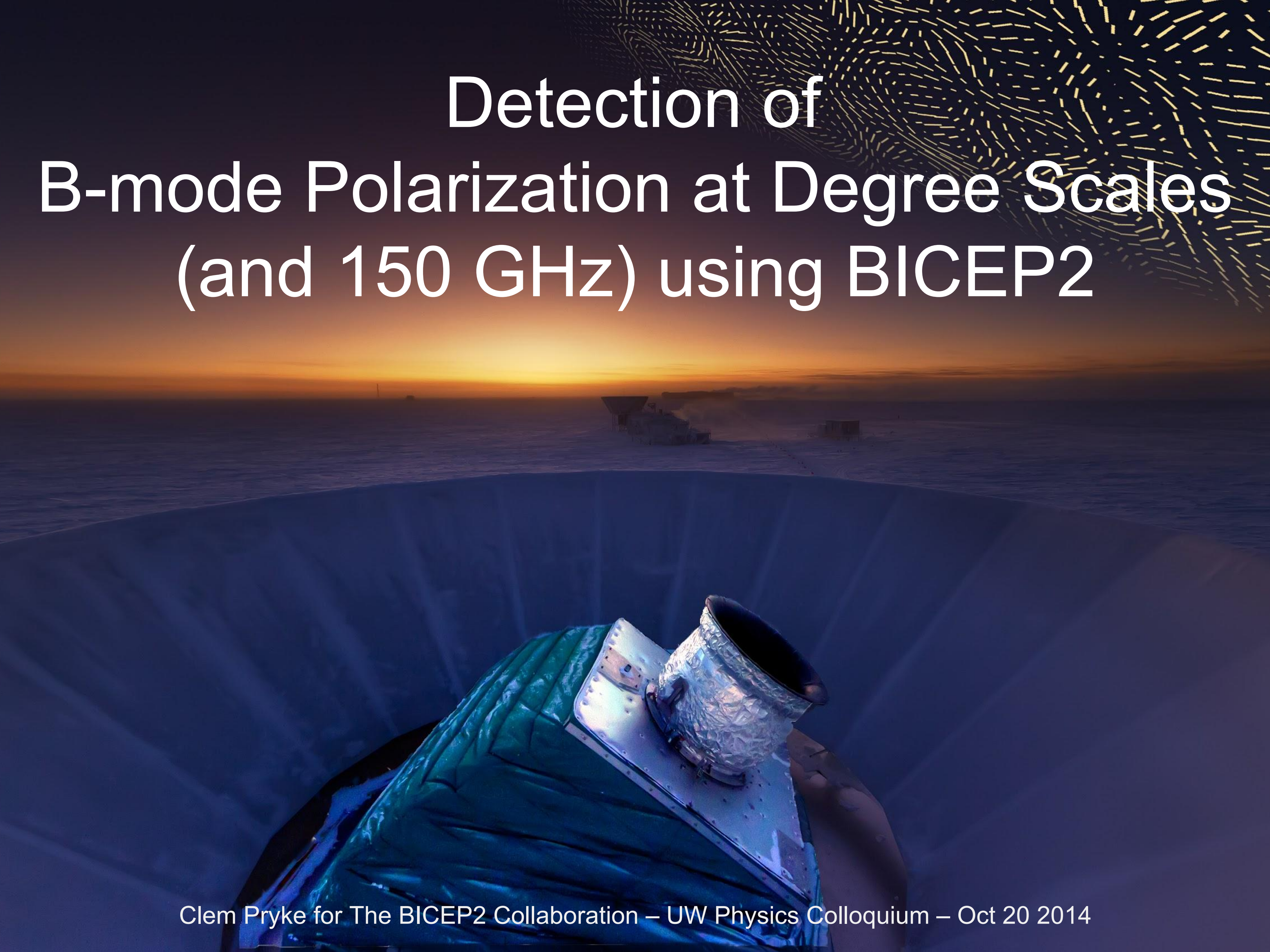
Detection of B-mode Polarization at Degree Scales (and 150 GHz) using BICEP2



Clem Pryke for The BICEP2 Collaboration – UW Physics Colloquium – Oct 20 2014


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

The BICEP2 Postdocs

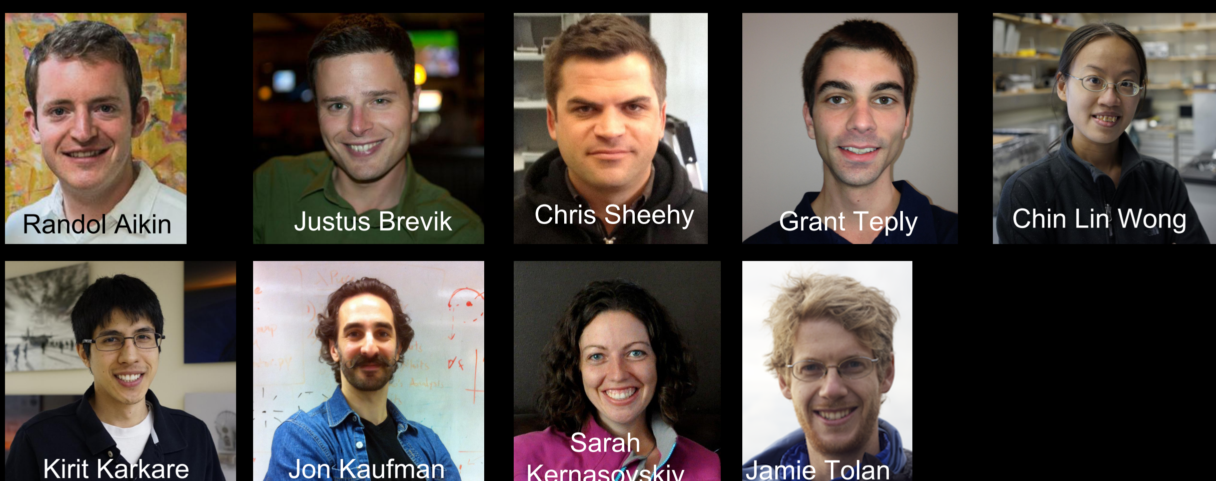
BICEP2 Winterovers

2010

2011

2012

The BICEP2 Graduate Students



Modern cosmology in a nutshell:

Edwin Hubble

1) The universe is expanding.

(Hubble, 1920s)

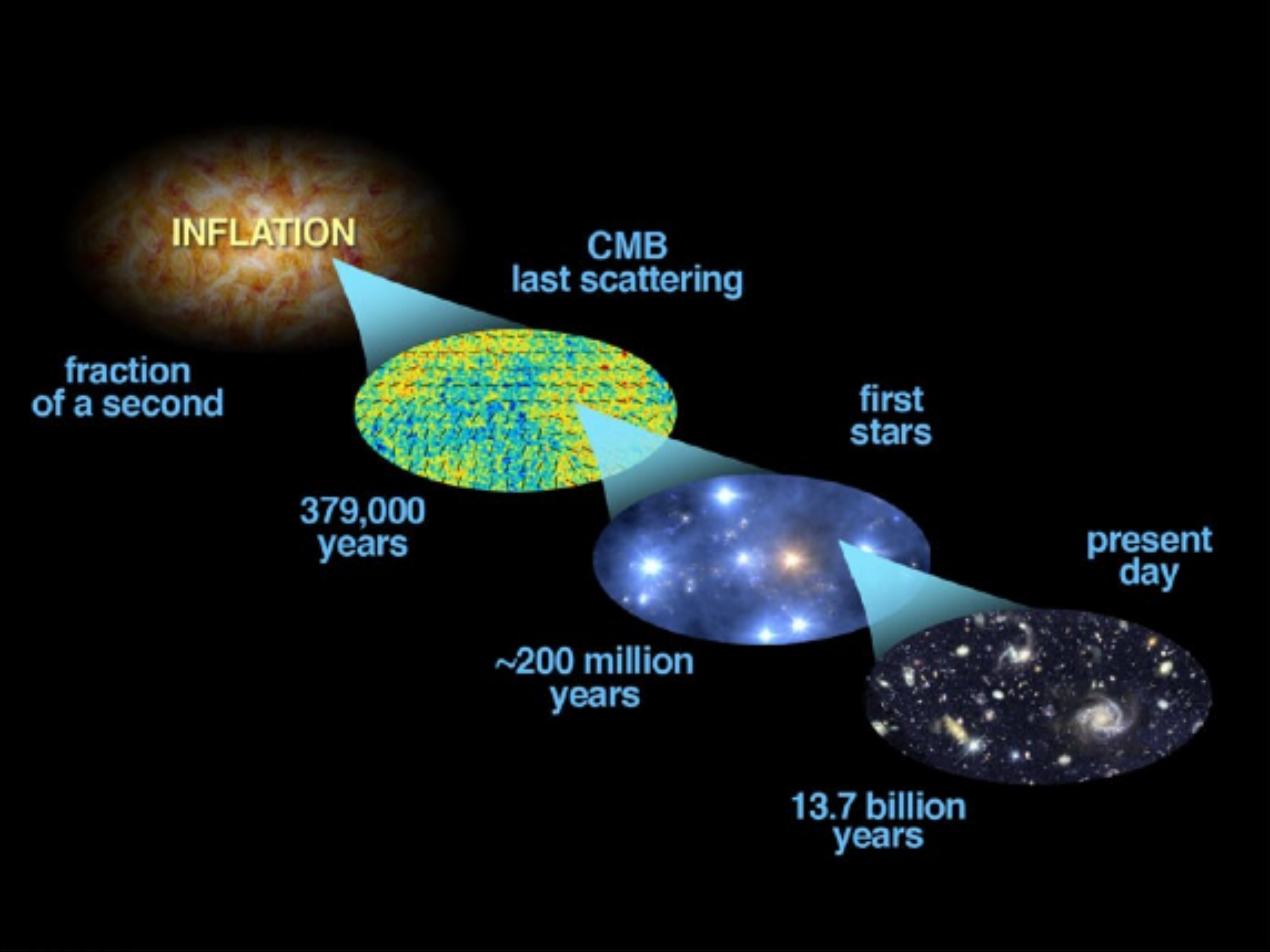
2) It was once hot and dense, like the inside of the Sun.

(Alpher, Gamow, Herman, 1940s)

3) You can still see the glow!
The *Cosmic Microwave Background*
(Penzias & Wilson, 1964)

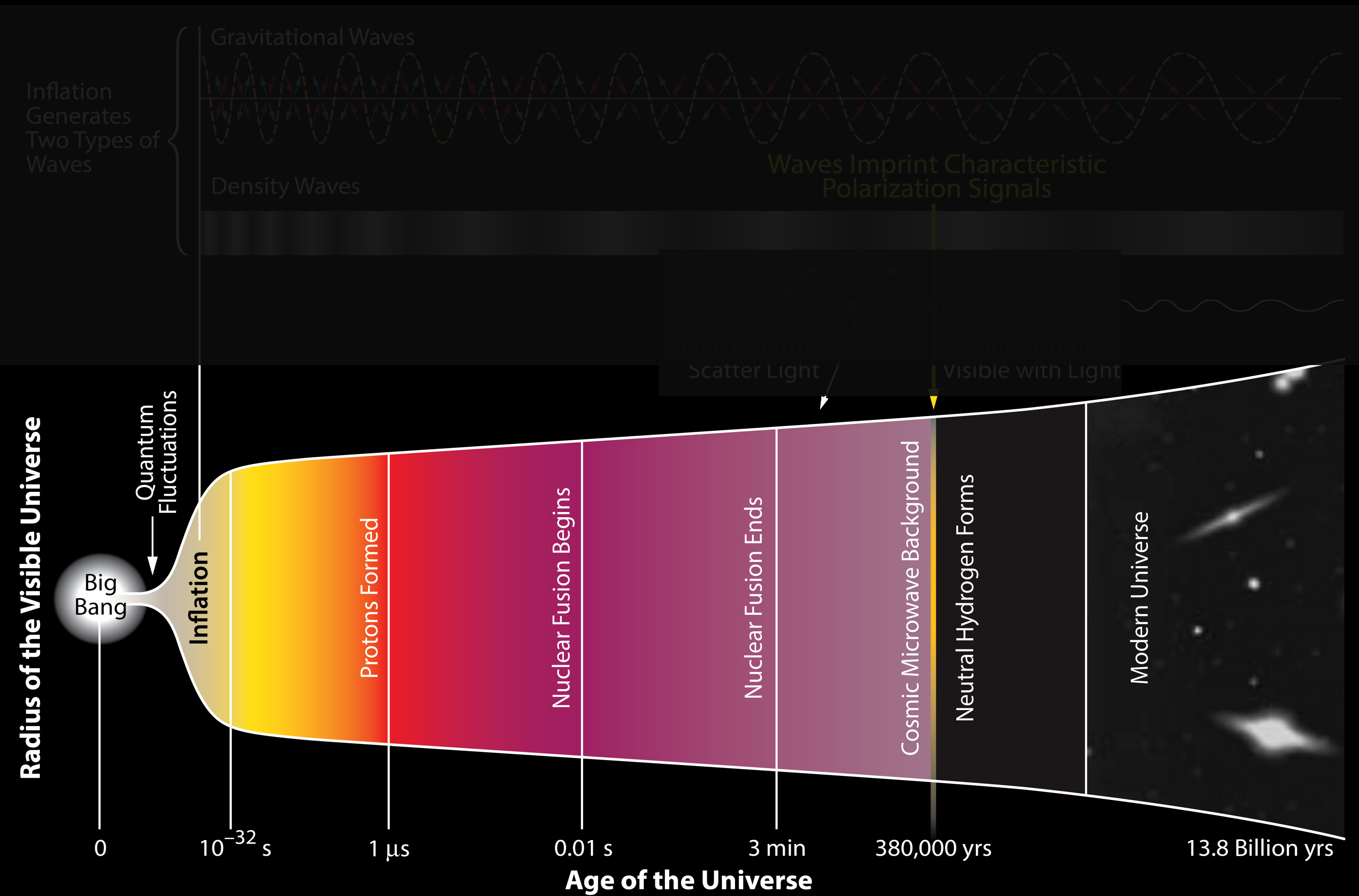
Bob Wilson & Arno Penzias
1978 Nobel Prize

⇒ acceptance of the "HOT BIG BANG"

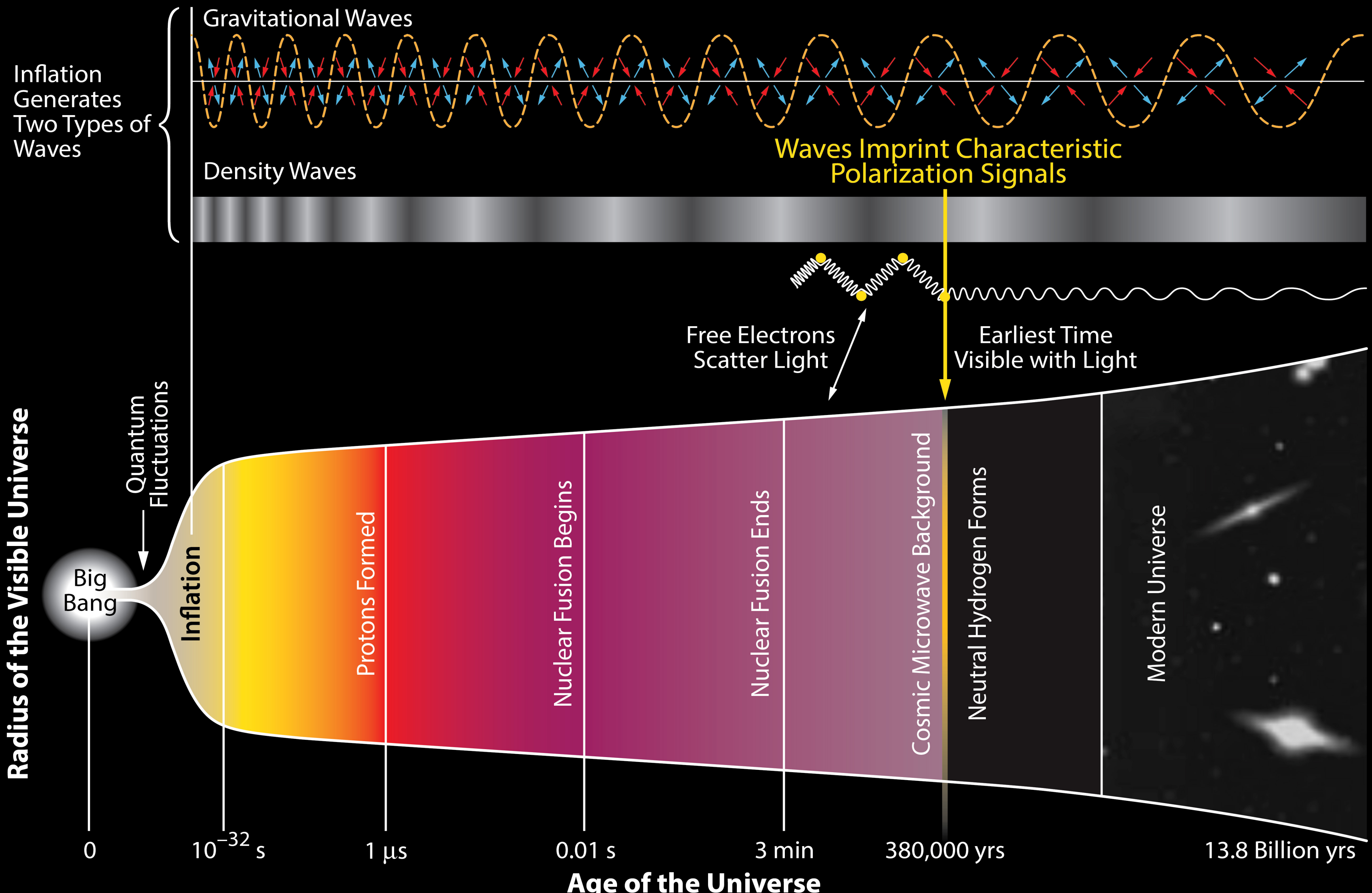


INFLATION
CMB
last scattering
fraction
of a second
first
stars
379,000
years
present
day
~200 million
years
13.7 billion
years

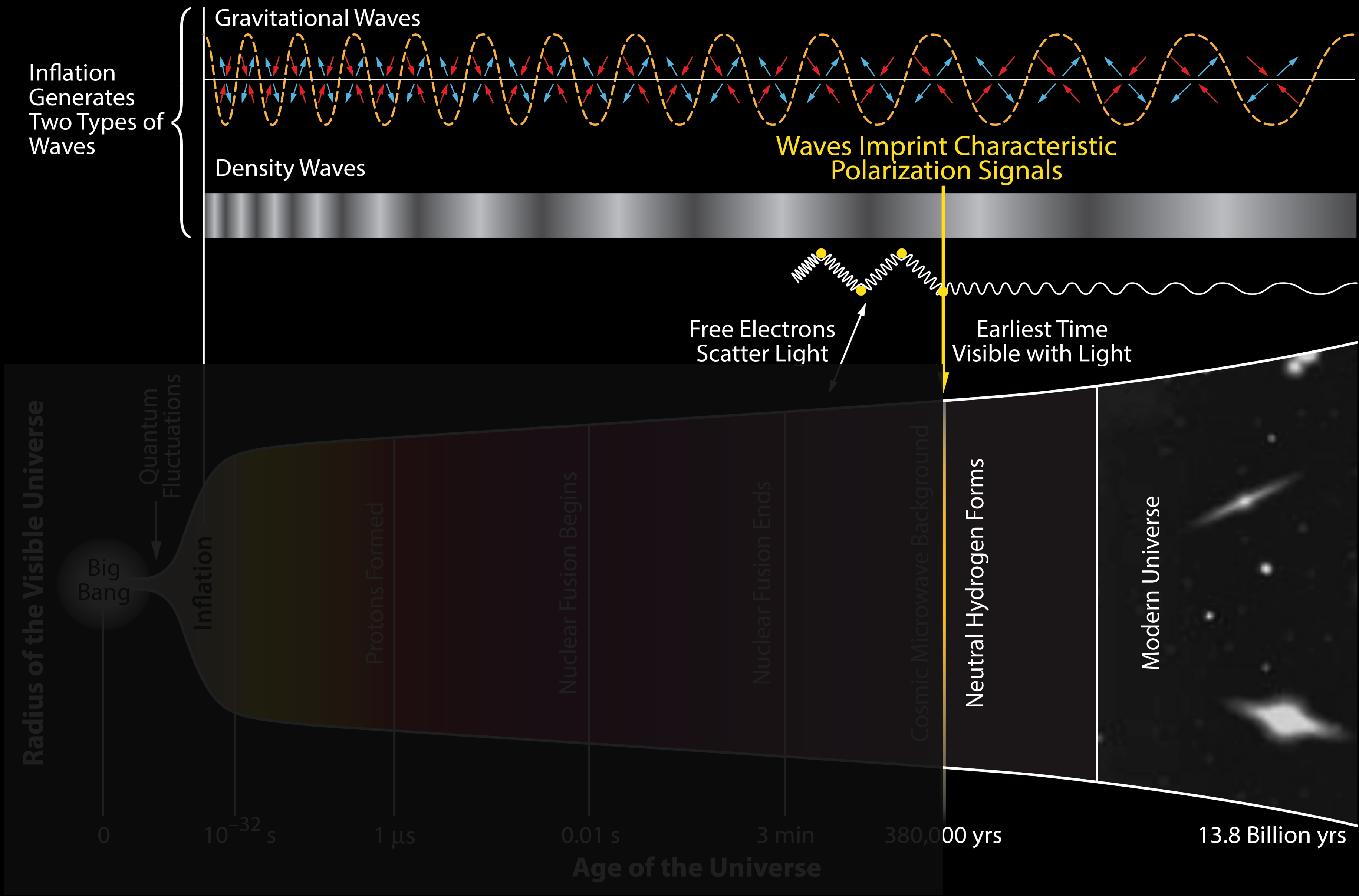
History of the Universe



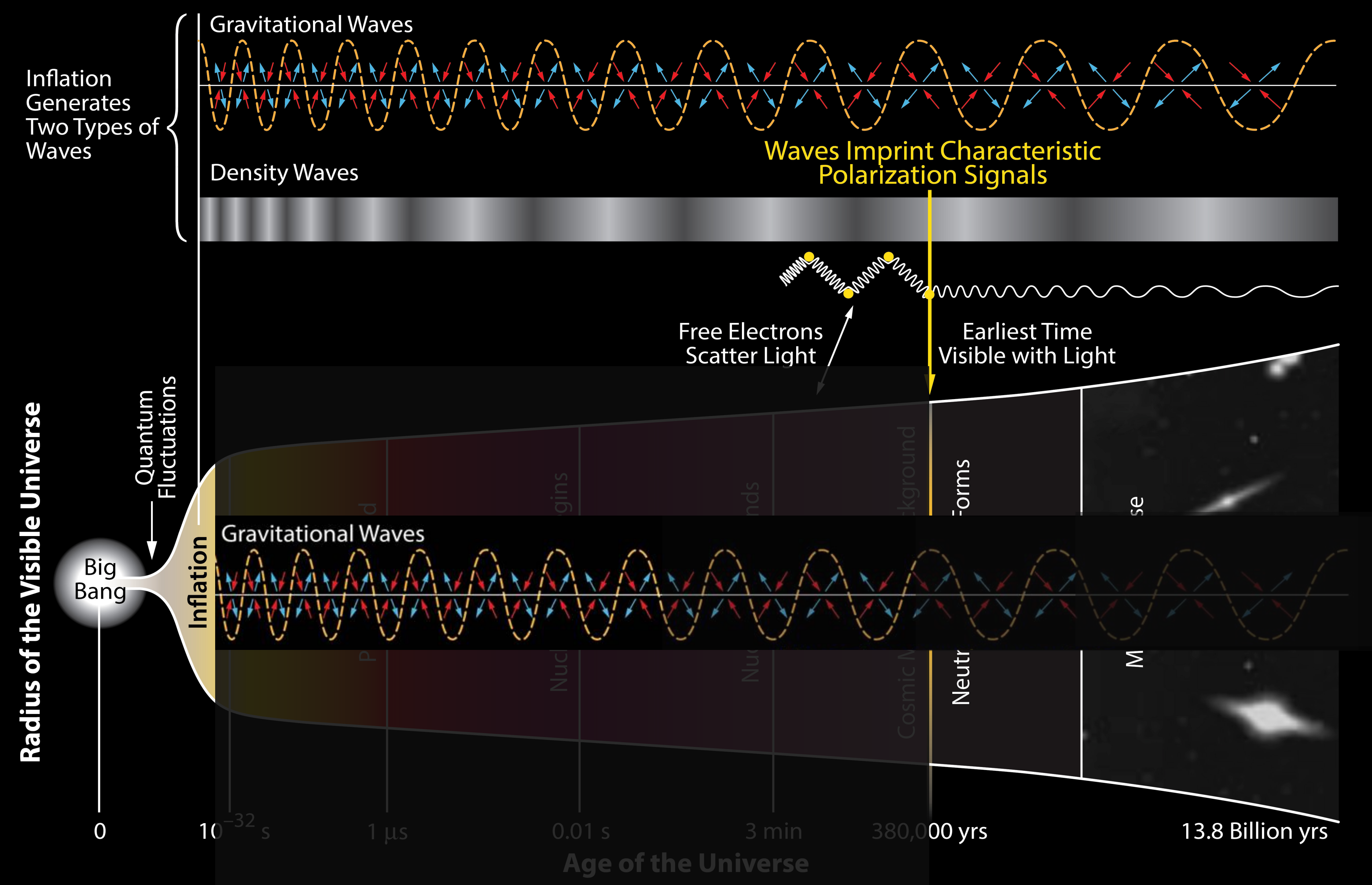
History of the Universe

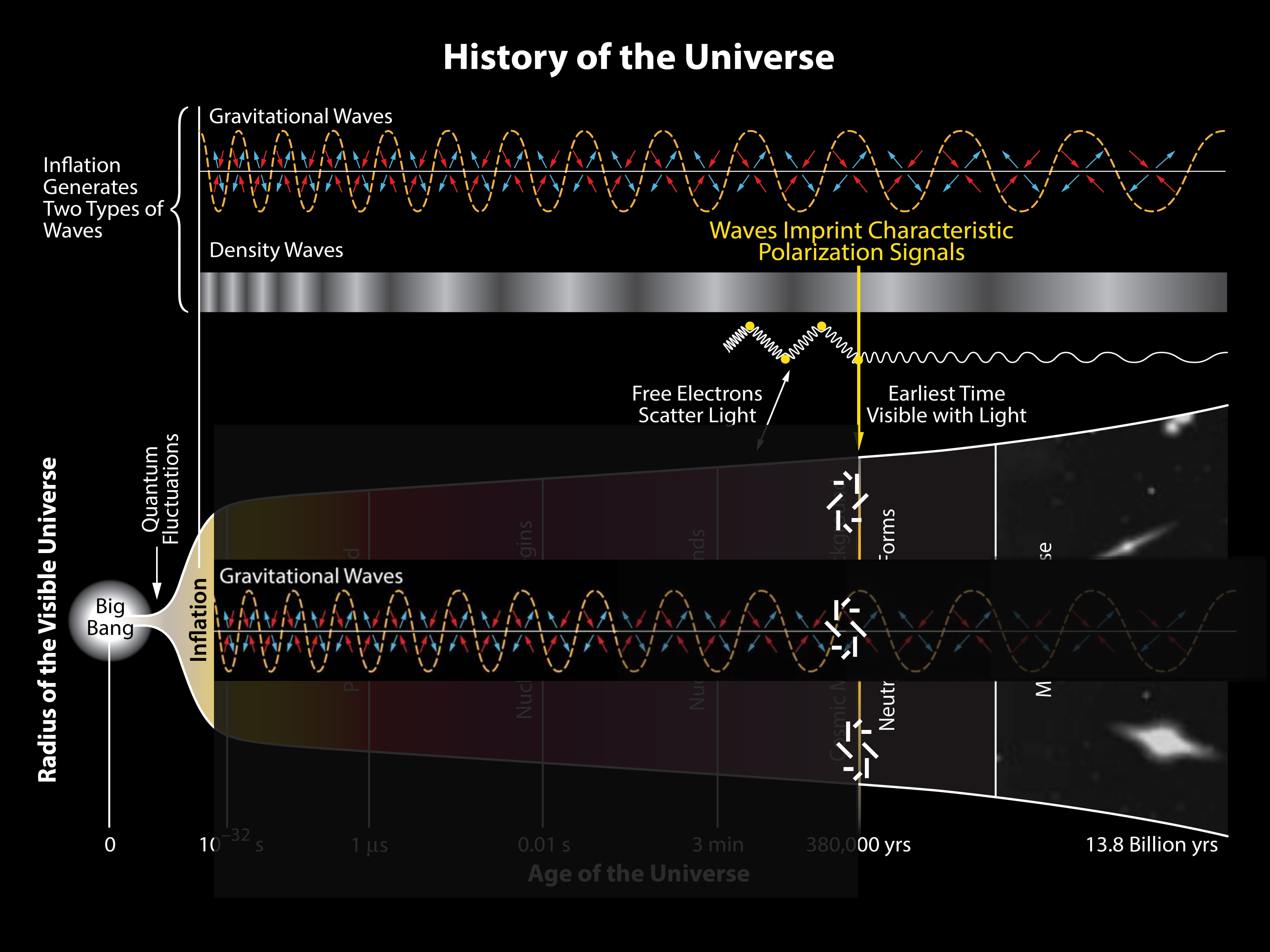


History of the Universe



History of the Universe




History of the Universe
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Quantum Fluctuations
Big Bang
Inflation
Radius of the Visible Universe
Gravitational Waves
0
10^-32 s
1 µs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

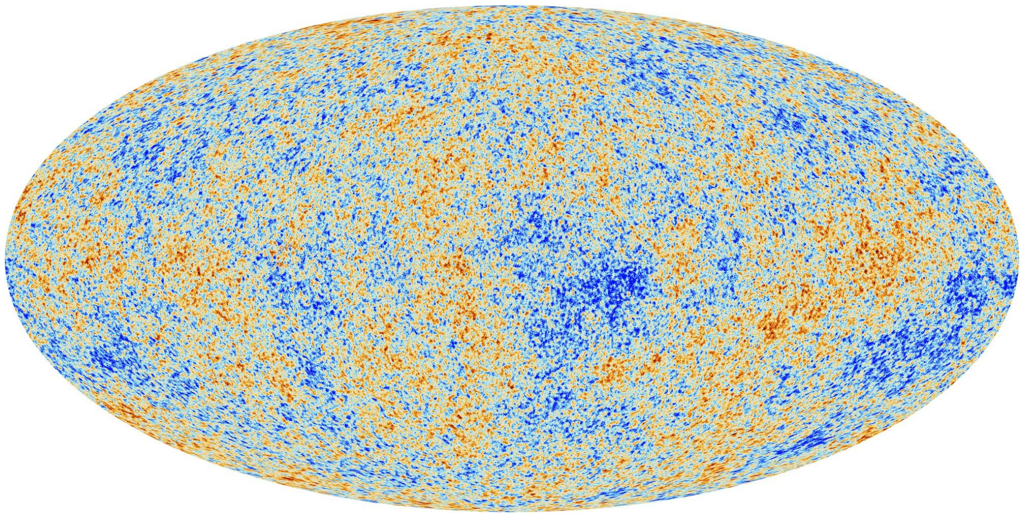
CMB Temperature Measurements / Inflation

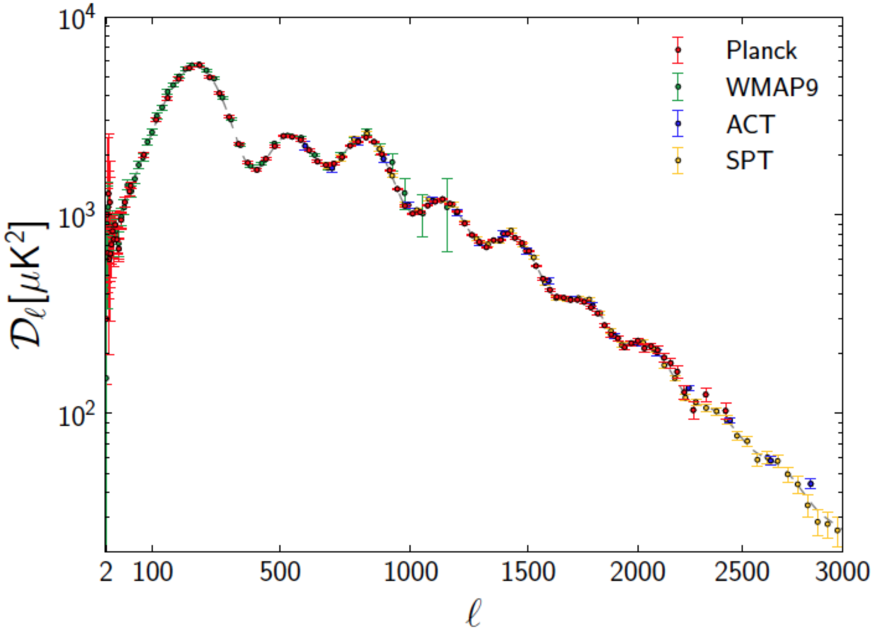
CMB temperature anisotropy now measured over full range of angular scales.

Consistent with ΛCDM paradigm(?) and constrains its parameters to sub percent accuracy.

Inflation "invented" in 1980s to explain facts about the Universe which were known or suspected.

Makes additional prediction of a background of gravitational waves (aka tensor modes) – which will imprint a specific CMB polarization pattern…
→ so-called "smoking gun"
→ amplitude tells us the energy scale at which inflation ocurred





Planck Collaboration & ESA

Why Inflation?

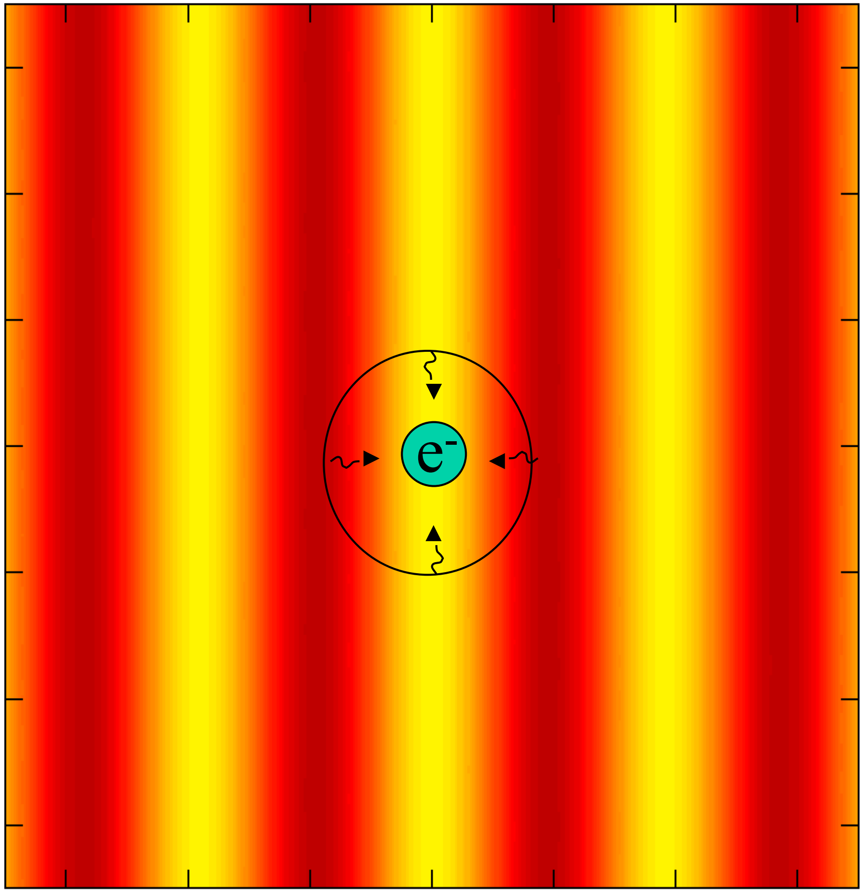
Solves the horizon problem: Why is the CMB nearly uniform? How do apparently causally disconnected regions of space get set to the same temperature? → A volume much larger than our entire observable universe today was once a caussally connected sub atomic spec.

Solves the flatness problem: Why is the net spatial curvature close to zero? → Any initial spatial curvature is diluted away to undetectabilty by the hyper expansion.

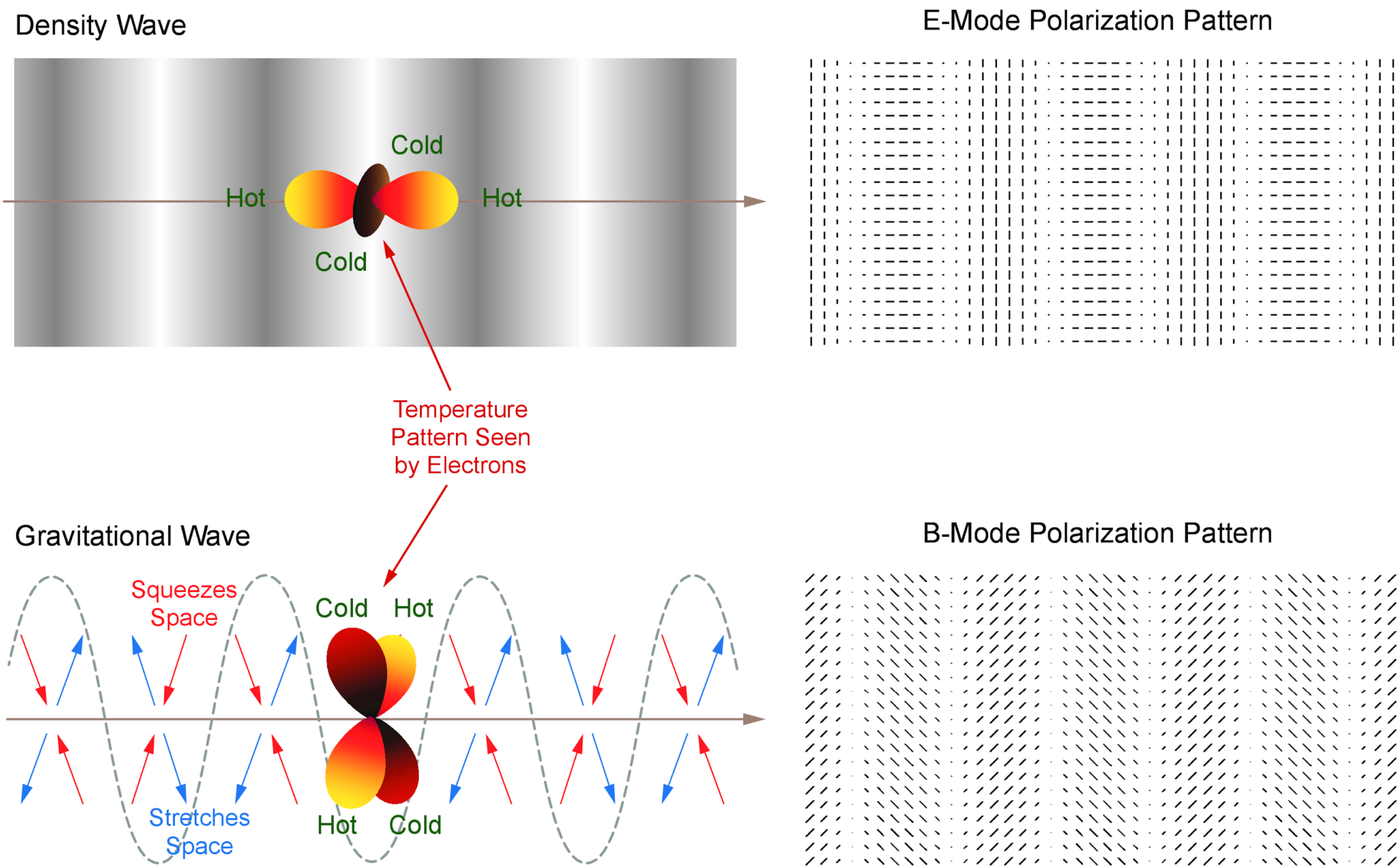
Explains the initial perturbation spectrum: Why was it close to flat power law? → Equal amount of perturbations are injected at each step in the exponential expansion.

Solves the monopole problem: Why do we not observe magnetic monopoles in the Universe today? → Monopoles are diluted away to undetectability.

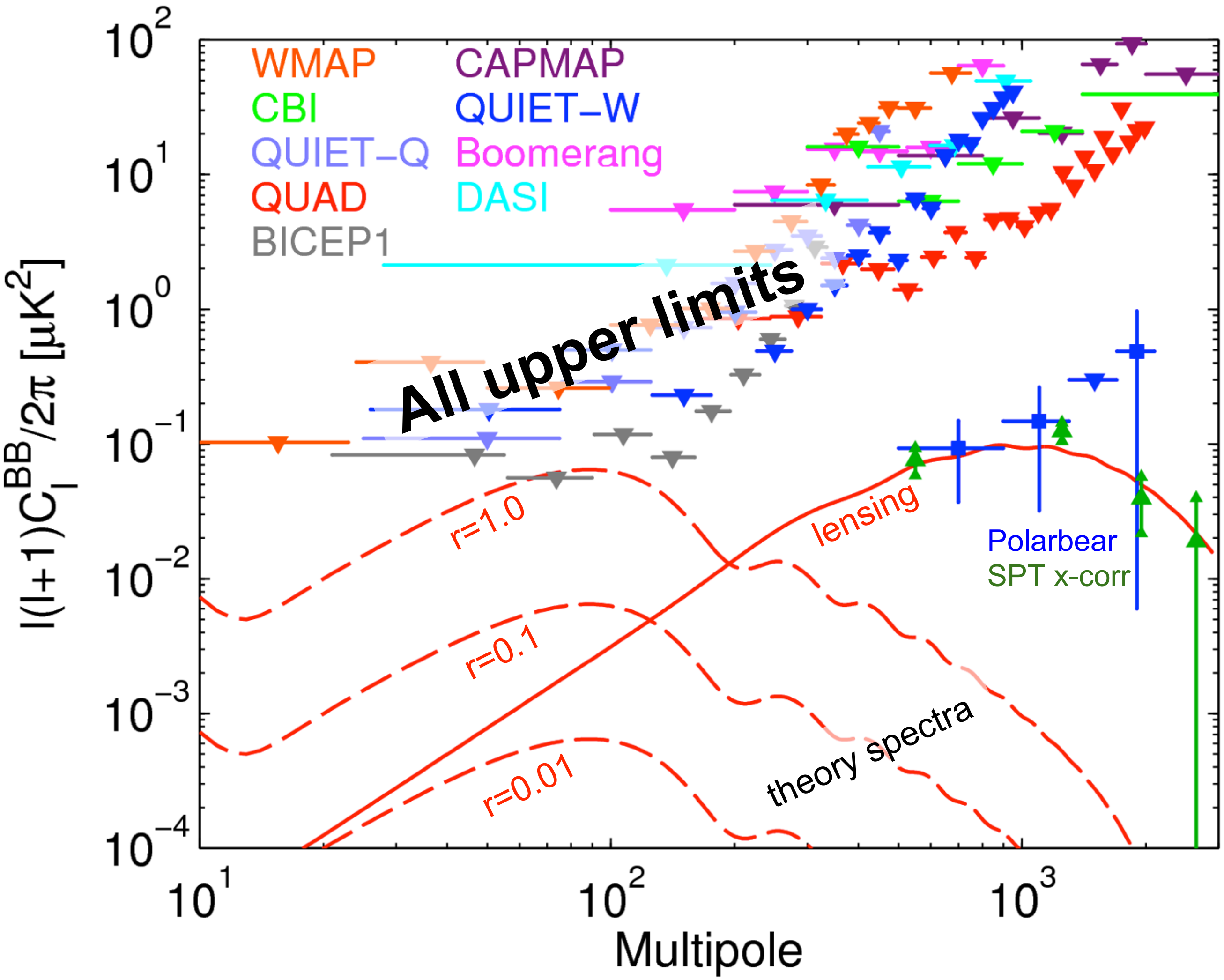
CMB polarization:
arises at last scattering
from local radiation quadrupole



CMB polarization



The Long 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.

Before BICEP2: only 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

Clem Pryke for The Bicep2 Collaboration

BICEP2 Experimental Strategy

- Deep, concentrated coverage
- Foreground avoidance (limited frequency)
- Systematic control with in-situ calibration
- Large detector count, rapid technology cycle
- Relentless observing

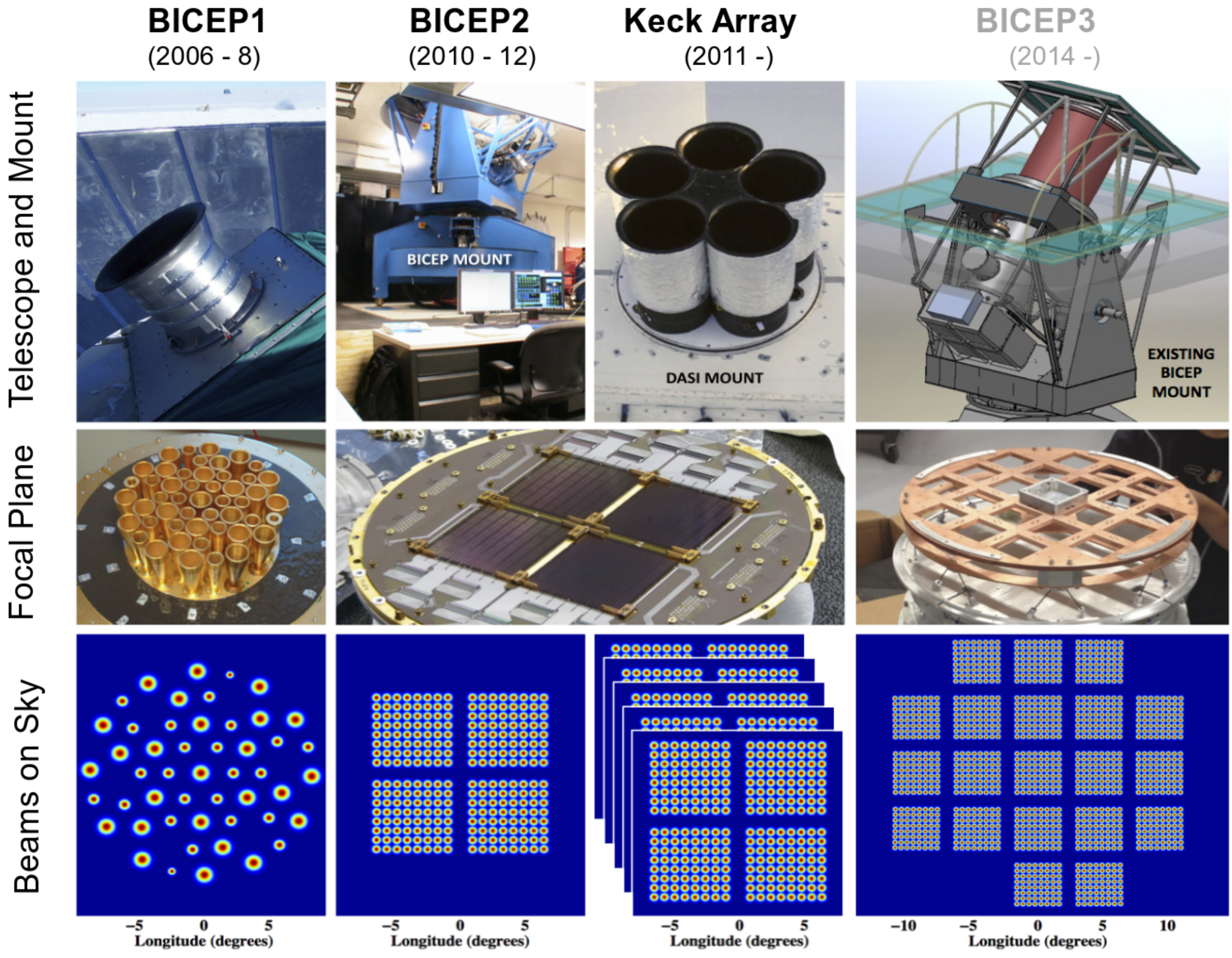
→ powerful recipe for initial detection

South Pole CMB telescopes

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

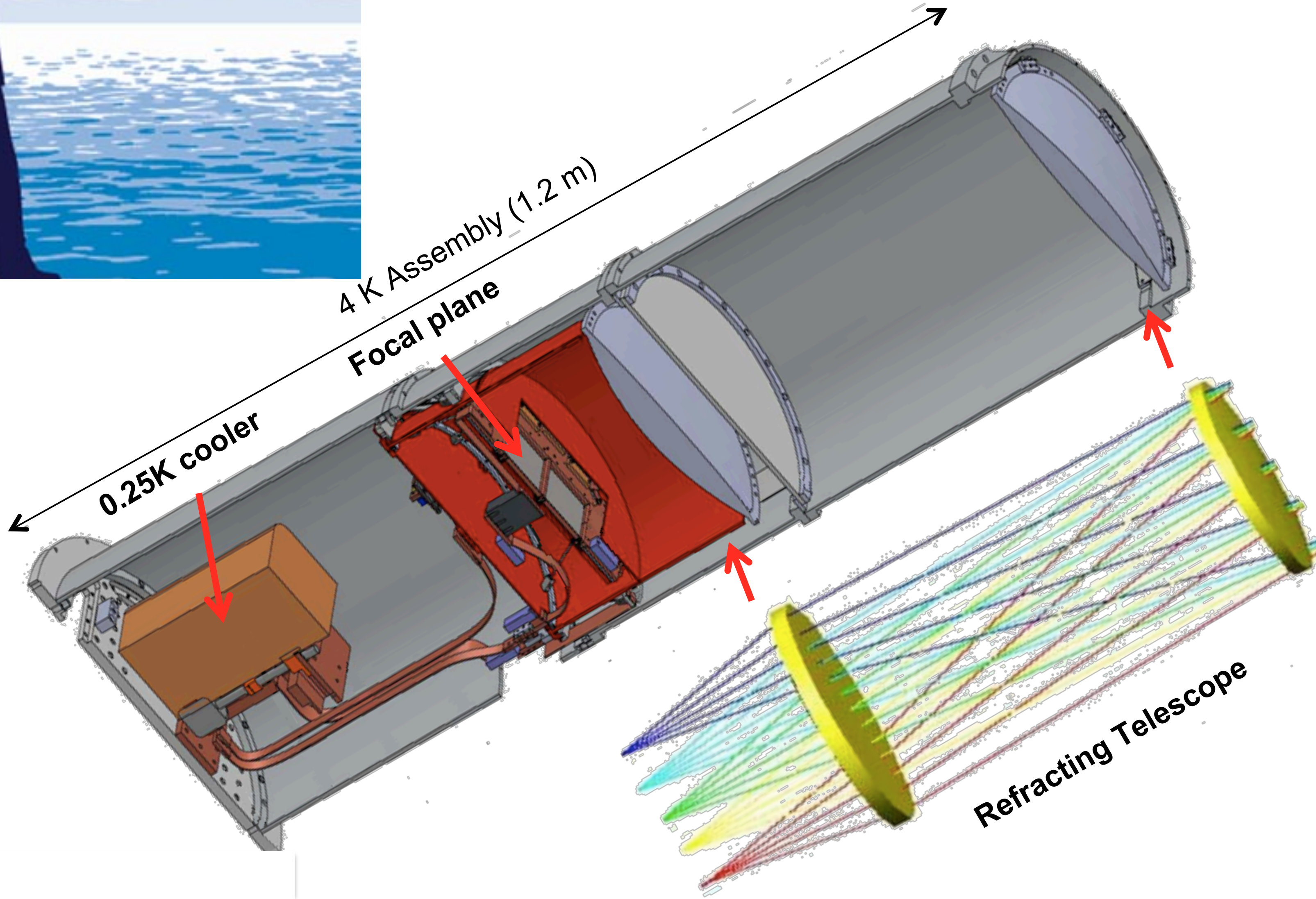
Super dry atmosphere and 24h coverage of low foreground sky.

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

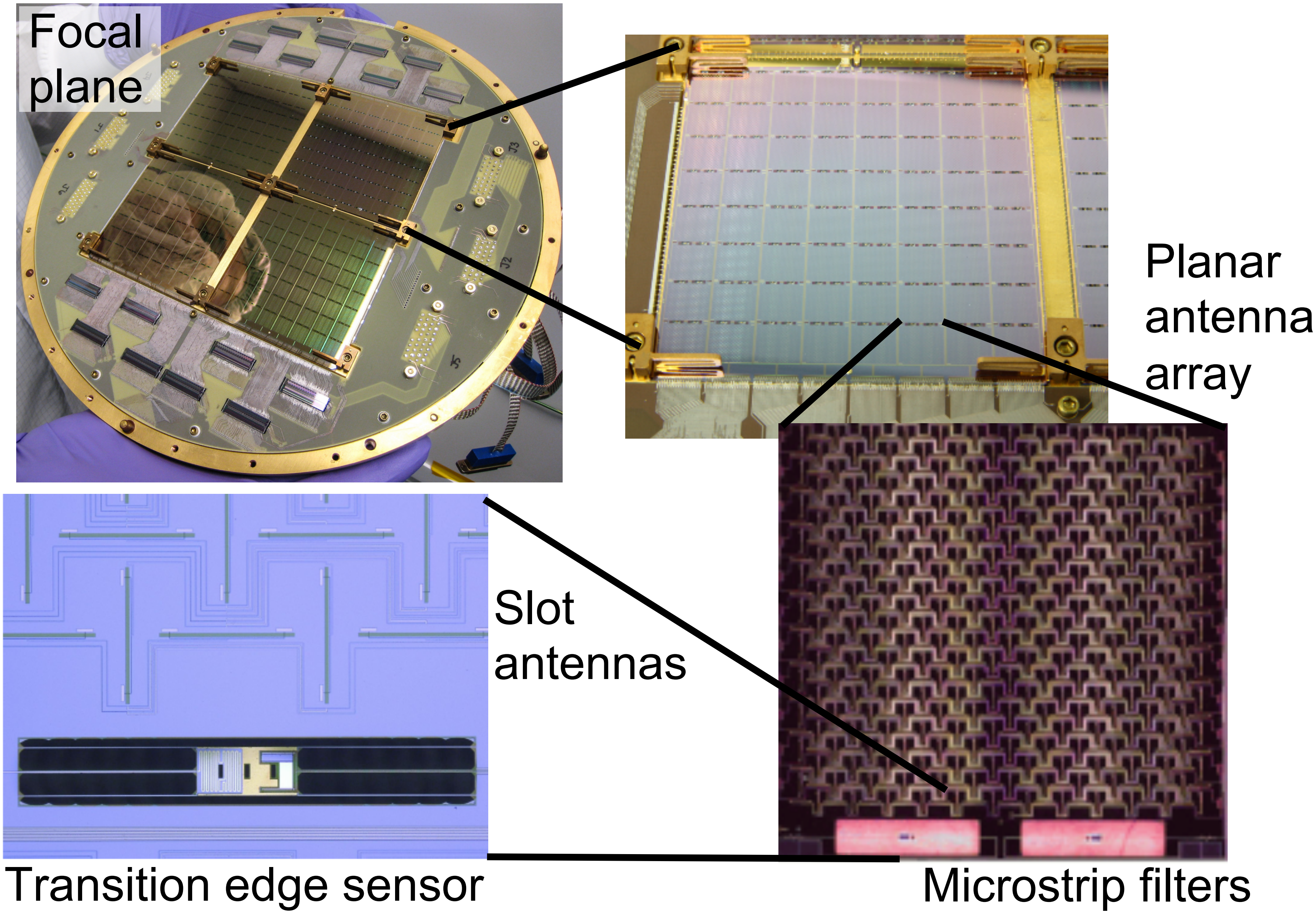

BICEP1
(2006 - 8)
BICEP2
(2010 - 12)
Keck Array
(2011 -)
BICEP3
(2014 -)
Telescope and Mount
BICEP MOUNT
DASI MOUNT
EXISTING
BICEP
MOUNT
Focal Plane
Beams on Sky
−5
0
5
Longitude (degrees)
−5
0
5
Longitude (degrees)
−5
0
5
Longitude (degrees)
−10
−5
0
5
10
Longitude (degrees)

BICEP2 Experimental Concept

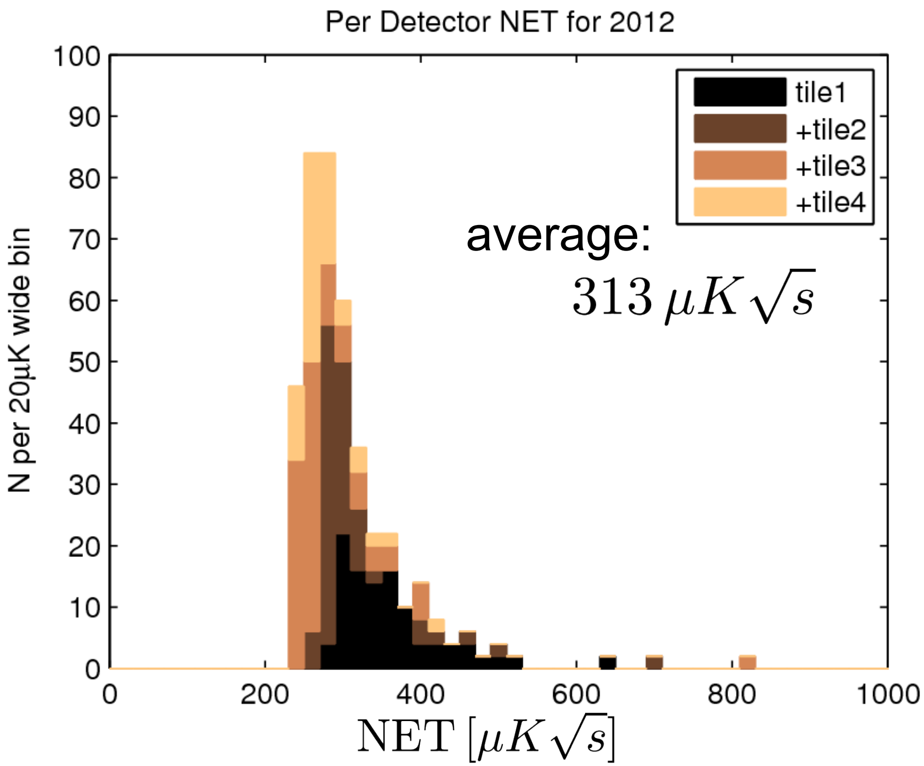
- Small aperture
- Wide field of view
- Cold refractor



Mass-produced superconducting detectors



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

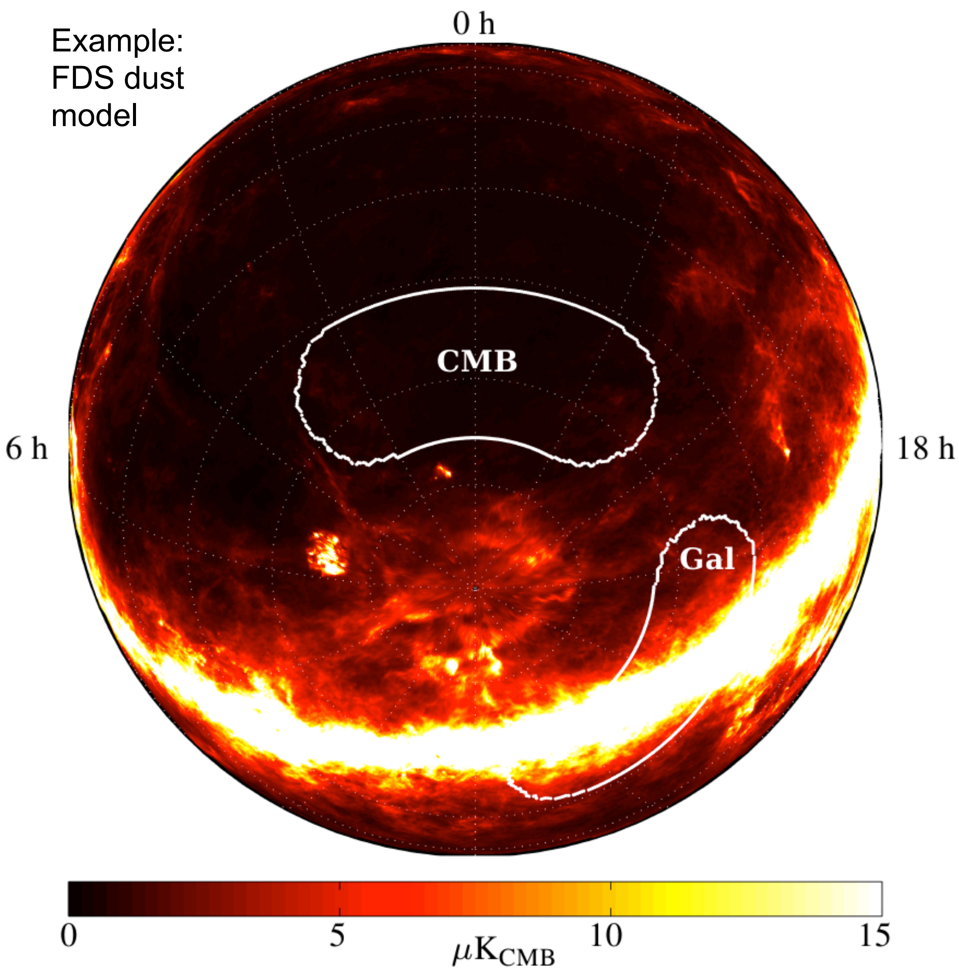
→ Cold optics
Low loading/photon noise
Low thermal conductance, and thus low phonon noise

→ High detector count

Total Sensitivity for full BICEP2 instrument: $15.8\,\mu K\sqrt{s}$

Observational Strategy

Example:
FDS dust model

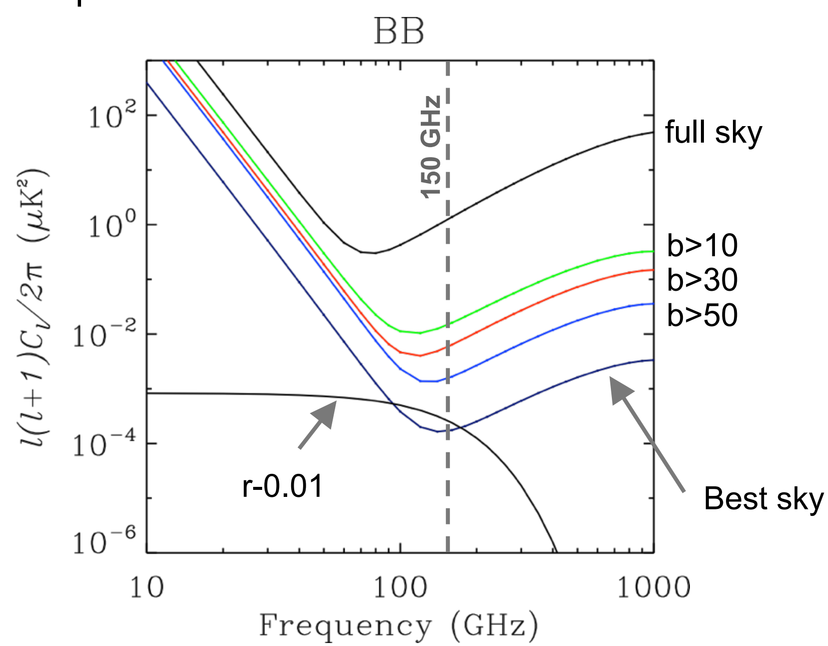


Target the "Southern Hole" - a region of the sky exceptionally free of dust and synchrotron foregrounds in total intensity.

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

Sync falls with increasing frequency while dust rises - cross over below 150 GHz

Foreground contamination of the B-mode power in clean regions previously projected to be equivalent to r ≤ ~0.01.



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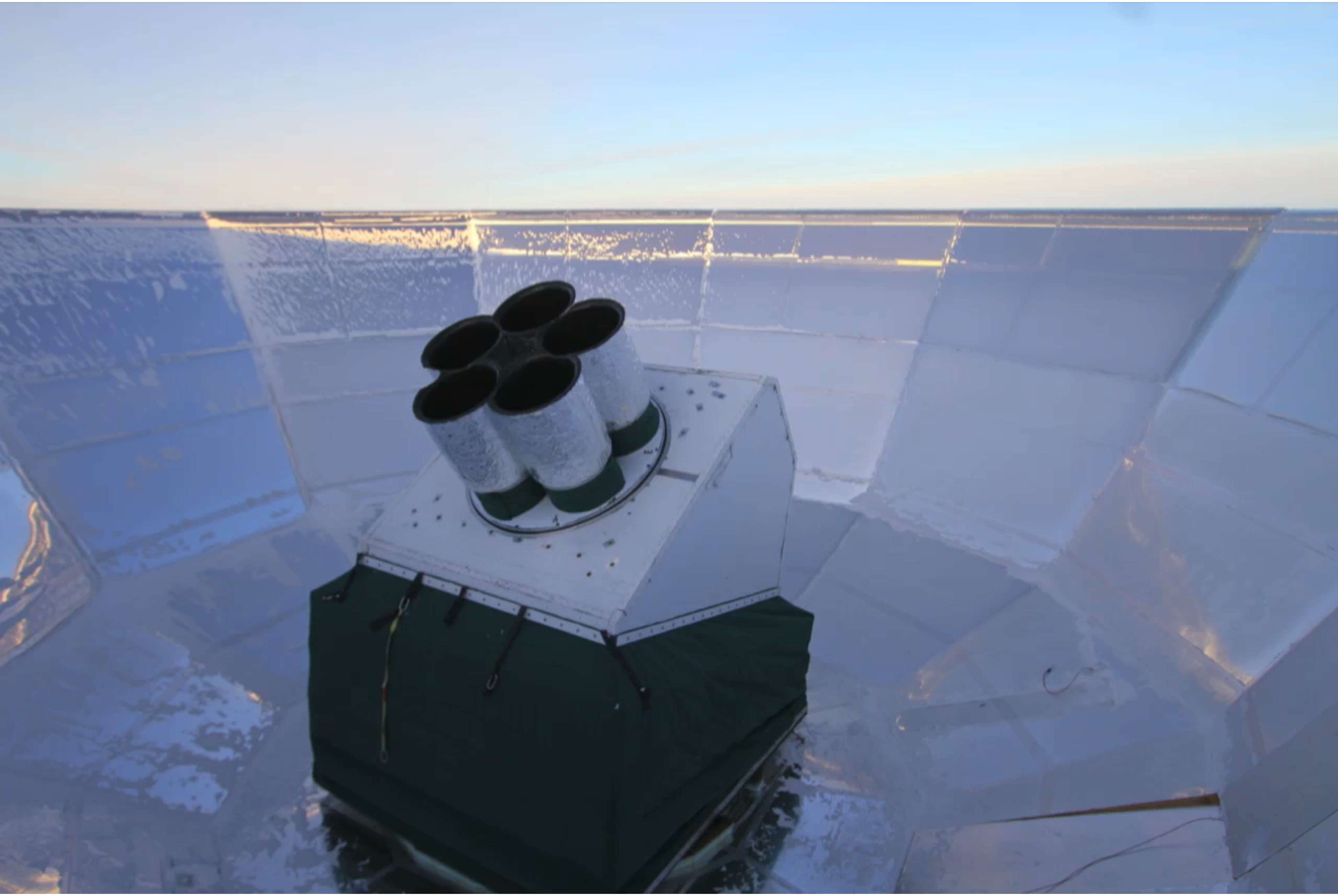
From Dunkley et al arxiv/0811.3915



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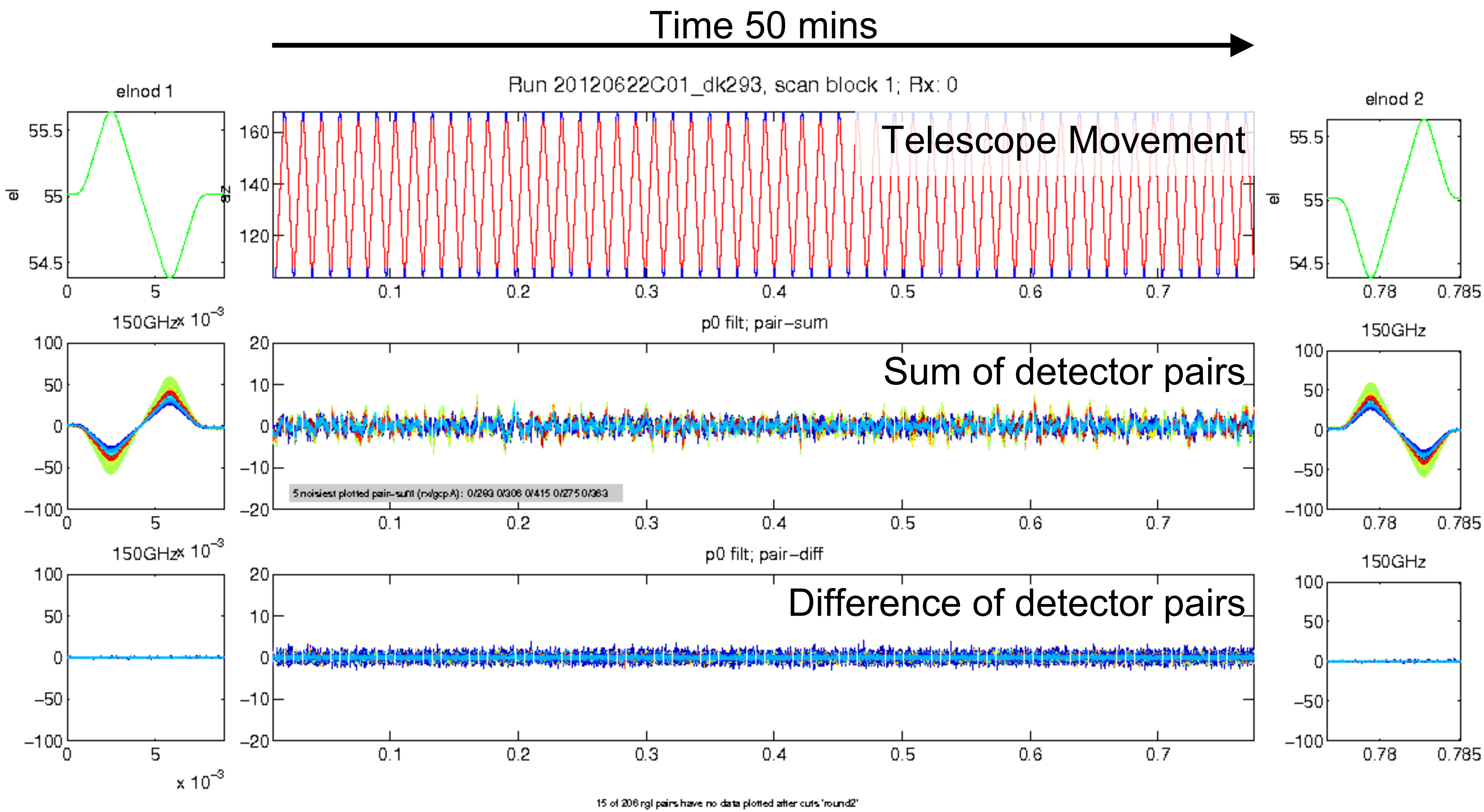
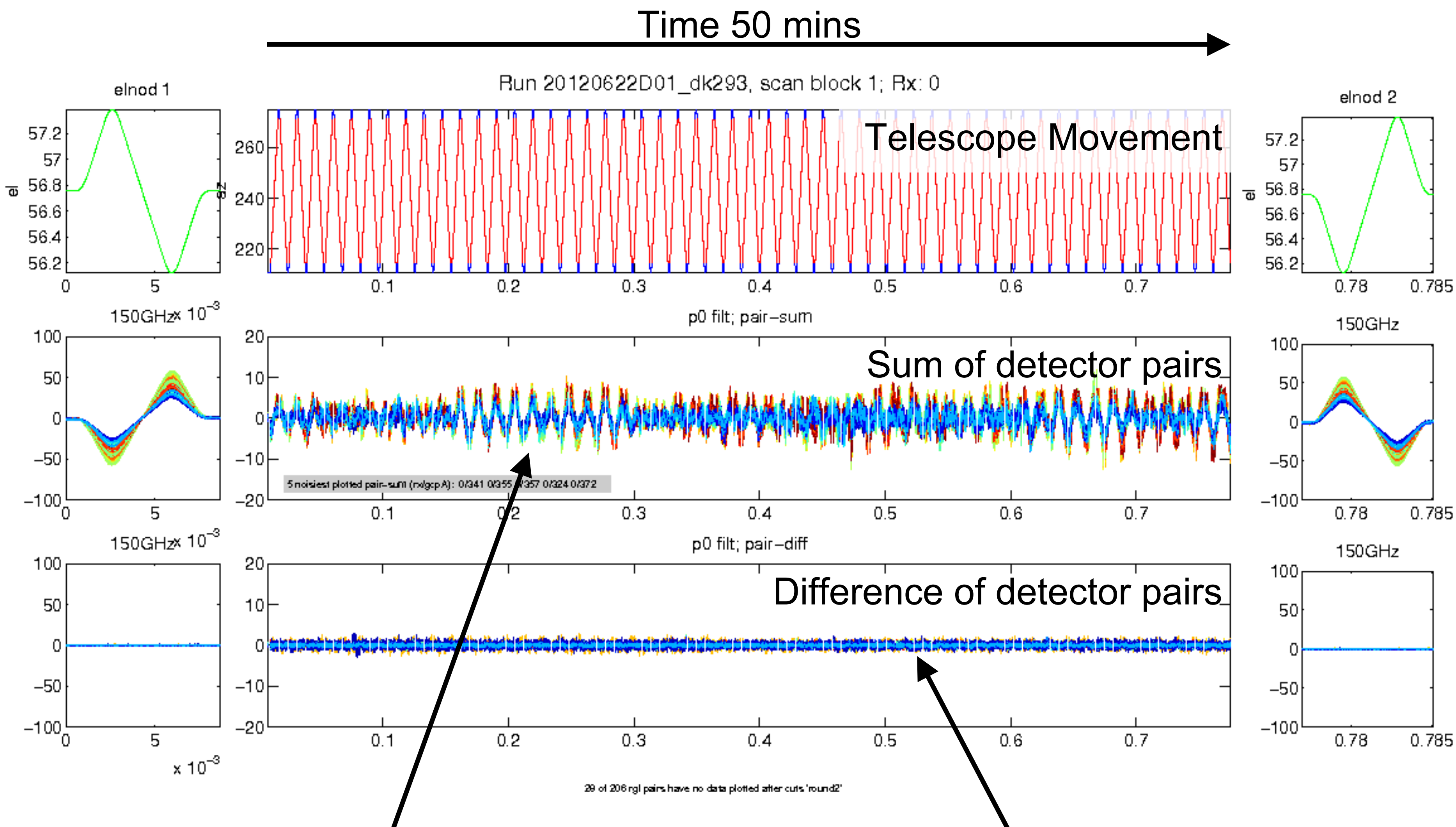
Raw Data - Perfect Weather



- ➢ Cover the whole field in 60 such scansets then start over at new boresight rotation
- ➢ Scanning modulates the CMB signal to freqs < 4 Hz

Raw Data - Worse Weather



- ➢ Scanning over lumpy atmosphere → “clouds”
- ➢ Pair difference still clean → atmosphere is unpolarized

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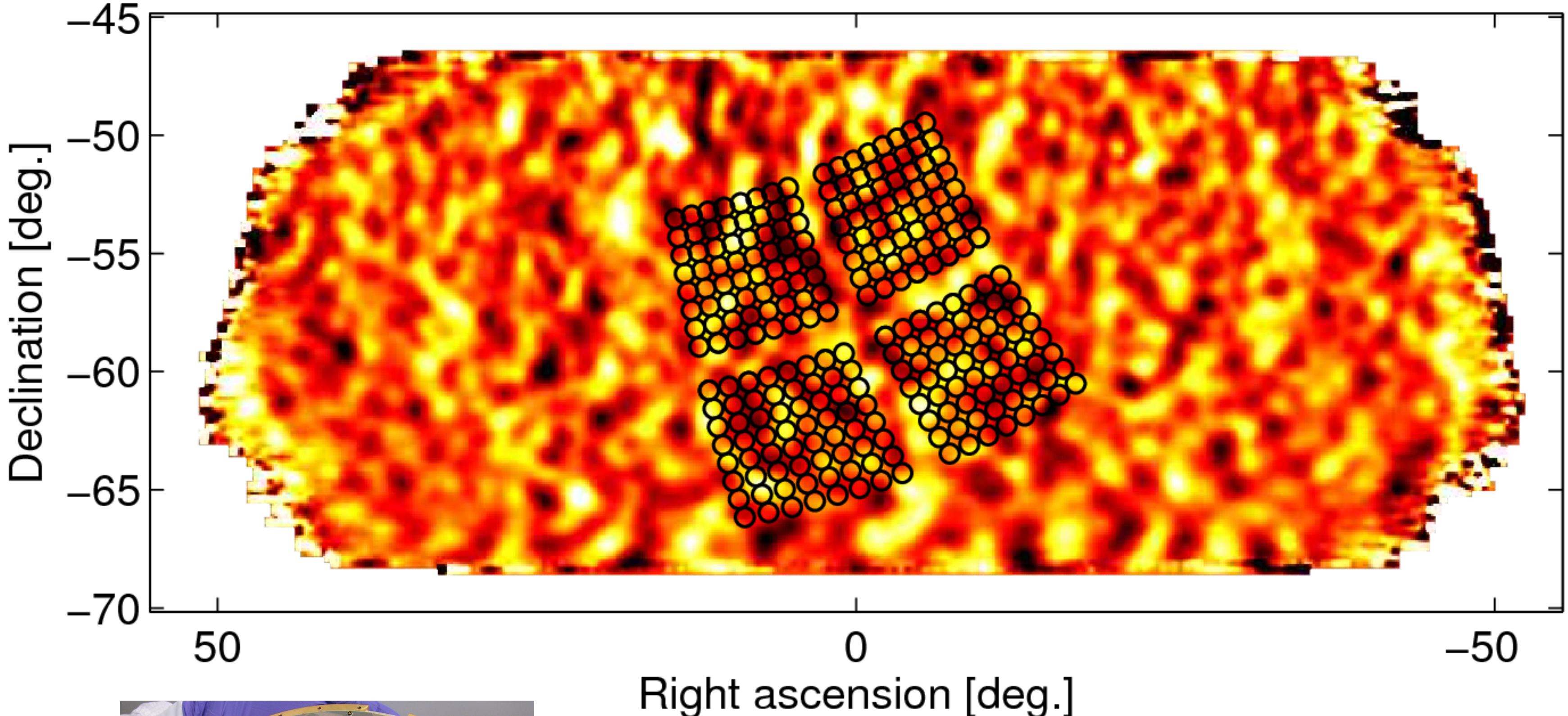
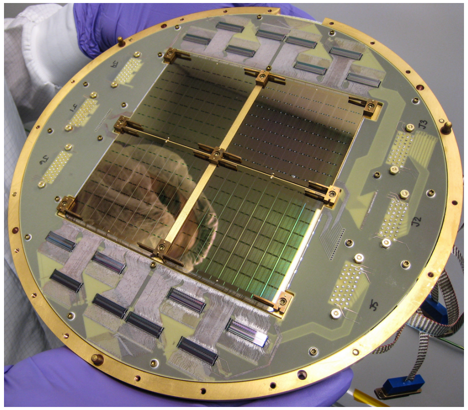
BICEP2 on the Sky



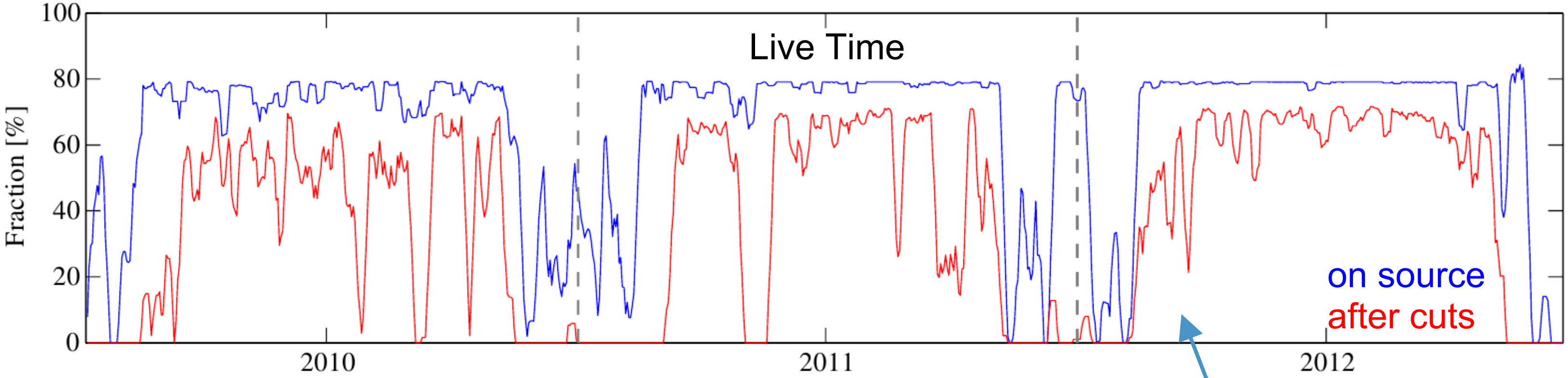


Projection of the BICEP2 focal plane on the sky

The focal plane is 20 degrees across

Background is the CMB temperature map as measured with BICEP2

Data Quality Cuts



Cut parameter	Total time [10^6 s]	Integration [10^9 det · s]	Fraction cut [%]
Before cuts	36.5	14.8	–
Channel cuts	36.5	13.2	10.9
Synchronization	35.3	12.7	3.1
Deglitching	33.6	10.7	13.8
Per-scan noise	33.6	10.7	$< 0.01\%$
Passing channels	33.3	10.7	0.22
Manual cut	33.0	10.6	0.43
Elevation nod	31.0	9.2	9.5
Fractional resistance	31.0	9.2	0.16
Skewness	31.0	9.1	0.41
Time stream variance	30.9	9.0	0.52
Correlated noise	30.9	9.0	$< 0.01\%$
Noise stationarity	30.7	8.9	0.64
FPU temperature	30.6	8.9	0.20
Passing data	27.6	8.6	1.7

Table from Instrument Paper

3 years of data!

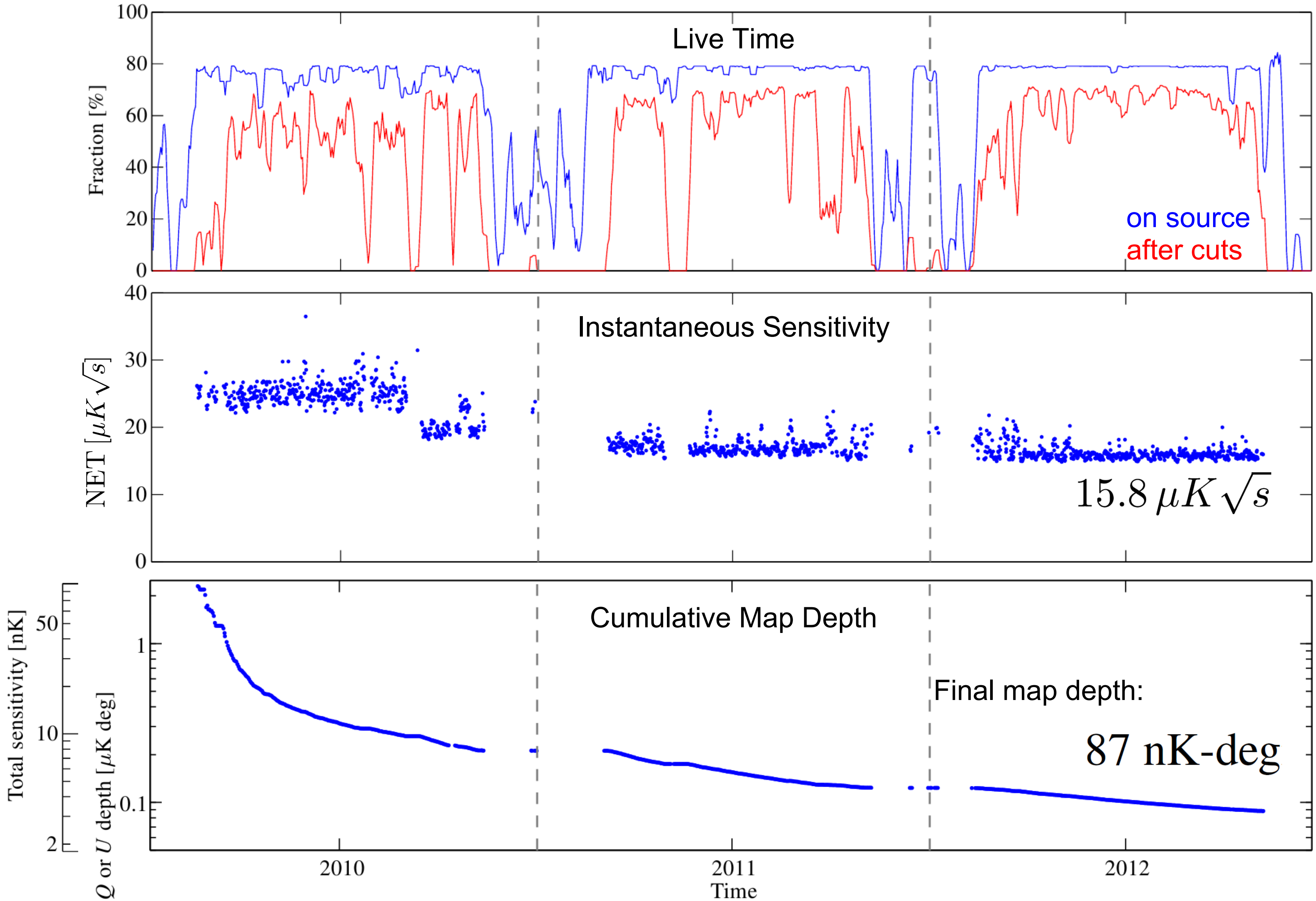
Multistage cut procedure:

Ensures all data used in map making is taken when the experiment is operating properly and has stationary, well-behaved noise

Many cuts identify periods of exceptionally bad weather and are redundant.

BICEP2 data very well-behaved:
pass fraction = 63%

BICEP2 3-year Data Set



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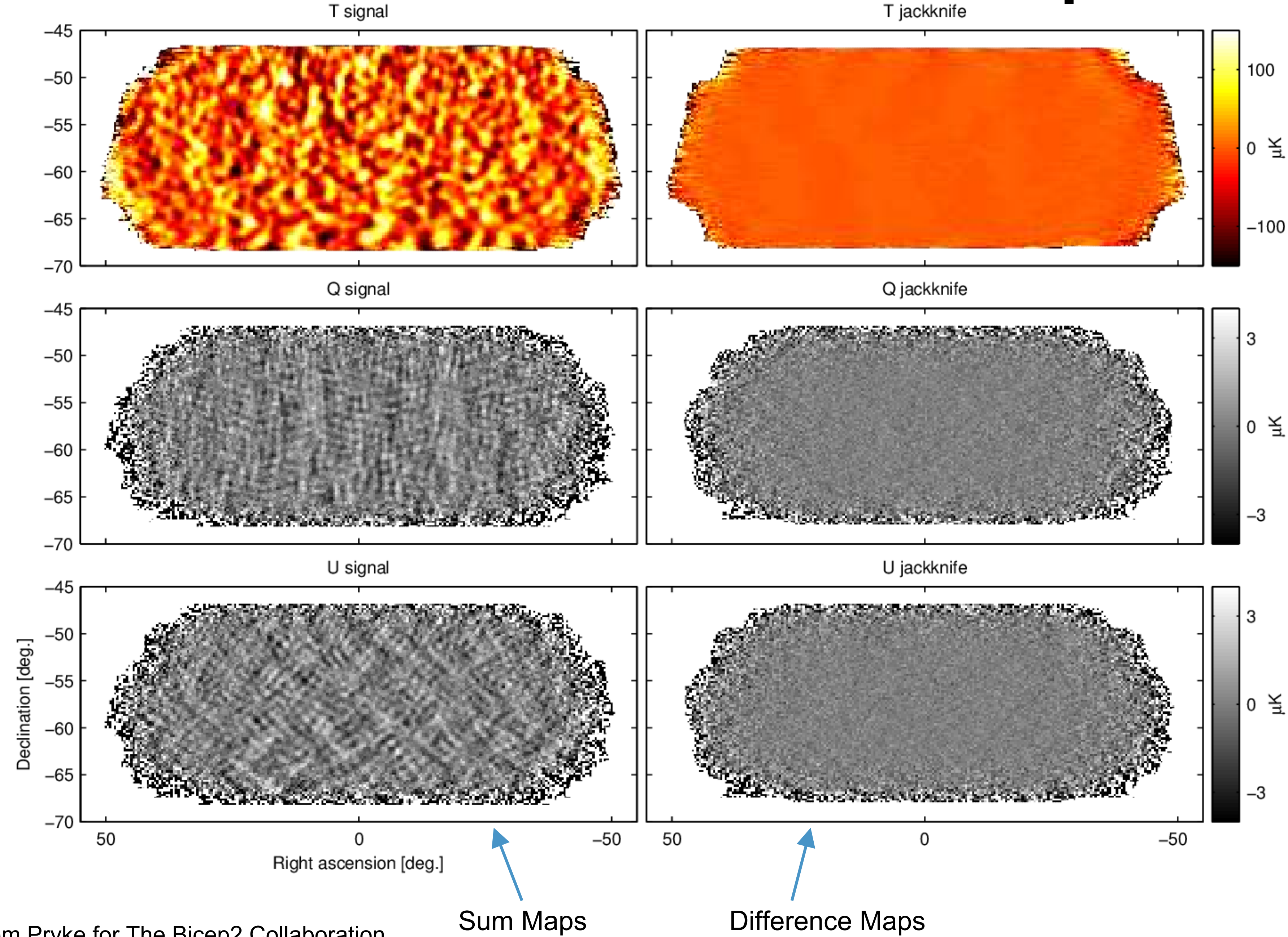
BICEP2 T and Stokes Q/U Maps



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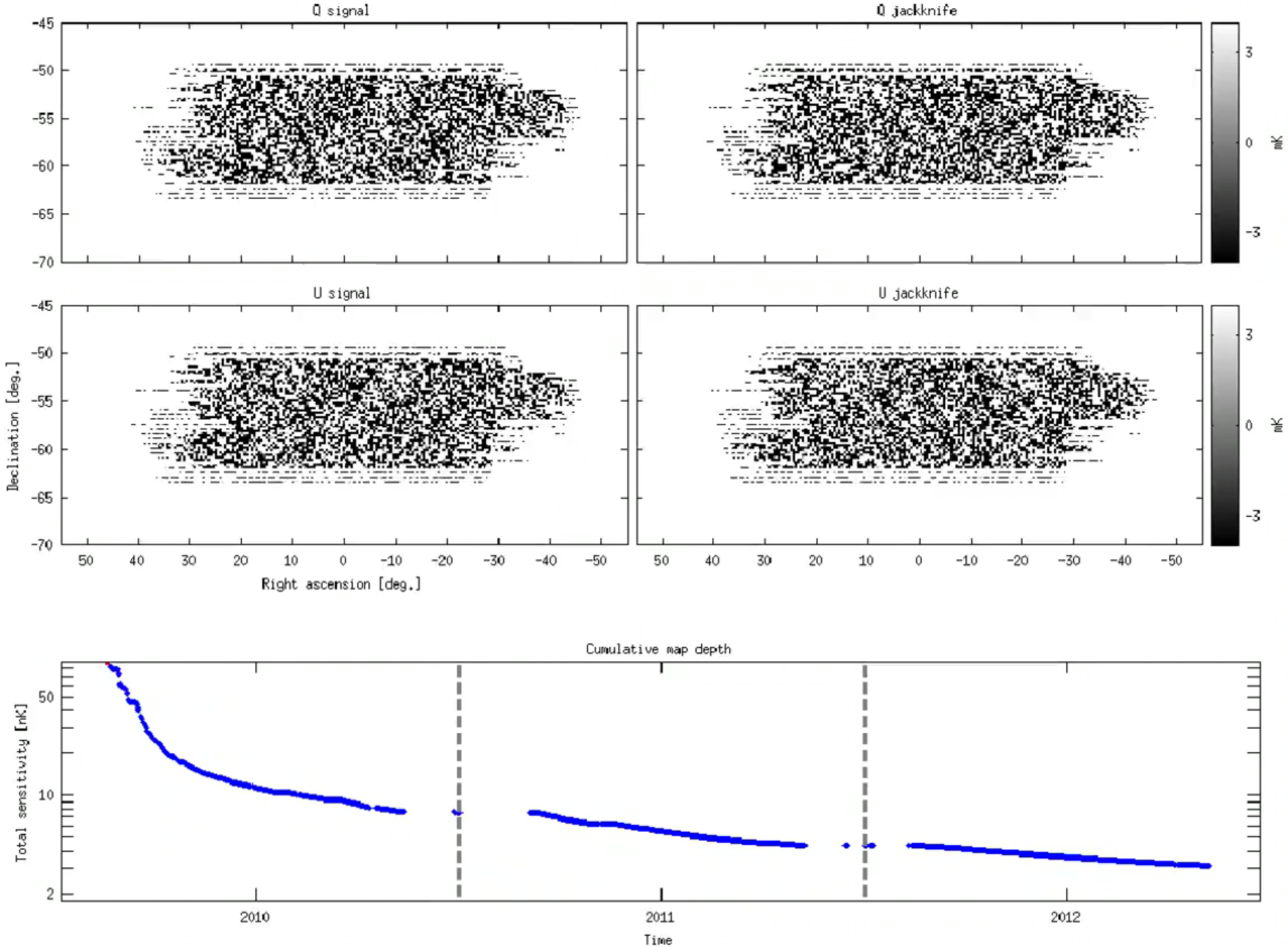
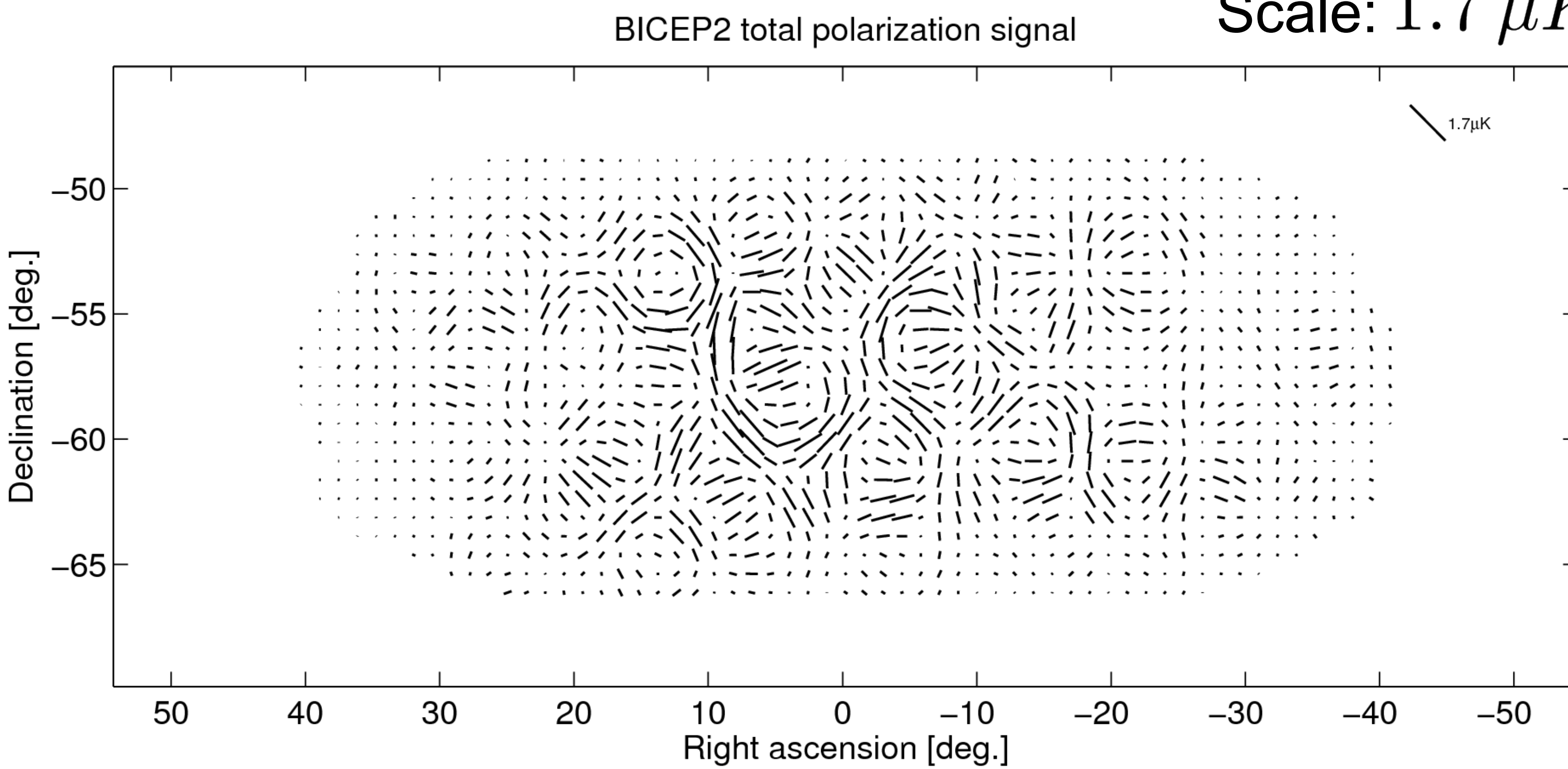

Q signal
Q jackknife
U signal
U jackknife
Declination [deg.]
Right ascension [deg.]
mK
Cumulative map depth
Total sensitivity [nK]
Time
2010
2011
2012

Total Polarization

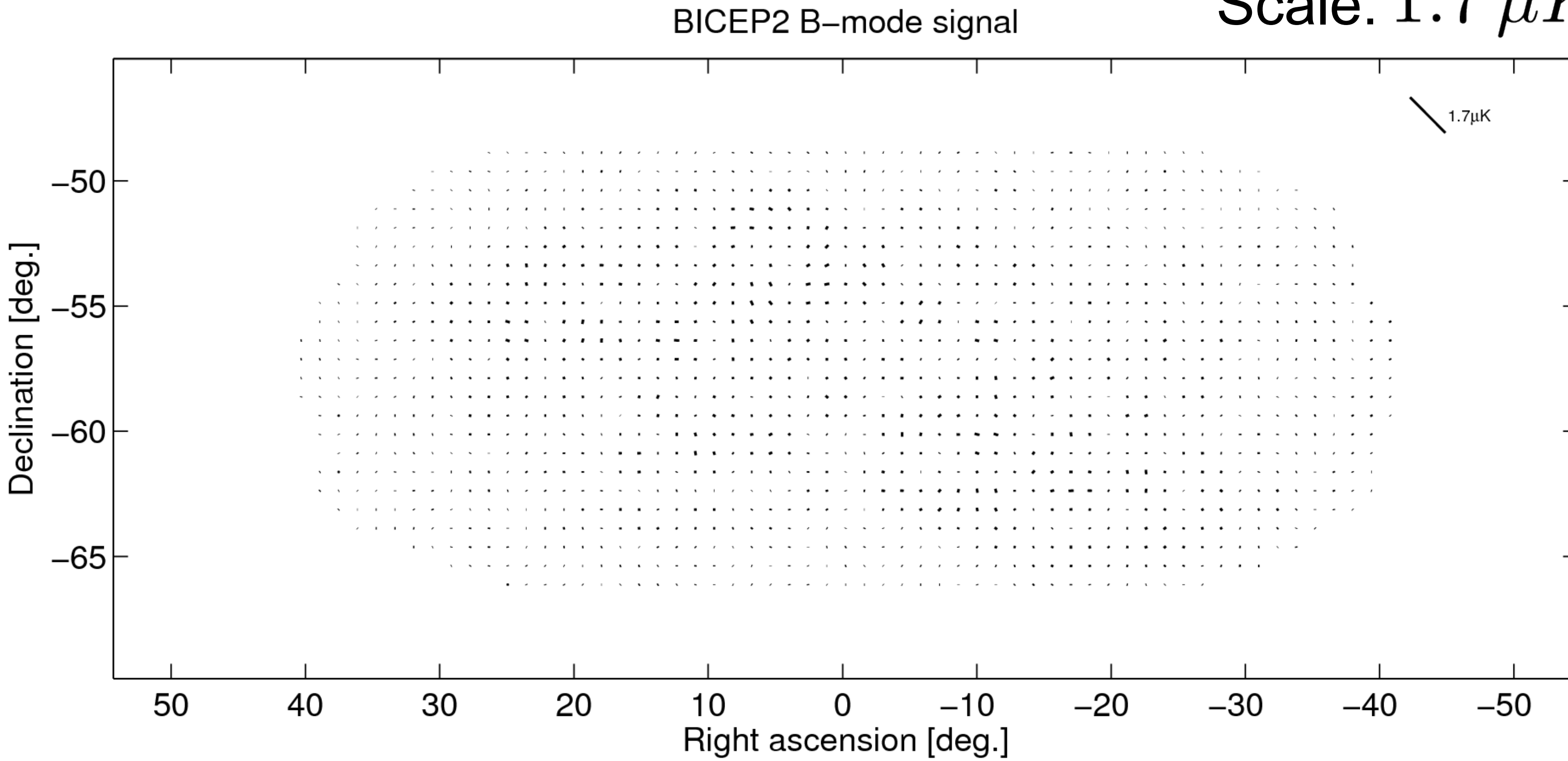
Scale: $1.7\,\mu K$



E-mode dominated pattern – no obvious curl component

B-mode Contribution

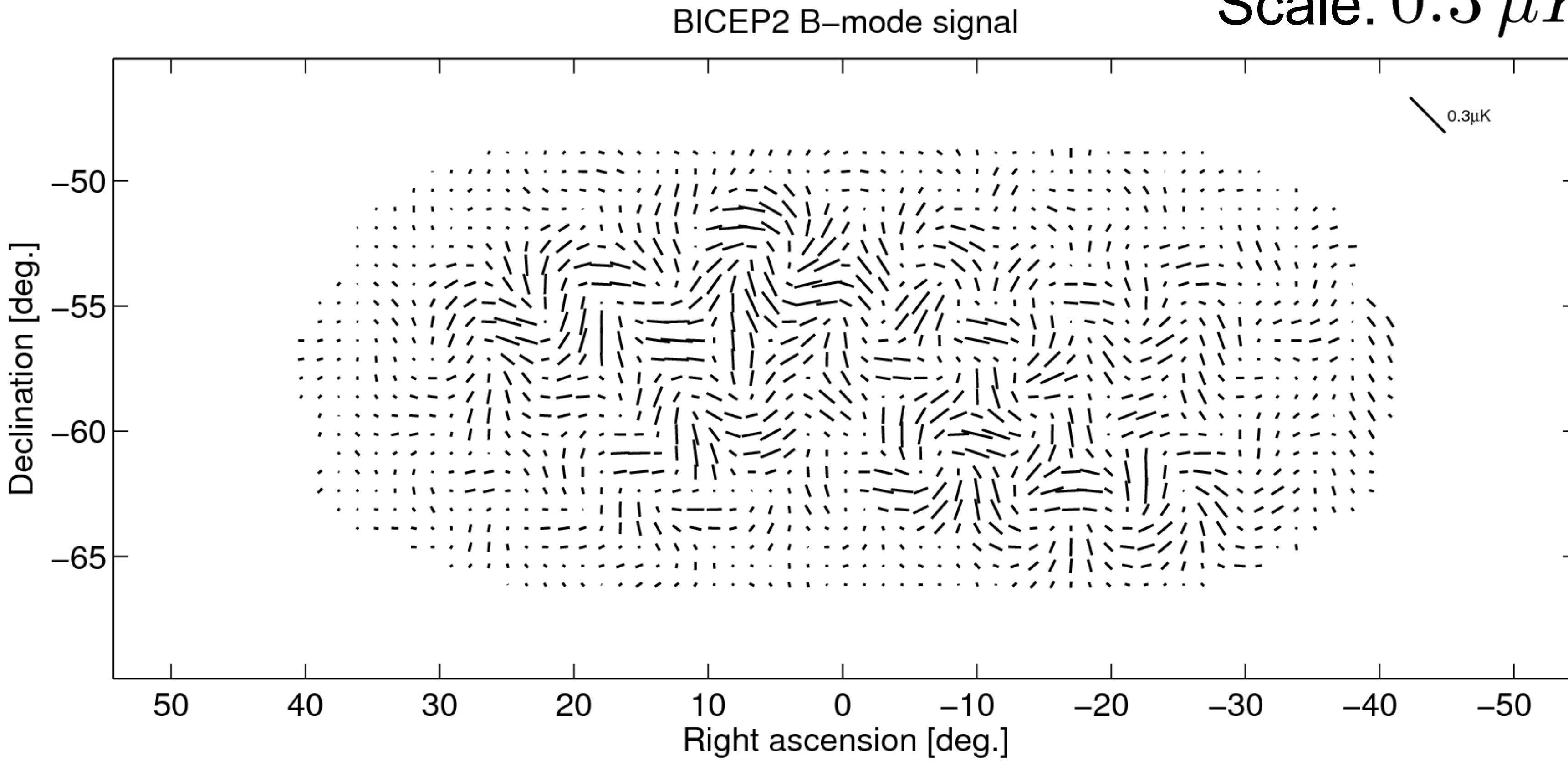
Scale: $1.7\,\mu K$



Apply purification operation to Q/U maps which leaves only pure B-modes (given all timestream filterings etc.)

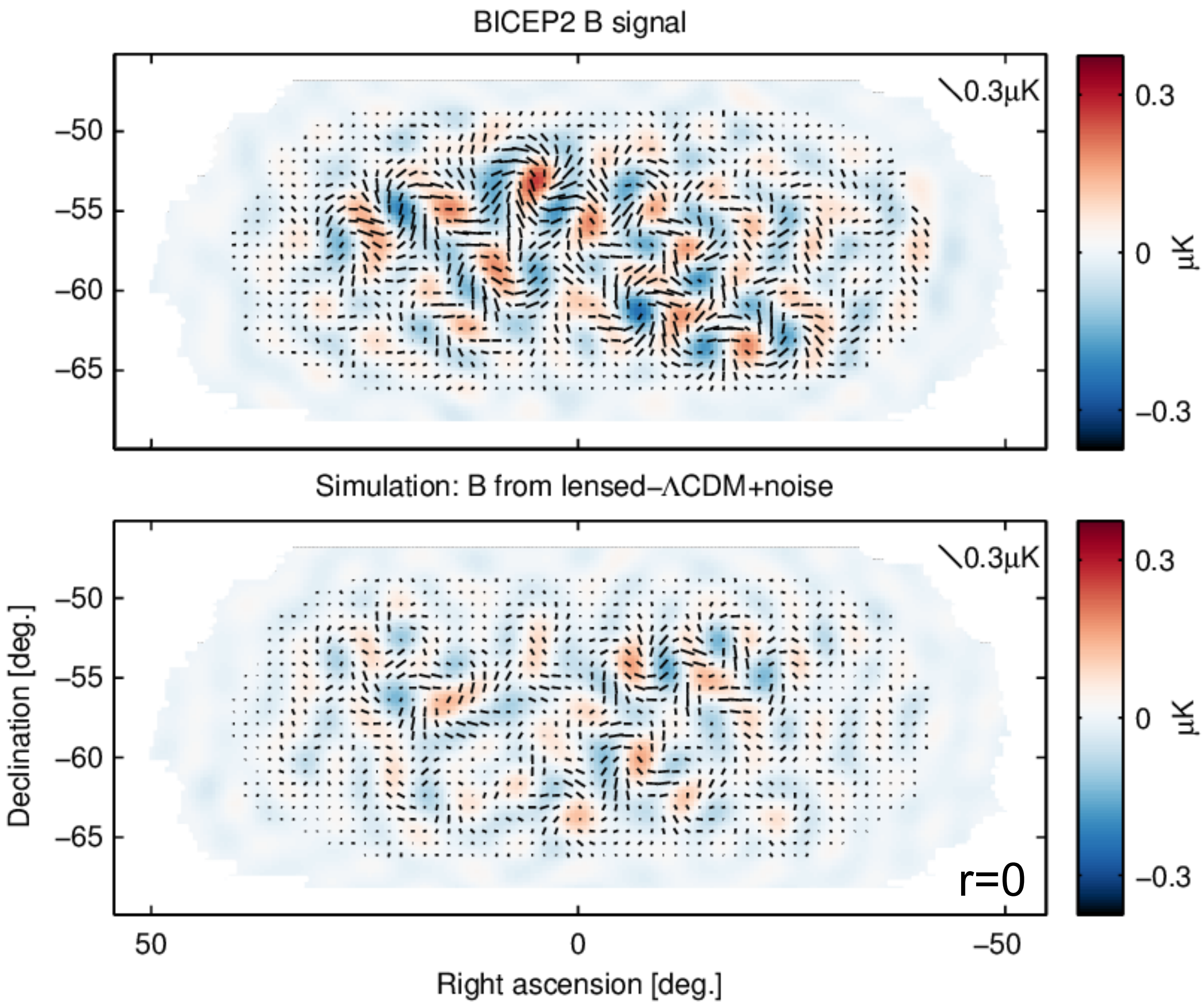
B-mode Contribution

Scale: $0.3\,\mu K$



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

B-mode Map vs. Simulation



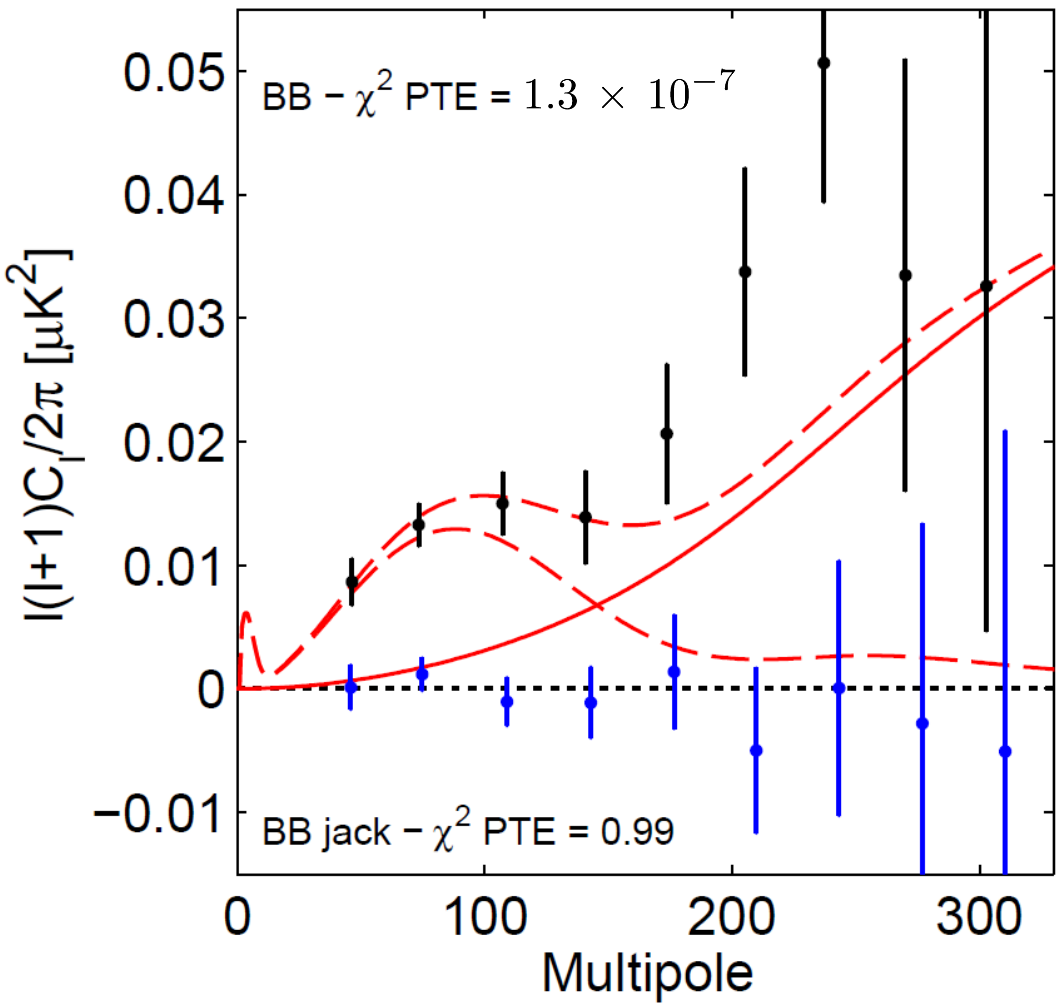
Analysis "calibrated" using lensed-ΛCDM+noise simulations.

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

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, including map based "purification" to avoid E→B mixing

Consistent with lensing expectation at higher l. (yes – a few points are high but not excessively…)

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	$5.3\,\sigma$

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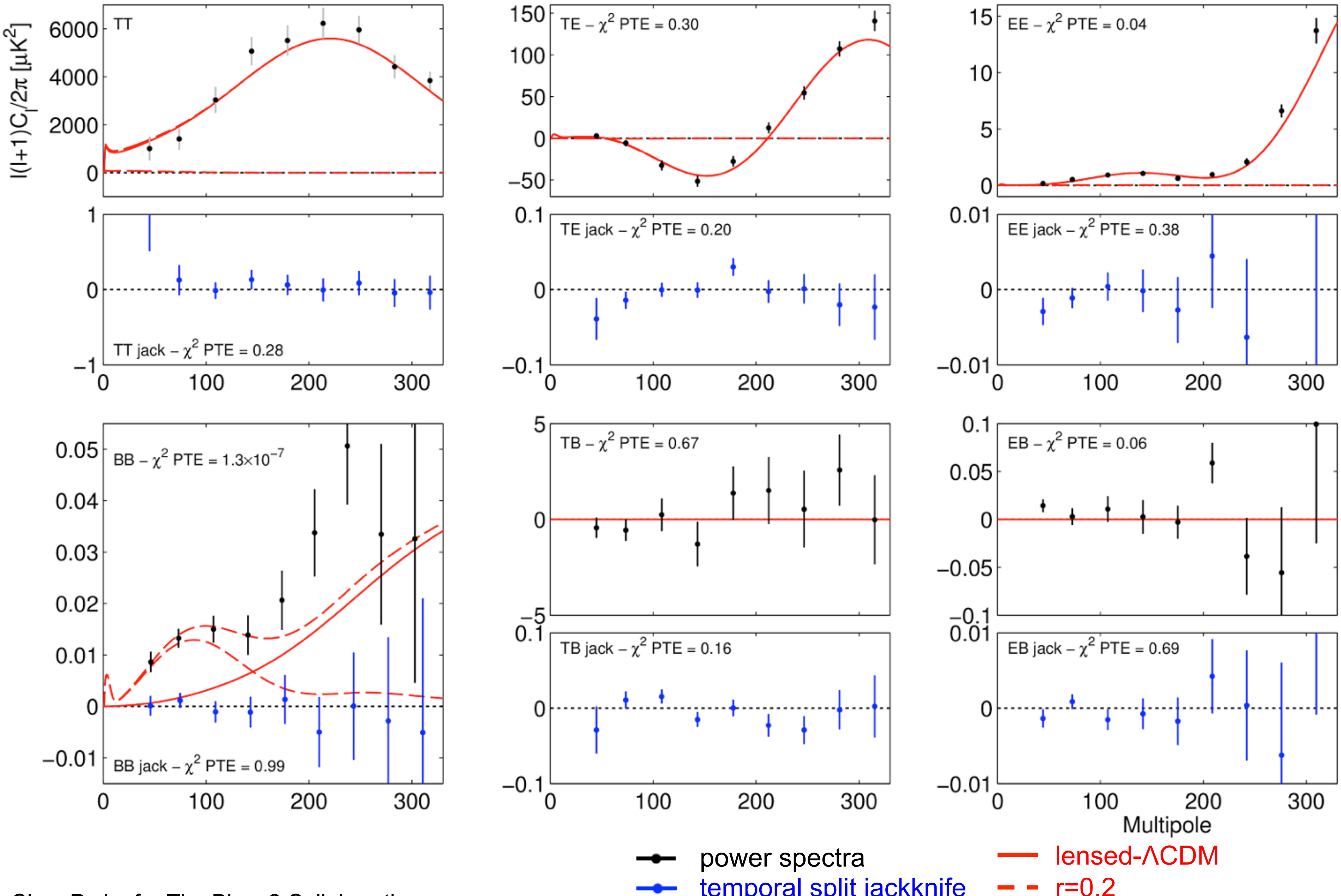
Temperature and Polarization Spectra



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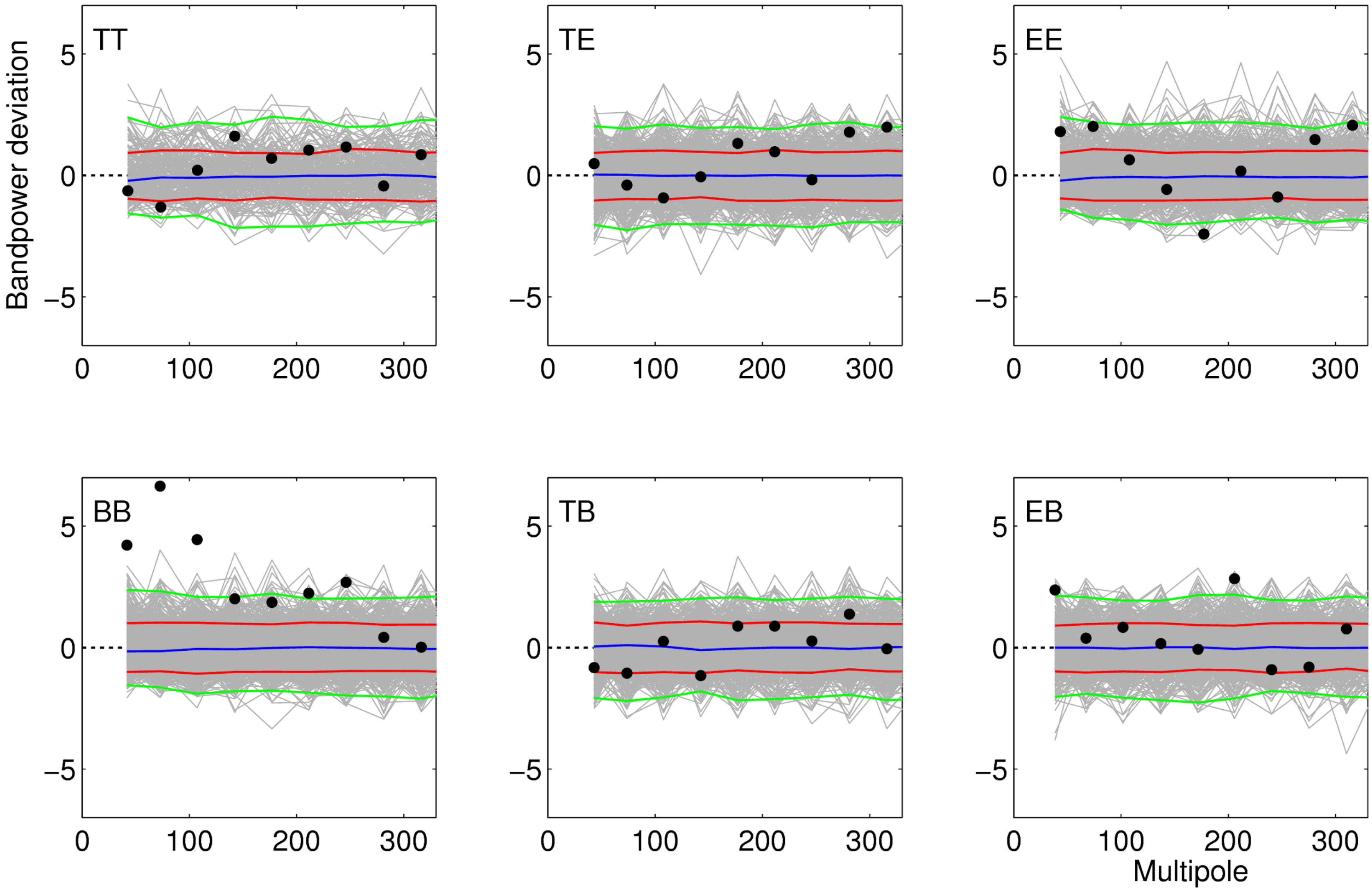
Bandpower Deviations



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

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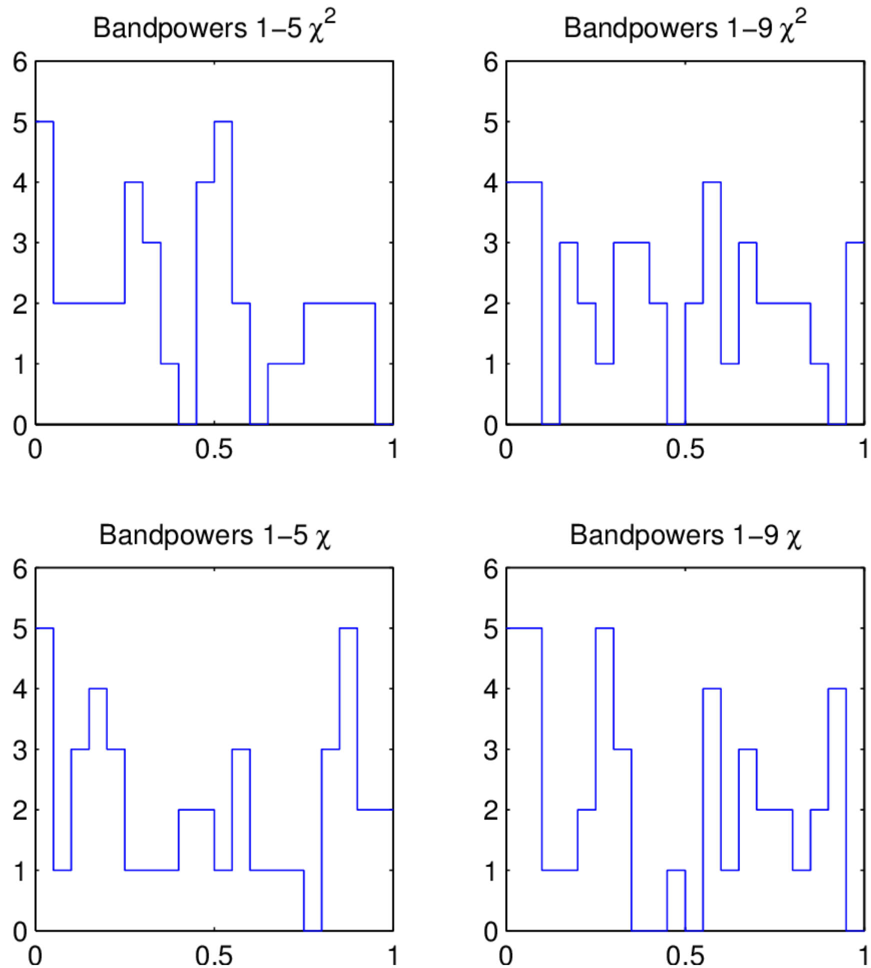
Check Systematics: Jackknifes

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

14 jackknife tests applied to 3 spectra, 4 statistics

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



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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

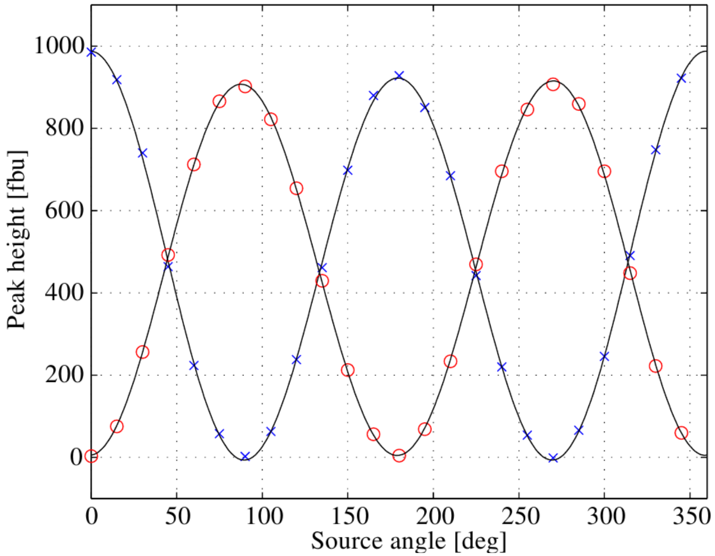
Checks for contamination from detectors with best/worst differential pointing. "Tile/dk" divides the data by the orientation of the detector on the sky.

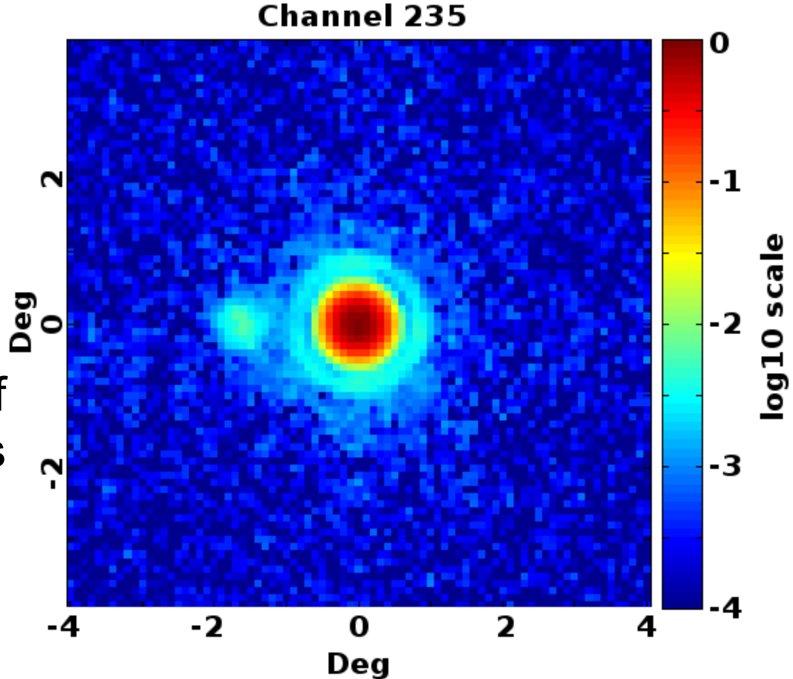
In-Situ Calibration Measurements

For instance...

Far field beam mapping

Detector Polarization Calibration

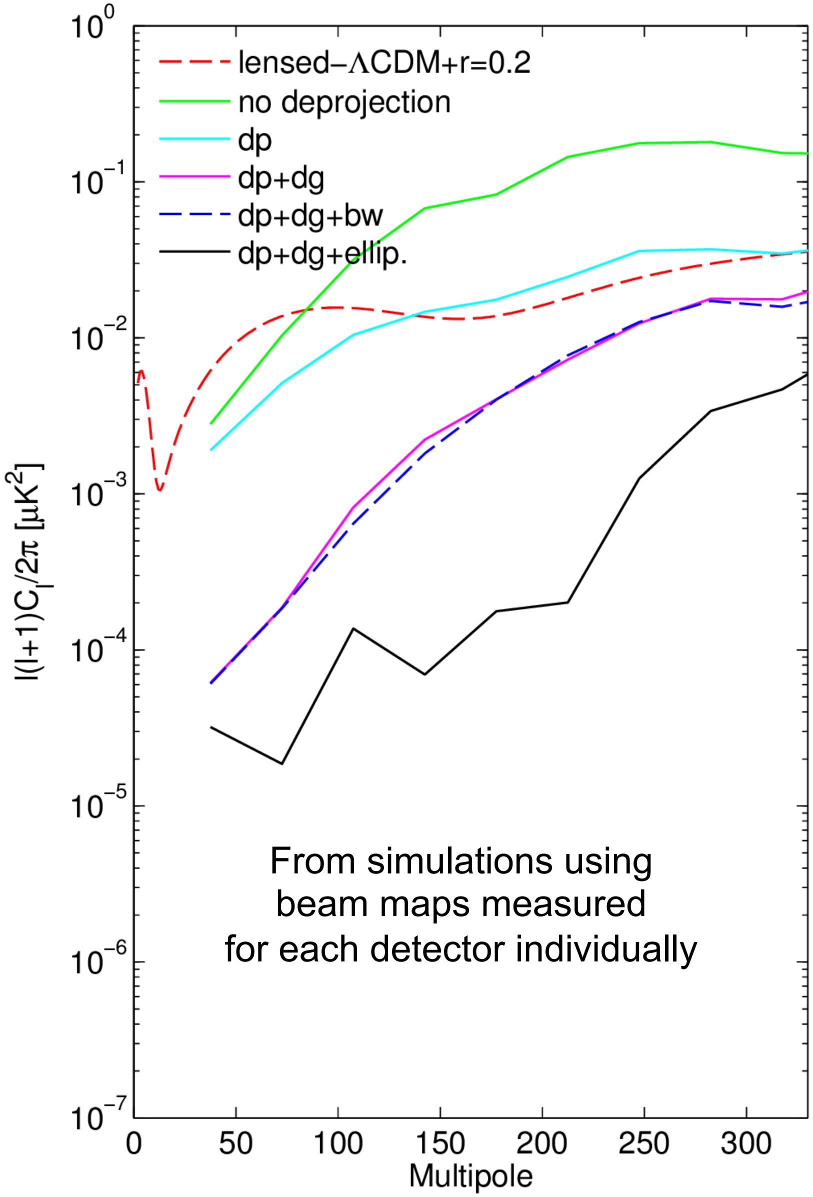




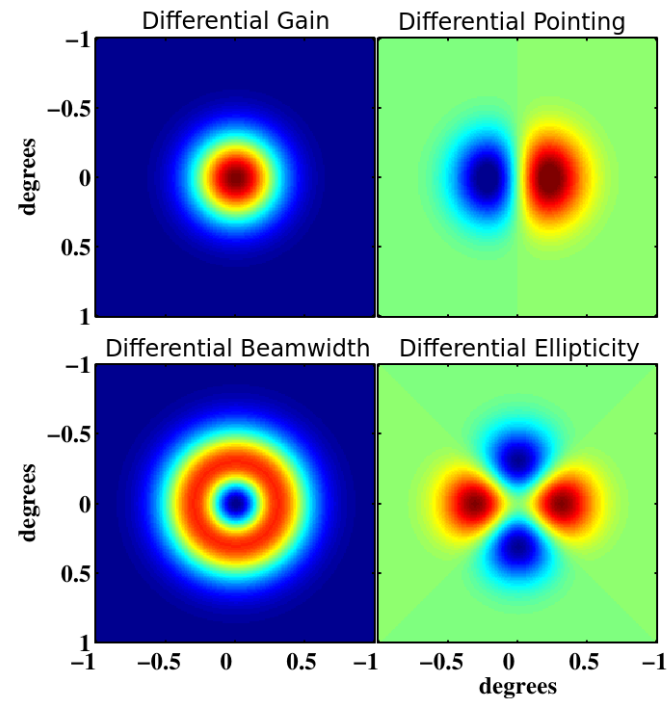
Hi-Fi beam maps of individual detectors

Detailed description in Instrument Paper arxiv:1403.4302

Systematics Removal: Deprojection



Technique developed to remove all types of leakage induced by differences of detector pair beam shapes

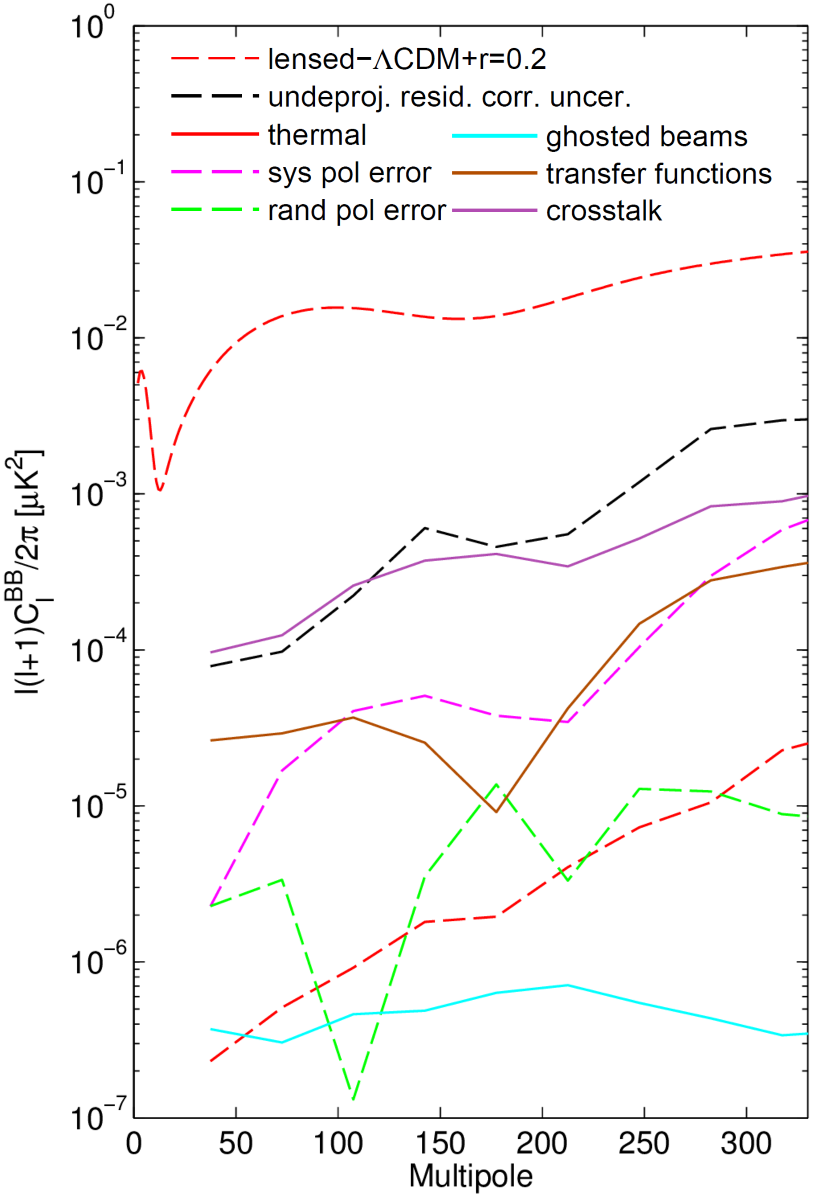


Use the Planck 143 GHz map to form template of the leakage

Deproject diff gain and pointing (& subtract diff ellipticity)

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

Systematics beyond Beam imperfections

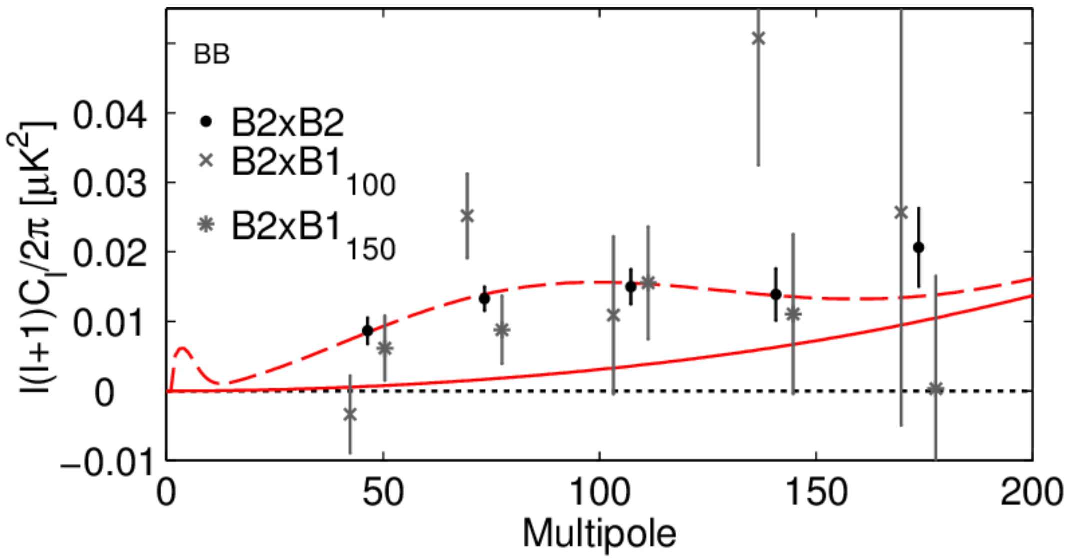


All systematic effects that we could imagine were investigated!

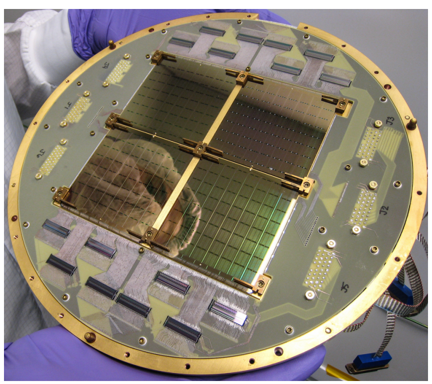
We find with high confidence that the apparent signal *cannot be explained* by instrumental systematics!

Systematics and beams papers nearly ready…

Cross Correlation with BICEP1



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



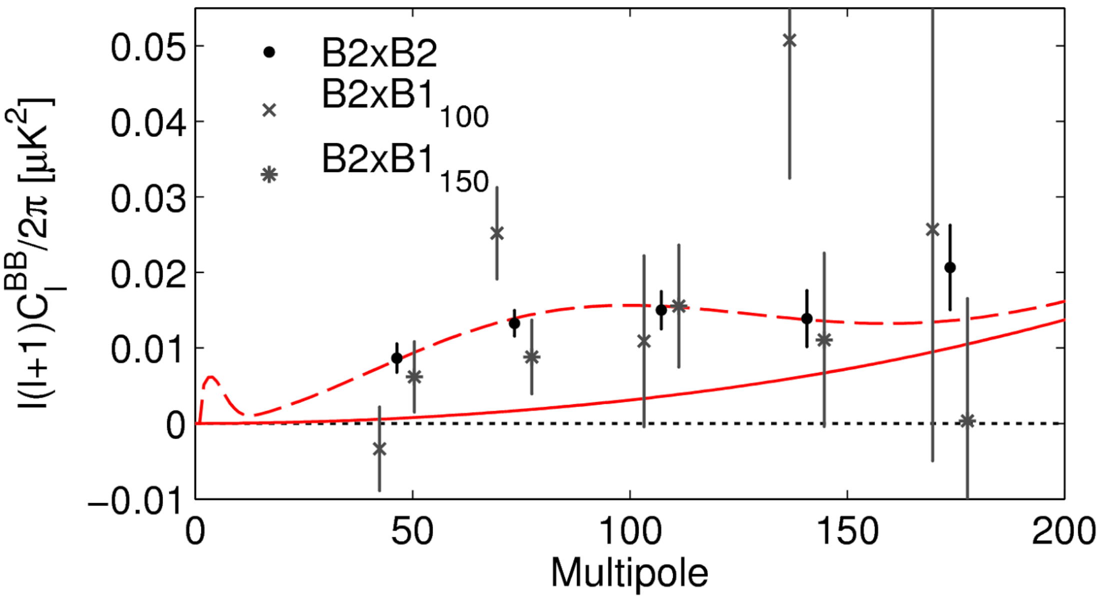
BICEP2: Phased antenna array and TES readout 150 GHz

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

BICEP1: Feedhorns and NTD readout 150 and 100 GHz

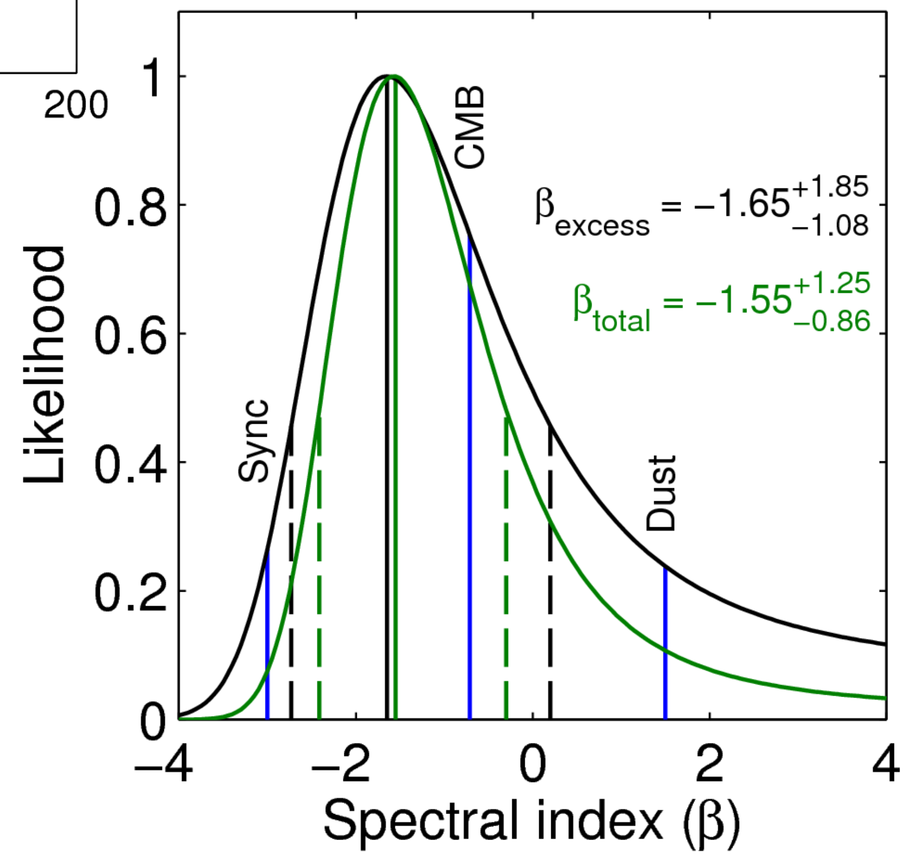
Cross with BICEP1$_{100}$ shows **~3σ** detection of BB power

Spectral Index Constraint using BICEP1 100GHz



Likelihood ratio test: consistent with CMB spectrum, disfavor pure dust/sync at **1.7/1.6σ**

green: total signal
black : excess signal over ΛCDM



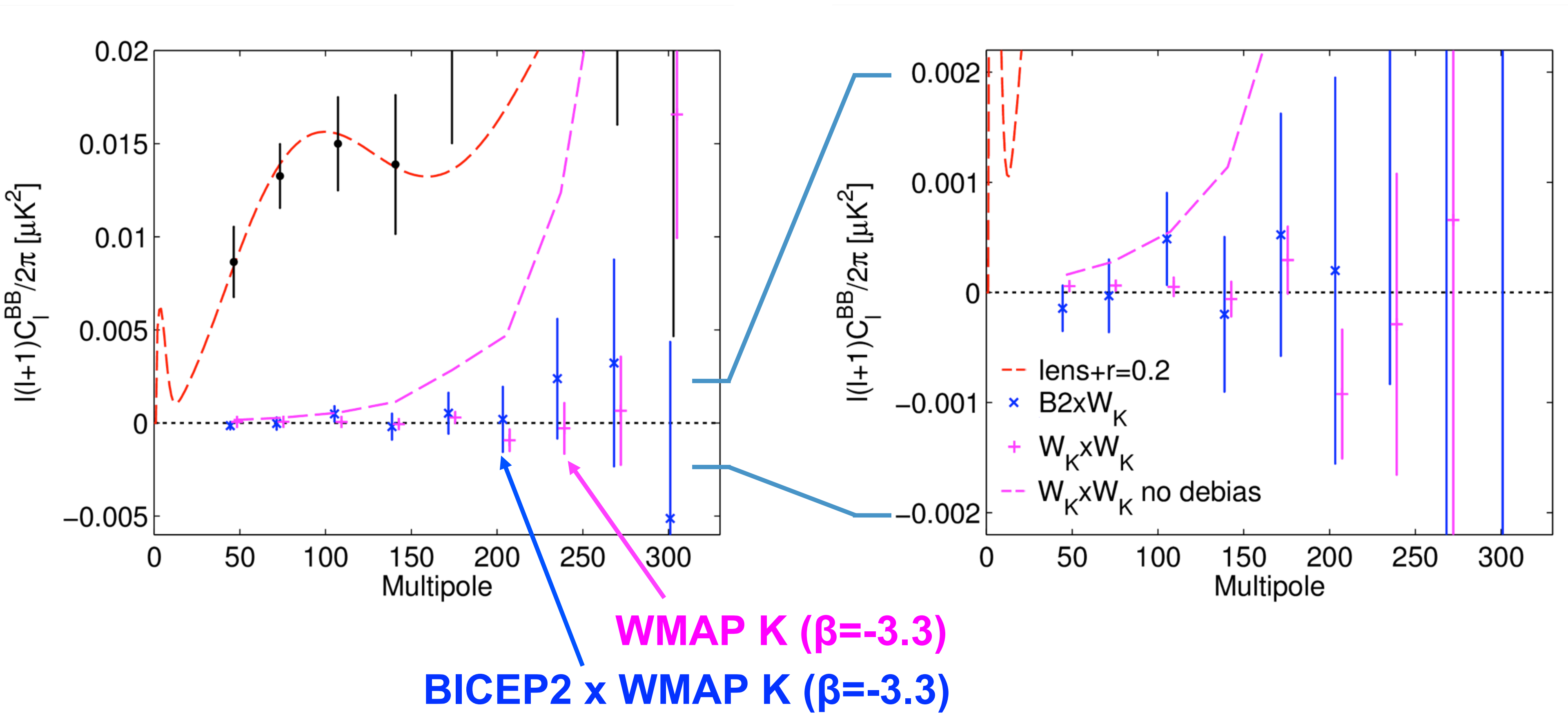
Comparison of B2 auto with $B2_{150}$ x $B1_{100}$ constrains signal frequency dependence:

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

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

Synchrotron Foreground?

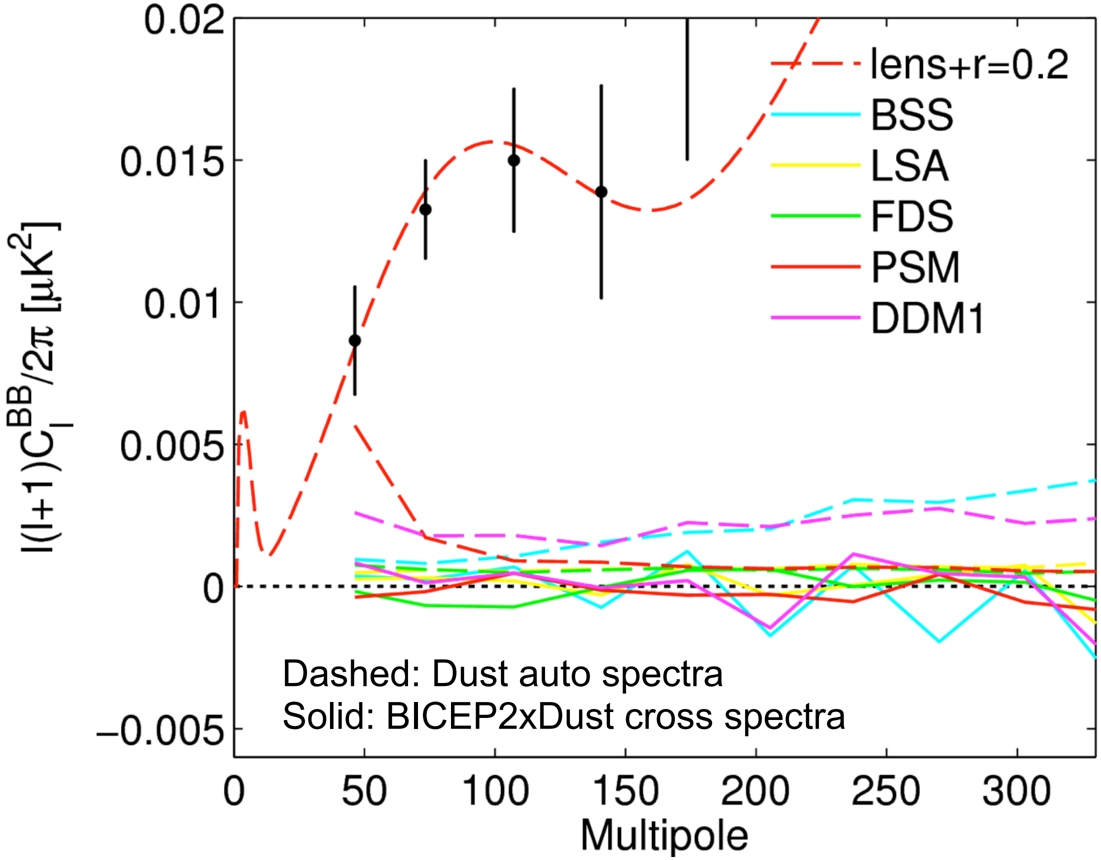
BICEP2 x WMAP 22 GHz polarization (extrapolated to 150 GHz with beta=-3.3*) is noise dominated but limits synchrotron to r<0.008 at 95% confidence.

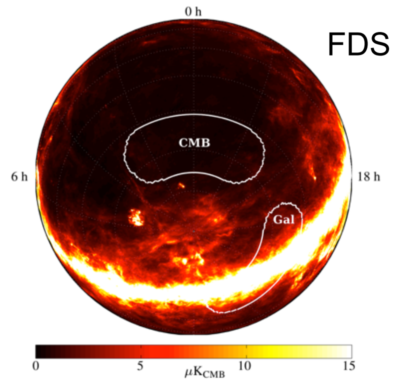


The Bicep2 Collaboration

* = -3.3 is the mean sync spectral index given by WMAP within BICEP2 field

Pre-Planck Polarized Dust Foreground Projections





FDS Model

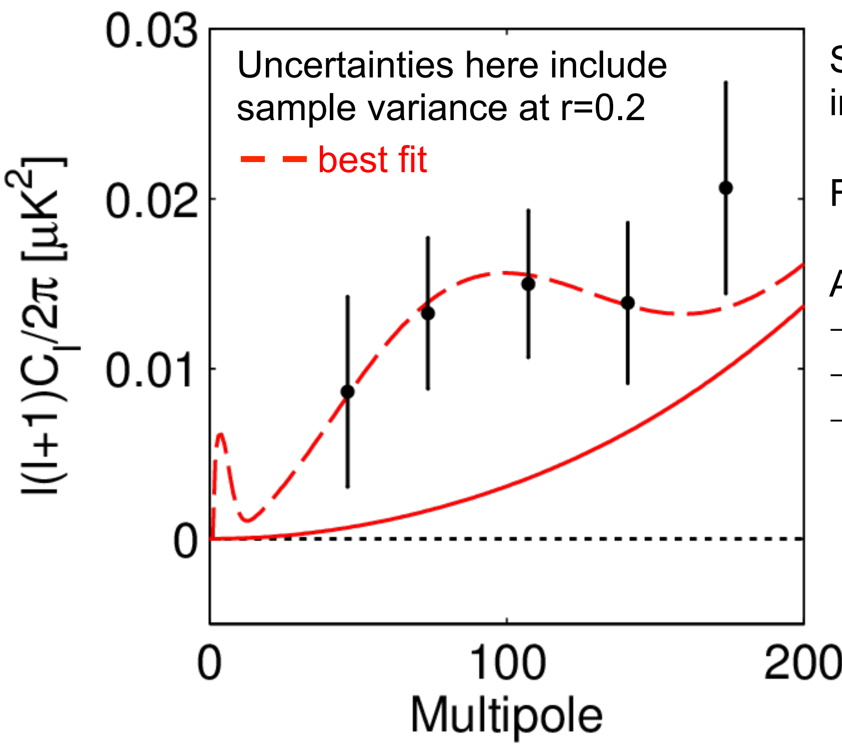
The BICEP2 region was chosen on the basis of extremely low unpolarized dust power.

Used various models of polarized dust emission to estimate dust power.

Result: All auto spectra were well below observed signal level. (and cross spectra consistent with zero.)

But considerable uncertainty in these models...

Fitting Without Dust Subtraction…



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

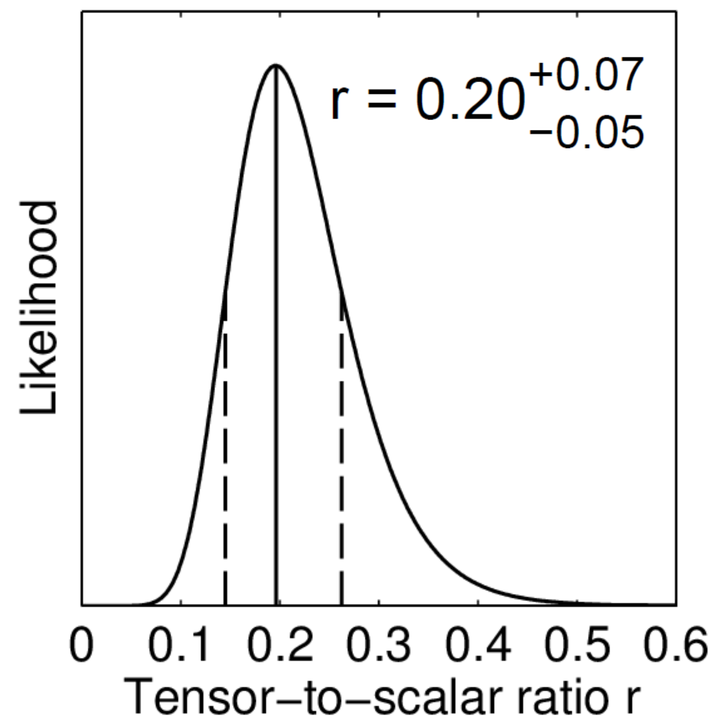
Find the most likely value of the tensor-to-scalar ratio r

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)



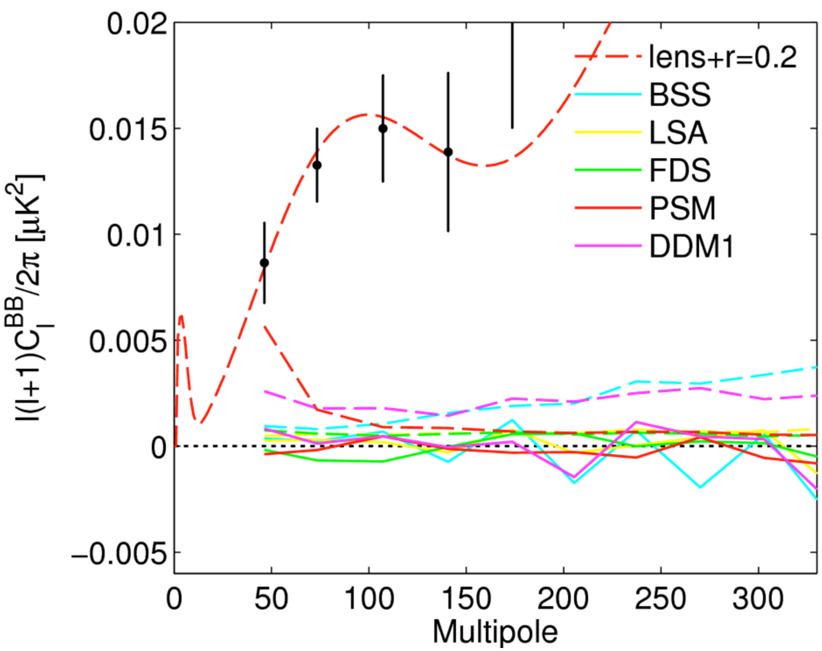
Within this simplistic model we find:

r = 0.2 with uncertainties dominated by sample variance

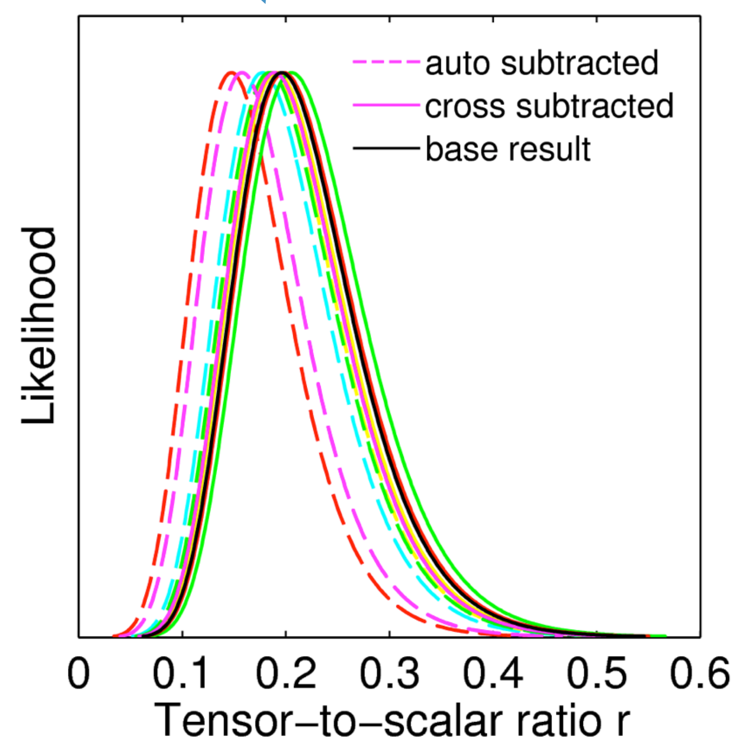
PTE of fit to data: 0.9
→ model is perfectly acceptable fit to the data

r = 0 ruled out at 7.0σ

Fitting with Dust Projections Subtracted…



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

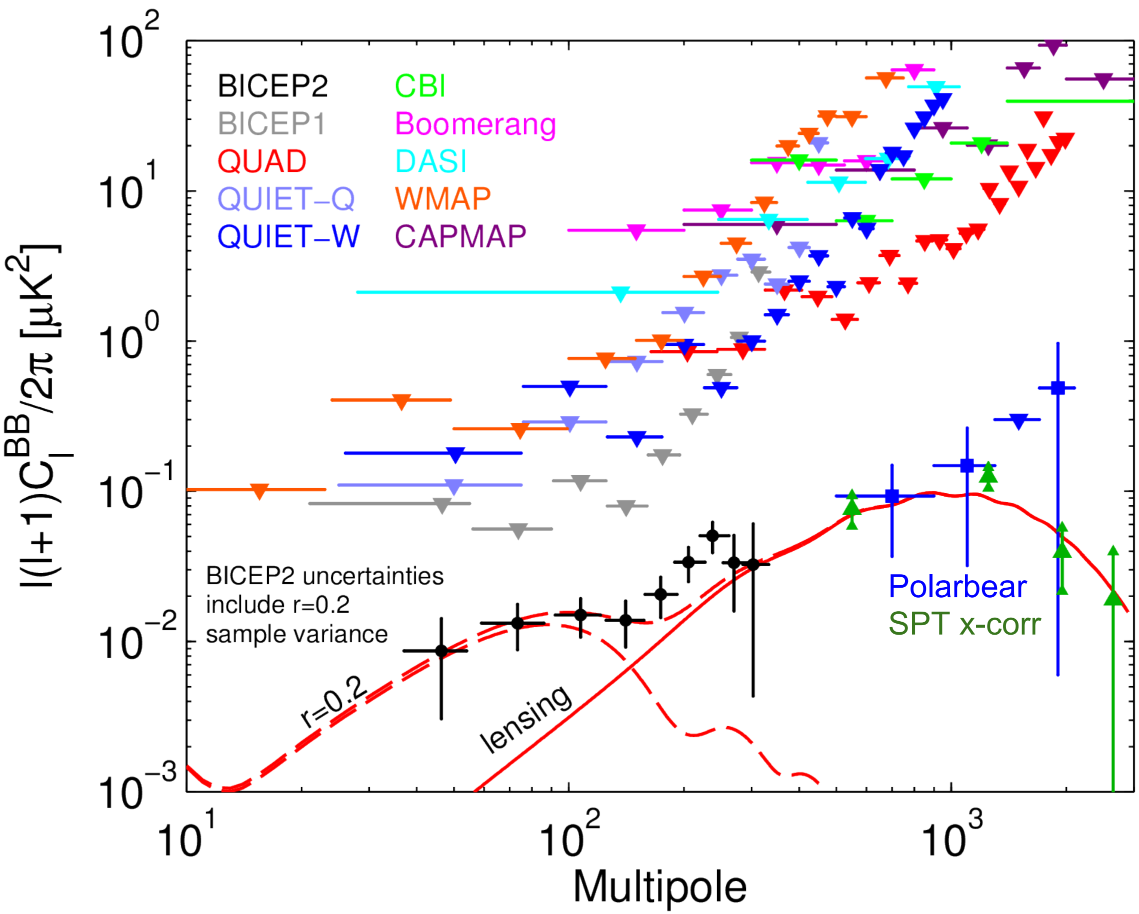


Probability that each of these models reflected reality was hard to assess.

DDM1 used all publicly available information from Planck. Polarization fraction here assumed p = 5%. p ~ 13% would explain the full excess under this model.

Conclusions circa March 17th

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 tests strongly argue against systematics as the origin

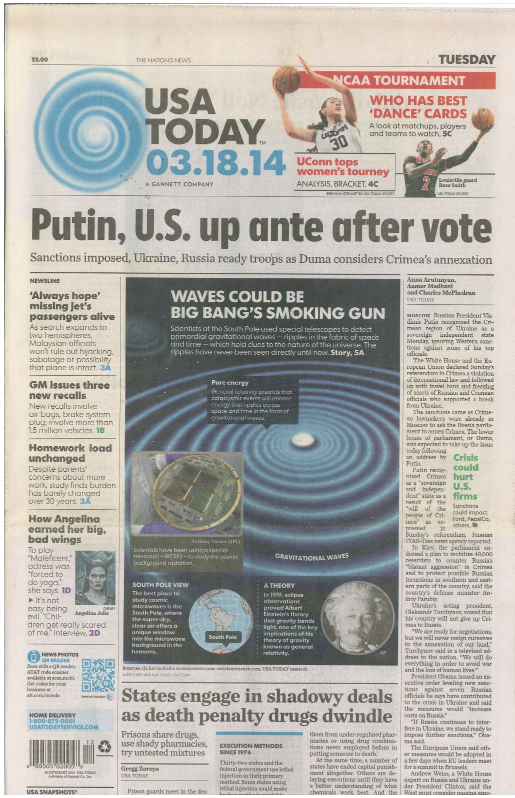
Data fit well to LCDM+r=0.2 expectation

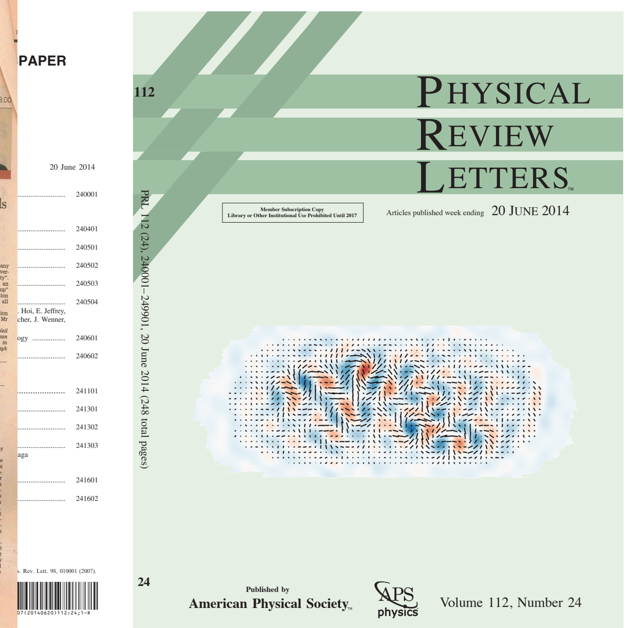
Foregrounds did not appear to be a large fraction of the signal:
→ foreground projections
→ lack of cross correlations
→ CMB-like spectral index
→ spatial and spectral shape of the B-mode signal

Clem Pryke for The Bicep2 Collaboration

Press Conference at Harvard/CfA March 17

Storm of Media Attention





Actually not a lot of fun…

Developments Since…

- Intense media and science community interest…
- Many early instrumental queries – faded away – everybody now seems to trust the measurement.
- Concerns about synchrotron – also faded away.
- But persistent concerns about dust…
  - Mostly based on online pdf's of Planck talks
- Paper published 20 June in PRL (with "note added" about dust concerns etc) (25 pages)
- As of 19 Sept we finally have some solid information from Planck about the actual level of polarized dust emission in the BICEP2 field (arxiv:1409.5738). Looks to be much higher than any of the projections…

New Information from Planck

“Planck intermediate results XXX” (1409.5738) Fig. 9:

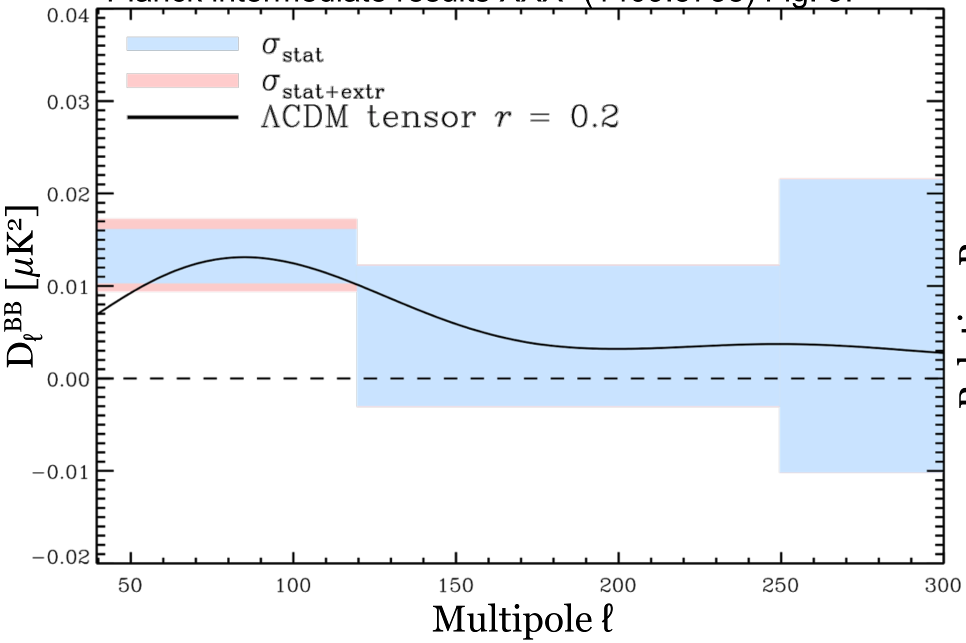
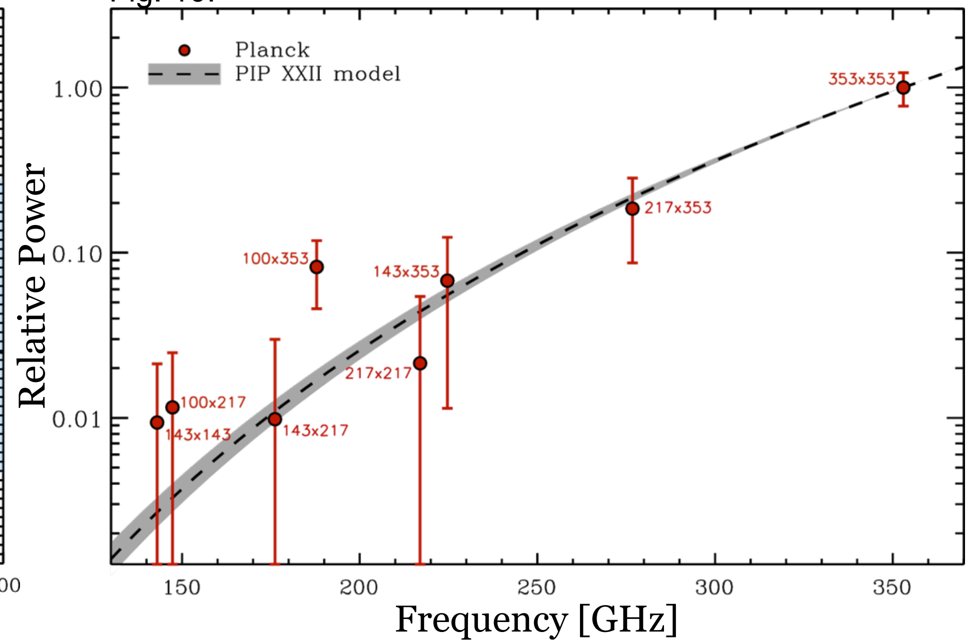


Fig. 10:



- ➢ The 353x353 spectrum scaled to 150 GHz (Bicep2’s frequency)
- ➢ Scaling and uncertainty thereon is derived from average over large sky fraction
- ➢ In a single broad bin roughly matches the power seen by BICEP2

- ➢ **Planck intermediate results paper XXX states: “ The present uncertainties are large and will be reduced through an ongoing, joint analysis of the Planck and BICEP2 data sets. ”**

What's Next?

- We are actively working with the Planck collaboration on a joint analysis of the two data sets:
  - The combination of the two is more powerful than either alone
  - Goal is a joint paper in late Nov. (meeting at UMN in a few weeks to discuss)
- We ran two of the Keck Array receivers this season at 100GHz:
  - Data in the can probably offers a stronger constraint on the value of r than BICEP2+Planck
  - Guys are gearing up to analyze as fast as possible when the data taking finishes on Nov 1
- We are right now preparing to deploy BICEP3 which is an all 100GHz super receiver…