BICEP constraints on Primordial Gravitational waves, current and future

John Kovac, Harvard University

COSPAR 2018 July 21

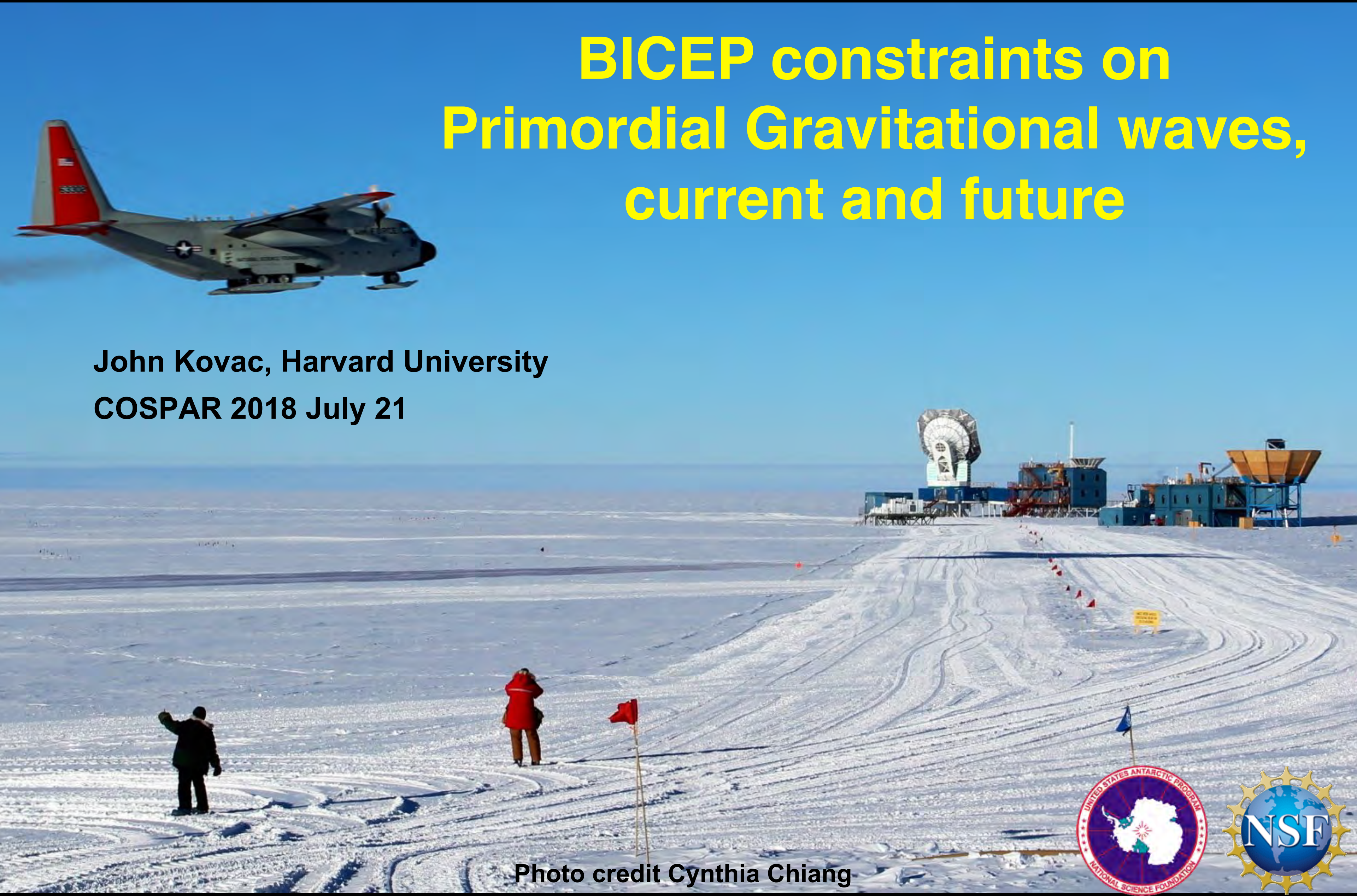
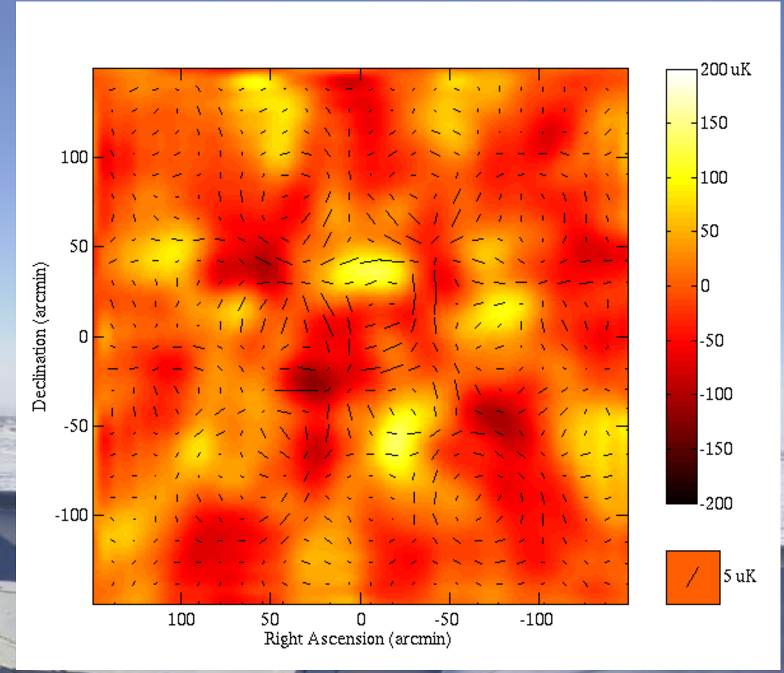


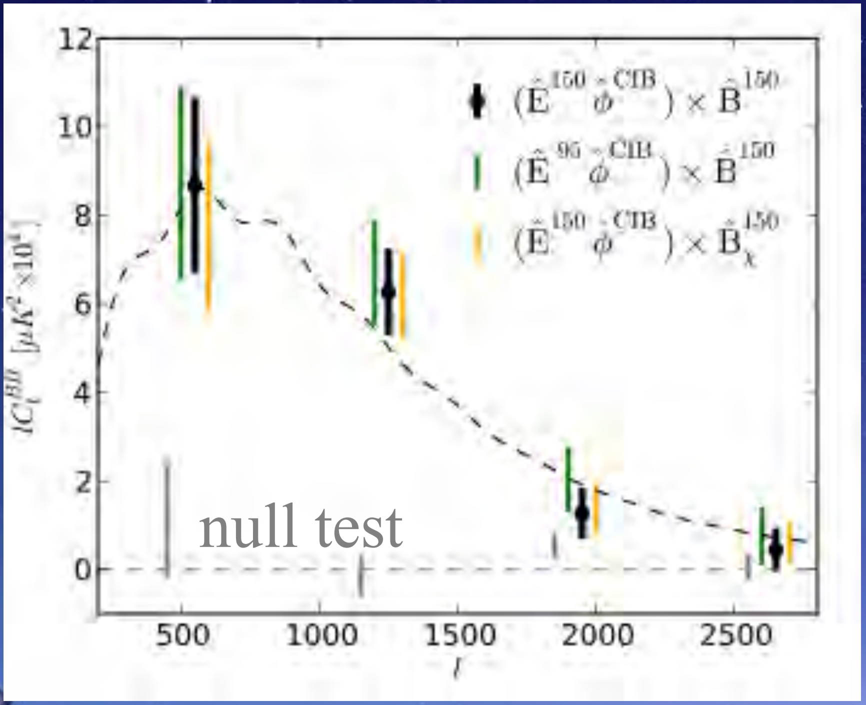
Photo credit Cynthia Chiang

South Pole CMB efforts started in 1980's

CMB polarization first detected in 2002, at South Pole



CMB B-mode Polarization first detected in 2013, at South Pole



Physics World
Breakthrough of the Year 2013

A *Physics World* Top 10 Breakthrough of the Year is awarded for physics research published in 2013 and the decision is based on the following criteria:

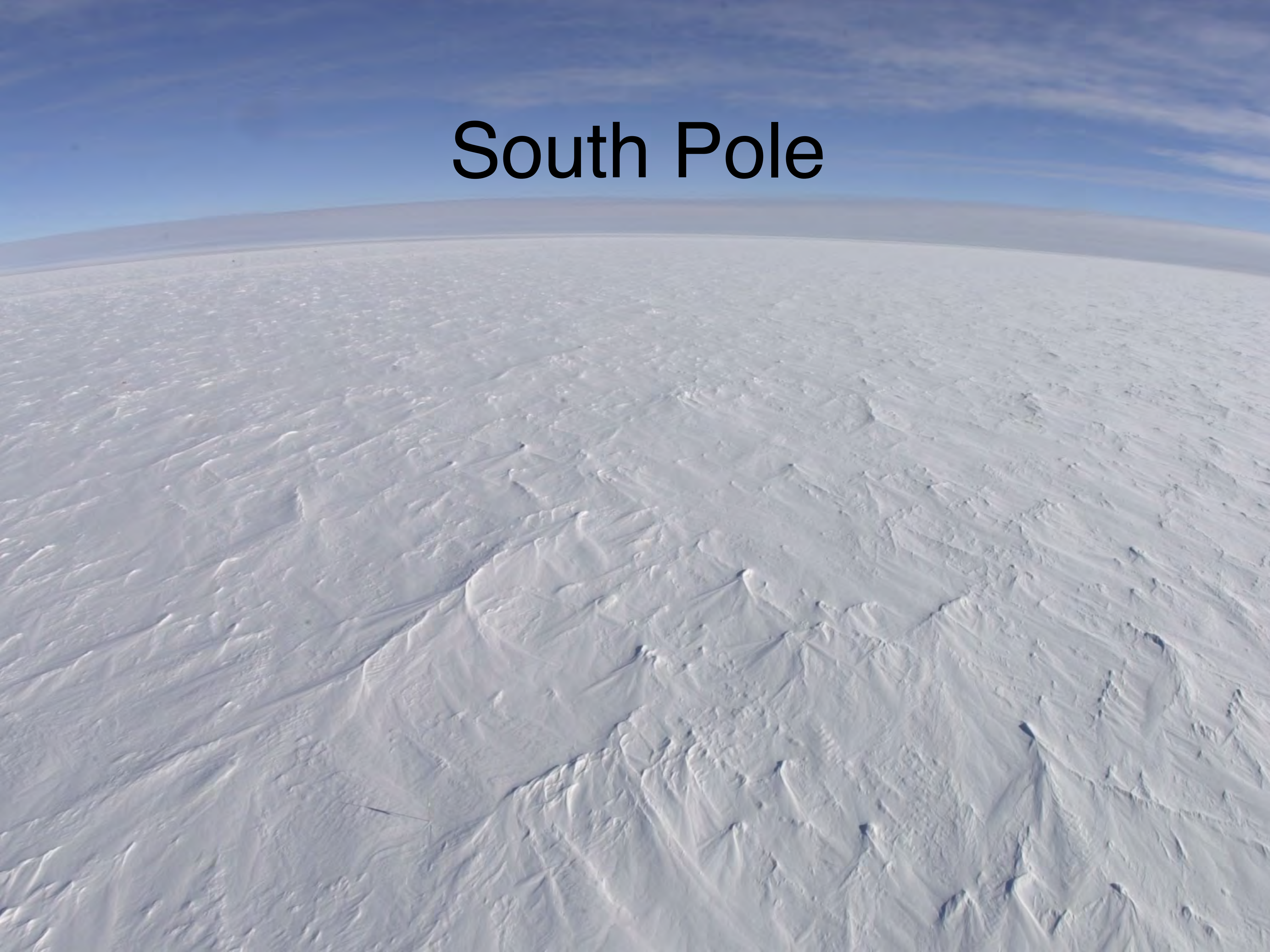
- Fundamental importance of research
- Significant advance in knowledge
- Strong connection between theory and experiment
- General interest to all physicists

This is to certify that a *Physics World* Top 10 Breakthrough of the Year has been given to

The astronomers working on the South Pole Telescope

... the first to measure B-mode polarization in the cosmic ...

South Pole



South Pole

- High, cold site ~ 10,500 feet.
- **<u>Extremely dry, uniquely stable atmosphere</u>.**
  - the sky at 150 GHz has $\gtrsim$30x less power fluctuations than Chajnantor Chile (e.g., Bussmann et al. 2005, Kuo 2017)
- Sun below horizon for 6 months.
- Unique geographical location - We can observe the clearest view through our Galaxy 24h/day, 365 days/yr
- Excellent support from NSF research station
- Steady investment by NSF in South Pole CMB
  - CMB is one of 3 major priorities of Antarctic Science for coming decade

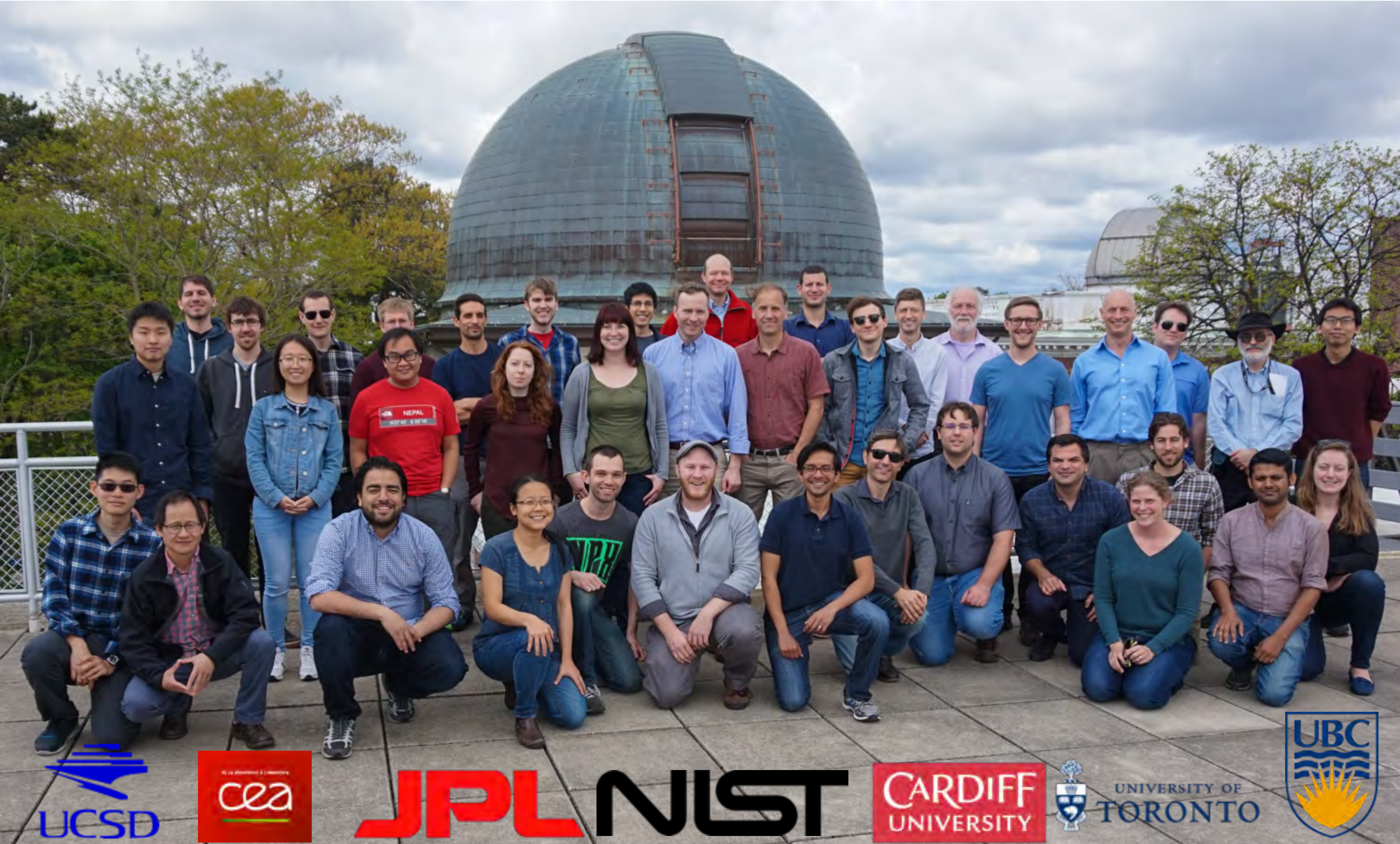
→Best developed site for ultra-deep CMB measurements

VE RI TAS
HARVARD

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891

UNITED STATES ANTARCTIC PROGRAM
NATIONAL SCIENCE FOUNDATION

NSF



UCSD

cea

JPL

NIST

CARDIFF UNIVERSITY

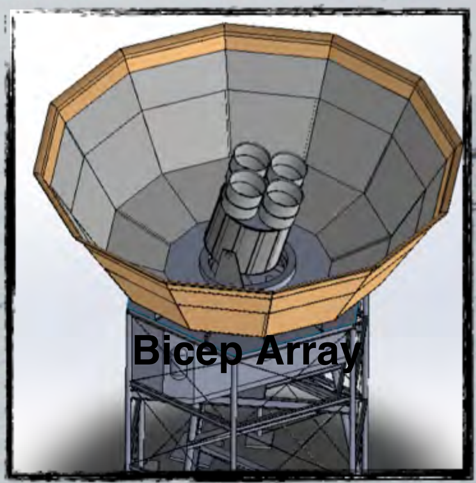
UNIVERSITY OF TORONTO

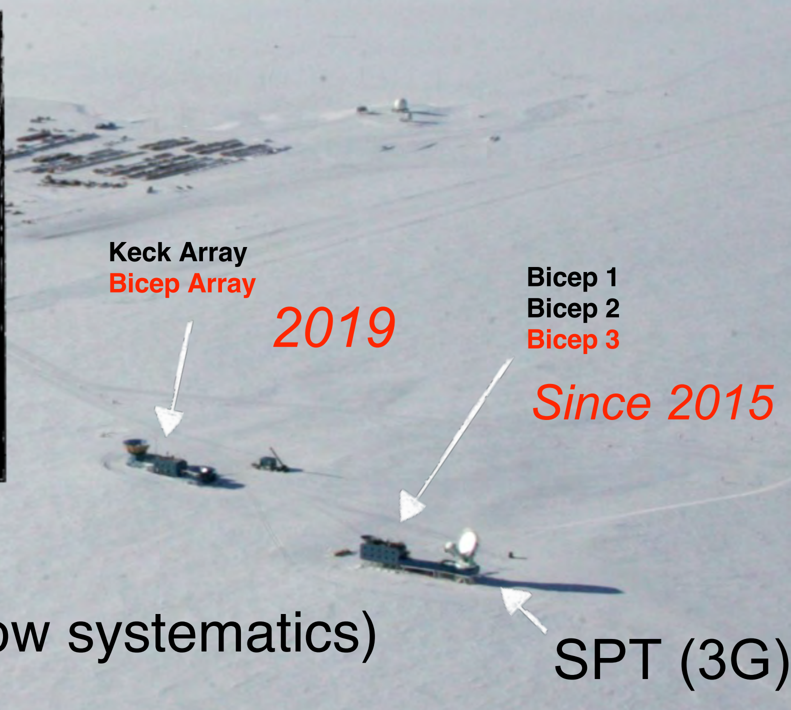
UBC

Photo Credit: USAP, NSF

x5 =

x4 =

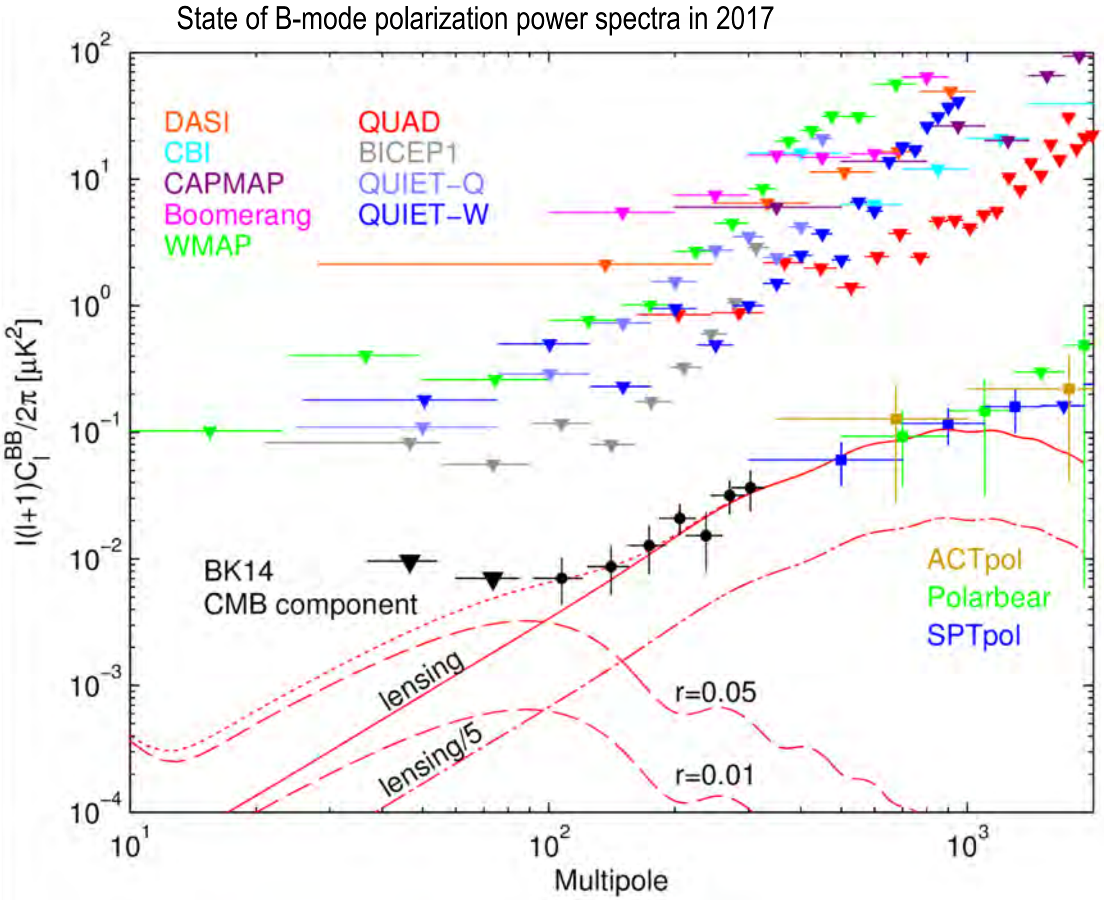


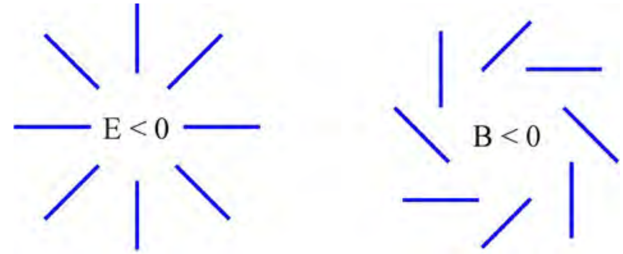


→ Small aperture telescopes (cheap, fast, low systematics)
→ Target the 2 degree peak of the B-mode
→ Integrate continuously from South Pole
→ Observe 1-2% patch of sky

BICEP-Keck Constraints on Inflation to Date

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

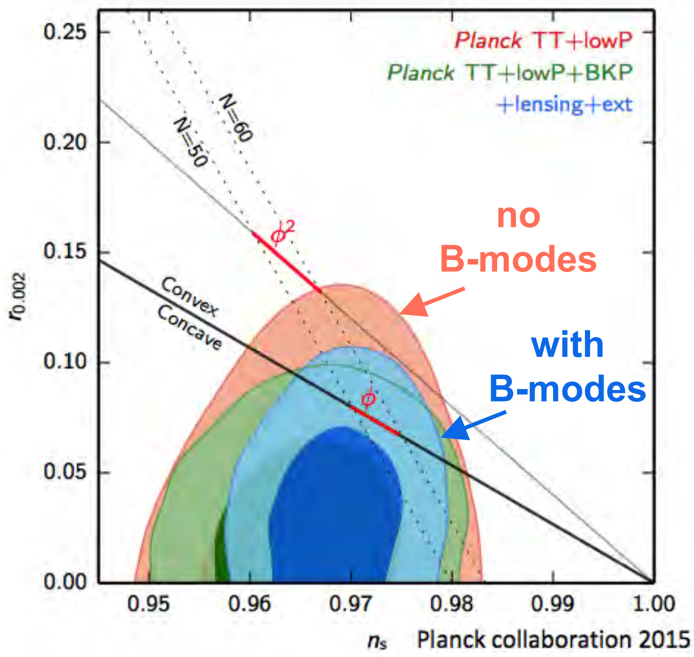


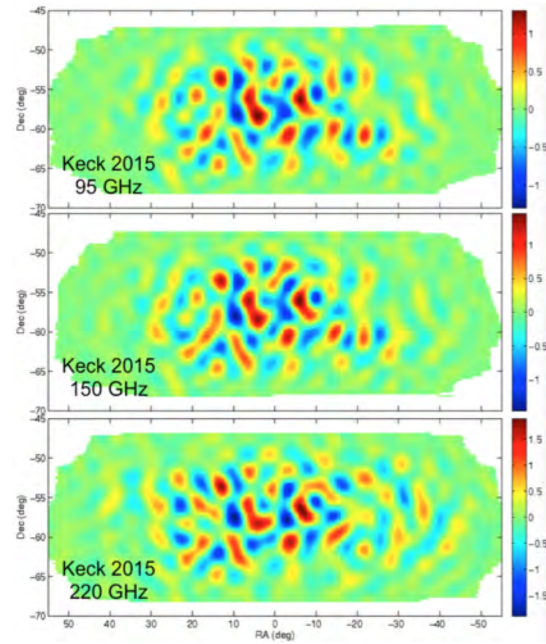


Published B-Mode Sensitivity to r

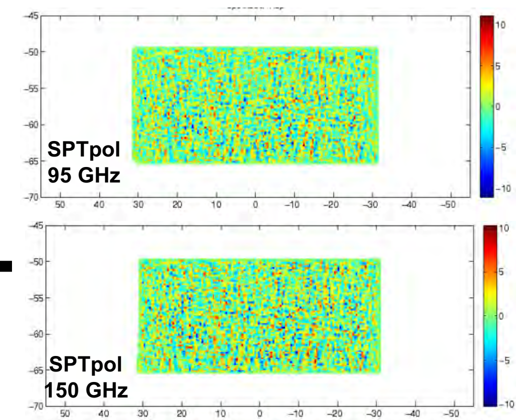
Experiment	Year	Bands [GHz]	σ(r)
DASI	2004	26…36	7.5
BICEP1 2yr	2009	100, 150	0.28
WMAP 7yr	2010	30…60	1.1
QUIET-Q	2010	43	0.97
QUIET-W	2012	95	0.85
BICEP1 3yr	2013	100, 150	0.25
BICEP2	2014	150	0.10
BK + Planck	2015	150 + Planck	0.034
BK14	2015	95, 150 + P	0.024
ABS	2018	150	0.7
BK15	2018	95,150,220 + P	0.020
BK17	2019?	95,150,220 + P	0.010 (est)

BICEP/Keck data: B-modes and progress on *r*





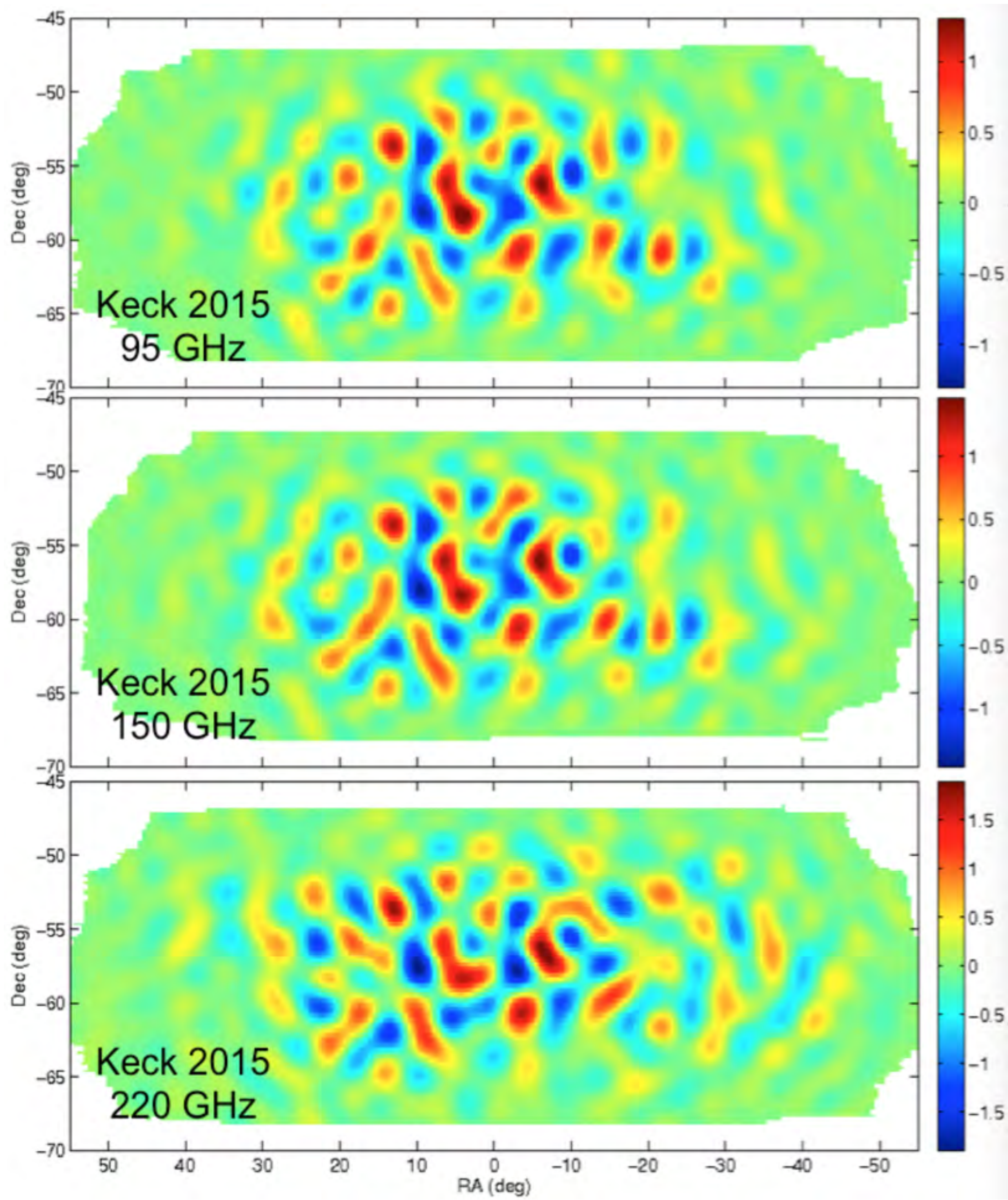
Deep degree-scale maps:
multiband for **foreground separation**



Deep high-resolution maps:
precision delensing

- BICEP-Keck / Planck joint analysis (published Feb 2015) **$\sigma(r)$ = 0.034** arXiv:1502.00612
- **2014 BICEP/Keck** adds deep 95 GHz **$\sigma(r)$ = 0.025** arXiv:1510.09217
  raw sensitivity with no foregrounds or lensing: **$\sigma(r)$ = 0.005**
  it is now all about component separation!
- **2015 BICEP/Keck** adds deep 220 GHz expect **$\sigma(r)$ = 0.019** next month
- **2017 BICEP/Keck** (data all in the can) expect **$\sigma(r)$ = 0.010** coming next year
- **2019-2023 BICEP Array** + SPT3G forecast **$\sigma(r)$ ~ 0.003**

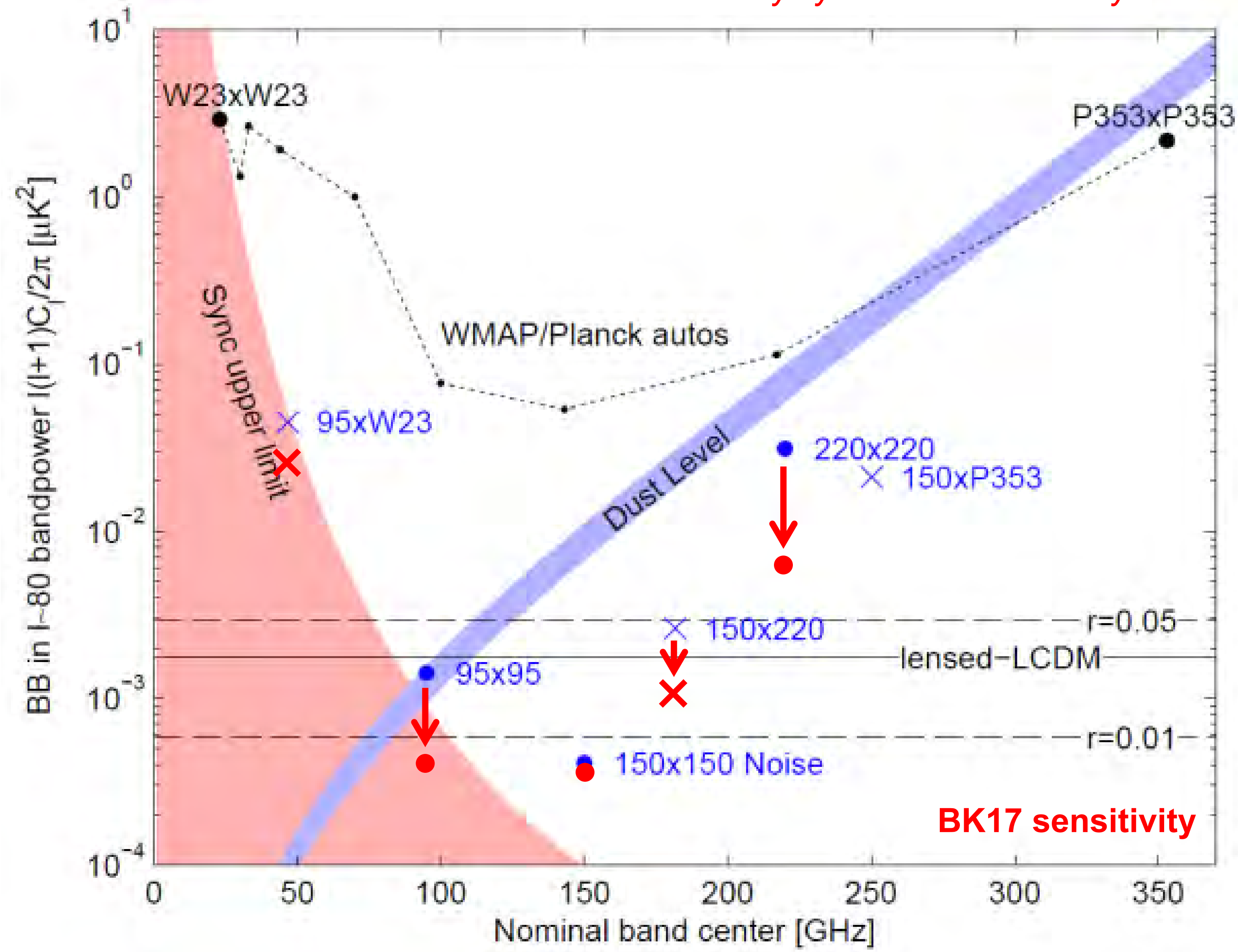
Upcoming BK15 E-Mode Maps



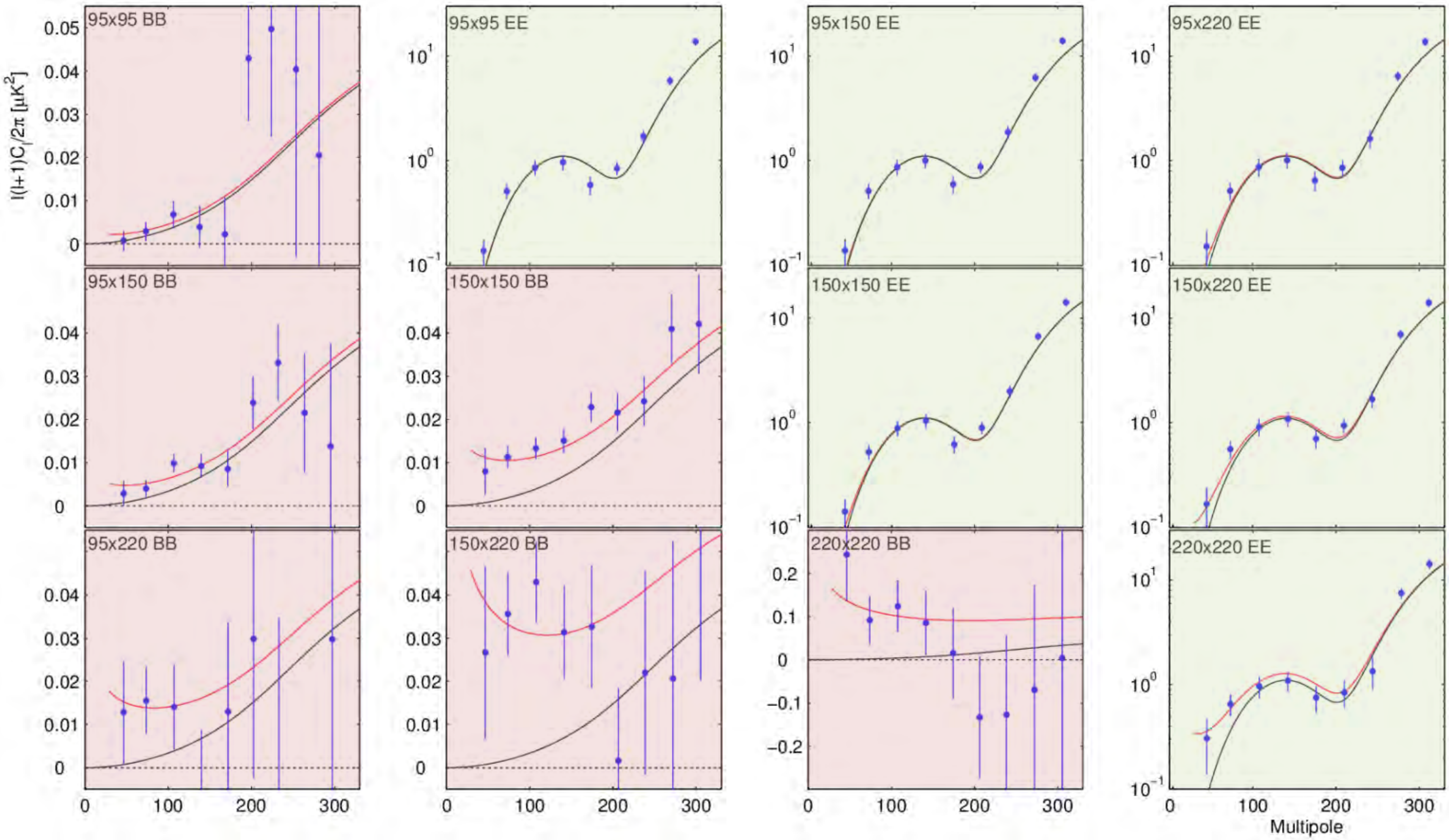
The BICEP/Keck Collaboration

BK15 Band Sensitivity (at ℓ = 80)

BK17 errors on r will be dominated by synchrotron sensitivity



Upcoming BK15 spectra



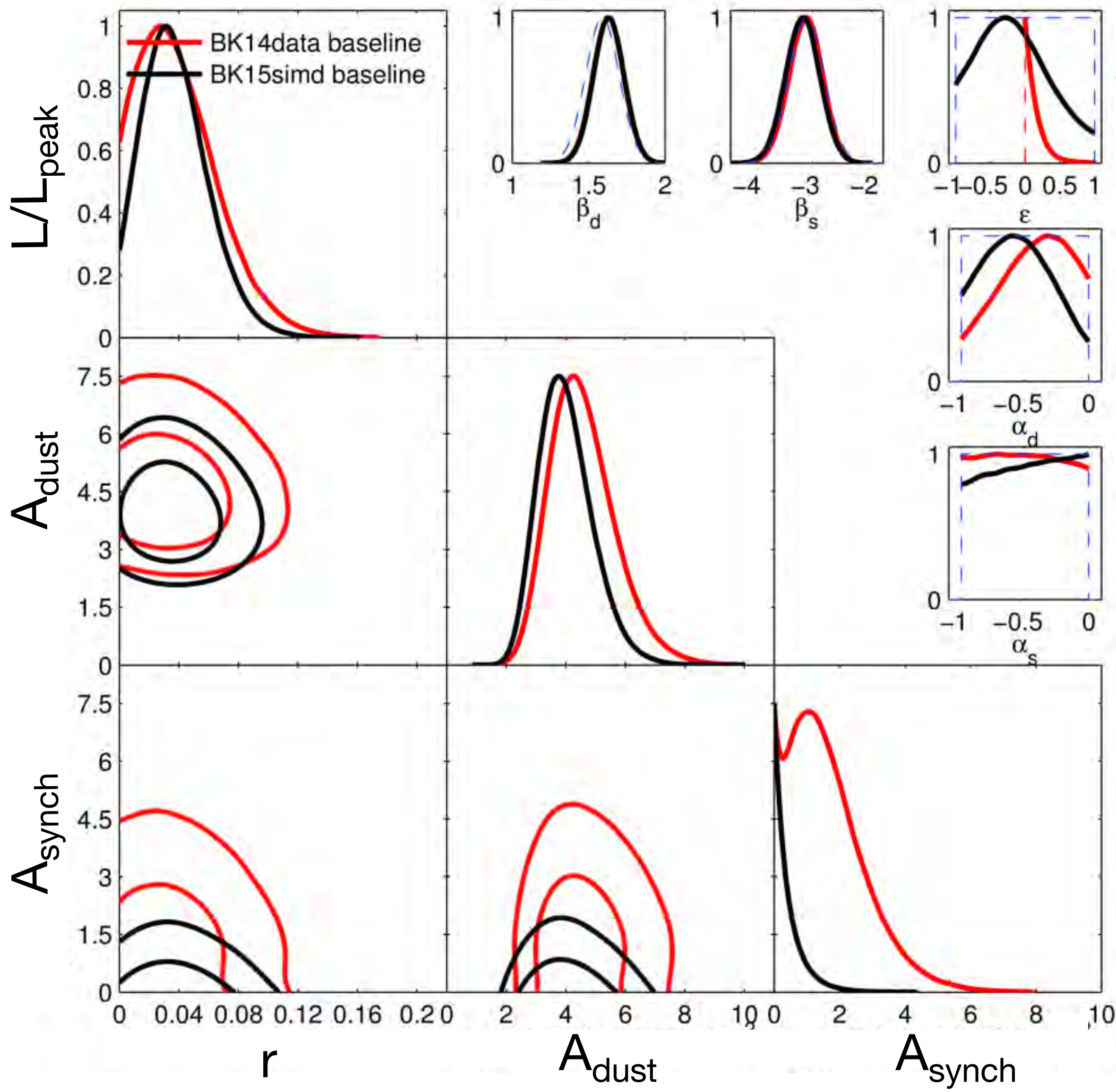
Red lines: BK14 CMB + polarized dust model with r = 0

Spectra using all data up to and including 2015 - for the first time adding Keck 220GHz

220 GHz data in excellent agreement with Planck 353 GHz at similar dust sensitivity

The BICEP/Keck Collaboration

BK15 Simulated Results



Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation

Marginalize over generous ranges in spatial spectral indices

Plus: many alternate analyses presented

- Foreground priors
- Dust EE/BB ratio
- WMAP/Planck data
- Dust decorrelation

Dust Decorrelation?

Planck 2016

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

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[70], 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.

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**

Planck 2018

Planck intermediate results. LIV. Polarized dust foregrounds

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

(Affiliations can be found after the references)

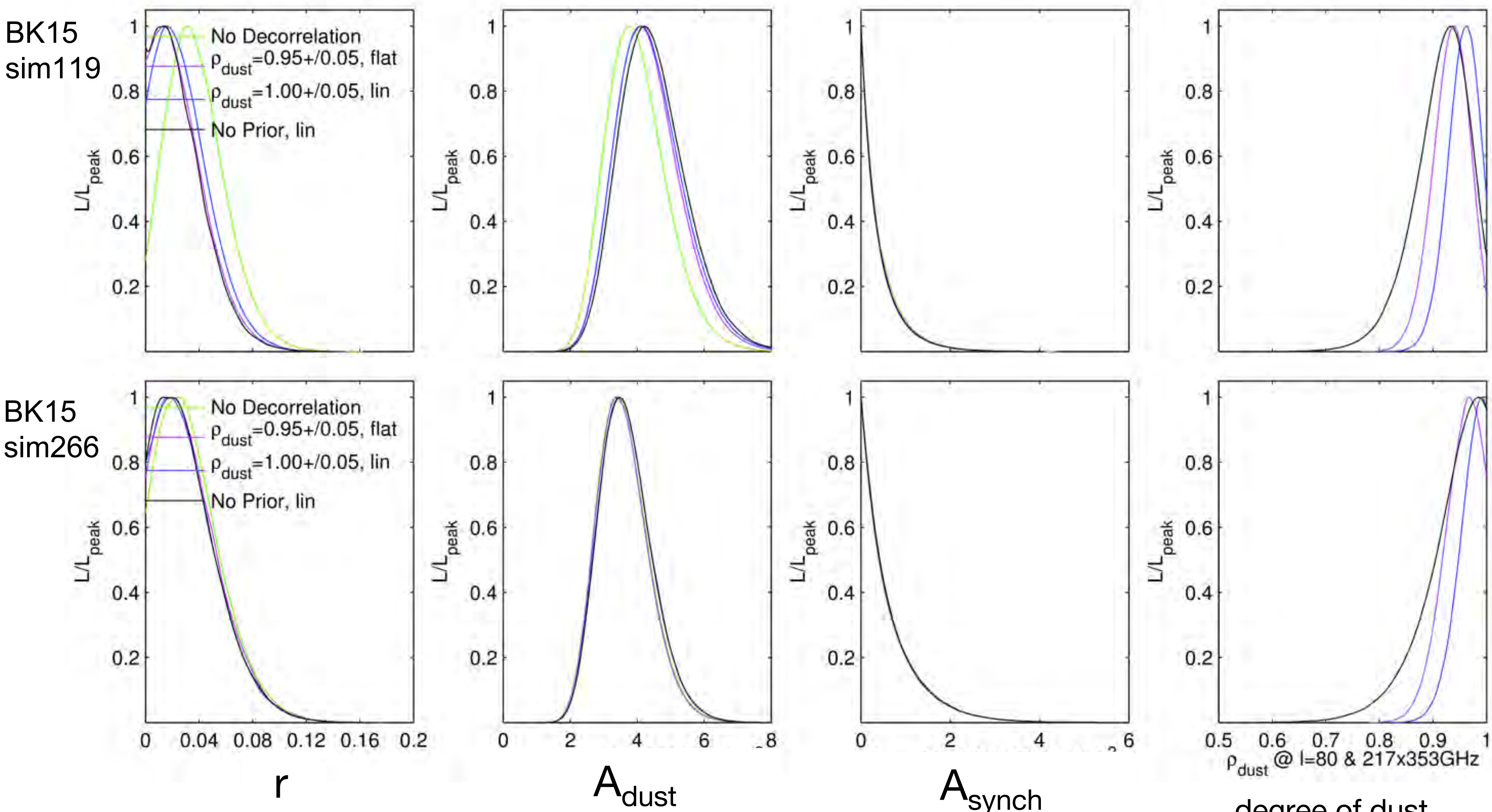
Preprint online version: January 17, 2018

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* PR3-2017 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.

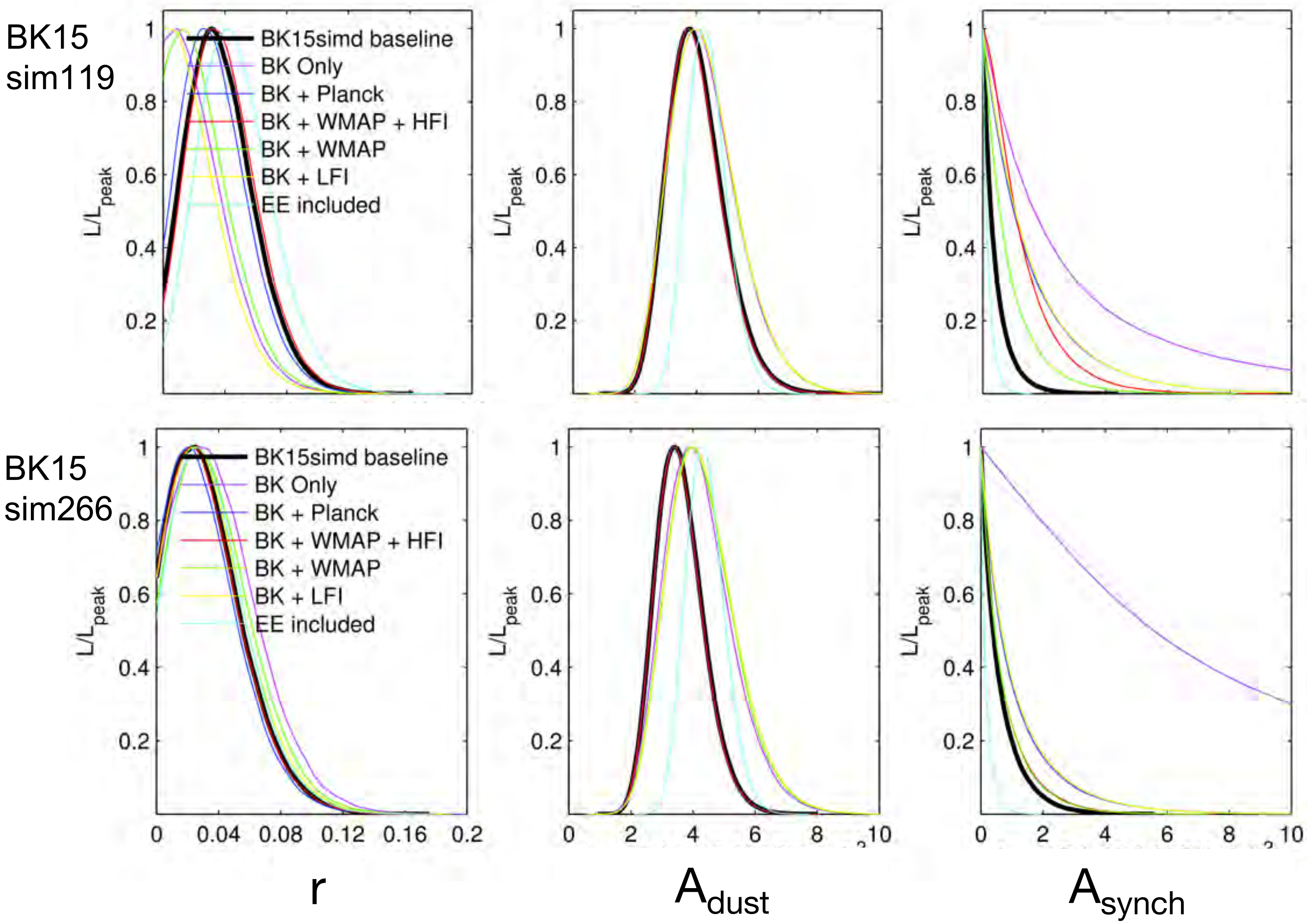
We find no evidence for a loss of correlation.
… might not be a problem for CMB experiments aiming at a primordial B-mode detection limit on the tensor-to-scalar ratio r ~ 0.01…

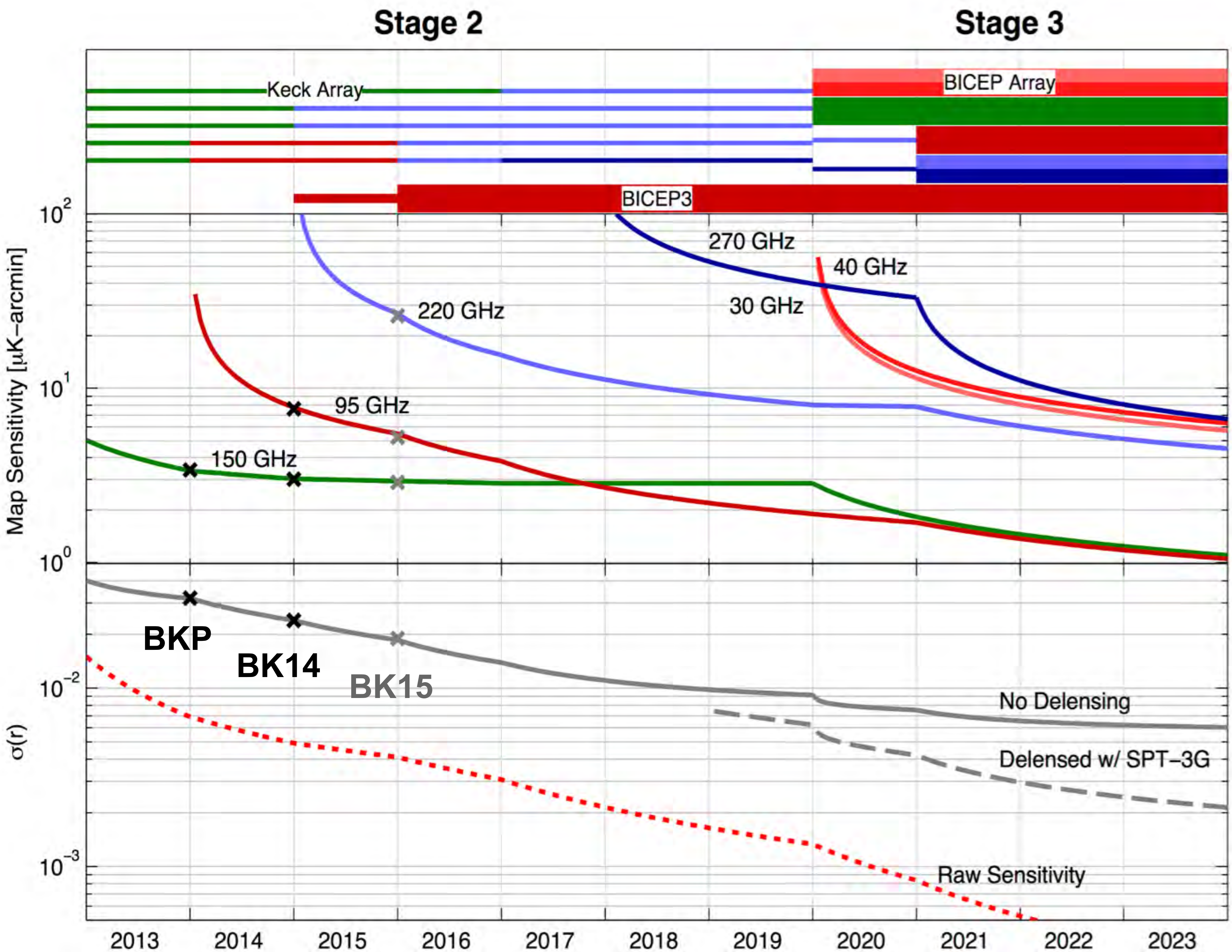
BK15 simulated results: variations with dust modeling



degree of dust "decorrelation" from spatial SED variation

BK15 simulated results: variations with data selection

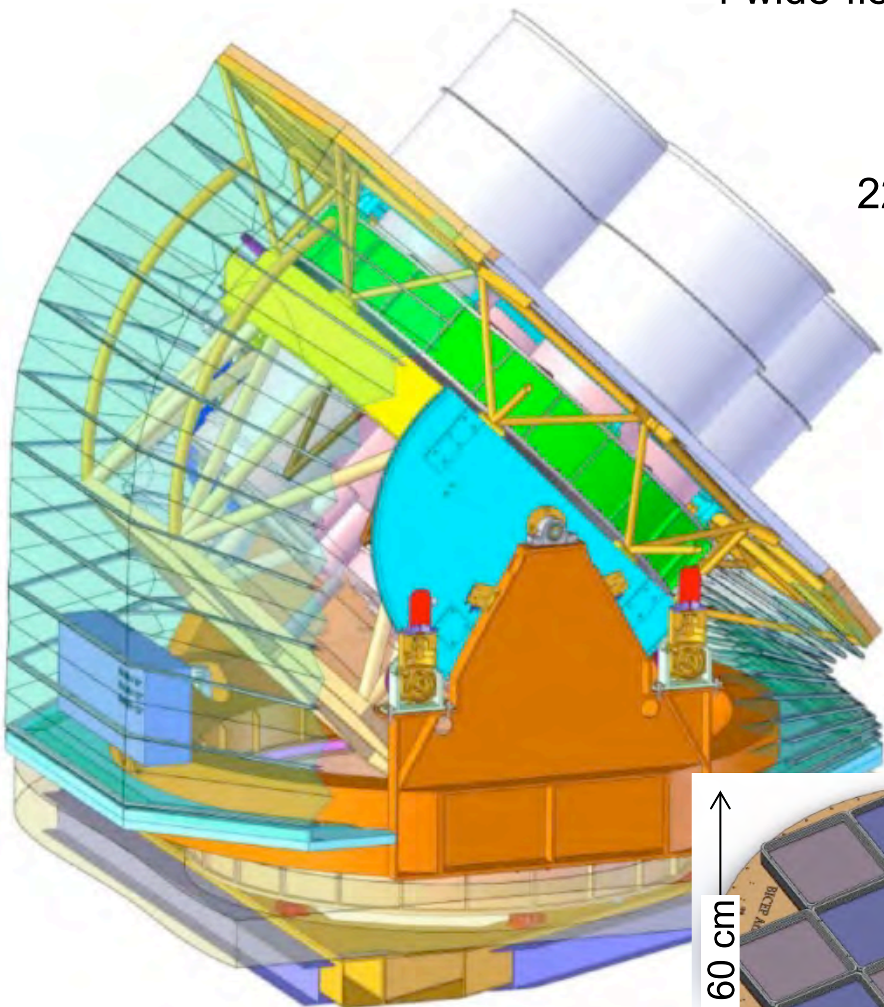


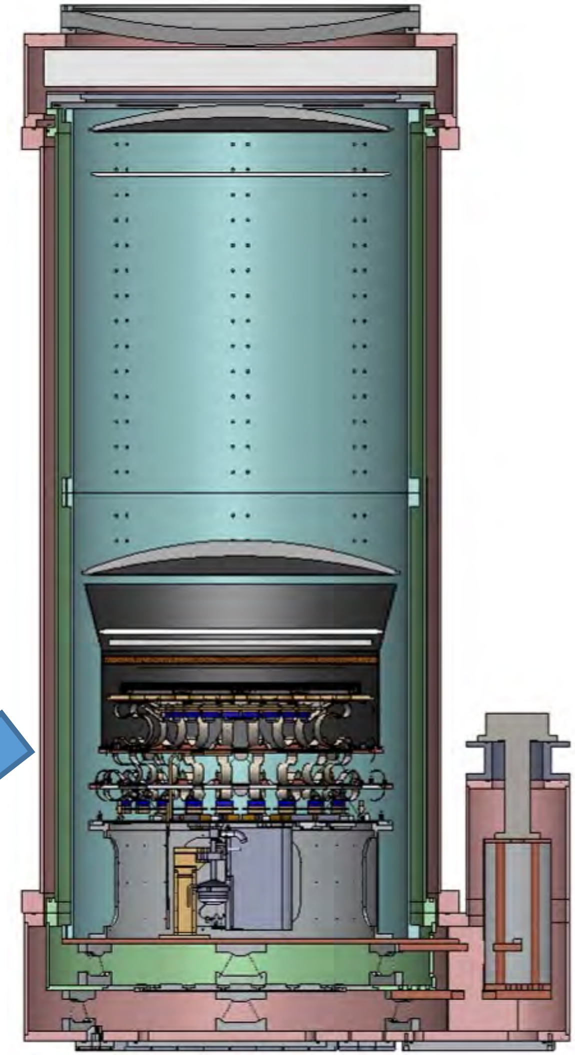


Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
Map Sensitivity [μK−arcmin]
σ(r)
BKP
BK14
BK15
No Delensing
Delensed w/ SPT−3G
Raw Sensitivity
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023

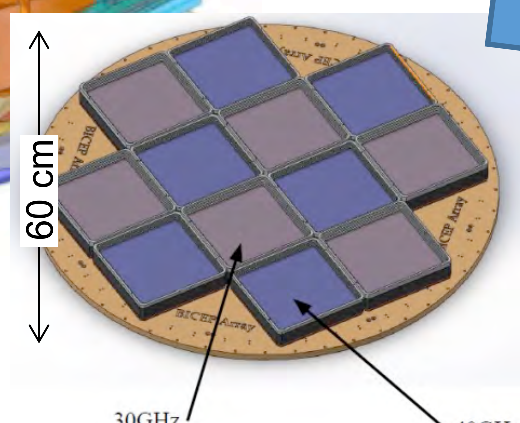
BICEP Array Under Construction

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





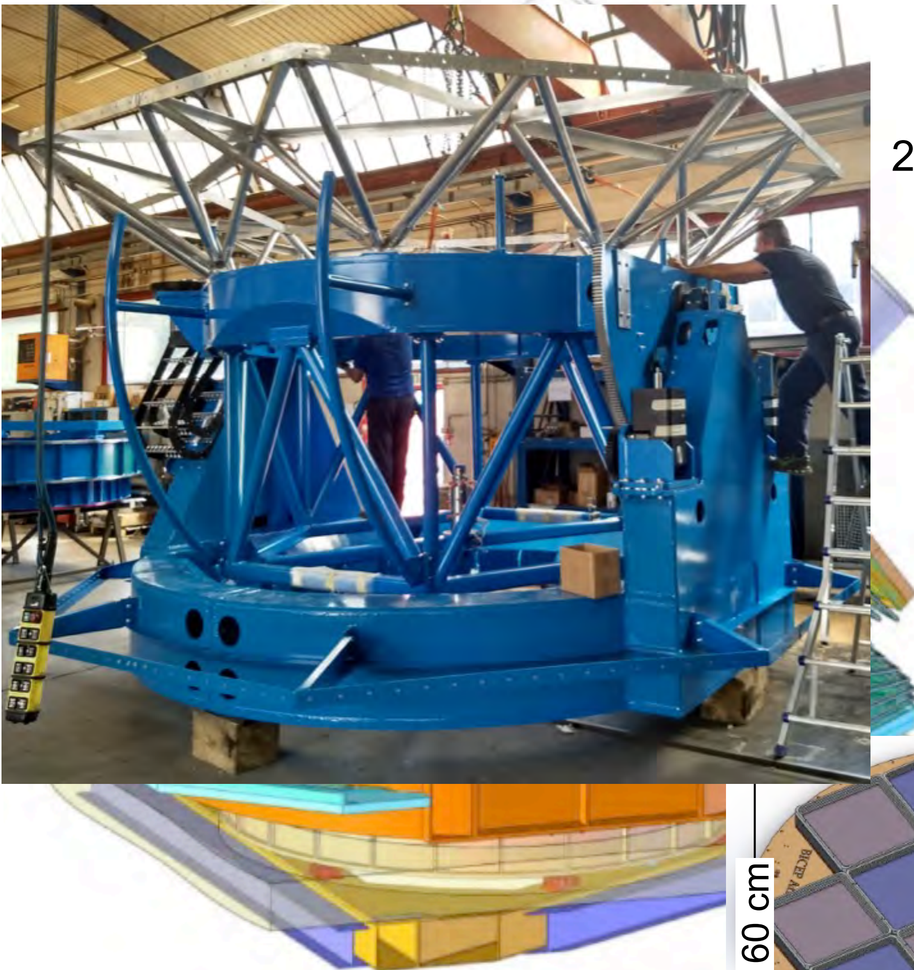
Wide-field cryogenic receiver



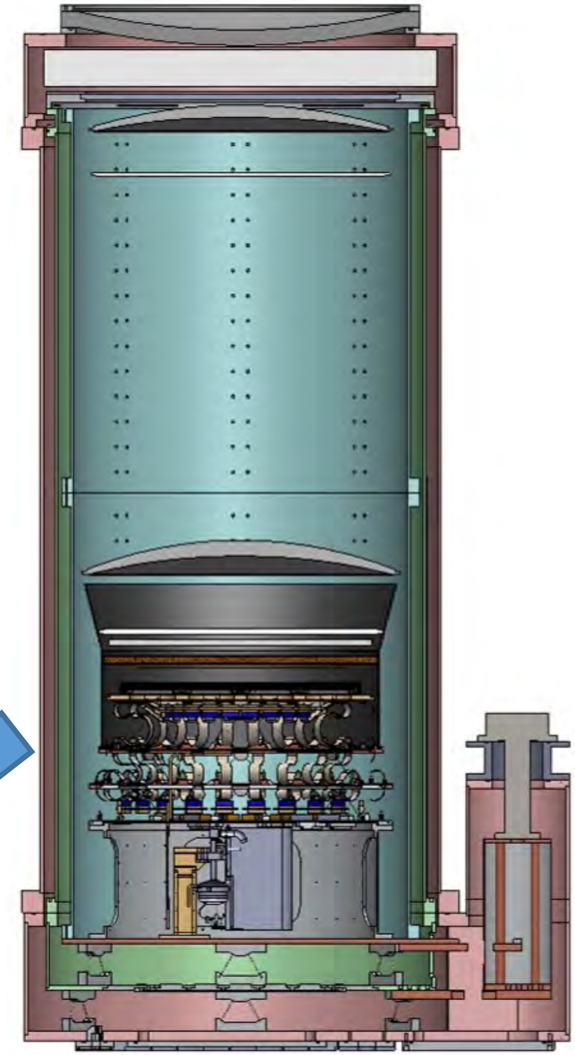
Focal plane layout

BICEP Array Under Construction

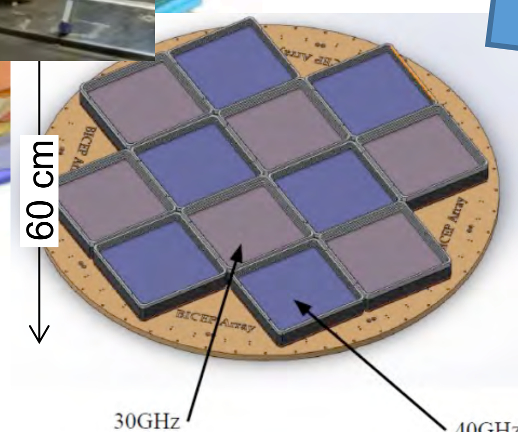
photo: Clem Pryke



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

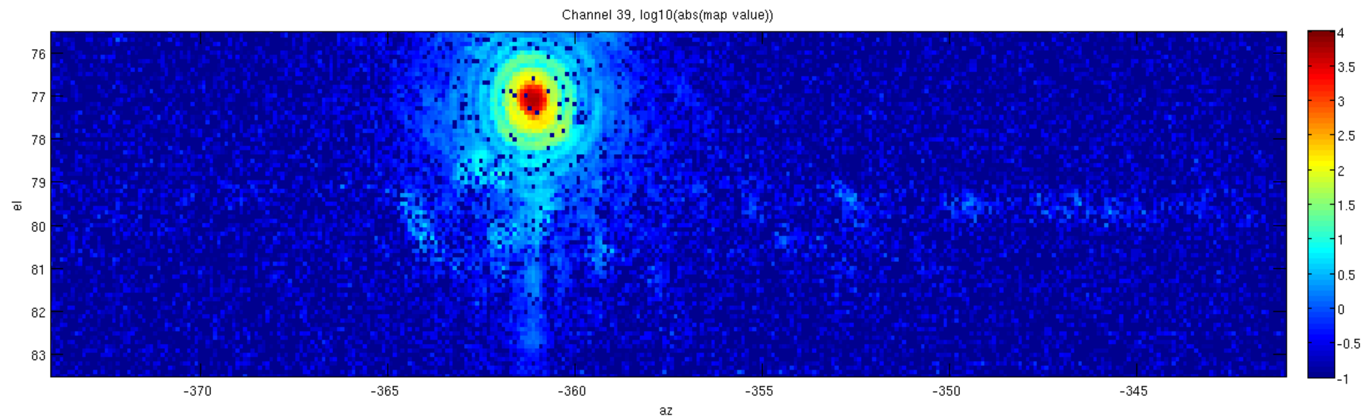


Wide-field cryogenic receiver

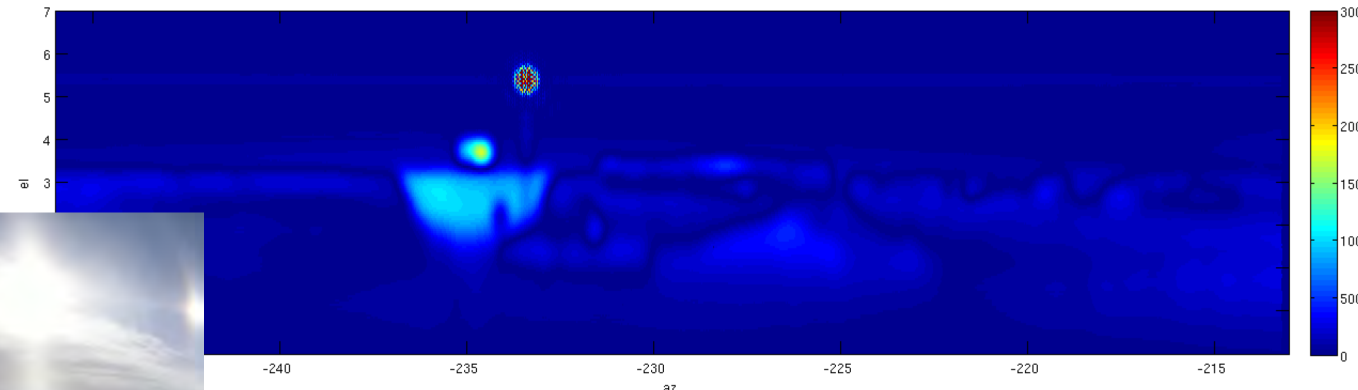


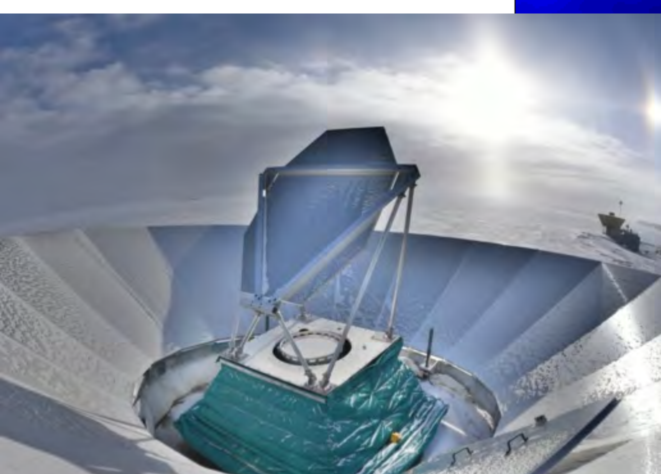
Focal plane layout

This season @ Pole: BICEP3/Keck are observing 95, 210, 220, 270 GHz



ultra-deep beam calibrations: BICEP3 viewing an amplified polarized calibration source over the ground shield using a mirror

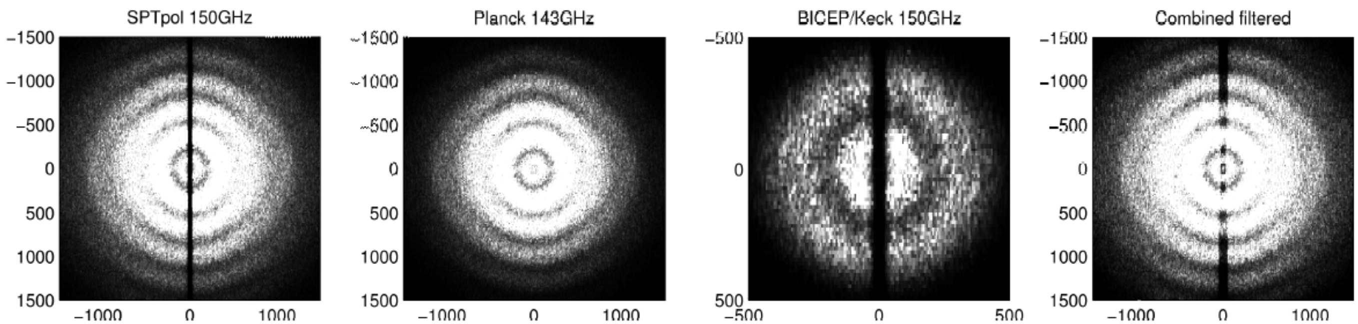




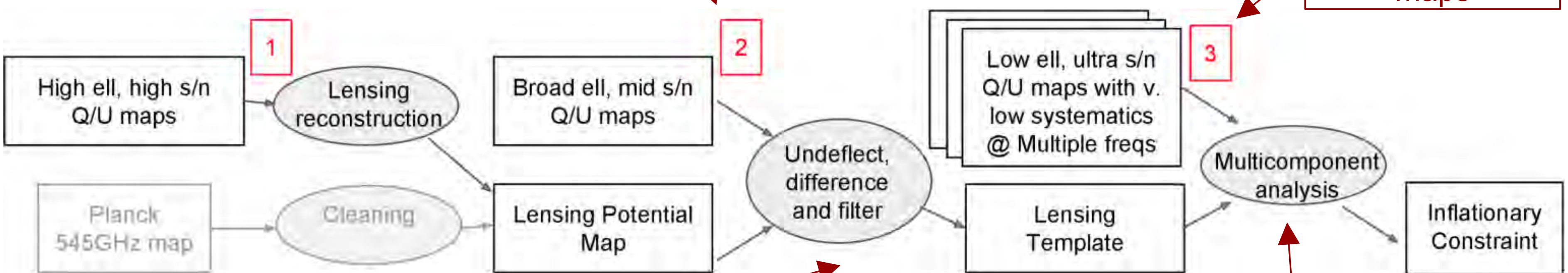
The BICEP/Keck Collaboration

De-lensing with BK/SPT/Planck:

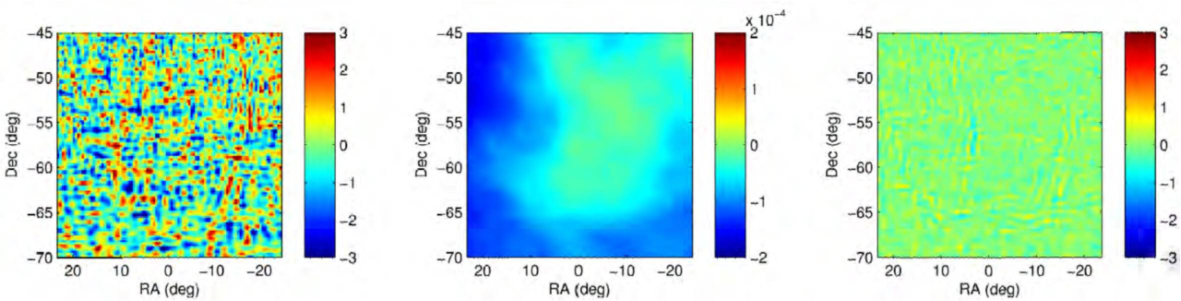
Combine SPT/Planck/BK Q/U maps



The usual BK maps

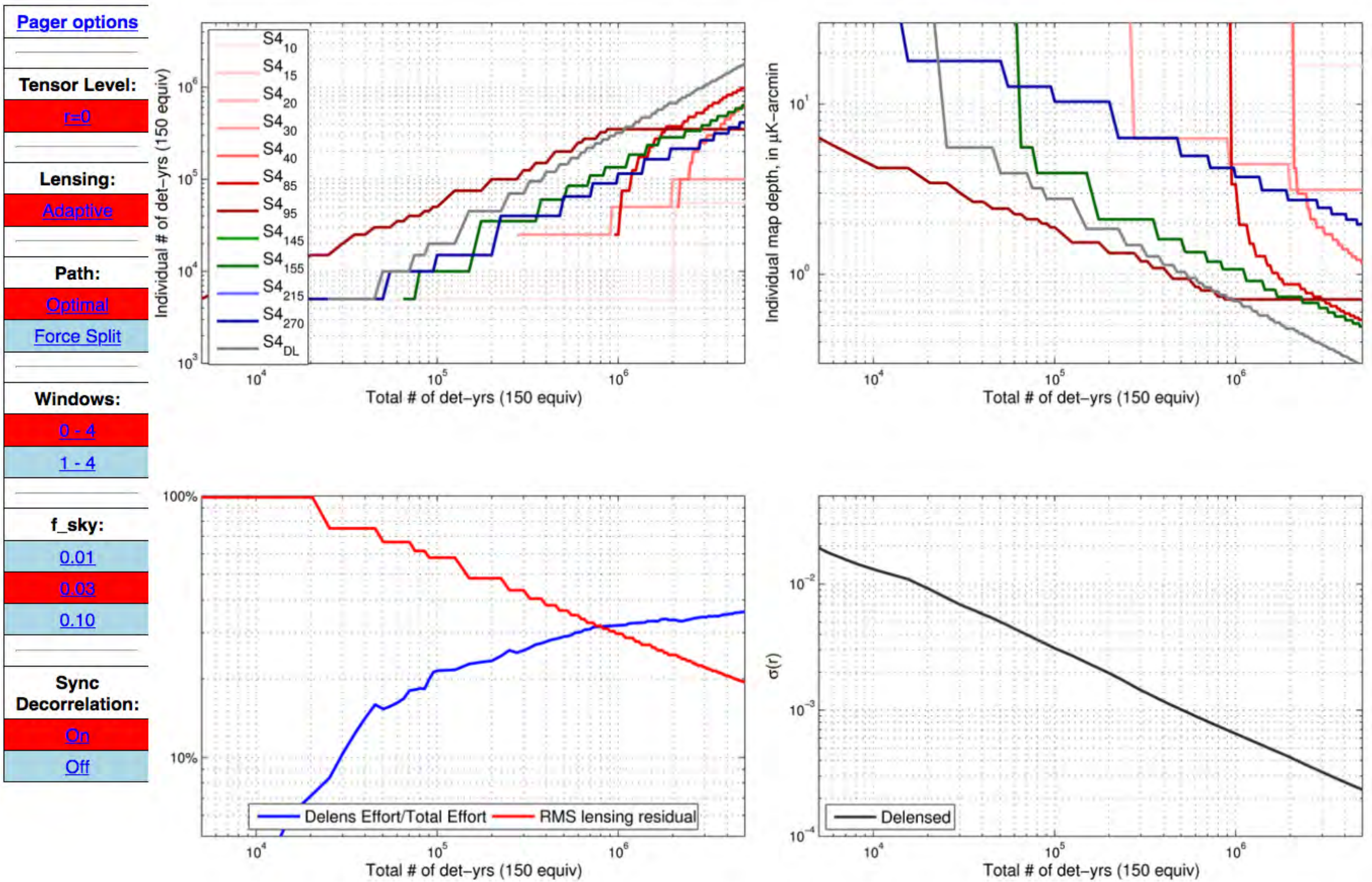


At the moment doing *map space* un-deflect operation



Natural extension: don't "delens" maps and take spectra - instead add a "lensing template" virtual band to the stack of multi-frequency input maps. So long as we can calculate expectation values for the auto and cross spectra it fits right in.

Component Separation plan for CMB S4



V. Buza / Harvard (from CMB-S4 working group wiki)

Conclusions

r constraints using B-modes are being advanced by BICEP/Keck

- New BK15 with 220GHz data: results next month

Vigorous Stage 3 efforts underway now!

- progress is COMPLETELY driven by component separation
- biggest uncertainty is in FG complexity
- small & large dishes complementary: galactic FGs & delensing

BICEP Array + SPT3G should achieve $\sigma(r) \sim 0.003$ by 2022

CMB-S4 working groups point the way for open collaboration

- sky modeling, lensing separation, data challenges
- sharing S3 experience in instrumental design, achieved performance and systematic control