News from the BICEP/Keck CMB program

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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

Radius of the Visible Universe

Quantum Fluctuations

Big Bang

Inflation

Protons Formed

Nuclear Fusion Begins

Nuclear Fusion Ends

Cosmic Microwave Background

Neutral Hydrogen Forms

Modern Universe

0

10^{-32} s

1 μs

0.01 s

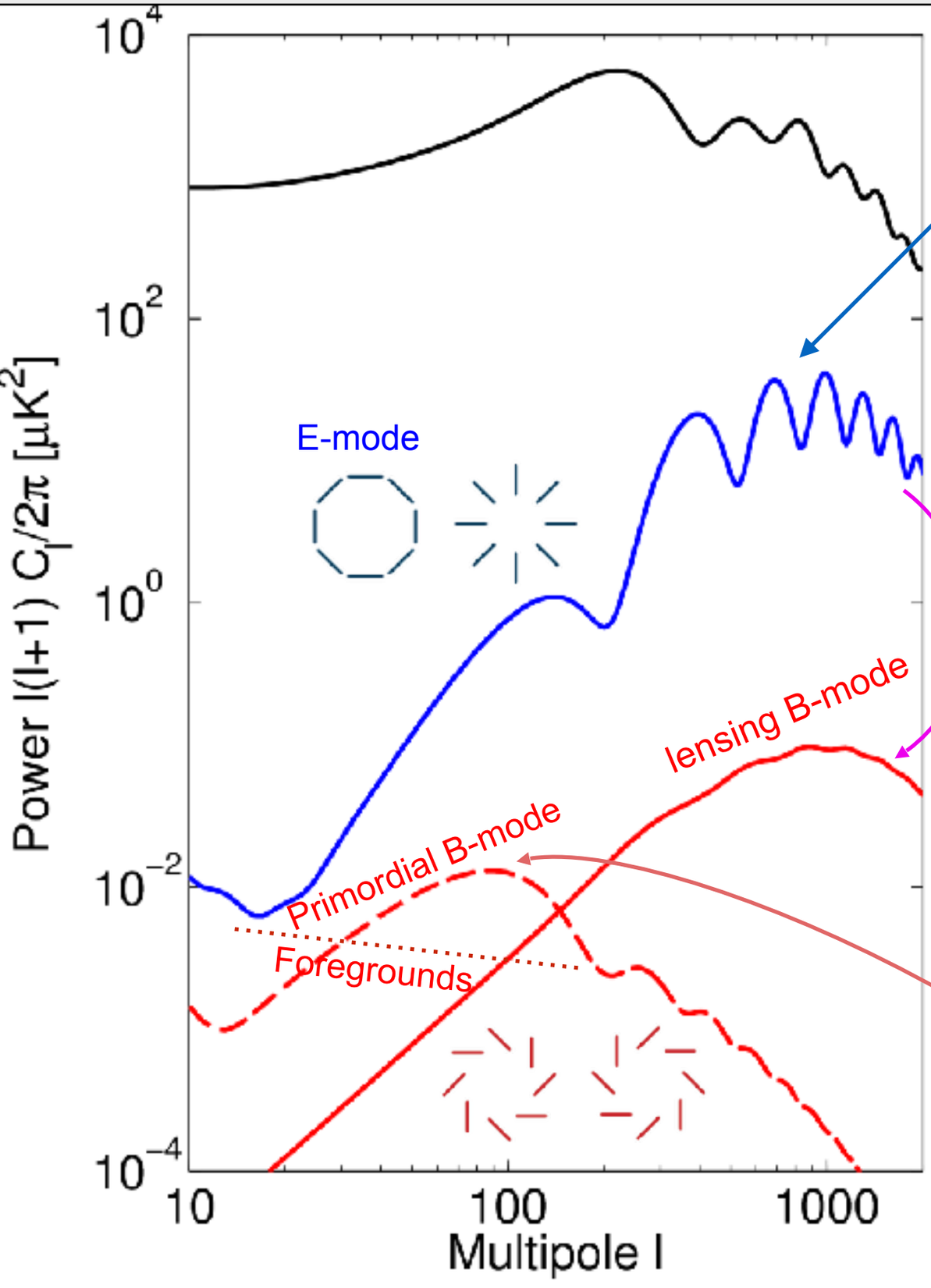
3 min

380,000 yrs

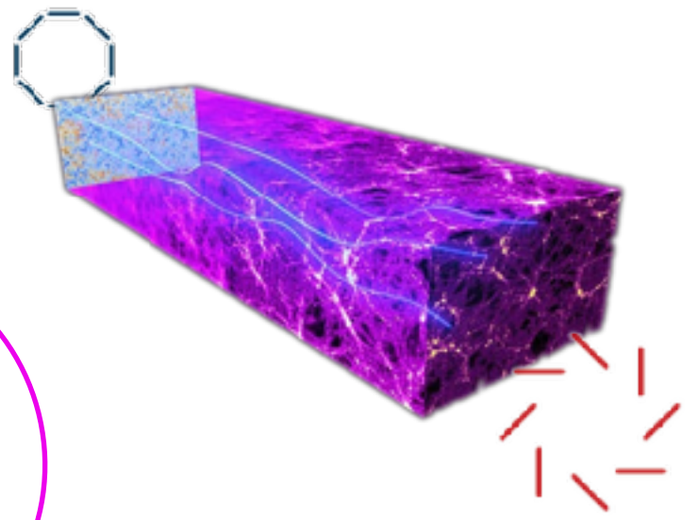
13.8 Billion yrs

Age of the Universe

CMB Polarization anisotropy angular power



In standard ΛCDM only E-modes are present at last scattering

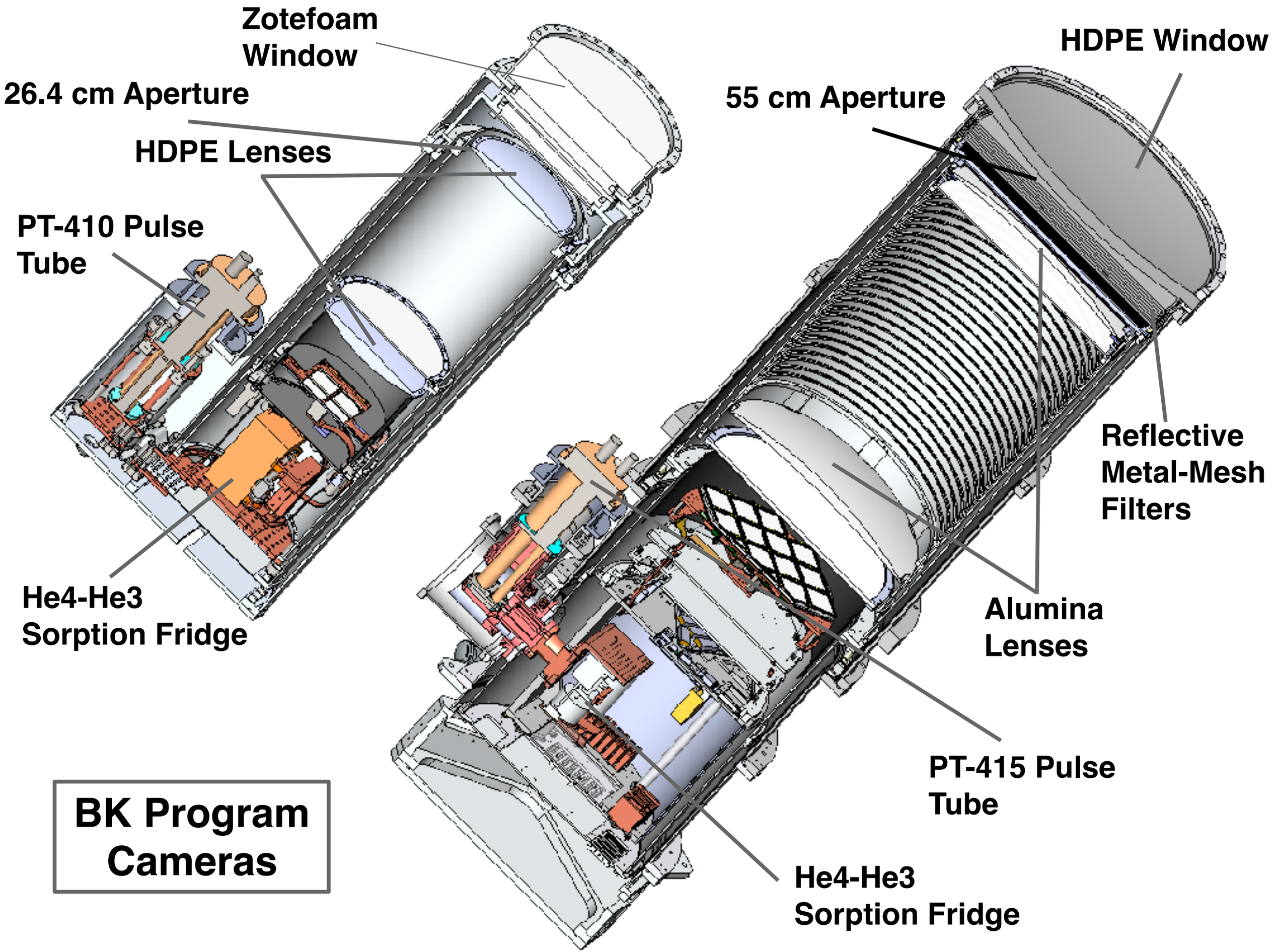


Lensing by intervening structure converts some to B-modes

Inflationary gravity waves produce B-modes peaking at l≈100 : degree scales. Measure tensor-to-scalar ratio, *r*

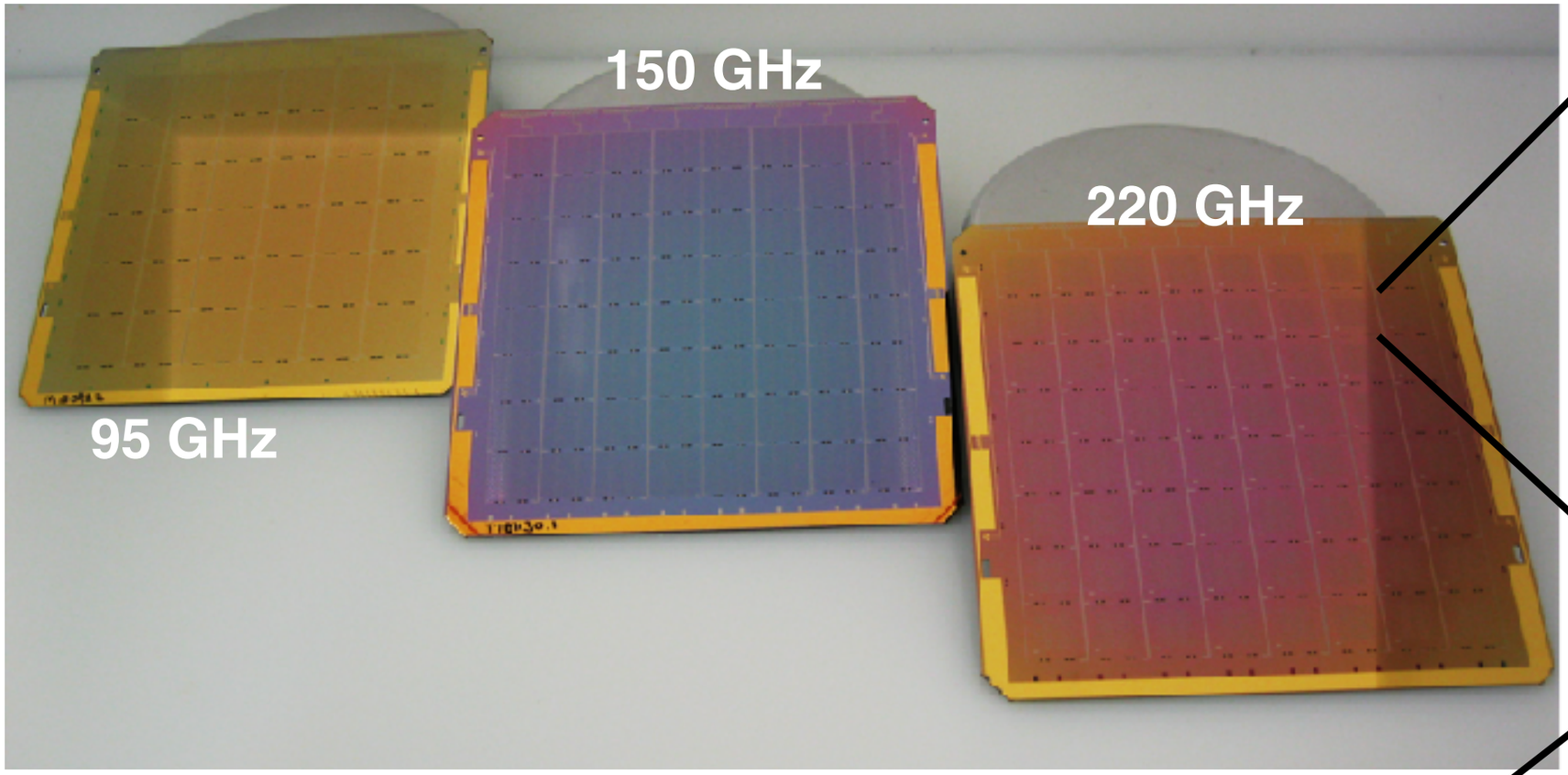
Foregrounds also generate polarized emission. Can be teased apart from different spectral dependence cf CMB

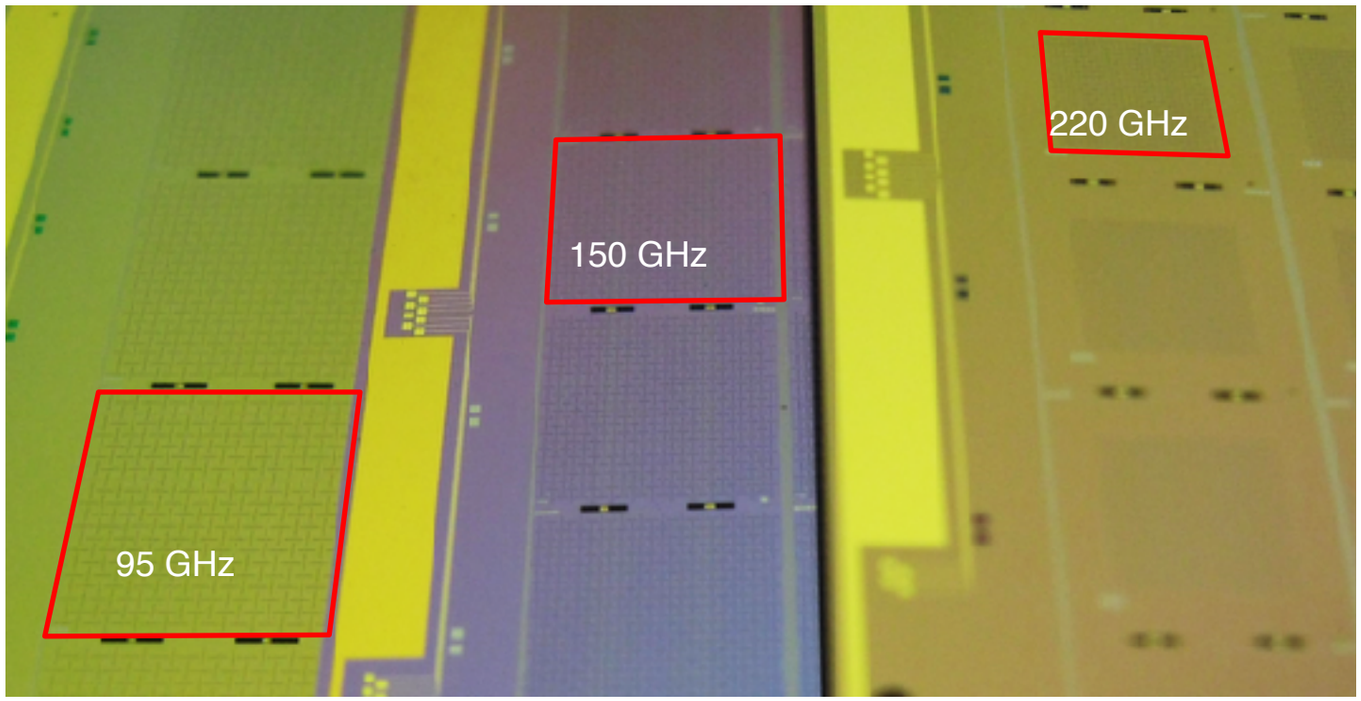

NEPAL
N27°42' E 85°18'

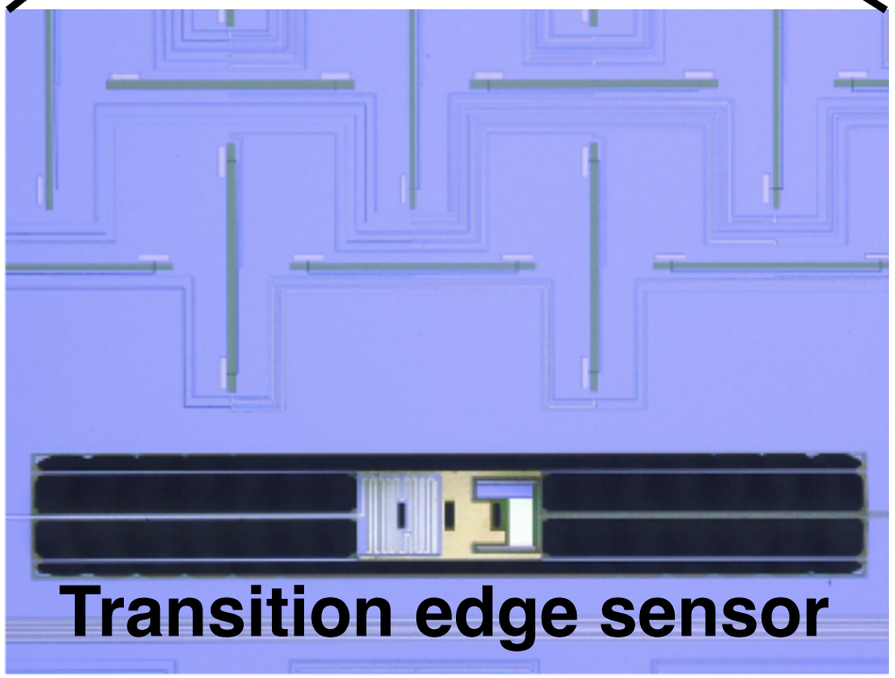


BK Program Cameras

Antenna-coupled TES detectors at multiple frequencies







Stage 2

Stage 3

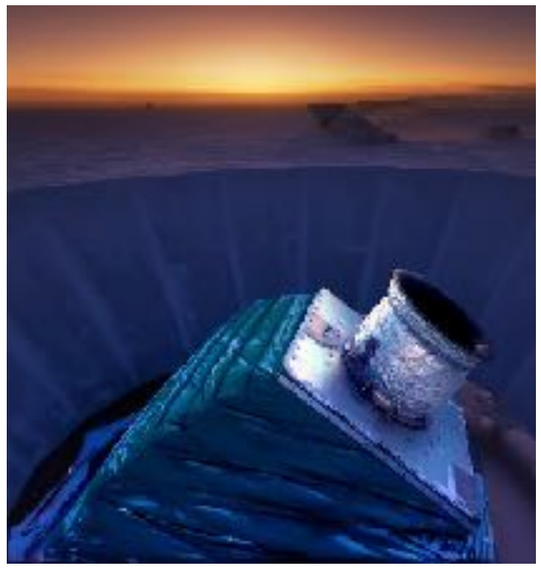
BICEP2
(2010-2012)

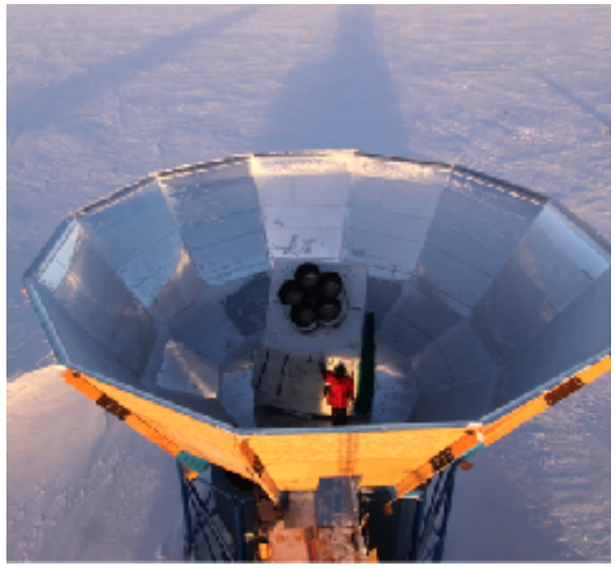
Keck Array
(2012-2017)

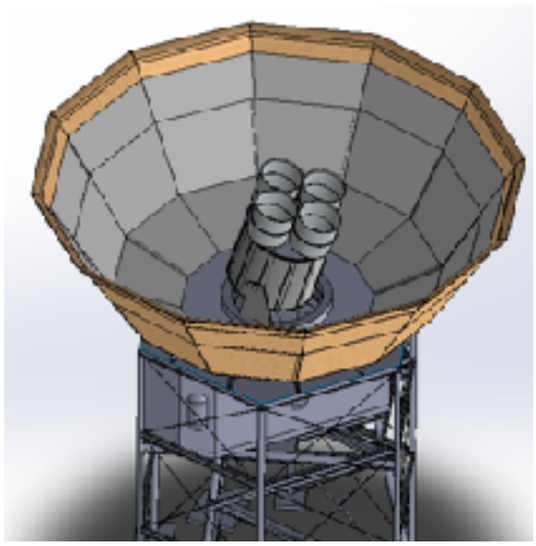
BICEP3
(2015-)

BICEP Array
(2018-)

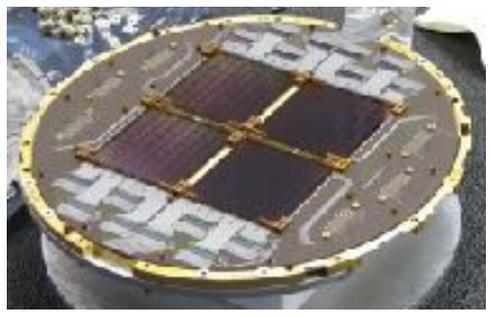
Telescope and Mount



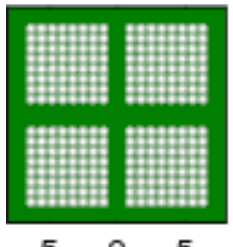


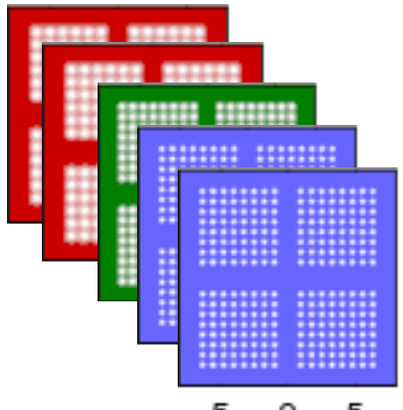


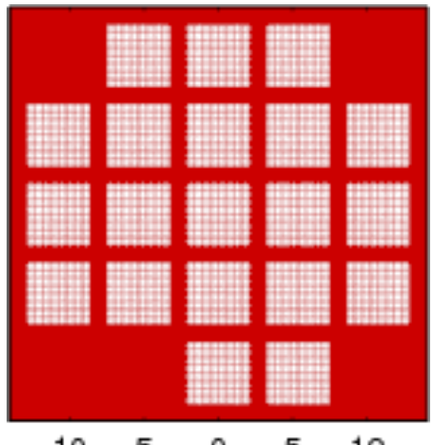
Focal Plane

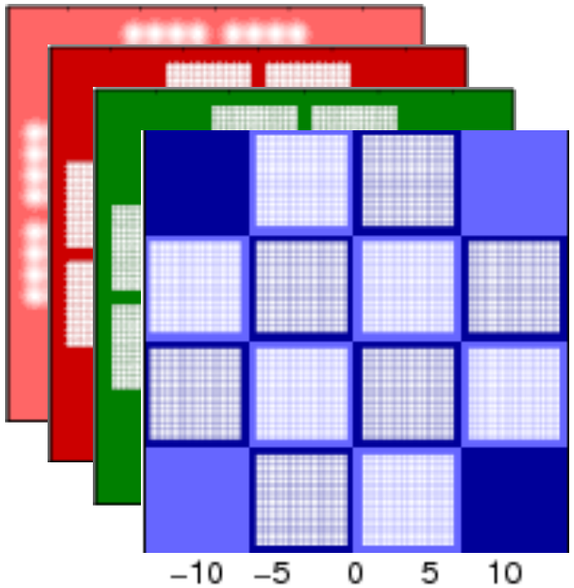


Beams on Sky









Situated at a high, dry desert

BICEP2/3

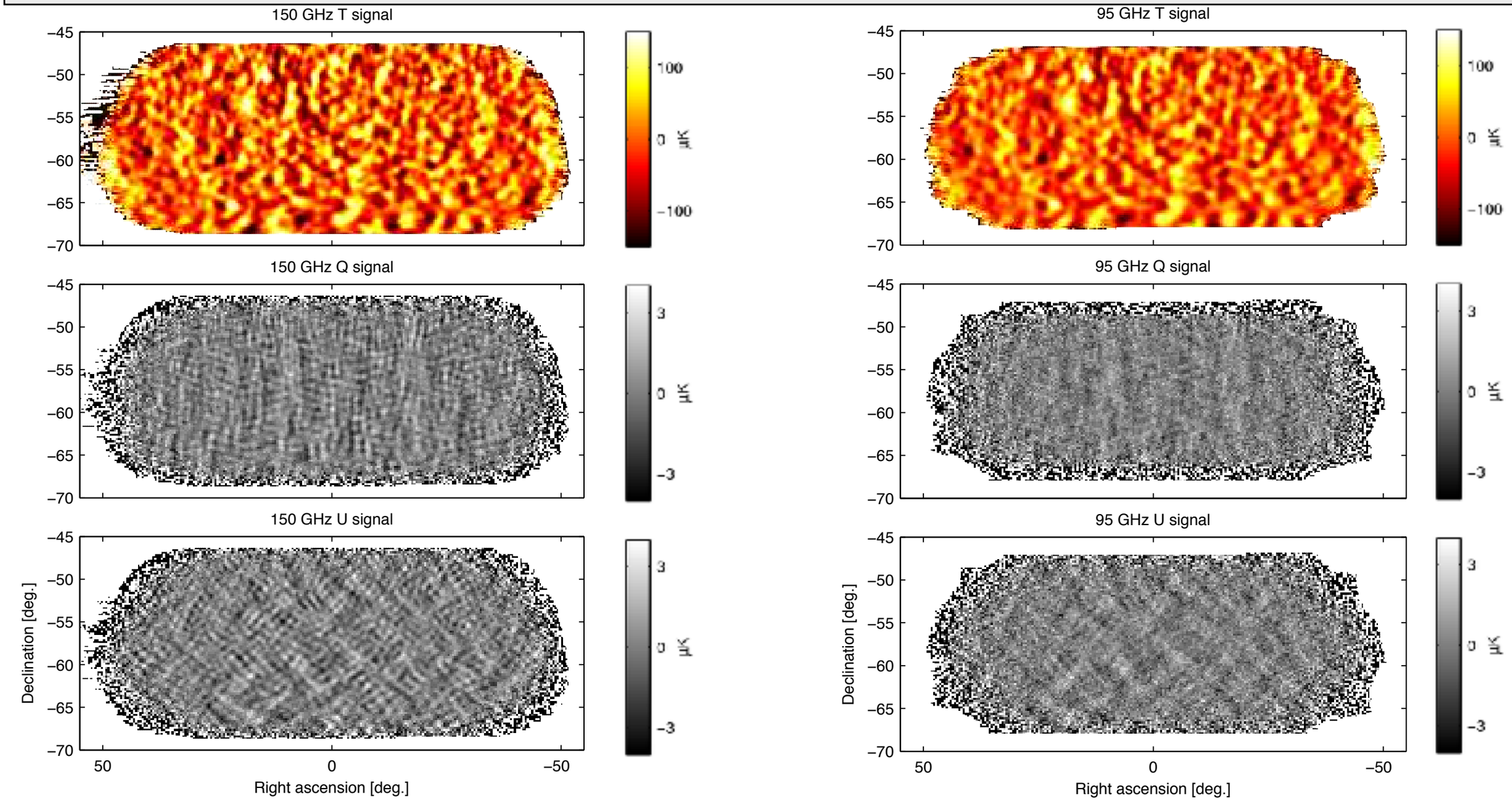
Keck Array

South Pole Research Station, Antarctica

~10,000ft, ~0.25mm PWV

6 months of cold, stable winter sky with uninterrupted integration

BICEP2+Keck through 2014 (150 + 95 GHz)



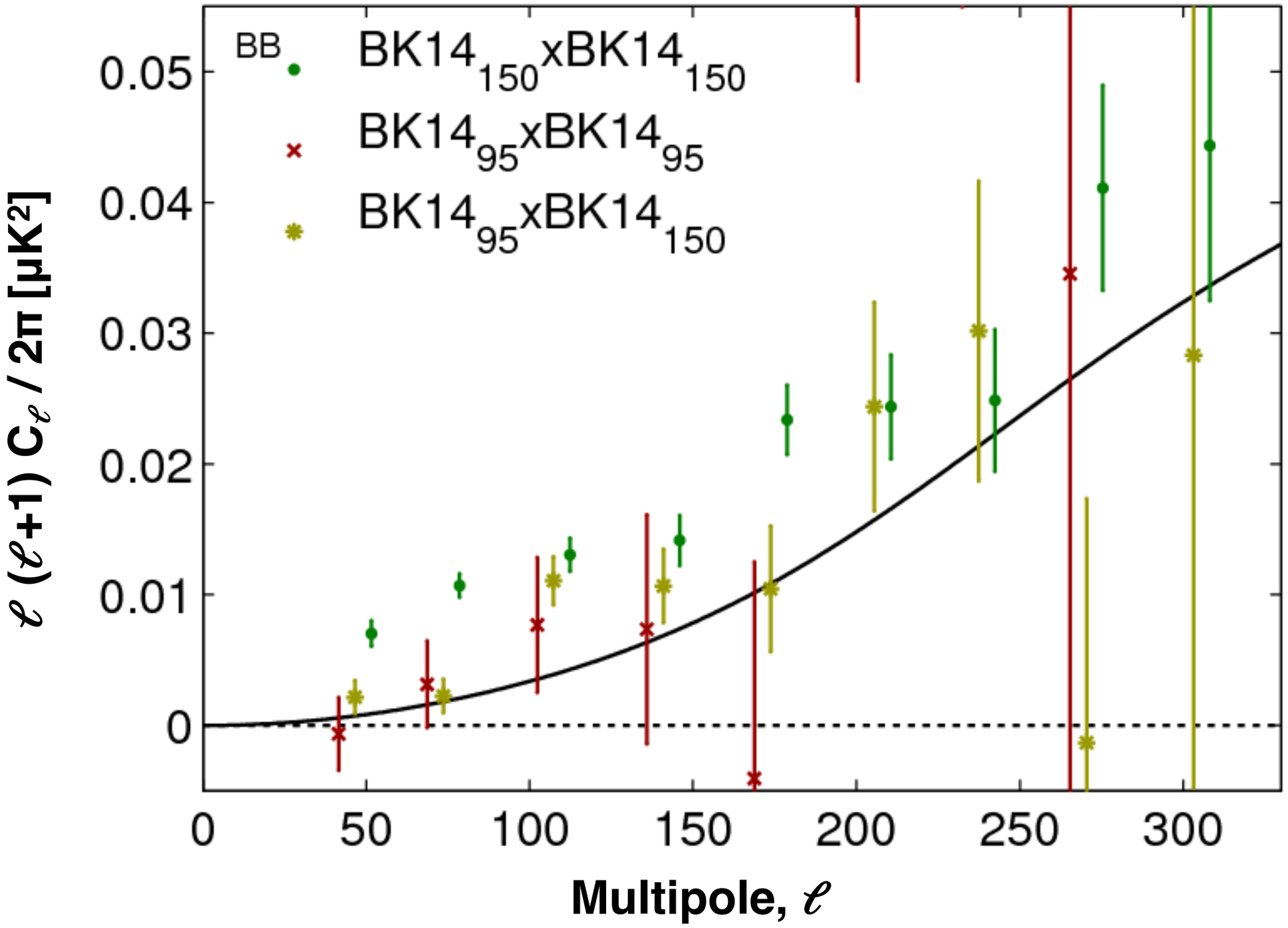
B2 + Keck thru 2014 (150 GHz) → Final map depth: 3.0 μK'

Keck 2014 (95 GHz)→ Final map depth: 7.6 μK'

Observations focused on ~**400 deg²** patch = 1% of the sky

BK14: PRL 116.031302

BK14 BB Spectra (150x150, 95x95 and 95x150 GHz)



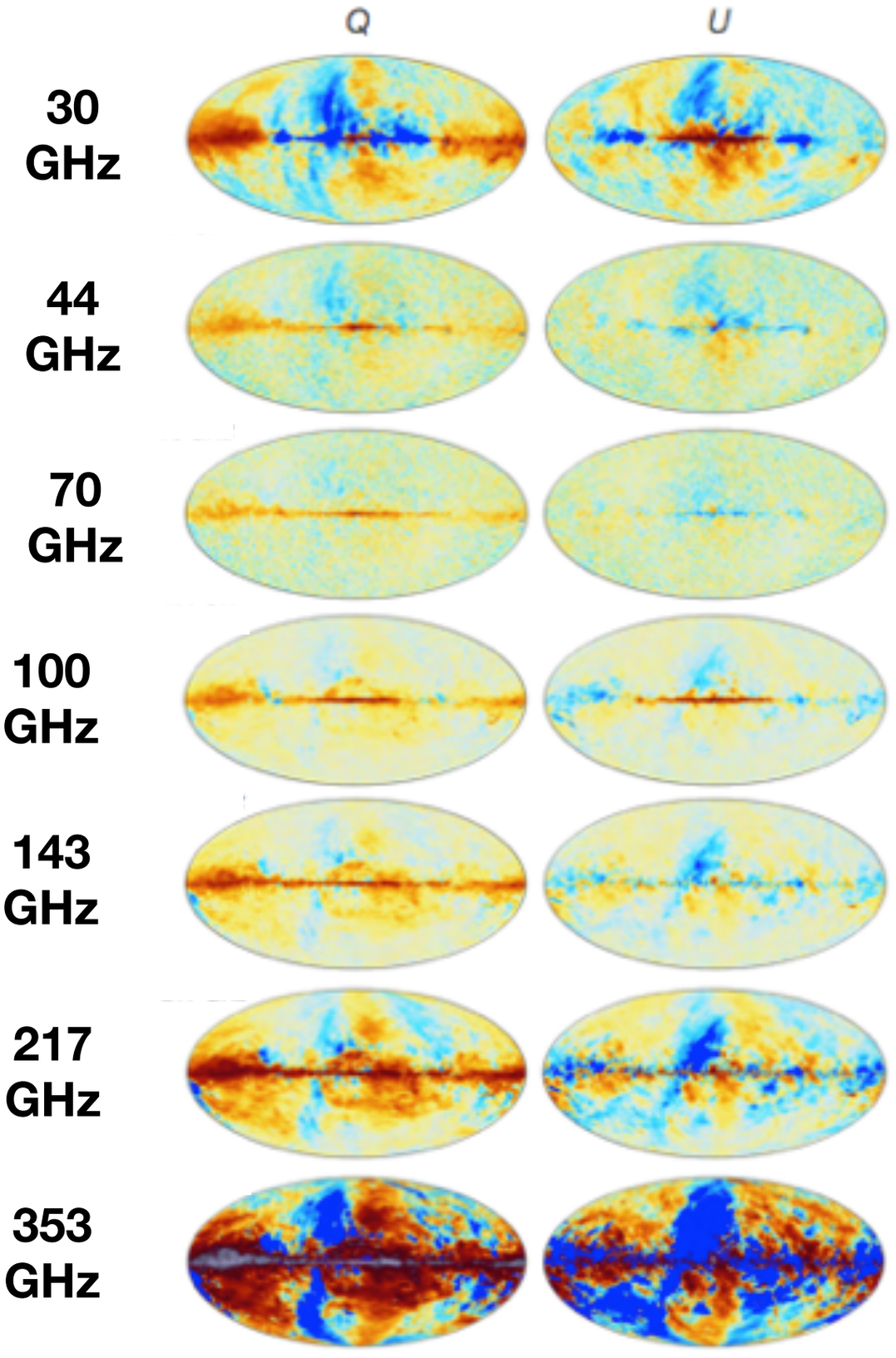
BK14: PRL 116.031302

Add data from Planck and WMAP

Polarized galactic **synchrotron** dominates at low frequencies

Planck provides polarization measurements in 7 other bands at lower S/N, but can be included in analysis. Two WMAP bands as well.

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

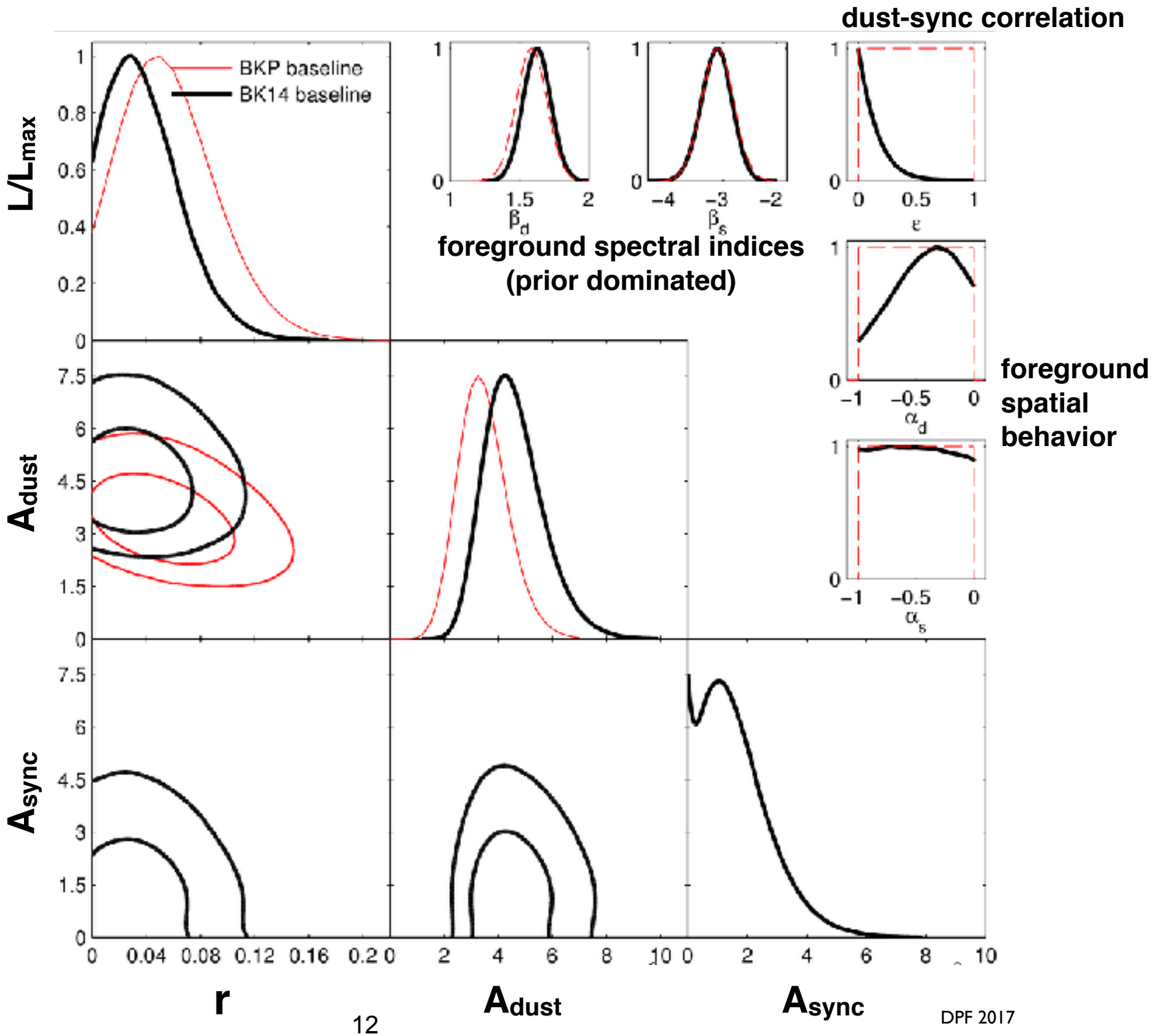


BK14 Parameter constraints

$r_{0.05}$ < 0.09 at 95% confidence

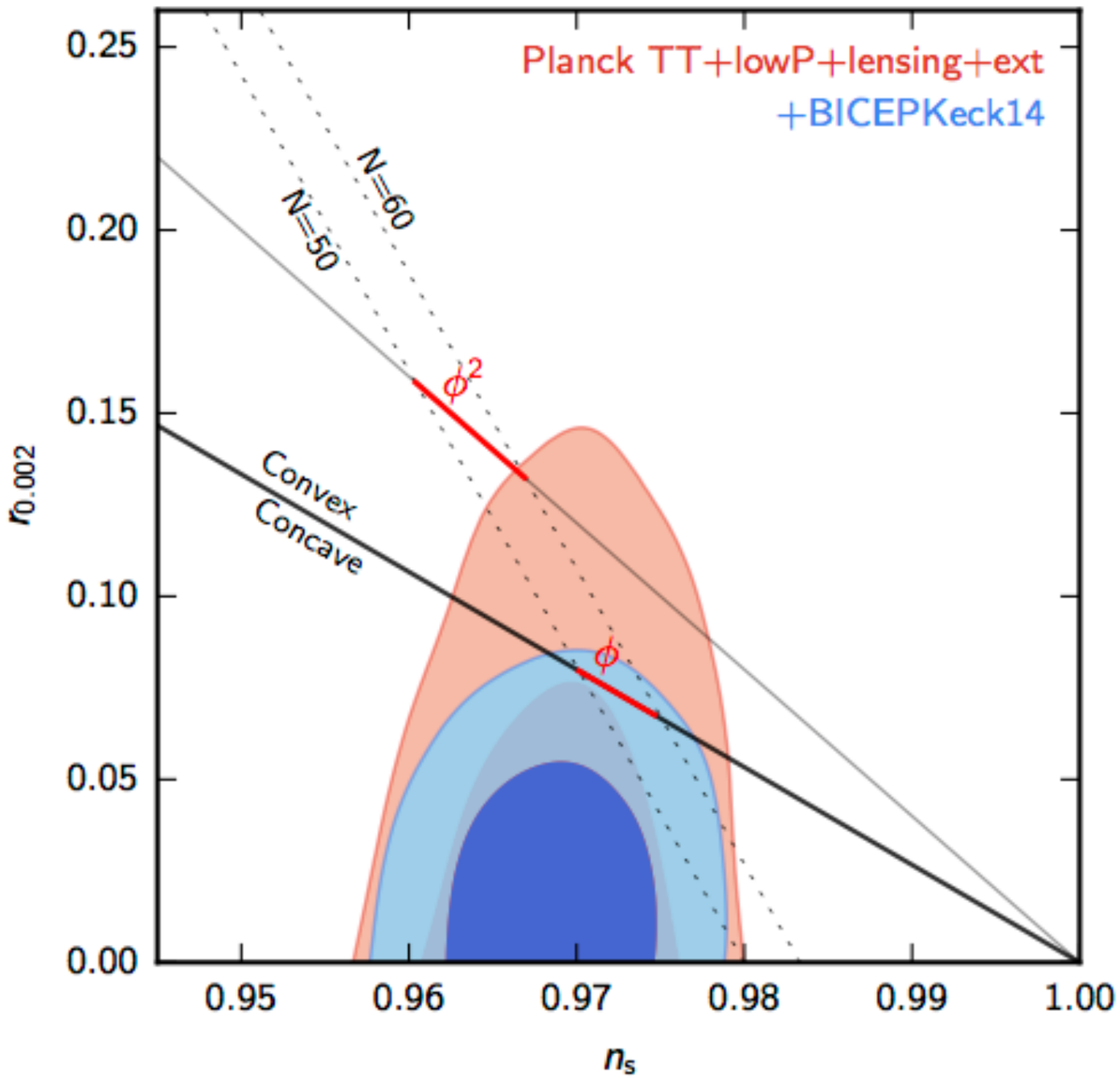
Now beats the best constraints from temperature data

Keck 95 GHz maps help break CMB–dust degeneracy



Constraints on inflation from B modes and T

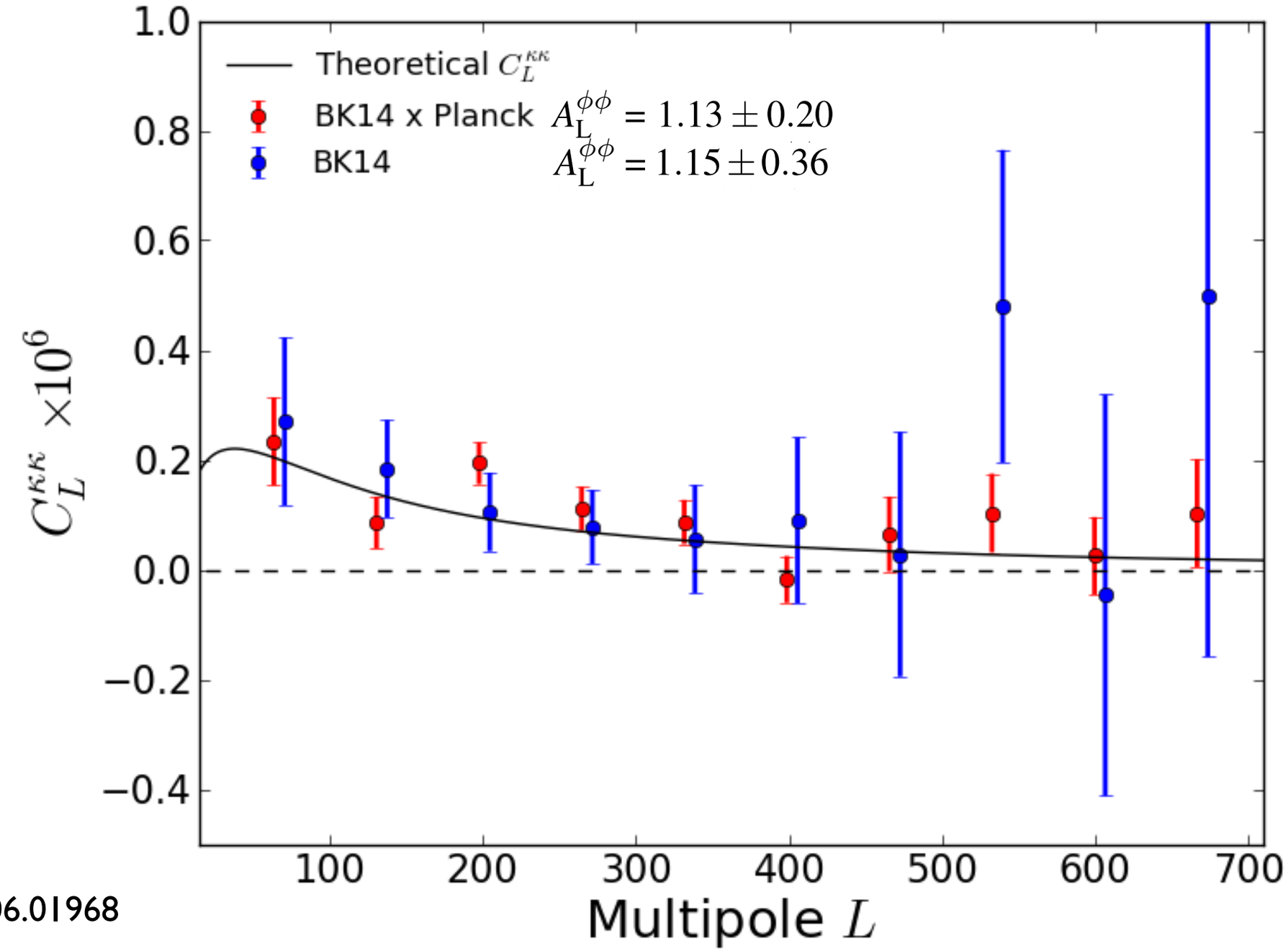
BK14: PRL 116.031302



Combined 95% upper limit: $r_{0.05} < 0.07$

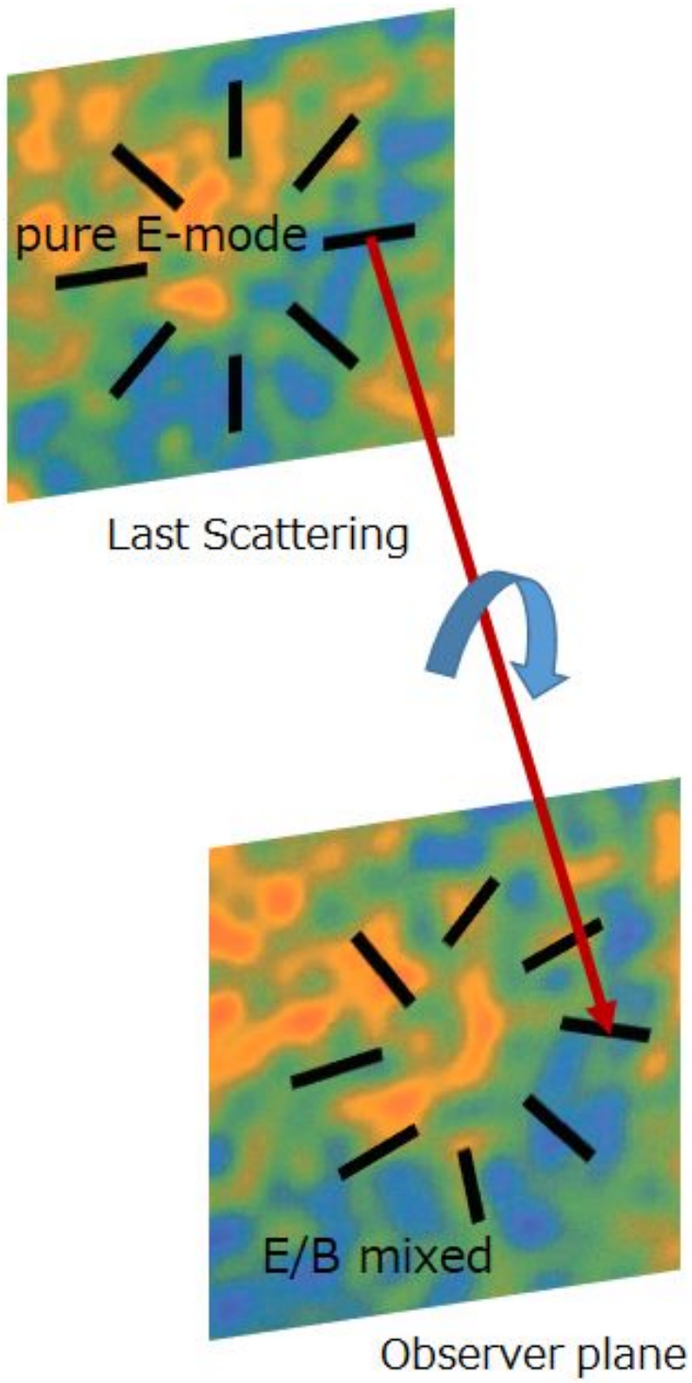
Direct measurement of Gravitational Lensing

Despite modest resolution (0.5°), BK map depth (3μK') makes it possible to directly reconstruct lensing potential ϕ using information at large angular scales only (ell≤700)



arXiv: 1606.01968

Physics from anisotropic cosmic birefringence



- **Axion-like particles**

String theory generally predicts presence of axion-like particles coupled with electromagnetic fields (e.g. Pospelov+'09, Caldwell+'11)

$$\text{Lagrangian} \supset \frac{\phi}{2f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$\frac{1}{f_a}$: Coupling constant

This coupling leads to spatial variation of polarization angle rotation

rotation angle $\alpha(n) = \frac{\Delta\phi(n)}{f_a}$ ← Changes in phi during photon propagation

- **Primordial magnetic fields**

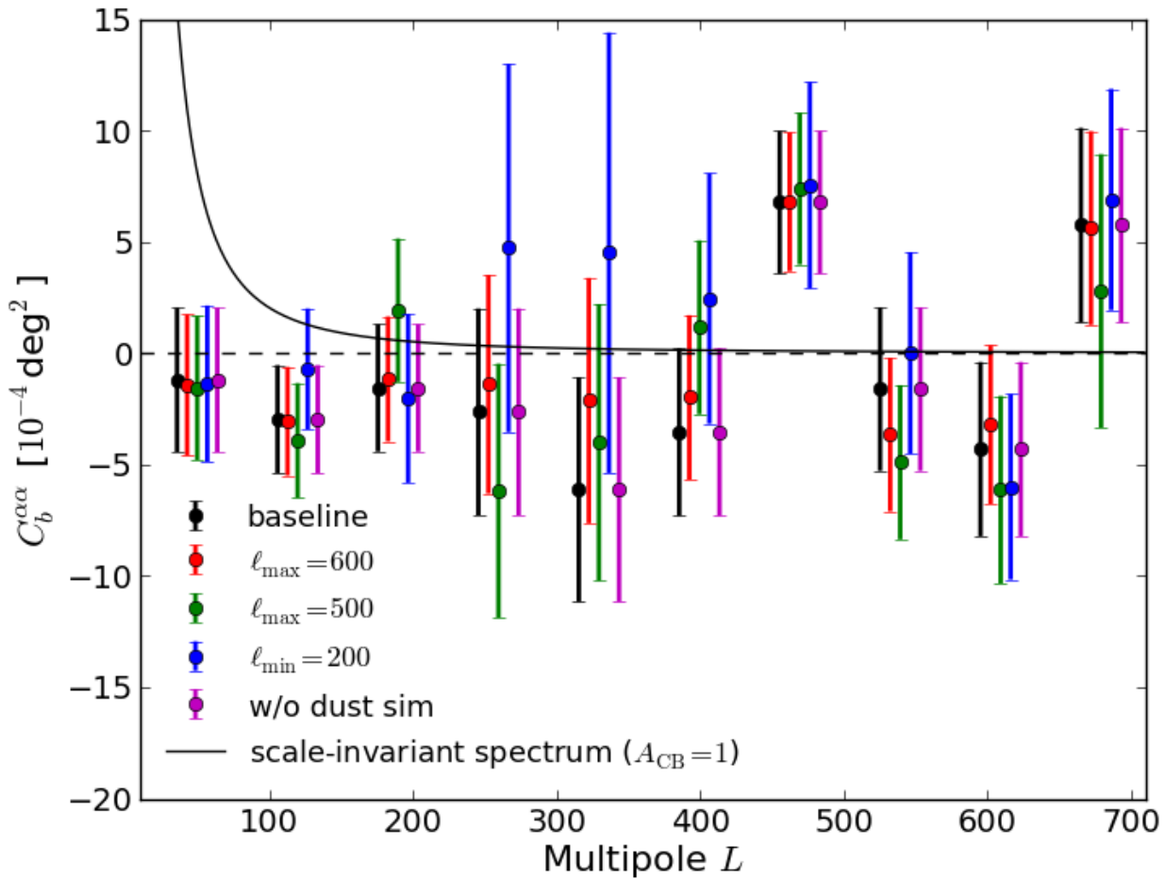
Lead to the polarization rotation by Faraday rotation (e.g. Kosowsky&Loeb'96, Harari+'97)

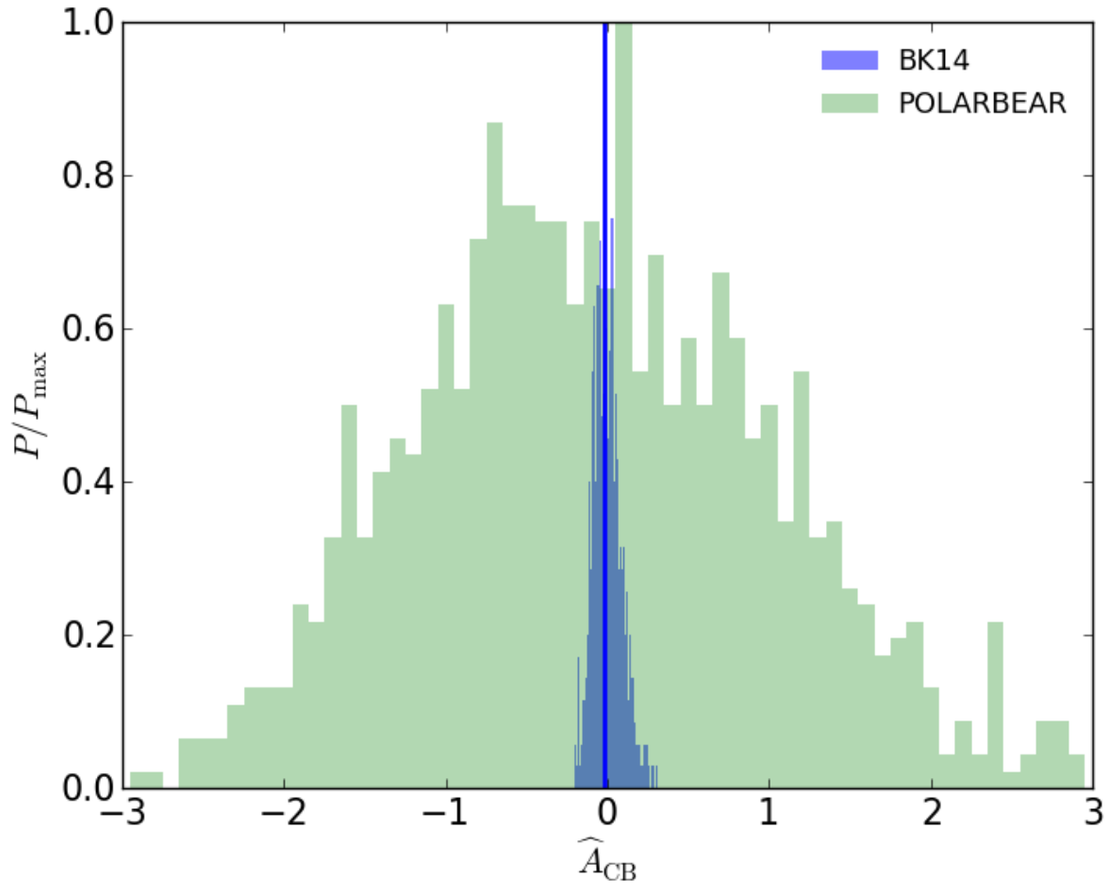
Total rotation angle $\alpha(n) = \frac{3c^2}{16\pi e^2} \nu^{-2} \int \dot{\tau}\, \vec{B} \cdot d\vec{l}$

$\vec{B}$: Magnetic field

Measurement of the anisotropic polarization rotation is a unique probe of the early universe and provides important implications for high energy physics!

Constraints from rotation anisotropy power





Scale-invariant cosmic birefringence amplitude (95%CL)

$$A_{\rm CB} \leq 0.33$$

Chern-Simons coupling of Nambu-Goldstone boson to photons

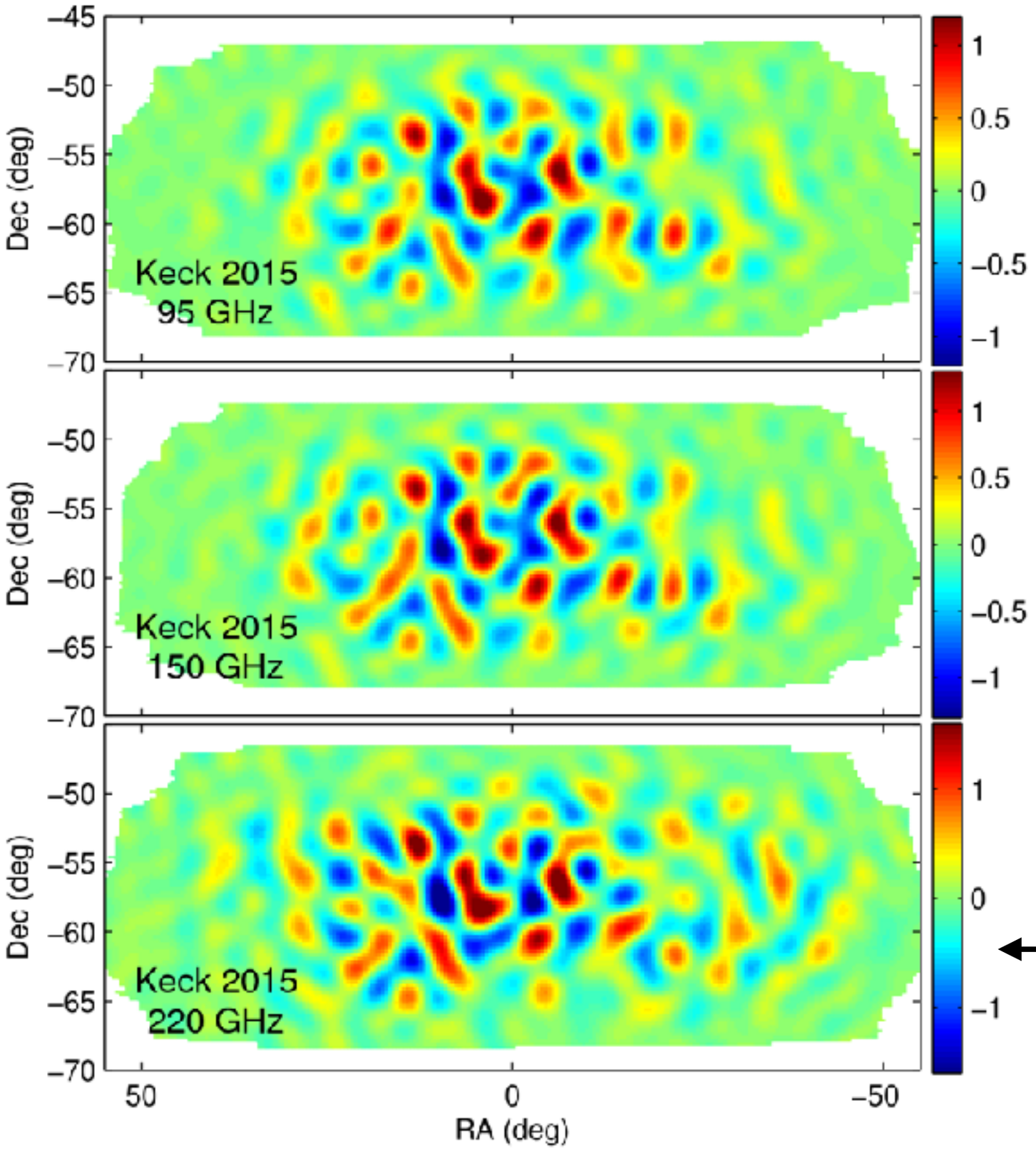
$$f_a \geq 1.7 \times 10^2 \frac{H_I}{2\pi}$$

Primordial Magnetic Fields

$$B_{1Mpc} \leq 30\mathrm{nG}$$

arXiv: 1705.02523

BK 2015 preview



- Include our own 220 GHz data
- Dust decorrelation will be included in likelihood model
- Marginalize over instrumental systematic nuisance parameters
  - T to P leakage from undeprojected beam systematics
  - Uncertainties in band centers

Keck 220 GHz now 3x deeper than Planck 217 GHz!

Stage 2

Stage 3

Keck Array

BICEP Array

BICEP3

270 GHz

220 GHz

40 GHz

95 GHz

30 GHz

150 GHz

BKP

BK14

BK15

A_L=1.0

A_L=0.5

A_L=0.2

Raw Sensitivity

Map Sensitivity [μK–arcmin]

σ(r)

10^2

10^1

10^0

10^{-2}

10^{-3}

2013

2014

2015

2016

2017

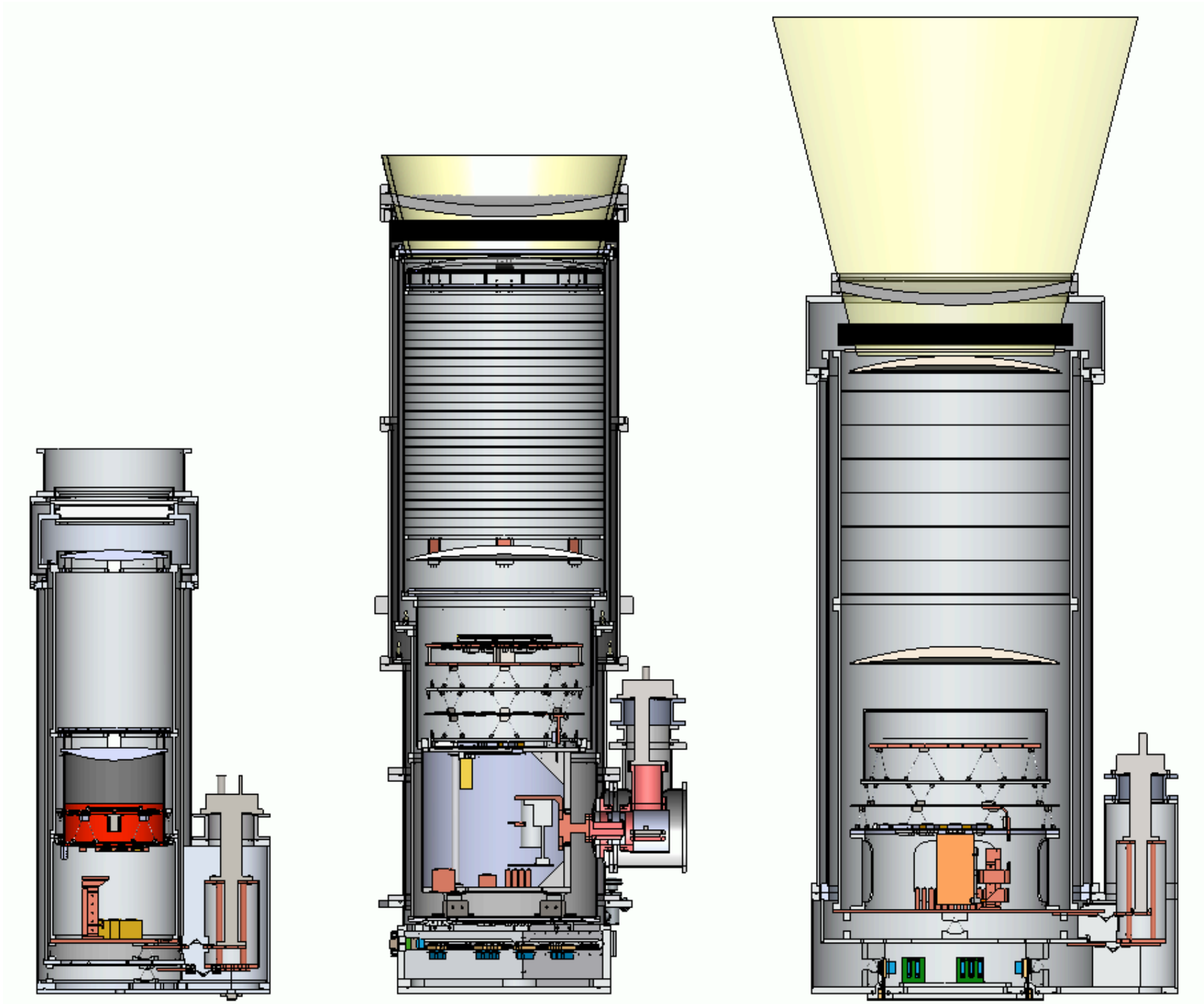
2018

2019

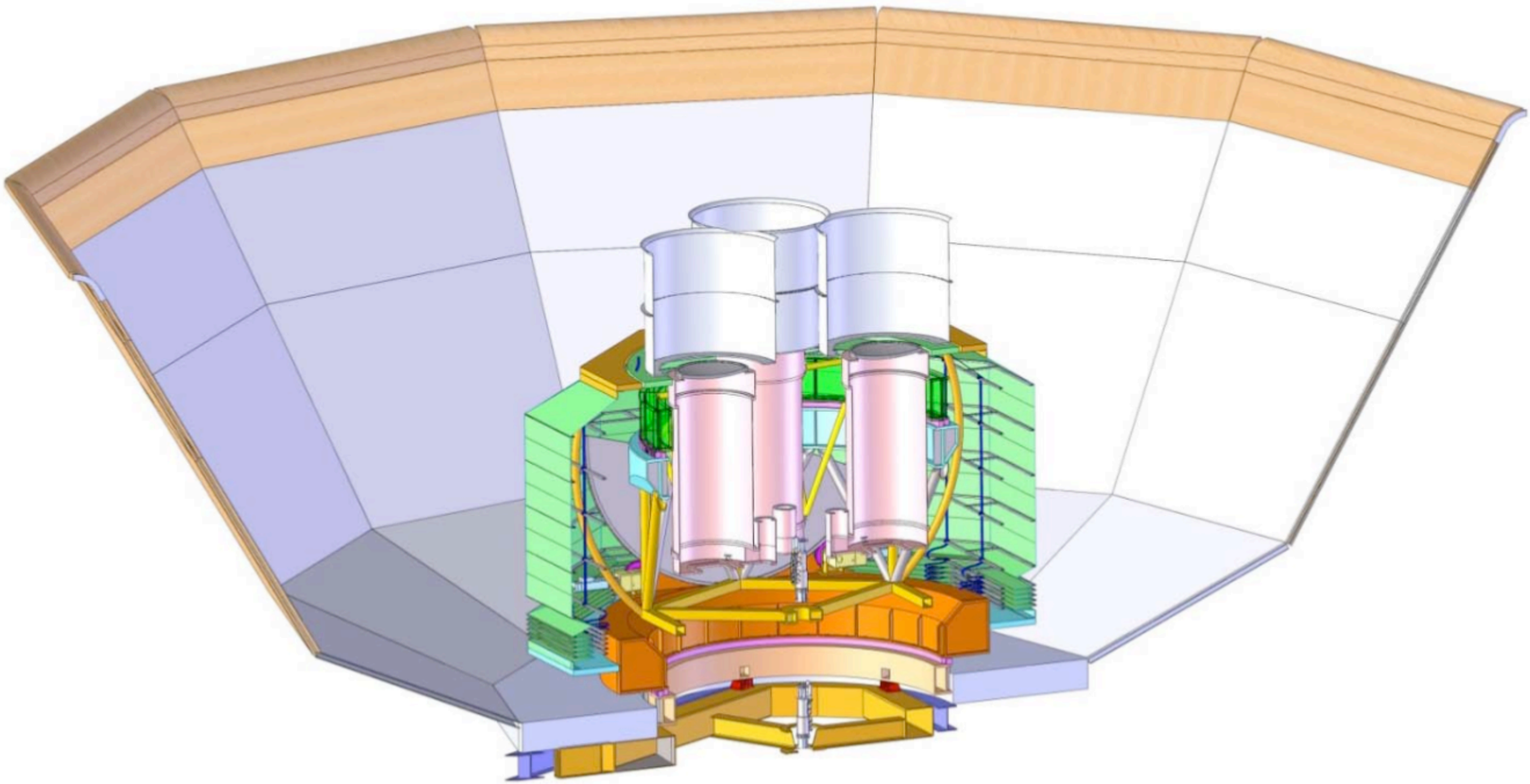
2020

2021

BICEP Array (30k sensors over 30, 40, 95, 150, 220, 270 GHz)

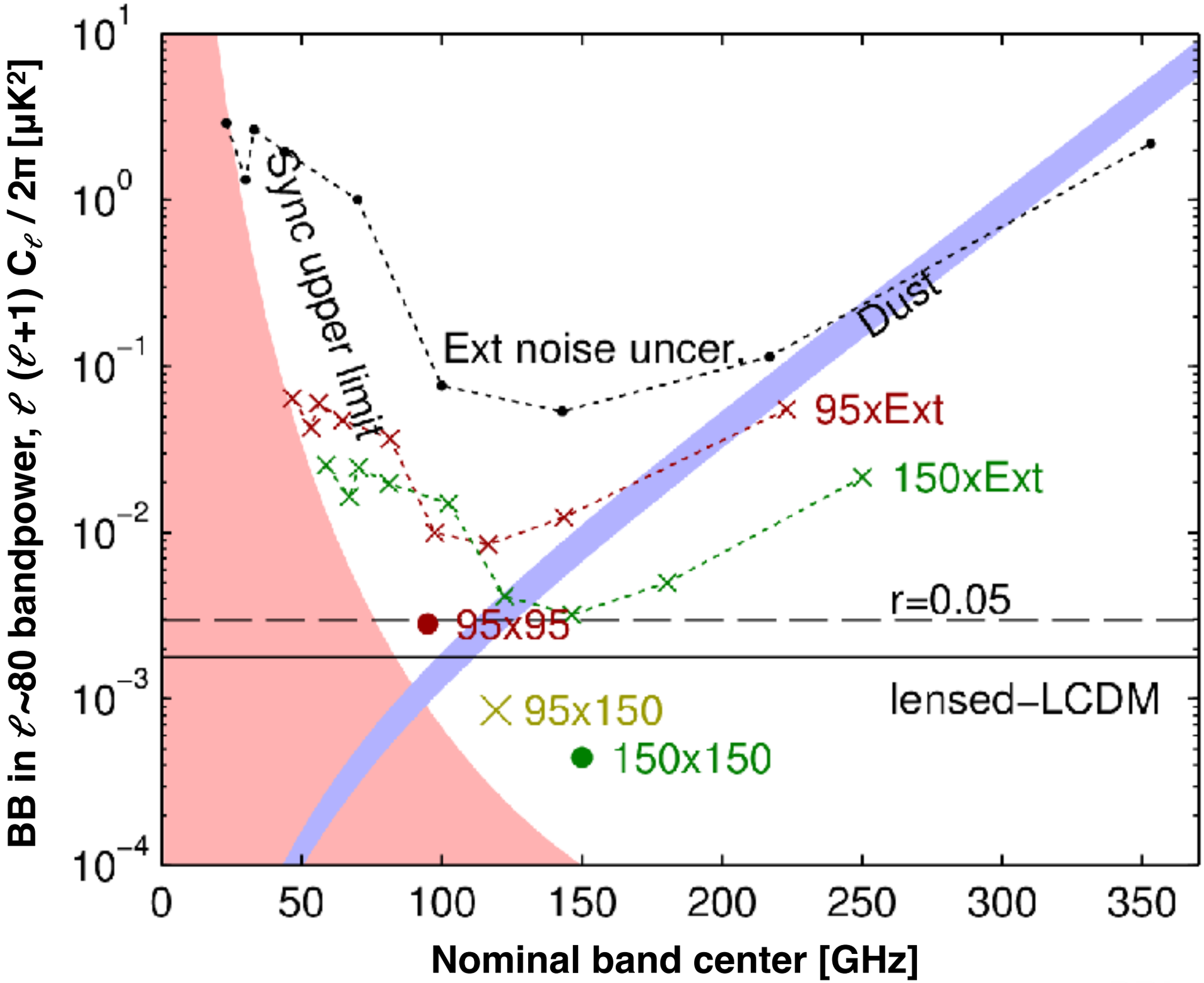


BICEP Array mount fabrication to start imminently



Thanks for your attention!

Summary of sensitivity



PRL 116, 031302