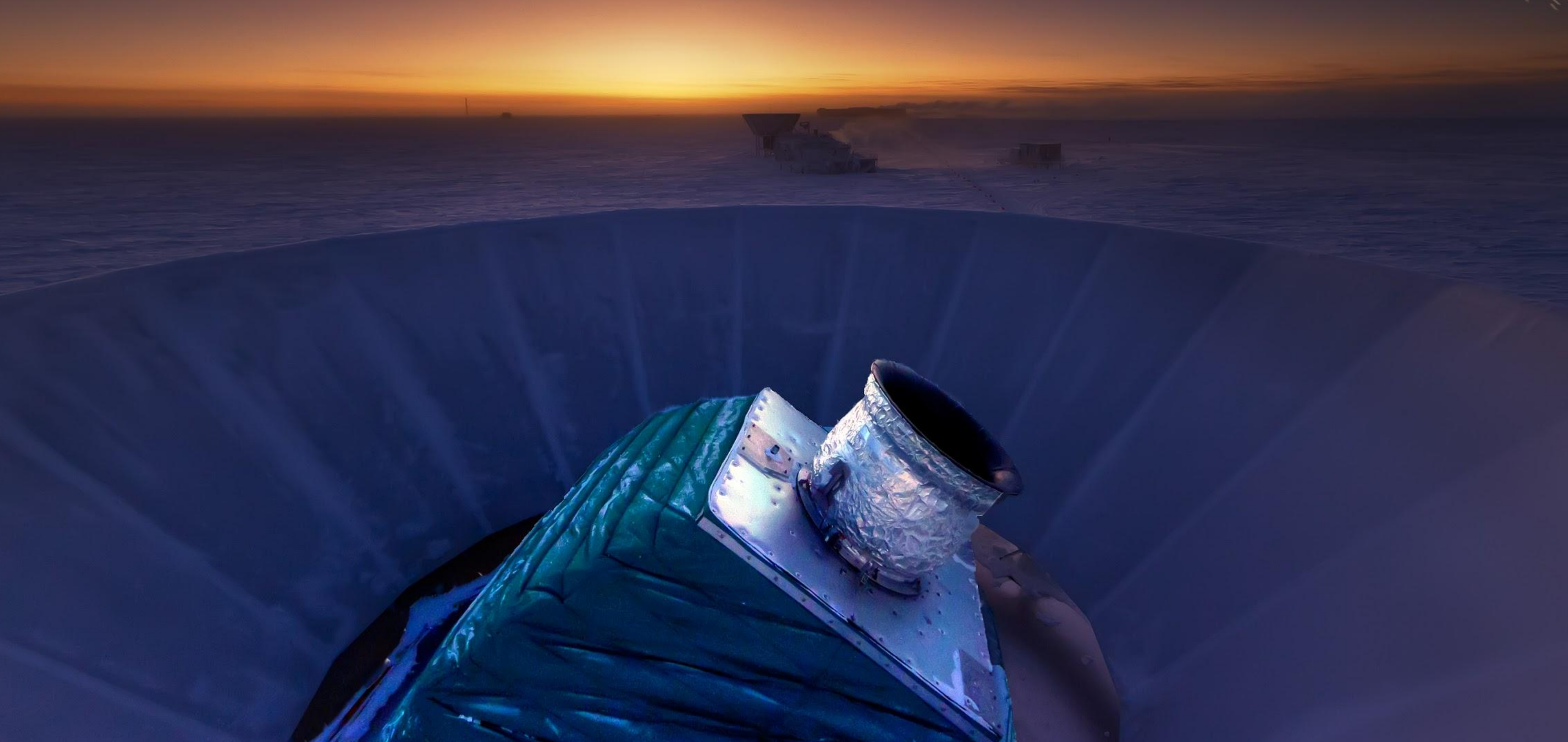
The search for primordial gravitational waves: latest results from BICEP/Keck



Clem Pryke for the BICEP/Keck Collaboration – Cambridge Cosmology Lunch Talk – Oct 30 2023

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

VE RI TAS HARVARD

DE LA RECHERCHE À L'INDUSTRIE cea

NIST

CARDIFF UNIVERSITY

UNIVERSITY OF Cincinnati

UBC

SLAC

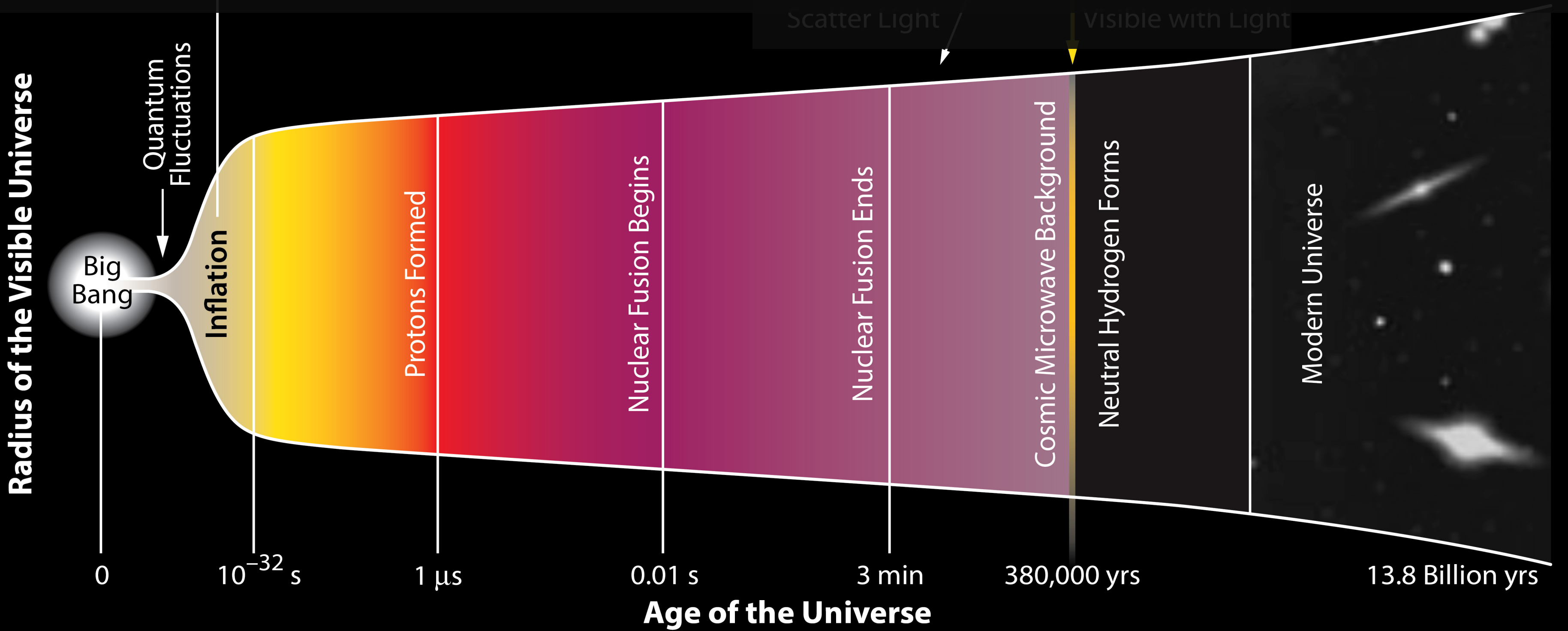
JPL

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?

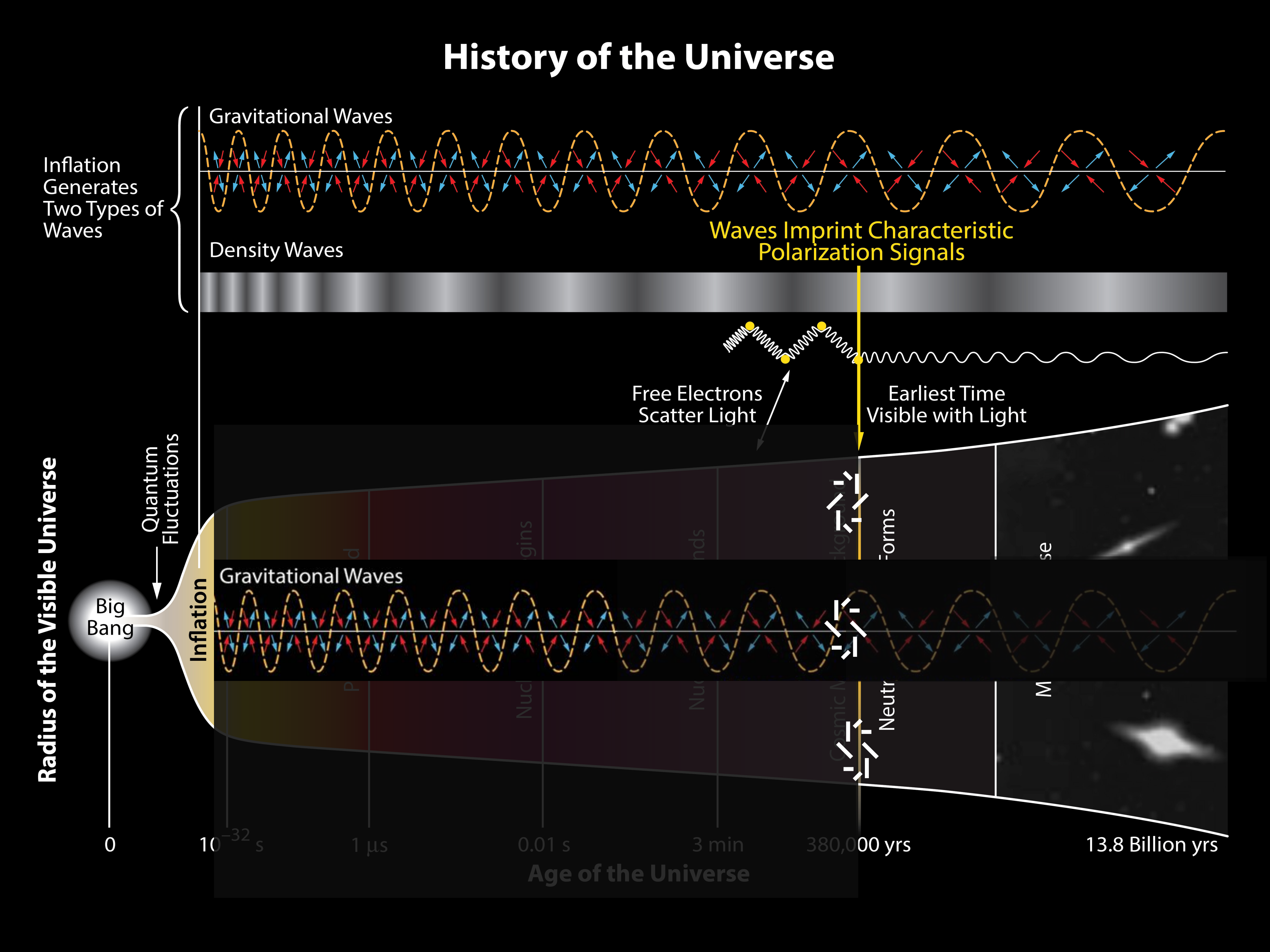
→ Any initial spatial curvature is diluted away to undetectabilty by the hyper expansion.

Explains the initial perturbations: Why Gaussian with close to flat power law spectrum? ($n_s \approx 1$)

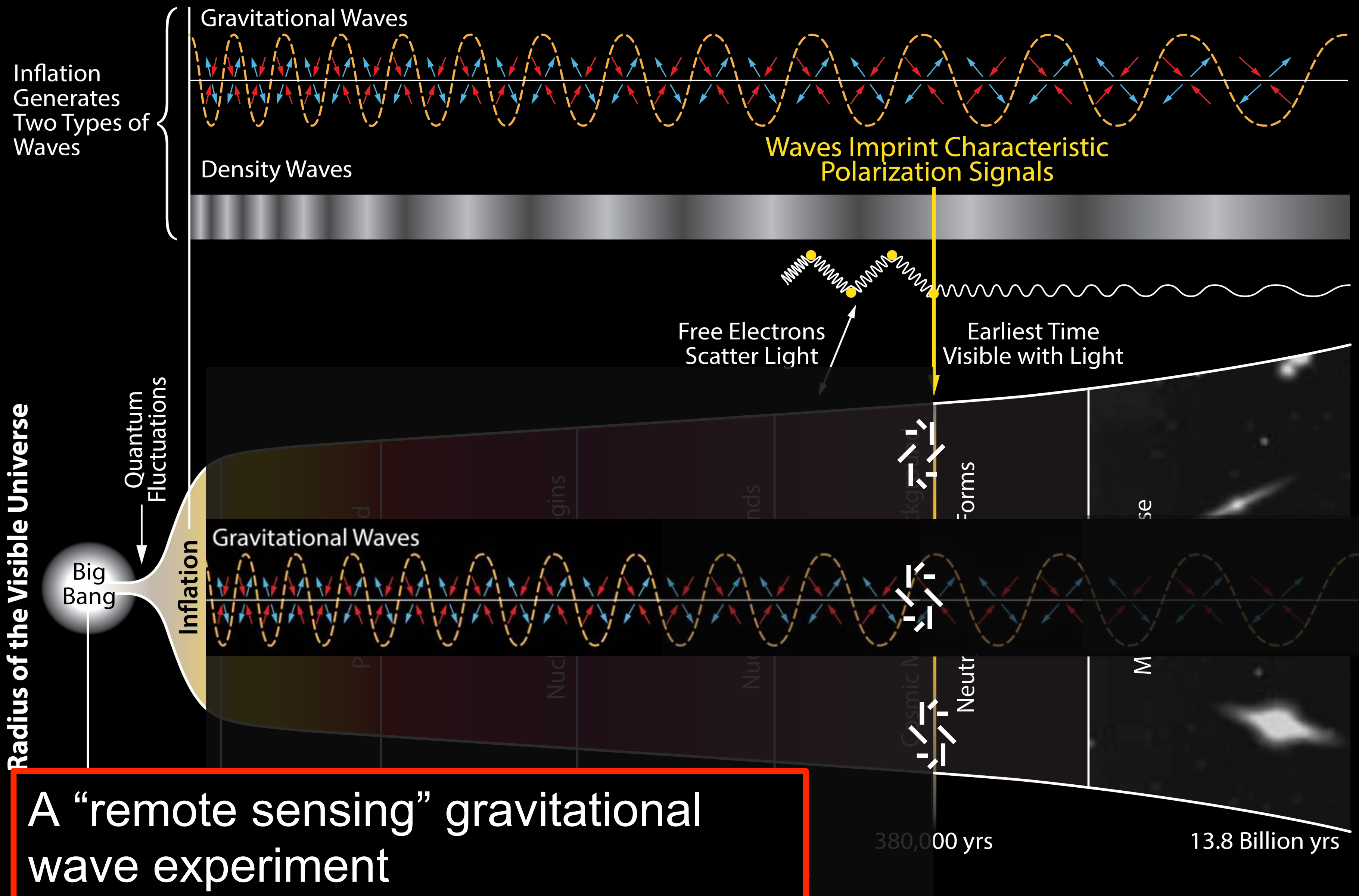
→ Equal amounts of perturbations are injected by quantum fluctuations at each step in the exponential expansion.

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
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Gravitational Waves
0
10⁻³² s
1 µs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

History of the Universe

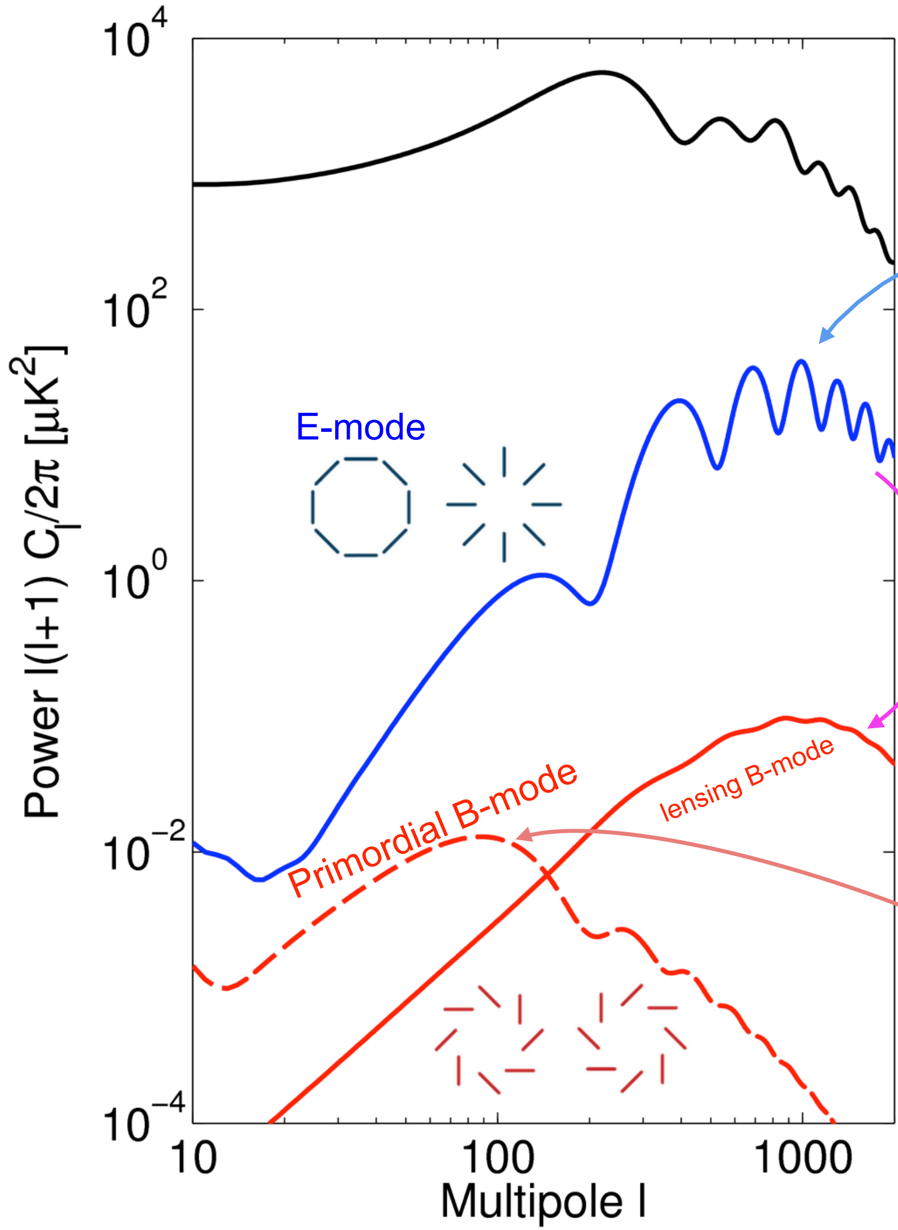


A “remote sensing” gravitational wave experiment

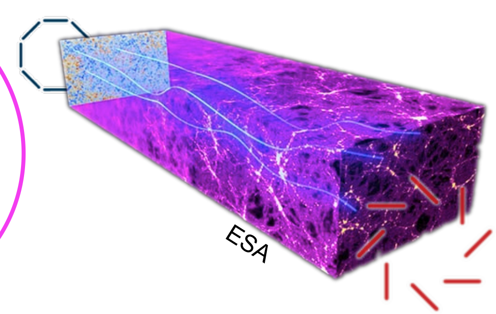
CMB Polarization, B-modes and *r*

- 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



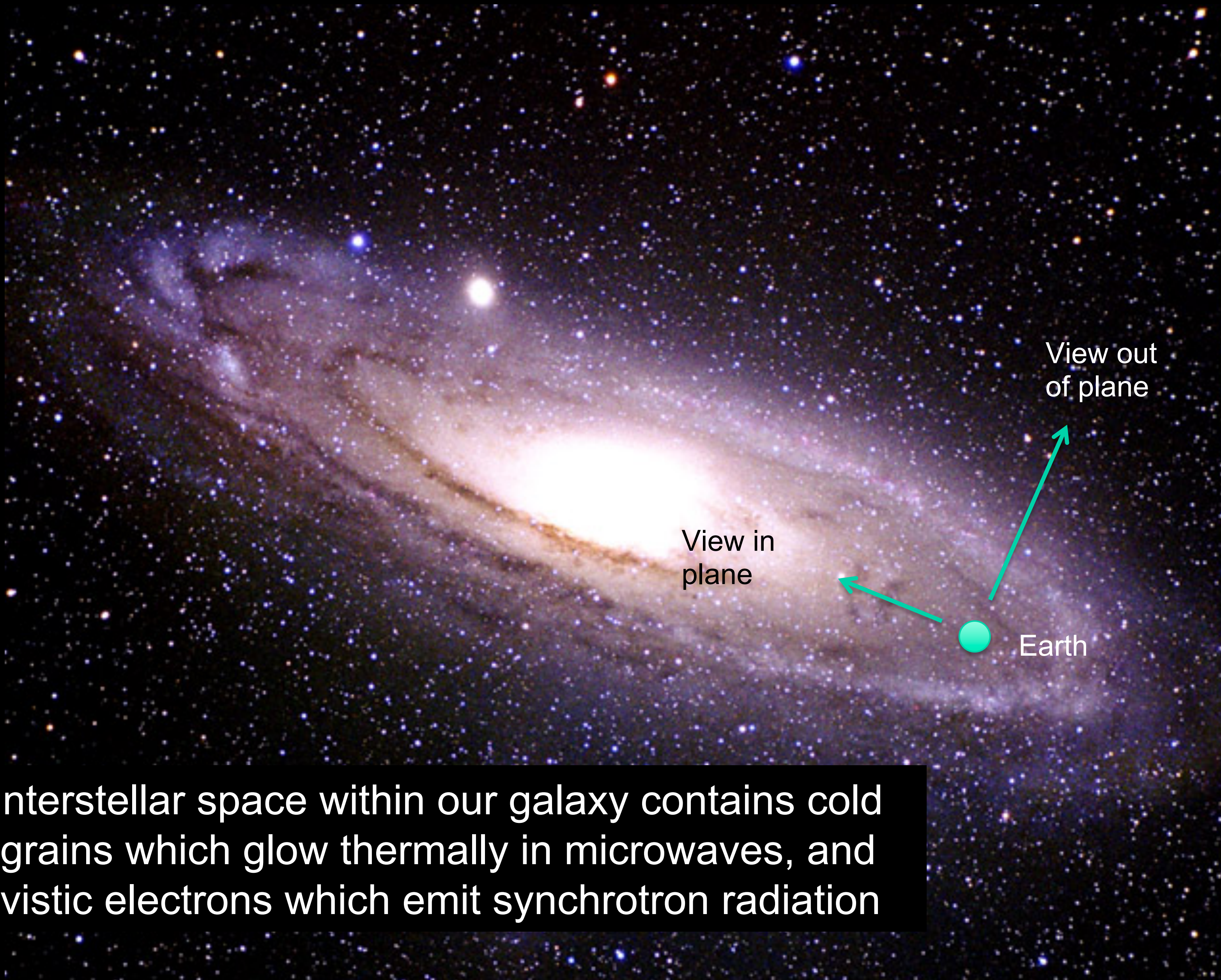
During propagation some of the E-modes are confused into B-modes by lensing

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



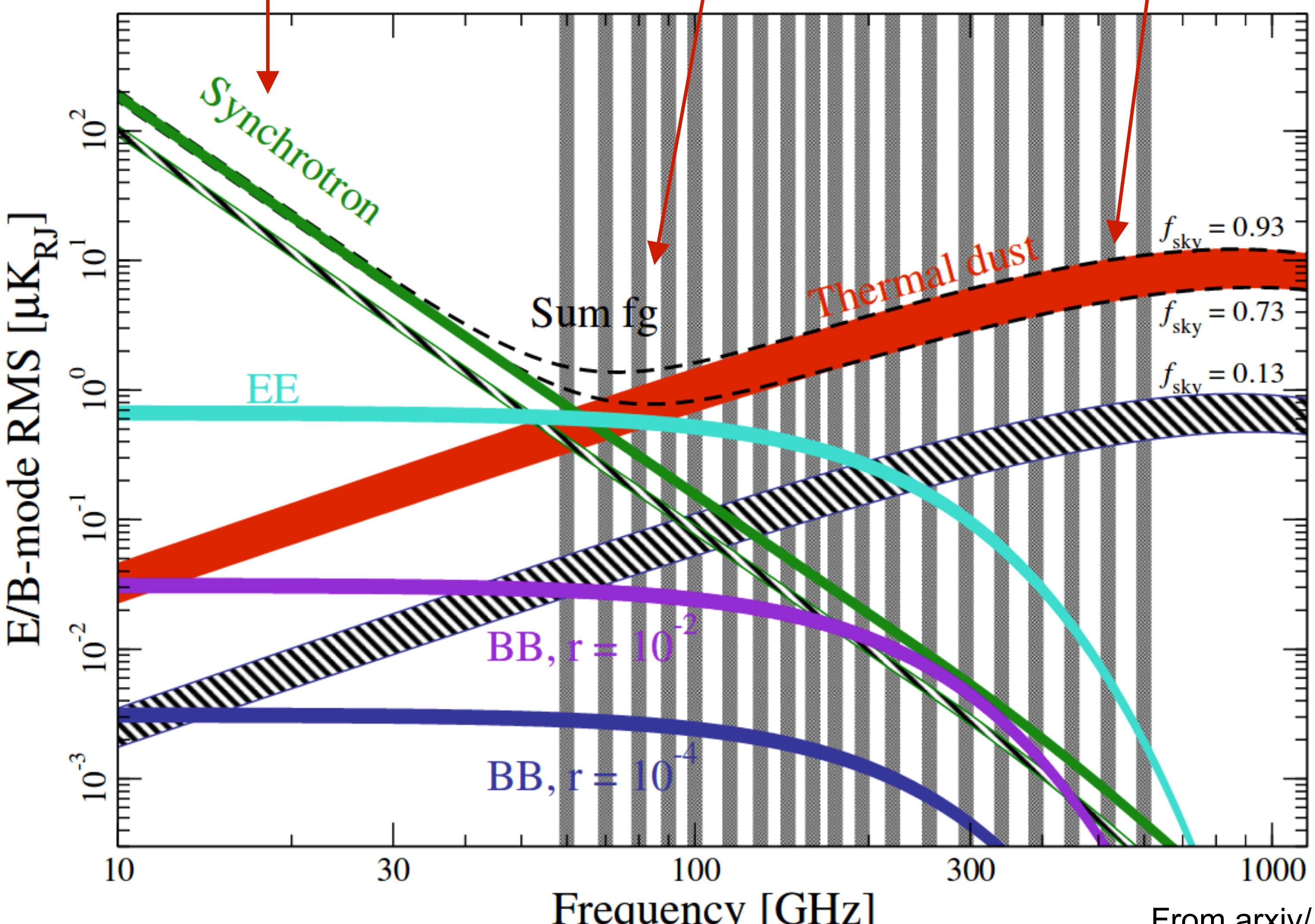
The interstellar space within our galaxy contains cold dust grains which glow thermally in microwaves, and relativistic electrons which emit synchrotron radiation

Overcoming Polarized Foreground Contamination

At low frequency synchrotron contamination

Mid frequencies minimum contamination

At high frequency dust contamination



Going to smaller/ cleaner sky patch

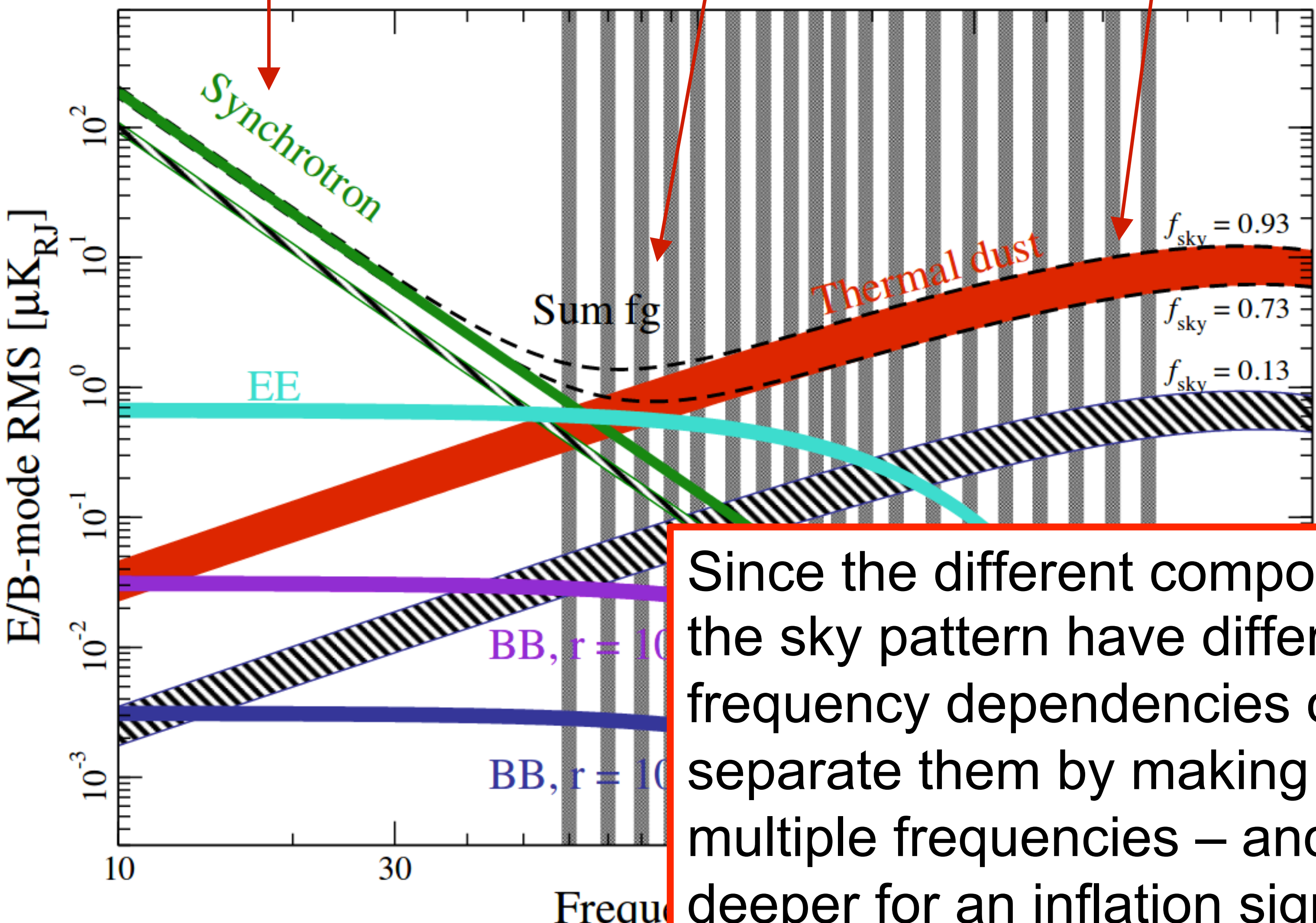
From arxiv/1704.04501

Overcoming Polarized Foreground Contamination

At low frequency synchrotron contamination

Mid frequencies minimum contamination

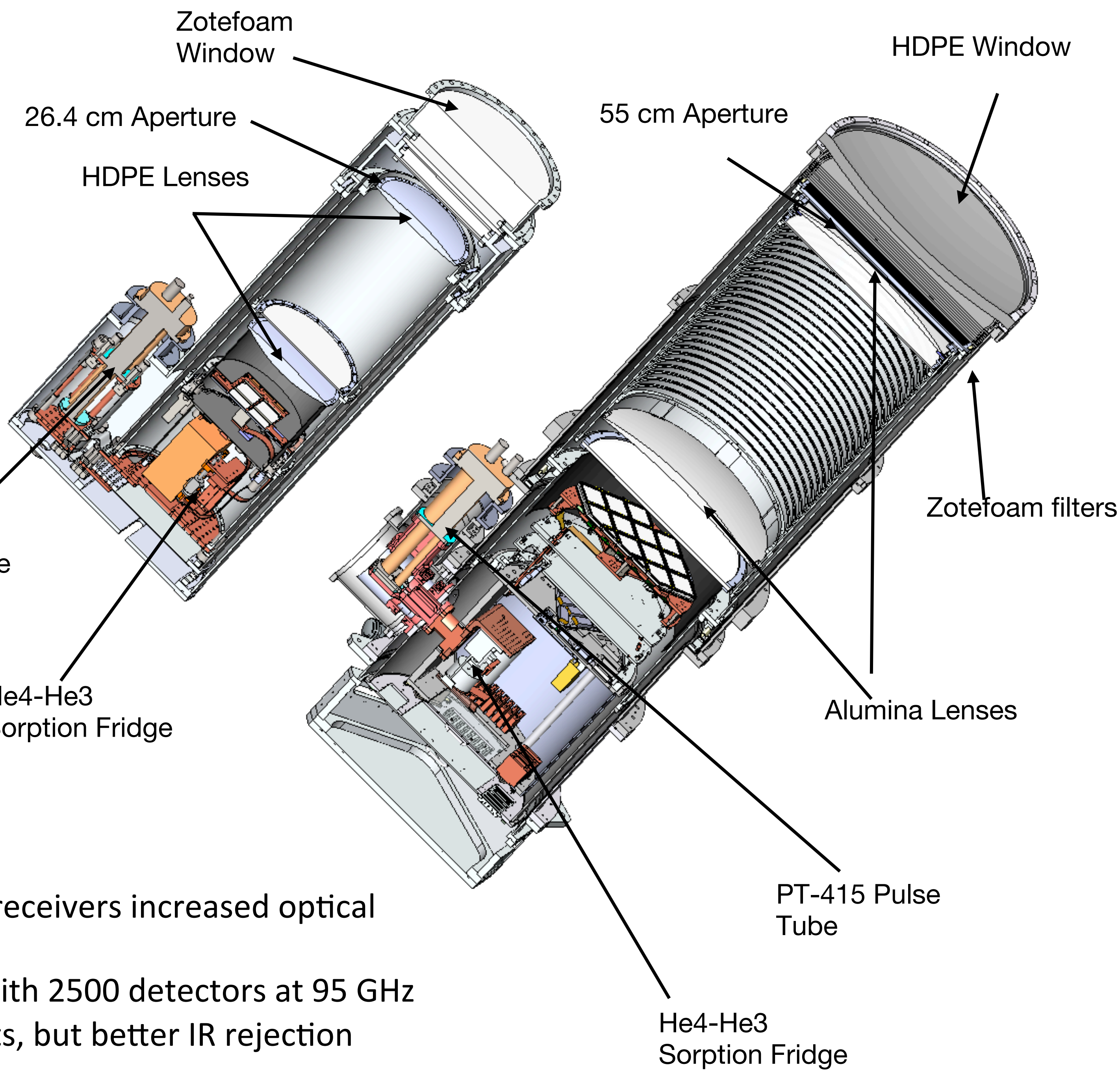
At high frequency dust contamination



Going to smaller/ cleaner sky patch

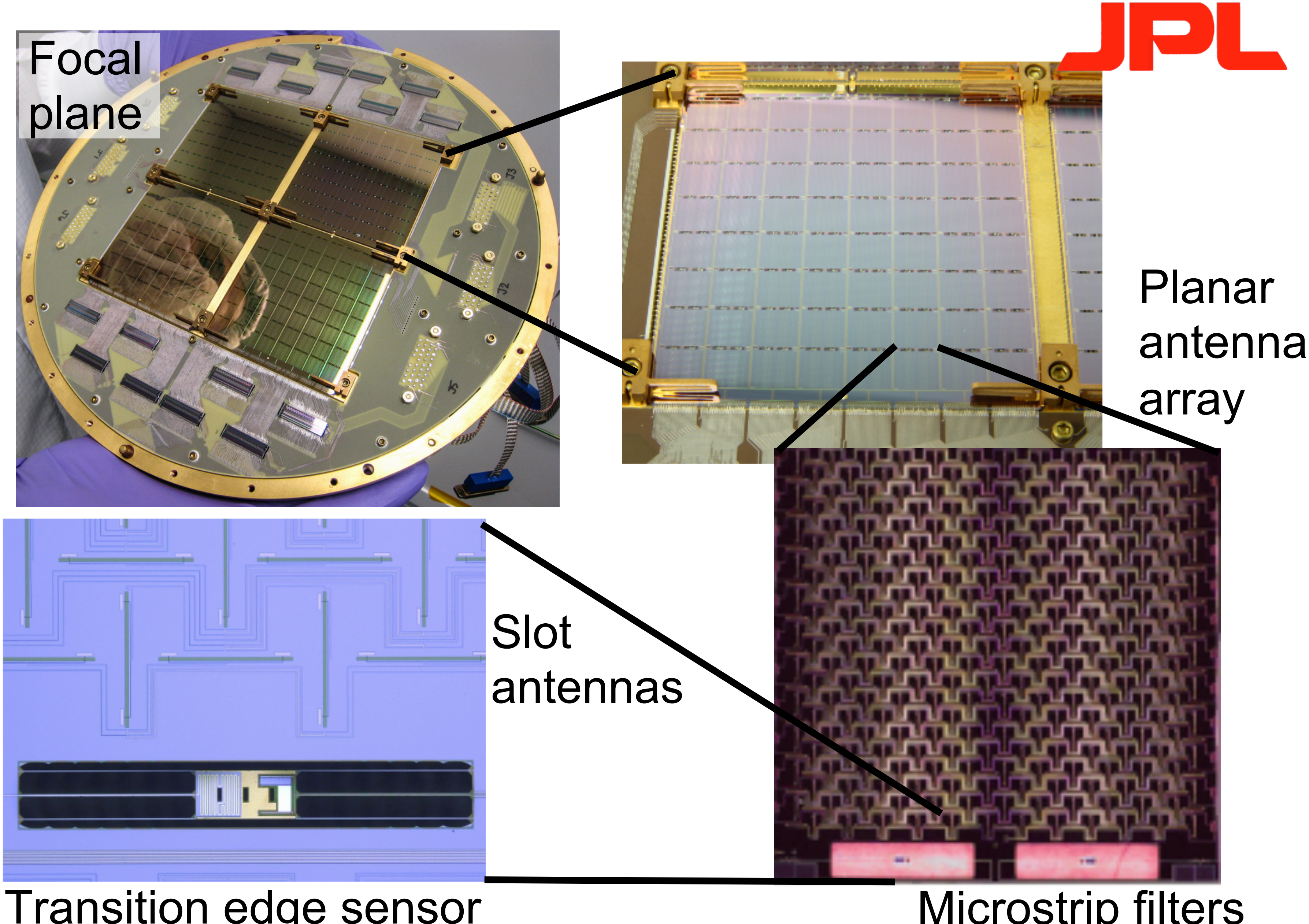
Since the different components of the sky pattern have different frequency dependencies one can separate them by making maps at multiple frequencies – and probe deeper for an inflation signal

The BICEP Telescopes



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

Mass-produced Superconducting Detectors



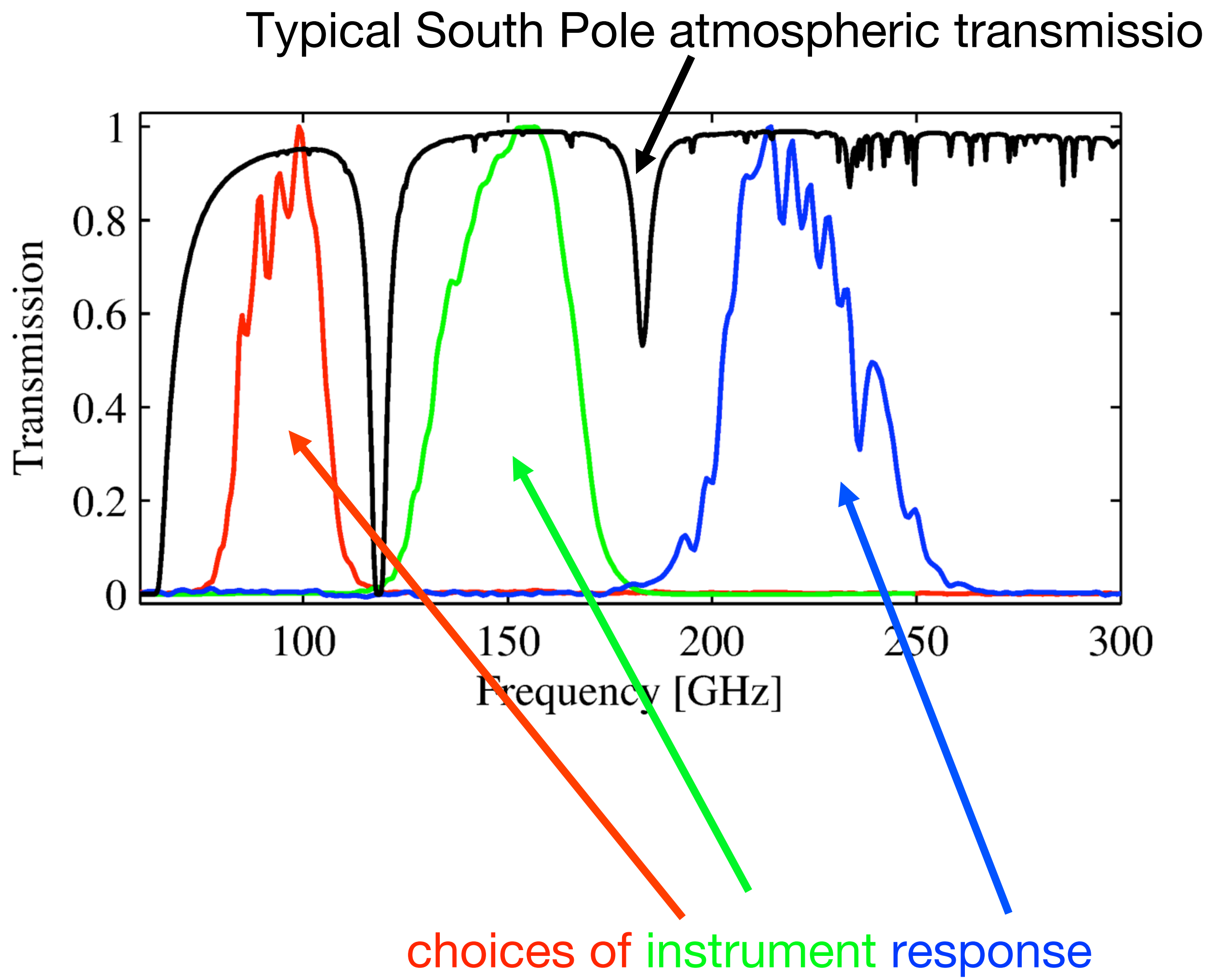
BICEP/Keck Band Passes

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

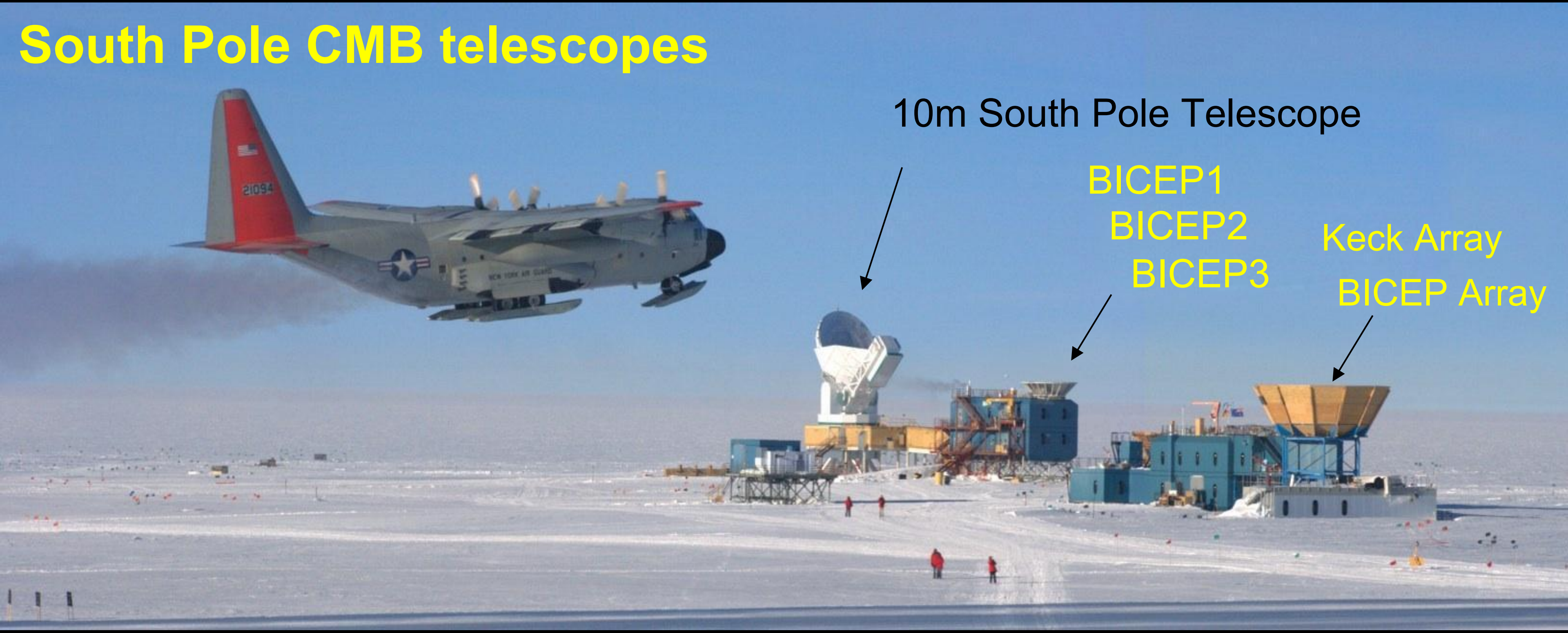
The approx. 30% fractional bandpasses fit within atmospheric transmission windows straddled by oxygen and water lines.

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

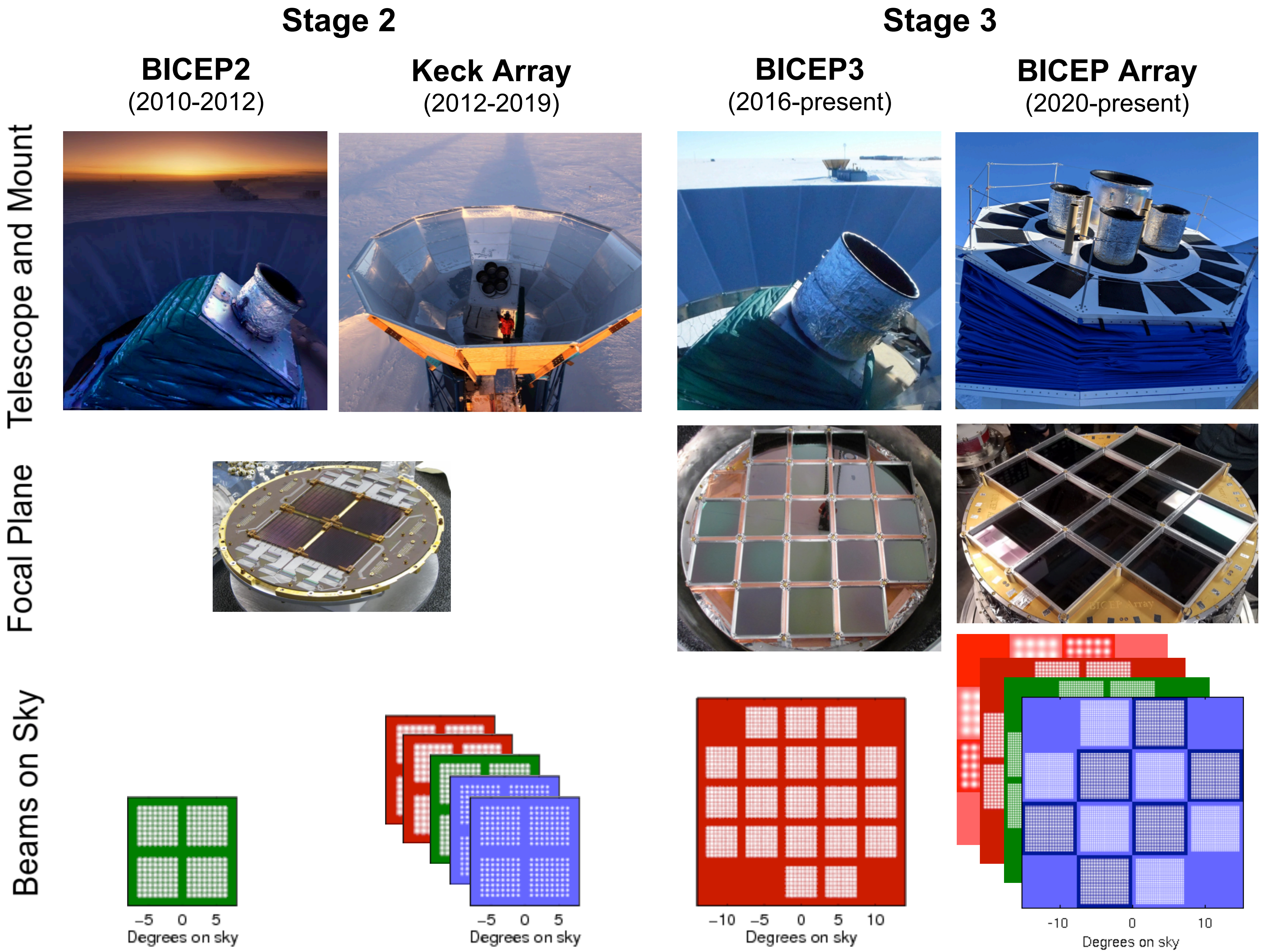
The detector passbands are defined by a filter printed directly onto the focal plane wafers.

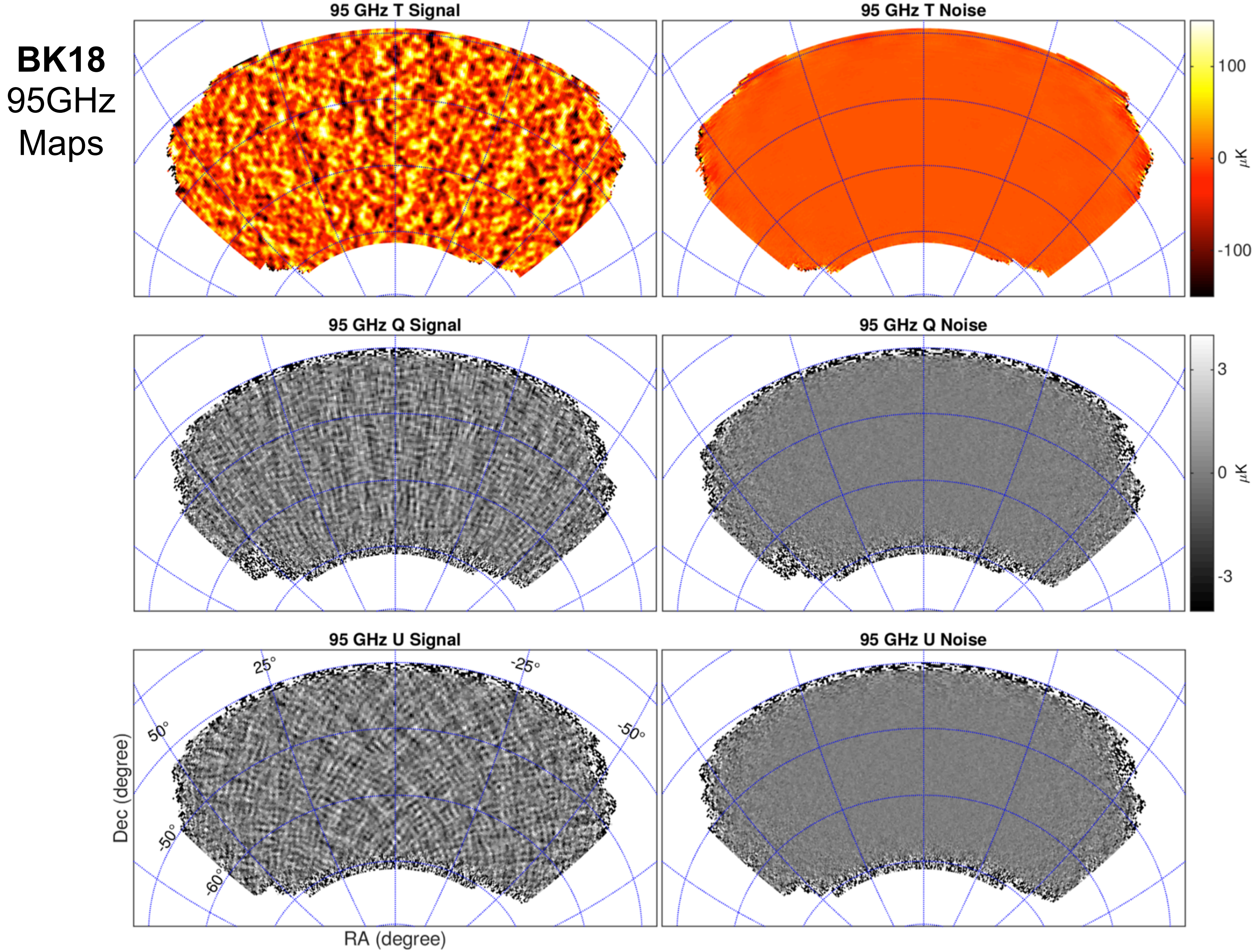


Why do this at the Pole?

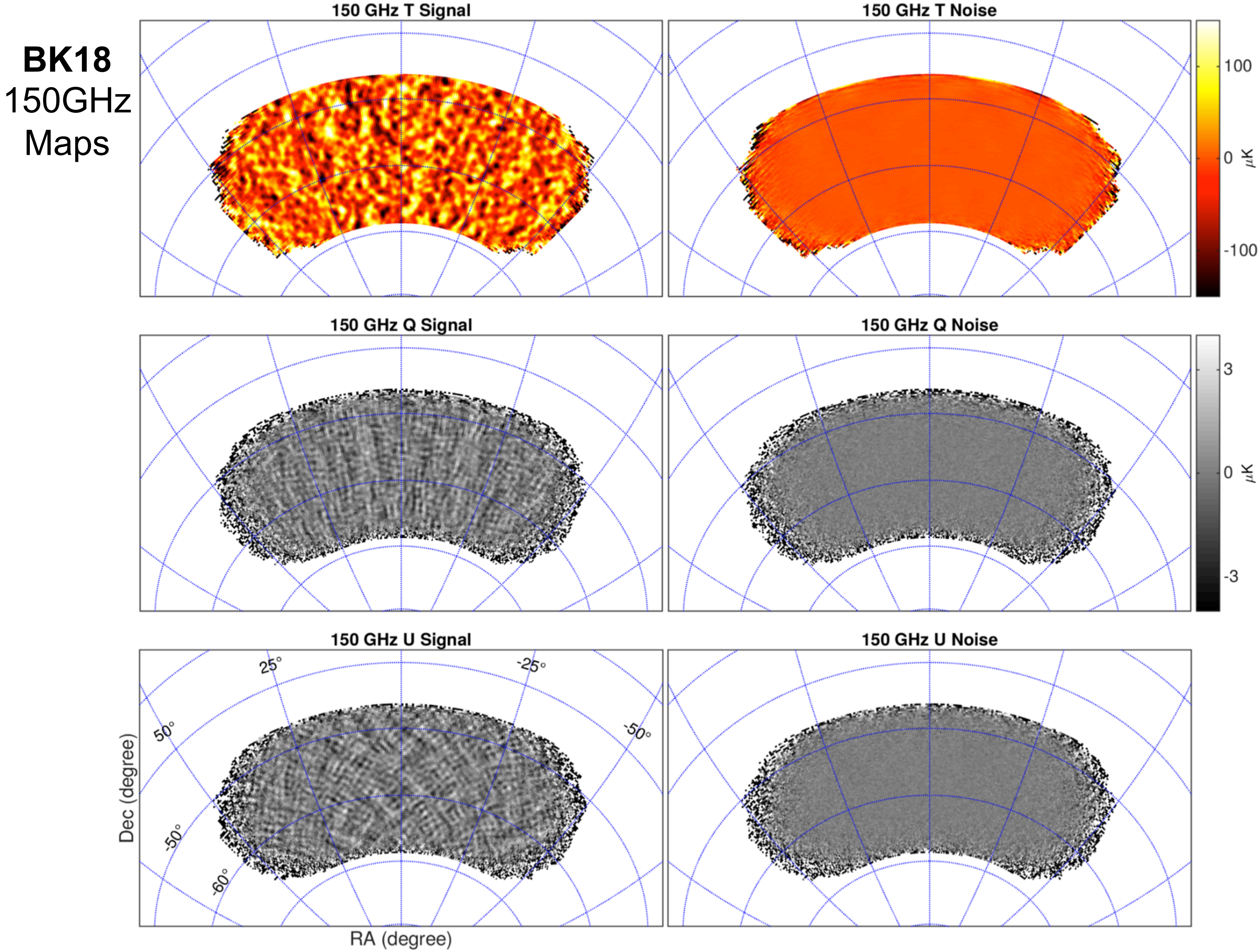


- High and *dry* – see out into space
- On Earth's rotational axis - One day/night cycle per year
  - Long night makes for great quality data
- Good support infrastructure – power, cargo, data comm
- Food and accommodation provided
- Even Tuesday night bingo…


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

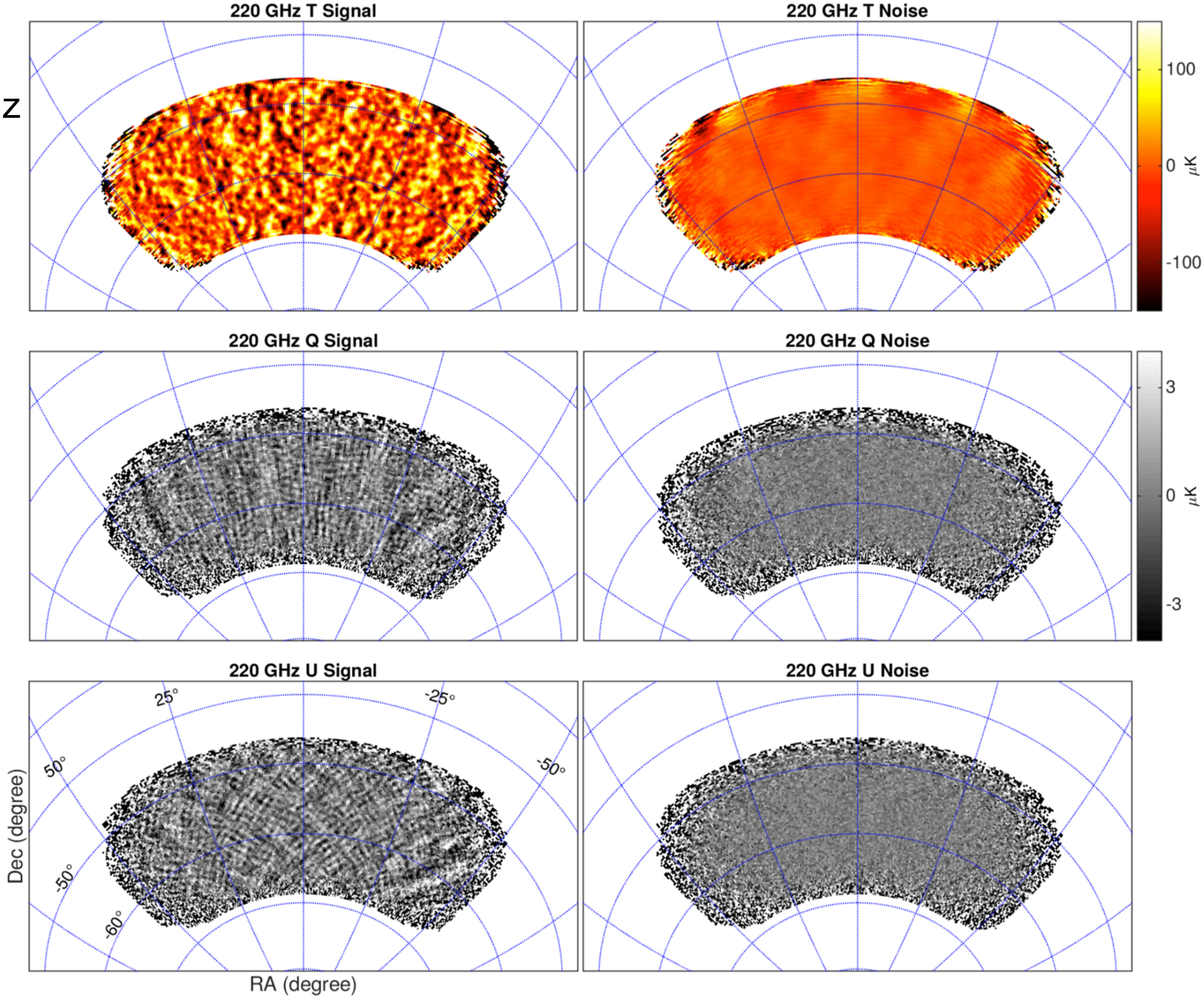


BK18
95GHz
Maps
95 GHz T Signal
95 GHz T Noise
95 GHz Q Signal
95 GHz Q Noise
95 GHz U Signal
95 GHz U Noise
100
0
-100
μK
3
0
-3
μK
25°
-25°
50°
-50°
-50°
-60°
Dec (degree)
RA (degree)



BK18
150GHz
Maps
150 GHz T Signal
150 GHz T Noise
100
0
-100
μK
150 GHz Q Signal
150 GHz Q Noise
3
0
-3
μK
150 GHz U Signal
150 GHz U Noise
25°
-25°
50°
-50°
-50°
-60°
Dec (degree)
RA (degree)

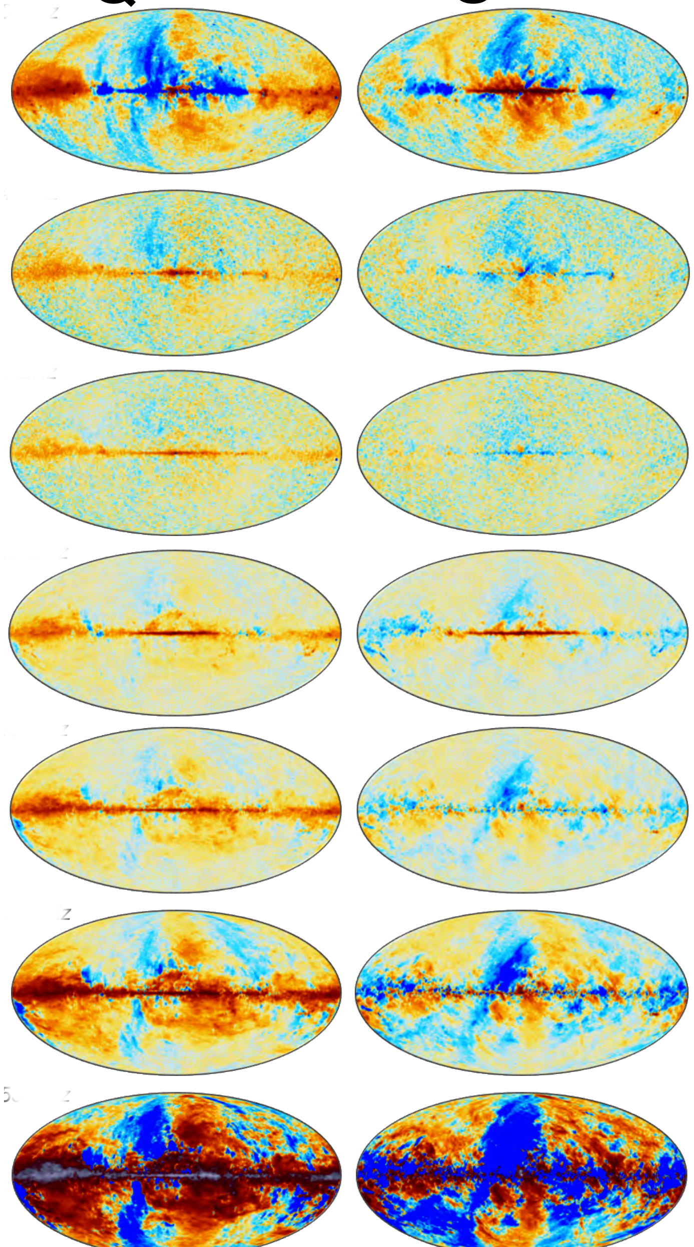
BK18
220GHz
Maps



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

Q U

30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz

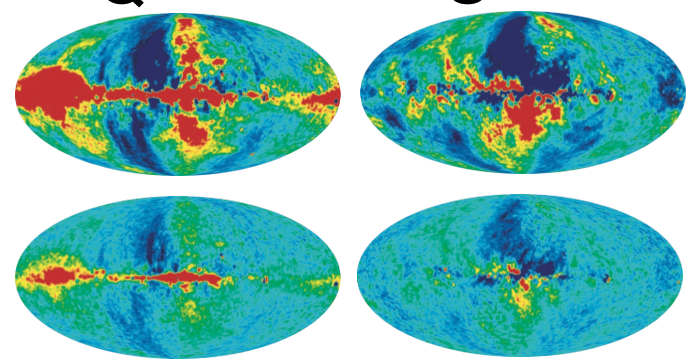


From arxiv 1502.01582

Polarized galactic **synchrotron** dominates at low frequencies

Q U

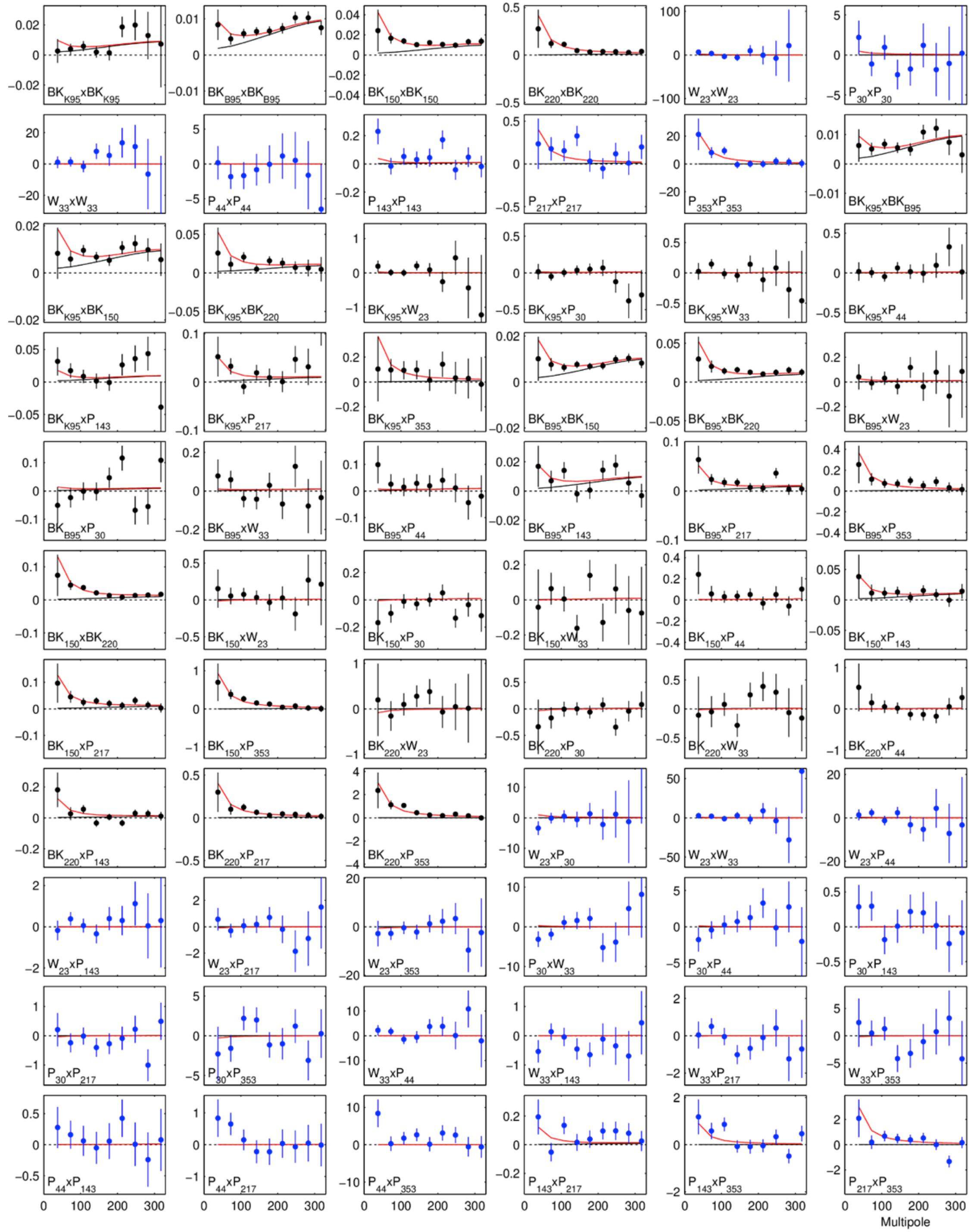
23 GHz
33 GHz



From arxiv 1212.5225

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

Basic 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?

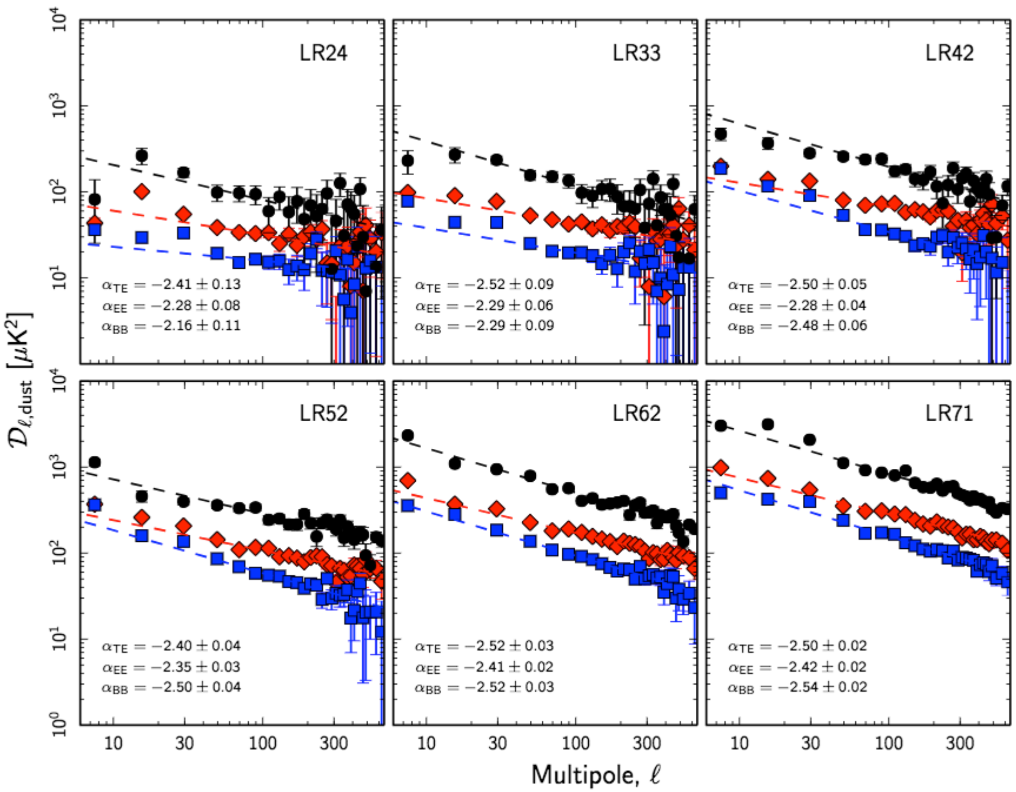


Fig 2 of arxiv/1801.04945 – Planck dust analysis

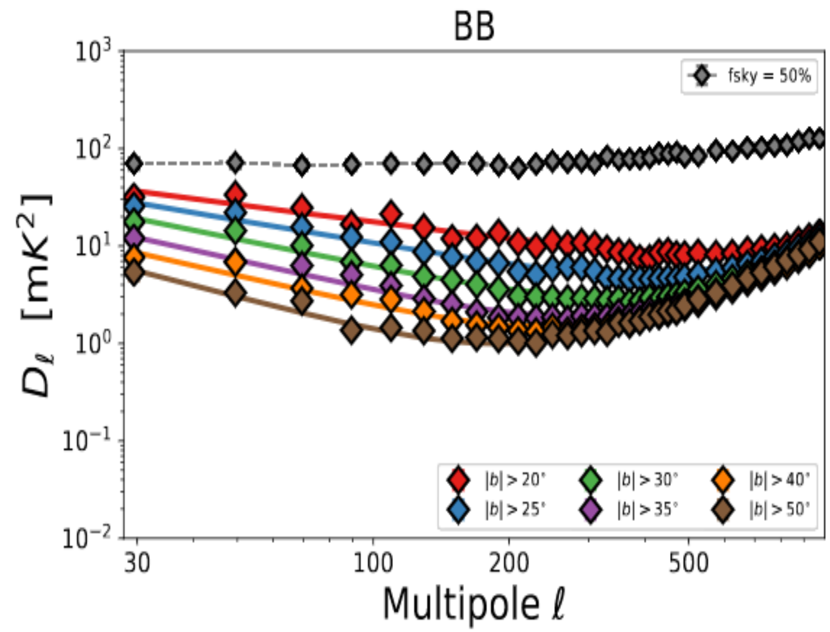
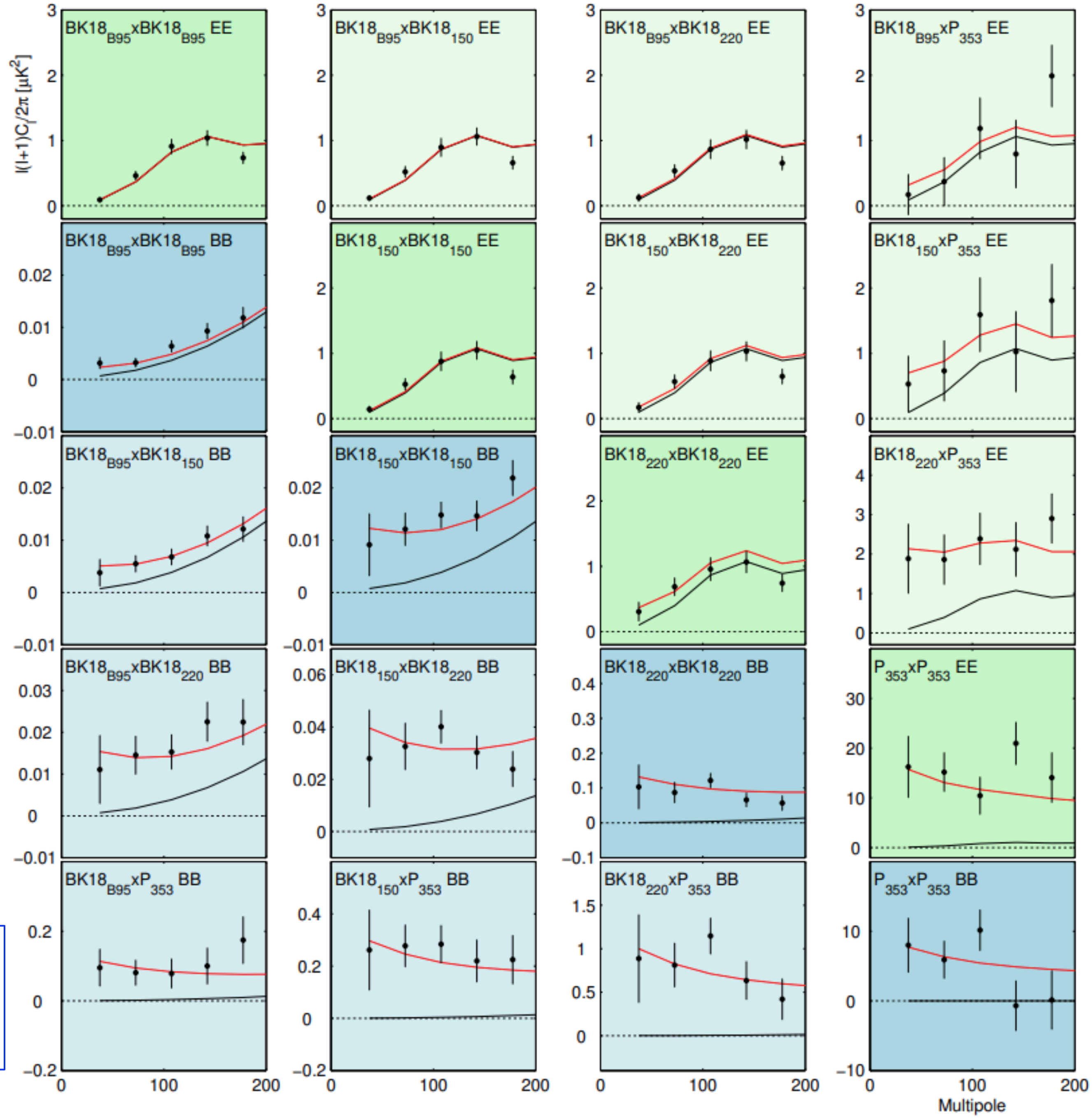


Fig 2 of arxiv/1802.01145. – S-PASS sync analysis

- 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

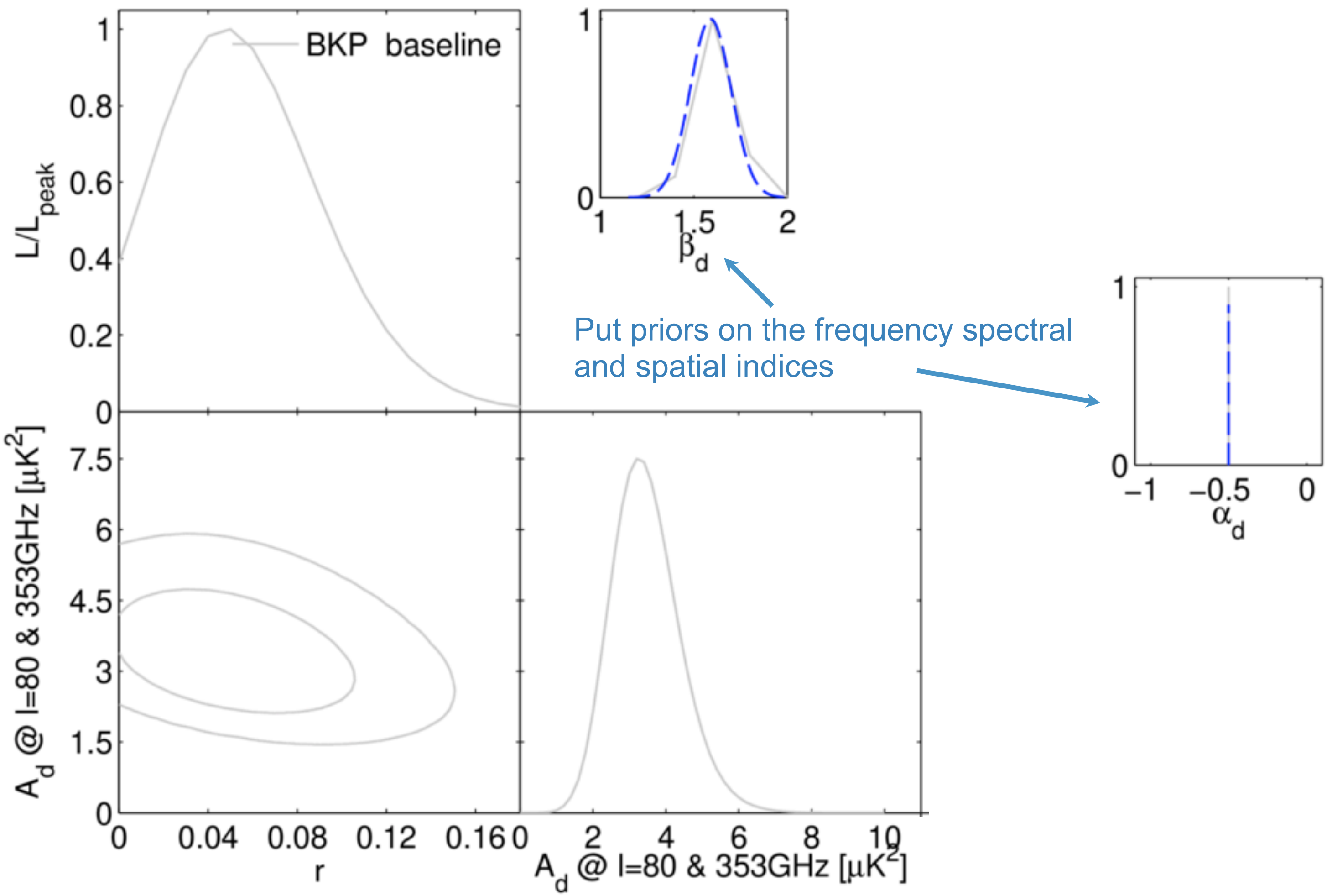


Green panels are EE spectra

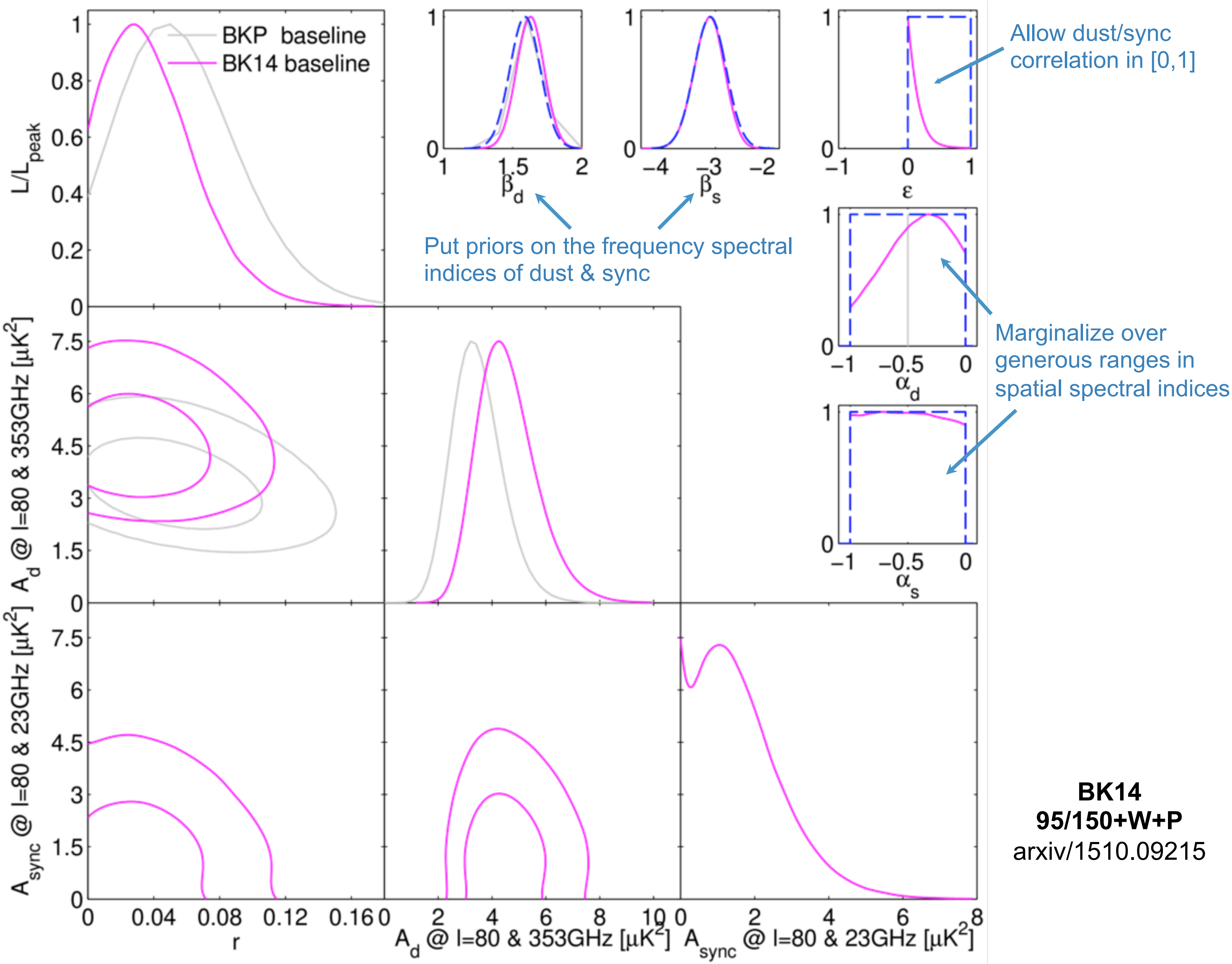
Black lines are LCDM

Red lines are LCDM+dust

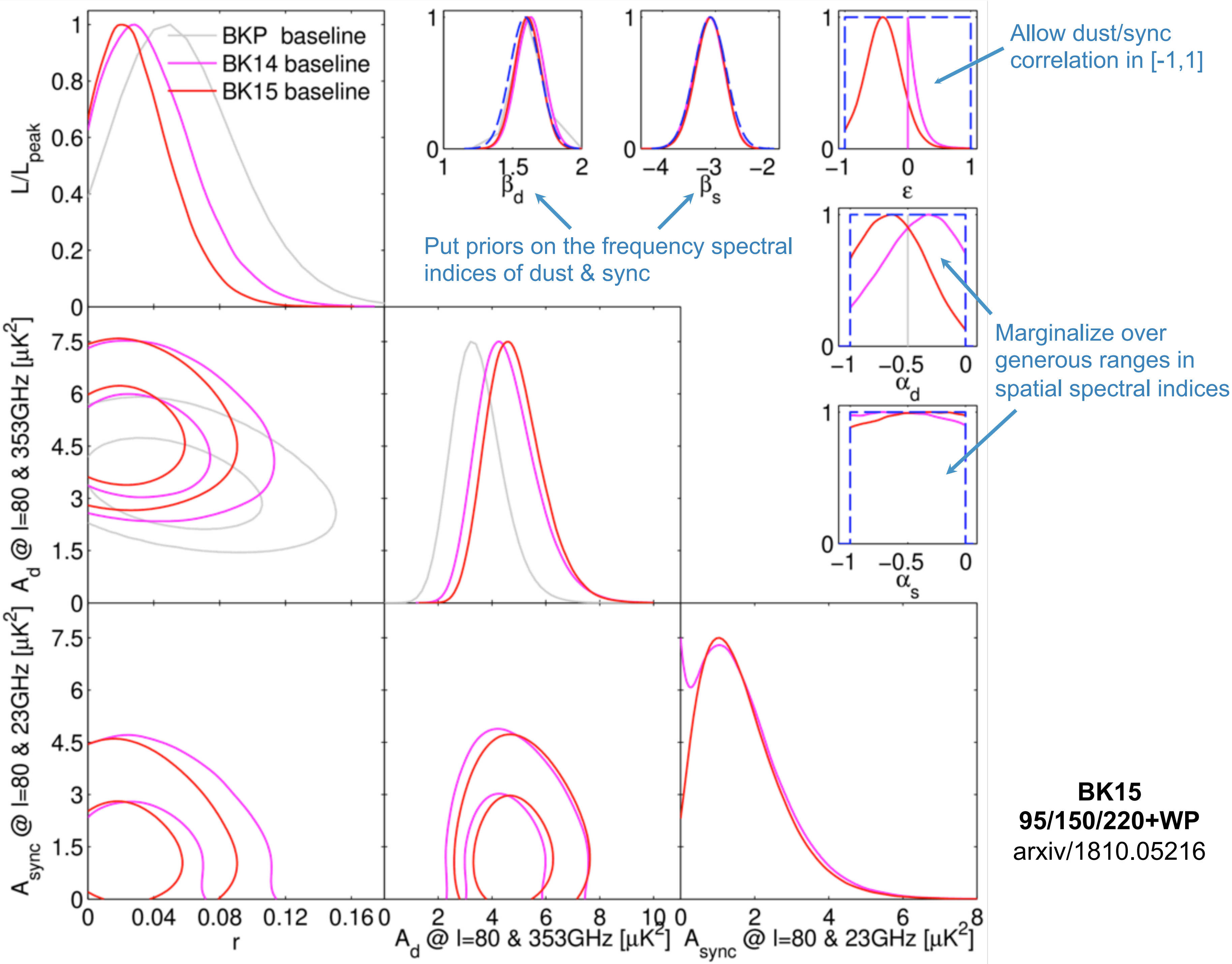
Blue panels are BB spectra



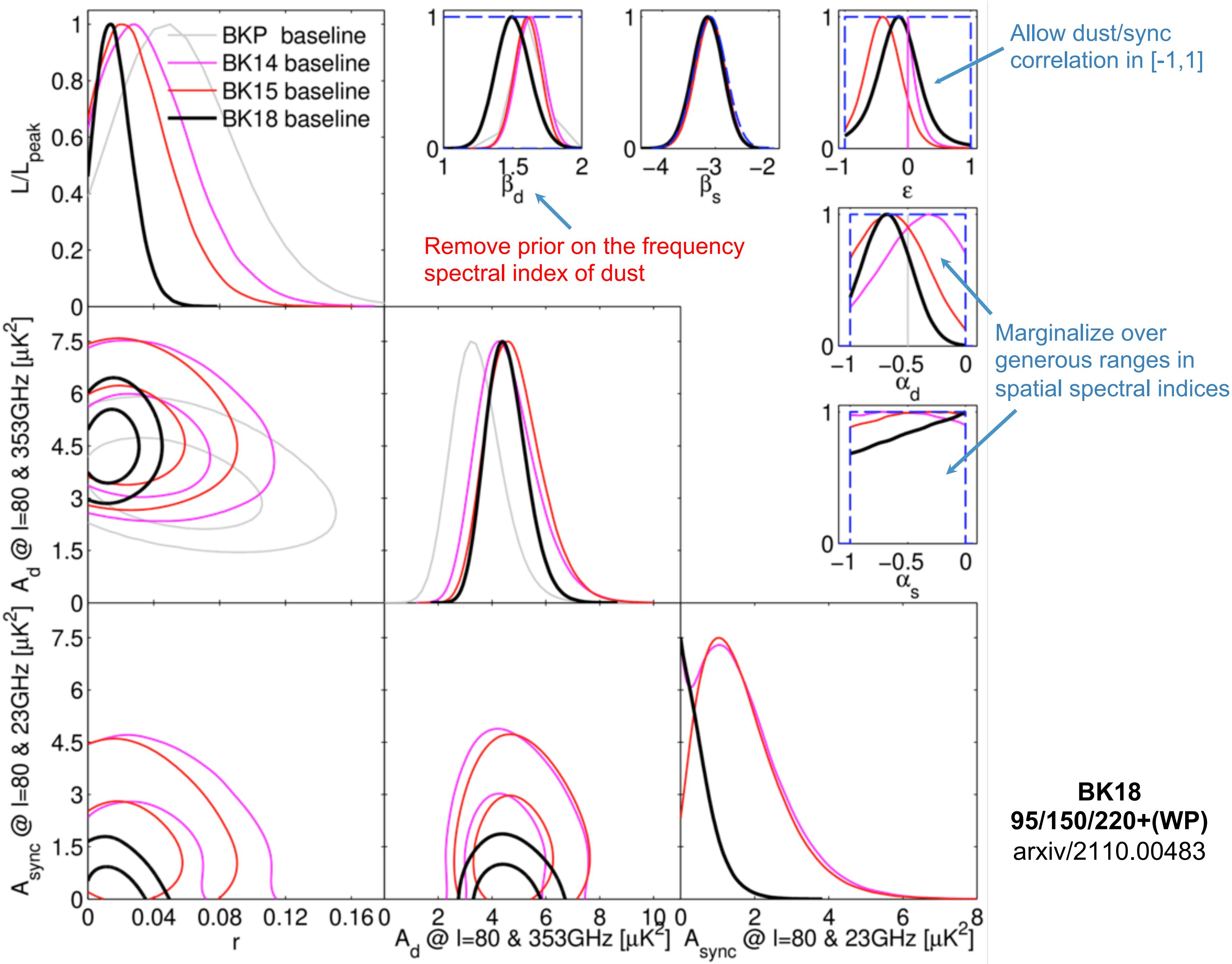
BKP
150GHz+P
arxiv/1502.00612



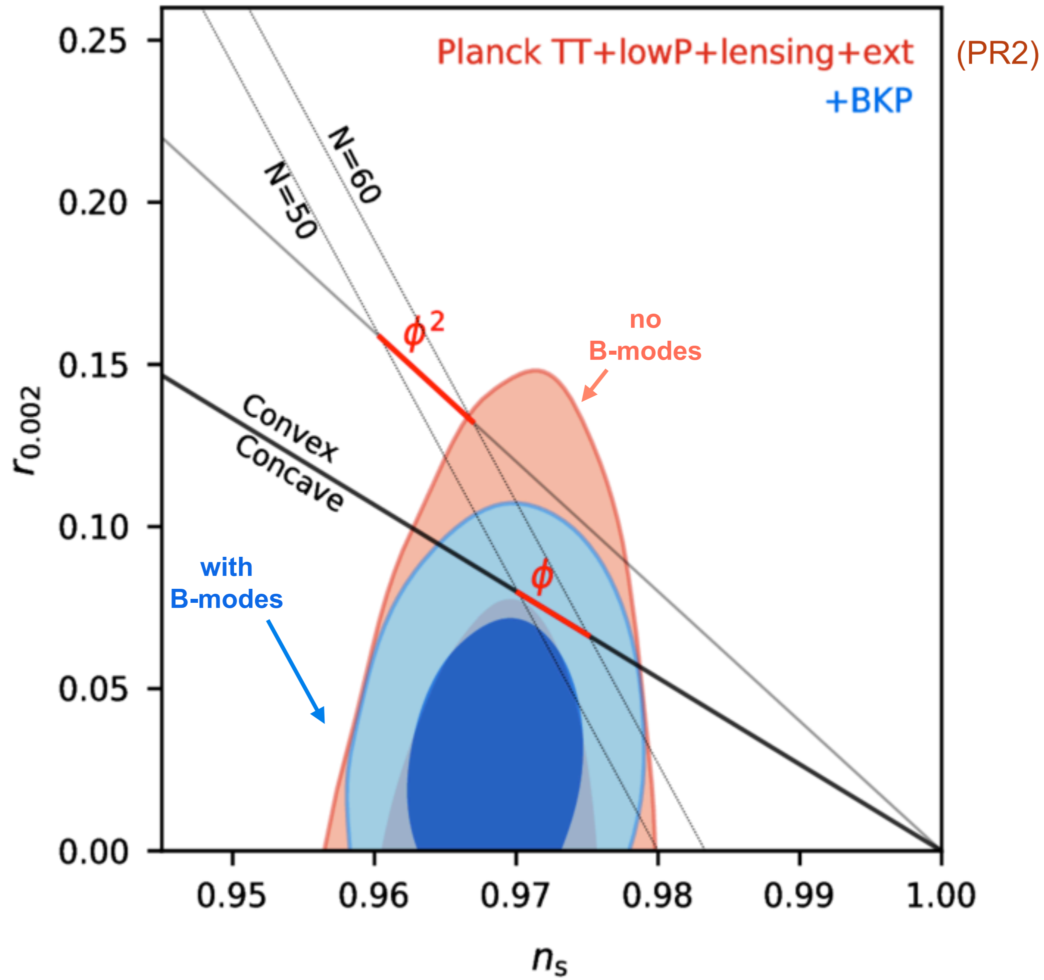
BK14
95/150+W+P
arxiv/1510.09215



BK15
95/150/220+WP
arxiv/1810.05216



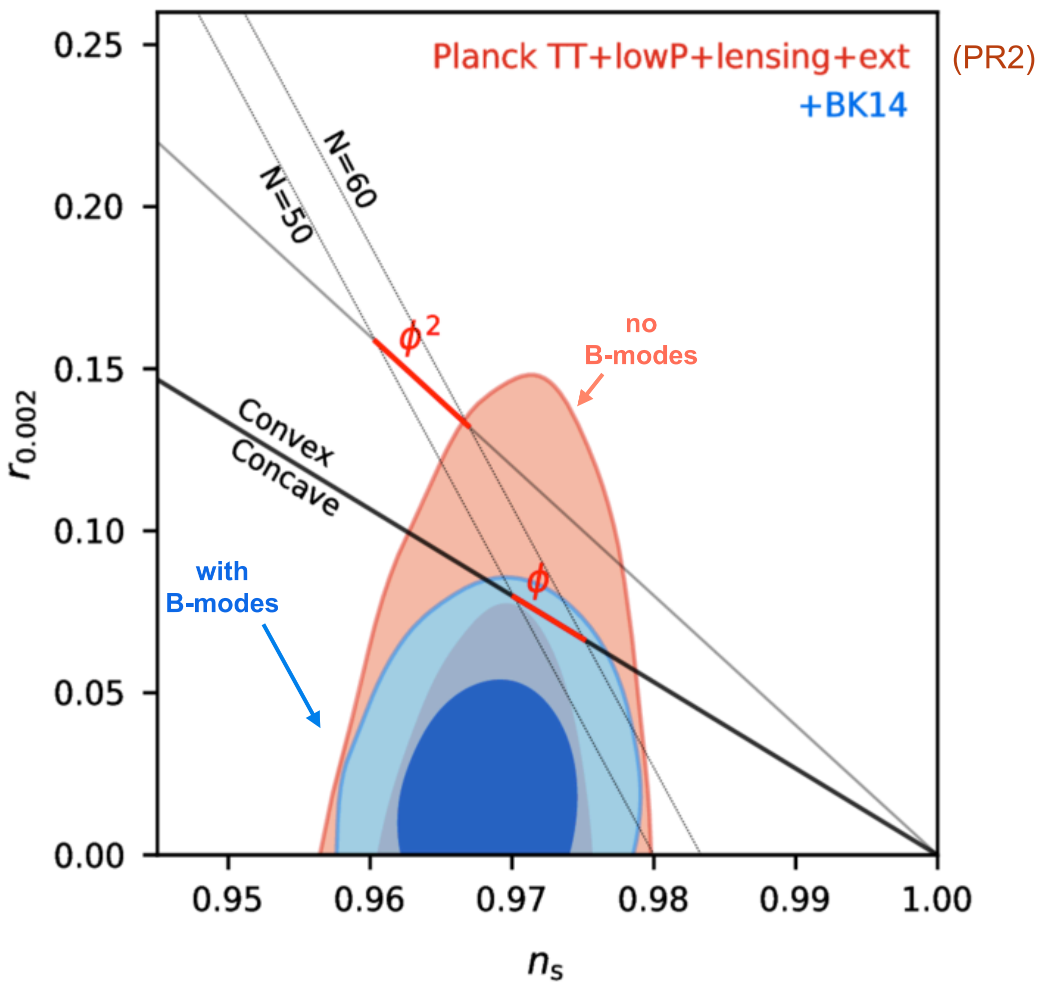
BK18
95/150/220+(WP)
arxiv/2110.00483



$r_{.05} < 0.09$

BKP

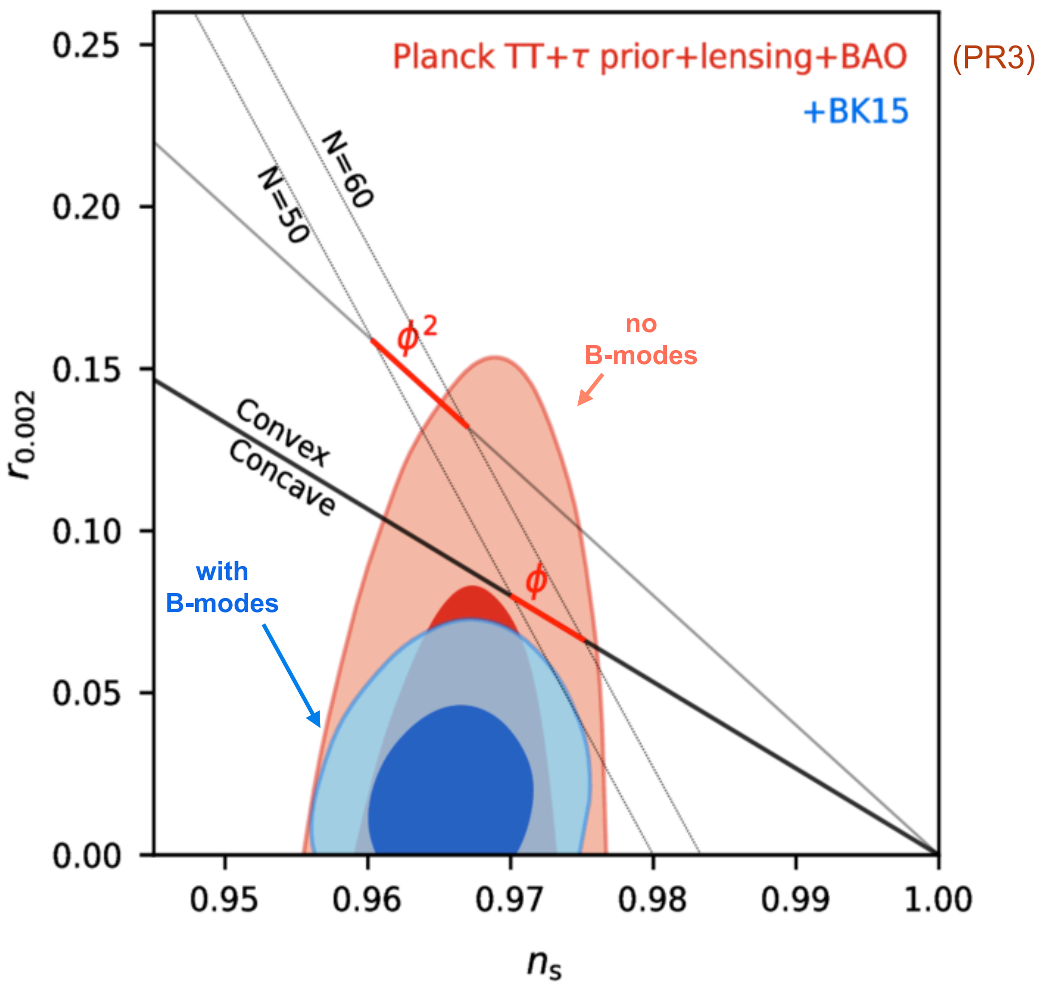
arxiv/1502.00612



$r_{.05} < 0.07$

BK14

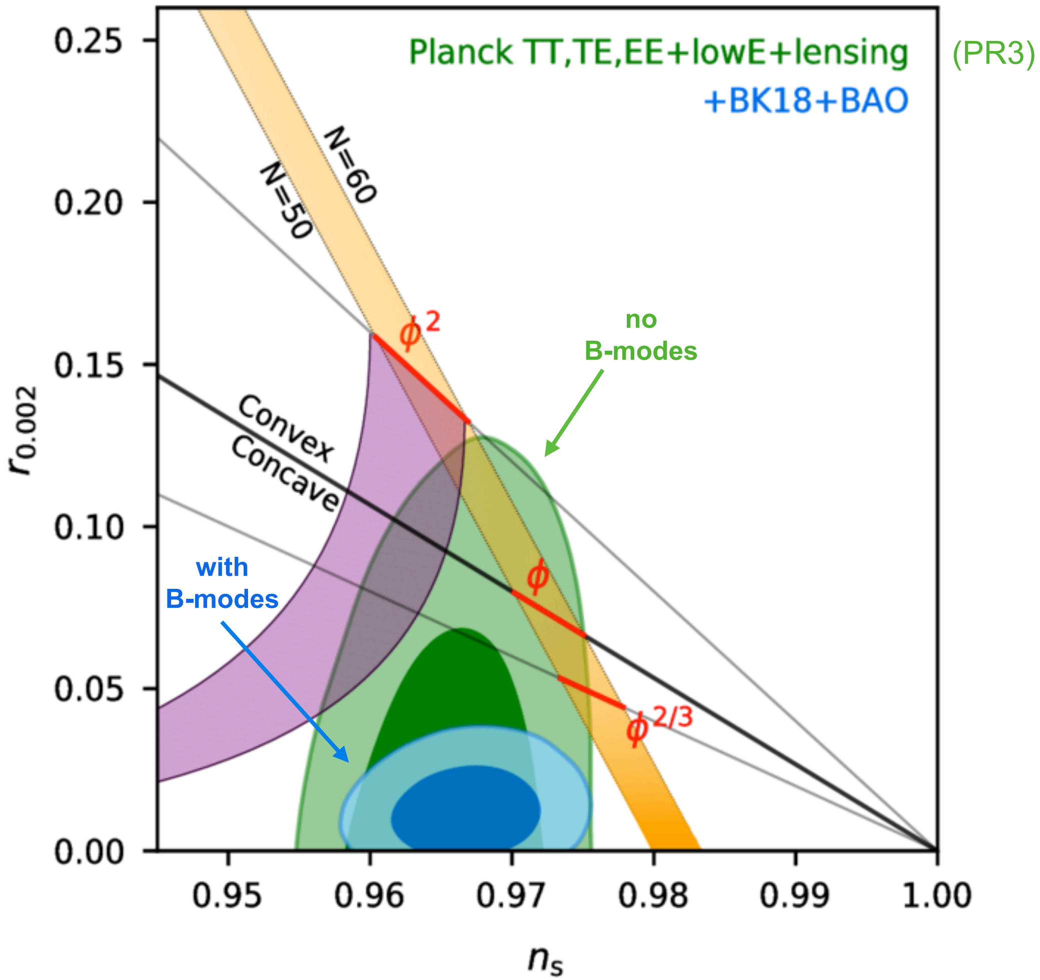
arxiv/1510.09217



BK15

arxiv/1810.05216

$r_{.05}$ < 0.06

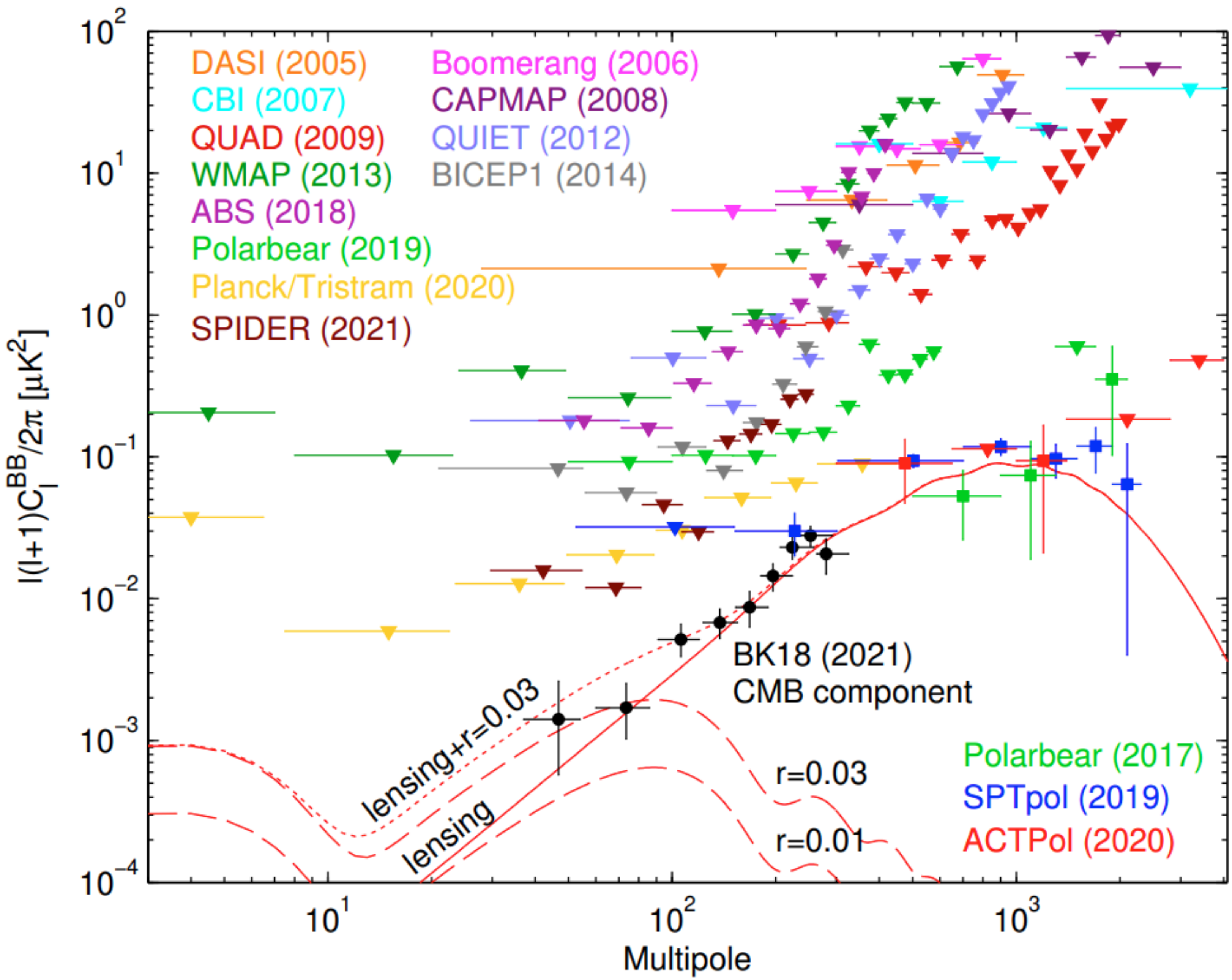


BK18

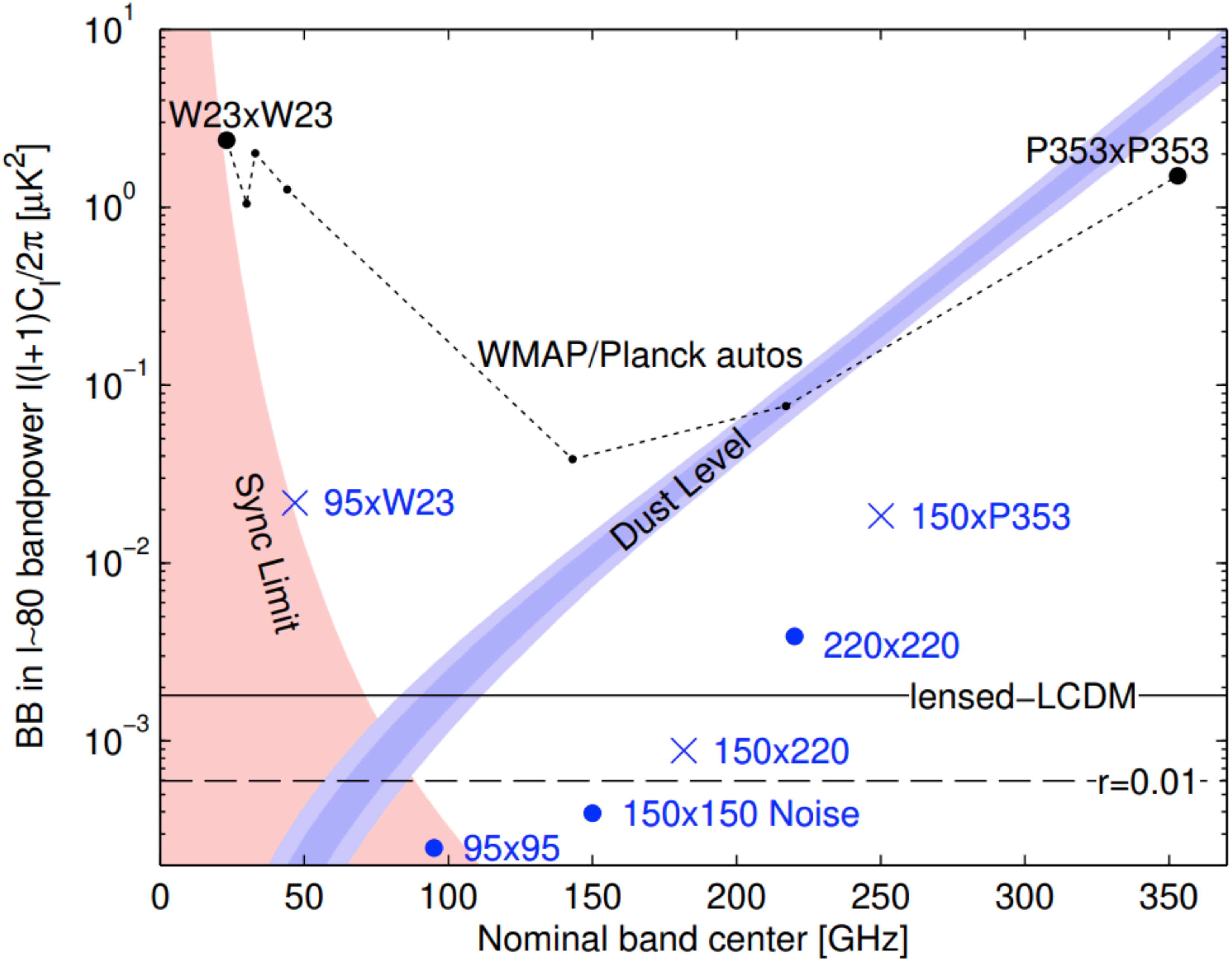
arxiv/2110.00483

$r_{.05} < 0.035$

Per bandpower CMB component extraction



BK18 ell=80 bandpower noise/signal



What limits BK18?

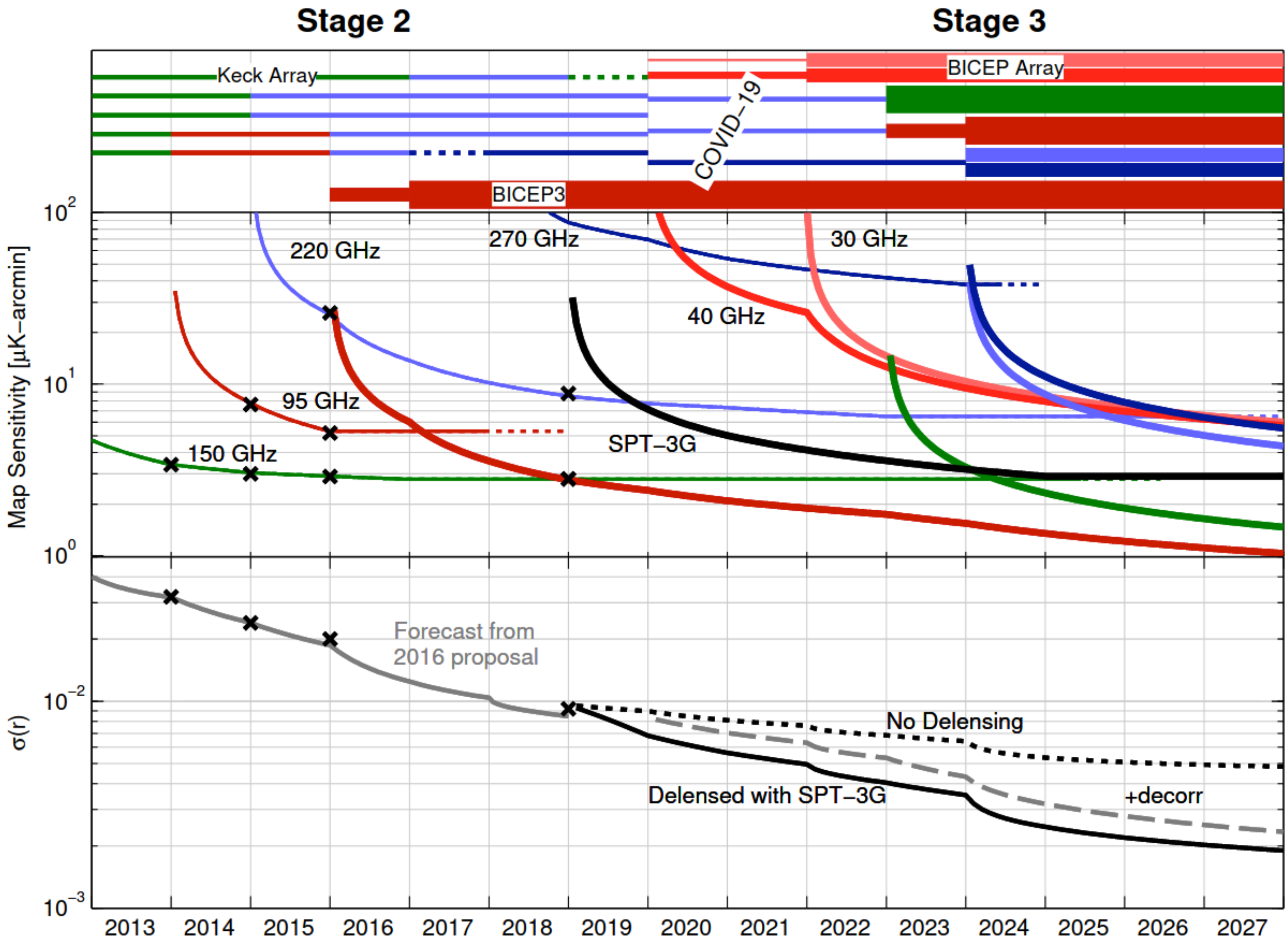
- BK18 mainline simulations with dust and lensing give σ(r)=0.009
- Running without foreground parameters on simulations where the dust amplitude is set to zero gives σ(r)=0.007

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.

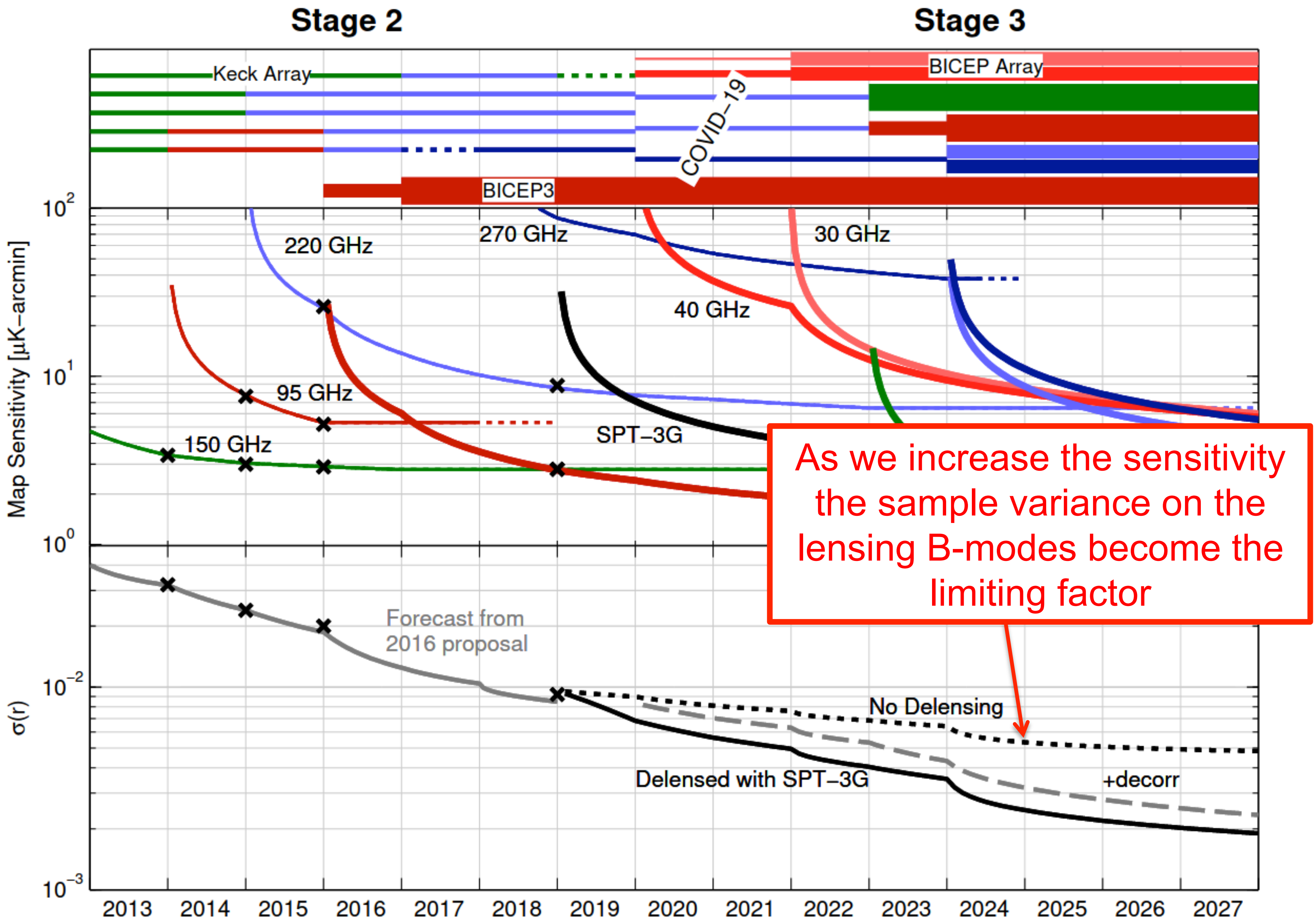
- Running on simulations which contain no lensing gives σ(r)=0.004

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



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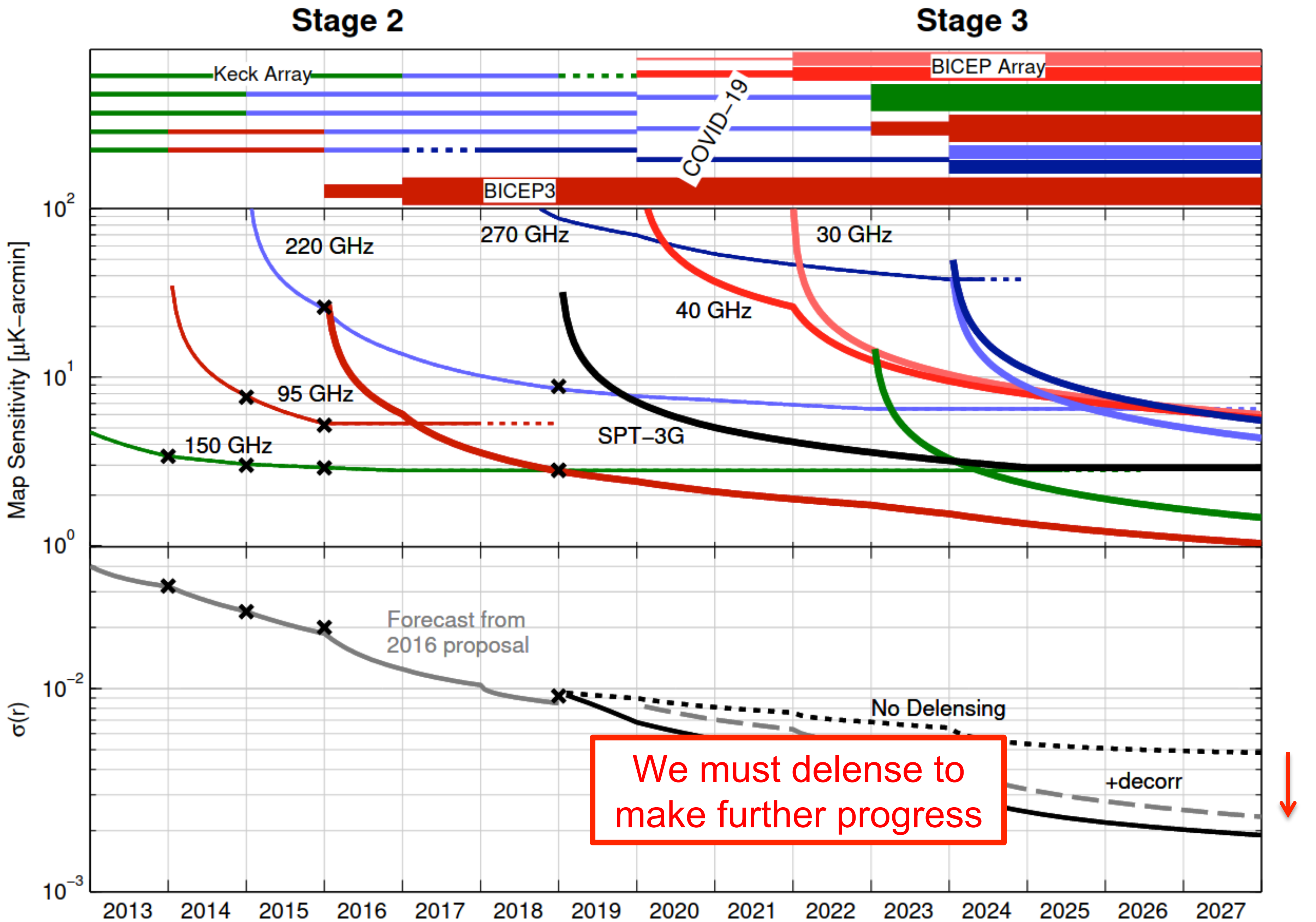
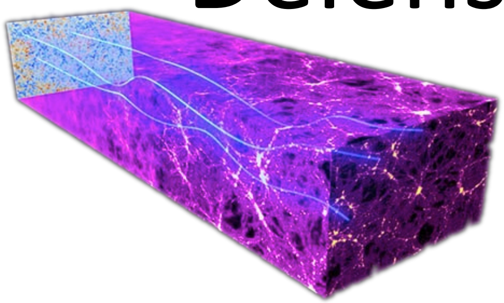
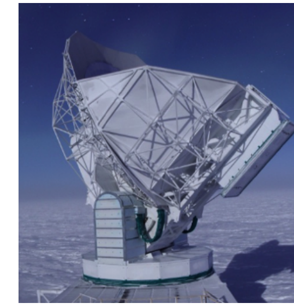
Keck Array
BICEP Array
COVID–19
BICEP3
220 GHz
270 GHz
30 GHz
40 GHz
95 GHz
150 GHz
SPT–3G
Map Sensitivity [μK–arcmin]
10^2
10^1
10^0
10^{-2}
10^{-3}
σ(r)
Forecast from
2016 proposal
No Delensing
Delensed with SPT–3G
+decorr
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
As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



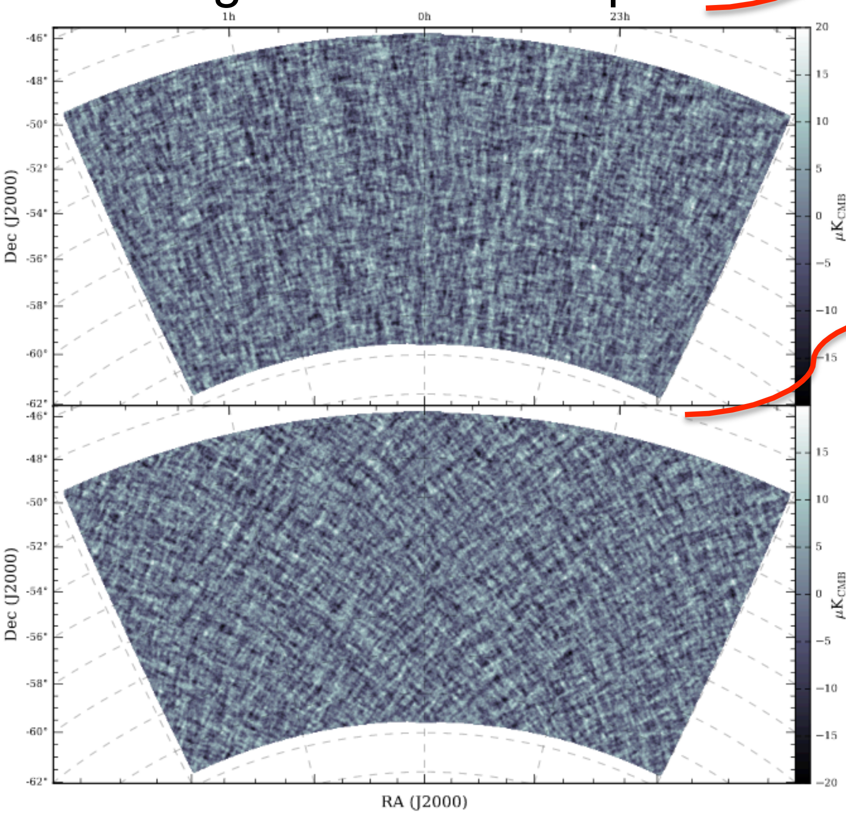
Stage 2
Stage 3
Keck Array
BICEP Array
COVID–19
BICEP3
Map Sensitivity [μK–arcmin]
10^2
10^1
10^0
220 GHz
270 GHz
30 GHz
40 GHz
95 GHz
150 GHz
SPT–3G
σ(r)
10^{-2}
10^{-3}
Forecast from
2016 proposal
No Delensing
+decorr
We must delense to
make further progress
2013
2014
2015
2016
2017
2018
2019
2020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

Delensing with SPT-3G data

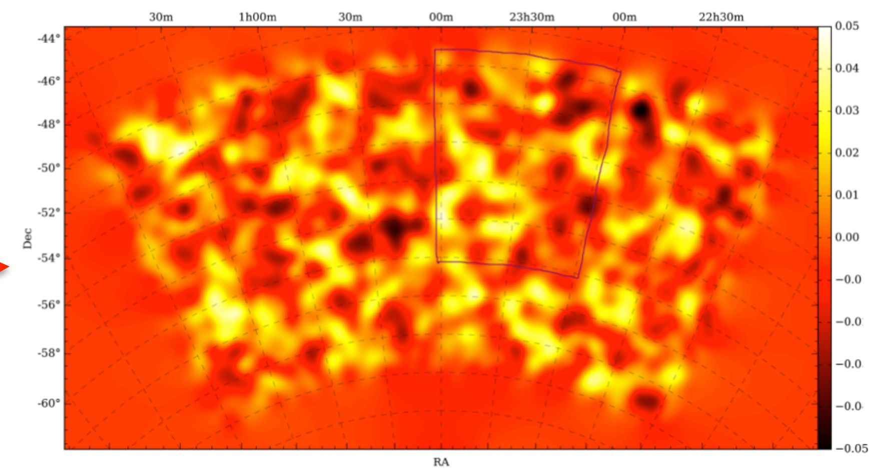




High resolution maps



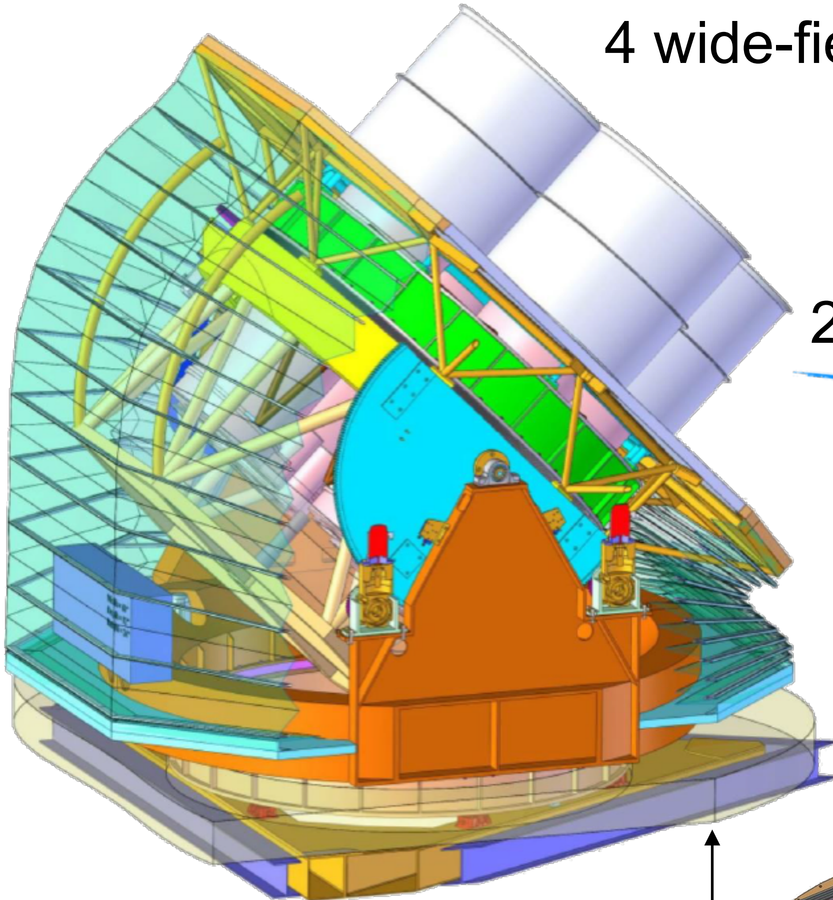
Can be used to reconstruct the lensing deflection map…



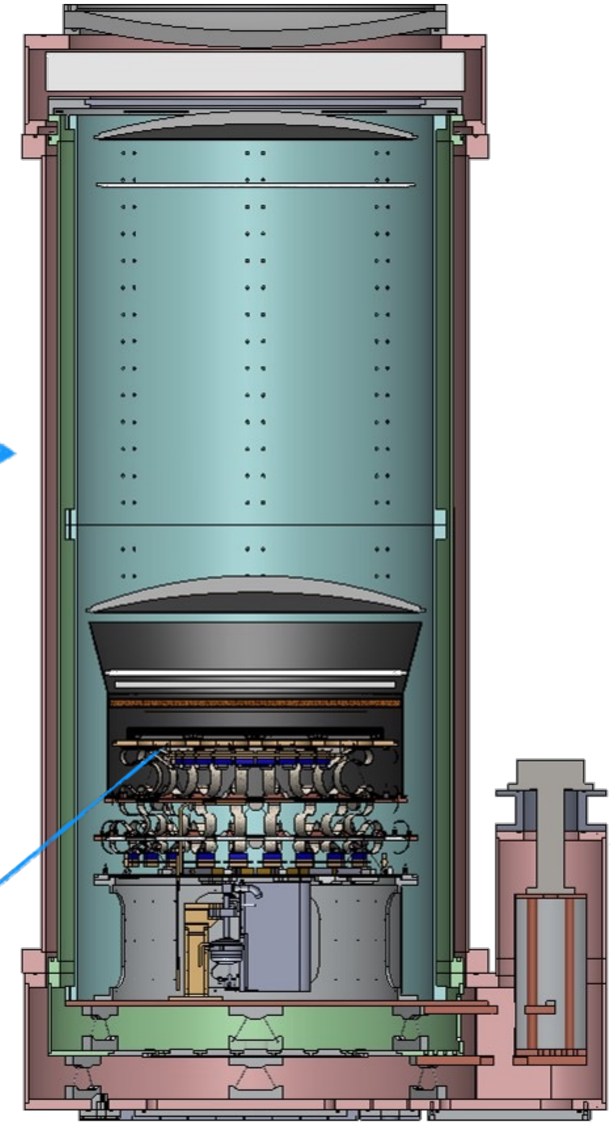
…which can then be used to calculate the lensing signal enabling a deeper search for inflationary gravitational waves

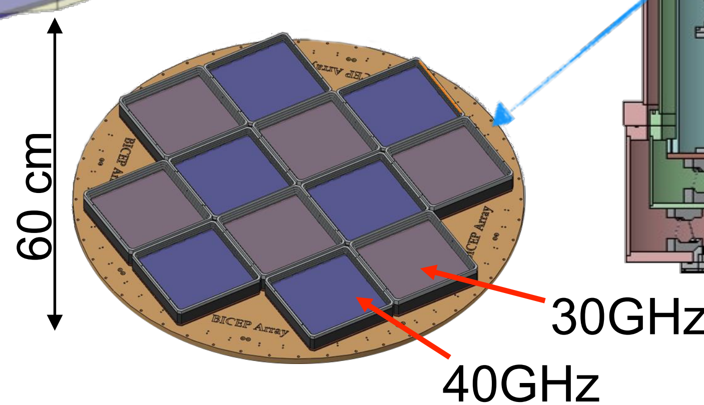
Demo delensing analysis in arXiv: 2011.08163

Latest Generation Experiment "BICEP Array"

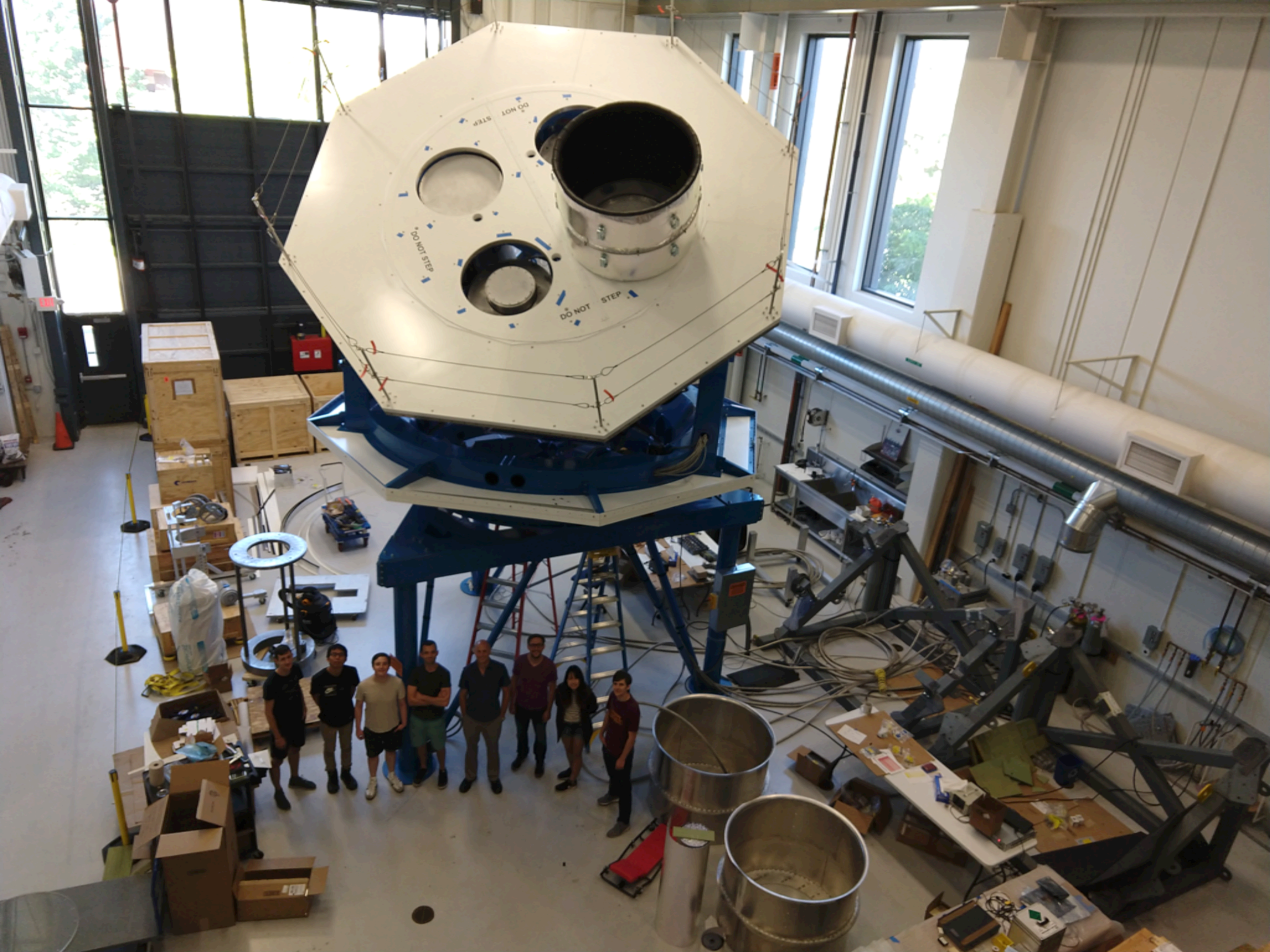


4 wide-field receivers
30/40 GHz
95 GHz
150 GHz
220/270 GHz





Focal plane layout


DO NOT STEP
DO NOT STEP
EXIT

BICEP Array 2019-20 initial deployment

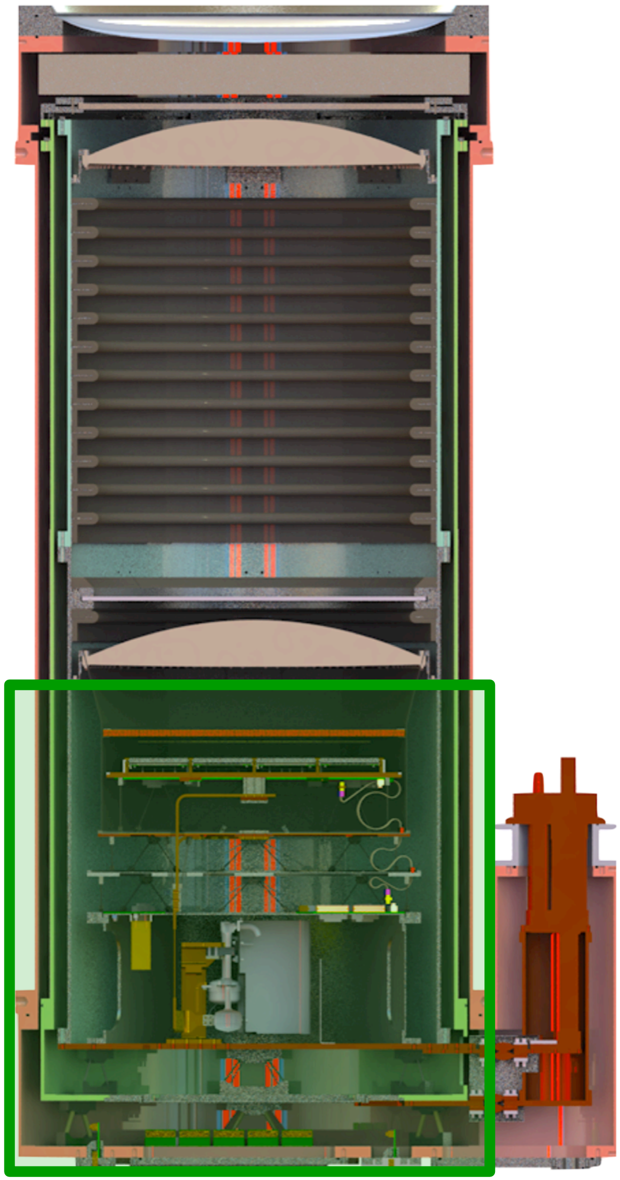
Three-month window during the Antarctic summer to perform:

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

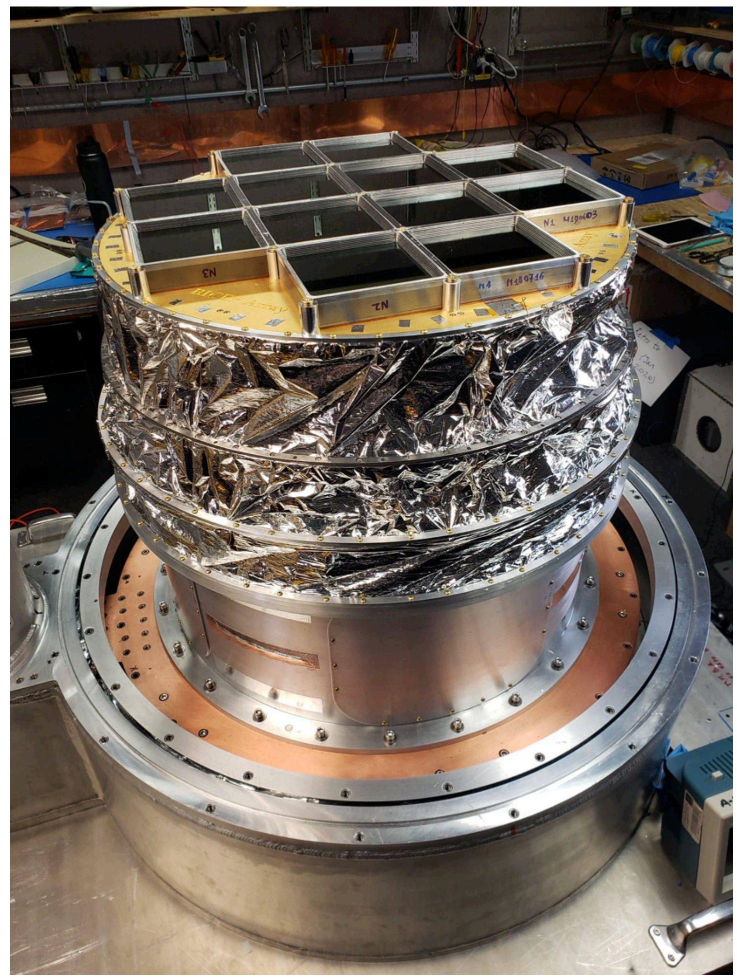
60,000 lbs of cargo, equivalent to 3 dedicated LC-130 Hercules flights to the South Pole.

30+ personnel:
- 2/3 scientists
- 1/3 contractors

2020 BA1 (30/40GHz) Instrument Operating



Camera insert

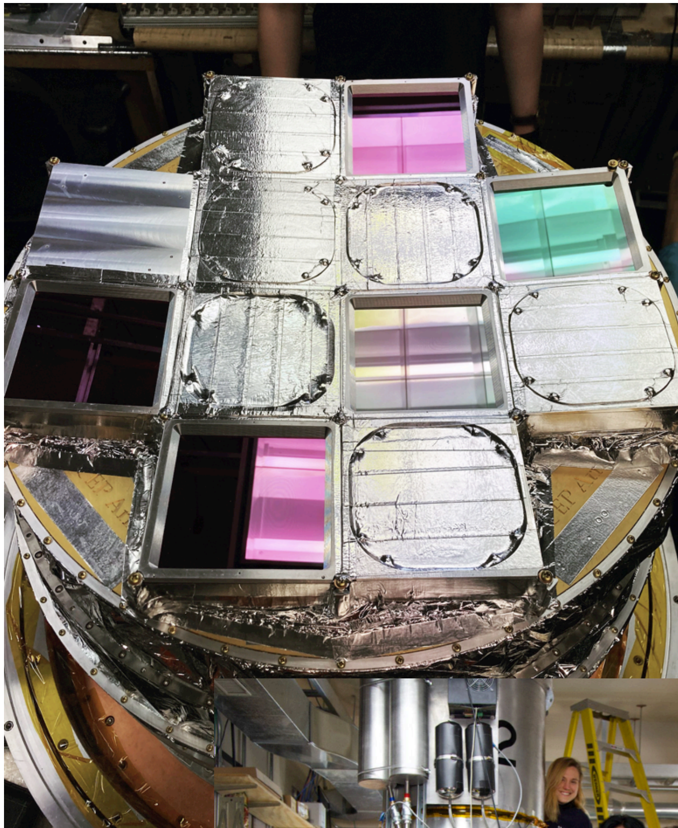


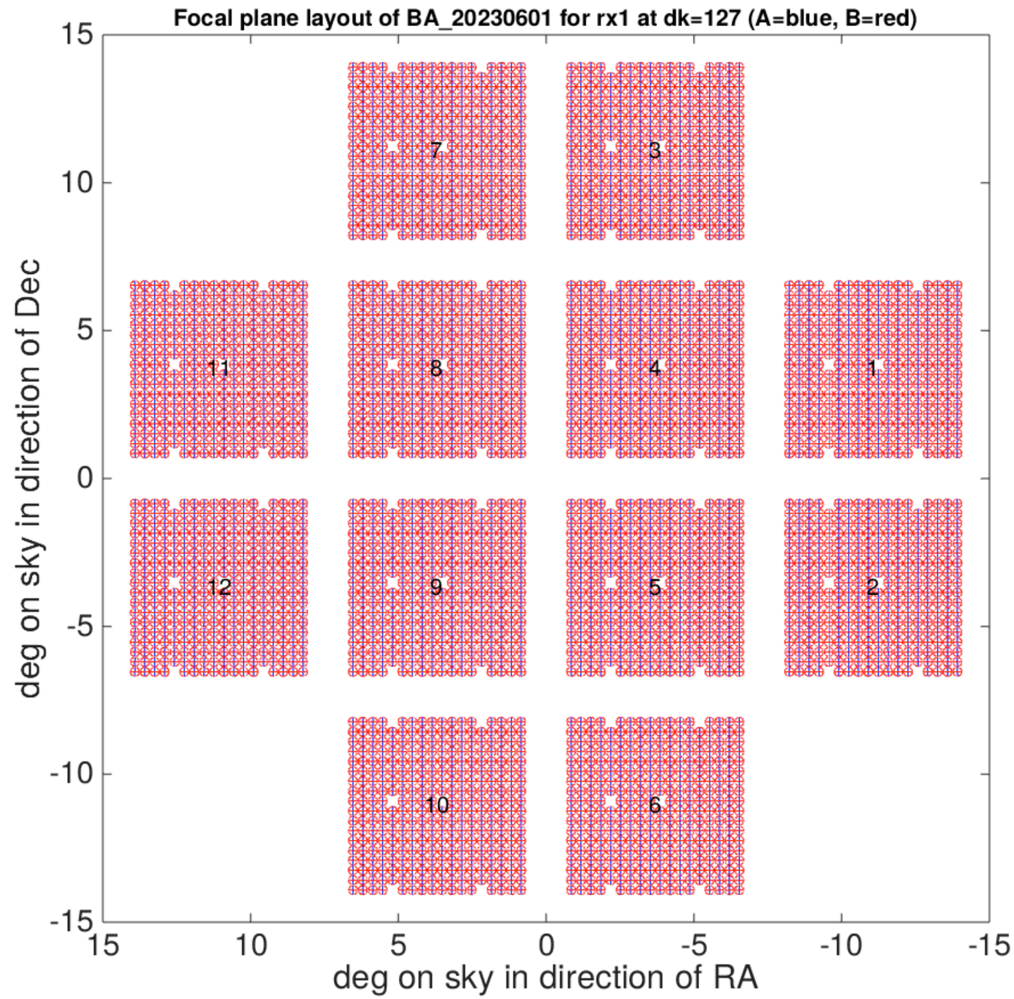
192/300 TES detectors at 30/40 GHz.

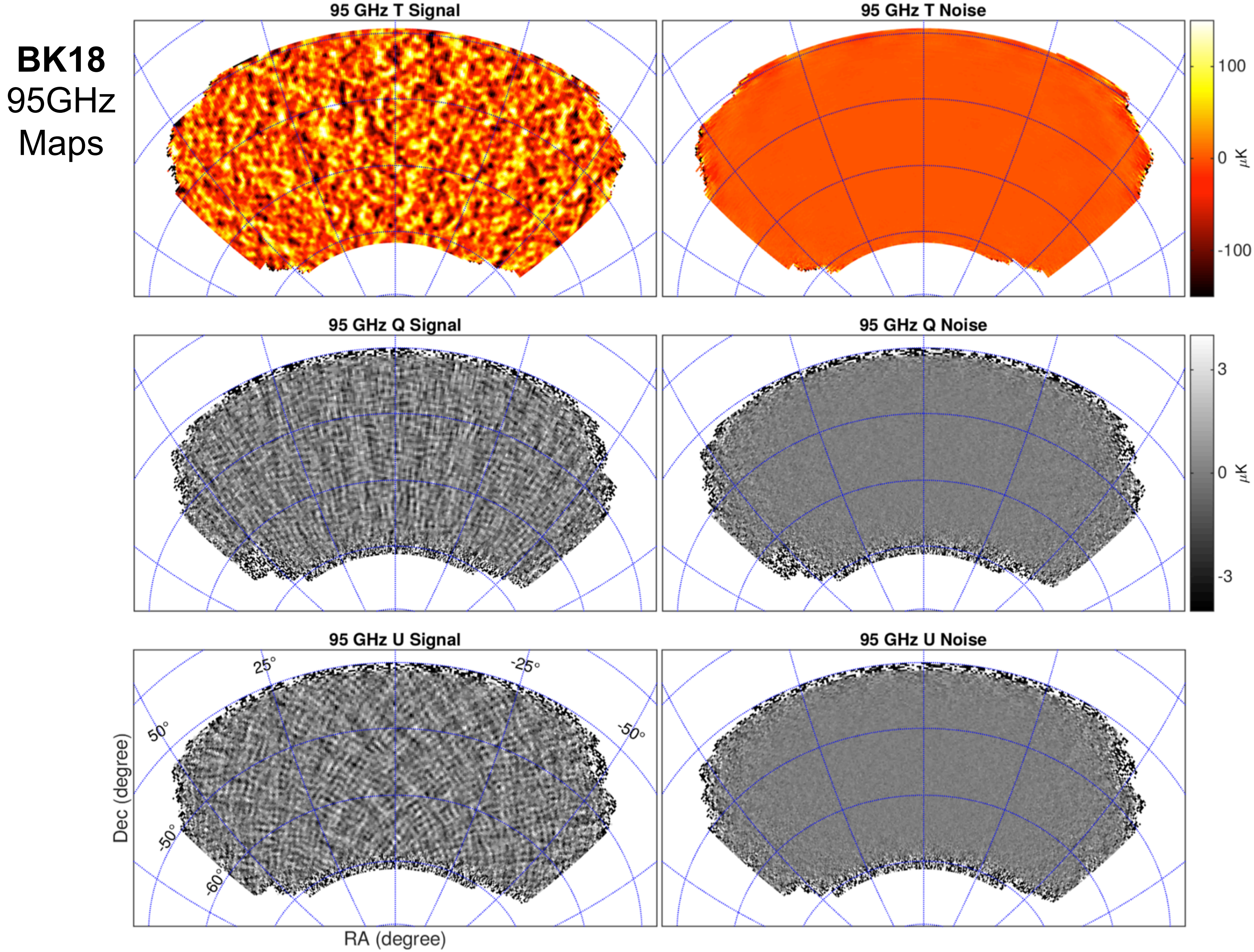
Integrated in 12 shielded modules, each with a low-pass mesh filters.

Time-Domain multiplexed readout.

2023 BA2 (150GHz) Instrument Operating



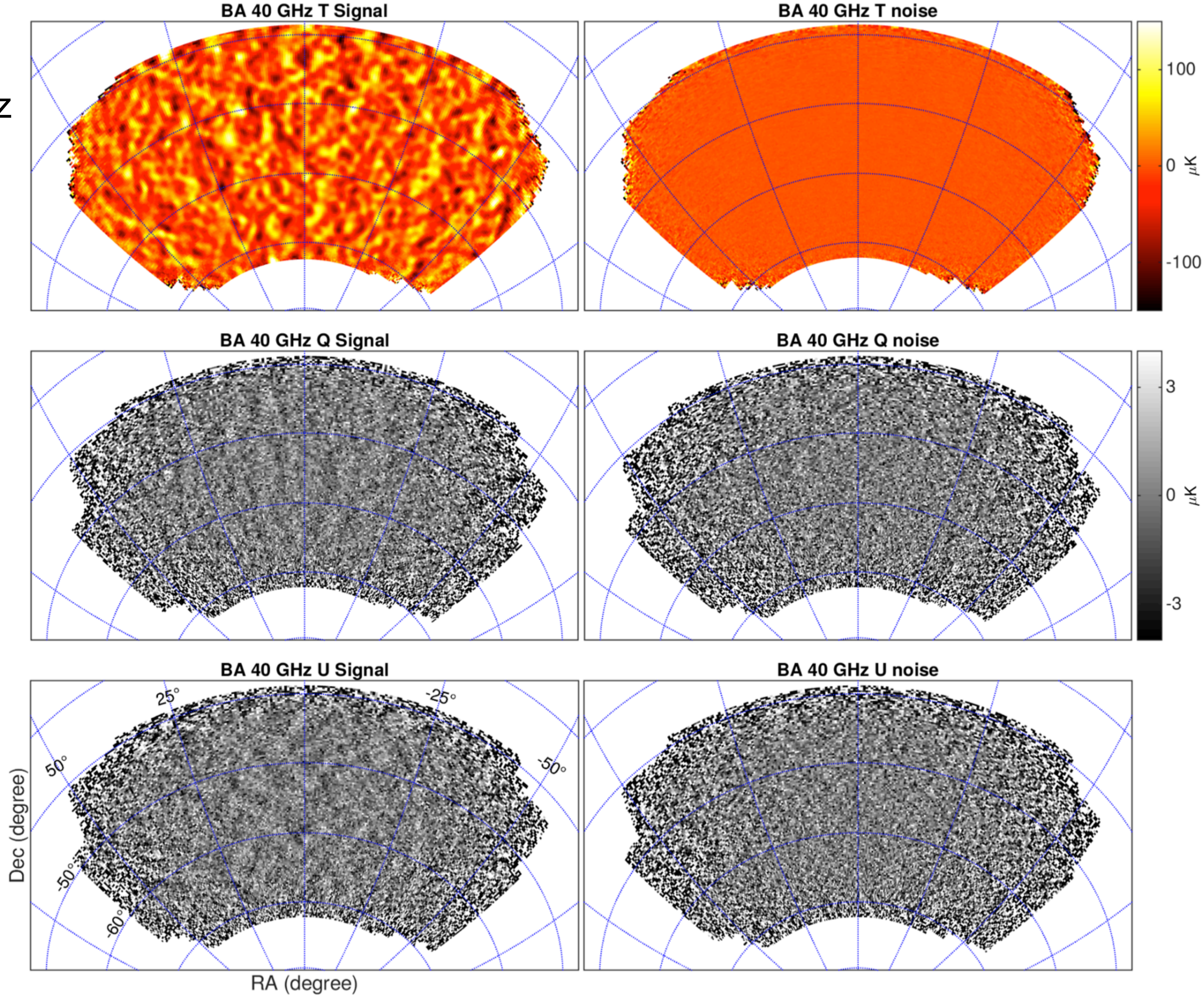




BK18
95GHz
Maps
95 GHz T Signal
95 GHz T Noise
100
0
-100
μK
95 GHz Q Signal
95 GHz Q Noise
3
0
-3
μK
95 GHz U Signal
95 GHz U Noise
25°
-25°
50°
-50°
-50°
-60°
Dec (degree)
RA (degree)

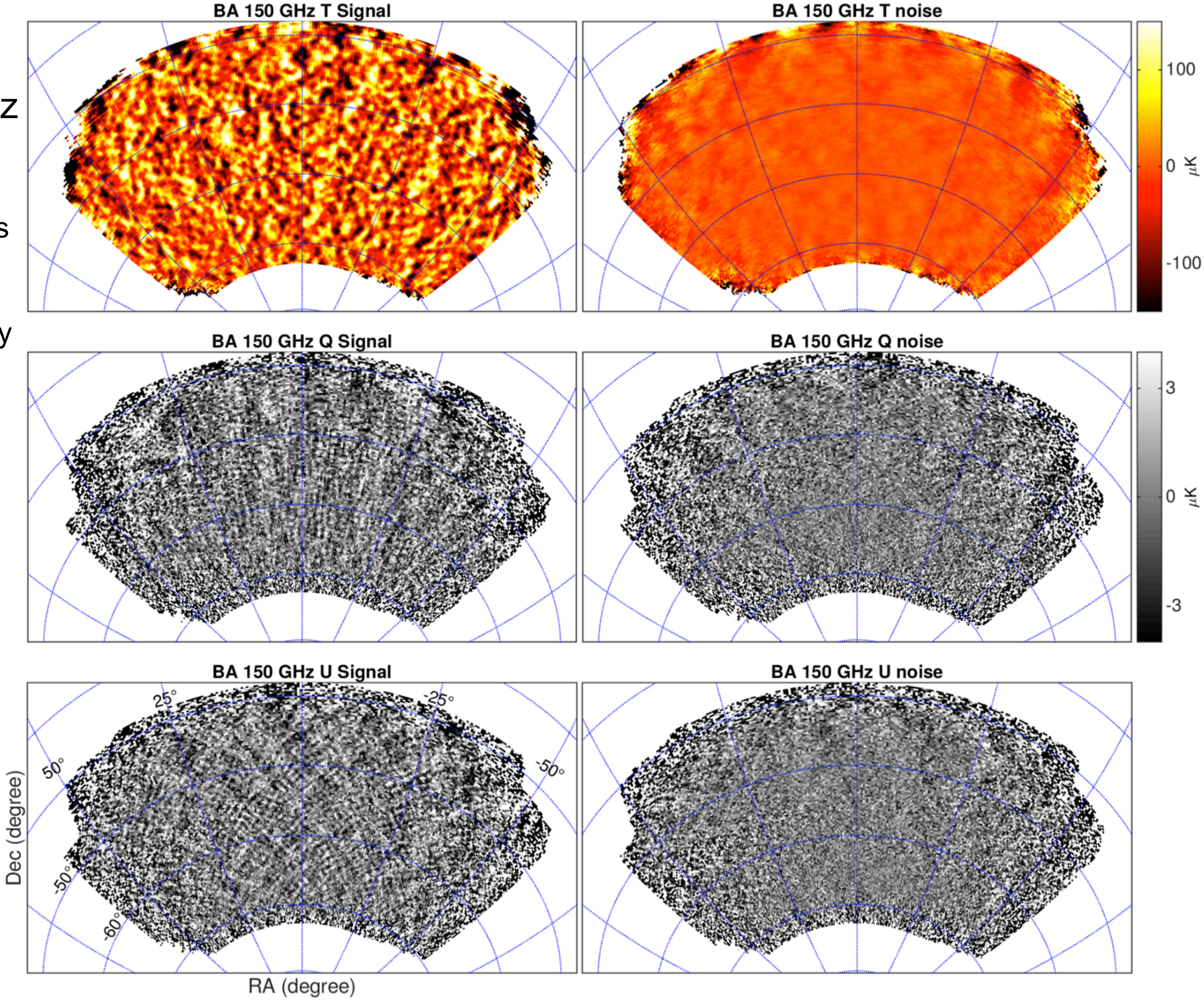
BA1
40GHz
Maps

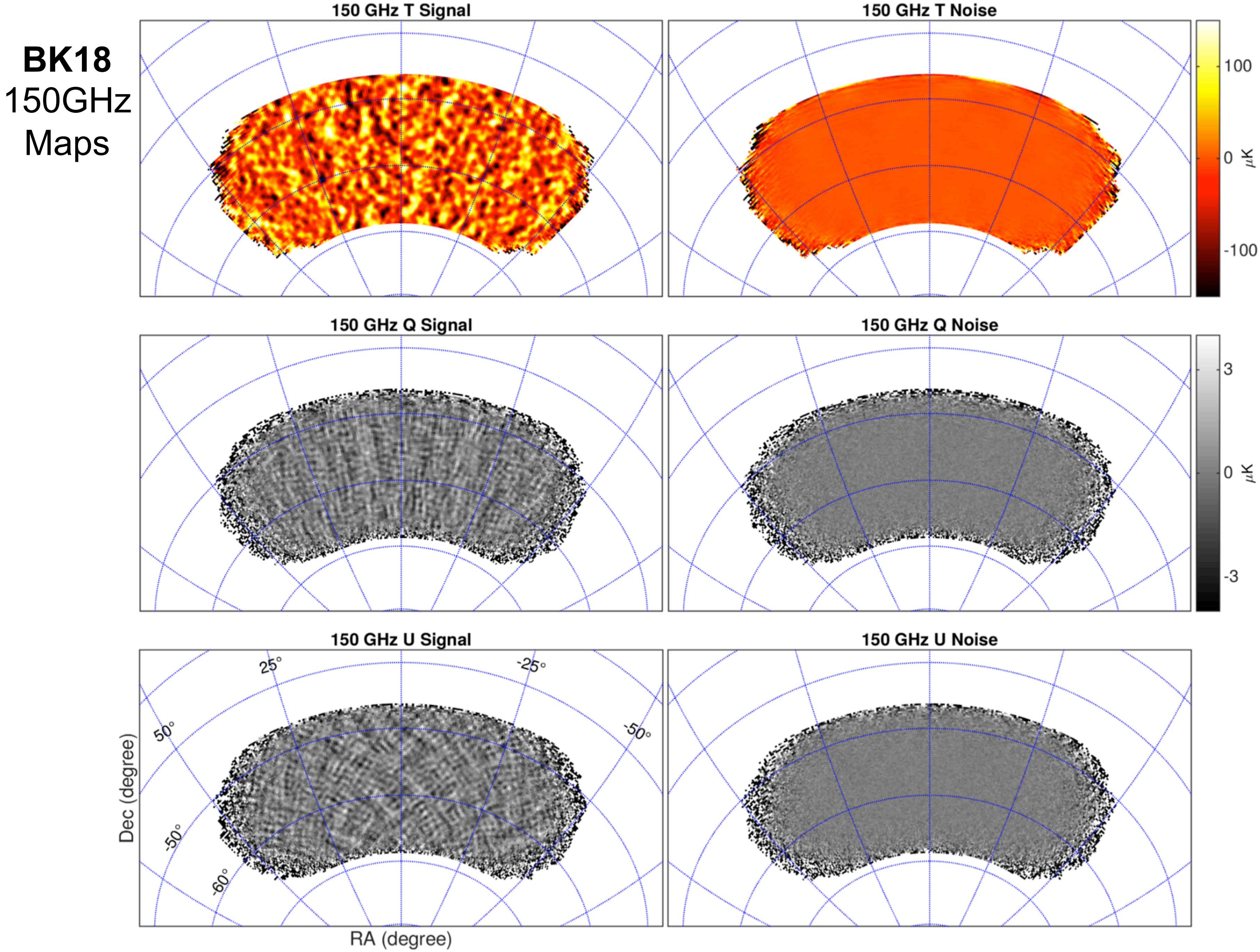
First 3
years of
data



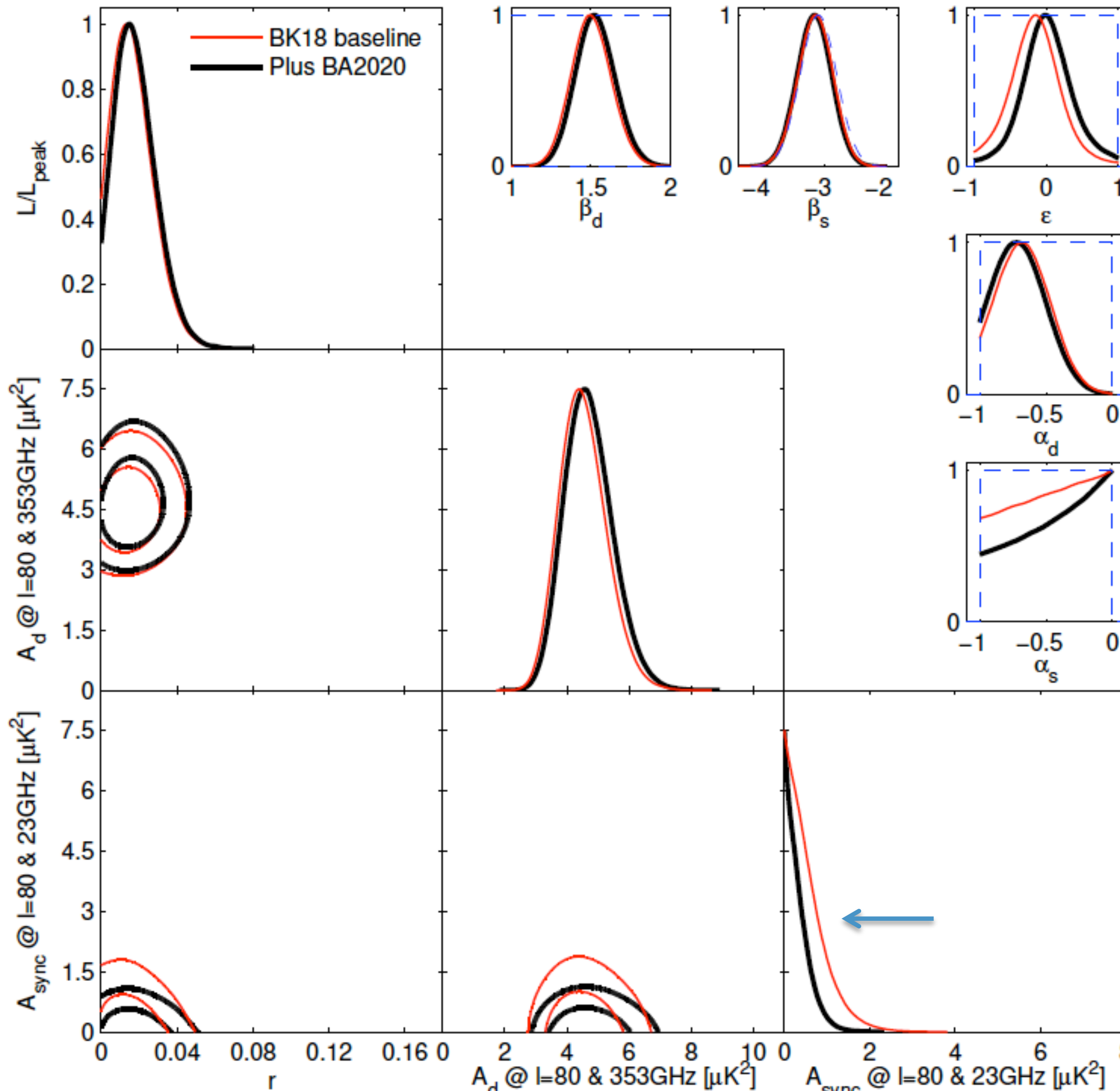
BA2
150GHz
Maps

~2 months of data – Very preliminary




BK18
150GHz
Maps
150 GHz T Signal
150 GHz T Noise
100
0
-100
μK
150 GHz Q Signal
150 GHz Q Noise
3
0
-3
μK
150 GHz U Signal
150 GHz U Noise
25°
-25°
50°
-50°
-50°
-60°
Dec (degree)
RA (degree)

Prelim analysis adding first year 30/40GHz – still do not detect synchrotron – just pushes the upper limit further down

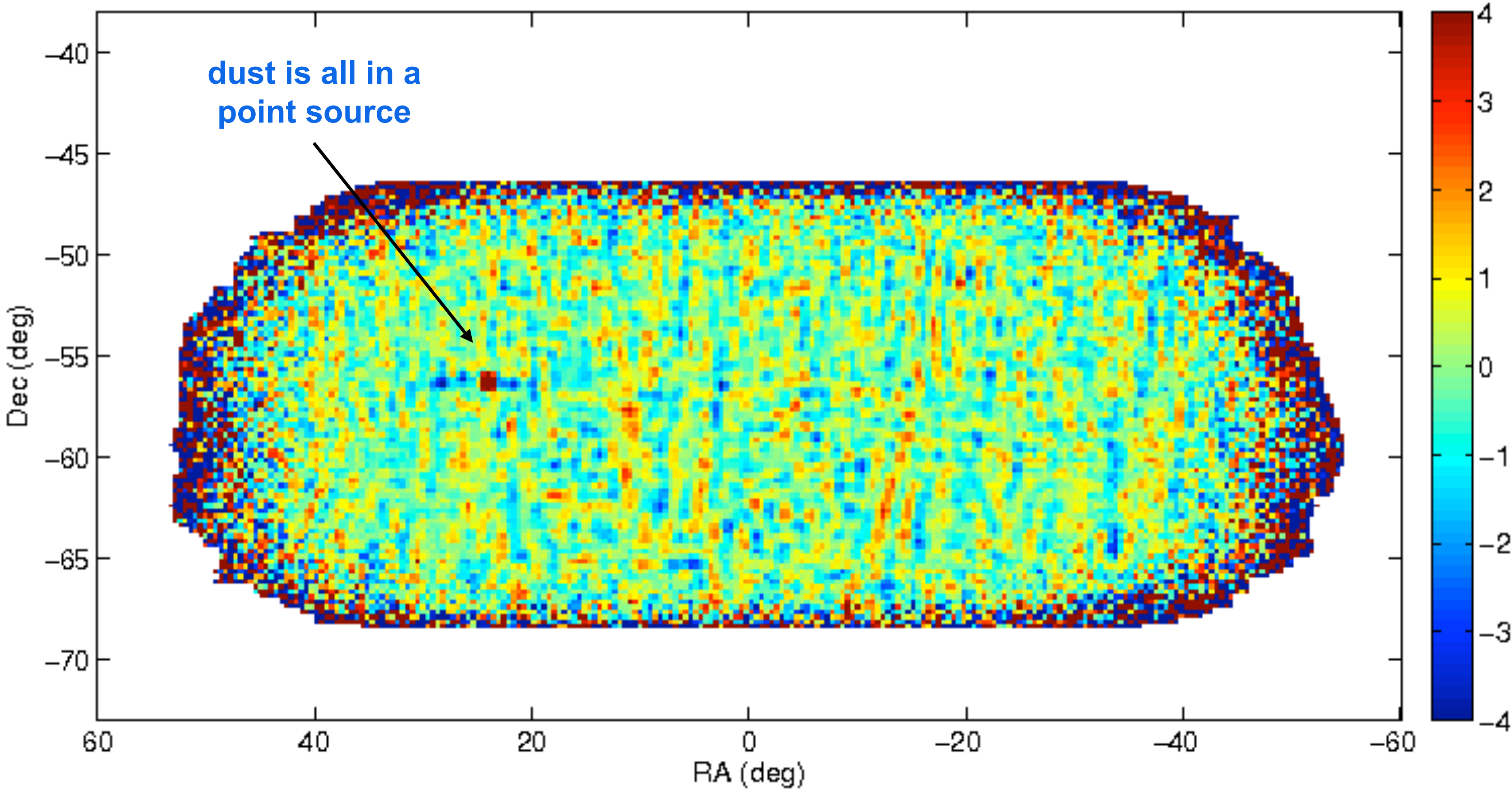


Does it matter that dust is not a Gaussian random field?

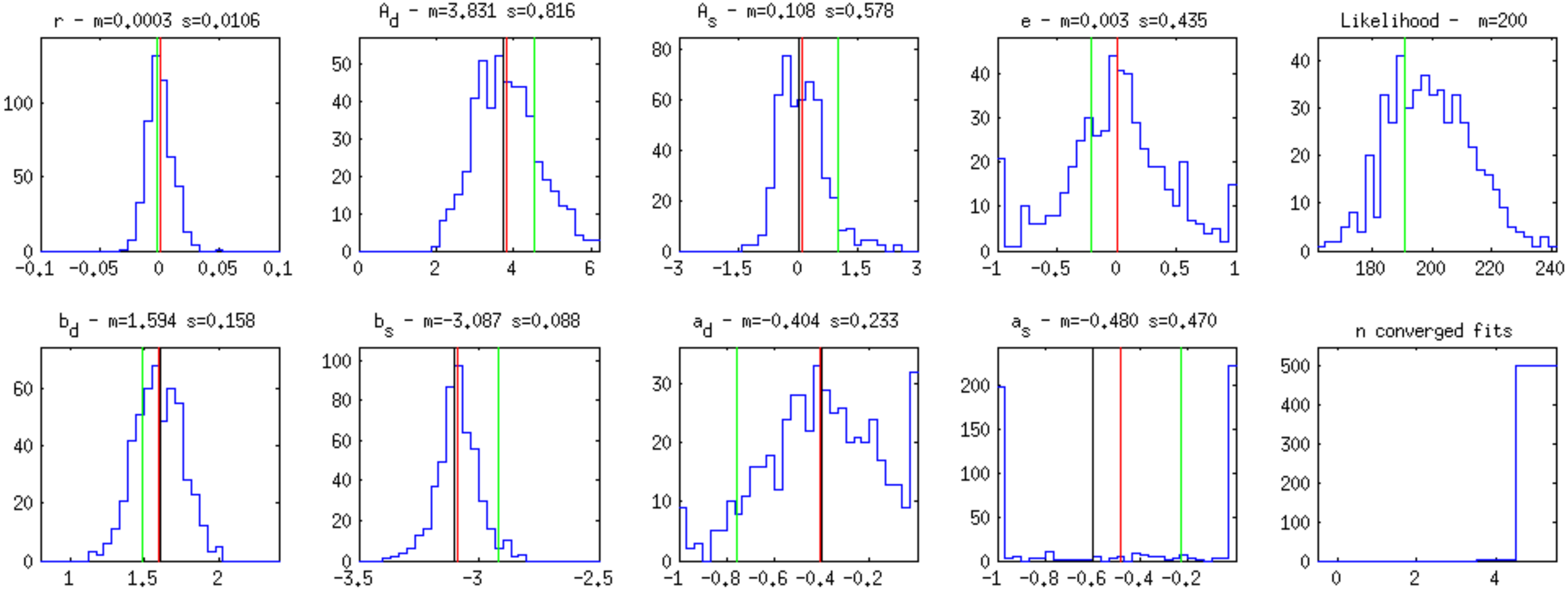
- The error bars we put on power spectrum plots assume the sky pattern is a Gaussian random fields
- Nominally our Hamimeche and Lewis (HL) based likelihood does as well(?)
- To empirically test if it matters we make some sims where the dust sky pattern is extremely non-Gaussian – make it a single point source at some random location on the field
- Then run these lensed-LCDM+dust+noise realizations through the analysis pipeline as usual…

- In a power spectrum sense such dust realizations have only a single (amplitude) degree of freedom – so in a sense the exact opposite of Gaussian (maximal degrees of freedom)

Simulated 150GHz lensed-LCDM+”dust”+noise Q Map



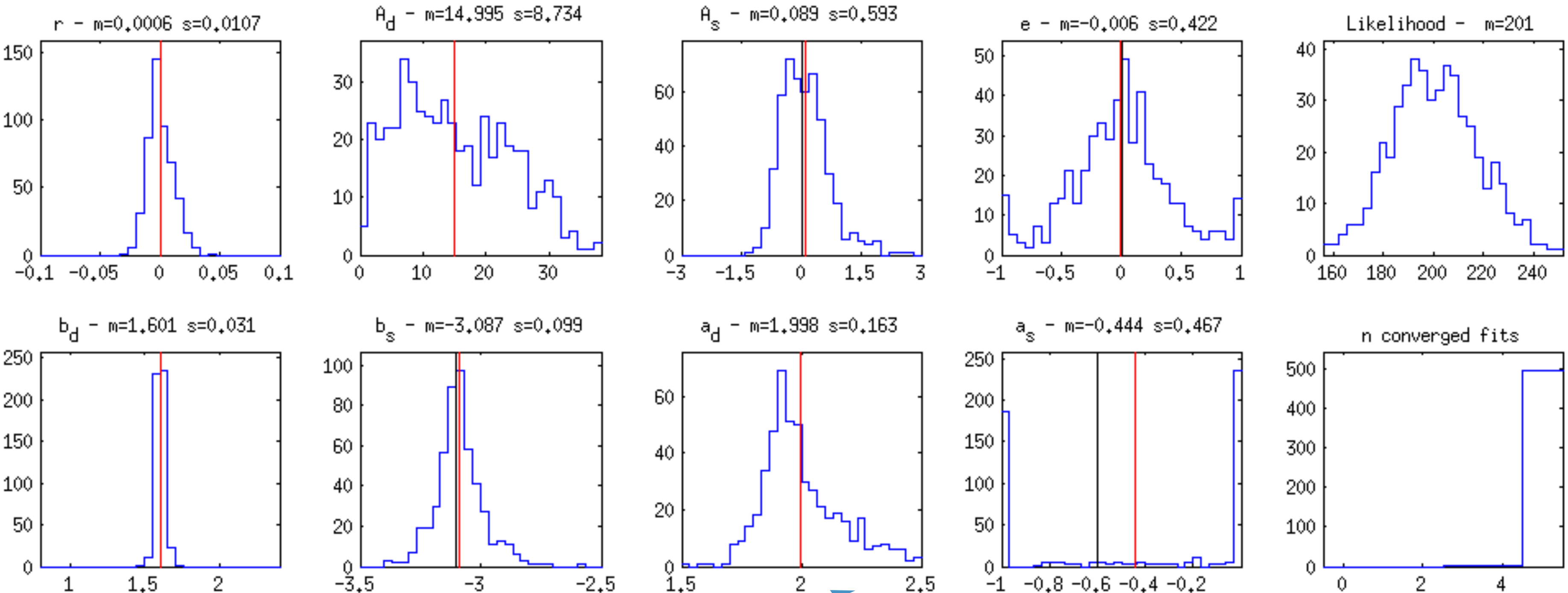
Maximum Likelihood Search Results on lensed-LCDM+dust+noise Simulations
Standard Gaussian dust realizations



Each panel is a model parameter – numbers above are mean and sigma over sim realizations
Vertical red lines are mean value over realizations, black is sim input value (and green is real data value)

Maximum Likelihood Search Results on lensed-LCDM+dust+noise Simulations
Special “point source dust” realizations

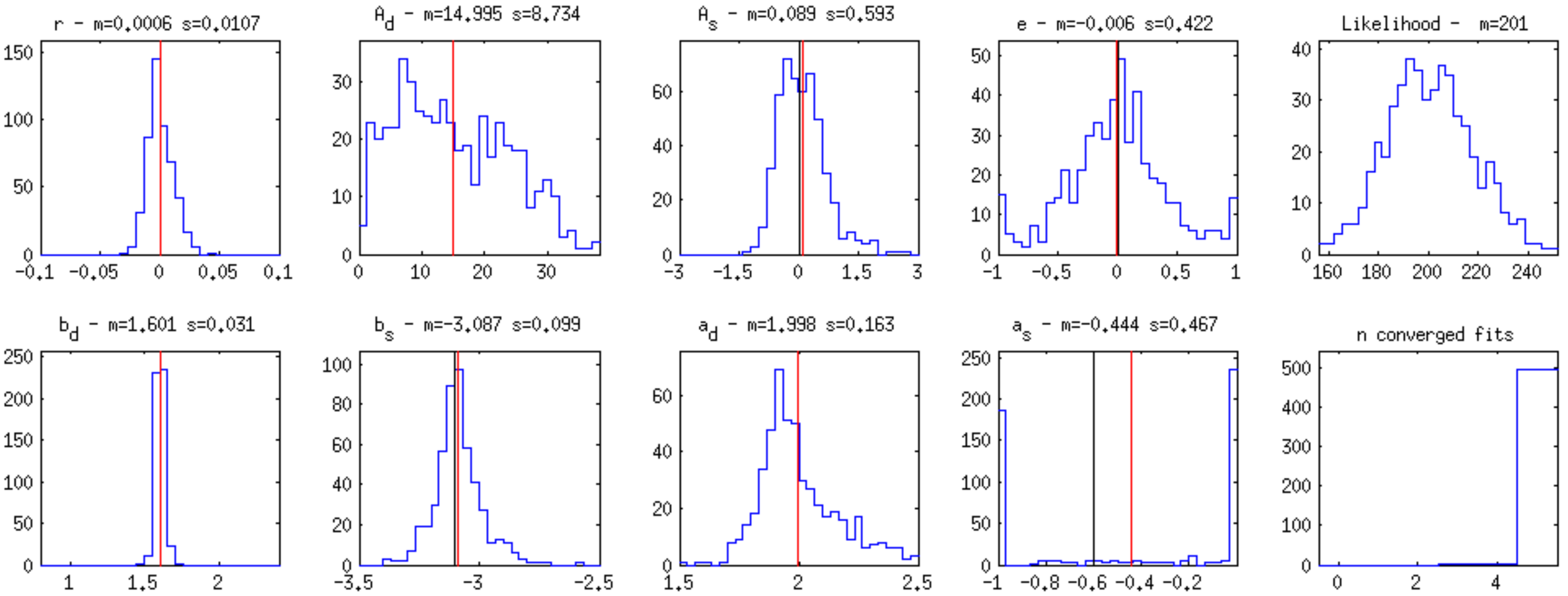
no increase in bias
or fluctuation of *r*



expected alpha=2
for point source

Each panel is a model parameter – numbers above are mean and sigma over sim realizations
Vertical red lines are mean value over realizations, black is sim input value (and green is real data value)

Maximum Likelihood Search Results on lensed-LCDM+dust+noise Simulations
Special “point source dust” realizations



Each panel is a model parameter – numbers above are mean and sigma over sim realizations
Vertical red lines are mean value over realizations, black is sim input value (and green is real data value)

Seemingly weird result – it all works fine when dust is highly non-Gaussian!

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 systematics control at degree angular scales

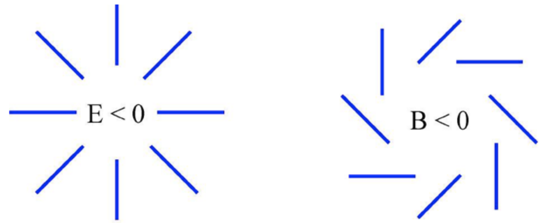
- Using data up to 2018 now at $\sigma(r)=0.009$ and $r_{0.05}<0.036$ (95%)
- For the first time no foreground priors from other regions of sky
- Rules out two entire classes of previously popular inflation models (monomial models and Natural Inflation)

- And we can keep going:
- BICEP Array mount and first two receivers running
- Delensing in conjunction with SPT3G under development
- Projecting $\sigma(r)<0.003$ using data up to 2027 (sorry for COVID delay!)

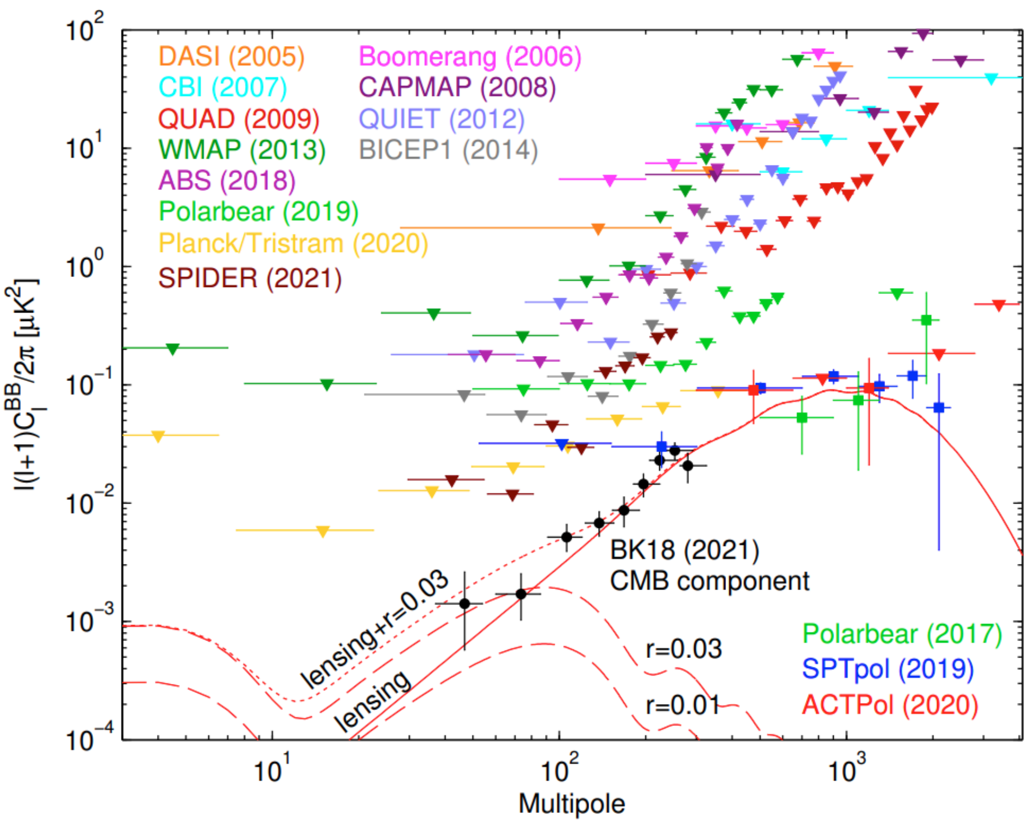
Backup slides

Constraints on Inflation to Date

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



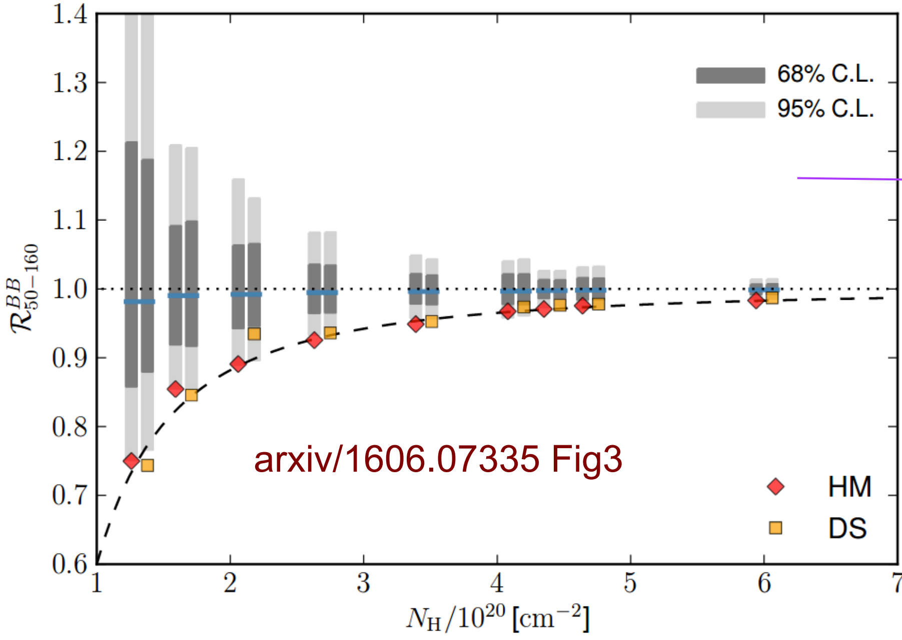
State of B-mode polarization power spectra in 2021

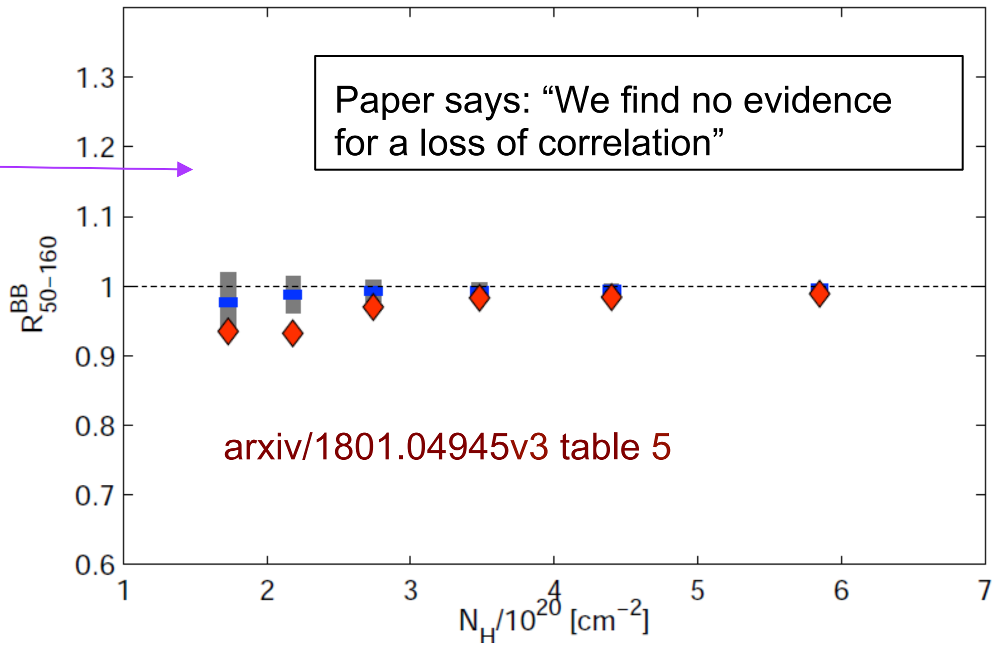


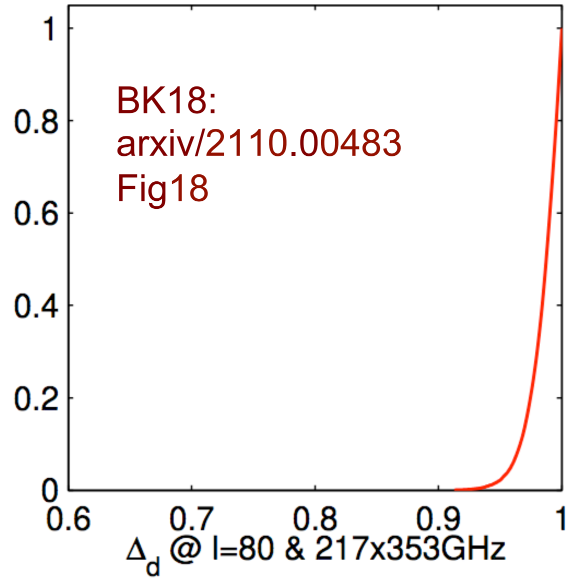
Posted B-Mode Sensitivity to r

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

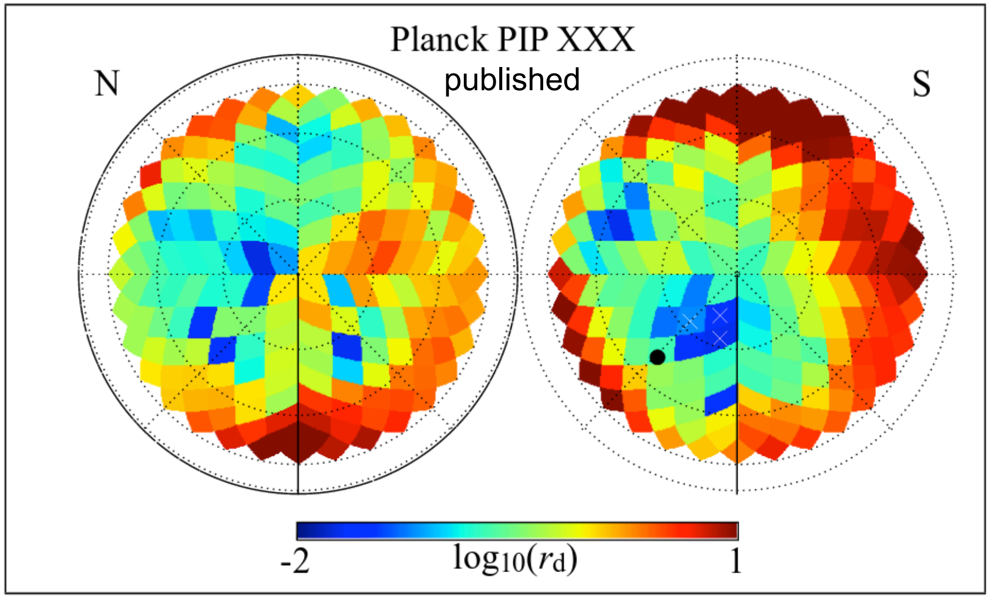
Planck Evidence for Dust Decorr Went Away and BK18 doesn't see any evidence for it

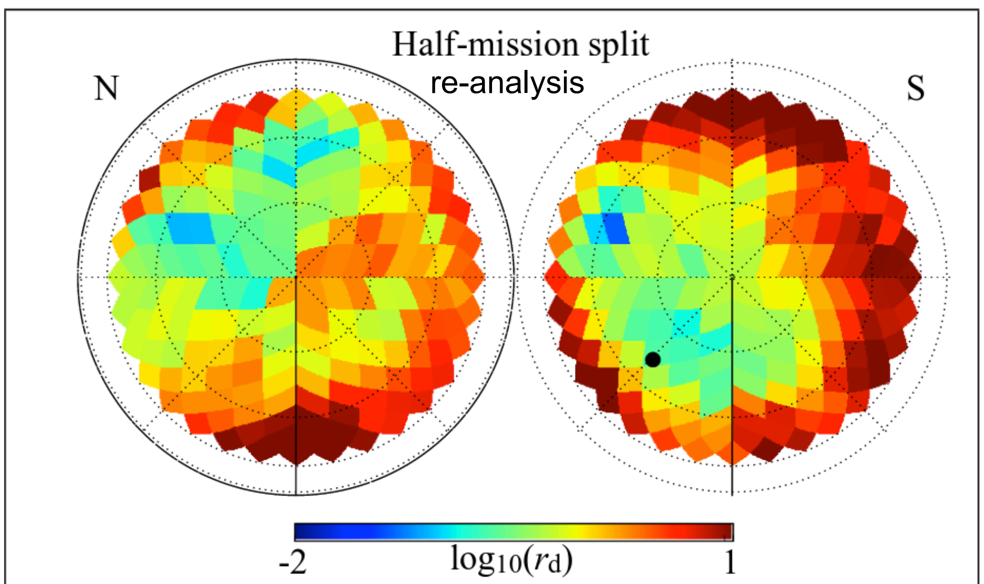






Is there a cleaner small field than the BICEP field?

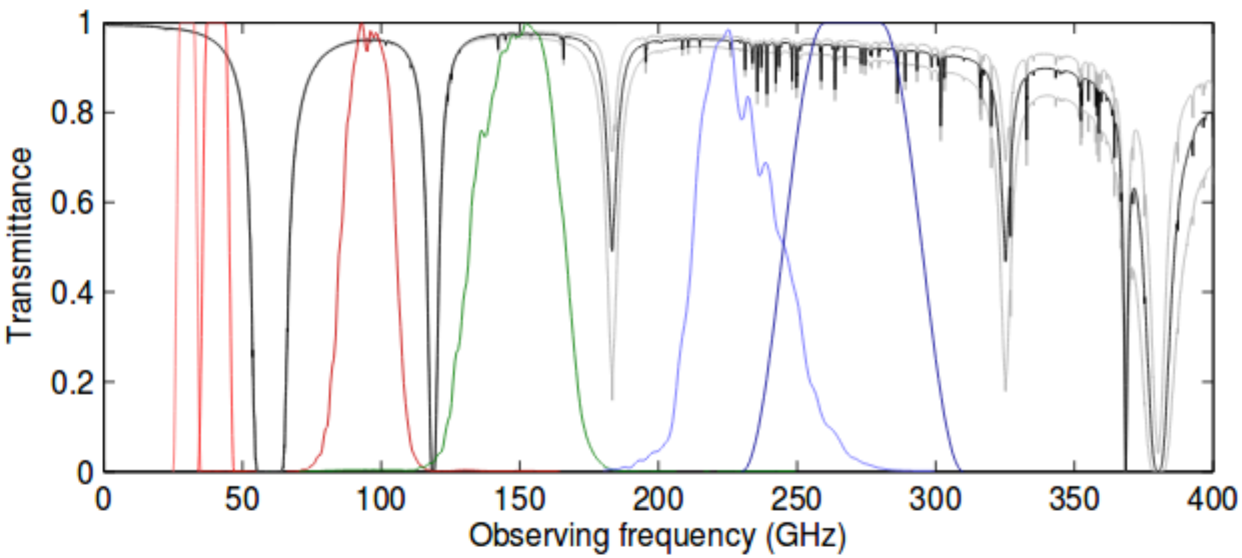


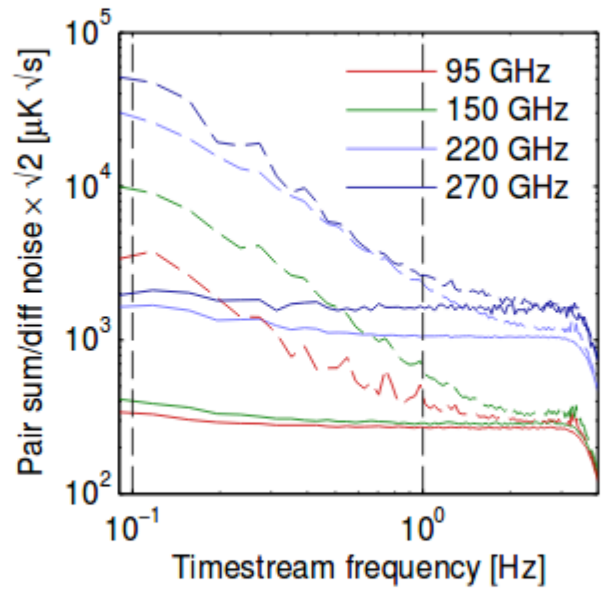


- The Planck 353GHz Q/U maps hit their noise floor in the cleanest regions
  - From this data it is not really possible to tell if there are cleaner small regions than the BICEP/Keck field
- When we attempt to reproduce the Planck PIPXXX analysis we find that the apparent cleaner regions shift around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

Pair Differencing Works Well 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)

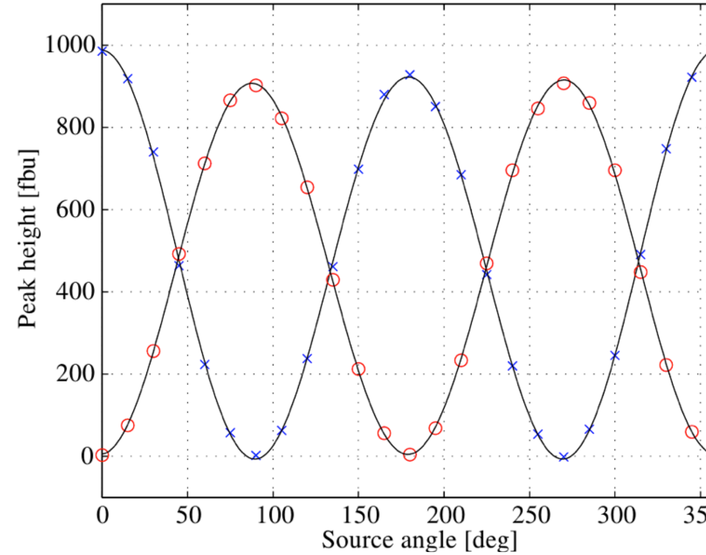
Adding a modulator is no silver bullet - they often carry a noise penalty and have their own systematics issues

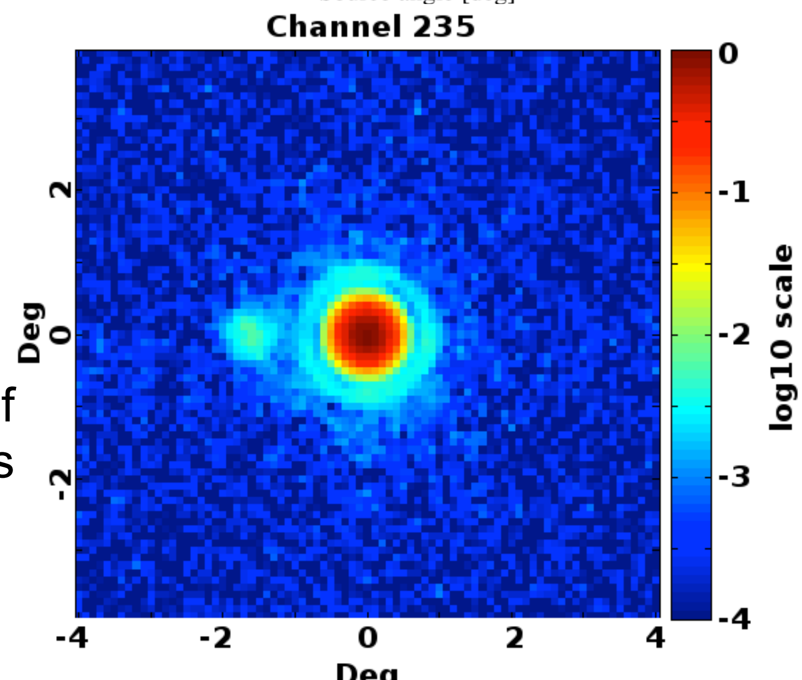
Calibration Measurements

For instance...

Far field beam mapping

Detector Polarization Calibration



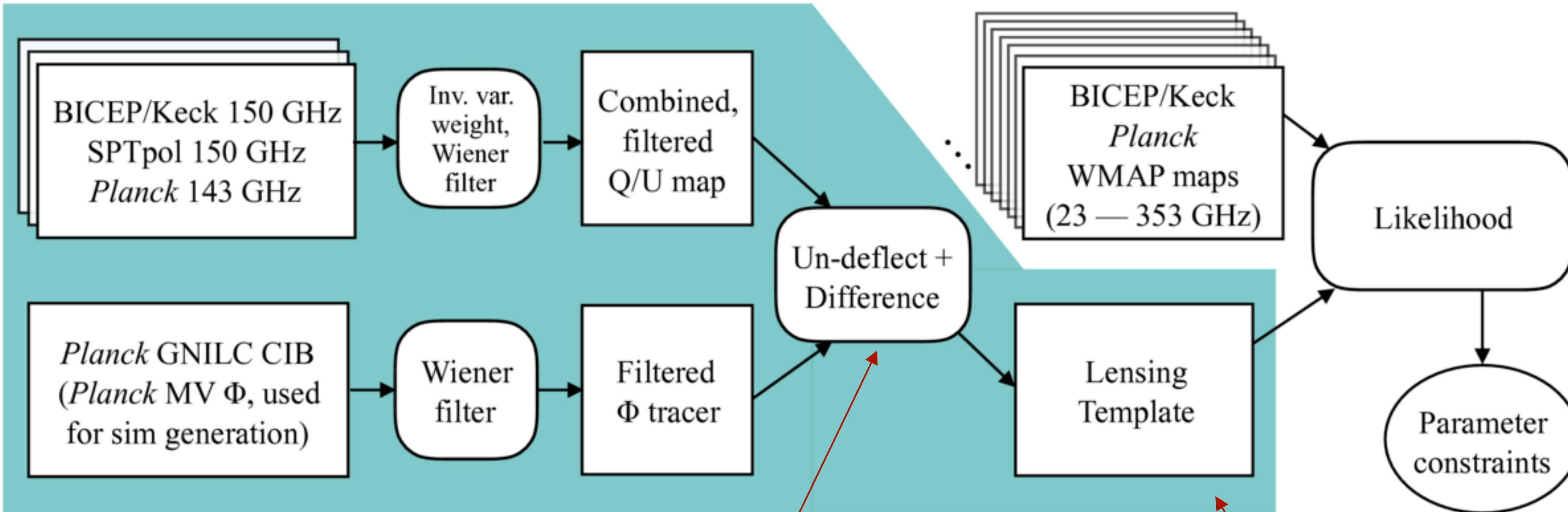


Hi-Fi beam maps of
individual detectors

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"



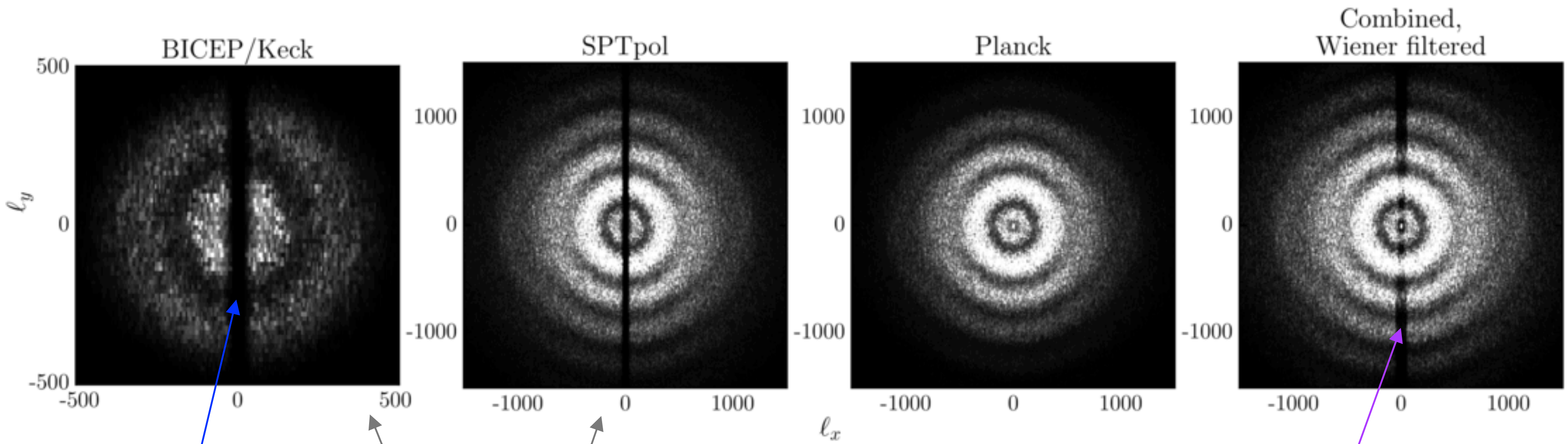
map space un-deflect operation

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

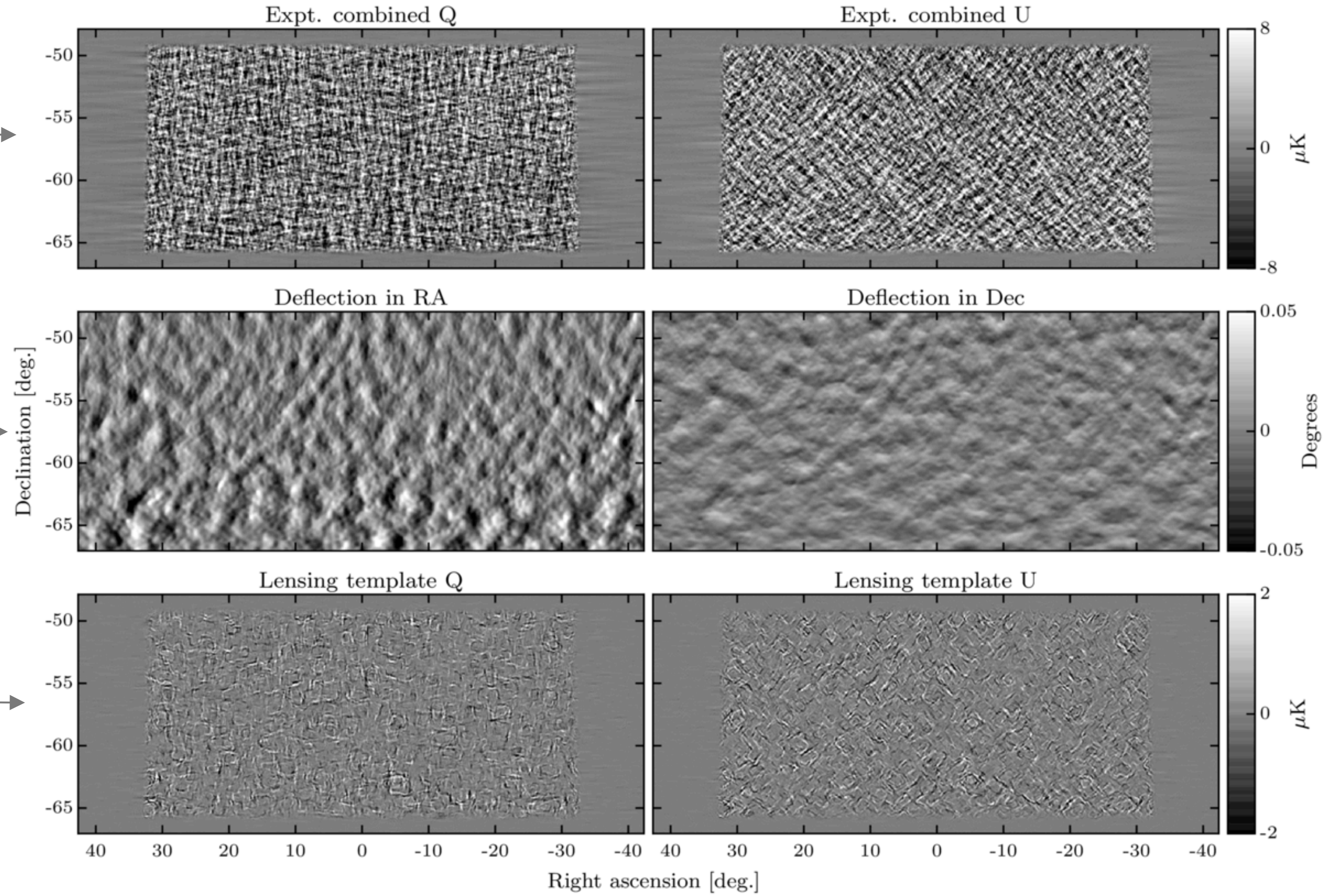
arXiv: 2011.08163

Making the lensing template

Combined map back in image space

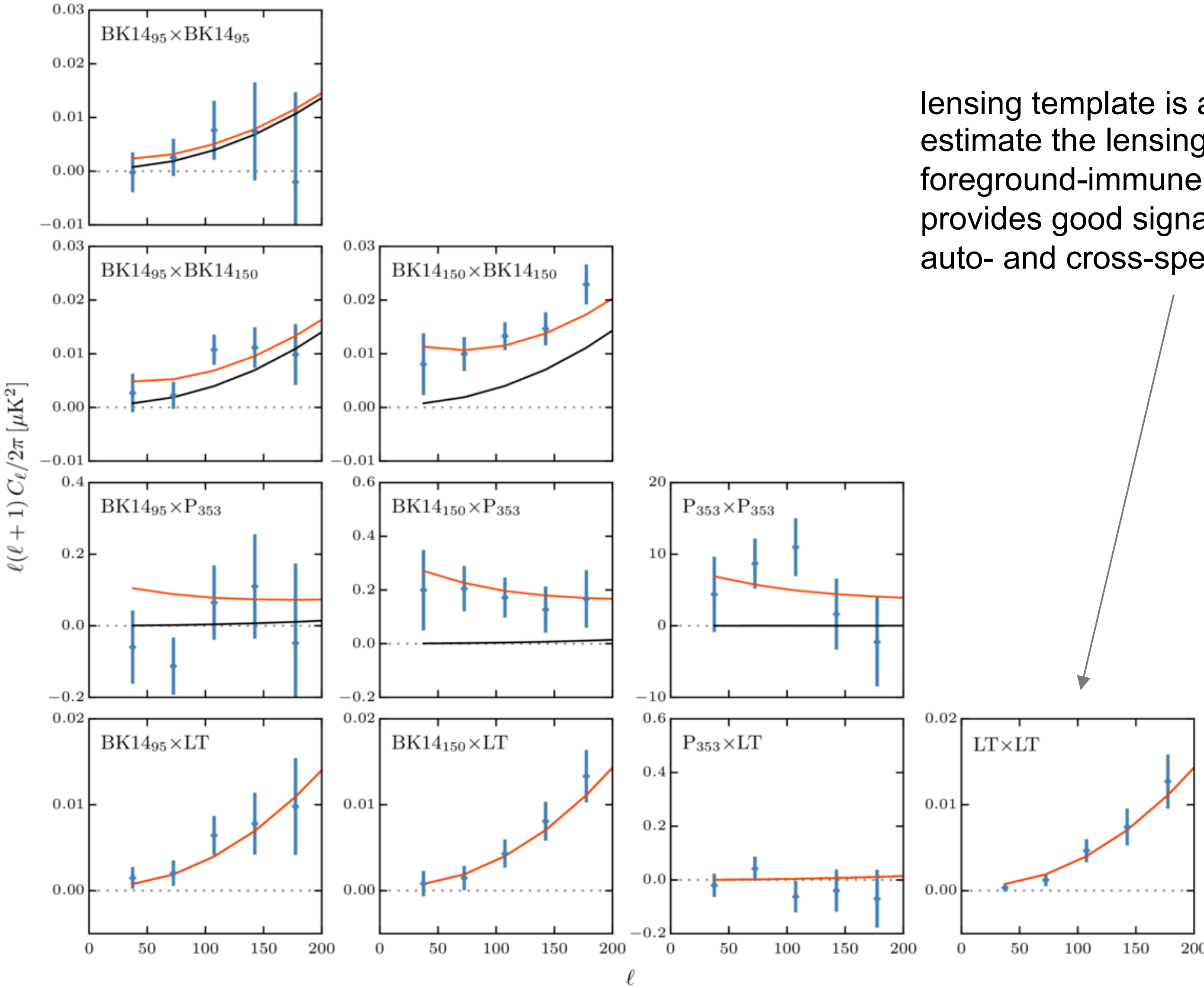
Weiner filtered lensing deflection field estimate from Planck CIB map

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



arXiv: 2011.08163

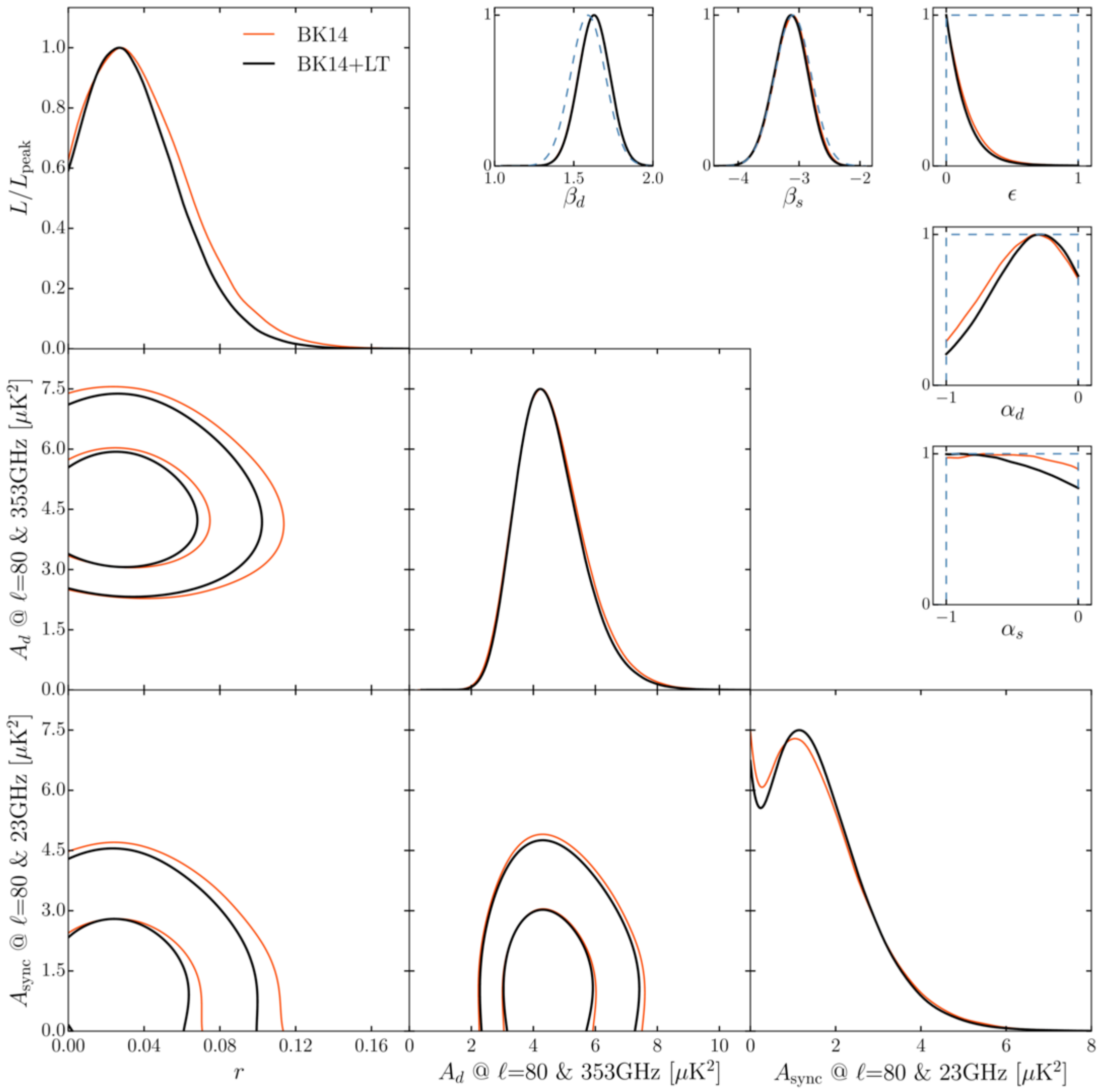
Auto/cross spectra of the lensing template



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

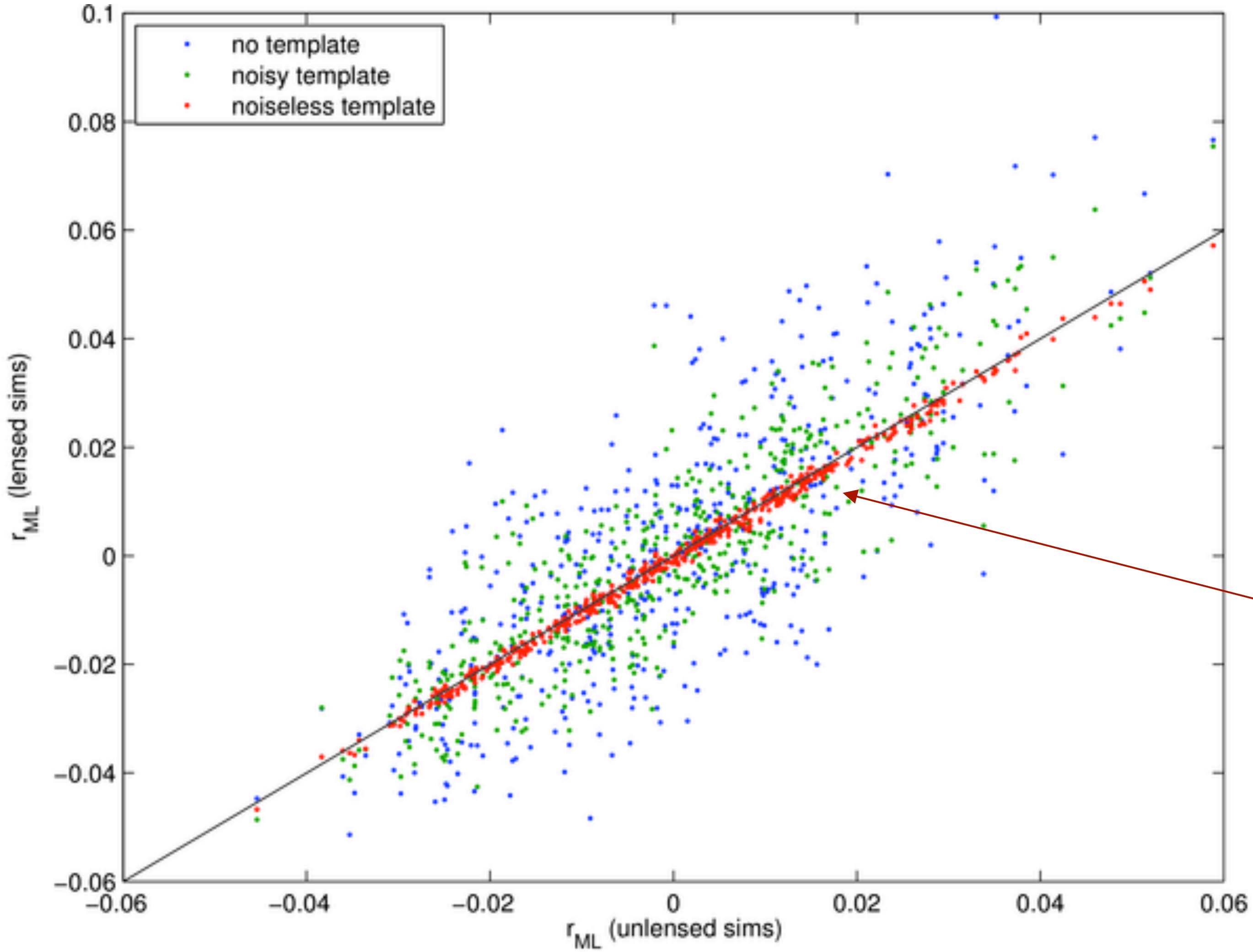


Adding CIB+SPTpol lensing template to BK14 makes little difference to bottom line *r* constraint - reduces width by 10%

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)