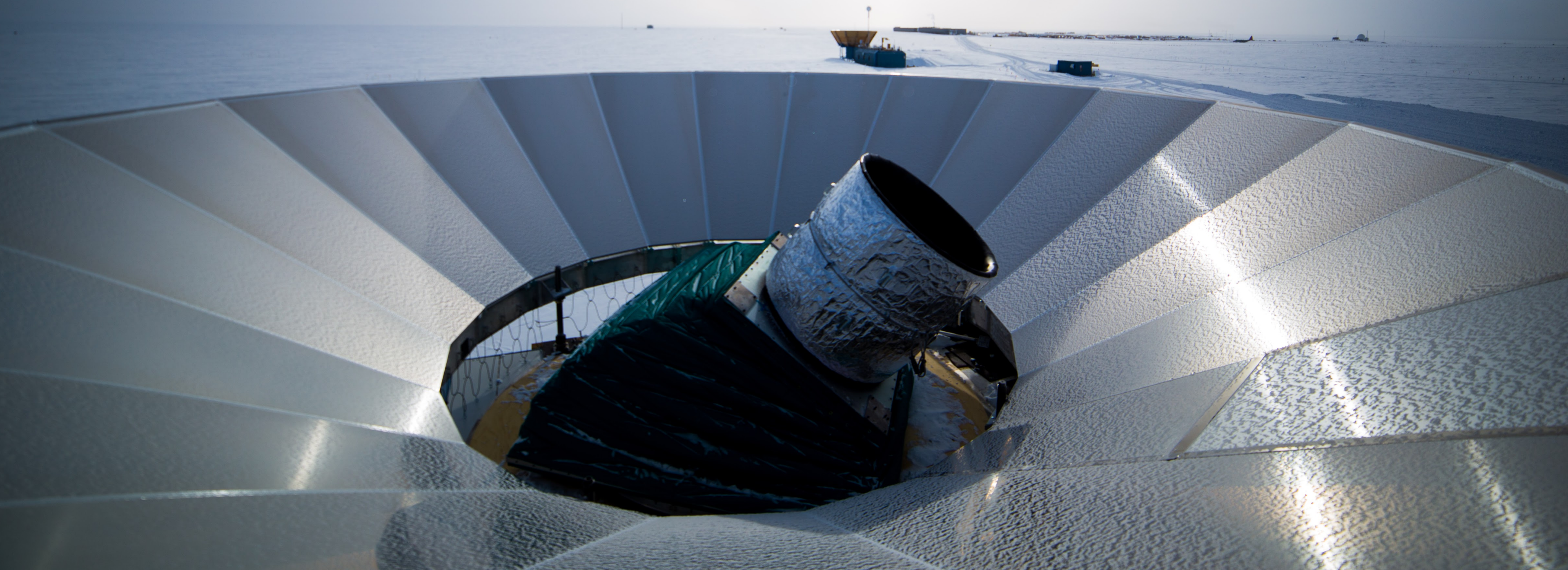
The search for primordial gravitational waves: latest results from BICEP

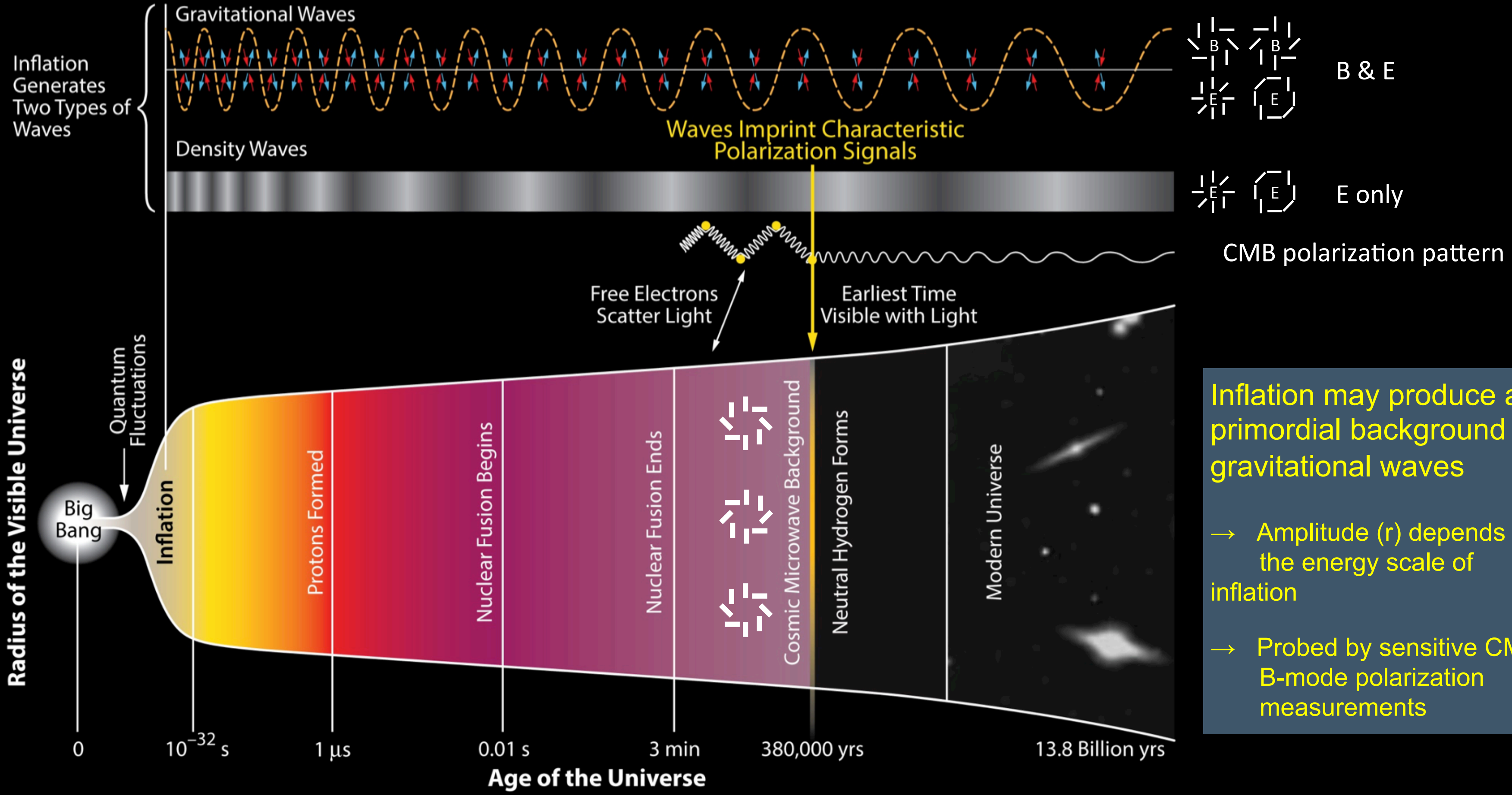
Clem Pryke for the BICEP/SPO Collaboration

mm Universe – Chicago June 30 2025



The BICEP Collaboration

SEARCHING FOR INFLATIONARY B-MODES



Inflation may produce a primordial background of gravitational waves

→ Amplitude (r) depends on the energy scale of inflation

→ Probed by sensitive CMB B-mode polarization measurements

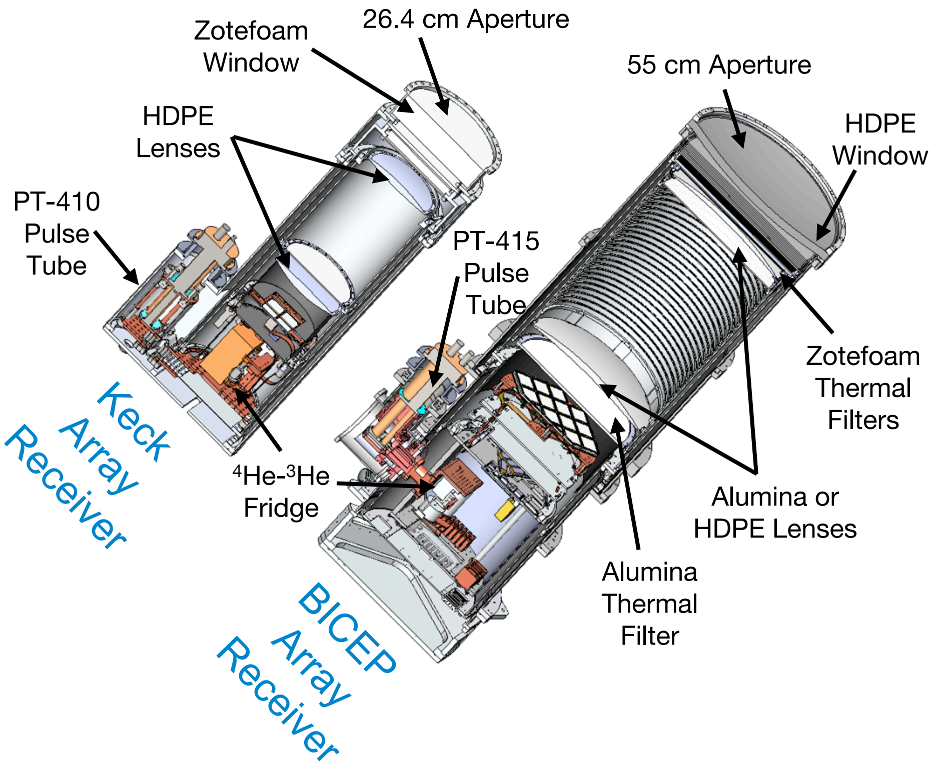
SOUTH POLE: THE CLOSEST THING TO SPACE ON THE EARTH

High and dry site
1 diurnal cycle per year: low-noise and stable atmosphere
Featureless horizon
24/7 observing access to cleaner sky regions
Excellent logistics for power, data, & cargo

THE SOUTH POLE OBSERVATORY

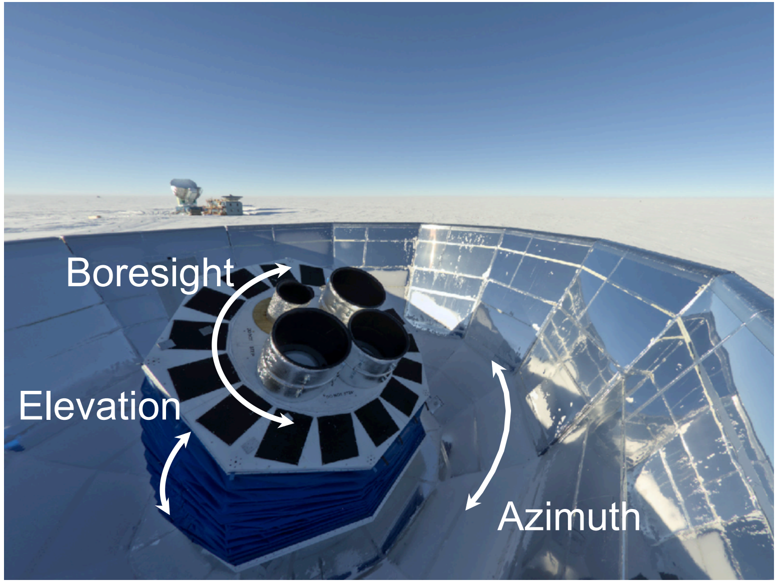
Observatories mostly reuse existing facilities and remain state of the art by upgrading receivers!

BICEP SMALL APERTURE CONCEPT



- Small aperture, large field of view
- Refracting 4K optics with low sidelobes
- 55-cm design increases mapping speed by ~15x

BICEP Array Telescope Mount



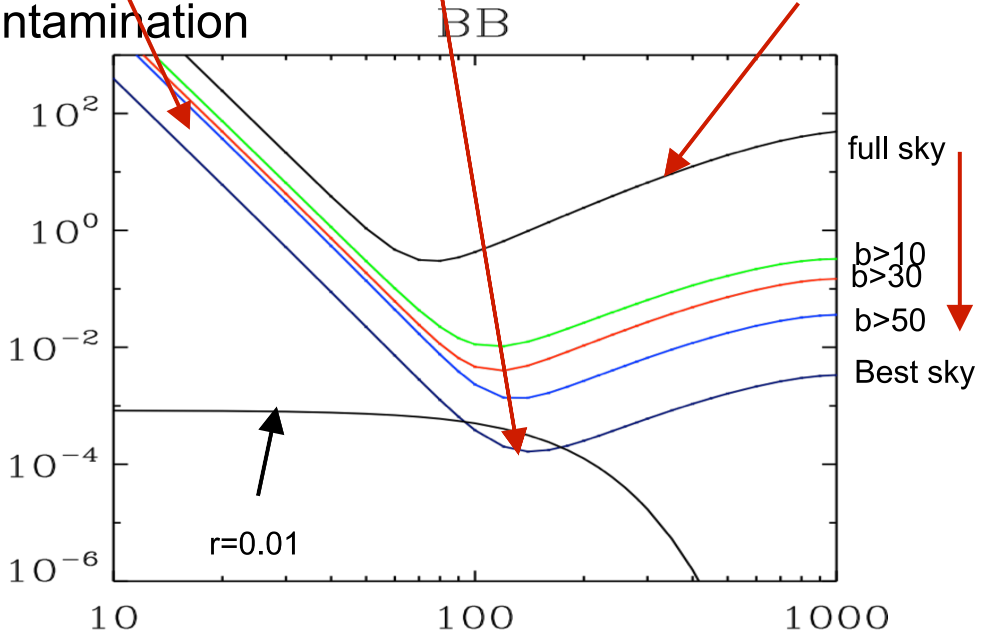
- Small aperture enables boresight rotation
- Co-rotating absorbing forebaffle
- Reflecting ground shield

Polarized Foreground Contamination from Our Galaxy

At low frequency synchrotron contamination

Sweetest spot

At high frequency dust contamination



Amount of Contamination

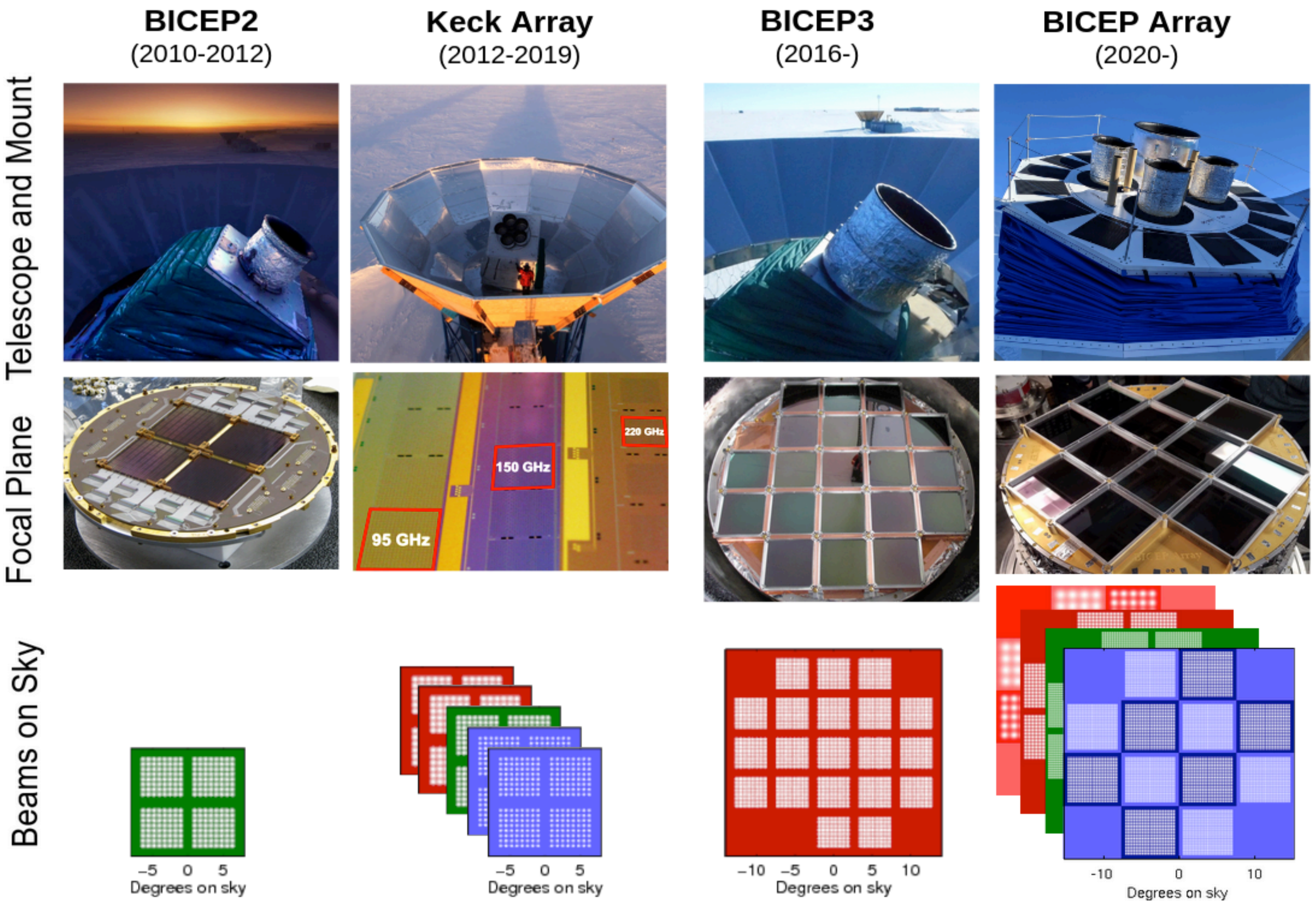
Observing Frequency (GHz)

Pick a cleaner patch of sky

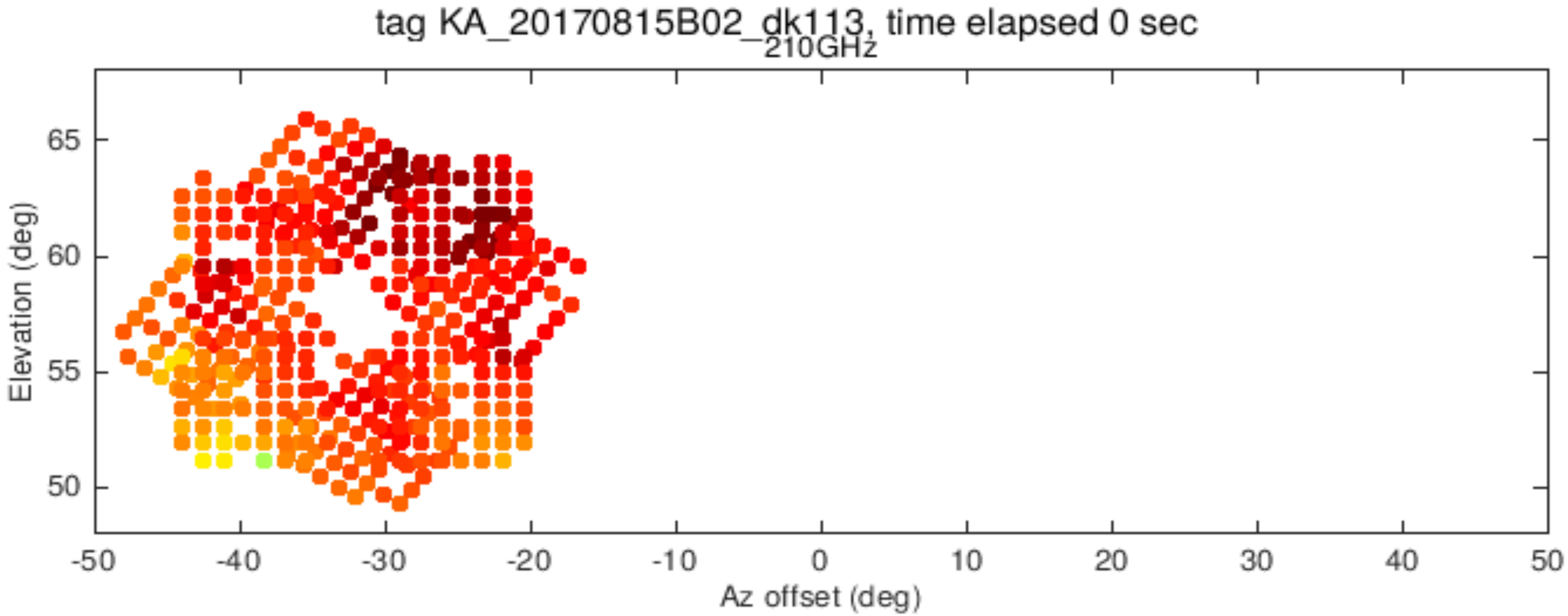
Since the different components of the sky pattern have different frequency dependencies one can separate them by making maps at multiple frequencies – and probe deeper for an inflation signal

(Plot from Dunkley et al arxiv/0811.3915)

BICEP EXPERIMENTAL PHASES SINCE 2010



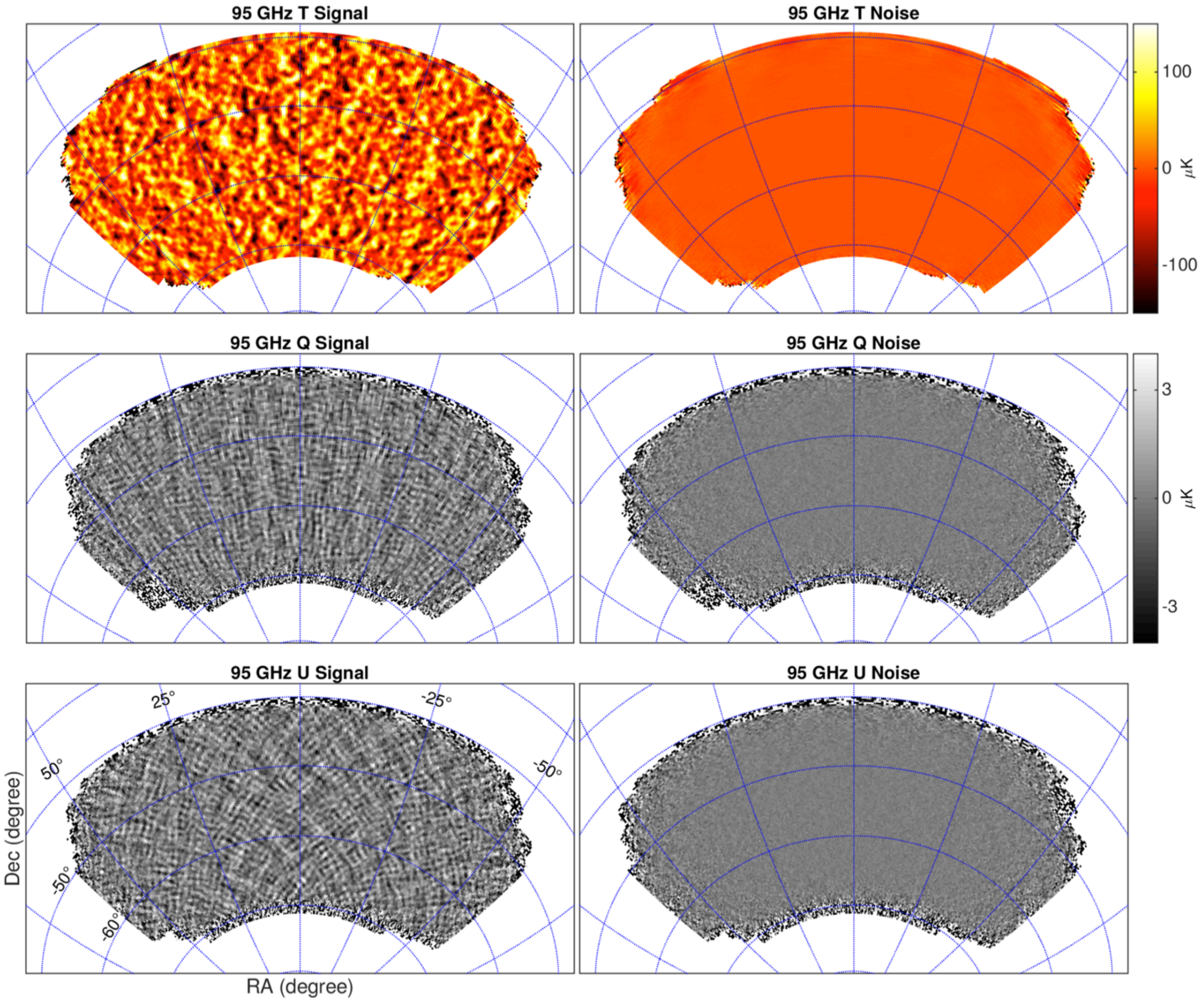
Bolometer readouts as the telescope scans back and forth



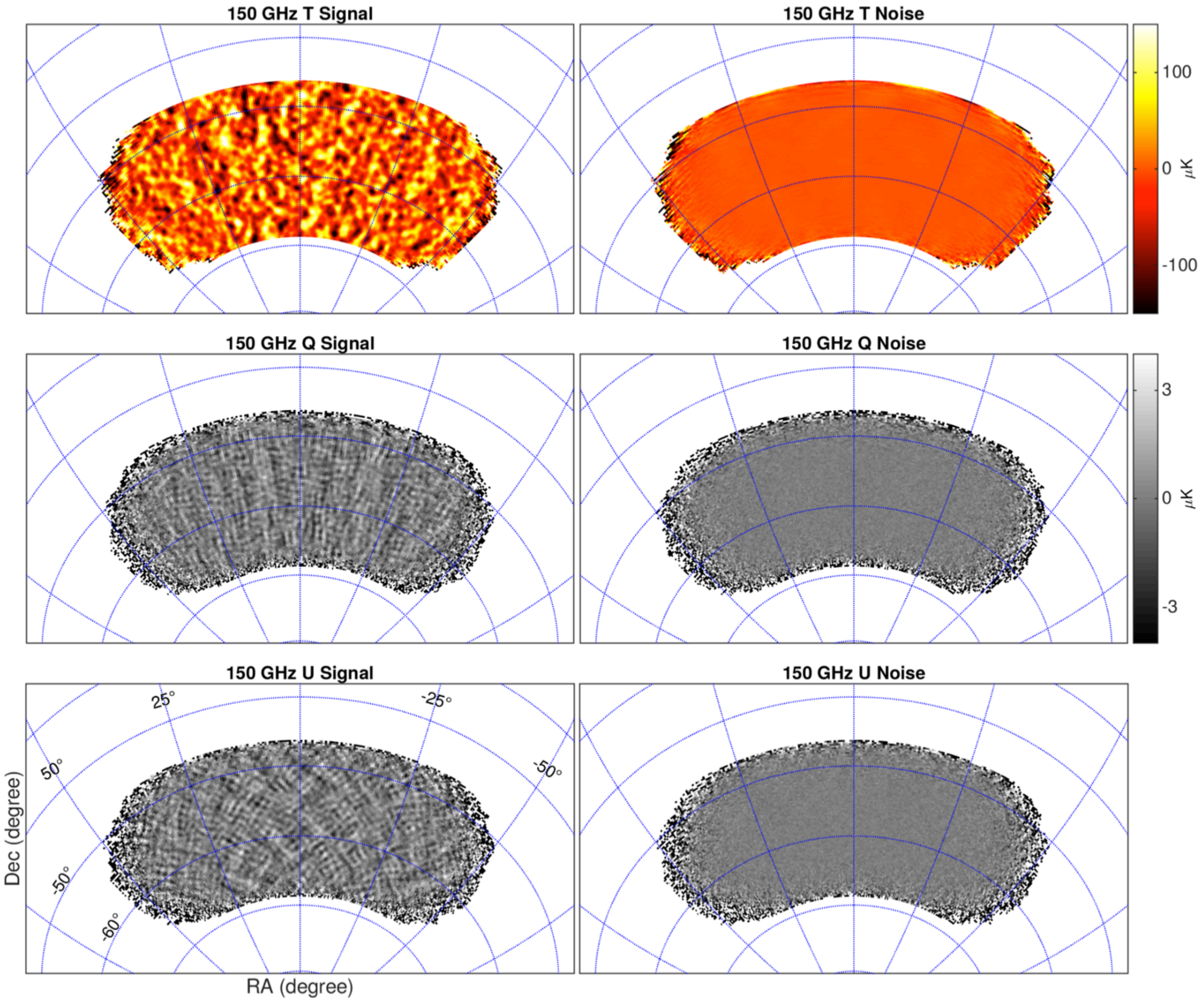
The physical temperature of the detectors tracks the intensity of the incoming radiation from little “spots” on the sky.
This plot is unpolarized – we are seeing “clouds” blowing across the scan region.

BK18
95GHz
Maps

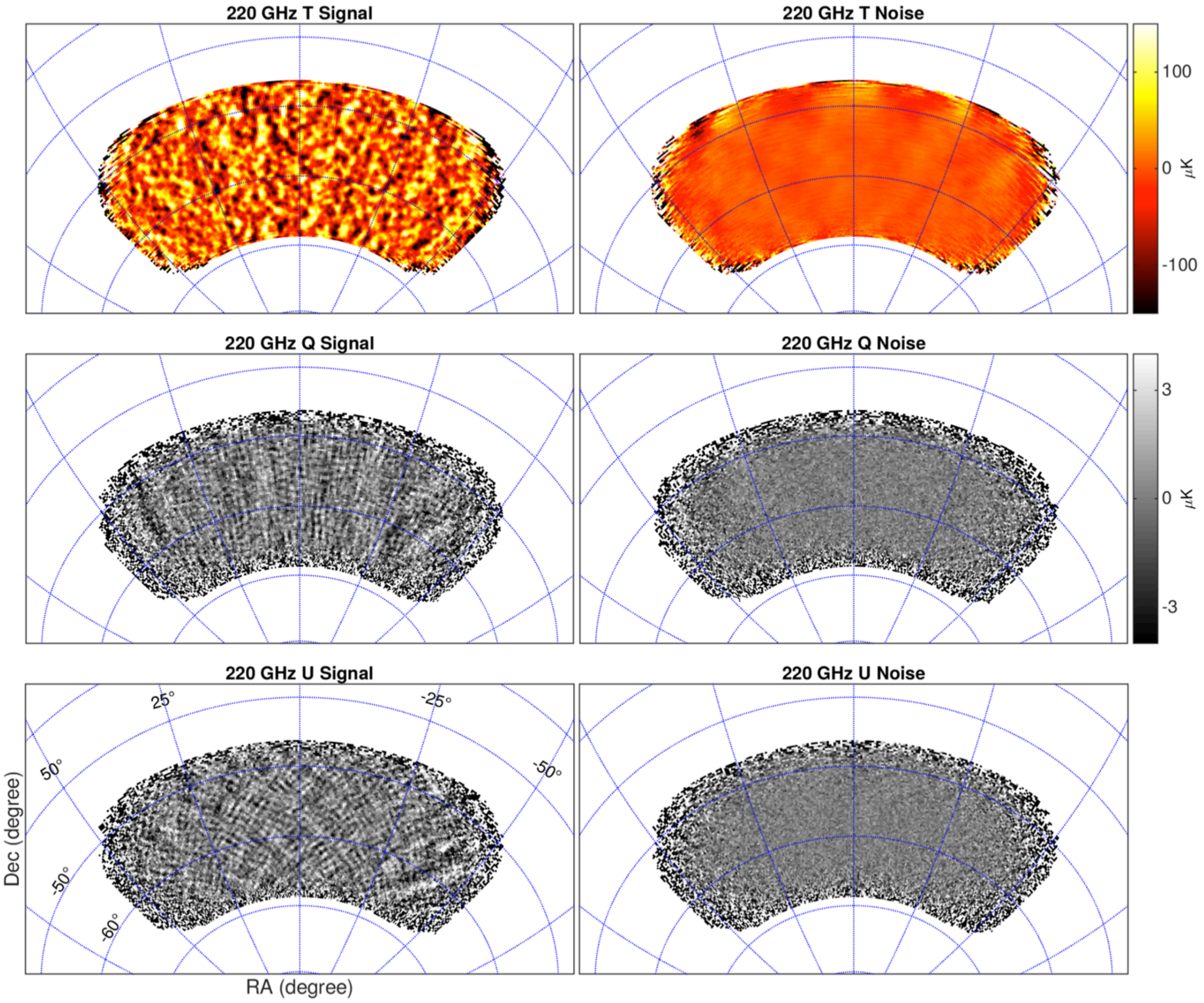
BK18 uses all BICEP/Keck data taken up to 2018. This result actually came out in fall 2021 – it takes time to go from raw data to final result!



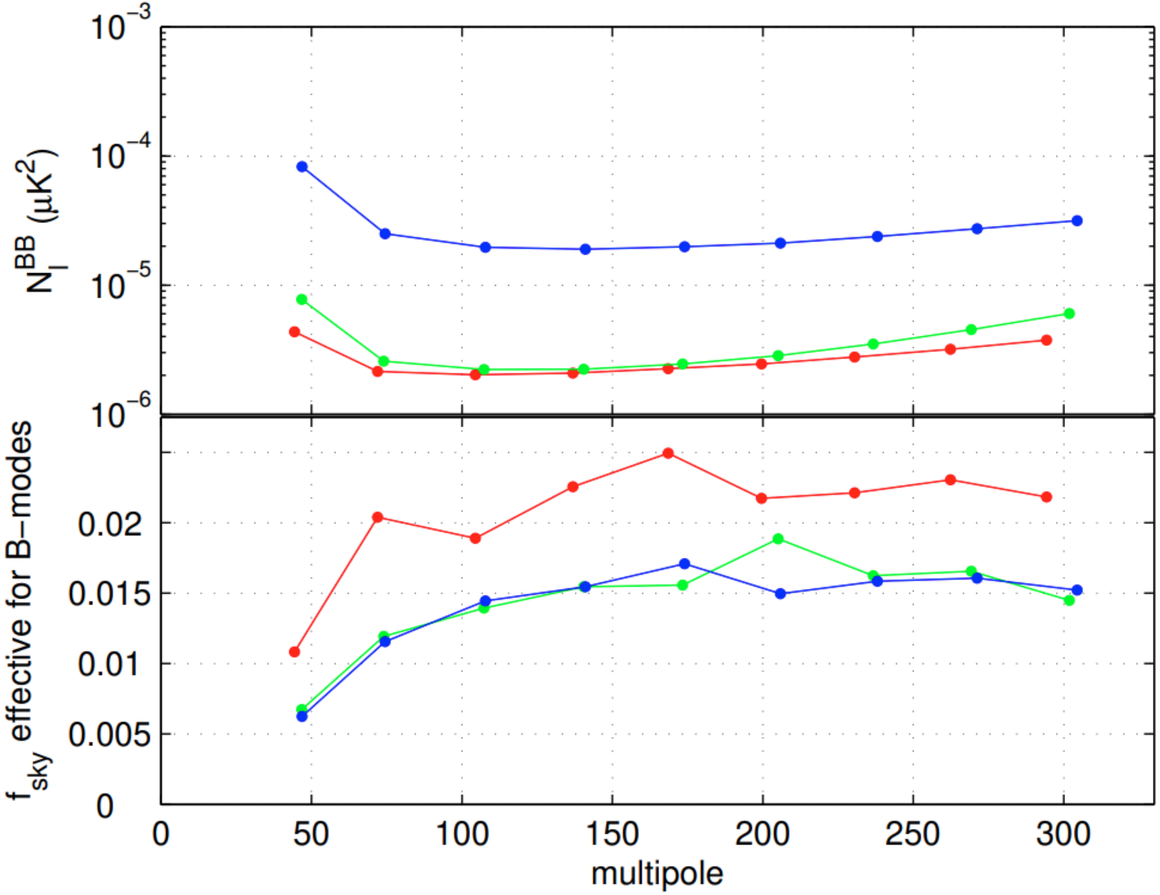
BK18 150GHz Maps



BK18 220GHz Maps

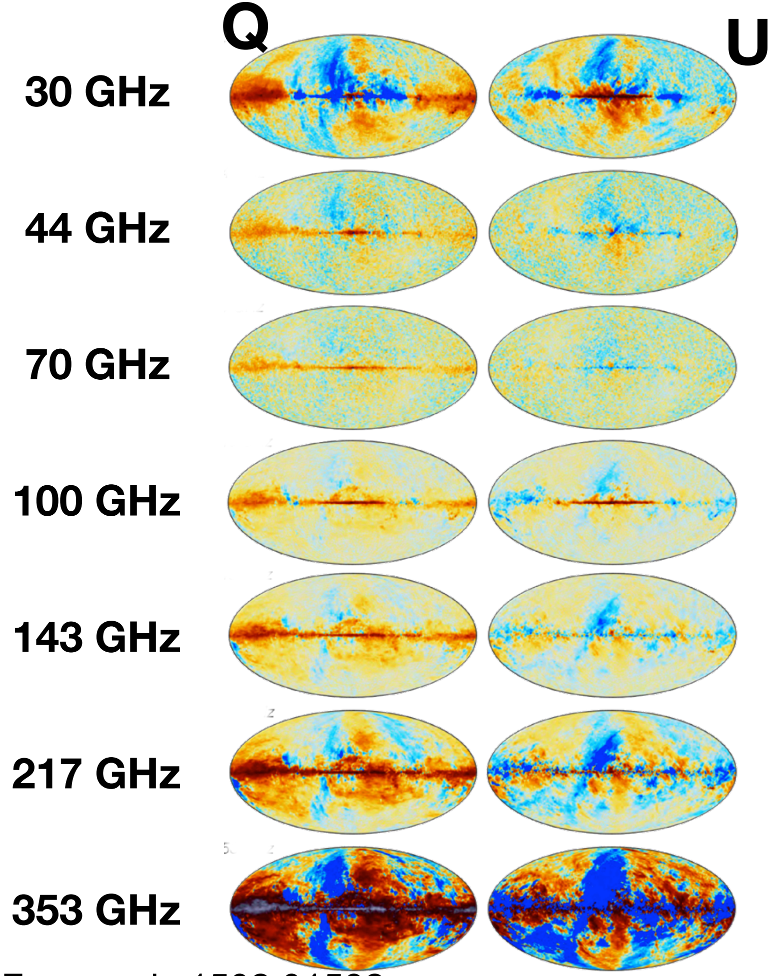


BK18 Noise Spectra and f_{sky} Effective



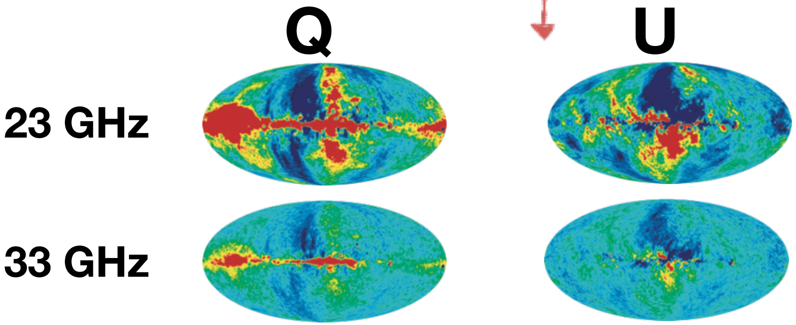
Red 95GHz
Green 150GHz
Blue 220GHz

Add to the mix: Planck at 7 frequencies and WMAP at 2 frequencies



From arxiv 1502.01582

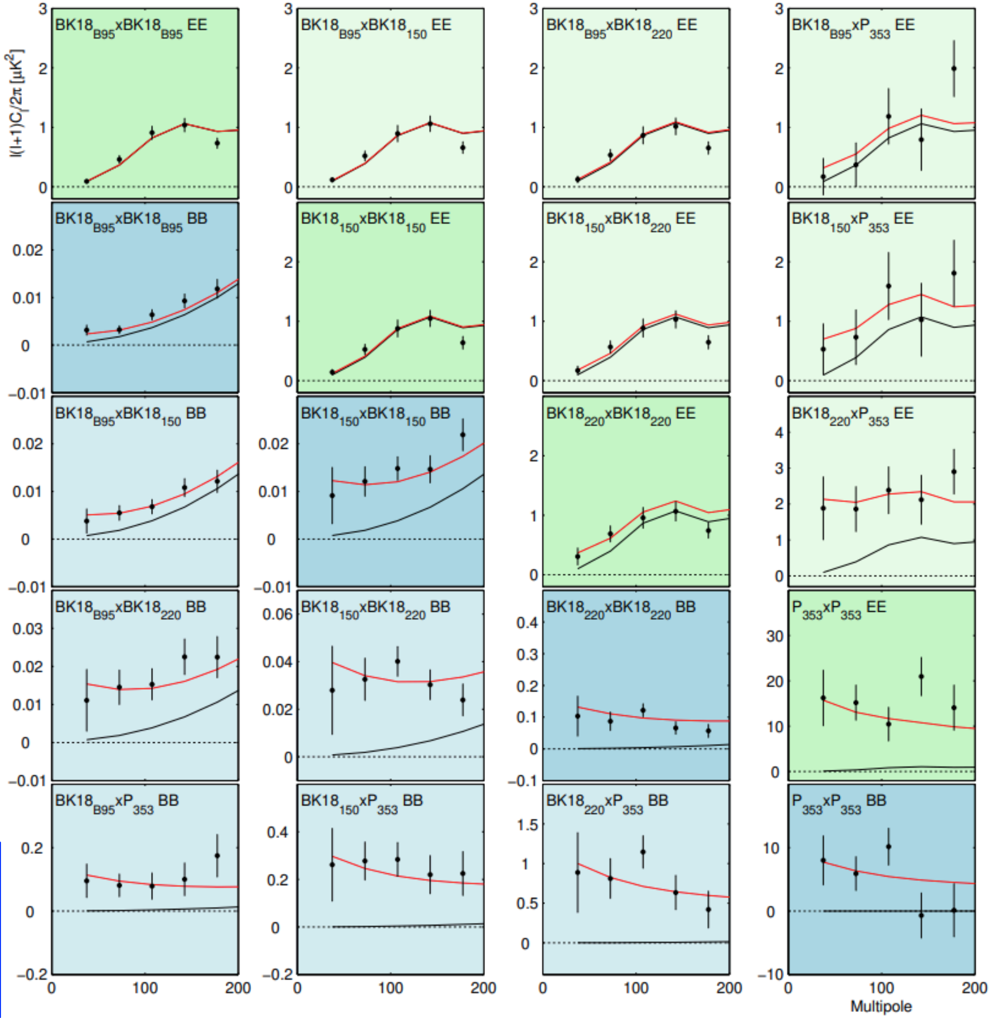
Polarized galactic **synchrotron** dominates at low frequencies



From arxiv 1212.5225

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

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



Black lines are LCDM

Red lines are LCDM+foreground

Blue panels are BB spectra

Green panels are EE spectra

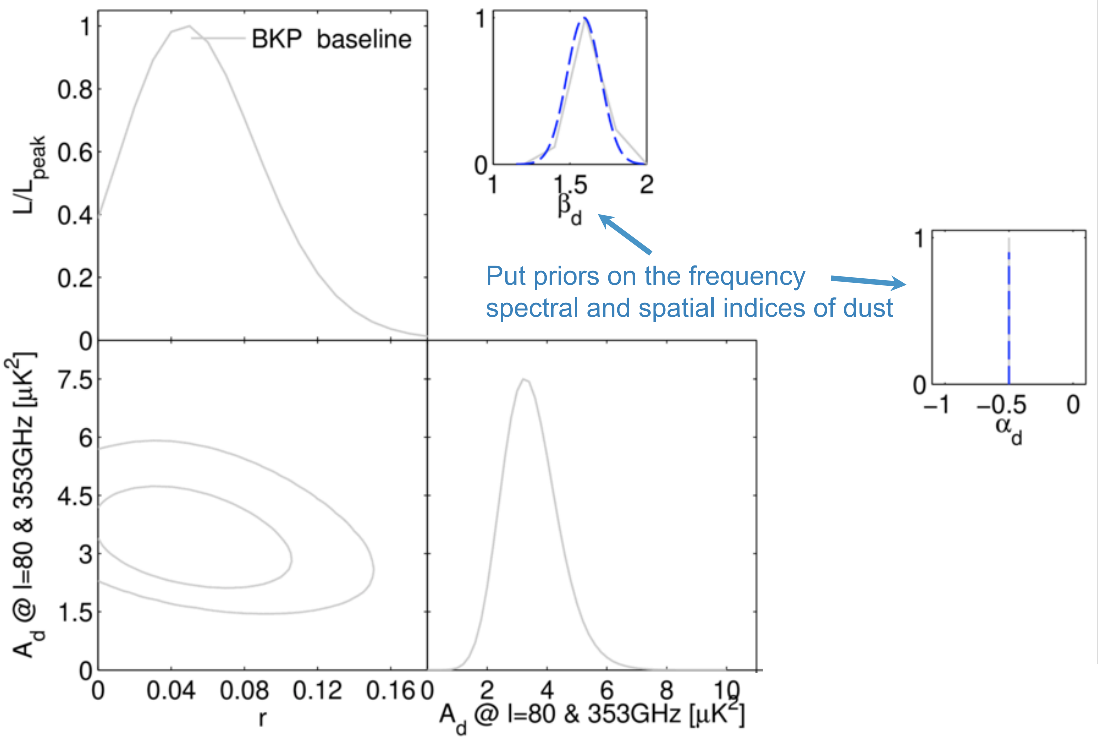
Multicomponent likelihood analysis

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

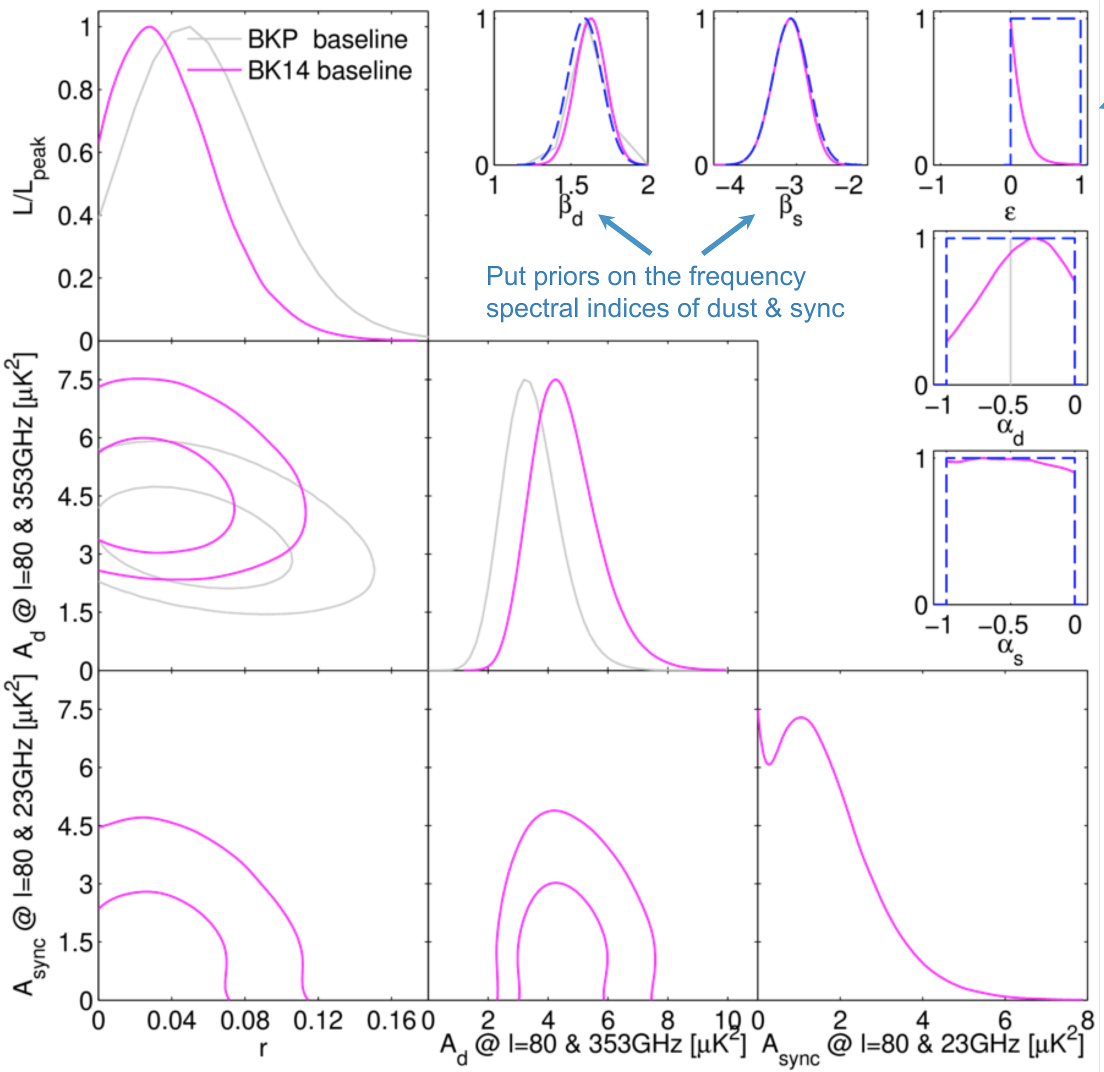
foreground model = dust + synchrotron

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



BKP
arxiv/1502.00612

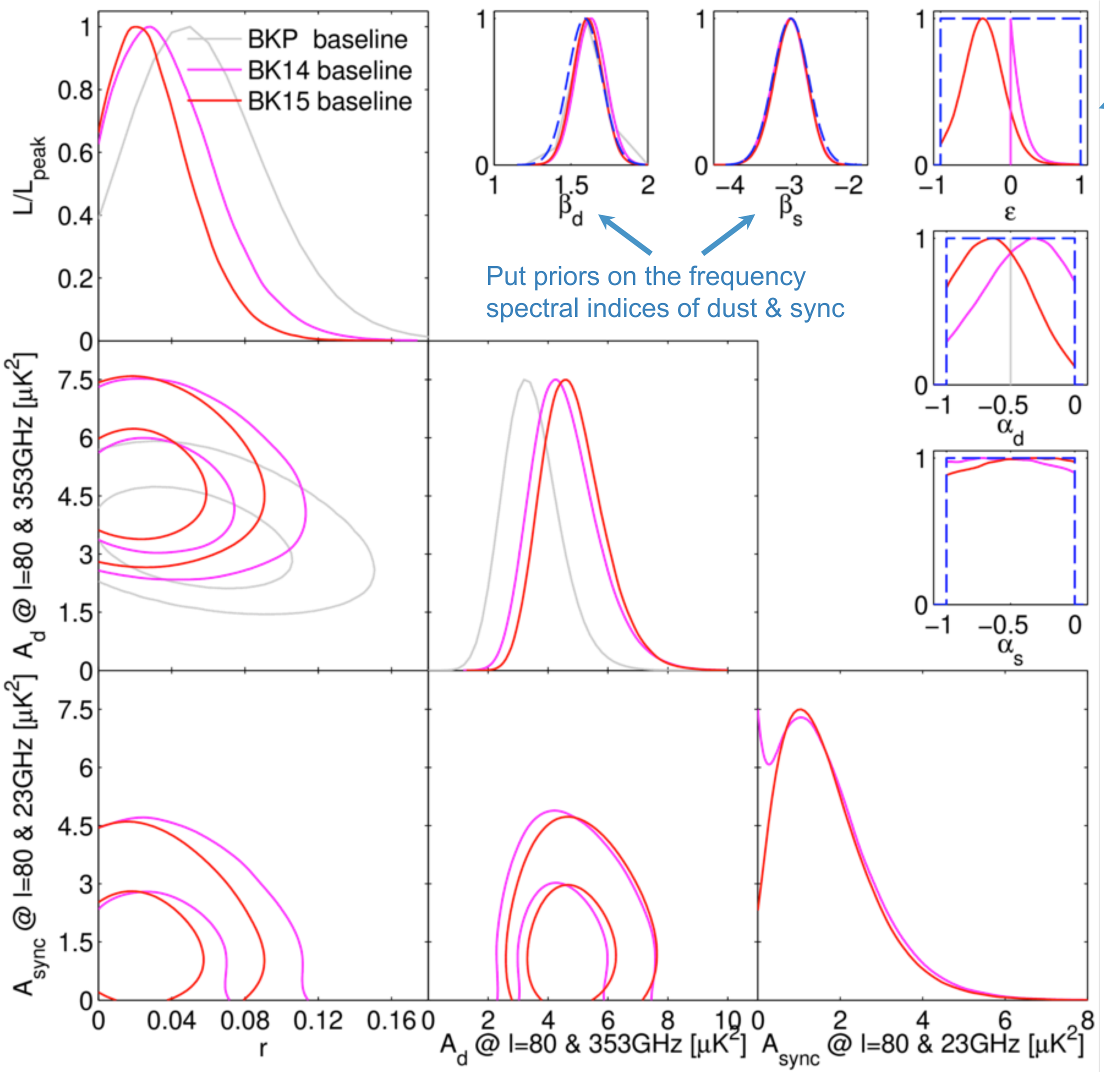


Allow dust/sync correlation in [0,1]

Put priors on the frequency spectral indices of dust & sync

Marginalize over generous ranges in spatial spectral indices

BK14
arxiv/1510.09215



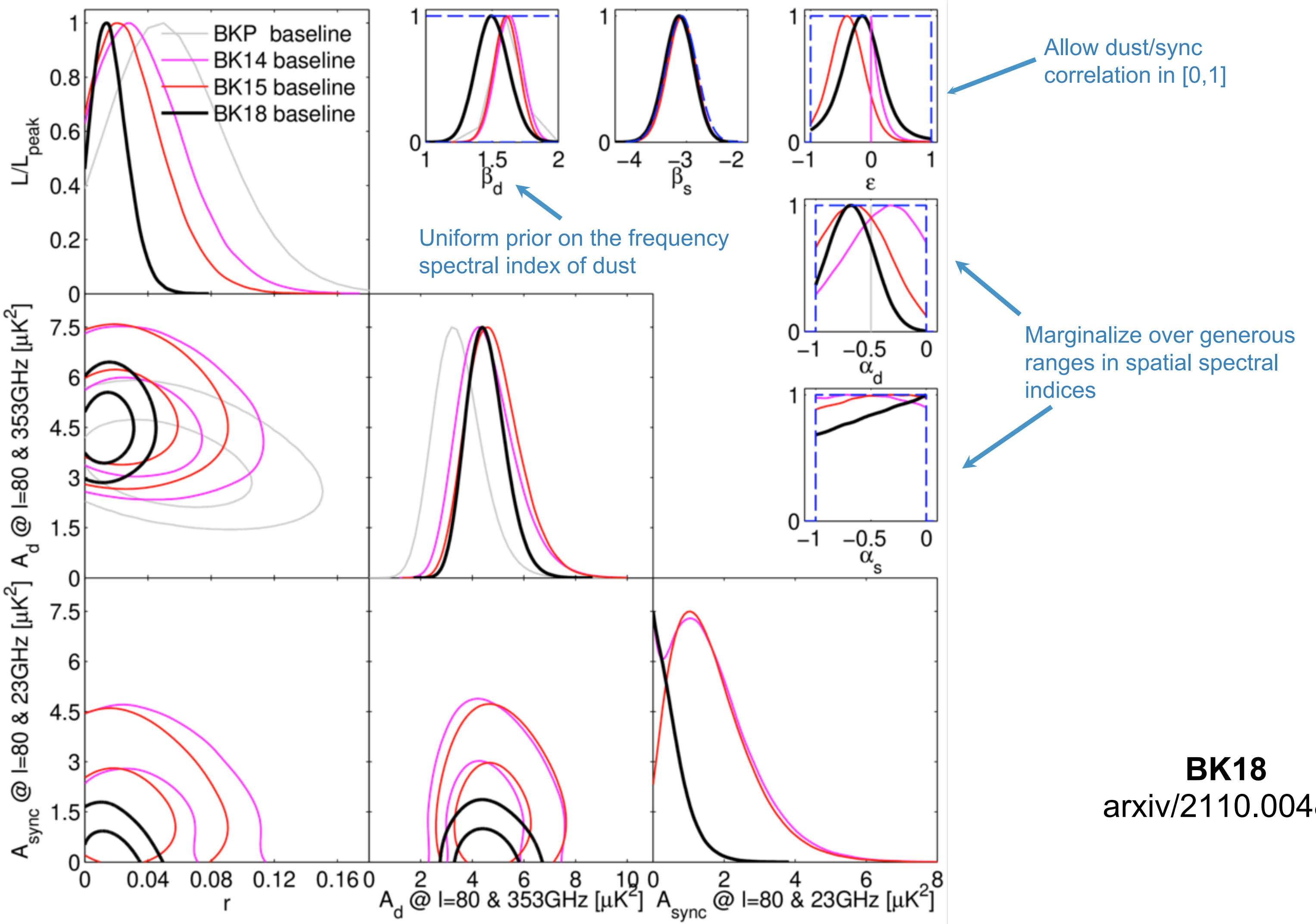
Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation in [0,1]

Marginalize over generous ranges in spatial spectral indices

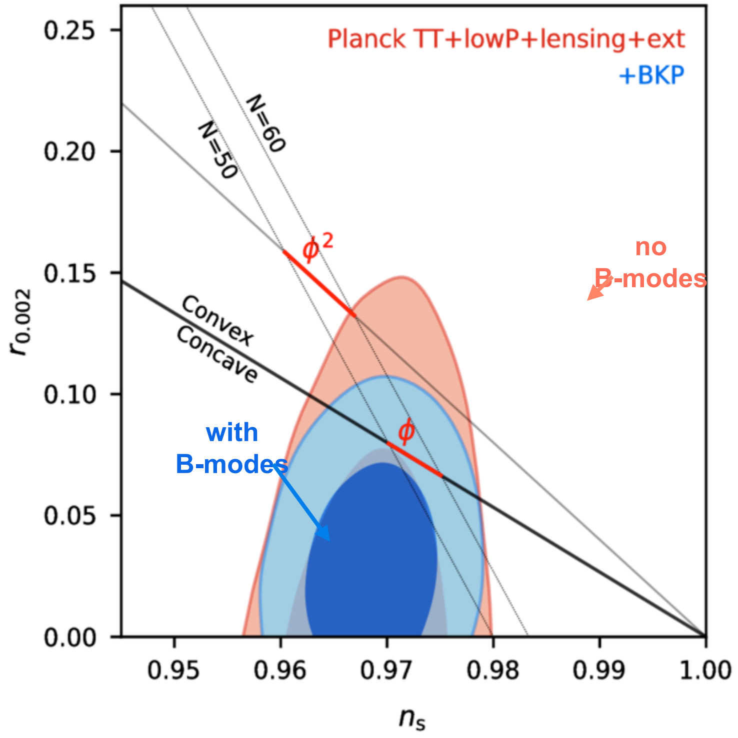
BK15

arxiv/1810.05216



BK18

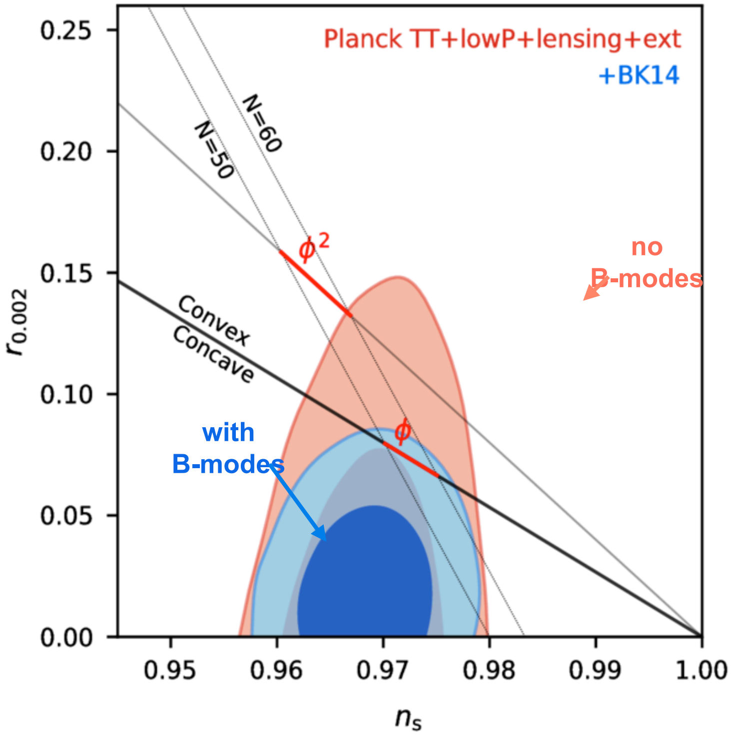
arxiv/2110.00483



$r_{.05} < 0.09$

BKP

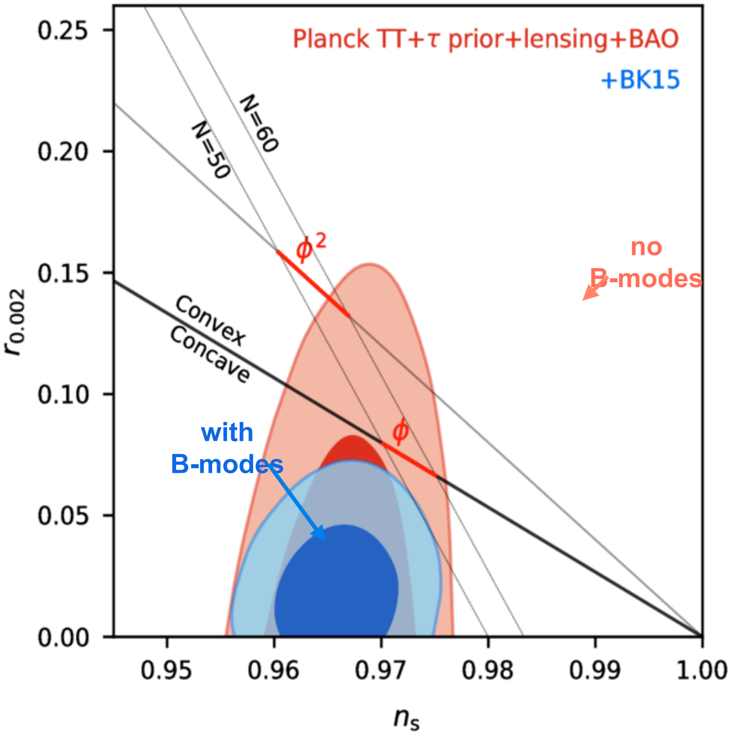
arxiv/1502.00612



$r_{.05} < 0.07$

BK14

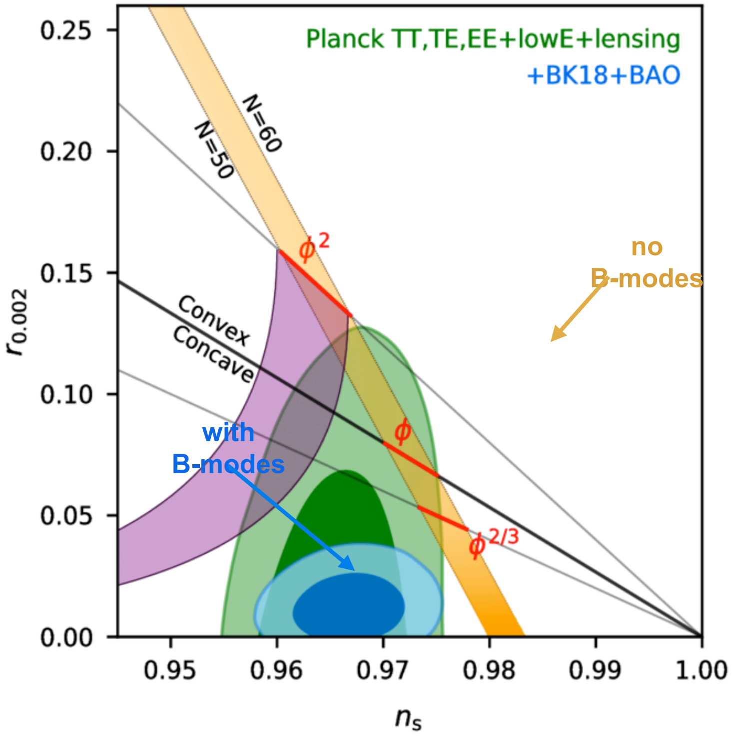
arxiv/1510.09217



$r_{.05}$ < 0.06

BK15

arxiv/1810.05216

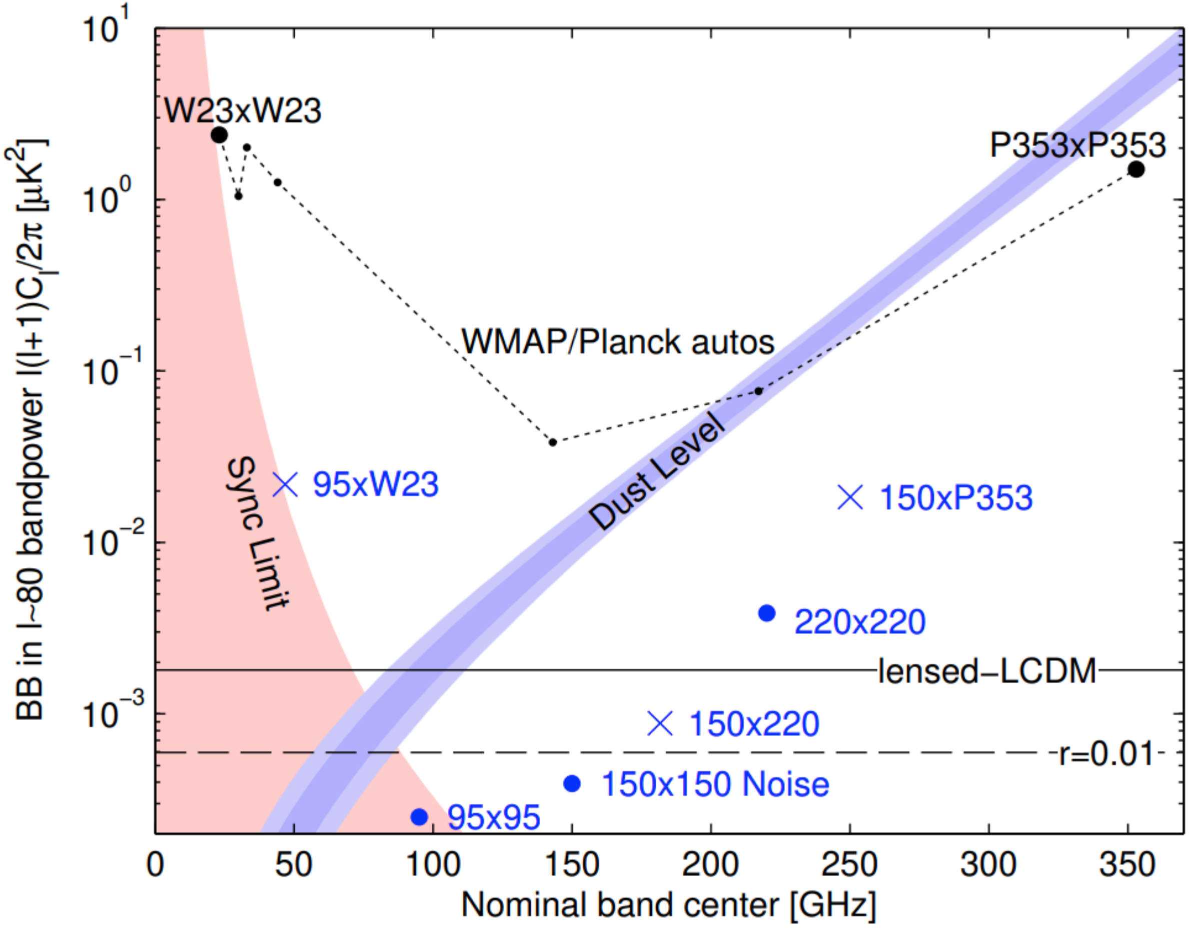


$r_{.05} < 0.035$

BK18

arxiv/2110.00483

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 $\sigma(r)=0.007$

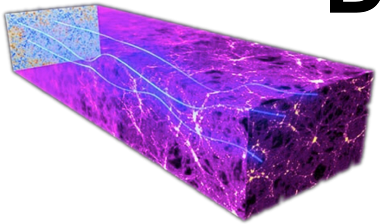
The above is as it should be - we have correctly tuned the relative sensitivity of the 95/150/220 bands such that we don't suffer much penalty due to the presence of foregrounds.

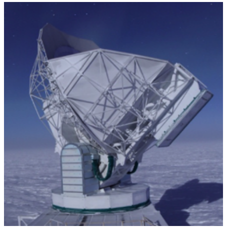
- Running on simulations which contain no lensing gives $\sigma(r)=0.004$

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 $\sigma(r)=0.002$

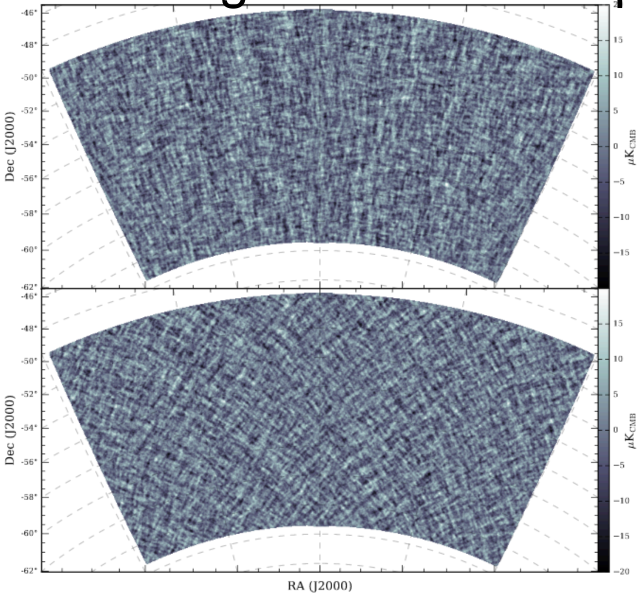
Delensing with SPT-3G data

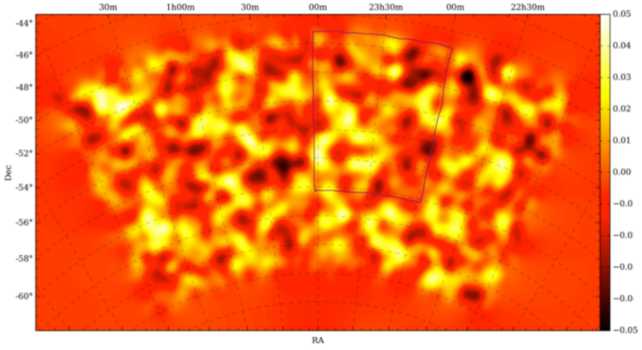




Can be used to reconstruct the lensing deflection map…

High resolution maps

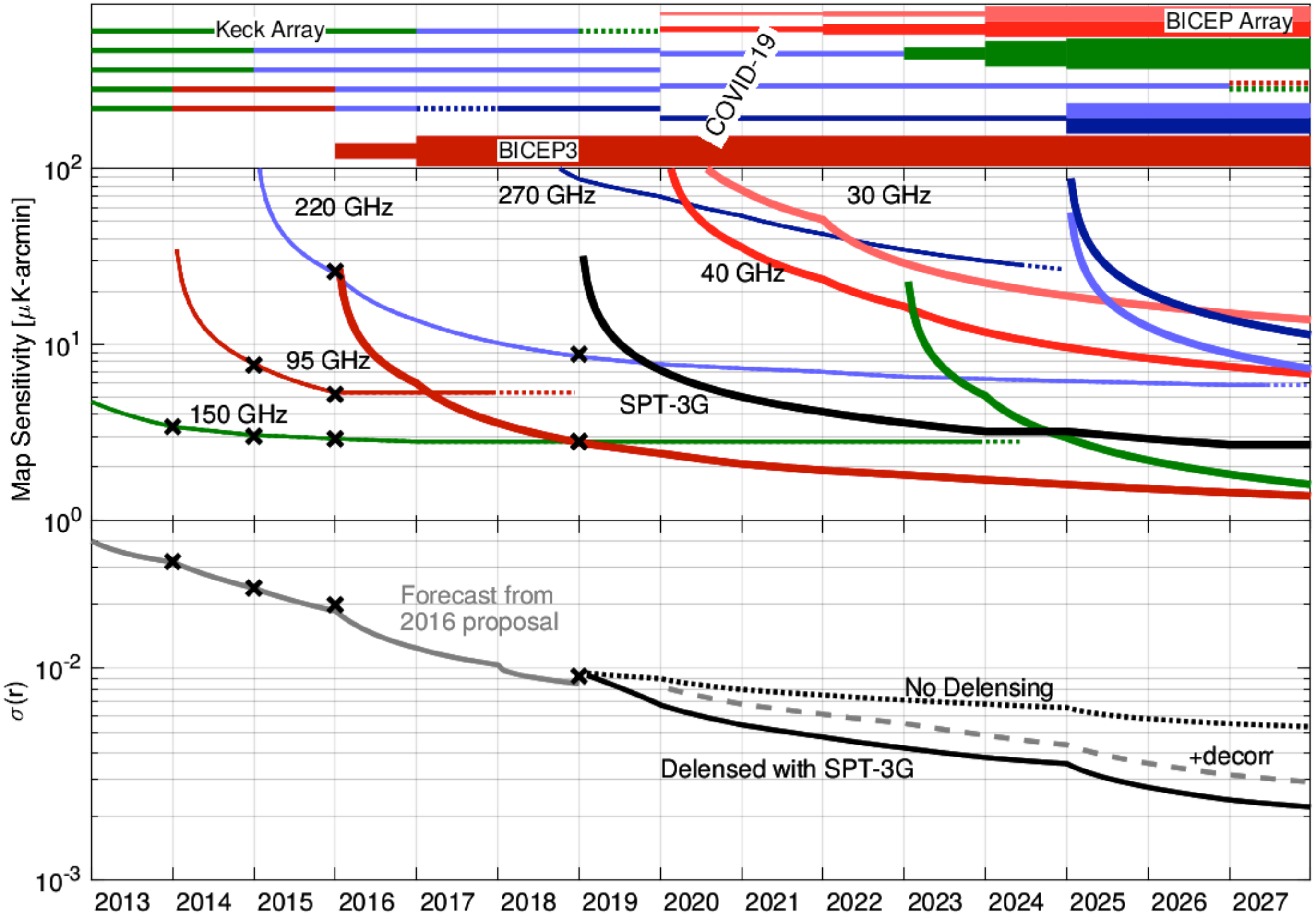




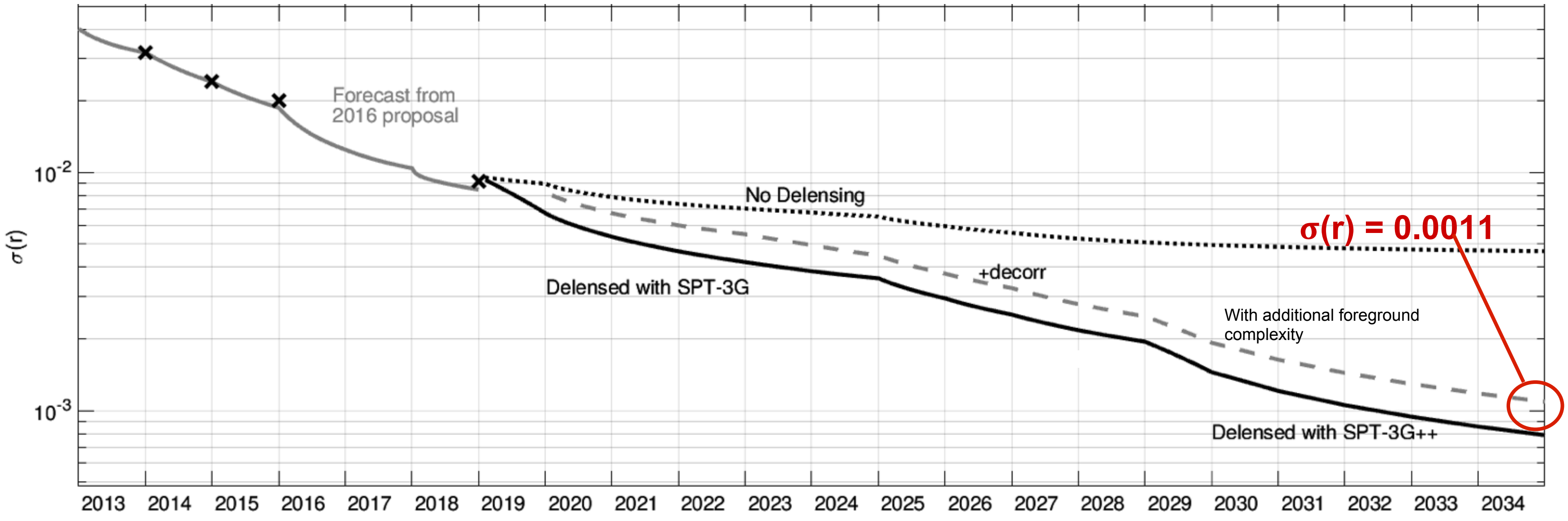
…which can then be used to calculate and remove the lensing signal enabling a deeper search for inflationary gravitational waves

BICEP+SPT=SPO (South Pole Observatory)

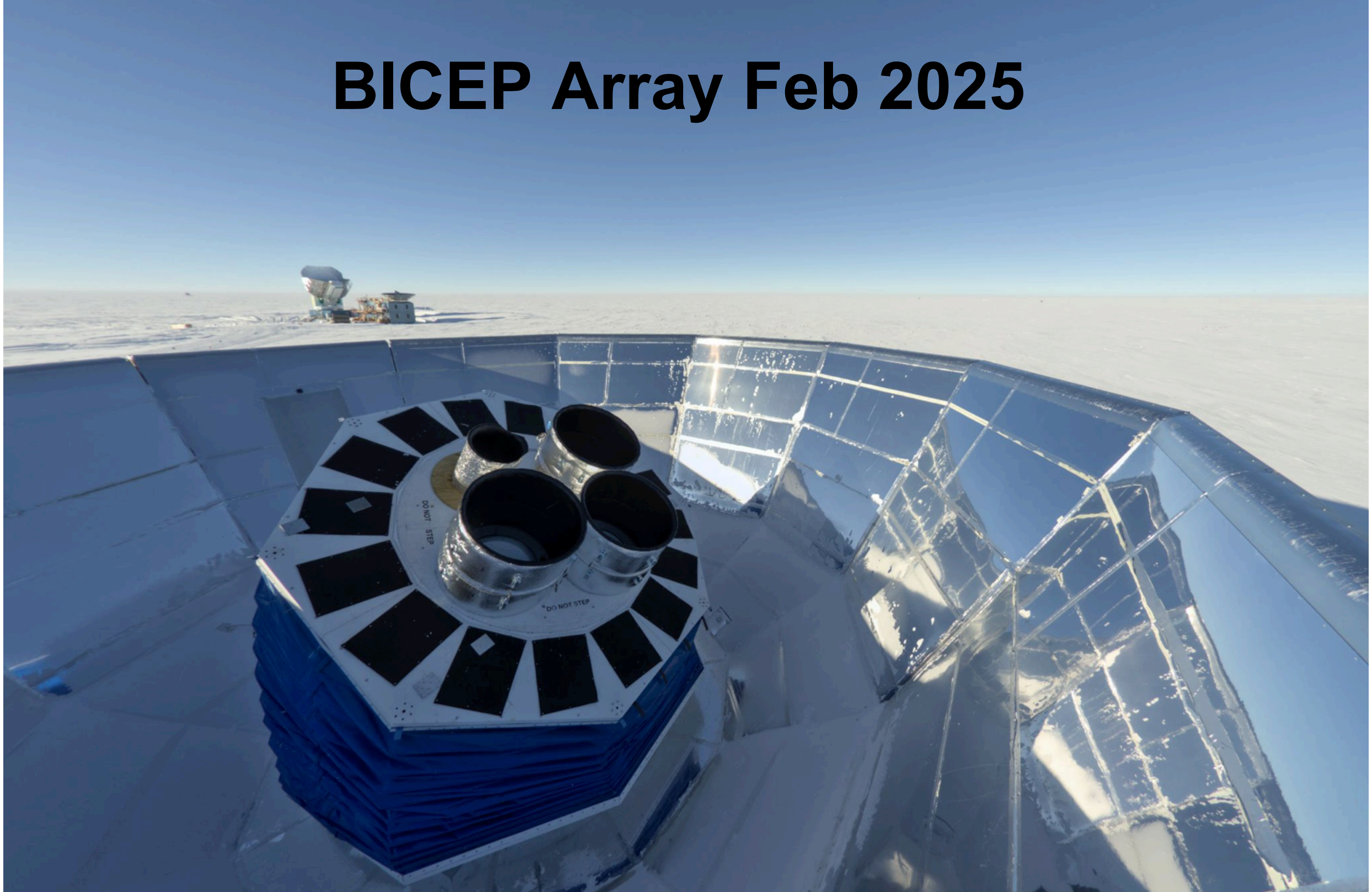
Past sensitivity and near future projection using instrumentation which exists or soon will



Projection out to 2034 assuming SPT-3G+ starts to observe in 2029 season and BICEP Array receives some upgrades.

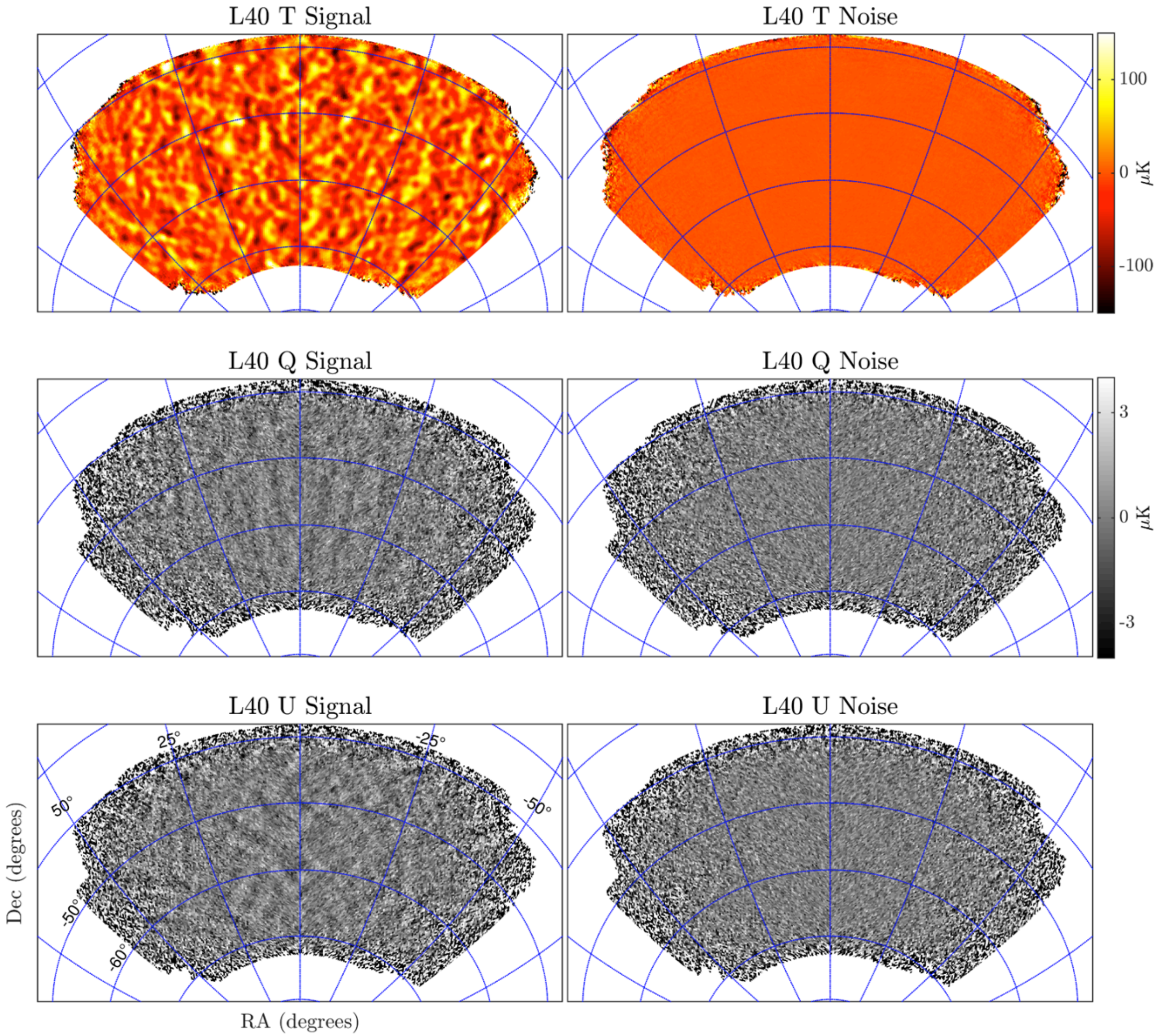


BICEP Array Feb 2025

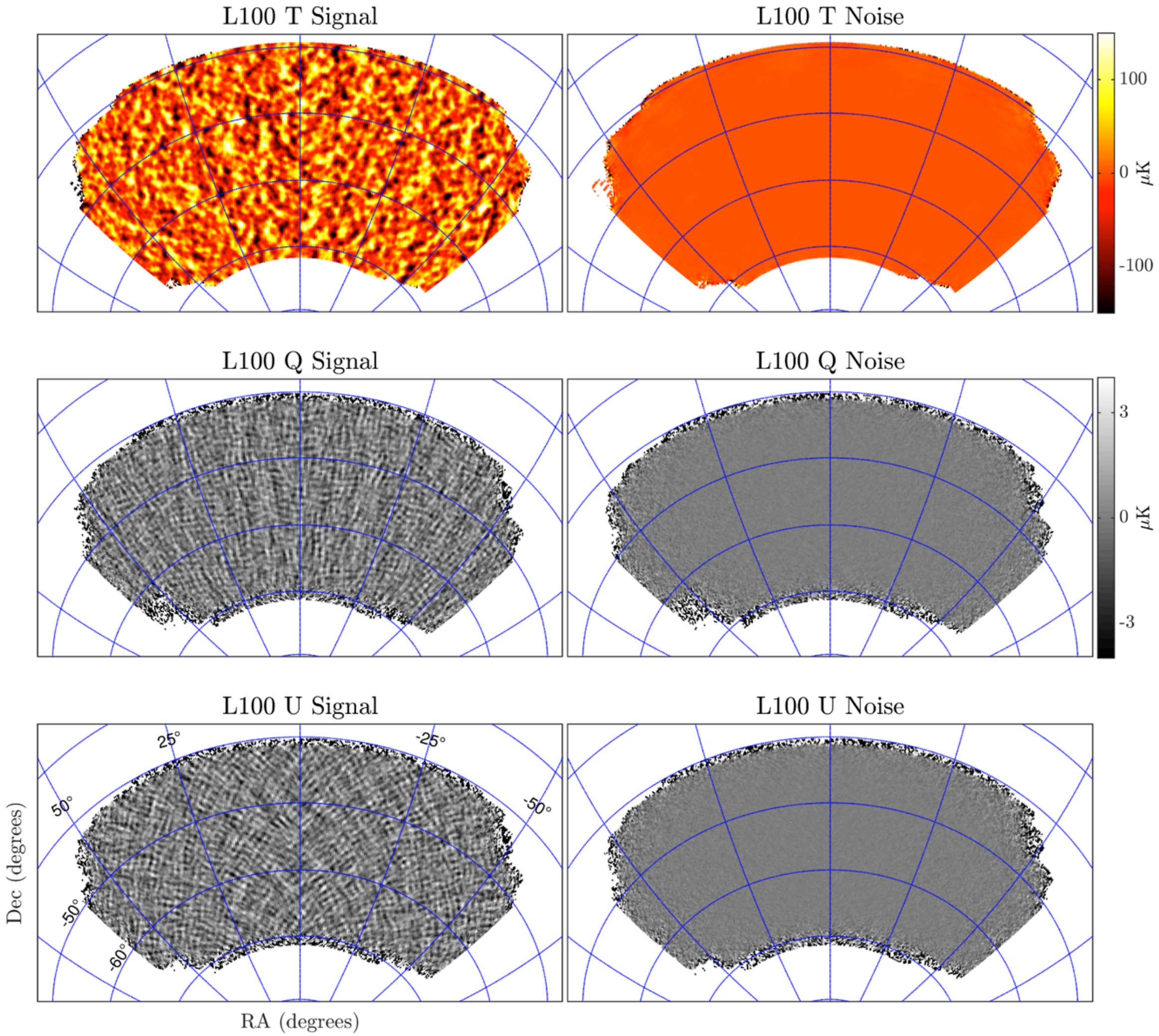


BICEP Array Feb 2025

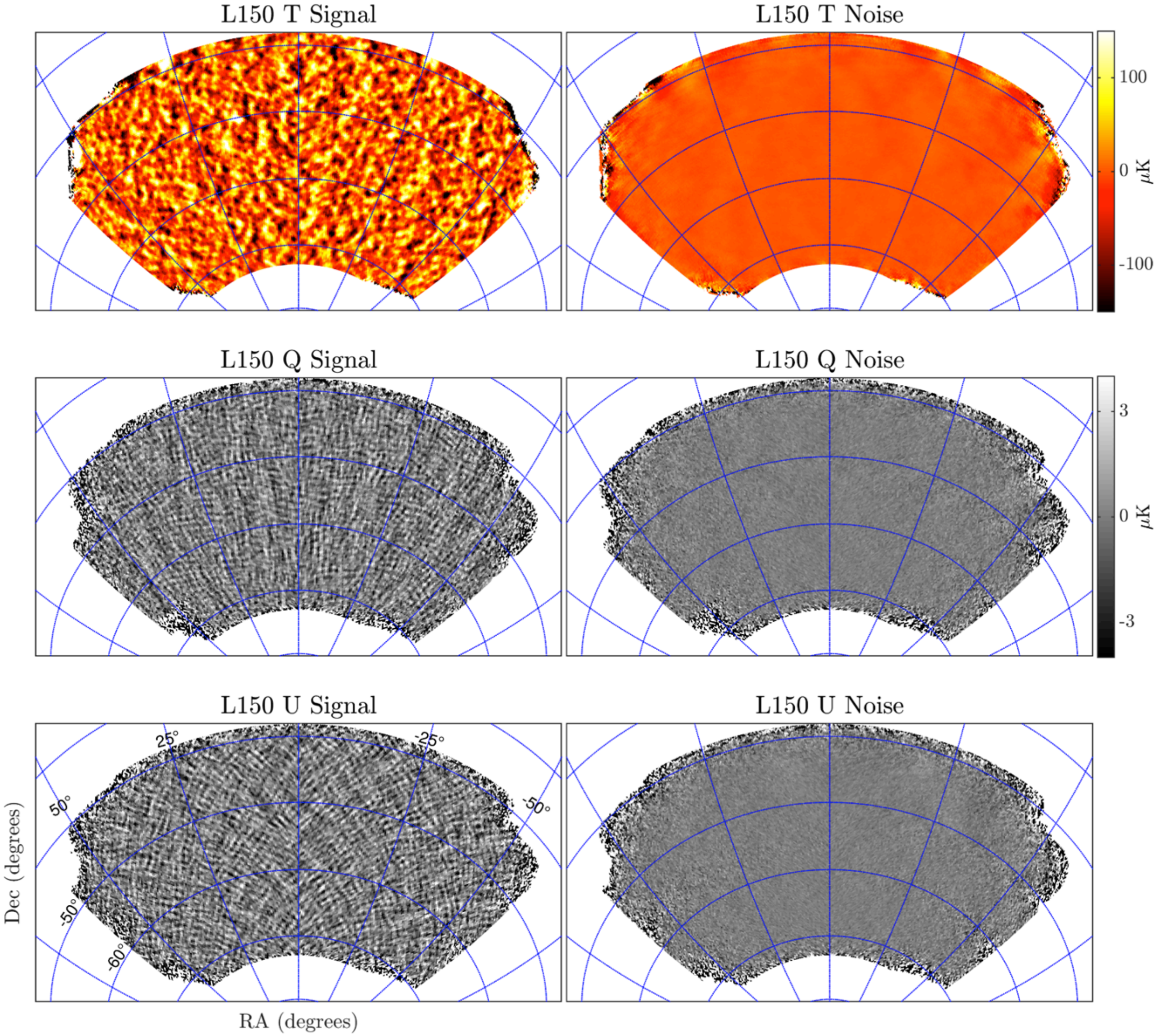
BK24
40GHz
Maps
5 years of
data



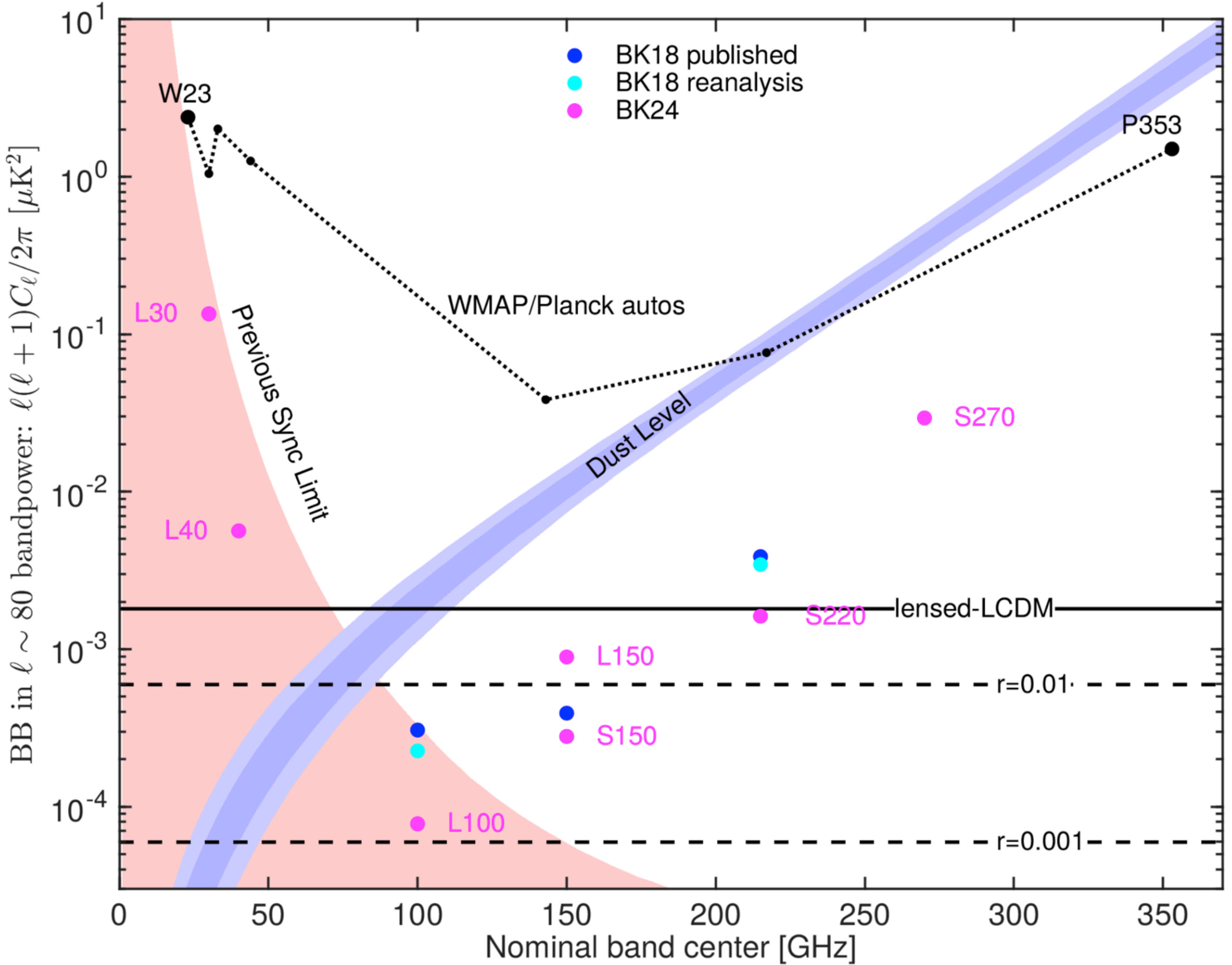
BK24
100GHz
Maps
9 years of
data



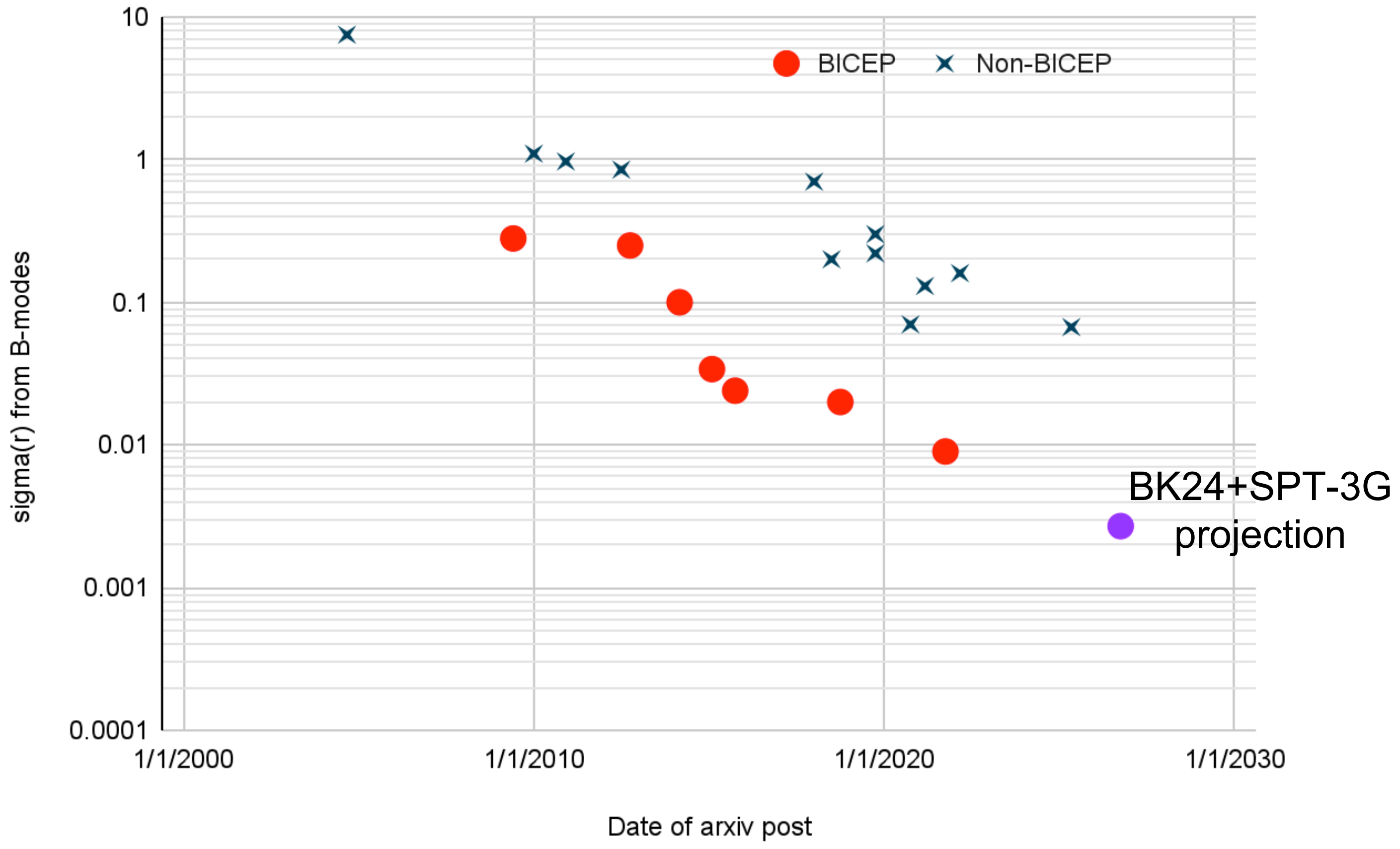
BK24
150GHz
Maps
2 years of
data



BK24 noise level in the ell=80 bandpower



Published sensitivity to *r* from B-modes over time

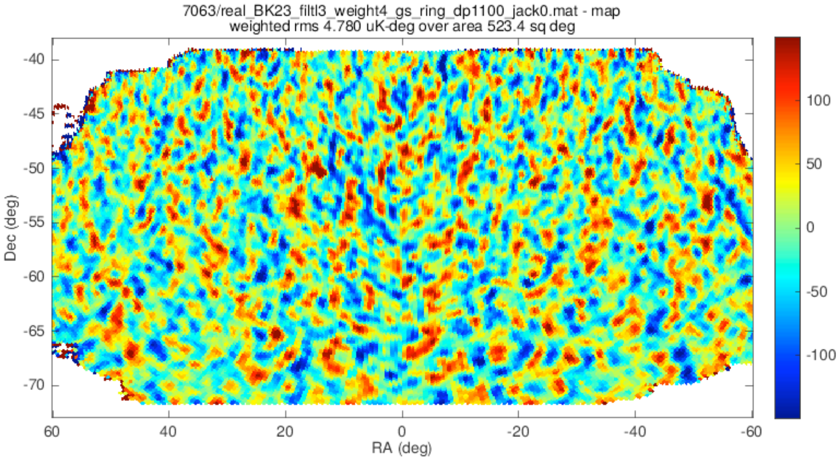


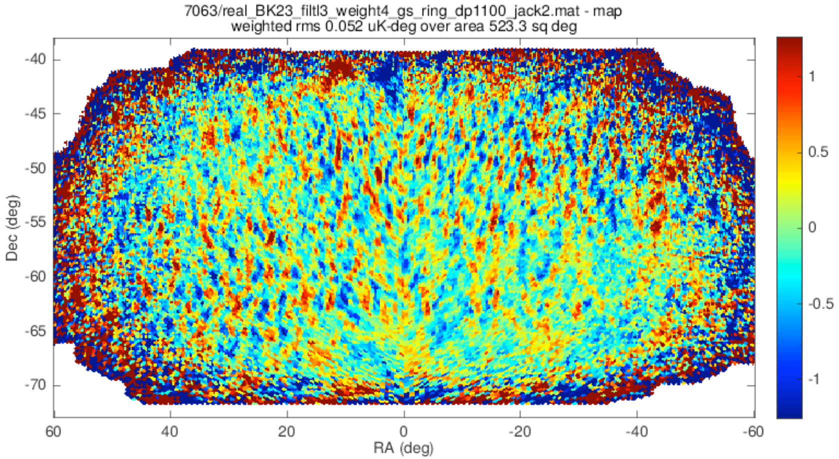
So why so slow?

- BK18 (data up to 2018) came out in fall 2021 – approaching 4 years ago – a ~3 year "analysis delay"
- "So why no new result yet?" you may ask.
- We are trying to get to a BK24 result (data up to 2024) so if that comes out next year (2026) we will actually be catching up on real time
- Up to 2024 each result built on top of the analysis and data products of the previous release
- This was no longer sustainable and for BK24 we have reworked everything pretty much from the ground up – this took time
- But the main delay has been getting the data to pass internal consistency tests – getting rid of real but subtle systematic contamination in the ultra deep BICEP3 9-year map
- This is not optional – it would be a piece of cake to publish a result with a few sigma false upward bias on the r constraint curve
- Until the null tests pass we do not look at the real data result

Null tests aka jackknives

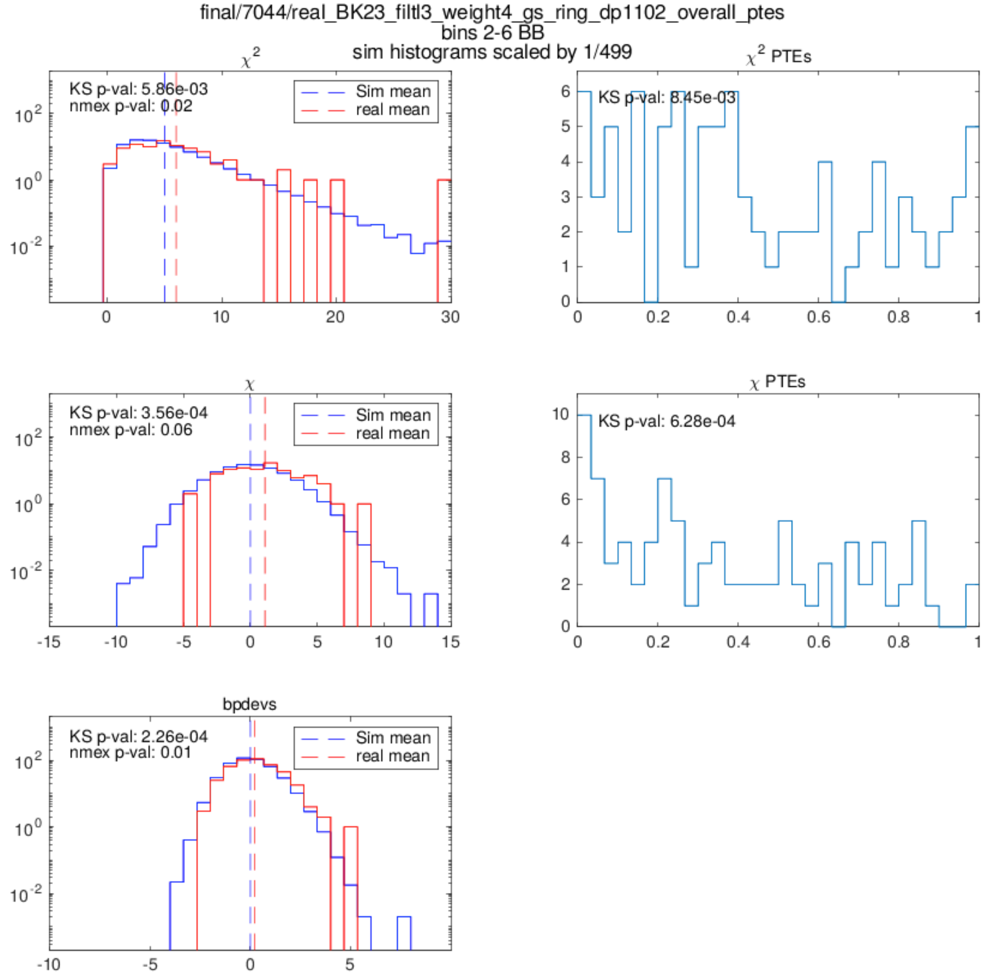
➢ Traditionally our main empirical test for systematic contamination
➢ Split the data set into two parts (usually roughly equal), form Q/U maps of the sky with each part, take the difference of these maps, and take the power spectrum of that.
➢ In an ideal world the true sky signal exactly cancels but systematic contamination may not do so - depending on how one has selected the split.





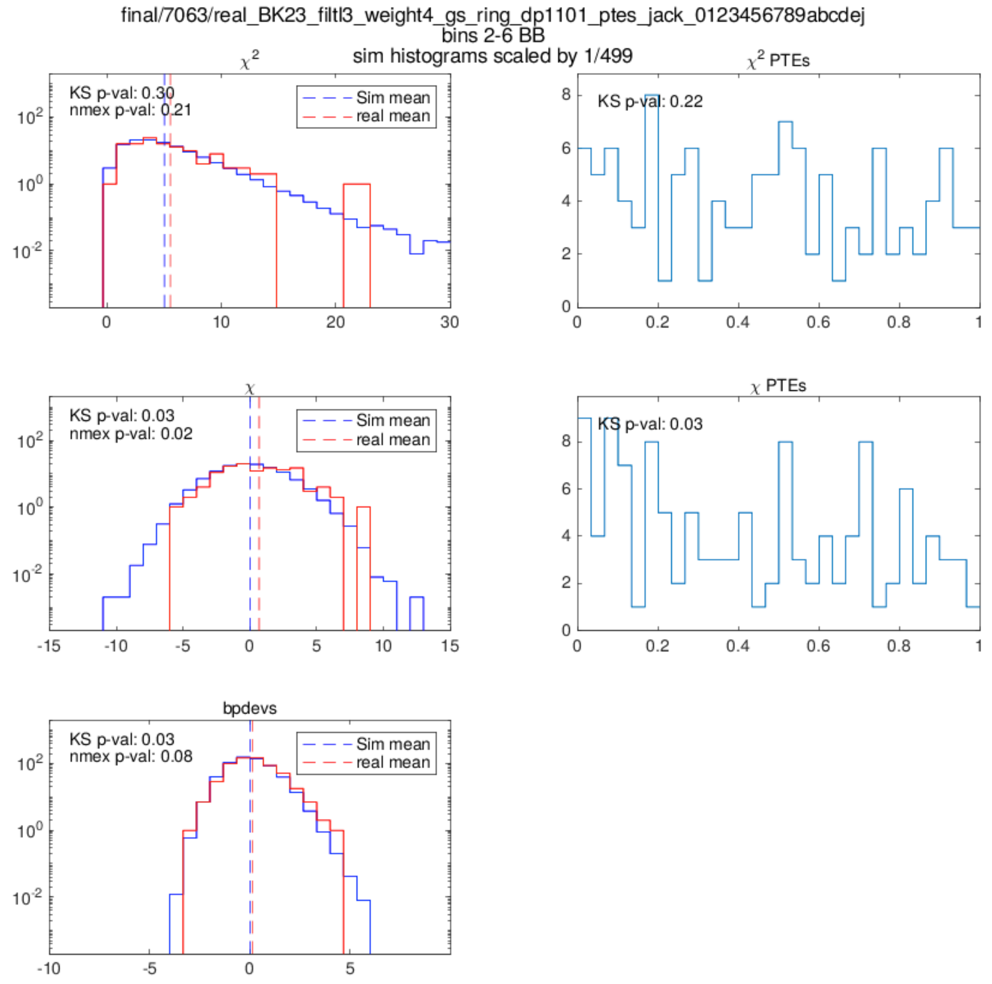
The above is BICEP3 scan direction T map and scan direction difference – percent level residuals
It is rarely possible to actually see polarization jackknife failures in the maps

BB jackknife summary statistics as of 2024/09

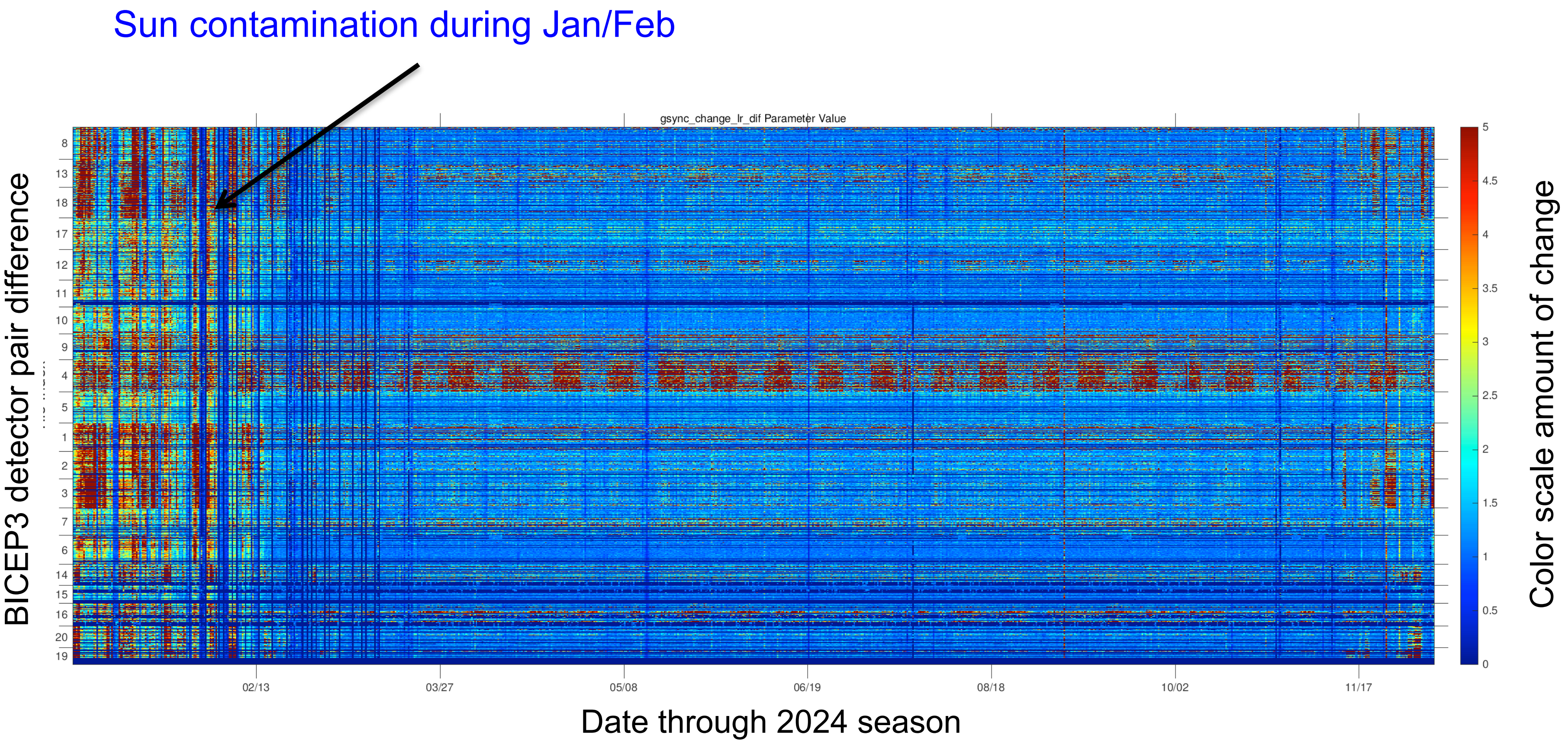


BB jackknife summary statistics as of 2025/05

We are cleaning out subtle systematic contamination. Kill the most obvious outlier and other jacks get better as well…



Parameter designed to look for change in scan synchronous pickup left vs right scan direction



Conclusions

- BICEP/Keck leads 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 (BK18):
- r<0.036 and sigma(r)=0.009 - ruling out multiple model classes
- For the first time no foreground priors from other regions of sky

- Next gen BICEP Array is now running and delensing with SPT being implemented
- With data in the can we expect sigma(r)~0.003 out next year (2026)
- With upgrades to BICEP and SPT we project sigma(r)~0.001 by 2034