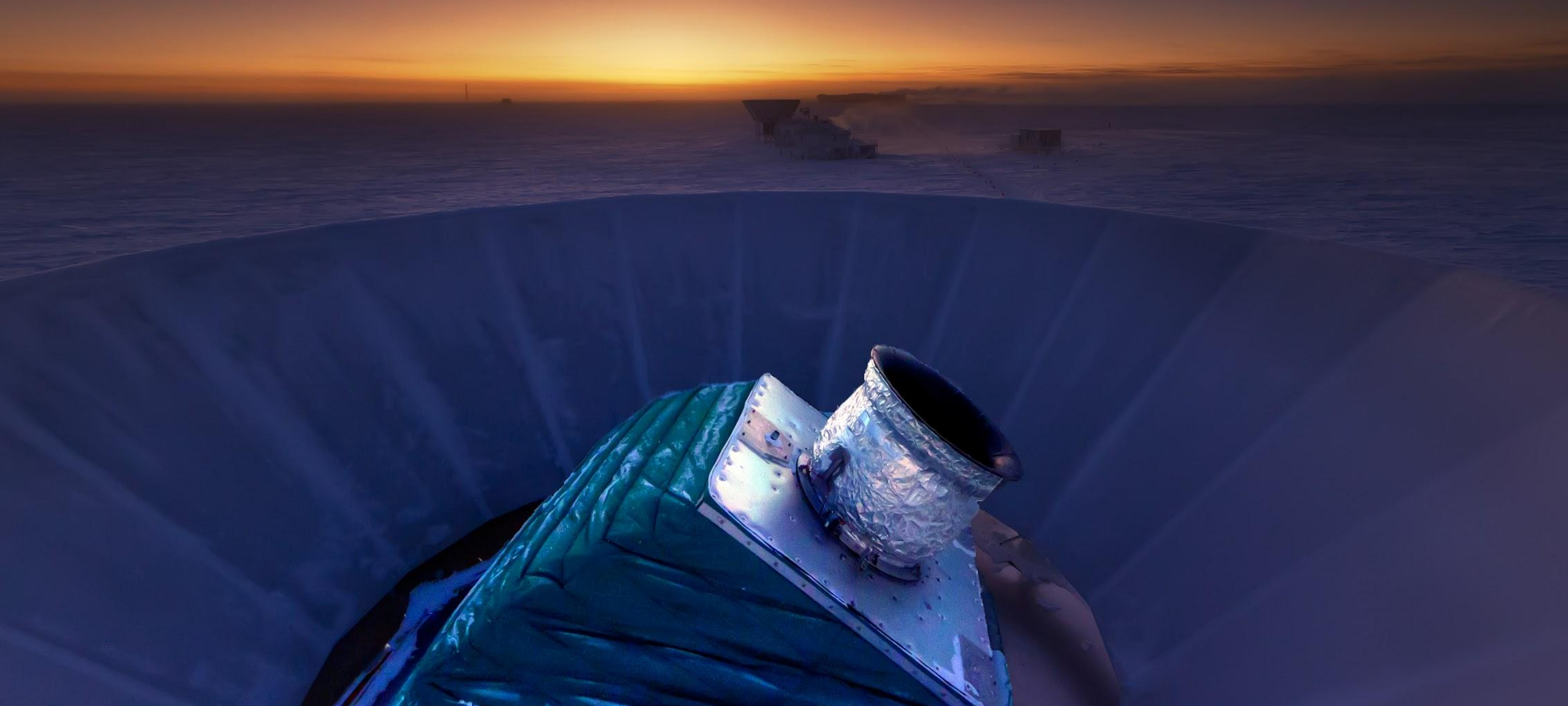
The search for primordial gravitational waves: latest results from BICEP/Keck



Clem Pryke for the BICEP/Keck Collaboration – CMB France Meeting, Paris – Dec 4 2023

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

VE RI TAS HARVARD

DE LA RECHERCHE À L'INDUSTRIE cea

NIST

CARDIFF UNIVERSITY

UNIVERSITY OF Cincinnati

UBC

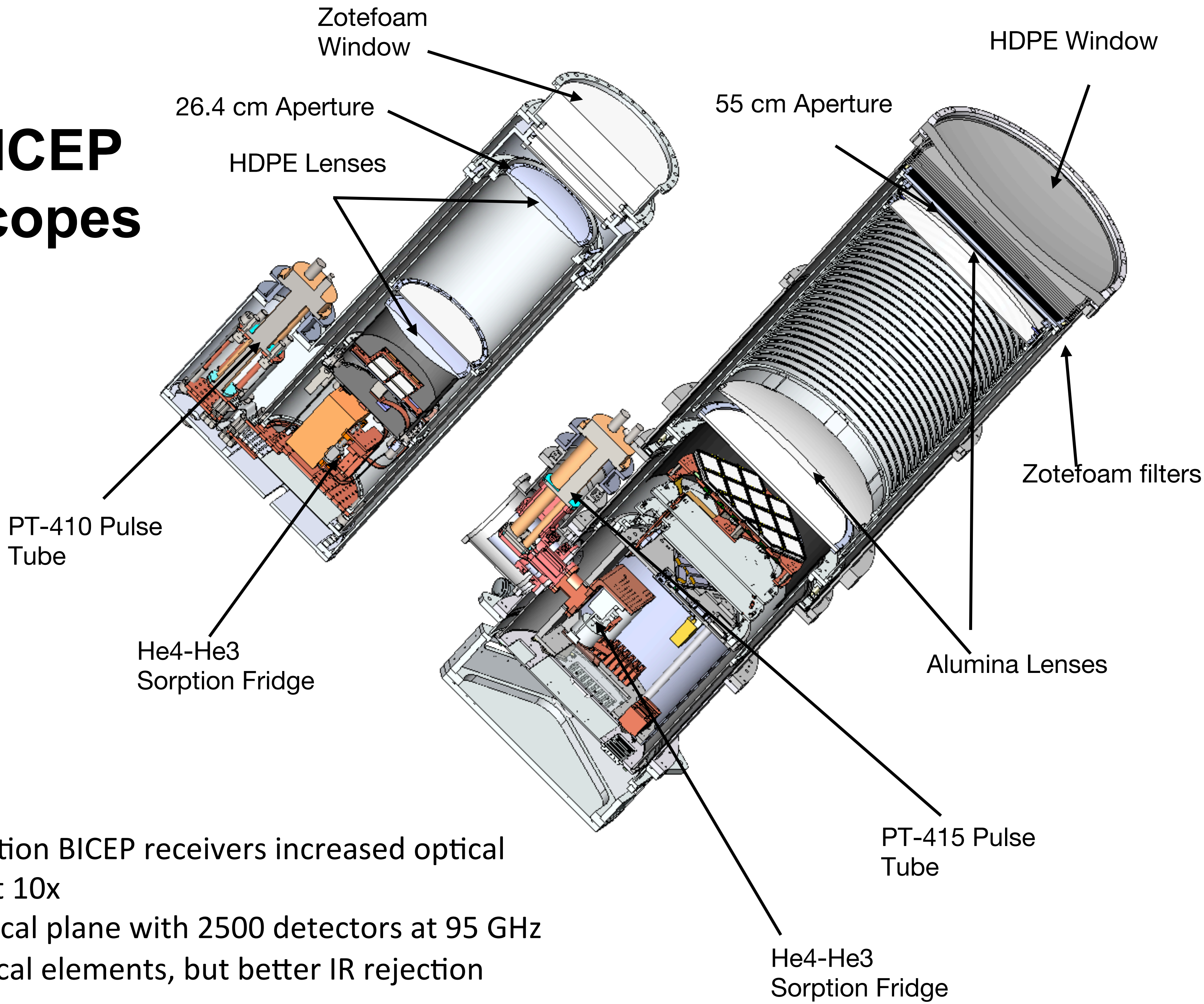
SLAC

JPL

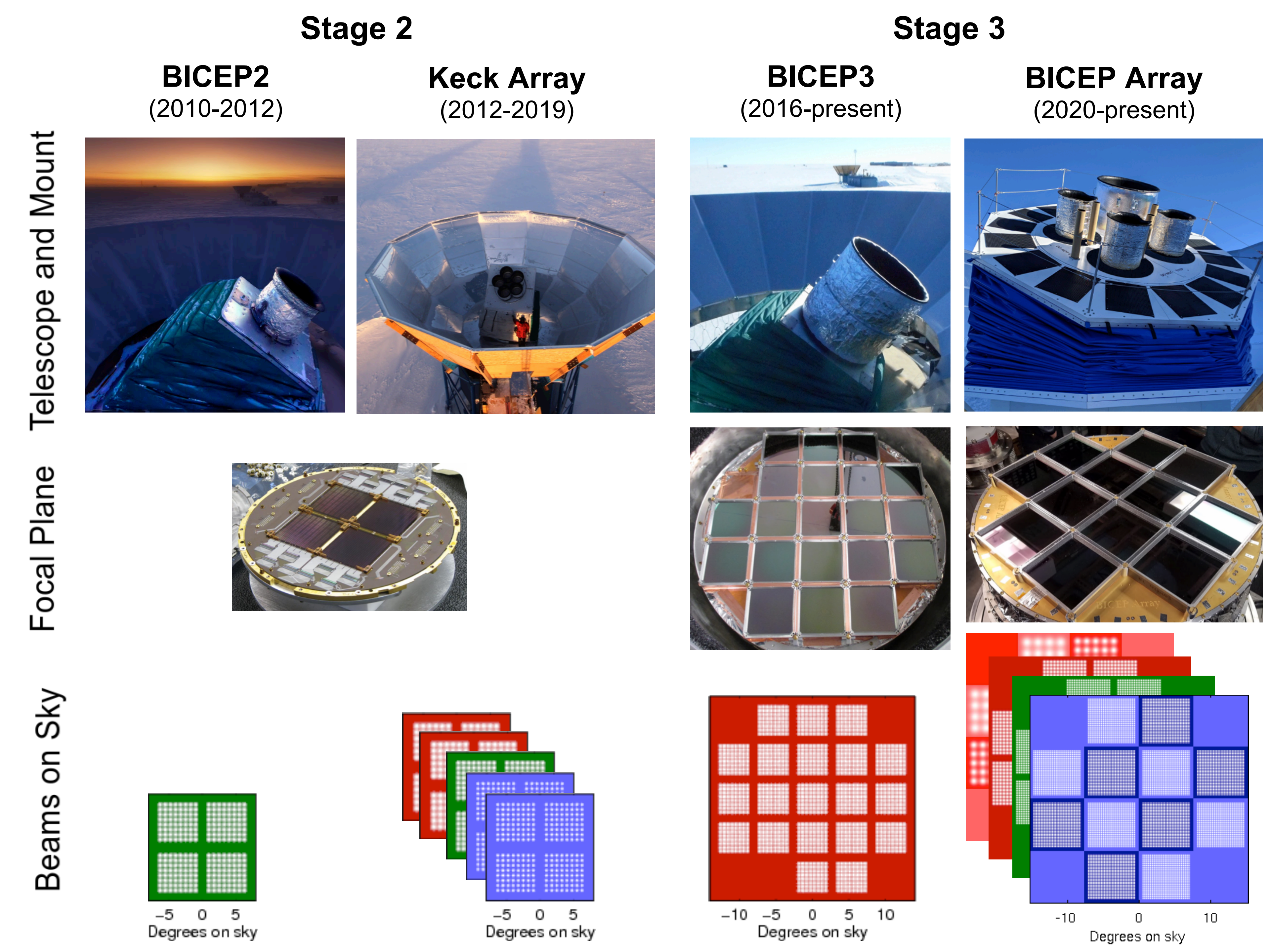
BICEP/Keck Basic Experimental Strategy

→ 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

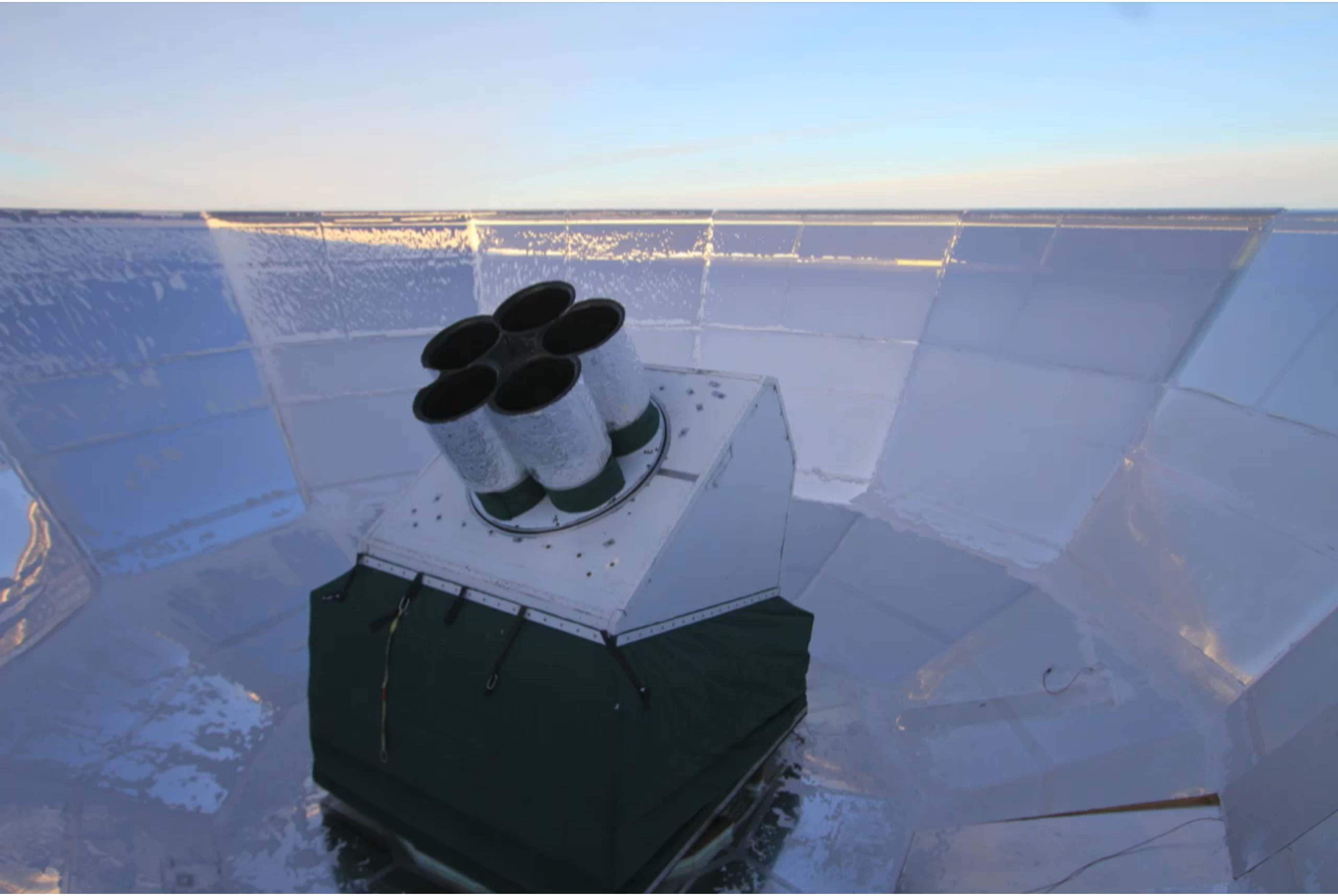
The BICEP Telescopes

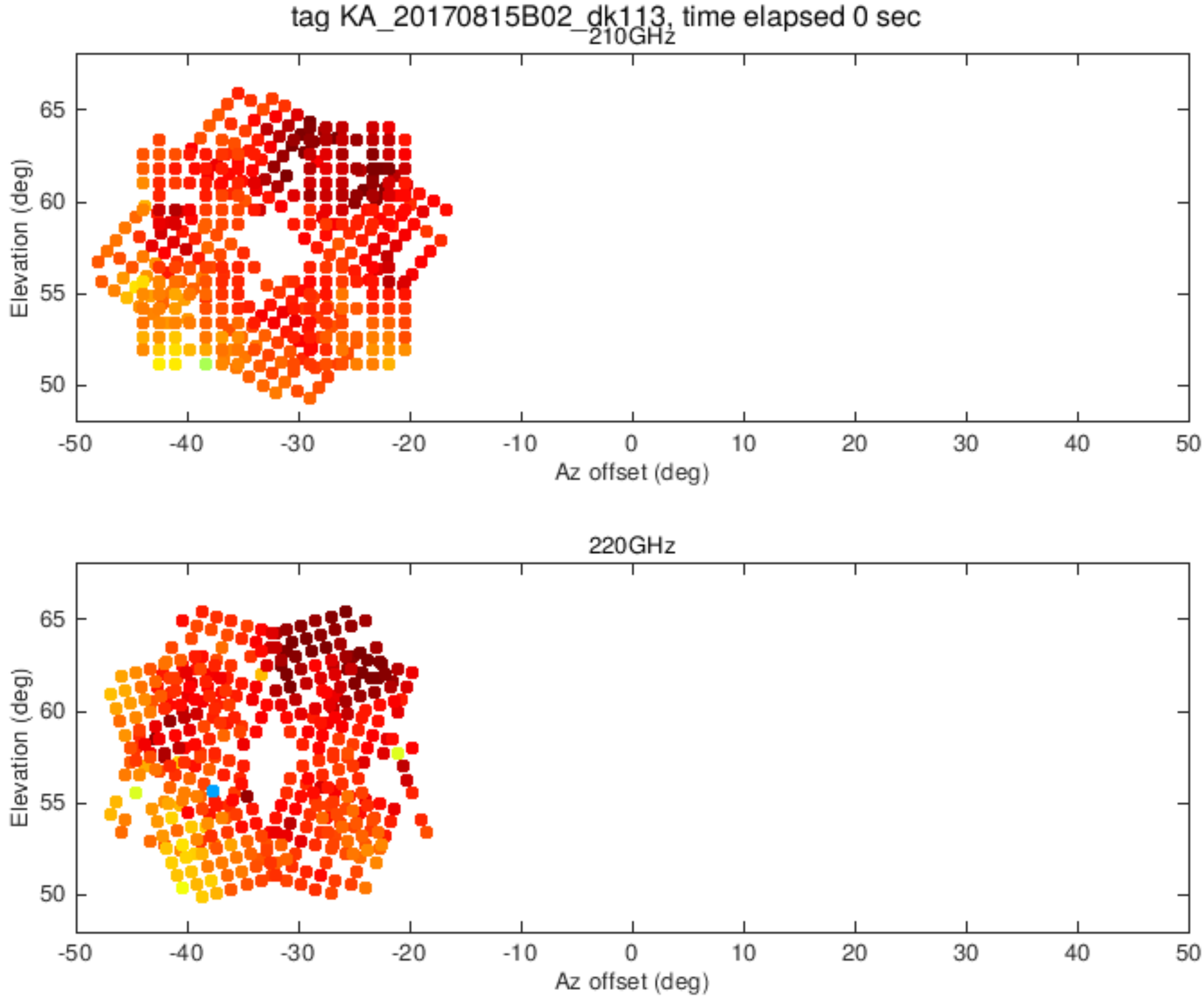


- 3rd generation BICEP receivers increased optical throughput 10x
- Modular focal plane with 2500 detectors at 95 GHz
- Larger optical elements, but better IR rejection



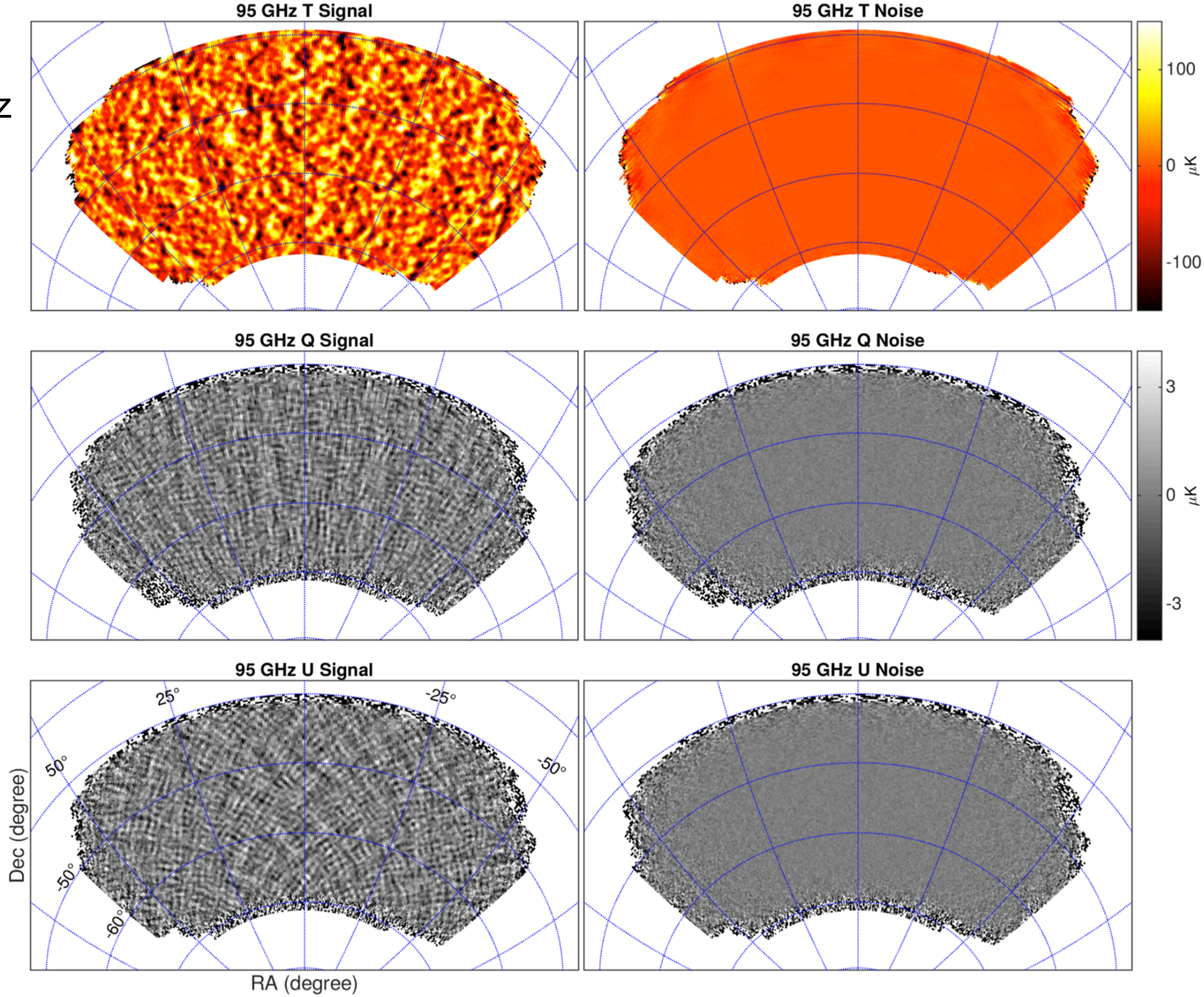
Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2016-present)
BICEP Array
(2020-present)
Telescope and Mount
Focal Plane
Beams on Sky
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
-10 0 10
Degrees on sky



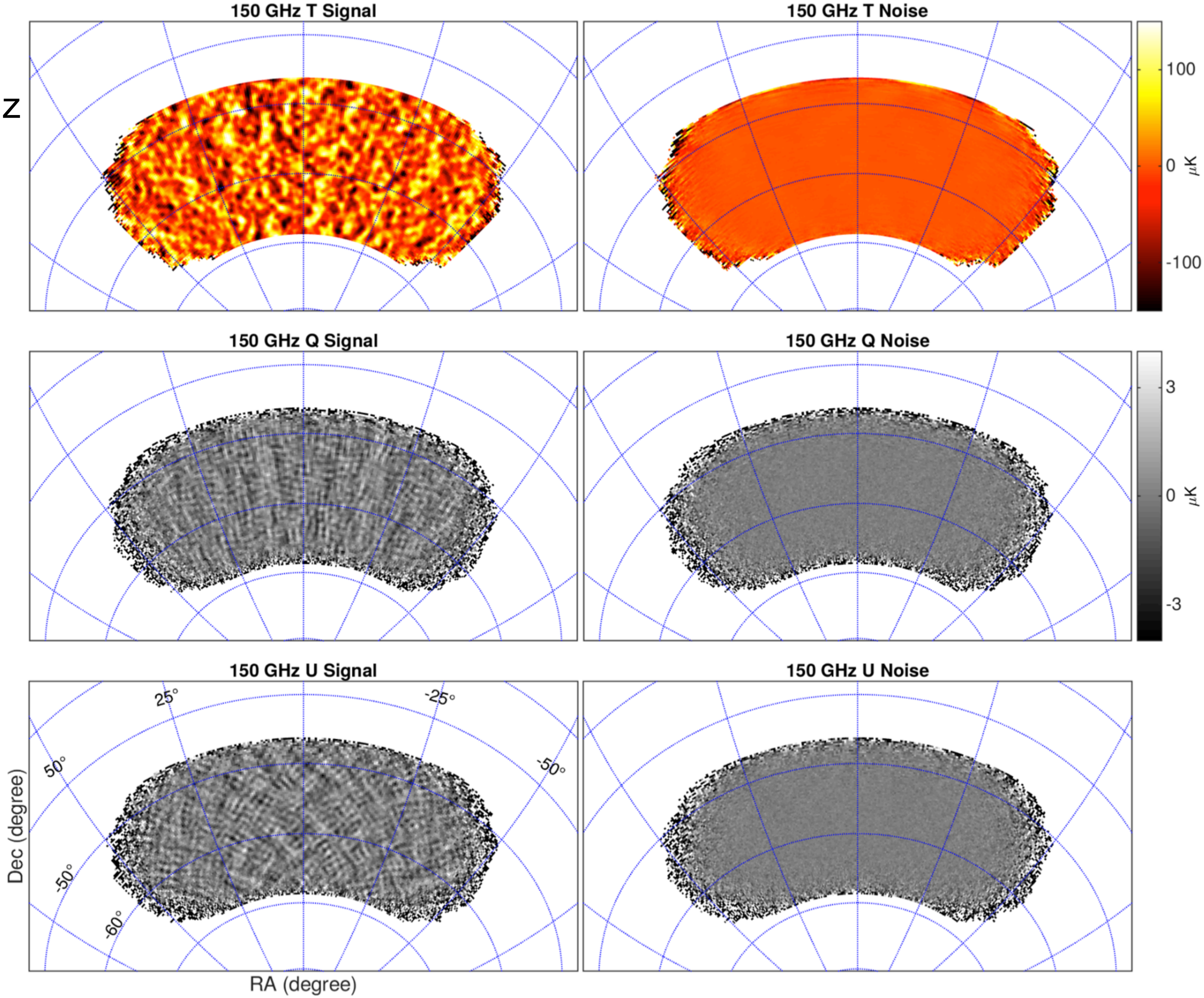


tag KA_20170815B02_dk113, time elapsed 0 sec
210GHz
220GHz
Elevation (deg)
Az offset (deg)

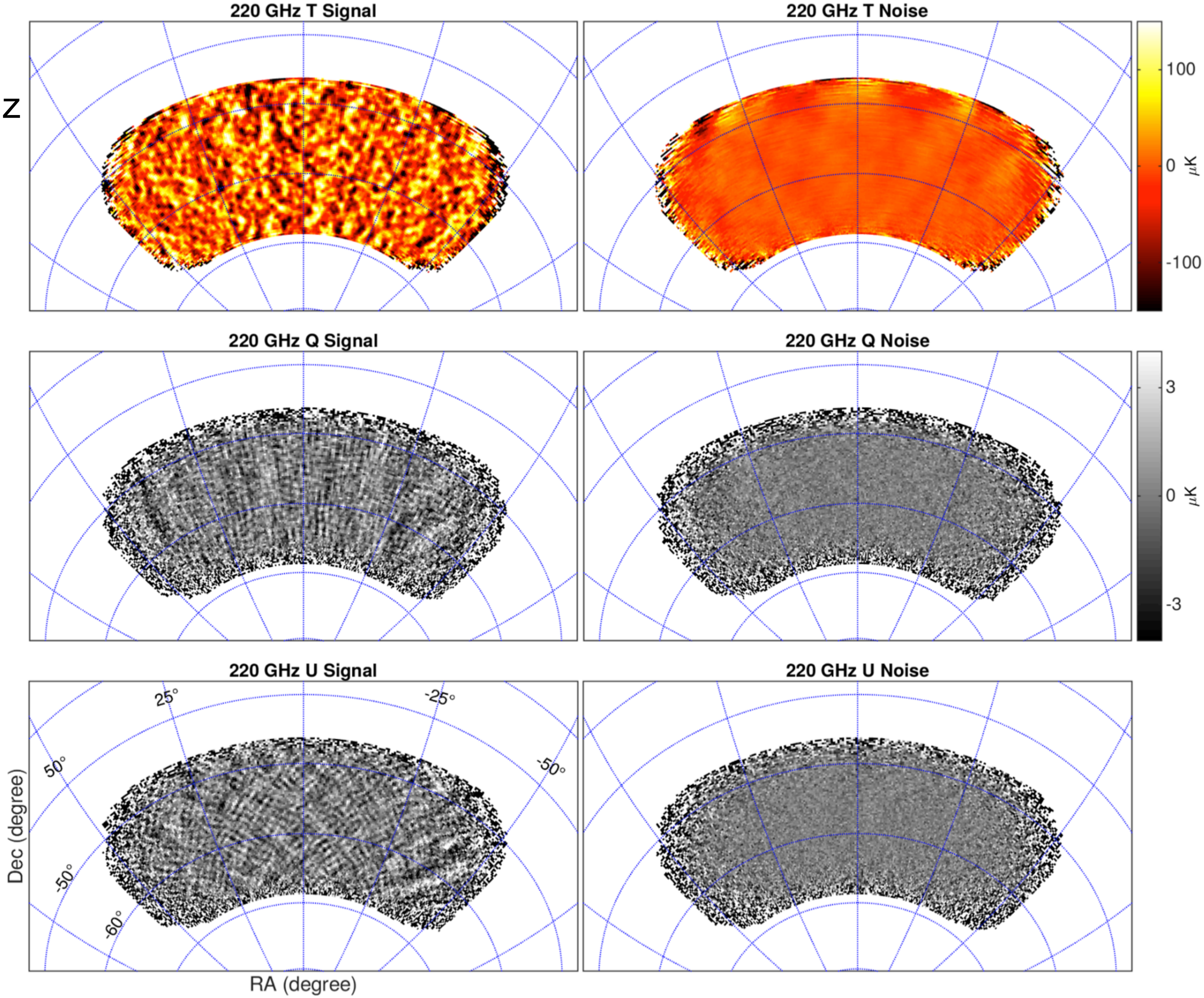
BK18
95GHz
Maps



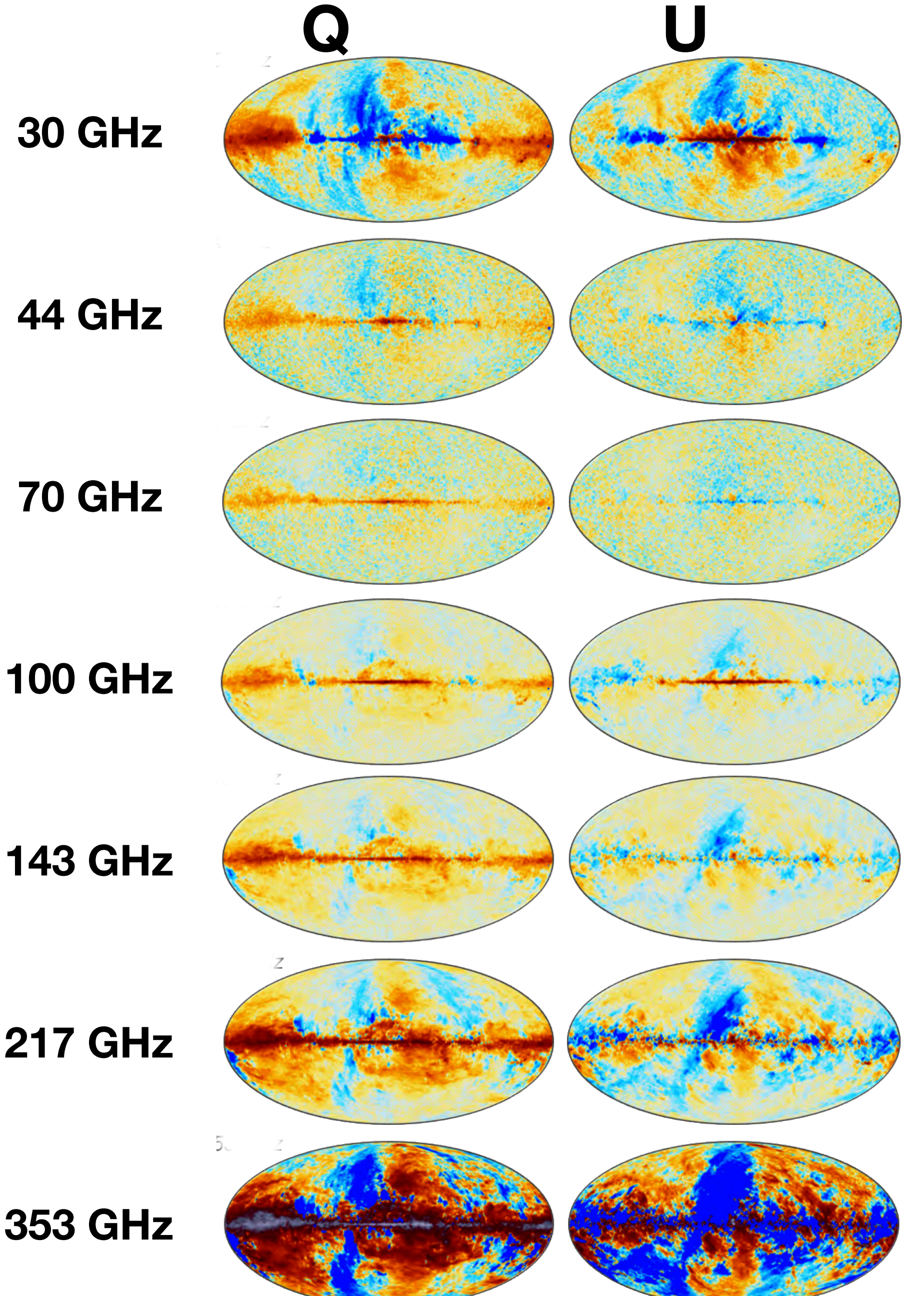
BK18
150GHz
Maps



BK18
220GHz
Maps

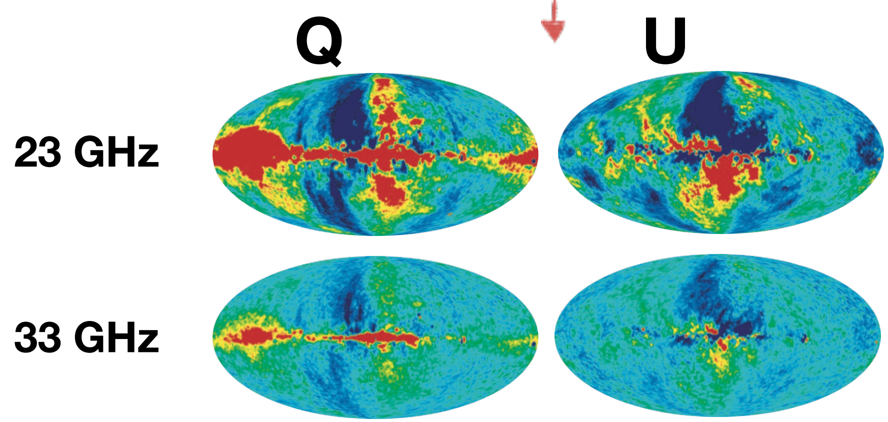


Add to the mix: Planck at 5 frequencies and WMAP at 2 frequencies



From arxiv 1502.01582

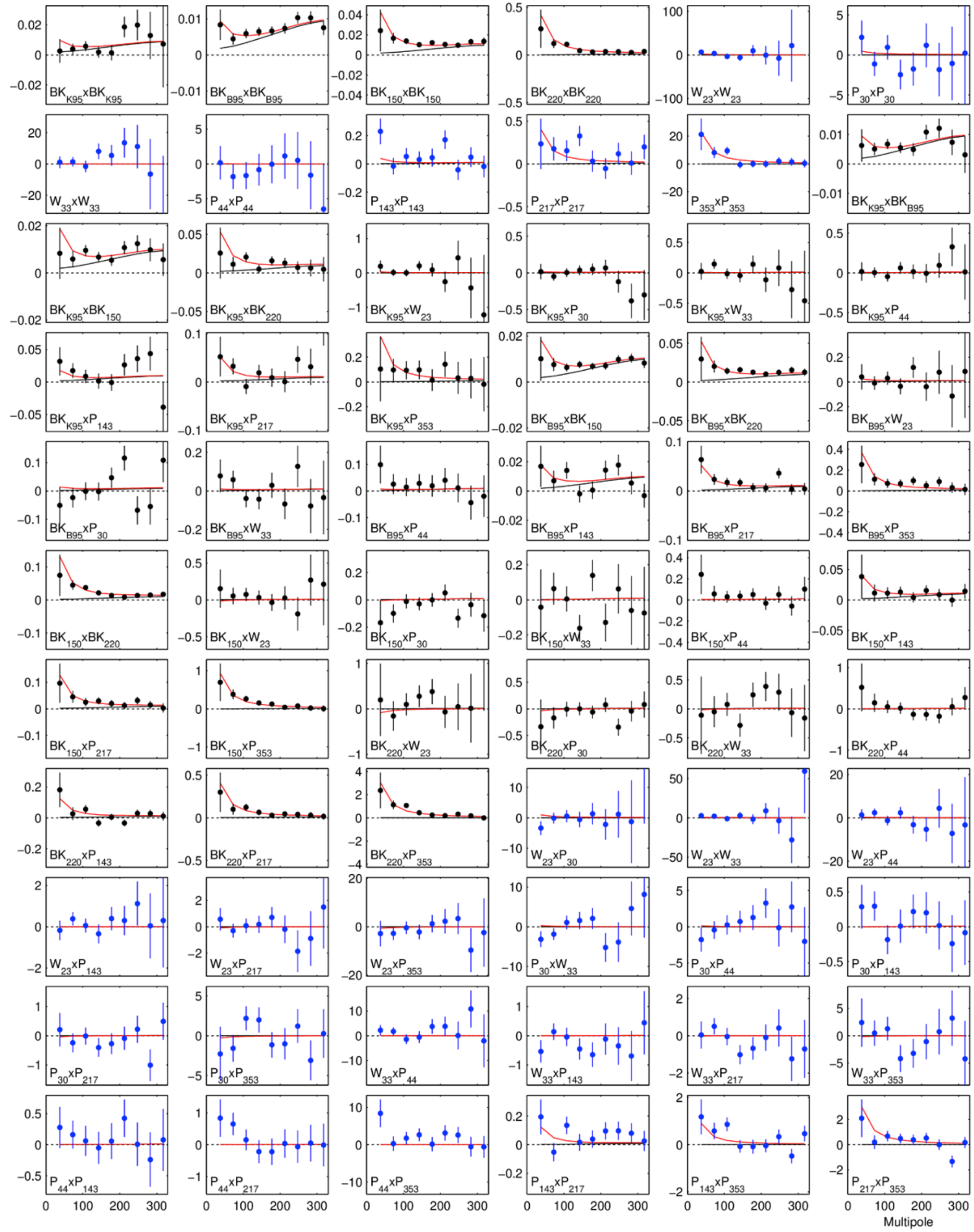
Polarized galactic **synchrotron** dominates at low frequencies



From arxiv 1212.5225

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

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



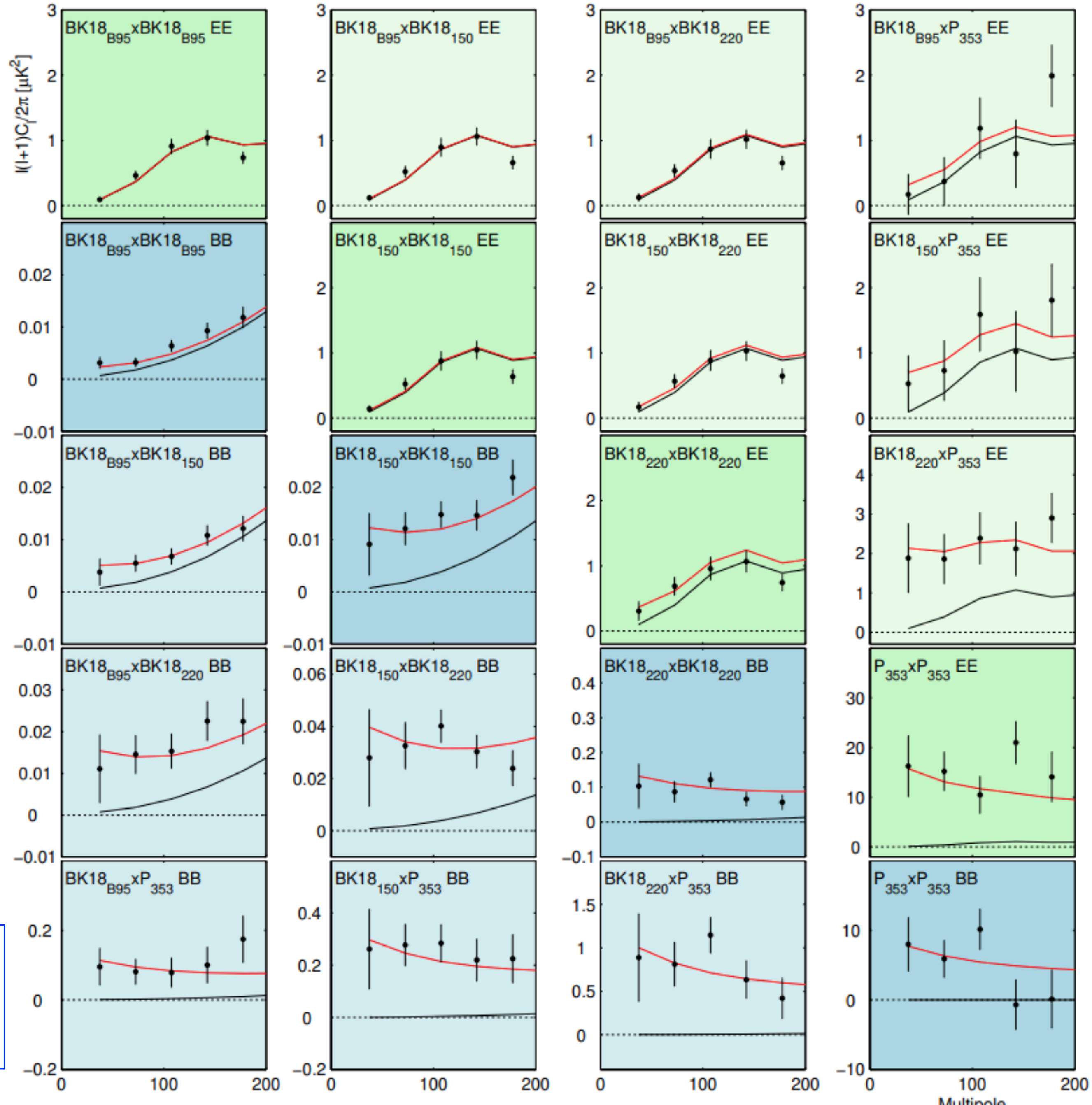
Multicomponent parametric likelihood analysis

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

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

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

Dust/Sync Spatial Power Laws?

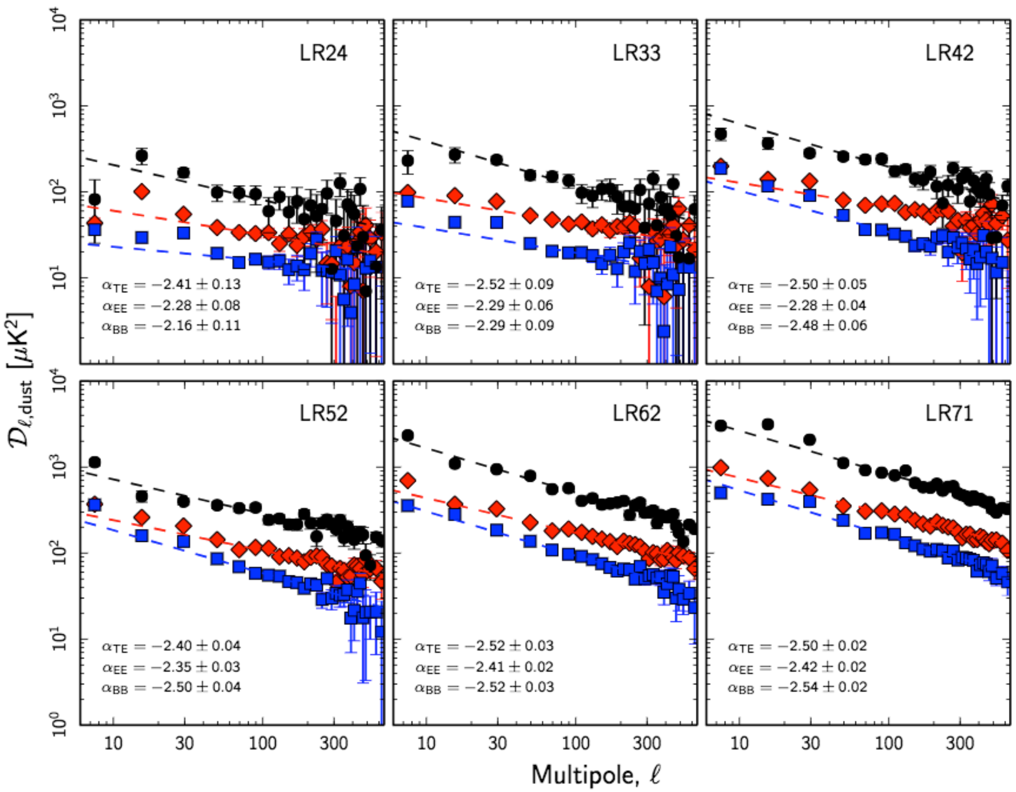


Fig 2 of arxiv/1801.04945 – Planck dust analysis

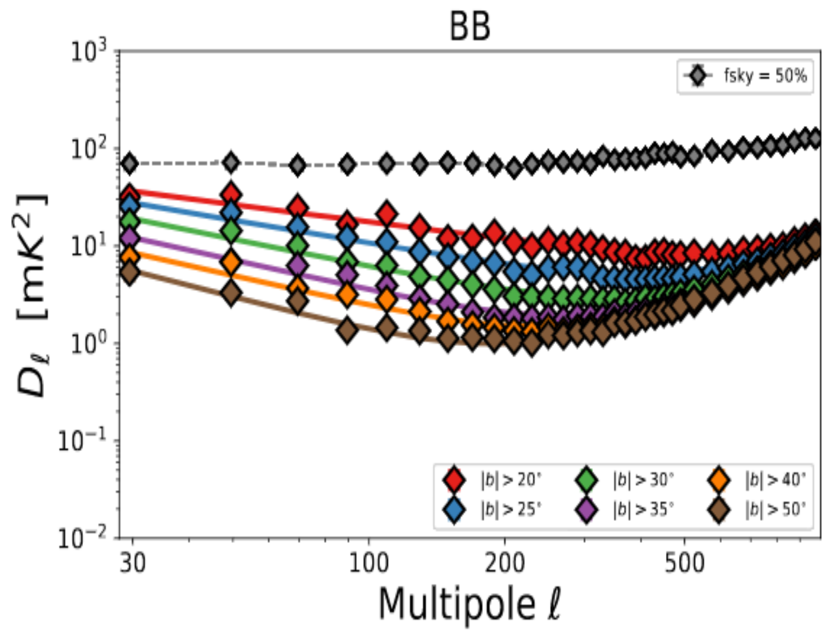
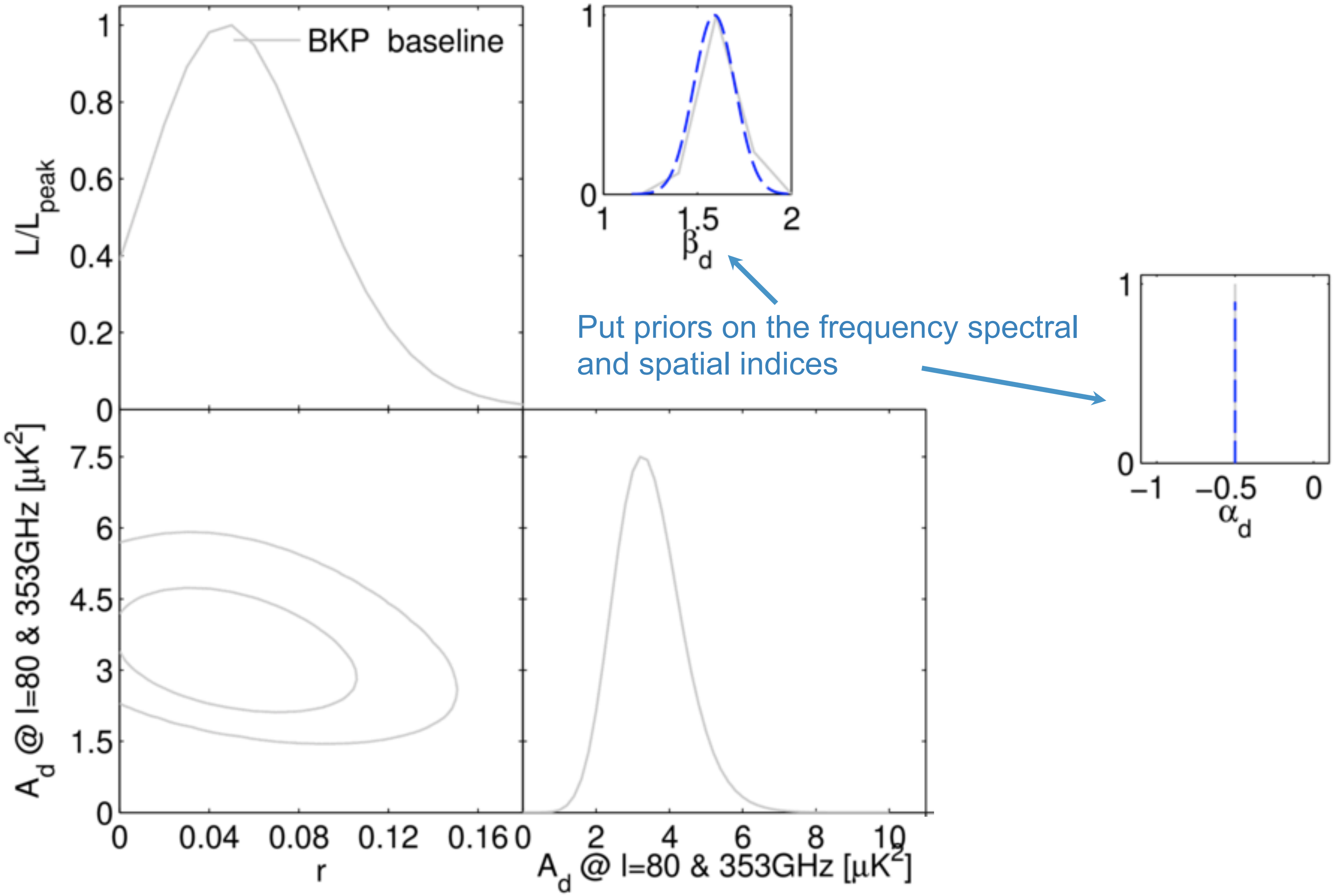
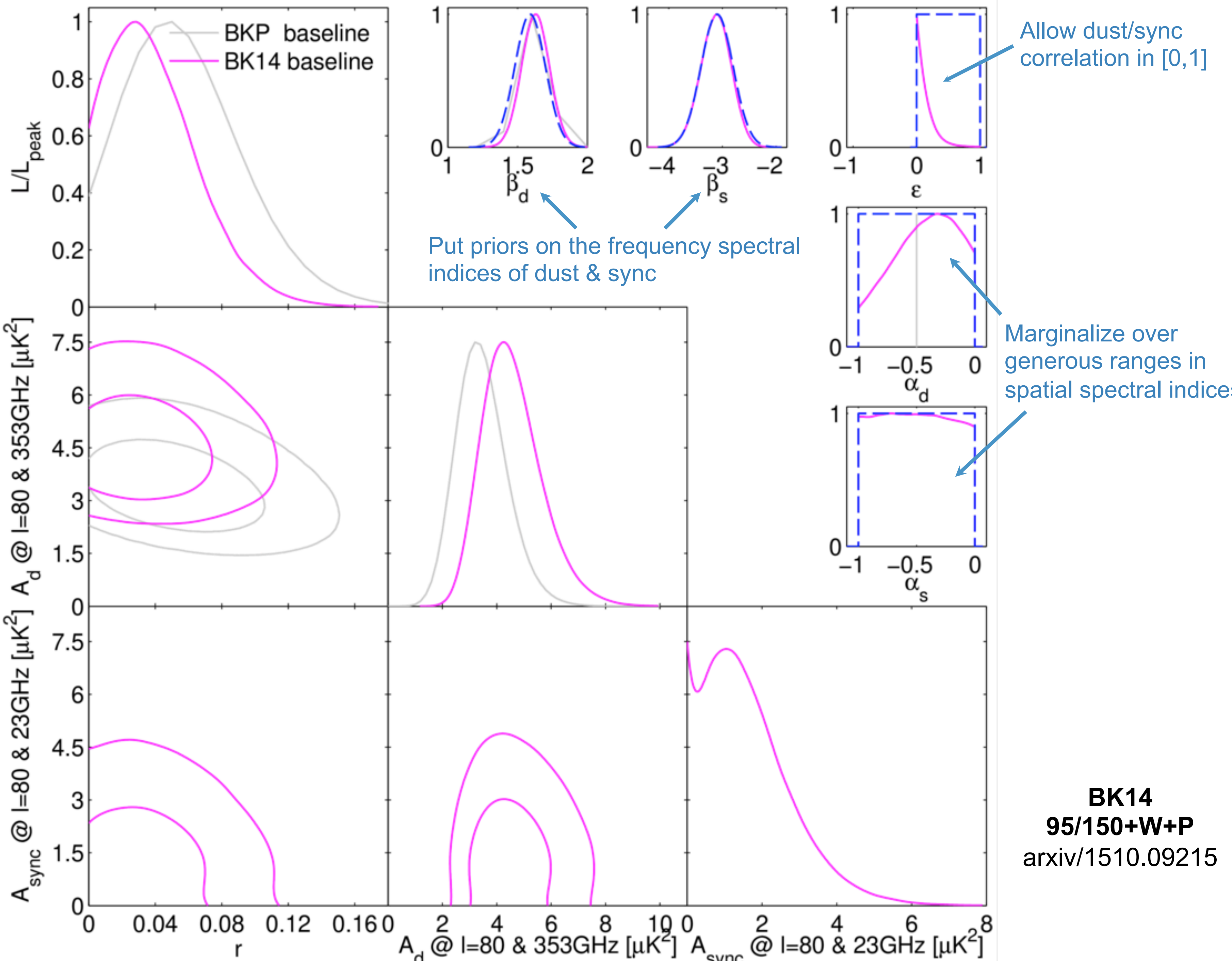


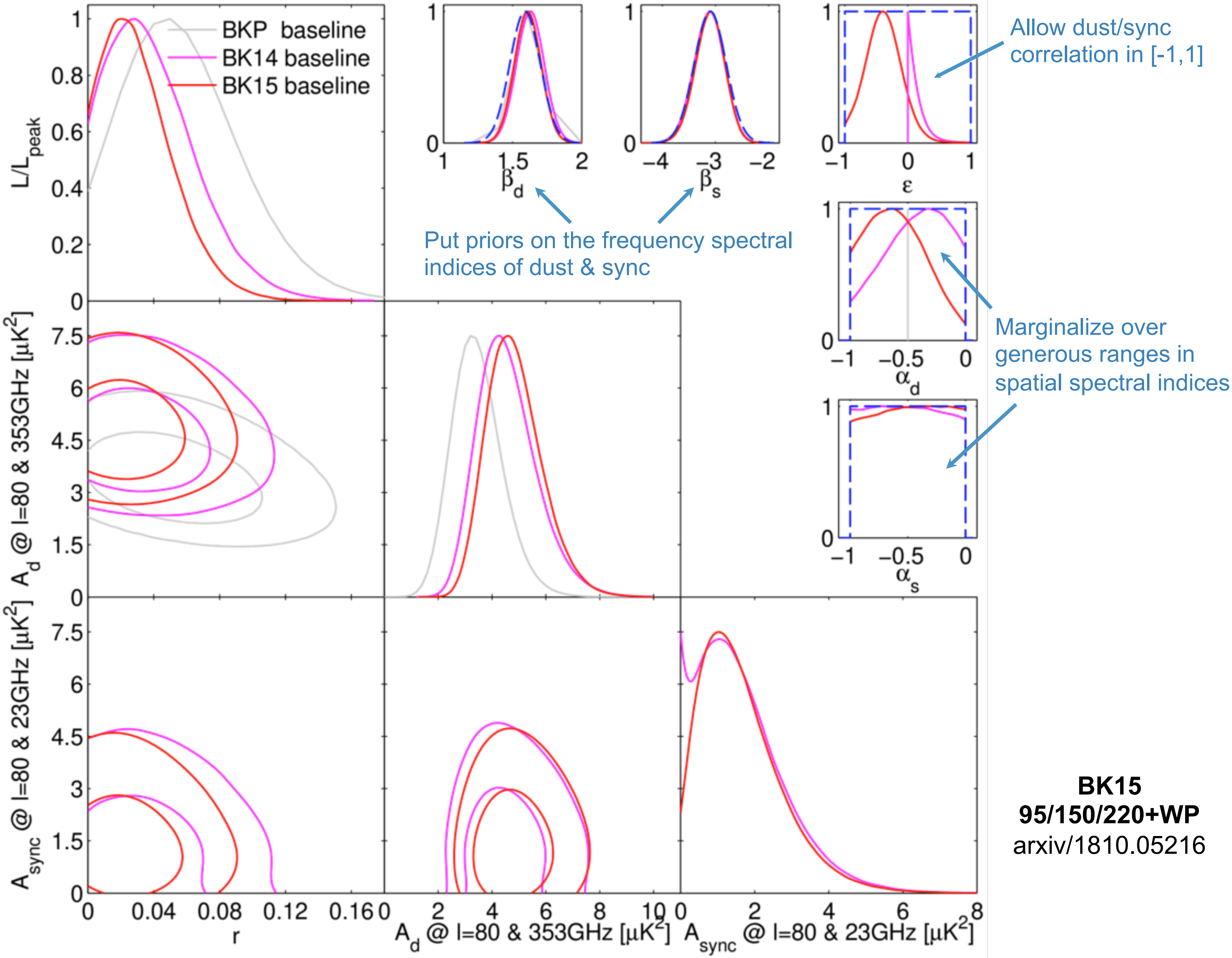
Fig 2 of arxiv/1802.01145. – S-PASS sync analysis

- 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



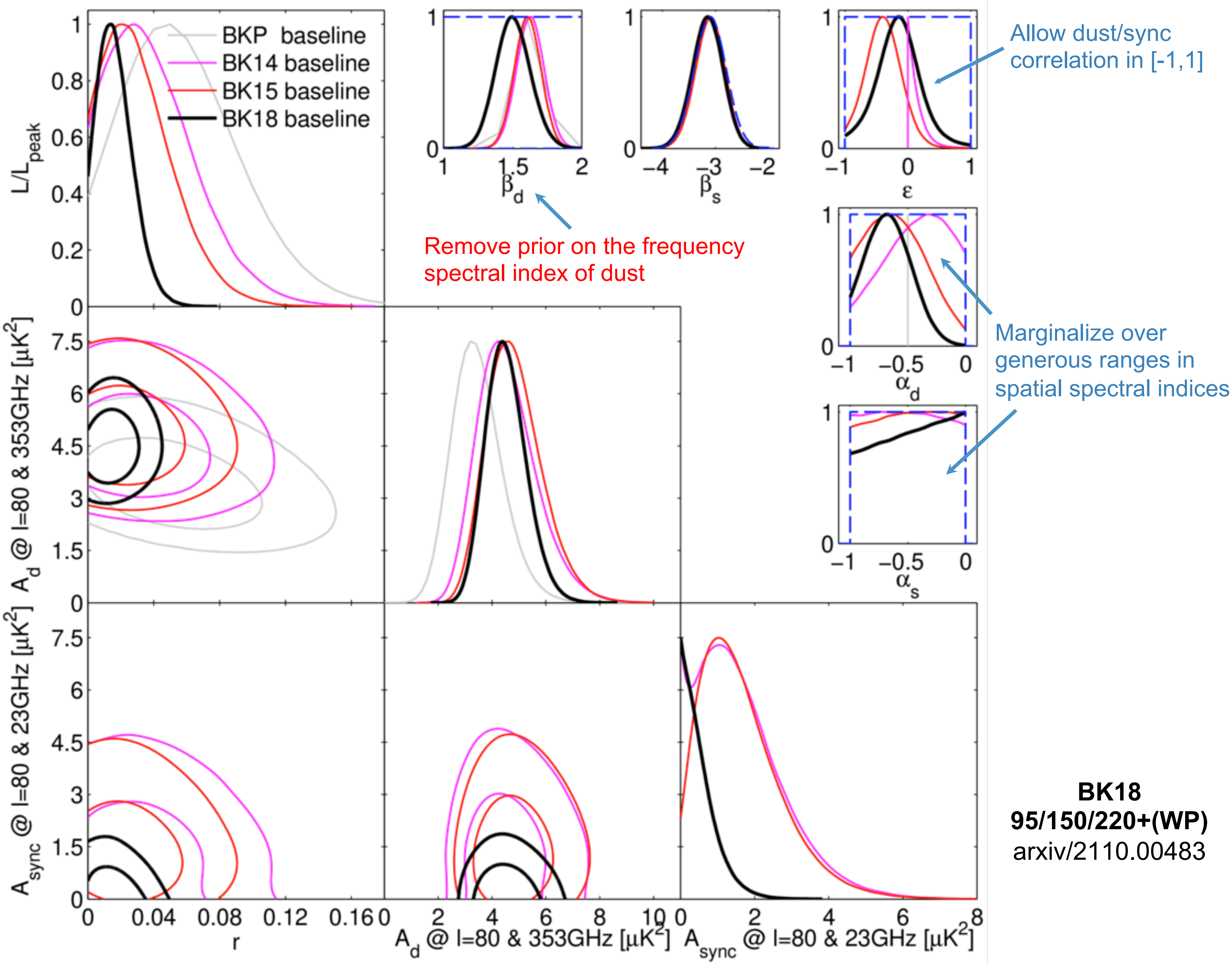
BKP
150GHz+P
arxiv/1502.00612


BKP baseline
BK14 baseline
L/L_peak
r
A_d @ l=80 & 353GHz [μK²]
A_sync @ l=80 & 23GHz [μK²]
β_d
β_s
ε
α_d
α_s
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
95/150+W+P
arxiv/1510.09215

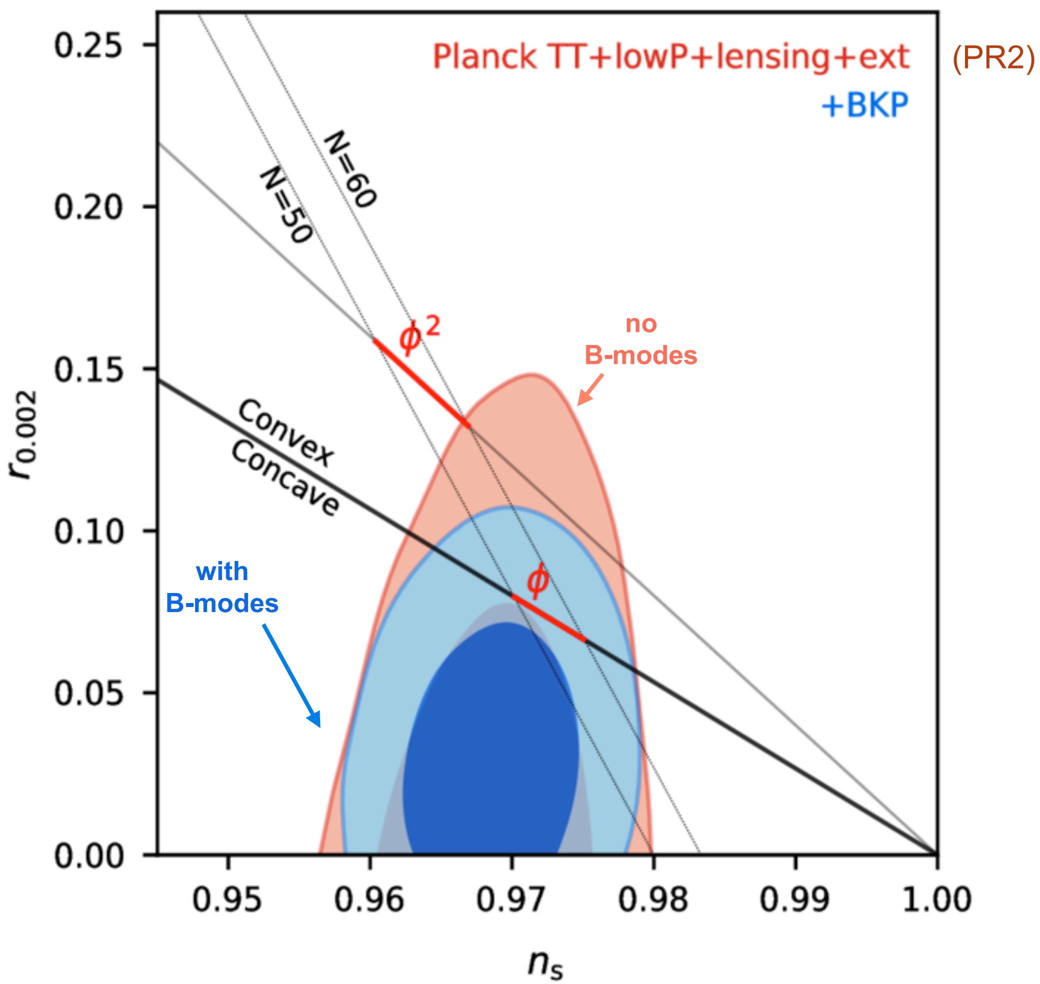


BK15 95/150/220+WP

arxiv/1810.05216



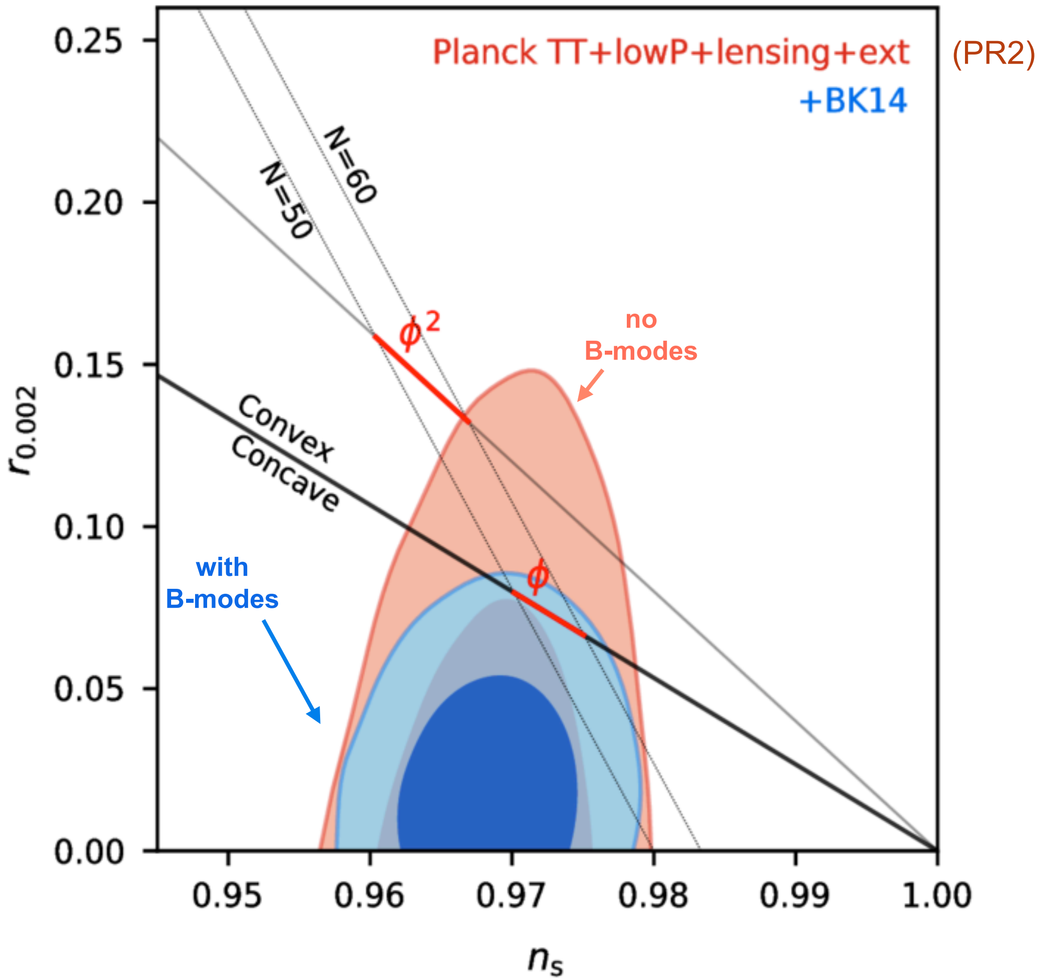
BK18
95/150/220+(WP)
arxiv/2110.00483



$r_{.05} < 0.09$

BKP

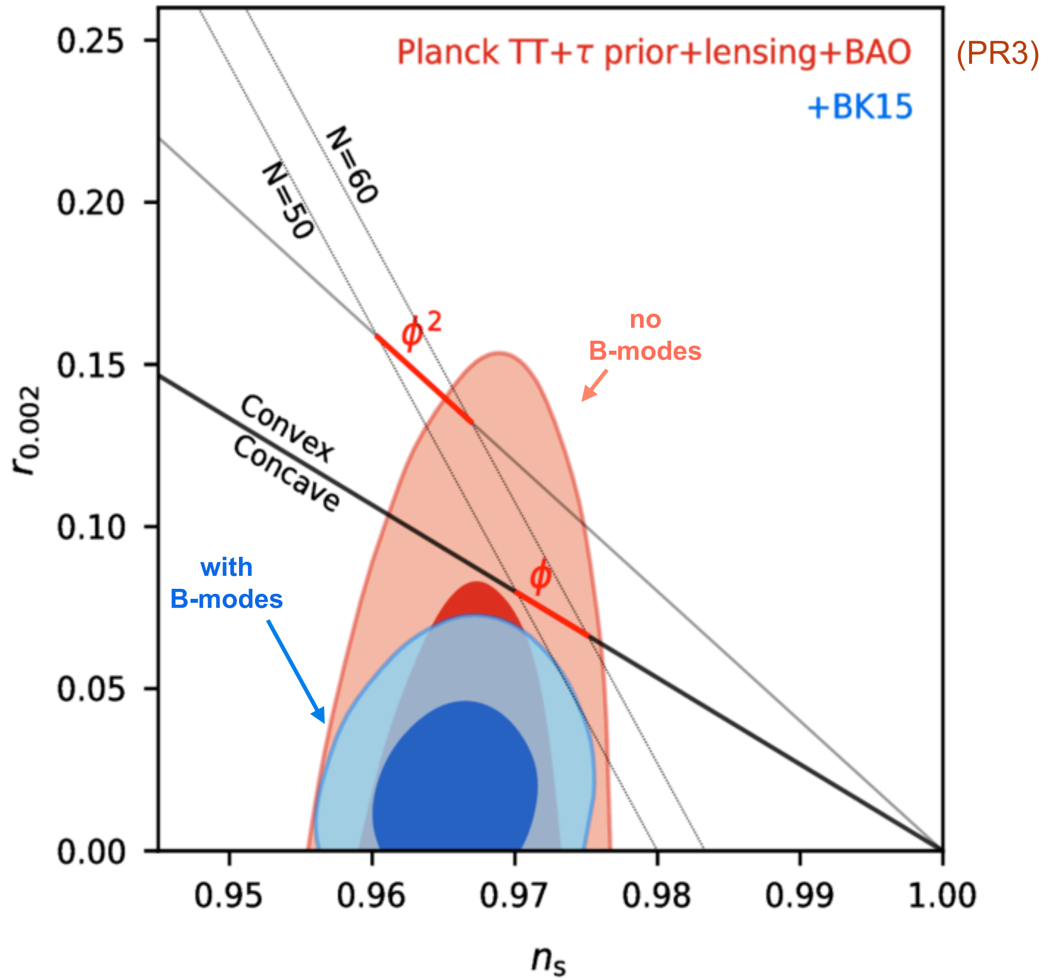
arxiv/1502.00612



BK14

arxiv/1510.09217

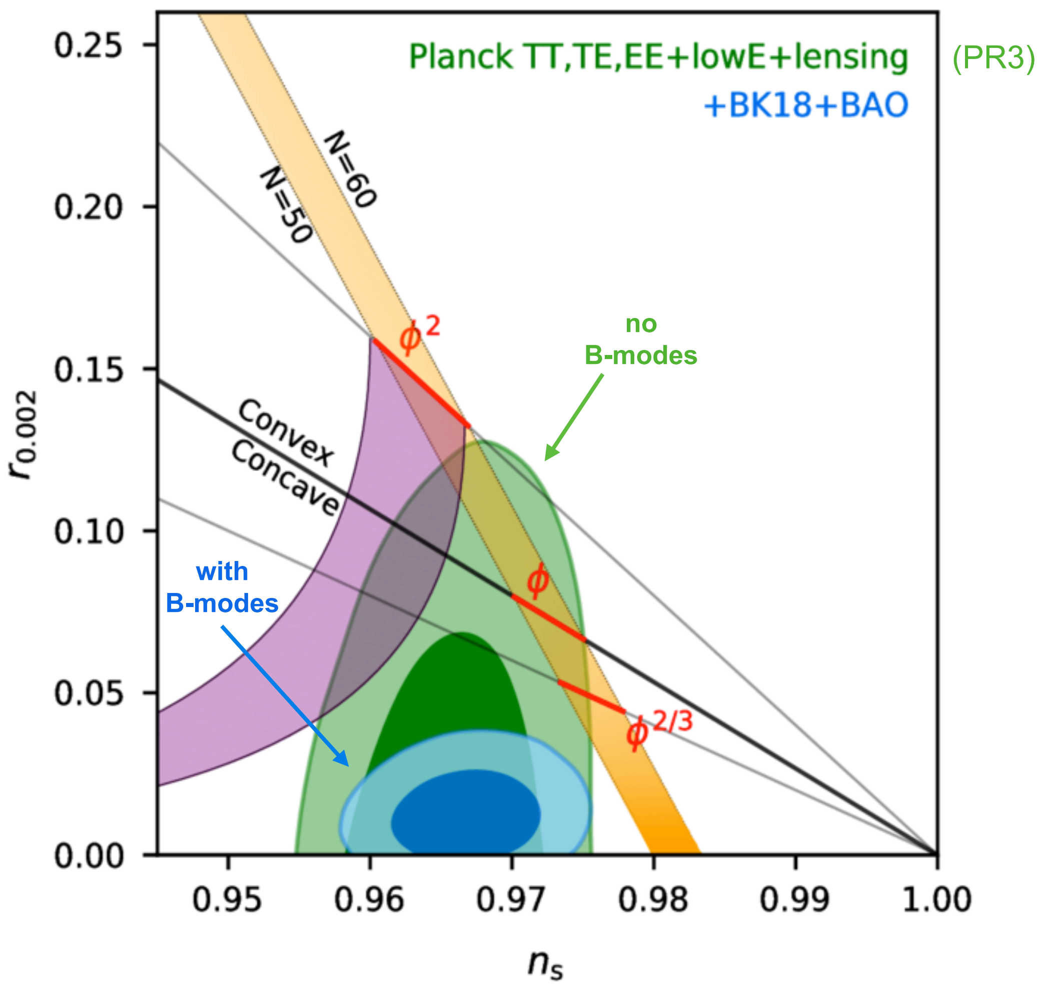
$r_{.05} < 0.07$



$r_{.05} < 0.06$

BK15

arxiv/1810.05216

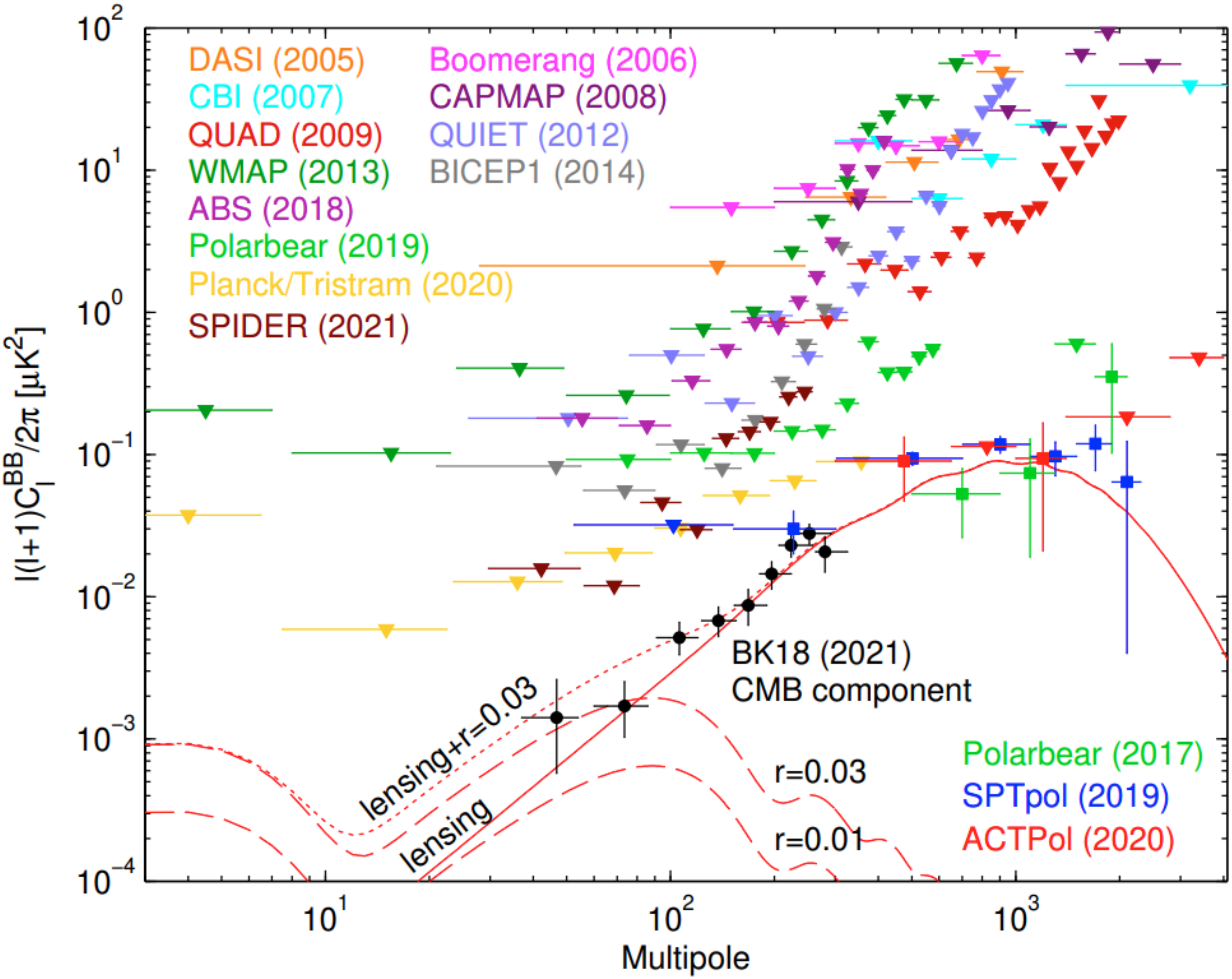


$r_{.05} < 0.035$

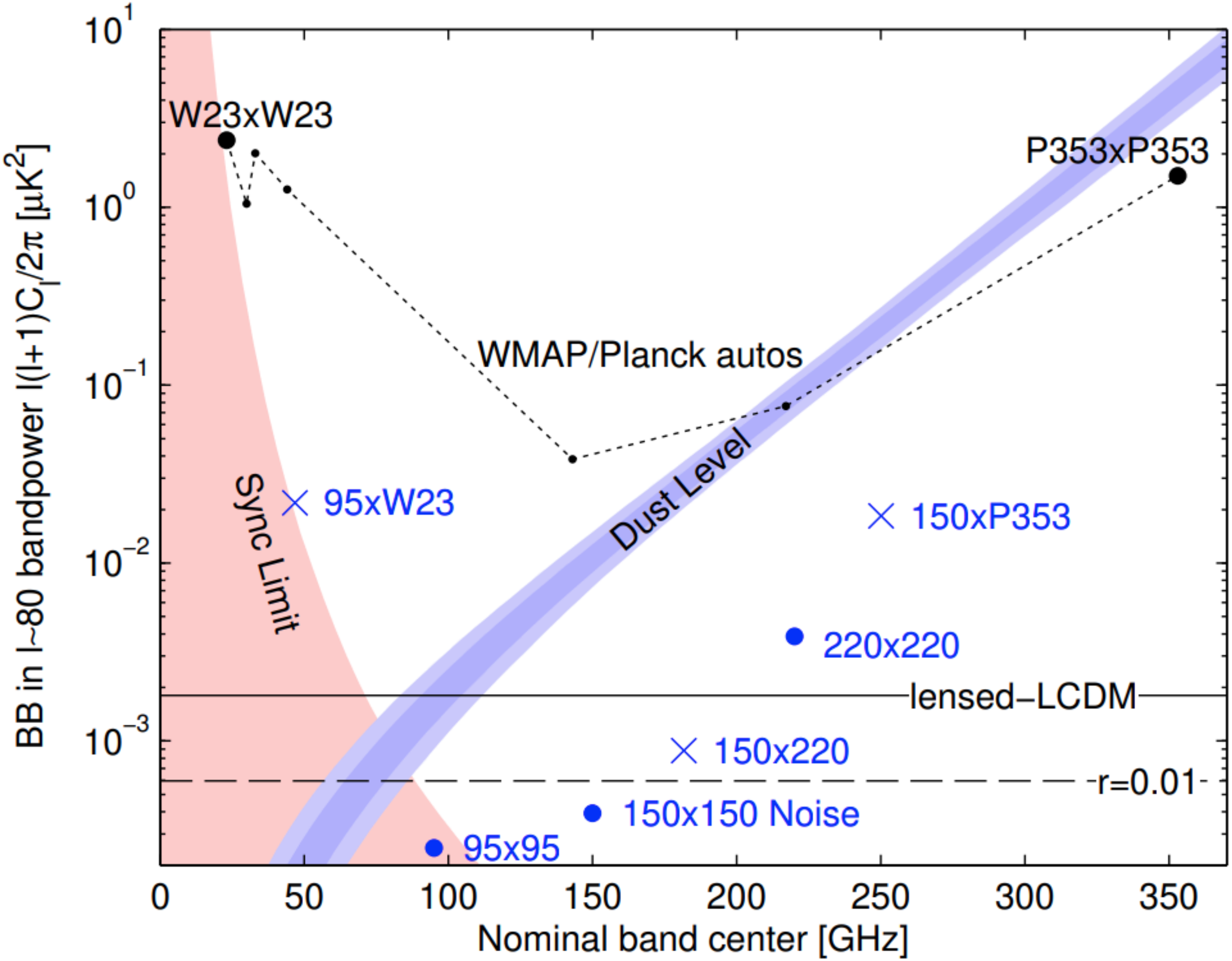
BK18

arxiv/2110.00483

Per bandpower CMB component extraction



BK18 ell=80 bandpower noise/signal



What limits BK18?

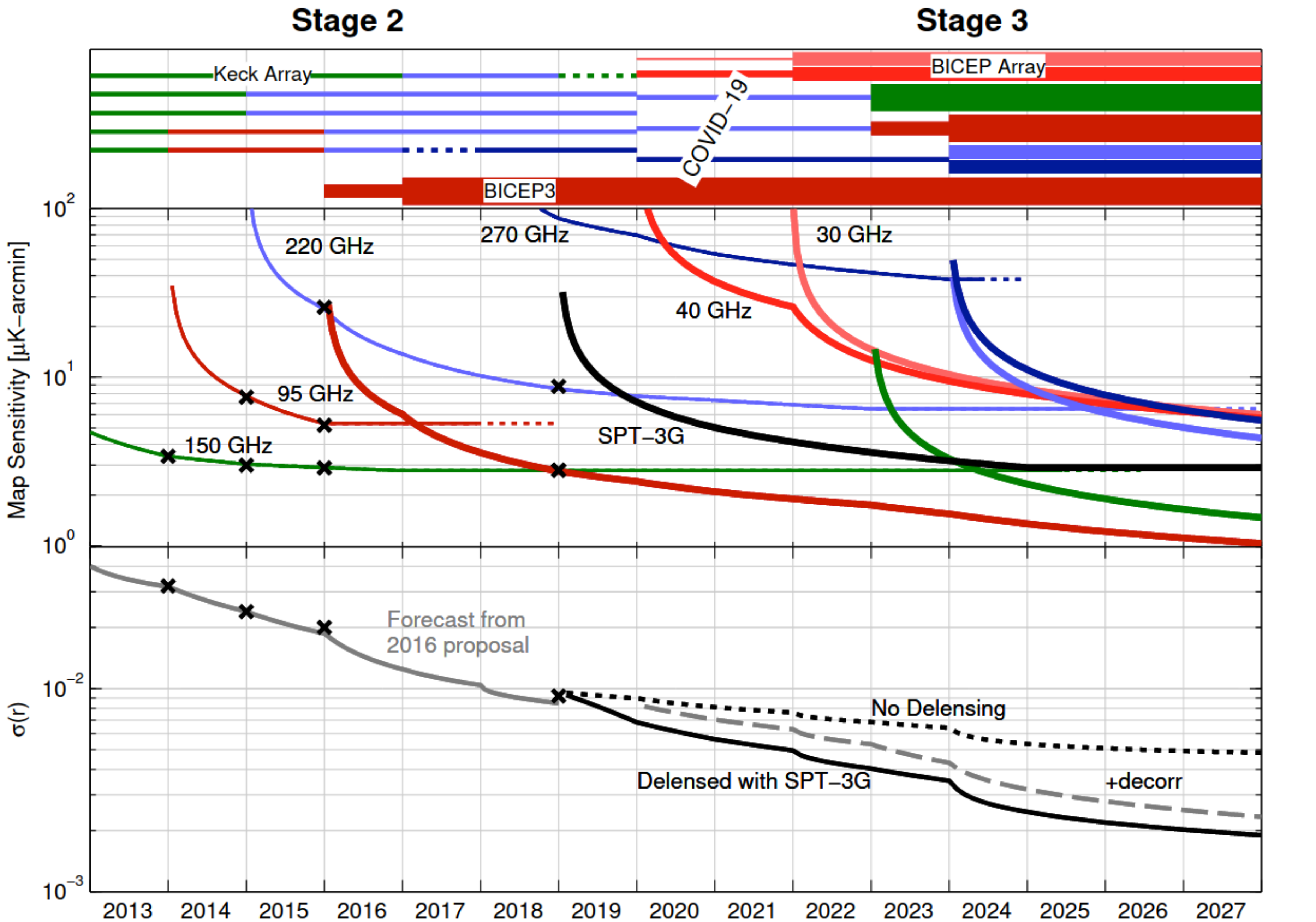
- BK18 mainline simulations with dust and lensing give σ(*r*)=0.009
- Running without foreground parameters on simulations where the dust amplitude is set to zero gives σ(*r*)=0.007

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.

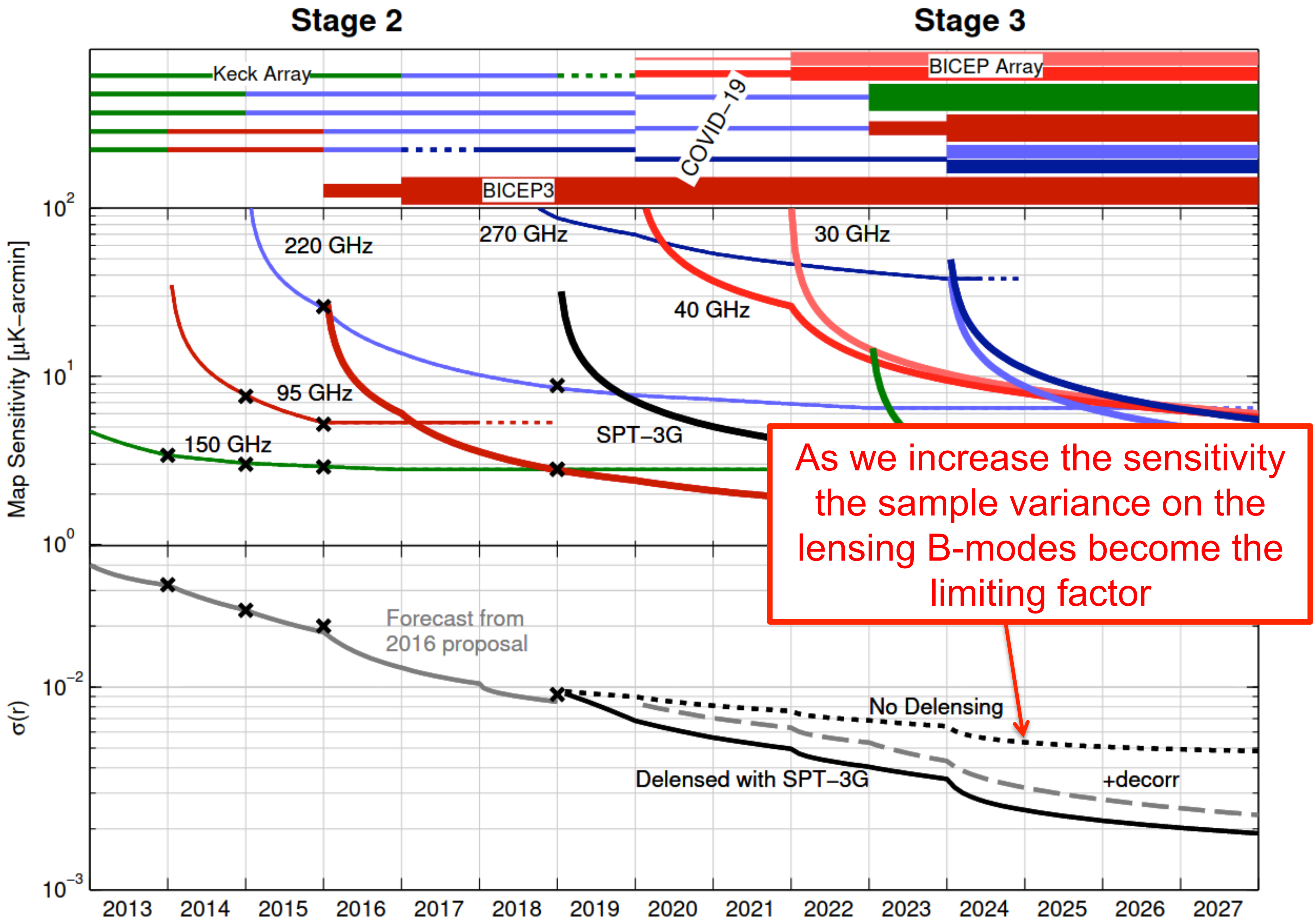
- Running on simulations which contain no lensing gives σ(*r*)=0.004

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

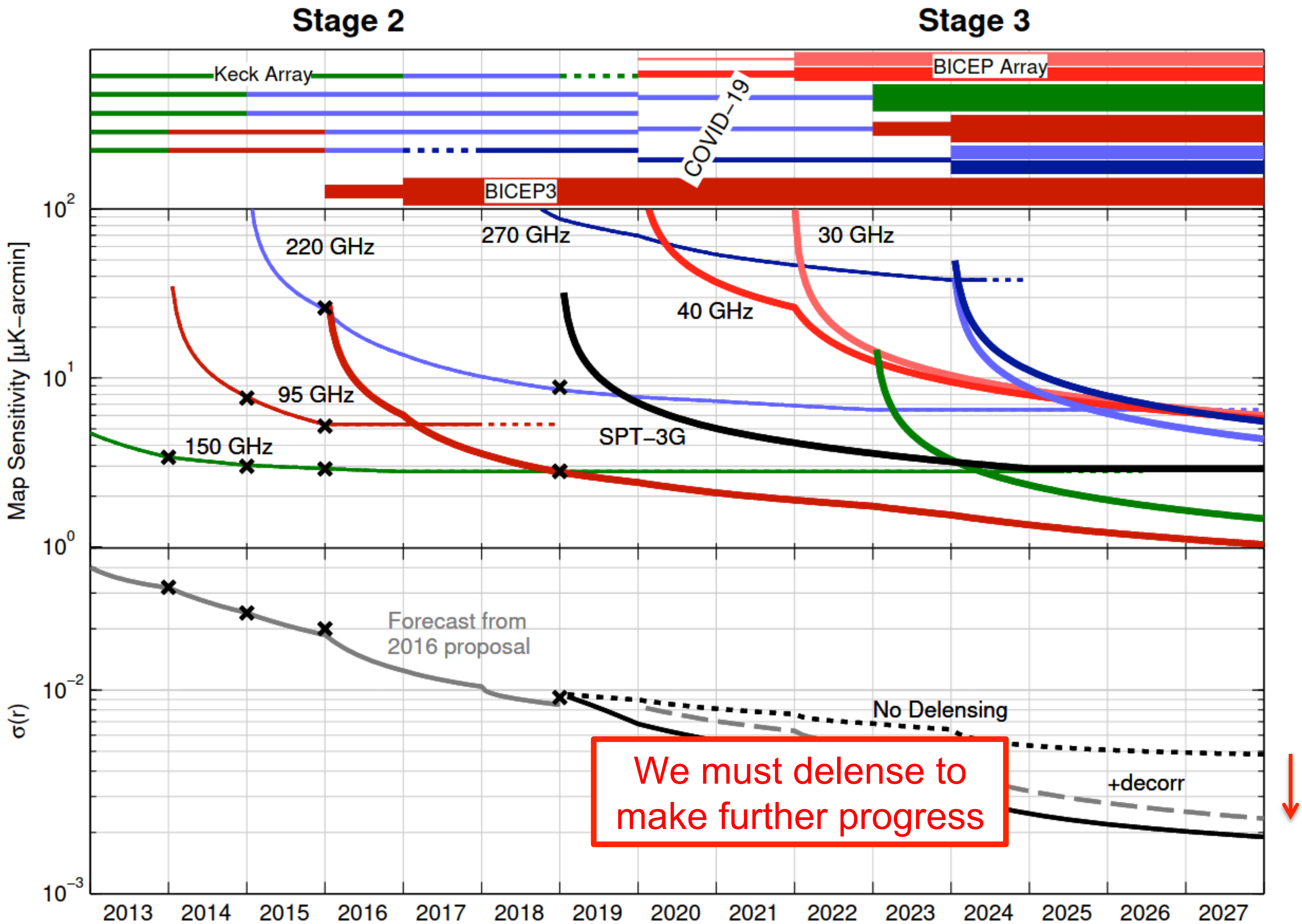
- Running without foreground parameters on simulations which have neither dust or lensing gives σ(*r*)=0.002



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

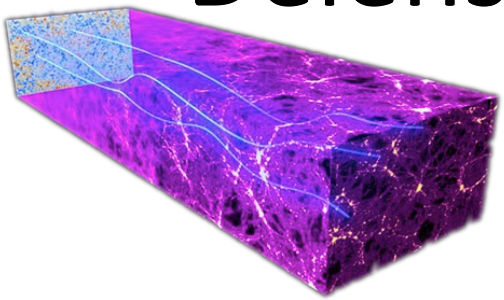


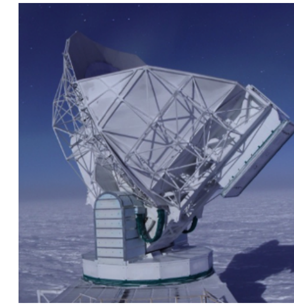
Stage 2
Stage 3
Keck Array
BICEP Array
COVID–19
BICEP3
220 GHz
270 GHz
30 GHz
40 GHz
95 GHz
150 GHz
SPT–3G
Map Sensitivity [μK–arcmin]
As we increase the sensitivity the sample variance on the lensing B-modes become the limiting factor
Forecast from 2016 proposal
No Delensing
Delensed with SPT–3G
+decorr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



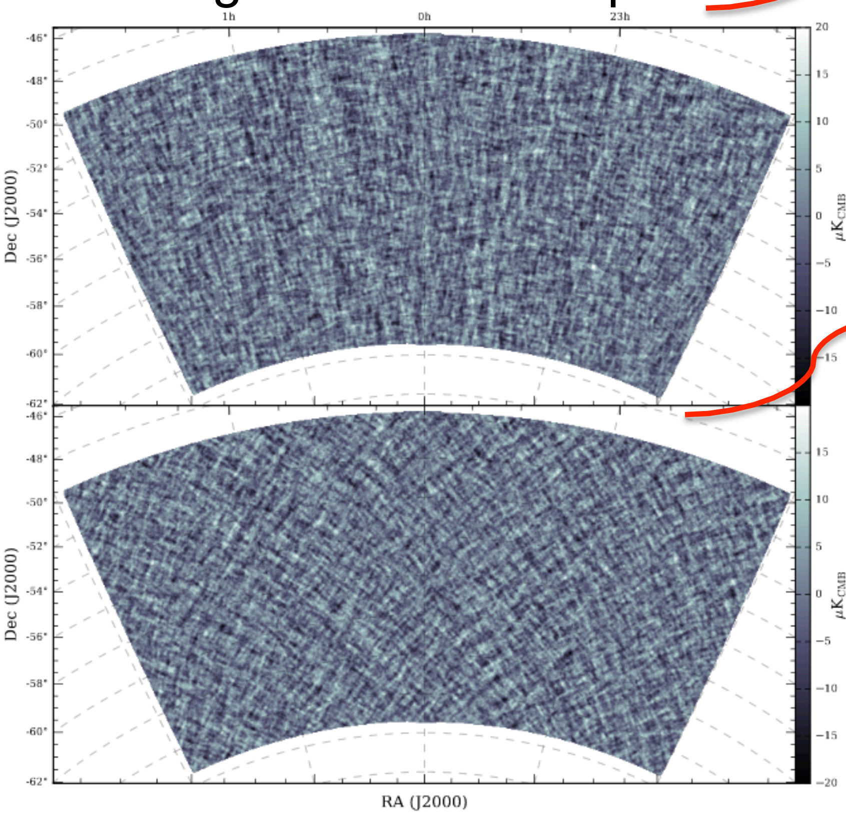
Stage 2
Stage 3
Keck Array
BICEP Array
COVID–19
BICEP3
220 GHz
270 GHz
30 GHz
40 GHz
95 GHz
150 GHz
SPT–3G
Map Sensitivity [μK–arcmin]
10^2
10^1
10^0
Forecast from
2016 proposal
No Delensing
+decorr
We must delense to
make further progress
σ(r)
10^{-2}
10^{-3}
2013
2014
2015
2016
2017
2018
2019
2020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

Delensing with SPT-3G data

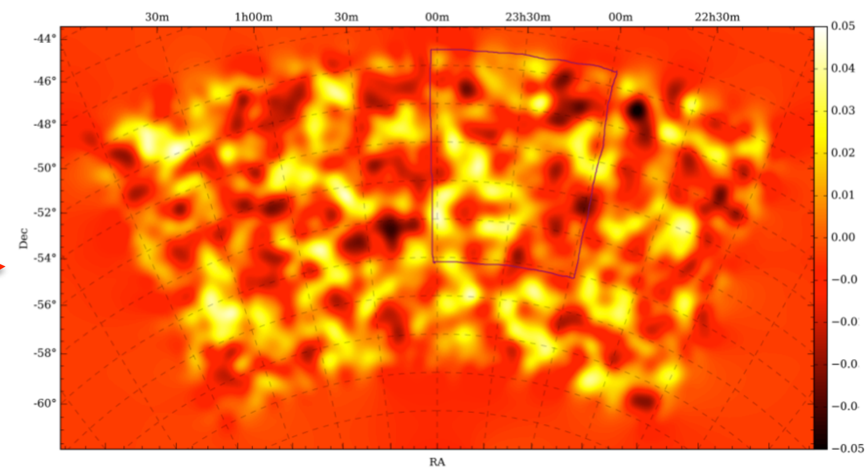




High resolution maps



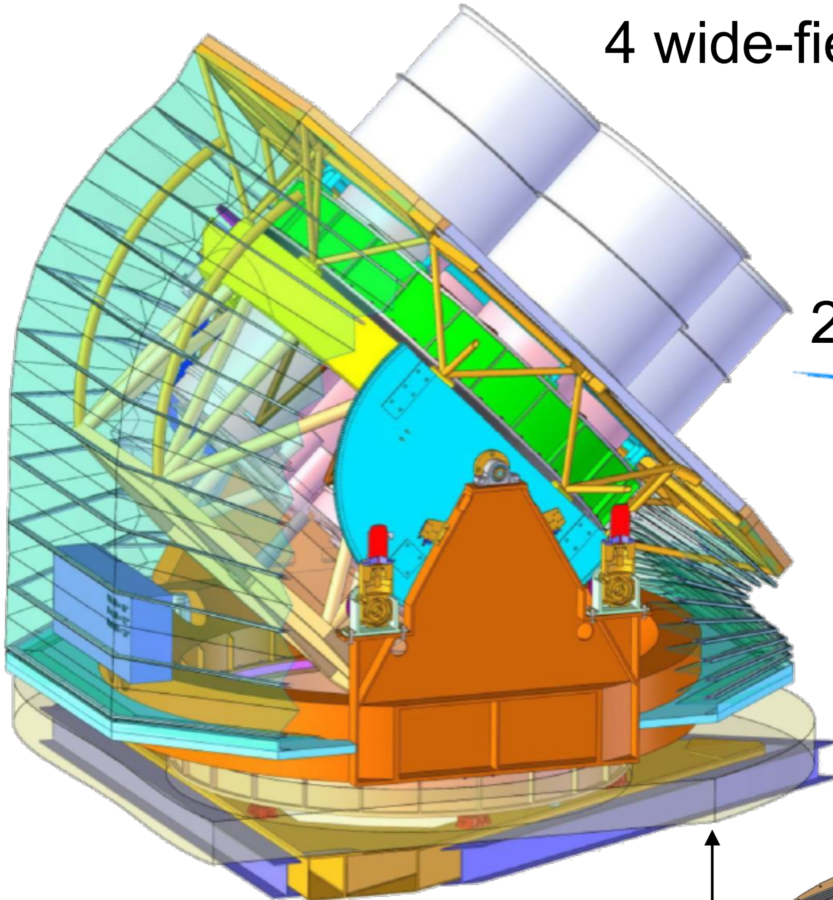
Can be used to reconstruct the lensing deflection map…



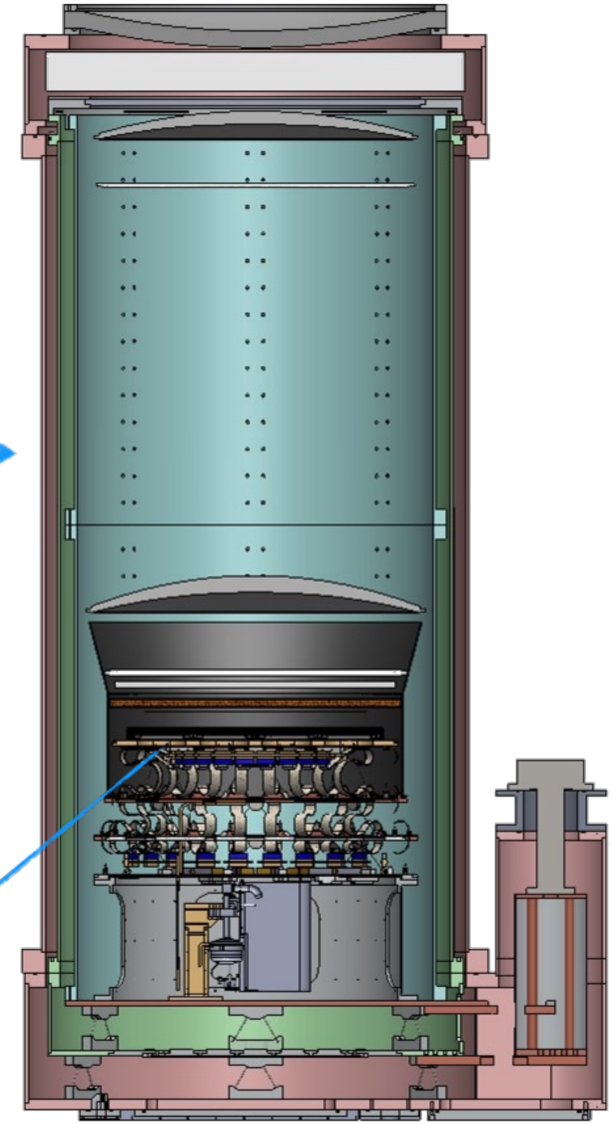
…which can then be used to calculate the lensing signal enabling a deeper search for inflationary gravitational waves

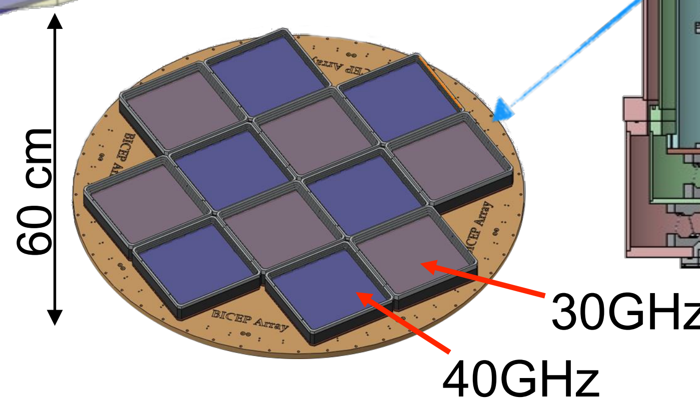
Demo delensing analysis in arXiv: 2011.08163

Latest Generation Experiment “BICEP Array"

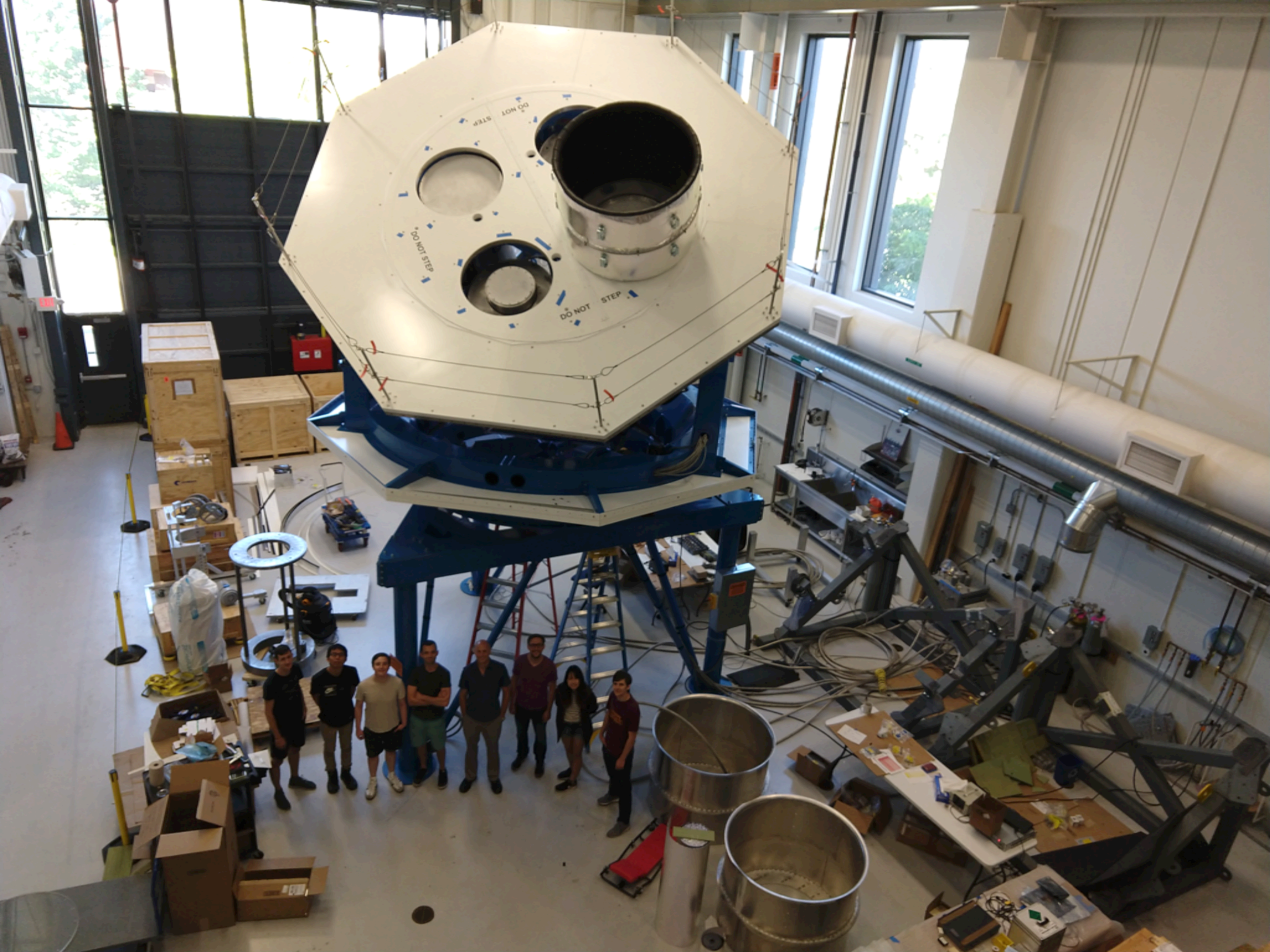


4 wide-field receivers
30/40 GHz
95 GHz
150 GHz
220/270 GHz





Focal plane layout


DO NOT STEP
DO NOT
STEP
DO NOT
STEP
EXIT

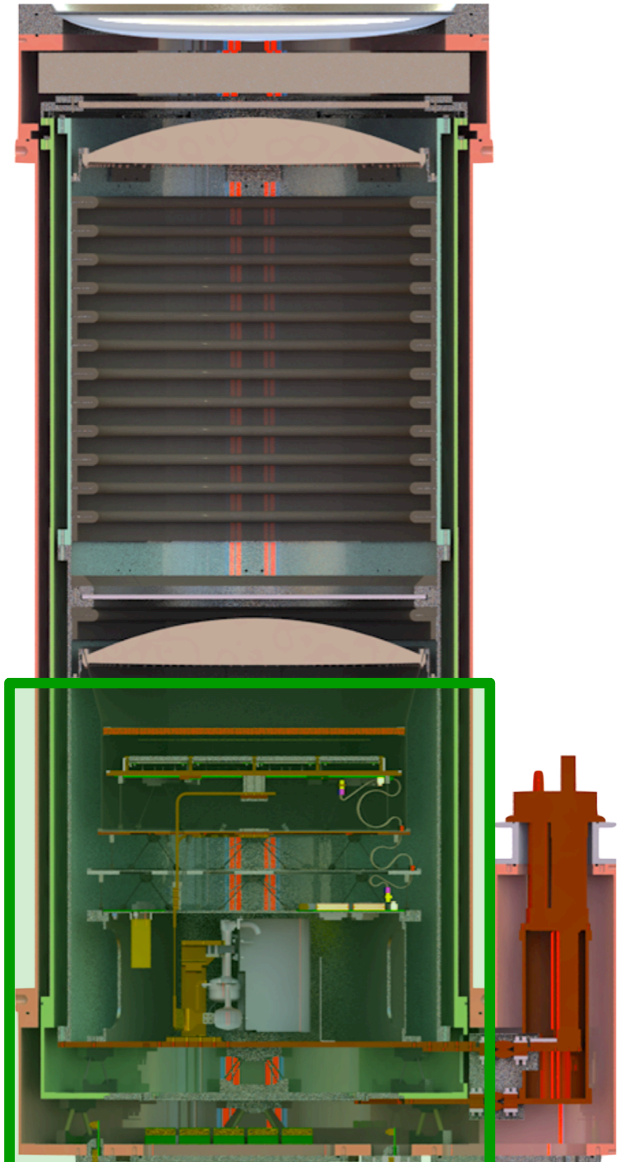
BICEP Array 2019-20 initial deployment

Three-month window during the Antarctic summer to perform:
- Keck Array demolition
- BA mount installation
- BA1 receiver assembly
- Full system integration

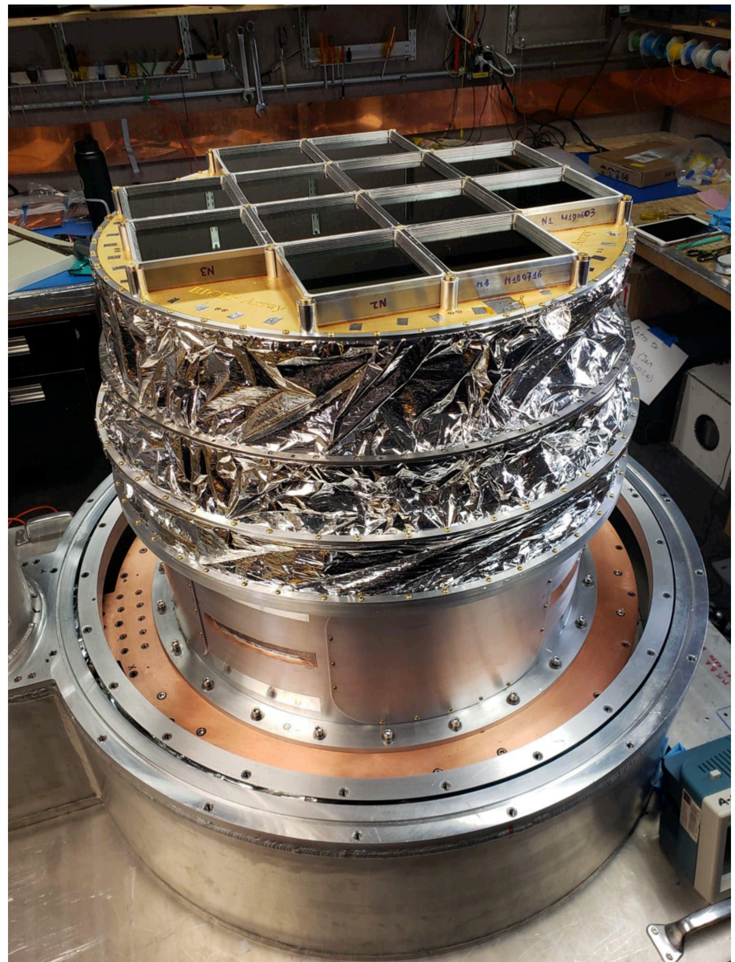
60,000 lbs of cargo, equivalent to 3 dedicated LC-130 Hercules flights to the South Pole.

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

2020 BA1 (30/40GHz) Instrument Operating



Camera insert

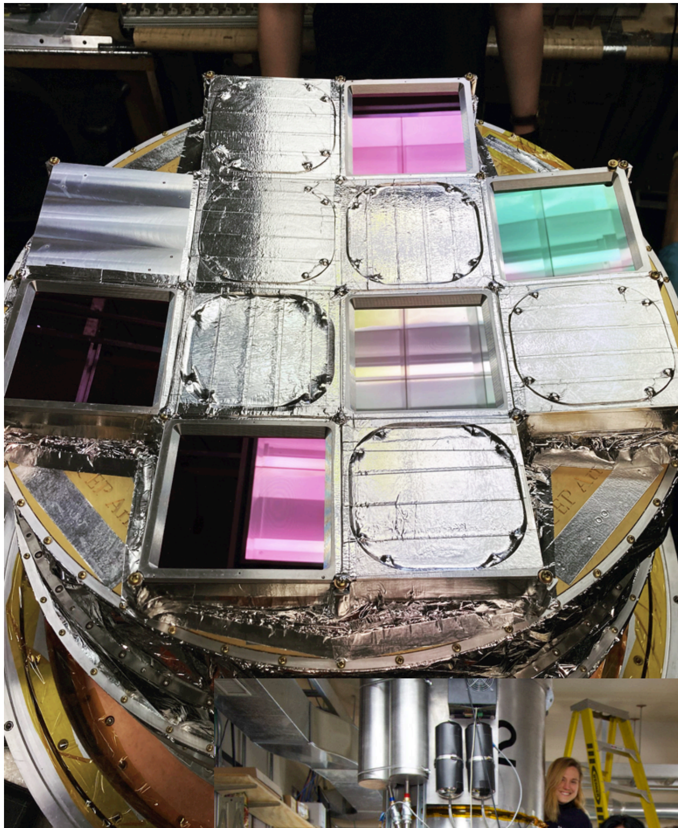


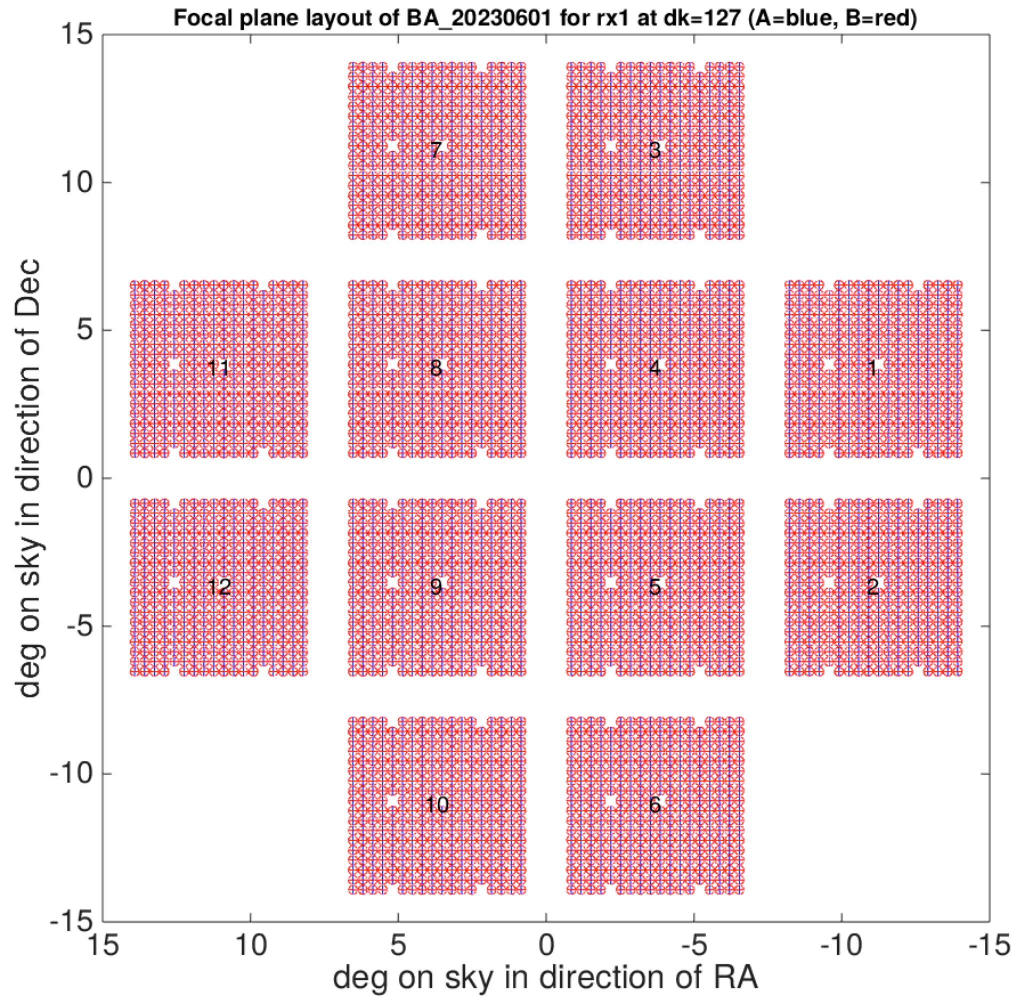
192/300 TES detectors at 30/40 GHz.

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

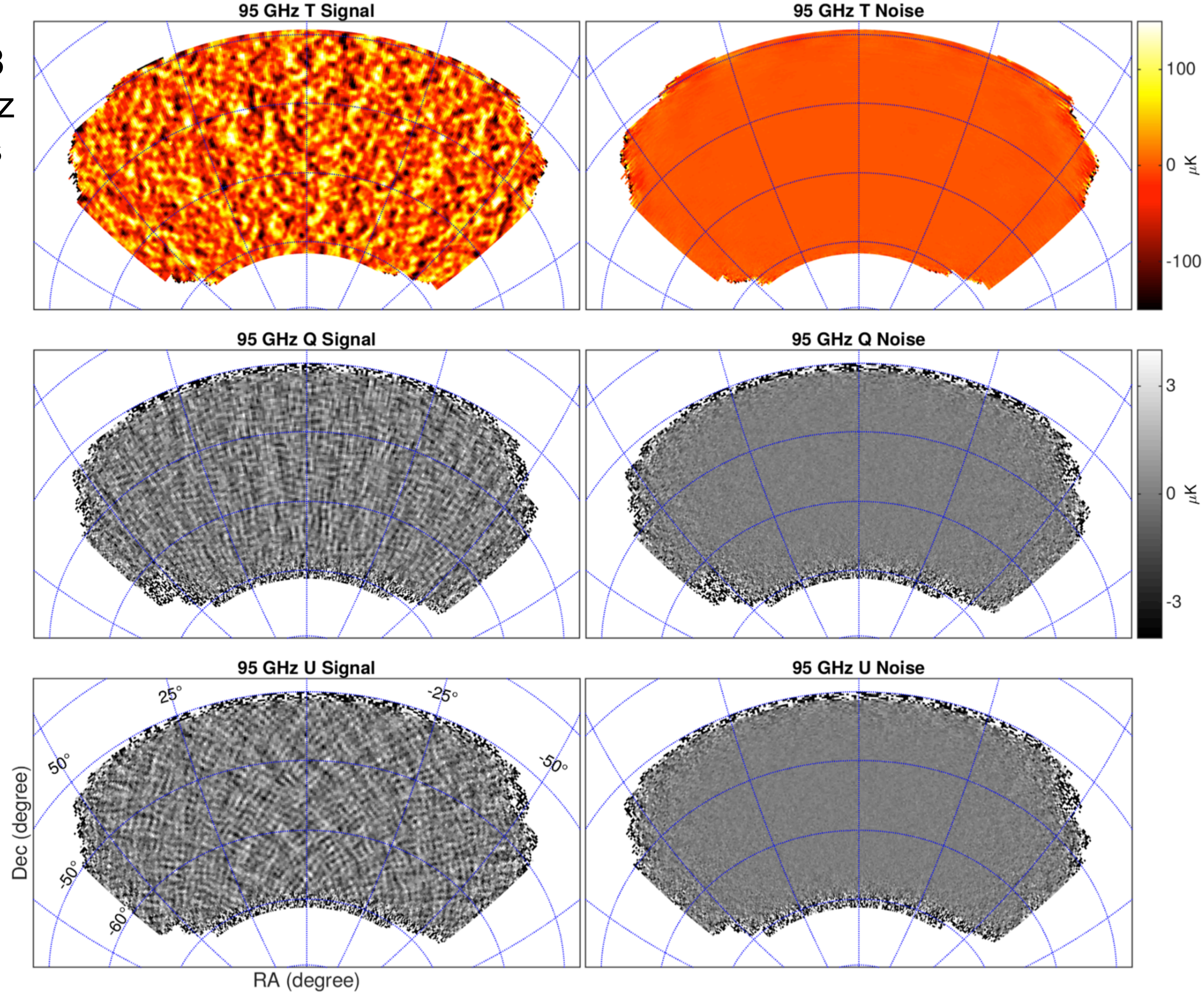
Time-Domain multiplexed readout.

2023 BA2 (150GHz) Instrument Operating



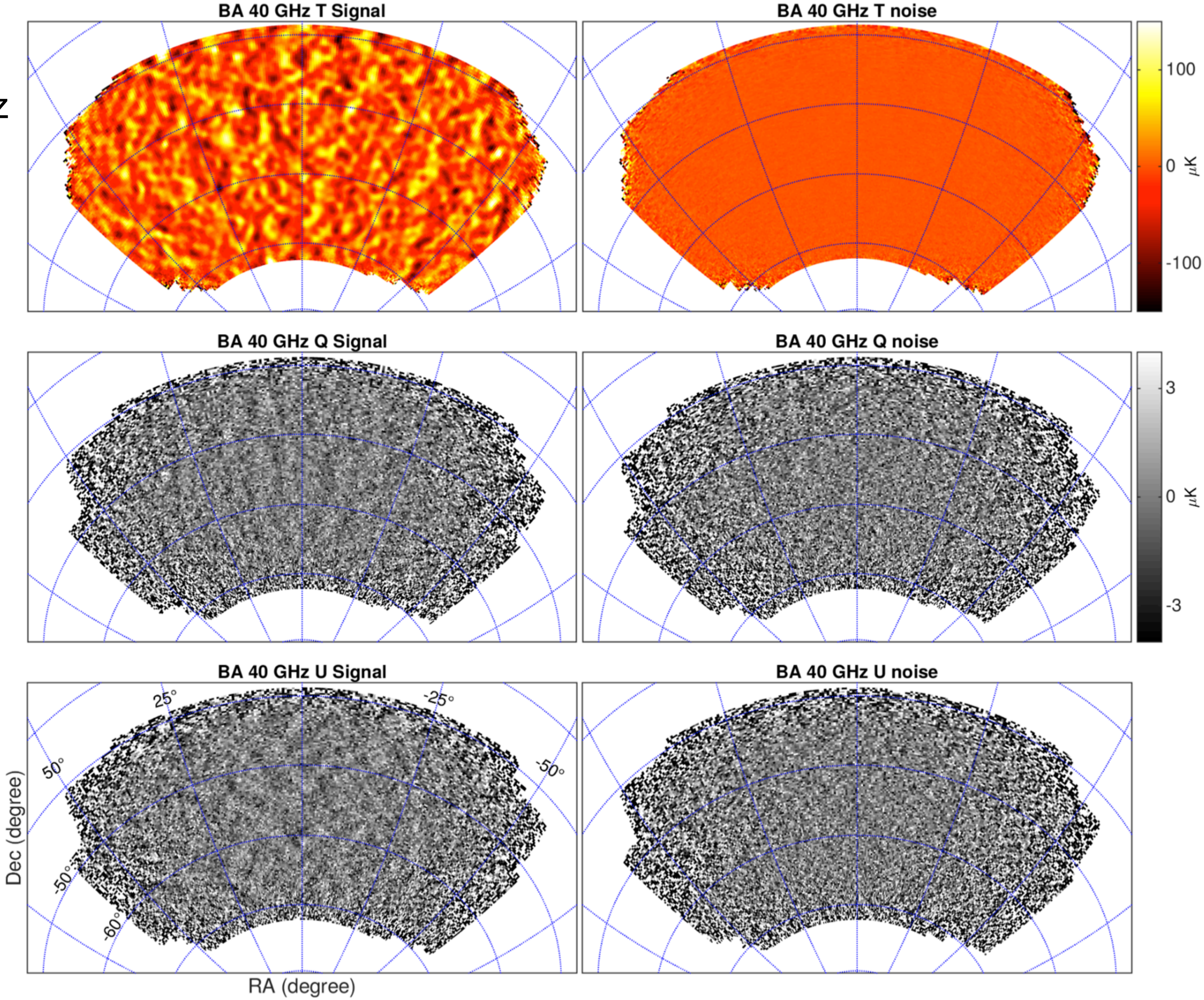


BK18
95GHz
Maps



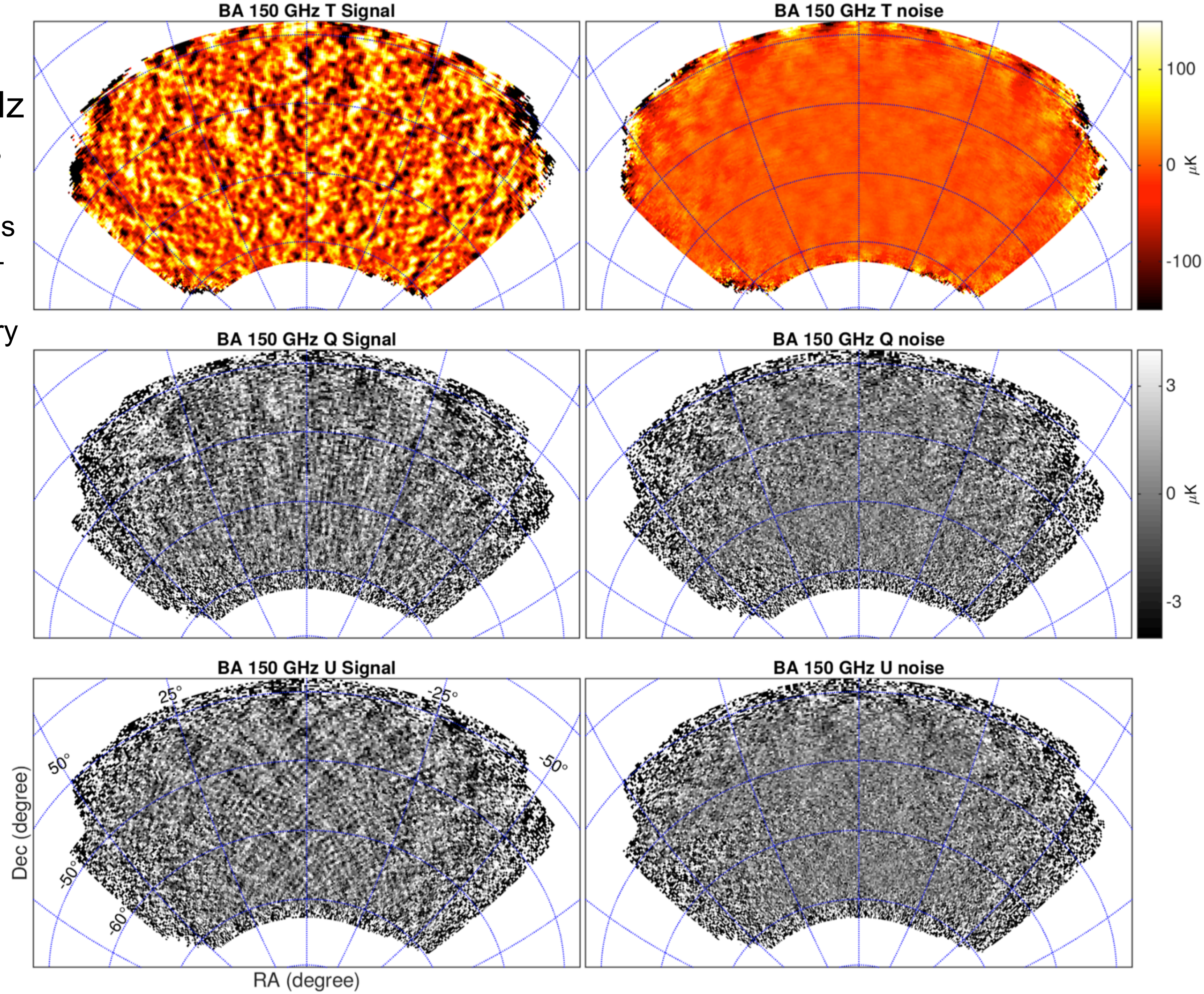
BA1
40GHz
Maps

First 3 years of data

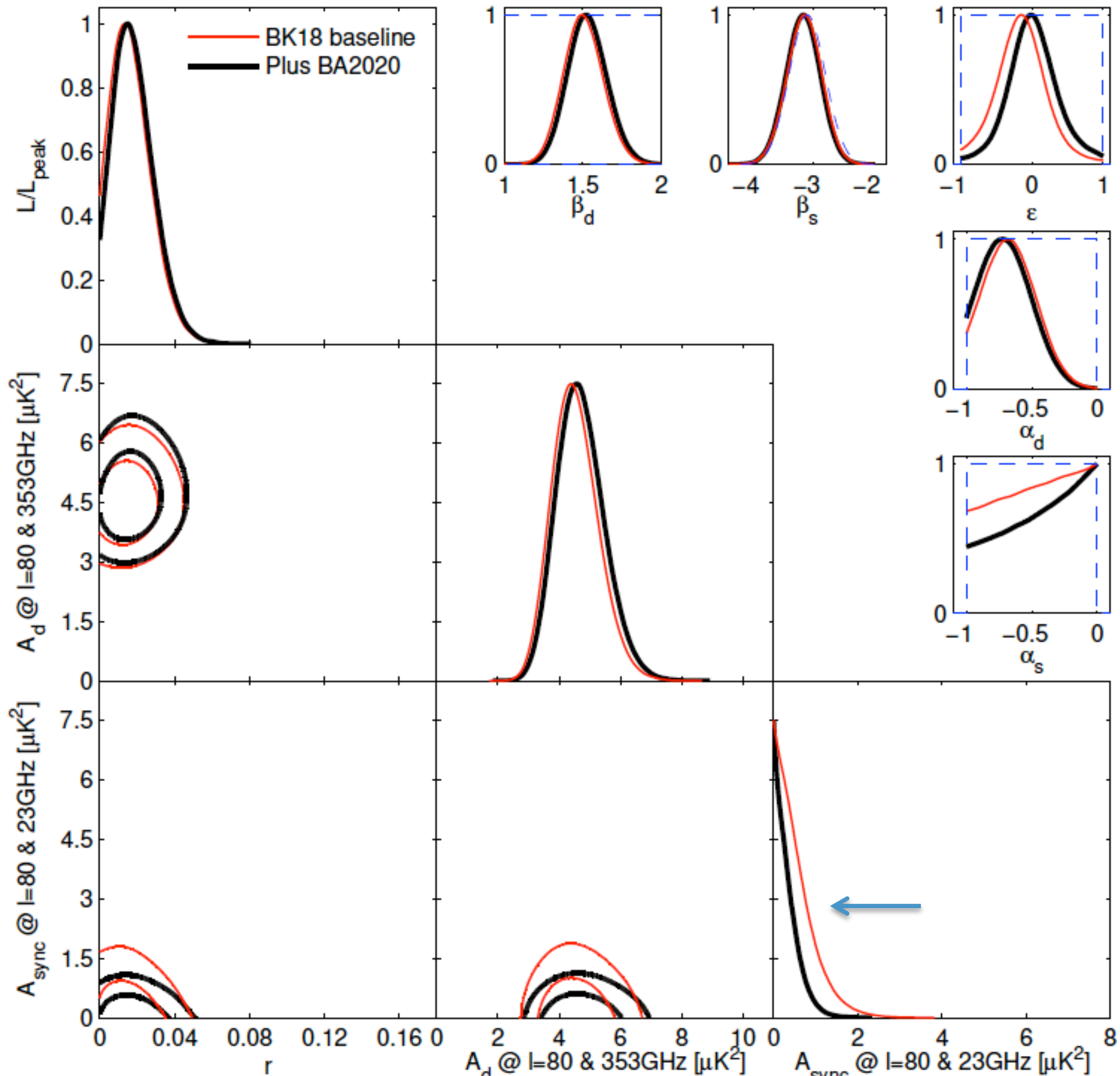


BA2
150GHz
Maps

~2 months of data – Very preliminary



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

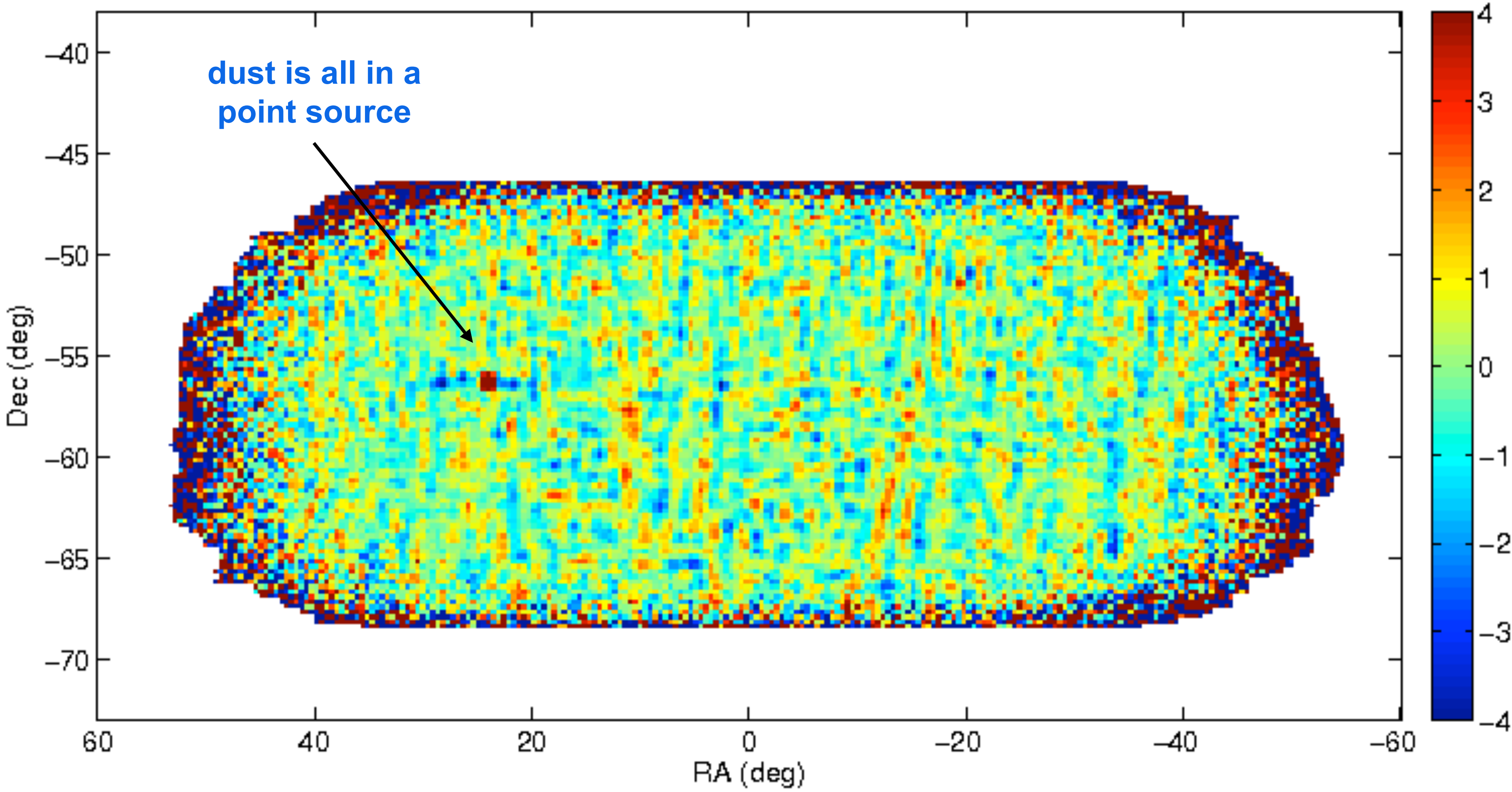


Does it matter that dust is not a Gaussian random field?

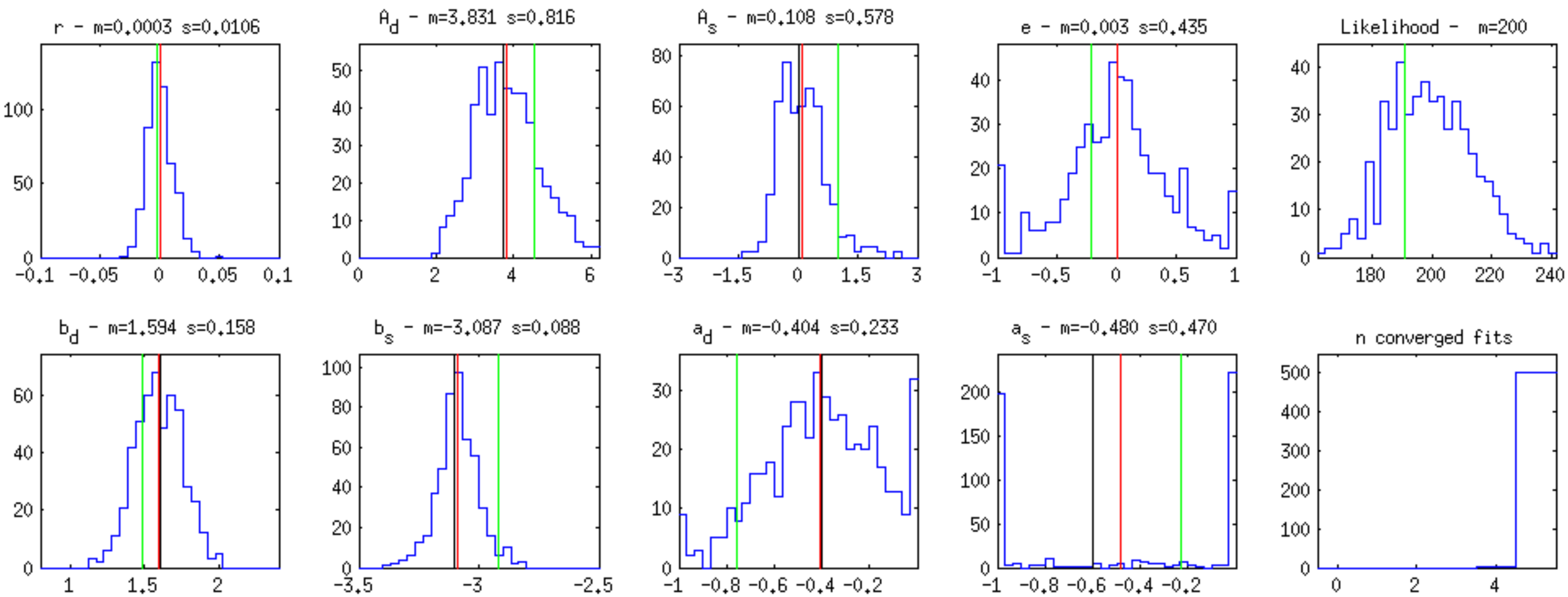
- The error bars we put on power spectrum plots assume the sky pattern is a Gaussian random fields
- Nominally our Hamimeche and Lewis (HL) based likelihood does as well(?)
- To empirically test if it matters we make some sims where the dust sky pattern is extremely non-Gaussian – make it a single point 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

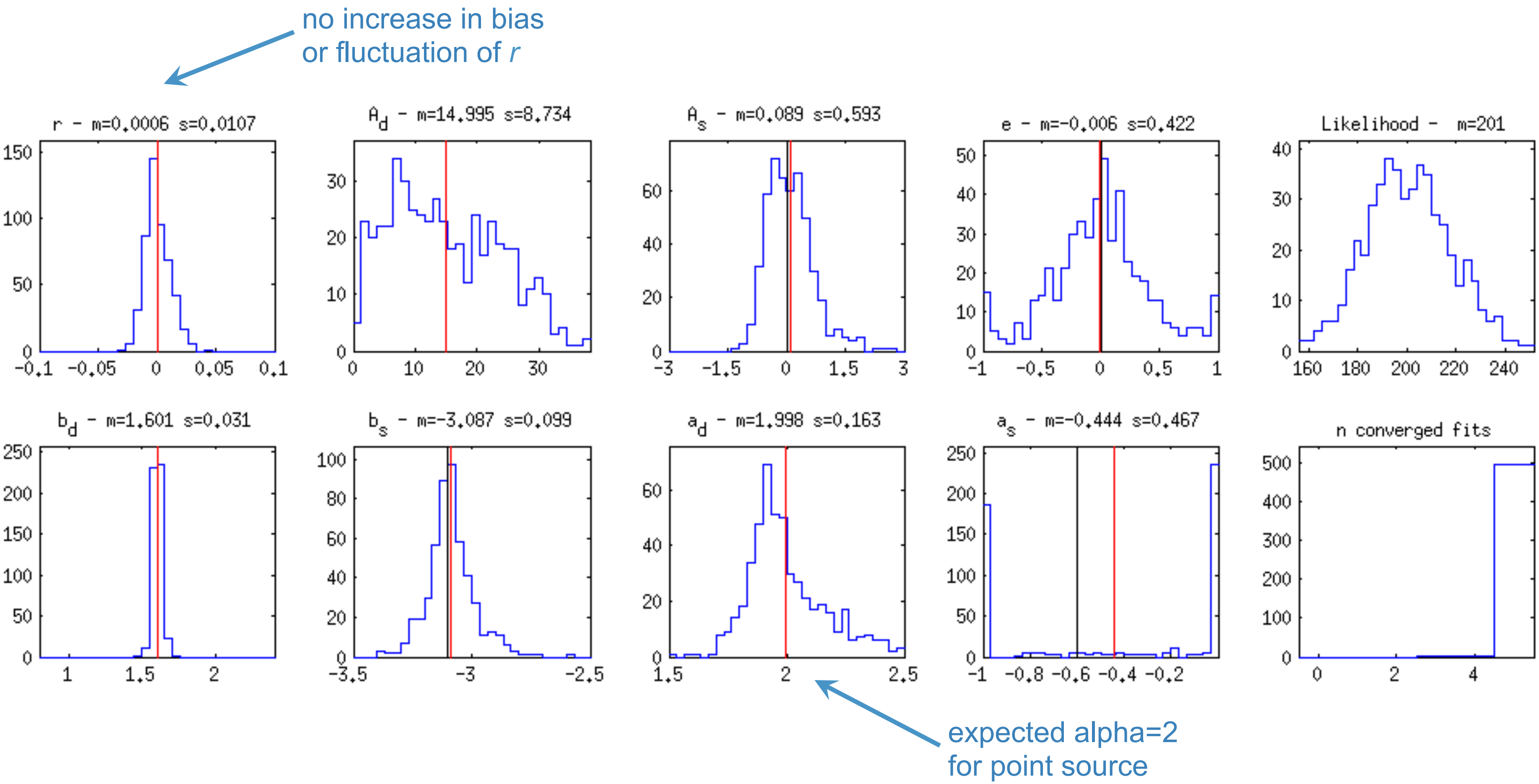


Maximum Likelihood Search Results on lensed-LCDM+dust+noise Simulations
Standard Gaussian dust realizations



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)

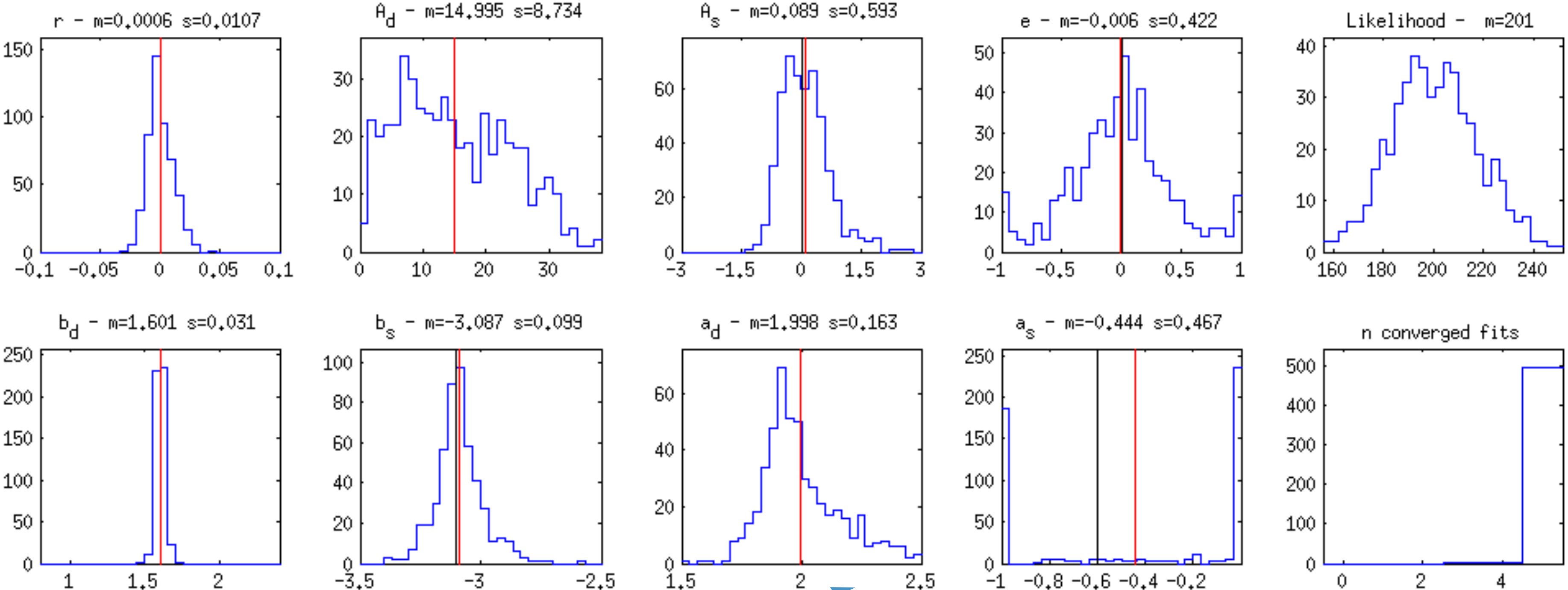
Maximum Likelihood Search Results on lensed-LCDM+dust+noise Simulations
Special "point source dust" realizations



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*



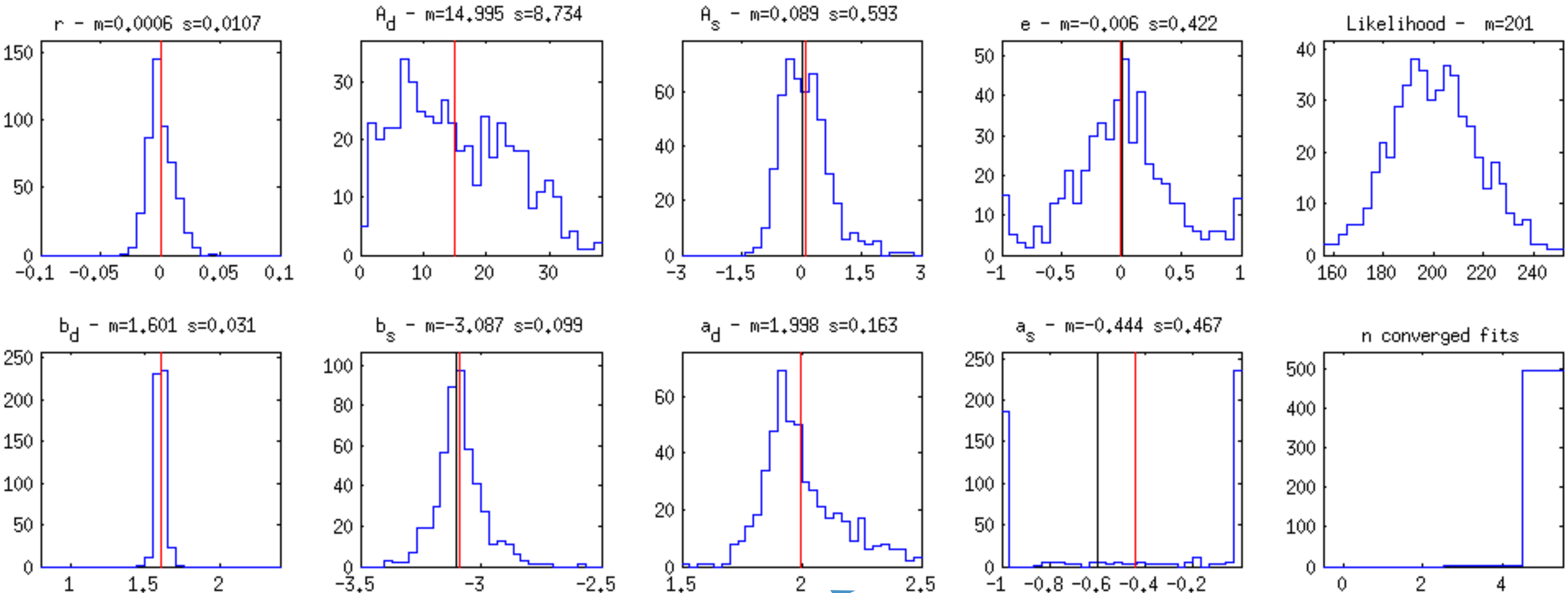
expected alpha=2
for point source

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)

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

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

no increase in bias
or fluctuation of *r*



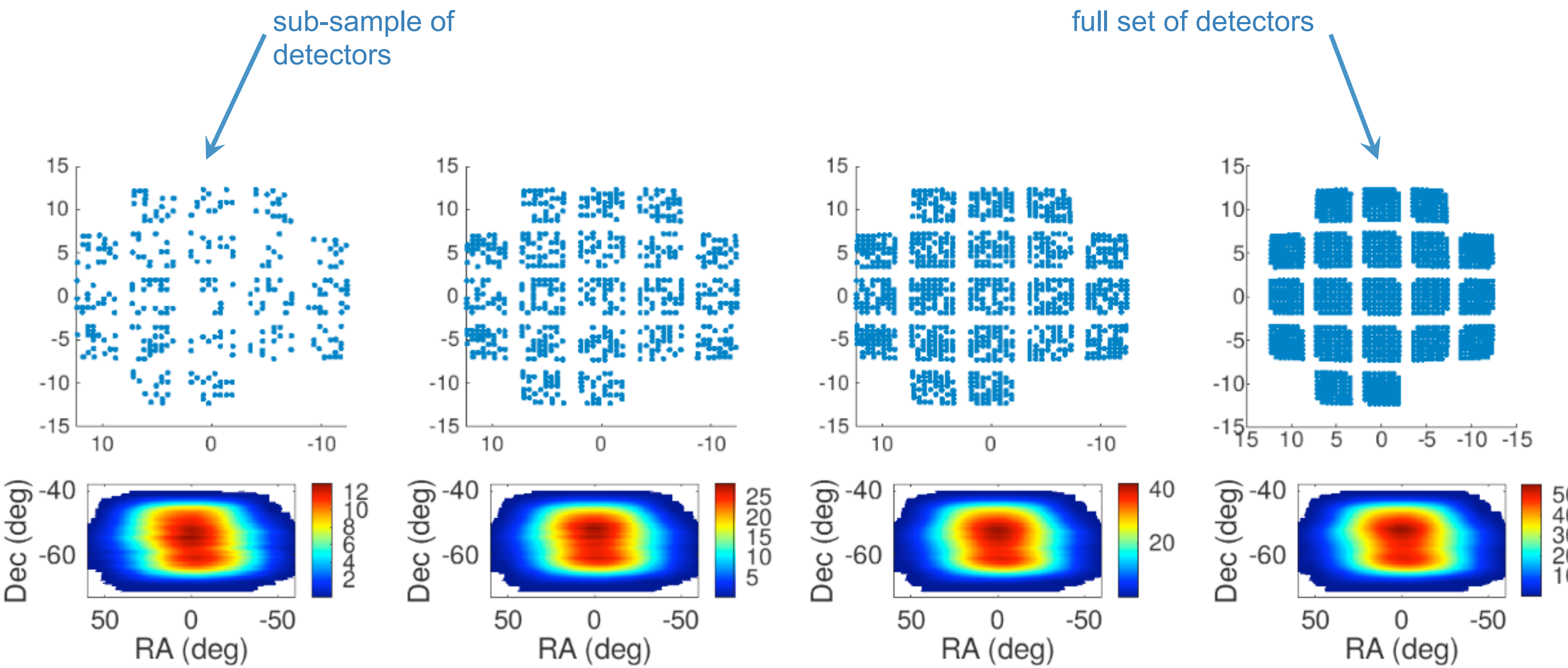
expected alpha=2
for point source

Each panel is a model parameter – numbers above
Vertical red lines are mean value over realizations, black

Seemingly weird result – it all works fine

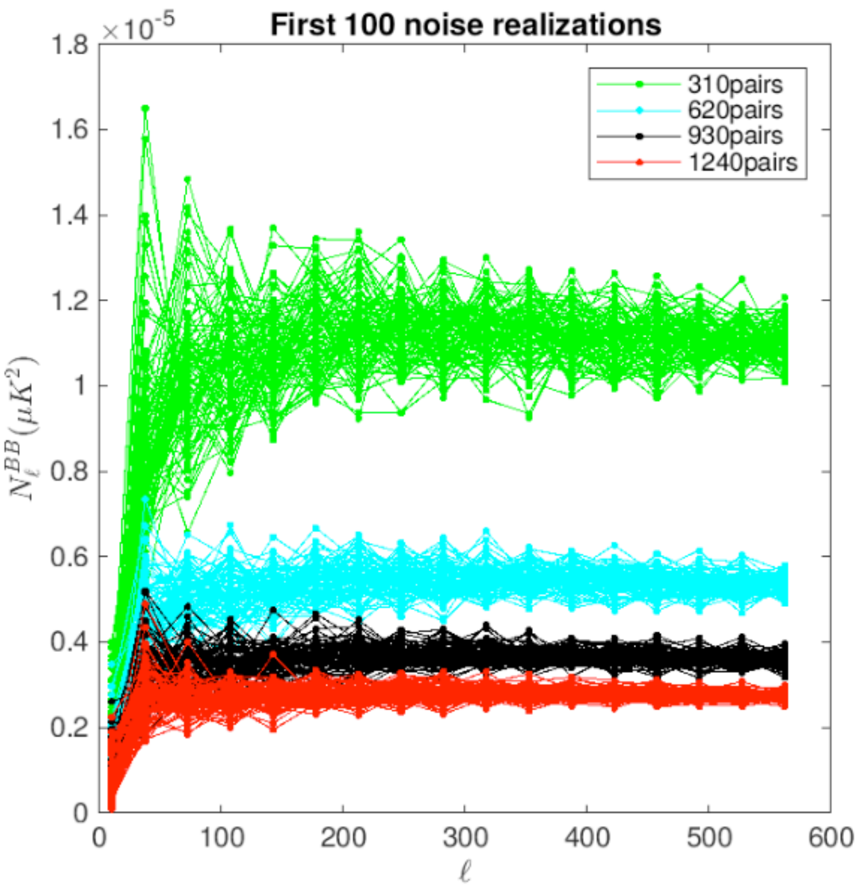
See also arxiv/2309.09978 from Cambridge guys where they find something similar

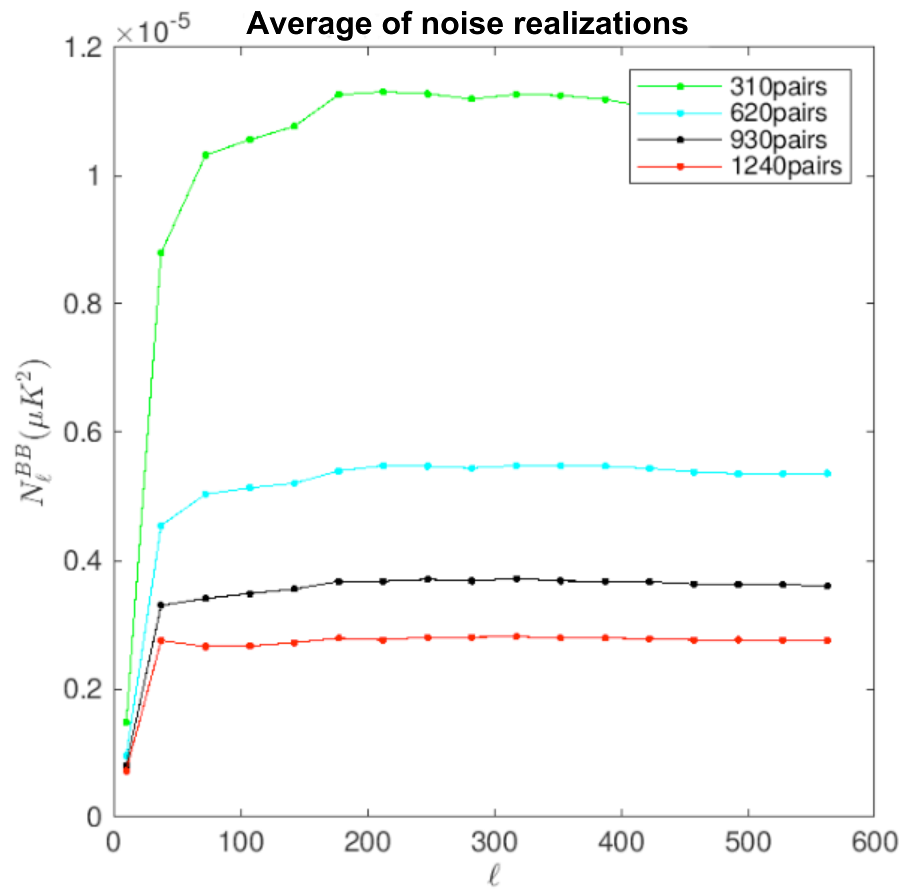
Probe How Noise Averages Down as Increase the Number of Simultaneously Observing Detectors



Take a year of BICEP3 data and build maps using increasingly dense sub-sets of the full set of detectors – sample from full field of view so maps have approx. same sky coverage

Probe How Noise Averages Down as Increase the Number of Simultaneously Observing Detectors





As expected noise goes down as add more detectors…

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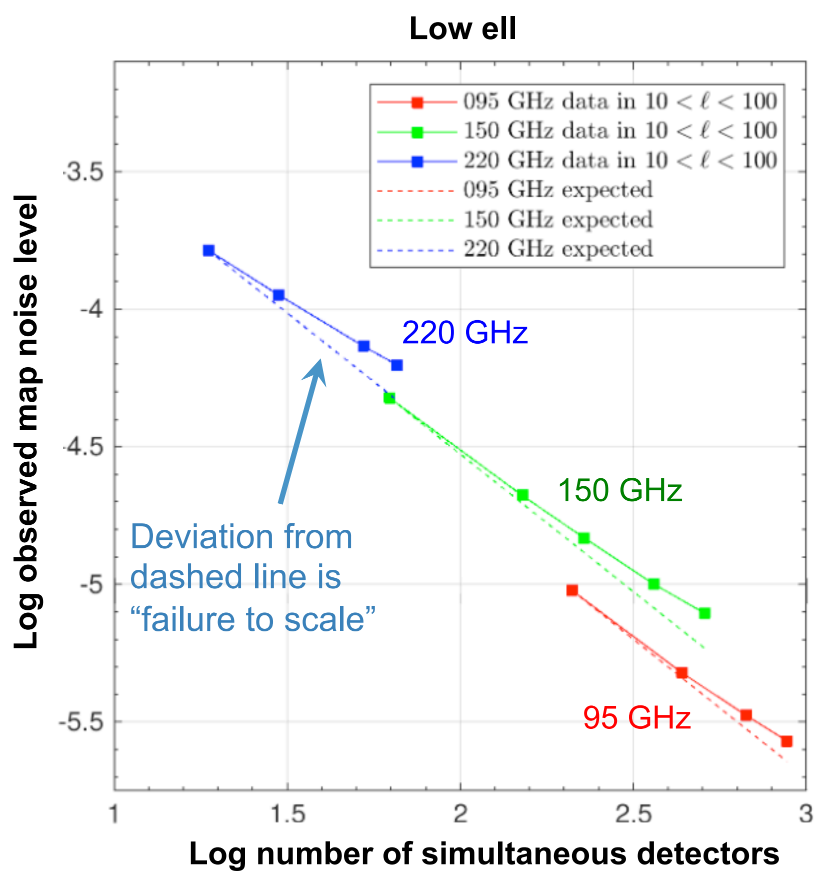

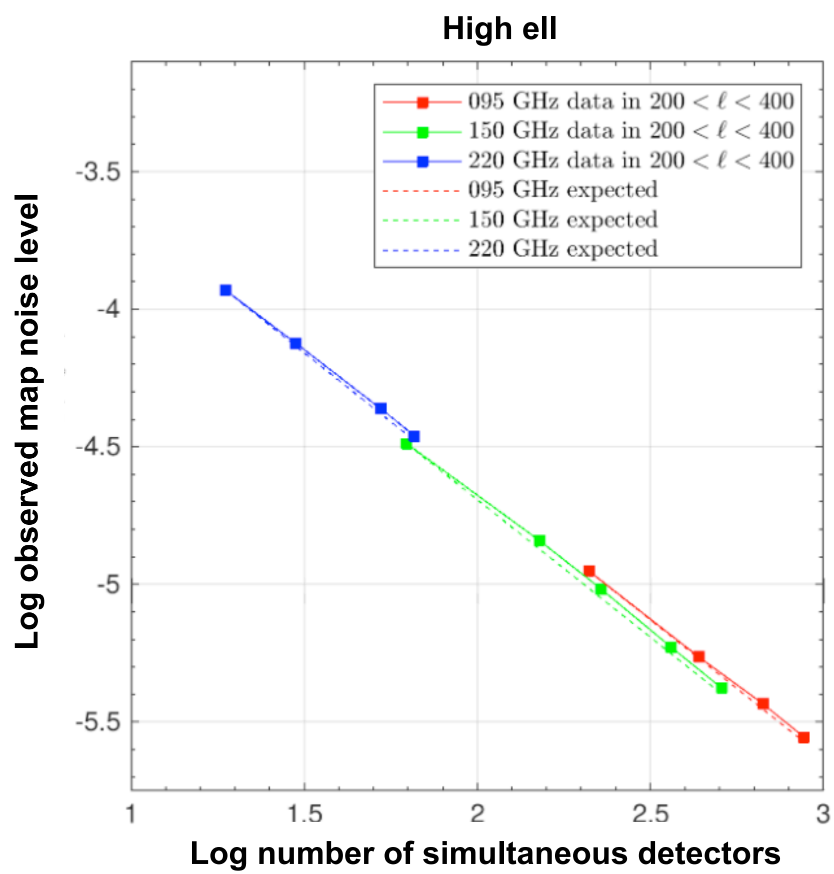

But the noise doesn’t go down quite as fast as it should – and the “failure to scale” gets worse with increasing observing frequency

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 dust priors from other regions of sky
- ➢ Rules out two entire classes of previously popular inflation models (monomial models and Natural Inflation)

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