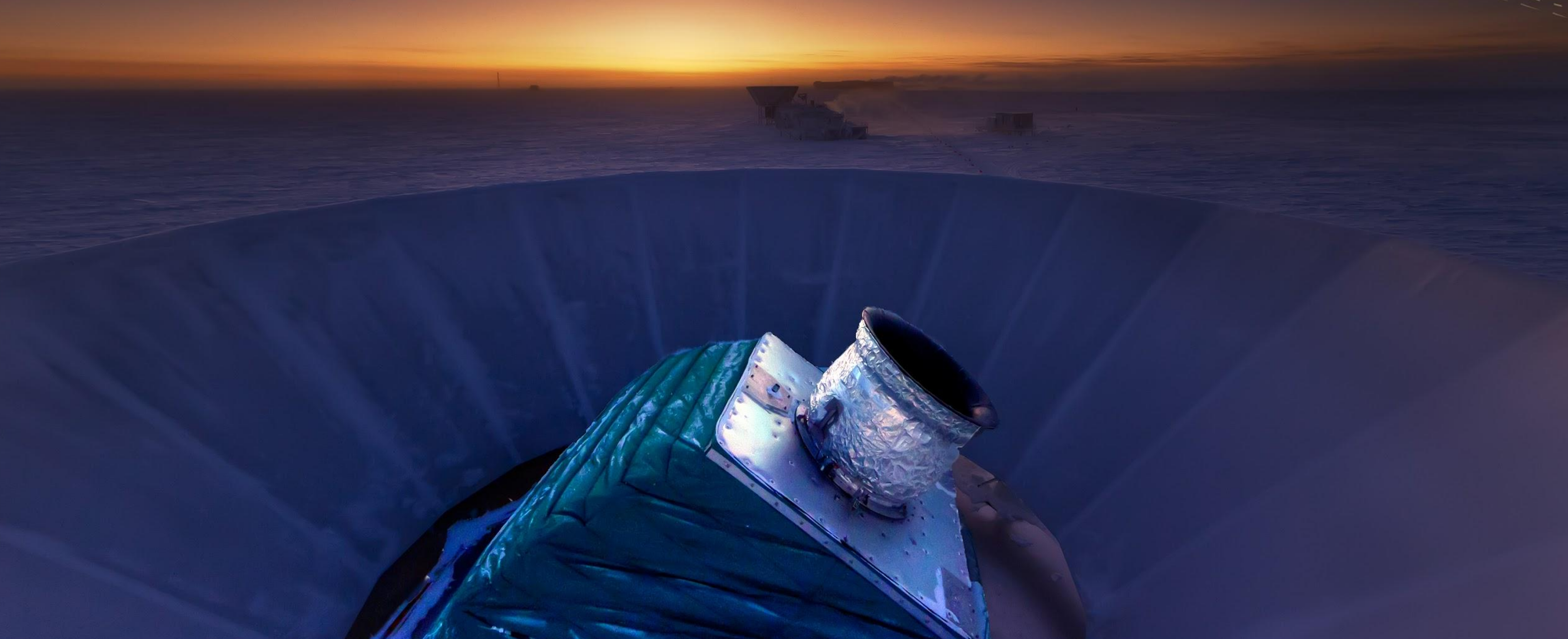
Detection of B-mode Polarization at Degree Scales using BICEP2



Angiola Orlando for the BICEP2 Collaboration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CARDIFF UNIVERSITY
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UNIVERSITY OF TORONTO
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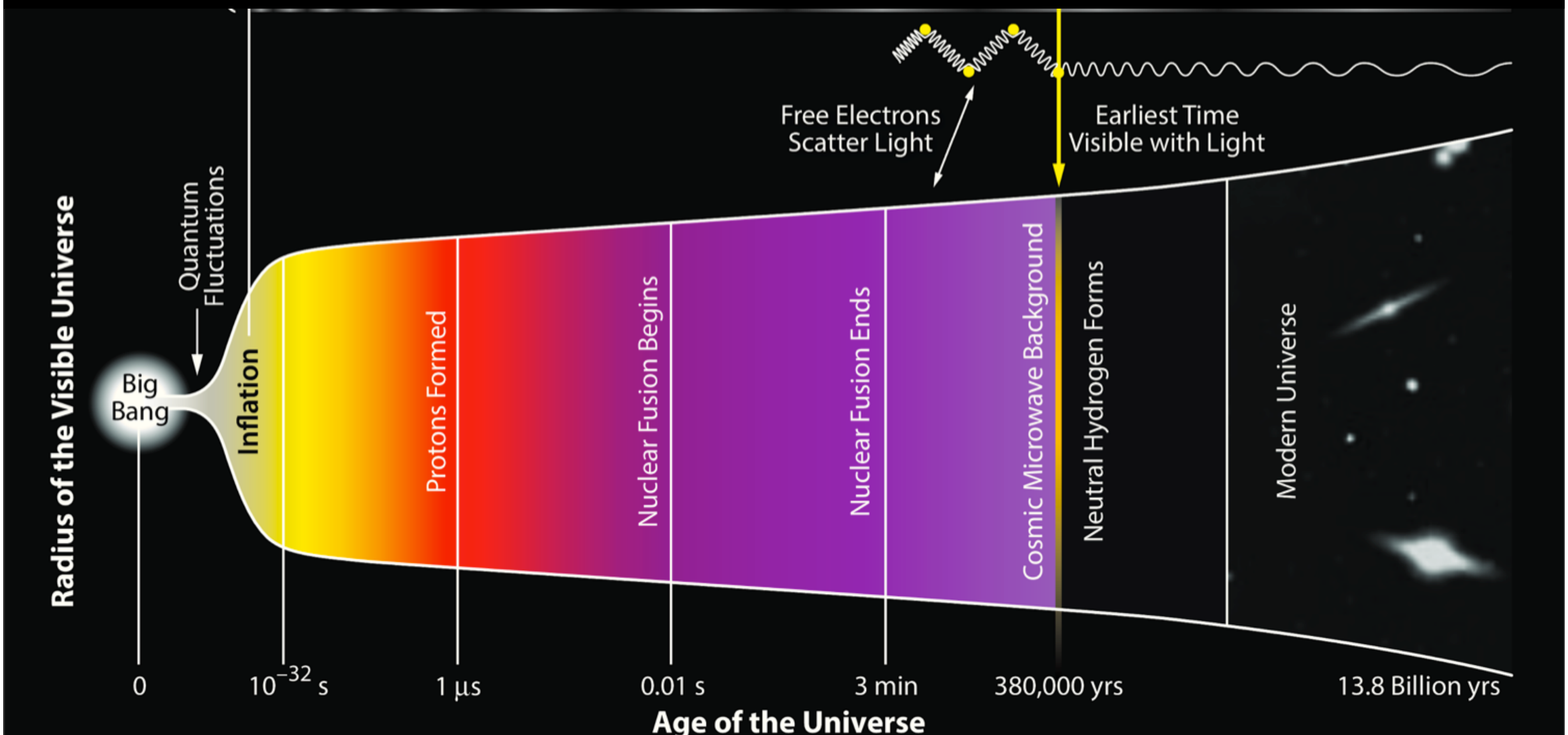
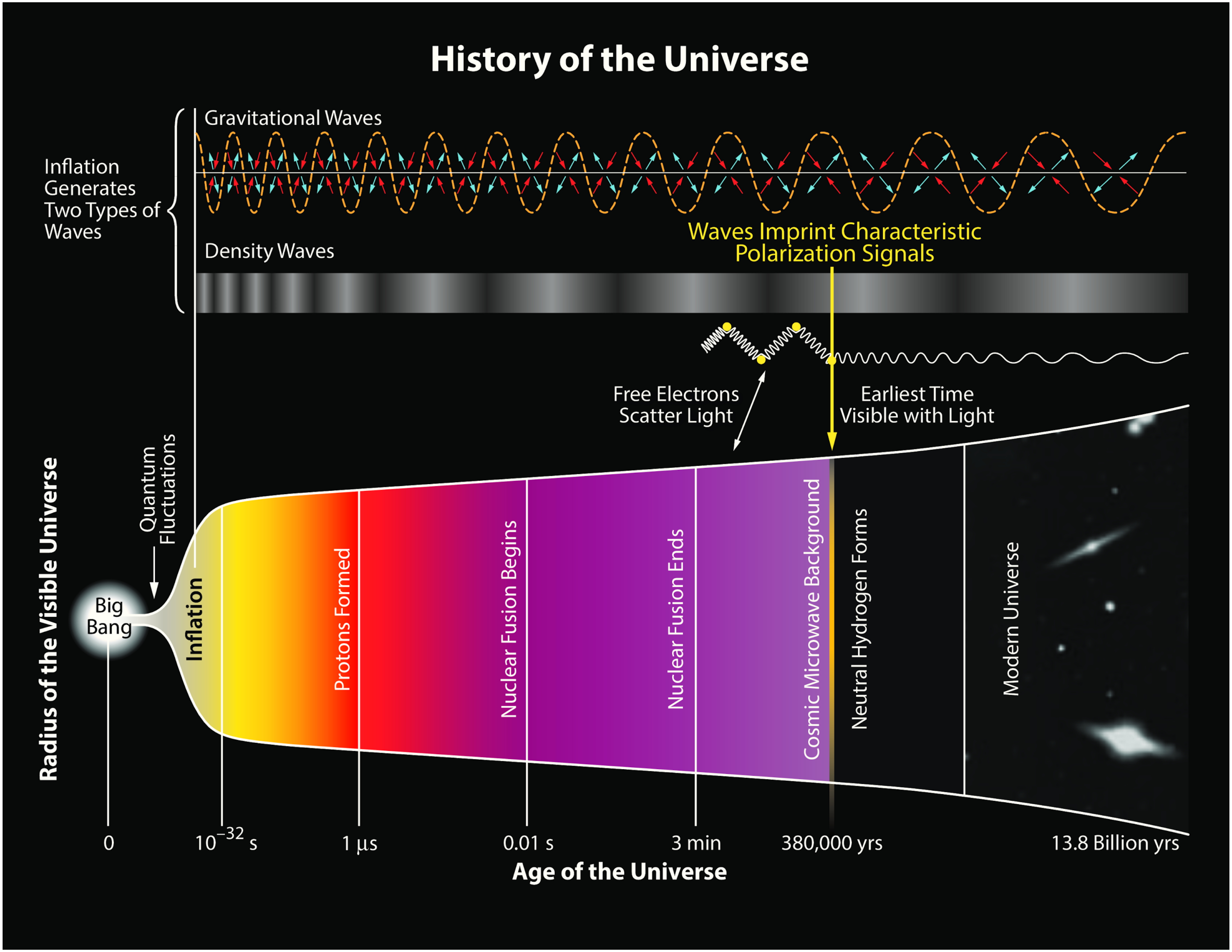
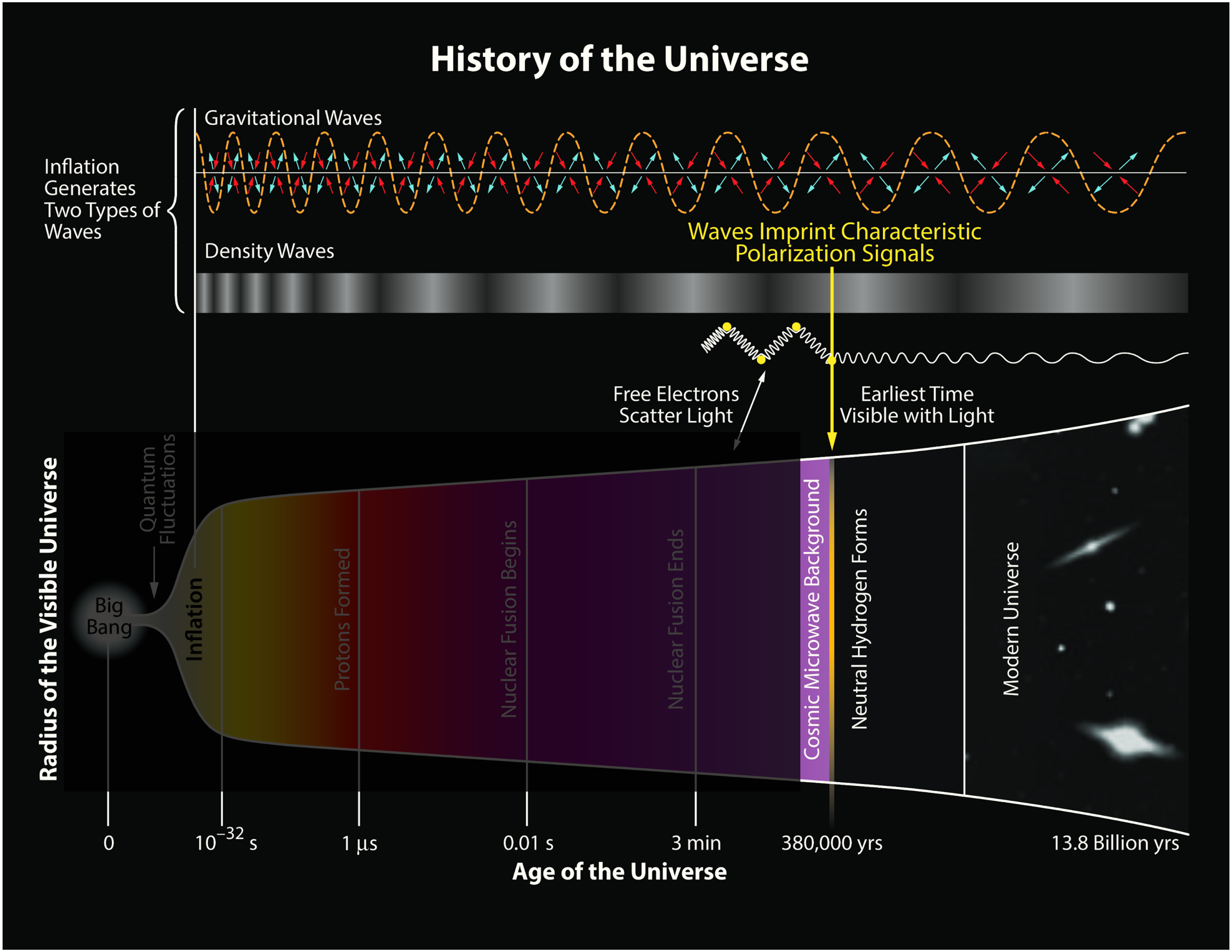
History of the Universe

Universe becomes transparent





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
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



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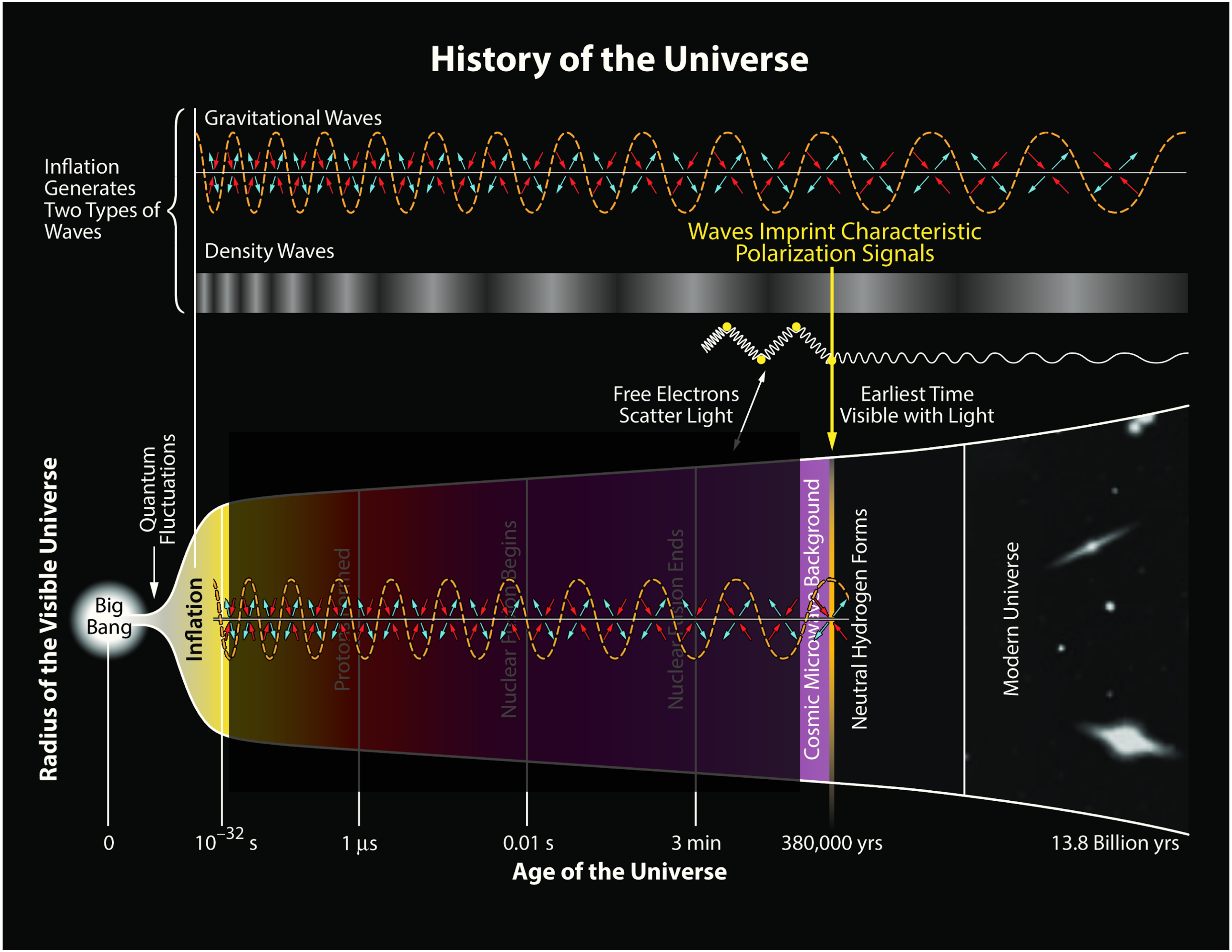
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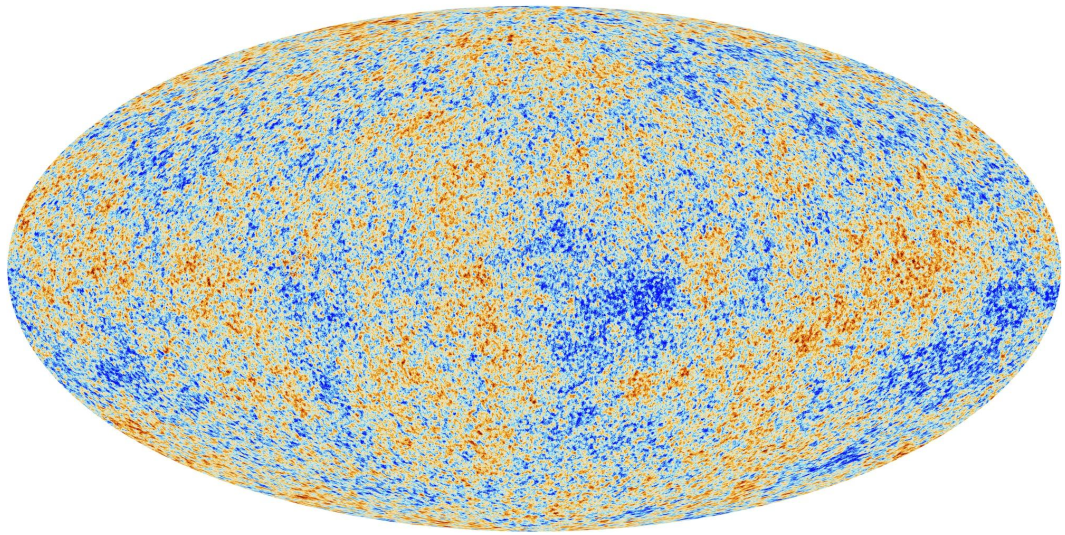
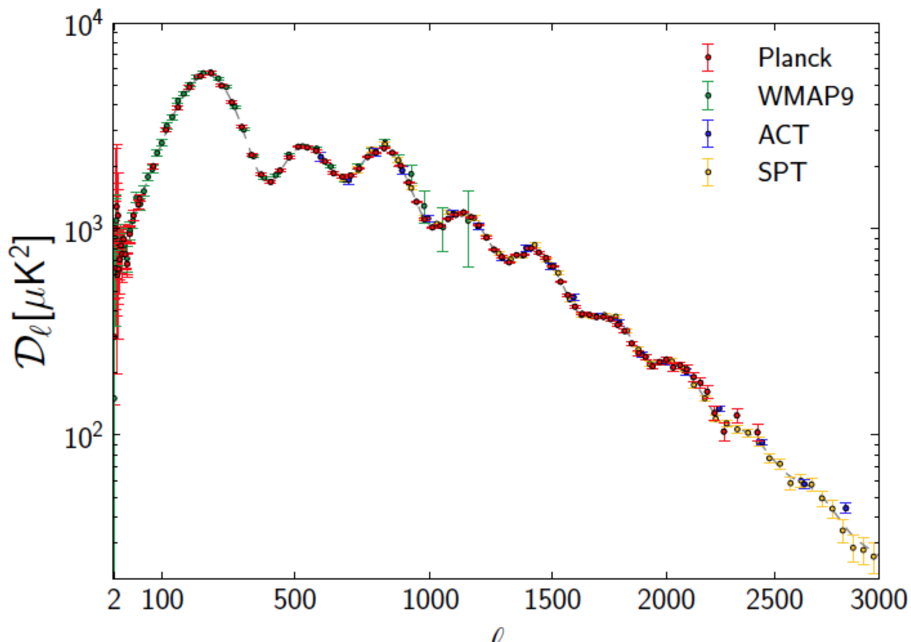
The Cosmic Microwave Background (CMB)

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.

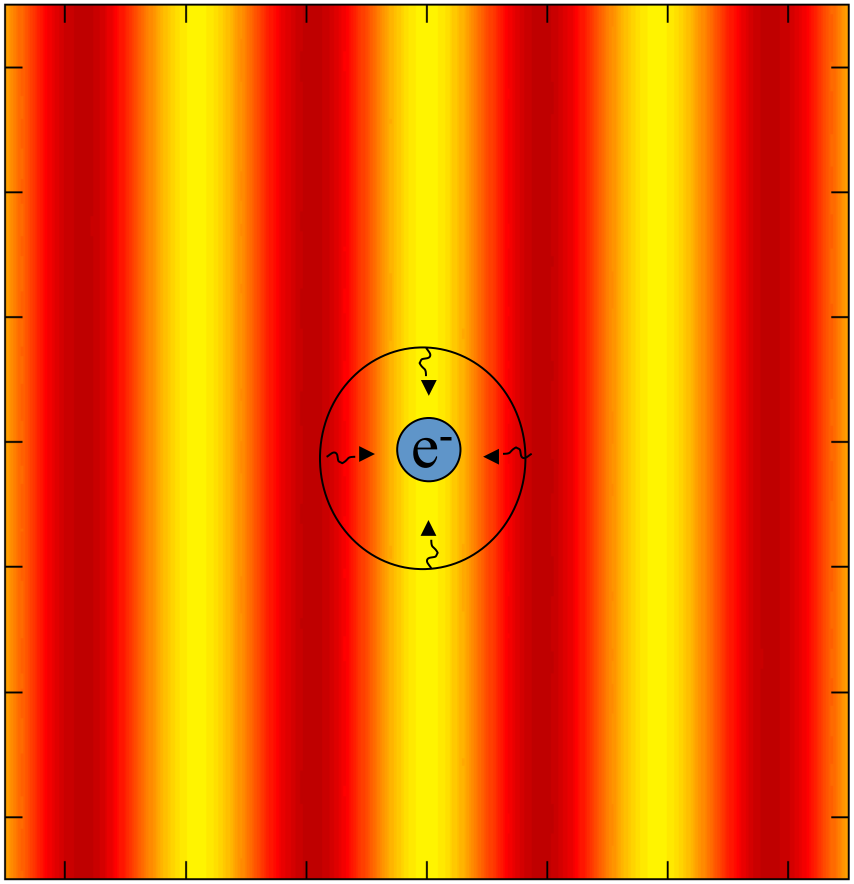
However, any imprint of the inflationary gravitational waves have so far eluded detection in the CMB.





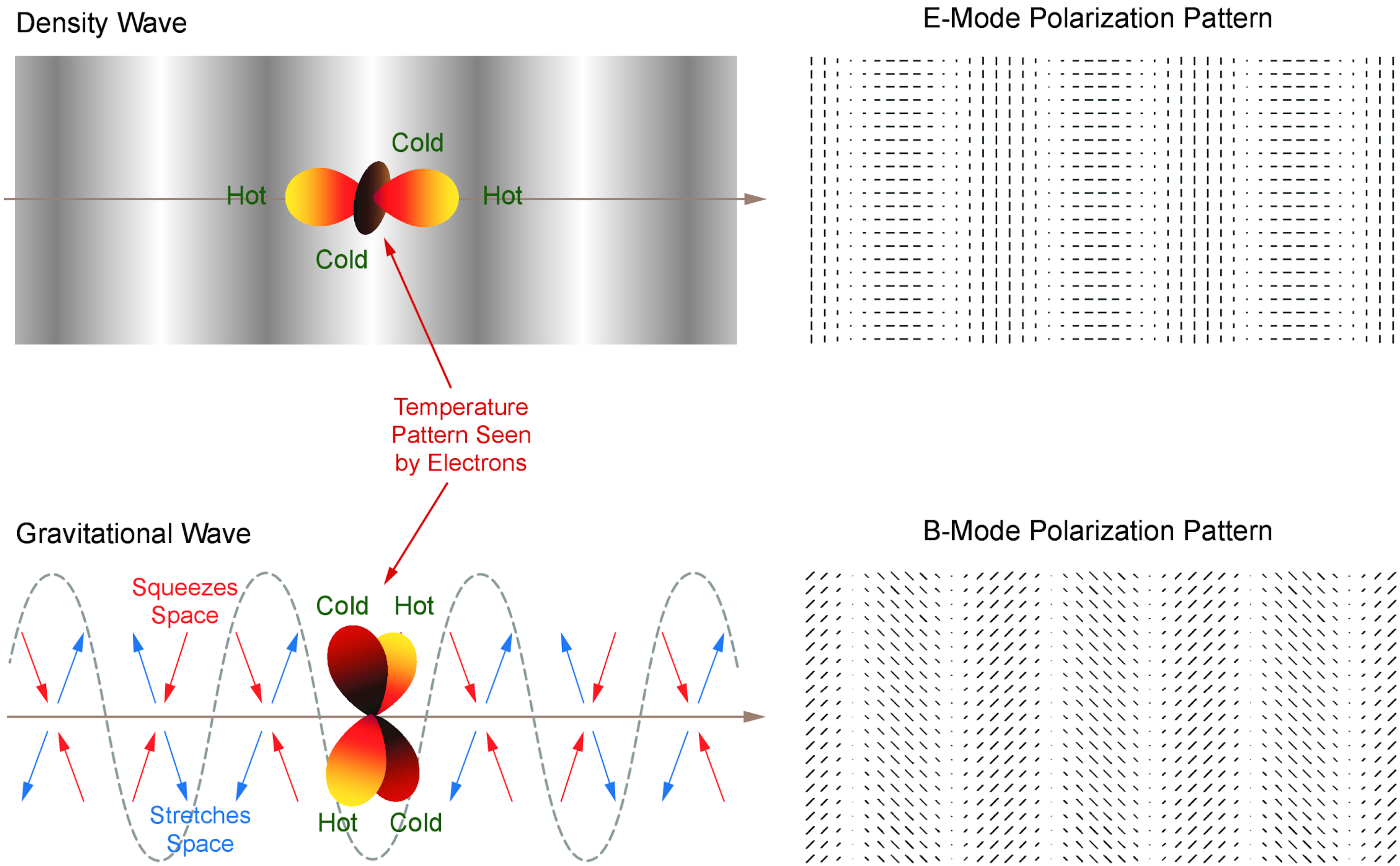
Planck Collaboration & ESA

CMB polarization: arises at last scattering from local radiation quadrupole

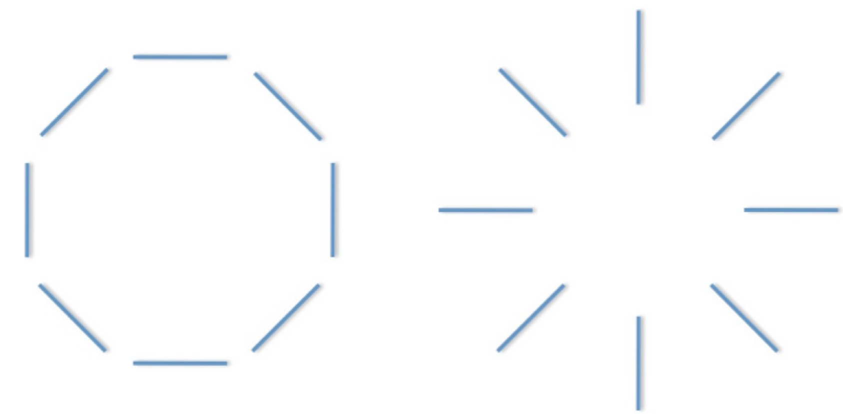


From Thomson scattering wherever there is ionized gas and quadrupole anisotropy

CMB polarization



CMB Polarization



E-mode

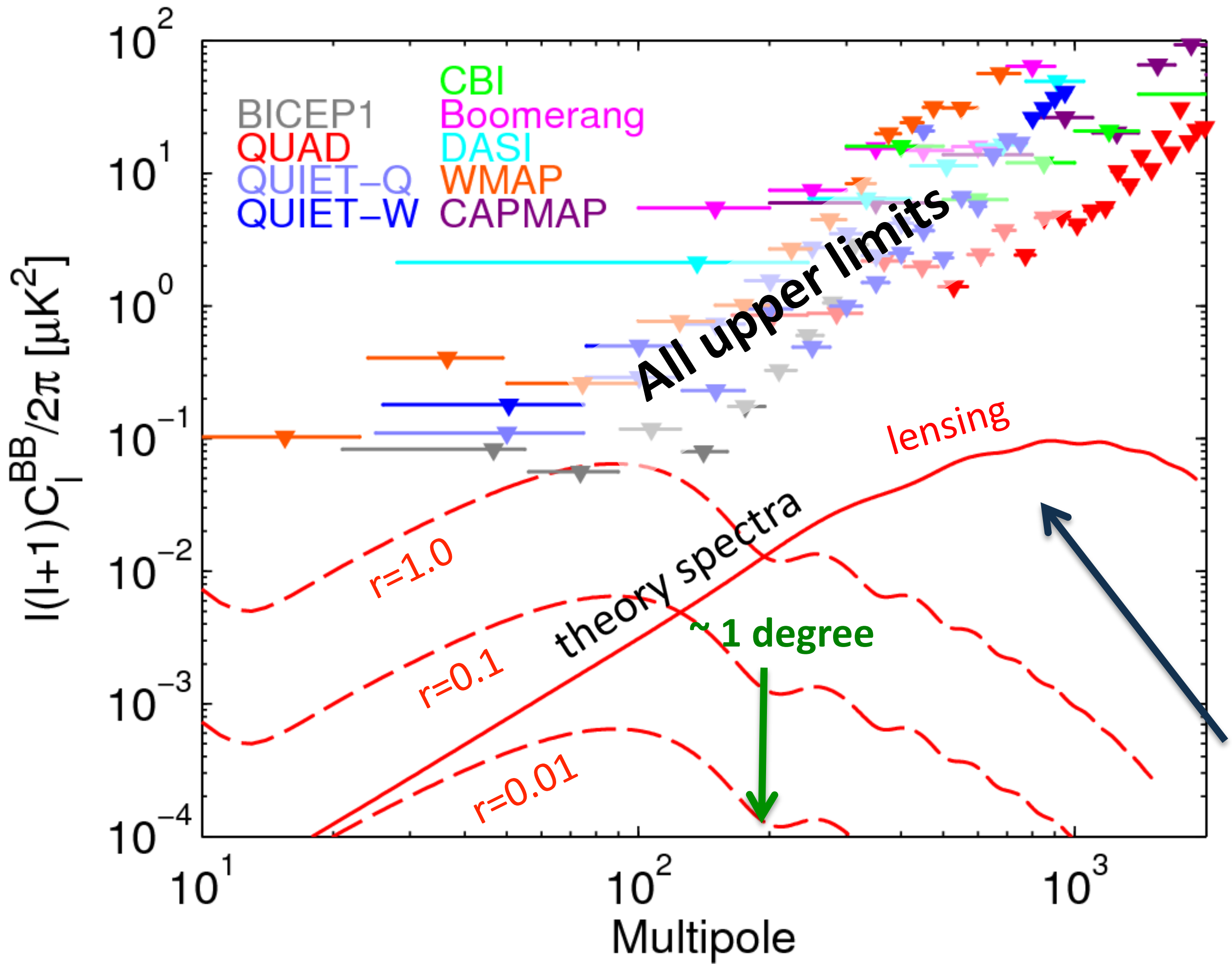
B-mode

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

Density fluctuations *cannot* make B-mode patterns.

A measurement of degree-scale B-modes would be direct evidence for the gravitational wave background.

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.

Until March 17 only upper limits

Best previous limit on r from BICEP1: **r < 0.7 (95% CL)**

Lensing deflects CMB photons, slightly mixing the dominant E-modes into B-modes -- dominant at high multipoles

B-modes from the ground

- Deep, Concentrated coverage
- Foreground avoidance (limited frequency)
- Systematic control with in-situ calibration
- Large detector count, rapid technology cycle
- Relentless observing & large number of null tests

→ powerful recipe for high-confidence initial discovery

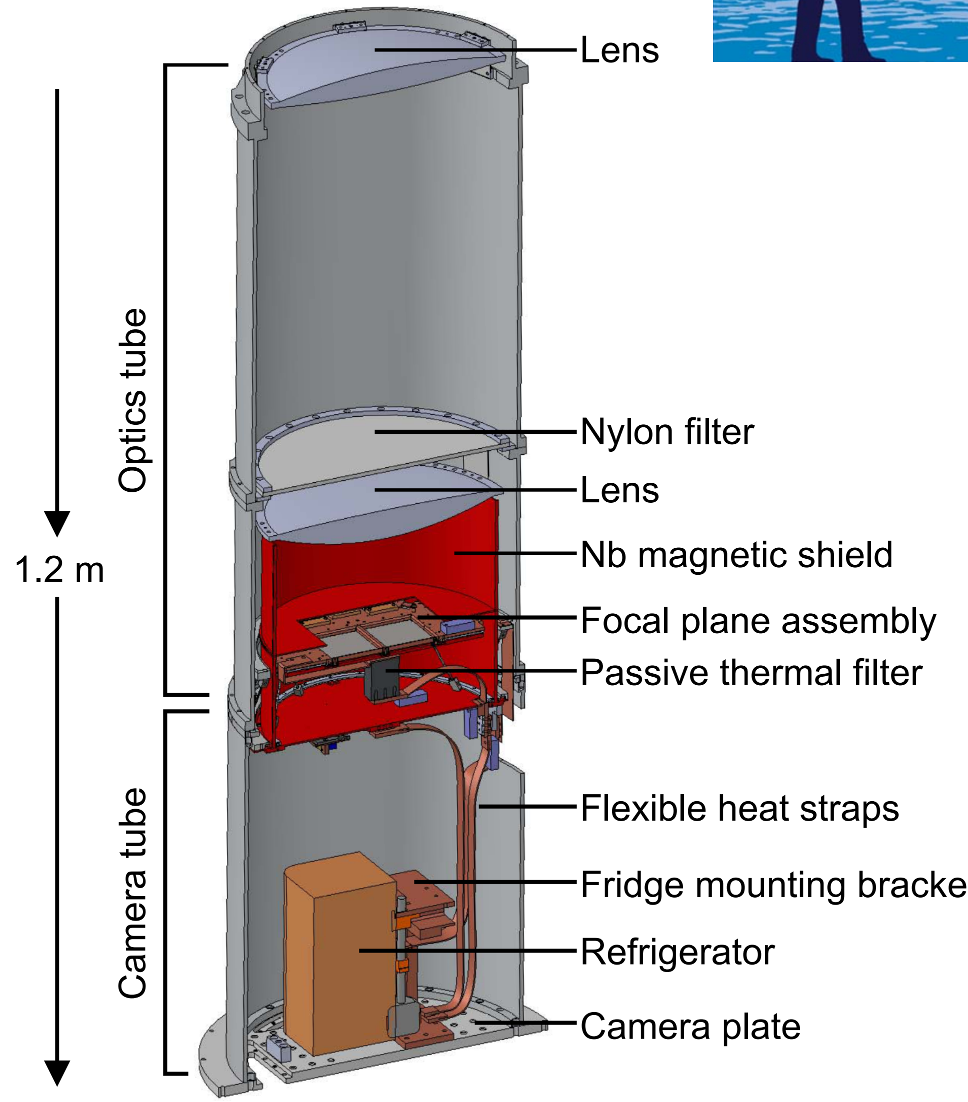
BICEP2 Strategy: Unique Optics

Telescope as compact as possible while still having the angular resolution to observe degree-scale features (target the 2 degree peak of the B-mode)

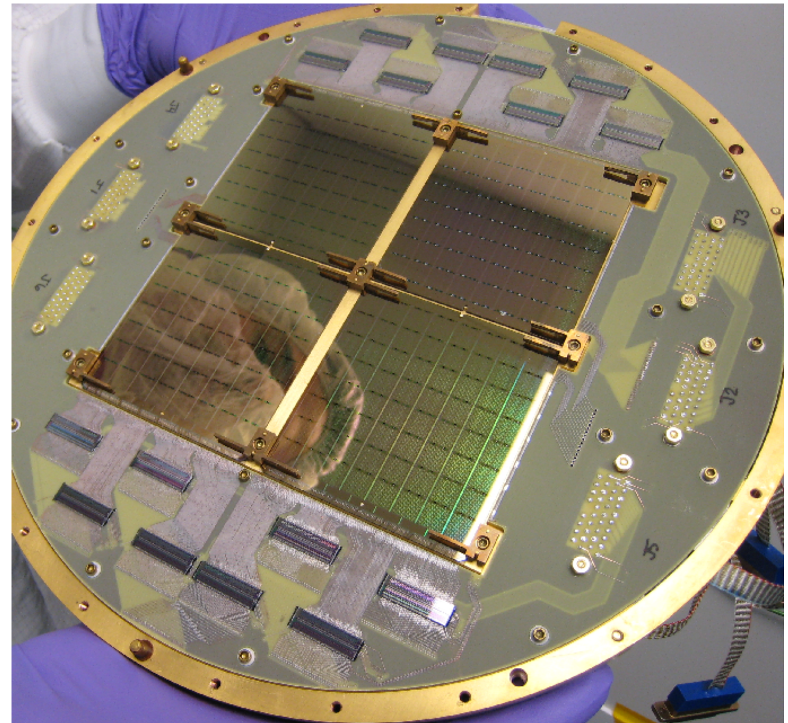
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

Liquid helium cools the optical elements to 4.2 K.

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



BICEP2 Strategy: Revolutionary detectors

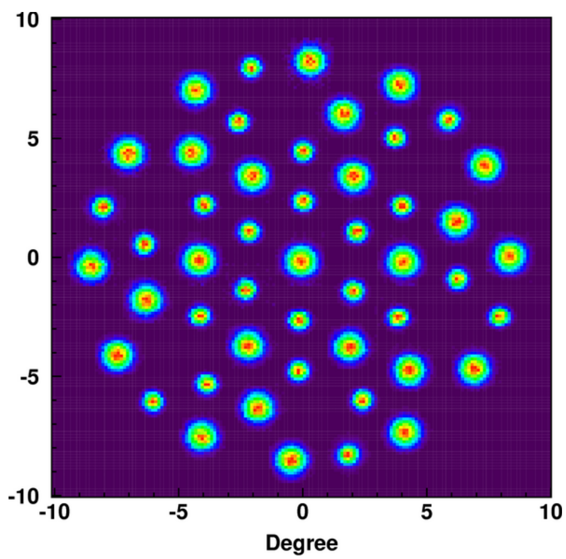


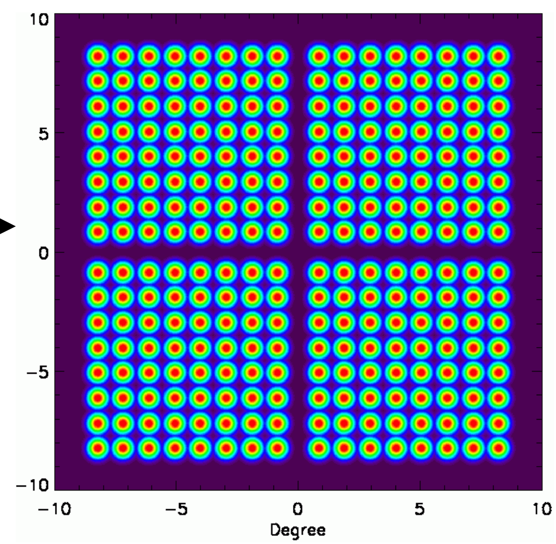
JPL : antenna-coupled TES arrays

BICEP1

48

150 GHz detectors



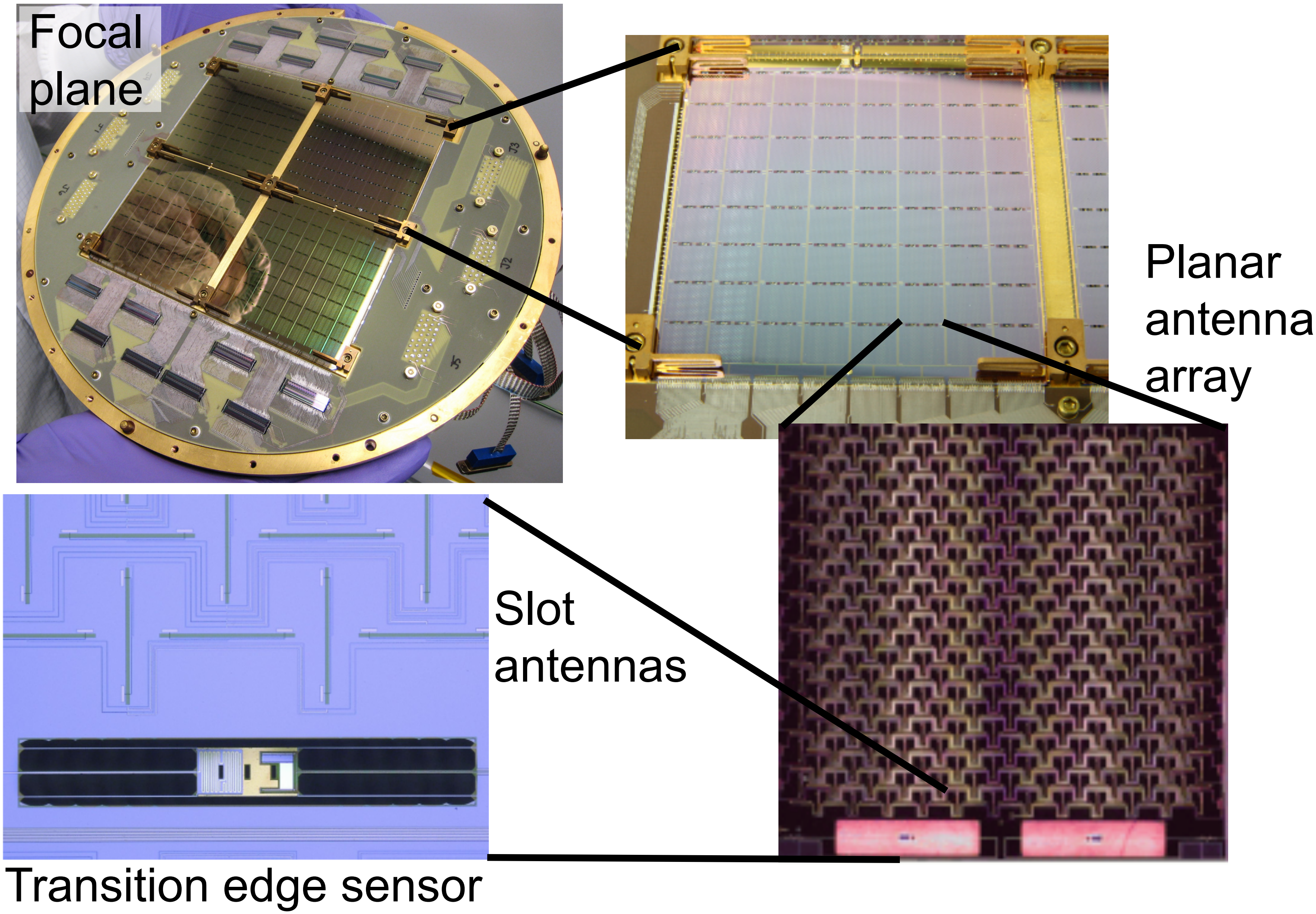


BICEP2

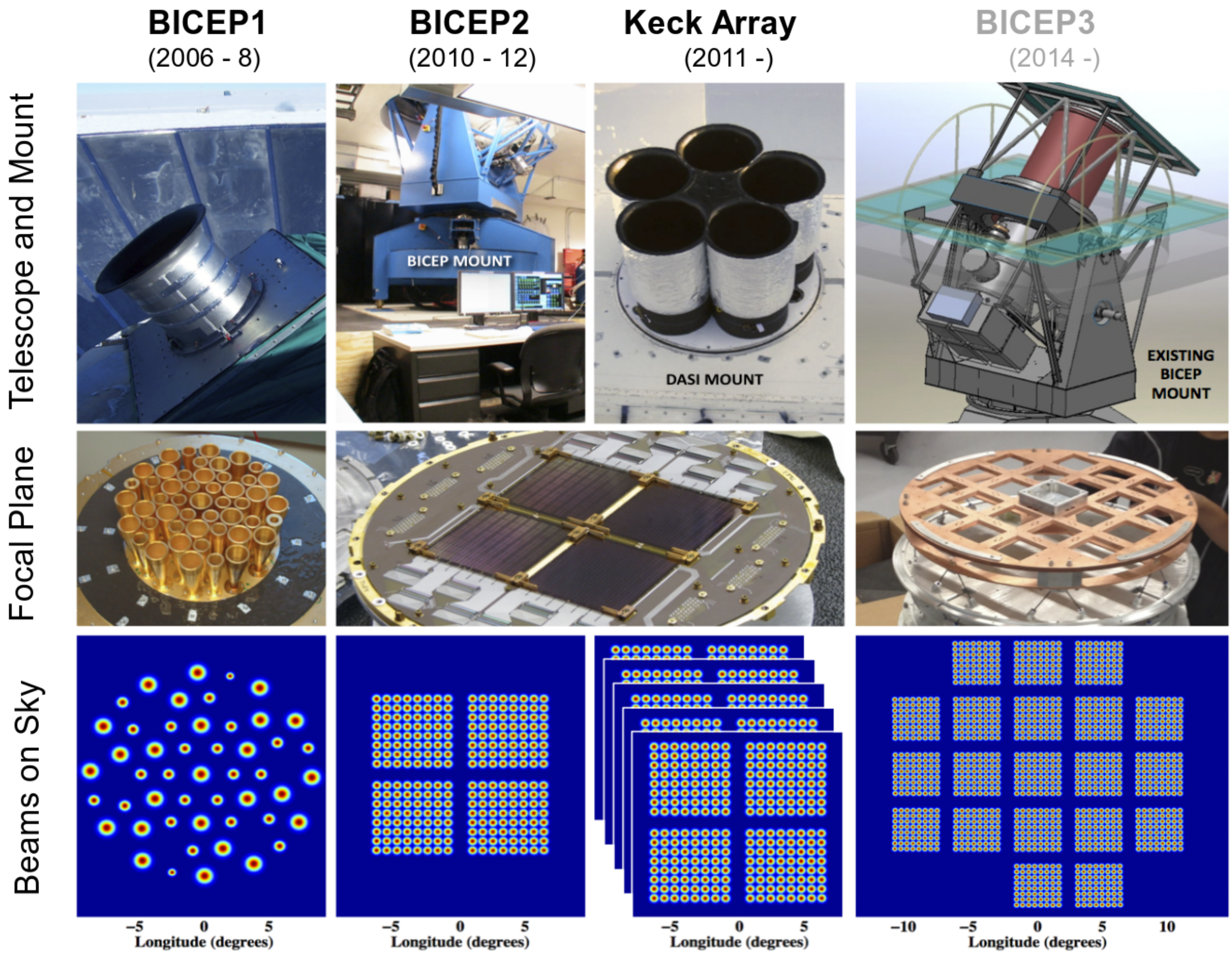
512

150 GHz detectors

Mass-produced superconducting detectors

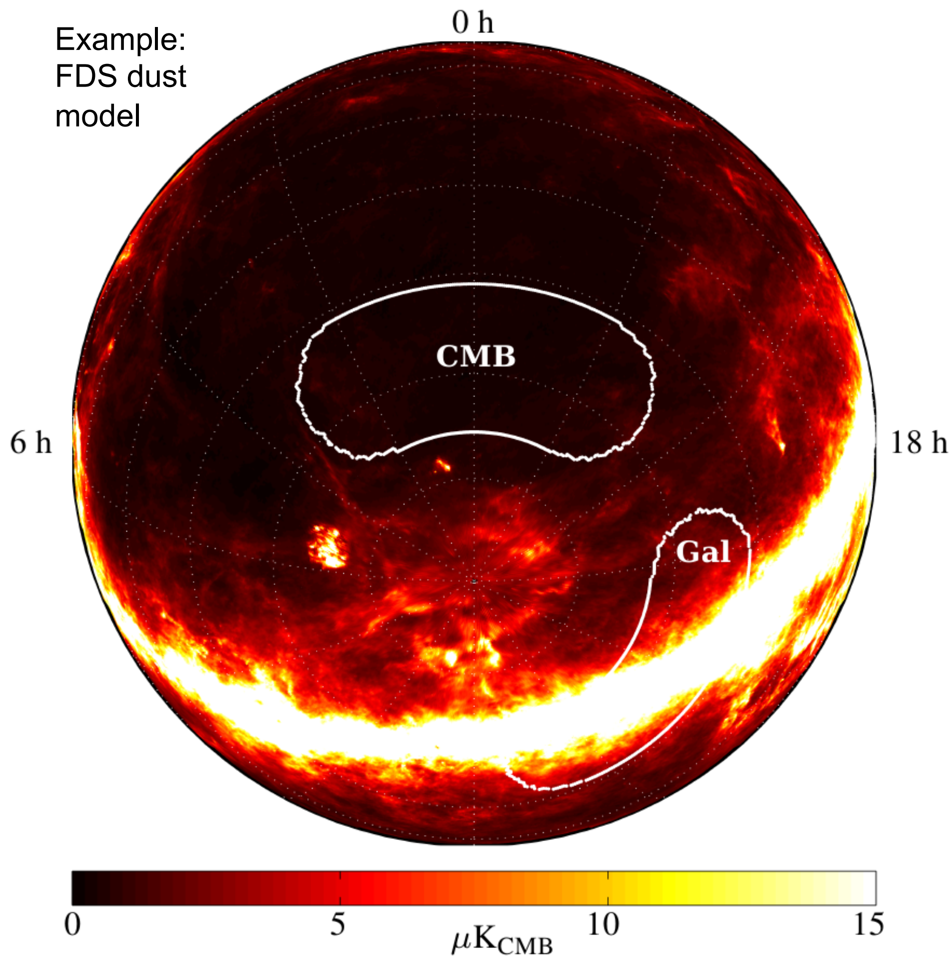


Sensitivity through detector count increase



BICEP2 Observational Strategy

Example:
FDS dust
model



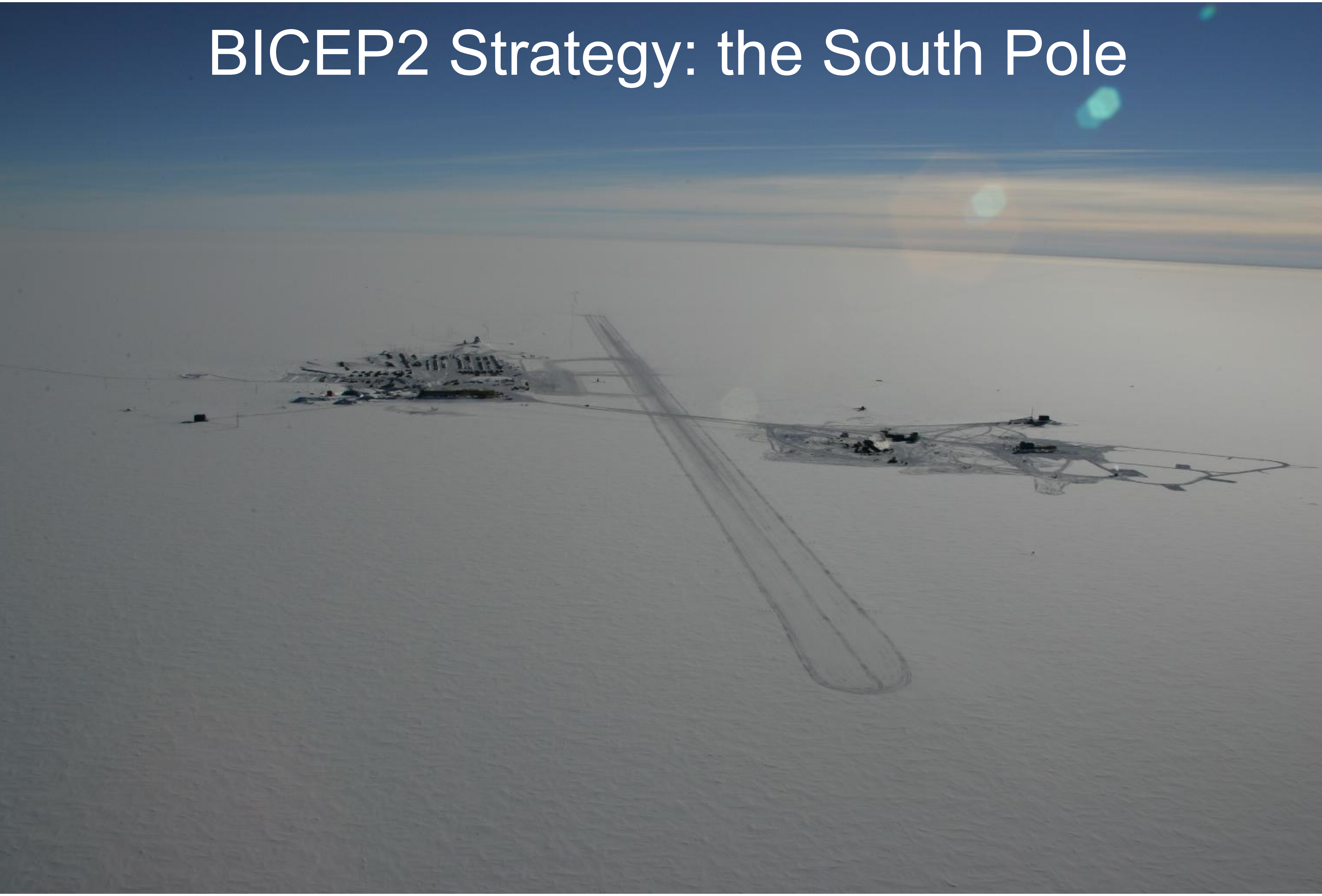
Target the "Southern Hole" - a region of the sky exceptionally free of dust and synchrotron foregrounds.

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

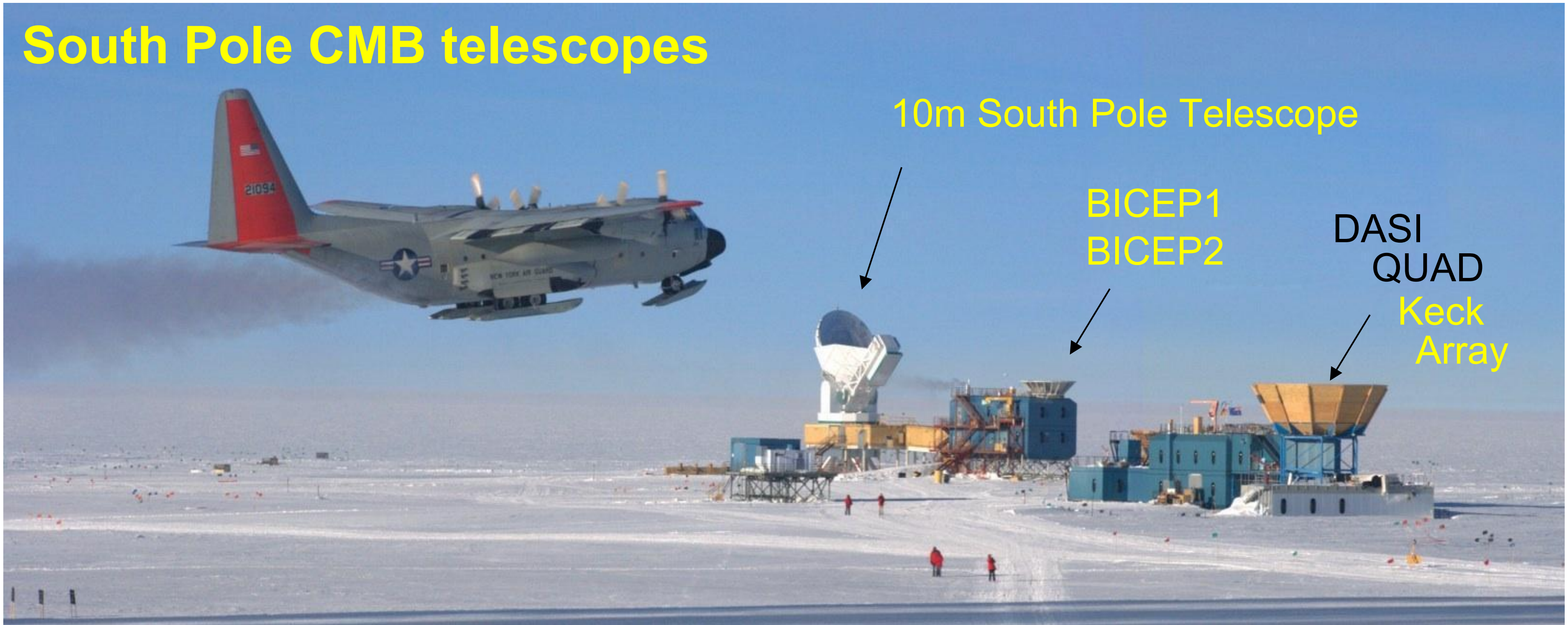
At 150 GHz the combined dust and synchrotron spectrum is predicted to be at a minimum in the Southern Hole.

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

BICEP2 Strategy: the South Pole



South Pole CMB telescopes



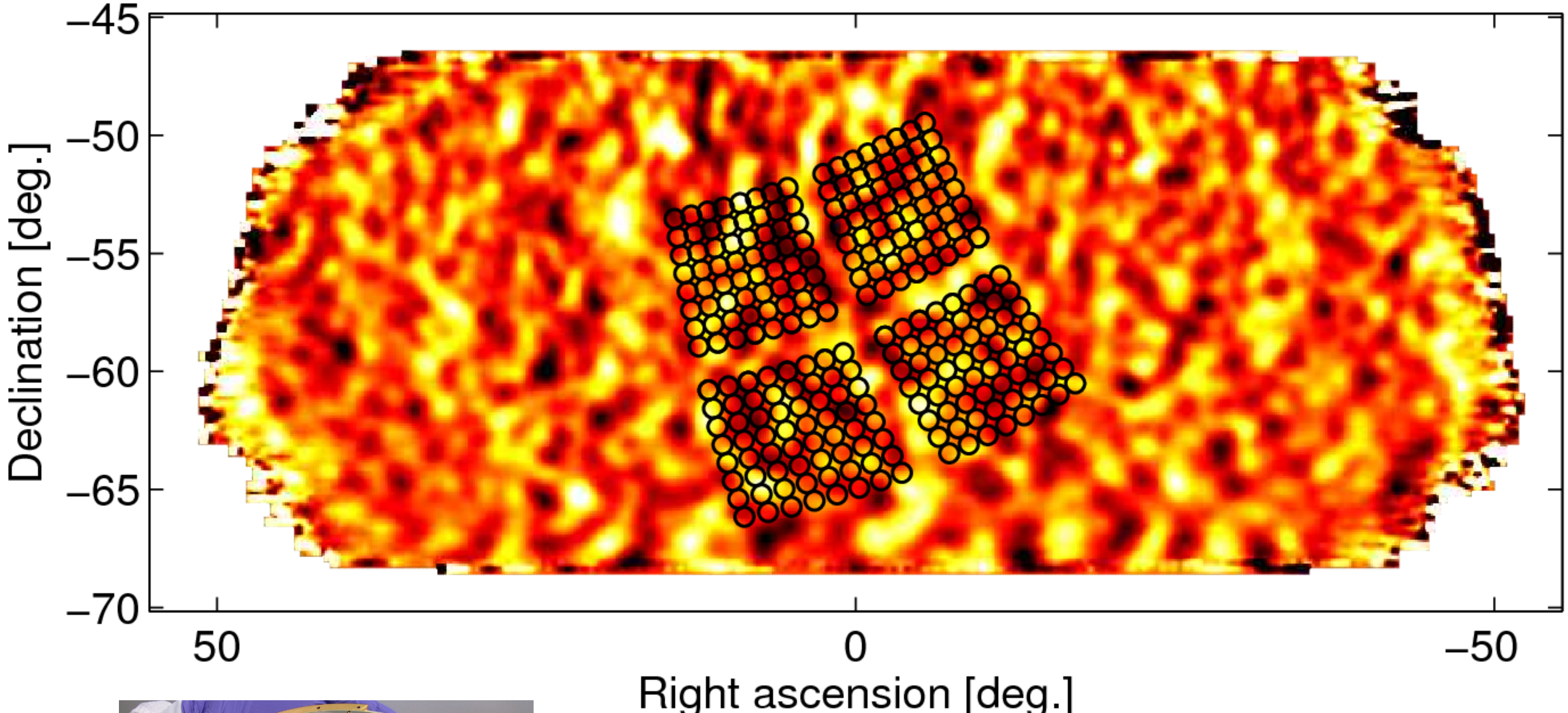
NSF's South Pole Station:
A popular place with CMB Experimentalists!

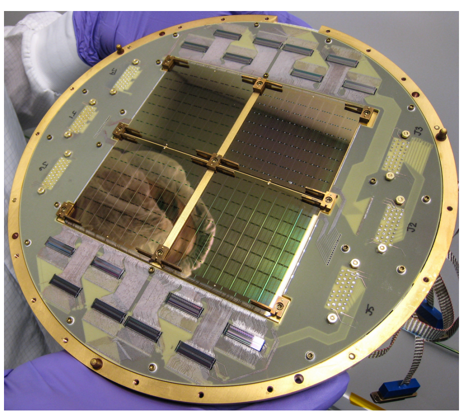
Super dry atmosphere and 24h coverage of "Southern Hole".

Also power, LHe, LN_2, 200 GB/day, 3 square meals,...


photo: Keith Vanderlinde

BICEP2 on the Sky



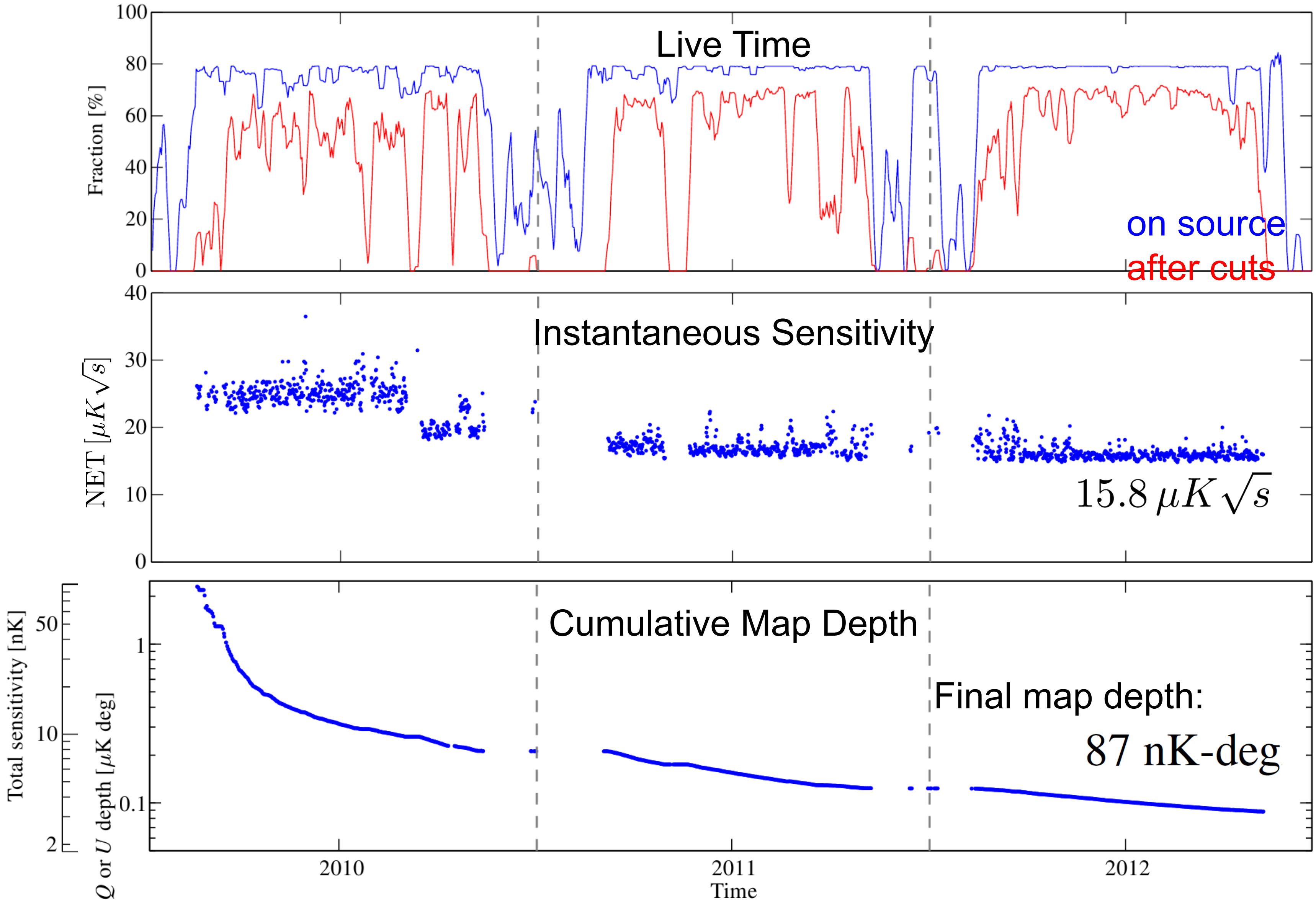


Projection of the BICEP2 focal plane on the sky

The focal plane is 20 degrees across

Background is the CMB temperature map as measured with BICEP2

BICEP2 3-year Data Set



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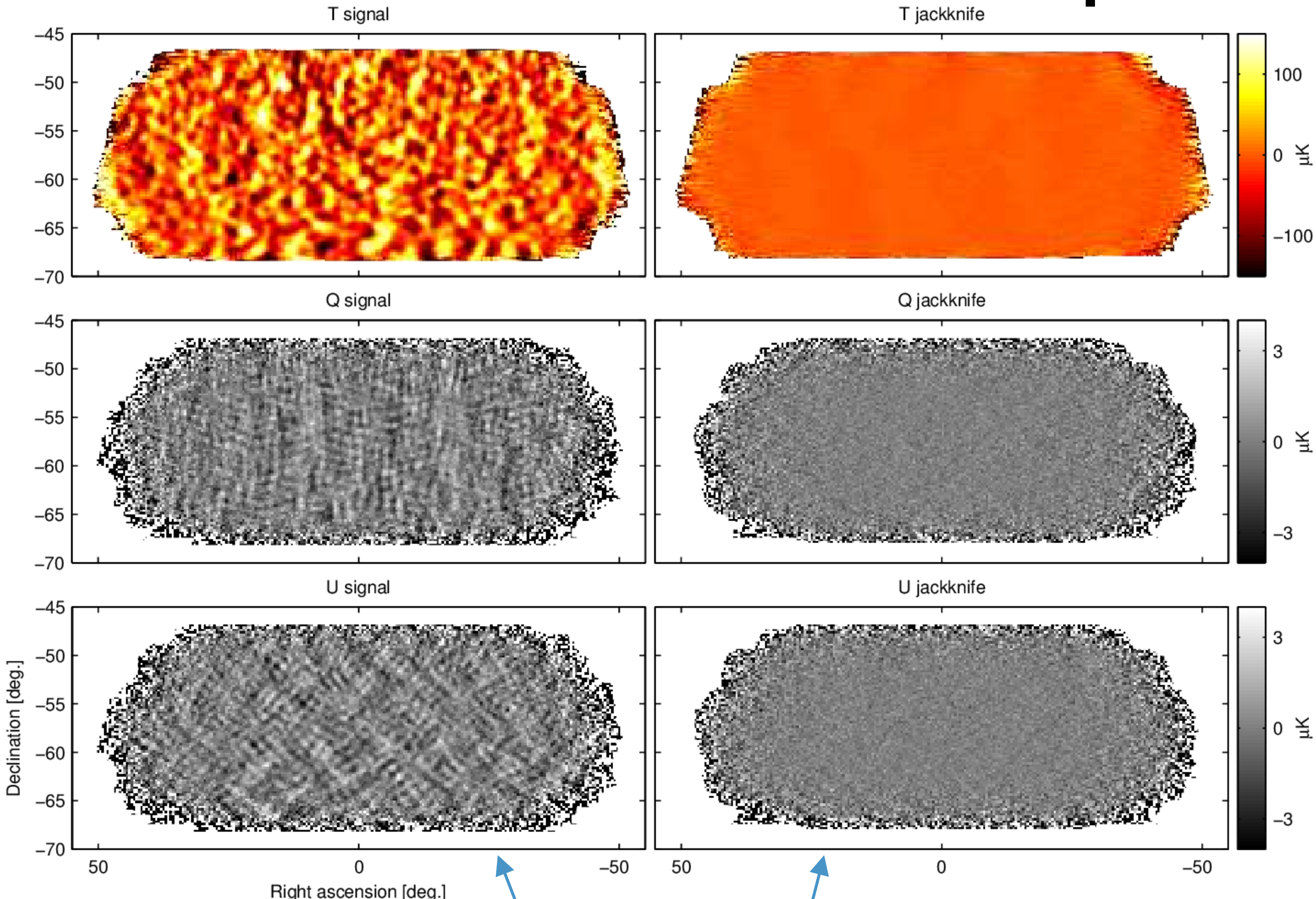
BICEP2 T and Stokes Q/U Maps



Signal Maps

Difference (“Jackknife”) Maps

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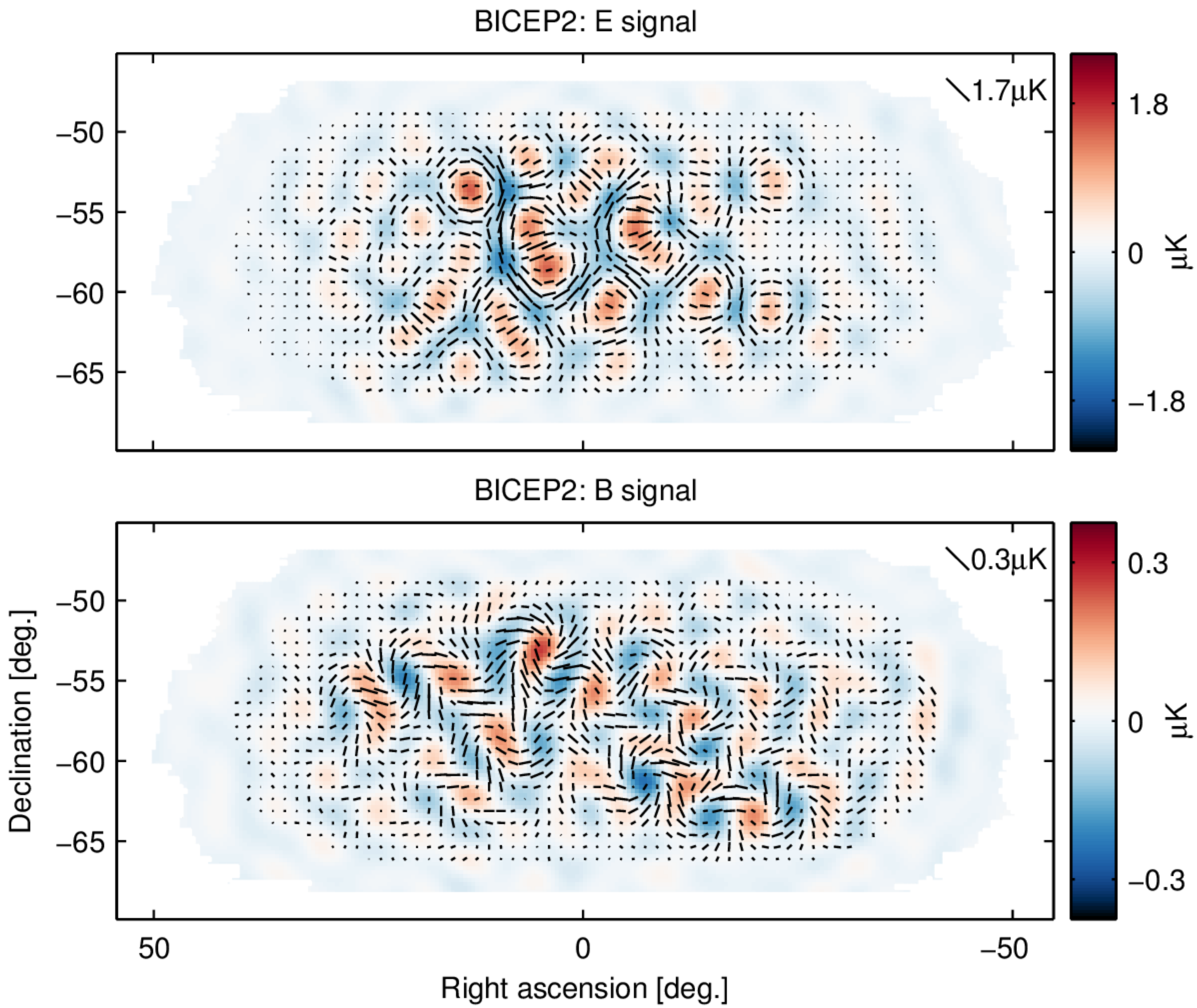
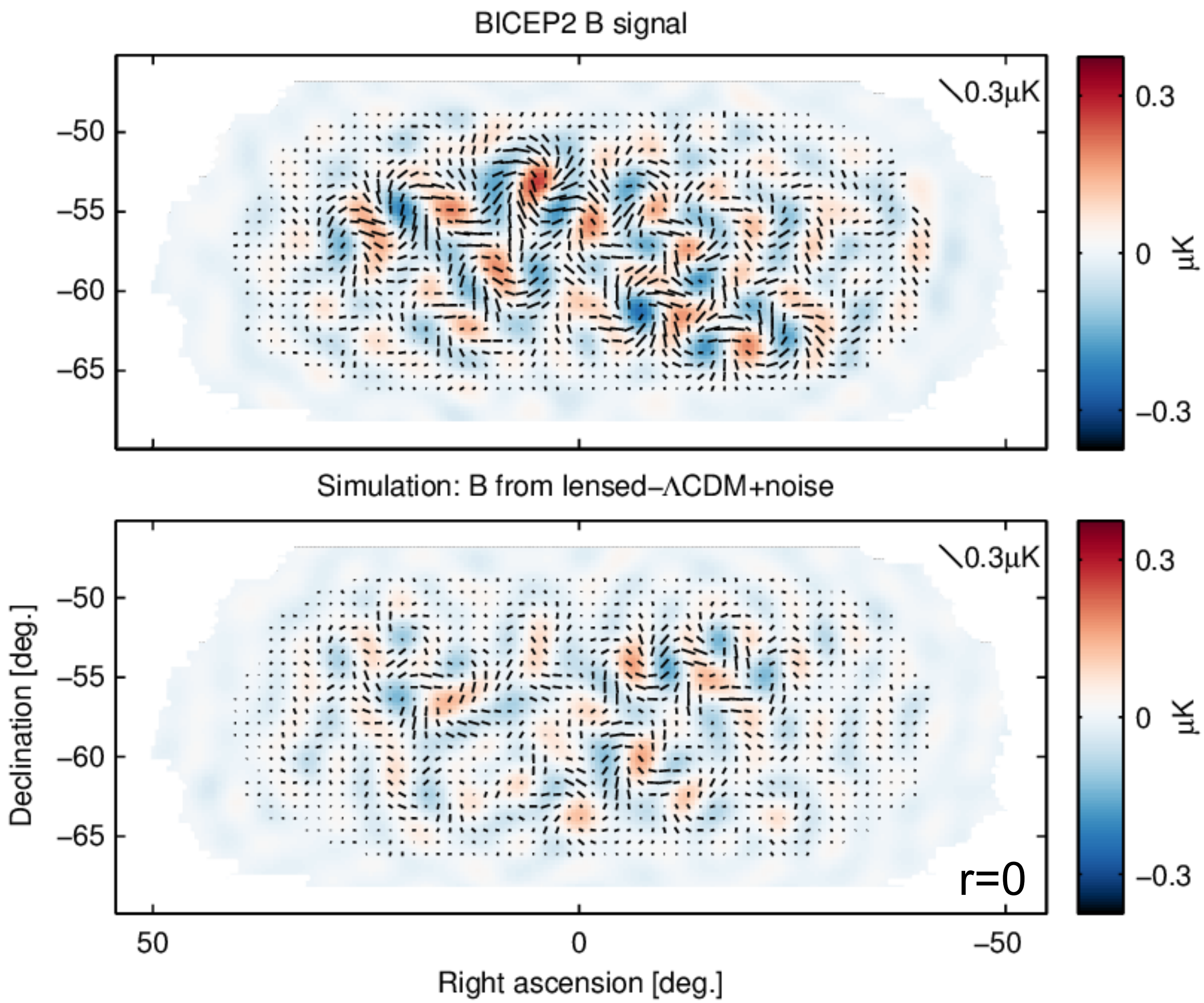
BICEP2 E- and B-mode Maps



The Bicep2 Collaboration

B-mode Map vs. Simulation



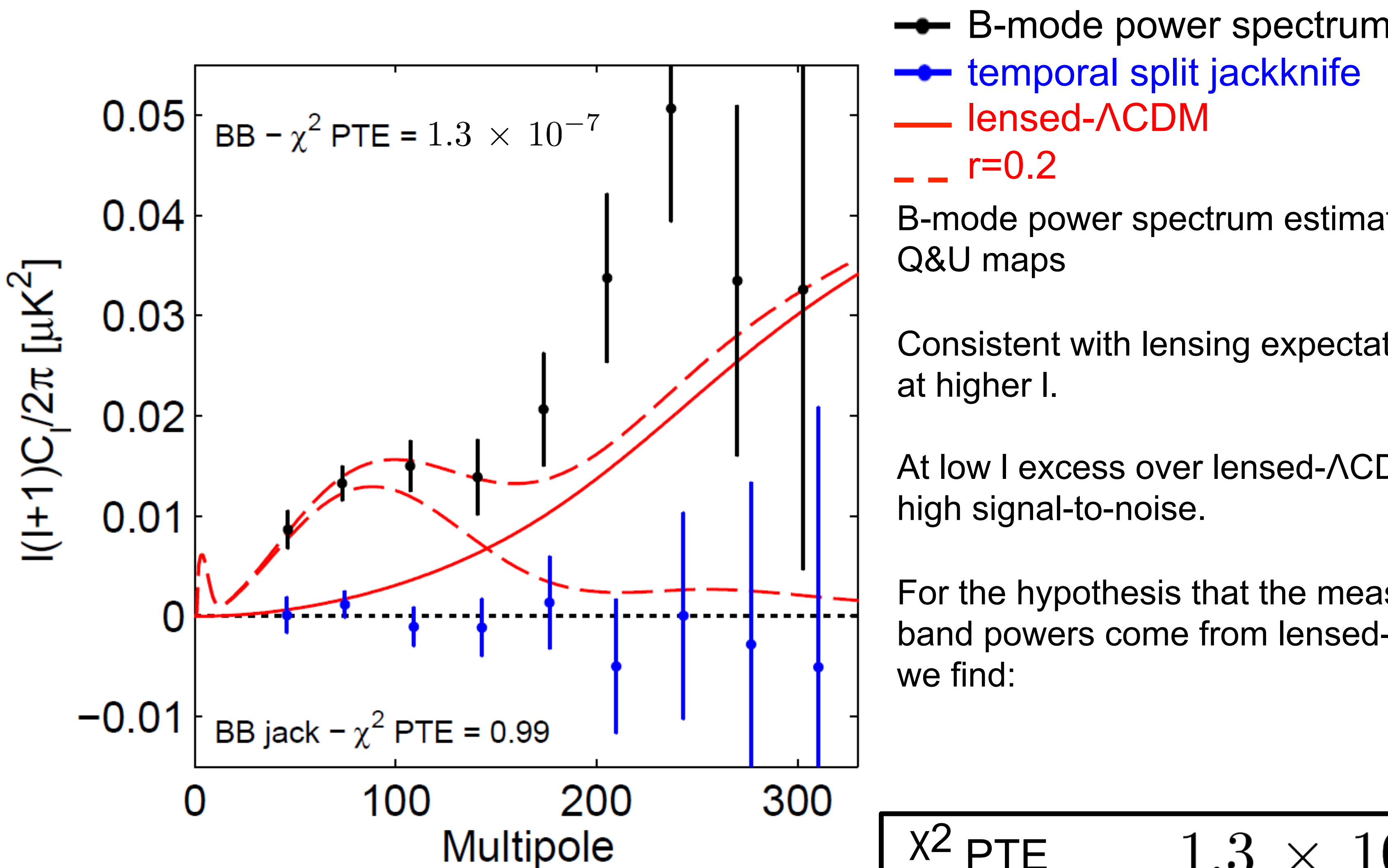
Simulation pipeline:
generate realizations of the full observation and all filtering operations.

Compare real data to 500 lensed-ΛCDM+noise simulations each at various levels of *r*.

We perform various filtering operations: use the sims to correct for these.

Also use the sims to derive the final uncertainties (error bars)

BICEP2 B-mode Power Spectrum



B-mode power spectrum estimated from Q&U maps

Consistent with lensing expectation at higher l.

At low l excess over lensed-ΛCDM with high signal-to-noise.

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

χ^2 PTE	1.3×10^{-7}
significance	$5.2\,\sigma$

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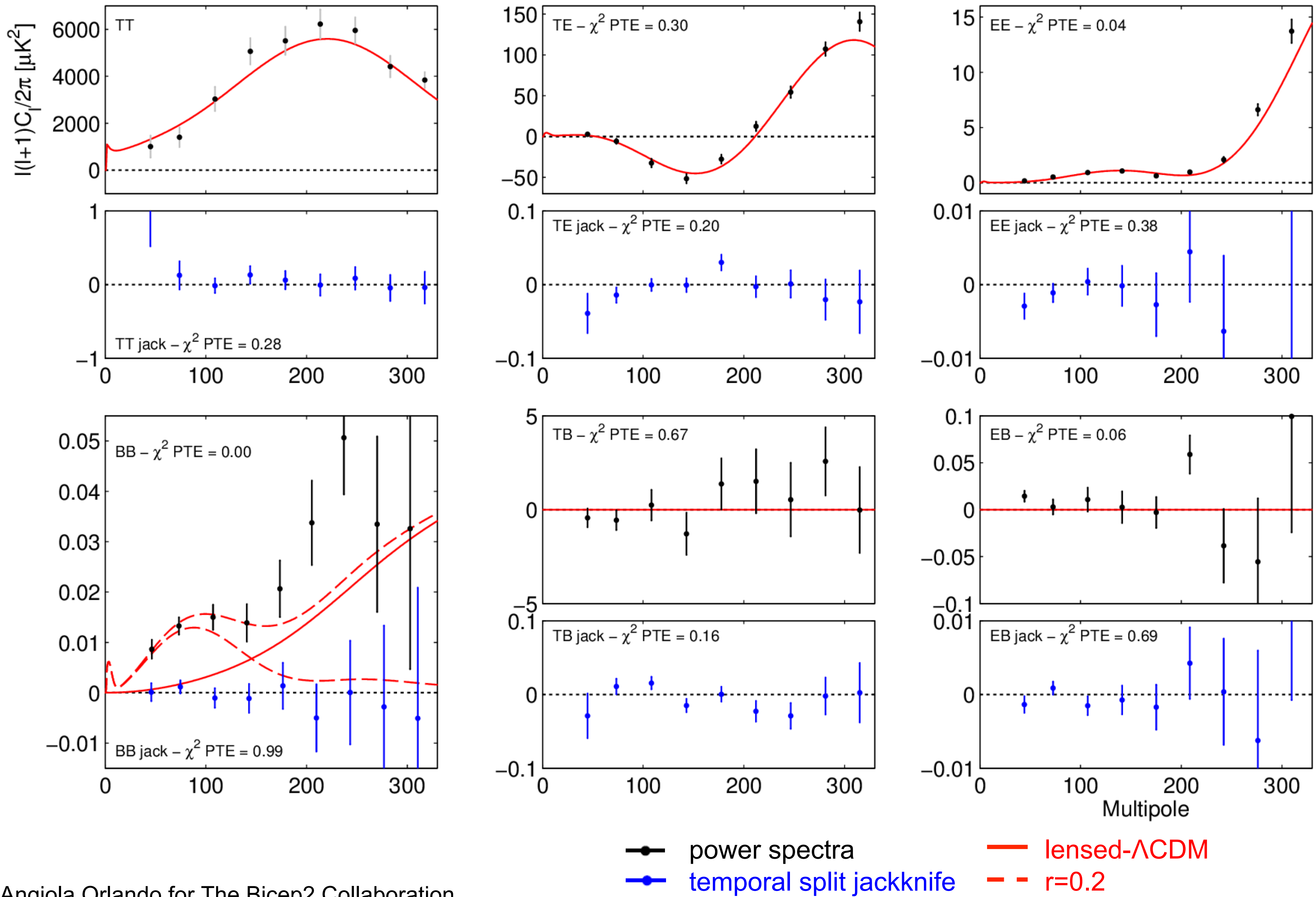
Temperature and Polarization Power Spectra



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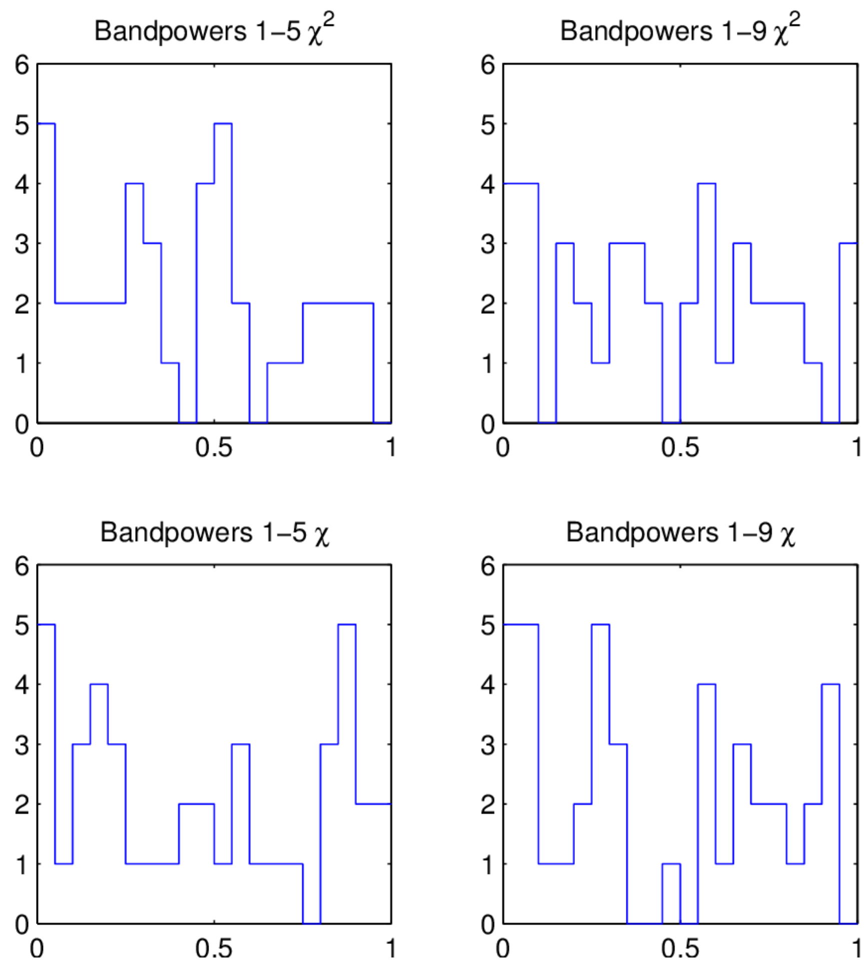
Check Systematics: Jackknifes

TABLE 1
JACKKNIFE PTE VALUES FROM χ^2 AND χ (SUM-OF-DEVIATION) TESTS

Jackknife	Bandpowers 1–5 χ^2	Bandpowers 1–9 χ^2	Bandpowers 1–5 χ	Bandpowers 1–9 χ
Deck jackknife				
EE	0.046	0.030	0.164	0.299
BB	0.774	0.329	0.240	0.082
EB	0.337	0.643	0.204	0.267
Scan Dir jackknife				
EE	0.483	0.762	0.978	0.938
BB	0.531	0.573	0.896	0.551
EB	0.898	0.806	0.725	0.890
Tag Split jackknife				
EE	0.541	0.377	0.916	0.938
BB	0.902	0.992	0.449	0.585
EB	0.477	0.689	0.856	0.615
Tile jackknife				
EE	0.004	0.010	0.000	0.002
BB	0.794	0.752	0.565	0.331
EB	0.172	0.419	0.962	0.790
Phase jackknife				
EE	0.673	0.409	0.126	0.339
BB	0.591	0.739	0.842	0.944
EB	0.529	0.577	0.840	0.659
Mux Col jackknife				
EE	0.812	0.587	0.196	0.204
BB	0.826	0.972	0.293	0.283
EB	0.866	0.968	0.876	0.697
Alt Deck jackknife				
EE	0.004	0.004	0.070	0.236
BB	0.397	0.176	0.381	0.086
EB	0.150	0.060	0.170	0.291
Mux Row jackknife				
EE	0.052	0.178	0.653	0.739
BB	0.345	0.361	0.032	0.008
EB	0.529	0.226	0.024	0.048
Tile/Deck jackknife				
EE	0.048	0.088	0.144	0.132
BB	0.908	0.840	0.629	0.269
EB	0.050	0.154	0.591	0.591
Focal Plane inner/outer jackknife				
EE	0.230	0.597	0.022	0.090
BB	0.216	0.531	0.046	0.092
EB	0.036	0.042	0.850	0.838
Tile top/bottom jackknife				
EE	0.289	0.347	0.459	0.599
BB	0.293	0.236	0.154	0.028
EB	0.545	0.683	0.902	0.932
Tile inner/outer jackknife				
EE	0.727	0.533	0.128	0.485
BB	0.255	0.086	0.421	0.036
EB	0.465	0.737	0.208	0.168
Moon jackknife				
EE	0.499	0.689	0.481	0.679
BB	0.144	0.287	0.898	0.858
EB	0.289	0.359	0.531	0.307
A/B offset best/worst				
EE	0.317	0.311	0.868	0.709
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.790

14 jackknife tests applied to 3 spectra, 4 statistics

All 4 jackknife statistics have uniform probability to exceed (PTE) distributions:



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Splits the 4 boresight rotations

Amplifies differential pointing in comparison to fully added data. Important check of deprojection.

Splits by time

Checks for contamination on long ("Temporal Split") and short ("Scan Dir") timescales. Short timescales probe detector transfer functions.

Splits by channel selection

Checks for contamination in channel subgroups, divided by focal plane location, tile location, and readout electronics grouping

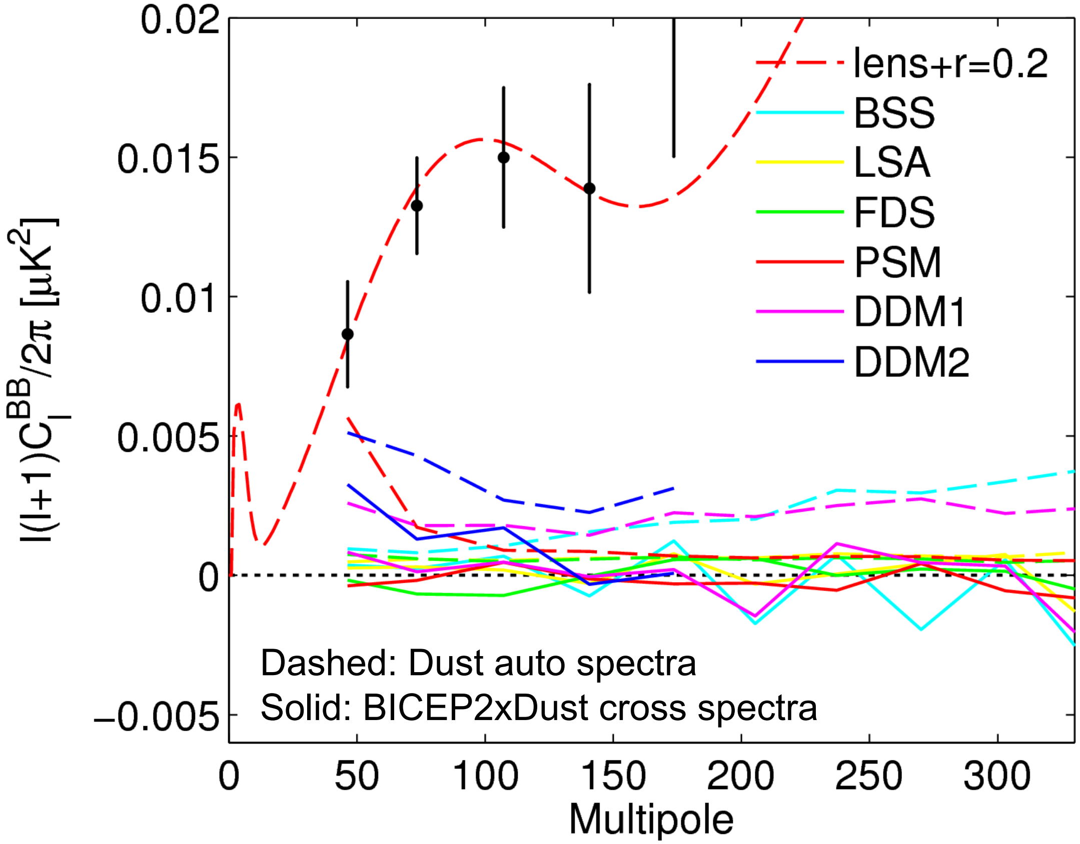
Splits by possible external contamination

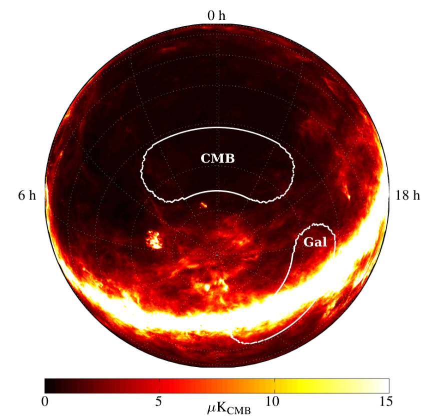
Checks for contamination from ground-fixed signals, such as polarized sky or magnetic fields, or the moon

Splits to check intrinsic detector properties

Checks for contamination from detectors with best/worst differential pointing. "Tile/dk" divides the data by the orientation of the detector on the sky.

Polarized Dust Foreground Projections





FDS Model

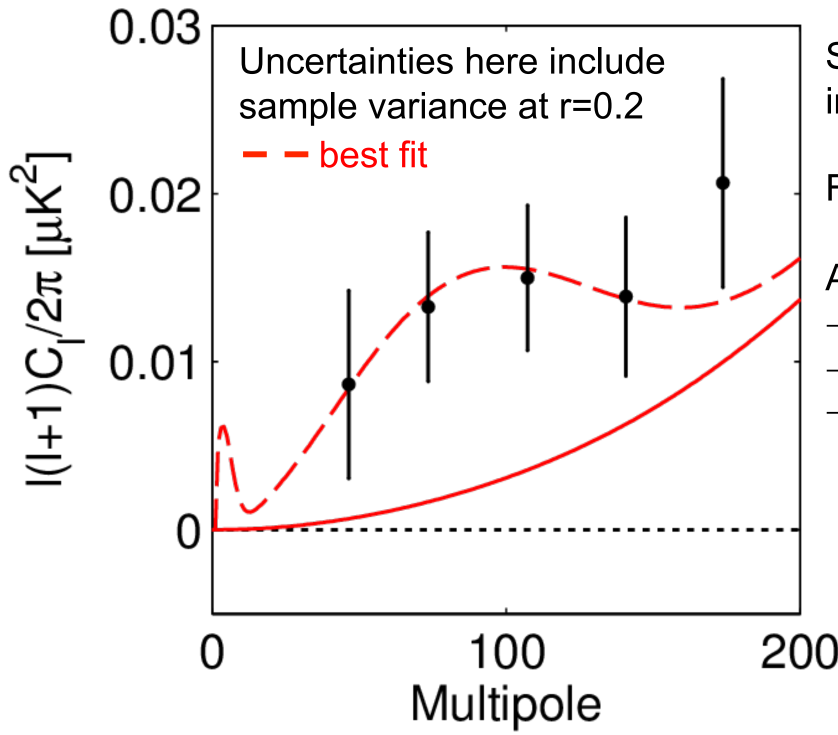
The BICEP2 region is chosen to have extremely low foreground emission.

Use various models of polarized dust emission to estimate foregrounds.

All dust auto spectra well below observed signal level.

Cross spectra consistent with zero.

Constraint on Tensor-to-scalar Ratio r

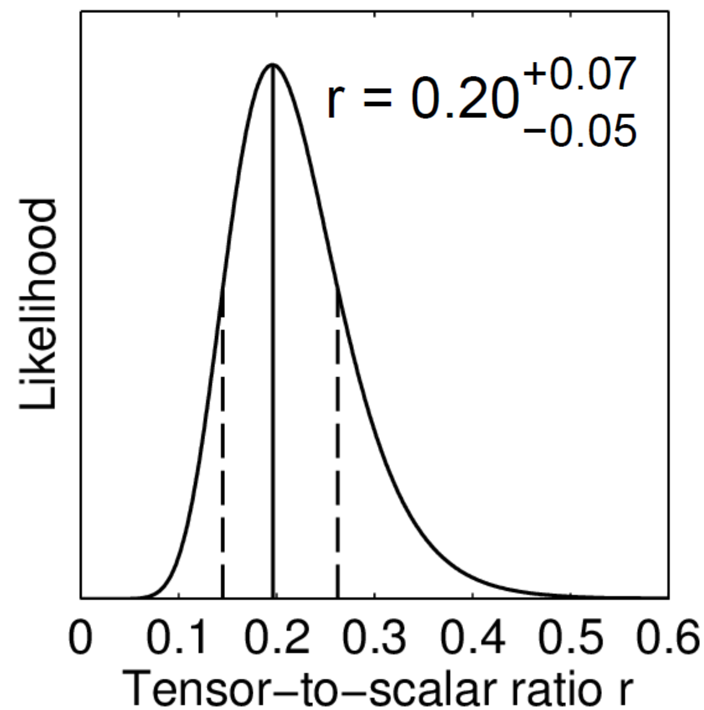


Substantial excess power in the region where the inflationary gravitational wave signal is expected to peak

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:

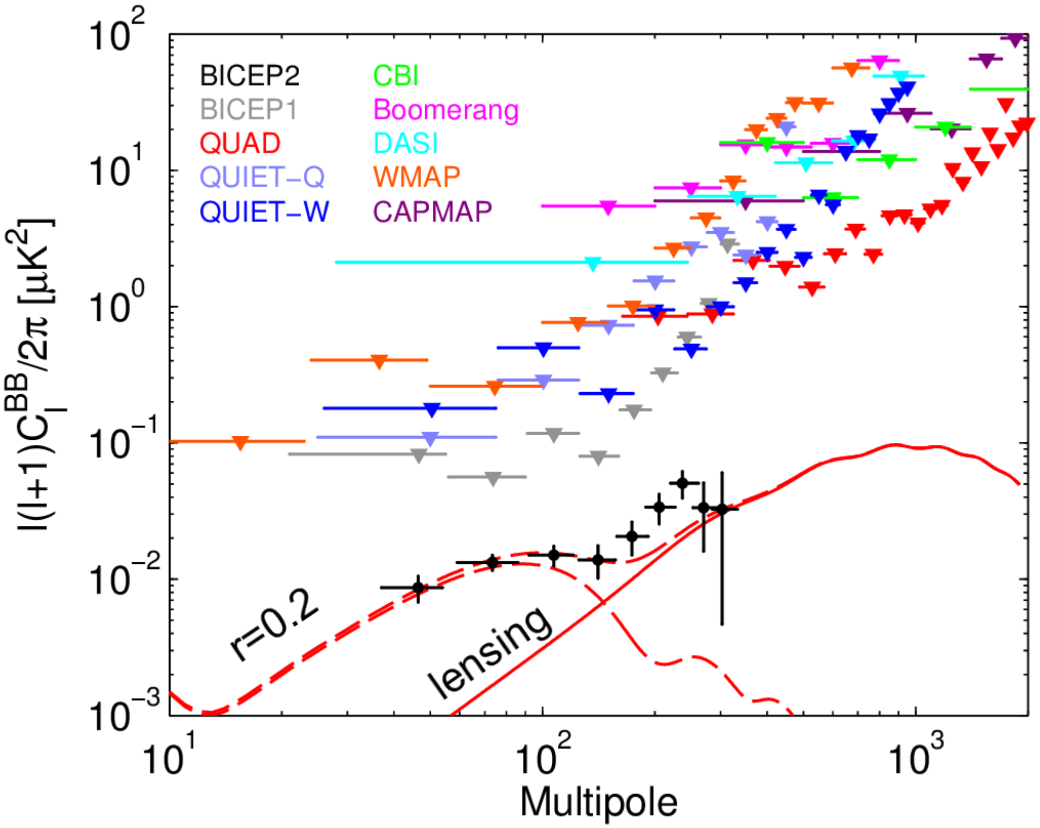
r = 0.2 with uncertainties dominated by sample variance

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

r = 0 disfavored at 7.0σ

Conclusions

BICEP2 and upper limits from other experiments:



Consistent with expectations for **primordial gravitational waves** from **GUT-scale inflation**

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 (l~100)!

7σ preference for non-zero r above lensed ΛCDM

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 gravitational wave model:

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

What's Next?

Confirm:

- Keck Array 2012/13 results coming soon
- Planck may be able to confirm at either reionization (ell<10) or recombination (ell=80) bump.
- SPTpol has data over same sky patch at 100 and 150 GHz
  - Should be able to see signal alone and/or in cross correlation with BICEP2/Keck
- Keck 2014 running with two 100 GHz receivers – will rapidly surpass BICEP1 100 GHz sensitivity.
- Polarbear, ACTpol, ABS running…
- EBEX has data… Spider will fly later this year… plus many others like LSPE (Italian Space Agency)

Refine:

- Need more sky/sensitivity to reduce uncertainty on r
- Need longer lever arm to measure tensor spectral index n_T
  - De-lense to push to higher ell
  - Full sky to push to lower ell