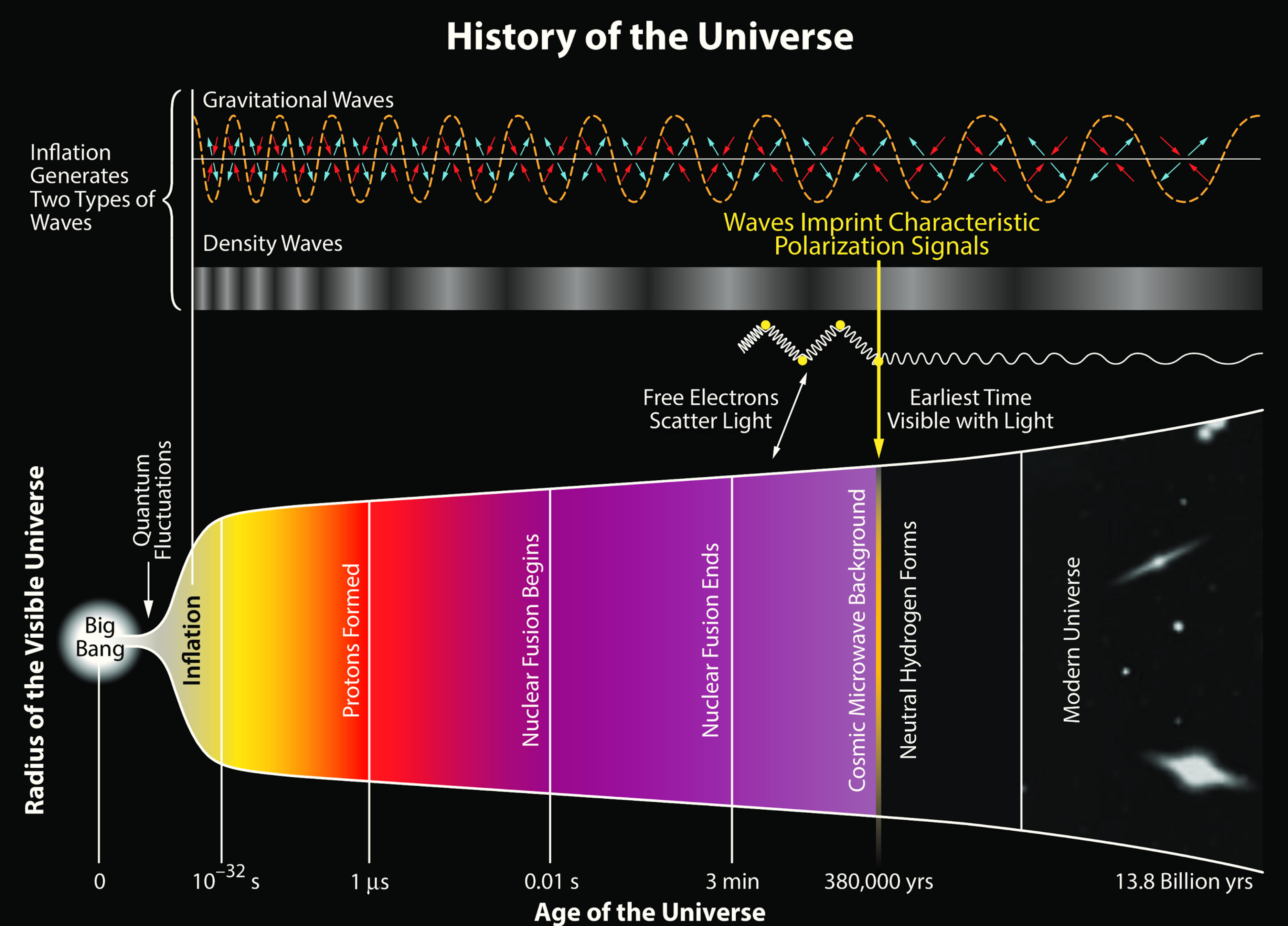
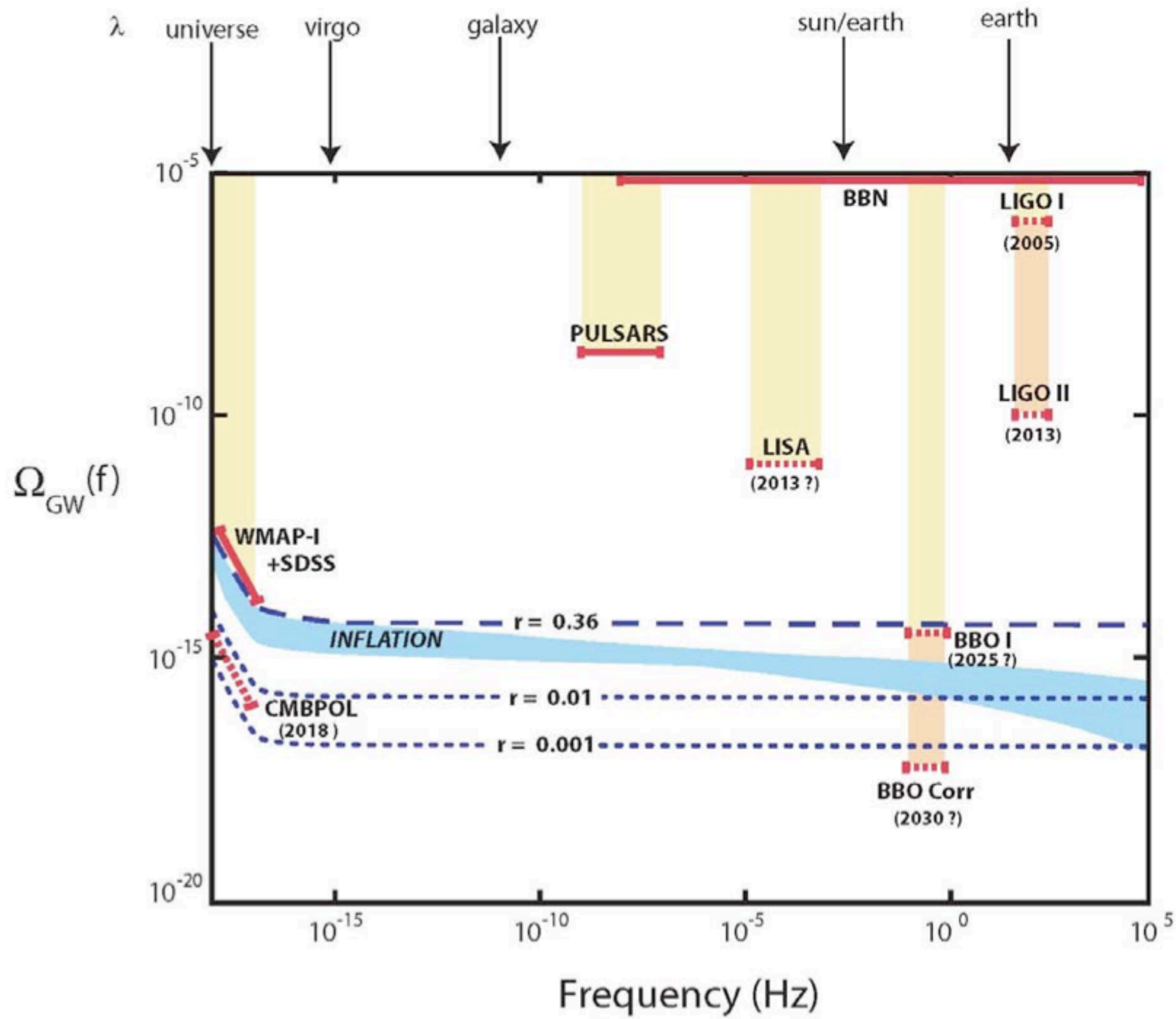
BICEP2 and the echoes of cosmic inflation

Walt Ogburn
SLAC/KIPAC

May 19, 2014
LISA Symposium X


History of the Universe
Gravitational Waves
Inflation Generates Two Types of 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

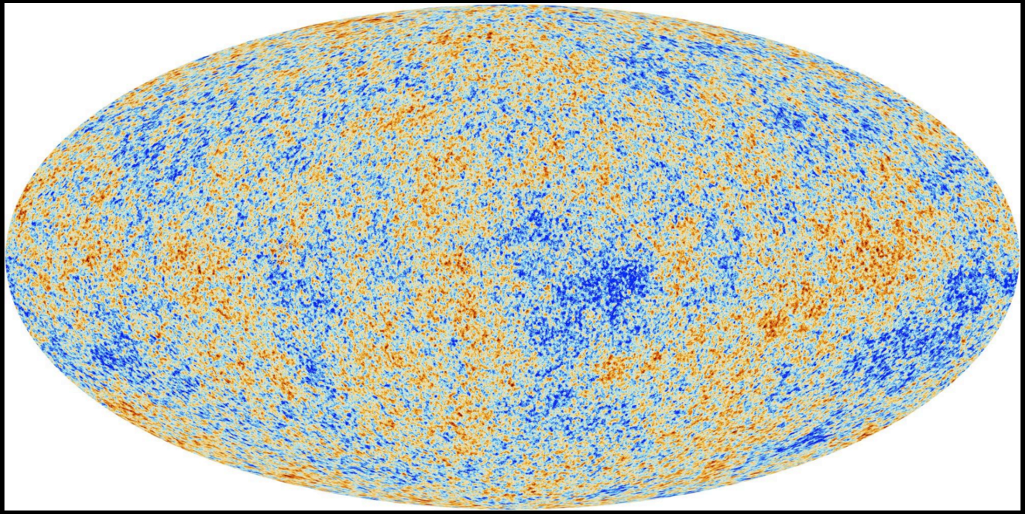

λ
universe
virgo
galaxy
sun/earth
earth
10^{-5}
10^{-10}
10^{-15}
10^{-20}
$\Omega_{GW}(f)$
BBN
LIGO I
(2005)
PULSARS
LIGO II
(2013)
LISA
(2013 ?)
WMAP-I
+SDSS
r = 0.36
INFLATION
BBO I
(2025 ?)
r = 0.01
CMBPOL
(2018)
r = 0.001
BBO Corr
(2030 ?)
10^{-15}
10^{-10}
10^{-5}
10^{0}
10^{5}
Frequency (Hz)

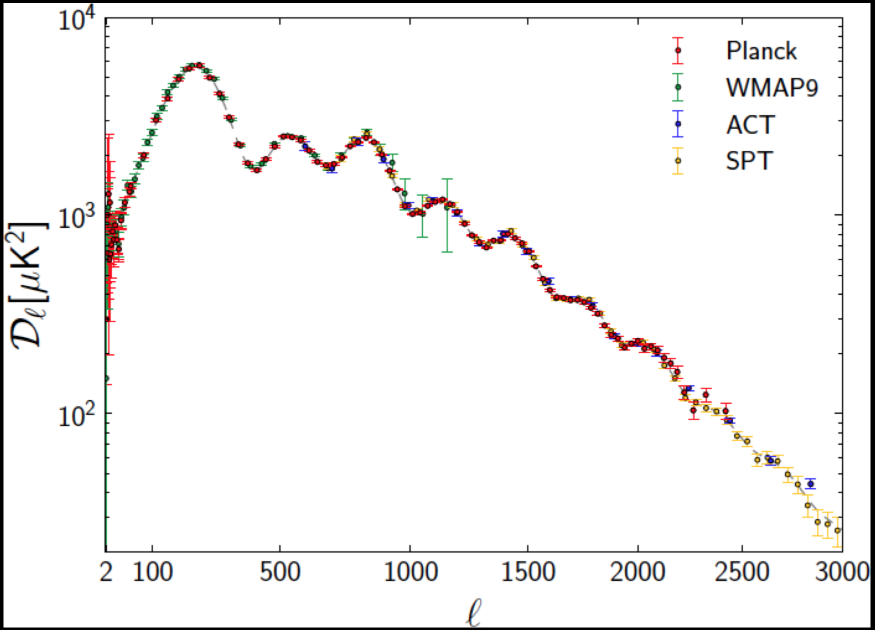
Cosmic Microwave Background (CMB)

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.

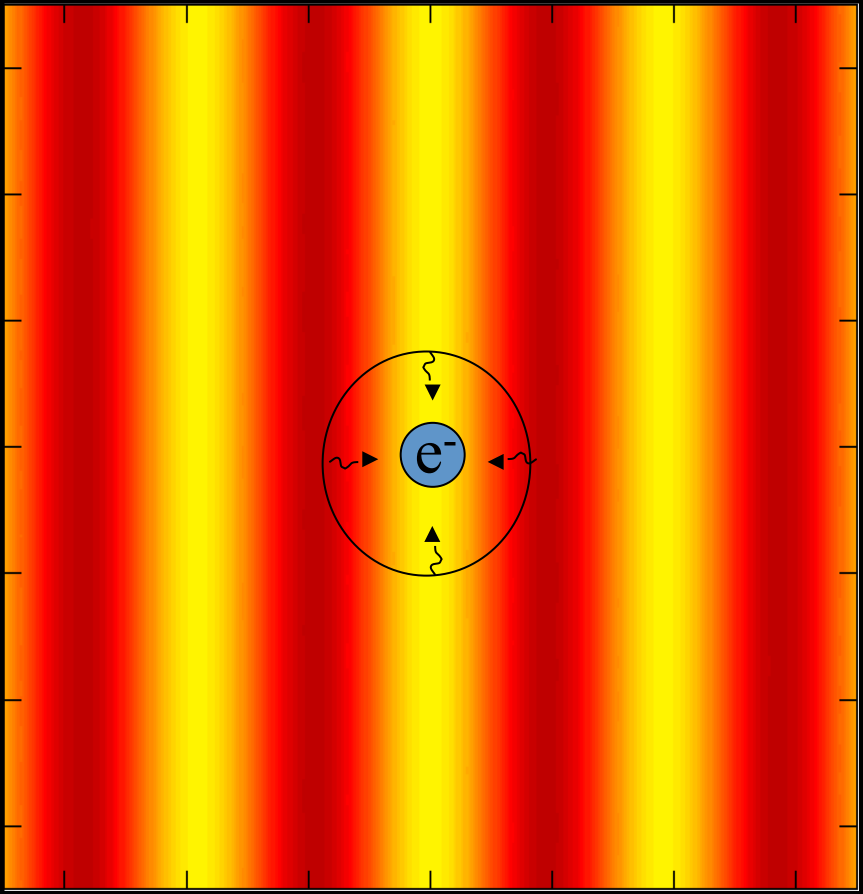
However, any imprint of the inflationary gravitational waves have so far eluded detection in the CMB.

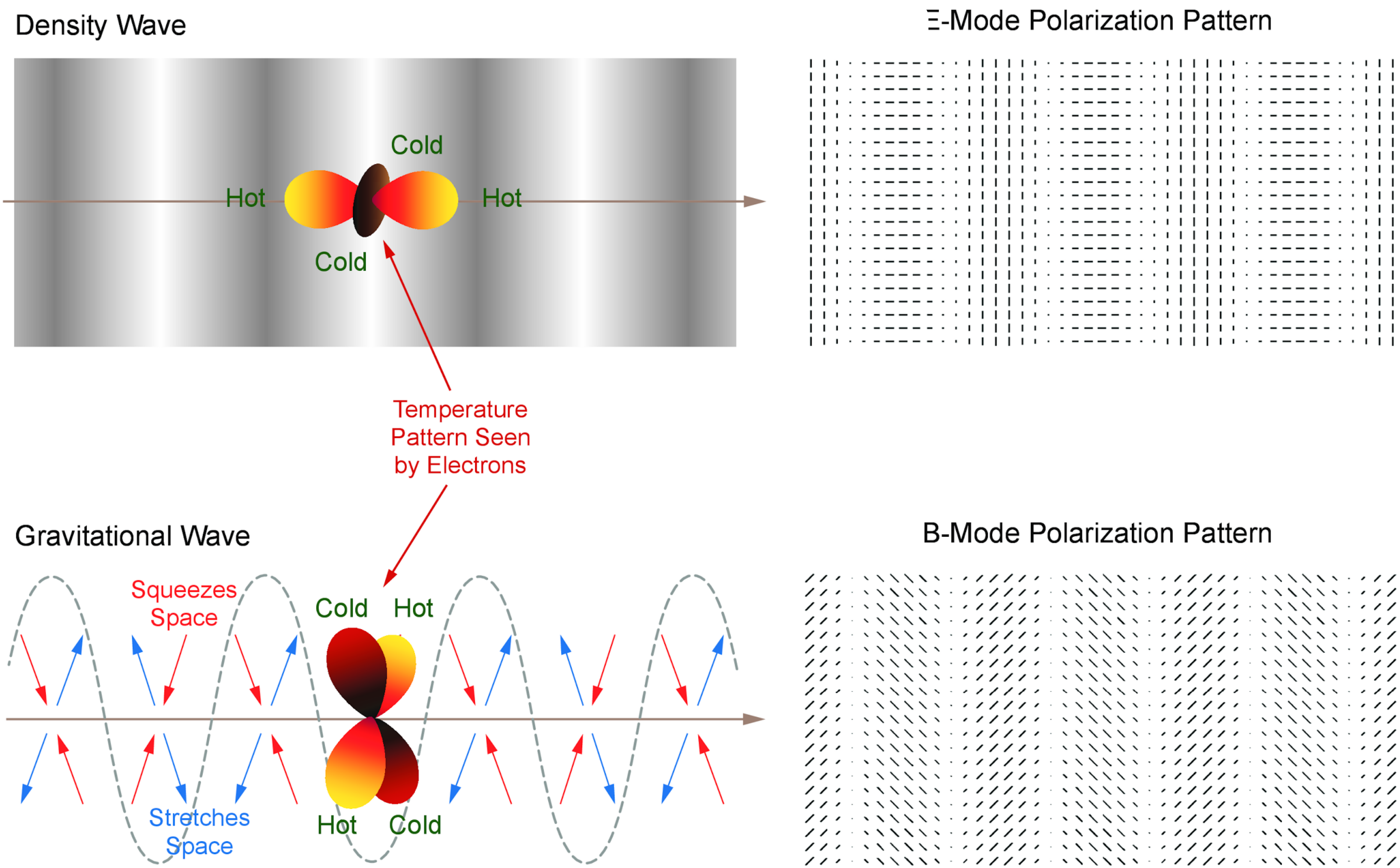




Planck Collaboration & ESA

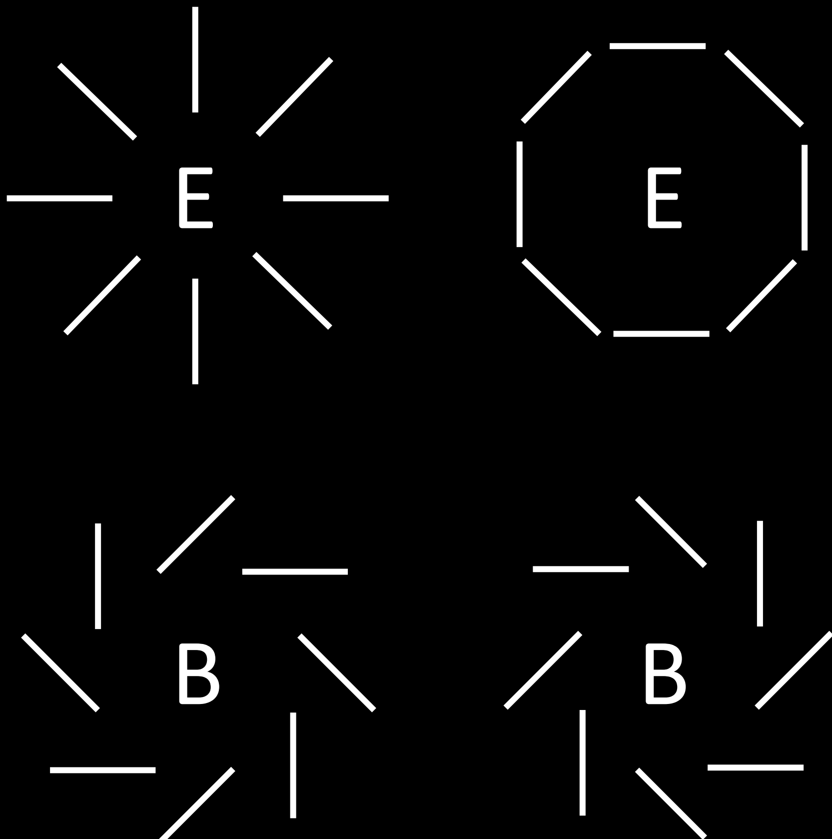
CMB polarization: scattering from sound waves





Density Wave
Cold
Hot
Hot
Cold
Ξ-Mode Polarization Pattern
Temperature
Pattern Seen
by Electrons
Gravitational Wave
B-Mode Polarization Pattern
Squeezes
Space
Cold
Hot
Stretches
Space
Hot
Cold

CMB Polarization



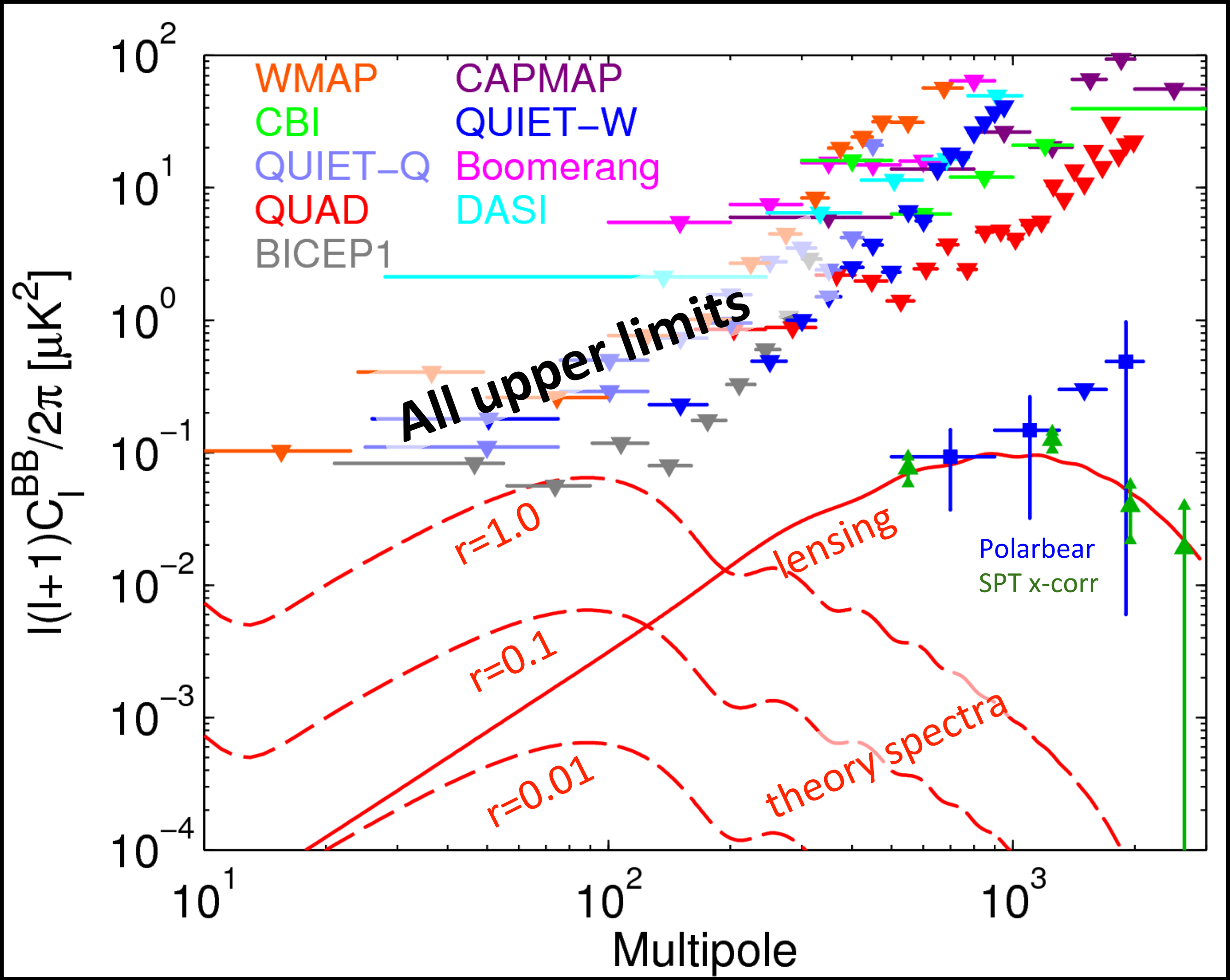
The plasma physics of the early universe causes the CMB to become slightly polarized.

Polarization can be described as the sum of E-modes and B-modes.

Only inflationary gravitational waves can induce significant B-mode polarization on degree angular scales.

A measurement of degree-scale B-modes would be direct evidence for the gravitational wave background, free of the parameter degeneracies and cosmic variance inherent to temperature measurements.

Search for B-modes



In simple inflationary gravitational wave models the

tensor-to-scalar ratio r

is the only parameter to the B-mode spectrum.

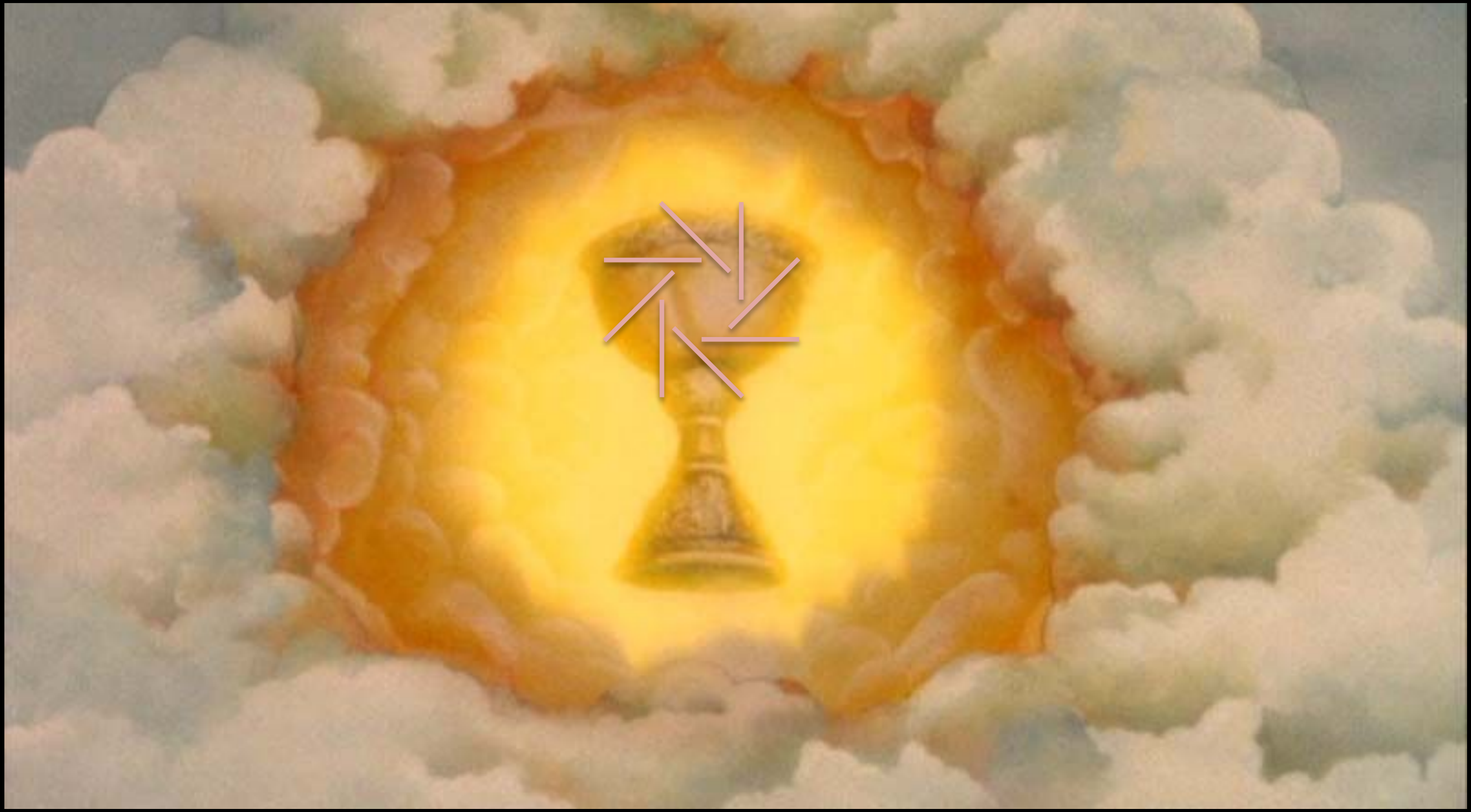
Up to now: just upper limits from searches for B-modes in the CMB polarization

Best limit on r:

r < 0.7 (95% CL)
At high multipoles lensing B-mode dominant.

SPT x-corr: lower limits on lensing B-mode from cross correlation using the CIB

“Holy grail” of cosmology?

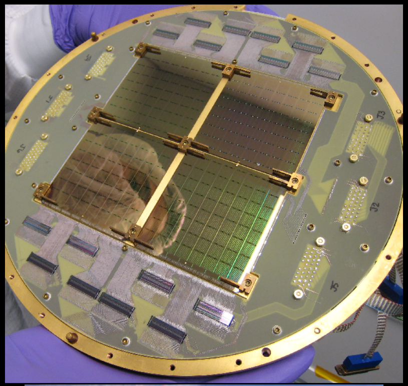


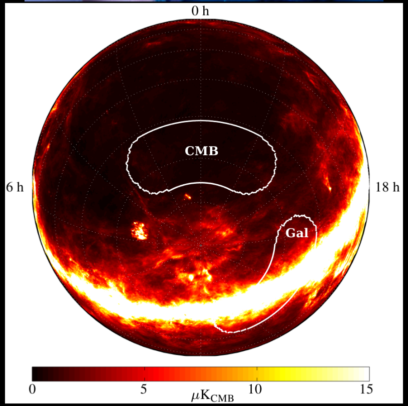
…or a wild goose chase?


VE RI TAS
HARVARD
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
cea
UCSD
JPL
NIST
CARDIFF UNIVERSITY
UNIVERSITY OF TORONTO
UBC

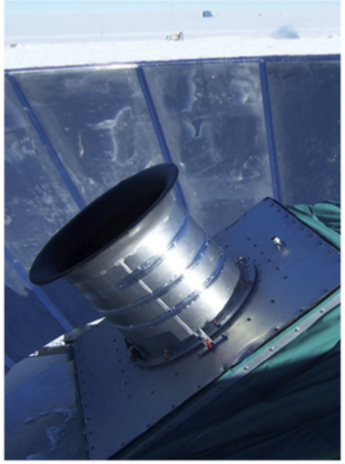
The Challenge

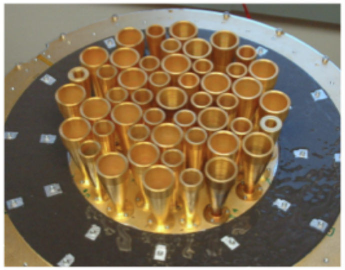
- Extremely faint signal demands a map that is…
- **Precise**
  Enormous raw sensitivity (10s of nK signal)
  Approach <u>photon noise limit</u>
  <u>Many</u> detectors (*multiplexing*)
  Observe from <u>pristine site</u>
- **Accurate**
  Rigid control of polarized <u>systematics</u>
- **Uncontaminated**
  Avoidance (or subtraction) of polarized <u>foregrounds</u>

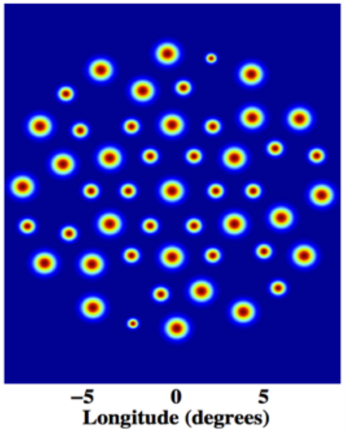




BICEP (2006–2008)

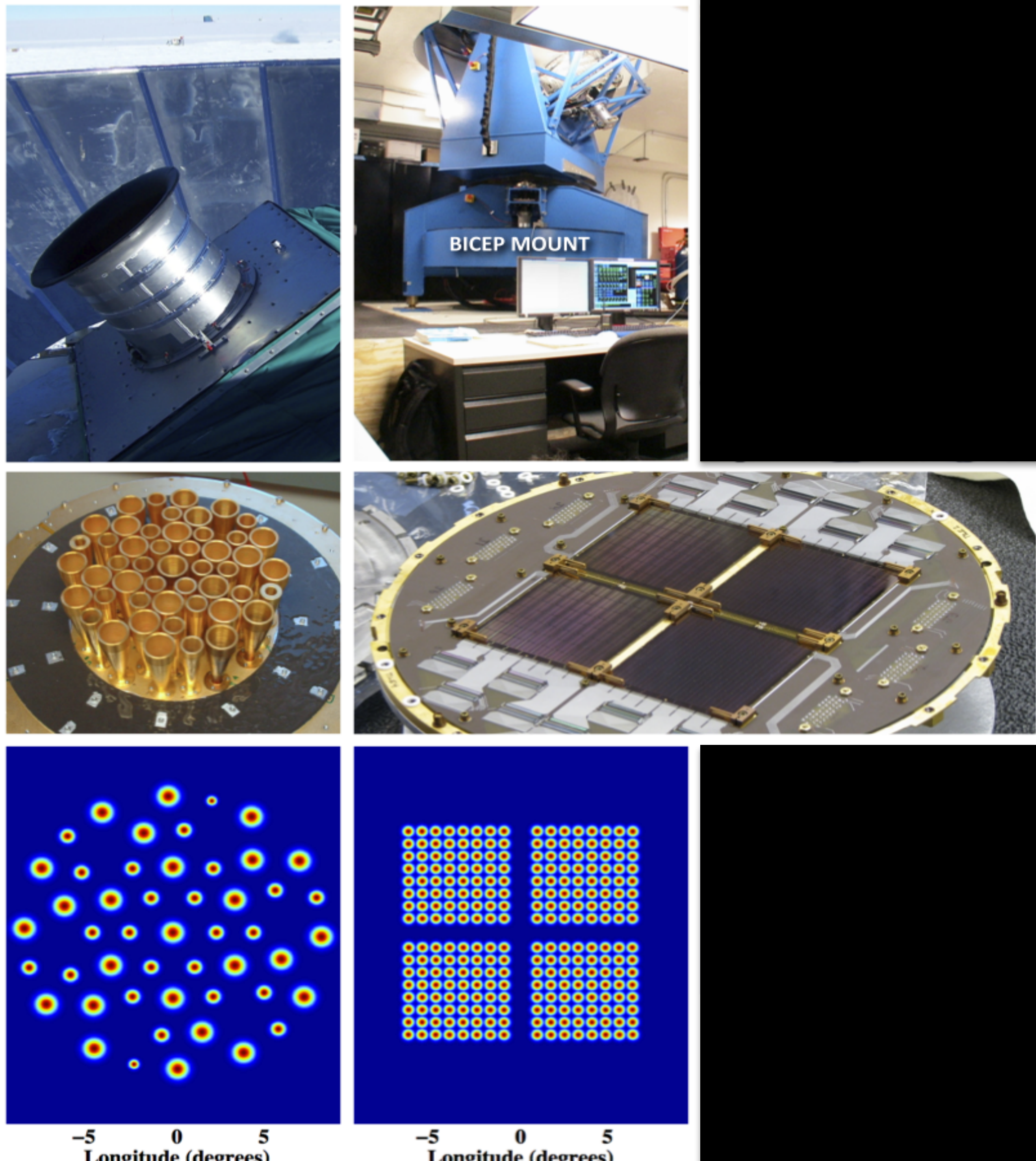






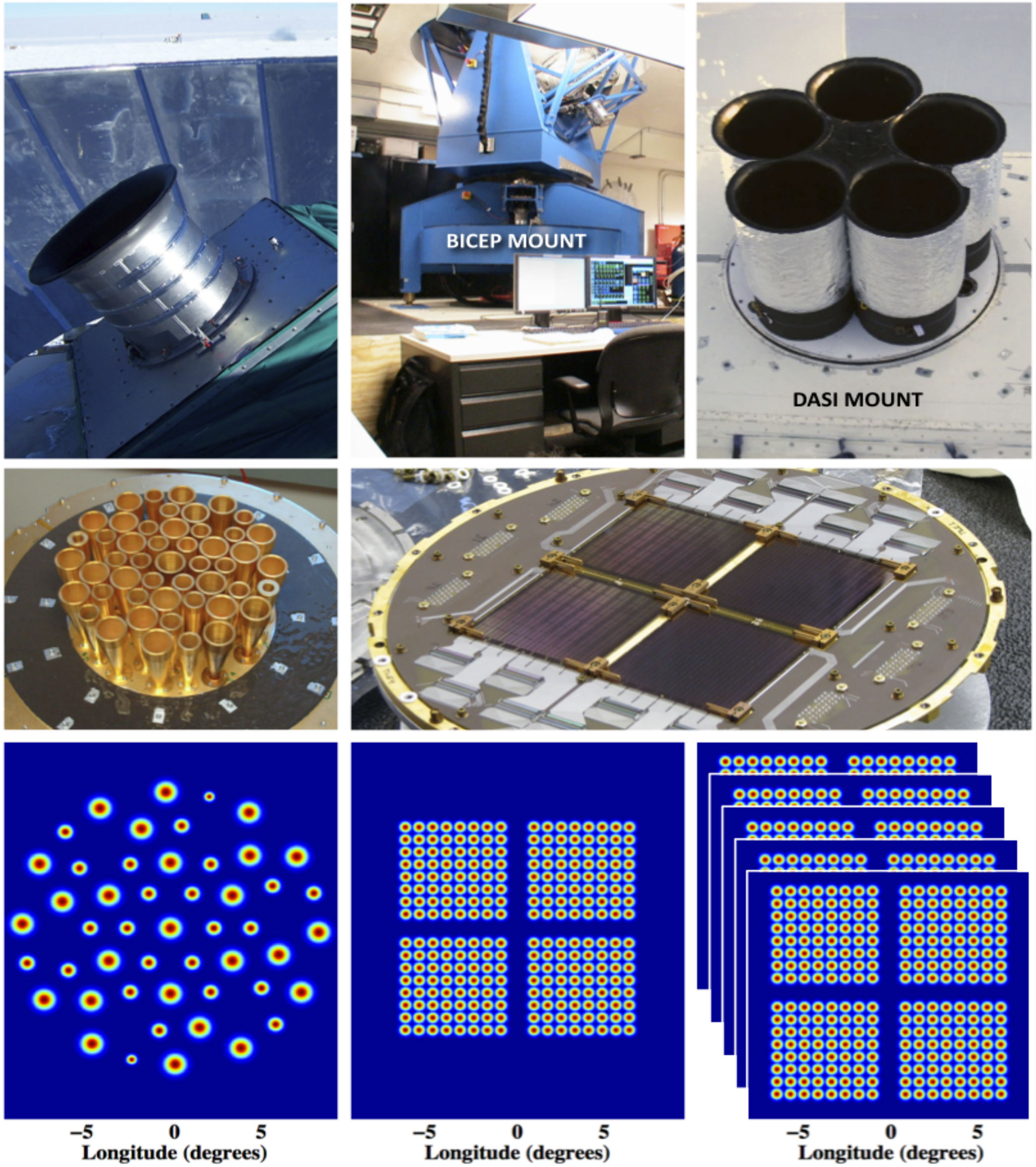
98 NTDs (95/150 GHz)
0.93°/0.60° FWHM
18° FOV
44 m² deg² AΩ

BICEP (2006–2008)	BICEP2 (2010–2012)



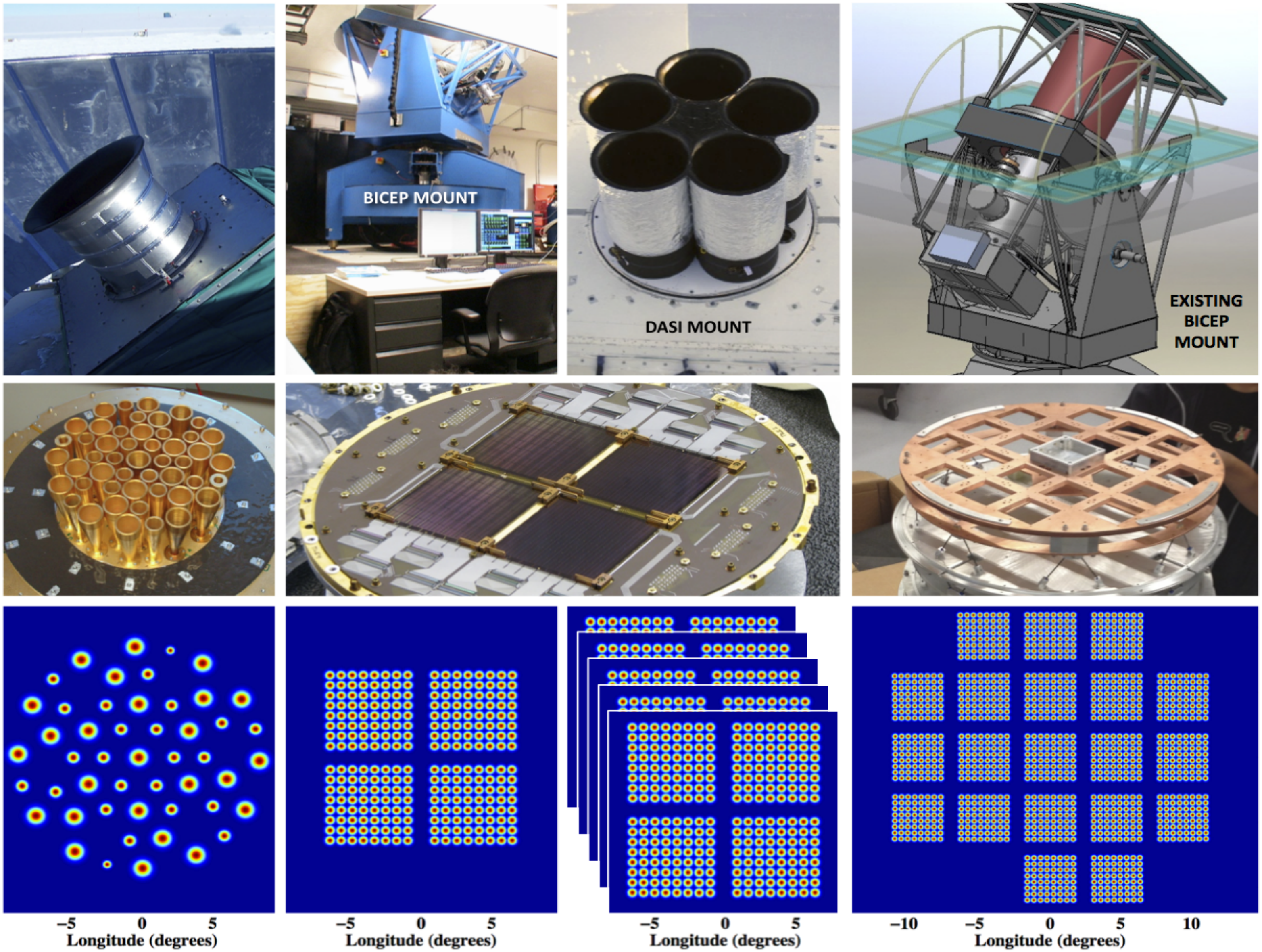
98 NTDs (95/150 GHz)	512 TESs (150 GHz)
0.93°/0.60° FWHM	0.52° FWHM
18° FOV	17° FOV
44 m² deg² AΩ	44 m² deg² AΩ

BICEP (2006–2008)	BICEP2 (2010–2012)	SPUD (2011–)



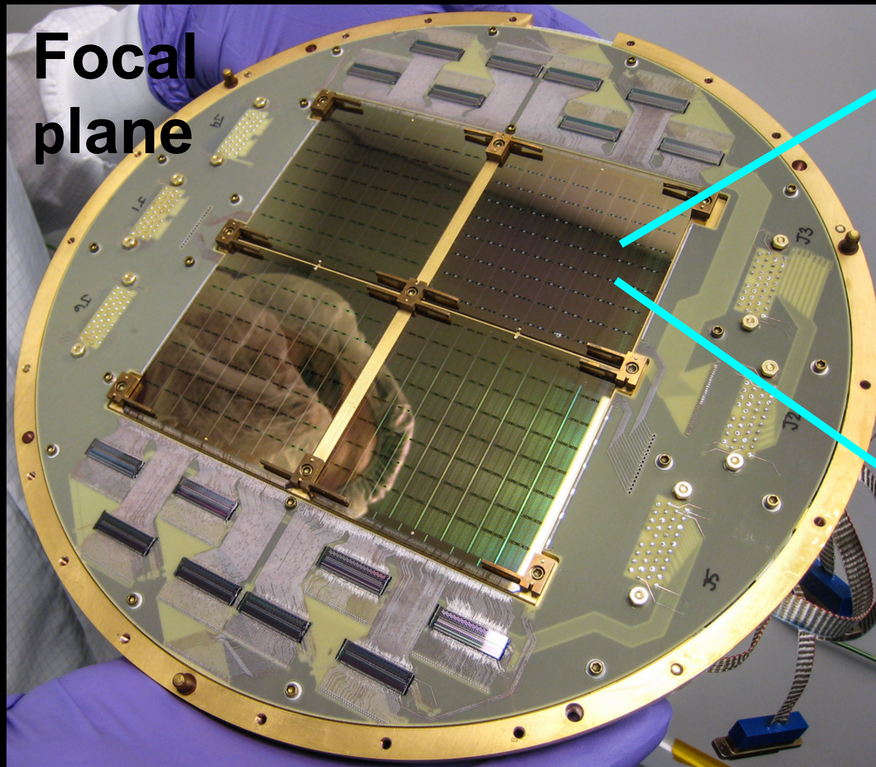
BICEP (2006–2008)	BICEP2 (2010–2012)	SPUD (2011–)
98 NTDs (95/150 GHz)	512 TESs (150 GHz)	2560 TESs (150 GHz)
0.93°/0.60° FWHM	0.52° FWHM	
18° FOV	17° FOV	
44 m² deg² AΩ	44 m² deg² AΩ	222 m² deg² AΩ

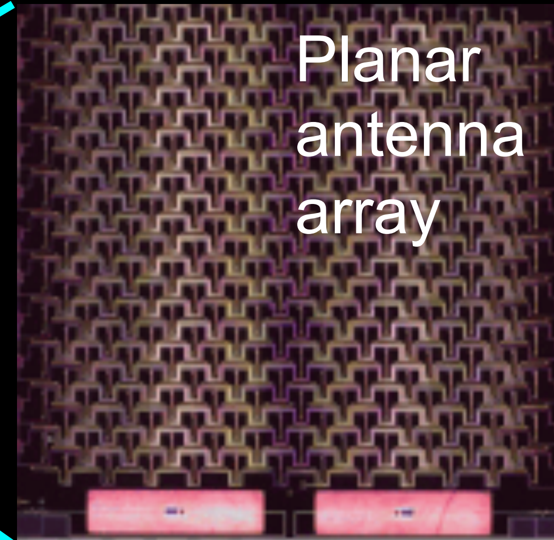
BICEP (2006–2008)	BICEP2 (2010–2012)	SPUD (2011–)	BICEP3 (2014-)

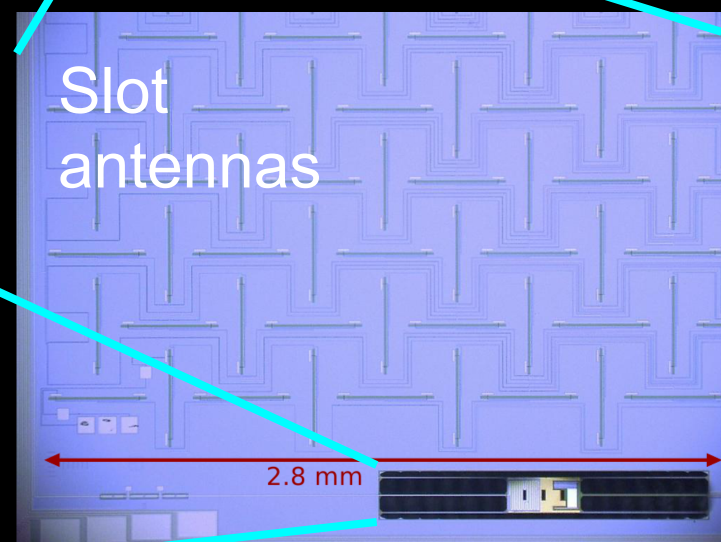


98 NTDs (95/150 GHz)	512 TESs (150 GHz)	2560 TESs (150 GHz)	2560 TESs (95 GHz)
0.93°/0.60° FWHM	0.52° FWHM		0.37° FWHM
18° FOV	17° FOV		26° FOV
44 m² deg² AΩ	44 m² deg² AΩ	222 m² deg² AΩ	502 m² deg² AΩ optical throughput

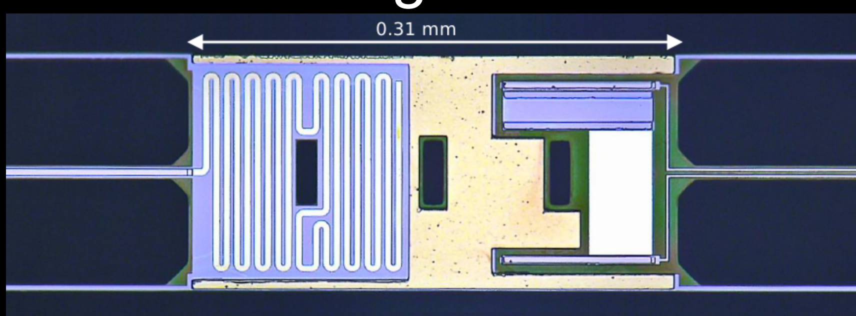
“Polarimeter on a chip”





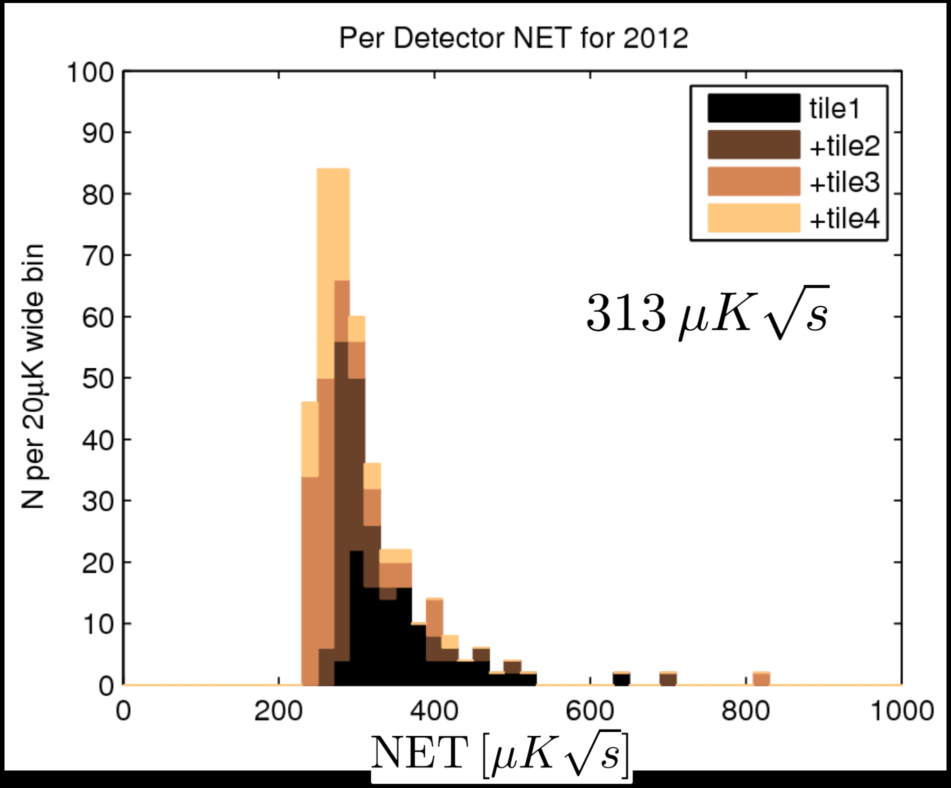


Transition edge sensor



Microstrip filters

BICEP2 Sensitivity



Histogram shows per-detector noise equivalent temperature (NET) for data taken in 2012

Our recipe for high sensitivity:

→ High optical efficiency
40% end-to-end

→ Cold optics
Low loading/photon noise
Low thermal conductance, and thus low phonon noise

→ High detector count

Total Sensitivity for full BICEP2 instrument: 15.8 μK √s

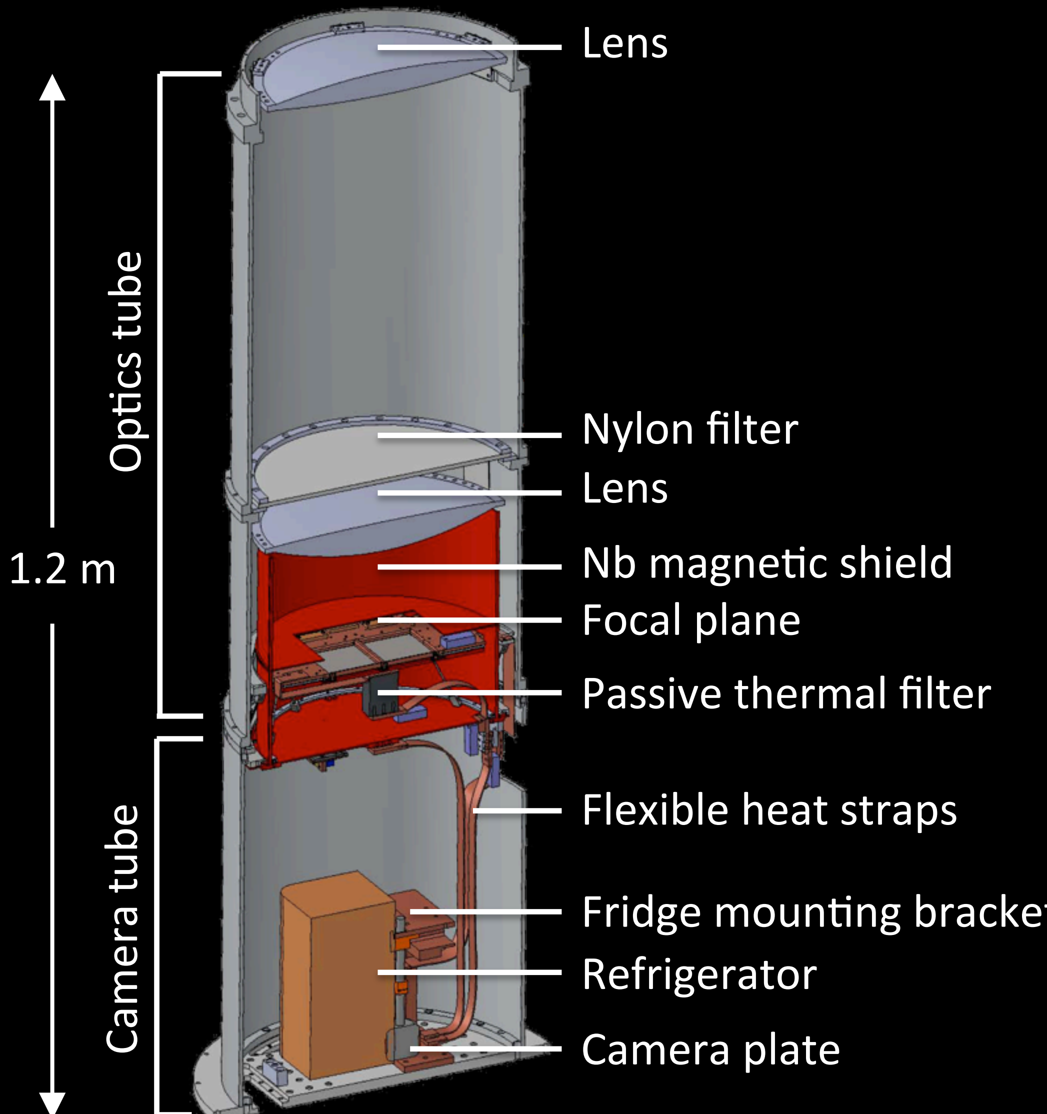
“Telescope in a can”

Telescope as compact as possible while still having the angular resolution to observe degree-scale features.

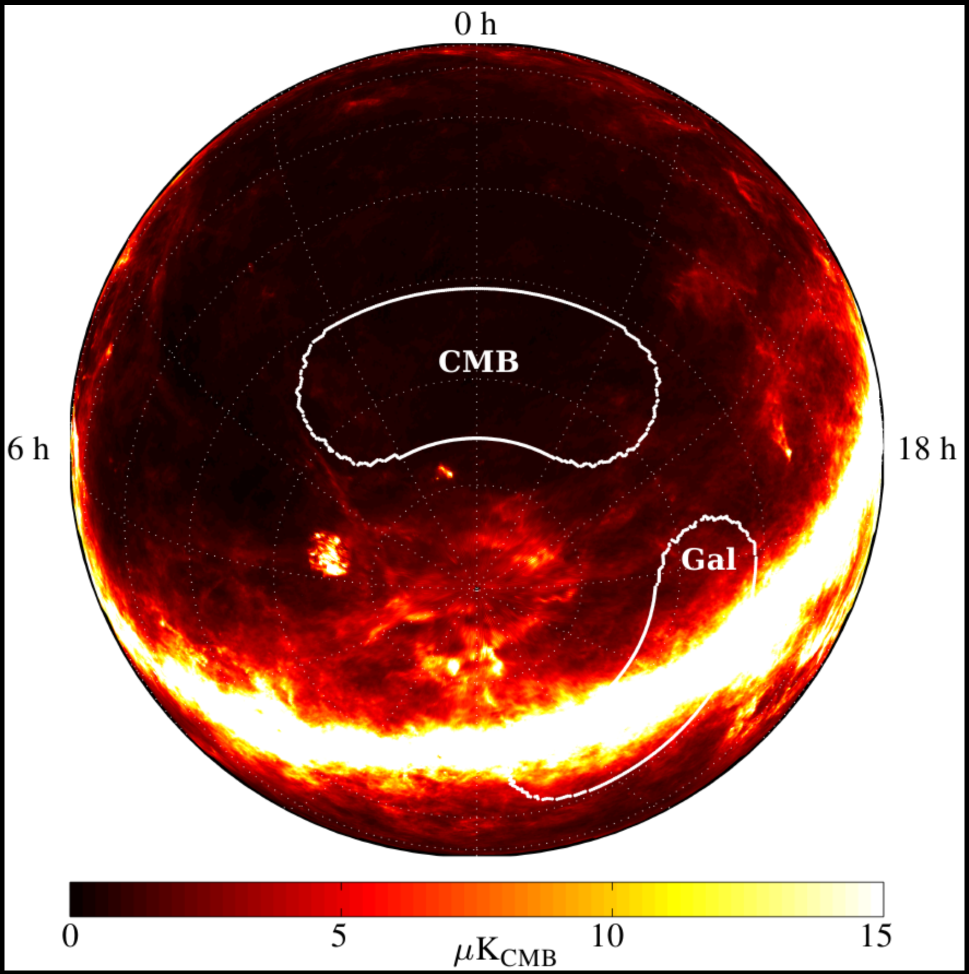
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

Liquid helium cools the optical elements to 4.2 K.

A 3-stage helium sorption refrigerator further cools the detectors to 0.27 K.



Observational Strategy



Target the "Southern Hole" - a region of the sky exceptionally free of dust and synchrotron foregrounds.

Detectors tuned to 150 GHz, near the peak of the CMB's 2.7 K blackbody spectrum.

At 150 GHz the combined dust and synchrotron spectrum is predicted to be at a minimum in the Southern Hole.

Expected foreground contamination of the B-mode power: r ≤ ~0.01.

South Pole CMB telescopes

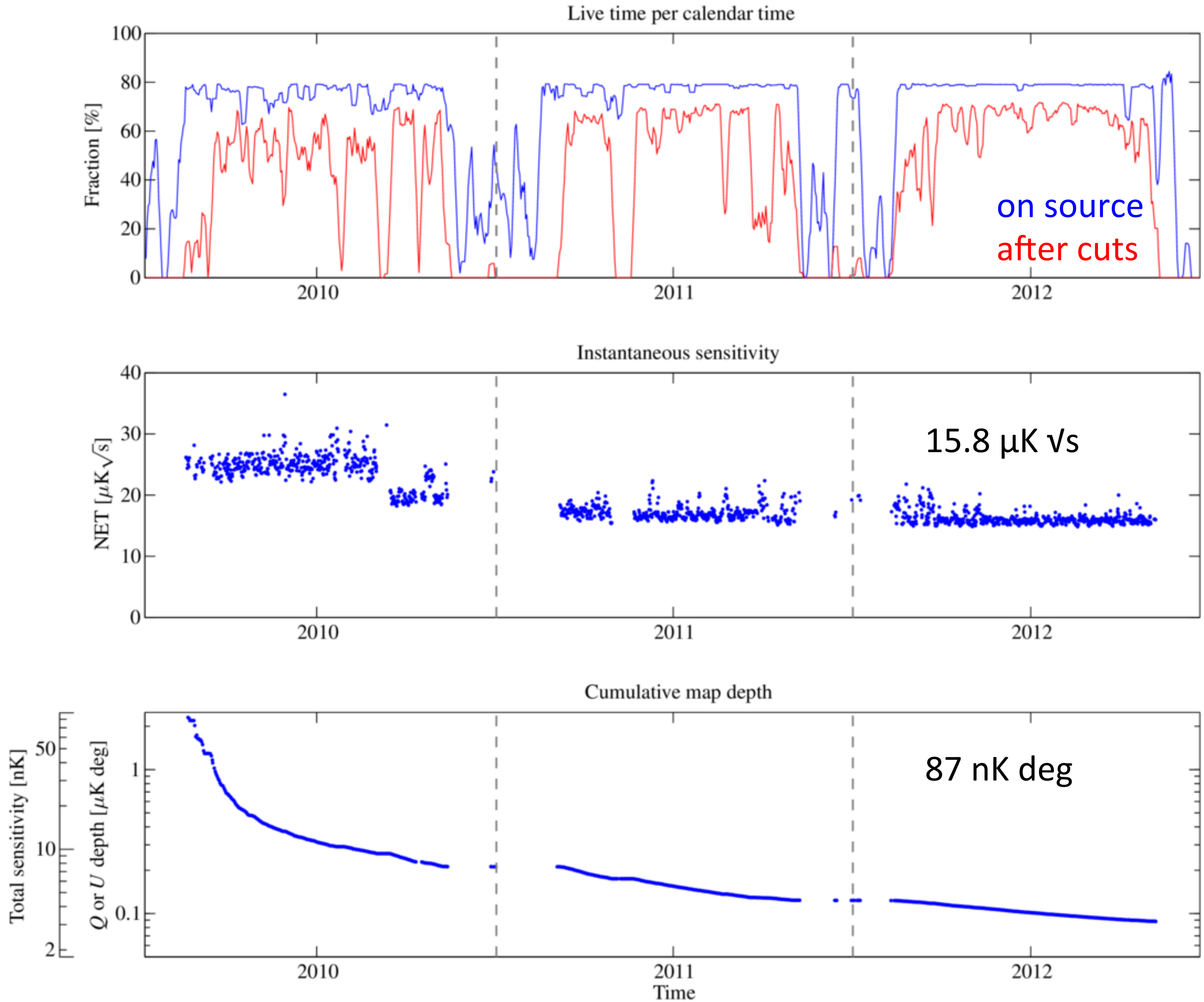
A popular place for CMB Experimentalists:

Power, LHe, LN2, 200 GB/day, 3 square meals, Open Mic Night...

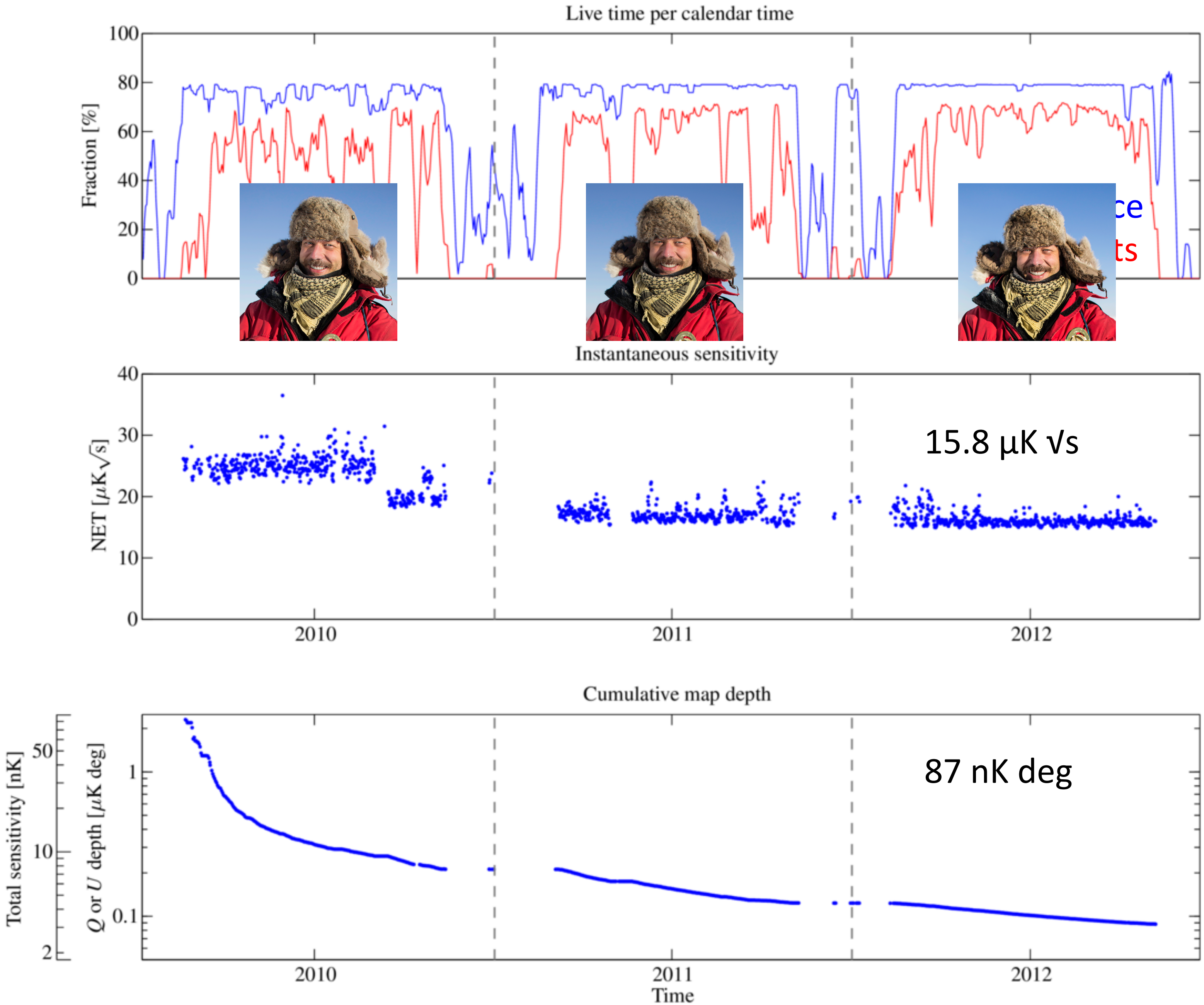
24h coverage of “Southern Hole”

South Pole CMB telescopes

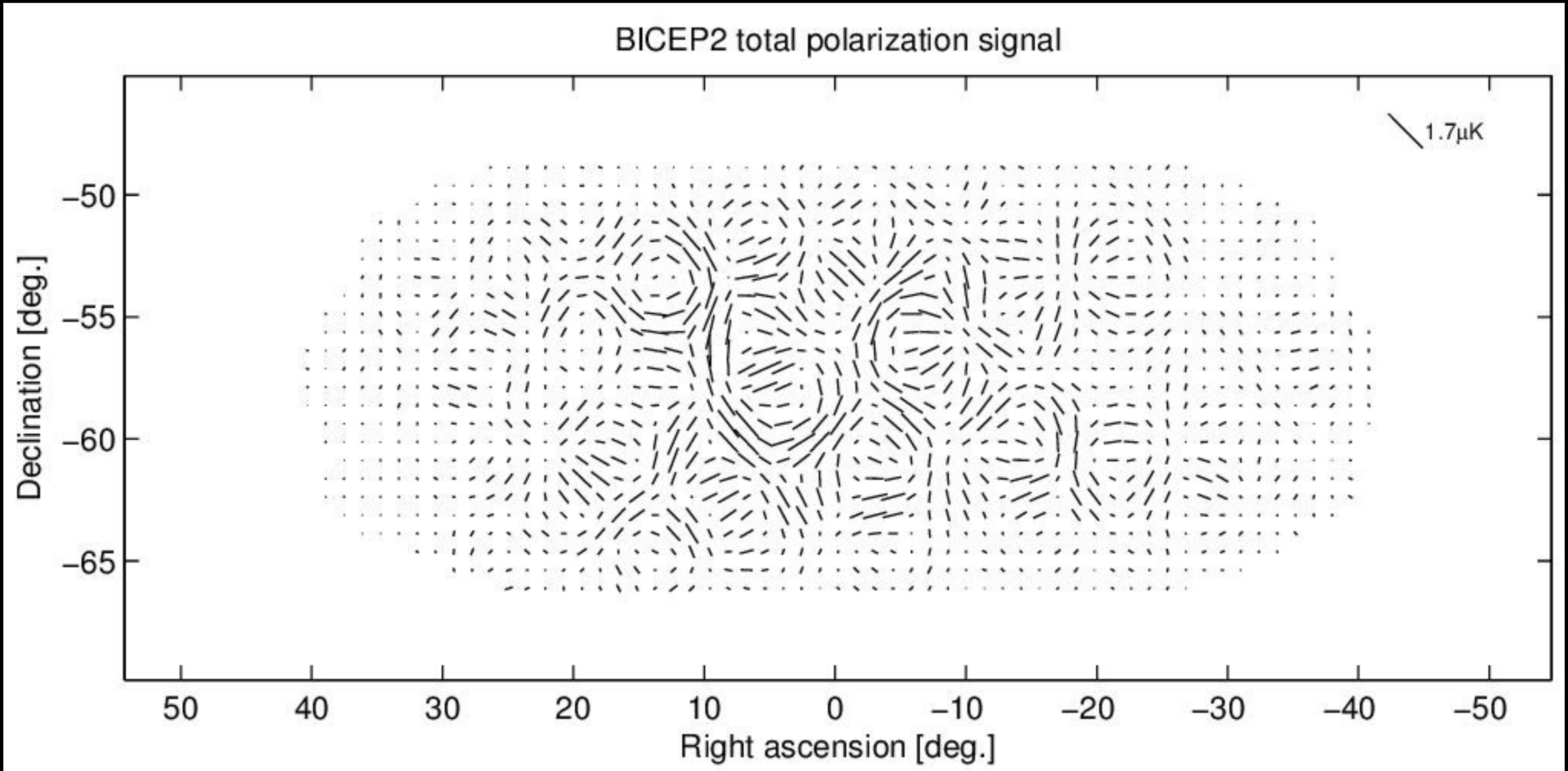
BICEP2 3-year Data Set



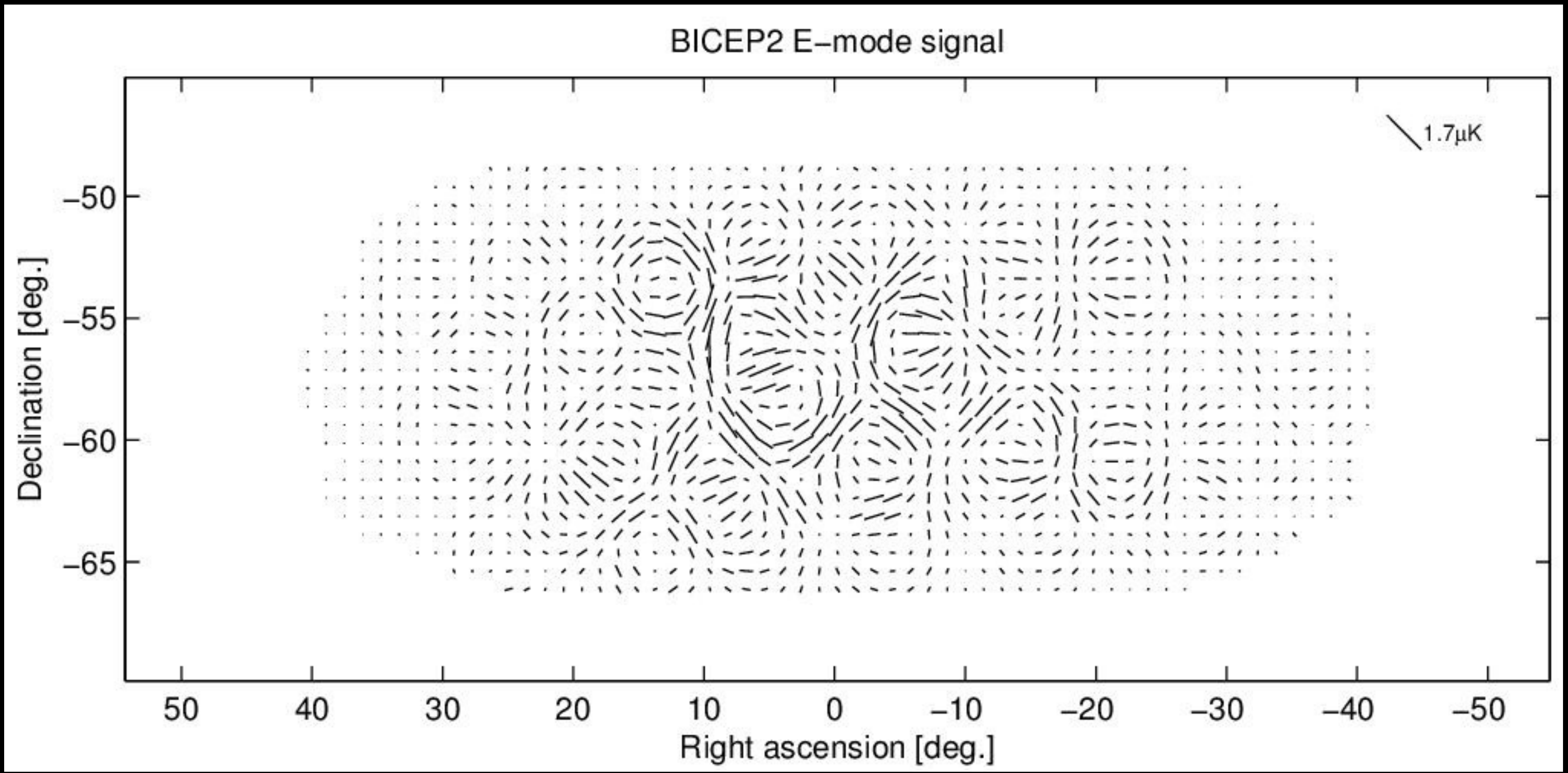
BICEP2 3-year Data Set



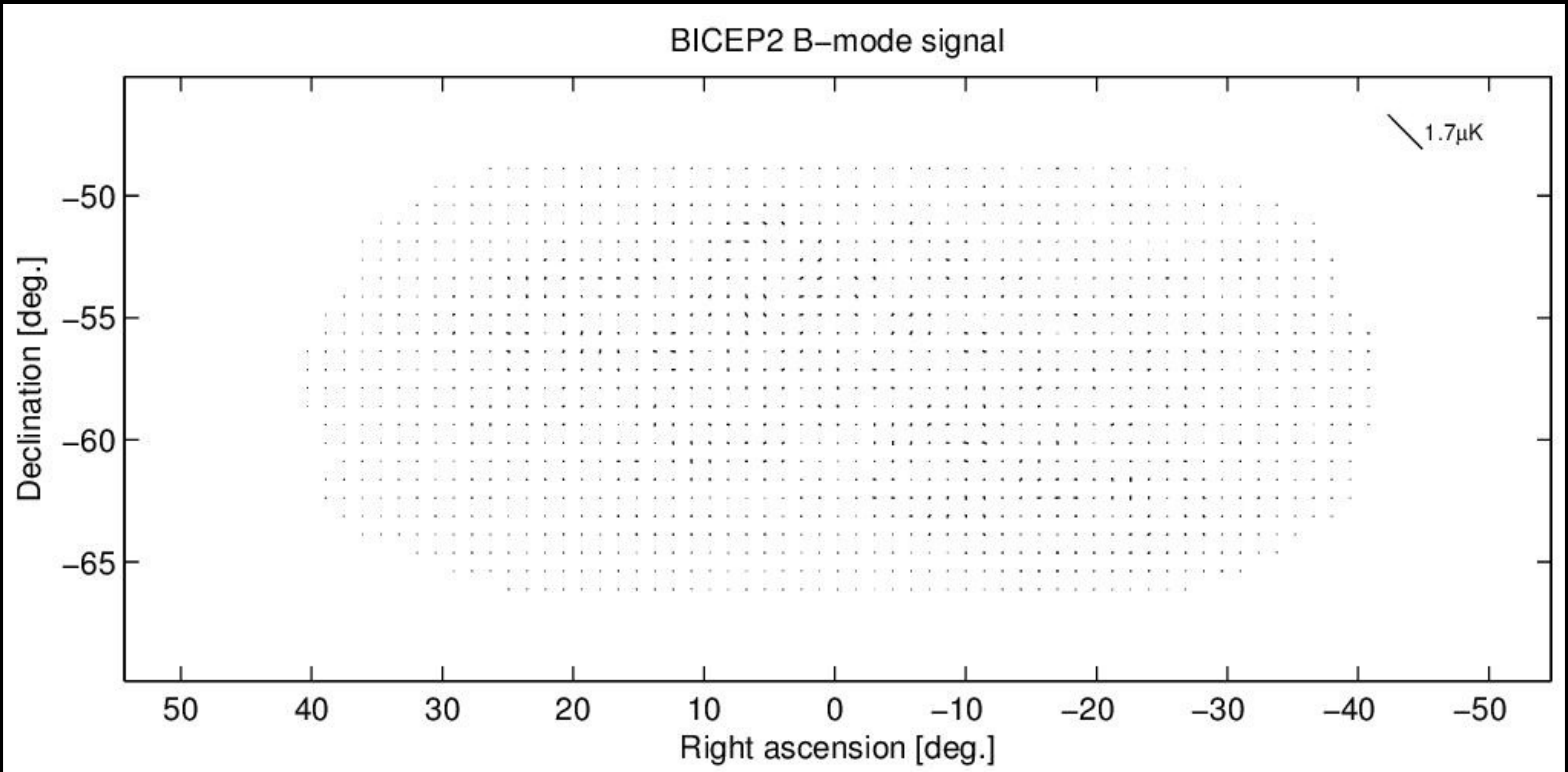
Total Polarization



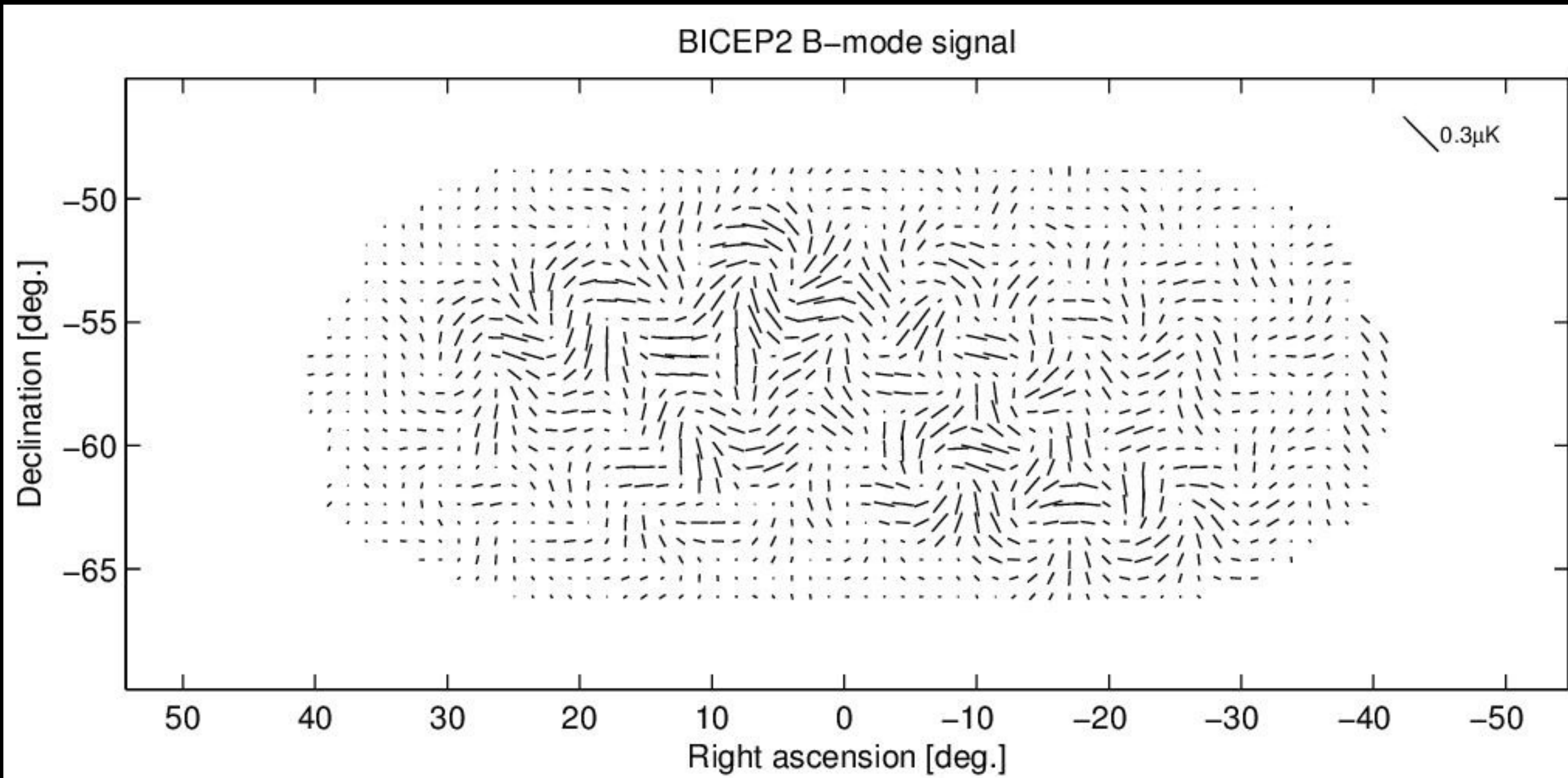
E-mode Signal



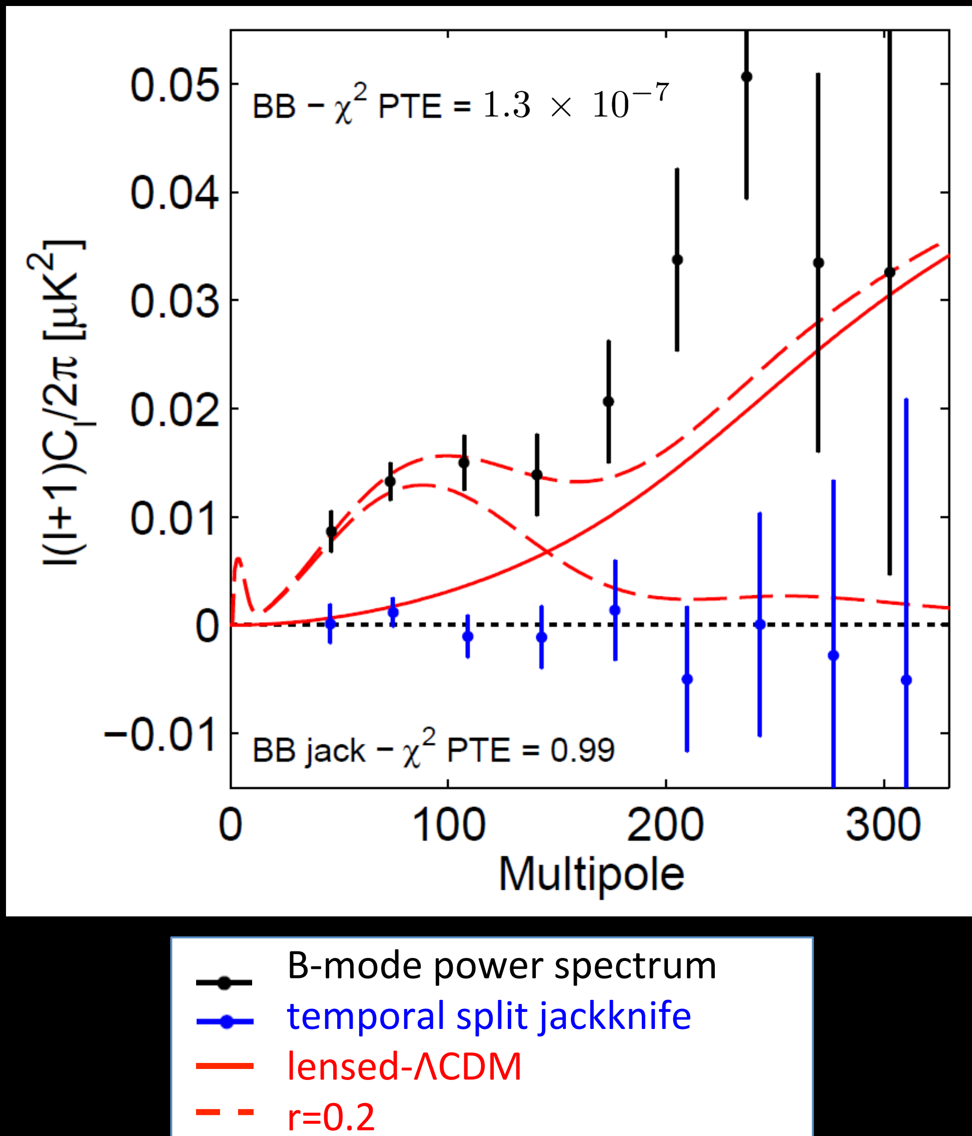
B-mode Signal



B-mode Signal



BICEP2 B-mode Power Spectrum



B-mode power spectrum estimated directly from Q&U maps, including map based "purification" to avoid E→B mixing

Consistent with lensing expectation at higher l.

At low l excesses over lensed-ΛCDM at high signal-to-noise.

For the hypothesis that the measured band powers come from lensed-ΛCDM we find:

PTE: 1.3×10^{-7}

Significance: 5.2σ

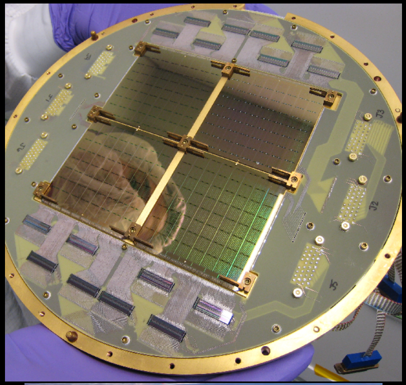
The Challenge

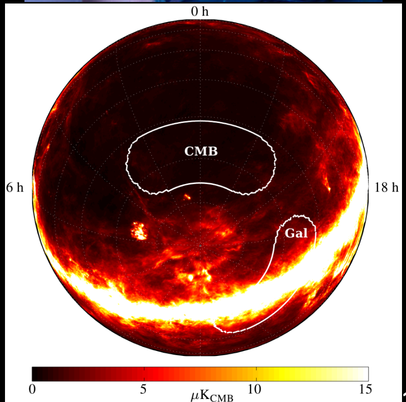
- Extremely faint signal demands a map that is...

- **Precise**
  Enormous raw sensitivity (10s of nK signal)
  Approach <u>photon noise limit</u>
  <u>Many</u> detectors (*multiplexing*)
  Observe from <u>pristine site</u>

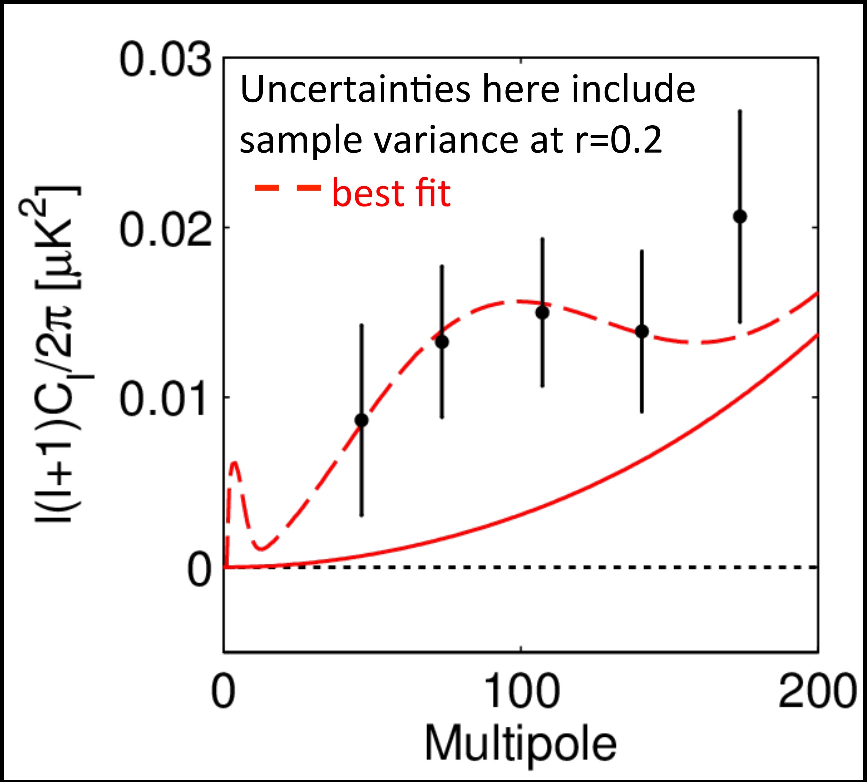
- **Accurate**
  Rigid control of polarized <u>systematics</u>
  Extensive instrument characterization
  Null tests, simulation of systematics

- **Uncontaminated**
  Avoidance (or subtraction) of polarized <u>foregrounds</u>
  Comparison with external dust+synchrotron maps
  Spectral index constraint





Constraint on Tensor-to-scalar Ratio r



Substantial excess power in the region where the inflationary gravitational wave signal is expected to peak

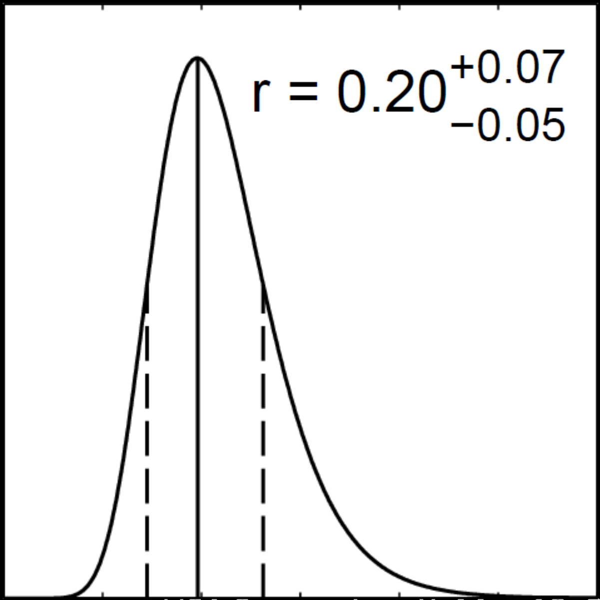
Find the most likely value of the tensor-to-scalar ratio r

Apply “direct likelihood” method, uses:

→ lensed-ΛCDM + noise simulations

→ weighted version of the 5 bandpowers

→ B-mode sims scaled to various levels of r (n_T=0)



Within this simplistic model we find:

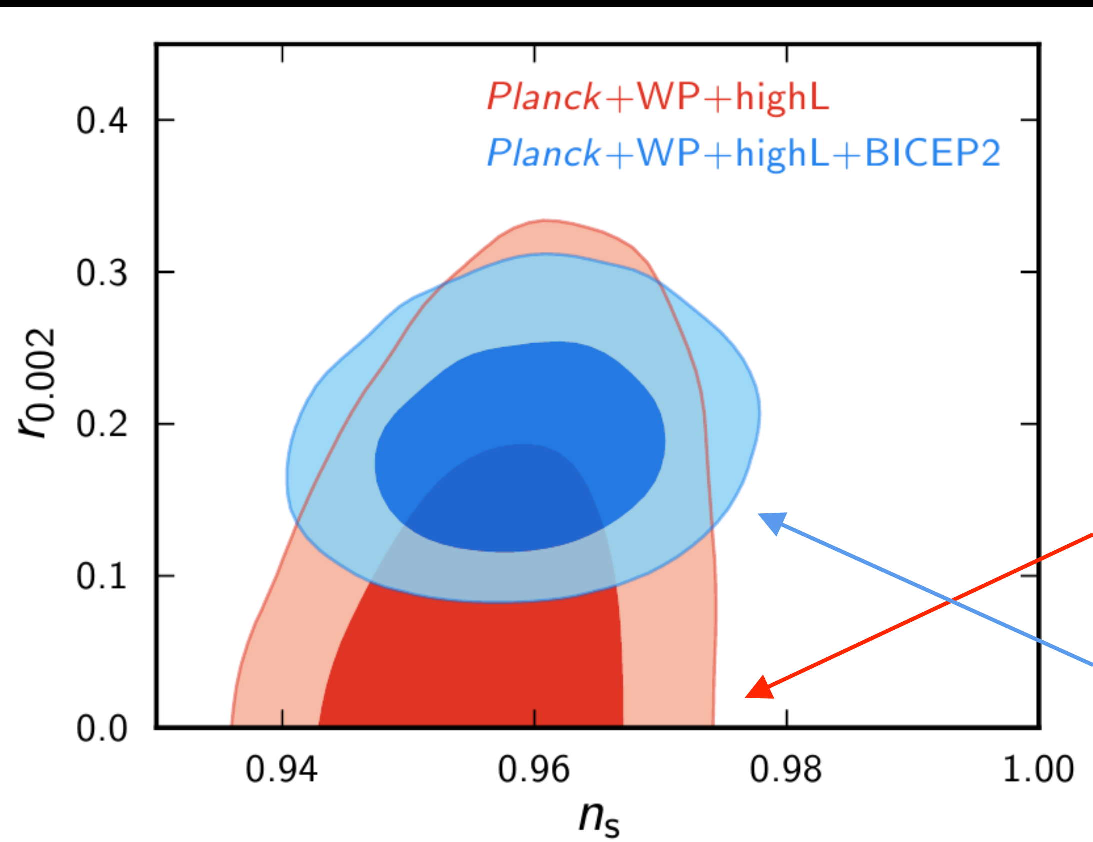
r = 0.2 with uncertainties dominated by sample variance

PTE of fit to data: 0.9
→ model is perfectly acceptable fit to the data

Non-existence of inflationary gravity waves r=0 ruled out at 7.0

Compatibility with Indirect Limits on r

Constraint on r *with running allowed*:



Indirect limit on r from combination of temperature data over a wide range of angular scales:

SPT+WMAP+BAO+H_0: r < 0.11
Planck+SPT+ACT+$WMAP_{pol}$: r < 0.11

This apparent tension can be relieved with various extensions to lensed ΛCDM.

Example: running of the spectral index

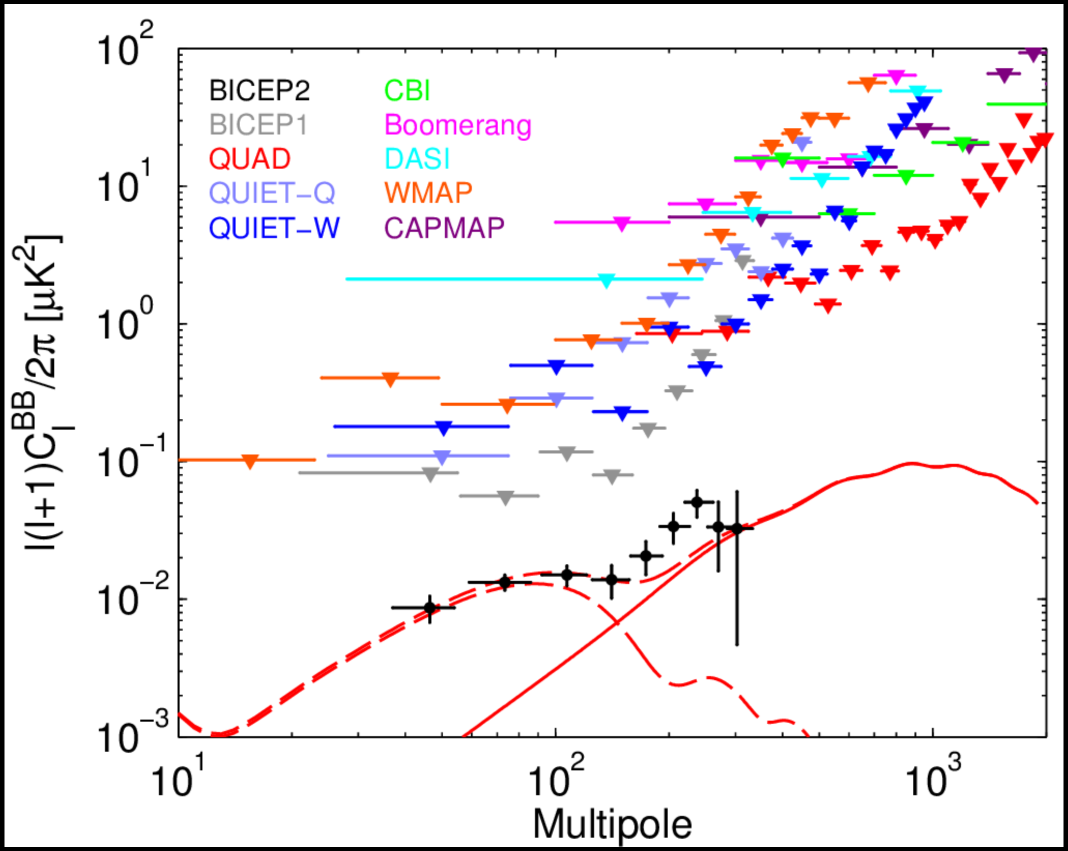
Planck likelihood chains for lensed ΛCDM + *tensors* + *running*

Same chains, importance sampled with the BICEP2 r likelihood

Other possibilities within ΛCDM?...

Conclusions

BICEP2 and upper limits from other experiments:



http://www.bicepkeck.org/bicep2_2014_release

Most sensitive polarization maps ever made

Power spectra perfectly consistent with lensed-ΛCDM except:
5.2σ excess in the B-mode spectrum at low multipoles!

Extensive studies and jackknife test strongly argue against systematics as the origin

Foregrounds do not appear to be a large fraction of the signal:

- → foreground projections
- → lack of cross correlations
- → CMB-like spectral index
- → shape of the B-mode spectrum

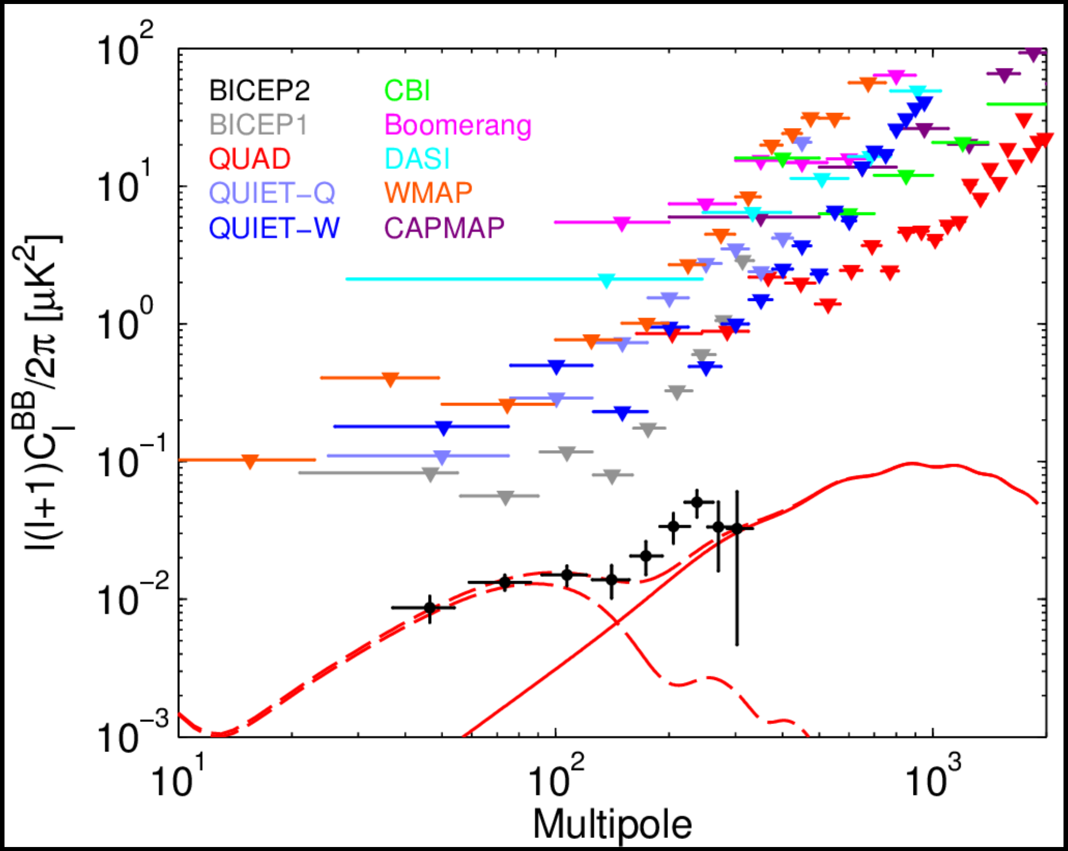
Constraint on tensor-to-scalar ratio r in simple inflationary gravity wave model:

$$r=0.20^{+0.07}_{-0.05}\ .$$

With r=0 is ruled out at 7.0σ.

Conclusions… so far

BICEP2 and upper limits from other experiments:



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