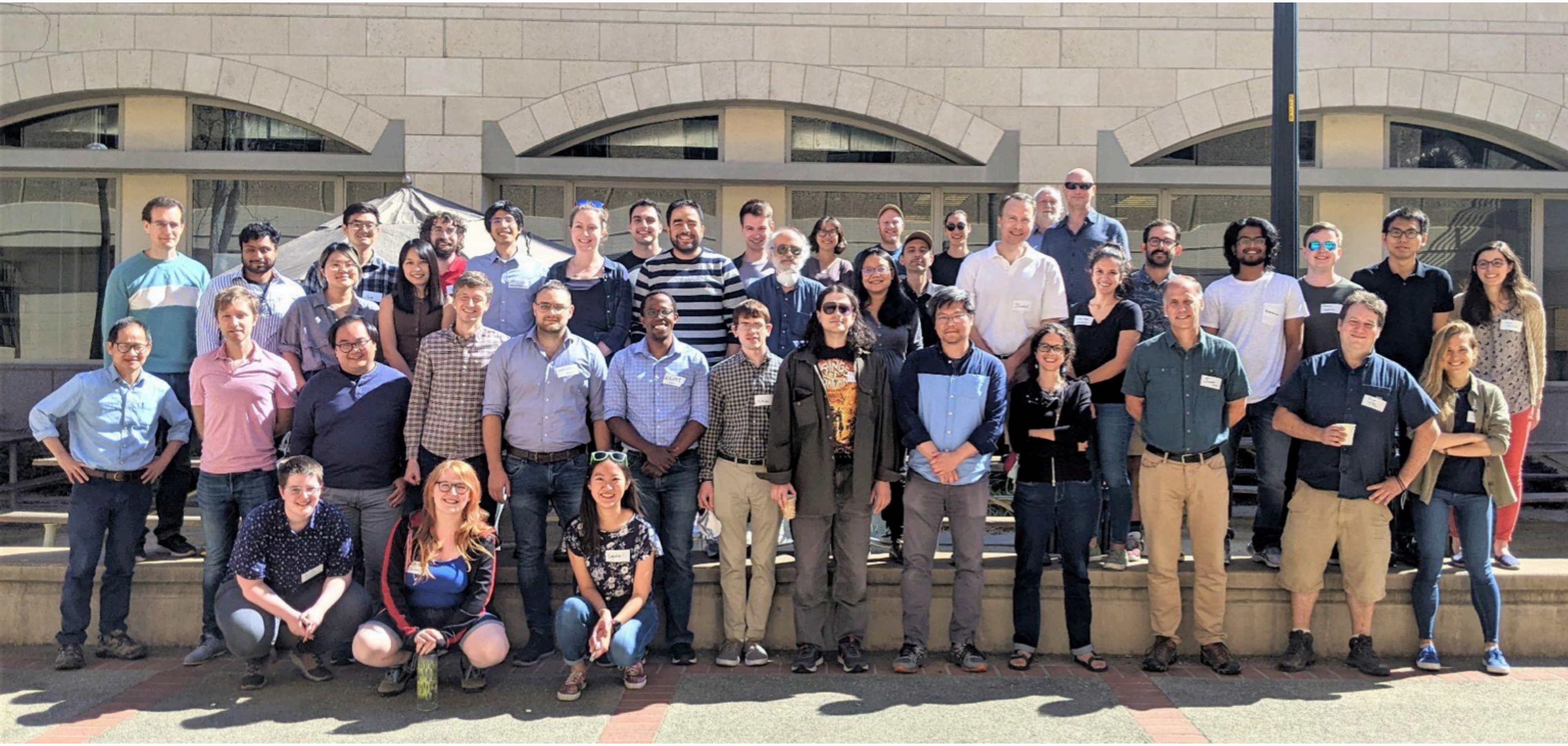
The search for primordial gravitational waves: latest results from BICEP/Keck

Clem Pryke for the BICEP/Keck Collaboration – Cambridge Seminar – July 1 2022

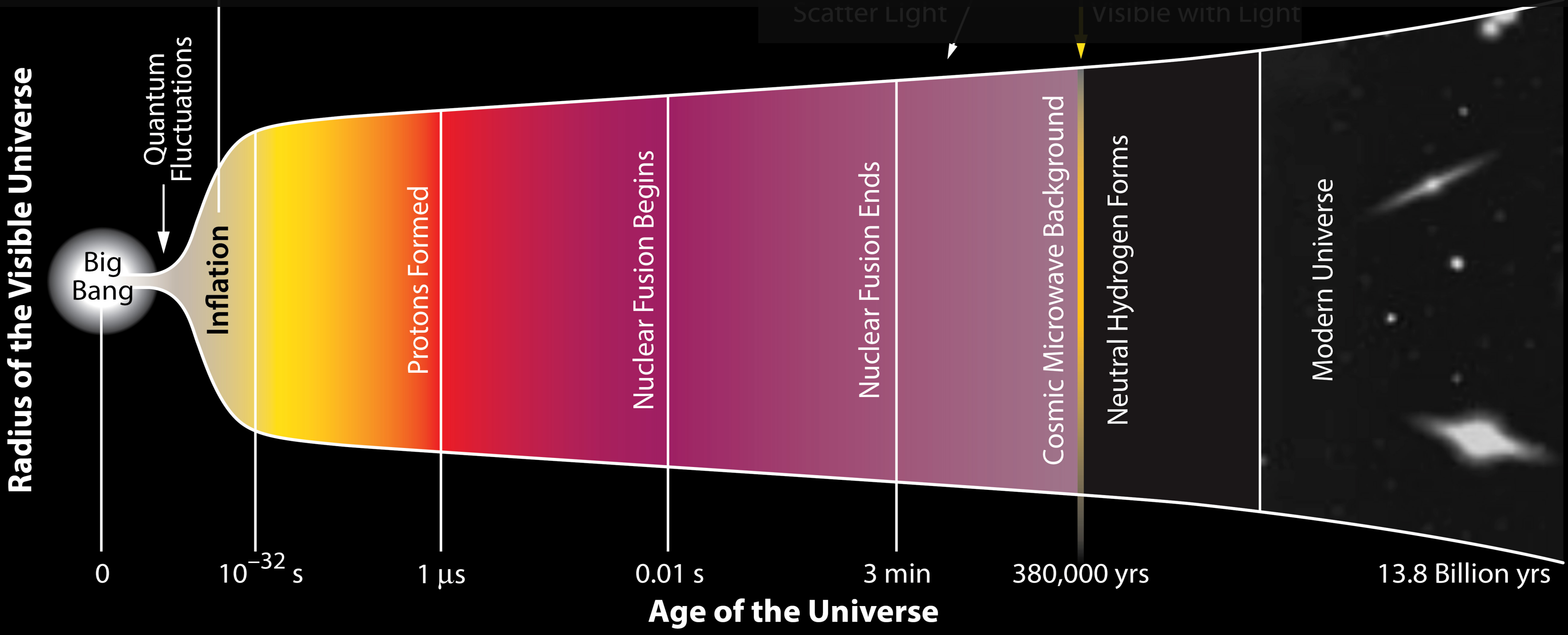


History of the Universe

Inflation posits a pre-phase of exponential expansion

Alan Guth

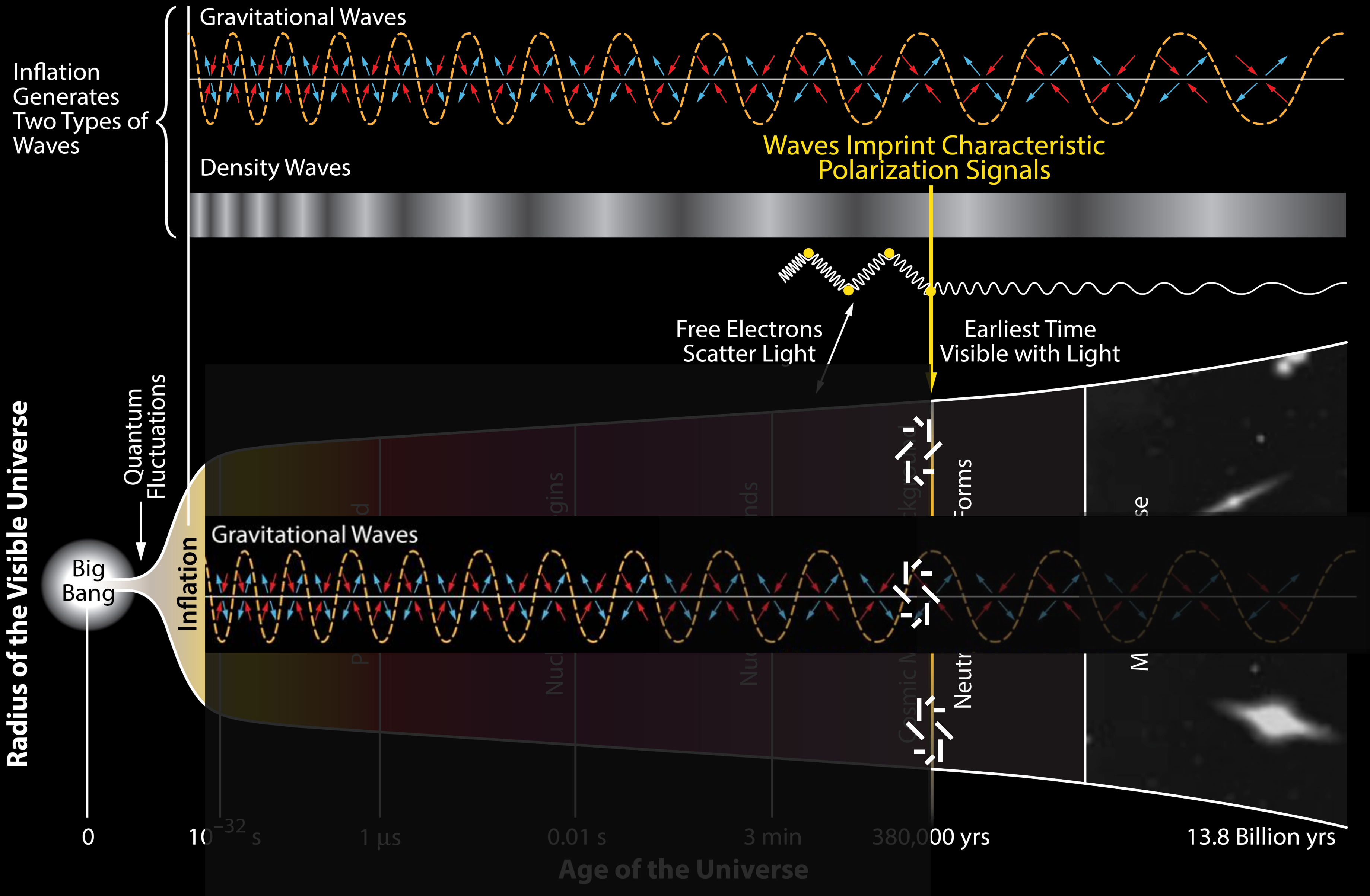
Andrei Linde



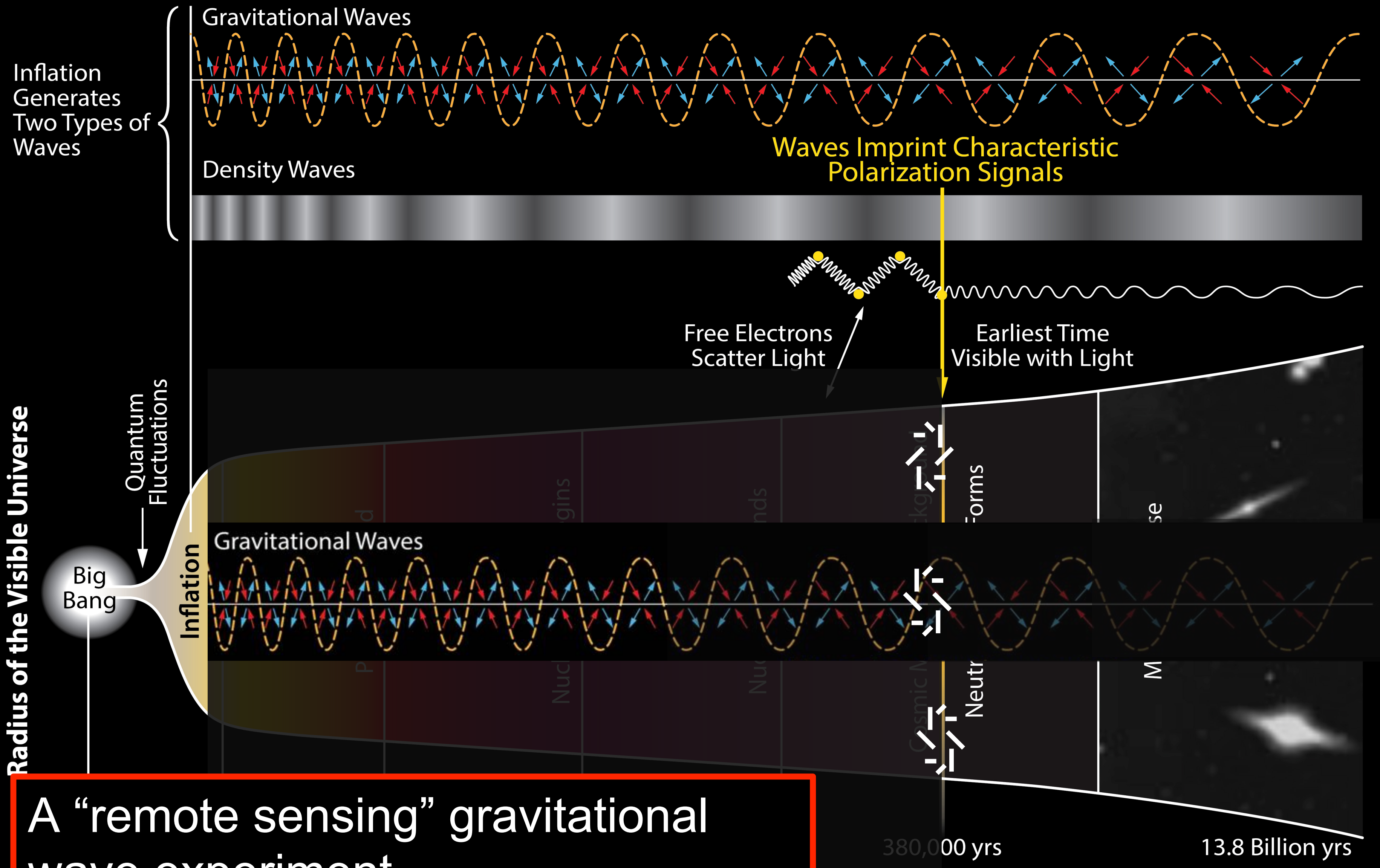
What Does Inflation Do For Us?

Solves the horizon problem: Why is the CMB nearly uniform? How do apparently causally disconnected regions of space get set to the same temperature?	→	A volume much larger than our entire observable universe today was once a caussally connected sub atomic speck.
Solves the flatness problem: Why is the net spatial curvature so close to zero?	→	Any initial spatial curvature is diluted away to undetectabilty by the hyper expansion.
Explains the initial perturbations: Why Gaussian with close to flat power law spectrum? ($n_s \approx 1$)	→	Equal amounts of perturbations are injected by quantum fluctuations at each step in the exponential expansion.
Solves the monopole problem: Why do we not observe magnetic monopoles in the Universe today?	→	Monopoles are diluted away to undetectability.

History of the Universe



History of the Universe

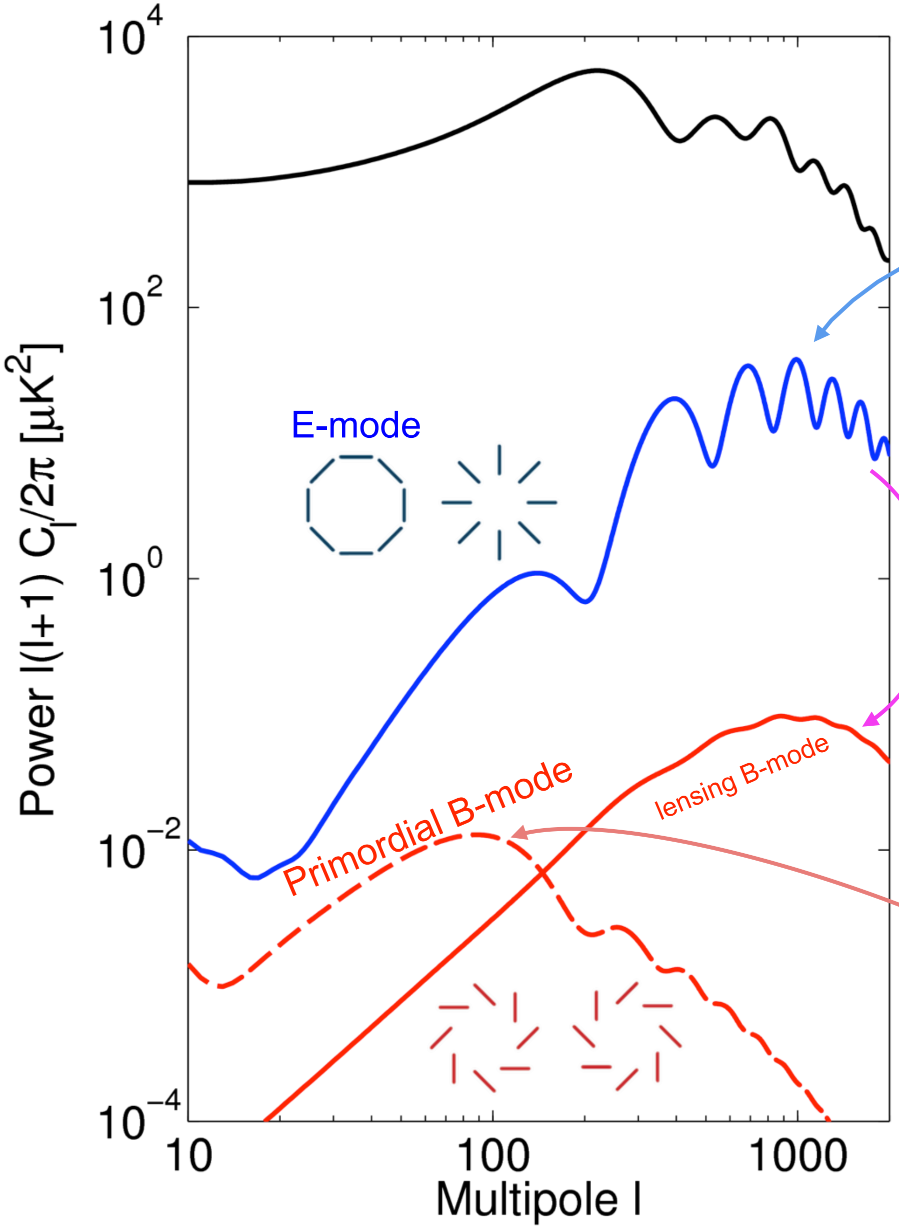


A “remote sensing” gravitational wave experiment

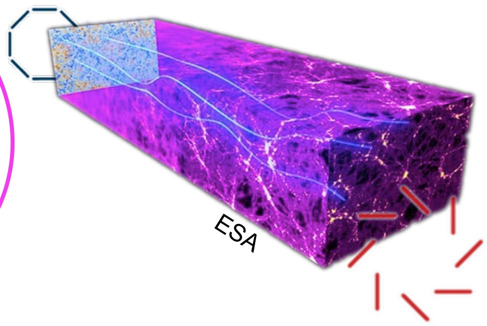
CMB Polarization, B-modes and *r*

- The CMB is partially polarized (due to local radiation quadrupoles at last scattering)
- Any polarization pattern can be decomposed into E-modes (gradient modes) and B-modes (curl modes)
- Basic LCDM makes only E-modes at last scattering – although lensing deflections in flight produce a bit of a B-mode
- Primordial gravitational waves produce both E-modes and B-modes – but best to look for the B-modes since most distinct there
- Theory gives us a good template shape for the gravitational wave signal – but it does *not* tell us the amplitude
- The amplitude is parameterized by a single number *r*
- A wide range of inflation theories exist – the simplest are already ruled out – more complex ones can produce *r* which is undetectably small
- The experimental mission is to obtain the best possible sensitivity to *r*
- If we can detect *r* we determine the energy scale of inflation – if not we can rule out additional inflationary models

CMB power spectra



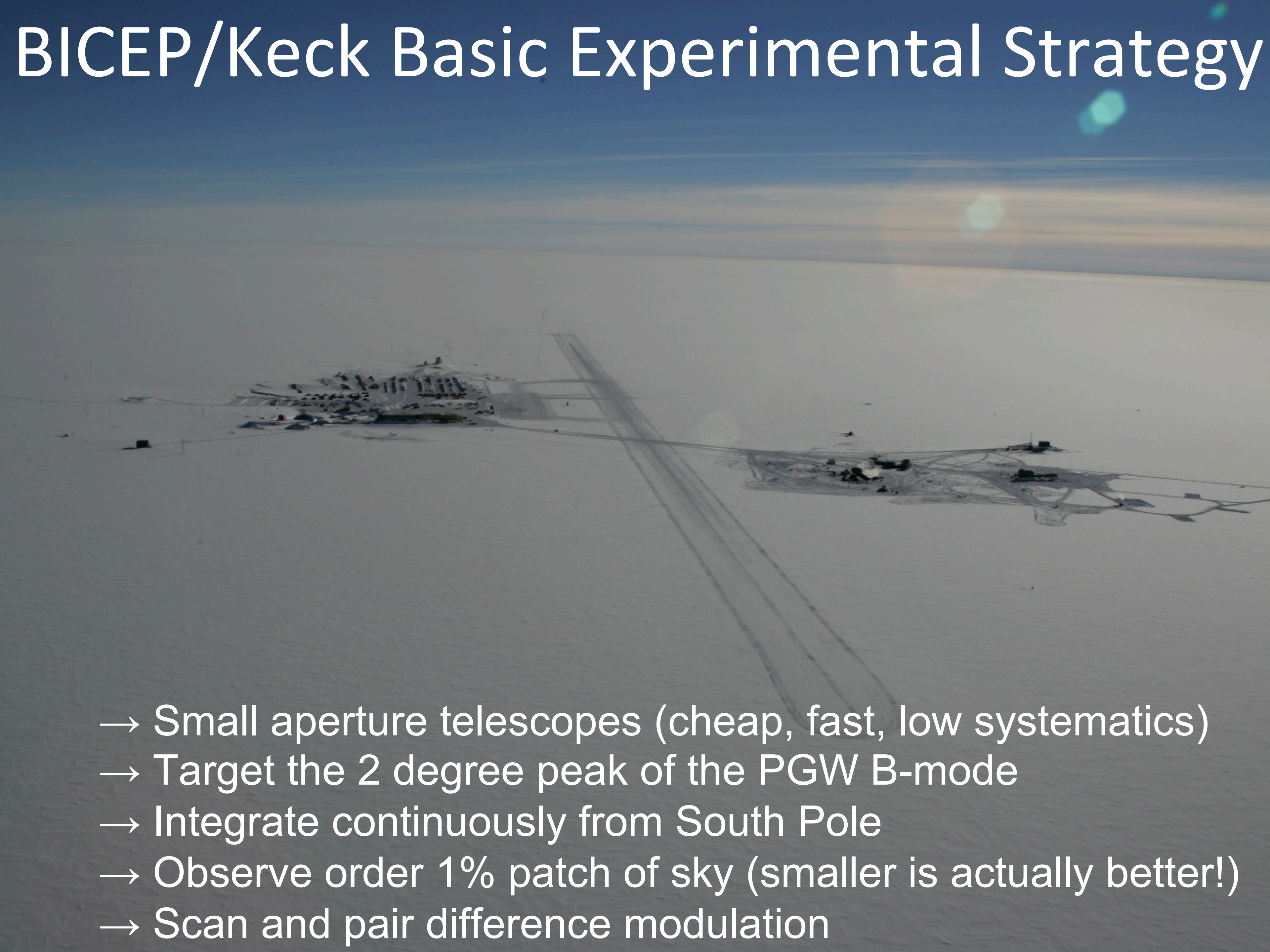
In standard ΛCDM only E-modes are present at last scattering



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

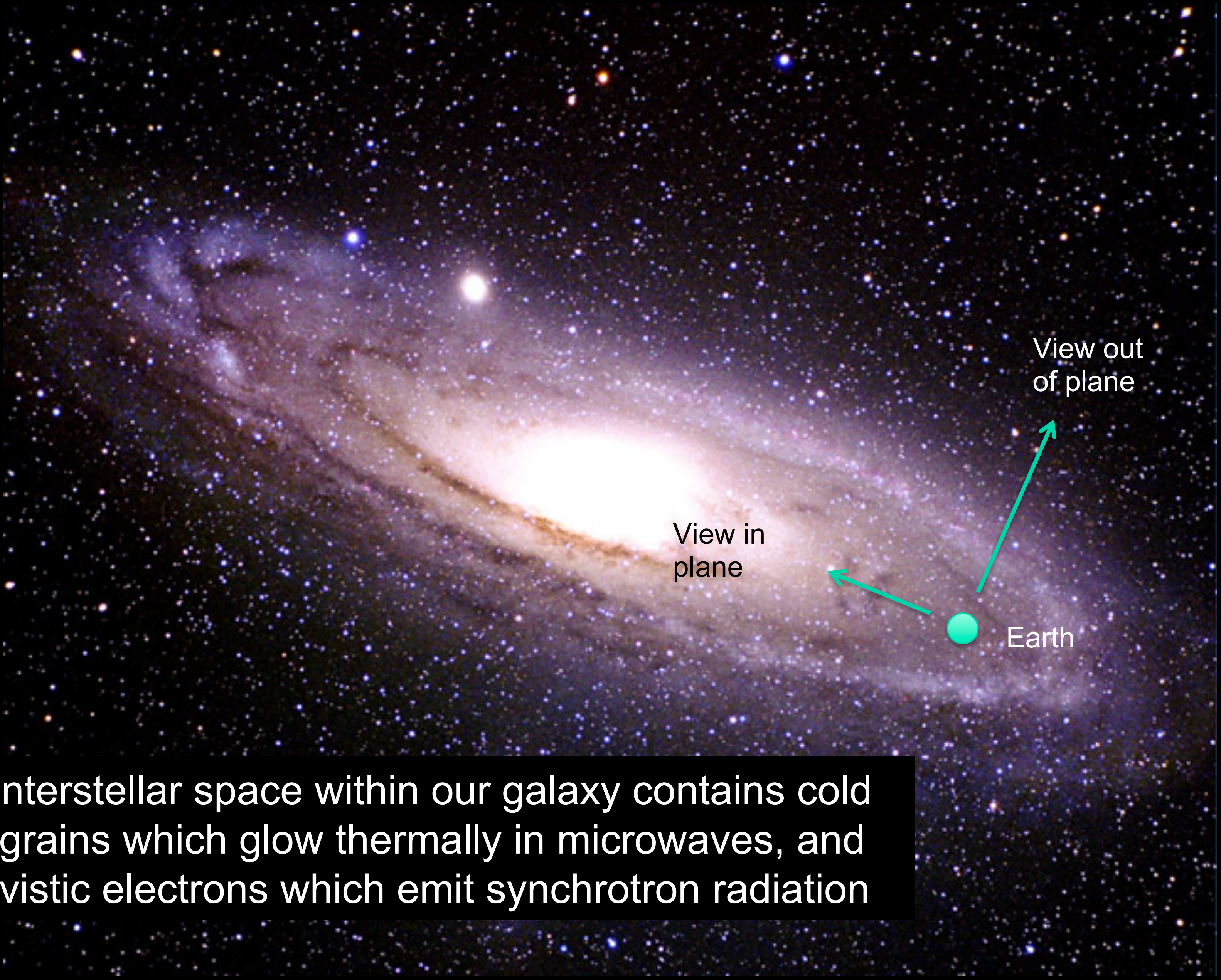
Inflationary gravitational waves are unique source of intrinsic B-modes
→ peaking at l≈80 : few degree scales

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 order 1% patch of sky (smaller is actually better!)
→ Scan and pair difference modulation

Foreground emission from our galaxy



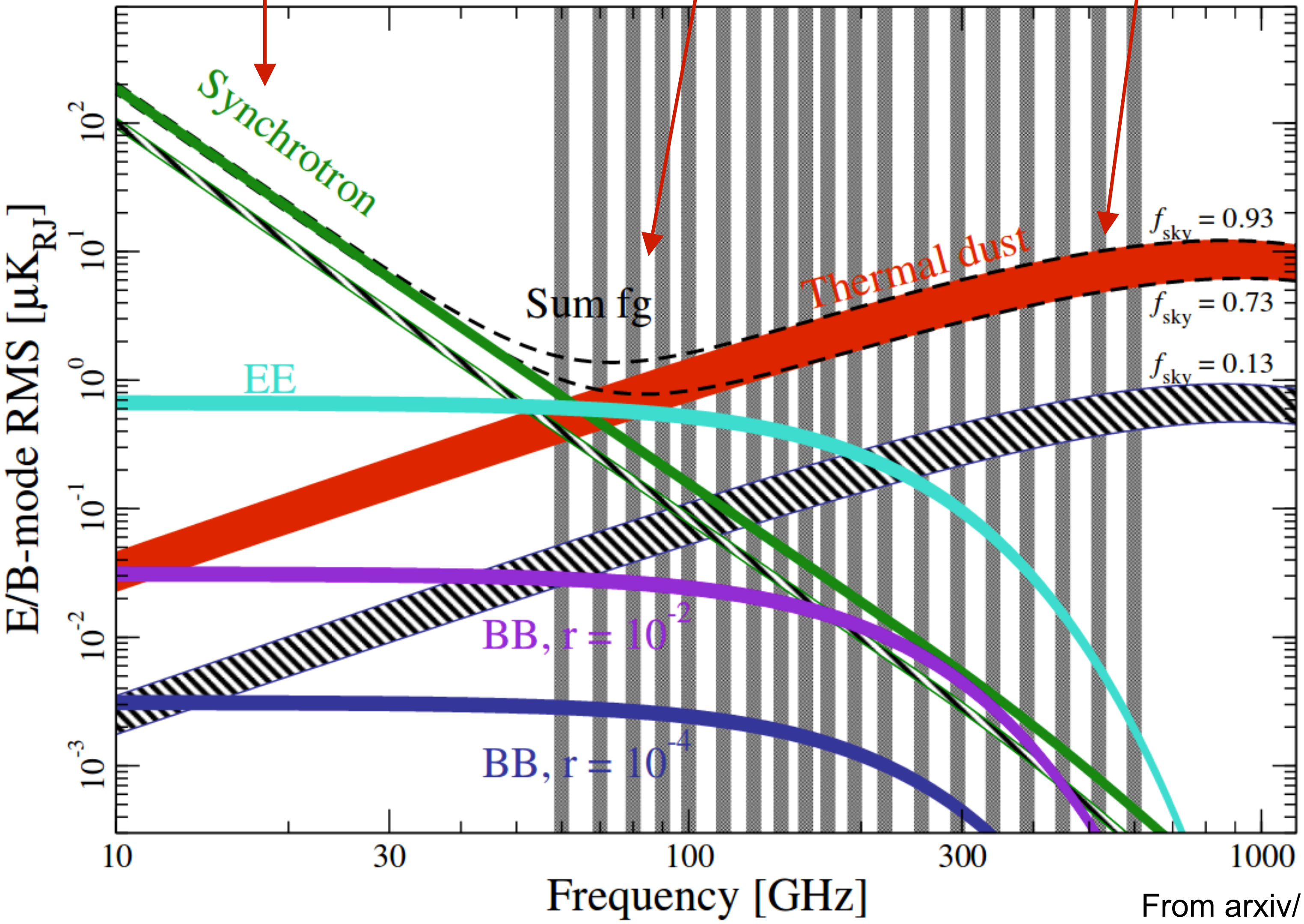
The interstellar space within our galaxy contains cold dust grains which glow thermally in microwaves, and relativistic electrons which emit synchrotron radiation

Overcoming Polarized Foreground Contamination

At low frequency synchrotron contamination

Mid frequencies minimum contamination

At high frequency dust contamination



Going to smaller/ cleaner sky patch

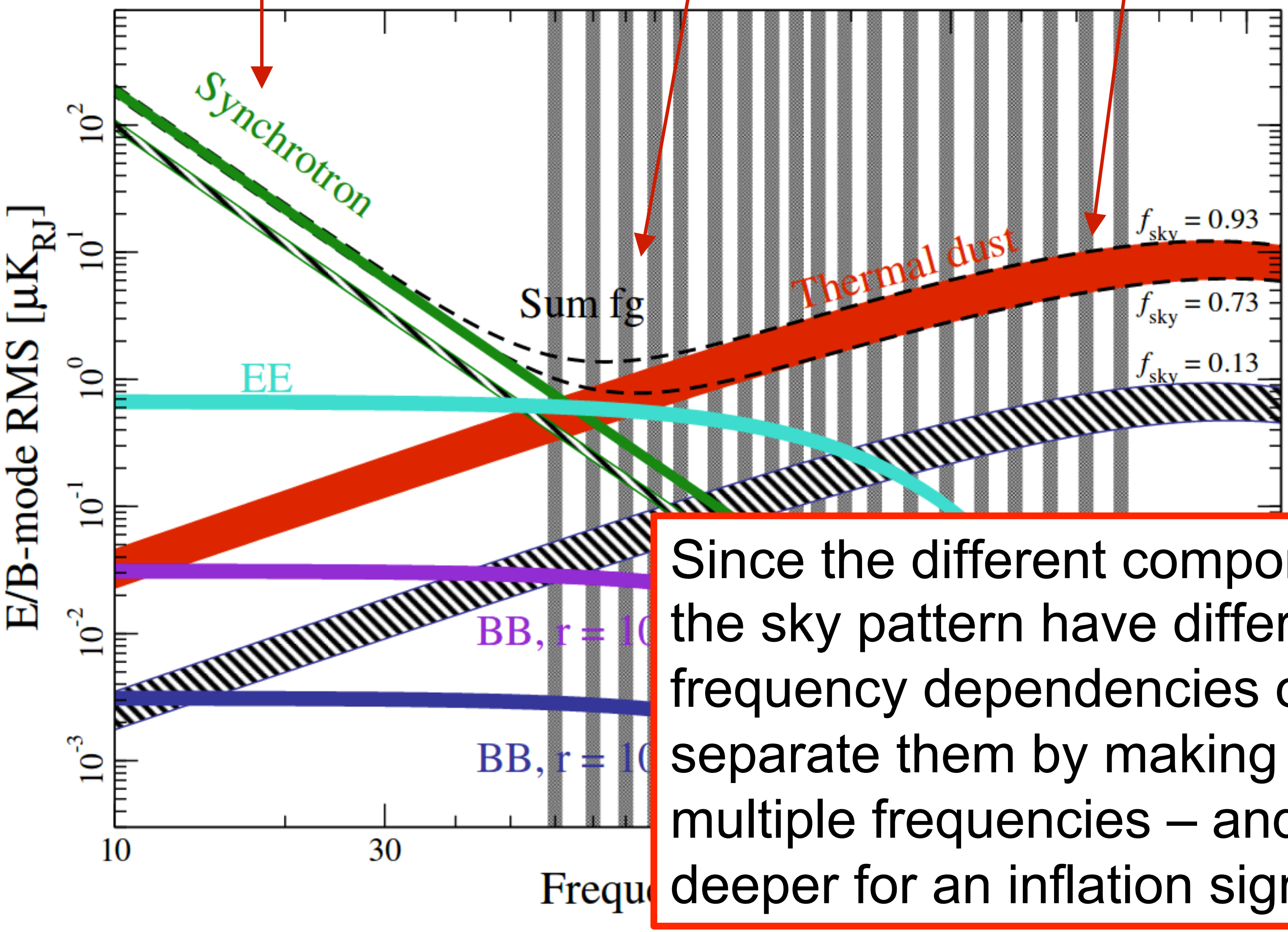
From arxiv/1704.04501

Overcoming Polarized Foreground Contamination

At low frequency synchrotron contamination

Mid frequencies minimum contamination

At high frequency dust contamination



Going to smaller/ cleaner sky patch

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

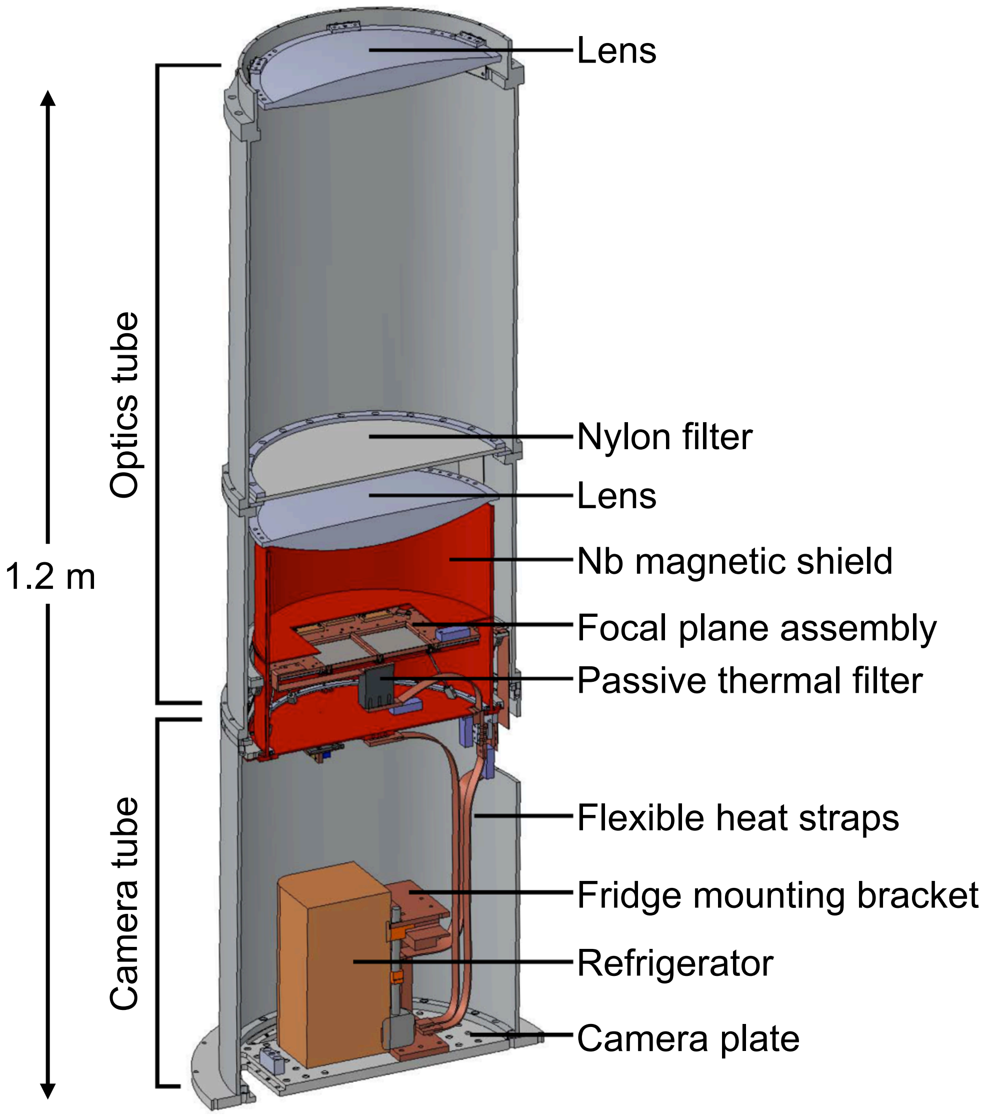
The BICEP/Keck Telescopes

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

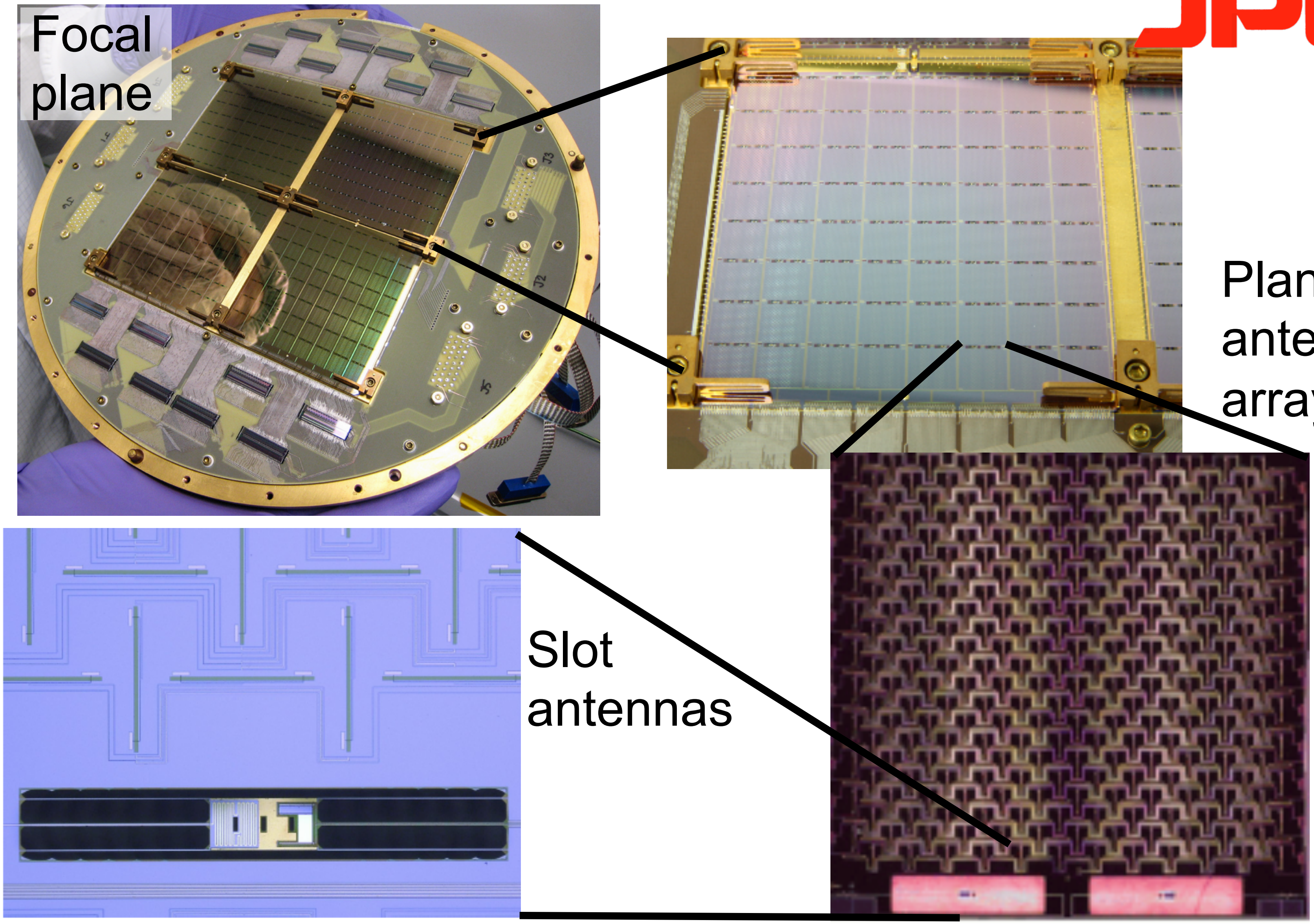
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

Pulse tube cooler cools the optical elements to 4.2 K.

3-stage helium sorption refrigerator further cools the detectors to 0.3 K.



Mass-produced Superconducting Detectors



Focal plane

Planar antenna array

Slot antennas

Transition edge sensor

Microstrip filters

BICEP/Keck Band Passes

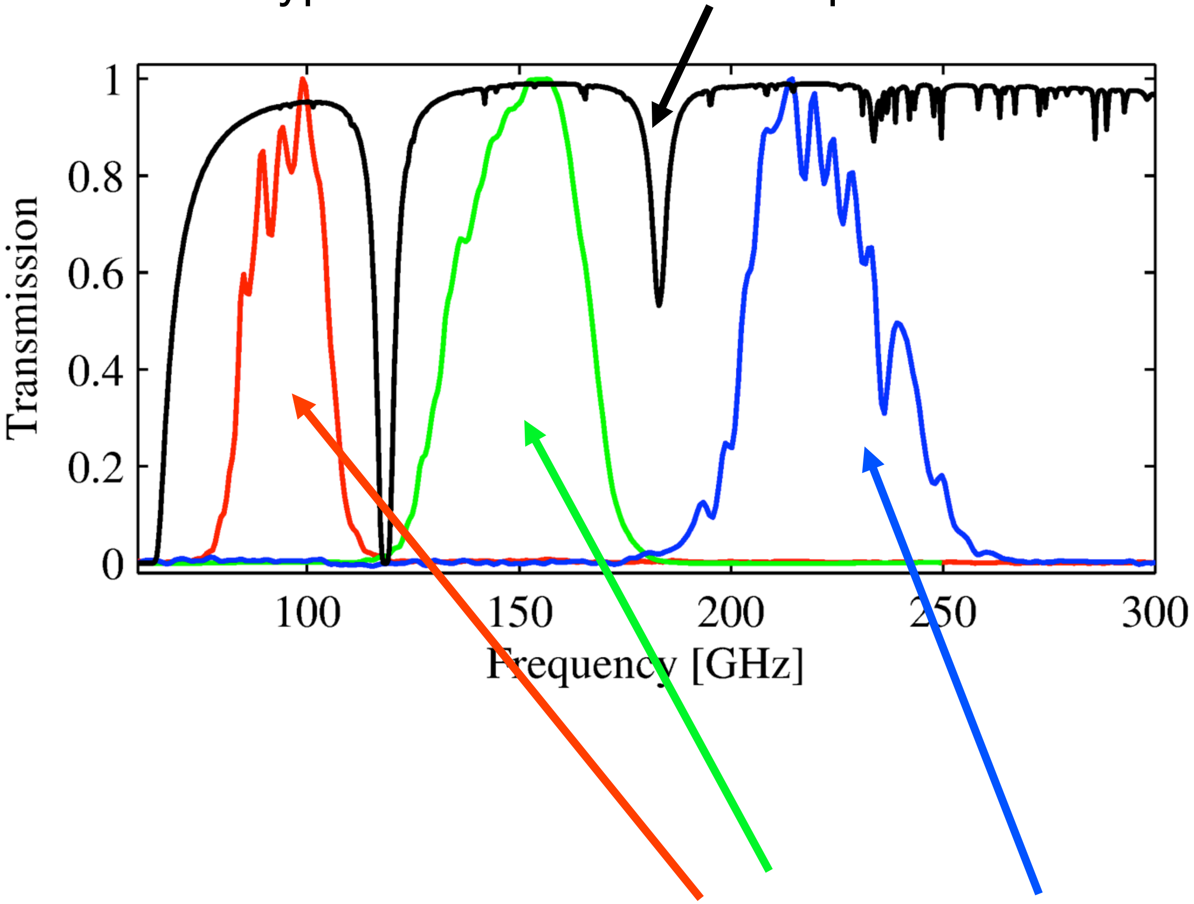
The dry South Pole atmosphere provides excellent observing conditions most of the year.

The approx. 30% fractional bandpasses fit within atmospheric transmission windows straddled by oxygen and water lines.

In these windows, the atmosphere is quite transparent to microwaves.

The detector passbands are defined by a filter printed directly onto the focal plane wafers.

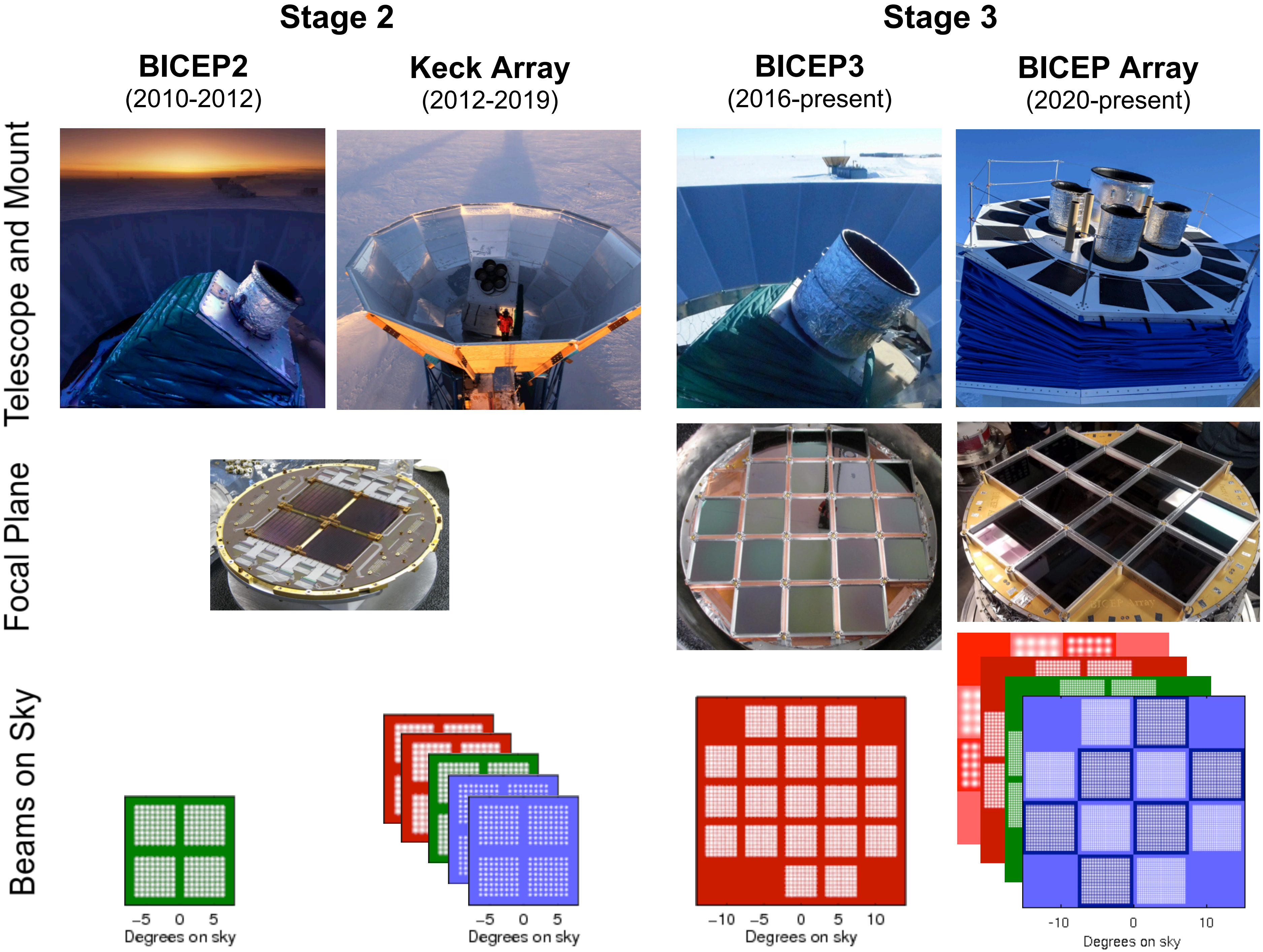
Typical South Pole atmospheric transmissio



choices of instrument response

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…

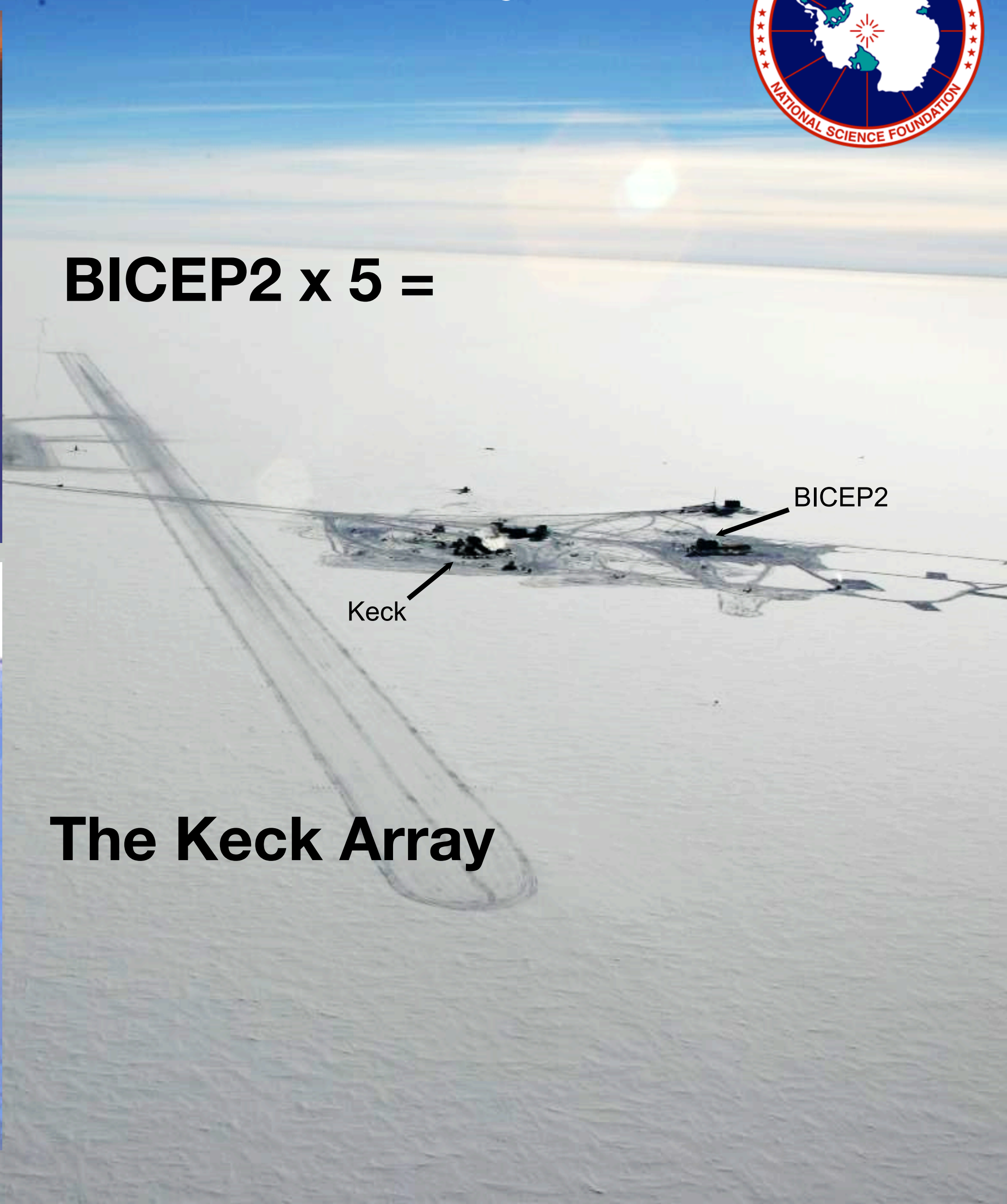

Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2016-present)
BICEP Array
(2020-present)
Telescope and Mount
Focal Plane
Beams on Sky
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
−10 0 10
Degrees on sky

South Pole Site

BICEP2 and Keck Array


BICEP2 2010-2012

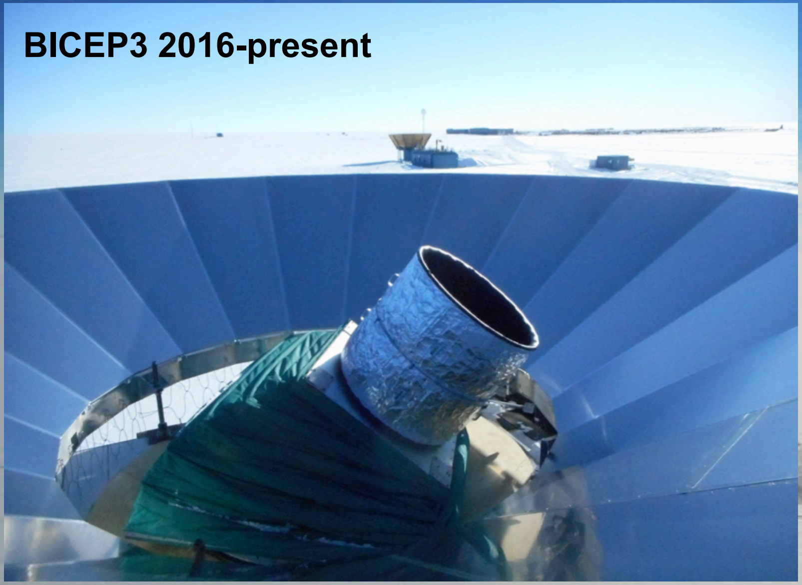
Keck Array 2012-2019



BICEP2 x 5 =

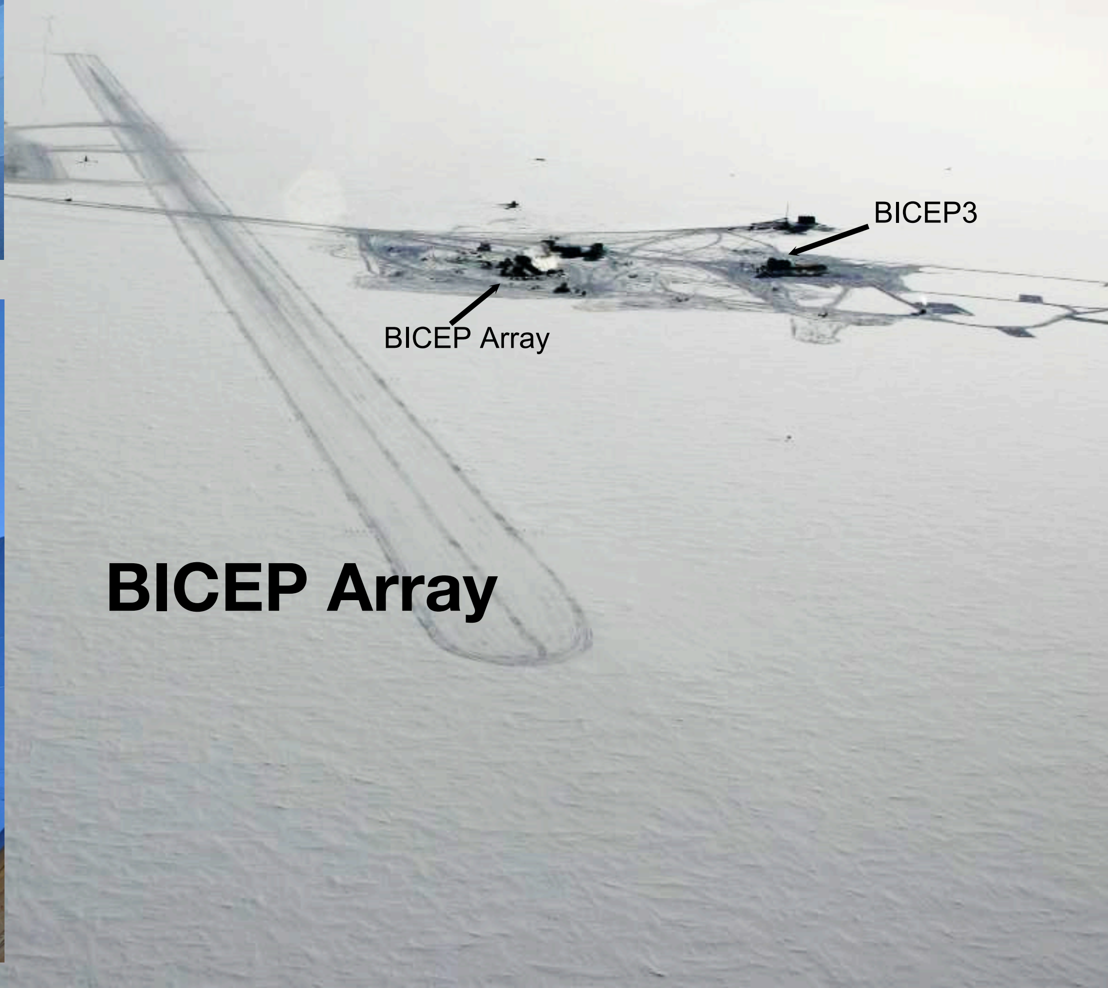
The Keck Array

BICEP3 and BICEP Array


BICEP3 2016-present

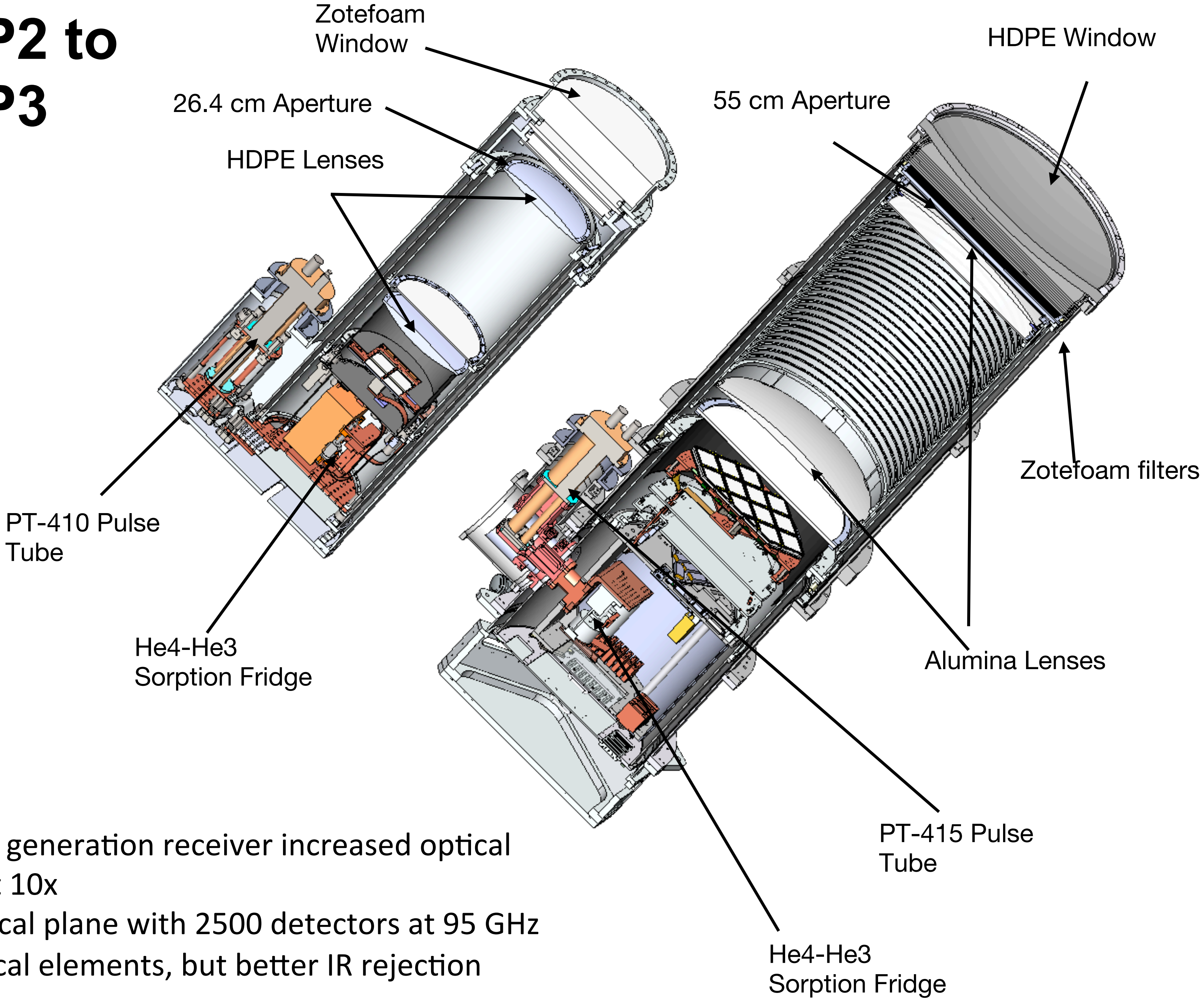

BICEP Array 2020-present

BICEP3 x 4 =

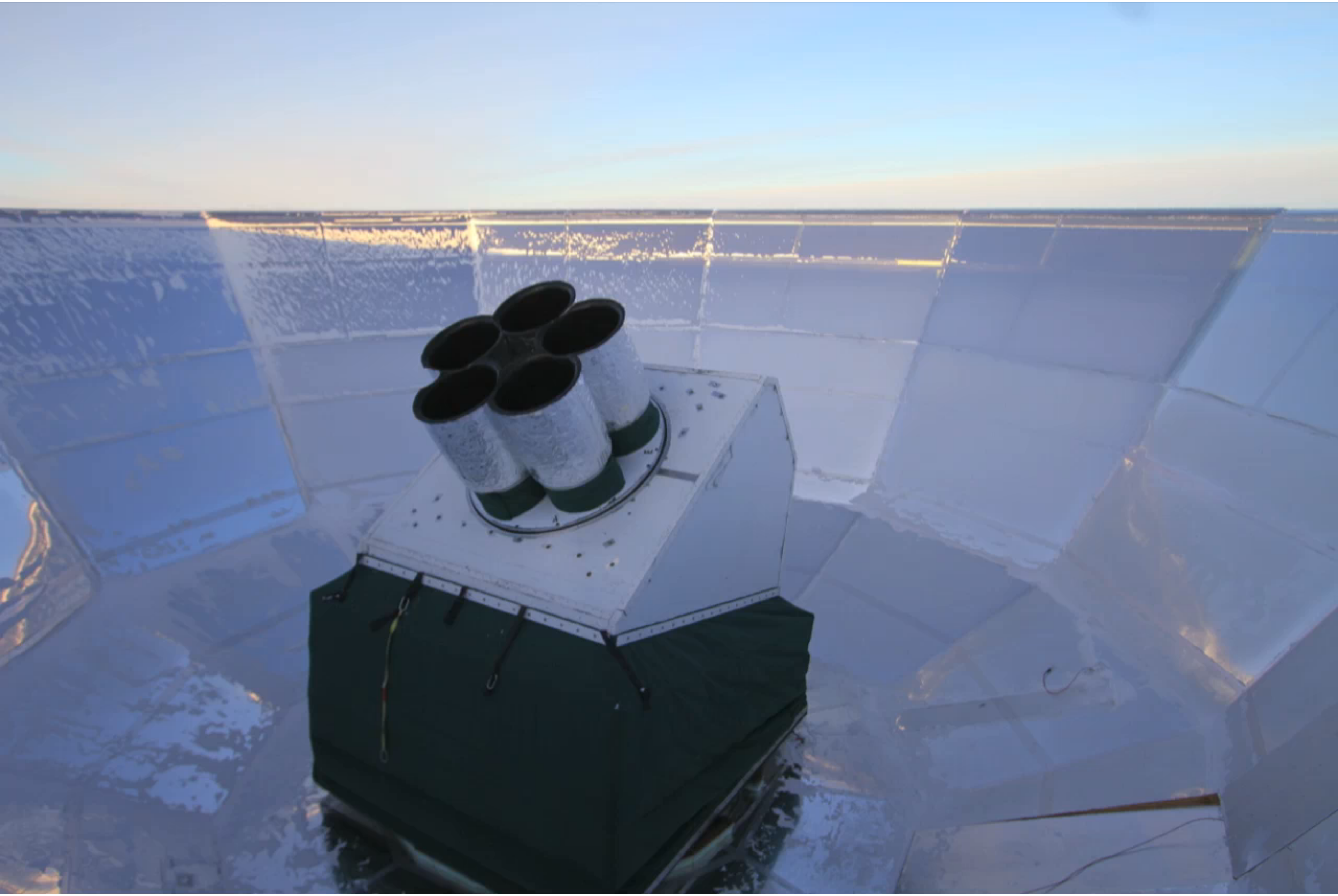


BICEP Array

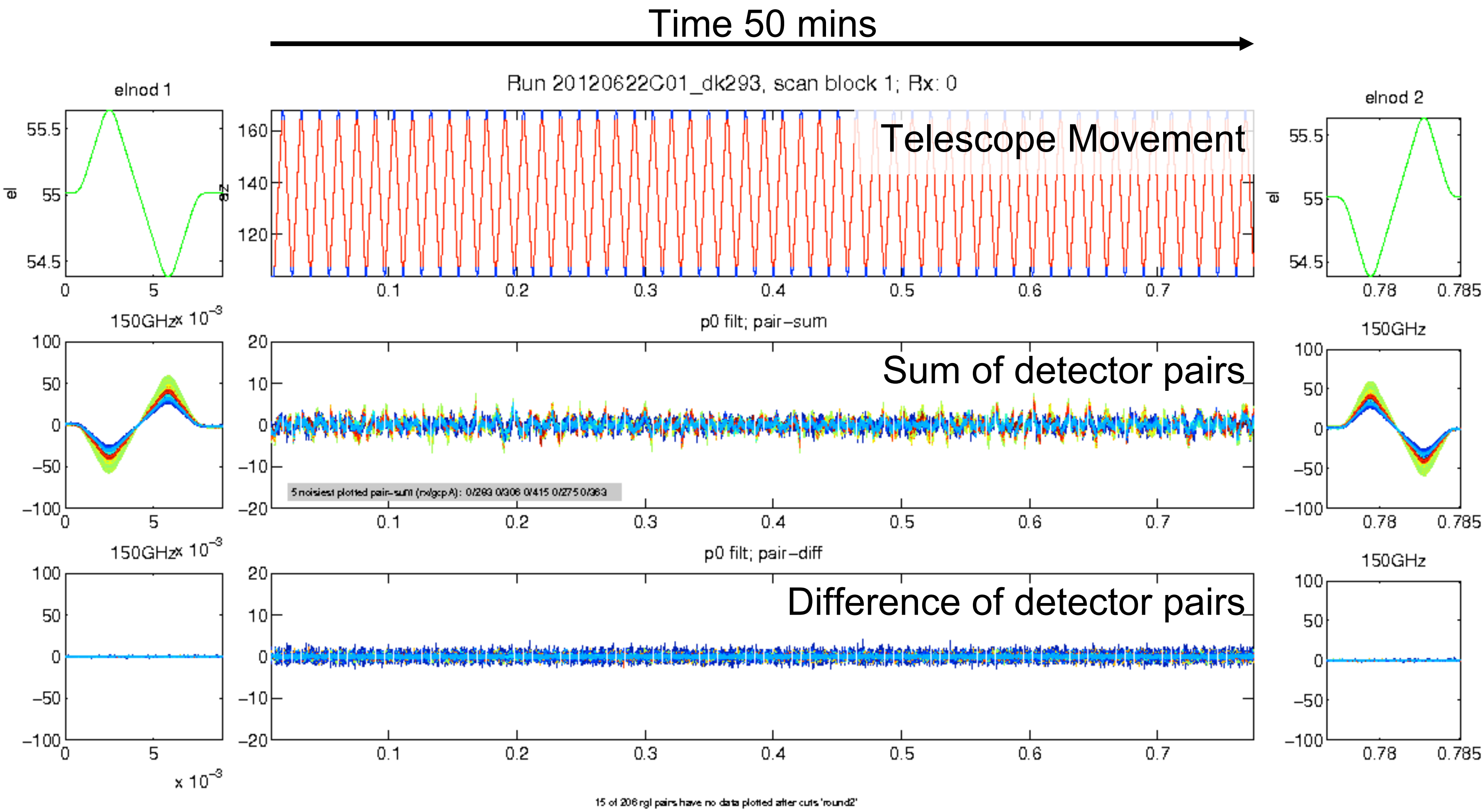
BICEP2 to BICEP3



- BICEP's 3rd generation receiver increased optical throughput 10x
- Modular focal plane with 2500 detectors at 95 GHz
- Larger optical elements, but better IR rejection



Raw Data - Perfect Weather



Time 50 mins

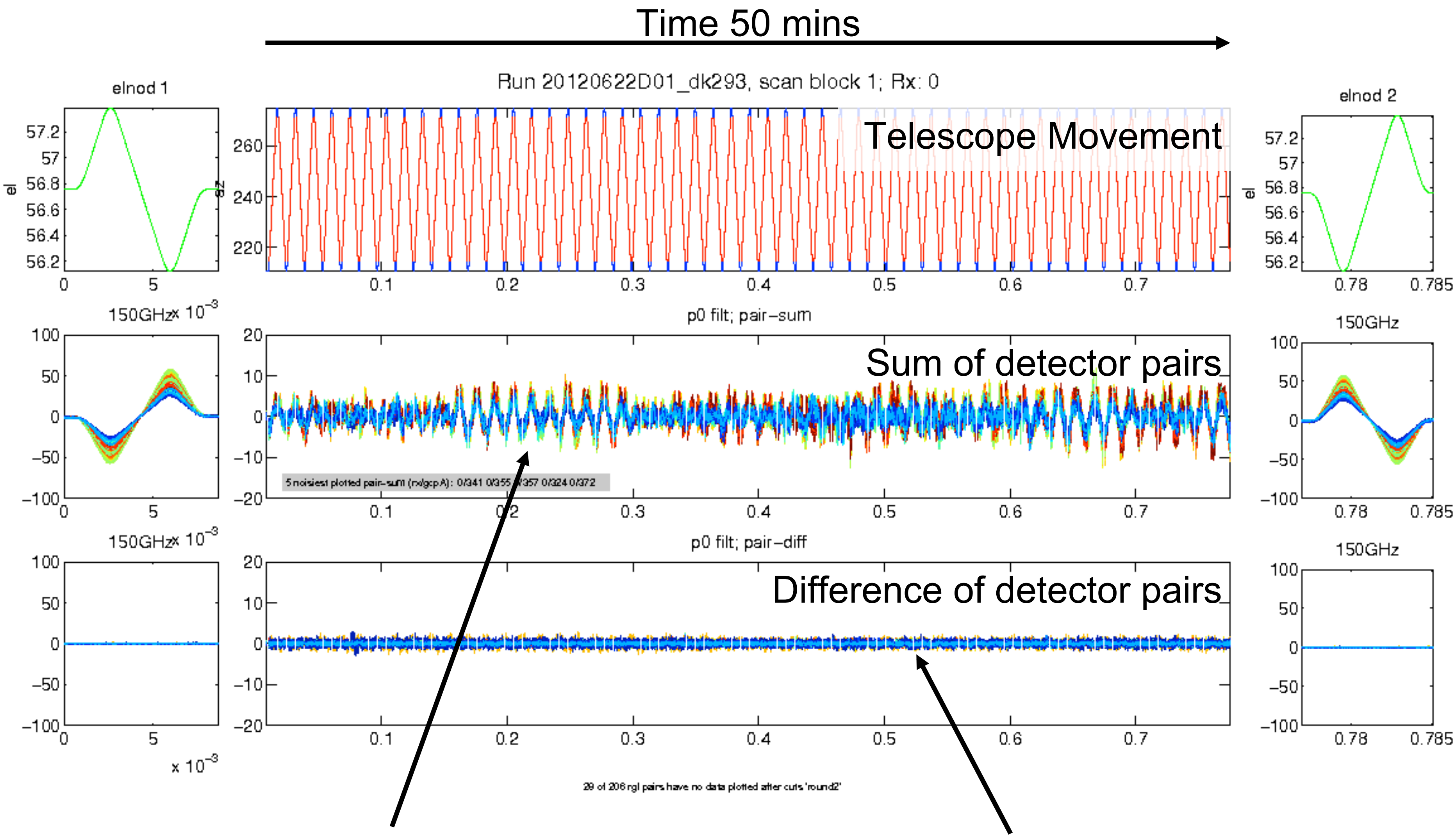
Telescope Movement

Sum of detector pairs

Difference of detector pairs

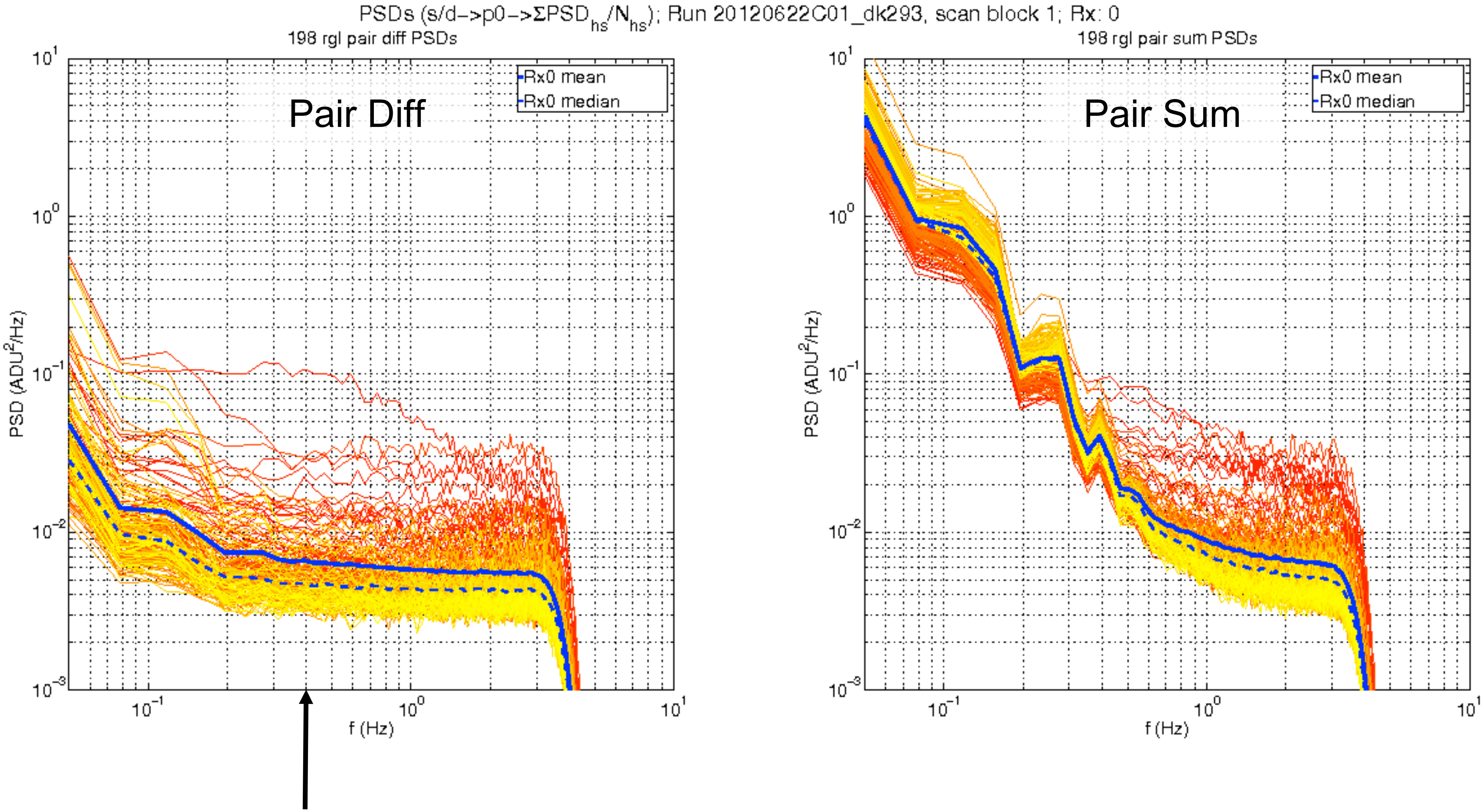
- ➢ Cover the whole field in 60 such scansets then start over at new boresight rotation
- ➢ Scanning modulates the CMB signal to freqs < 4 Hz

Raw Data - Worse Weather

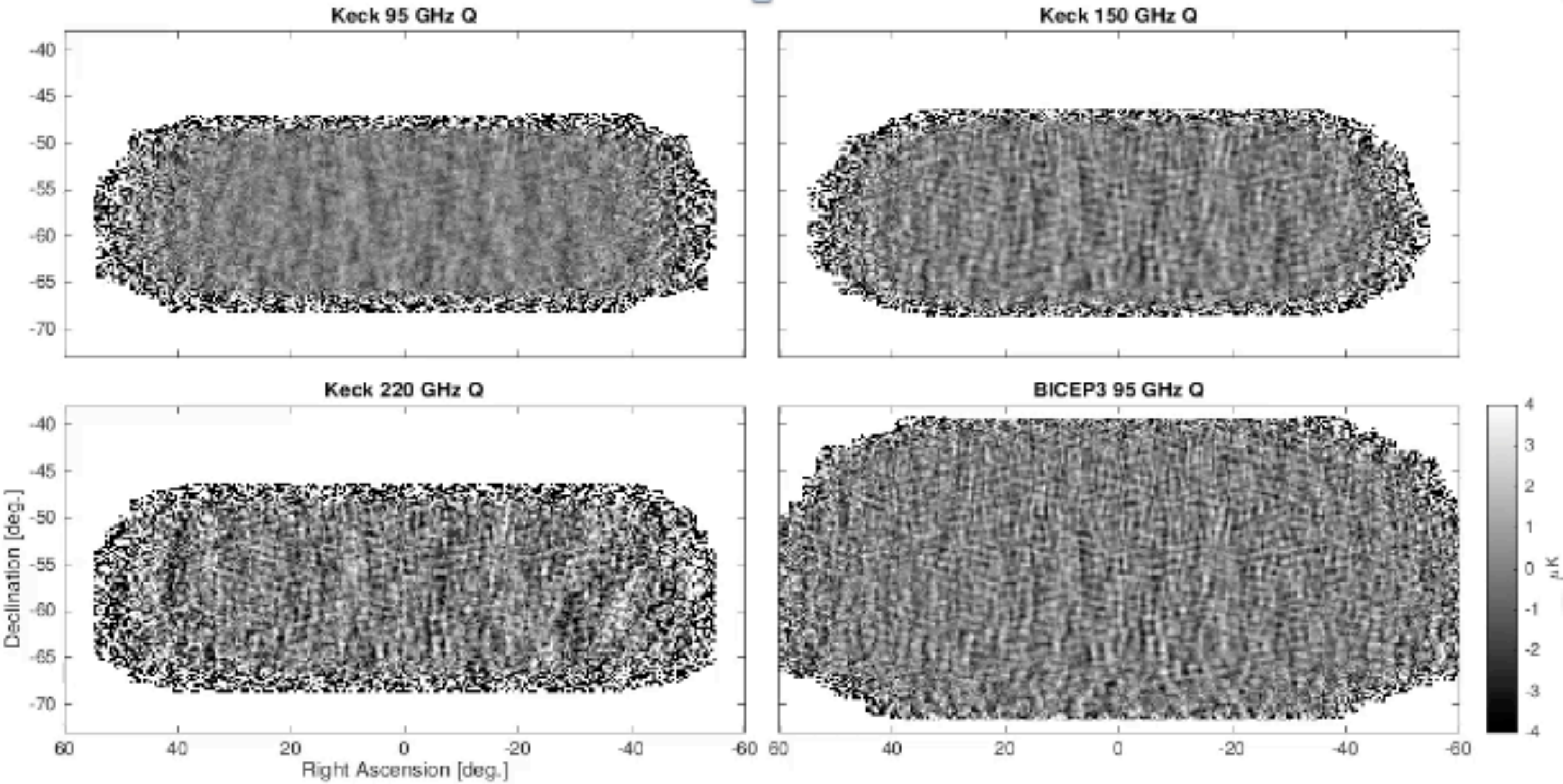


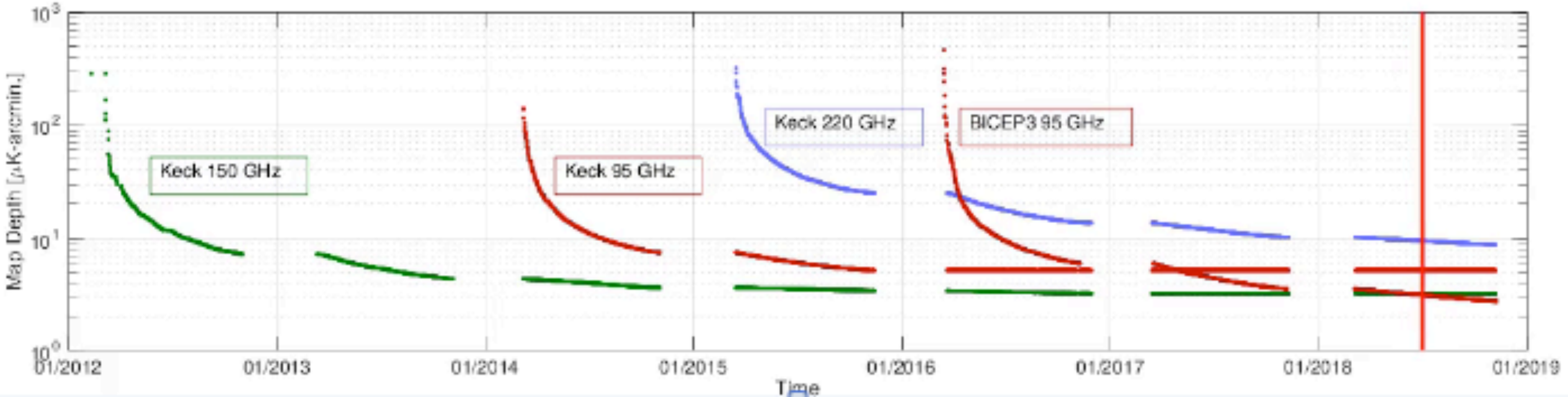
- ➢ Scanning over lumpy atmosphere → "clouds"
- ➢ Pair difference still clean → atmosphere is unpolarized

Timestream PSDs

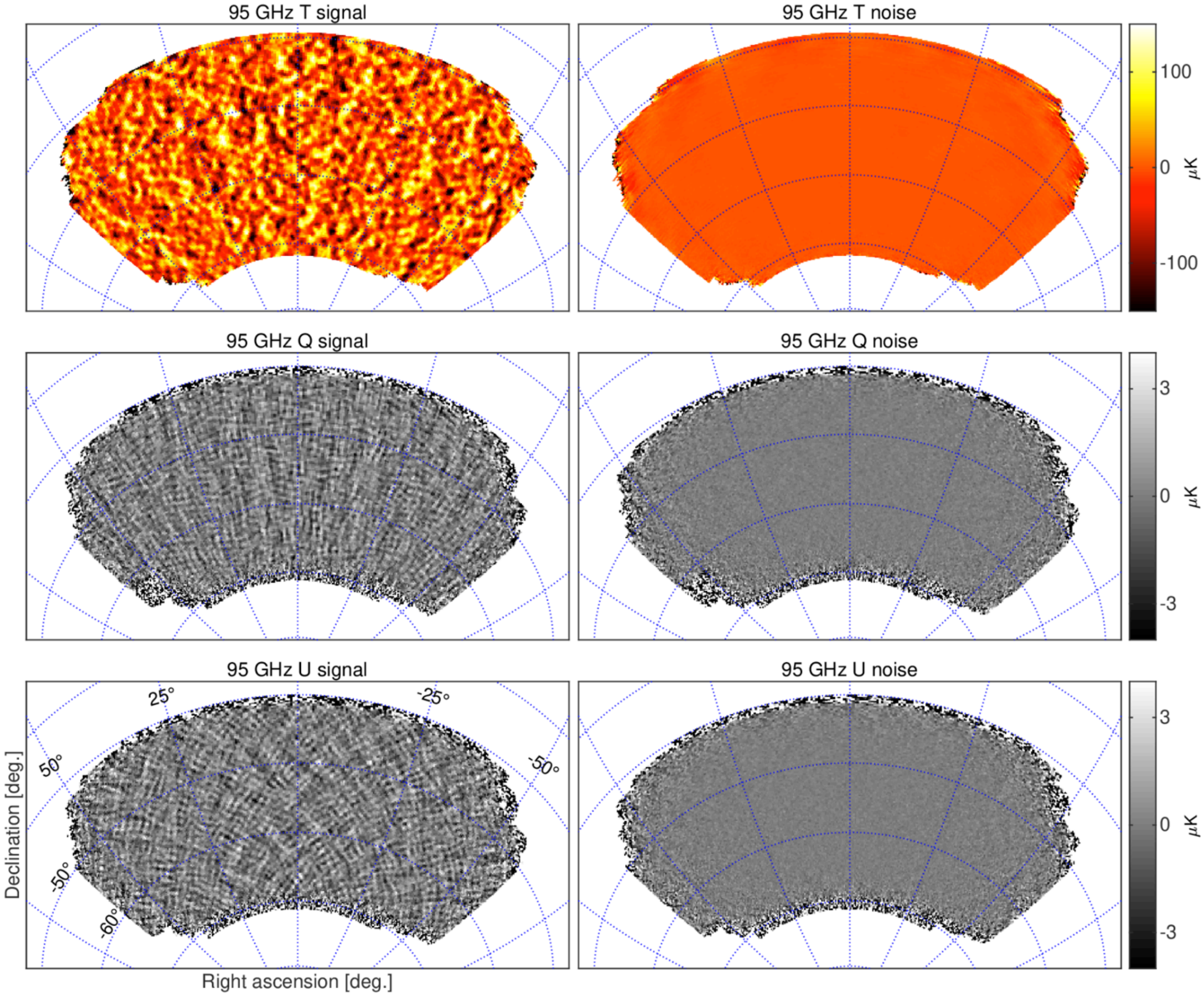


- ➢ Multipole 100 at 0.4Hz

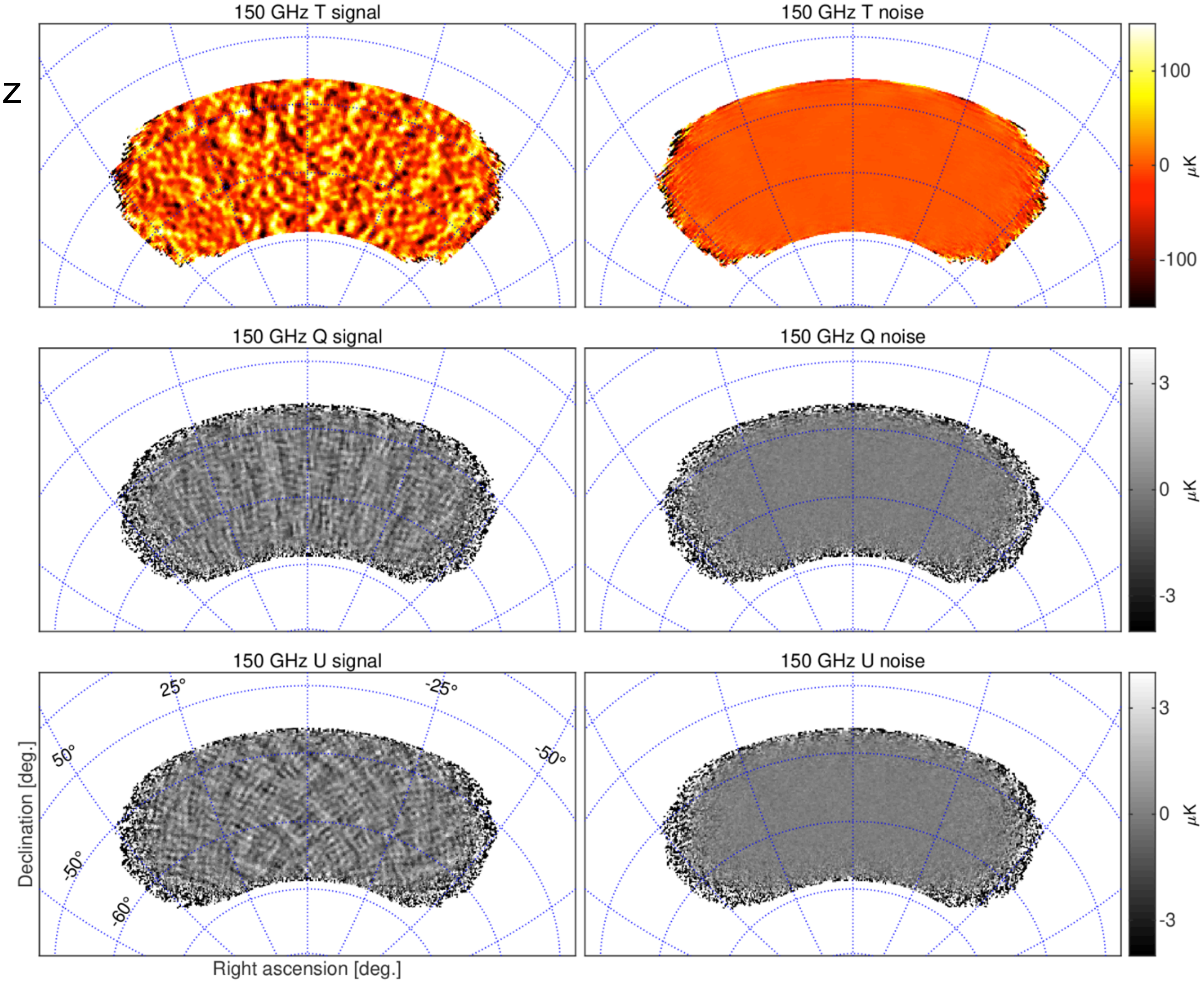

Keck 95 GHz Q
Keck 150 GHz Q
Keck 220 GHz Q
BICEP3 95 GHz Q
Declination [deg.]
Right Ascension [deg.]
-40
-45
-50
-55
-60
-65
-70
60
40
20
0
-20
-40
-60
μK
4
3
2
1
0
-1
-2
-3
-4


Map Depth [μK-arcmin.]
Time
10^3
10^2
10^1
10^0
01/2012
01/2013
01/2014
01/2015
01/2016
01/2017
01/2018
01/2019
Keck 150 GHz
Keck 95 GHz
Keck 220 GHz
BICEP3 95 GHz

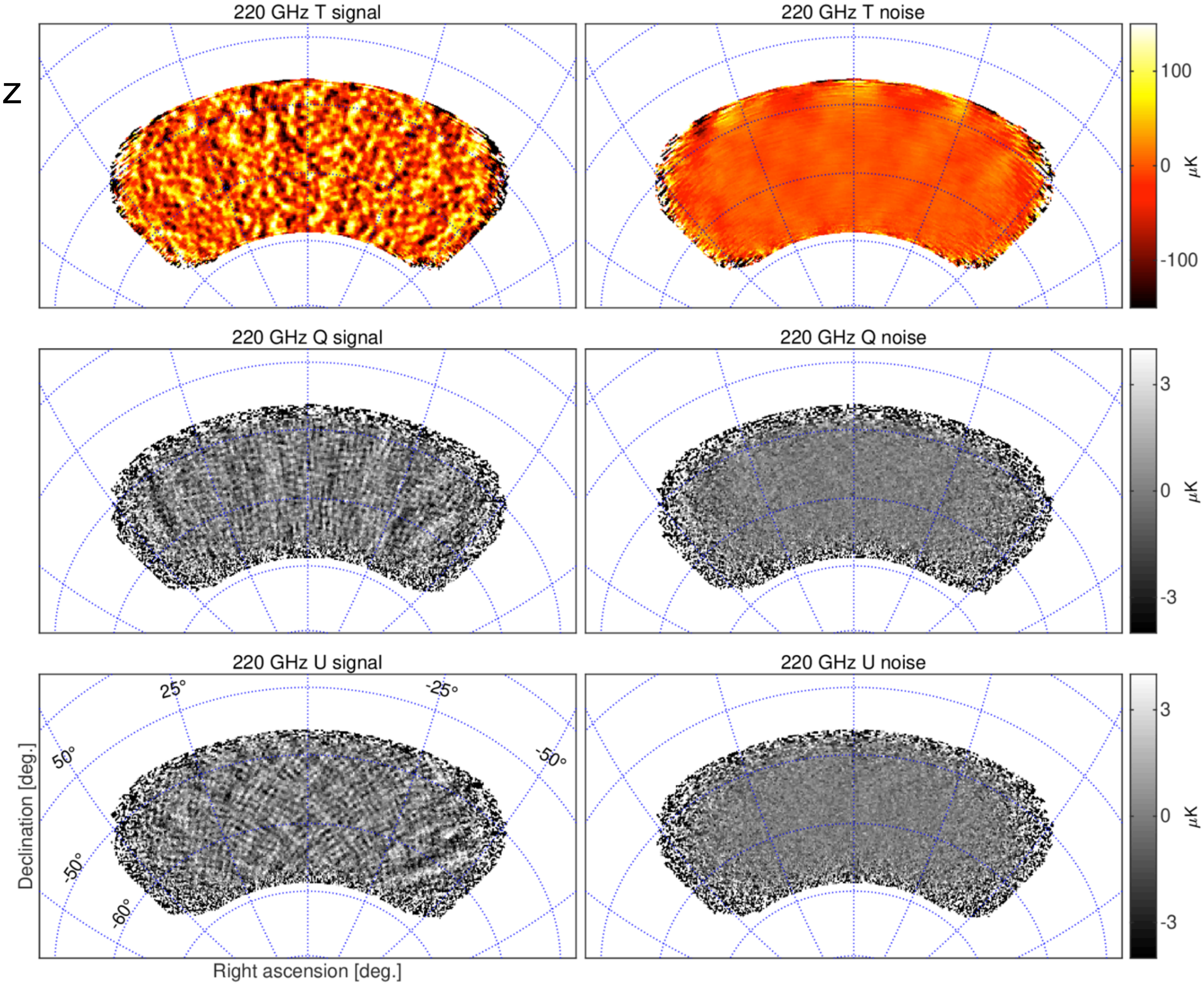
BK18
95GHz
Maps



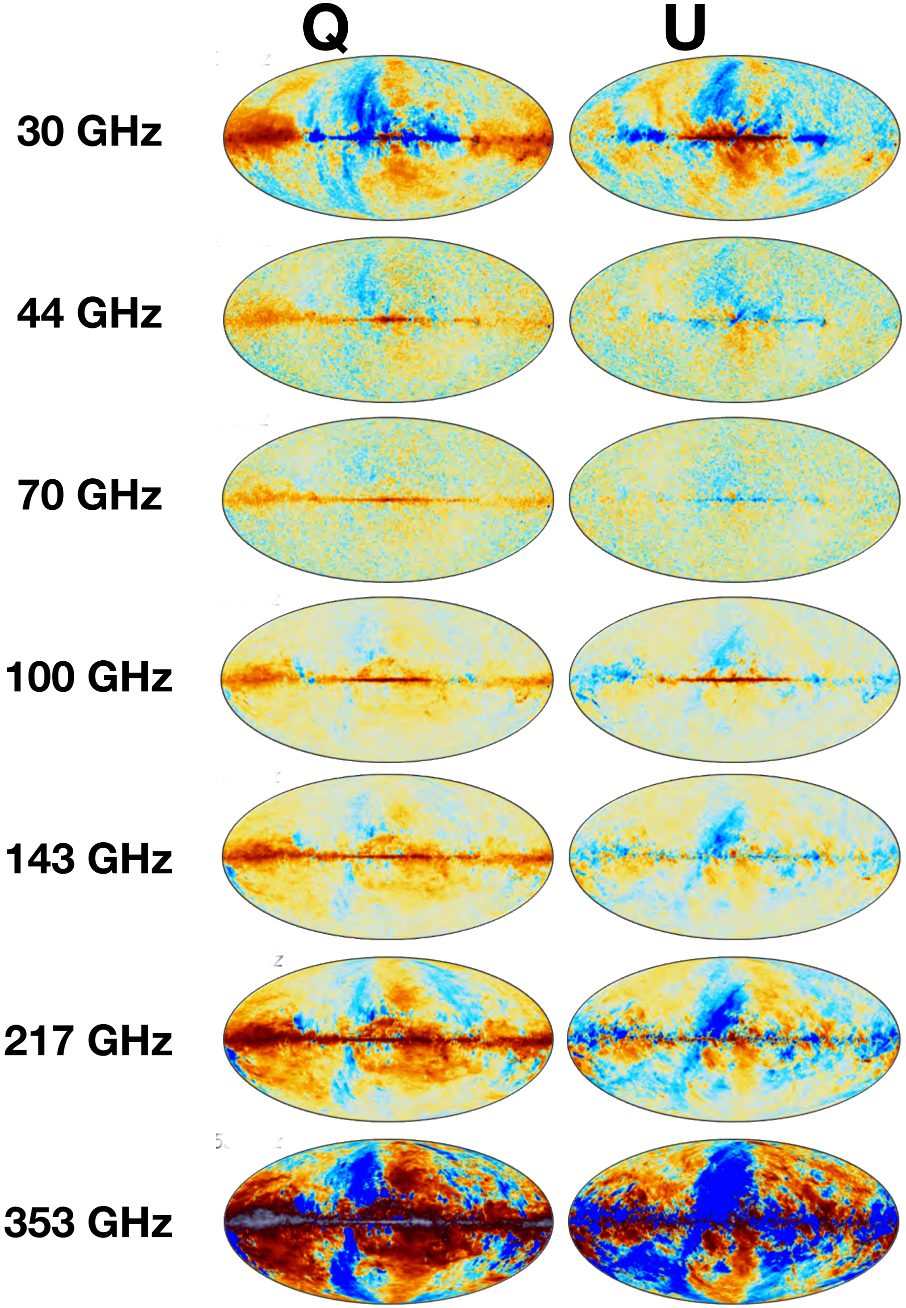
BK18
150GHz
Maps



BK18
220GHz
Maps

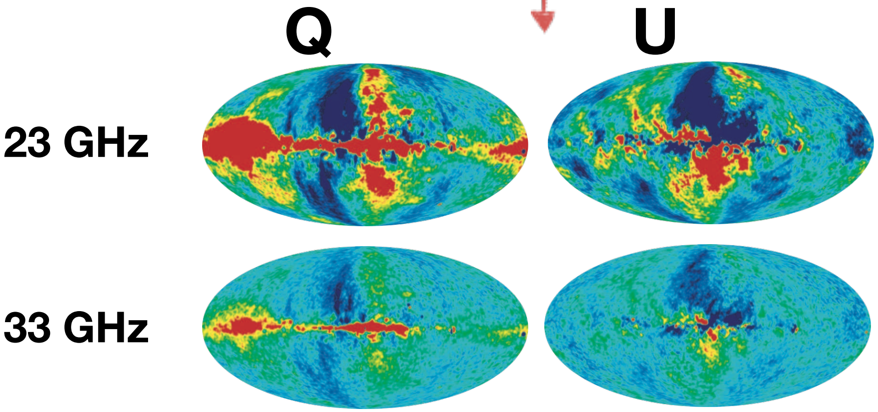


Add to the mix: Planck at 5 frequencies and WMAP at 2 frequencies



From arxiv 1502.01582

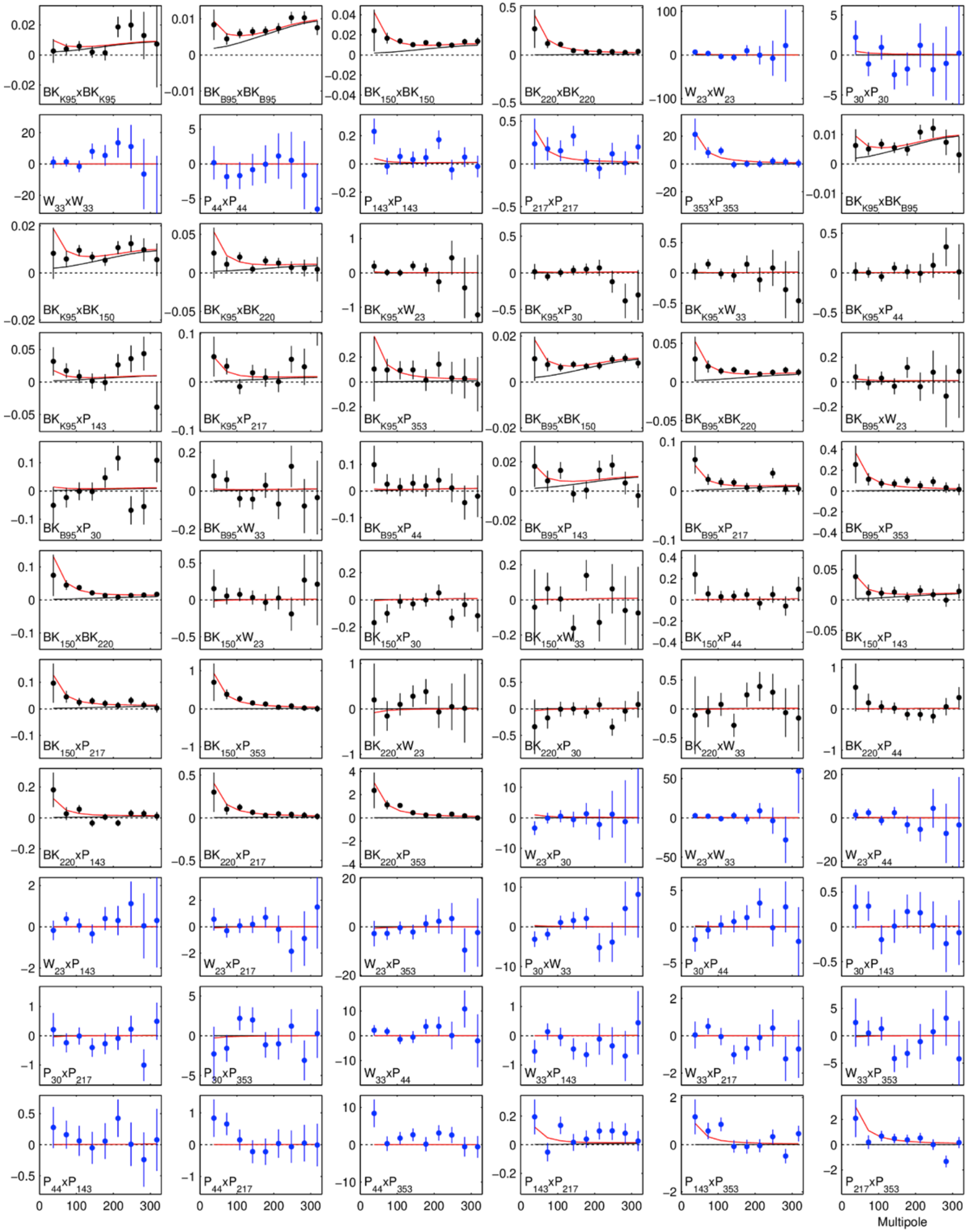
Polarized galactic **synchrotron** dominates at low frequencies



From arxiv 1212.5225

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

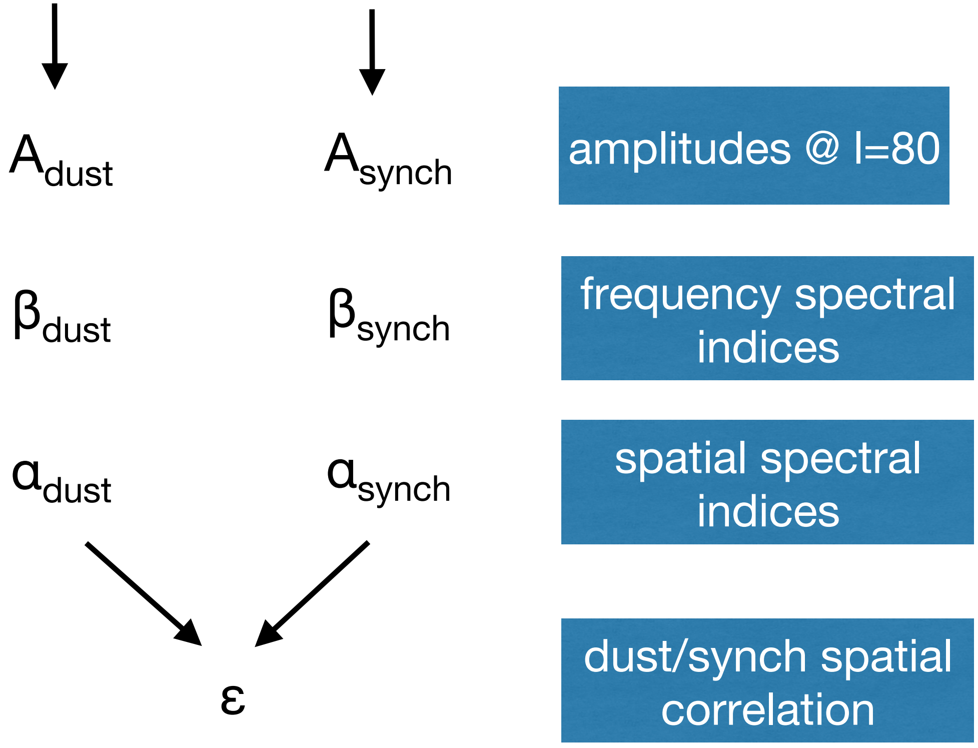
Analysis Technique: Take all possible auto- and cross spectra between the BICEP/Keck, WMAP, and Planck bands (66 of them) and compare to model of CMB +foregrounds



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



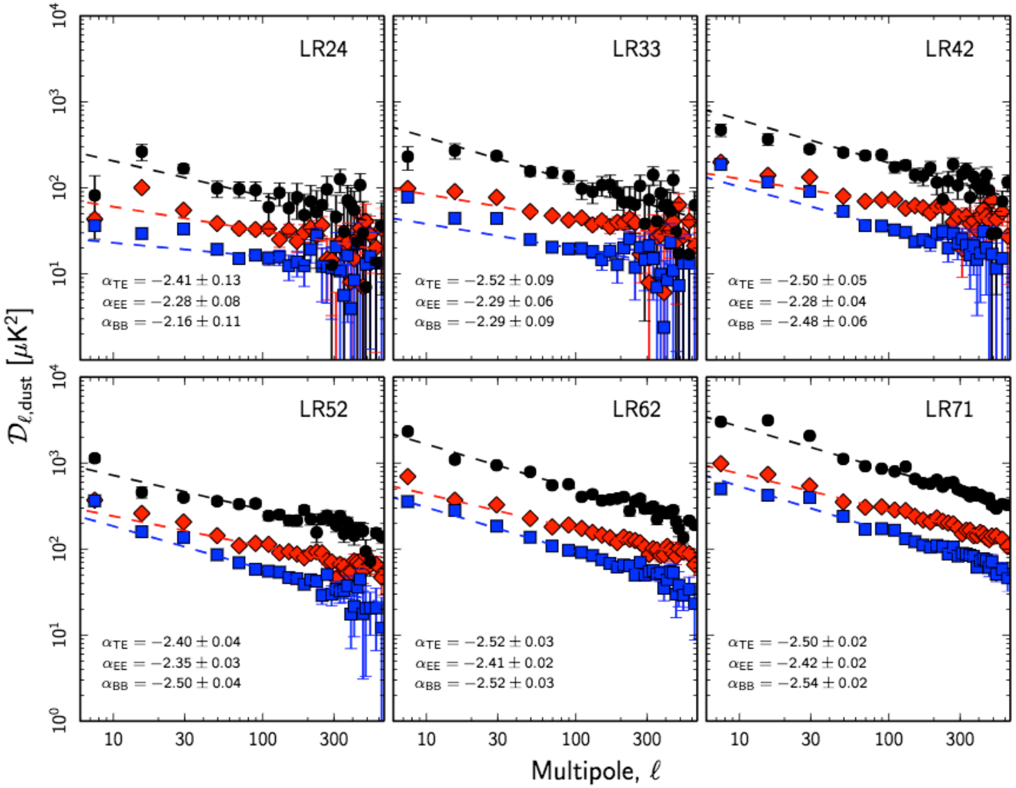
A_{dust} A_{synch} amplitudes @ l=80

β_{dust} β_{synch} frequency spectral indices

α_{dust} α_{synch} spatial spectral indices

ε dust/synch spatial correlation

Dust/Sync Spatial Power Laws?



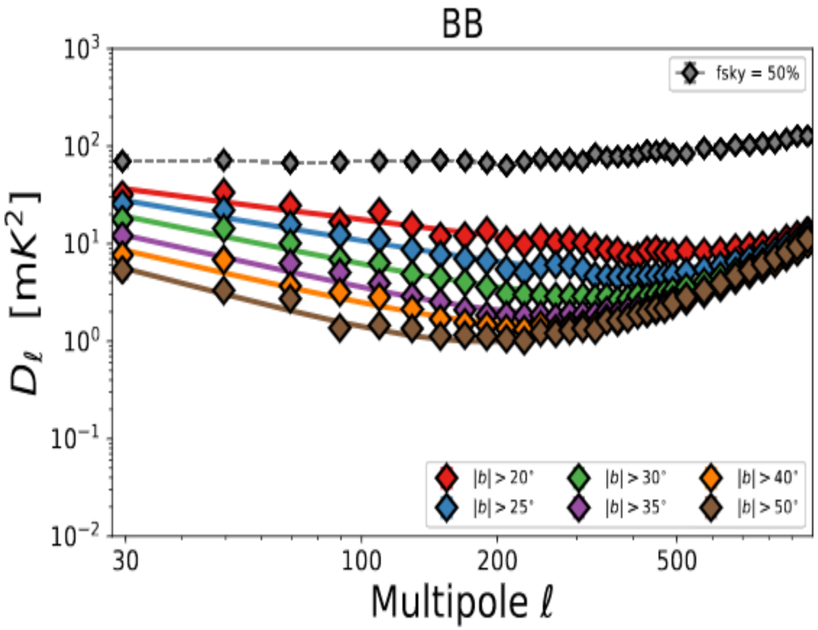


Fig 2 of arxiv/1801.04945 – Planck dust analysis

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

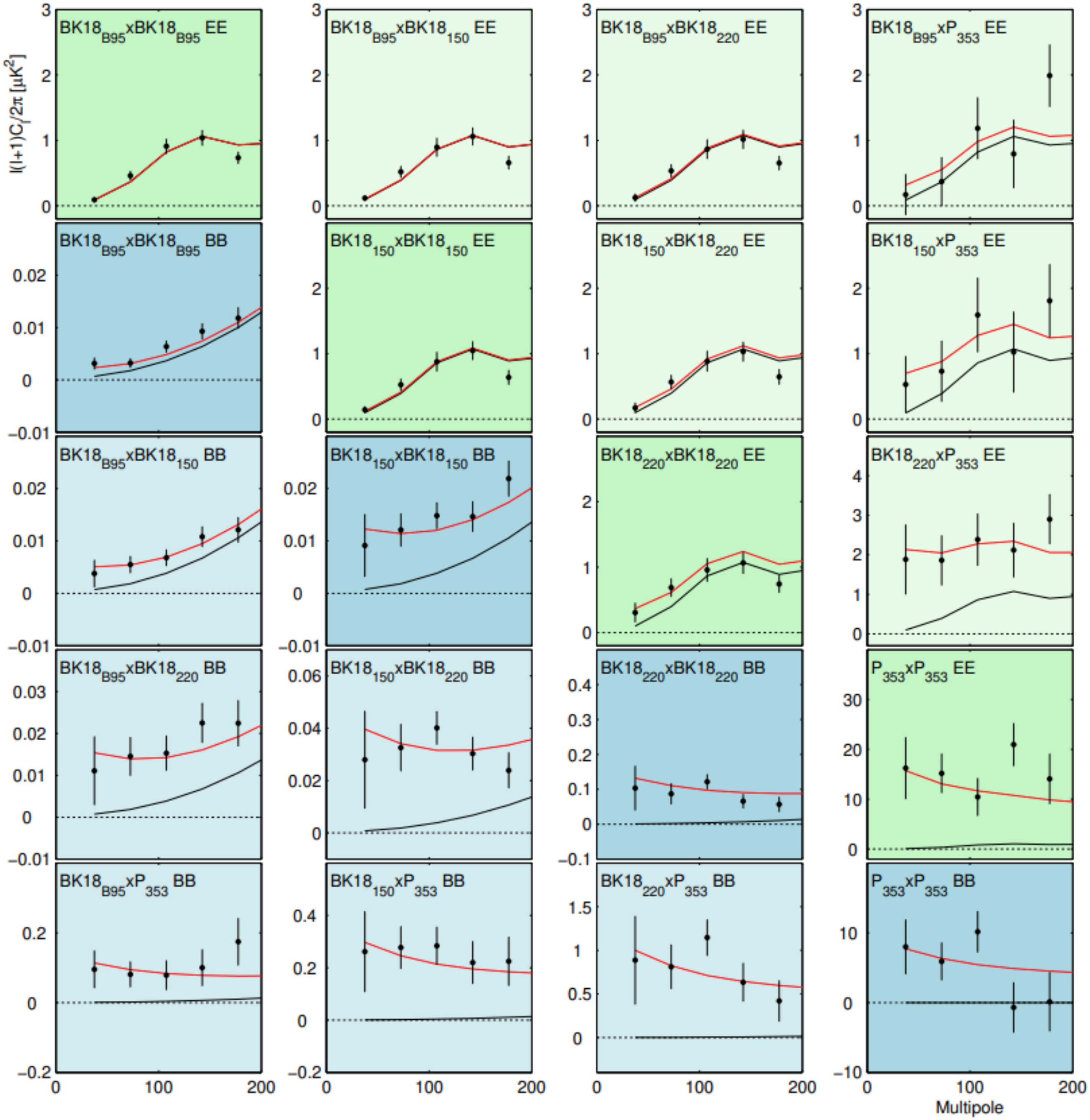
- ➢ Averaged over large regions of sky it is an empirical fact that dust and sync have roughly power law angular power spectra
- ➢ Not enough signal-to-noise in Planck data to investigate fluctuations about this behavior for small sky patches

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

Black lines are LCDM

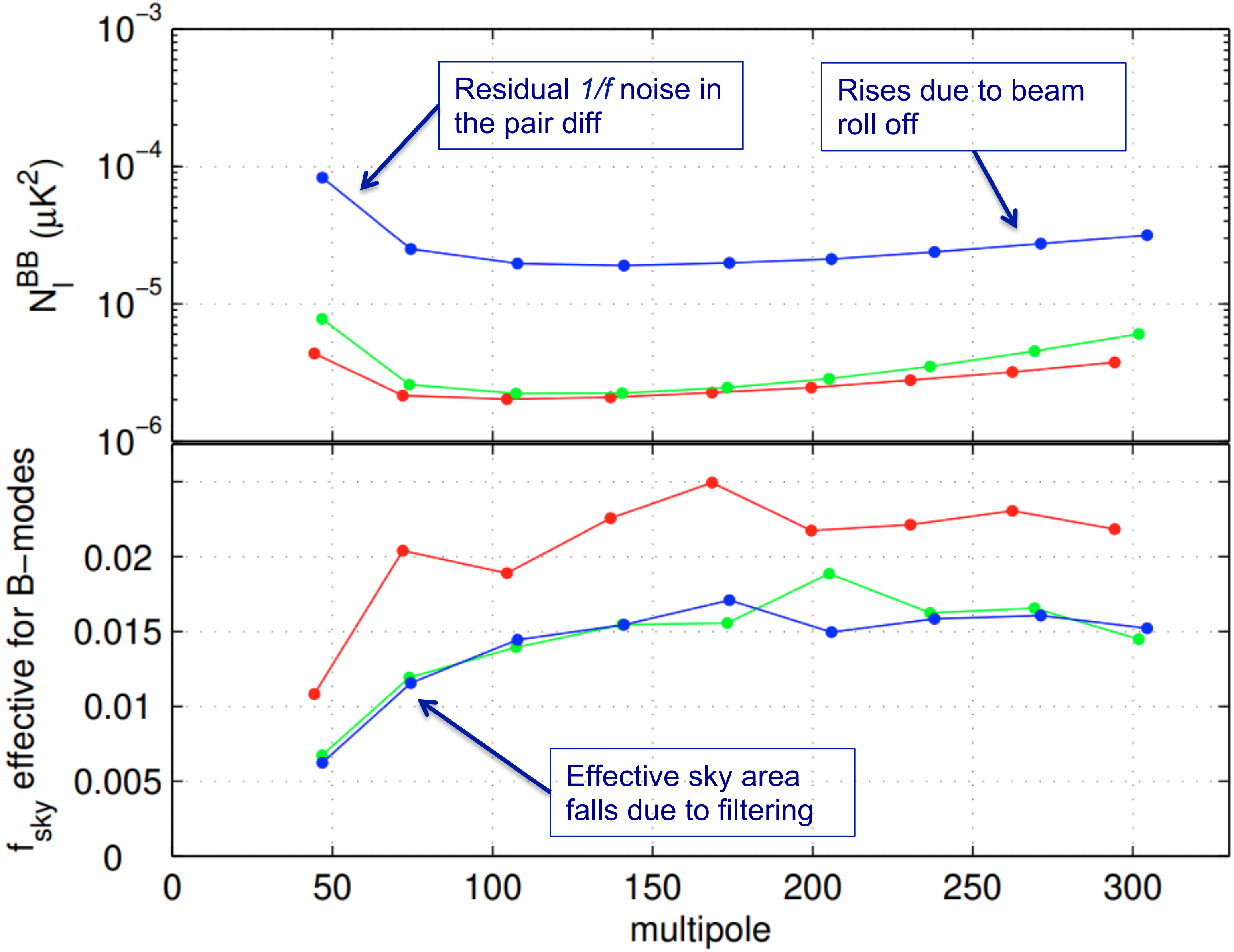
Red lines are LCDM+dust

Blue panels are BB spectra



Green panels are EE spectra

BK18 Noise Spectra and f_{sky} Effective

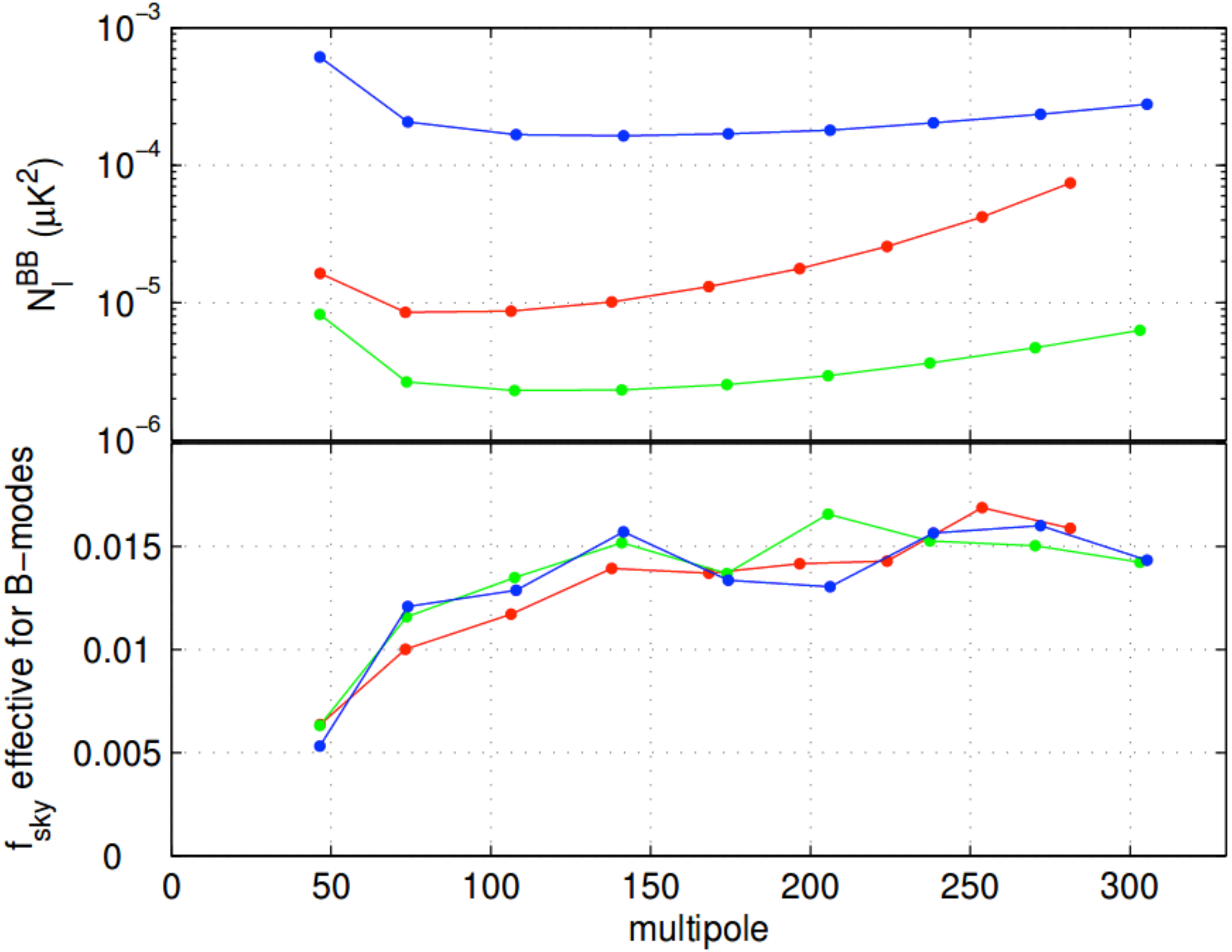


Residual *1/f* noise in the pair diff

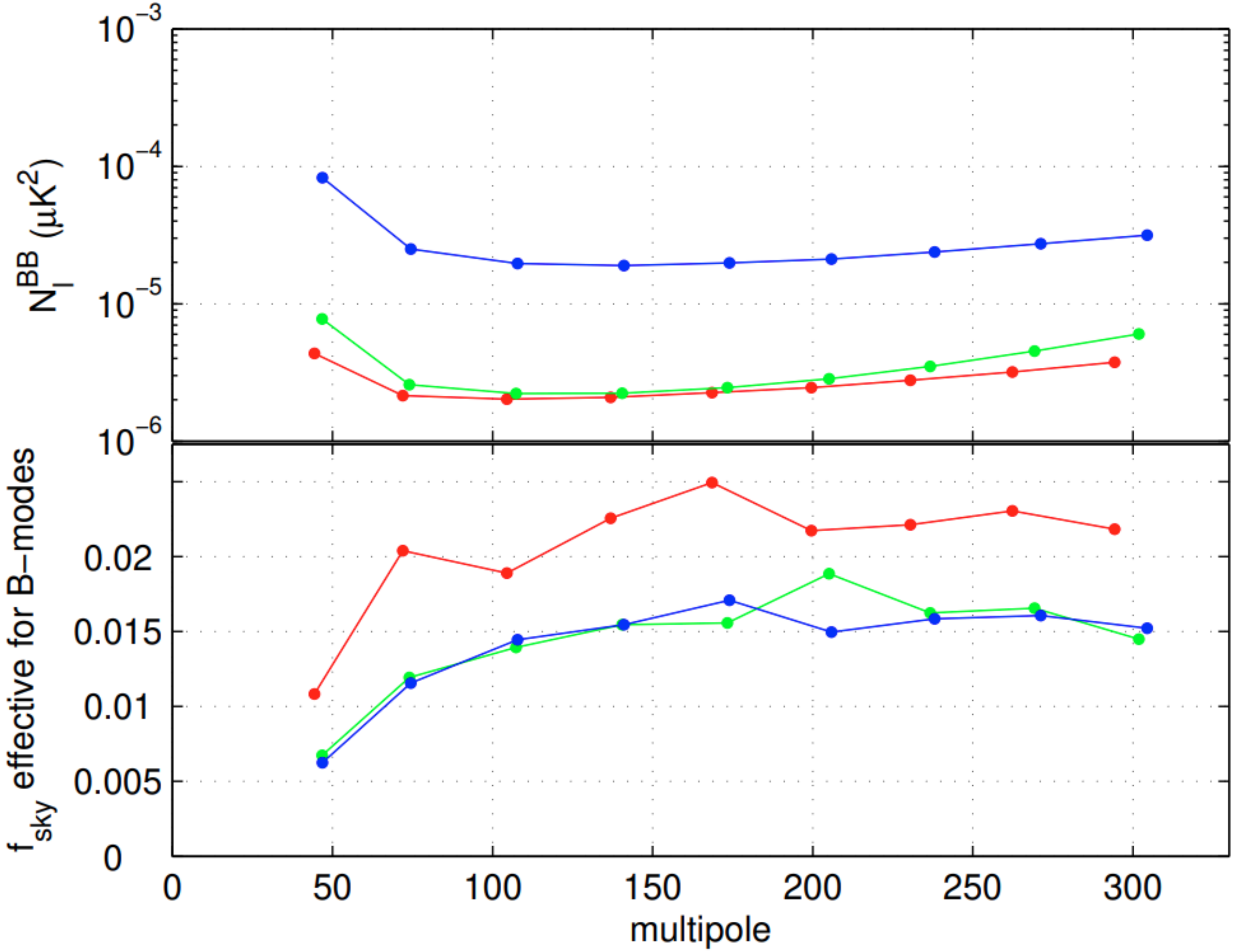
Rises due to beam roll off

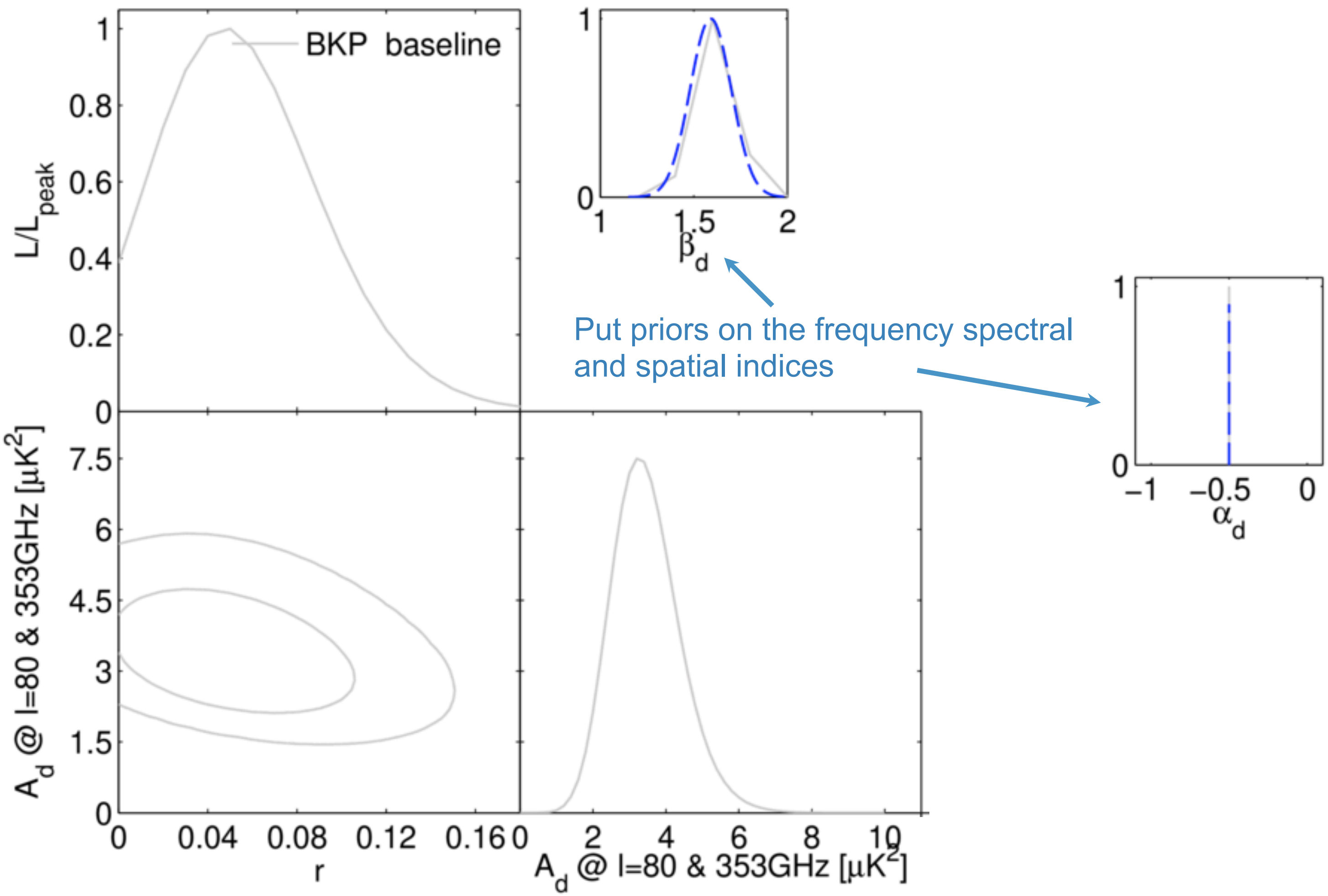
Effective sky area falls due to filtering

BK15 Noise Spectra and f_{sky} Effective



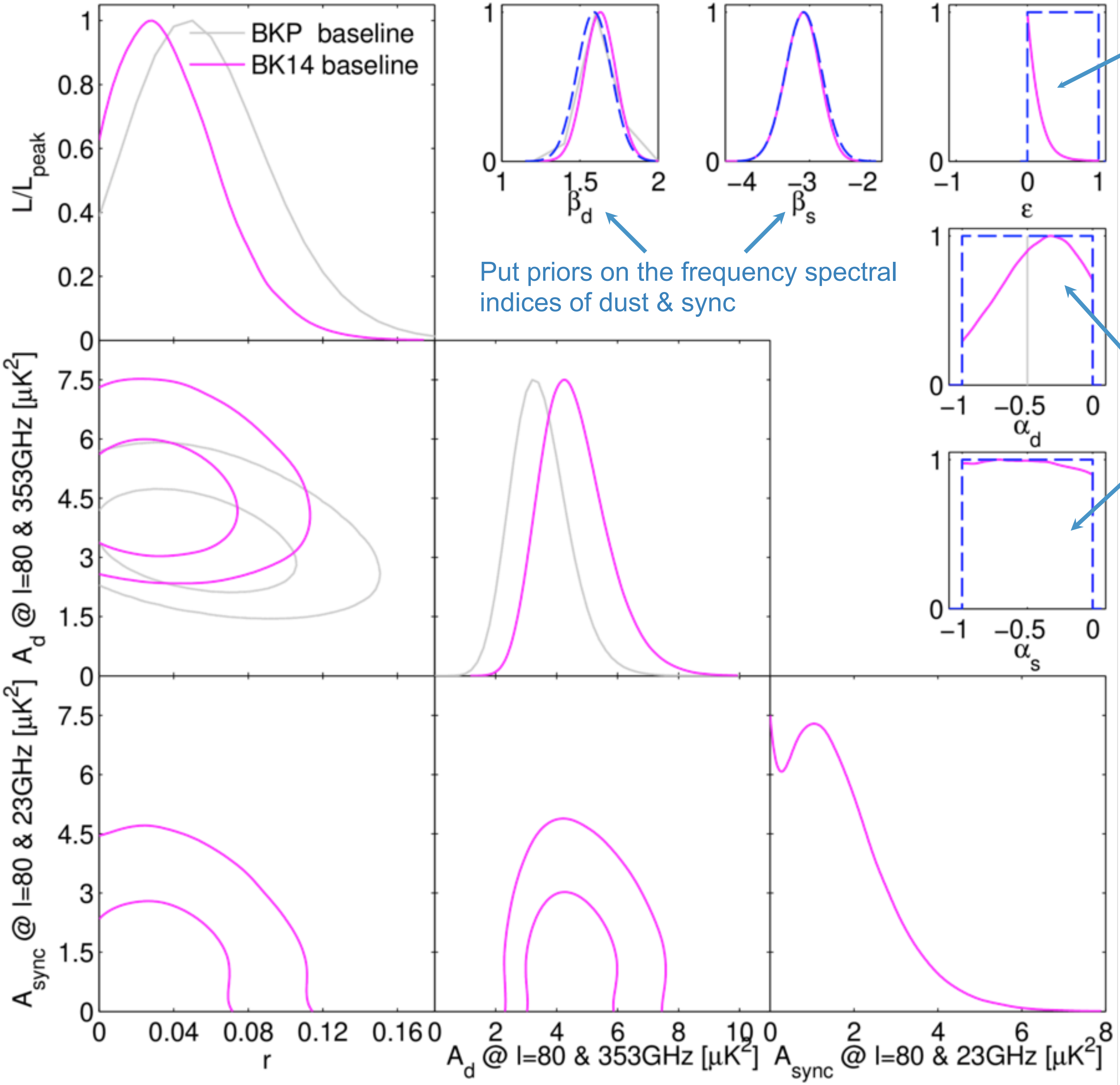
BK18 Noise Spectra and f_{sky} Effective





Put priors on the frequency spectral and spatial indices

BKP
arxiv/1502.00612

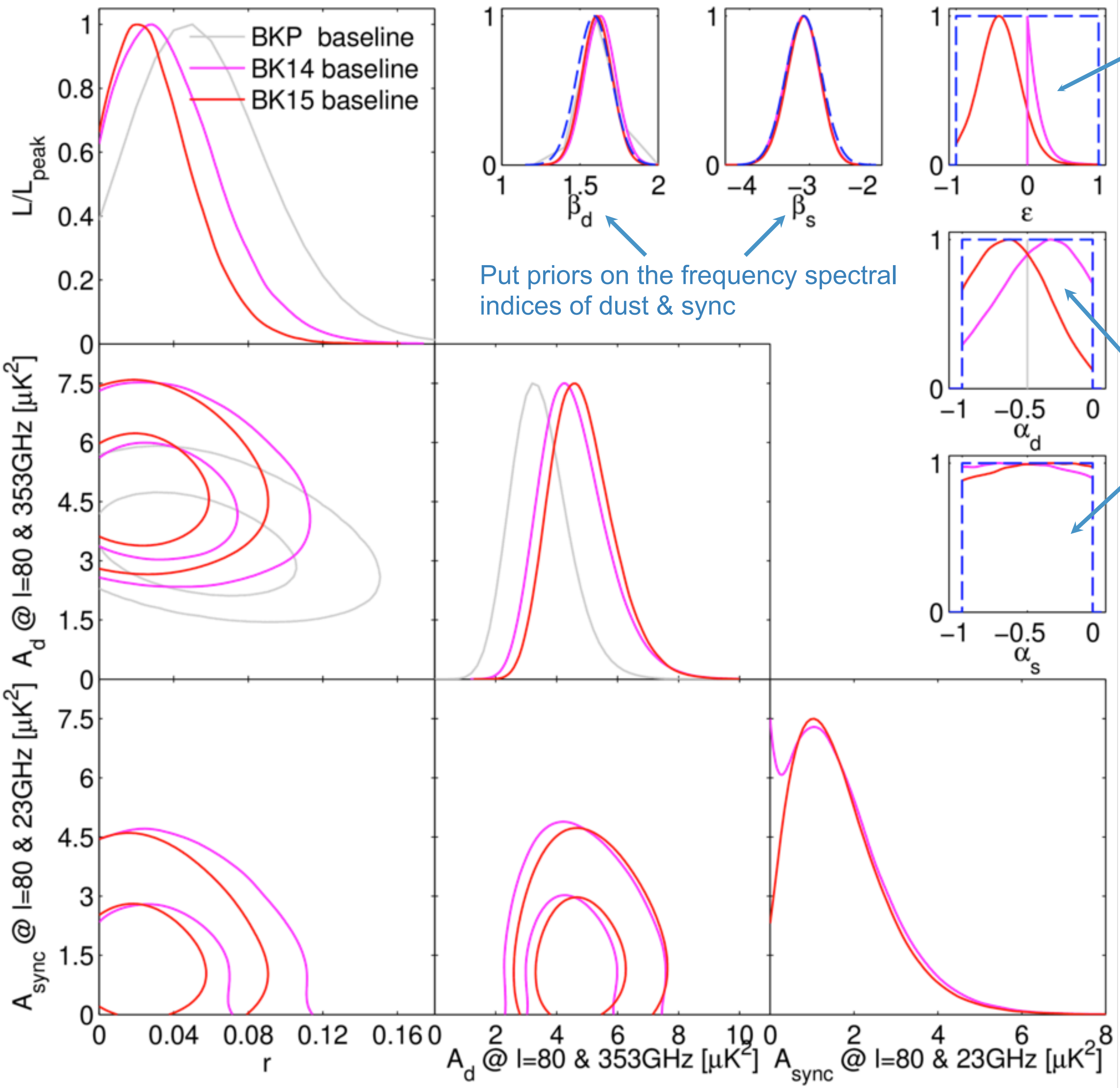


Allow dust/sync correlation in [0,1]

Put priors on the frequency spectral indices of dust & sync

Marginalize over generous ranges in spatial spectral indices

BK14
arxiv/1510.09215

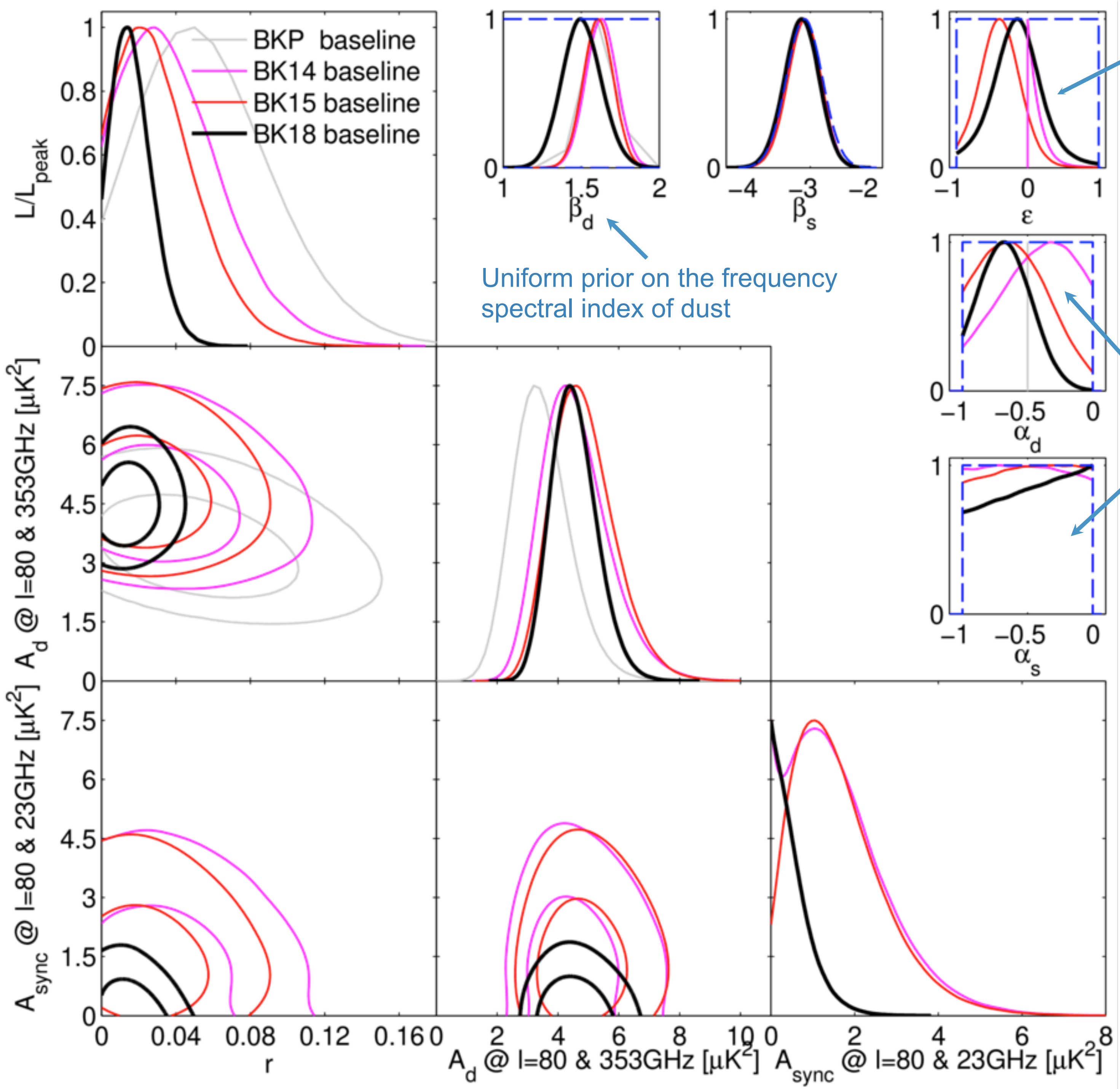


Allow dust/sync correlation in [-1,1]

Put priors on the frequency spectral indices of dust & sync

Marginalize over generous ranges in spatial spectral indices

BK15
arxiv/1810.05216

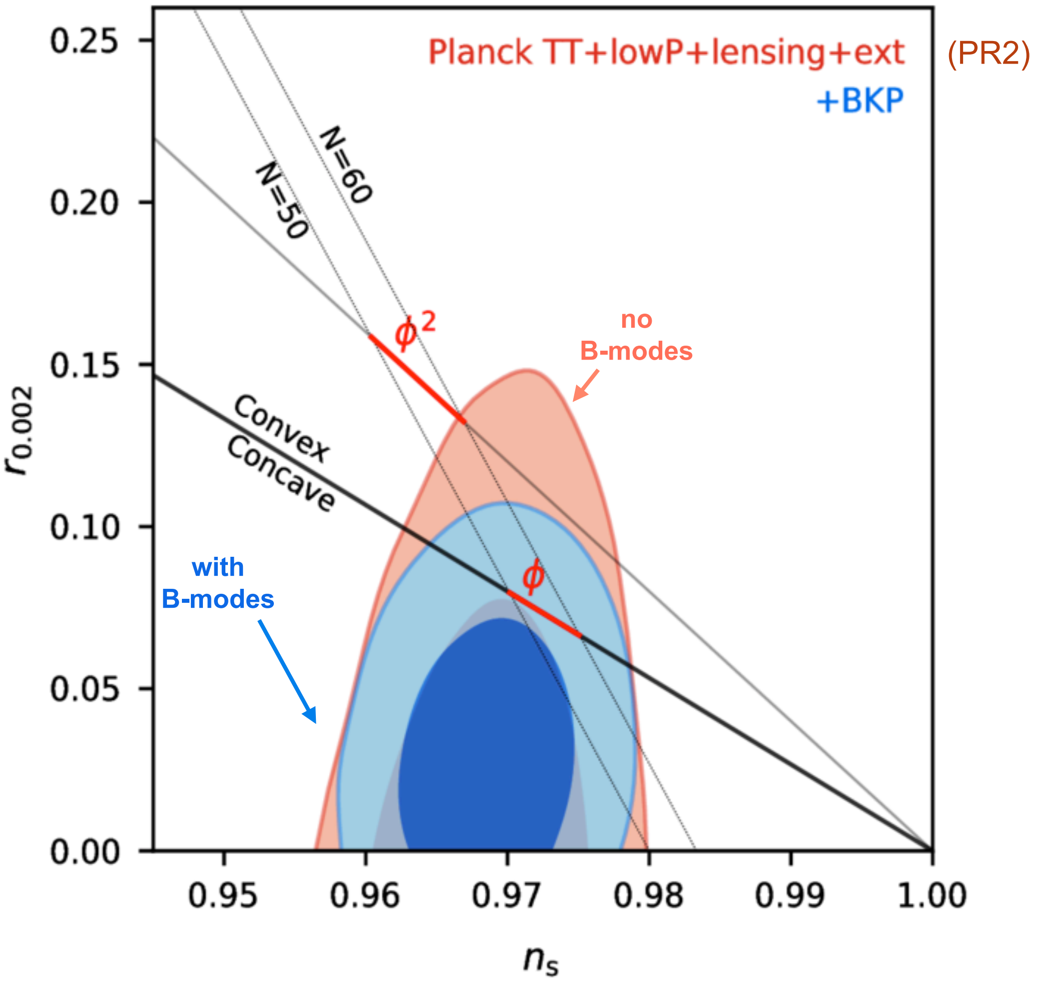


Allow dust/sync correlation in [-1,1]

Uniform prior on the frequency spectral index of dust

Marginalize over generous ranges in spatial spectral indices

BK18
arxiv/2110.00483



(PR2)

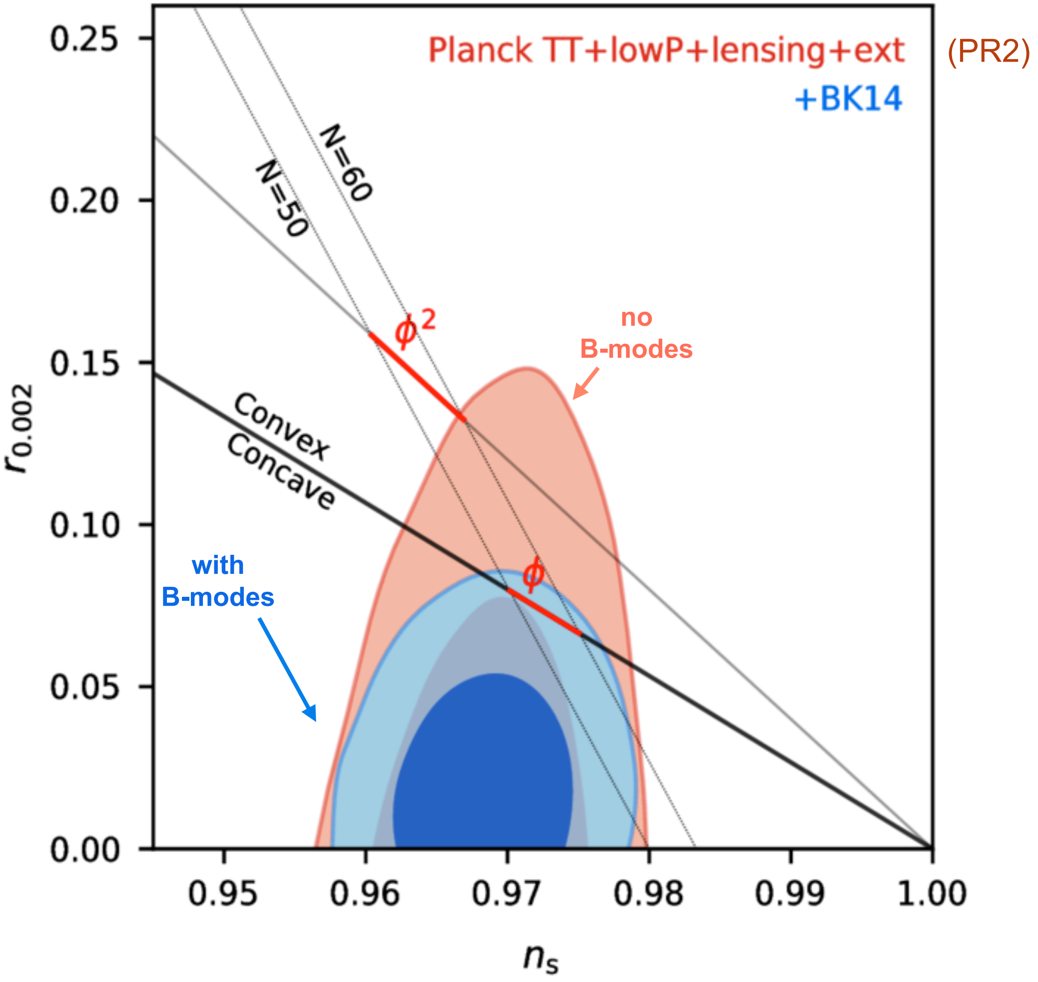
no B-modes

with B-modes

$r_{.05} < 0.09$

BKP

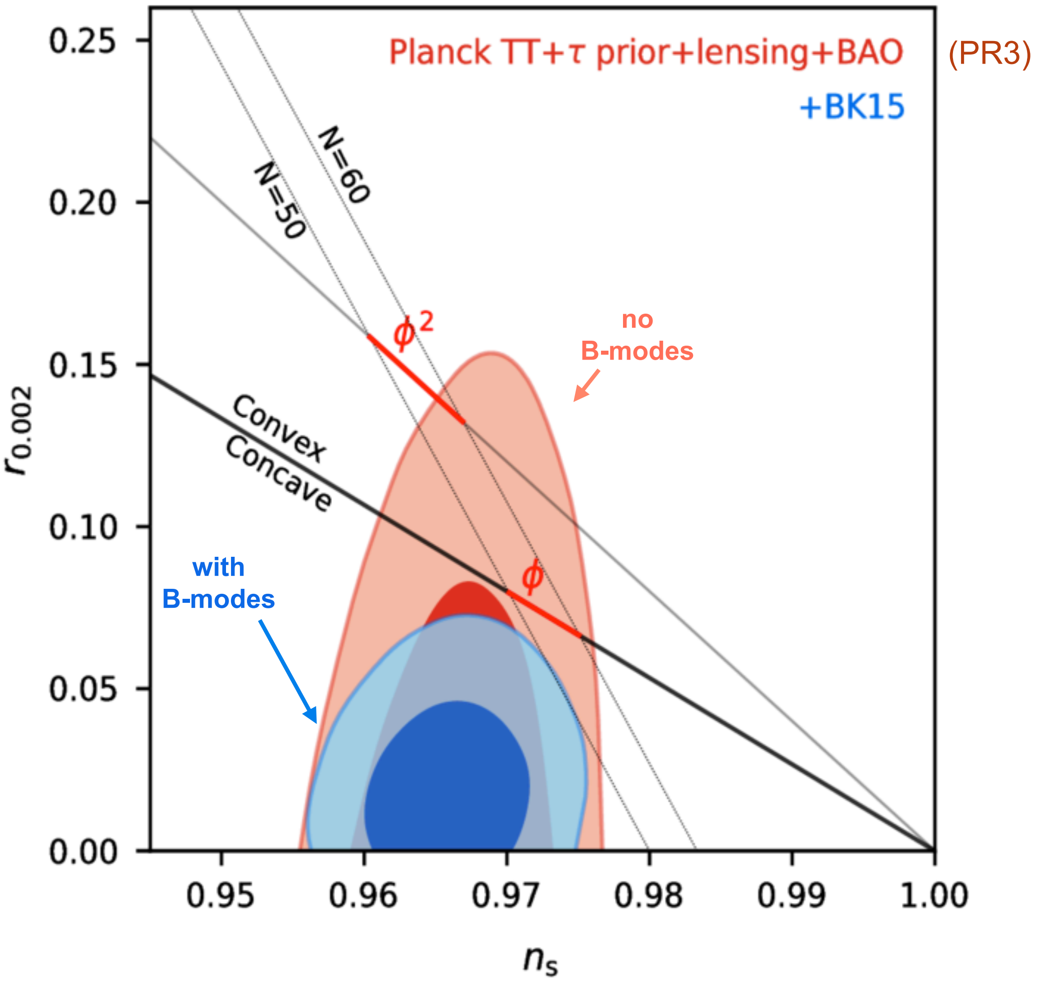
arxiv/1502.00612



$r_{.05} < 0.07$

BK14

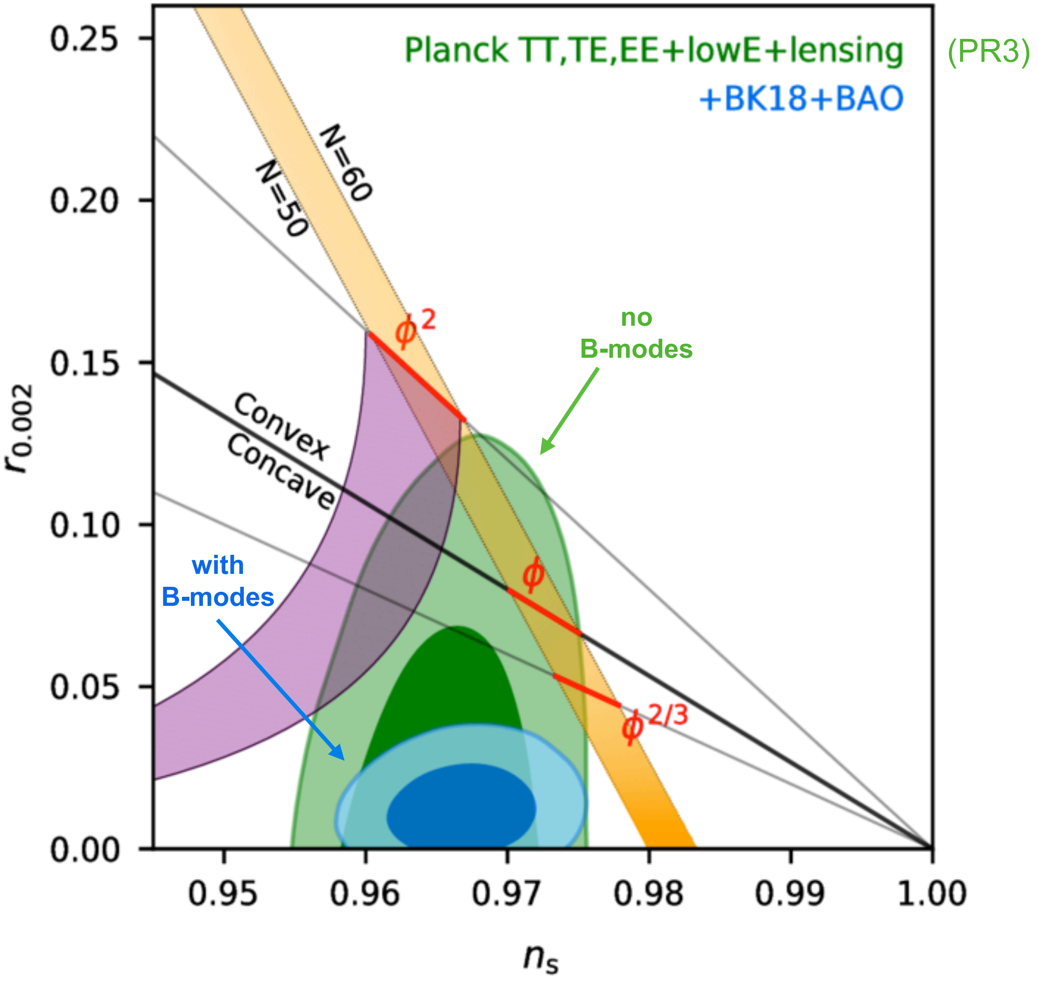
arxiv/1510.09217



$r_{.05} < 0.06$

BK15

arxiv/1810.05216

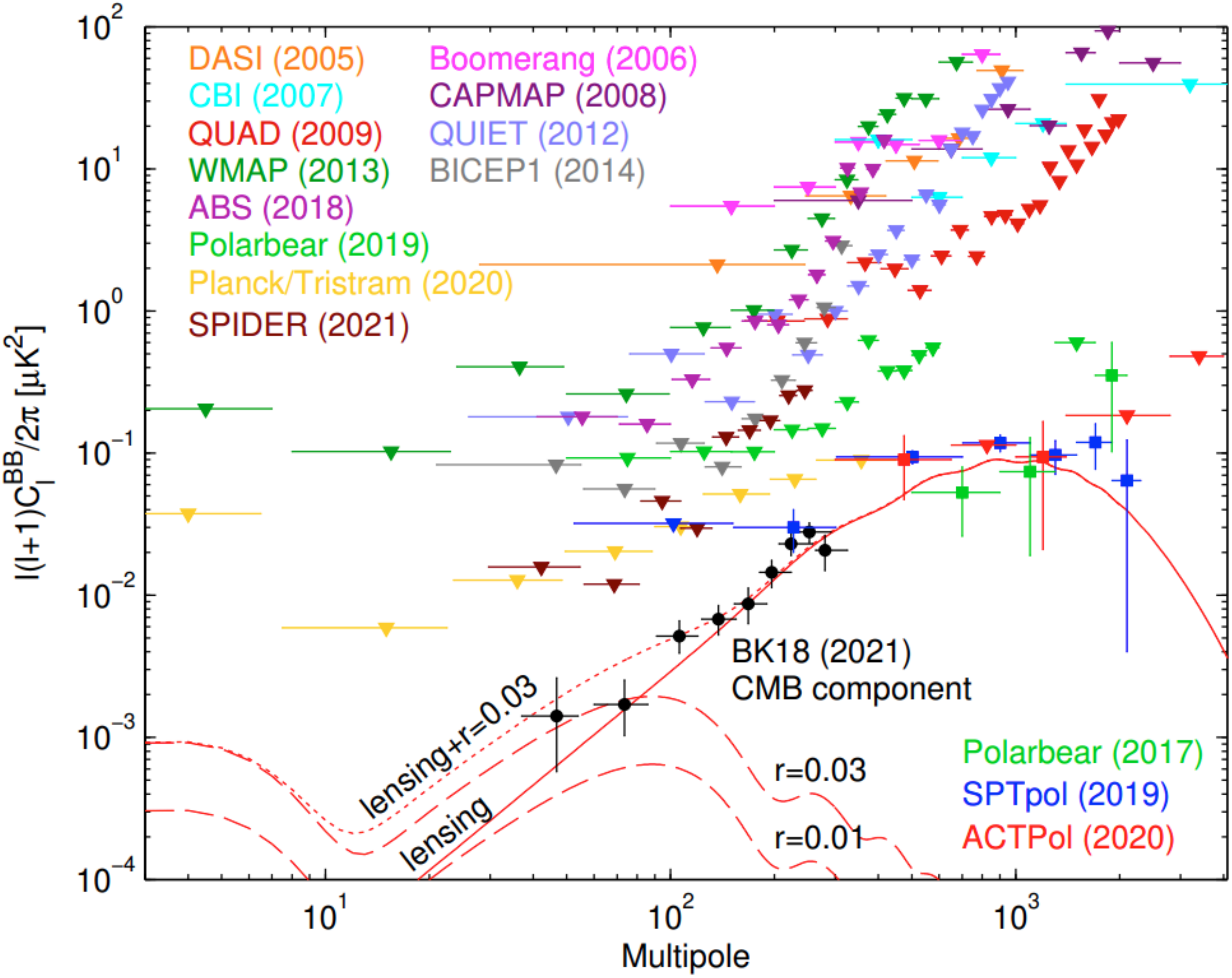


$r_{.05} < 0.035$

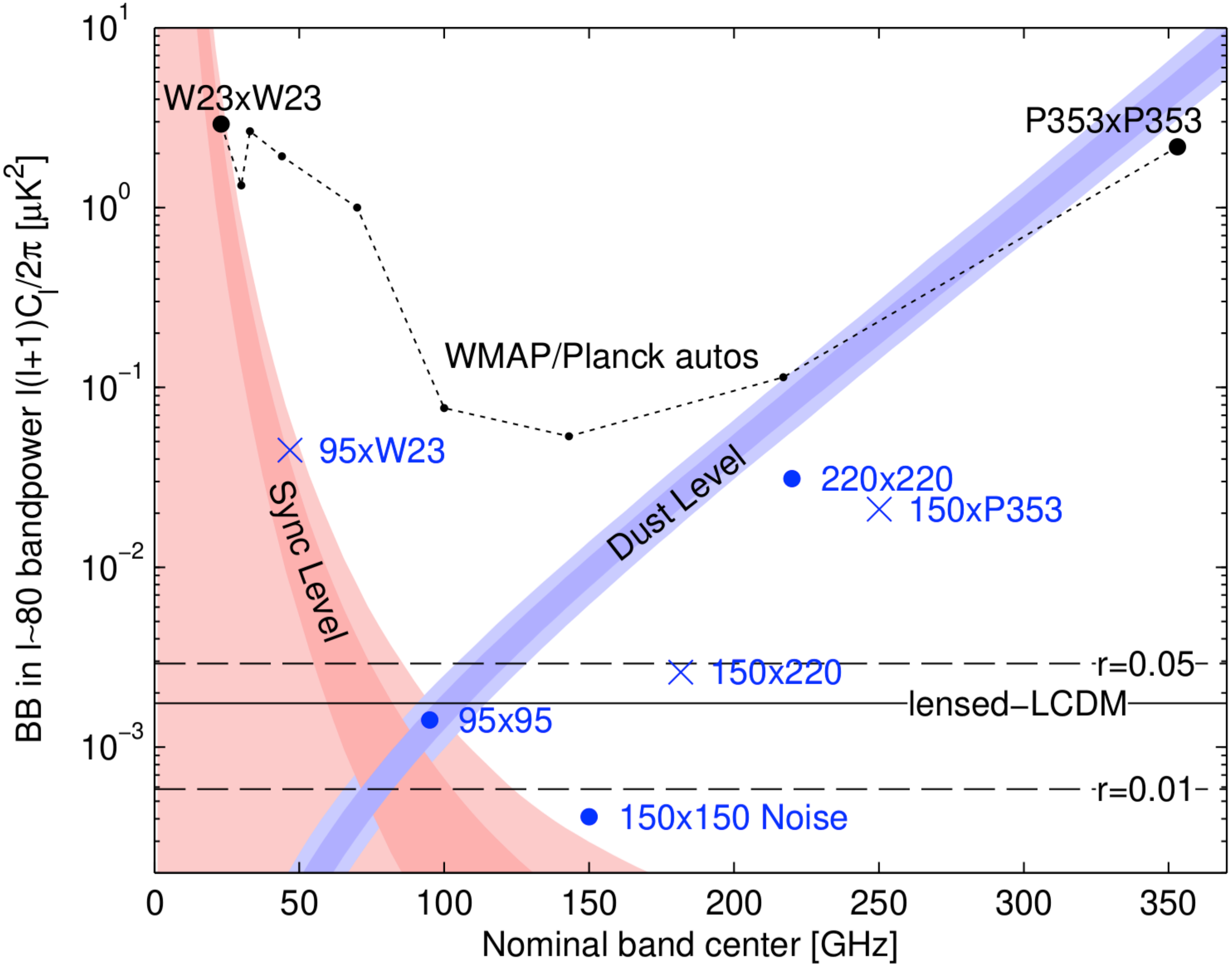
BK18

arxiv/2110.00483

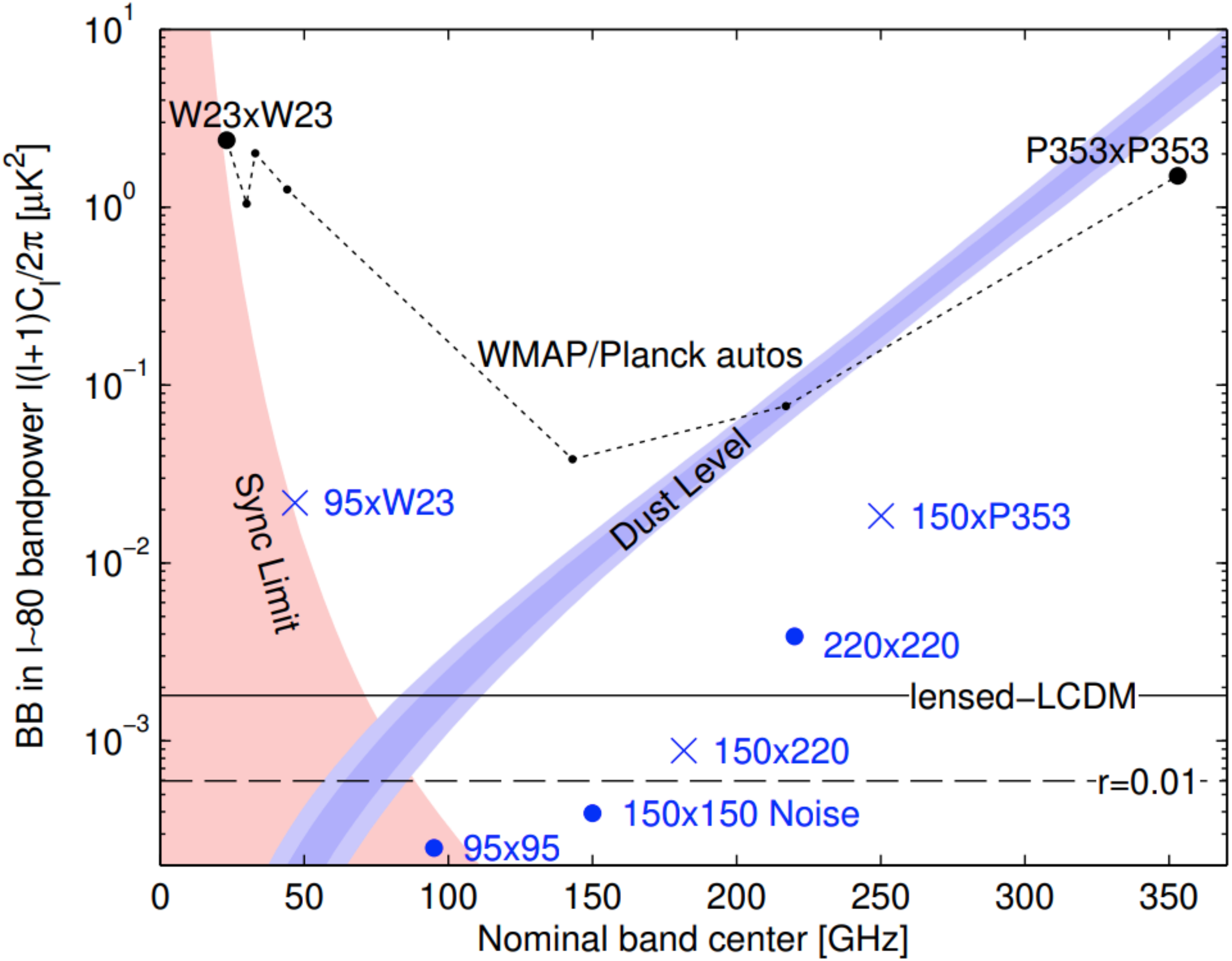
Per bandpower CMB component extraction



BK15 ell=80 bandpower noise/signal



BK18 ell=80 bandpower noise/signal



What limits BK18?

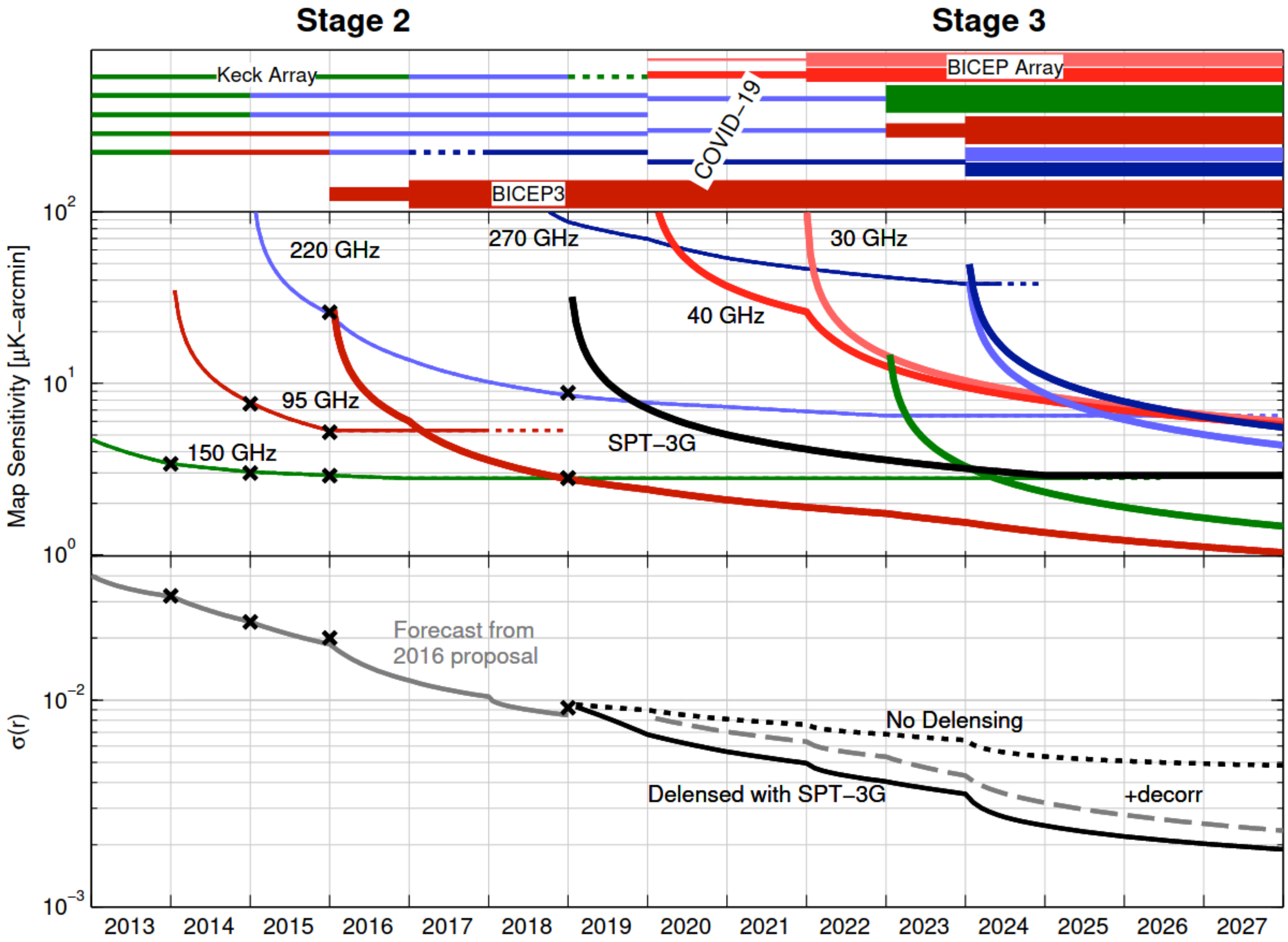
- BK18 mainline simulations with dust and lensing give σ(*r*)=0.009
- Running without foreground parameters on simulations where the dust amplitude is set to zero gives σ(*r*)=0.007

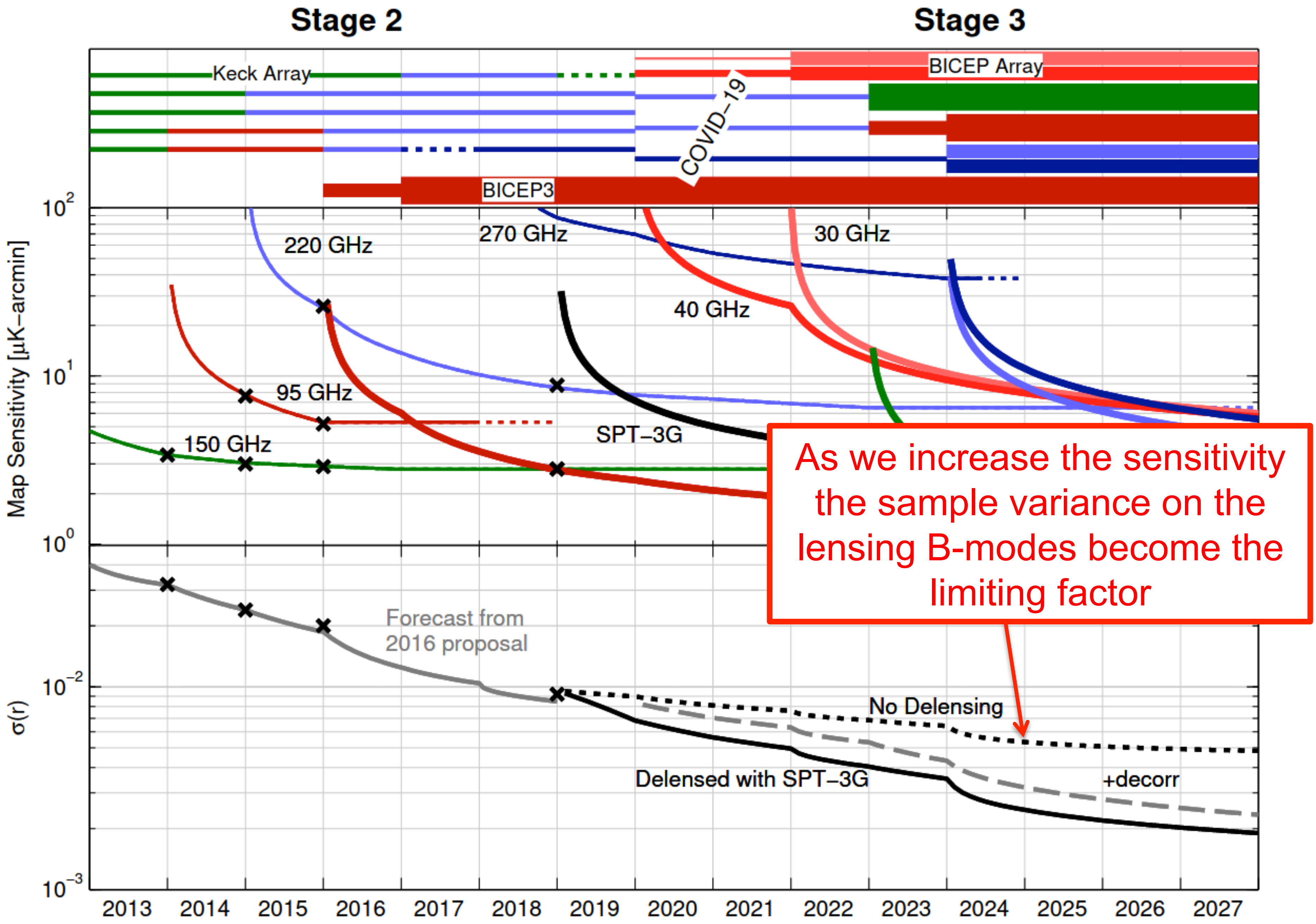
The above is as it should be - we have correctly tuned the relative sensitivity of the 95/150/220 bands such that we don't suffer much penalty due to the presence of foregrounds.

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

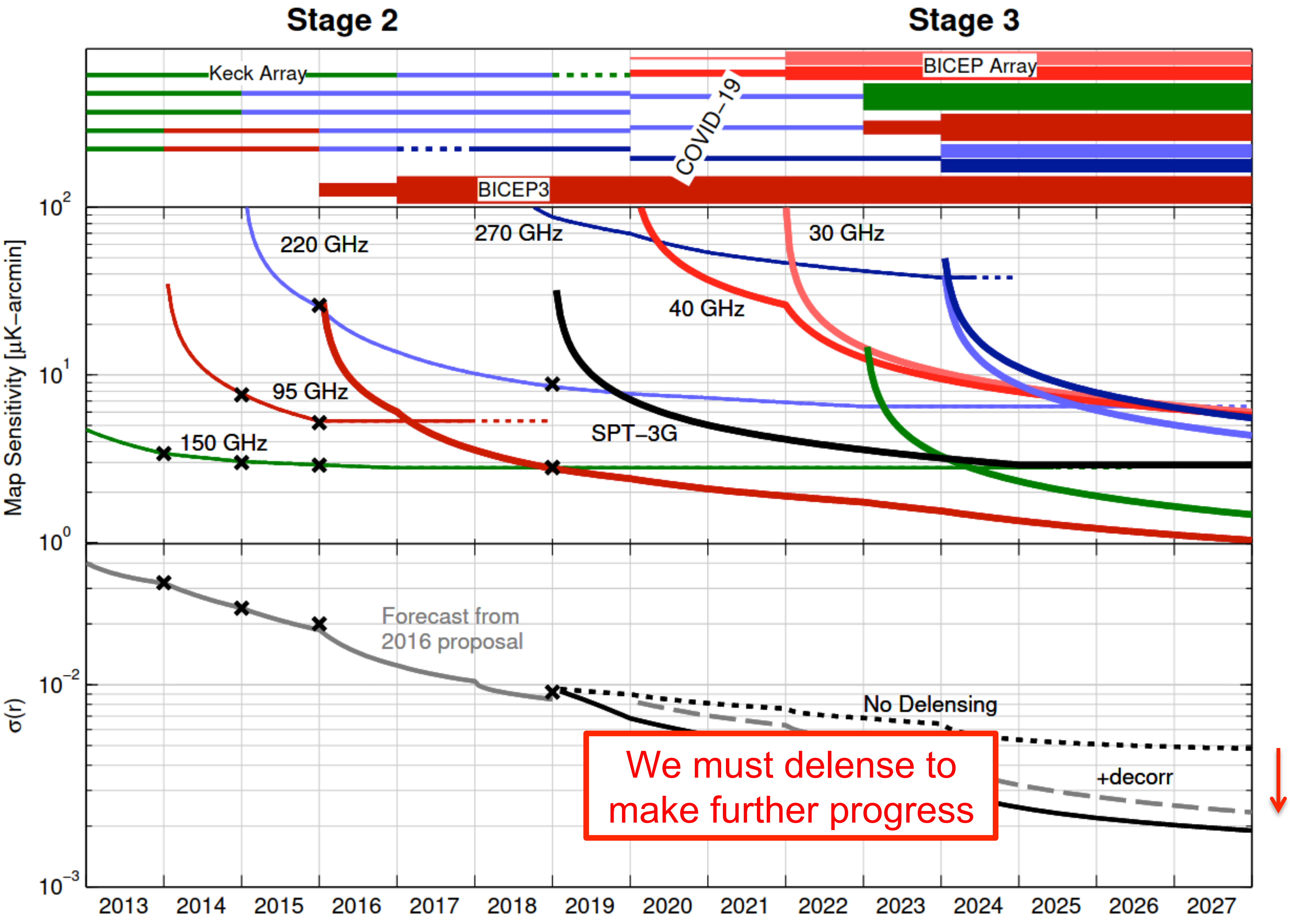
The sample variance of the achromatic lensing foreground is a major limiting factor - we need delensing via high resolution measurements.

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


Stage 2
Stage 3
Keck Array
BICEP Array
COVID–19
BICEP3
220 GHz
270 GHz
30 GHz
40 GHz
95 GHz
150 GHz
SPT–3G
Map Sensitivity [μK–arcmin]
10^2
10^1
10^0
Forecast from
2016 proposal
No Delensing
Delensed with SPT–3G
+decorr
σ(r)
10^{-2}
10^{-3}
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027

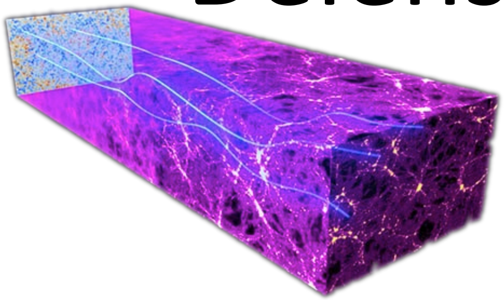


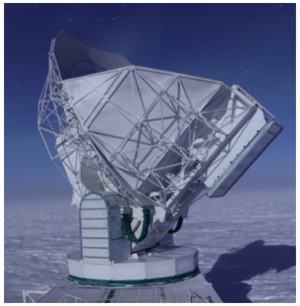
As we increase the sensitivity the sample variance on the lensing B-modes become the limiting factor



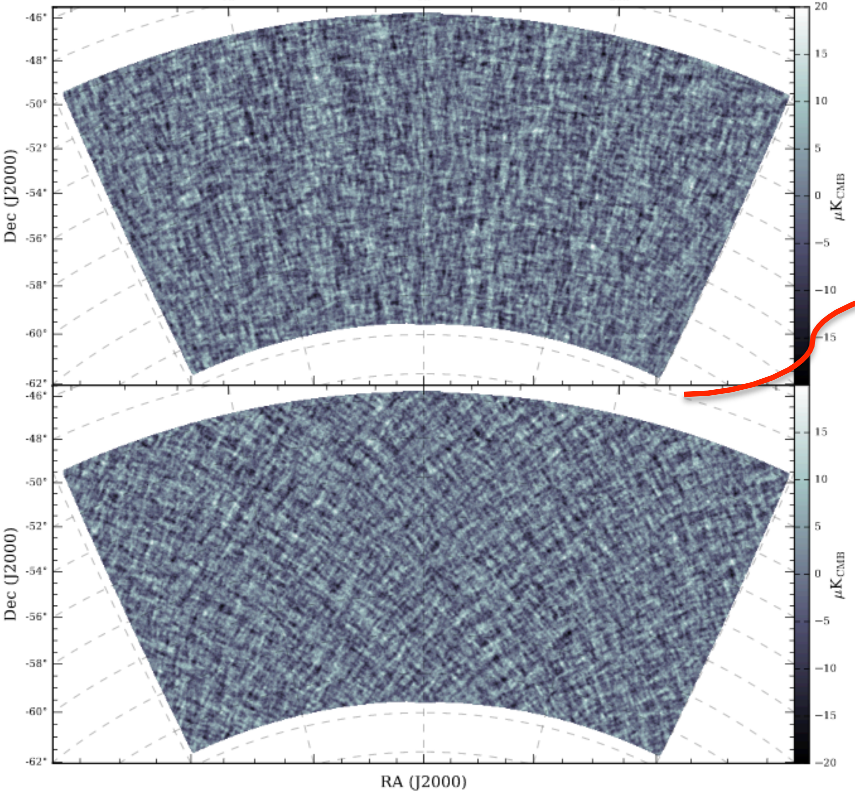
We must delense to make further progress

Delensing with SPT-3G data

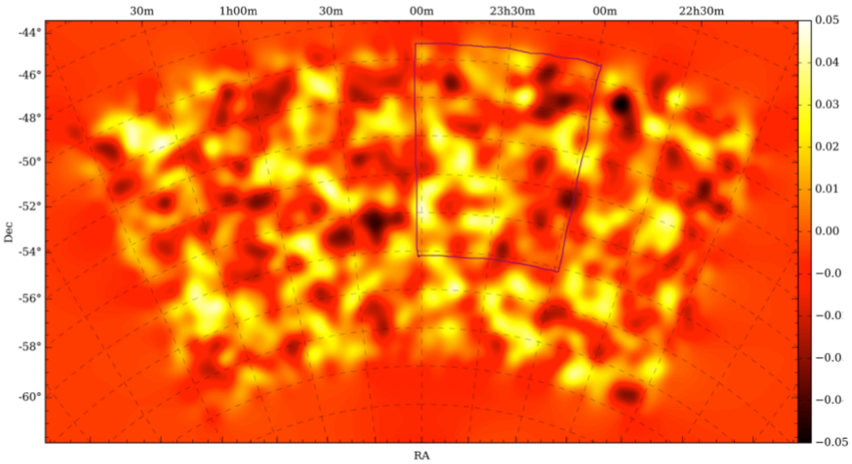




High resolution maps

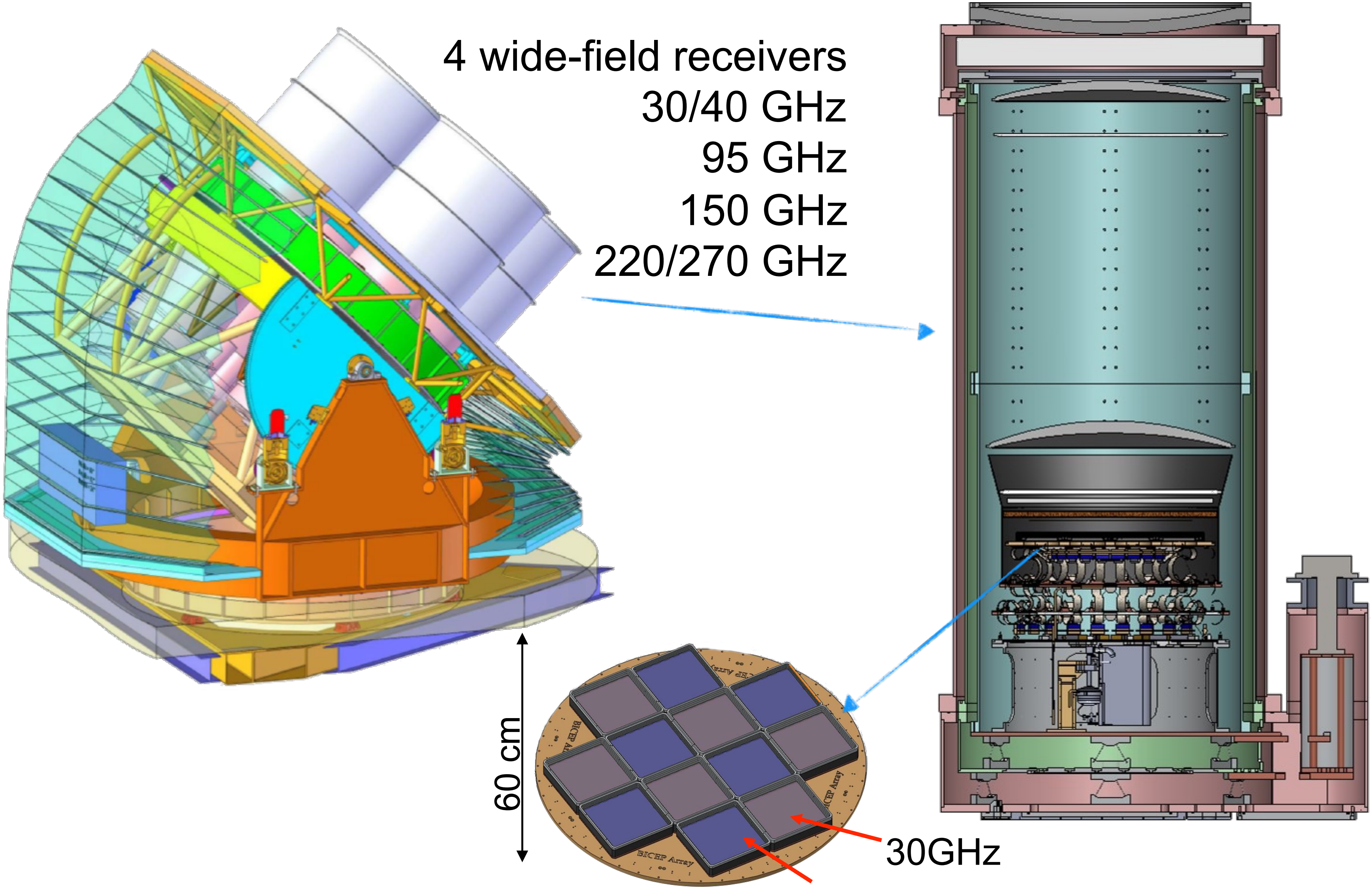


Can be used to reconstruct the lensing deflection map…



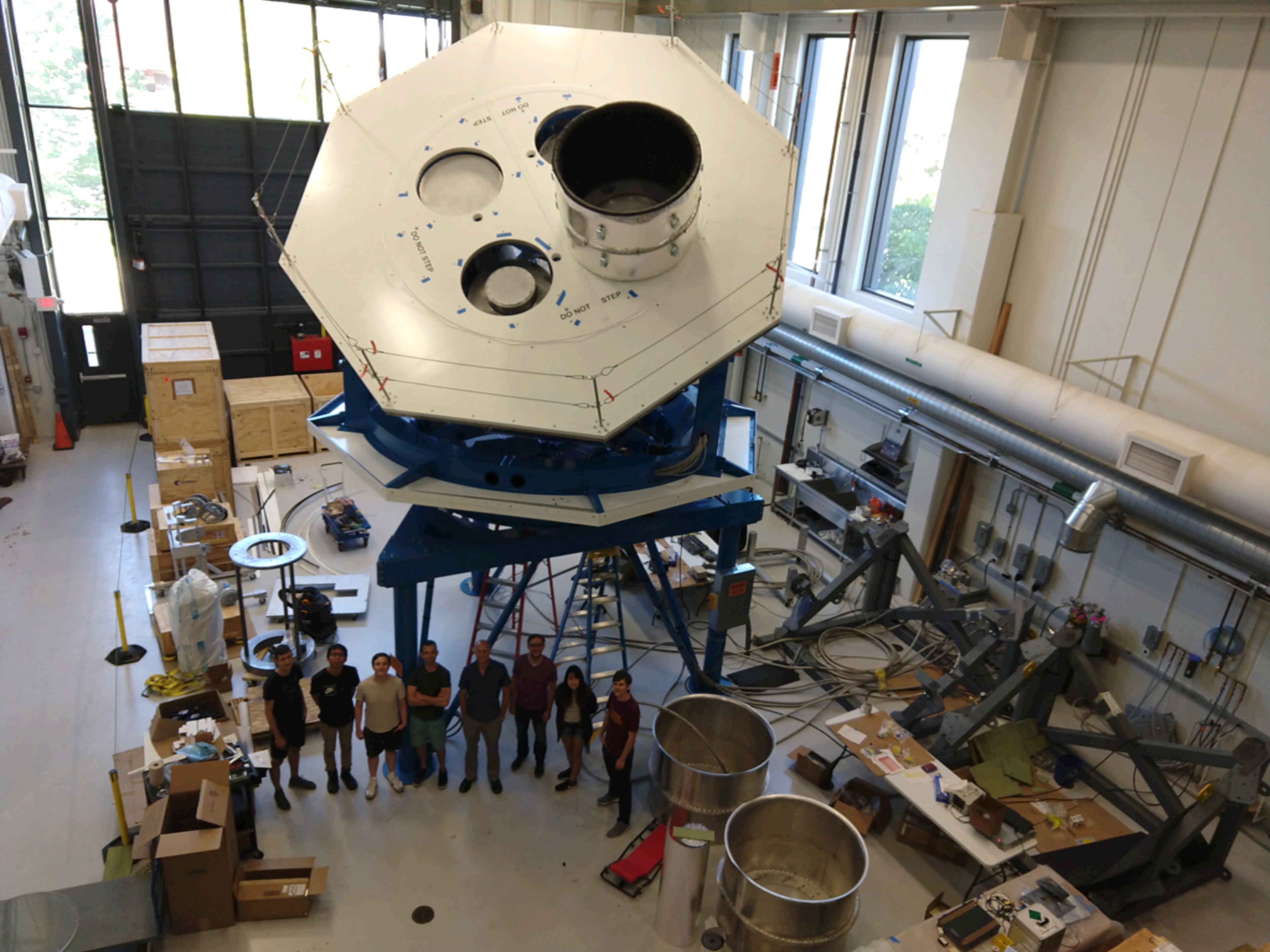
…which can then be used to calculate the lensing signal enabling a deeper search for inflationary gravitational waves

Latest Generation Experiment “BICEP Array"



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

Focal plane layout


DO NOT STEP
DO NOT STEP
DO NOT STEP
EXIT

BICEP Array 2019-20 initial deployment

Three-month window during the Antarctic summer to perform:

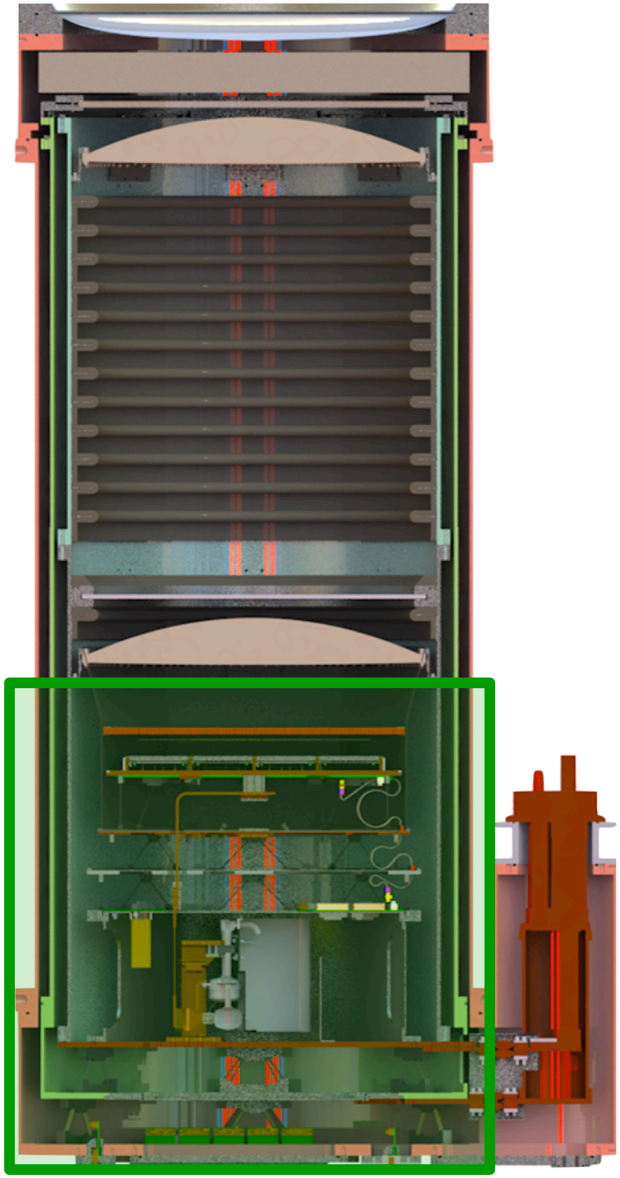
- Keck Array demolition
- BA mount installation
- BA1 receiver assembly
- Full system integration

60,000 lbs of cargo, equivalent to 3 dedicated LC-130 Hercules flights to the South Pole.

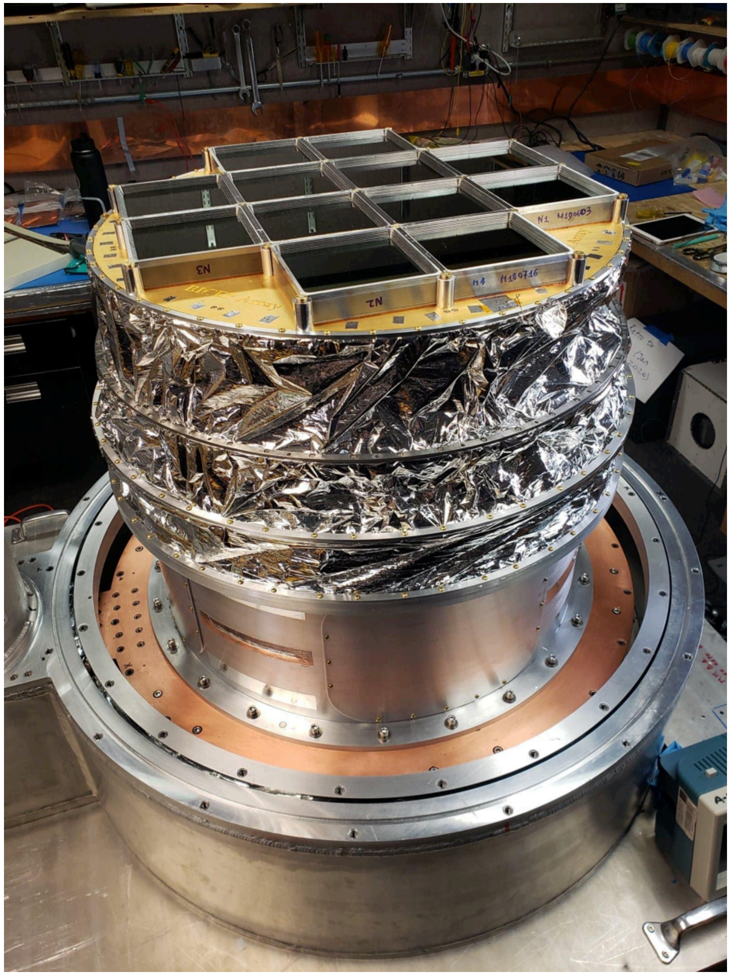
30+ personnel:

- 2/3 scientists
- 1/3 contractors

First new receiver: BA1 instrumental highlights



Camera insert



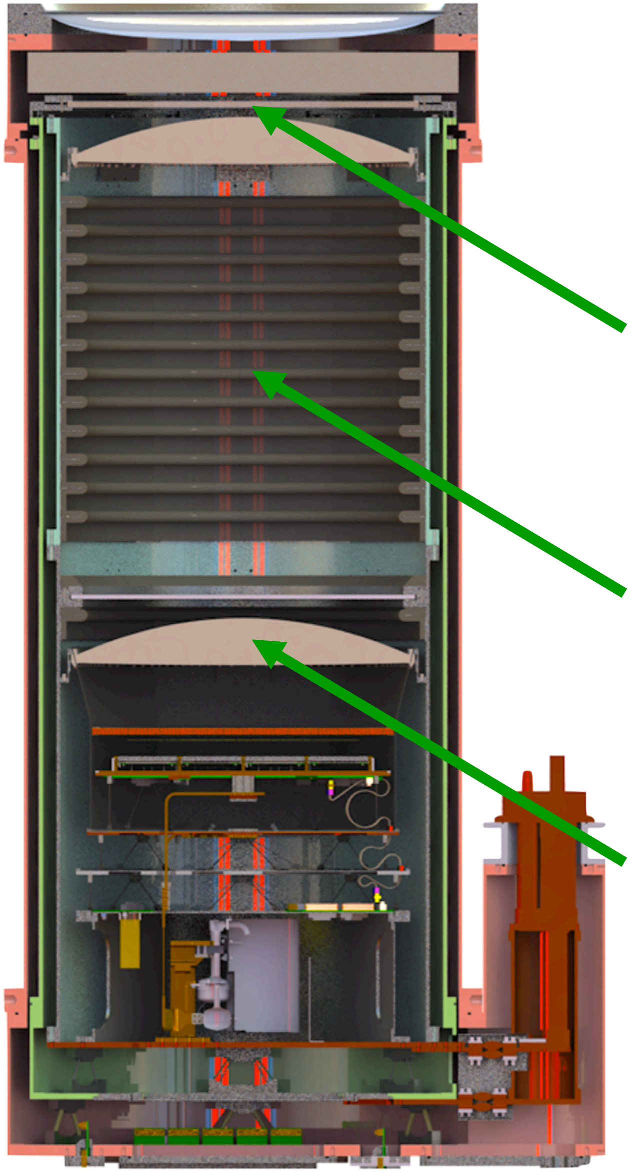
192/300 TES detectors at 30/40 GHz.

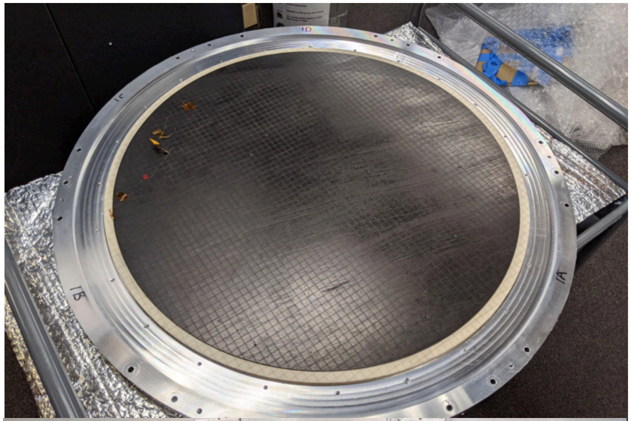
Integrated in 12 shielded modules, each with a low-pass mesh filters.

Time-Domain multiplexed readout.

First new receiver: BA1 instrumental highlights

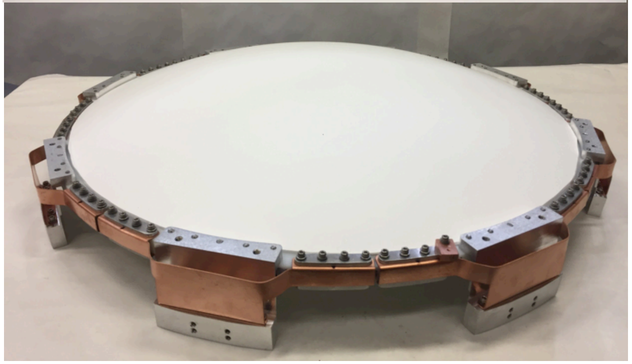
Optics





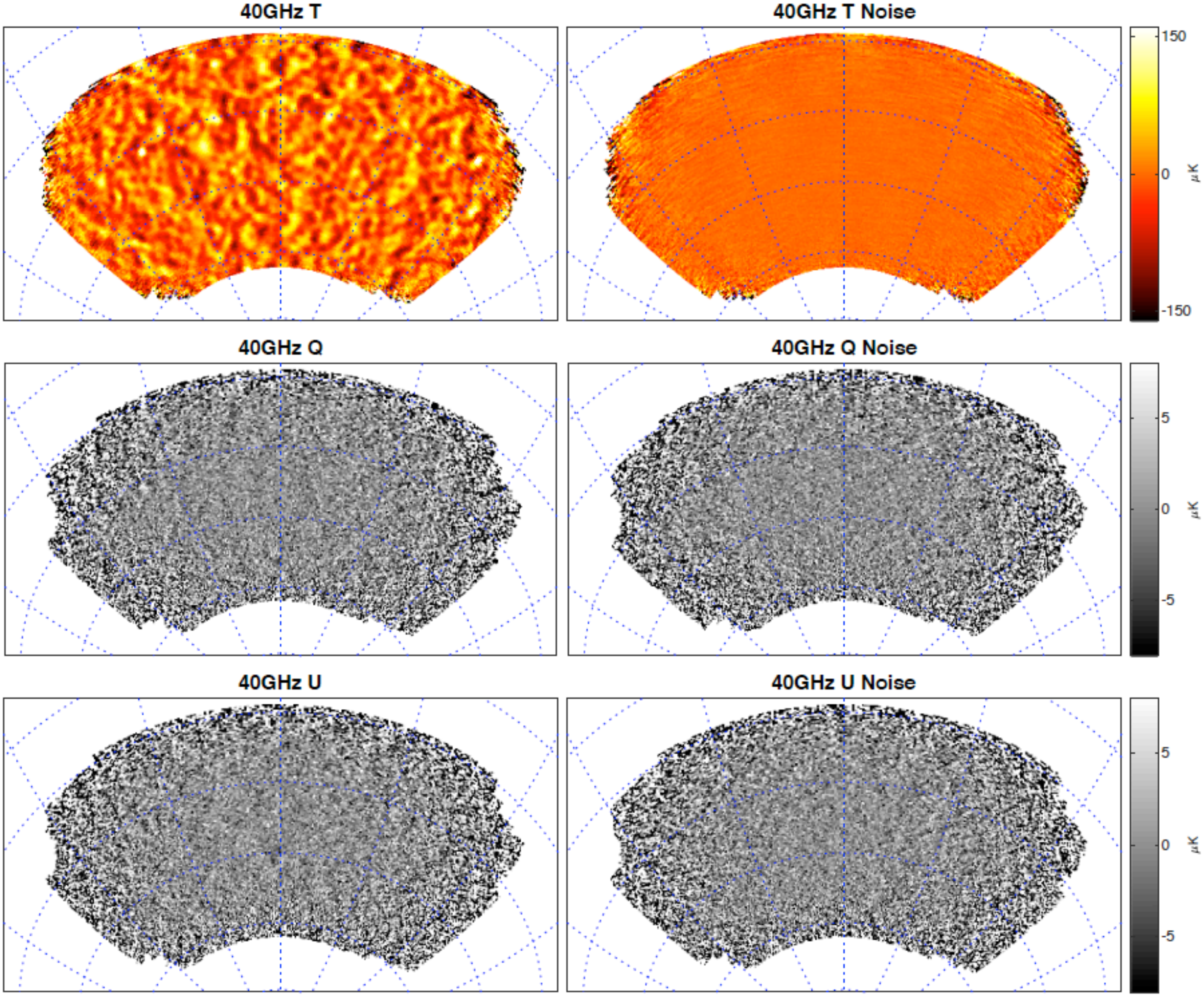
Alumina absorptive IR filter, AR-coated with laser-diced epoxy.

Internal absorptive baffling for scattering control.

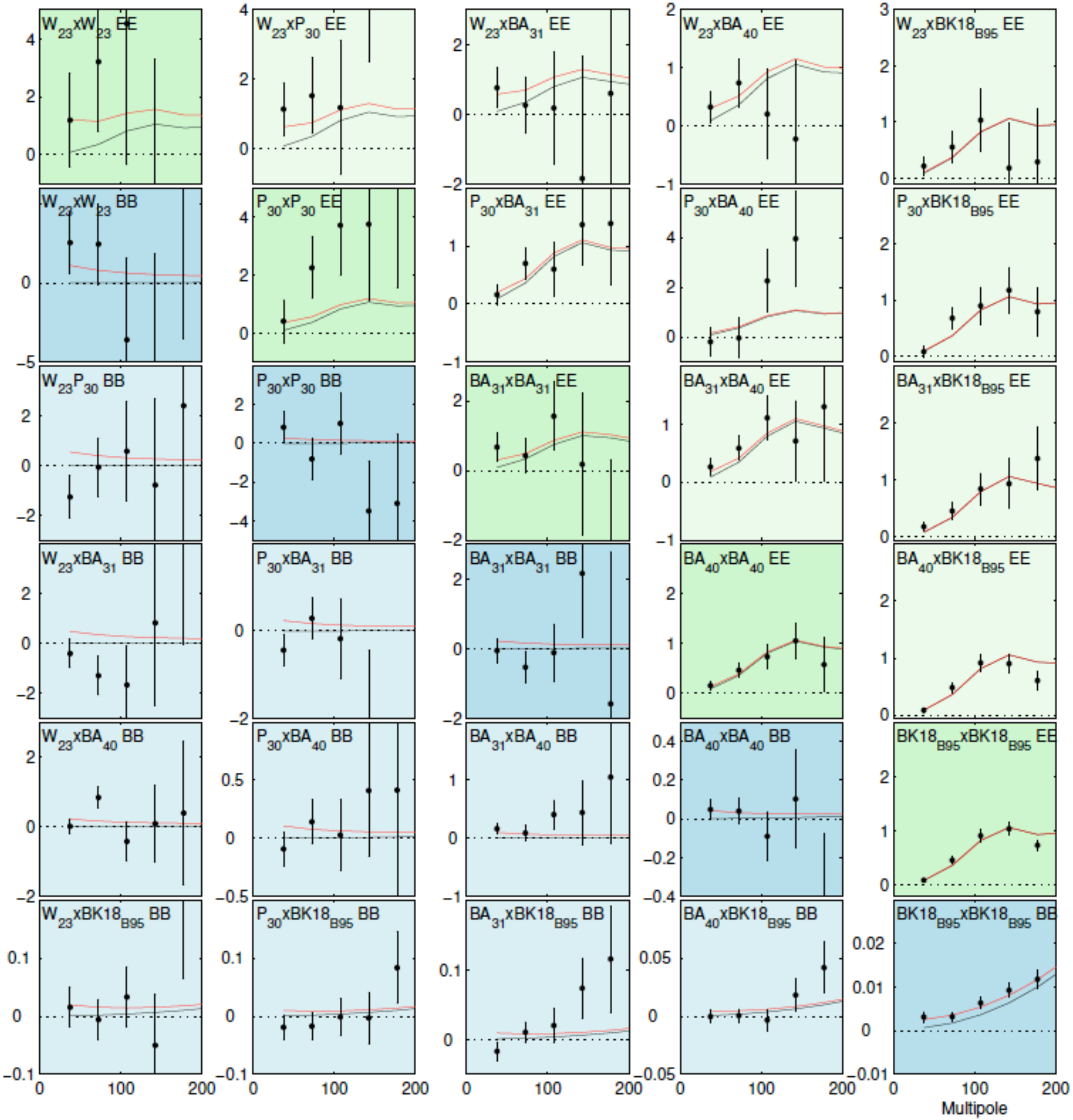


Polyethylene lenses, AR-coated with expanded Teflon.
550mm clear aperture.

BA1
2020
maps



Synchrotron Bands including new BICEP Array 30/40 GHz data

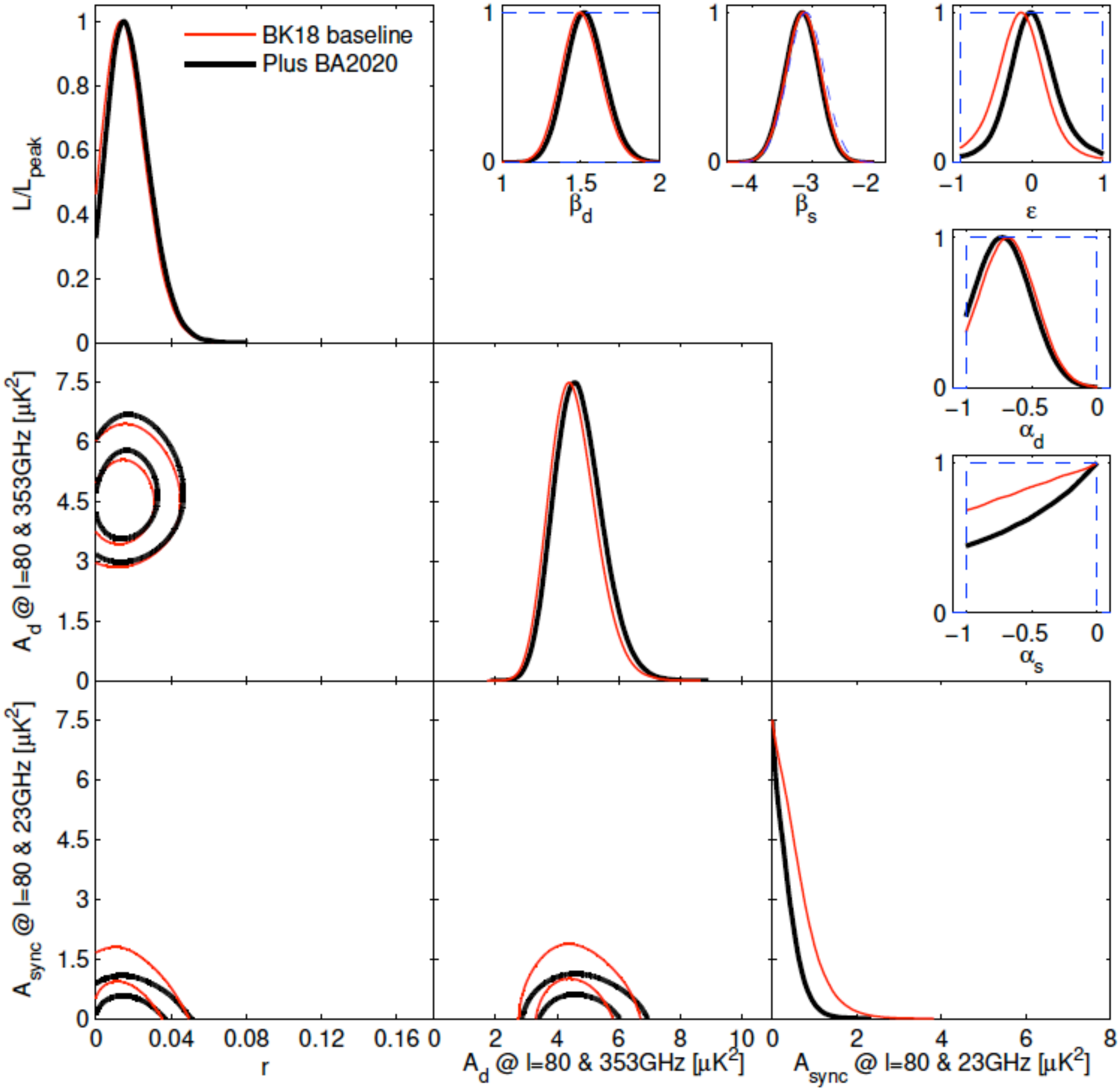


Green panels are EE spectra

Black lines are LCDM

Red lines are LCDM+sync +dust

Blue panels are BB spectra


BK18 baseline
Plus BA2020
L/L$_{peak}$
1
0.8
0.6
0.4
0.2
0
β_d
1
1.5
2
β_s
−4
−3
−2
ε
−1
0
1
α_d
−1
−0.5
0
α_s
−1
−0.5
0
A$_d$ @ l=80 & 353GHz [μK^2]
7.5
6
4.5
3
1.5
0
A$_{sync}$ @ l=80 & 23GHz [μK^2]
7.5
6
4.5
3
1.5
0
r
0
0.04
0.08
0.12
0.16
A$_d$ @ l=80 & 353GHz [μK^2]
0
2
4
6
8
10
A$_{sync}$ @ l=80 & 23GHz [μK^2]
0
2
4
6
8

Conclusions

- ➢ BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:
- ➢ Best published sensitivity to date
- ➢ Best proven systematic control at degree angular scales

- ➢ Adding 2016-18 data (from BK15 to BK18):
- ➢ Goes from $r_{0.05}<0.07$ to $r_{0.05}<0.036$
- ➢ For the first time no priors from other regions of sky
- ➢ Rules out two entire classes of previously popular inflation models (monomial models and Natural Inflation)

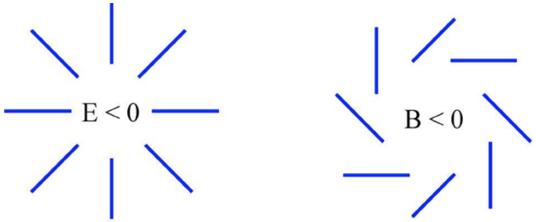
- ➢ And we can keep going:
- ➢ BICEP Array mount and first receiver running
- ➢ Delensing in conjunction with SPT3G

- ➢ Other things I can talk about:
- ➢ Delensing technique (lensing template)
- ➢ E/B separation (matrix purification)
- ➢ Beam systematics and deprojection thereof
- ➢ Detailed beam measurements to predict undeprojected residual

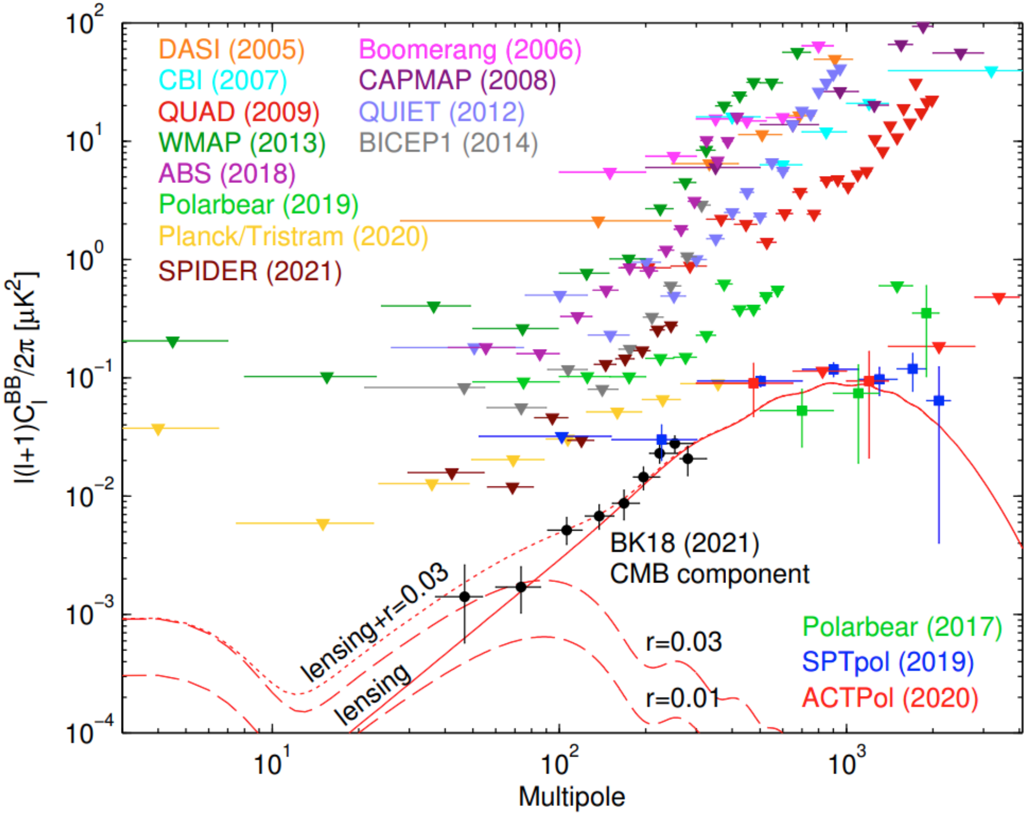
Backup slides

Constraints on Inflation to Date

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



State of B-mode polarization power spectra in 2021

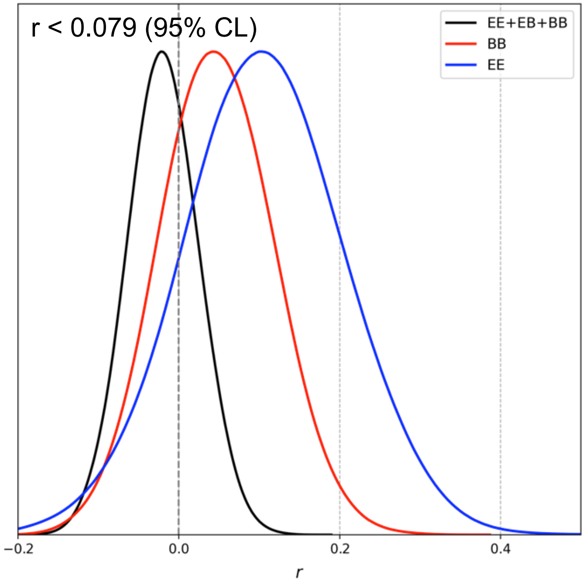


Posted B-Mode Sensitivity to r

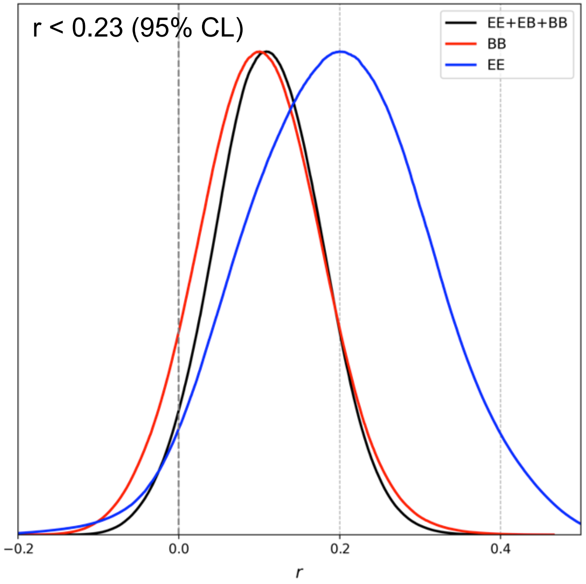
Experiment	arxiv post	Bands [GHz]	σ(r)
DASI	0409357	26…36	7.5
BICEP1 2yr	0906.1181	100, 150	0.28
WMAP 7yr	1001.4538	30…60	1.1
QUIET-Q	1012.3191	43	0.97
QUIET-W	1207.5034	95	0.85
BICEP1 3yr	1310.1422	100, 150	0.25
BICEP2	1403.3985	150	0.10
BK13 + Planck	1502.00612	150 + Planck	0.034
BK14 + WP	1510.09217	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
Polarbear	2203.02495	150 + P	~0.16

Covariance matrix conditioning in Tristram et al. 2020

E-only, B-only and combined r-posteriors of the Tristram et al. 2020 low-ell likelihood (“LoLLiPoP”)



Full covariance matrix, as used in Tristram et al. 2020 and provided in the public likelihood



With covariance matrix conditioning (zeroing elements not detected above Monte Carlo noise) → combined posterior does not move to negative r

Beck at al
arxiv/2202.05949

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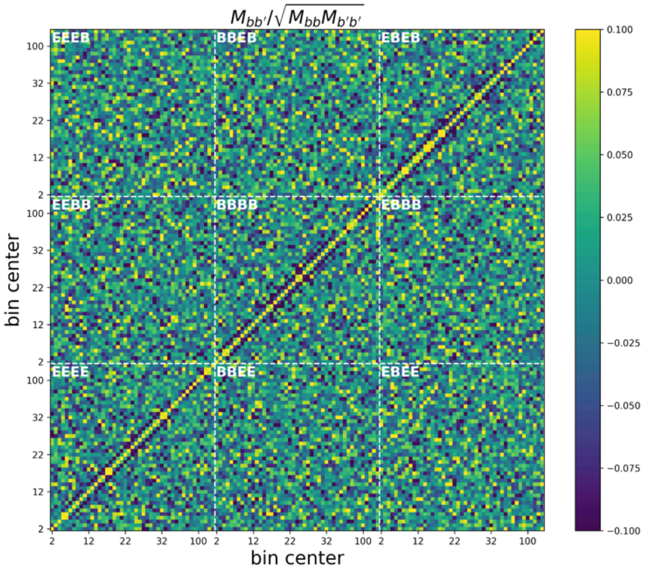

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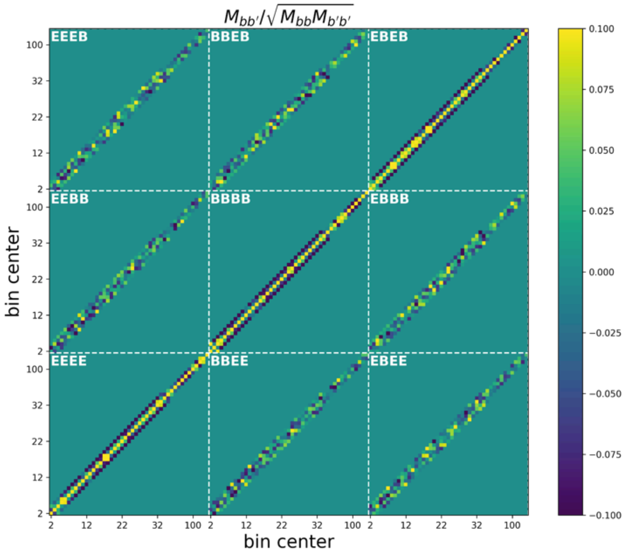

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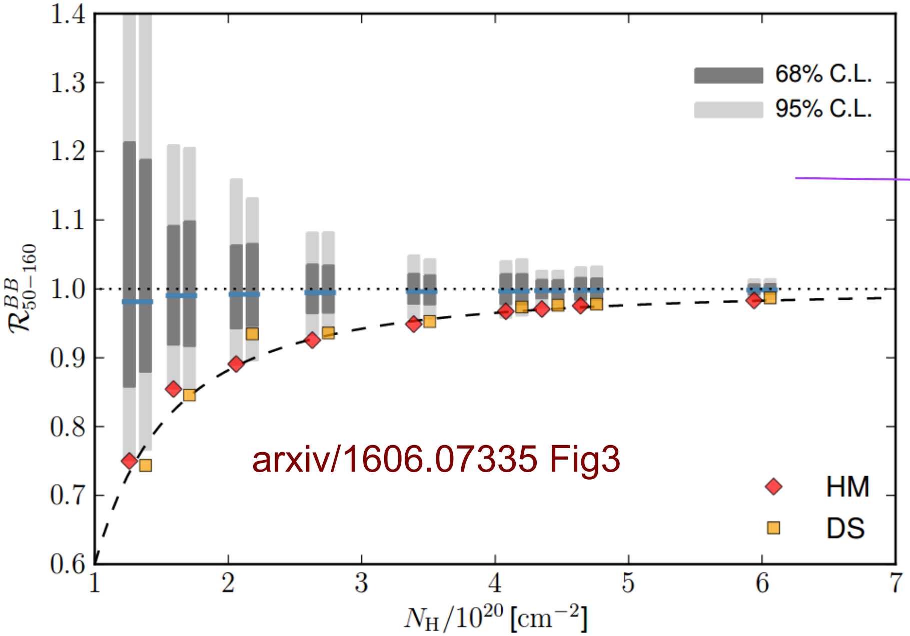
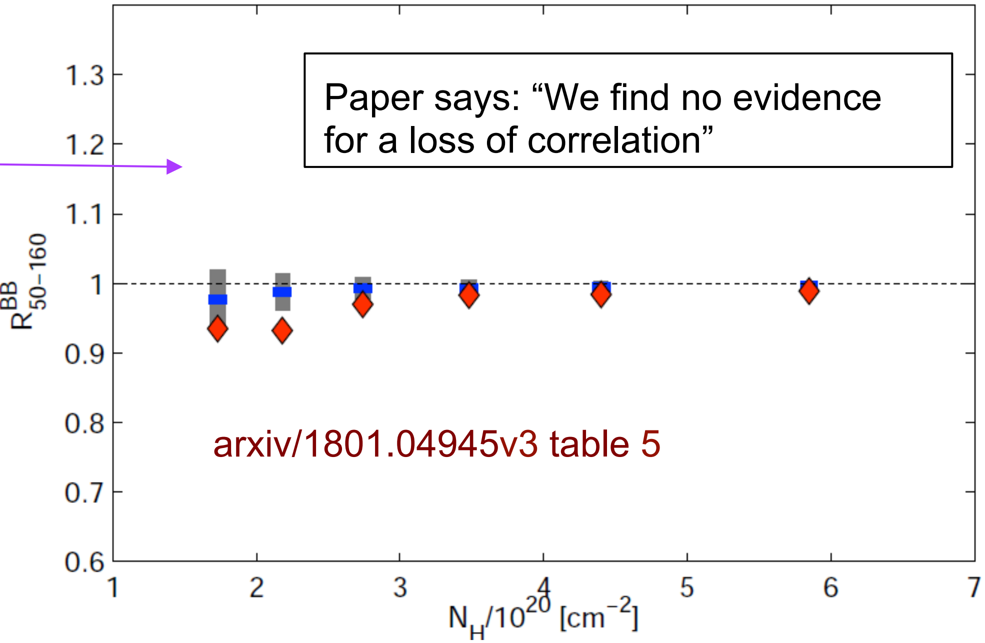
Beck at al
arxiv/2202.05949

Planck Evidence for Dust Decorr Went Away and BK18 doesn't see any evidence for it

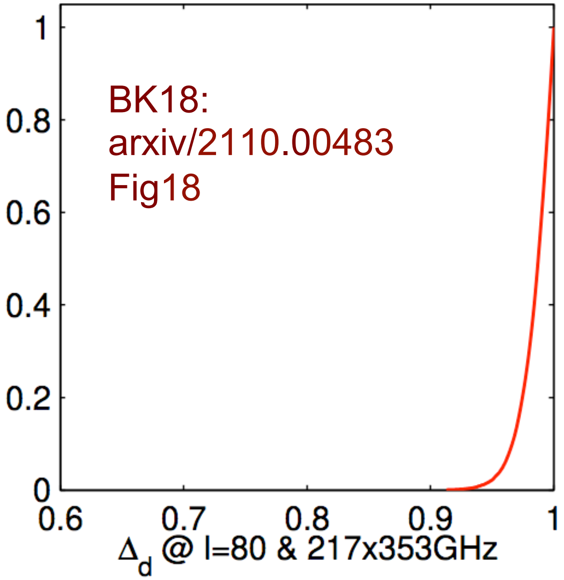


arxiv/1606.07335 Fig3



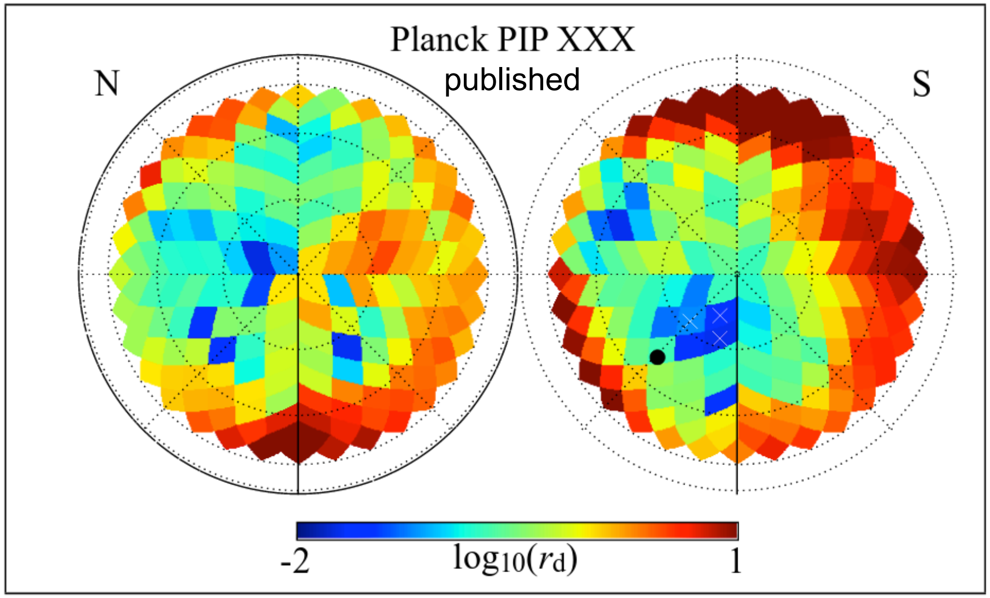
Paper says: "We find no evidence for a loss of correlation"

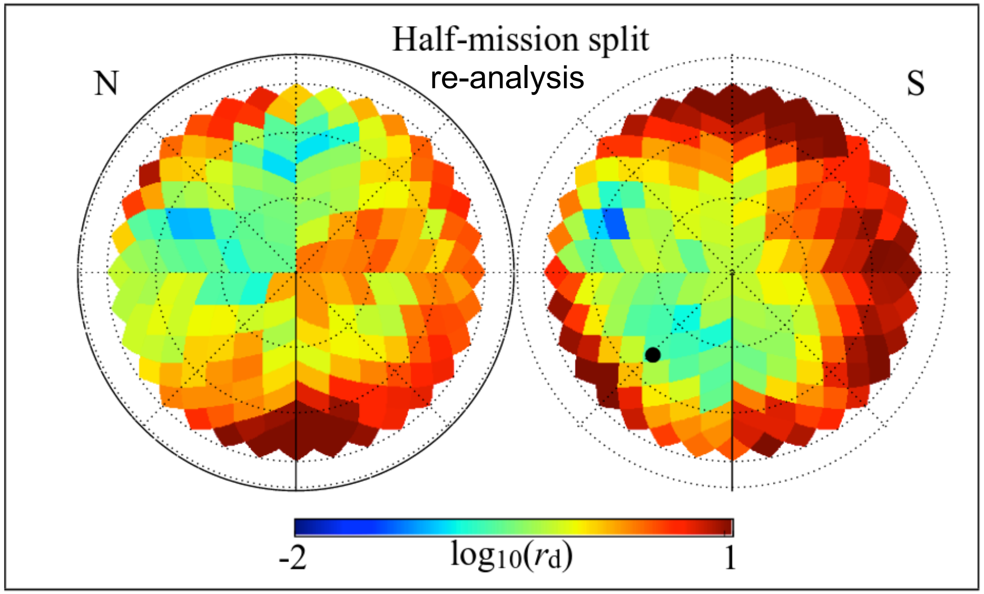
arxiv/1801.04945v3 table 5



BK18:
arxiv/2110.00483
Fig18

Is there a cleaner small field than the BICEP field?





- ❖ The Planck 353GHz Q/U maps hit their noise floor in the cleanest regions
  - ➢ From this data it is not really possible to tell if there are cleaner small regions than the BICEP/ Keck field
- ❖ When we attempt to reproduce the Planck PIPXXX analysis we find that the apparent cleaner regions shift around depending on the data split selected
- ❖ The BK patch is currently the only low dust field where we actually know the dust level!

Covariance matrix conditioning in Tristram et al. 2020

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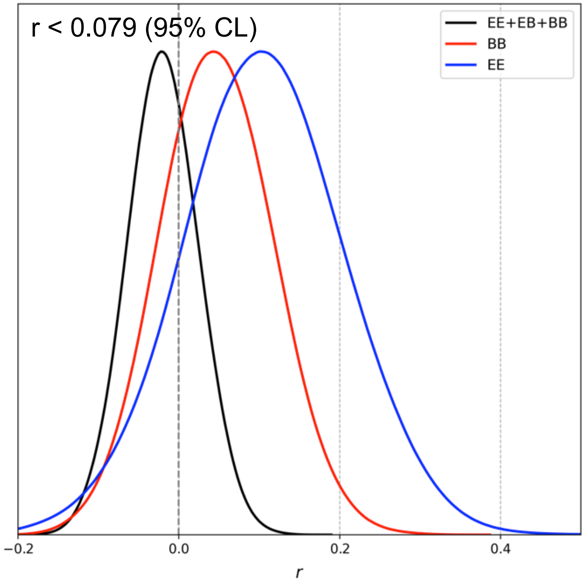

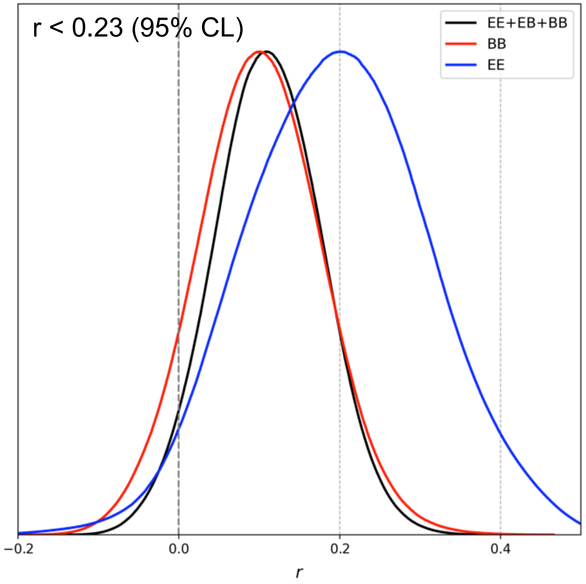

Full covariance matrix, as used in Tristram et al. 2020 and provided in the public likelihood

With covariance matrix conditioning (zeroing elements not detected above Monte Carlo noise) → combined posterior does not move to negative r

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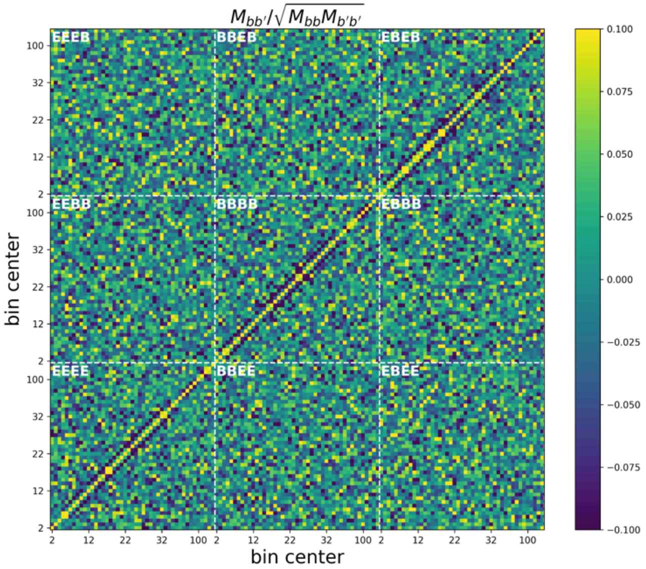

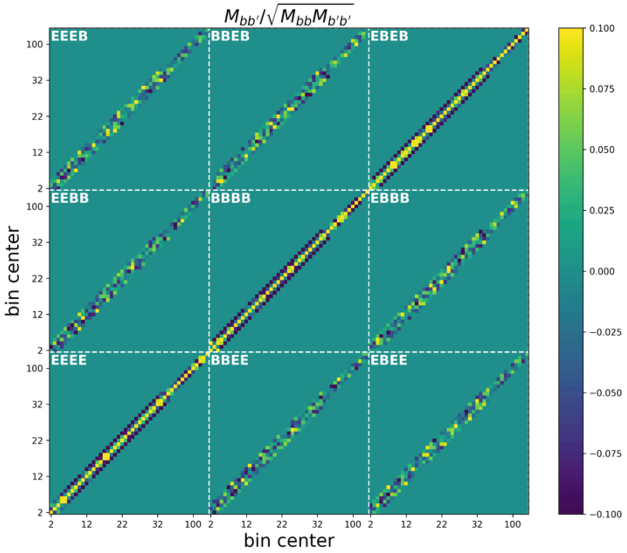

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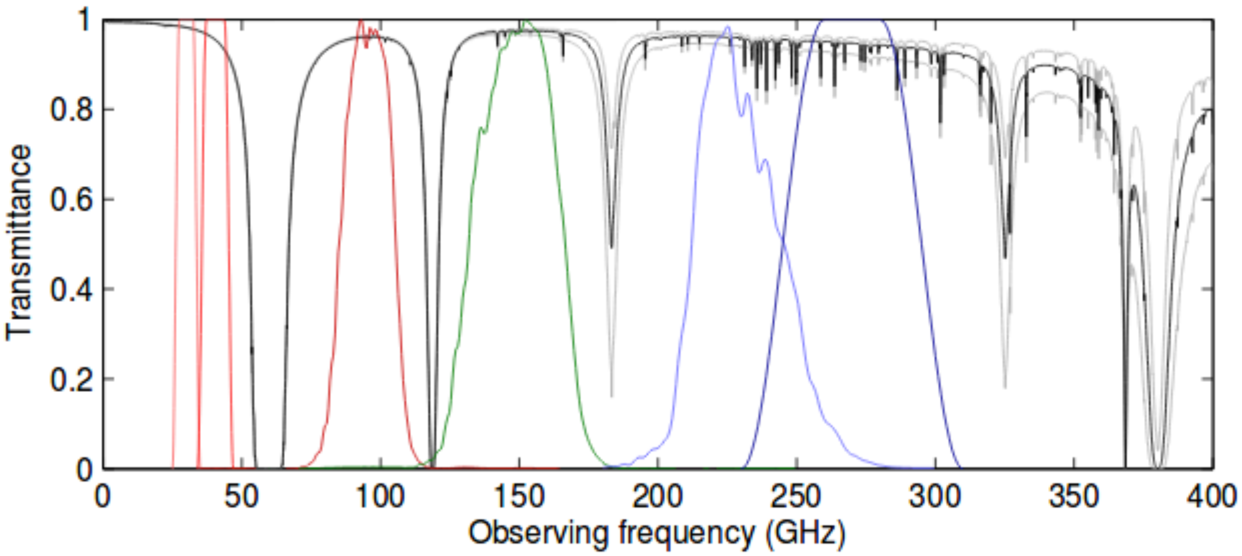
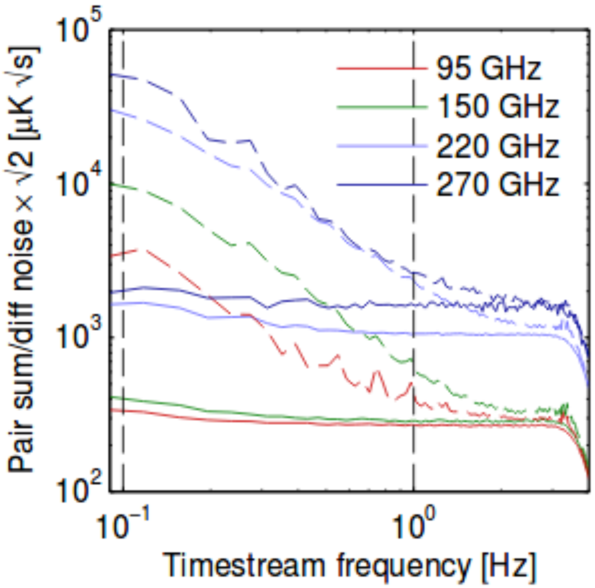
Pair Differencing Can Work at Pole

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 (next slide)

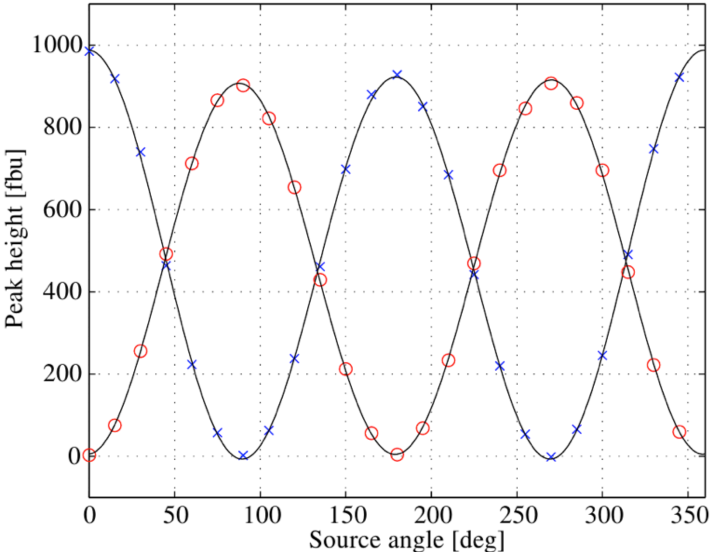
Adding a modulator is no silver bullet - they often carry a noise penalty and have their own systematics issues

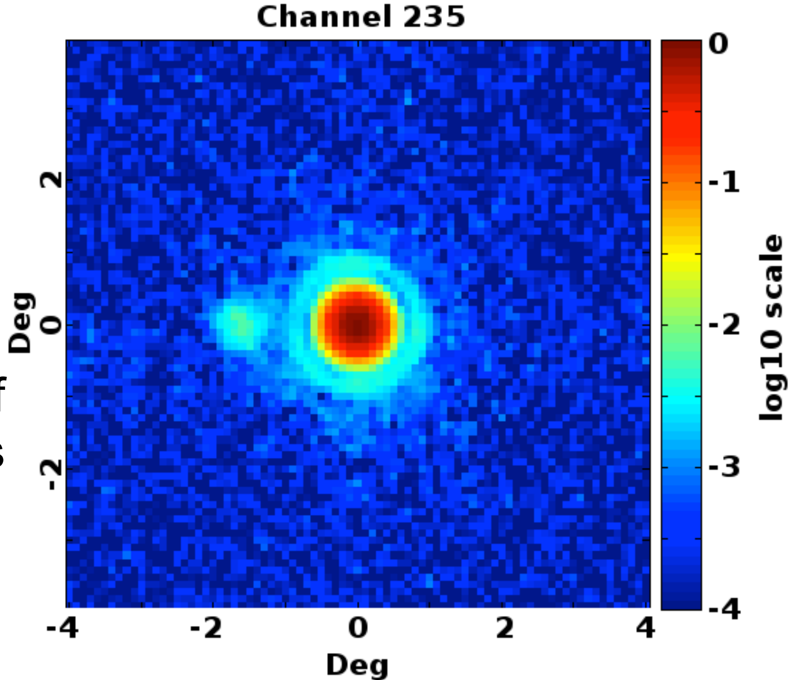
Calibration Measurements

For instance...

Far field beam mapping

Detector Polarization Calibration



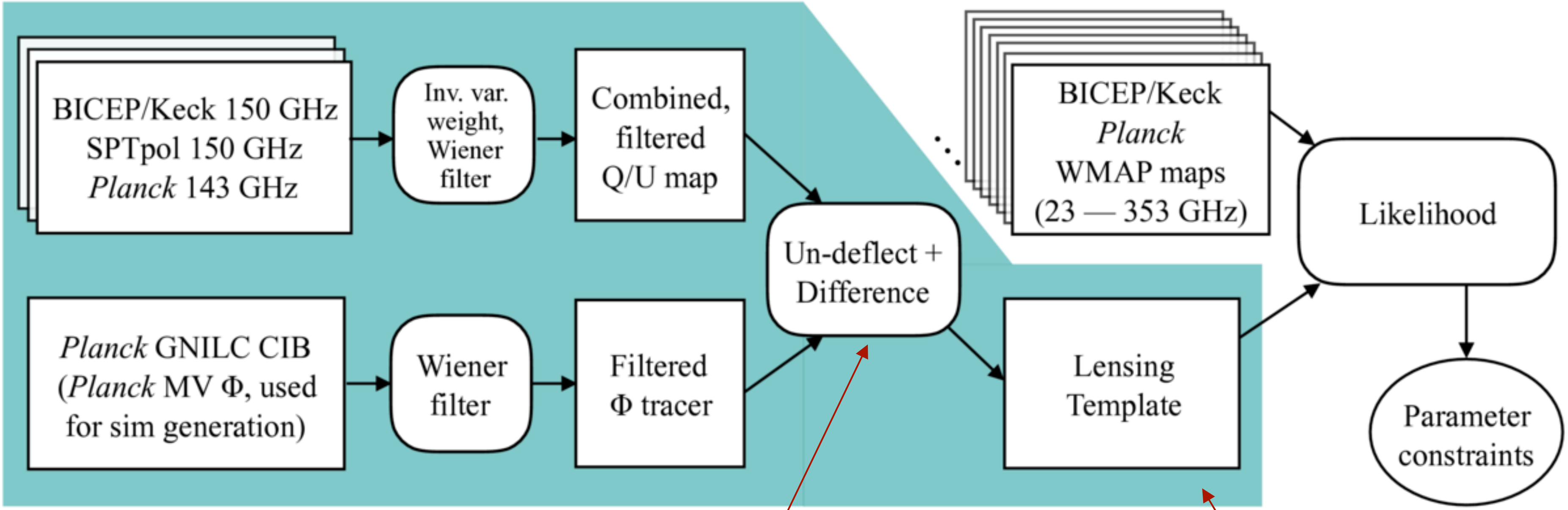


Hi-Fi beam maps of individual detectors

Detailed description in Instrument and beams papers arxiv/1403.4302 and 1502.00596

Delensing slides
From BK14+SPTpol paper
arxiv/2011.08163

Making/Using a “Lensing Template”



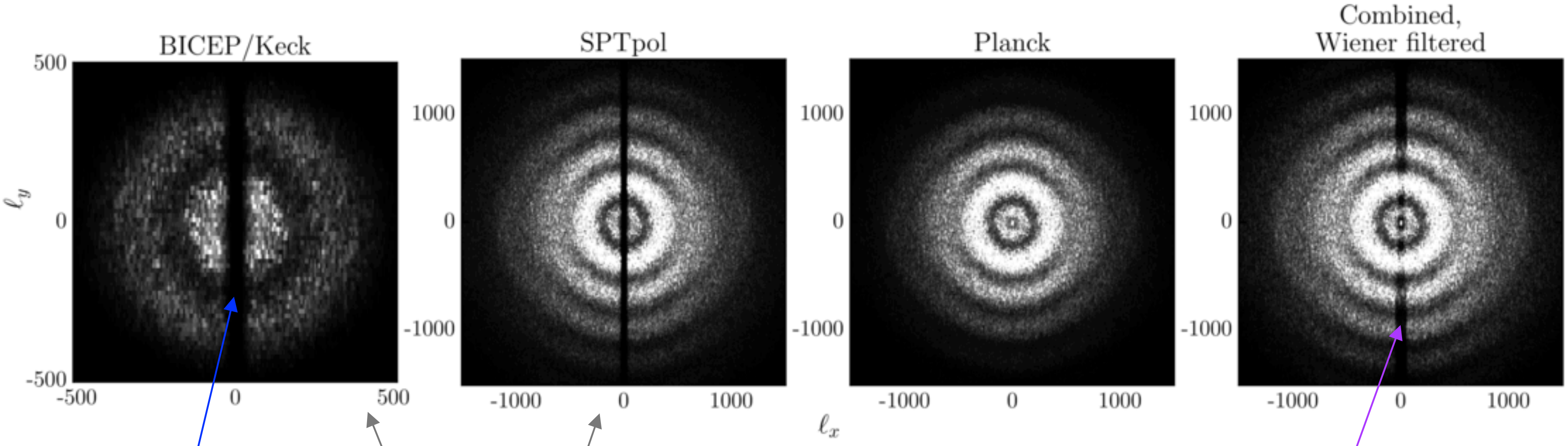
map space un-deflect operation

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.

arXiv: 2011.08163

Combining the BK/SPT/Planck maps

E-modes in the 2d Fourier Plane



“Trench” due to scan-wise filtering

Note different axis scales

These modes not measured above noise by any experiment

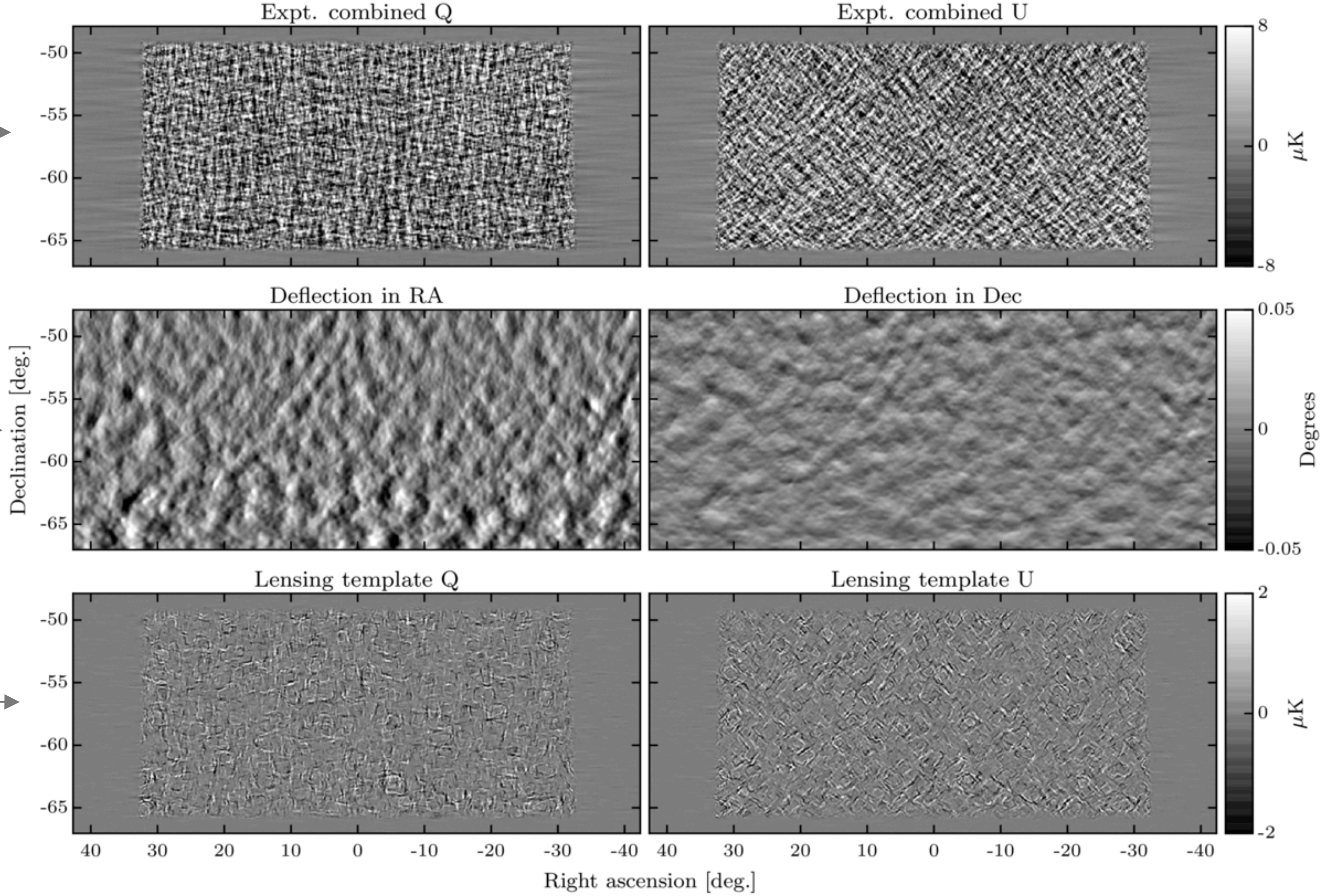
arXiv: 2011.08163

Making the lensing template

Combined map back in image space

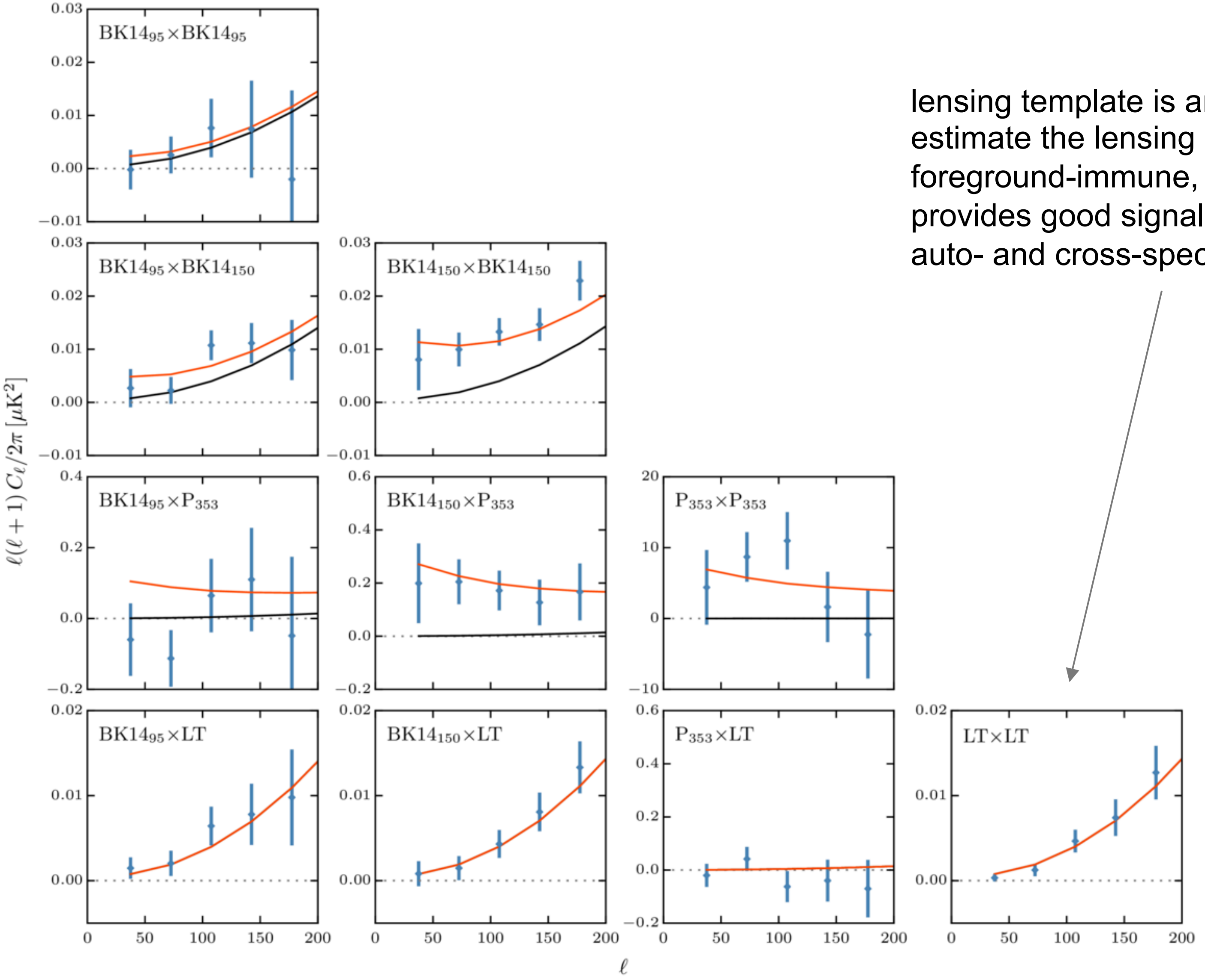
Weiner filtered lensing deflection field estimate from Planck CIB map

Undeflect top row with middle row and subtract top row
- the lensing contribution estimate



arXiv: 2011.08163

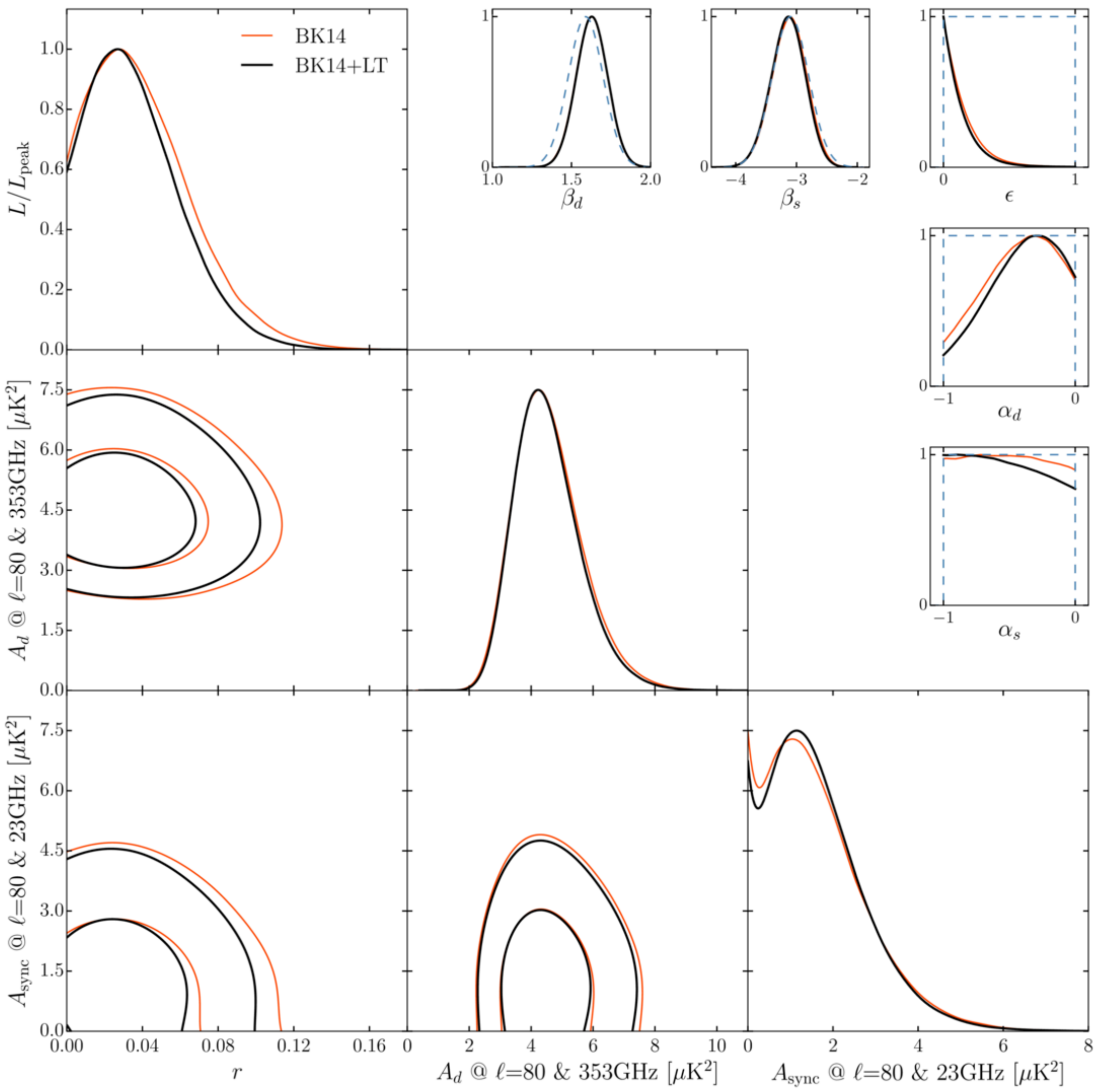
Auto/cross spectra of the lensing template



lensing template is an alternate way to estimate the lensing B-modes which is largely foreground-immune, and, as we see here, provides good signal-to-noise in the resulting auto- and cross-spectra.

arXiv: 2011.08163

Effect of lensing template on likelihood results

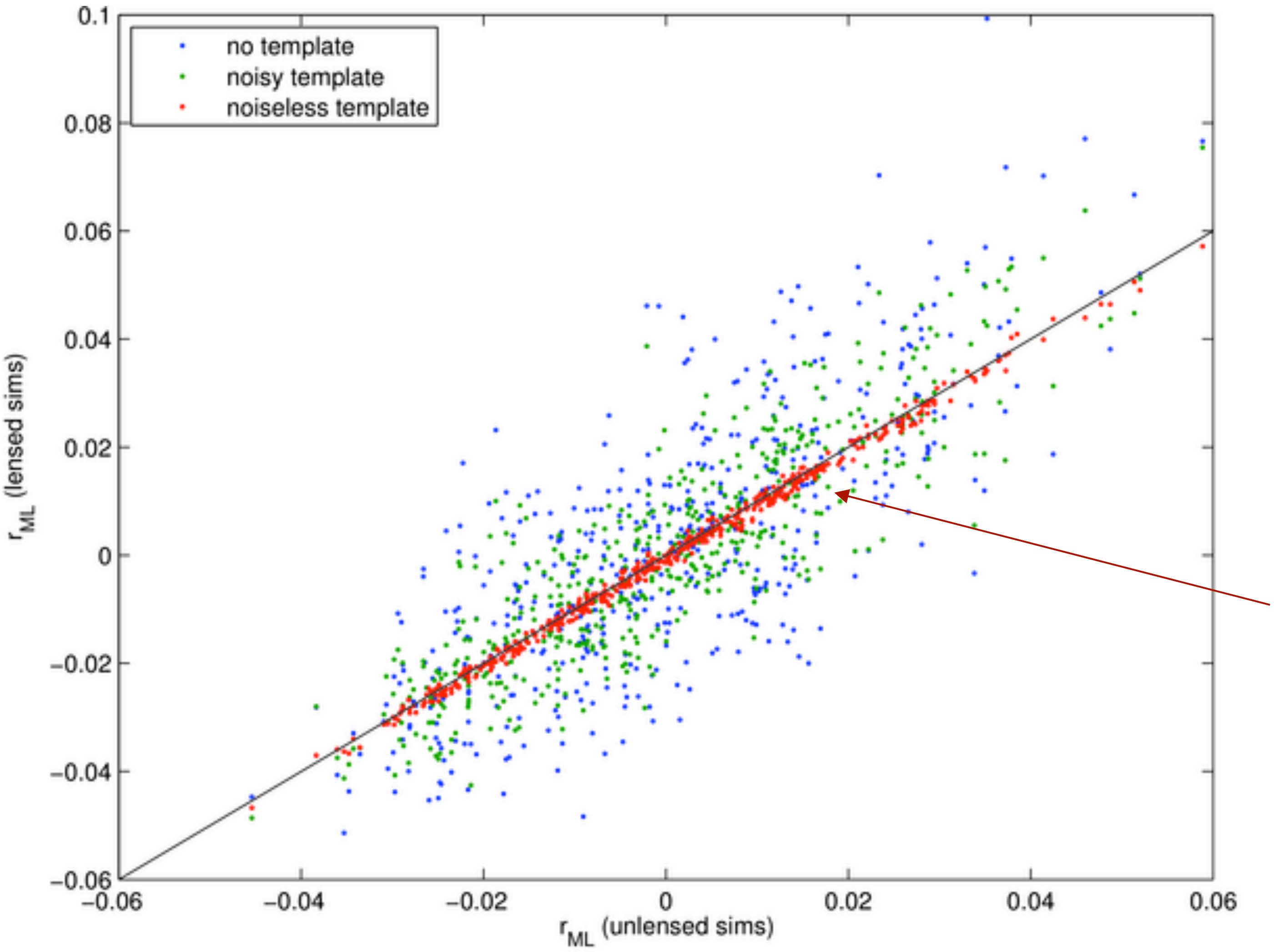


Adding CIB+SPTpol lensing template to BK14 makes little difference to bottom line *r* constraint - reduces width by 10%

Next step will be to use SPT3G data to reconstruct deflection field - adding to BK18 much bigger gain will be possible - and in the further future will become critically important.

arXiv: 2011.08163

Perfect lensing template works perfectly on realization-by-realization basis



If we have a perfect lensing template then "delensing" works perfectly - the ML *r* values are identical between unlensed and delensed sims on a *realization-by-realization* basis. (red points)

E/B Purification slides
From BK-VII paper
arxiv/1603.05976

Map-based E - B purification

Giant vector representing Q/U
measured at each point on the sky

$$\tilde{\mathbf{m}} = \mathbf{R}\mathbf{m} \qquad \tilde{\mathbf{C}} = \mathbf{R}\mathbf{C}\mathbf{R}^{\mathrm{T}}$$

Giant matrix representing all
linear filtering of the data

Giant covariance matrix

$$(\tilde{\mathbf{C}}_{\mathbf{E}} + \sigma^2\mathbf{I})\mathbf{e} = \lambda_{\mathbf{e}}(\tilde{\mathbf{C}}_{\mathbf{B}} + \sigma^2\mathbf{I})\mathbf{e}$$

$$(\tilde{\mathbf{C}}_{\mathbf{B}} + \sigma^2\mathbf{I})\mathbf{b} = \lambda_{\mathbf{b}}(\tilde{\mathbf{C}}_{\mathbf{E}} + \sigma^2\mathbf{I})\mathbf{b}$$

Solve the generalized
eigenvalue problem.

$$\lambda_{\mathbf{b}} = \frac{1}{\lambda_{\mathbf{e}}}$$

$$\xcancel{\lambda_{\mathbf{b}} = 1}$$

~~The mode is
ambiguous.
DISCARD!~~

$$\lambda_{\mathbf{b}} \gg 1$$

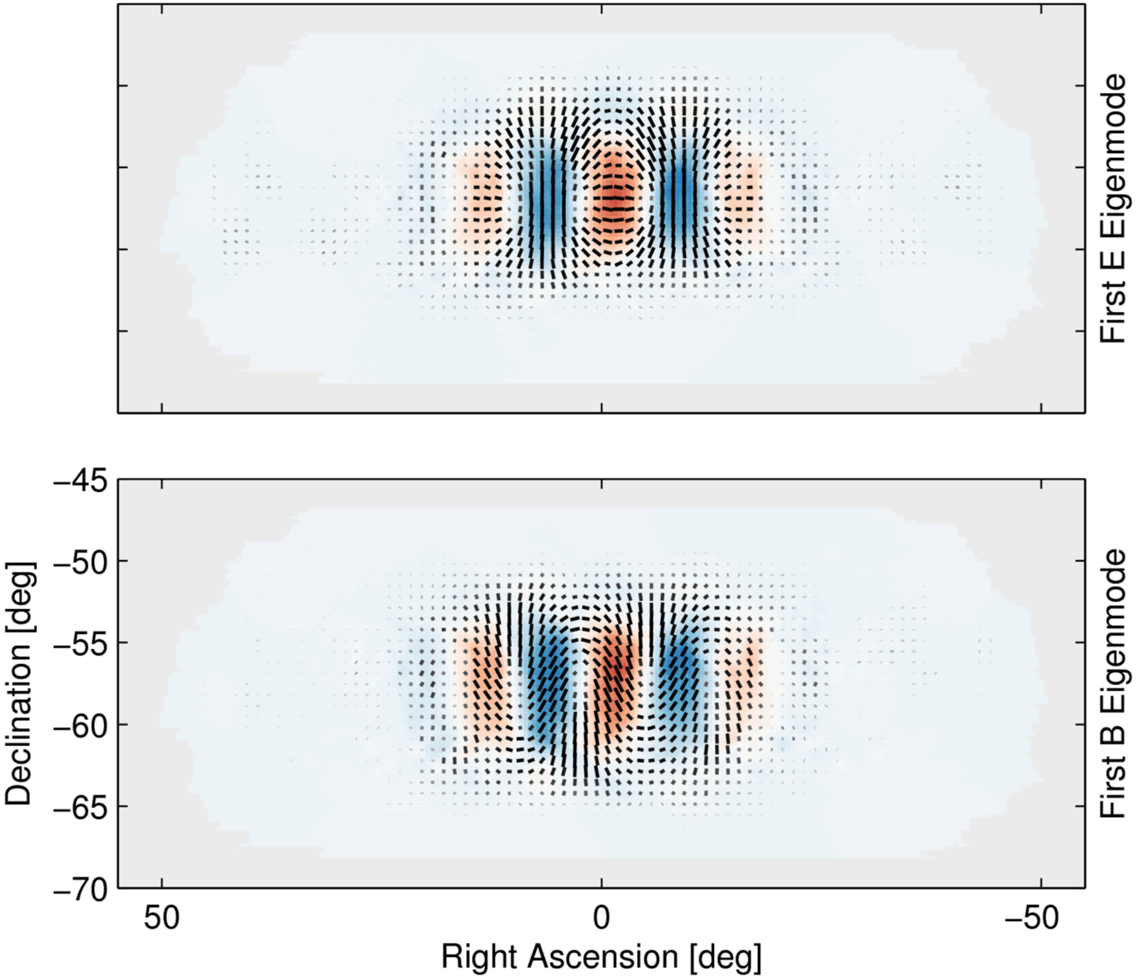
Build a projection operator
that only selects the
unambiguous modes.

$$\mathbf{\Pi}_{\mathbf{b}} = \sum_i \mathbf{b}_i \mathbf{b}_i^{\mathrm{T}}$$

$$\tilde{\mathbf{m}}_{pure} = \mathbf{\Pi}_{\mathbf{b}}\tilde{\mathbf{m}}$$

Map-based E - B purification

Eigenmode Decomposition



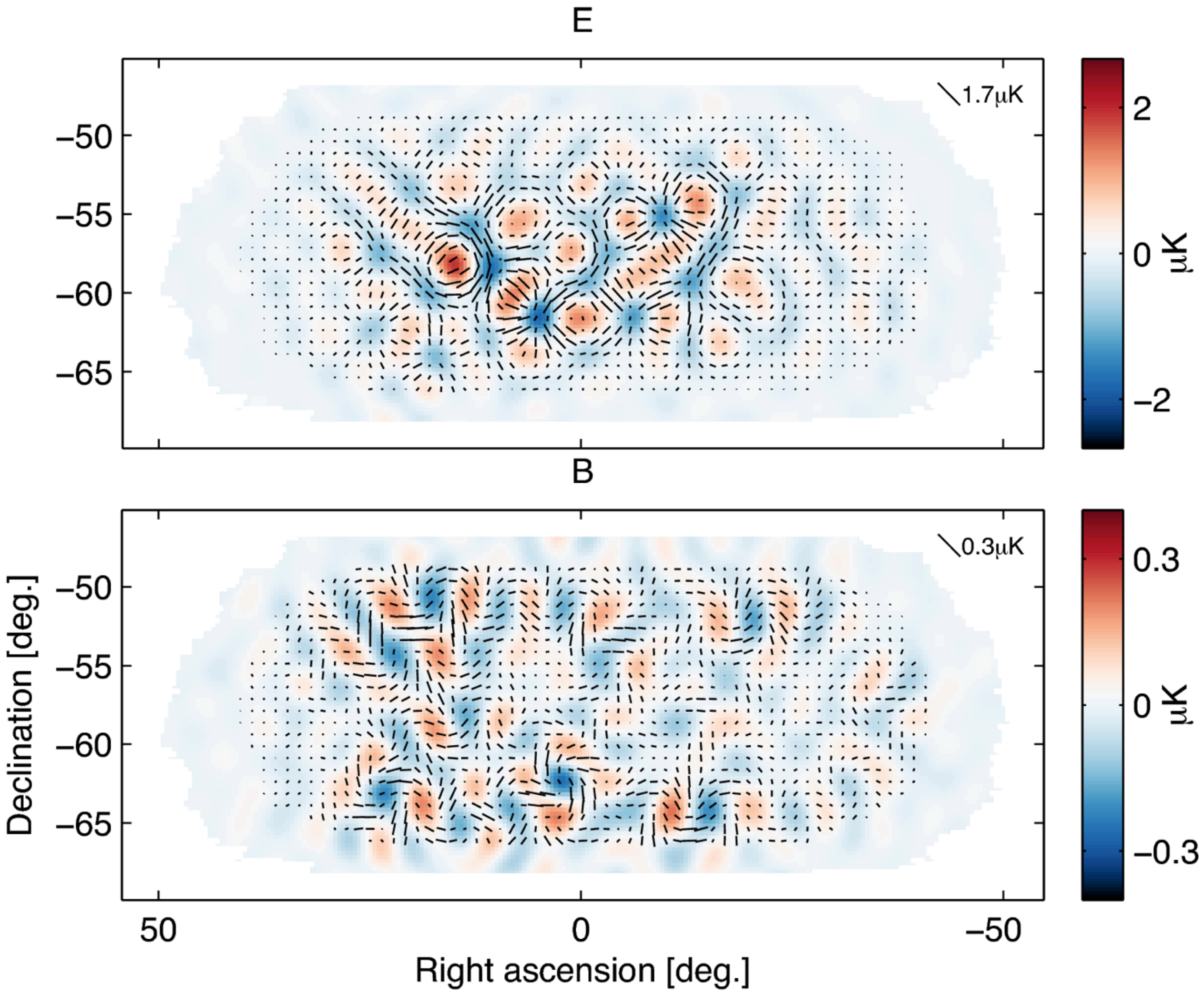
Filtering, deprojection, sky-cut can create B-mode power from a purely E-mode sky

We form a basis of ‘pure E’ and ‘pure B’ modes, for our particular filtering operations

Projecting onto the ‘pure-B’ mode basis prevents LCDM E-modes from leaking into B-modes

Map-based E - B purification

Simulation : LCDM (w/o lensing), no noise
filtered to 20< **l** <150

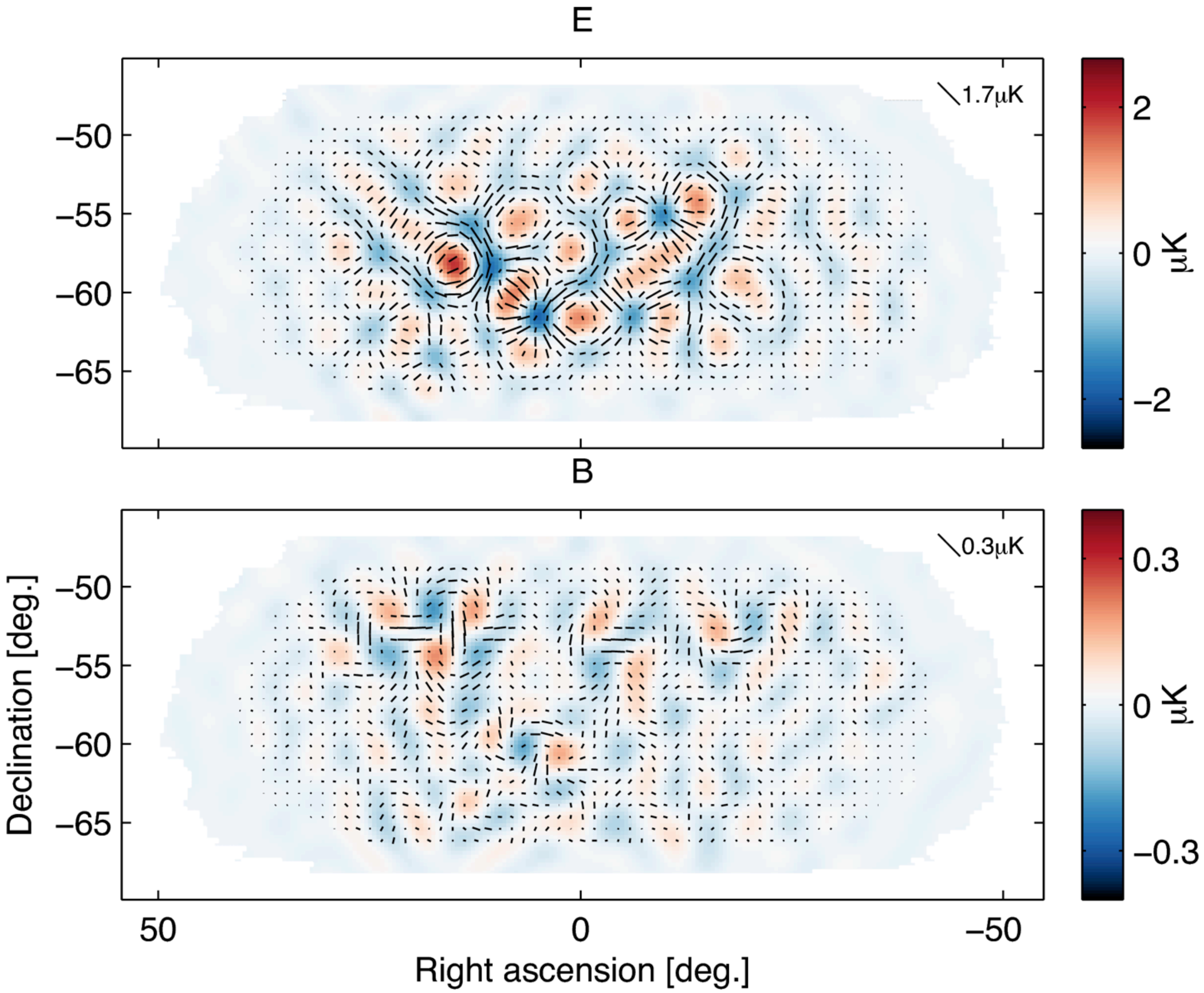


E-mode signal is converted into B-mode power through filtering operations

E to B leakage **without** purification is unacceptably high

Map-based E - B purification

Simulation : LCDM (w/o lensing), no noise
filtered to 20< **l** <150

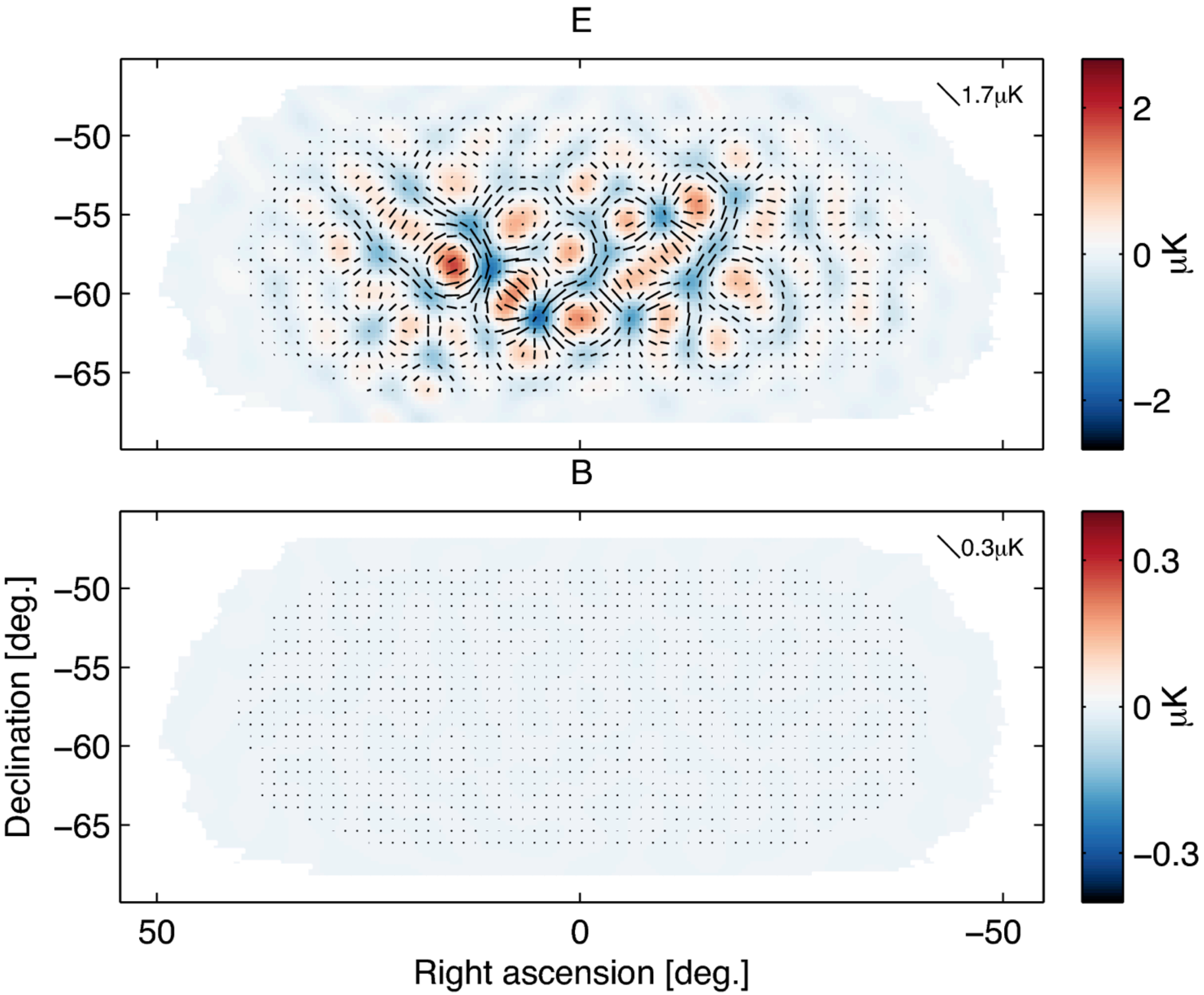


E-mode signal is converted into B-mode power through filtering operations

E to B leakage **with Smith et al 2006** method is still high due to filtering operations

Map-based E - B purification

Simulation : LCDM (w/o lensing), no noise
filtered to 20< **l** <150



Pure E is very similar to the raw E, since B to E leakage is comparatively small

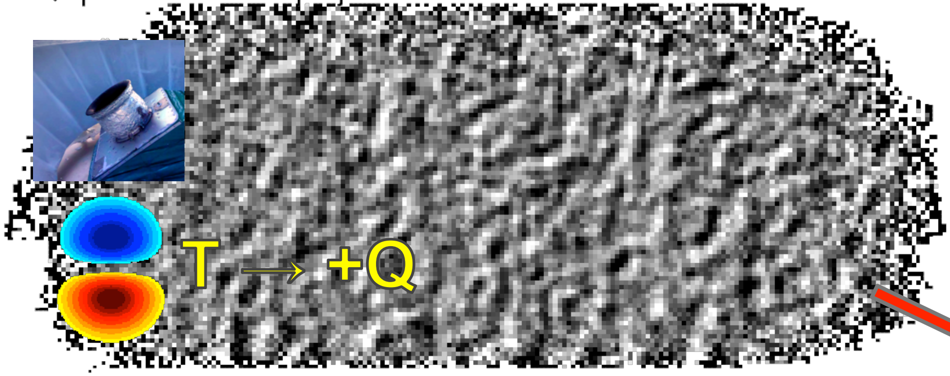
E to B leakage **with** purification is orders of magnitude smaller

Beam systematics and deprojection
From BK-III paper
Arxiv/1502.00608

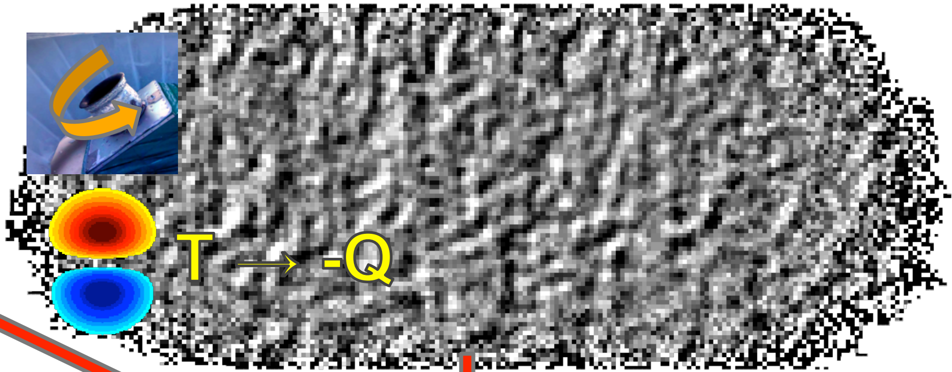
Cancellation of Systematics

Maps using just half the boresight rotation angles:

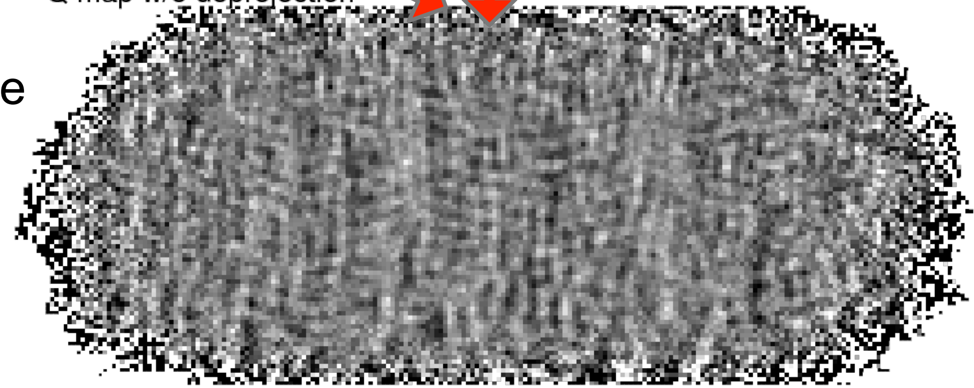
Q split half A w/o deprojection



Q split half B w/o deprojection



Q map w/o deprojection



w/o boresight rotation

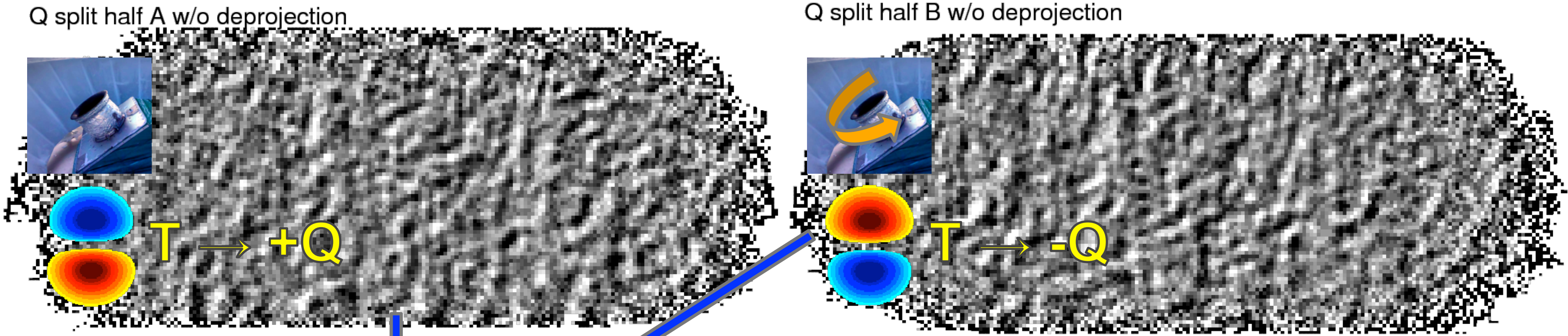
- ➢ Differential pointing leaks temperature sky into polarization maps

with boresight rotation

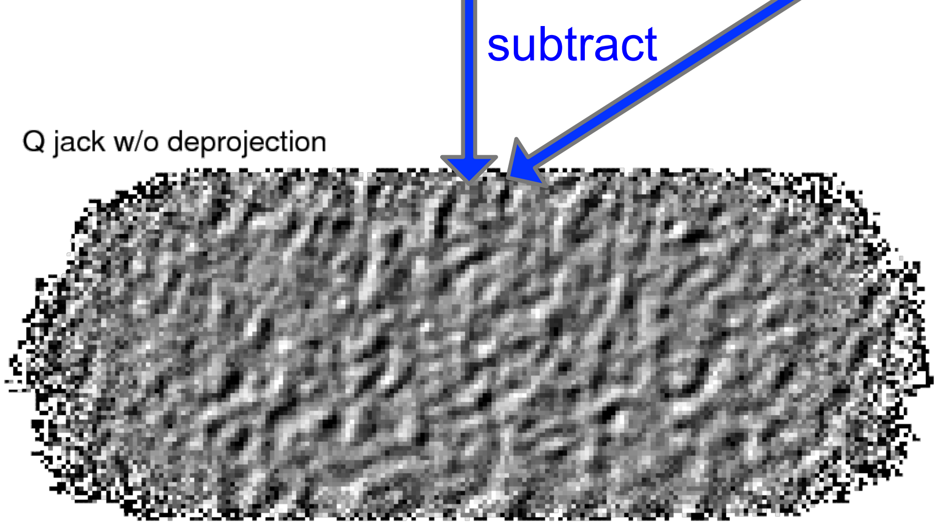
- ➢ systematic heavily suppressed in the full map (real signal remains)

Jackknife: Sensitive Test of Systematics

Maps using just half the boresight rotation angles:


Q split half A w/o deprojection

Q split half B w/o deprojection



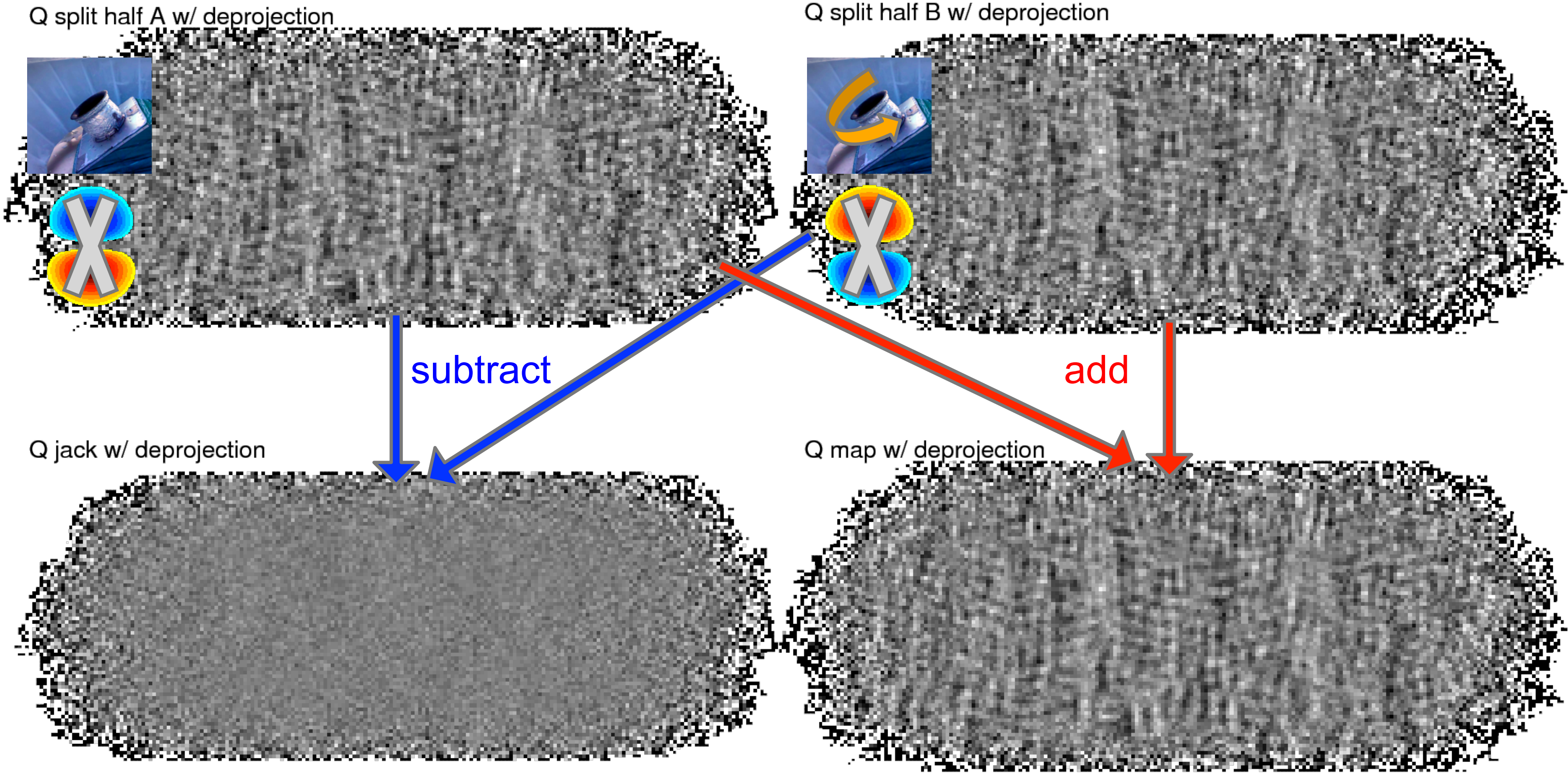
Q jack w/o deprojection

“Jackknife”:

- Difference the two halves instead of adding them
- Real signal cancels
- Systematic enhanced!

Systematics Removal: Deprojection

Maps using just half the boresight rotation angles:



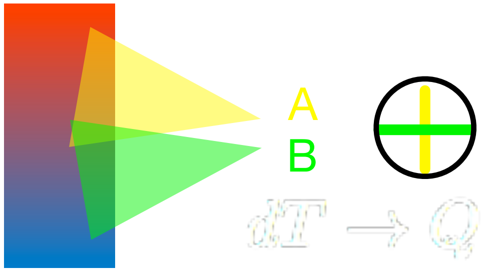
“Deprojection”:

- From well-known temperature sky form a prediction of the leakage and remove it
- Cleans up maps even without cancellation from boresight rotation

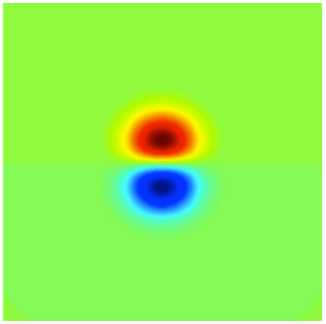
Beam Systematics

example: pointing center mismatch

“A” and B” beams

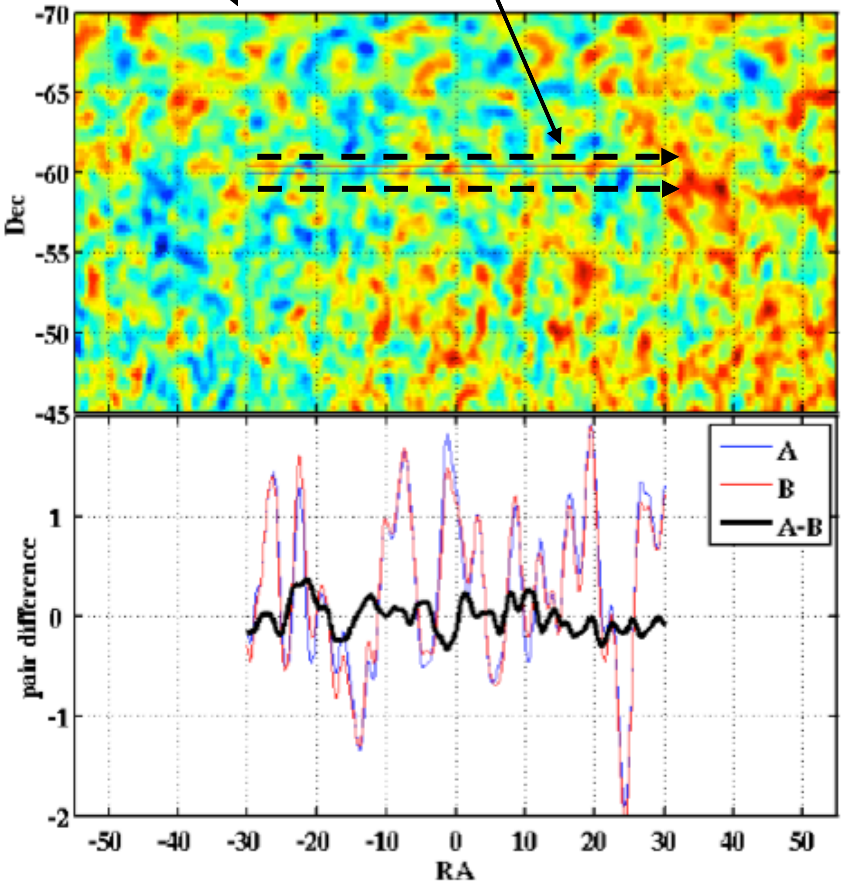


A-B difference beam



Planck T map

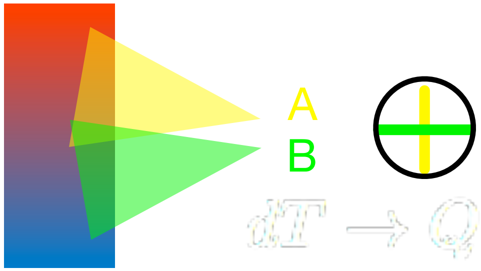
A and B’s path along the sky as the telescope scans



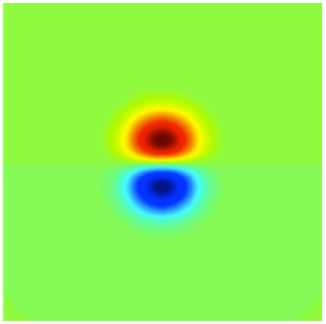
Systematics Removal: Deprojection

example: pointing center mismatch

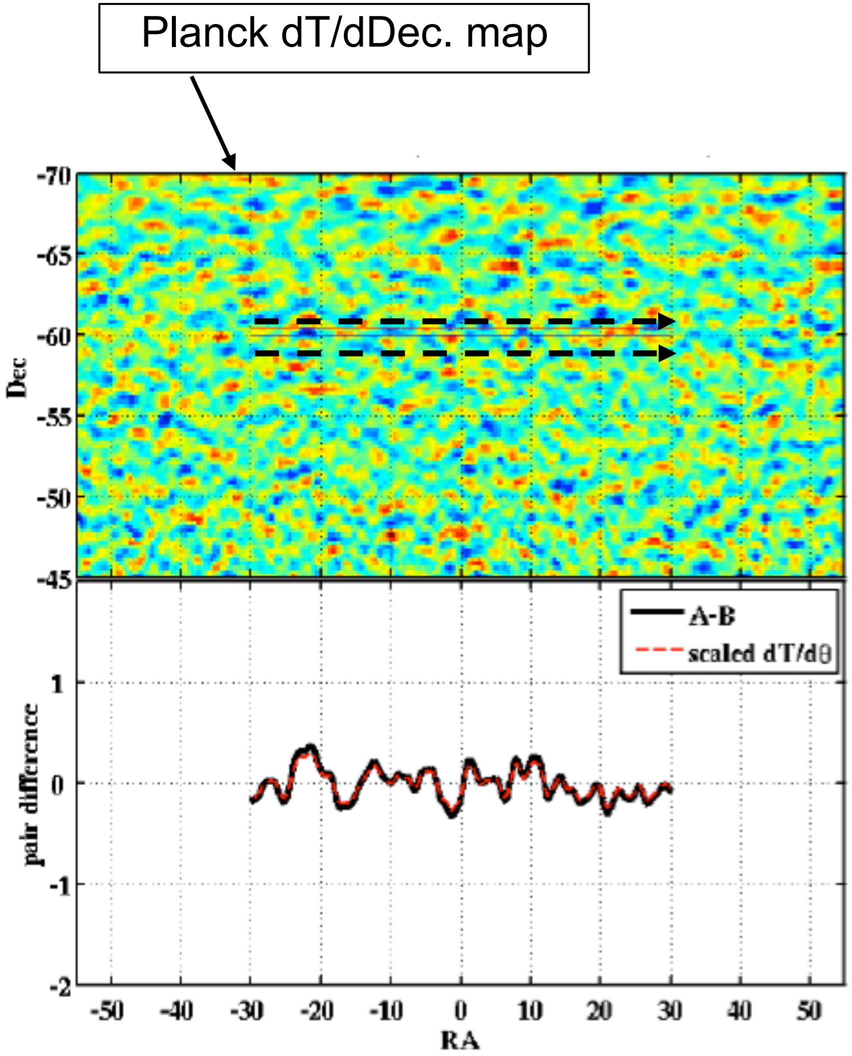
“A” and B” beams



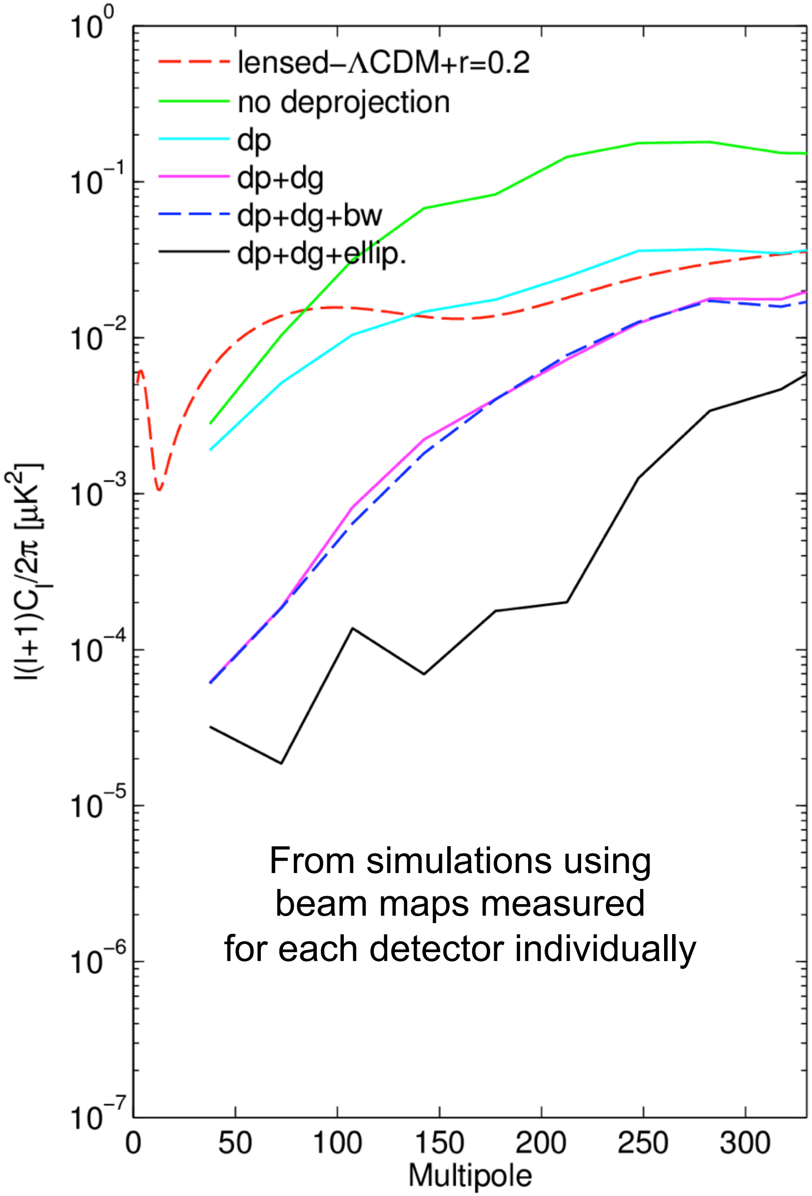
A-B difference beam



Regress template against pair diff timestream and subtract

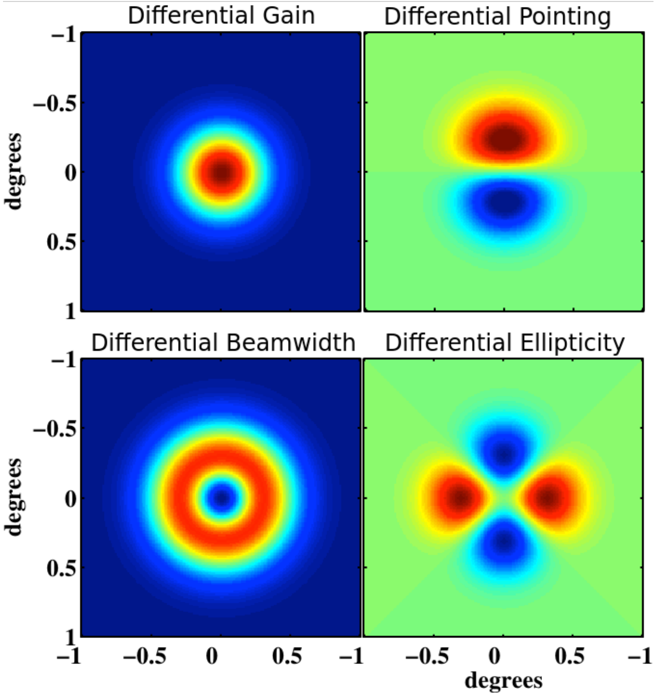

Planck dT/dDec. map

Systematics Removal: Deprojection



From simulations using
beam maps measured
for each detector individually

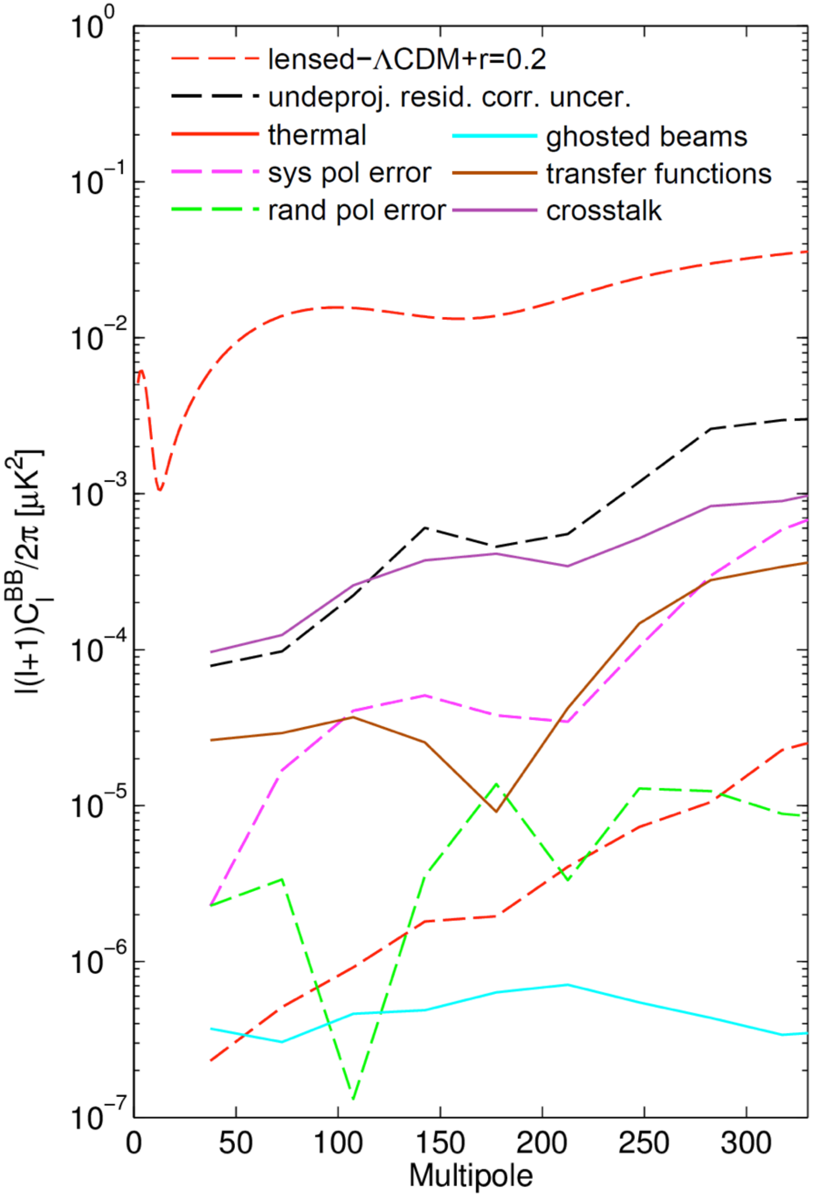
Technique developed to remove
all types of leakage induced by differences
of detector pair beam shapes



Use the Planck 143 GHz map to form
template of the leakage

Deproject diff gain and pointing (& subtract
diff ellipticity)

Systematics beyond Beam imperfections

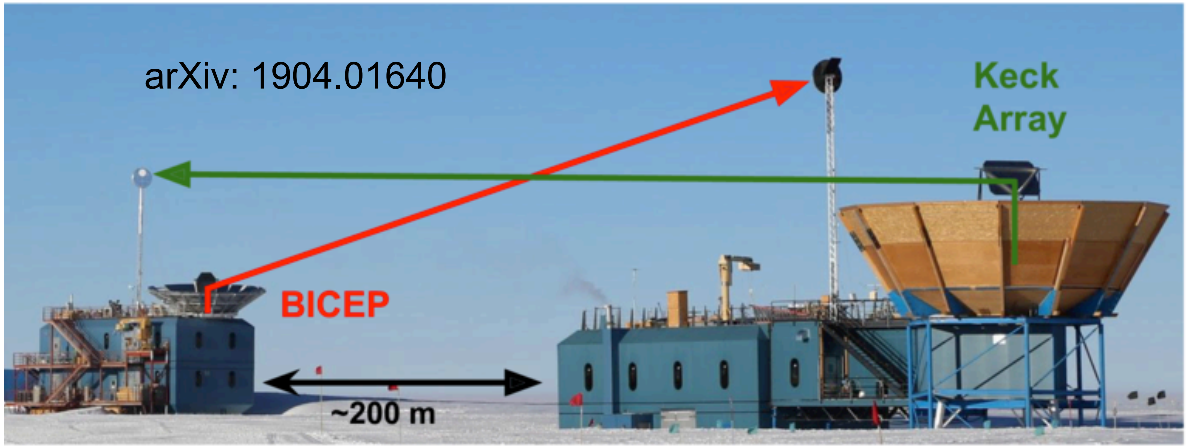


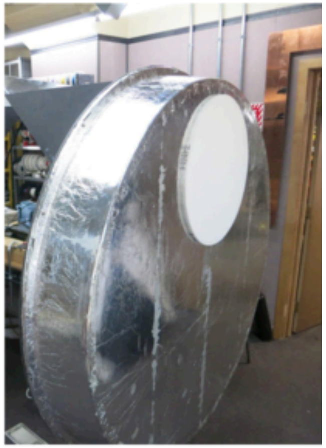
Other systematic effects investigated

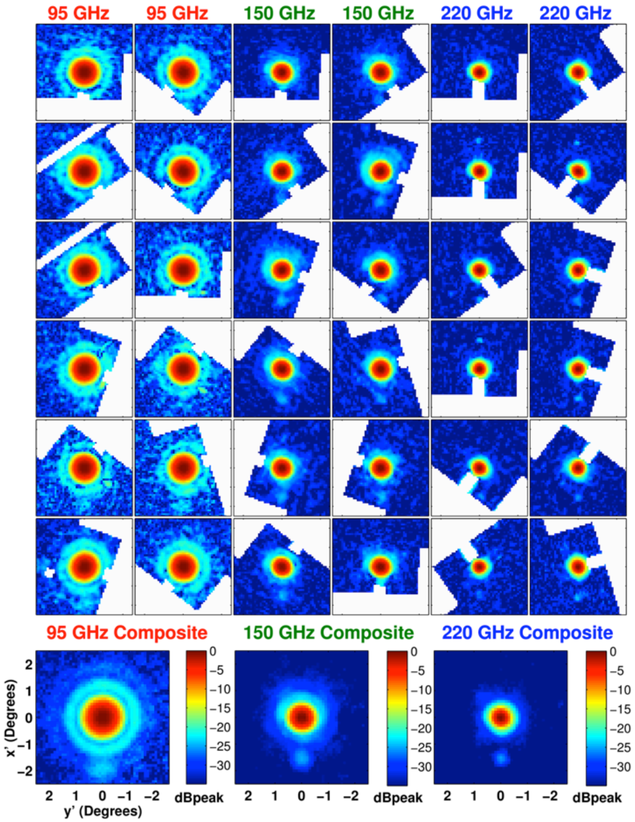
arXiv: 1904.01640

Slides summarizing BK-XI: Beam Characterization and Temperature-to-Polarization Leakage in the BK15 Dataset

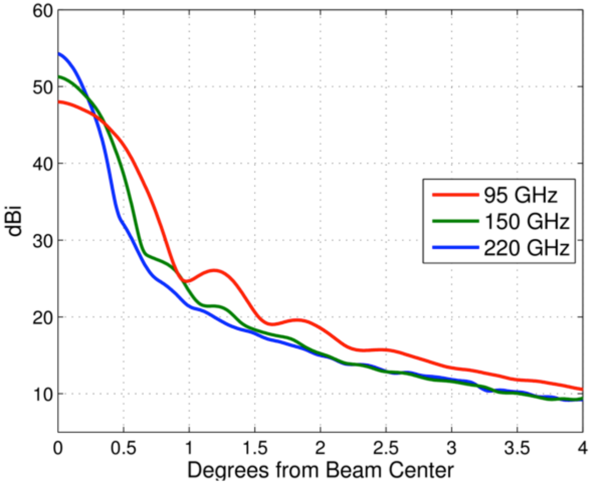
Precision Beam Measurements *in situ* at South Pole

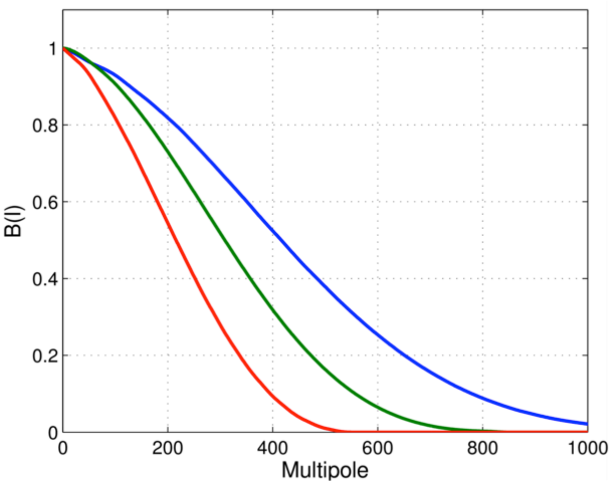

arXiv: 1904.01640





Small aperture -> far field close by
Chopped blackbody source, 24” aperture spinning at 14 Hz
Scan across source at multiple boresight angles
Mask out ground-fixed contamination and coadd to form composite
From 2010-2015, measured 10368 distinct beam patterns

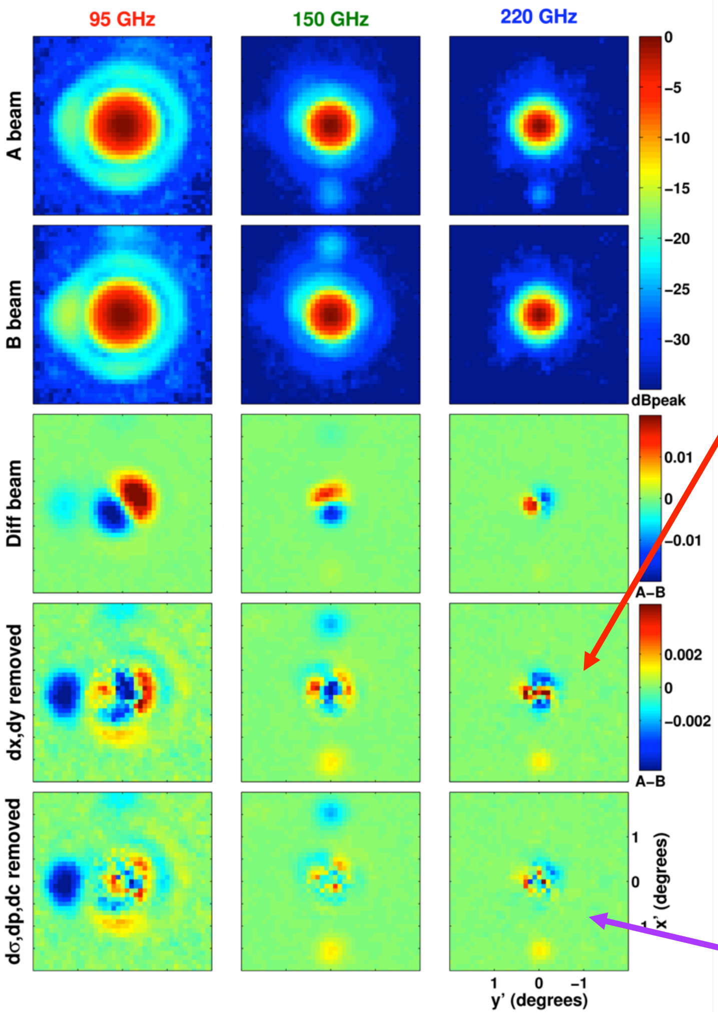


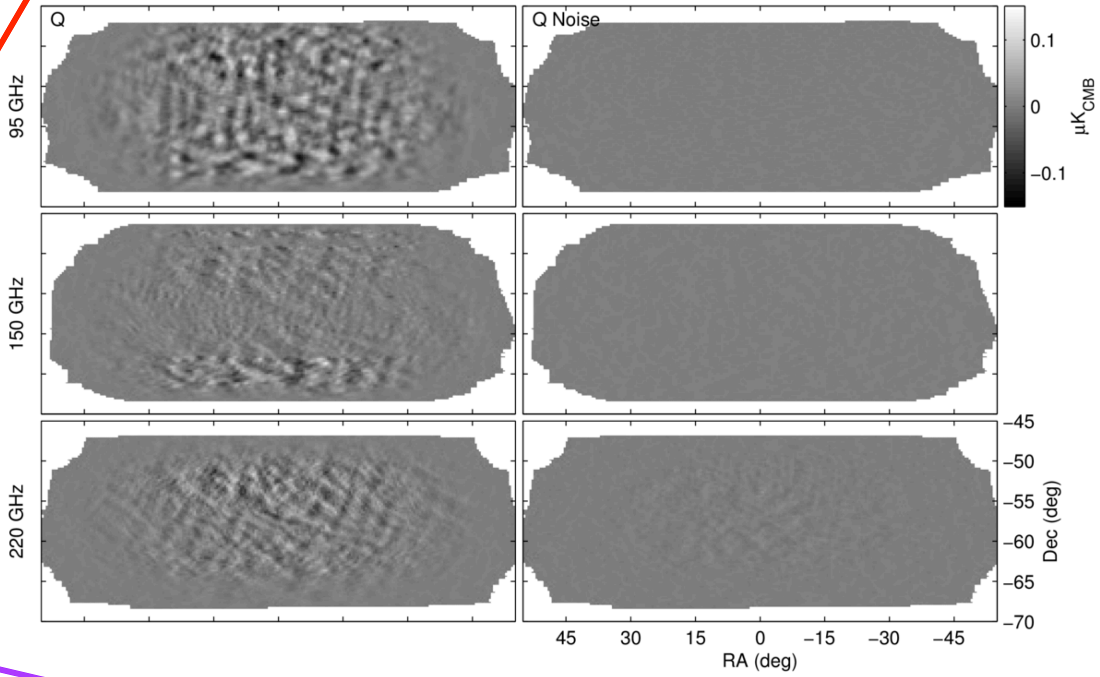


Predicting T->Pol Leakage from Differential Beams

Deprojection in analysis marginalizes over lowest-order beam difference modes
(diff pointing, ellipticity, beamwidth)

arXiv: 1904.01640





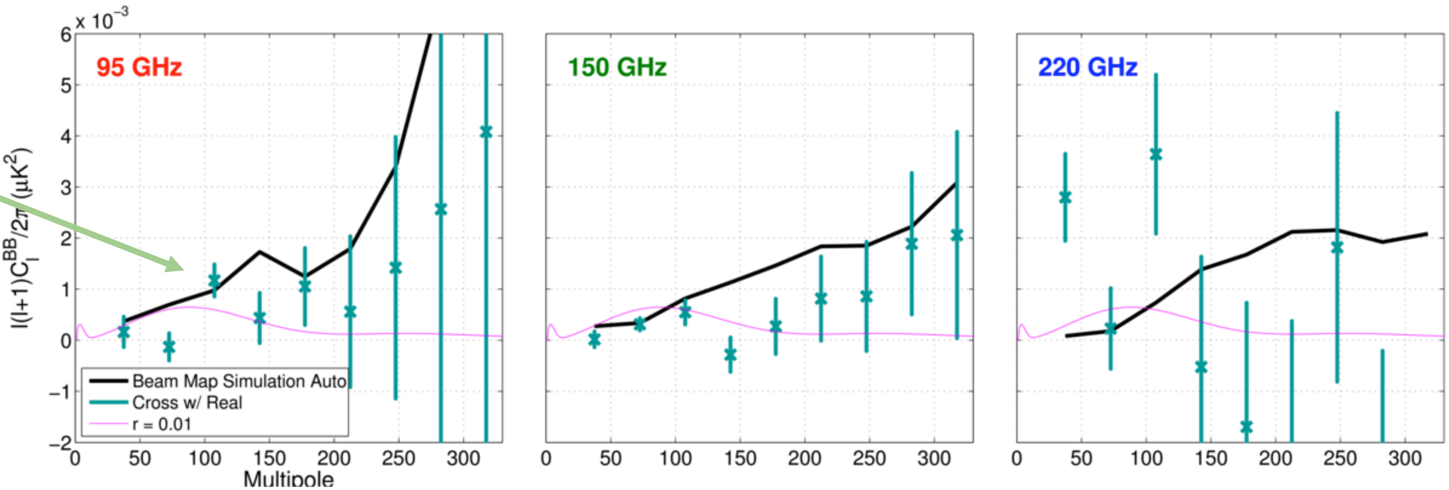
High S/N measurements of beam shape differences within a polarization pair

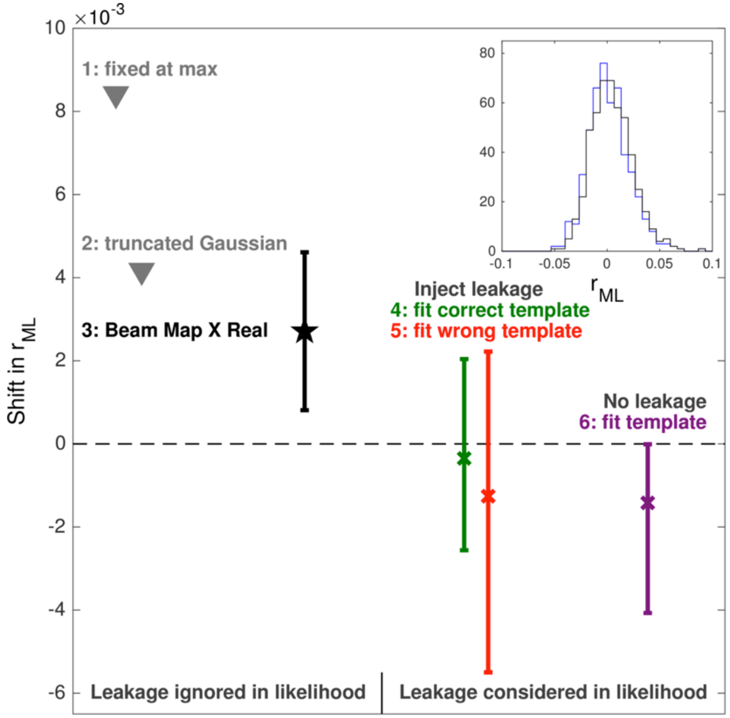
Propagate higher-order *undeprojected* residual beams through entire pipeline (convolve with Planck T sky) to predict leakage at the map level

Impact on *r* analysis

arXiv: 1904.01640

Cross spectra of beam map sims and real BK15 maps offer marginal evidence for leakage (but not conclusive)





Propagate T->P leakage through BK15 multicomponent analysis and analyze the shift in maximum-likelihood *r* value, for various scenarios

Leakage consistent with cross spectra yields Δr = 0.0027 +/ 0.0019 (compare to BK15 σ(r) = 0.020)

Can also fit and marginalize over a leakage template, but since template uncertainty is large, it is possible to incur a similar negative bias when imposing physical-only prior (i.e. positive leakage)

BICEP3 undeprojected residual estimate