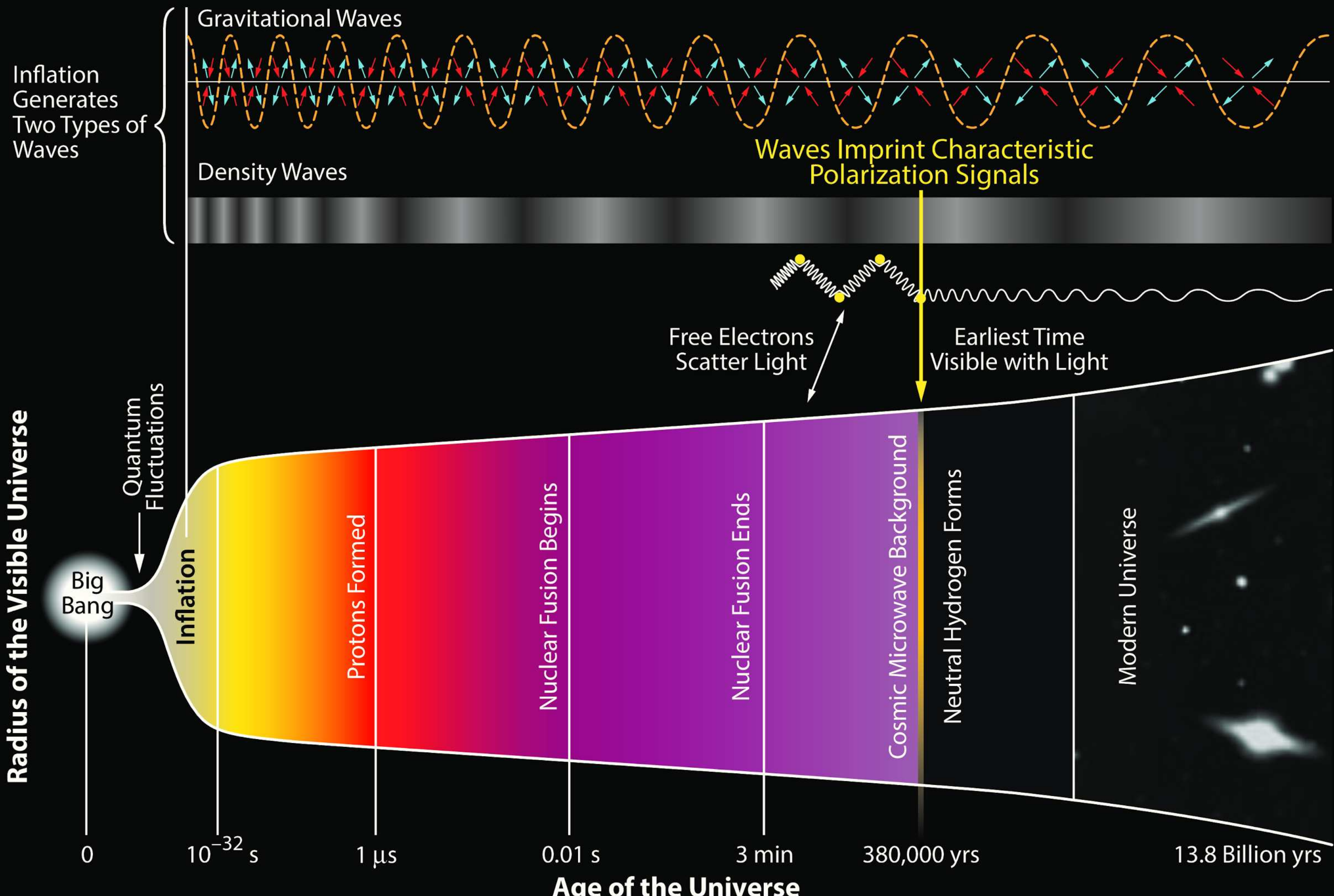
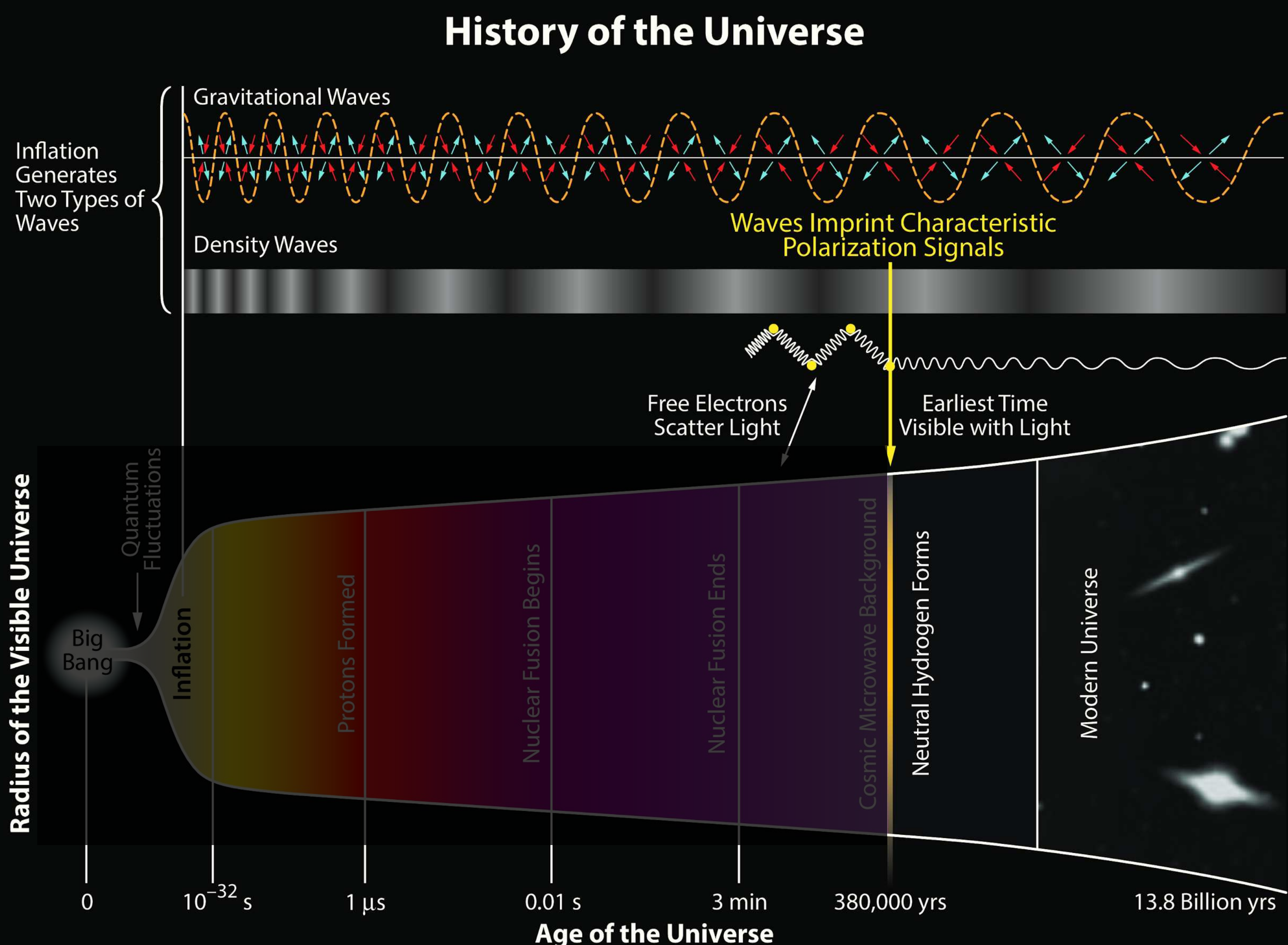
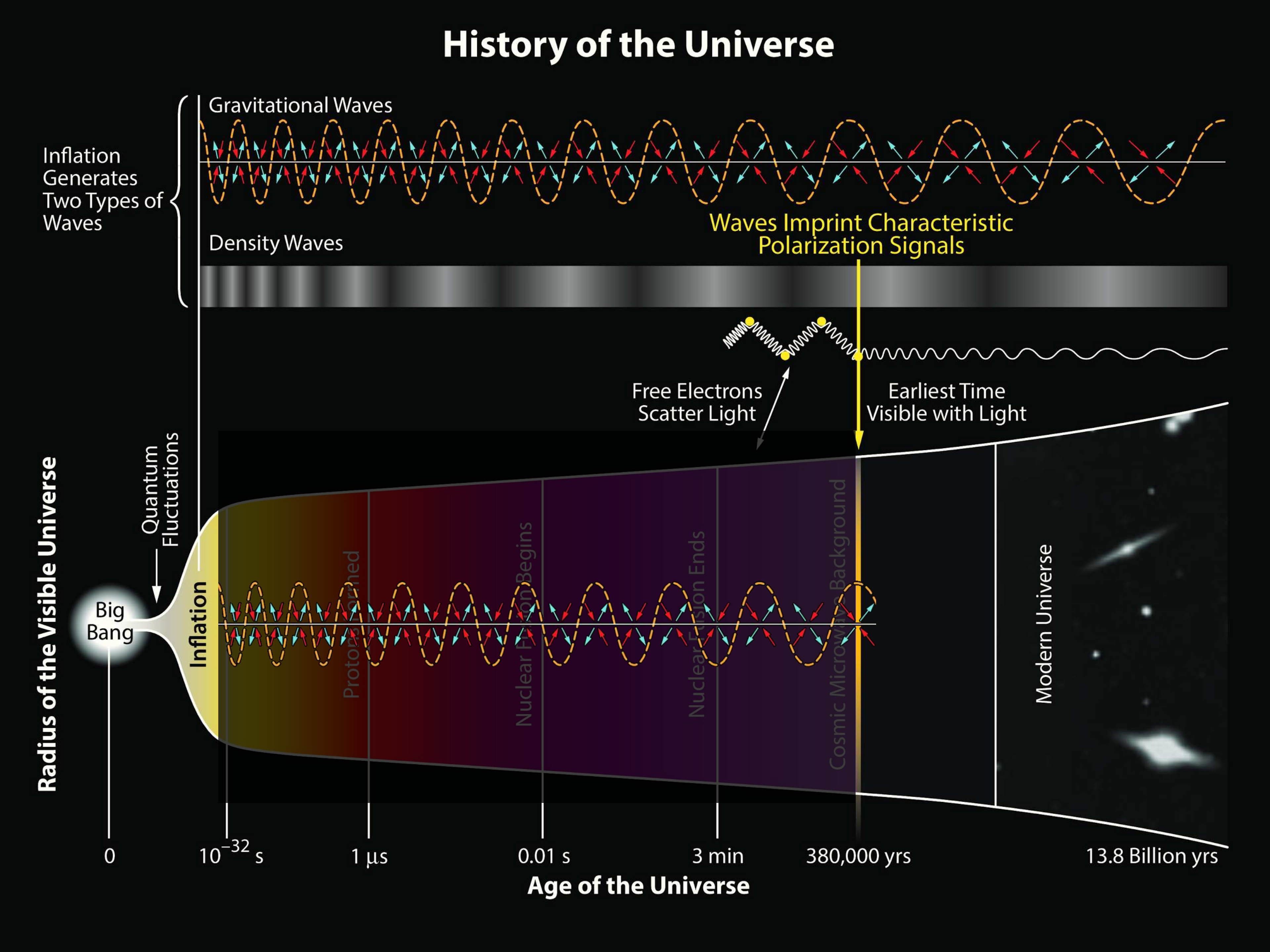
Detection of B-mode Polarization at Degree Scales using BICEP2

Stefan Fliescher for the BICEP2 team
9. Kosmologietag, Bielefeld University, 05/09/14

History 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
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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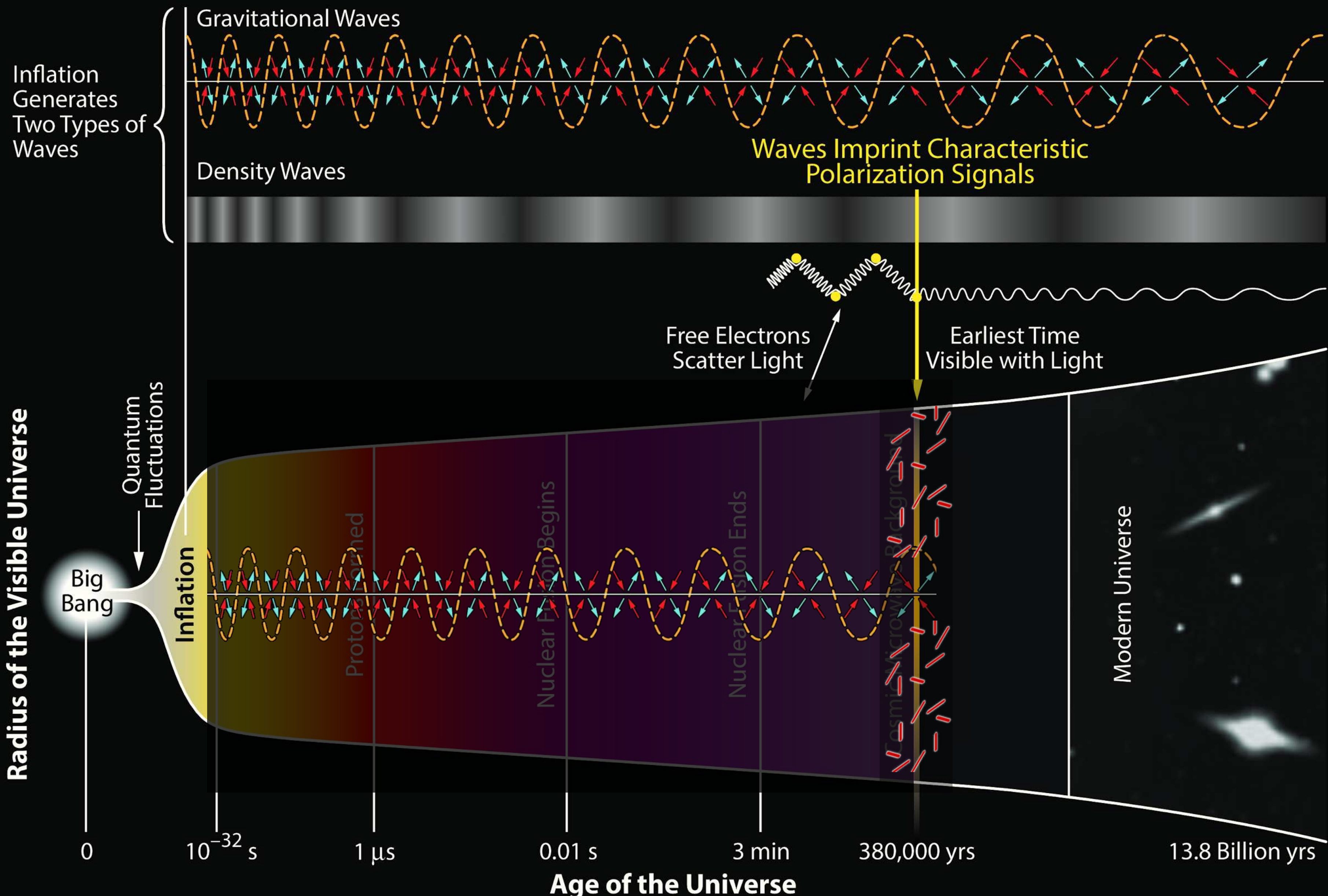
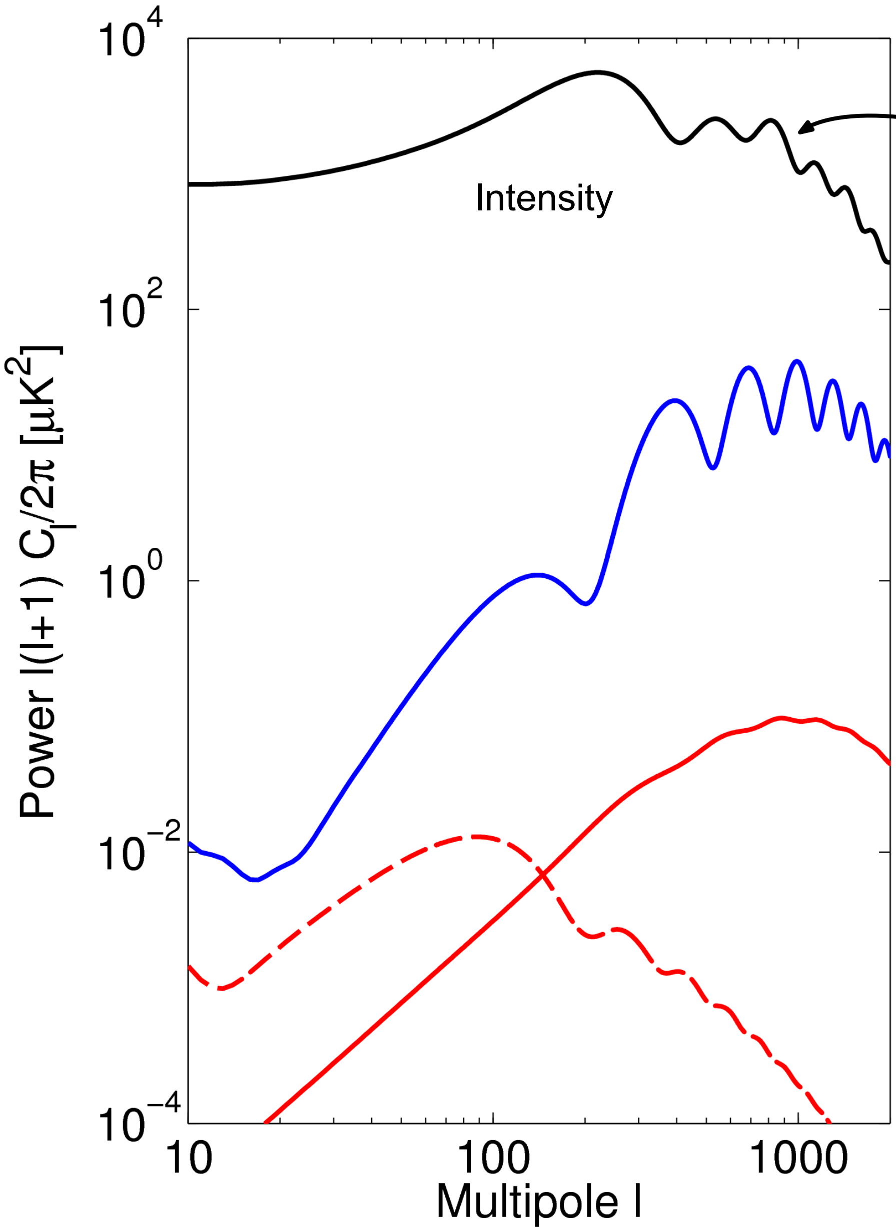
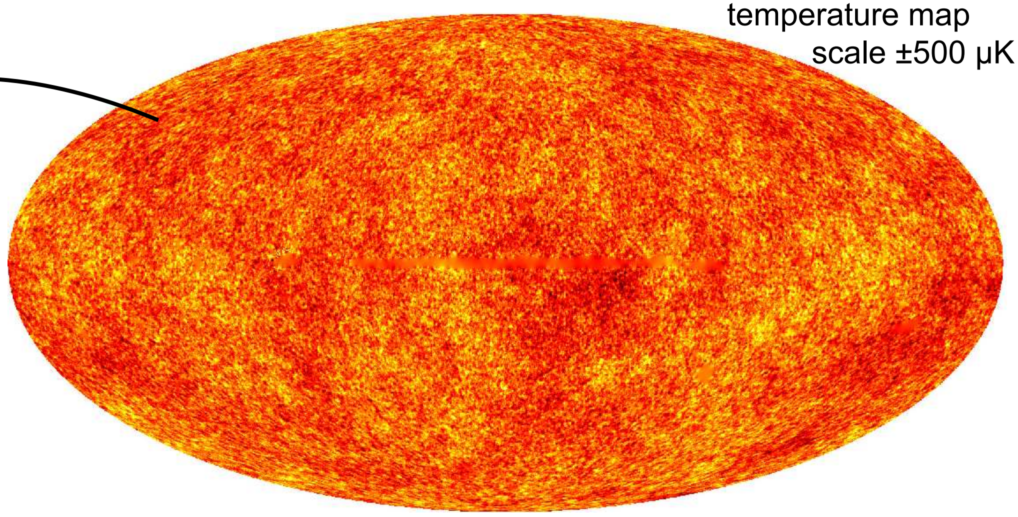


CMB Spectra



Planck's all sky CMB temperature map scale ±500 μK



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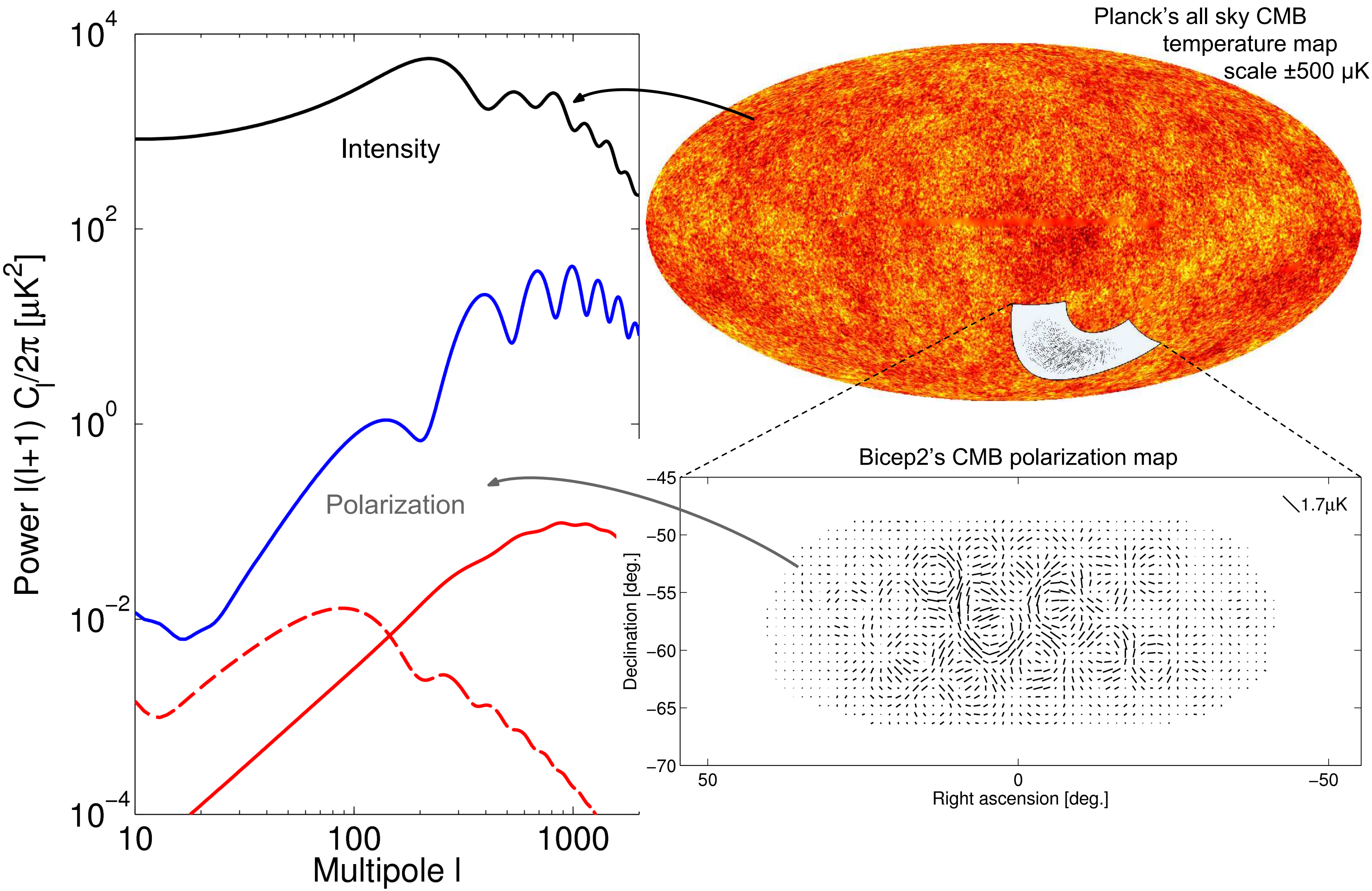
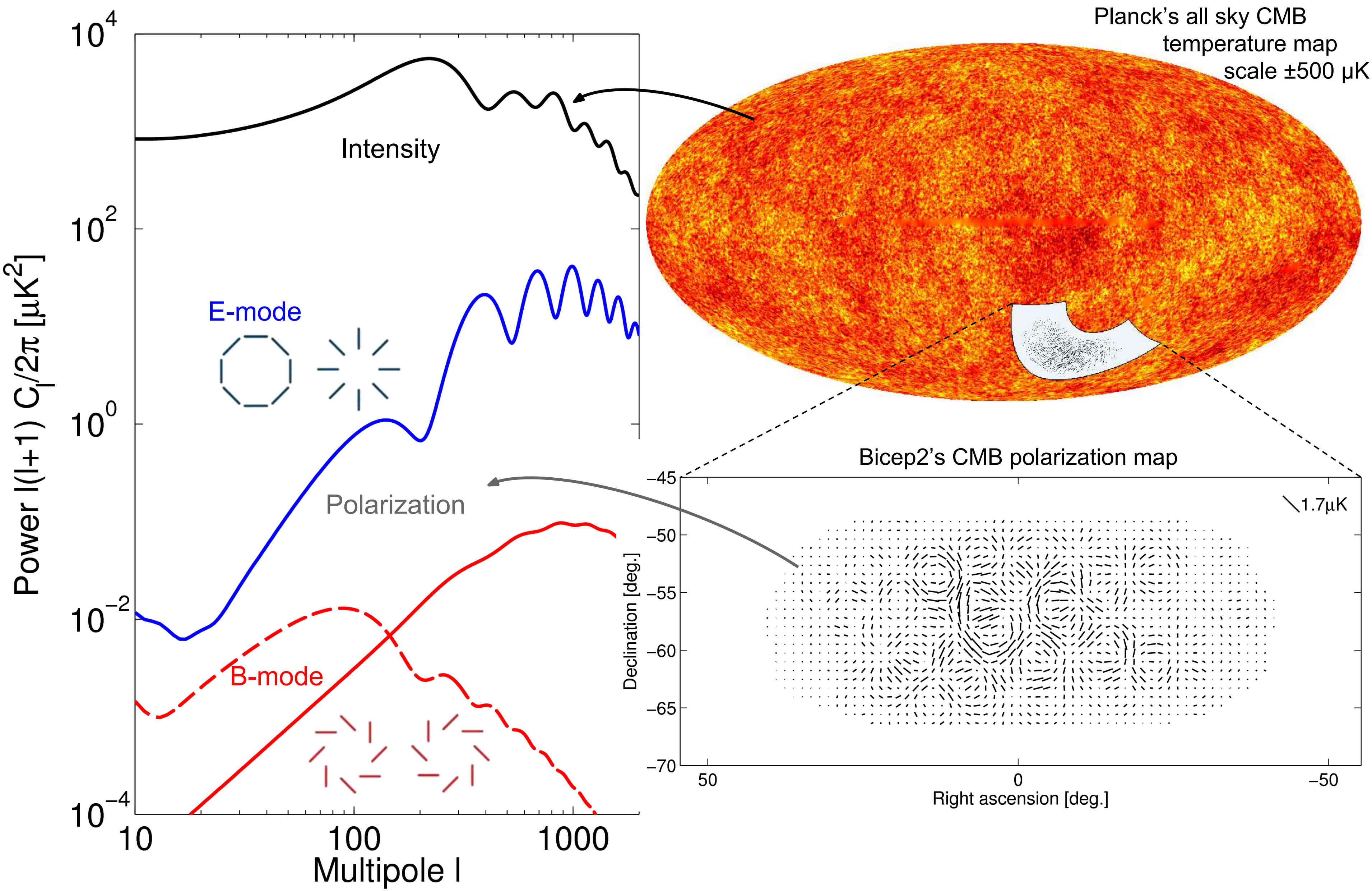


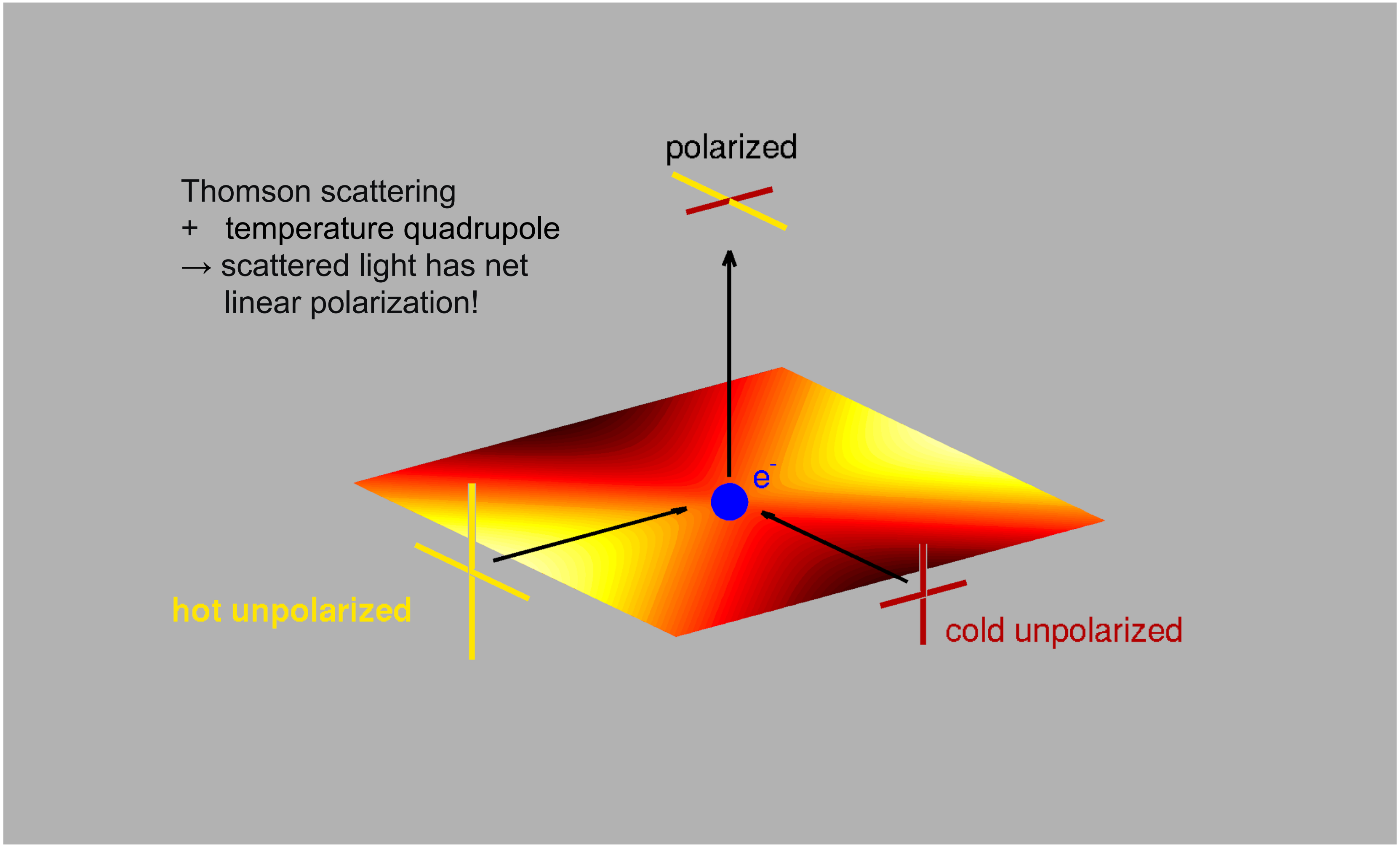
Planck's all sky CMB
temperature map
scale ±500 μK
Intensity
Polarization
Bicep2's CMB polarization map
1.7μK
Power l(l+1) $C_l/2\pi$ [μK^2]
Multipole l
Declination [deg.]
Right ascension [deg.]
10^4
10^2
10^0
10^{-2}
10^{-4}
10
100
1000
−45
−50
−55
−60
−65
−70
50
0
−50

CMB Spectra



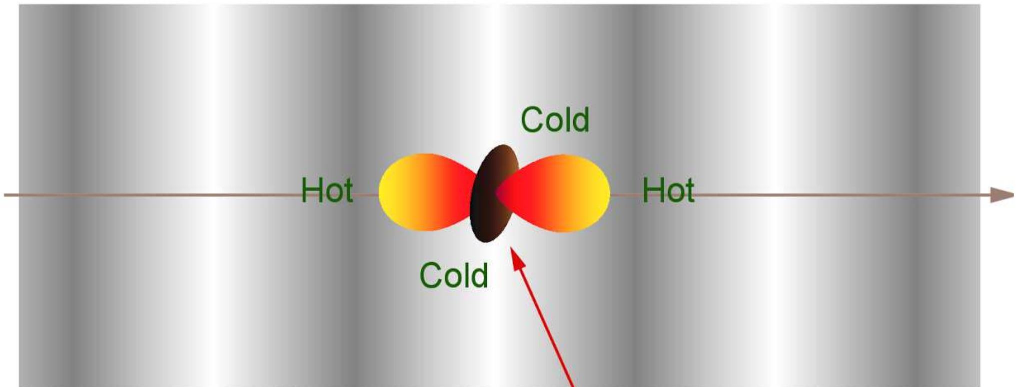
Planck's all sky CMB temperature map scale ±500 μK
Intensity
E-mode
Polarization
B-mode
Power l(l+1) C_l/2π [μK²]
Multipole l
Bicep2's CMB polarization map
1.7μK
Declination [deg.]
Right ascension [deg.]

Polarization from Scattering

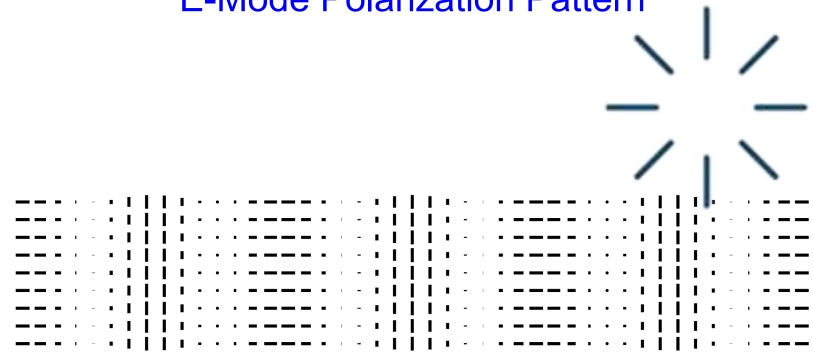


CMB Polarization

Density Waves only generate E-mode patterns...

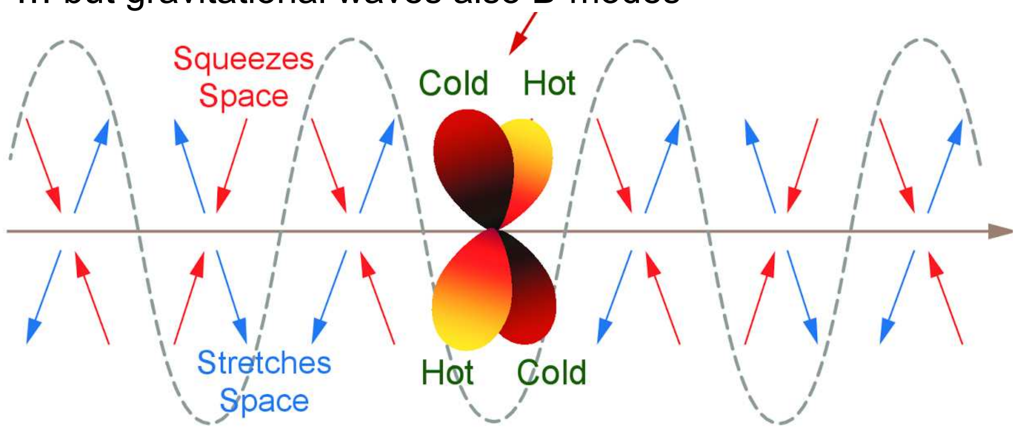


E-Mode Polarization Pattern



Temperature
Pattern Seen
by Electrons

… but gravitational waves also B-modes



B-Mode Polarization Pattern

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CMB Polarization

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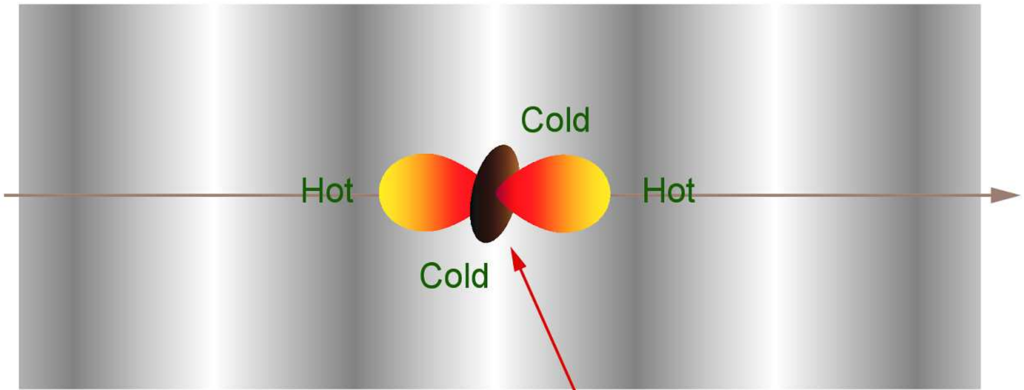

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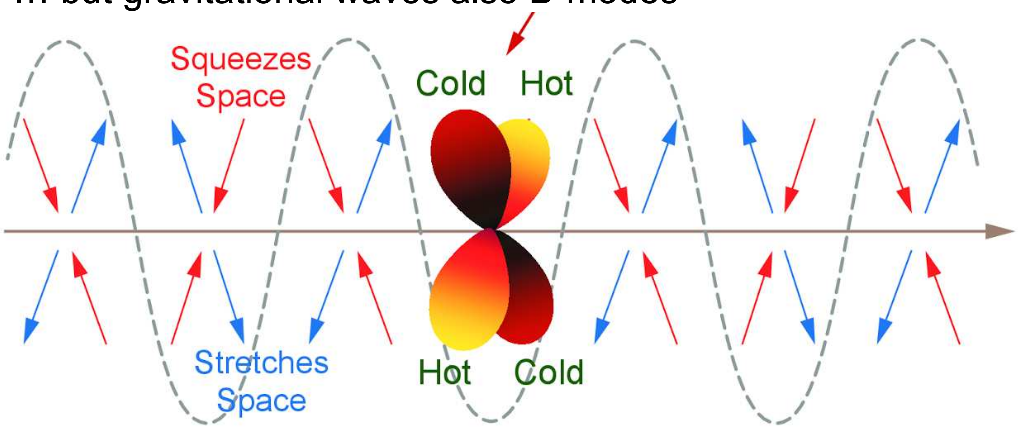

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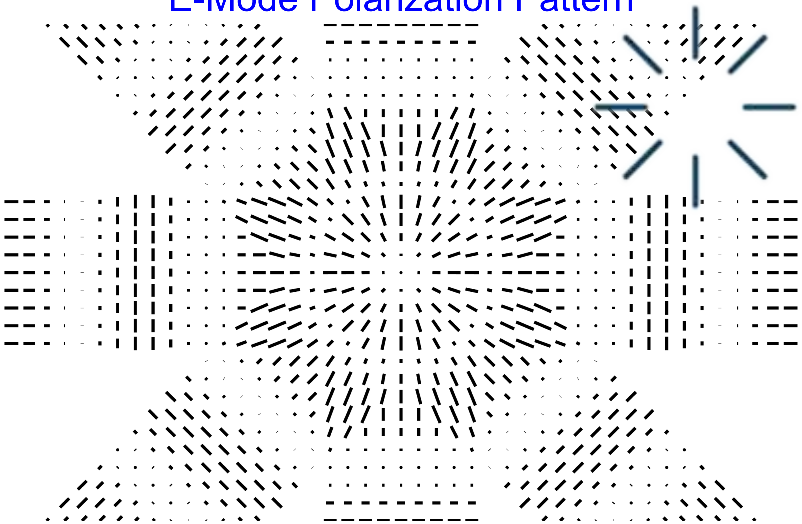
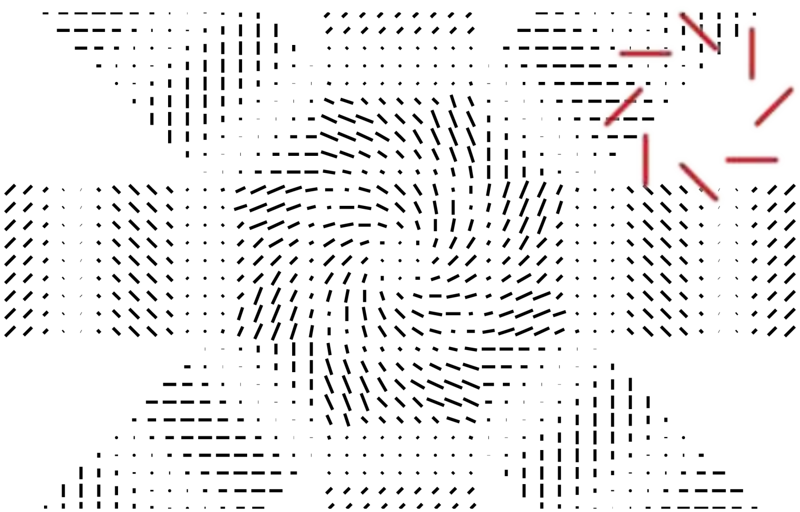


B-Mode Polarization Pattern



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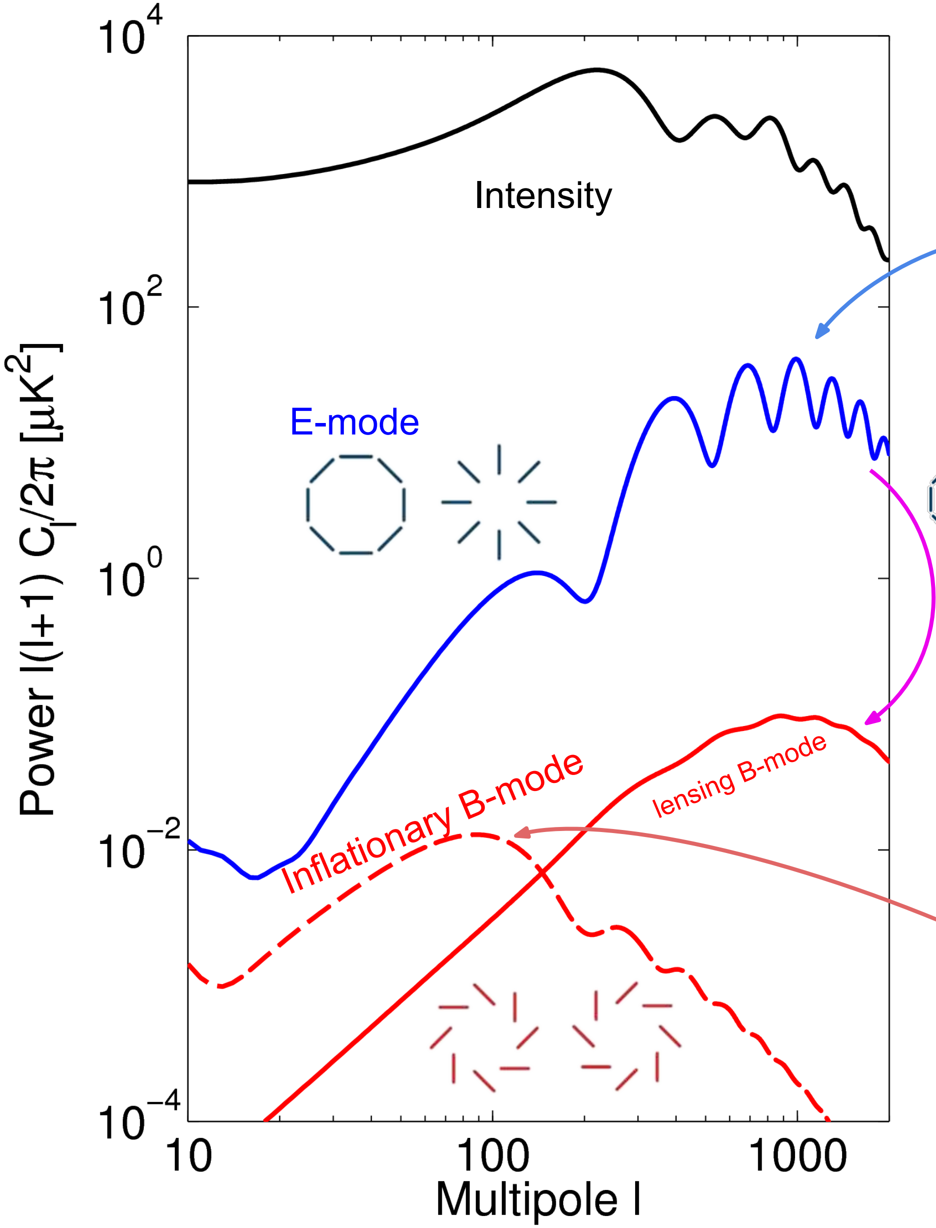
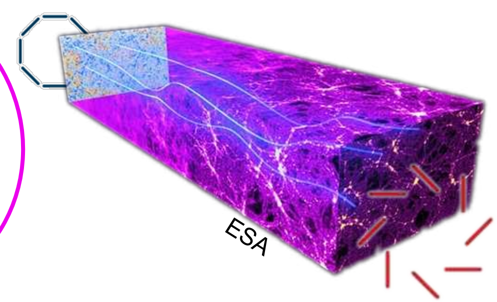
CMB Polarization



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



During propagation some of the E-modes are confused into B-modes by lensing

Gravitational waves are unique source of B-modes
→ predicted by theory of Inflation
→ peaking at l≈100 : degree scales

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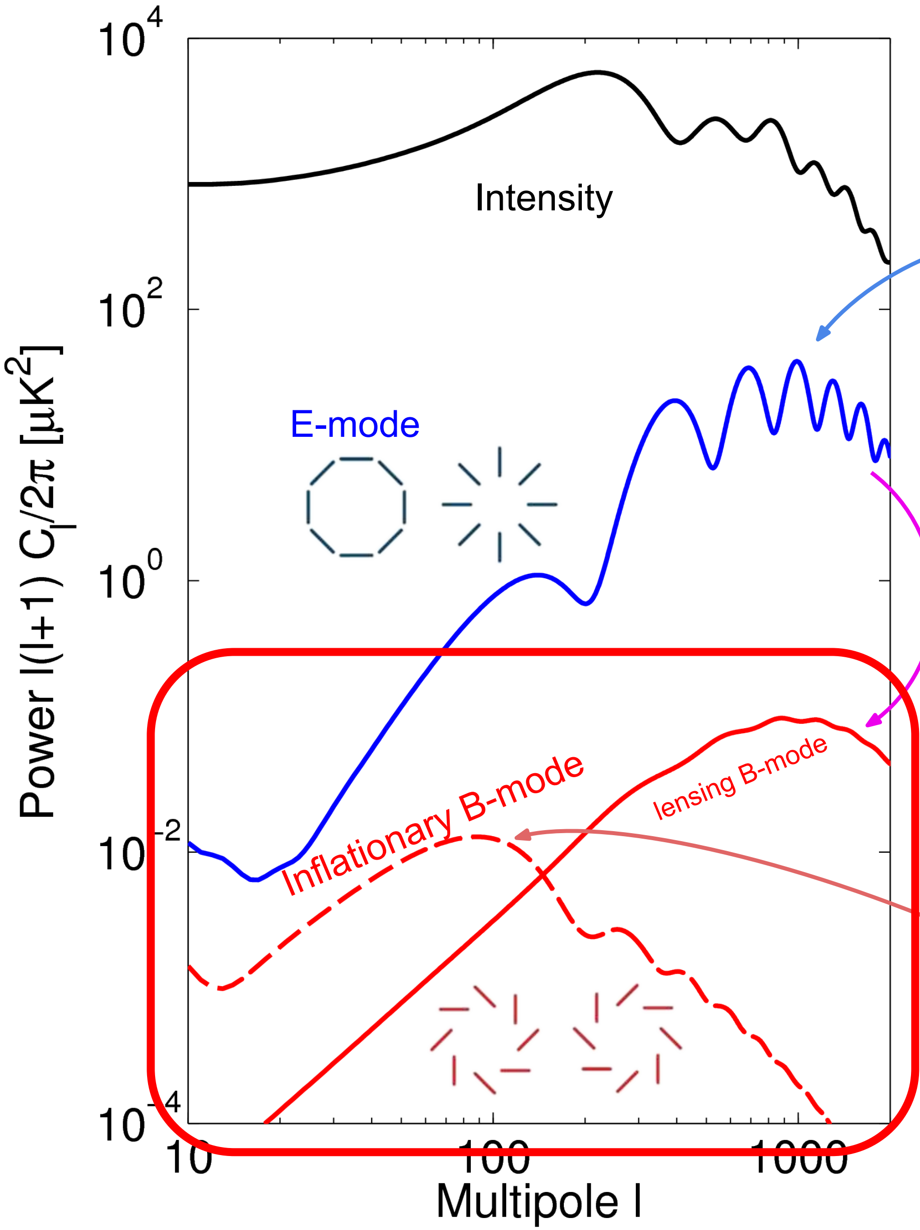
CMB Polarization



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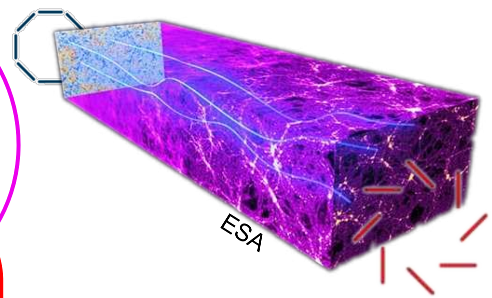

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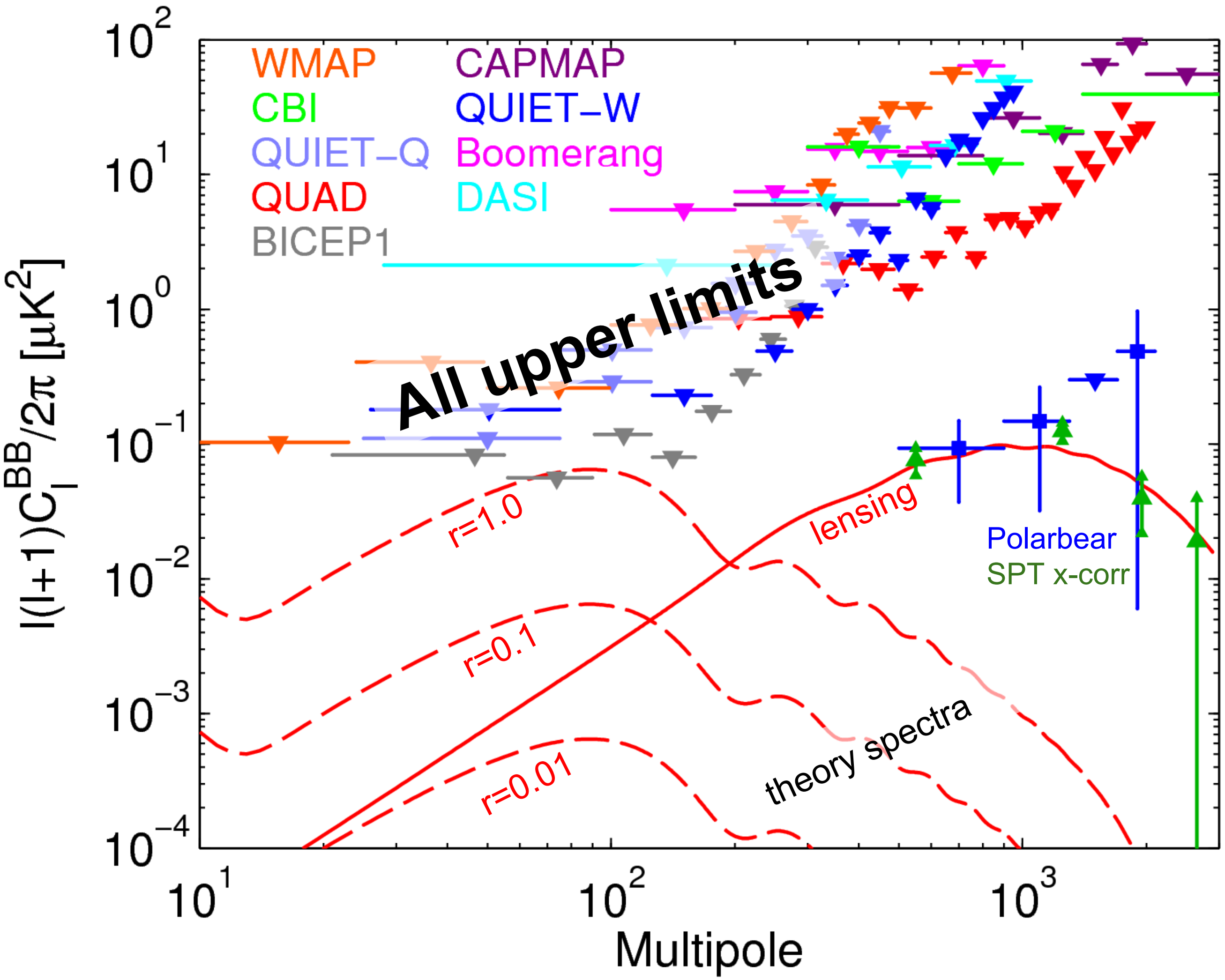
Search for Inflationary B-modes



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 Inflationary B-modes

Best limit on r from BICEP1:

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

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VE RI TAS HARVARD

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

cea

UCSD

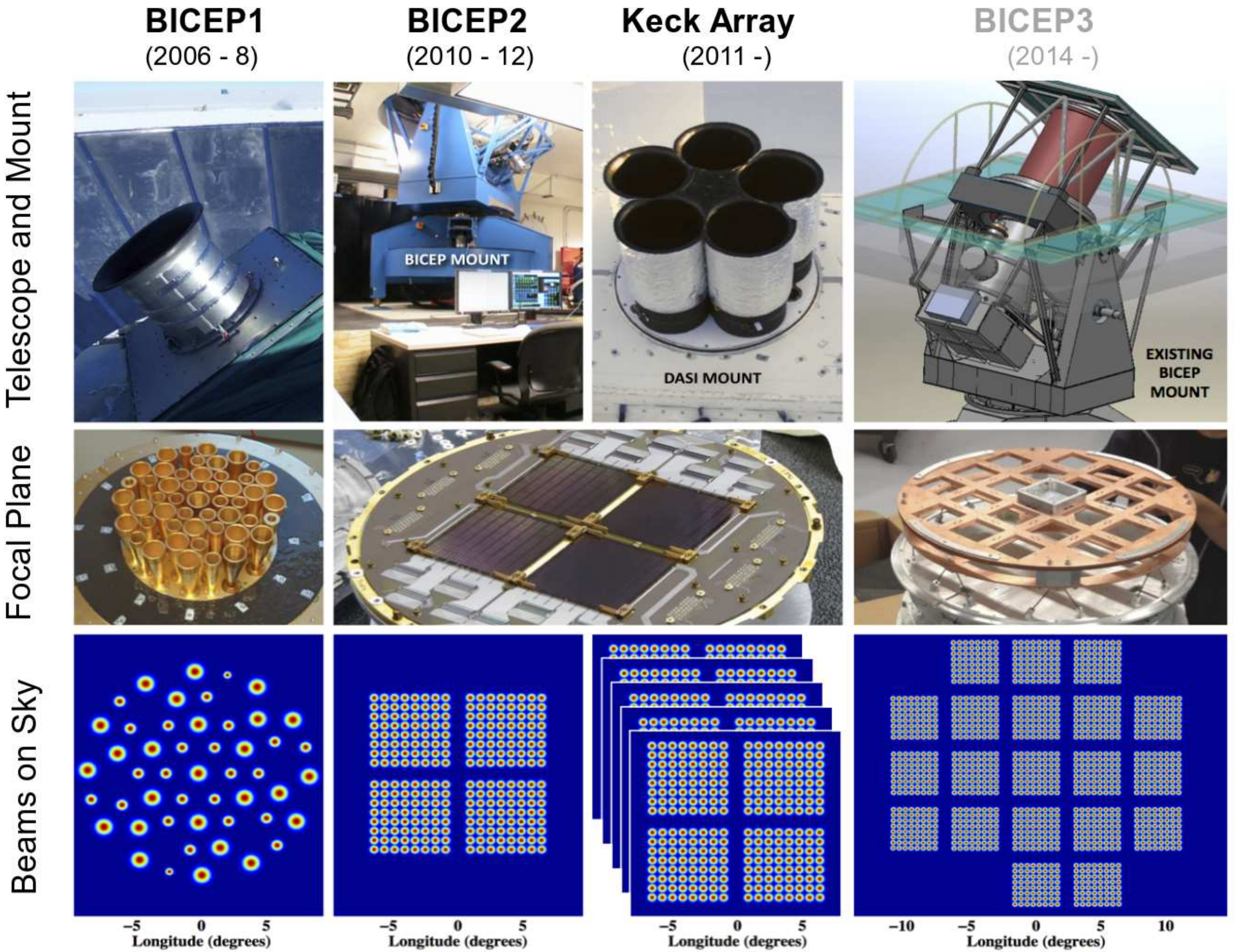
JPL

NIST

CARDIFF UNIVERSITY

UNIVERSITY OF TORONTO

UBC



BICEP1
(2006 - 8)
BICEP2
(2010 - 12)
Keck Array
(2011 -)
BICEP3
(2014 -)
Telescope and Mount
BICEP MOUNT
DASI MOUNT
EXISTING BICEP MOUNT
Focal Plane
Beams on Sky
-5 0 5
Longitude (degrees)
-5 0 5
Longitude (degrees)
-5 0 5
Longitude (degrees)
-10 -5 0 5 10
Longitude (degrees)

	BICEP1 (2006 - 8)	BICEP2 (2010 - 12)	Keck Array (2011 -)	BICEP3 (2014 -)

Telescope and Mount

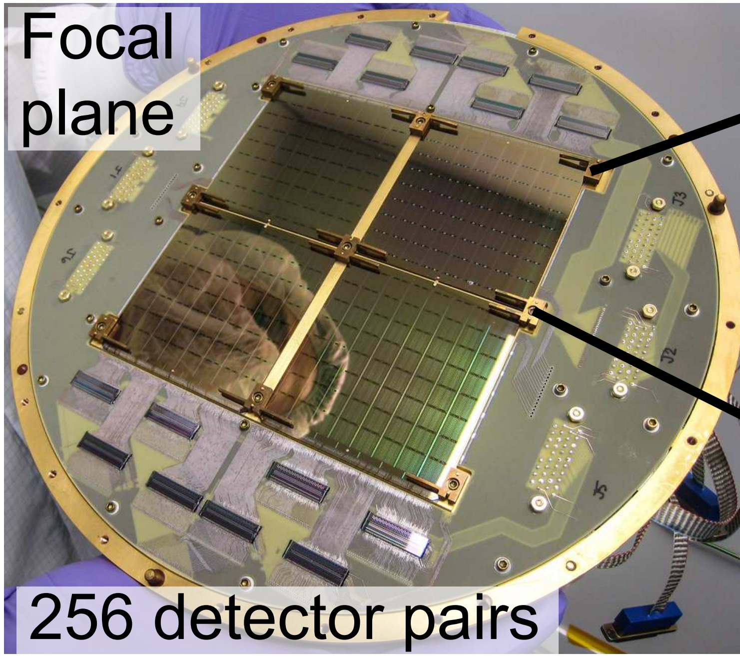
Focal Plane

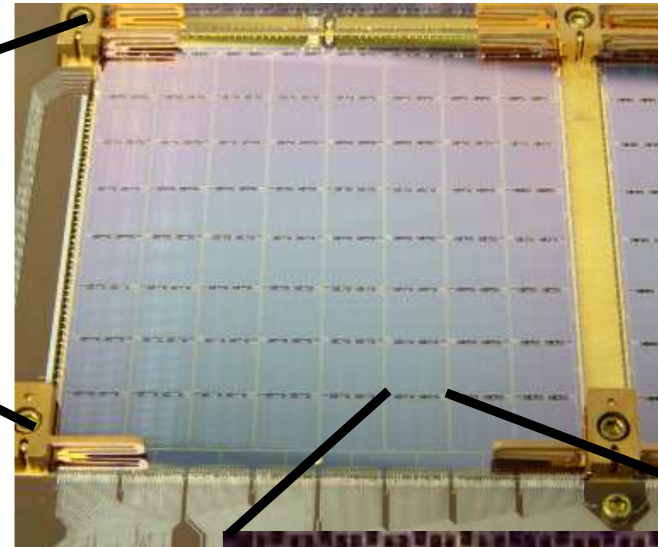
10x denser pixels

Upper limit vs. Detection

Bicep1 Bicep2

Mass-produced Superconducting Detectors





Planar
antenna
array

Slot
antennas

Transition edge sensor

Microstrip filters

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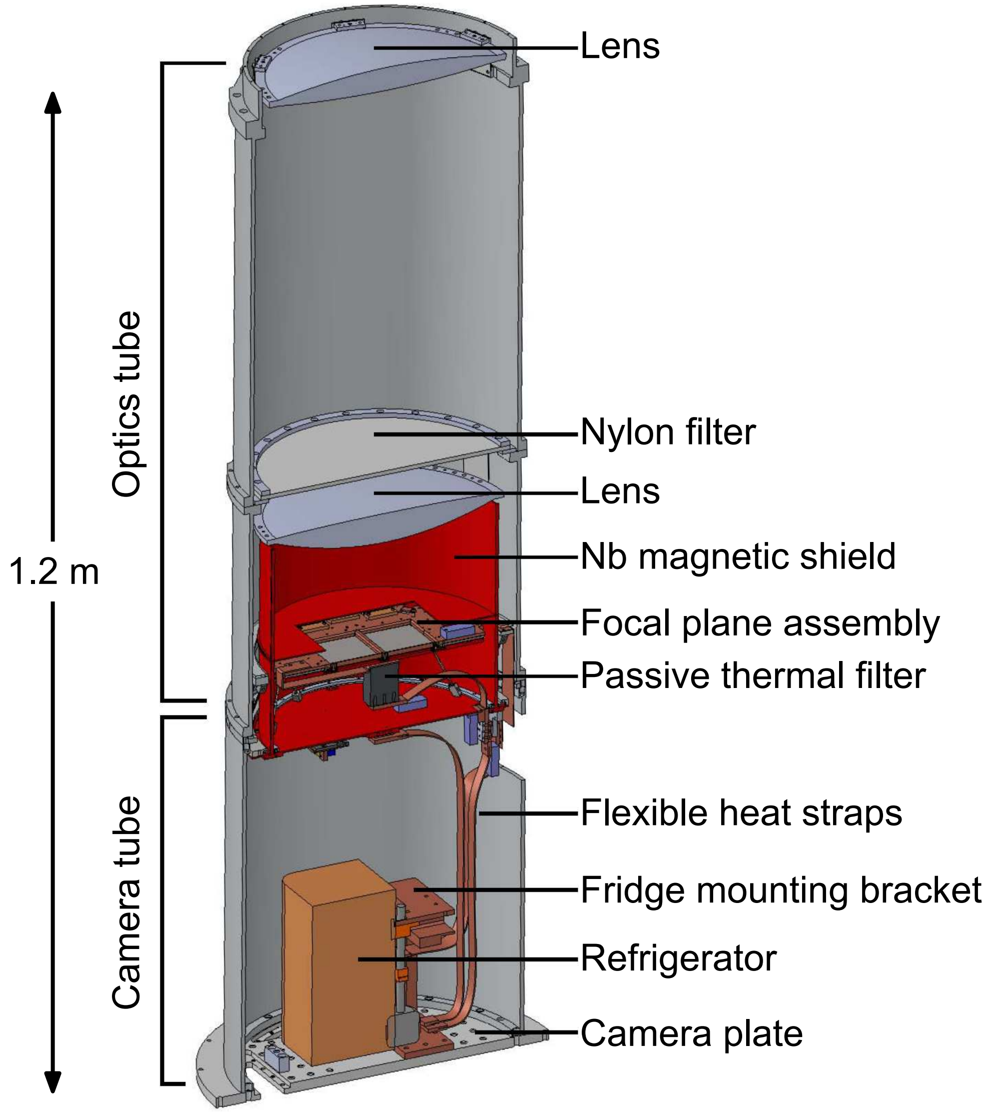
The BICEP2 Telescope

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.



South Pole CMB telescopes

A popular place for CMB Experimentalists:

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

Our experimental strategy:

→ Small aperture telescope

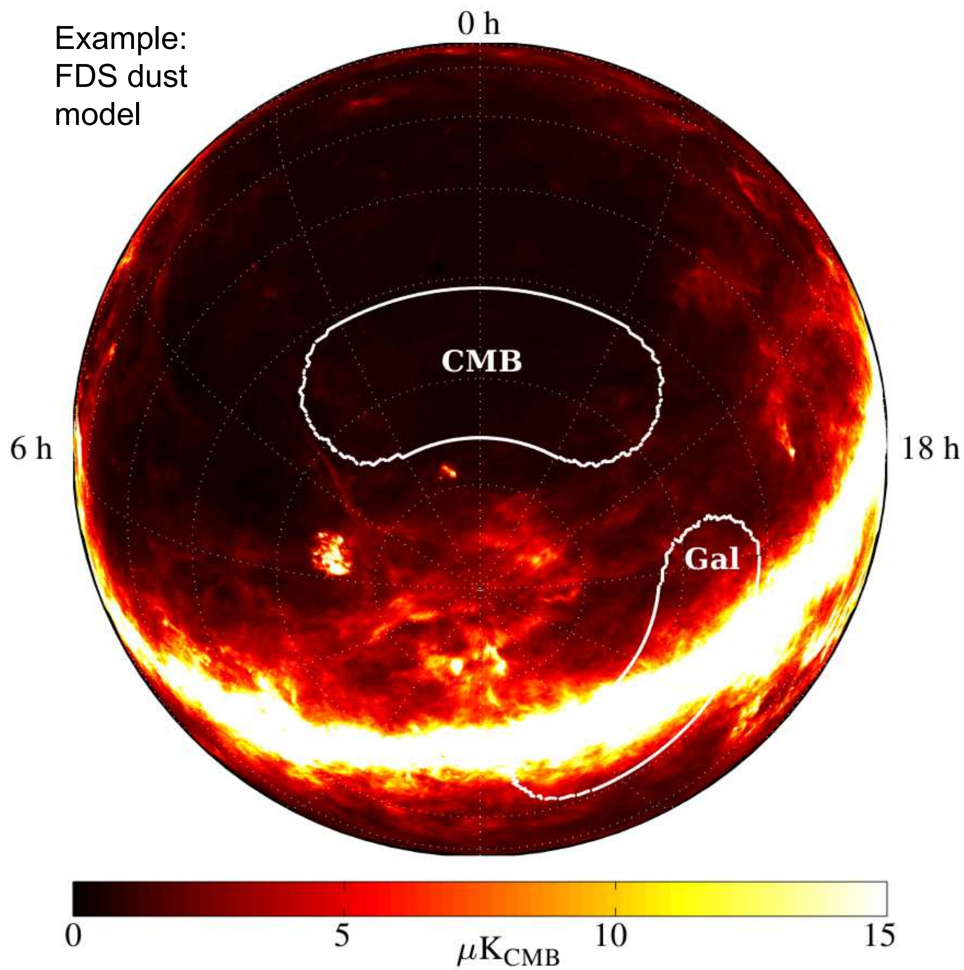
→ Target the 2 degree peak of the inflationary B-mode

→ 24/7 access to the “Southern Hole”


photo: Keith Vanderlinde

Observational Strategy

Example:
FDS dust
model



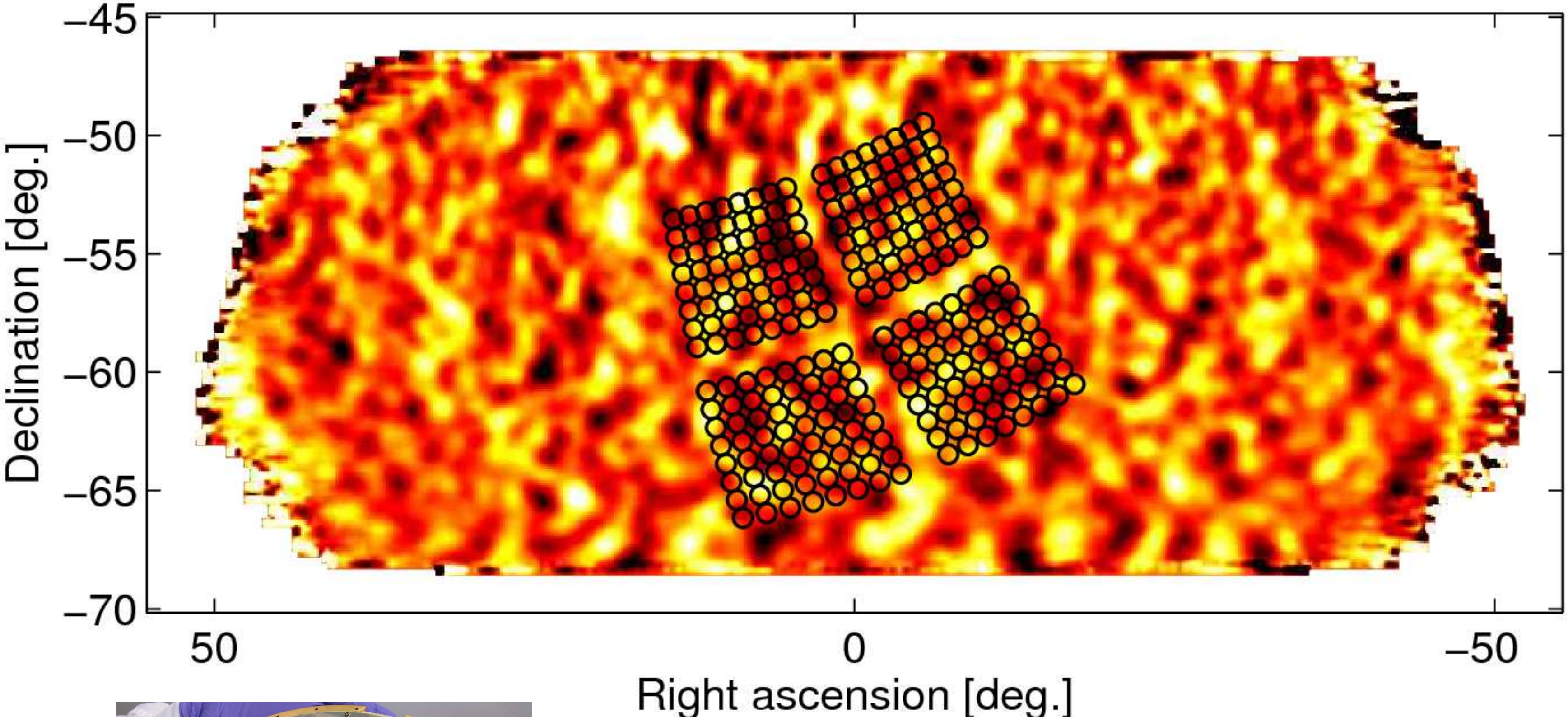
Target the “Southern Hole” - a region of the sky exceptionally free of dust and synchrotron foregrounds.

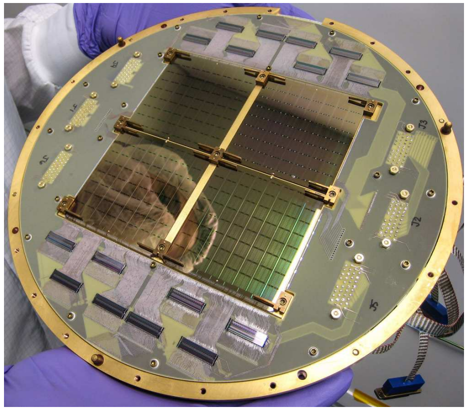
Detectors tuned to 150 GHz, near the peak of the CMB’s 2.7 K blackbody spectrum.

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: $r \leq \sim 0.01$.

BICEP2 on the Sky



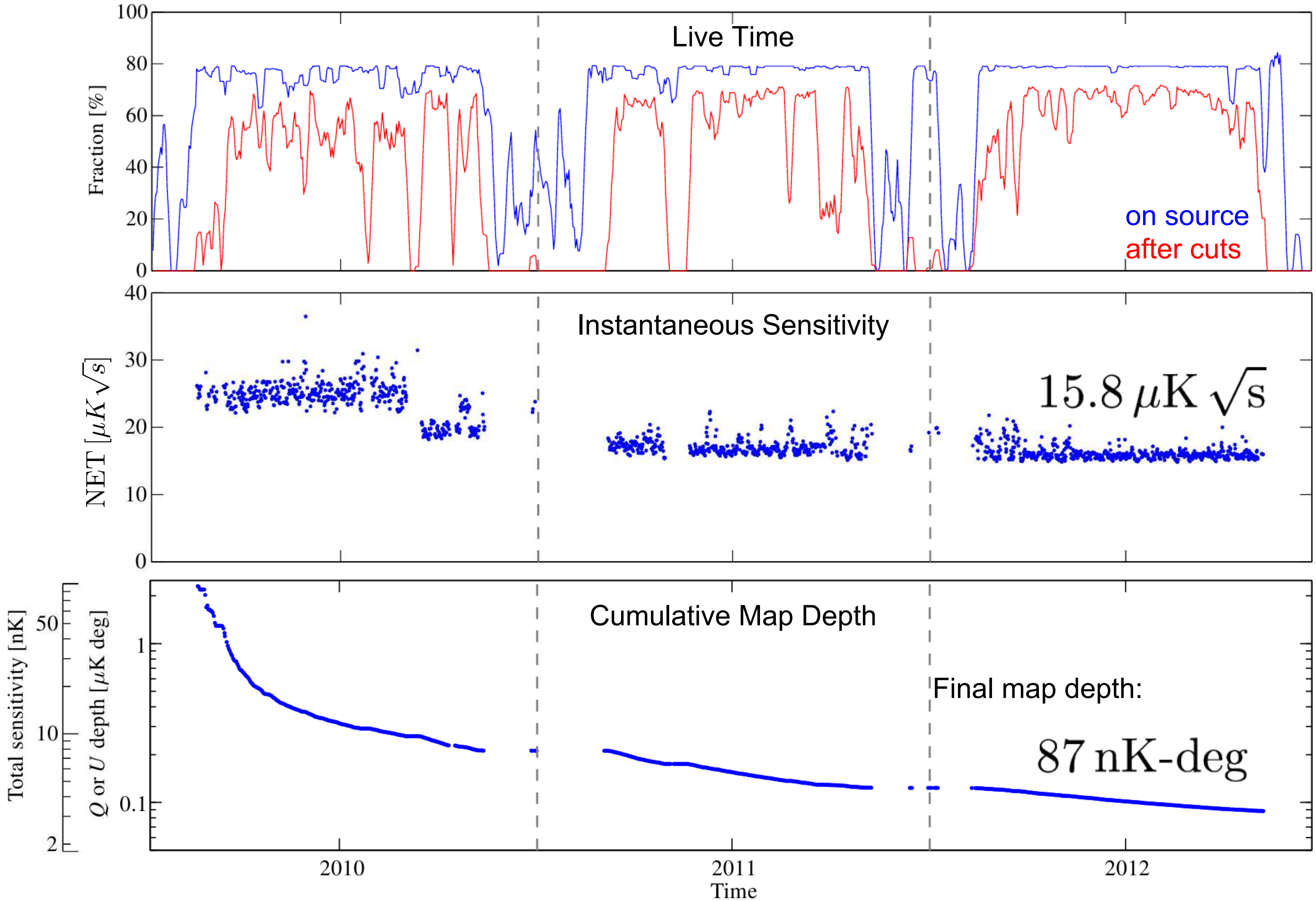


Projection of the BICEP2 focal plane on the sky

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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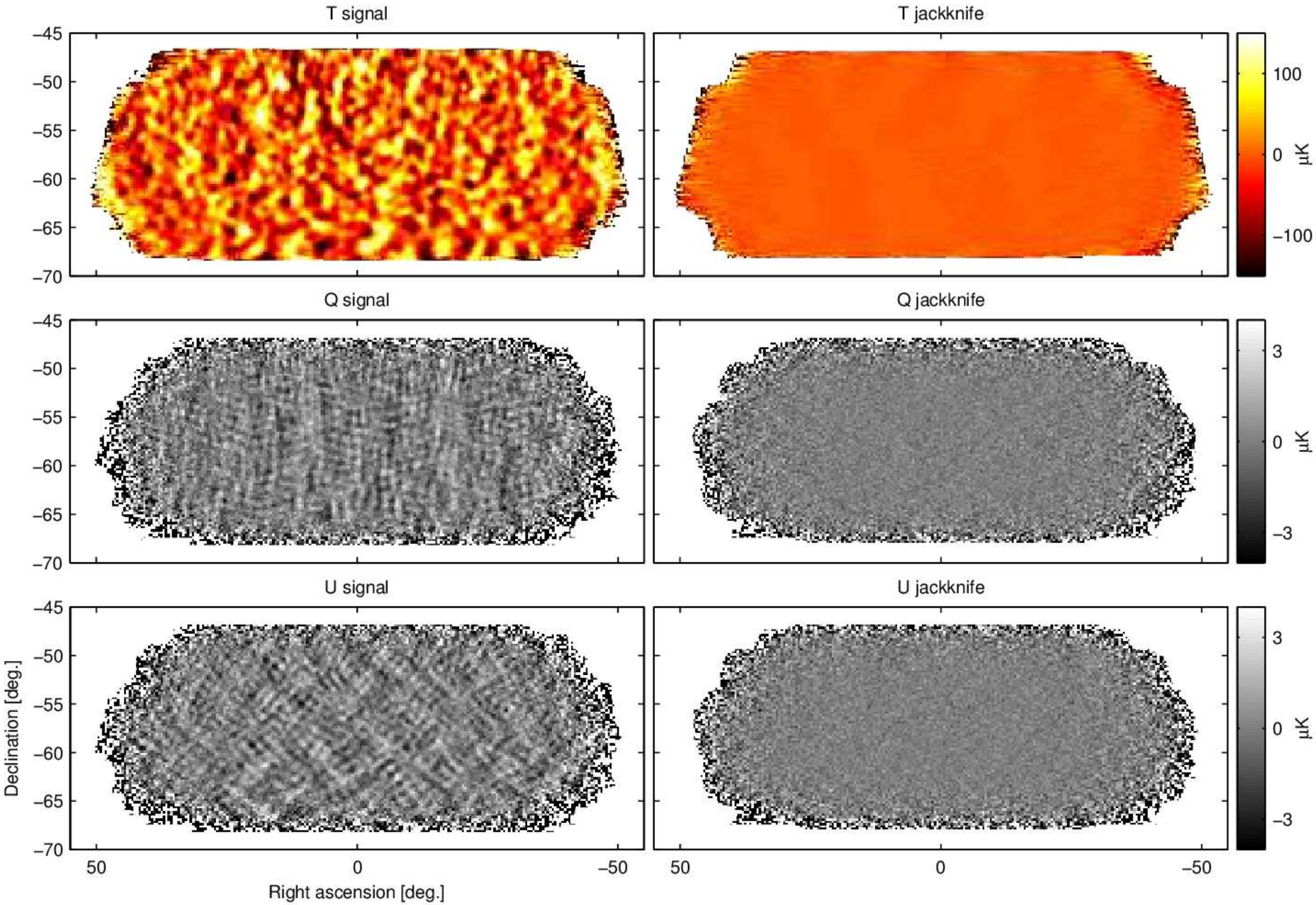
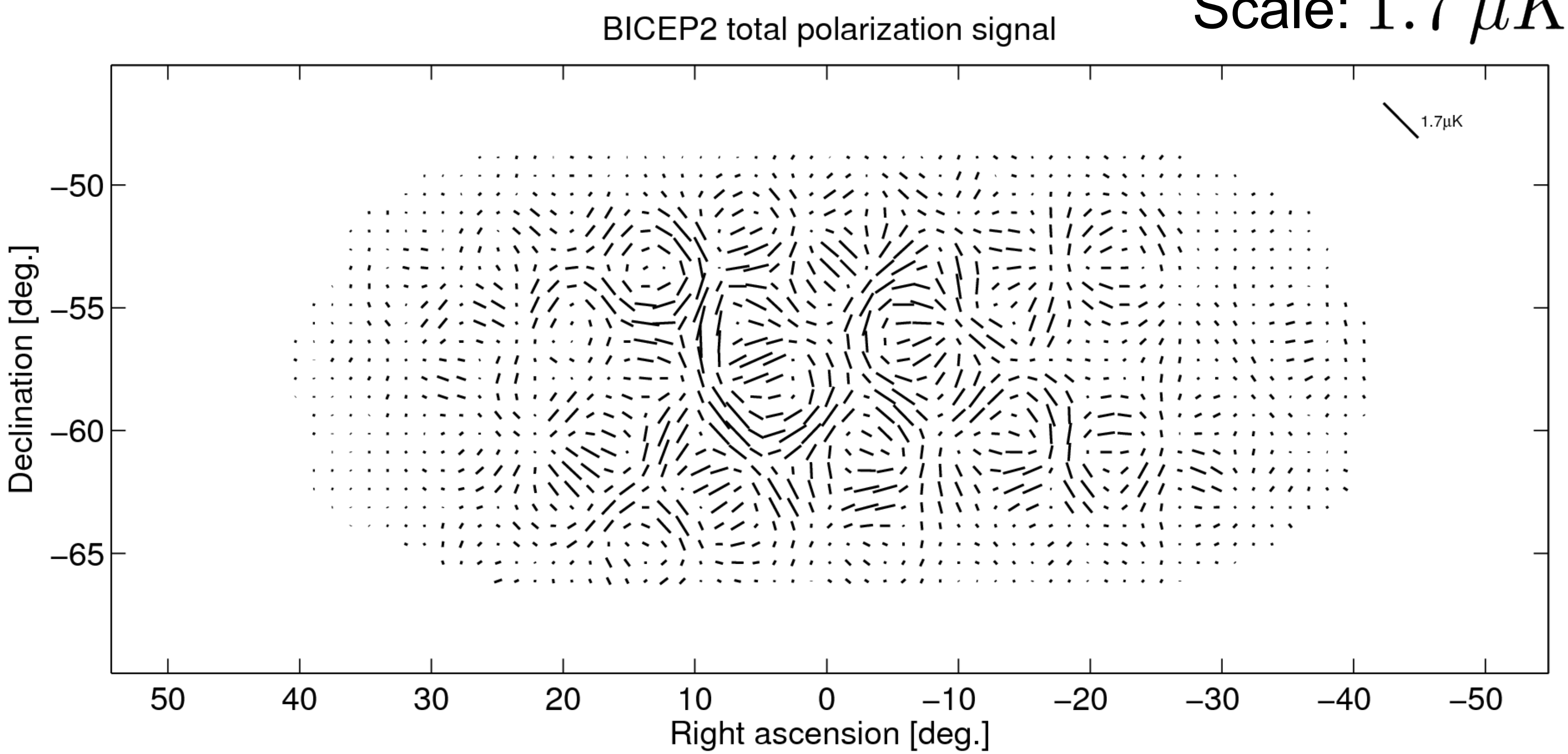
BICEP2 T and Stokes Q/U Maps



Total Polarization

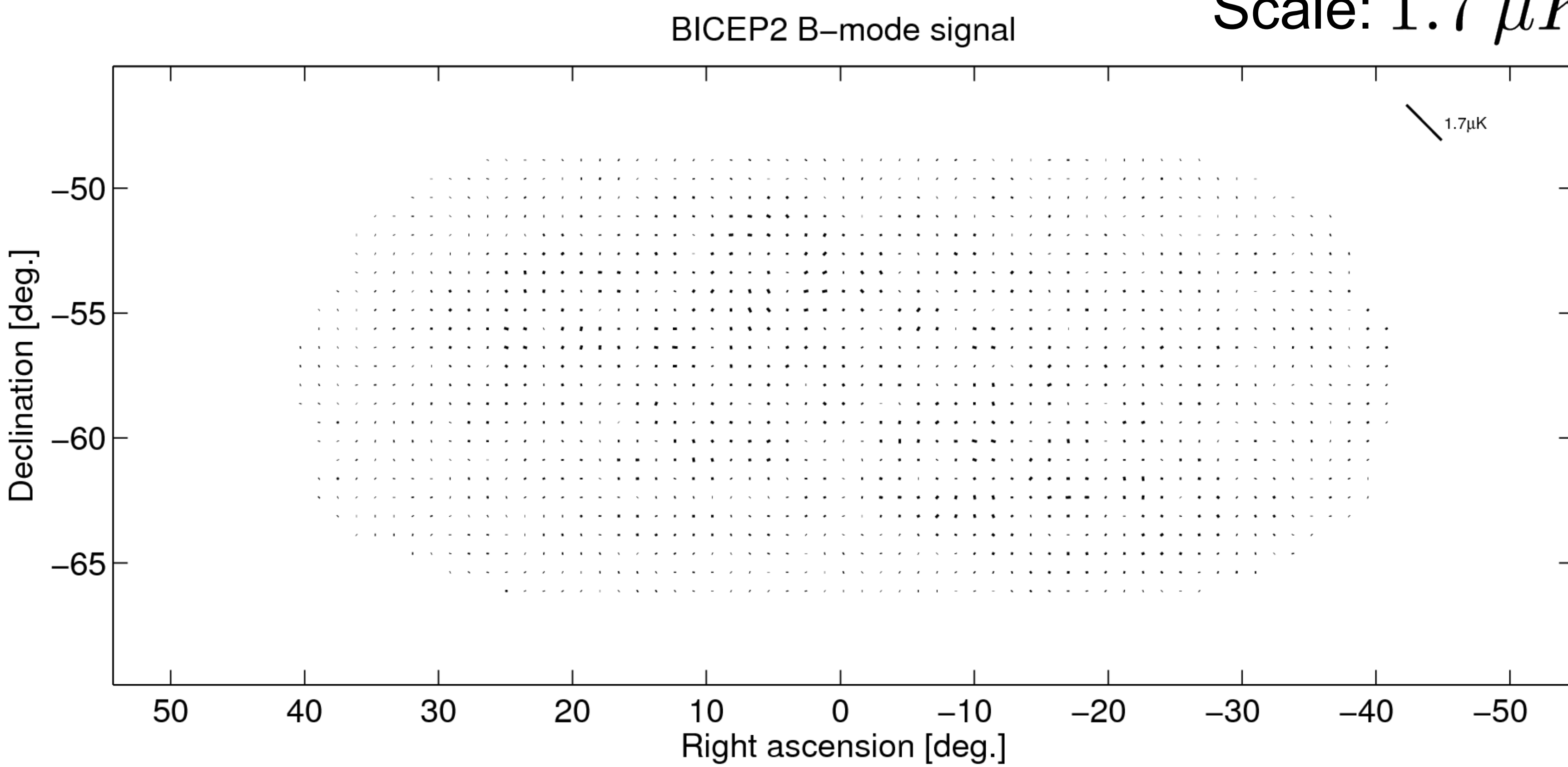
Scale: $1.7\,\mu K$



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

B-mode Contribution

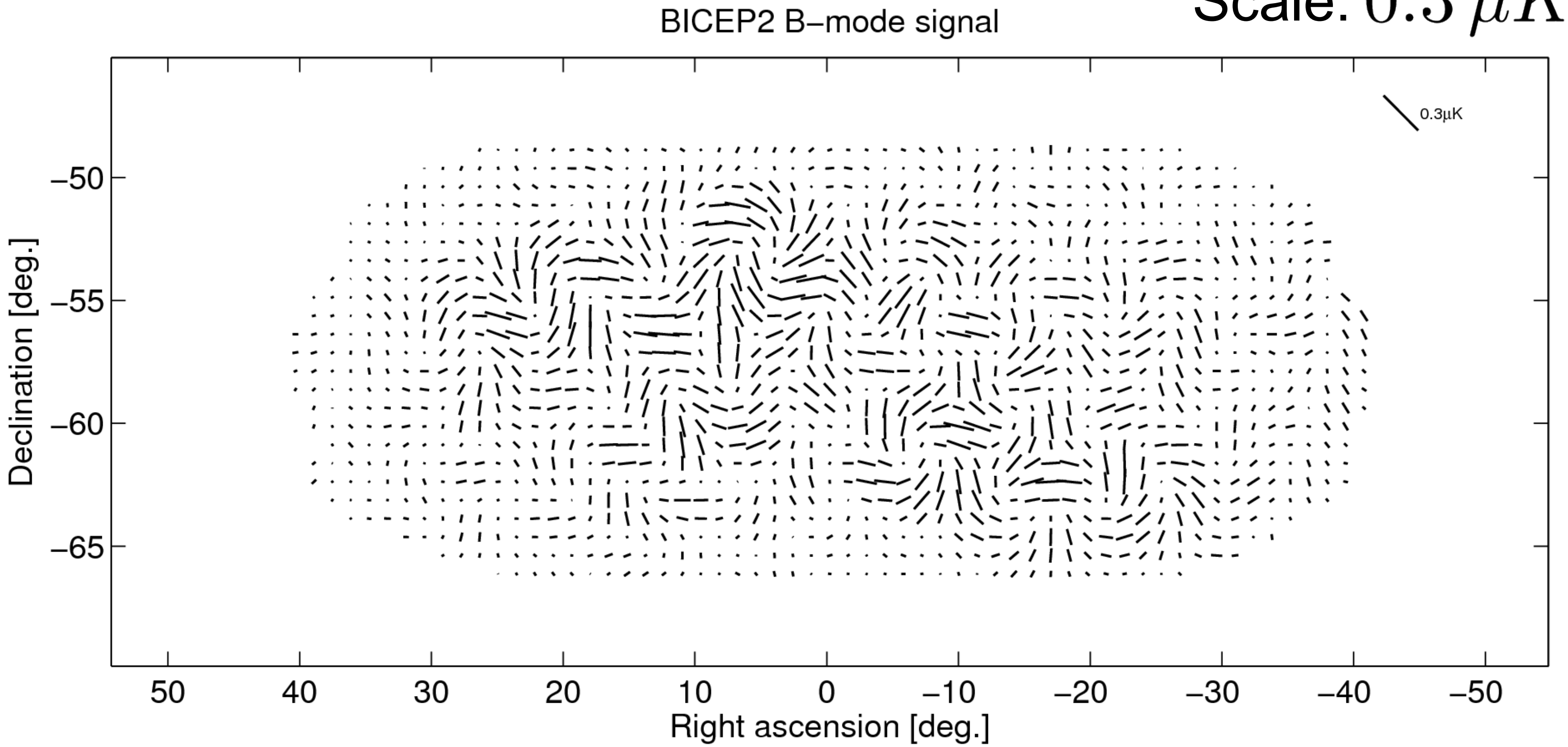
Scale: $1.7\,\mu K$



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

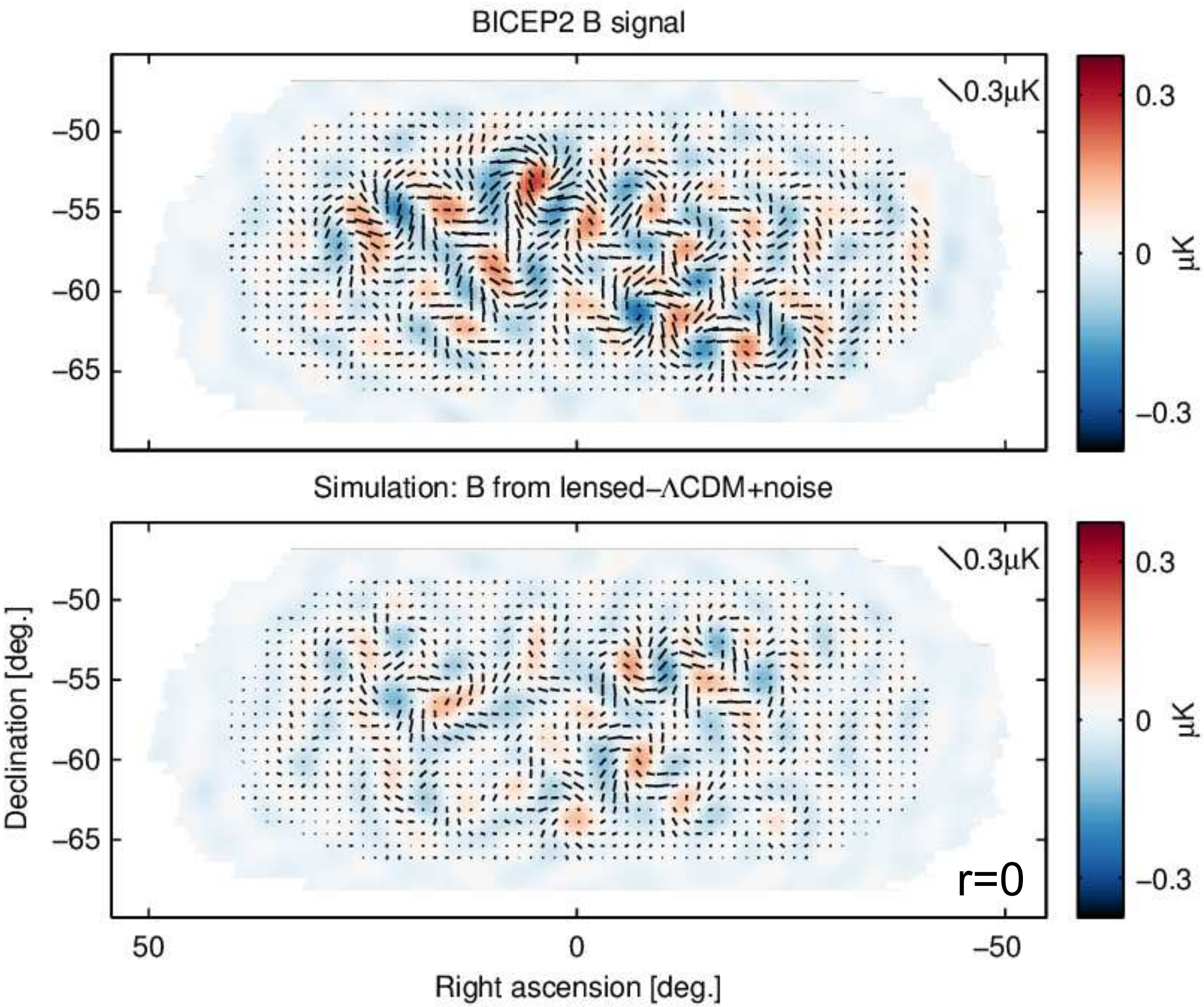
B-mode Contribution

Scale: $0.3\,\mu K$



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

B-mode Map vs. Simulation



Analysis calibrated by 500 lensed-ΛCDM+noise simulations.

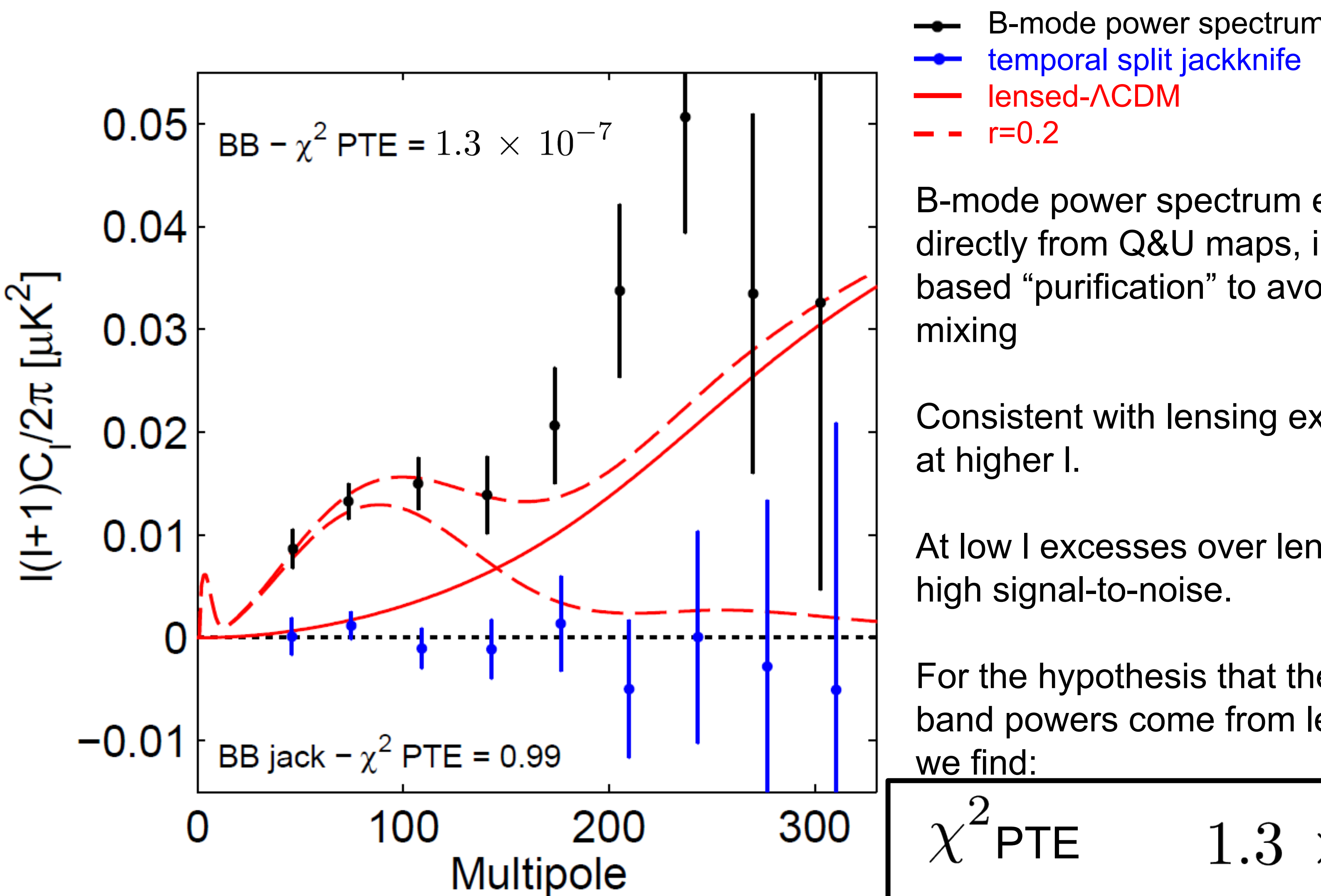
The simulations repeat the full observation at the timestream level -- including all filtering operations.

Allows us to perform arbitrary filtering operations.

The resulting removal and mixing of modes is controlled observing their impact on the distribution of simulated realizations.

From the simulations we derive the uncertainties on our measurements.

BICEP2 B-mode Power Spectrum



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

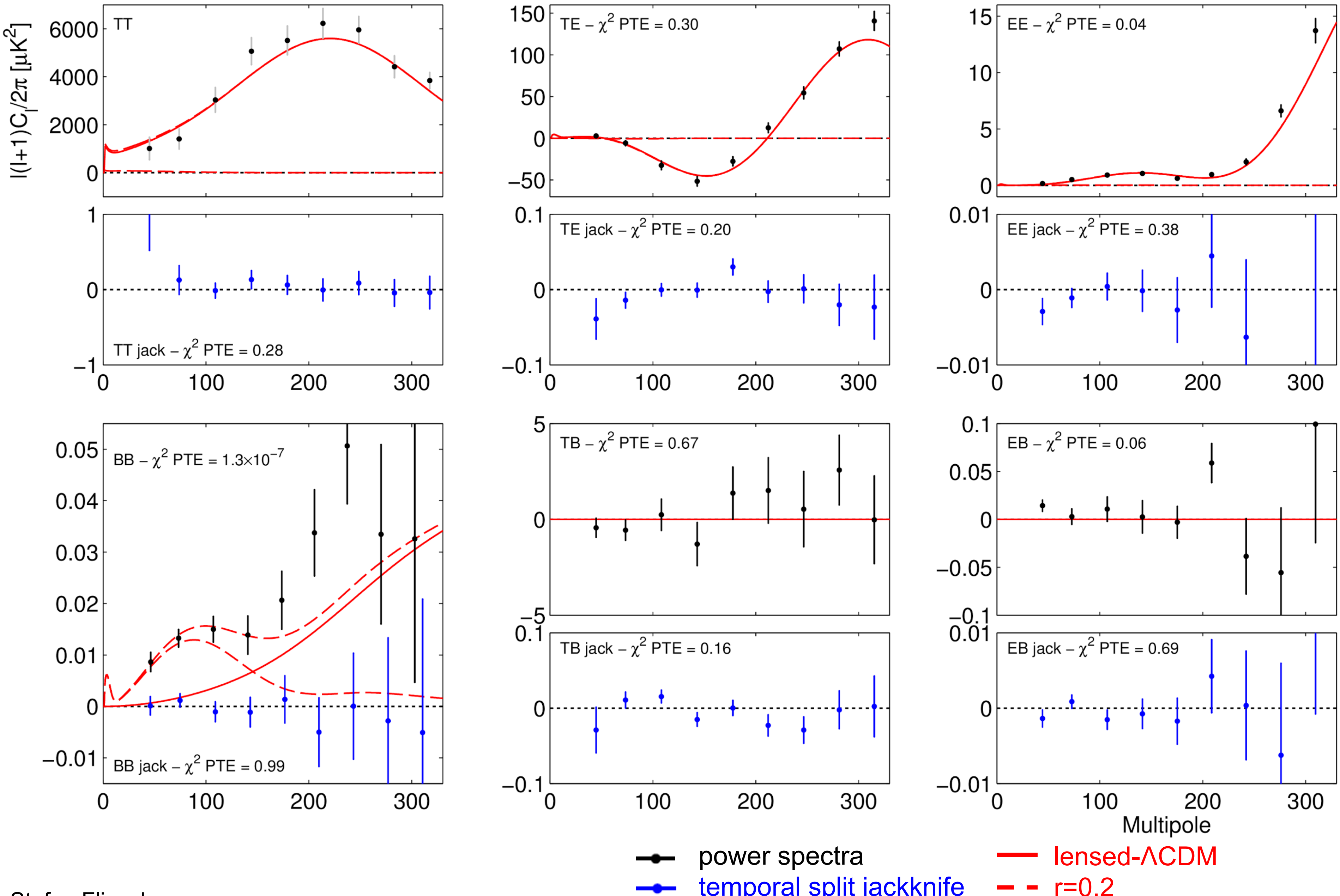
Consistent with lensing expectation at higher l.

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:

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

Temperature and Polarization Spectra



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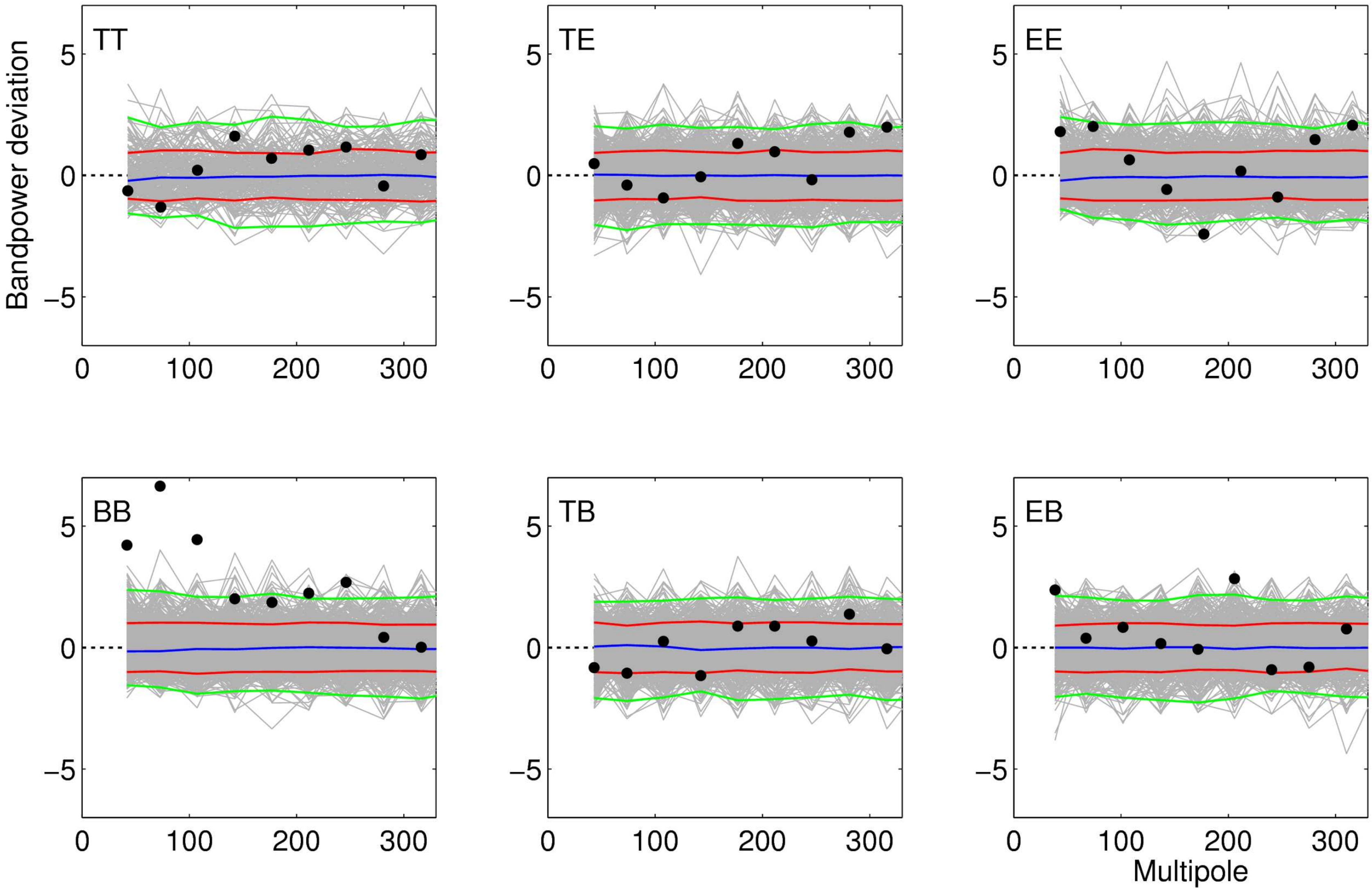
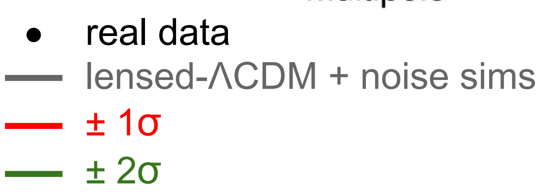
Bandpower Deviations



Bandpower deviations from mean of lensed-ΛCDM+noise simulations and normalized by the std of those sims



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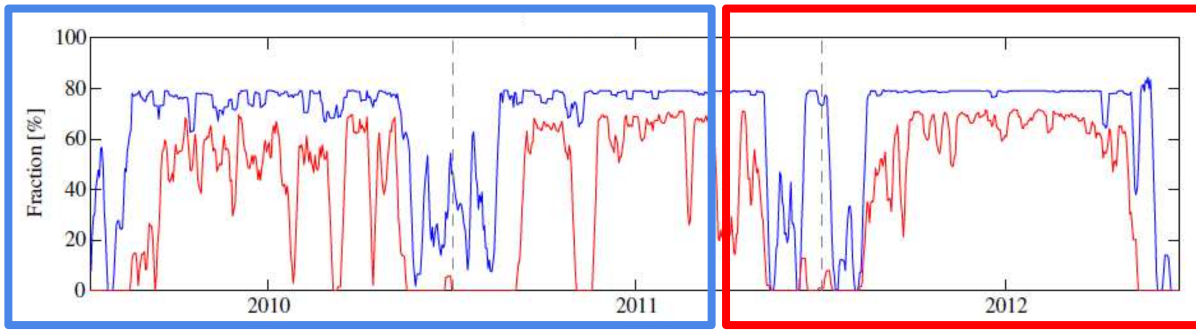
Check Systematics: Jackknifes

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

Splits by time

Live Time



A

B

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

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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. See later slides.

Splits by time

Checks for contamination on long (“Tag 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.

Stefan Fliescher

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				
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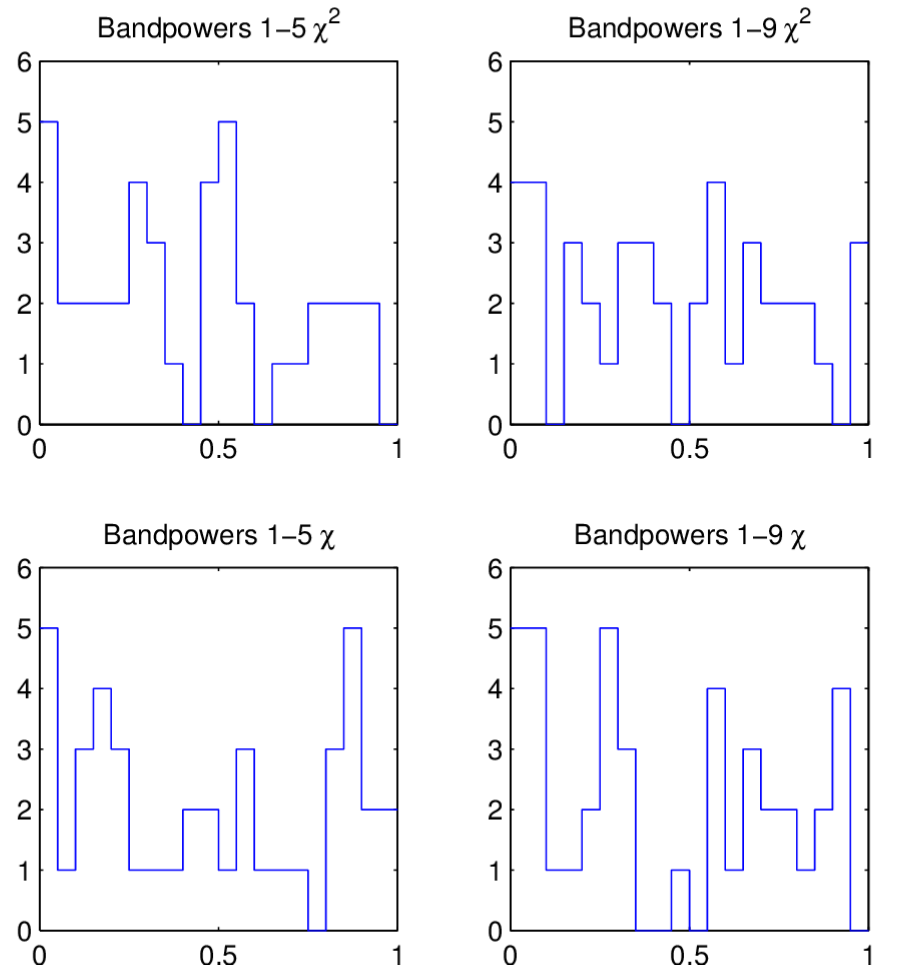
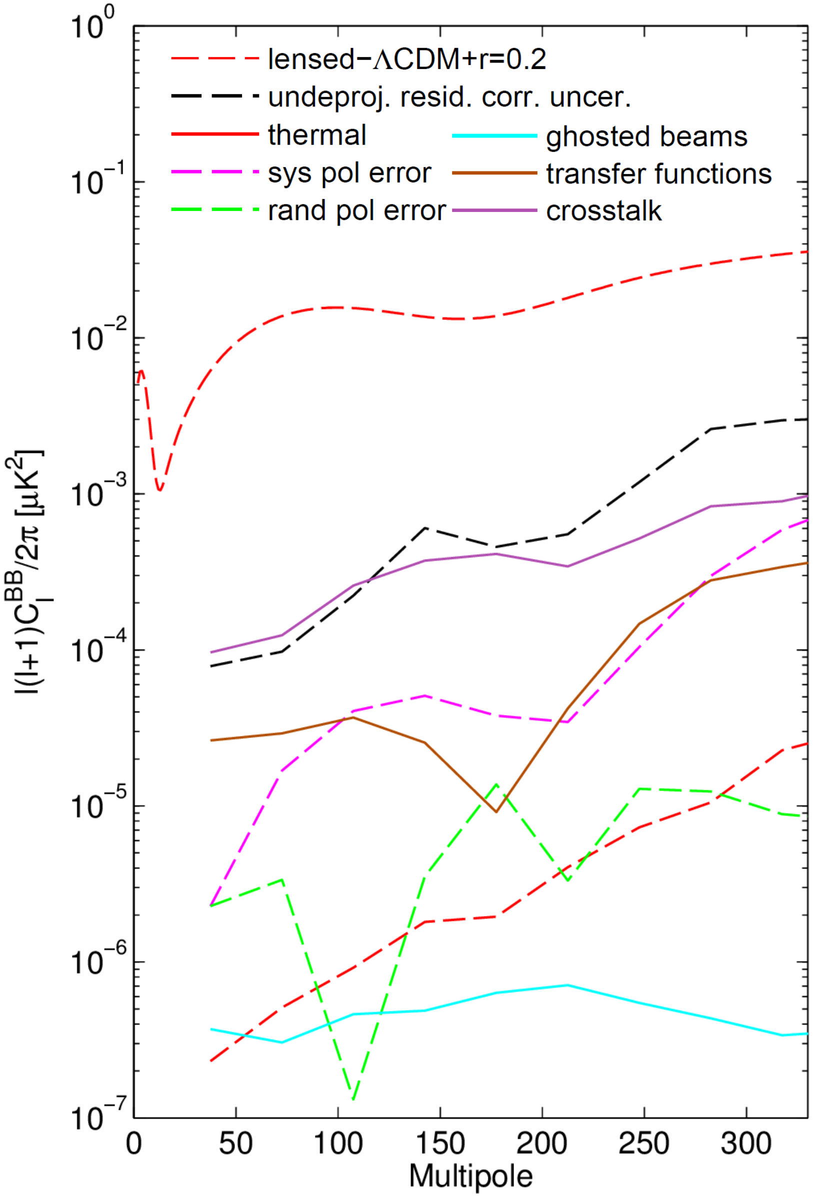
EB	0.589	0.872	0.599	0.790

14 jackknife tests applied to 3 spectra, 4 statistics

All 4 statistics defined from the jackknife tests result in uniform probability to exceed (PTE) distributions:



Simulation of Systematics



All systematic effects that we could imagine were investigated!

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

Stefan Fliescher

Two Very Different Experiments

Different approaches to:
- beam matching
- stray radiation
- detection
- amplification

Comparing BICEP1 and BICEP2 is a strong test of systematic errors

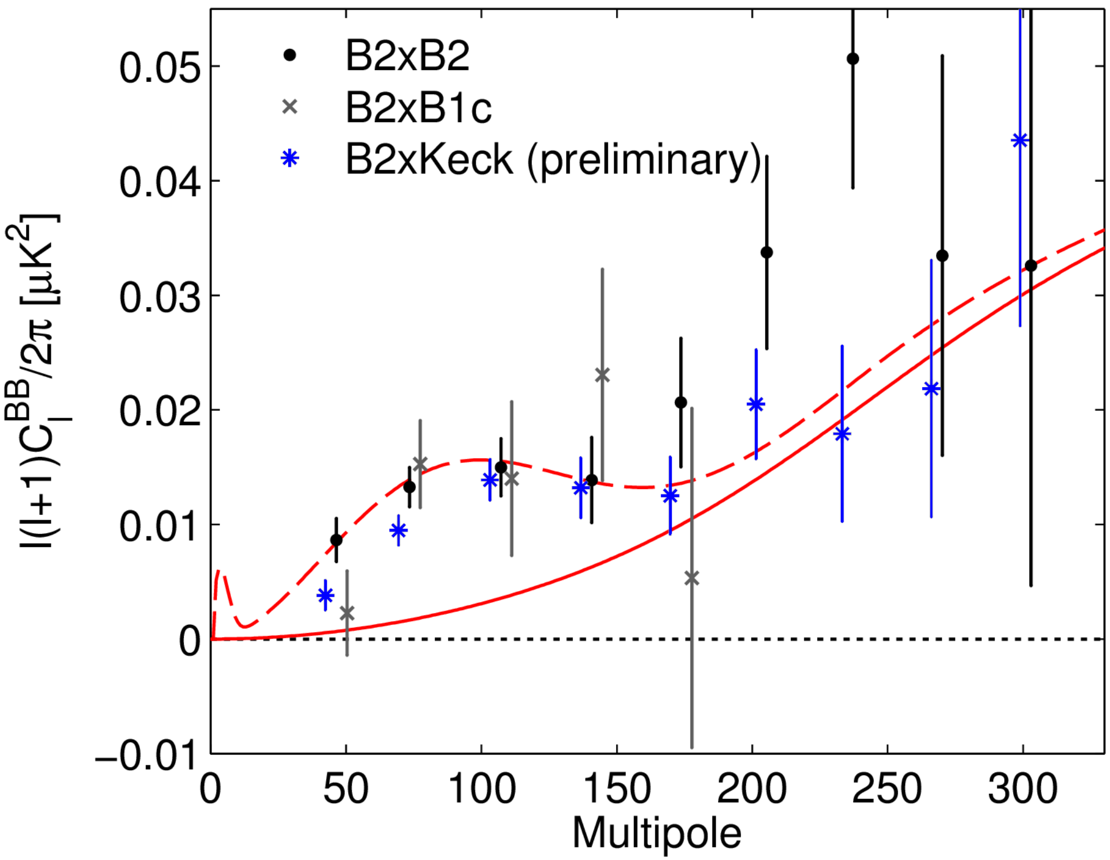
BICEP2
Antenna-Coupled Bolometers

A polarization-sensitive camera built on a micro circuit board!

Uses superconductivity to gather, filter, detect, and amplify millimeter-wave light

Cross Spectra with BICEP1 and Keck

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

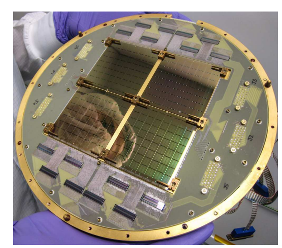


BICEP2 auto spectrum compatible with B2xB1c cross spectrum

~3σ evidence of excess power in the cross spectrum

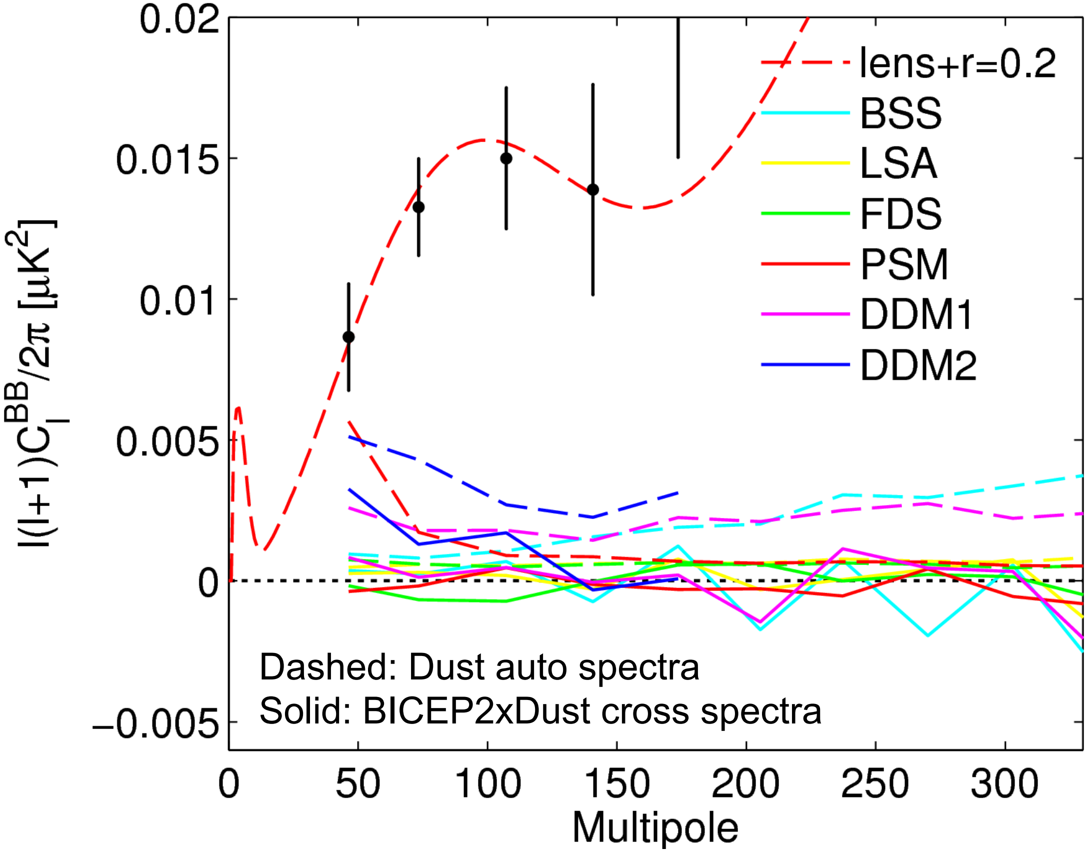
Additionally form cross spectrum with 2 years of data from *Keck Array*, the successor to BICEP2

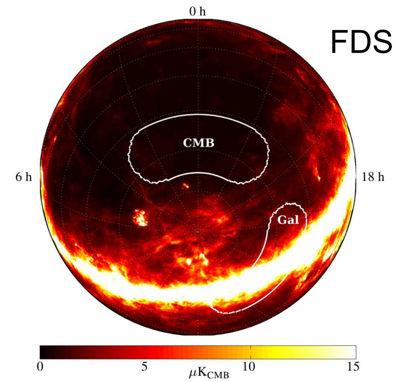
Excess power is also evident in the B2xKeck cross spectrum



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

Polarized Dust Foreground Projections





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

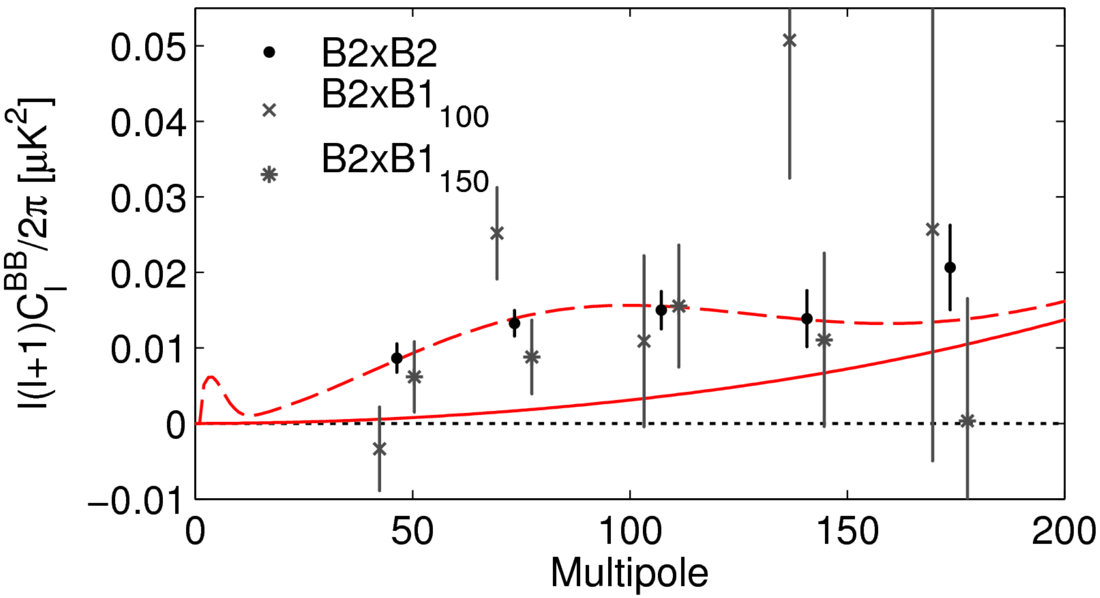
Use various models of polarized dust emission to estimate foregrounds.

All dust auto spectra well below observed signal level.

Cross spectra consistent with zero.

Stefan Fliescher

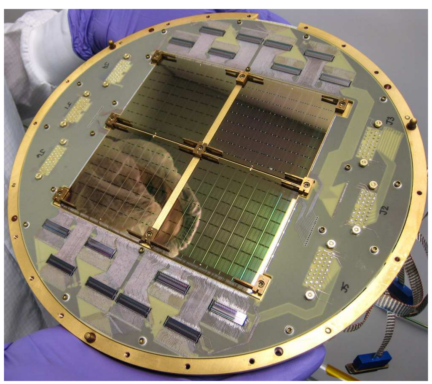
Cross Correlation with BICEP1



Though less sensitive, BICEP1 used **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

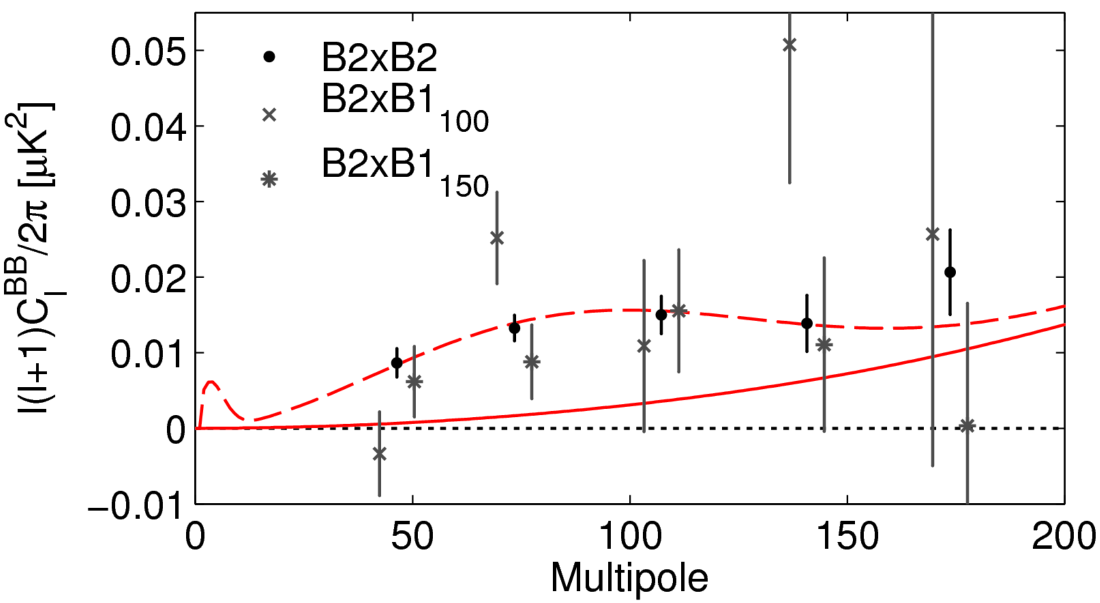
Cross with BICEP1$_{100}$ shows **~3σ** detection of BB power



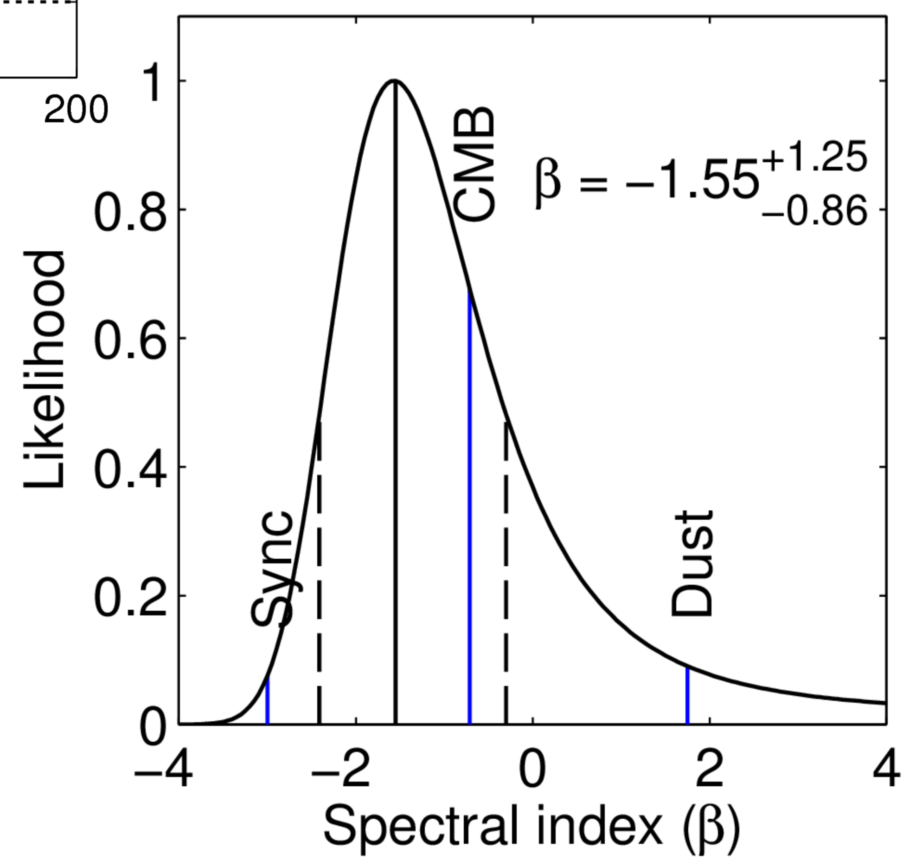
BICEP2: Phased antenna array and TES readout 150 GHz

BICEP1: Feedhorns and NTD readout 150 and 100 GHz

Spectral Index of the B-mode Signal



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

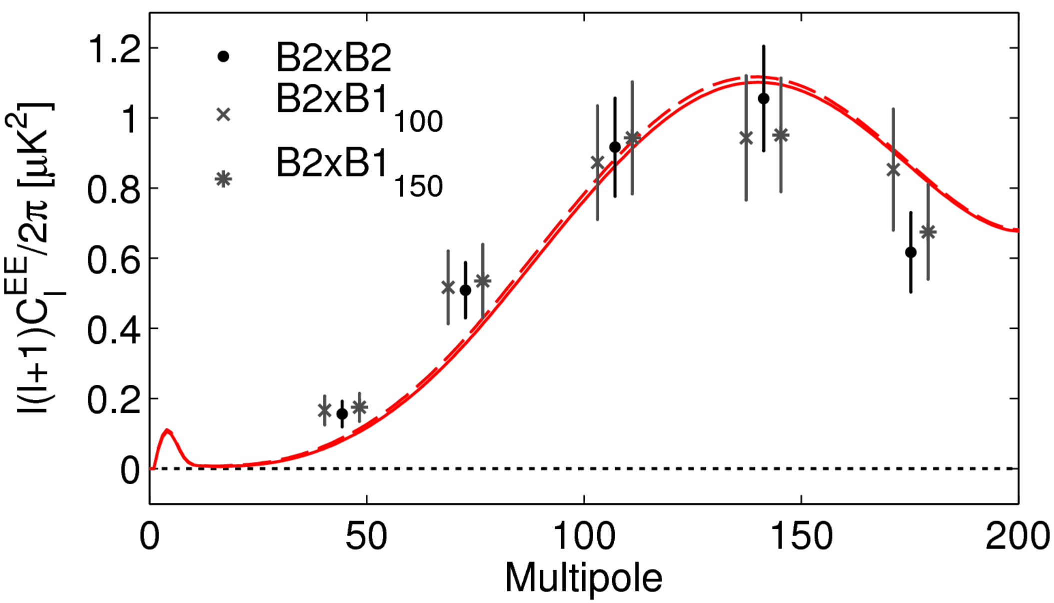


Comparison of B2 auto with $B2_{\mathbf{150}}$ x $B1_{\mathbf{100}}$ constrains signal frequency dependence, independent of foreground projections

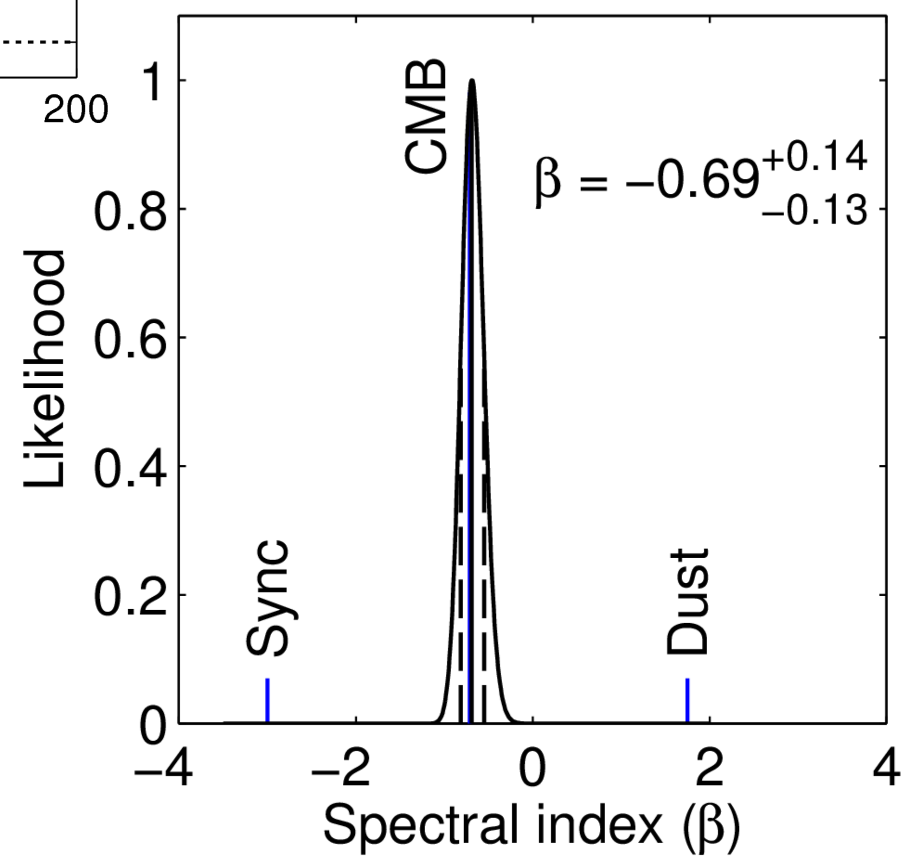
If **dust**, expect little cross-correlation

If **synchrotron**, expect cross higher than auto

Spectral Index of the E-mode Signal



Likelihood ratio test: consistent with CMB spectrum, disfavor pure dust/sync at **11/30σ**

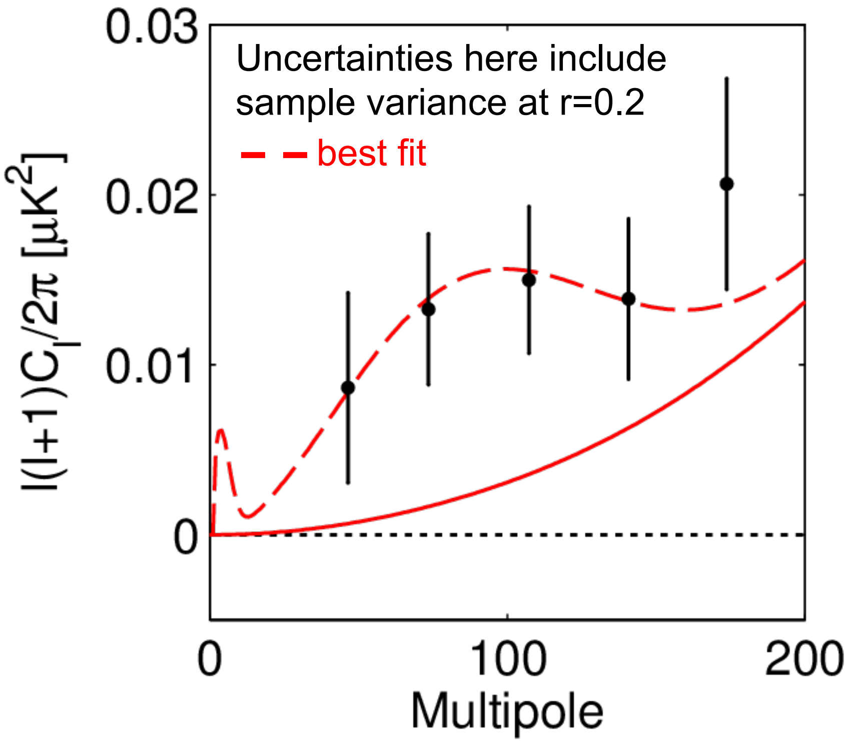


Comparison of B2 auto with $B2_{150}$ x $B1_{100}$ constrains signal frequency dependence, independent of foreground projections

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

If **synchrotron**, expect cross higher than auto

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

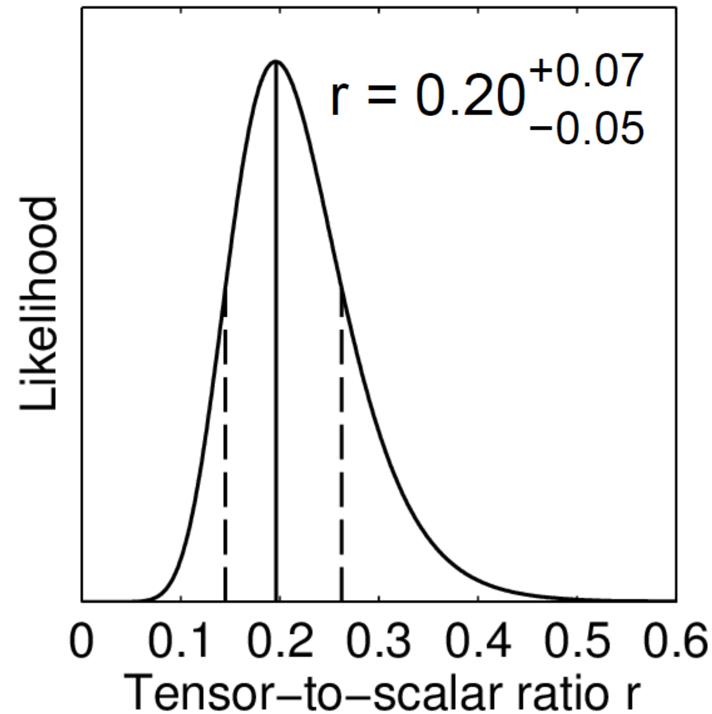
→ B-mode sims scaled to various levels of r (n_T=0)

Within this simplistic model we find:

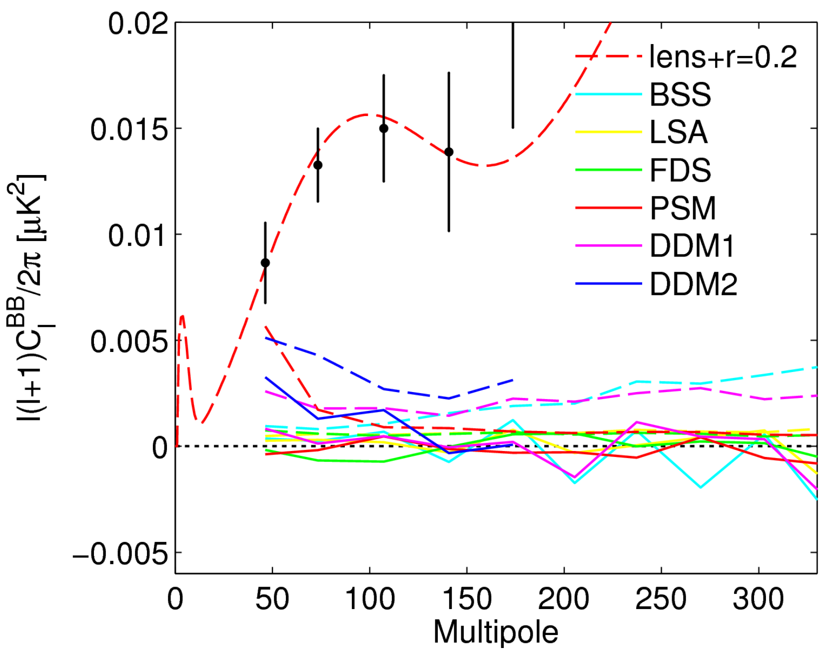
r = 0.2 with uncertainties dominated by sample variance

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

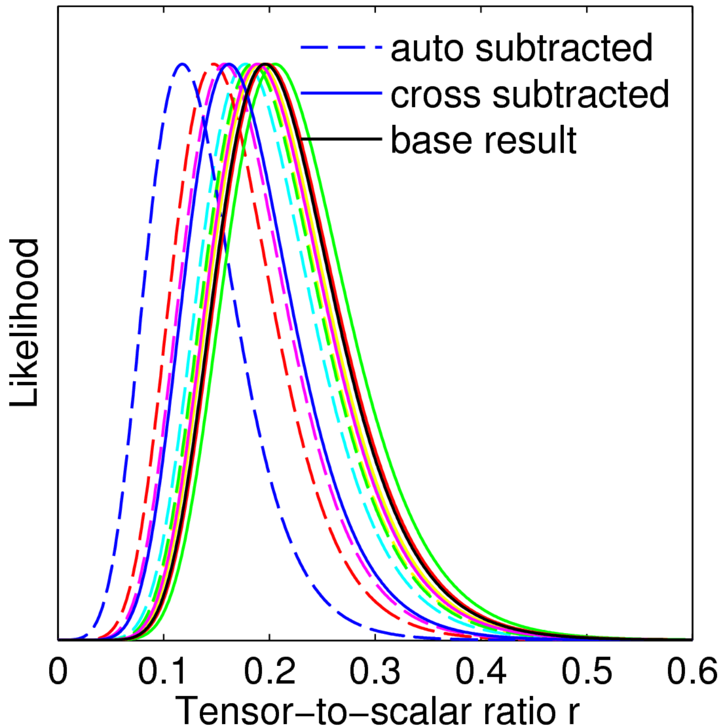
r=0 ruled out at 7.0σ



Constraint on r under Foreground Projections



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



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 ruled out at 5.9σ

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

Compatibility with Temperature Based Limits on r

Using temperature data over a wide range of angular scales limits on r have been set:

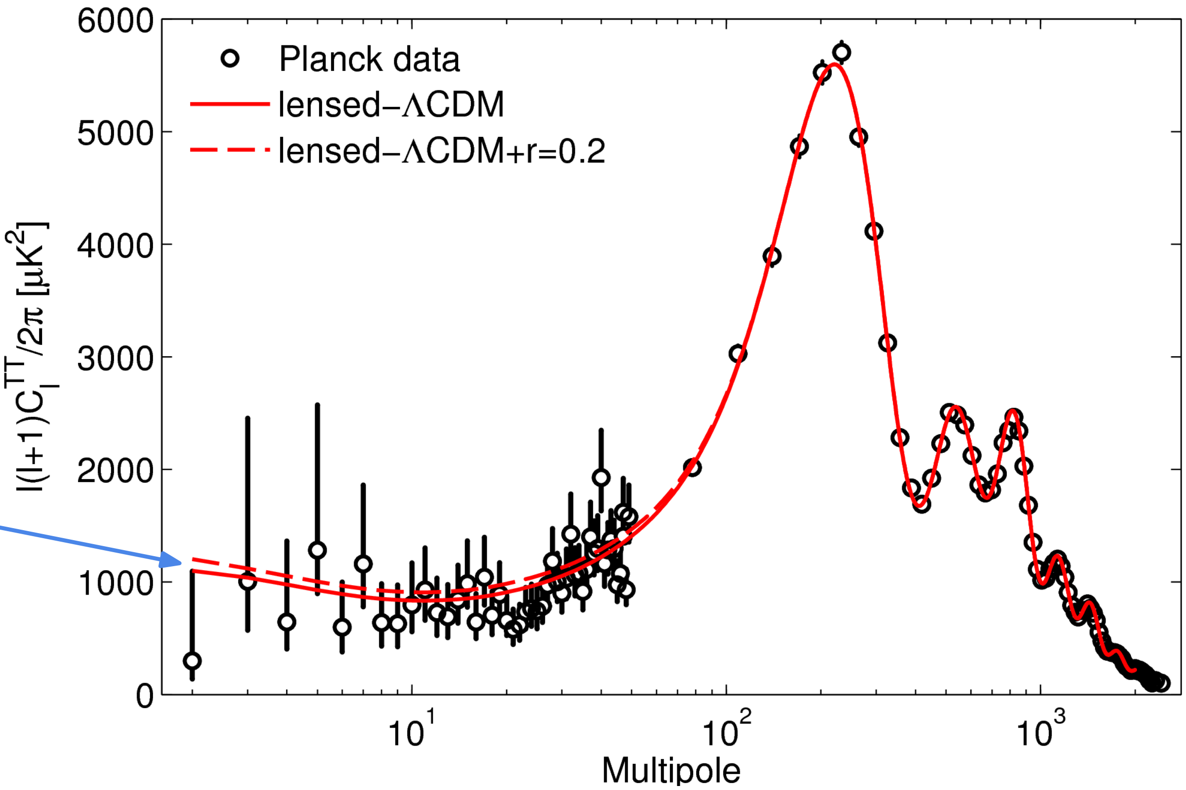
SPT+WMAP+BAO+H_0 : $r < 0.11$

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

(95% CL)

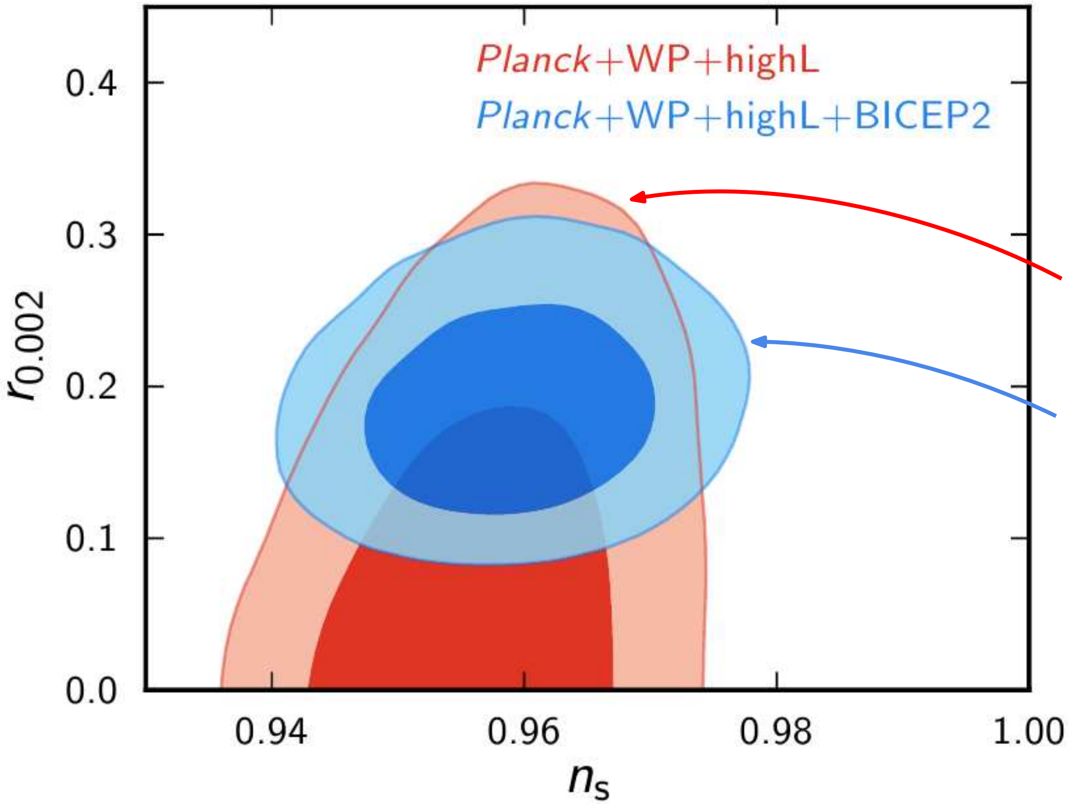
However, r=0.2 just makes a small change to the temperature spectrum.

(In this plot r=0.2 simply added to Planck best fit model with no re-optimization of other parameters)



Compatibility with Temperature Based Limits on r

Constraint on r *with running allowed*:



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

Example: running of the spectral index

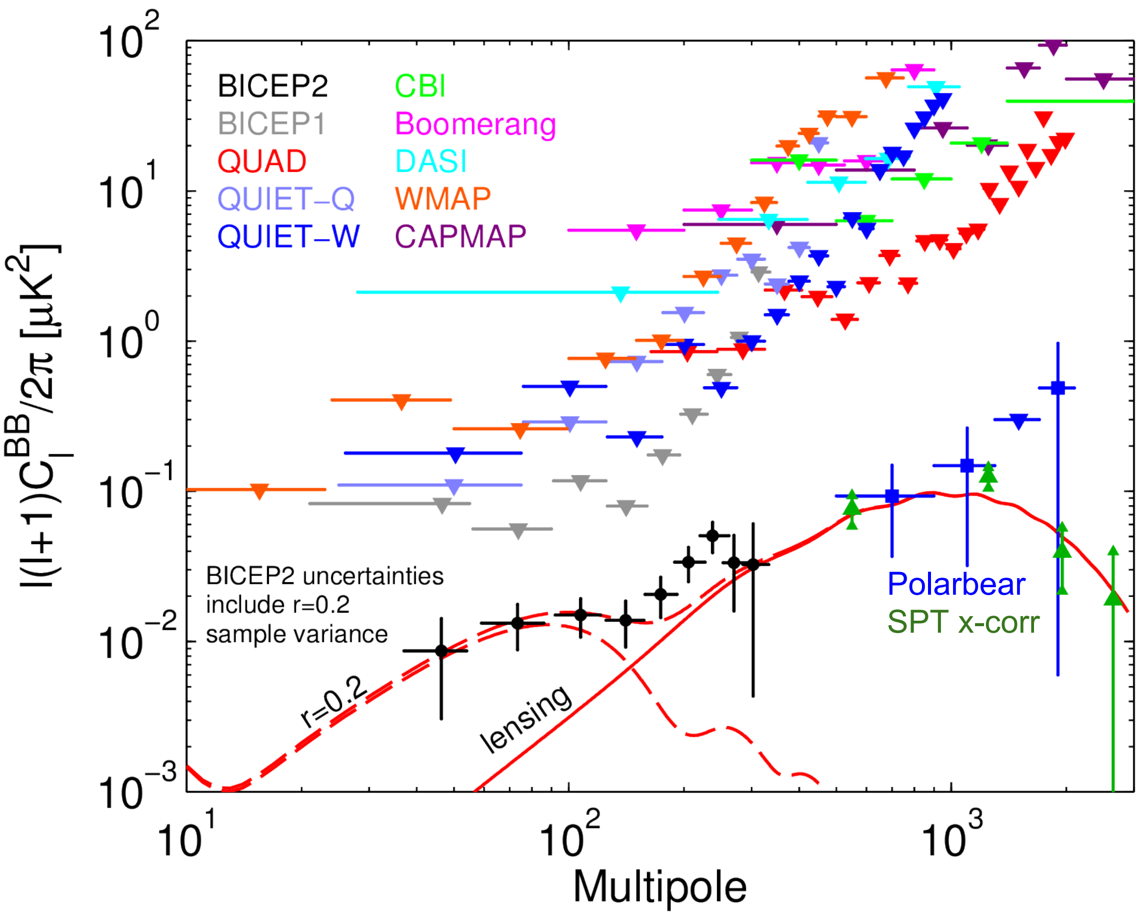
Planck likelihood chains for lensed ΛCDM + *tensors* + *running*

Same chains, importance sampled with the BICEP2 r likelihood

Other possibilities within ΛCDM?...

Conclusions

BICEP2 and upper limits from other experiments:



http://bicepkeck.org

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 gravitational wave model:

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

With r=0 is ruled out at 7.0σ.