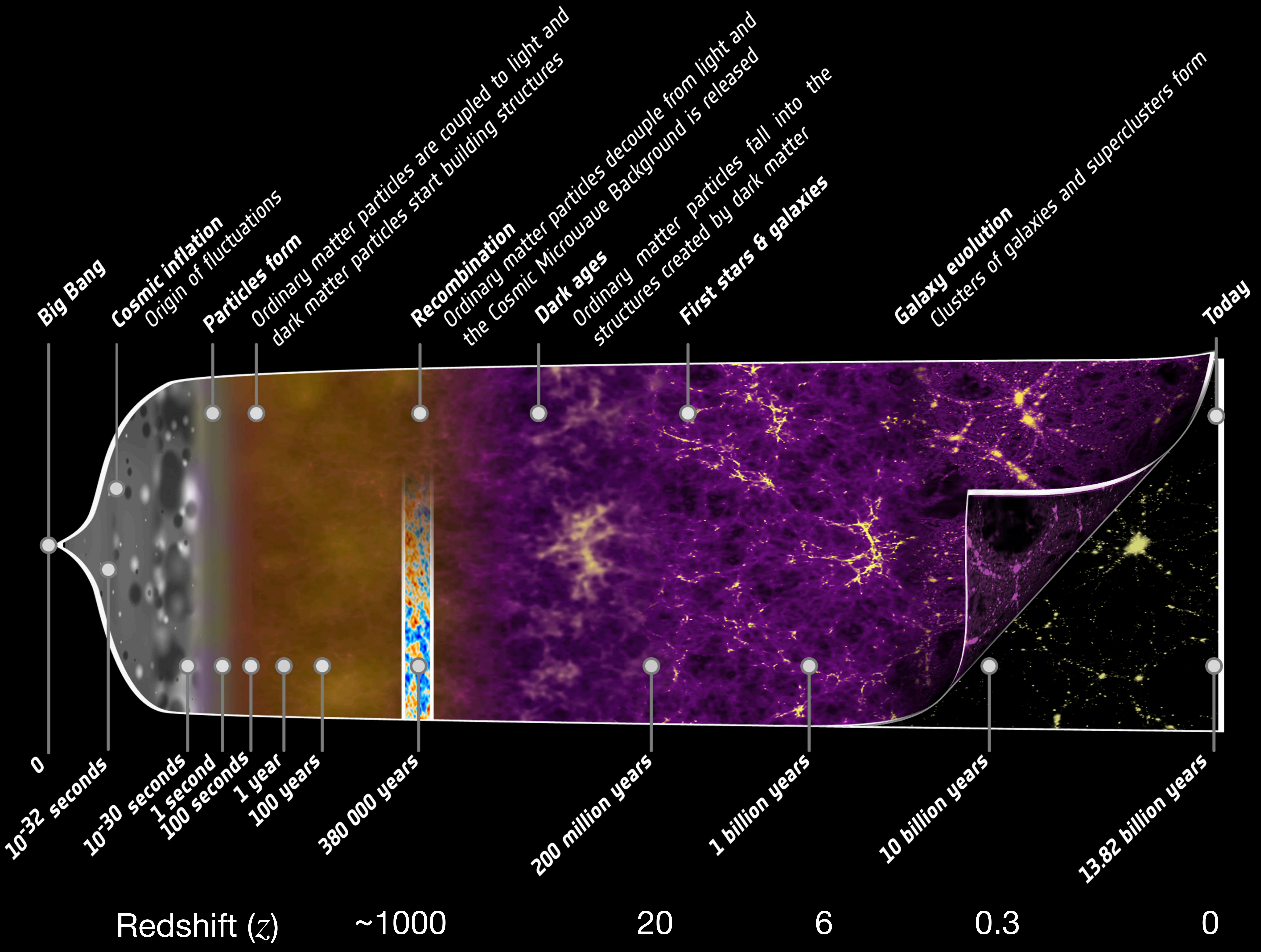
Latest results from the BICEP/ Keck Collaboration

Constraints on primordial gravitational waves and cosmic inflation with data collected through 2018

Zeeshan Ahmed
Kavli Institute for Particle Astrophysics and Cosmology, SLAC National Accelerator Laboratory
CIPANP, August 31, 2022

Photo by Keith Vanderlinde

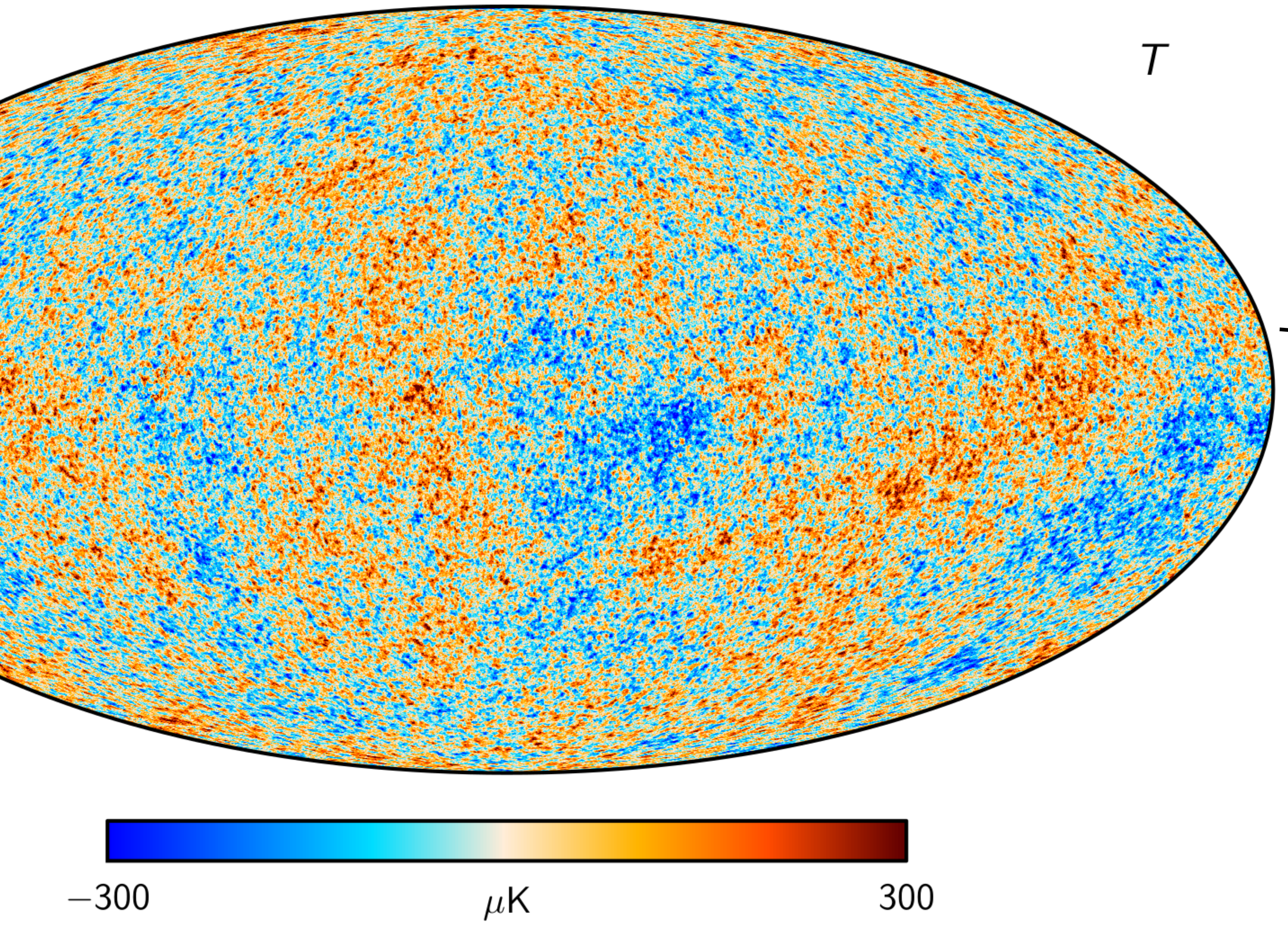


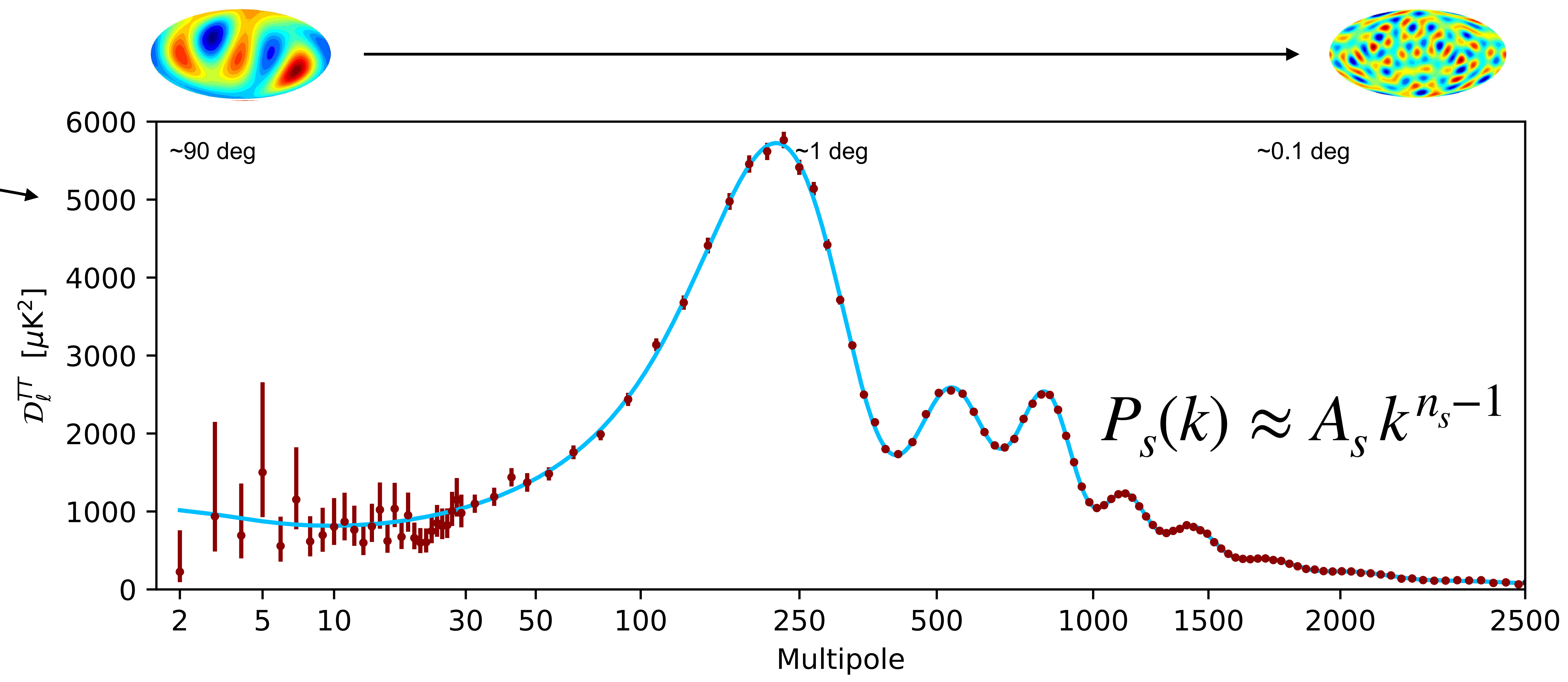
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years
Redshift (z)
~1000
20
6
0.3
0

ESA/Planck

Statistical information from CMB

Suggests primordial seeds of structure





We measure a simple, flat power spectrum for primordial fluctuations. When evolved forward, it matches the matter power spectrum observed today.

Figures from Planck Legacy Release 2018

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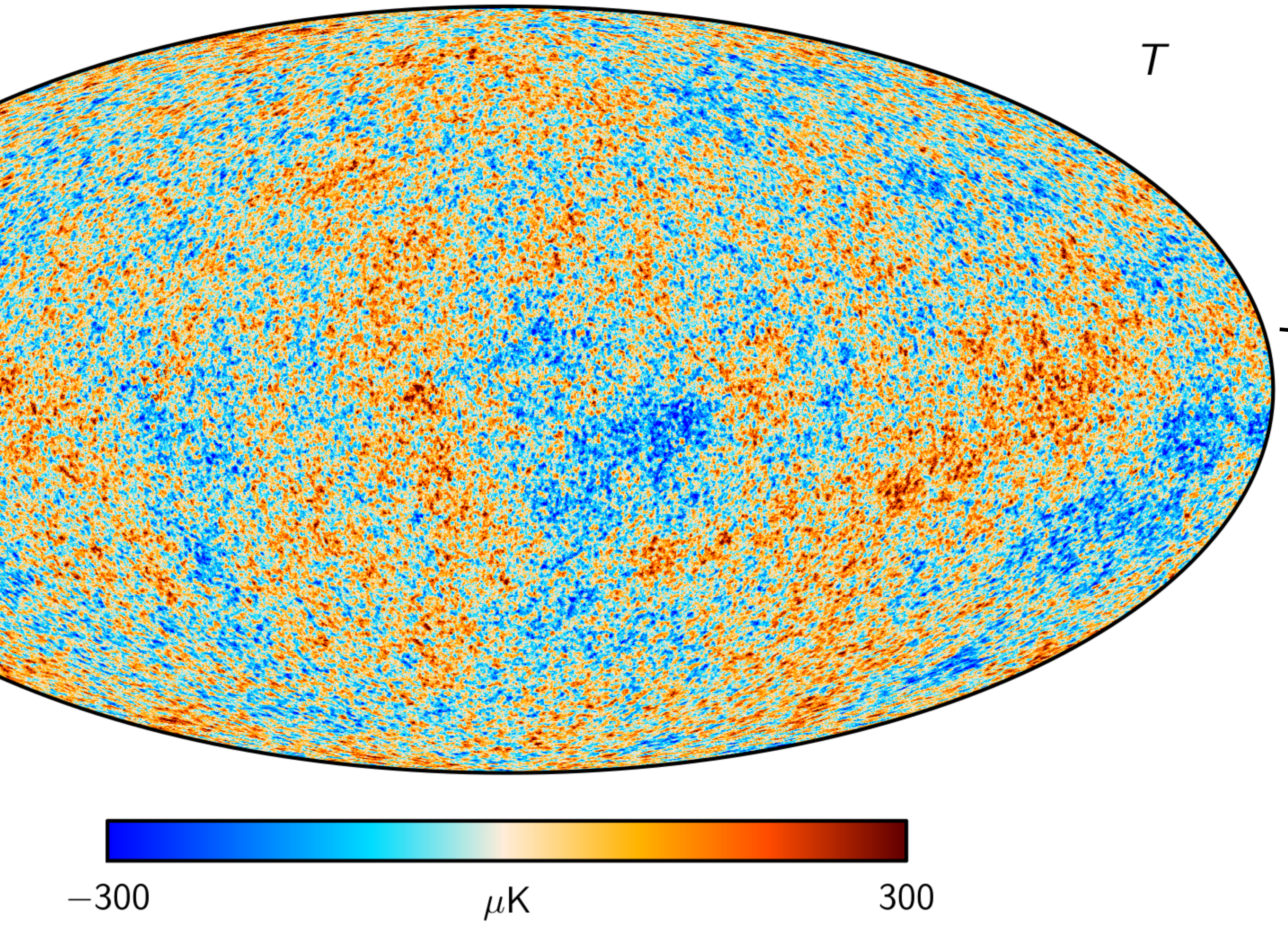

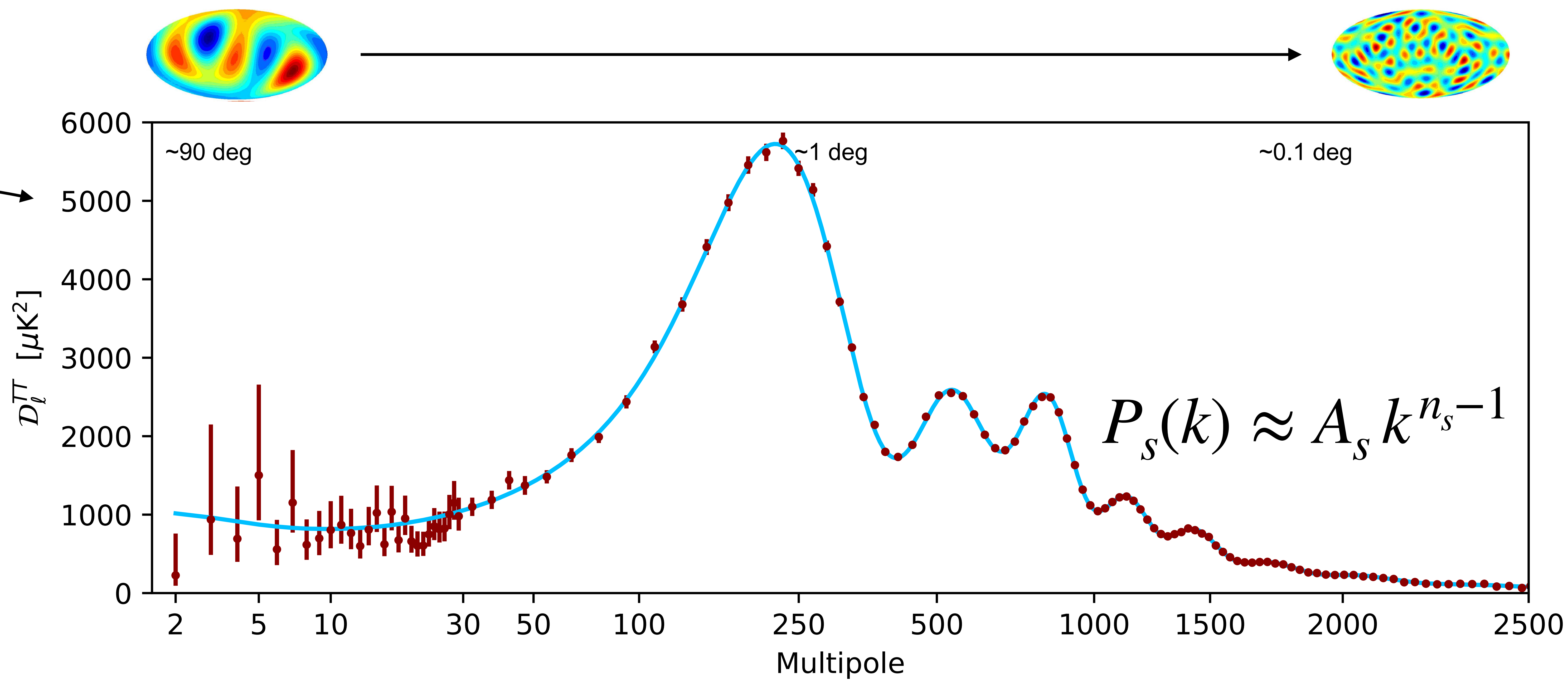

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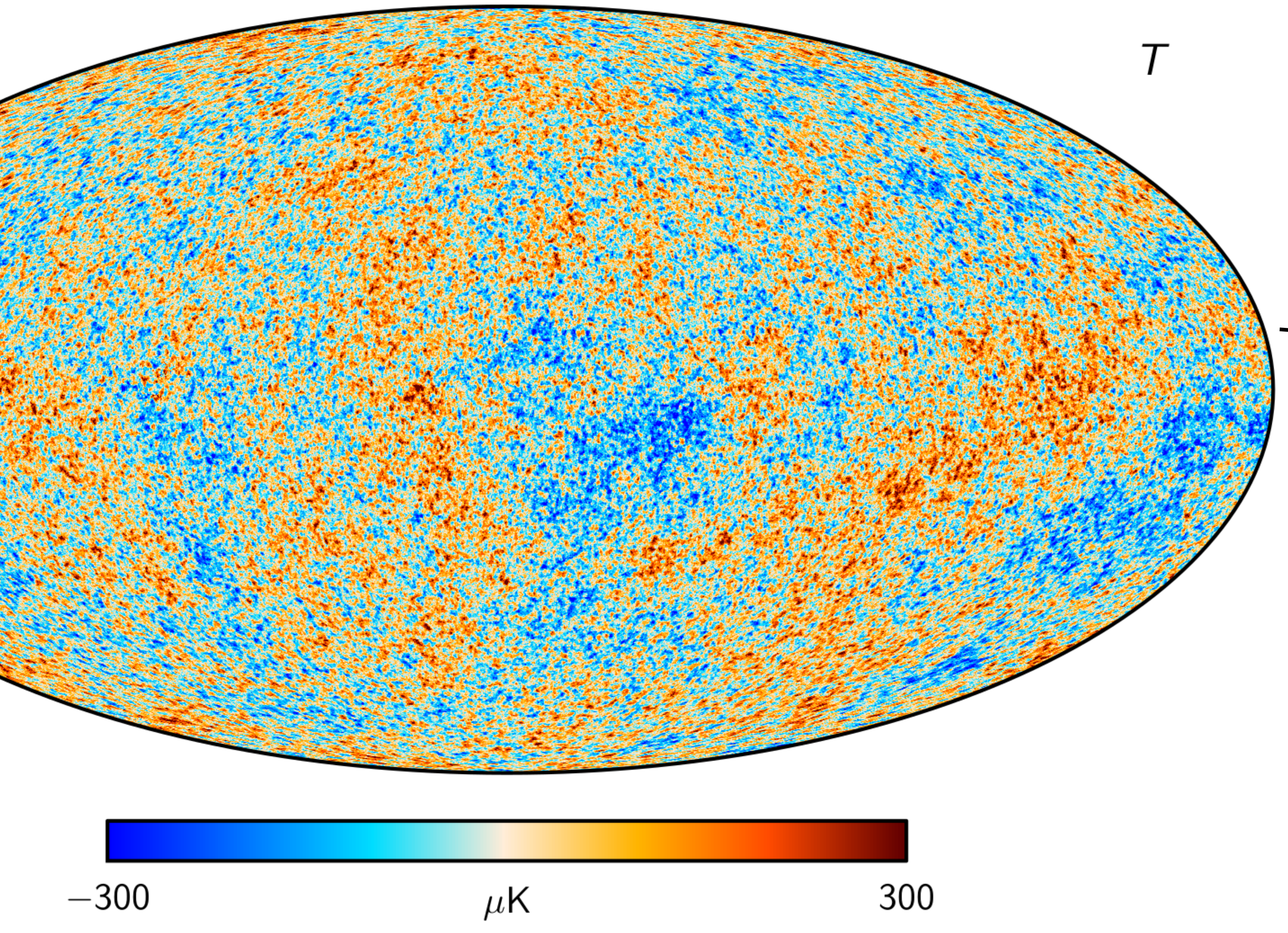

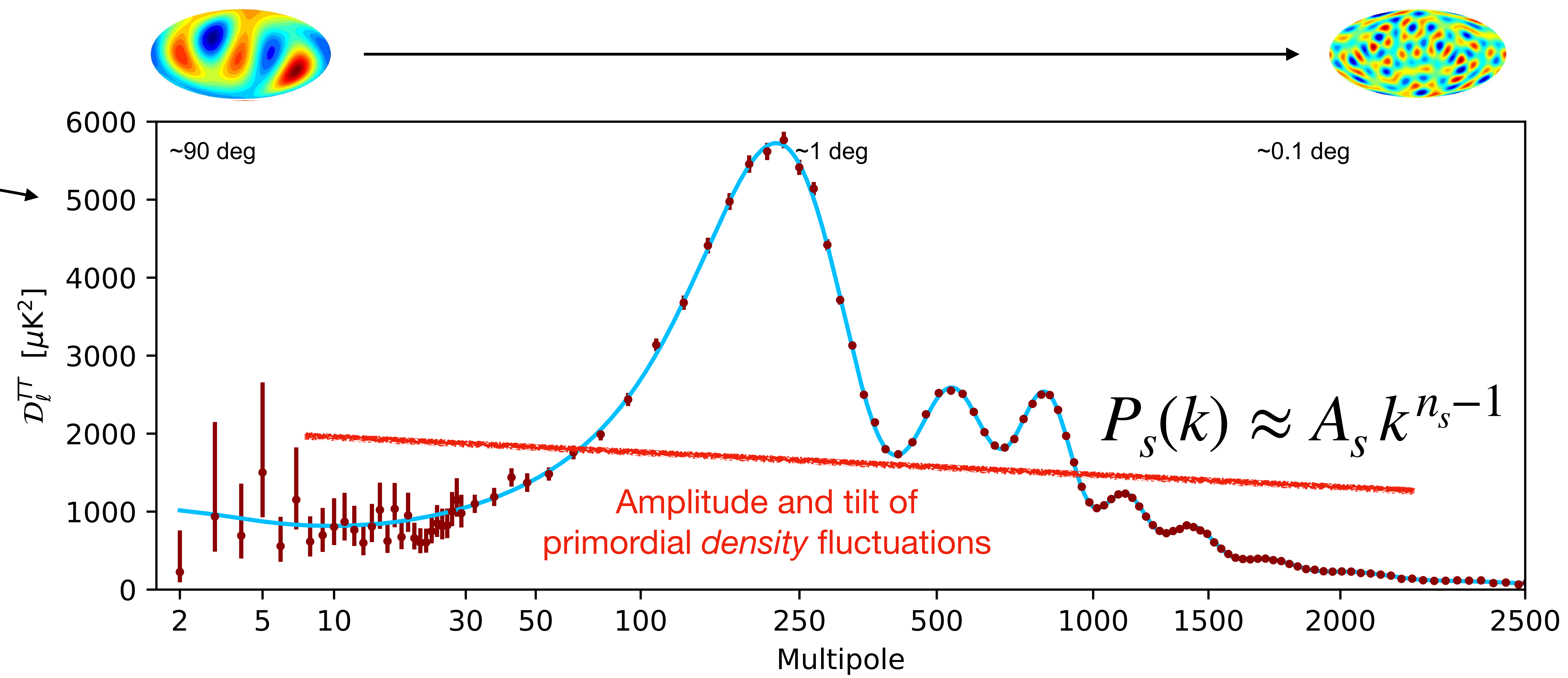

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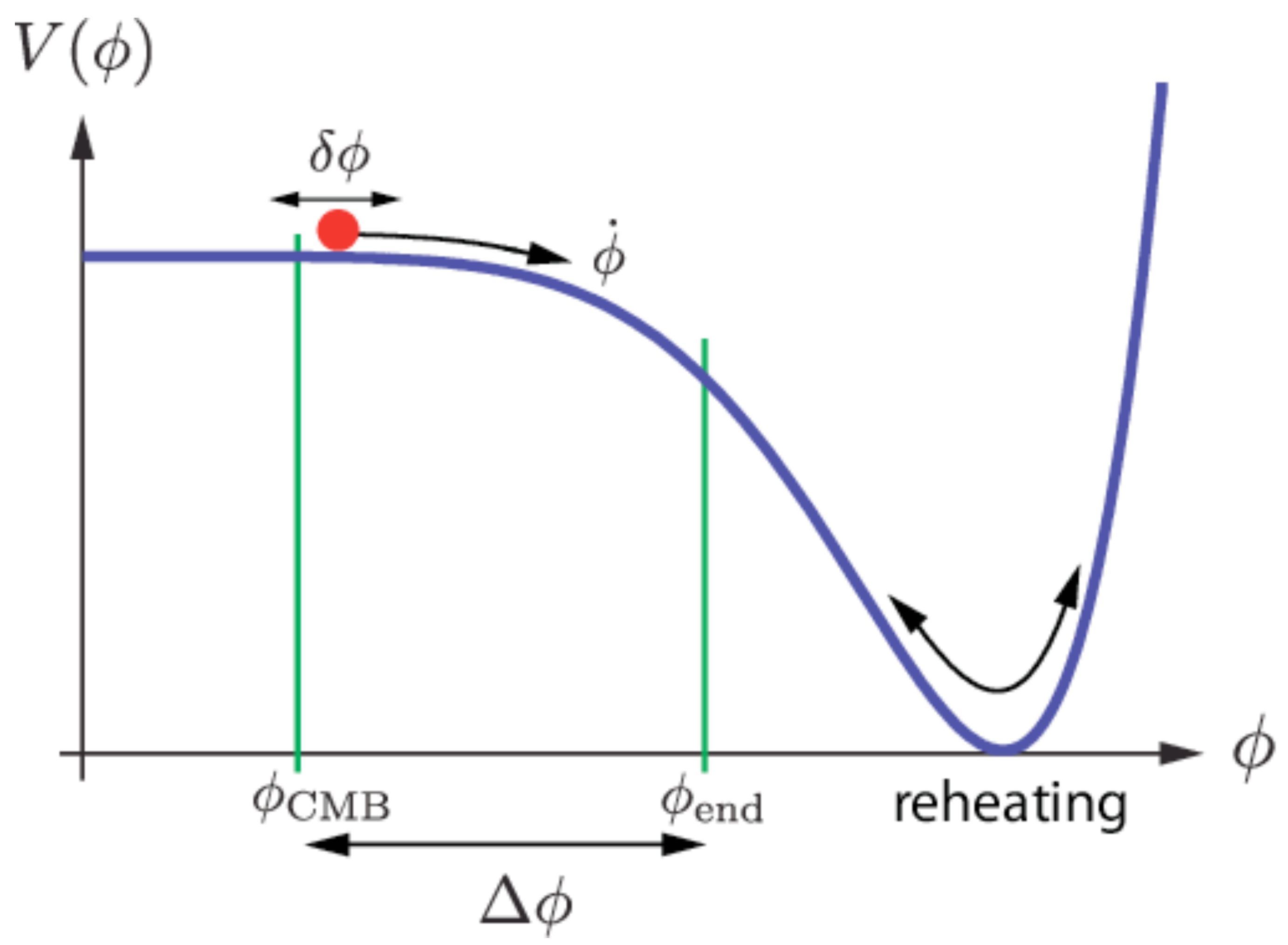
Figures from Planck Legacy Release 2018

Inflation seeds primordial structure

Scalar field(s) for exponential expansion



Figures from Baumann/Peiris 2009, Astronomy Today and Planck 2018

Inflation seeds primordial structure

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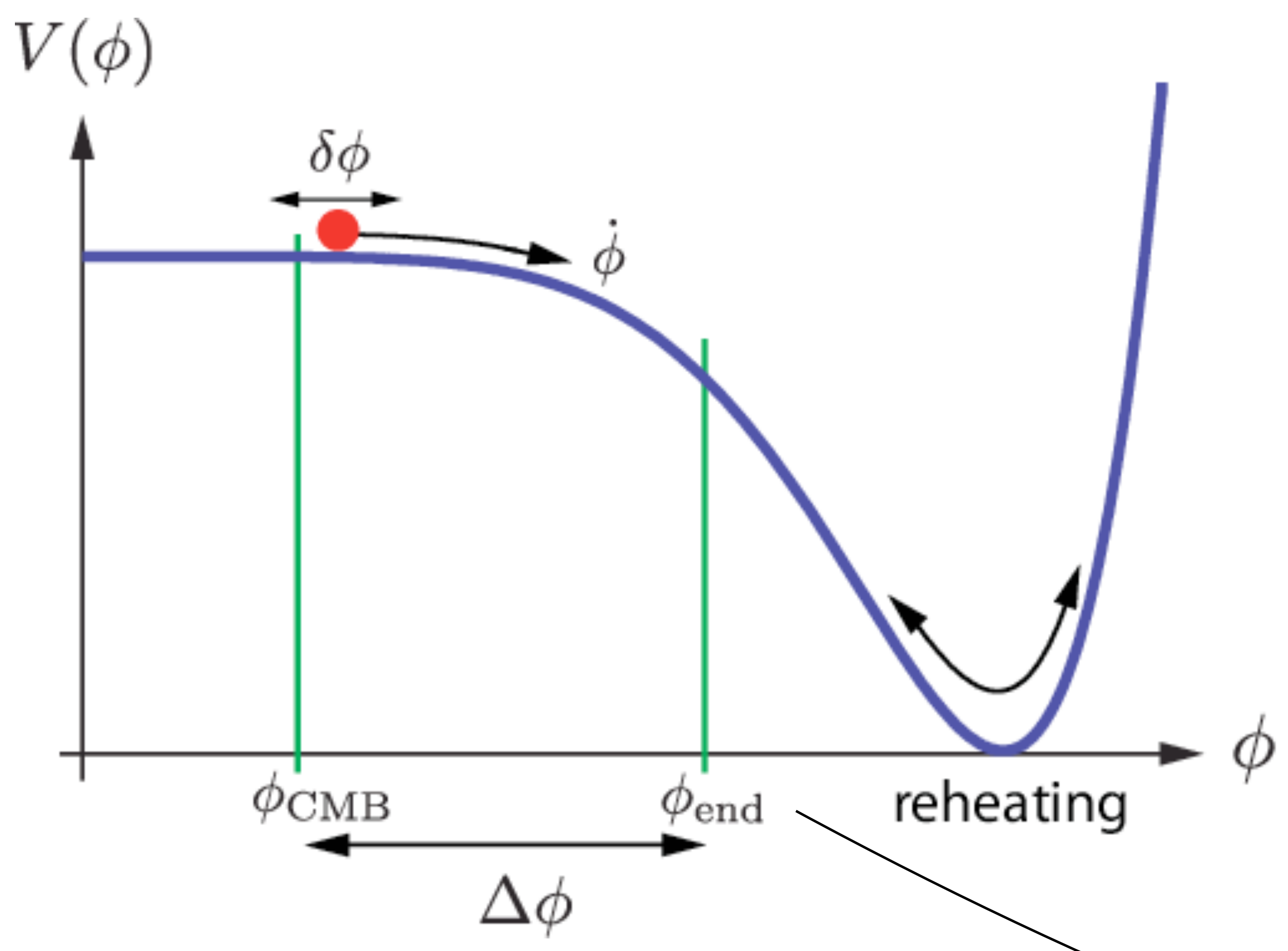
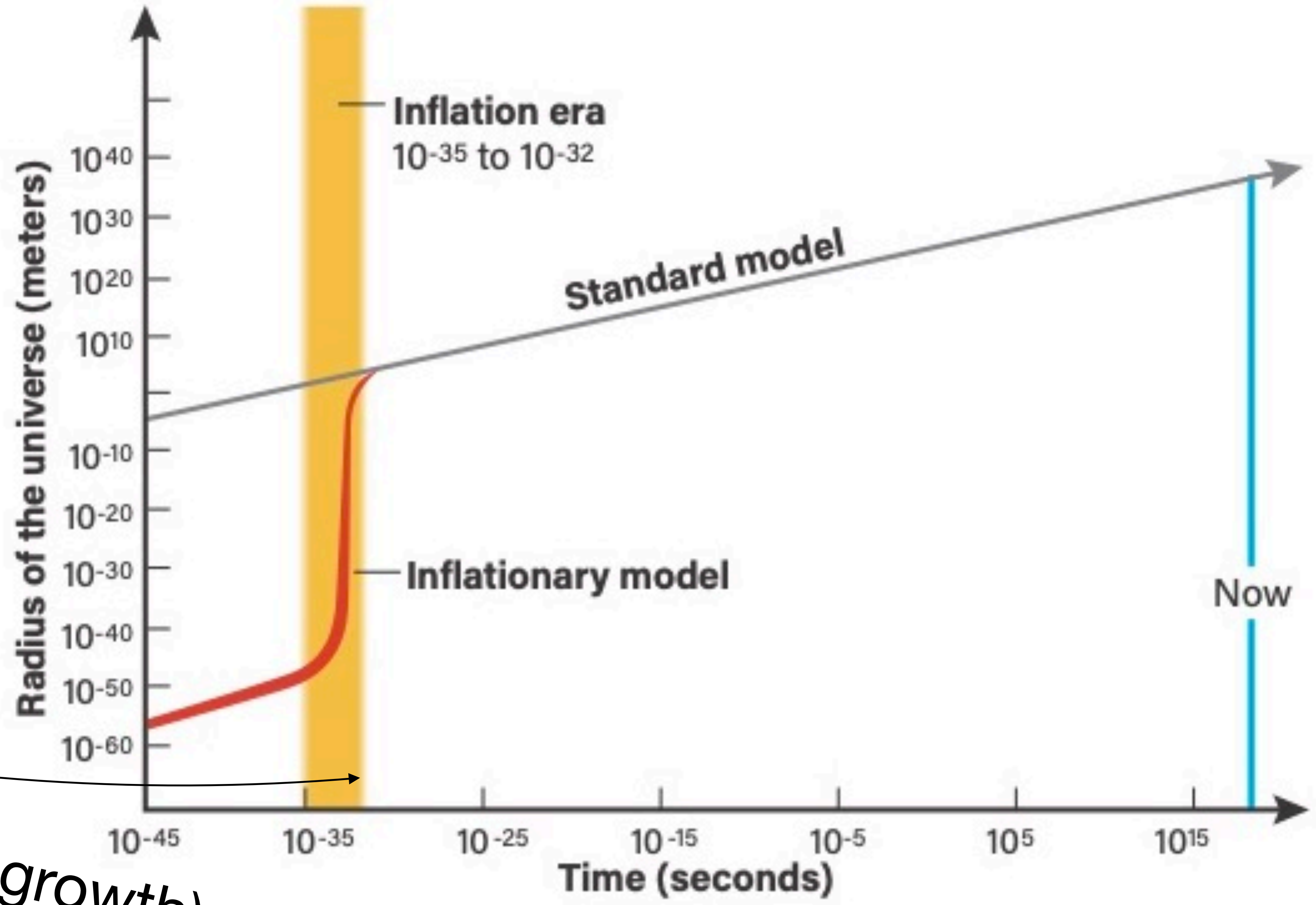


While "ball rolls slowly", $a \propto e^{Ht}$ (exponential growth)

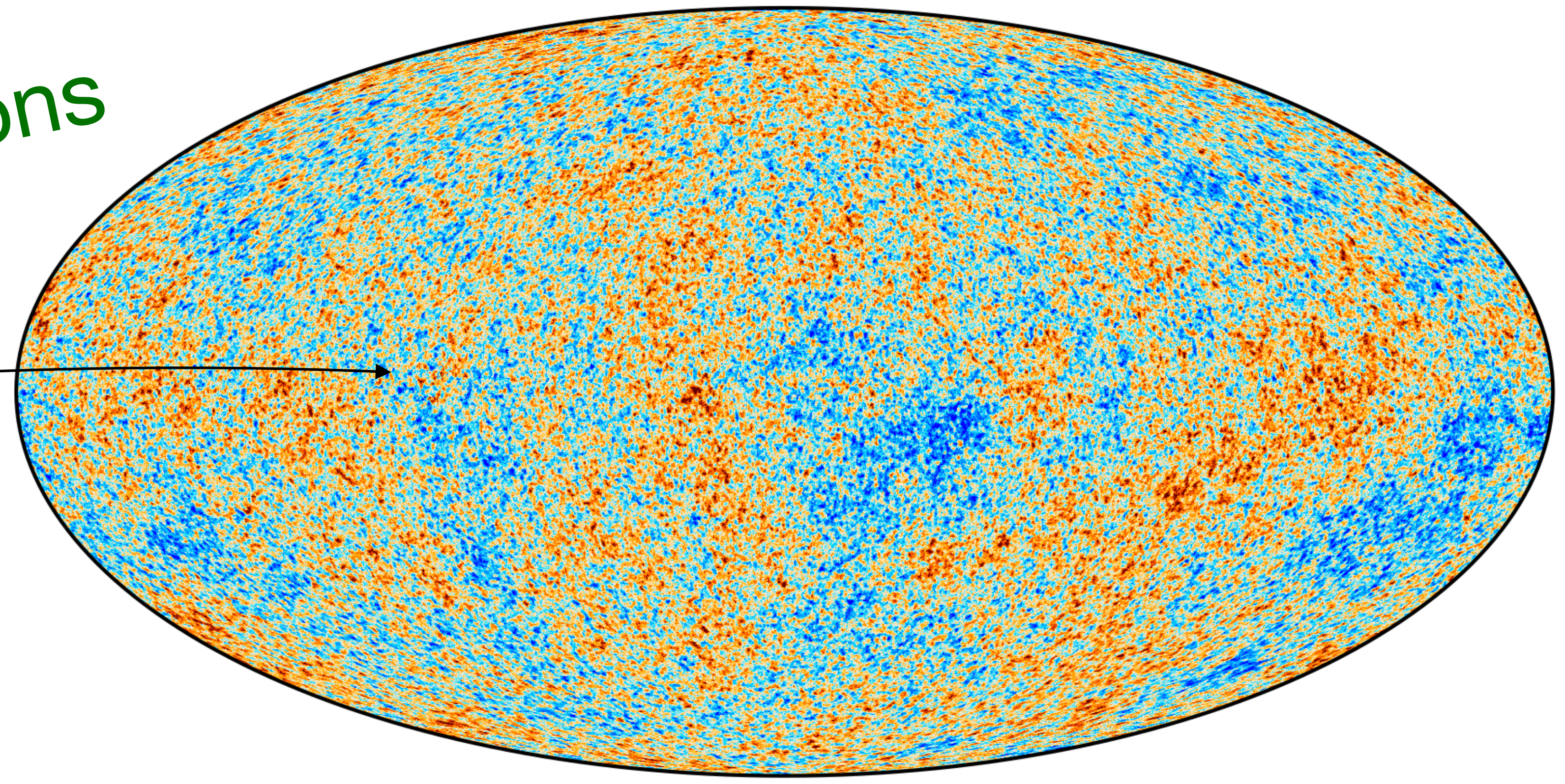


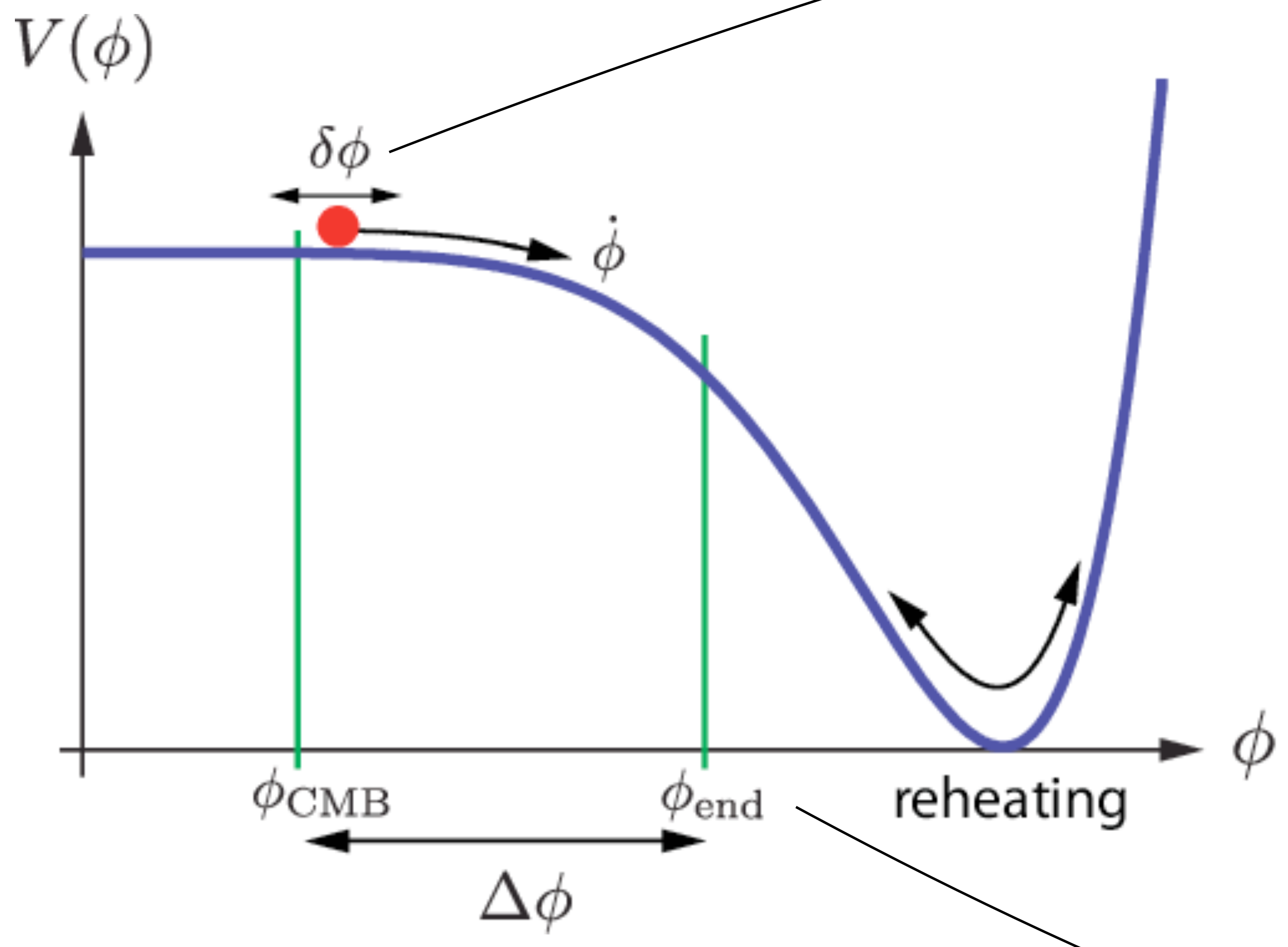
Figures from Baumann/Peiris 2009, Astronomy Today and Planck 2018

Inflation seeds primordial structure

Scalar field(s) for exponential expansion

Quantum fluctuations of ϕ source primordial density fluctuations





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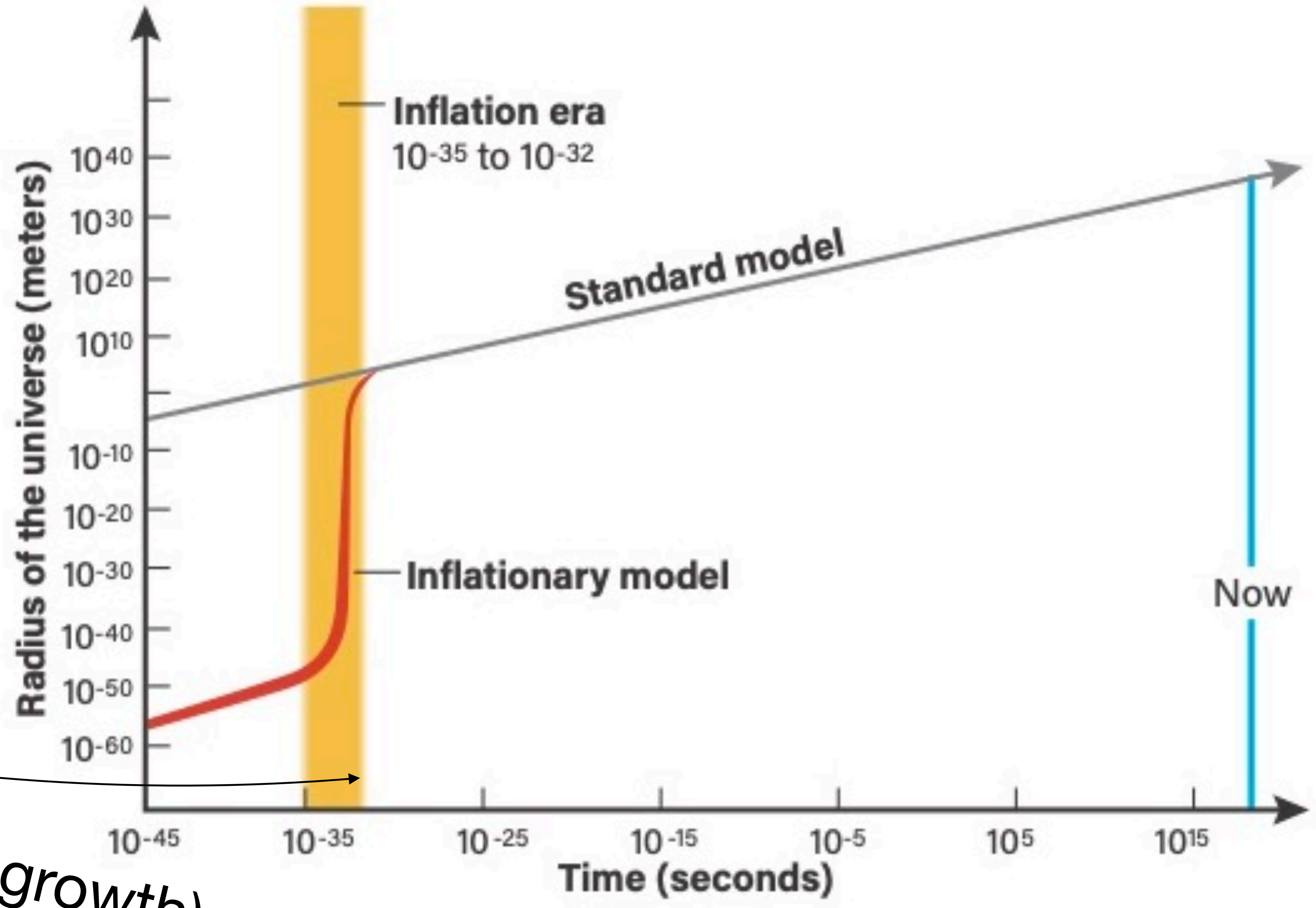
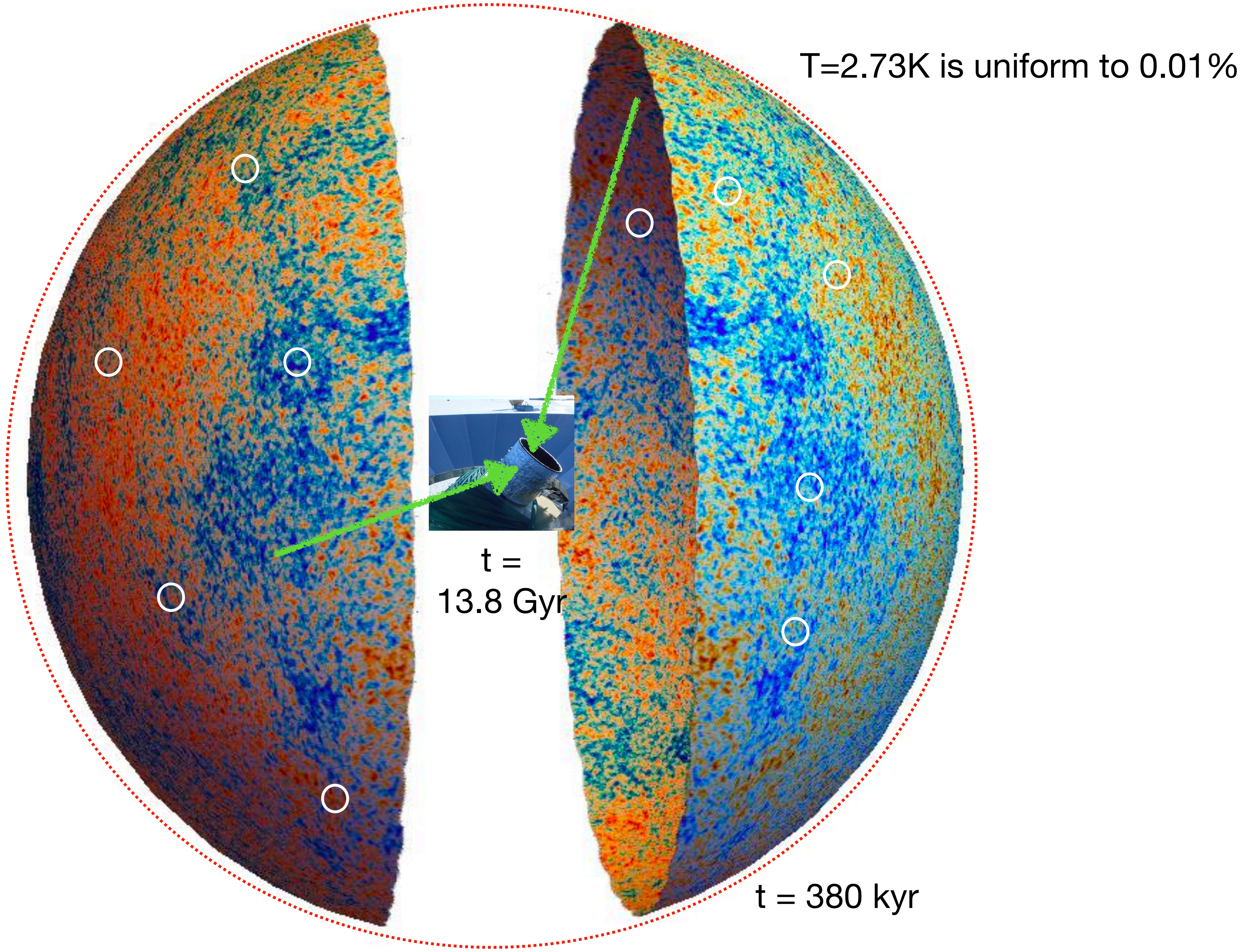


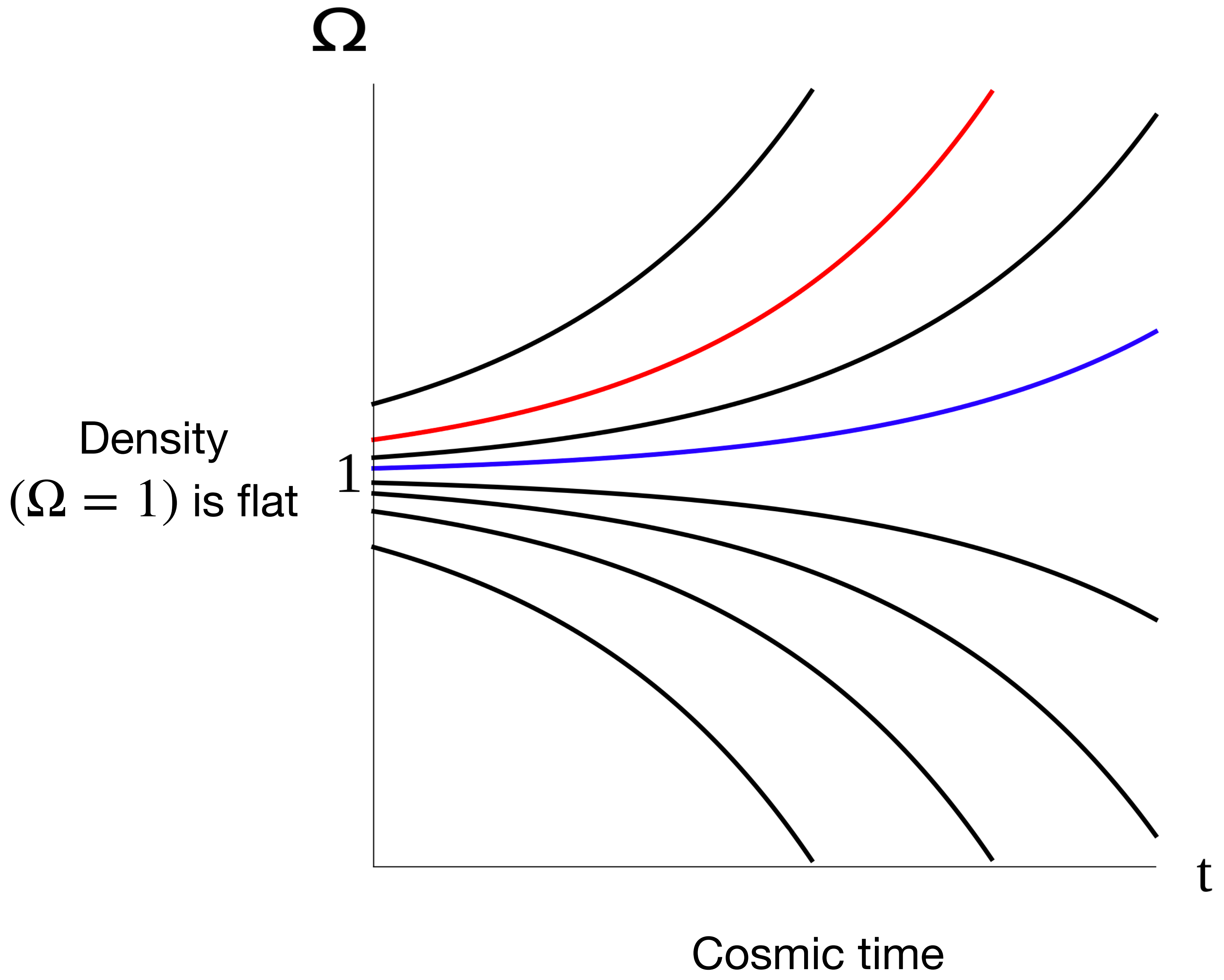
Figures from Baumann/Peiris 2009, Astronomy Today and Planck 2018

Inflation also fixes horizon and flatness problems

The particle horizon at CMB time *should* at least be the red circle, but instead is the white circle. All these white areas should be causally disconnected

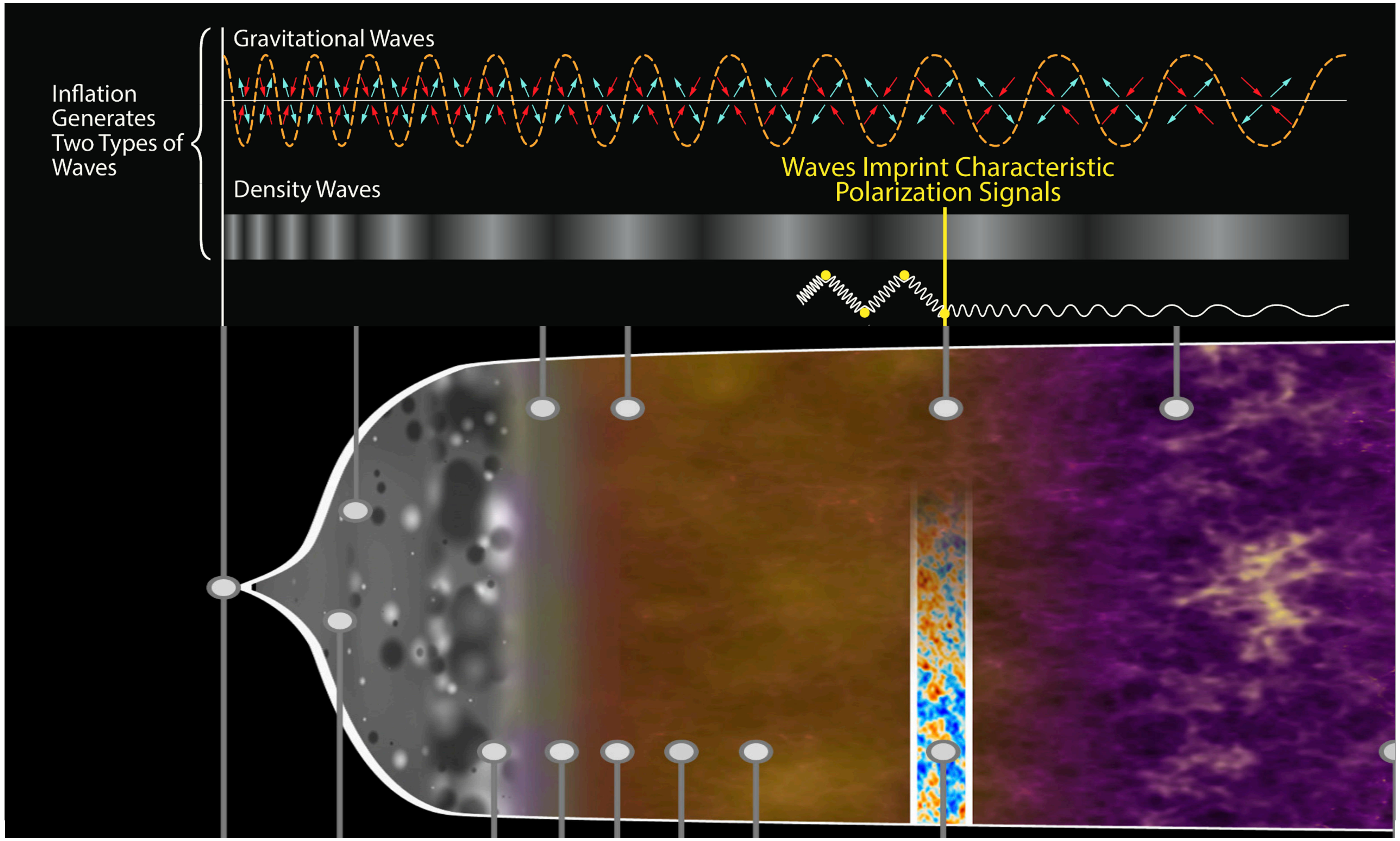


The Universe appears flat to better than 1% today. Even the slightest curvature ought to grow quickly. Needs $|1 - \Omega| \sim 10^{-60}$ at Planck time!



Figures from Wikipedia and Mathematica Stack Exchange

Inflation models generically predict primordial gravitational waves (PGWs)



Figures from ESA/Planck and JPL/BICEP

Tensor/GW

$$P_t(k) \approx A_t\, k^{n_t}$$

$$P_s(k) \approx A_s\, k^{n_s - 1}$$

Scalar/ density waves

Tensor-to-scalar Ratio

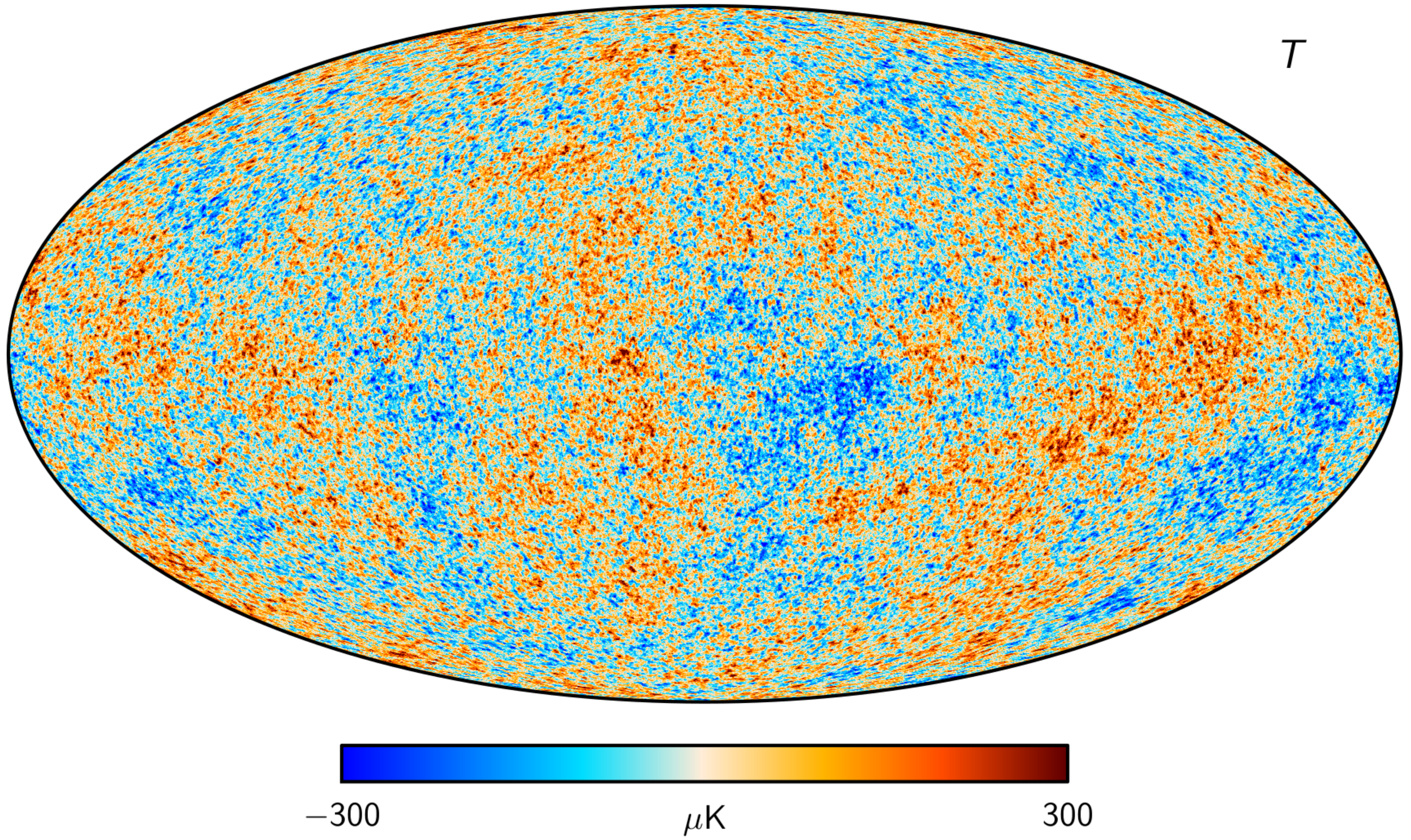
$$r \equiv \frac{A_t}{A_s}$$

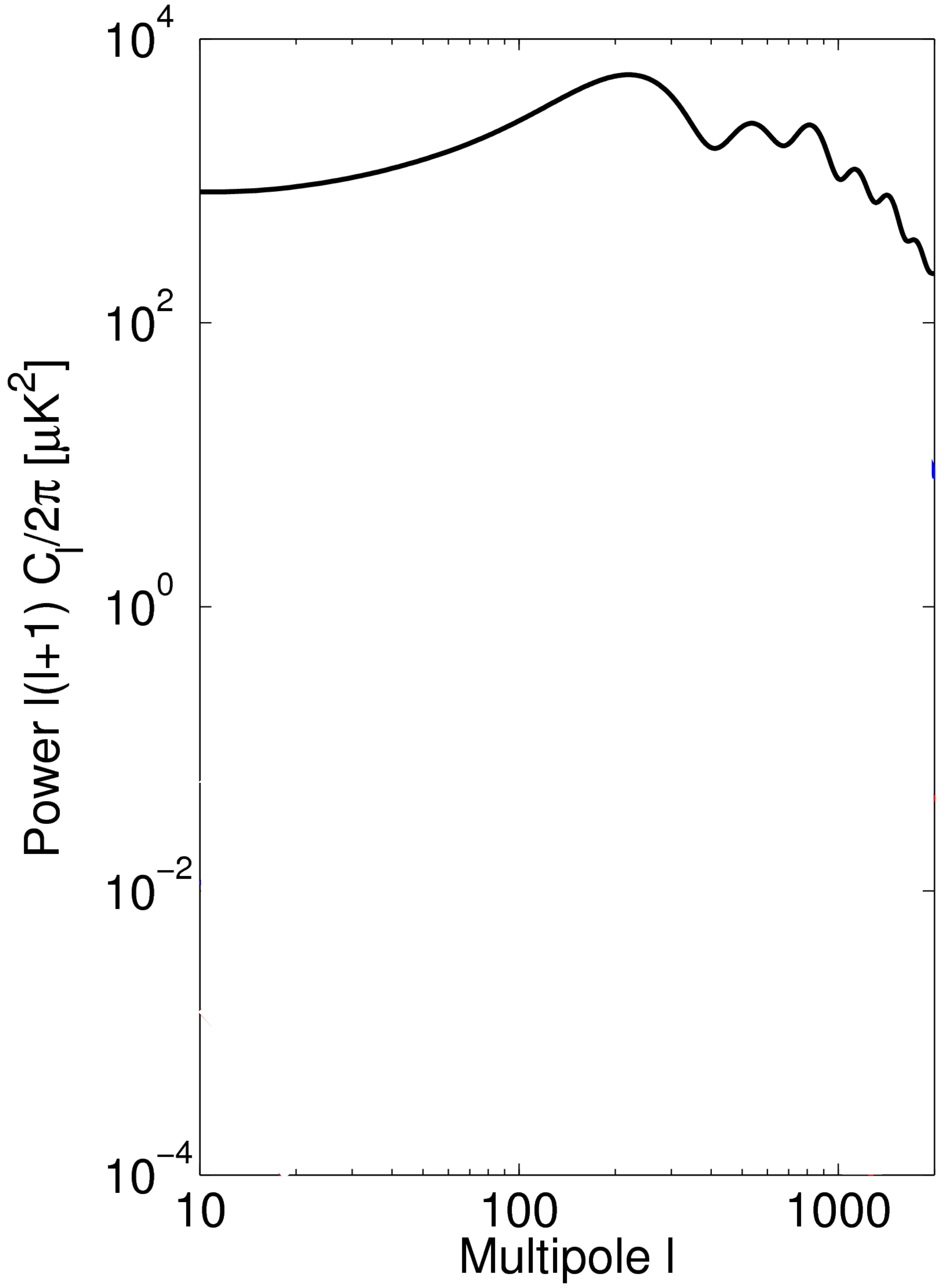
Inflation energy scale

$$V^{1/4} = 1.04 \times 10^{16}\text{GeV} \left(\frac{r}{0.01}\right)^{1/4}$$

Search for inflation by looking for PGWs

Imprinted into polarization of CMB light





Figures from
Planck 2018 and BICEP

Search for inflation by looking for PGWs

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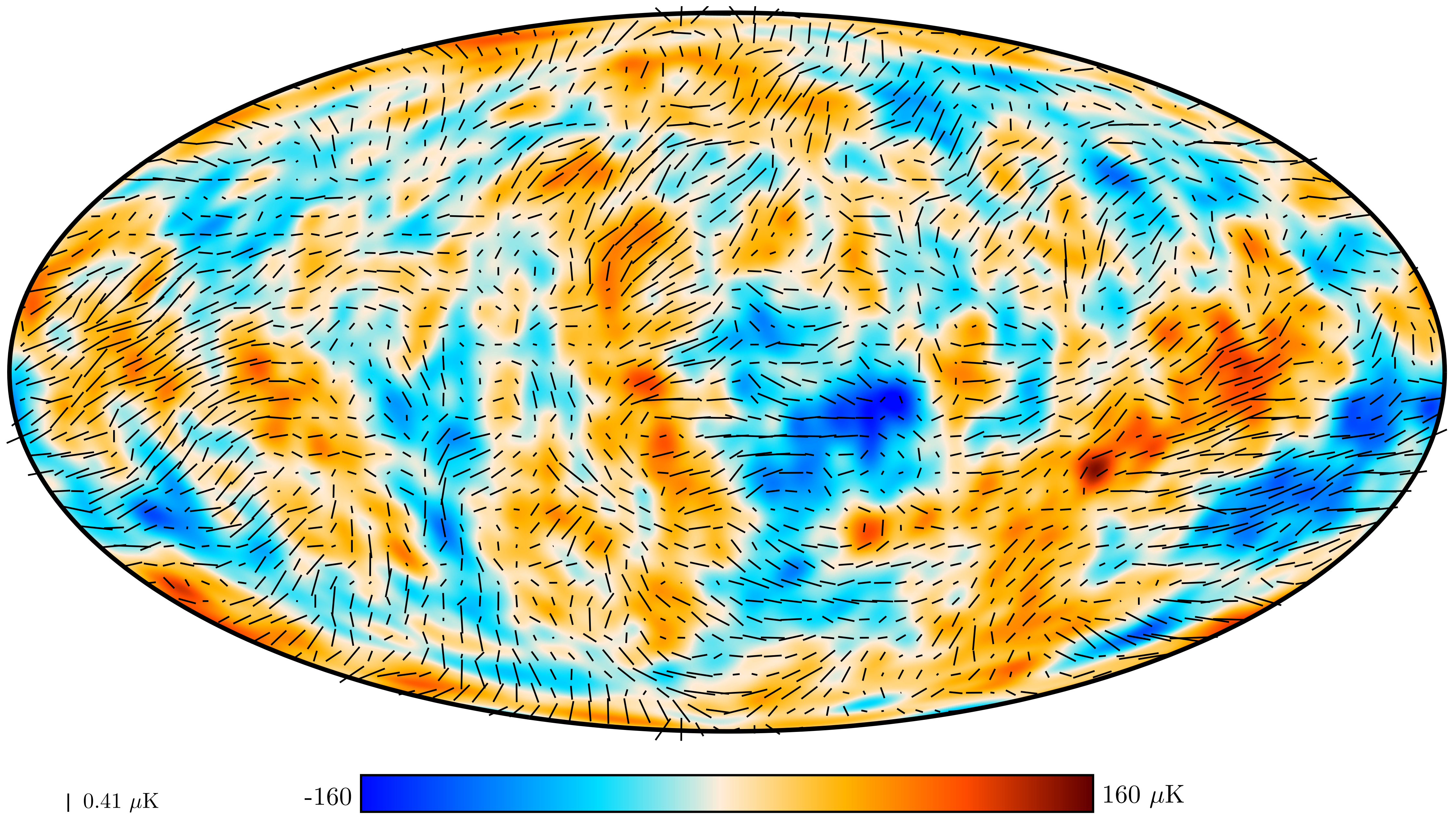

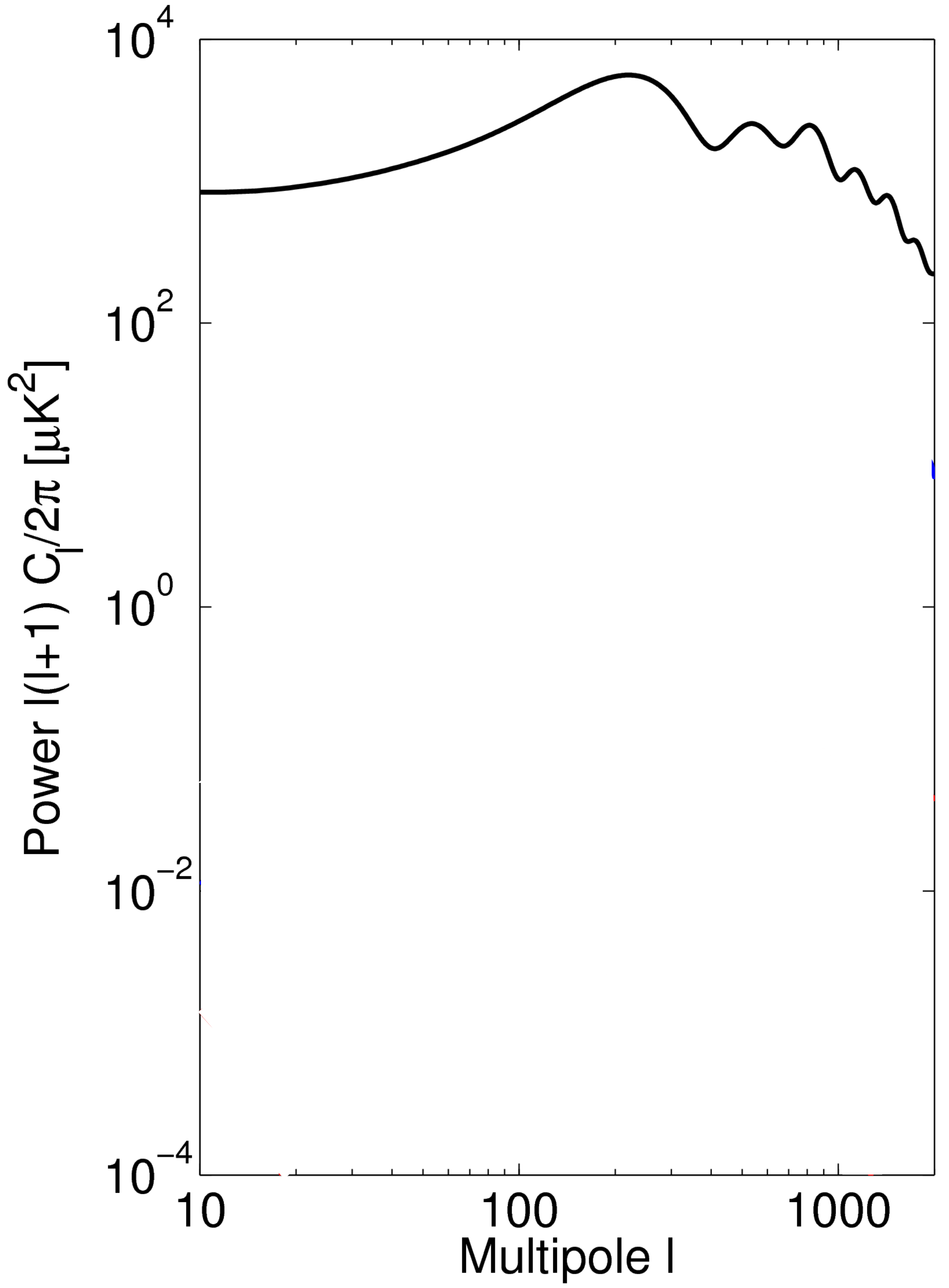

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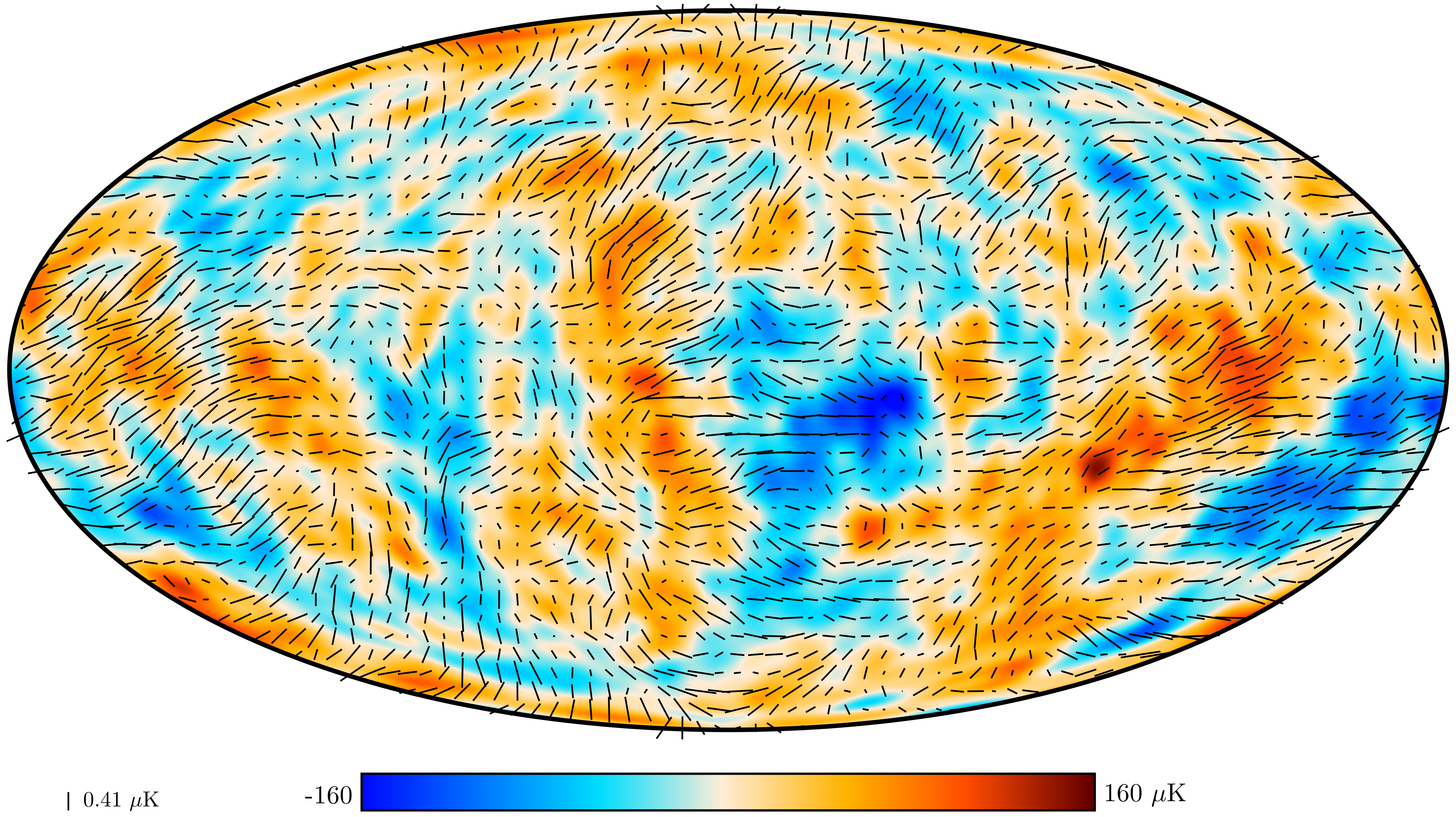

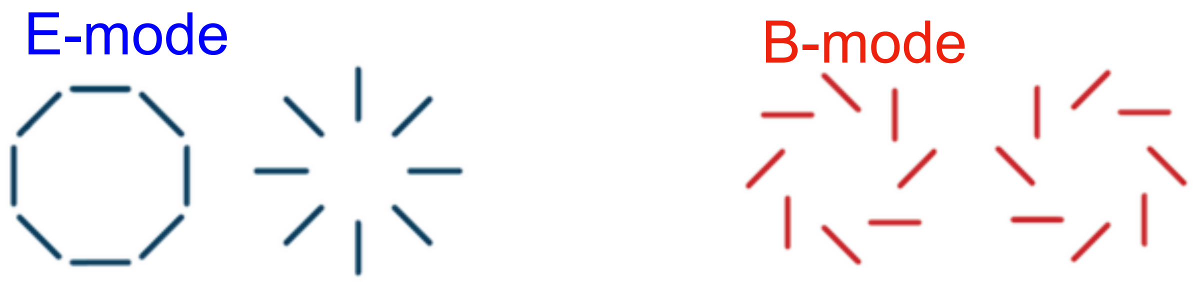

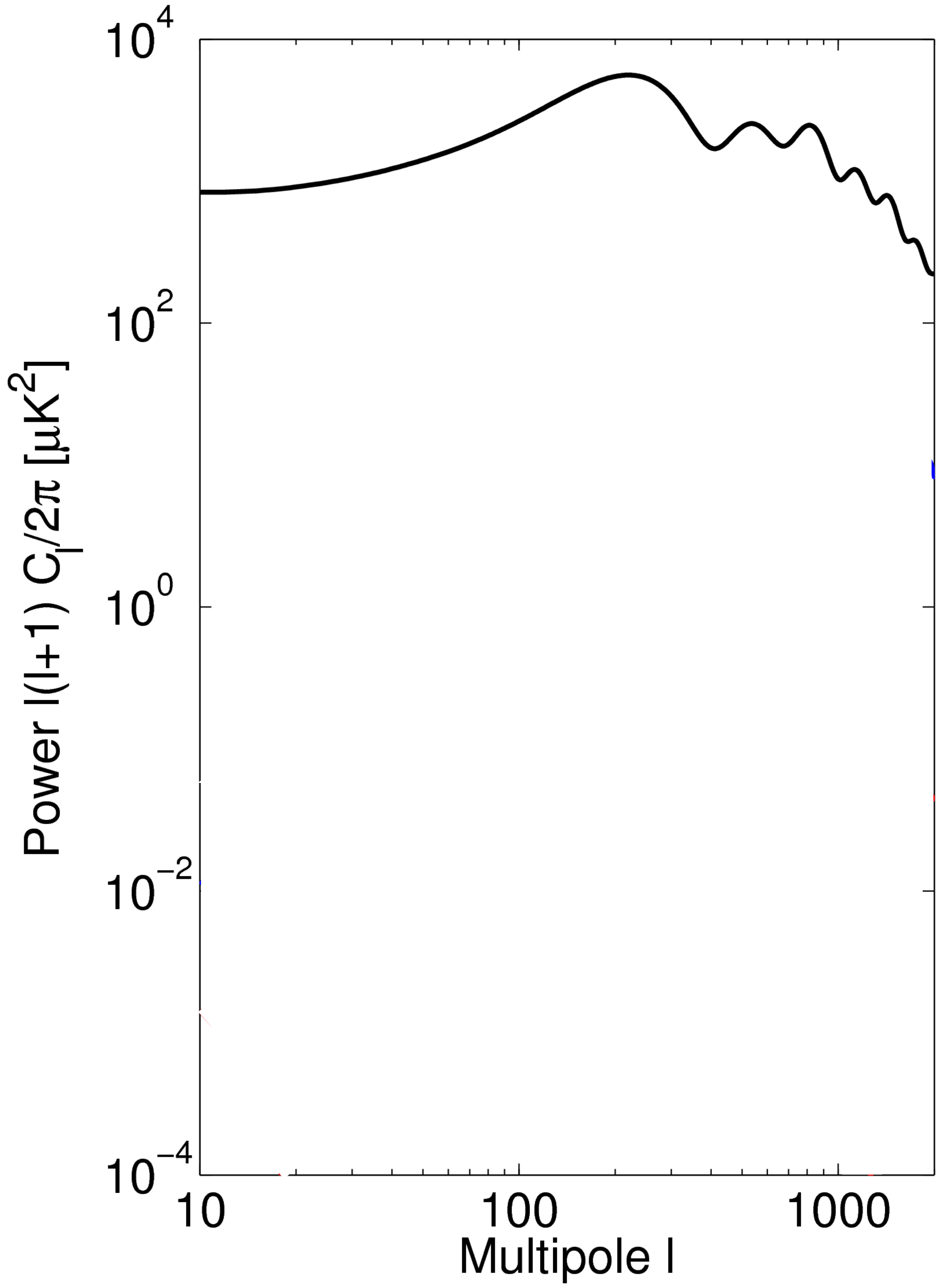

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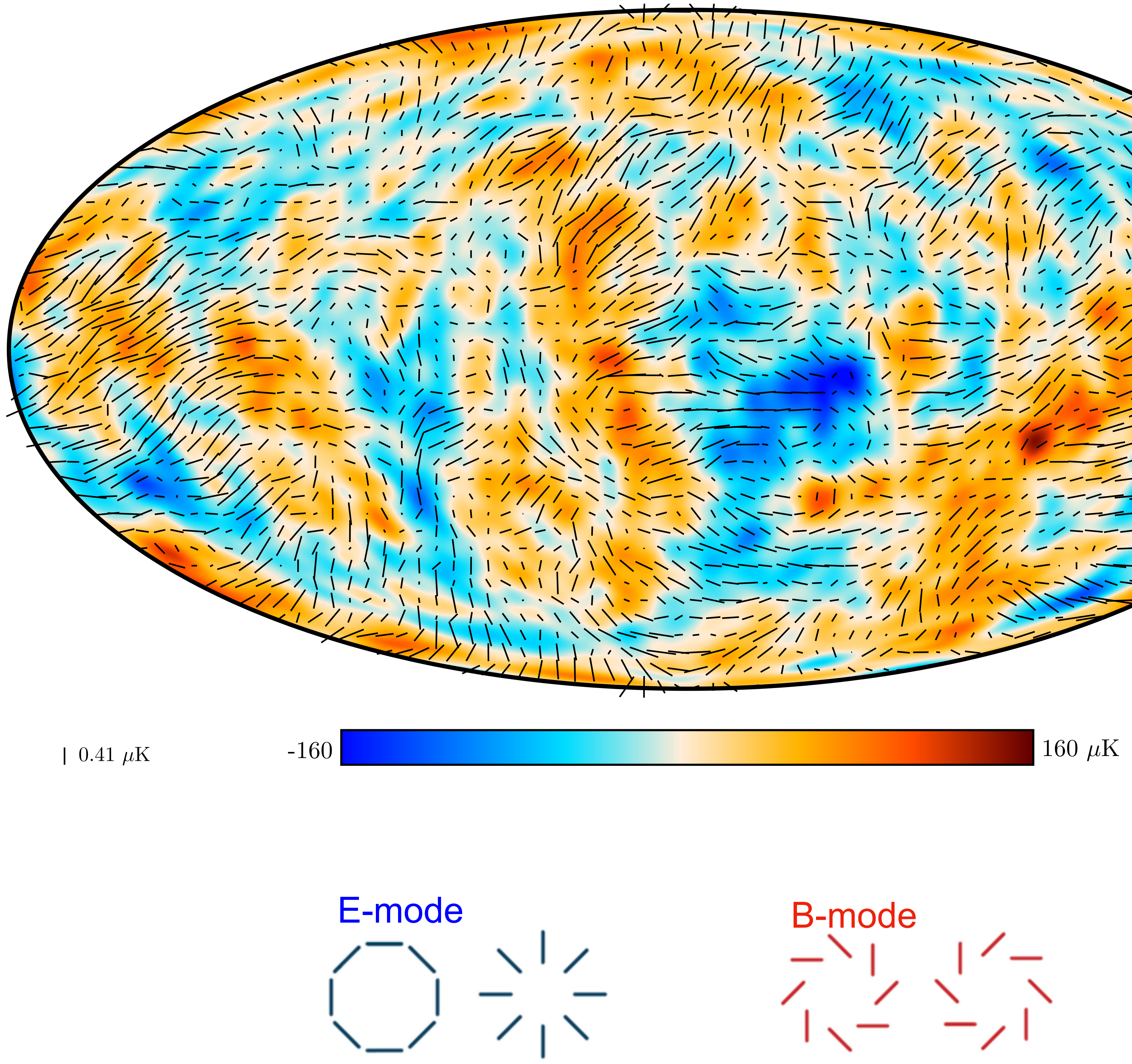
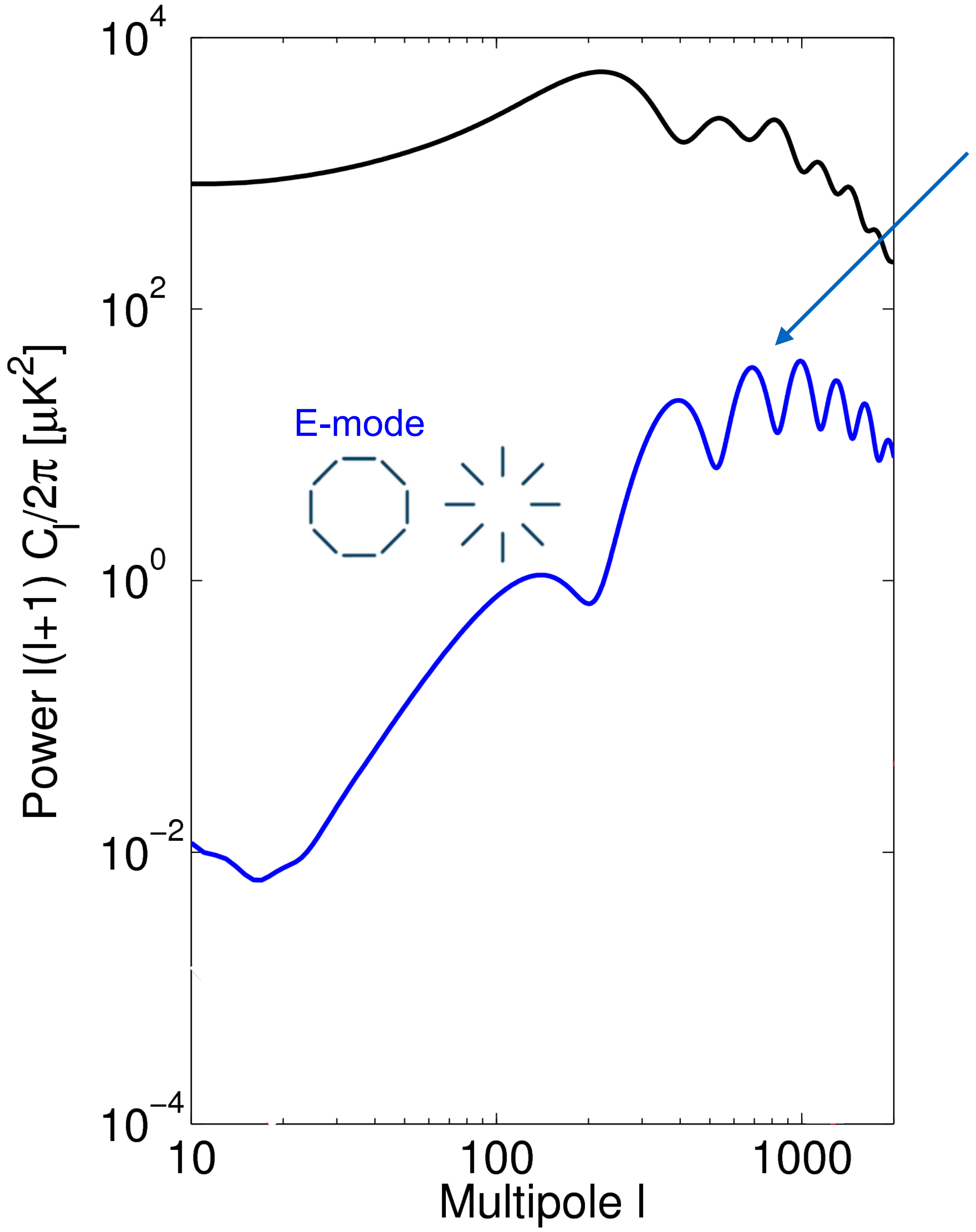


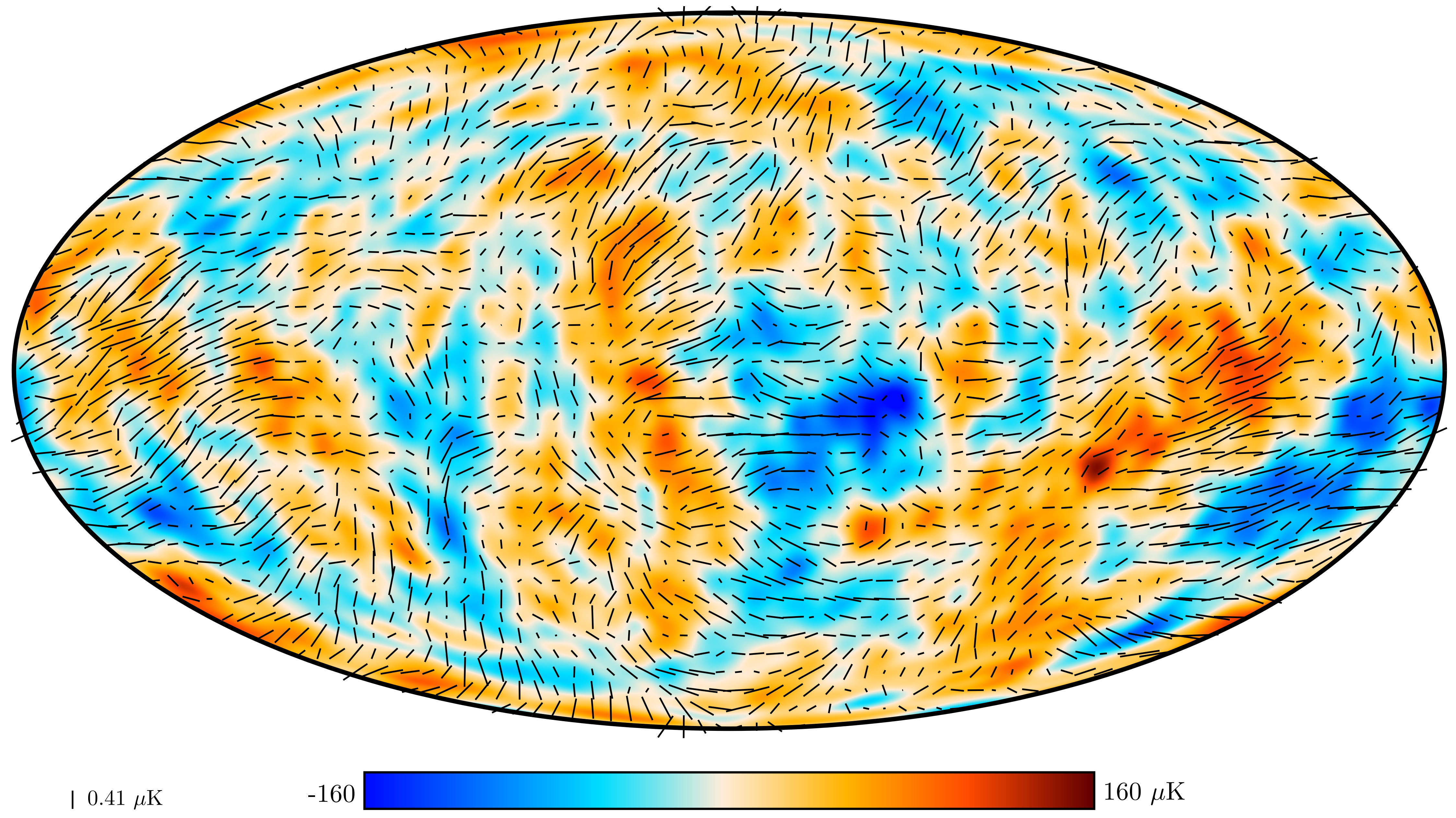


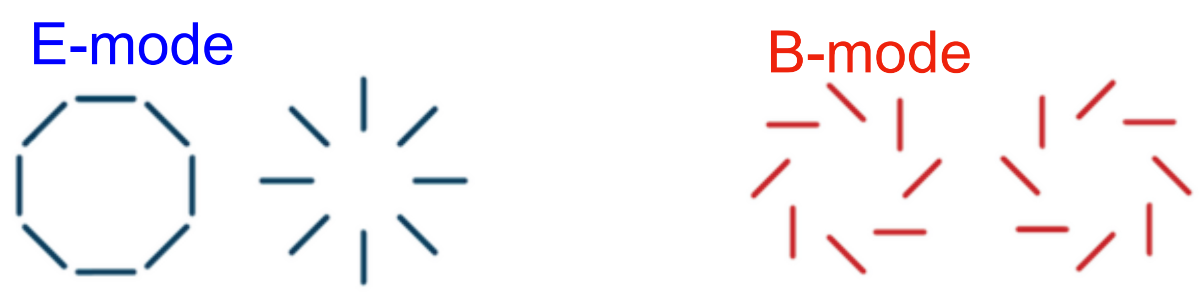
In standard ΛCDM only E-modes are present when CMB released.

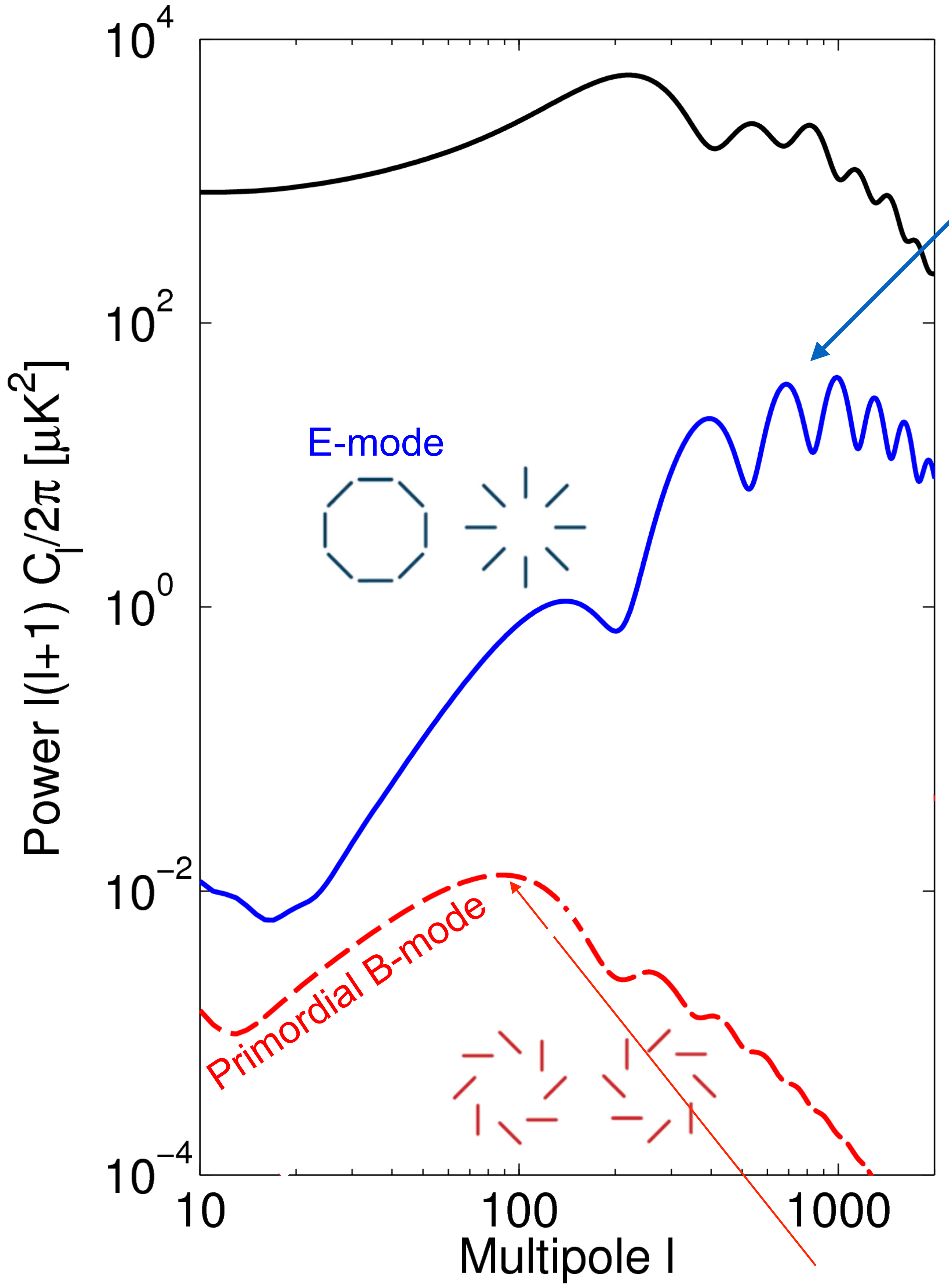
Figures from
Planck 2018 and BICEP

Search for inflation by looking for PGWs

Imprinted into polarization of CMB light







In standard ΛCDM only E-modes are present when CMB released.

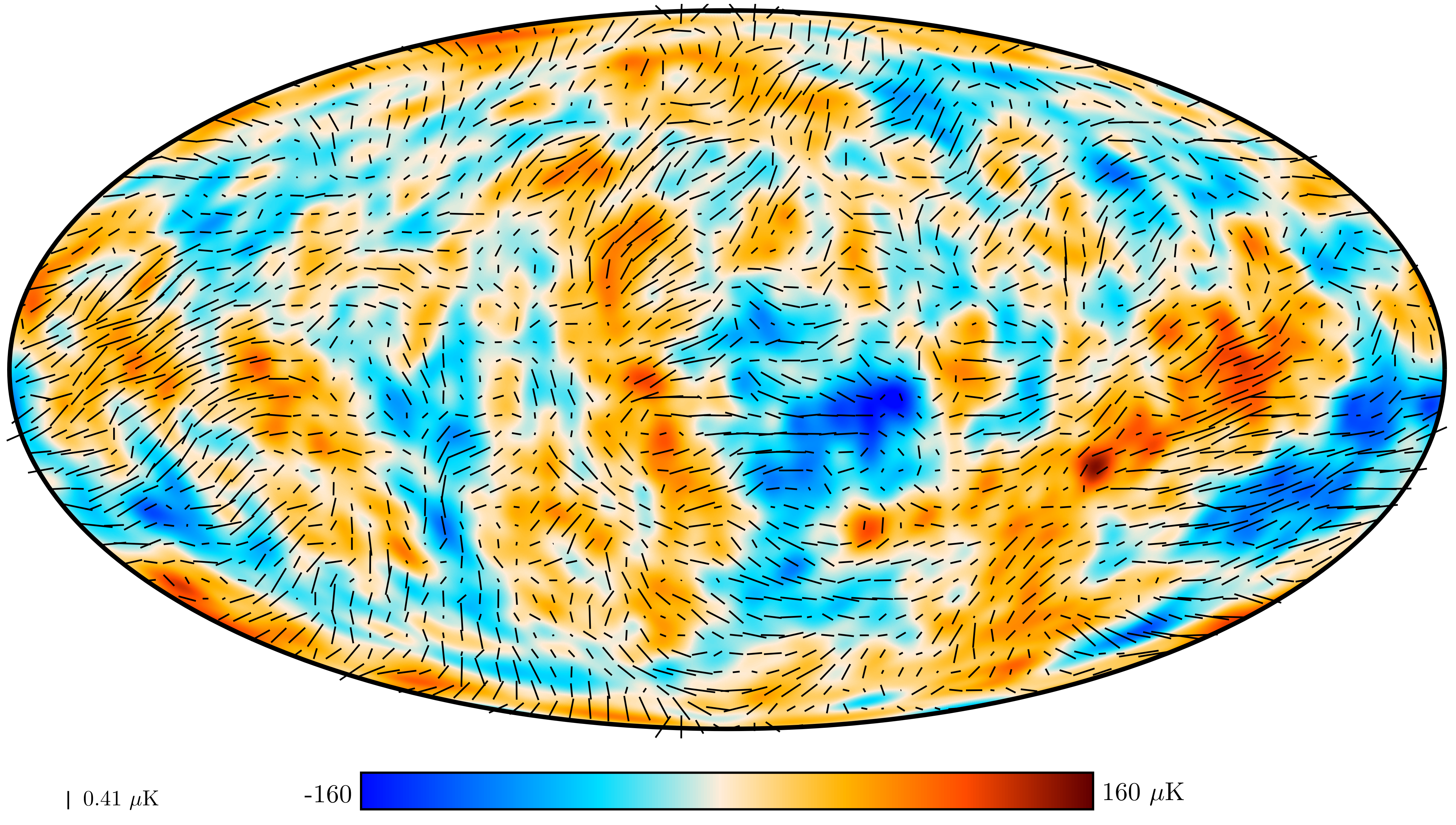
Primordial gravitational waves produce B-modes peaking at degree scales.

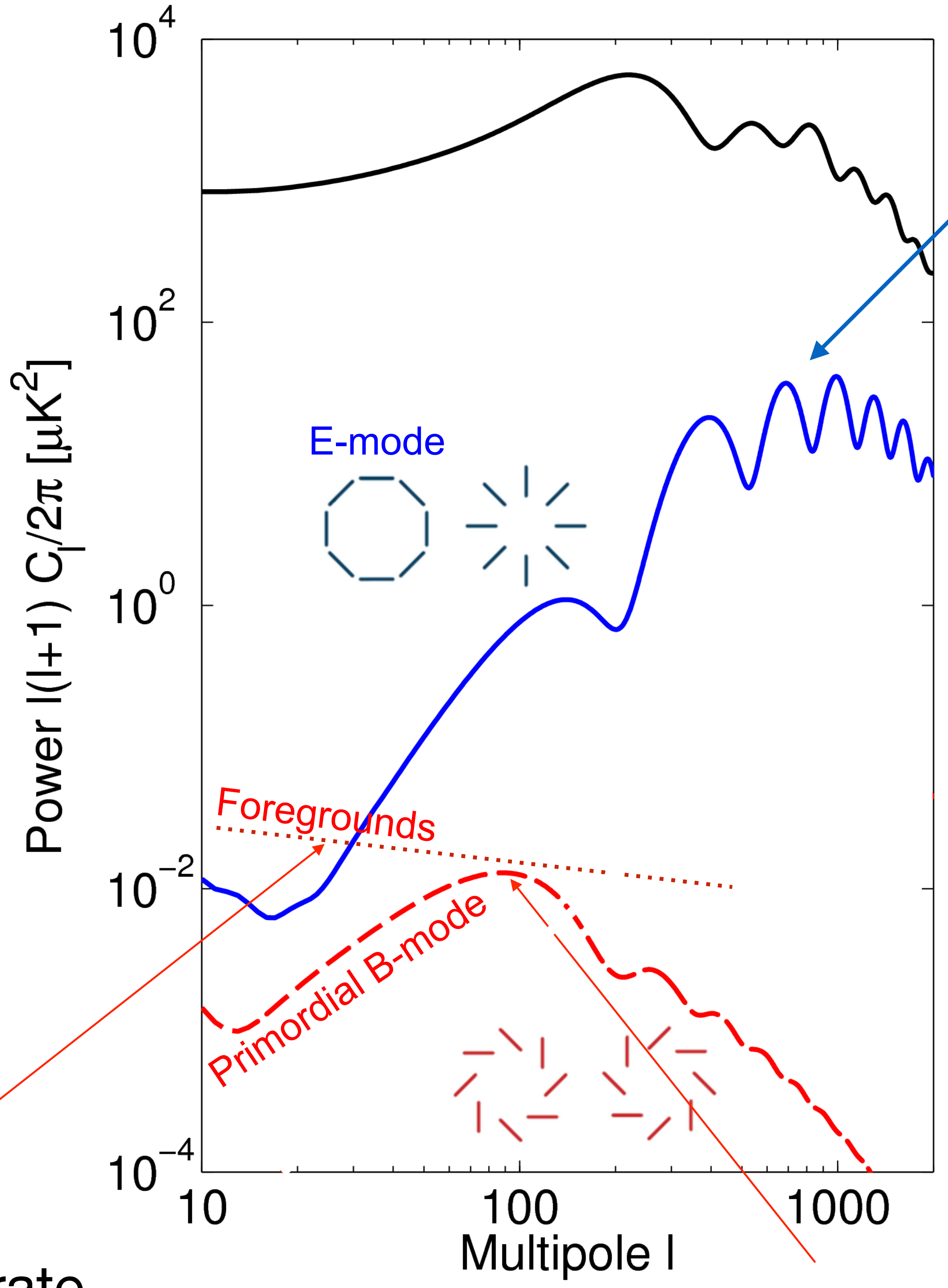
Amplitude set by r

Figures from Planck 2018 and BICEP

Search for inflation by looking for PGWs

Imprinted into polarization of CMB light





In standard ΛCDM only E-modes are present when CMB released.

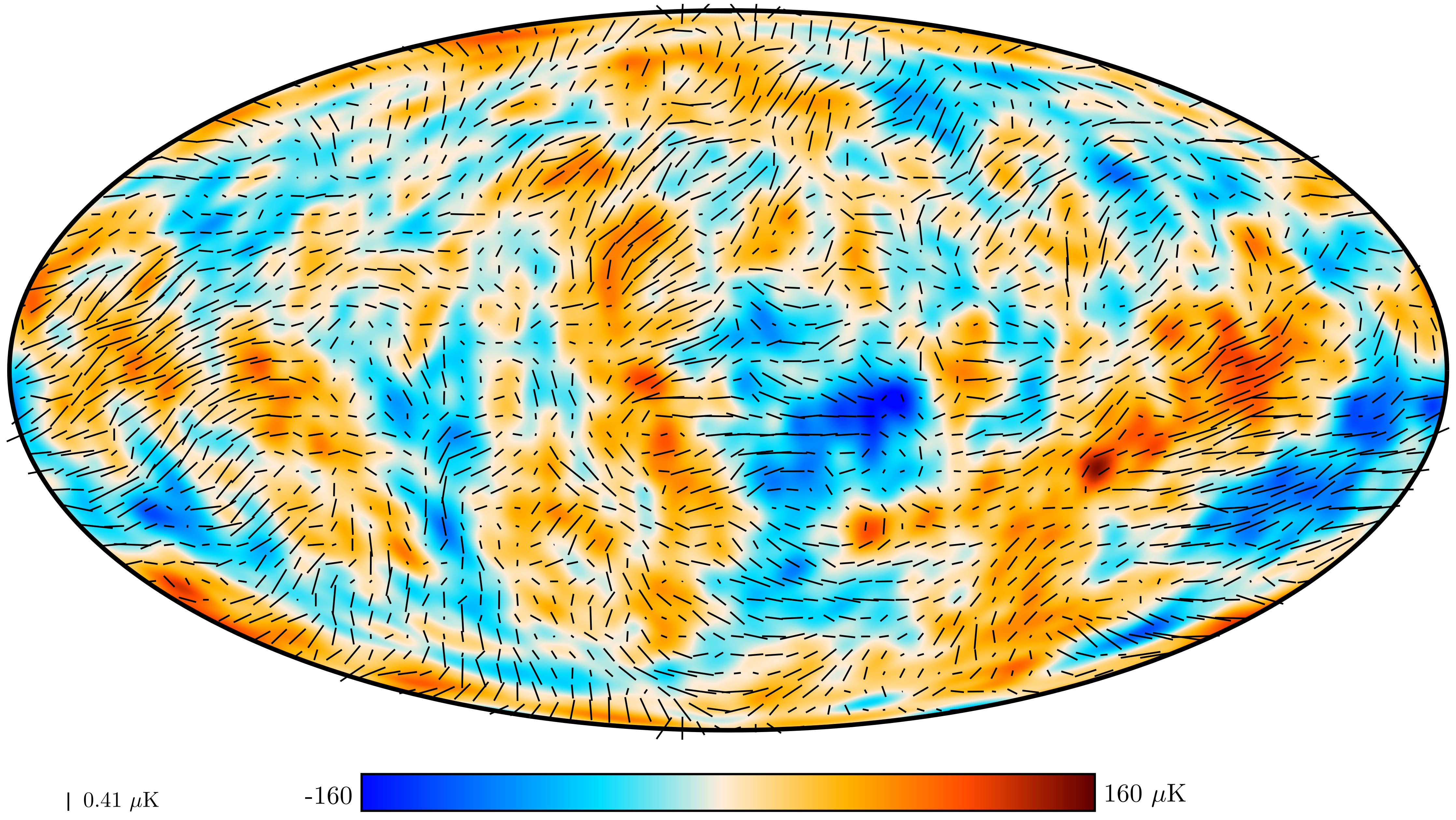
Galactic Foregrounds also generate polarized emission. Can be teased apart using spectral properties

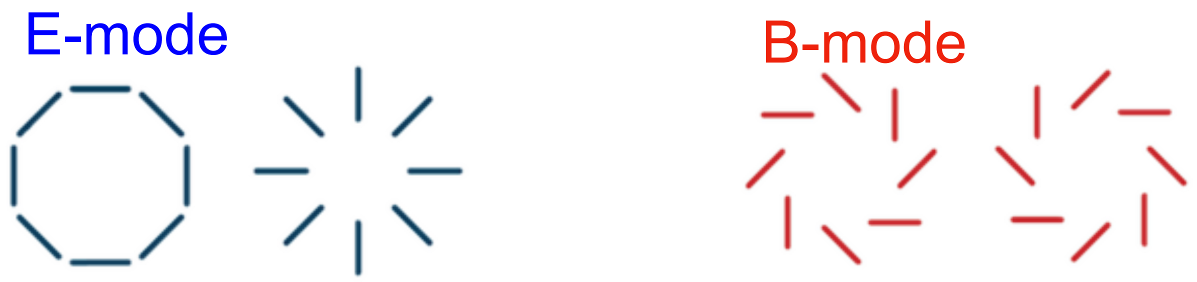
Primordial gravitational waves produce B-modes peaking at degree scales. Amplitude set by r

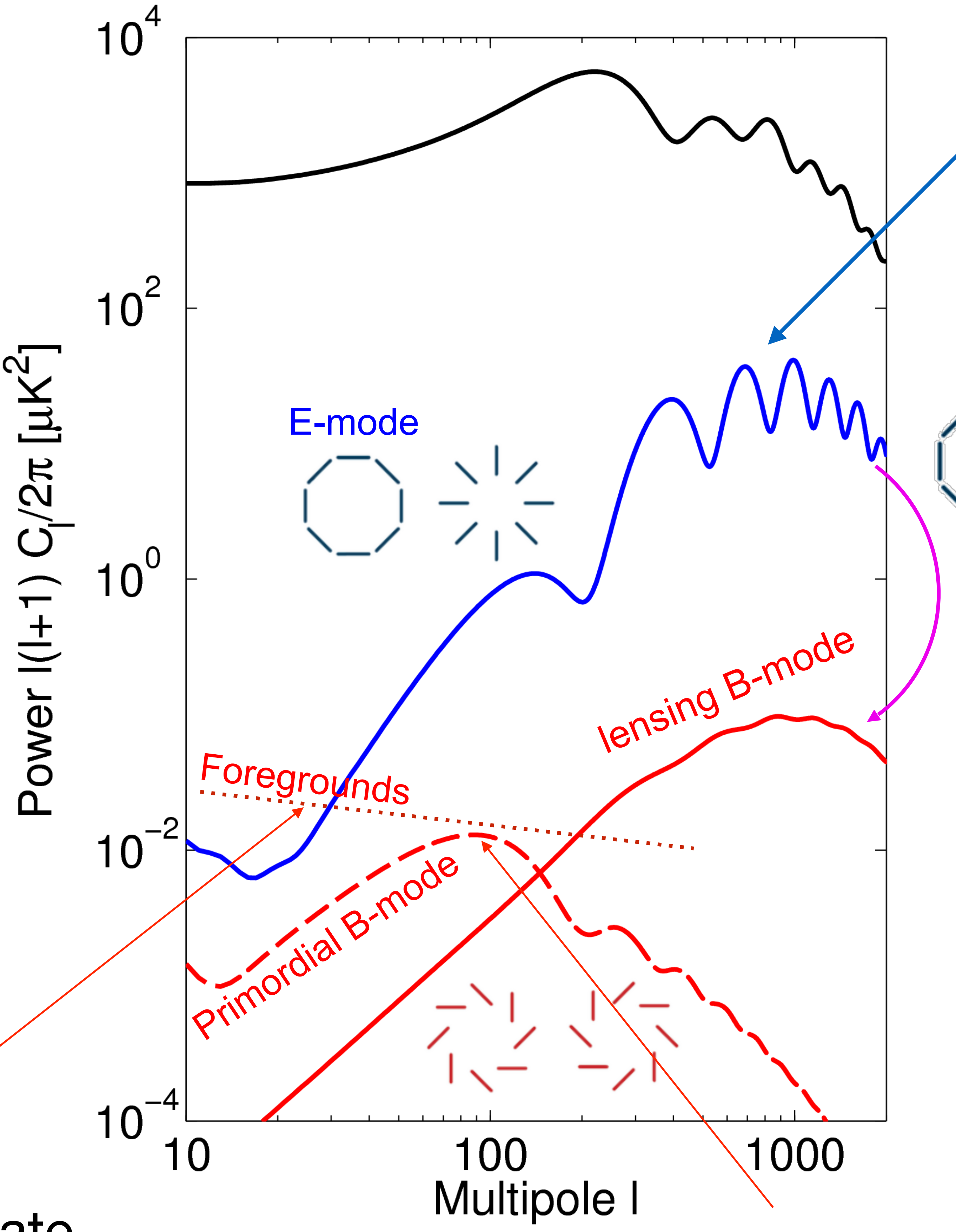
Figures from Planck 2018 and BICEP

Search for inflation by looking for PGWs

Imprinted into polarization of CMB light







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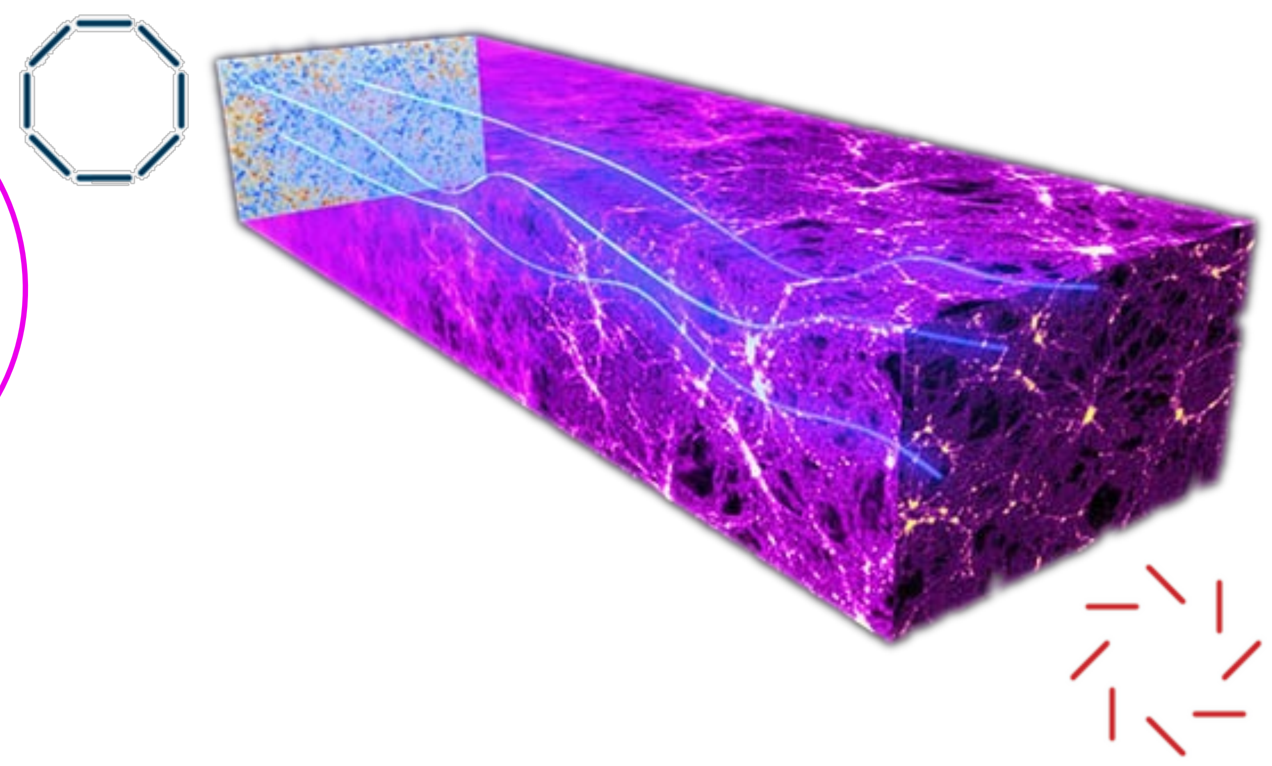


Lensing by intervening structure converts some to B-modes

Galactic Foregrounds also generate polarized emission. Can be teased apart using spectral properties

Primordial gravitational waves produce B-modes peaking at degree scales. Amplitude set by r

Figures from Planck 2018 and BICEP

BICEP/Keck Program and 2021 results

Three generations of CMB cameras with increasing sensitivity to target inflation signal

Photo by Steffen Richter

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

VE RI TAS HARVARD

cea

UBC

CARDIFF UNIVERSITY

JPL

NIST

VELUT ARBOR ÆVO

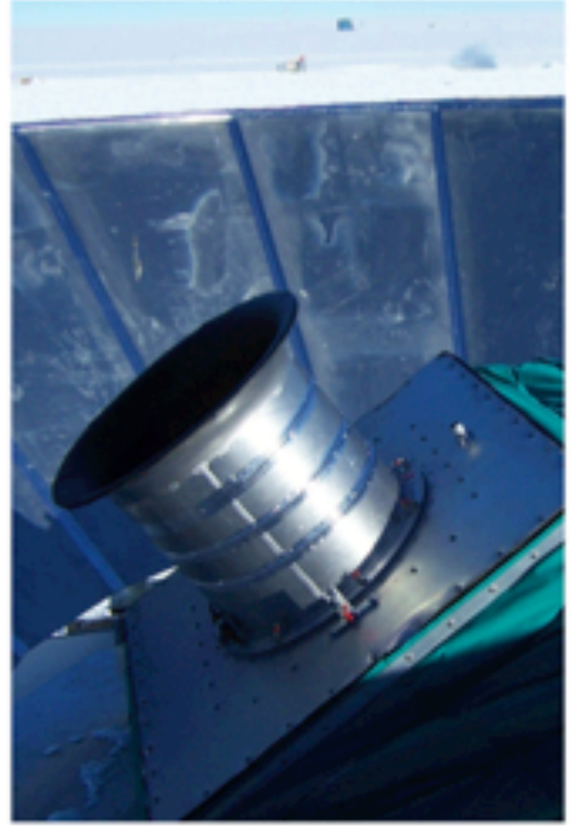
SLAC

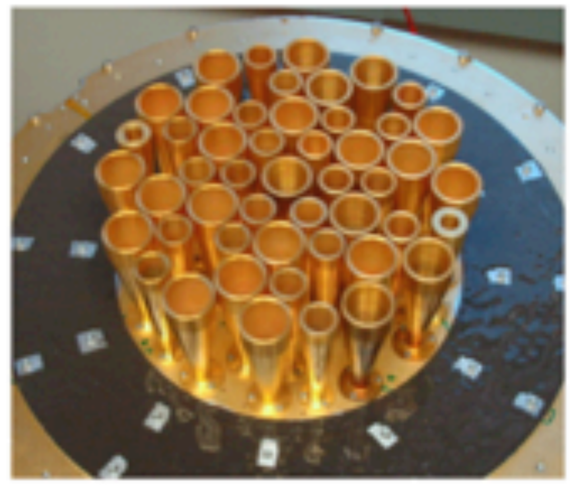
BICEP program 2007- present

Three generations of CMB cameras with increasing sensitivity to inflation

Generation 1

BICEP1
(2006-2008)
100, 150 GHz

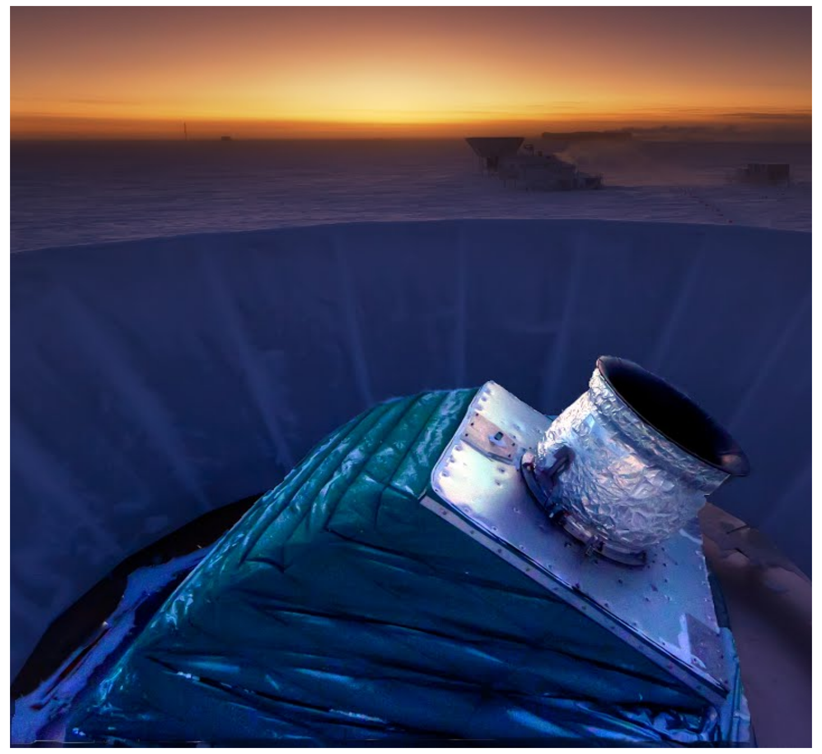


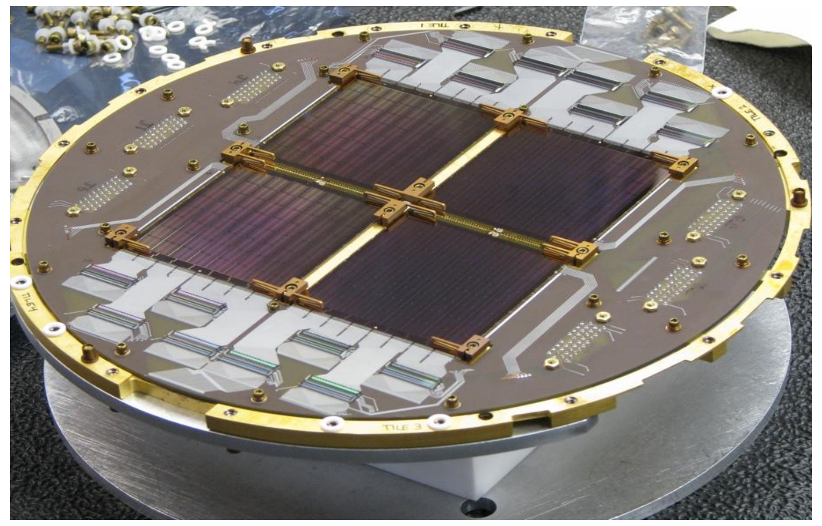


~100 sensors

Generation 2 →

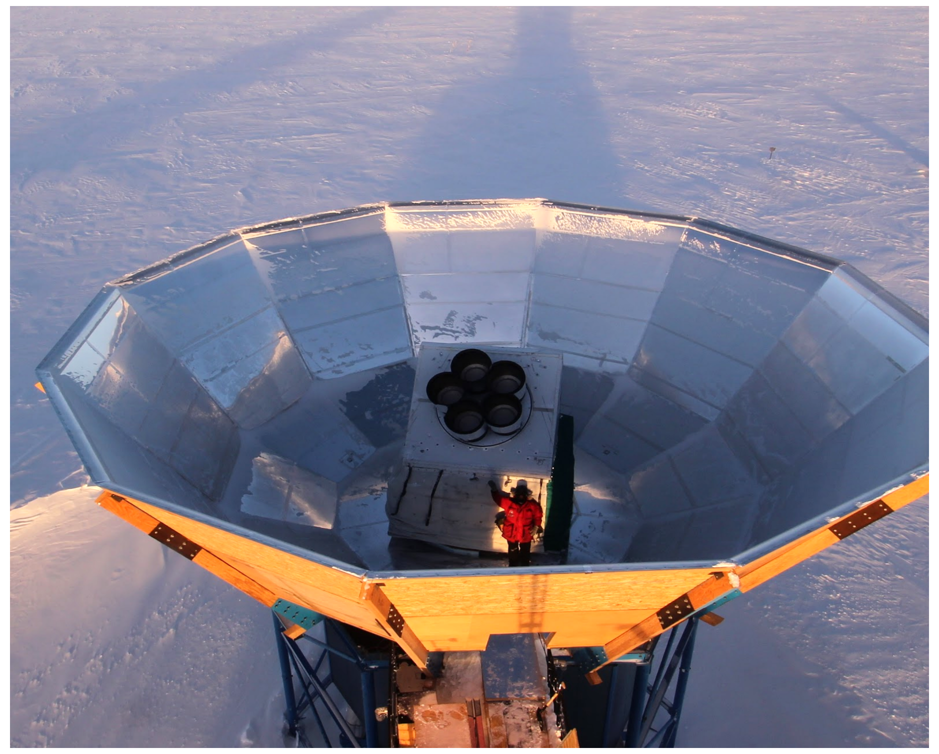
BICEP2
(2010-2012)
150 GHz

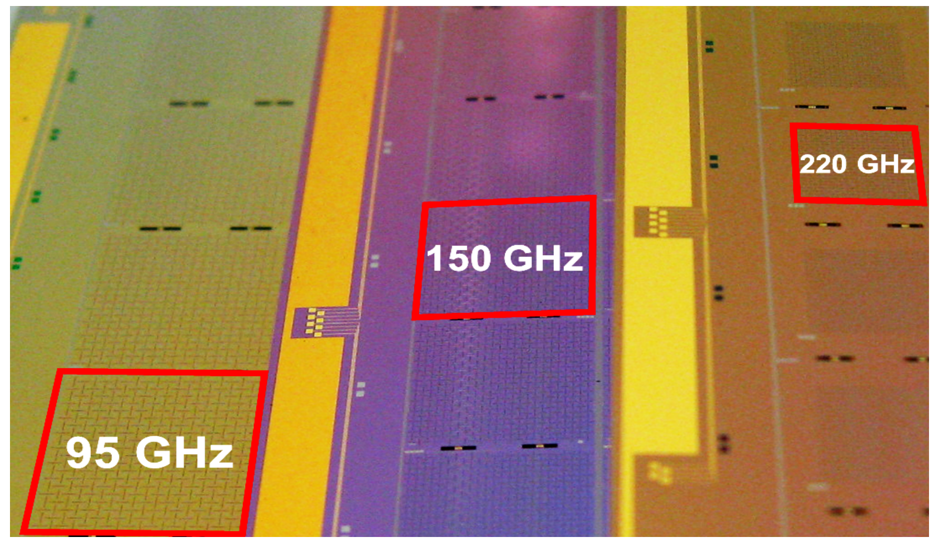




~500 sensors

Keck Array
(2012-2019)
95, 150, 220, 270 GHz

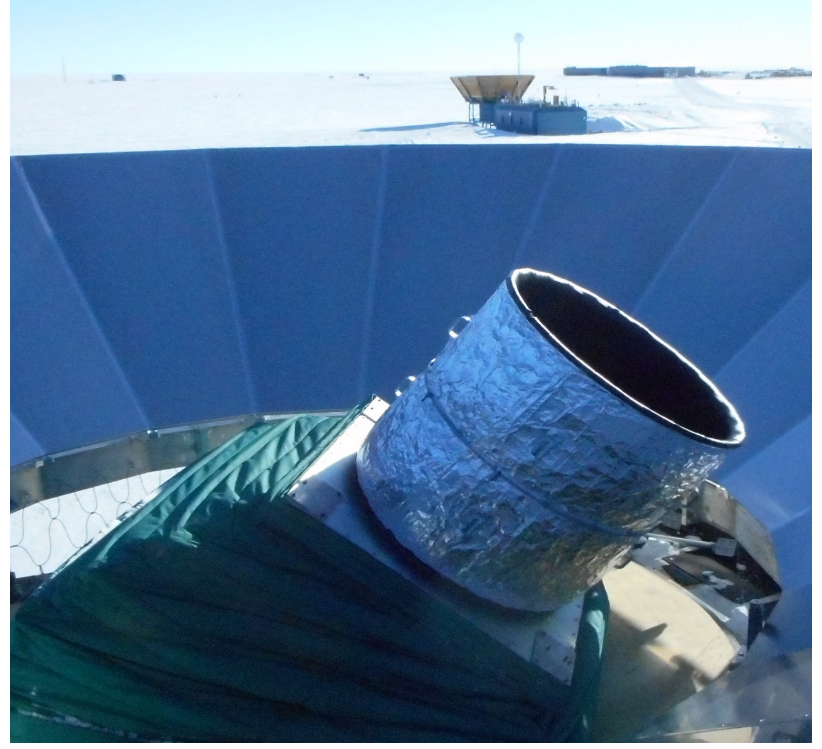


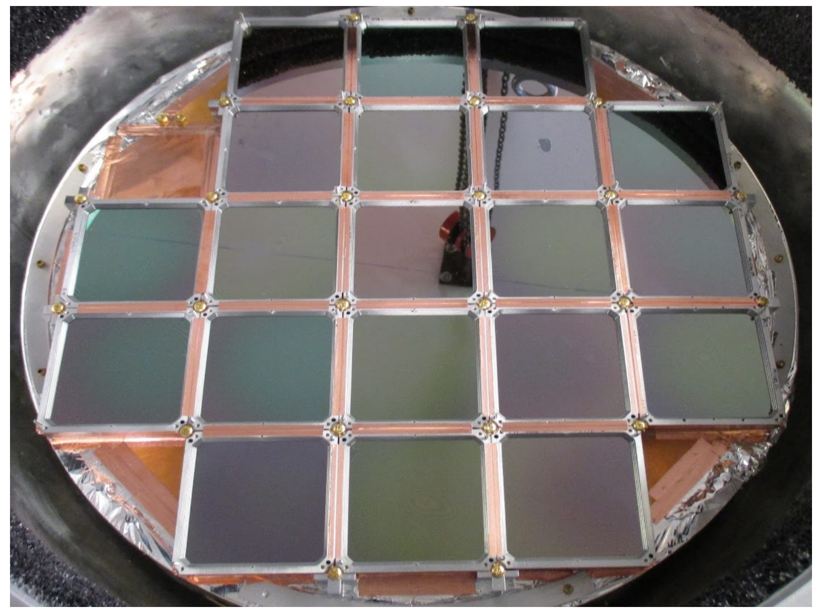


~2500 sensors in five BICEP2-like cameras

Generation 3 →

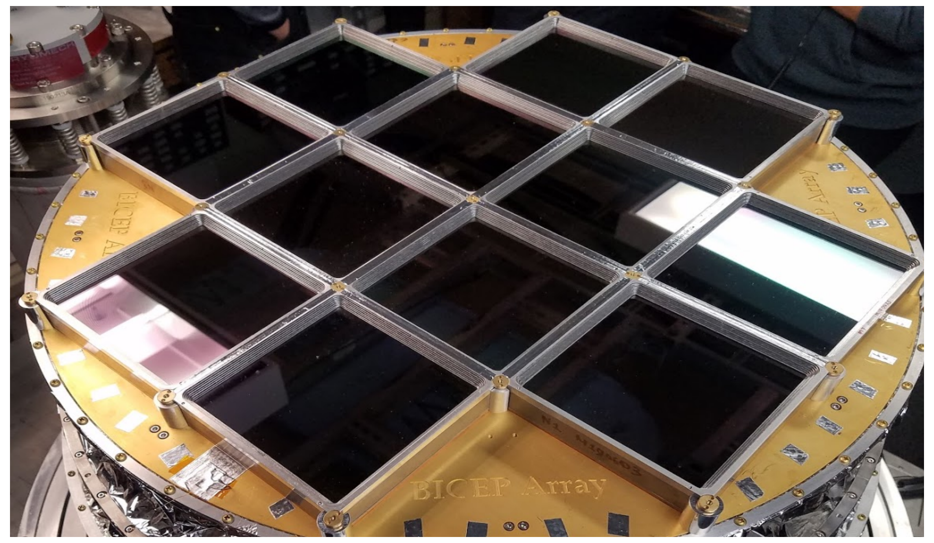
BICEP3
(2015+) $\sigma(r) \sim 0.01$
95 GHz





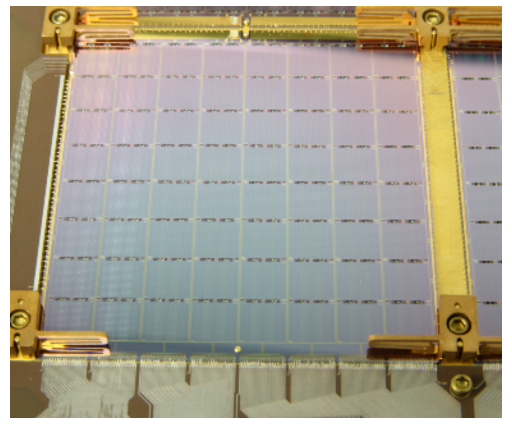
~2500 sensors

BICEP Array
(2019-2027) $\sigma(r) \sim 0.002$
30, 40, 95, 150, 220, 270 GHz



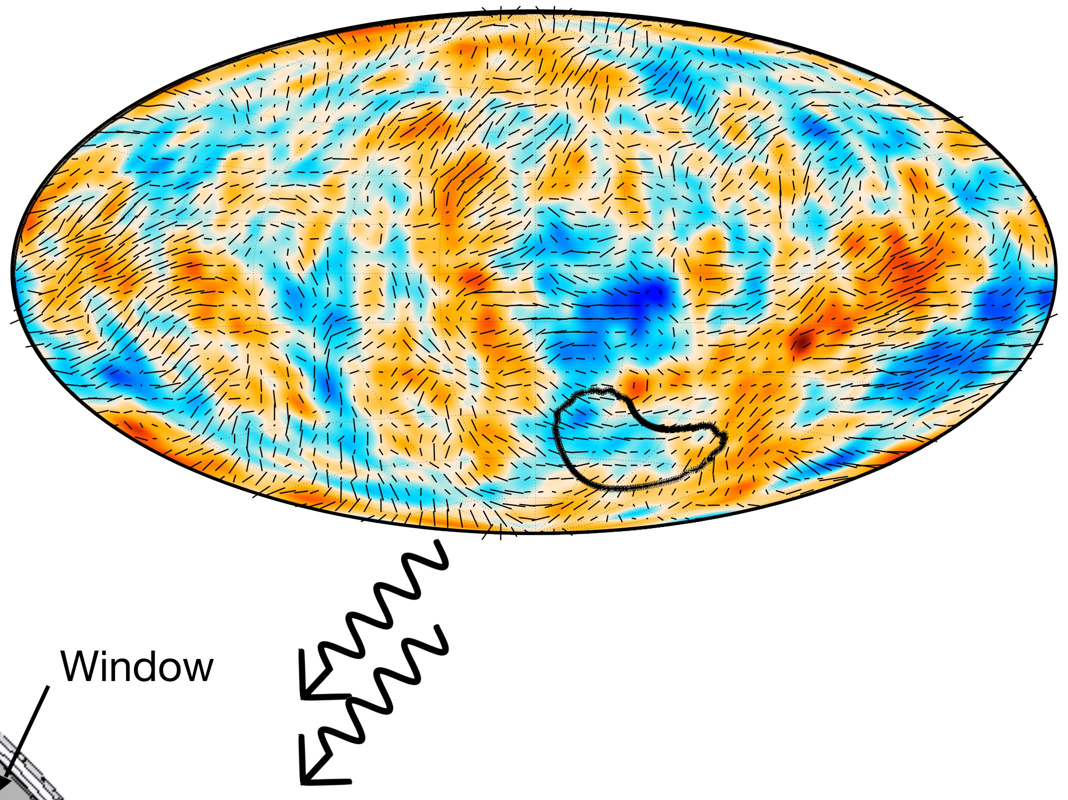
~30k sensors in four BICEP3-like cameras

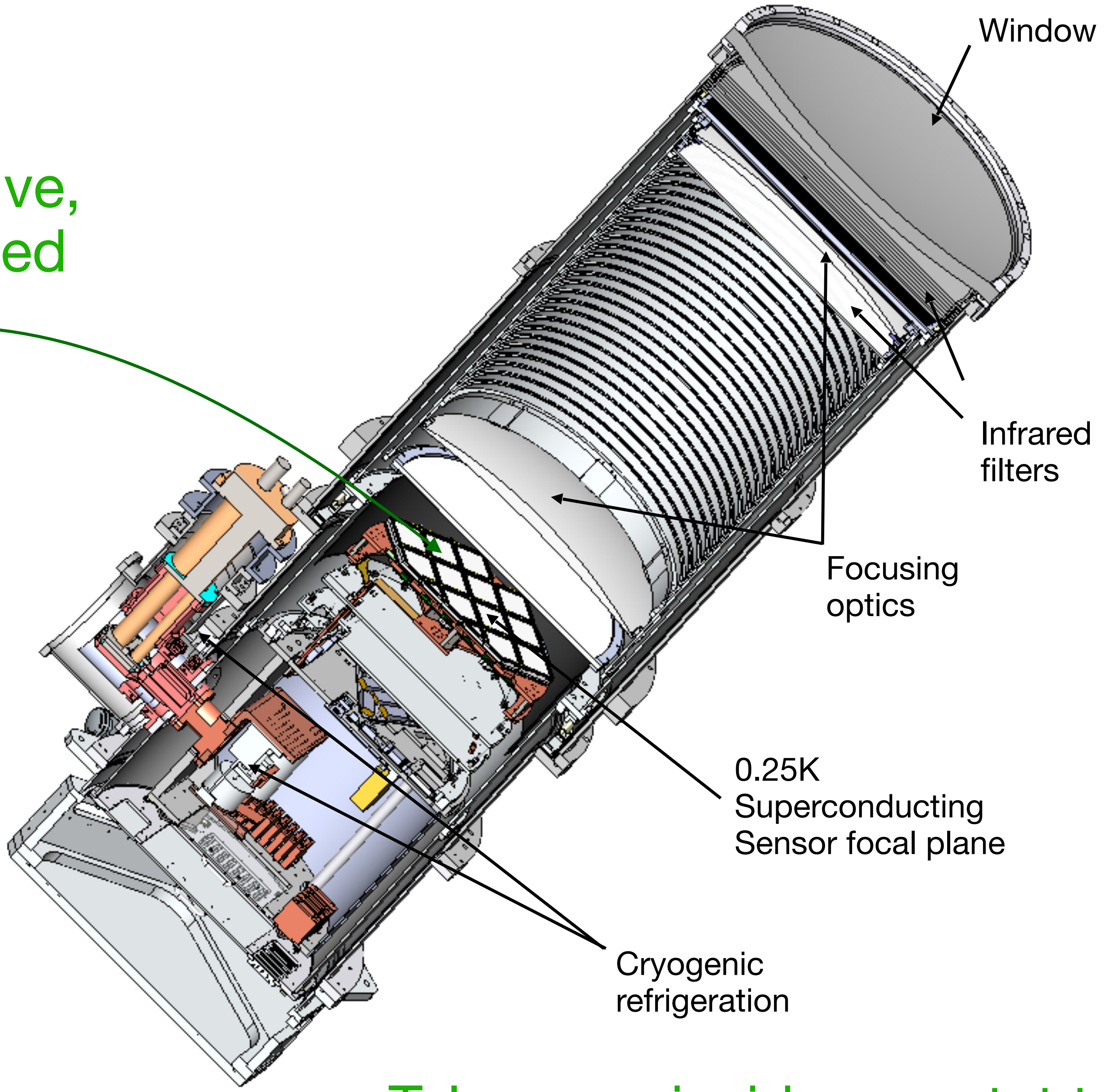
BICEP program designed to maximize sensitivity



Polarization-sensitive, photon-noise-limited sensors

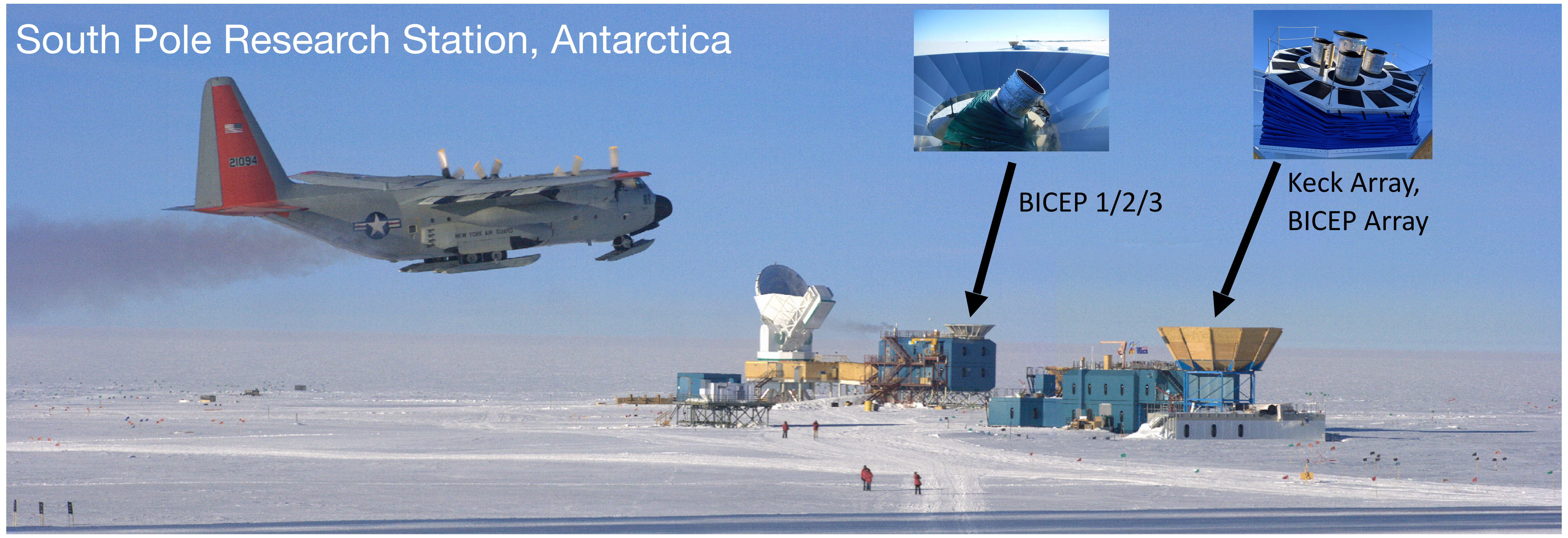
Integrate deeply on a small patch of sky





The BICEP3 camera

Telescope inside cryostat to reduce instrument's own thermal noise

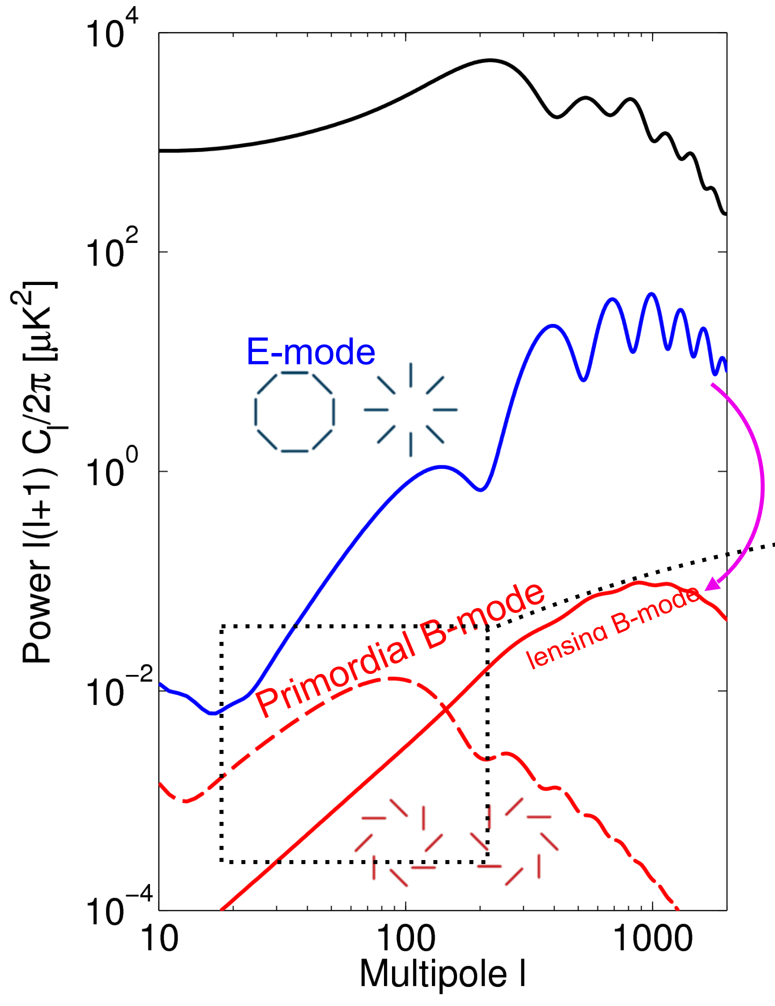


~10,000ft, ~0.25mm precipitable water vapor
High atmospheric transmission in mm-wave windows

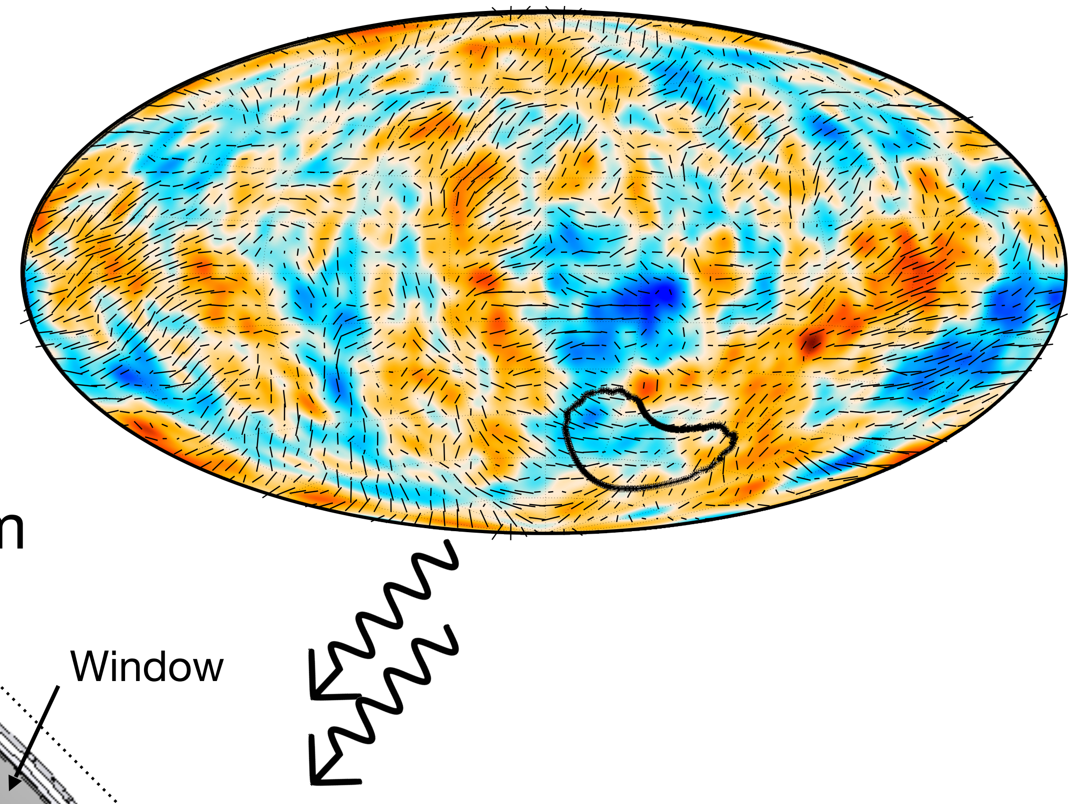
6 months of cold, stable winter sky (no diurnal variation)
Long periods of uninterrupted integration

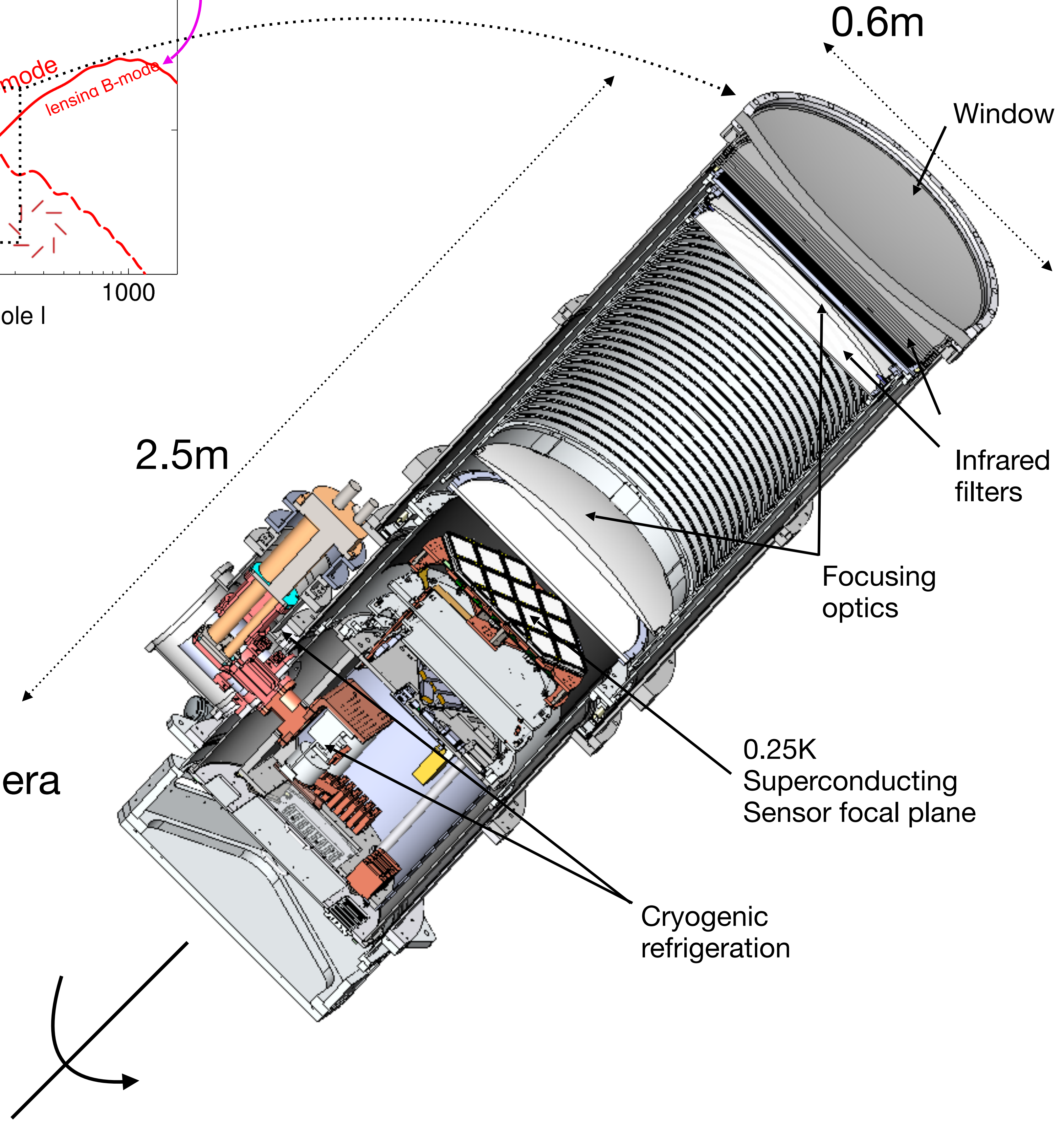
BICEP/Keck Collaboration, ApJ 927 77 (2022)

BICEP program designed to control systematic effects



Only sufficient resolution for degree scale B-modes, so can make compact

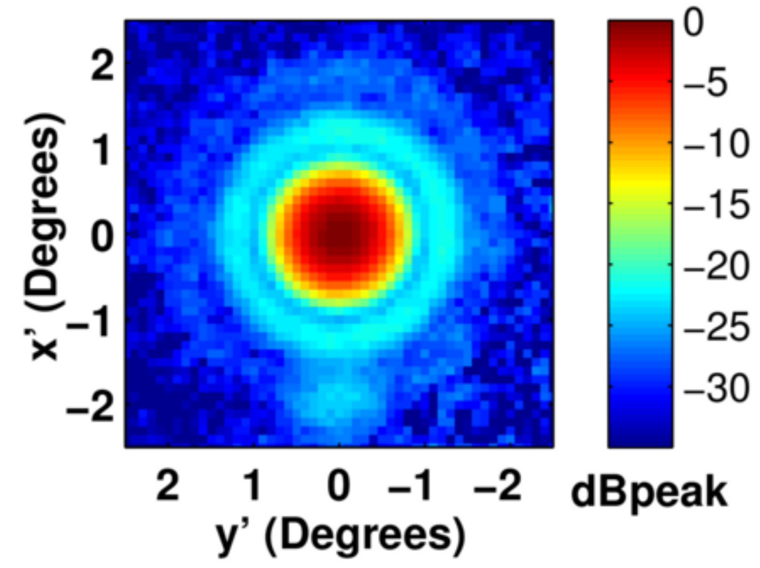


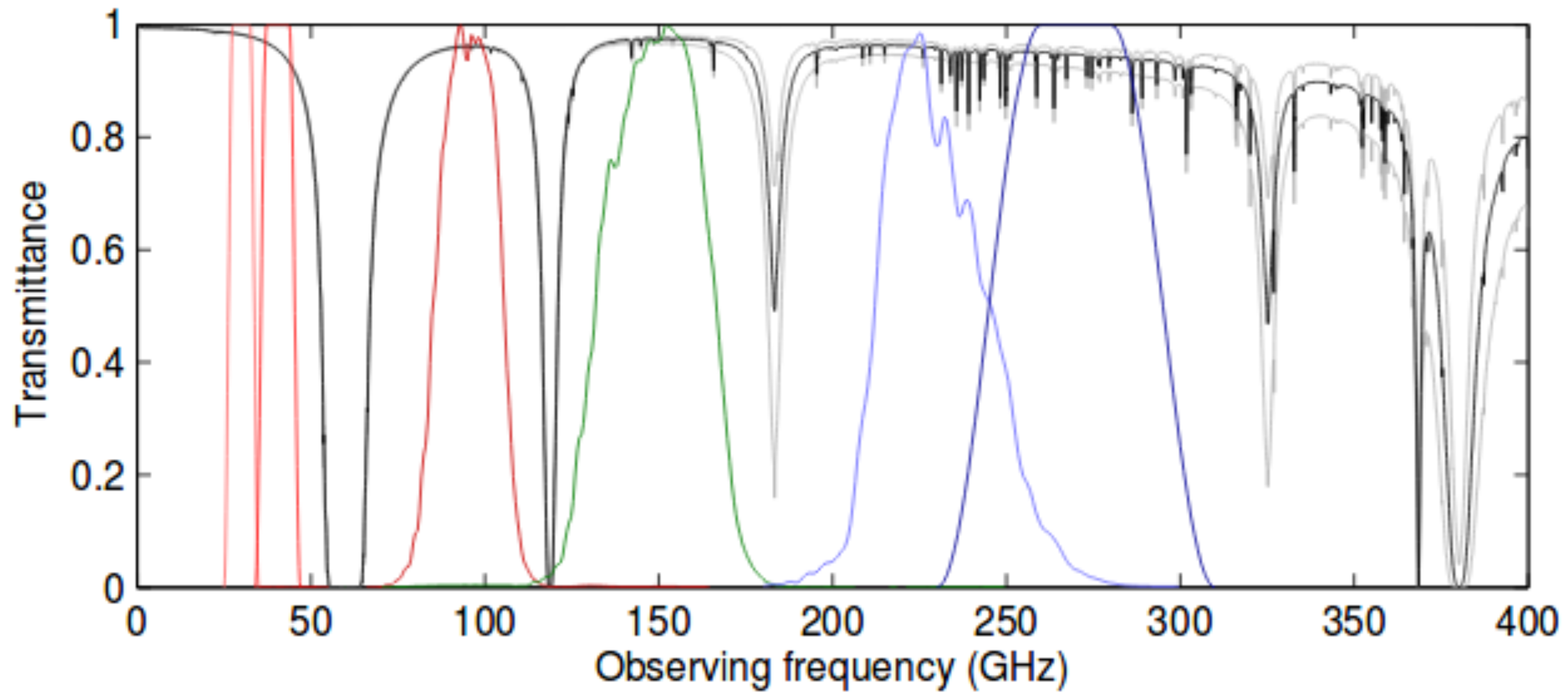


BICEP3 camera

Boresight rotation to average down certain classes of systematics

Extensive characterization of instrument response (point spread function, spectral response etc.)



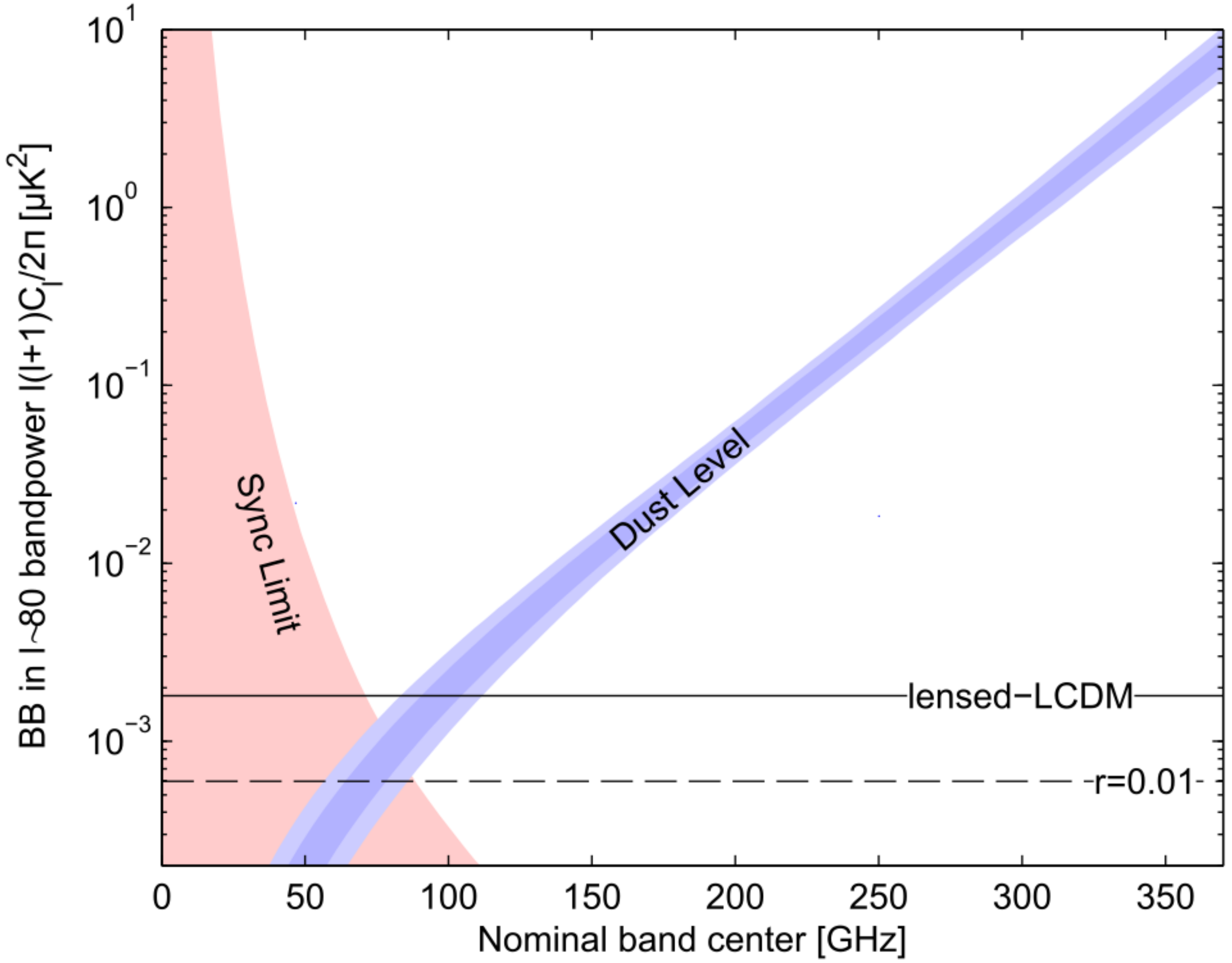


Observe in multiple frequencies (30, 40, 90, 150, 220, 270 GHz) to tease apart CMB from dust and synchrotron foregrounds

BICEP/Keck Collaboration, ApJ 927 77 (2022)

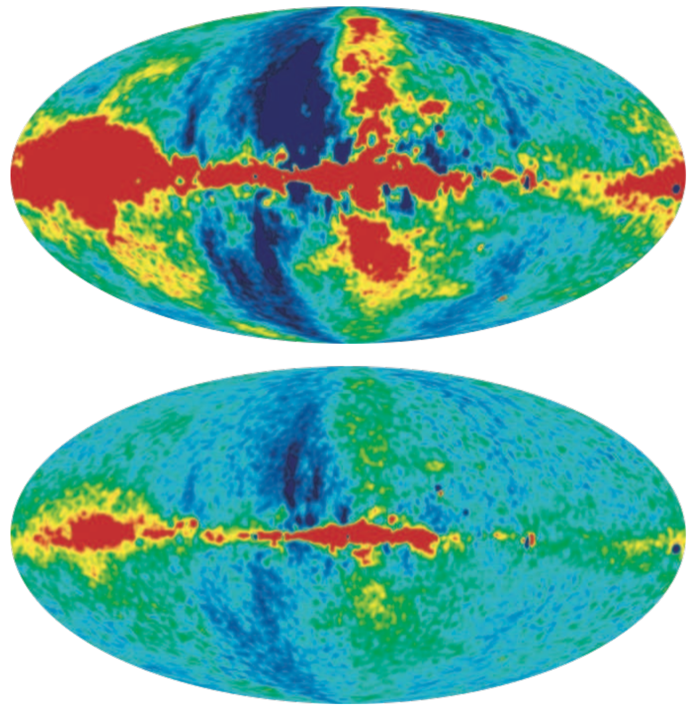
Galactic Foregrounds

Different spectral behavior

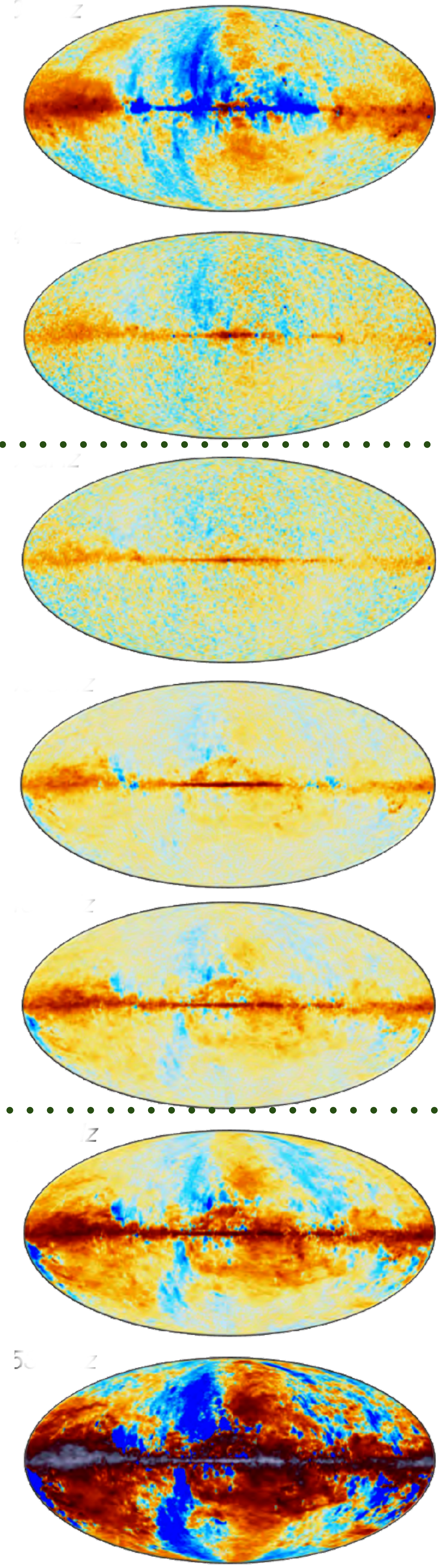


WMAP **Planck**

23 GHz
33 GHz



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



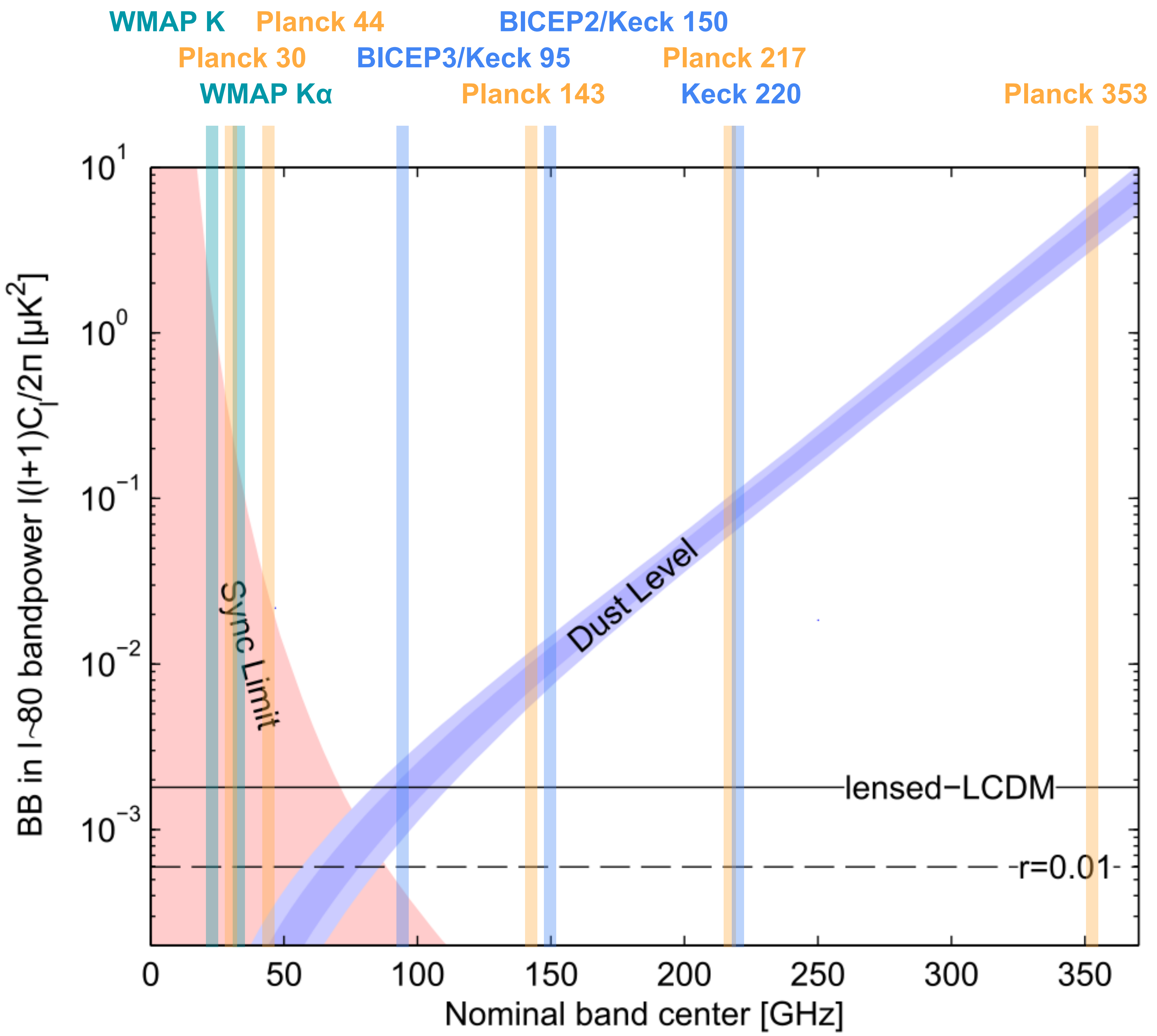
Polarized Synchrotron dominated

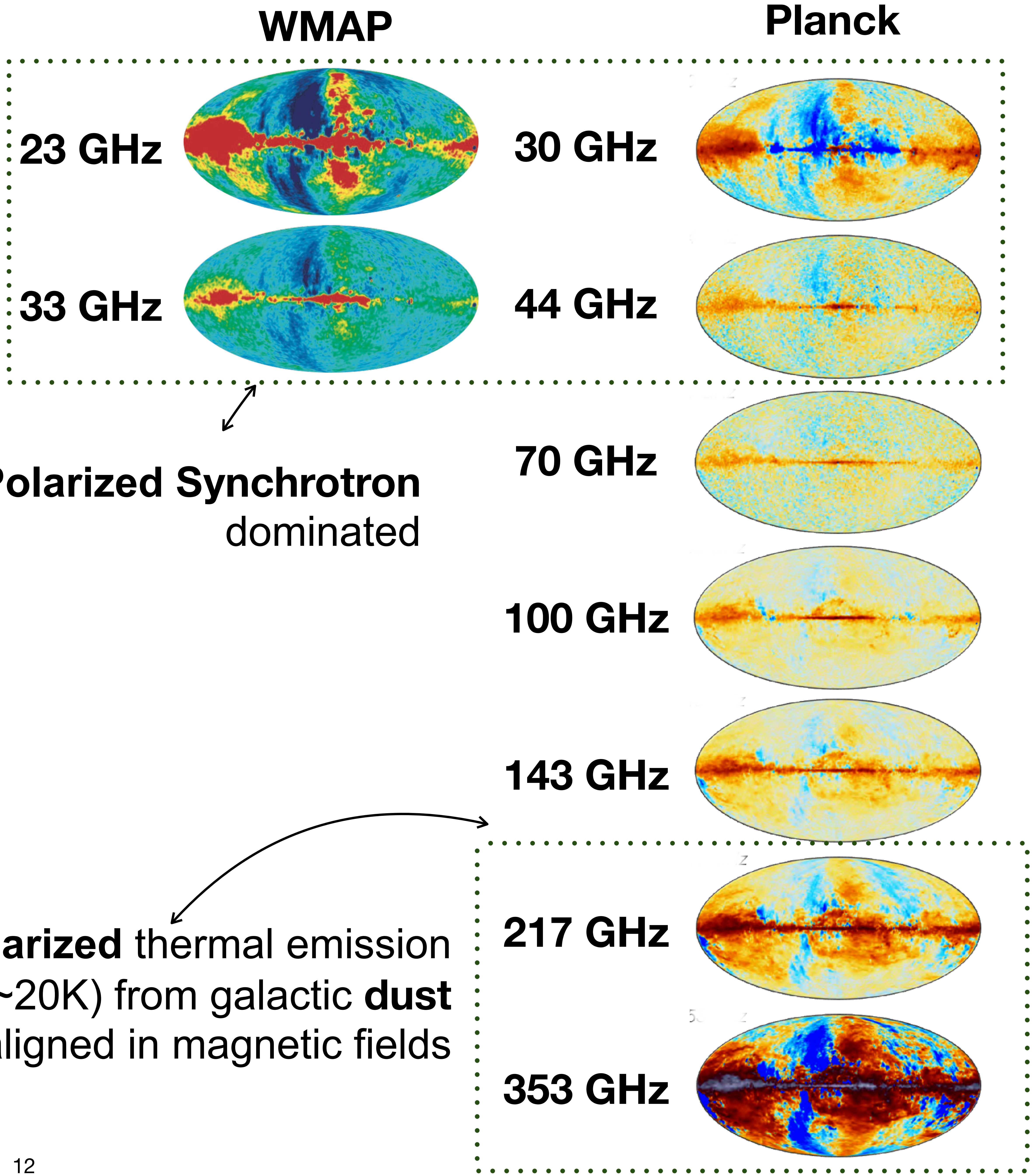
Polarized thermal emission (~20K) from galactic **dust** aligned in magnetic fields

Figures from BICEP, Planck and WMAP

Galactic Foregrounds

Different spectral behavior





Polarized Synchrotron dominated

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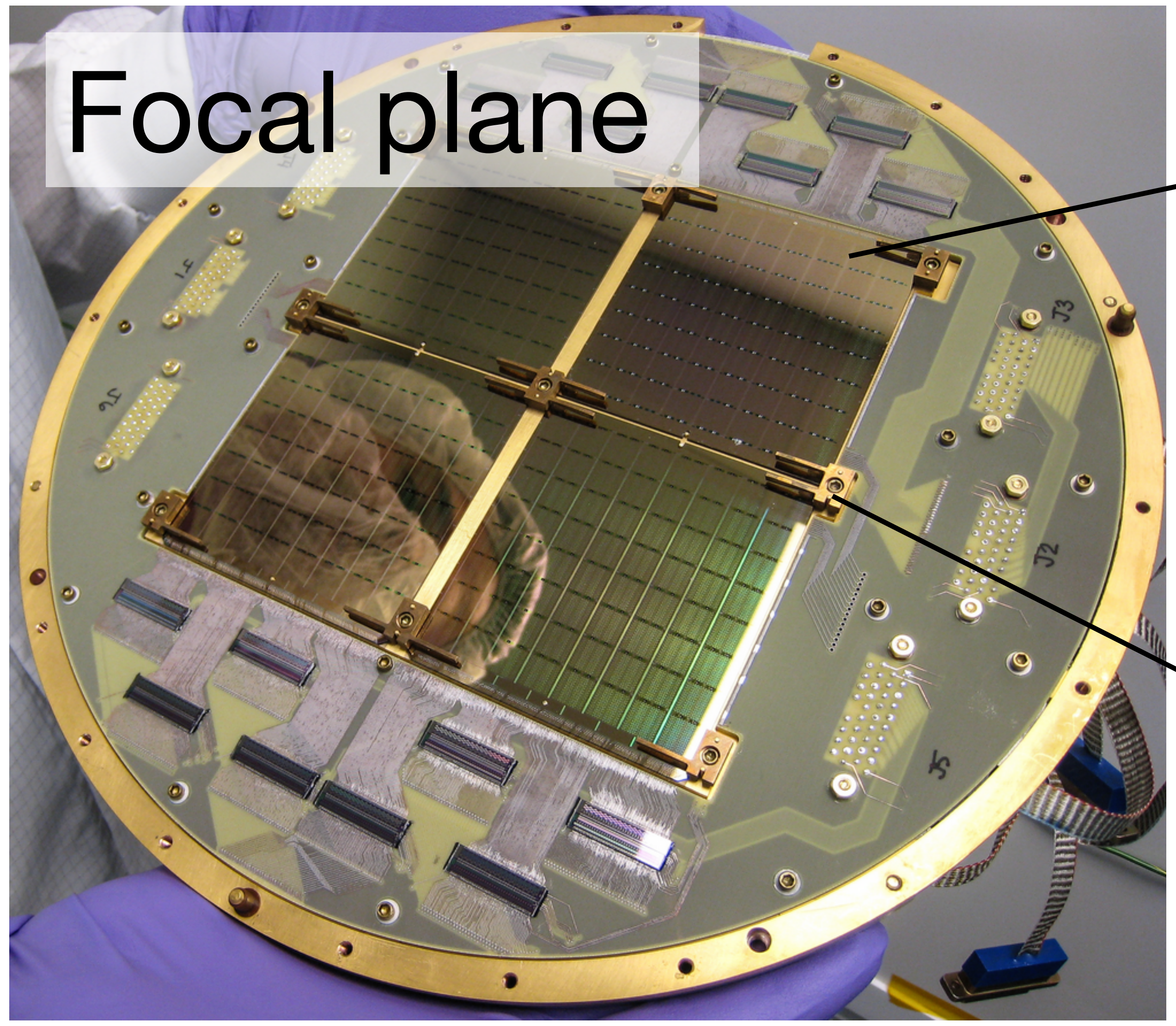
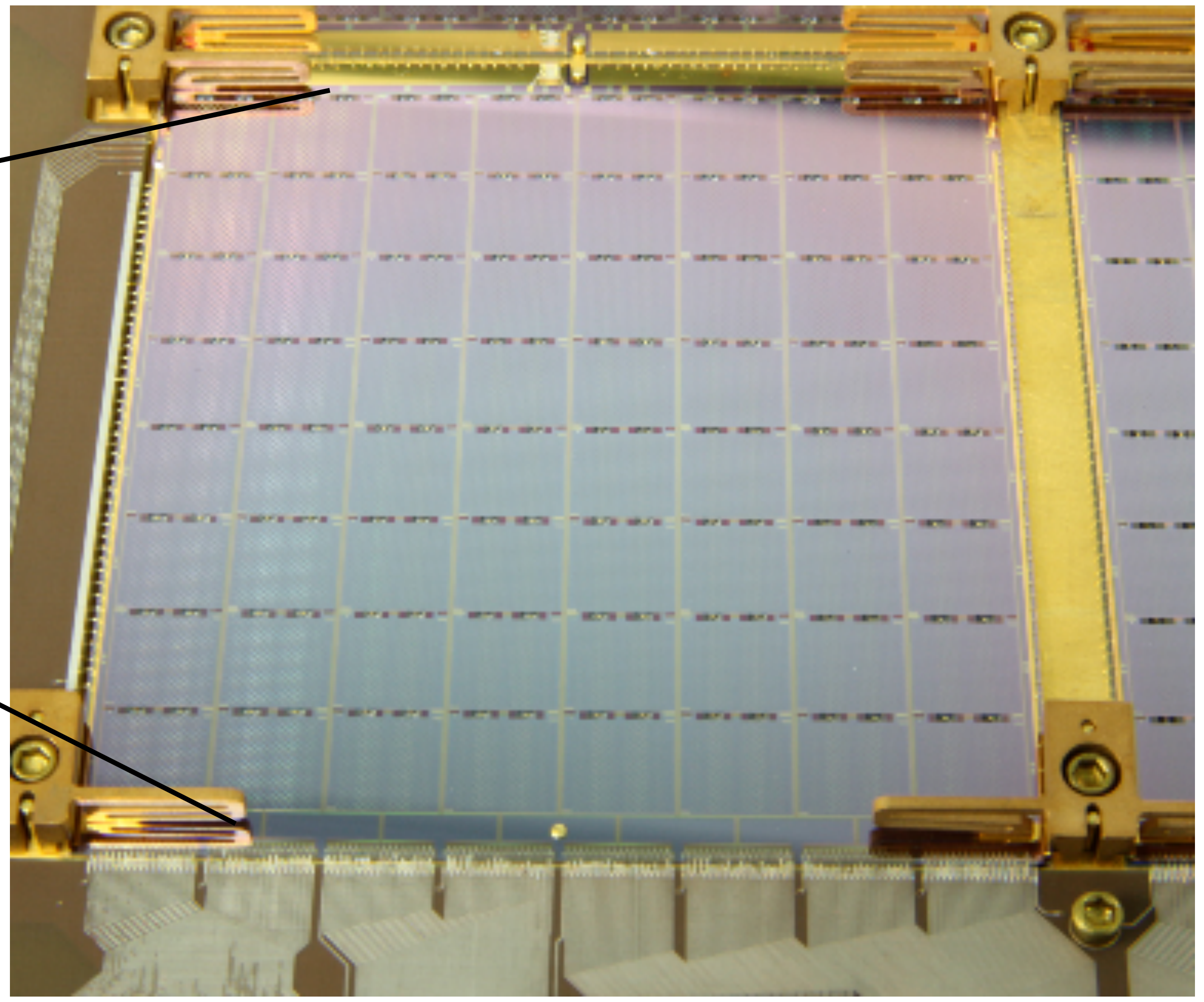
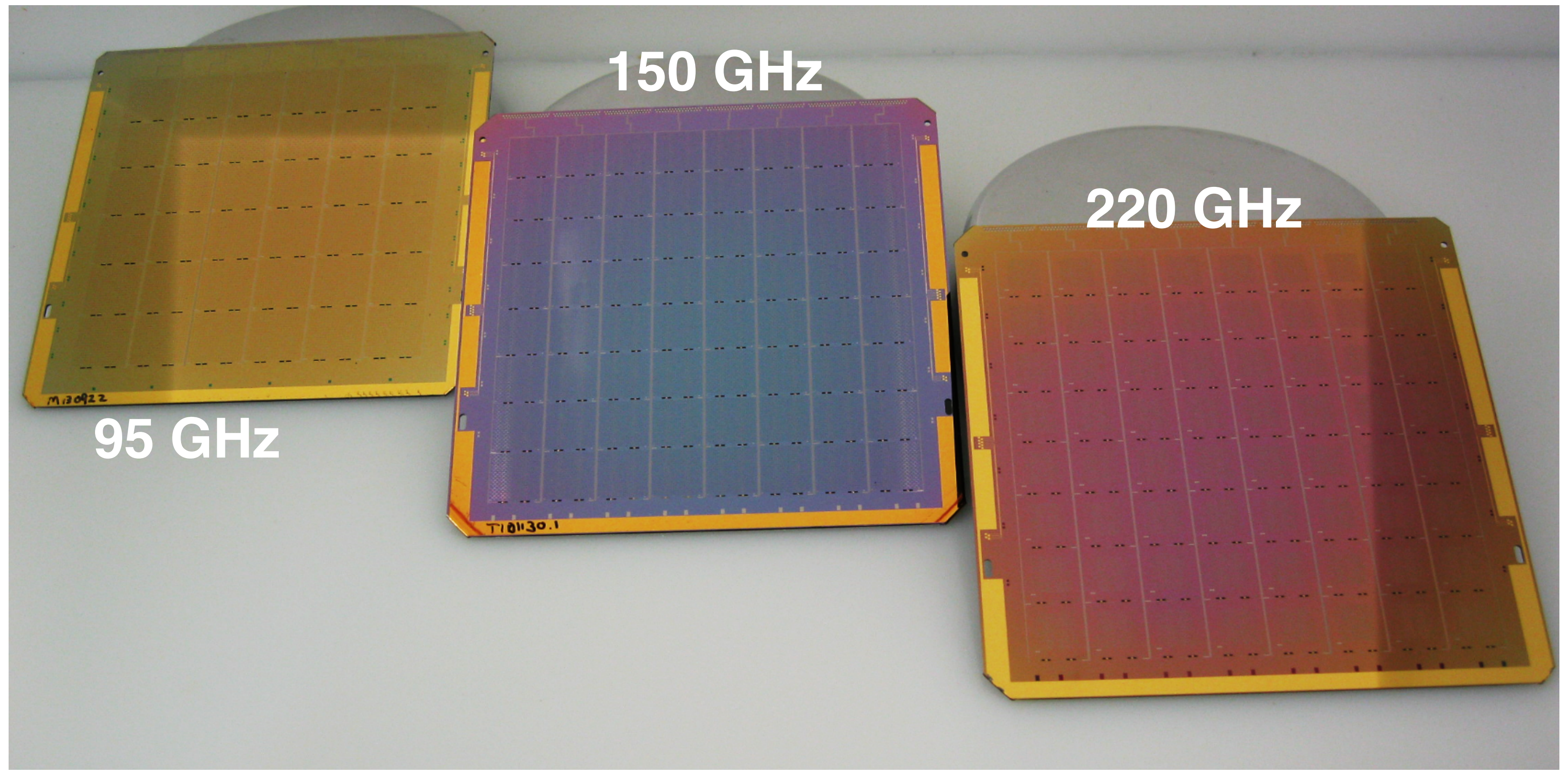
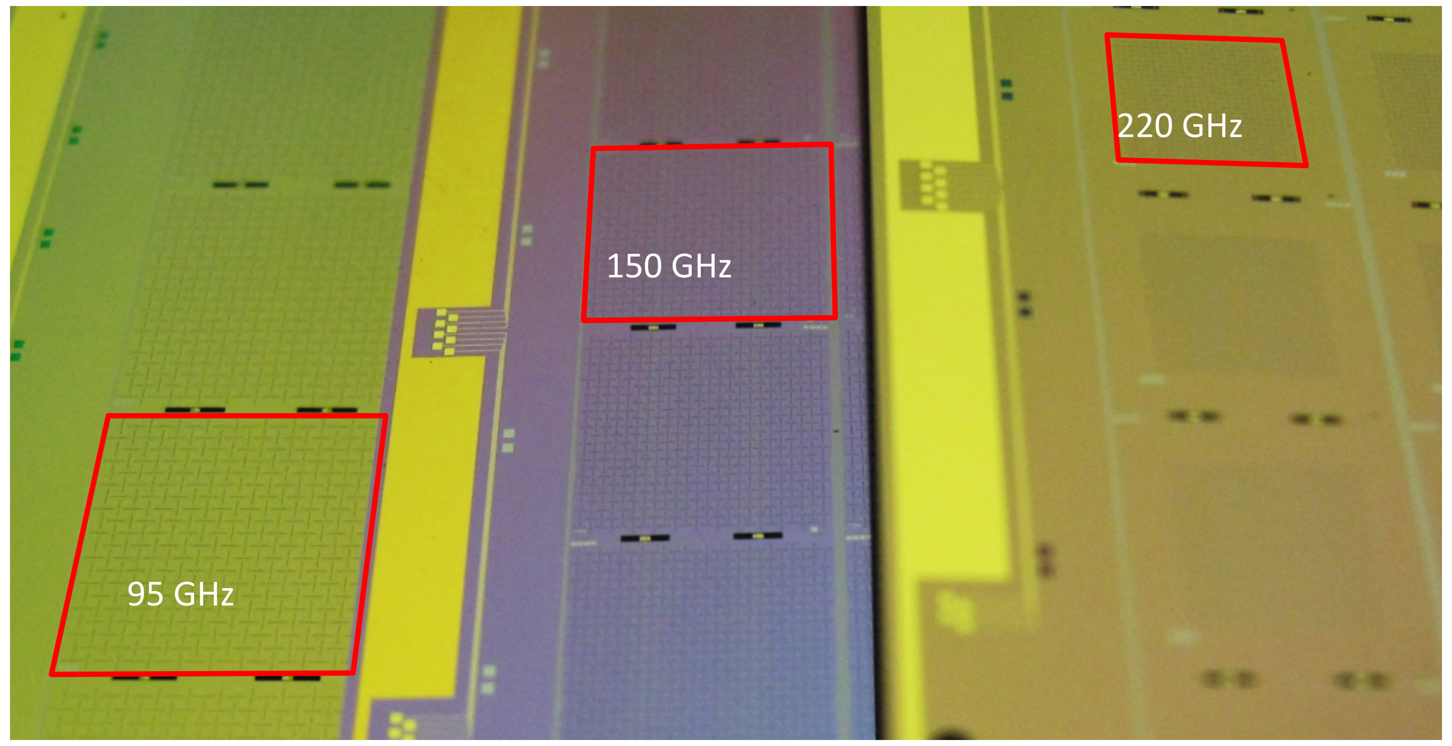
Figures from BICEP, Planck and WMAP

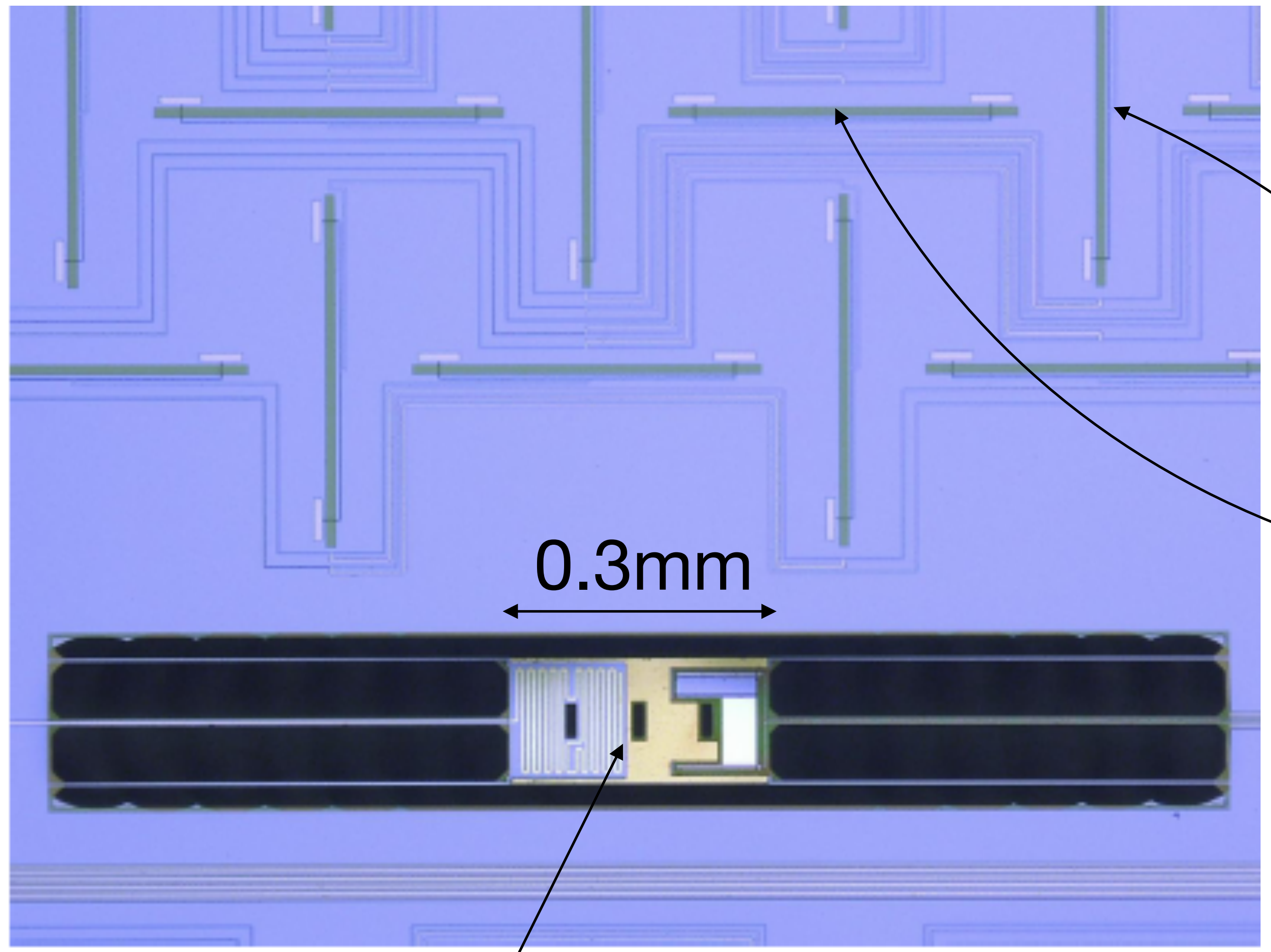
Detectors operated at 0.25K, at photon-noise limit!



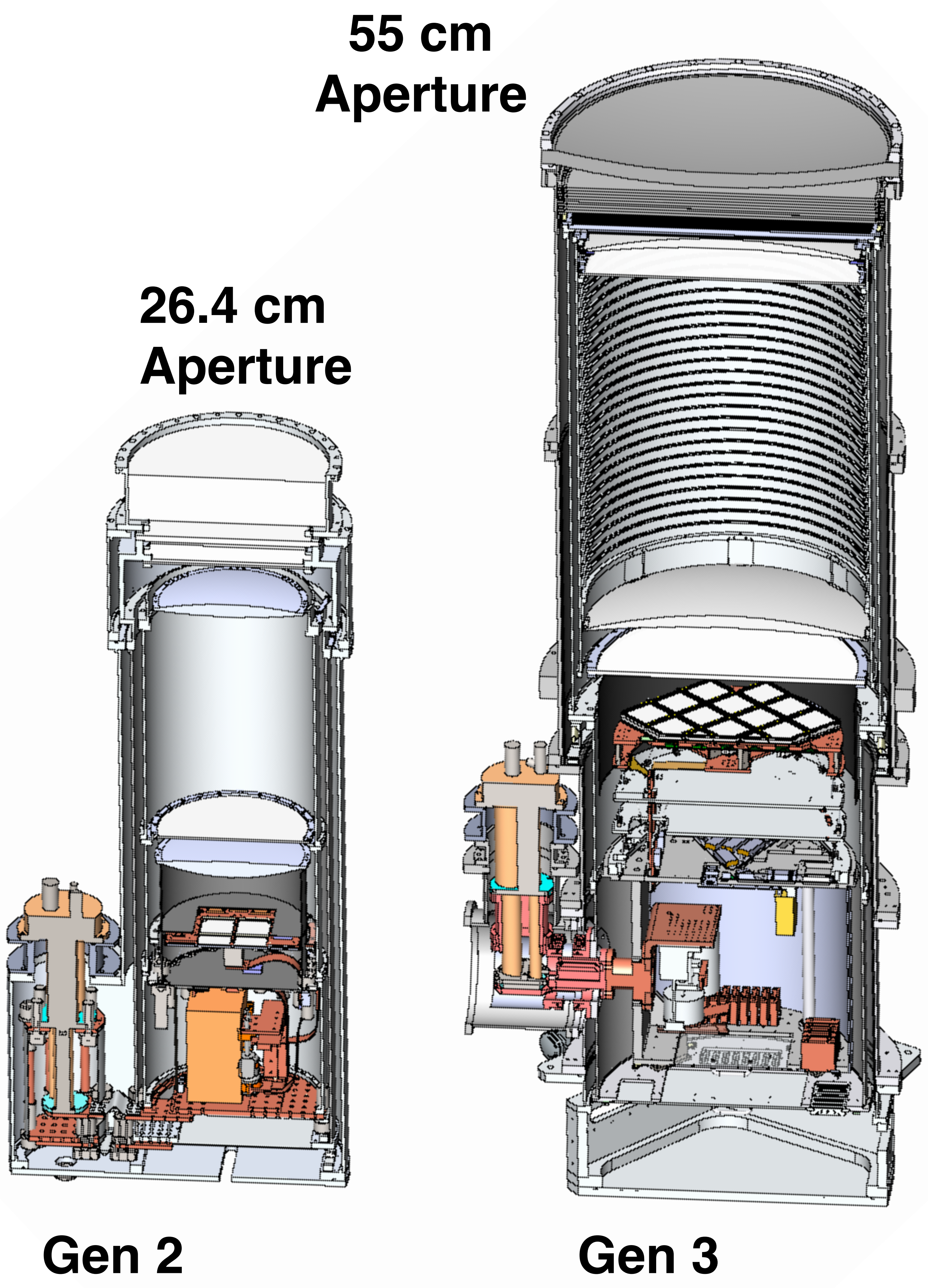


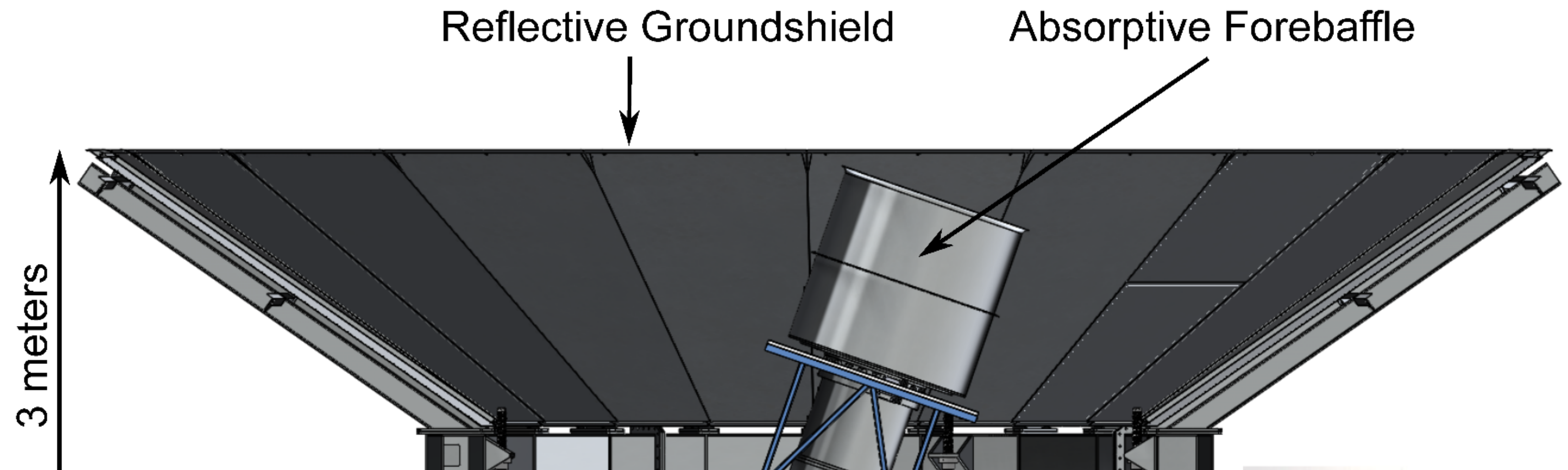






BICEP integrated instrument



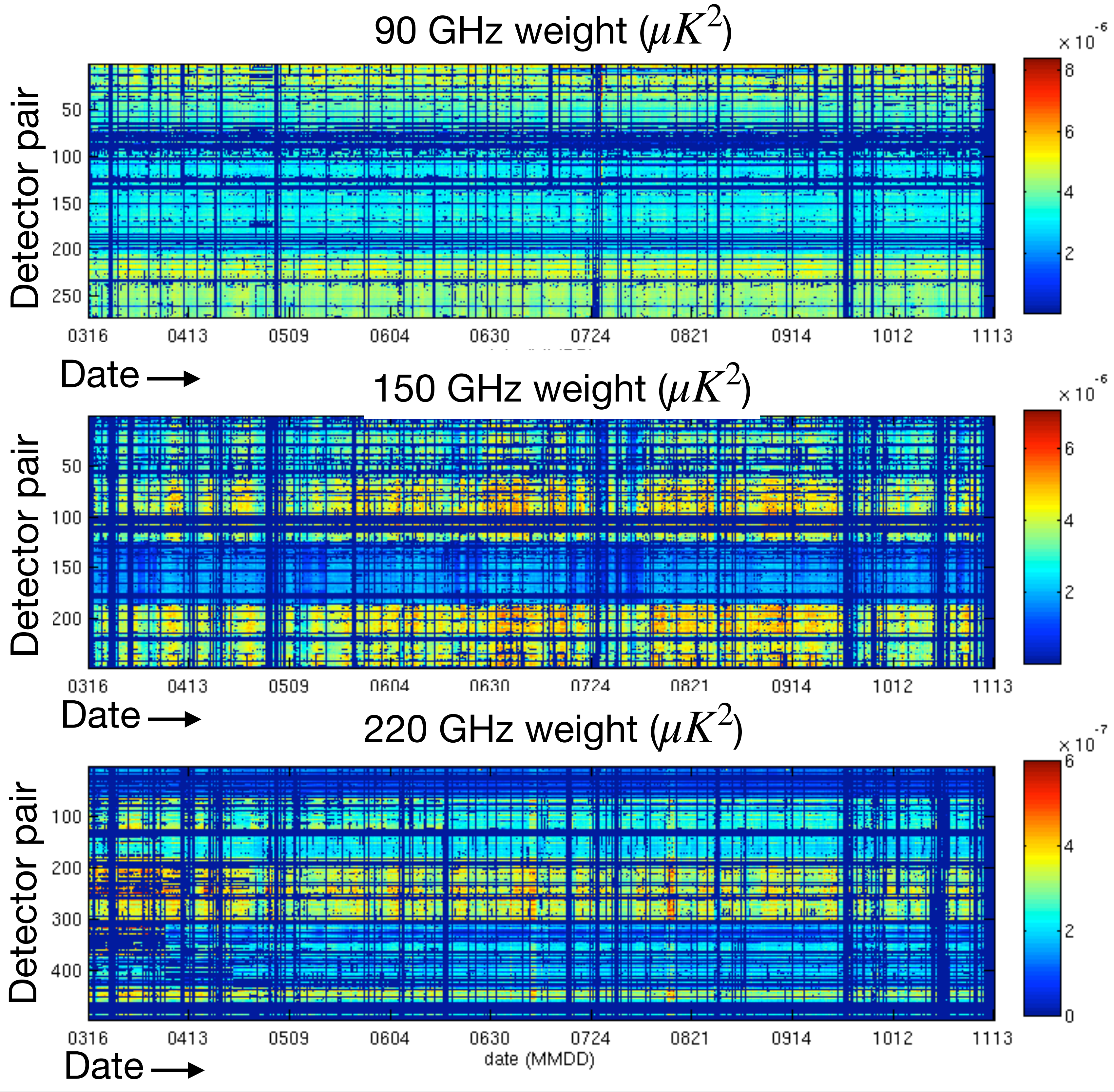


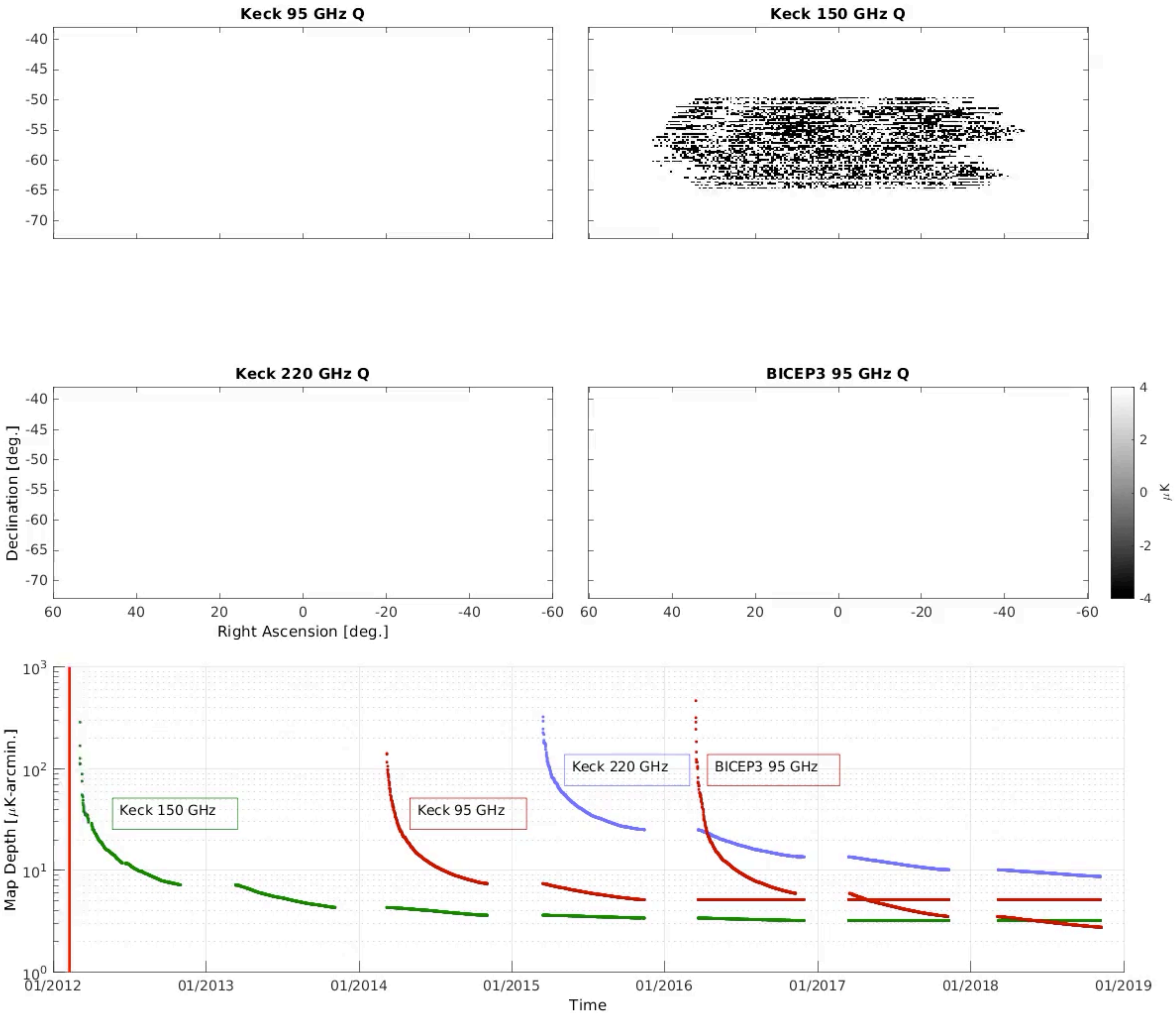
BICEP3

Signal Integration

2012-2018 (BK18)

Extensive automated & manual data quality monitoring and cuts





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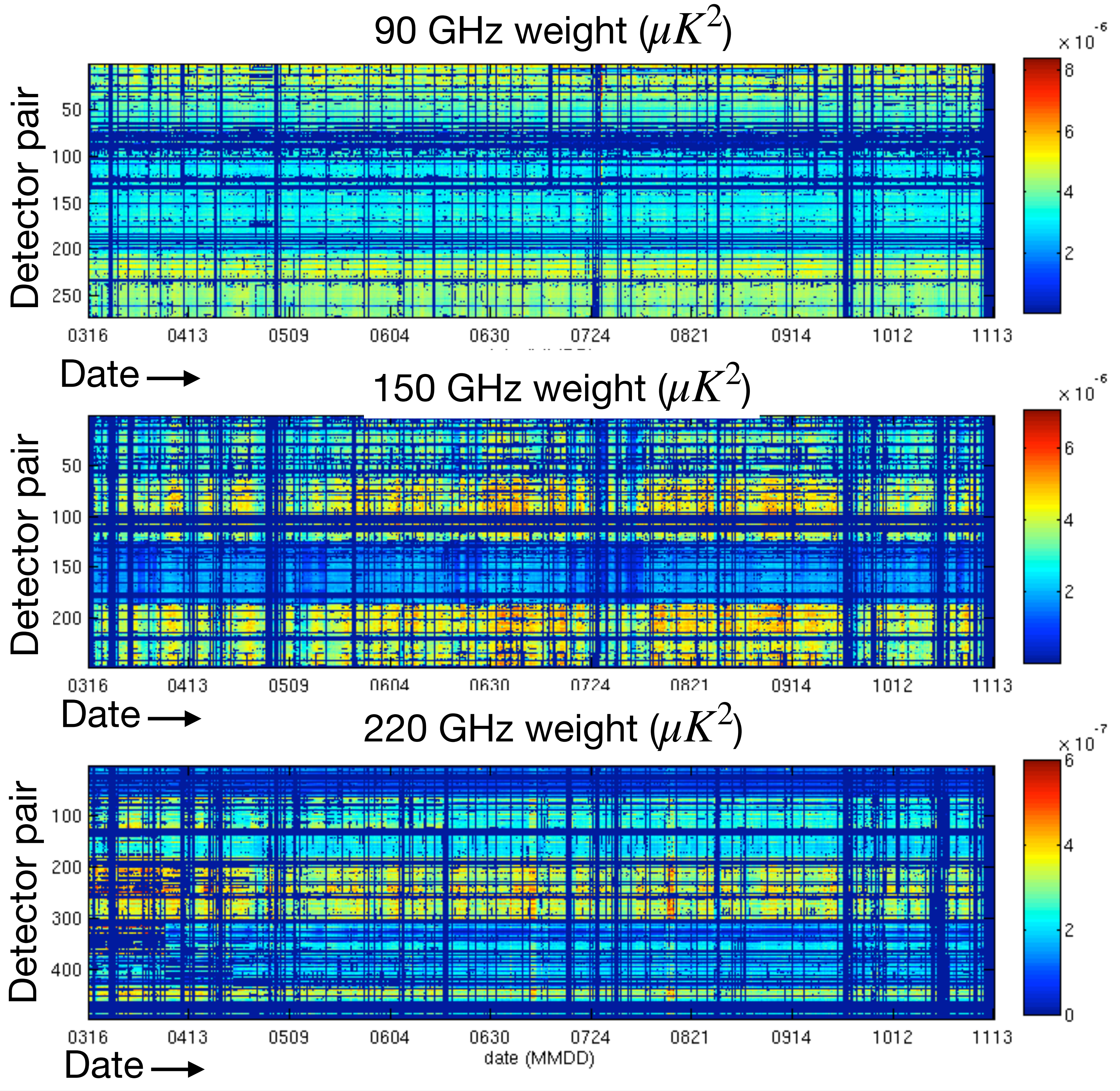

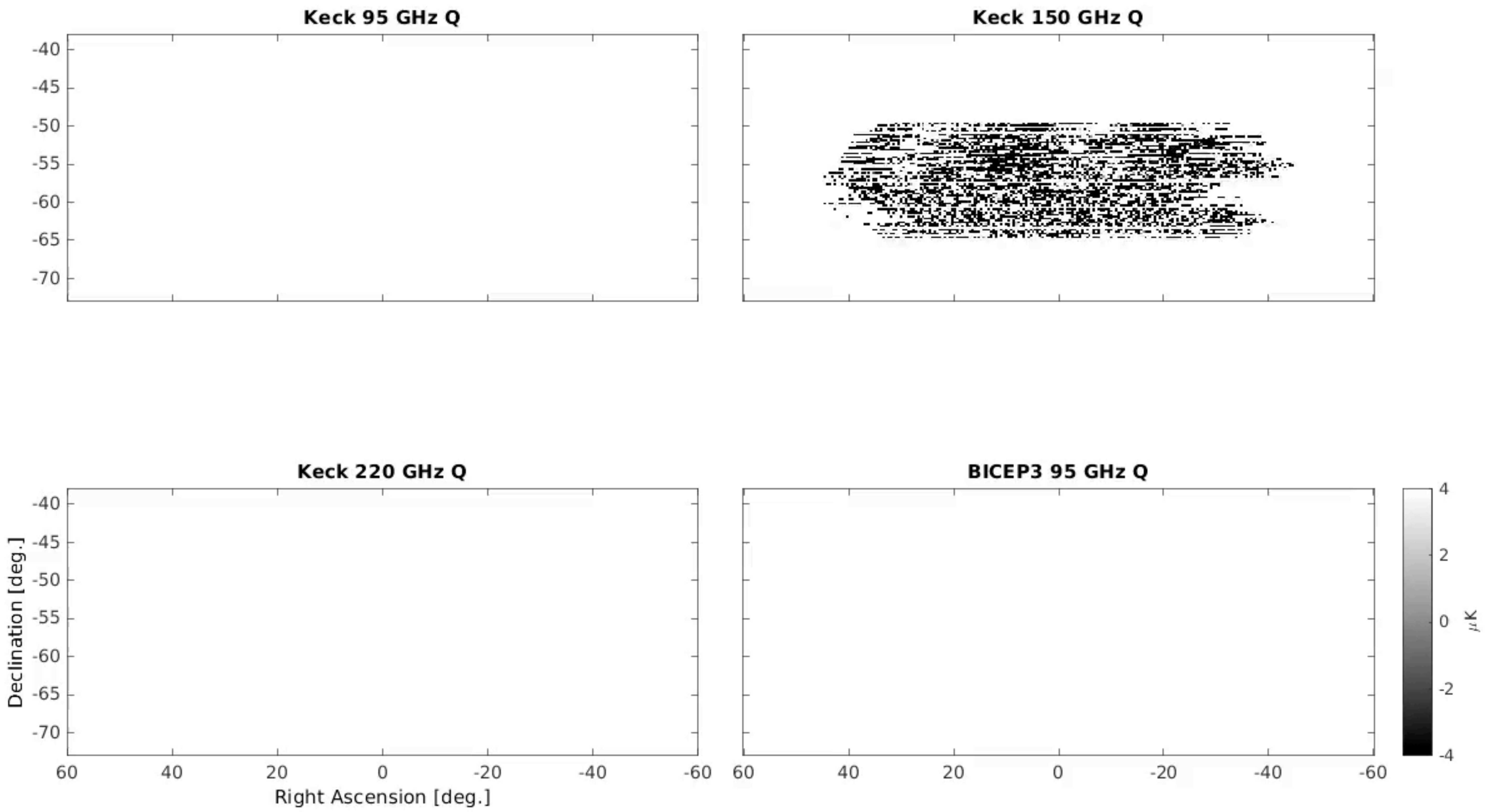

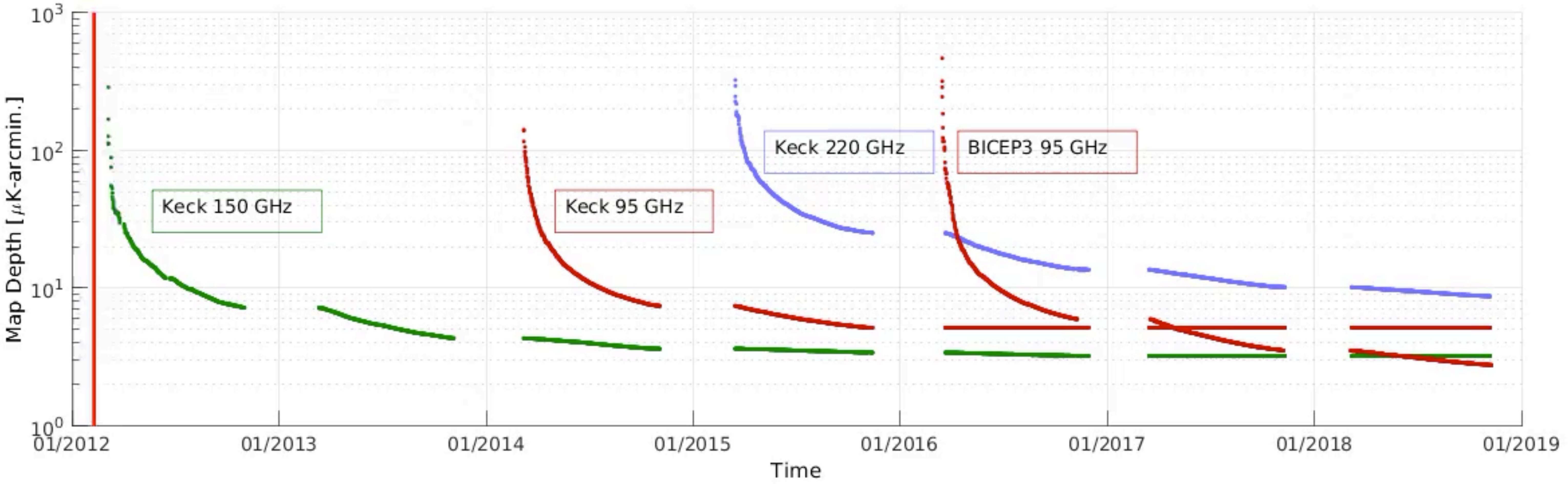

Signal Integration
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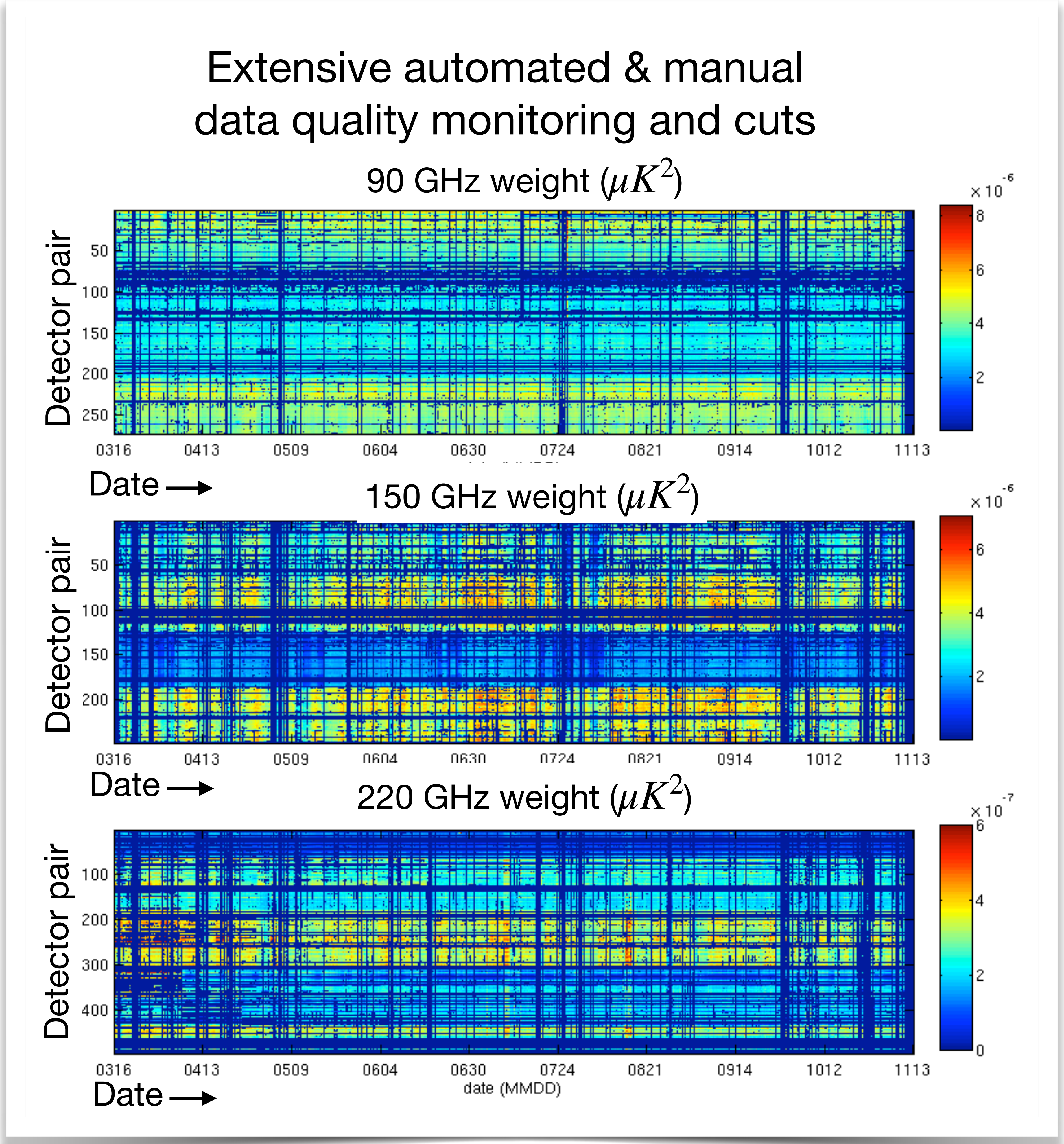
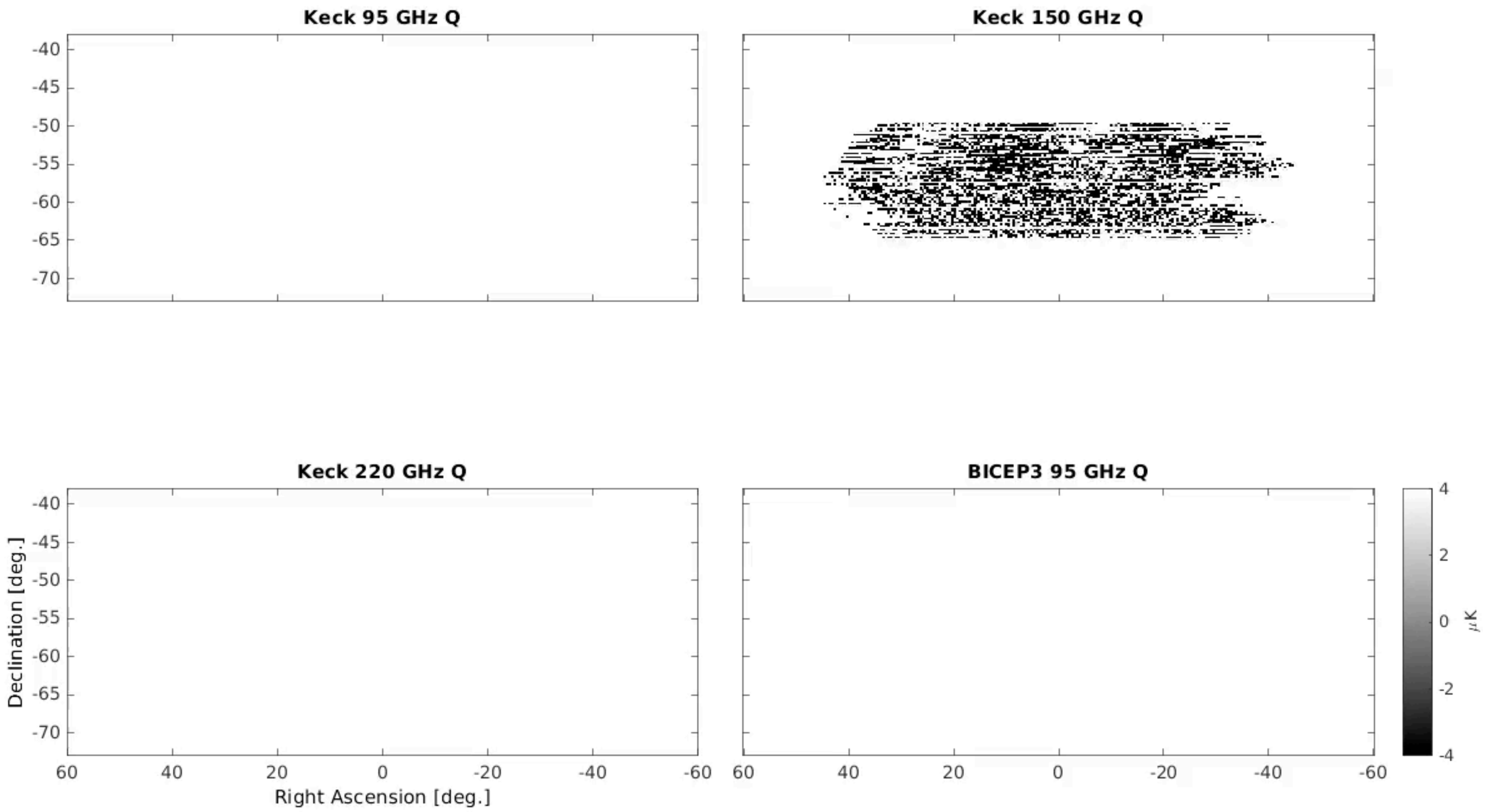
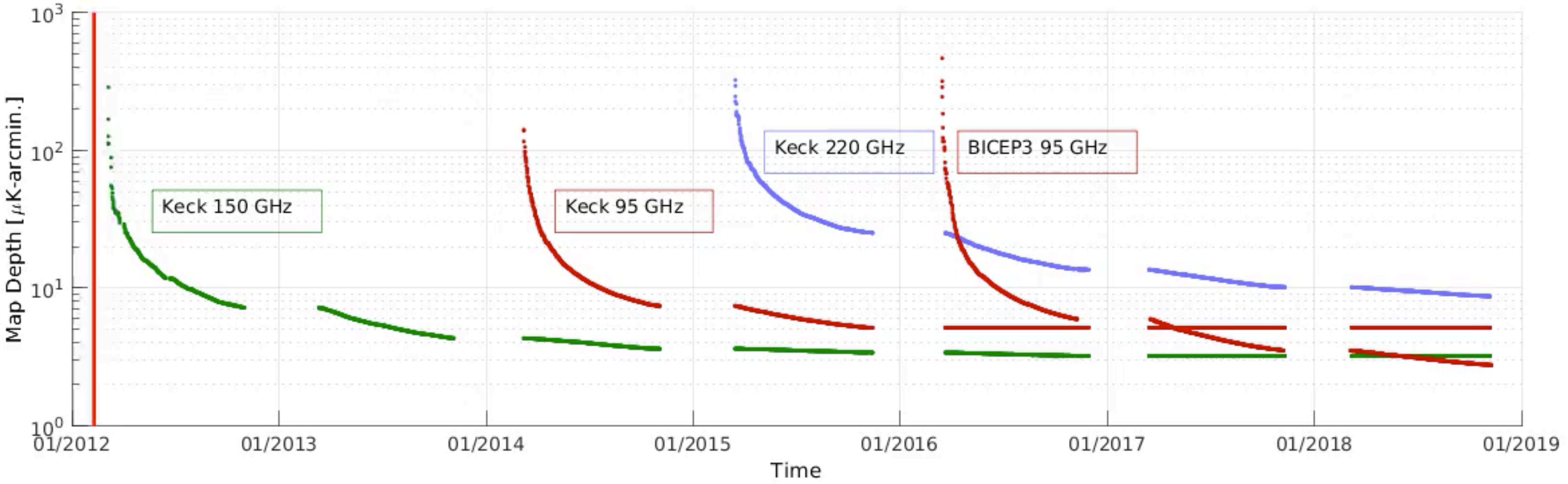
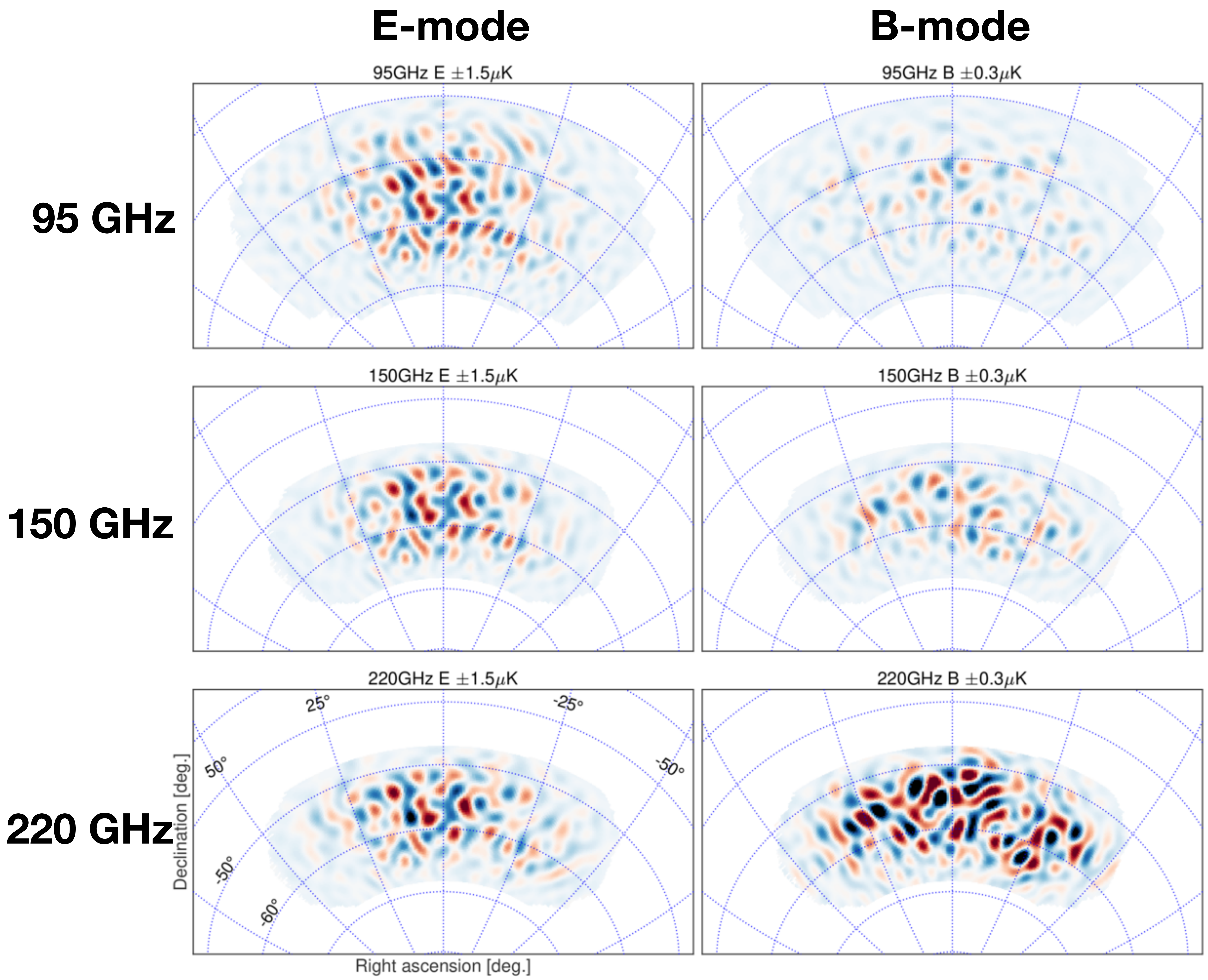






Deepest CMB polarization maps to date (BK18)



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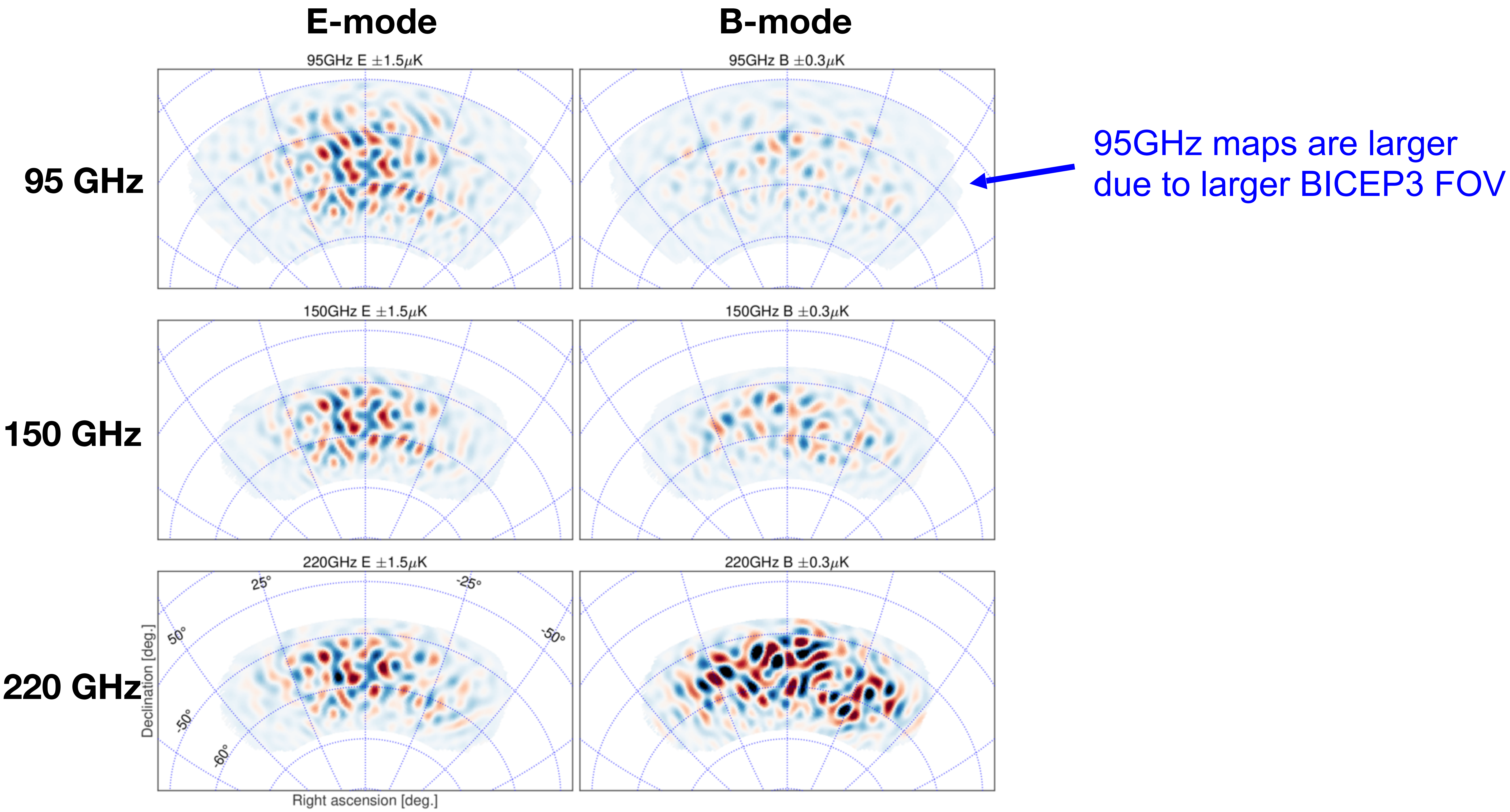

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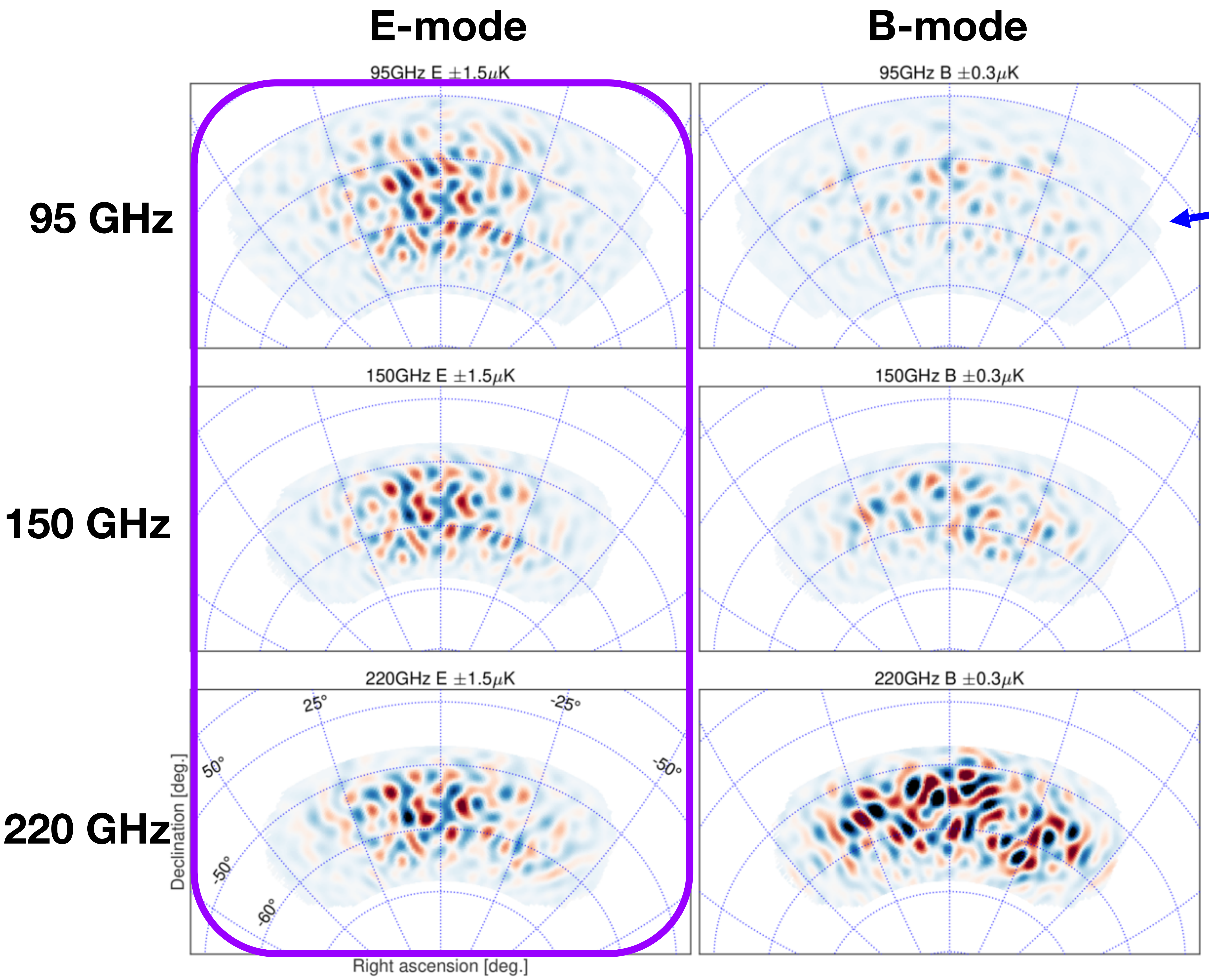

95GHz maps are larger due to larger BICEP3 FOV

E maps are bright and correlated: robust detection of LCDM E-modes

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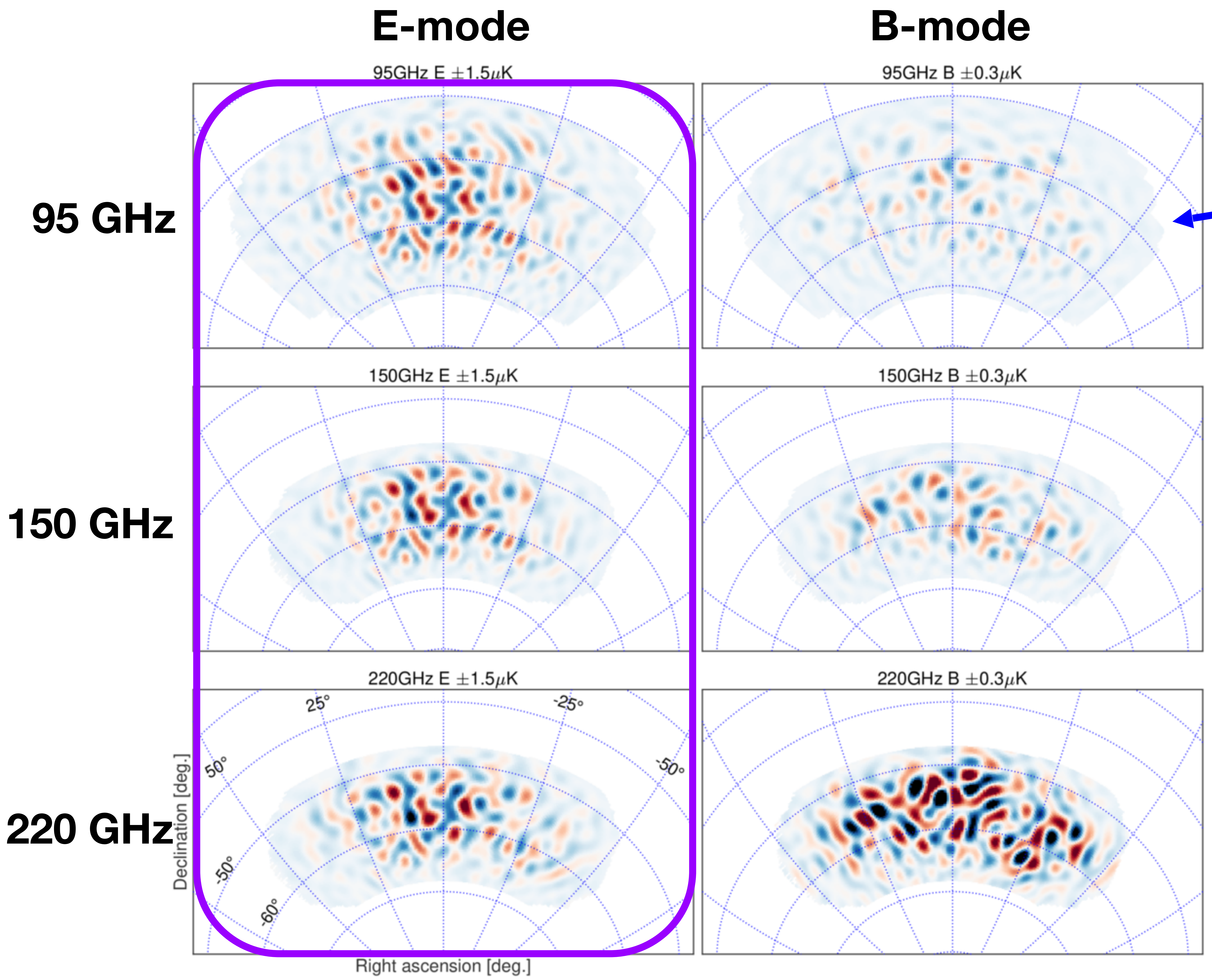


95GHz maps are larger due to larger BICEP3 FOV

E maps are bright and correlated: robust detection of LCDM E-modes

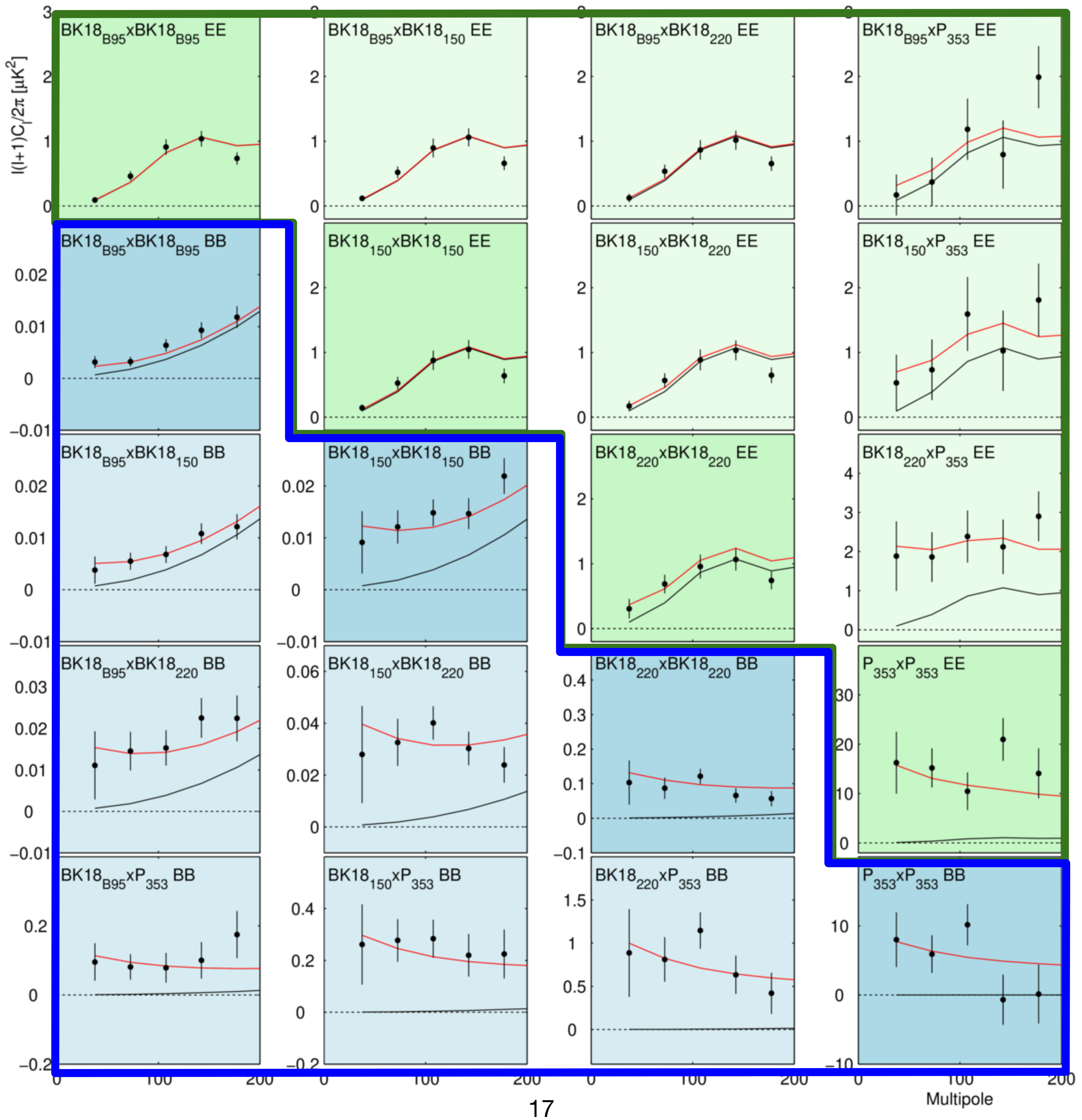
B maps are increasing in brightness: detection of polarized galactic dust

Robust detection of lensed-LCDM + dust

Data points are BK18

Black line = lensed LCDM model prediction

Red line = lensed LCDM + dust model fit from BK15 B-modes prediction



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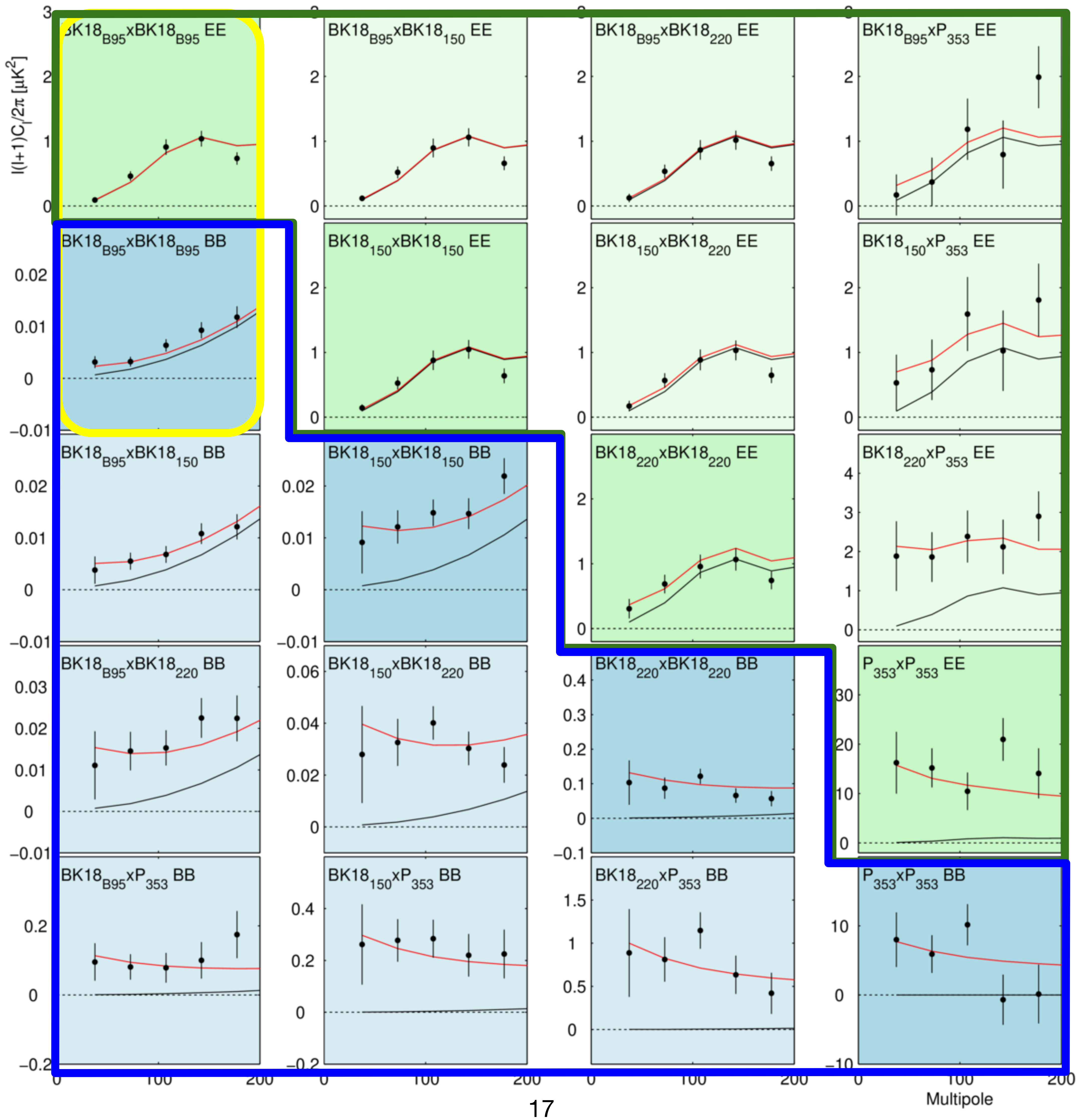

New BICEP3-only spectra: smaller error bars!

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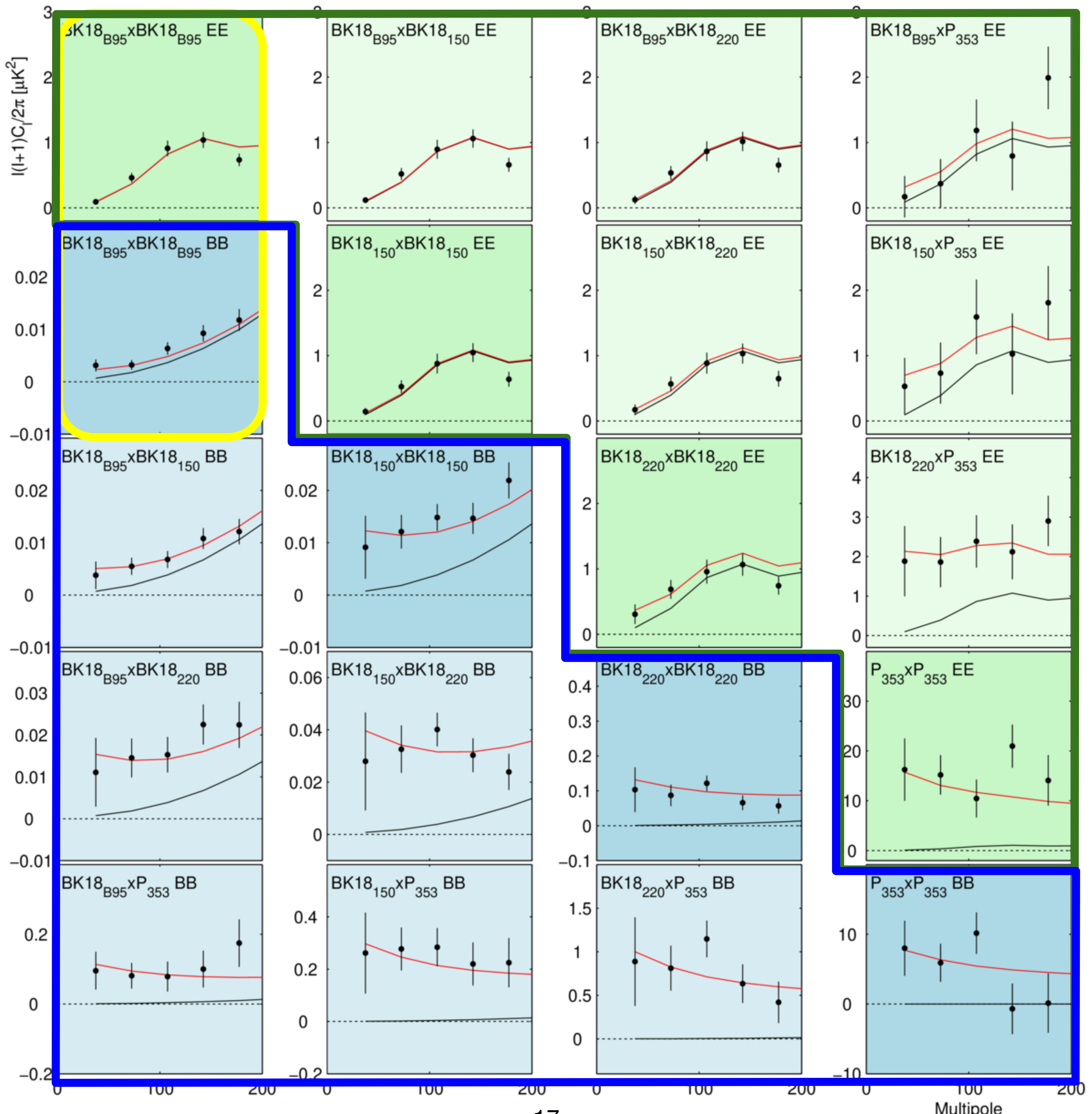

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E-mode spectra only provide validation of model; not included in analysis

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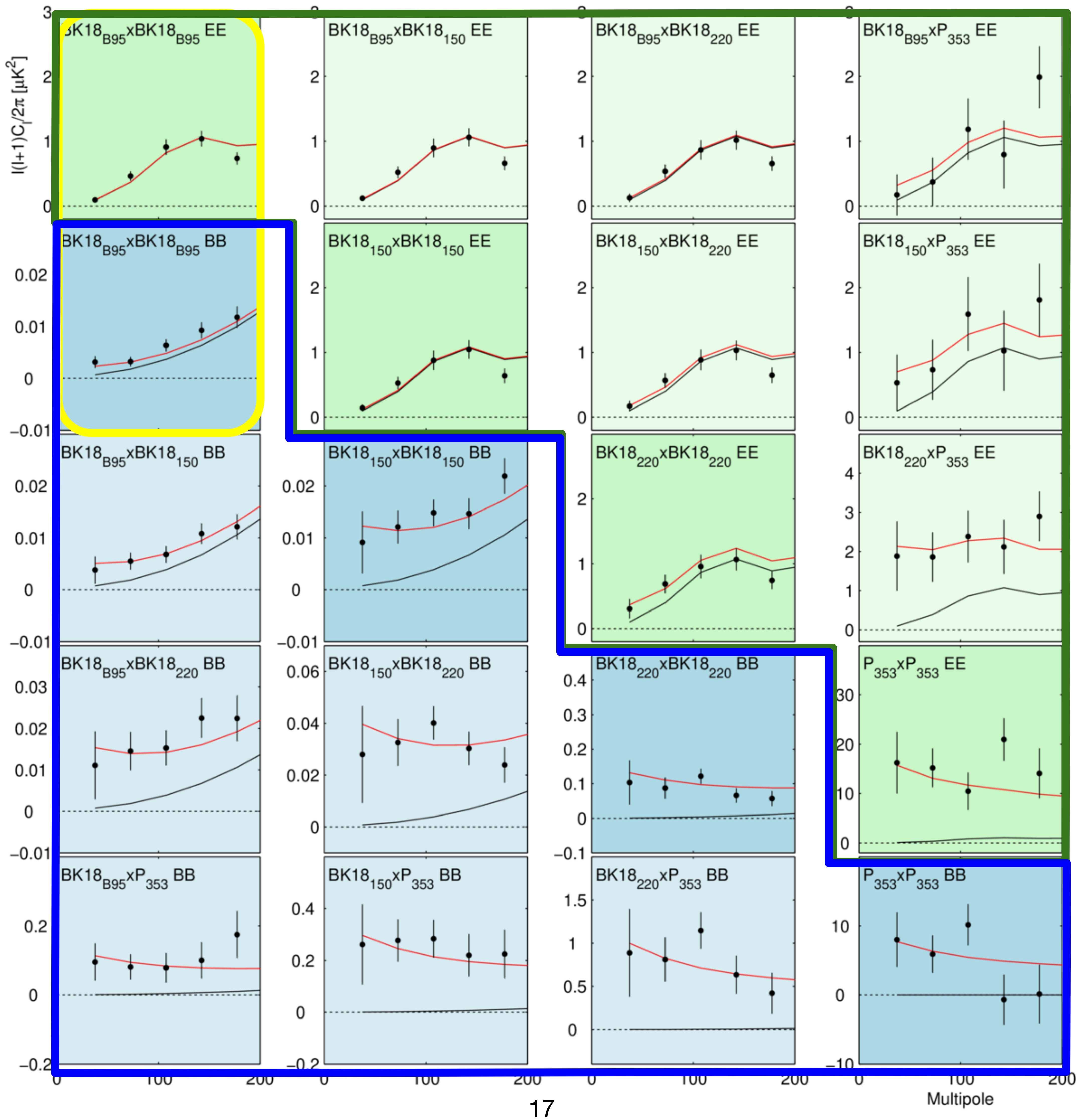
B-mode auto/cross spectra are inputs to multicomponent likelihood



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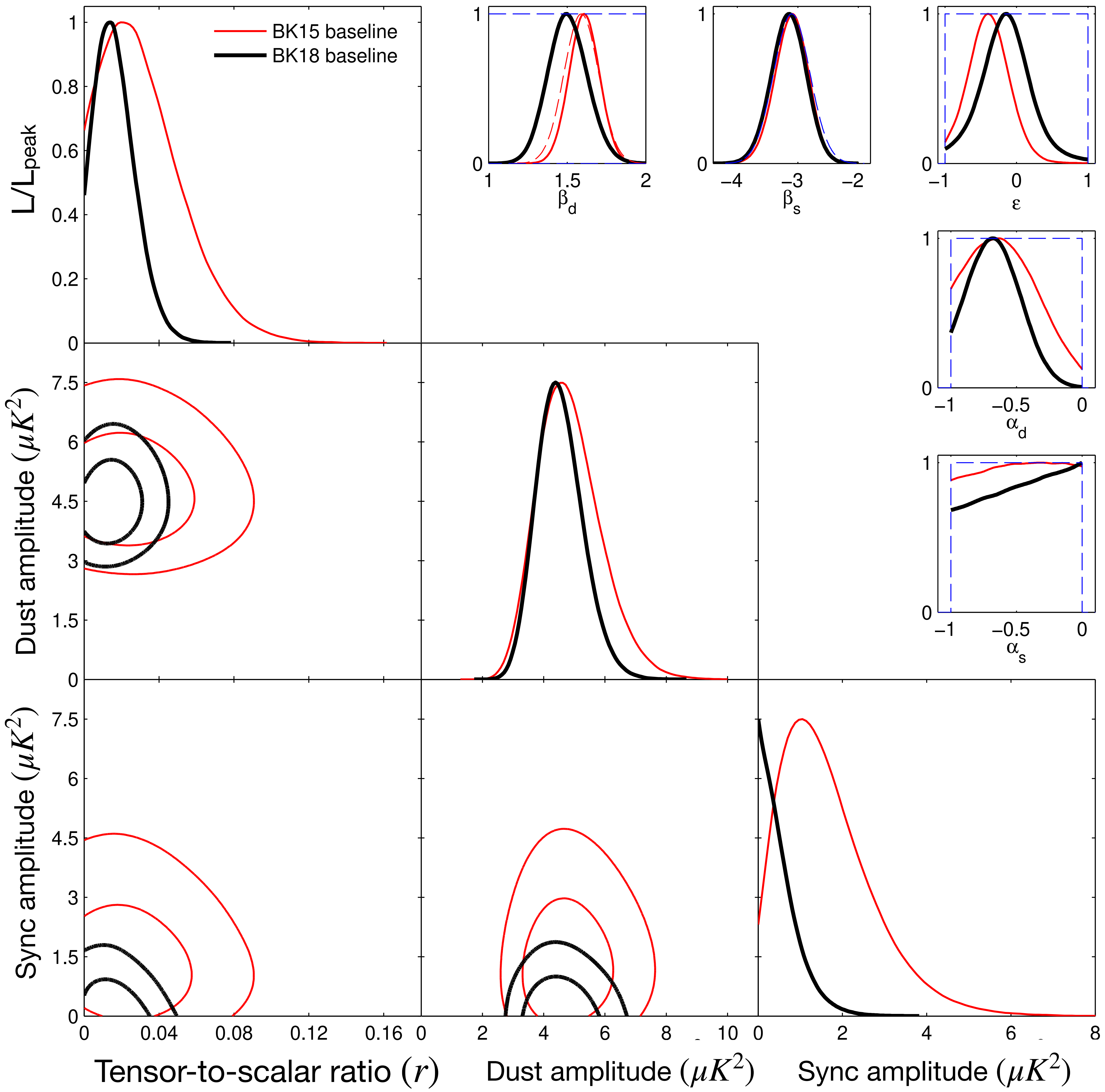
Likelihood Model

Jointly constrains r, CMB lensing amplitude, dust, synchrotron



Oct 2021 result

r < 0.036

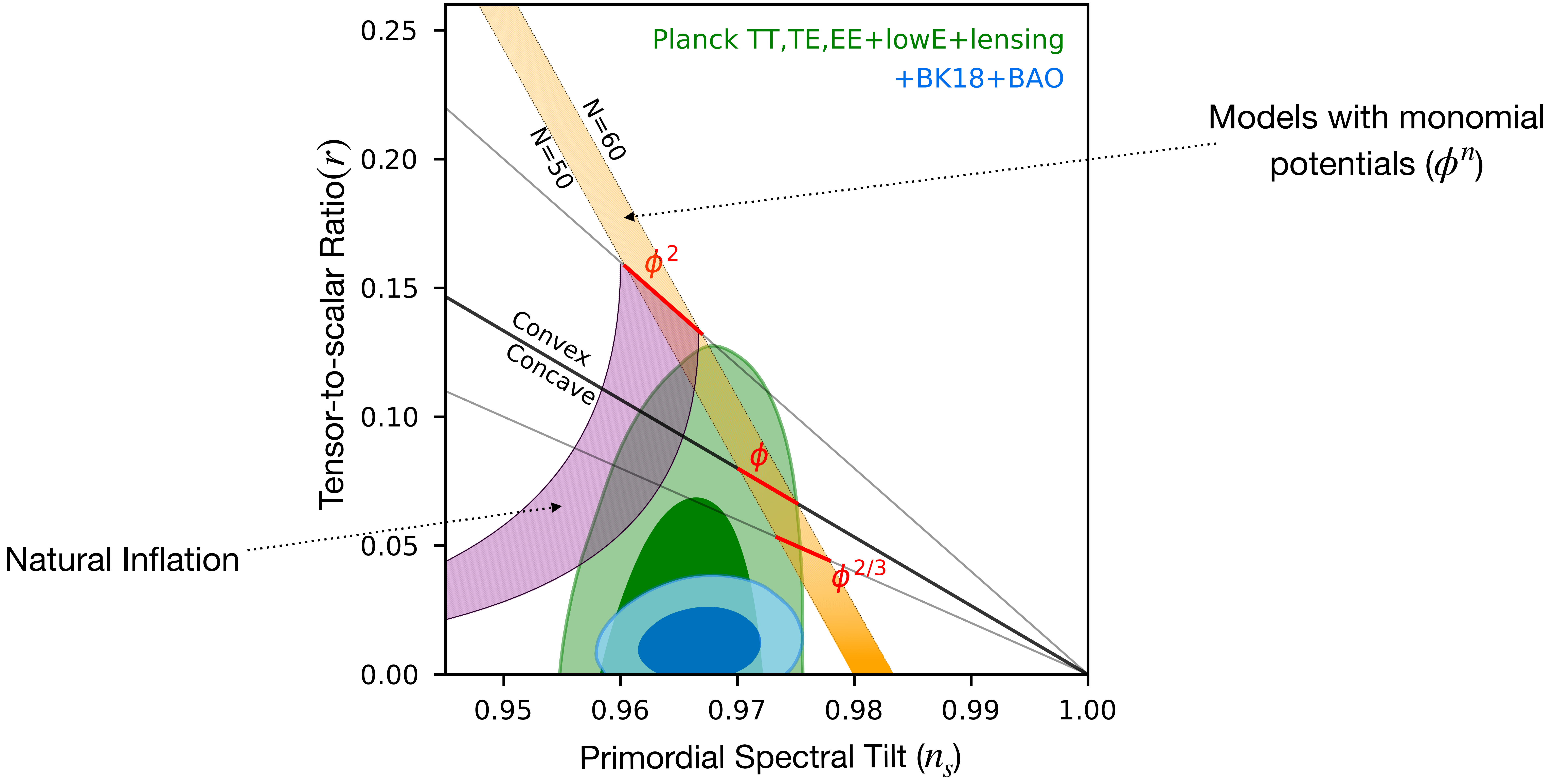
(95% C.L.)

$\sigma(r) \sim 0.01$

BICEP/Keck Collaboration, PRL 127, 151301 (2021)

What do these results mean for inflation?

Single-field slow-roll inflation models with monomial potentials* ruled out

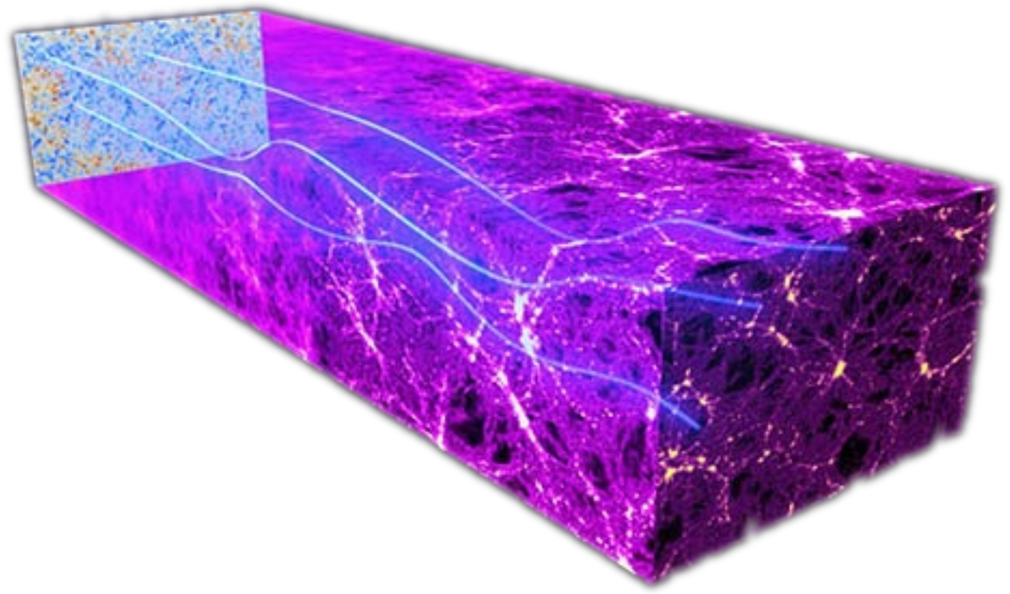


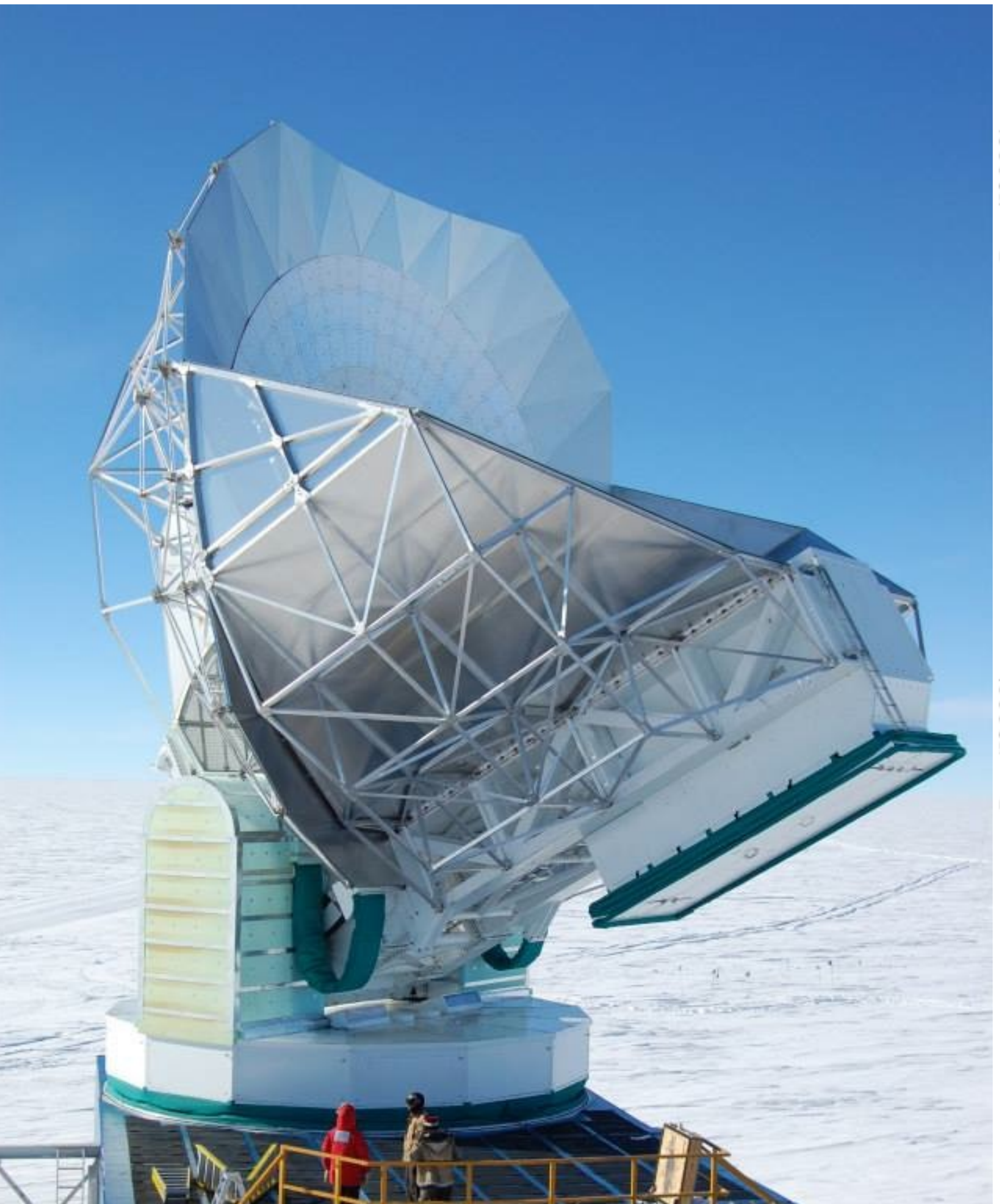
*= with canonical kinetic terms

BICEP/Keck Collaboration, PRL 127, 151301 (2021)

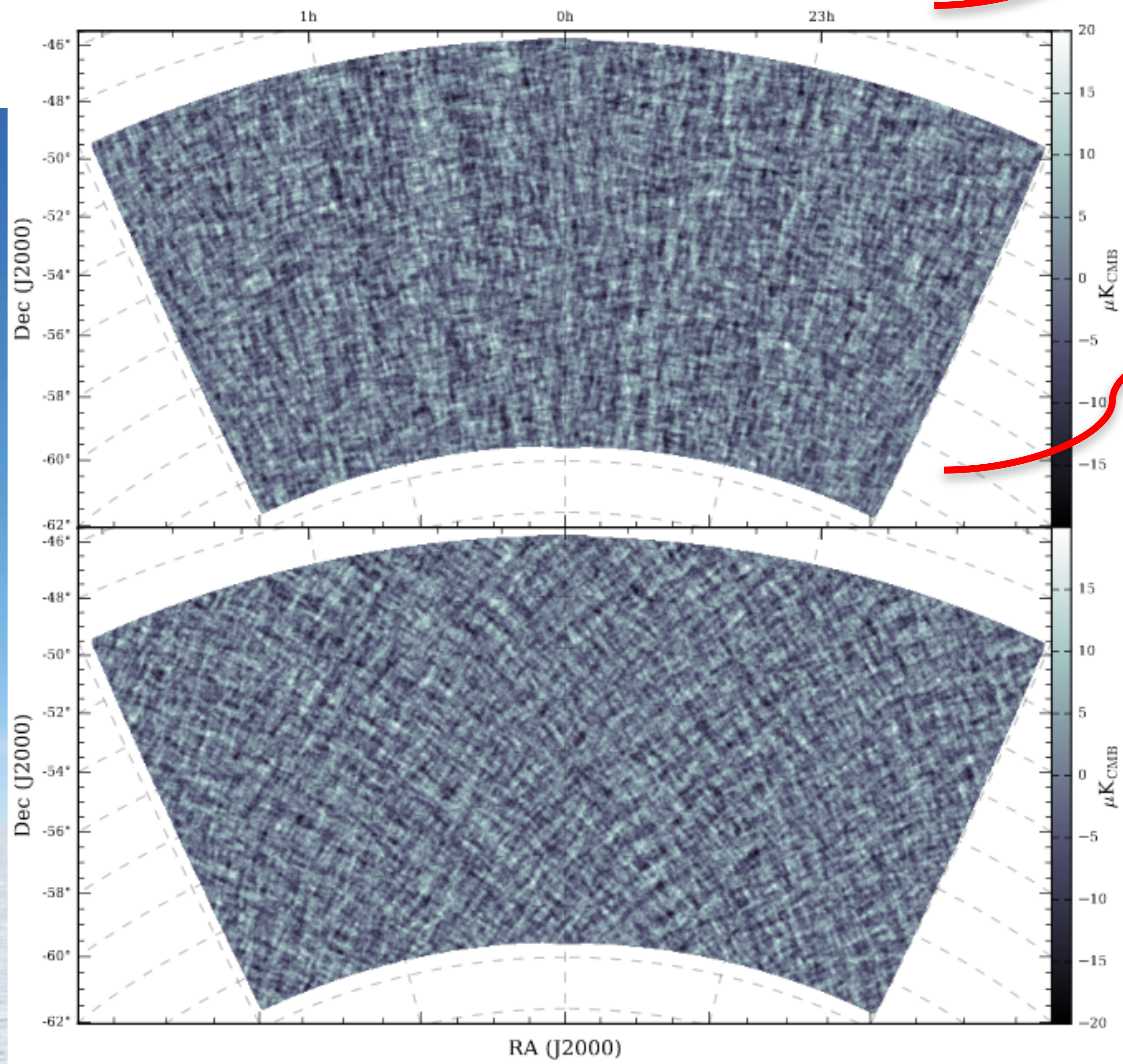
Improve $\sigma(r)$ by measuring lensing B-modes

SPT-3G will provide “de-lensing”

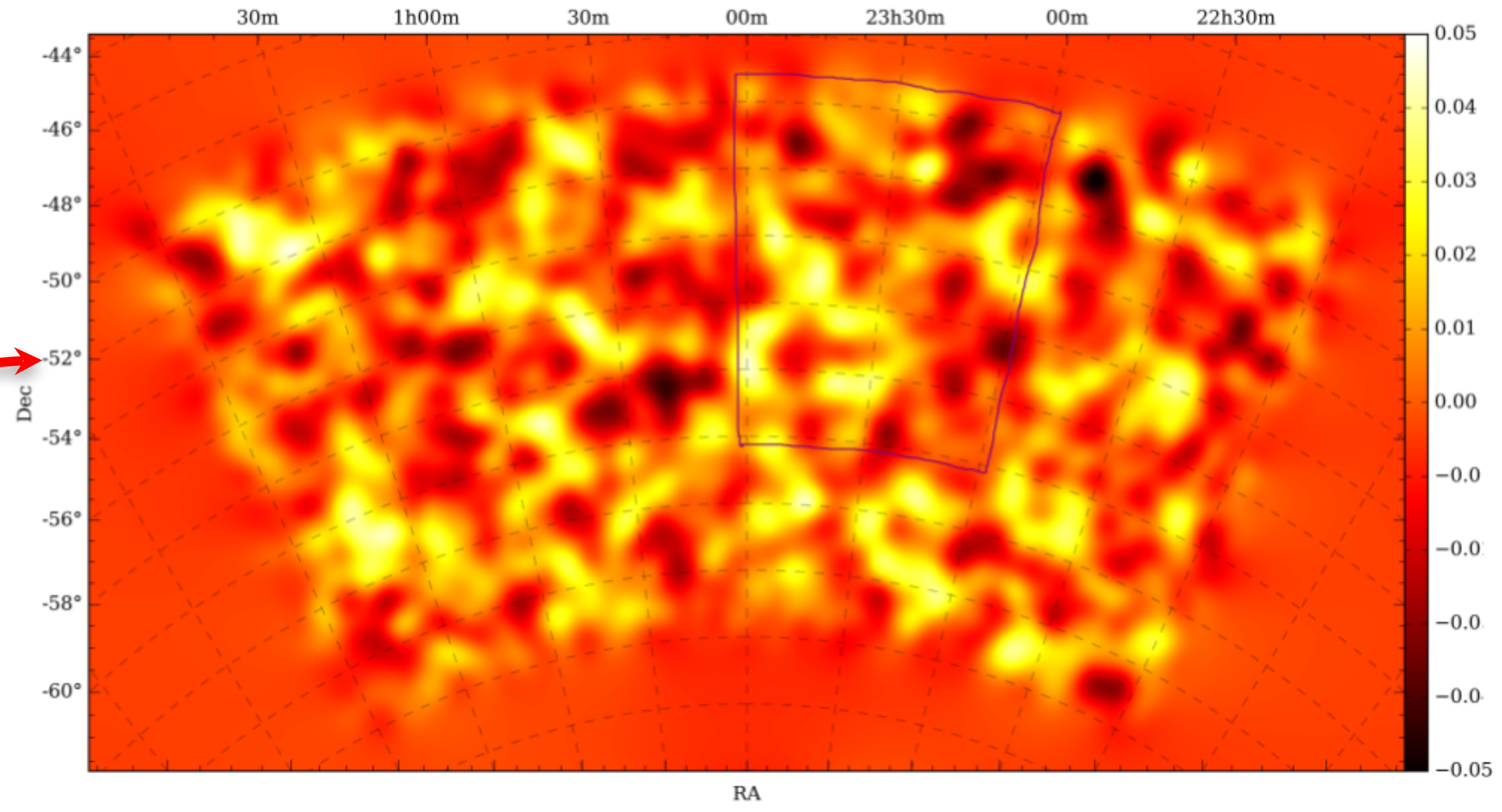




High resolution maps



Can be used to reconstruct the lensing deflection map…



…which can then be used to calculate and remove the lensing signal and improve $\sigma(r)$

BICEP + SPT = South Pole Observatory (SPO)

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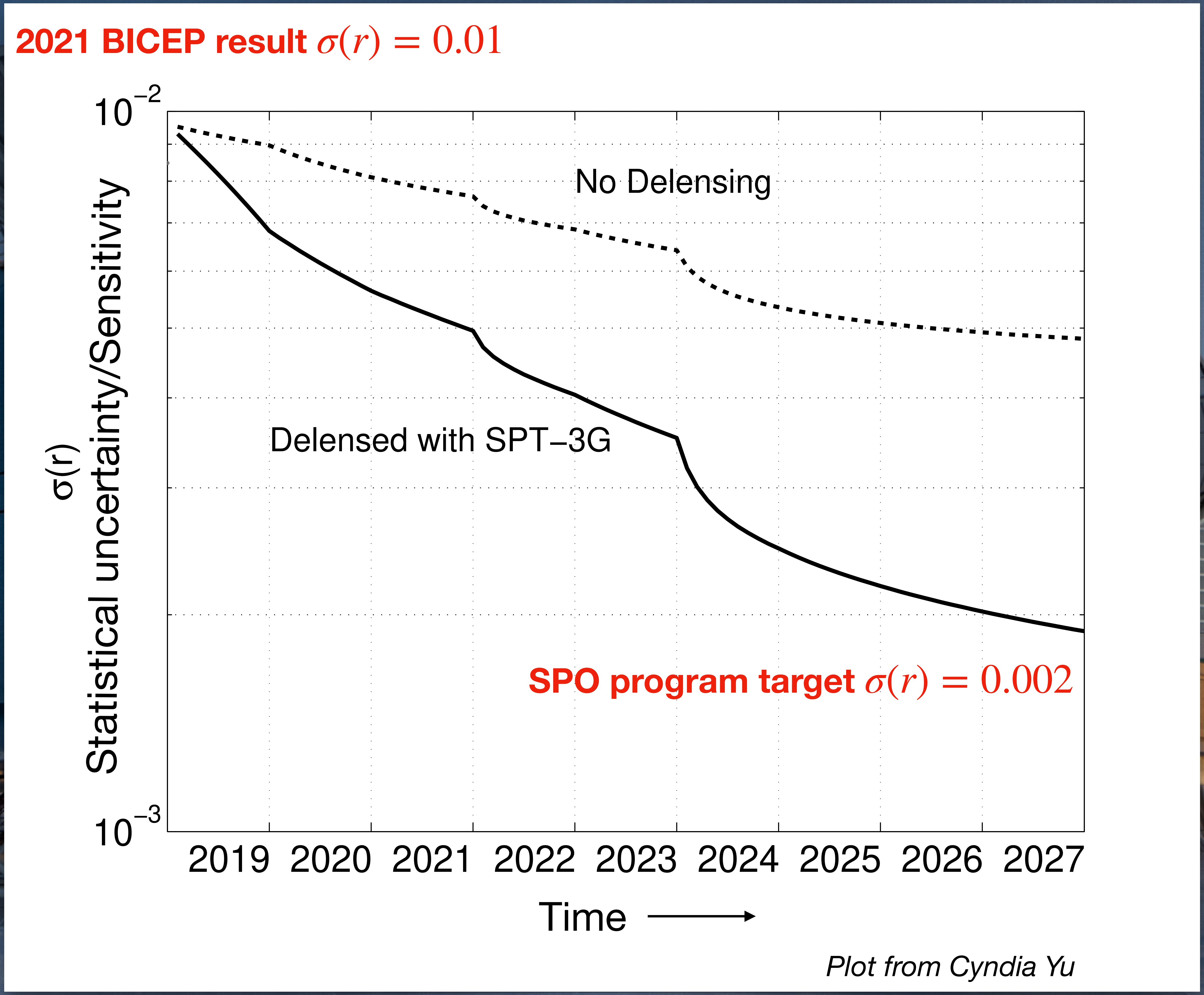
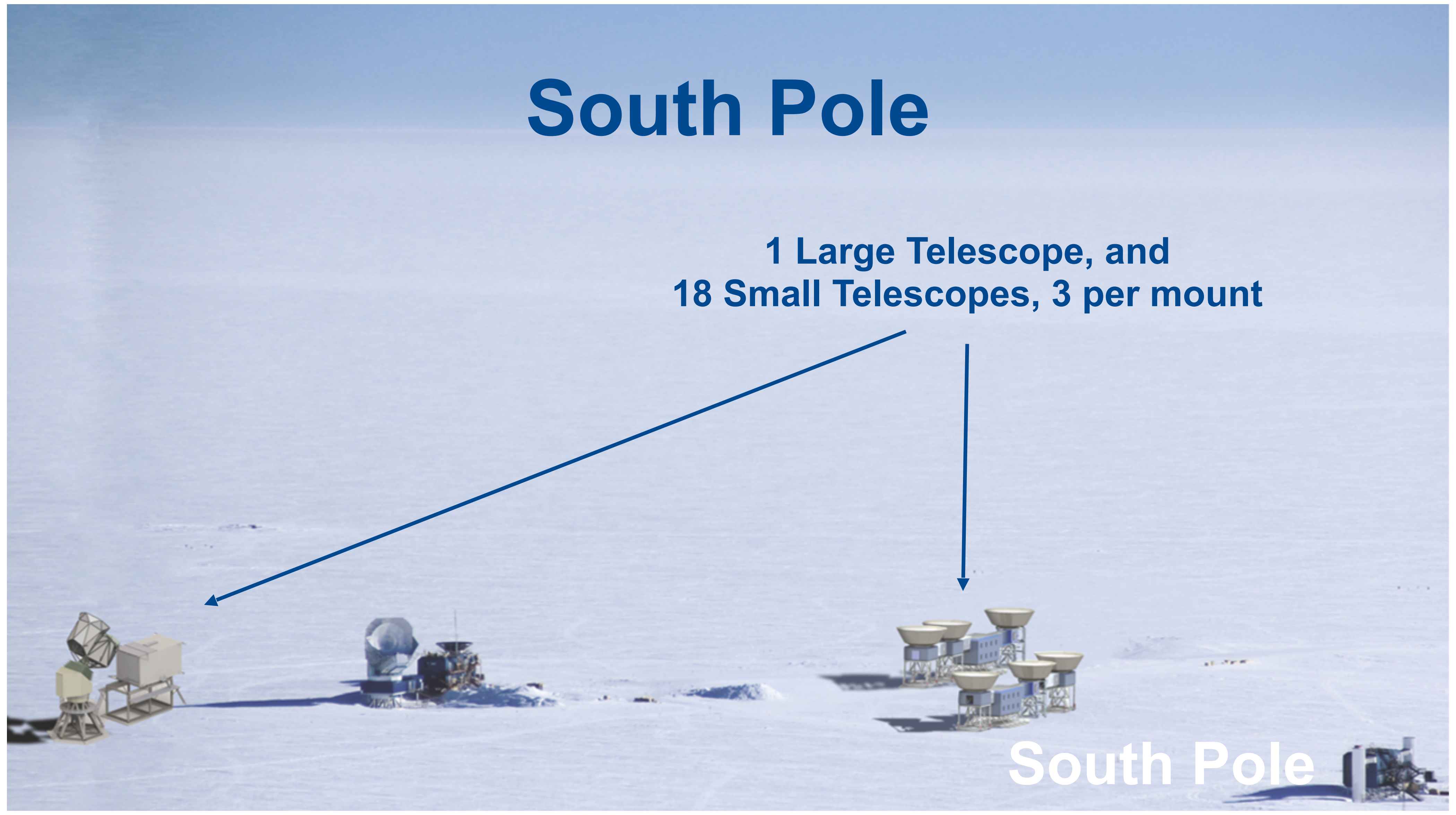
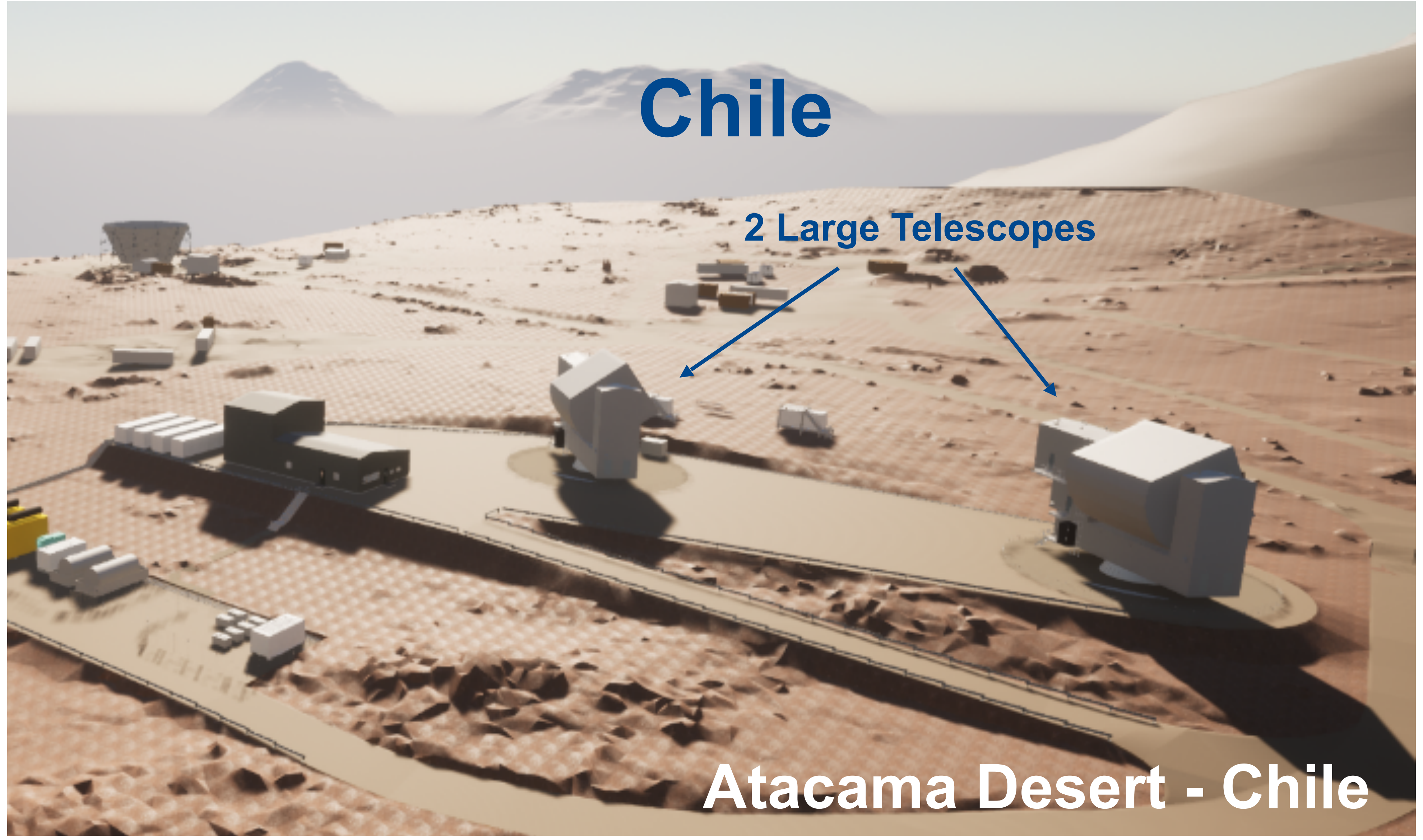


CMB-S4 Collaboration,
arXiv:1610.02743
arXiv:1706.02464
arXiv:1907.04473

CMB-S4

The ultimate ground-based CMB survey experiment





Berkeley Lab · The University of Chicago · Argonne National Laboratory · Jet Propulsion Laboratory, California Institute of Technology · The University of Arizona · Michigan State University · Berkeley University of California · University of Minnesota · Caltech · NIST National Institute of Standards and Technology · Case Western Reserve University · UC San Diego · Cornell University · SLAC · Fermilab · Washington University in St. Louis · Harvard University · Yale University · University of Illinois Urbana-Champaign · Center for Astrophysics Harvard & Smithsonian

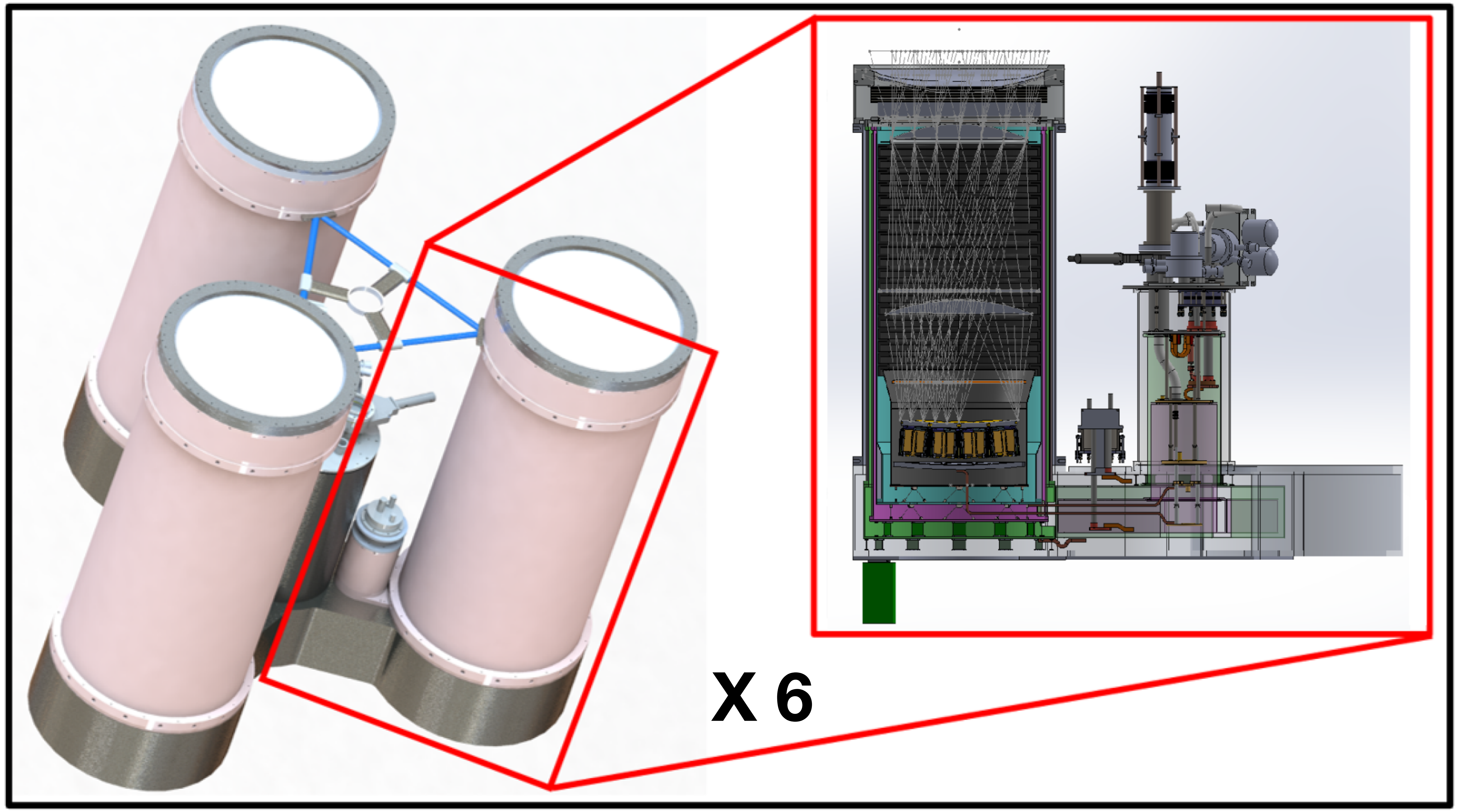
A DOE-NSF joint project to build **21 CMB telescopes at the South Pole and in Chile** incorporating ~**550,000** photon-noise-limited sub-Kelvin, superconducting detectors. **First light in 2032**

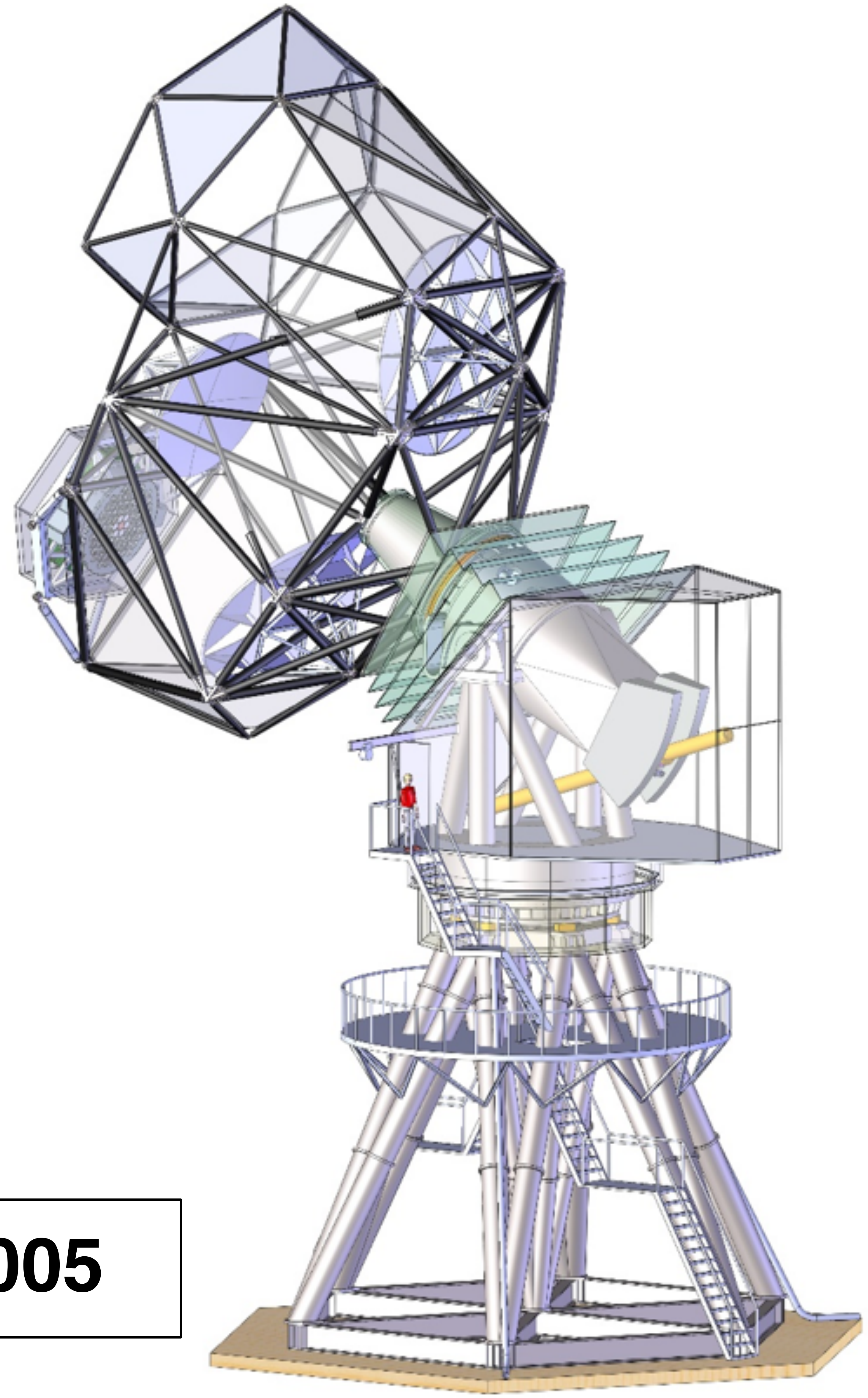
Recommended by last P5, and by Astro2020

Site renderings from CMB-S4 collaboration

CMB-S4 Proposed Inflation survey

18 x BICEP3-style cameras targeting ≥ 3% of sky with and a dedicated **5-m de-lensing telescope**. 280,000 detectors.





Target sensitivity $\sigma(r) = 0.0005$

Renderings from CMB-S4 Project Office

Summary

- Inflation is an attractive solution to plant the primordial seeds of the structure we see today.
- The BICEP/Keck program searches for the signature of inflation-induced primordial gravitational waves in CMB polarization.
- BICEP/Keck has placed stringent constraints on tensor-to-scalar ratio ($r<0.036$) ruling out once popular models with single-field monomial potentials.
- Continue to integrate down, but progress will come from removing lensing contamination using data from SPT-3G.
- Next decade, CMB-S4 will fully explore the parameter space of Lyth Bound, searching for hints of quantum gravity