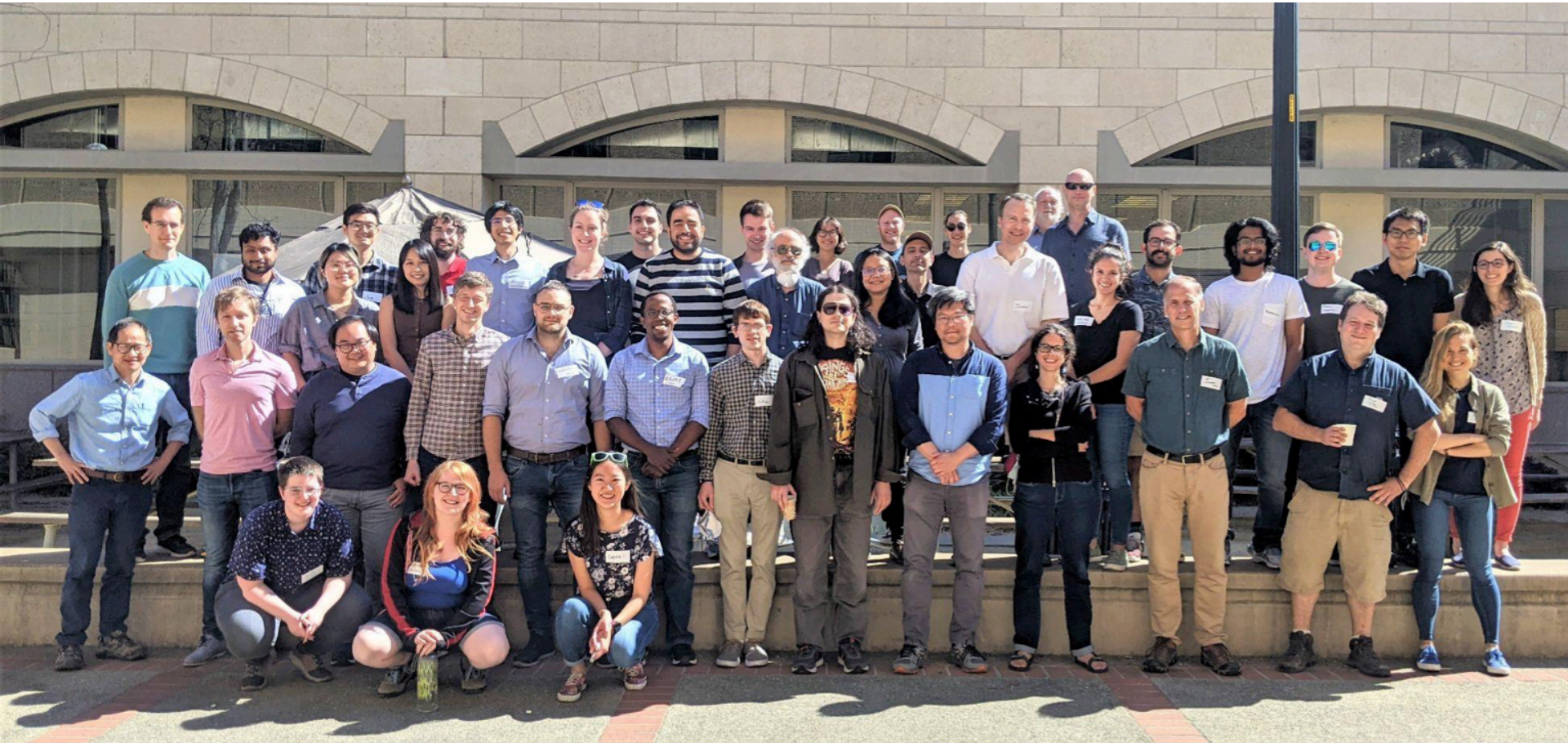
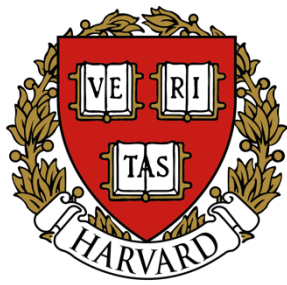


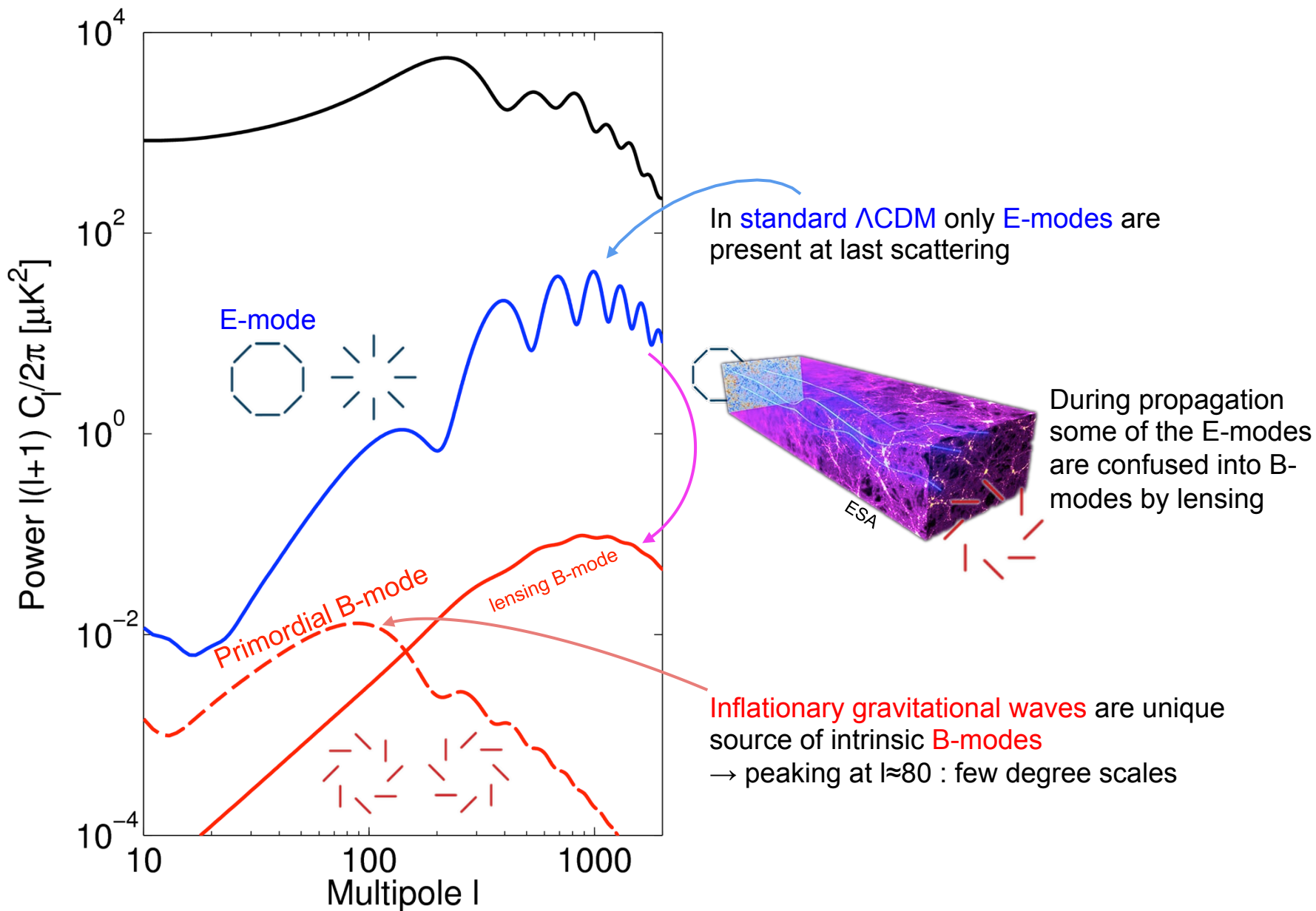
The search for primordial gravitational waves: latest results from BICEP/Keck



Motivation/Background

- Using the CMB and other data the Λ CDM cosmological paradigm has been developed – it works great and allows us to understand the development of the universe all the way back to a high energy state.
- However, Λ CDM leaves many unanswered questions such as the “horizon problem” and how the empirically simple conditions at the start of the plasma phase were set up.
- Theory of “Inflation” added on the beginning of Λ CDM to explain.
- If it happened Inflation will have made a background of gravitational waves which will have imprinted a B-mode (curl) into the polarization pattern of the CMB.
- We may be able to detect these if we can make a sensitive enough telescope – a wide range of inflation models exist – the simplest are already ruled out – more complex ones can produce r which is undetectably small...

CMB power spectra

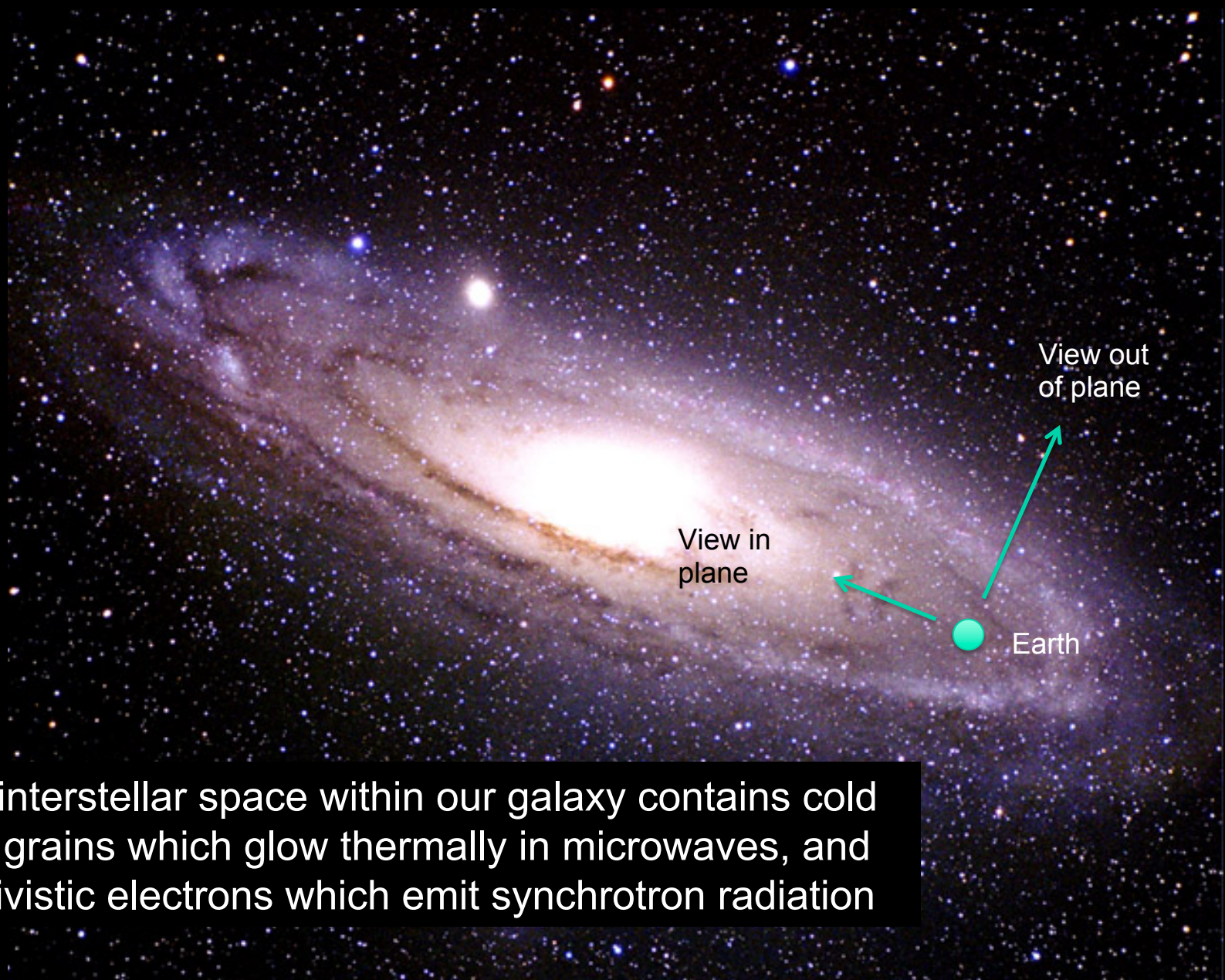


BICEP/Keck Basic Experimental Strategy



- 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



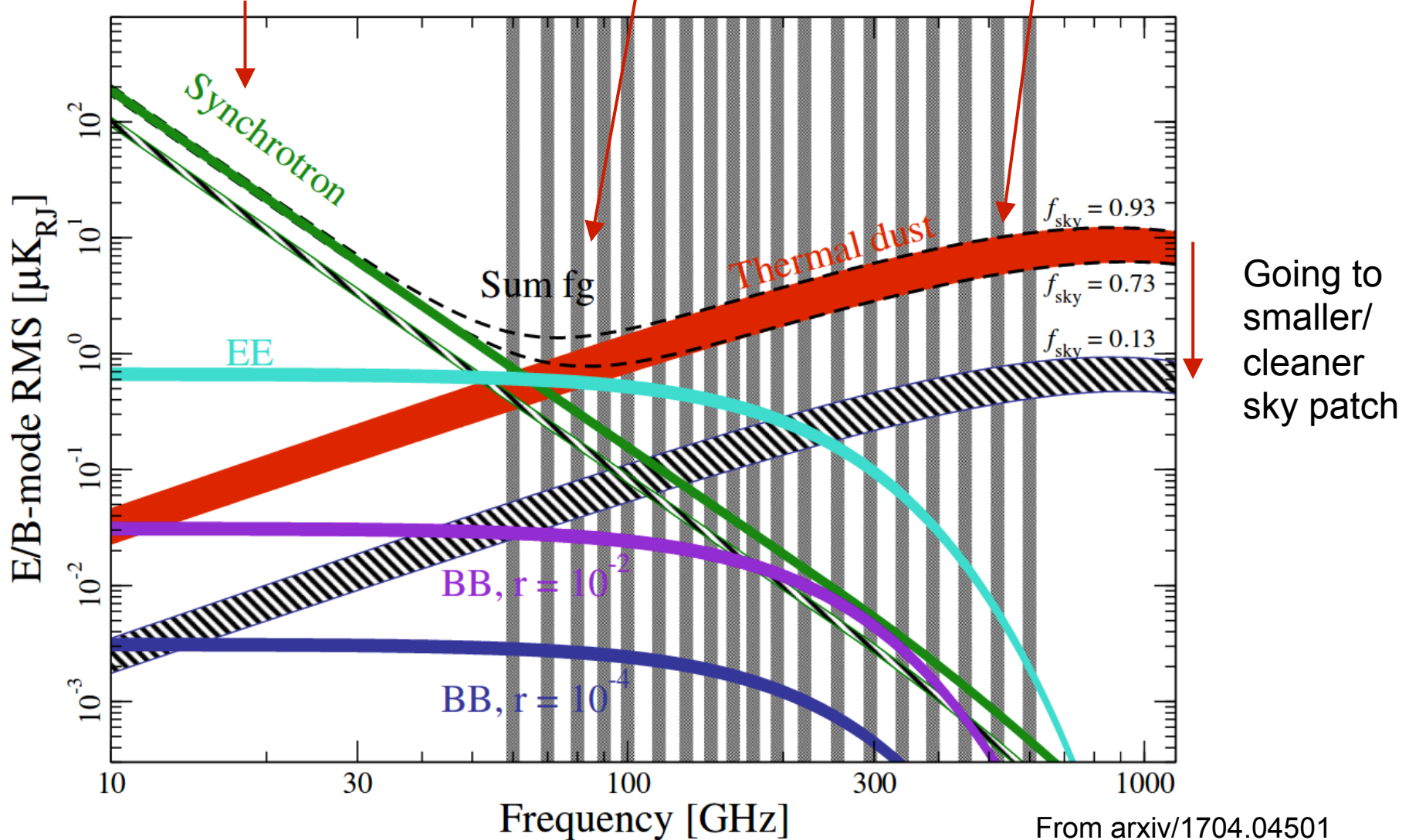
The interstellar space within our galaxy contains cold dust grains which glow thermally in microwaves, and relativistic electrons which emit synchrotron radiation

Overcoming Polarized Foreground Contamination

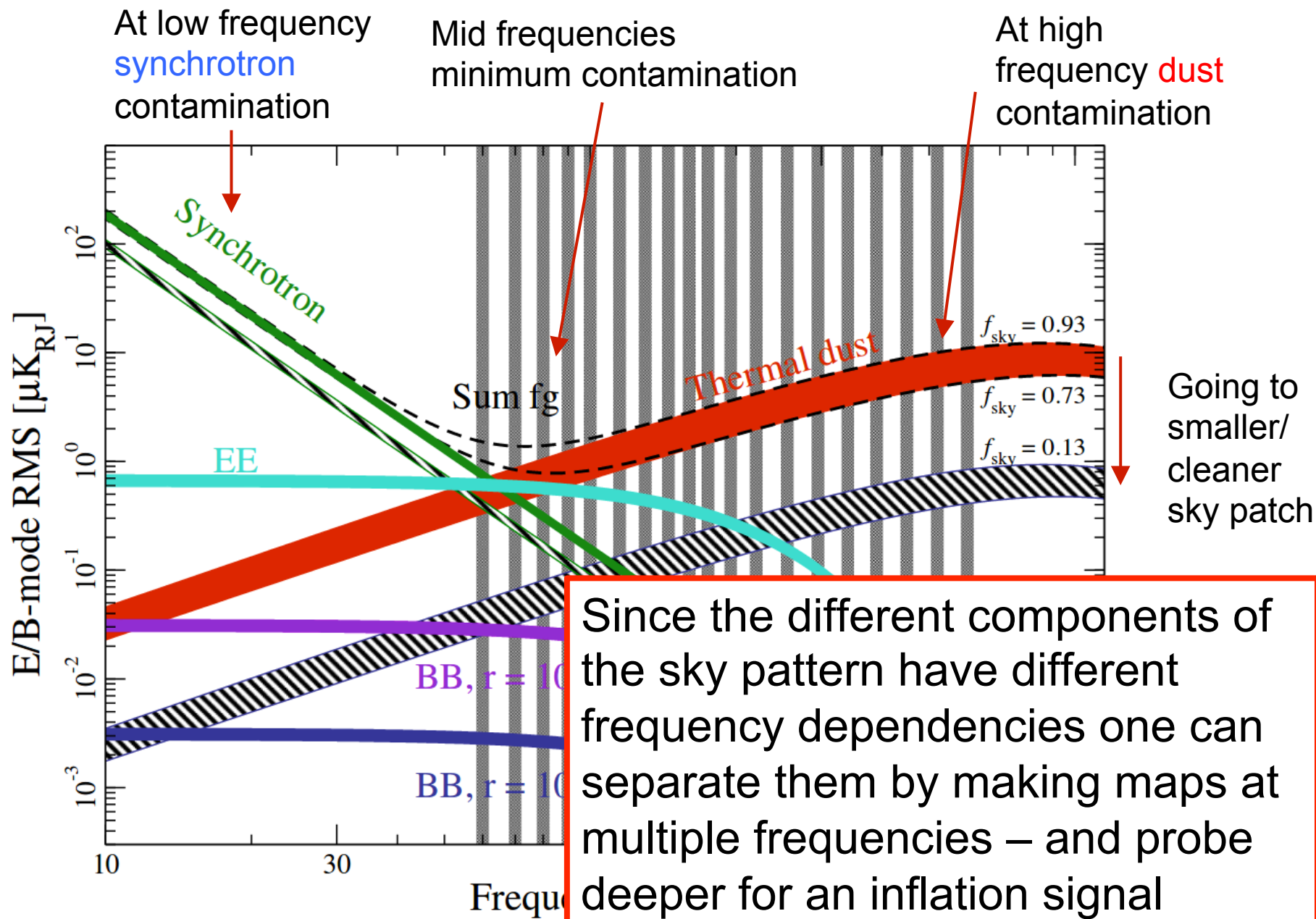
At low frequency
synchrotron
contamination

Mid frequencies
minimum contamination

At high
frequency dust
contamination



Overcoming Polarized Foreground Contamination



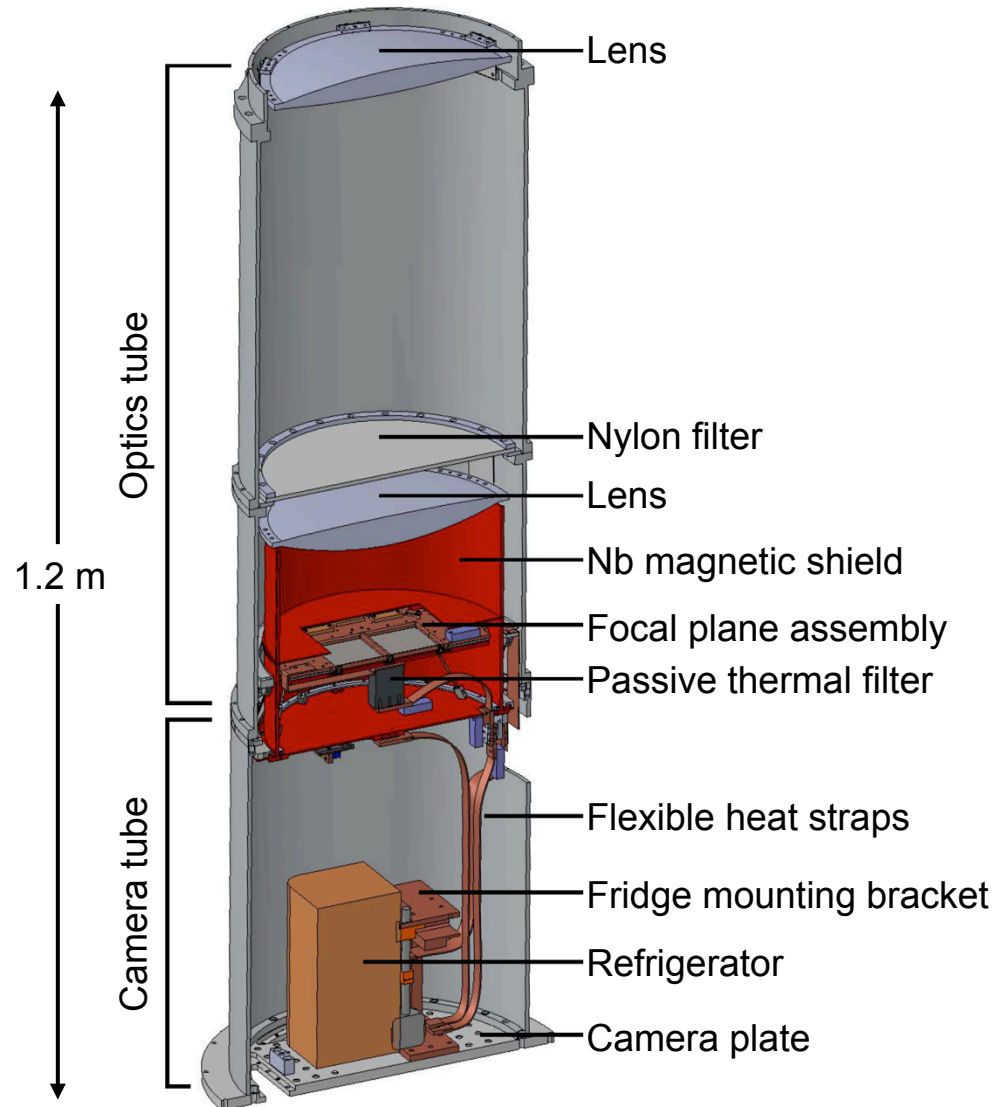
The BICEP/Keck Telescopes

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

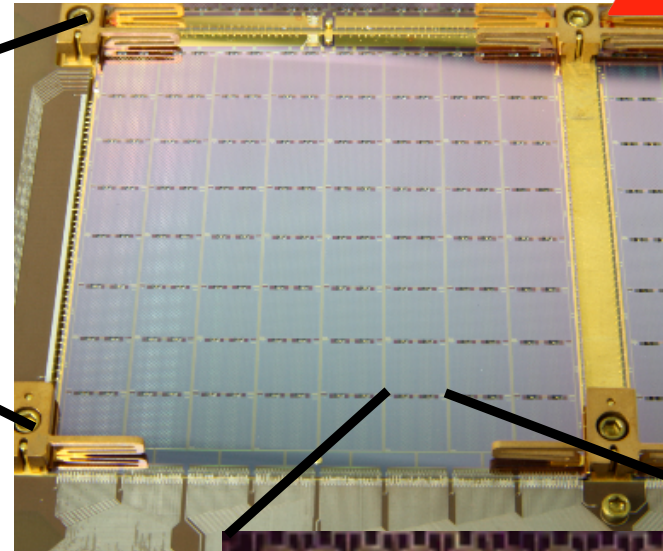
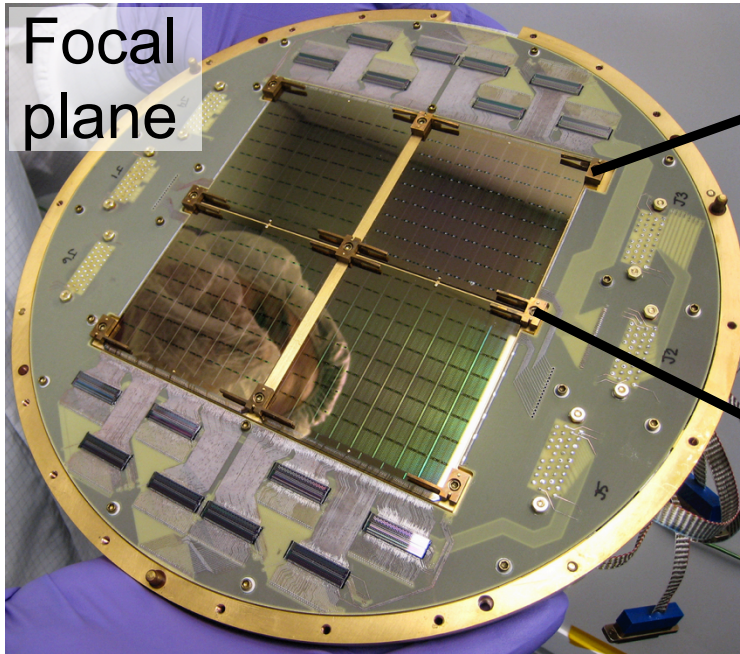
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

Pulse tube cooler cools the optical elements to 4.2 K.

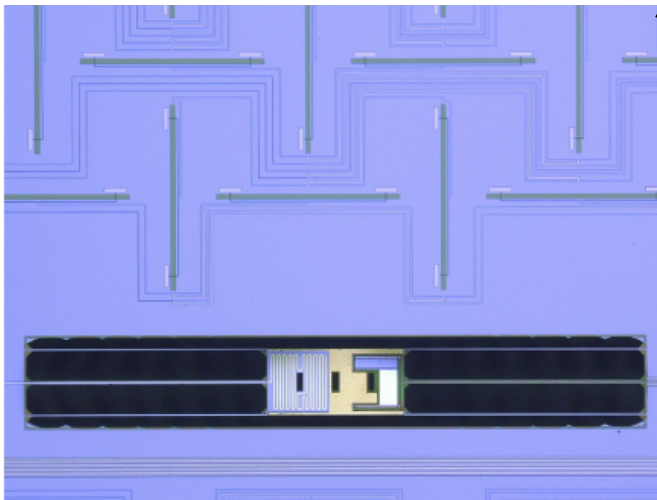
3-stage helium sorption refrigerator further cools the detectors to 0.3 K.



Mass-produced Superconducting Detectors



Planar antenna array



Transition edge sensor

Slot antennas



Microstrip filters

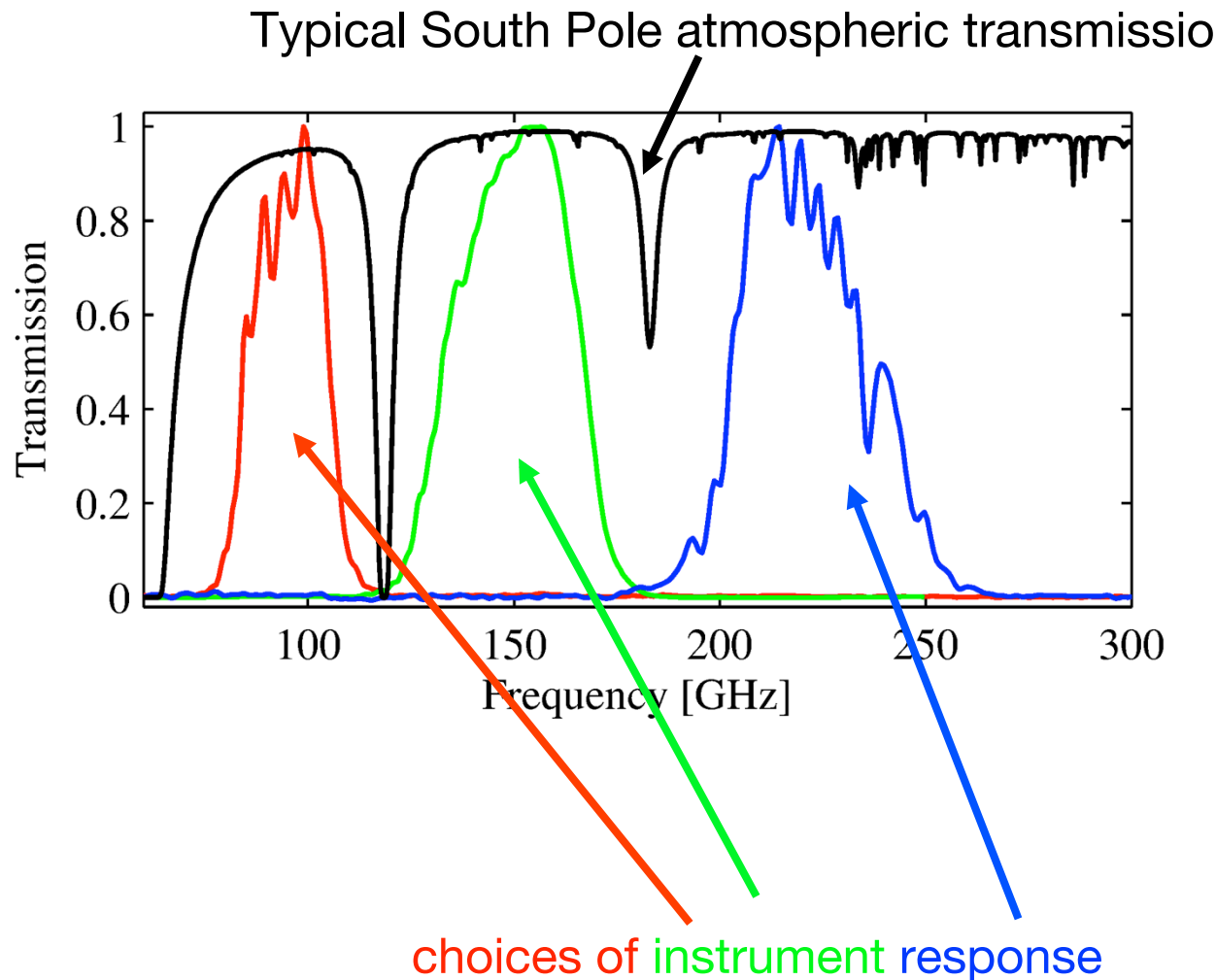
BICEP/Keck Band Passes

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.



Why do this at the Pole?

South Pole CMB telescopes



- 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

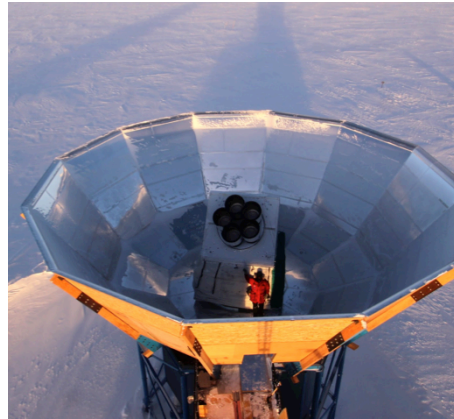
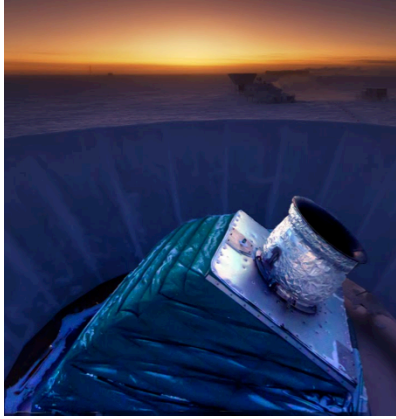
BICEP2
(2010-2012)

Keck Array
(2012-2019)

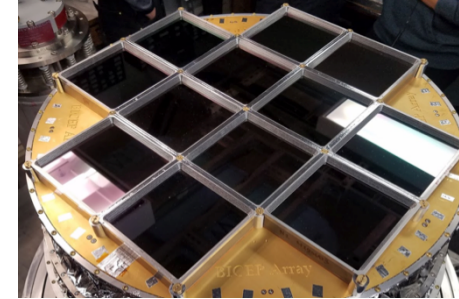
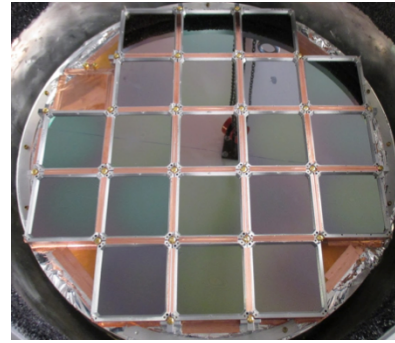
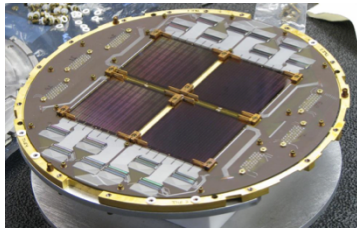
BICEP3
(2016-present)

BICEP Array
(2020-present)

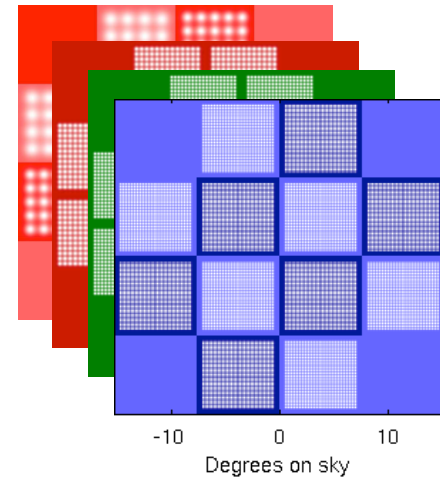
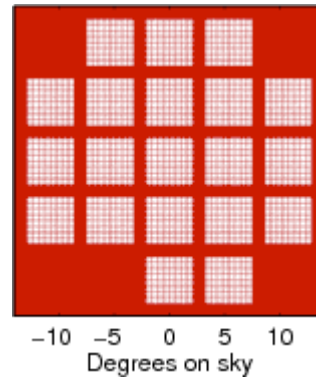
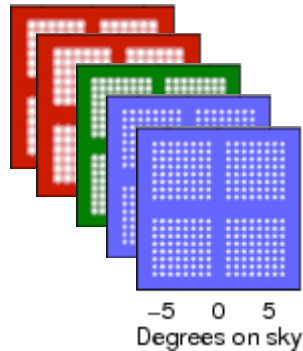
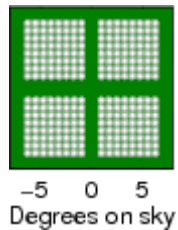
Telescope and Mount



Focal Plane



Beams on Sky



South Pole Site



MAPO

DSL

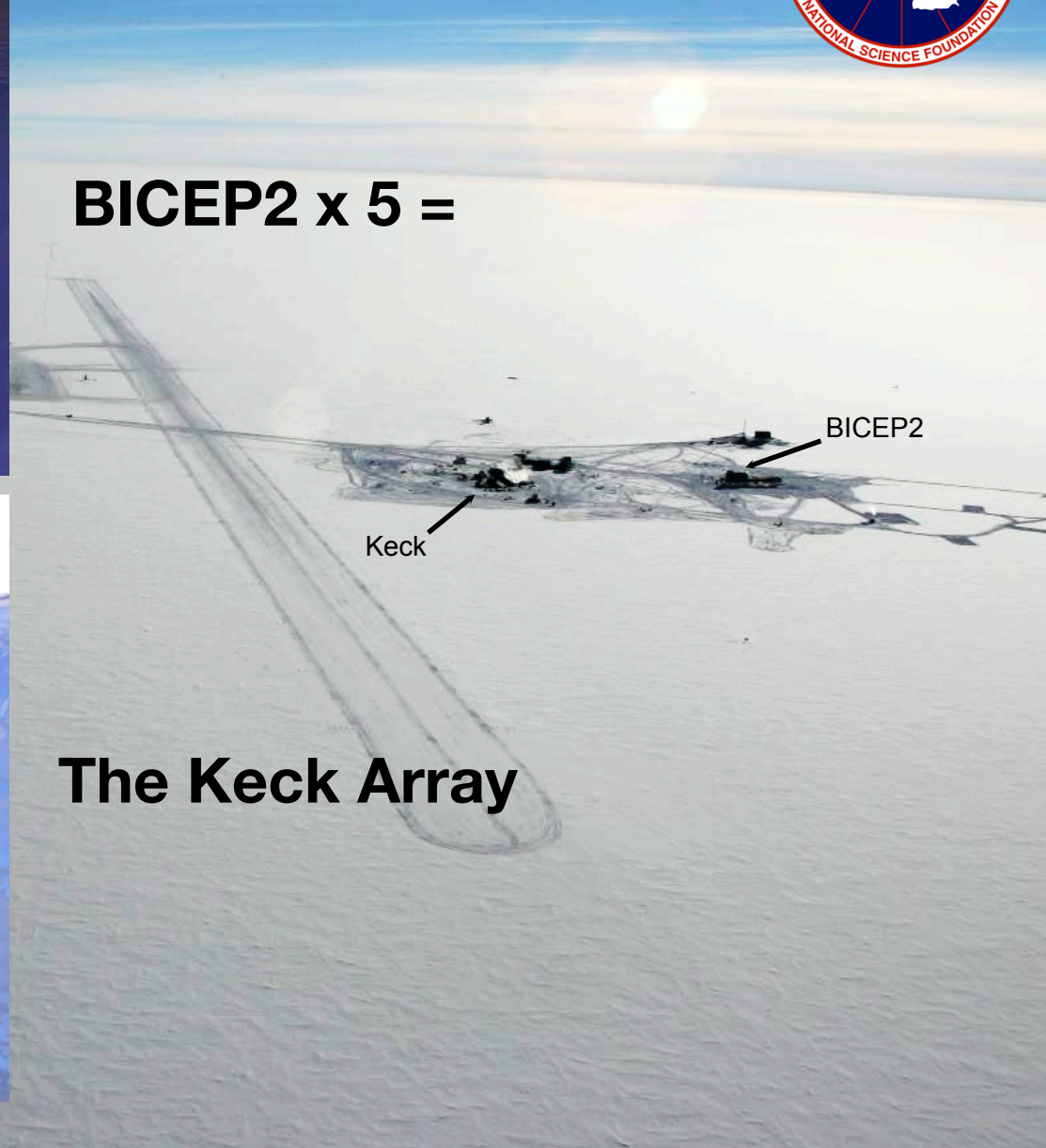
BICEP2 and Keck Array



BICEP2 2010-2012



BICEP2 x 5 =



Keck Array 2012-2019



The Keck Array

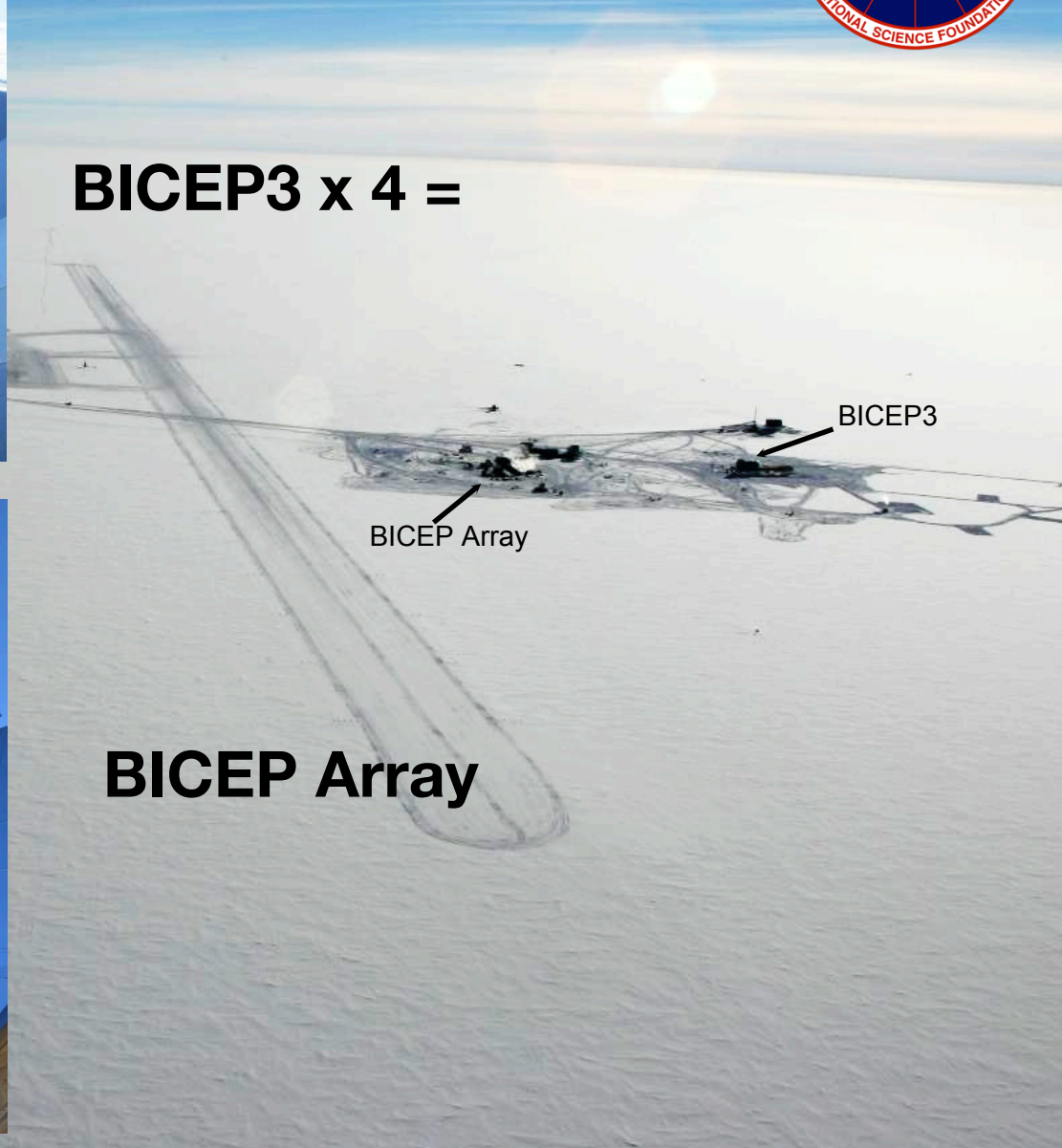
BICEP3 and BICEP Array



BICEP3 2016-present



BICEP3 x 4 =



BICEP3

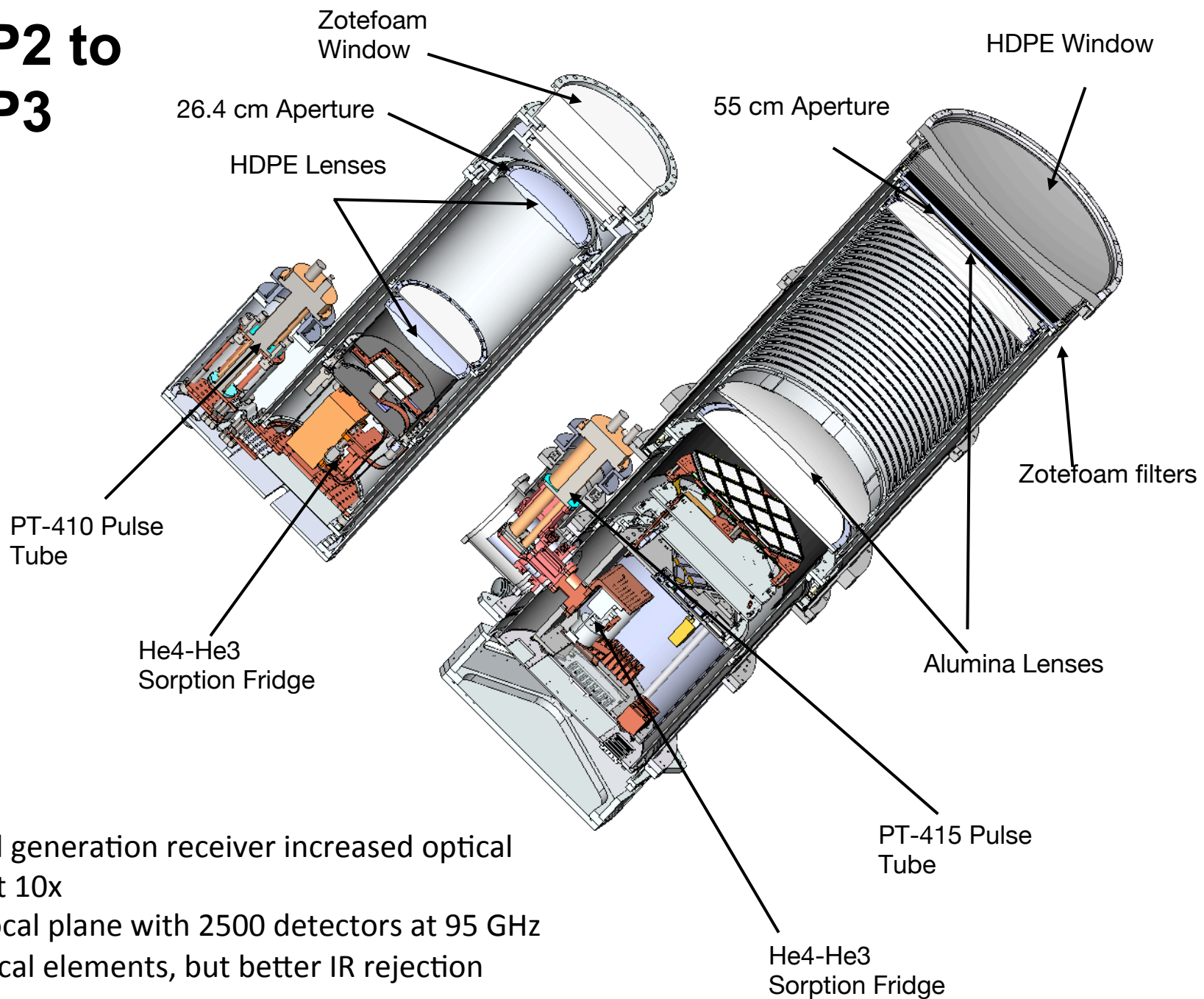
BICEP Array

BICEP Array 2020-present

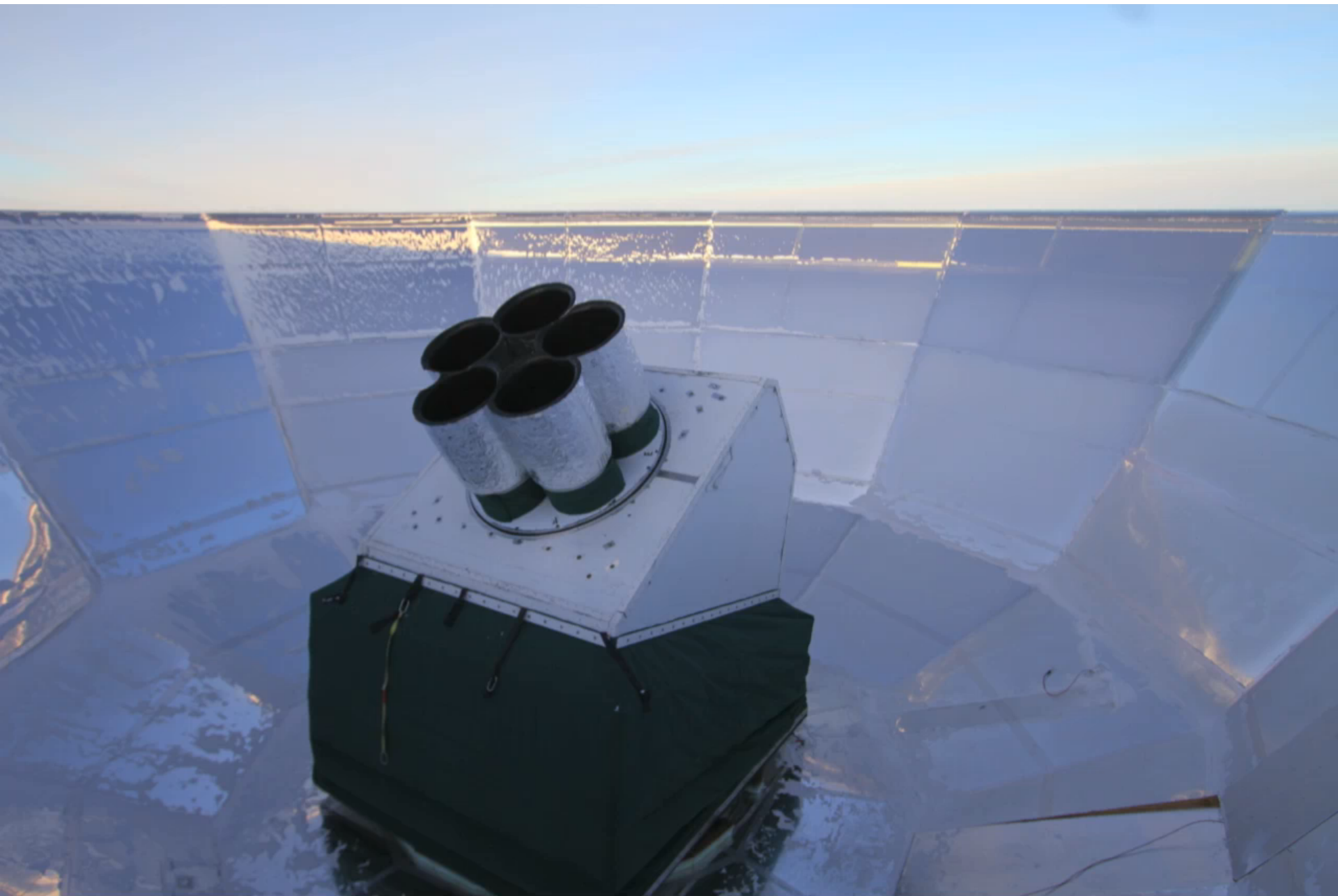


BICEP Array

BICEP2 to BICEP3

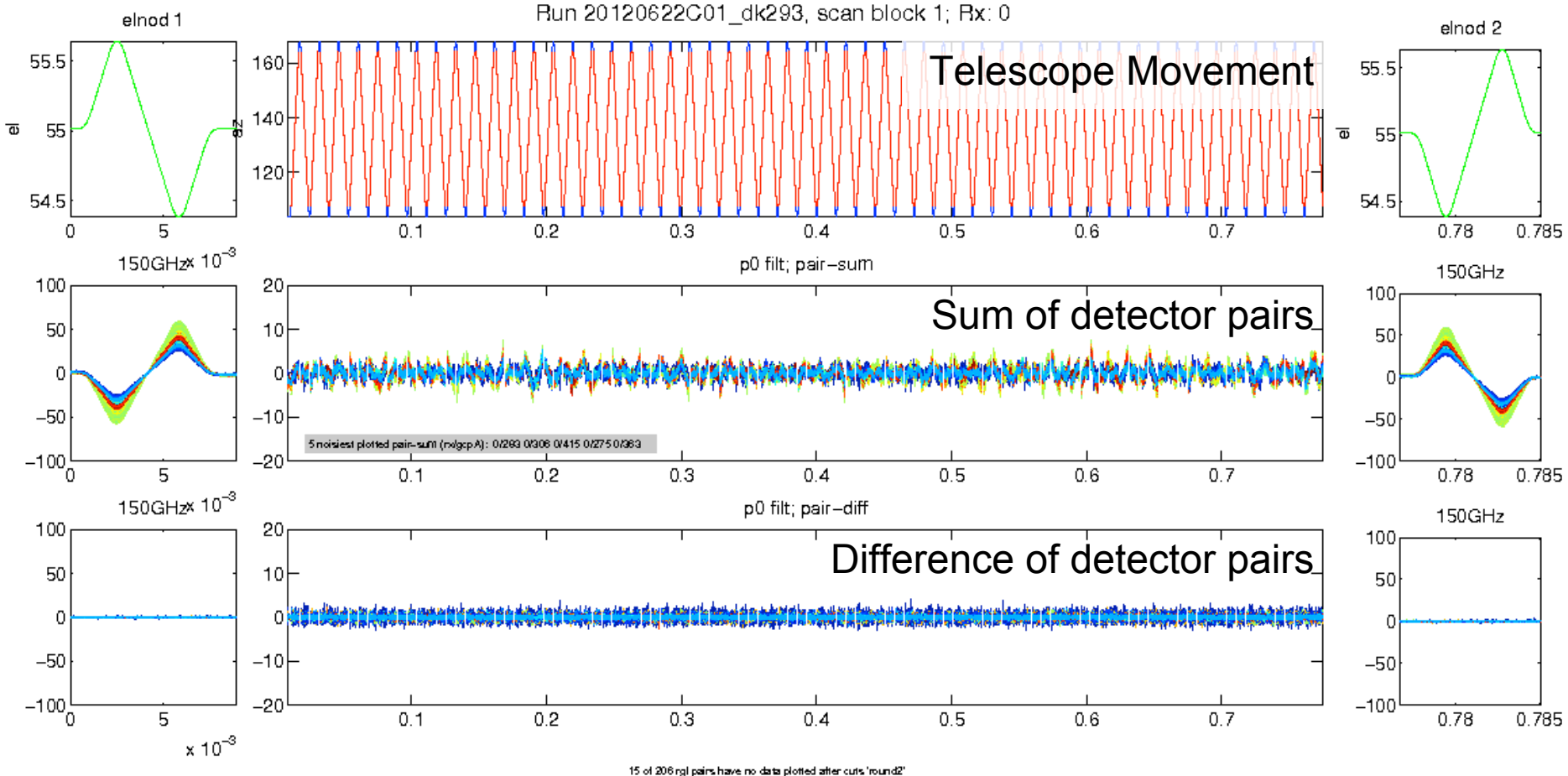


- BICEP's 3rd generation receiver increased optical throughput 10x
- Modular focal plane with 2500 detectors at 95 GHz
- Larger optical elements, but better IR rejection



Raw Data - Perfect Weather

Time 50 mins

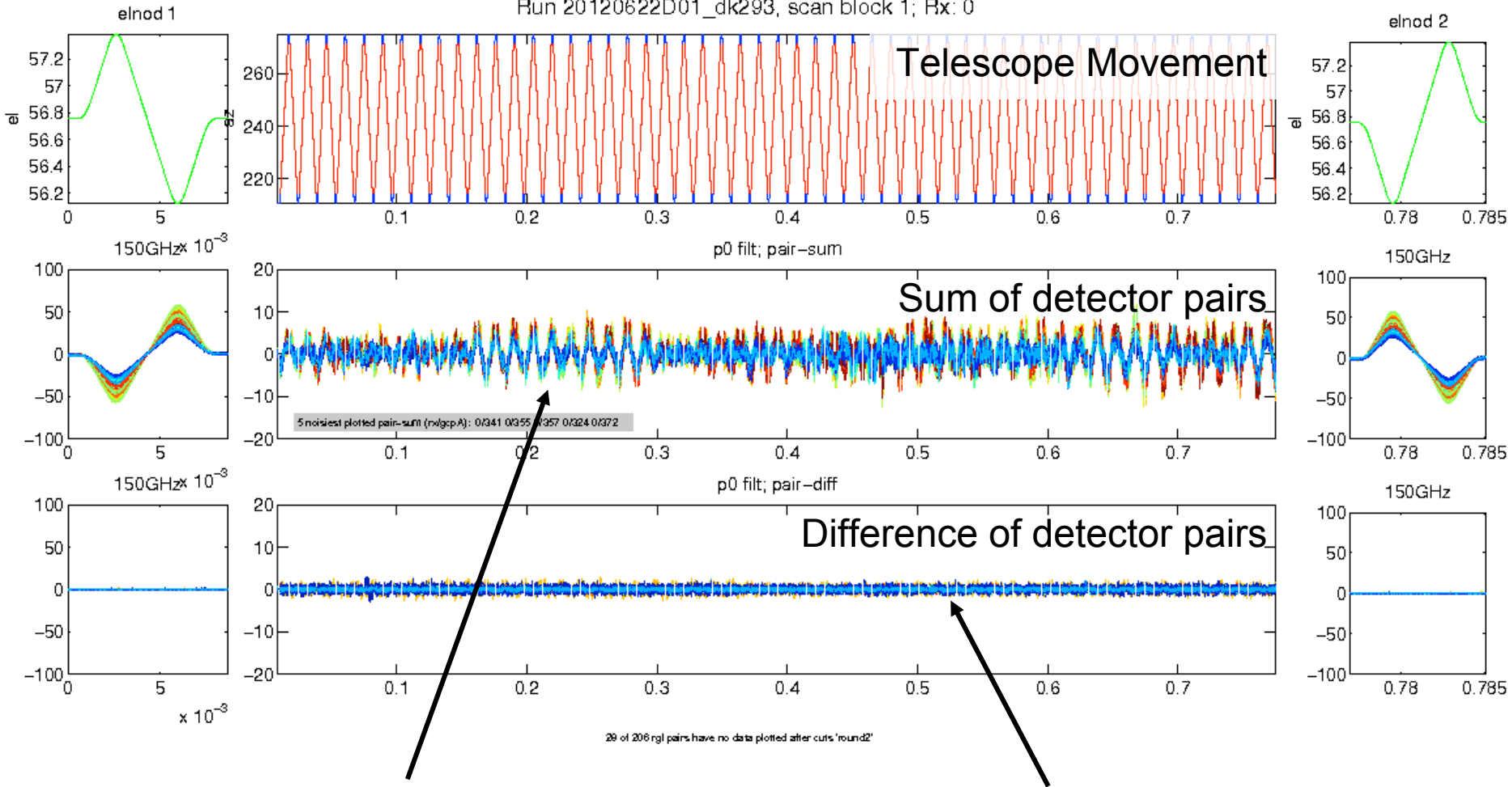


➤ Cover the whole field in 60 such scansets then start over at new boresight rotation

➤ Scanning modulates the CMB signal to freqs < 4 Hz

Raw Data - Worse Weather

Time 50 mins

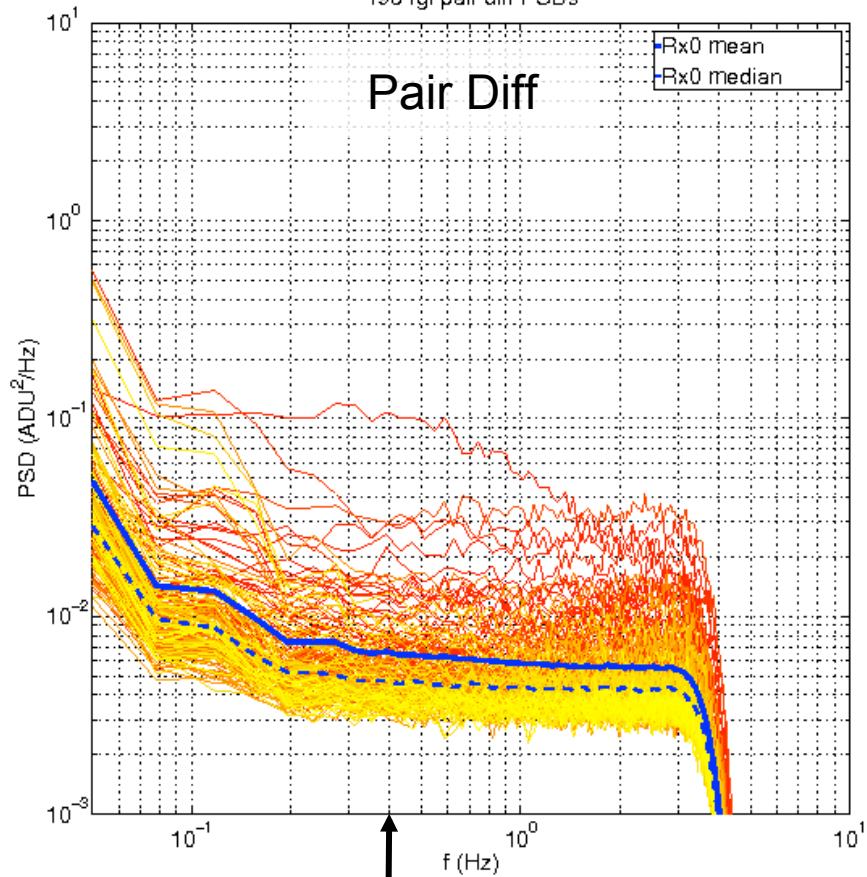


➤ Scanning over lumpy atmosphere
→ “clouds”

➤ Pair difference still clean
→ atmosphere is unpolarized

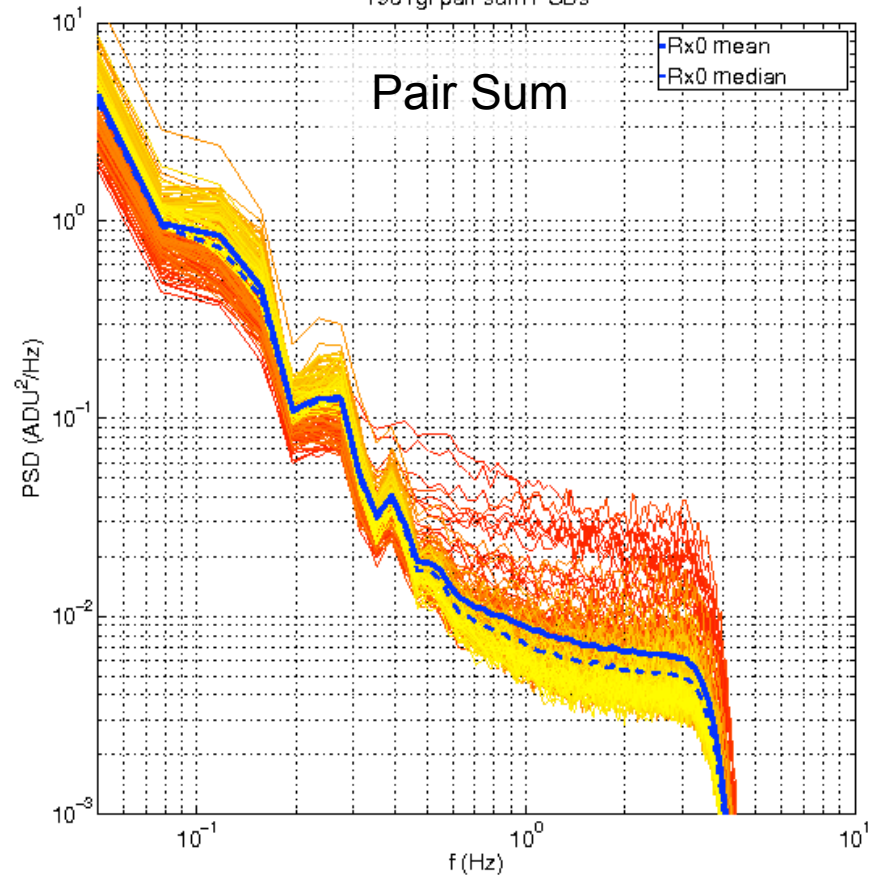
Timestream PSDs

PSDs (s/d→p0→ Σ PSD_{hs}/N_{hs}); Run 20120622C01_dk293, scan block 1; Rx: 0
198 rgl pair diff PSDs

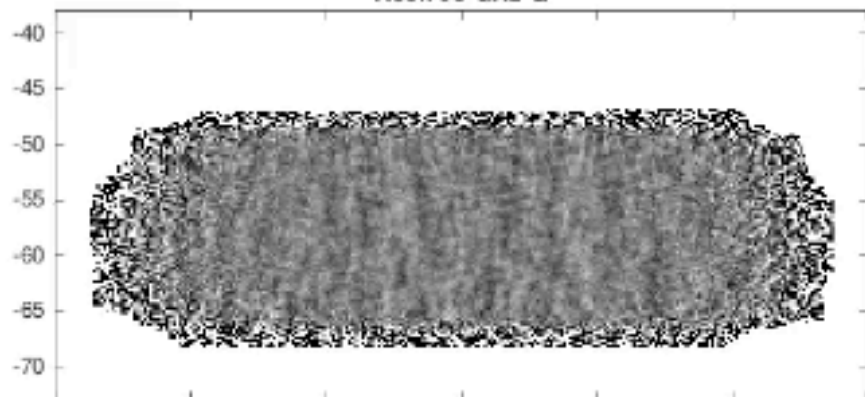


➤ Multipole 100 at 0.4Hz

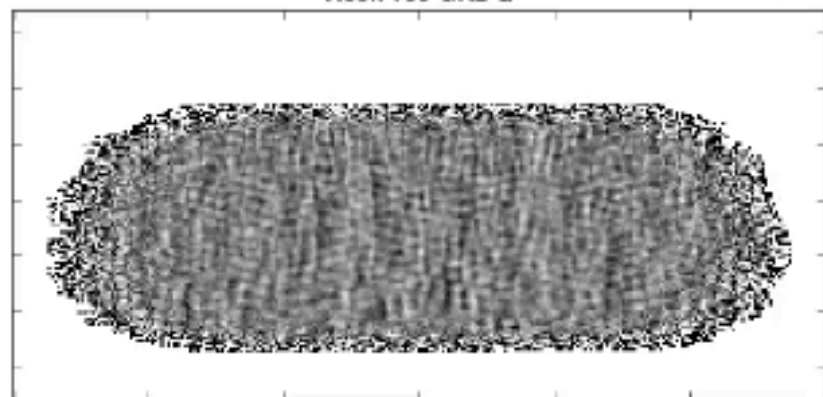
198 rgl pair sum PSDs



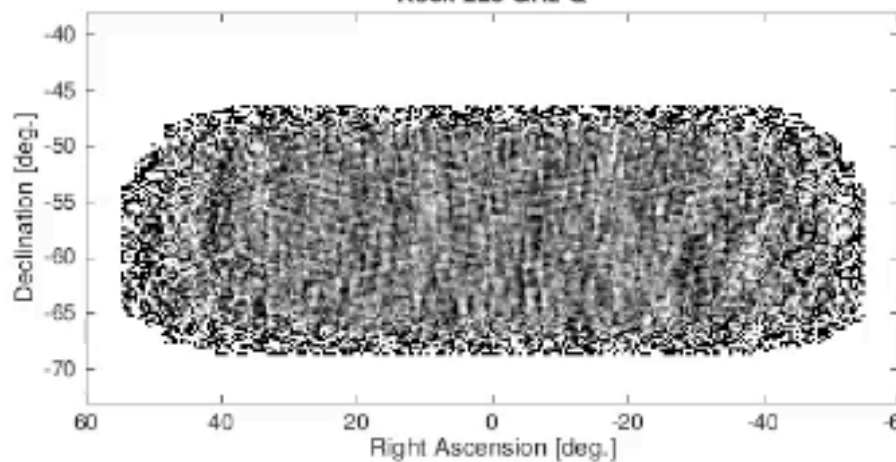
Keck 95 GHz Q



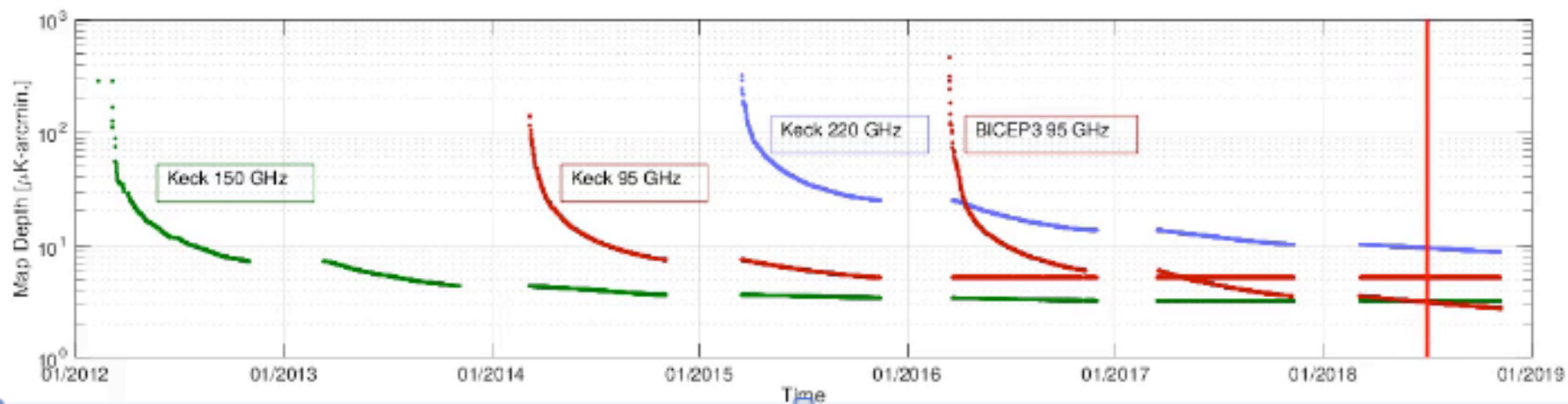
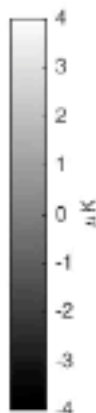
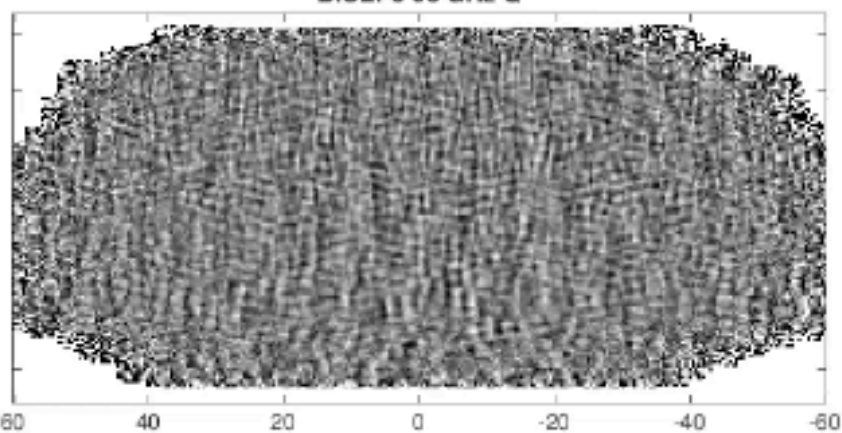
Keck 150 GHz Q



Keck 220 GHz Q

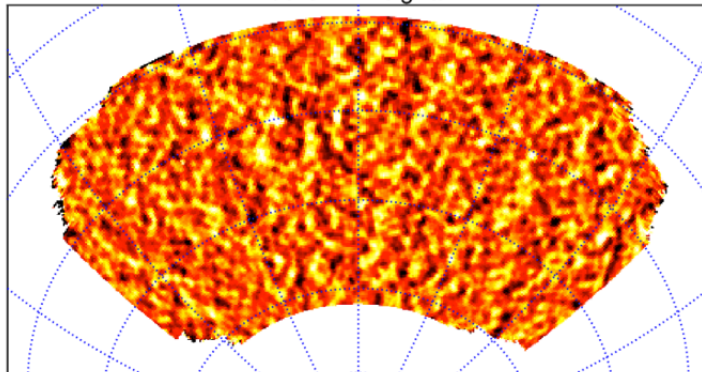


BICEP3 95 GHz Q

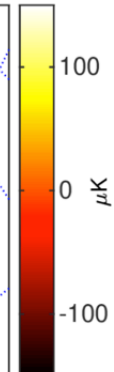
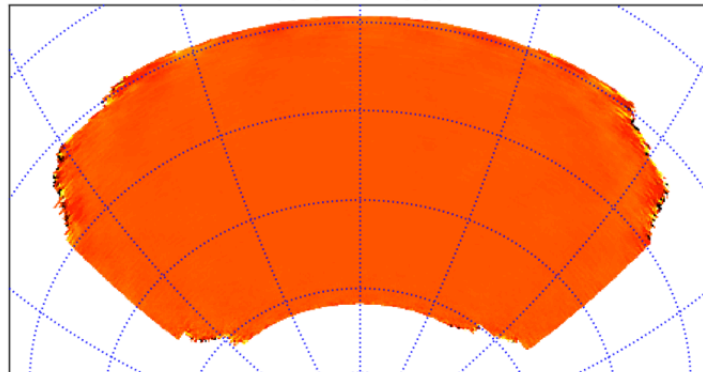


BK18 95GHz Maps

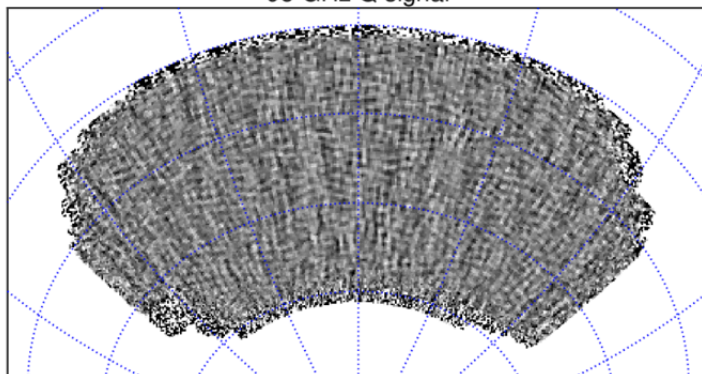
95 GHz T signal



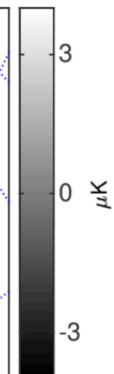
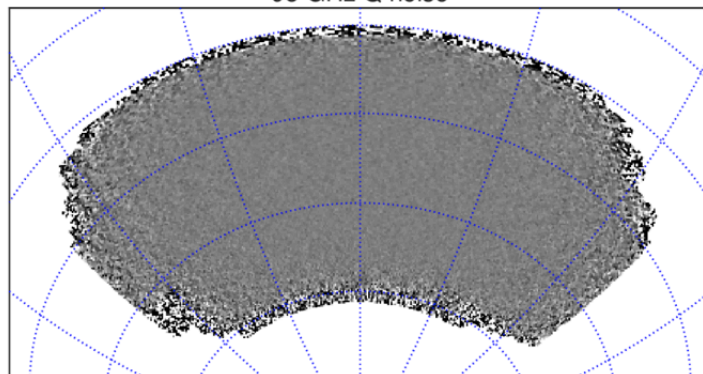
95 GHz T noise



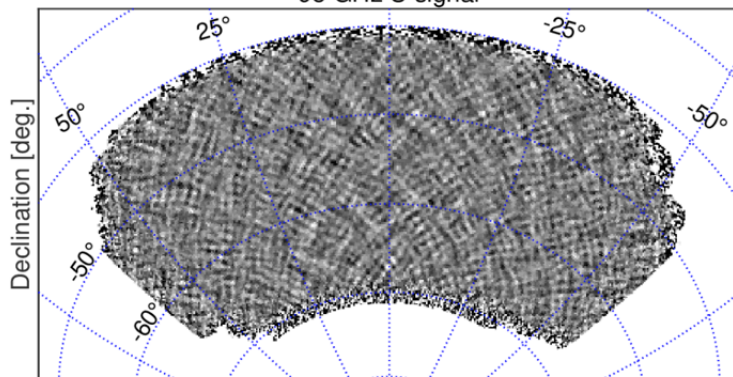
95 GHz Q signal



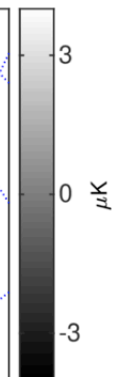
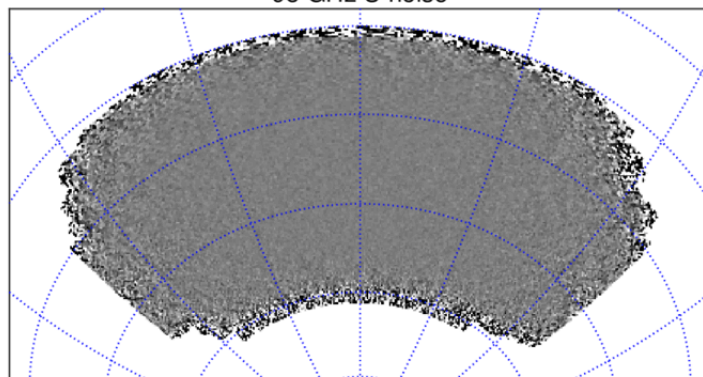
95 GHz Q noise



95 GHz U signal

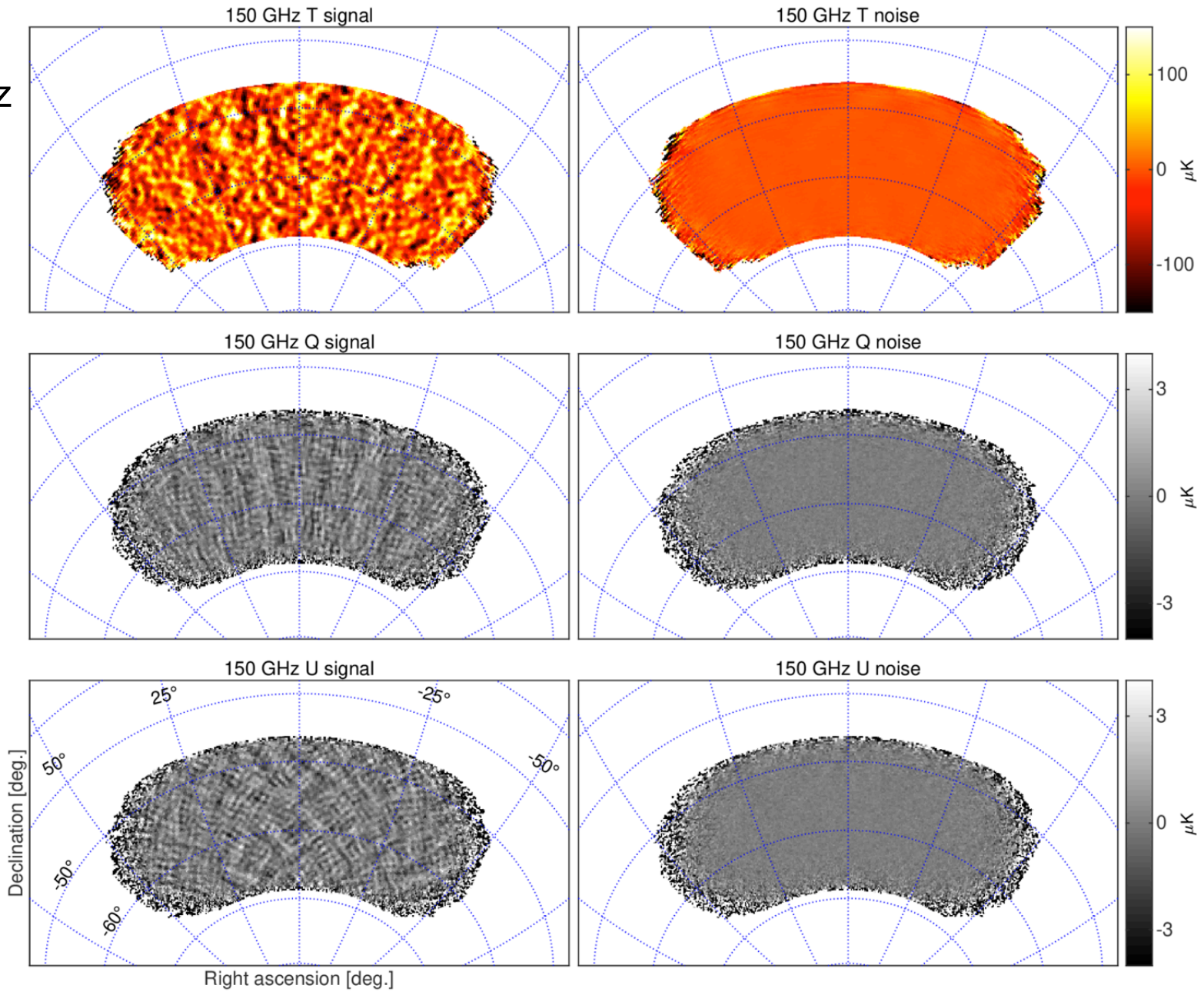


95 GHz U noise

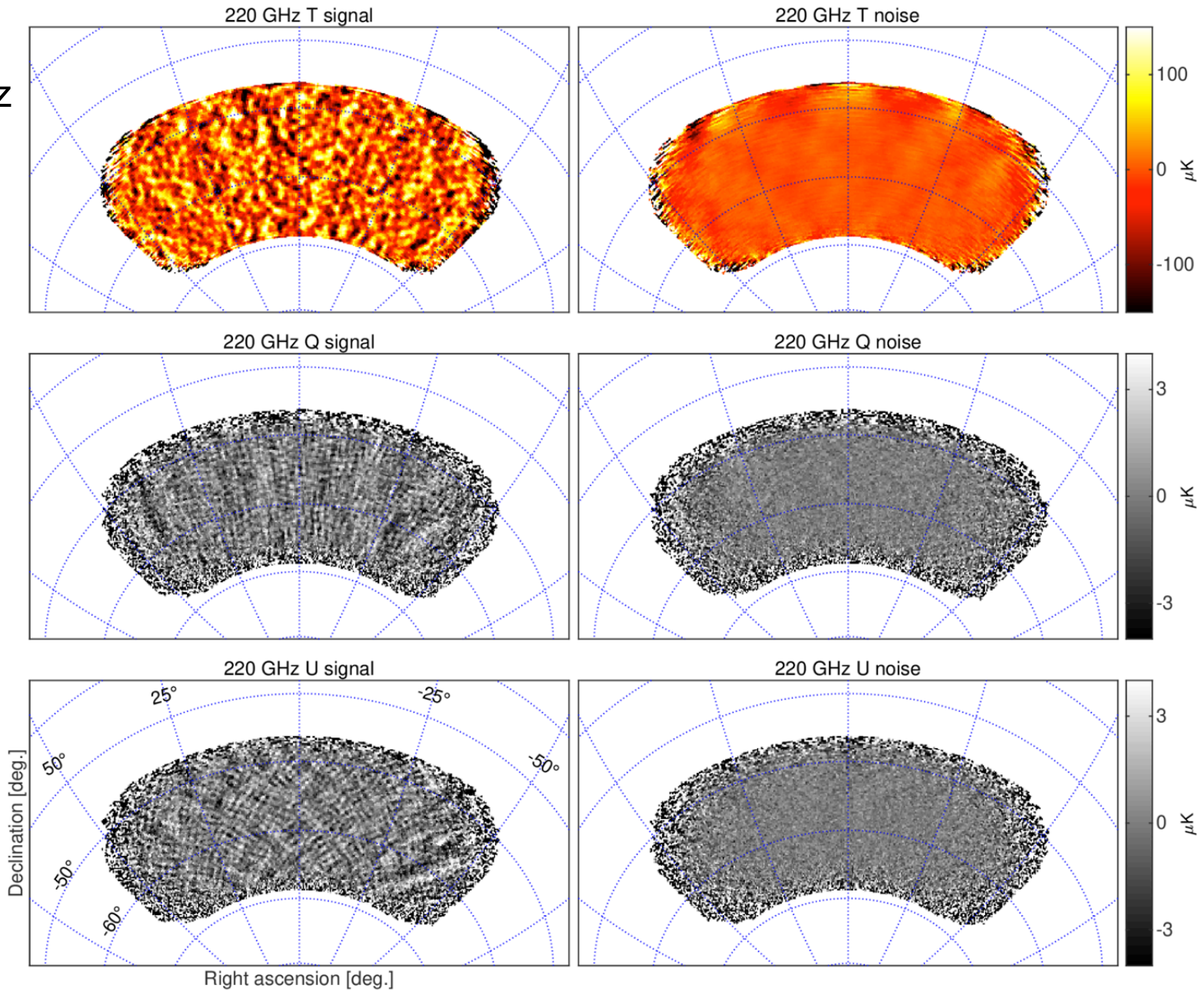


Right ascension [deg.]

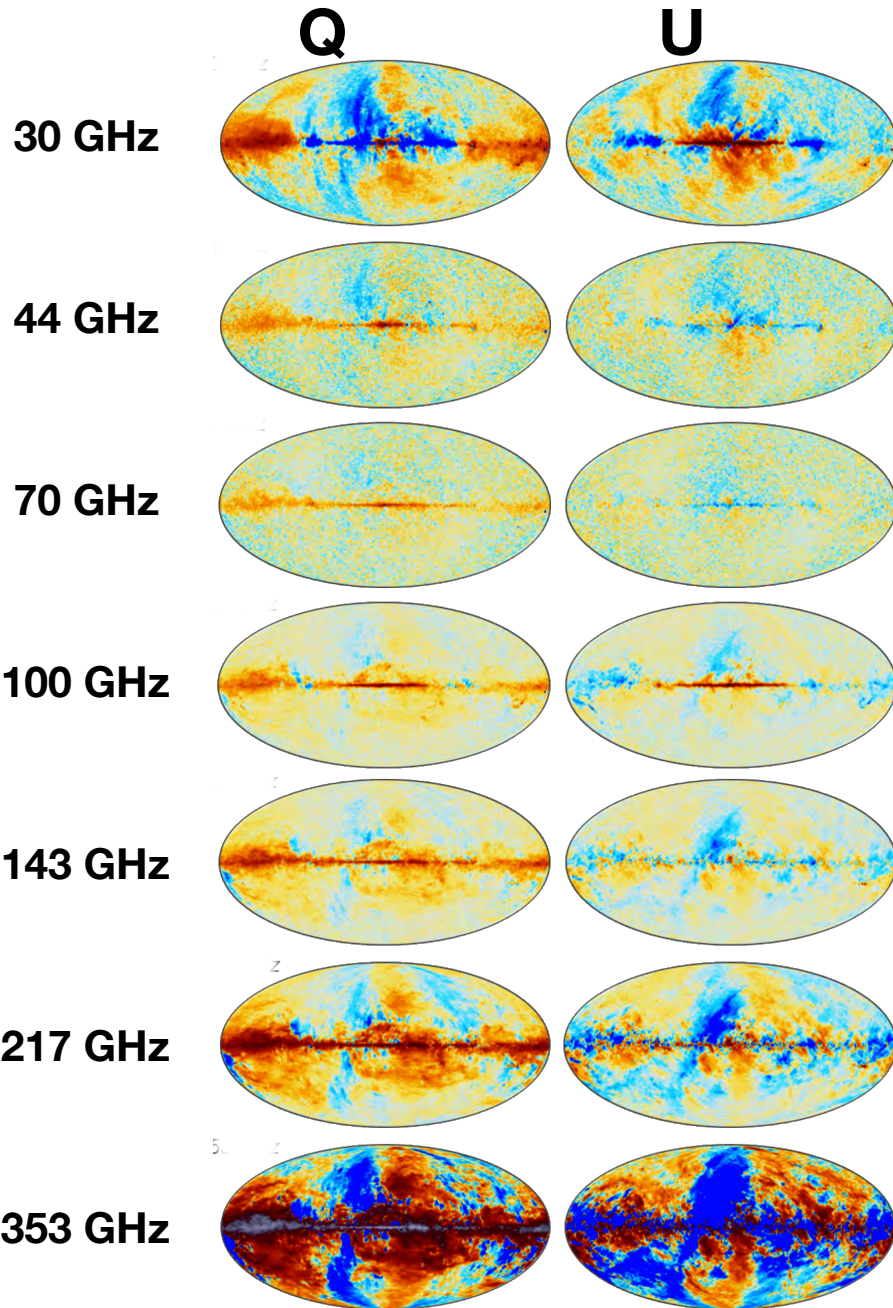
BK18 150GHz Maps



BK18 220GHz Maps



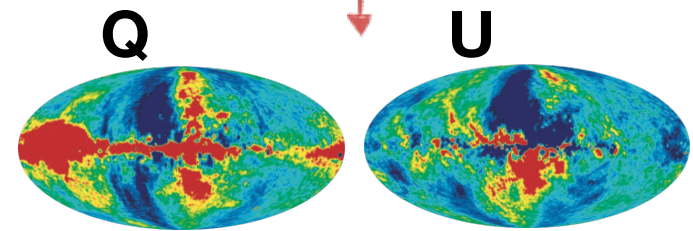
Add to the mix: Planck at 5 frequencies and WMAP at 2 frequencies



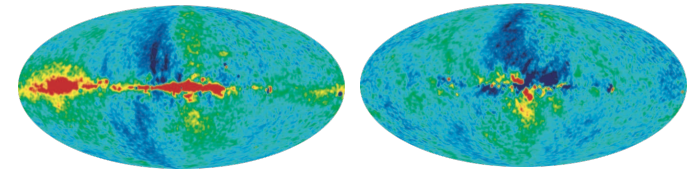
Polarized galactic **synchrotron** dominates at low frequencies



23 GHz



33 GHz



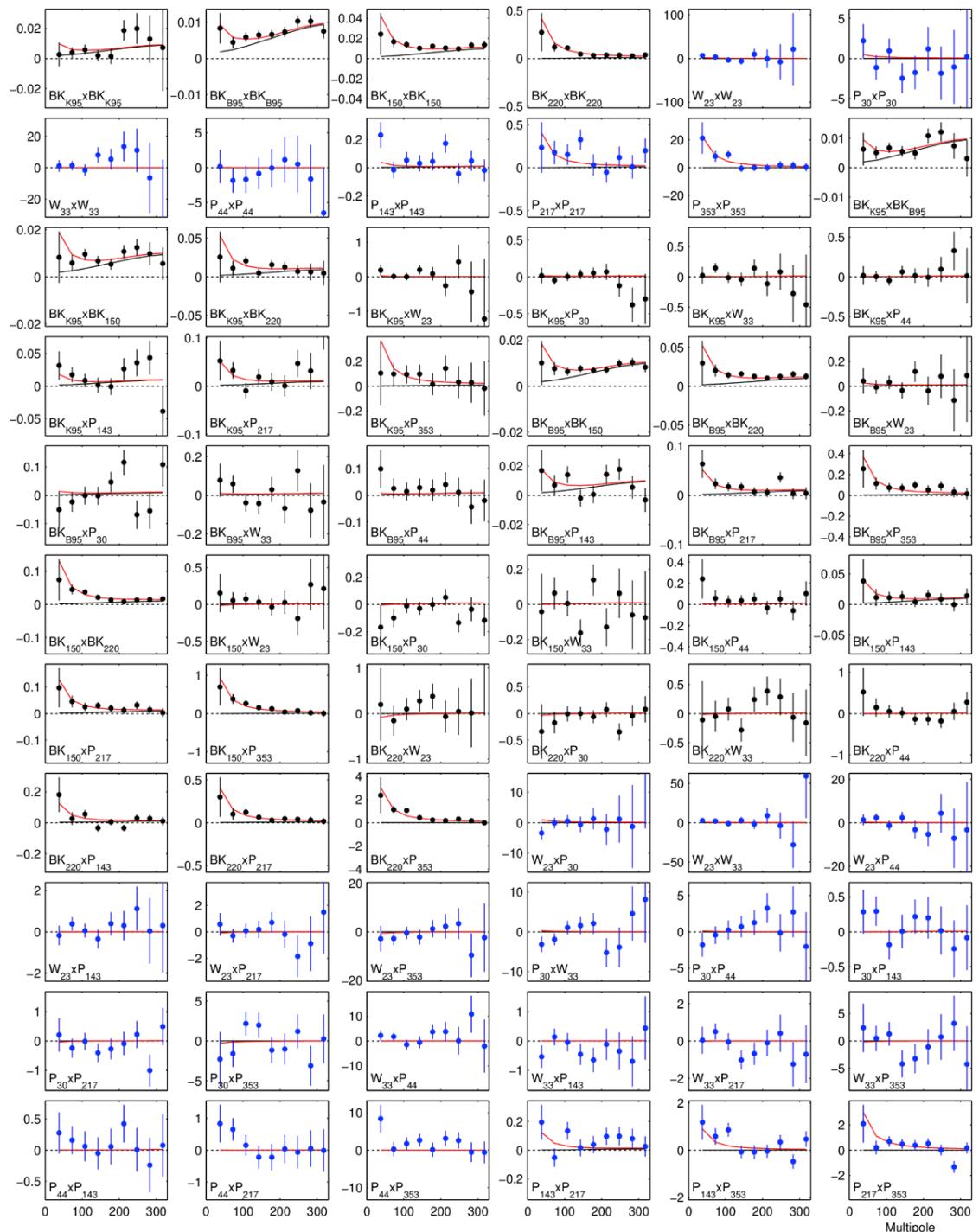
From arxiv 1212.5225

Polarized thermal emission ($\sim 20\text{K}$) from galactic **dust** aligned in magnetic fields dominates at high frequencies



From arxiv 1502.01582

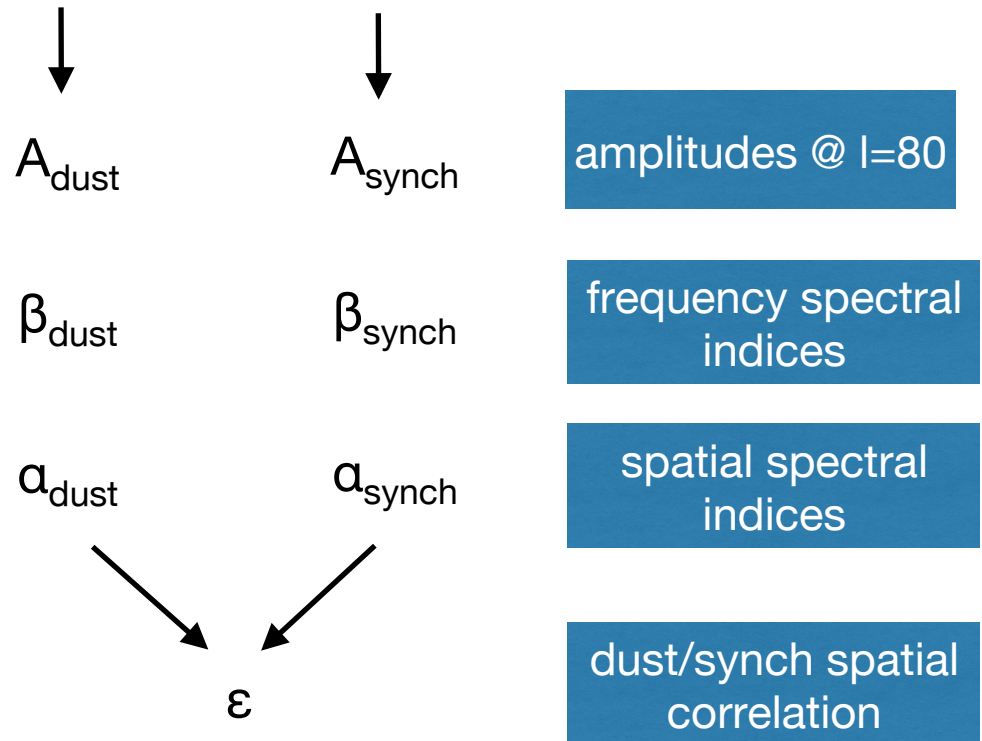
Analysis
Technique: Take all possible auto- and cross spectra between the BICEP/Keck, WMAP, and Planck bands (66 of them) and compare to model of CMB + foregrounds



Multicomponent parametric likelihood analysis

Take the joint likelihood of all the spectra simultaneously vs. model for BB that is the Λ CDM lensing expectation + 7 parameter foreground model + r

foreground model = dust + synchrotron



Dust/Sync Spatial Power Laws?

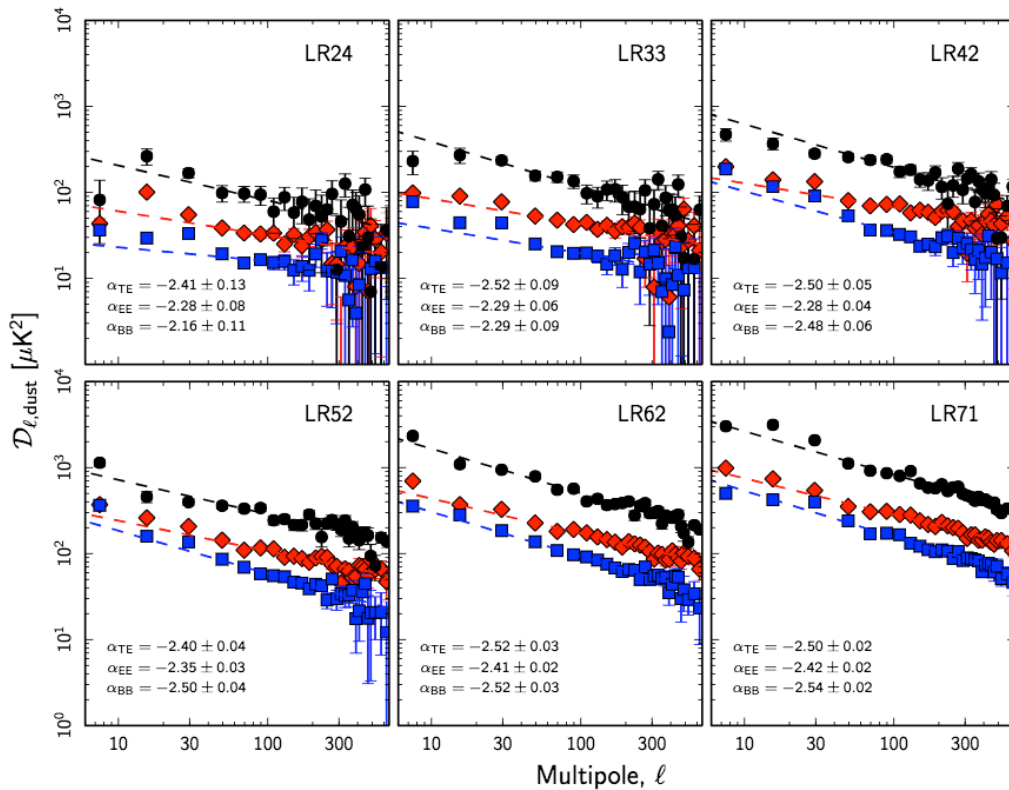


Fig 2 of arxiv/1801.04945 – Planck dust analysis

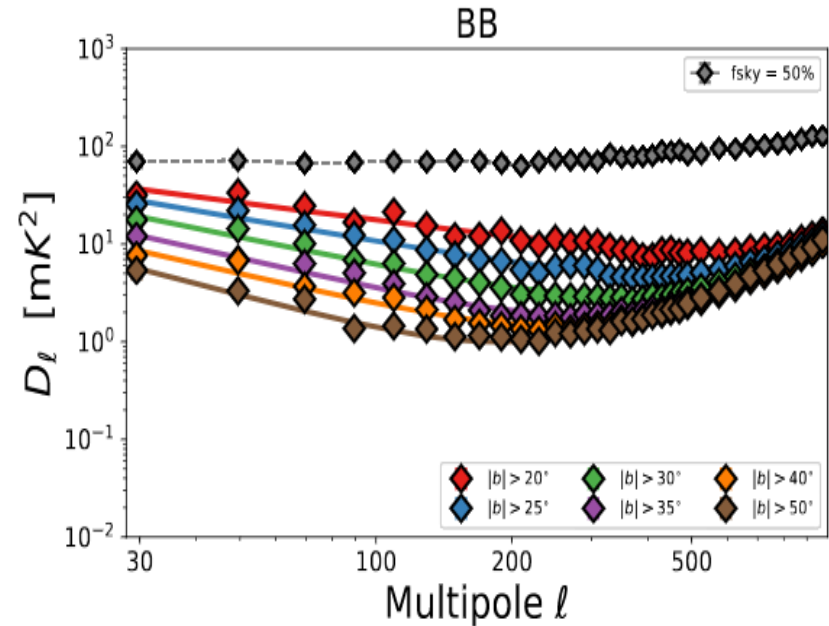


Fig 2 of arxiv/1802.01145. – S-PASS sync analysis

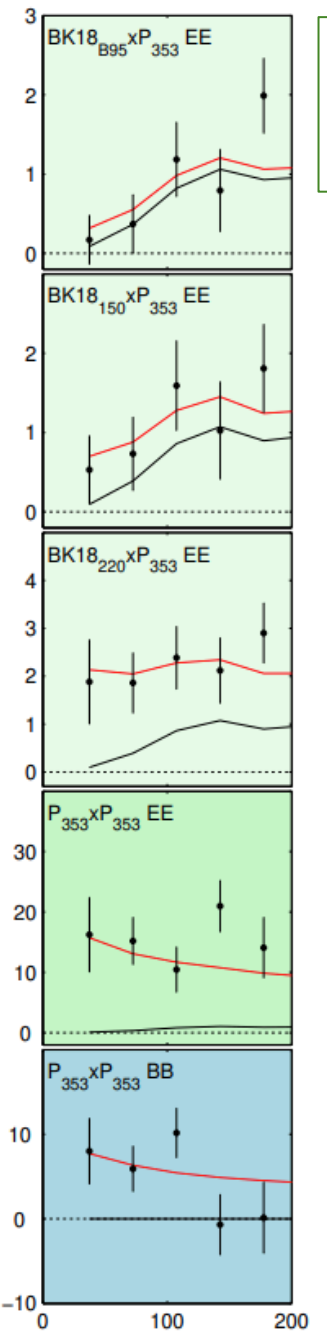
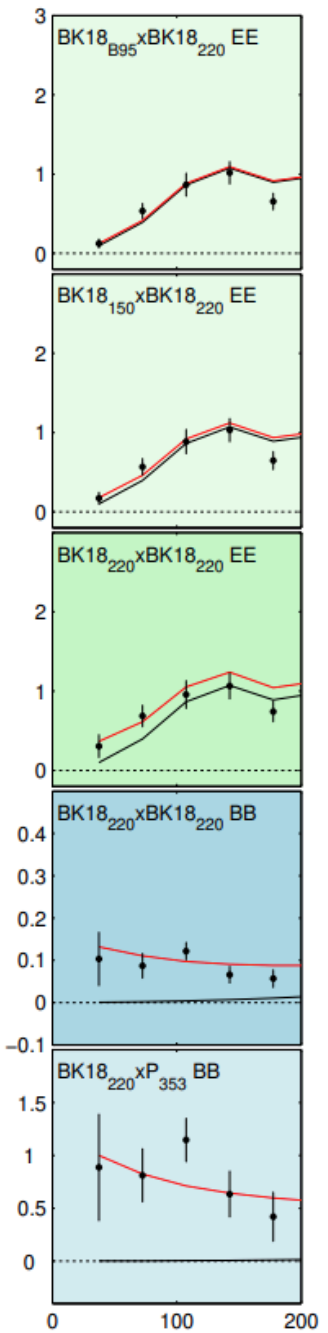
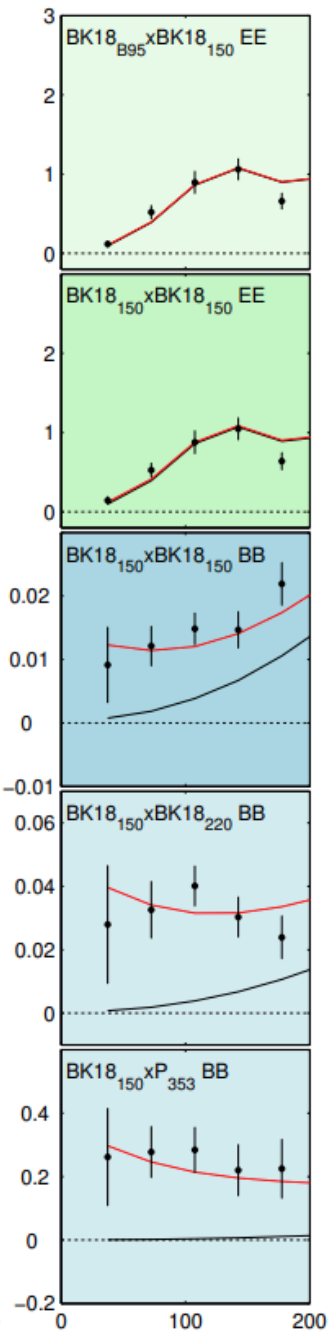
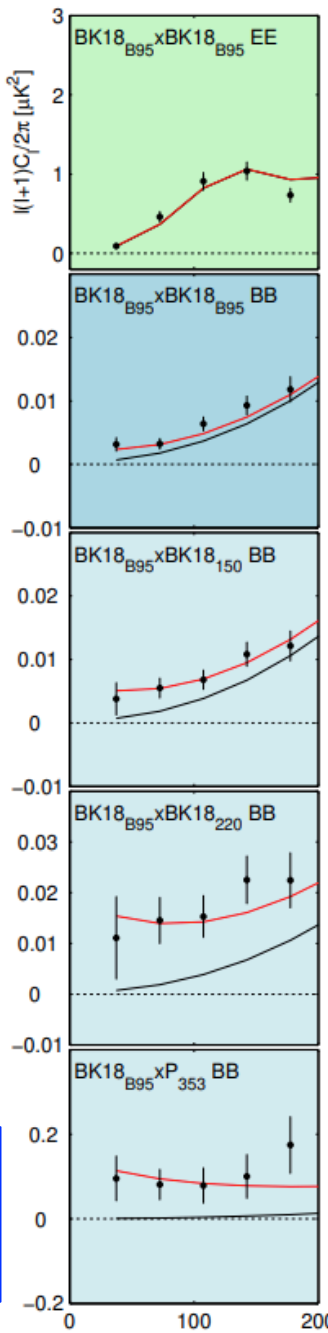
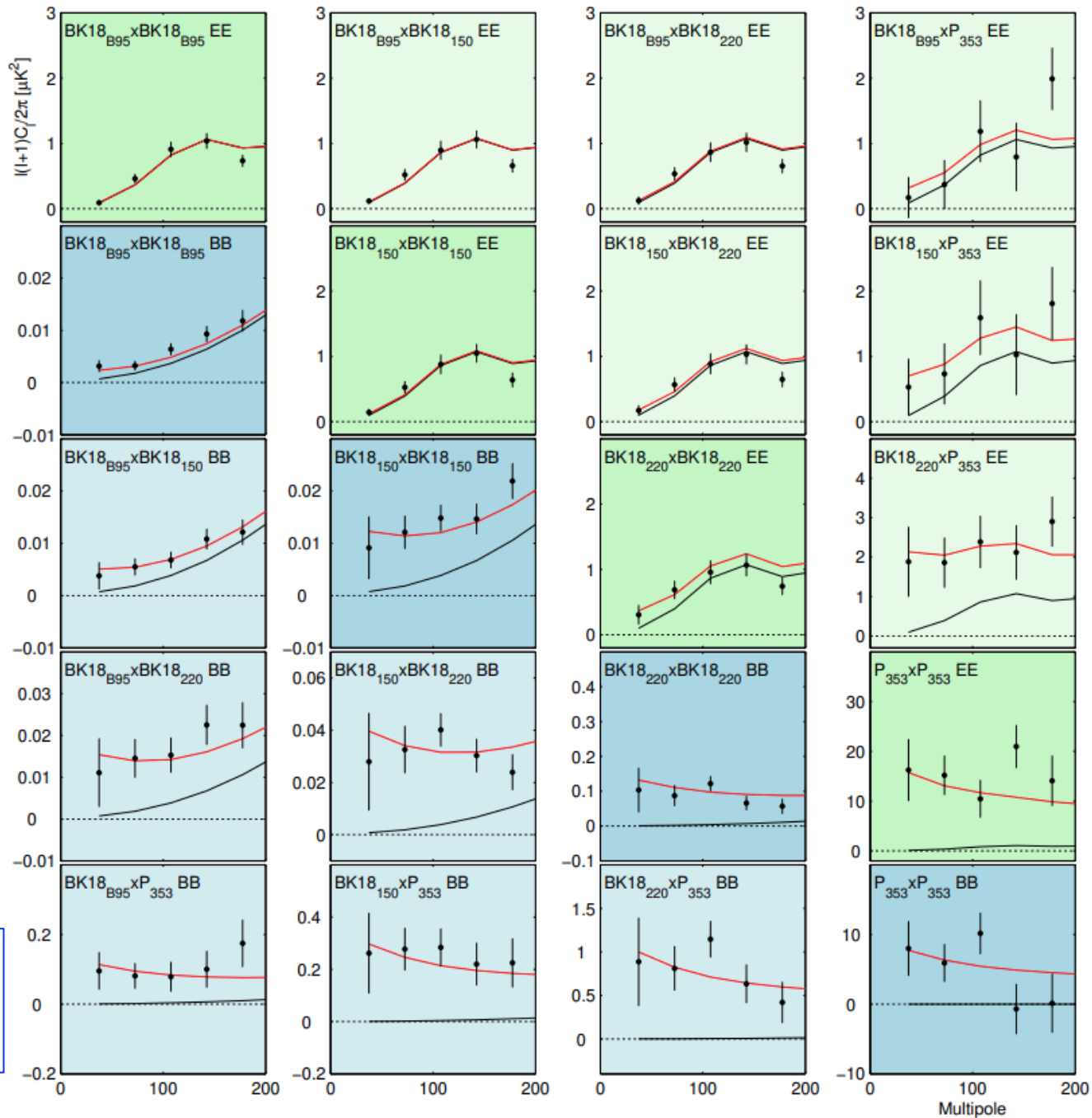
- Averaged over large regions of sky it is an empirical fact that dust and sync have roughly power law angular power spectra
- Not enough signal-to-noise in Planck data to investigate fluctuations about this behavior for small sky patches

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

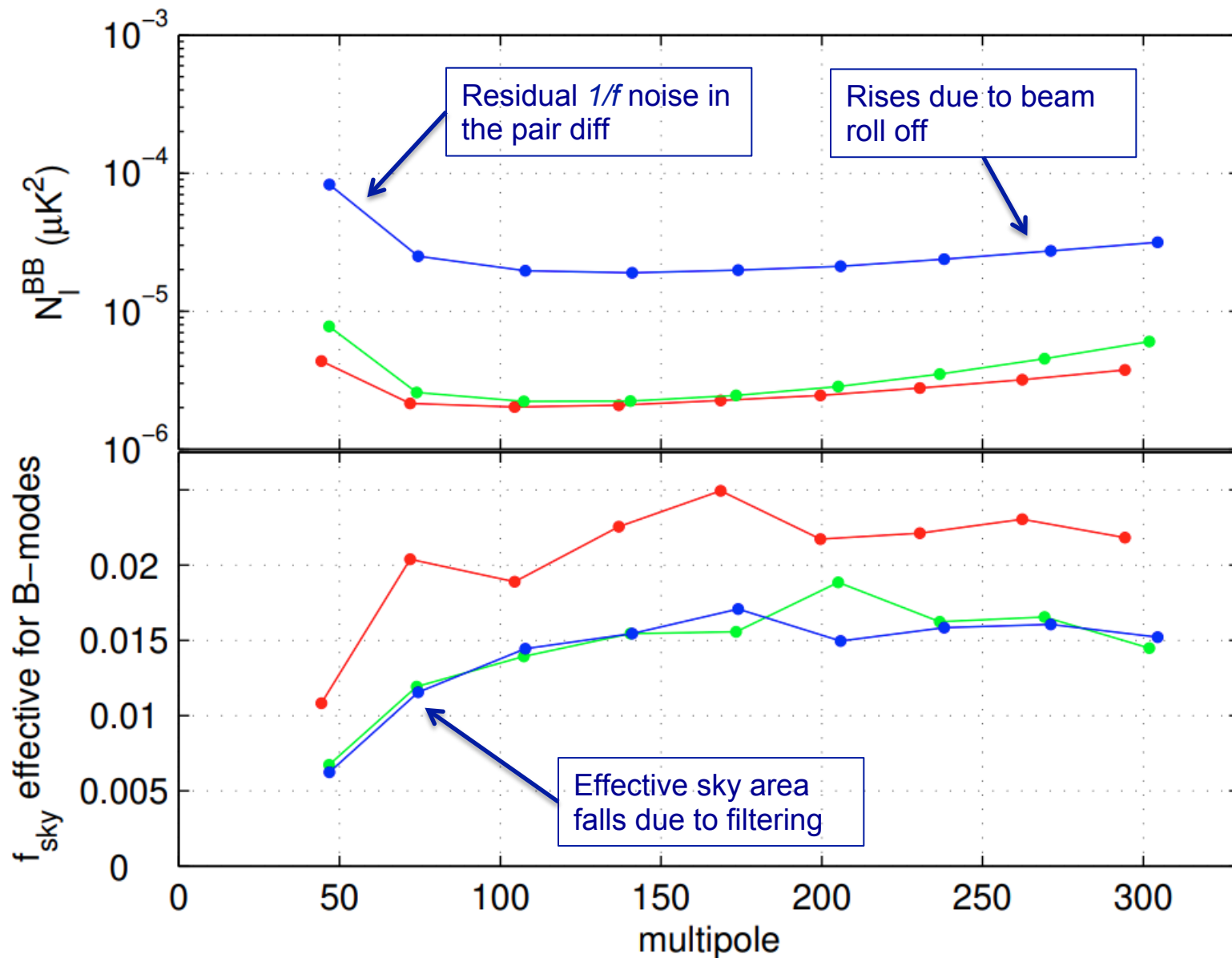
Black lines are
 LCDM
 Red lines are
 LCDM+dust

Blue panels are
 BB
 spectra

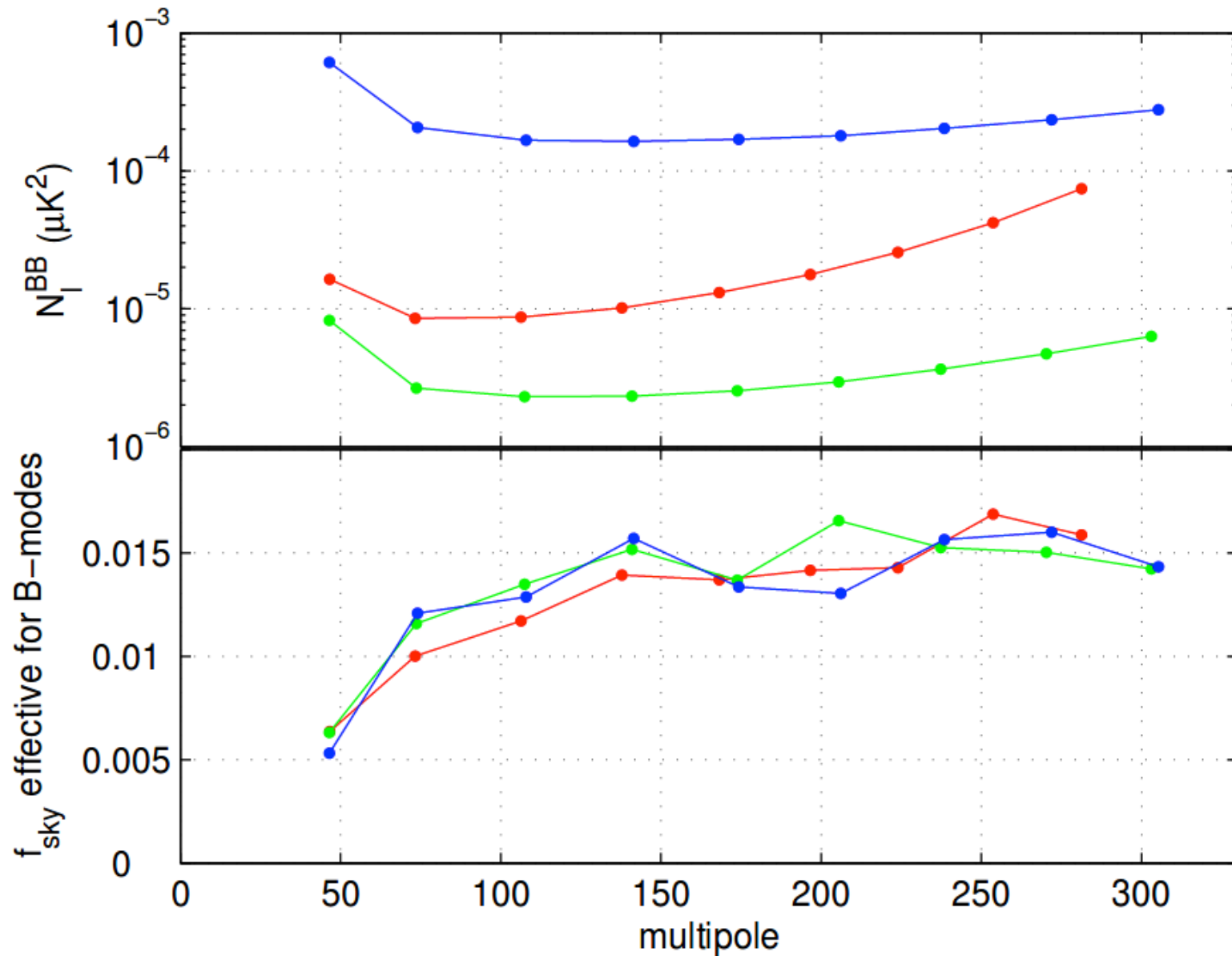
Green
 panels are
 EE
 spectra



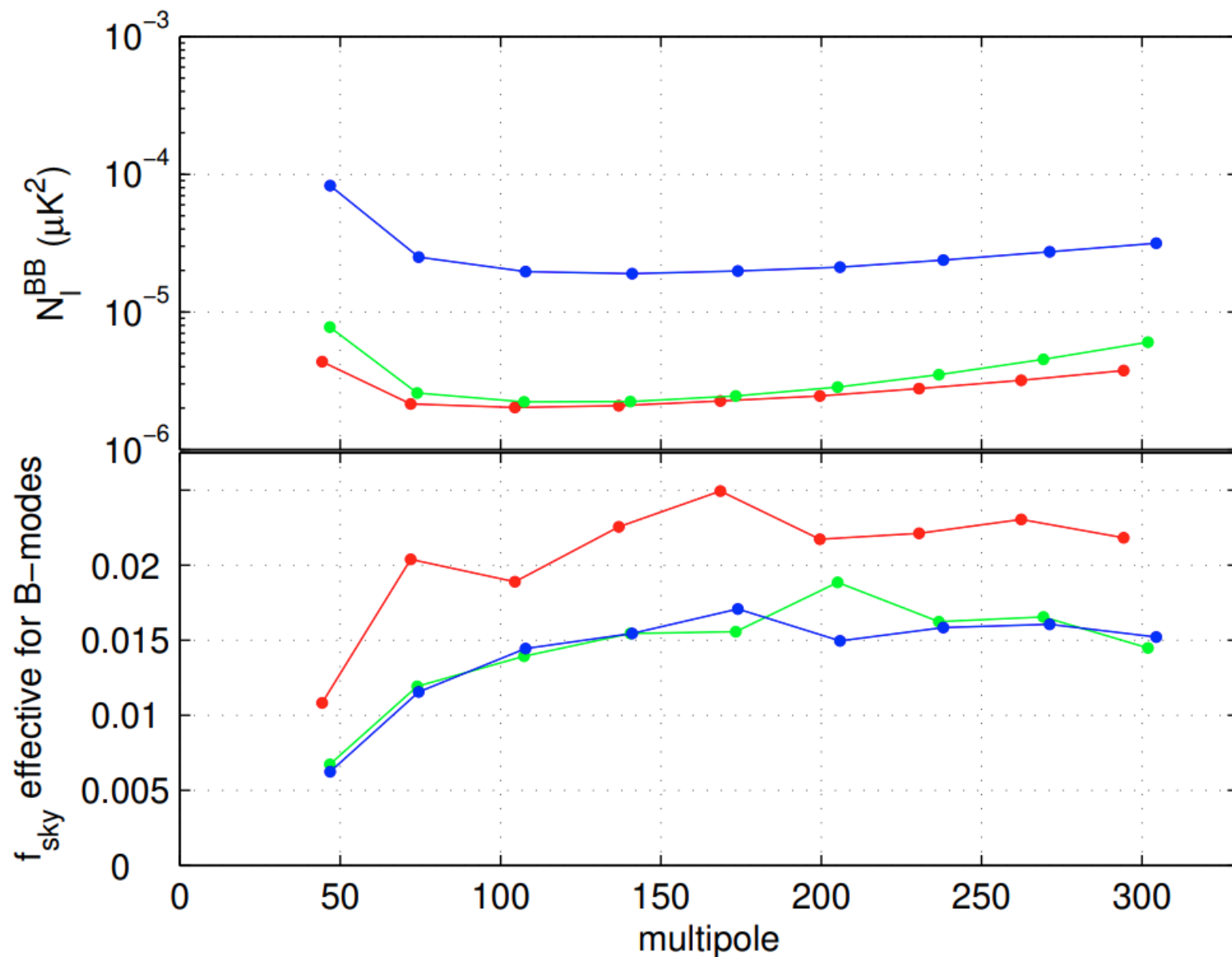
BK18 Noise Spectra and f_{sky} Effective

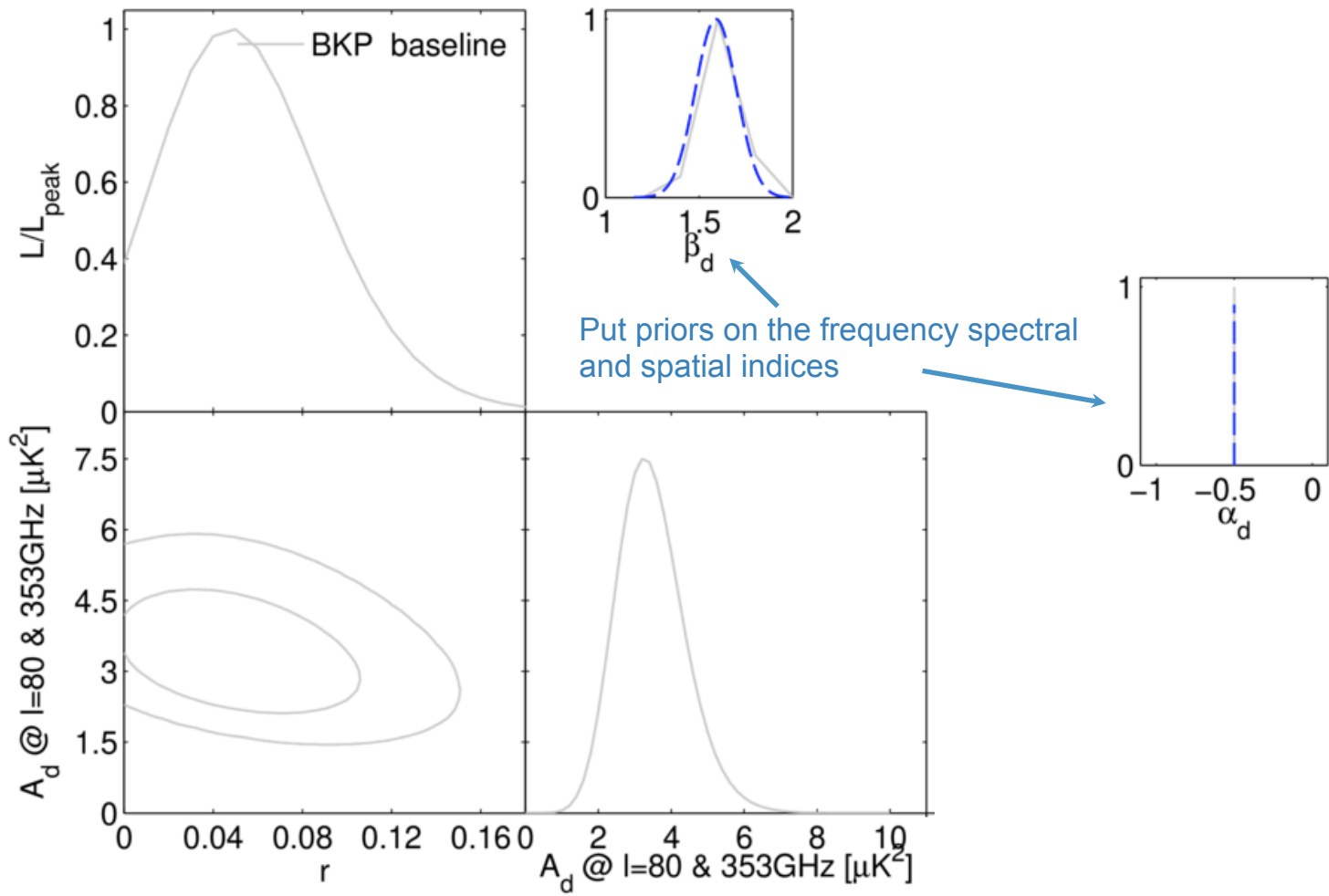


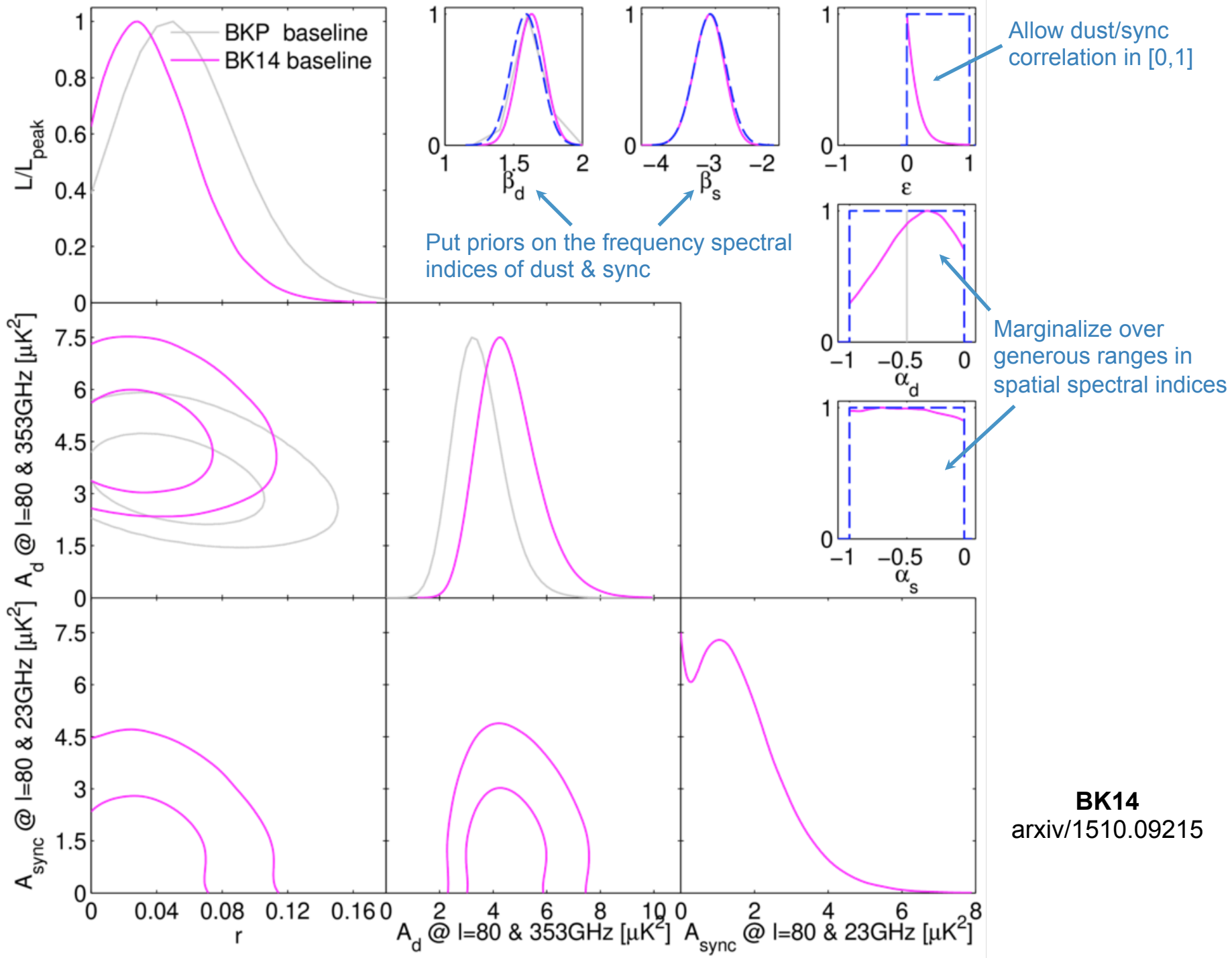
BK15 Noise Spectra and f_{sky} Effective



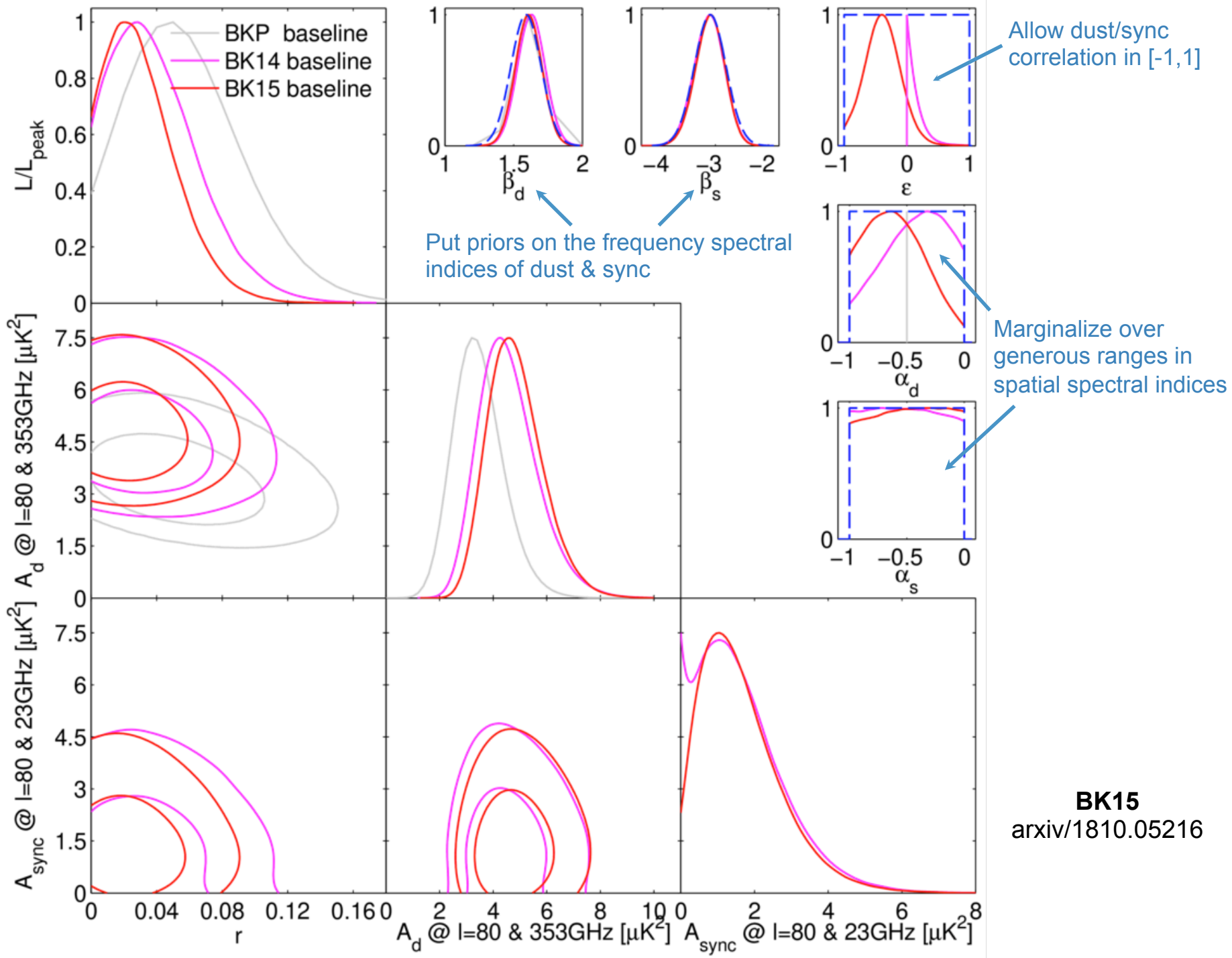
BK18 Noise Spectra and f_{sky} Effective

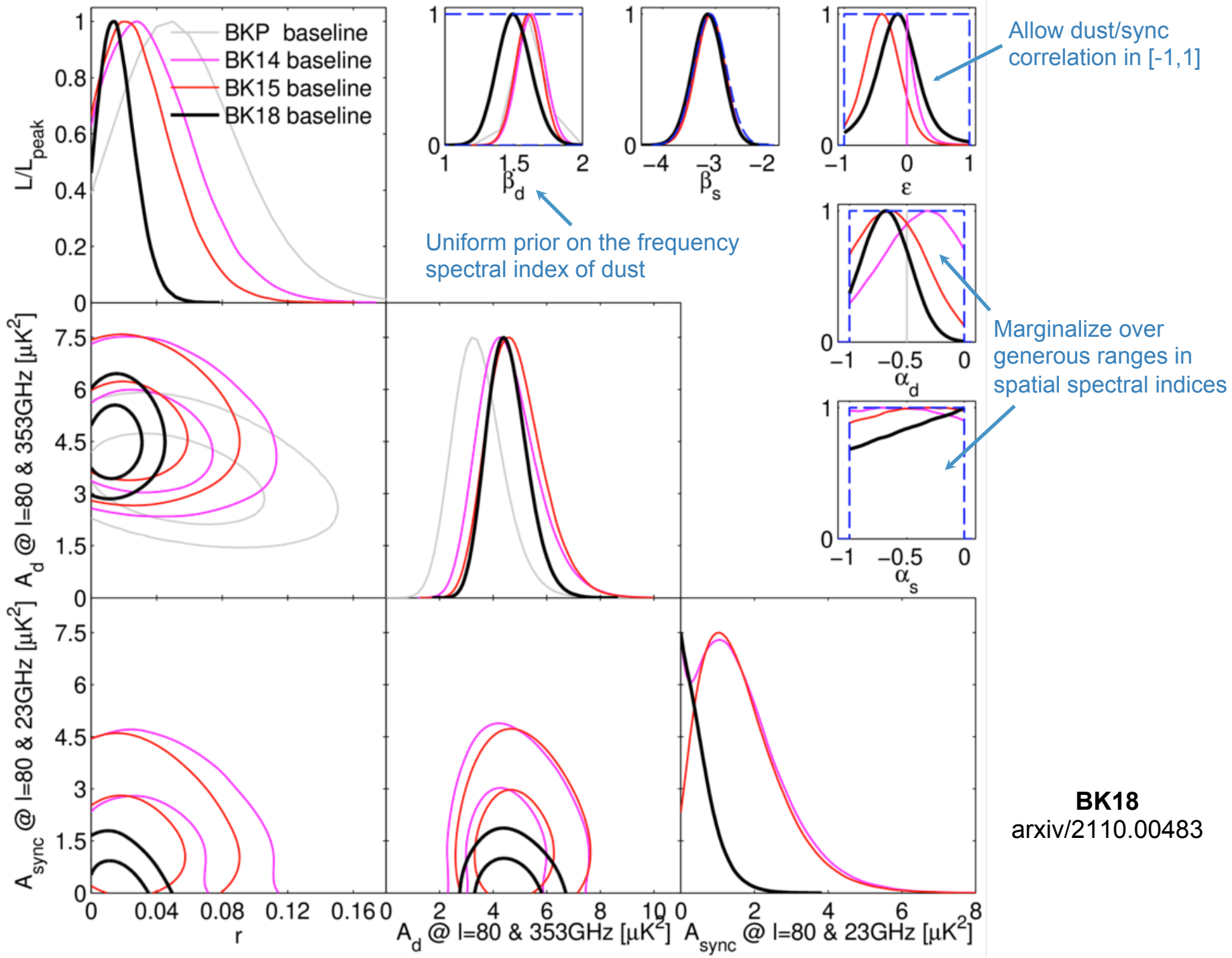


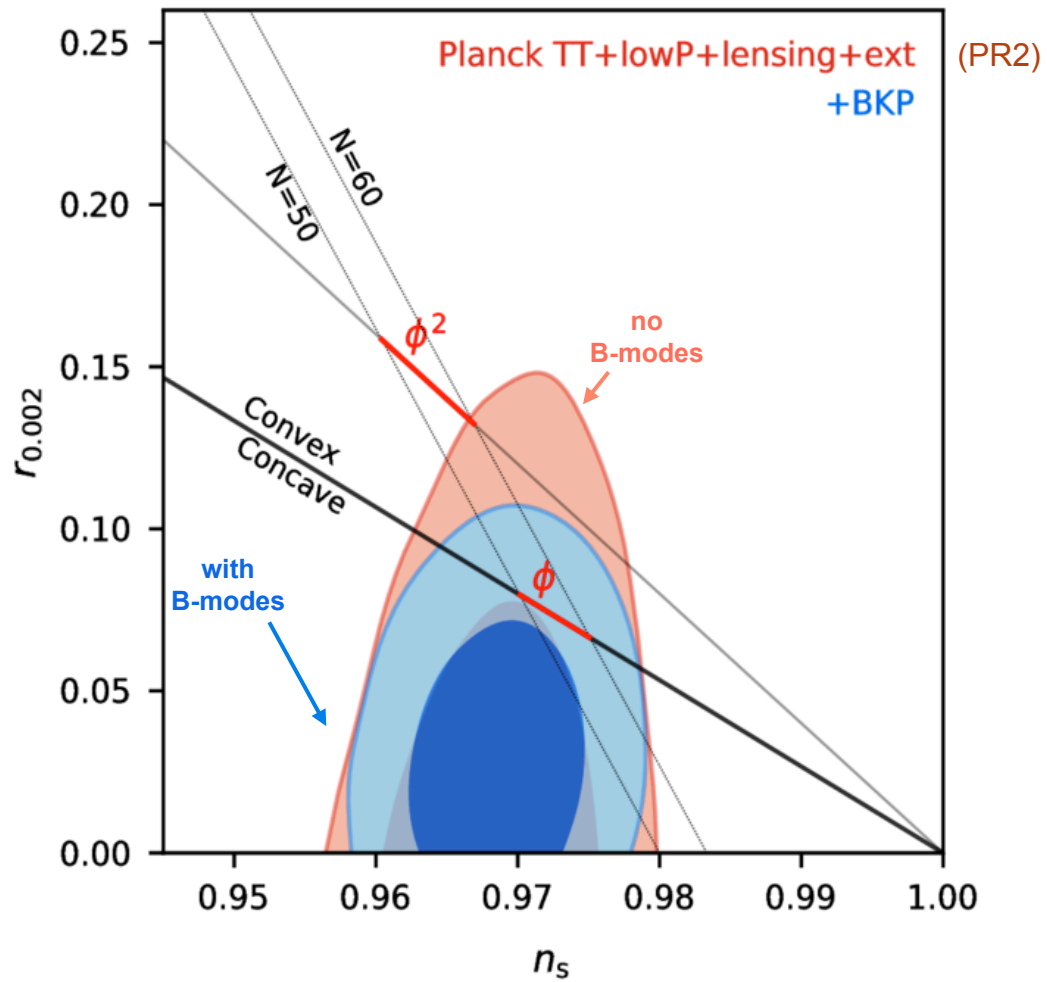




BK14
 arxiv/1510.09215



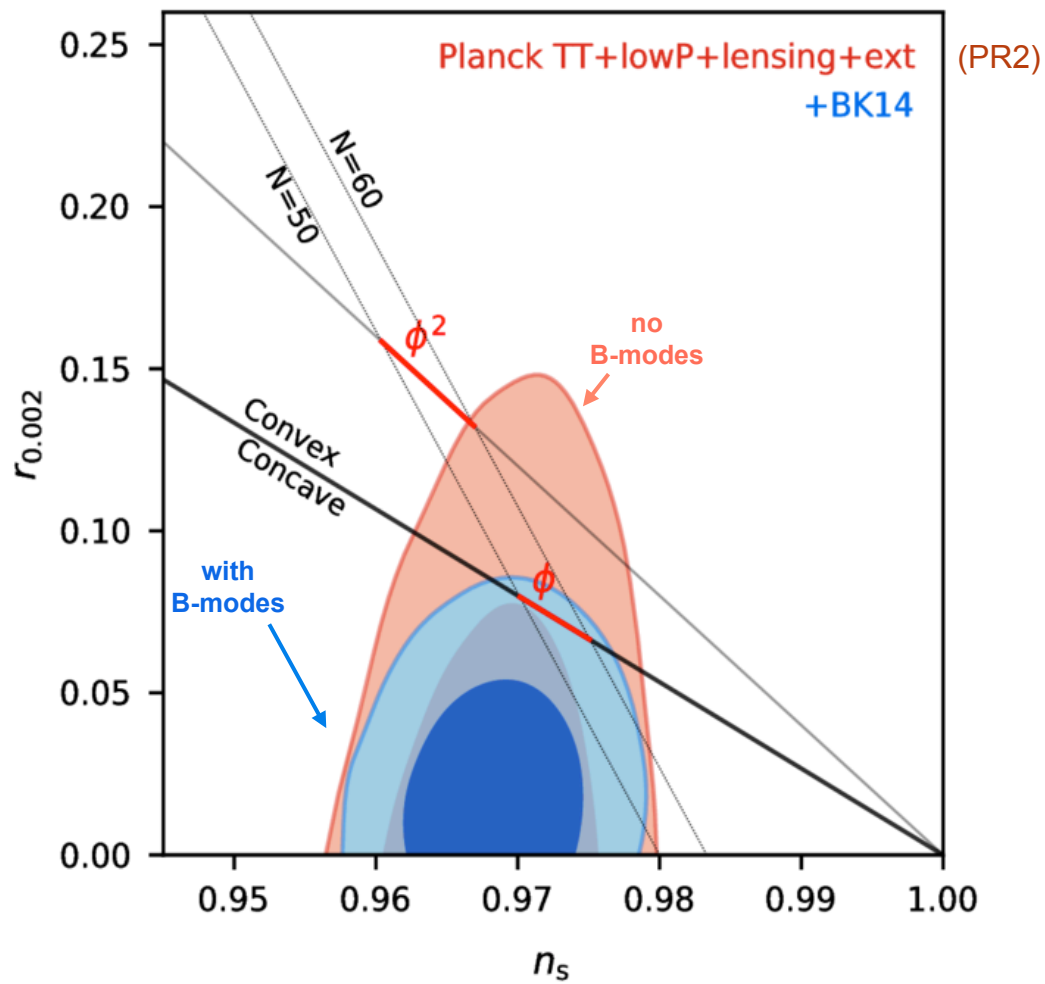




$r_{.05} < 0.09$

BKP

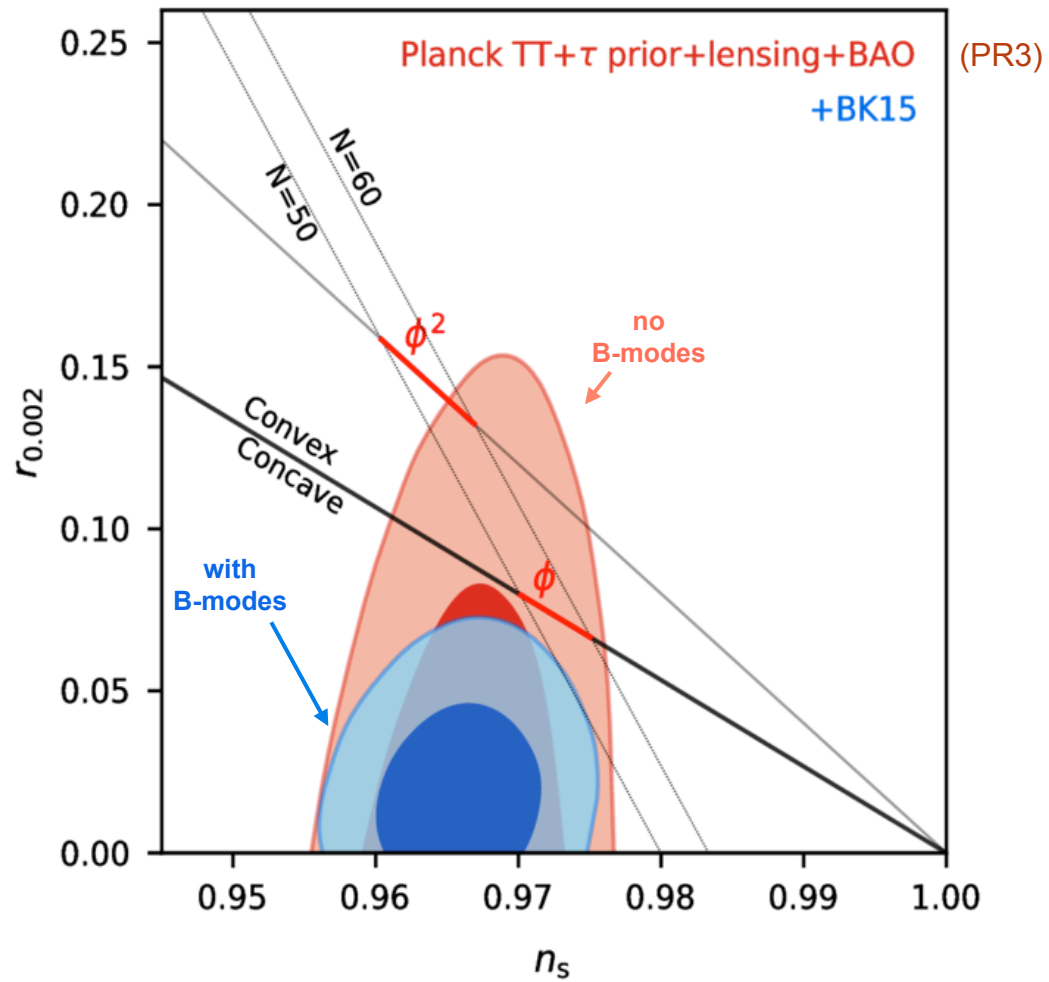
arxiv/1502.00612



$r_{.05} < 0.07$

BK14

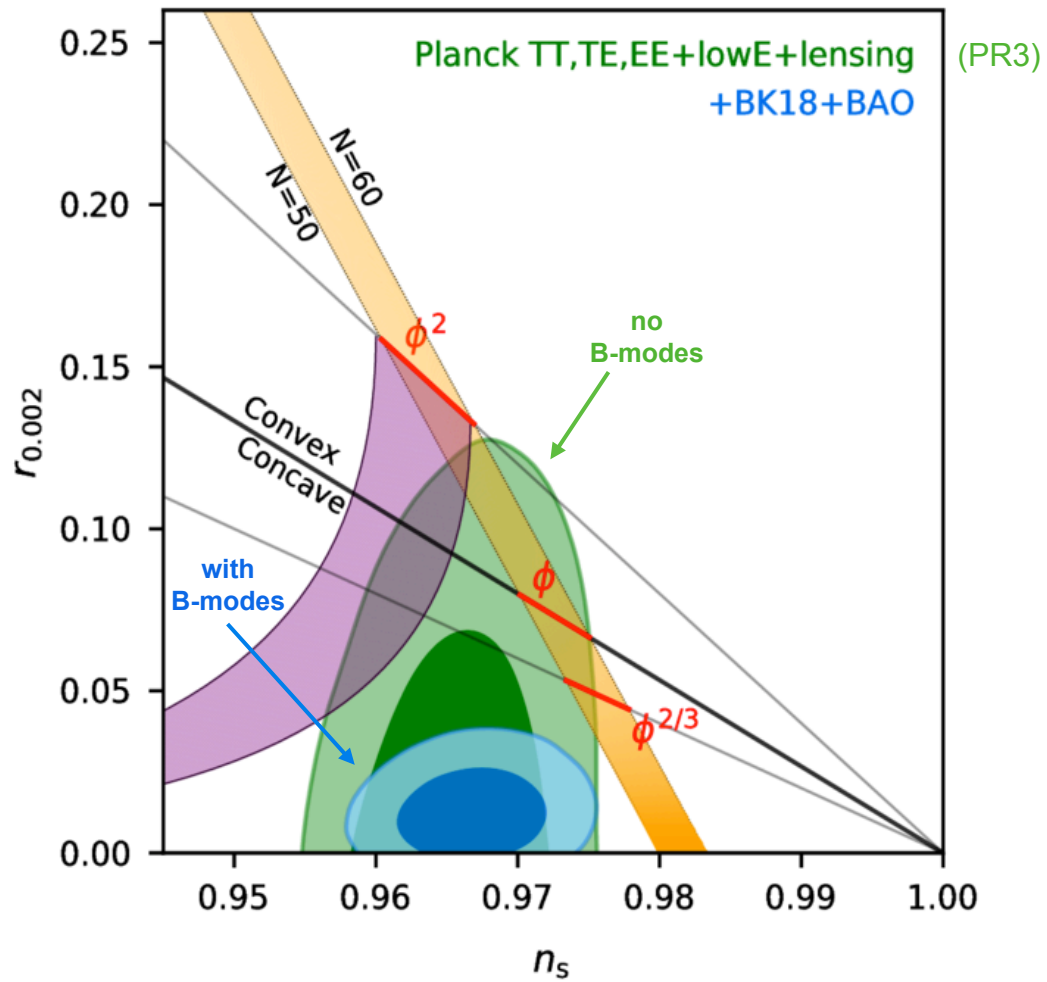
arxiv/1510.09217



$r_{.05} < 0.06$

BK15

arxiv/1810.05216

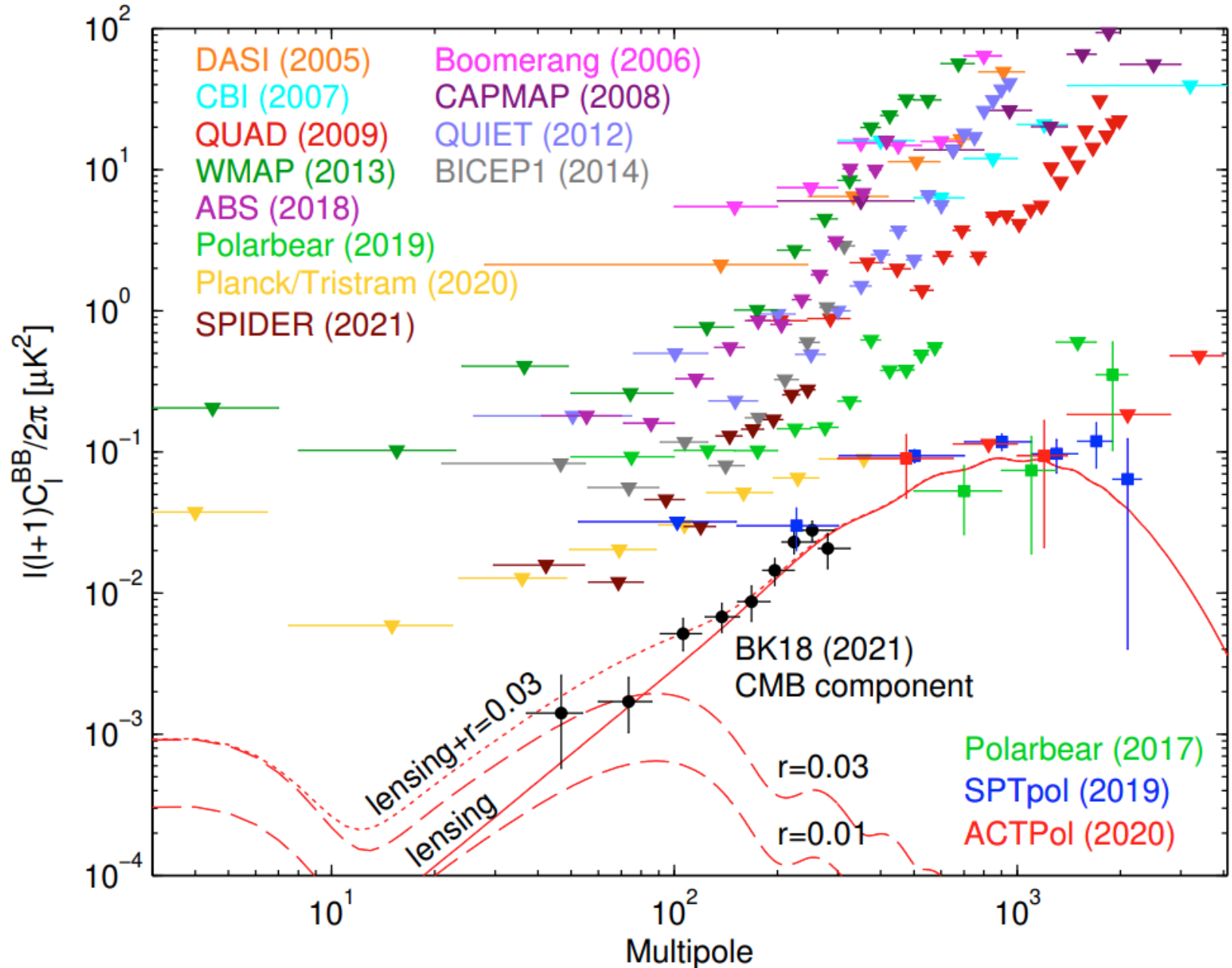


$r_{.05} < 0.035$

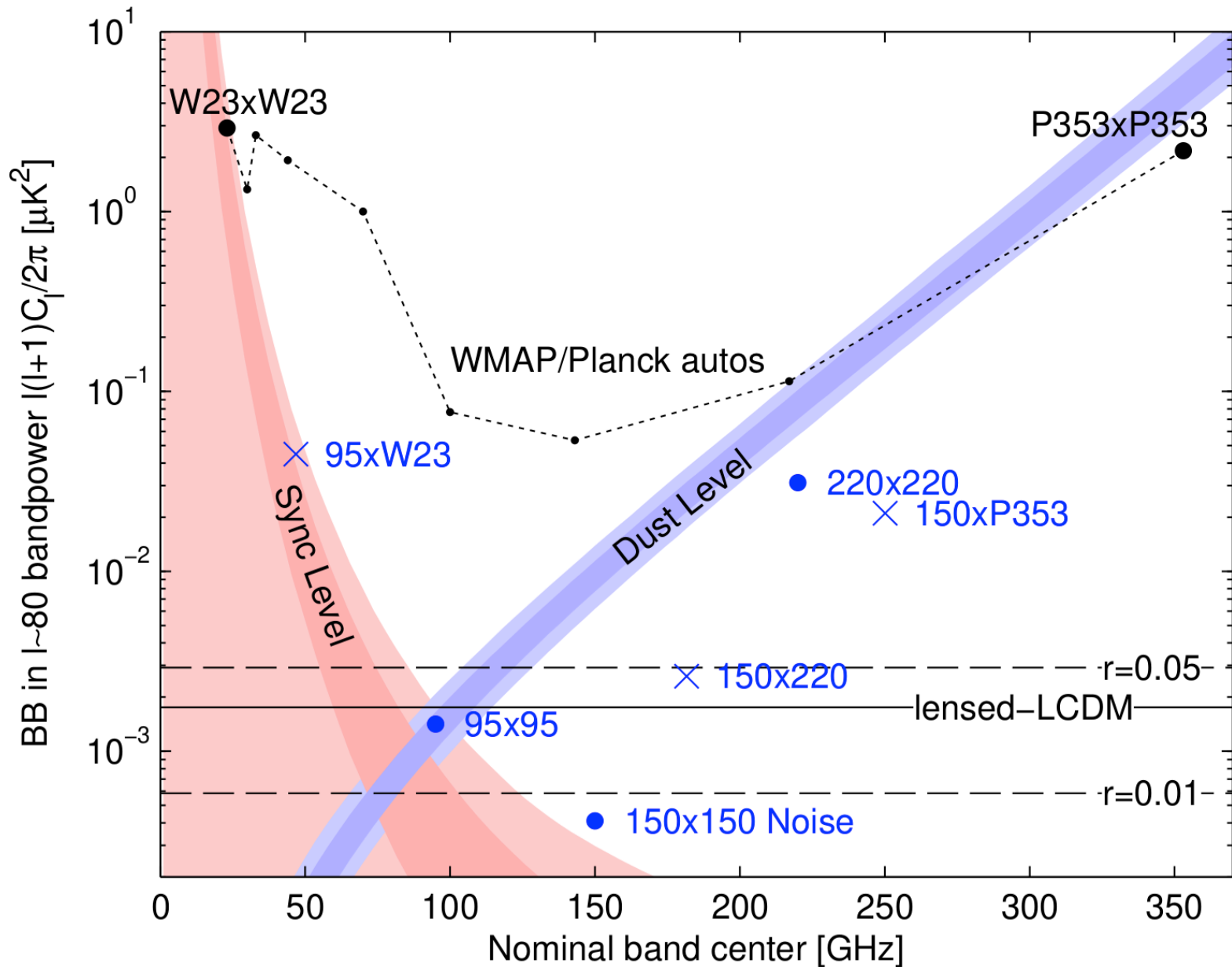
BK18

arxiv/2110.00483

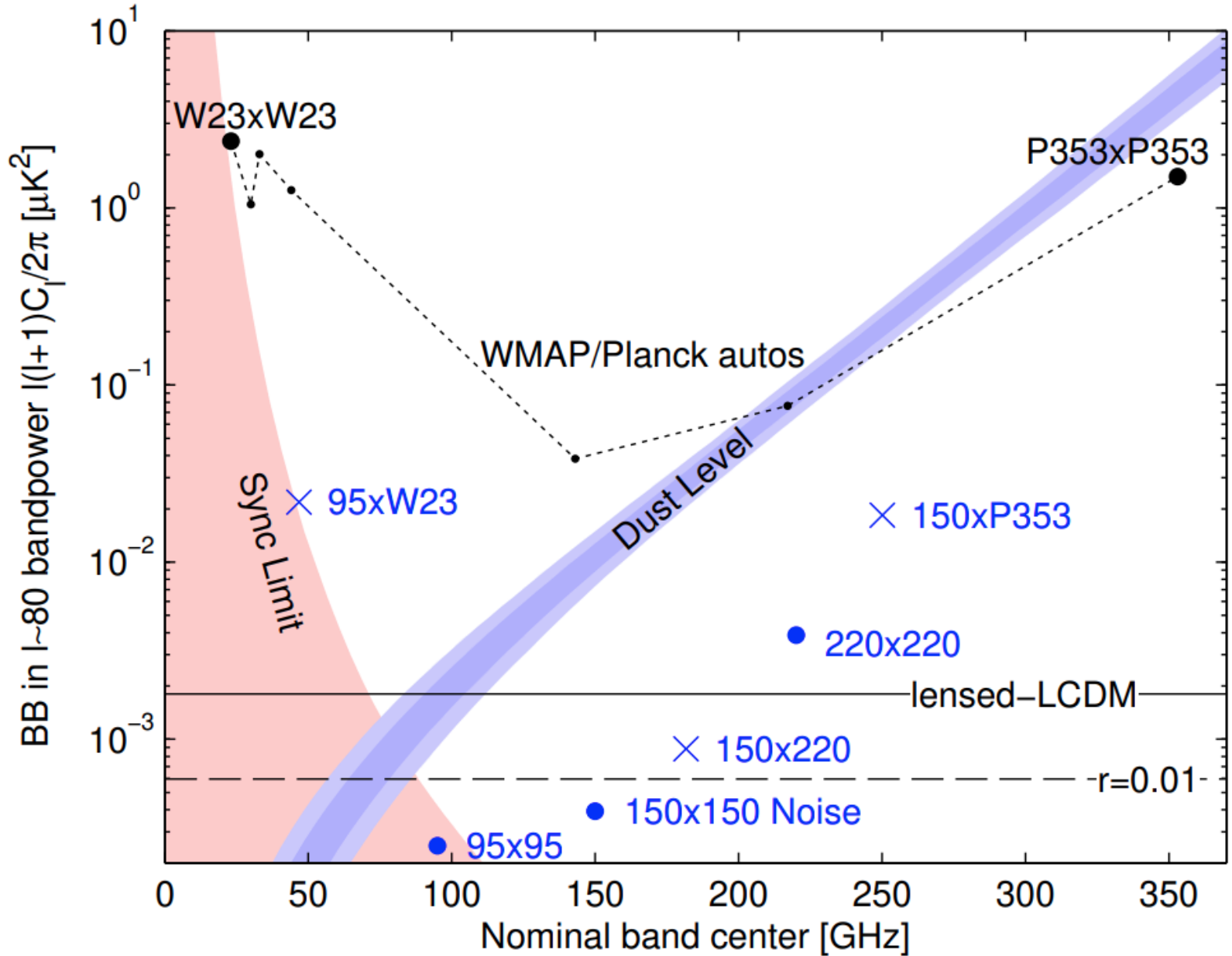
Per bandpower CMB component extraction



BK15 $ell=80$ bandpower noise/signal



BK18 $ell=80$ bandpower noise/signal



What limits BK18?

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

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.

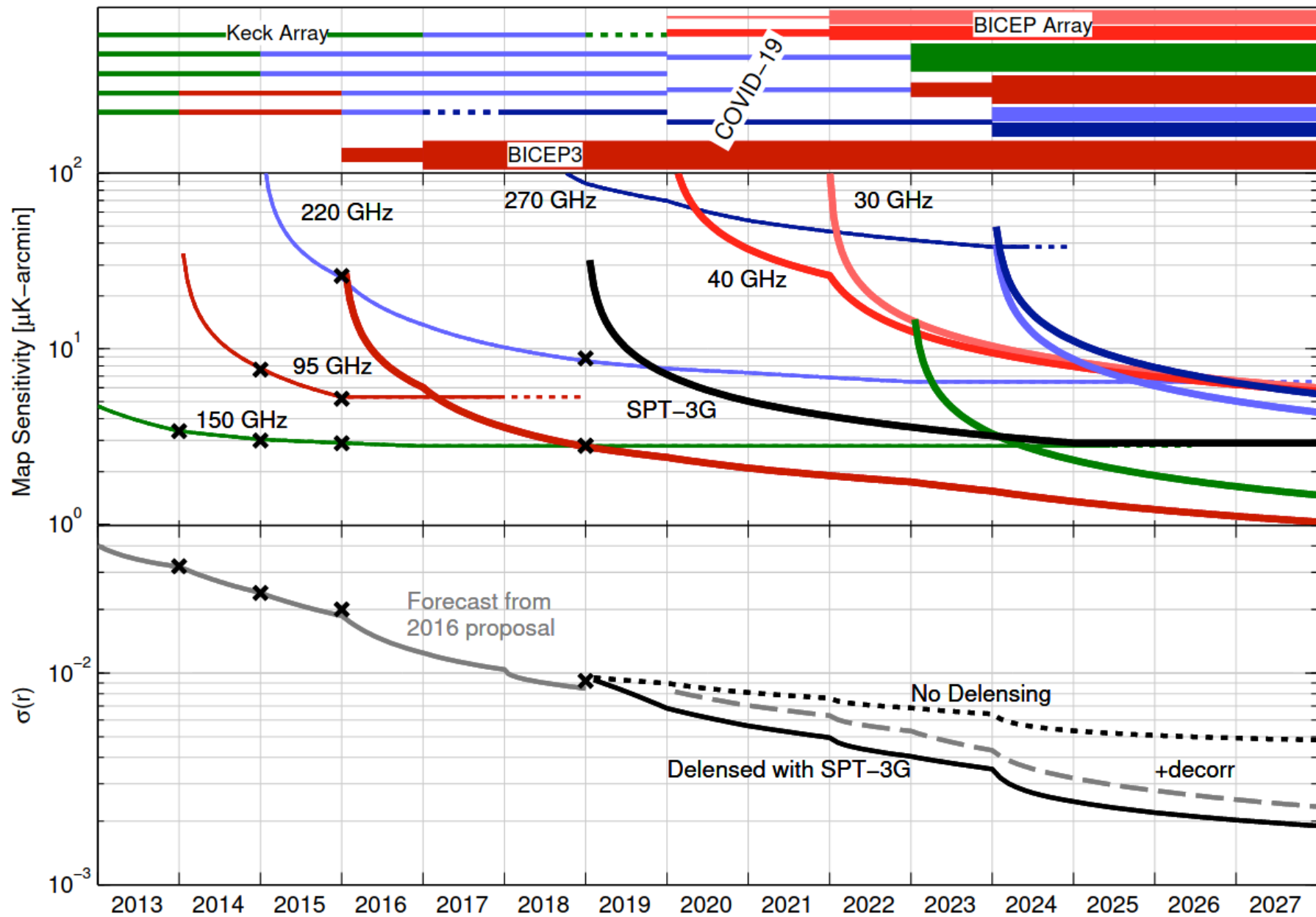
- ❖ Running on simulations which contain no lensing gives $\sigma(r)=0.004$

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 $\sigma(r)=0.002$

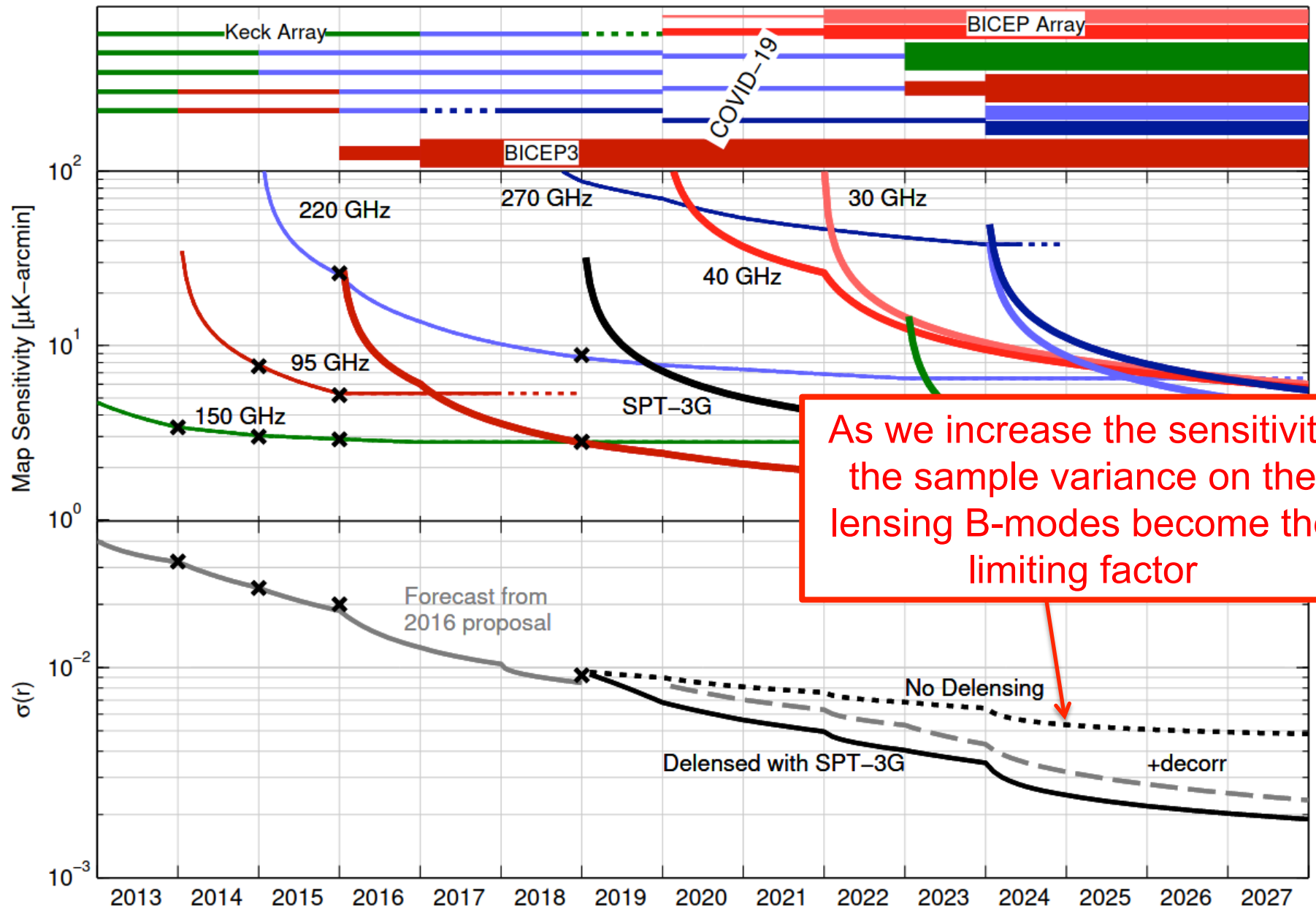
Stage 2

Stage 3



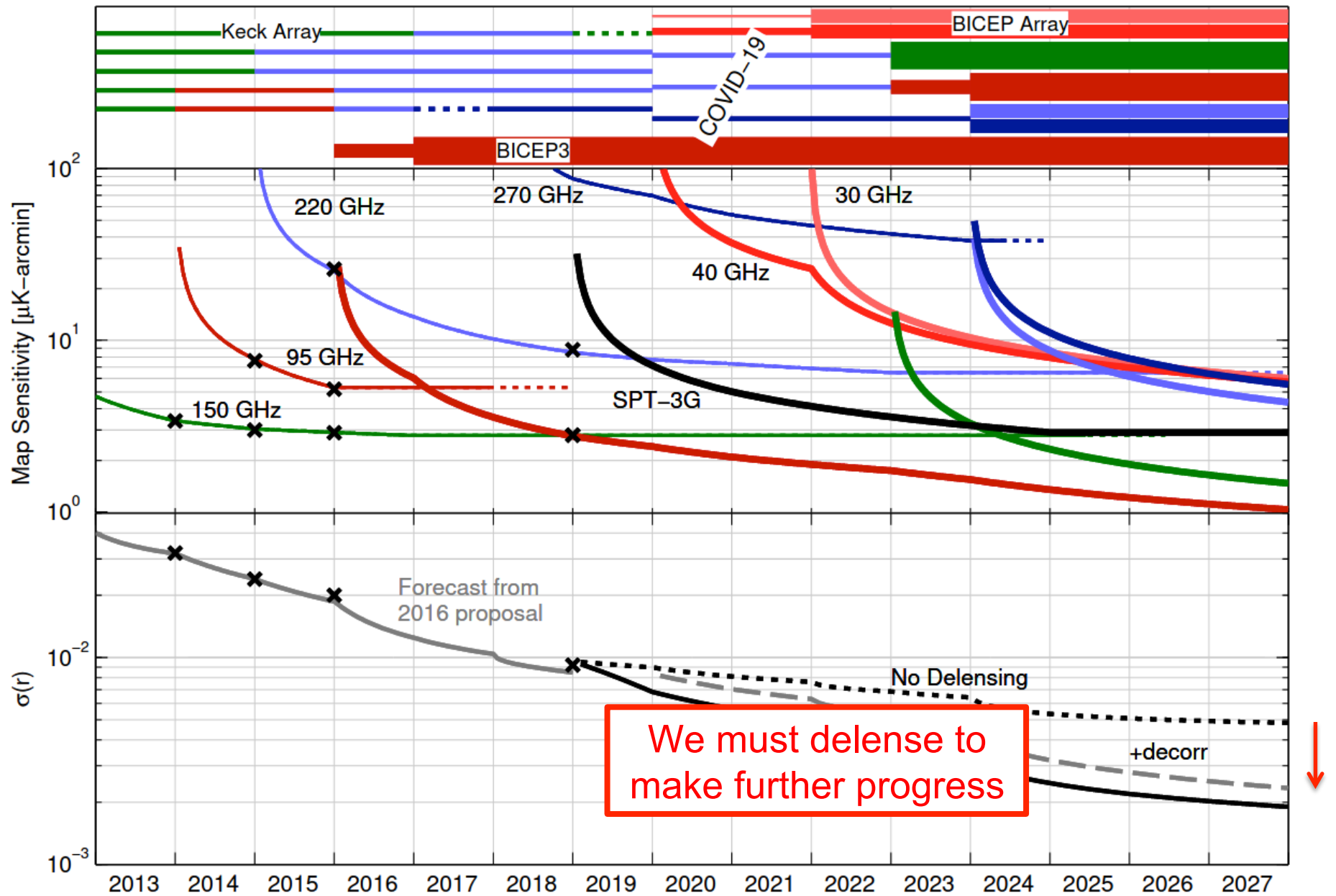
Stage 2

Stage 3

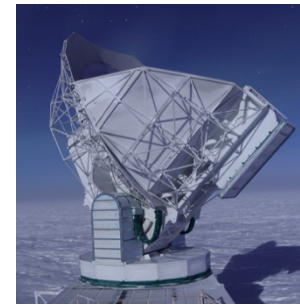
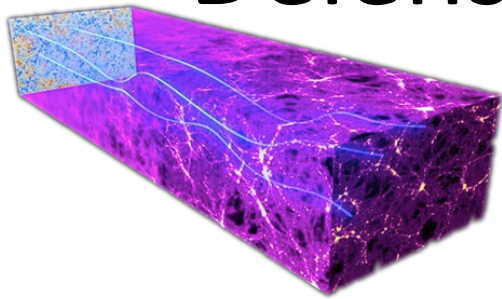


Stage 2

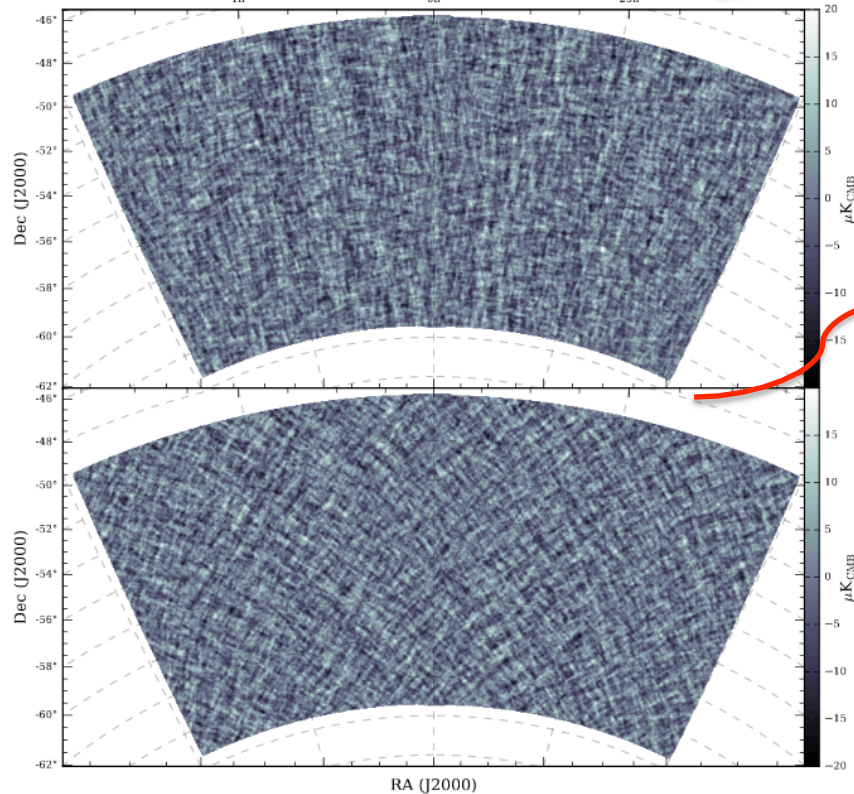
Stage 3



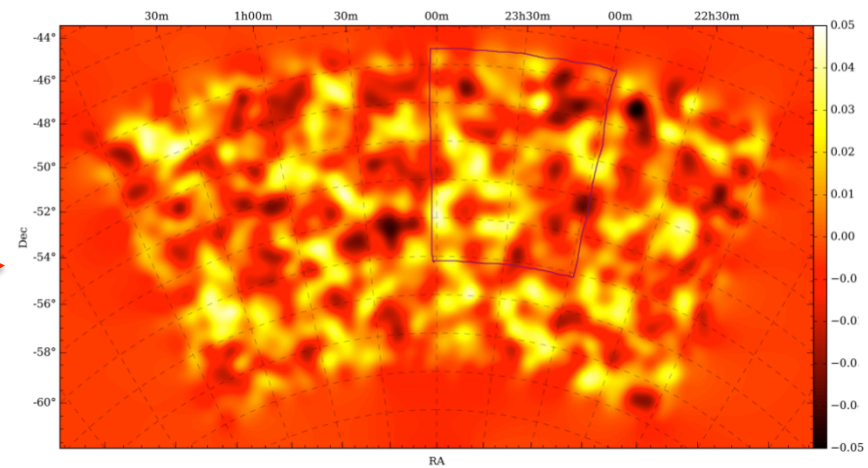
Delensing with SPT-3G data



High resolution maps

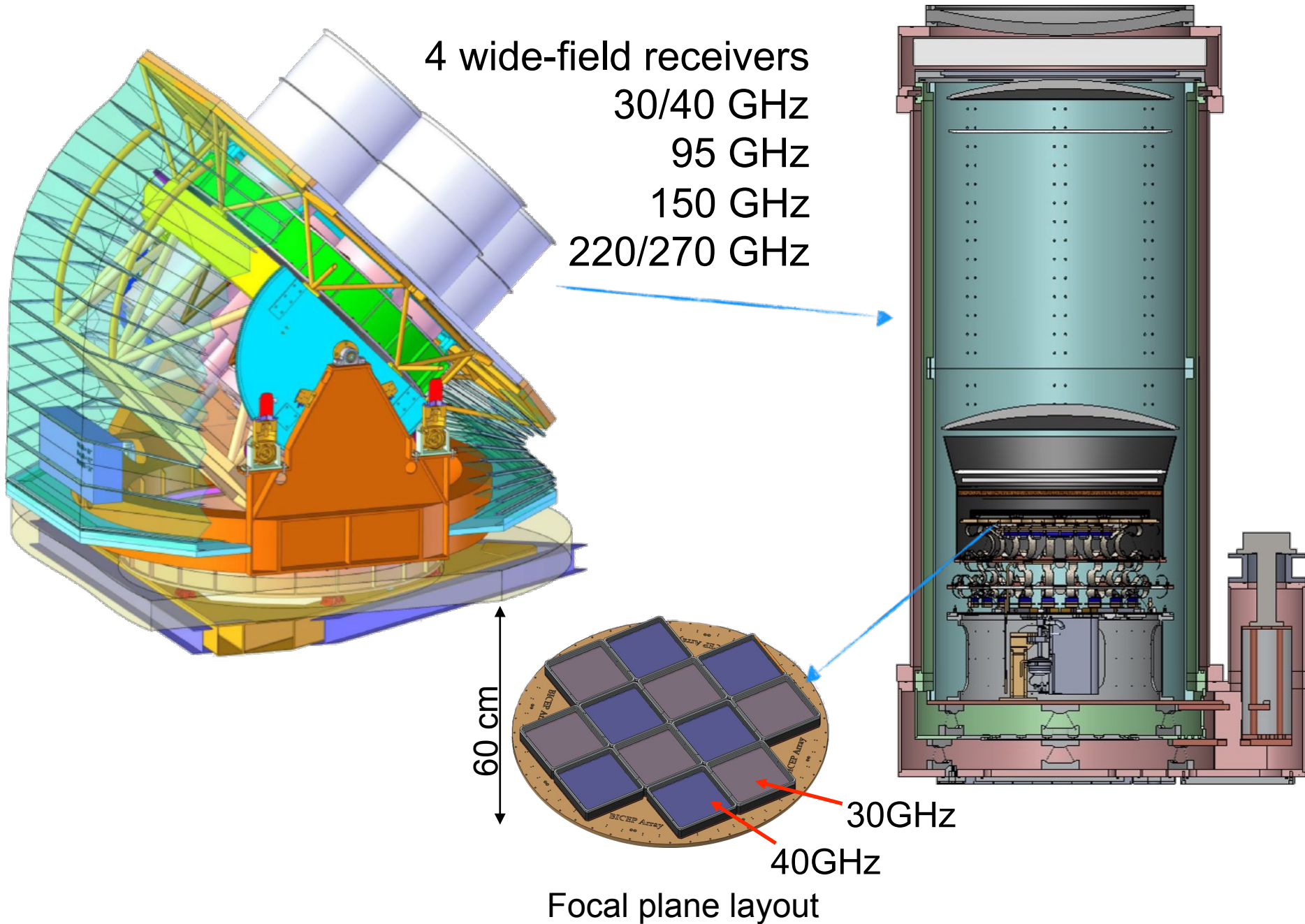


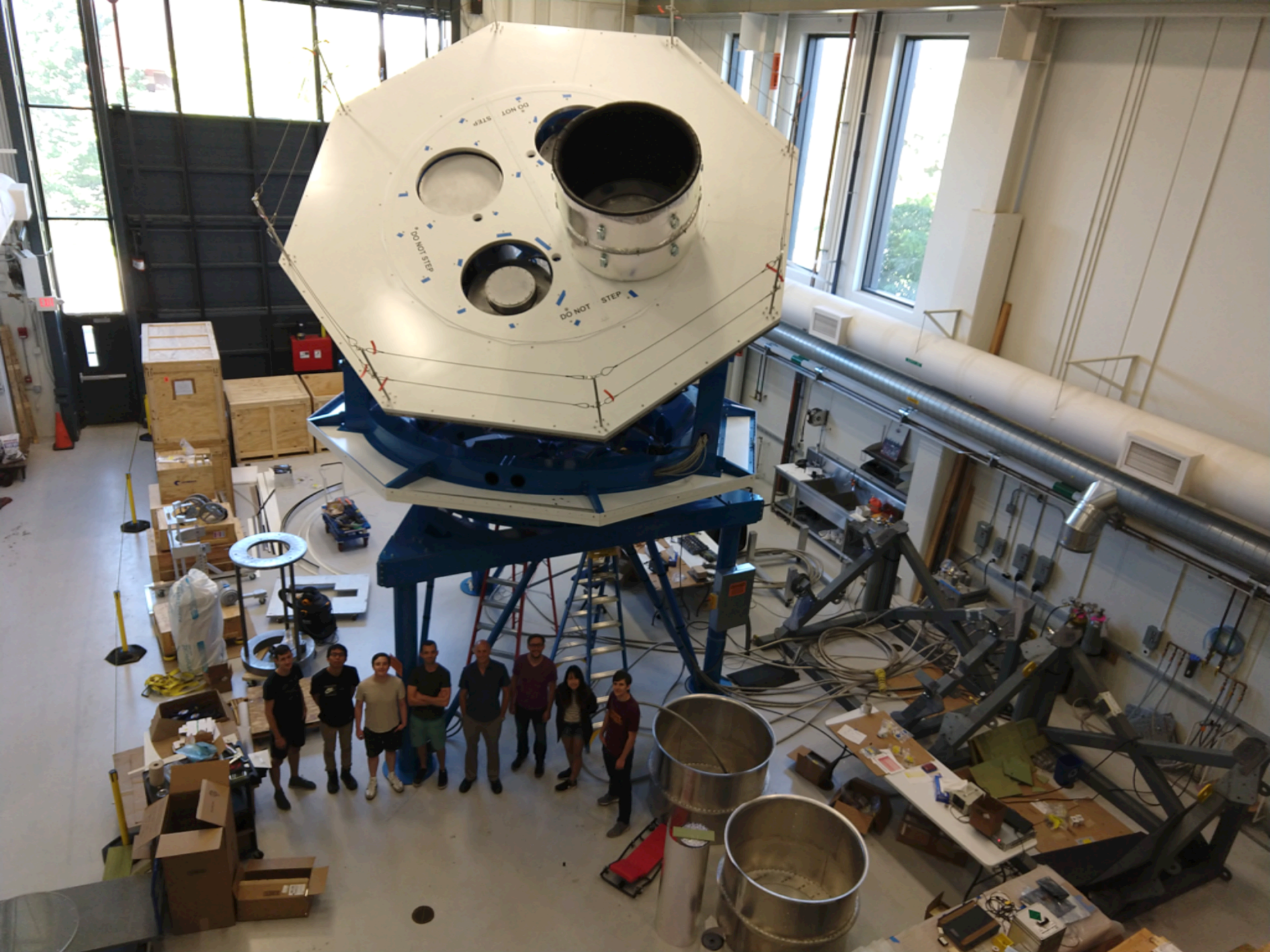
Can be used to reconstruct the lensing deflection map...



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

Latest Generation Experiment "BICEP Array"







BICEP Array 2019-20 initial deployment

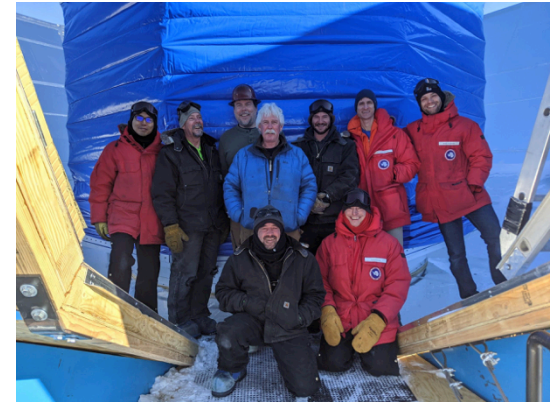


Three-month window during the Antarctic summer to perform:

- 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.



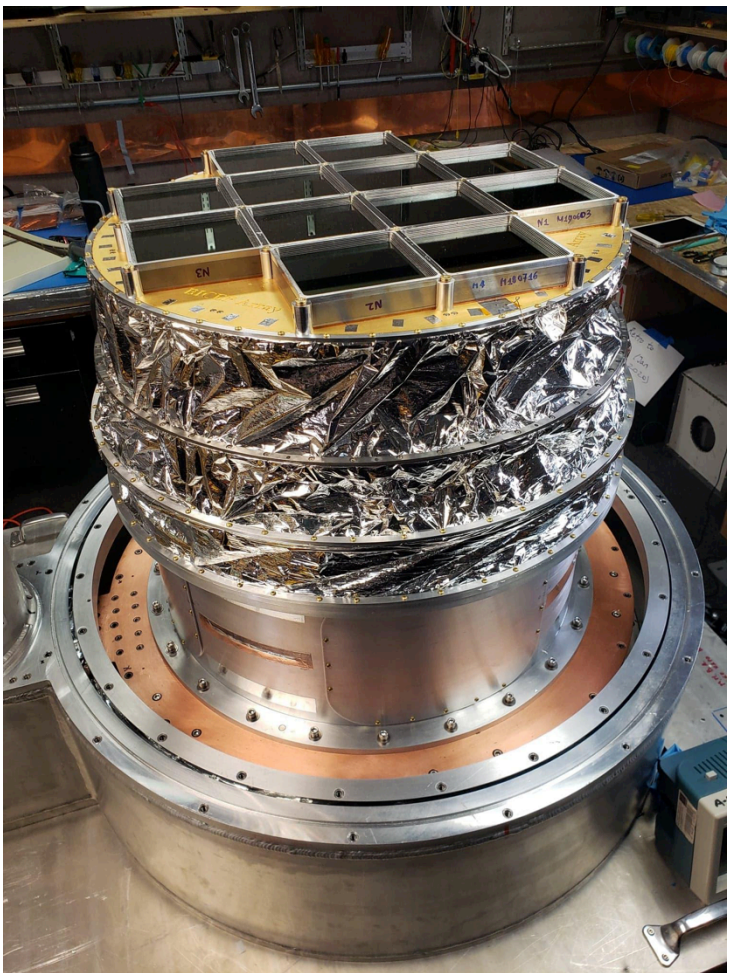
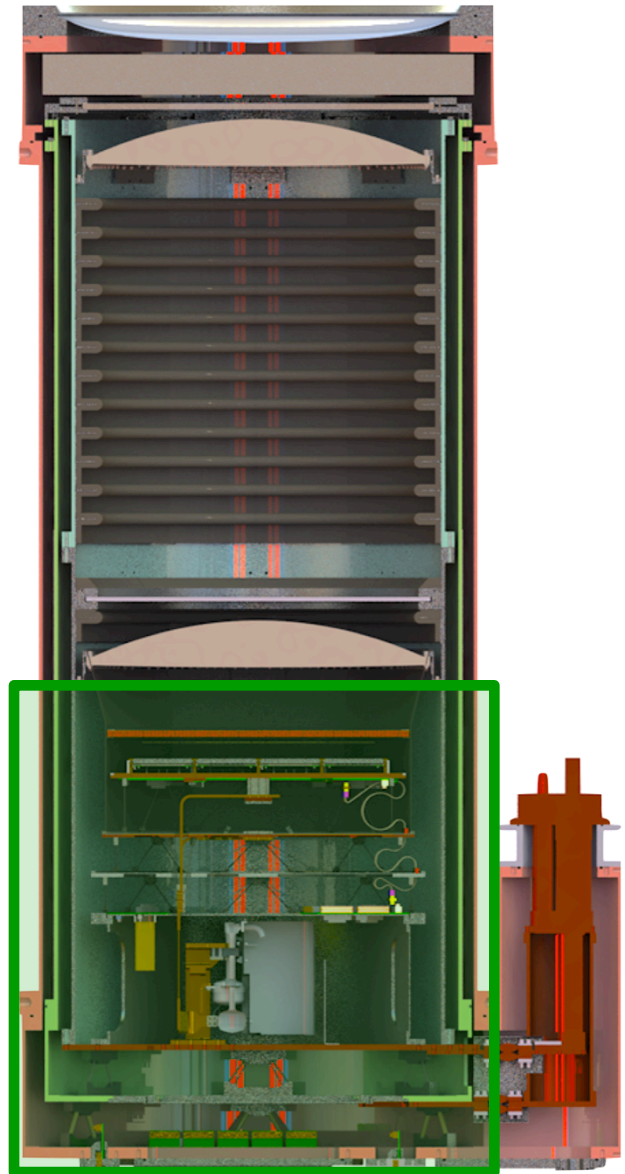
30+ personnel:

- 2/3 scientists
- 1/3 contractors



First new receiver: BA1 instrumental highlights

Camera insert



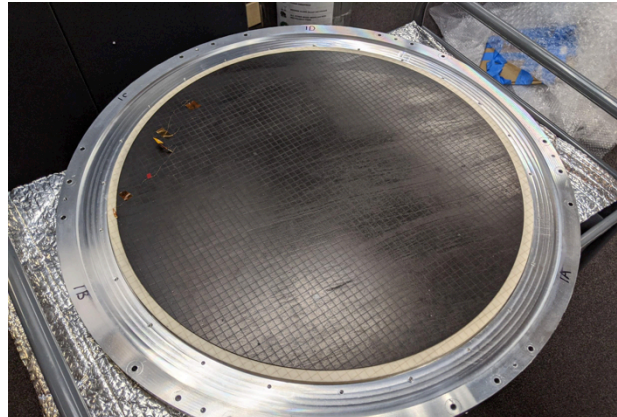
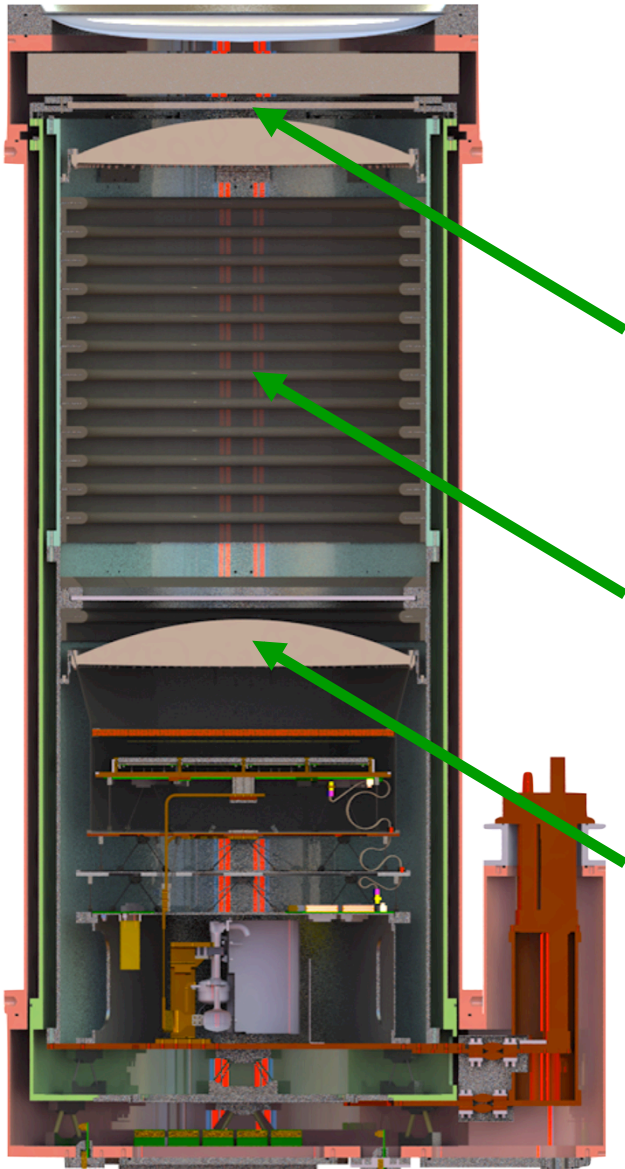
192/300 TES detectors at 30/40 GHz.

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

Time-Domain multiplexed readout.

First new receiver: BA1 instrumental highlights

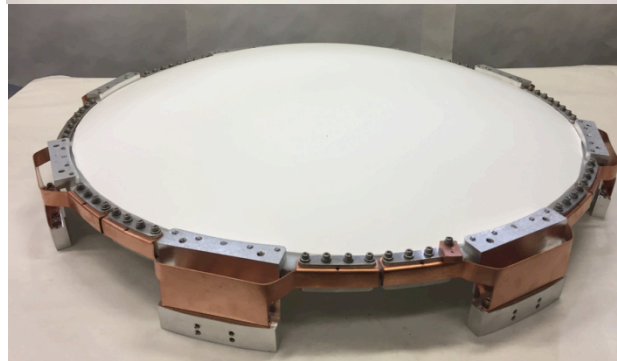
Optics



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



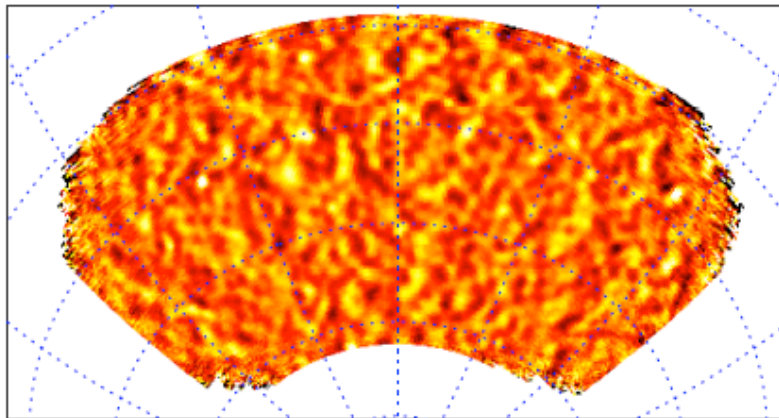
Internal absorptive baffling for scattering control.



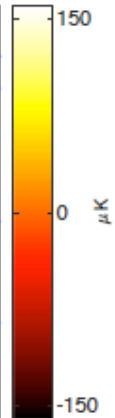
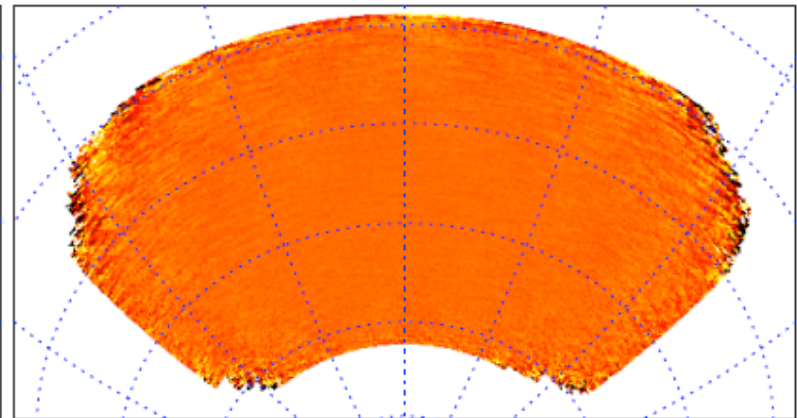
Polyethylene lenses, AR-coated with expanded Teflon. 550mm clear aperture.

BA1
2020
maps

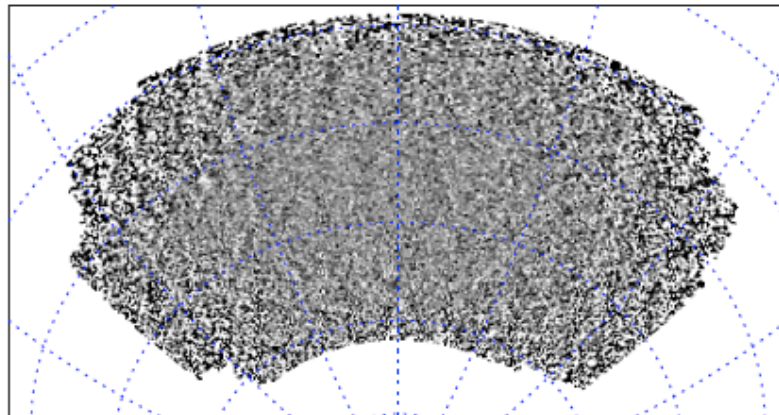
40GHz T



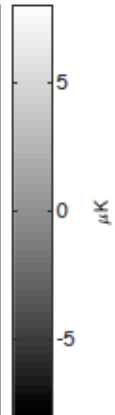
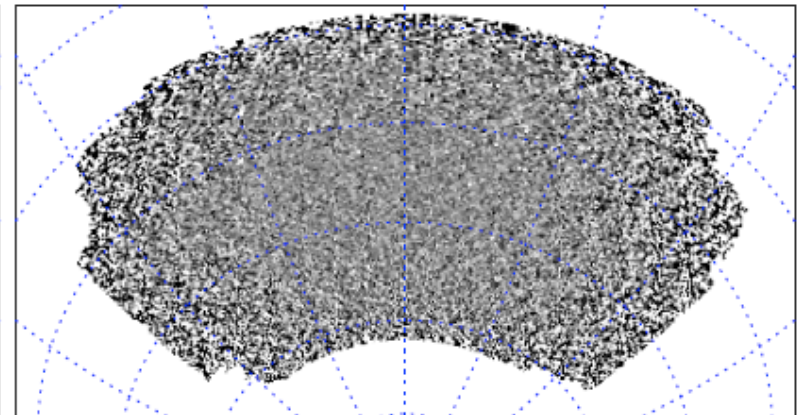
40GHz T Noise



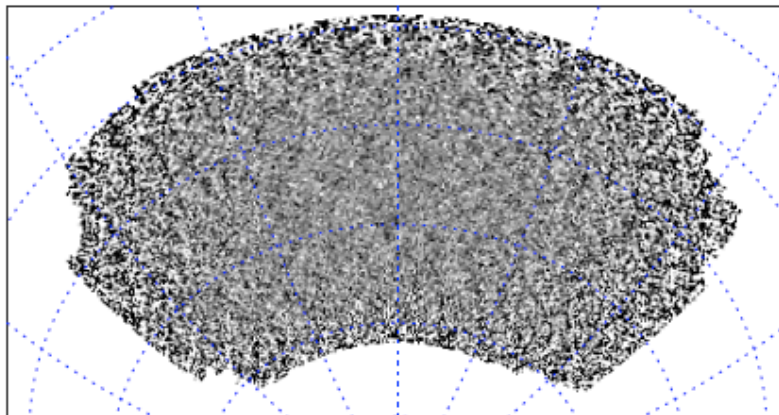
40GHz Q



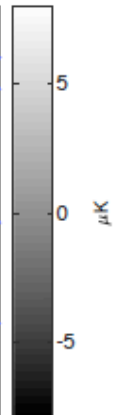
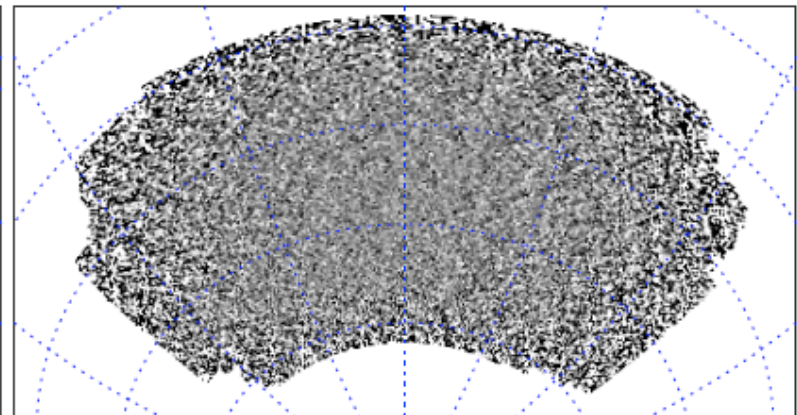
40GHz Q Noise



40GHz U



40GHz U Noise

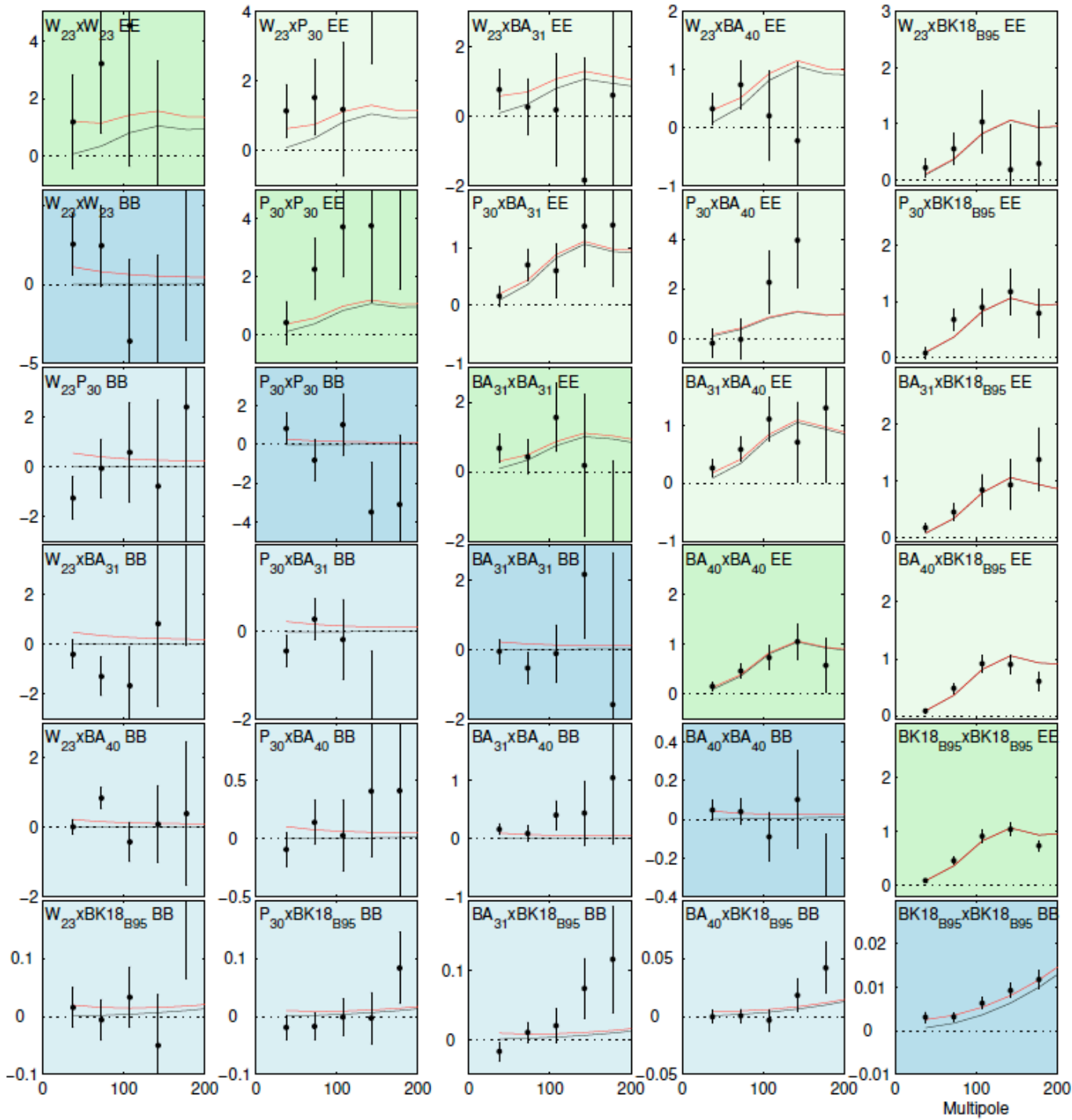


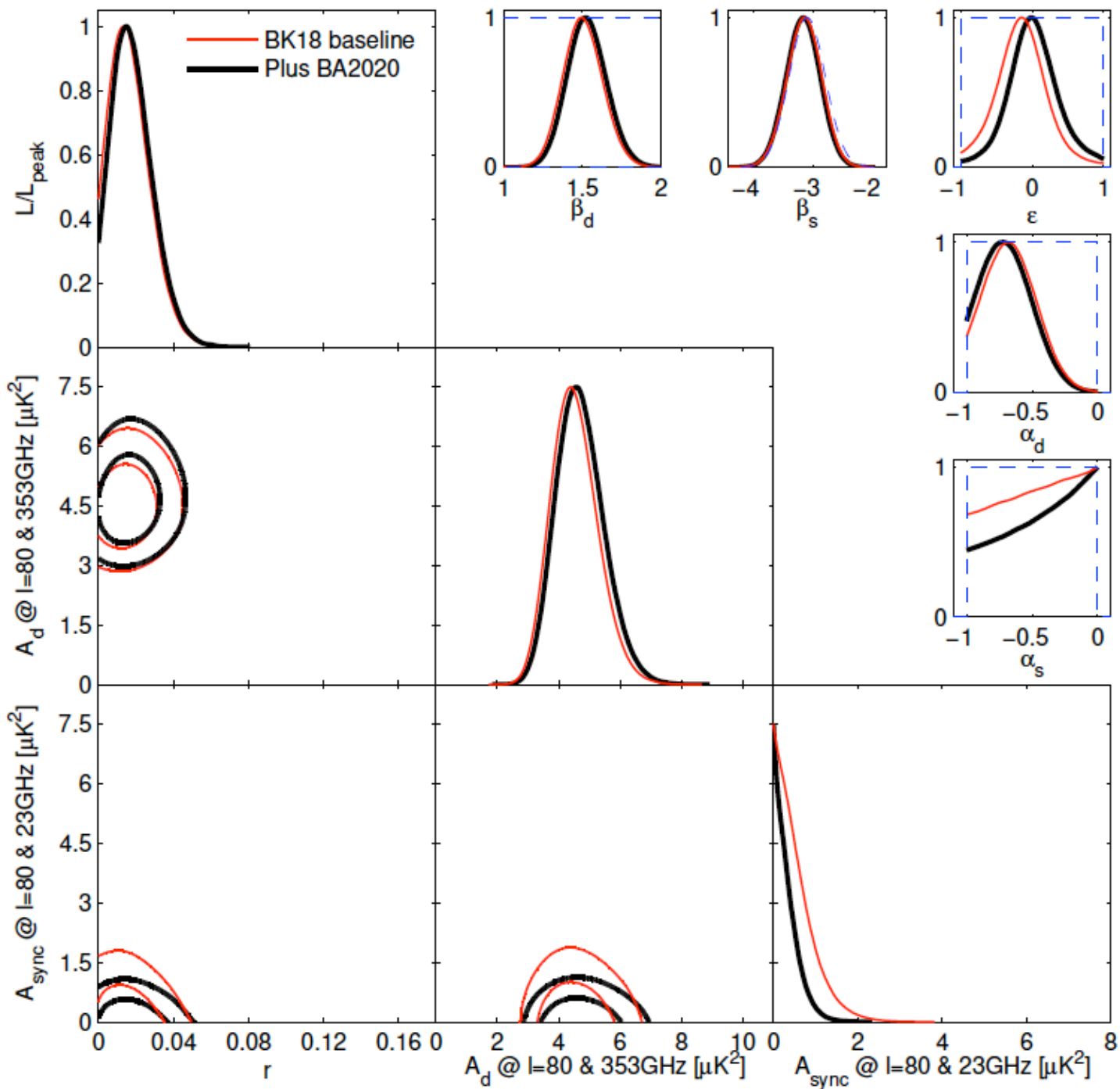
Synchrotron Bands including new BICEP Array 30/40 GHz data

Black lines are LCDM
Red lines are LCDM+sync+dust

Blue panels are BB spectra

Green panels are EE spectra





Conclusions

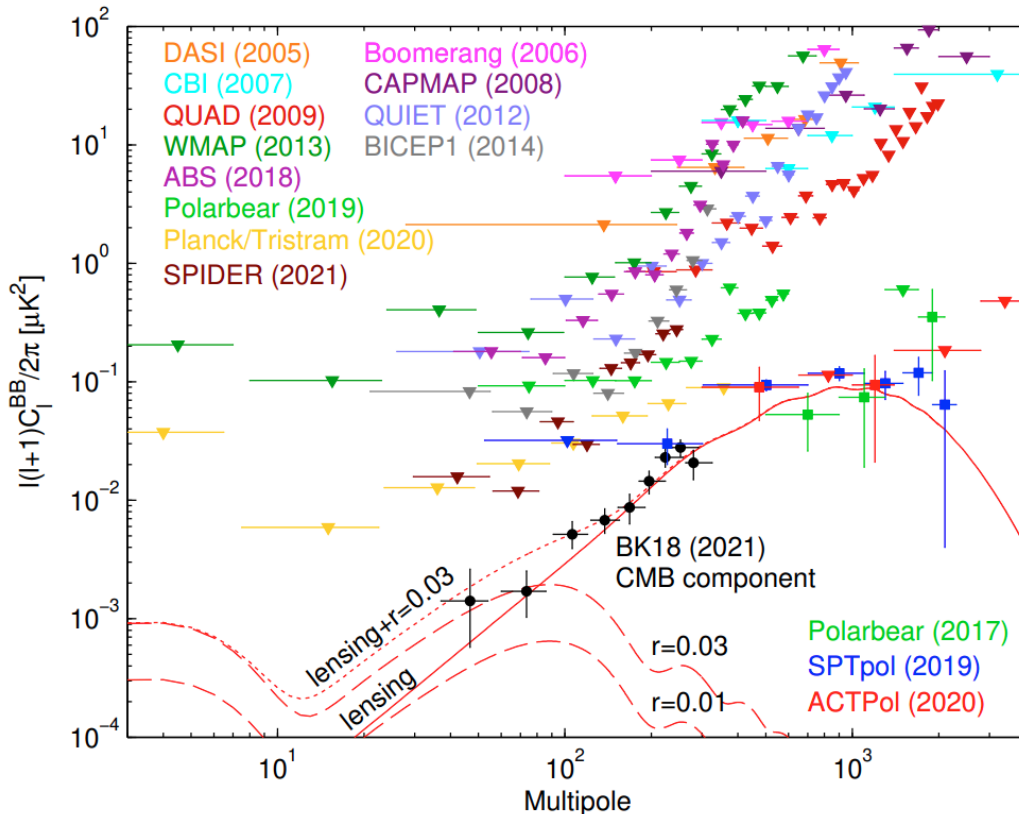
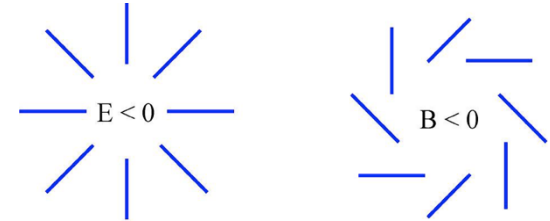
- BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:
 - Best published sensitivity to date
 - Best proven systematic control at degree angular scales
- Adding 2016-18 data (from BK15 to BK18):
 - Goes from $r_{0.05} < 0.07$ to $r_{0.05} < 0.036$
 - For 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

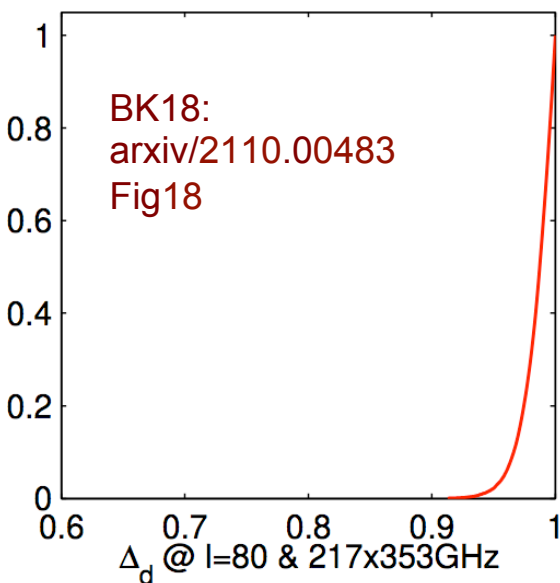
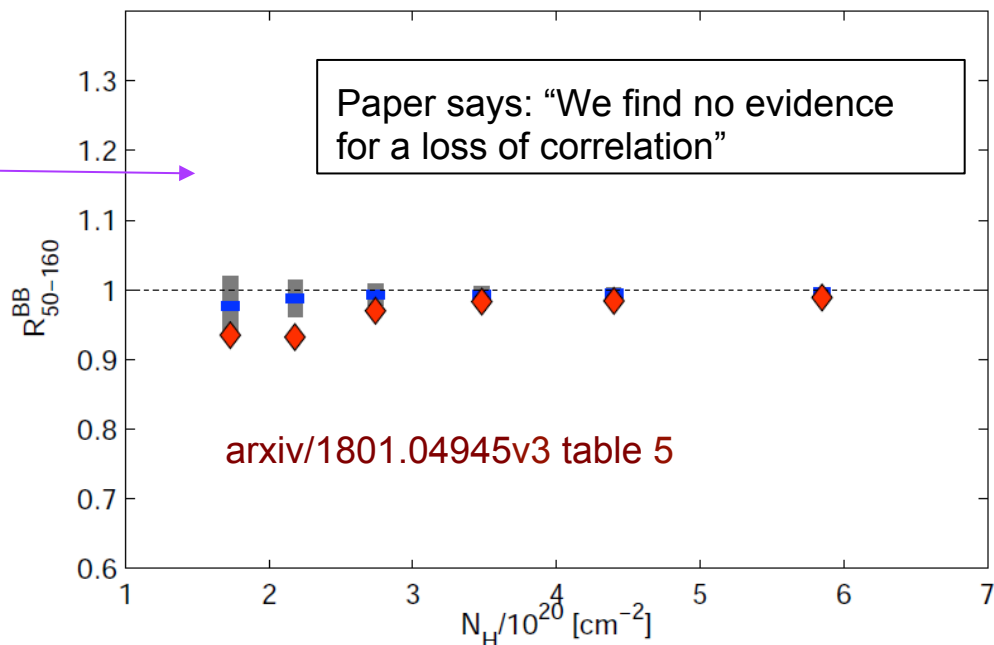
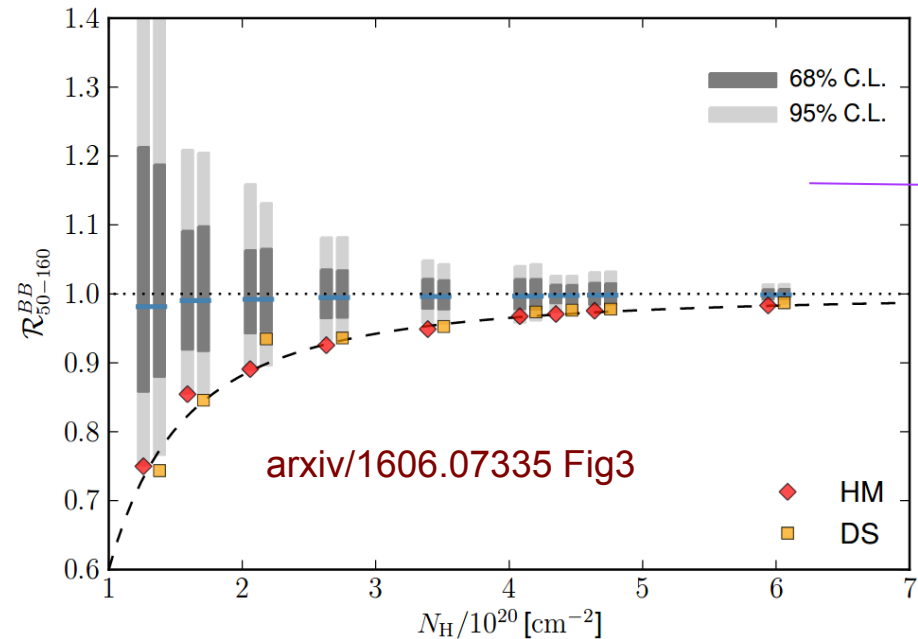
State of B-mode polarization power spectra in 2021



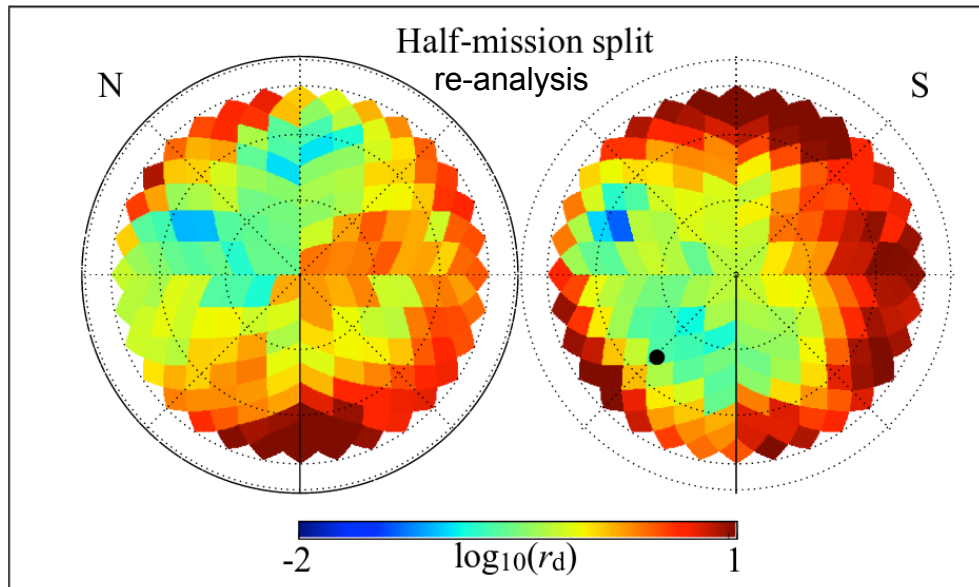
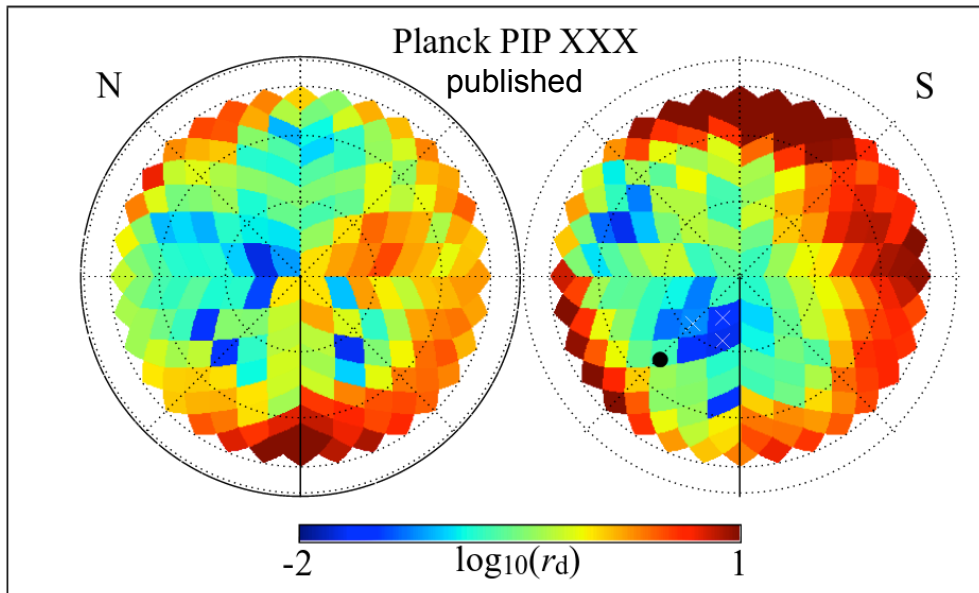
Posted B-Mode Sensitivity to r

Experiment	arxiv post	Bands [GHz]	$\sigma(r)$
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

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



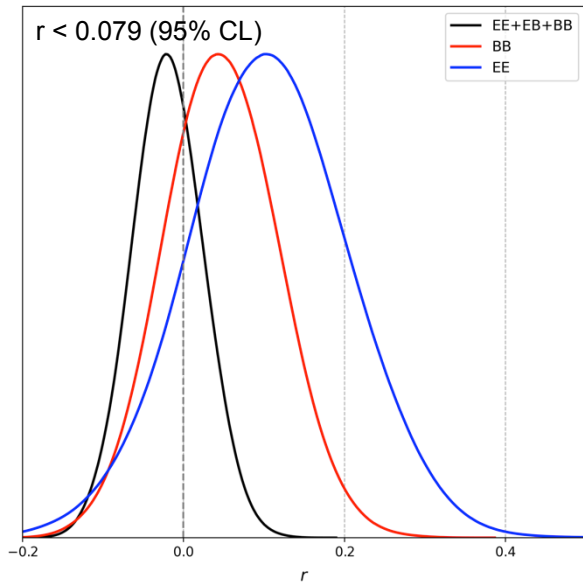
Is there a cleaner small field than the BICEP field?



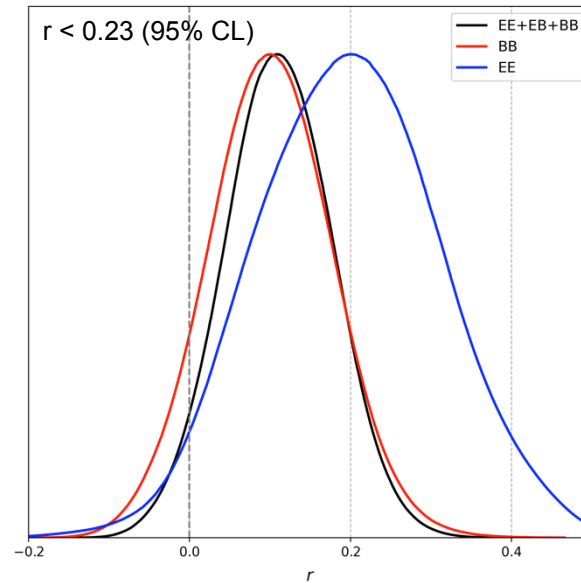
- ❖ The Planck 353GHz Q/U maps hit their noise floor in the cleanest regions
 - From this data it is not really possible to tell if there are cleaner small regions than the BICEP/Keck field
- ❖ When we attempt to reproduce the Planck PIPXXX analysis we find that the apparent cleaner regions shift around 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

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



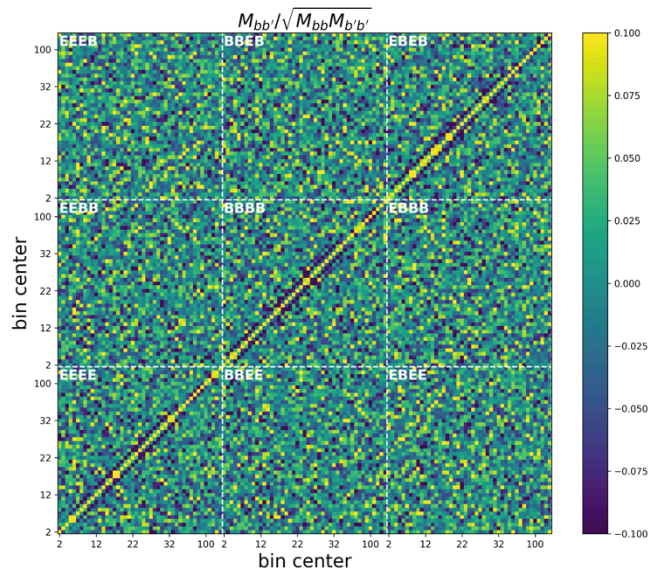
Full covariance matrix, as used in Tristram et al. 2020 and provided in the public likelihood



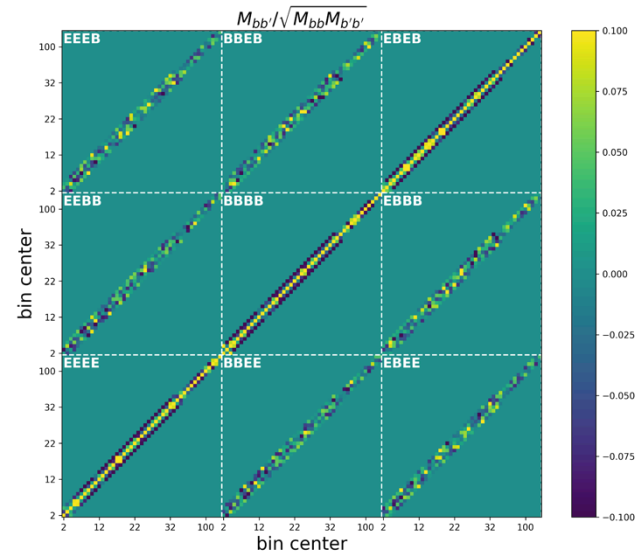
With covariance matrix conditioning (zeroing elements not detected above Monte Carlo noise)
→ combined posterior does not move to negative r

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”)



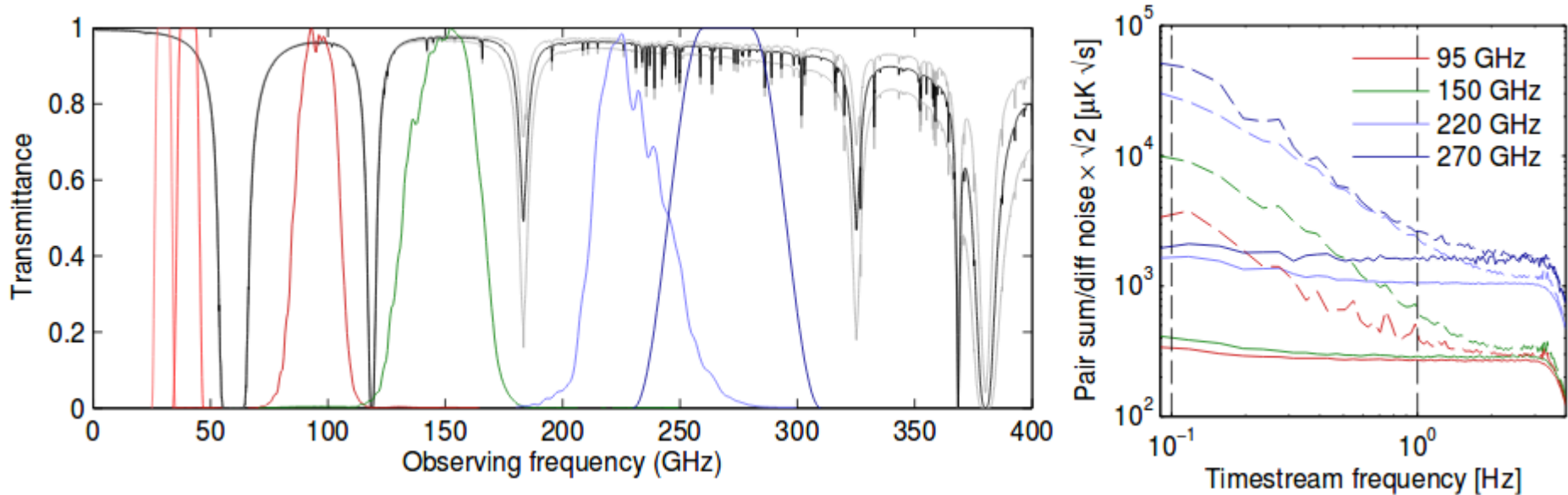
Full covariance matrix, as used in Tristram et al. 2020 and provided in the public likelihood



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

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...

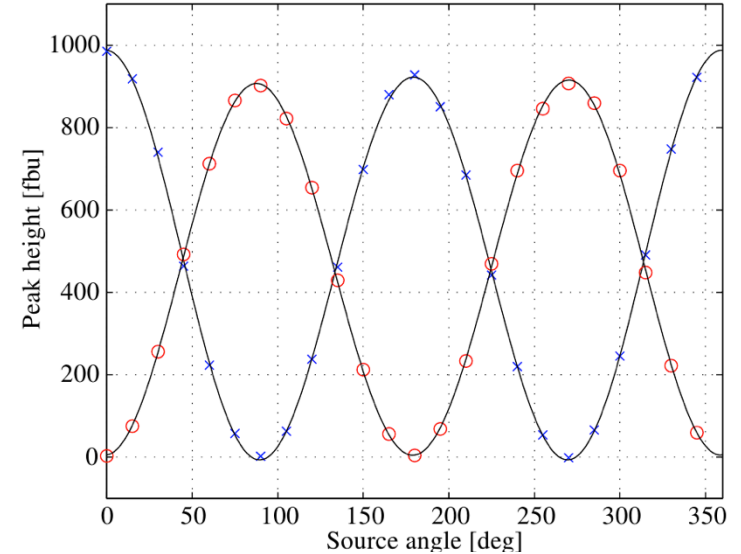
Far field beam mapping



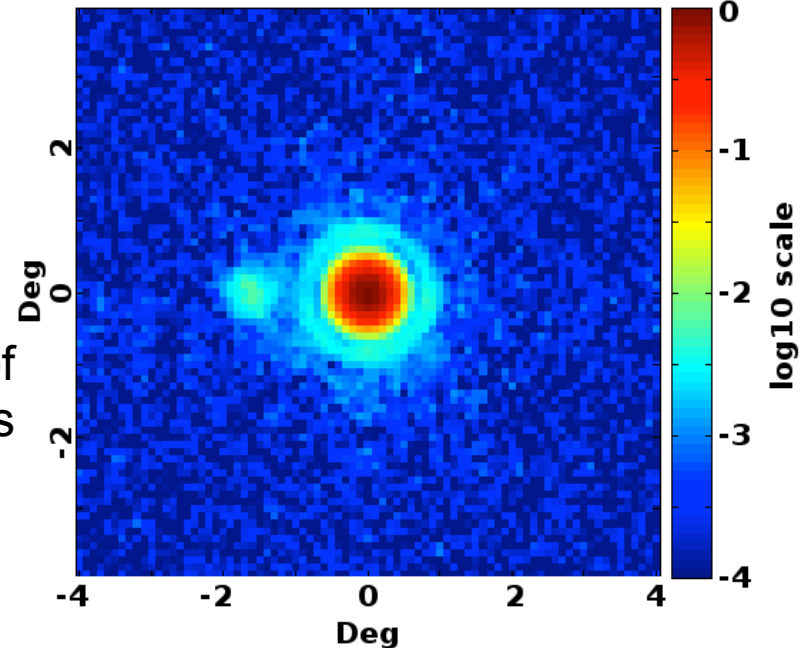
Detailed description in
Instrument and beams papers
[arxiv/1403.4302](https://arxiv.org/abs/1403.4302) and [1502.00596](https://arxiv.org/abs/1502.00596)

Hi-Fi beam maps of
individual detectors

Detector Polarization Calibration

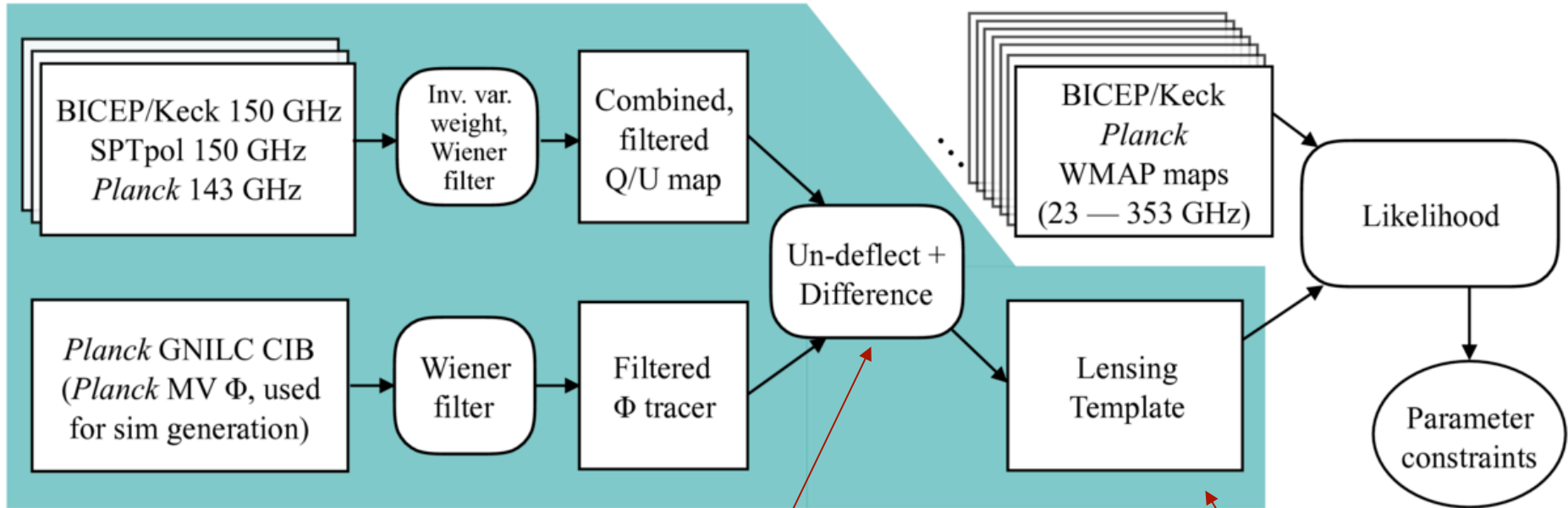


Channel 235



Delensing slides
From BK14+SPTpol paper
[arxiv/2011.08163](https://arxiv.org/abs/2011.08163)

Making/Using a “Lensing Template”

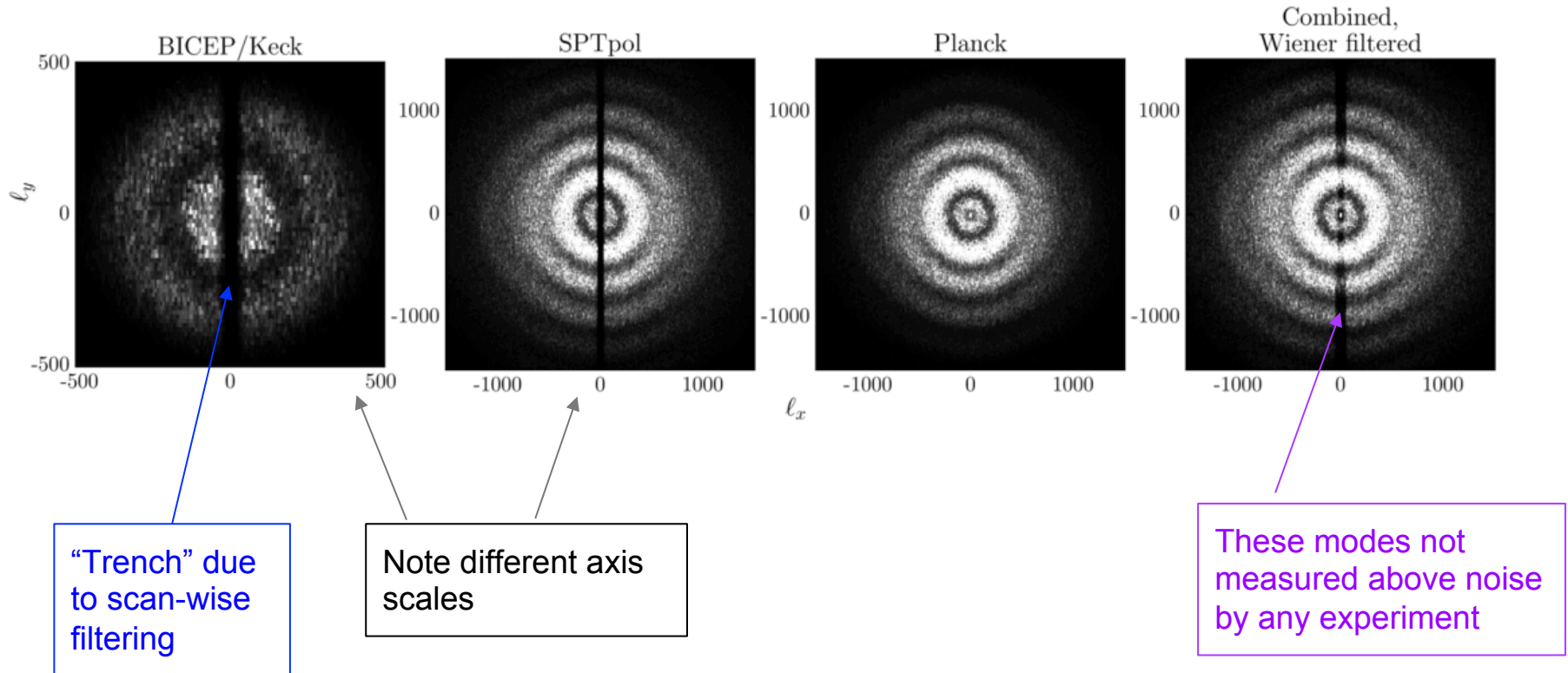


map space un-deflect operation

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.

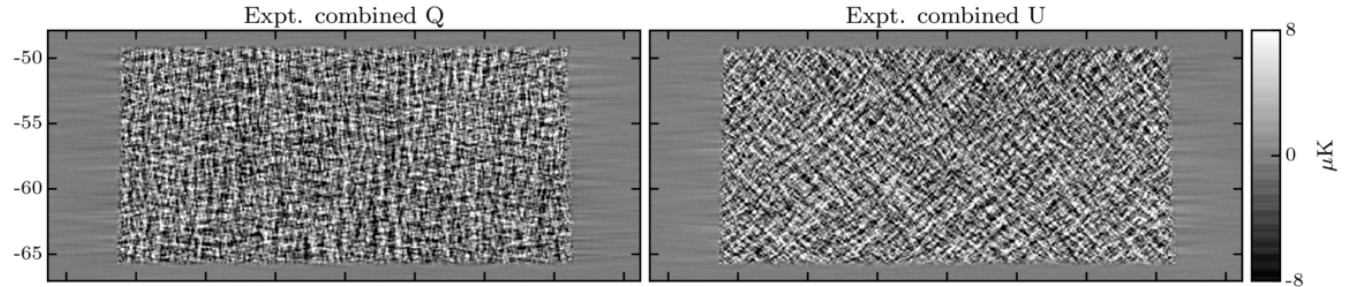
Combining the BK/SPT/Planck maps

E-modes in the 2d Fourier Plane

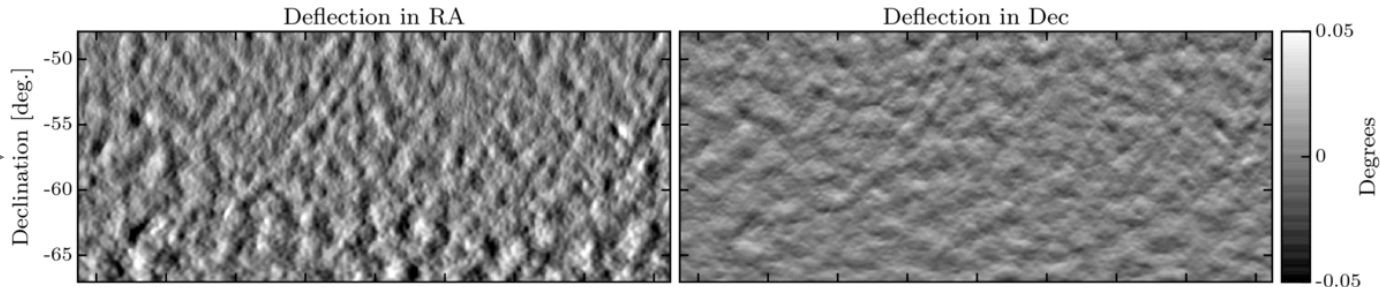


Making the lensing template

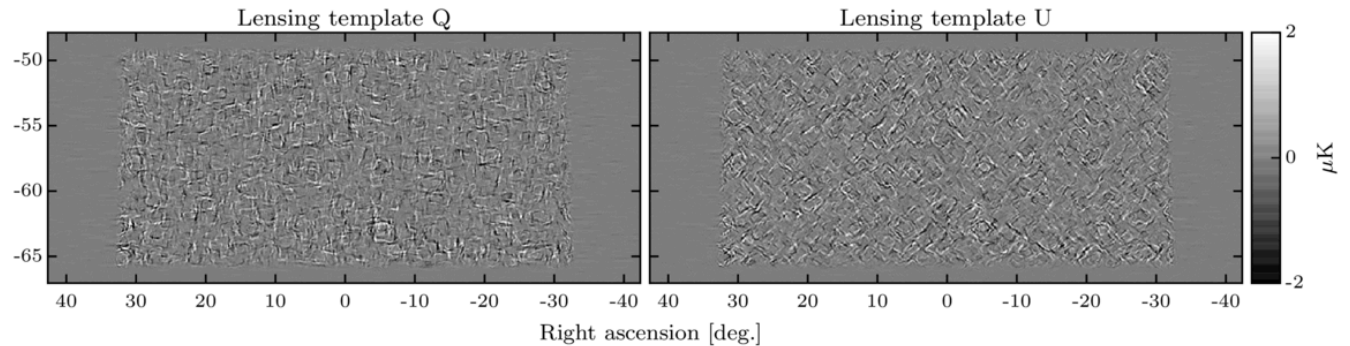
Combined map back
in image space



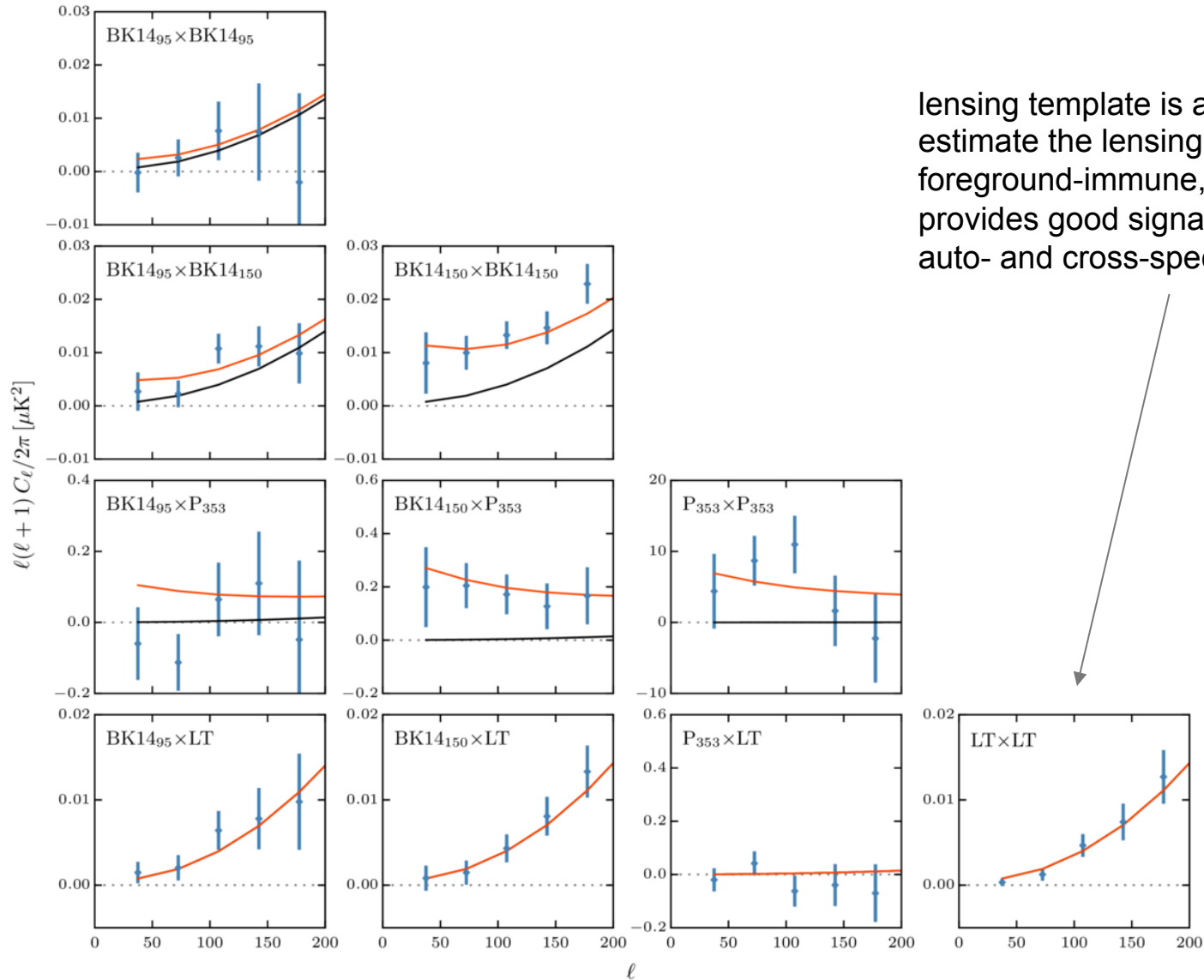
Weiner filtered
lensing deflection
field estimate from
Planck CIB map



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



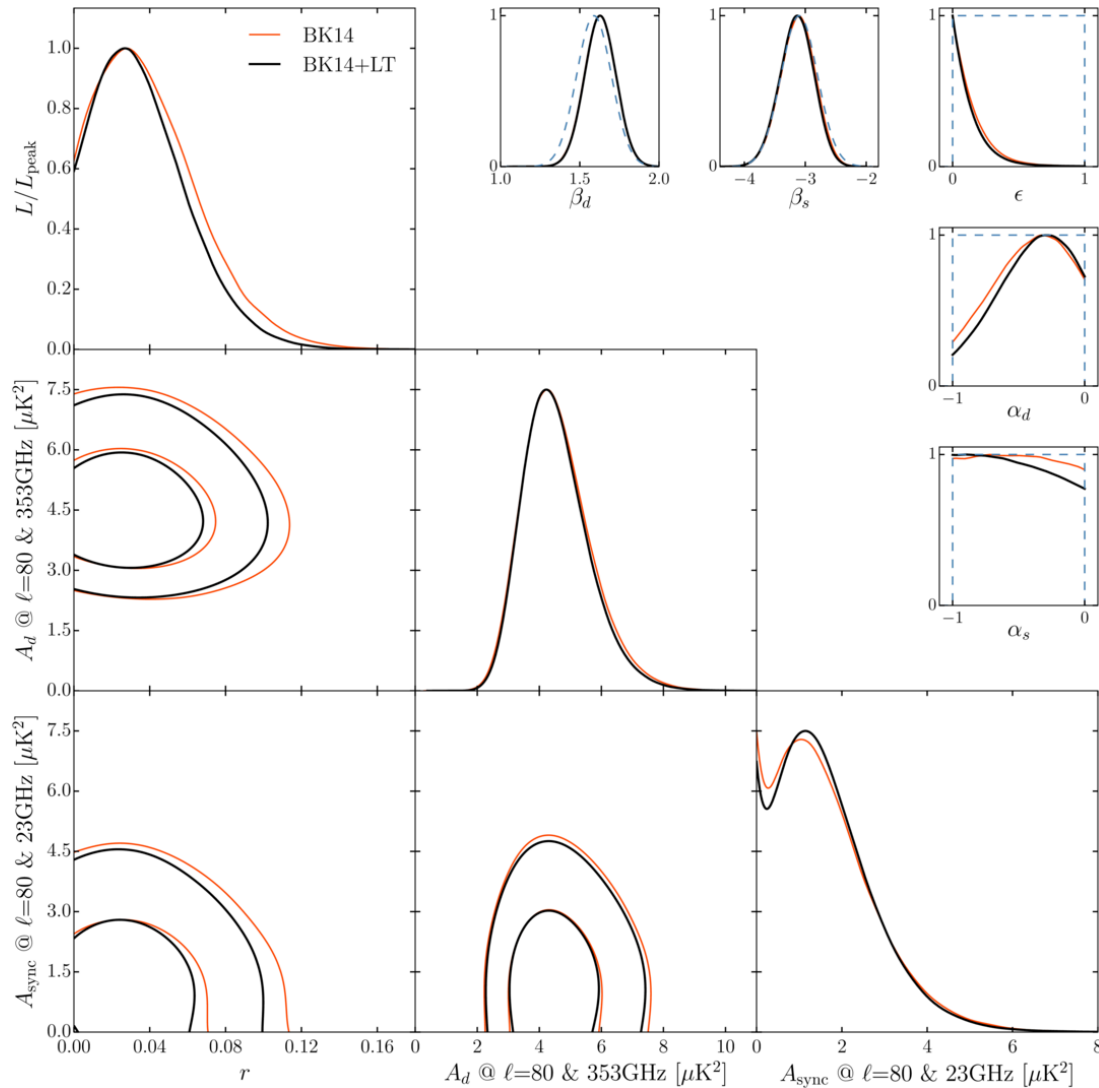
Auto/cross spectra of the lensing template



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.



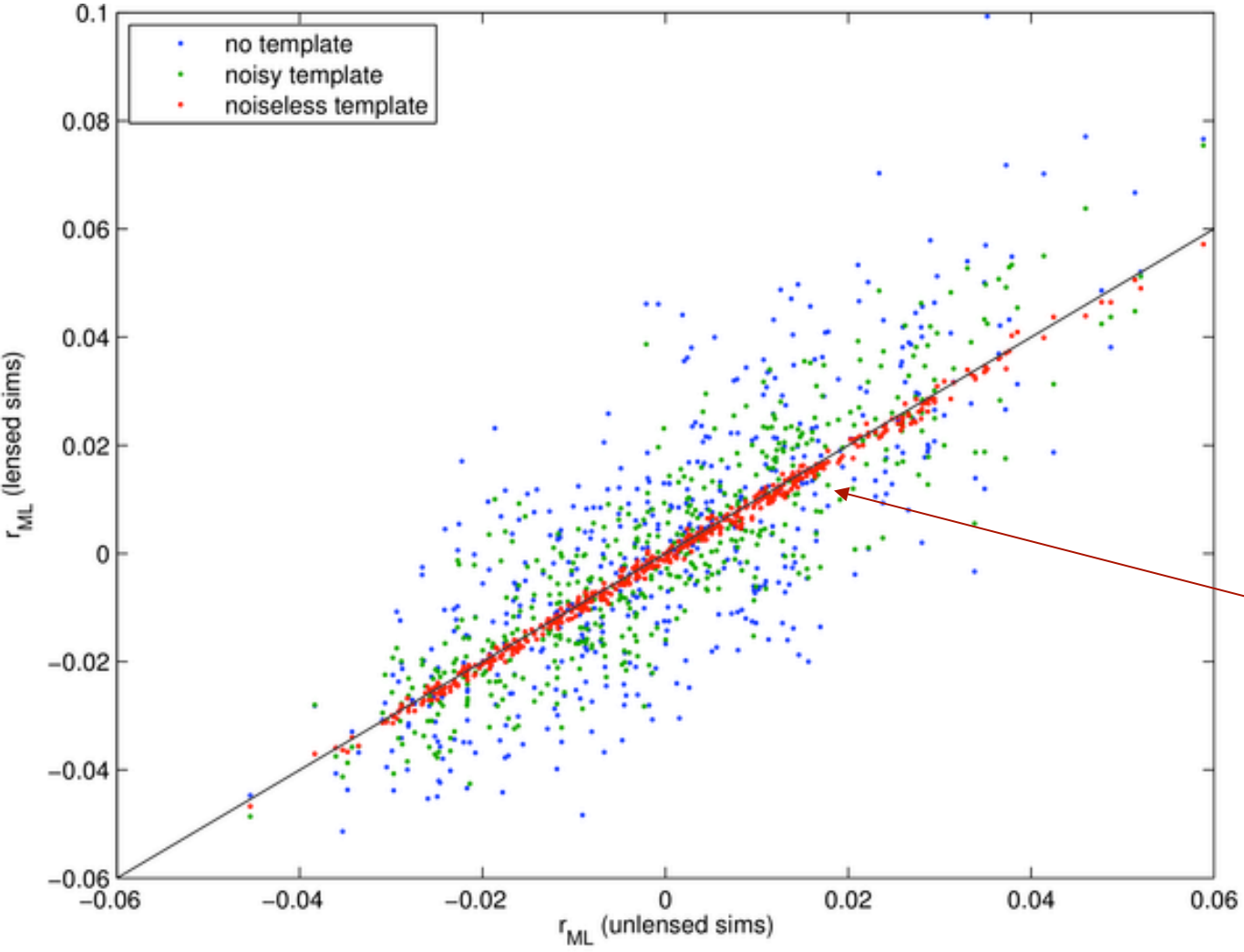
Effect of lensing template on likelihood results



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.

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](https://arxiv.org/abs/1603.05976)

Map-based E - B purification

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

$$\tilde{\mathbf{m}} = \mathbf{R}\mathbf{m}$$

Giant matrix representing all
linear filtering of the data

$$\tilde{\mathbf{C}} = \mathbf{R}\mathbf{C}\mathbf{R}^T$$

Giant covariance matrix

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

Solve the generalized
eigenvalue problem.

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

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

The mode is
ambiguous.
DISCARD!

Build a projection operator
that only selects the
unambiguous modes.

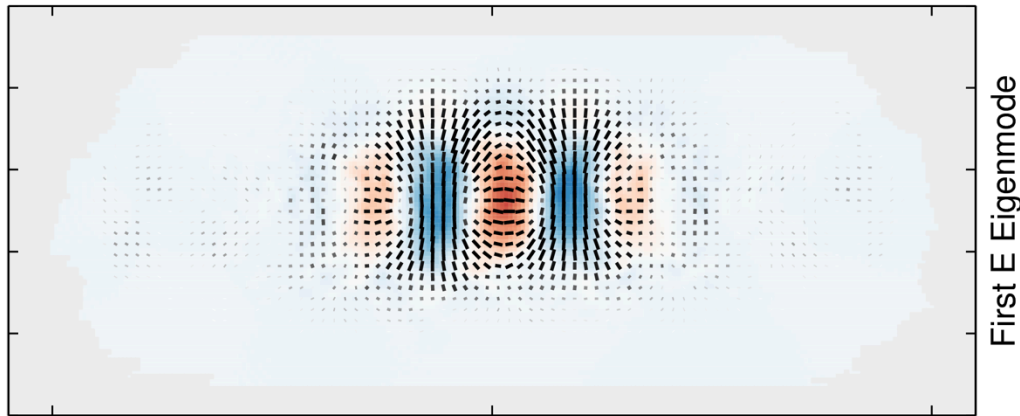
$$\lambda_{\mathbf{b}} \gg 1$$

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

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

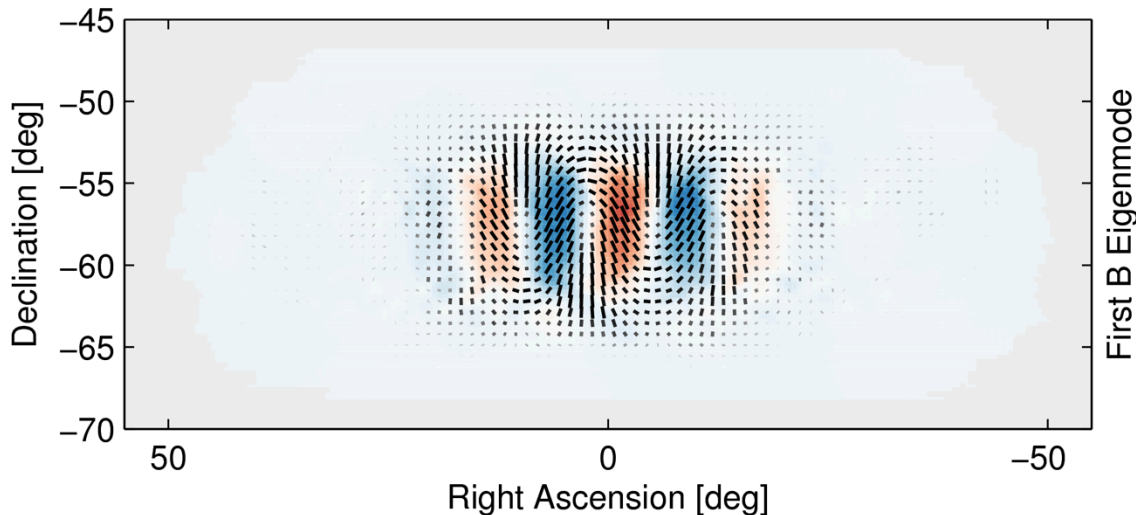
Map-based E - B purification

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

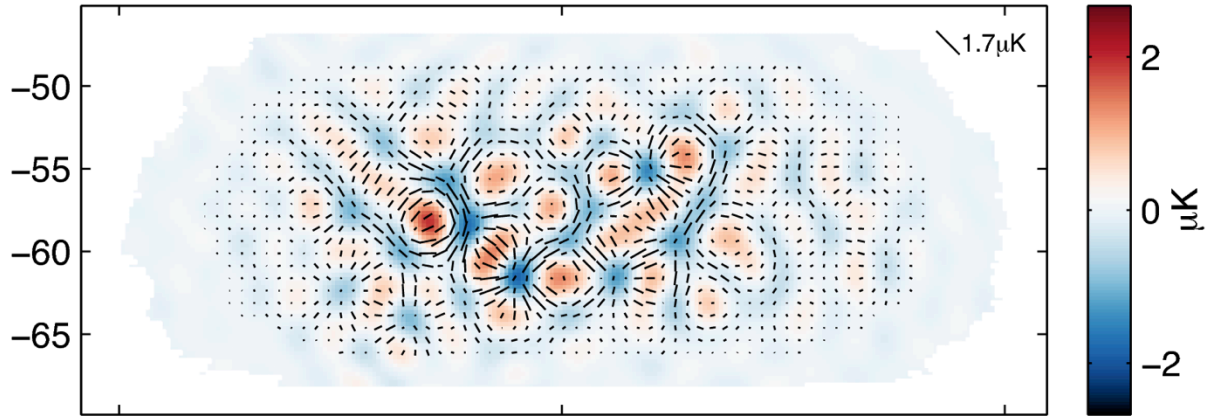


Projecting onto the 'pure-B' mode basis prevents LCDM E-modes from leaking into B-modes

Map-based E - B purification

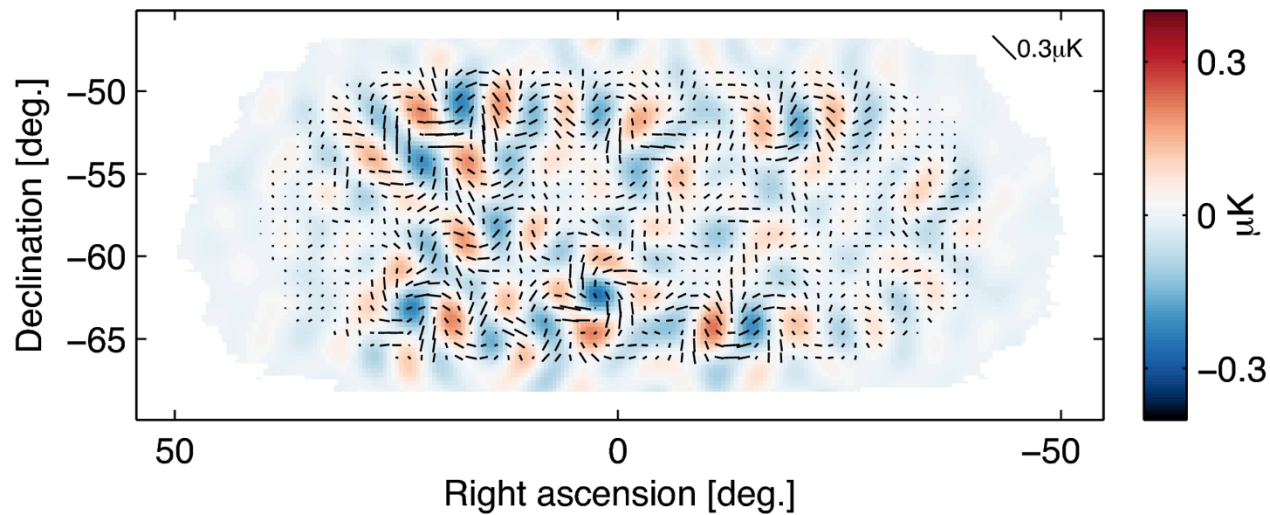
Simulation : LCDM (w/o lensing), no noise
filtered to $20 < \ell < 150$

E



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

B

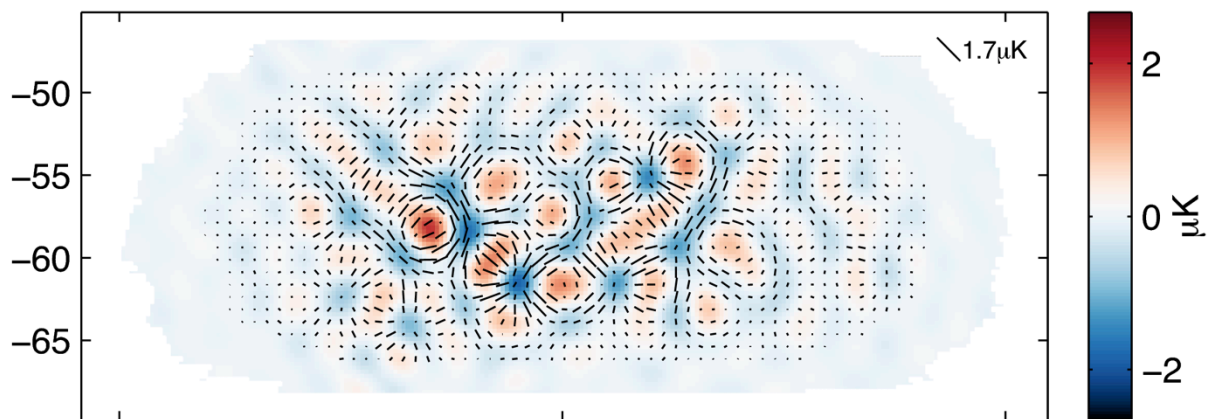


E to B leakage **without**
purification is unacceptably high

Map-based E - B purification

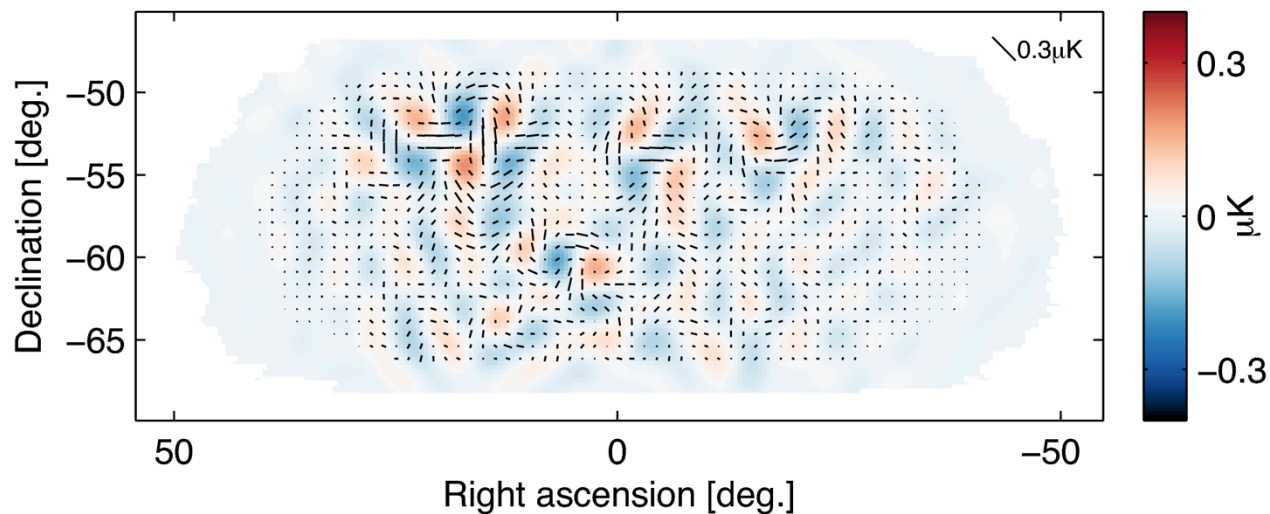
Simulation : LCDM (w/o lensing), no noise
filtered to $20 < l < 150$

E



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

B

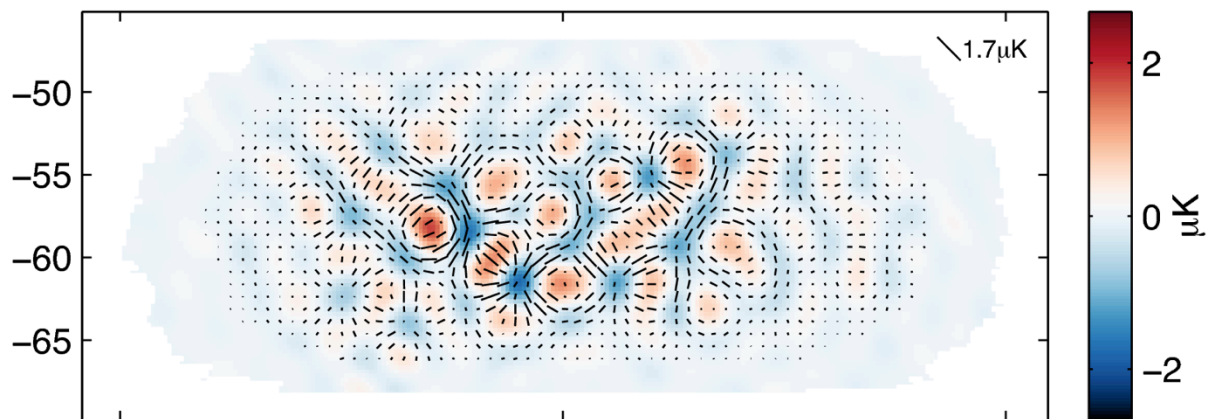


E to B leakage **with Smith et al 2006** method is still high due to filtering operations

Map-based E - B purification

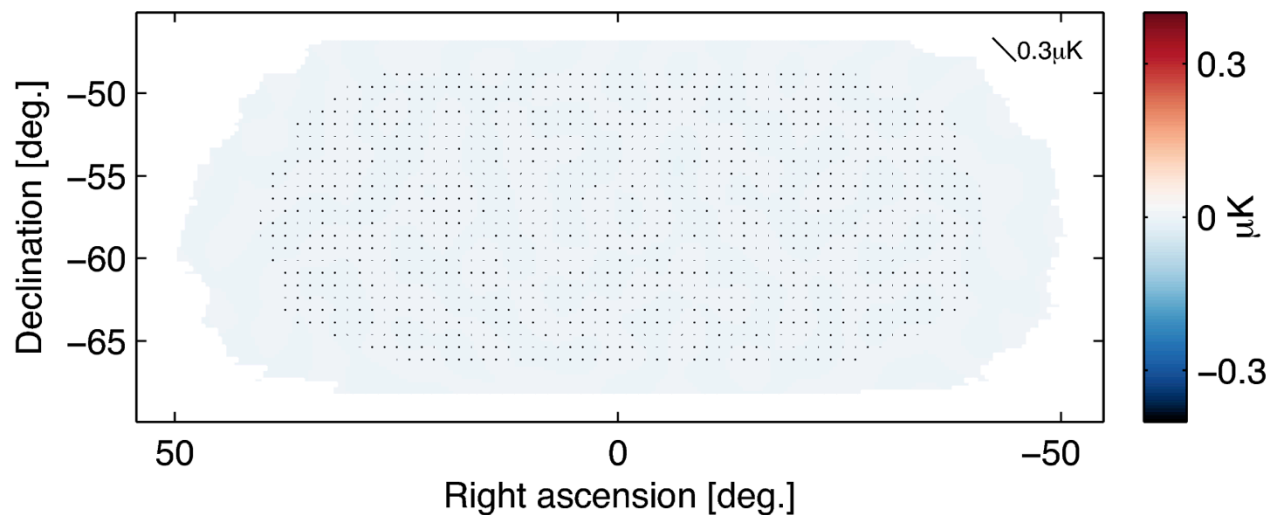
Simulation : LCDM (w/o lensing), no noise
filtered to $20 < \ell < 150$

E



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

B



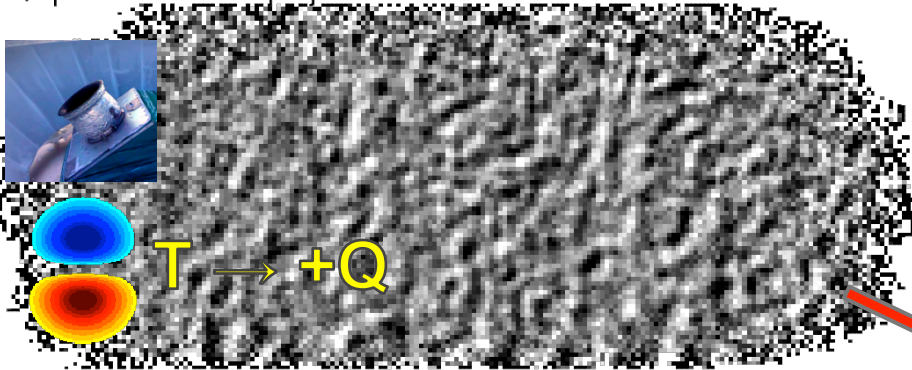
E to B leakage **with** purification is orders of magnitude smaller

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

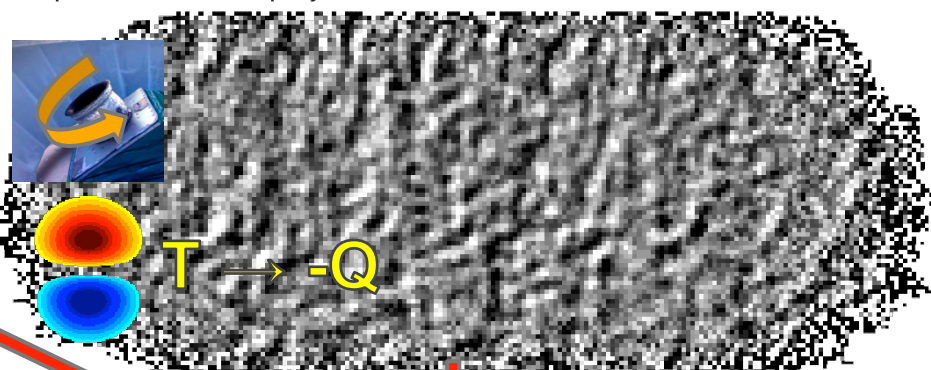
Cancellation of Systematics

Maps using just half the boresight rotation angles:

Q split half A w/o deprojection

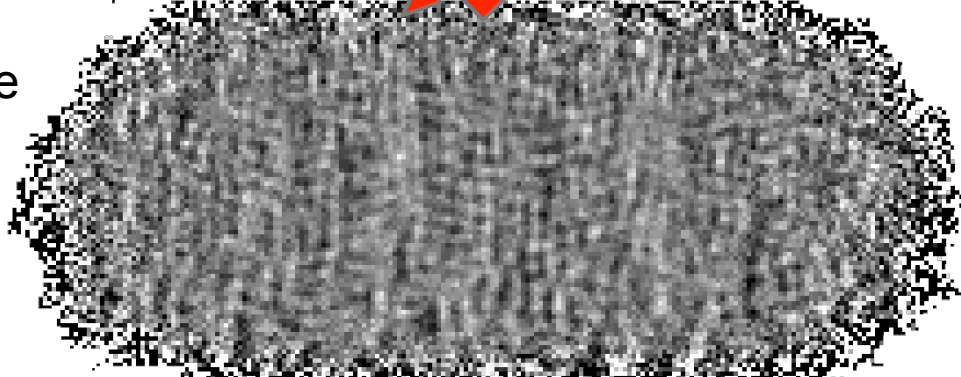


Q split half B w/o deprojection



add

Q map w/o deprojection



w/o boresight rotation

- Differential pointing leaks temperature sky into polarization maps

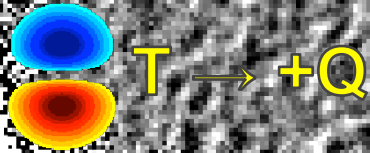
with boresight rotation

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

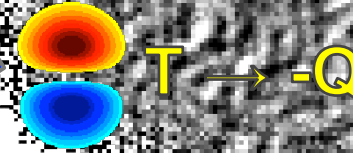
Jackknife: Sensitive Test of Systematics

Maps using just half the boresight rotation angles:

Q split half A w/o deprojection

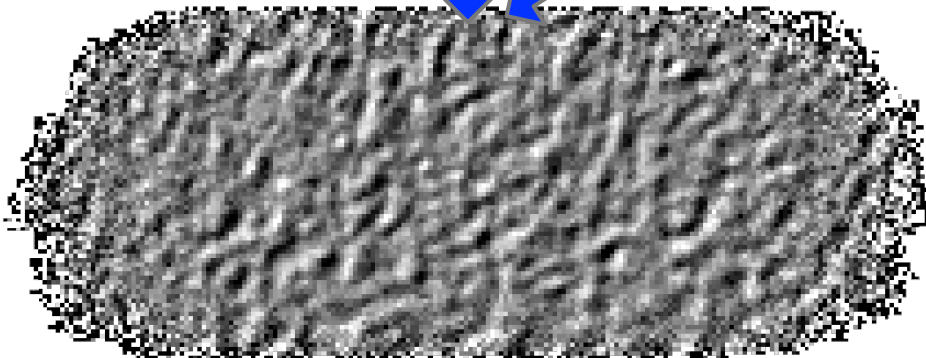


Q split half B w/o deprojection



subtract

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:

Q split half A w/ deprojection



Q split half B w/ deprojection

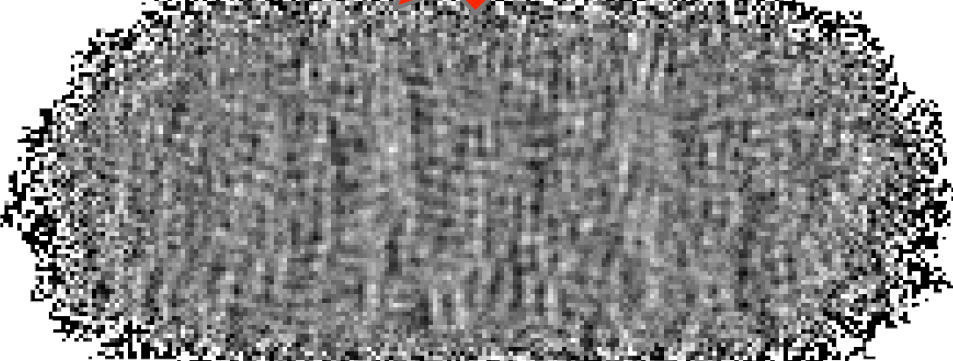
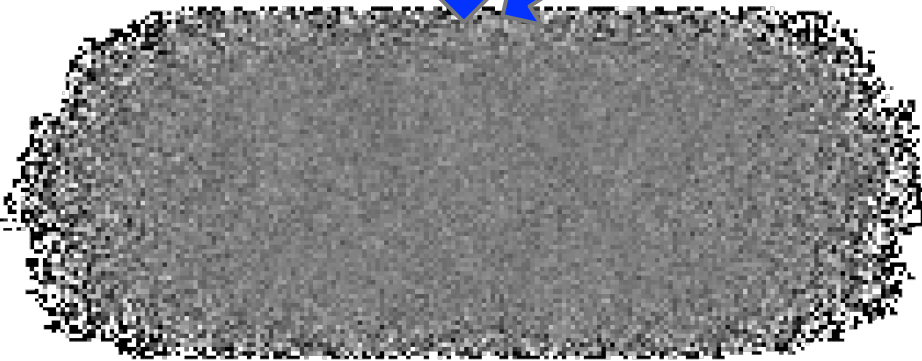


subtract

add

Q jack w/ deprojection

Q map w/ deprojection

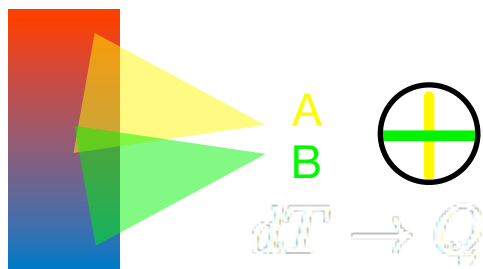


- “Deprojection”:
- From well-known temperature sky form a prediction of the leakage and remove it
 - Cleans up maps even without cancellation from boresight rotation

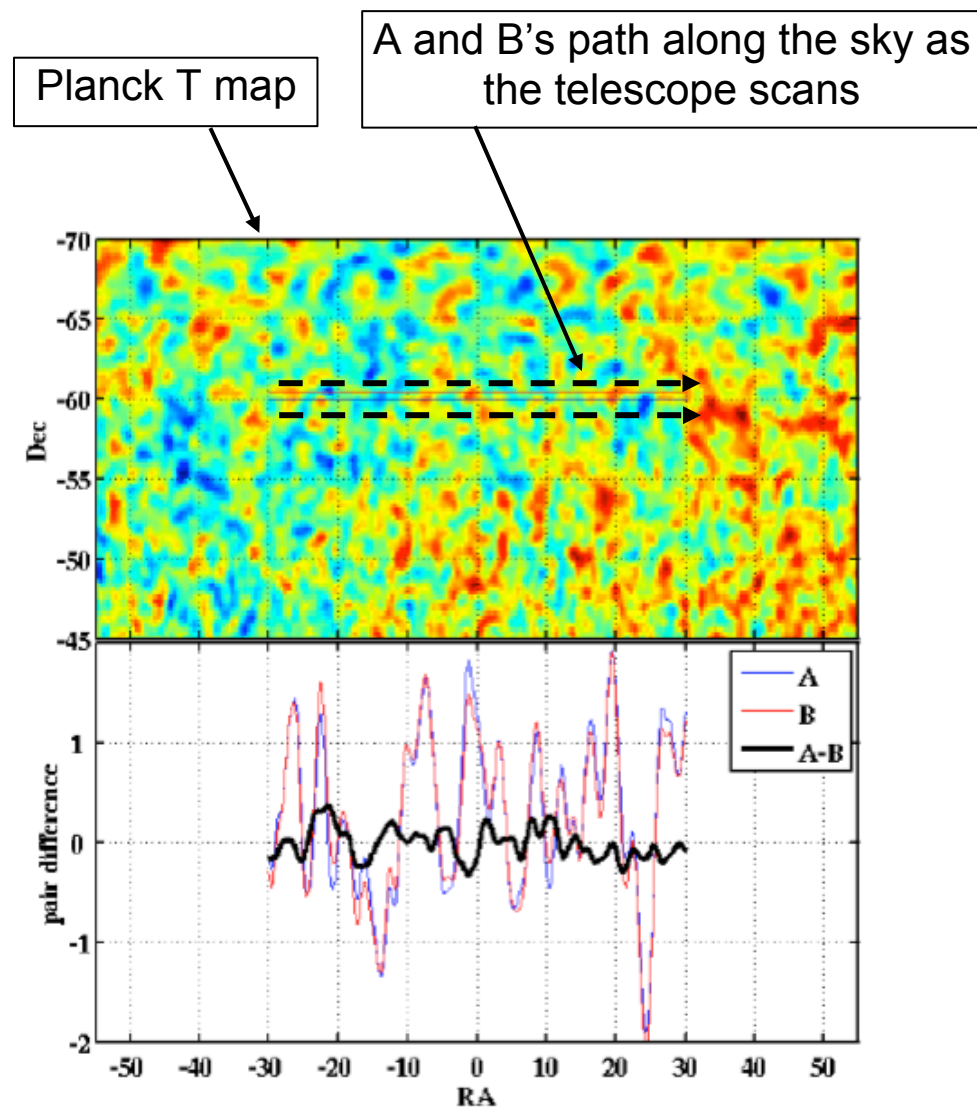
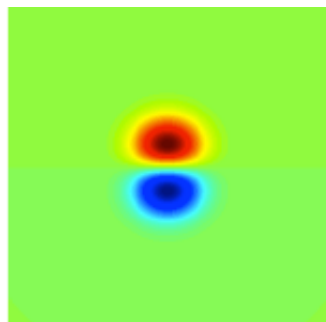
Beam Systematics

example: pointing center mismatch

“A” and B” beams



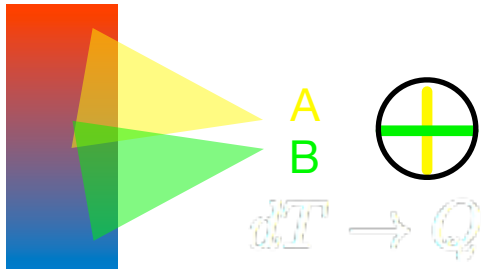
A-B difference beam



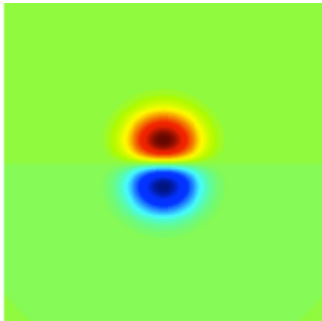
Systematics Removal: Deprojection

example: pointing center mismatch

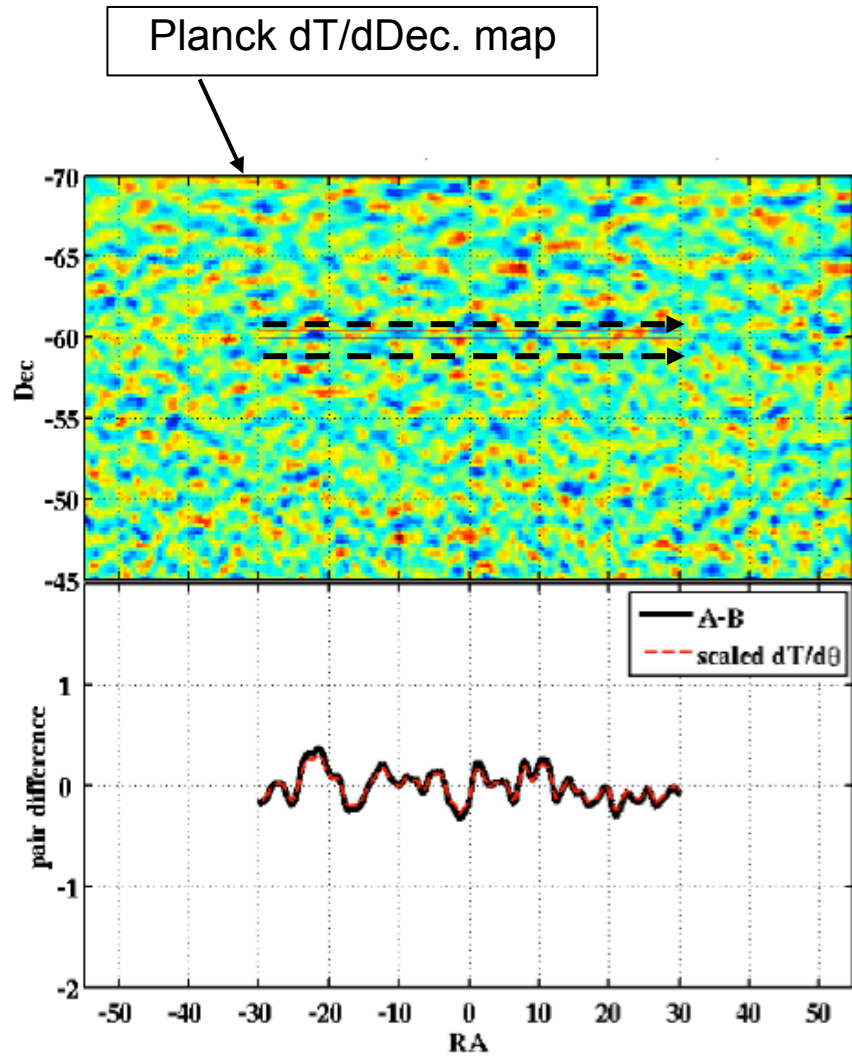
“A” and B” beams



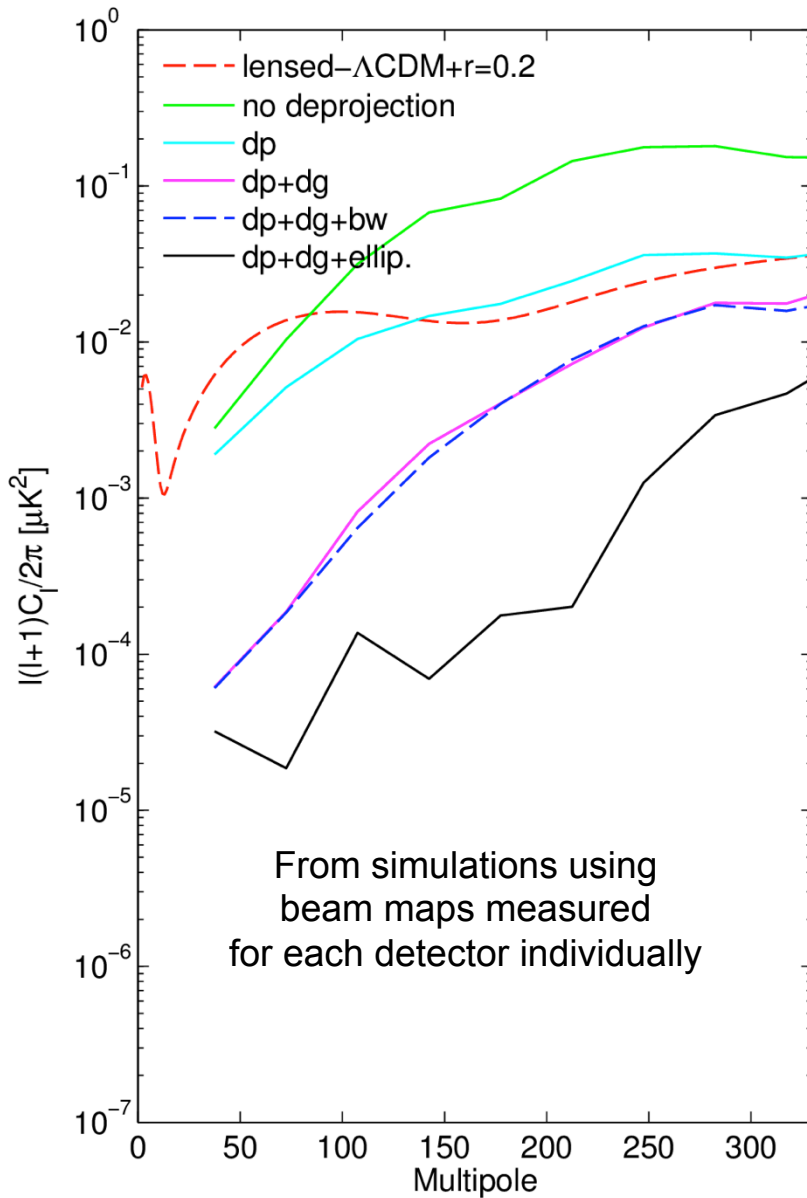
A-B difference beam



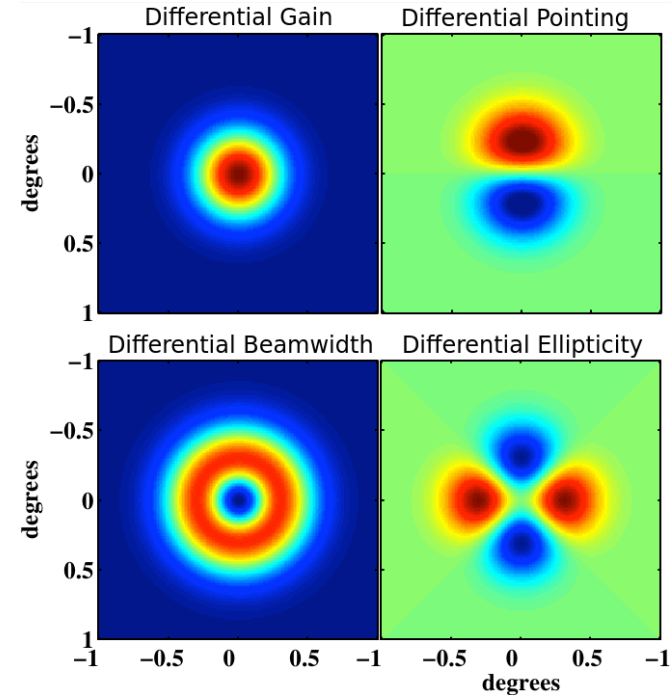
Regress template against pair diff timestream and subtract



Systematics Removal: Deprojection



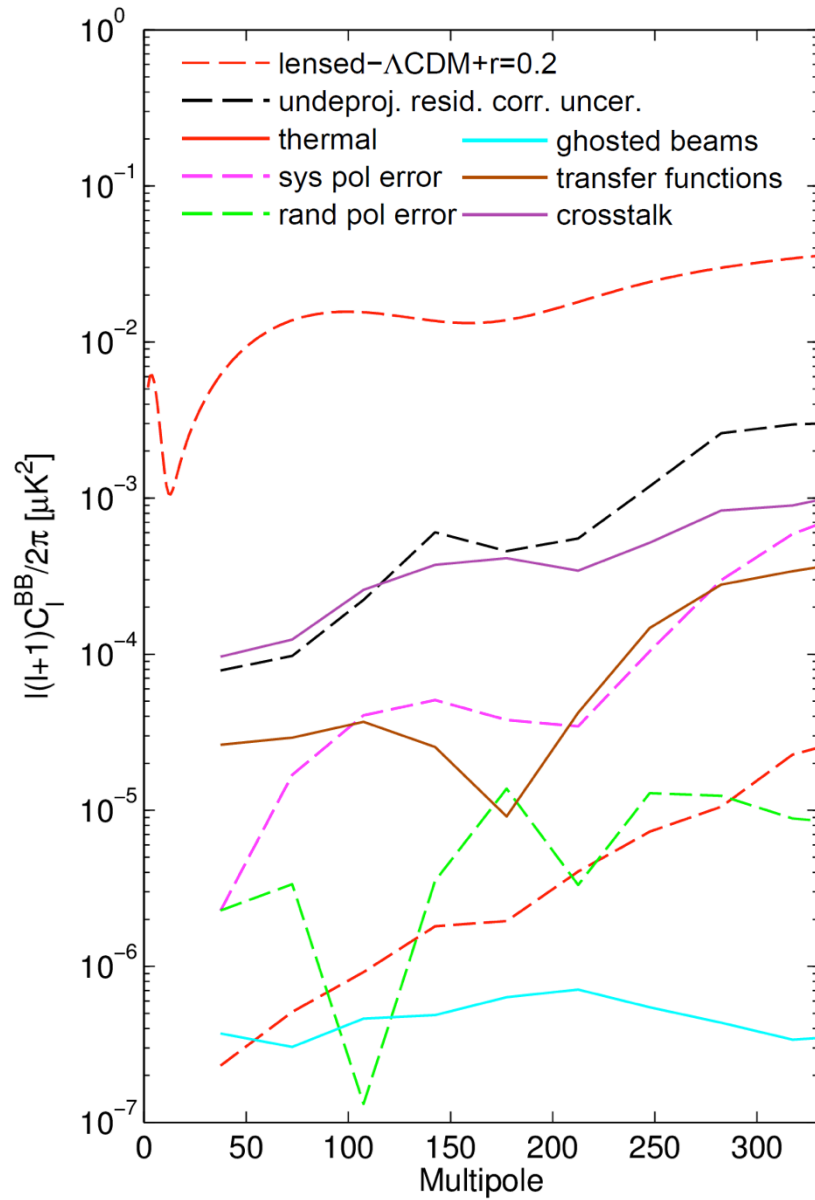
Technique developed to remove all types of leakage induced by differences of detector pair beam shapes



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

Deproject diff gain and pointing (& subtract diff ellipticity)

Systematics beyond Beam imperfections

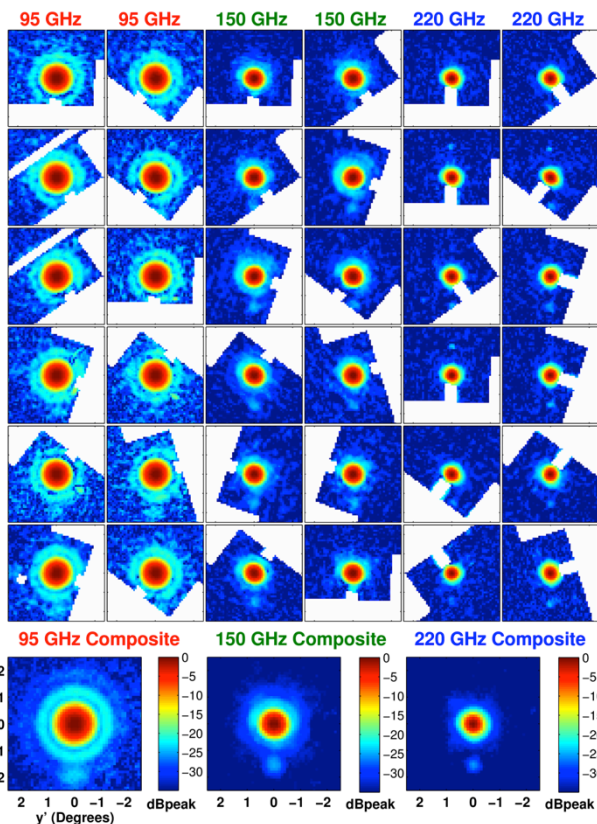
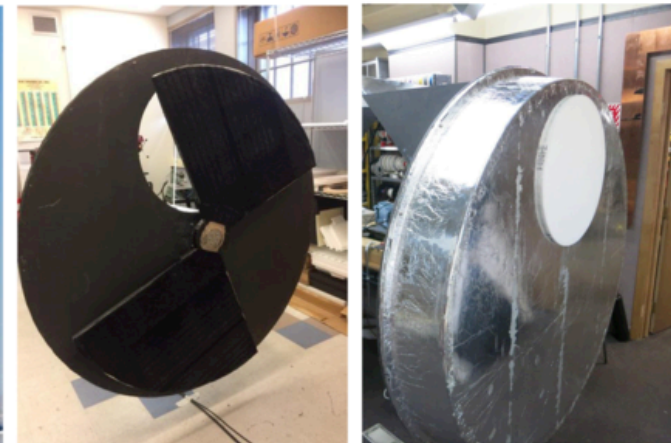
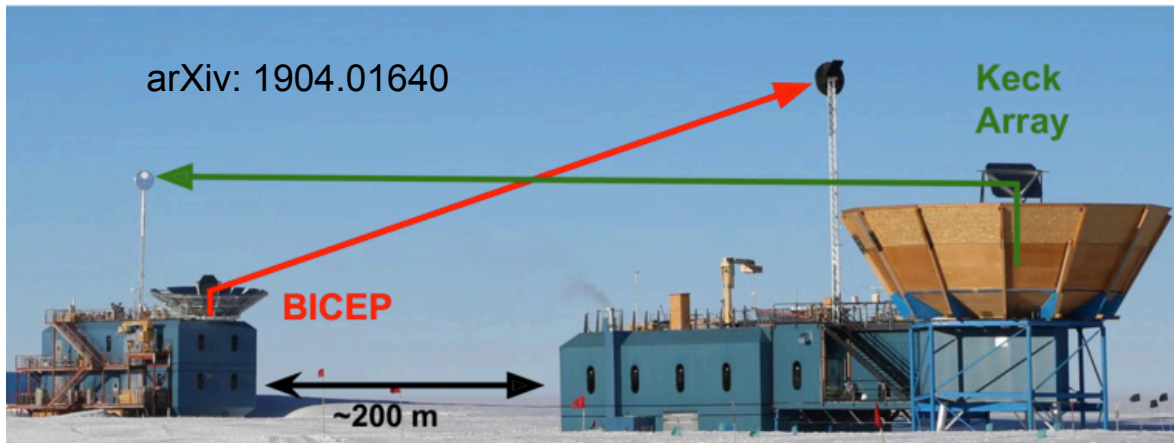


Other systematic effects investigated

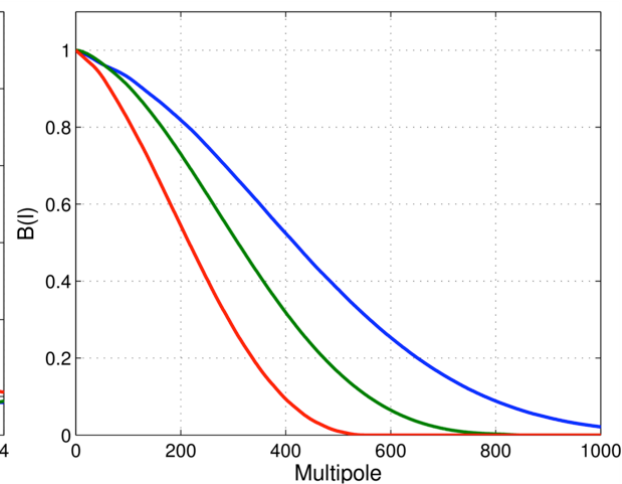
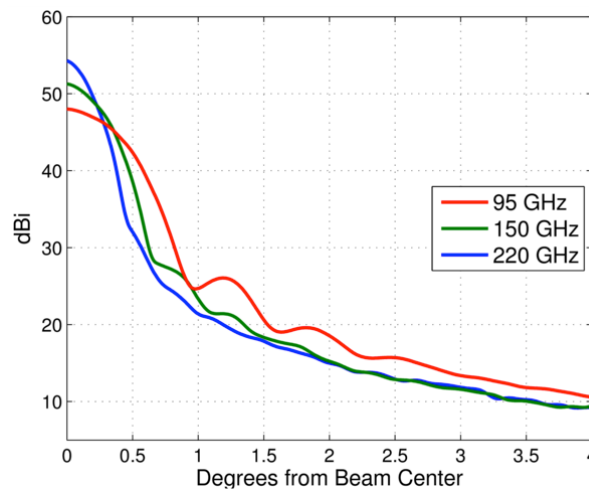
arXiv: 1904.01640

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

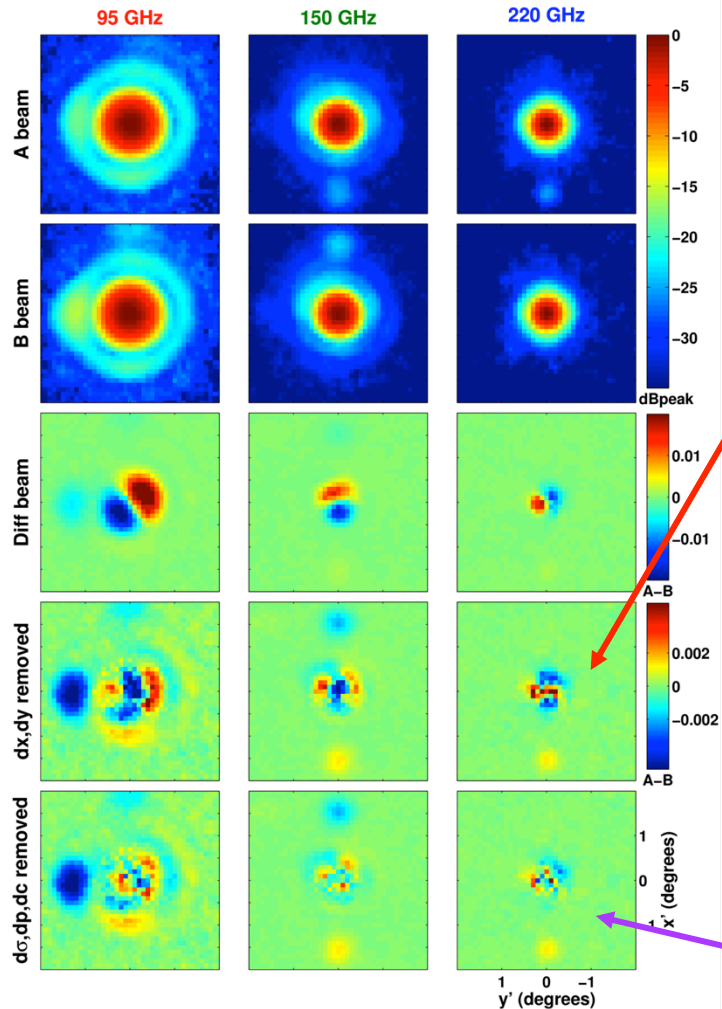
Precision Beam Measurements *in situ* at South Pole



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

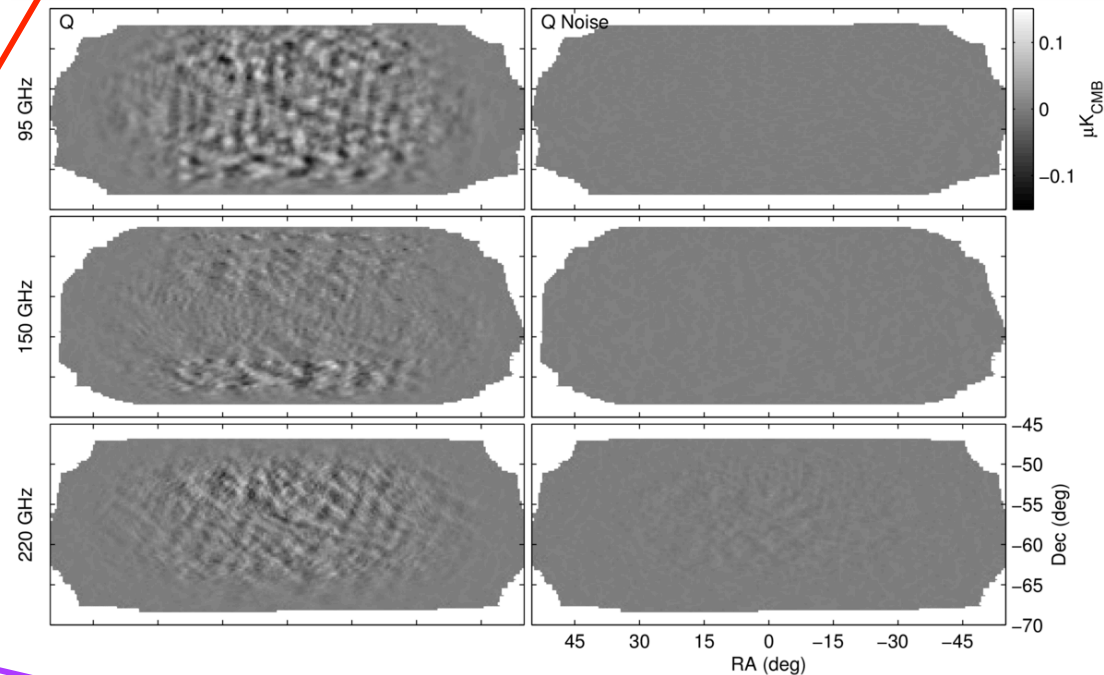


Predicting T->Pol Leakage from Differential Beams



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

arXiv: 1904.01640



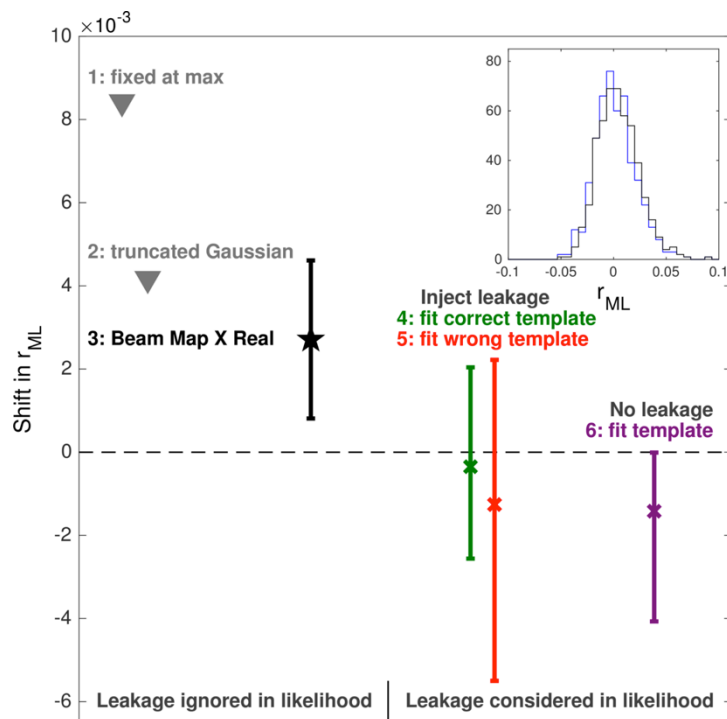
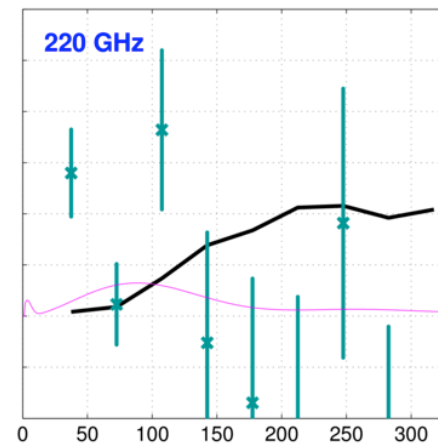
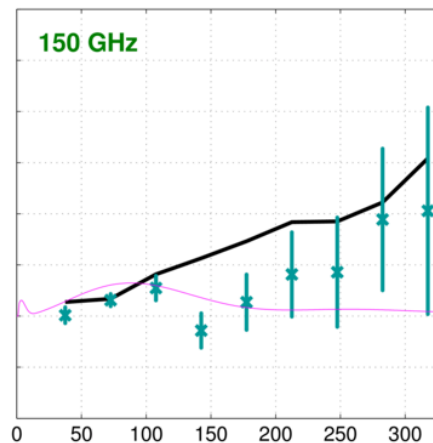
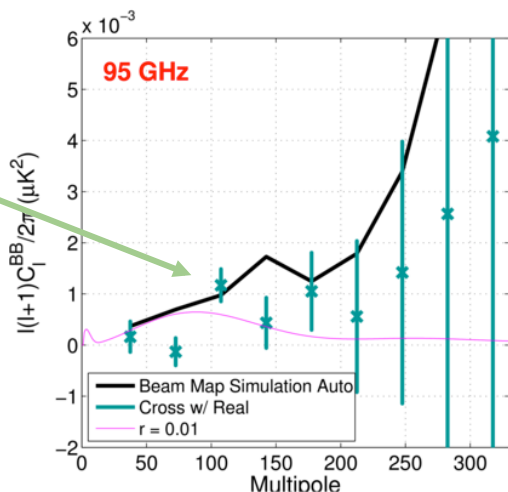
High S/N measurements of beam shape differences within a polarization pair

Propagate higher-order *unprojected* 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 $\Delta r = 0.0027 \pm 0.0019$ (compare to BK15 $\sigma(r) = 0.020$)

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

