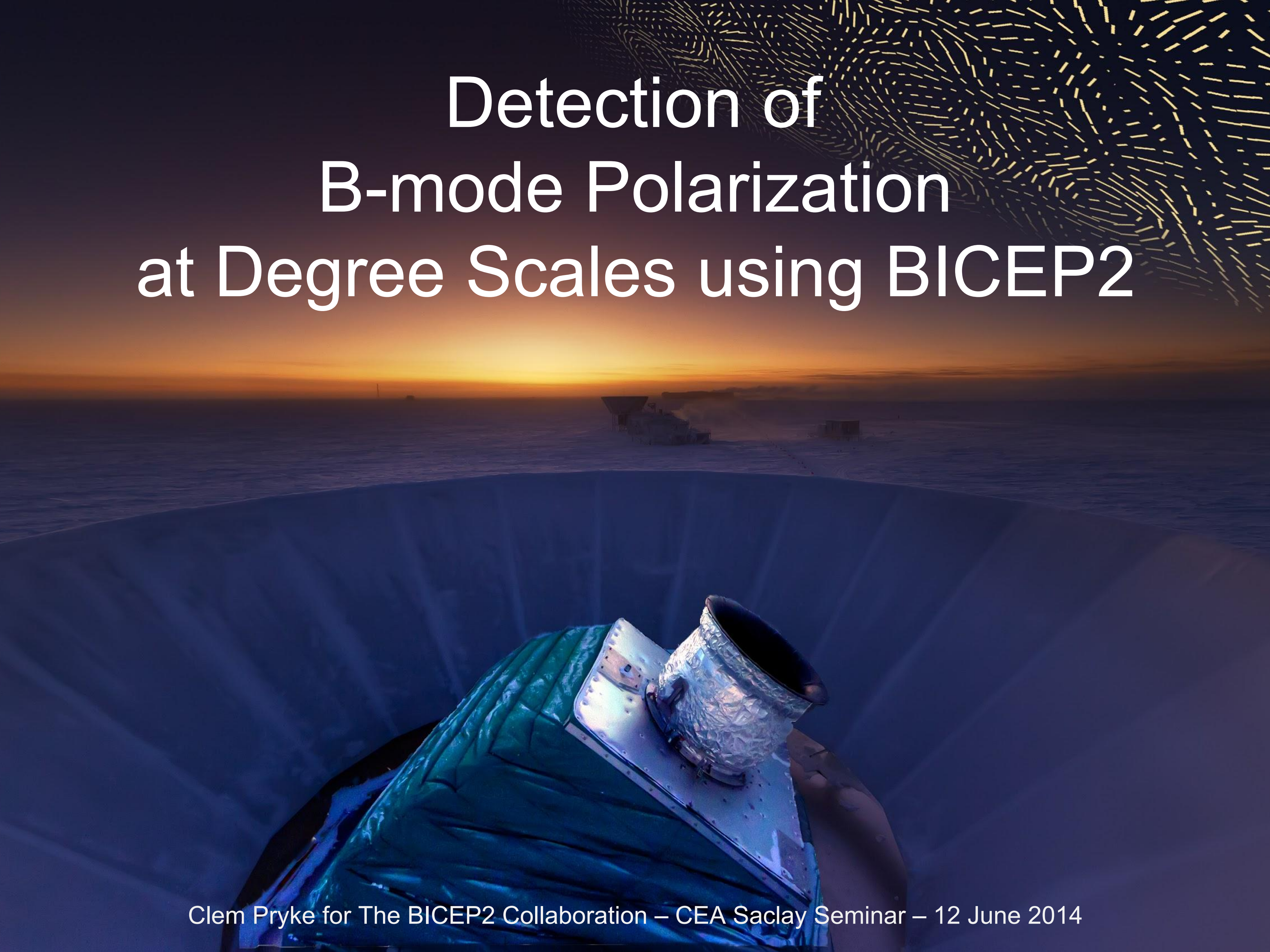
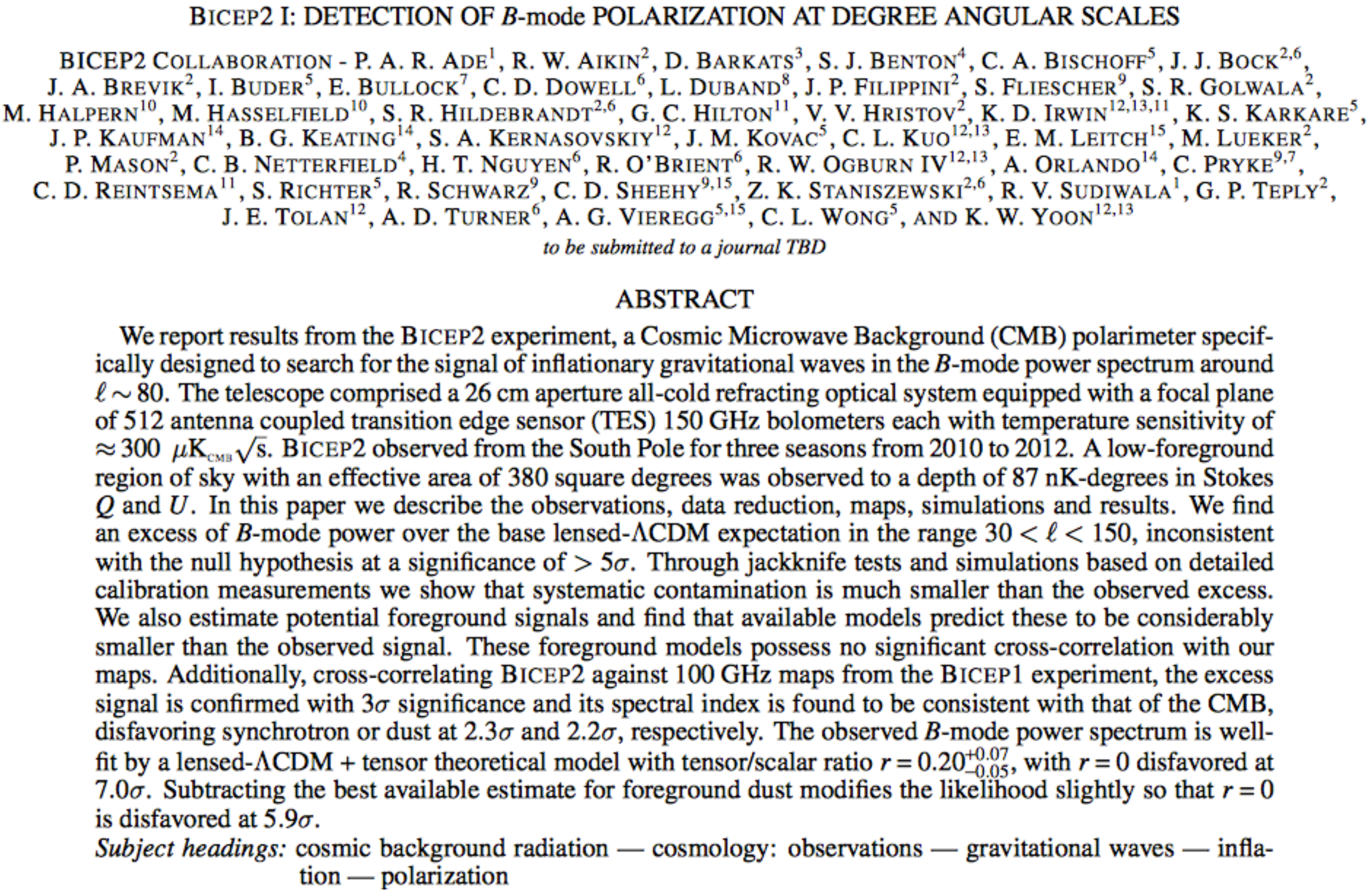


Detection of B-mode Polarization at Degree Scales using BICEP2

Clem Pryke for The BICEP2 Collaboration – CEA Saclay Seminar – 12 June 2014



BICEP2 I: DETECTION OF *B*-mode POLARIZATION AT DEGREE ANGULAR SCALES

BICEP2 COLLABORATION - P. A. R. ADE[1], R. W. AIKIN[2], D. BARKATS[3], S. J. BENTON[4], C. A. BISCHOFF[5], J. J. BOCK[2,6],
J. A. BREVIK[2], I. BUDER[5], E. BULLOCK[7], C. D. DOWELL[6], L. DUBAND[8], J. P. FILIPPINI[2], S. FLIESCHER[9], S. R. GOLWALA[2],
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P. MASON[2], C. B. NETTERFIELD[4], H. T. NGUYEN[6], R. O'BRIENT[6], R. W. OGBURN IV[12,13], A. ORLANDO[14], C. PRYKE[9,7],
C. D. REINTSEMA[11], S. RICHTER[5], R. SCHWARZ[9], C. D. SHEEHY[9,15], Z. K. STANISZEWSKI[2,6], R. V. SUDIWALA[1], G. P. TEPLY[2],
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to be submitted to a journal TBD

ABSTRACT

We report results from the BICEP2 experiment, a Cosmic Microwave Background (CMB) polarimeter specifically designed to search for the signal of inflationary gravitational waves in the *B*-mode power spectrum around $\ell \sim 80$. The telescope comprised a 26 cm aperture all-cold refracting optical system equipped with a focal plane of 512 antenna coupled transition edge sensor (TES) 150 GHz bolometers each with temperature sensitivity of $\approx 300\ \mu\mathrm{K}_{\mathrm{CMB}}\sqrt{\mathrm{s}}$. BICEP2 observed from the South Pole for three seasons from 2010 to 2012. A low-foreground region of sky with an effective area of 380 square degrees was observed to a depth of 87 nK-degrees in Stokes Q and U. In this paper we describe the observations, data reduction, maps, simulations and results. We find an excess of *B*-mode power over the base lensed-ΛCDM expectation in the range $30 < \ell < 150$, inconsistent with the null hypothesis at a significance of $> 5\sigma$. Through jackknife tests and simulations based on detailed calibration measurements we show that systematic contamination is much smaller than the observed excess. We also estimate potential foreground signals and find that available models predict these to be considerably smaller than the observed signal. These foreground models possess no significant cross-correlation with our maps. Additionally, cross-correlating BICEP2 against 100 GHz maps from the BICEP1 experiment, the excess signal is confirmed with 3σ significance and its spectral index is found to be consistent with that of the CMB, disfavoring synchrotron or dust at 2.3σ and 2.2σ, respectively. The observed *B*-mode power spectrum is well-fit by a lensed-ΛCDM + tensor theoretical model with tensor/scalar ratio $r = 0.20^{+0.07}_{-0.05}$, with $r = 0$ disfavored at 7.0σ. Subtracting the best available estimate for foreground dust modifies the likelihood slightly so that $r = 0$ is disfavored at 5.9σ.

Subject headings: cosmic background radiation — cosmology: observations — gravitational waves — inflation — polarization

arXiv:1403.3985

VE RI TAS
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The BICEP2 Postdocs


Colin Bischoff


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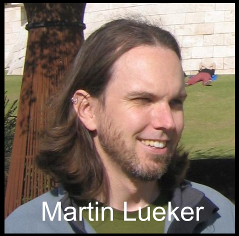
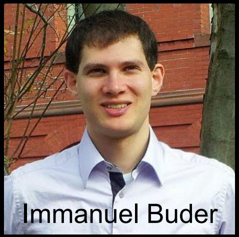

Martin Lueker


Walt Ogburn


Abigail Vieregg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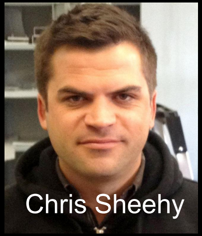
Zak Staniszewski

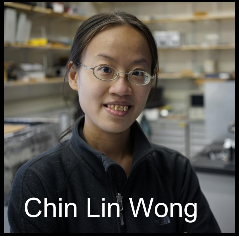
The BICEP2 Graduate Students


Randol Aikin


Justus Brevik

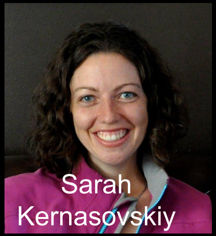

Chris Sheehy


Grant Teply


Chin Lin Wong


Kirit Karkare


Jon Kaufman


Sarah Kernasovskiy


Jamie Tolan

BICEP2 Winterovers


Steffen Richter 2010


Steffen Richter 2011


Steffen Richter 2012

Modern cosmology in a nutshell:

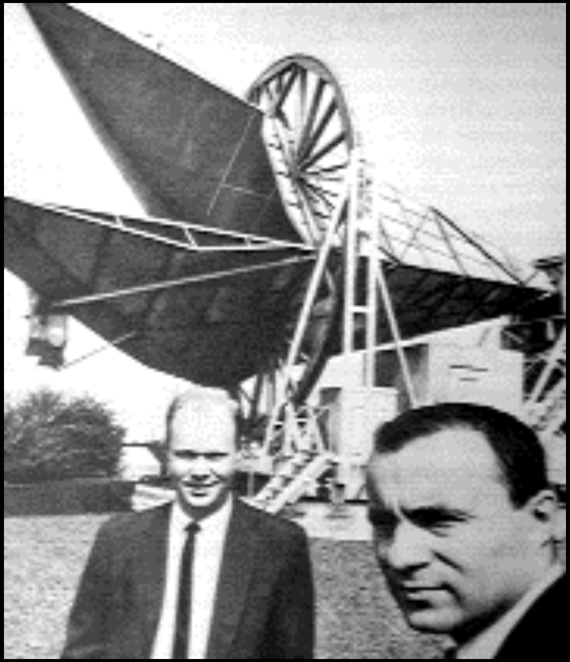
Edwin Hubble

1) The universe is expanding.

(Hubble, 1920s)

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

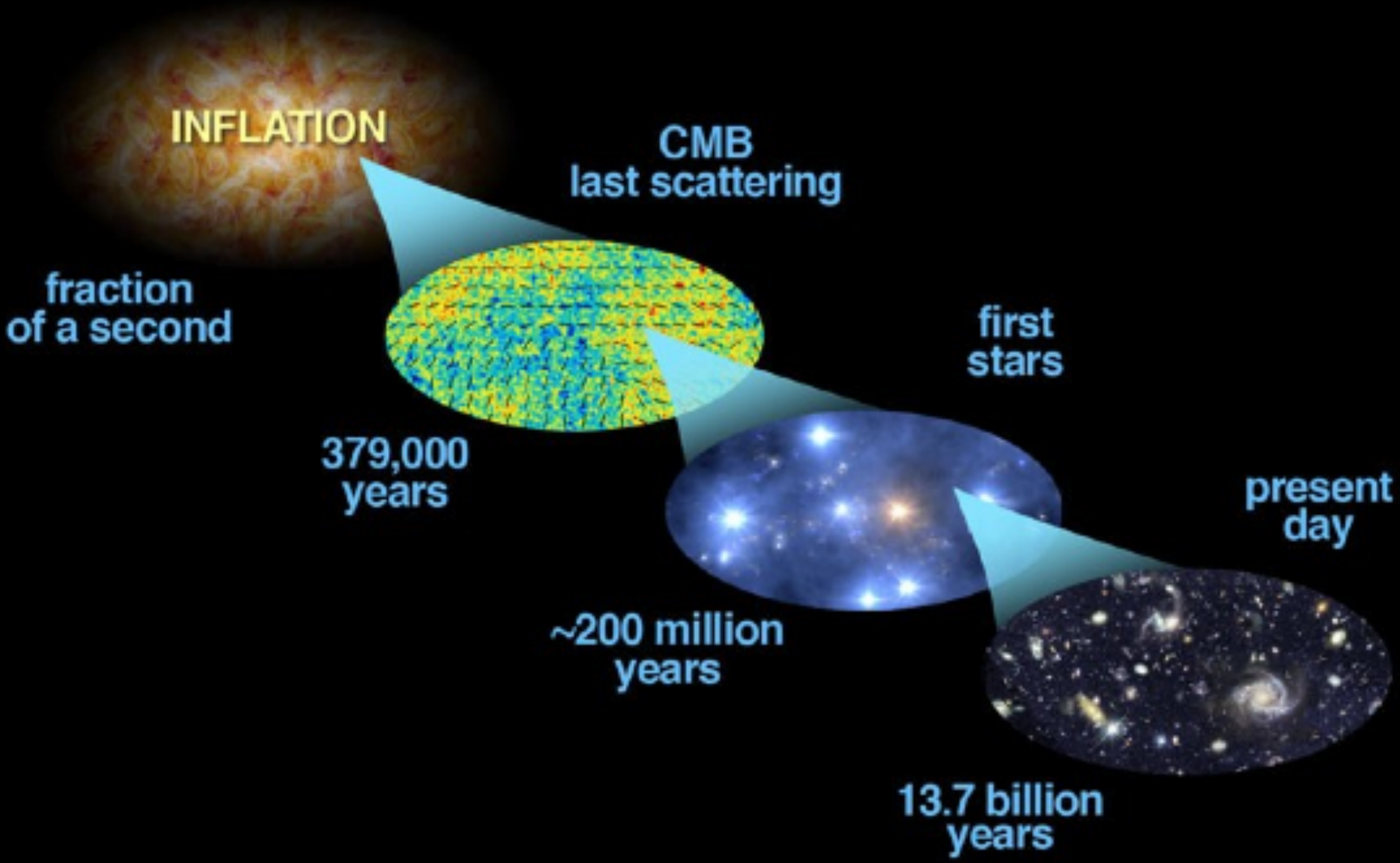
(Alpher, Gamow, Herman, 1940s)



Bob Wilson & Arno Penzias
1978 Nobel Prize

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

⇒ acceptance of the "HOT BIG BANG"



INFLATION

fraction
of a second

CMB
last scattering

379,000
years

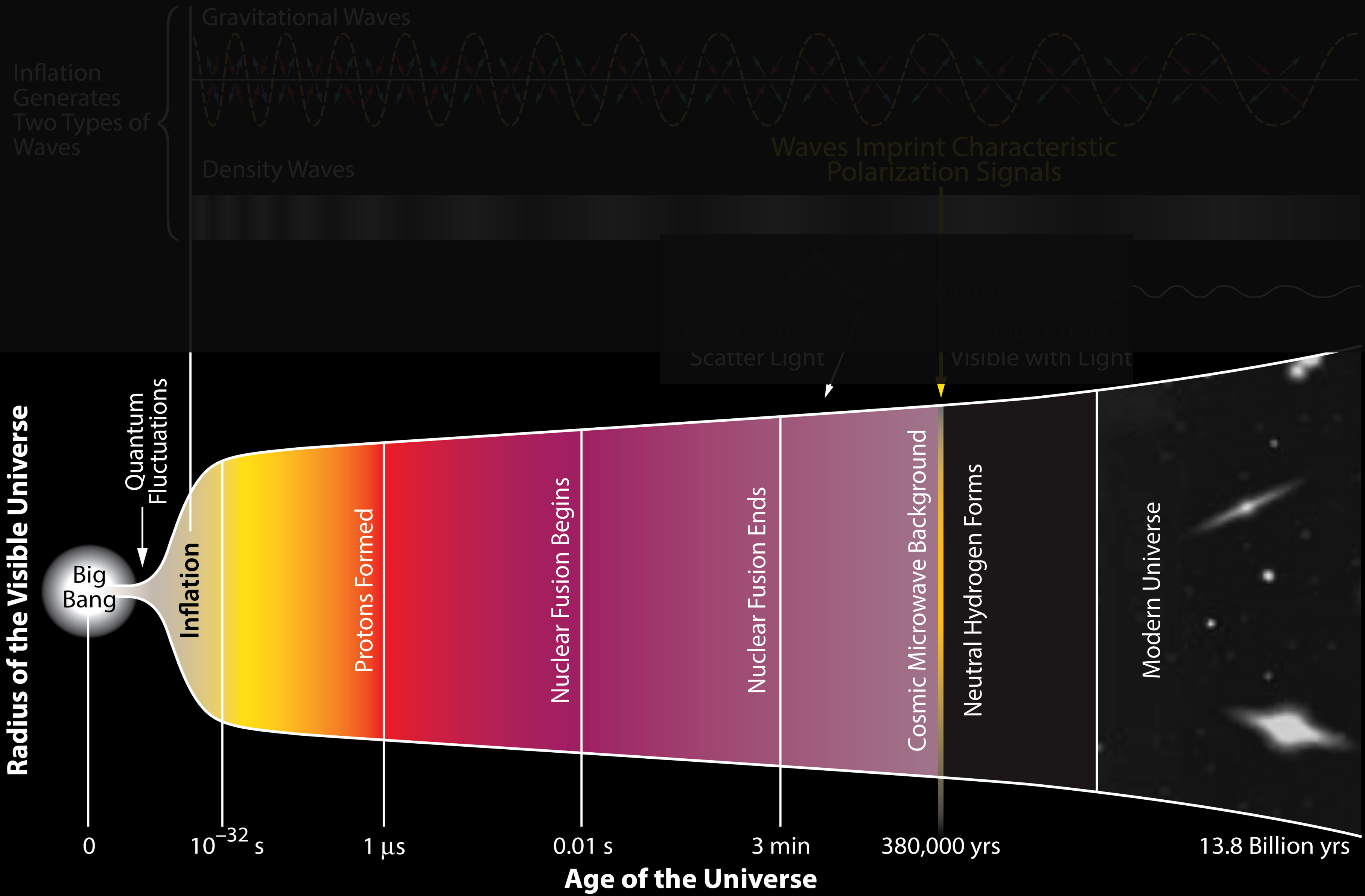
first
stars

~200 million
years

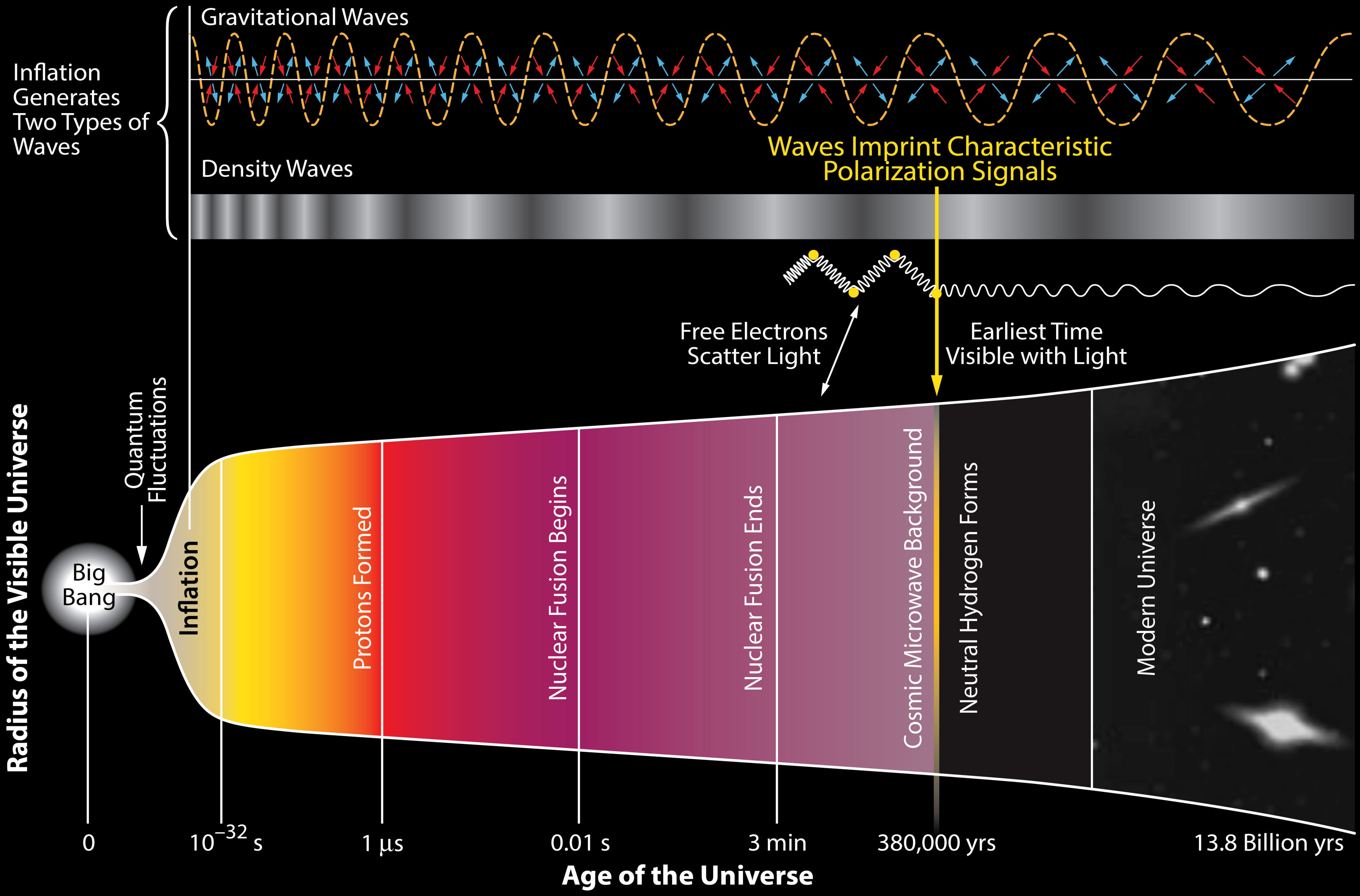
present
day

13.7 billion
years

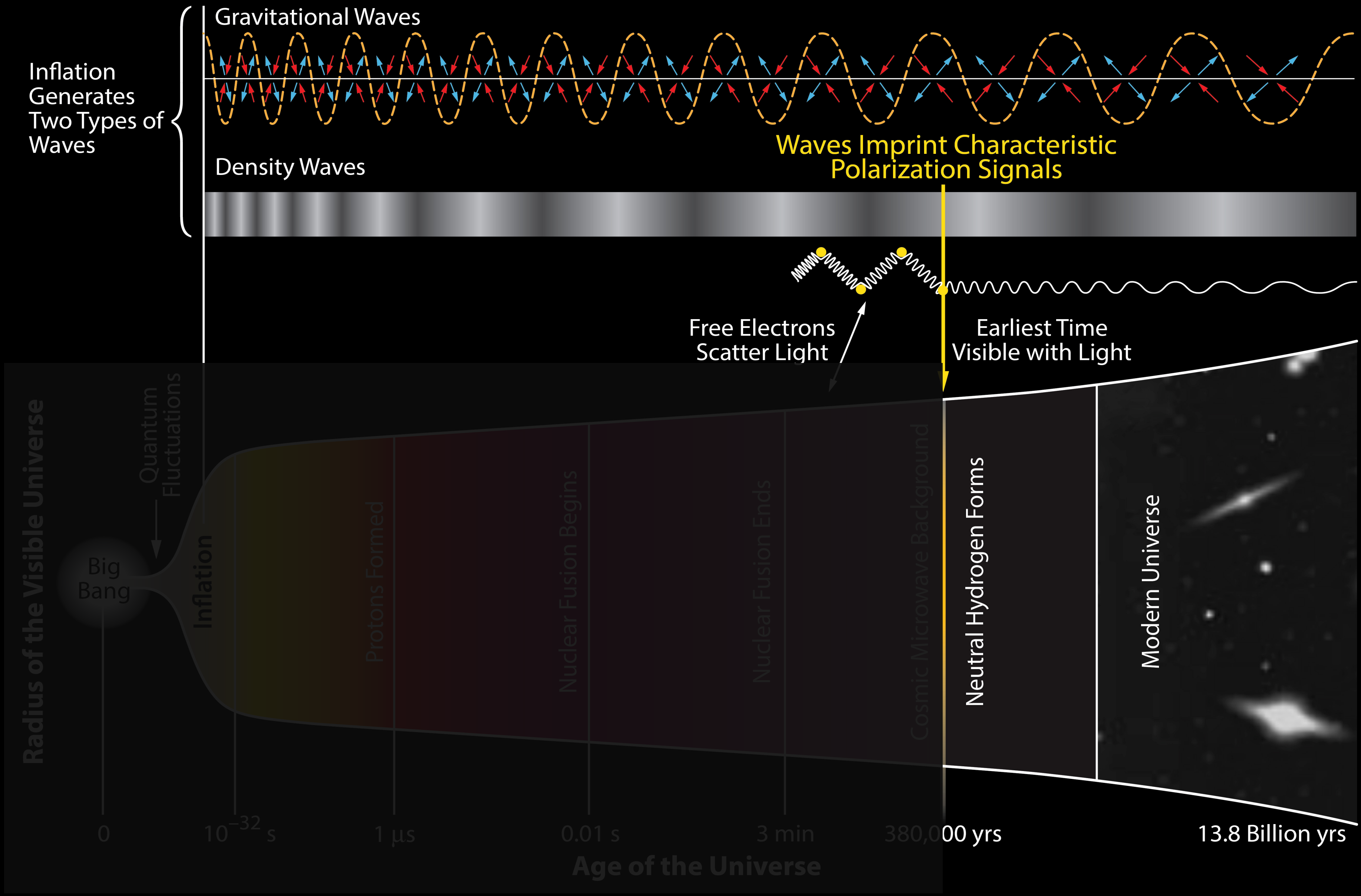
History of the Universe



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

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

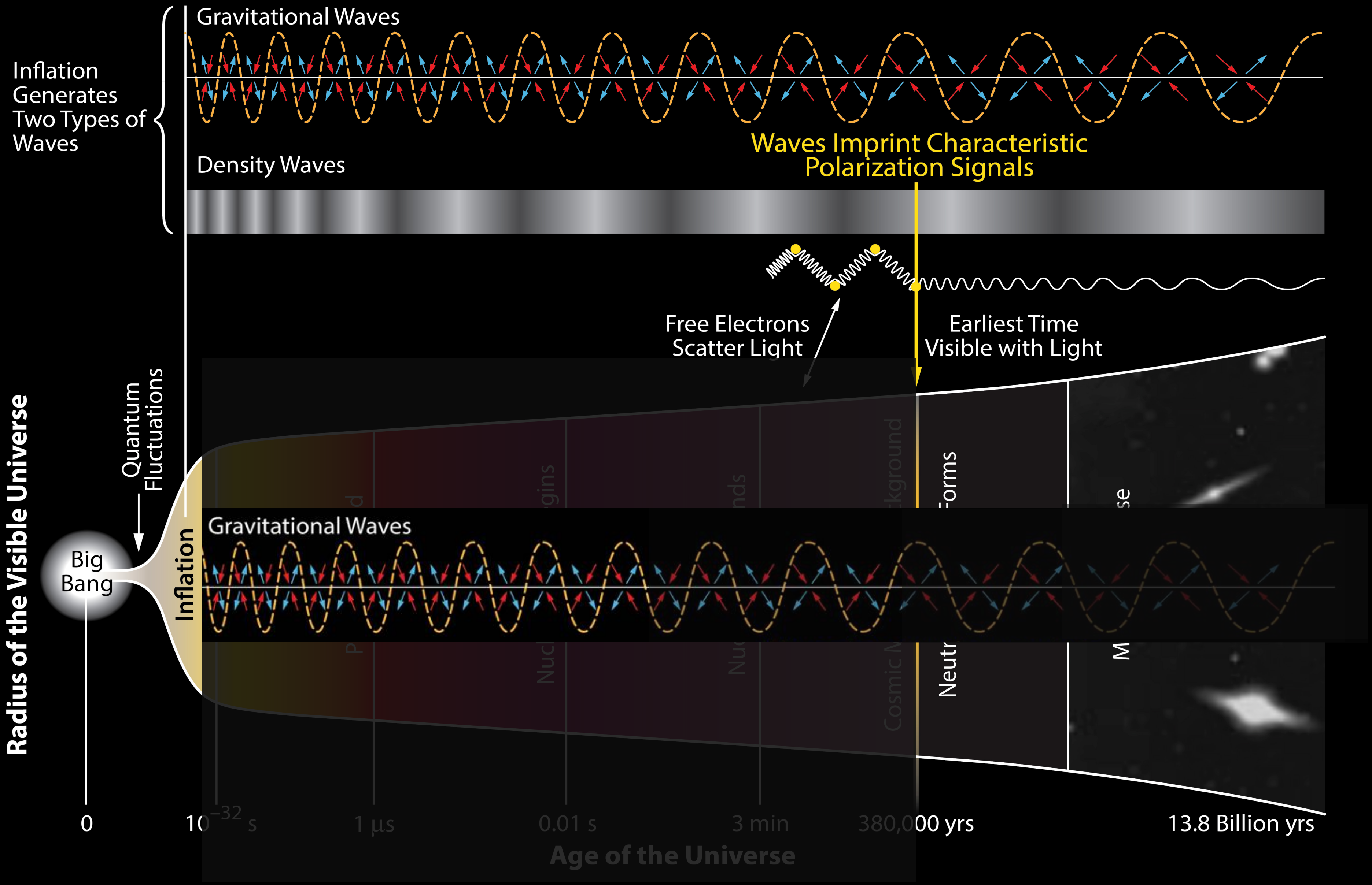
3 min

380,000 yrs

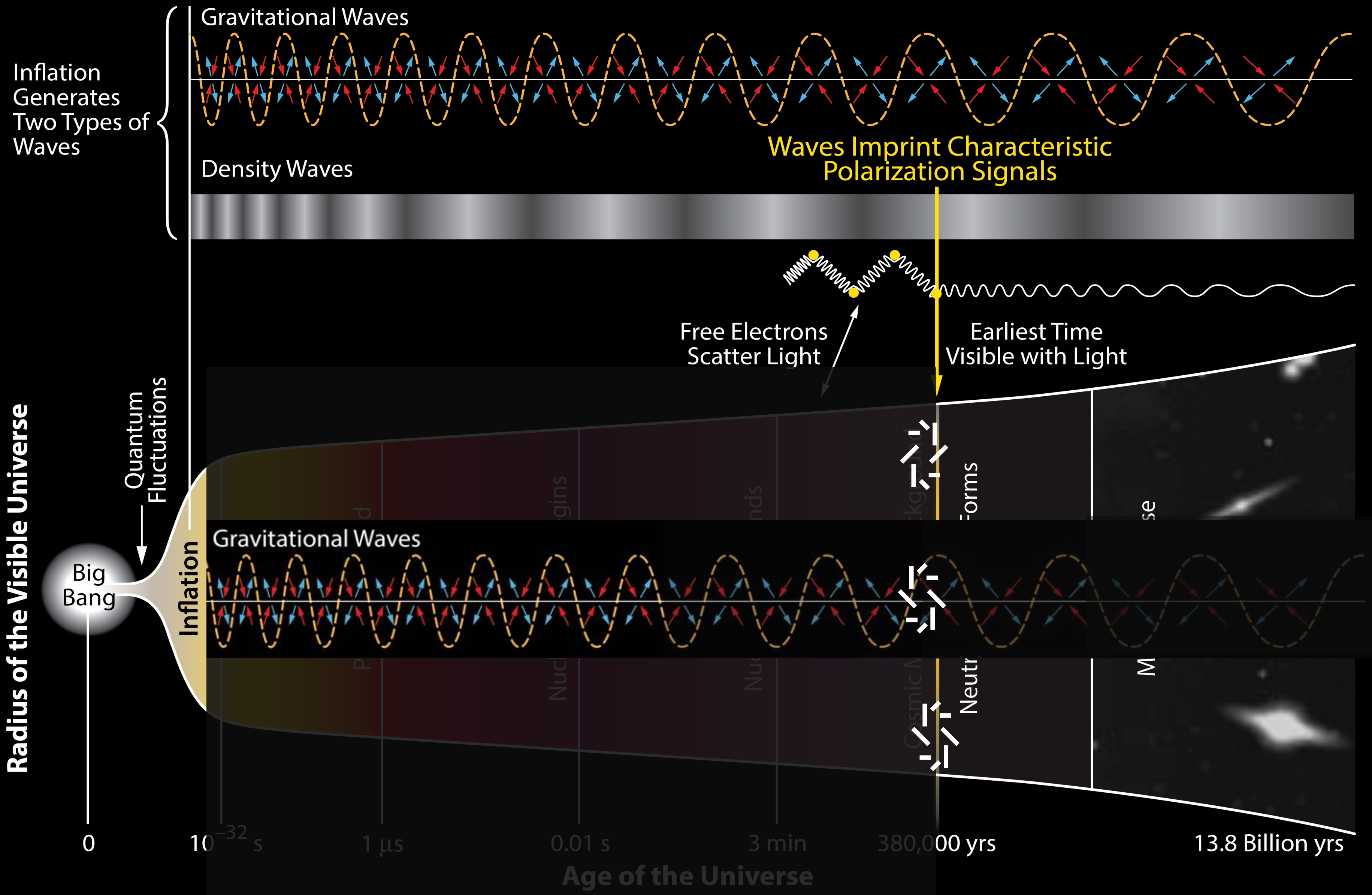
13.8 Billion yrs

Age of the Universe

History of the Universe



History of the Universe



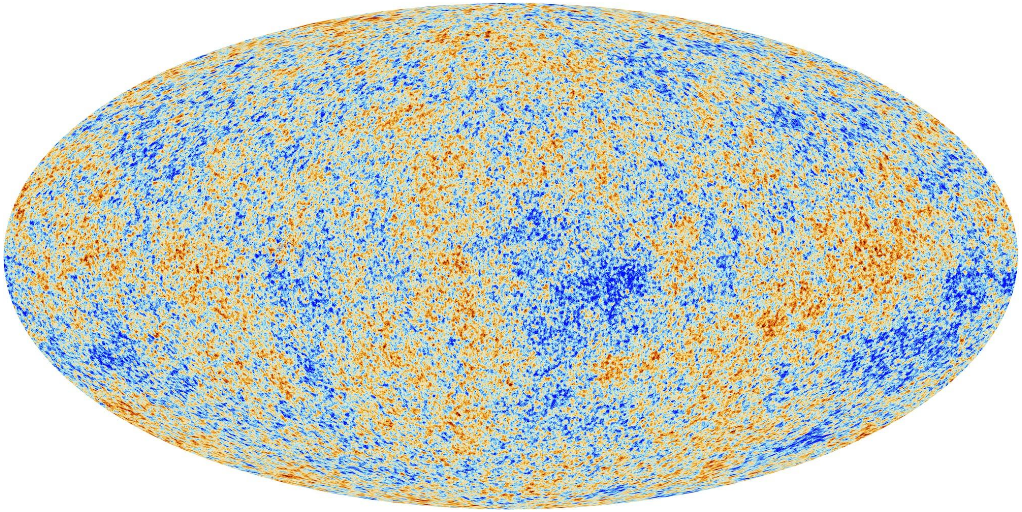
CMB Temperature Measurements / Inflation

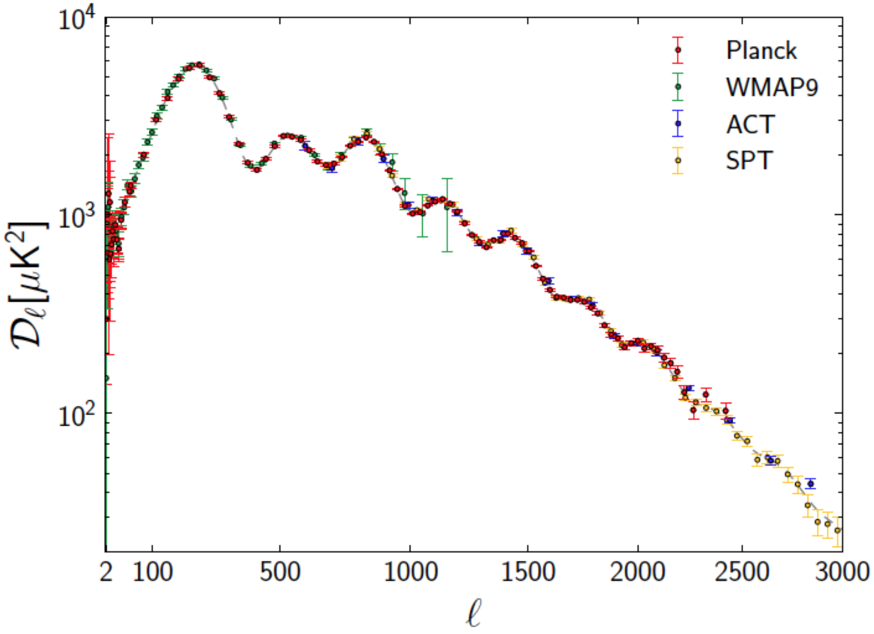
CMB temperature anisotropy now measured over full range of angular scales.

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?

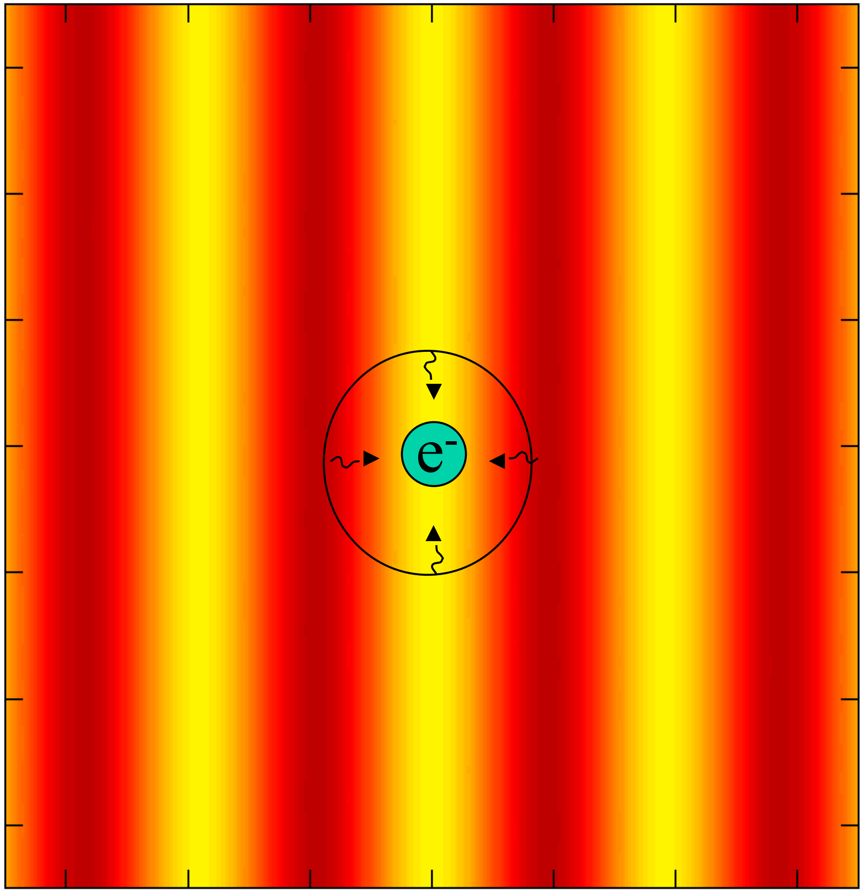
Solves the horizon problem: Why is the CMB nearly uniform? How do apparently causally disconnected regions of space get set to the same temperature? → A volume much larger than our entire observable universe today was once a caussally connected sub atomic spec.

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.

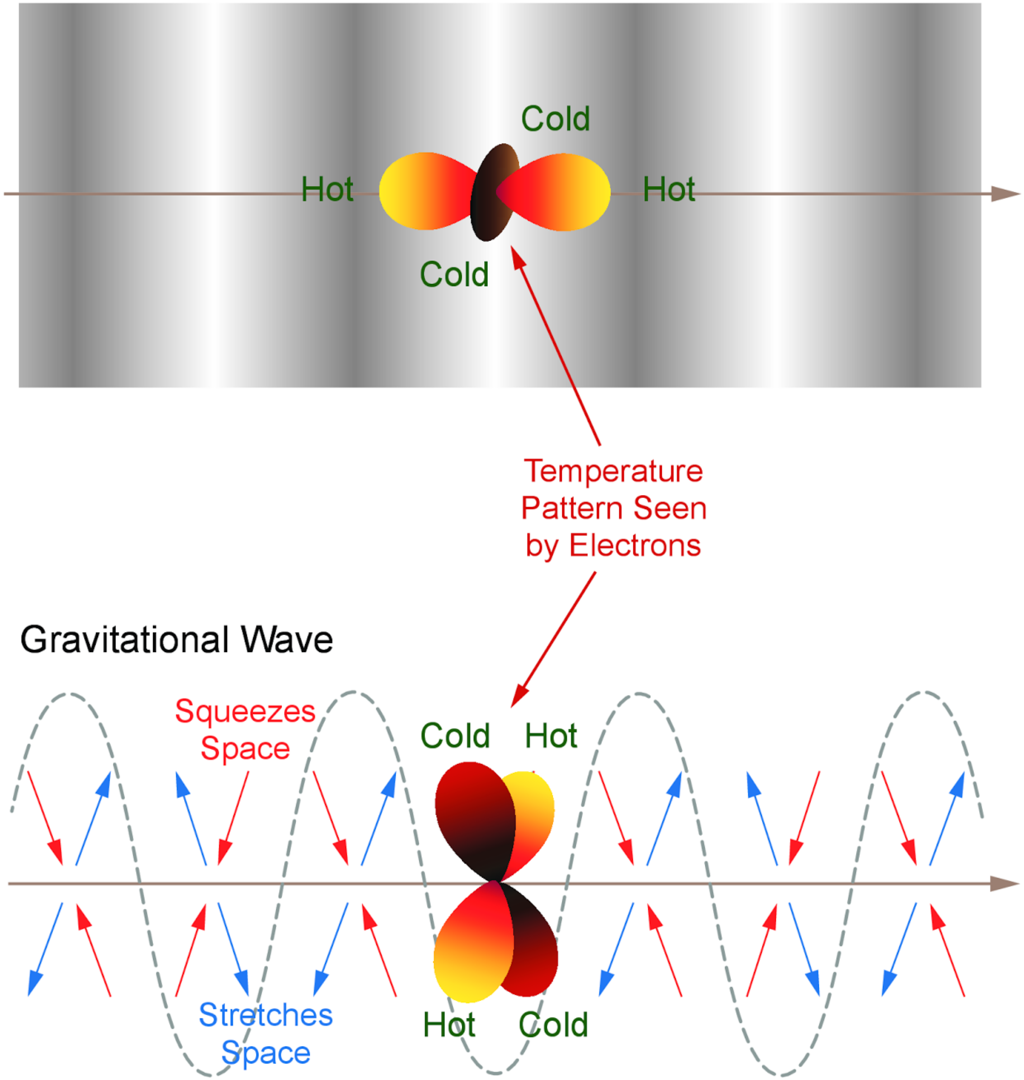
Solves the monopole probem: Why do we not observe magnetic monopoles in the Universe today? → Monopoles are diluted away to undetectability.

CMB polarization: arises at last scattering from local radiation quadrupole



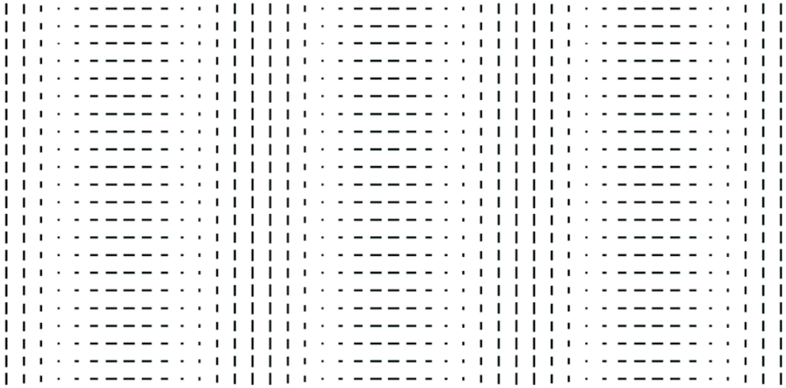
CMB polarization

Density Wave

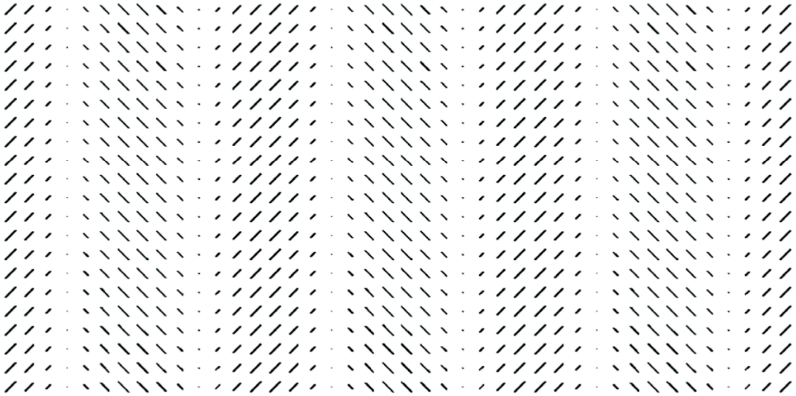


Gravitational Wave

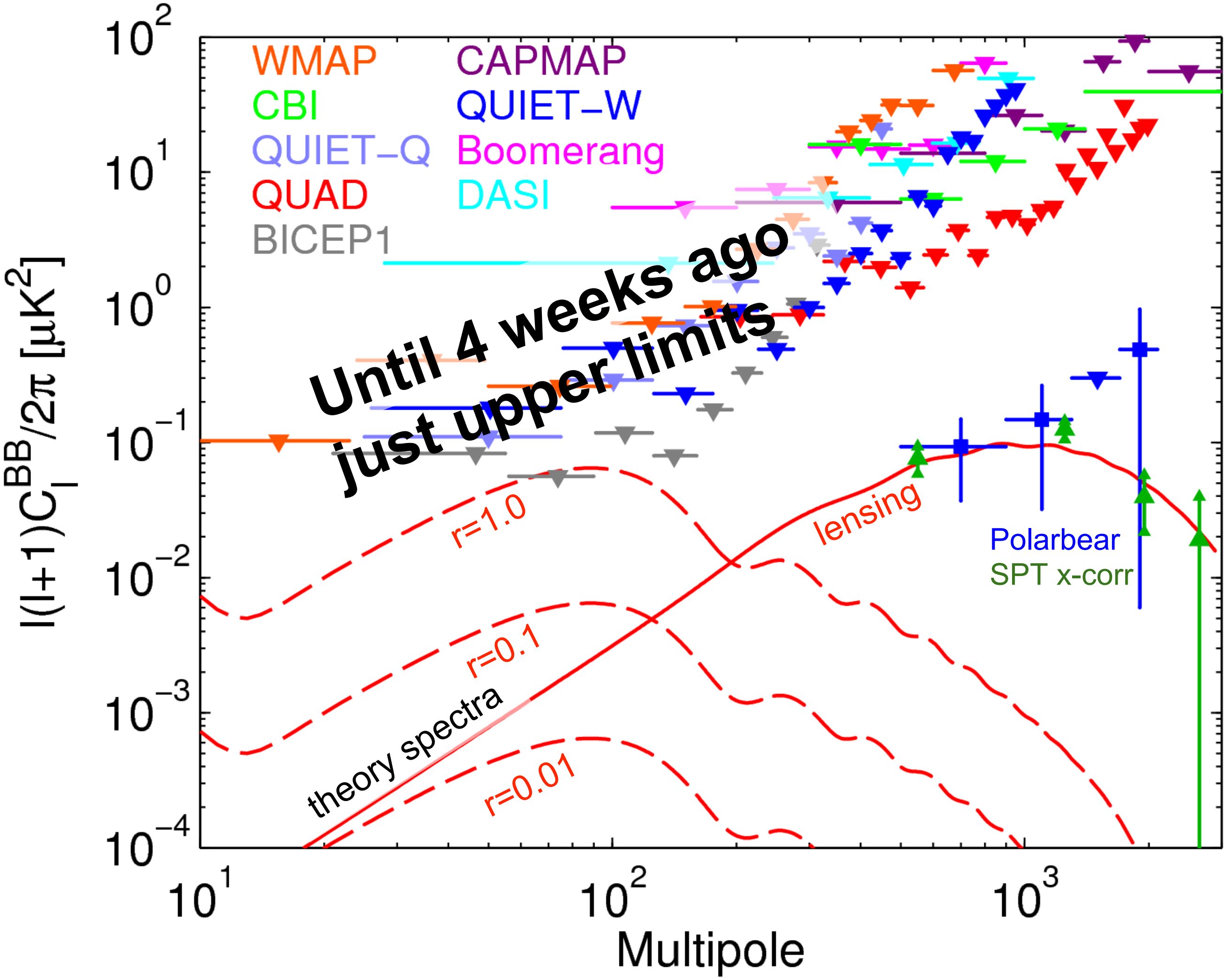
E-Mode Polarization Pattern



B-Mode Polarization Pattern



The long search for Inflationary B-modes



Until 4 weeks ago just upper limits

In simple inflationary gravitational wave models the

tensor-to-scalar ratio r

is the only parameter to the B-mode spectrum.

Until recently only upper limits from searches for Inflationary B-modes

Best previous limit on r from BICEP1:

r < 0.7 (95% CL)

Note at high multipoles lensing B-mode dominant.

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

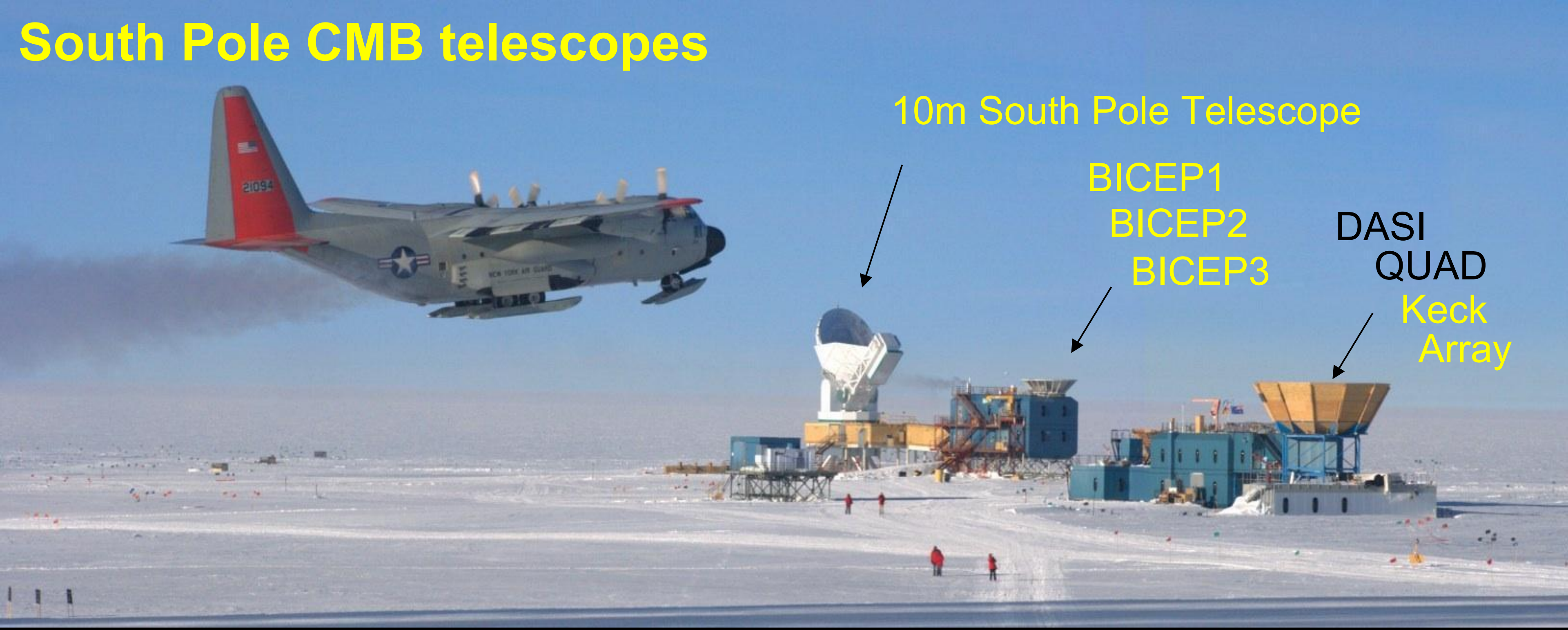
Clem Pryke for The Bicep2 Collaboration

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

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, and bingo night...

BICEP1
(2006 - 8)

BICEP2
(2010 - 12)

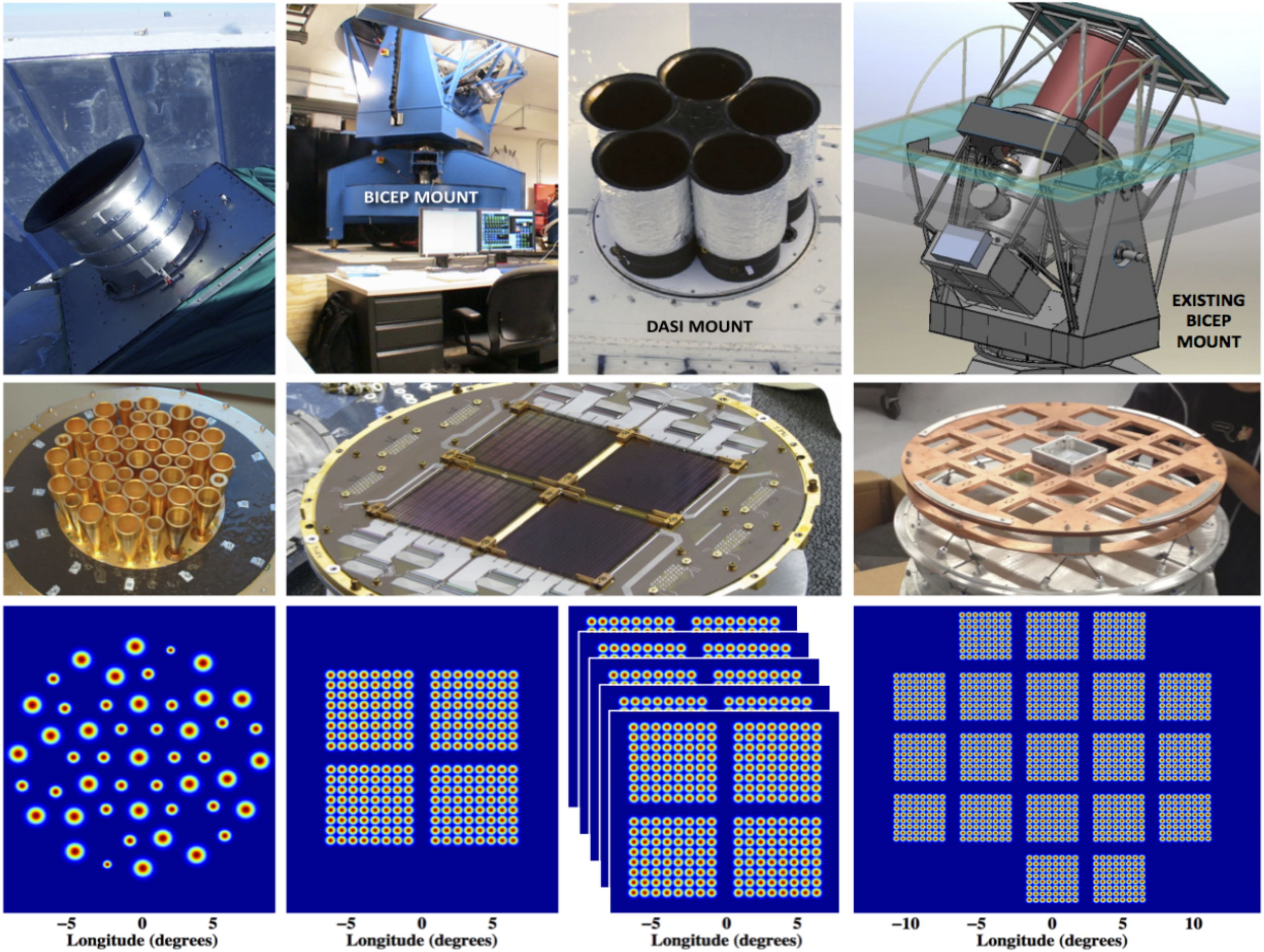
Keck Array
(2011 -)

BICEP3
(2014 -)

Telescope and Mount

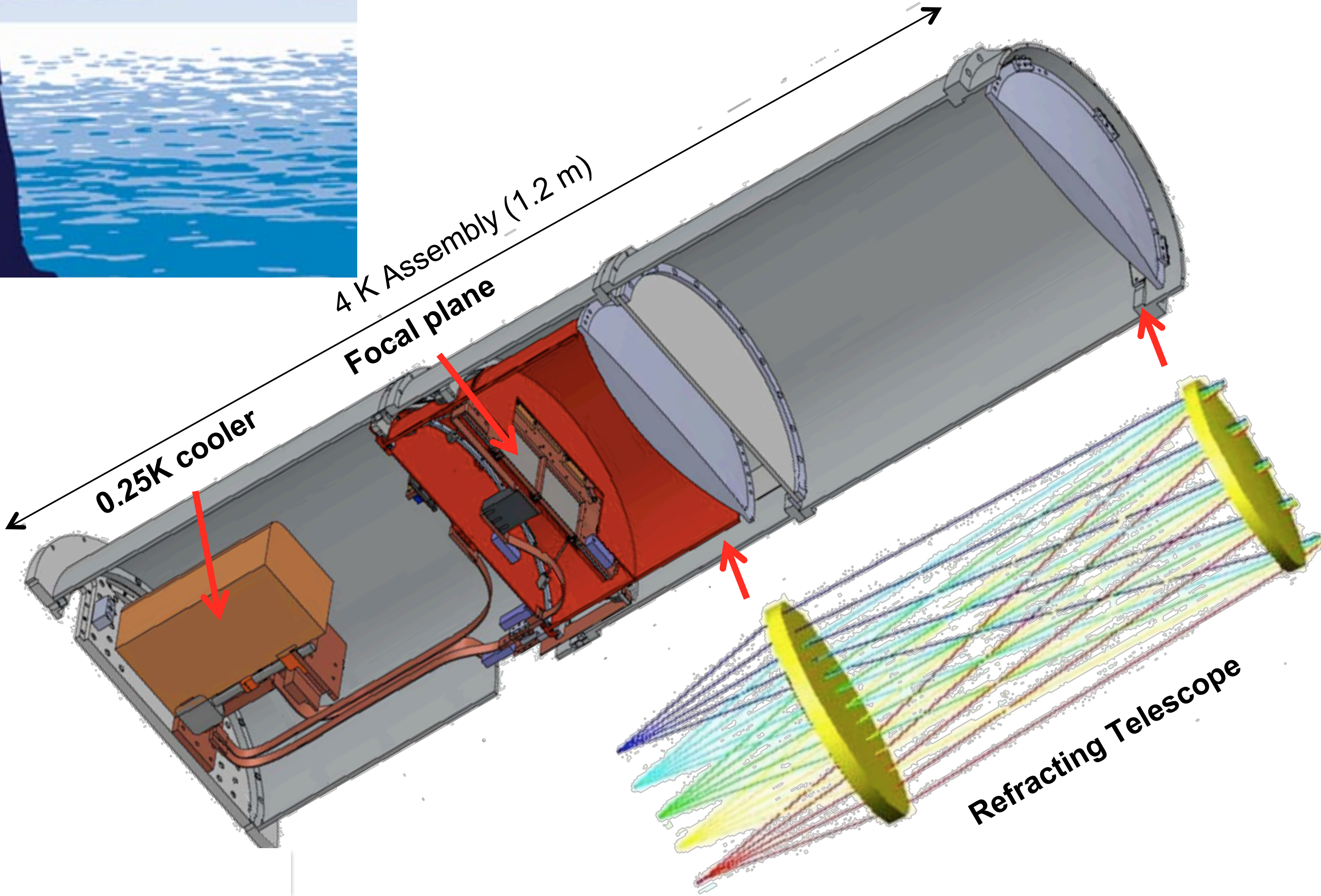
Focal Plane

Beams on Sky

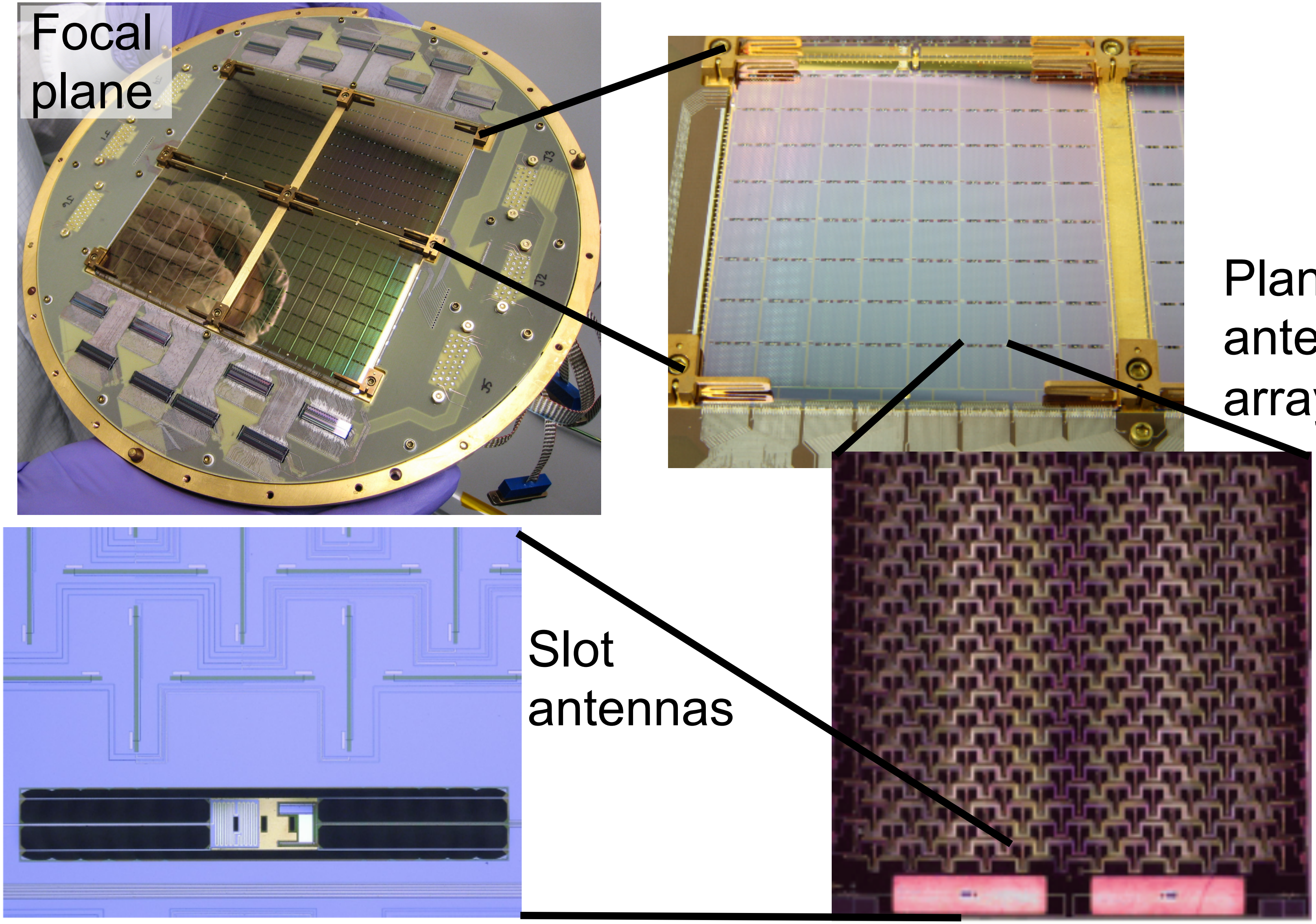


BICEP2 Experimental Concept

- Small aperture
- Wide field of view
- Cold refractor



Mass-produced superconducting detectors



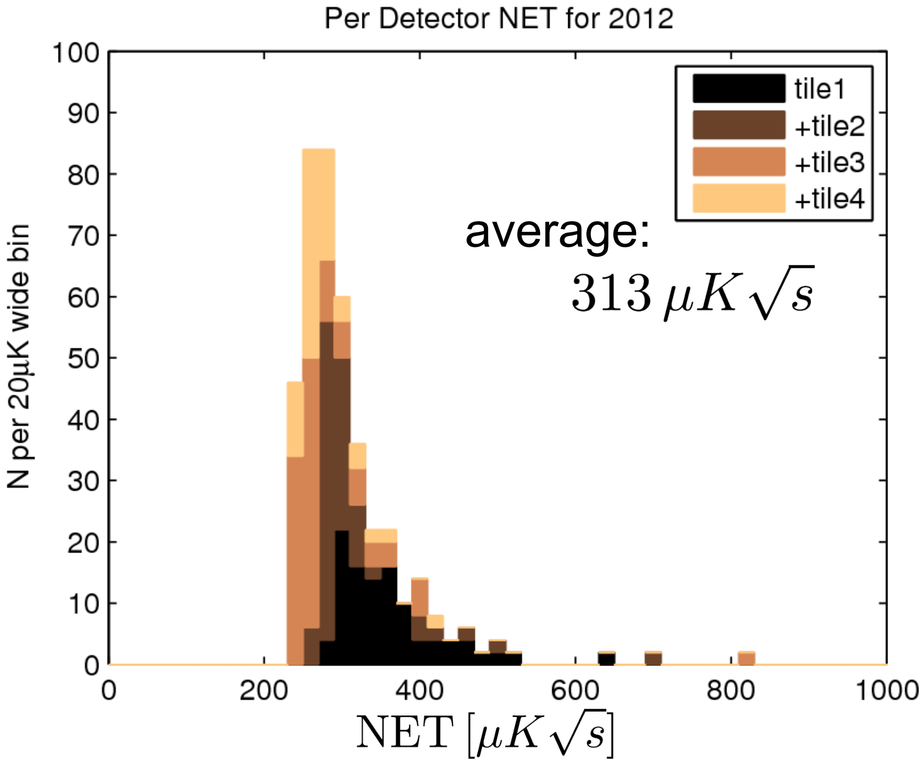
Planar antenna array

Slot antennas

Transition edge sensor

Microstrip filters

BICEP2 Sensitivity



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

Our recipe for high sensitivity:

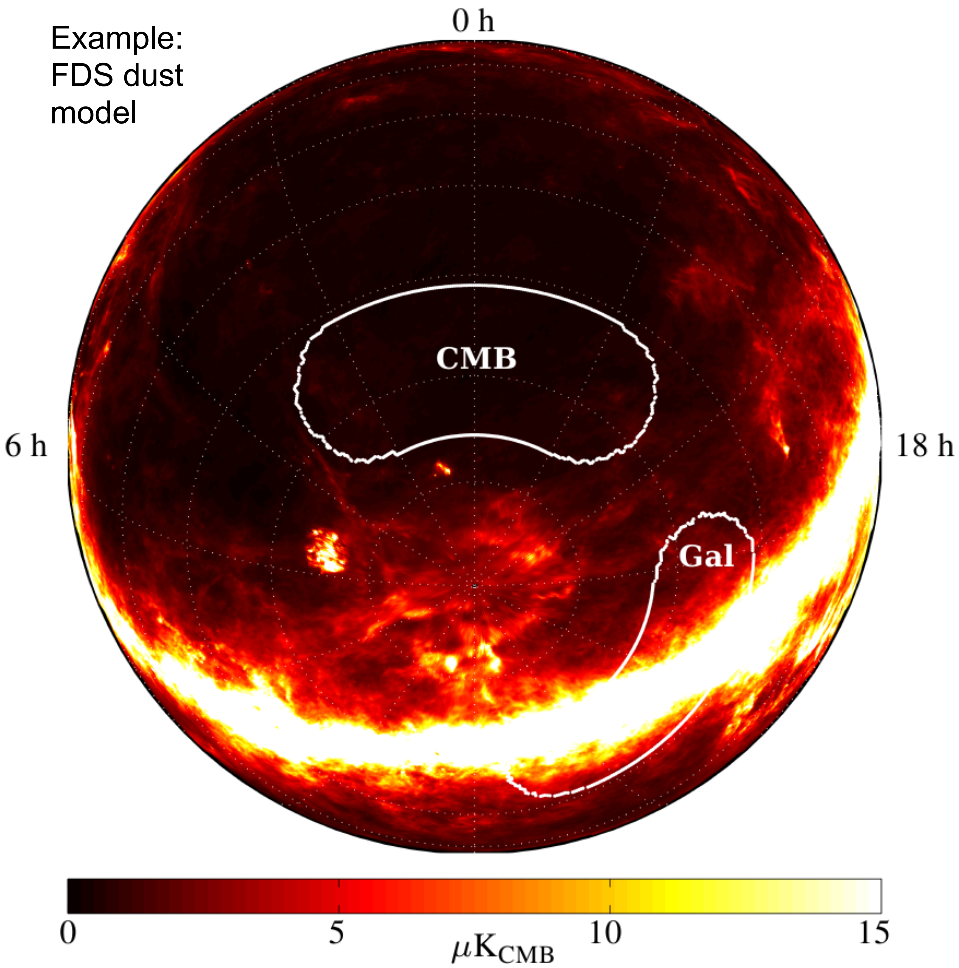
→ High optical efficiency
40% end-to-end

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

→ High detector count

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

Observational Strategy

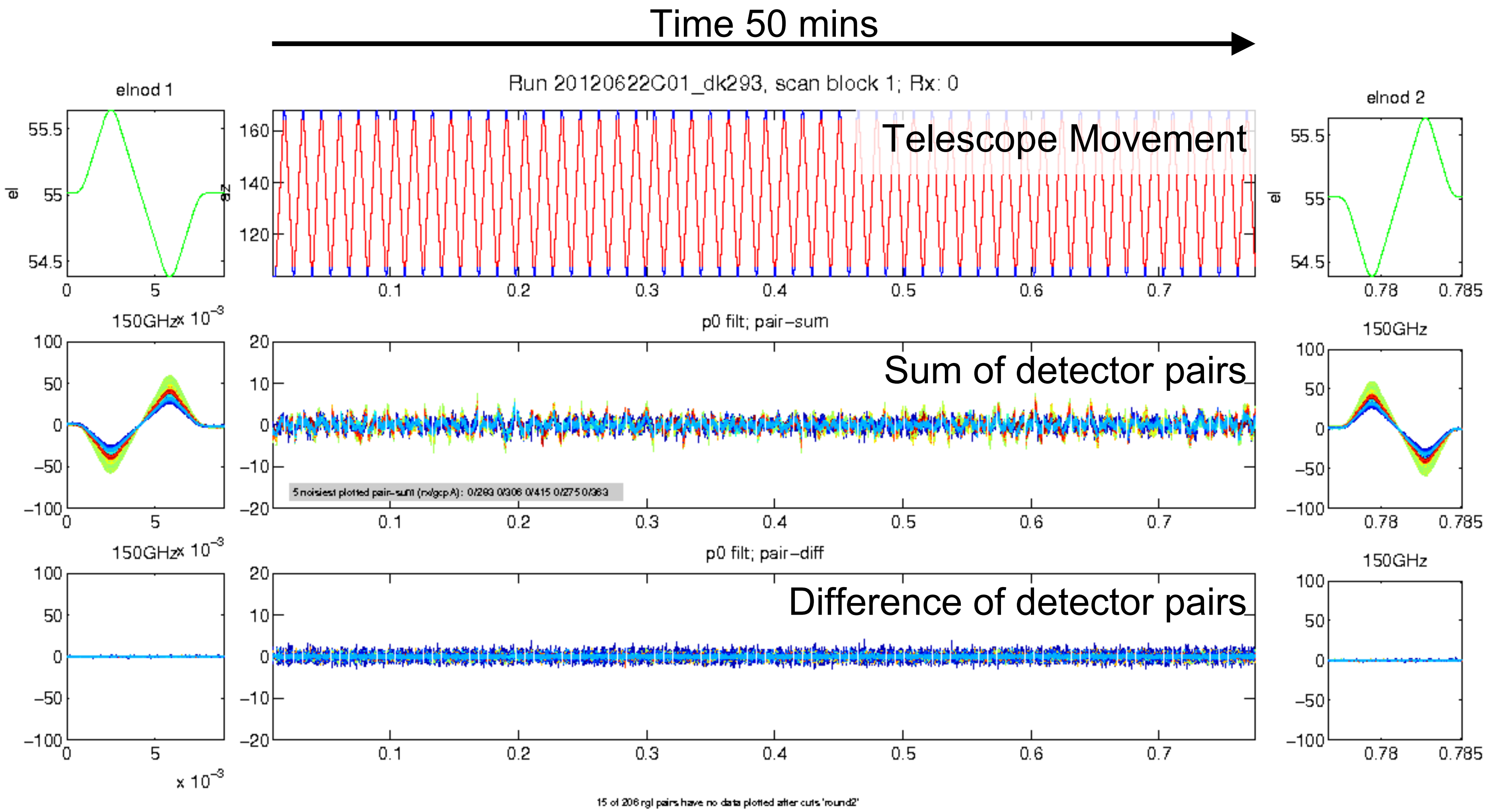


Target the “Southern Hole” - a region of the sky exceptionally free of dust and synchrotron foregrounds.

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

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

Raw Data - Perfect Weather



Time 50 mins

Telescope Movement

Sum of detector pairs

Difference of detector pairs

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

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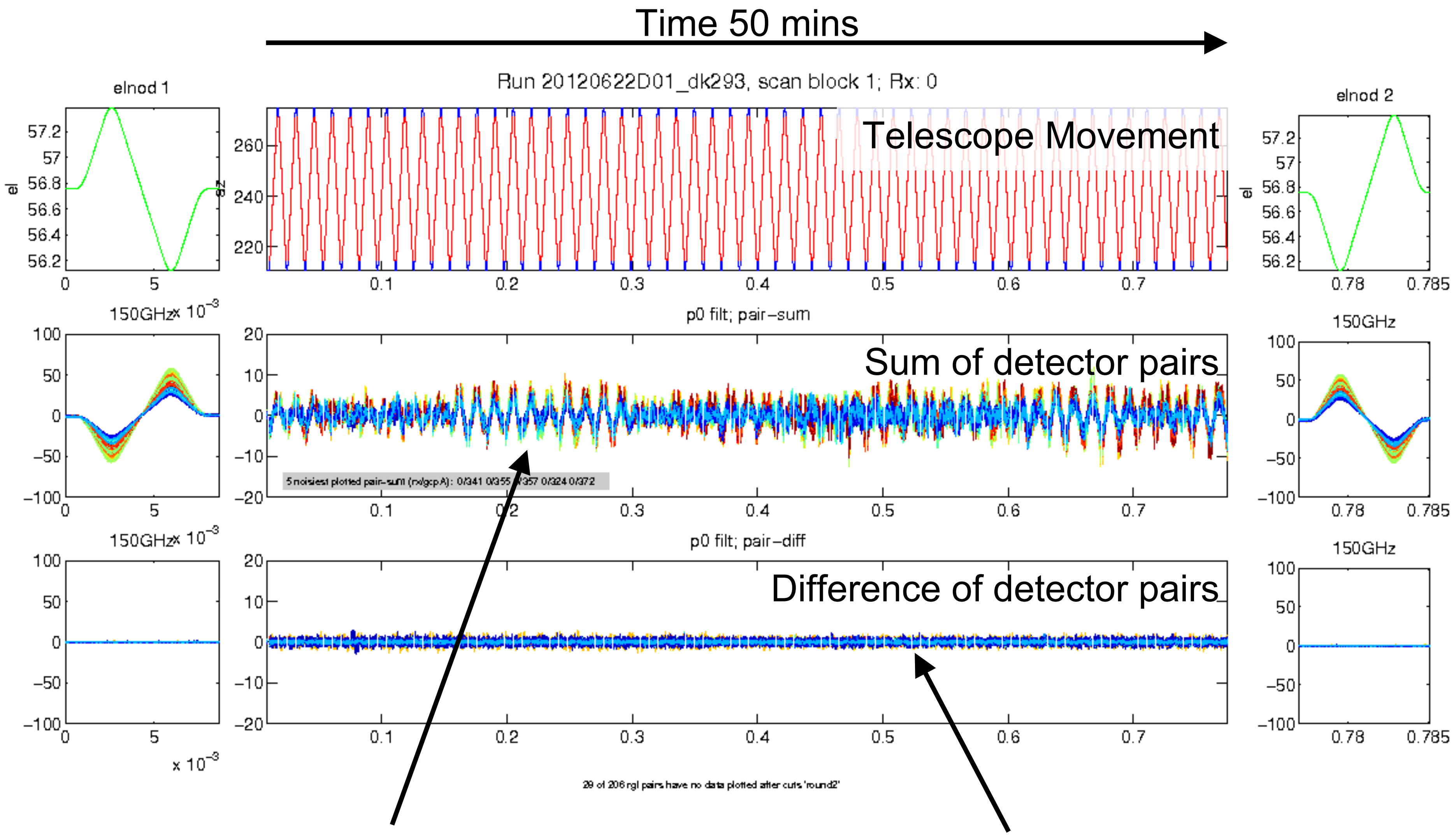
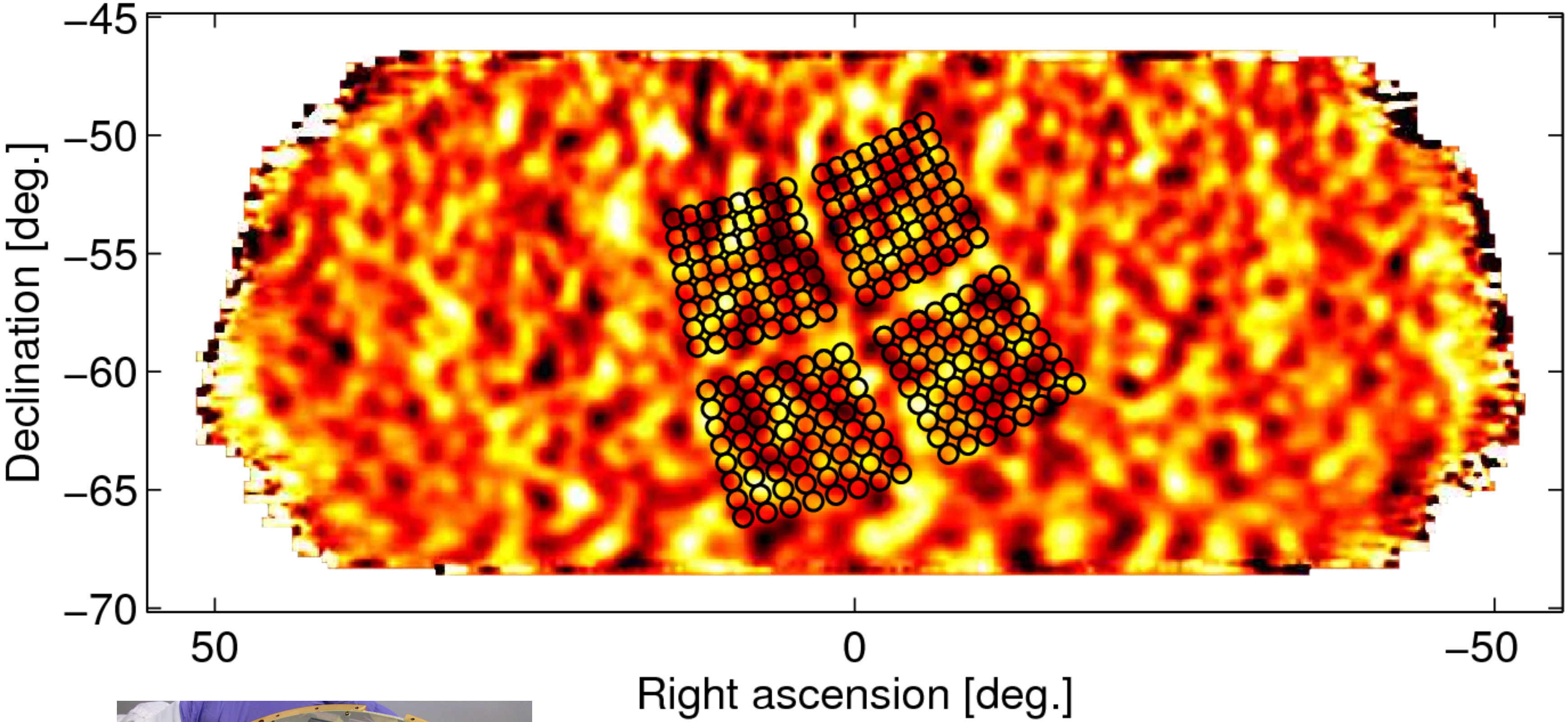
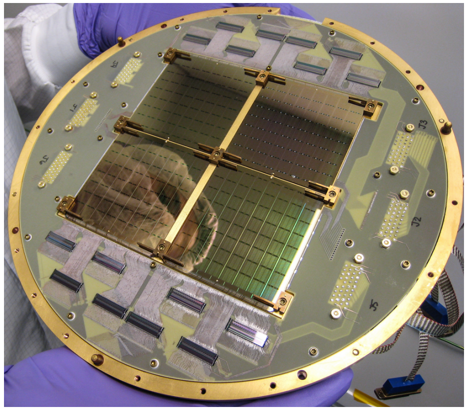
Raw Data - Worse Weather



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

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

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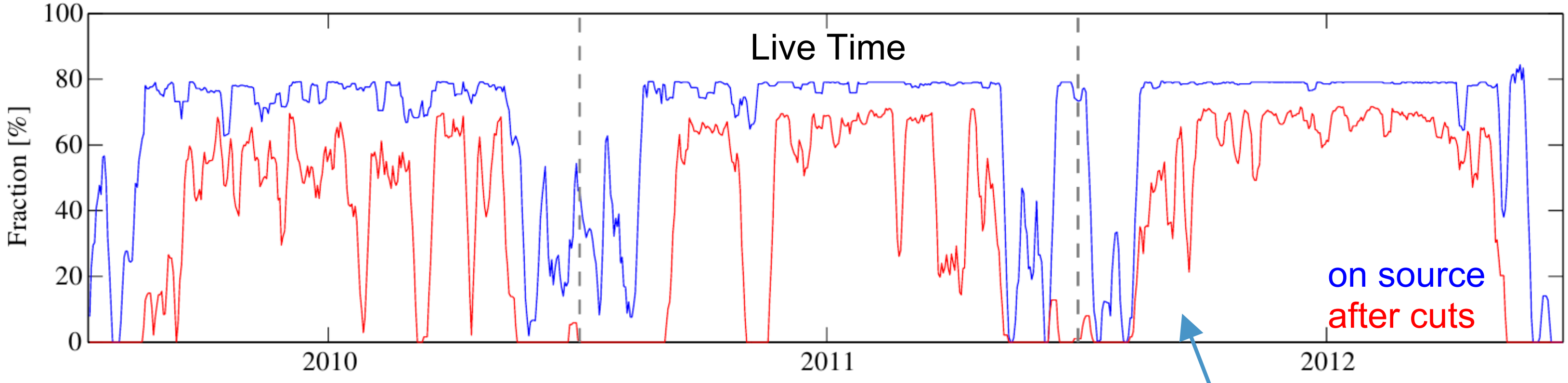
Data Quality Cuts



3 years of data!

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

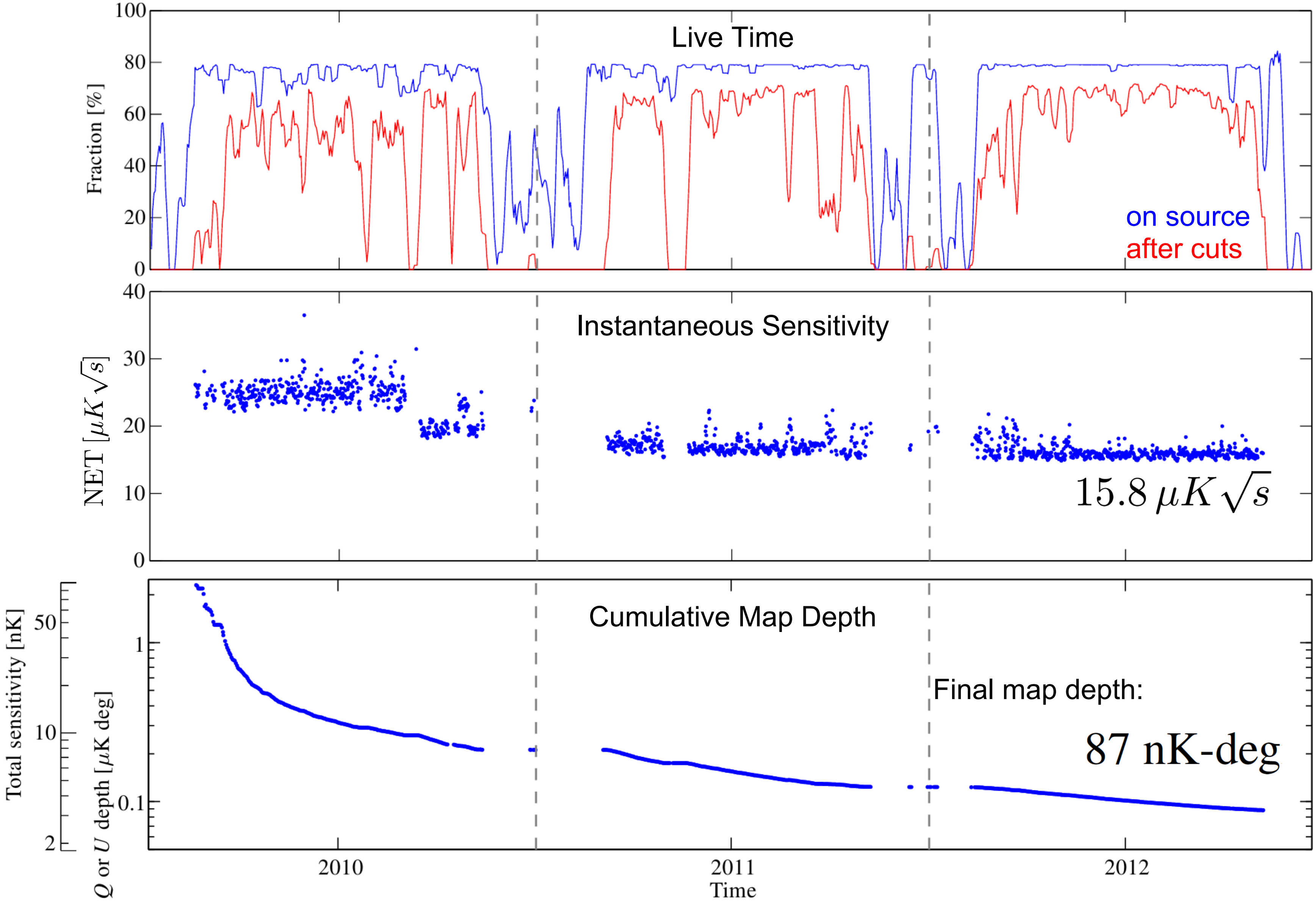
Multistage cut procedure:

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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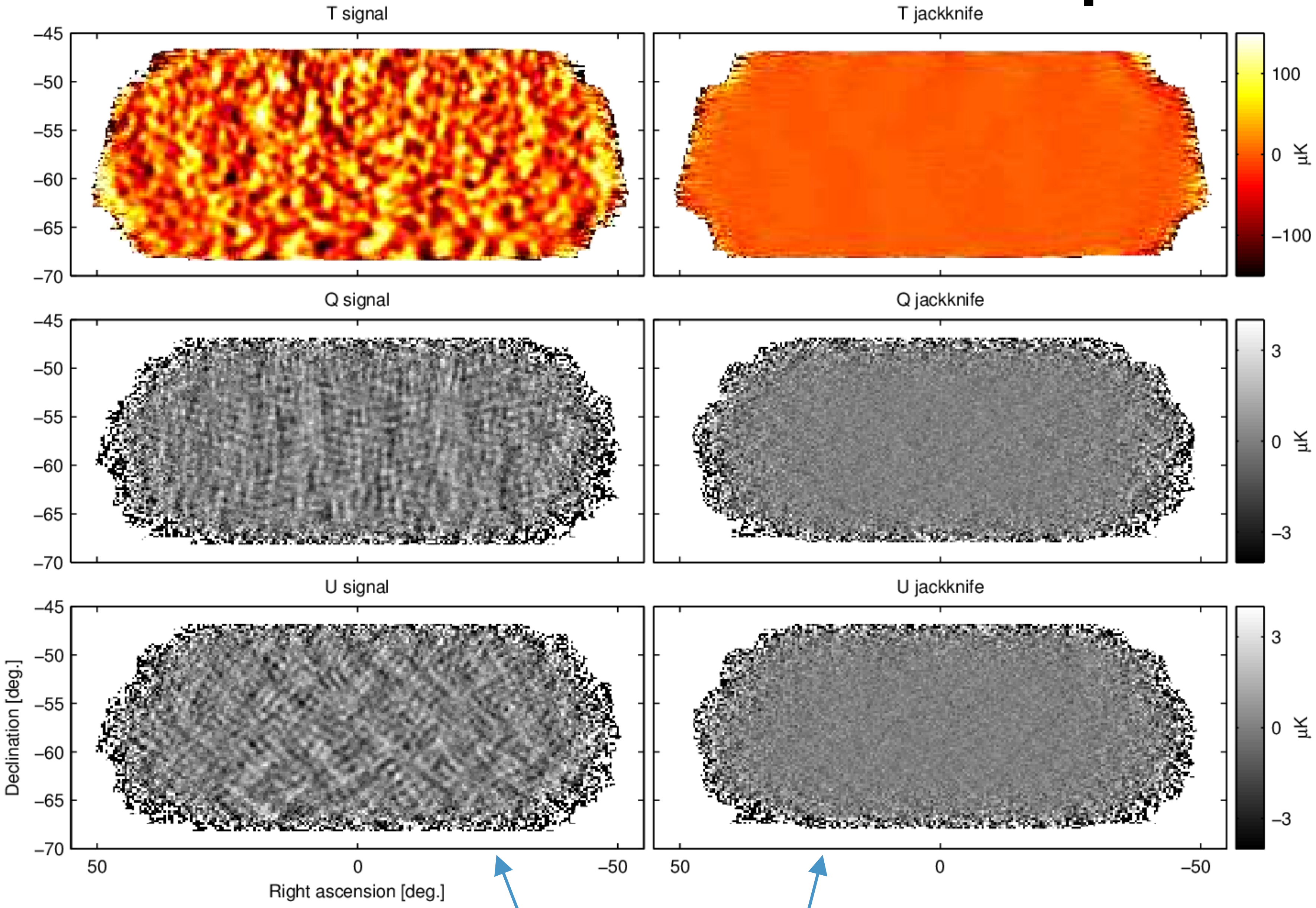
BICEP2 T and Stokes Q/U Maps



Sum Maps

Difference Maps

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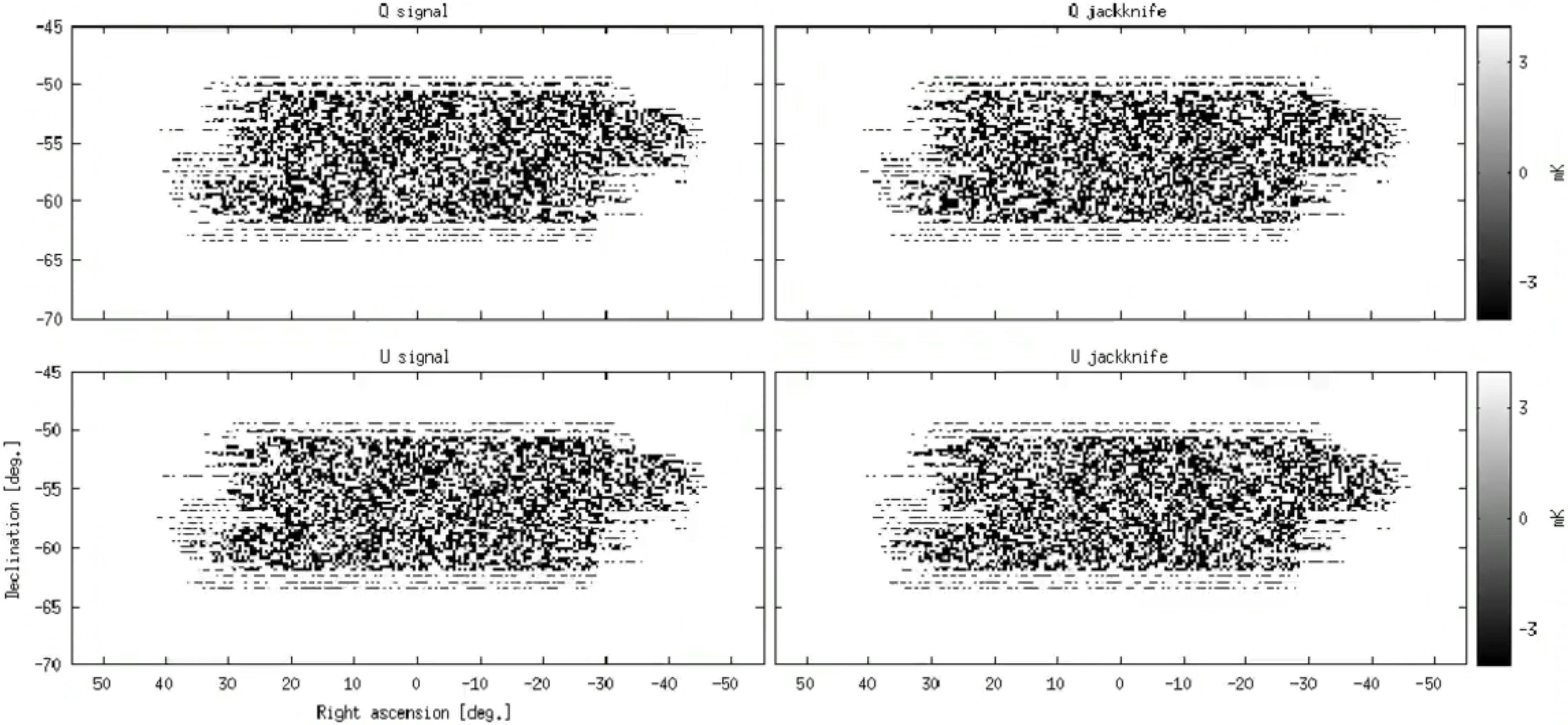
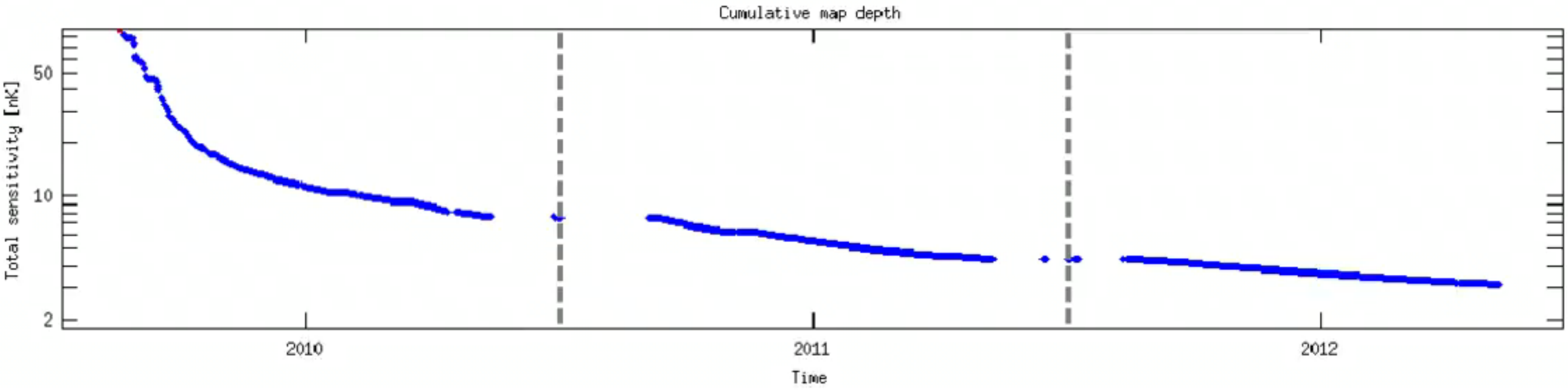
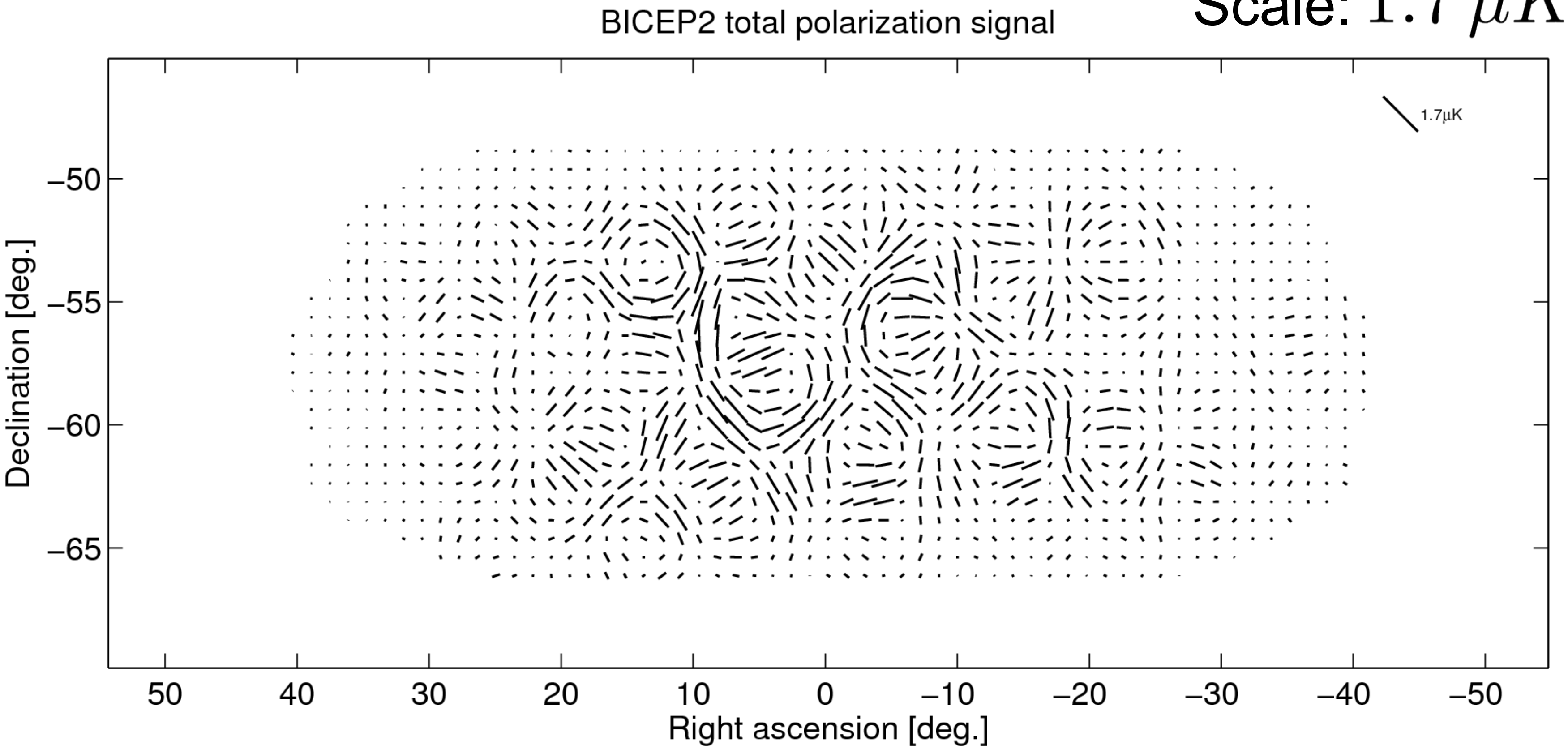

Q signal
Q jackknife
U signal
U jackknife
-45
-50
-55
-60
-65
-70
Declination [deg.]
50
40
30
20
10
0
-10
-20
-30
-40
-50
Right ascension [deg.]
3
0
-3
mK


Cumulative map depth
Total sensitivity [nK]
50
10
2
2010
2011
2012
Time

Total Polarization

Scale: $1.7\,\mu K$



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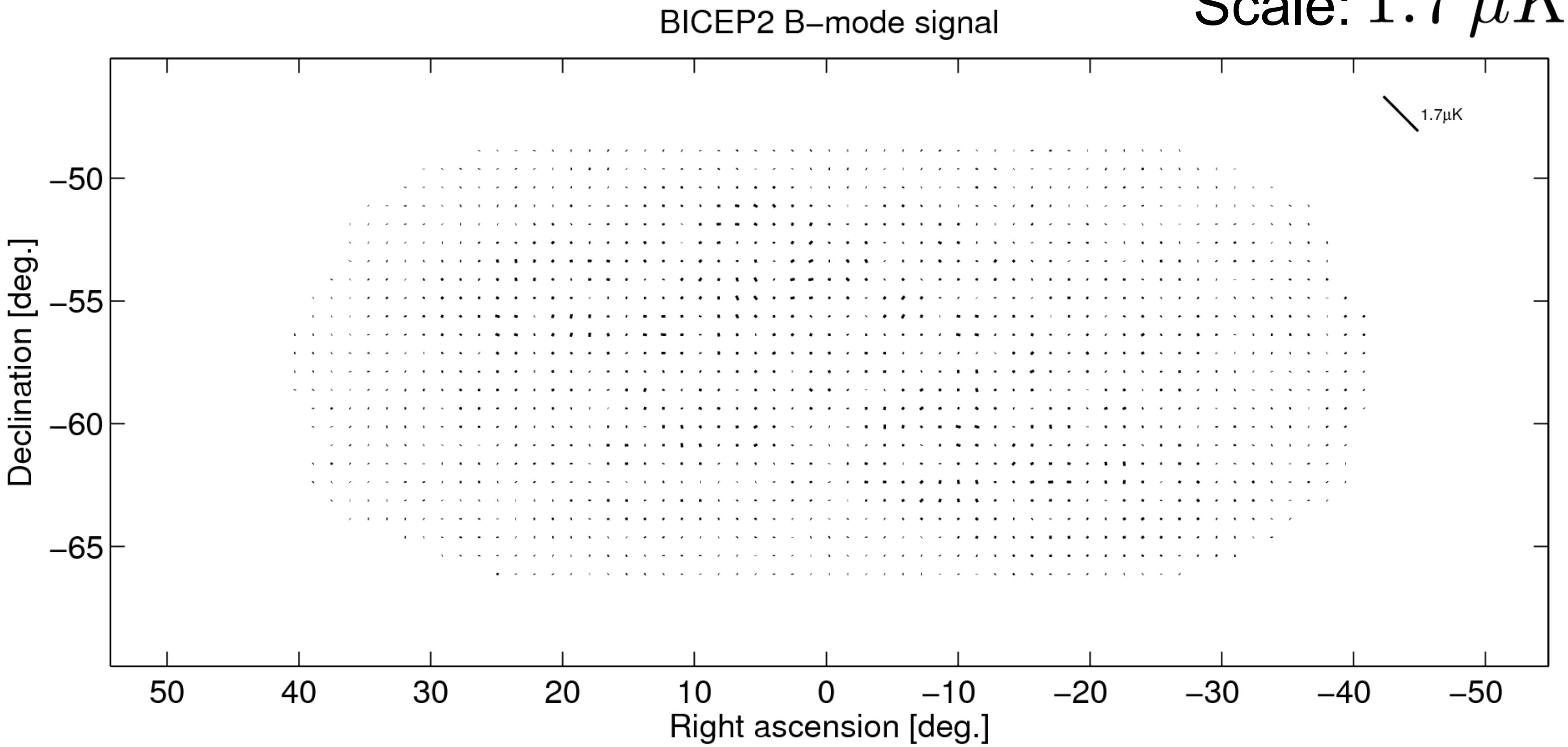
B-mode Contribution

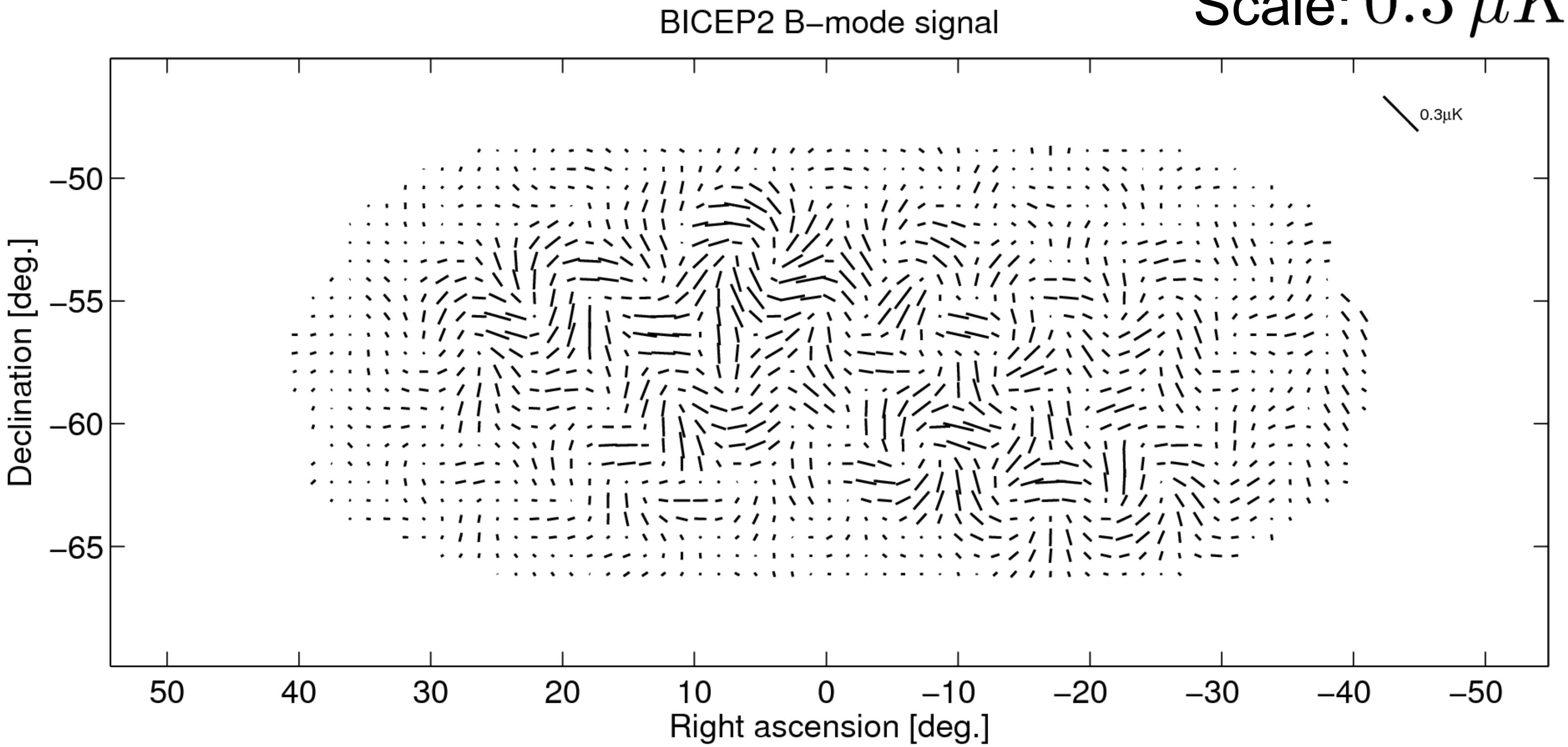
Scale: $1.7\,\mu K$



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

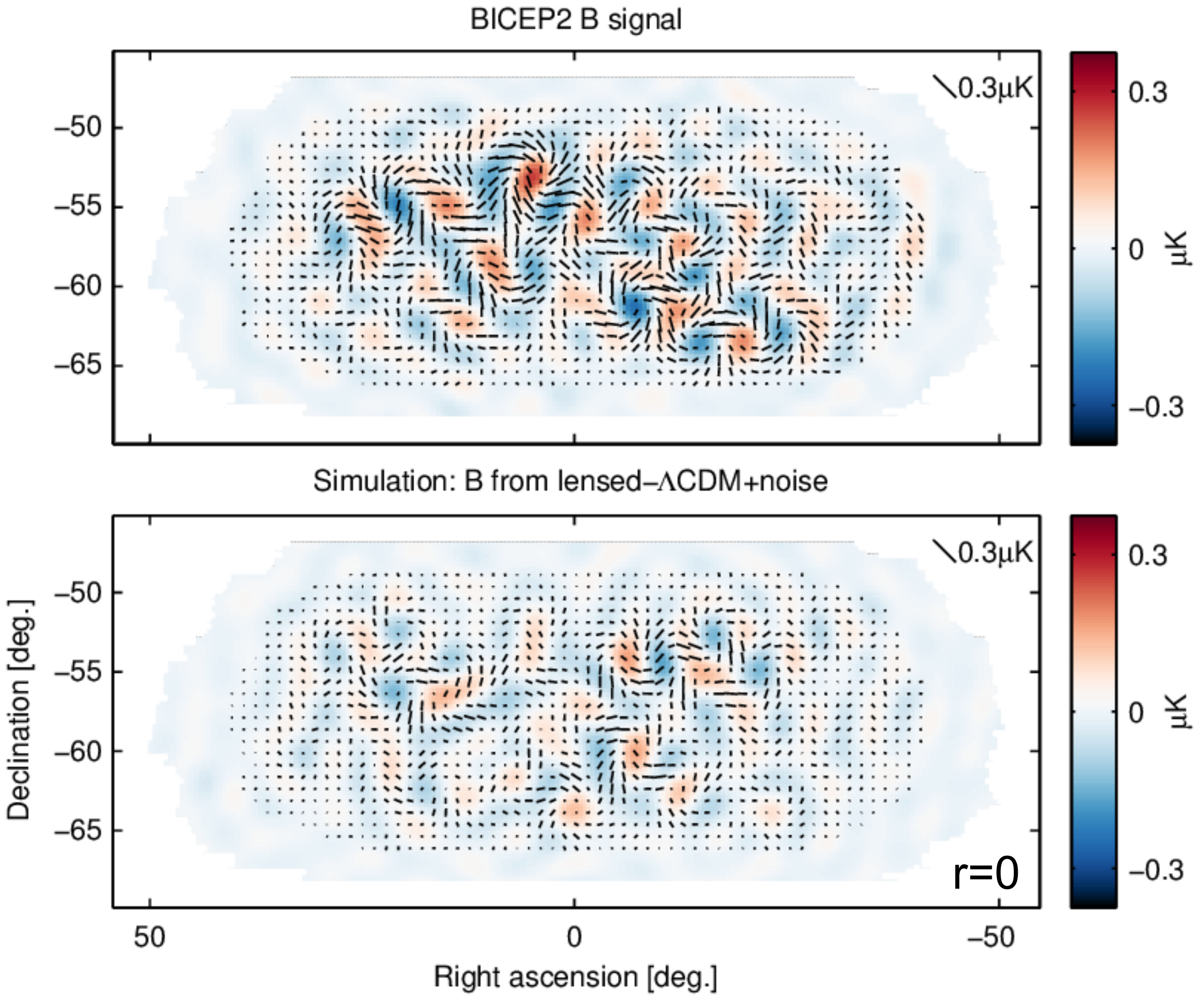
B-mode Contribution

Scale: $0.3\,\mu K$



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

B-mode Map vs. Simulation



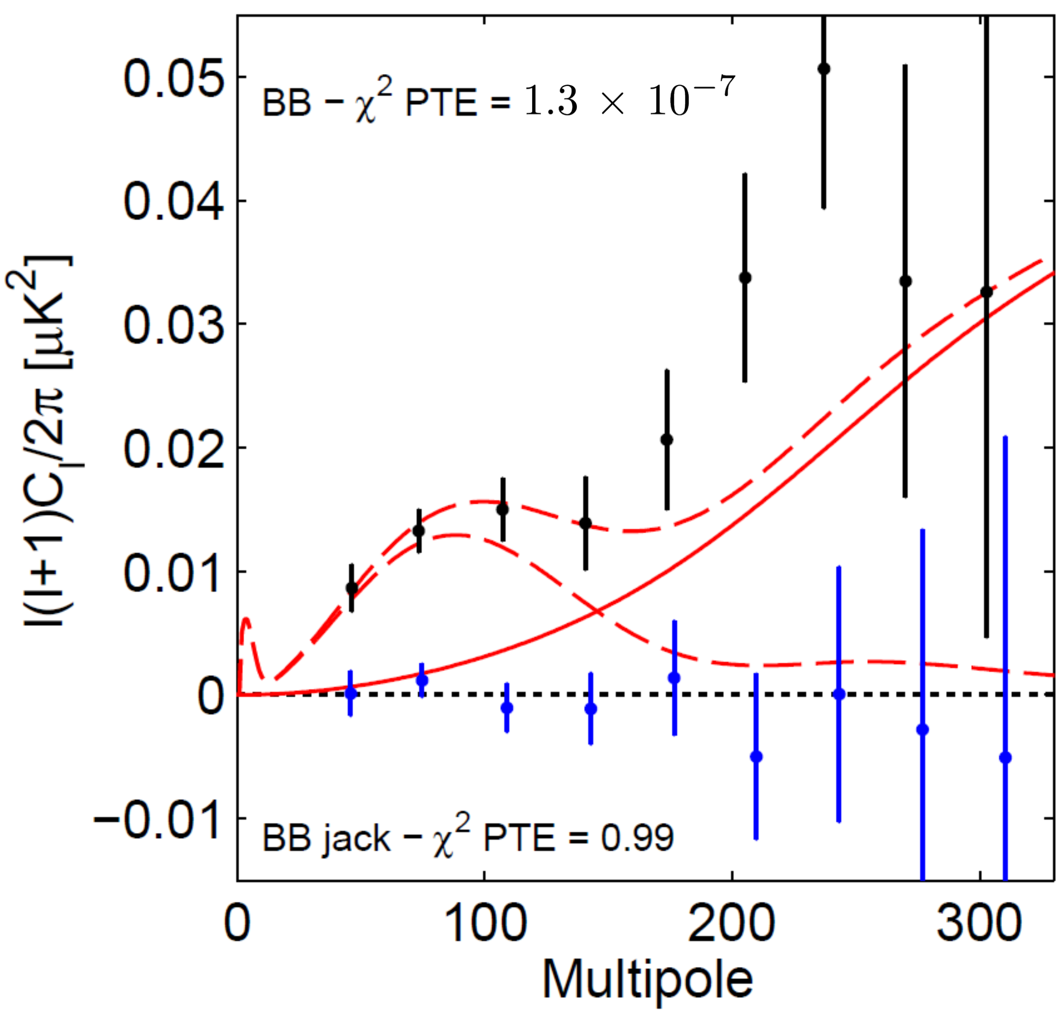
Analysis “calibrated” using lensed-ΛCDM+noise simulations.

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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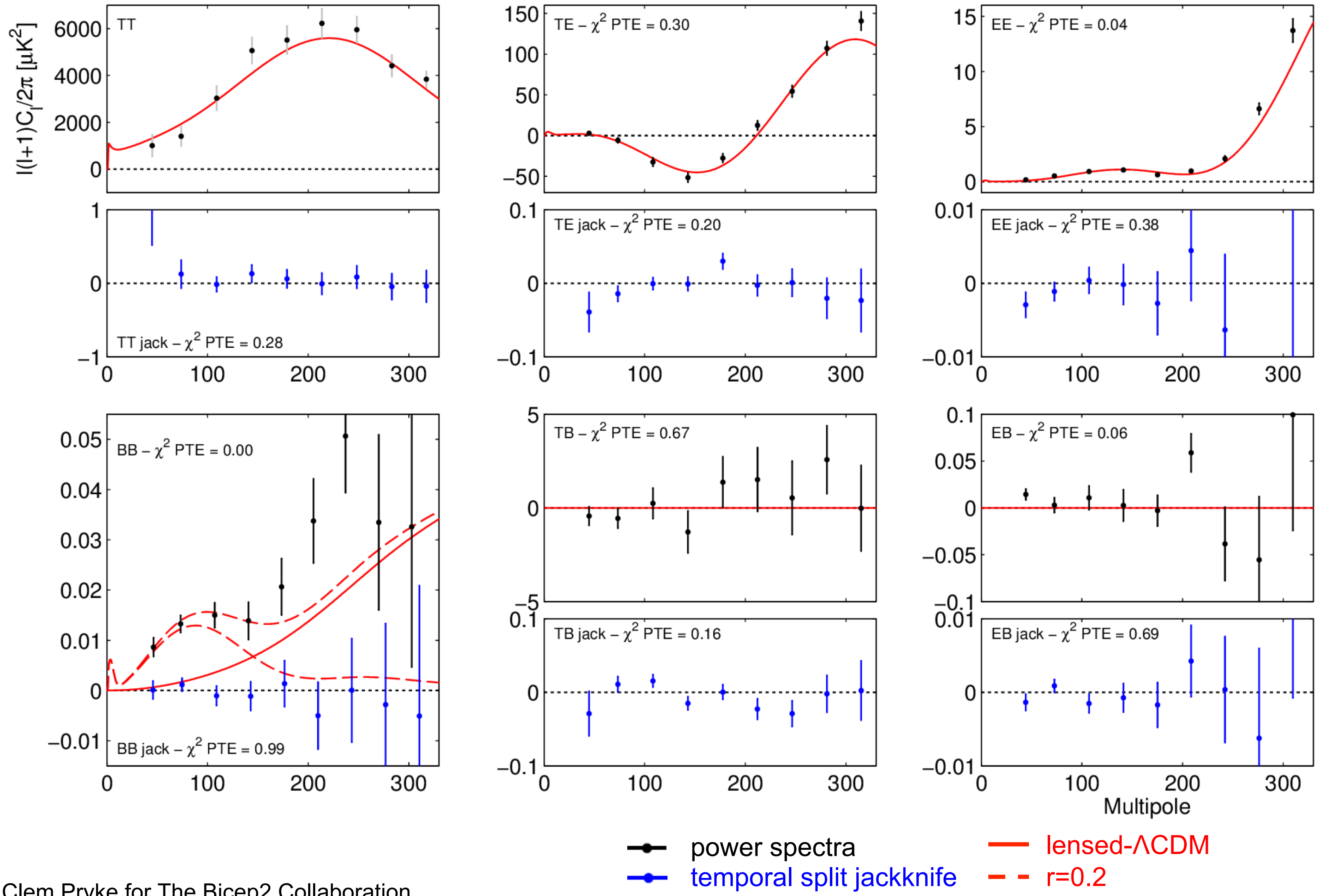
Temperature and Polarization Spectra



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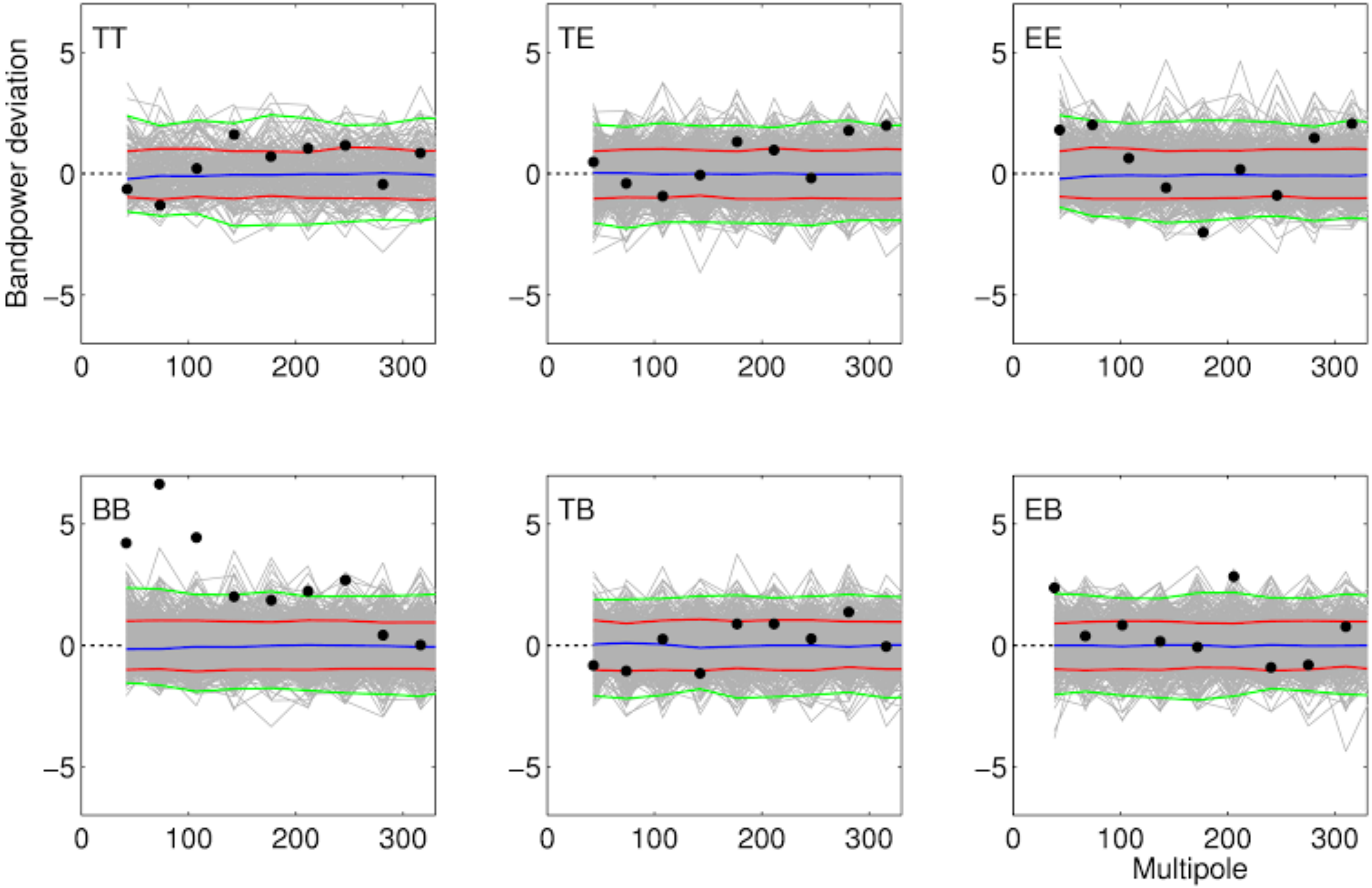
Bandpower Deviations

Points are (Data - Expectation) / errorbar, green/red/blue lines are 2/1 sigma percentiles and median, lines are sims:



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Check Systematics: Jackknifes

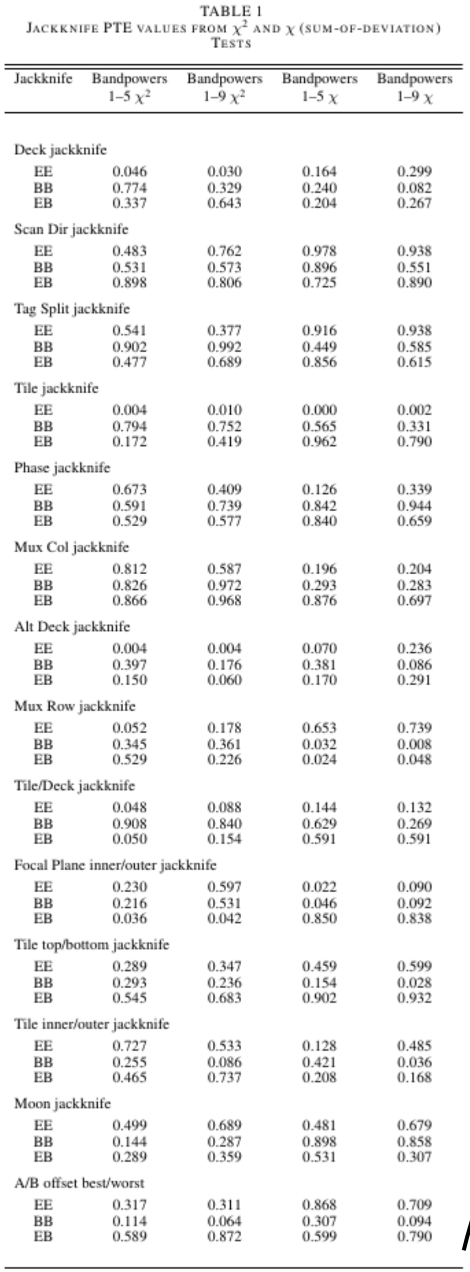
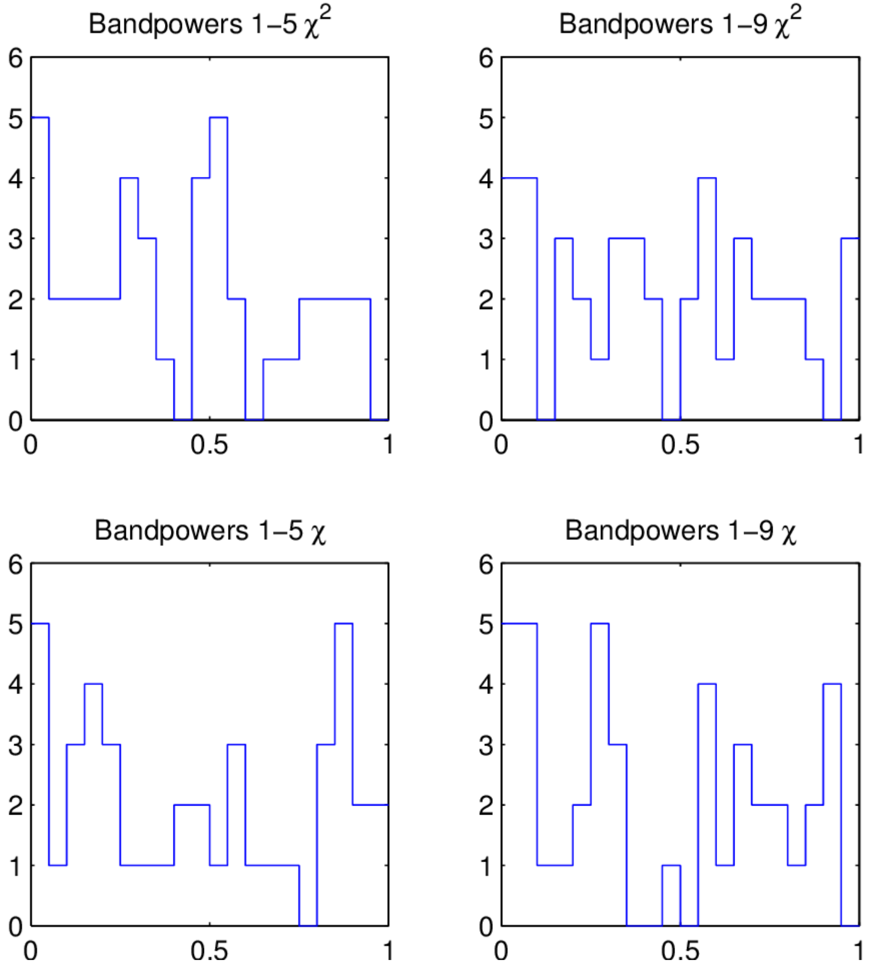


TABLE 1
JACKKNIFE PTE VALUES FROM χ^2 AND χ (SUM-OF-DEVIATION) TESTS

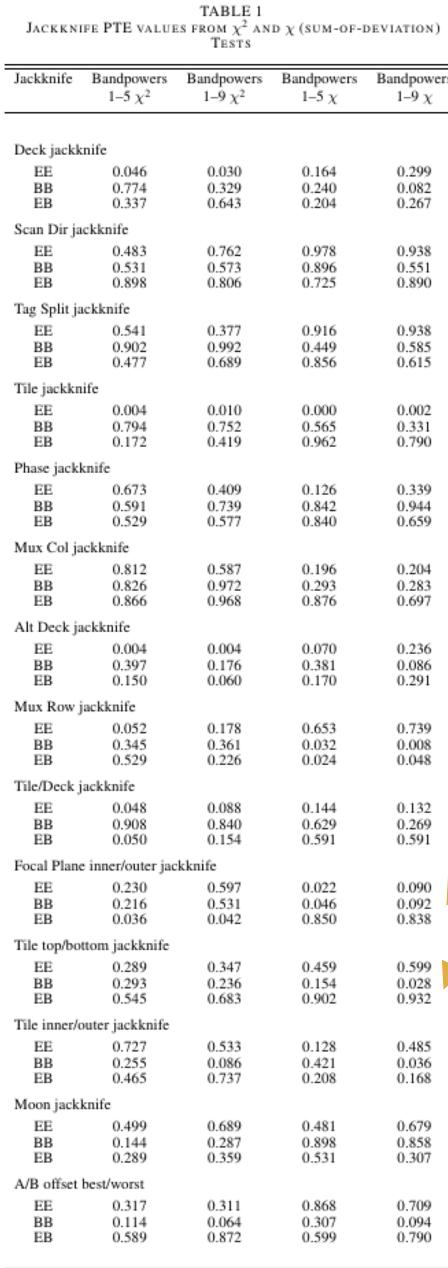
Jackknife	Bandpowers 1–5 χ^2	Bandpowers 1–9 χ^2	Bandpowers 1–5 χ	Bandpowers 1–9 χ
Deck jackknife				
EE	0.046	0.030	0.164	0.299
BB	0.774	0.329	0.240	0.082
EB	0.337	0.643	0.204	0.267
Scan Dir jackknife				
EE	0.483	0.762	0.978	0.938
BB	0.531	0.573	0.896	0.551
EB	0.898	0.806	0.725	0.890
Tag Split jackknife				
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:



Check Systematics: Jackknifes



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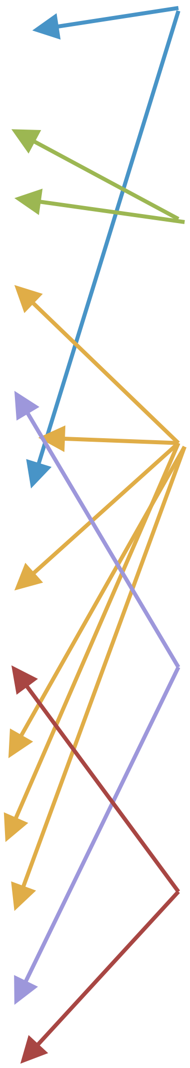


Splits the 4 boresight rotations

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

Splits by time

Checks for contamination on long (“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.

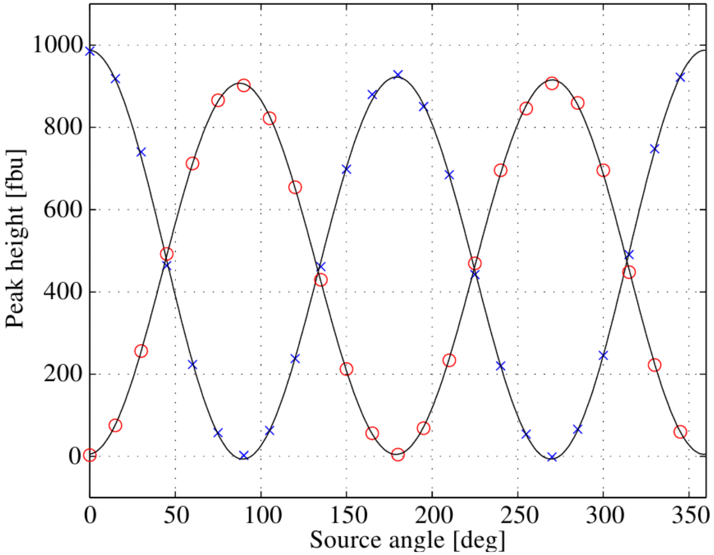
Systematics paper nearly ready – and see Chris Sheehy poster

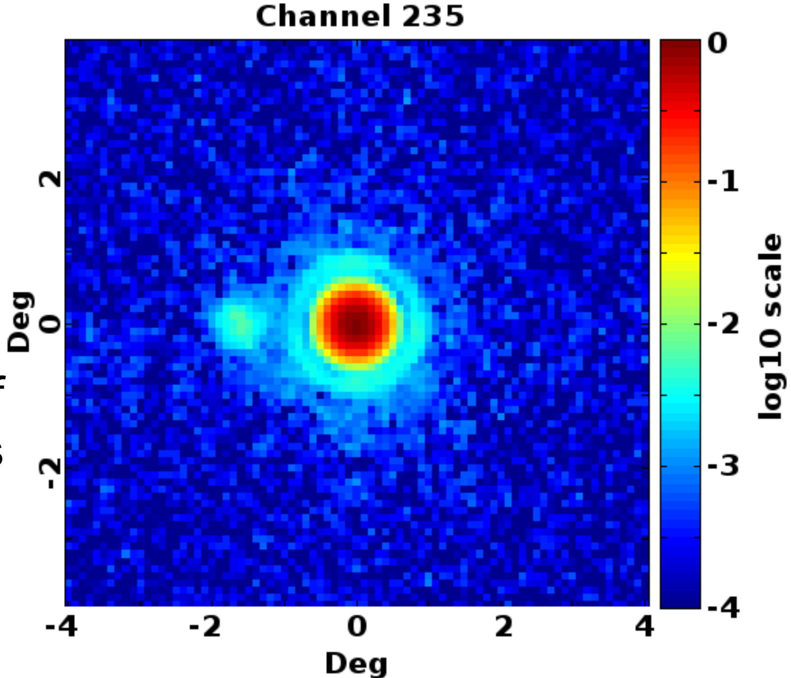
Calibration Measurements

For instance...

Far field beam mapping

Detector Polarization Calibration

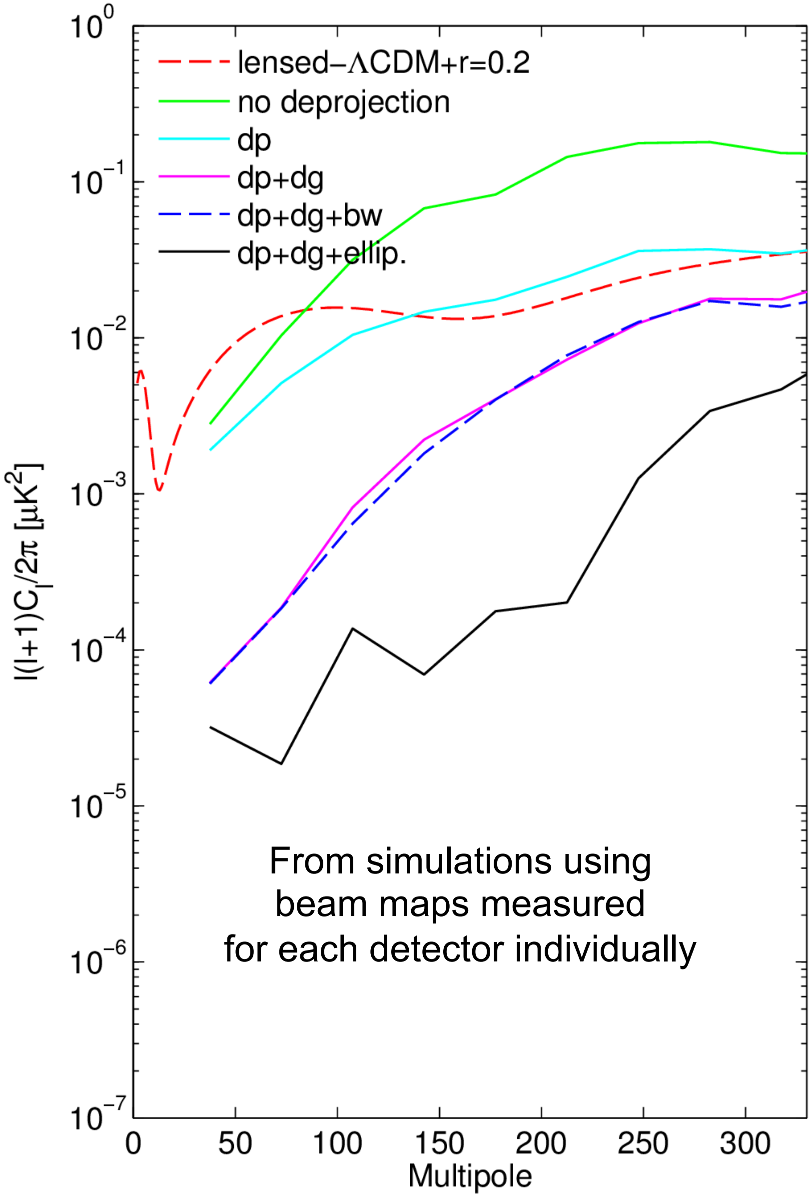




Hi-Fi beam maps of individual detectors

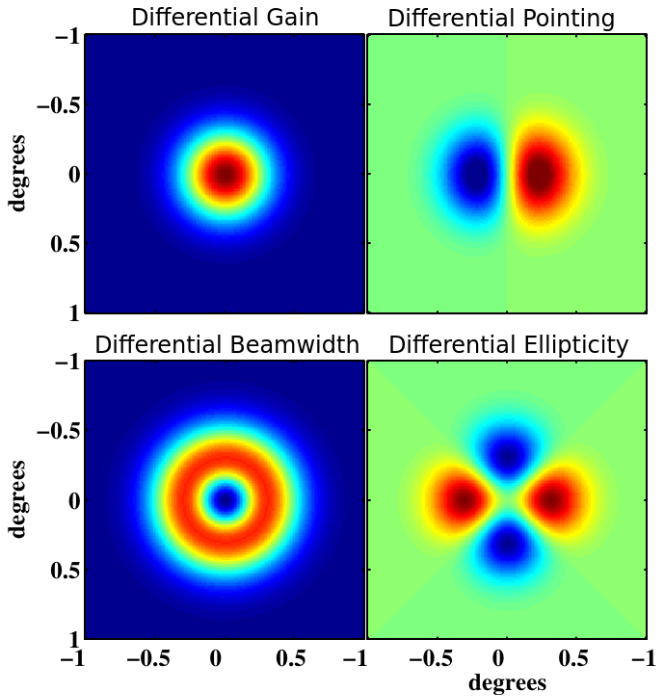
Detailed description in companion Instrument Paper

Systematics Removal: Deprojection



From simulations using
beam maps measured
for each detector individually

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

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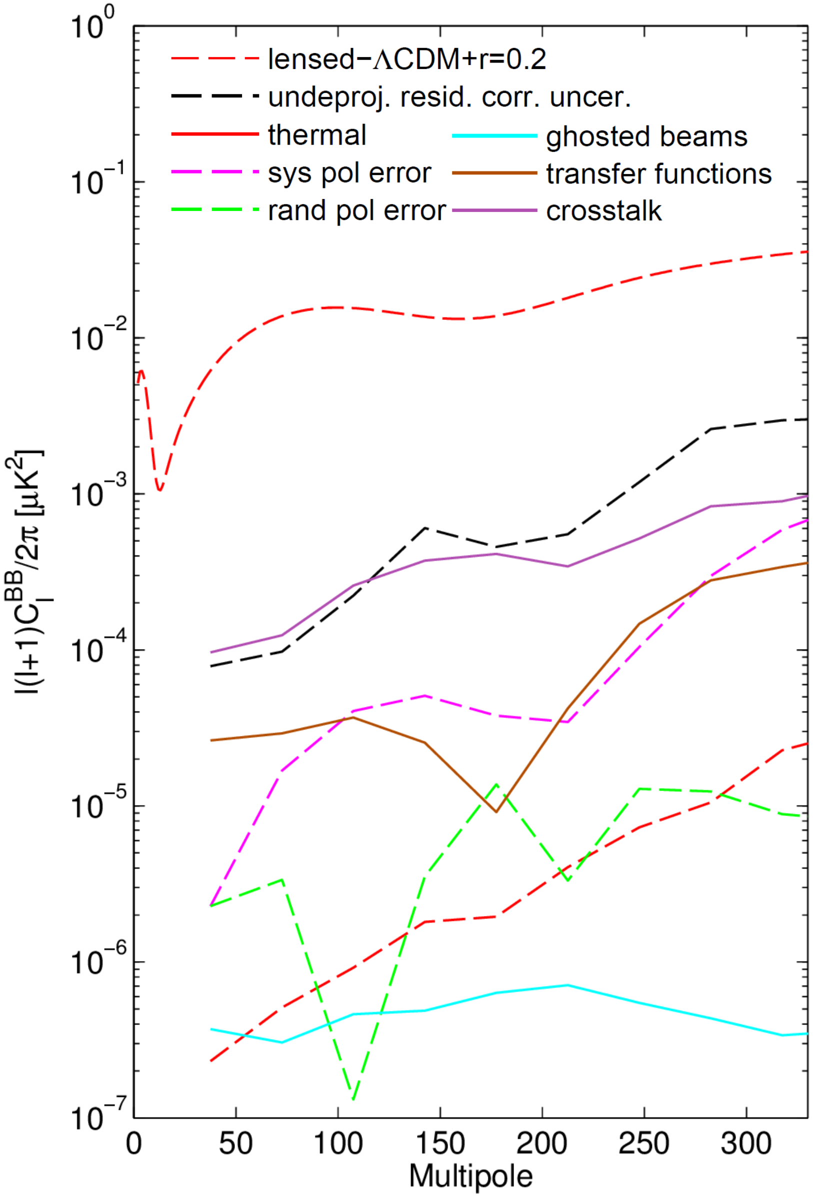
Systematics beyond Beam imperfections



All systematic effects that we could imagine were investigated!

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

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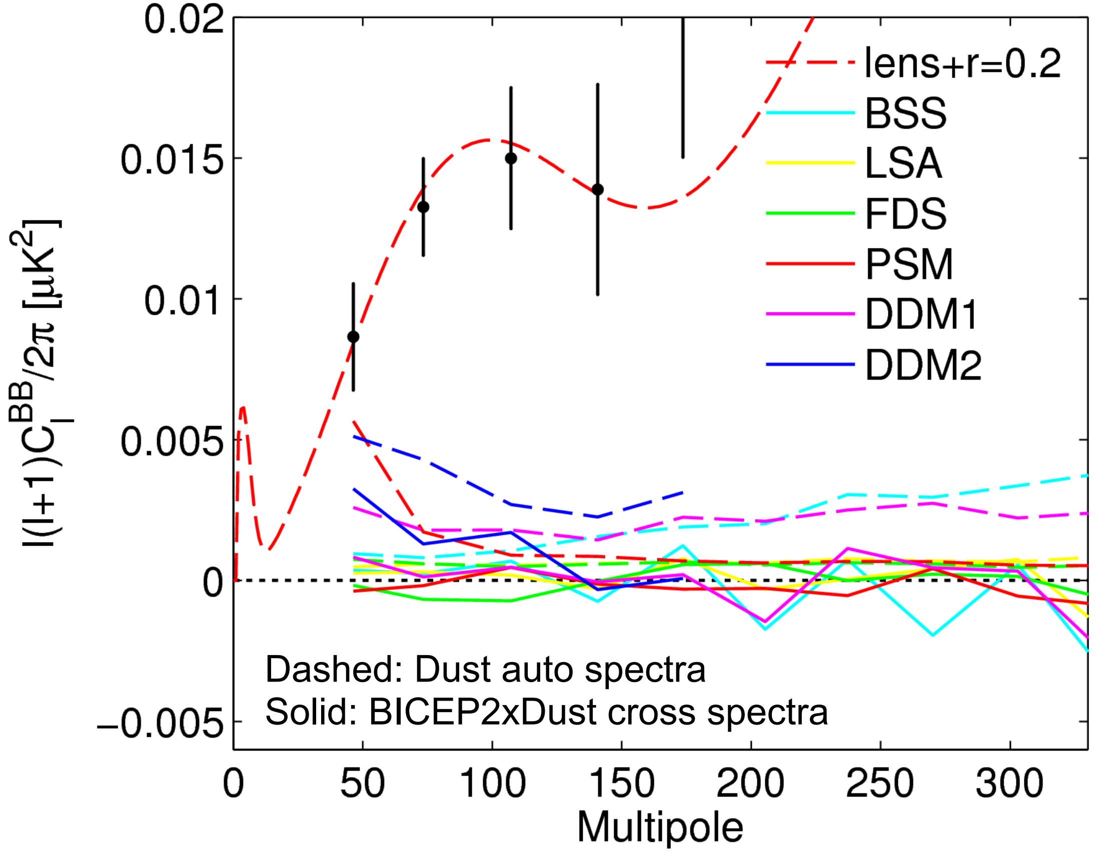
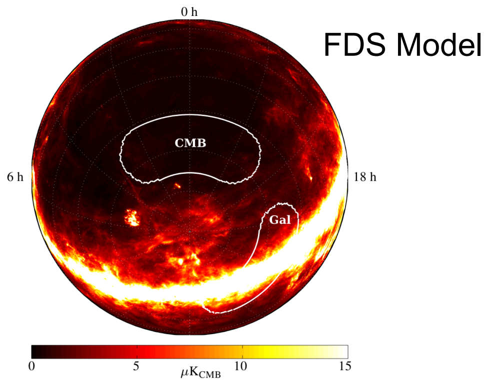
Polarized Dust Foreground Projections



Dashed: Dust auto spectra
Solid: BICEP2xDust cross spectra



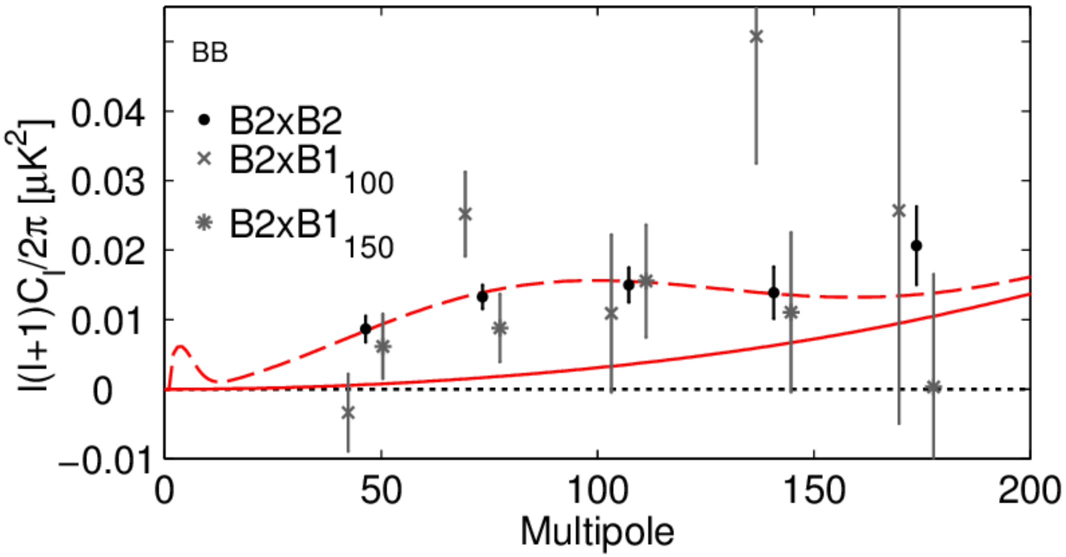
The BICEP2 region is chosen to have extremely low foreground emission.

Use various models of polarized dust emission to estimate foregrounds.

All dust auto spectra well below observed signal level.

Cross spectra consistent with zero.

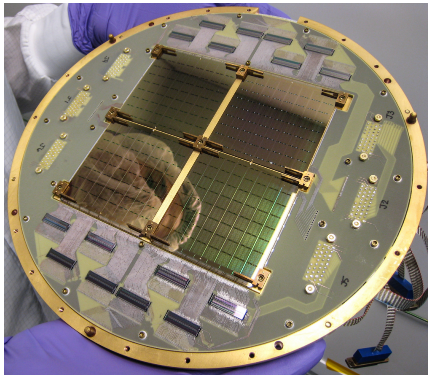
Cross Correlation with BICEP1



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

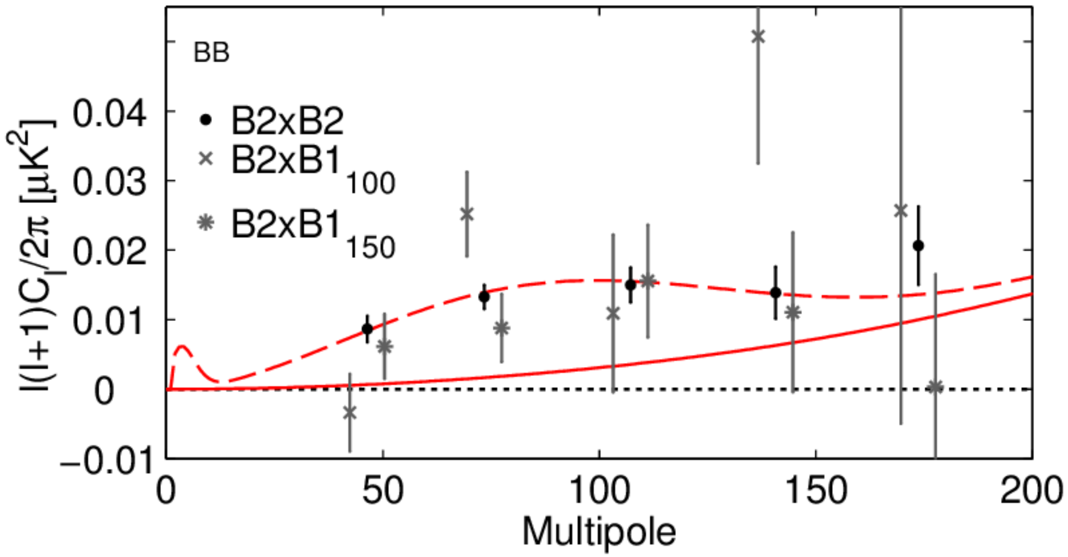
Cross with BICEP1$_{100}$ shows **~3σ** detection of BB power



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

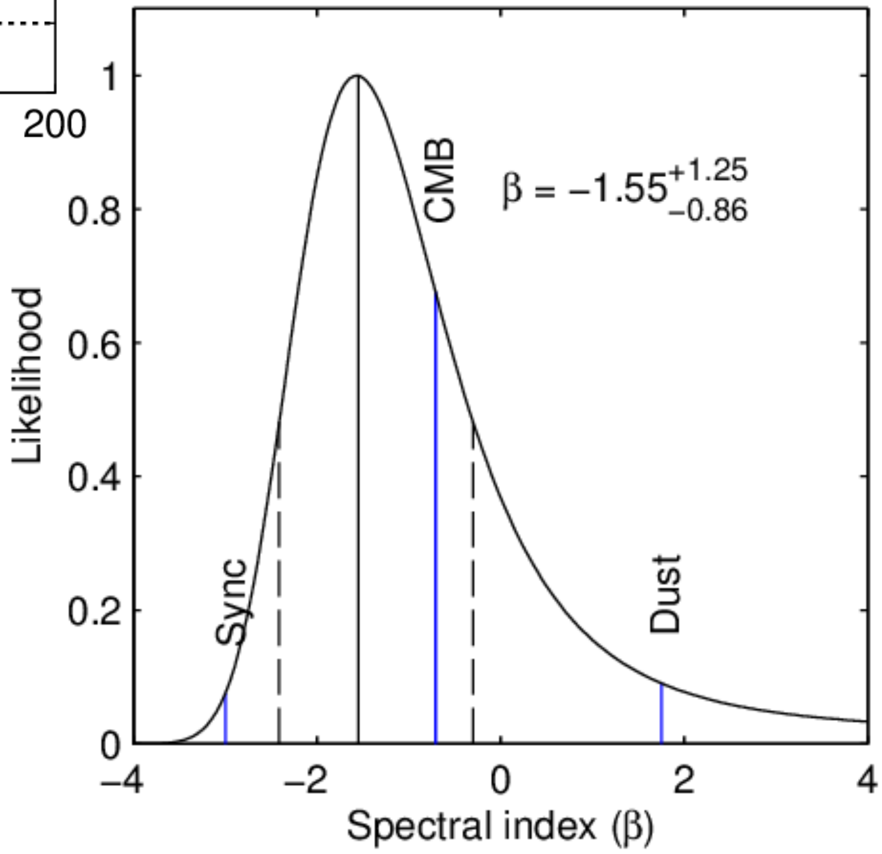


Likelihood ratio test: consistent with CMB spectrum, disfavor pure dust/sync at **2.2/2.3σ**

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

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

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



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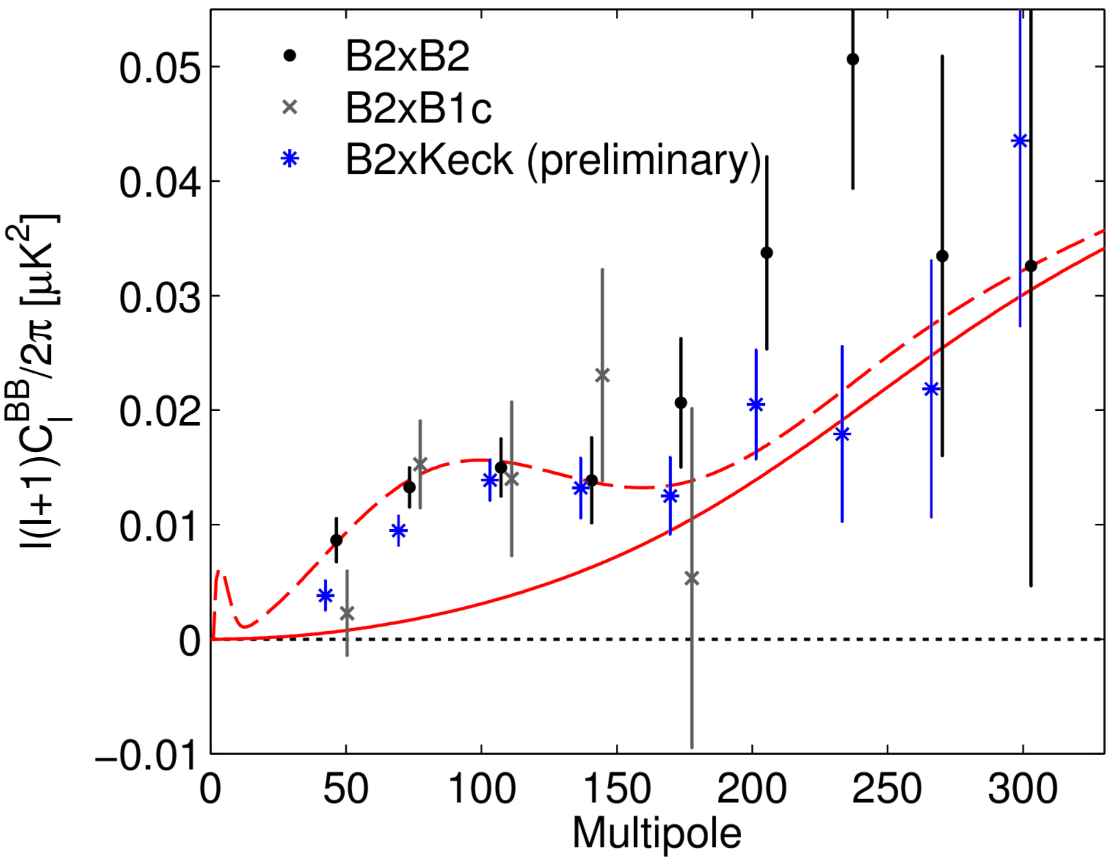
Cross Spectra between 3 Experiments

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

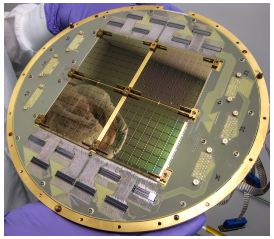


BICEP2 auto spectrum compatible with B2xB1c cross spectrum

- ~3σ evidence of excess power in the cross spectrum

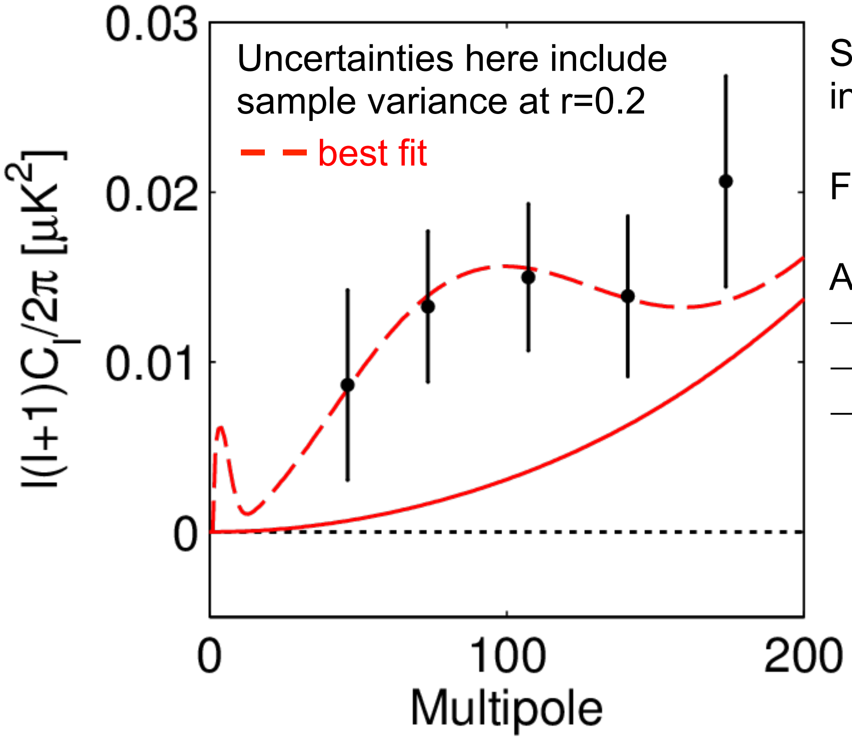
Additionally form cross spectrum with 2 years of data from *Keck Array*, the successor to BICEP2

- Excess power is also evident in the B2xKeck cross spectrum



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

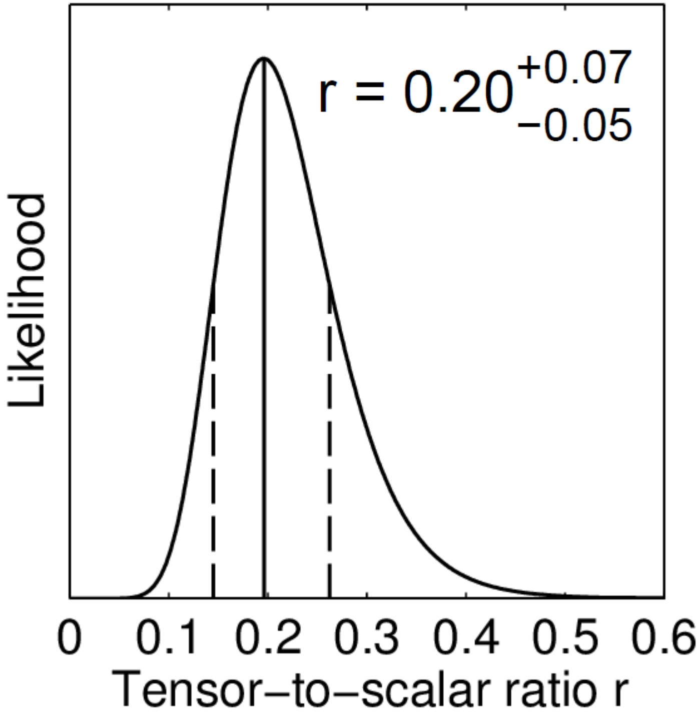
Constraint on Tensor-to-scalar Ratio r



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 ruled out at 7.0σ

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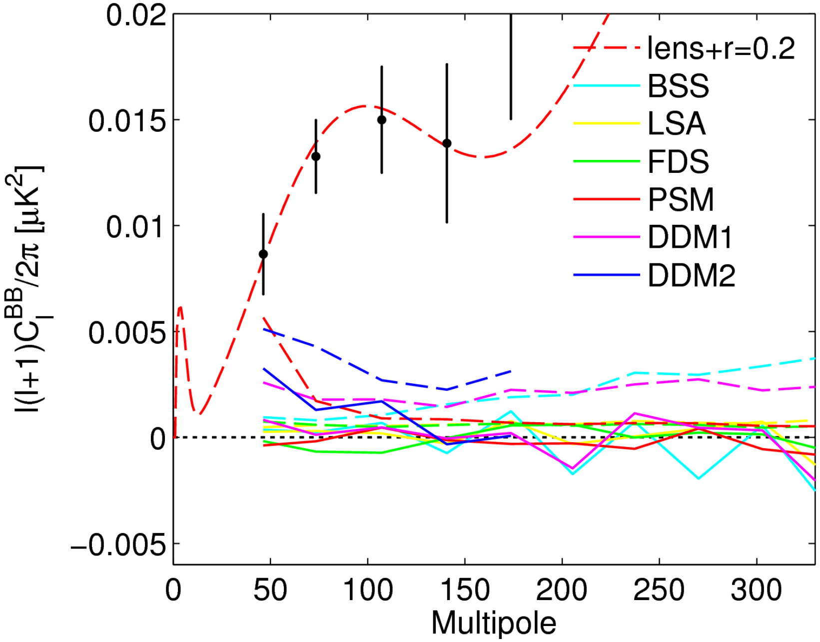
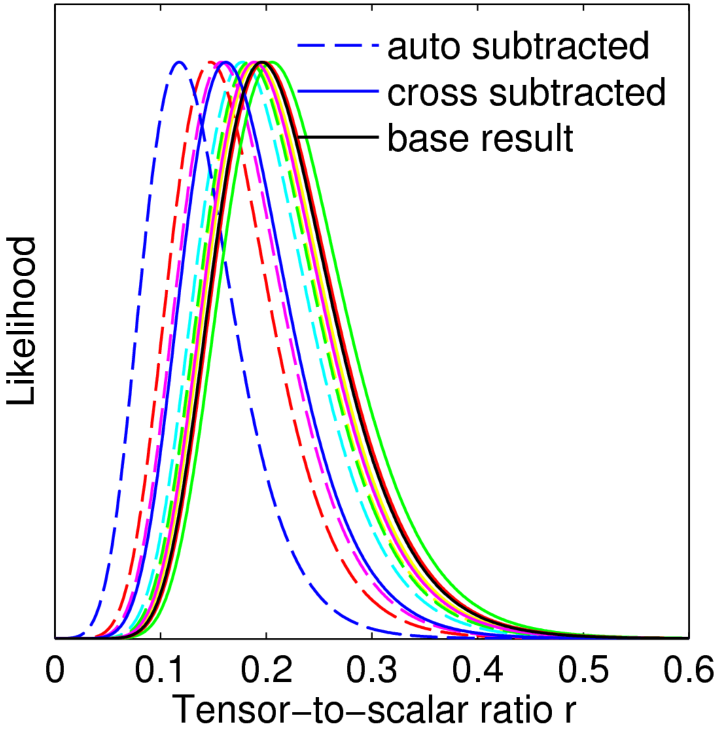
Constraint on r under Foreground Projections



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



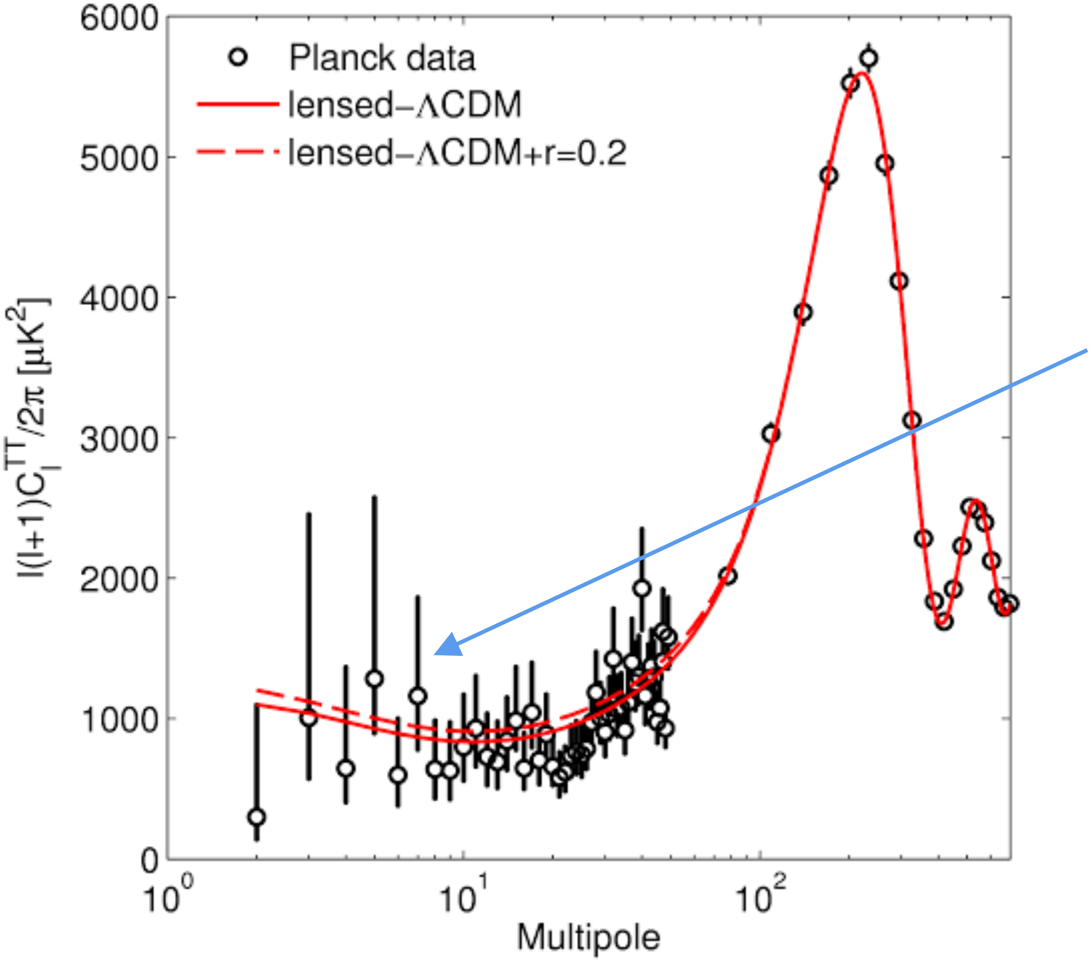
Probability that each of these models reflect reality hard to assess

DDM2 uses all publicly available information from Planck - modifies constraint to $r = 0.16^{+0.06}_{-0.05}$
r = 0 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 Indirect Limits on r?

:



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

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

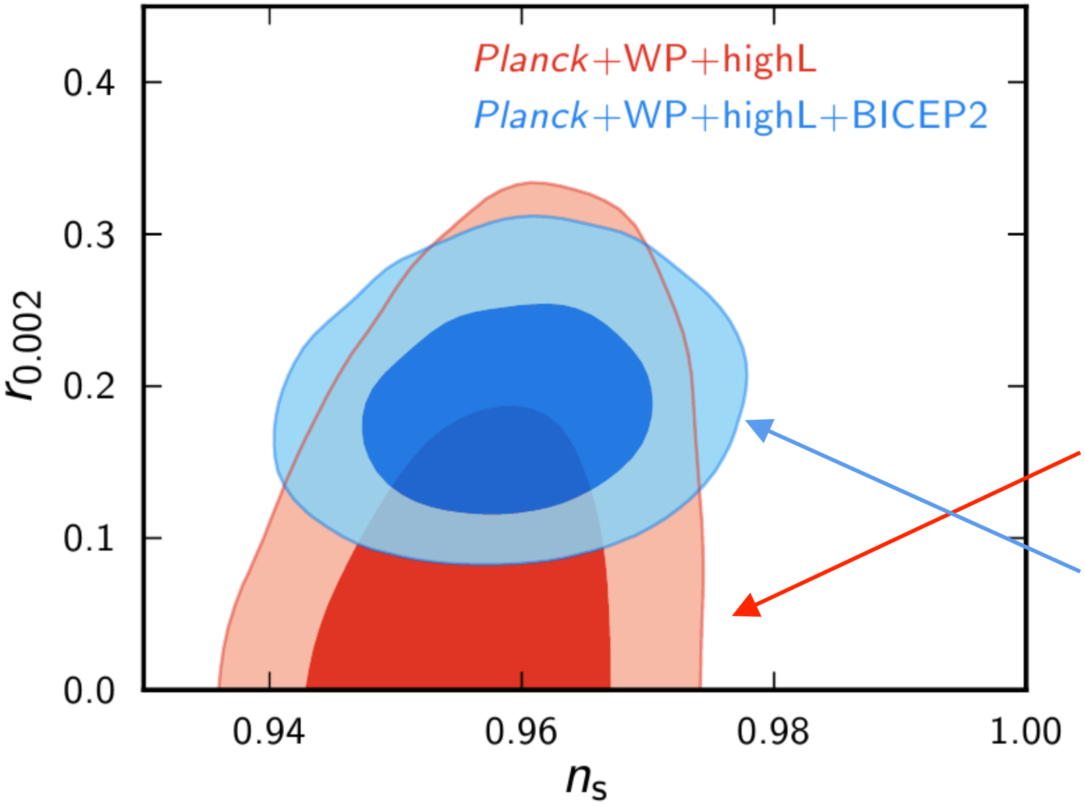
Planck+SPT+ACT+$WMAP_{pol}$: $r < 0.11$

However note that r=0.2 makes only a small change to temperature spectrum.

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

Compatibility with Indirect Limits on r?

Constraint on r *with running allowed*:



The apparent tension can be relieved with various extensions to lensed ΛCDM.
Example: running of the spectral index

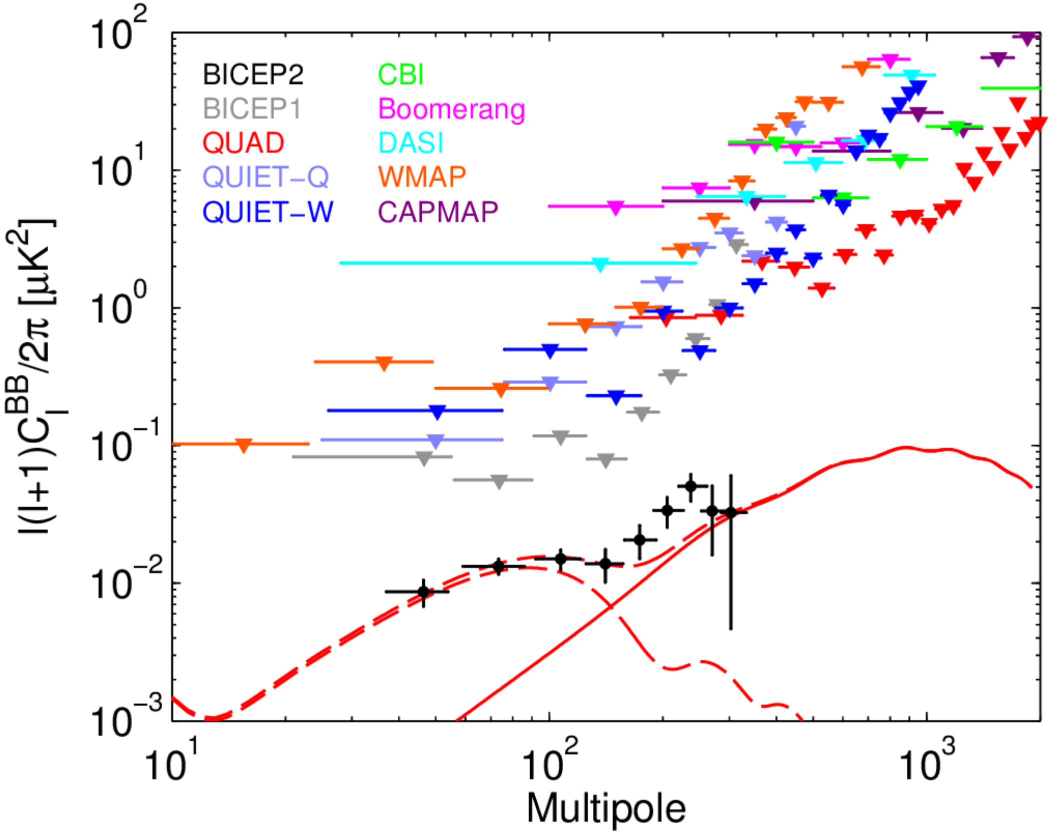
Planck likelihood chains for lensed ΛCDM + *tensors* + *running*

Same chains, importance sampled with the BICEP2 r likelihood

Other possibilities within ΛCDM?...

Conclusions circa March 17th

BICEP2 and upper limits from other experiments:



http://www.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:

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

r = 0 is ruled out at 7.0σ.

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Developments Since…

- Intense media and science community interest…
- Many early instrumental queries… mostly seem to have faded
- Concerns seem to have boiled down to:
  - Spectral index constraint includes lensing signal – true – but a small effect
  - Polarized dust foreground may be stronger than previously projected…
- Since our release a paper on dust polarization has appeared from Planck
  - But specifically masks out low foreground regions like ours (due to “non small systematics and not dust dominated”)
- Keck 2014 is running right now with 2 receivers at 100GHz
  - Sensitivity of BICEP1 already surpassed
  - We plan an analysis asap which will tighten spectral index constraint
- Meanwhile many other experiments in the running:
  - Full Planck release by the end of the year (and maybe another dust paper sooner)

What's Next?

Confirm:

- Keck Array 2012/13 results coming soon (within few months)
- Planck may be able to confirm at either reionization (ell<10) or recombination (ell=80) bump.
- SPTpol has data in the can 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 in the can… Spider will fly later this year… plus many others…

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
  - Big sky to push to lower ell
- Add small apertures to S4? Renewed interest in future space mission? Ground based spinners? (Cf. CLASS)