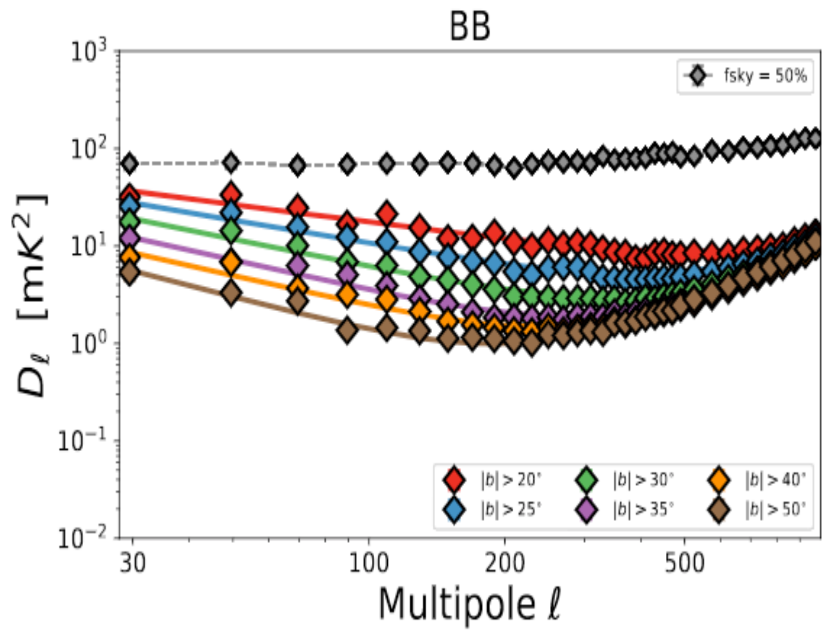
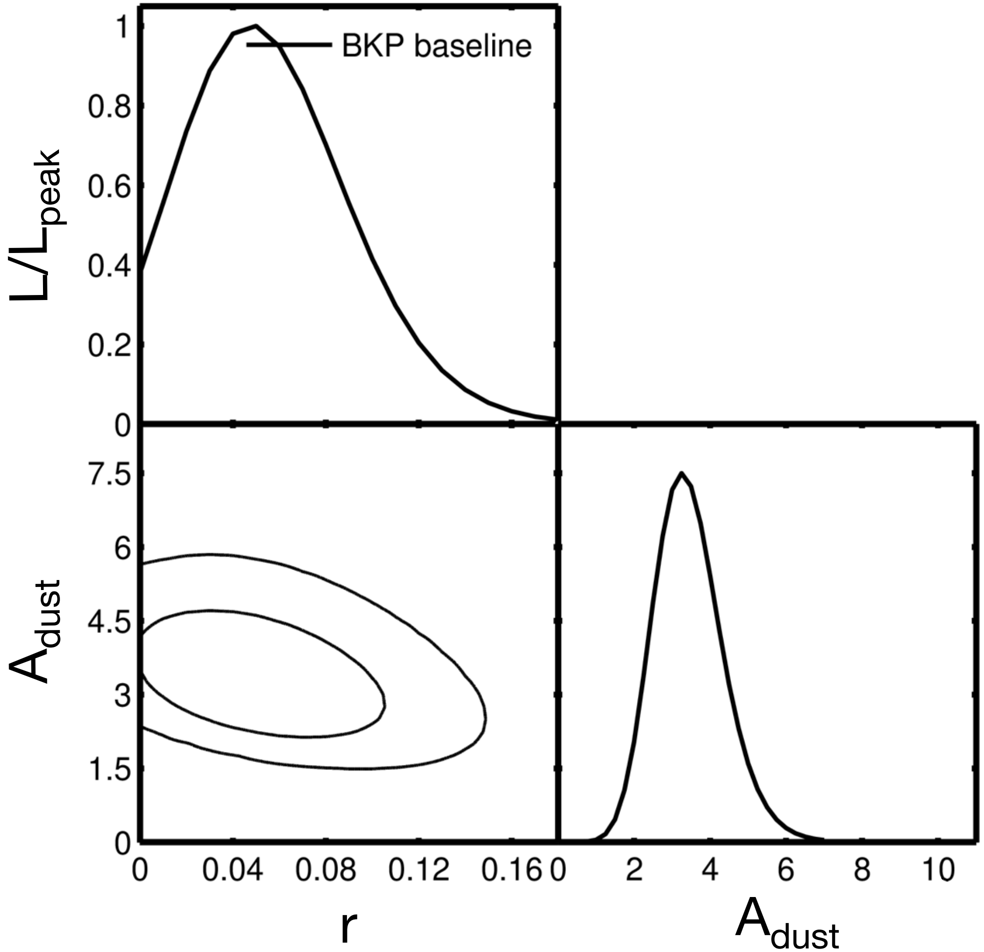


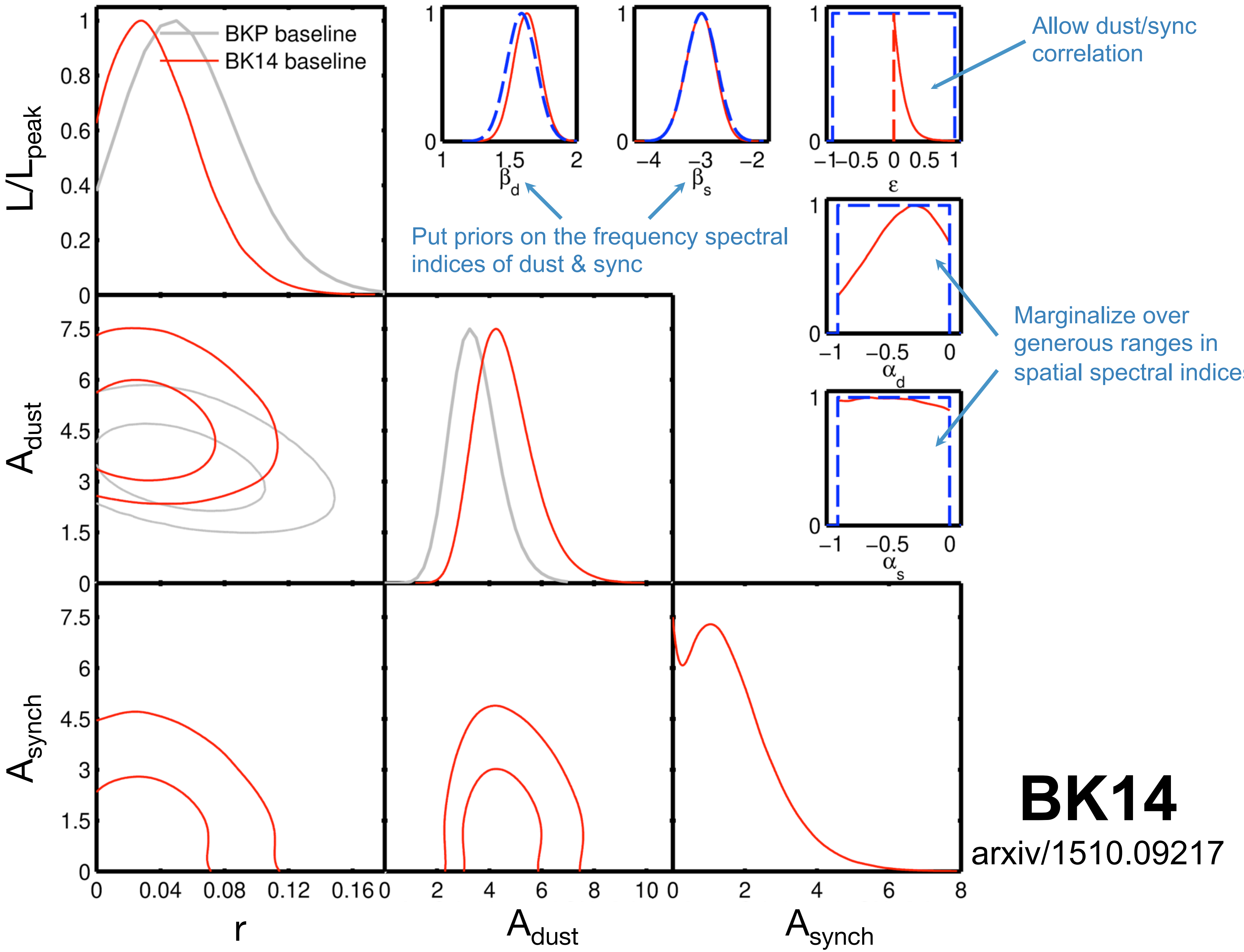
Fig 2 of arxiv/1802.01145. – S-PASS sync analysis

- Averaged over large regions of sky it is an empirical fact that dust and sync have roughly power law angular power spectra
- Not enough signal-to-noise in Planck data to investigate fluctuations about this behavior for small sky patches

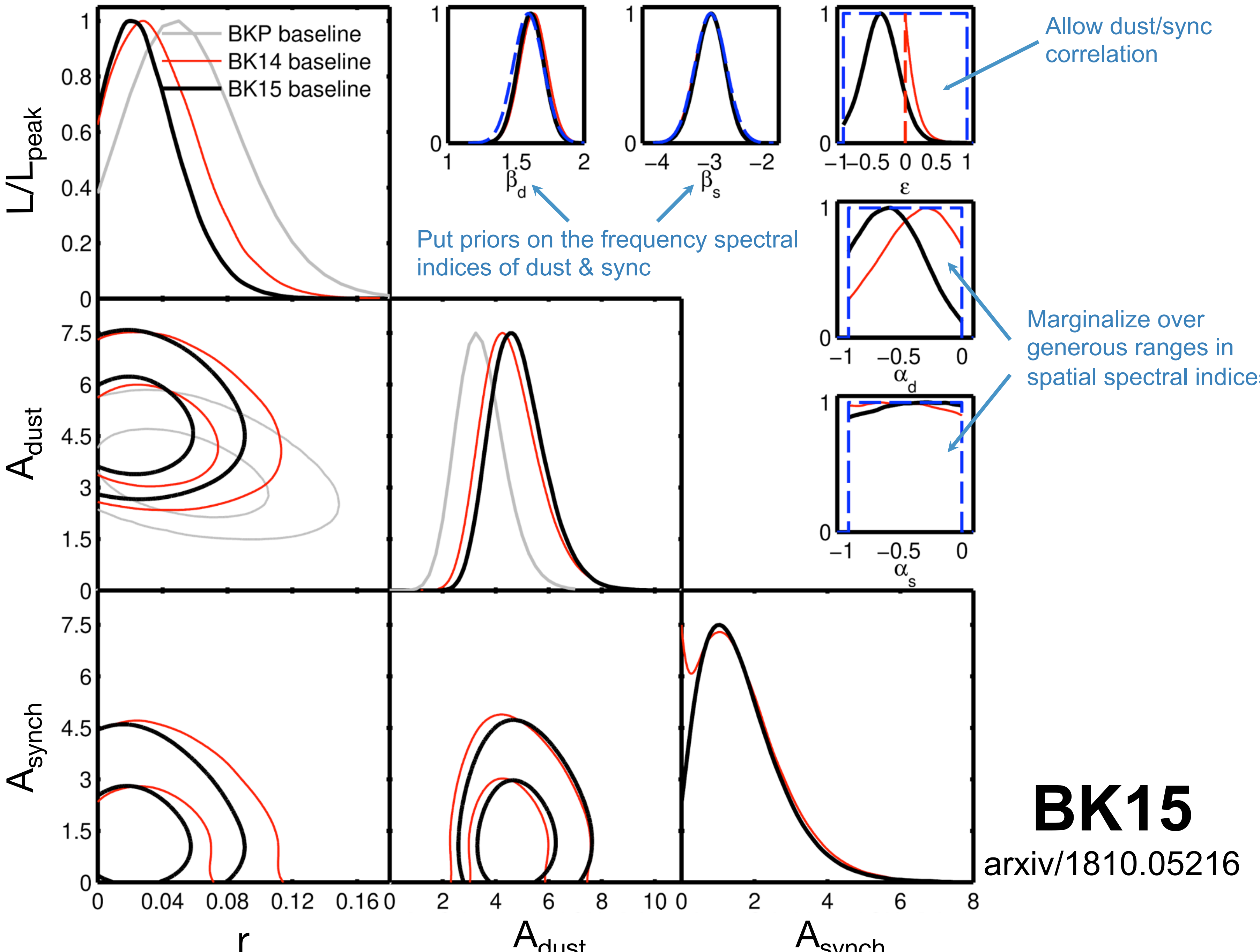


BKP

arxiv/1502.00612

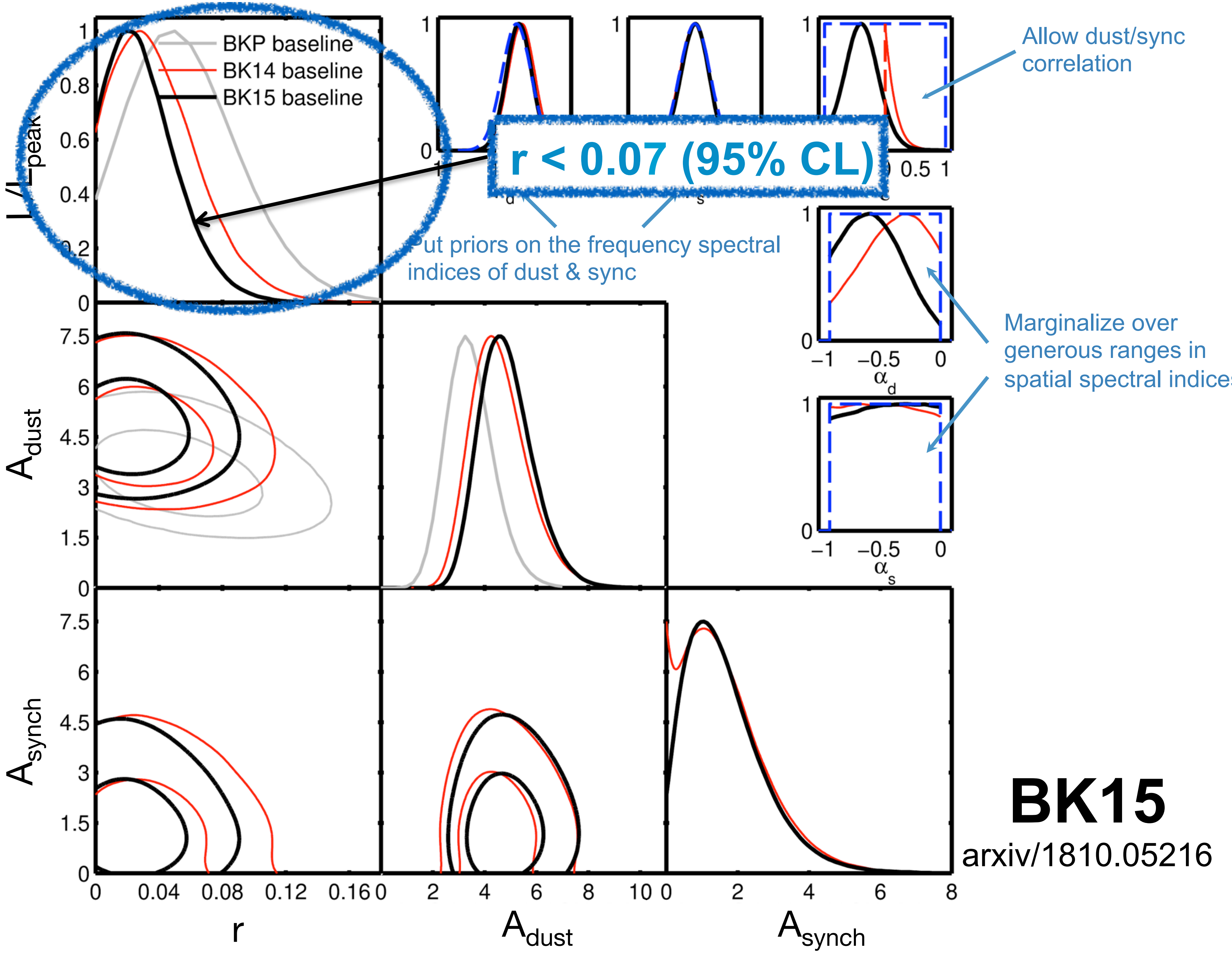


BKP baseline
BK14 baseline
L/L_peak
A_dust
A_synch
r
A_dust
A_synch
β_d
β_s
ε
α_d
α_s
Allow dust/sync correlation
Put priors on the frequency spectral indices of dust & sync
Marginalize over generous ranges in spatial spectral indices
BK14
arxiv/1510.09217

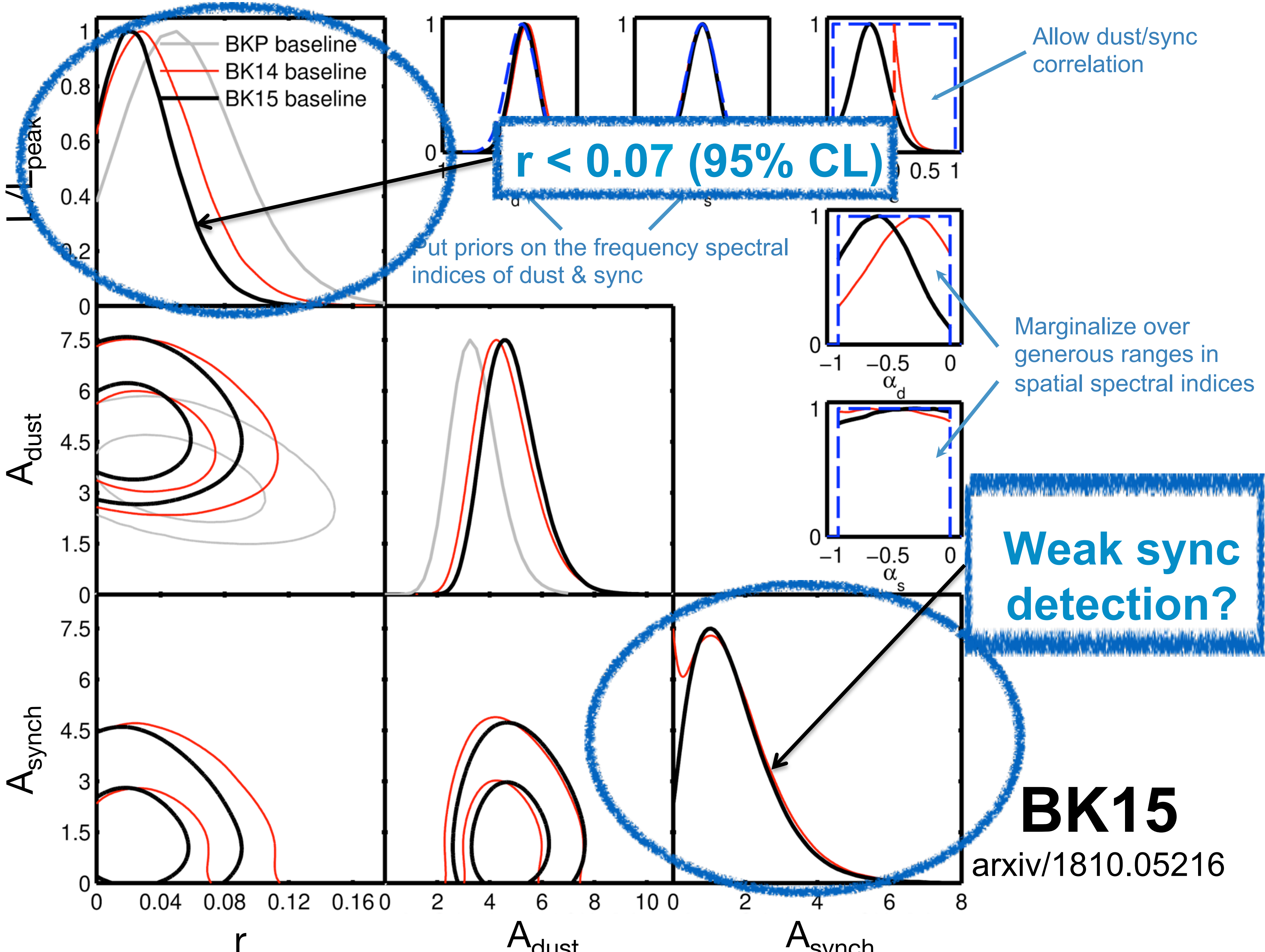


BK15

arxiv/1810.05216

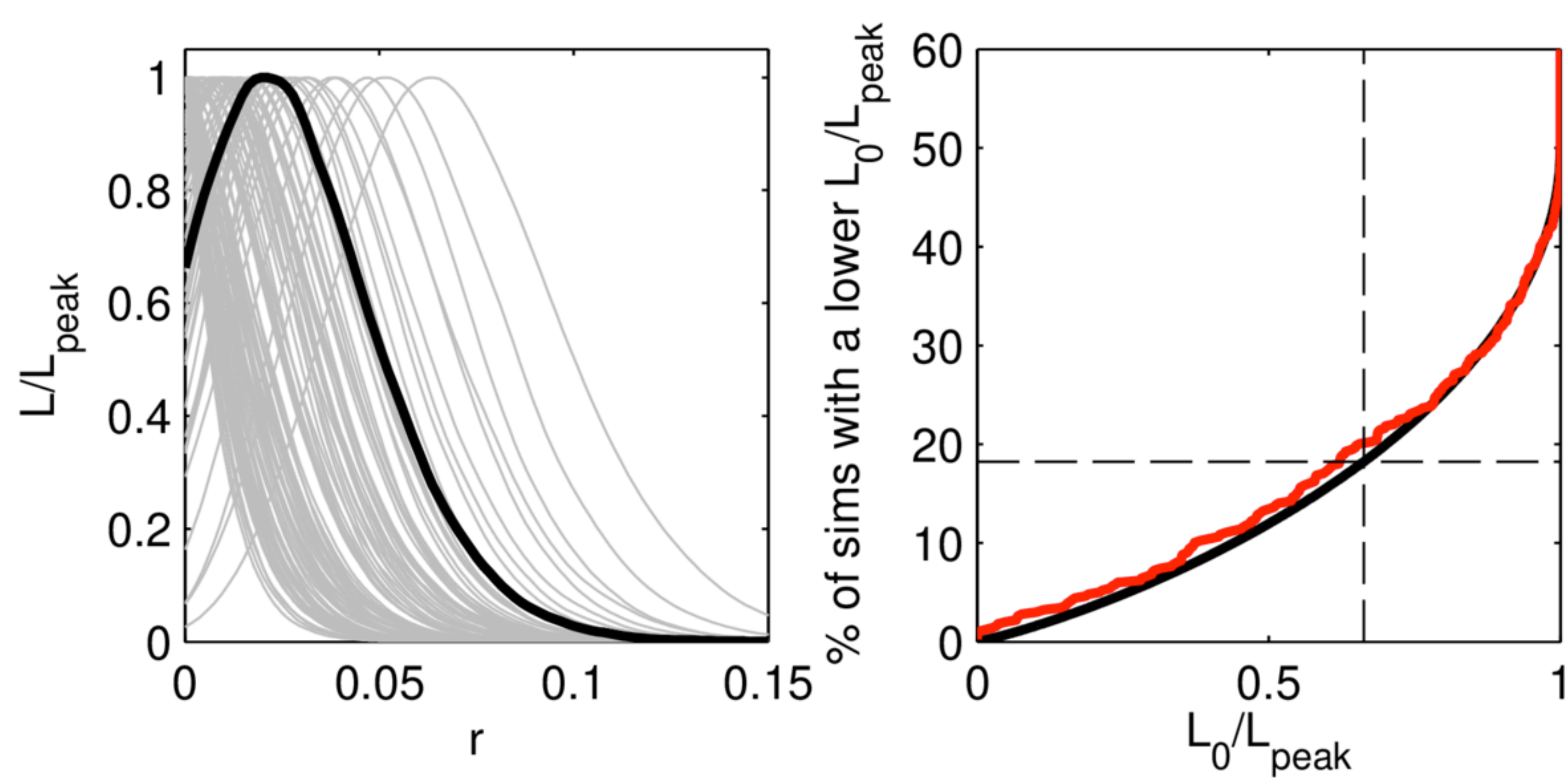


BKP baseline
BK14 baseline
BK15 baseline
r < 0.07 (95% CL)
Allow dust/sync correlation
Put priors on the frequency spectral indices of dust & sync
Marginalize over generous ranges in spatial spectral indices
r
A_dust
A_synch
α_d
α_s
L/L_peak
BK15
arxiv/1810.05216



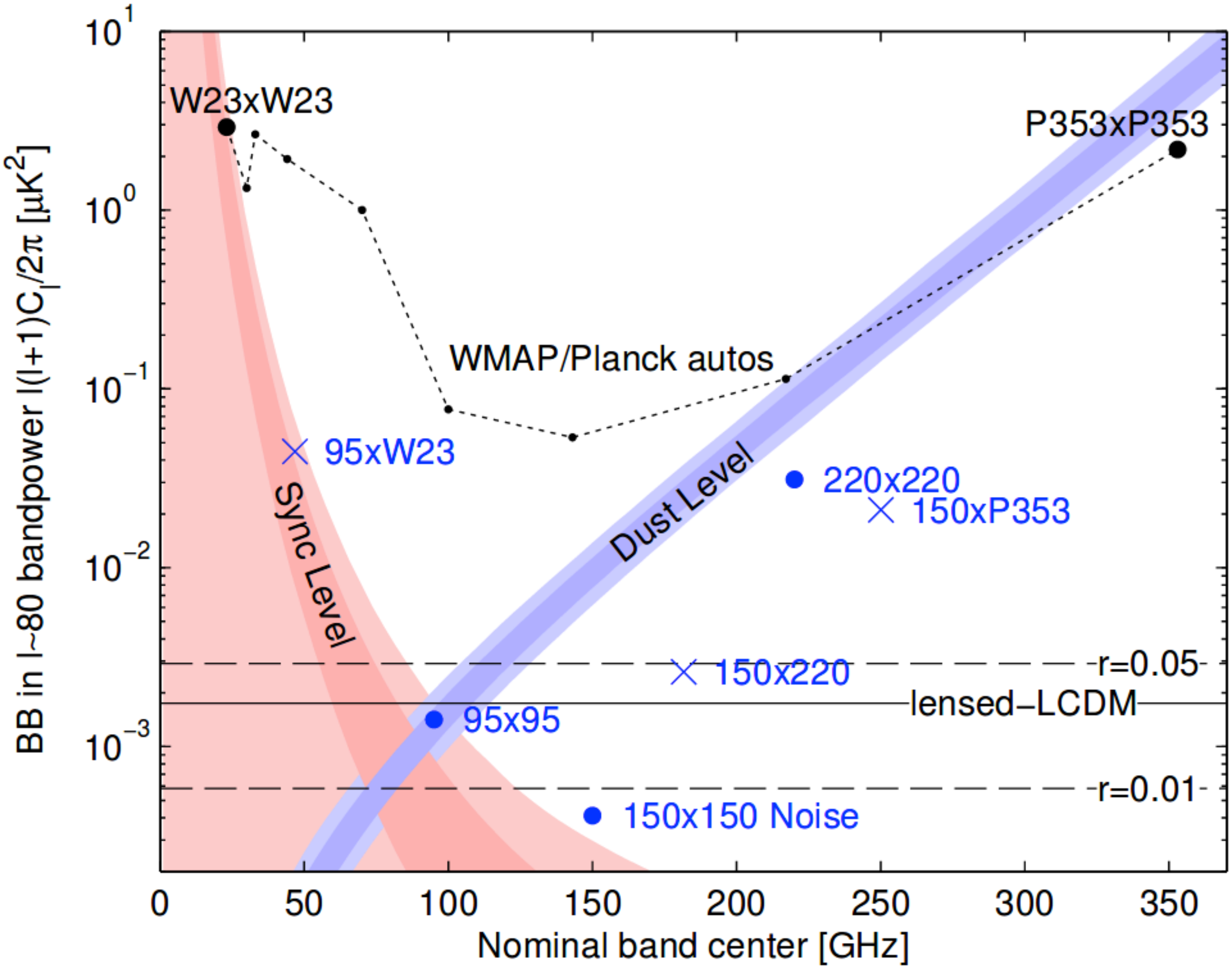
BKP baseline
BK14 baseline
BK15 baseline
r < 0.07 (95% CL)
Allow dust/sync correlation
Put priors on the frequency spectral indices of dust & sync
Marginalize over generous ranges in spatial spectral indices
Weak sync detection?
L/L_{peak}
A_{dust}
A_{synch}
r
α_d
α_s
BK15
arxiv/1810.05216

Likelihood curves for lensed-LCDM+dust+noise sims



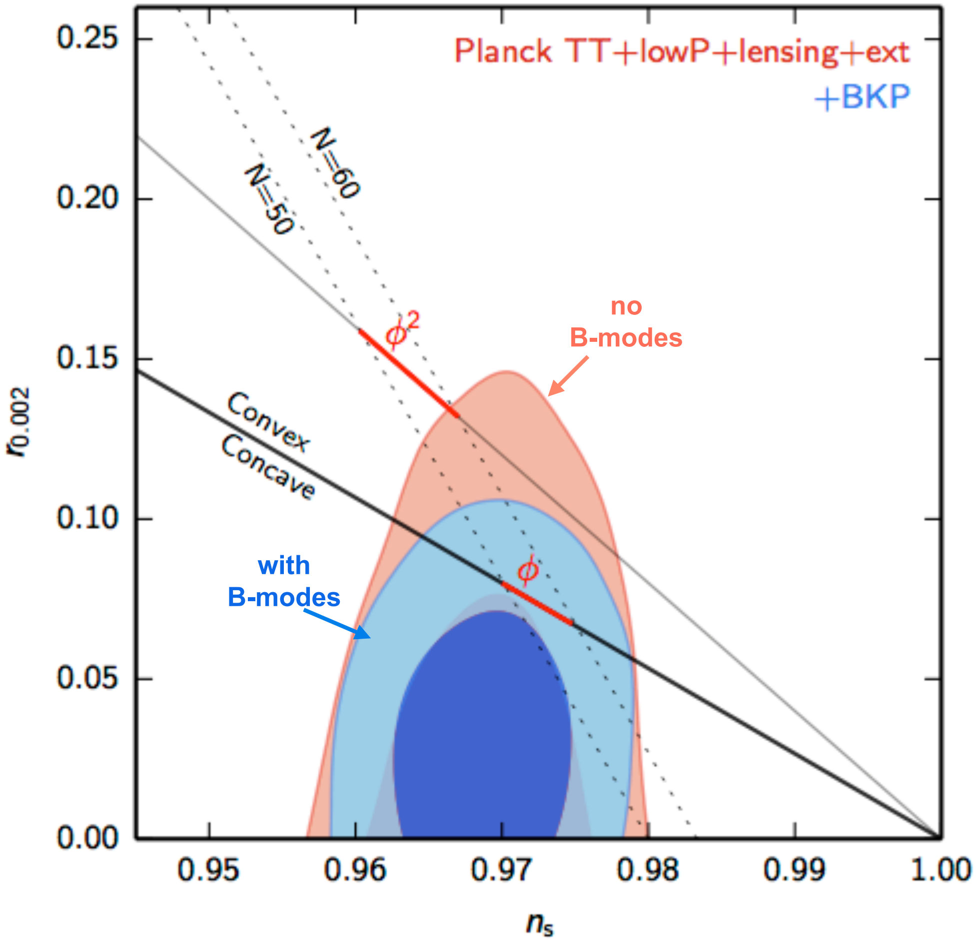
Likelihood is well behaved – 50% of curves for sims peak at zero and cdf of L_0/L_{peak} follows simple form

BK15 ell=80 bandpower noise/signal



The BICEP/Keck Collaboration

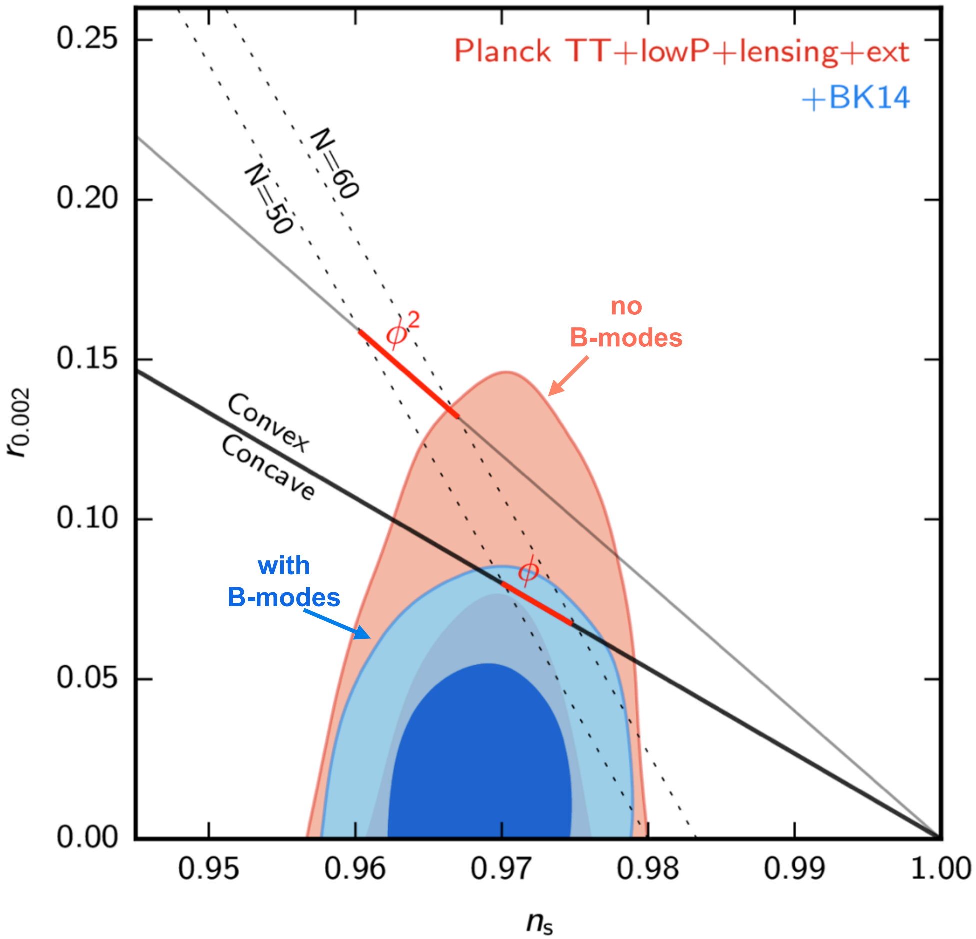
Adding in temperature



r < 0.09

BKP
arxiv/1502.00612

Adding in temperature

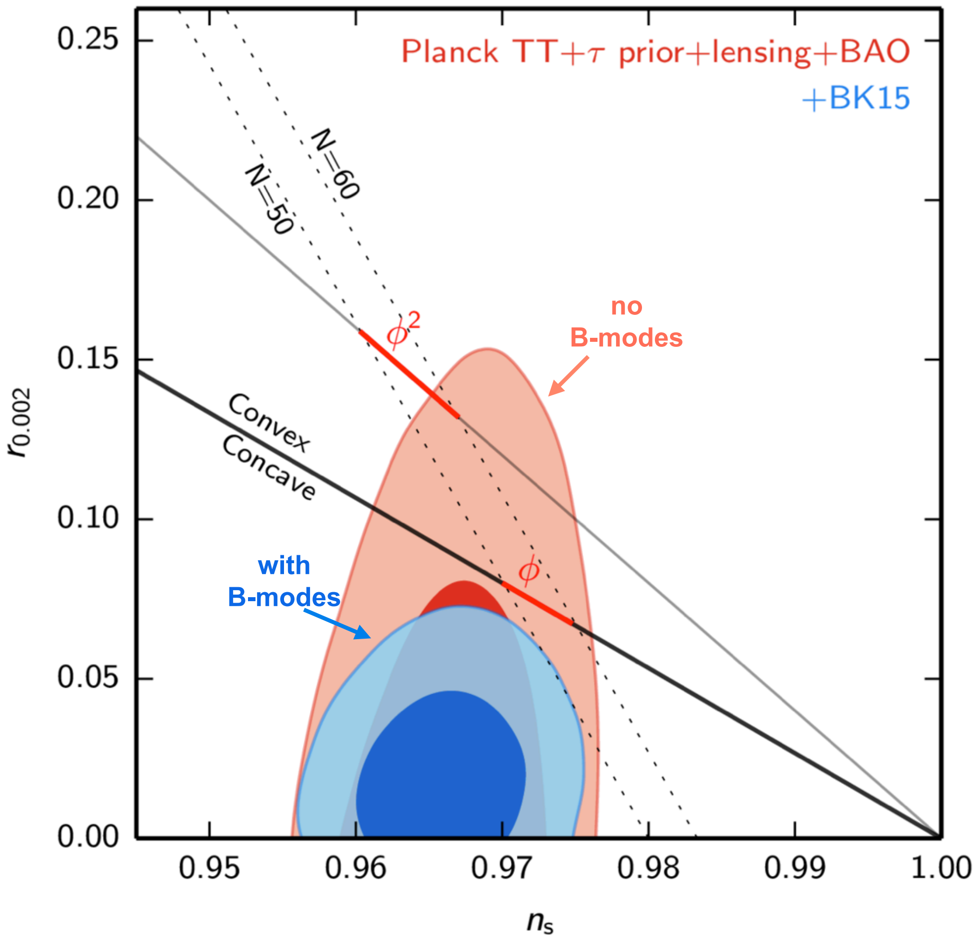


$r_{.05} < 0.07$

BK14

arxiv/1510.09217

Adding in temperature



$r_{.05} < 0.06$

BK15

arxiv/1810.05216

Why BK15 comes 3 years after BK14…

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

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(Affiliations can be found after the references)

Preprint online version: June 24, 2016

ABSTRACT

The characterization of the Galactic foregrounds has been shown to be the main obstacle in the challenging quest to detect primordial *B*-modes in the polarized microwave sky. We make use of the *Planck*-HFI 2015 data release at high frequencies to place new constraints on the properties of the polarized thermal dust emission at high Galactic latitudes. Here, we specifically study the spatial variability of the dust polarized spectral energy distribution (SED), and its potential impact on the determination of the tensor-to-scalar ratio, r. We use the correlation ratio of the C_ℓ^{BB} angular power spectra between the 217- and 353-GHz channels as a tracer of these potential variations, computed on different high Galactic latitude regions, ranging from 80 % to 20 % of the sky. The new insight from *Planck* data is 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. The effect is marginally detected on each region, but the statistical combination of all the regions gives more than 99 % confidence for this variation in polarized dust properties. In addition, we show that the decorrelation increases when there is a decrease in the mean column density of the region of the sky being considered, and we propose a simple power-law empirical model for this dependence, which matches what is seen in the *Planck* data. We explore the effect that this measured decorrelation has on simulations of the BICEP2-*Keck* Array/*Planck* analysis and show that the 2015 constraints from those data still allow a decorrelation between the dust at 150 and 353 GHz of the order of the one we measure. Finally, using simplified models, we show that either spatial variation of the dust SED or of the dust polarization angle could produce decorrelations between 217- and 353-GHz data similar to those we observe in the data.

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**

arxiv/1606.07335

Planck 2018

Planck 2018 results. XI. Polarized dust foregrounds

Planck Collaboration: Y. Akrami[46,48], M. Ashdown[55,4], J. Aumont[82], C. Baccigalupi[69], M. Ballardini[17,32], A. J. Banday[82,7], R. B. Barreiro[50], N. Bartolo[22,51], S. Basak[75], K. Benabed[44,81], J.-P. Bernard[82,7], M. Bersanelli[25,36], P. Bielewicz[67,7,69], J. R. Bond[6], J. Borrill[10,79], F. R. Bouchet[44,77], F. Boulanger[57,43,44 *], A. Bracco[68,45], M. Bucher[2,5], C. Burigana[35,23,37], E. Calabrese[73], J.-F. Cardoso[44], J. Carron[18], H. C. Chiang[20,5], C. Combet[60], B. P. Crill[52,9], P. de Bernardis[24], G. de Zotti[33,69], J. Delabrouille[2], J.-M. Delouis[44,81], E. Di Valentino[53], C. Dickinson[53], J. M. Diego[50], A. Ducout[44,42], X. Dupac[28], G. Efstathiou[55,47], F. Elsner[64], T. A. Enßlin[64], E. Falgarone[56], Y. Fantaye[3,15], K. Ferrière[82,7], F. Finelli[32,37], F. Forastieri[23,38], M. Frailis[34], A. A. Fraisse[20], E. Franceschi[32], A. Frolov[76], S. Galeotta[34], S. Galli[54], K. Ganga[2], R. T. Génova-Santos[49,12], T. Ghosh[72,8], J. González-Nuevo[13], K. M. Górski[52,83], A. Gruppuso[32,37], J. E. Gudmundsson[80,20], V. Guillet[43,59], W. Handley[55,4], F. K. Hansen[48], D. Herranz[50], Z. Huang[74], A. H. Jaffe[42], W. C. Jones[20], E. Keihänen[19], R. Keskitalo[10], K. Kiiveri[19,31], J. Kim[64], N. Krachmalnicoff[69], M. Kunz[11,43,3], H. Kurki-Suonio[19,31], J.-M. Lamarre[56], A. Lasenby[4,55], M. Le Jeune[2], F. Levrier[56], M. Liguori[22,51], P. B. Lilje[48], V. Lindholm[19,31], M. López-Caniego[28], P. M. Lubin[21], Y.-Z. Ma[53,71,66], J. F. Macías-Pérez[60], G. Maggio[34], D. Maino[25,36,39], N. Mandolesi[32,23], A. Mangilli[7], P. G. Martin[6], E. Martínez-González[50], S. Matarrese[22,51,30], J. D. McEwen[65], P. R. Meinhold[21], A. Melchiorri[24,40], M. Migliaccio[78,41], M.-A. Miville-Deschênes[58], D. Molinari[23,32,38], A. Moneti[44], L. Montier[82,7], G. Morgante[32], P. Natoli[23,78,38], L. Pagano[43,56], D. Paoletti[32,37], V. Pettorino[1], F. Piacentini[24], G. Polenta[78], J.-L. Puget[43,44], J. P. Rachen[14], M. Reinecke[64], M. Remazeilles[53], A. Renzi[51], G. Rocha[52,9], C. Rosset[2], G. Roudier[2,56,52], J. A. Rubiño-Martín[49,12], B. Ruiz-Granados[49,12], L. Salvati[43], M. Sandri[32], M. Savelainen[19,31,62], D. Scott[16], J. D. Soler[63], L. D. Spencer[73], J. A. Tauber[29], D. Tavagnacco[34,26], L. Toffolatti[13,32], M. Tomasi[25,36], T. Trombetti[35,38], J. Valiviita[19,31], F. Vansyngel[43], B. Van Tent[61], P. Vielva[50], F. Villa[32], N. Vittorio[27], I. K. Wehus[52,48], A. Zacchei[34], and A. Zonca[70]

(Affiliations can be found after the references)

Preprint online version: July 19, 2018

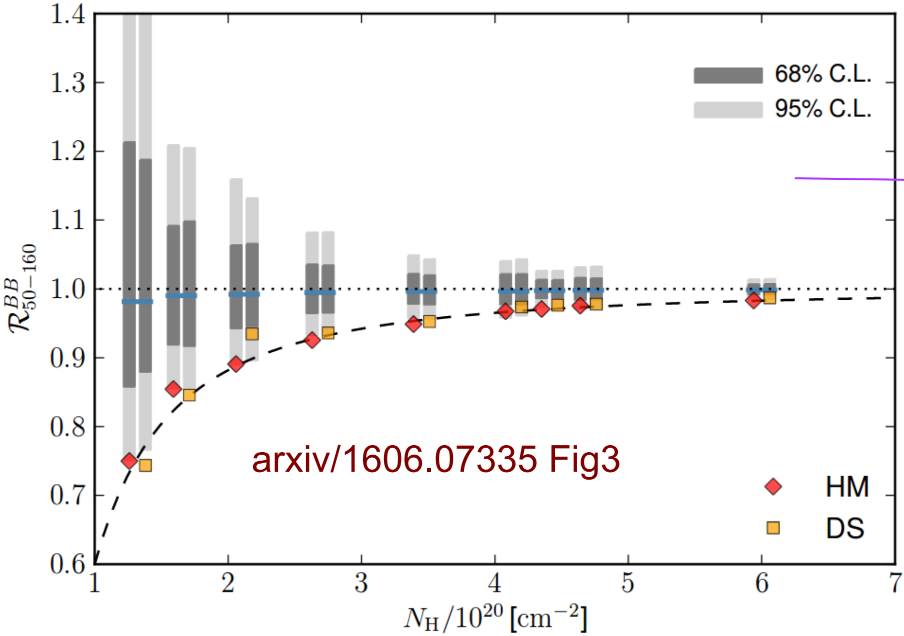
ABSTRACT

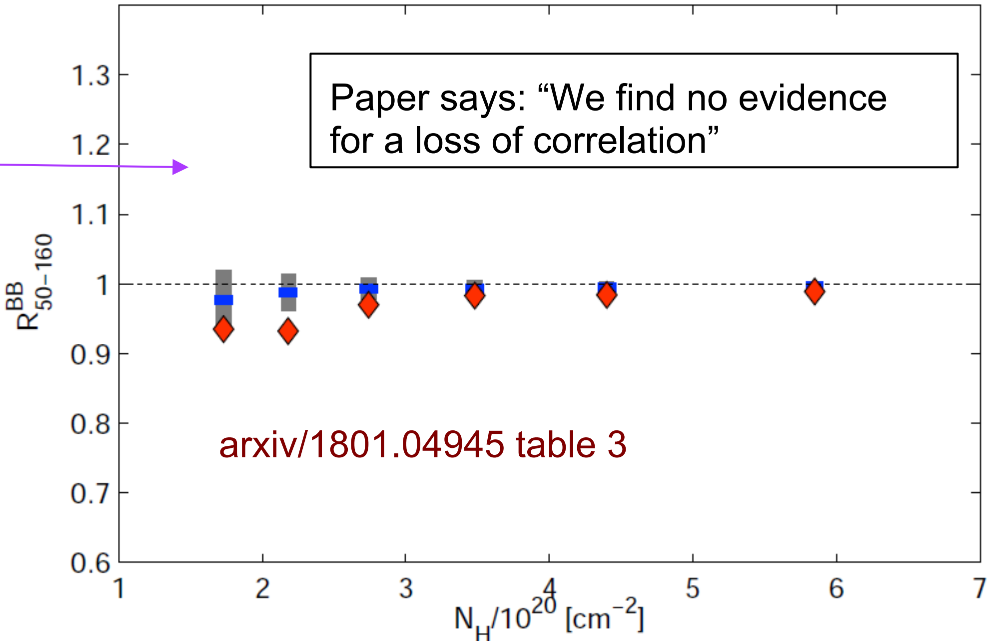
The study of polarized dust emission has become entwined with the analysis of the cosmic microwave background (CMB) polarization in the quest for the curl-like *B*-mode polarization from primordial gravitational waves and the low-multipole *E*-mode polarization associated with the reionization of the Universe. We use the new *Planck* PR3 maps to characterize Galactic dust emission at high latitudes as a foreground to the CMB polarization and use end-to-end simulations to compute uncertainties and assess the statistical significance of our measurements. We present *Planck* EE, BB, and TE power spectra of dust polarization at 353 GHz for a set of six nested high-Galactic-latitude sky regions covering from 24 to 71 % of the sky. We present power-law fits to the angular power spectra, yielding evidence for statistically significant variations of the exponents over sky regions and a difference between the values for the EE and BB spectra, which for the largest sky region are $\alpha_{EE} = -2.42 \pm 0.02$ and $\alpha_{BB} = -2.54 \pm 0.02$, respectively. The spectra show that the TE correlation and E/B power asymmetry discovered by *Planck* extend to low multipoles that were not included in earlier *Planck* polarization papers due to residual data systematics. We also report evidence for a positive TB dust signal. Combining data from *Planck* and WMAP, we determine the amplitudes and spectral energy distributions (SEDs) of polarized foregrounds, including the correlation between dust and synchrotron polarized emission, for the six sky regions as a function of multipole. This quantifies the challenge of the component-separation procedure that is required for measuring the low-ℓ reionization CMB *E*-mode signal and detecting the reionization and recombination peaks of primordial CMB *B* modes. The SED of polarized dust emission is fit well by a single-temperature modified blackbody emission law from 353 GHz to below 70 GHz. For a dust temperature of 19.6 K, the mean dust spectral index for dust polarization is $\beta_d^P = 1.53 \pm 0.02$. The difference between indices for polarization and total intensity is $\beta_d^P - \beta_d^I = 0.05 \pm 0.03$. By fitting multi-frequency cross-spectra between *Planck* data at 100, 143, 217, and 353 GHz, we examine the correlation of the dust polarization maps across frequency. We find no evidence for a loss of correlation and provide lower limits to the correlation ratio that are tighter than values we derive from the correlation of the 217- and 353-GHz maps alone. If the *Planck* limit on decorrelation for the largest sky region applies to the smaller sky regions observed by sub-orbital experiments, then frequency decorrelation of dust polarization might not be a problem for CMB experiments aiming at a primordial *B*-mode detection limit on the tensor-to-scalar ratio $r \simeq 0.01$ at the recombination peak. However, the *Planck* sensitivity precludes identifying how difficult the component-separation problem will be for more ambitious experiments targeting lower limits on r.

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…

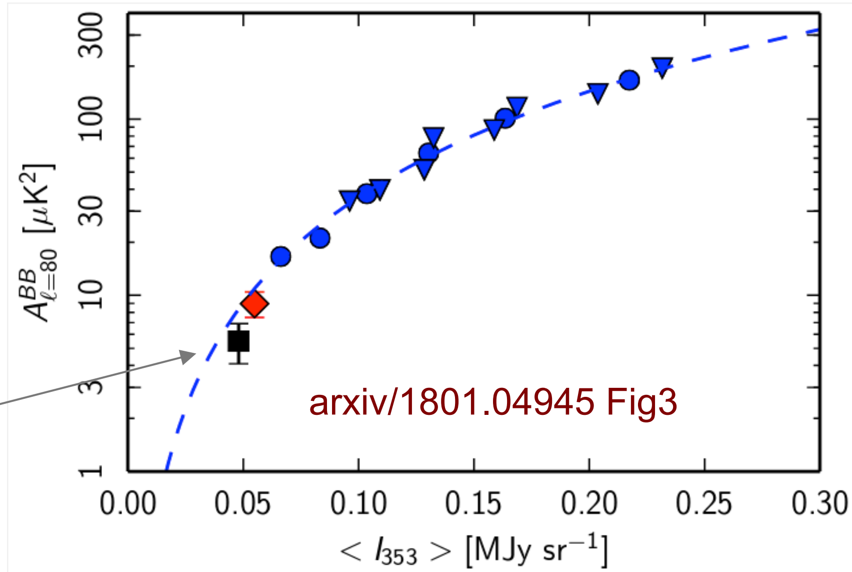
arxiv/1801.04945

Evolving Planck Dust Analysis



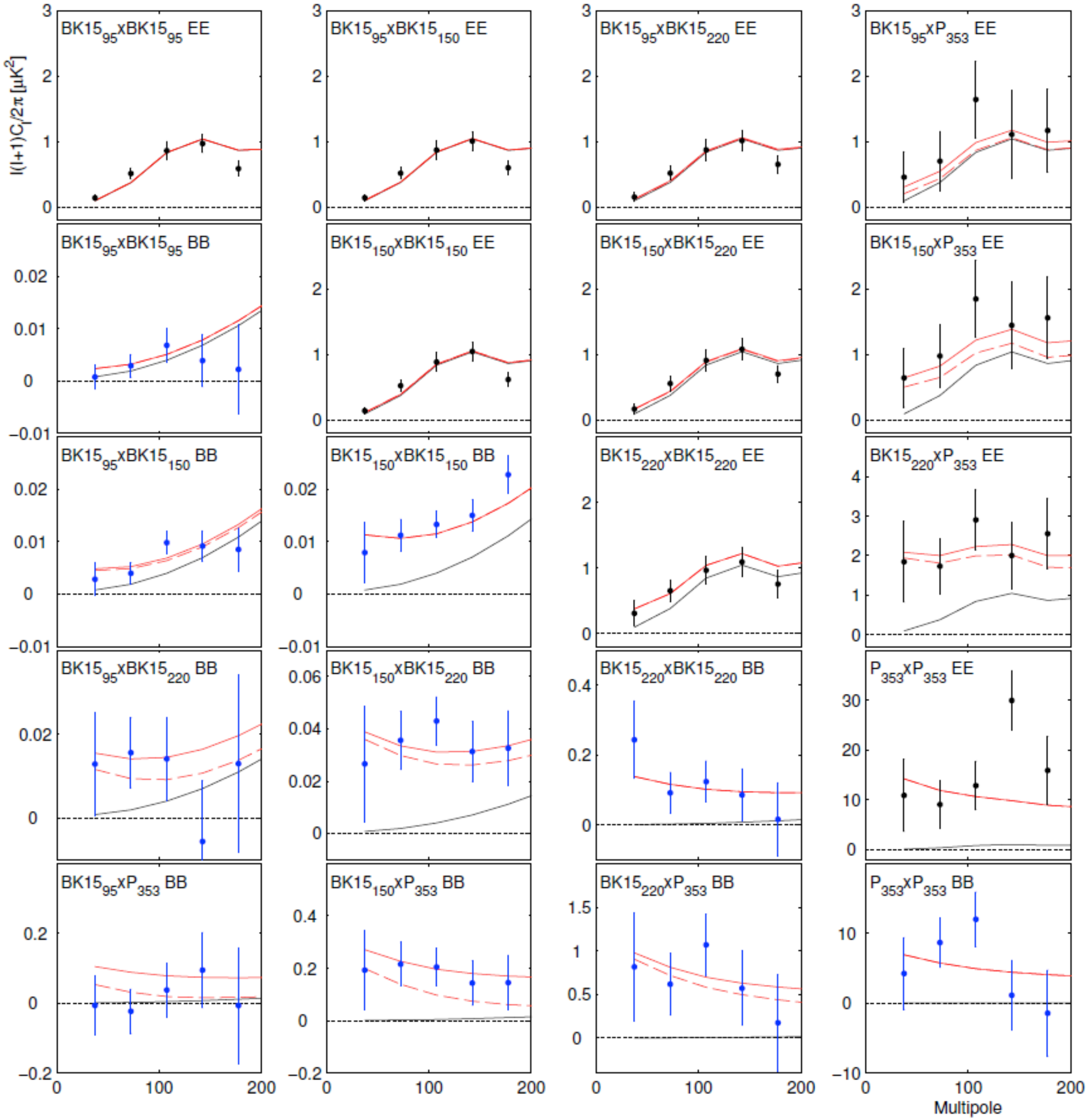


Paper says: “We find no evidence for a loss of correlation”



BK patch a few times cleaner than extrapolation

BK15+P353 Spectra



Upper/right plots are EE (black points)

Lower/left plots are BB (blue points)

220GHz auto/ cross spectra are all new

Red solid line is best fit multicomponent model from previous (BK14) analysis - It fits all the spectra

Red dashed line is same model but with strong decorrelation – better for 95x353, worse for 150x353

Need better data to say for sure

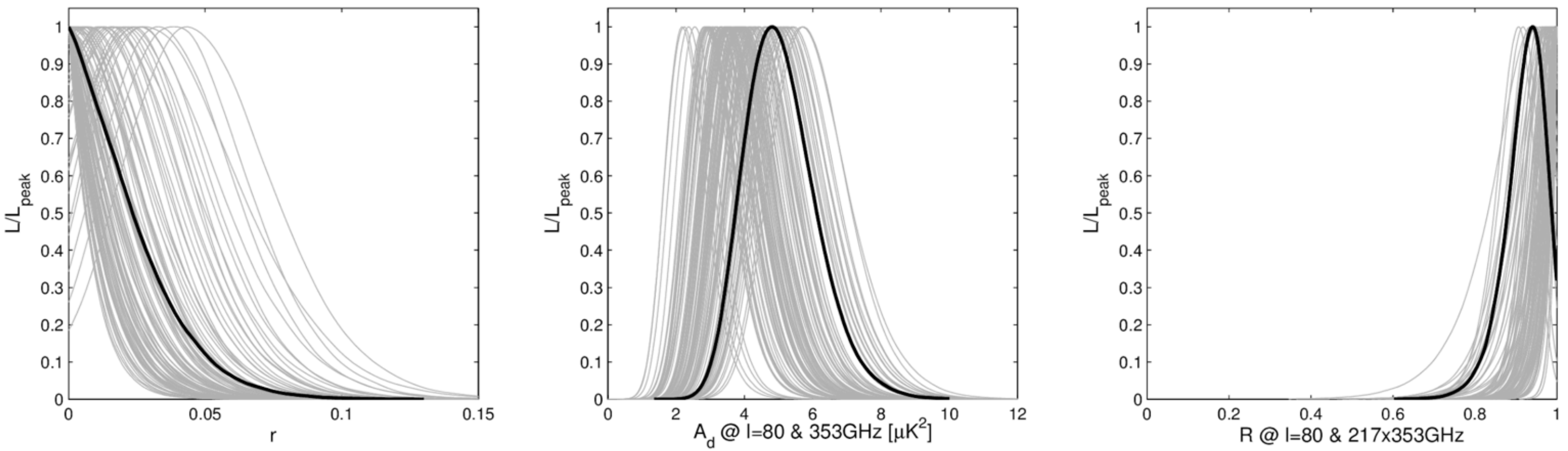
Include dust correlation parameter?

- The standard BK15 marginalized likelihood analysis (COSMOMC style) is unbiased for *r* – i.e. when run on lensed-LCDM+dust+noise sims 50% of the r curves peak at zero.

- However, if add a dust correlation parameter and restrict to physical range (<1) then *r* becomes biased – 72% of curves peak at zero

- This is because *r* and dust correlation parameter are partially degenerate

Likelihood curves for lensed-LCDM+dust+noise sims when including decorrelation parameter



When add decorrelation parameter to re-analysis of sims which do not contain decorralation 72% of *r* curves peak at zero – the analysis becomes biased

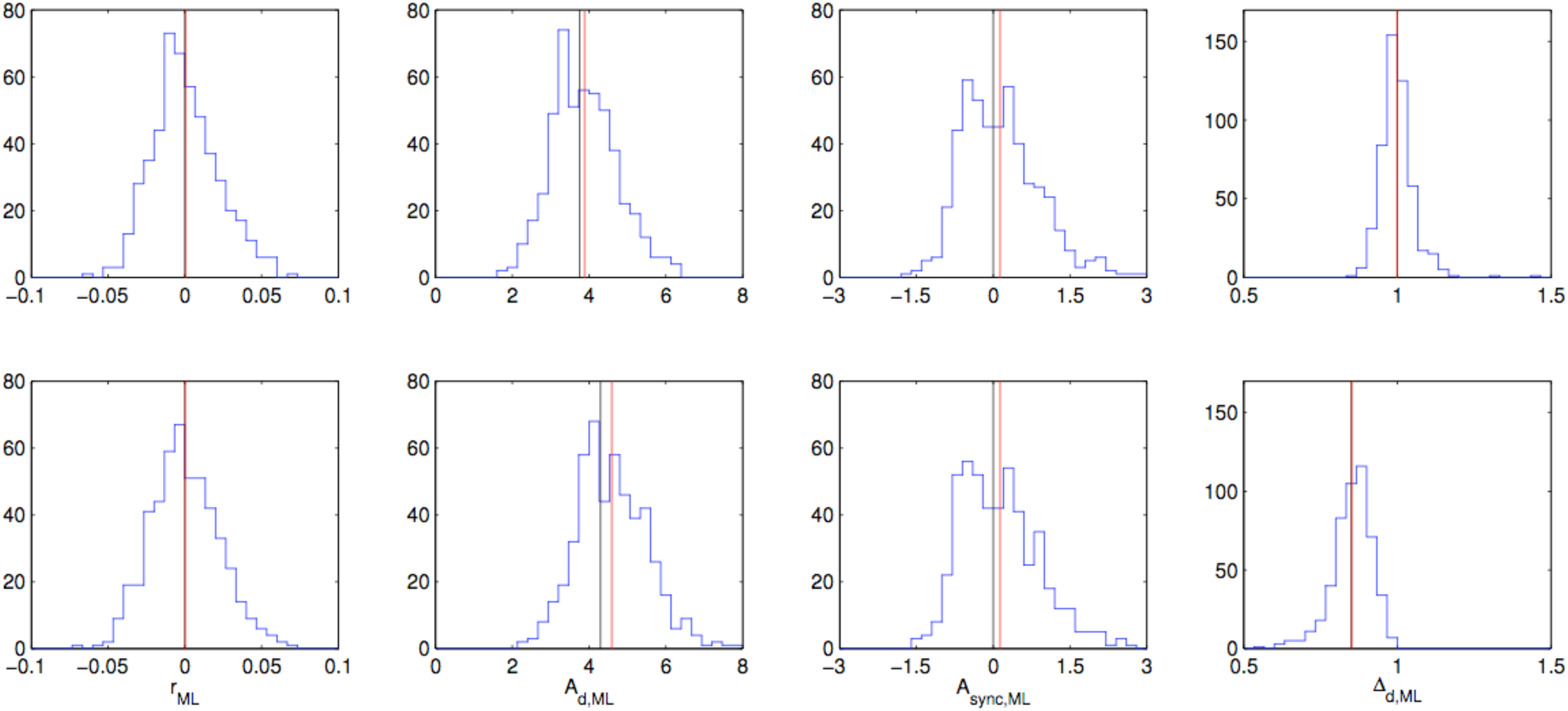
Likelihood Validation Studies Using ML Search

- Can run alternate maximum likelihood searches where parameters are allowed to take unphysical values ($r<0$ and dust correlation >1)

- These really should be unbiased…

Including Decorr Works in ML Search

Upper = standard lensed-LCDM+dust+noise sims



Lower = lensed-LCDM+dust+noise sims with strong dust decorrelation

$$\Delta_{\rm d} = \frac{\mathcal{D}_{80}(217 \times 353)}{\sqrt{\mathcal{D}_{80}(217 \times 217)\mathcal{D}_{80}(353 \times 353)}}$$

Results for 3rd Party Foreground Models

Also run ML search on sims containing 3rd party foreground models which do not necessarily conform to the foreground parameterization we are using in the re-fit. For the models considered so far bias is small compared to sigma(r)

Model	$\overline{A_d}$ (μK^2)	$\overline{A_s}$ (μK^2)	$\sigma(r)$, $\overline{r}/\sigma(r)$ β_d prior	β_d free	with decorr.
Gaussian	3.8	0.1	$0.020, +0.1\sigma$	$0.023, 0.0\sigma$	$0.021, +0.0\sigma$
PySM 1	10.9	1.1	$0.026, +0.2\sigma$	$0.028, +0.2\sigma$	$0.028, +0.1\sigma$
PySM 2	24.2	0.9	$0.028, +0.1\sigma$	$0.029, +0.1\sigma$	$0.032, +0.1\sigma$
PySM 3	12.1	1.1	$(0.030, +0.4\sigma)$	$0.031, +0.1\sigma$	$(0.032, +0.2\sigma)$
MHDv2	2.9	5.6	$0.020, +0.2\sigma$	$0.027, -0.2\sigma$	$0.021, -0.1\sigma$
G. Decorr.	4.6	0.1	$(0.023, +1.5\sigma)$	$(0.026, +1.3\sigma)$	$0.022, +0.0\sigma$

2016 onwards: BICEP3 “Super receiver”

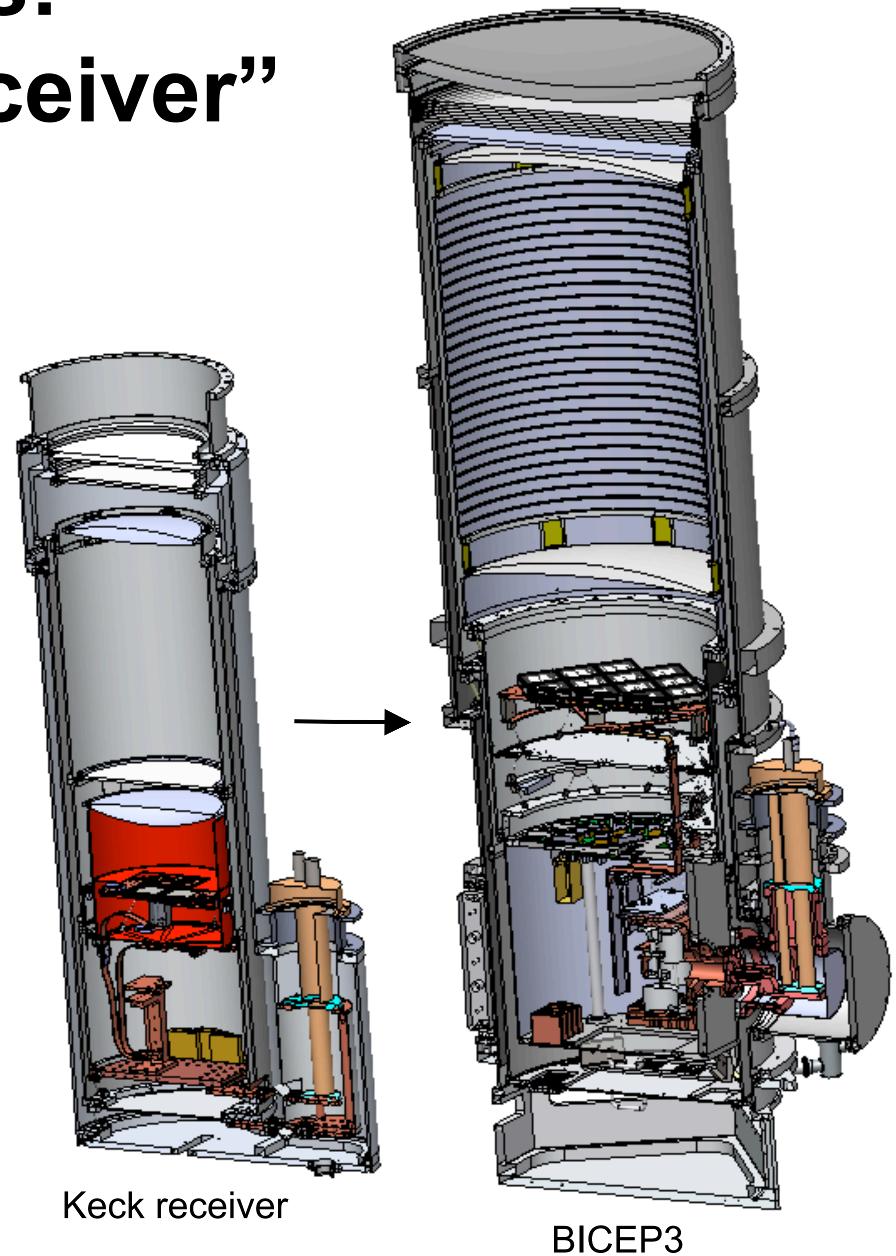
All 95 GHz

2560 detectors in modular focal plane

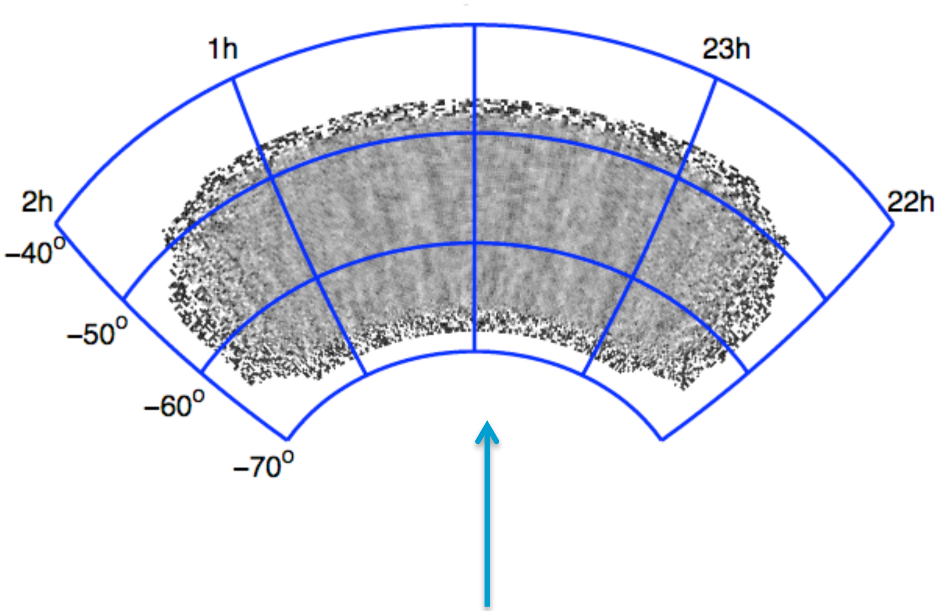
Larger-aperture optics

> 10x optical throughput of single BICEP2/Keck receiver

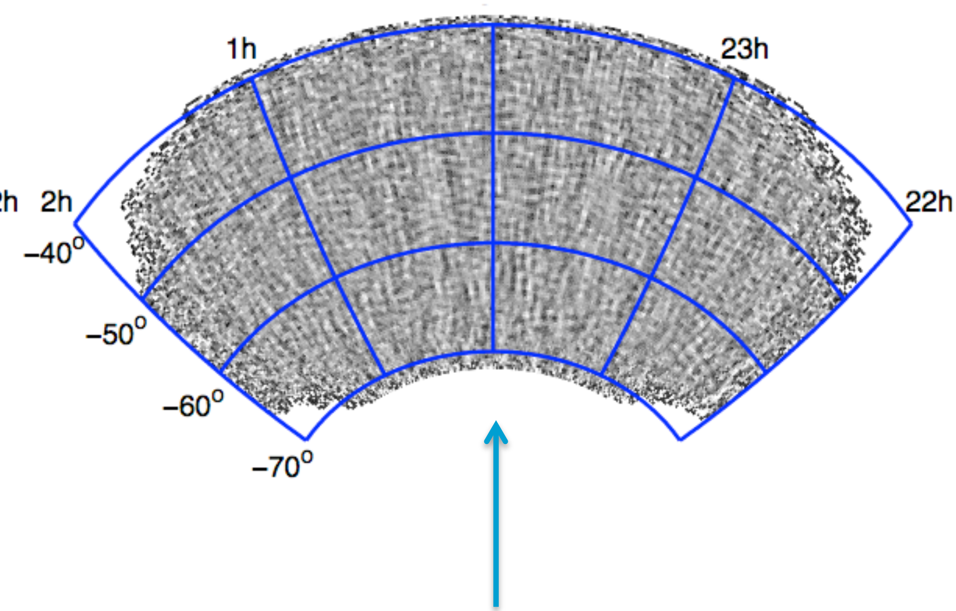
Means larger field of view and lower noise faster



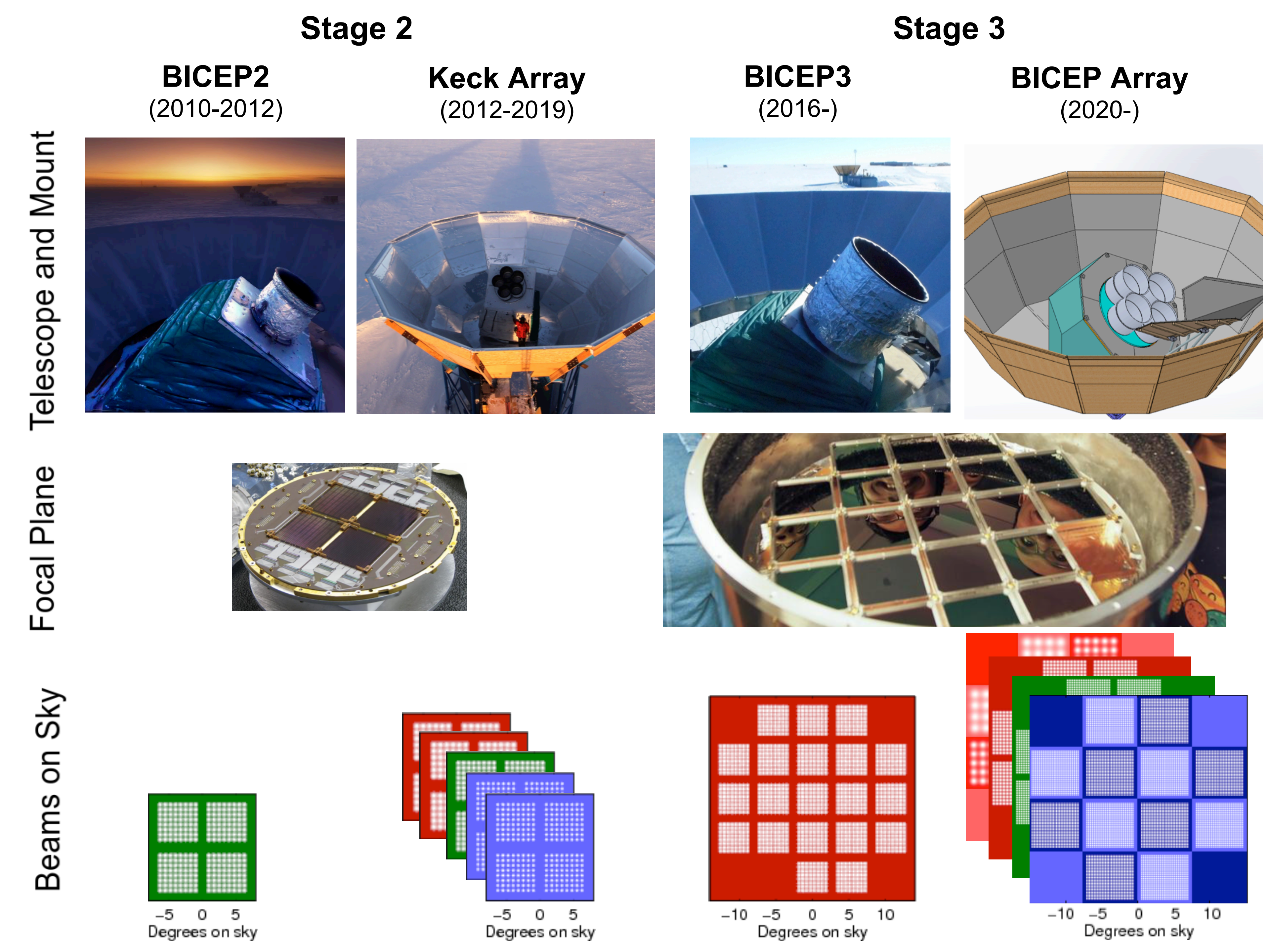
Larger receiver = more sky area



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)



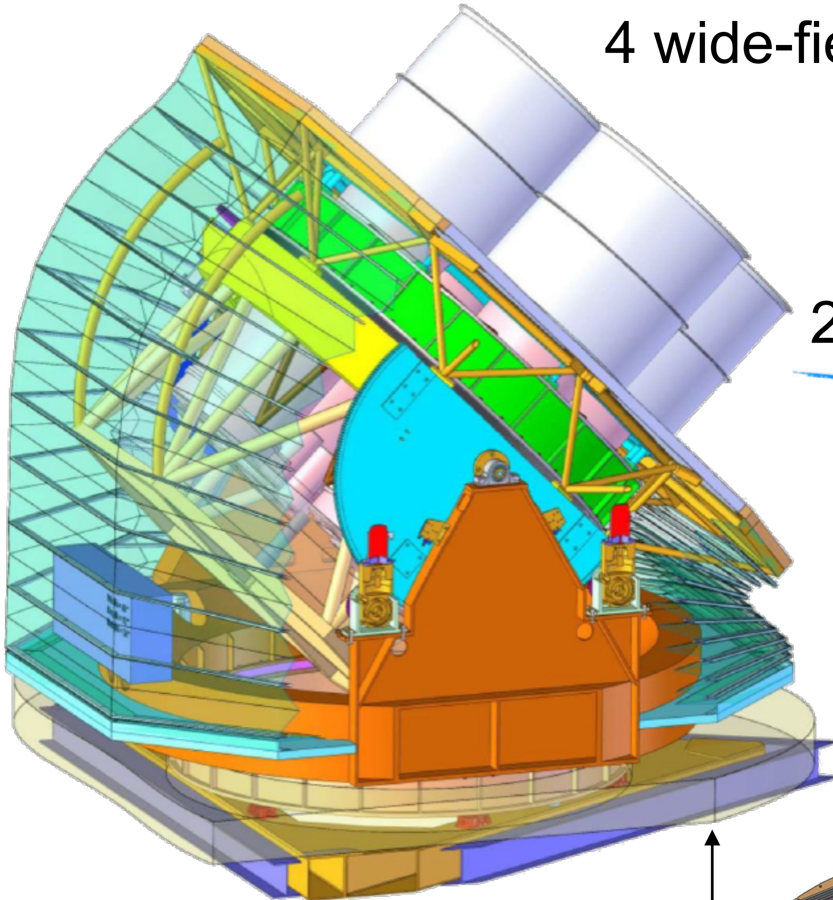
Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2016-)
BICEP Array
(2020-)
Telescope and Mount
Focal Plane
Beams on Sky
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
−10 −5 0 5 10
Degrees on sky

Detector numbers

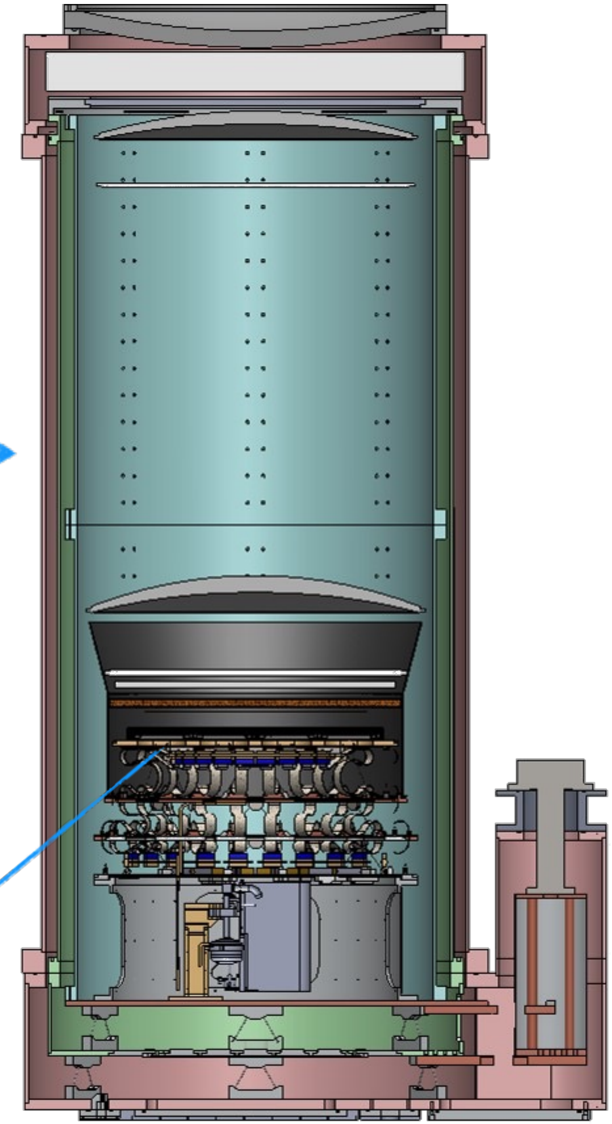
Receiver Observing Band (GHz)	Nominal Number of Detectors	Nominal Single Detector NET ($\mu K_{cmb}\sqrt{s}$)	Beam FWHM (arcmin)	Survey Weight Per Year $(\mu K_{cmb})^{-2}\ yr^{-1}$
Keck Array				
95	**288**	288	**43**	**24,000**
150	**512**	313	**30**	**30,000**
220	**512**	837	**21**	**2,000**
270	**512**	1310	**17**	800
BICEP3				
95	**2560**	288	**24**	**213,000**
BICEP Array				
⟨ 30	192	260	76	19,500
40	300	318	57	20,500
95	4056	288	24	287,000
150	7776	336	15	453,000
⟨ 220	8112	699	11	37,000
270	13068	1196	9	15,000

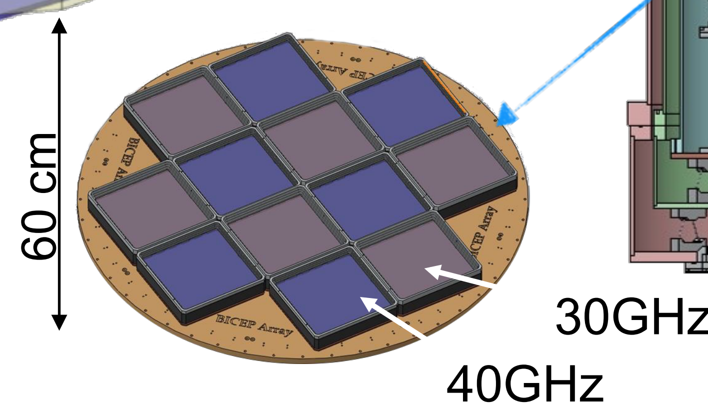
The BICEP/Keck Collaboration

Next Gen Experiment BICEP Array Under Construction



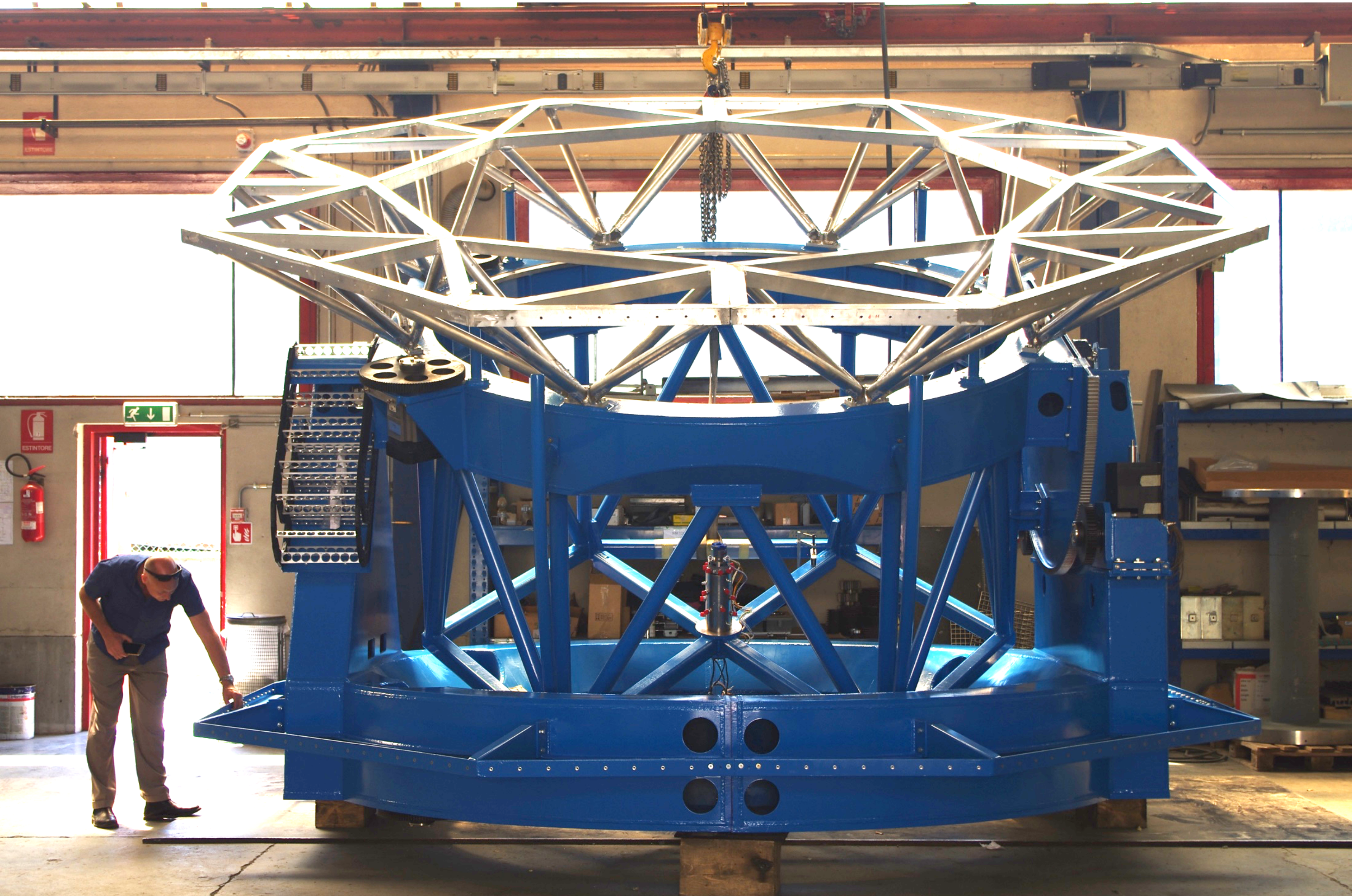
4 wide-field receivers
30/40 GHz
95 GHz
150 GHz
220/270 GHz



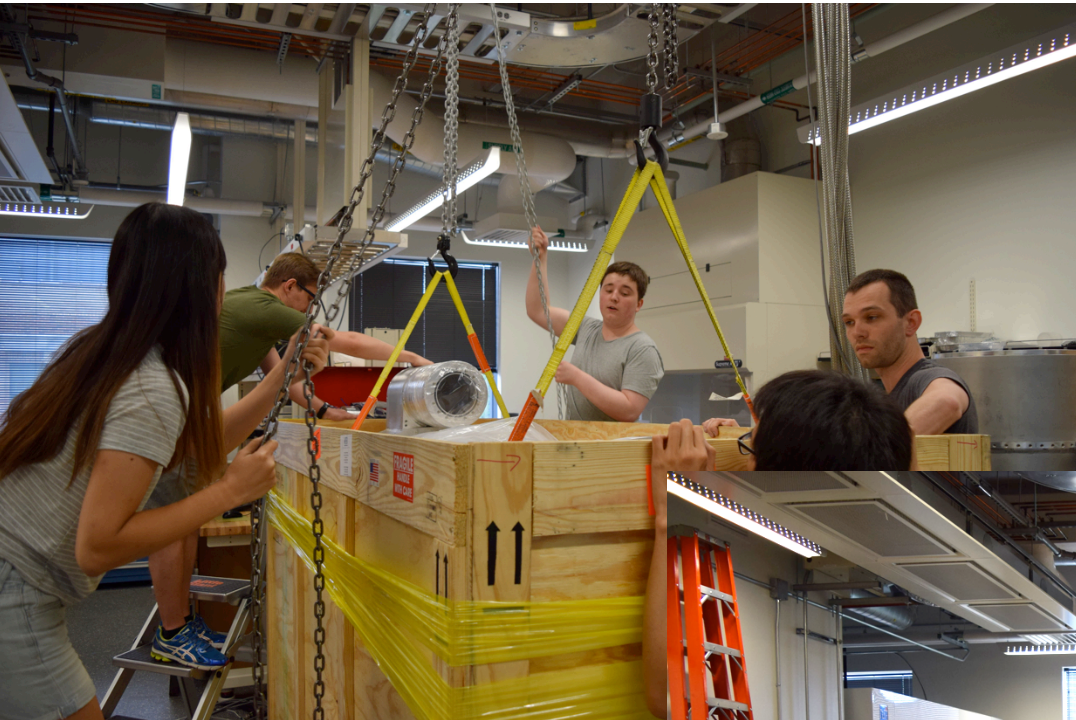


Focal plane layout

Mount under construction outside Milan



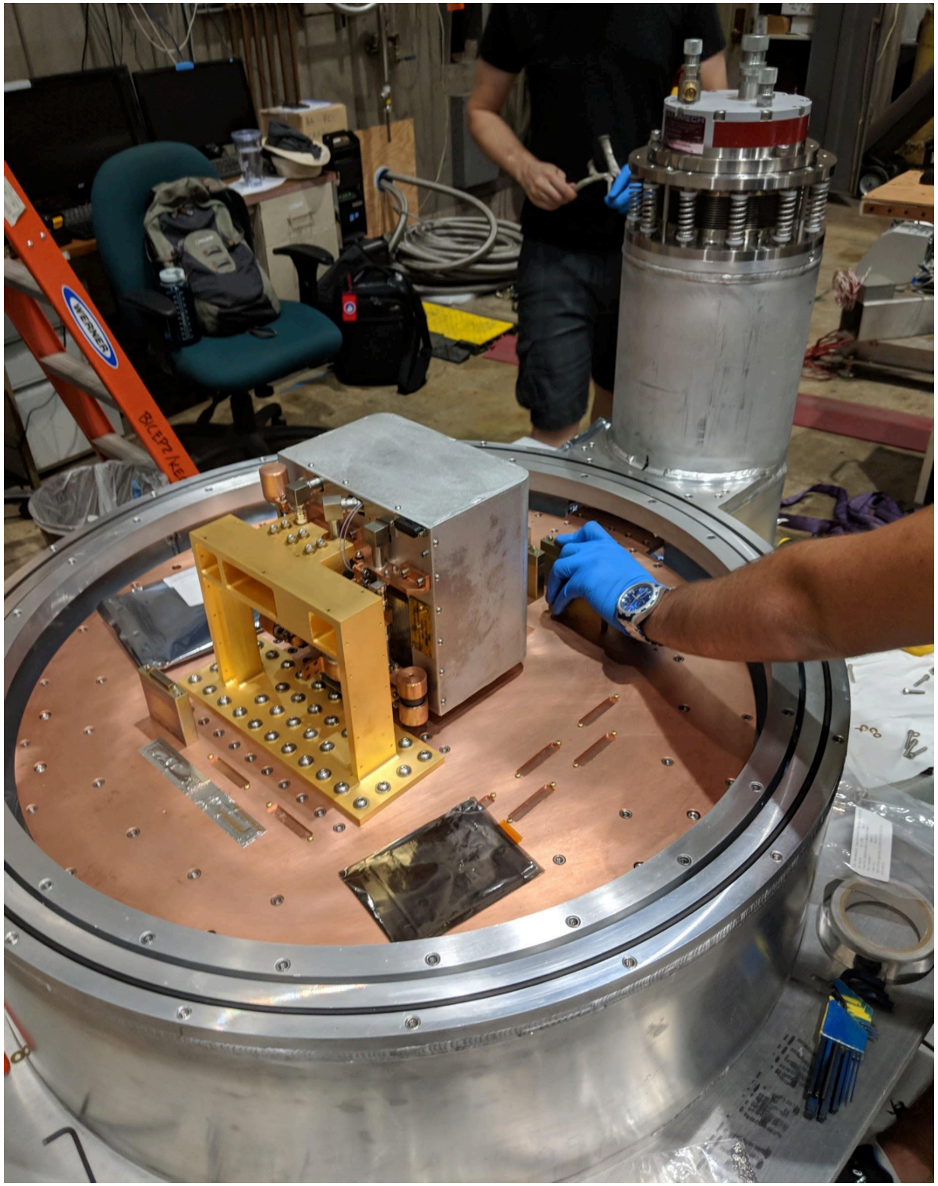
Cryostat Arrival at University of Minnesota

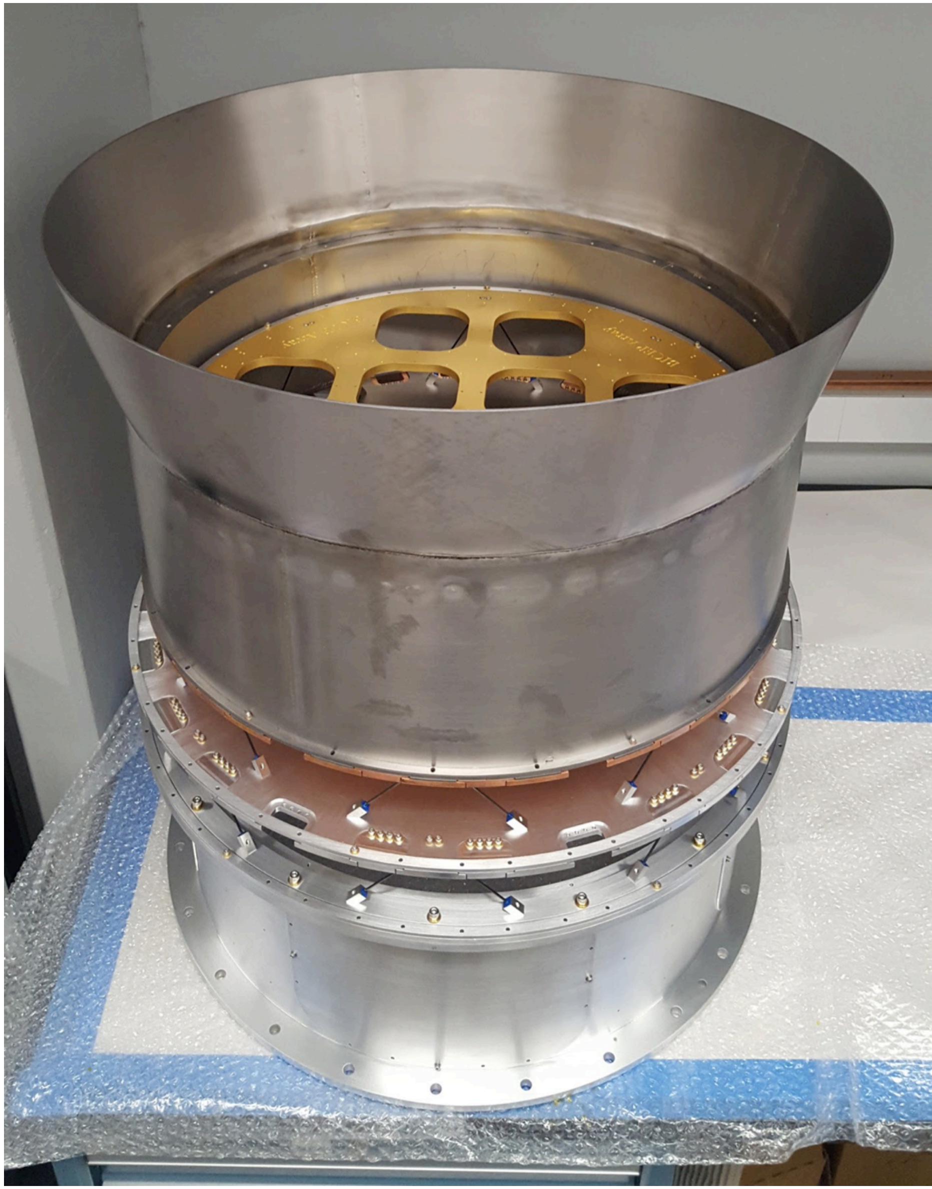


The BICEP/Keck Collaboration

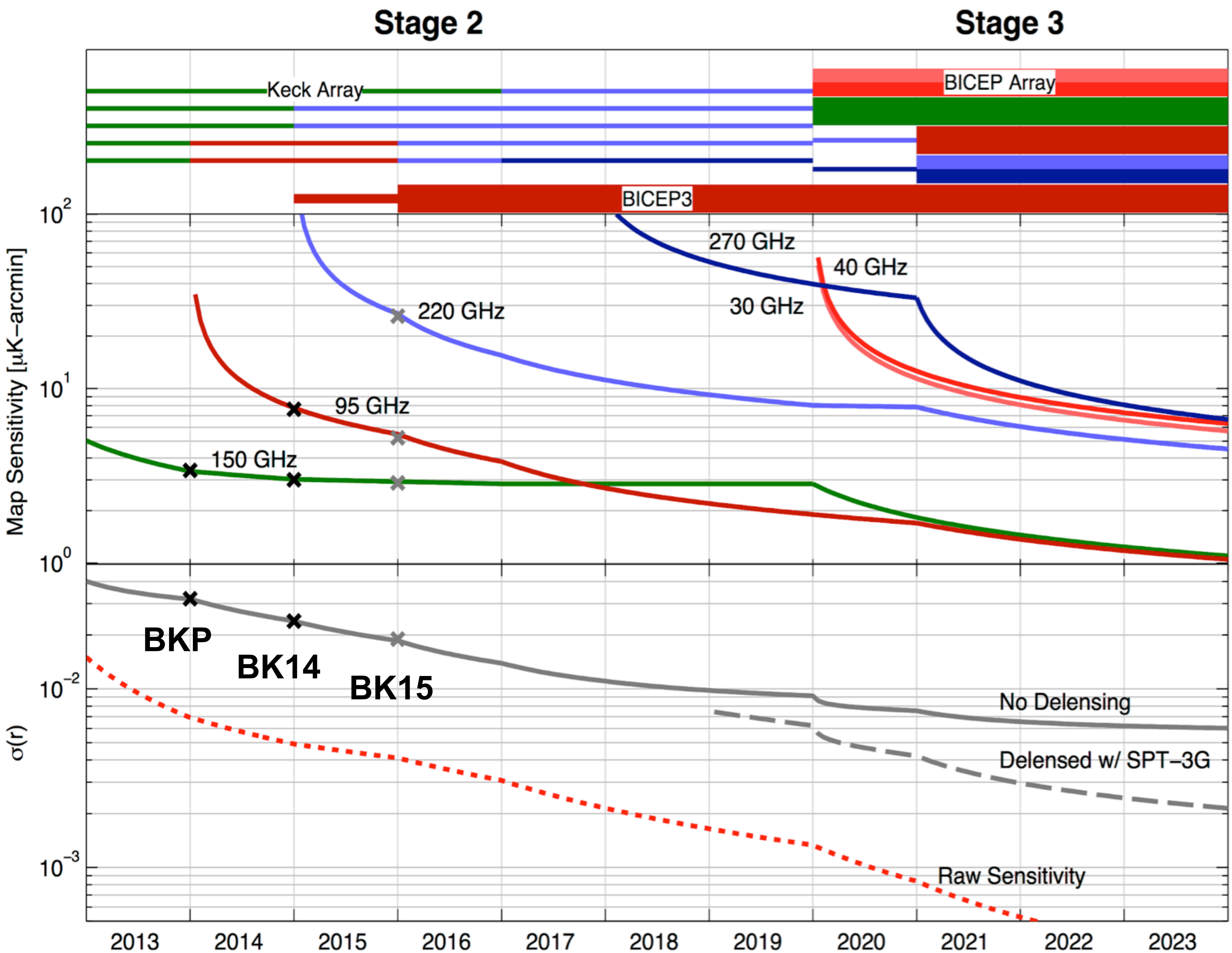
BICEP Array Mount in PAN High Bay

30/40 GHz Receiver Prep at Caltech



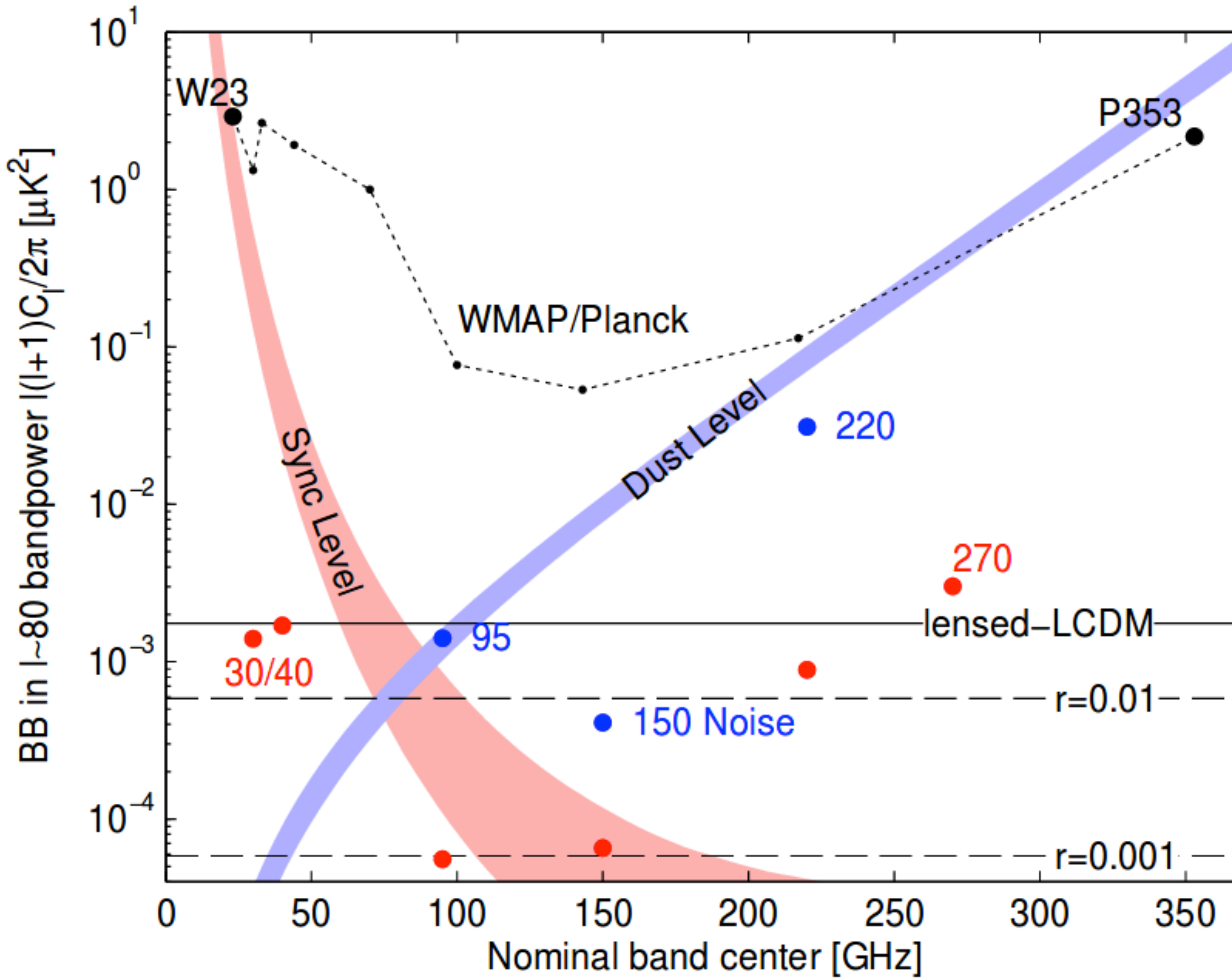


The BICEP/Keck Collaboration



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

BK23 Noise levels



The BICEP/Keck Collaboration

Conclusions

- BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:
- New 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 BK17 (or 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 will remain a serious issue – the hope is that we can measure it *and* constrain *r* simultaneously without a large loss of sensitivity. Additional ground/balloon measurements at low/high frequencies may be able to help.