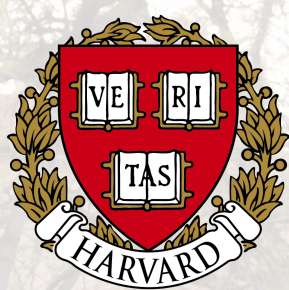


Detection of B-mode Polarization at Degree Scales (and 150 GHz) using BICEP2



UNIVERSITY OF
TORONTO



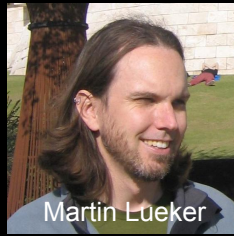
The BICEP2 Postdocs



Colin Bischoff



Jeff Filippini



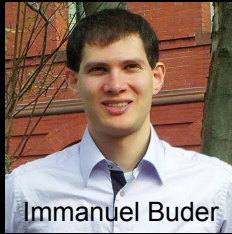
Martin Lueker



Walt Ogburn



Abigail Viereggs



Immanuel Buder



Stefan Fliescher



Roger O'Brient



Angiola Orlando

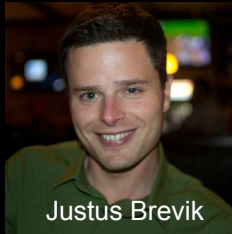


Zak Staniszewski

The BICEP2 Graduate Students



Randol Aikin



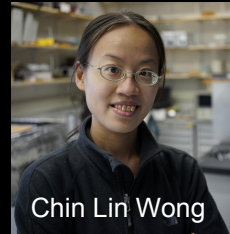
Justus Brevik



Chris Sheehy



Grant Teply



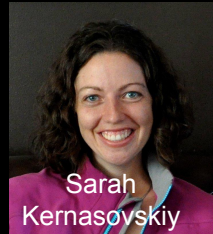
Chin Lin Wong



Kirit Karkare



Jon Kaufman



Sarah
Kernasovskiy



Jamie Tolan

BICEP2 Winterovers



Steffen Richter

2010



Steffen Richter

2011



Steffen Richter

2012

Modern cosmology in a nutshell:



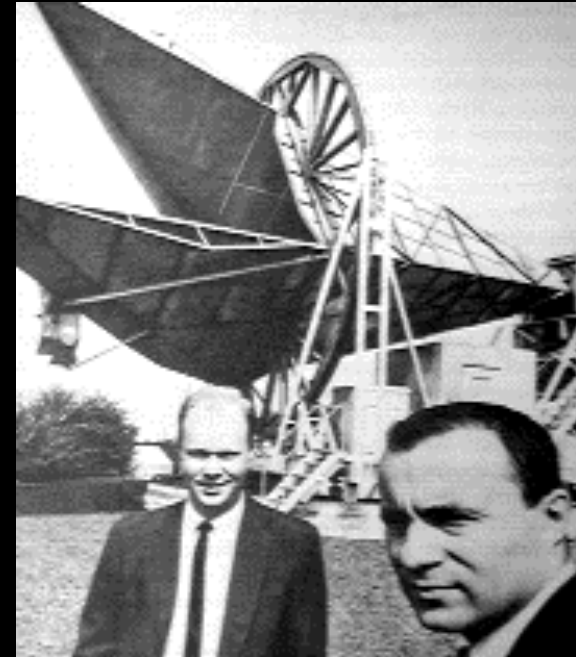
Edwin Hubble

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

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

(Alpher, Gamow, Herman, 1940s)

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

**fraction
of a second**

**CMB
last scattering**

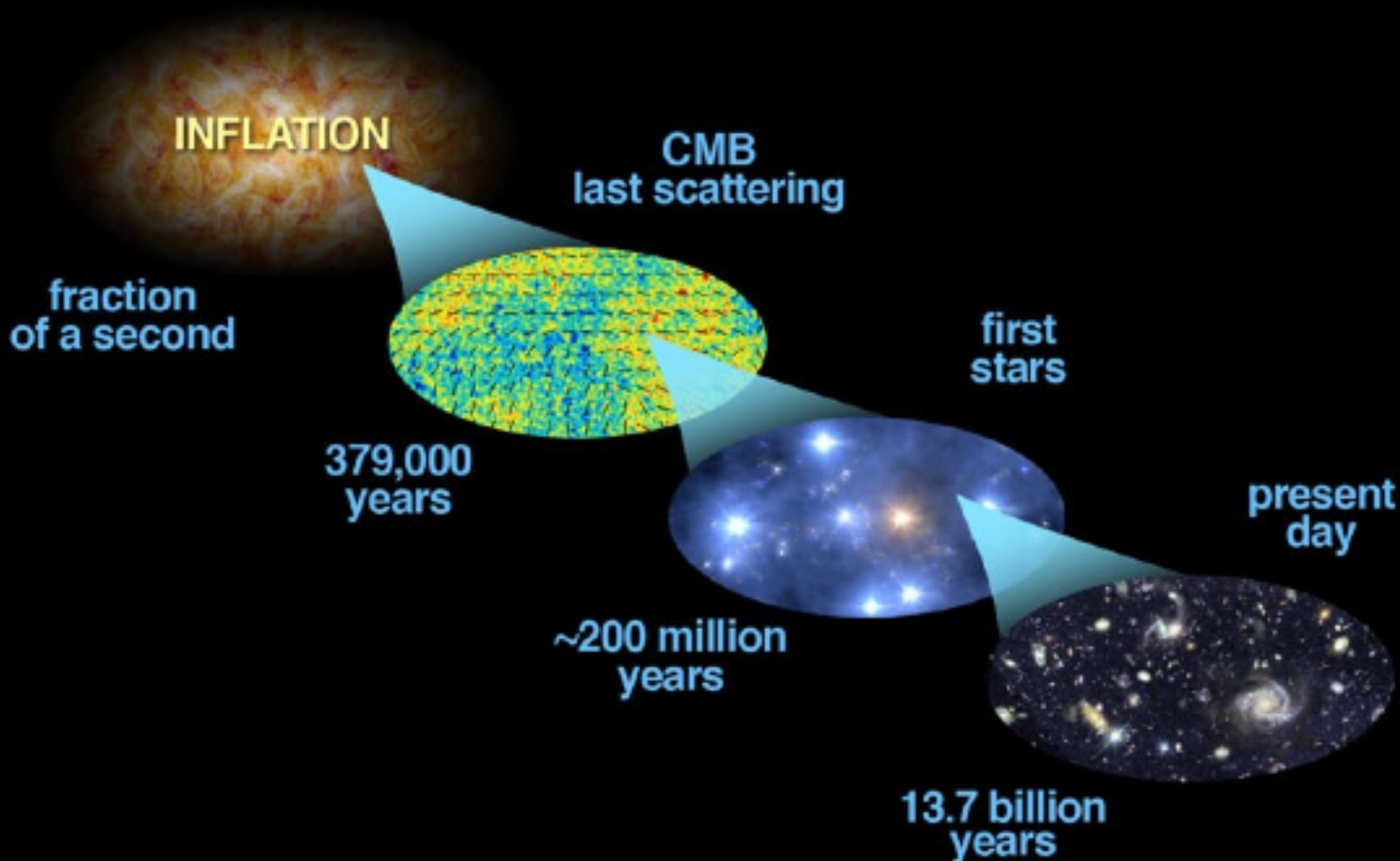
**379,000
years**

**first
stars**

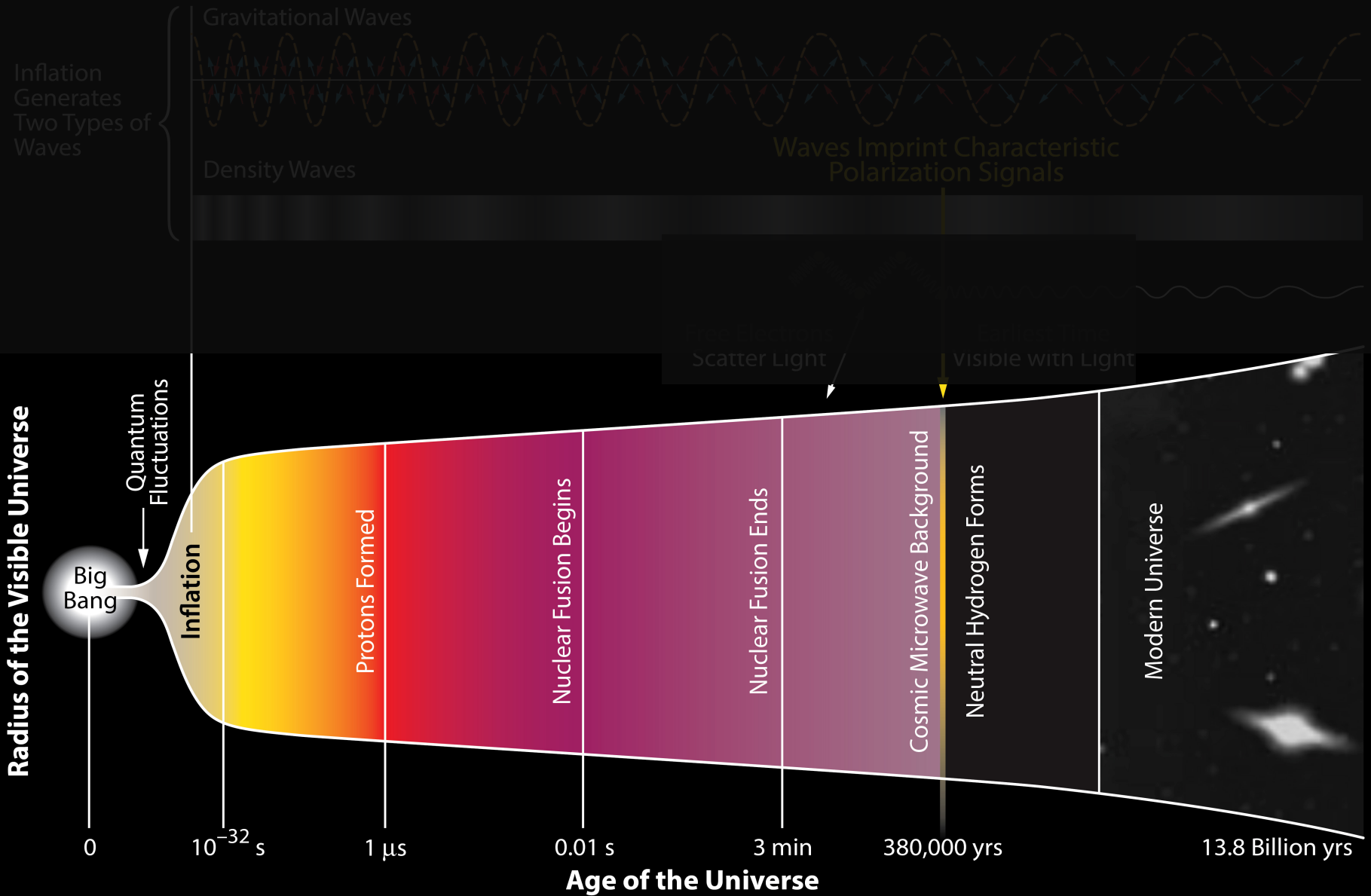
**~200 million
years**

**present
day**

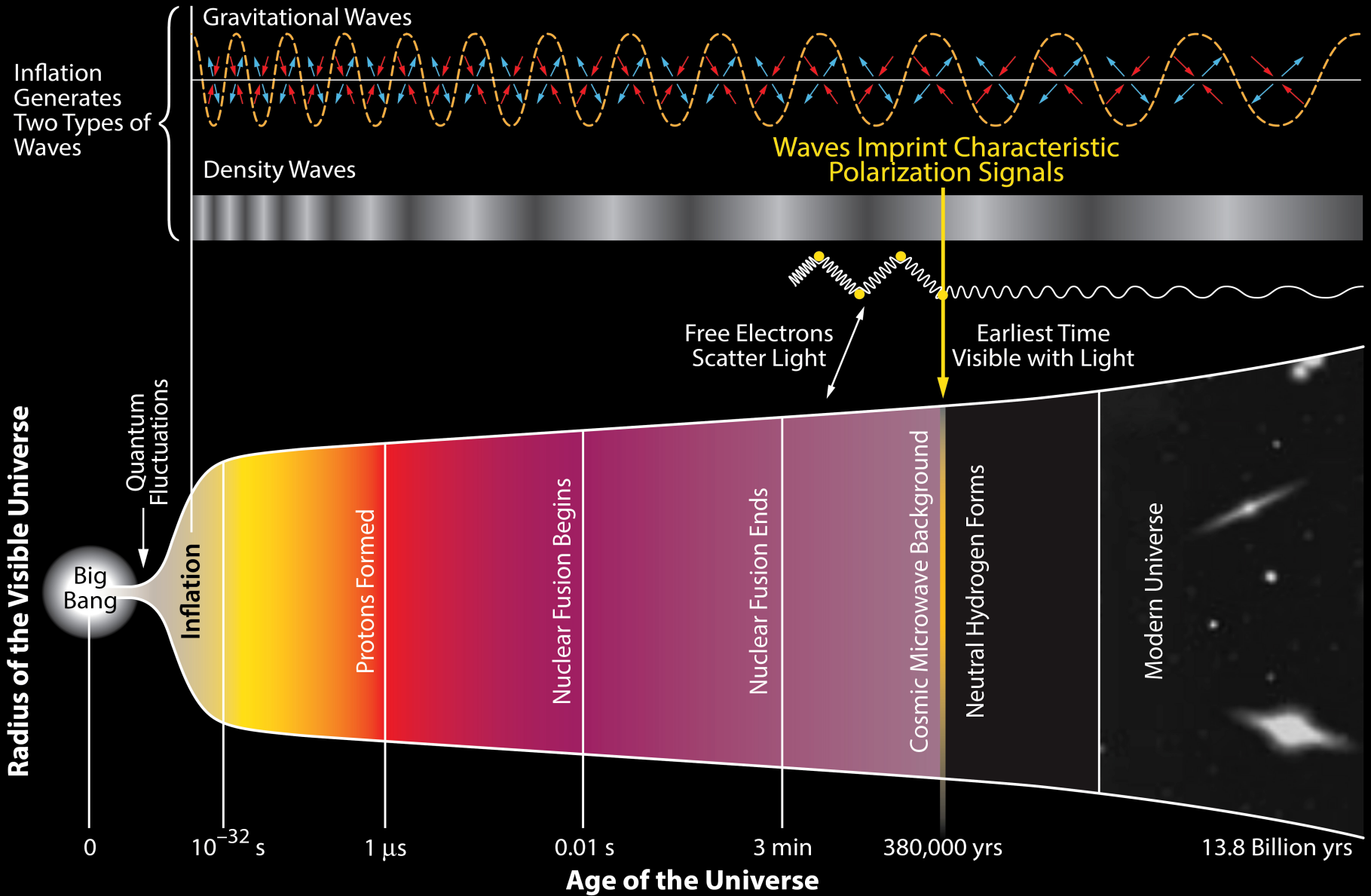
**13.7 billion
years**



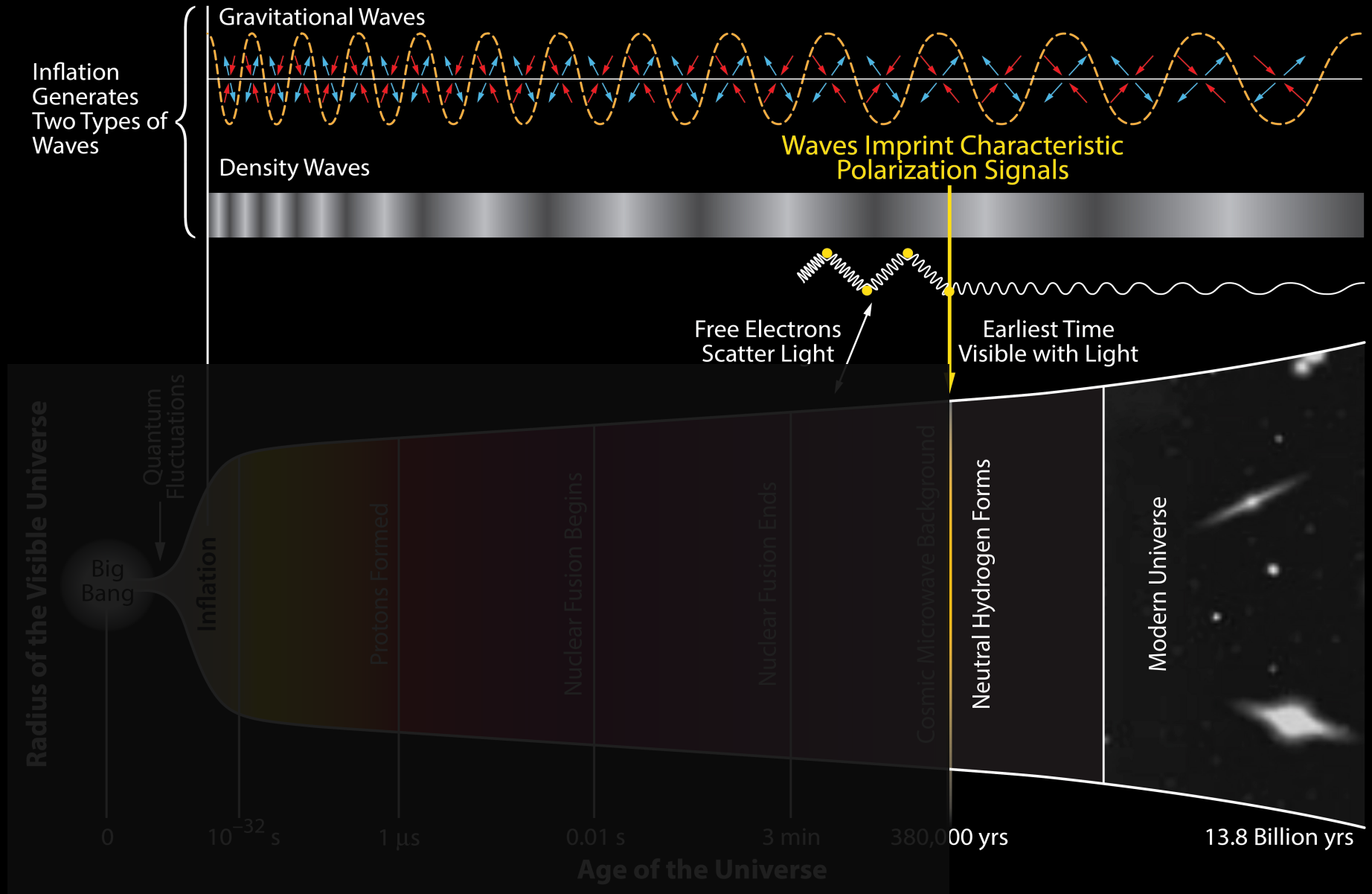
History of the Universe



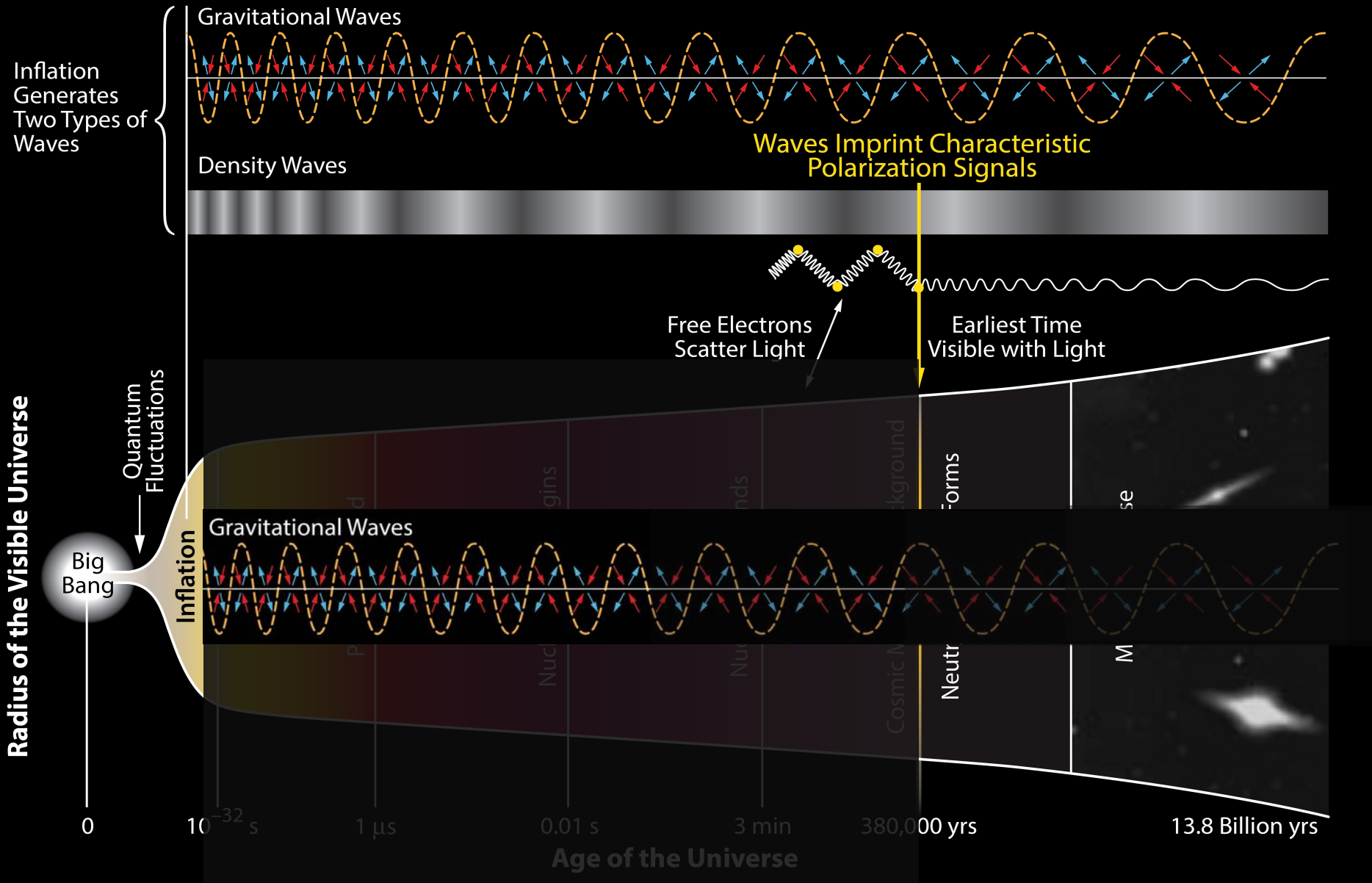
History of the Universe



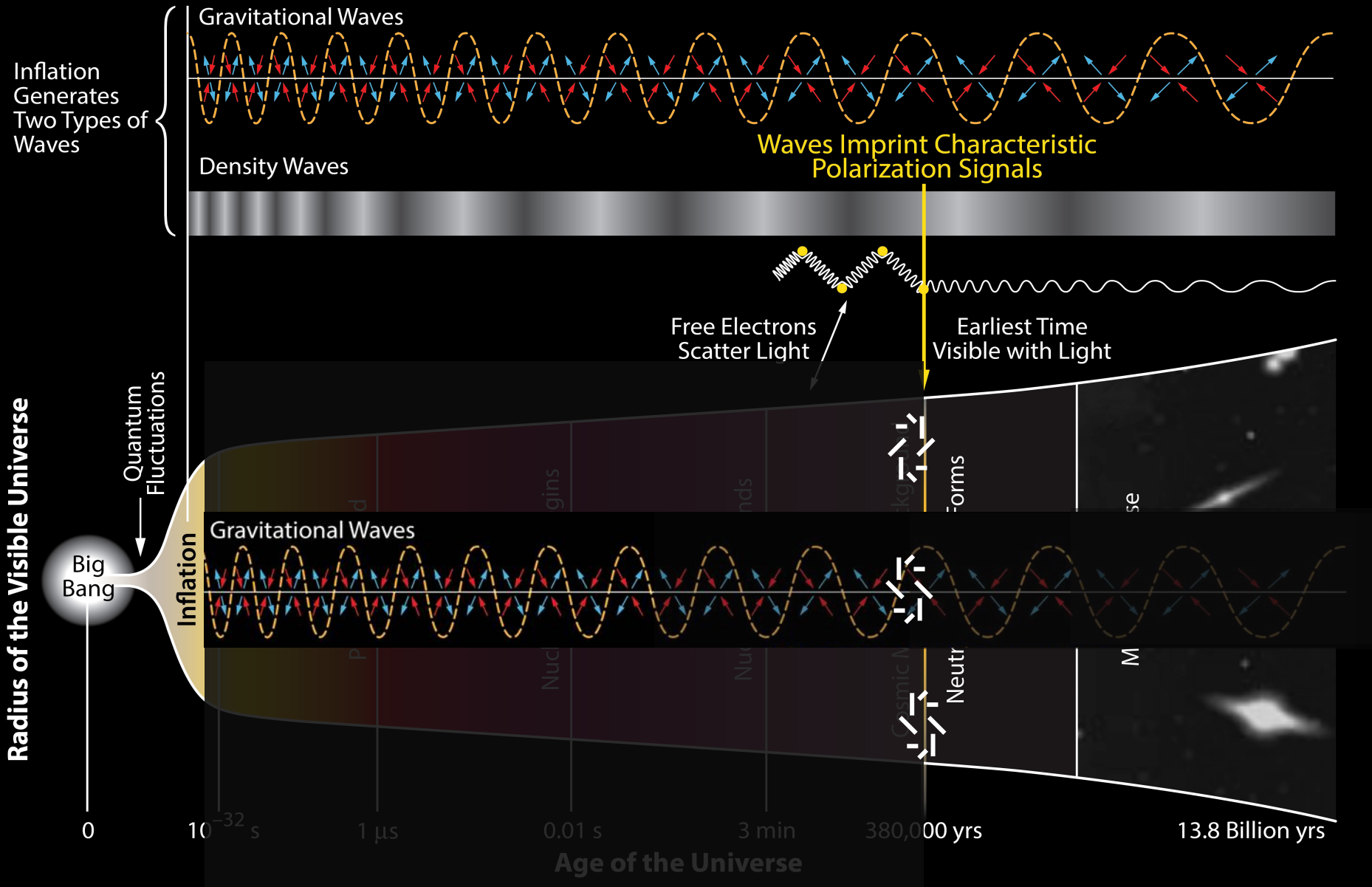
History of the Universe



History of the Universe



History of the Universe



CMB Temperature Measurements / Inflation

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

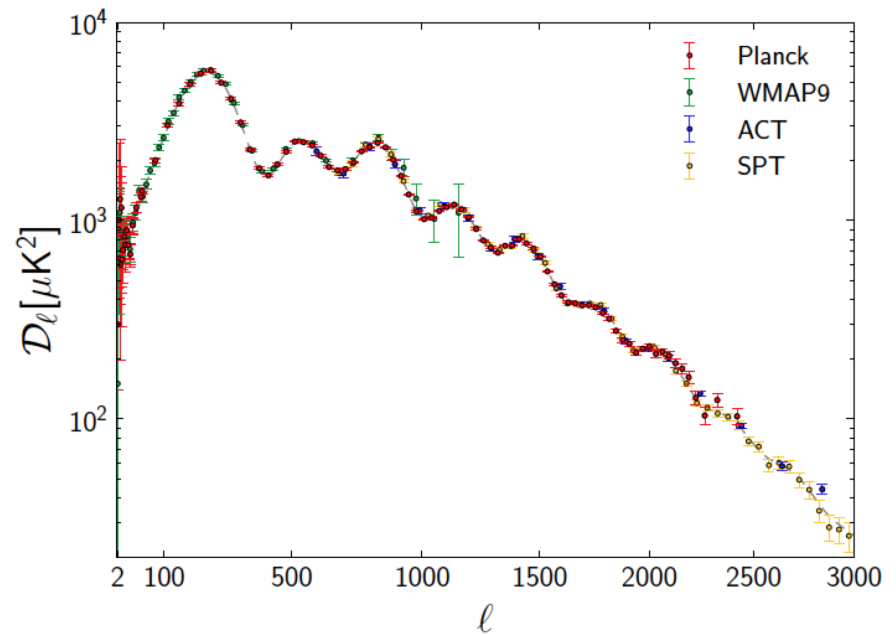
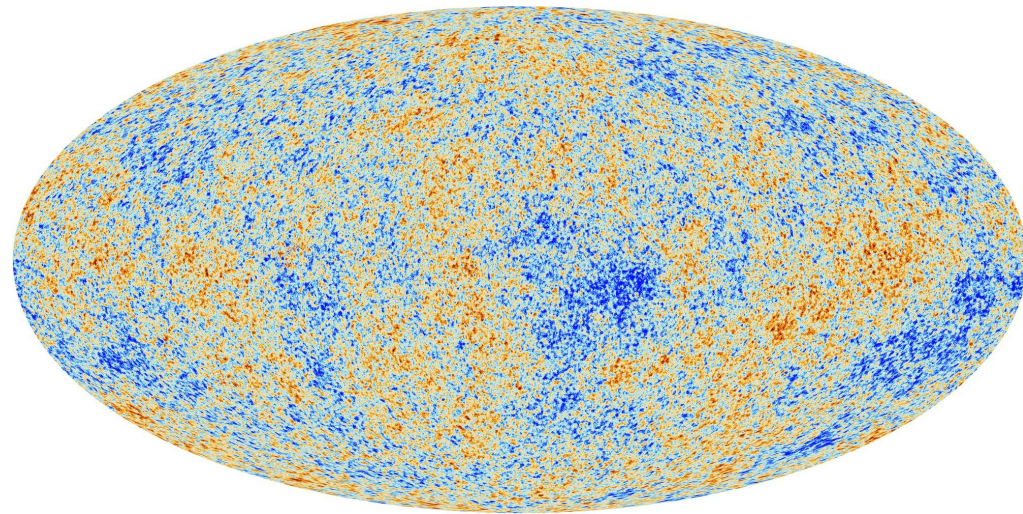
Consistent with Λ CDM paradigm(?) and constrains its parameters to sub percent accuracy.

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 occurred



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 causally 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 undetectability by the hyper expansion.

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



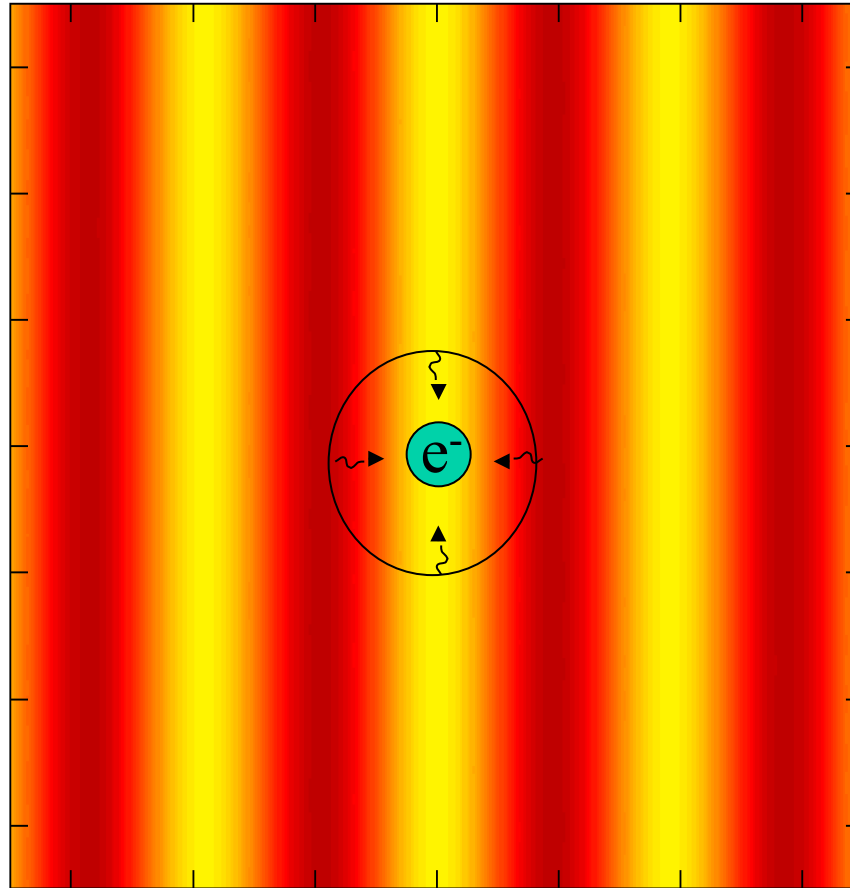
Equal amount of perturbations are injected at each step in the exponential expansion.

Solves the monopole problem:
Why do we not observe magnetic monopoles in the Universe today?



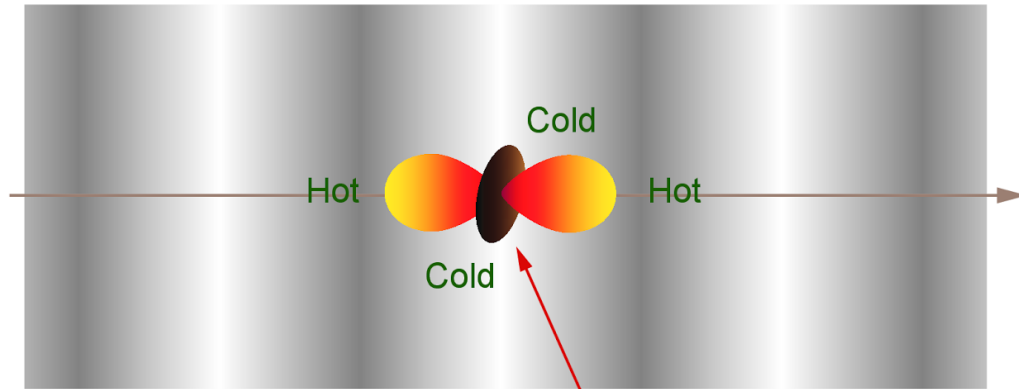
Monopoles are diluted away to undetectability.

**CMB polarization:
arises at last scattering
from local radiation quadrupole**

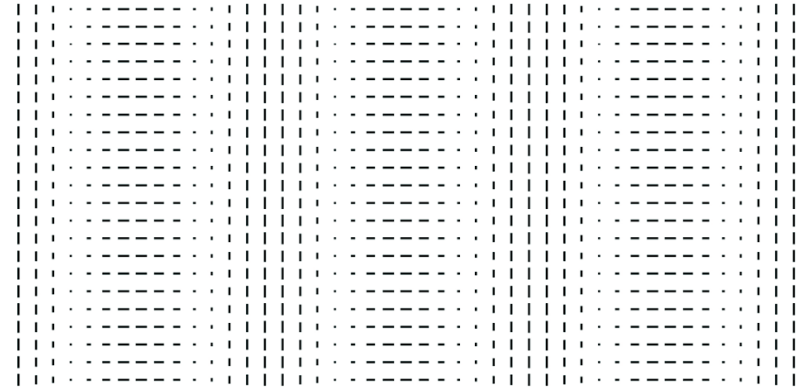


CMB polarization

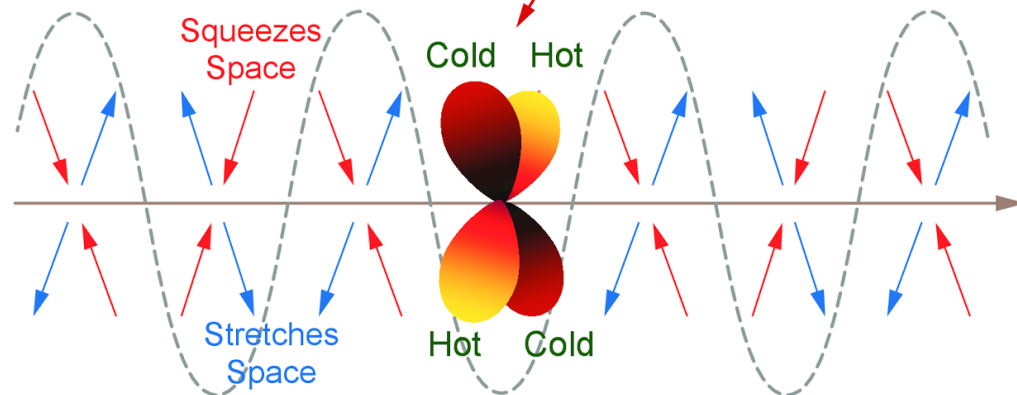
Density Wave



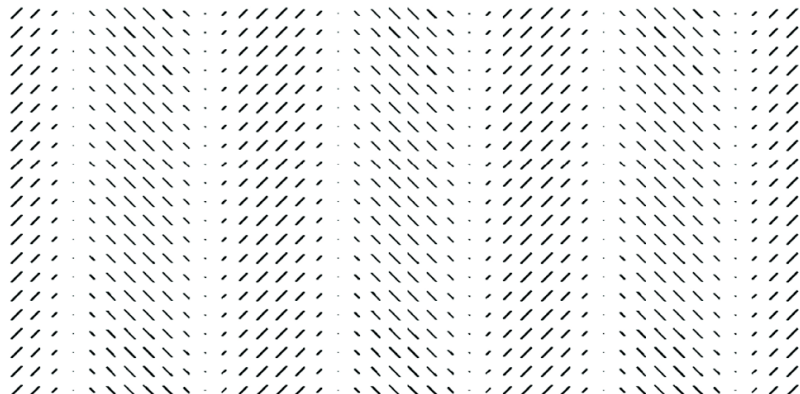
E-Mode Polarization Pattern



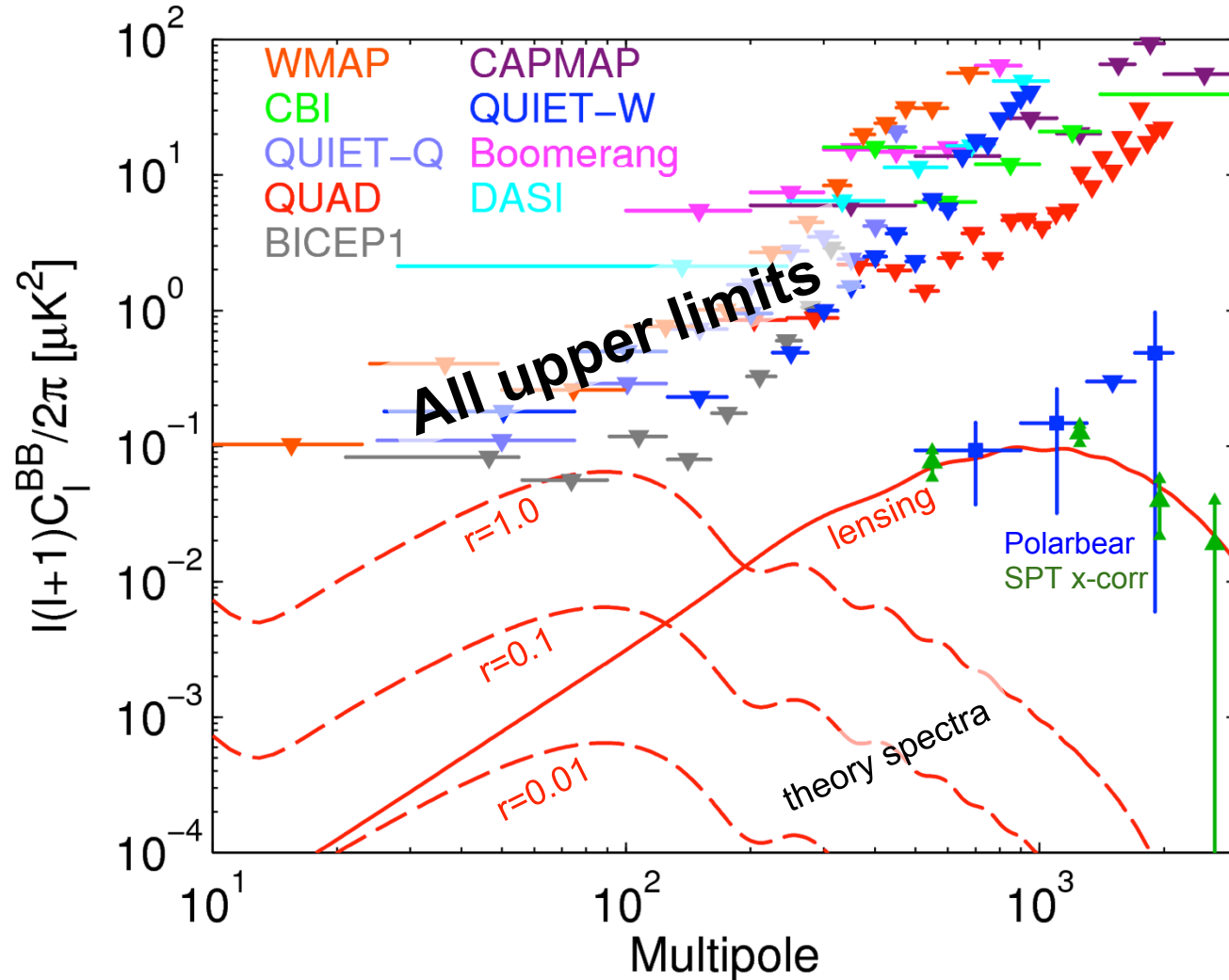
Gravitational Wave



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.

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

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...

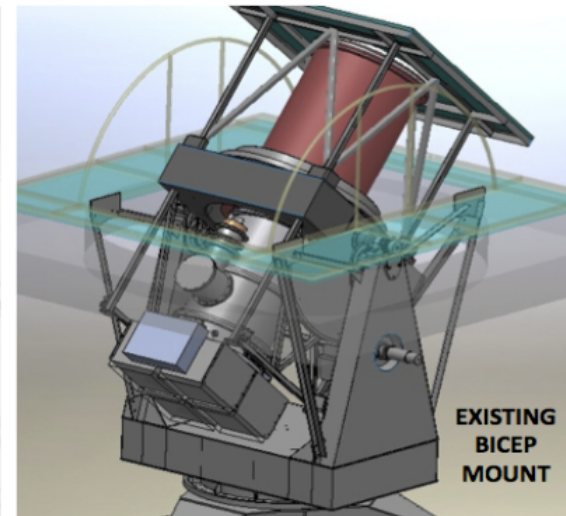
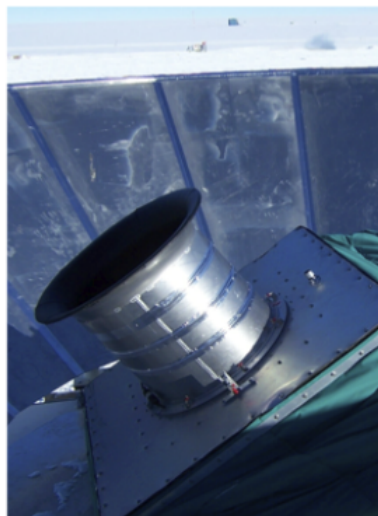
BICEP1
(2006 - 8)

BICEP2
(2010 - 12)

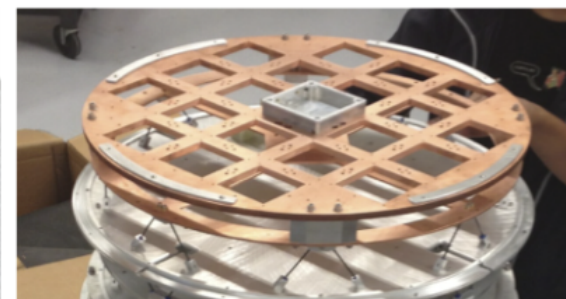
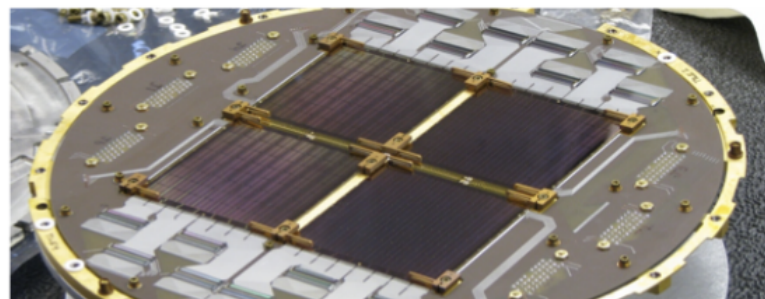
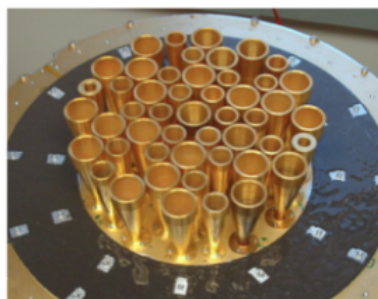
Keck Array
(2011 -)

BICEP3
(2014 -)

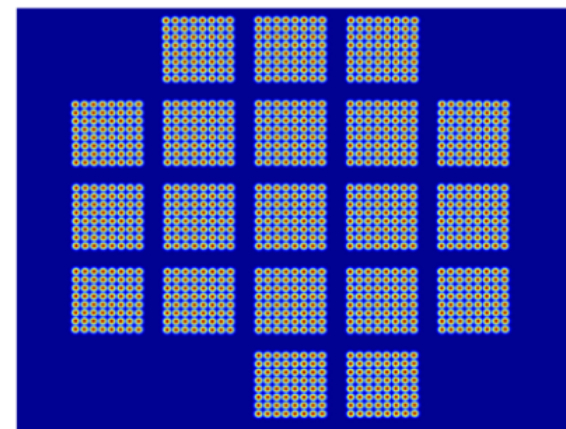
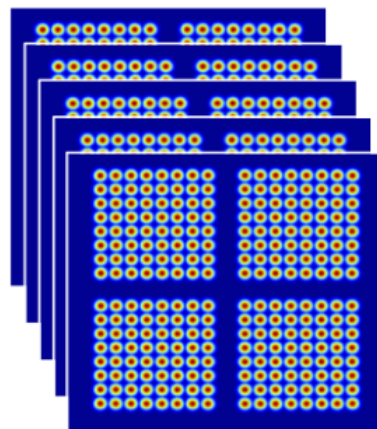
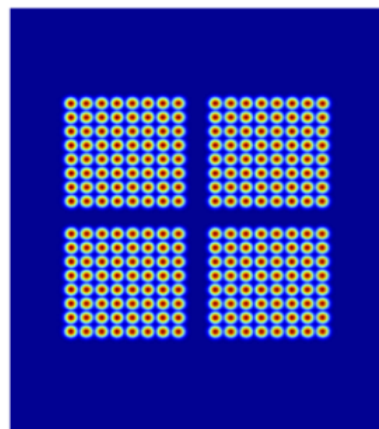
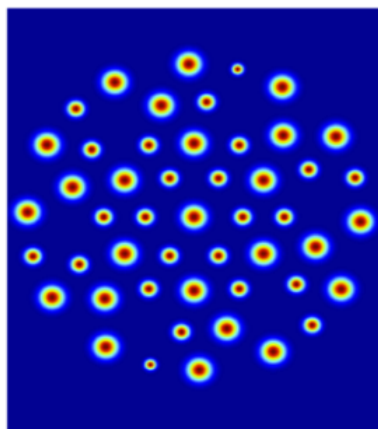
Telescope and Mount



Focal Plane



Beams on Sky



-5 0 5
Longitude (degrees)

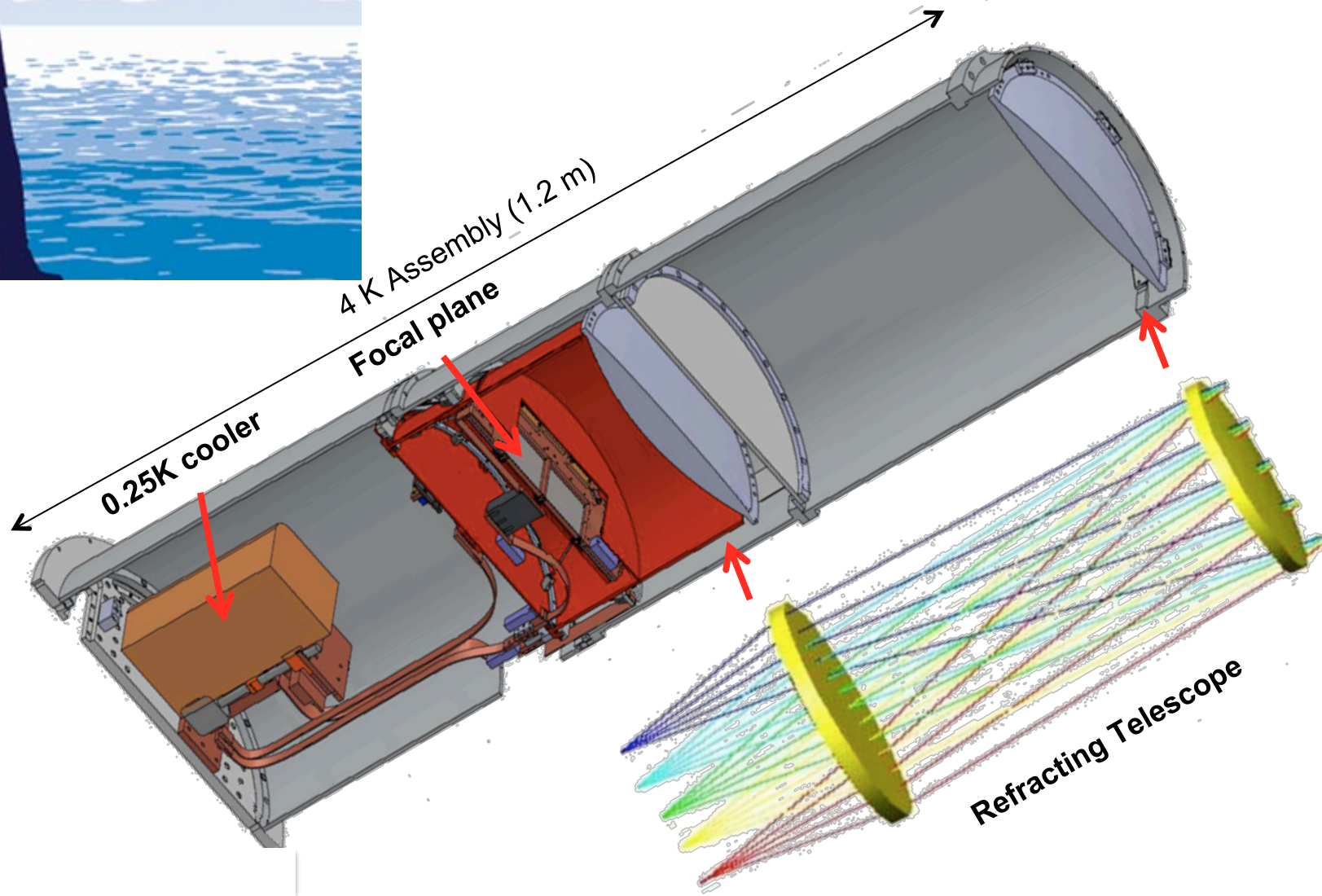
-5 0 5
Longitude (degrees)

-5 0 5
Longitude (degrees)

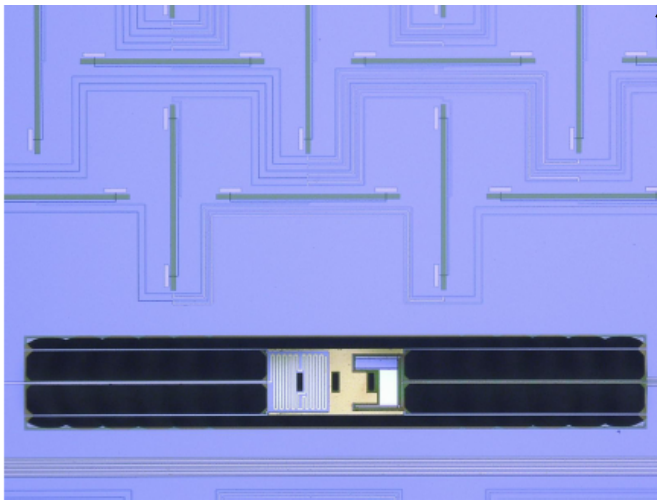
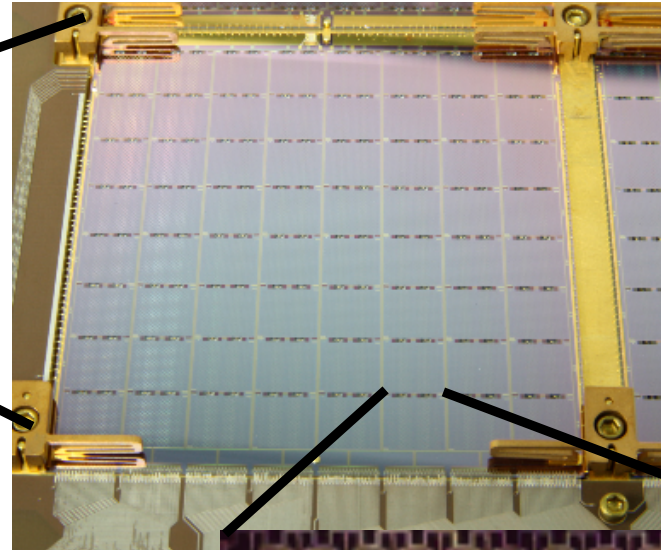
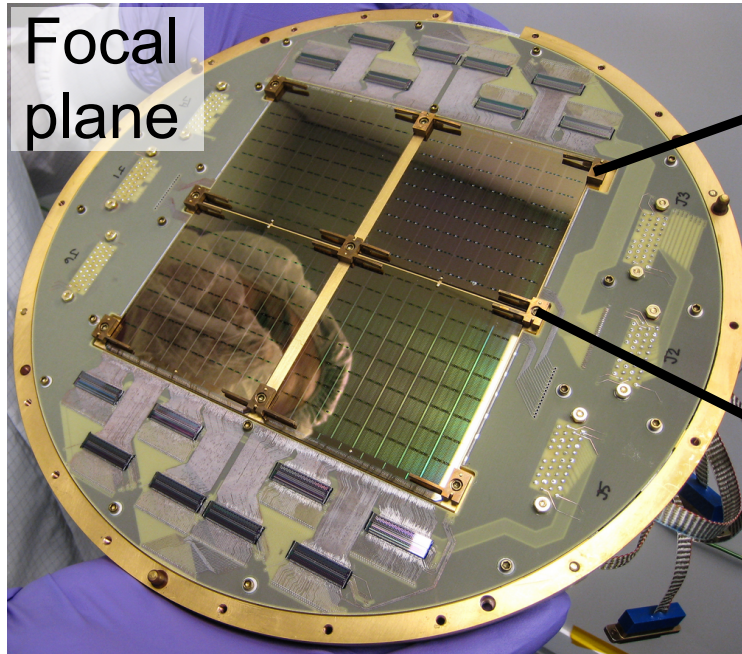
-10 -5 0 5 10
Longitude (degrees)

BICEP2 Experimental Concept

- Small aperture
- Wide field of view
- Cold refractor



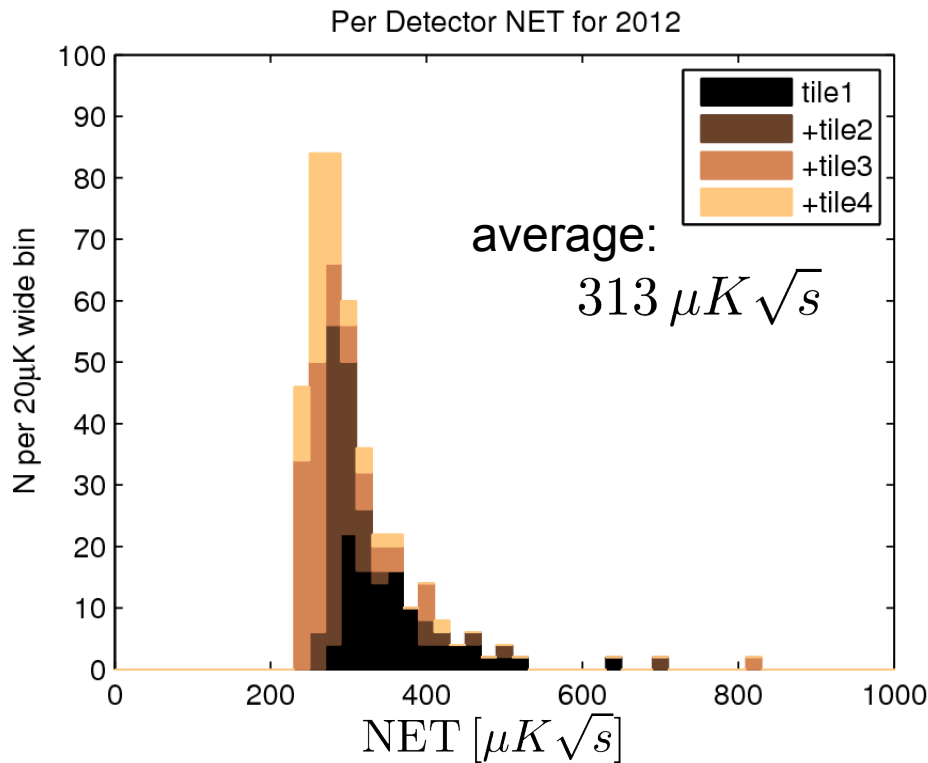
Mass-produced superconducting detectors



Slot antennas



BICEP2 Sensitivity



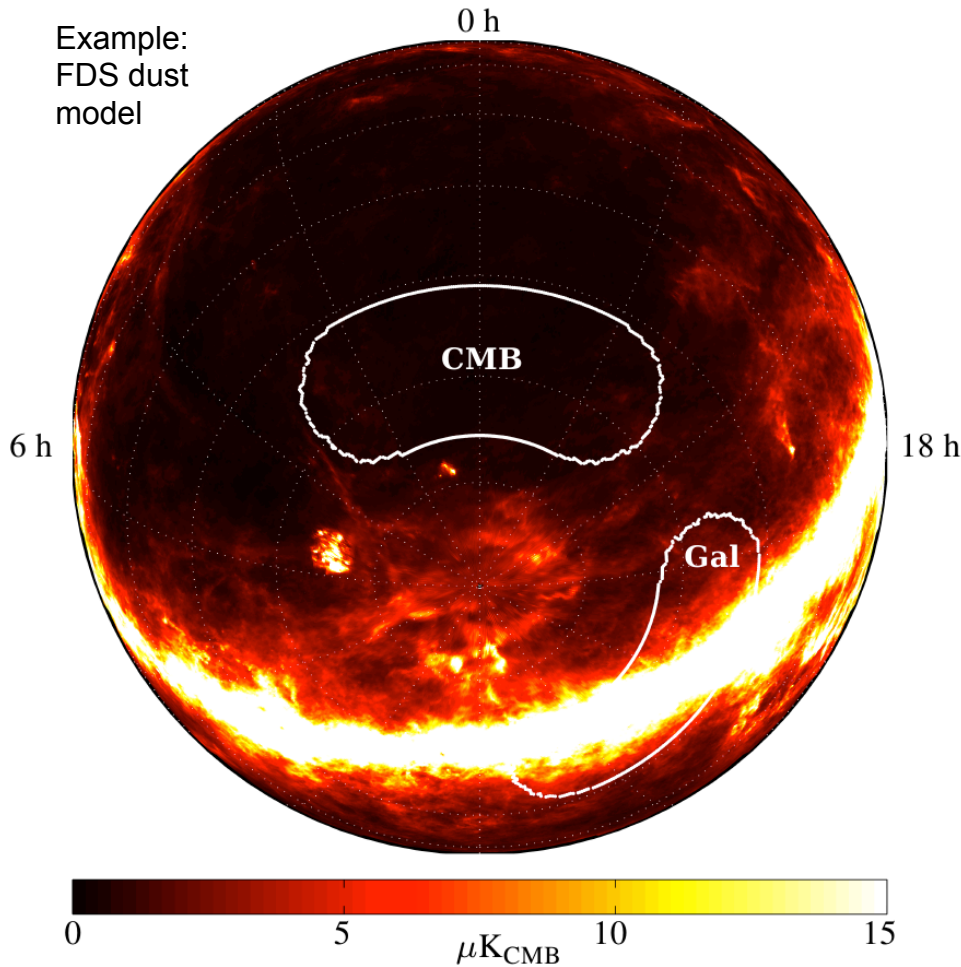
Histogram shows per-detector noise equivalent temperature (NET) for data taken in 2012

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

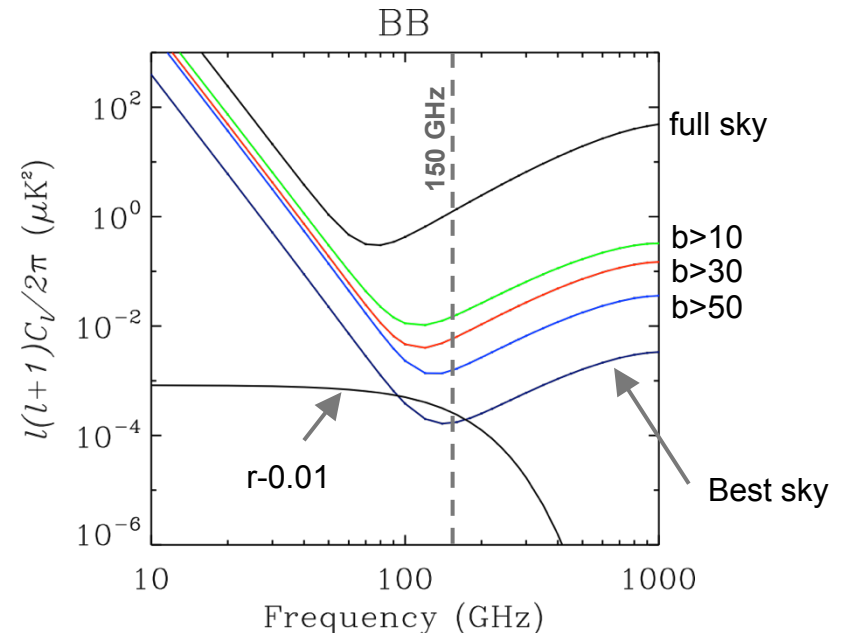


Target the “Southern Hole” - a region of the sky exceptionally free of dust and synchrotron foregrounds in total intensity.

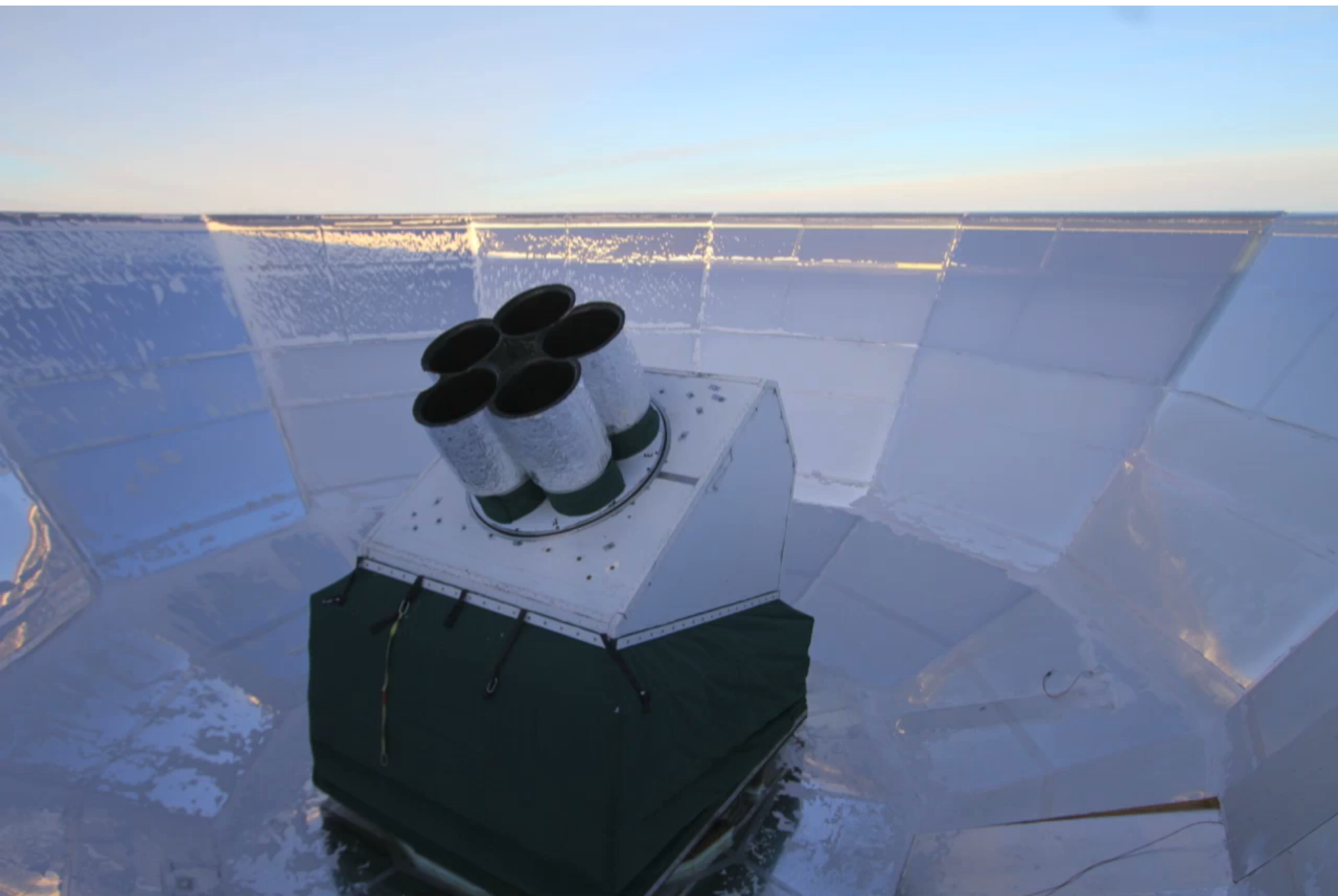
Detectors tuned to 150 GHz, near the peak of the CMB’s 2.7 K blackbody spectrum.

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 $r \leq \sim 0.01$.



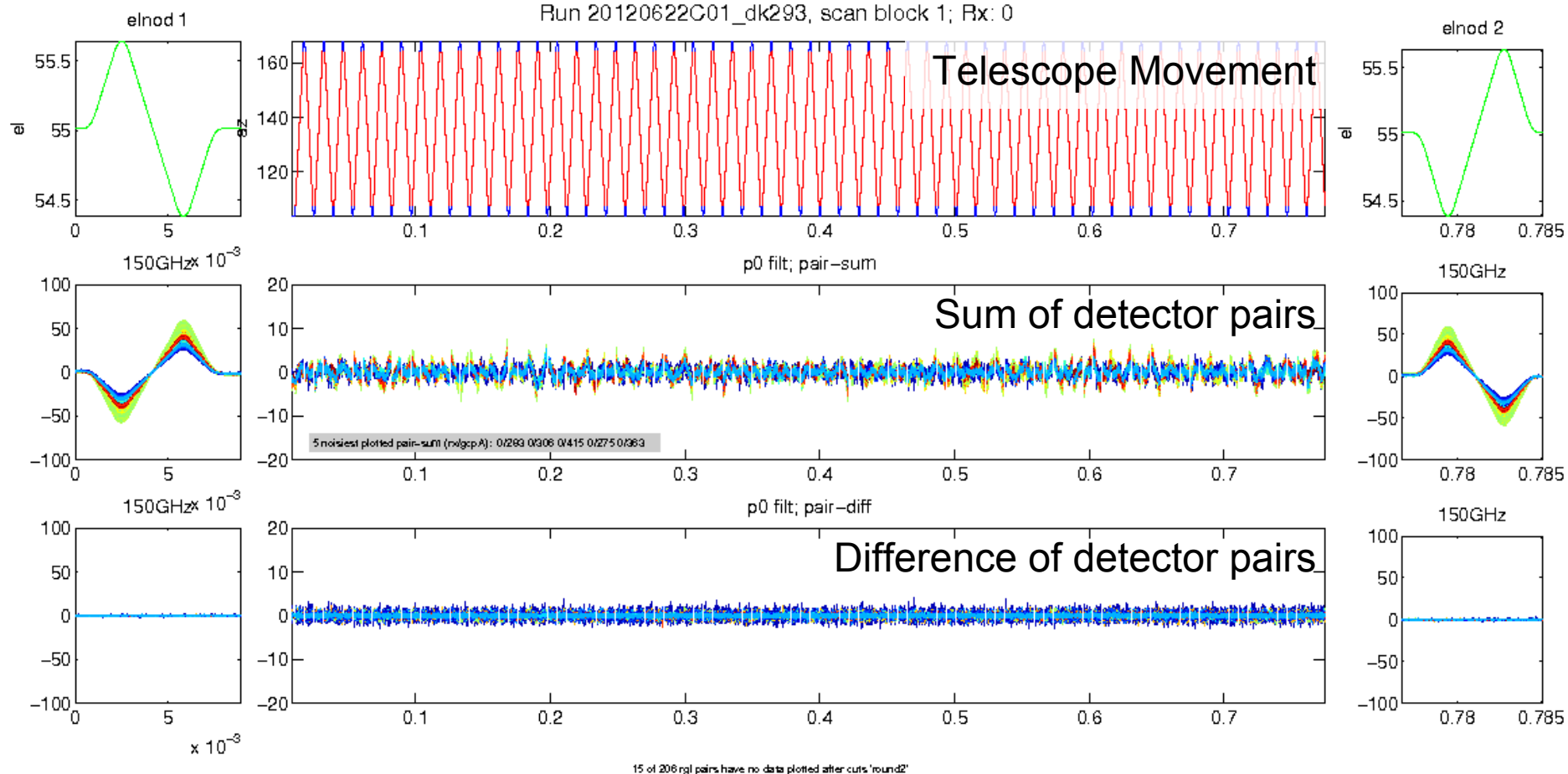
From Dunkley et al arxiv/0811.3915



Clem Pryke for The Bicep2 Collaboration

Raw Data - Perfect Weather

Time 50 mins



➤ Cover the whole field in 60 such scansets then start over at new boresight rotation

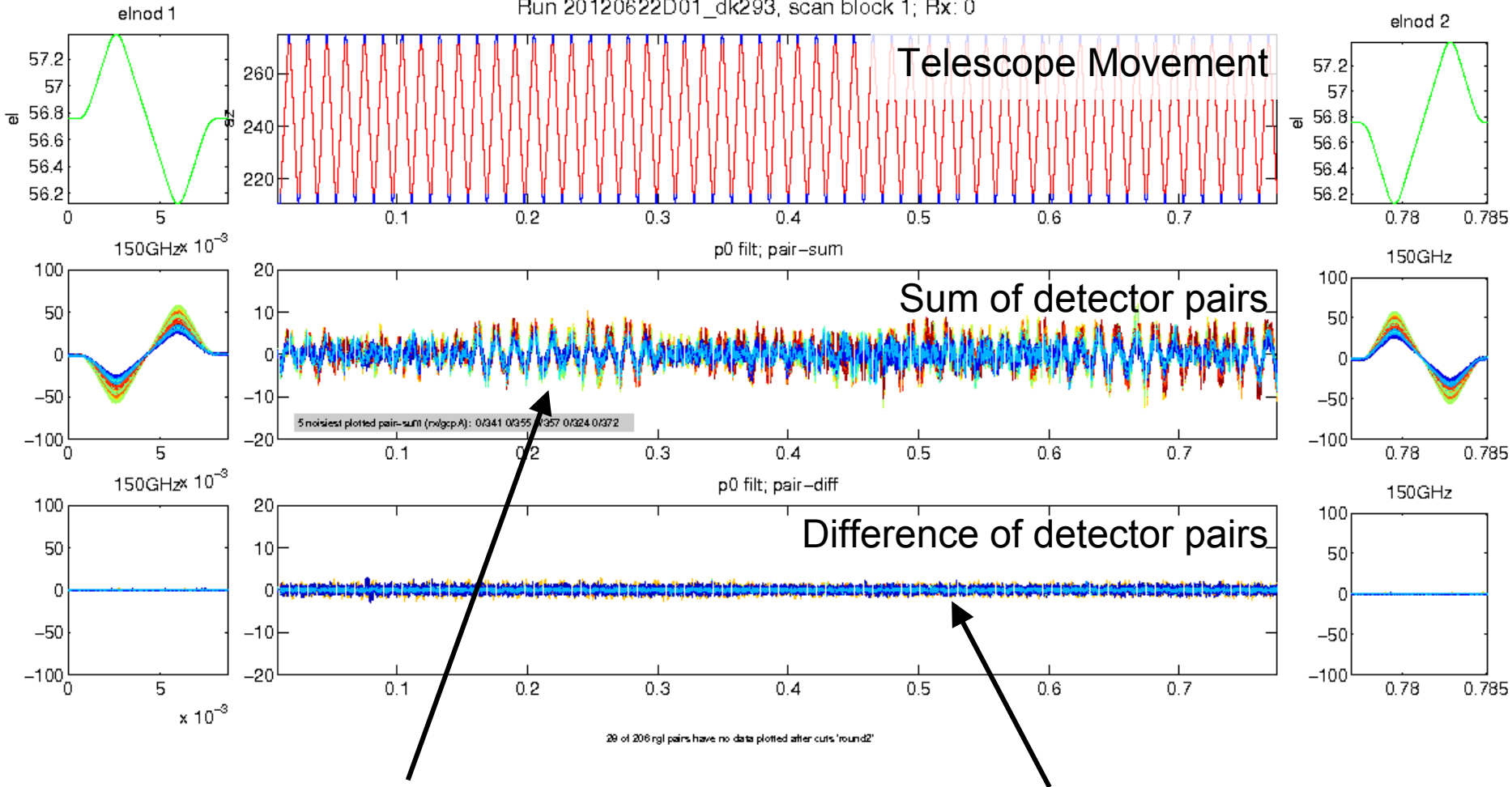
➤ Scanning modulates the CMB signal to freqs < 4 Hz

Raw Data - Worse Weather

Time 50 mins



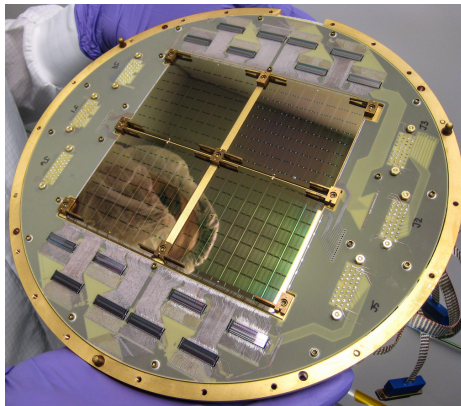
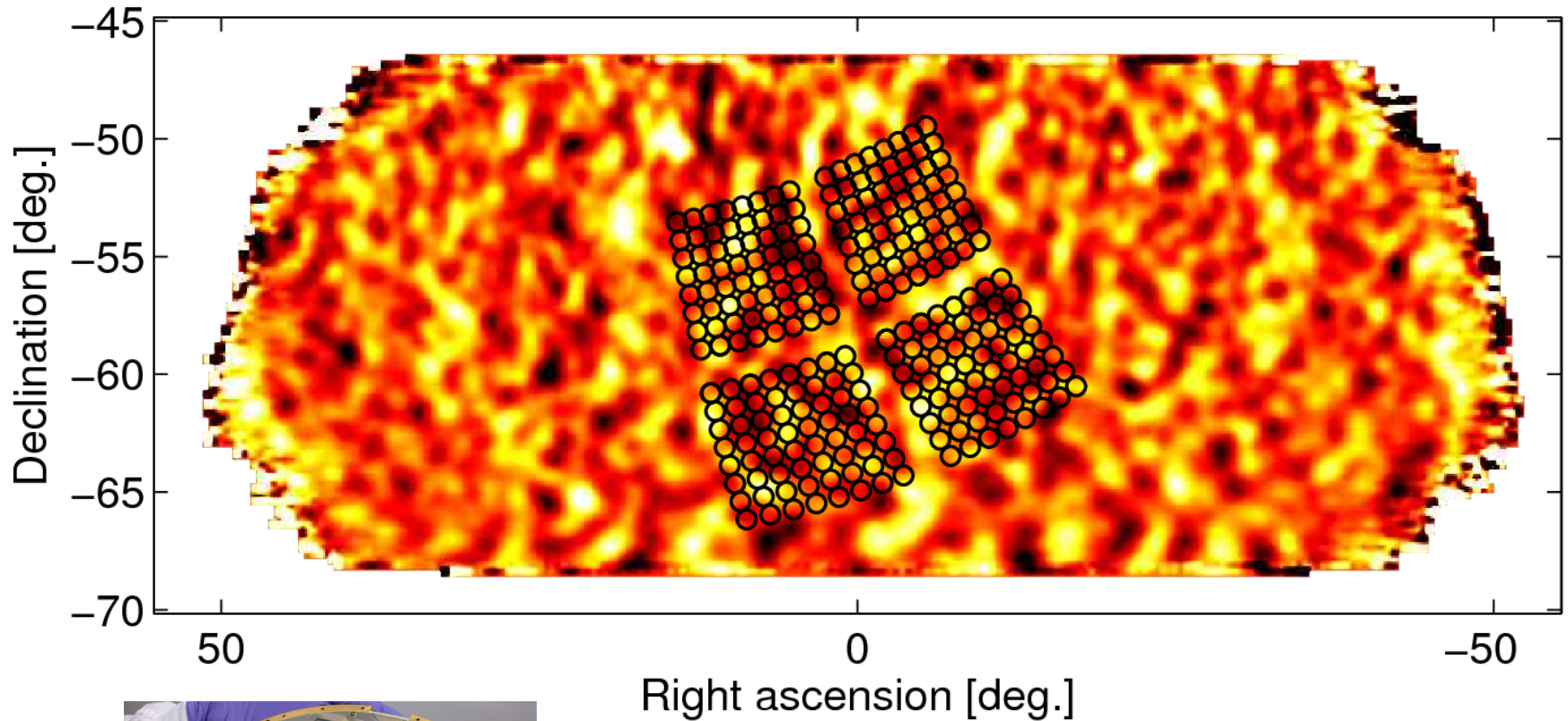
Run 20120622D01_dk293, scan block 1; Rx: 0



➤ Scanning over lumpy atmosphere
→ “clouds”

➤ Pair difference still clean
→ atmosphere is unpolarized

BICEP2 on the Sky

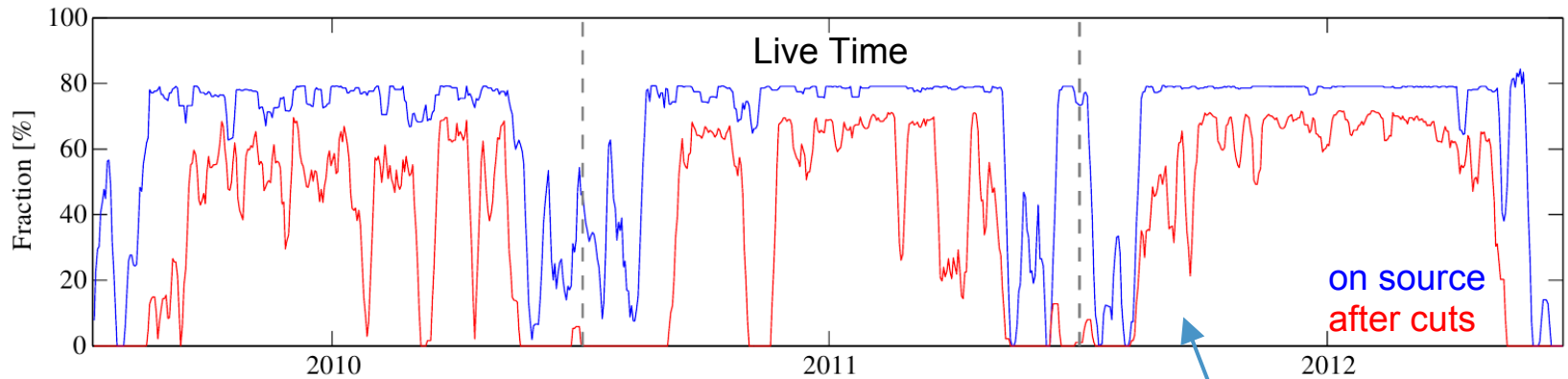


Projection of the BICEP2 focal plane on the sky

The focal plane is 20 degrees across

Background is the CMB temperature map as measured with BICEP2

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:

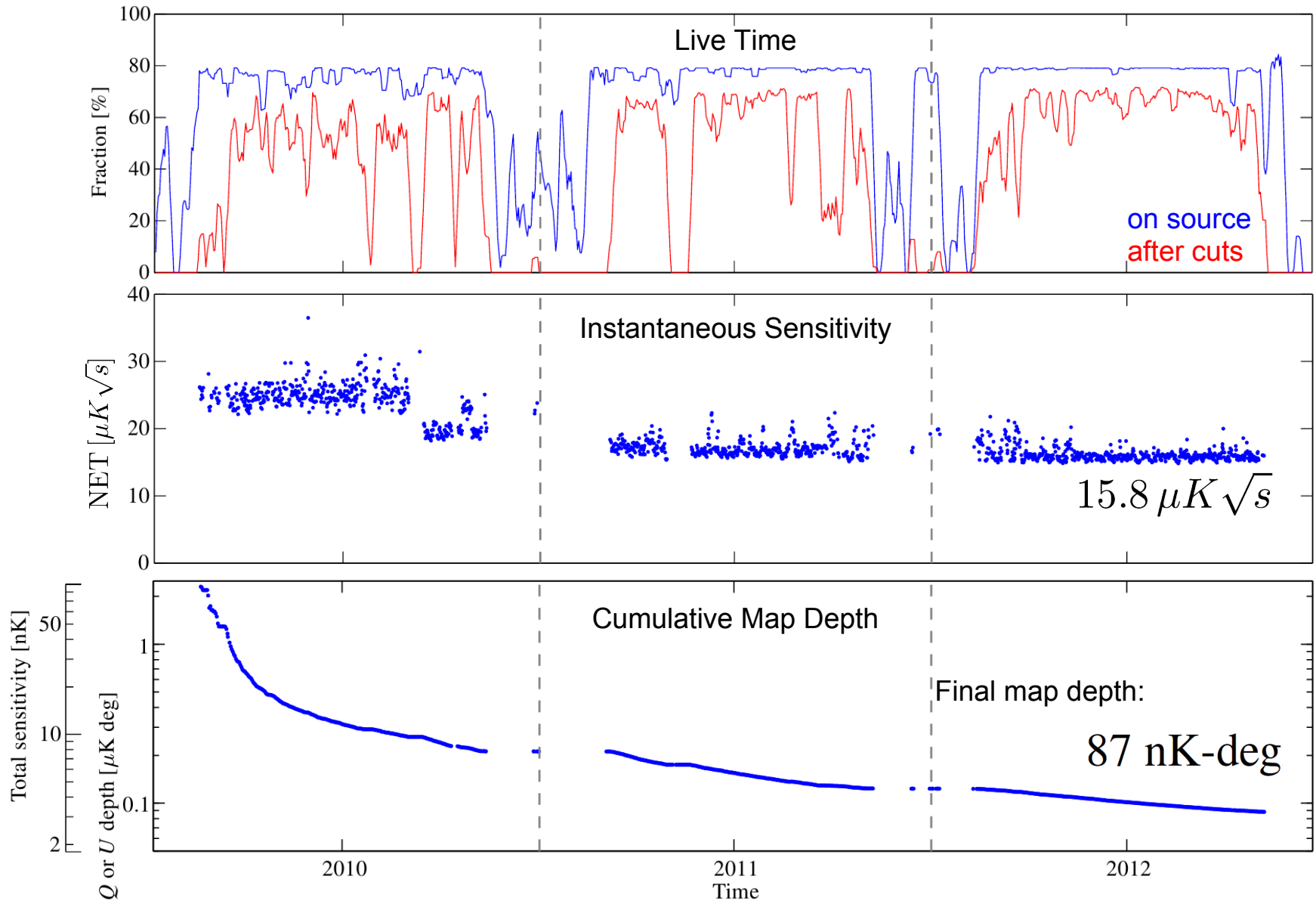
Ensures all data used in map making is taken when the experiment is operating properly and has stationary, well-behaved noise

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

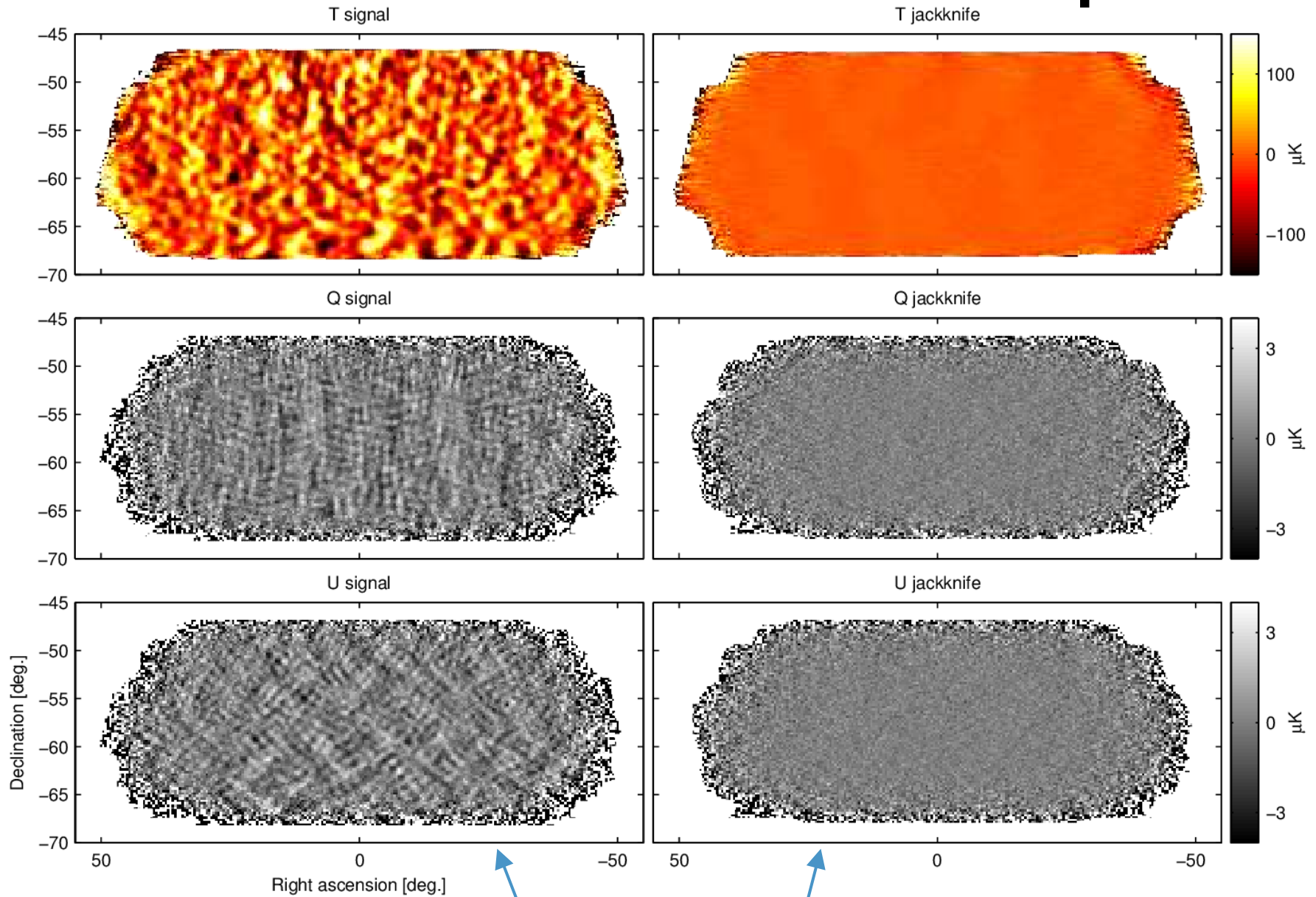
BICEP2 data very well-behaved:
pass fraction = 63%

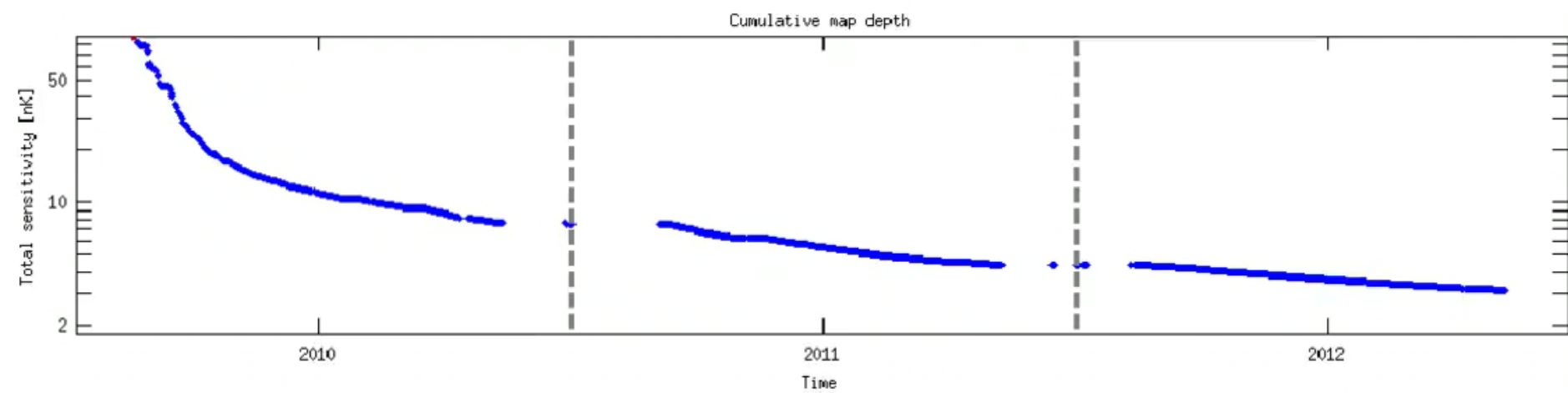
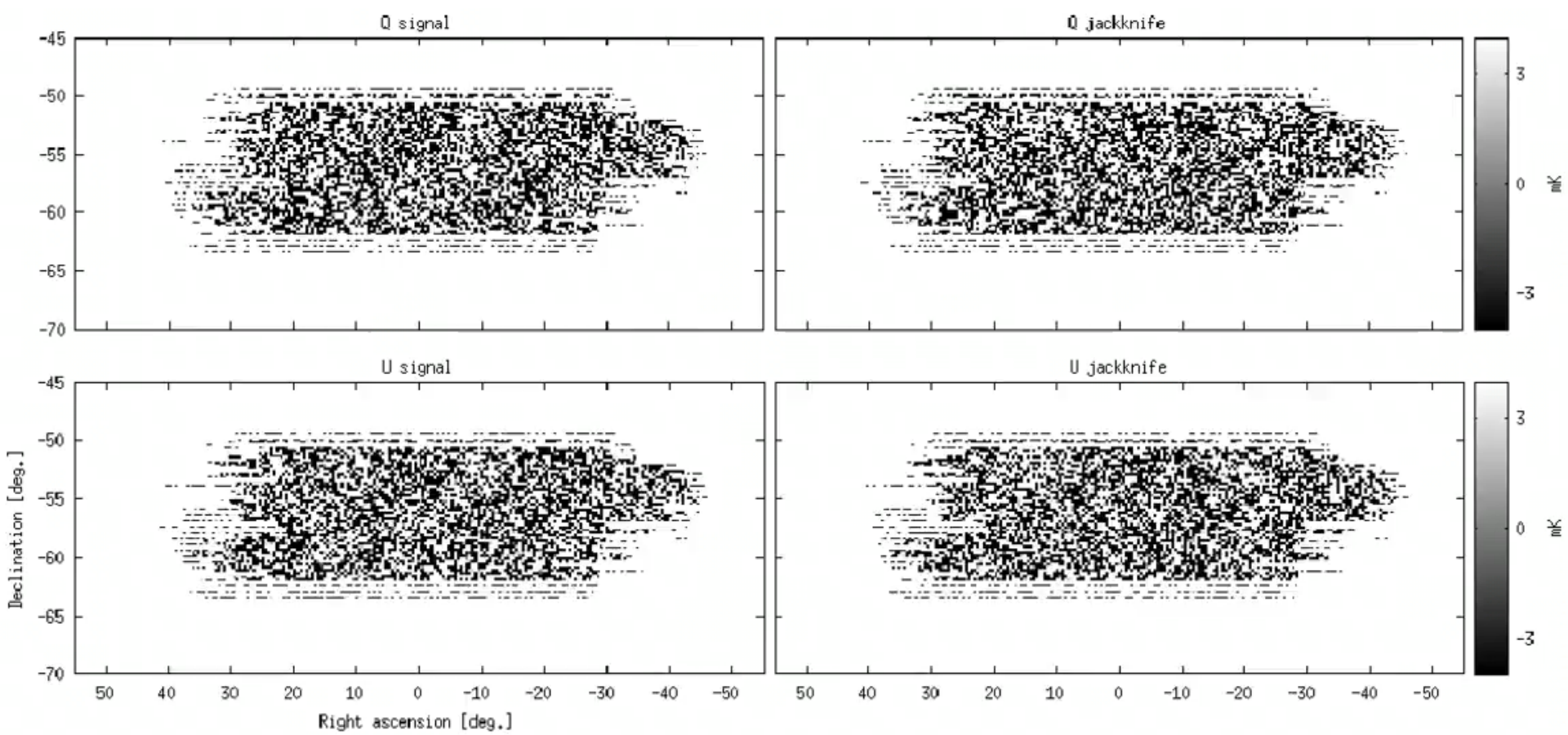
Table from Instrument Paper

BICEP2 3-year Data Set

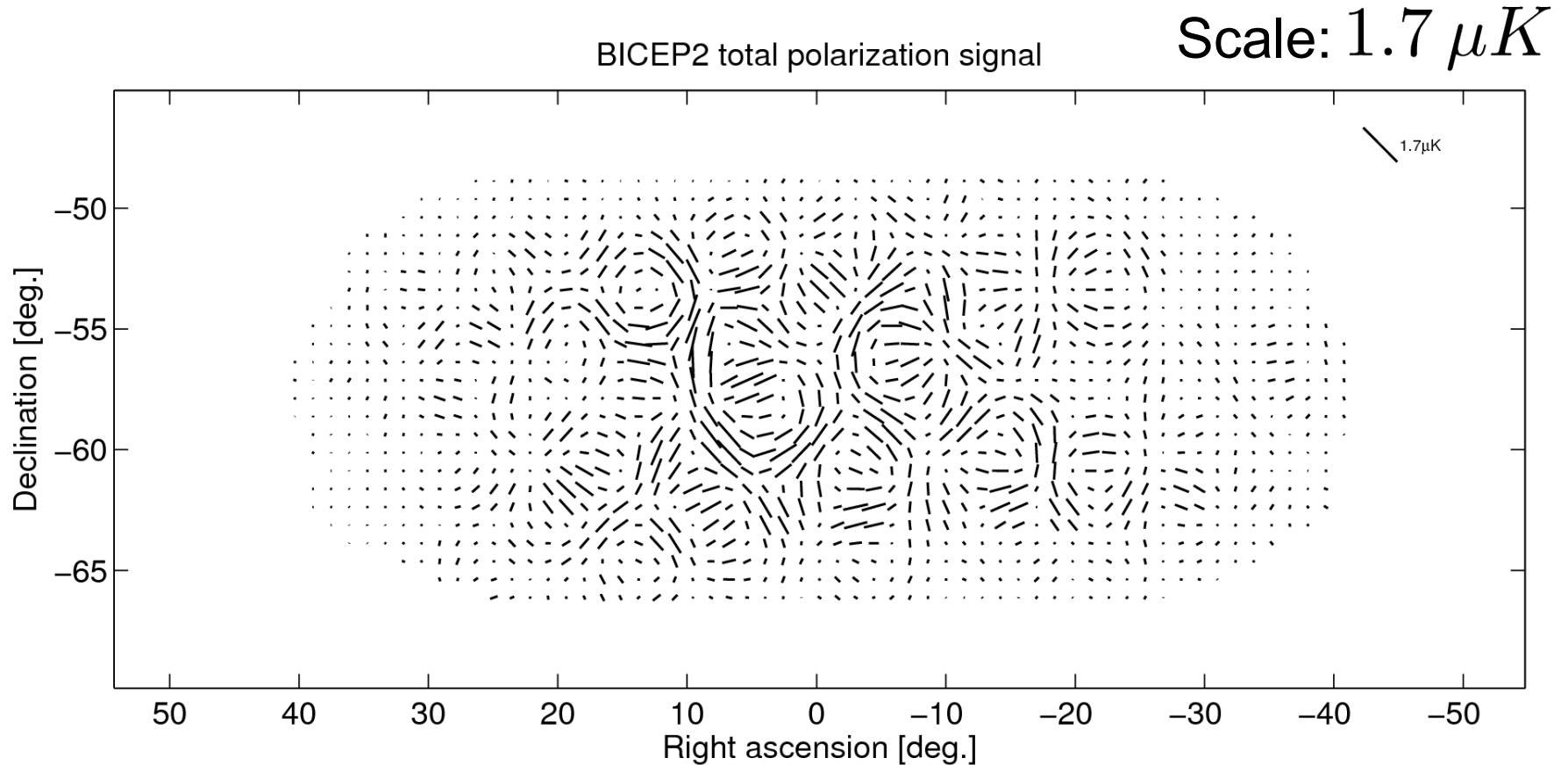


BICEP2 T and Stokes Q/U Maps





Total Polarization

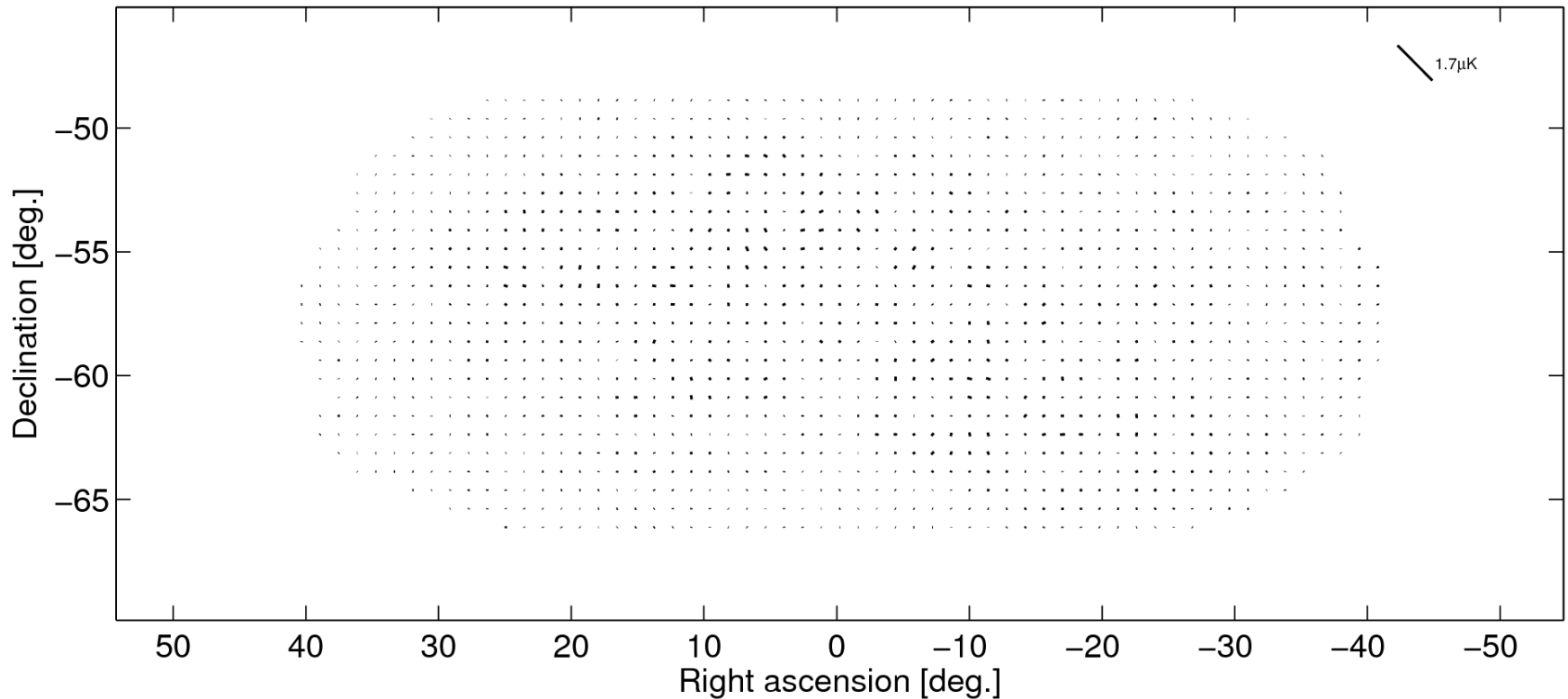


E-mode dominated pattern – no obvious curl component

B-mode Contribution

BICEP2 B-mode signal

Scale: $1.7 \mu K$

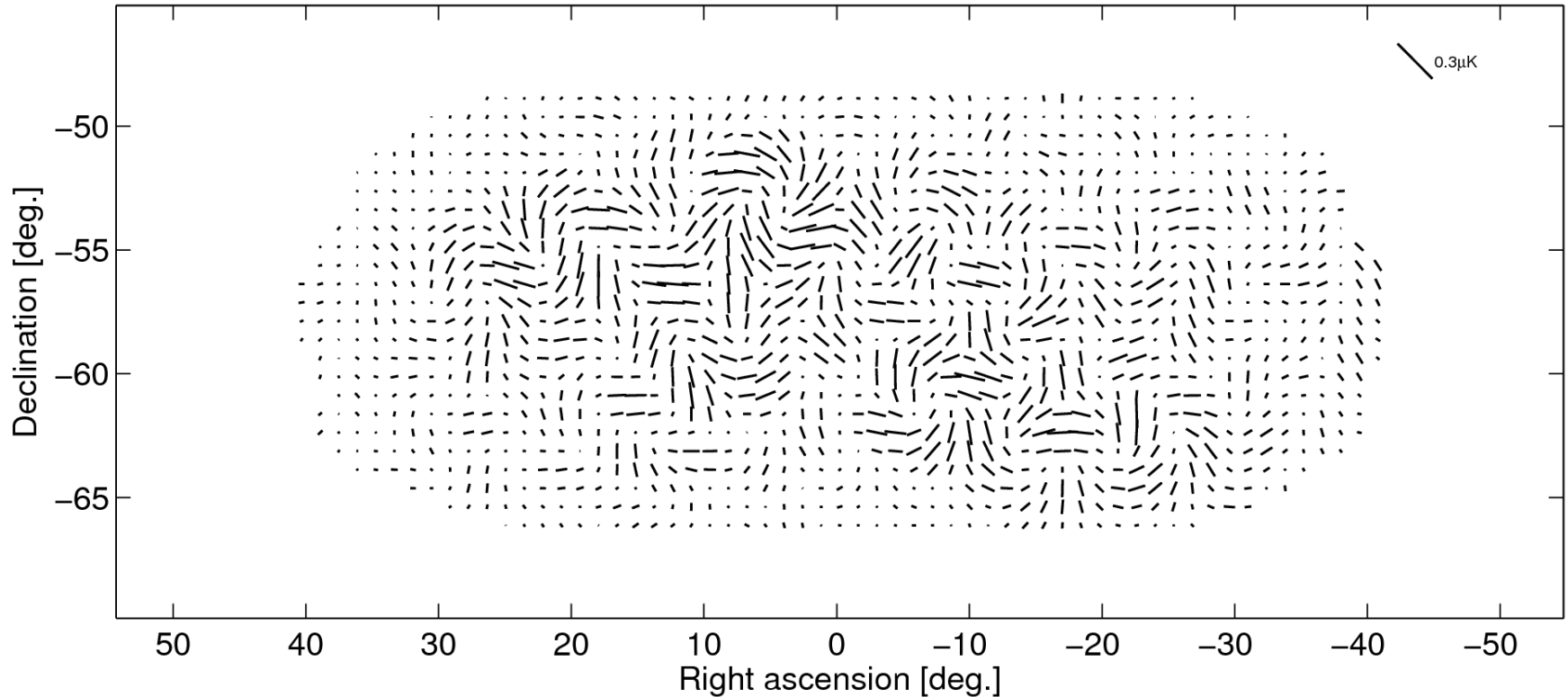


Apply purification operation to Q/U maps which leaves only pure B-modes
(given all timestream filterings etc.)

B-mode Contribution

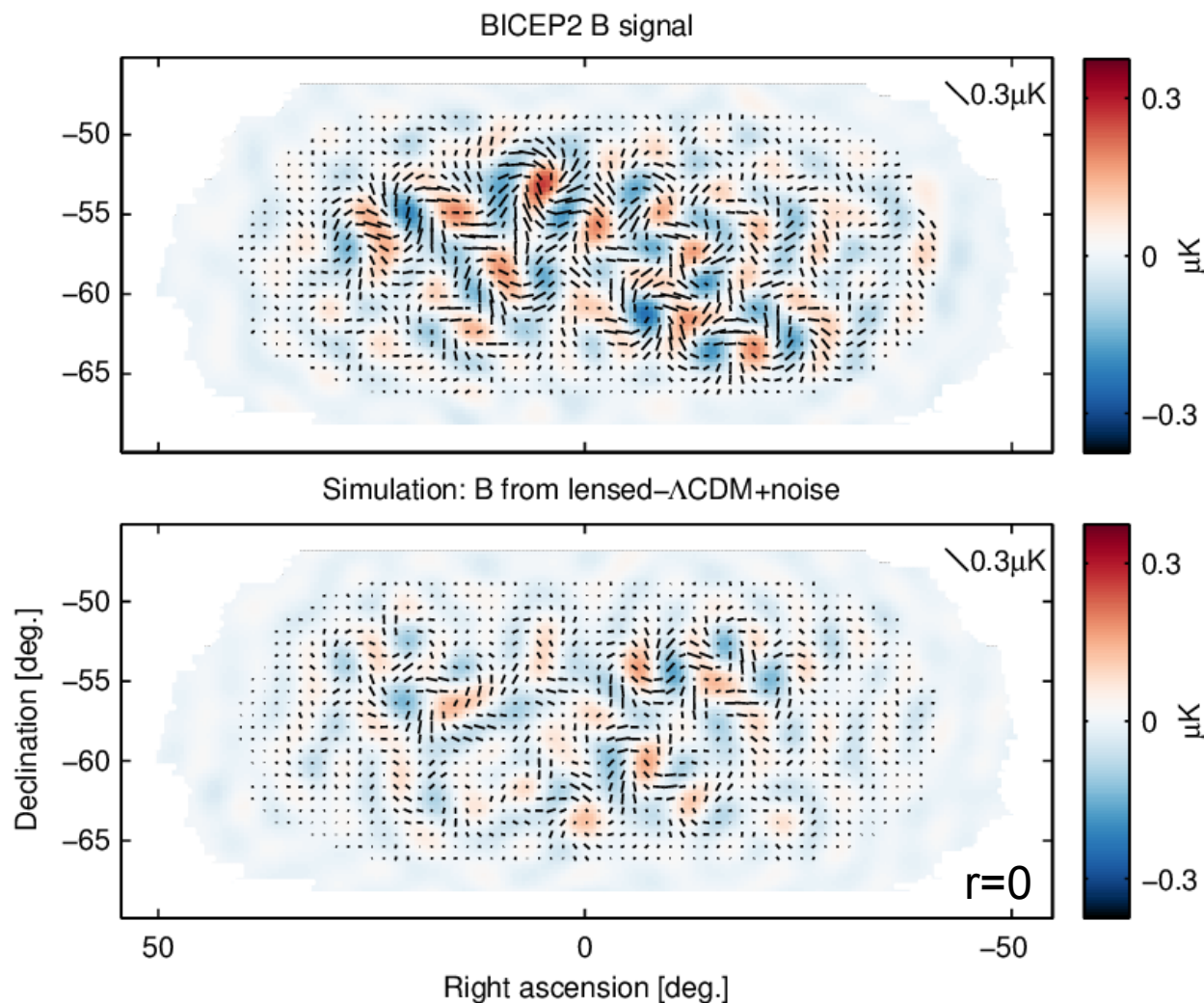
BICEP2 B-mode signal

Scale: $0.3 \mu K$



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

B-mode Map vs. Simulation



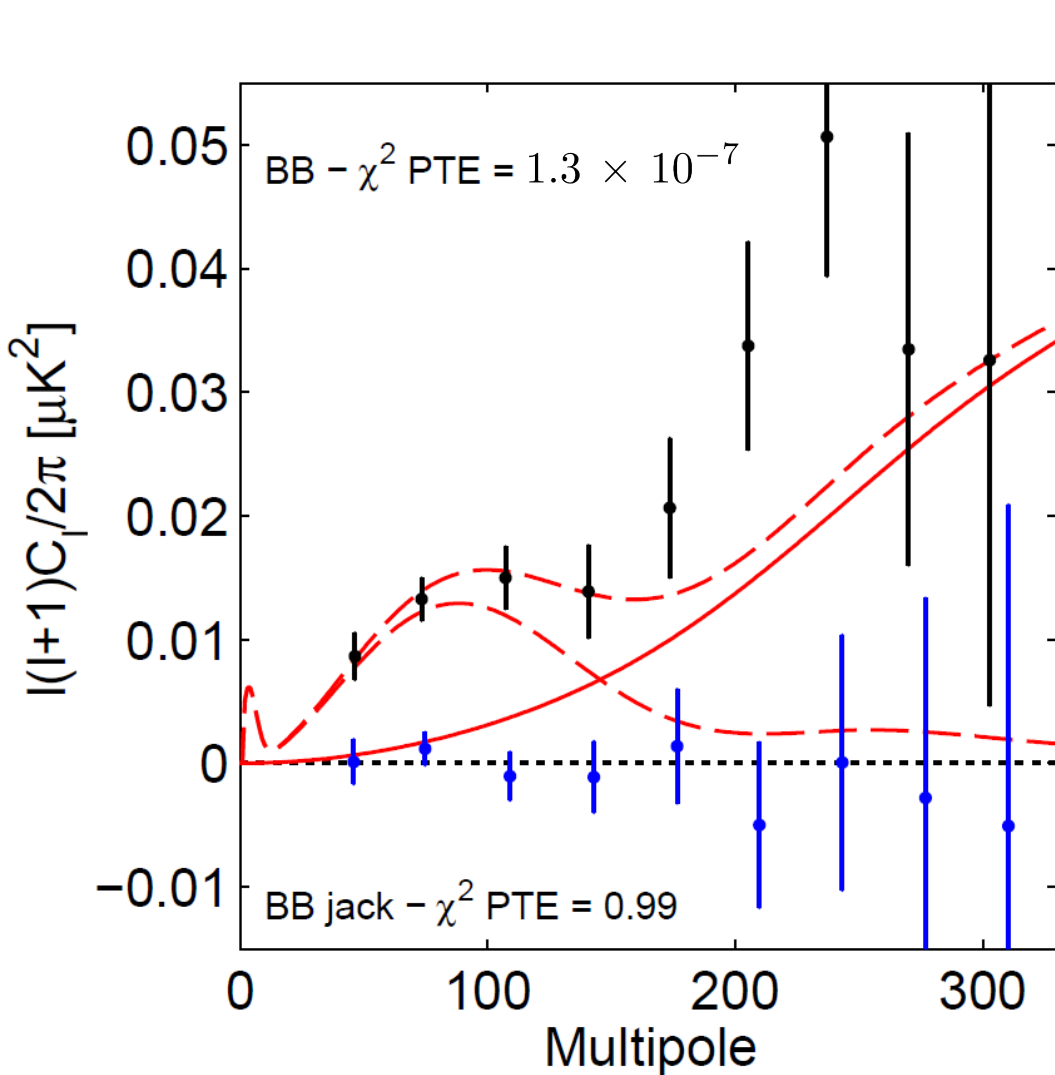
Analysis “calibrated” using lensed- Λ CDM+noise simulations.

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- Λ CDM
- - - $r=0.2$

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

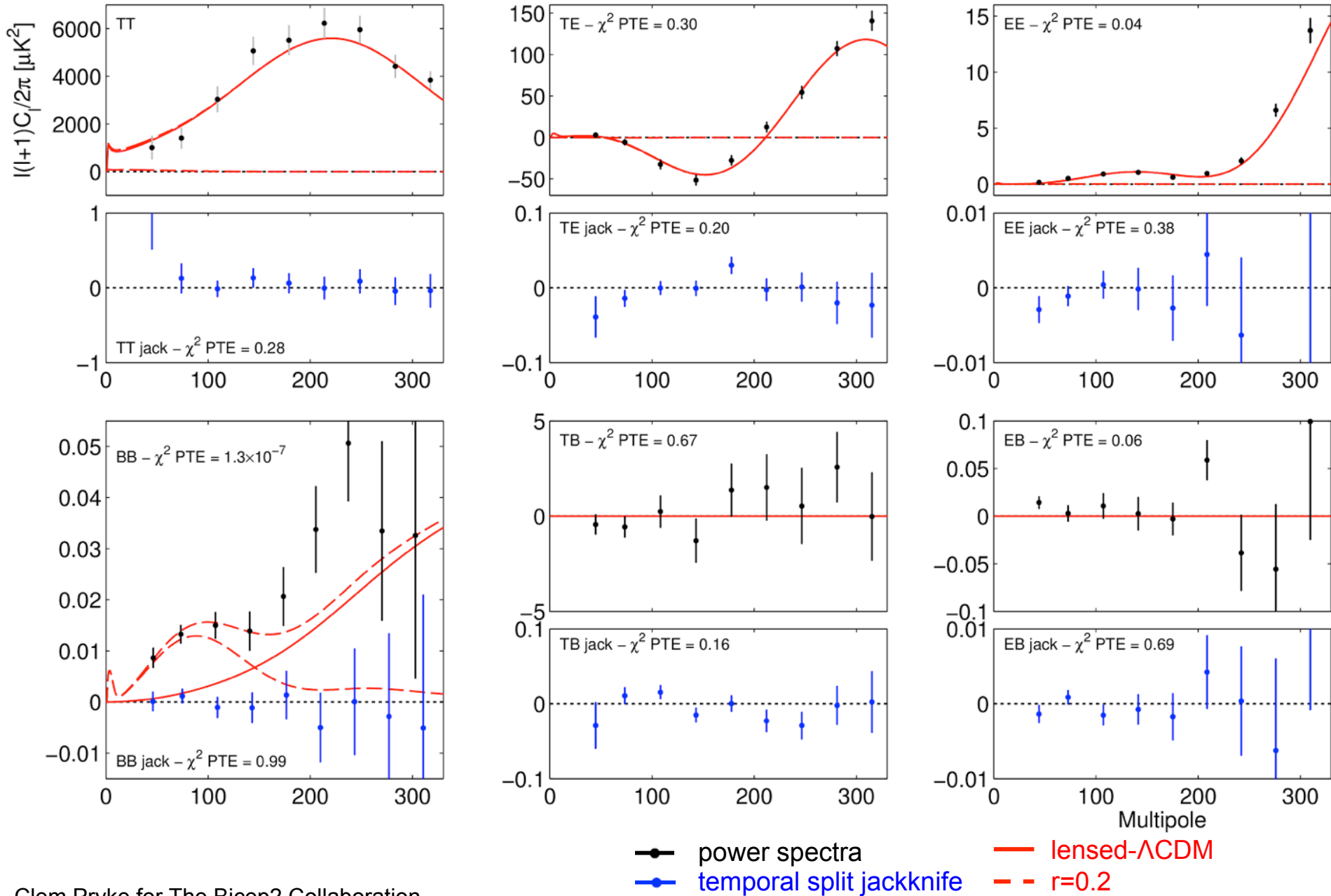
Consistent with lensing expectation at higher l . (yes – a few points are high but not excessively...)

At low l excess over lensed- Λ CDM with high signal-to-noise.

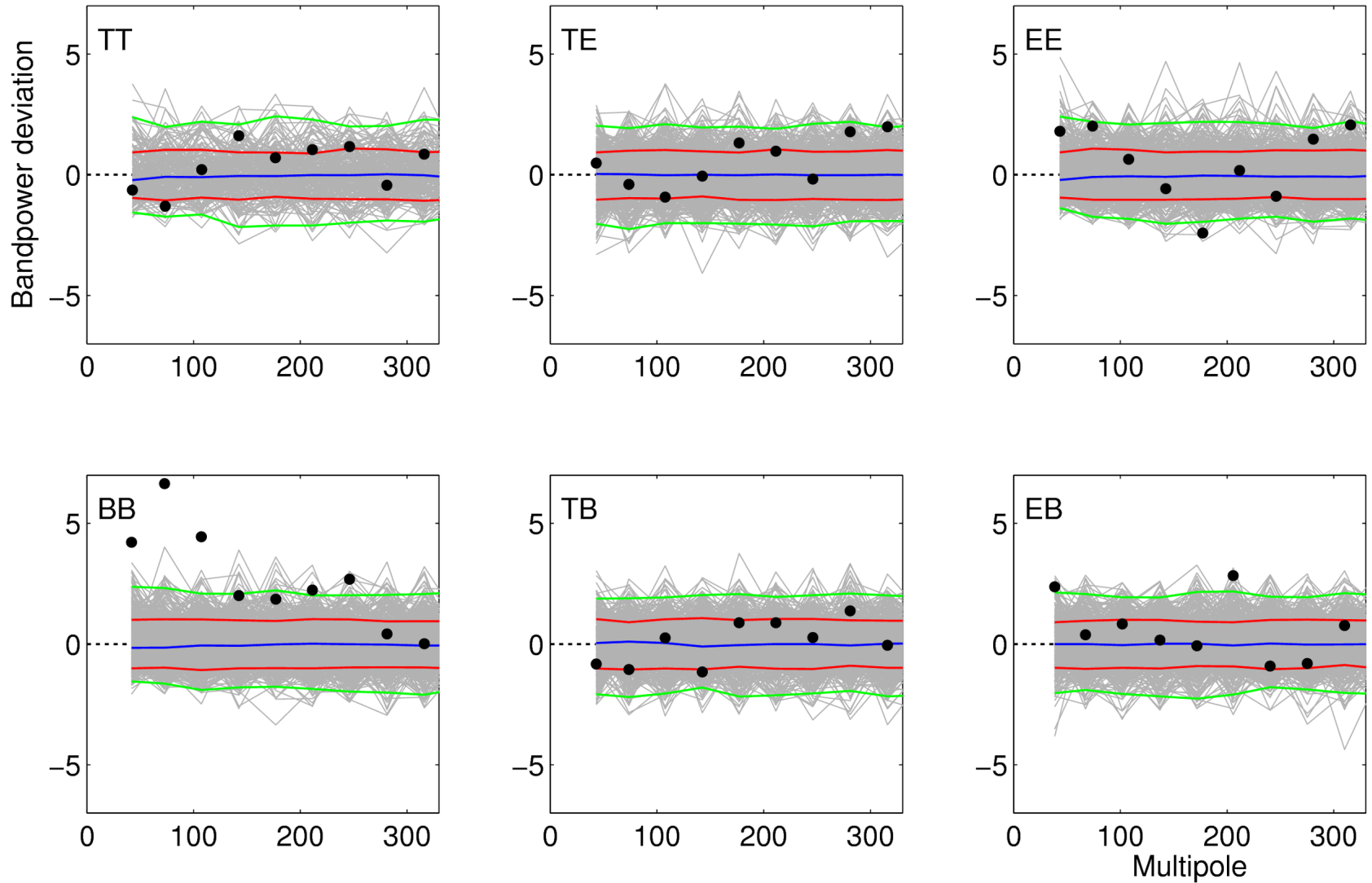
For the hypothesis that the measured band powers come from lensed- Λ CDM we find:

χ^2 PTE	1.3×10^{-7}
significance	5.3σ

Temperature and Polarization Spectra



Bandpower Deviations



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

- real data
- lensed- Λ CDM + noise sims
- $\pm 1\sigma$
- $\pm 2\sigma$

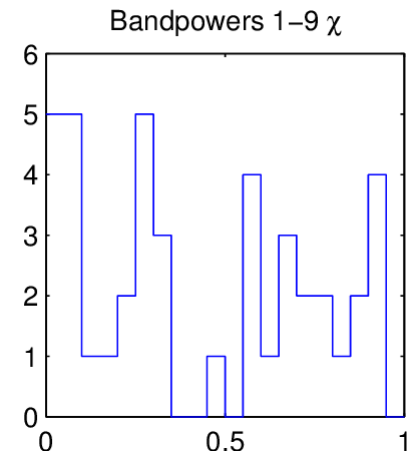
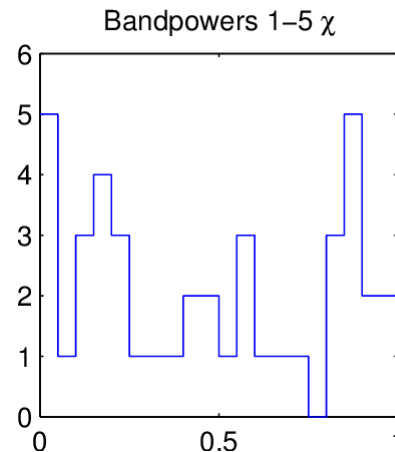
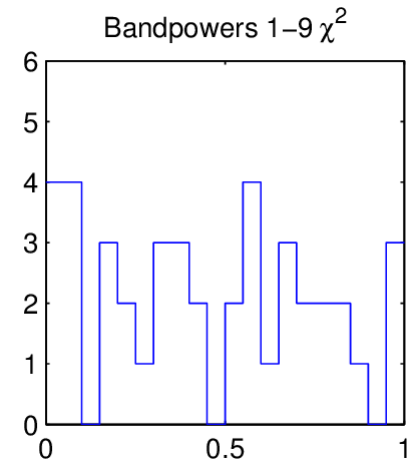
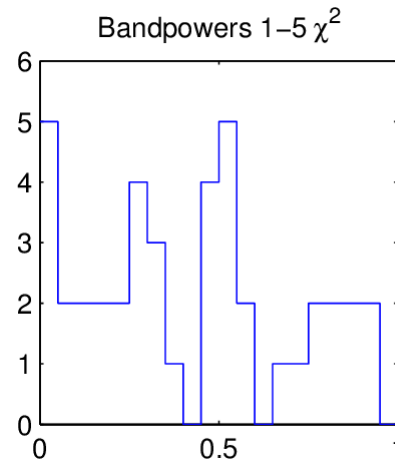
Check Systematics: Jackknives

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: Jackknives

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

Jackknife	Bandpowers 1-5 χ^2	Bandpowers 1-9 χ^2	Bandpowers 1-5 χ	Bandpowers 1-9 χ
Deck jackknife				
EE	0.046	0.030	0.164	0.299
BB	0.774	0.329	0.240	0.082
EB	0.337	0.643	0.204	0.267
Scan Dir jackknife				
EE	0.483	0.762	0.978	0.938
BB	0.531	0.573	0.896	0.551
EB	0.898	0.806	0.725	0.890
Tag Split jackknife				
EE	0.541	0.377	0.916	0.938
BB	0.902	0.992	0.449	0.585
EB	0.477	0.689	0.856	0.615
Tile jackknife				
EE	0.004	0.010	0.000	0.002
BB	0.794	0.752	0.565	0.331
EB	0.172	0.419	0.962	0.790
Phase jackknife				
EE	0.673	0.409	0.126	0.339
BB	0.591	0.739	0.842	0.944
EB	0.529	0.577	0.840	0.659
Mux Col jackknife				
EE	0.812	0.587	0.196	0.204
BB	0.826	0.972	0.293	0.283
EB	0.866	0.968	0.876	0.697
Alt Deck jackknife				
EE	0.004	0.004	0.070	0.236
BB	0.397	0.176	0.381	0.086
EB	0.150	0.060	0.170	0.291
Mux Row jackknife				
EE	0.052	0.178	0.653	0.739
BB	0.345	0.361	0.032	0.008
EB	0.529	0.226	0.024	0.048
Tile/Deck jackknife				
EE	0.048	0.088	0.144	0.132
BB	0.908	0.840	0.629	0.269
EB	0.050	0.154	0.591	0.591
Focal Plane inner/outer jackknife				
EE	0.230	0.597	0.022	0.090
BB	0.216	0.531	0.046	0.092
EB	0.036	0.042	0.850	0.838
Tile top/bottom jackknife				
EE	0.289	0.347	0.459	0.599
BB	0.293	0.236	0.154	0.028
EB	0.545	0.683	0.902	0.932
Tile inner/outer jackknife				
EE	0.727	0.533	0.128	0.485
BB	0.255	0.086	0.421	0.036
EB	0.465	0.737	0.208	0.168
Moon jackknife				
EE	0.499	0.689	0.481	0.679
BB	0.144	0.287	0.898	0.858
EB	0.289	0.359	0.531	0.307
A/B offset best/worst				
EE	0.317	0.311	0.868	0.709
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.790

Splits the 4 boresight rotations

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

Splits by time

Checks for contamination on long (“Temporal Split”) and short (“Scan Dir”) timescales. Short timescales probe detector transfer functions.

Splits by channel selection

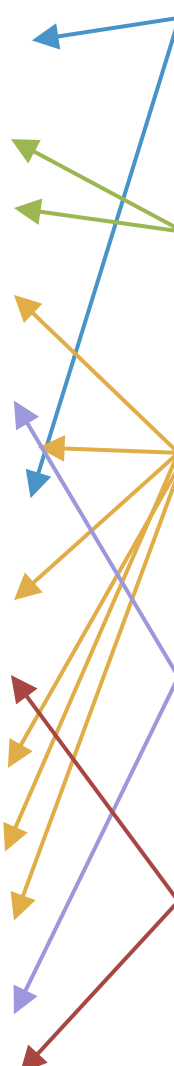
Checks for contamination in channel subgroups, divided by focal plane location, tile location, and readout electronics grouping

Splits by possible external contamination

Checks for contamination from ground-fixed signals, such as polarized sky or magnetic fields, or the moon

Splits to check intrinsic detector properties

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



In-Situ Calibration Measurements

For instance...

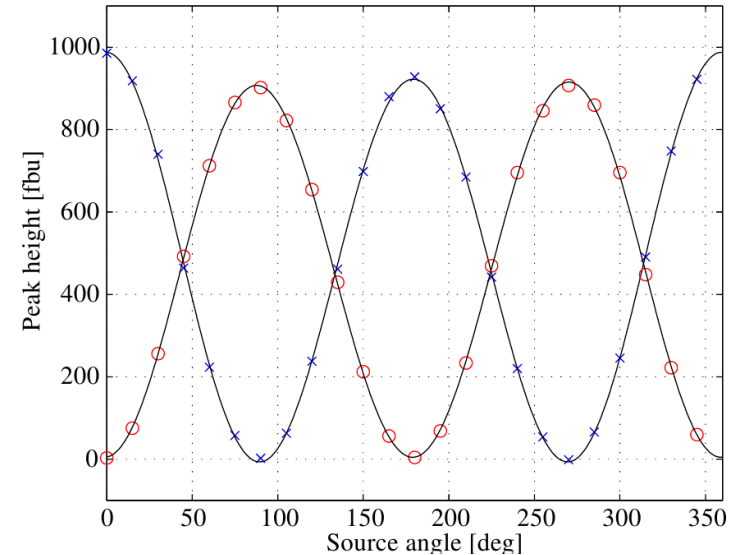
Far field beam mapping



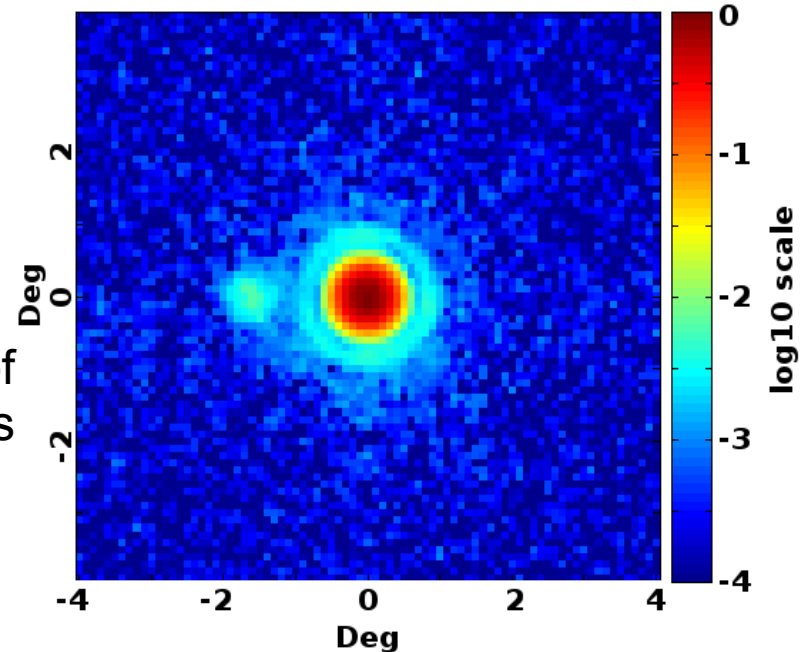
Hi-Fi beam maps of
individual detectors

**Detailed description in
Instrument Paper [arxiv:1403.4302](https://arxiv.org/abs/1403.4302)**

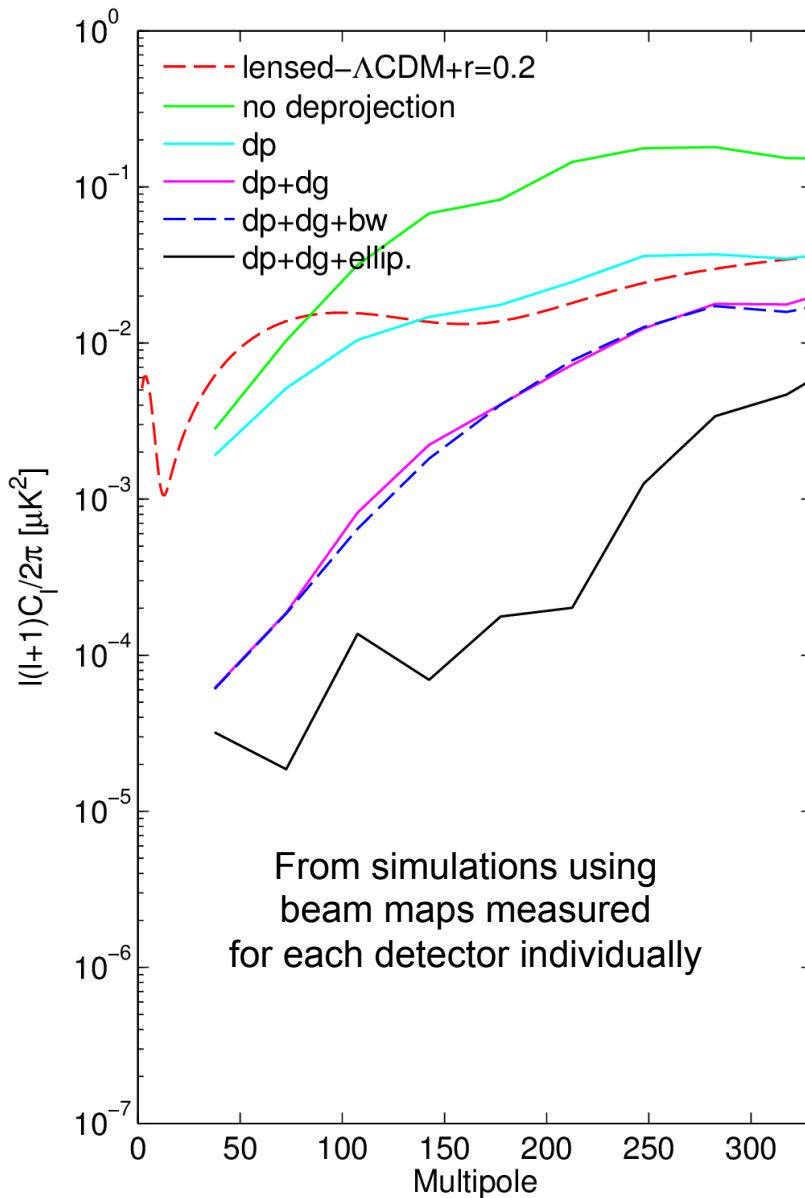
Detector Polarization Calibration



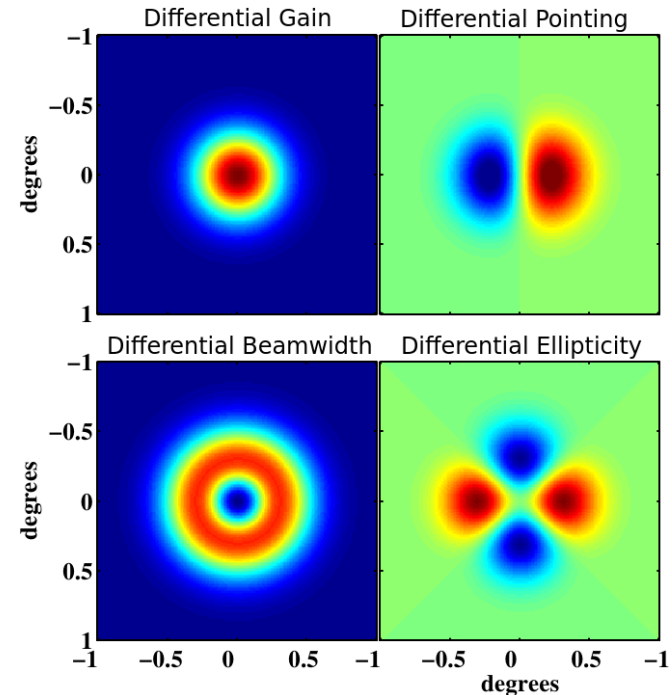
Channel 235



Systematics Removal: Deprojection



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

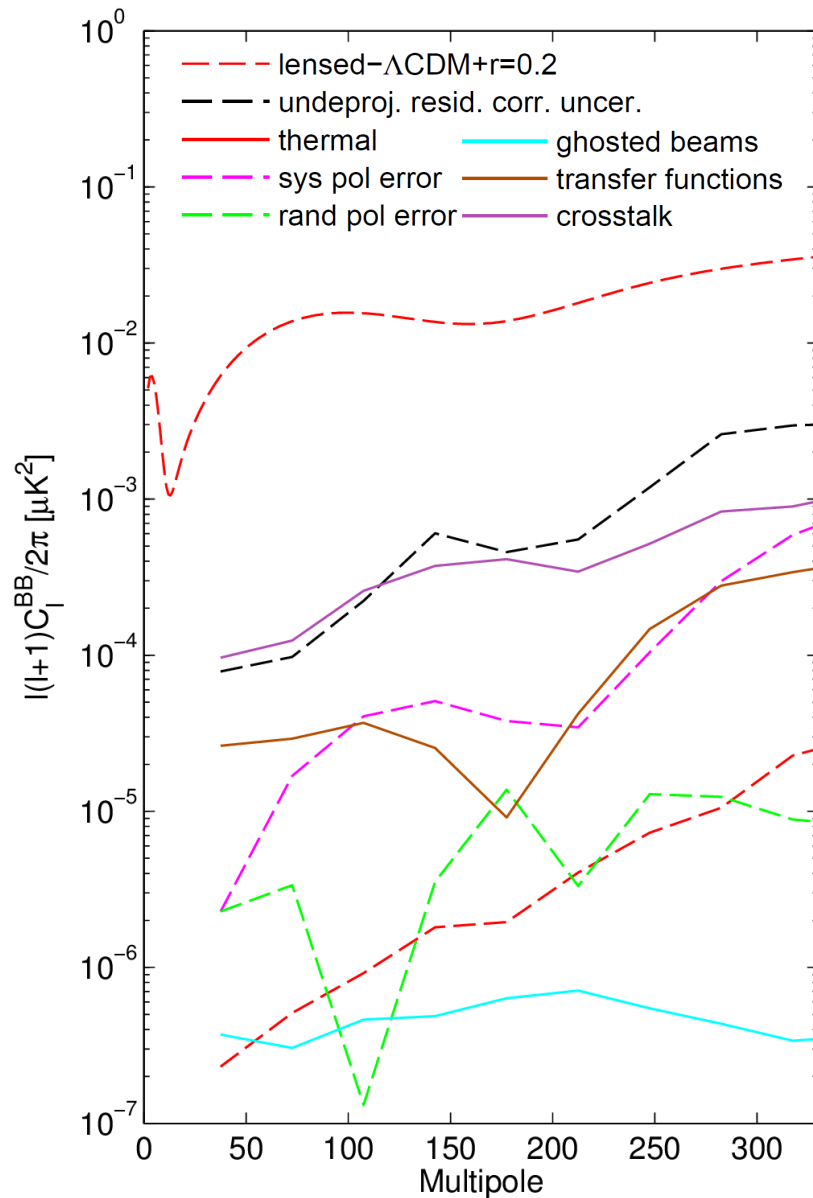


Use the Planck 143 GHz map to form template of the leakage

Deproject diff gain and pointing (& subtract diff ellipticity)

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

Systematics beyond Beam imperfections

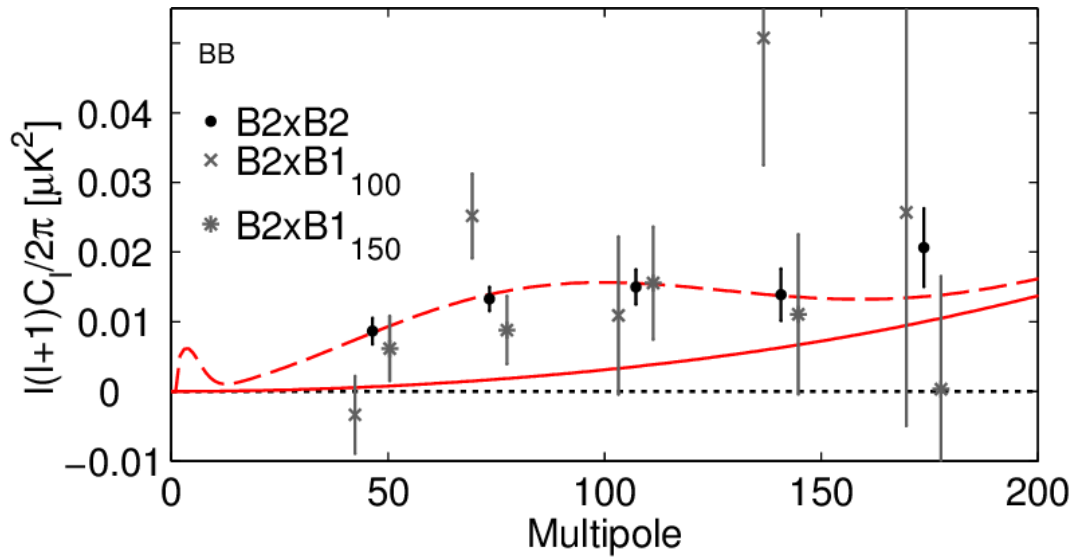


All systematic effects that we could imagine were investigated!

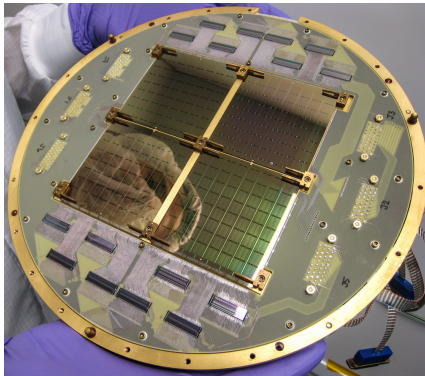
We find with high confidence that the apparent signal *cannot be explained* by instrumental systematics!

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

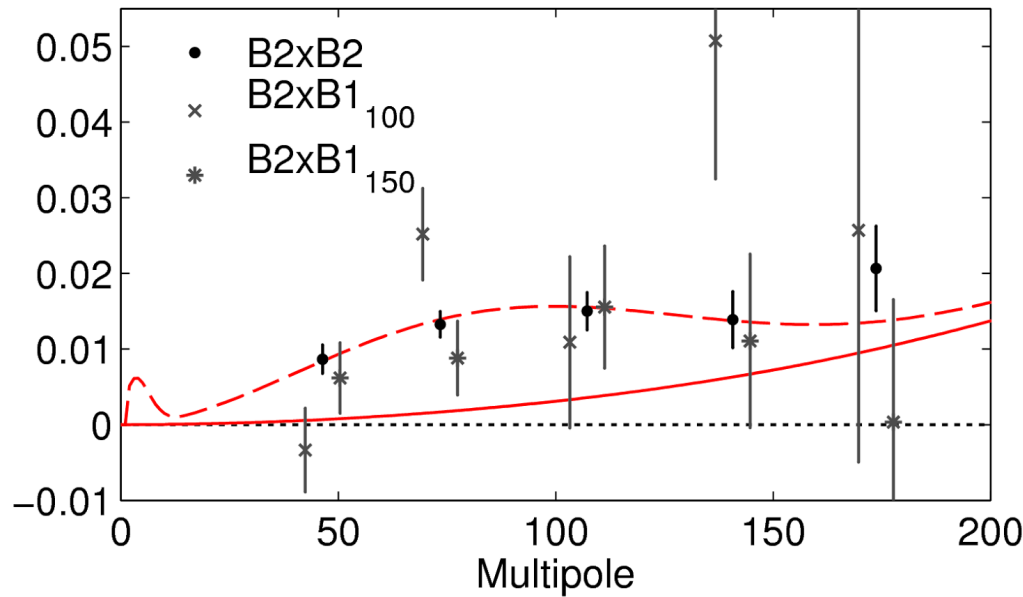
BICEP1: Feedhorns
and NTD readout
150 and 100 GHz



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

Cross with BICEP1₁₀₀ shows **~3σ** detection of BB power

Spectral Index Constraint using BICEP1 100GHz



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

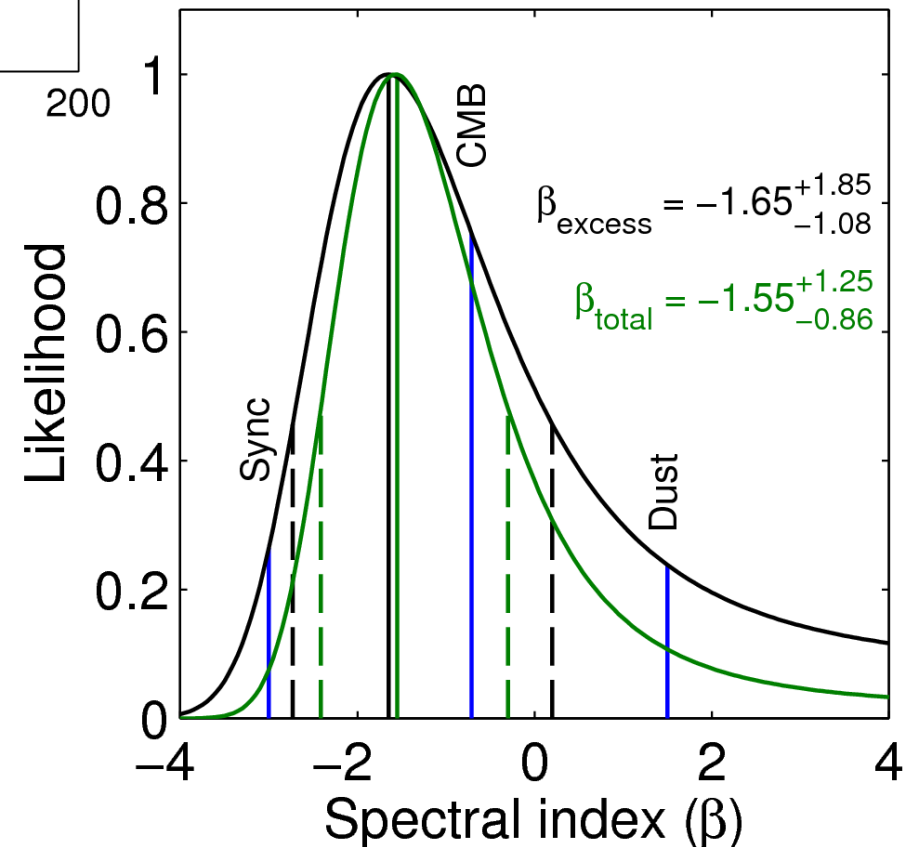
green: total signal

black : excess signal over Λ CDM

Comparison of B2 auto with B2₁₅₀ × B1₁₀₀ constrains signal frequency dependence:

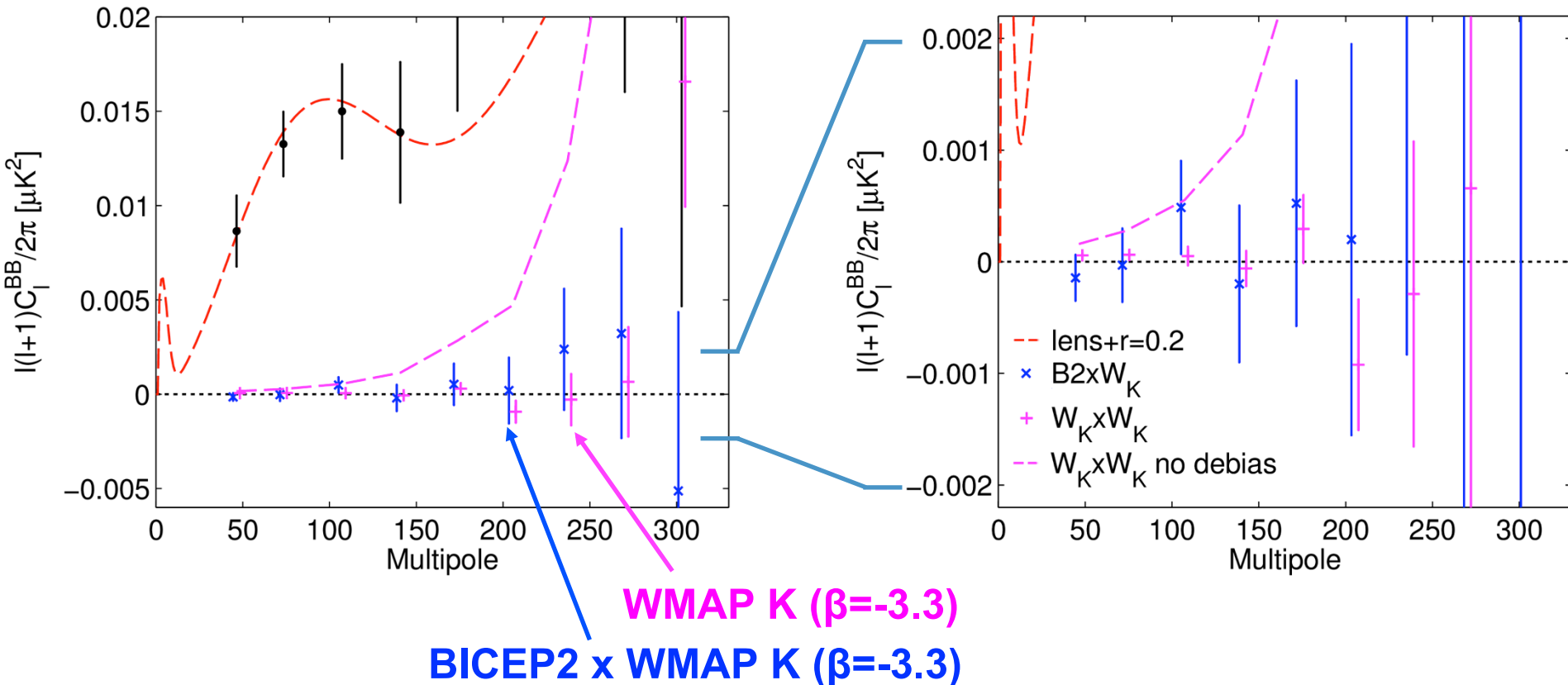
If **dust**, expect little cross-correlation

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

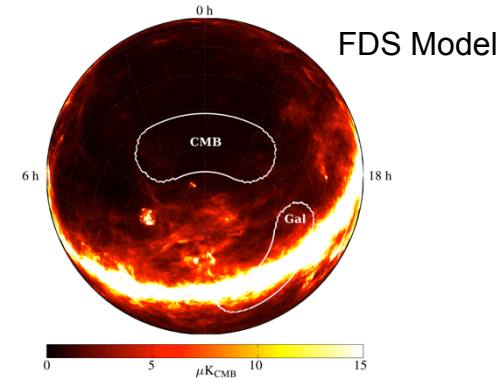
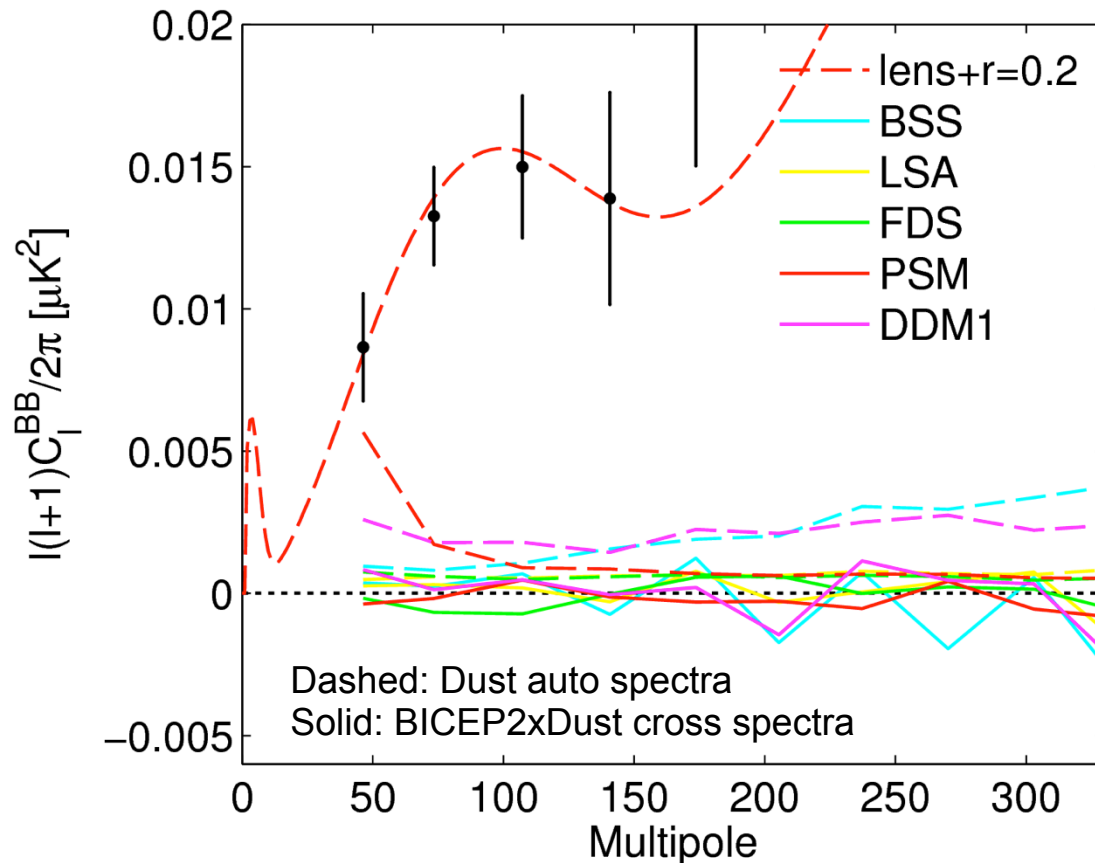


Synchrotron Foreground?

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.



Pre-Planck Polarized Dust Foreground Projections



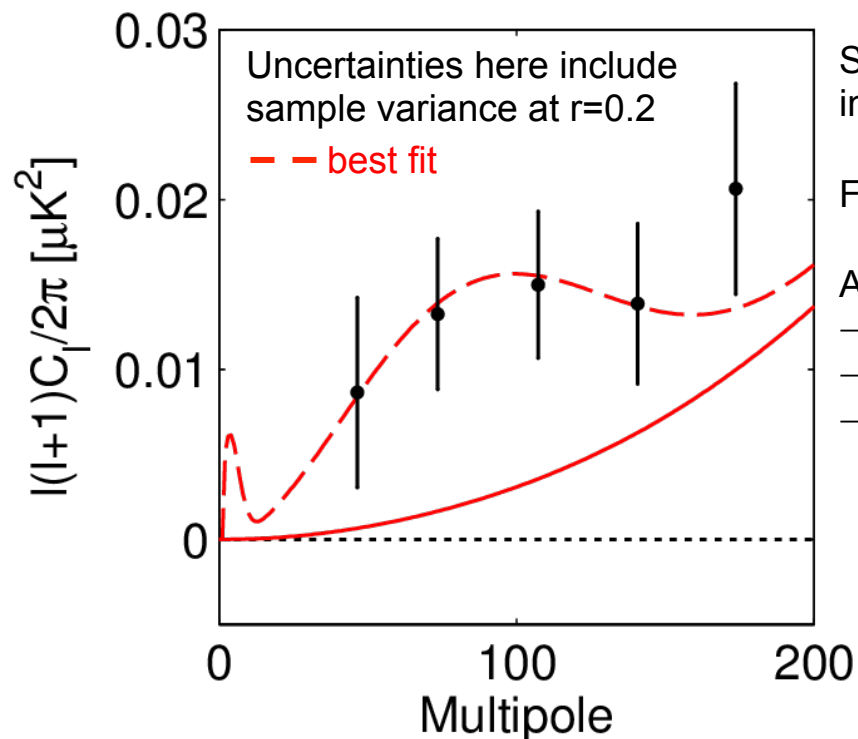
The BICEP2 region was chosen on the basis of extremely low unpolarized dust power.

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- Λ CDM + noise simulations
- weighted version of the 5 bandpowers
- B-mode sims scaled to various levels of r ($n_T=0$)

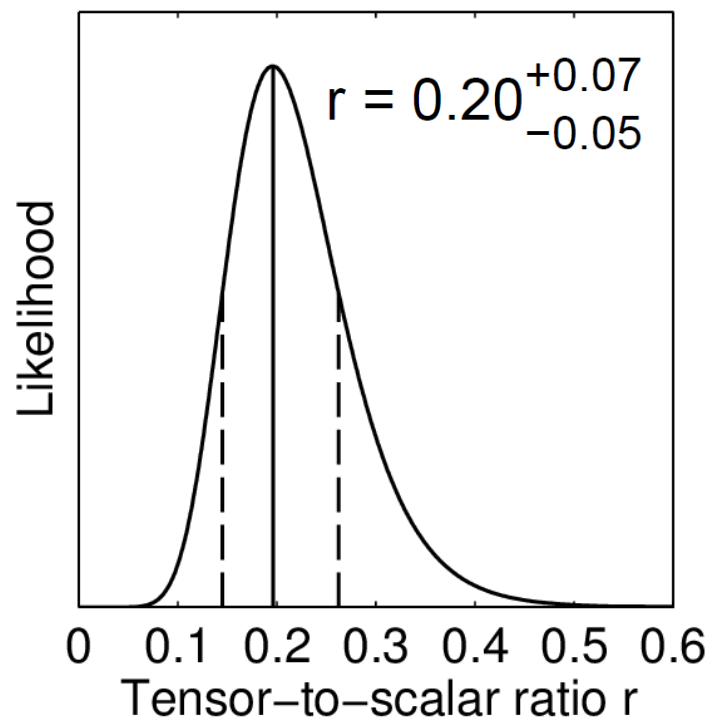
Within this simplistic model we find:

$r = 0.2$ with uncertainties dominated by sample variance

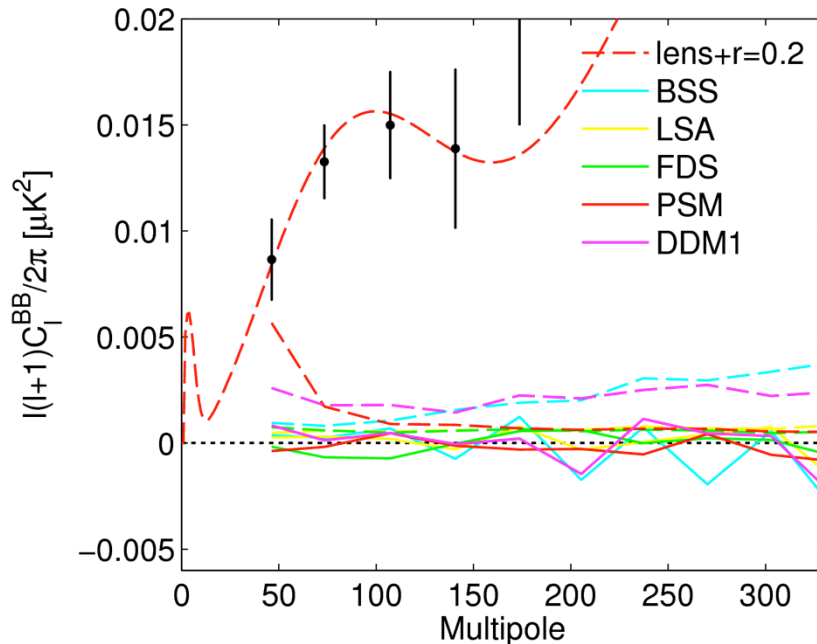
PTE of fit to data: 0.9

→ model is perfectly acceptable fit to the data

$r = 0$ ruled out at 7.0σ



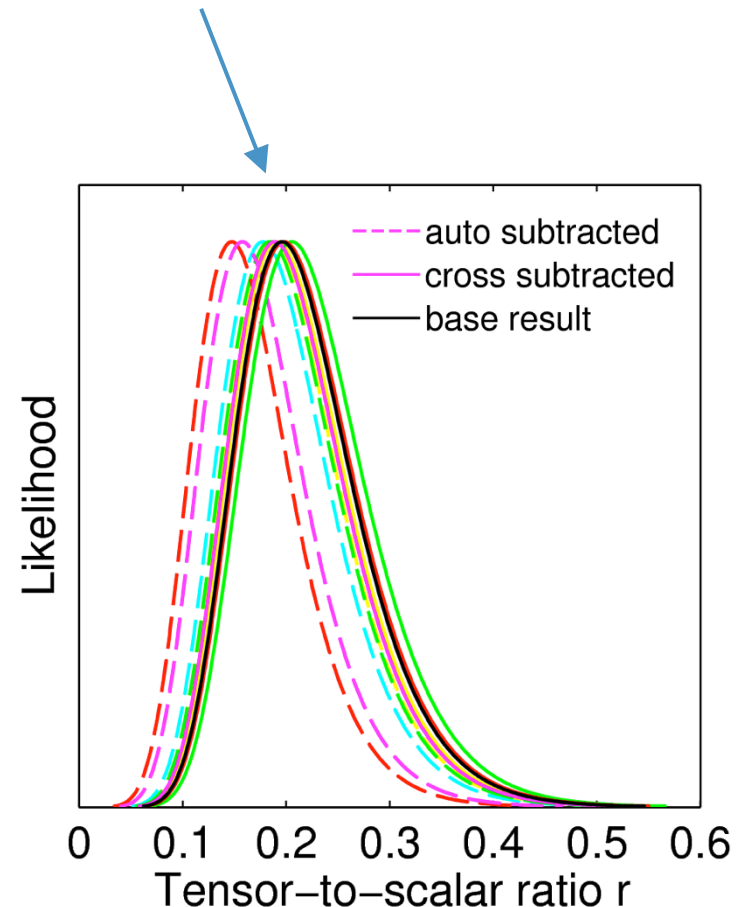
Fitting with Dust Projections Subtracted...



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

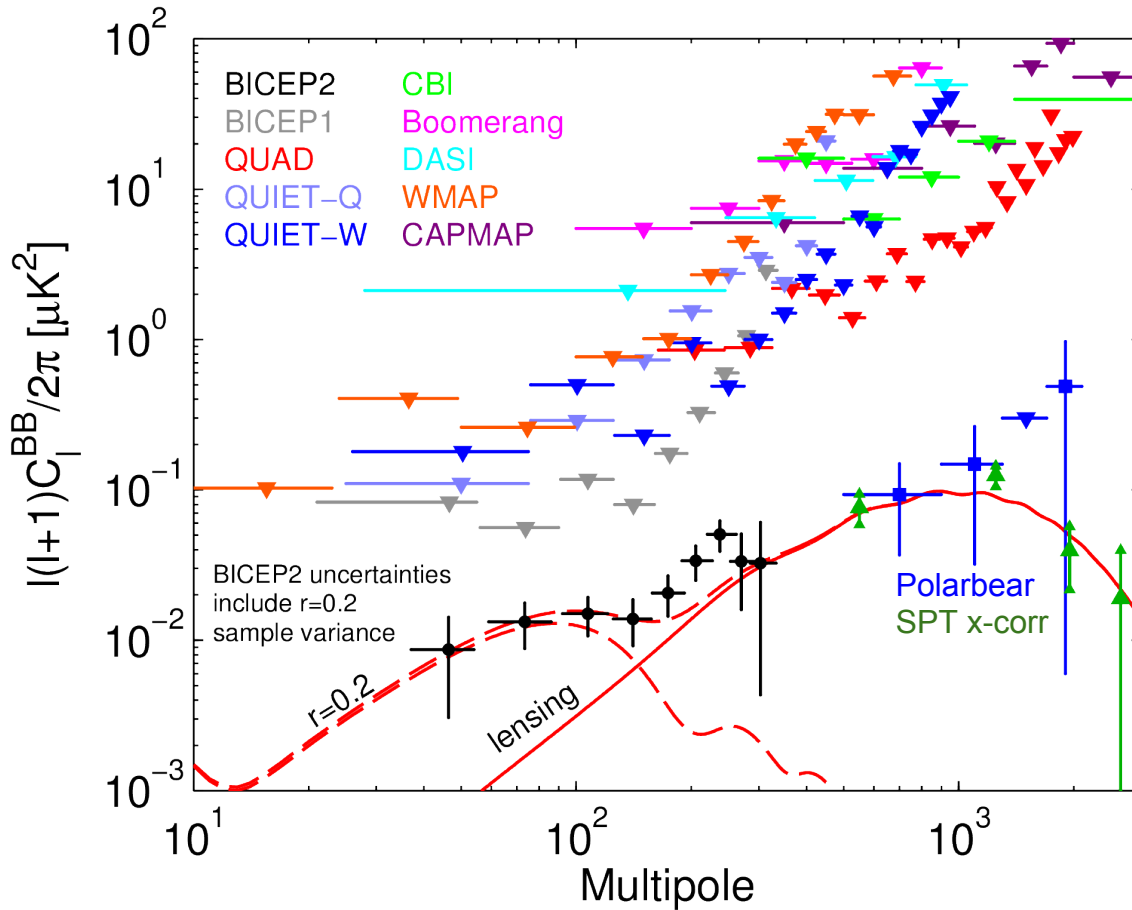
DDM1 used all publicly available information from Planck. Polarization fraction here assumed $p = 5\%$. $p \sim 13\%$ would explain the full excess under this model.

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



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- Λ CDM except:
5.2 σ 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

Press Conference at Harvard/CfA March 17



Storm of Media Attention

USA TODAY
03.18.14
A GANNETT COMPANY

NCAA TOURNAMENT
WHO HAS BEST "DANCE CARDS"
A look at matchups, players and teams to watch, 5C

UConn tops women's tourney
ANALYSIS, BRACKET, 4C

Putin, U.S. up ante after vote

Sanctions imposed, Ukraine, Russia ready troops as Duma considers Crimean annexation

'Always hope' missing jet's passengers alive
As search expands to two helicopters, Malaysian officials won't rule out possibility that plane is intact. **3A**

GM issues three new recalls
New recalls involve all cars, truck system plug, involve more than 15 million vehicles. **1B**

Homework load unchanged
Despite parents' concerns about more work, study finds burden has barely changed over 30 years. **3A**

How earnings earner big, bad wings
To play 'Mad Max' critics won't let go of you? **1D**

South Pole view
The first time the South Pole, where the majority of our efforts to understand the universe, has been imaged in the heavens. **3D**

Gravitational waves
Scientists have been gazing across the cosmos for decades, but only now have they seen the universe's hidden ripples. **1B**

A theory
In 1915, Albert Einstein's theory of gravity predicted that gravity would warp space and time. Now, scientists have found evidence that gravity warps space and time. **1B**

States engage in shadowy deals as death penalty drugs dwindle
Prisoners have drug, use shady pharmacies, try untested methods. **1B**

Prisoners have drug, use shady pharmacies, try untested methods
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"All the News That's Fit to Print"

The New York Times

VOL. CLXXIII, No. 56,444

TUESDAY, MARCH 18, 2014

52.50



Chinese relatives of those on the missing Malaysian plane watched news from Malaysia in Beijing, Page A8.

Lost Jet's Path Seen as Altered

By **CHRISTOPHER L. BARNETT**
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Space Ripples Reveal Big Bang's Smoking Gun

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Gravitational Waves

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PUTIN RECOGNIZES CRIMEA SECESSION, DEFEYING THE WEST

Decree Increases Fears of Annexation by Russia, Despite More Sanctions

By **CHRISTOPHER L. BARNETT**

WASHINGTON — President Vladimir Putin on Tuesday announced that Russia recognizes the Crimean peninsula as an independent state, a move that defies the West and increases fears of Russian annexation. The announcement came after a referendum in Crimea, which was held last month, in which the majority of voters chose to join Russia. Putin's announcement was a clear signal that Russia is moving forward with its plan to annex Crimea, despite the fact that the United States and other Western countries have imposed sanctions on Russia in response to the move.

Mr. Putin made his statement in a speech to the Russian parliament, in which he said that Russia was recognizing the Crimean peninsula as an independent state. He said that this was a necessary step to ensure the stability and security of the region. He also said that Russia was committed to the peaceful resolution of the conflict in Ukraine, but that it was necessary to take this step to protect the interests of the Russian people. The announcement was met with widespread condemnation from the West, with the United States and other countries calling for further sanctions on Russia.

The announcement also came as the Russian government was preparing to hold a referendum in Crimea on whether to join Russia. The referendum was held last month, and the results showed that a large majority of voters in Crimea chose to join Russia. This was a significant victory for the Russian government, as it showed that the people of Crimea were in favor of joining Russia. The Russian government is now moving forward with its plan to annex Crimea, and it is expected that the annexation will be formalized in the coming weeks.

FINANCIAL TIMES

The Apple alumni
Steve Jobs' acolytes are taking over the world, Page 8

The trouble with tinkering with textbooks
Gideon Rachman, Page 7

EU and US take action • More severe measures prepared • Putin lays out Crimea demands

Sanctions hit Russian top brass

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Gravitational waves captured by the LIGO experiment, which is a collaboration between the University of Wisconsin and the University of Maryland. The image shows a satellite dish on a ship, likely part of the LIGO experiment, capturing gravitational waves.

宇宙急速膨張の証拠、検出される

Telescope captures view of gravitational waves

Ros Cohen 2014年3月18日 09時 54分

宇宙が急速に膨張しているという証拠が、重力波の観測によって得られました。重力波は、宇宙の膨張によって生じる波であり、重力波の観測によって宇宙の膨張の速度が測定されます。重力波の観測は、宇宙の膨張の速度を測定するための重要な手段であり、重力波の観測によって宇宙の膨張の速度が測定されます。

重力波は、宇宙の膨張によって生じる波であり、重力波の観測によって宇宙の膨張の速度が測定されます。重力波の観測は、宇宙の膨張の速度を測定するための重要な手段であり、重力波の観測によって宇宙の膨張の速度が測定されます。重力波の観測は、宇宙の膨張の速度を測定するための重要な手段であり、重力波の観測によって宇宙の膨張の速度が測定されます。

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PHYSICAL REVIEW LETTERS

Articles published week ending 20 JUNE 2014

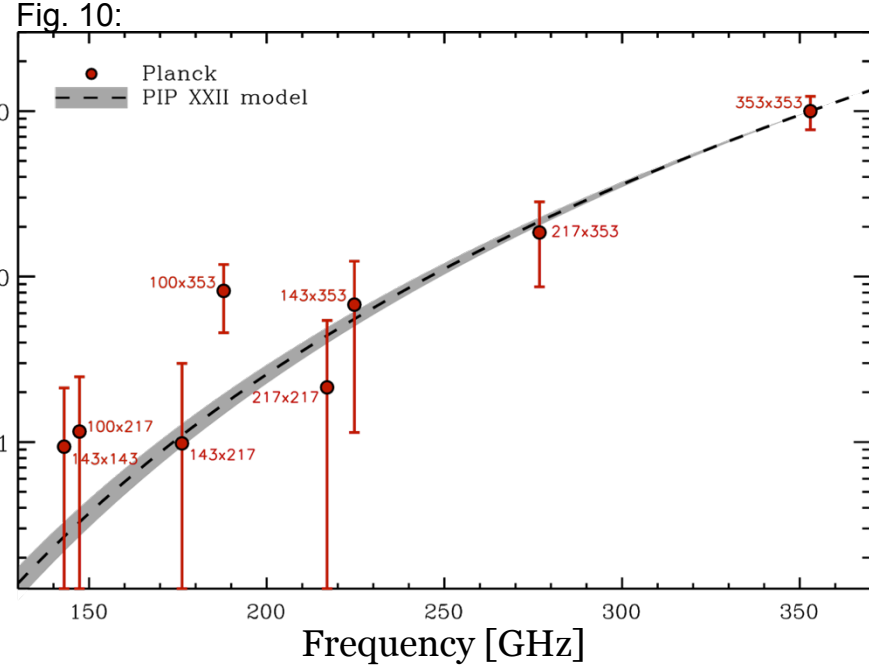
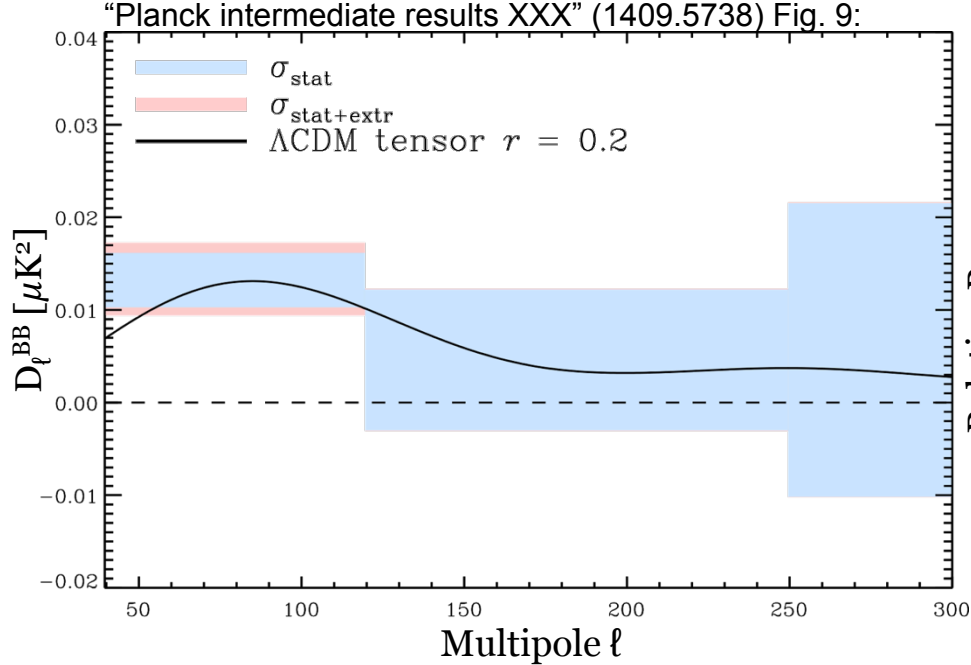
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Developments Since...

- 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



- 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...