The search for inflationary B-modes: latest results from BICEP/Keck

Denis Barkats for the BICEP/Keck Collaboration
Rencontres de Blois
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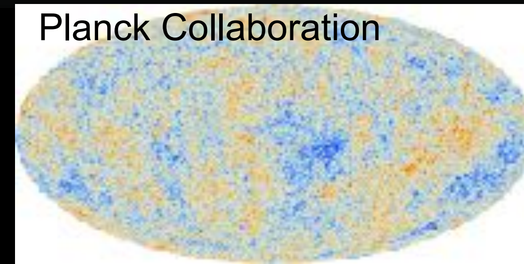
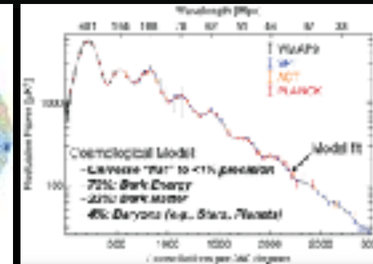
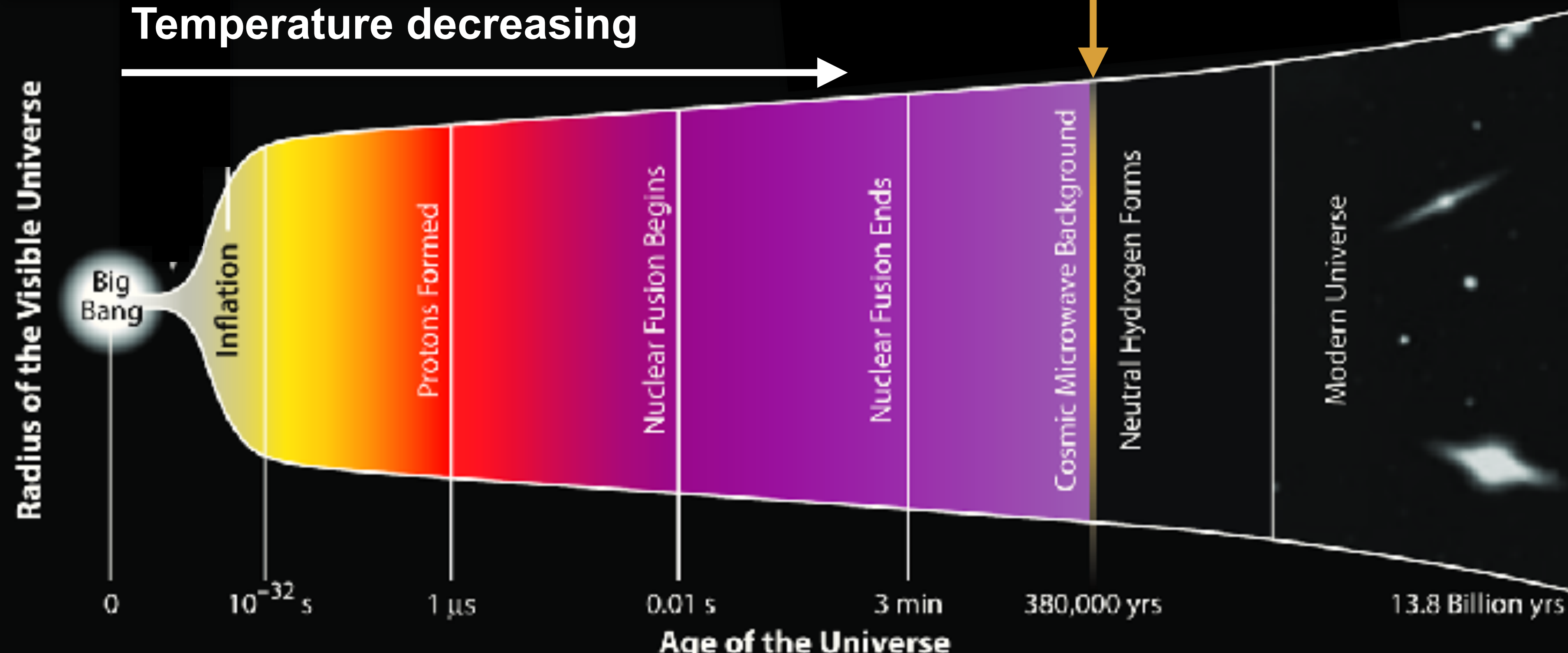
Physicist's view of the History of our Universe





Hydrogen recombination at z = 1100, T=3000K

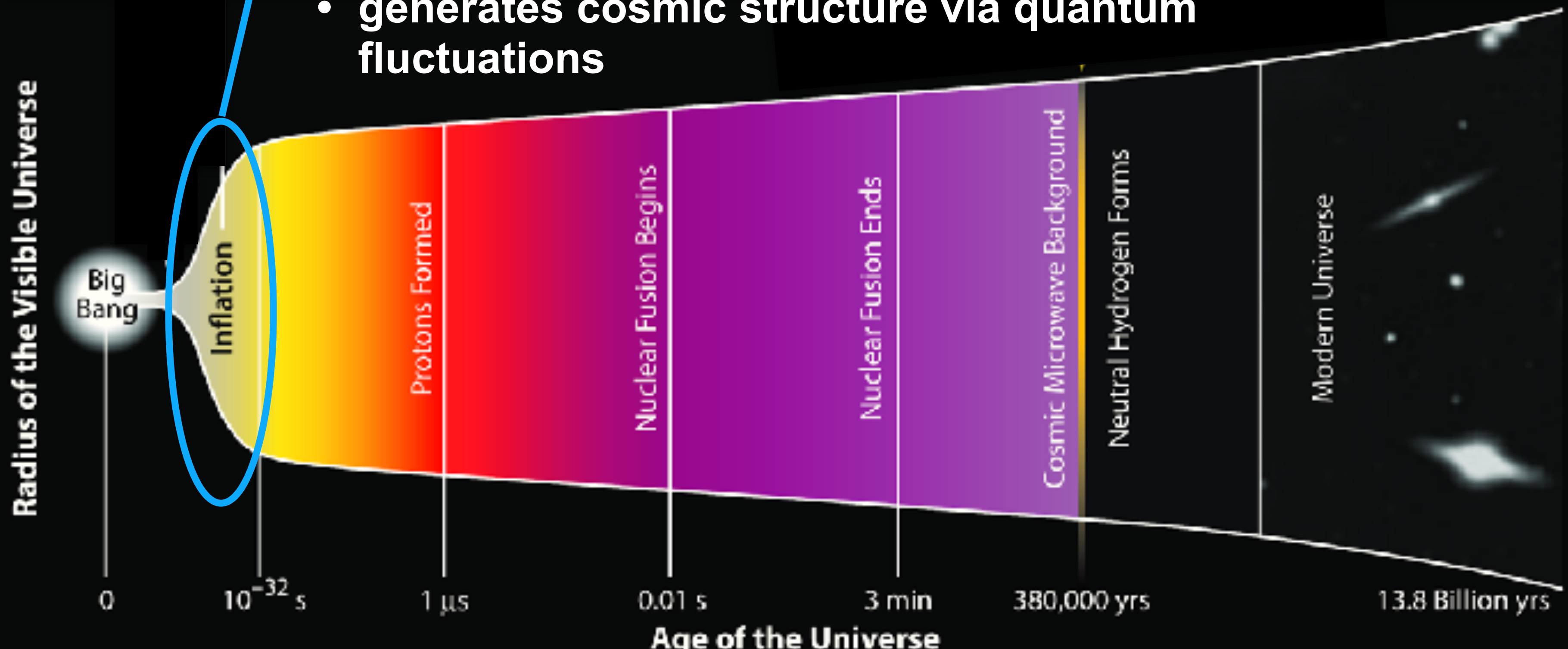
Time increasing
Size increasing
Temperature decreasing



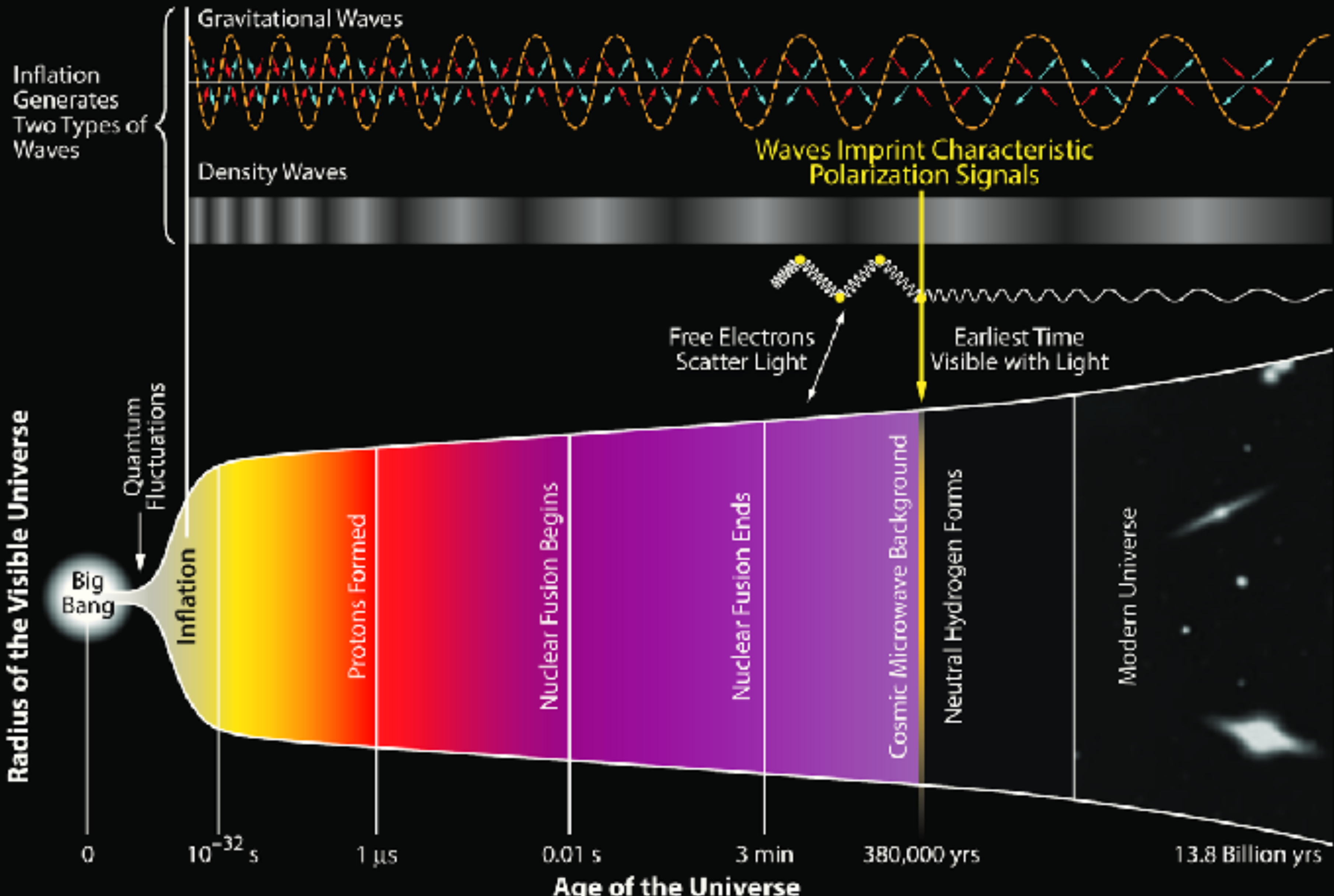
Physicist's view of the History of our Universe

Inflation: early accelerated super-expansion; proposed to explain:

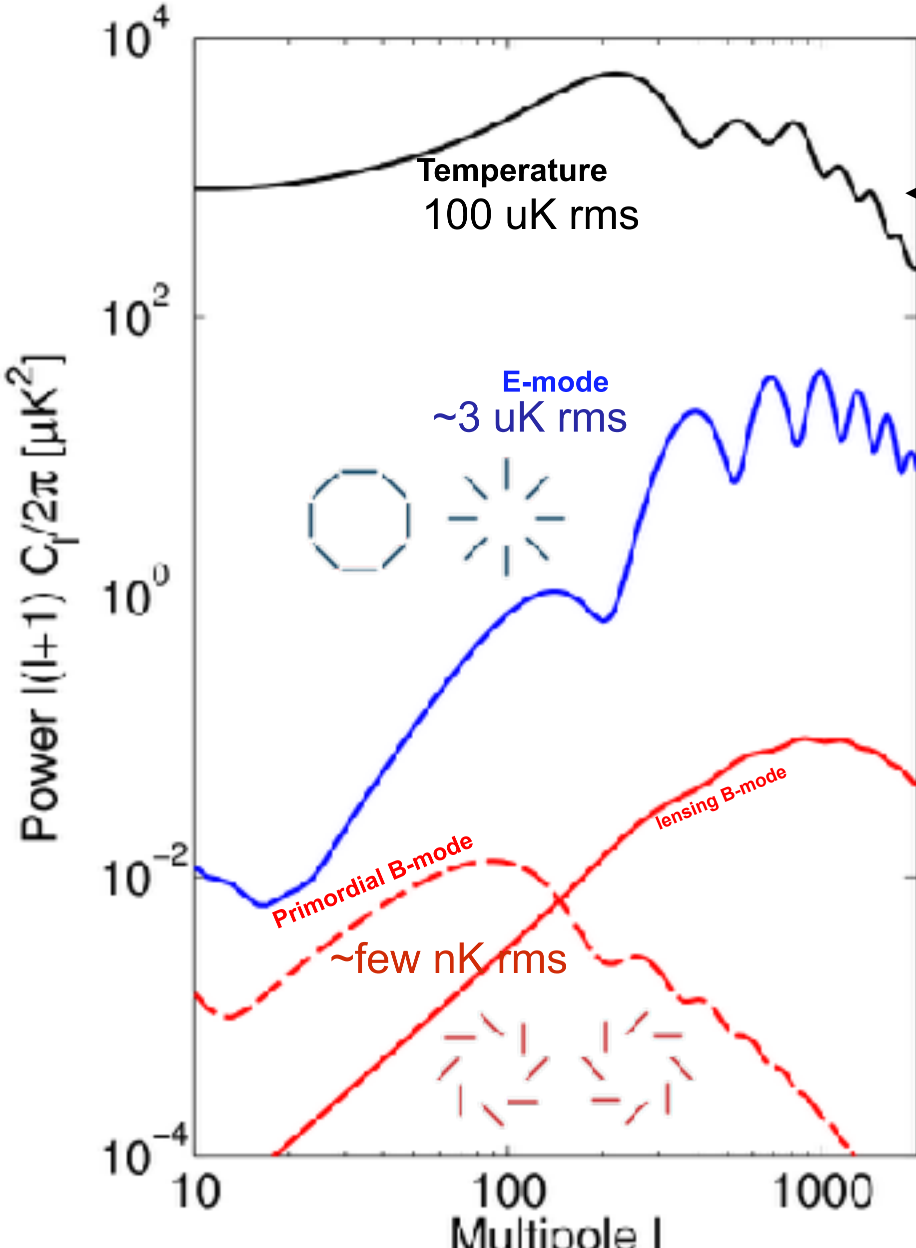
- **Homogeneity beyond causal horizon**
- **Spatial flatness**
- **generates cosmic structure via quantum fluctuations**



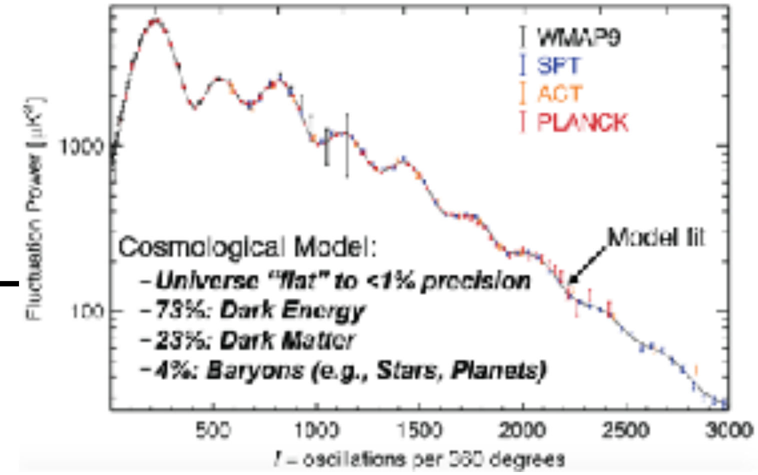
Physicist's view of the History of our Universe



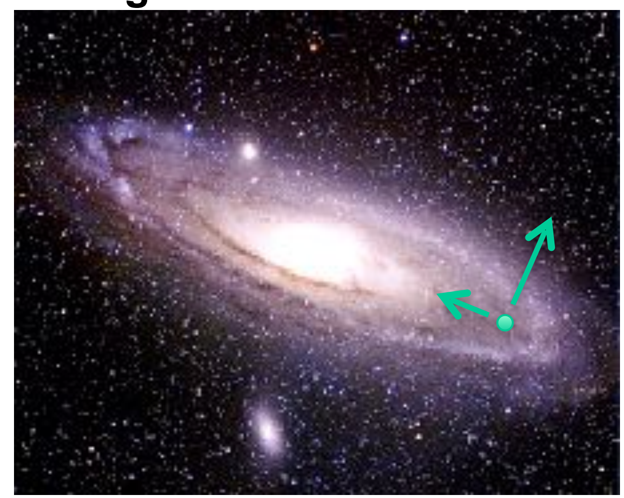
Experimental challenges !!



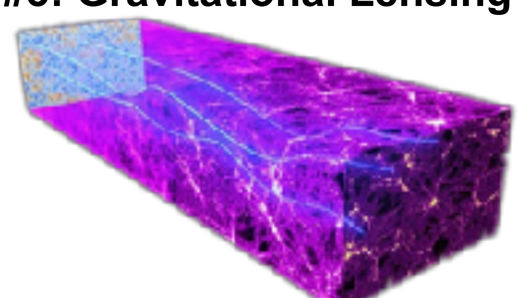
#1: Tiny signal



#2: Foreground emission



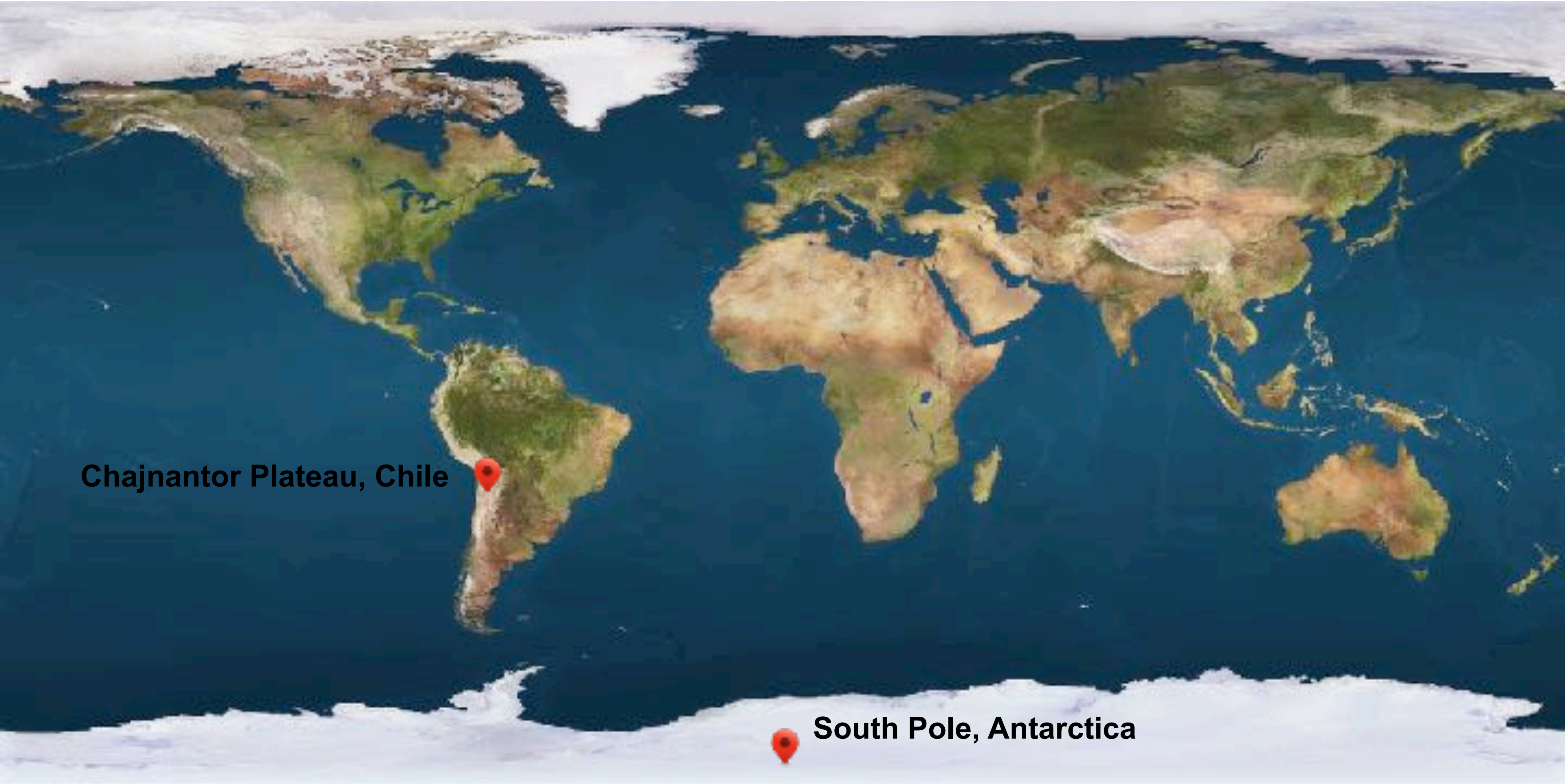
#3: Gravitational Lensing



BICEP/Keck Basic Experimental Strategy

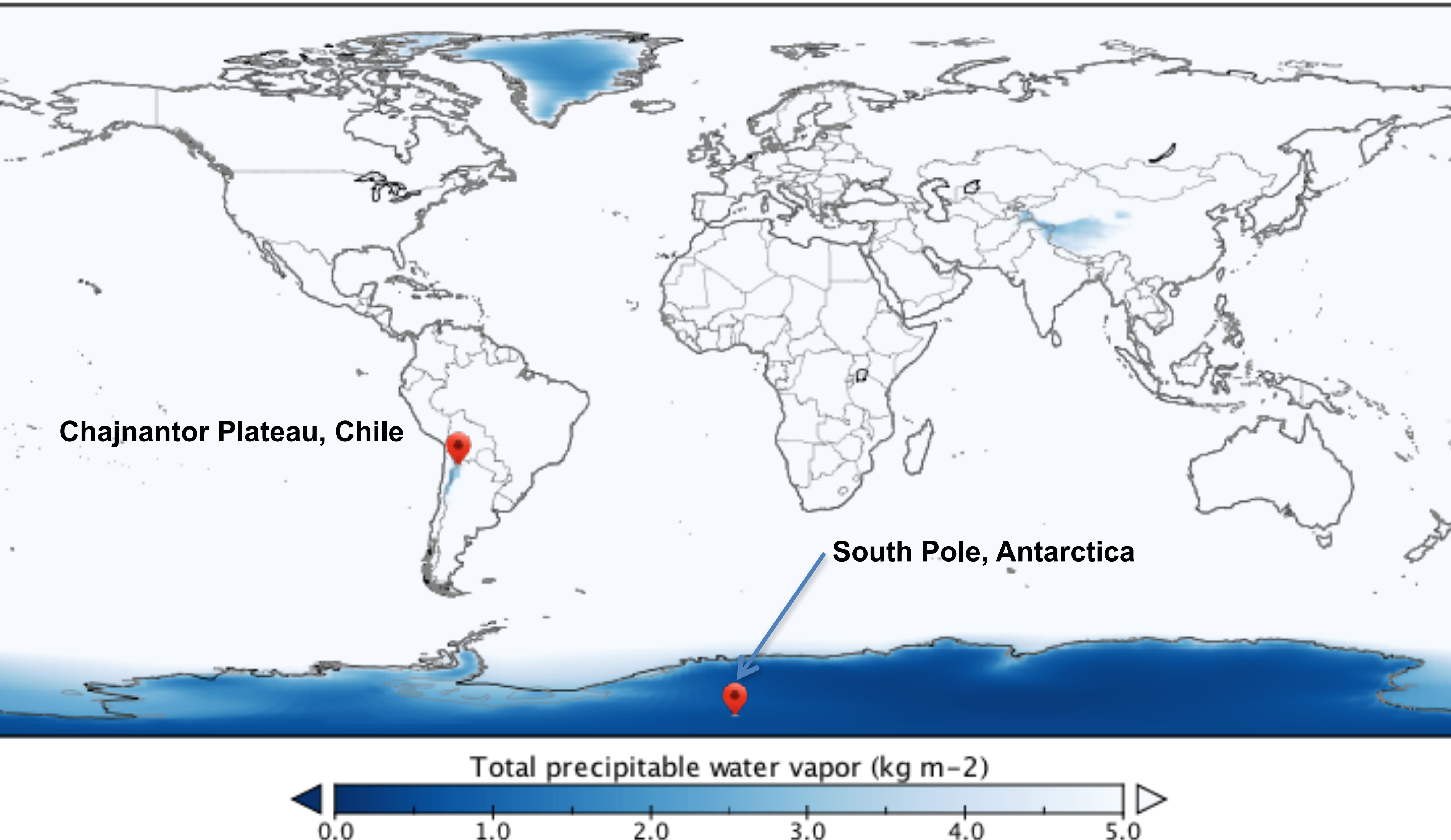
→ Target the 2 degree peak of the PGW B-mode
→ Small aperture telescopes (cheap, fast, low systematics)
→ Integrate continuously from South Pole
→ Observe ~ 1% patch of sky
→ Scan and pair difference modulation

Why do this at the South Pole?

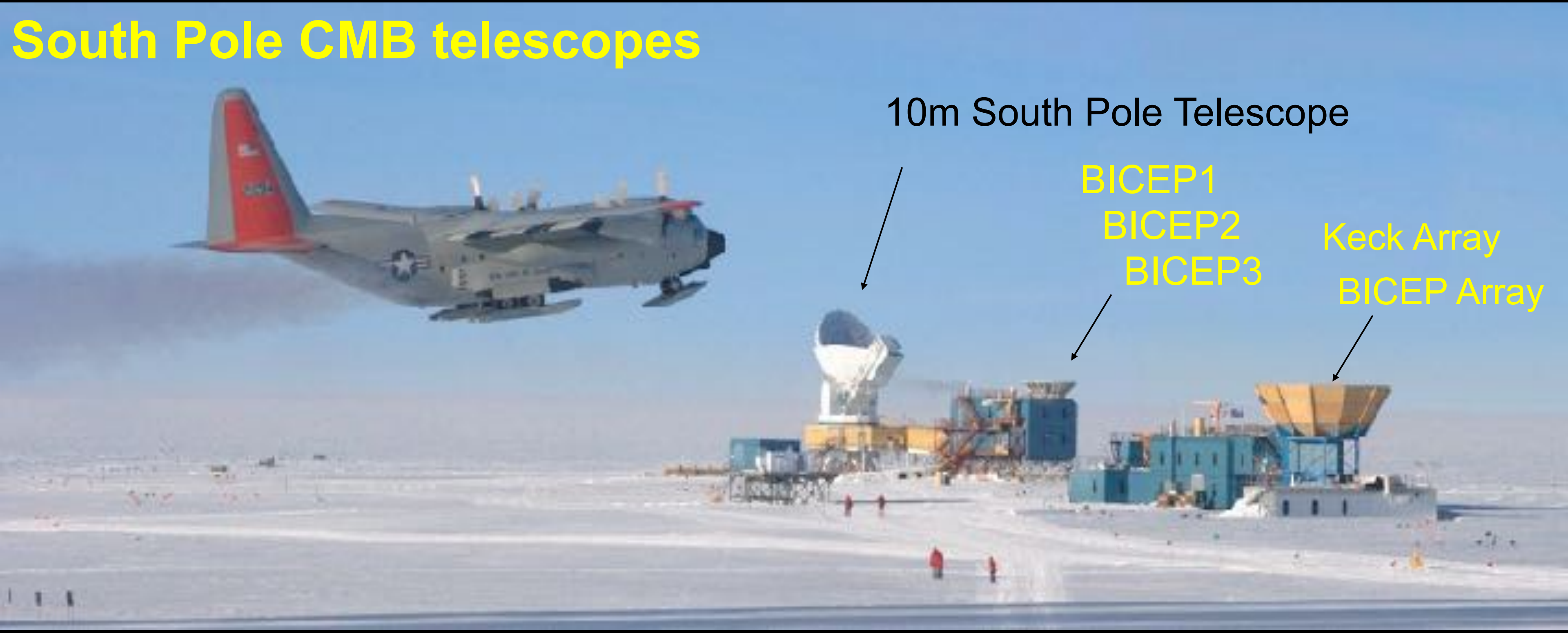


Why do this at the South Pole?

10-year average PWV 2006-2016: MERRA2

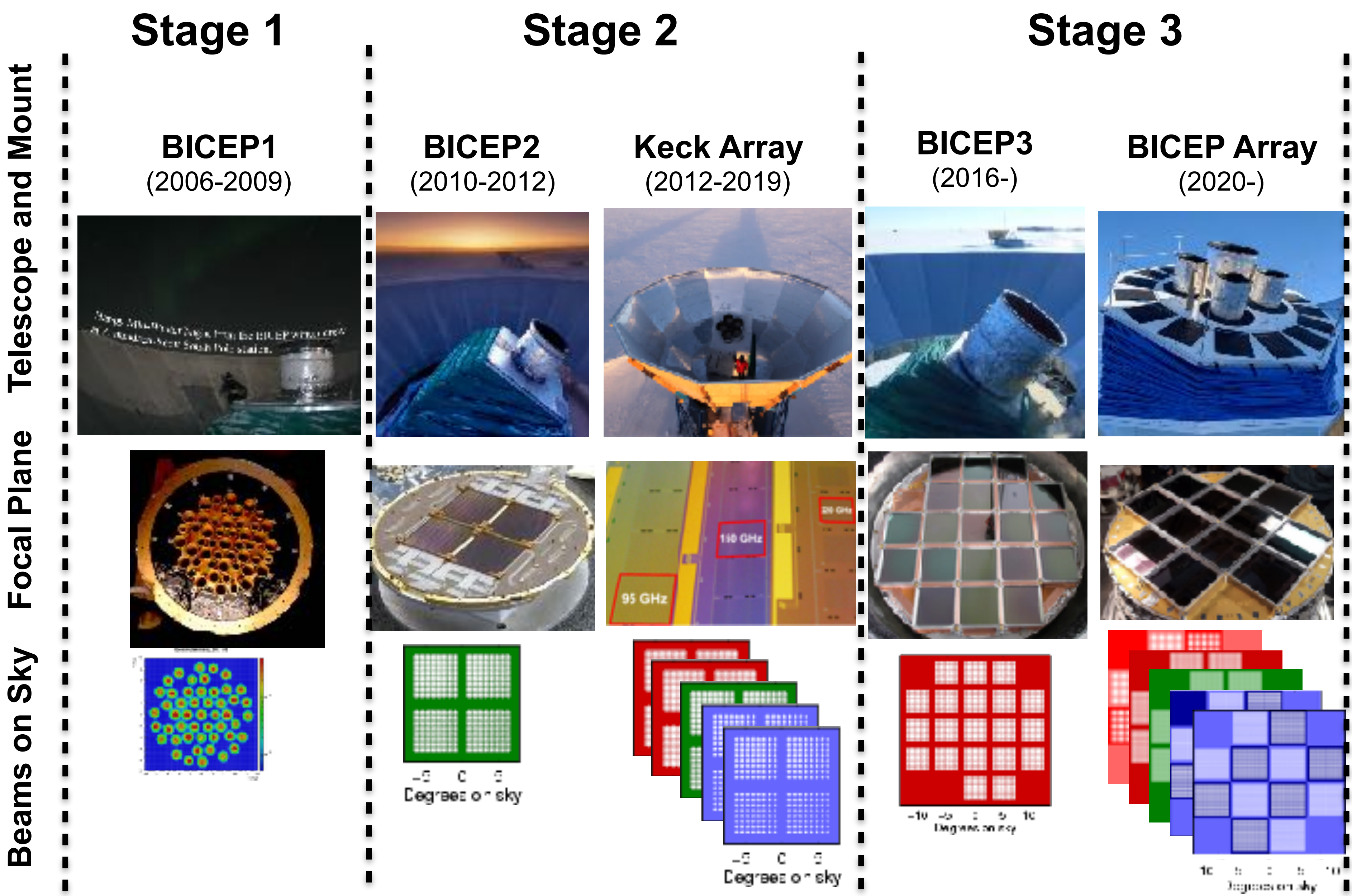


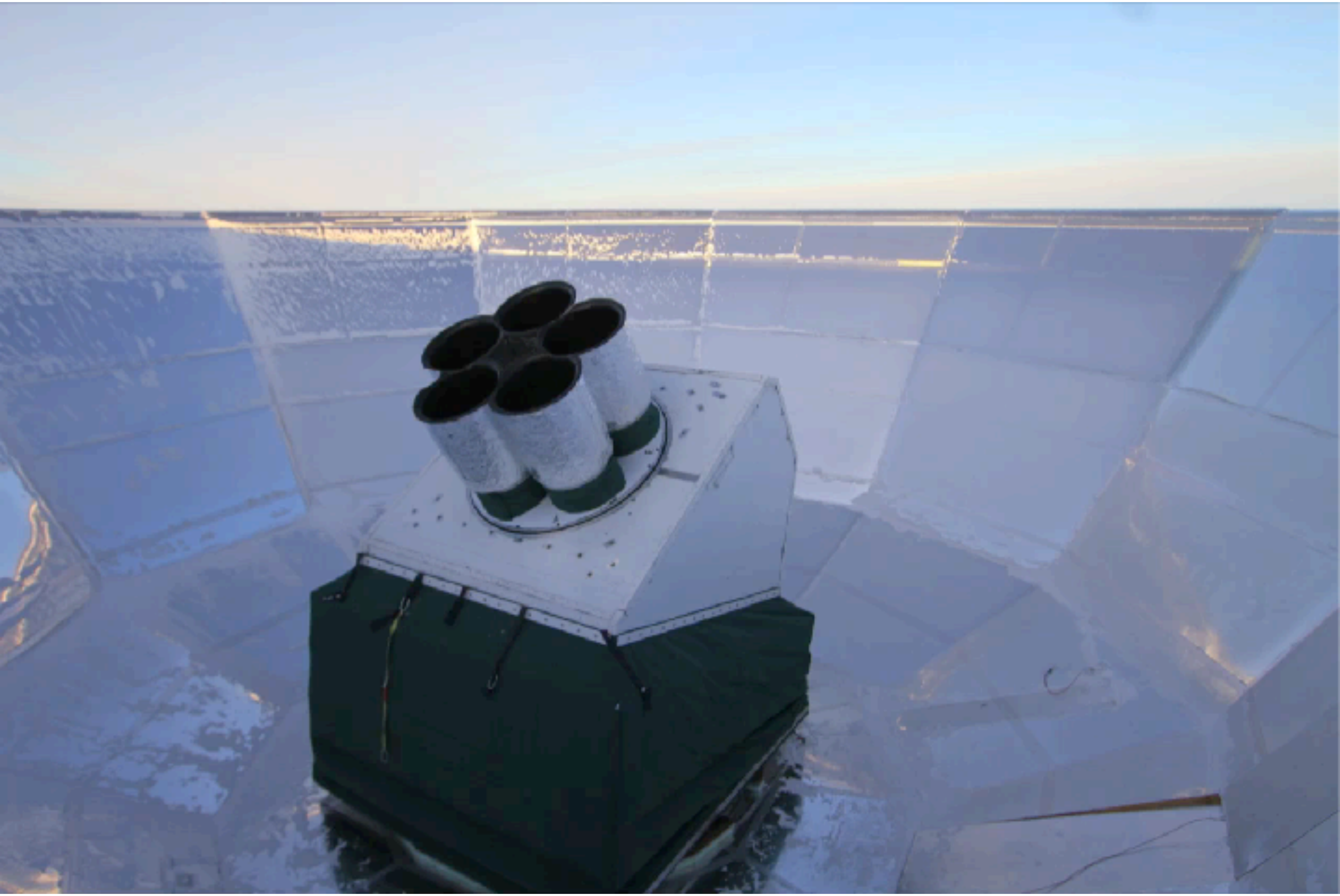
Why do this at the Pole?

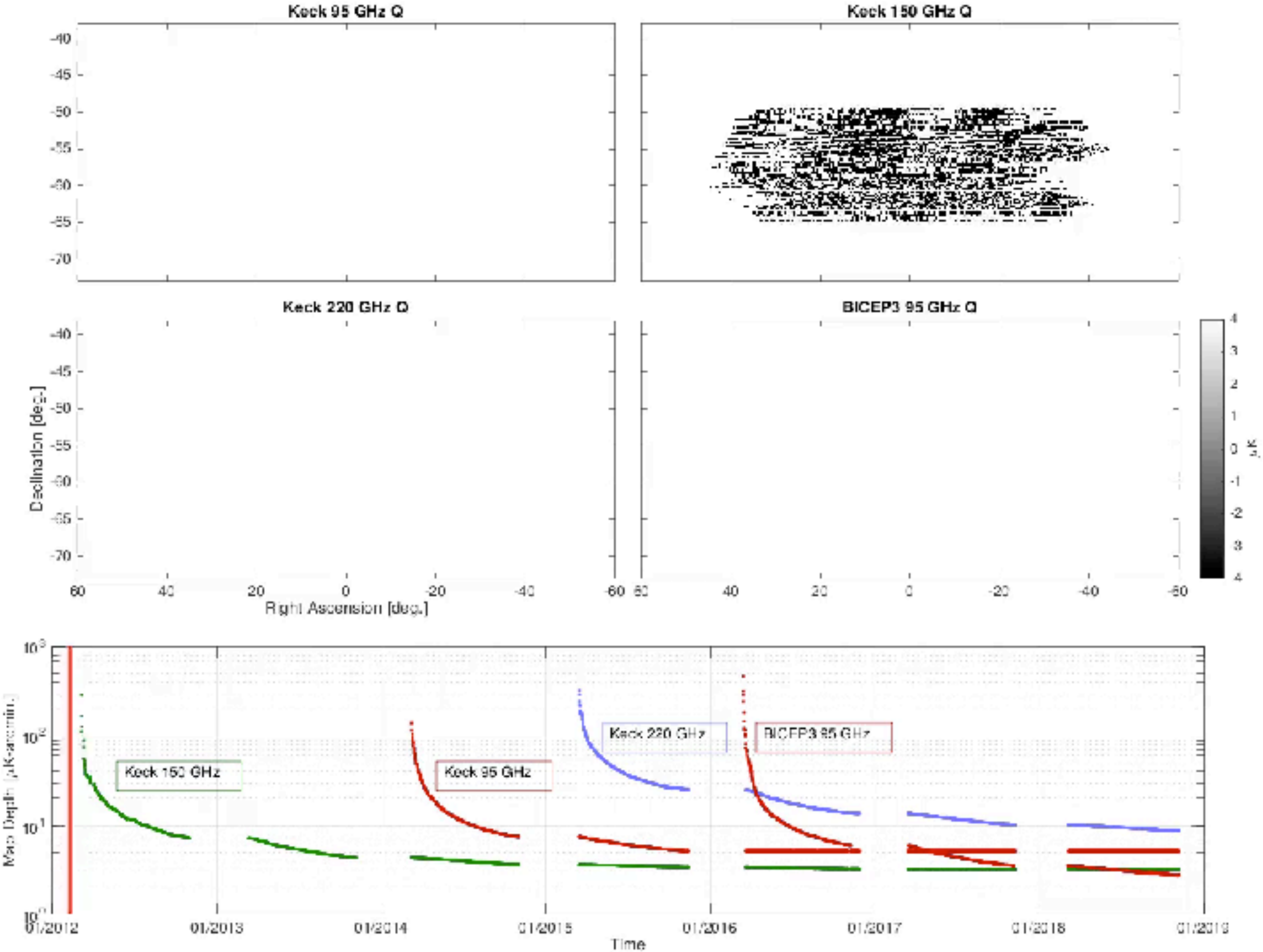


- High and *dry* – see out into space
- On Earth's rotational axis - One day/night cycle per year
  - Long night makes for great quality data
- Good support infrastructure – power, cargo, data comm
- Food and accommodation provided
- 24hr ice cream machine!

15+ years of experimental progress

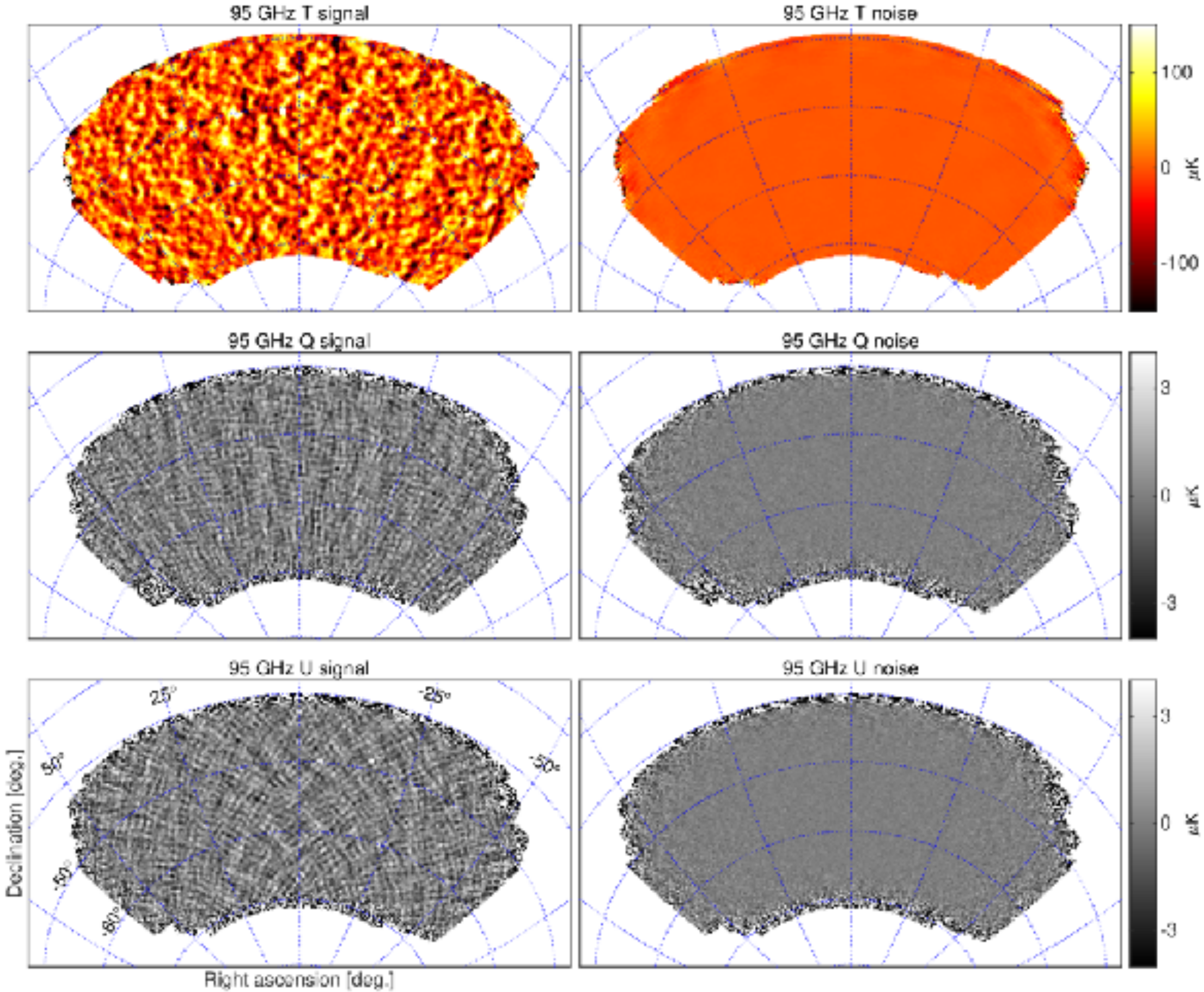




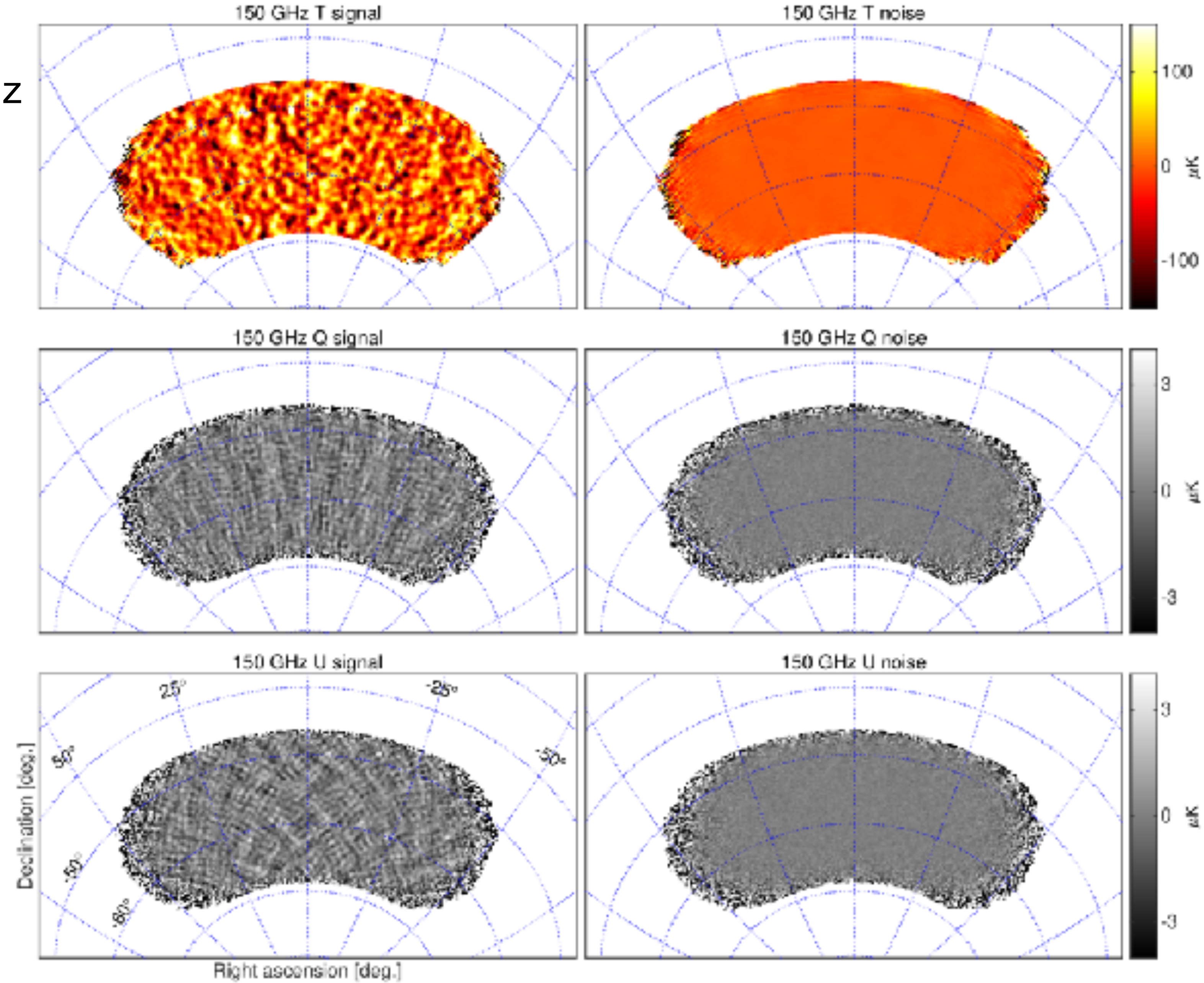


Keck 95 GHz Q
Keck 150 GHz Q
Keck 220 GHz Q
BICEP3 95 GHz Q
Declination [deg.]
Right Ascension [deg.]
μK
Map Depth [μK-arcmin]
Time
Keck 150 GHz
Keck 95 GHz
Keck 220 GHz
BICEP3 95 GHz
01/2012
01/2013
01/2014
01/2015
01/2016
01/2017
01/2018
01/2019

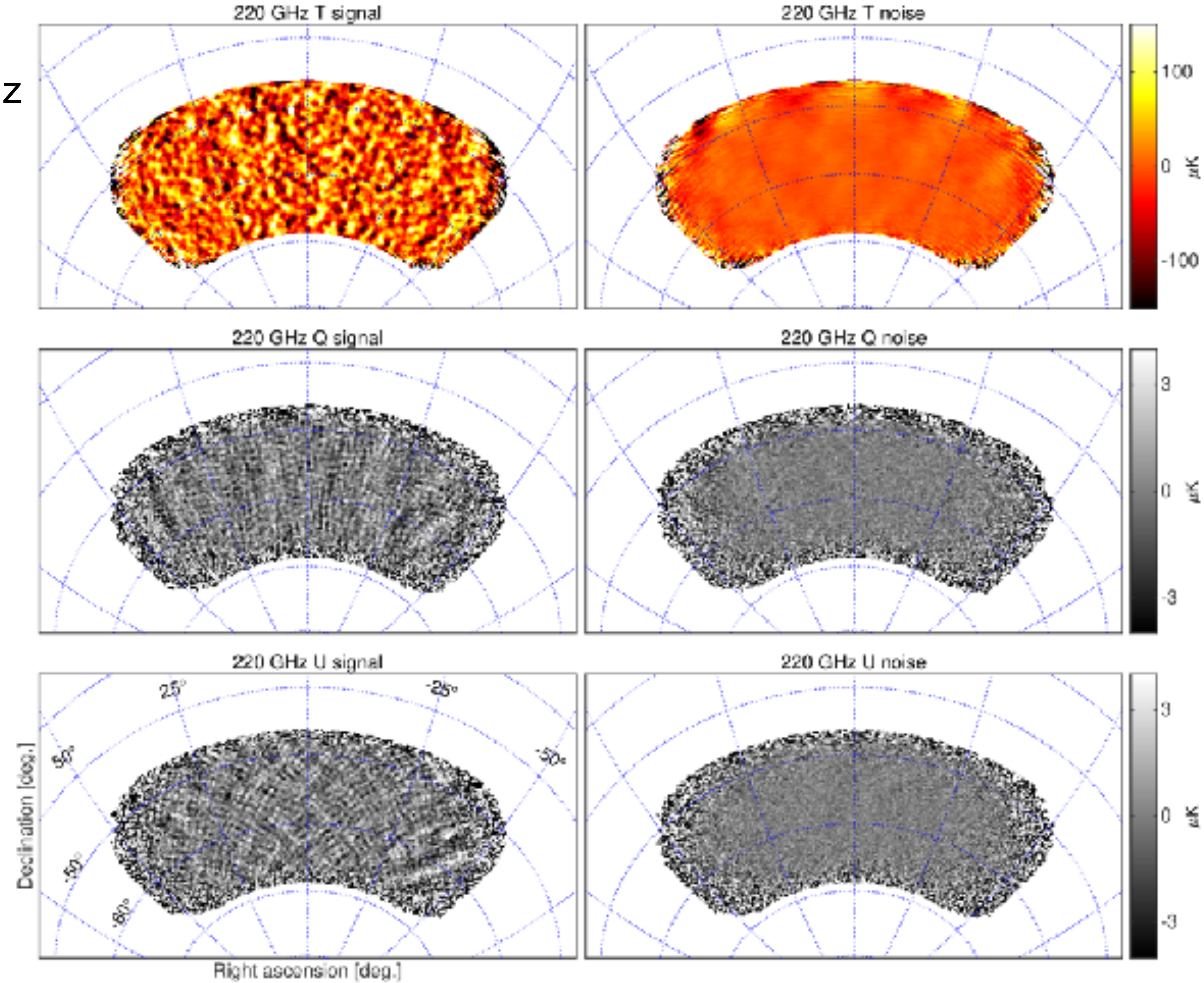
BK18
95GHz
Maps



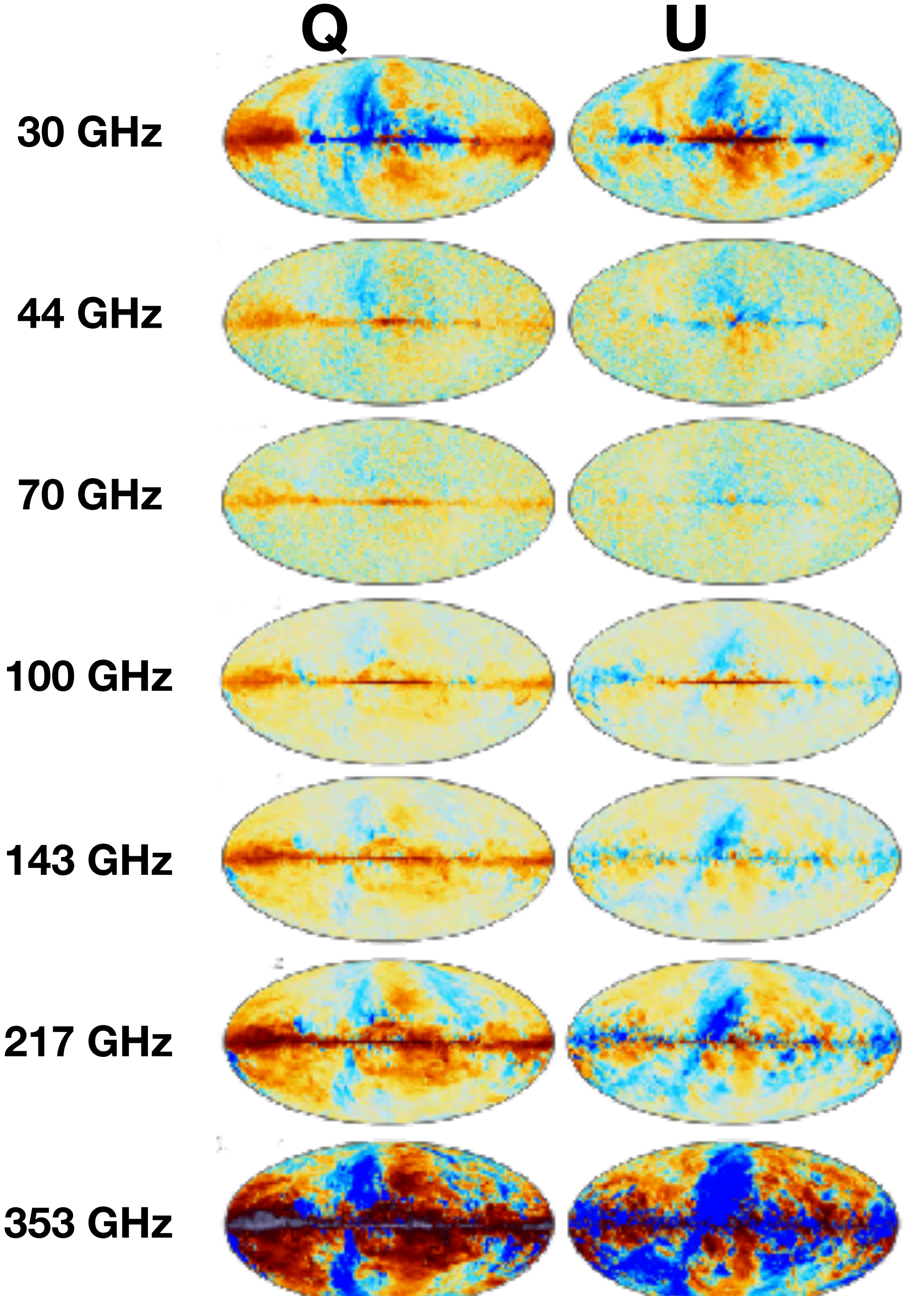
BK18
150GHz
Maps



BK18
220GHz
Maps

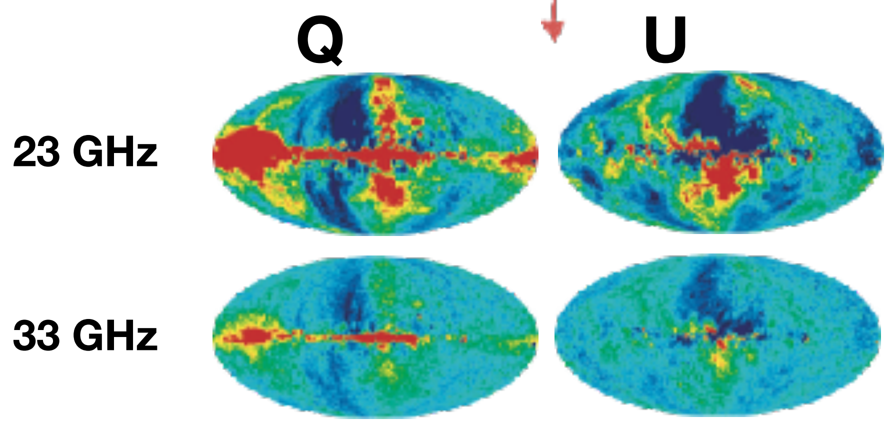


Add to the mix: Planck at 7 frequencies and WMAP at 2 frequencies



From arxiv 1502.01582

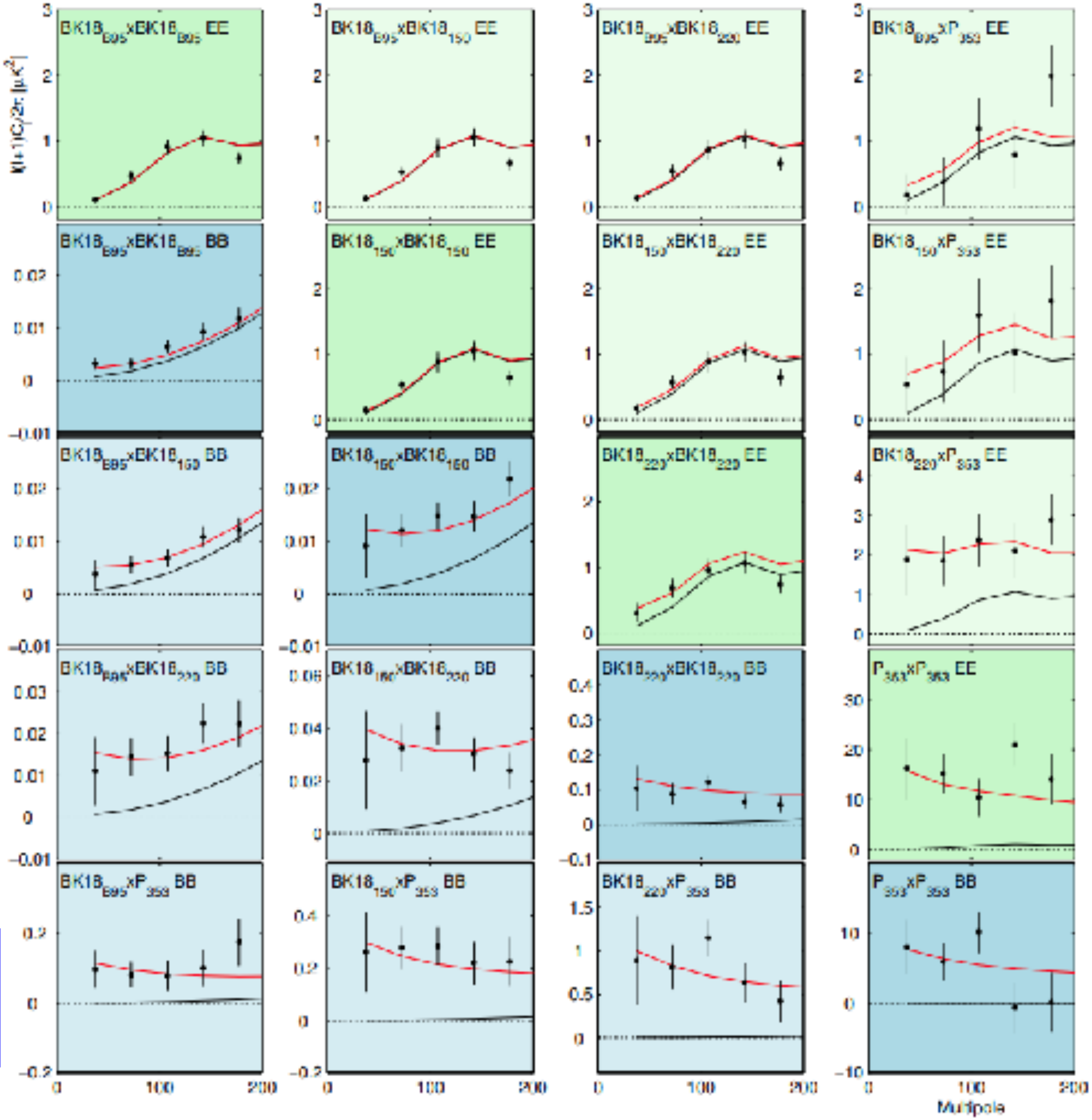
Polarized galactic **synchrotron** dominates at low frequencies



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



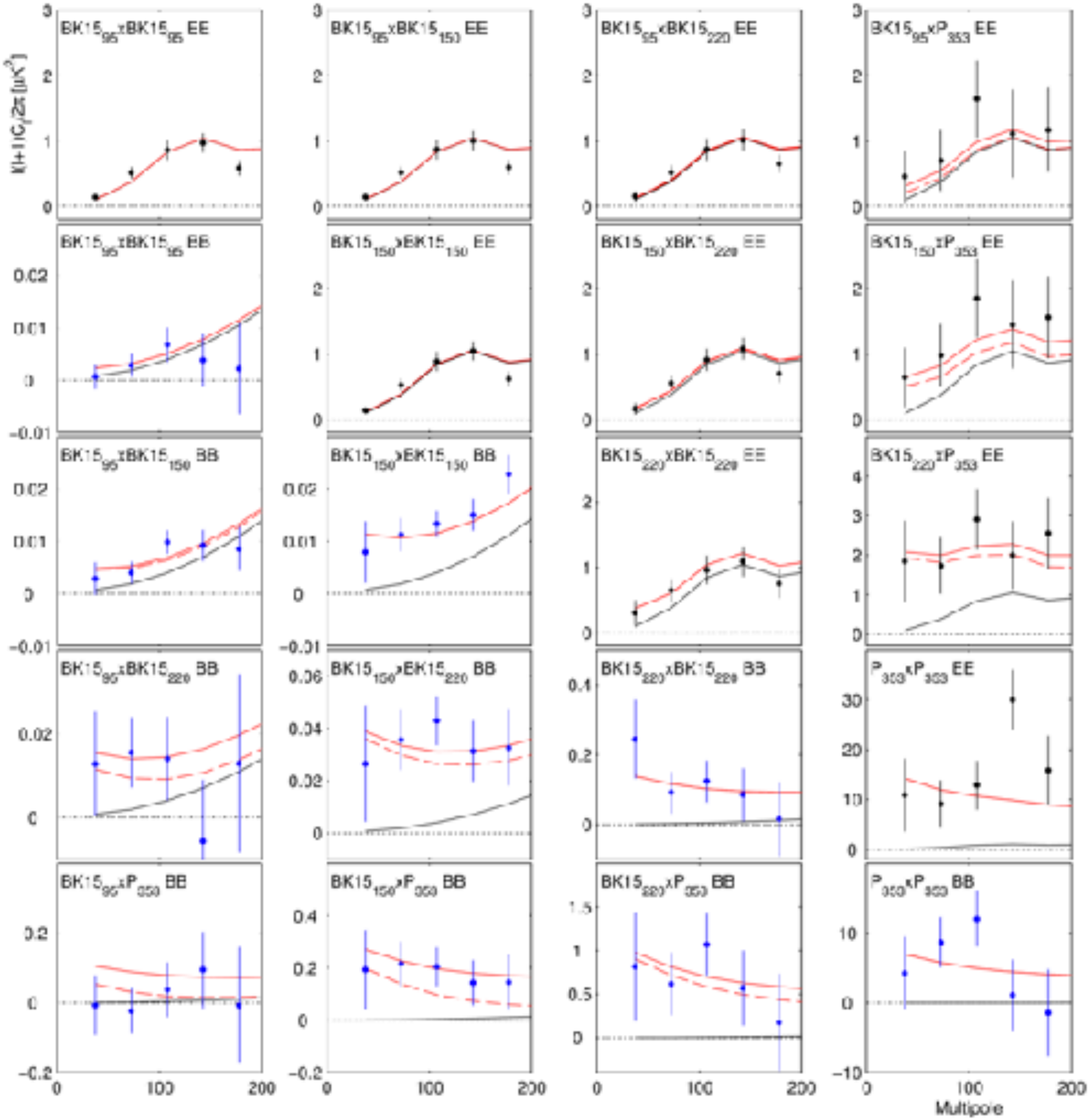
Green panels are EE spectra

Black lines are LCDM

Red lines are LCDM+dust from BK15 analysis

Blue panels are BB spectra

BK15 auto/cross spectra



Black lines are LCDM

Red lines are LCDM+dust from BK15 analysis

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

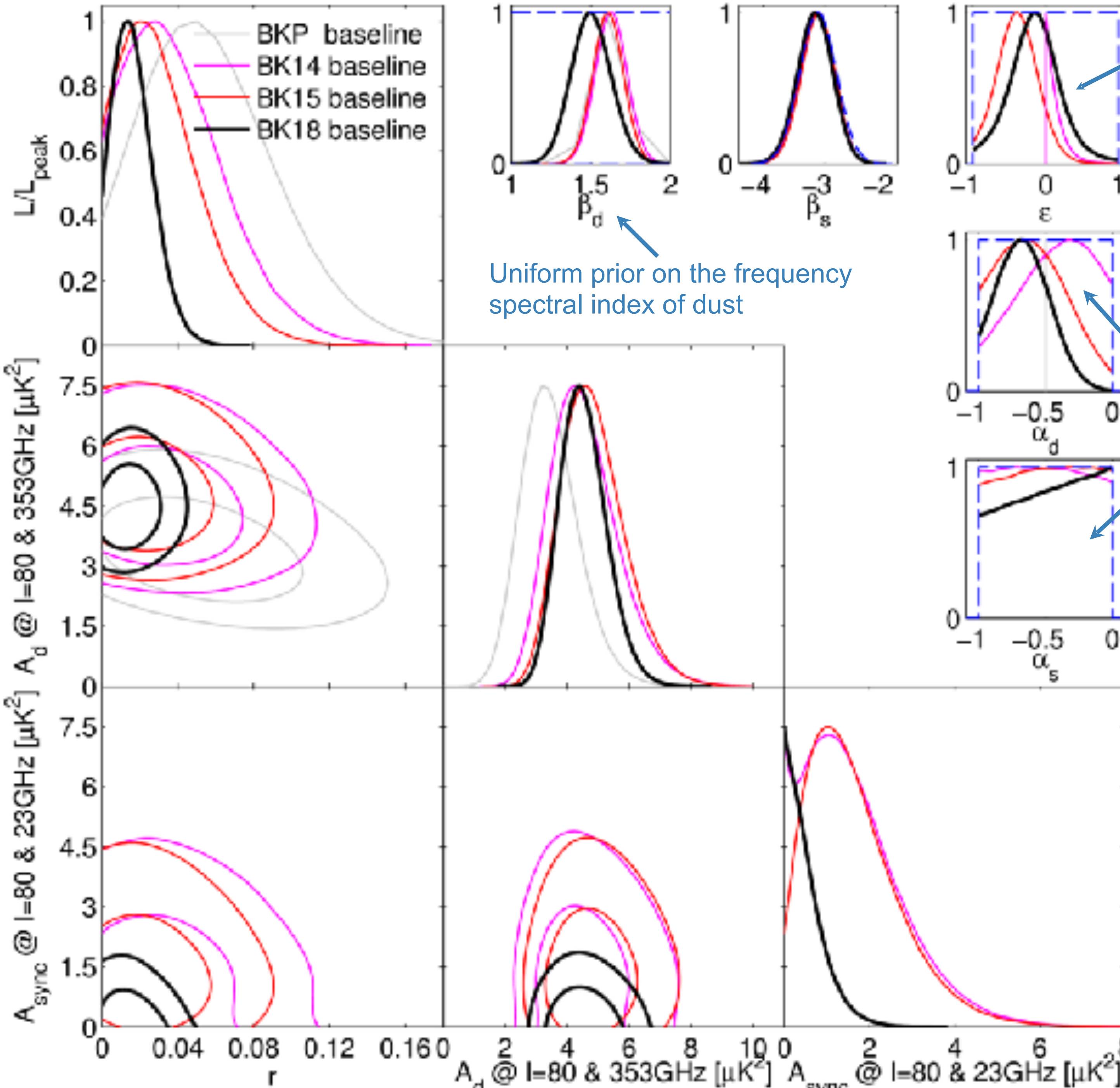
data model = r + ΛCDM + dust + synchrotron

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



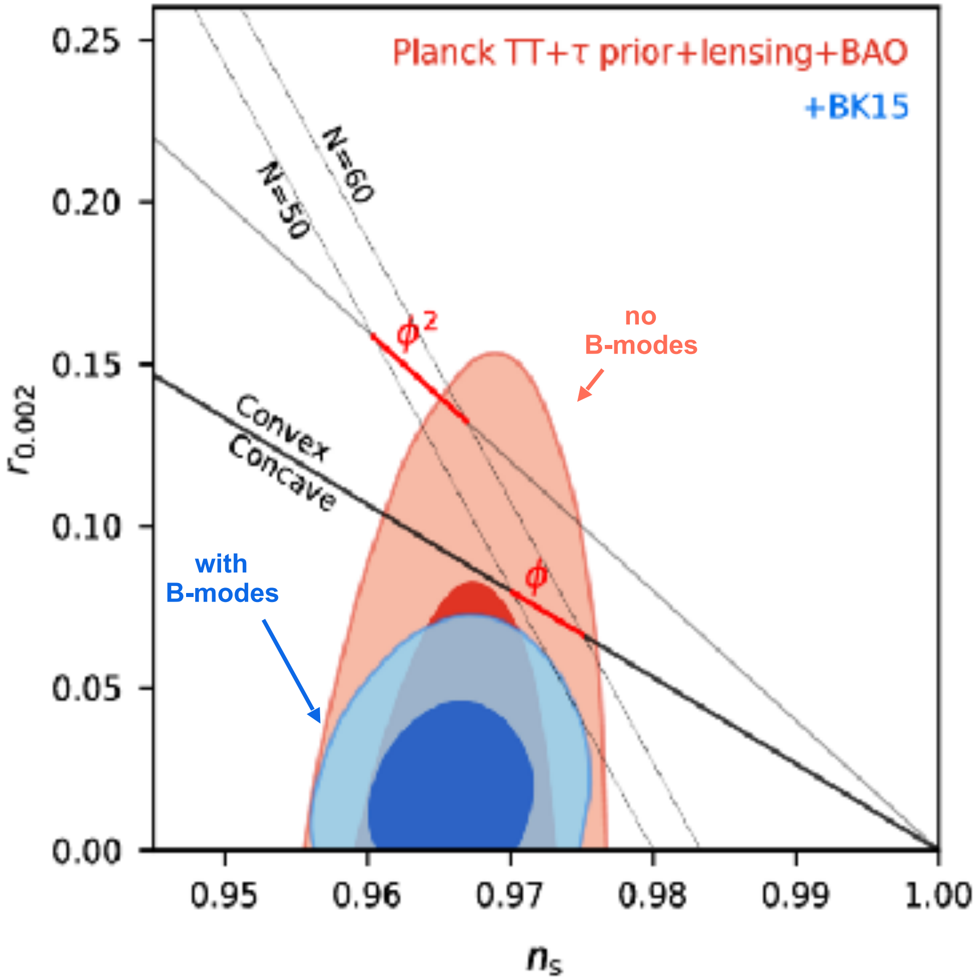
BK18

released Oct 2021:
B2/Keck 95+150+220
+ BICEP3 up to 2018

$\mathbf{r_{0.05} < 0.036}$

arxiv/2110.00483

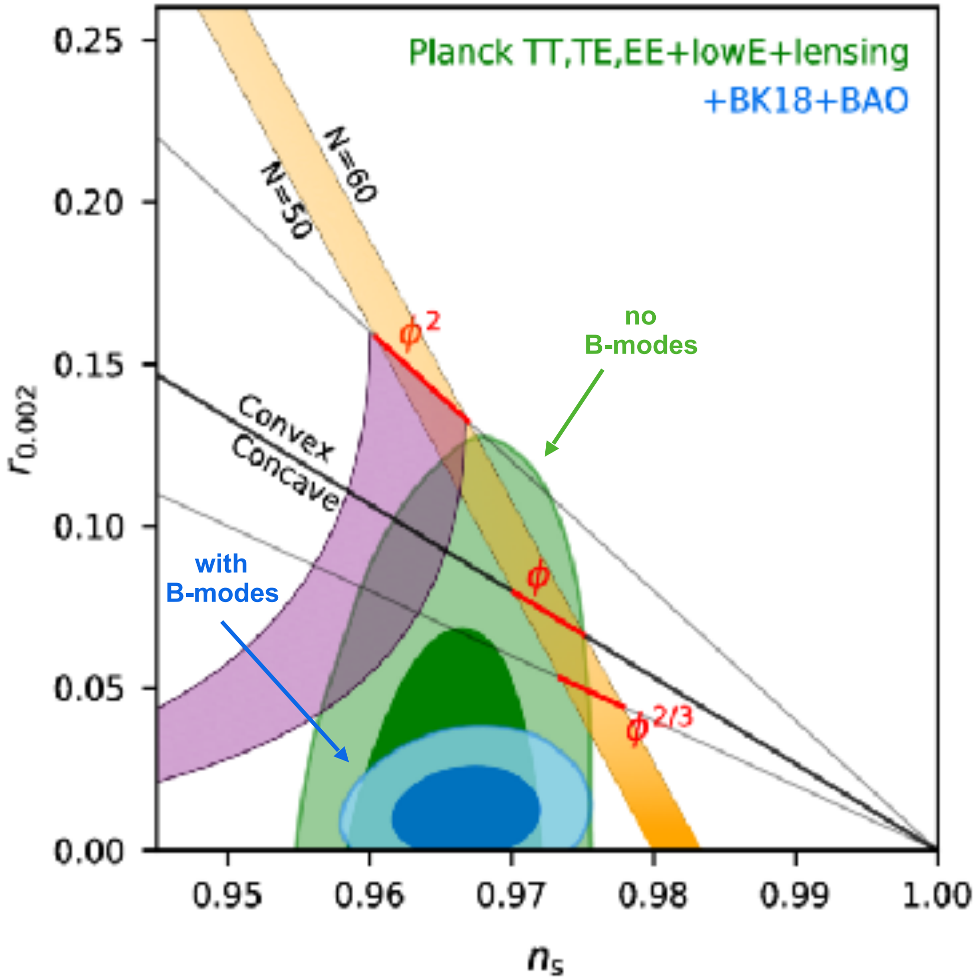
How inflation model space gets constrained by B-mode measurements



$r_{.05} < 0.06$
(95% CL)

BK15
arxiv/1810.05216

How inflation model space gets constrained by B-mode measurements



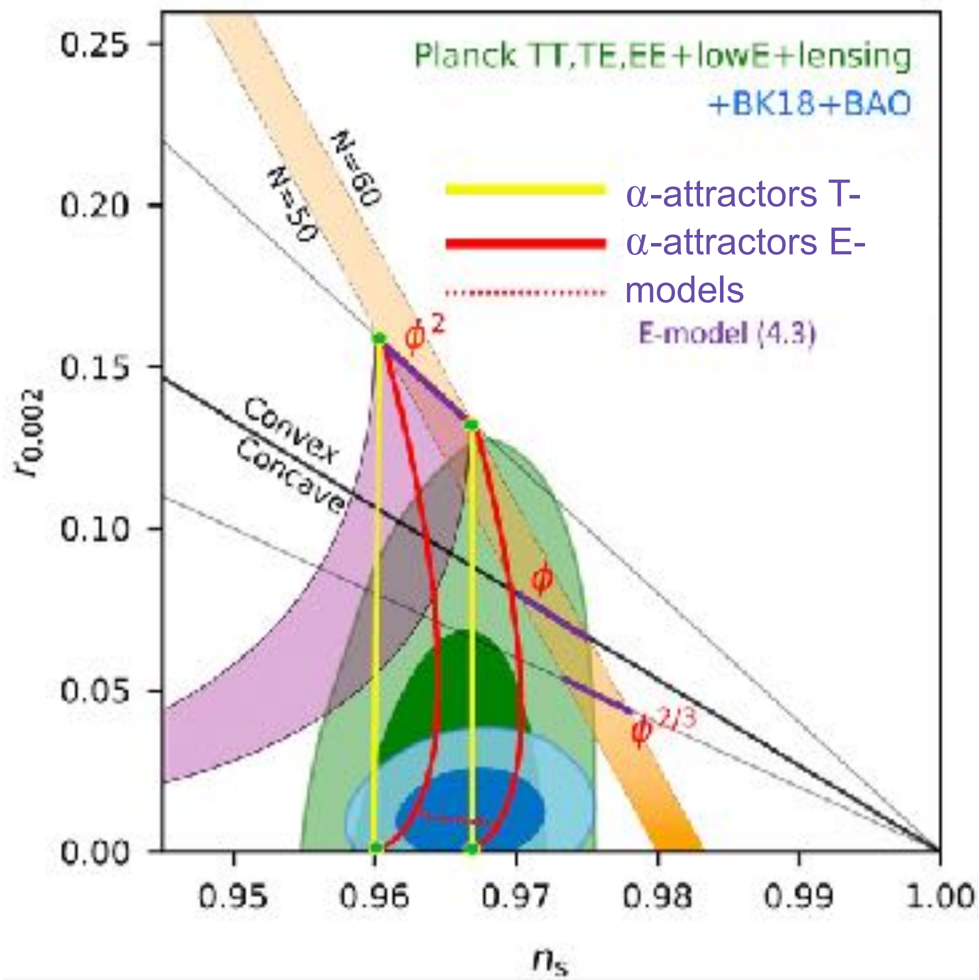
$r_{.05} < 0.036$

(95% CL)

BK18

arxiv/2110.00483

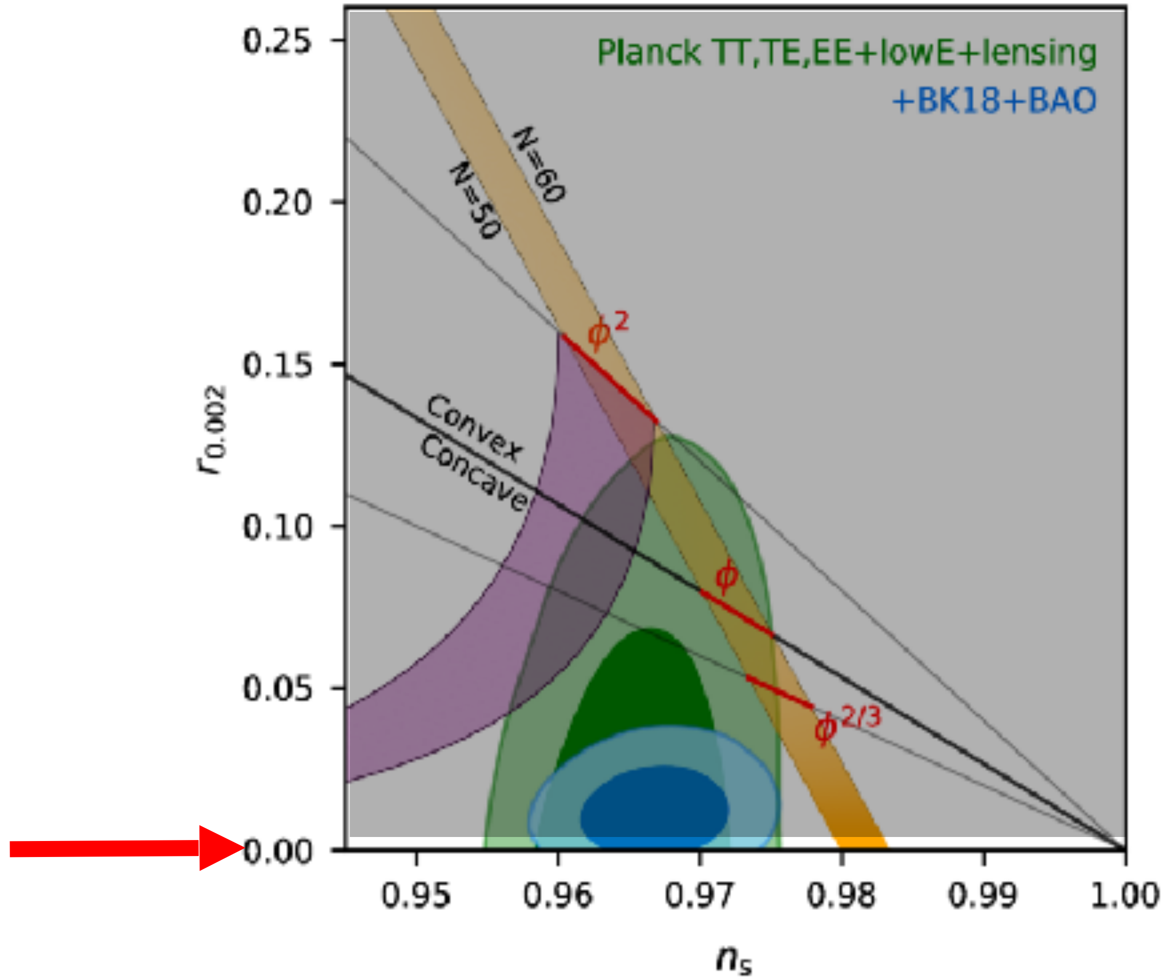
Enables our theorist colleagues to explore alternatives



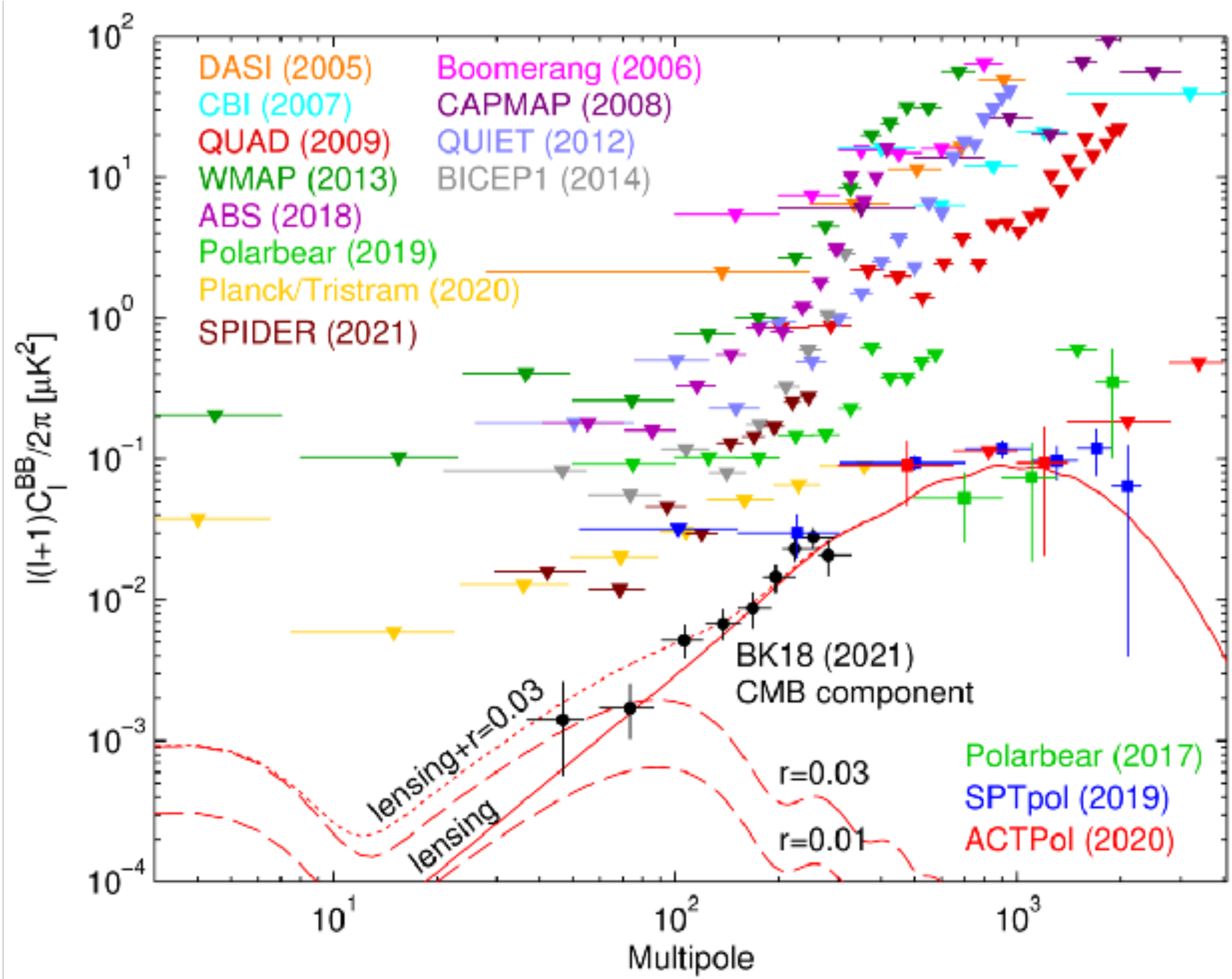
https://arxiv.org/abs/2108.08492

(Kallosh, Linde, Wrase, Yamada)

More work to do!
CMB-S4/Litebird target to detect $r \sim O(10^{-3})$.



BK18: Best measurement to date of large-scale B-modes



What currently limits our r measurement?

Contributions to σ(r): $C_\ell^{\mathrm{BB,fg}} + C_\ell^{\mathrm{BB,lens}} + N_\ell$

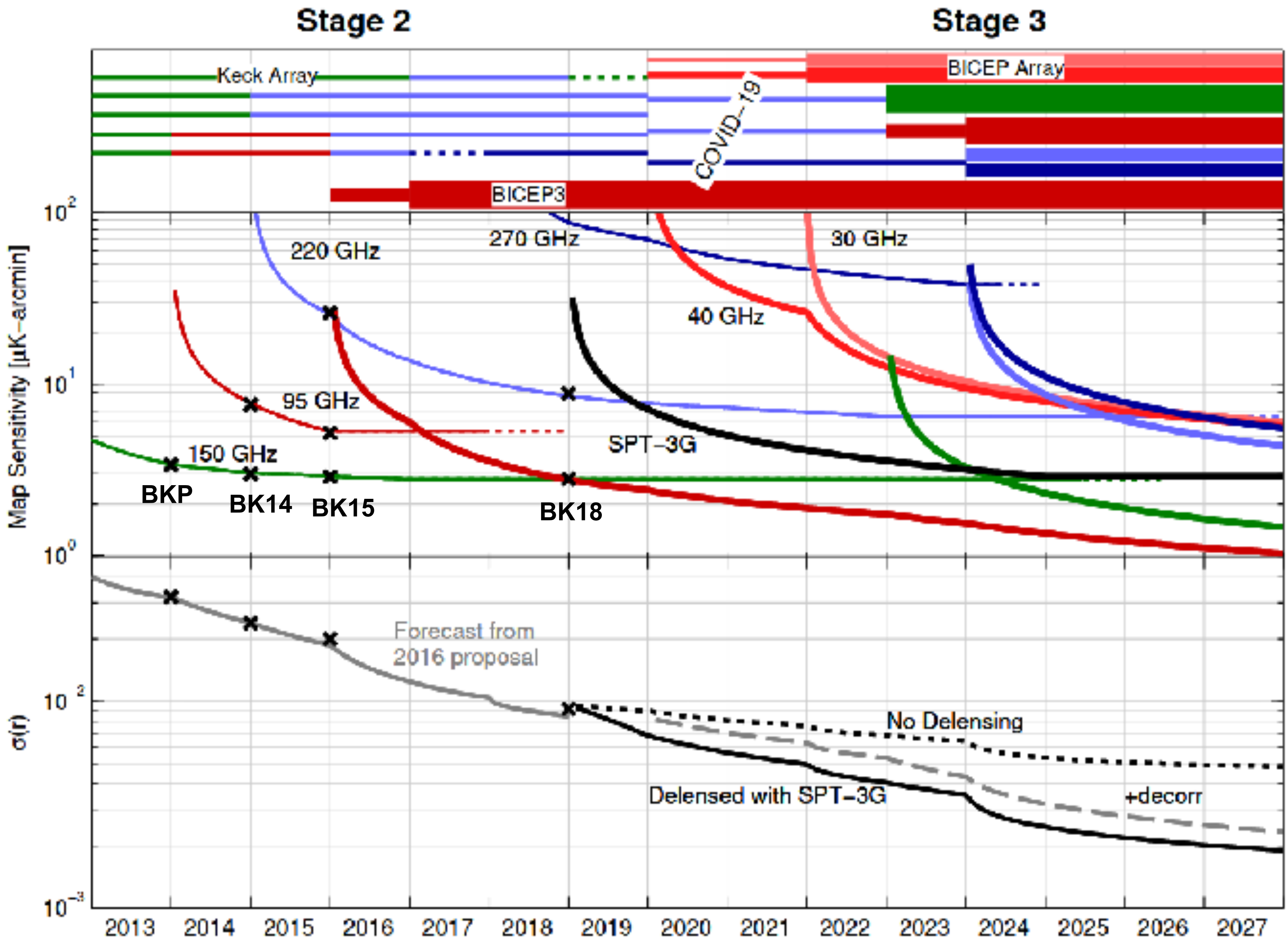
- BK18 mainline simulations with dust and lensing give **σ(*r*)=0.009**
- Running without foreground parameters on simulations where the dust amplitude is set to zero gives **σ(*r*)=0.007**

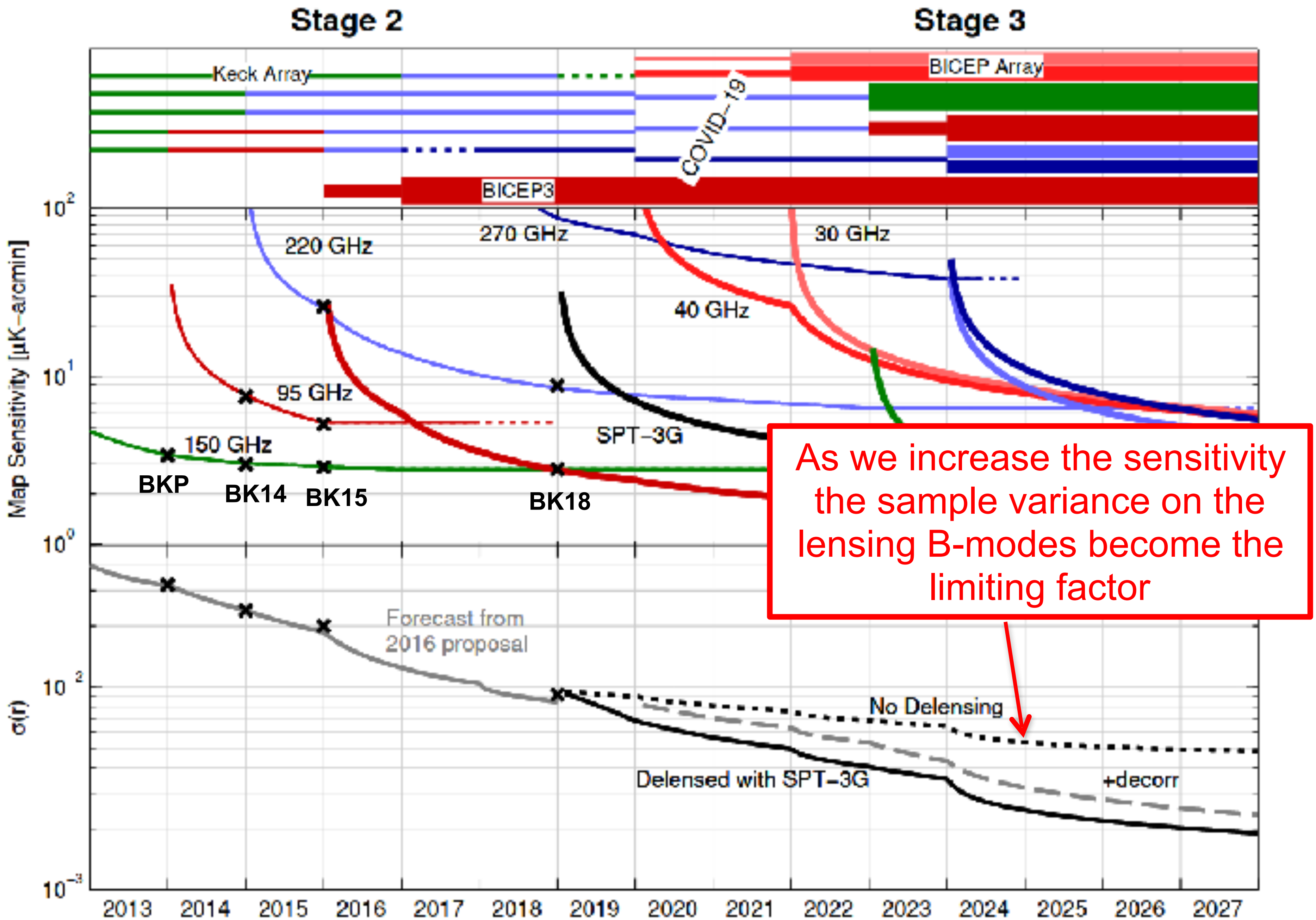
The above is as it should be - we have correctly tuned the relative sensitivity of the 95/150/220 bands such that we don't suffer much penalty due to the presence of foregrounds.

- 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
BKP
BK14
BK15
BK18
Map Sensitivity [μK–arcmin]
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



Stage 2
Stage 3
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220 GHz
270 GHz
30 GHz
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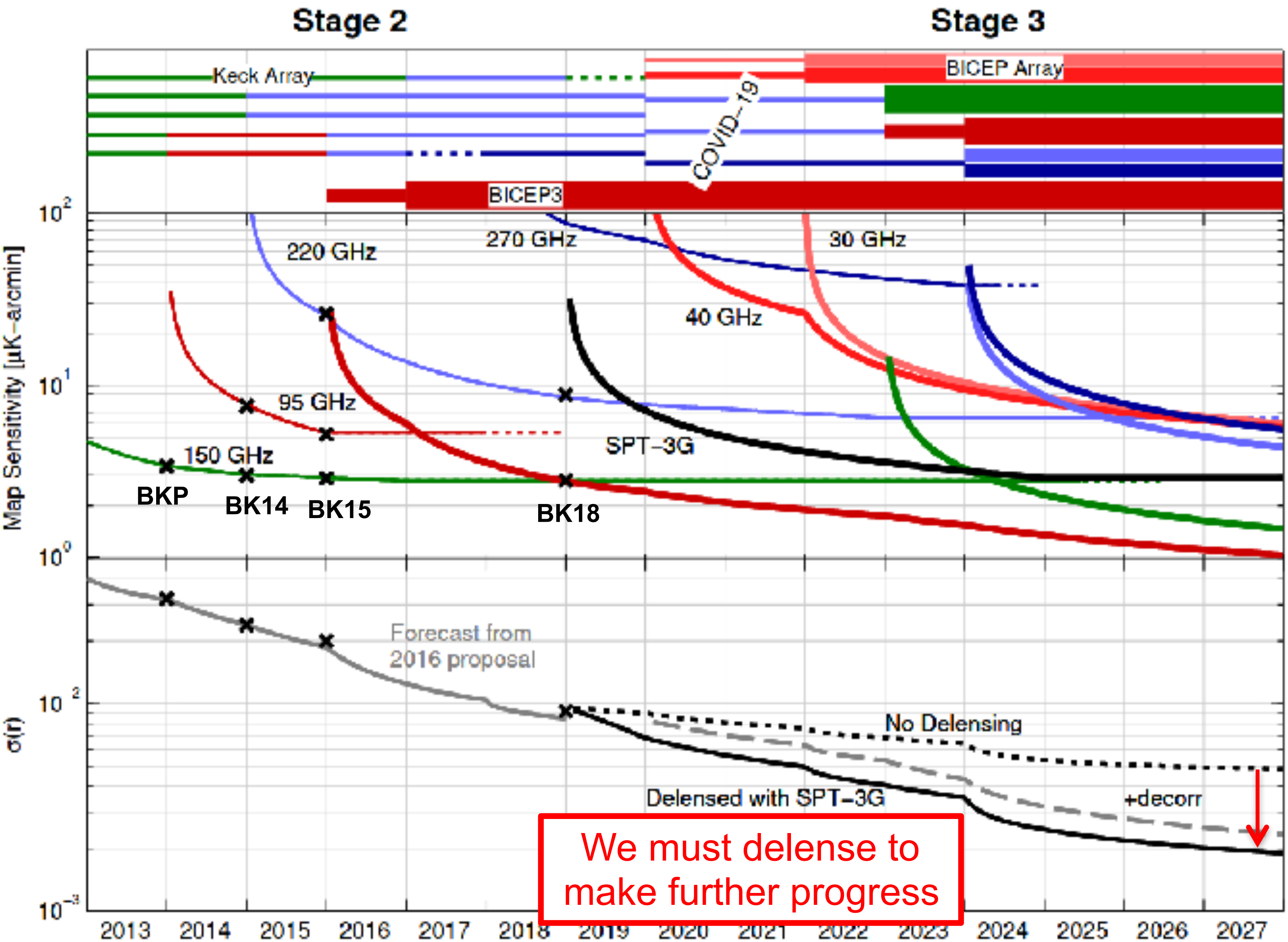
150 GHz
SPT-3G
BKP
BK14
BK15
BK18
Map Sensitivity [μK-arcmin]
10^2
10^1
10^0
10^{-2}
10^{-3}
σ(r)
Forecast from
2016 proposal
No Delensing
Delensed with SPT-3G
+decorr
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
As we increase the sensitivity the sample variance on the lensing B-modes become the limiting factor


Stage 2
Stage 3
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Map Sensitivity [μK–arcmin]
10^2
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220 GHz
270 GHz
30 GHz
40 GHz
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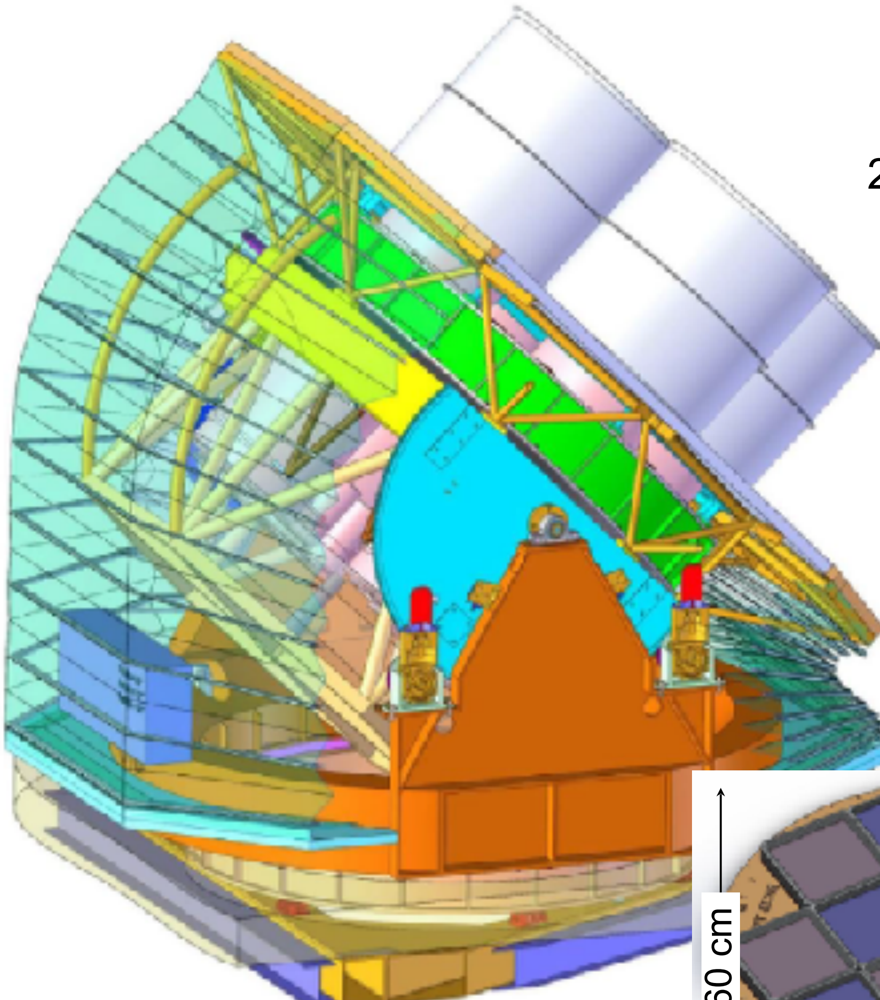
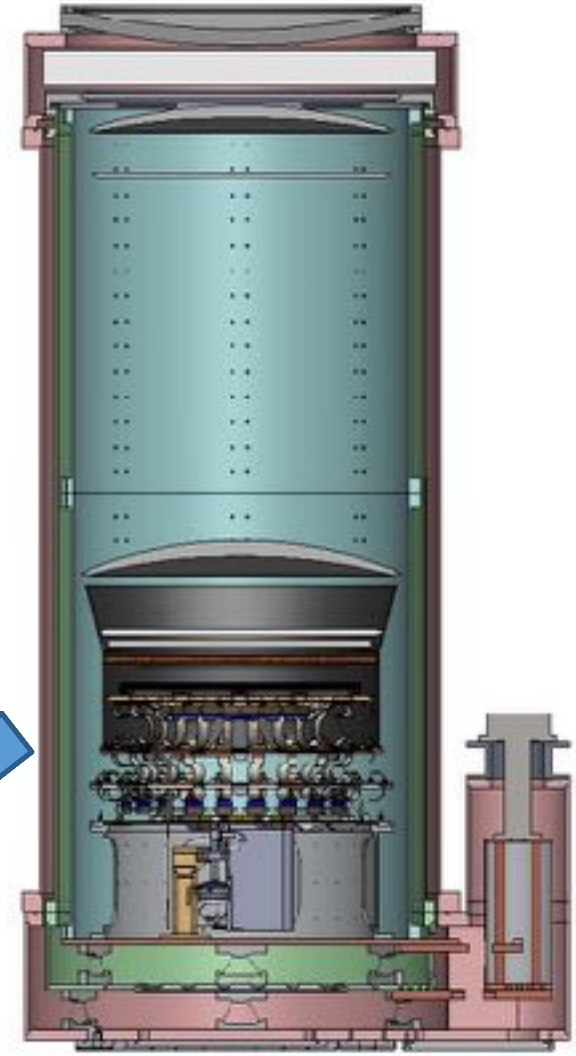
150 GHz
SPT–3G
BKP
BK14
BK15
BK18
σ(r)
10^-2
10^-3
Forecast from
2016 proposal
No Delensing
Delensed with SPT–3G
+decorr
We must delense to
make further progress
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027

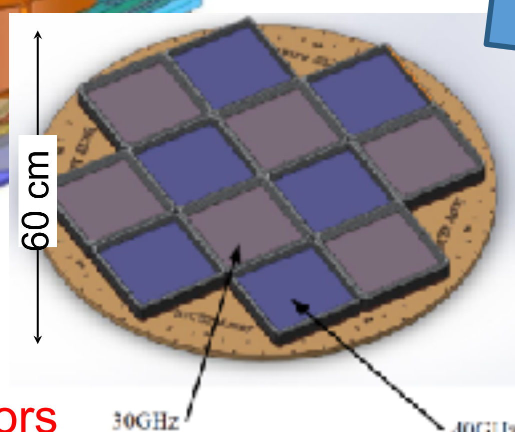
BICEP Array Under Construction

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





Wide-field cryogenic receiver



Focal plane layout

When complete >30,000 detectors

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

Conclusions

- BICEP/Keck measurements 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
- Ruling out popular class of inflationary models

- And we can keep going:
- BICEP Array mount and first receiver running
- Delensing in conjunction with SPT3G

Cheers

Denis Barkats for the BICEP/Keck Collaboration — Rencontres de Blois — May 25 2022