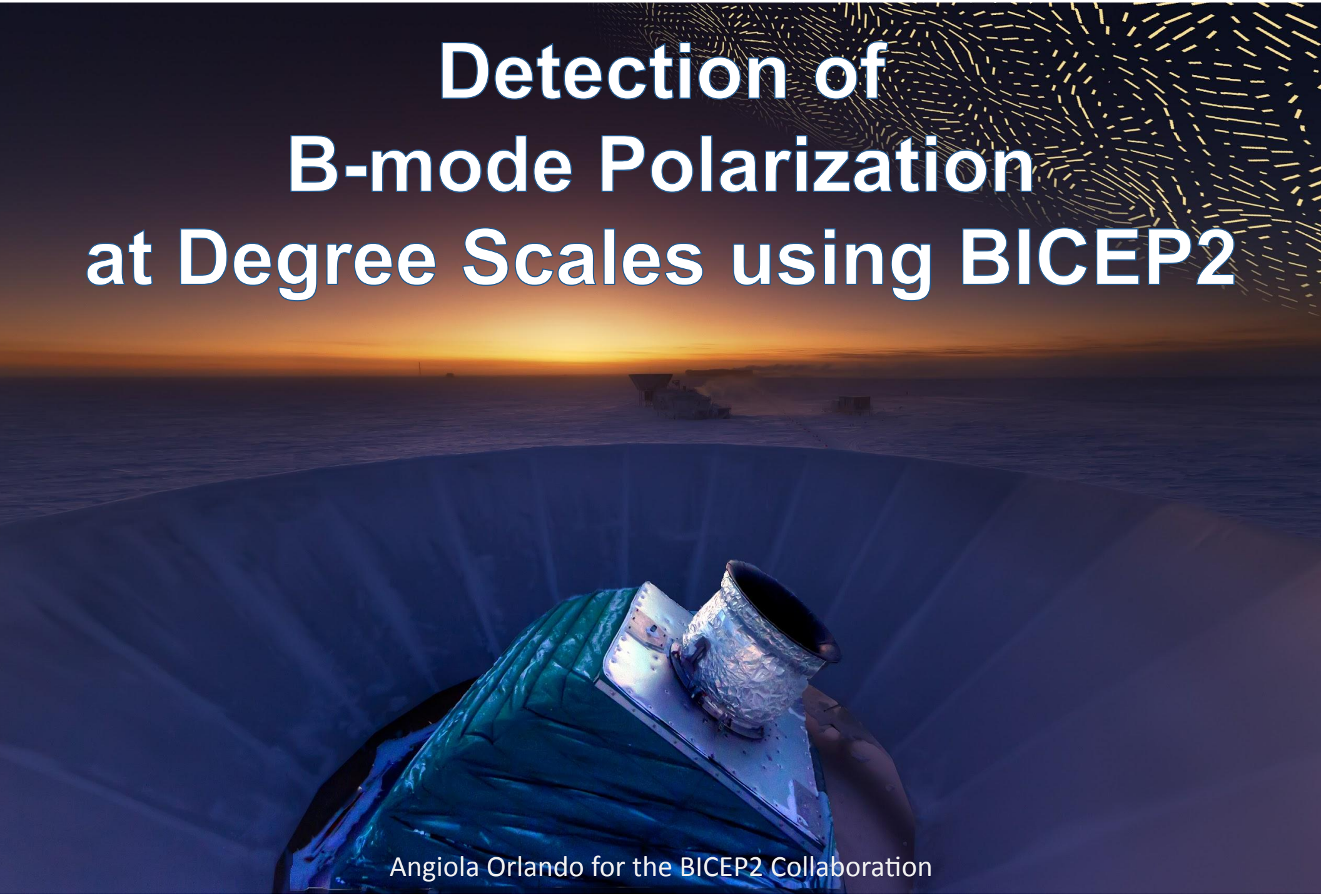
Detection of B-mode Polarization at Degree Scales using BICEP2

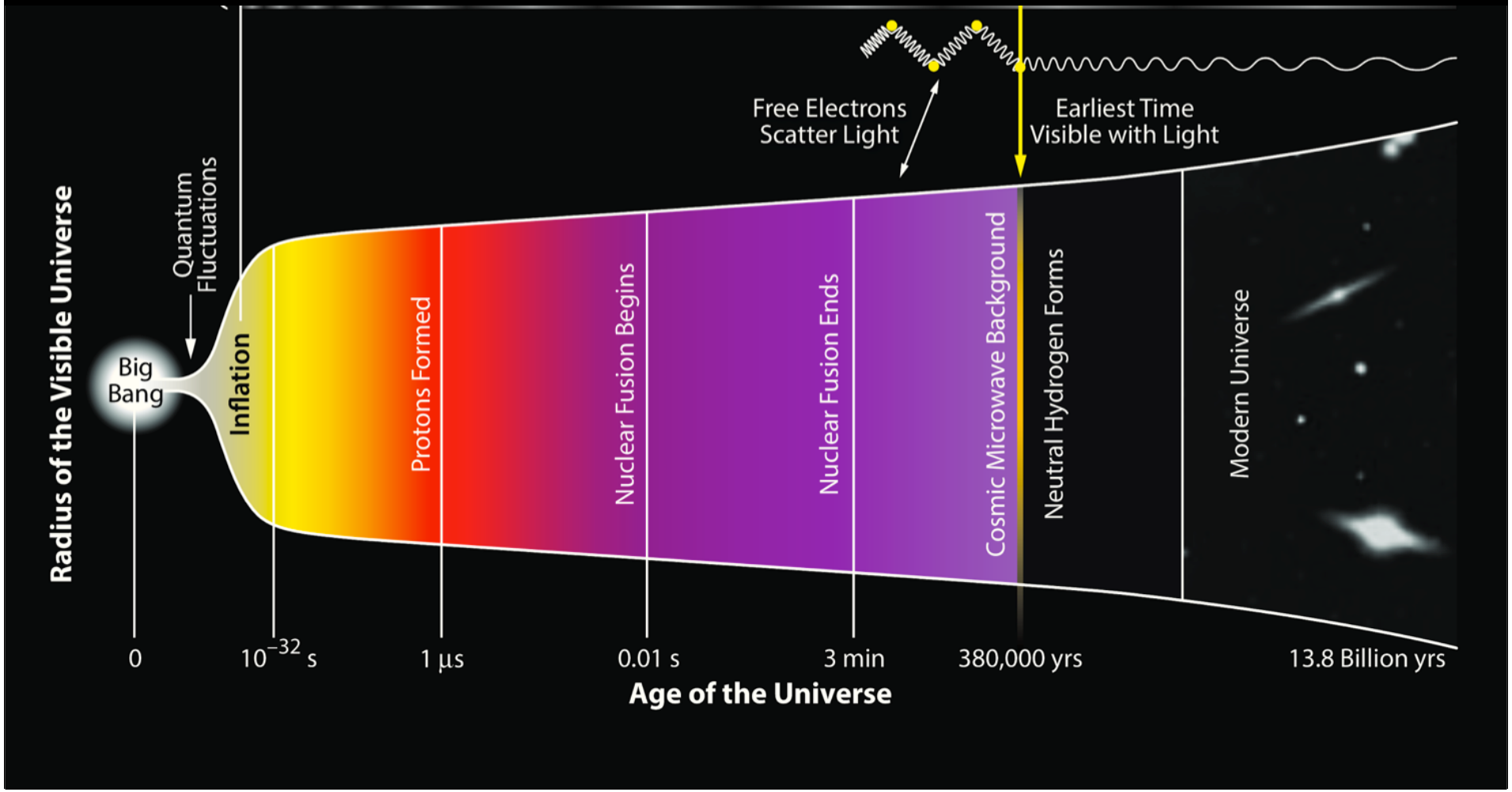


Angiola Orlando for the BICEP2 Collaboration

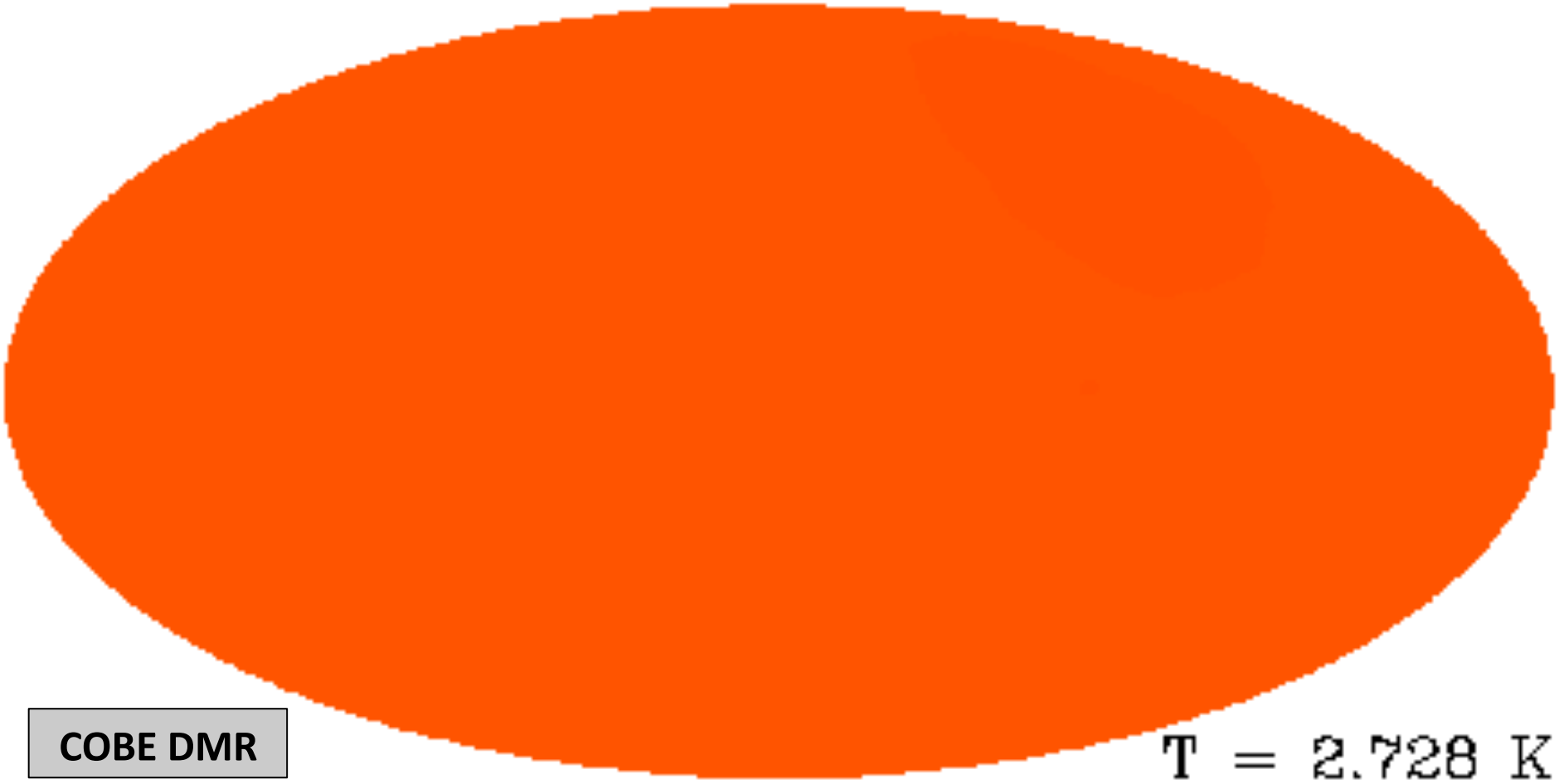

VE RI TAS
HARVARD
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
UCSD
JPL
NIST
CARDIFF UNIVERSITY
cea
UNIVERSITY OF TORONTO
UBC

History of the Universe

Universe becomes transparent



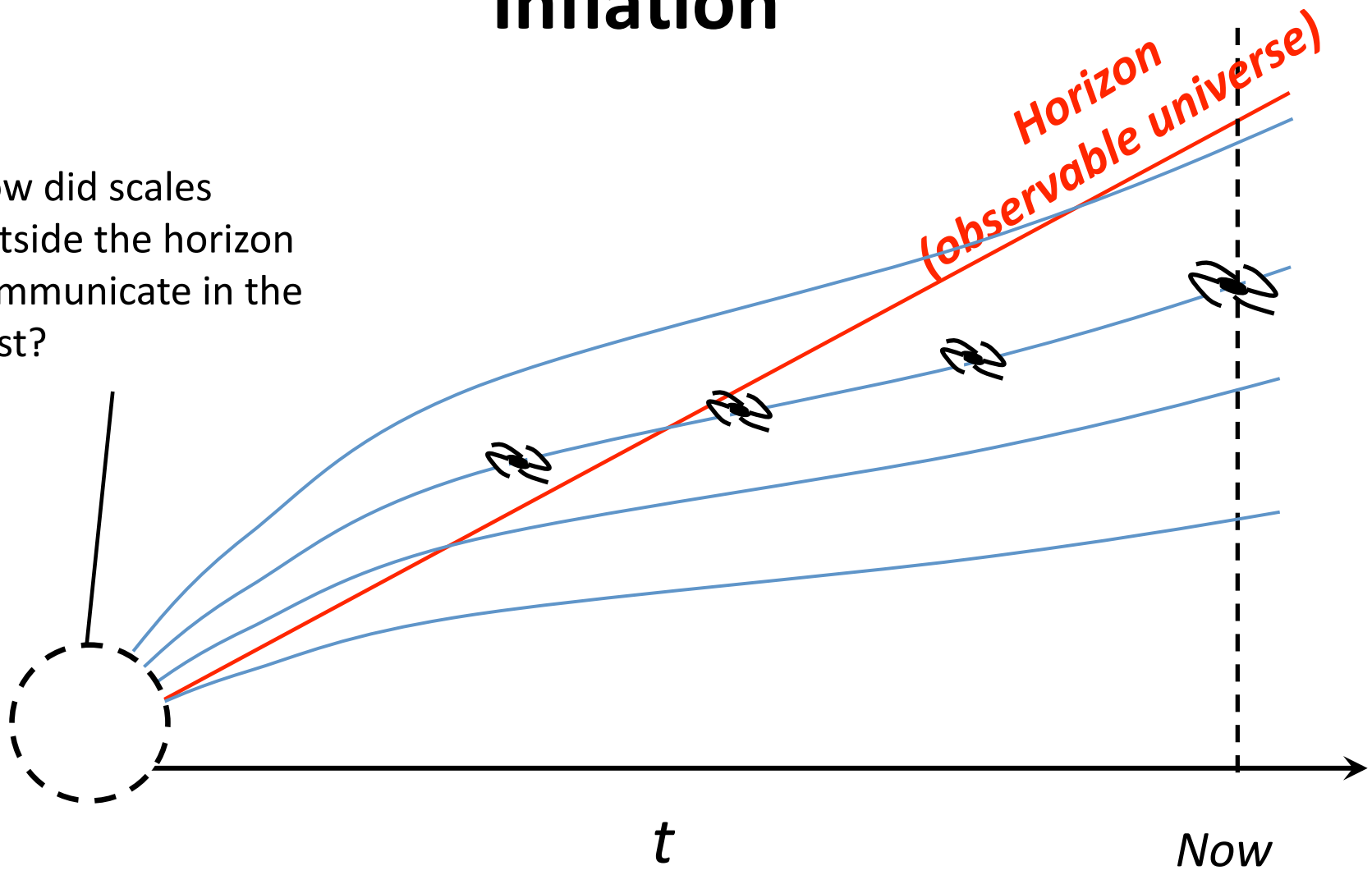
The Sky at Millimeter Wavelengths



Every Direction is the SAME Temperature to ~10 ppm!
How Can This BE? A Deeply Troubling Question for Cosmologists in 1980…

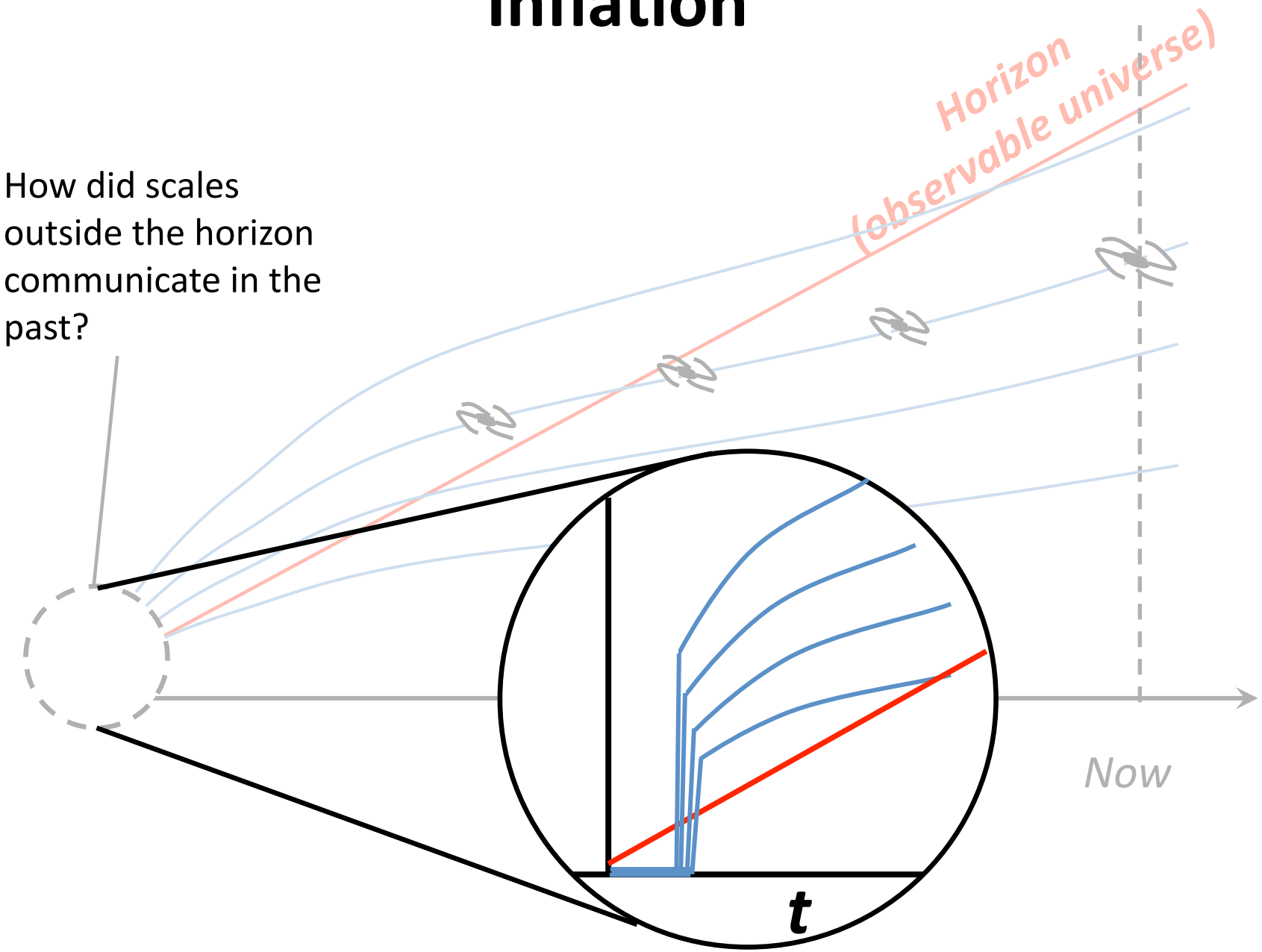
Inflation

How did scales outside the horizon communicate in the past?



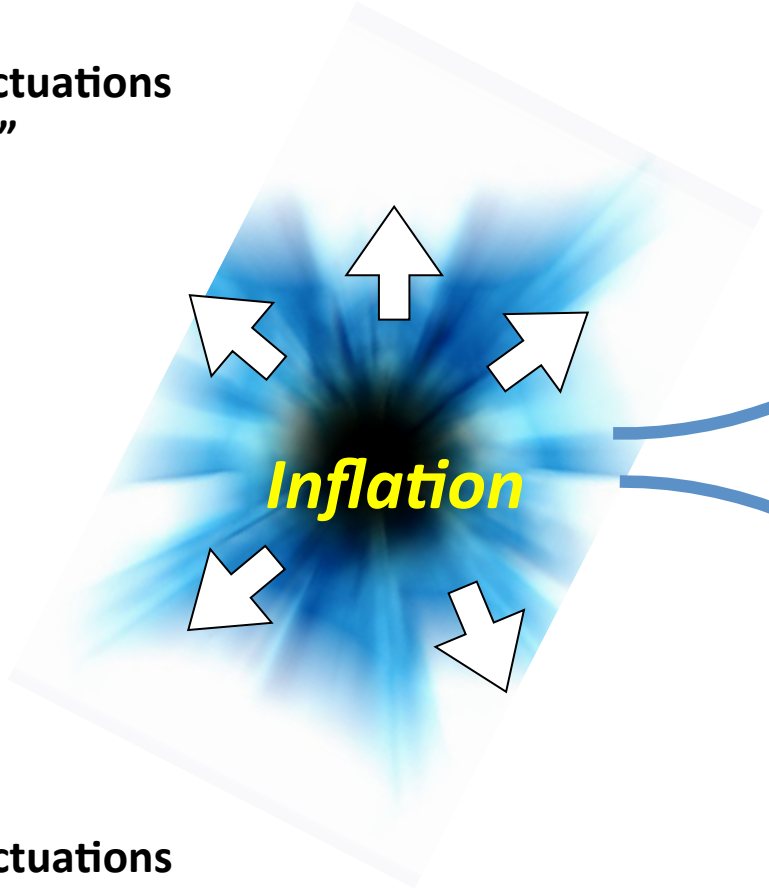
Inflation

How did scales outside the horizon communicate in the past?

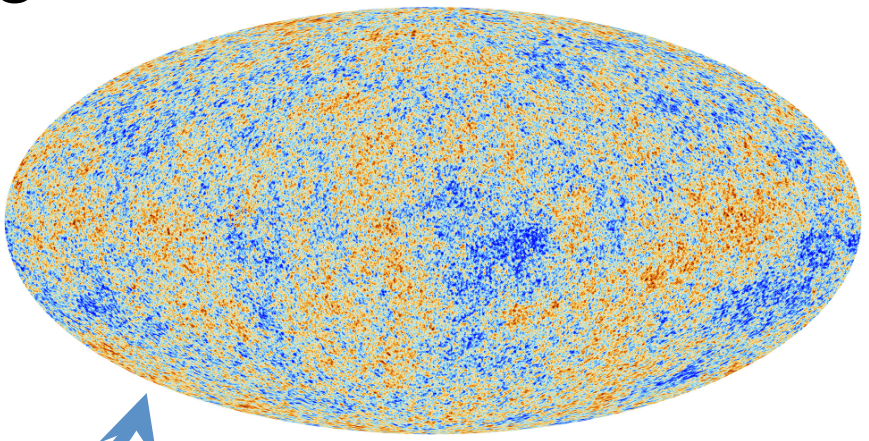


Density perturbations and *gravitational waves*

Sub-atomic vacuum fluctuations of "inflaton"

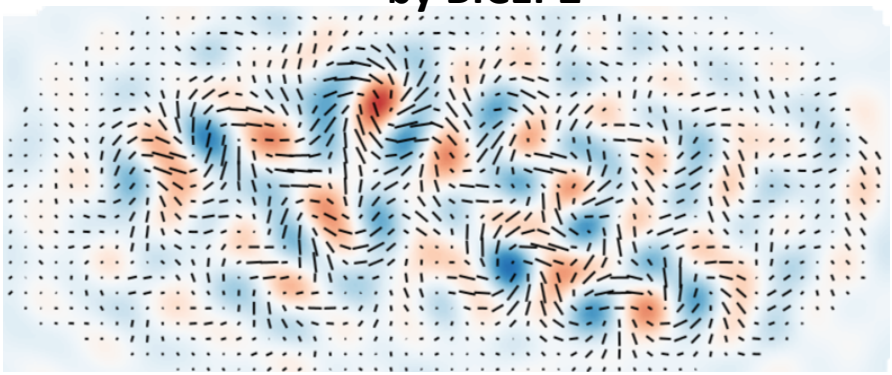


Sub-atomic vacuum fluctuations of *graviton* (quanta of gravity)

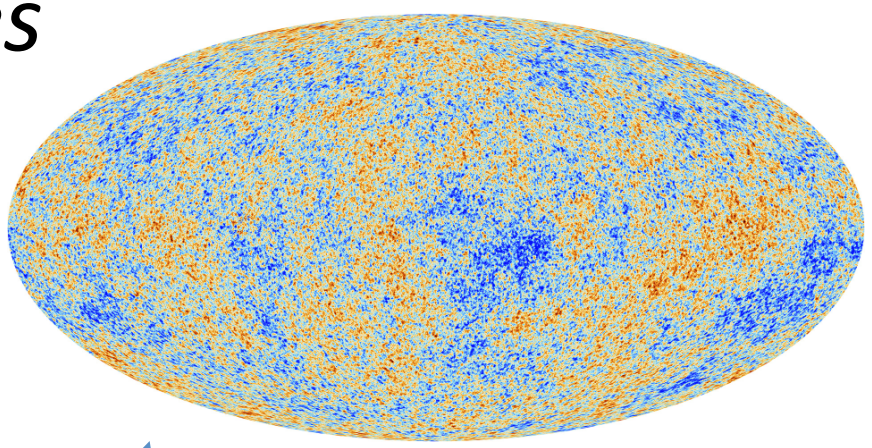


Density perturbations *studied* by Planck, WMAP, SPT, etc.

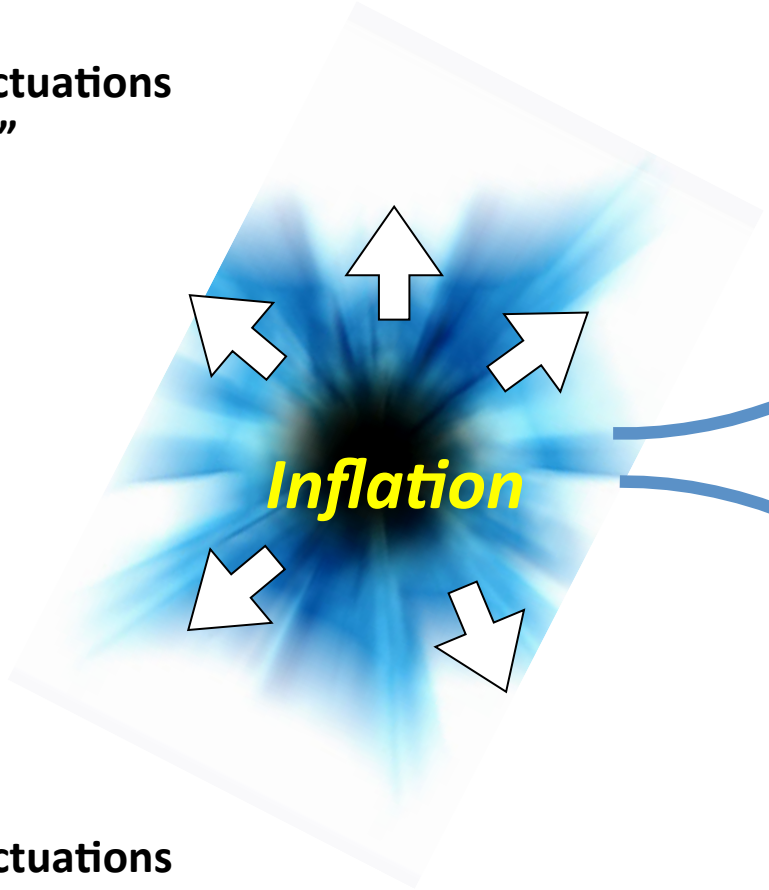
Gravitational waves detected by BICEP2



Density perturbations and *gravitational waves*



Sub-atomic vacuum fluctuations of "inflaton"

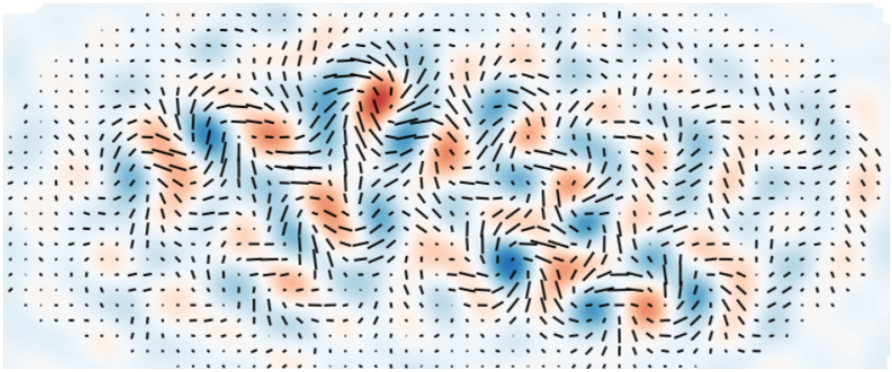


Density perturbations

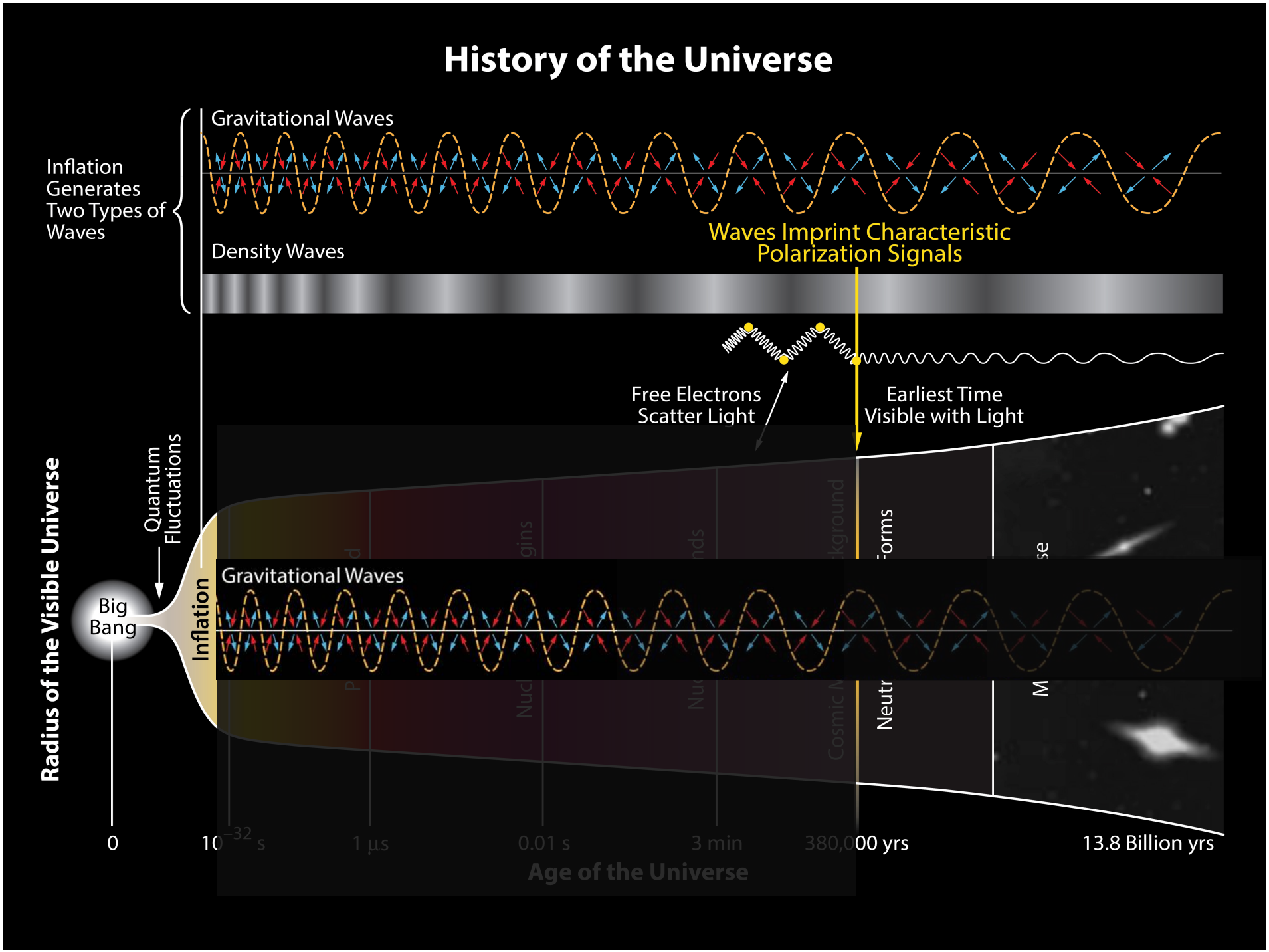
$$r \approx \frac{V[\phi]}{(4 \times 10^{16} GeV)^4}$$

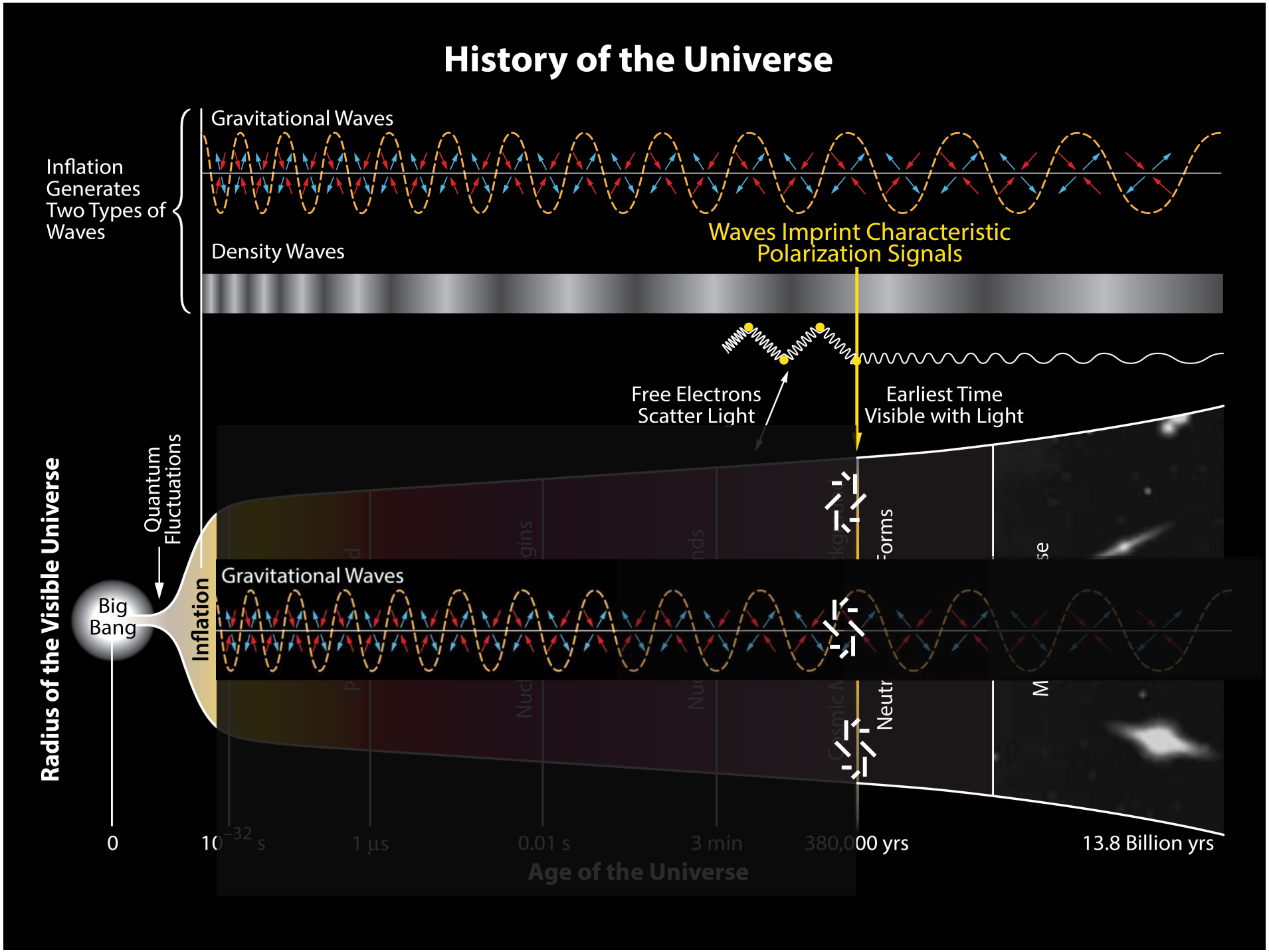
GUT scale physics!?

Gravitational waves



Sub-atomic vacuum fluctuations of *graviton* (quanta of gravity)


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
Gravitational Waves
Radius of the Visible Universe
0
1 µs
0.01 s
3 min
13.8 Billion yrs
Age of the Universe

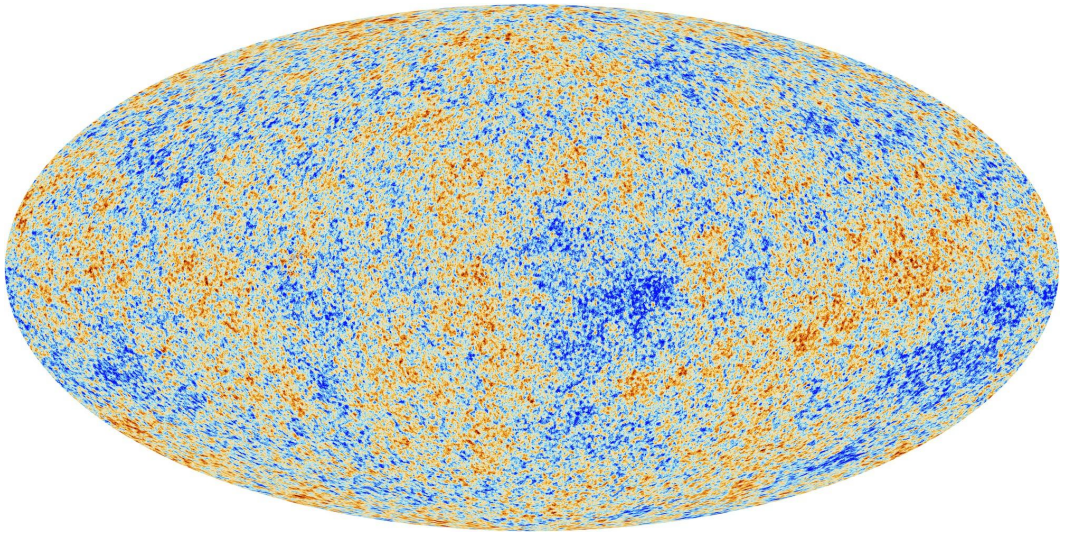

History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Quantum Fluctuations
Big Bang
Inflation
Gravitational Waves
Radius of the Visible Universe
0
1 µs
0.01 s
3 min
13.8 Billion yrs
Age of the Universe

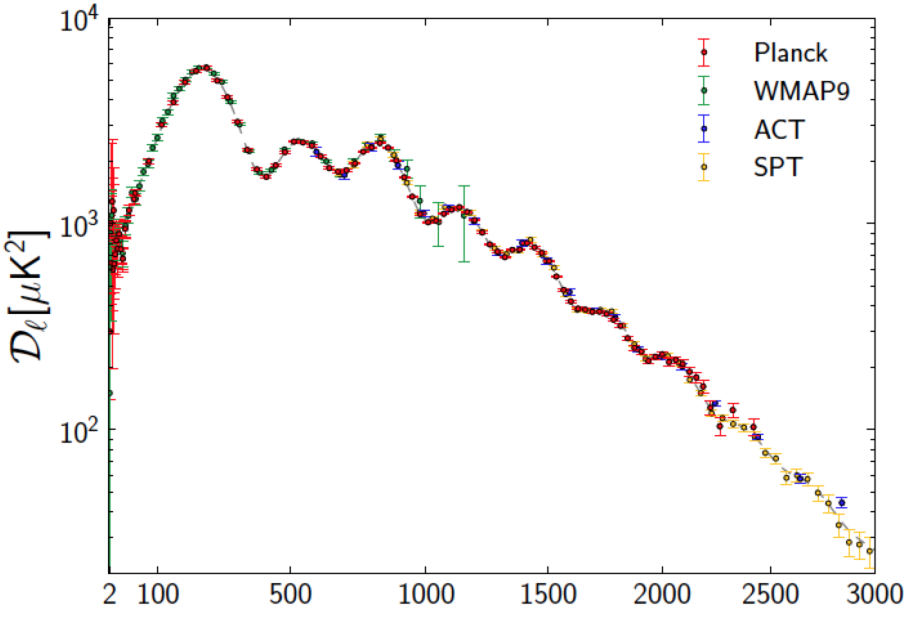
The Cosmic Microwave Background (CMB)

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.

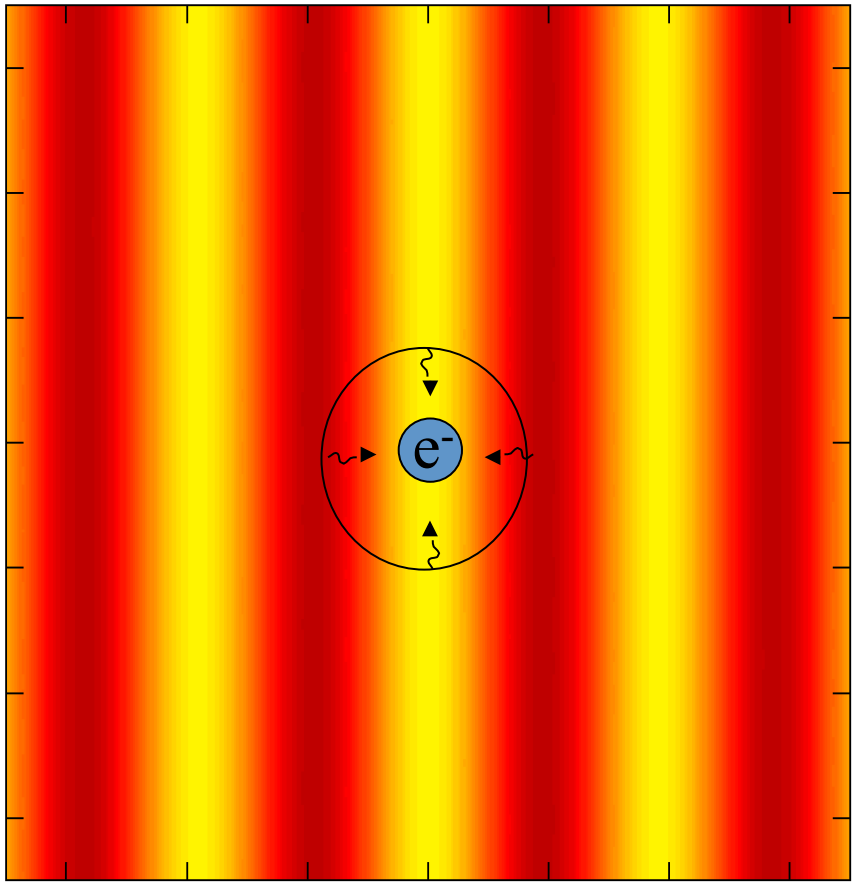
However, any imprint of the inflationary gravitational waves have so far eluded detection in the CMB.





Planck Collaboration & ESA

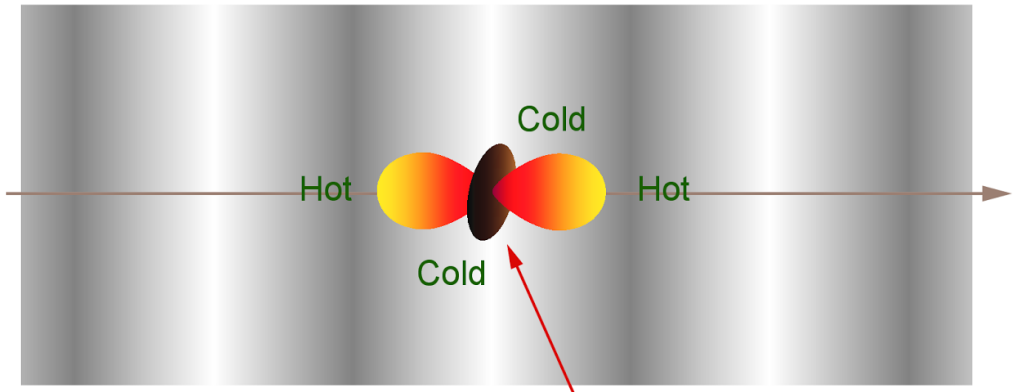
CMB polarization:
arises at last scattering
from local radiation quadrupole



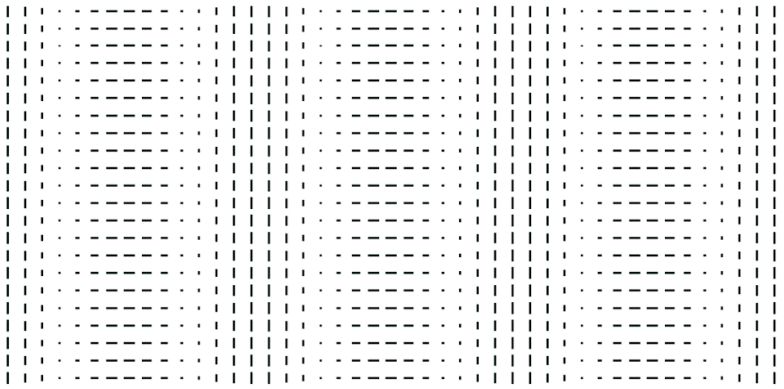
From Thomson scattering wherever there is ionized gas and quadrupole anisotropy

CMB polarization

Density Wave

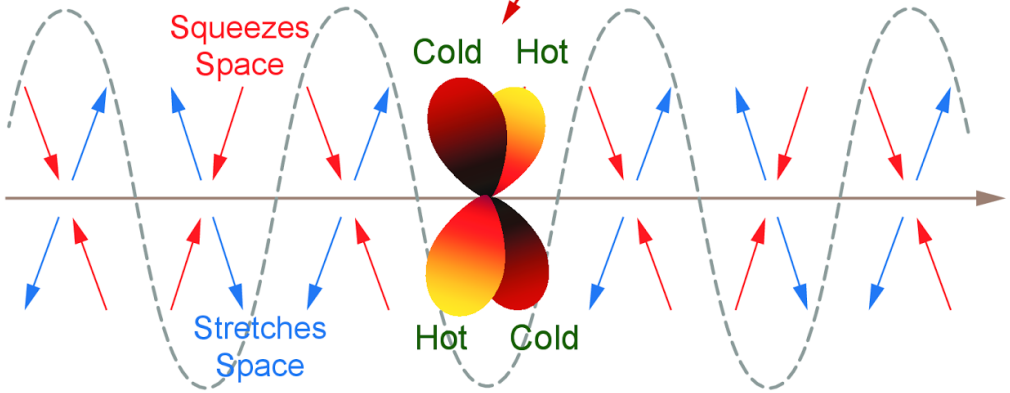


E-Mode Polarization Pattern

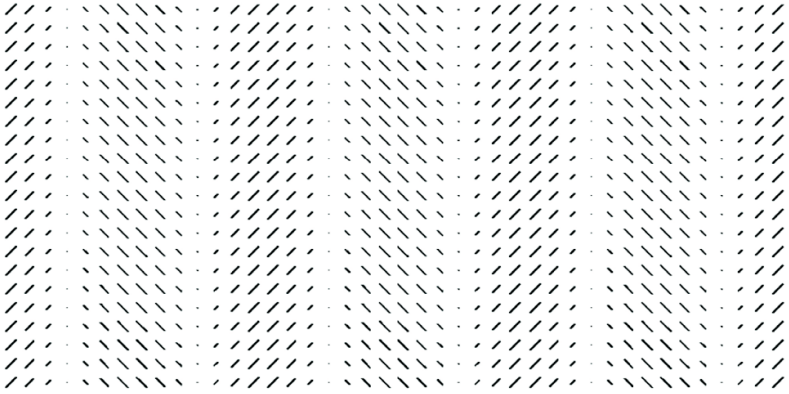


Temperature Pattern Seen by Electrons

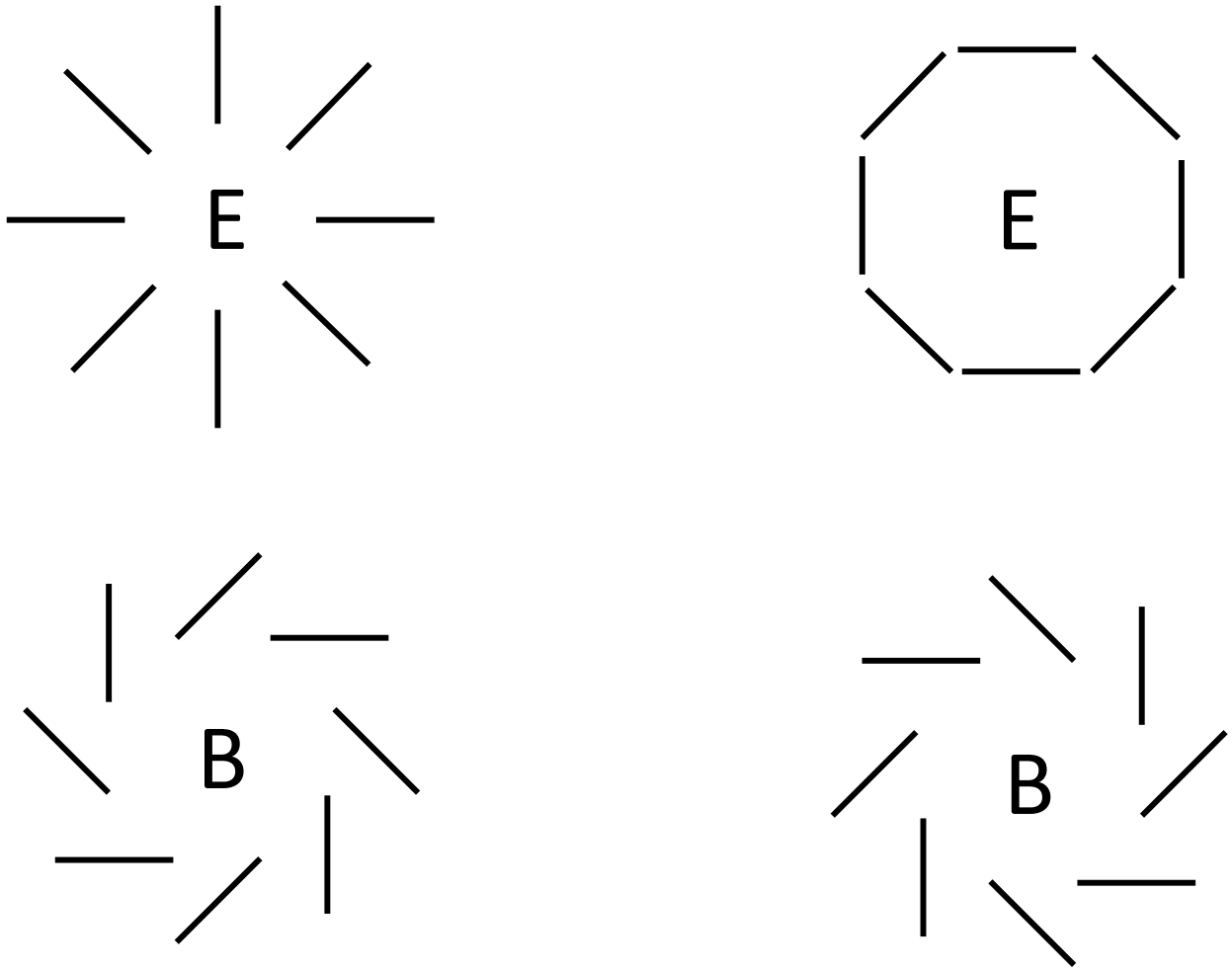
Gravitational Wave



B-Mode Polarization Pattern

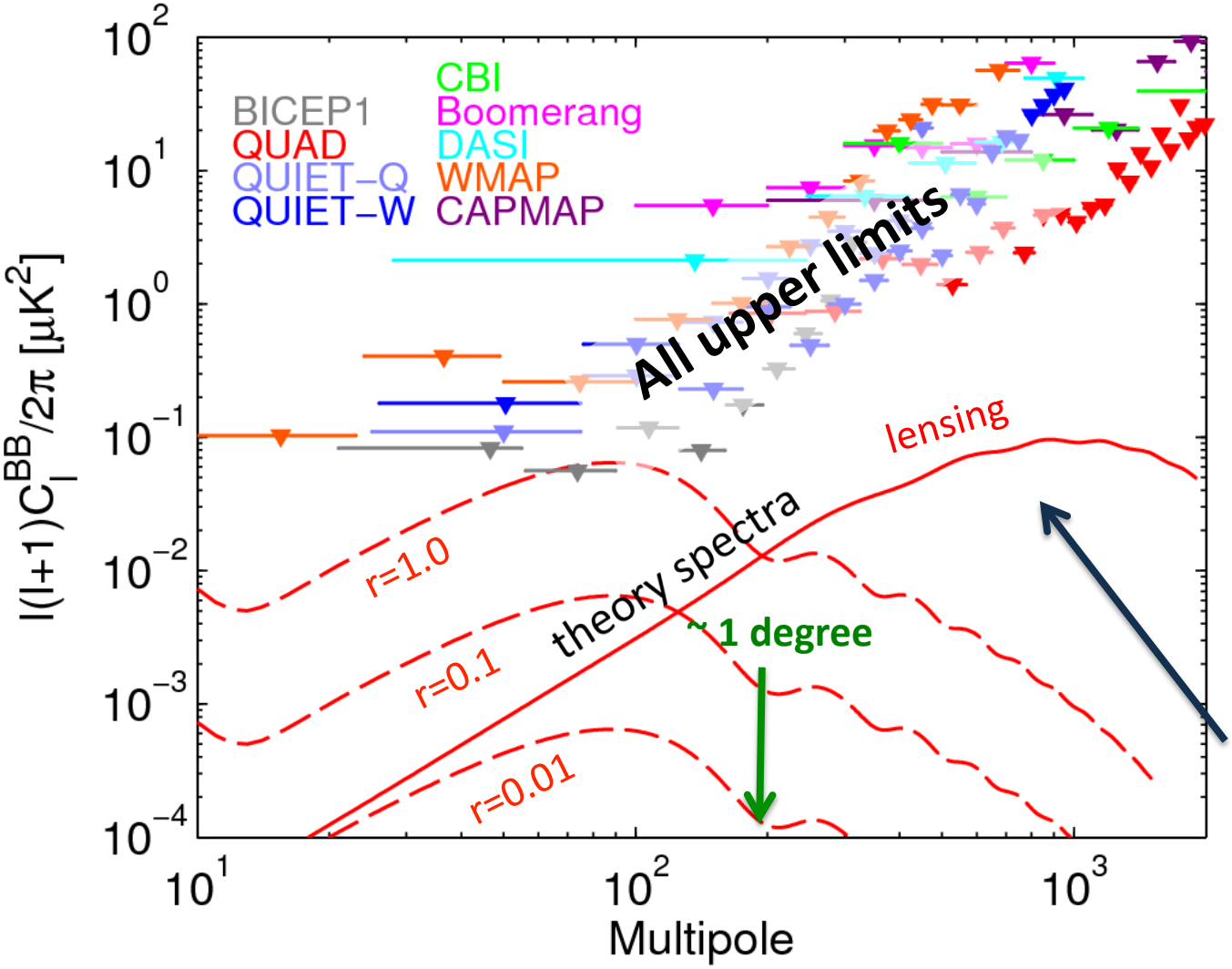


The signature of gravitational waves



Density fluctuations *cannot* make B-mode patterns

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

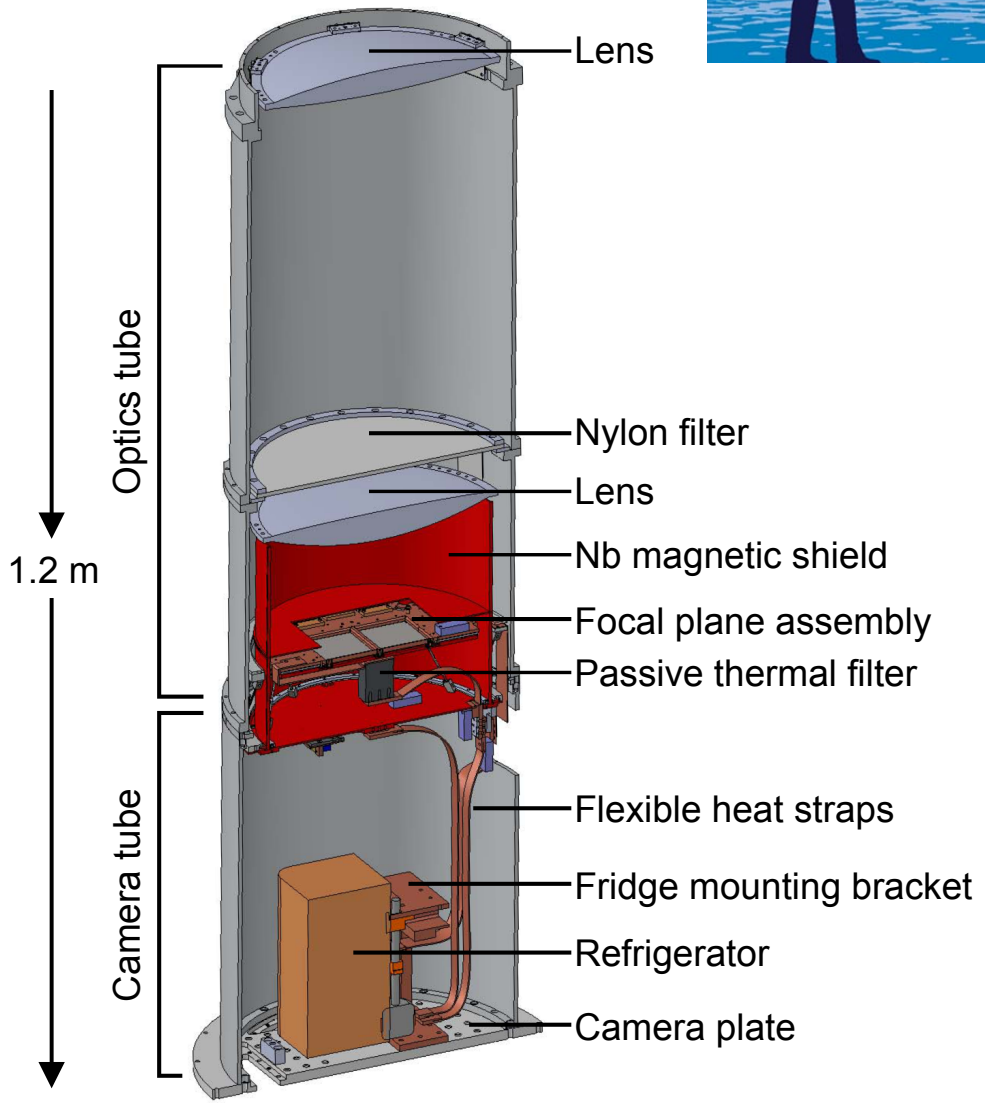
BICEP2 Strategy: Unique Optics

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

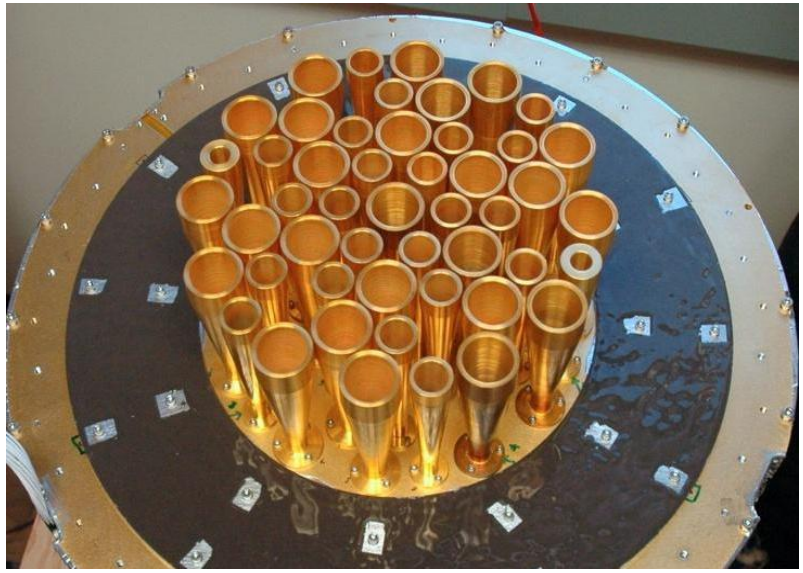
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

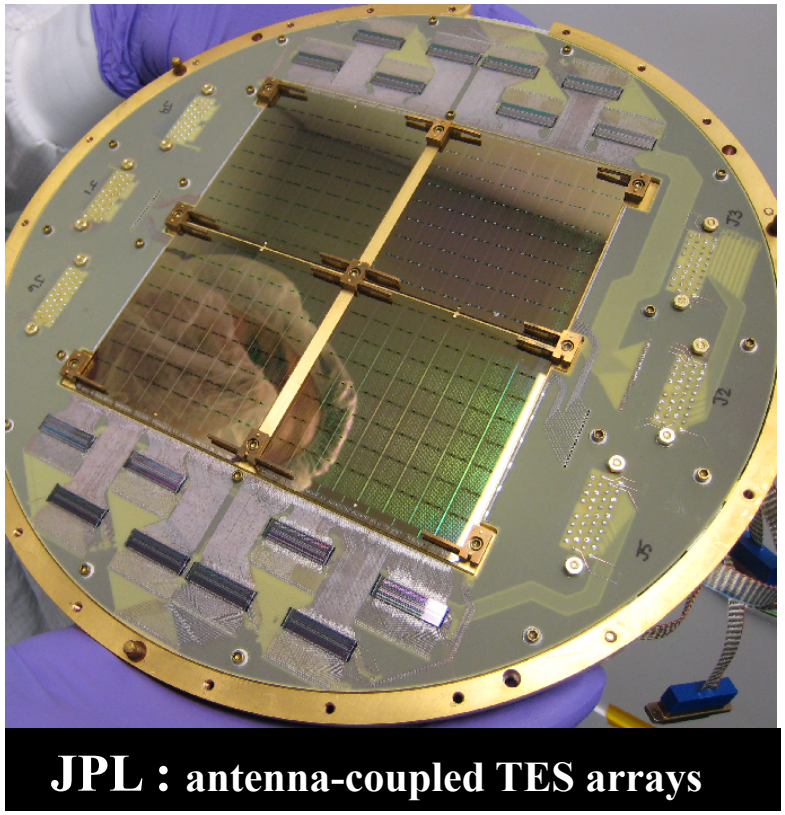
Liquid helium cools the optical elements to 4.2 K.

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



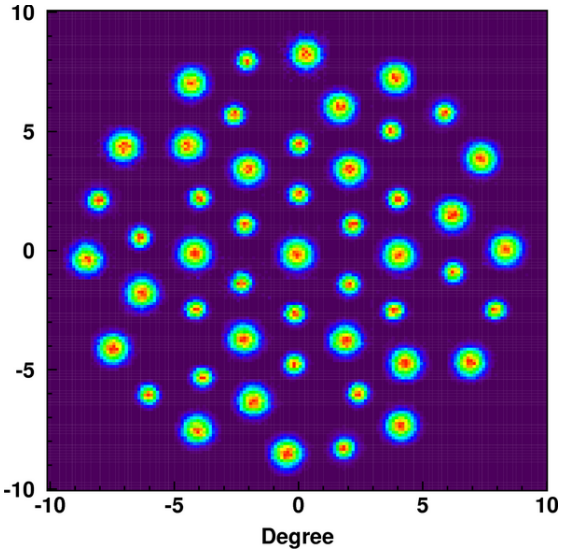
BICEP2 Strategy: Revolutionary detectors

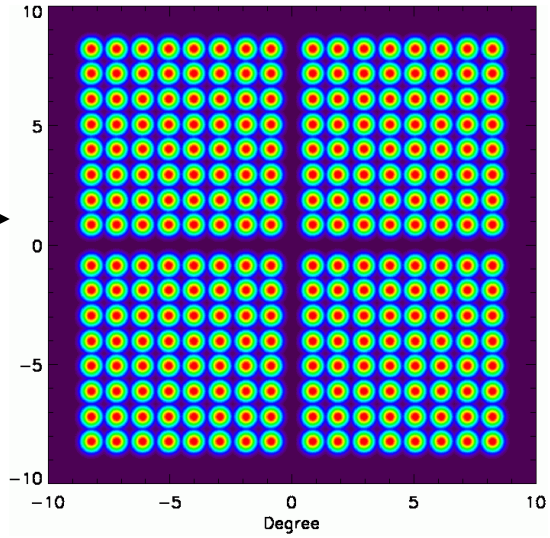




BICEP1

48
150 GHz
detectors

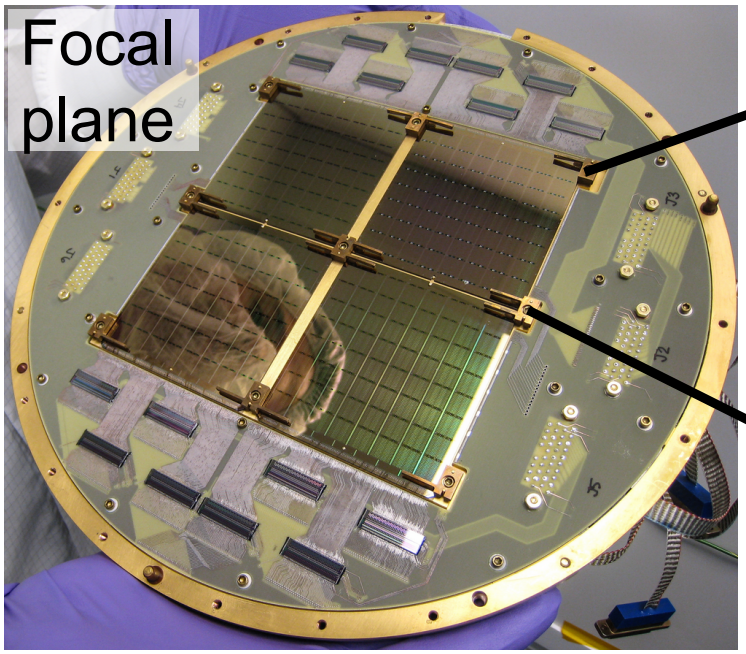


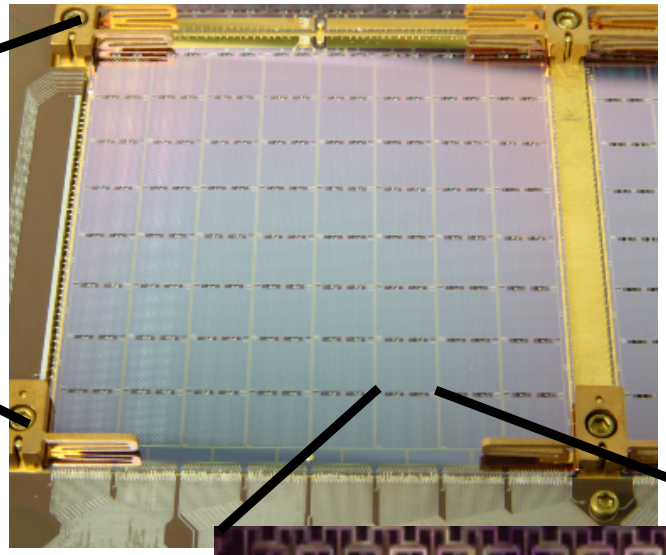


BICEP2

512
150 GHz
detectors

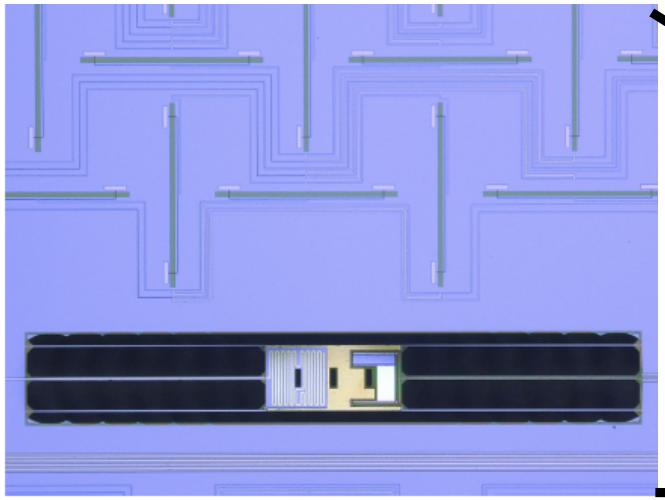
Mass-produced superconducting detectors





Planar
antenna
array

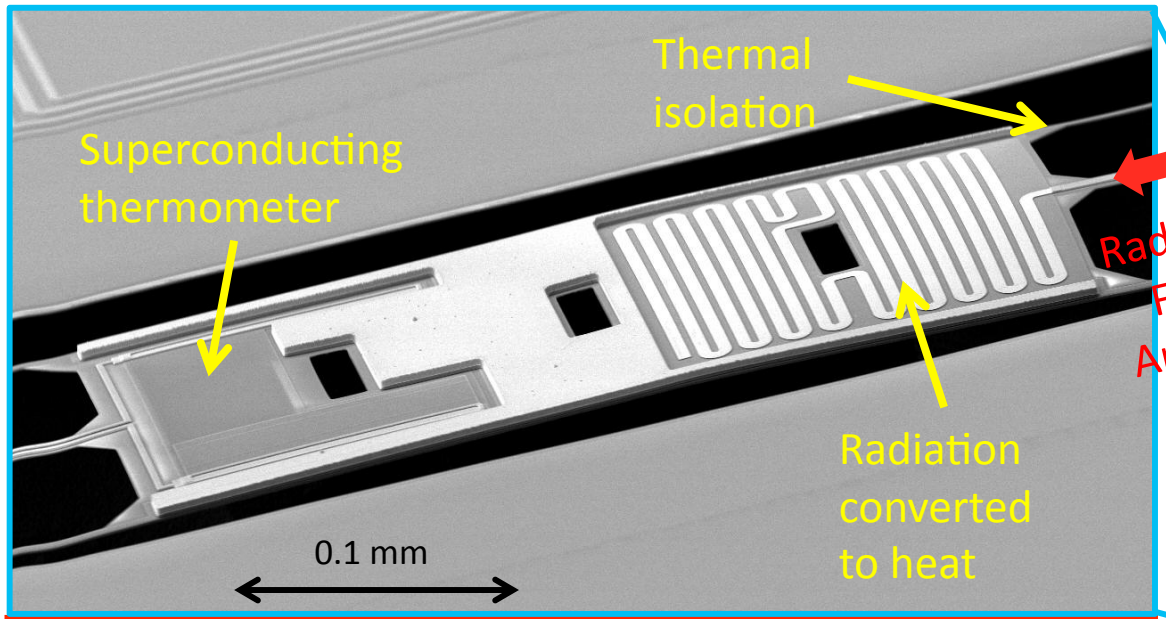
Slot
antennas



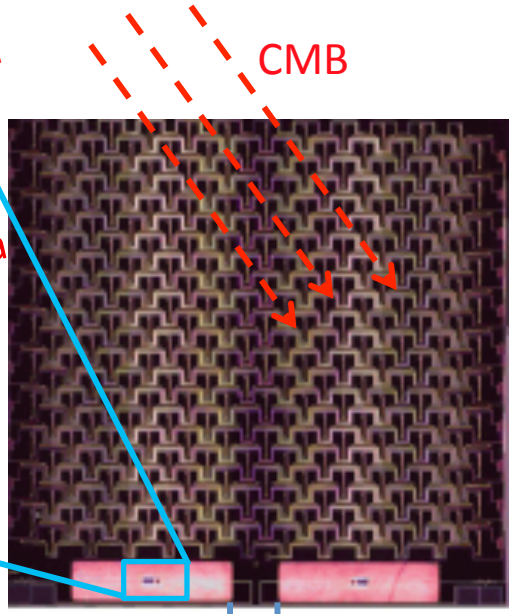
Transition edge sensor

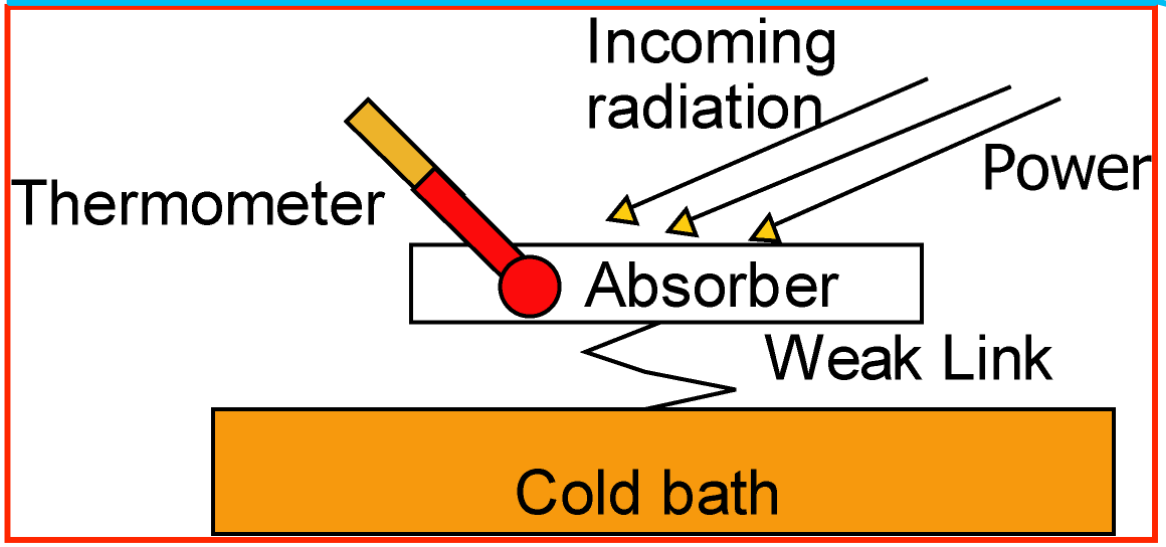
Detecting CMB Radiation

BICEP2 Detector: Transition-Edge Sensor

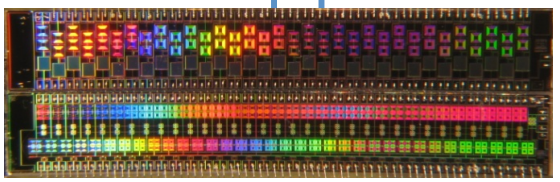


Printed Antenna Gathers CMB Light





Sensors cooled to 0.25 K to reduce thermal noise



SQUIDs Amplify and Multiplex Signals

SQUIDs developed at NIST

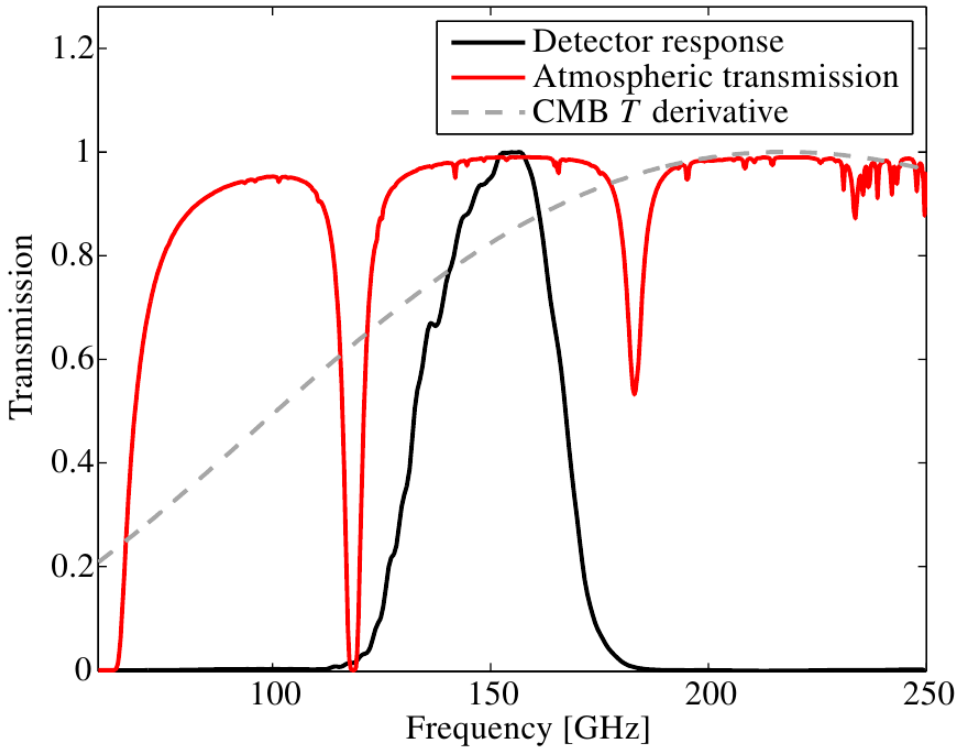
BICEP2 Frequency Response

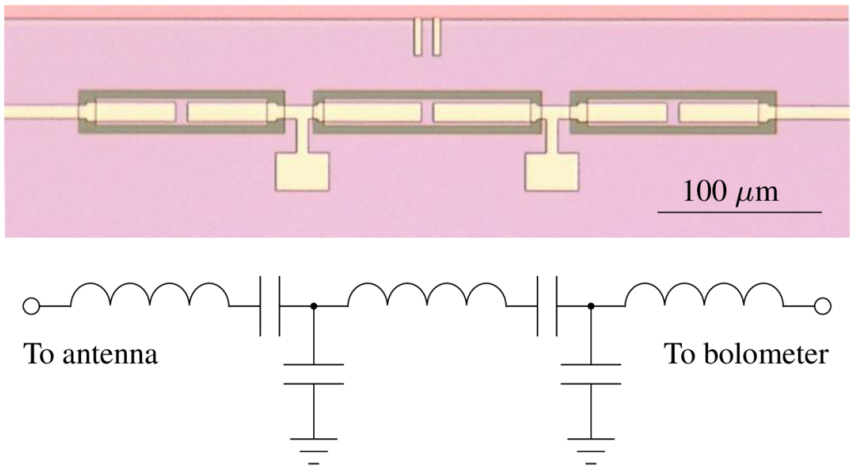
The dry South Pole atmosphere provides excellent observing conditions most of the year.

The 28% fractional bandwidth fits within an atmospheric transmission window straddled by oxygen and water lines.

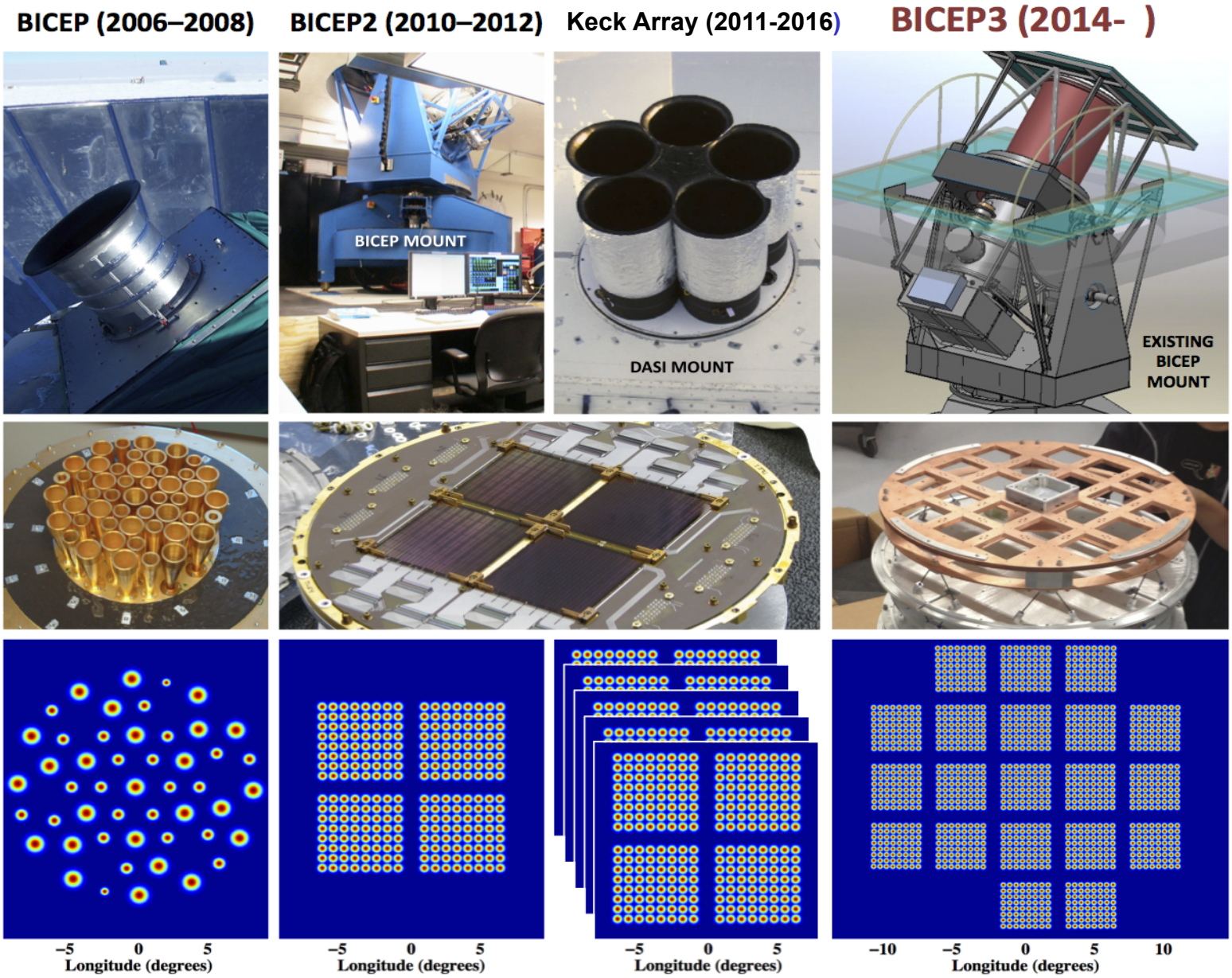
In this window, the atmosphere is transparent to microwaves.

The detector passband is defined by a filter printed directly onto the focal plane wafers.





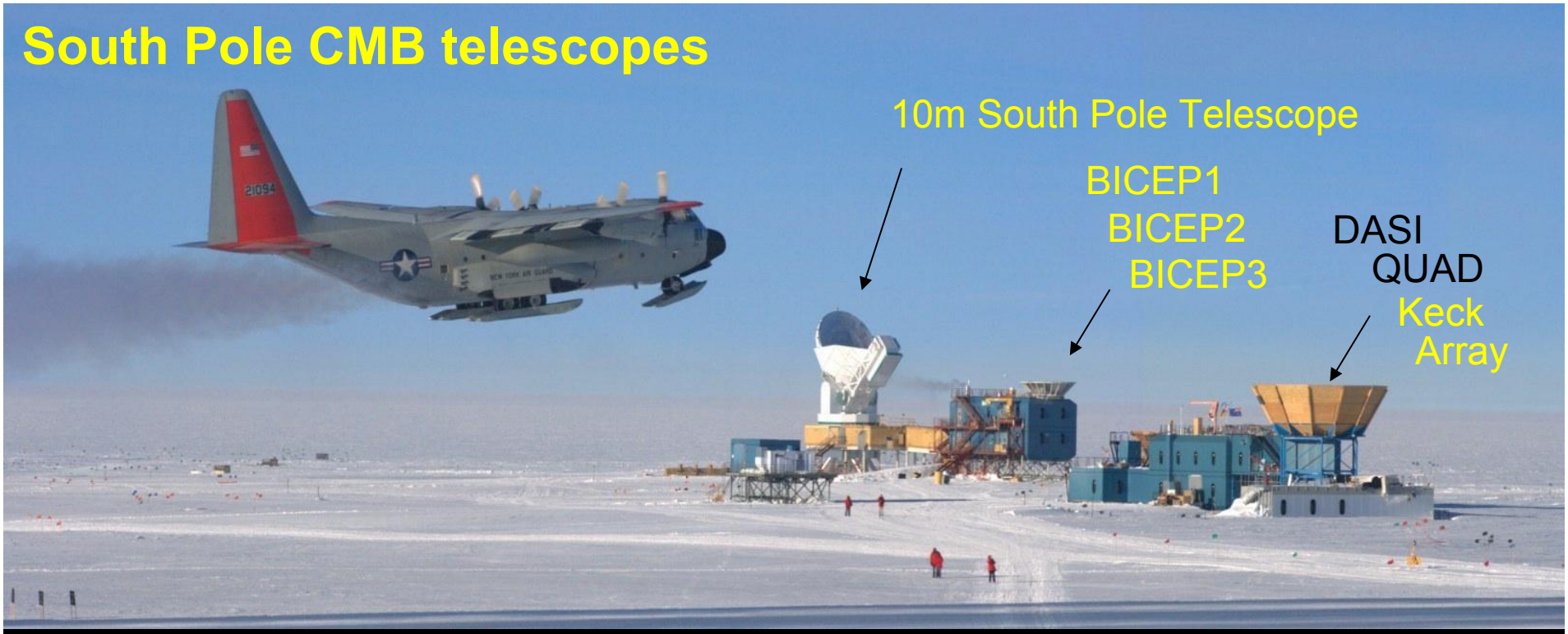
Sensitivity through detector count increase



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
4.4 m² deg² AQ	4.4 m² deg² AQ	22.2 m² deg² AQ	50.3 m² deg² AQ optical throughput

BICEP2 Strategy: the South Pole

South Pole CMB telescopes



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

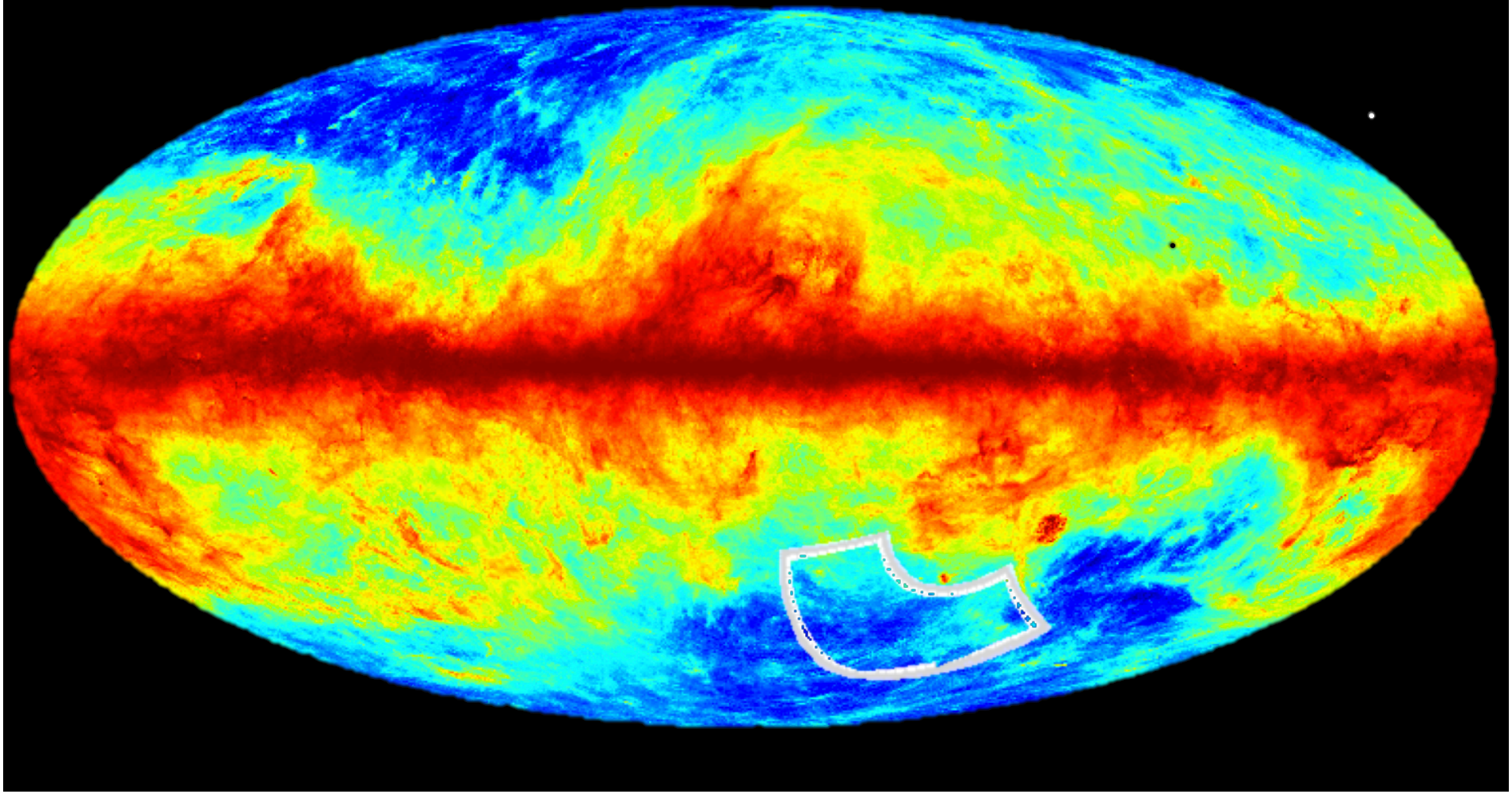
Super dry atmosphere and 24h coverage of "Southern Hole".

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

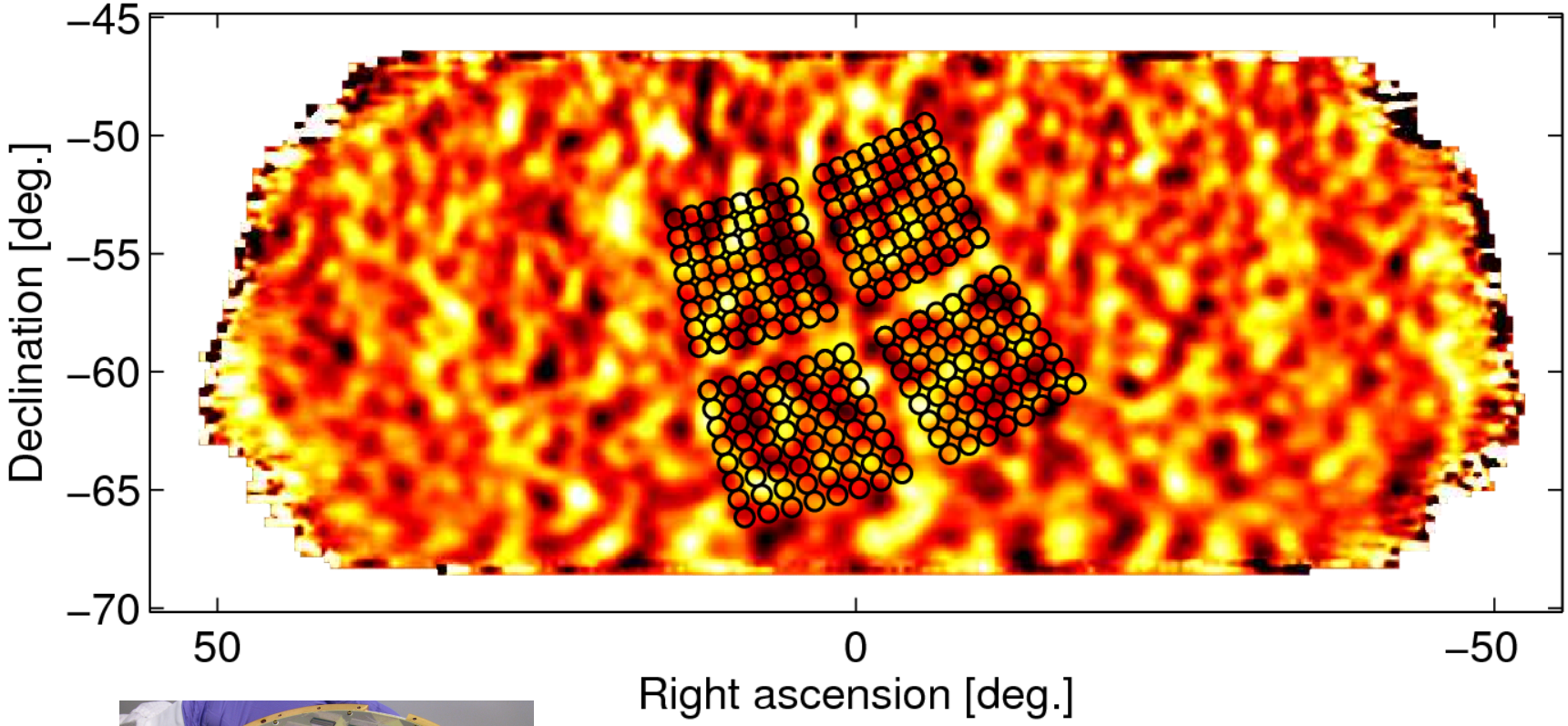

photo: Keith Vanderlinde

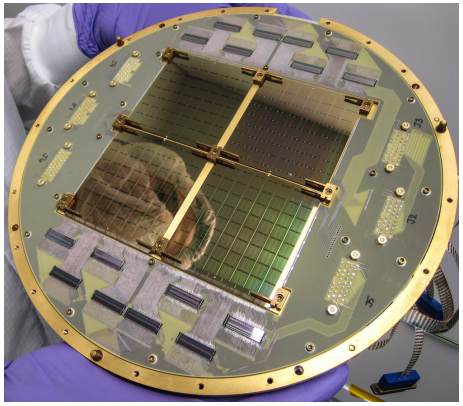
BICEP2 Strategy: The Best Field

- Observe the "Southern Hole" at 150 GHz
- a region of the sky exceptionally free of dust and radio emission from our galaxy



BICEP2 on the Sky





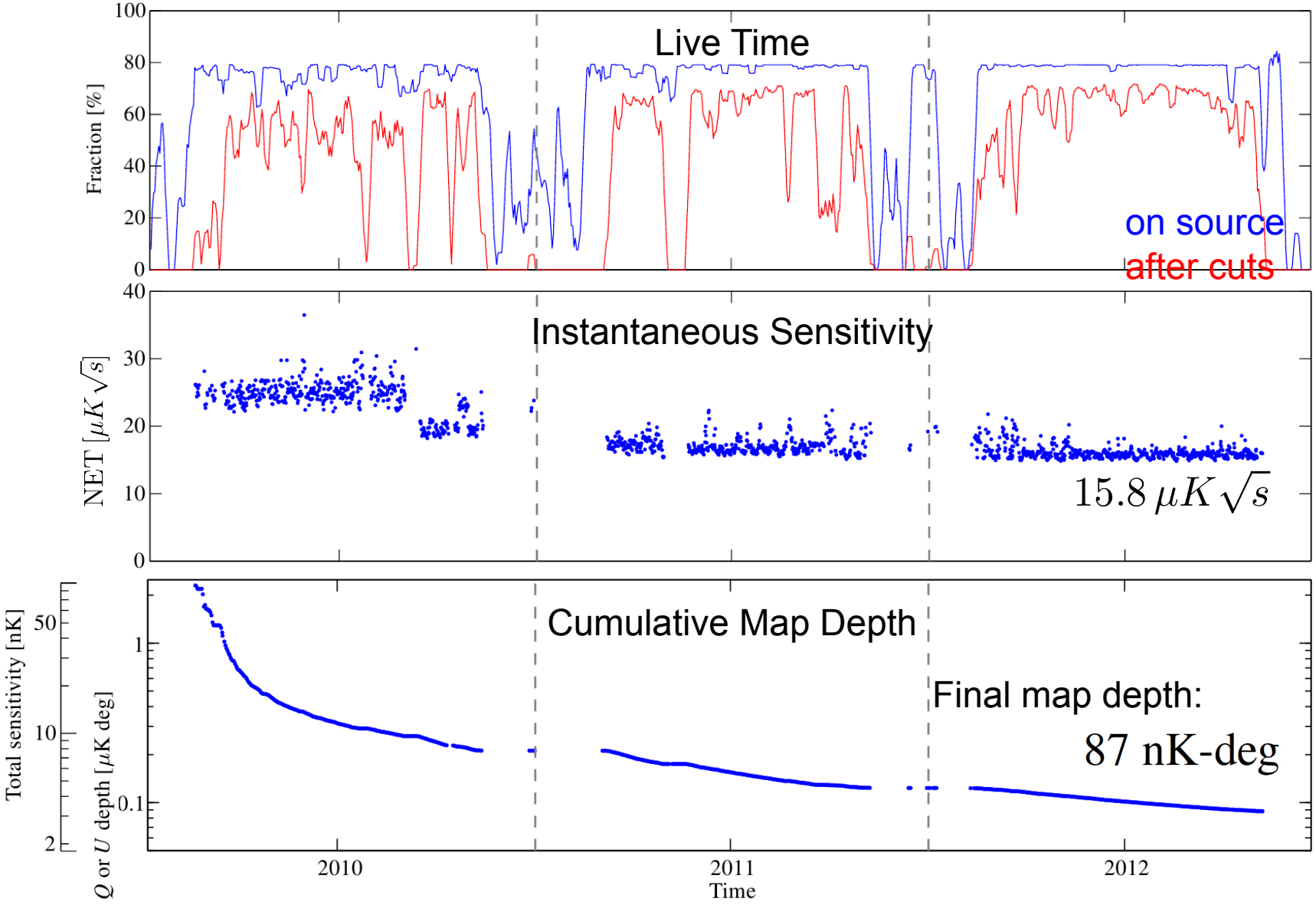
Projection of the BICEP2 focal plane on the sky

The focal plane is 20 degrees across

Background is the CMB temperature map as measured with BICEP2

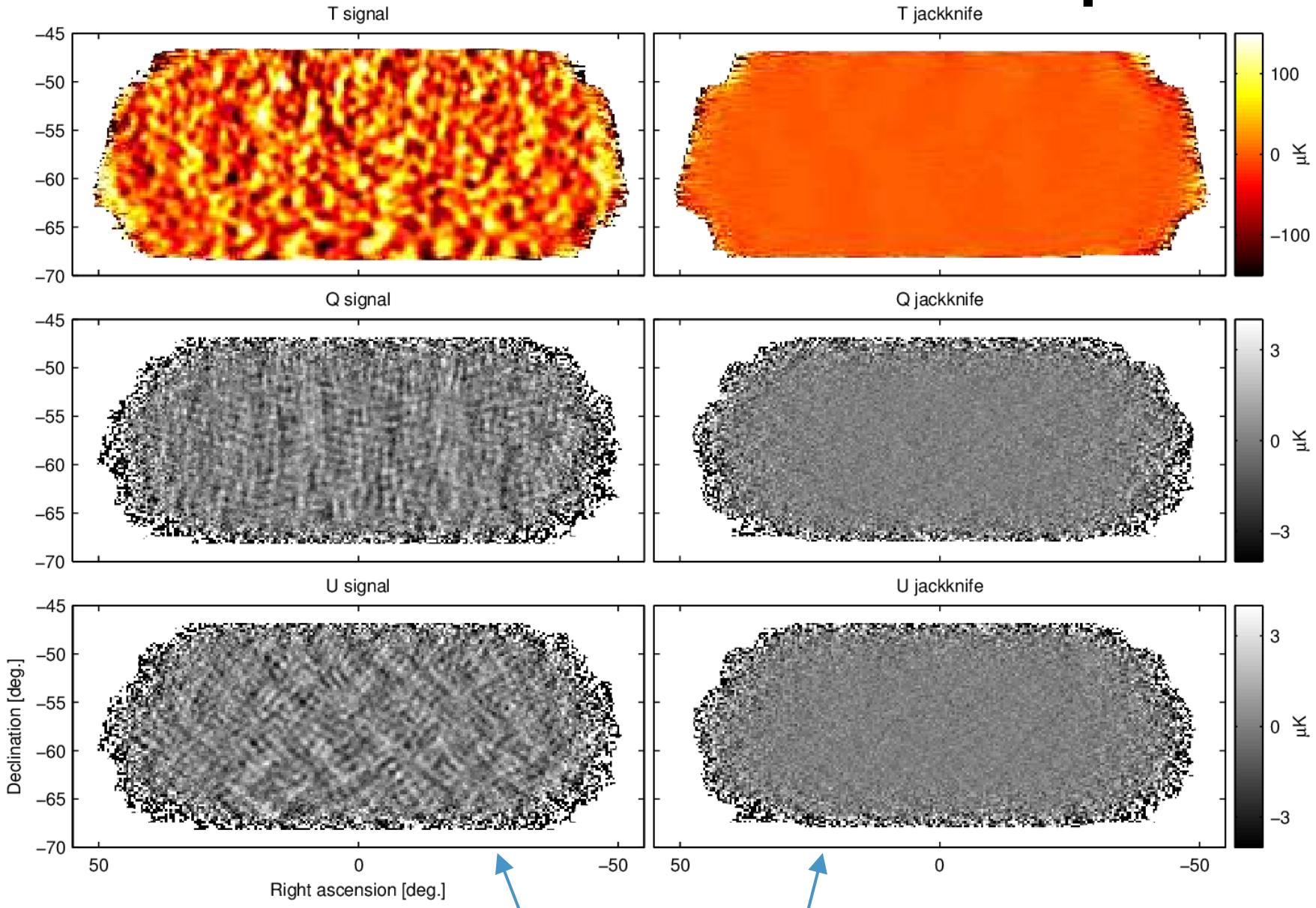
South Pole: “Relentless Observing”

BICEP2 3-year Data Set



Angiola Orlando for The Bicep2 Collaboration

BICEP2 T and Stokes Q/U Maps



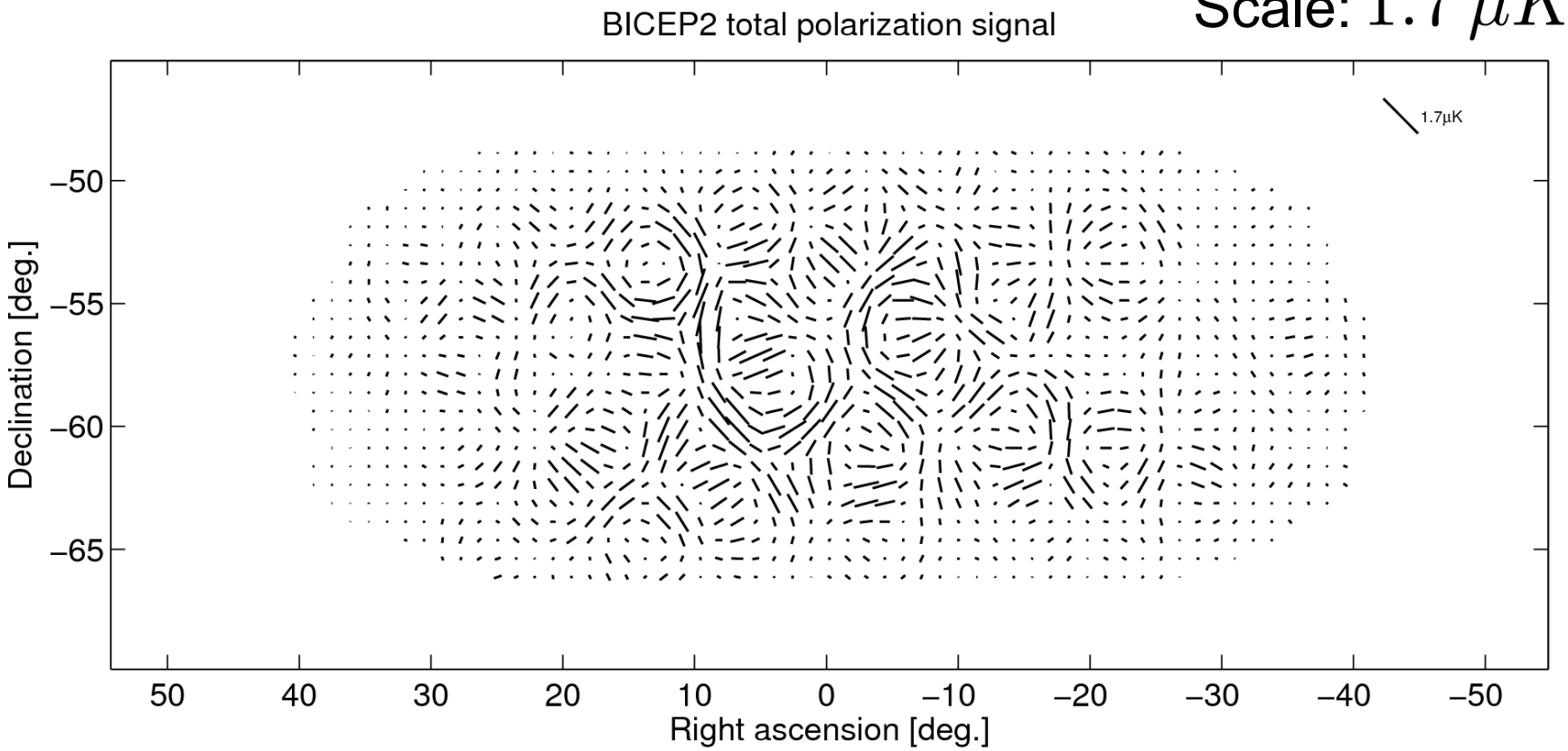
Signal Maps

Difference (“Jackknife”) Maps

Angiola Orlando for The Bicep2 Collaboration

Total Polarization

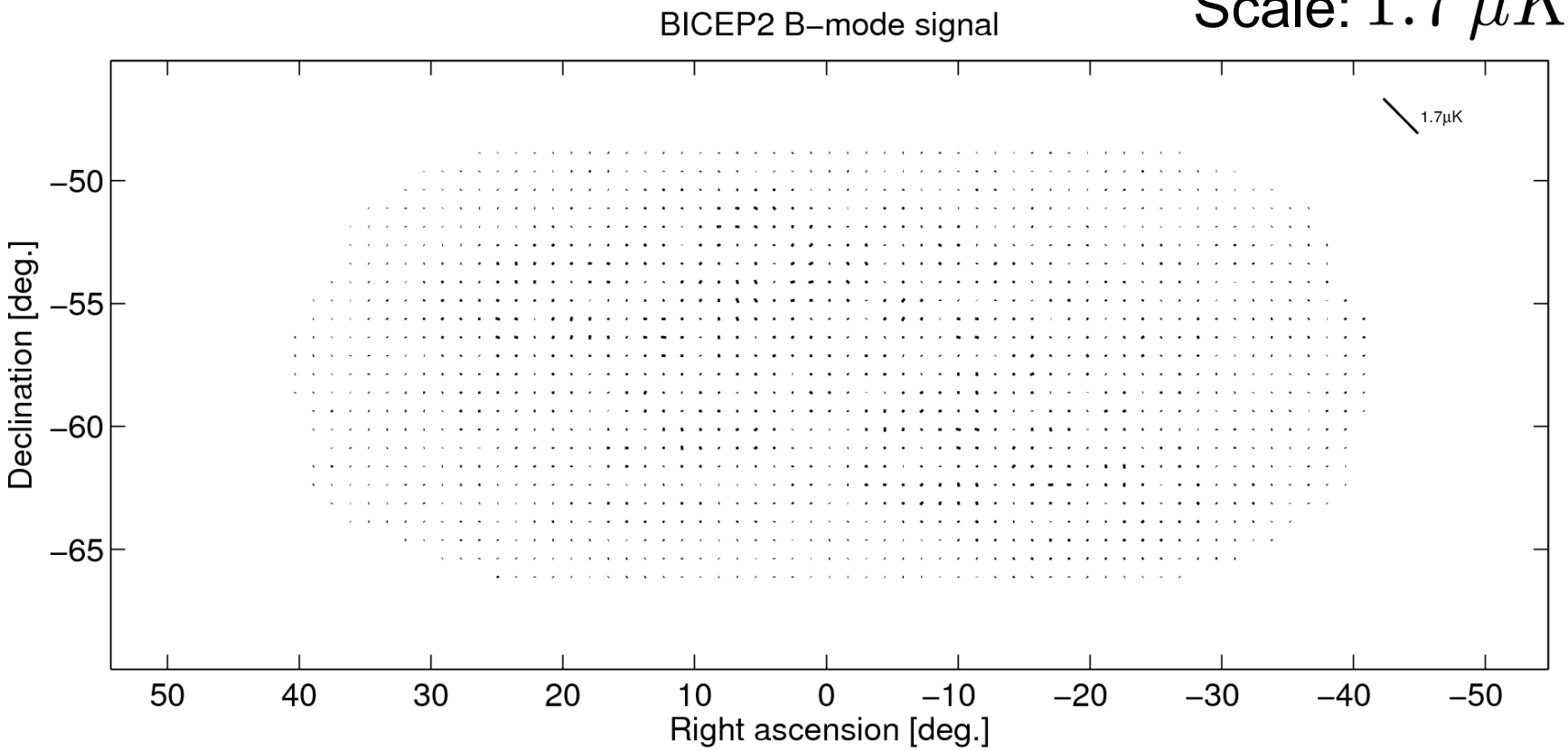
Scale: $1.7\ \mu K$



B-modes of r=0.1 contribute ~1/10 of the total polarization amplitude at l=100

B-mode Contribution

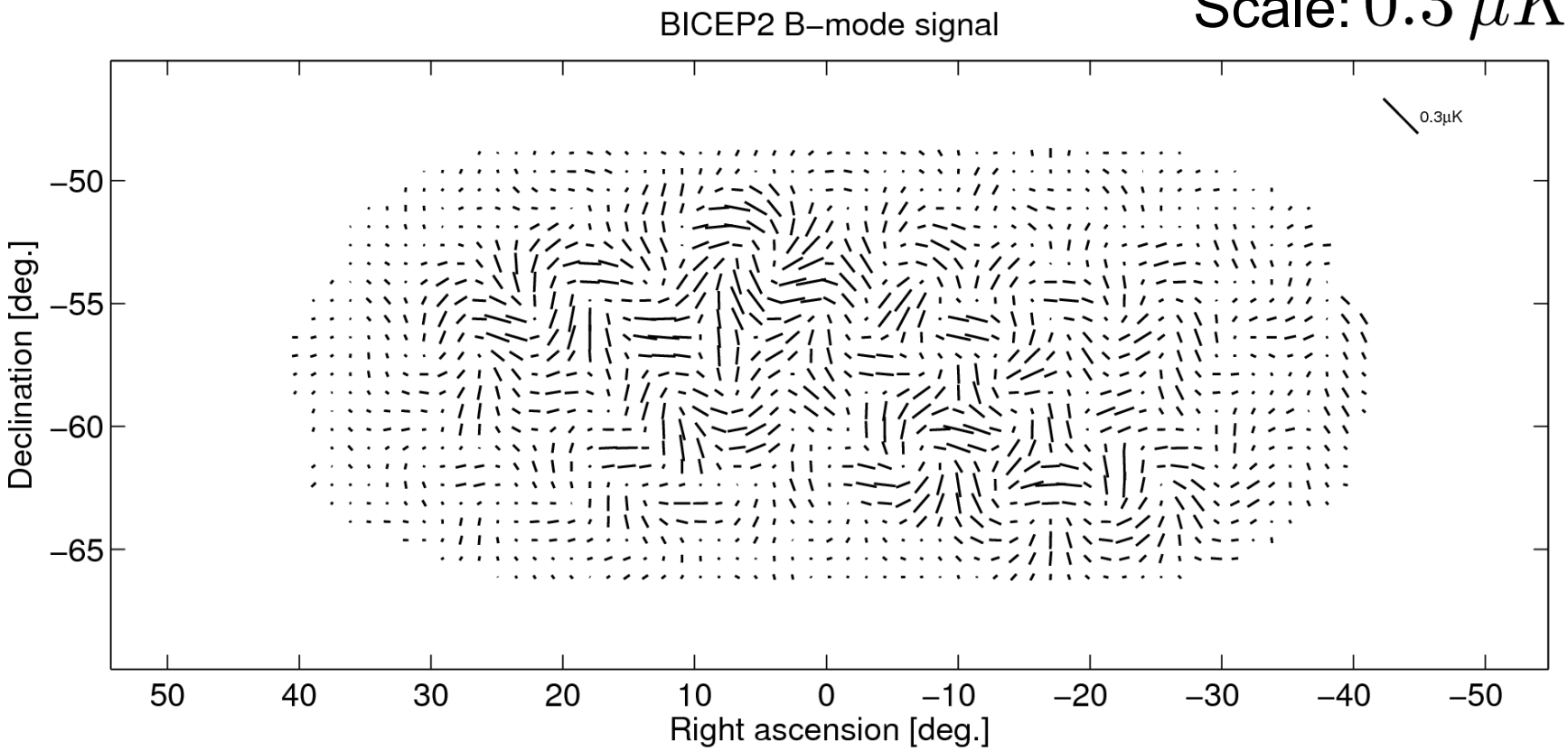
Scale: $1.7\ \mu K$



B-modes of r=0.1 contribute ~1/10 of the total polarization amplitude at l=100

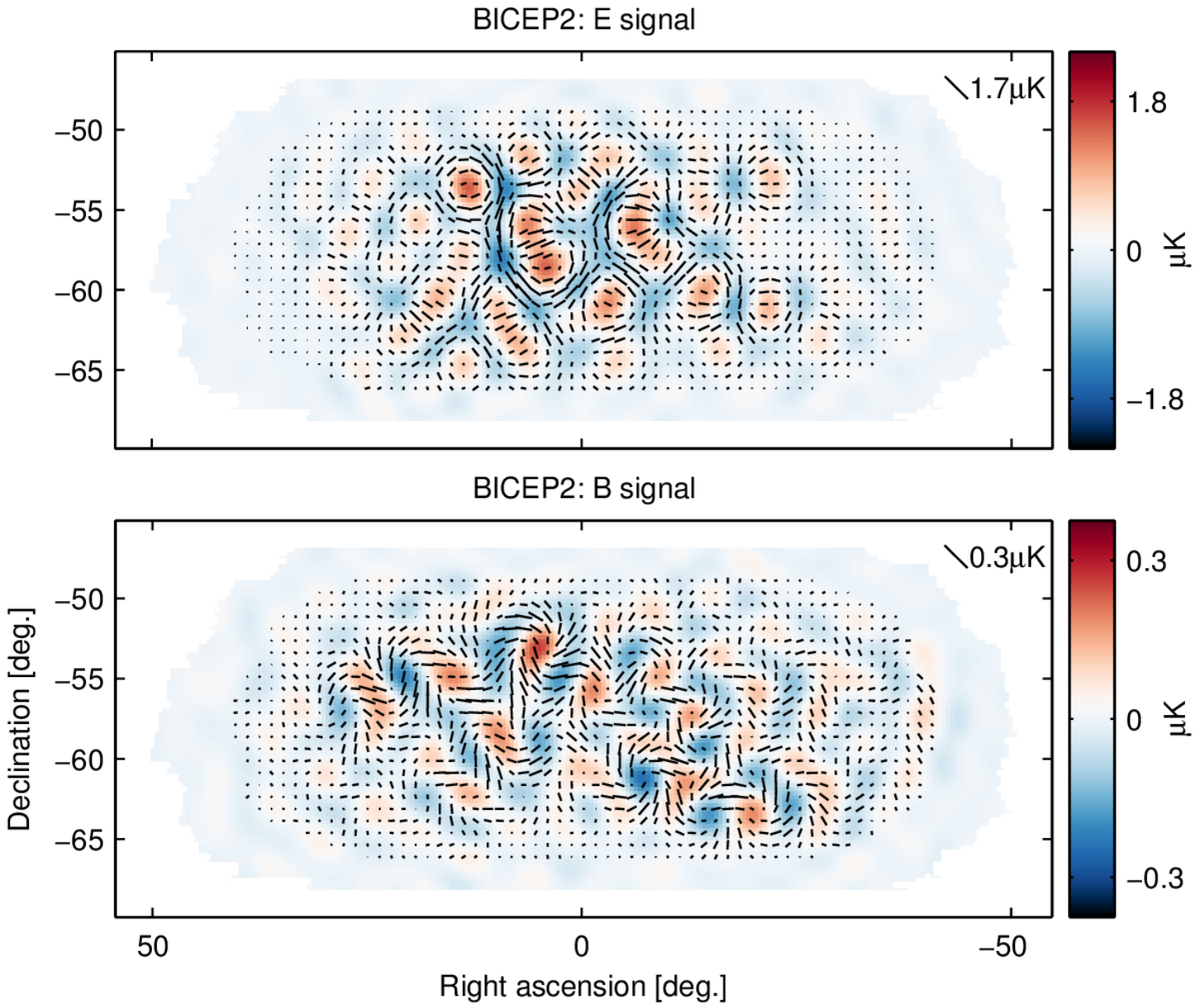
B-mode Contribution

Scale: $0.3\ \mu K$



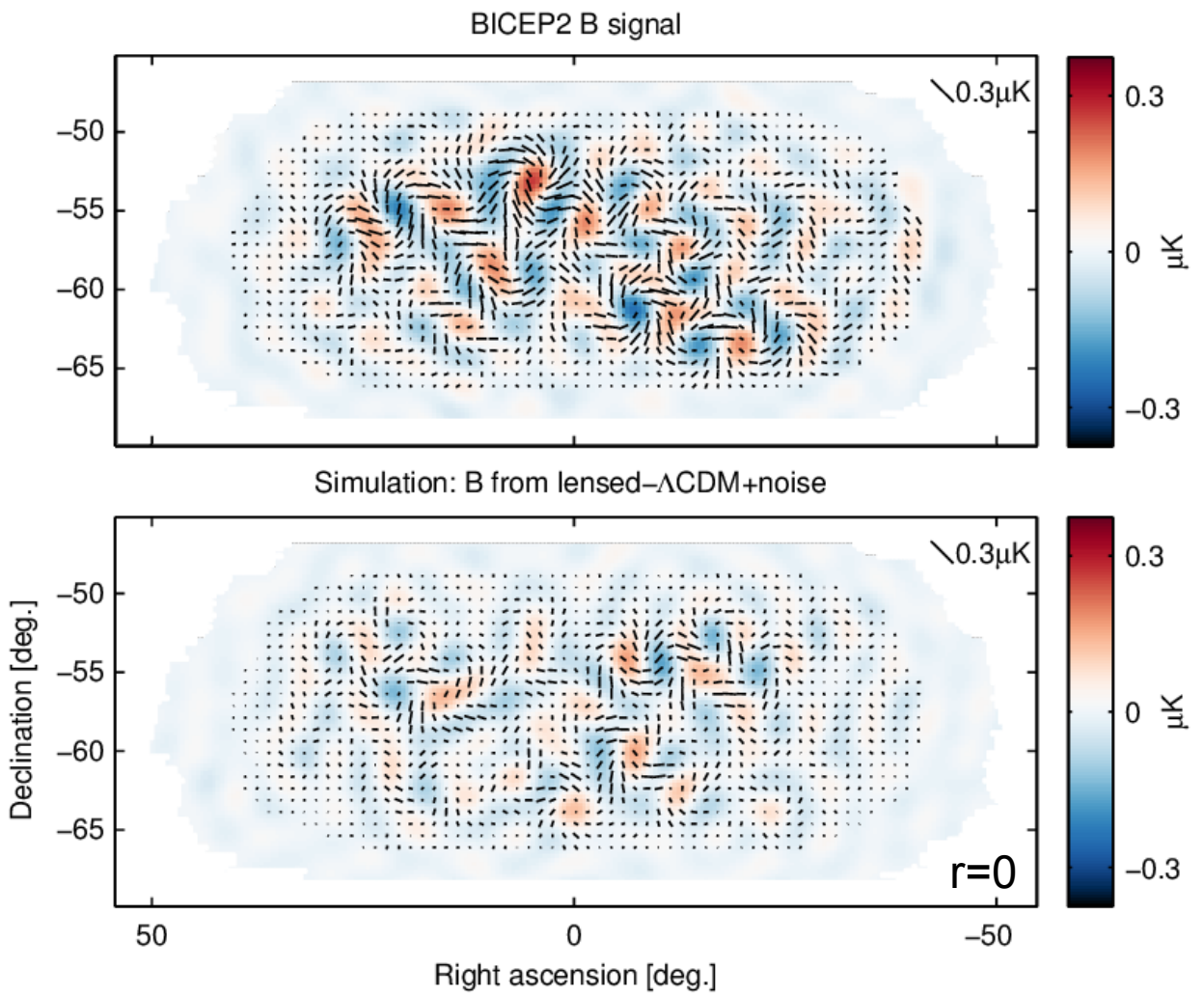
Zoom in by factor 6 – see “swirly” B-mode

BICEP2 E- and B-mode Maps



The Bicep2 Collaboration

B-mode Map vs. Simulation



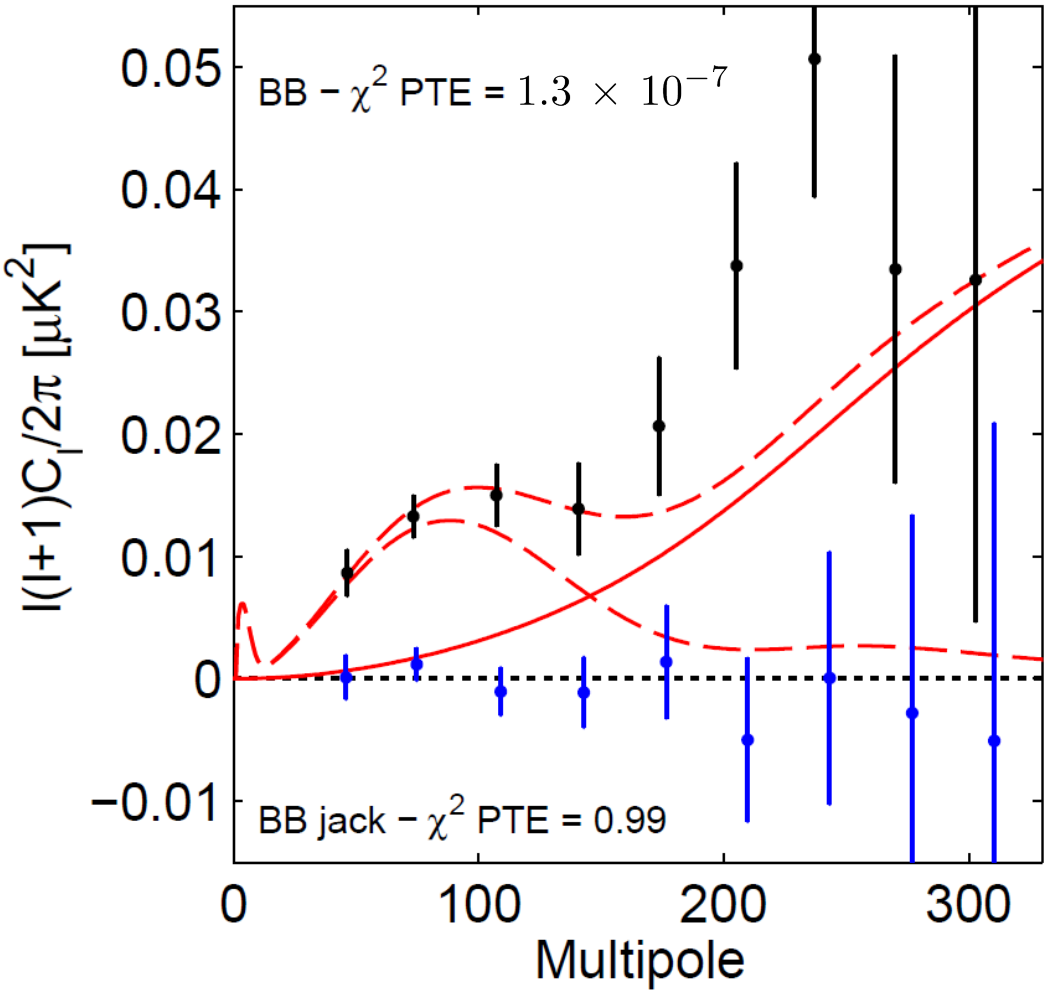
Simulation pipeline:
generate realizations of the full observation and all filtering operations.

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
temporal split jackknife
lensed-ΛCDM
r=0.2

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

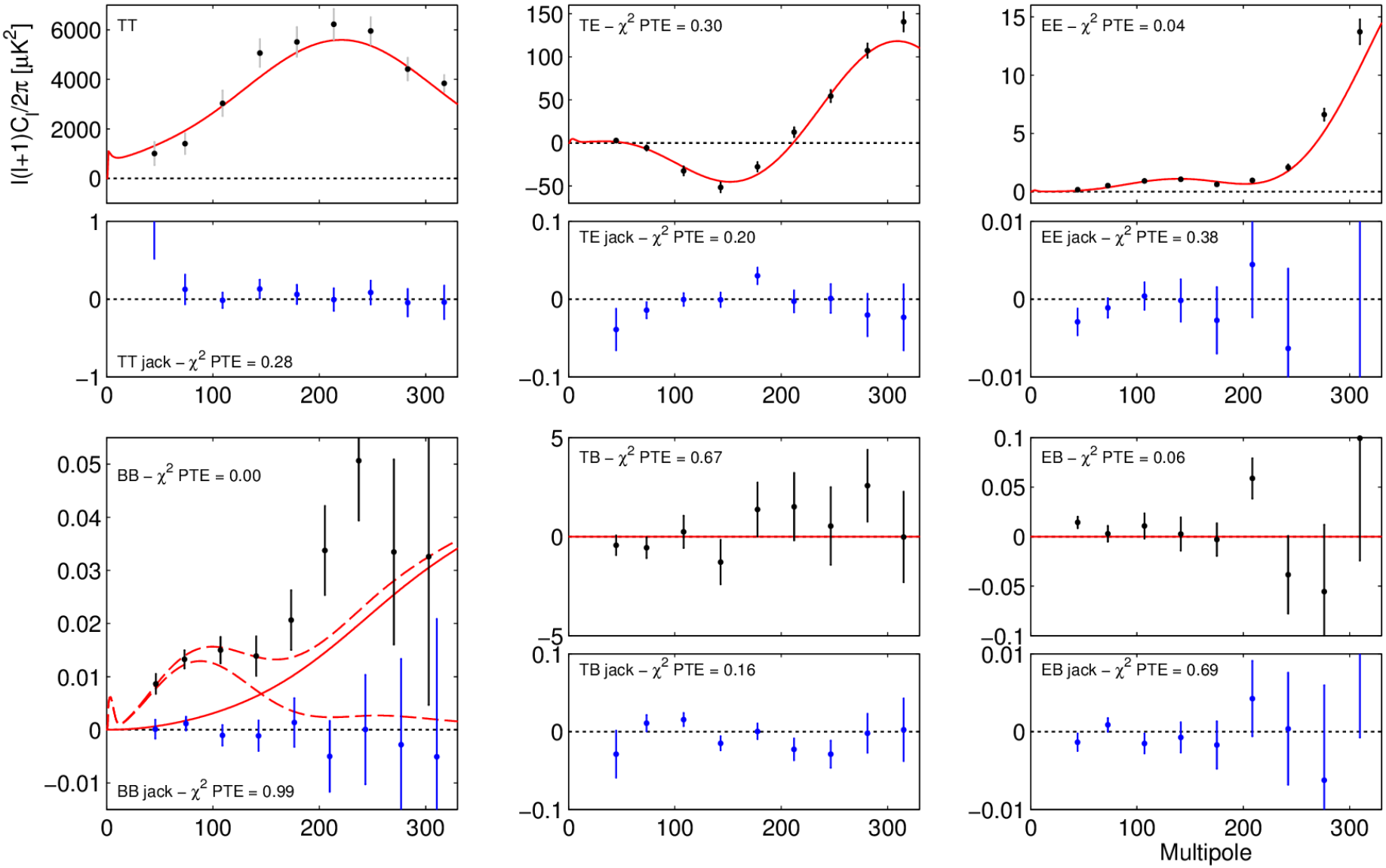
Consistent with lensing expectation at higher l.

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	$5.2\,\sigma$

Temperature and Polarization Power Spectra



Angiola Orlando for The Bicep2 Collaboration

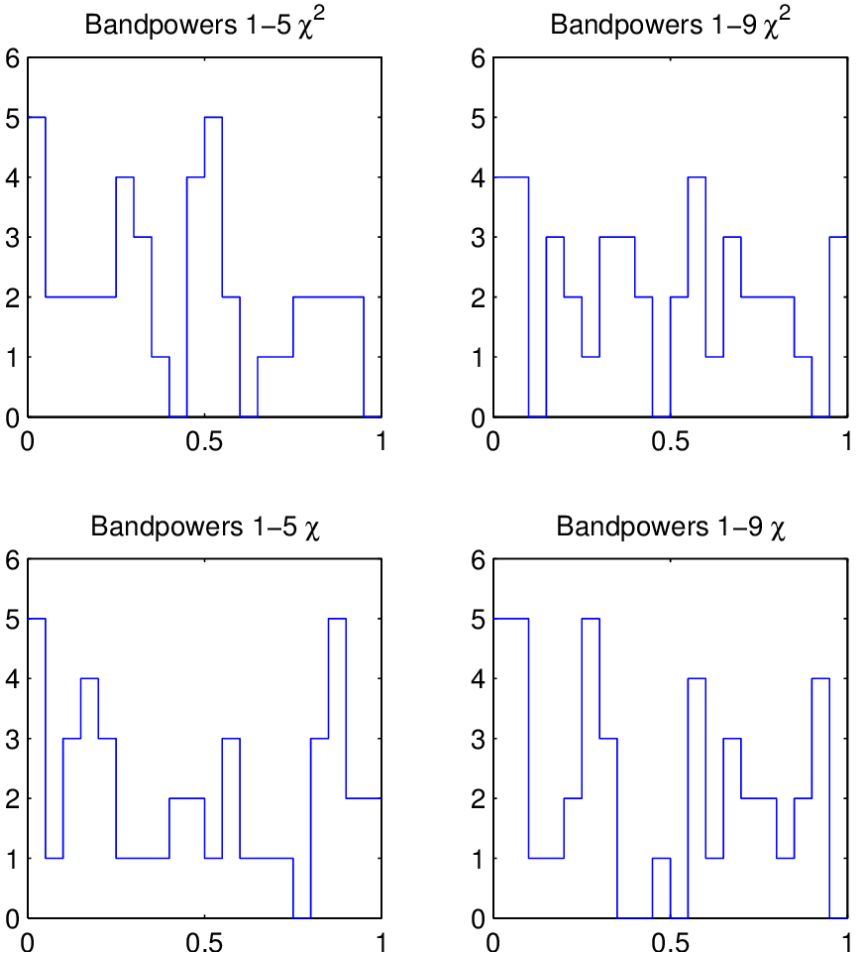
Check Systematics: Jackknifes

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:



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

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

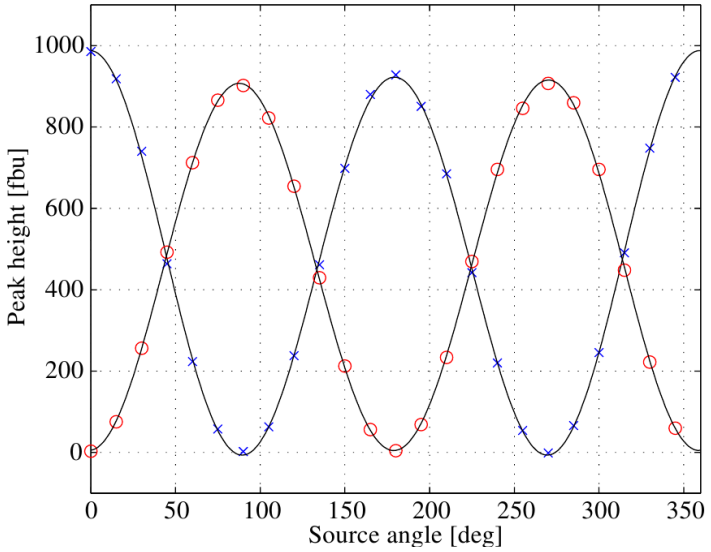
Checks for contamination from detectors with best/worst differential pointing. “Tile/dk” divides the data by the orientation of the detector on the sky.

Calibration Measurements

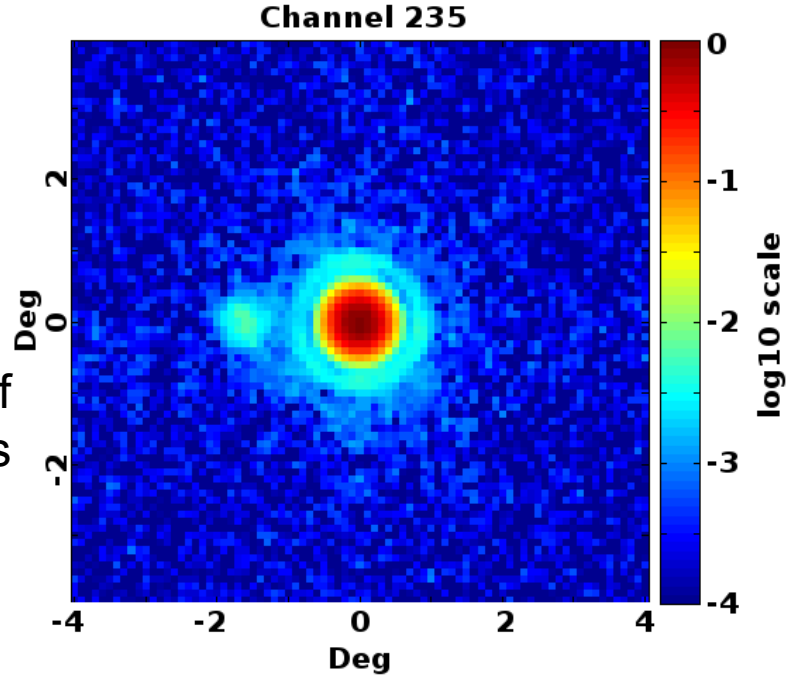
For instance...

Far field beam mapping

Detector Polarization Calibration

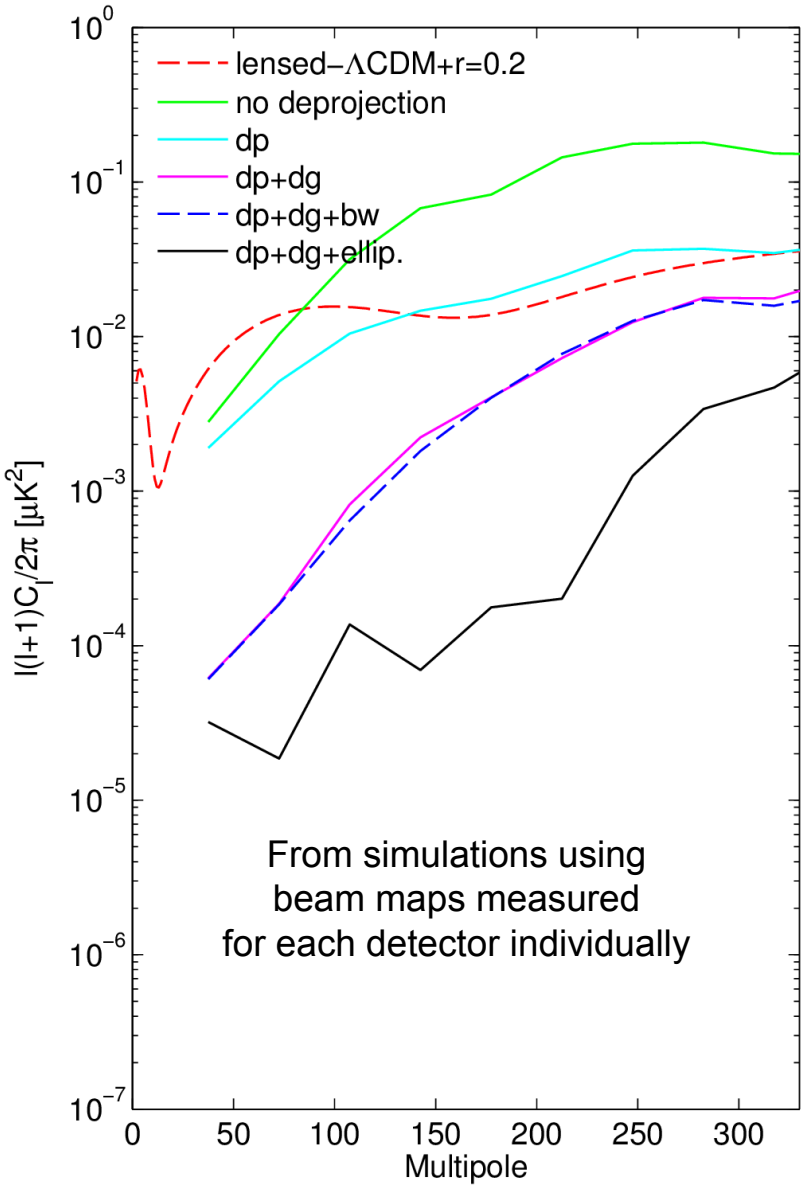


Beam maps of individual detectors

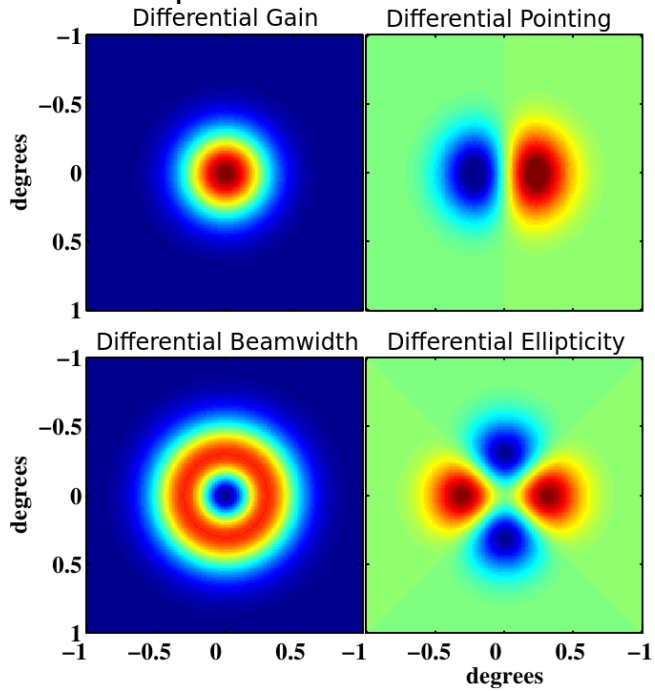


Detailed description in Instrument Paper

Systematics Removal: Deprojection



Technique developed to remove all types of leakage (false polarization) induced by differences of detector pair beam shapes

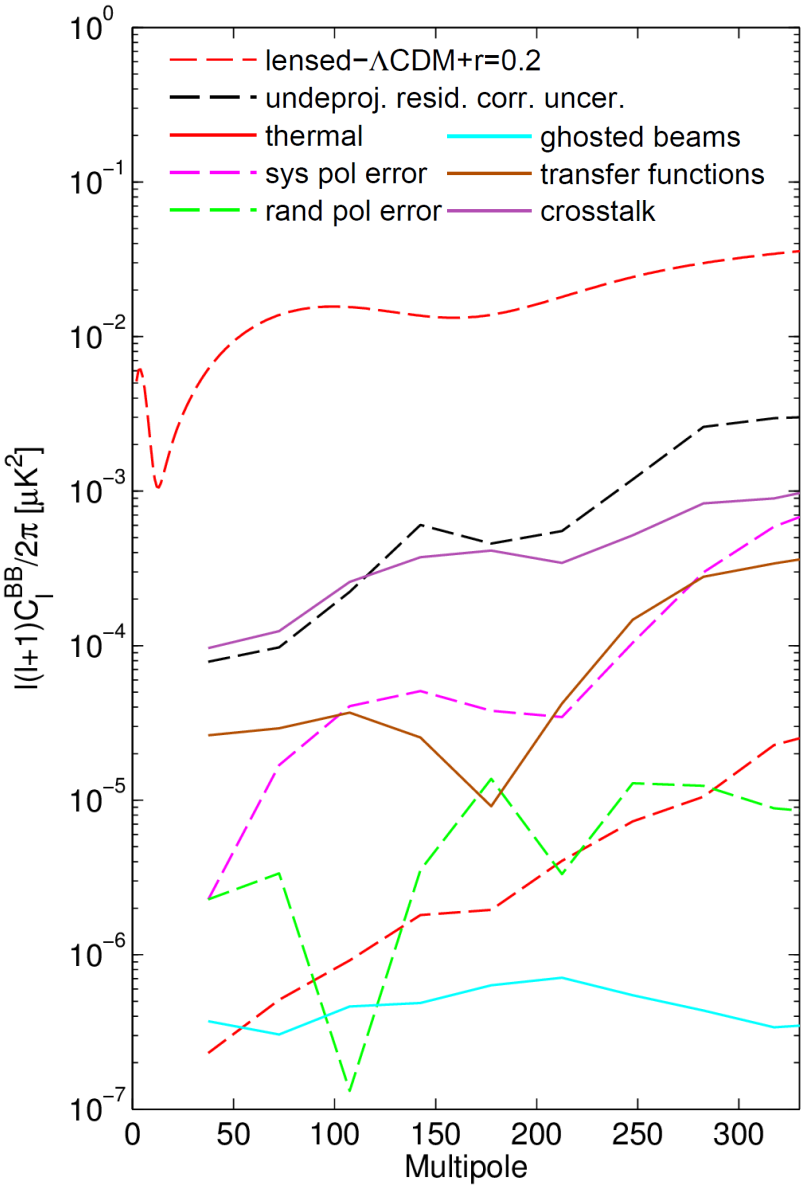


Use the Planck 143 GHz map to form template of the leakage

Deproject diff gain and pointing (& subtract measured diff ellipticity)

Subtract the residual (equiv to r=0.001) from the data

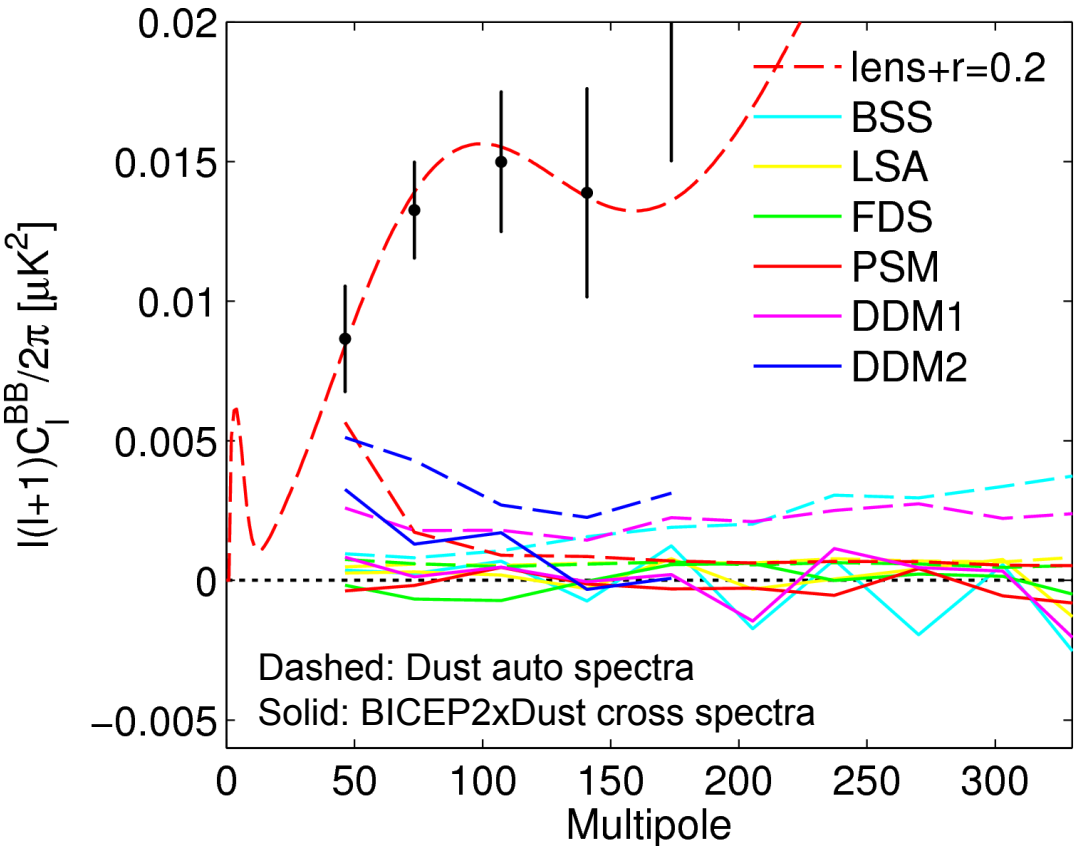
Systematics beyond Beam imperfections

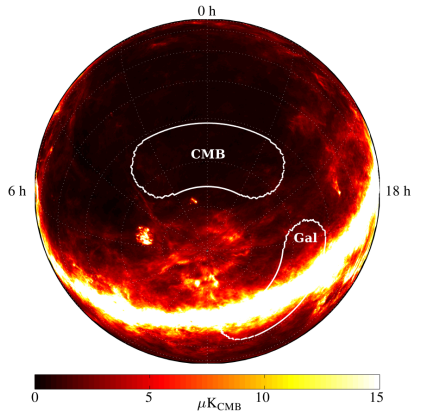


All systematic effects that we could imagine were simulated based upon measured imperfections!

We find with high confidence that the apparent signal *cannot be explained* by instrumental systematics!

Polarized Dust Foreground Projections





FDS Model

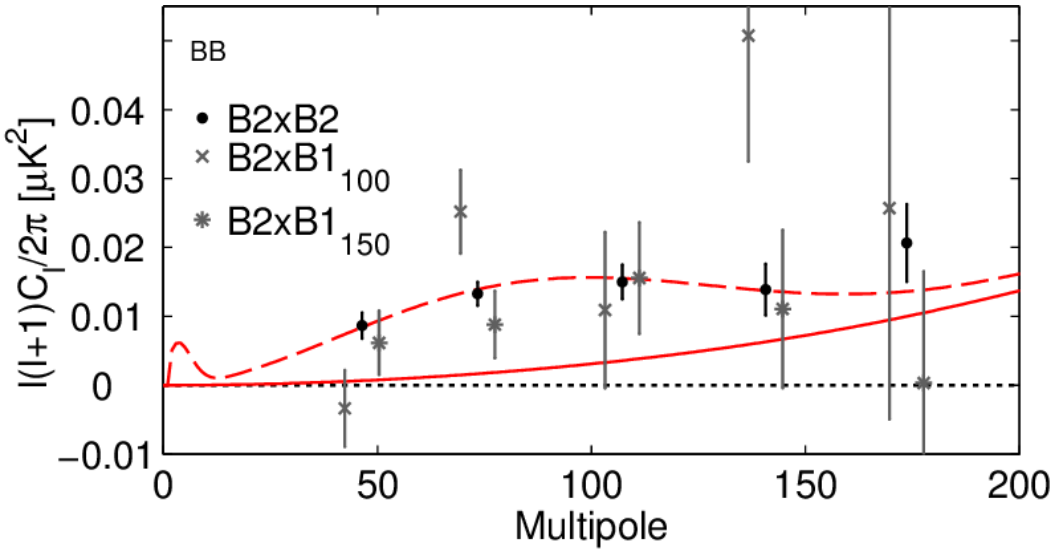
The BICEP2 region is chosen to have extremely low foreground emission.

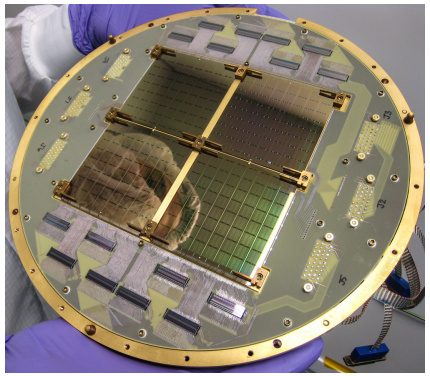
Use various models of polarized dust emission to estimate foregrounds.

All dust auto spectra well below observed signal level.

Cross spectra consistent with zero.

Cross Correlation with BICEP1





BICEP2: Phased antenna array and TES readout 150 GHz

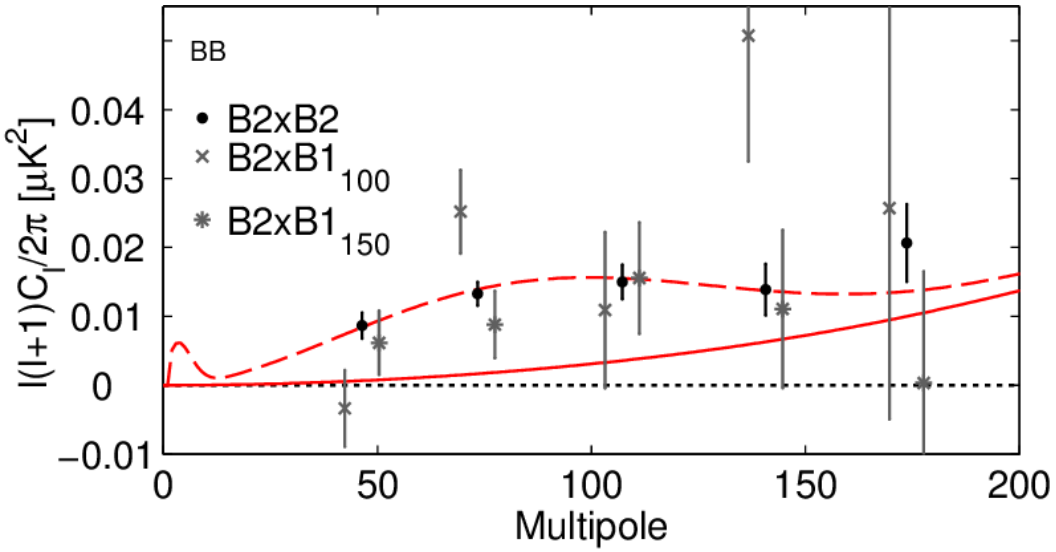
BICEP1: Feedhorns and NTD readout 150 and 100 GHz

Though less sensitive, BICEP1 applied **different technology** (systematics control) and **multiple colors** (foreground control) to the **same sky**.

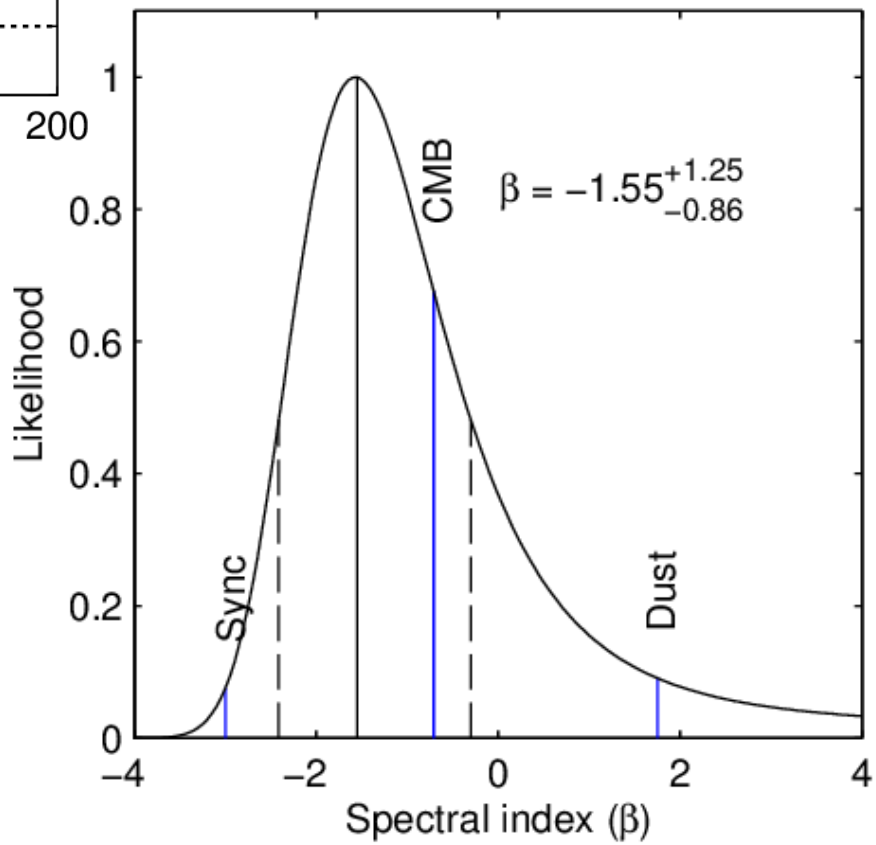
Cross-correlations with both colors are **consistent** with the B2 auto spectrum

Cross with $BICEP1_{100}$ shows **~3σ** detection of BB power

Spectral Index of the B-mode Signal



Likelihood ratio test: consistent with CMB spectrum, disfavor pure dust/sync at **2.2/2.3σ**



Comparison of B2 auto with $B2_{150}$ x $B1_{100}$ constrains signal frequency dependence, independent of foreground projections

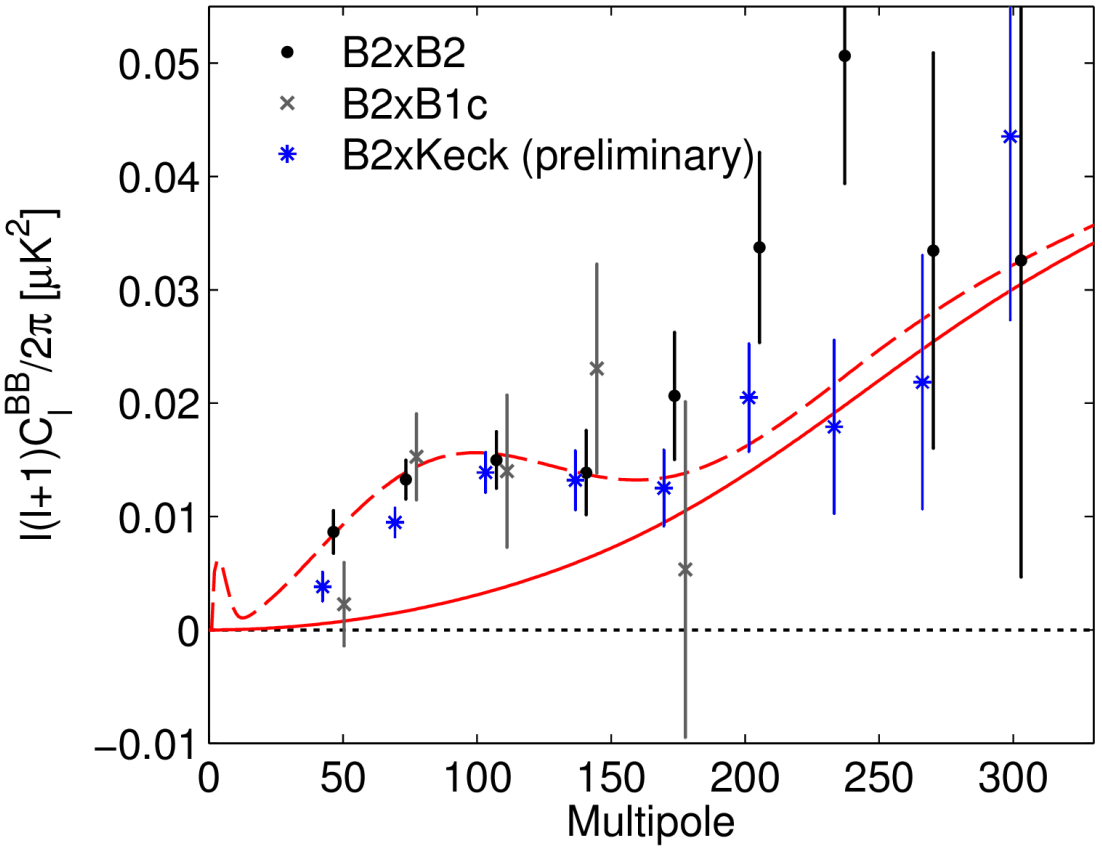
If **dust**, expect little cross-correlation

If **synchrotron**, expect bright correlation

Find **consistent with CMB**

Cross Spectra between 3 Experiments

Form cross spectrum between BICEP2 and BICEP1 combined (100 + 150 GHz):

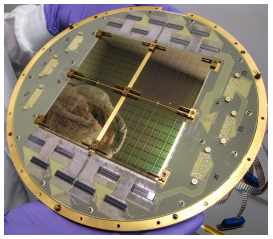


BICEP2 auto spectrum compatible with B2xB1c cross spectrum

~3σ evidence of excess power in the cross spectrum

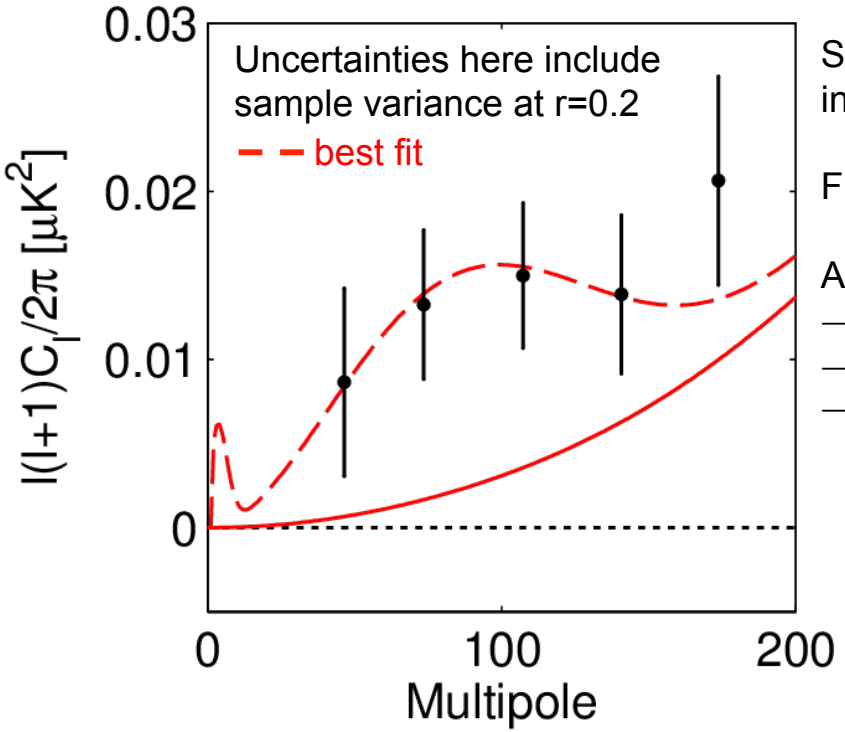
Additionally form cross spectrum with 2 years of data from *Keck Array*, the successor to BICEP2

Excess power is also evident in the B2xKeck cross spectrum



Cross spectra:
Powerful additional evidence against a systematic origin of the apparent signal

Constraint on Tensor-to-scalar Ratio r



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

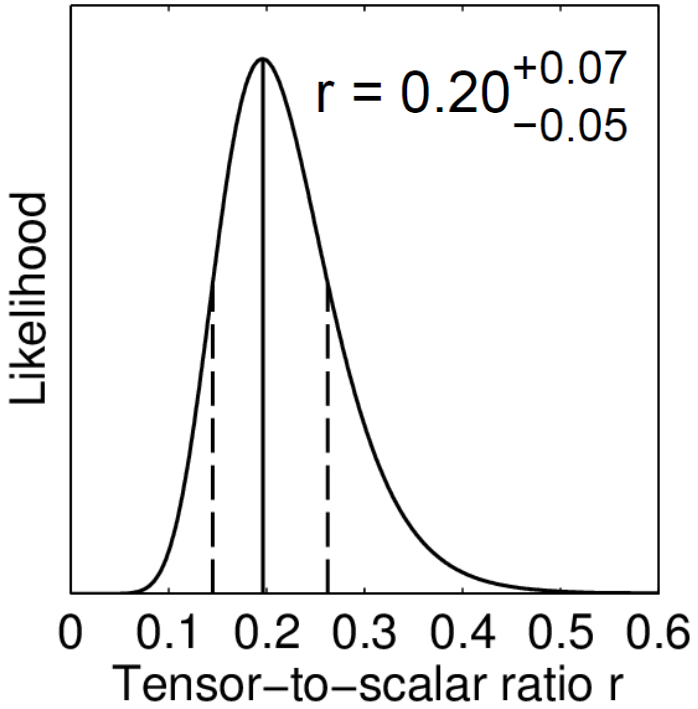
Find the most likely value of the tensor-to-scalar ratio r

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)



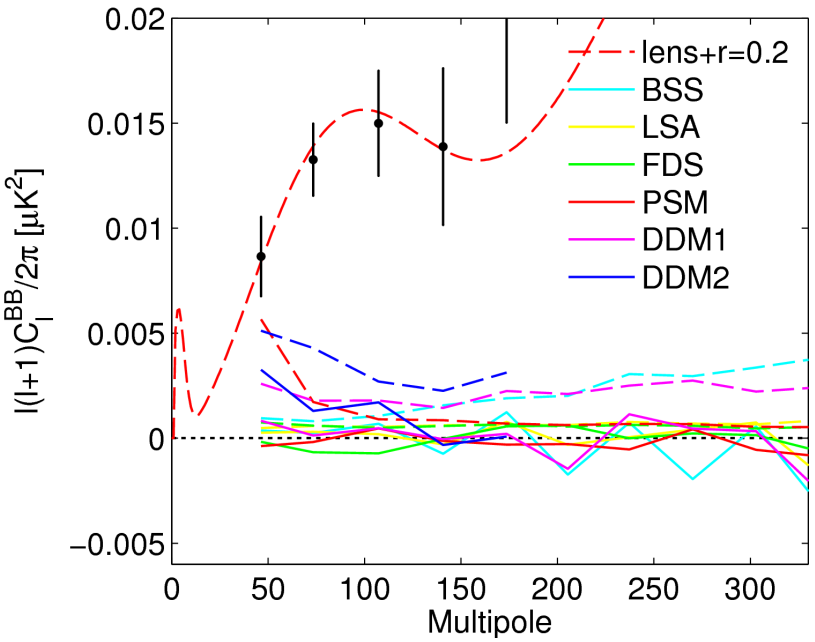
Within this simplistic model we find:

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

Constraint on r under Foreground Projections

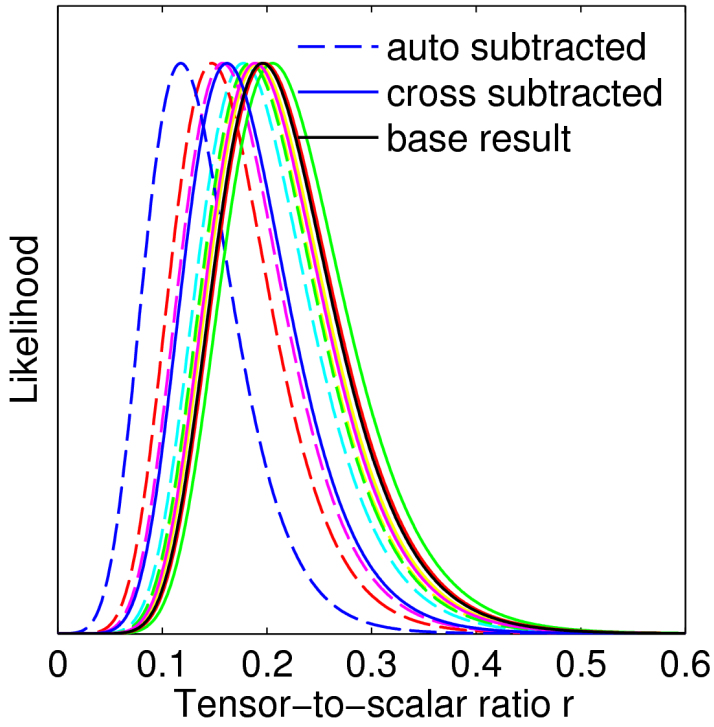


Probability that each of these models reflect reality hard to assess

DDM2 uses all publicly available information from Planck - modifies constraint to $r = 0.16^{+0.06}_{-0.05}$
r = 0 still disfavored at 5.9σ

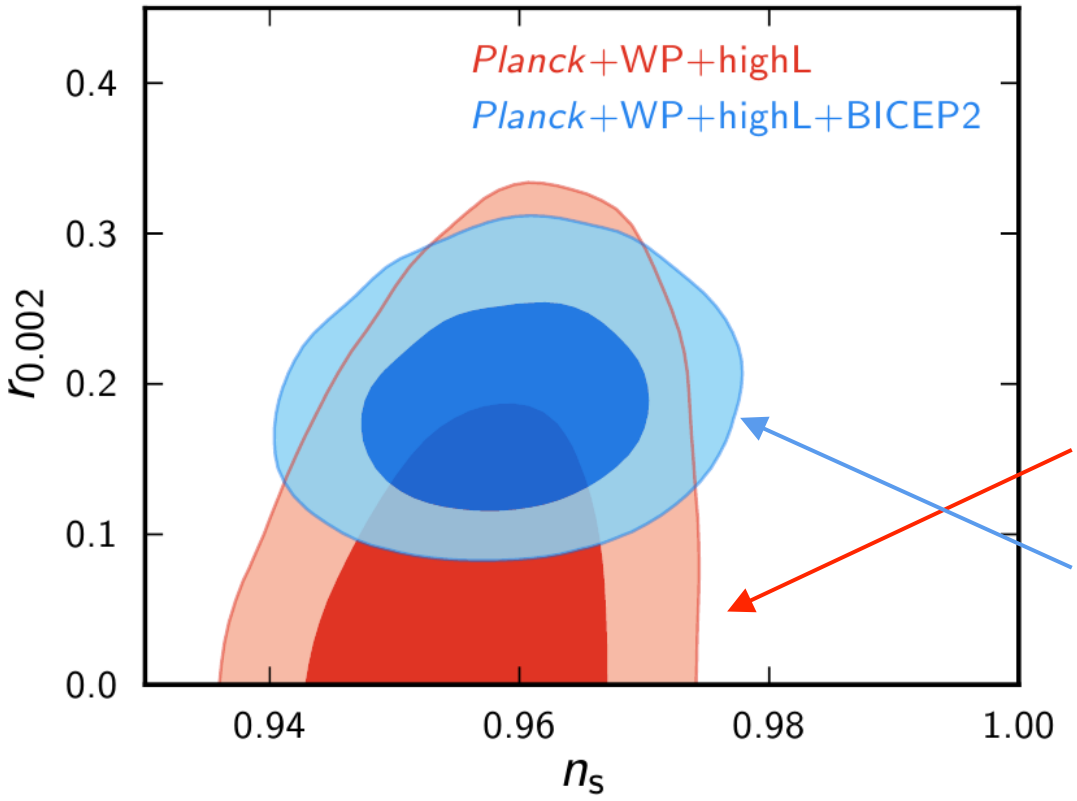
Dust contribution is largest in the first bandpower. Deweighting this bin would lead to less deviation from our base result.

Adjust likelihood curve by subtracting the dust projection auto and cross spectra from our bandpowers:



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

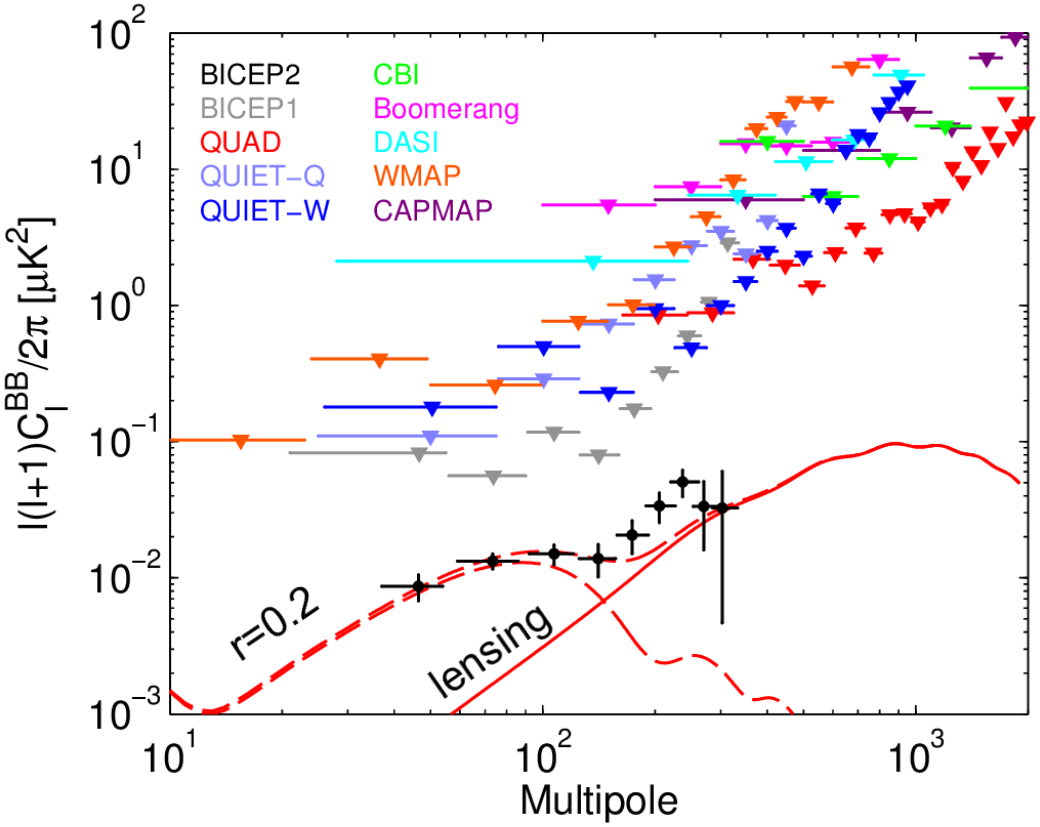
Planck likelihood chains for lensed ΛCDM + *tensors* + *running*

Same chains, importance sampled with the BICEP2 r likelihood

Other possibilities within ΛCDM?...

Conclusions

BICEP2 and upper limits from other experiments:



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:

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