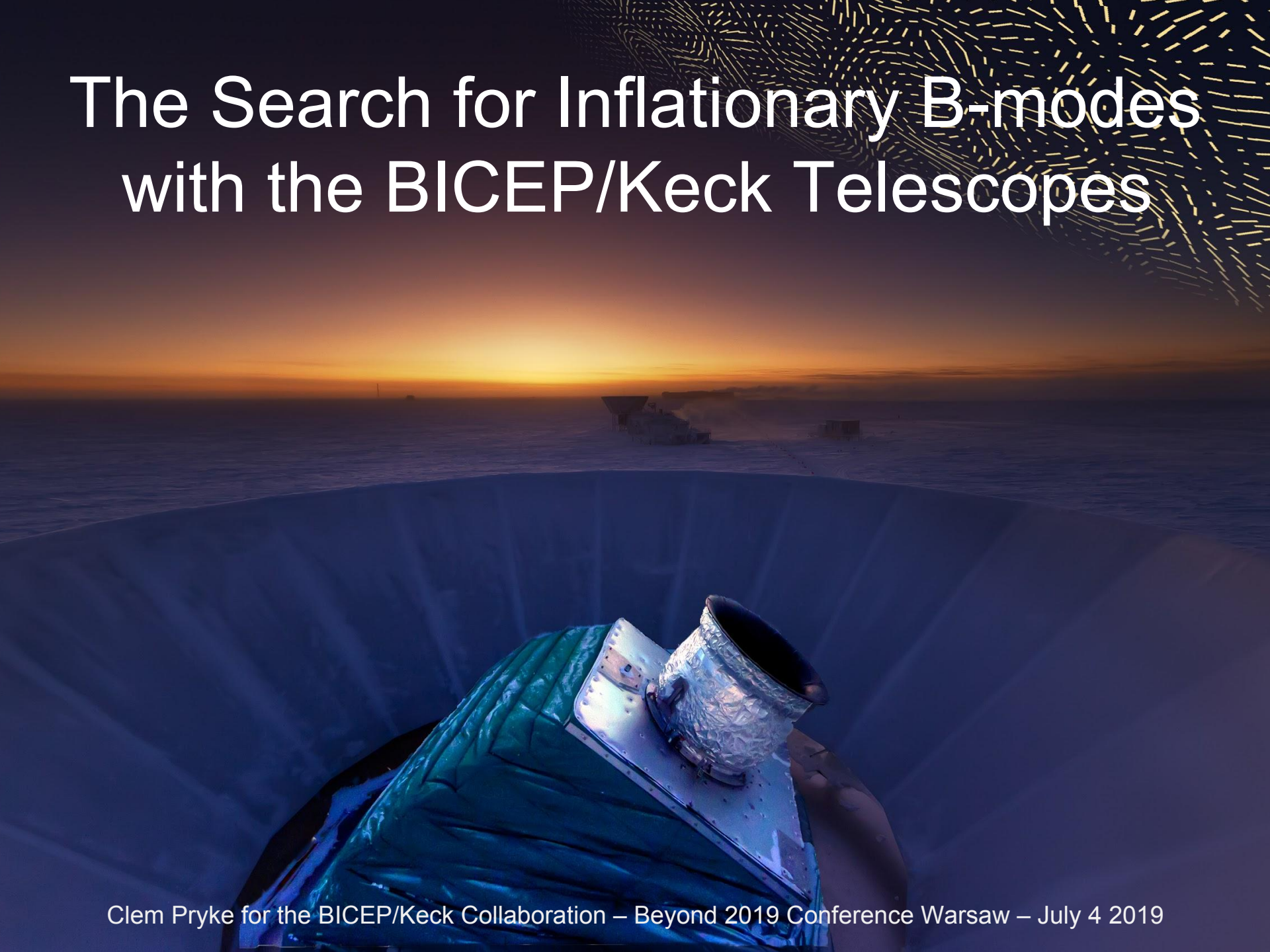
The Search for Inflationary B-modes with the BICEP/Keck Telescopes

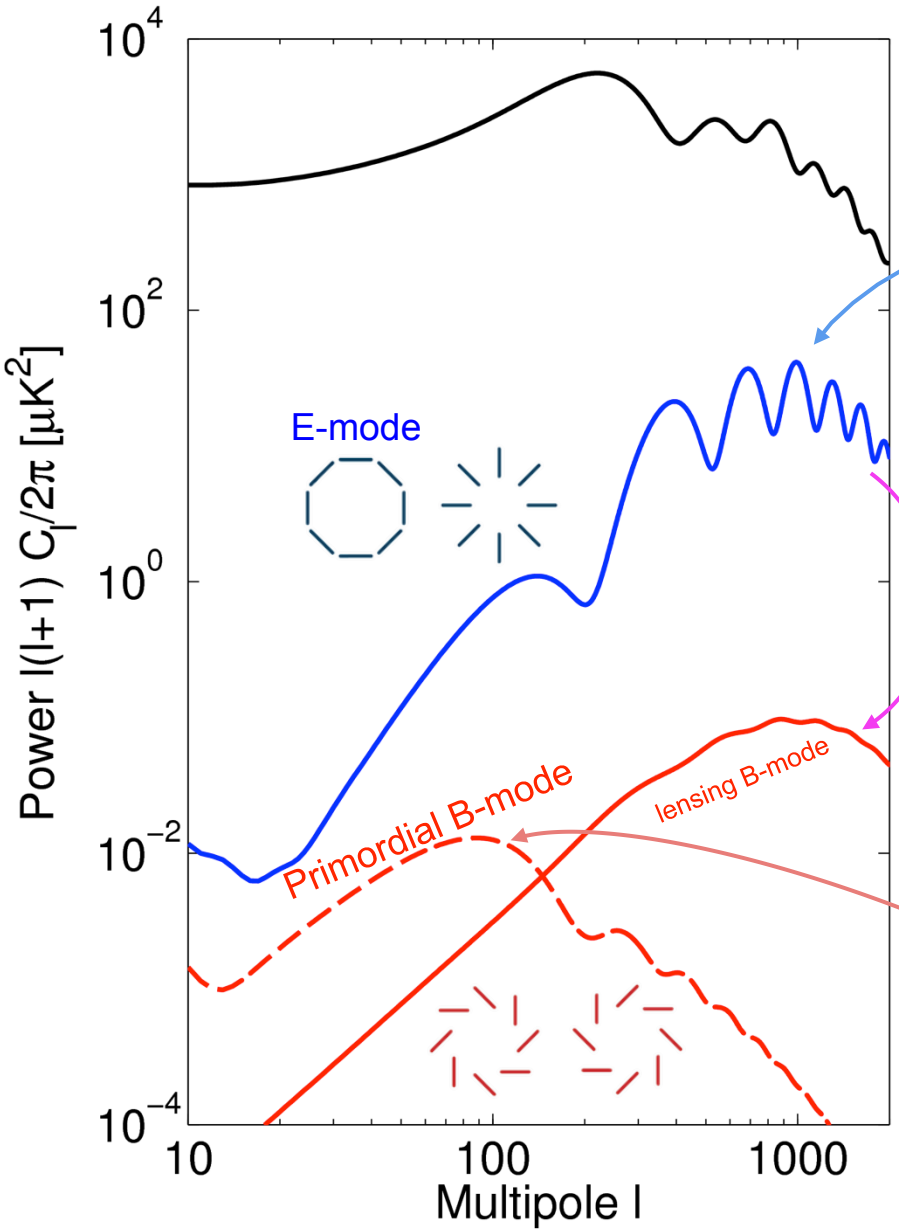


Clem Pryke for the BICEP/Keck Collaboration – Beyond 2019 Conference Warsaw – July 4 2019

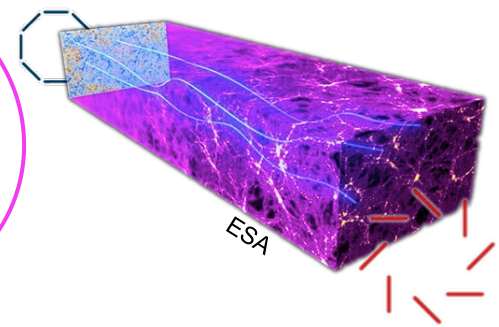
Motivation/Background

- 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 empirically simple conditions at the start of the plasma phase were set up.
- Theory of “Inflation” added on the beginning of LCDM to explain.
- If it happened 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



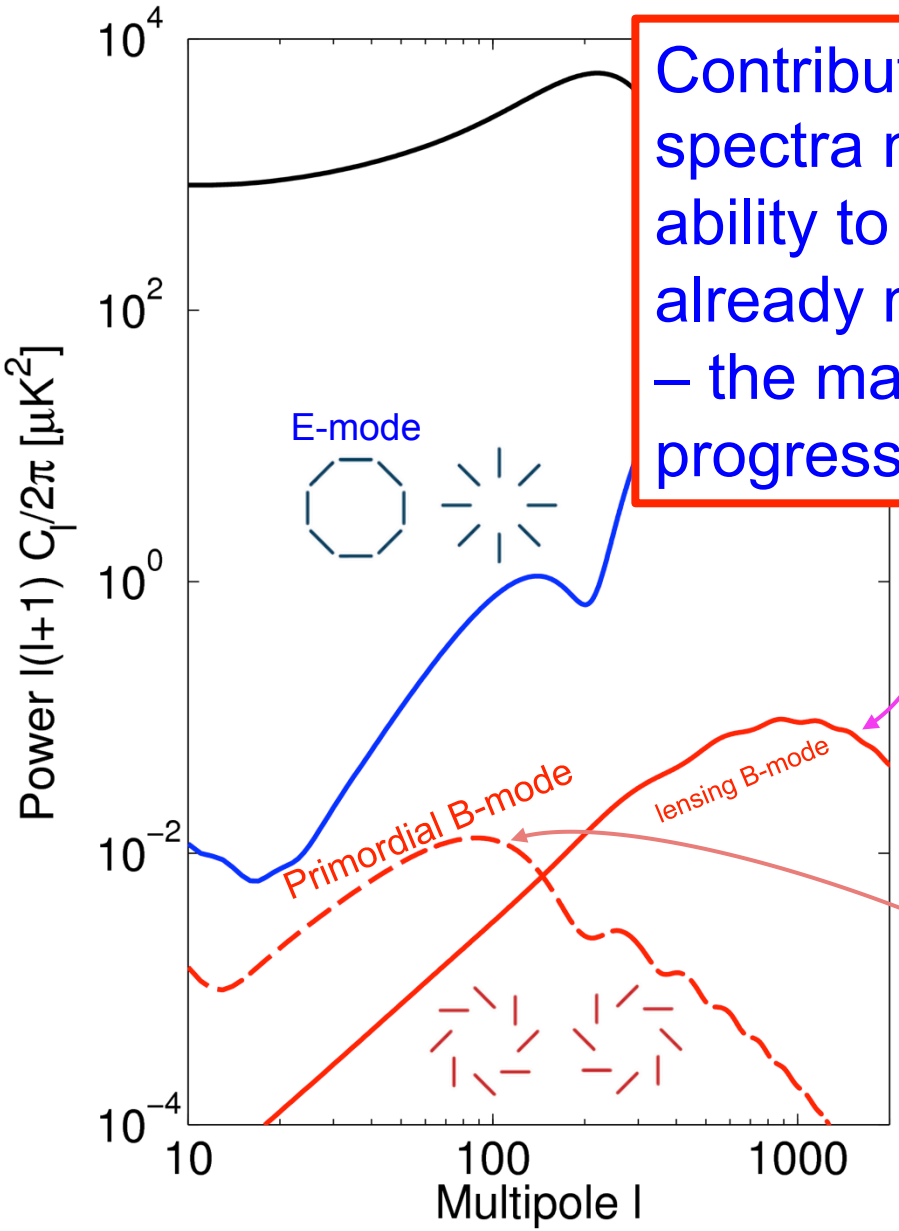
In standard ΛCDM only E-modes are present at last scattering



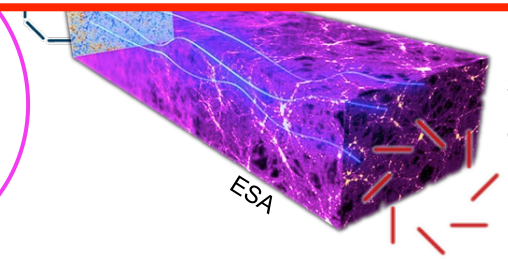
During propagation some of the E-modes are confused into B-modes by lensing

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

CMB power spectra



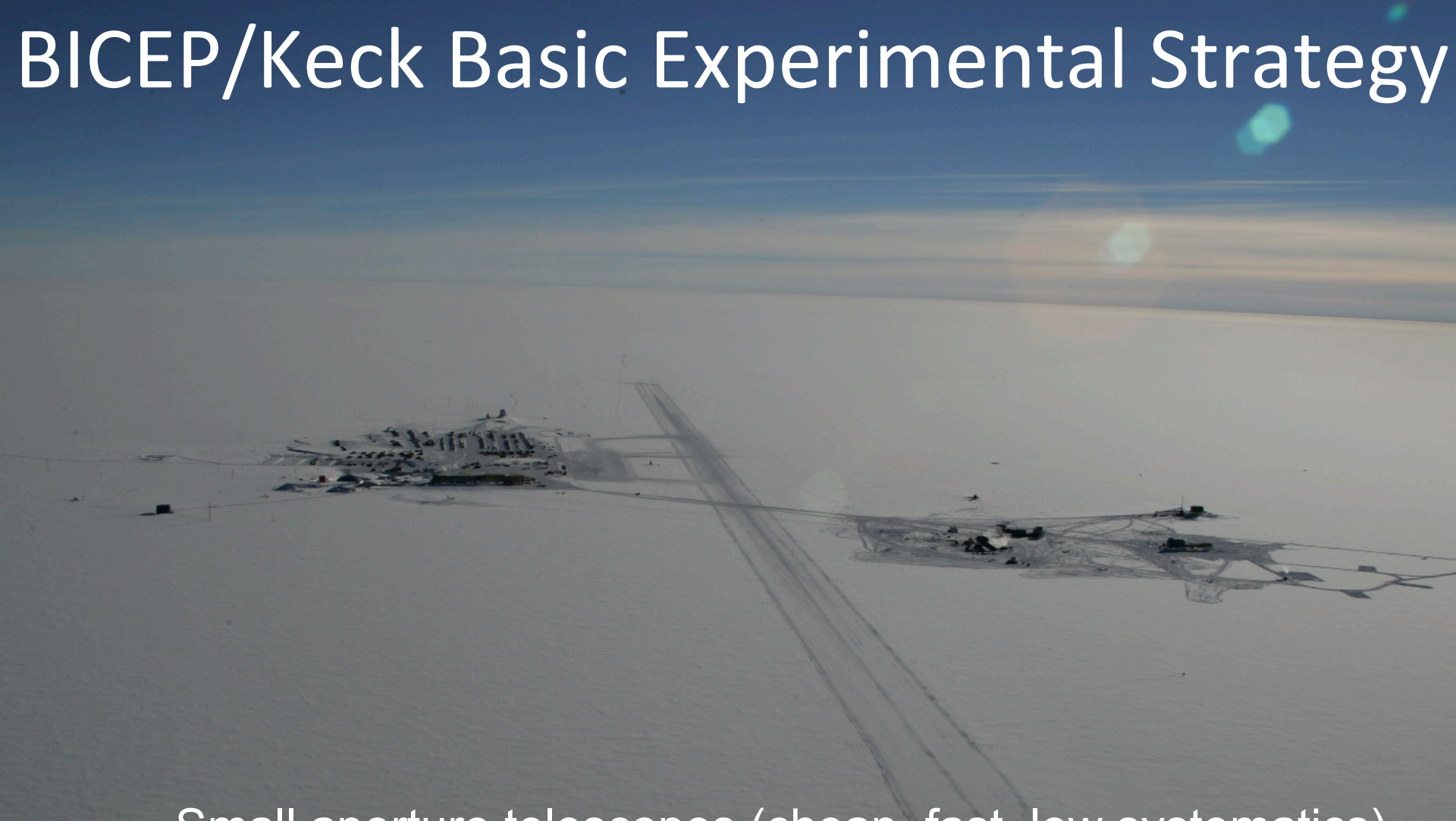
Contributions from PGW to T and E-spectra not shown here – However, ability to constrain *r* from these already maxed out at cosmic variance – the main way to make further progress is using B-modes…



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

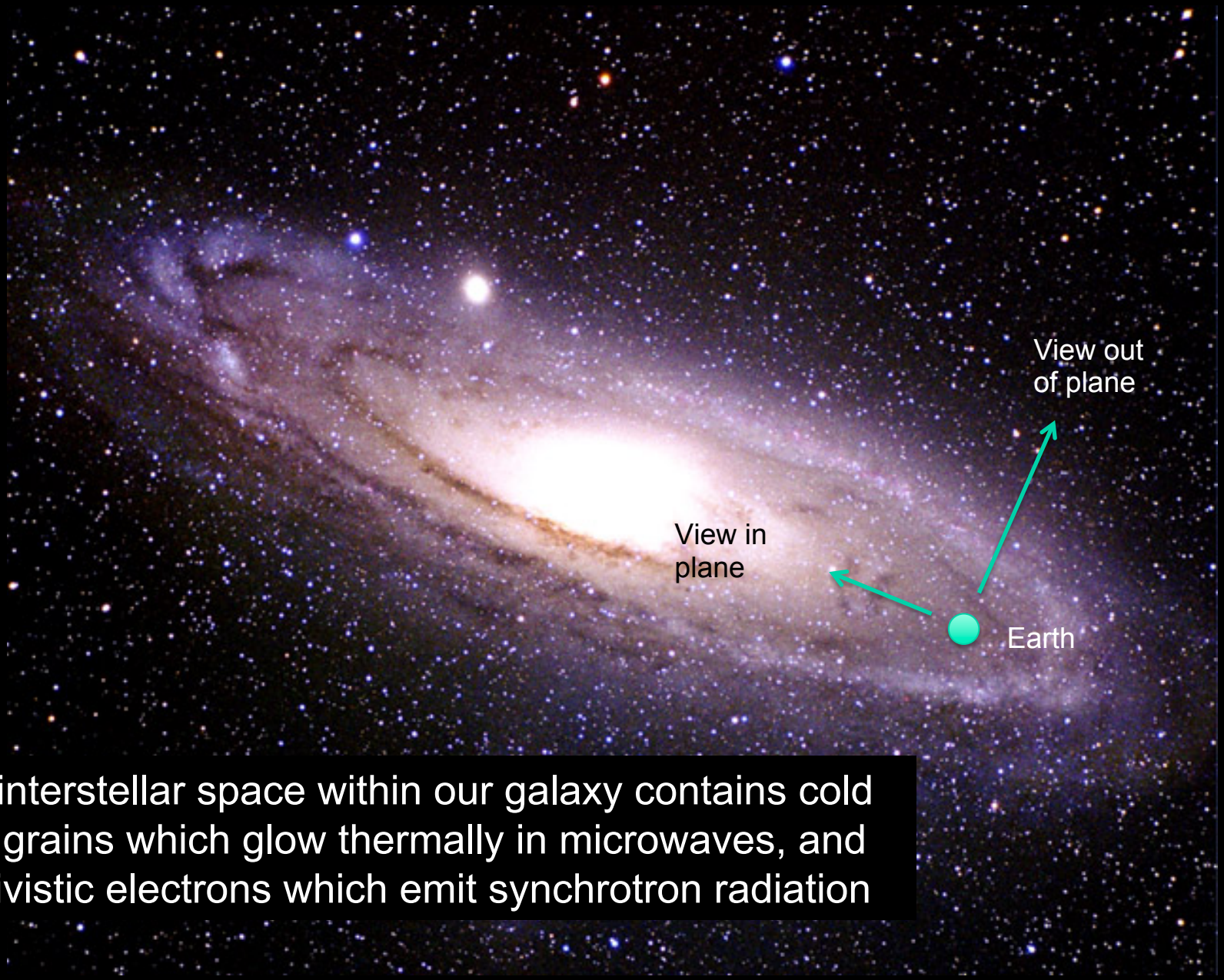
Inflationary gravitational waves are unique source of intrinsic B-modes
→ peaking at l≈80 : few degree scales

BICEP/Keck Basic Experimental Strategy



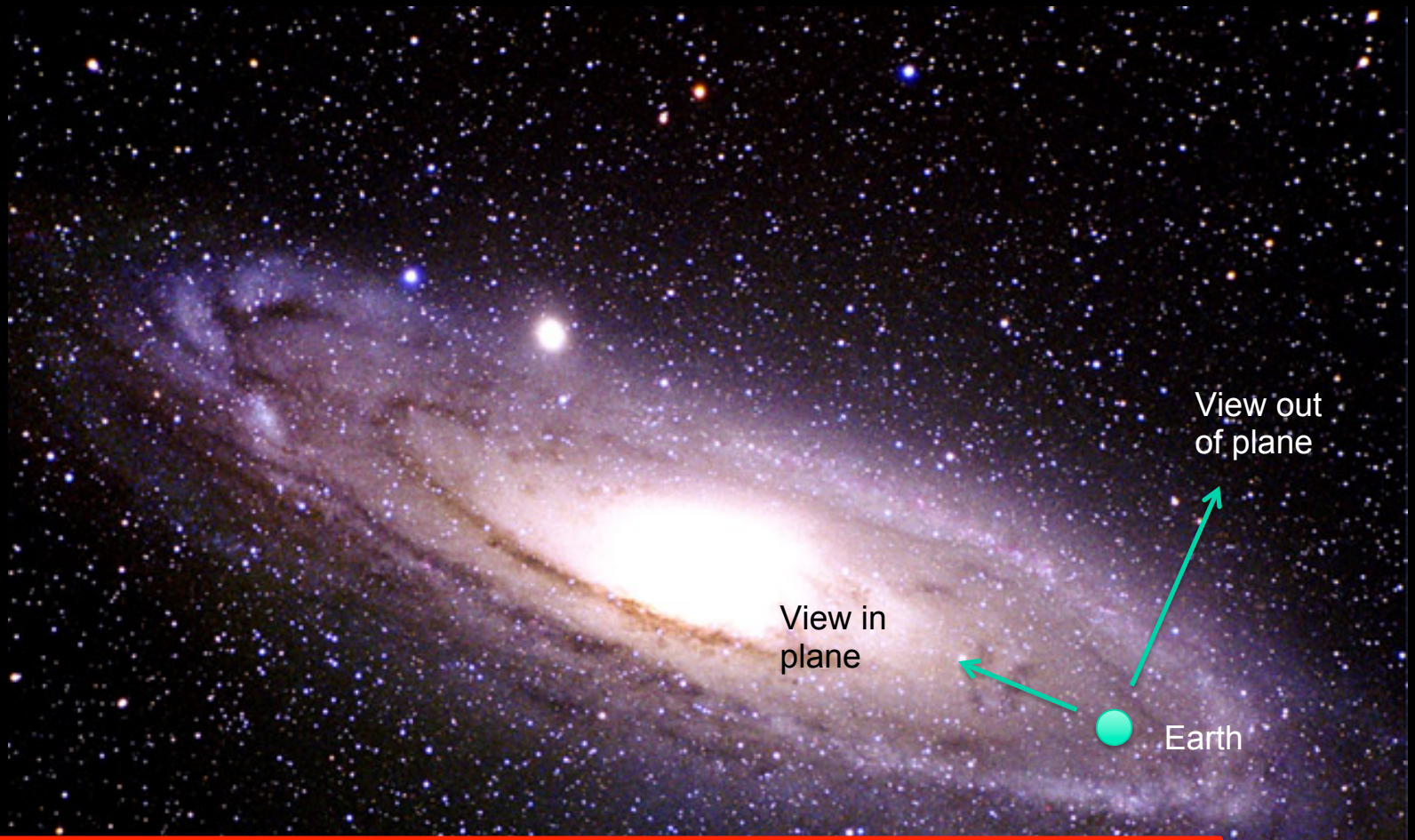
→ Small aperture telescopes (cheap, fast, low systematics)
→ Target the 2 degree peak of the PGW B-mode
→ Integrate continuously from South Pole
→ Observe 1% patch of sky (smaller is actually better!)
→ Scan and pair difference modulation

Foreground emission from our galaxy



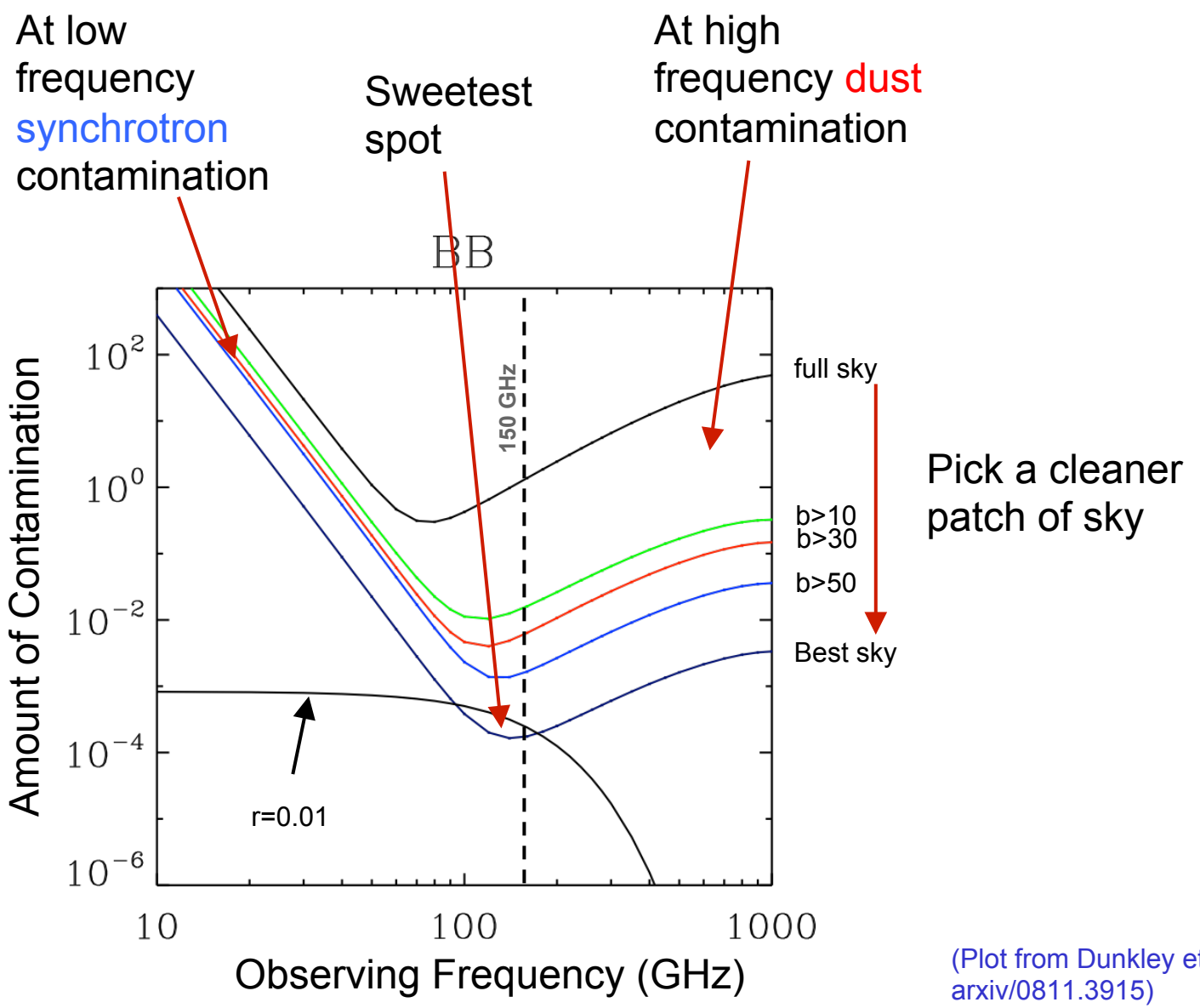
The interstellar space within our galaxy contains cold dust grains which glow thermally in microwaves, and relativistic electrons which emit synchrotron radiation

Foreground emission from our galaxy



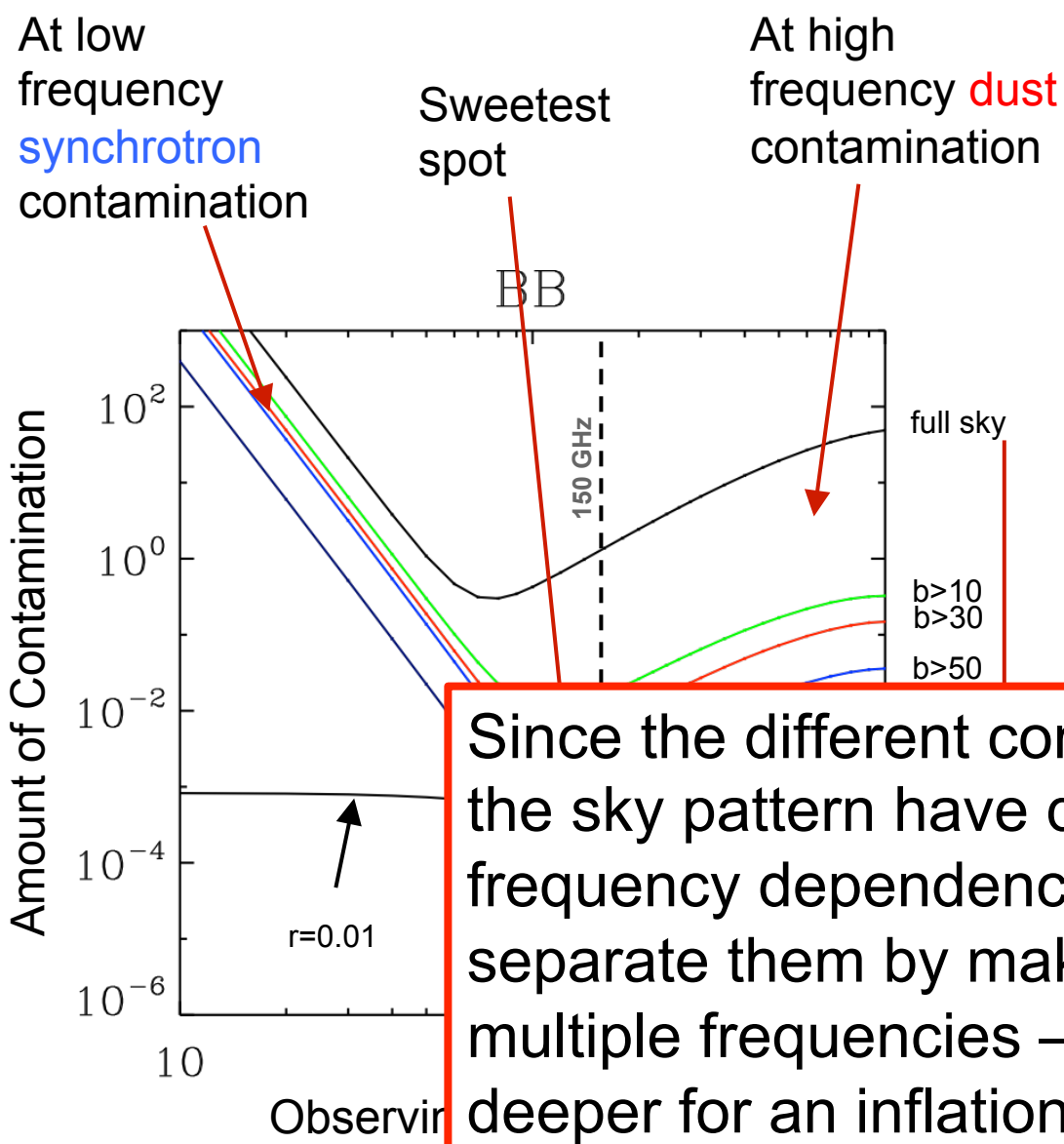
When CMB people talk about “foregrounds” it is analogous to what HEP people call “backgrounds” – something which gets in the way of the thing one is trying to measure.

Overcoming Polarized Foreground Contamination



(Plot from Dunkley et al arxiv/0811.3915)

Overcoming Polarized Foreground Contamination

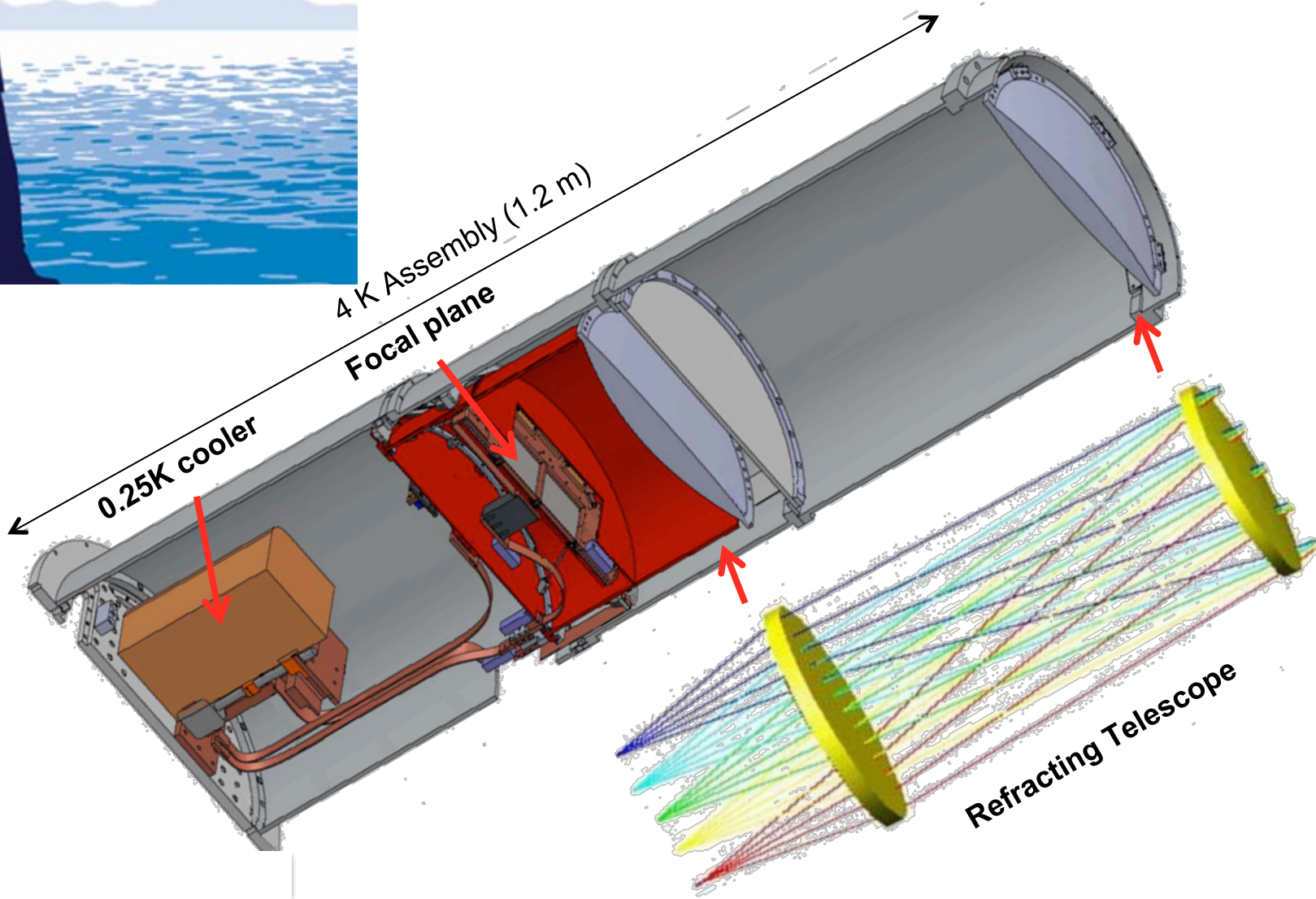


Pick a cleaner patch of sky

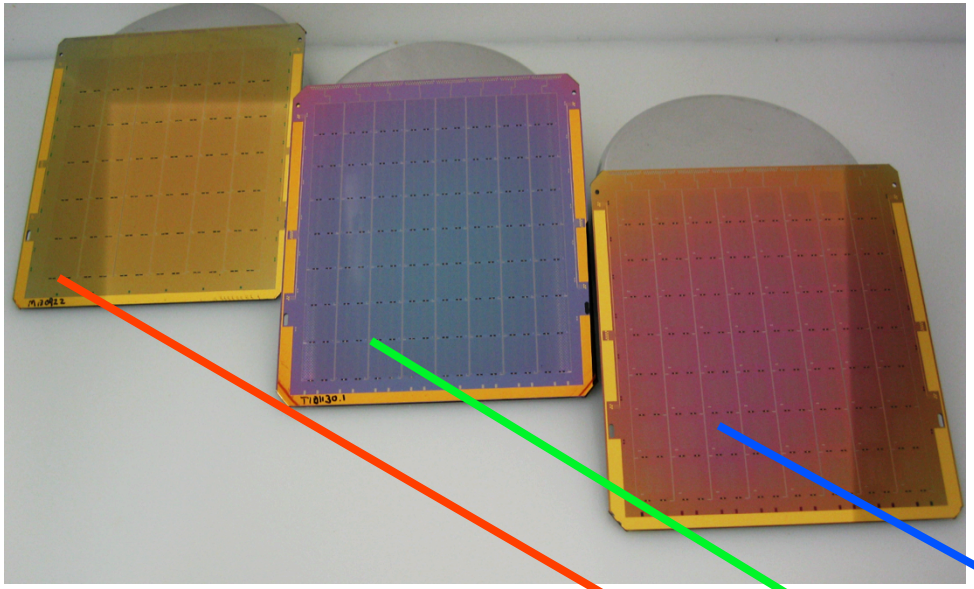
Since the different components of the sky pattern have different frequency dependencies one can separate them by making maps at multiple frequencies – and probe deeper for an inflation signal

BICEP/Keck Experimental Concept

- Small aperture
- Wide field of view
- Cold refractor

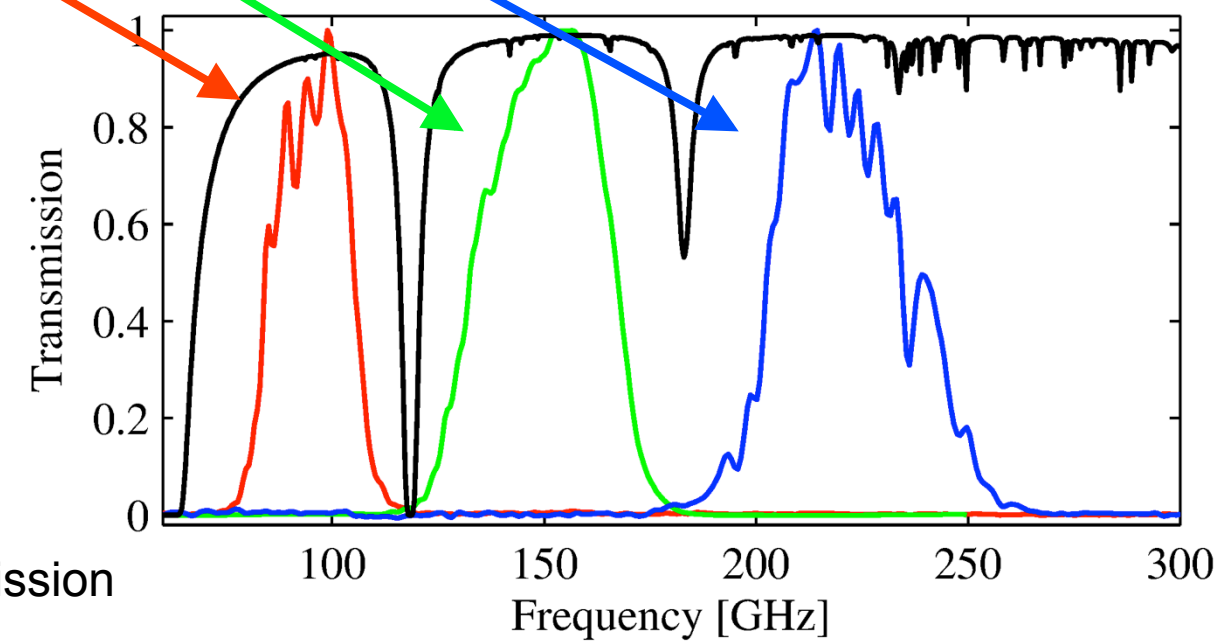


Planar superconducting detector arrays



…designed to scale
in frequency

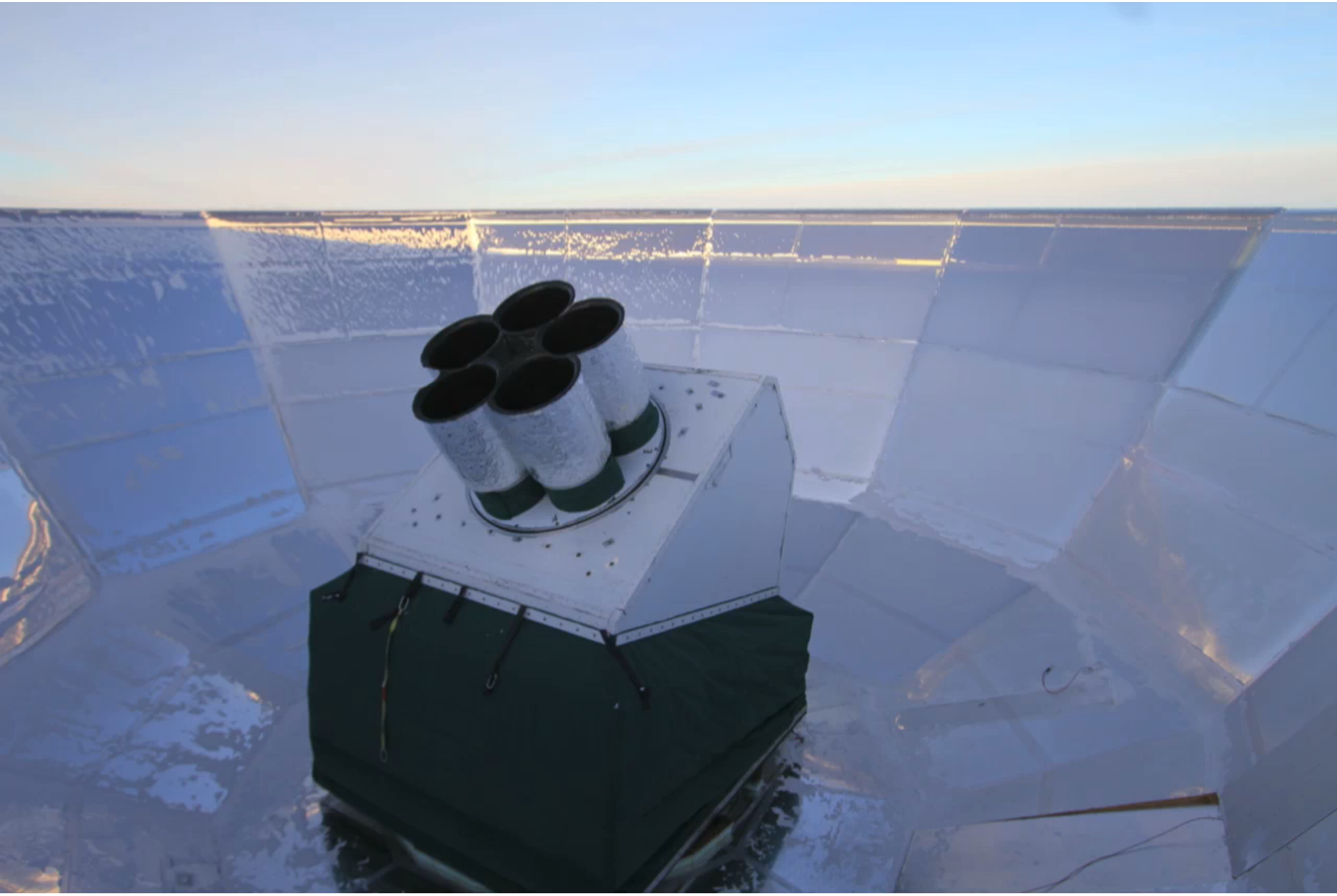
Up to 2013 – all 150GHz
2014 – 2x95 3x150GHz
2015 – 2x95 1x150 2x220GHz
2016 – B3 1x150 4x220GHz
2017 – B3 4x220 1x270GHz
2018 – B3 4x220 1x270GHz



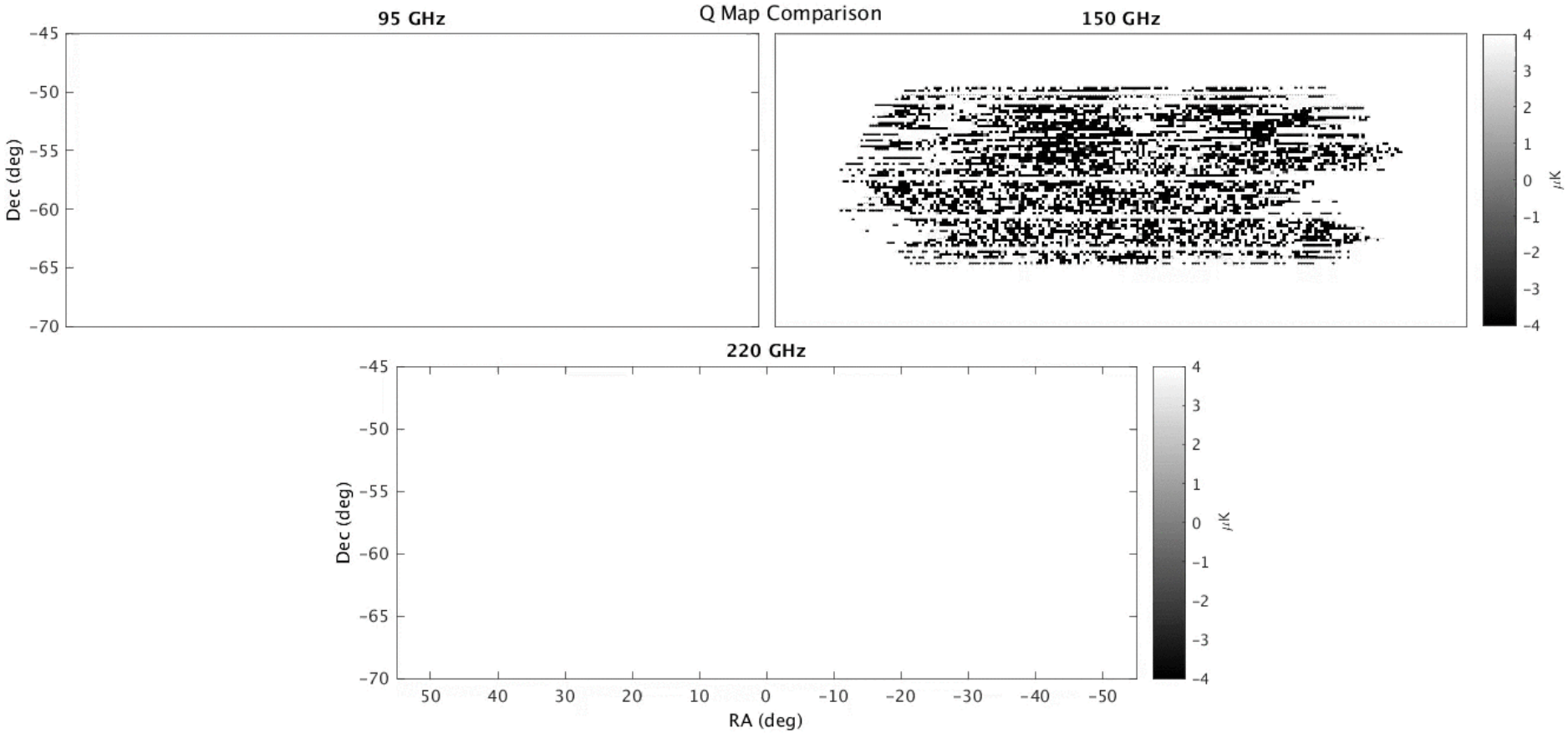
Typical South Pole
atmospheric transmission

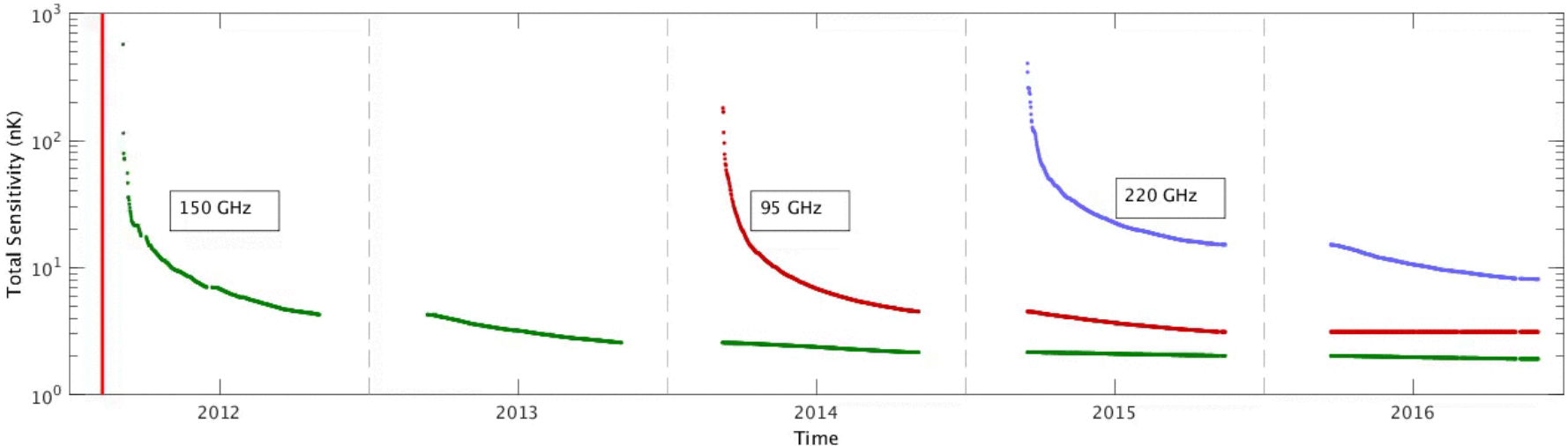
Why do this at the Pole?

- High and *dry* – see out into space
- On Earth's rotational axis - One day/night cycle per year
  - Long night makes for great quality data
- Good support infrastructure – power, cargo, data comm
- Food and accommodation provided
- Even Tuesday night bingo…



Clem Pryke for The Bicep2 Collaboration


Q Map Comparison
95 GHz
150 GHz
220 GHz
Dec (deg)
RA (deg)
μK


Total Sensitivity (nK)
Time
150 GHz
95 GHz
220 GHz
2012
2013
2014
2015
2016

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)

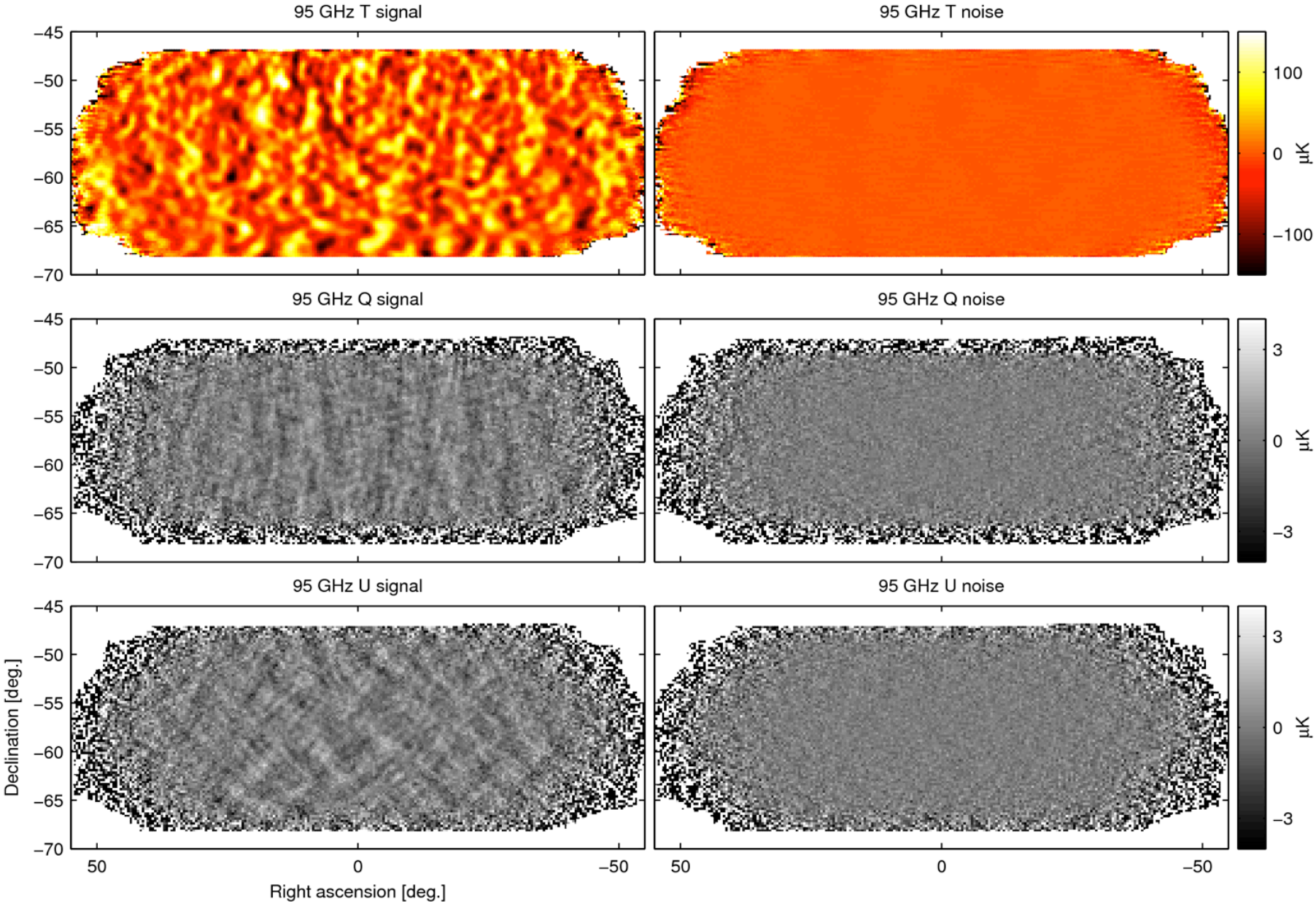
We present results from an analysis of all data taken by the BICEP2/*Keck* CMB polarization experiments up to and including the 2015 observing season. This includes the first *Keck Array* observations at 220 GHz and additional observations at 95 & 150 GHz. The Q/U maps reach depths of 5.2, 2.9 and 26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

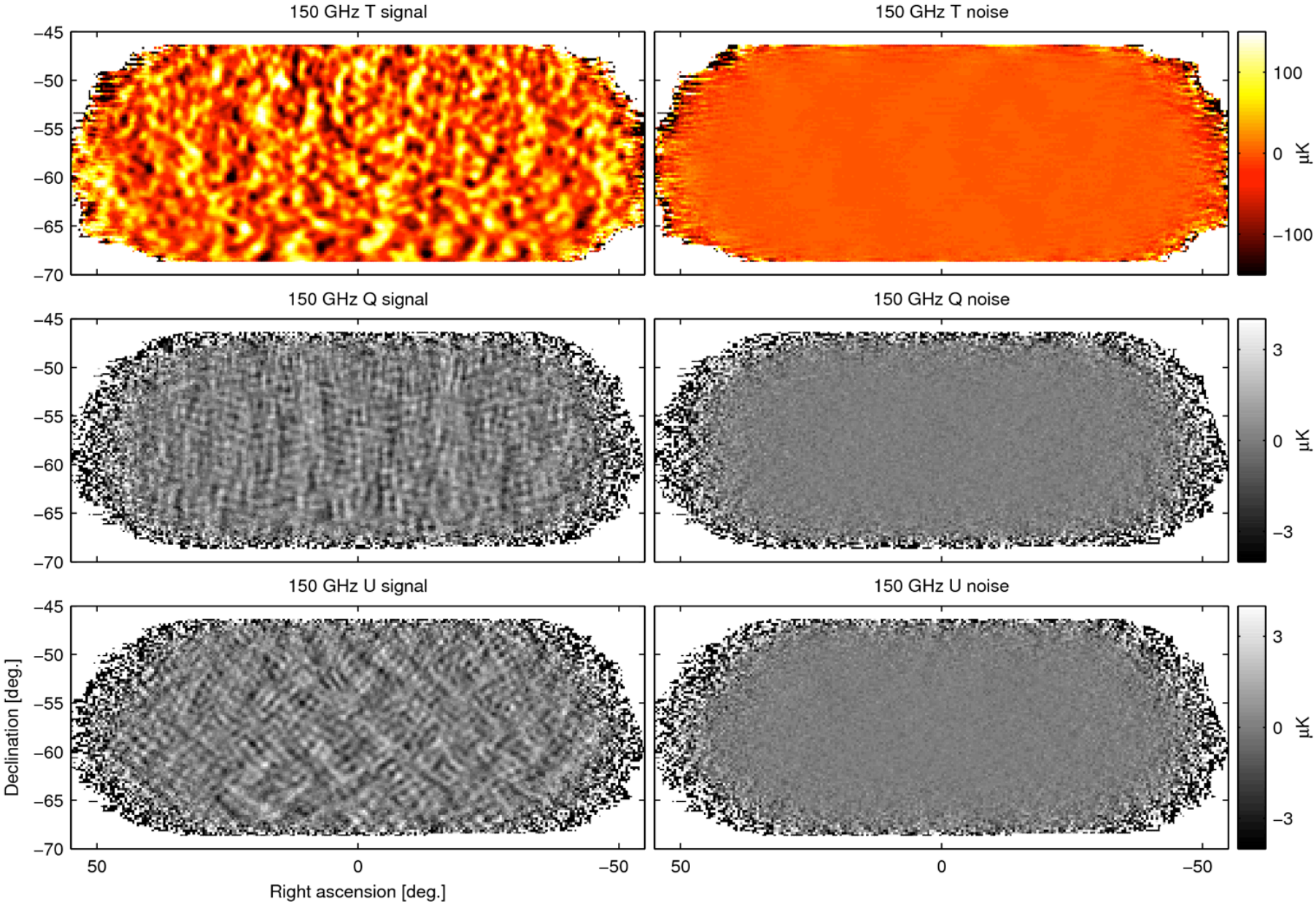
Came three years after BK14 – Sorry for the delay!

BK15 95GHz Maps



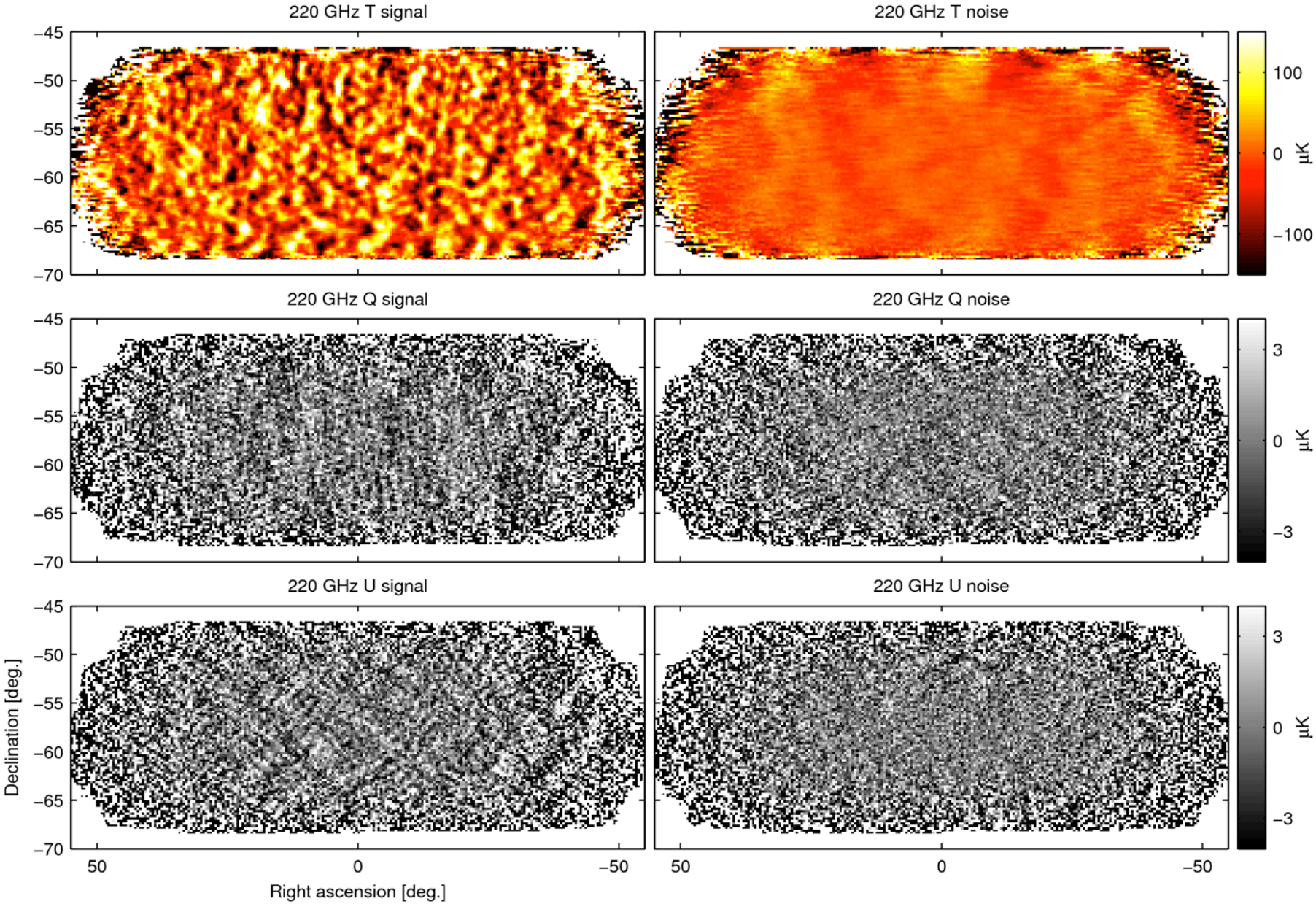
BK15 95GHz – noise 5 μK arcmin

BK15 150GHz Maps



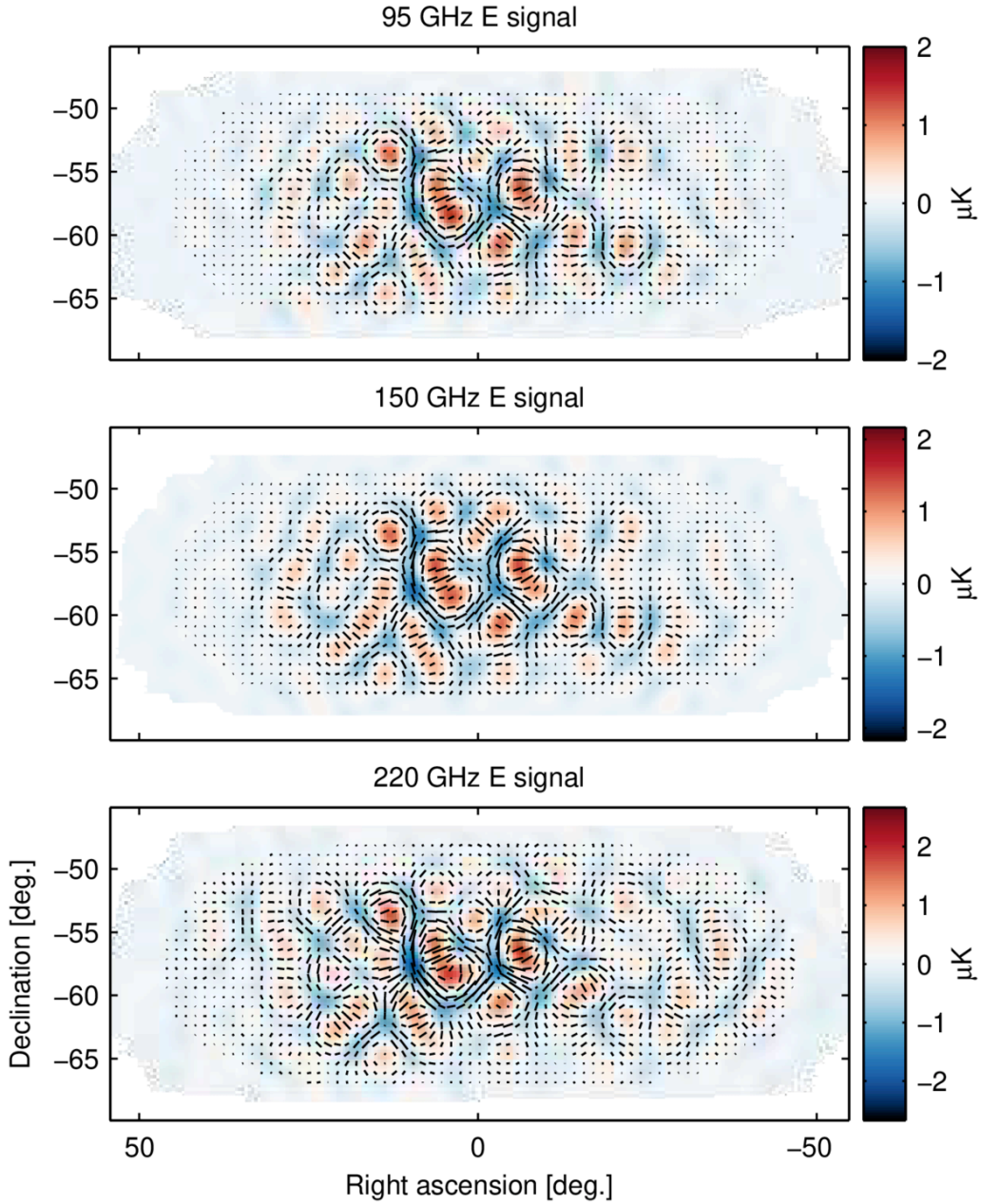
BK15 150GHz – noise 2.8 μK arcmin

BK15 220GHz Maps



BK15 220GHz – noise 25 μK arcmin

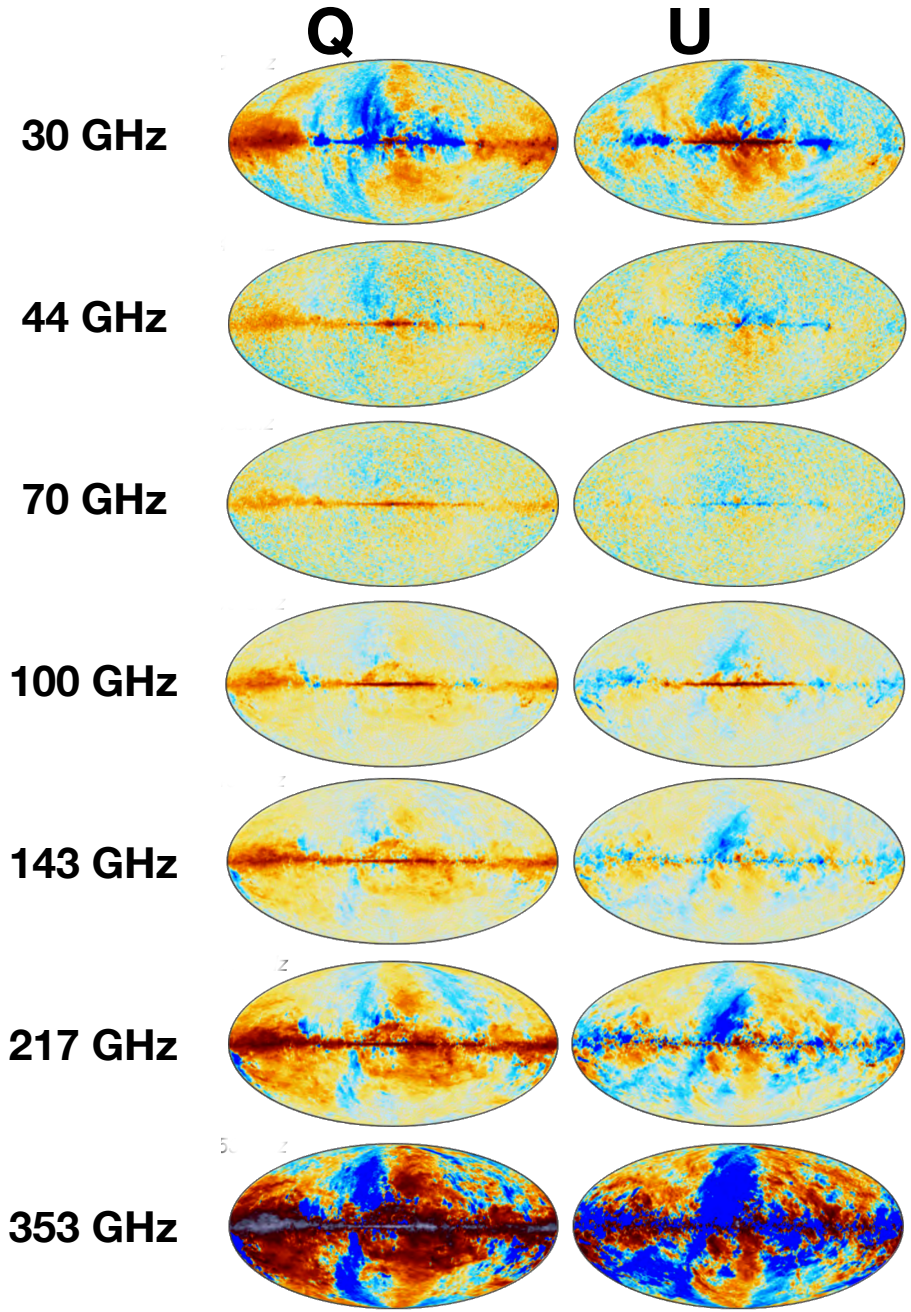
Just for fun: Keck 2015 single season E-mode maps



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

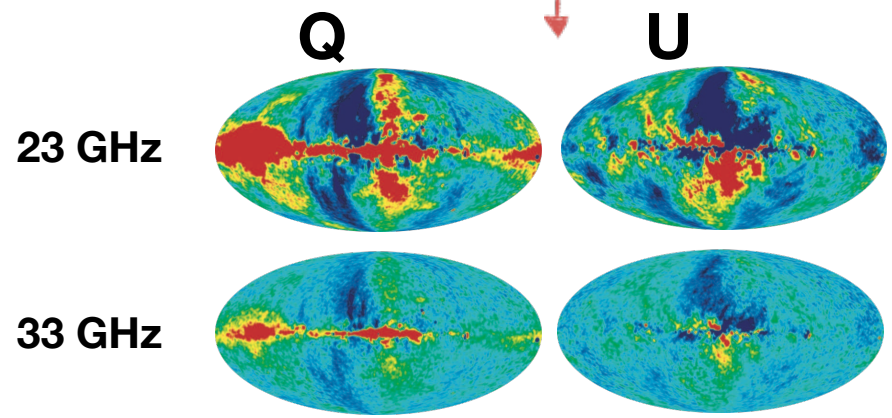
Already deeper than Planck 217 GHz

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



From arxiv 1502.01582

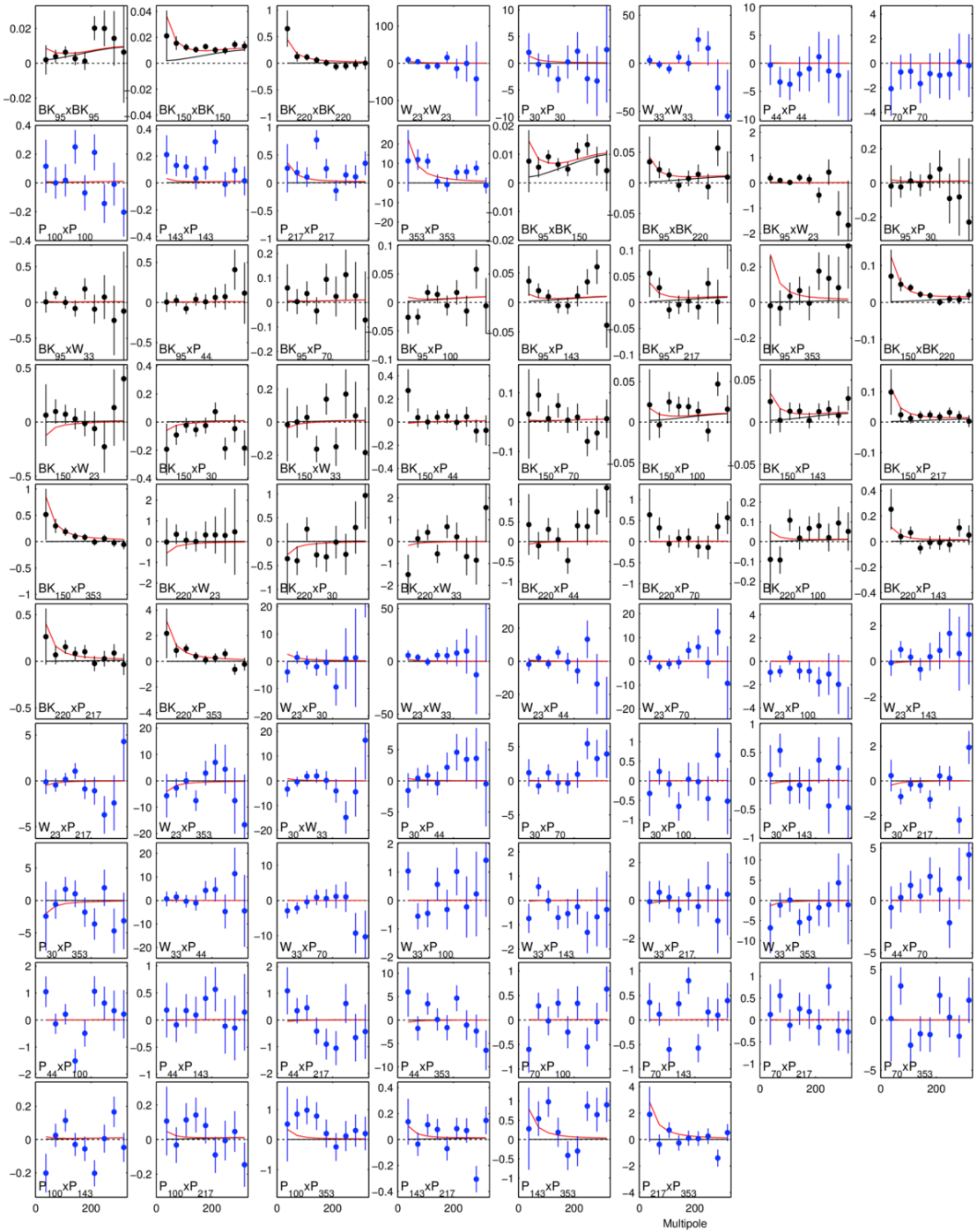
Polarized galactic **synchrotron** dominates at low frequencies



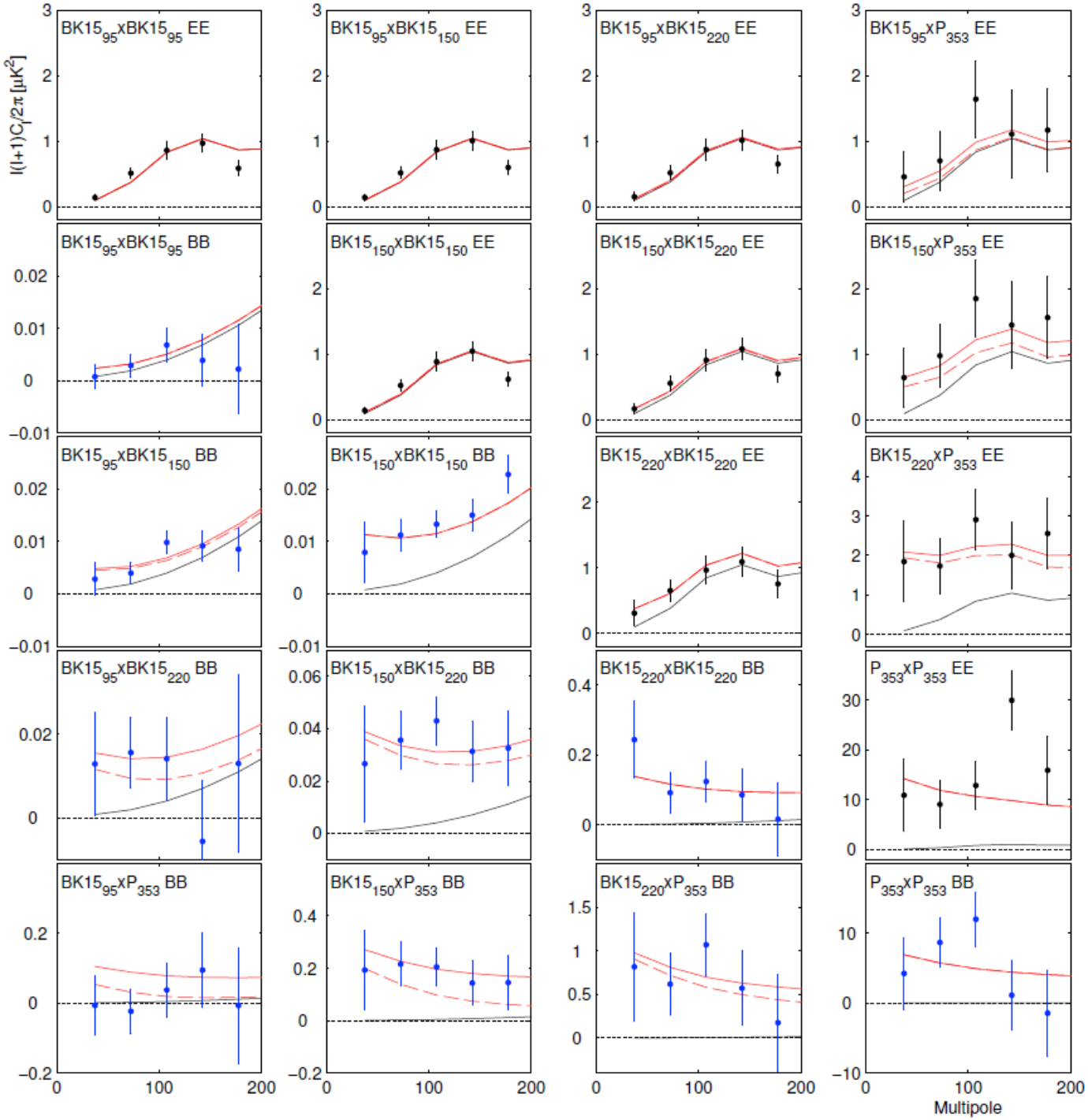
From arxiv 1212.5225

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

Analysis Technique: Take all possible auto- and cross spectra between the BICEP/Keck, WMAP, and Planck bands (78 of them) and compare to model of CMB +foregrounds



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

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?

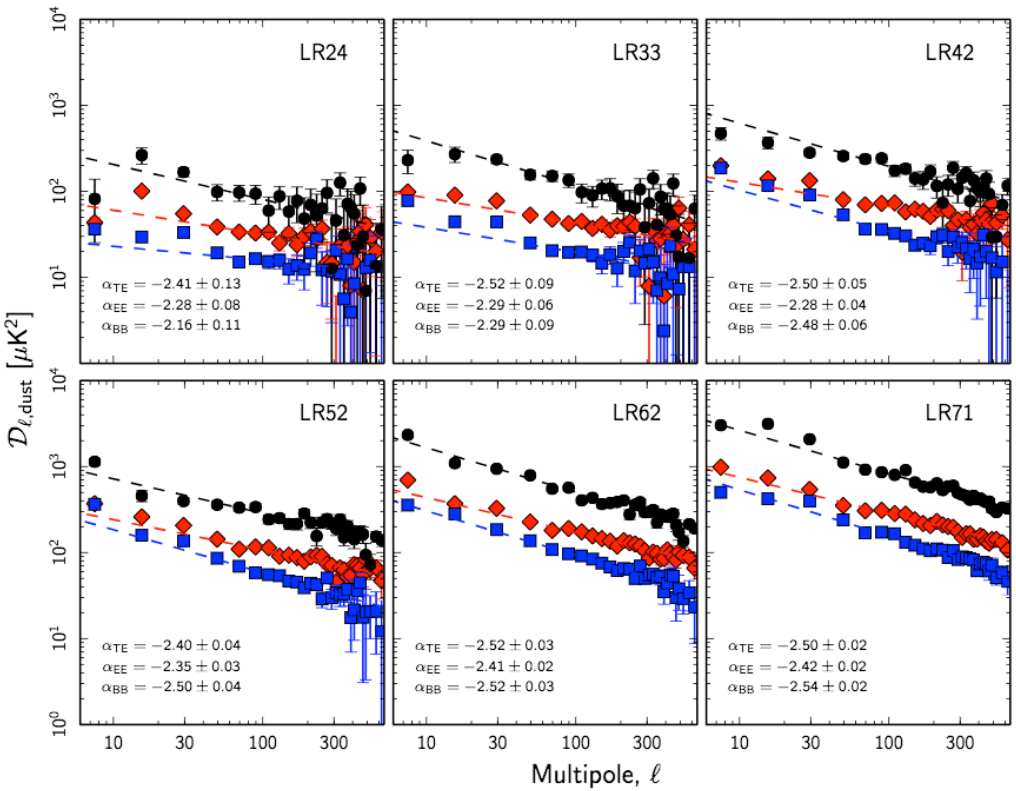


Fig 2 of arxiv/1801.04945 – Planck dust analysis

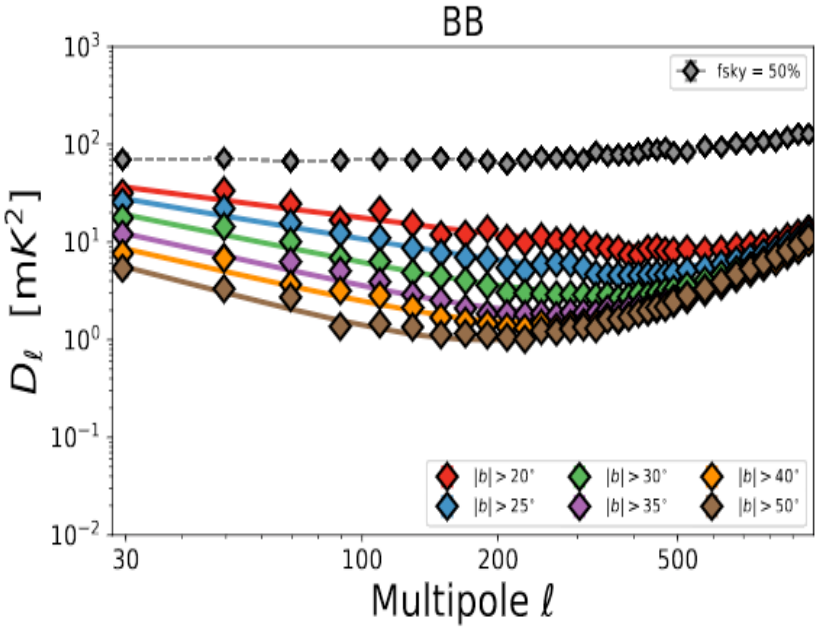
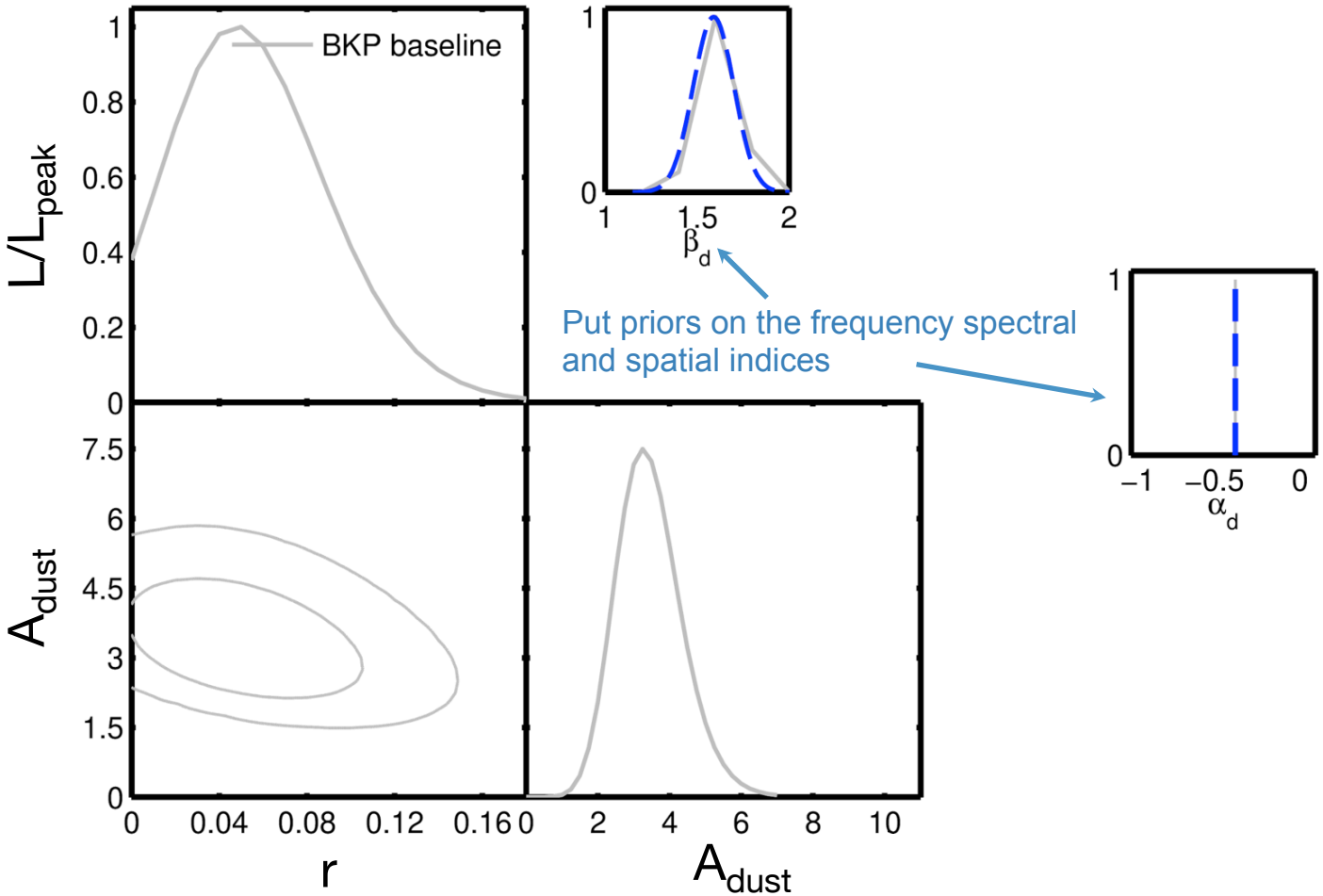


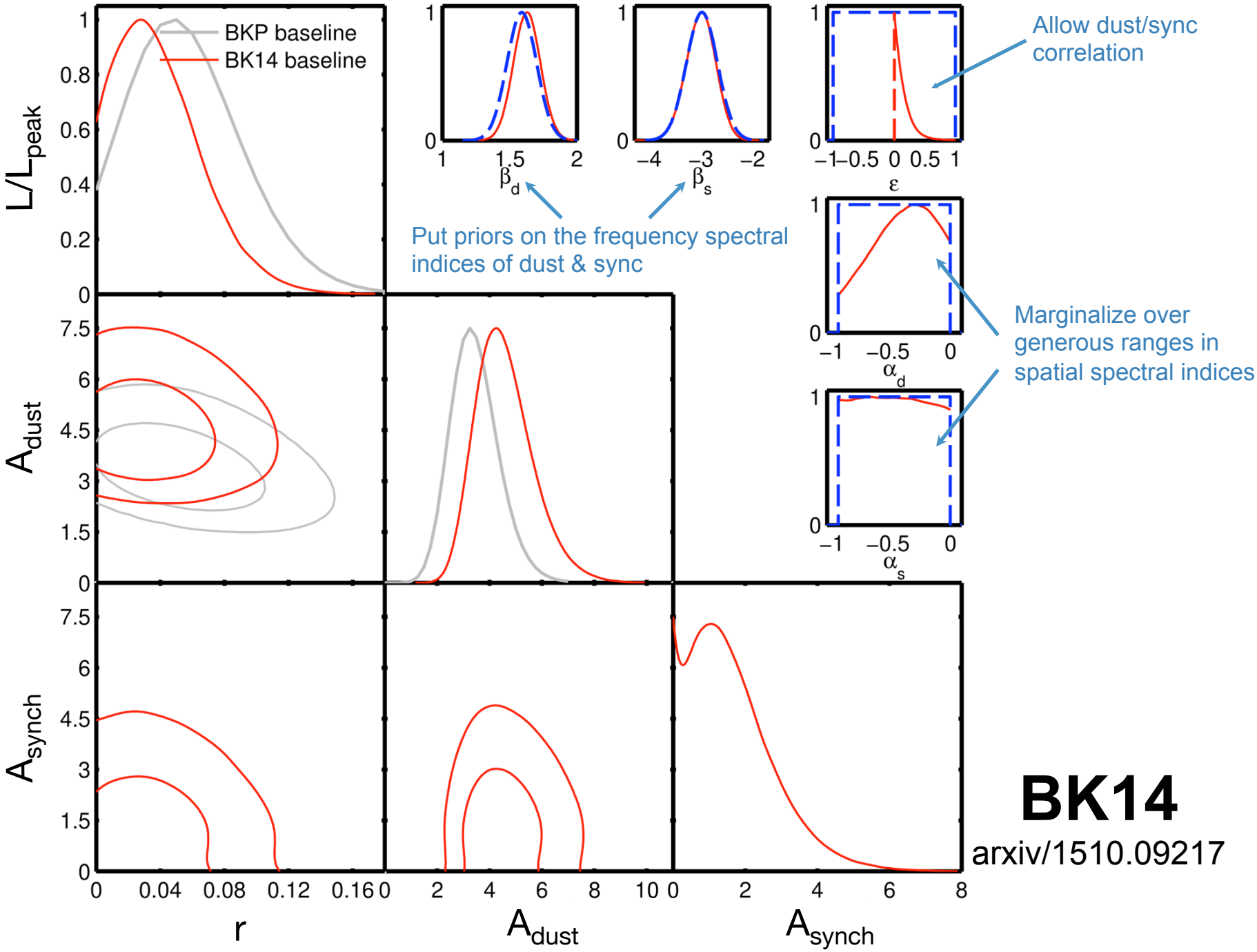
Fig 2 of arxiv/1802.01145. – S-PASS sync analysis

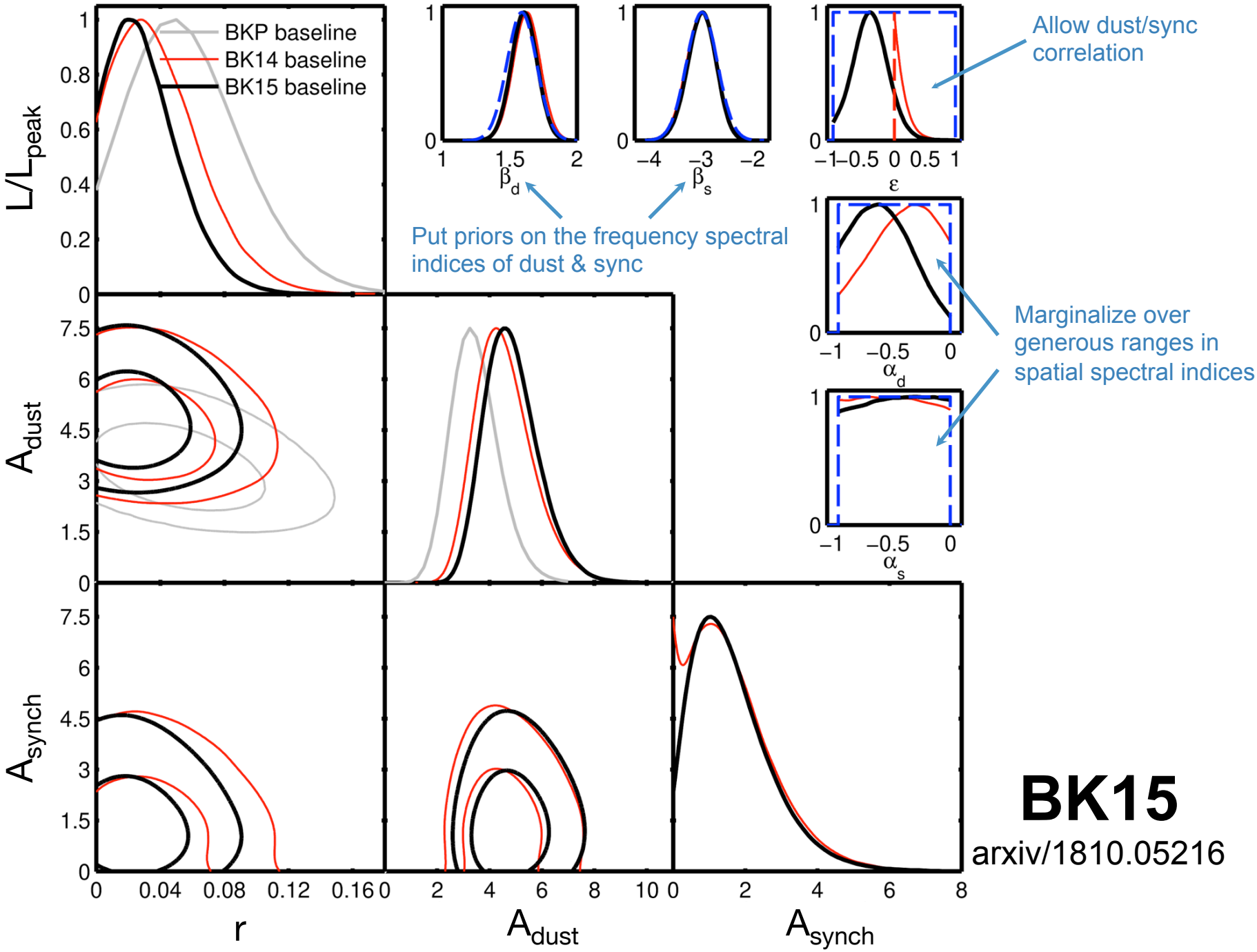
- Averaged over large regions of sky it is an empirical fact that dust and sync have roughly power law angular power spectra
- Not enough signal-to-noise in Planck data to investigate fluctuations about this behavior for small sky patches

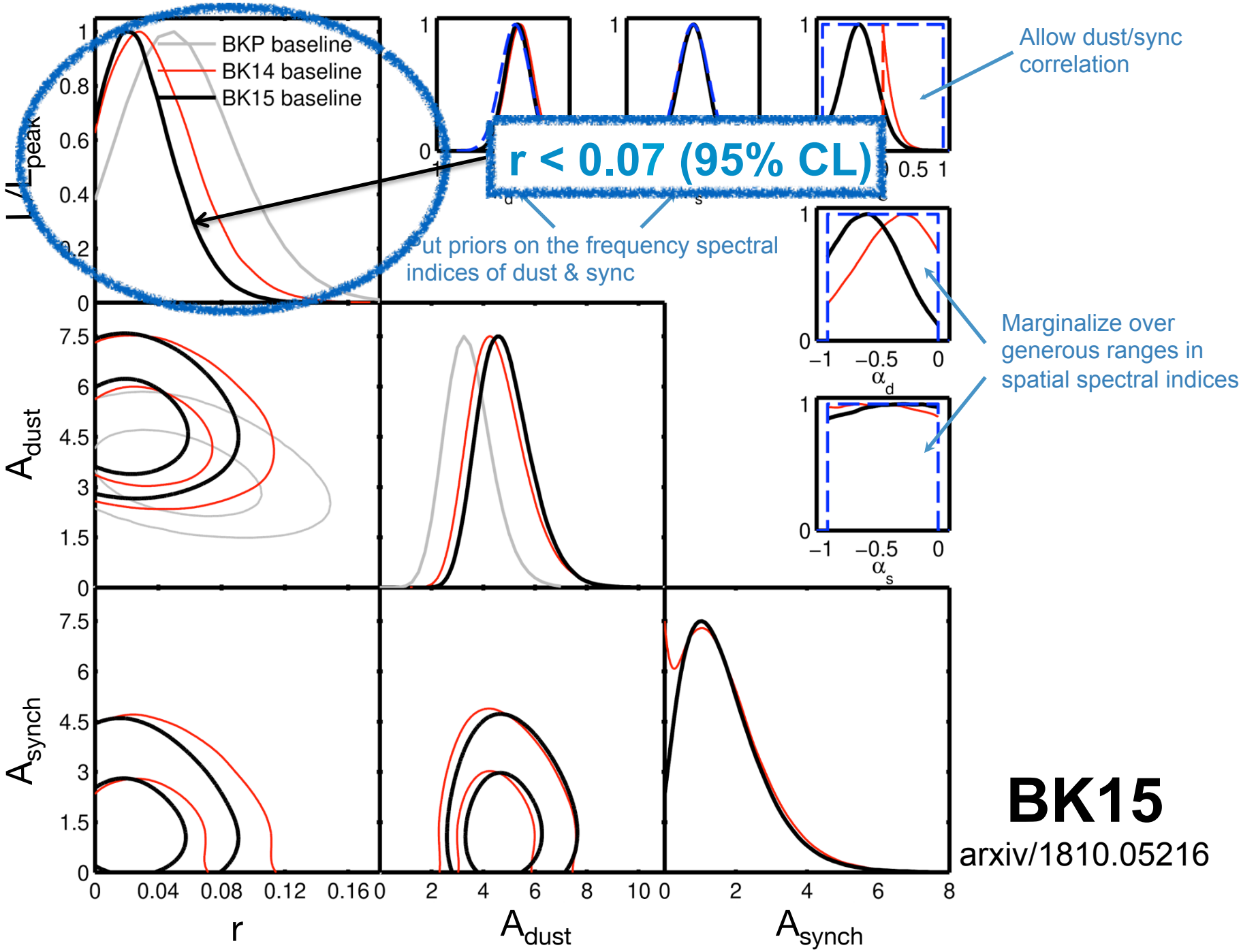


BKP

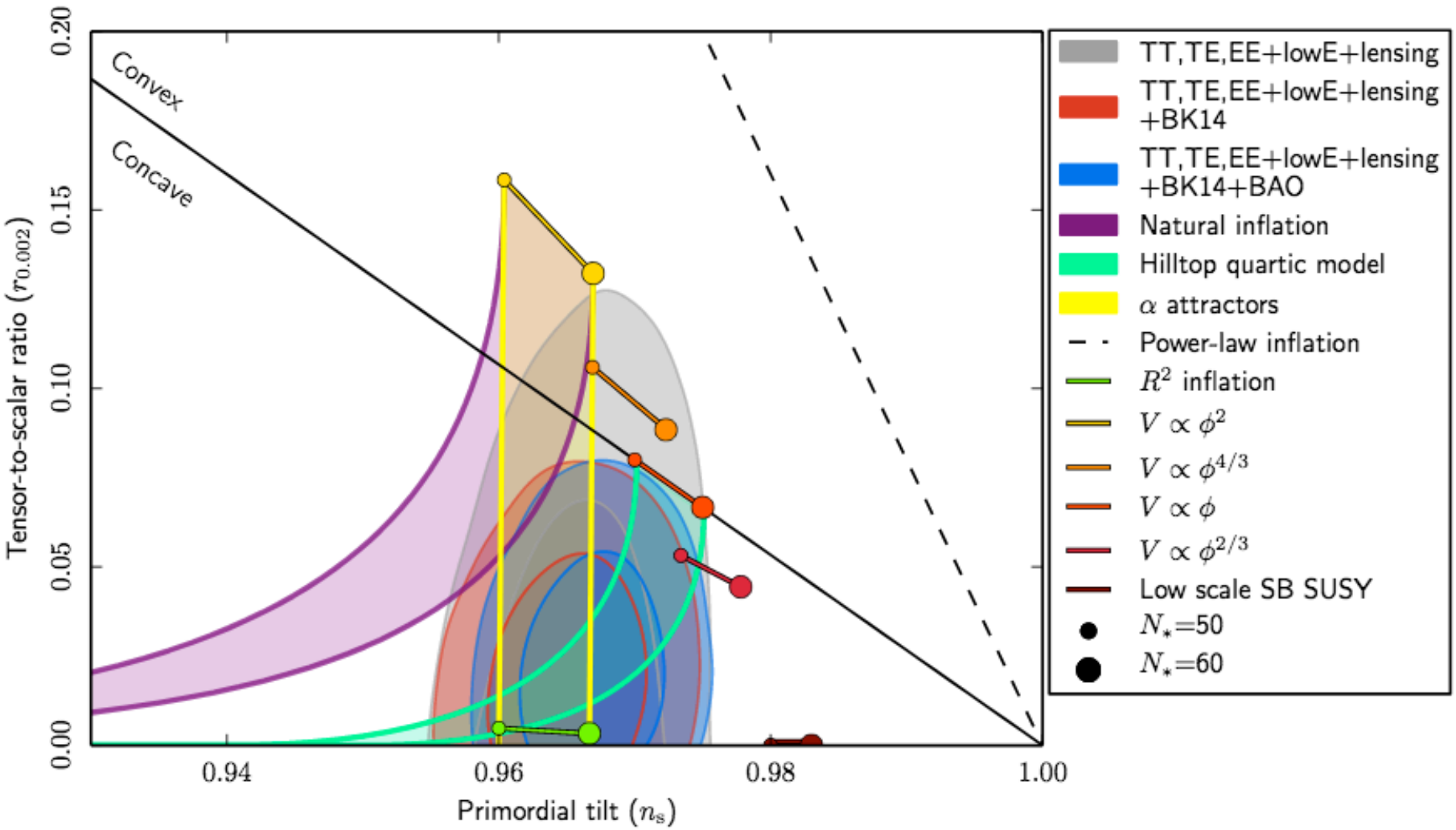
arxiv/1502.00612


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

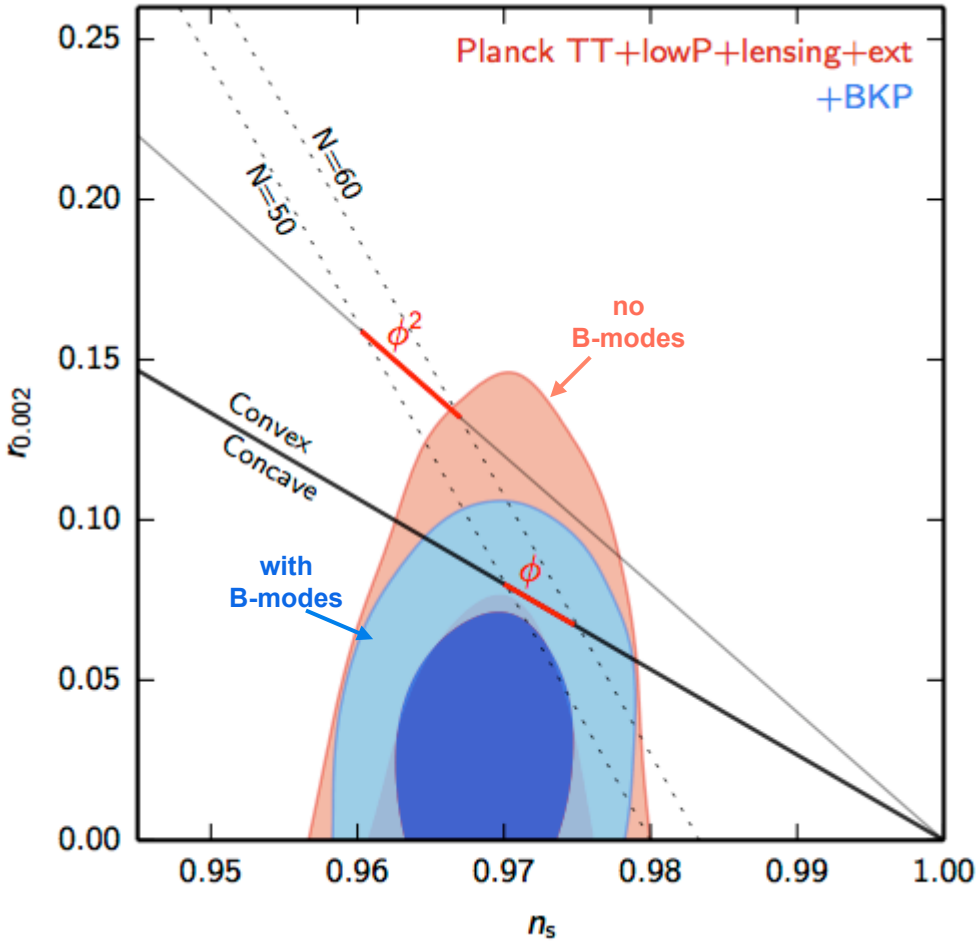

BKP baseline
BK14 baseline
BK15 baseline
L/L_peak
A_dust
A_synch
r
β_d
β_s
ε
α_d
α_s
Allow dust/sync correlation
Put priors on the frequency spectral indices of dust & sync
Marginalize over generous ranges in spatial spectral indices
BK15
arxiv/1810.05216


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

Aside: Planck results since 2015 release include BK data



Adding in temperature data



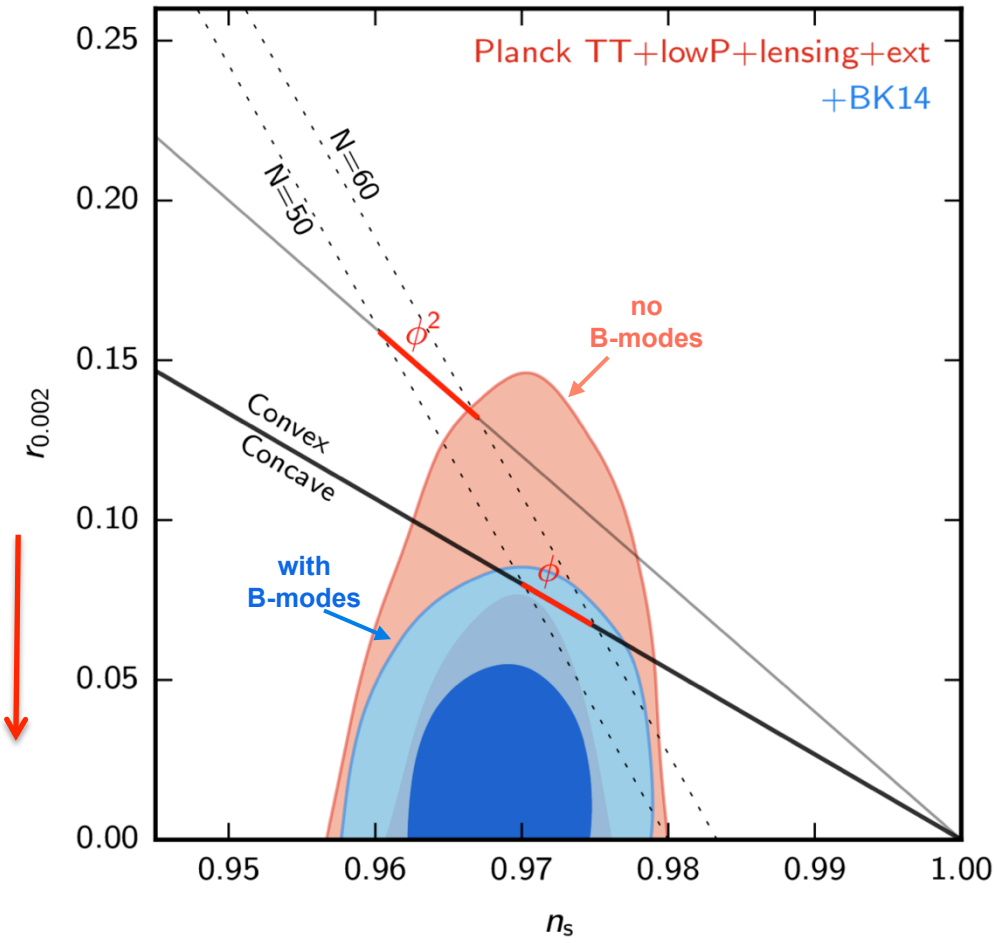
BKP

arxiv/1502.00612

r < 0.09

Adding in temperature data

Shift down due to additional polarization data



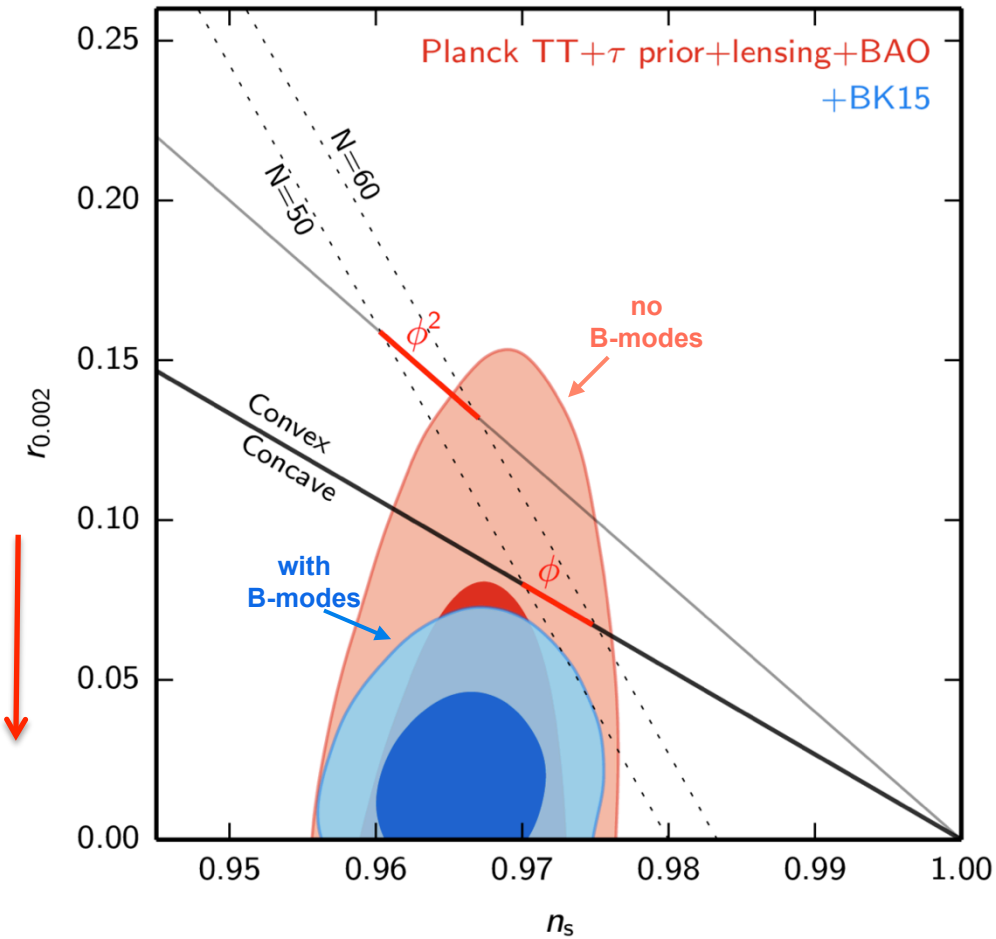
BK14

arxiv/1510.09217

r < 0.07

Adding in temperature data

Shift down due to additional polarization data



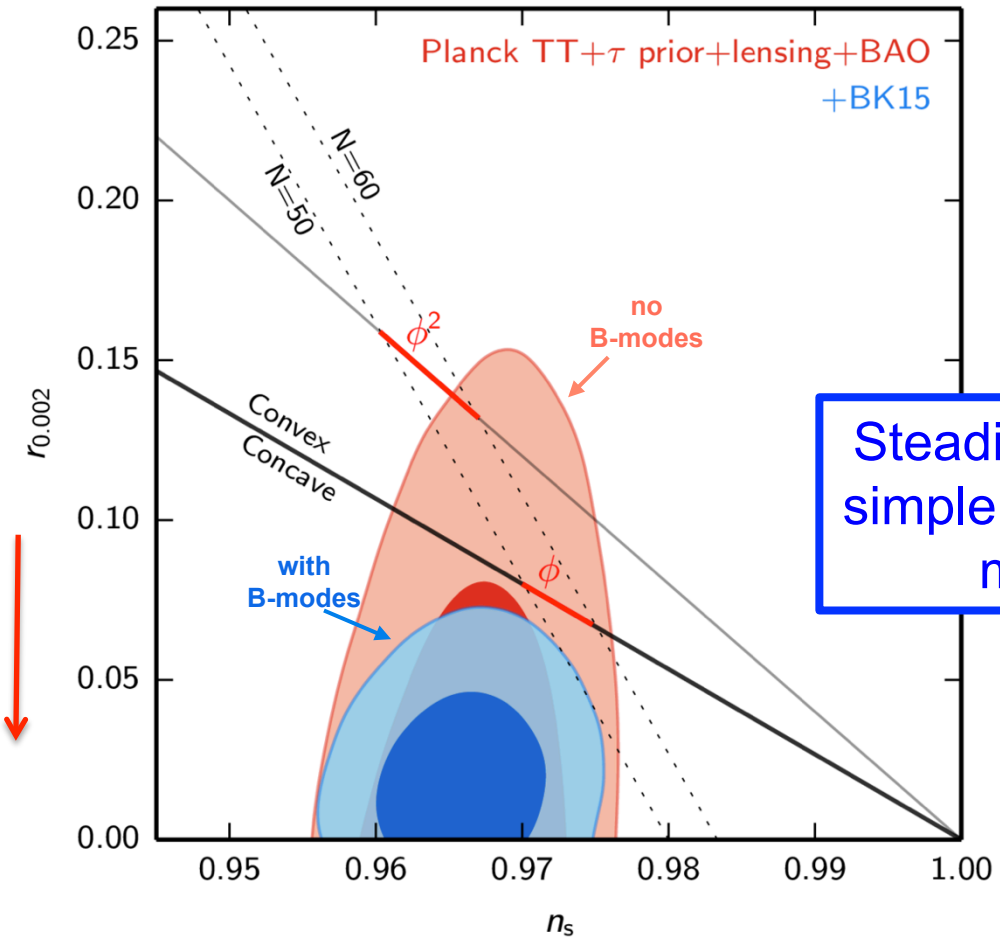
BK15

arxiv/1810.05216

r < 0.06

Adding in temperature data

Shift down due to additional polarization data



Steadily ruling out simpler inflationary models

BK15

arxiv/1810.05216

r < 0.06

Why BK15 came 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

Planck Collaboration: N. Aghanim[51], M. Ashdown[61,6], J. Aumont[51*], C. Baccigalupi[74], M. Ballardini[25,41,44], A. J. Banday[82,9], R. B. Barreiro[56], N. Bartolo[24,57], S. Basak[74], K. Benabed[52,81], J.-P. Bernard[82,9], M. Bersanelli[28,42], P. Bielewicz[71,9,74], A. Bonaldi[59], L. Bonavera[15], J. R. Bond[8], J. Borrill[11,78], F. R. Bouchet[52,77], F. Boulanger[51], A. Bracco[64], C. Burigana[41,26,44], E. Calabrese[79], J.-F. Cardoso[65,1,52], H. C. Chiang[21,7], L. P. L. Colombo[18,58], C. Combet[66], B. Comis[66], B. P. Crill[58,10], A. Curto[56,6,61], F. Cuttaia[41], R. J. Davis[59], P. de Bernardis[27], A. de Rosa[41], G. de Zotti[38,74], J. Delabrouille[1], J.-M. Delouis[52,81], E. Di Valentino[52,77], C. Dickinson[59], J. M. Diego[56], O. Doré[58,10], M. Douspis[51], A. Ducout[52,50], X. Dupac[32], S. Dusini[57], G. Efstathiou[61,53], F. Elsner[19,52,81], T. A. Enßlin[69], H. K. Eriksen[54], E. Falgarone[63], Y. Fantaye[30,3], F. Finelli[41,44], M. Frailis[40], A. A. Fraisse[21], E. Franceschi[41], A. Frolov[76], S. Galeotta[40], S. Galli[60], K. Ganga[1], R. T. Génova-Santos[55,14], M. Gerbino[80,73,27], T. Ghosh[51], M. Giard[82,9], J. González-Nuevo[15,56], K. M. Górski[58,84], A. Gregorio[29,40,48], A. Gruppuso[41,44], J. E. Gudmundsson[80,73,21], F. K. Hansen[54], G. Helou[10], D. Herranz[56], E. Hivon[52,81], Z. Huang[8], A. H. Jaffe[50], W. C. Jones[21], E. Keihänen[20], R. Keskitalo[11], T. S. Kisner[68], N. Krachmalnicoff[28], M. Kunz[13,51,3], H. Kurki-Suonio[20,37], G. Lagache[5,51], A. Lähteenmäki[2,37], J.-M. Lamarre[63], A. Lasenby[6,61], M. Lattanzi[26,45], C. R. Lawrence[58], M. Le Jeune[1], F. Levrier[63], M. Liguori[24,57], P. B. Lilje[54], M. López-Caniego[32], P. M. Lubin[22], J. F. Macías-Pérez[66], G. Maggio[40], D. Maino[28,42], N. Mandolesi[41,26], A. Mangilli[51,62], M. Maris[40], P. G. Martin[8], E. Martínez-González[56], S. Matarrese[24,57,34], N. Mauri[44], J. D. McEwen[70], A. Melchiorri[27,46], A. Mennella[28,42], M. Migliaccio[53,61], S. Mitra[49,58], M.-A. Miville-Deschênes[51,8], D. Molinari[26,41,45], A. Moneti[52], L. Montier[82,9 *], G. Morgante[41], A. Moss[75], P. Naselsky[72,31], H. U. Nørgaard-Nielsen[12], C. A. Oxborrow[12], L. Pagano[27,46], D. Paoletti[41,44], B. Partridge[36], L. Patrizii[44], O. Perdereau[62], L. Perotto[66], V. Pettorino[35], F. Piacentini[27], S. Plaszczynski[62], G. Polenta[4,39], J.-L. Puget[51], J. P. Rachen[16,69], M. Reinecke[69], M. Remazeilles[59,51,1], A. Renzi[30,47], G. Rocha[58,10], M. Rossetti[28,42], G. Roudier[1,63,58], J. A. Rubiño-Martín[55,14], B. Ruiz-Granados[83], L. Salvati[27], M. Sandri[41], M. Savelainen[20,37], D. Scott[17], C. Sirignano[24,57], G. Sirri[44], L. Stanco[57], A.-S. Suur-Uski[20,37], J. A. Tauber[33], M. Tenti[43], L. Toffolatti[15,56,41], M. Tomasi[28,42], M. Tristram[62], T. Trombetti[41,26], J. Valiviita[20,37], F. Vansyngel[51], F. Van Tent[67], P. Vielva[56], B. D. Wandelt[52,81,23], I. K. Wehus[58,54], A. Zacchei[40], and A. Zonca[22]

(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.

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 $r \approx 0.01$ 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*.

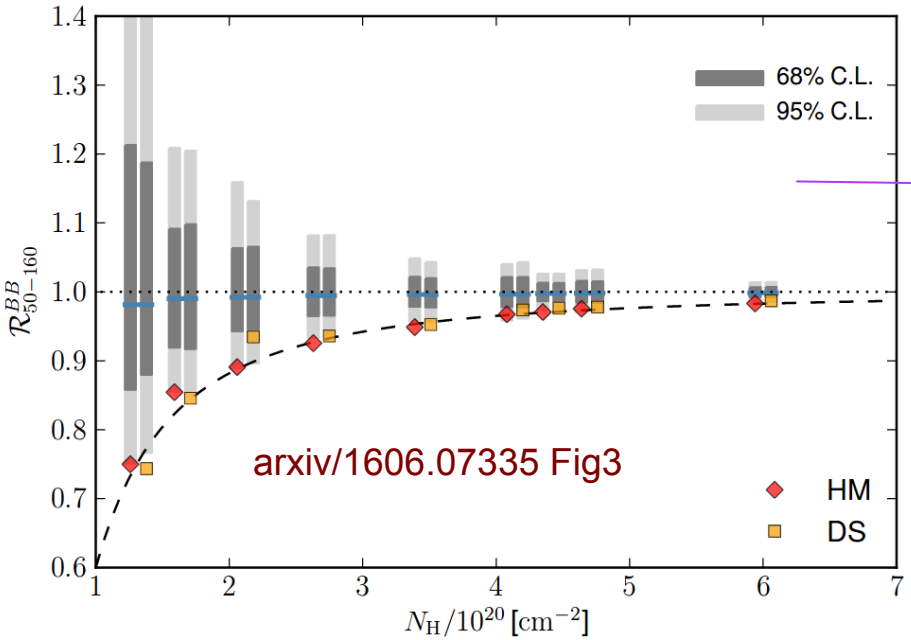
A departure of the correlation ratio from unity that cannot be attributed to a spurious decorrelation due to the cosmic microwave background, instrumental noise, or instrumental systematics… **detected at more than 99% confidence**

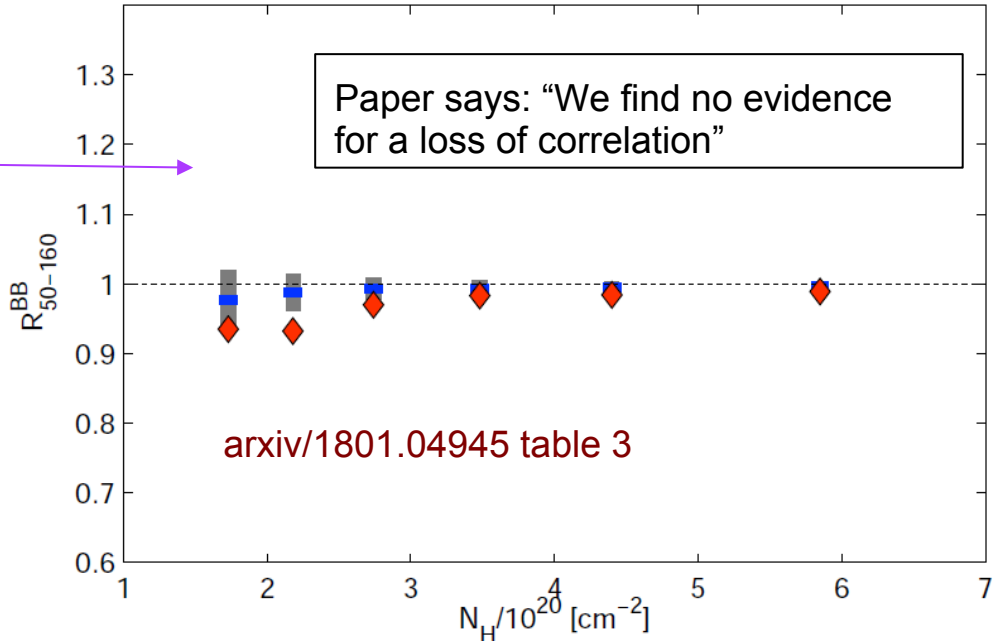
arxiv/1606.07335

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…

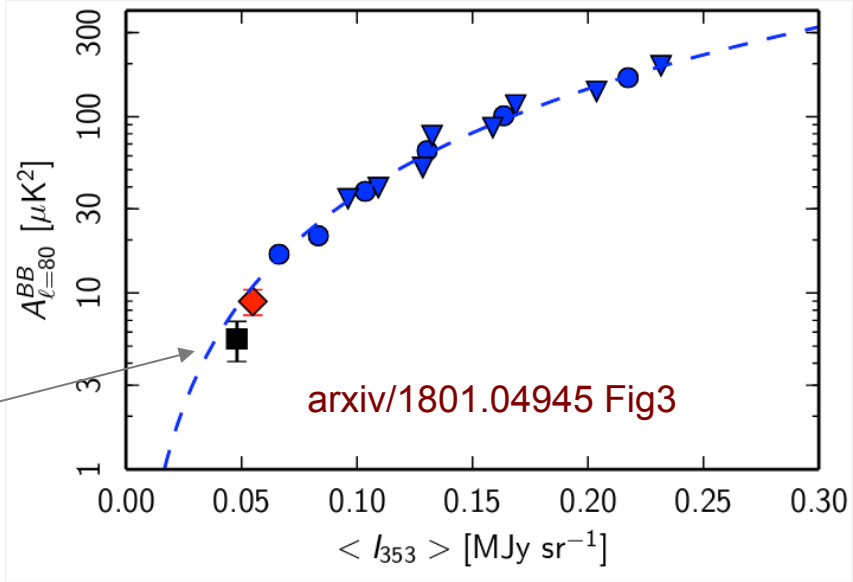
arxiv/1801.04945

…Evolving Planck Dust Analysis





BK patch a few times cleaner than extrapolation



Stage 2

Stage 3

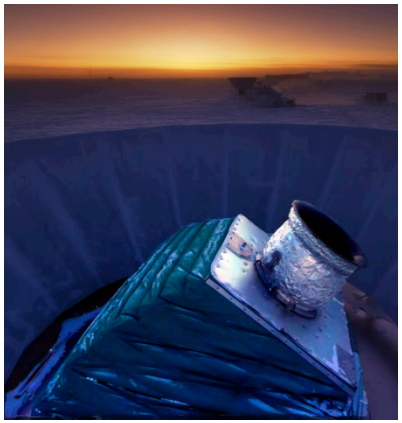
BICEP2
(2010-2012)

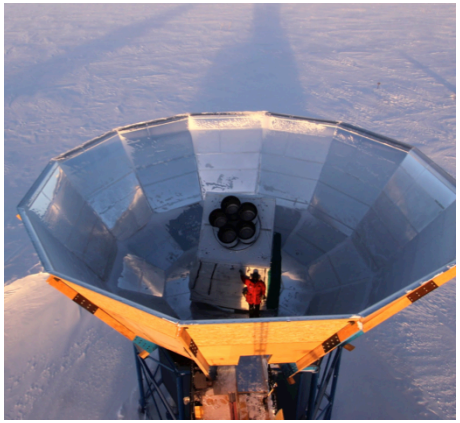
Keck Array
(2012-2019)

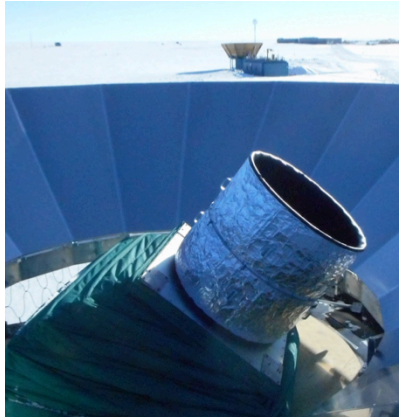
BICEP3
(2016-)

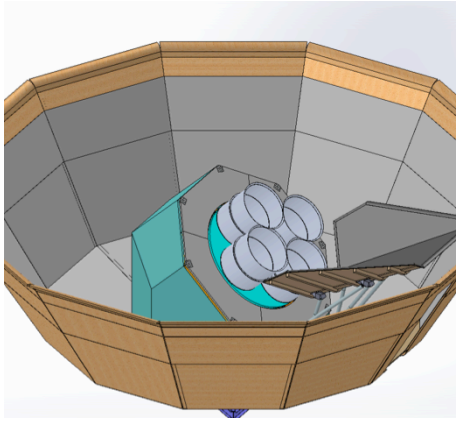
BICEP Array
(2020-)

Telescope and Mount

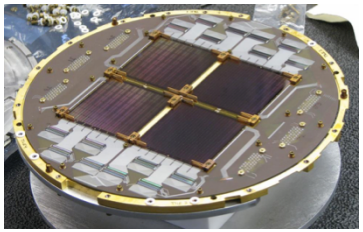


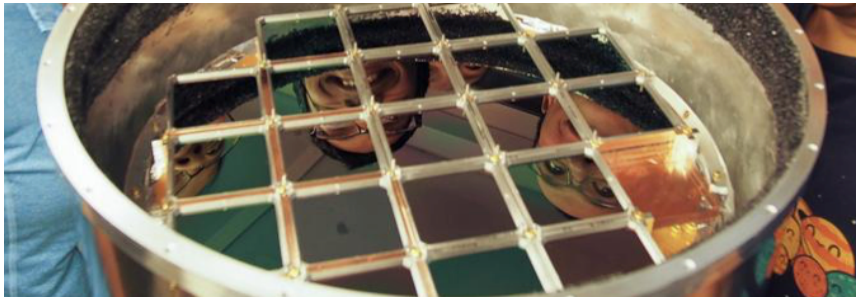




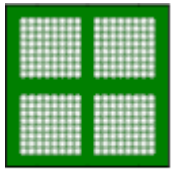


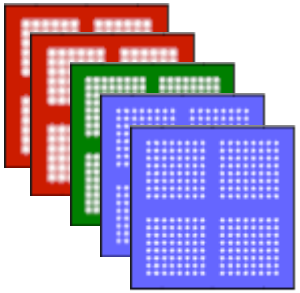
Focal Plane

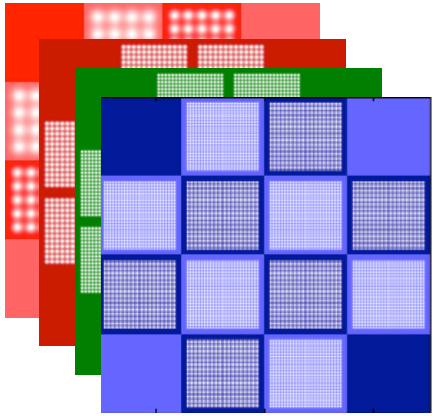




Beams on Sky







2016 onwards: BICEP3 "Super receiver"

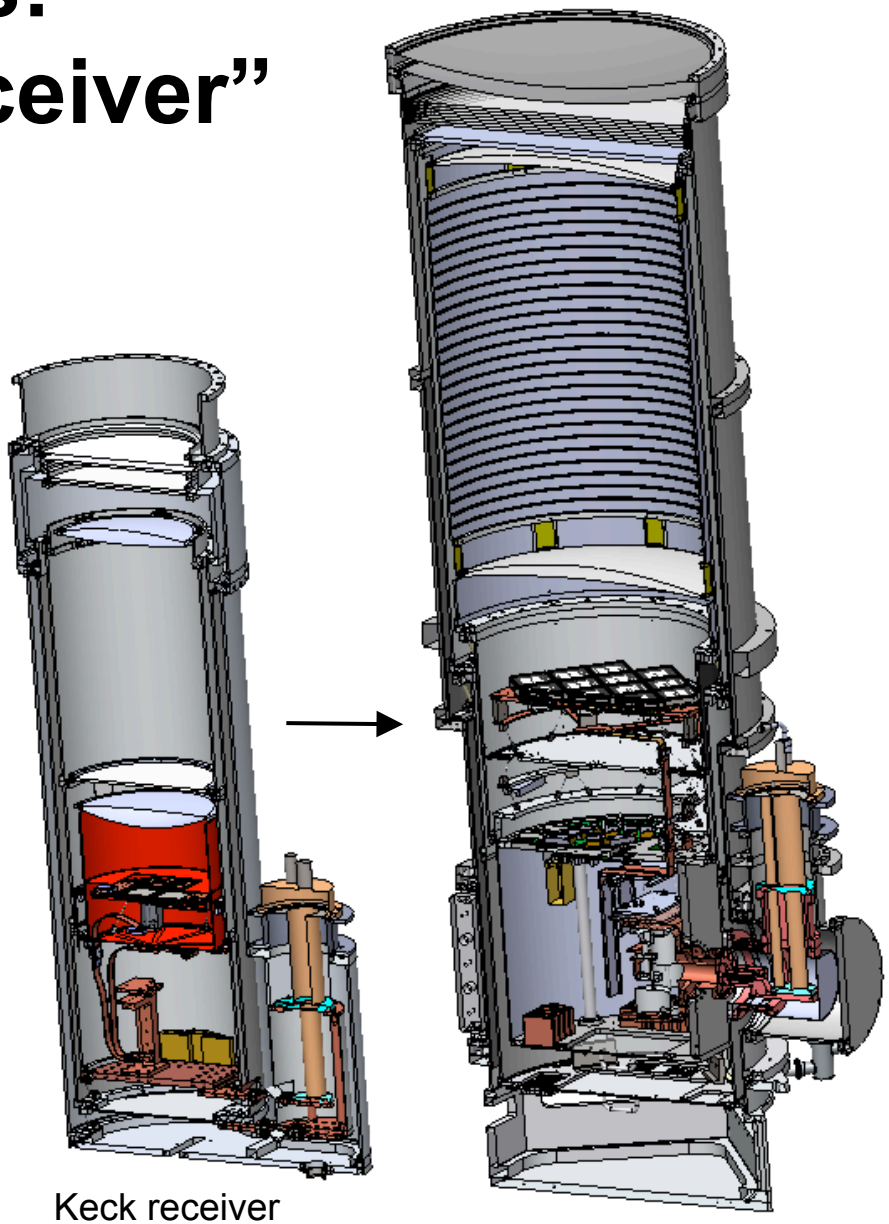
All 95 GHz

2560 detectors in modular focal plane

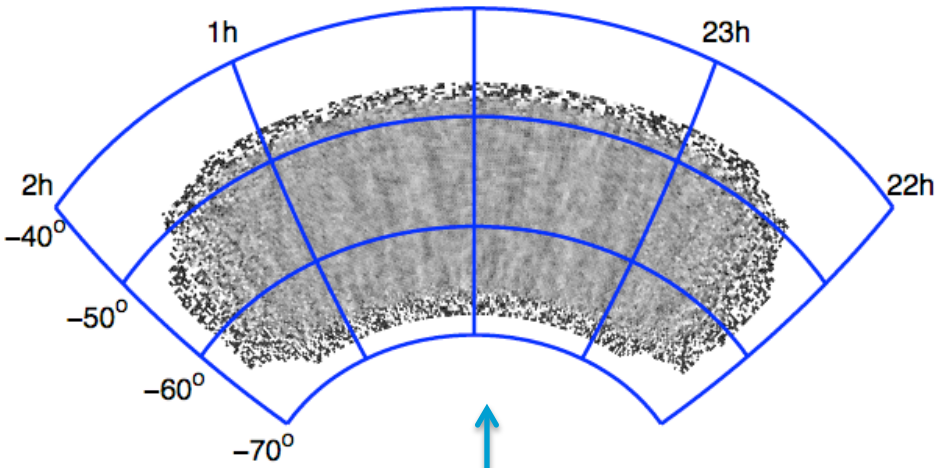
Larger-aperture optics

> 10x optical throughput of single BICEP2/Keck receiver

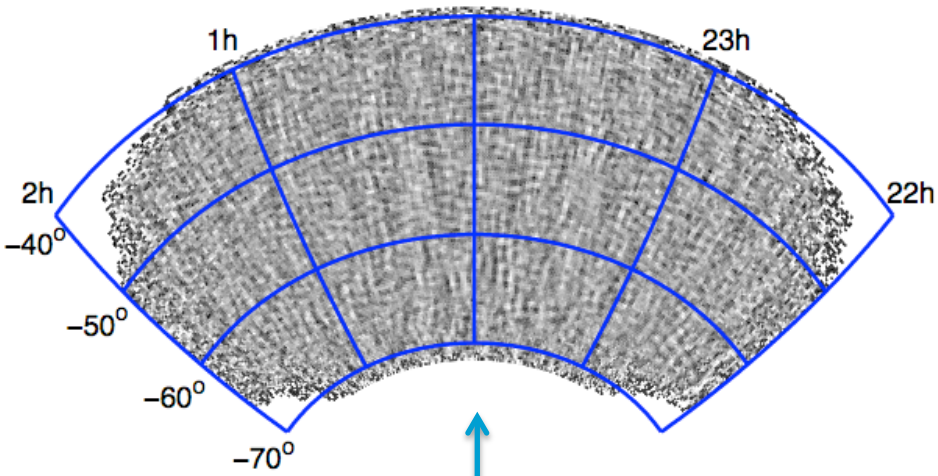
Means larger field of view and lower noise faster



Larger receiver = more sky area

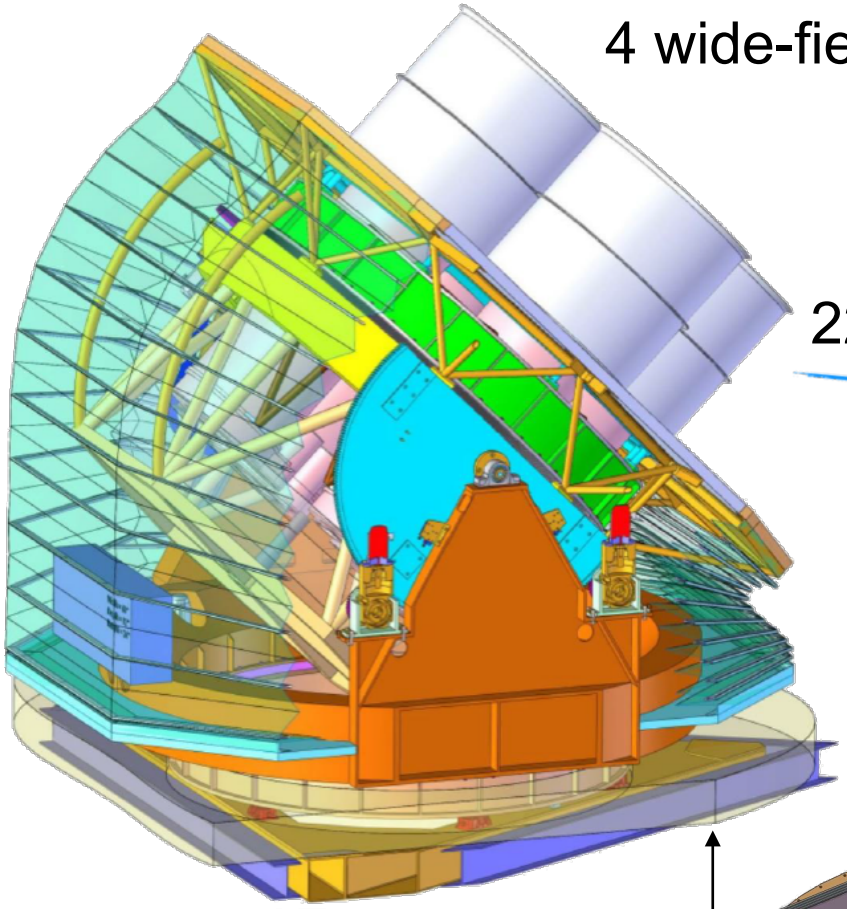


Keck 95 GHz *Q* map after 4 receiver years

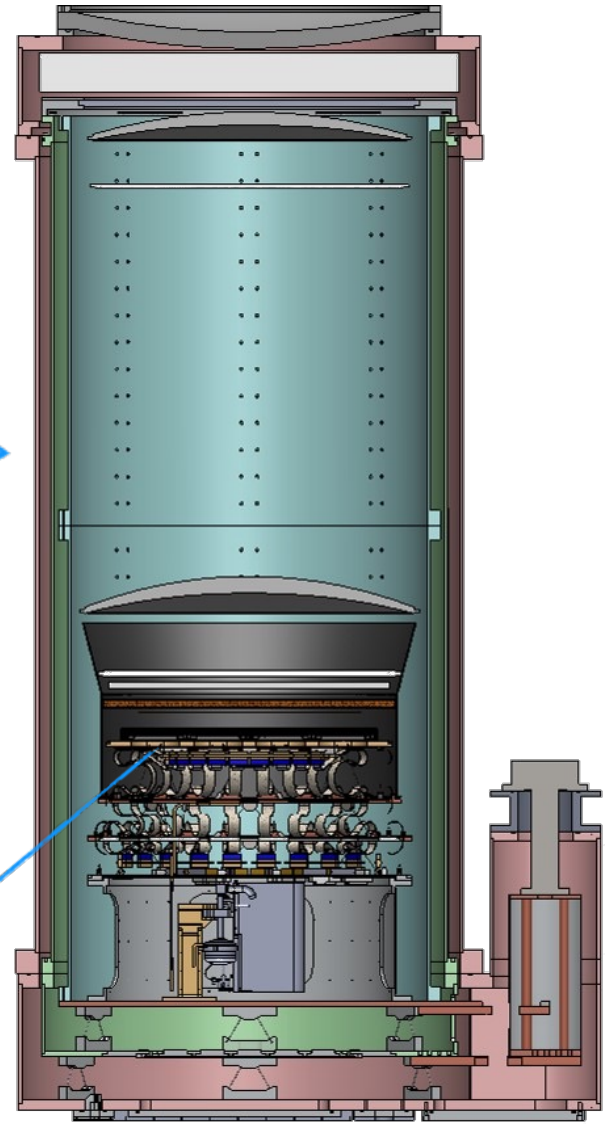


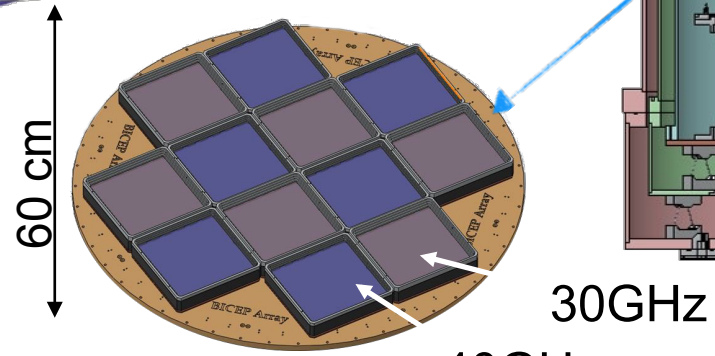
BICEP3 95 GHz *Q* map after 1 receiver year (2017) (Increased area, angular-resolution and sensitivity)

Next Gen Experiment BICEP Array Under Construction



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

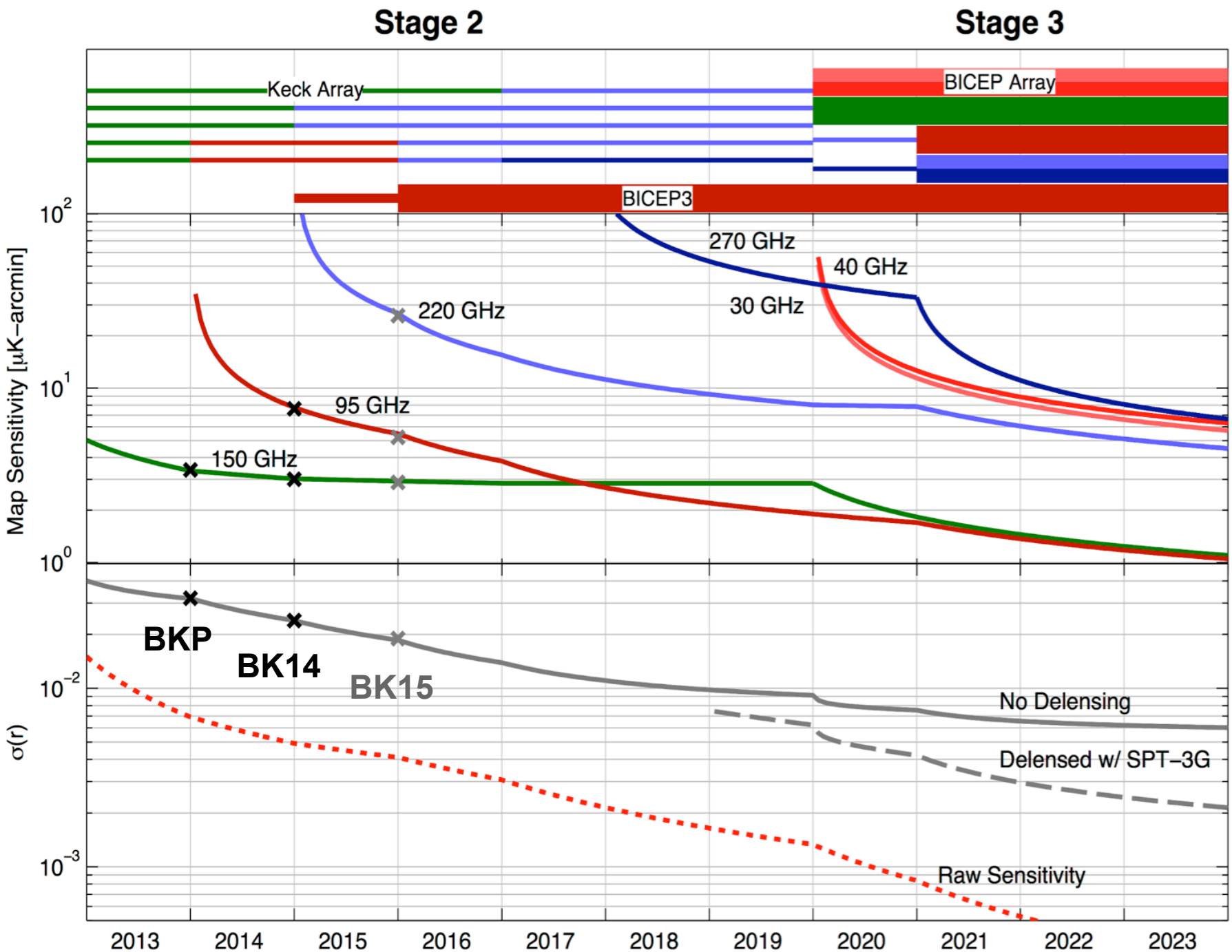


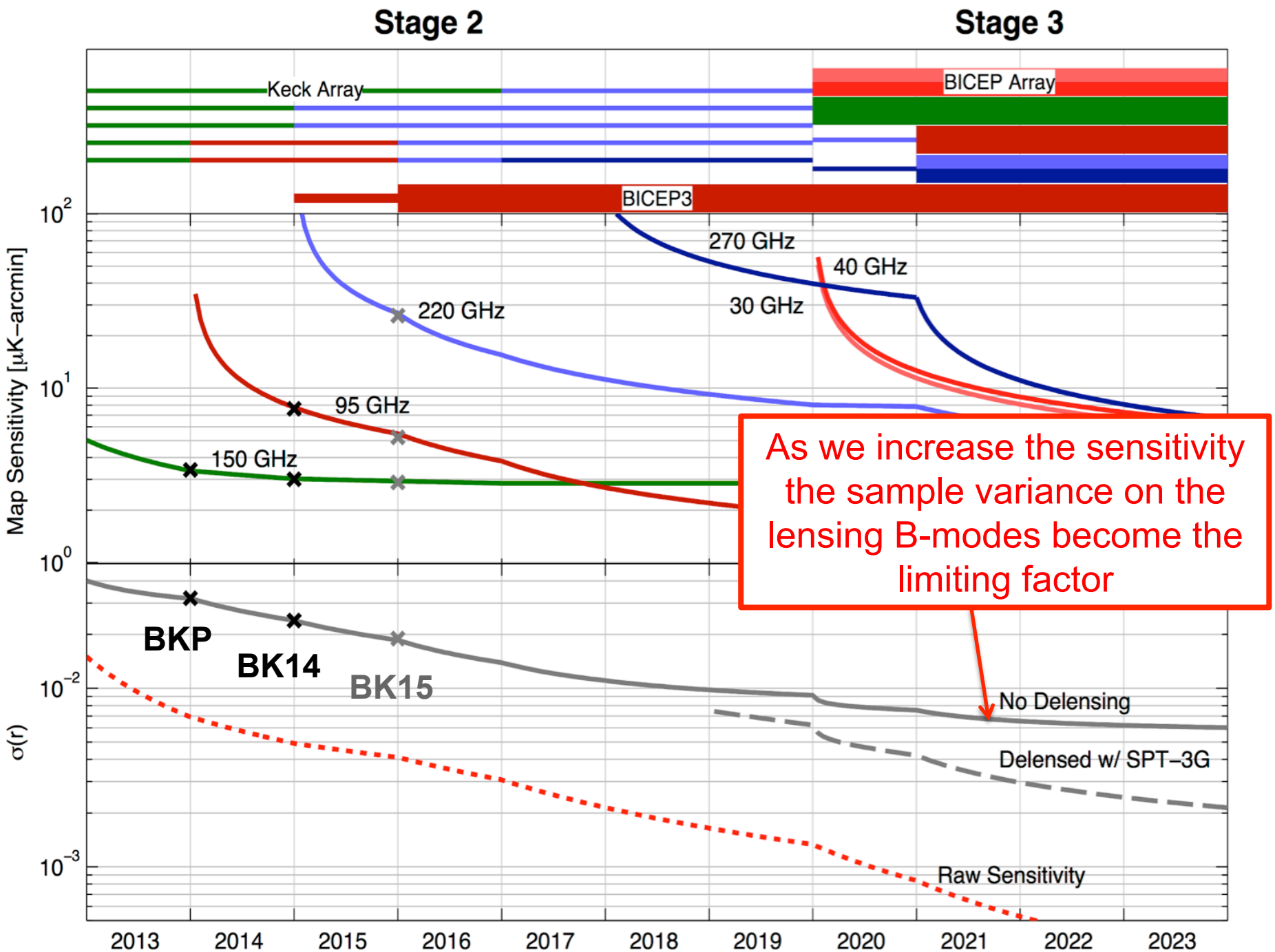


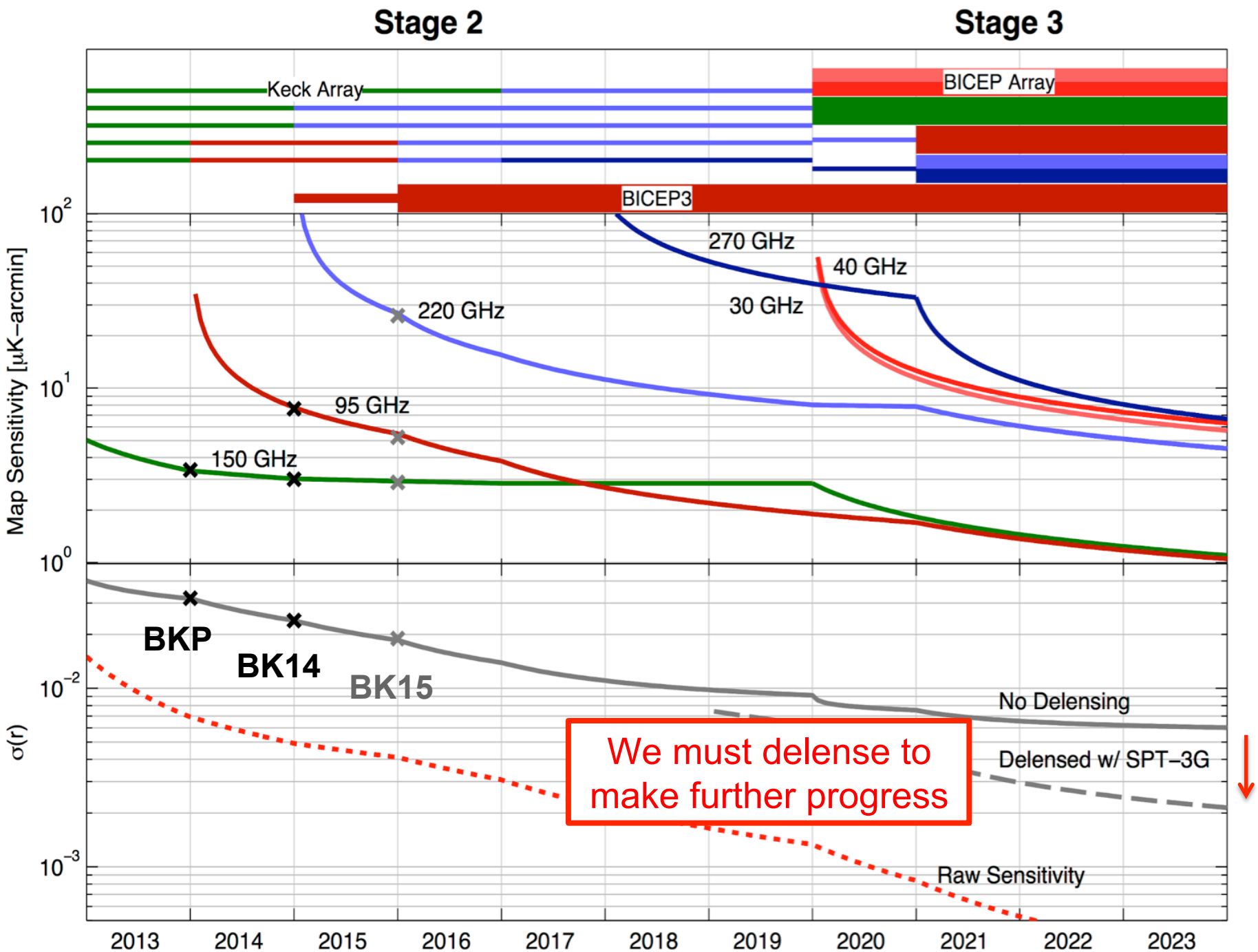
Focal plane layout

Right Now Assembling New Telescope at UMN

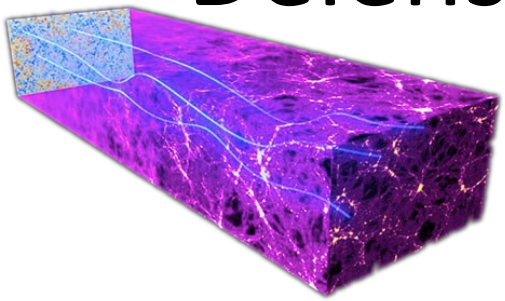
New Telescope Moving

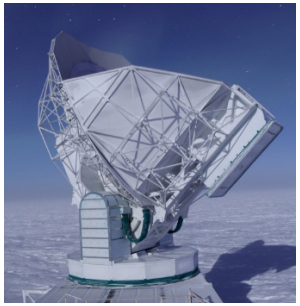

Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
Map Sensitivity [μK−arcmin]
10^2
10^1
10^0
BKP
BK14
BK15
No Delensing
Delensed w/ SPT−3G
Raw Sensitivity
σ(r)
10^{-2}
10^{-3}
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023


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
10^{-2}
10^{-3}
σ(r)
BKP
BK14
BK15
No Delensing
Delensed w/ SPT–3G
Raw Sensitivity
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
As we increase the sensitivity the sample variance on the lensing B-modes become the limiting factor

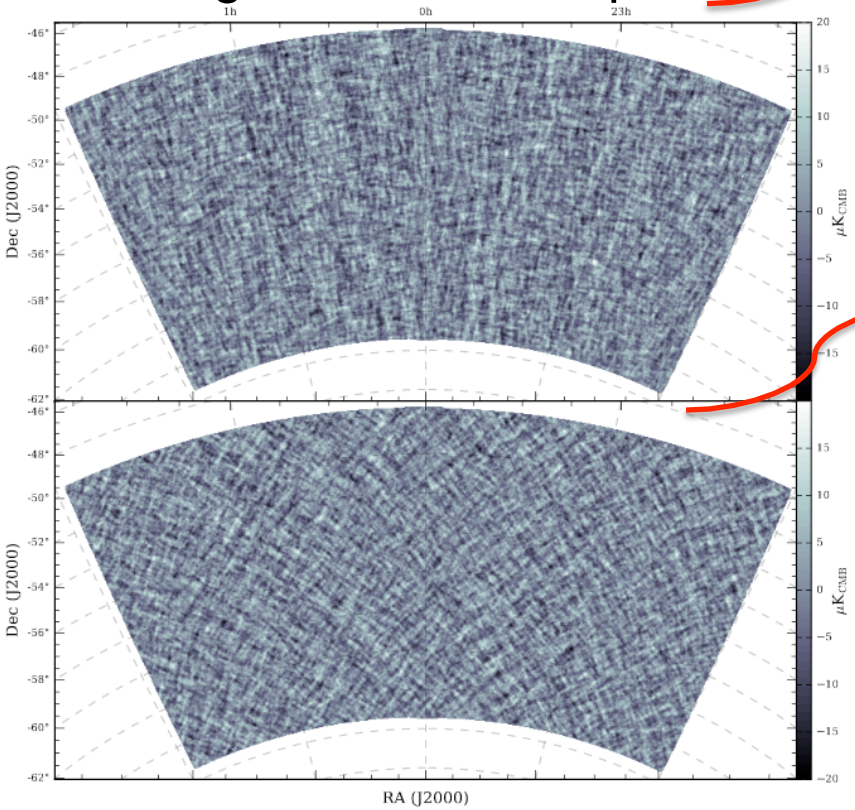

Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
Map Sensitivity [μK–arcmin]
10^2
10^1
10^0
BKP
BK14
BK15
No Delensing
Delensed w/ SPT–3G
Raw Sensitivity
We must delense to make further progress
σ(r)
10^{-2}
10^{-3}
2013
2014
2015
2016
2017
2018
2019
2020
2021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

Delensing with SPT-3G data

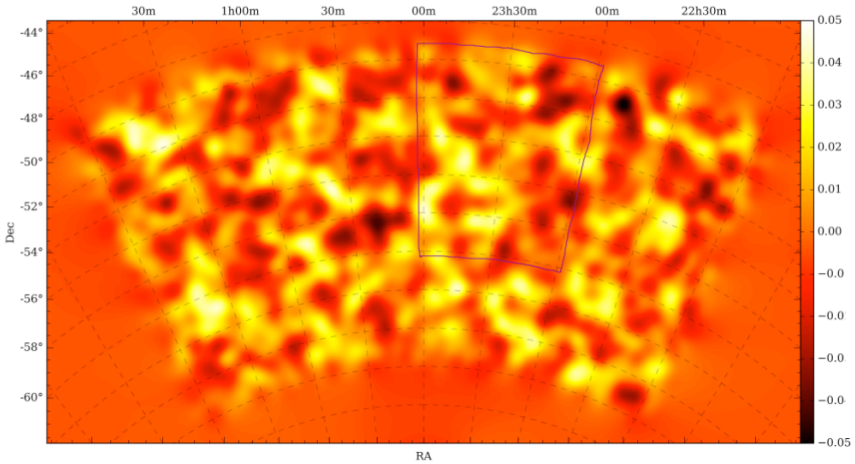




High resolution maps

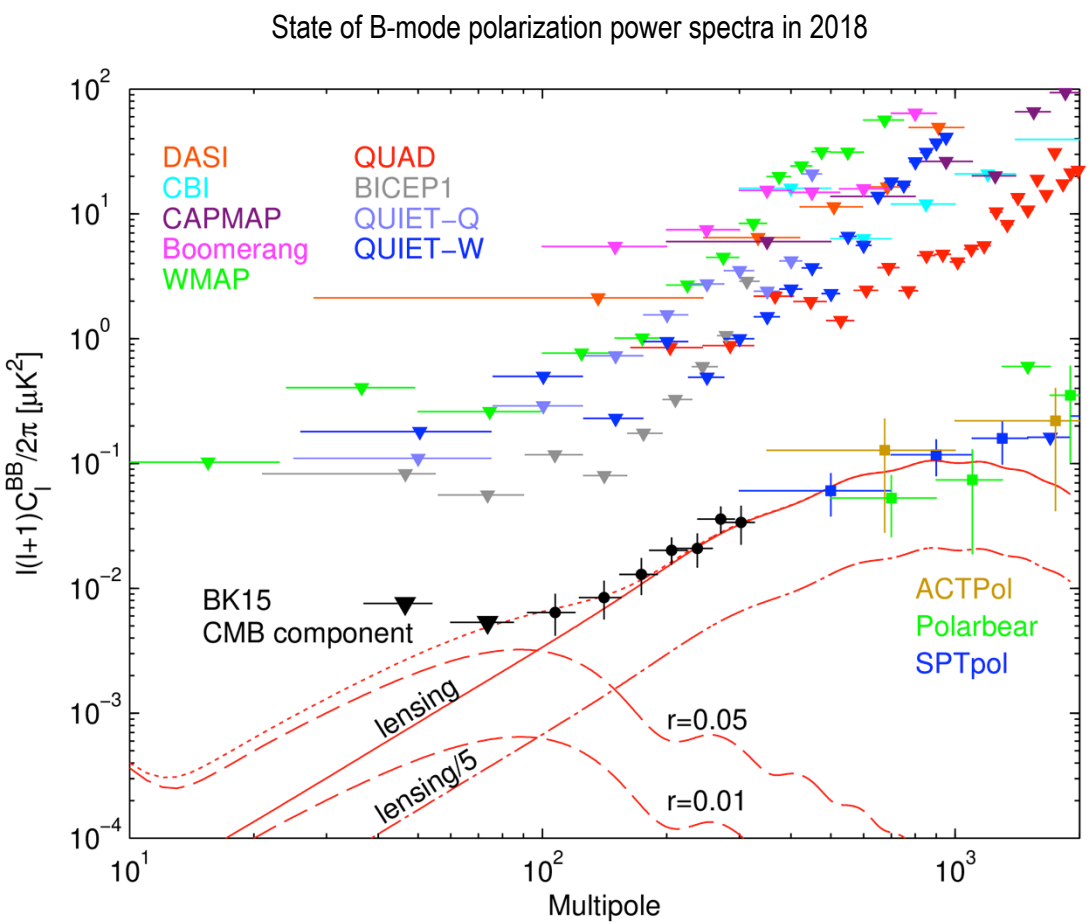


Can be used to reconstruct the lensing deflection map…



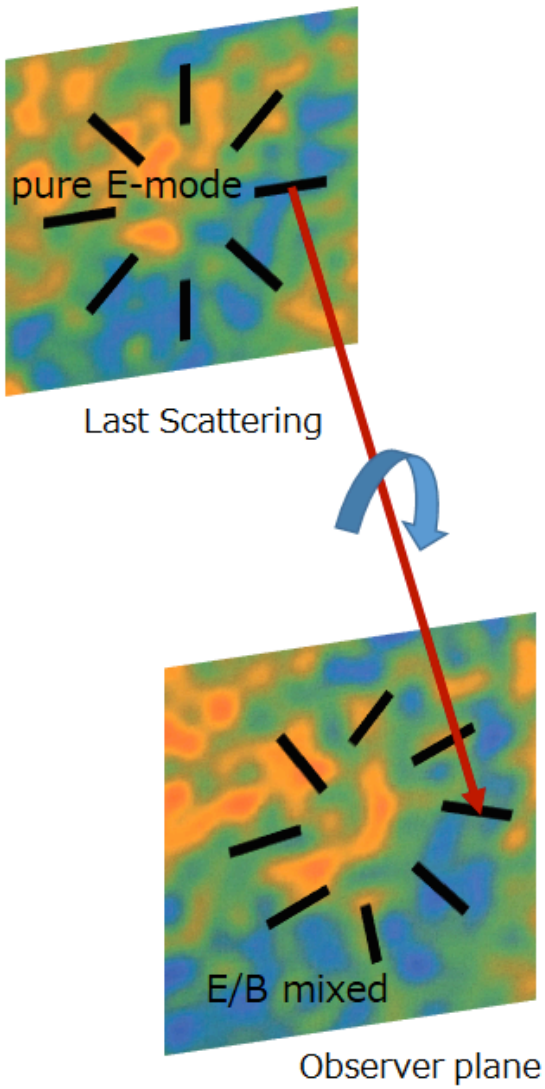
…which can then be used to calculate and remove the lensing signal enabling a deeper search for inflationary gravitational waves

Polarization Constraints on Inflation to Date



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)

Cosmological origins of anisotropic polarization rotation



- **Axion-like particles**

String theory generally predicts presence of axion-like particles coupled with electromagnetic fields (e.g. Pospelov+'09, Caldwell+'11)

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

Coupling constant

This coupling leads to spatially varying polarization angle rotation

rotation angle → $\alpha(n) = \frac{\Delta\phi(n)}{f_a}$ ← Changes in phi during photon propagation

- **Primordial magnetic fields**

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

Measurements of anisotropic polarization rotation are a unique probe of the early universe and provide important implications for high energy physics!

The BICEP/Keck Collaboration

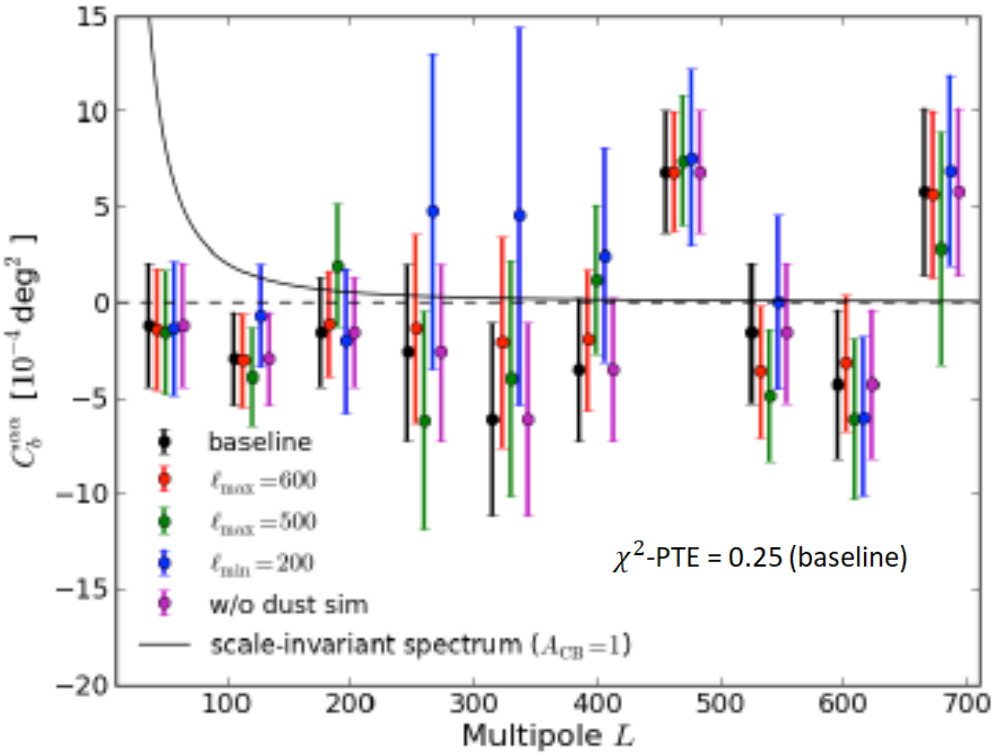
Measurement of the polarization rotation spectrum

- **Analysis Method**

  Anisotropic pol. rotation leads to mode-coupling between E and B modes (like lensing).

  Thus we can apply the same analysis method as for lensing reconstruction but using a different weight function to optimally reconstruct the rotation angle map

- **Measured spectrum**



- The spectrum is consistent with null

  (even if we change the analysis choices)

- The reconstructed spectra measured from our 14 jackknife maps are also consistent with null

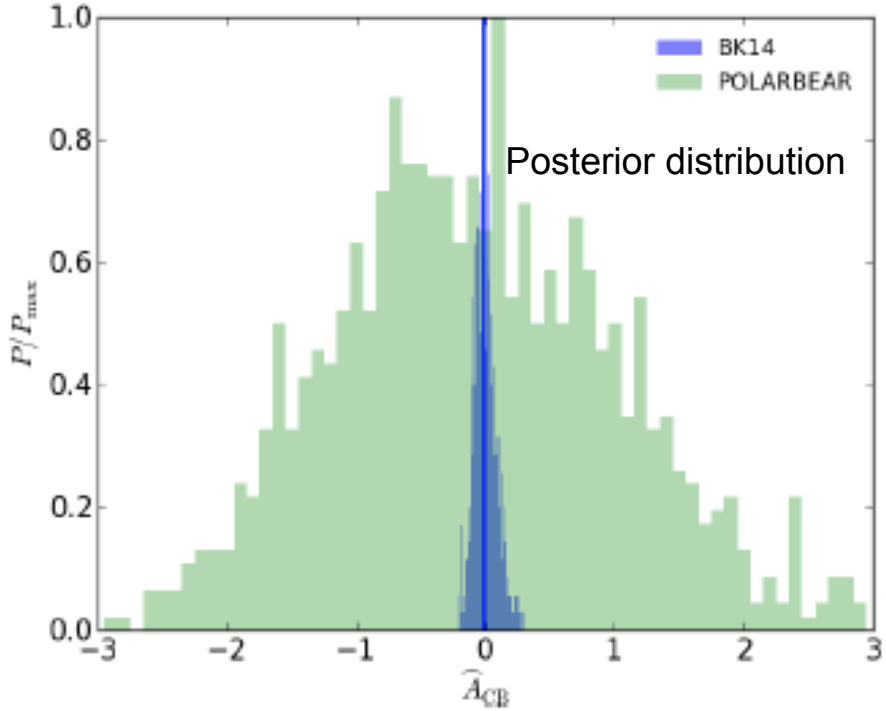
- Instrumental relative pol. rotation < 1% of the 1 sigma statistical error

From arxiv 1705.02523

The BICEP/Keck Collaboration

Comparison w/ previous work & cosmological implications

- **Improved constraints on inflationary pol. rotation spectrum**



If sources of pol. rotation are originated from inflation, the expected rotation spectrum has the following scale-invariant shape

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

Compared to previous attempts, we improve the constraints on this inflationary rotation spectrum by an order of magnitude.

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

From arxiv 1705.02523

- **Implications**

The above results lead to constraints on

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

an order of magnitude better than Pospelov et al. (2009) PRL

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

Conclusions

- BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:
- BK15 result sets $r_{0.05}<0.06$ 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 under development
- Projecting BK23 $\sigma(r)<0.003$ around 2025

- 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. Time will tell.