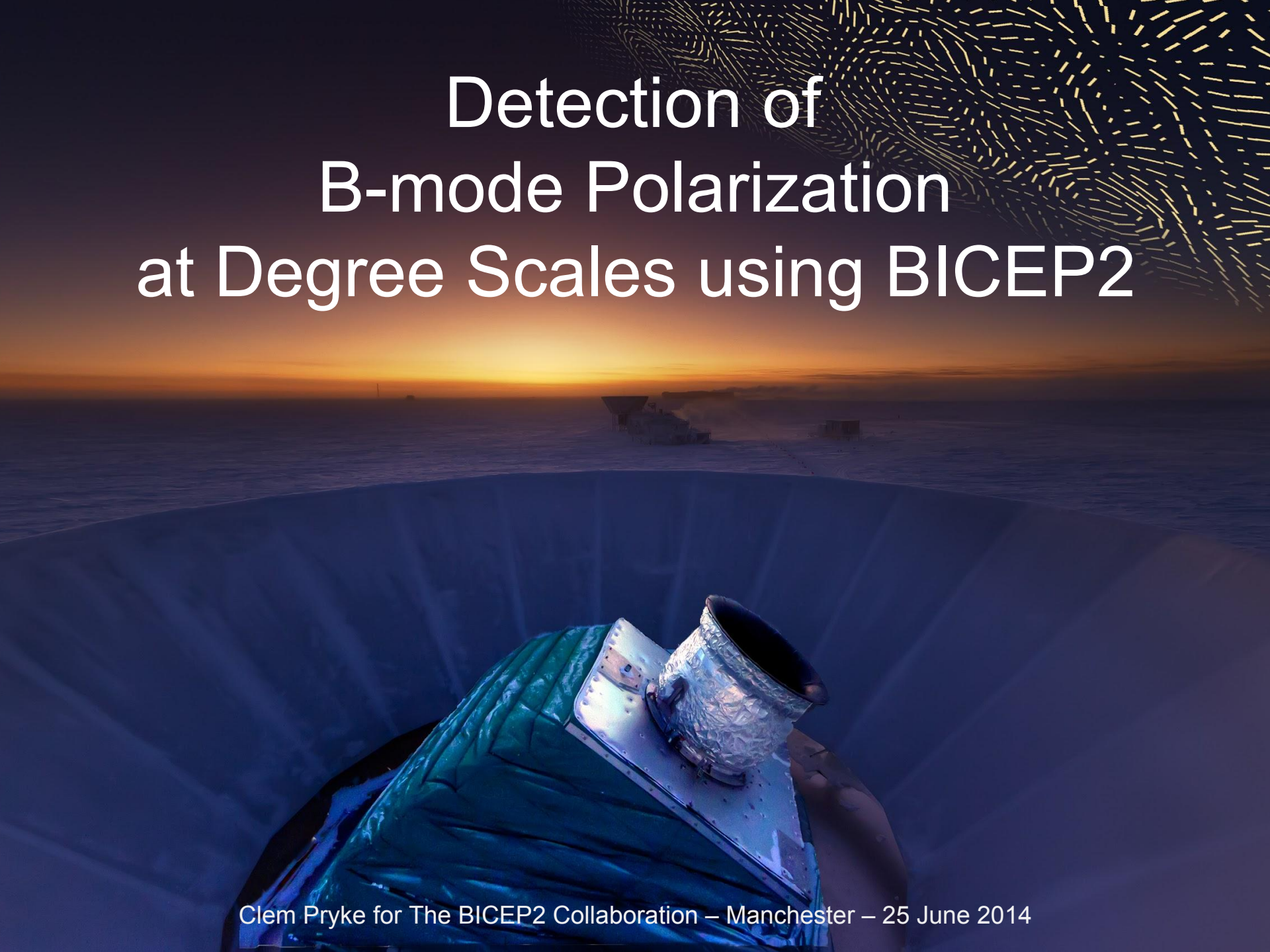
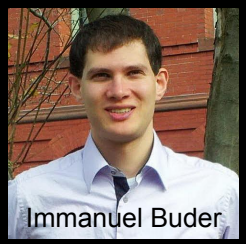
Detection of B-mode Polarization at Degree Scales using BICEP2



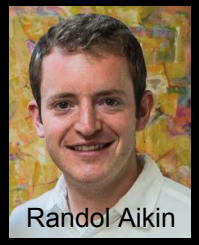
Clem Pryke for The BICEP2 Collaboration – Manchester – 25 June 2014

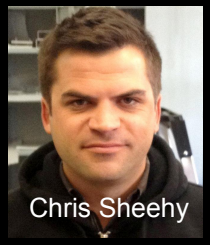
VE RI TAS
HARVARD
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
UCSD
JPL
NIST
CARDIFF UNIVERSITY
cea
DE LA RECHERCHE À L'INDUSTRIE
UNIVERSITY OF TORONTO
UBC

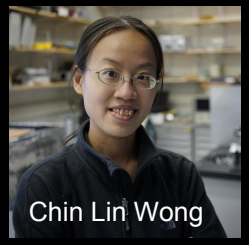
The BICEP2 Postdocs

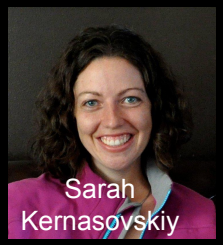


The BICEP2 Graduate Students









BICEP2 Winterovers

2010

2011

2012

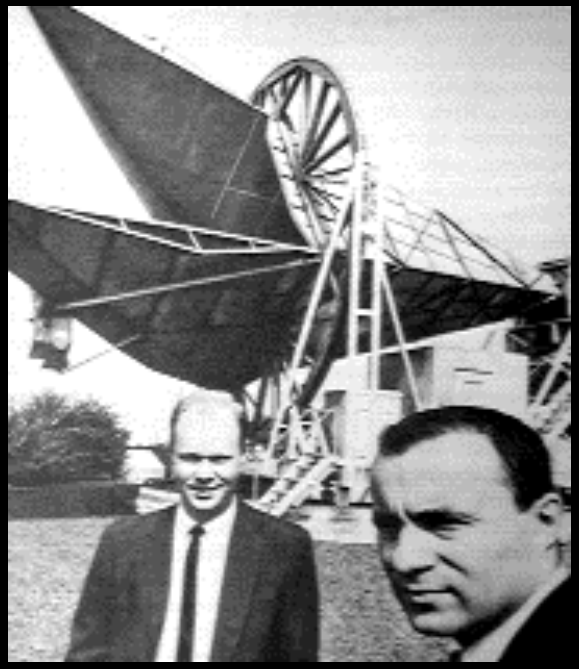
Modern cosmology in a nutshell:

Edwin Hubble

1) The universe is expanding.
(Hubble, 1920s)

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

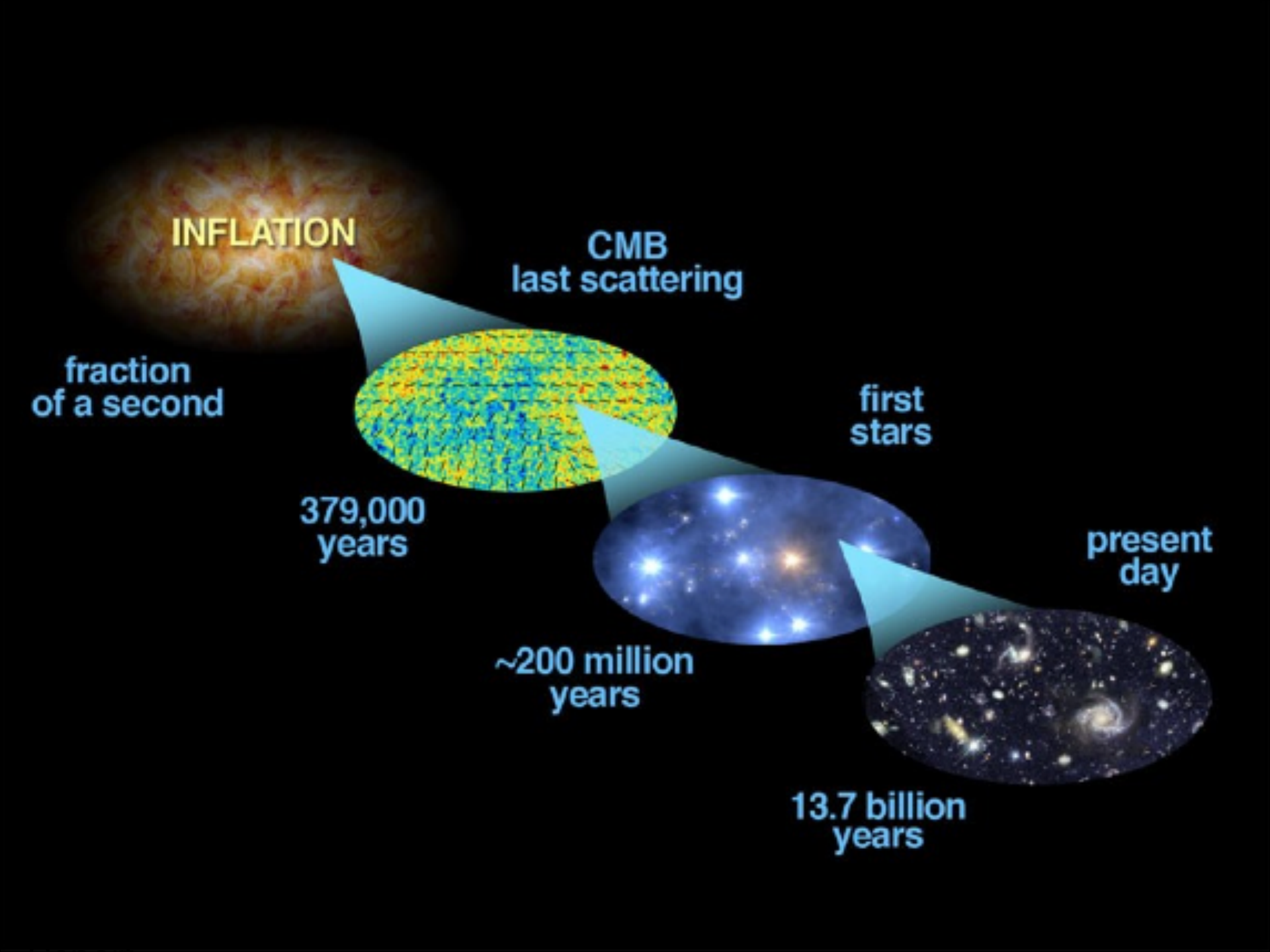
(Alpher, Gamow, Herman, 1940s)



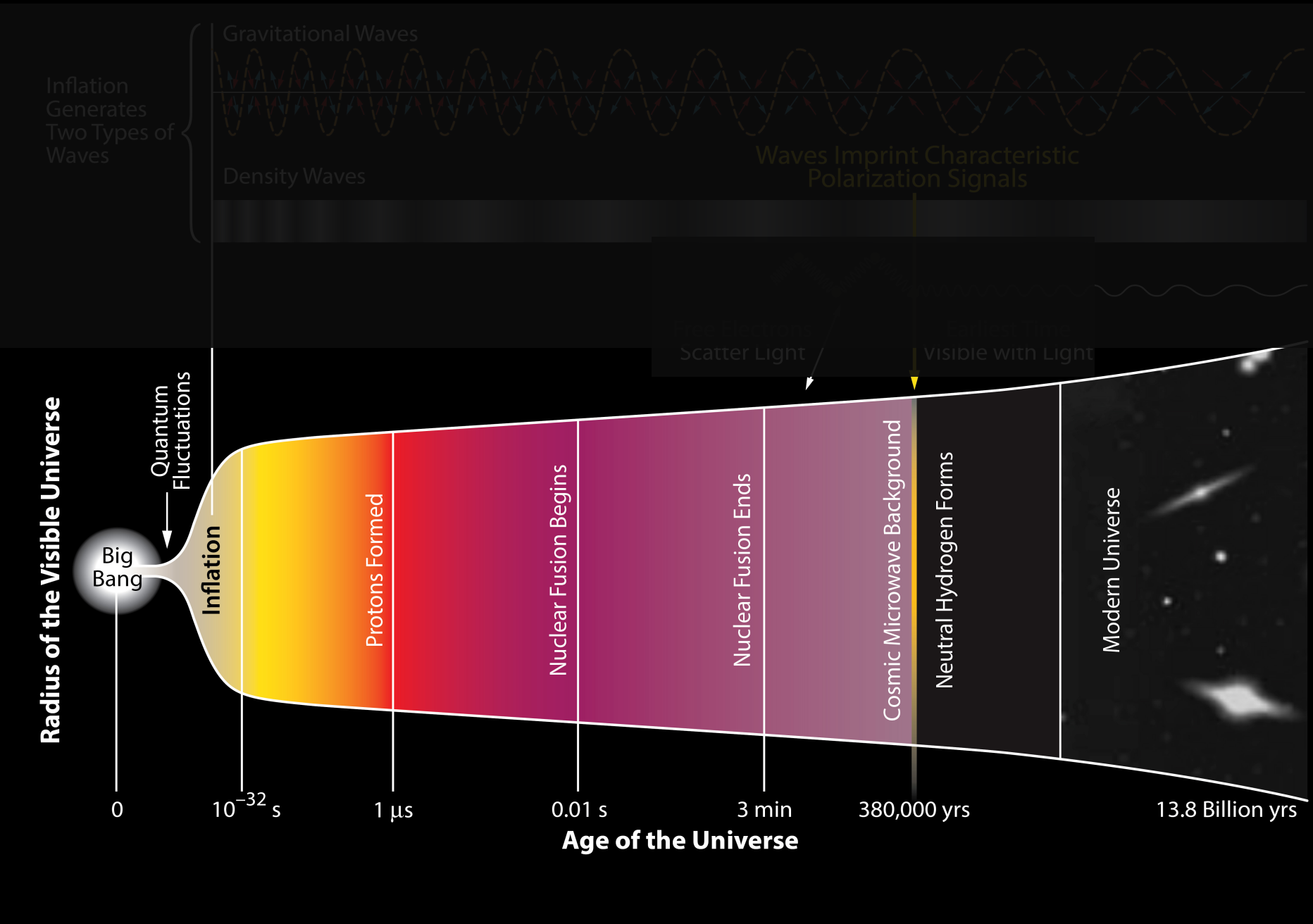
Bob Wilson & Arno Penzias
1978 Nobel Prize

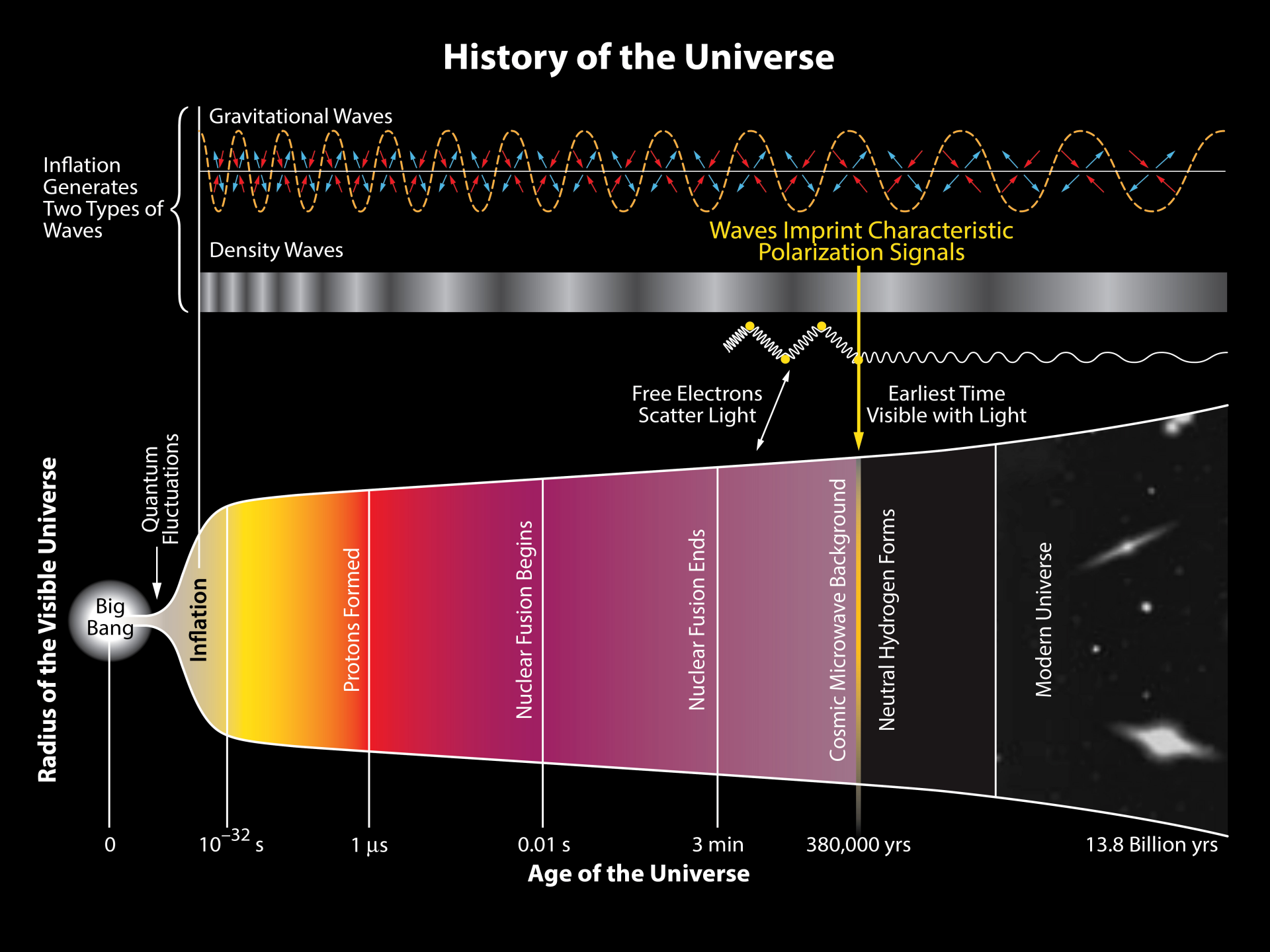
3) You can still see the glow!
The *Cosmic Microwave Background*
(Penzias & Wilson, 1964)

⇒ acceptance of the "HOT BIG BANG"

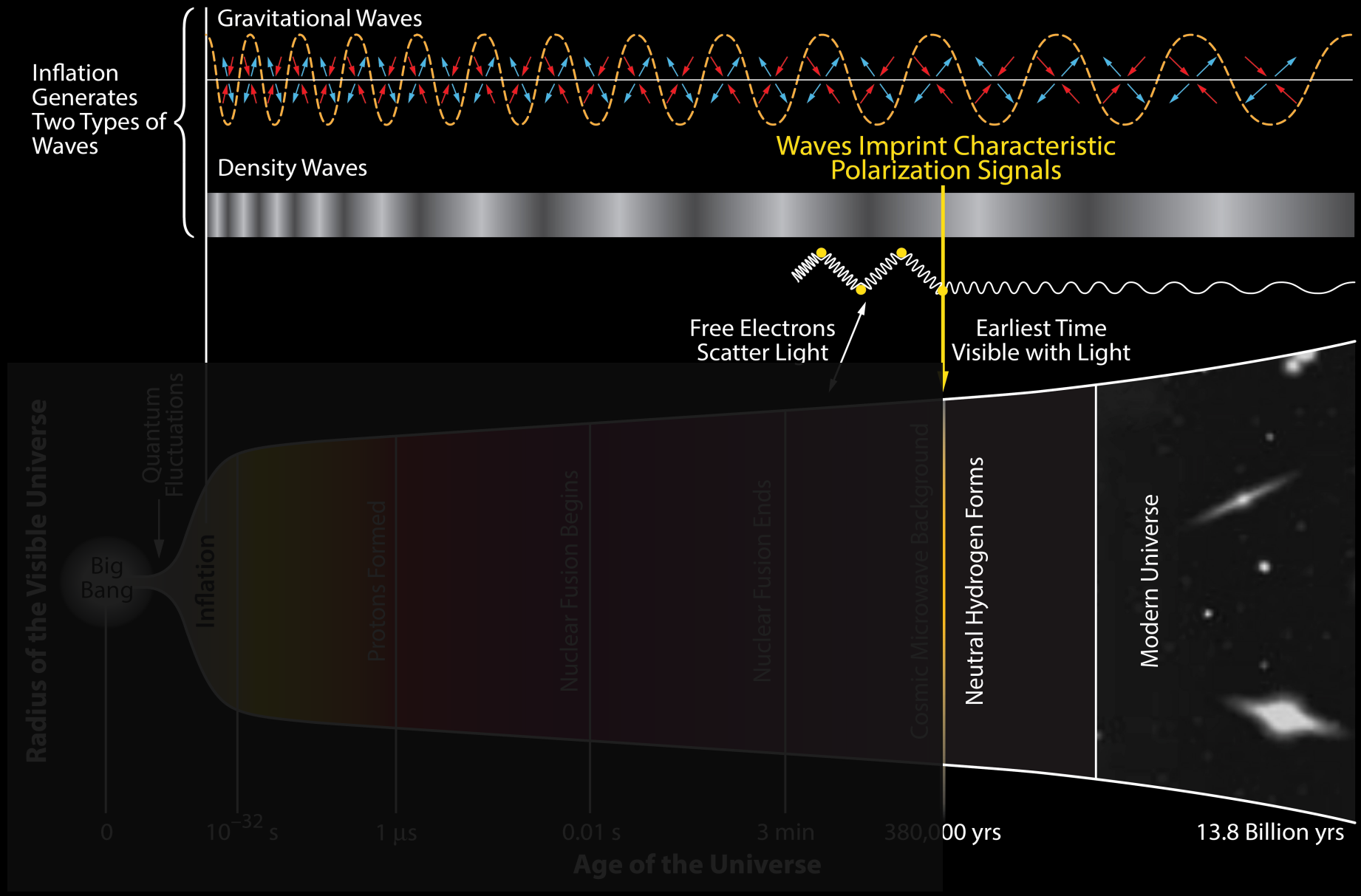

INFLATION
CMB
last scattering
fraction
of a second
379,000
years
first
stars
present
day
~200 million
years
13.7 billion
years

History of the Universe

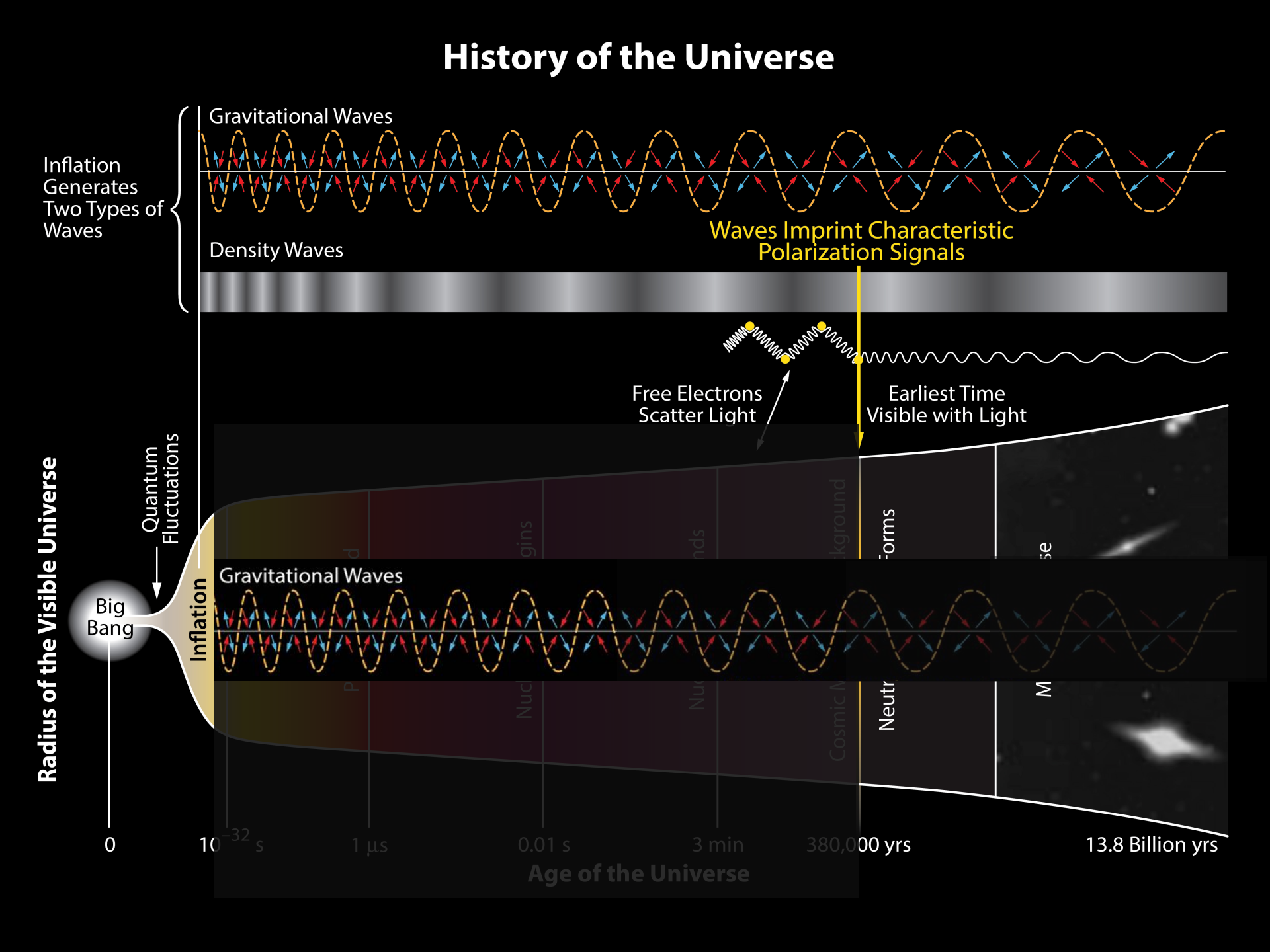



History of the Universe
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear 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

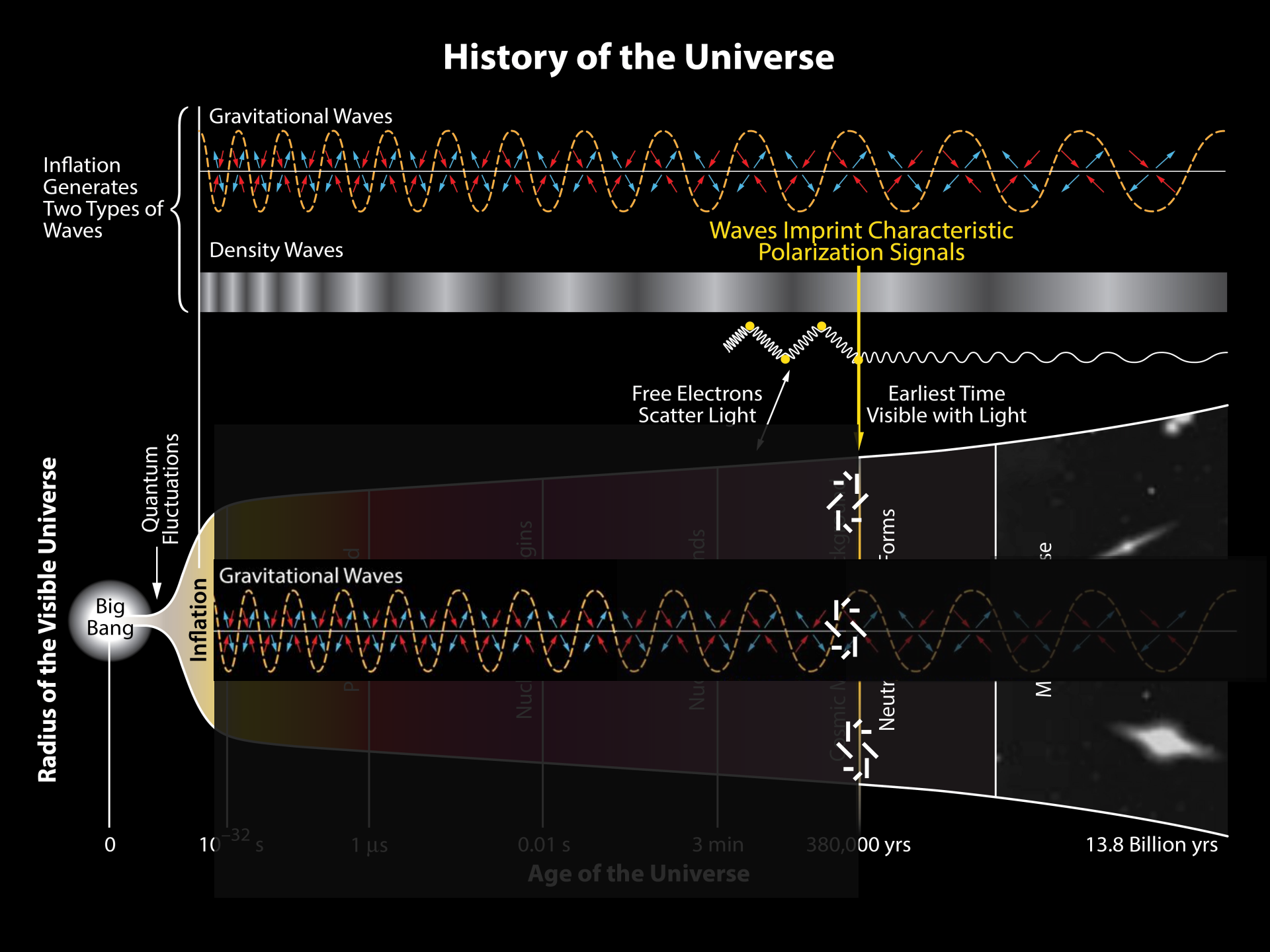
History of the Universe



History of the Universe



History of the Universe



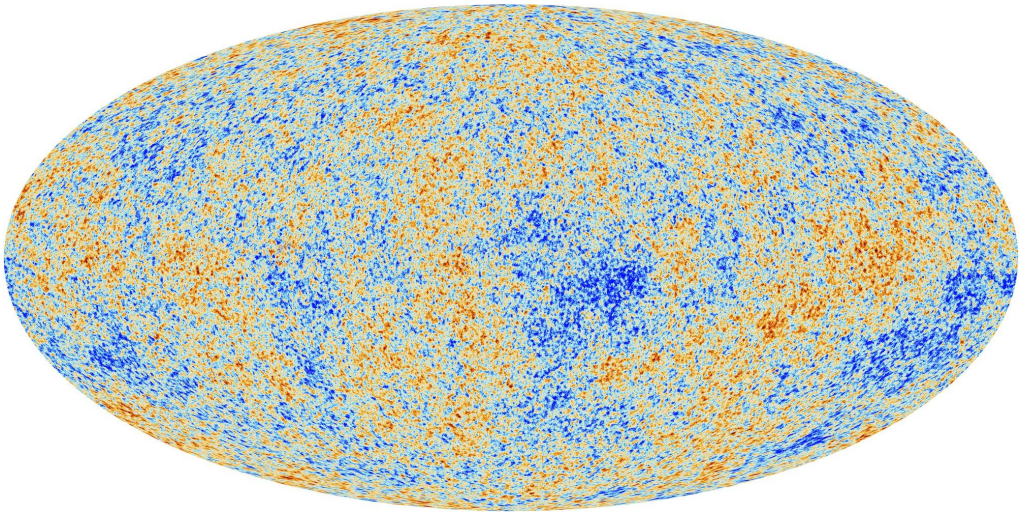
CMB Temperature Measurements / Inflation

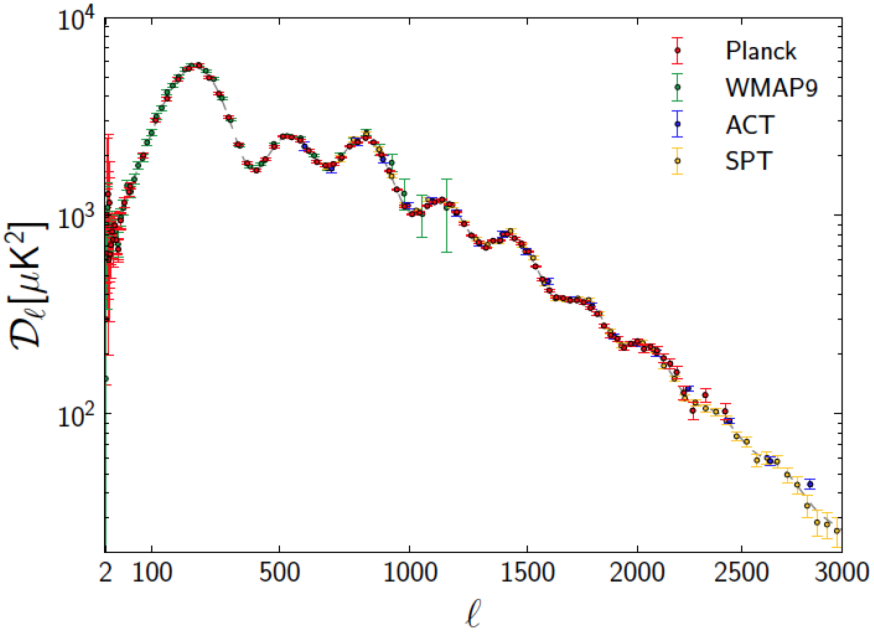
CMB temperature anisotropy now measured over full range of angular scales.

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.

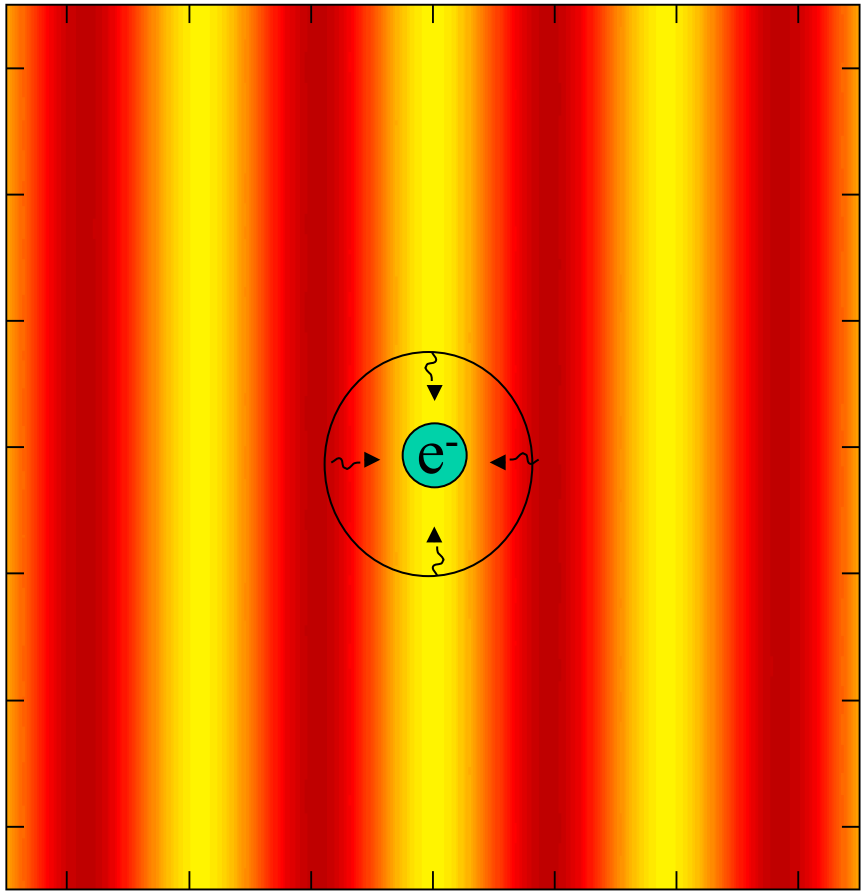
Explains the initial perturbation spectrum: Why was it close to flat power law?

→ 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?

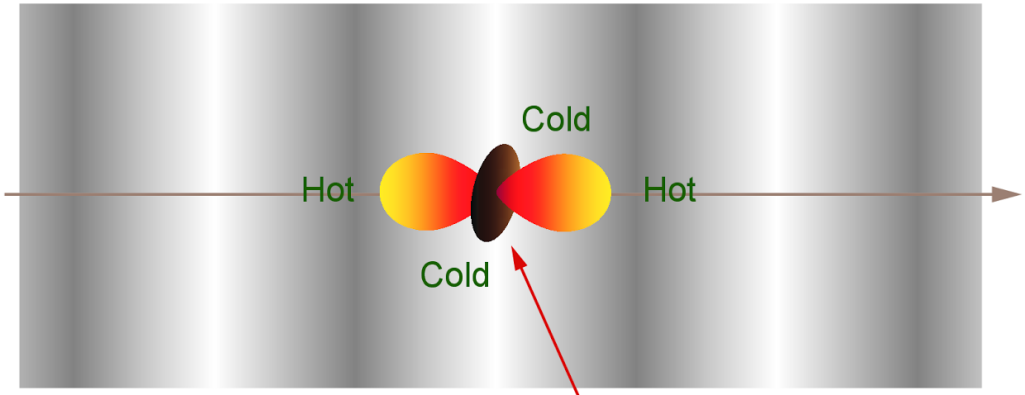
→ Monopoles are diluted away to undetectability.

CMB polarization: arises at last scattering from local radiation quadrupole

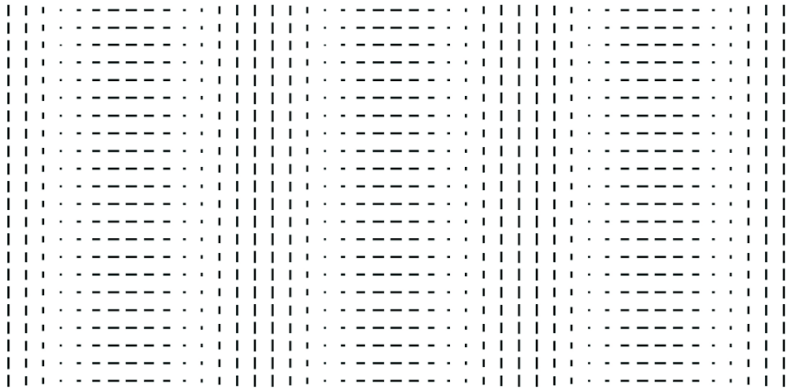


CMB polarization

Density Wave

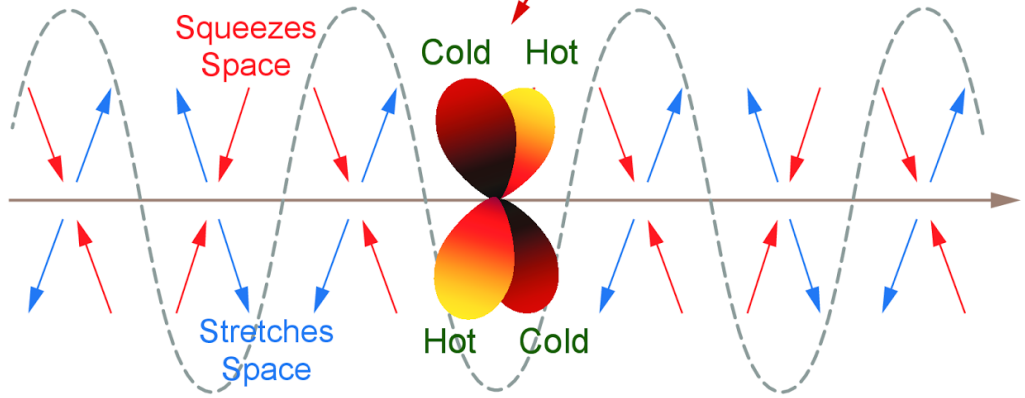


E-Mode Polarization Pattern

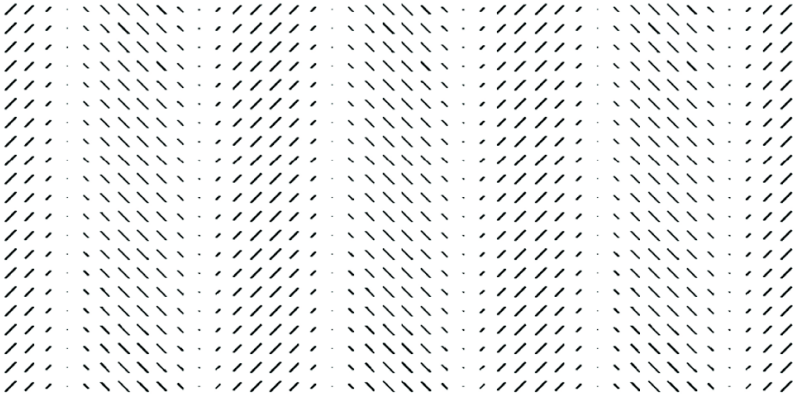


Temperature Pattern Seen by Electrons

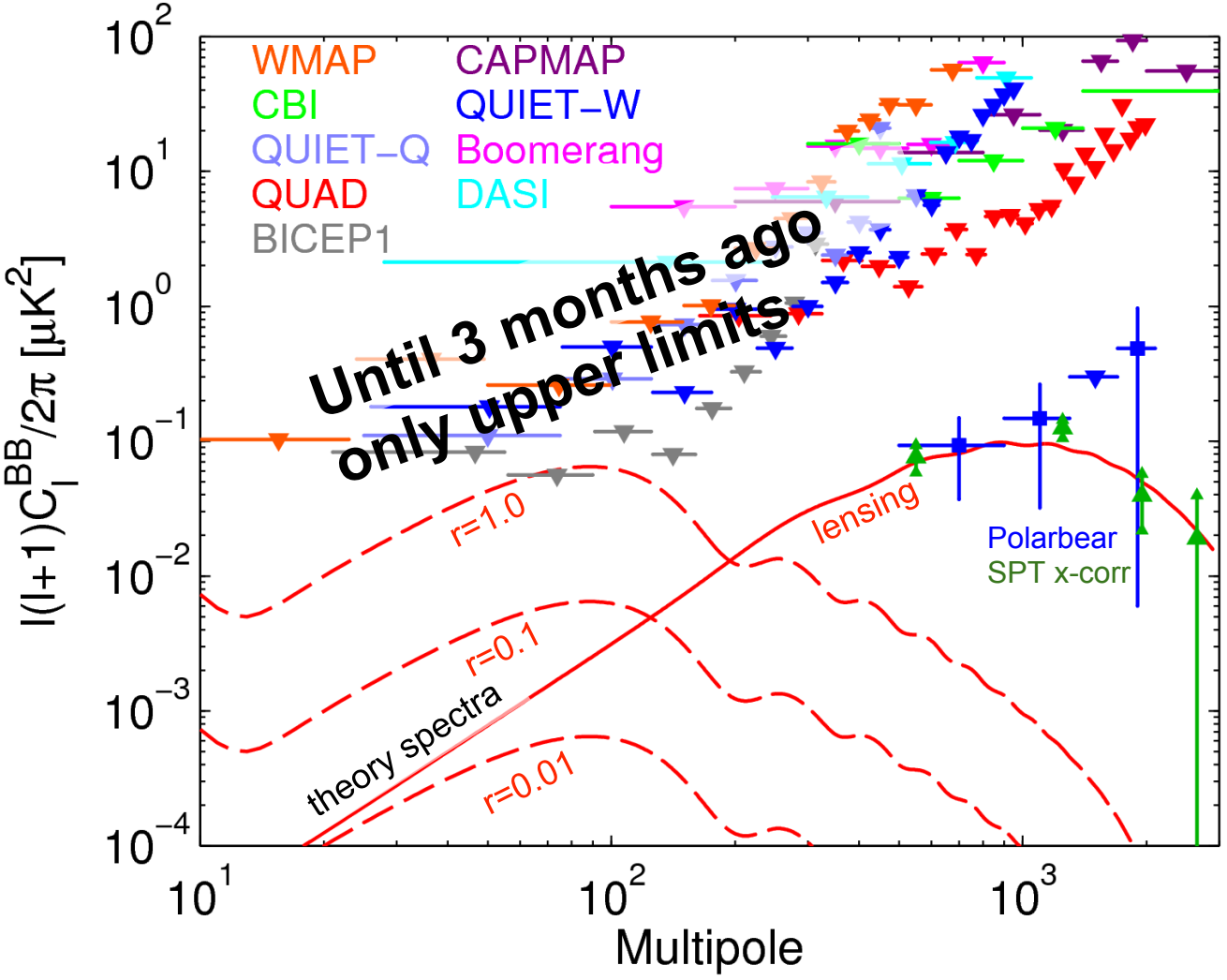
Gravitational Wave



B-Mode Polarization Pattern



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.

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

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

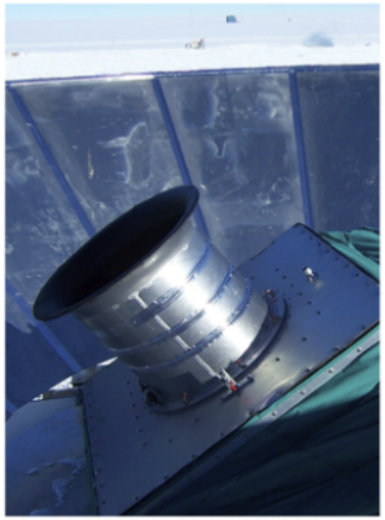
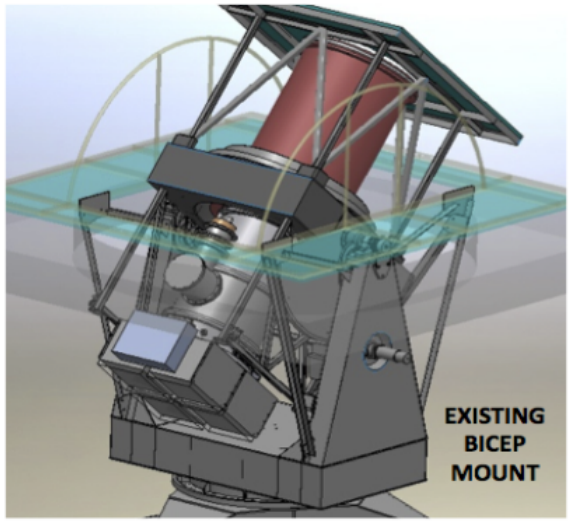
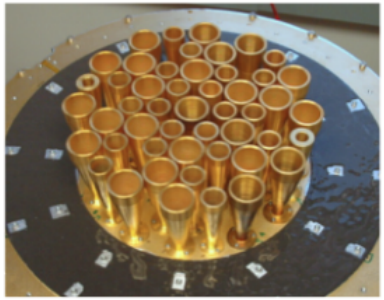
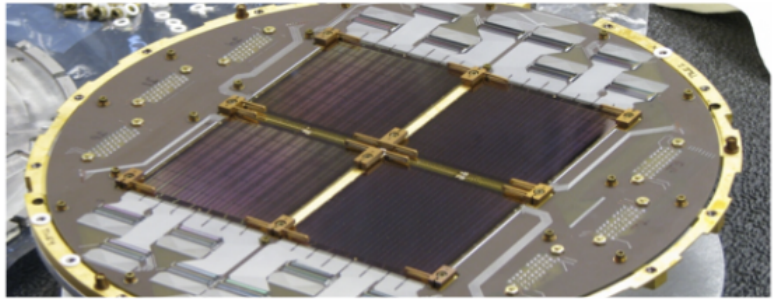
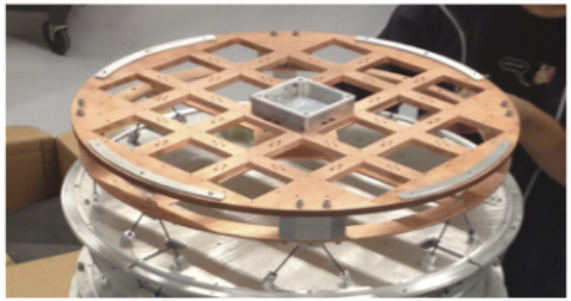
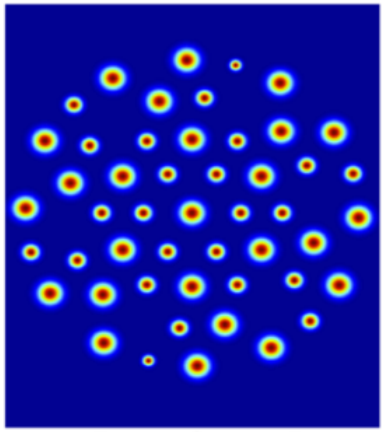
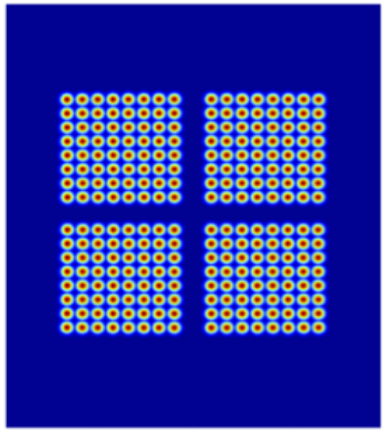
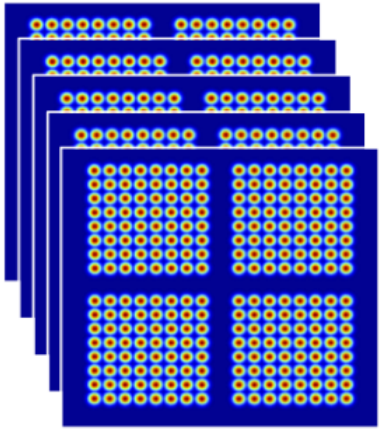
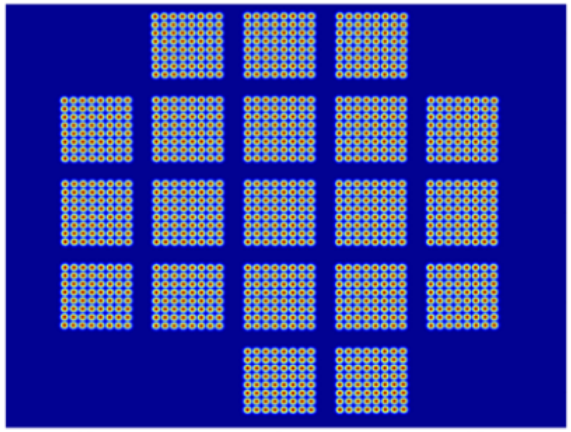
→ powerful recipe for high-confidence initial discovery

South Pole CMB telescopes

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

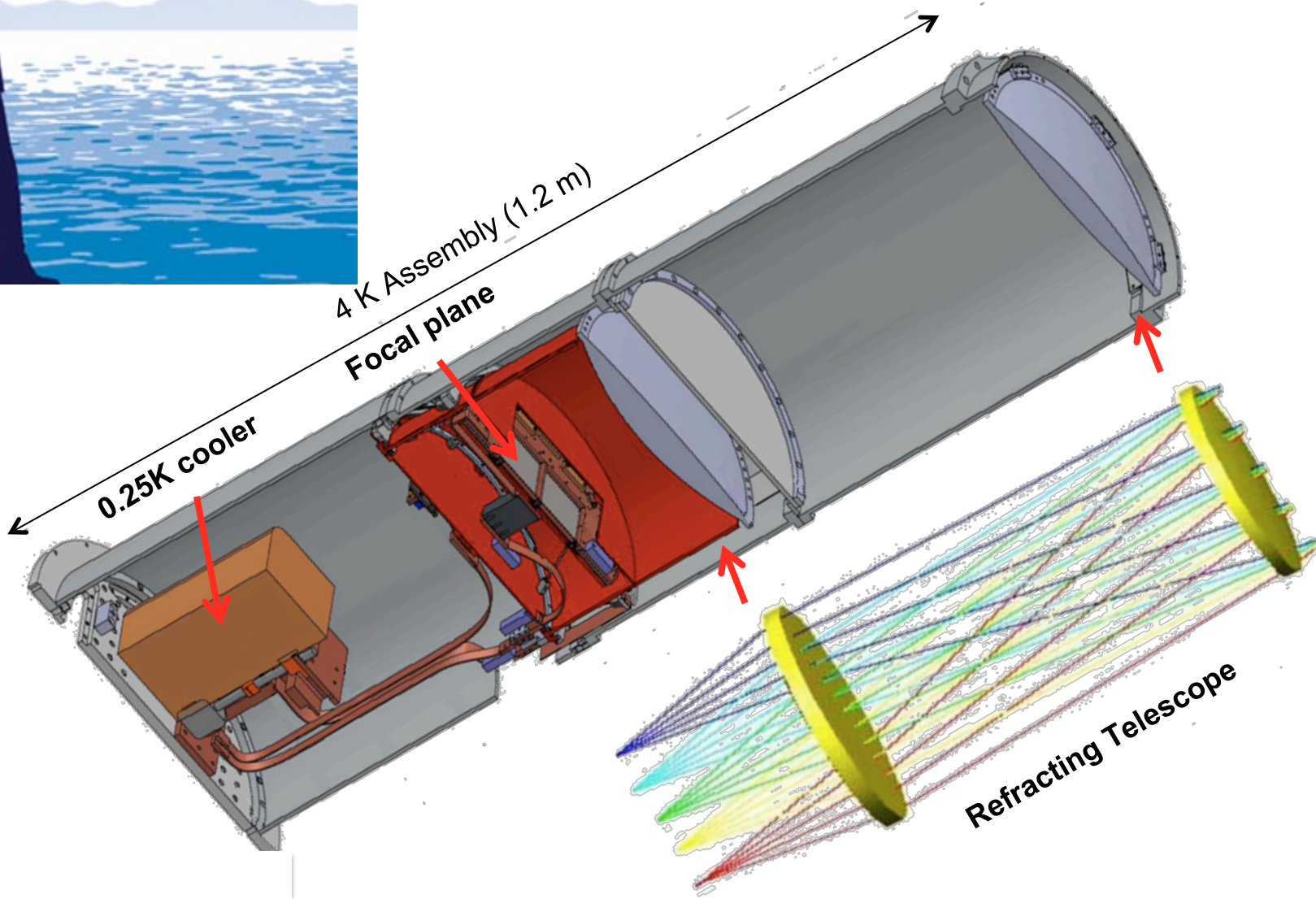
Super dry atmosphere and 24h coverage of "Southern Hole".

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

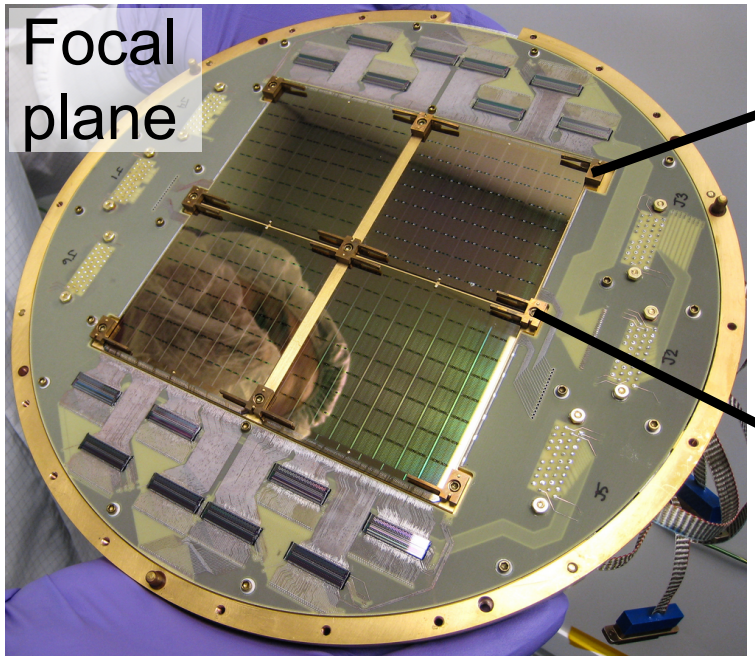
	BICEP1 (2006 - 8)	BICEP2 (2010 - 12)	Keck Array (2011 -)	BICEP3 (2014 -)
Telescope and Mount				
Focal Plane				
Beams on Sky				

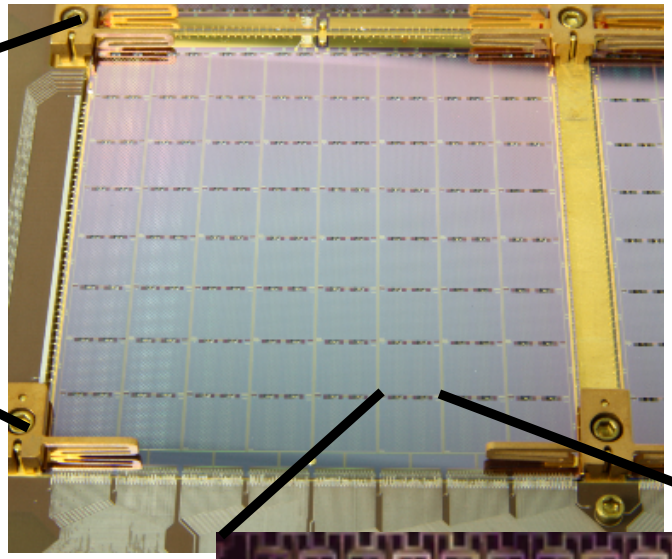
BICEP2 Experimental Concept

- Small aperture
- Wide field of view
- Cold refractor



Mass-produced superconducting detectors





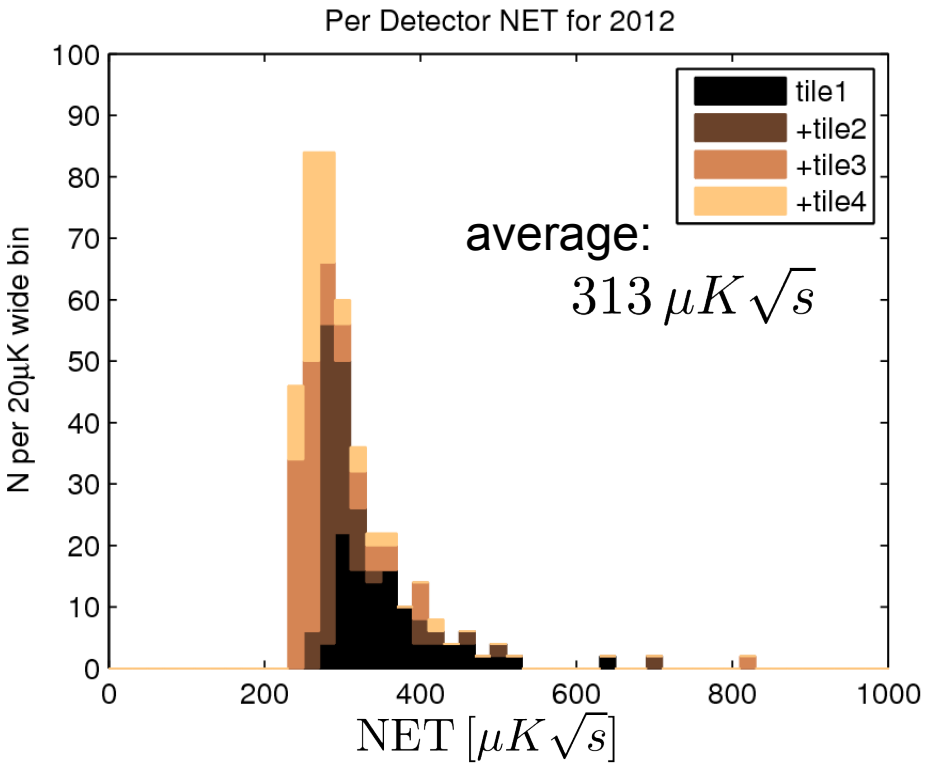
Planar
antenna
array

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:

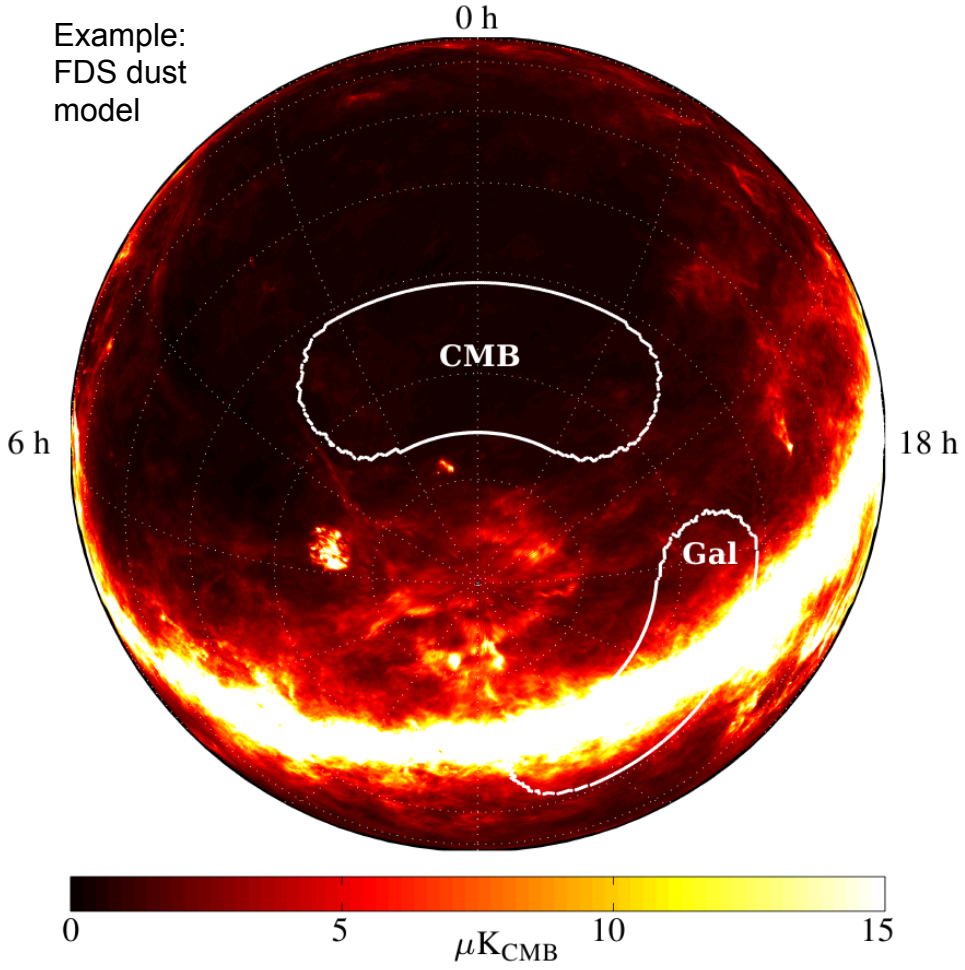
→ High optical efficiency
40% end-to-end

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

→ High detector count

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

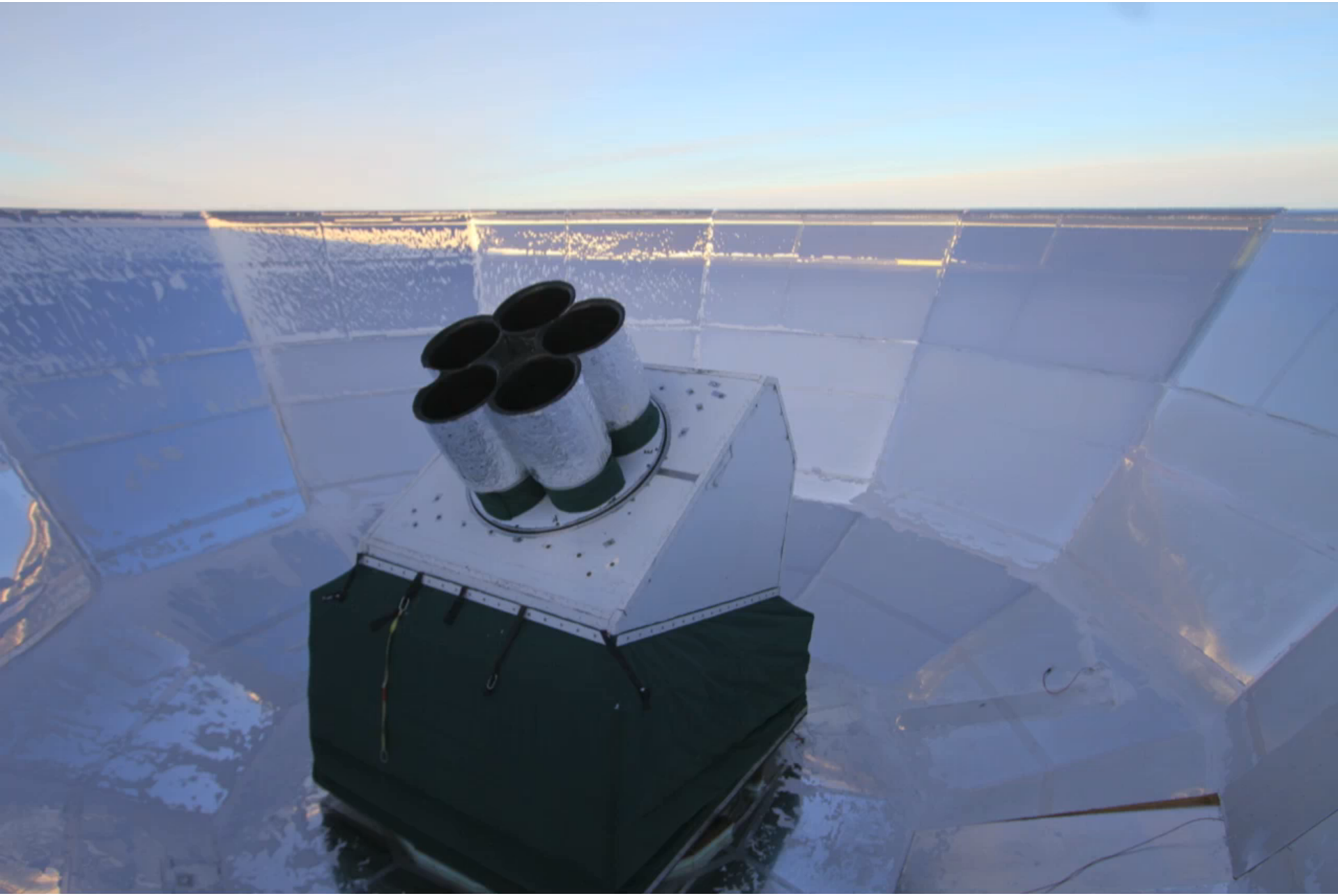
Observational Strategy



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

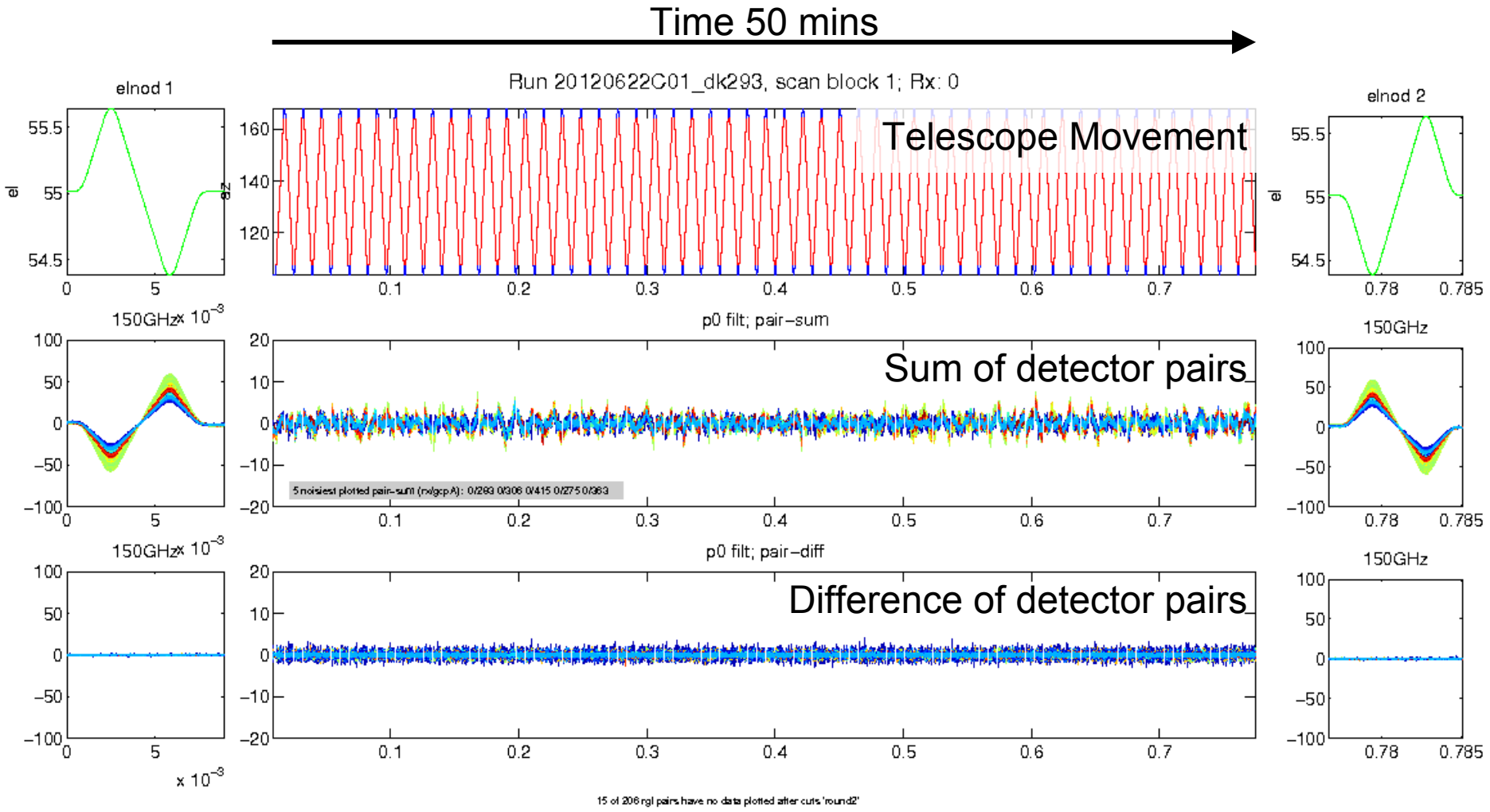
Detectors tuned to 150 GHz, near the peak of the CMB’s 2.7 K blackbody spectrum.

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



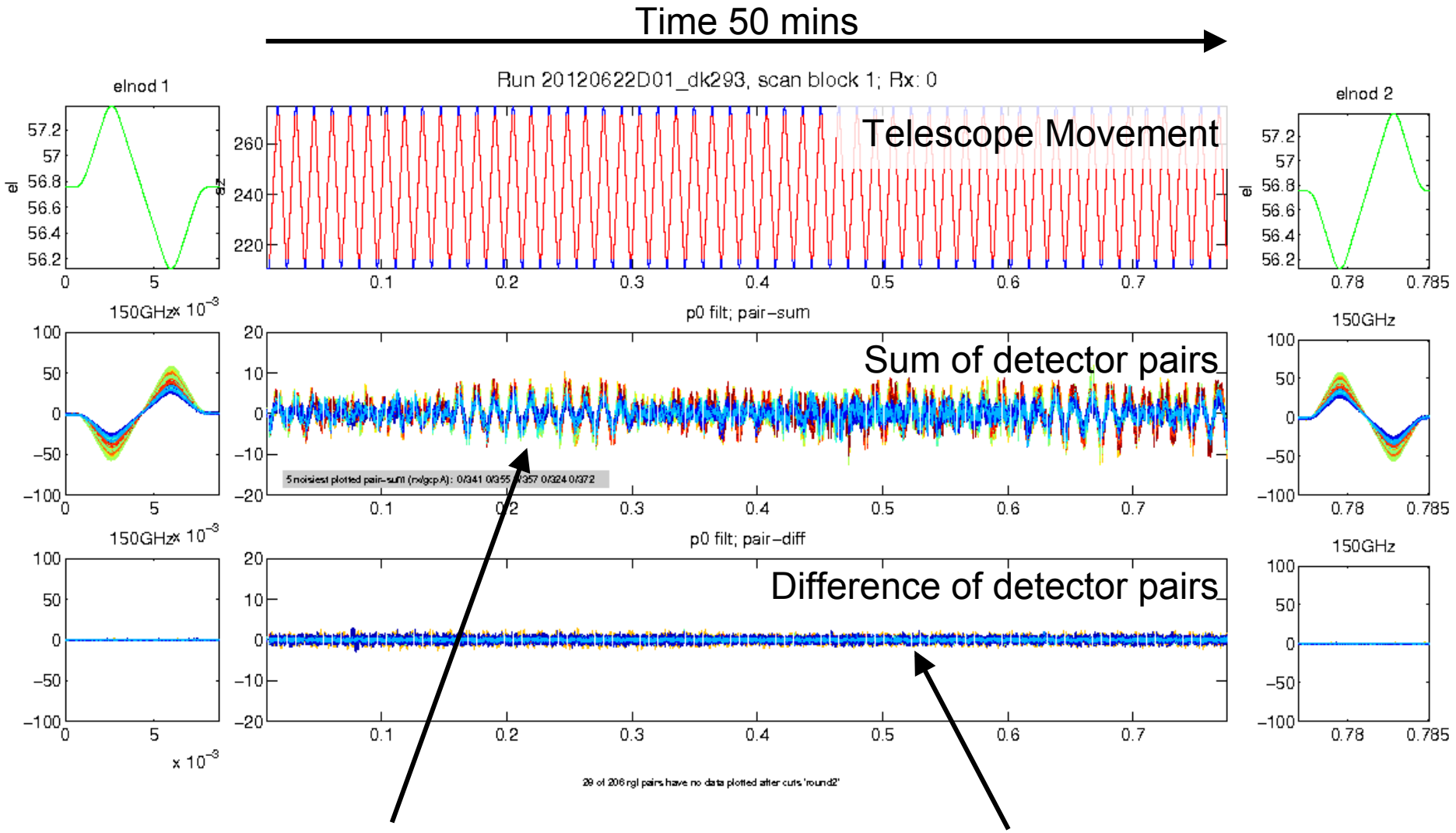
Clem Pryke for The Bicep2 Collaboration

Raw Data - Perfect Weather



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

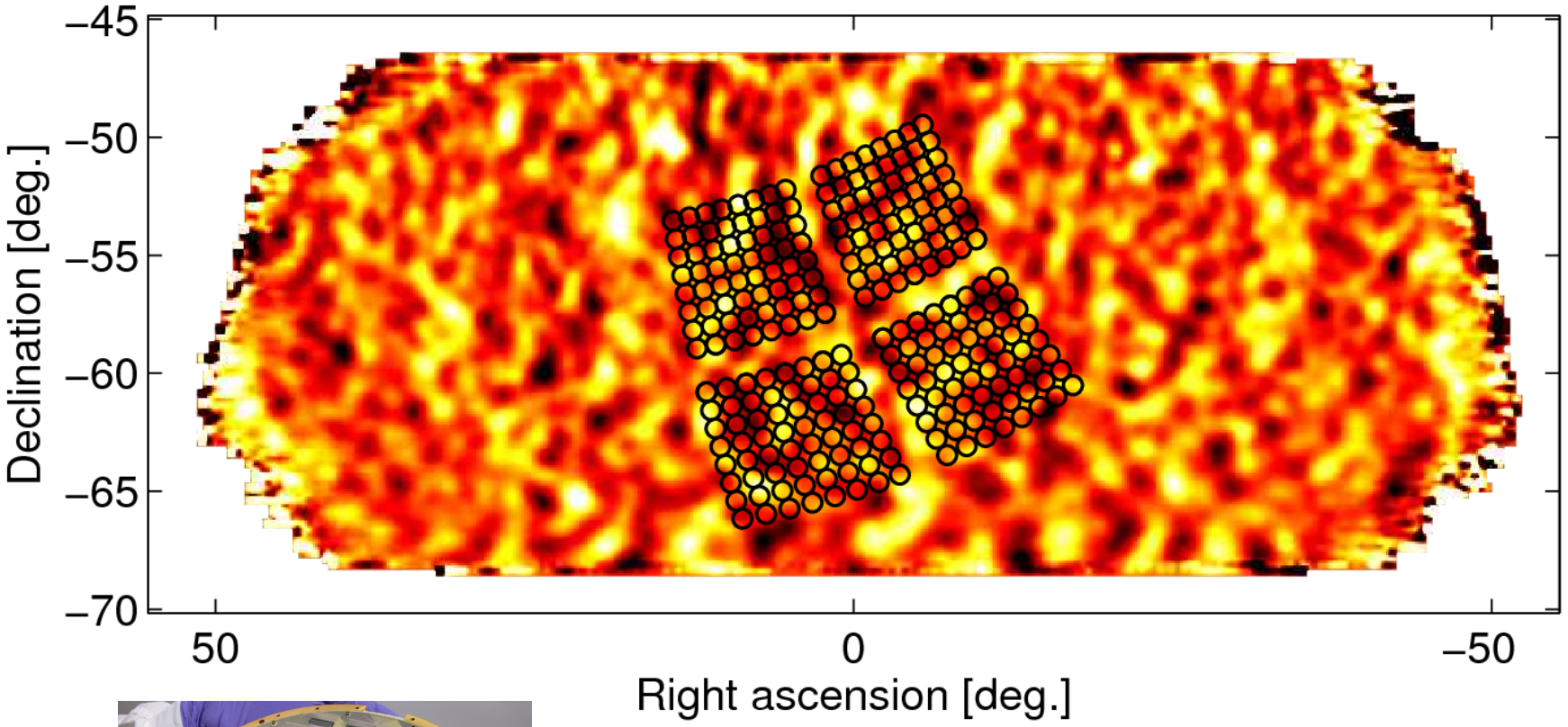
Raw Data - Worse Weather

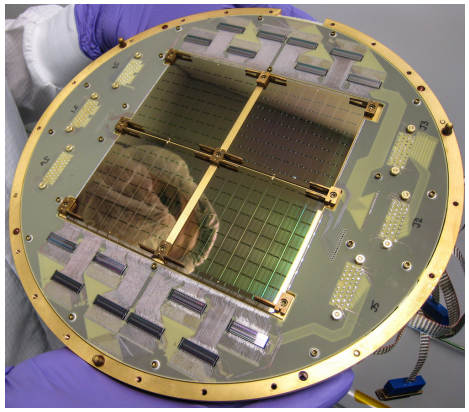


- Scanning over lumpy atmosphere → “clouds”
- Pair difference still clean → atmosphere is unpolarized

Clem Pryke for The Bicep2 Collaboration

BICEP2 on the Sky





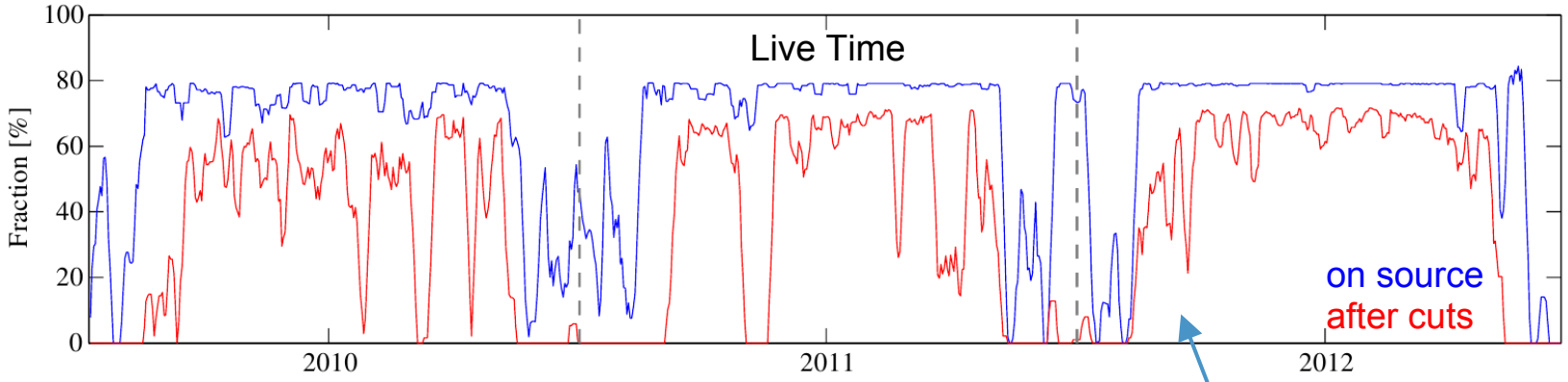
Projection of the BICEP2 focal plane on the sky

The focal plane is 20 degrees across

Background is the CMB temperature map as measured with BICEP2

Clem Pryke for The Bicep2 Collaboration

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

3 years of data!

Multistage cut procedure:

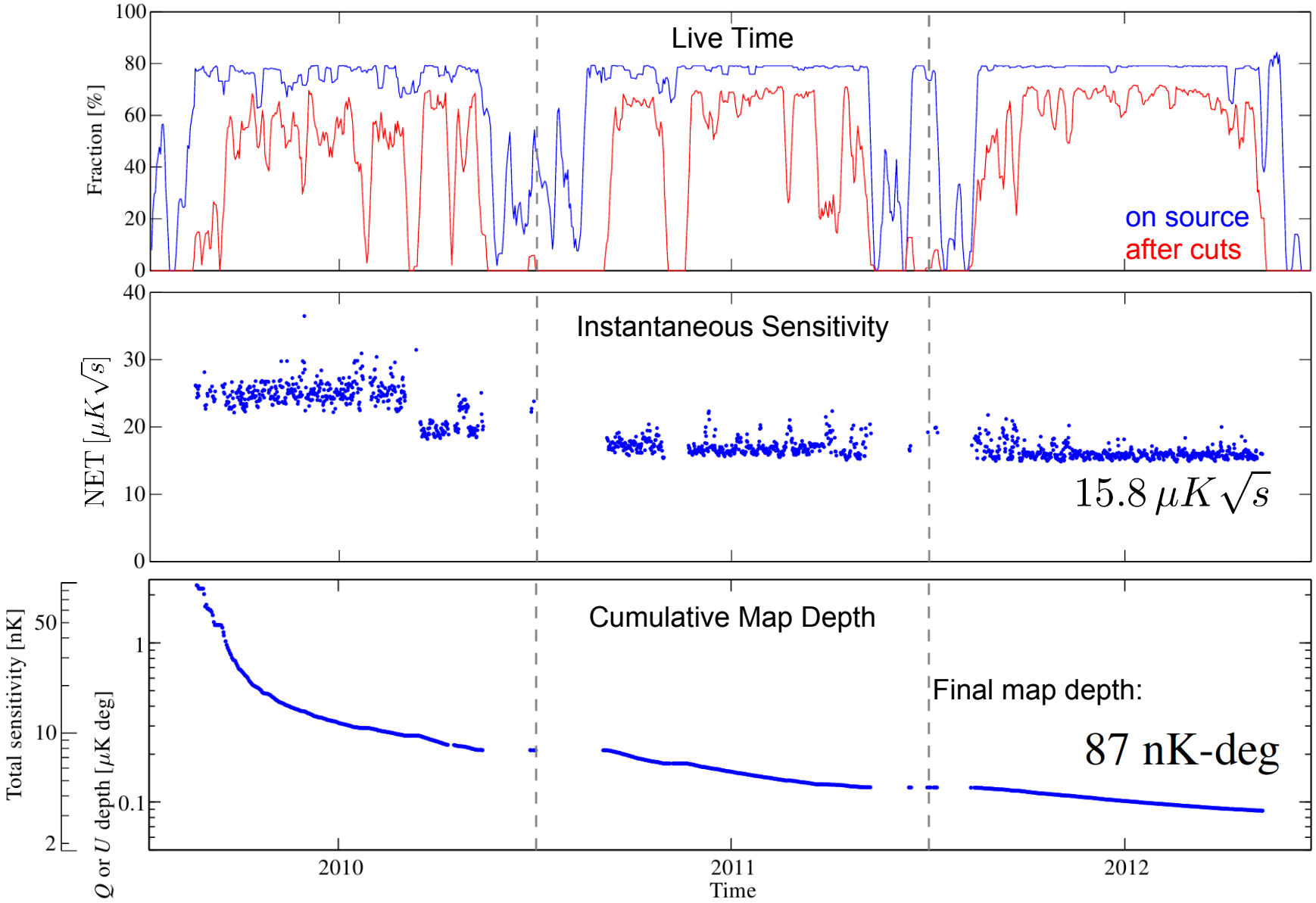
Ensures all data used in map making is taken when the experiment is operating properly and has stationary, well-behaved noise

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

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

Table from Instrument Paper

BICEP2 3-year Data Set



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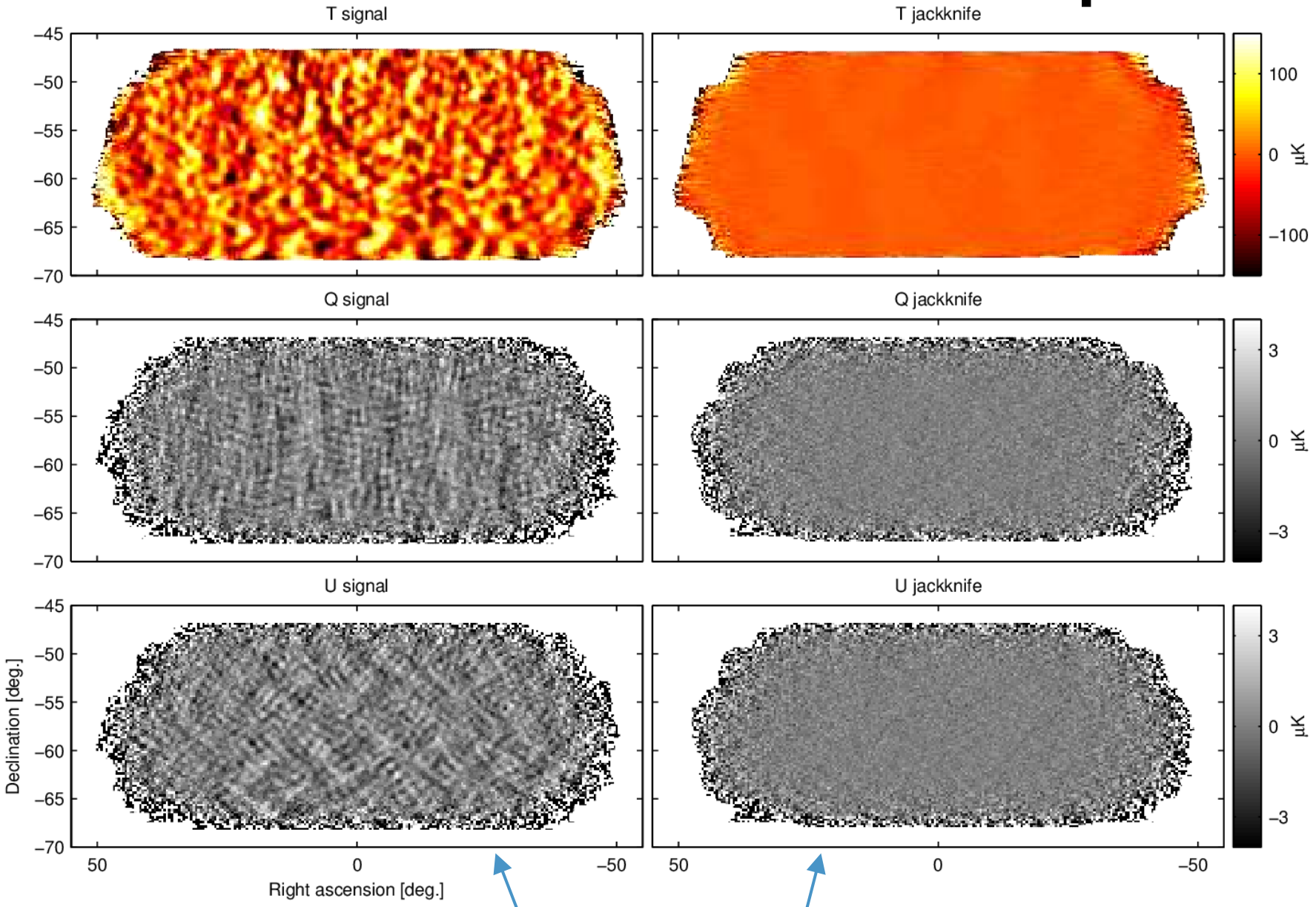
BICEP2 T and Stokes Q/U Maps



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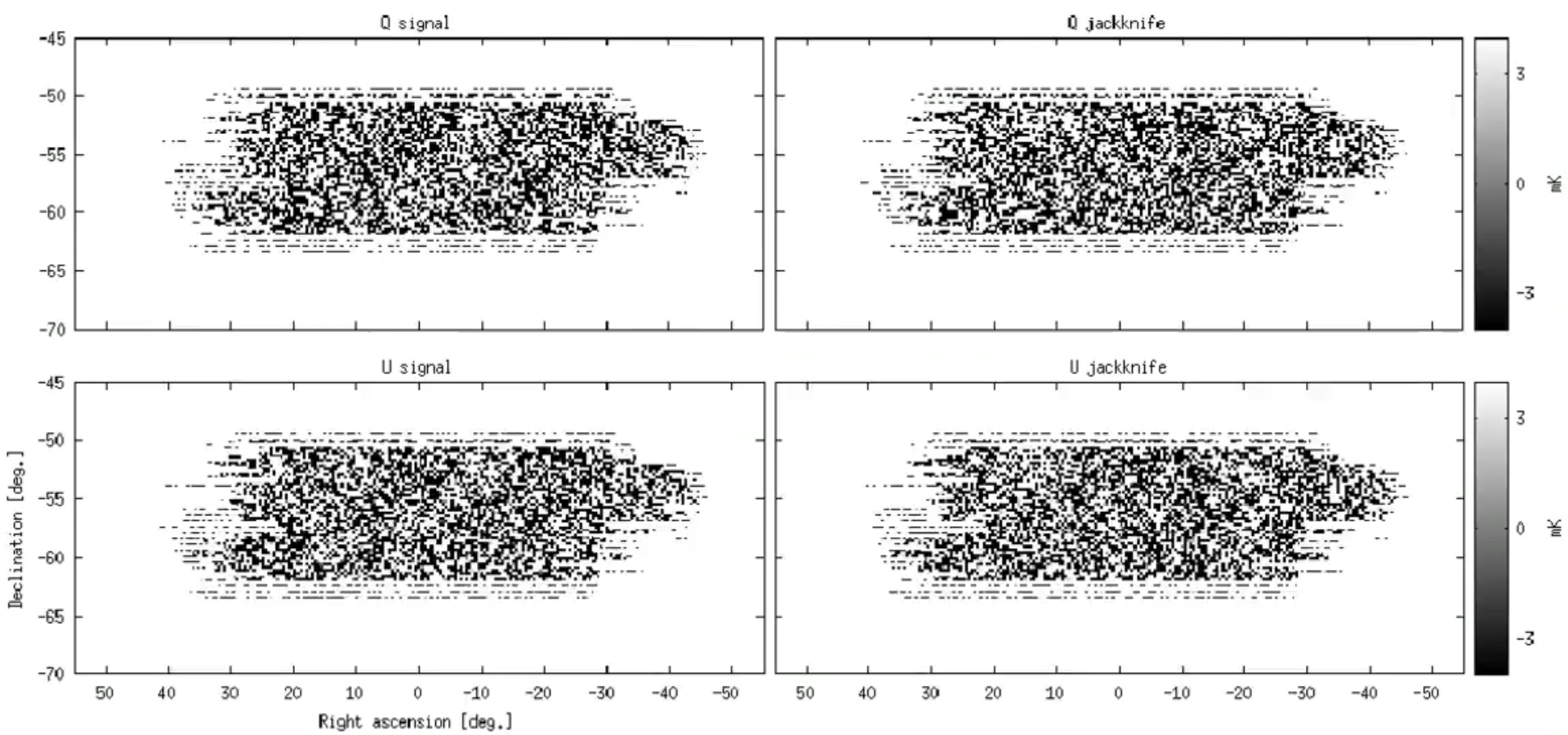
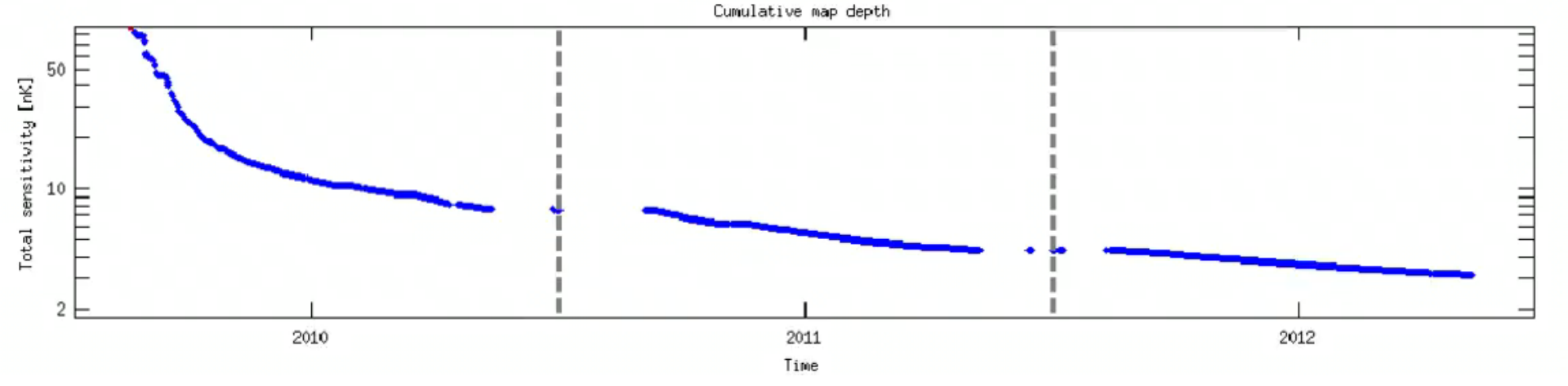
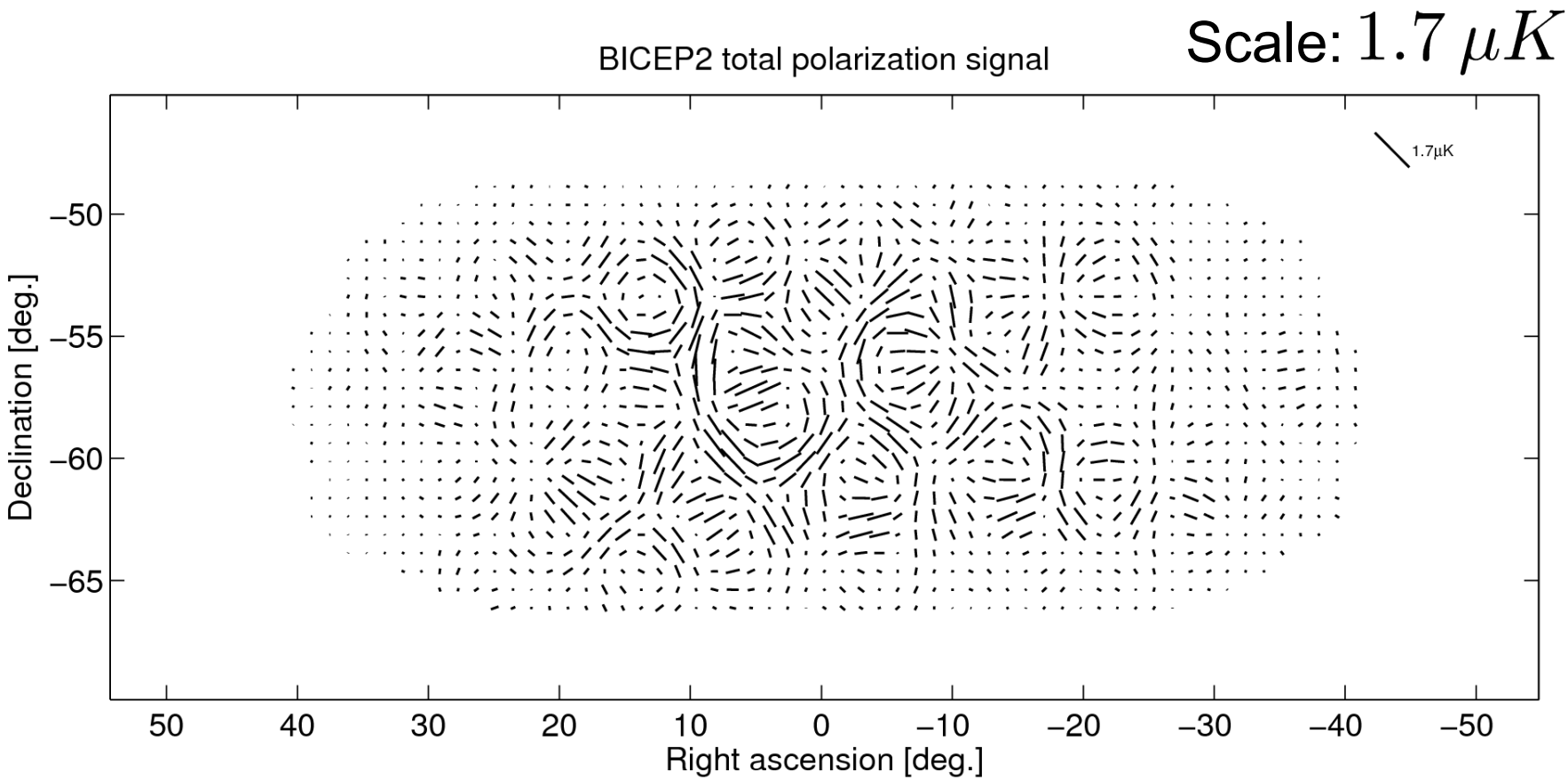

Q signal
Q jackknife
U signal
U jackknife
-45
-50
-55
-60
-65
-70
Declination [deg.]
50
40
30
20
10
0
-10
-20
-30
-40
-50
Right ascension [deg.]
3
0
-3
mK


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

Total Polarization



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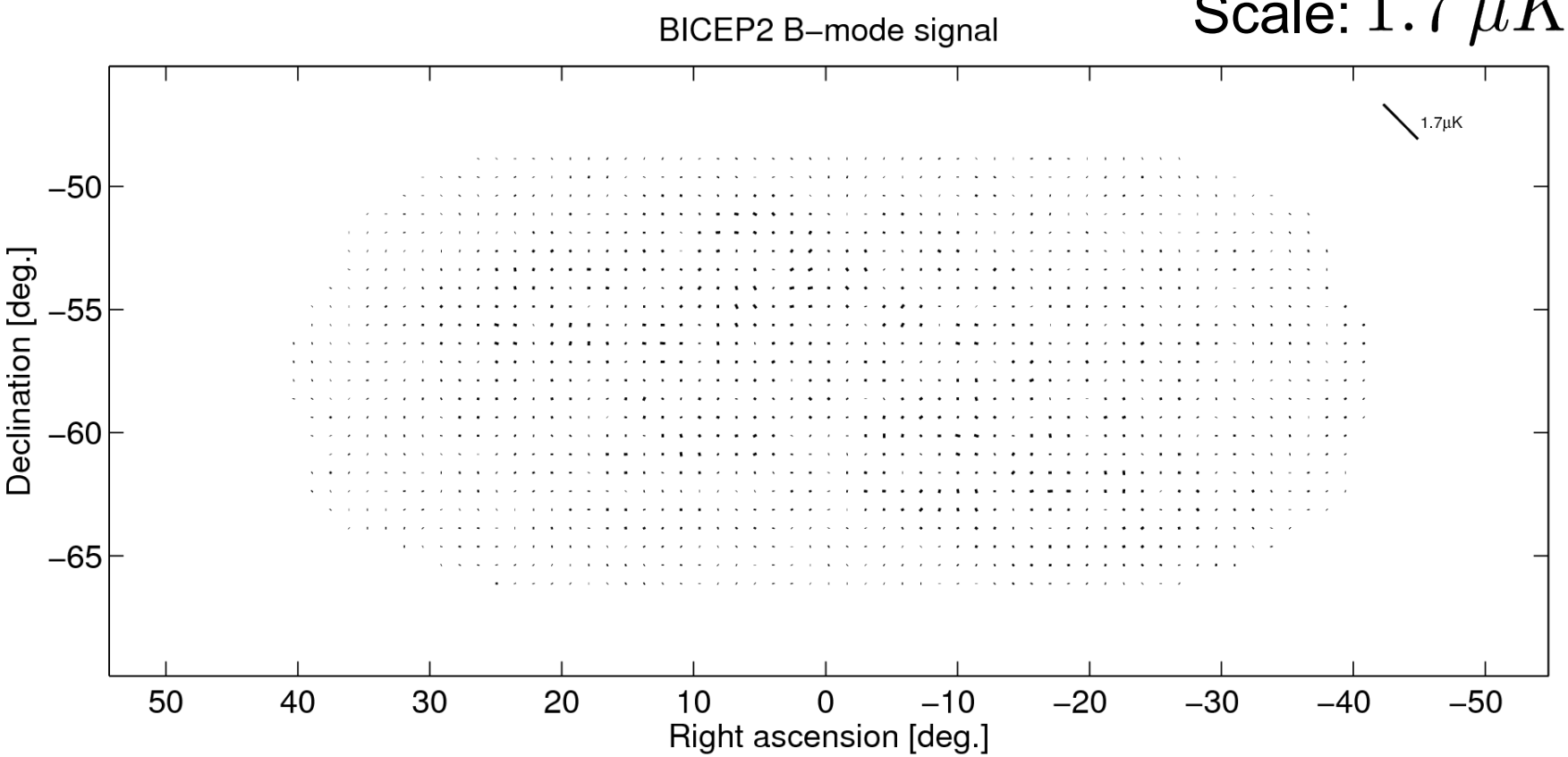
B-mode Contribution

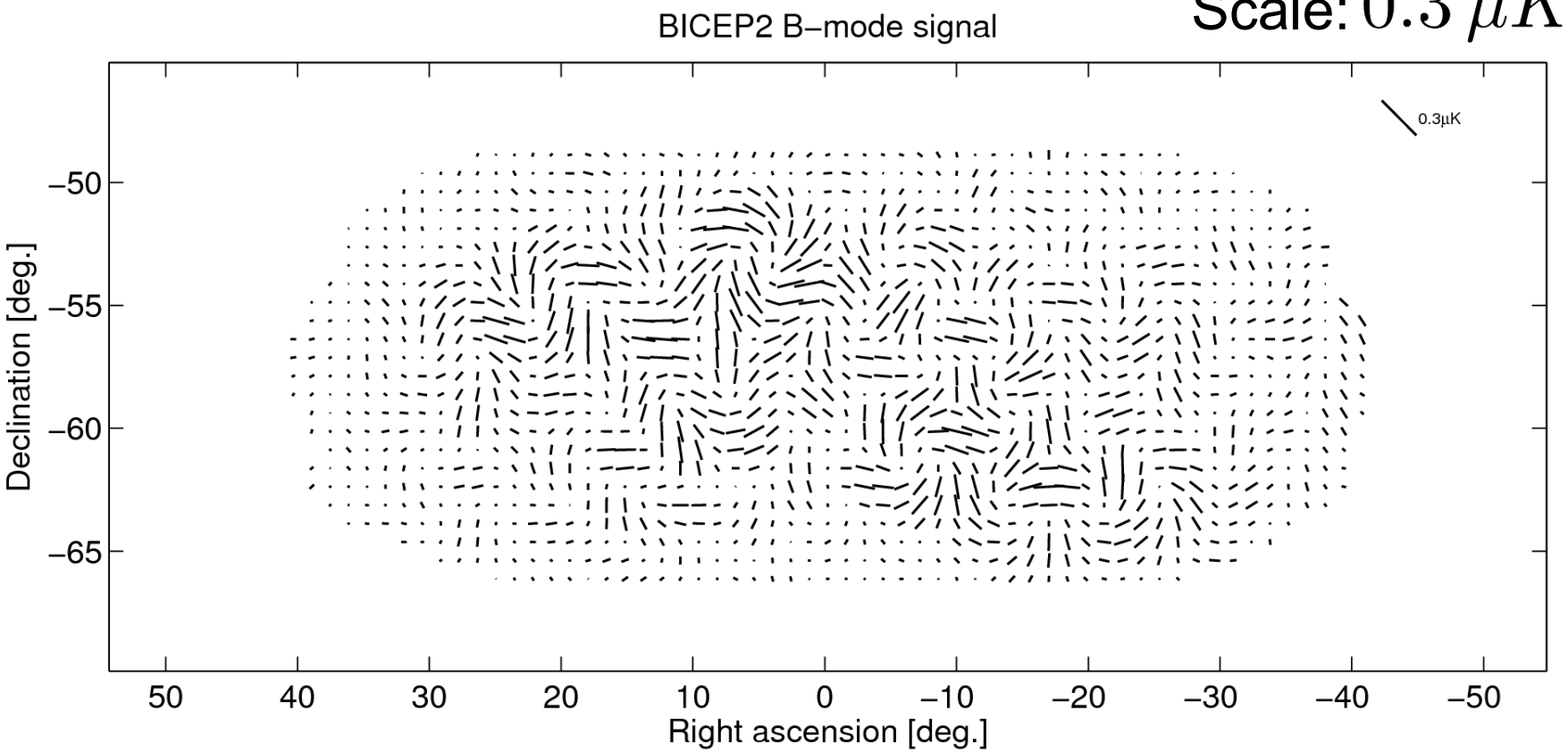
Scale: $1.7\,\mu K$



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

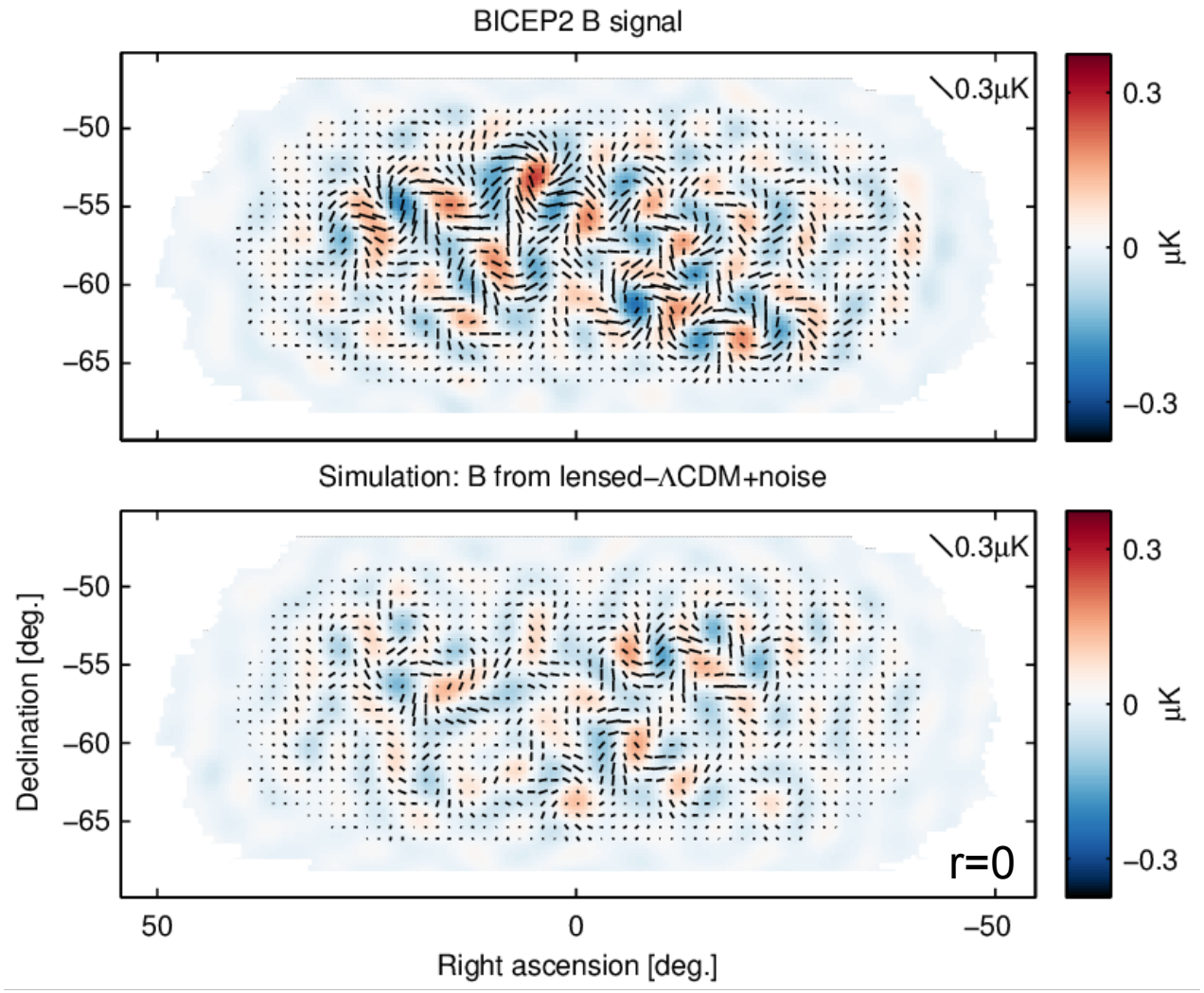
B-mode Contribution

Scale: $0.3\,\mu K$



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

B-mode Map vs. Simulation



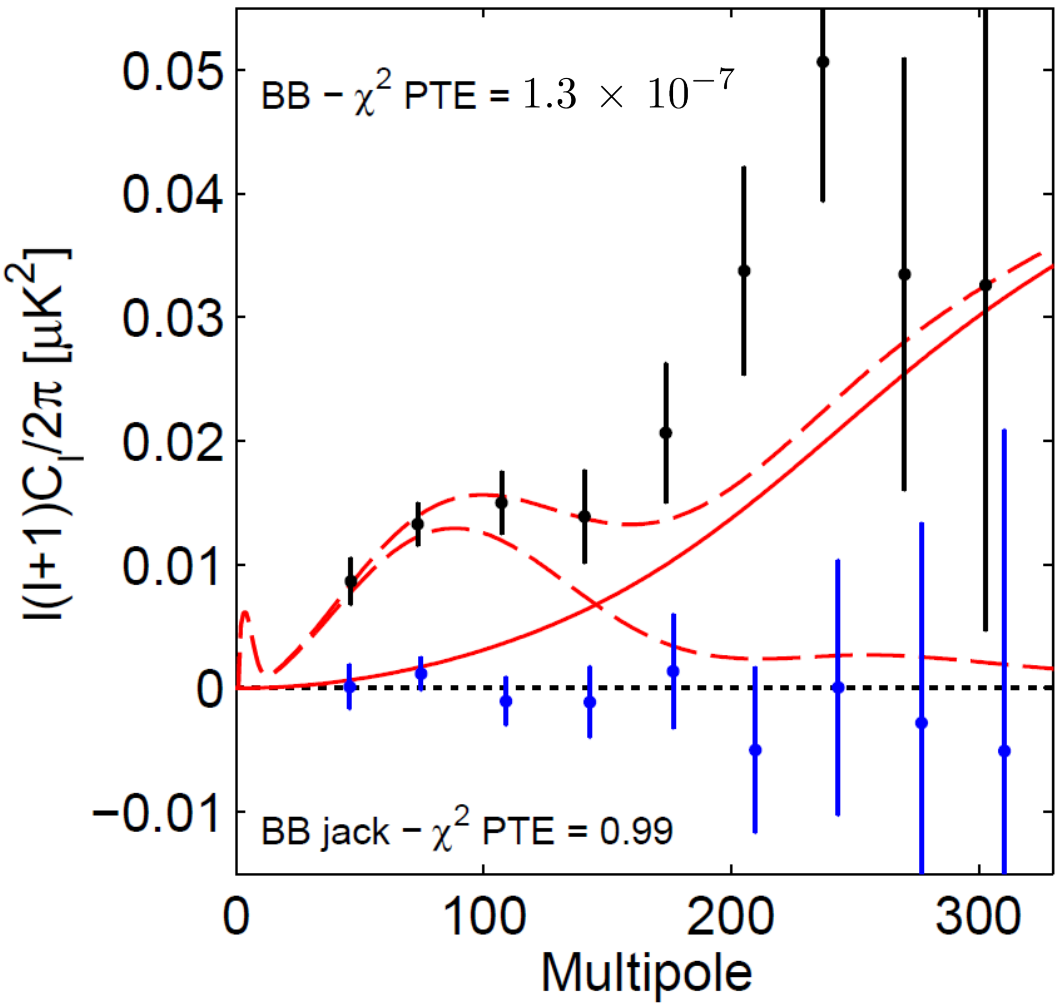
Analysis “calibrated” using lensed-ΛCDM+noise simulations.

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
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

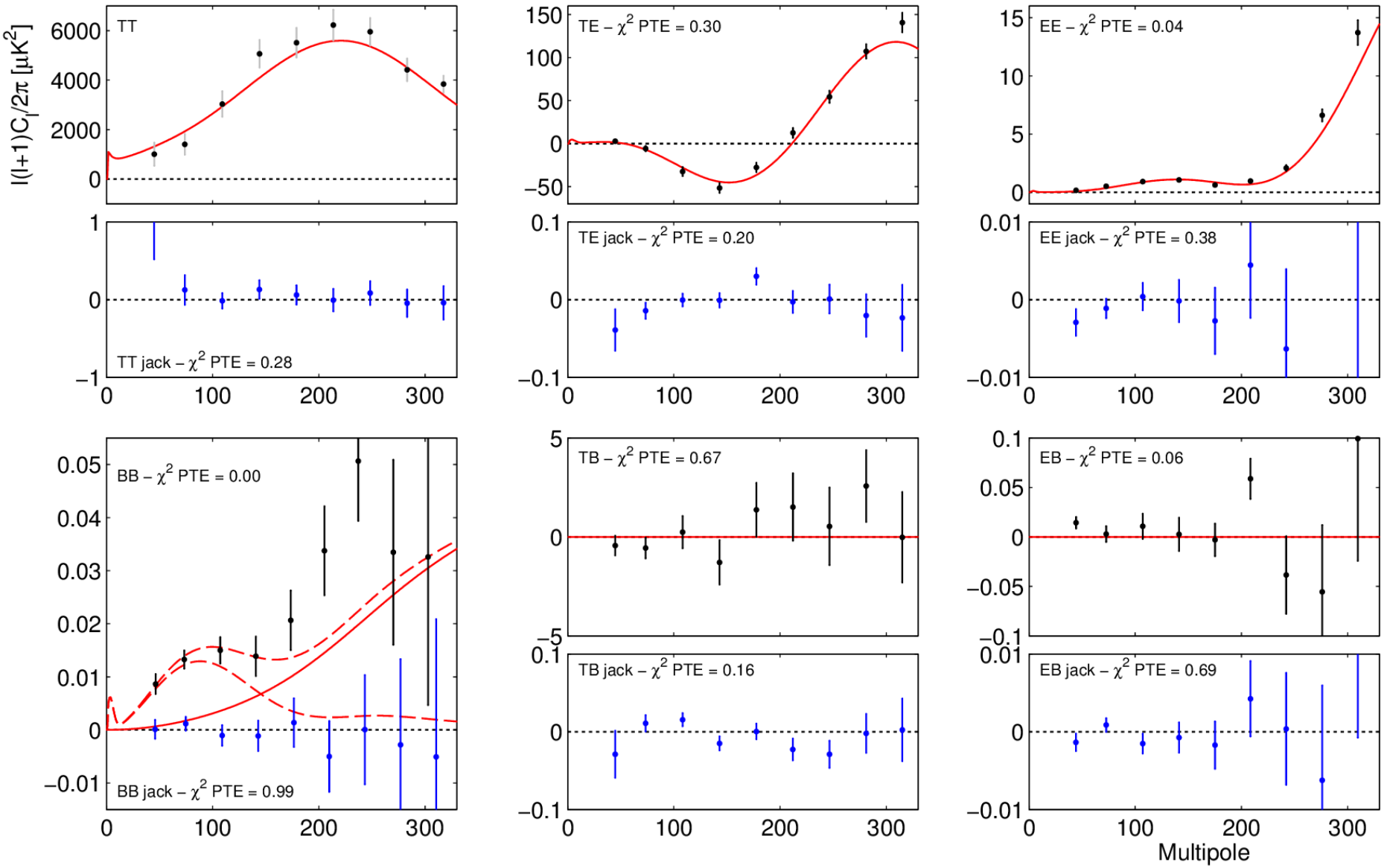
Consistent with lensing expectation at higher l. (yes – a few points are high but not excessively…)

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	$5.3\,\sigma$

Temperature and Polarization Spectra



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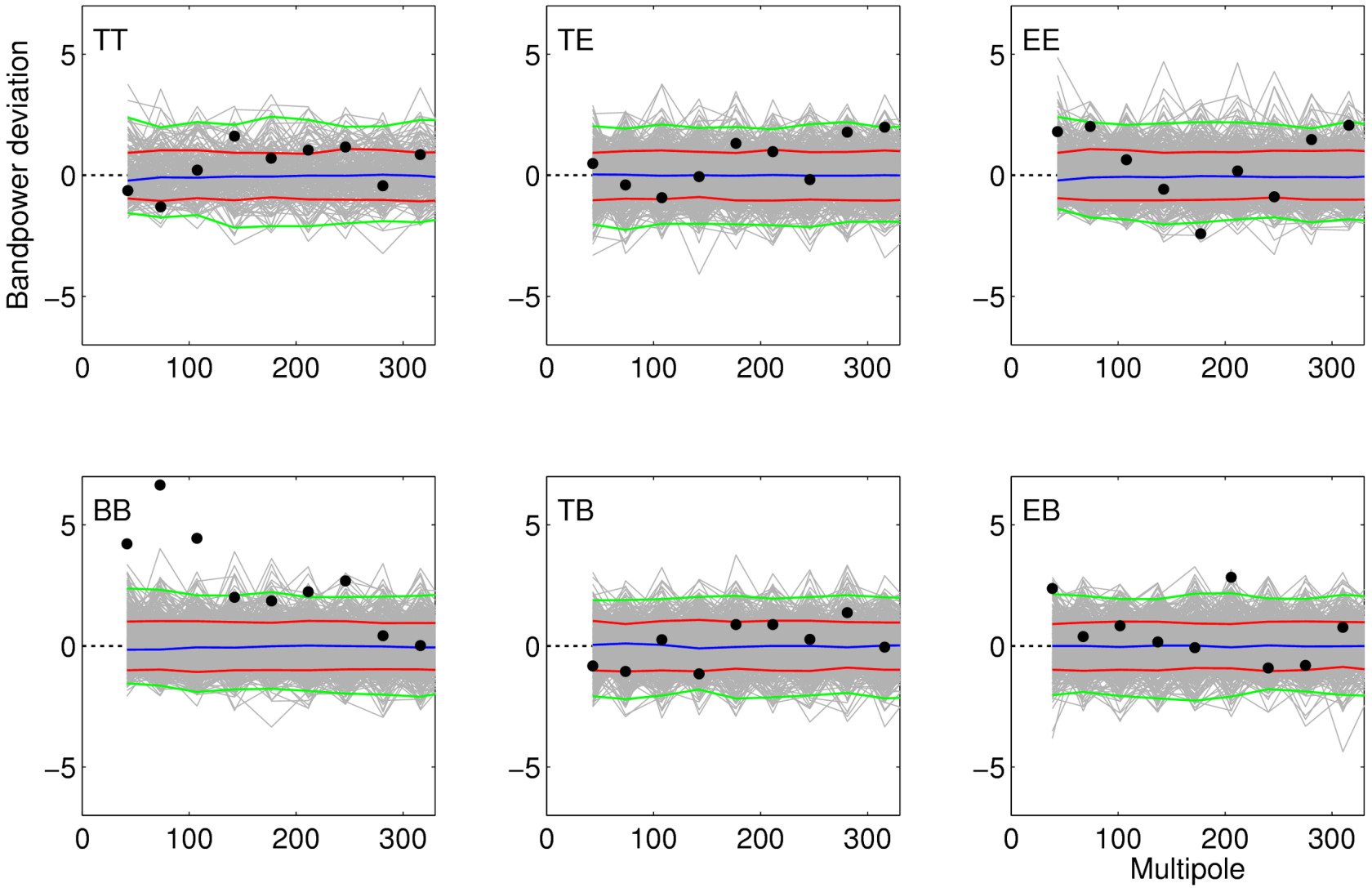
Bandpower Deviations



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

- real data
- lensed-ΛCDM + noise sims
- ± 1σ
- ± 2σ

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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
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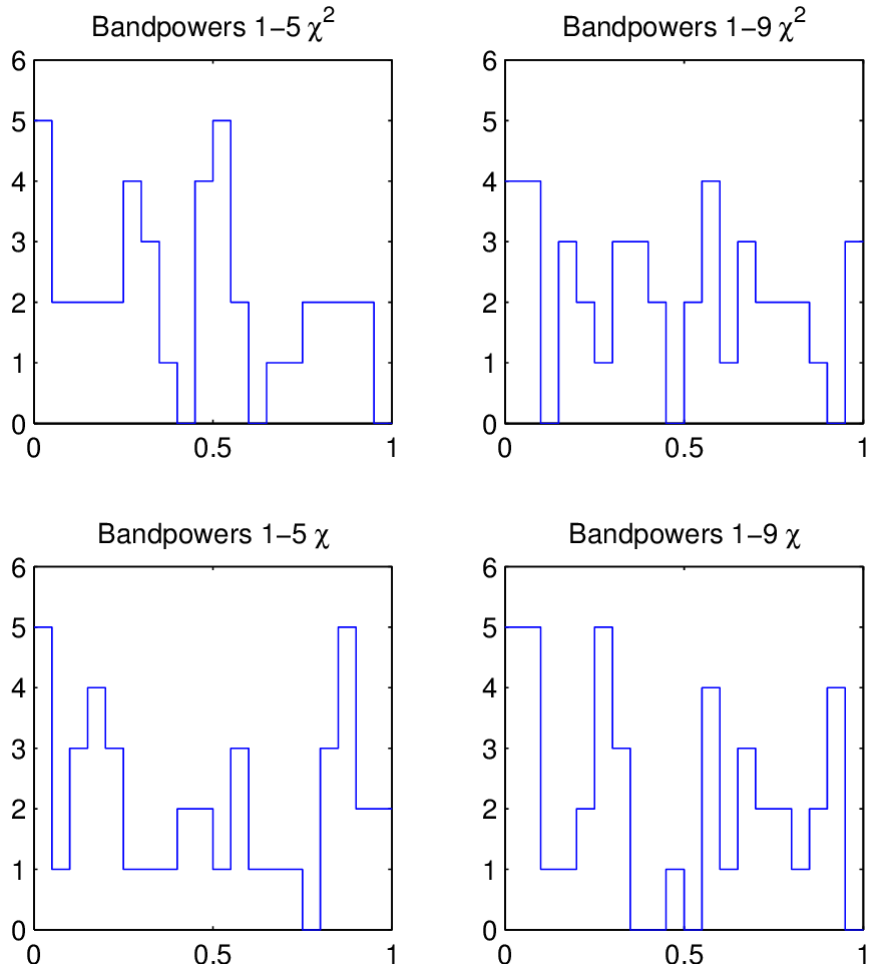
EE	0.727	0.533	0.128	0.485
BB	0.255	0.086	0.421	0.036
EB	0.465	0.737	0.208	0.168
Moon jackknife				
EE	0.499	0.689	0.481	0.679
BB	0.144	0.287	0.898	0.858
EB	0.289	0.359	0.531	0.307
A/B offset best/worst				
EE	0.317	0.311	0.868	0.709
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.790

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	0.317	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 (“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.

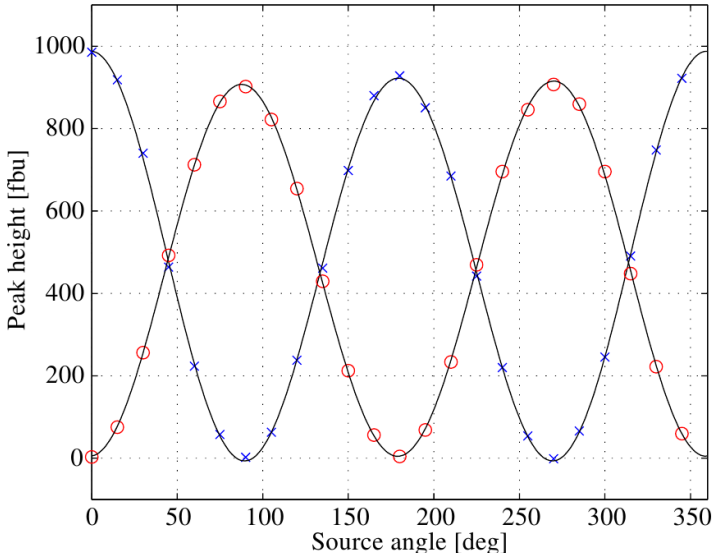
Systematics paper nearly ready – and see Chris Sheehy poster

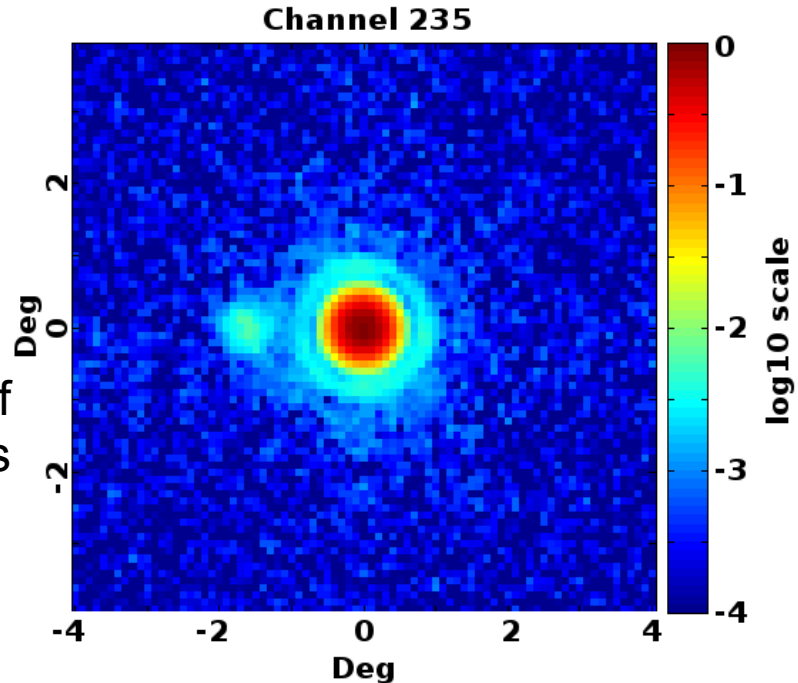
Calibration Measurements

For instance...

Far field beam mapping

Detector Polarization Calibration

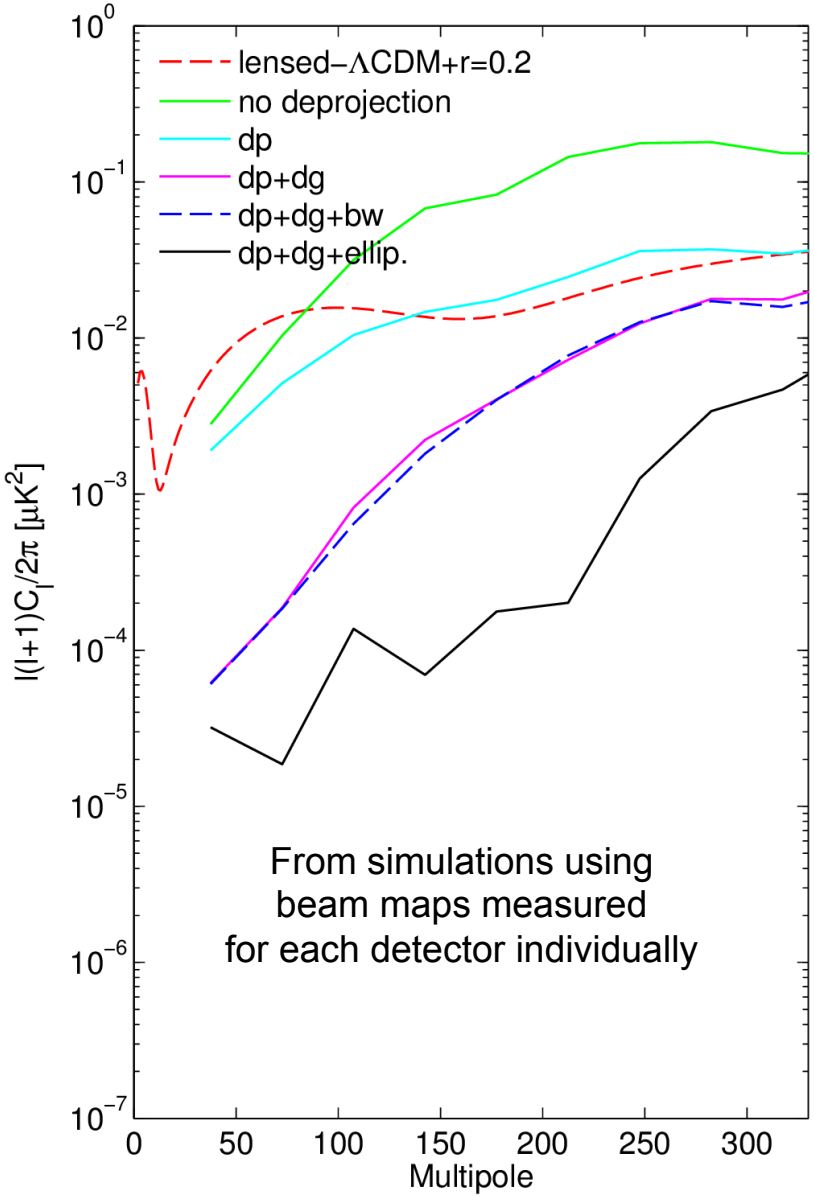




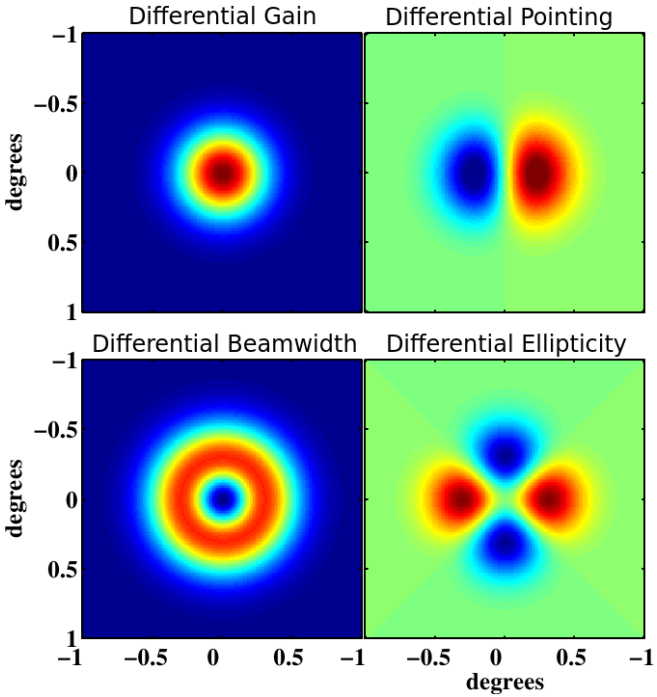
Hi-Fi beam maps of individual detectors

Detailed description in companion Instrument Paper

Systematics Removal: Deprojection



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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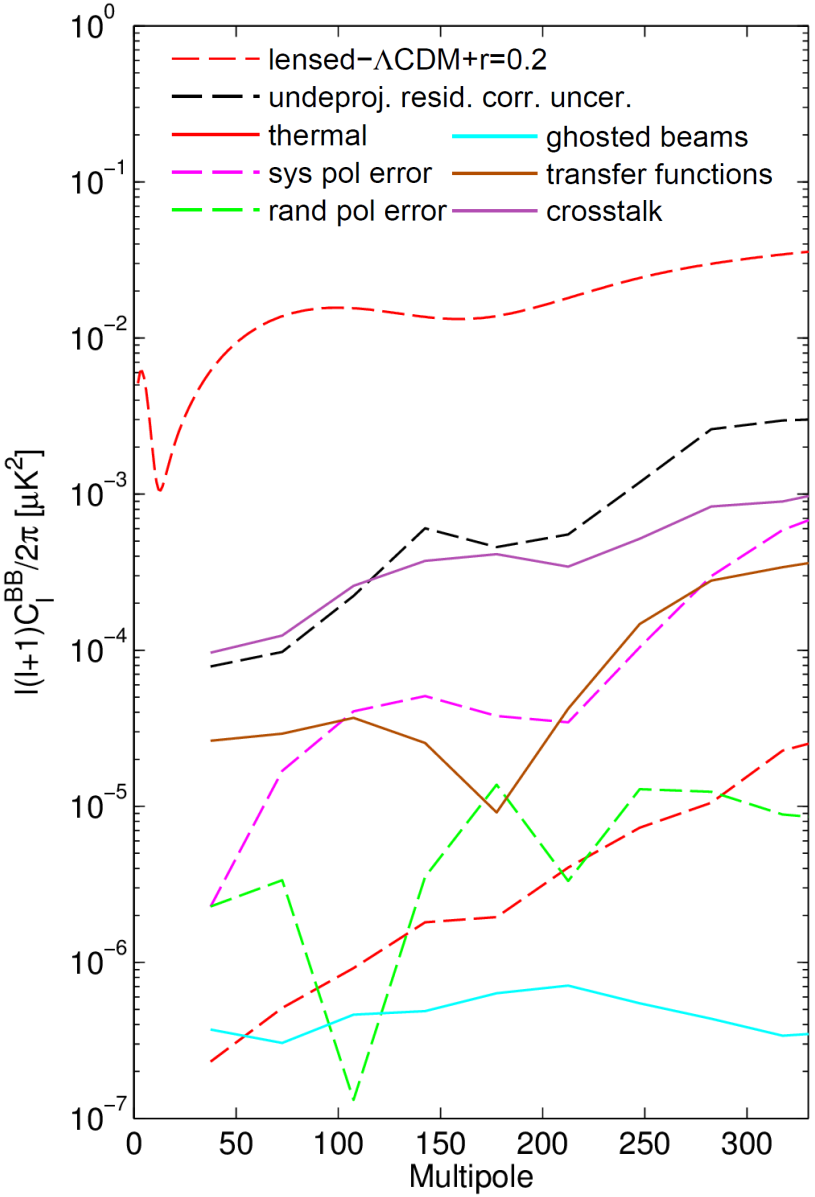
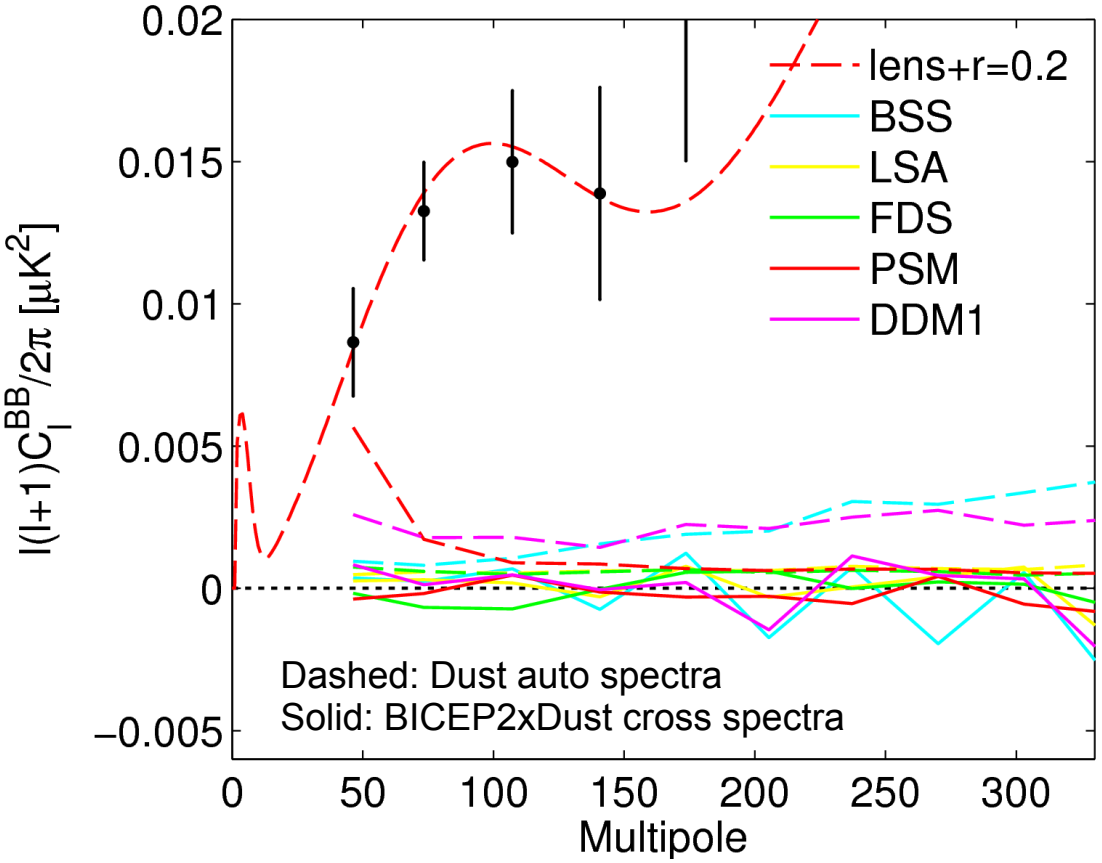
Systematics beyond Beam imperfections

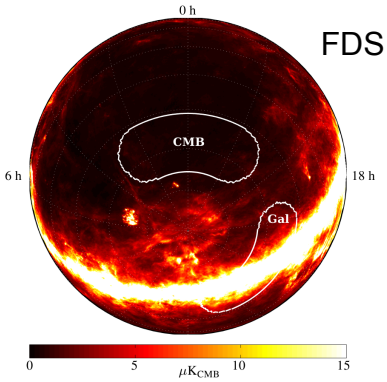


All systematic effects that we could imagine were investigated!

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

Polarized Dust Foreground Projections





FDS Model

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

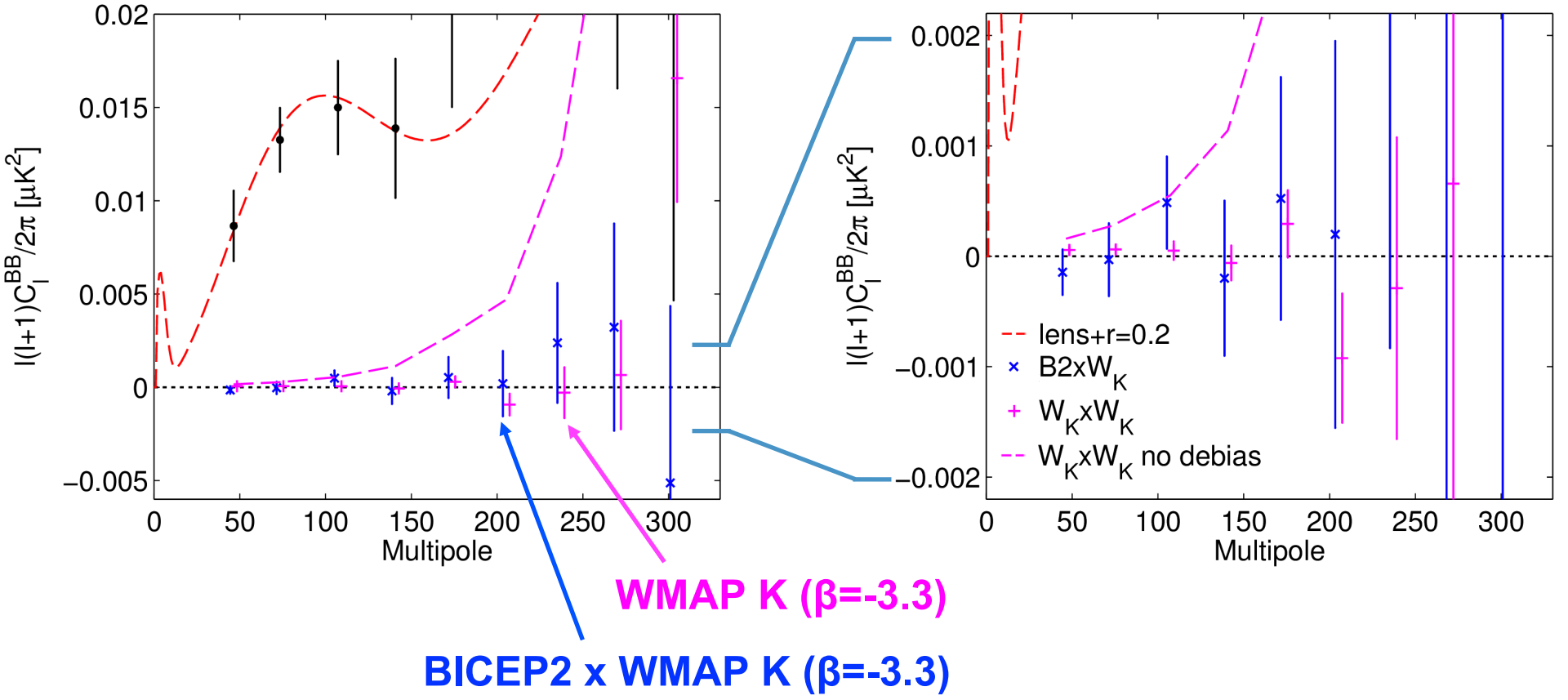
Use various models of polarized dust emission to estimate dust power.

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

But considerable uncertainty remains...

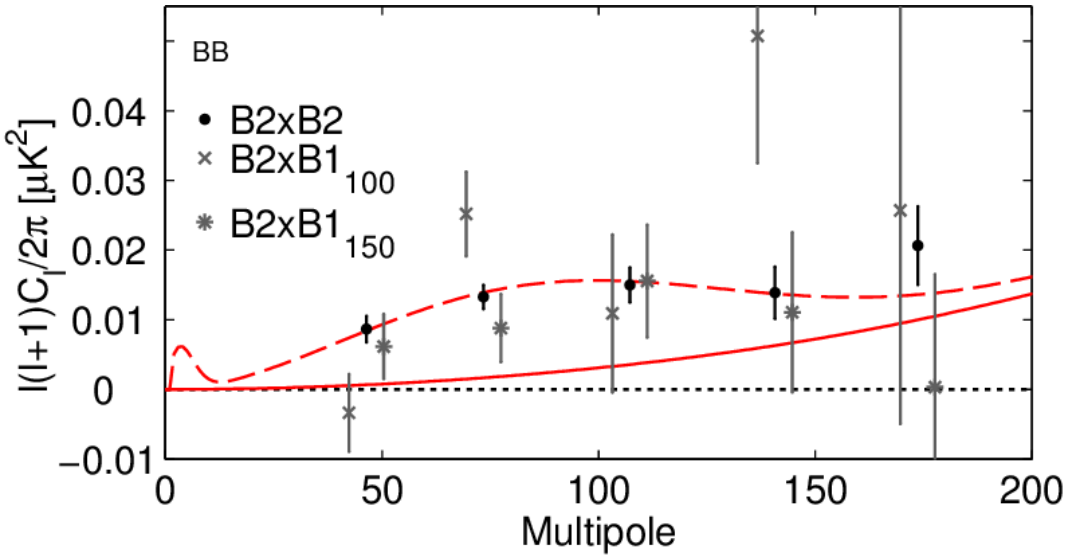
Synchrotron Foreground

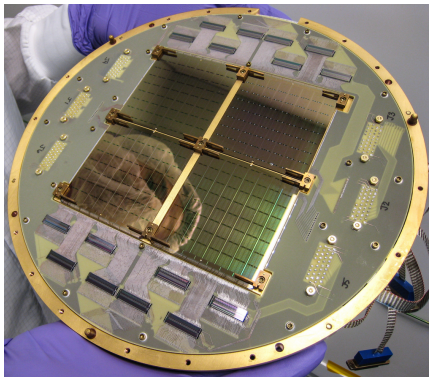
BICEP2 x WMAP 22 GHz polarization (extrapolated to 150 GHz with beta=-3.3*) is noise dominated but limits synchrotron to r<0.0008.



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

Cross Correlation with BICEP1





BICEP2: Phased antenna array and TES readout 150 GHz

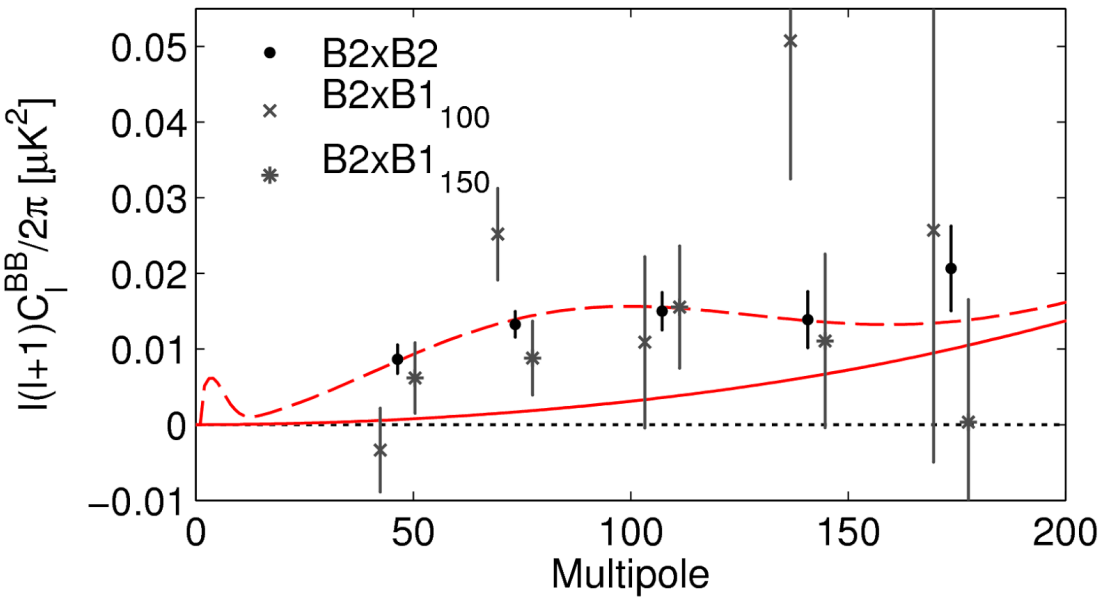
BICEP1: Feedhorns and NTD readout 150 and 100 GHz

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

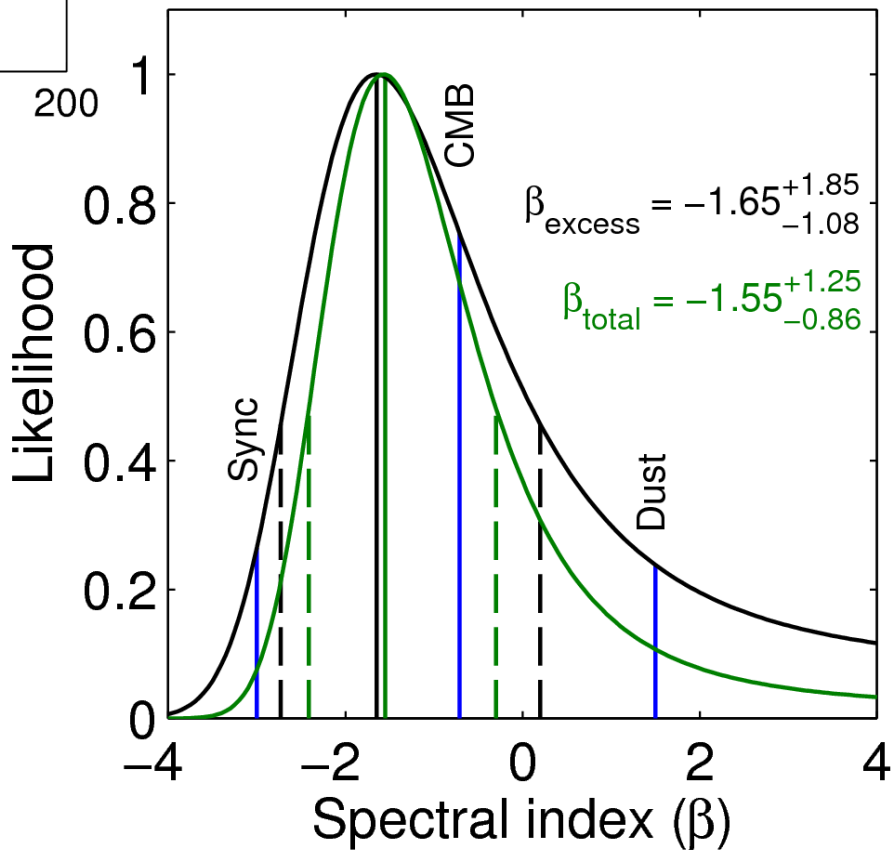
Cross with $BICEP1_{100}$ shows **~3σ** detection of BB power

Spectral Index of the B-mode Signal



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

green: total signal
black : excess signal over ΛCDM



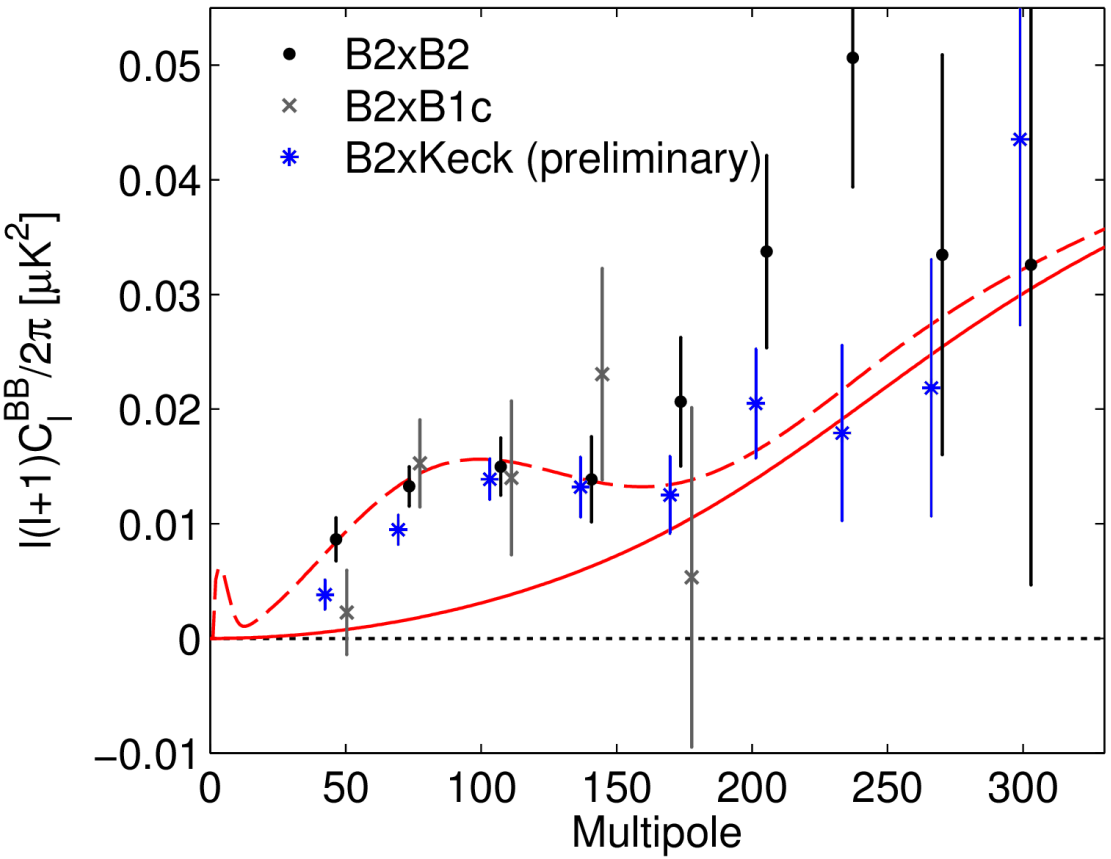
Comparison of B2 auto with $B2_{150}$ x $B1_{100}$ constrains signal frequency dependence, independent of foreground projections

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

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

Cross Spectra between 3 Experiments

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

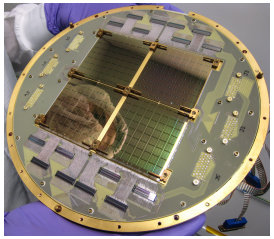


BICEP2 auto spectrum compatible with B2xB1c cross spectrum

~3σ evidence of excess power in the cross spectrum

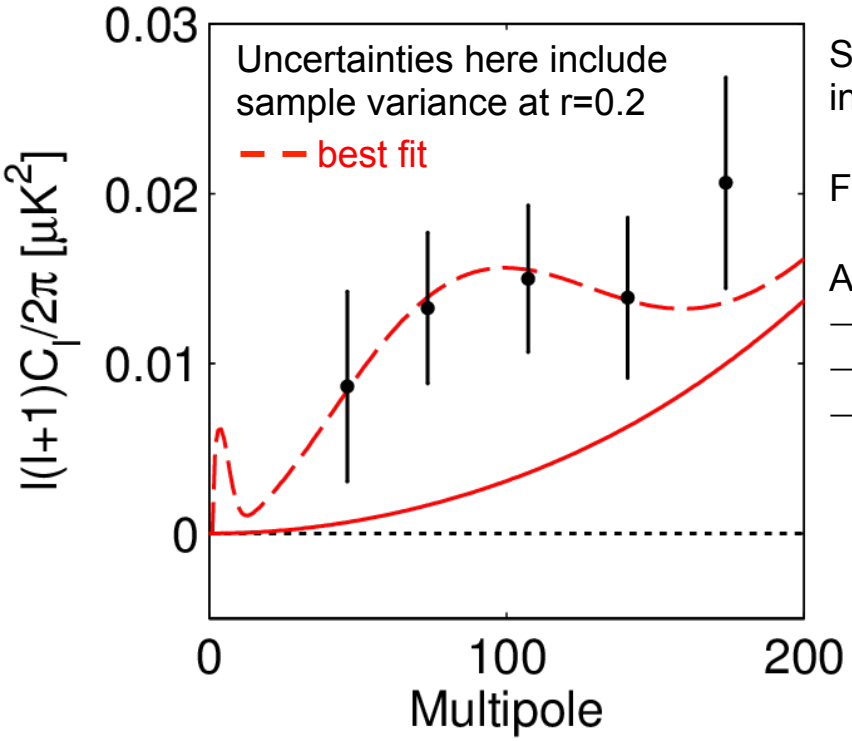
Additionally form cross spectrum with 2 years of data from *Keck Array*, the successor to BICEP2

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

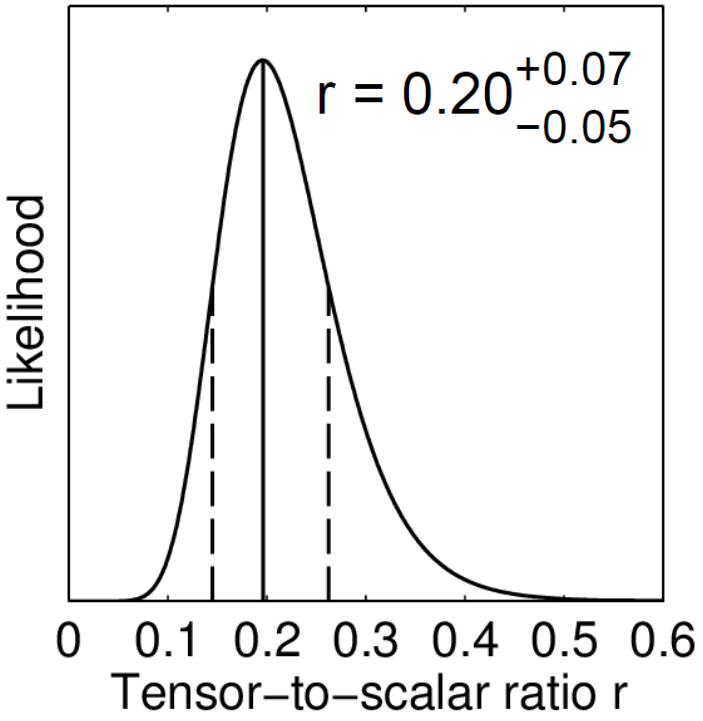
Find the most likely value of the tensor-to-scalar ratio r

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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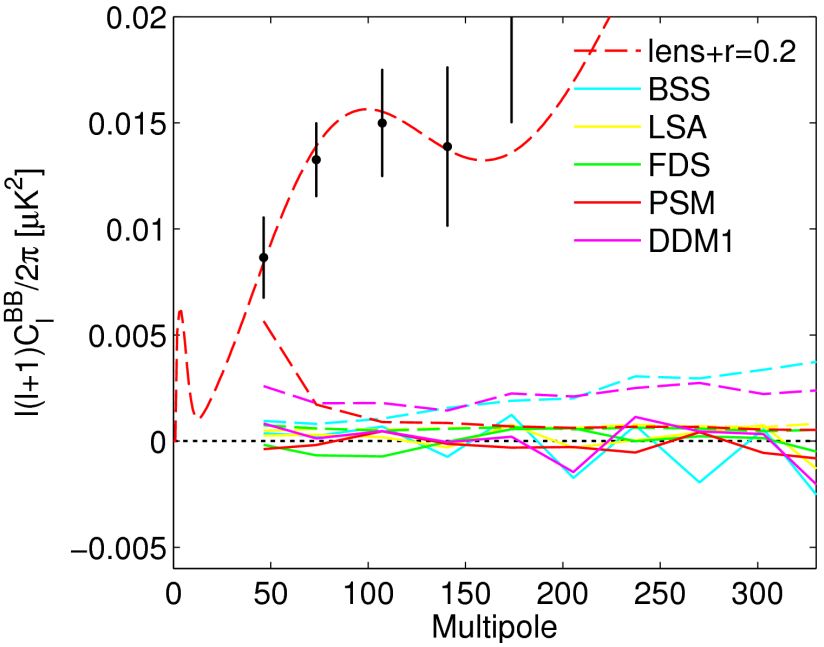
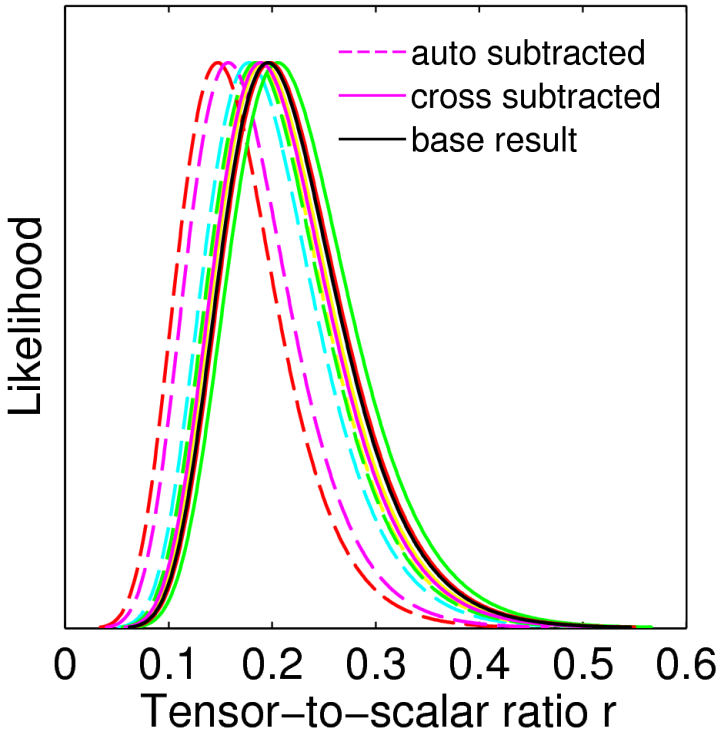
Constraint on r under Foreground Projections



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



Probability that each of these models reflect reality is hard to assess.

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

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

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Compatibility with Temperature Based Limits on r

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

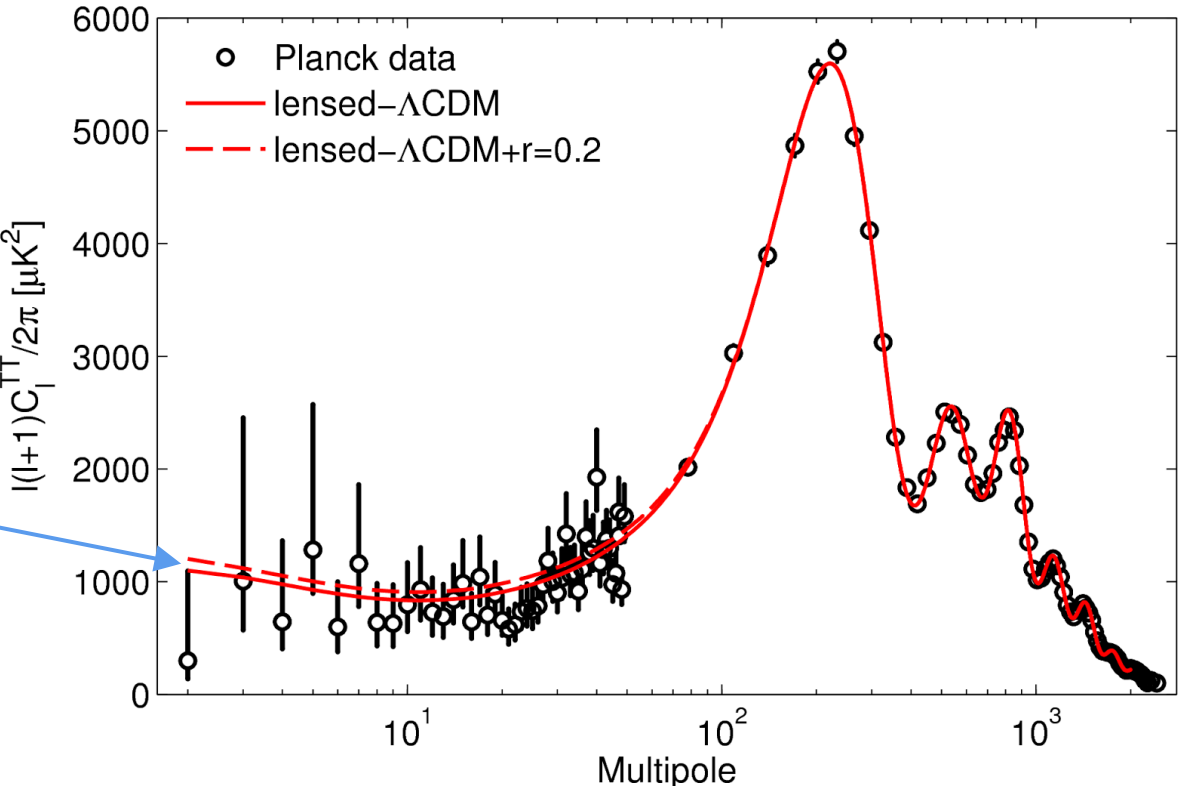
SPT+WMAP+BAO+H_0 : $r < 0.11$

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

(95% CL)

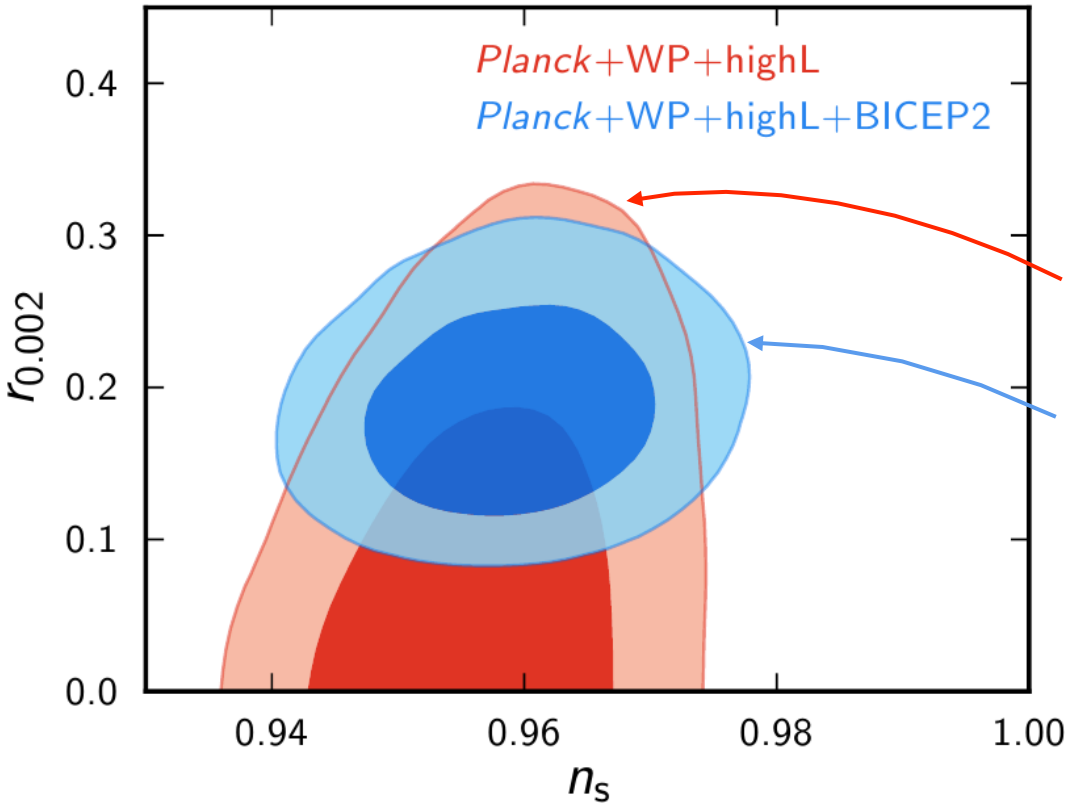
However, r=0.2 just makes a small change to the temperature spectrum.

(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

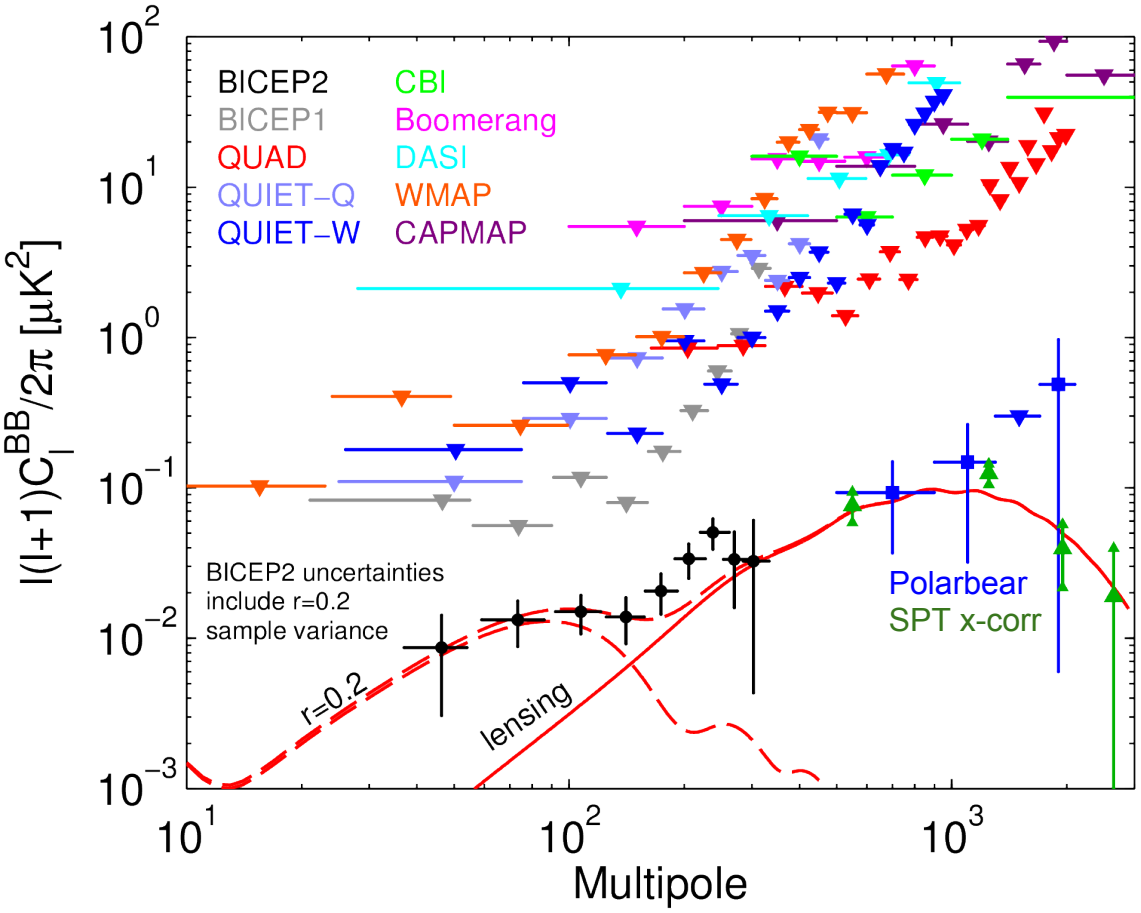
Planck likelihood chains for lensed ΛCDM + *tensors* + *running*

Same chains, importance sampled with the BICEP2 r likelihood

Other possibilities within ΛCDM?...

Conclusions 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

Foregrounds do 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

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.

Clem Pryke for The Bicep2 Collaboration

Developments Since…

- Intense media and science community interest…
- Many early instrumental queries… mostly seem to have faded
- Since our release papers on dust polarization have appeared from Planck
  - –But specifically mask out low foreground regions like ours (due to “non small systematics and not dust dominated”)
- Concerns with our result 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…
- Last Thursday our paper published in PRL (and updated on the arxiv)
- 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)