BICEP/*Keck*: Constraining primordial gravitational waves with CMB polarization observations from the South Pole

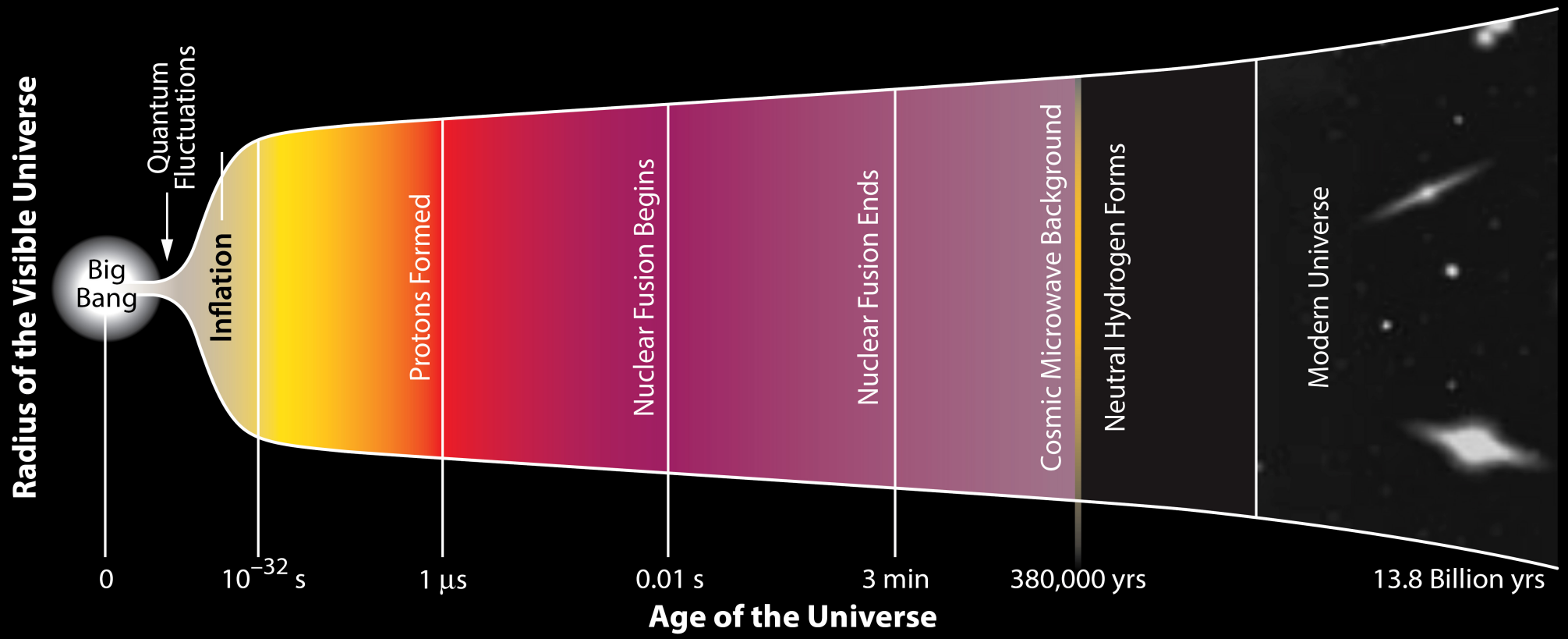
Marion Dierickx

SCAR AAA, Svalbard, September 21st 2023

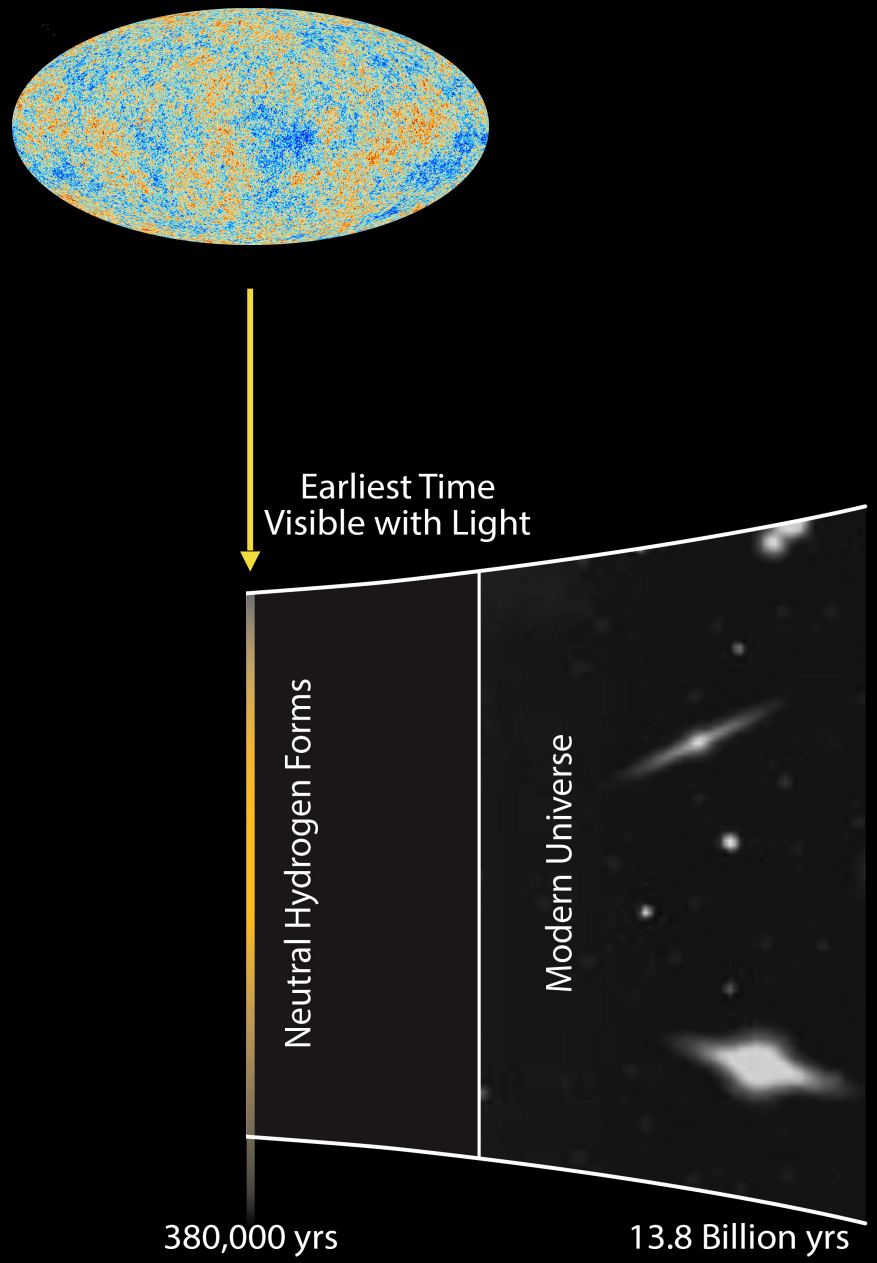
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

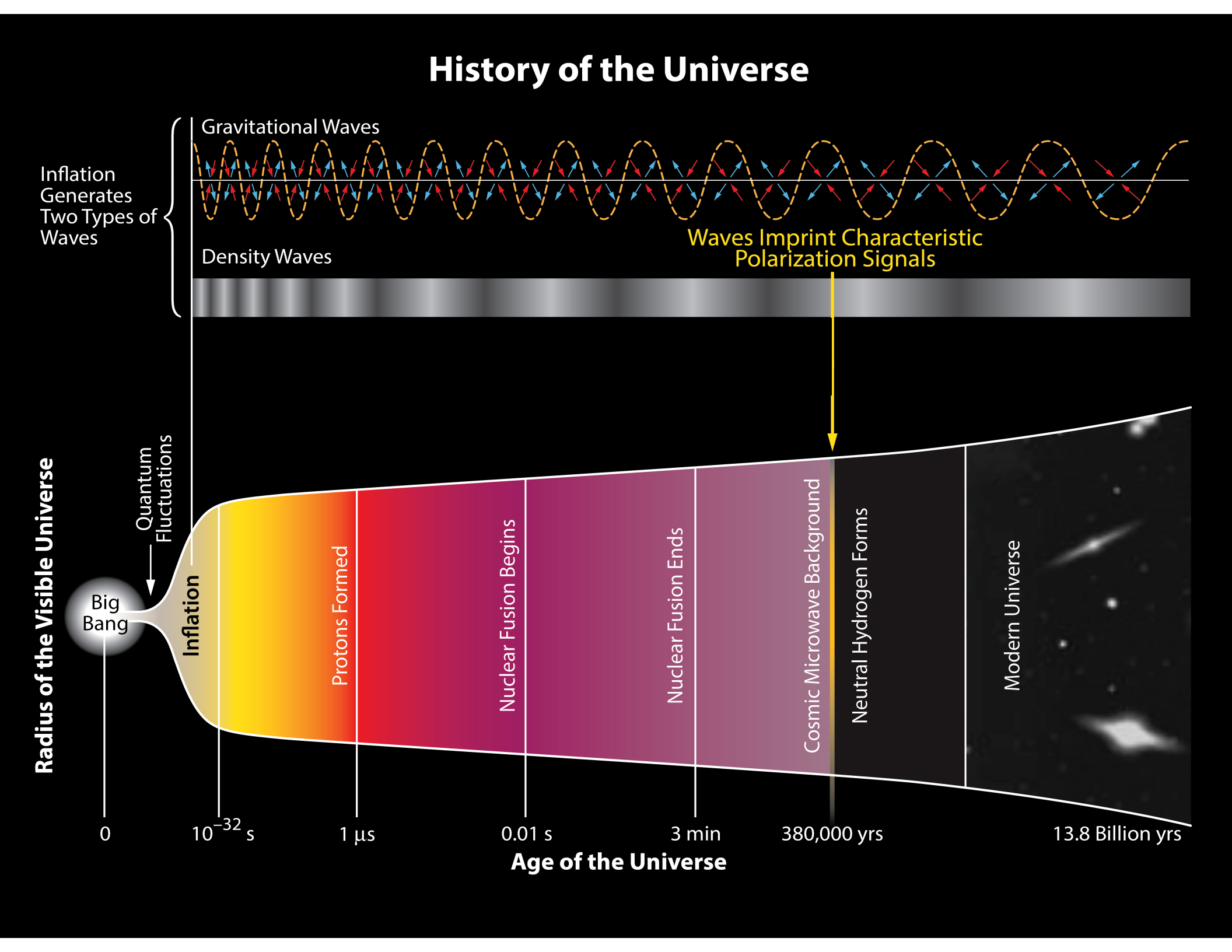
Photo credit: R. Schwarz

History of the Universe



History of the Universe




History of the Universe
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
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

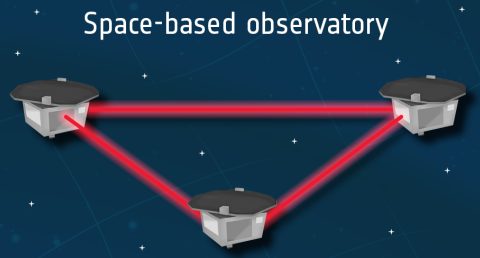
THE SPECTRUM OF GRAVITATIONAL WAVES

esa

Observatories & experiments

Ground-based experiment

Space-based observatory



Pulsar timing array

Cosmic microwave background polarisation

Timescales

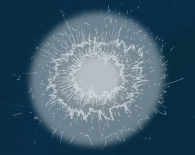
milliseconds — seconds — hours — years — billions of years

Frequency (Hz)

100 — 1 — 10^{-2} — 10^{-4} — 10^{-6} — 10^{-8} — 10^{-16}

Cosmic fluctuations in the early Universe

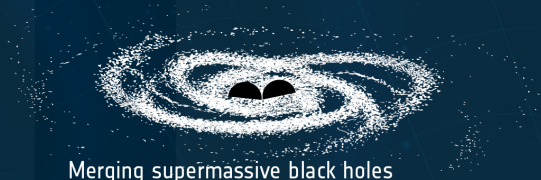
Cosmic sources



Supernova

Pulsar

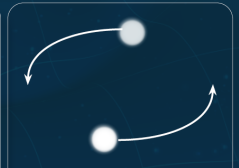
Compact object falling onto a supermassive black hole



Merging supermassive black holes

Merging neutron stars in other galaxies

Merging stellar-mass black holes in other galaxies

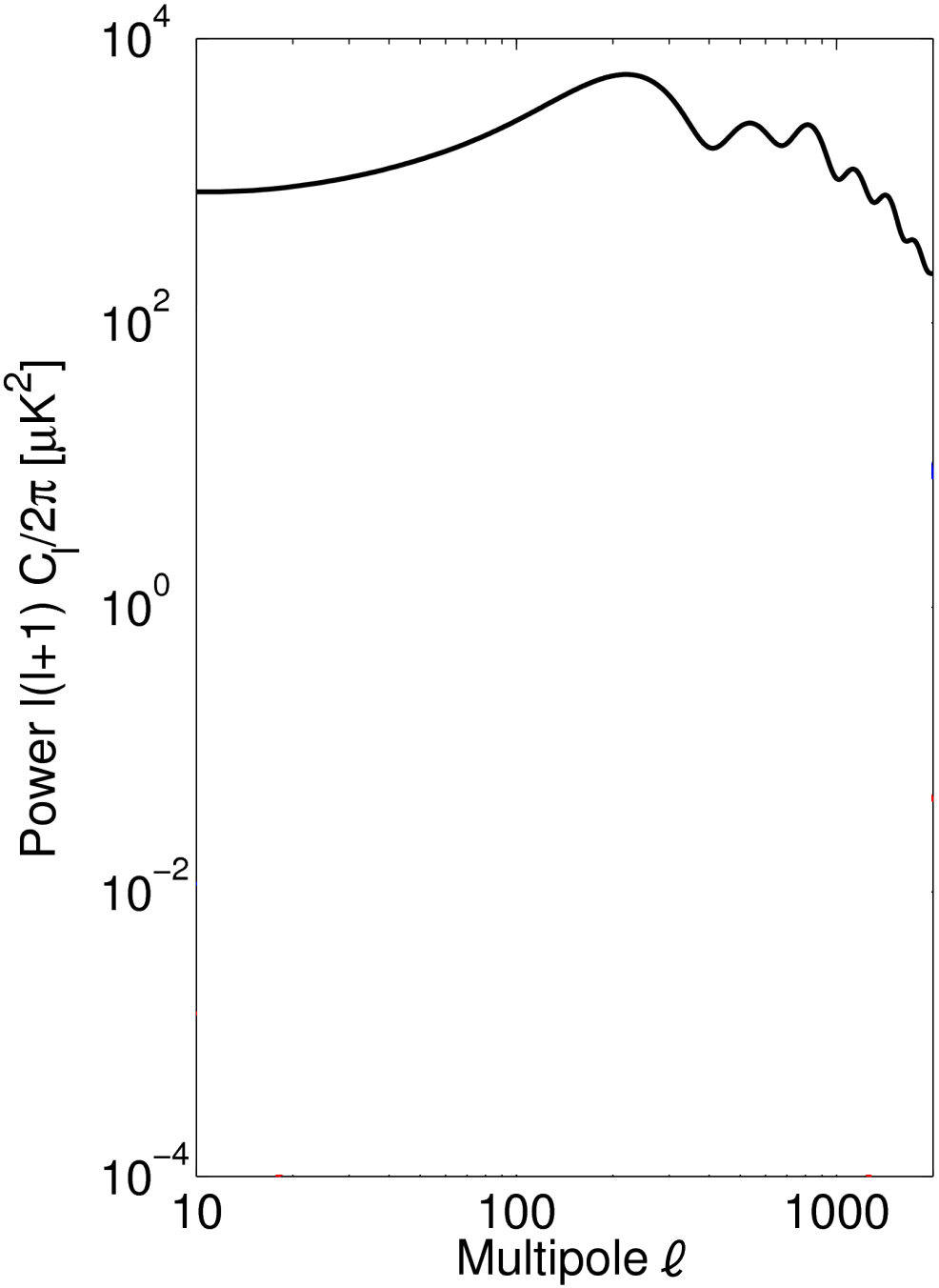


Merging white dwarfs in our Galaxy

#lisa

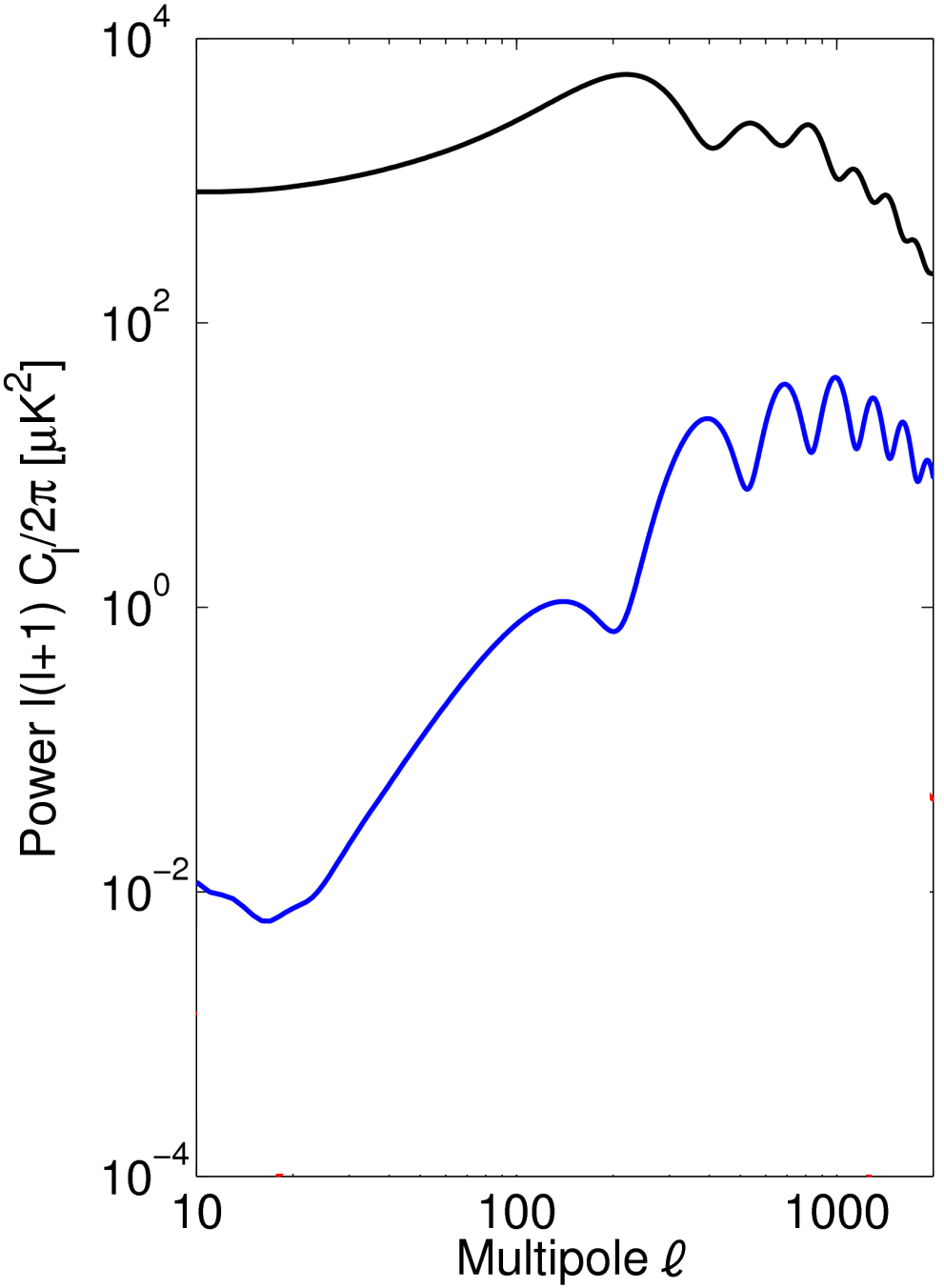
ESA | NASA lisa

CMB Polarization



Power spectrum of the CMB temperature signal.

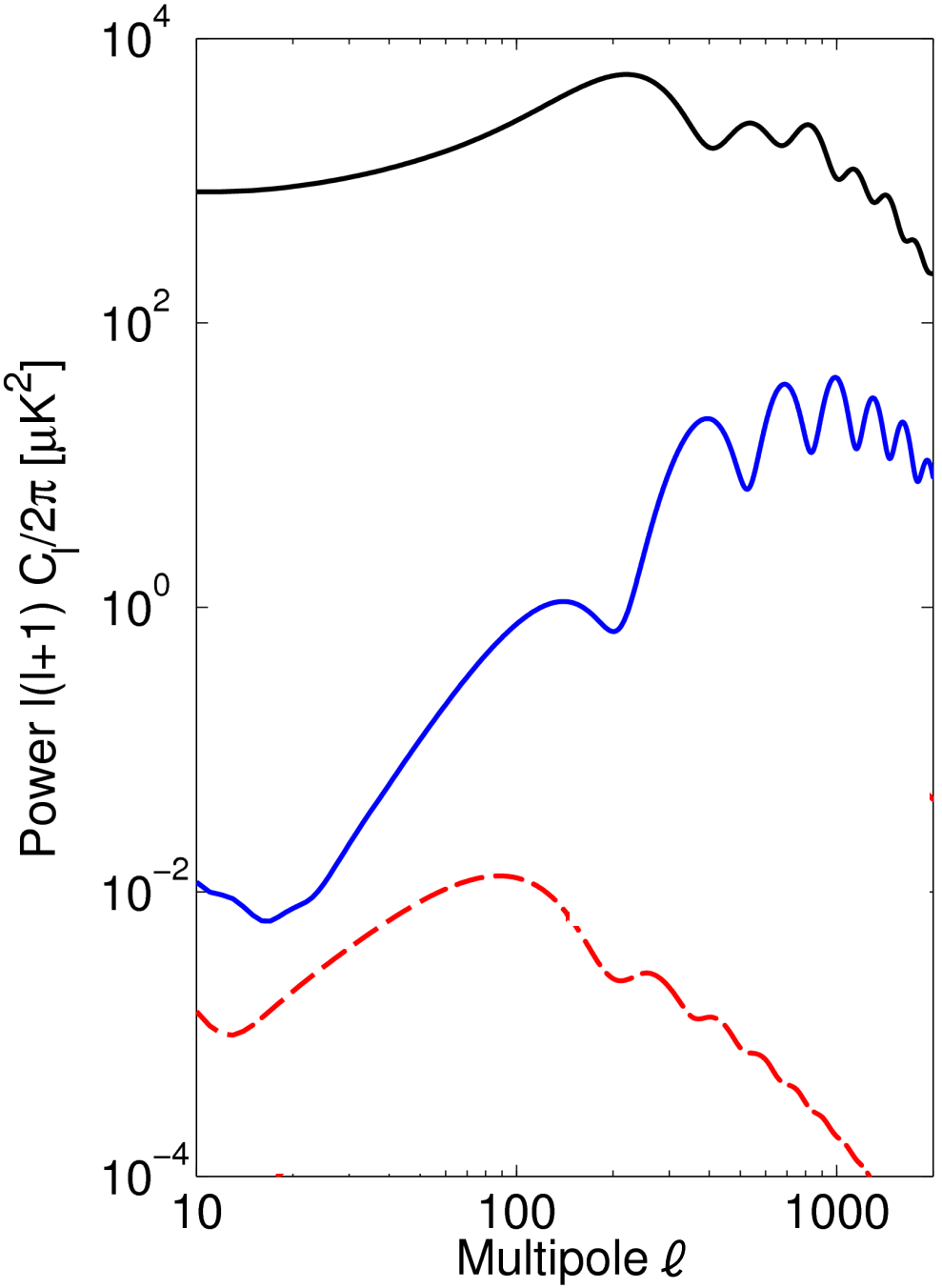
CMB Polarization



Power spectrum of the CMB temperature signal.

E-mode polarization spectrum, sourced by density fluctuations.

CMB Polarization

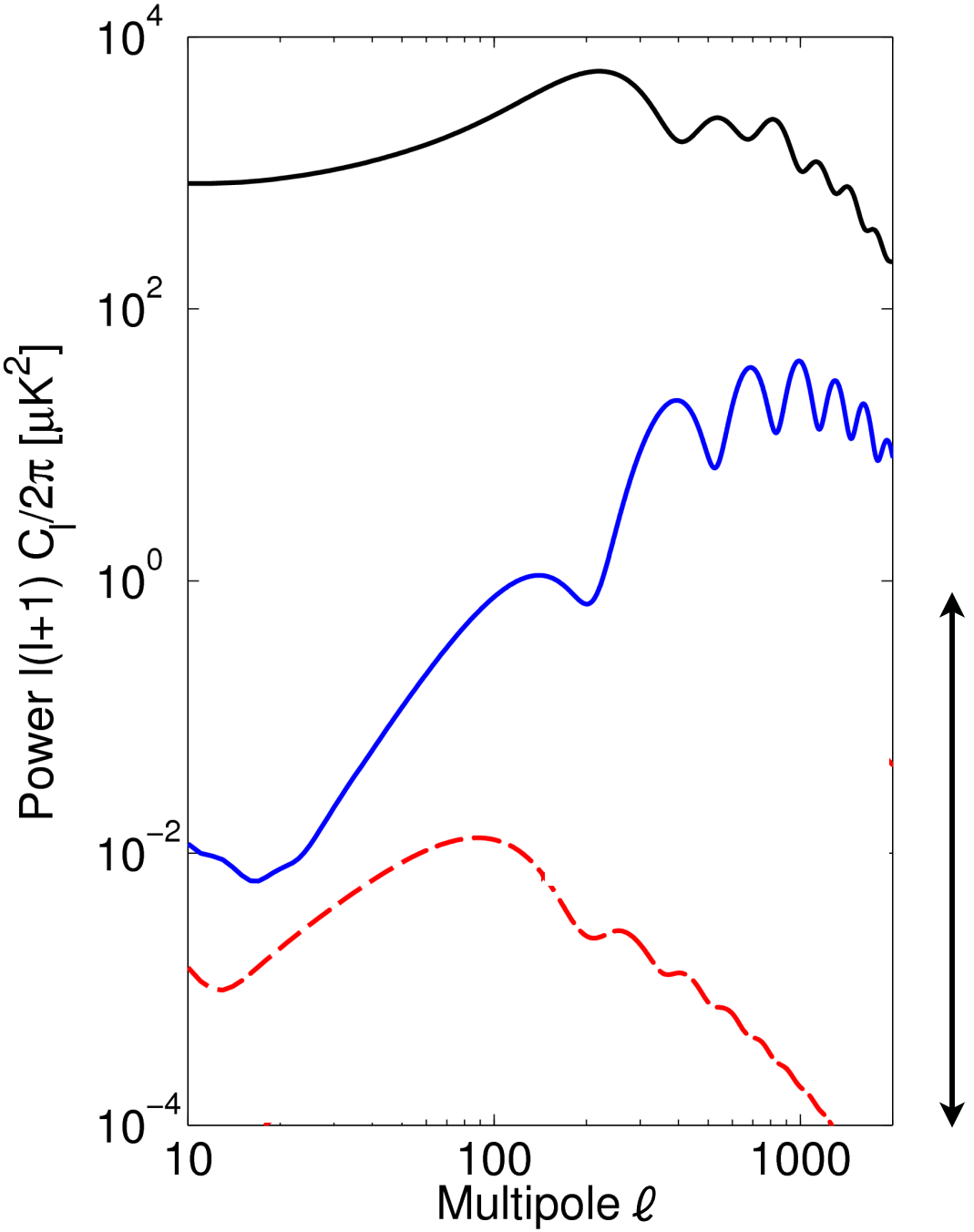


Power spectrum of the CMB temperature signal.

E-mode polarization spectrum, sourced by density fluctuations.

B-mode polarization spectrum, uniquely sourced by primordial gravitational waves.
Peak at ℓ~100: degree scales.

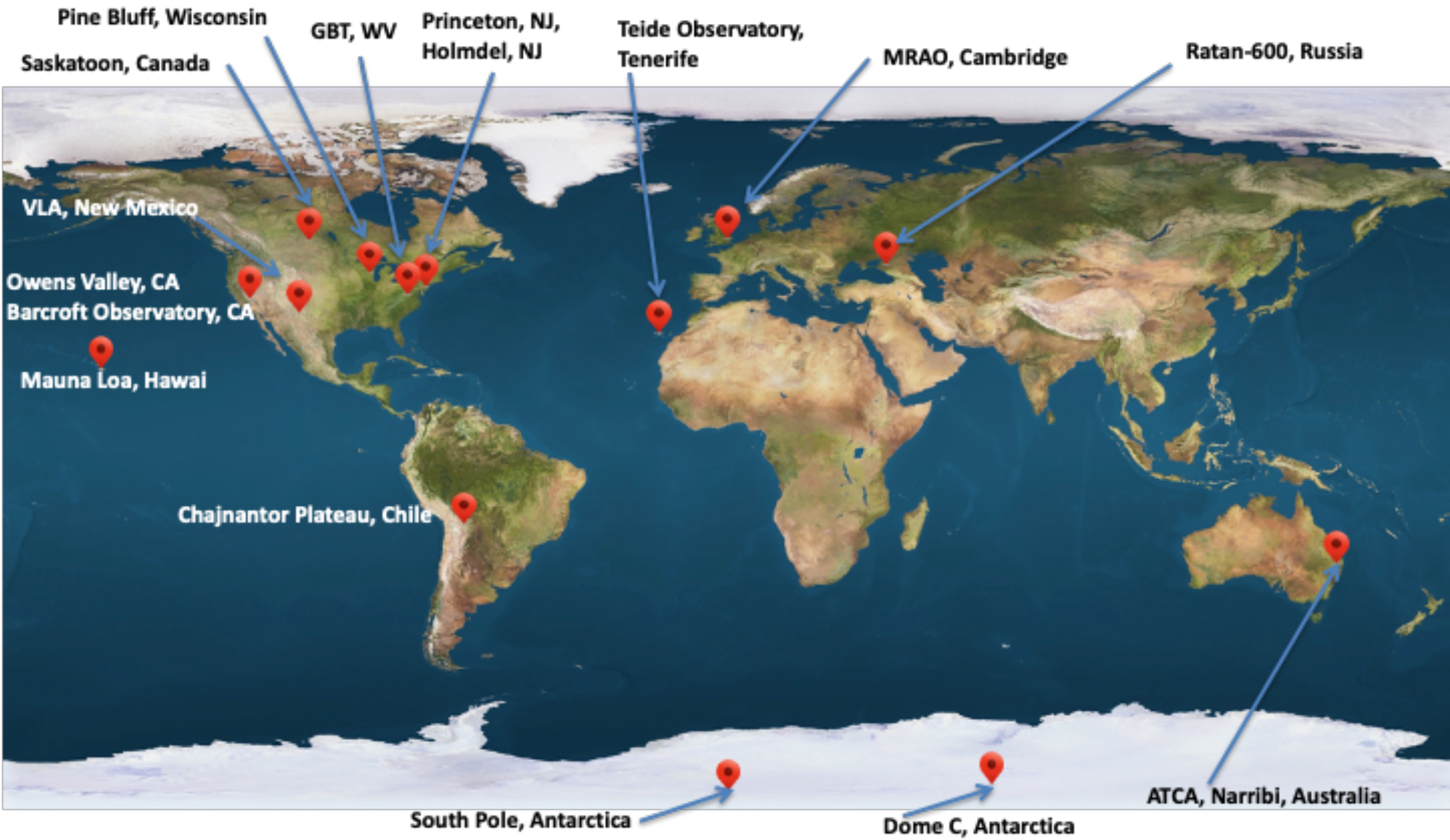
Challenge #1: The signal is very weak



The signal is parameterized by the tensor-to-scalar ratio *r.* Its exact amplitude is unknown.

To place meaningful constraints on primordial gravitational waves, we must be able to detect a signal at the nanokelvin level.

CMB telescope sites: 1960-2016



Slide adapted from D. Barkats

From CMB experiment database at lambda.gsfc.nasa.gov

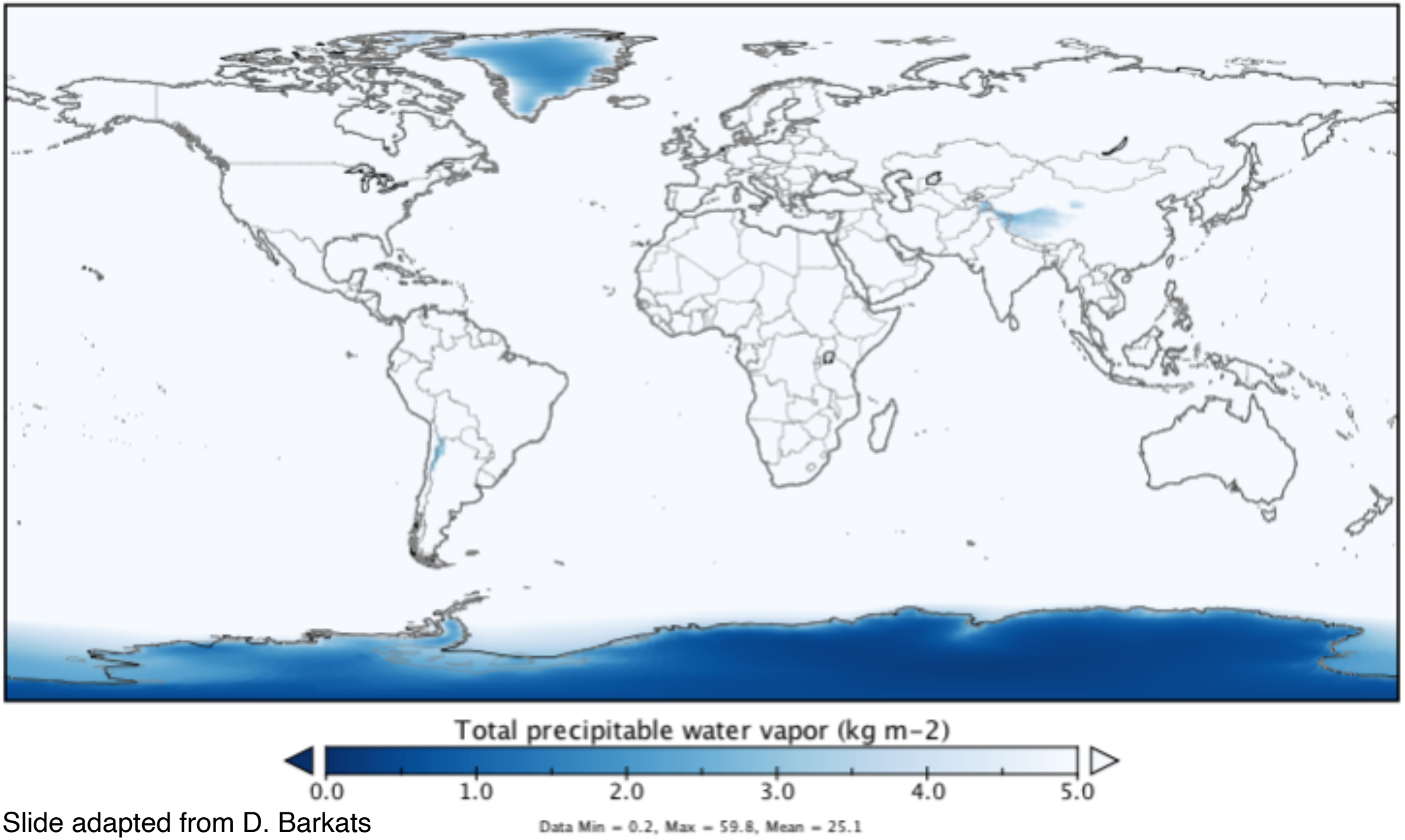
CMB telescope sites: last ~decade

High-precision CMB temperature and polarization experiments: past and current

Slide adapted from D. Barkats

Atmospheric transmission

Precipitable Water Vapor (2006-2016 average) from MERRA2 (NASA)



Slide adapted from D. Barkats

South Pole Dark Sector

South Pole Dark Sector

- Extremely dry.
- High altitude (9,300 ft = 2,800 m, most of it ice).
- Lack of day/night cycles makes for a very stable atmosphere.
- Southern sky observable for 6 months of continuous darkness.
- Minimal radio frequency interference.

South Pole Dark Sector

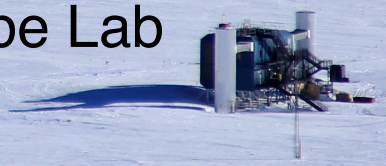
- Extremely dry.
- High altitude (9,300 ft = 2,800 m, most of it ice).
- Lack of day/night cycles makes for a very stable atmosphere.
- Southern sky observable for 6 months of continuous darkness.
- Minimal radio frequency interference.

BICEP1
BICEP2
BICEP3

DASI
QUAD
Keck Array
BICEP Array

South Pole Telescope:
SPT-SZ, SPTPol, SPT-3G

IceCube Lab

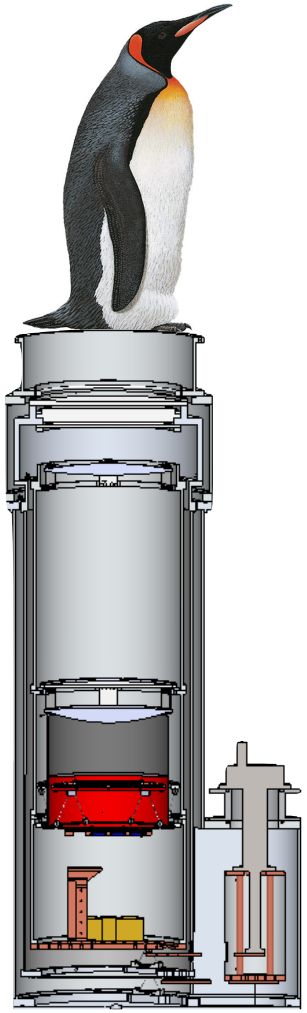


Anatomy of a BICEP CMB polarimeter

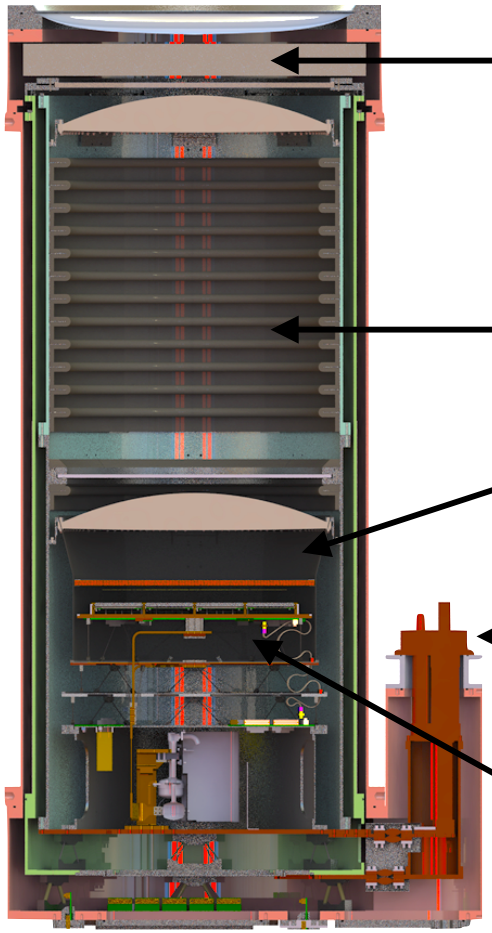
The cryostats are designed to be as compact as possible, with sufficient angular resolution to observe degree-scale features.

Hundreds/thousands of orthogonal detectors pairs. Take the difference to reconstruct polarized signal.

The on-axis, refractive optical design allows the tube to rotate around the boresight for polarization modulation and systematics cancellation.



BICEP2/*Keck*



BICEP Array

Utrathin vacuum window + BOPP membrane

Infrared filters: Zotefoam stack, Stycast-coated alumina, and/or Teflon-coated Nylon.

Absorptive baffling

Superconducting Niobium shield

A pulse tube cryocooler brings the optics to 4K.

The detectors are cooled to 250 mK by a 3-stage helium sorption refrigerator.

Focal planes are getting larger in order to pack more detectors per receiver.

BICEP Array 2019-20 deployment

Three months of Antarctic summer to perform:

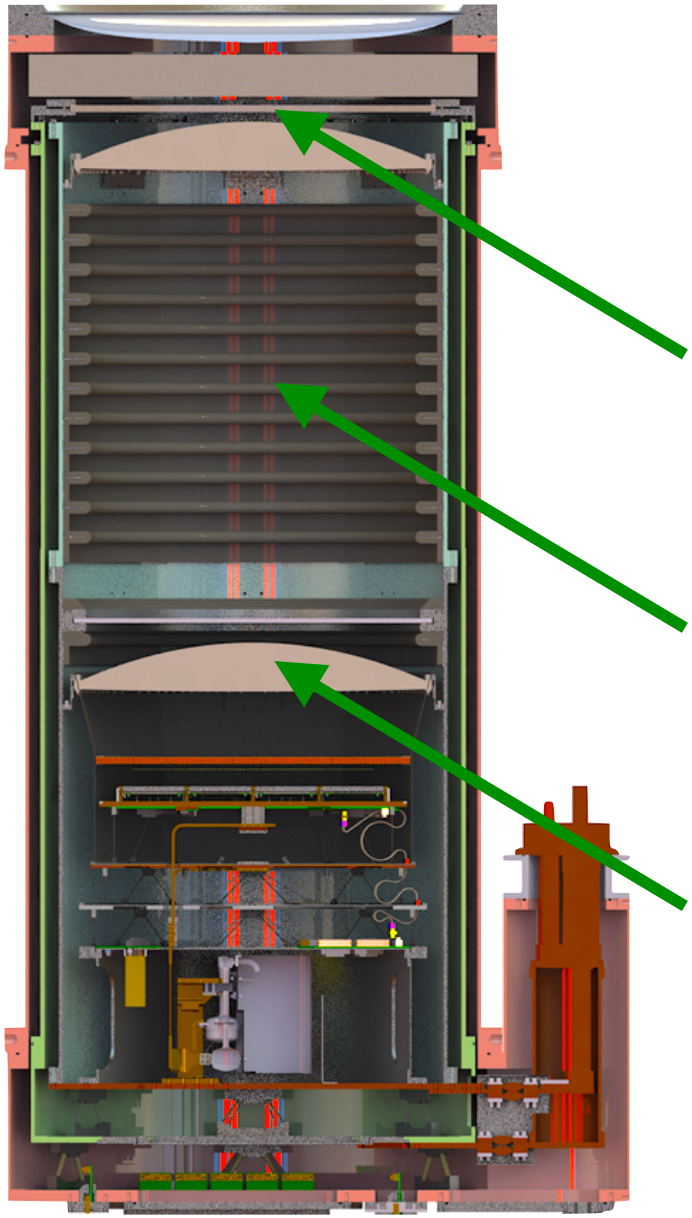
- *Keck Array* demolition
- BA mount installation
- BA1 receiver assembly
- Full system integration

60,000 lbs of cargo, equivalent to 3 dedicated LC-130 Hercules flights to the South Pole.

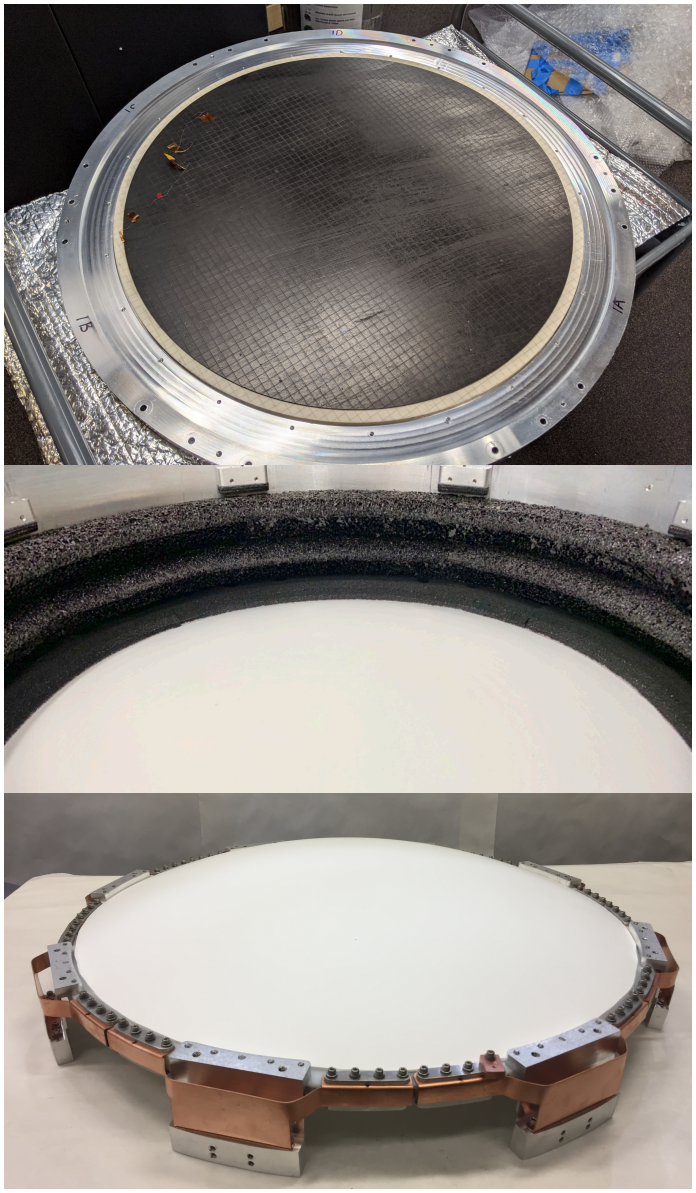
~30 personnel:

- 2/3 scientists
- 1/3 contractors

BA1 (30/40 GHz) instrument highlights



Optics



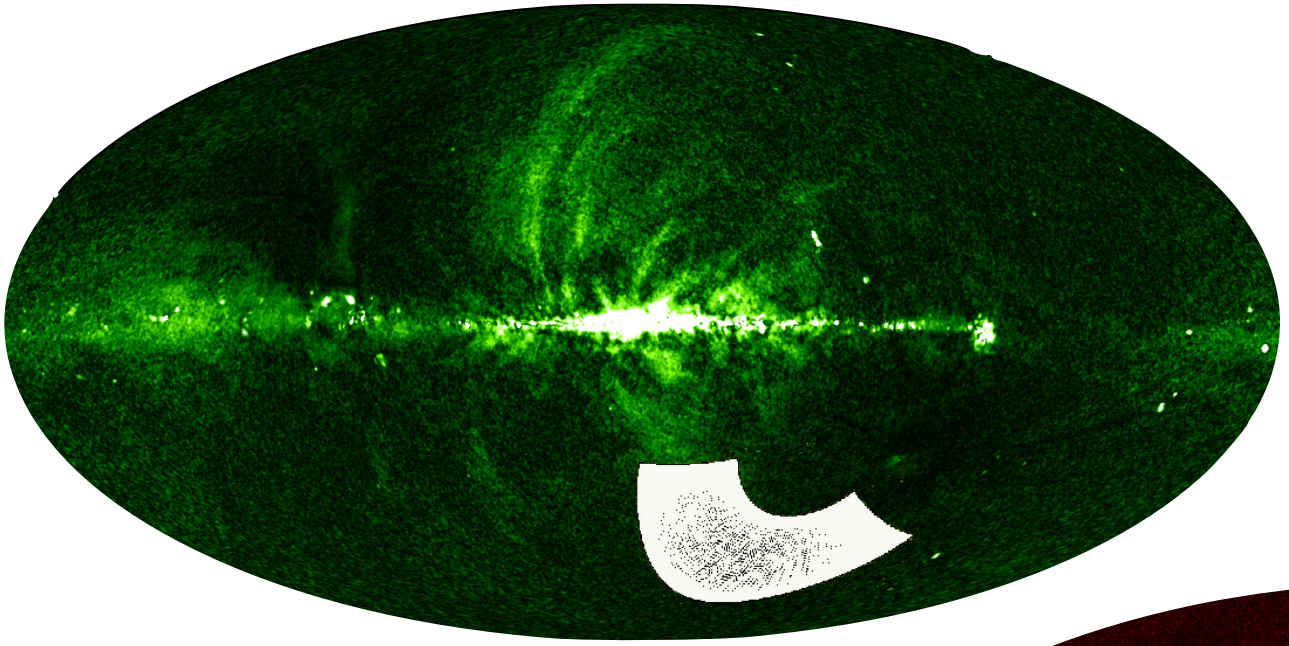
Alumina absorptive IR filter, AR-coated with laser-diced epoxy.

Internal absorptive baffling for scattering control.

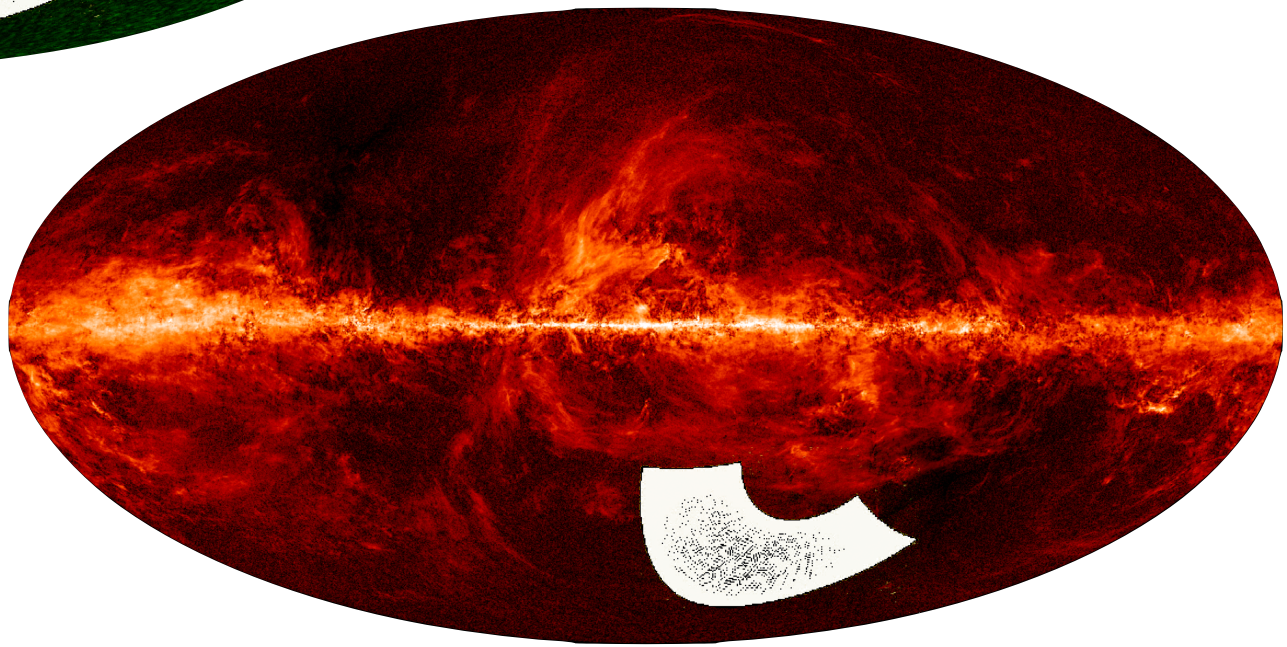
Polyethylene lenses, AR-coated with expanded Teflon.
550mm clear aperture.

Challenge #2: Galactic foregrounds

Two known additional sources of “foreground” E- and B-mode signals:



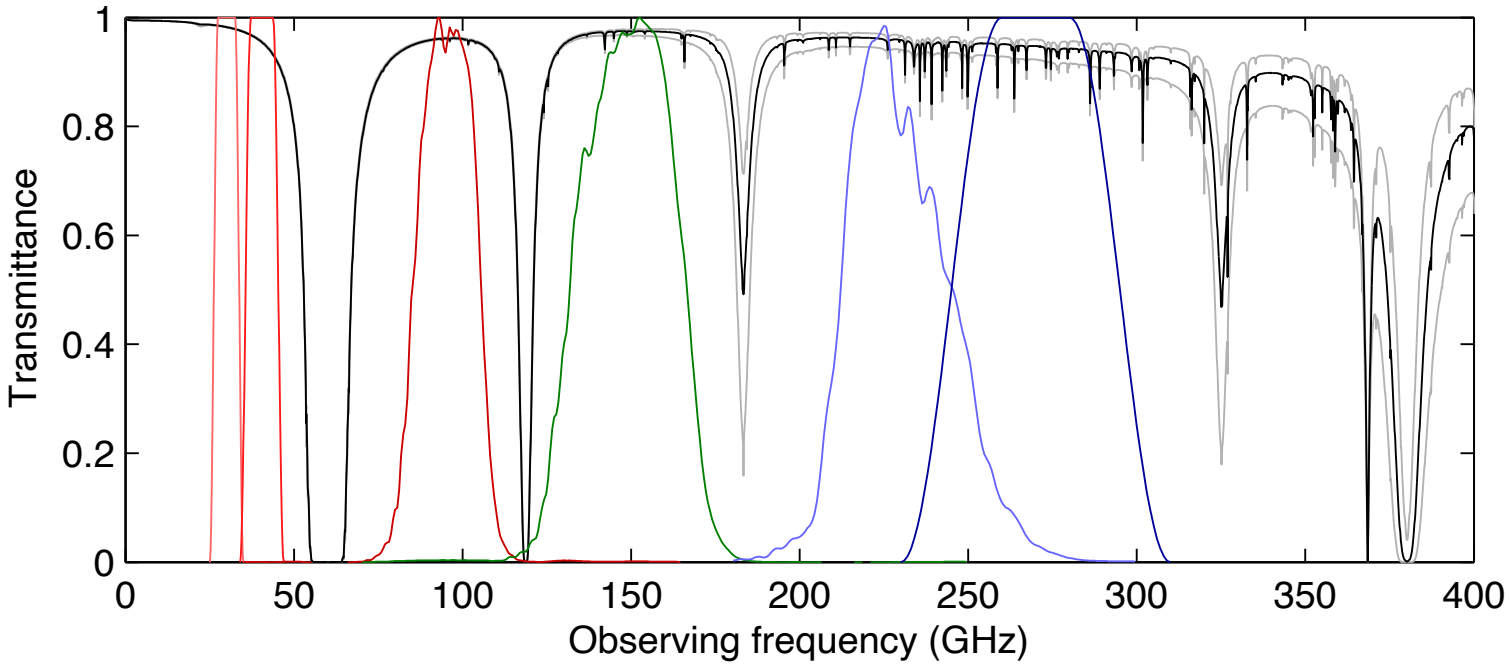
Synchrotron: Dominates at low frequencies. Comes from electrons spiraling in Galactic magnetic fields.



Dust: Dominates at high frequencies (IR). Comes from small interstellar dust grains aligned by magnetic fields.

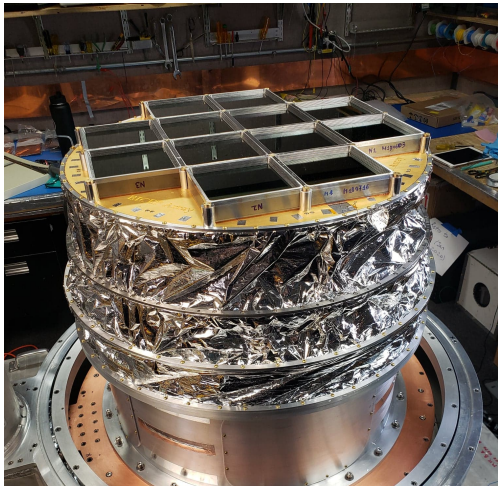
Planck Collaboration X: 1502.01588

Multi-band observations are the key to component separation



Black lines: atmospheric transmission
Colored lines: BICEP Array observing bands

Superconducting detector technology that scales in frequency (using the same optics) enables modularity of the telescope design.

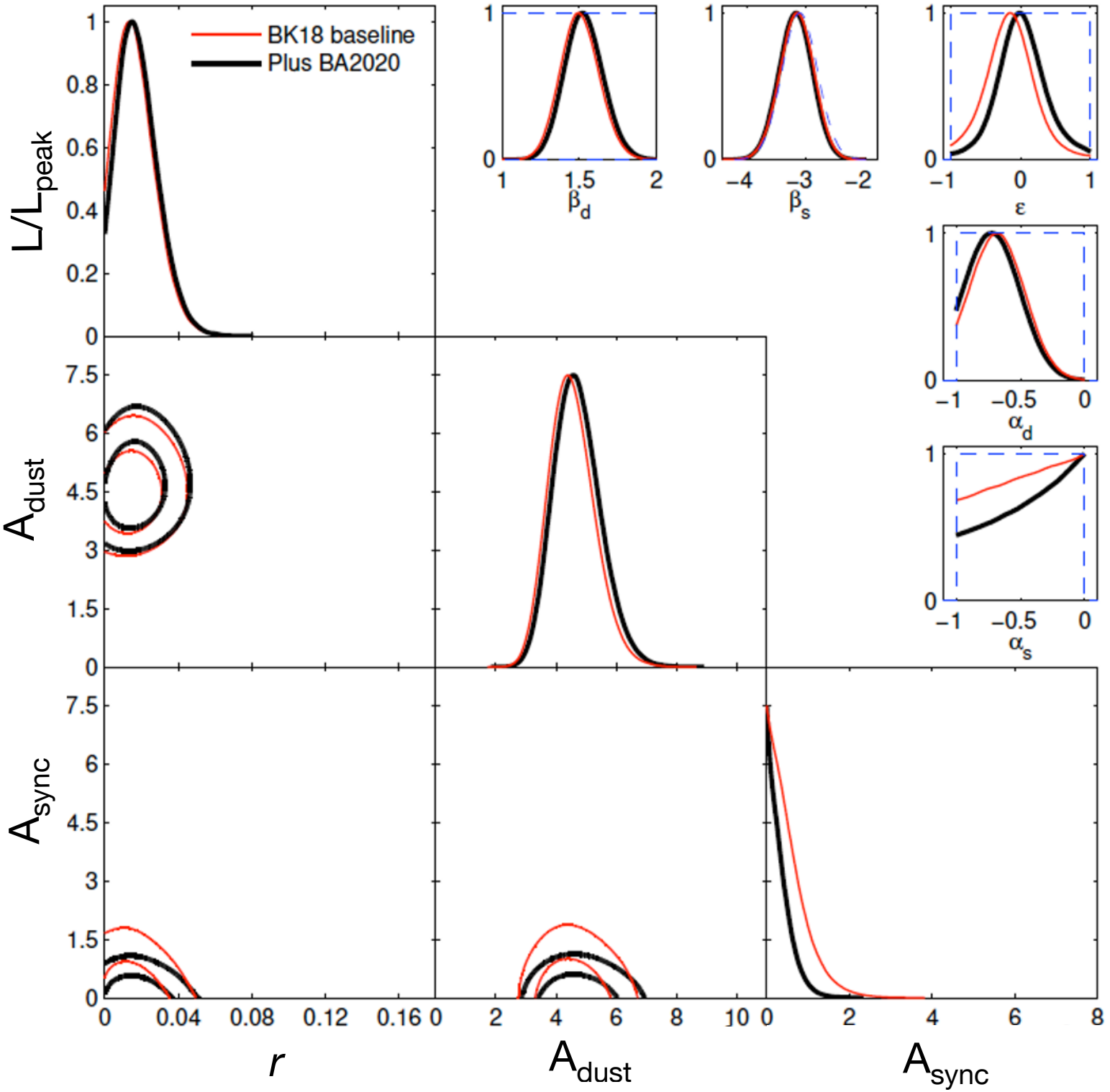


Camera inserts at
30/40 GHz and 150 GHz

Analysis

The most recent published analysis (with data up to 2018) is shown in red.

Preliminary analysis adding the first year of 30/40 GHz data (2020) is shown in a black line.

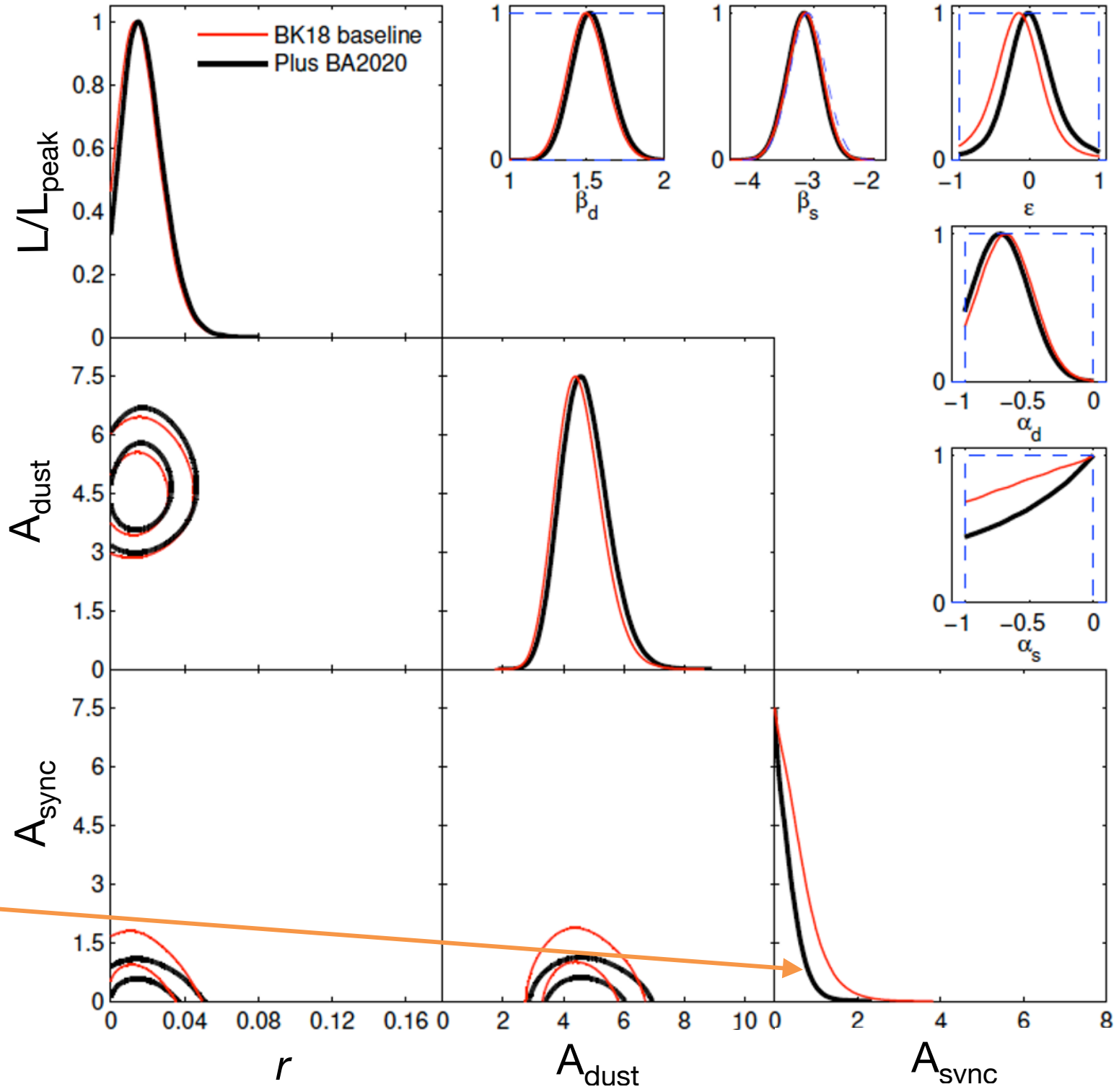


Analysis

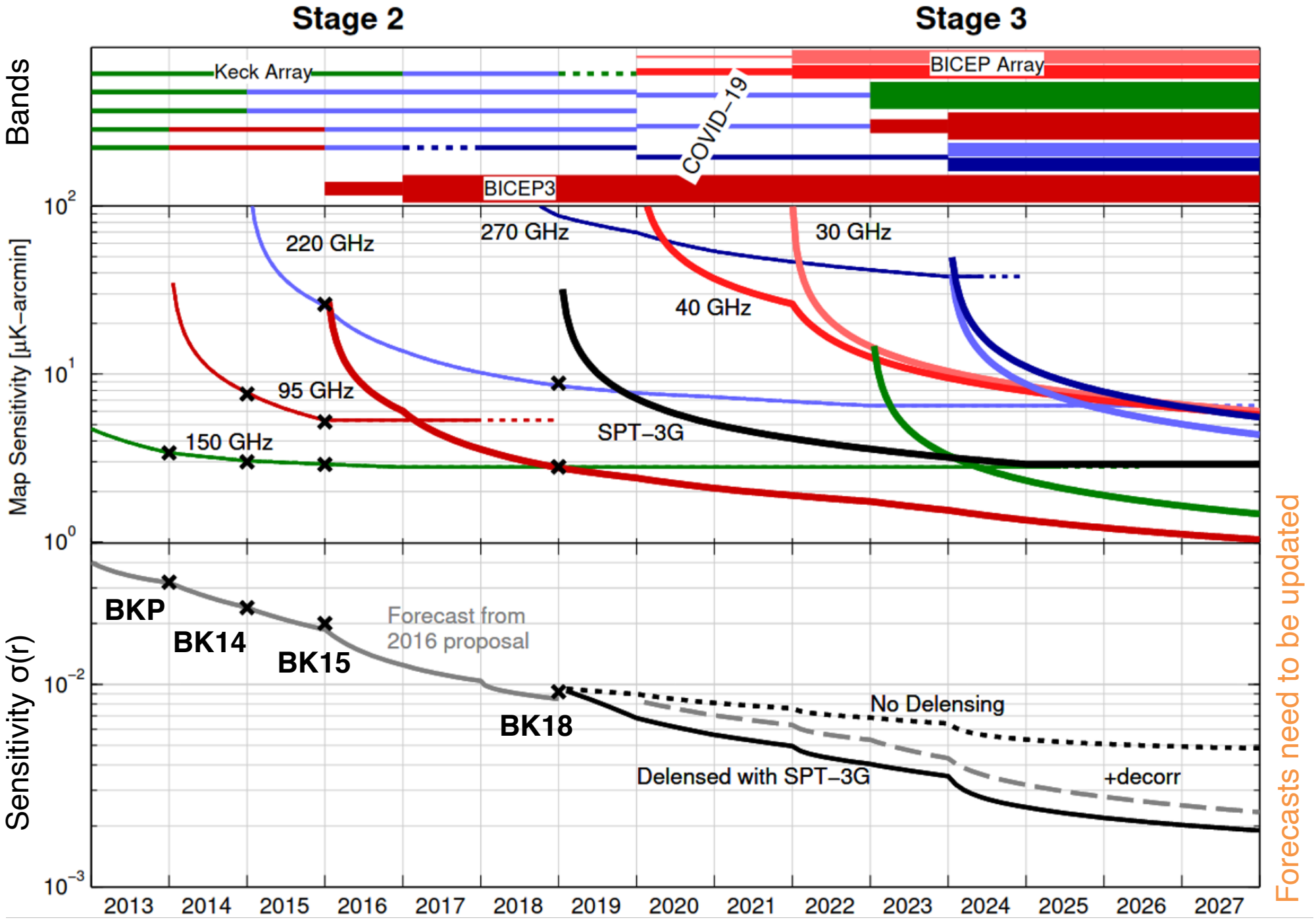
The most recent published analysis (with data up to 2018) is shown in red.

Preliminary analysis adding the first year of 30/40 GHz data (2020) is shown in a black line.

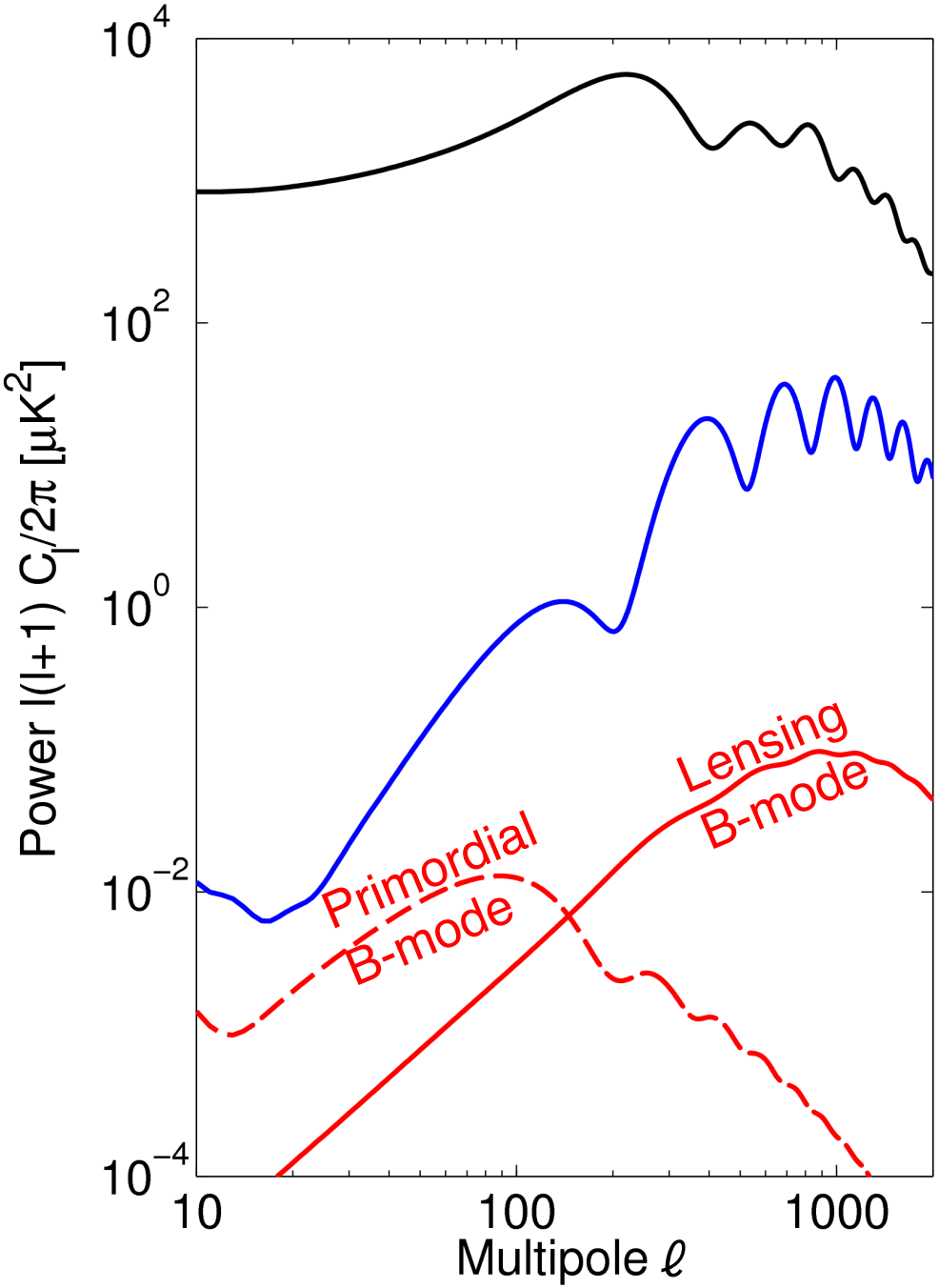
Synchrotron radiation is still undetected; the upper limit is pushed further down.

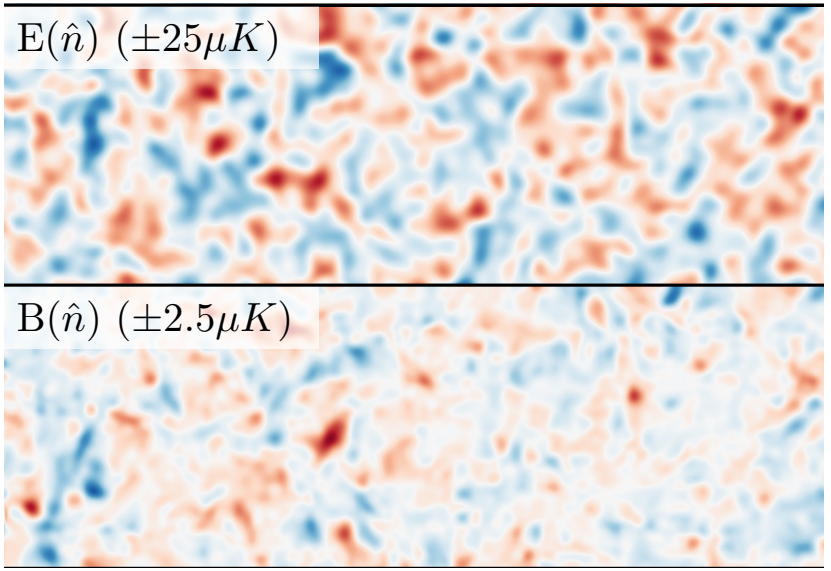


Progress in the measurement



Challenge #3: Gravitational lensing





Simulated effect of lensing
(no primordial B-modes)

Image from K. Wu

Conclusions

- The quest to constrain inflationary gravitational waves continues:
  - Using data up to 2018 gives $r_{0.05} < 0.036$ (95%), $\sigma(r) = 0.009$.
  - This result rules out two entire classes of previously popular inflation models (monomial models and Natural Inflation).
  - Proven systematics control at degree angular scales.

- Looking ahead:
  - Stage 3 deployment is ongoing: Projecting $\sigma(r) < 0.003$ by the end of the full BICEP Array survey ca. 2027.
  - Delensing with SPT-3G data is under development.
  - Next Generation CMB Experiment: CMB-S4.

Backup slides

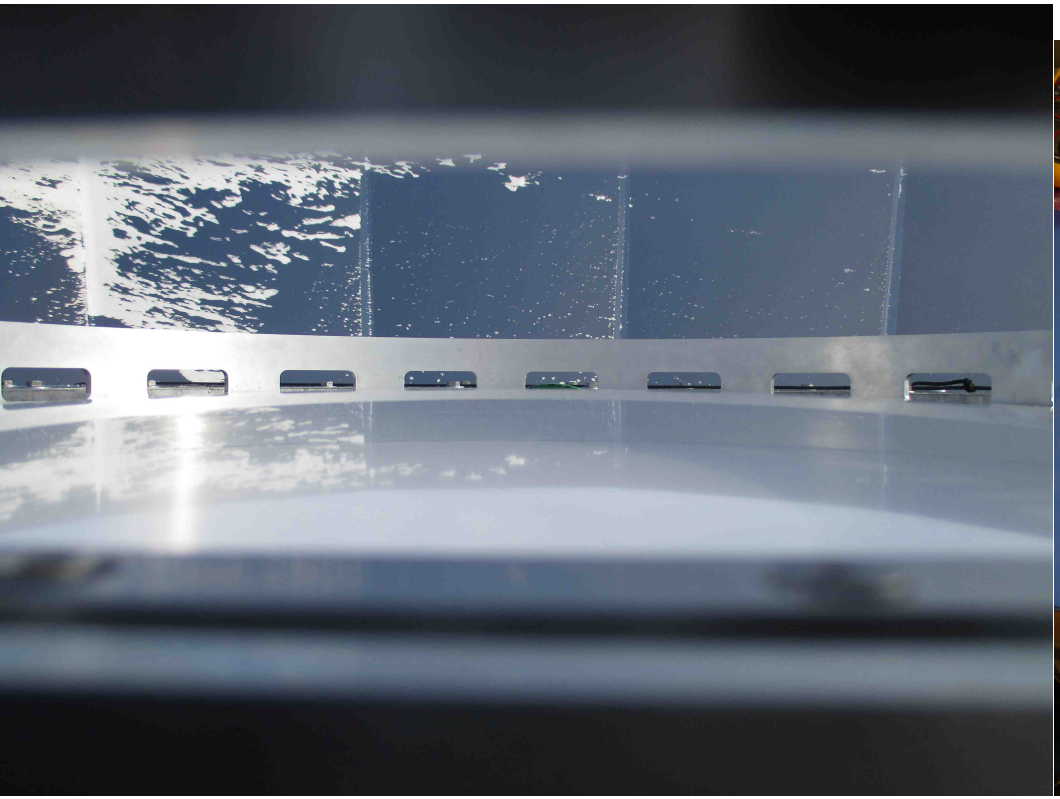
BICEP3 receiver inside control room

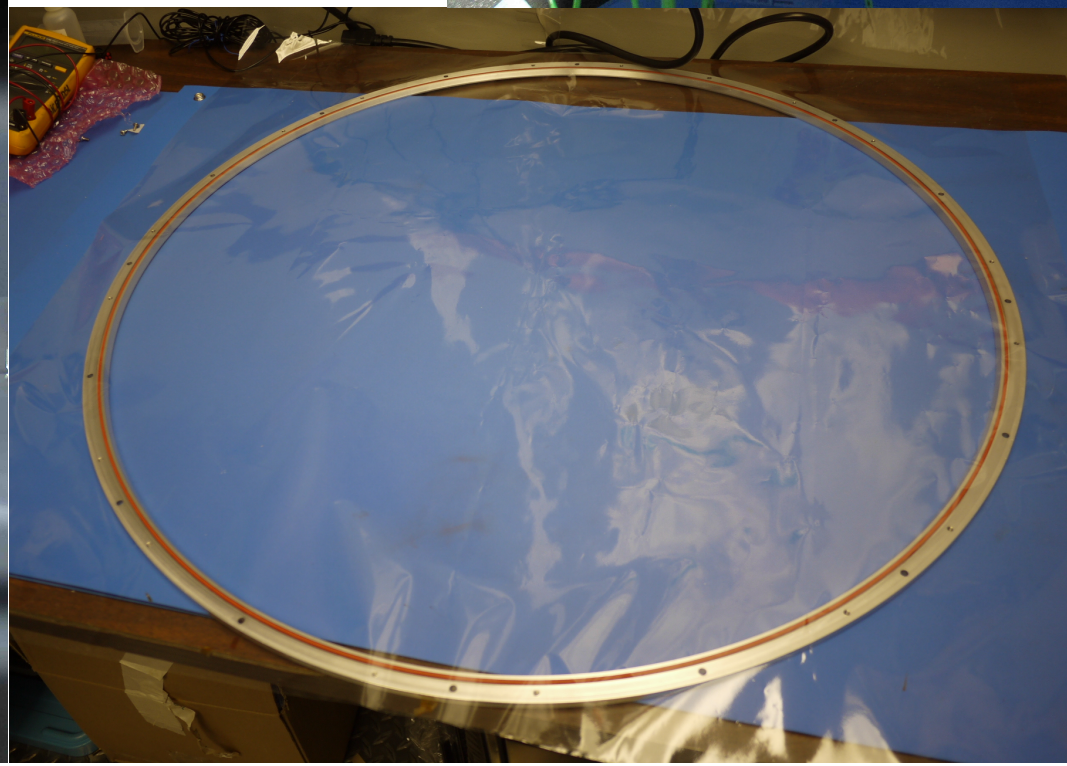
“Membrane”: window N2 purge

Pressurized volume of N2 above vacuum window

Regulation panel for N2 flow

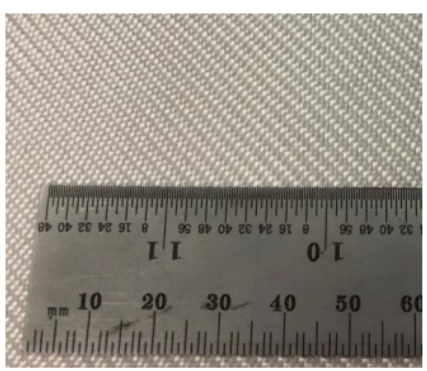
BOPP membrane

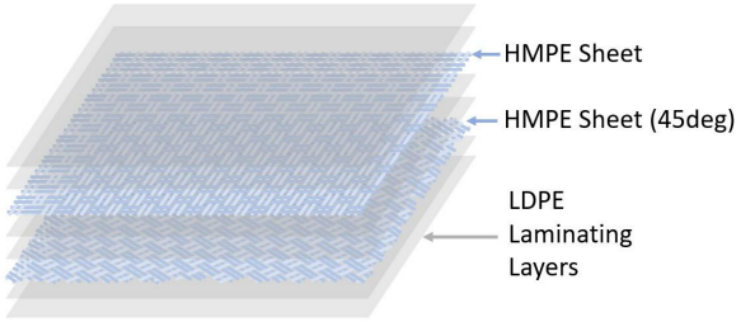




Ultrathin vacuum windows

See Eiben et al. SPIE Proceedings ArXiv: 2208.01088





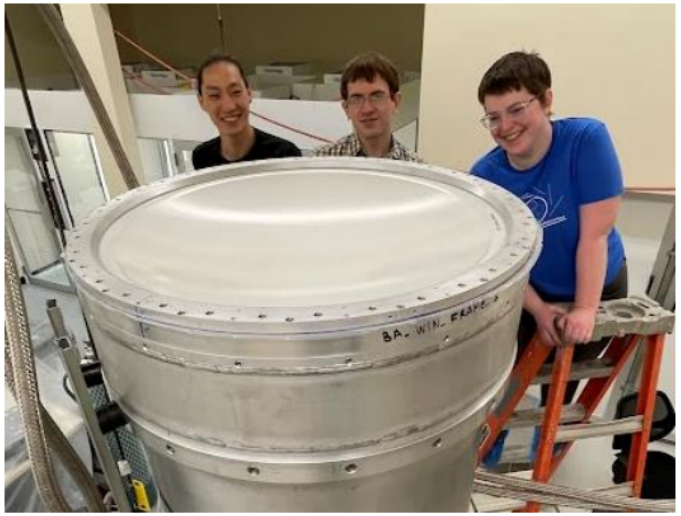
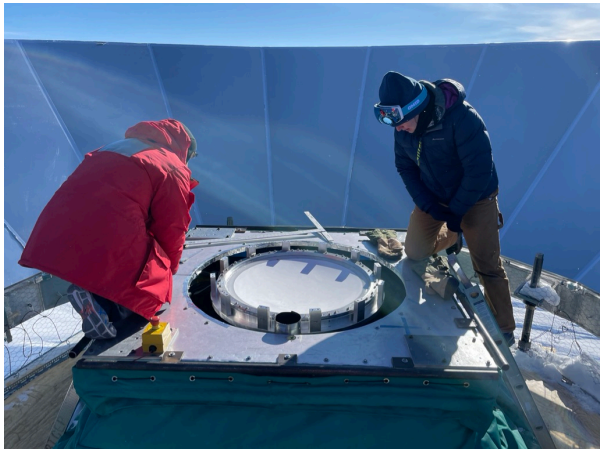


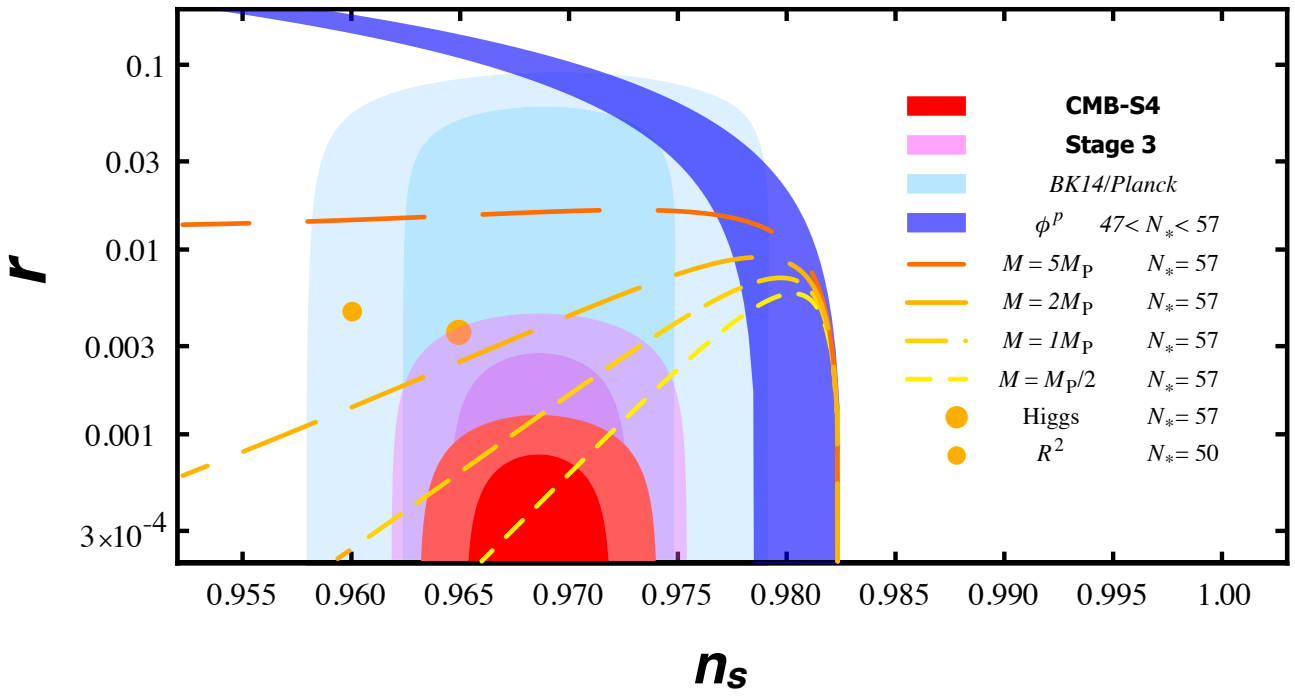
Fig. 6: [Top] Woven HMPE sheet, pre-lamination. [Top right] Example layer stack of HMPE and LDPE. Varying the amount of LDPE varies the thickness of the final laminate window. [Right] Laminate window on a BICEP Array cryostat, with people for scale.

Deployed on BICEP3 and BICEP Array in 2022-23 austral summer:



South Pole Observatory

- Joining forces with the 10-meter South Pole Telescope, which provides high-resolution maps of the small-scale polarization pattern.
- Recently achieved the first demonstration of reducing the uncertainty on the tensor-to scalar *r* through “delensing” (arXiv:2011.08163)
- Develop path forward for CMB-S4: infrastructure, data and methods.

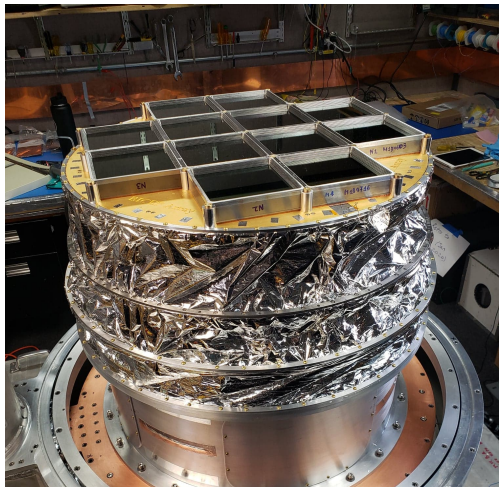


Goal for CMB-S4 measurement of primordial gravitational waves: $r < 0.001$ at 95%

CMB-S4 will be able to detect primordial gravitational waves for $r > 0.003$. It will probe energy scales far beyond the reach of any conceivable collider experiment, and a detection would point to inflationary physics near the scale associated with grand unified theories.

Figure from CMB-S4 DSR

Superconducting detector technology that scales in frequency is the key to multi-band observations.



Example: BICEP Array camera inserts at 30/40 GHz and at 150 GHz

Pair-summed (dash) and pair-differenced (solid) noise spectra: