New Constraints on Primordial Gravitational Waves
using *Planck*, WMAP, and BICEP/*Keck* Observations through the 2018 Observing Season

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on behalf of the BICEP/*Keck* Collaboration

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CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

May 2019 Collaboration meeting - Caltech

Outline

I. The BICEP/Keck program
II. BK18 analysis and results
   A. From timestreams to maps
   B. Multi-component likelihood analysis and results
   C. Data checks and systematics
III. Beyond BK18
IV. Other analysis

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I. **The BICEP/Keck program**

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Overview of the BICEP/Keck Program

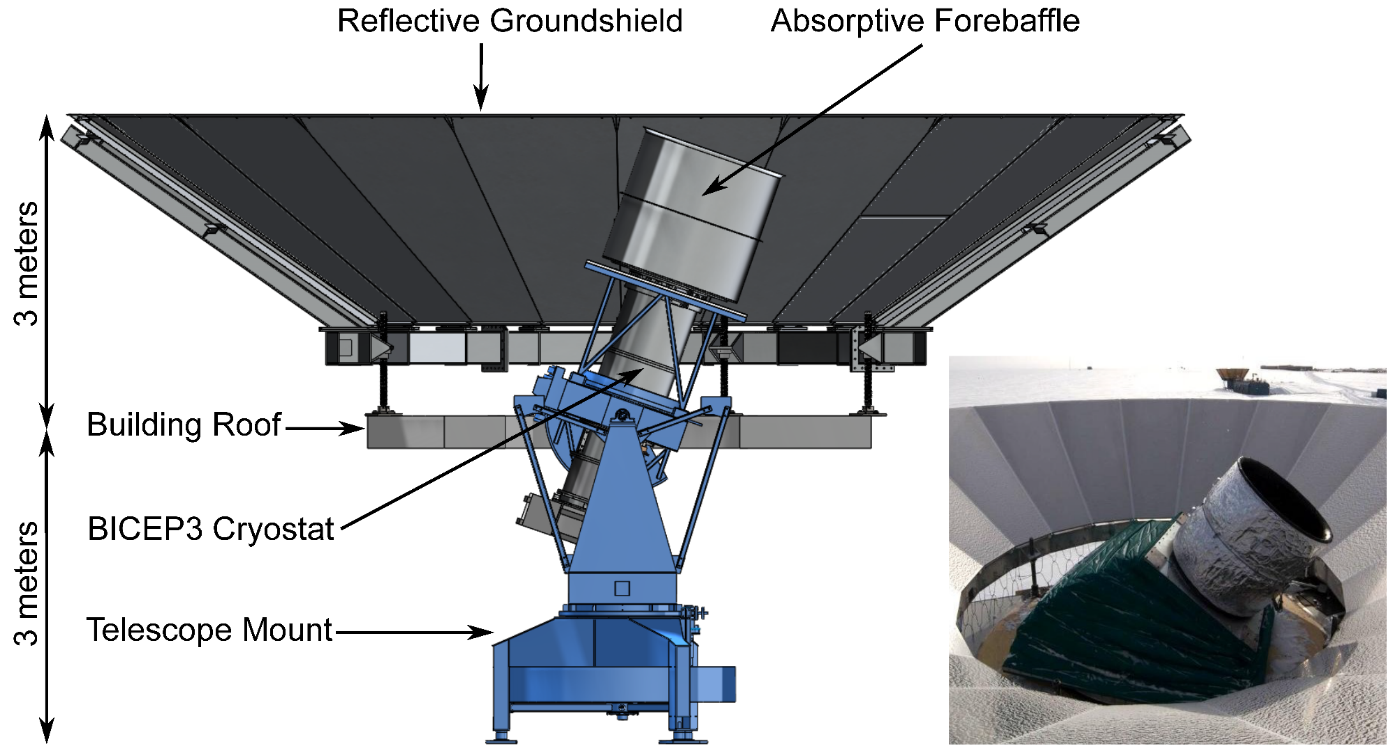
- Observations from the geographic South Pole
- Series of telescopes with similar designs
- Narrow and deep sky patch to target low-ℓ BB peak @ 2 deg
- Multi-frequency coverage for component separation

The South Pole Station

- High altitude (9,300 ft = 2800 m, most of it ice)
- Extremely dry
- Lack of day/night cycles
  - very stable atmosphere
  - sky observable for 6 months of continuous darkness
- Minimal radio frequency interference

Accumulating data on the same deep sky patch since 2006!

Small aperture strategy



- Compact, on-axis optics
- Boresight rotation
- Shielding from stray diffracted light + termination of sidelobes

Typical BICEP/Keck receiver

IR/thermal filtering to mitigate thermal load

Superconducting niobium shield to mitigate magnetic pick-up

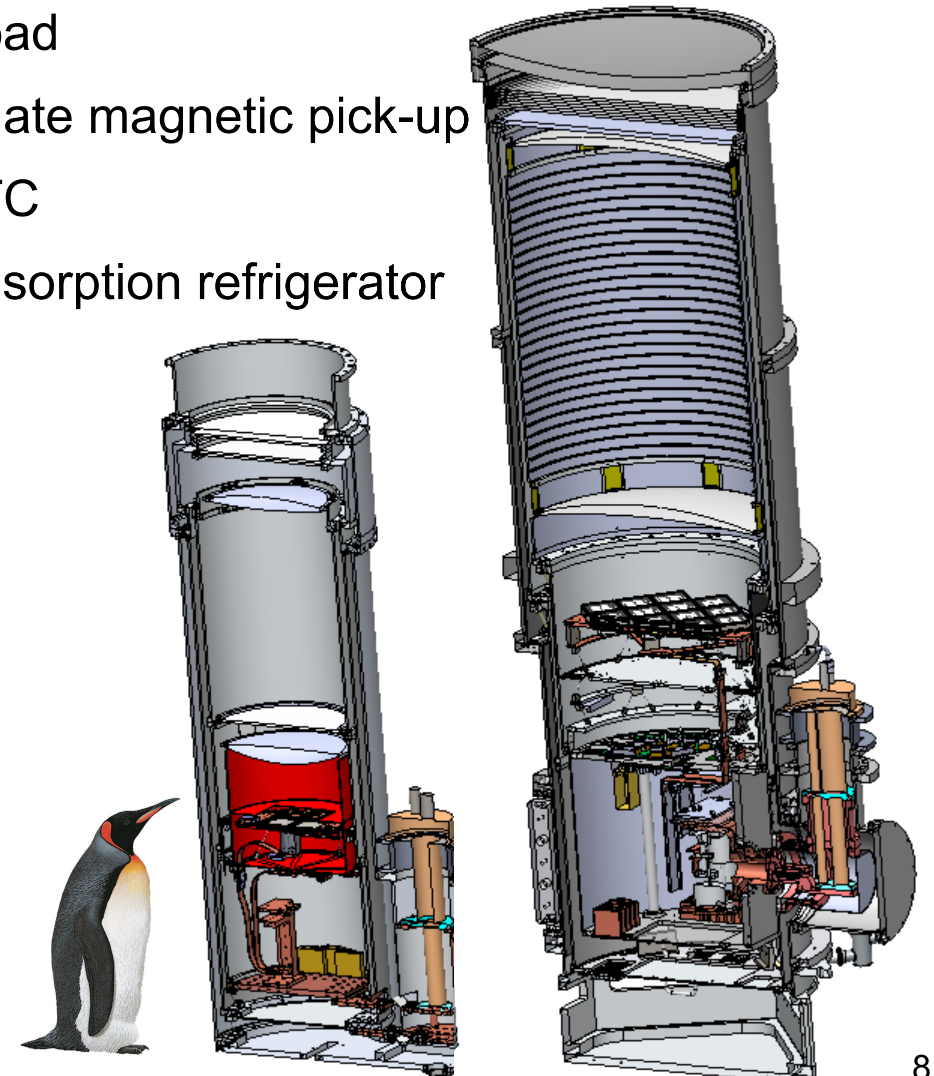
Refractive optics cooled to 4K with a PTC

FP cooled to 250 mK with a 3-stage He sorption refrigerator

New in BICEP3/BICEP Array

- ➢ Optics design
  - ○ Larger optics (680 mm)
  - ○ Better filtering
  - ○ Different materials
- ➢ Modular focal plane

→ 10x optical throughput
of a single BICEP2/Keck receiver



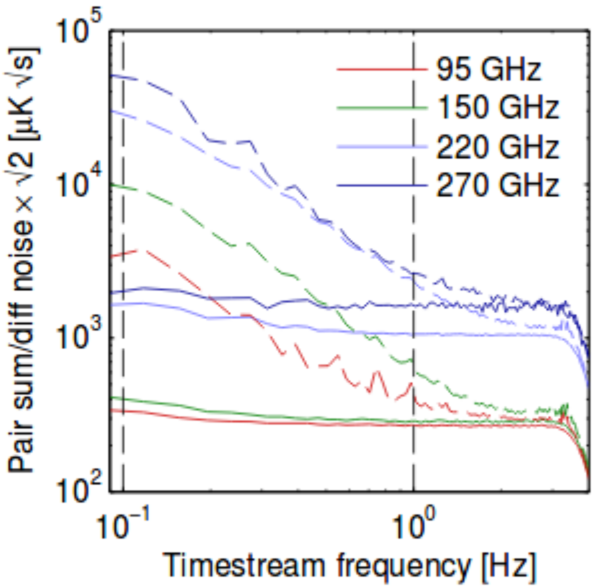
Detectors & Readout

Antenna-coupled superconducting TES bolometers

- 4'x4' tiles with 64 detector pairs per tile
- Dipole antenna that separates light polarisation in two orthogonal components
- Time domain multiplexing using DC biased SQUIDs
- Modular design as of BICEP3 to allow for easy replacement

Polarisation modulation?

- Pair-difference works at Pole up to high frequency thanks to atmosphere properties
- Requires extra attention to differential beams systematics



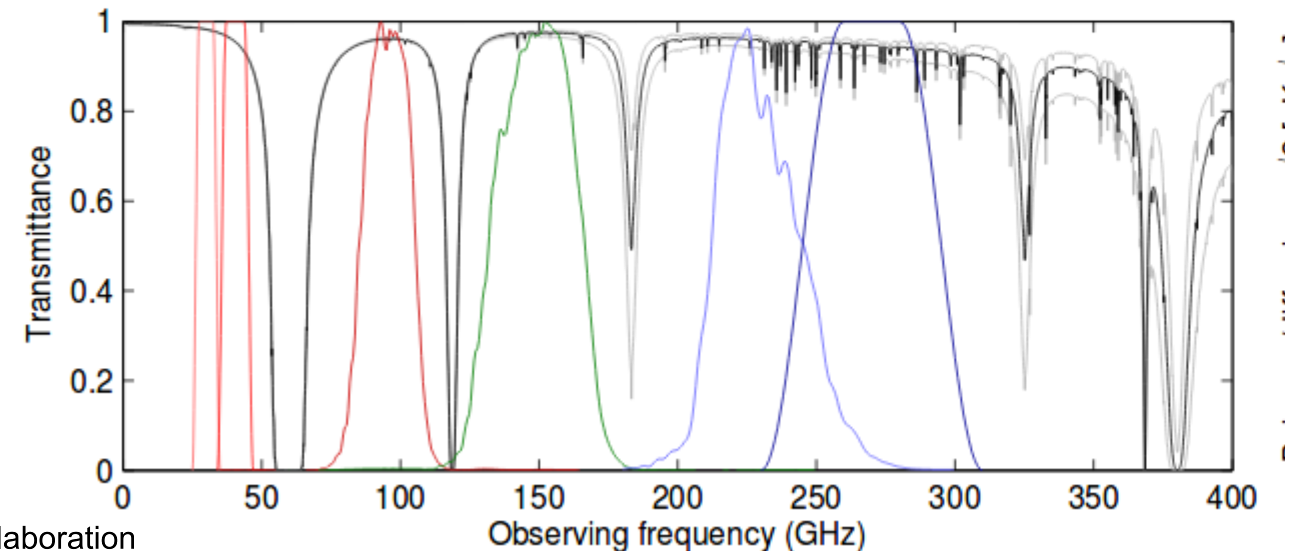
Bandpass & Frequency coverage

Bandpass

- LC filters printed directly onto the detector wafers
- Additional metal mesh low-pass edge filters on top of the modules to control out-of-band response
- ~30% bandwidth - *in-situ* calibration with FTS

BK18 observing bands: 95, 150 and 220 GHz

+ New in Keck Array (2018) **270 GHz**
+ New in BICEP Array (2019) **30/40 GHz +** future 95, 150 & 220/270 GHz



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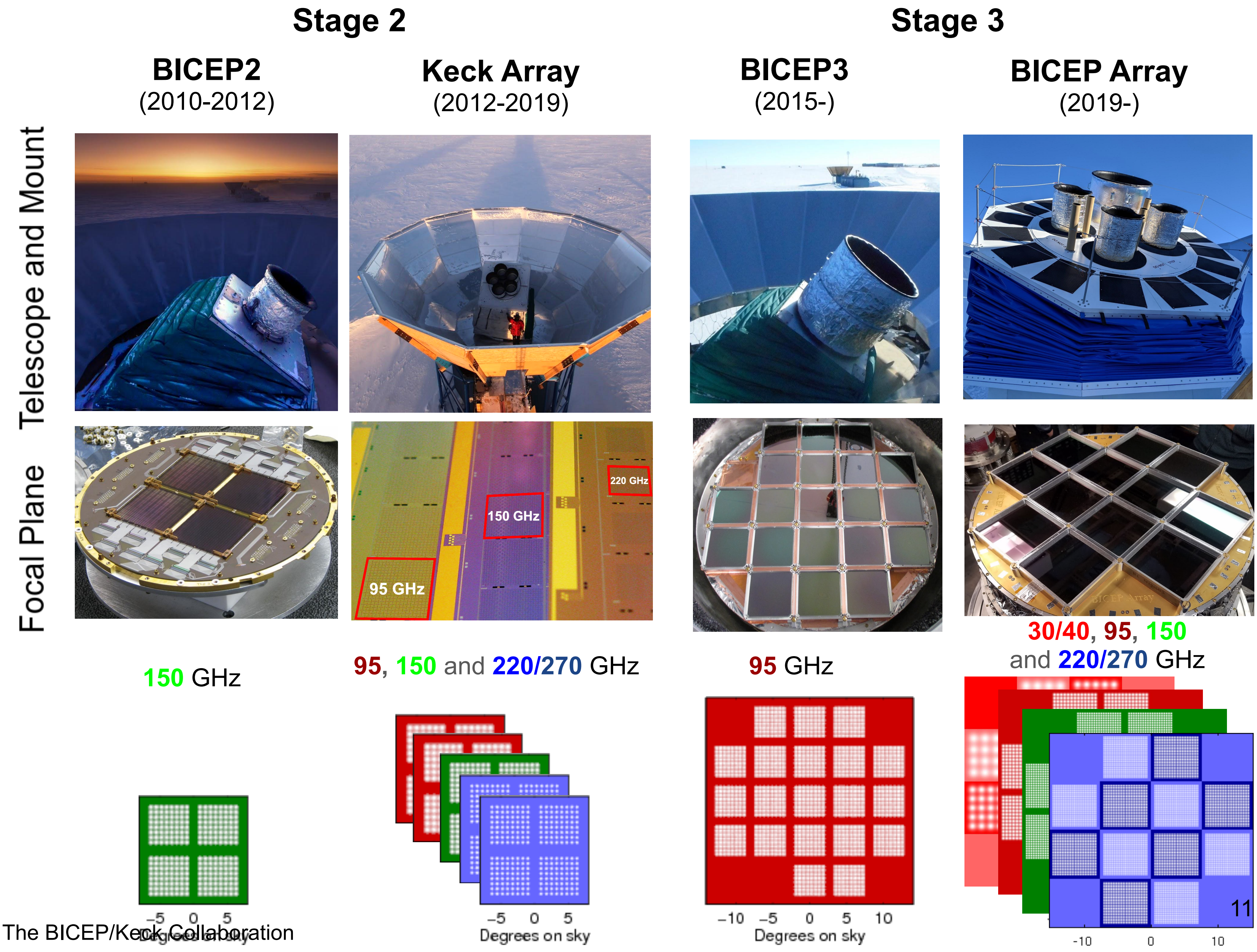
Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2015-)
BICEP Array
(2019-)
Telescope and Mount
Focal Plane
220 GHz
150 GHz
95 GHz
150 GHz
95, 150 and 220/270 GHz
95 GHz
30/40, 95, 150
and 220/270 GHz
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
-10 0 10

The BK18 data set

Frequency coverage

- 95GHz data from Keck Array + **BICEP3**
- 150GHz data from BICEP2 + Keck Array
- 220GHz data from Keck Array

Sky coverage

- Larger **BICEP3 field**: ~600 sq deg
- Smaller Keck/BICEP2 field ~400 sq deg

We include data taken up to the end of the 2018 observing season (Nov 2018)

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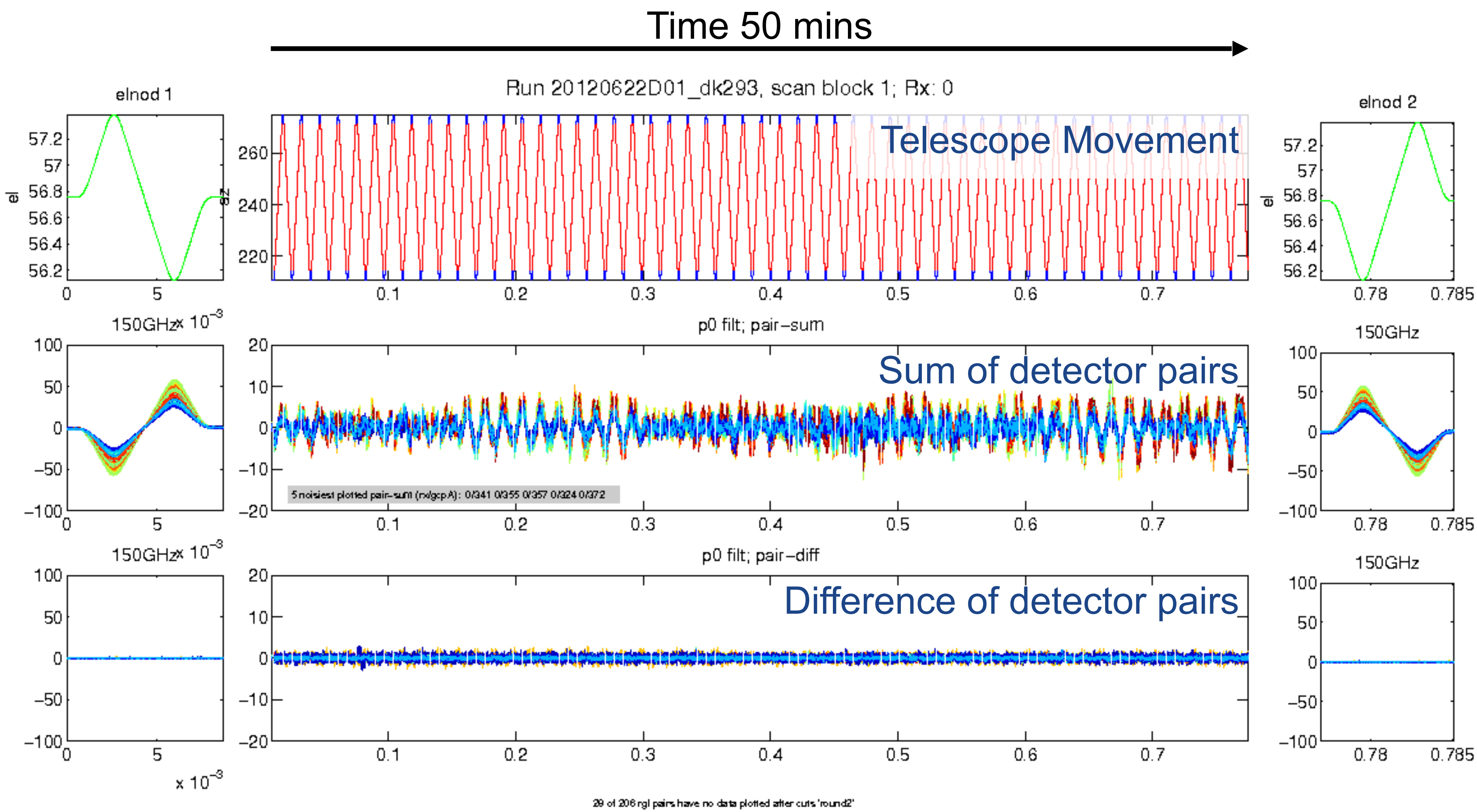
Raw Data



Cover the whole field in 60 such scans, then start over at new boresight rotation

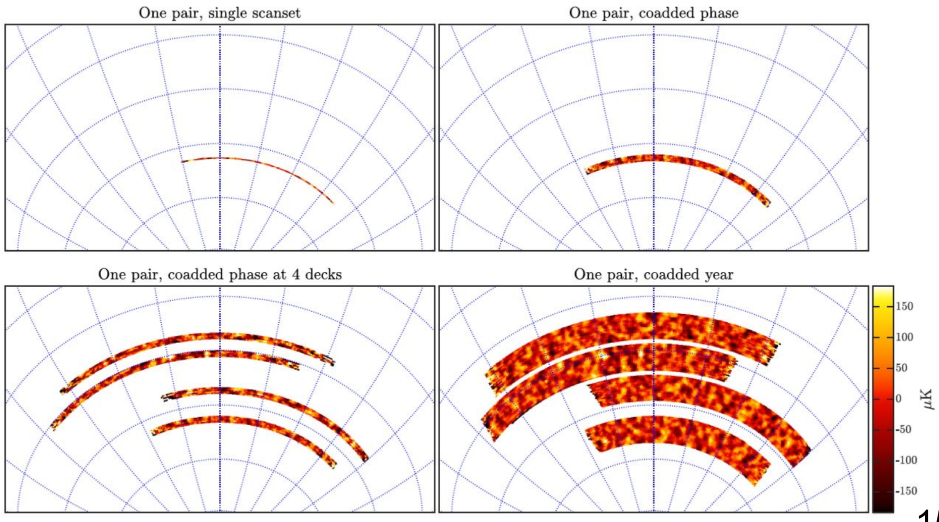
From timestreams to maps

Timestream filtering

- Polynomial filtering for atmosphere + ground template removal + scan-synchronous signal removal
- Differential beam systematics deprojection
  - Sample combination of smoothed Planck T map + its derivative
  - Regress against timestream to find fit coefficients
  - Subtract template in timestream space

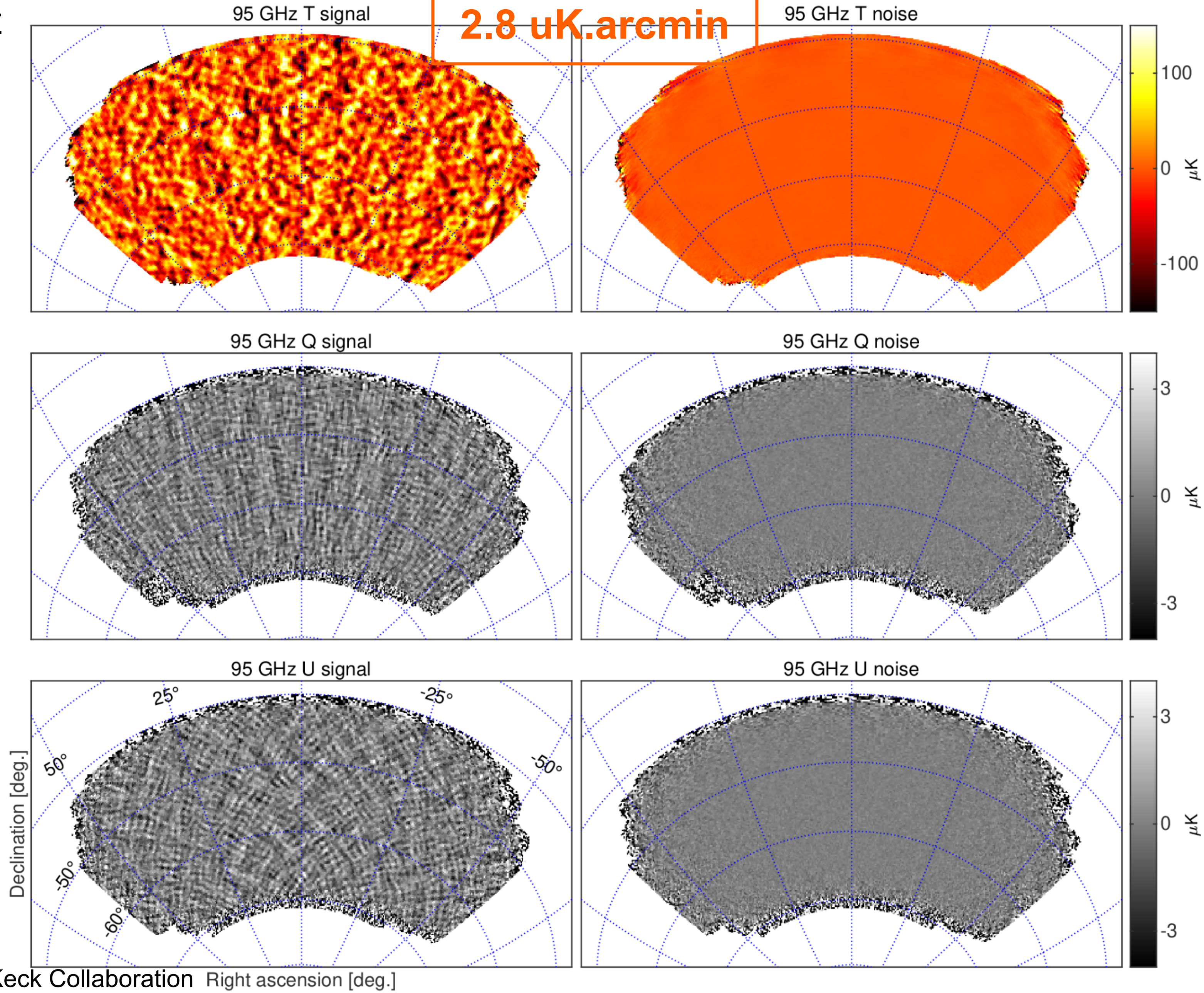
Map accumulation

- Accumulate data over each scanset (~50 min), then co-add per phase (9 scansets), per-deck angle and per year
- Do this for each detector pair



BK18
95GHz
maps

Q/U map depth 2.8 uK.arcmin



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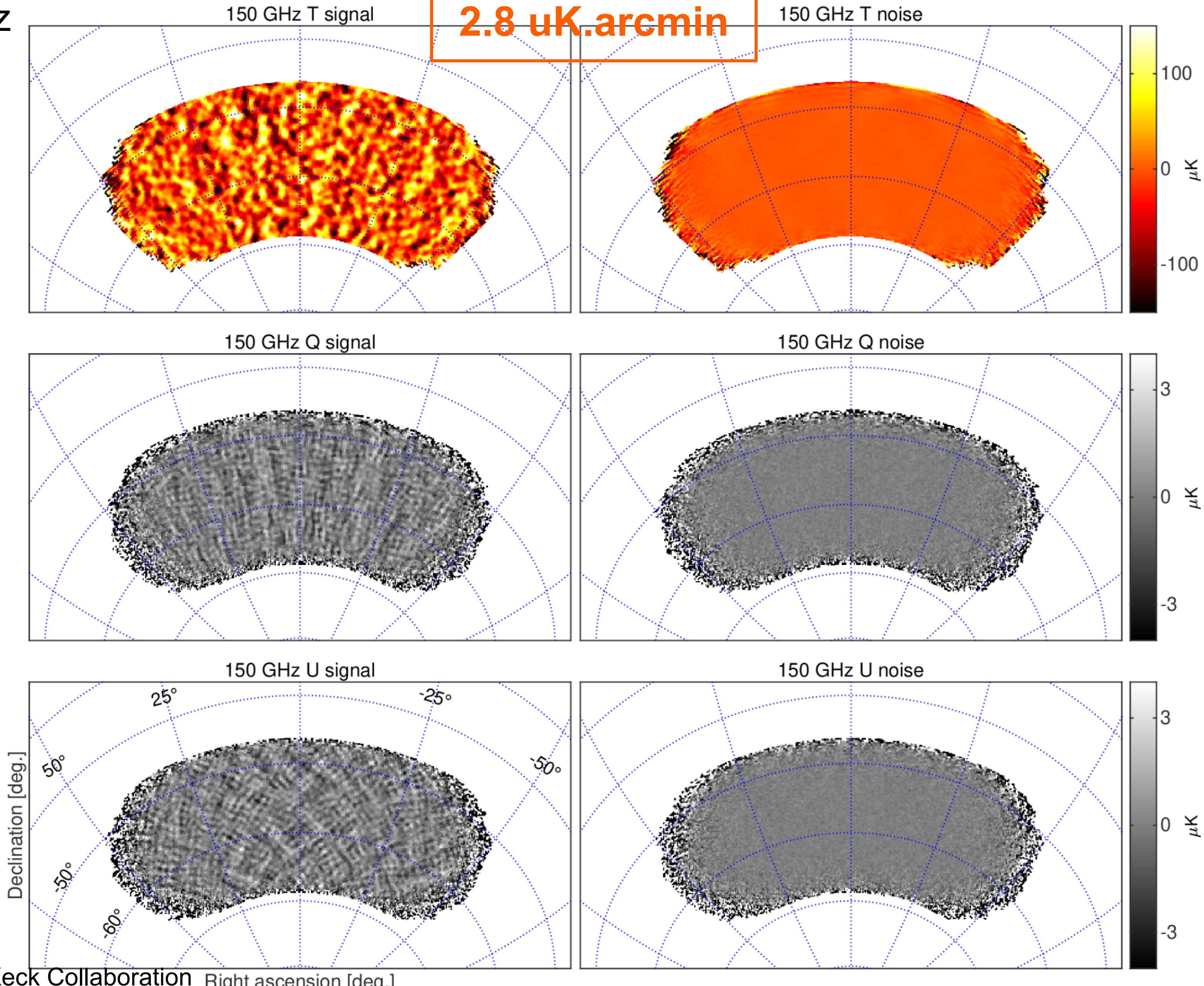
BK18
150GHz
Maps

Q/U map depth 2.8 uK.arcmin



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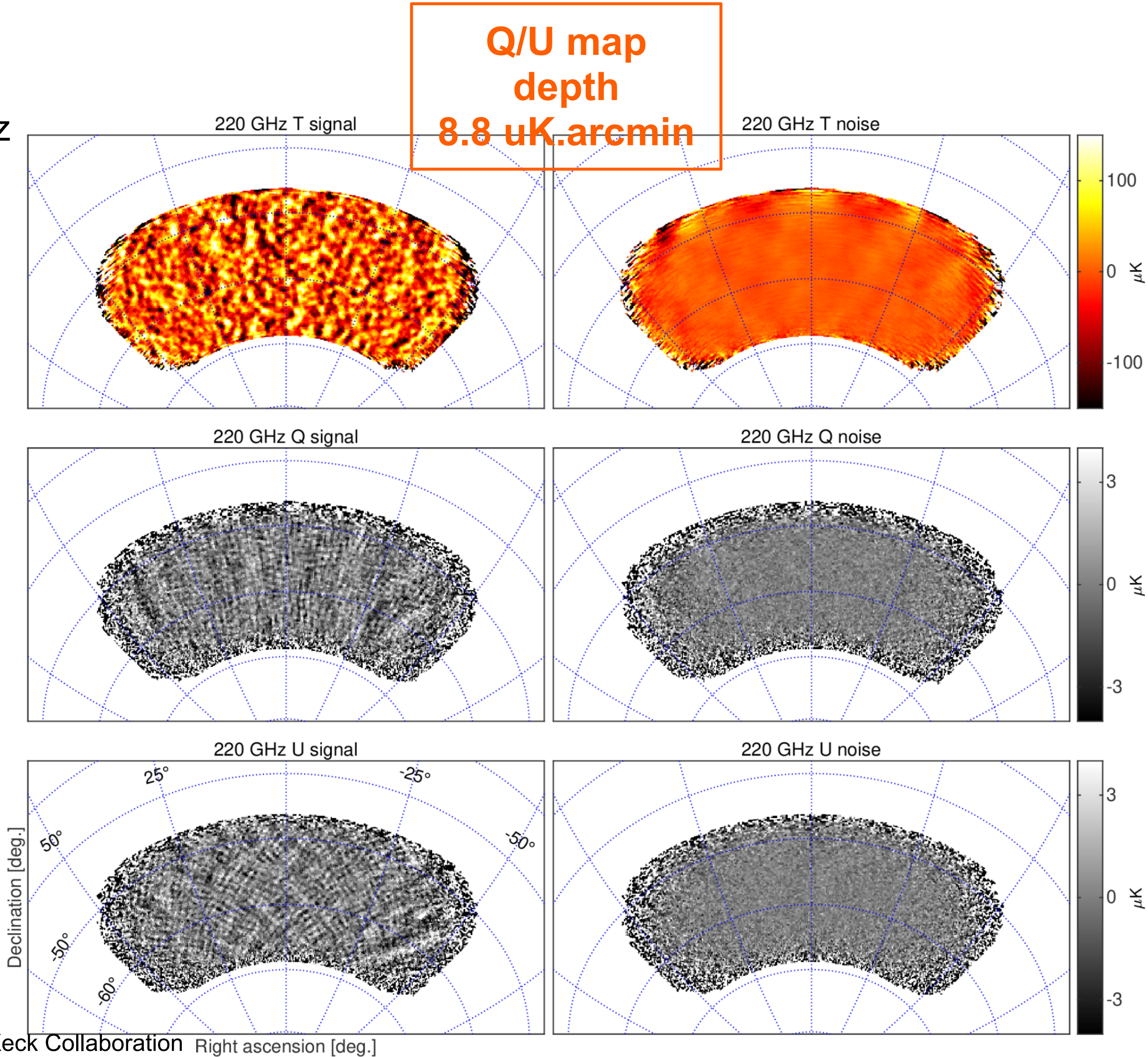
BK18
220GHz
Maps



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Matrix-based E/B separation

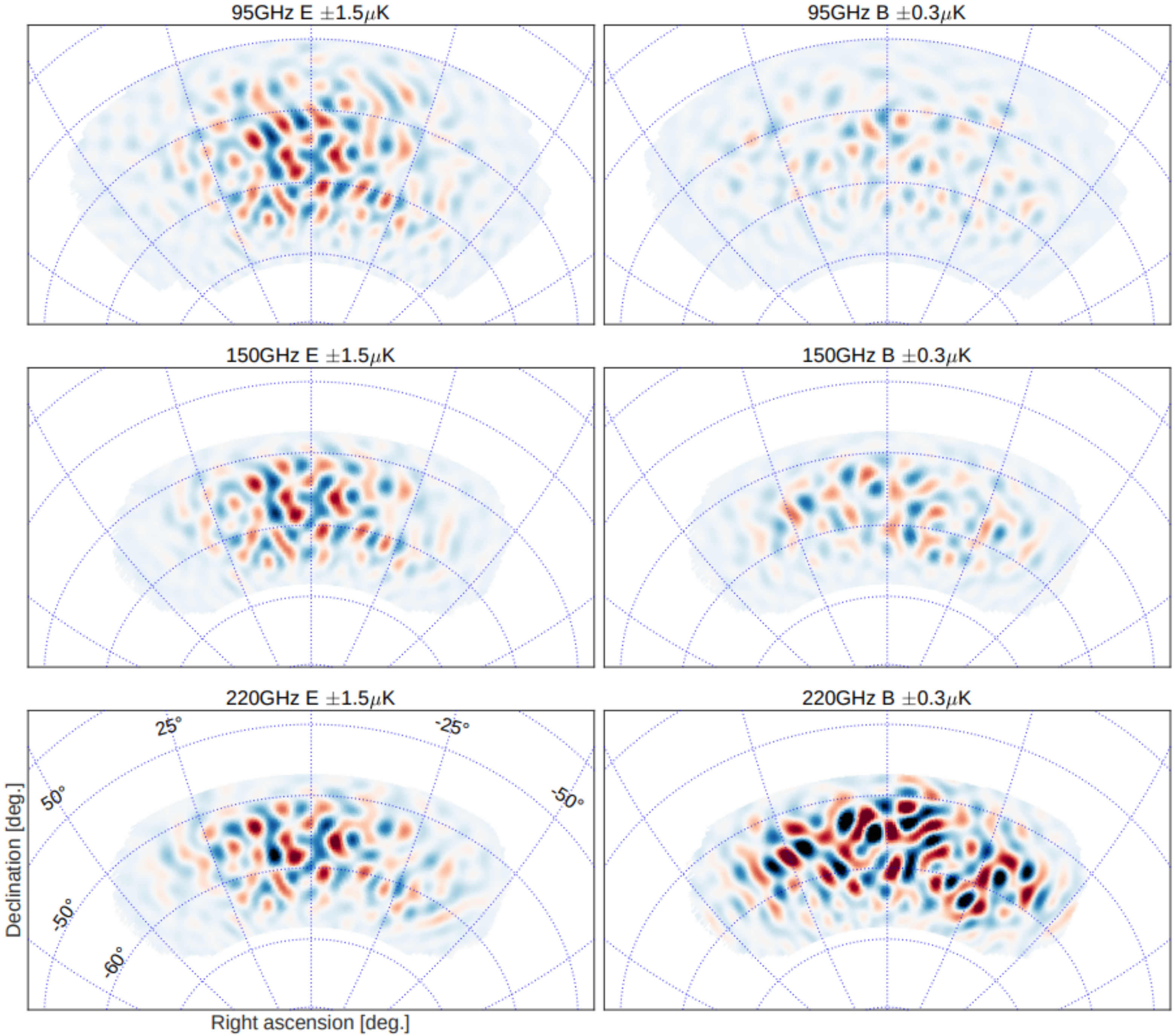
E → B leakage due to map-making

- Rotation from filtered, apodized Q/U maps to E/B maps mixes E/B
- E → B leakage that dominates real B modes
- Can be fully described by an observation matrix R that contains all operations from timestreams to map (including filtering, deprojection, apodization)

Purification matrix

- Construct a theory covariance matrix
- Observe it with the observation R
- Solve an eigenvalue problem to extract a “purification matrix” that removes leaked E and ambiguous modes from the maps

BK18
E/B purified maps



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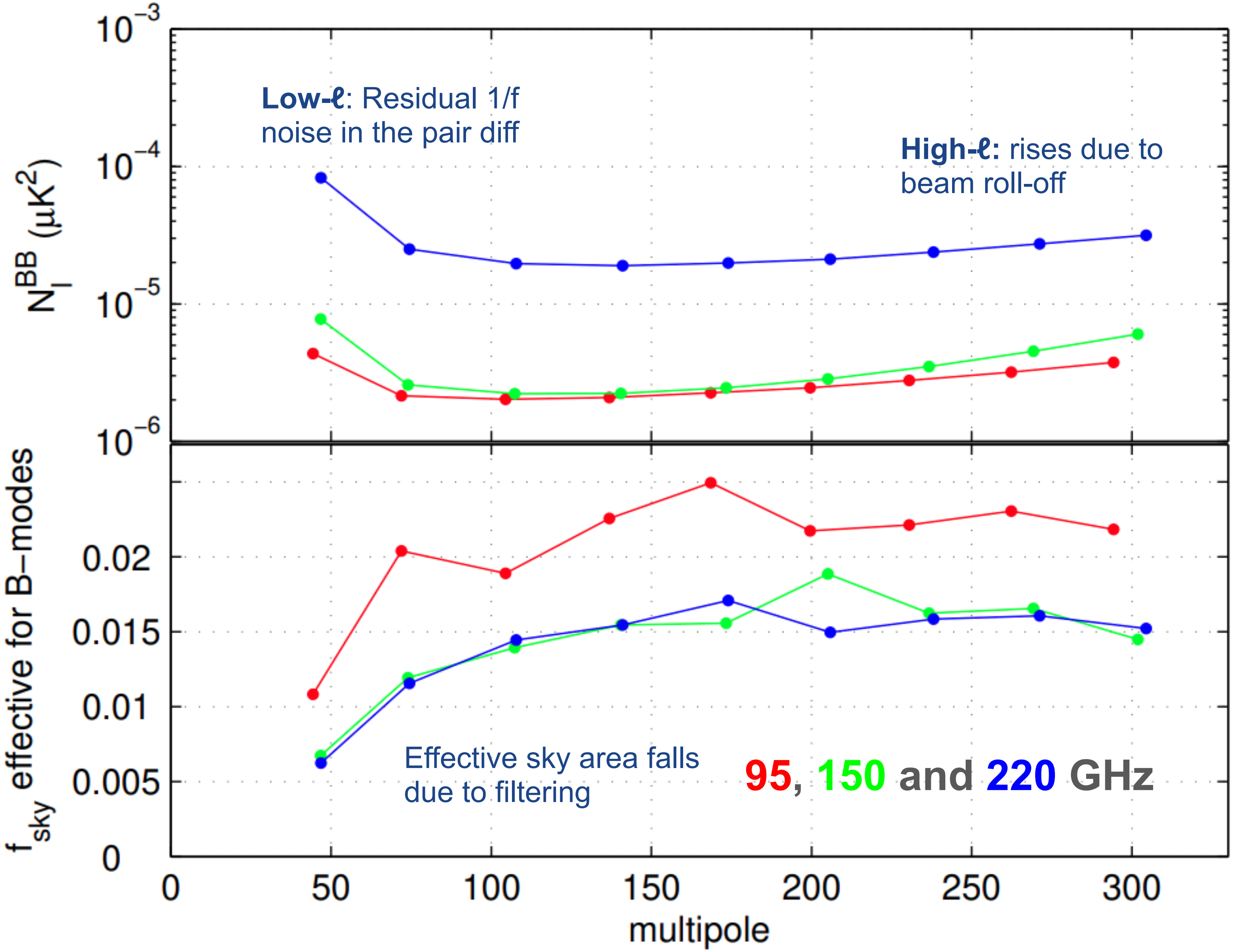
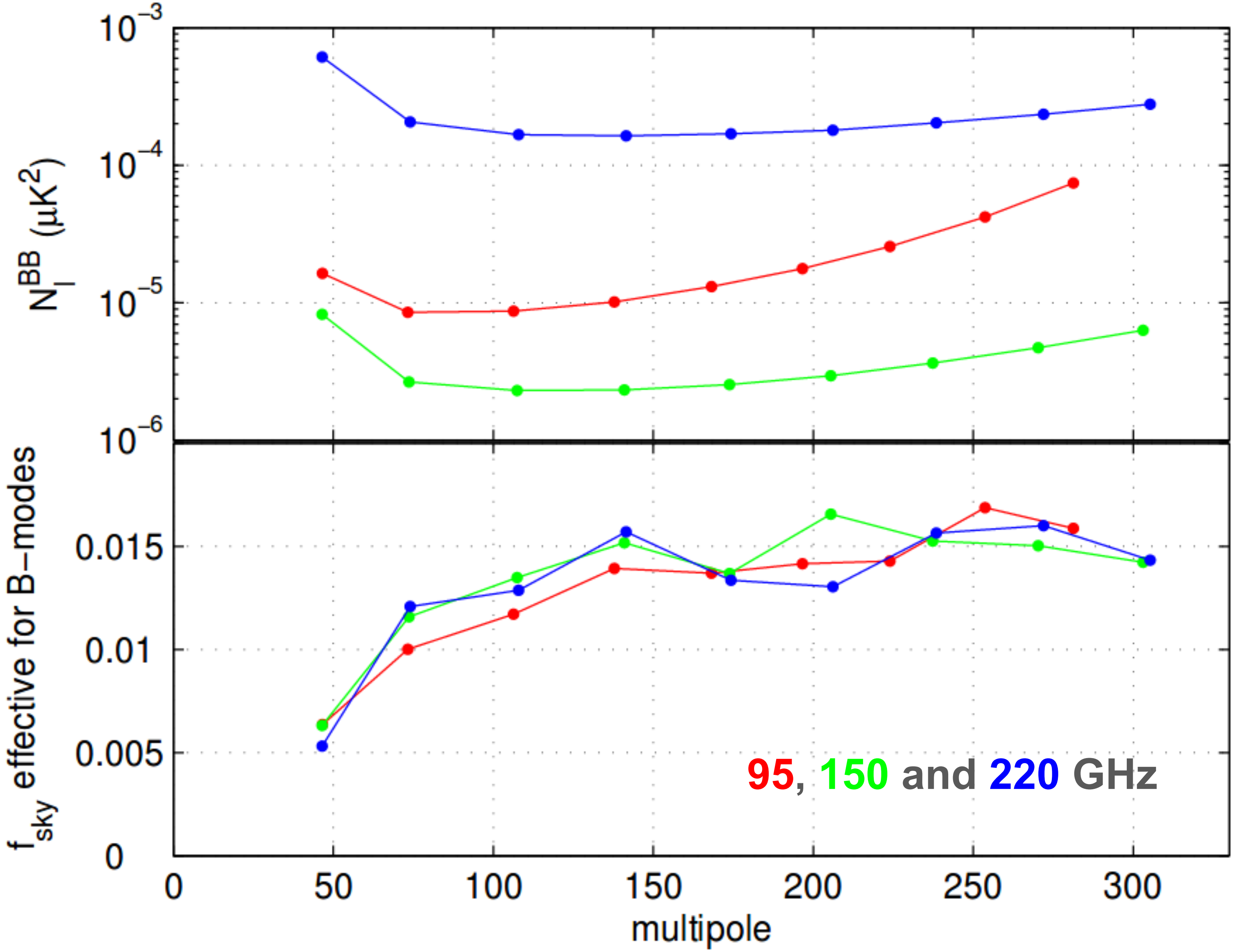
BK18 Noise Spectra and f_{sky}



BK15 Noise Spectra and f_{sky}



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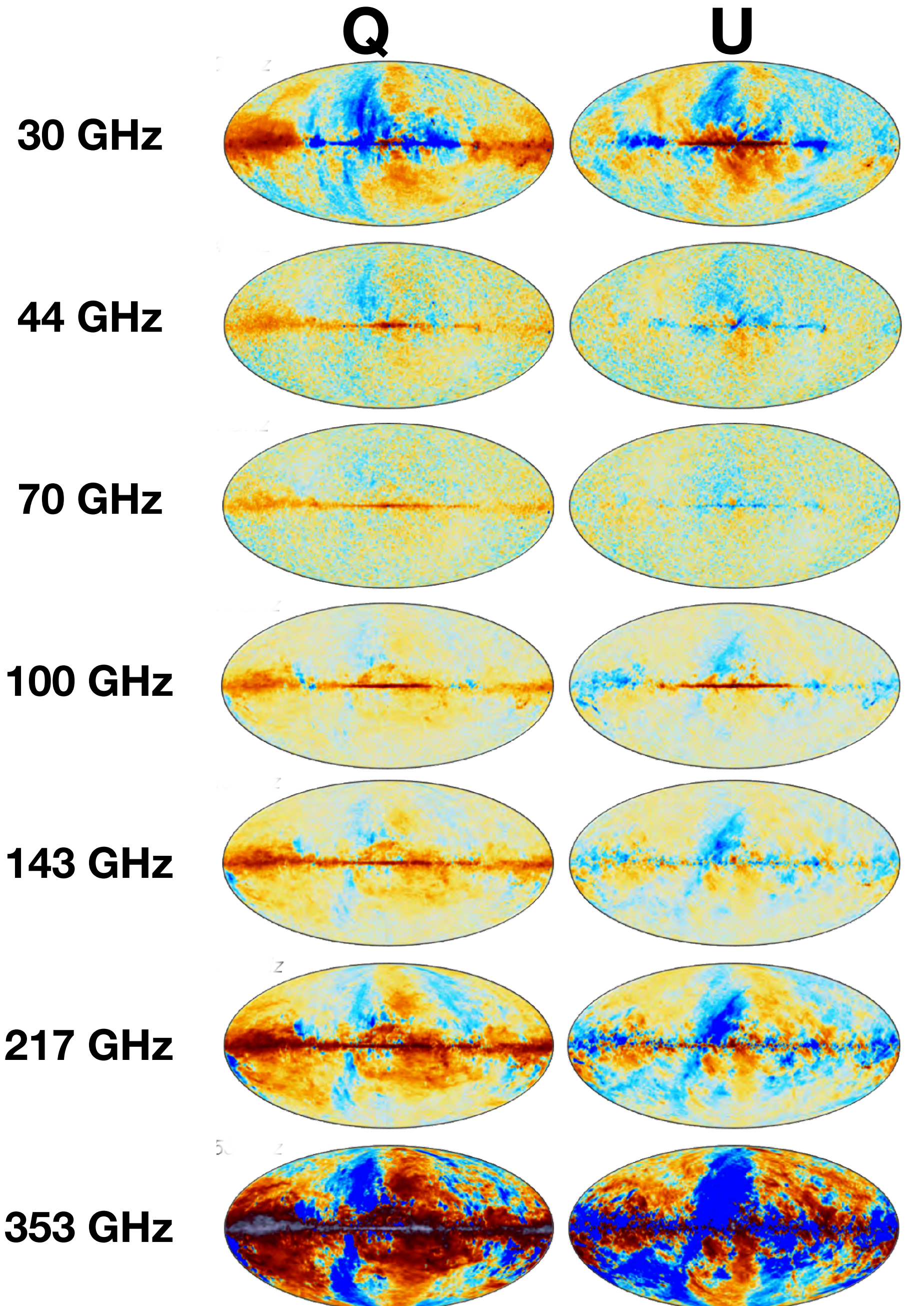
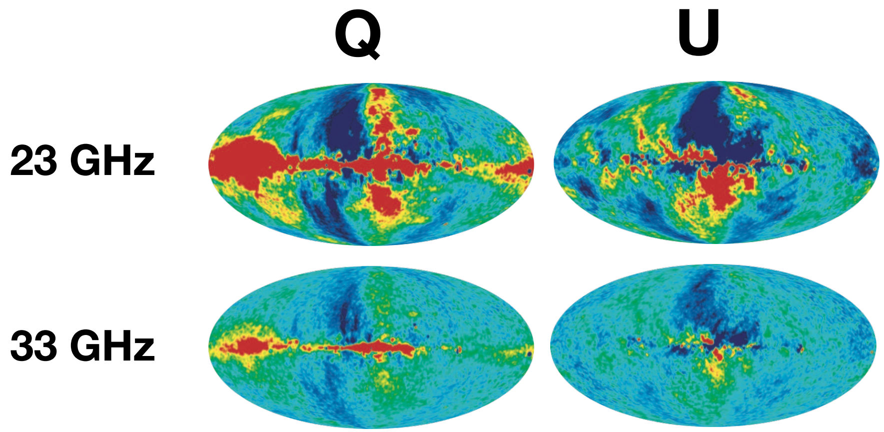
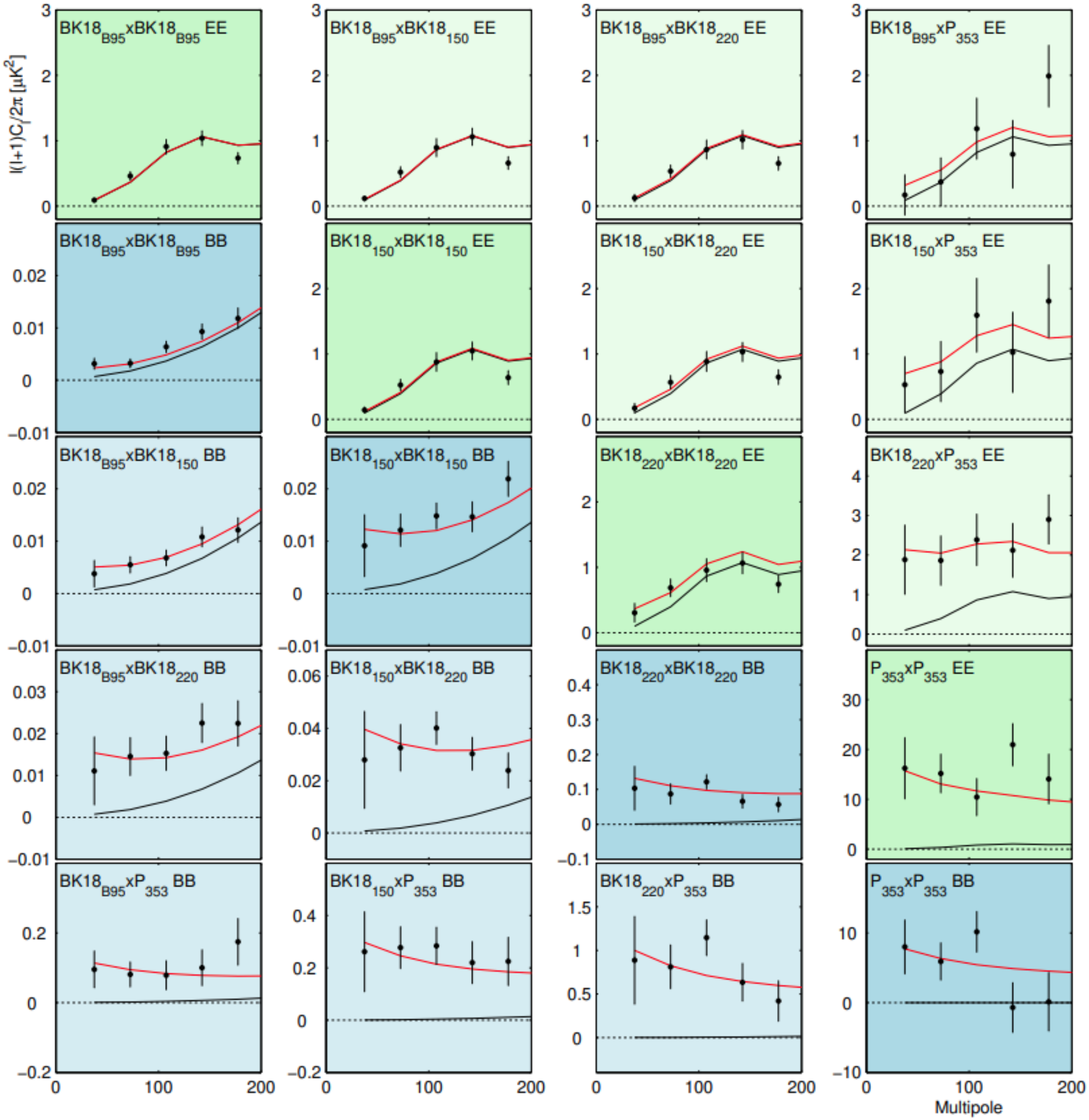
External Planck and WMAP Maps





From arxiv 1212.5225

BK18 auto/cross spectra between: BICEP3 95GHz, BICEP2/Keck 150GHz, Keck 220GHz, and Planck 353GHz

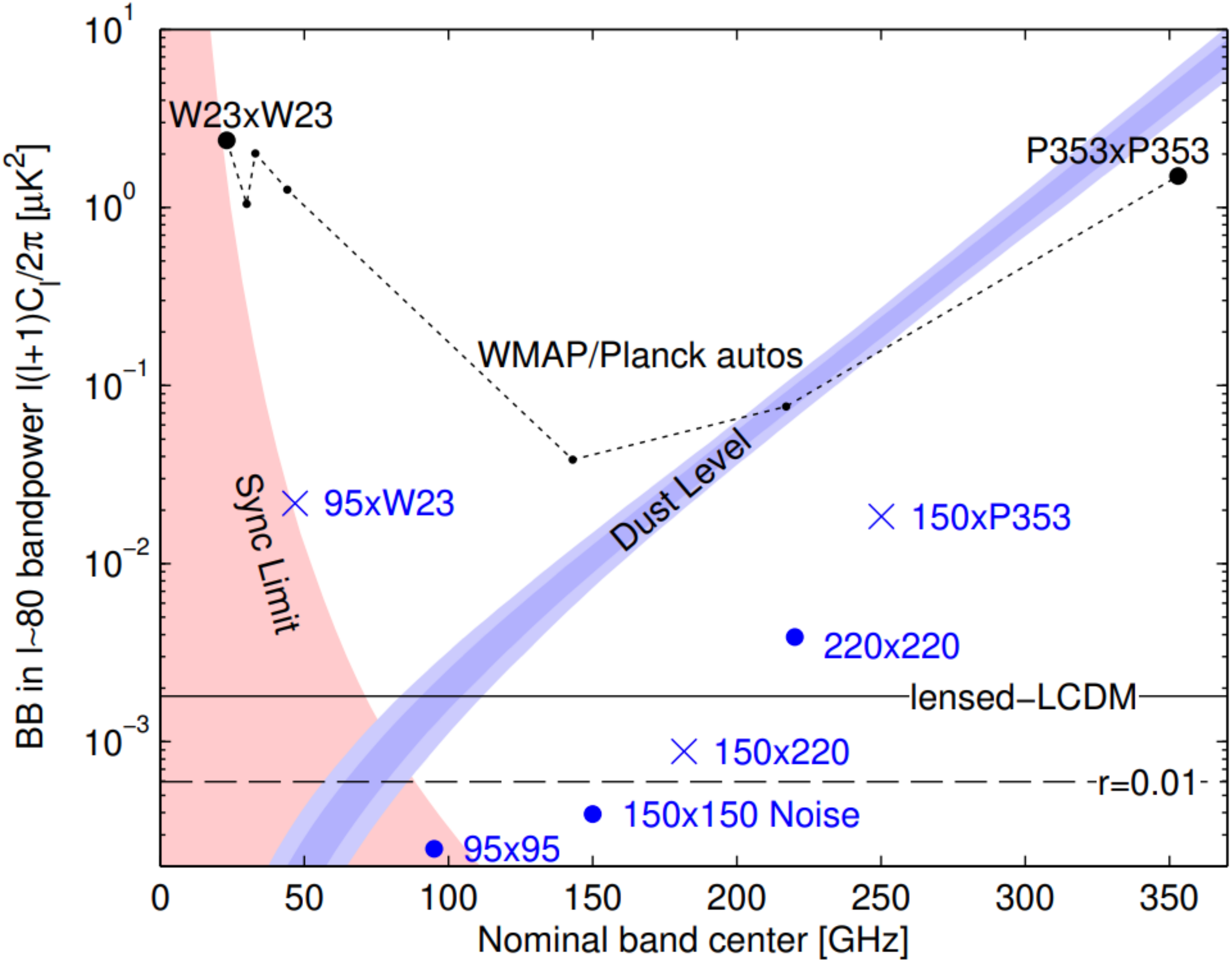


Green panels are EE spectra

Black lines are LCDM
Red lines are LCDM+foreground

Blue panels are BB spectra

BK18 ℓ=80 bandpower noise/signal



Multicomponent likelihood analysis

Take **all combinations of *BB* auto- and cross-spectra** between all BK and external maps, and evaluate the joint likelihood for a model containing:

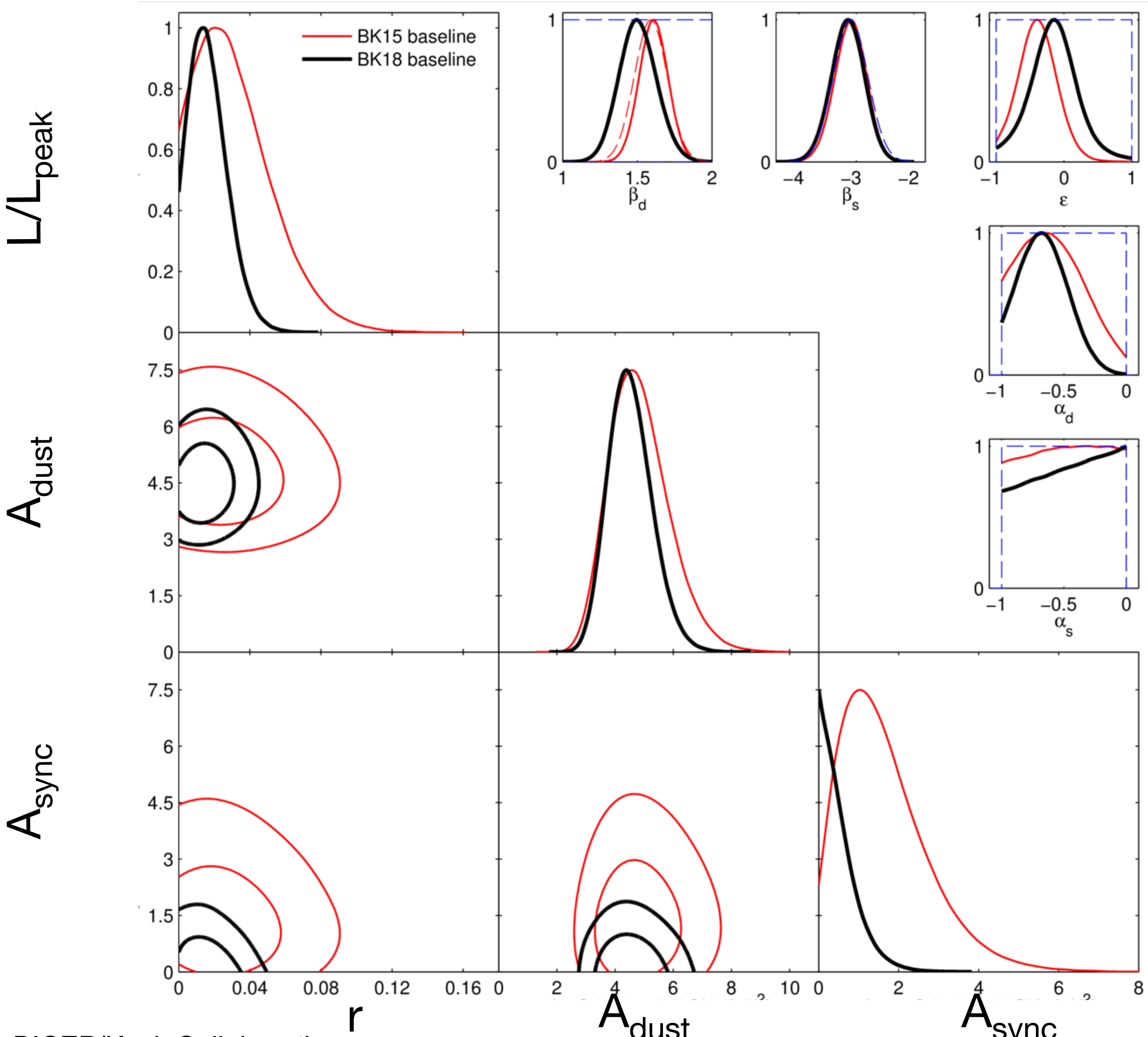
- Lensed ΛCDM
- Tensor-to-scalar ratio r
- Foreground model

Sample the posterior distributions using Markov Chain Monte Carlos. Also use maximum-likelihood estimation to extract best-fit parameter values.

Foreground model = Dust + Synchrotron

	Dust	Synchrotron
Amplitudes @ ℓ = 80	A_{dust}	A_{sync}
Frequency spectral indices	β_{dust}	β_{sync}
Spatial spectral indices	α_{dust}	α_{sync}
Dust/Sync spatial correlation	ε	

BK18 likelihood results



Allow dust/sync correlation

Marginalize over generous ranges in spatial spectral indices

$r < 0.036$ (95%)

Statistical uncertainty $\sigma(r) = 0.009$

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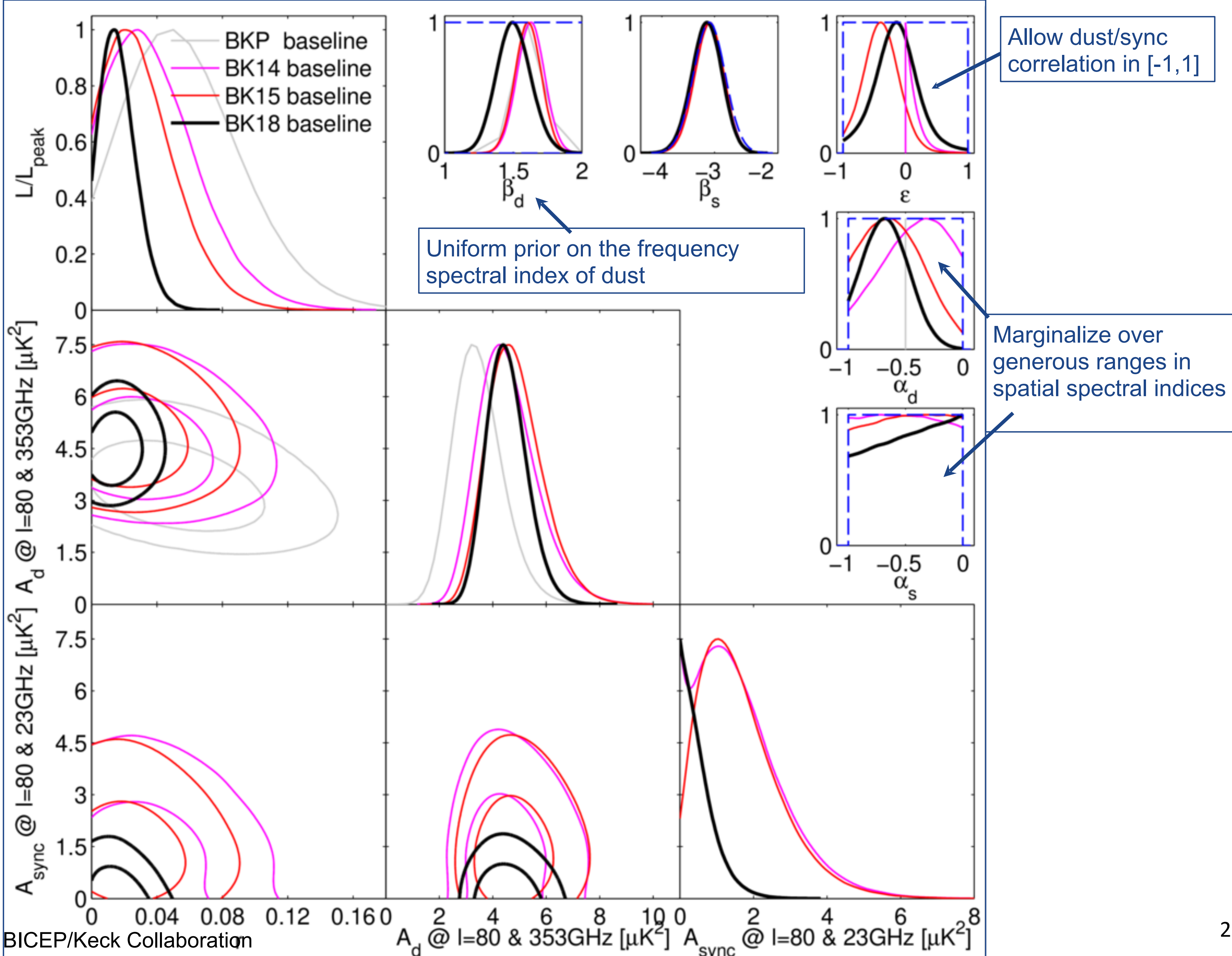

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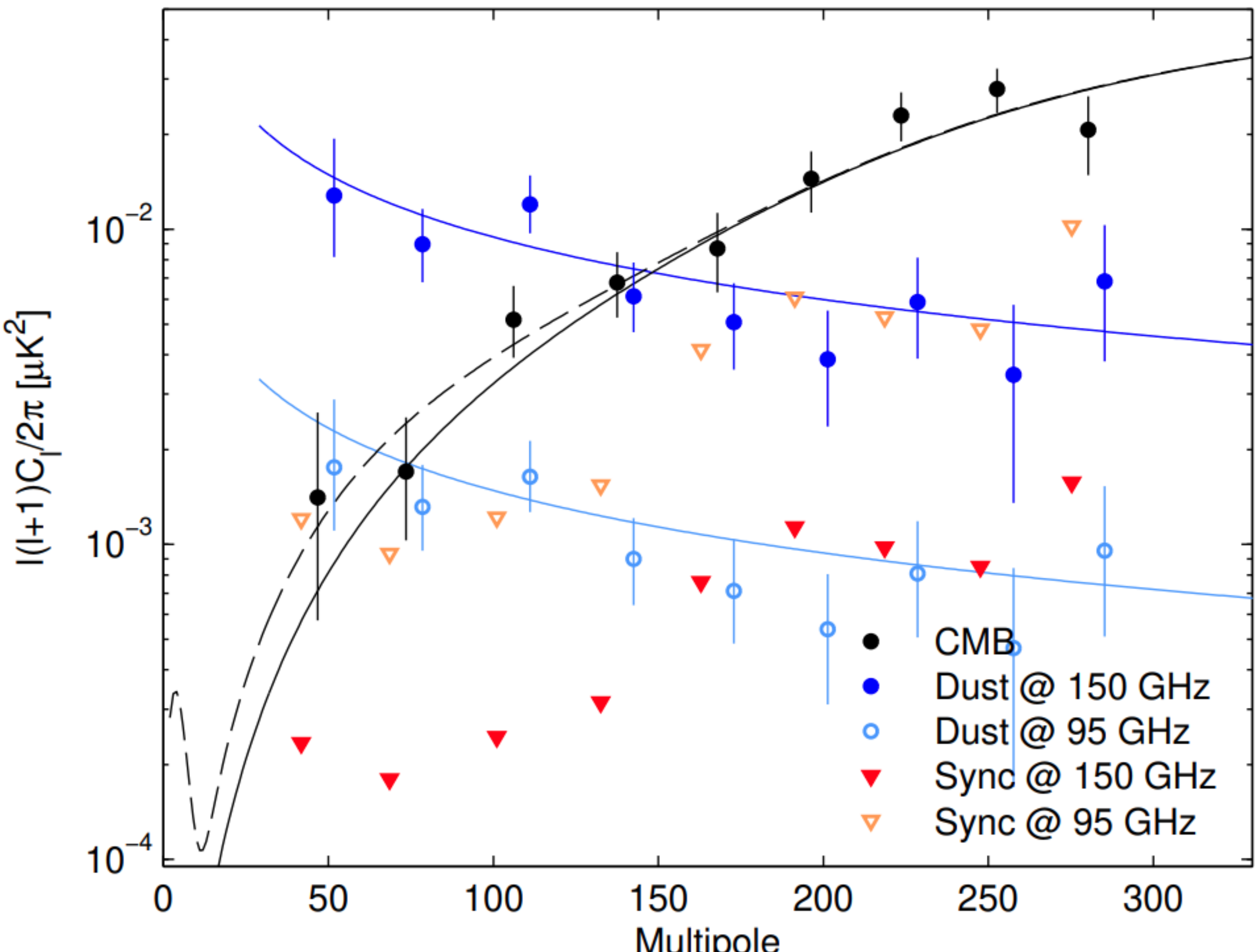
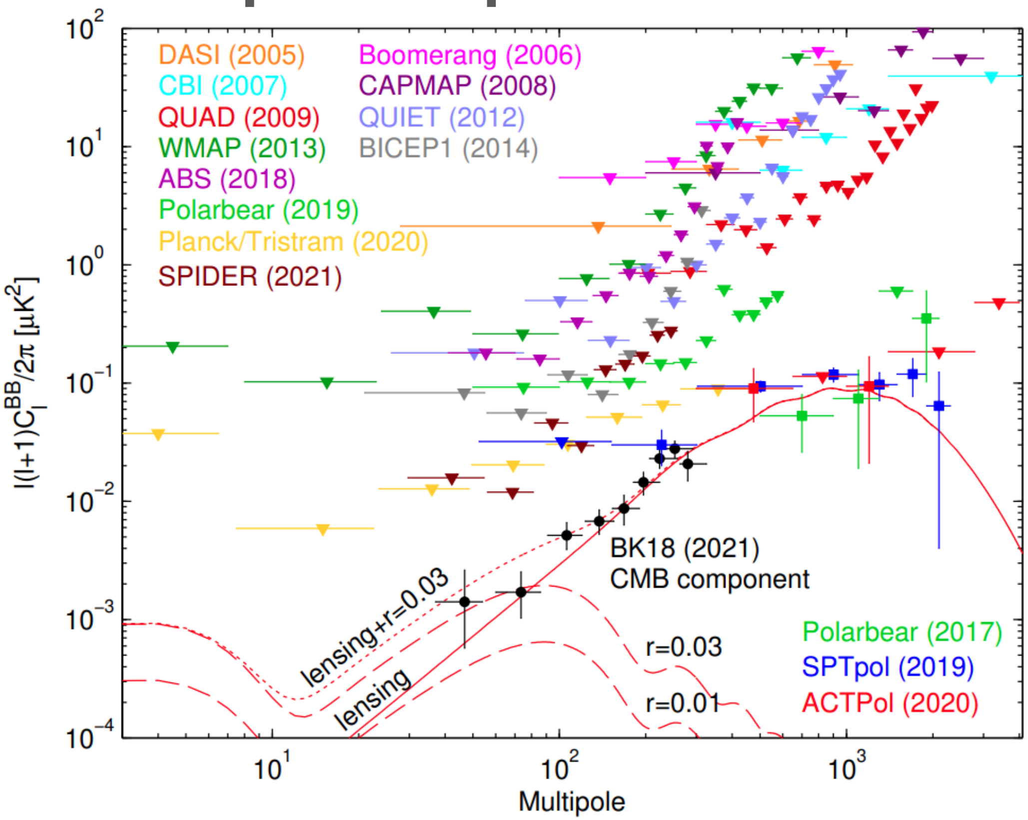
Spectral decomposition of BK18 data



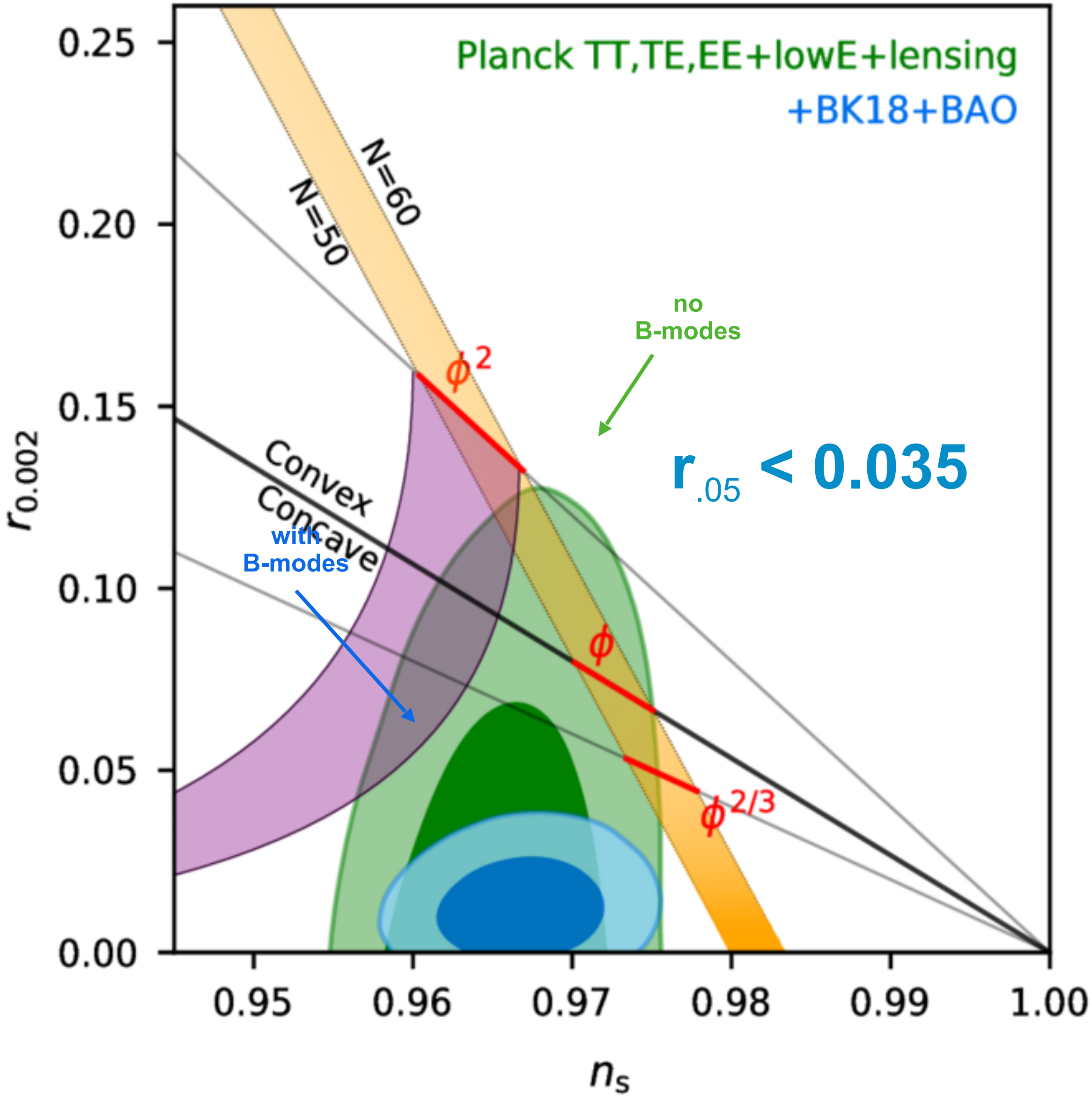
BK18 constraints on inflation

State of B-mode polarization power spectra in 2021



Posted B-Mode Sensitivity to r			
Experiment	**arxiv post**	**Bands [GHz]**	**σ(r)**
DASI	0409357	26…36	7.5
BICEP1 2yr	0906.1181	100, 150	0.28
WMAP 7yr	1001.4538	30…60	1.1
QUIET-Q	1012.3191	43	0.97
QUIET-W	1207.5034	95	0.85
BICEP1 3yr	1310.1422	100, 150	0.25
BICEP2	1403.3985	150	0.10
BK13 + Planck	1502.00612	150 + Planck	0.034
BK14 + WP	1510.09217	95, 150 + WP	0.024
ABS	1801.01218	150	0.7
Planck	1807.06209	30...353	~0.2
BK15 + WP	1810.05216	95,150,220+WP	0.020
Polarbear	1910.02608	150 + P	0.3
SPTpol	1910.05748	95 + 150	0.22
Planck/Tristram	2010.01139	30...353	0.07
SPIDER	2103.13334	95 + 150	0.13
BK18 + WP	2110.00483	95,150,220+WP	0.009

BK18 constraints on inflation



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Jackknife tests & data stability

Advantage of deep, narrow patch

- Error bar on a jackknife bandpower scales as $N_\ell/(f_{sky})^{1/2} \sim (f_{sky})^{1/2}$
- An additive systematic will be detected more easily on a deep patch
- Repetitive, highly symmetric scan strategy → helps reject some systematics and allows for construction of jackknives targeting them

Jackknife strategy for BK18

- 14 data splits: temporal, pair selection and hybrid
- Test each band/year separately
- χ and χ^2 tests twice on lowest five (ℓ<200) and lowest nine (ℓ<330) bandpowers
- Data compatibility with various receivers

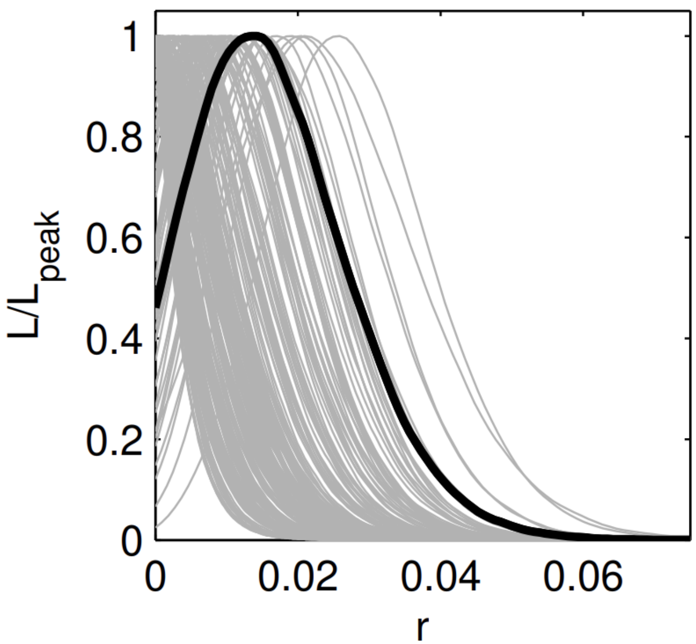
All jackknife tests are passed after two data cuts

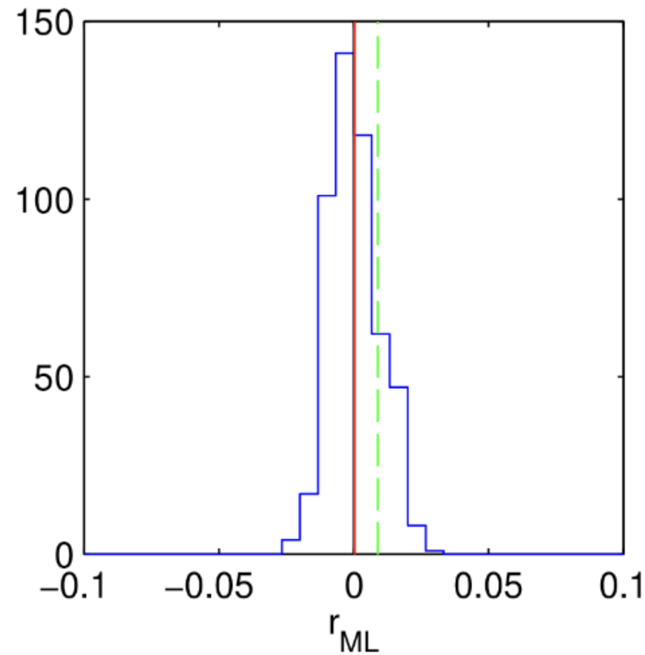
- November 2016 *Keck* data - taken during station summer opening
- BICEP3 Tile 1 - reflection and ghost beams due to an absent tile opposite of Tile 1

Likelihood validation

Validation on simulations

- Full COSMOMC runs on 200 sims
- Maximum likelihood searches on 499 sims
  - Unbiased results
  - Gives us σ(r)





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Likelihood variations

Likelihood variations

- Allowing for dust decorrelation
- Letting A_{llens} free
- Varying sky coverage
- Include EE spectra
- Alternate dust models

TABLE II. Uncertainty and bias on r in simulations using a variety of foreground models. For the strongly decorrelated model bias is expected when refit without a decorrelation parameter so this case is in parentheses.

Model	$\overline{A_d}$ (μK^2)	$\overline{A_s}$ (μK^2)	$\sigma(r)$, $\overline{r}/\sigma(r)$ no decorr.	$\sigma(r)$, $\overline{r}/\sigma(r)$ with decorr.
Gaussian	3.9	0.1	0.009, 0.0σ	0.010, 0.0σ
G. Decorr.	5.1	0.1	(0.012, $+2.1\sigma$)	0.014, -0.1σ
G. amp. mod.	4.4	0.0	0.009, 0.0σ	0.010, 0.0σ
PySM 1	11.3	0.9	0.010, $+0.1\sigma$	0.012, $+0.2\sigma$
PySM 2	25.6	0.8	0.011, 0.0σ	0.012, 0.0σ
PySM 3	11.6	0.9	0.011, 0.0σ	0.013, -0.1σ
MHDv3	3.2	7.1	0.012, -0.1σ	0.013, -0.4σ
MKD	3.9	0.1	0.009, 0.1σ	0.010, 0.0σ
Vansyngel	5.5	0.1	0.009, -0.1σ	0.010, 0.0σ

T→P leakage

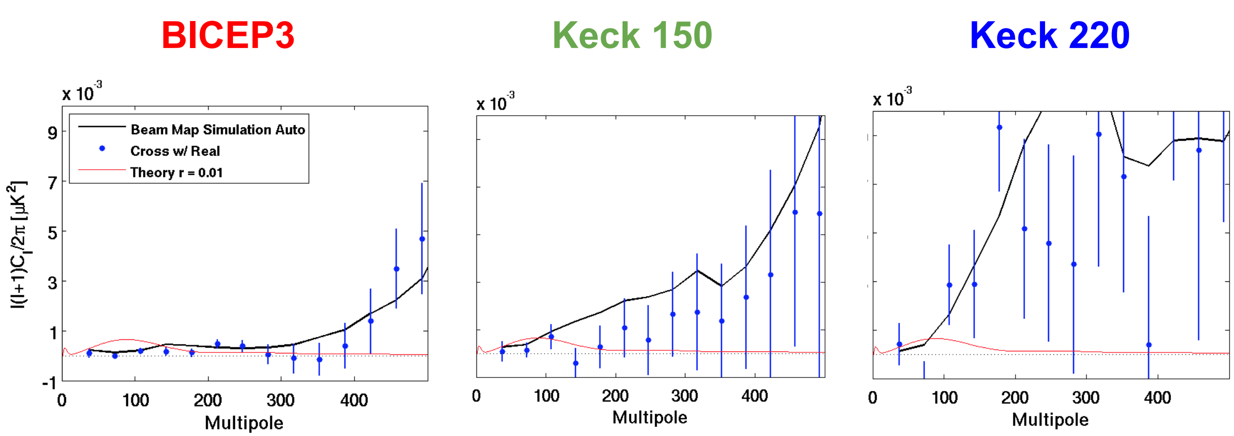
Differential beam systematics

- Leading order modes are deprojected at the time-stream level
- Undeprojected residuals beam map can be constructed using FFBM measurements

Specialised beam simulations

- Convlve undeprojected residuals beam map with Planck T map to get a T→P leakage map estimate
- Take auto- and cross-spectra of this map with our Q/U maps
- Add this extra bias in the likelihood analysis & run pipeline on 499 sims

→ $\Delta r = 1.5 \pm 1.1 \times 10^{-3}$



Other systematics

Point sources

- Filtering matrix purified maps with a "Mexican Hat" wavelet
- Cross-referencing wit SPT3G source catalog (preliminary)
- Construct source mask and compare with/without on 499 sims
  → **$\Delta r \sim 3 \times 10^{-3}$**

Bandpass uncertainty - important because of multi-component analysis

- Analysis of FTS measurements estimates ~ 1% bandpass uncertainty
  → we take 2% as conservative upper limit
- Simulate the effect of all possible combinations of ± 2% shifts in all bandpasses
  → worst case scenario is **$\Delta r = 8.4 \pm 5 \times 10^{-4}$**
- Add nuisance parameters in COSMOMC to marginalise over bandpass error → **$\Delta r = 3 \times 10^{-5}$**

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What limits BK18?

- BK18 mainline simulations with dust and lensing give σ(*r*)=0.009
- Running without foreground parameters on simulations where the dust amplitude is set to zero gives σ(*r*)=0.007

We have correctly tuned the relative sensitivity of the 95/150/220 bands such that we don't suffer much penalty due to the presence of foregrounds - but we can do better!

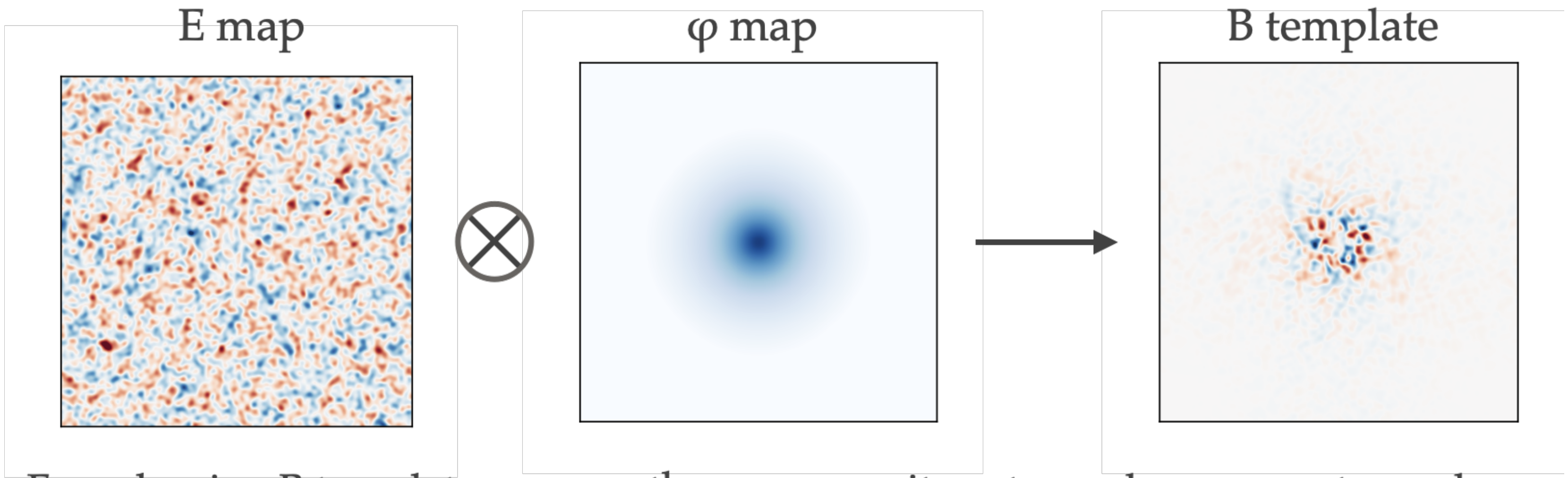
- Running on simulations which contain no lensing gives σ(*r*)=0.004

The sample variance of the achromatic lensing foreground is a major limiting factor - we need delensing via high resolution measurements.

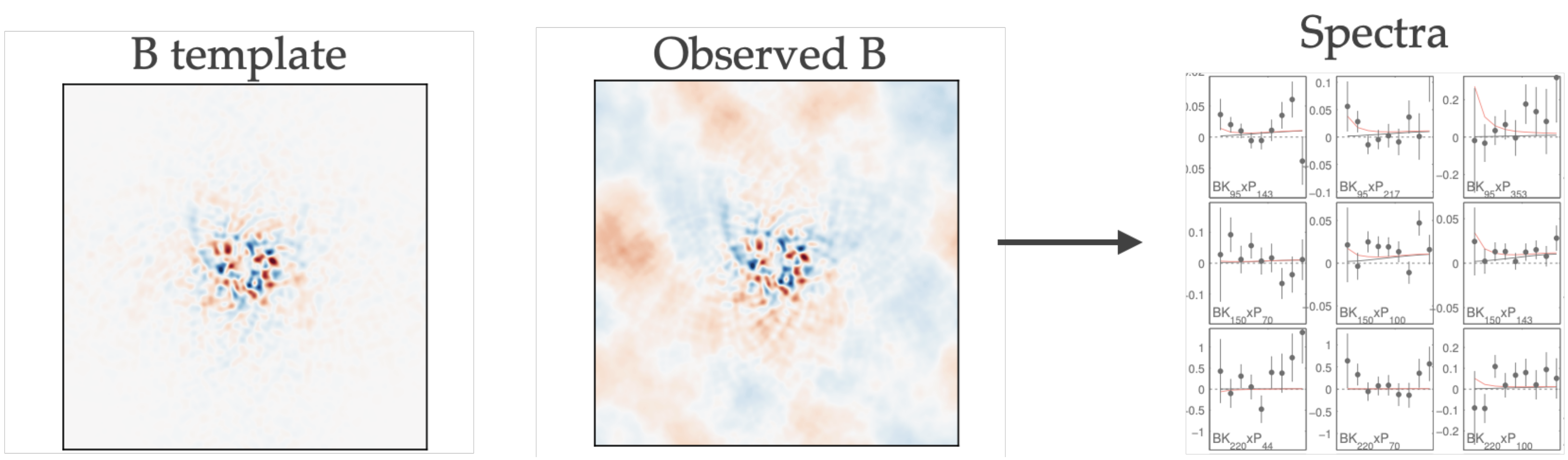
- Running without foreground parameters on simulations which have neither dust or lensing gives σ(*r*)=0.002

Delensing

1. Use φ to lens E-mode map to get expected lensing B template



2. From lensing B template, one can then measure its auto- and cross-spectra and constraint the lensing contribution to the B-mode spectrum measurement.



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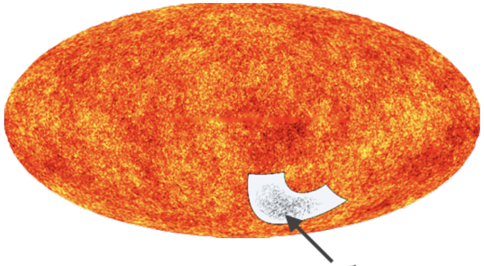
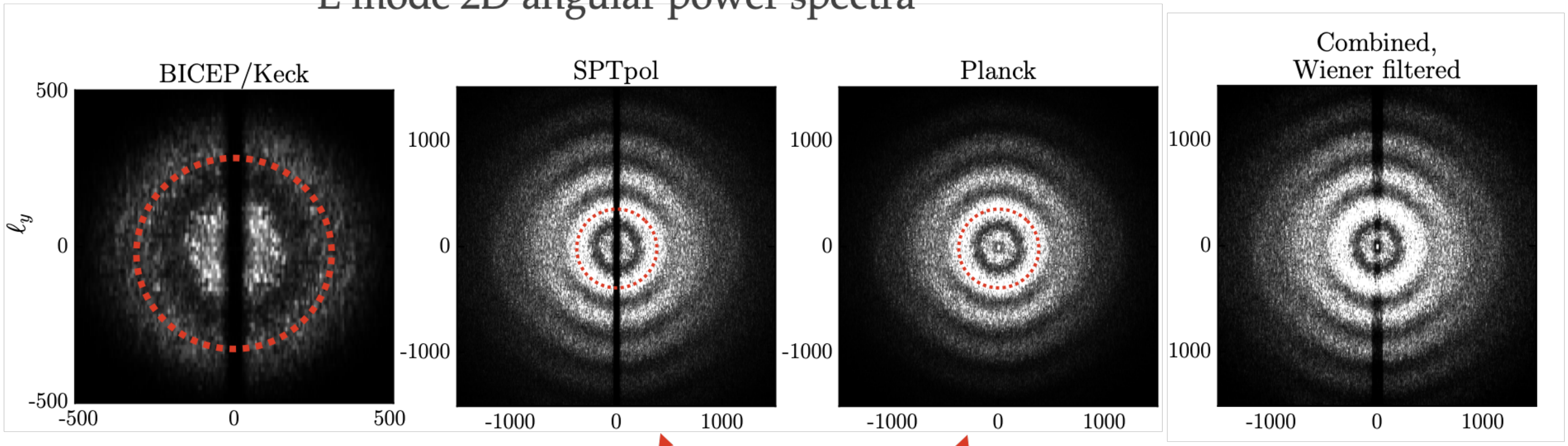
Lensing template inputs

Cosmic infrared background map from Planck as φ

E modes: combine Q/U maps from BICEP/Keck 150GHz, SPTpol 150GHz, and *Planck* 143GHz



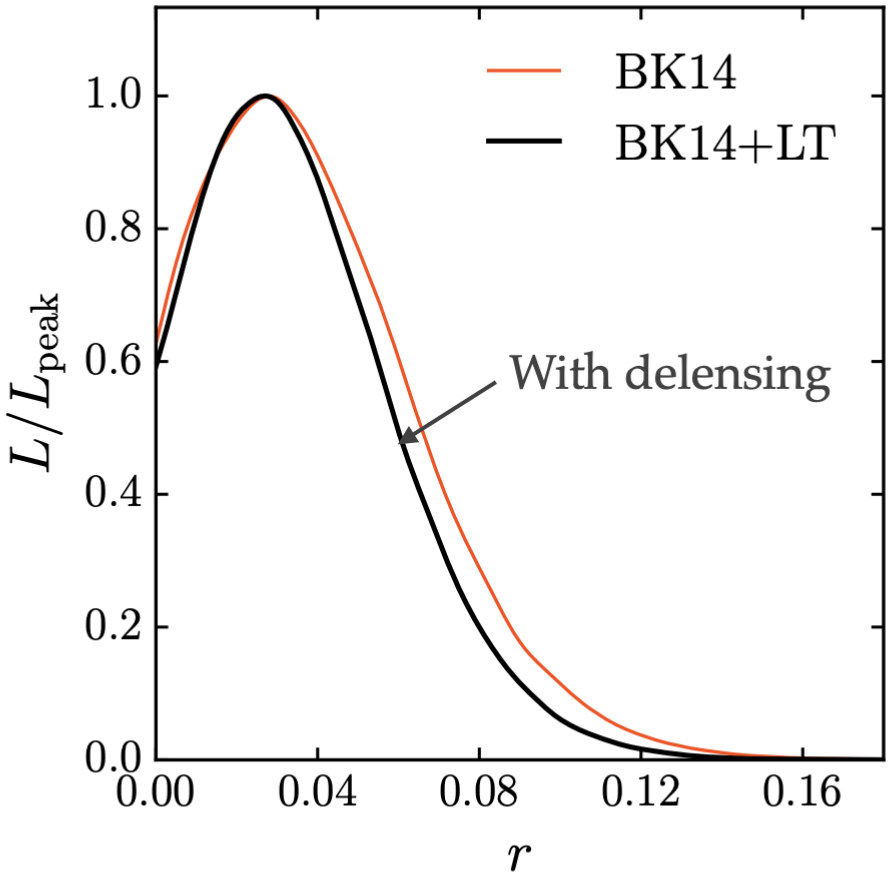
E mode 2D angular power spectra



Cover broader multipole range than BK

r posterior with and without delensing

The 95% upper limit for BK14 is reduced from r<0.09 to r<0.082



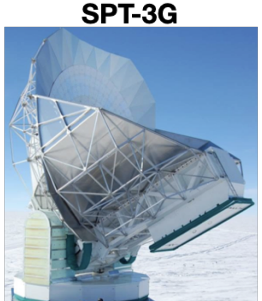
First demonstration of σ(r) reduction through delensing → pave a way for beyond BK18 analyses!

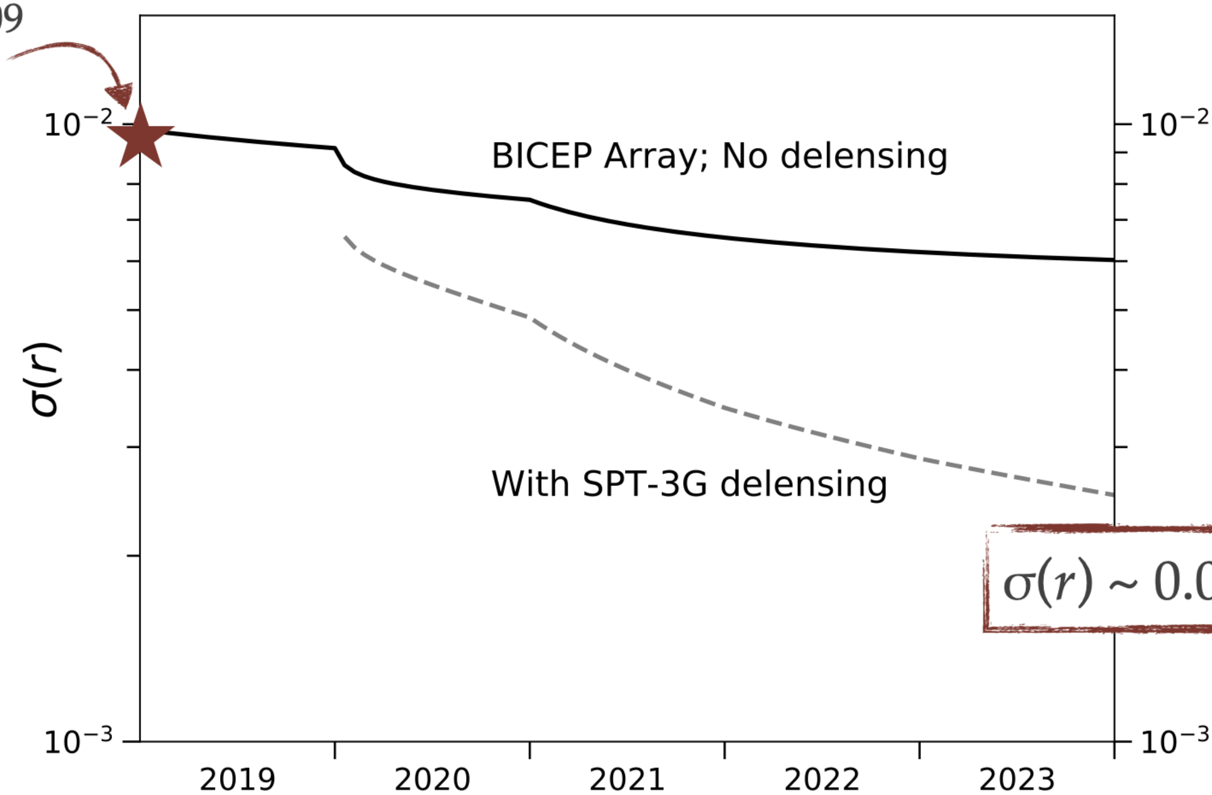
Delensing forecasts

Current $\sigma(r) = 0.009$
(BK18)

BICEP Array
(2018-)

SPT-3G





$\sigma(r) \sim 0.003$

The BICEP/Keck Collaboration

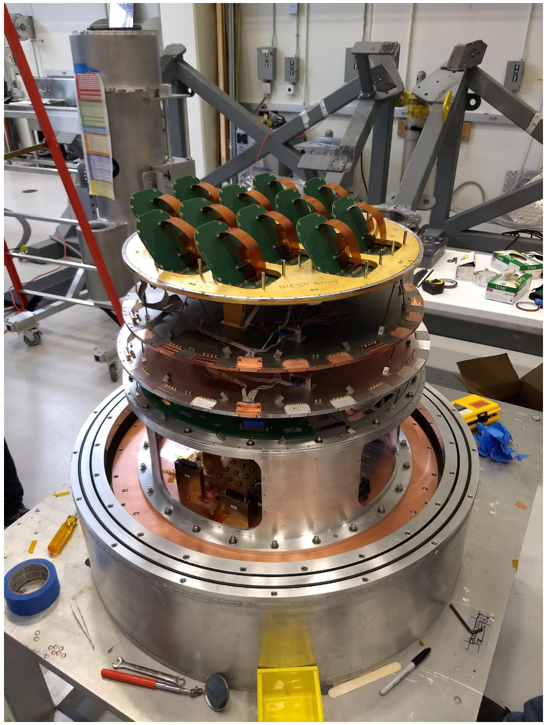
Kimmy Wu, SLAC

BICEP Array

4 wide-field, BICEP3-like receivers

- **30/40 GHz deployed during 2019/20 season**
- 95 GHz
- 150 GHz
- 220/270 GHz

30 000+ detectors when fully deployed!



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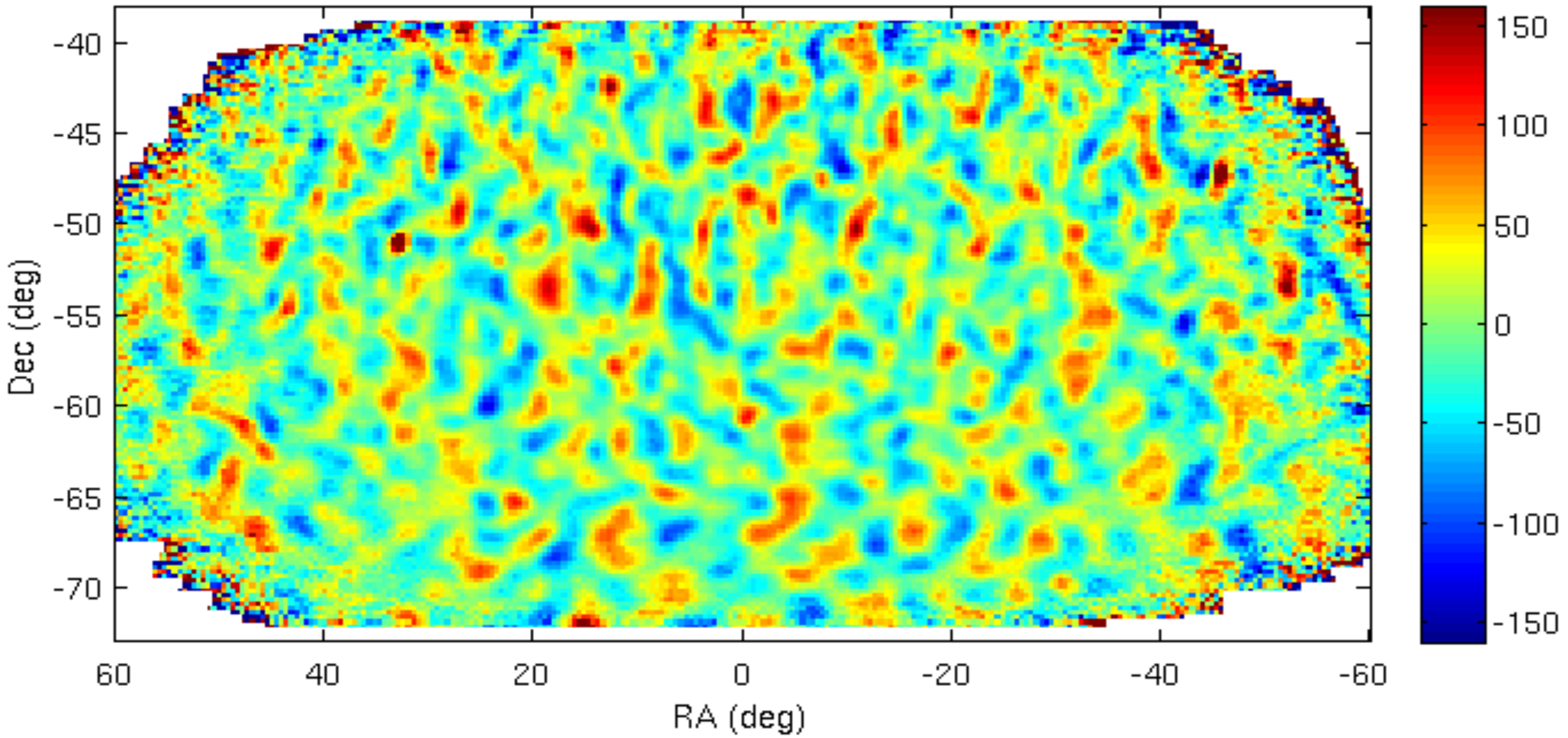
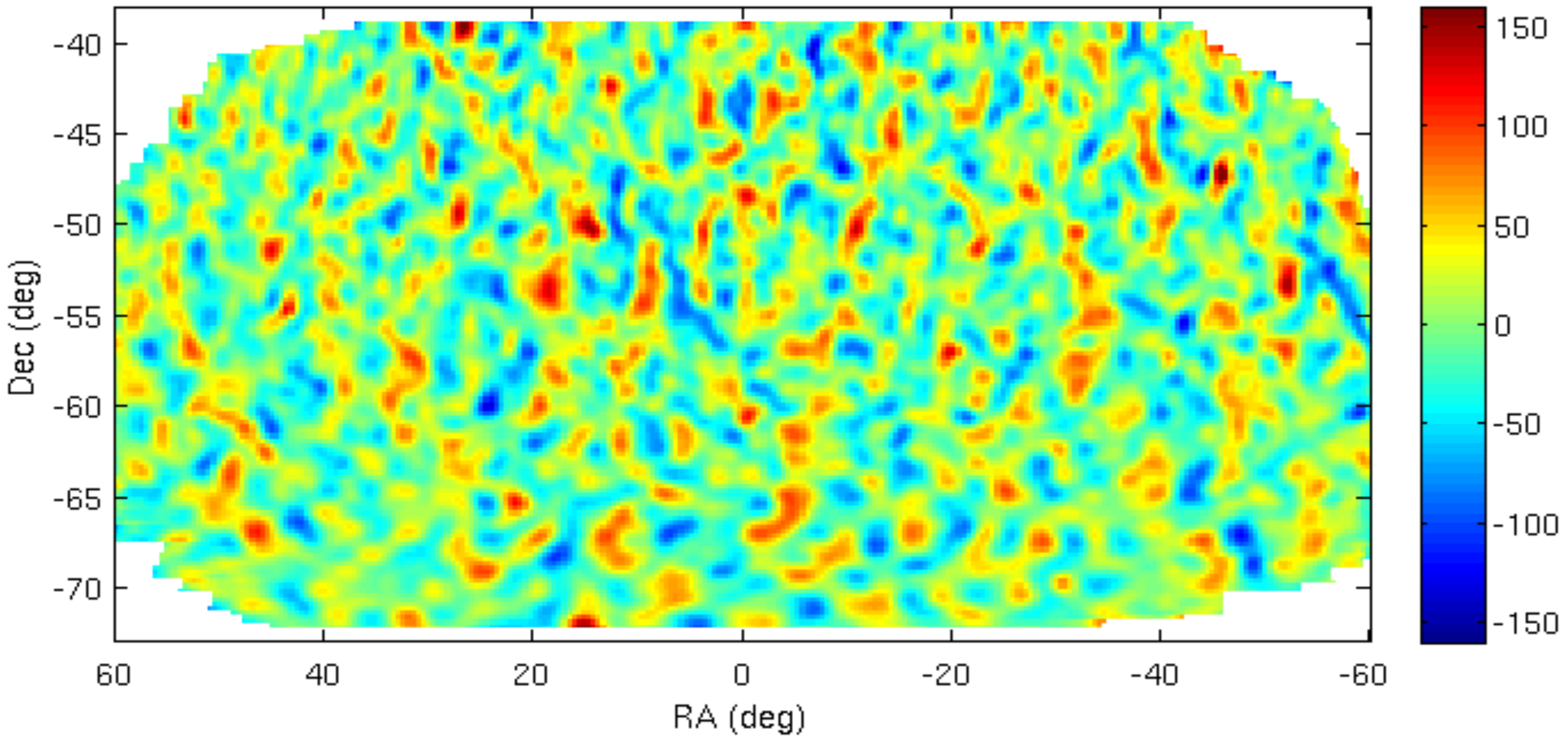
First year BA1 40GHz temperature map

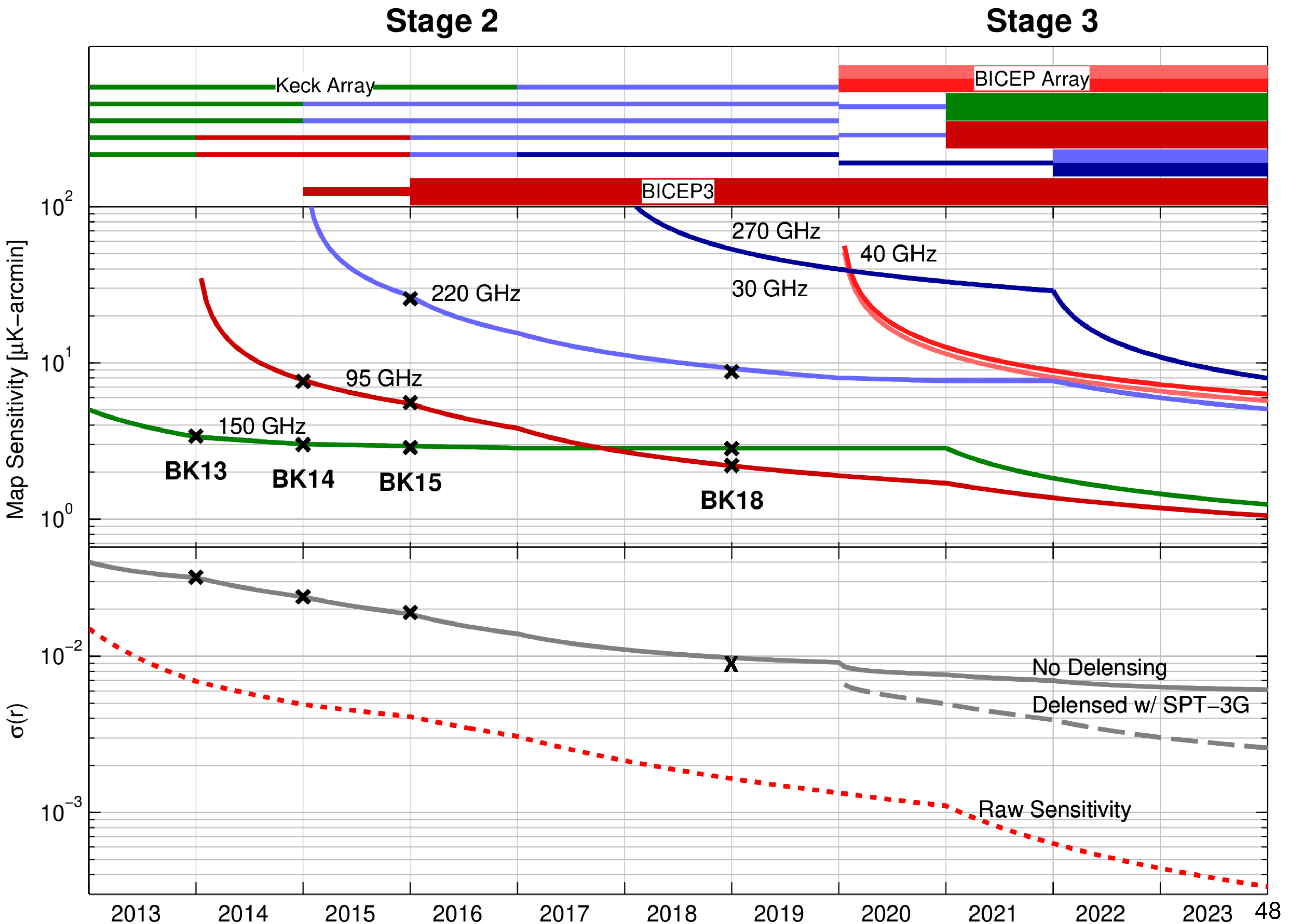


CMB temperature anisotropies from first year of observation

Re-observed Planck 44GHz



CMB temperature anisotropies from Planck LFI 4-year



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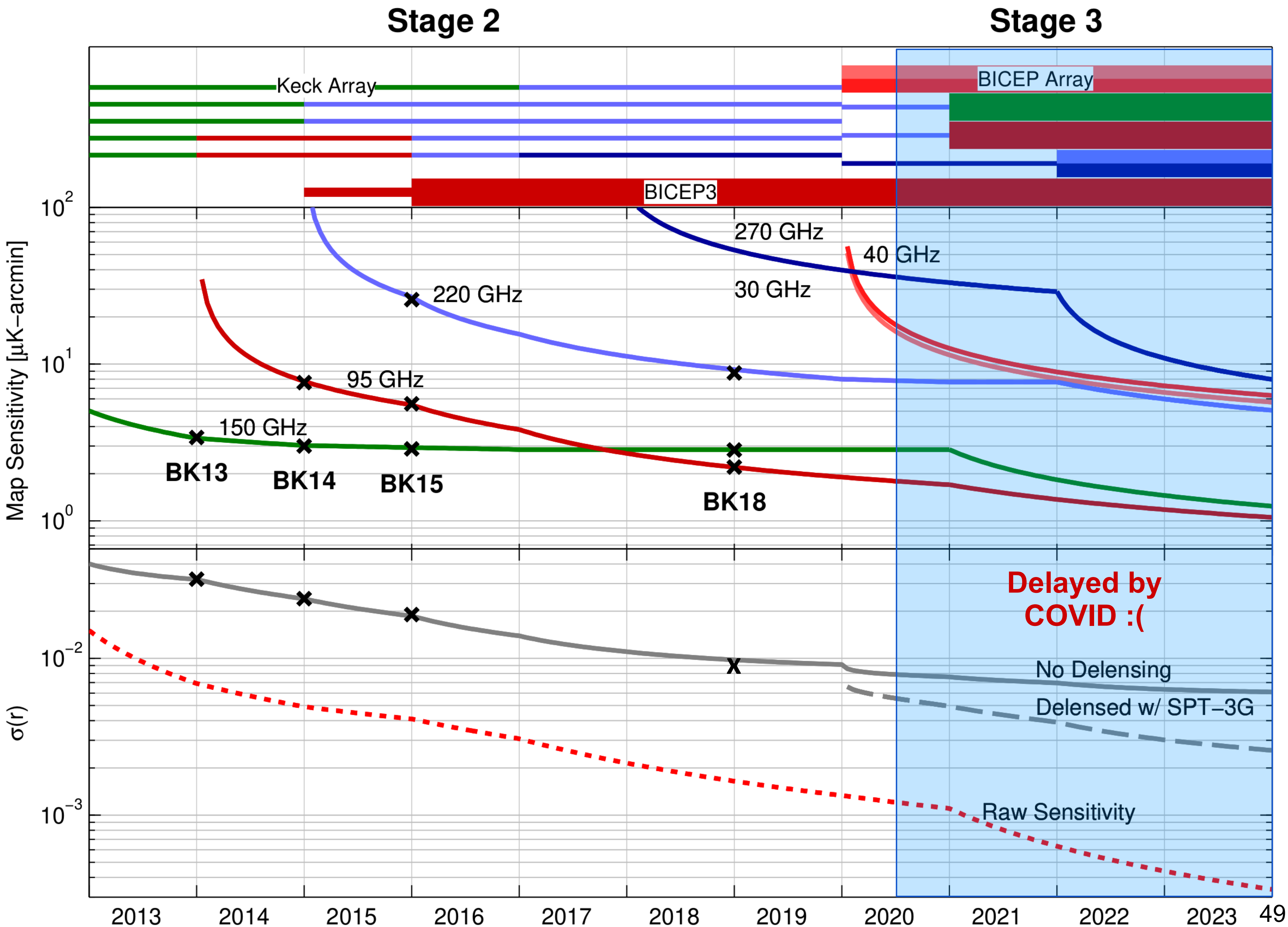

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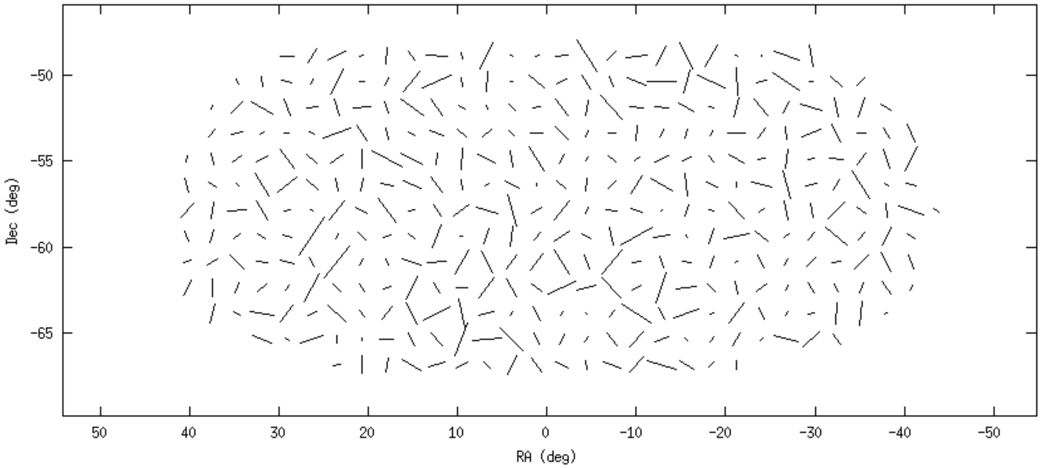
IV. Other analysis

Axion oscillations



Local axion-like dark matter produces time-variability in CMB polarization

- **Fedderke, Graham, Rajendran, 2019**

Masses 1e-23 - 1e-18 eV → periods of hours to years

“AC oscillation”

1. All-sky coherent oscillation of CMB polarization with **frequency m/(2π)**
2. Sensitive to **local** axion field
3. Form of **direct detection**

Limits on axion-photon coupling constant

Method and first demonstrations

- **"BICEP / Keck Array XII: Constraints on axion-like polarization oscillations in the cosmic microwave background"** (arXiv:2011.03483)
- **Improved constraints** (arXiv:2108.03316) under review

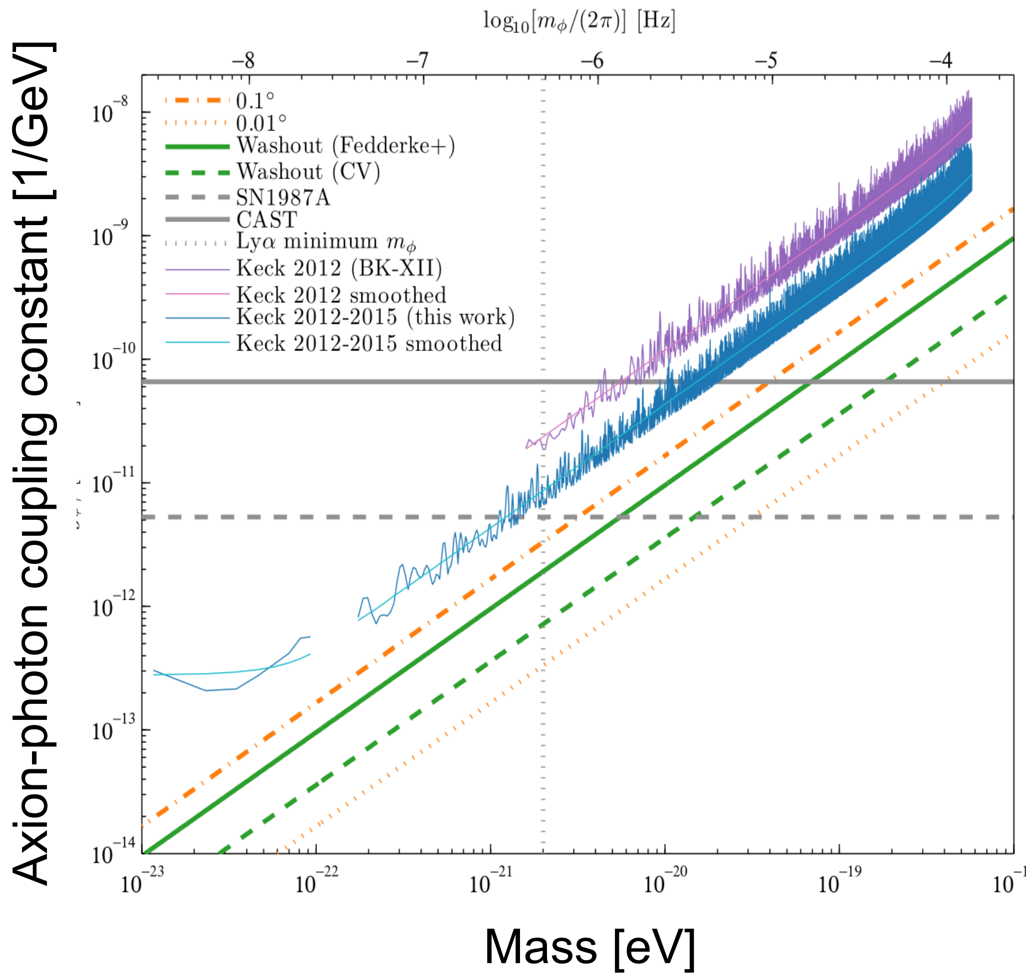
Oscillation sensitive to $g_{\phi\gamma}\phi_0$

Axion-photon coupling constant

Local axion field amplitude *today*

Limits scale as $g_{\phi\gamma} \propto m_\phi$

Axion mass



Keck 2012-2015 is a small fraction of total CMB dataset *already on disk*

Other on-going analysis projects

Polarisation angle calibration

- High-precision calibration of individual detector polarisation angles using a Rotating Polarised Source
- Constraints on isotropic cosmic birefringence

Line-of-sight distortion fields

- Use EB and TB quadratic estimators to reconstruct various distortion fields
- Both systematics check and probe for astrophysical and cosmological effects

Stay tuned for more incoming results and publications!

Conclusion

BICEP/Keck currently lead the field in the quest to detect or set limits on inflationary gravitational waves

- Sensitivity
- Control of systematics at degree angular scales

Adding 2016-18 data (from BK15 to BK18)

- **$r_{0.05}$<0.07 to $r_{0.05}$<0.036**
- **$\sigma(r)$=0.02 to $\sigma(r)$=0.009**
- For the first time no priors from other regions of sky

And we can keep going!

- BICEP Array mount and first receiver running
- Delensing in conjunction with SPT3G

\+ other analysis!

Thank you!

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References

- BICEP / Keck XIII: Improved Constraints on Primordial Gravitational Waves using Planck, WMAP, and BICEP/Keck Observations through the 2018 Observing Season
- BICEP / Keck XV: The BICEP3 CMB Polarimeter and the First Three Year Data Set
- BICEP2 / Keck Array XI: Beam Characterization and Temperature-to-Polarization Leakage in the BK15 Dataset
- BK + SPT: A Demonstration of Improved Constraints on Primordial Gravitational Waves with Delensing
- BICEP / Keck XII: Constraints on axion-like polarization oscillations in the cosmic microwave background + BK XIV Improved constraints
- Polarization Calibration of the BICEP3 CMB polarimeter at the South Pole
- Systematics diagnostics and self-calibration of CMB B-mode with distortion fields
- Receiver development for BICEP Array, a next-generation CMB polarimeter a the South Pole
- Design and performance of the first BICEP Array receiver