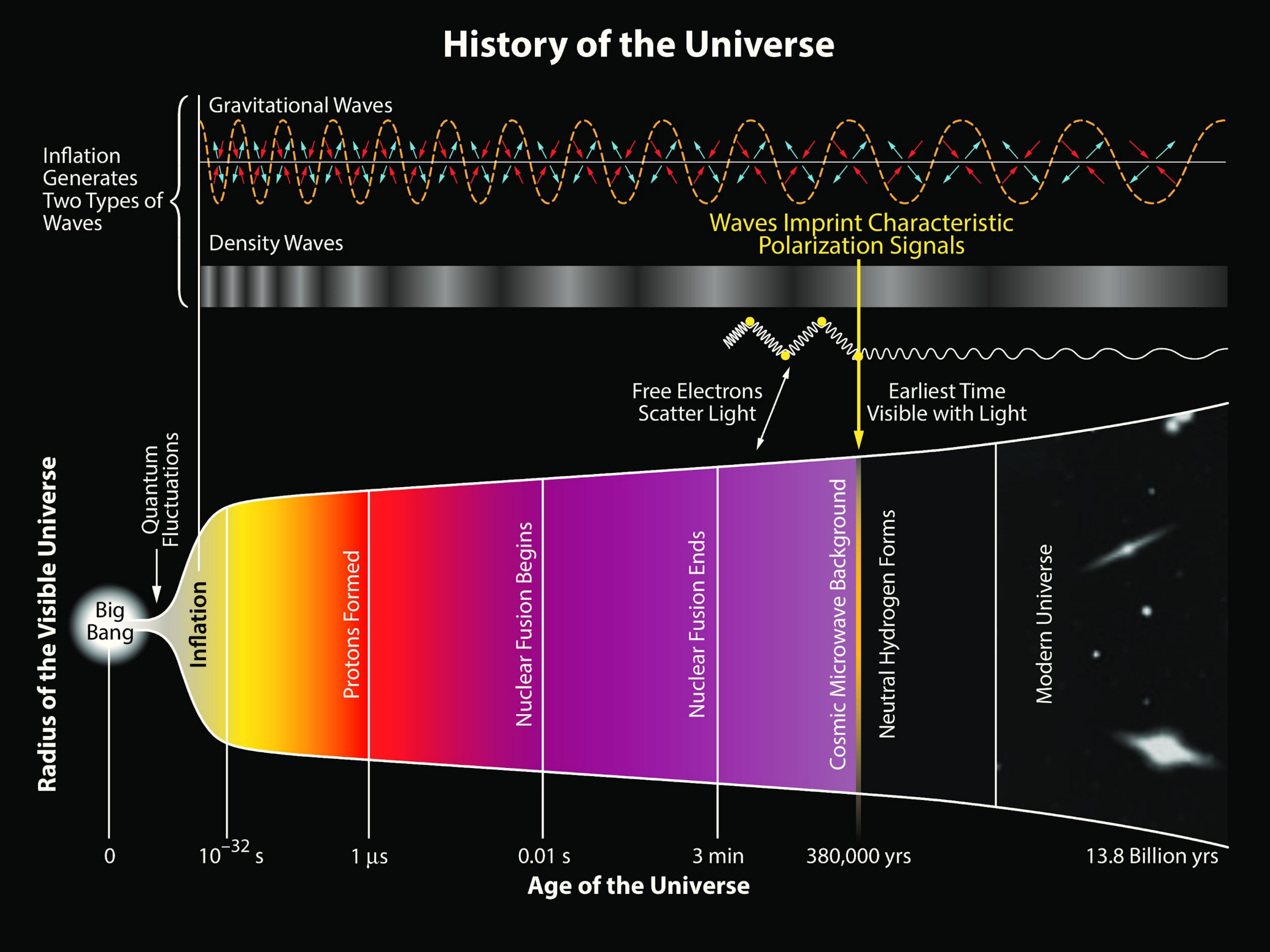
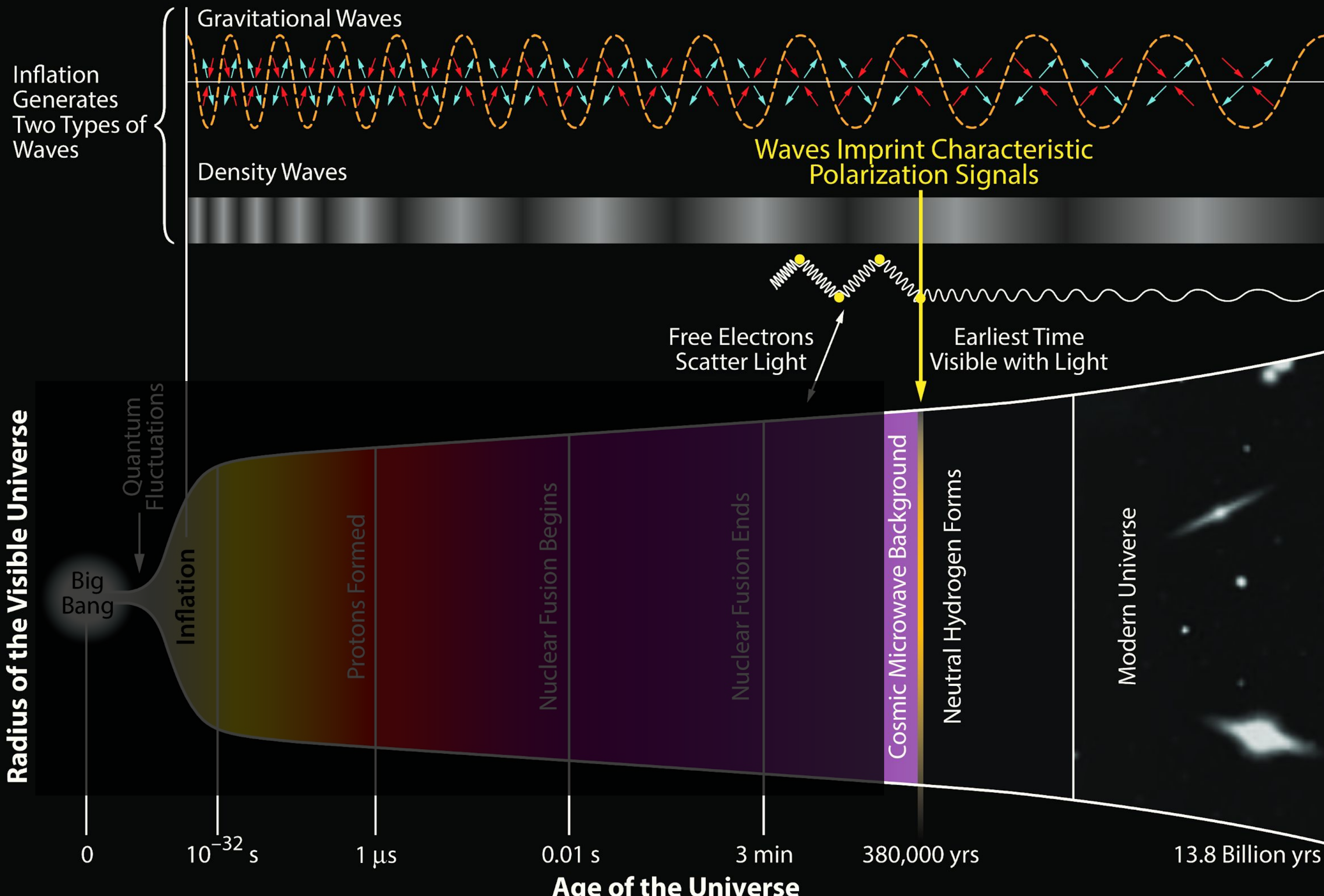
Searching for Evidence of Cosmic Inflation with BICEP Array

Aaron Steiger

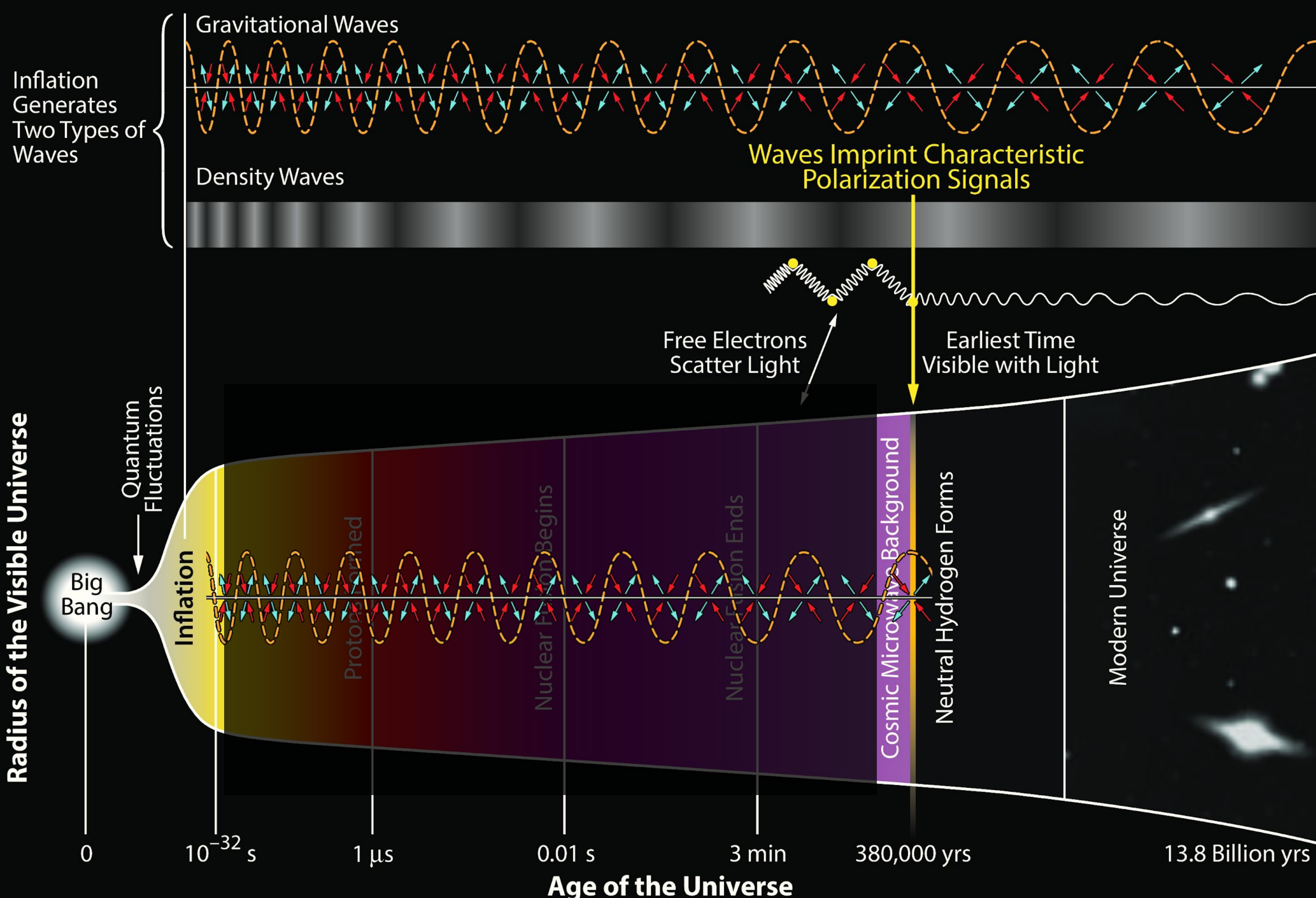


History of the Universe
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
Radius of the Visible Universe
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



History of the Universe

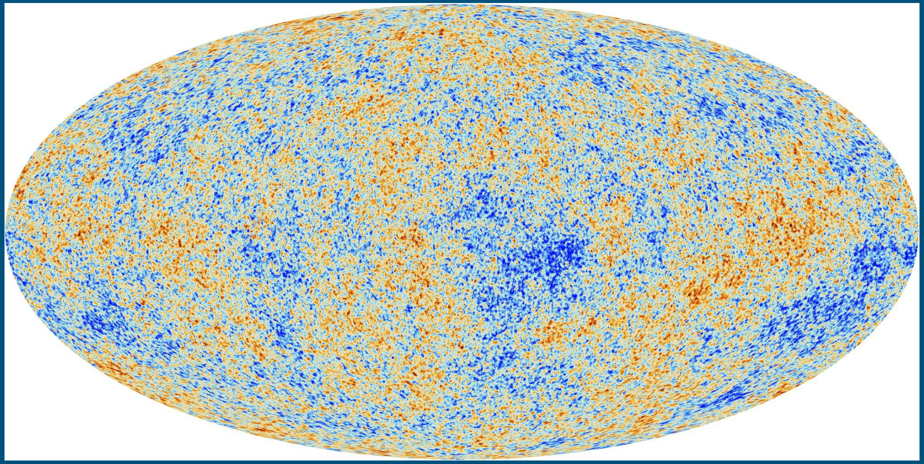


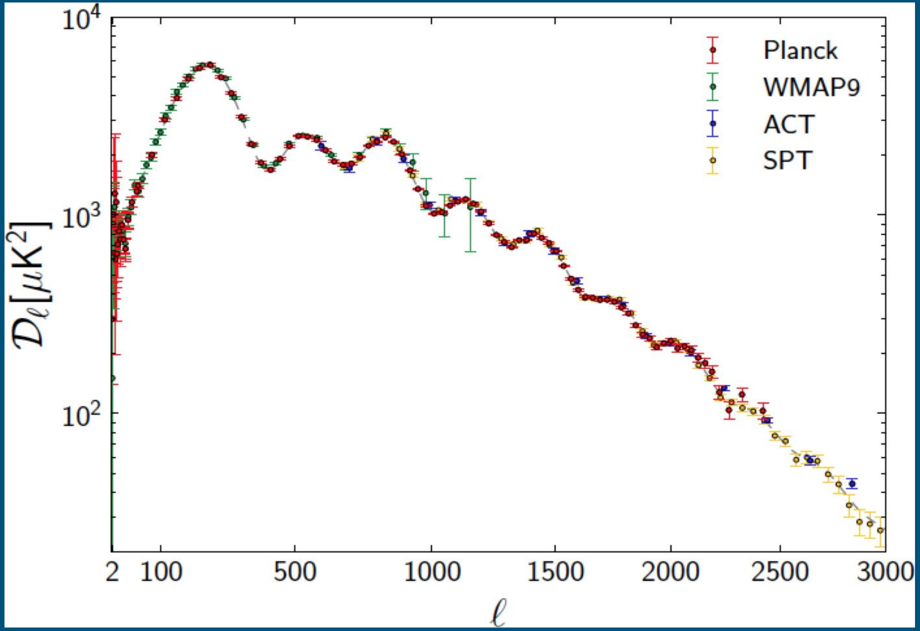
Cosmic Microwave Background (CMB) Experiments

The CMB traces the conditions of the universe at the time when atoms first began to form.

Precision measurements of the CMB temperature have provided a wealth of cosmological information consistent with the inflationary paradigm.

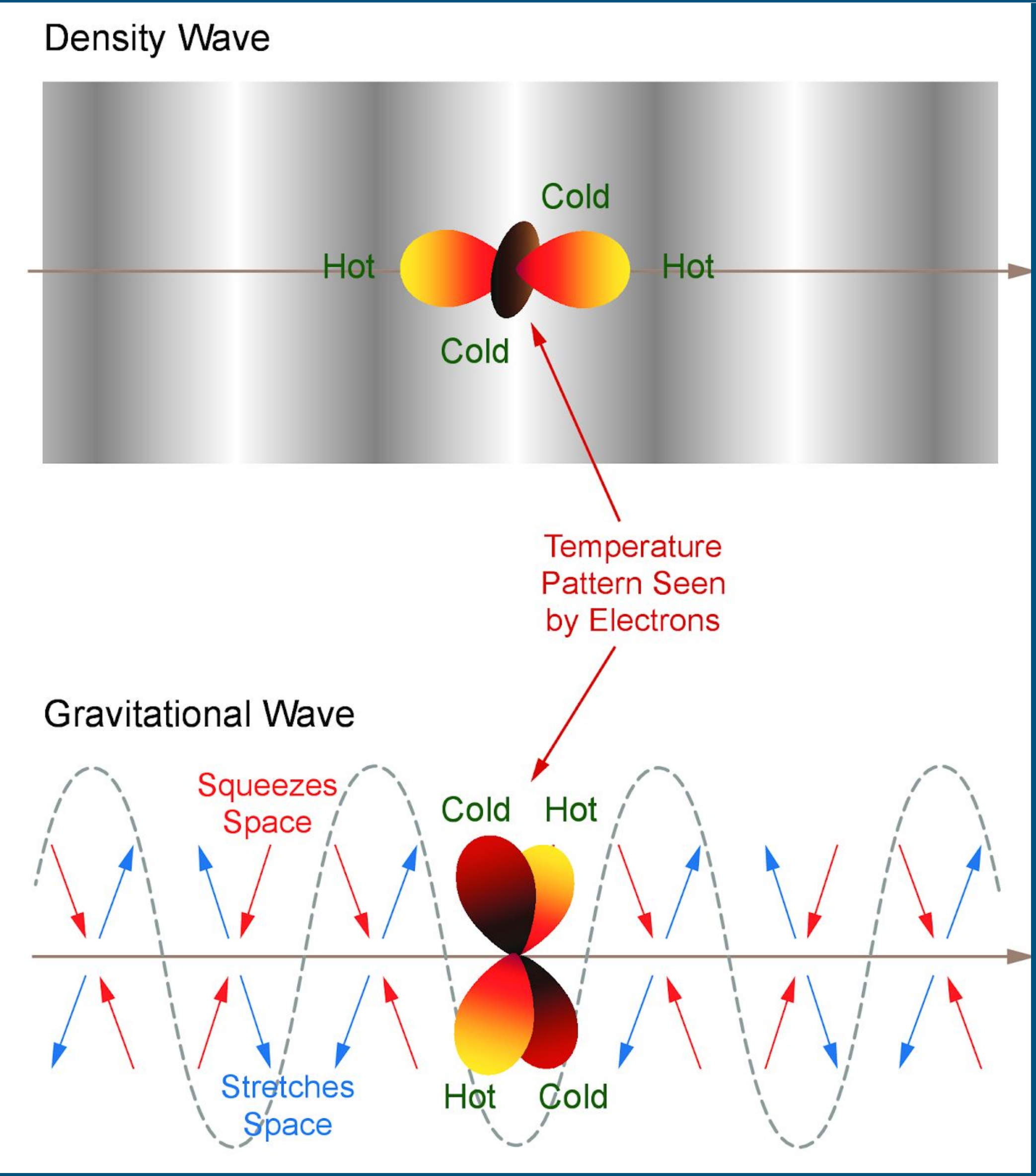
However, any imprint of the inflationary gravitational waves have so far eluded detection in the CMB.



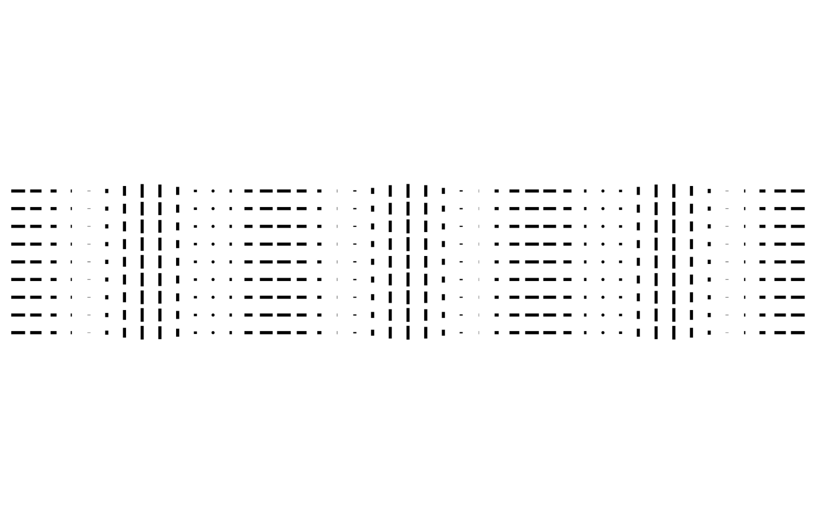


Planck Collaboration & ESA

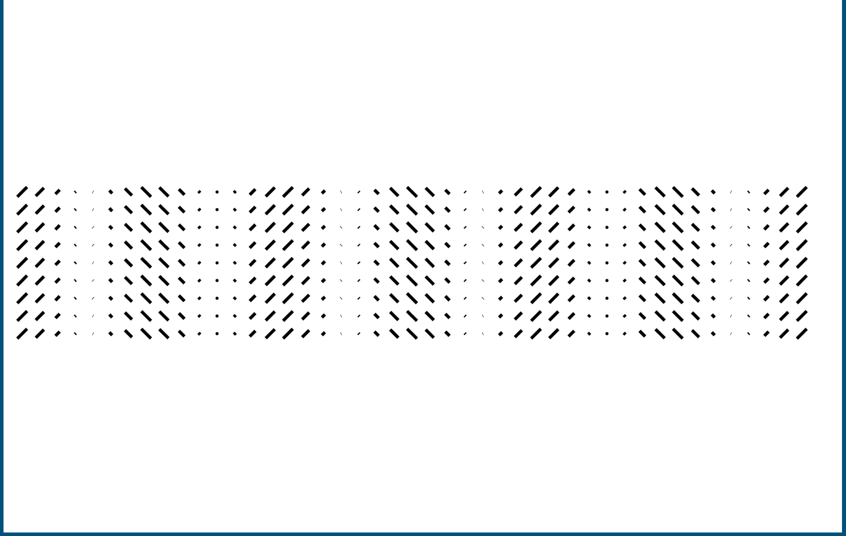
CMB Polarization



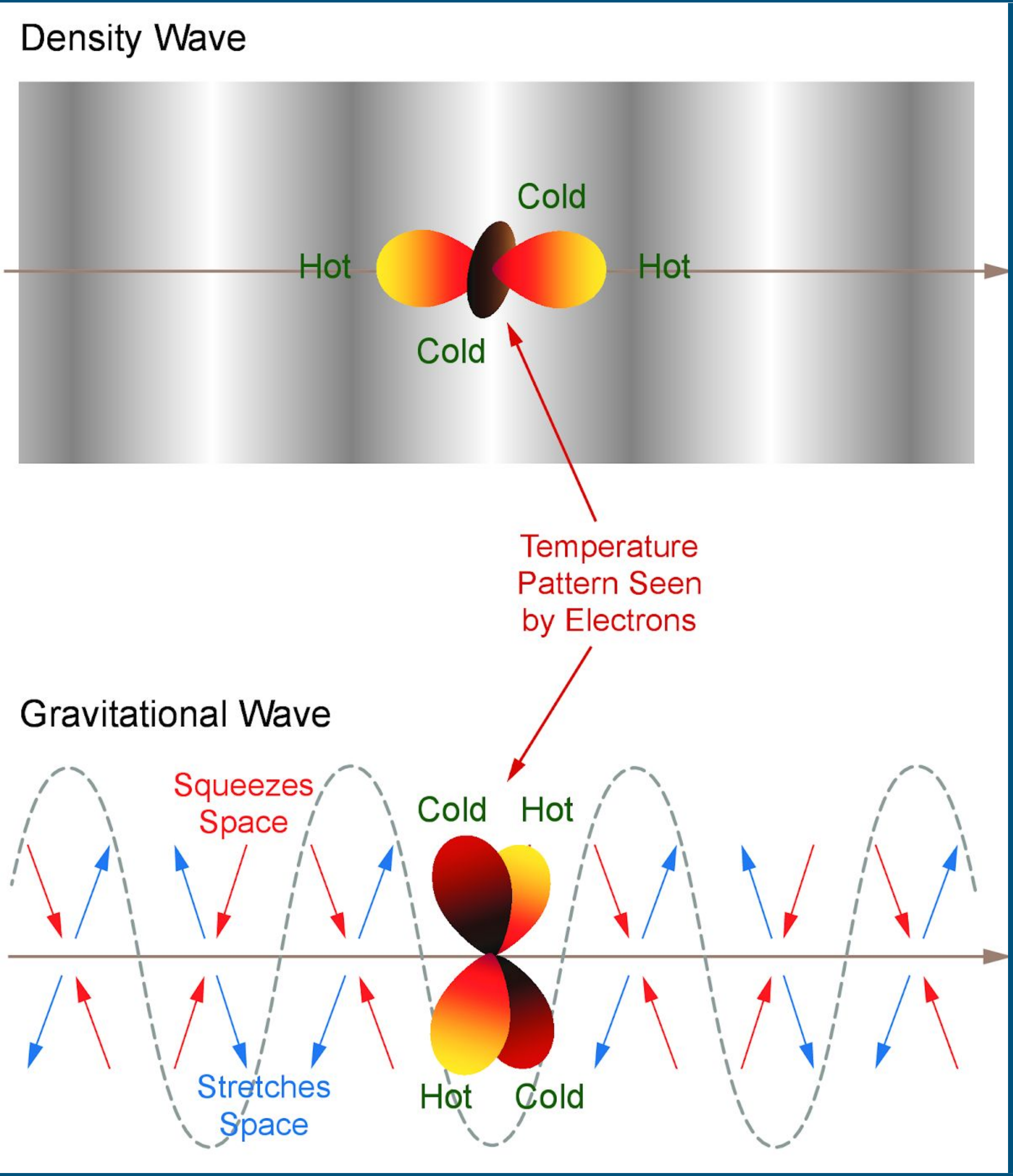
E-Mode Polarization Pattern

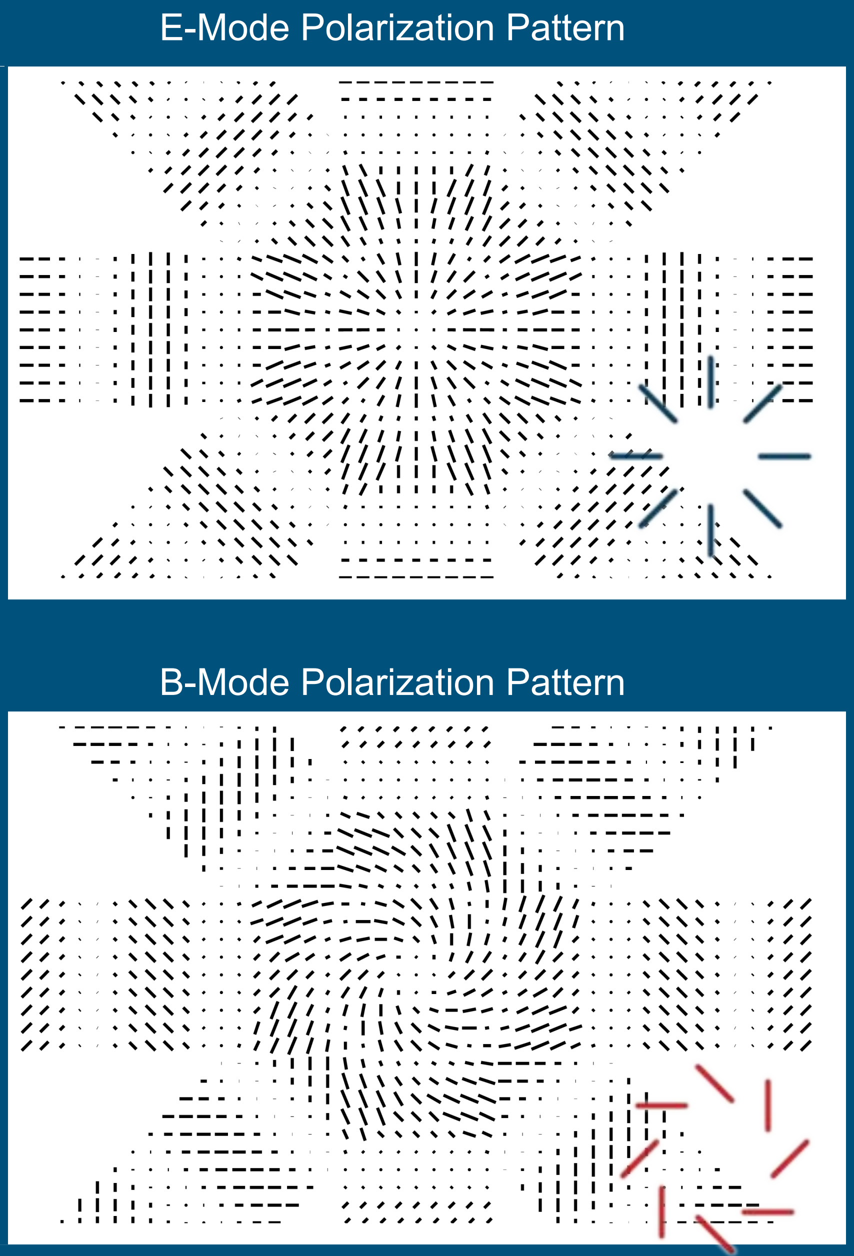


B-Mode Polarization Pattern



CMB Polarization





Creating E and B Power Spectra

The first step is creating maps of the Stokes parameters Q and U, conventionally defined as

$$I \equiv \langle |E_x|^2 \rangle + \langle |E_y|^2 \rangle$$

$$Q \equiv \langle |E_x|^2 \rangle - \langle |E_y|^2 \rangle$$

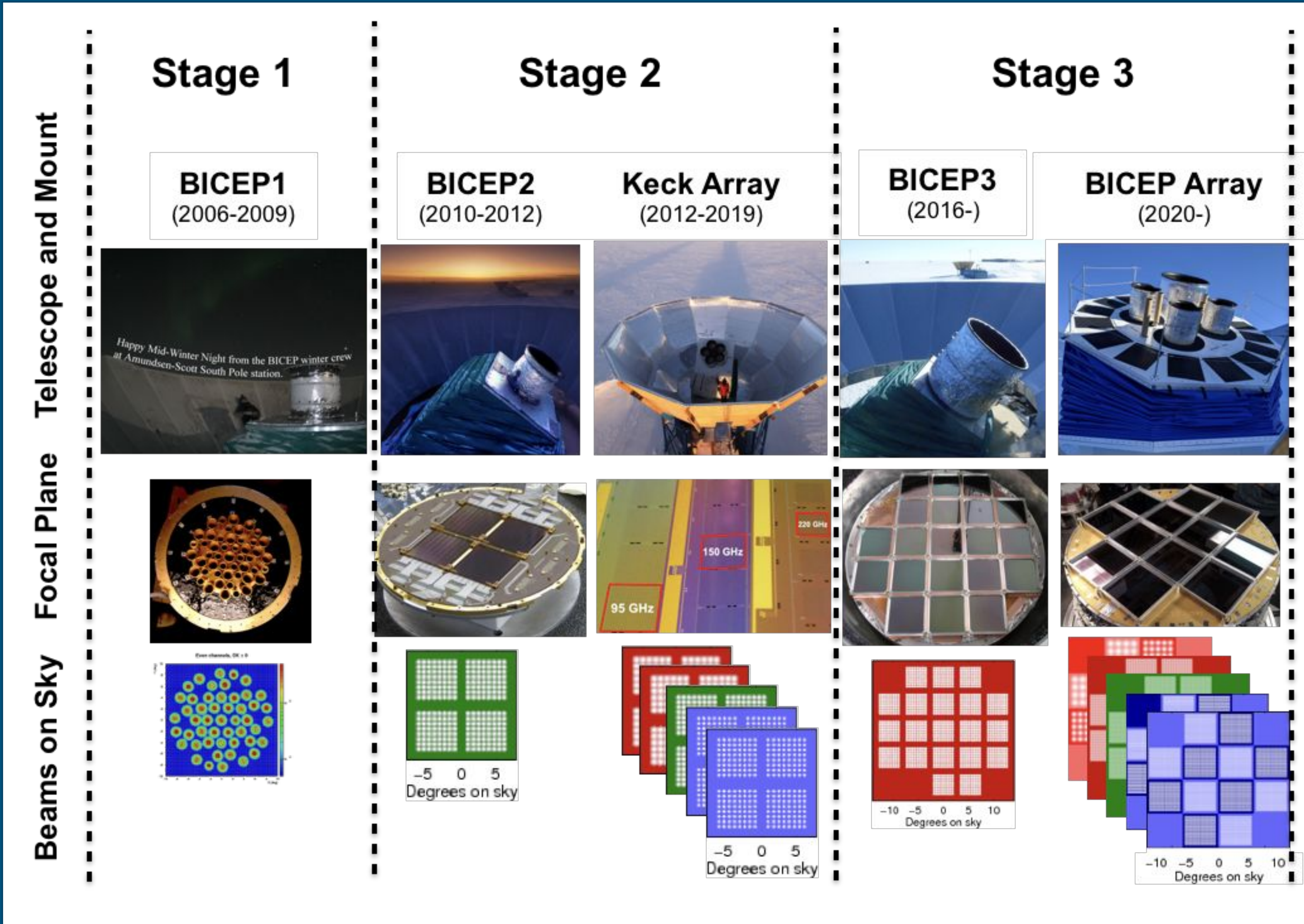
$$U \equiv 2\langle |E_x||E_y| \cos(\delta) \rangle$$

Full sky complex fields Q±iU can be decomposed into spherical harmonics, and E and B are simply related in Fourier space to the Q and U spectra as

$$\begin{bmatrix} \tilde{M}_E(\vec{\ell}) \\ \tilde{M}_B(\vec{\ell}) \end{bmatrix} = \begin{bmatrix} \cos(2\phi) & \sin(2\phi) \\ -\sin(2\phi) & \cos(2\phi) \end{bmatrix} \begin{bmatrix} \tilde{M}_Q(\vec{\ell}) \\ \tilde{M}_U(\vec{\ell}) \end{bmatrix}$$

The rotation angle here is twice the polar angle of each Fourier mode i.e.

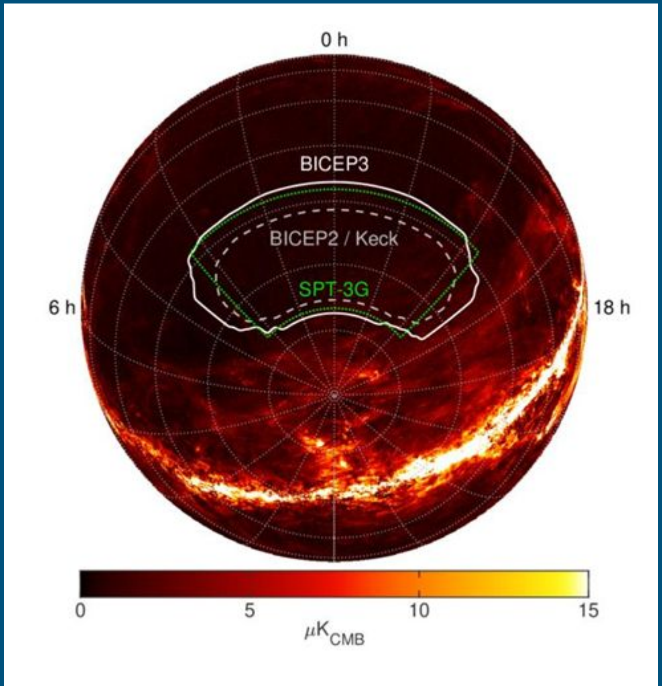
$$\vec{\ell} = (\ell_x, \ell_y) = (\ell \cos\phi, \ell \sin\phi)$$



Stage 1
Stage 2
Stage 3
BICEP1 (2006-2009)
BICEP2 (2010-2012)
Keck Array (2012-2019)
BICEP3 (2016-)
BICEP Array (2020-)
Telescope and Mount
Focal Plane
Beams on Sky
Happy Mid-Winter Night from the BICEP winter crew at Amundsen-Scott South Pole station.
220 GHz
150 GHz
95 GHz
–5 0 5
Degrees on sky
–5 0 5
Degrees on sky
–10 –5 0 5 10
Degrees on sky
–10 –5 0 5 10
Degrees on sky

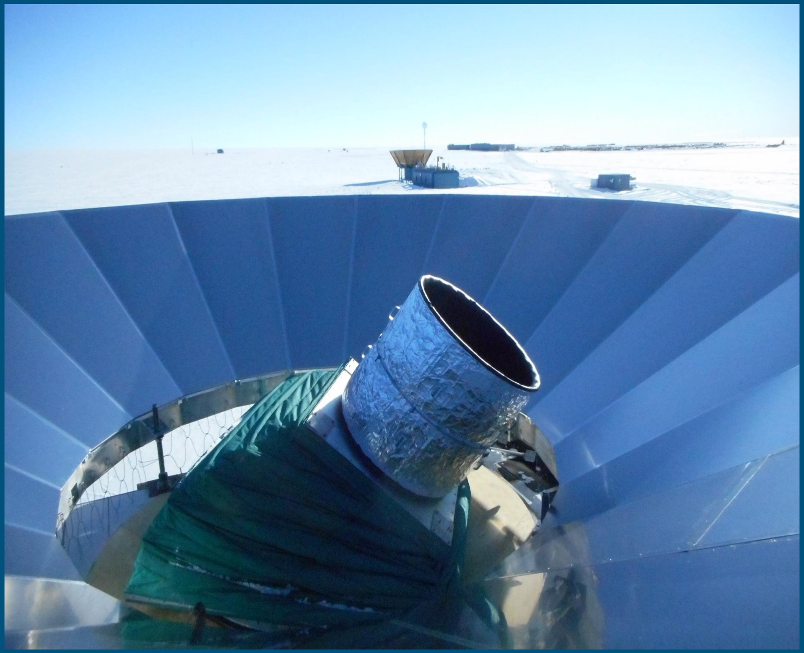
BICEP/Keck Sky Patch

One of the main advantages of observing from the south pole is we get to make very deep maps of one patch of sky, which we call the BICEP/Keck sky patch.



This patch of sky is comparatively quite low in galactic dust signal, it is centered at RA 0h, Dec. −57.5◦

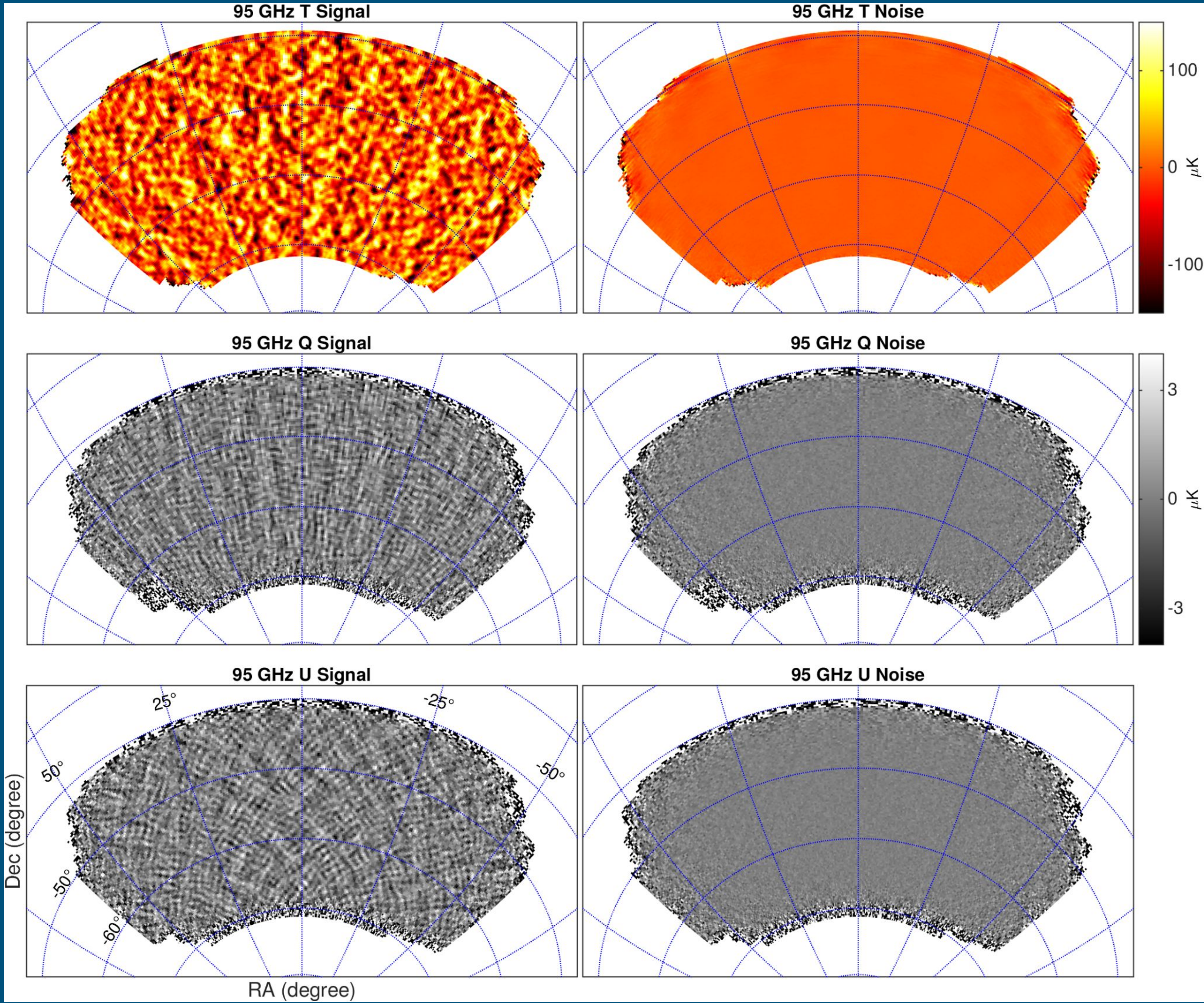
BK18 Dataset



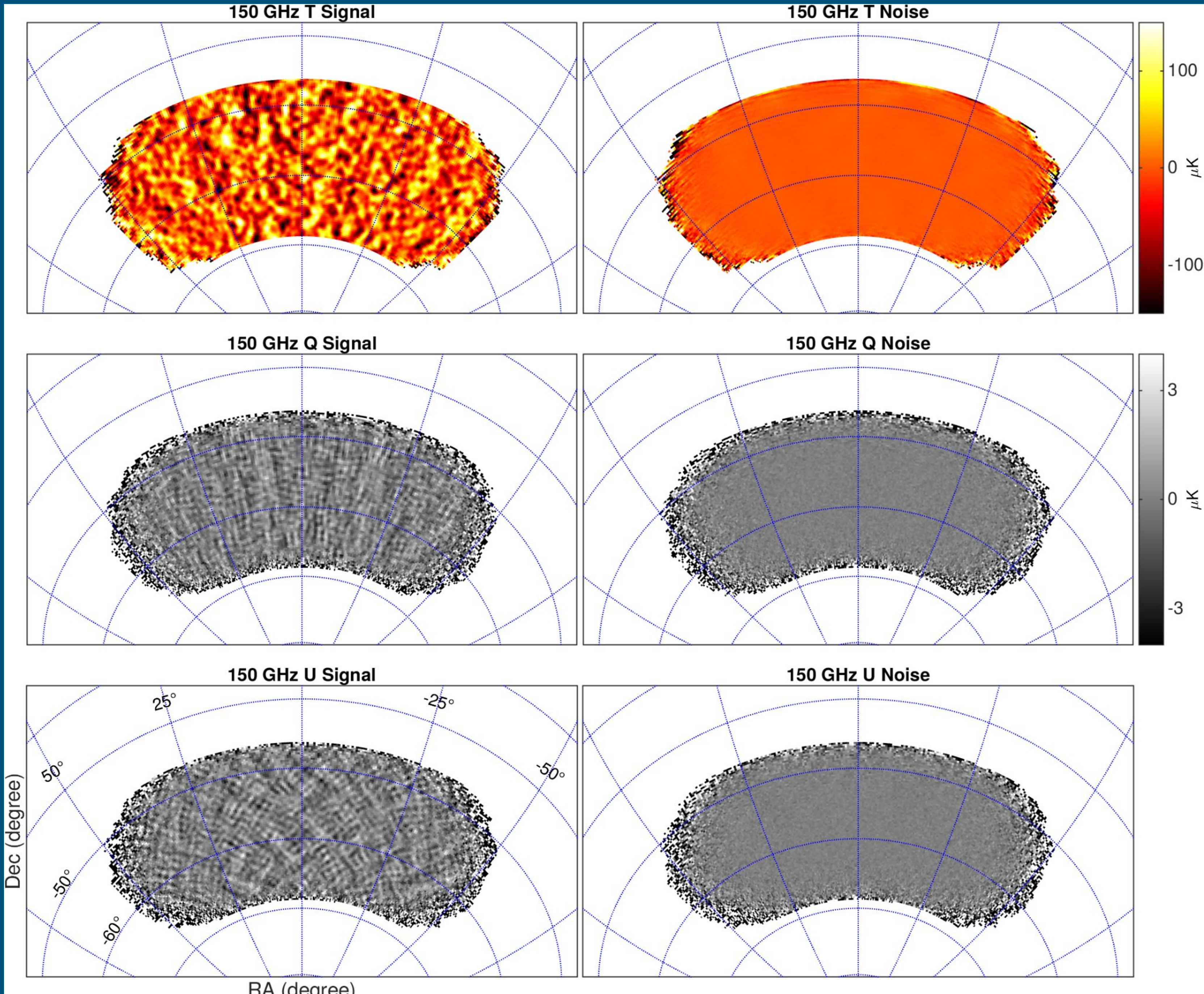
Keck Array @ 95, 150, 220 GHz
- Observed from 2012-2019
- Based on BICEP 2 design

BICEP3 @ 95 GHz
- Observing since 2016
- Significantly more sensitive than Keck receivers
- Model for BA receivers

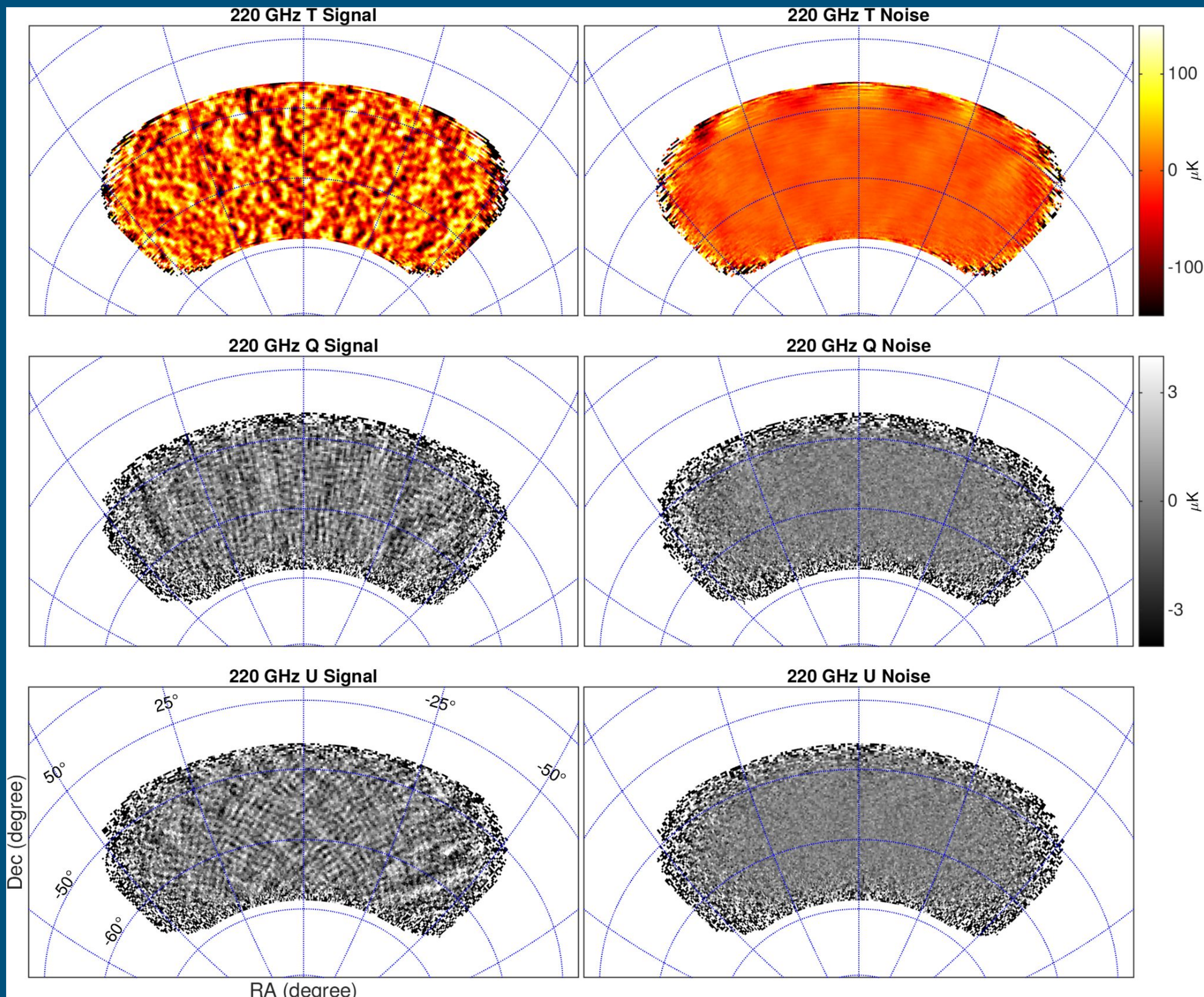
BK18
95GHz
Maps



BK18
150GHz
Maps



BK18
220GHz
Maps



LCDM Expectations

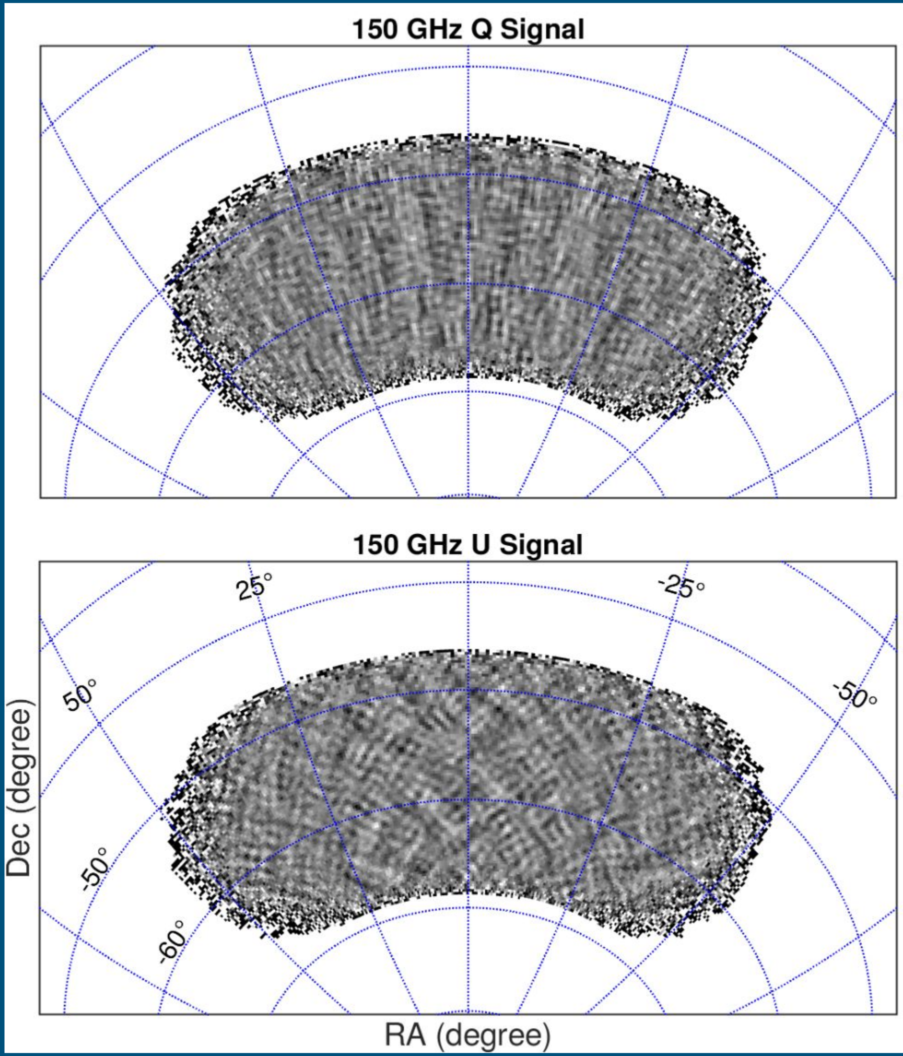
From LCDM we expect the CMB to be E mode dominated, in this case

$$\tilde{M}_Q(\vec{\ell}) \approx \cos(2\phi)\tilde{M}_E(\vec{\ell})$$

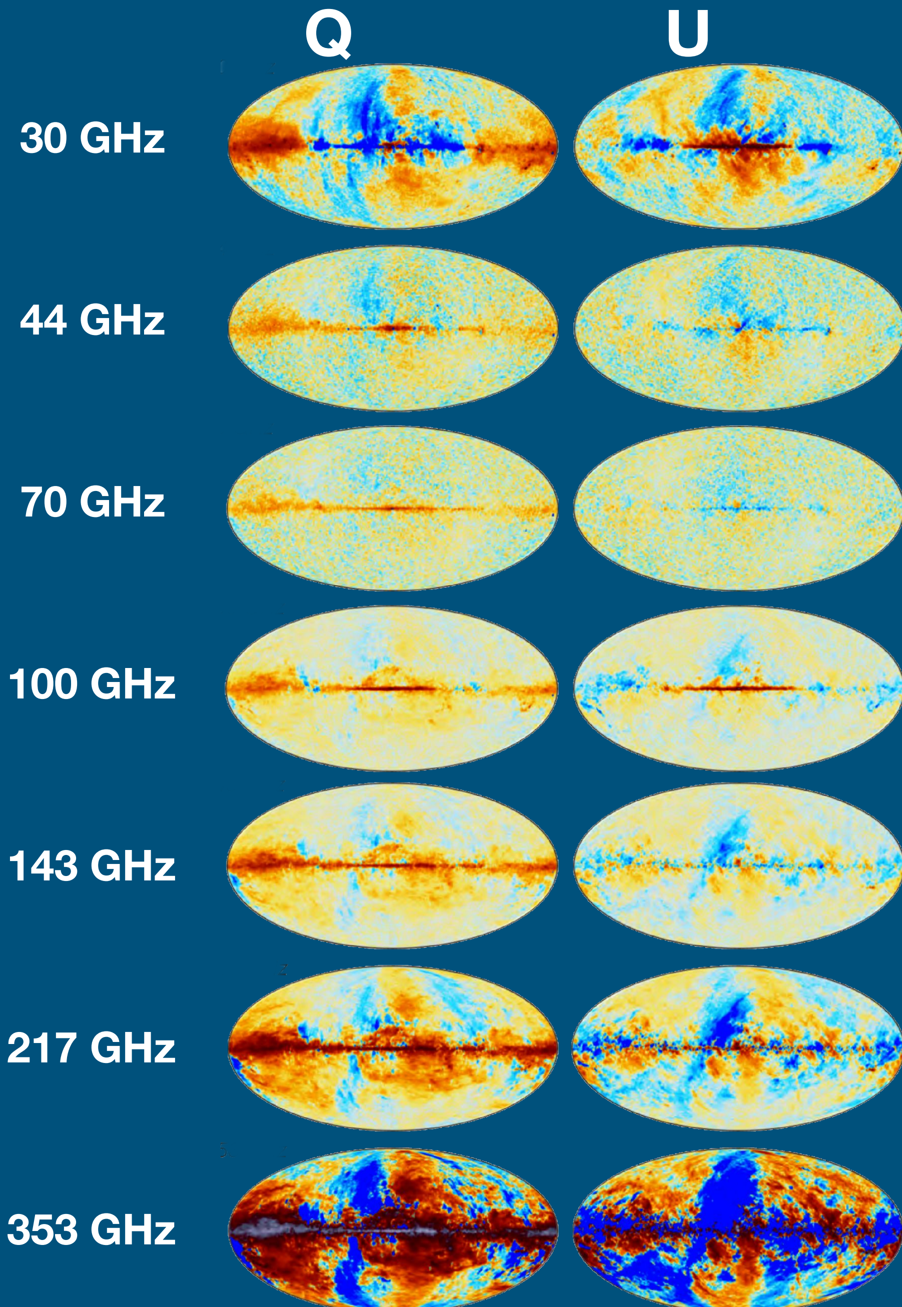
$$\tilde{M}_U(\vec{\ell}) \approx \sin(2\phi)\tilde{M}_E(\vec{\ell})$$

Then Q and U spectra are just attenuations of E, being highly suppressed when at a subset of rotation angles.

We expect E to be isotropic on sky in LCDM, so this suppression gives Q a plus pattern and U a cross pattern.

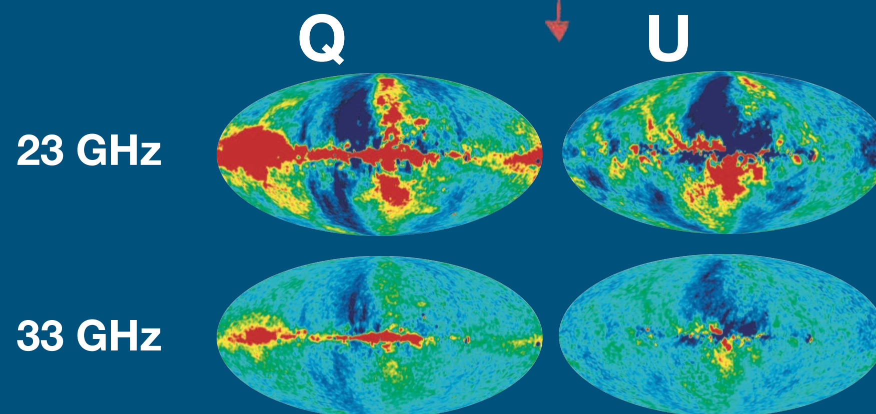


Add to the mix: Planck at 7 frequencies and WMAP at 2 frequencies



From arxiv 1502.01582

Polarized galactic **synchrotron** dominates at low frequencies

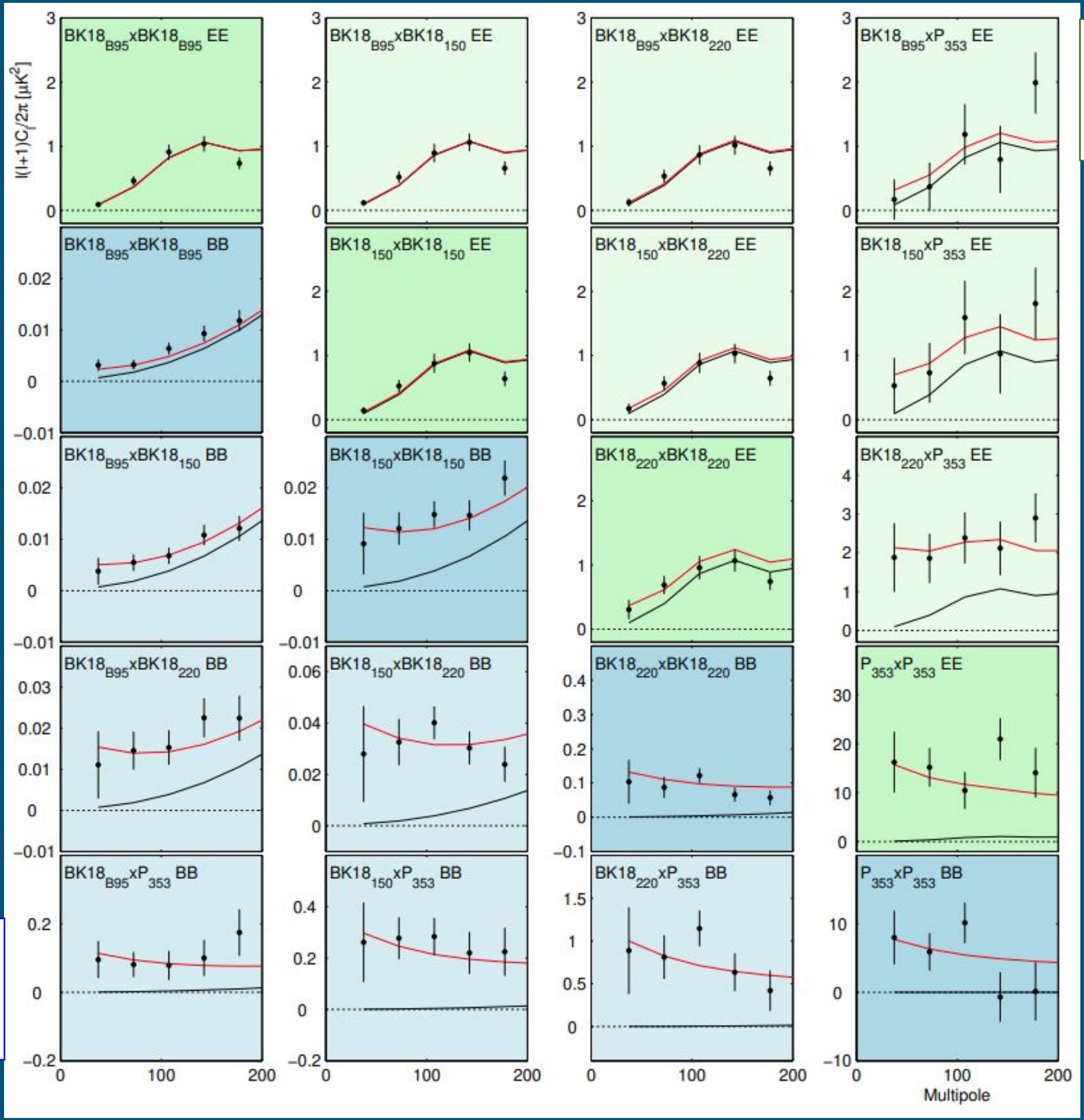


From arxiv 1212.5225

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

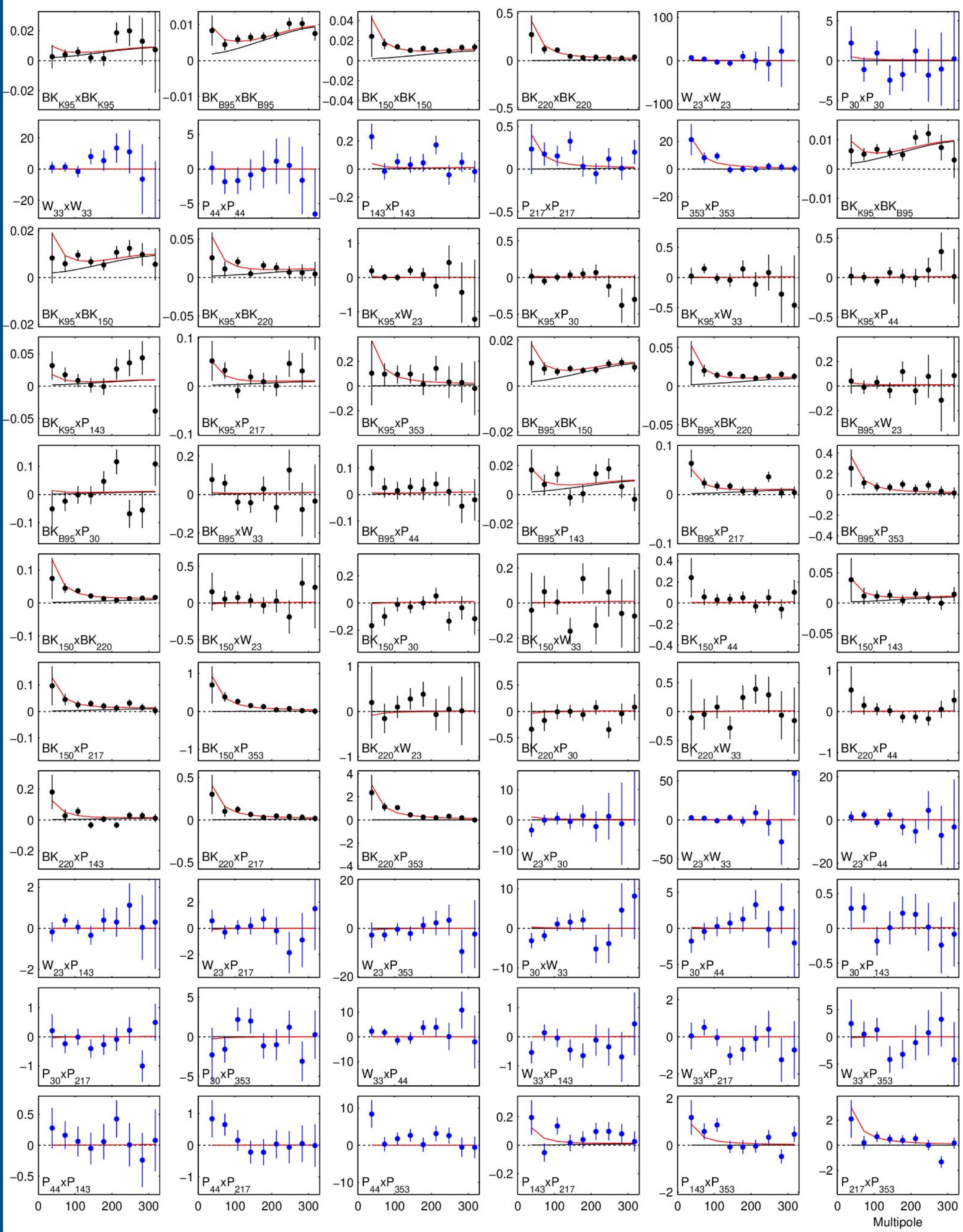


Green panels are EE spectra

Blue panels are BB spectra

BK18

All BB auto and cross spectra



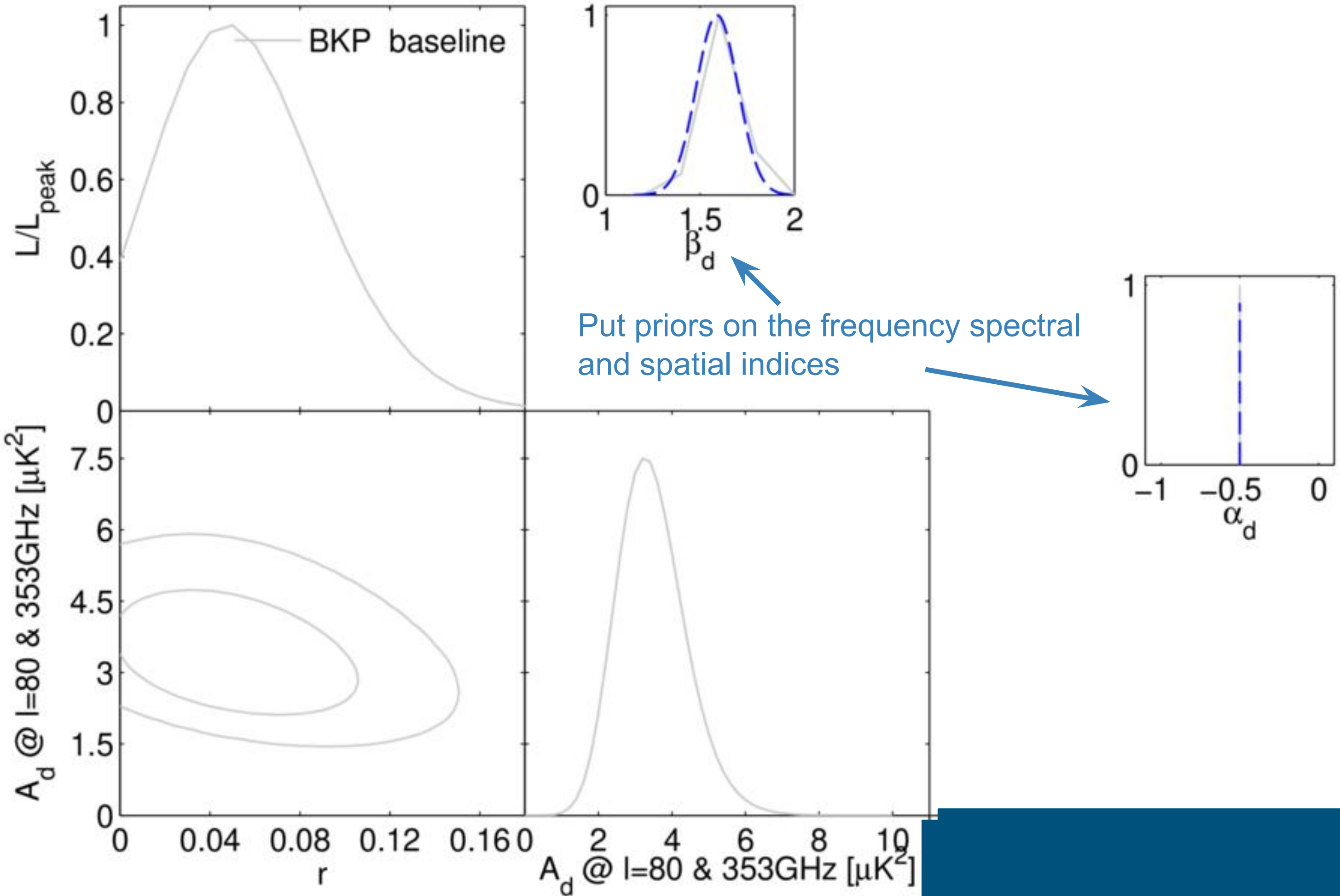
Multicomponent likelihood analysis

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

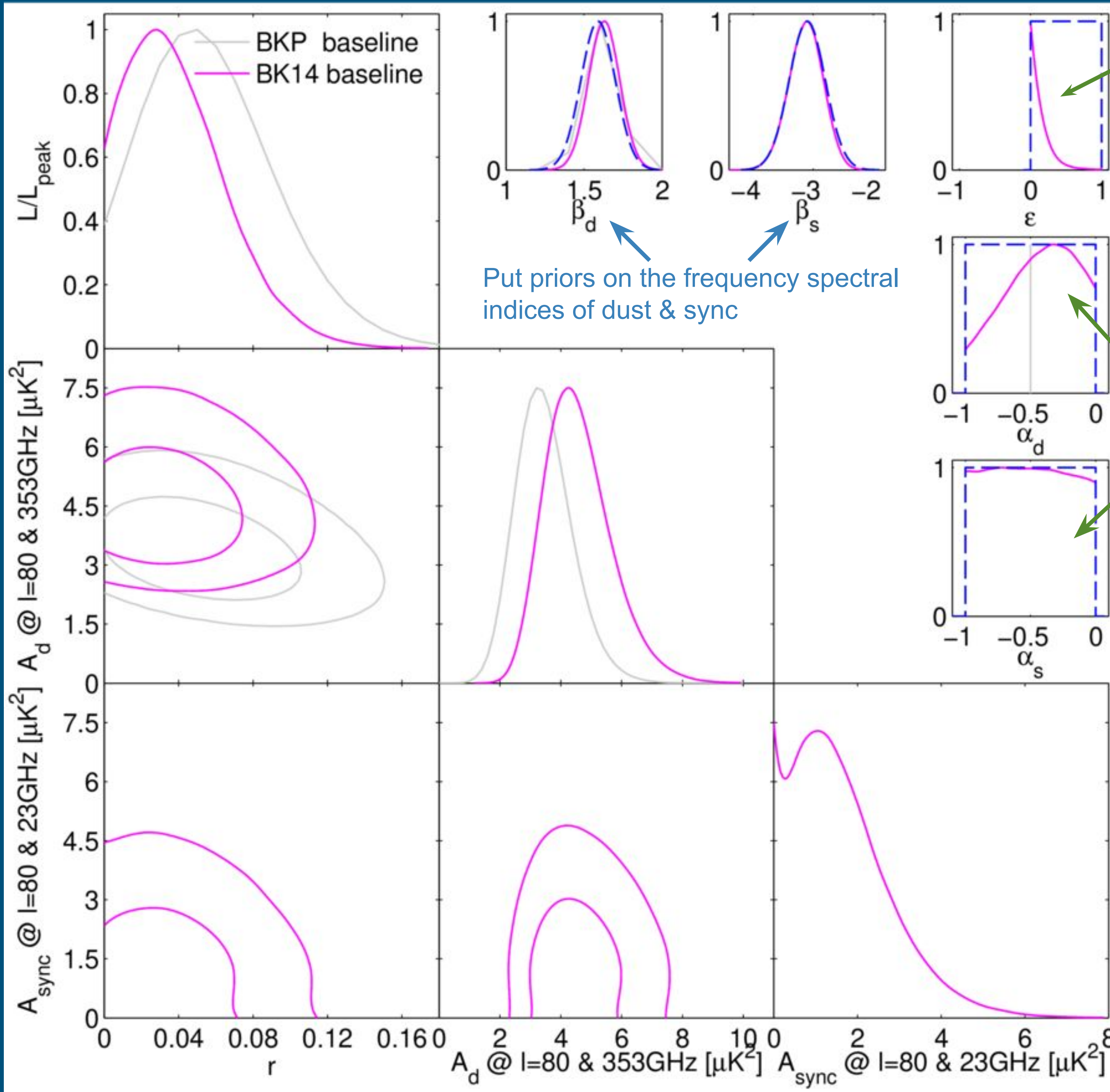
foreground model = dust + synchrotron

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



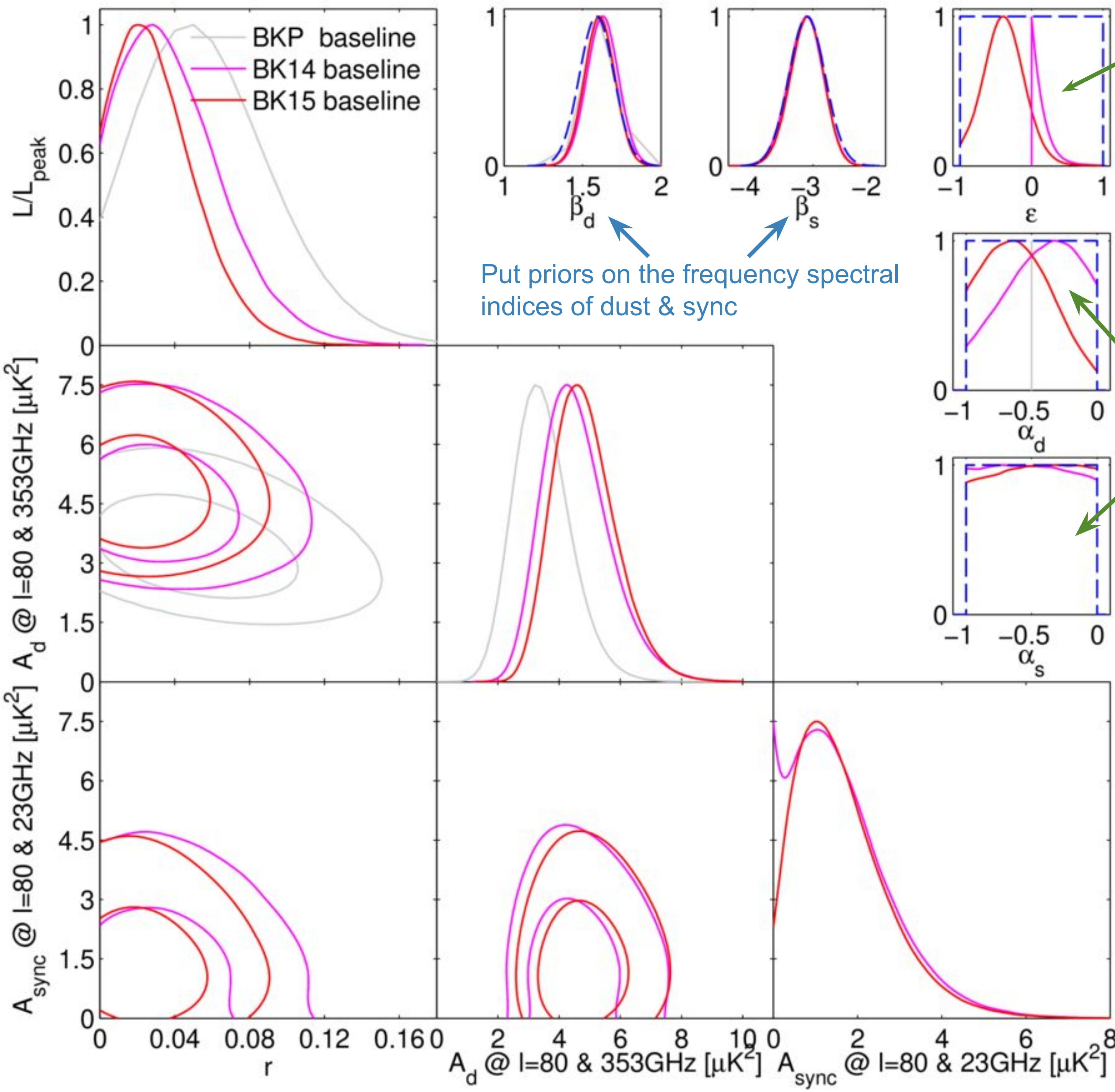
BKP
arxiv/1502.00612



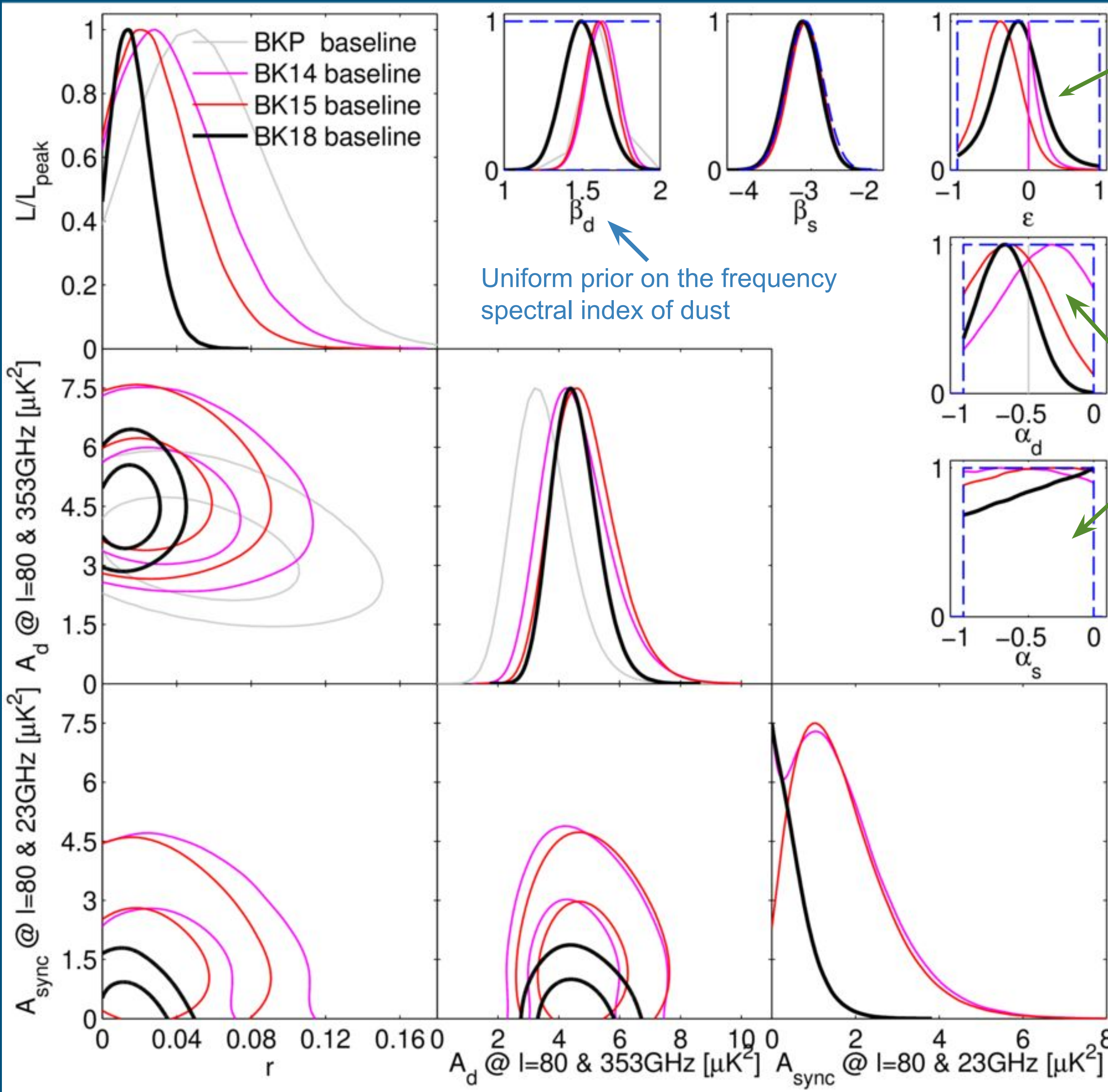
Allow dust/sync correlation in [0,1]

Marginalize over generous ranges in spatial spectral indices

BK14
arxiv/1510.09215



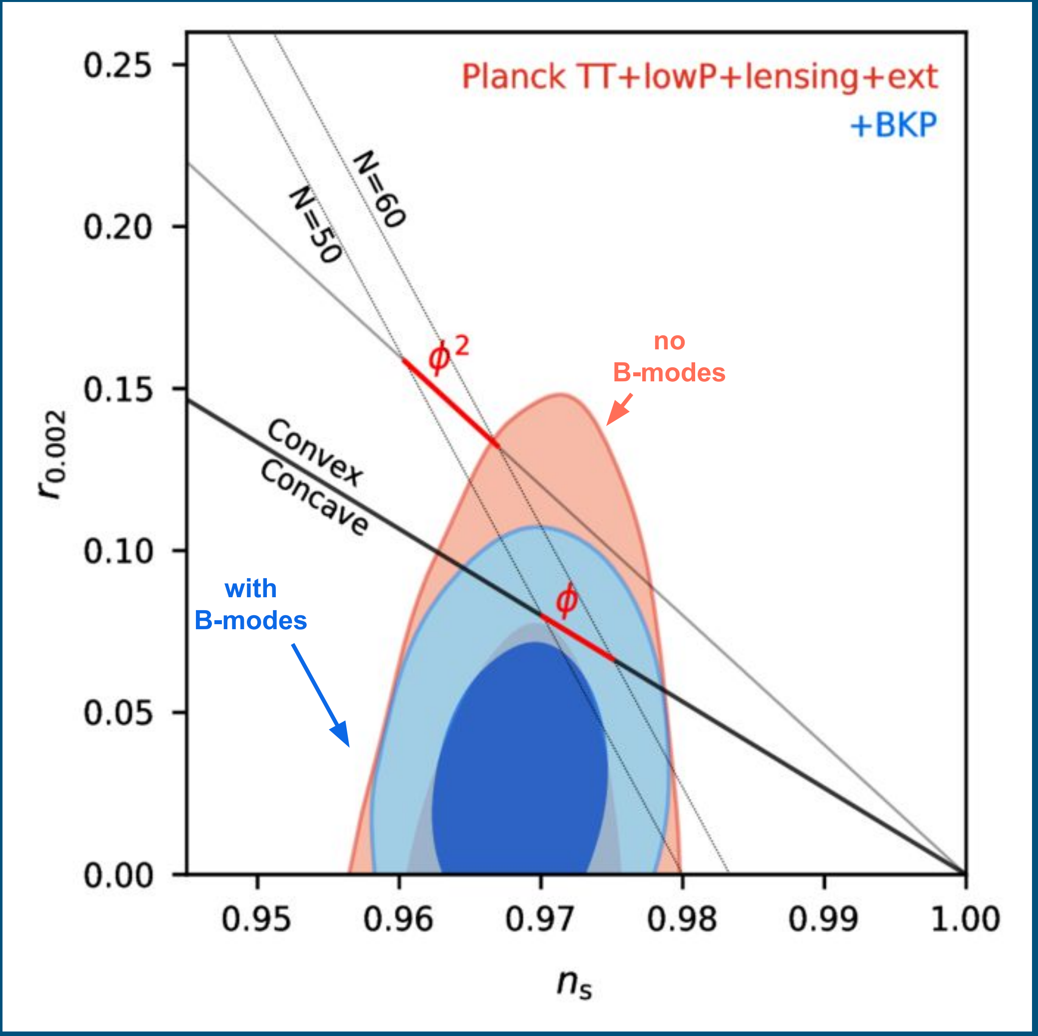
BK15
arxiv/1810.05216



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

Marginalize over generous ranges in spatial spectral indices

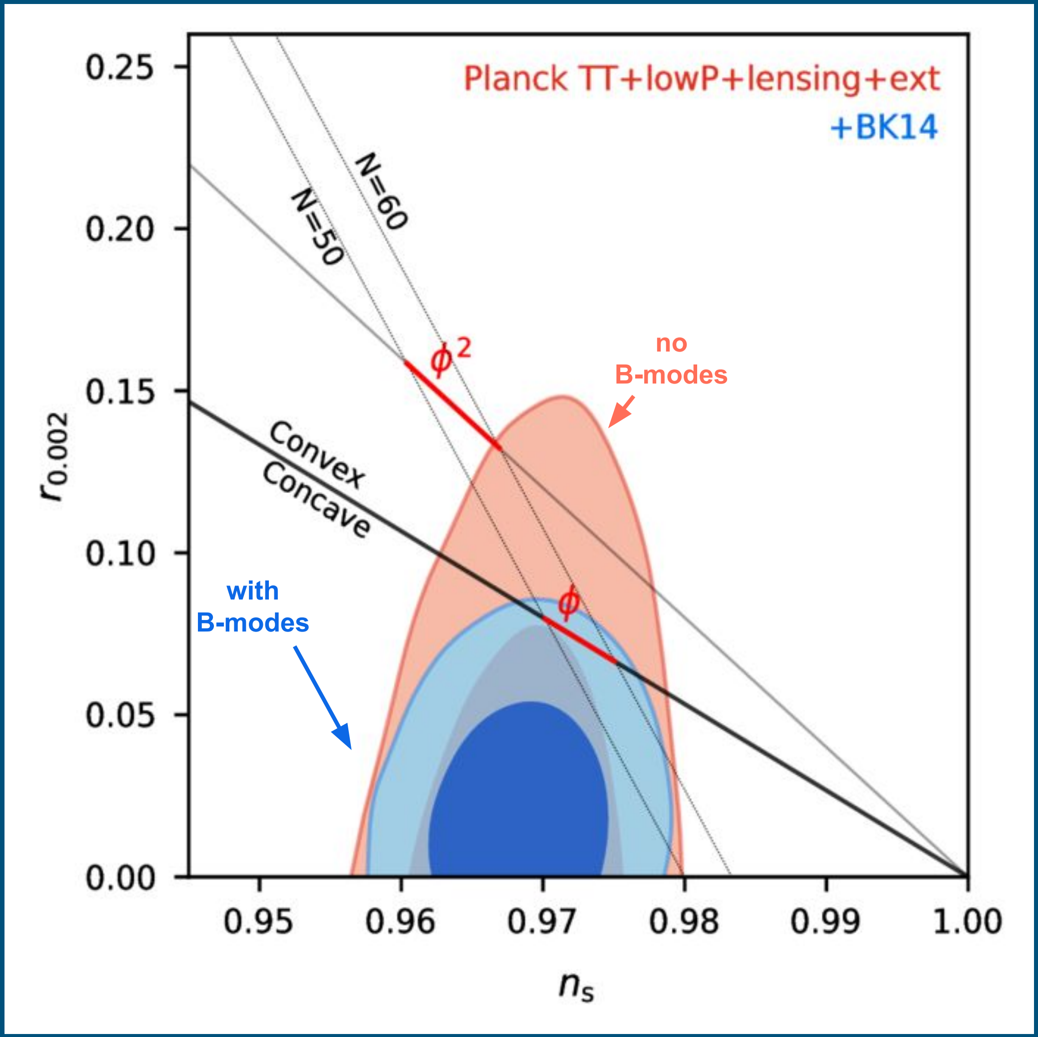
BK18
arxiv/2110.00483



$r_{.05} < 0.09$

BKP

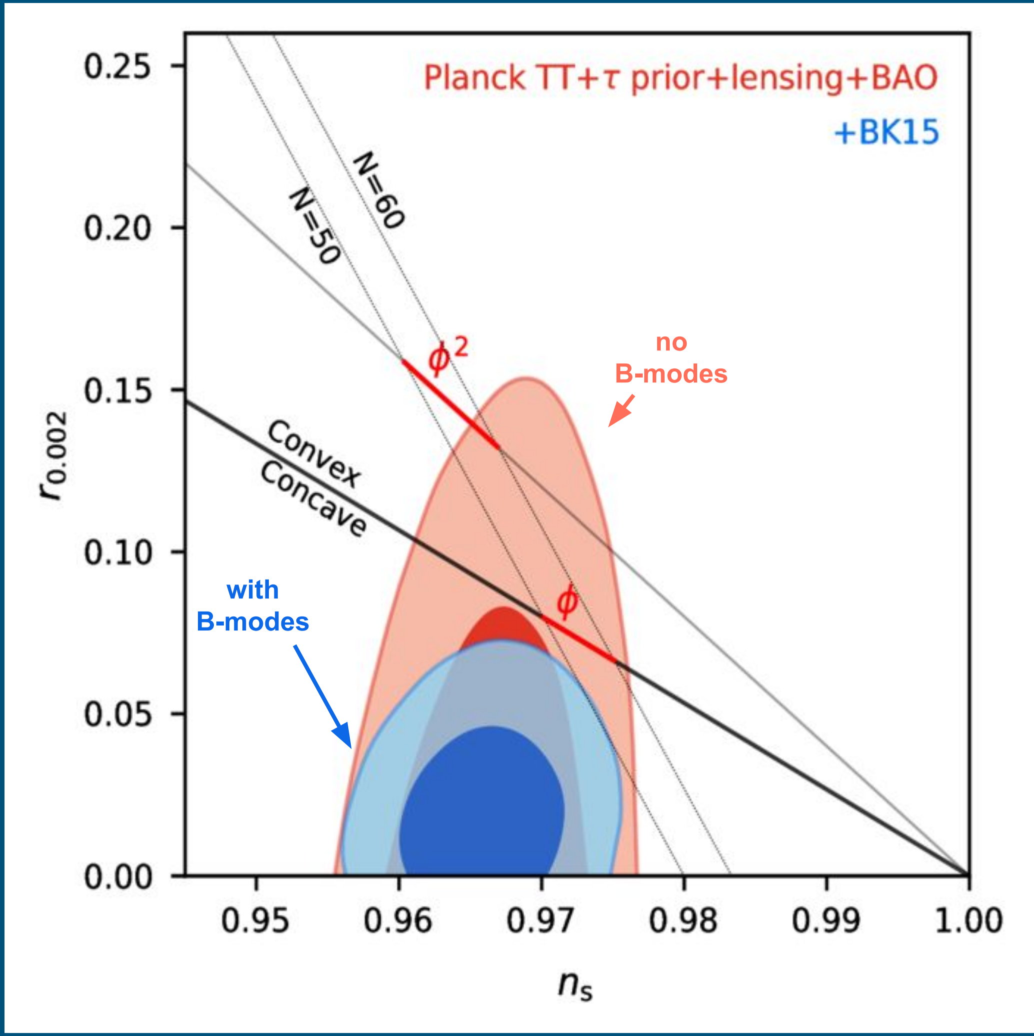
arxiv/1502.00612



$r_{.05} < 0.07$

BK14

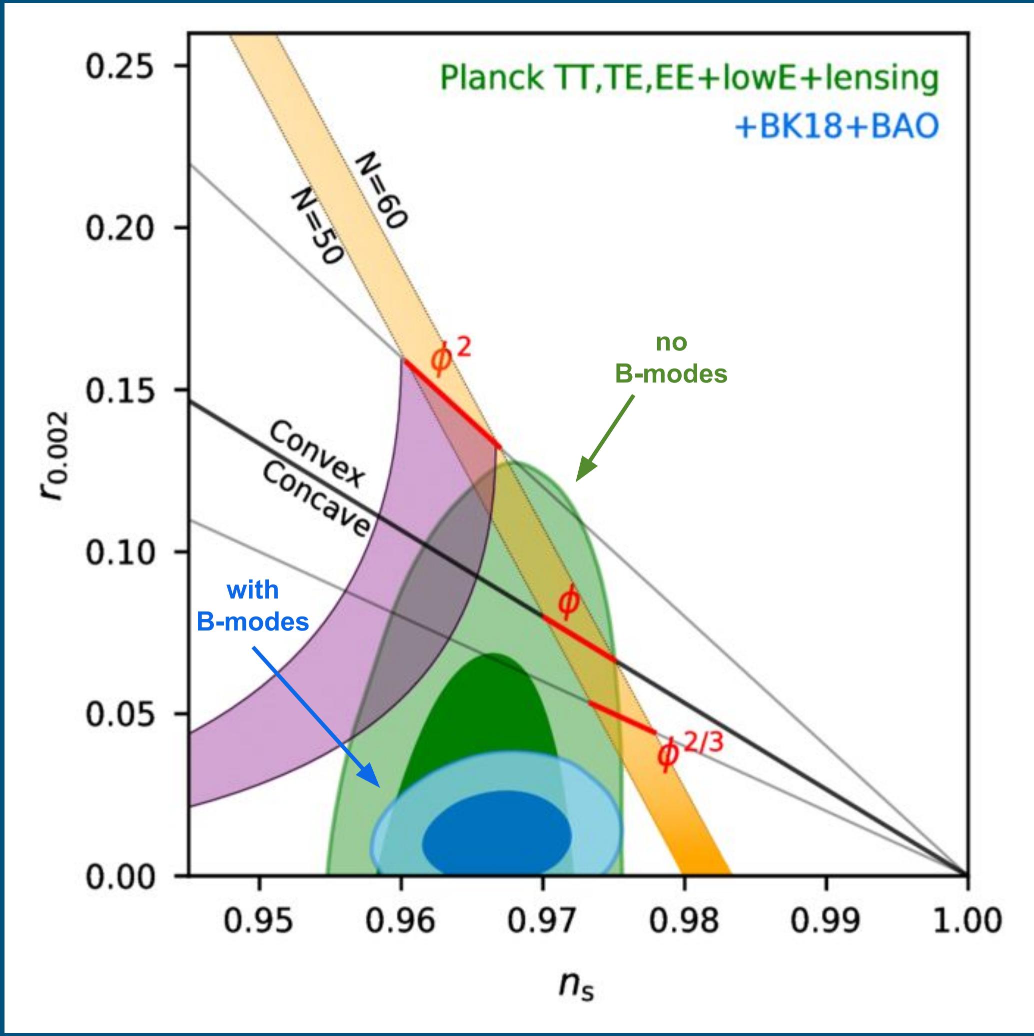
arxiv/1510.09217



$r_{.05} < 0.06$

BK15

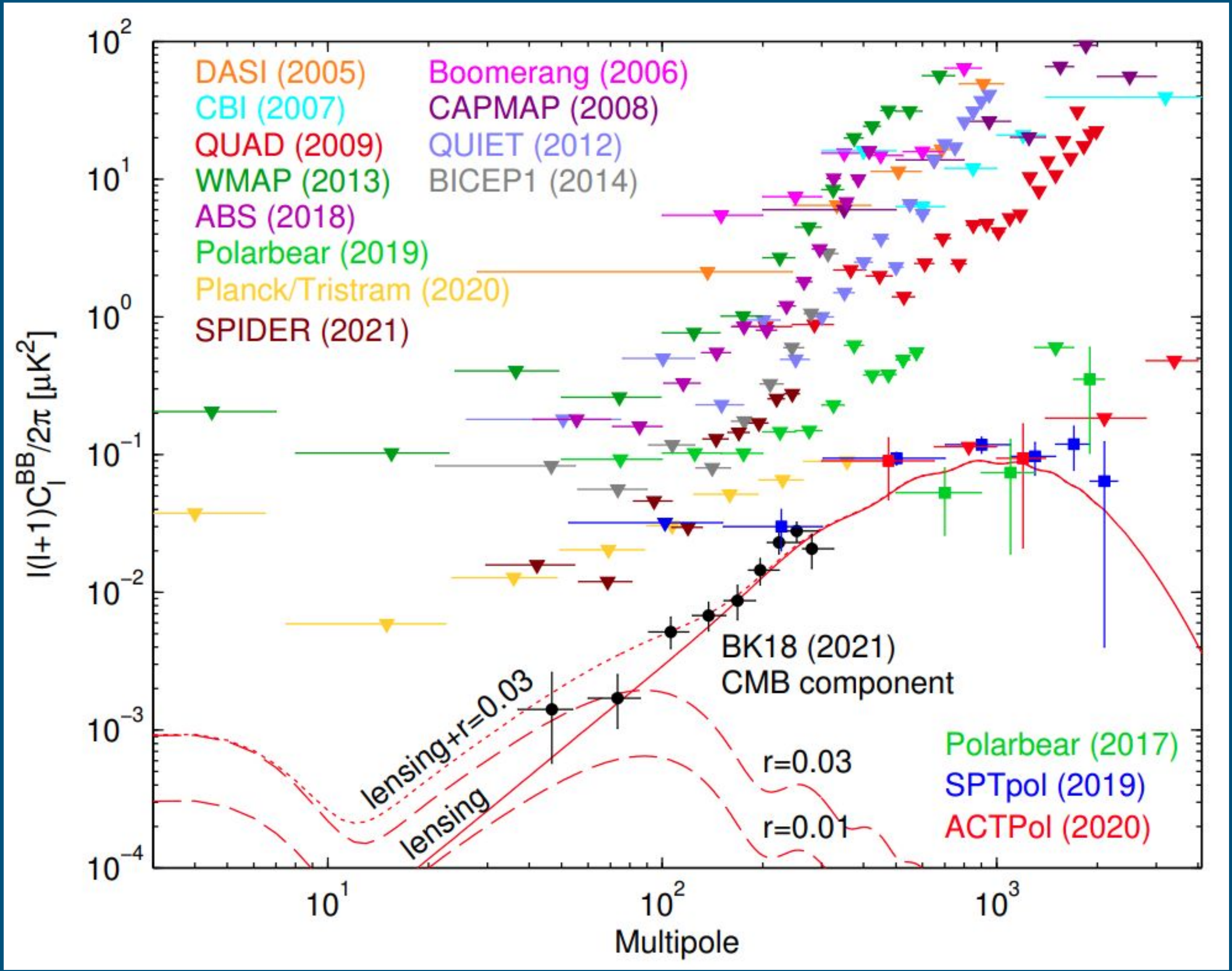
arxiv/1810.05216



$r_{.05} < 0.035$

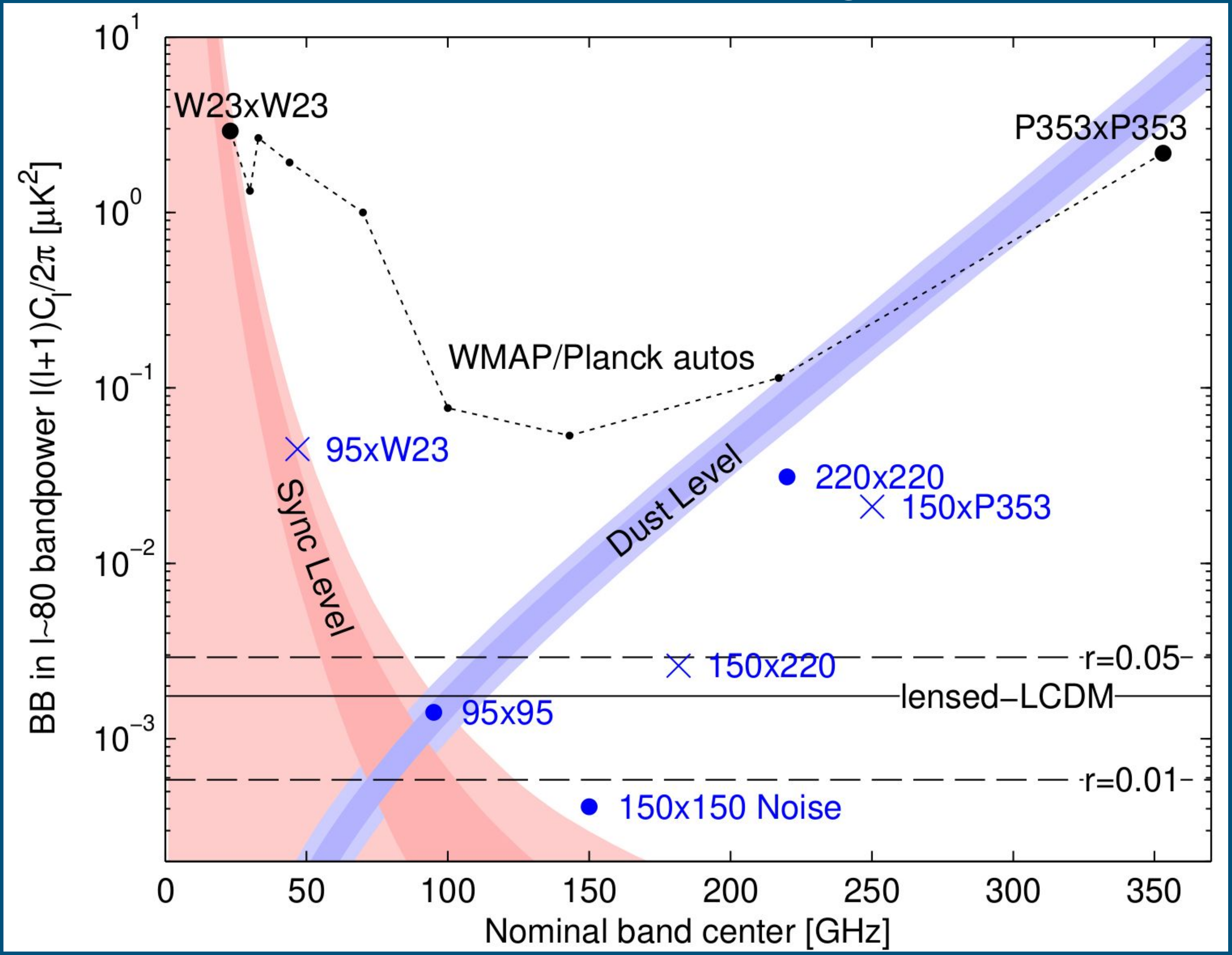
BK18

arxiv/2110.00483

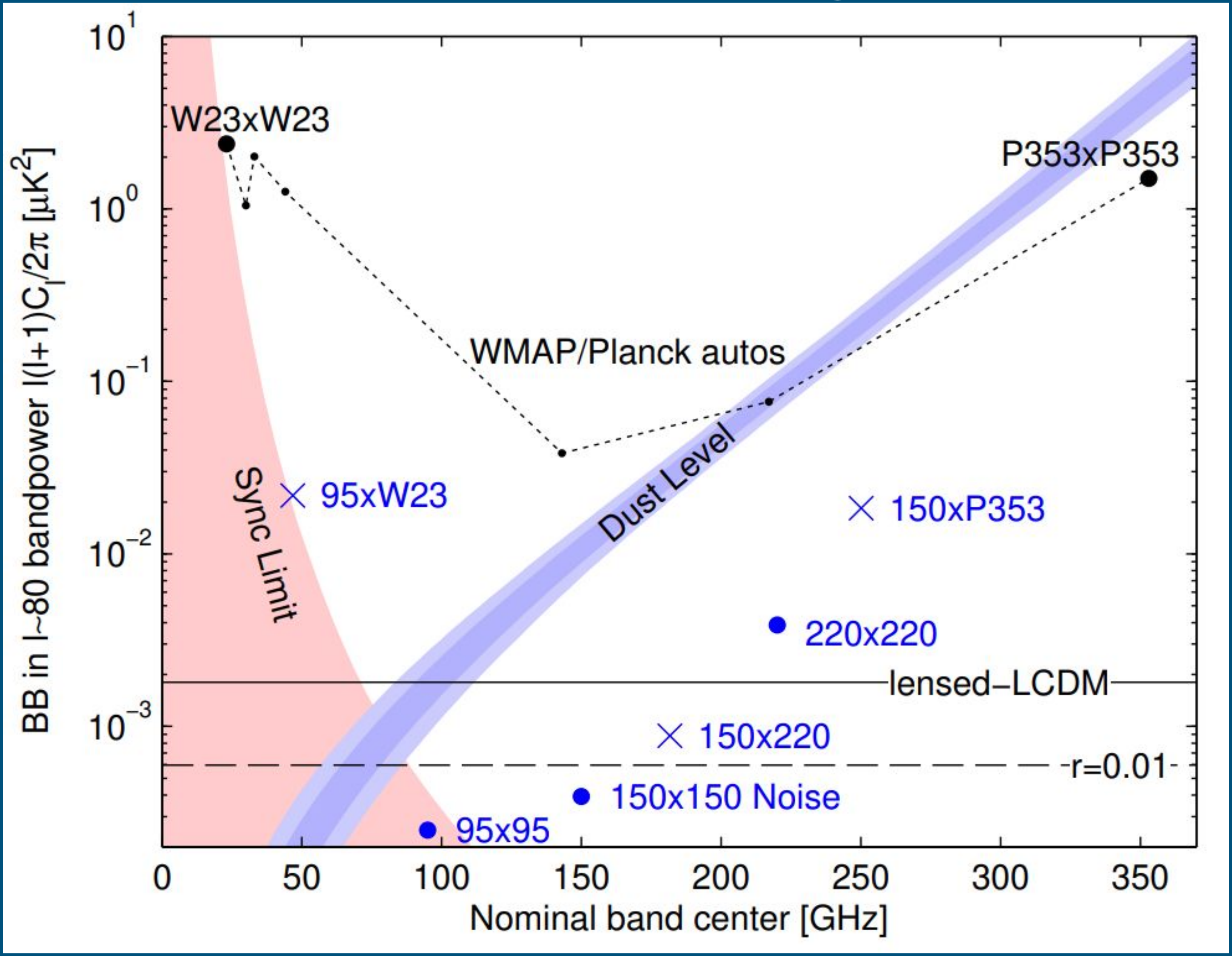


DASI (2005)
CBI (2007)
QUAD (2009)
WMAP (2013)
ABS (2018)
Polarbear (2019)
Planck/Tristram (2020)
SPIDER (2021)
Boomerang (2006)
CAPMAP (2008)
QUIET (2012)
BICEP1 (2014)
BK18 (2021)
CMB component
lensing+r=0.03
lensing
r=0.03
r=0.01
Polarbear (2017)
SPTpol (2019)
ACTPol (2020)
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
Multipole

BK15 ell=80 bandpower noise/signal



BK18 ell=80 bandpower noise/signal



What limits BK18?

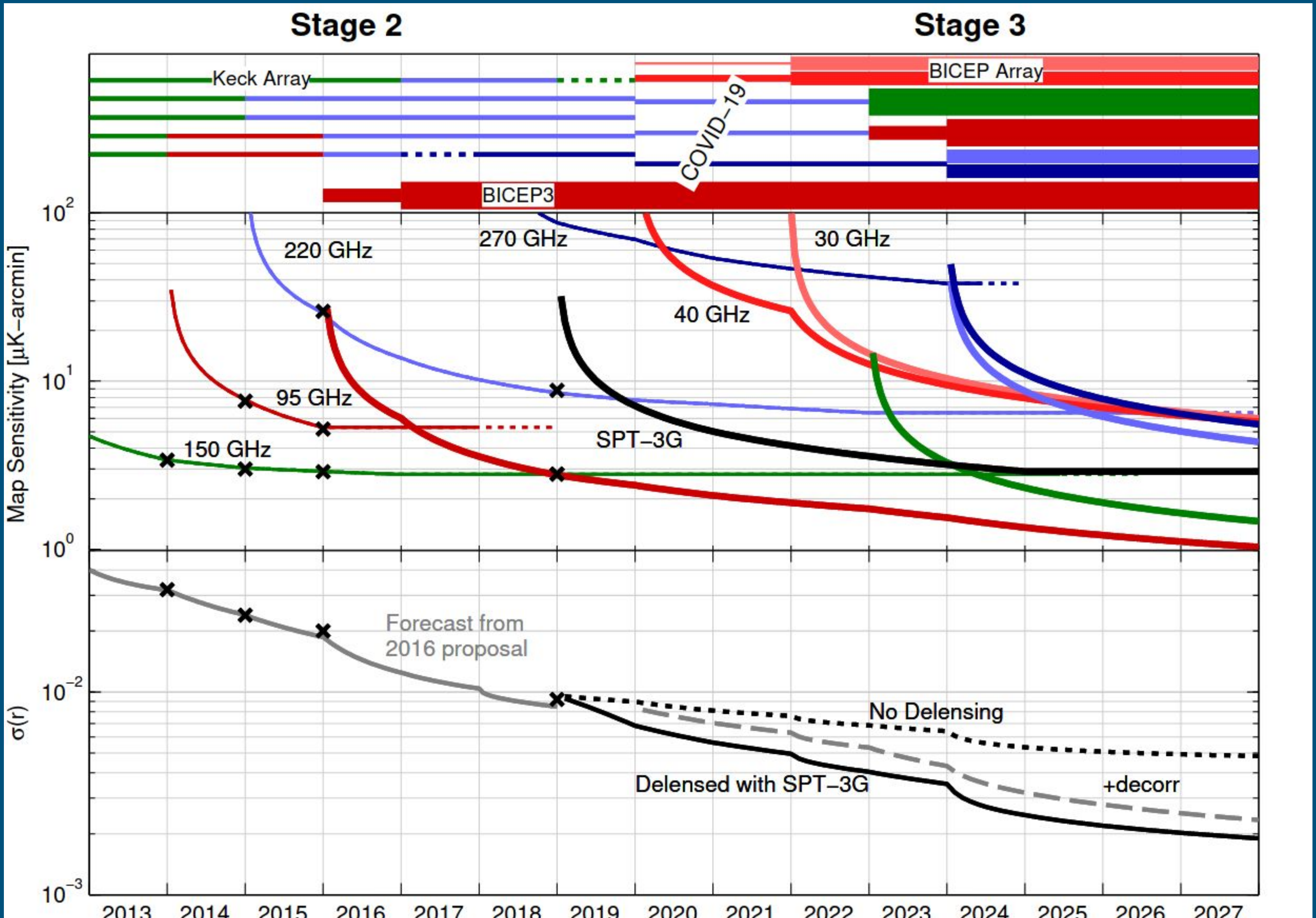
- BK18 mainline simulations with dust and lensing give σ(*r*)=0.009
- Running without foreground parameters on simulations where the dust amplitude is set to zero gives σ(*r*)=0.007

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

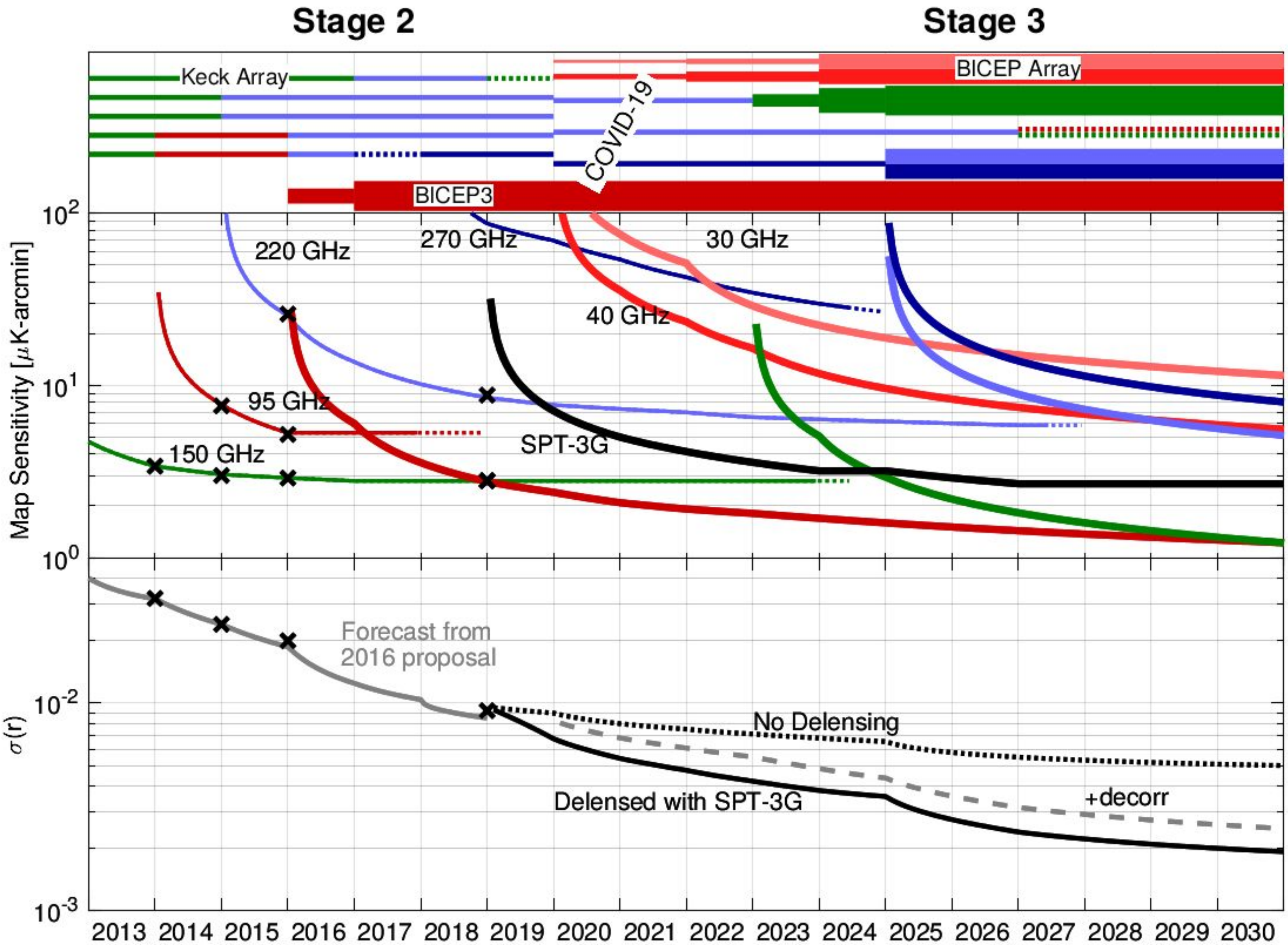
- Running on simulations which contain no lensing gives σ(*r*)=0.004

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

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



Stage 2
Stage 3
Keck Array
BICEP Array
COVID–19
BICEP3
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
Delensed with SPT–3G
+decorr
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027



Stage 2
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Map Sensitivity [μK-arcmin]
220 GHz
270 GHz
30 GHz
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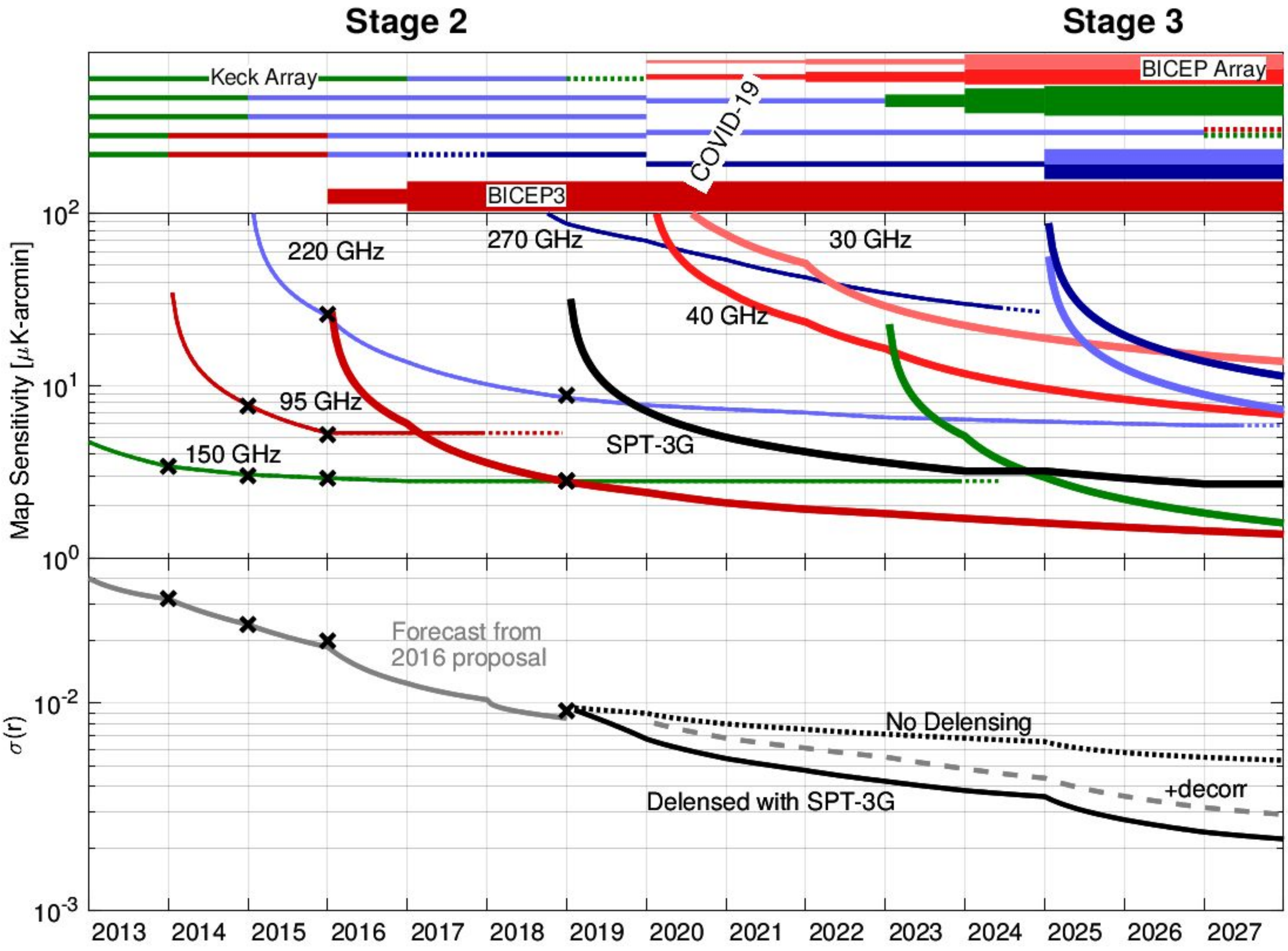
95 GHz
150 GHz
SPT-3G
σ(r)
Forecast from
2016 proposal
No Delensing
Delensed with SPT-3G
+decorr
10^2
10^1
10^0
10^-2
10^-3
2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030



Stage 2
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220 GHz
270 GHz
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SPT-3G
Map Sensitivity [μK-arcmin]
10^2
10^1
10^0
Forecast from
2016 proposal
No Delensing
+decorr
Delensed with SPT-3G
$\sigma(r)$
10^{-2}
10^{-3}
2013
2014
2015
2016
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2022
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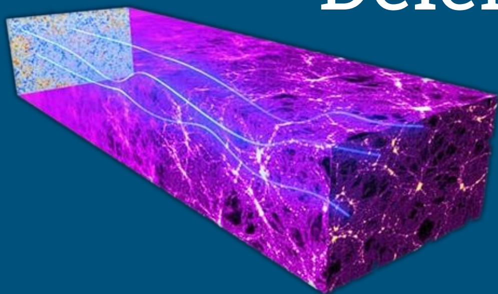
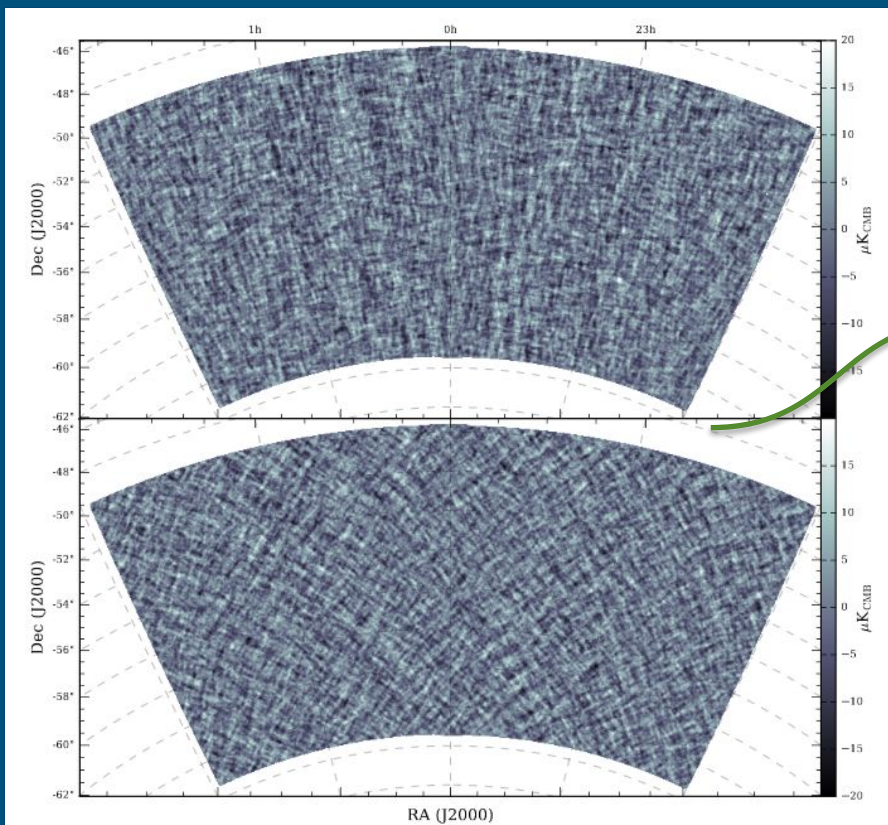
2026
2027

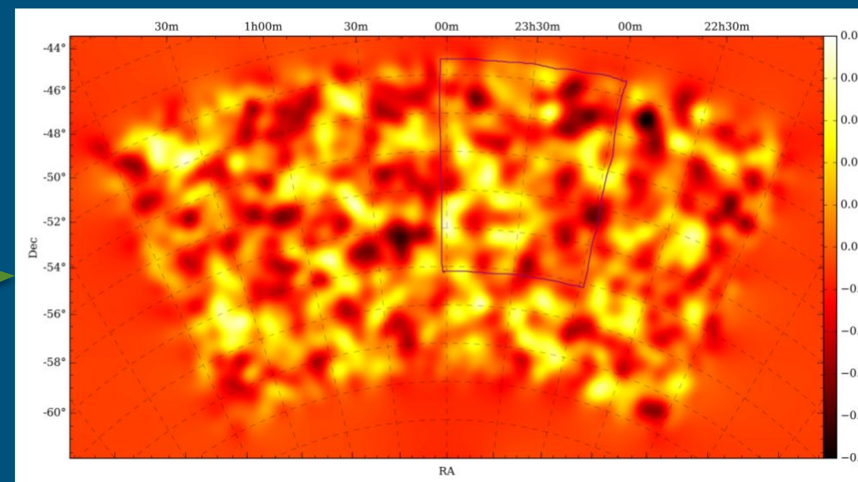
Delensing with SPT-3G data



High resolution maps



Can be used to reconstruct the lensing deflection map…

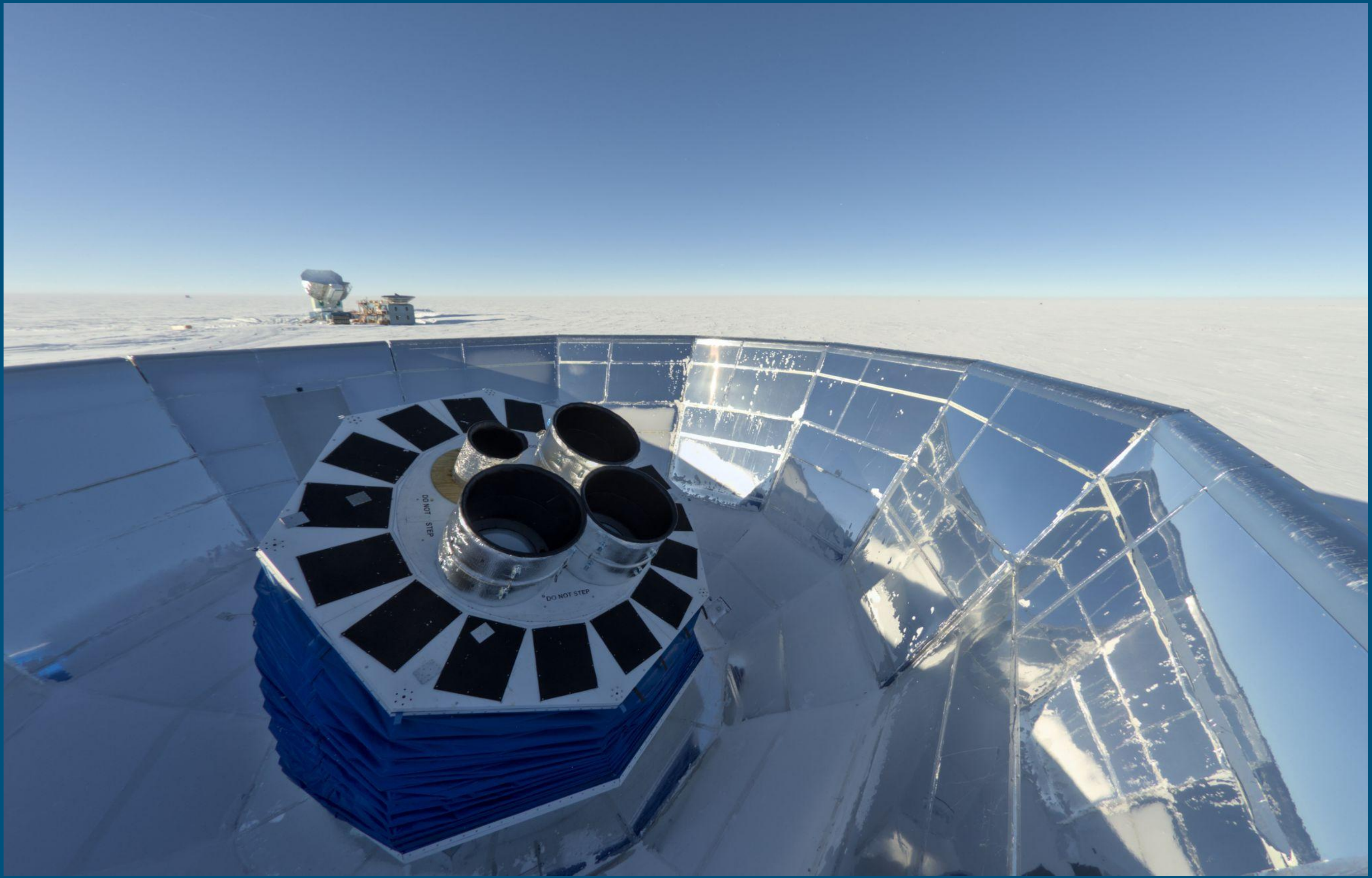


…which can then be used to calculate and remove the lensing signal enabling a deeper search for inflationary gravitational waves

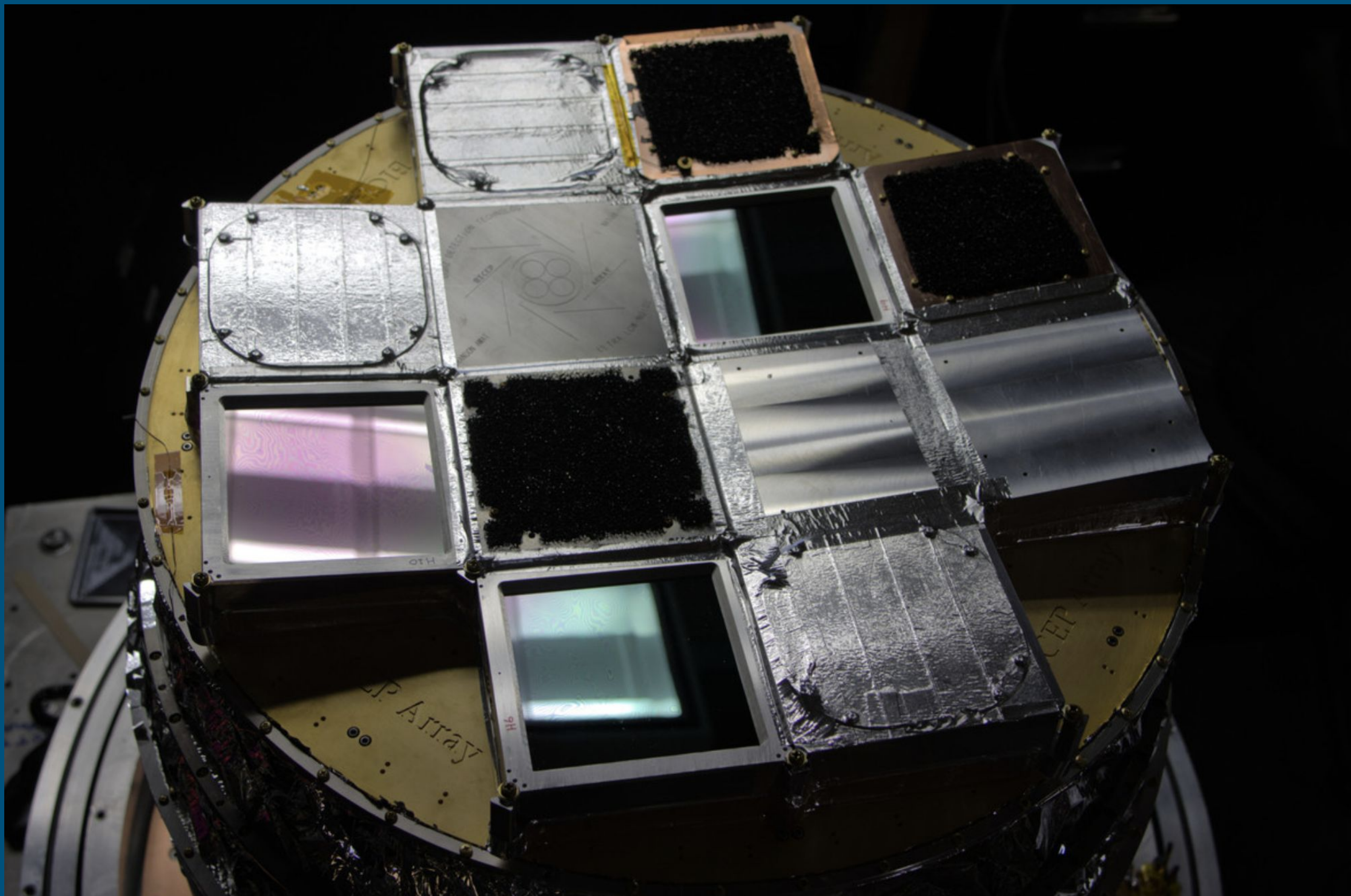
BA 220/270 - The De-Duster

- BICEP Array (BA) currently has 2 receivers observing the CMB full time.
    - BA 30/40 and BA 150
- BA 220/270 is the current work-in-progress for BA
    - Focal plane currently has 3 modules, can hold 12 total
- BA mount has 4 receiver spots, last one is currently holding Keck 270.

BA 220/270 - The De-Duster



BA 220/270 Pics



BA 220/270 Pics

BA 220/270 Pics

Conclusion + Next Steps

1. BICEP Array looks to constrain cosmic inflation by measuring the polarization of the CMB with high precision
2. The BICEP/Keck collaboration has been constraining the parameter space of important cosmology results steadily since 2014.

A. Delensing with SPT-3G will solve the lensing problem
B. BA 220/270 will help with the dust foreground, these two advances combined should significantly increase our sensitivity to r.