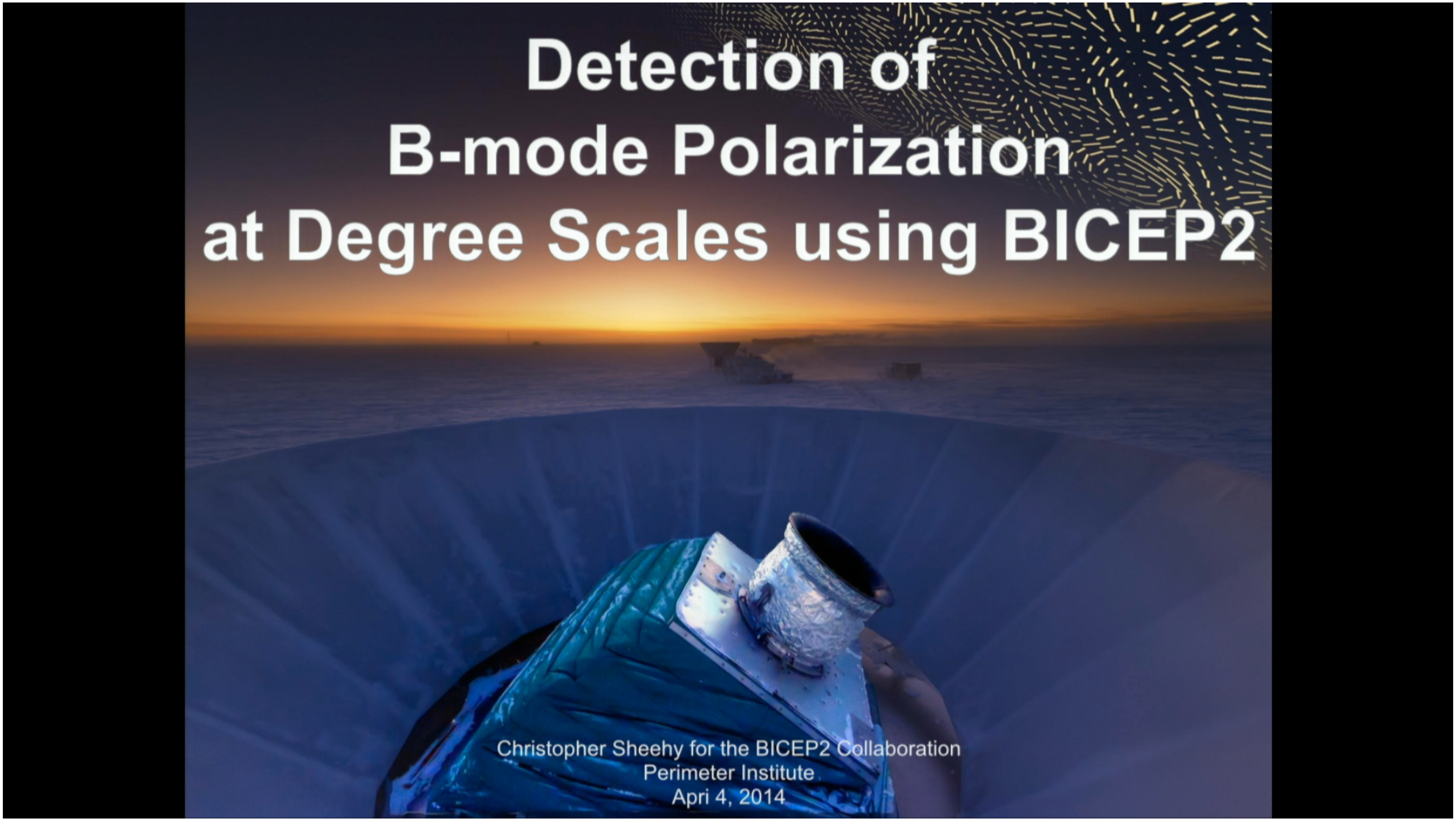
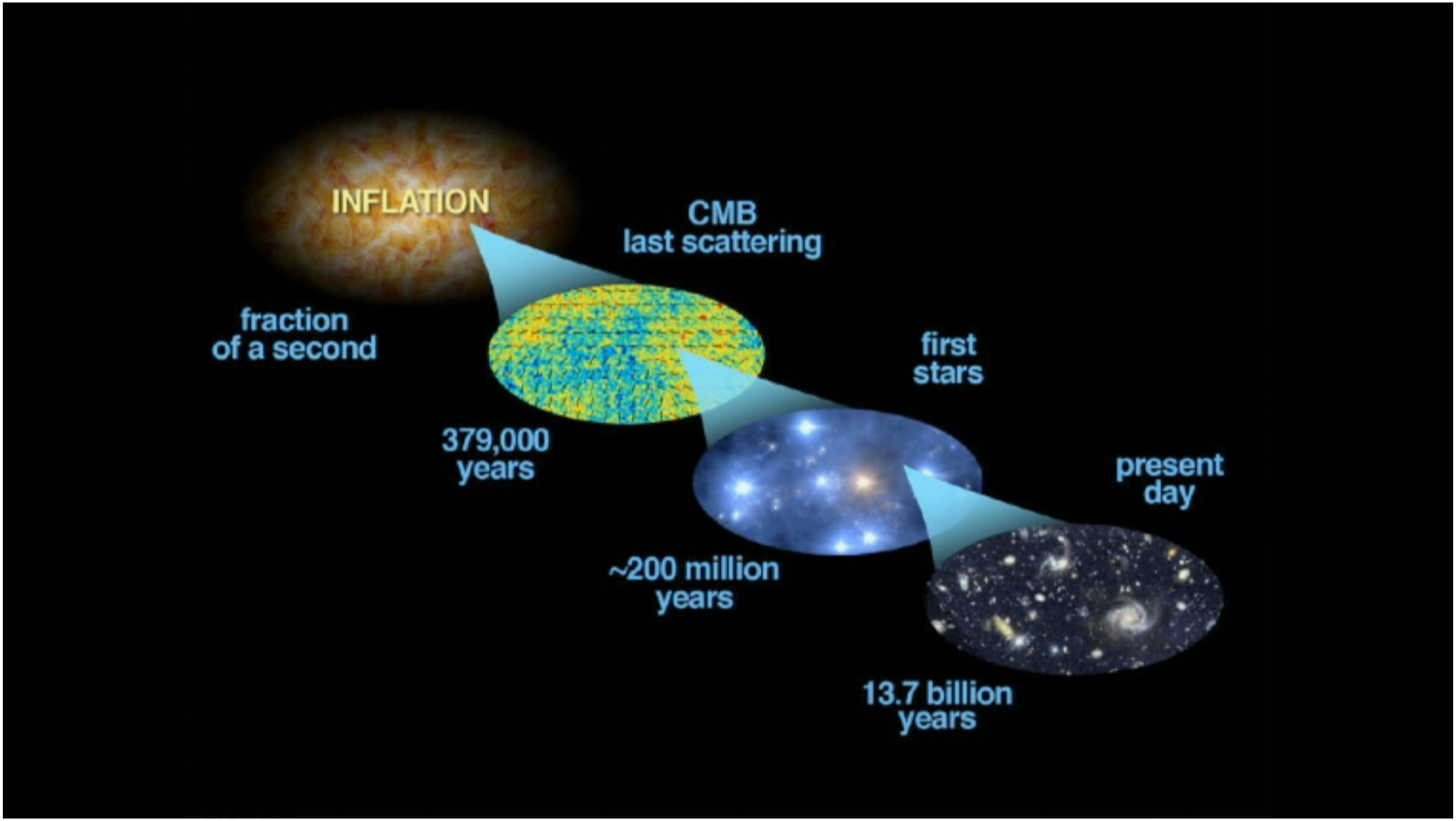
Title: Results from BICEP 2

Date: Apr 04, 2014 10:00 AM

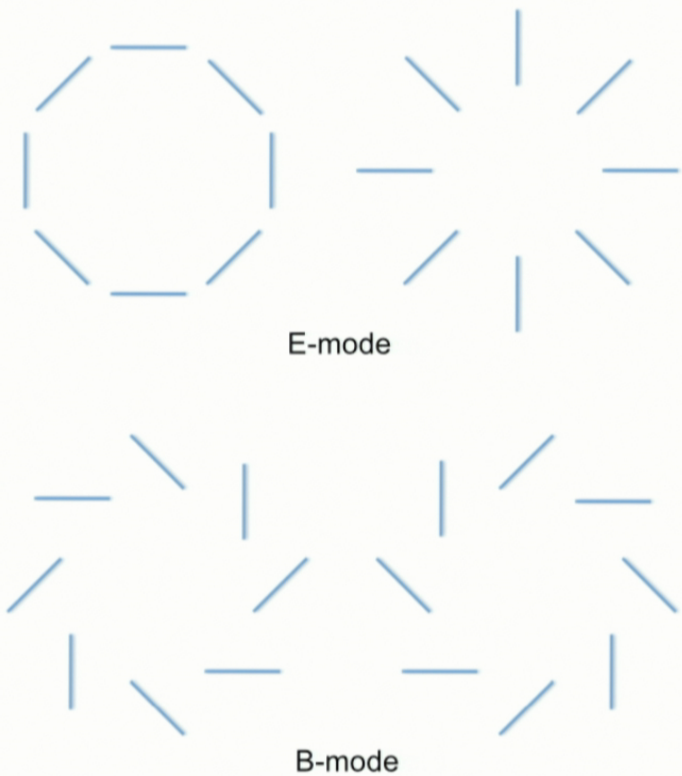
URL: http://pirsa.org/14040131

Abstract:


Detection of
B-mode Polarization
at Degree Scales using BICEP2
Christopher Sheehy for the BICEP2 Collaboration
Perimeter Institute
Apri 4, 2014


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

CMB Polarization



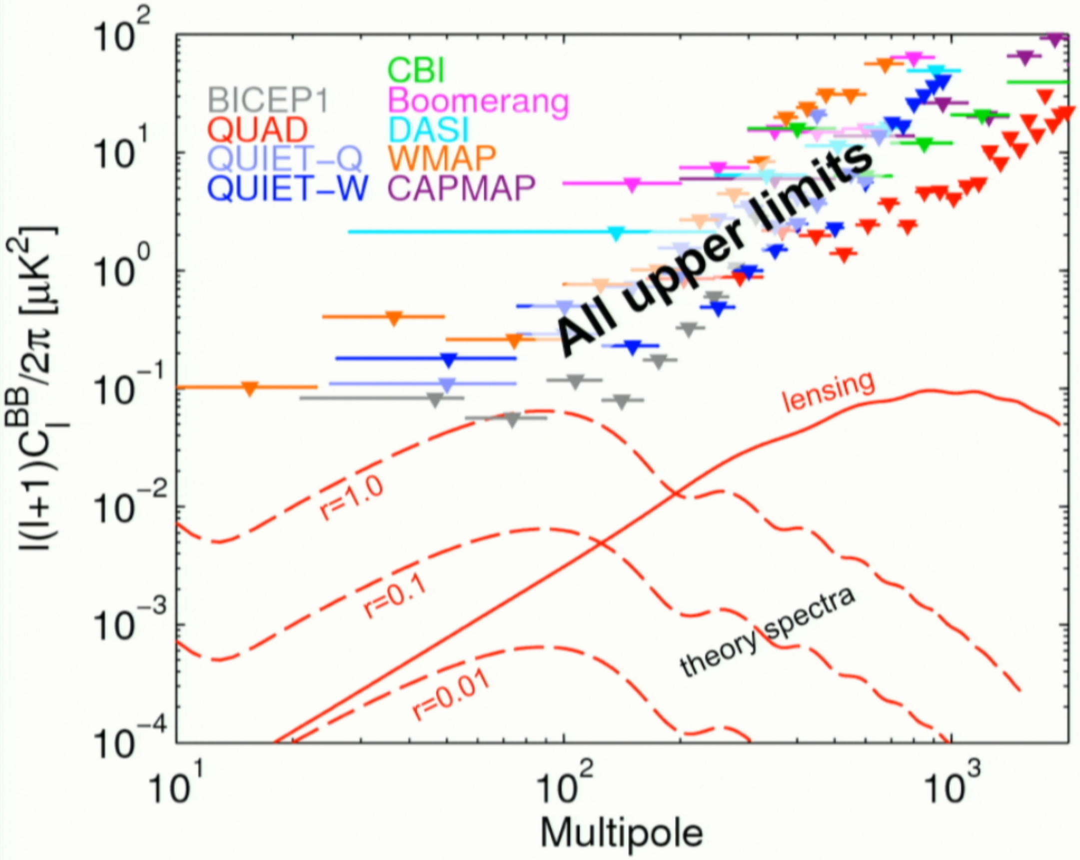
The plasma physics of the early universe causes the CMB to become slightly polarized.

Polarization can be described as the sum of E-modes and B-modes.

A measurement of degree-scale B-modes would be direct evidence for the gravitational wave background, free of the parameter degeneracies and cosmic variance inherent to temperature measurements.

Christopher Sheehy for the Bicep2 Collaboration

Search for B-modes



In simple inflationary gravitational wave models the

tensor-to-scalar ratio r

is the only parameter to the B-mode spectrum.

Up to now: just upper limits from searches for B-modes in the CMB polarization

Best limit on r from BICEP1:

r < 0.7 (95% CL)

At high multipoles lensing B-mode dominant.

Christopher Sheehy for the Bicep2 Collaboration

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], M. HALPERN[10], M. HASSELFIELD[10], S. R. HILDEBRANDT[2,6], G. C. HILTON[11], V. V. HRISTOV[2], K. D. IRWIN[12,13,11], K. S. KARKARE[5], J. P. KAUFMAN[14], B. G. KEATING[14], S. A. KERNASOVSKIY[12], J. M. KOVAC[5], C. L. KUO[12,13], E. M. LEITCH[15], M. LUEKER[2], 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], J. E. TOLAN[12], A. D. TURNER[6], A. G. VIEREGG[5,15], C. L. WONG[5], AND K. W. YOON[12,13]

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 $\approx 300\ \mu K_{CMB}\sqrt{s}$. 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.

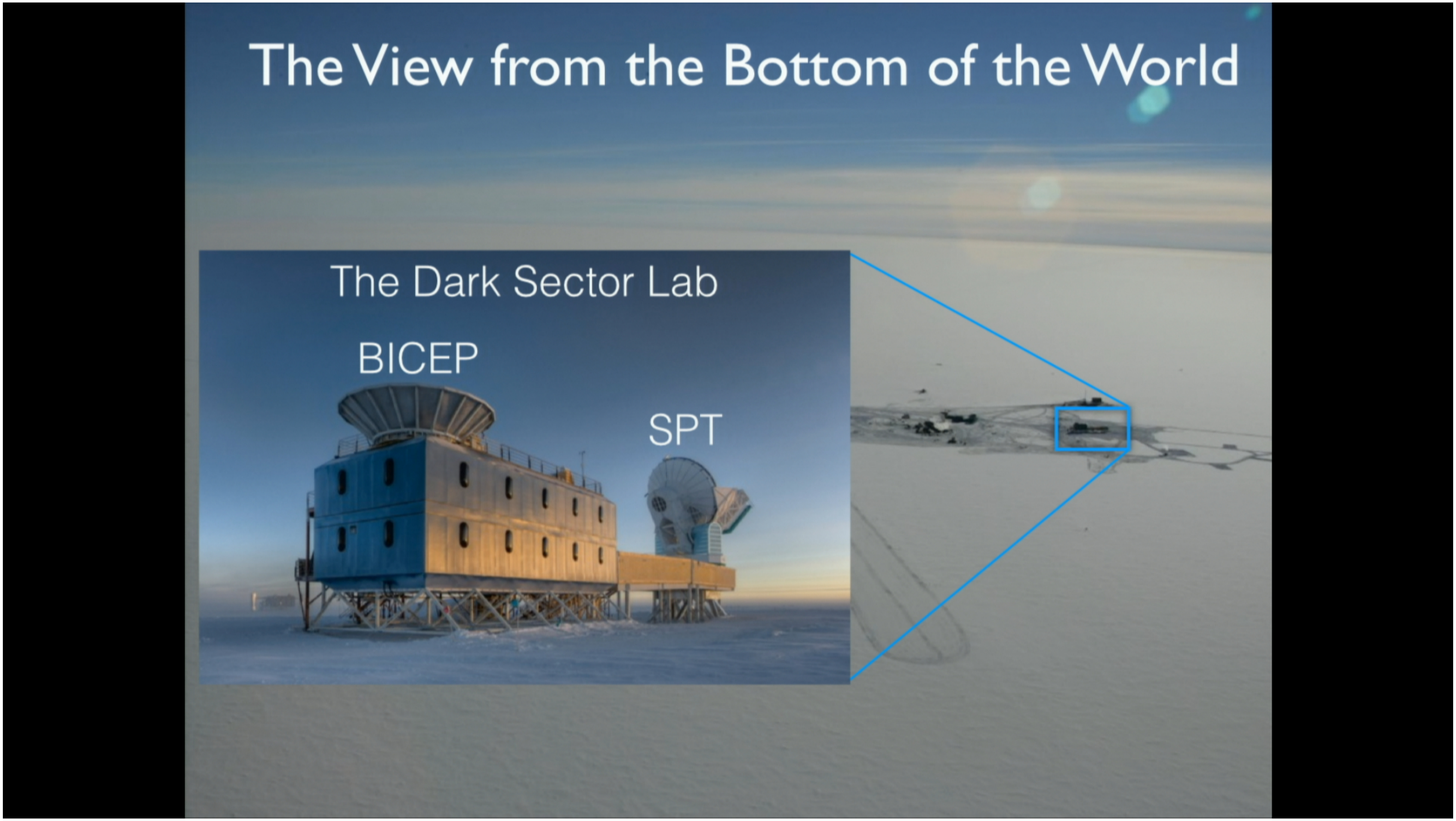
Subject headings: cosmic background radiation — cosmology: observations — gravitational waves — inflation — polarization


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

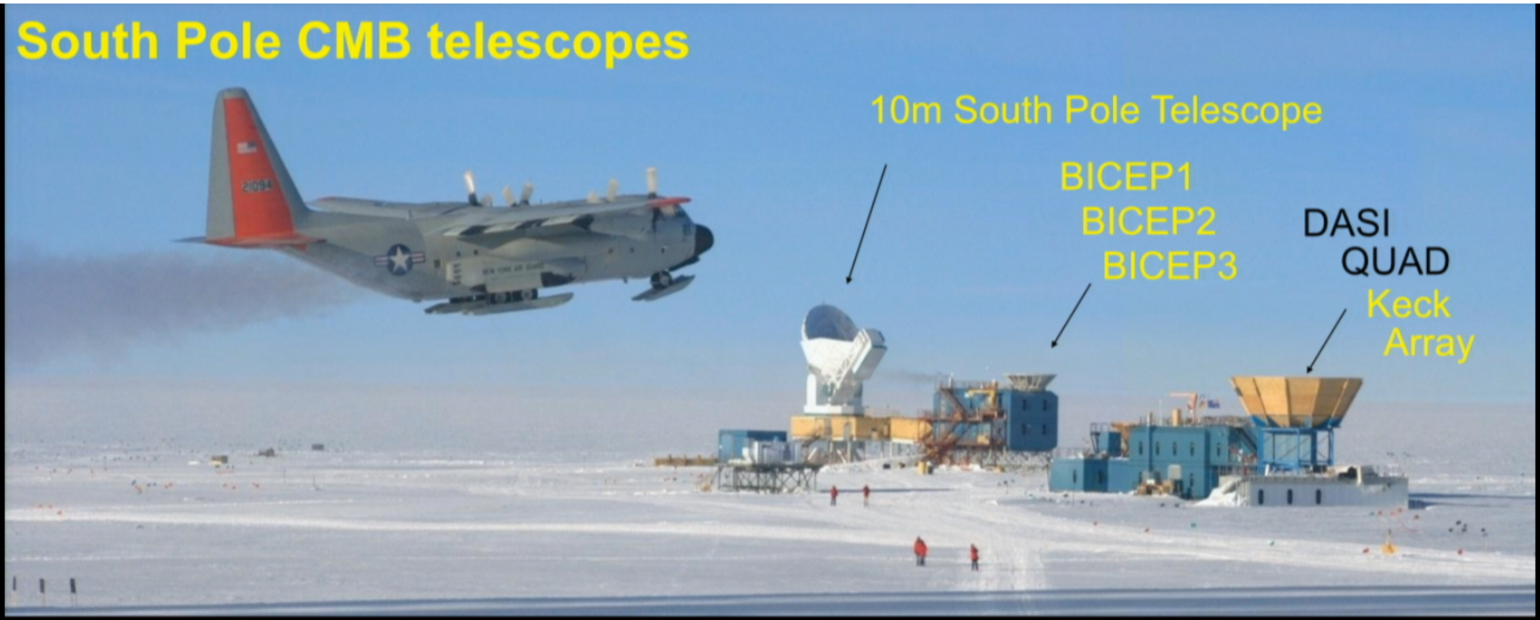
B-modes from the ground

- 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



The View from the Bottom of the World
The Dark Sector Lab
BICEP
SPT



A popular place for CMB Experimentalists:

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

- 24h coverage of “Southern Hole”
- High and dry (almost 10,000 ft.)


photo: Keith Vanderlinde

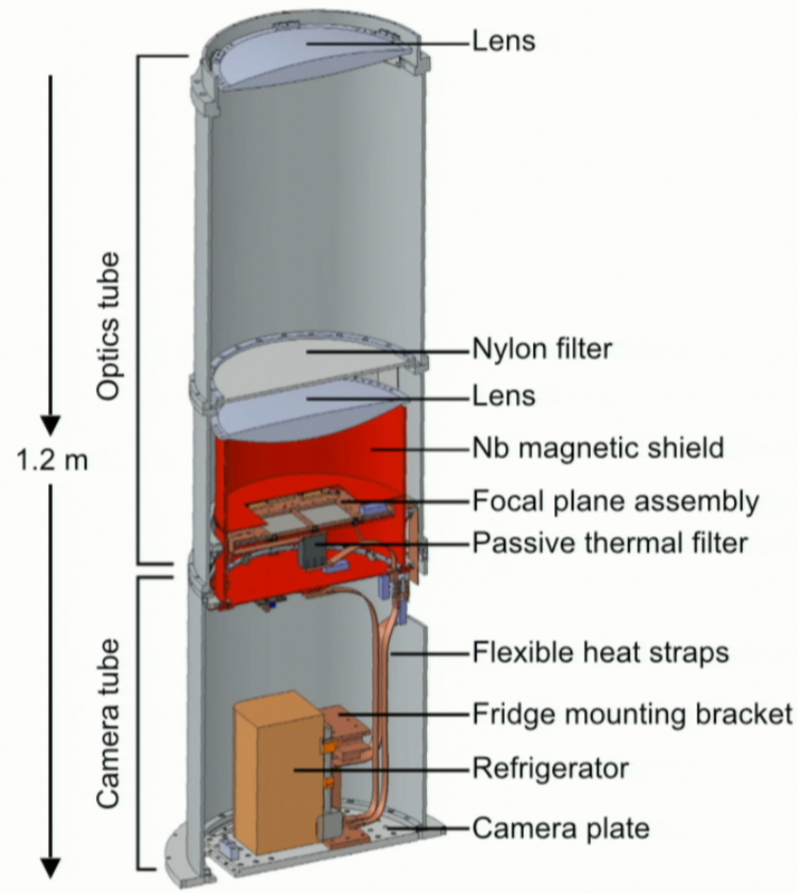
The BICEP2 Telescope

Telescope as compact as possible while still having the angular resolution to observe degree-scale features.

On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

Liquid helium cools the optical elements to 4.2 K.

A 3-stage helium sorption refrigerator further cools the detectors to 0.27 K.



Christopher Sheehy for the Bicep2 Collaboration

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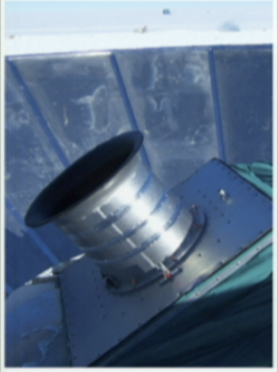
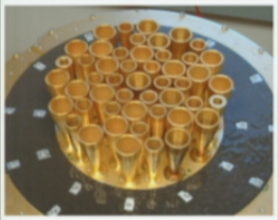
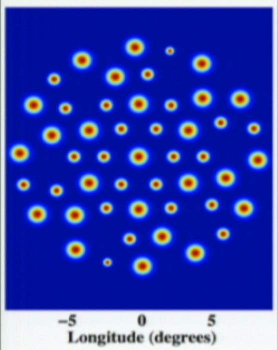
BICEP1

BICEP (2006–2008)





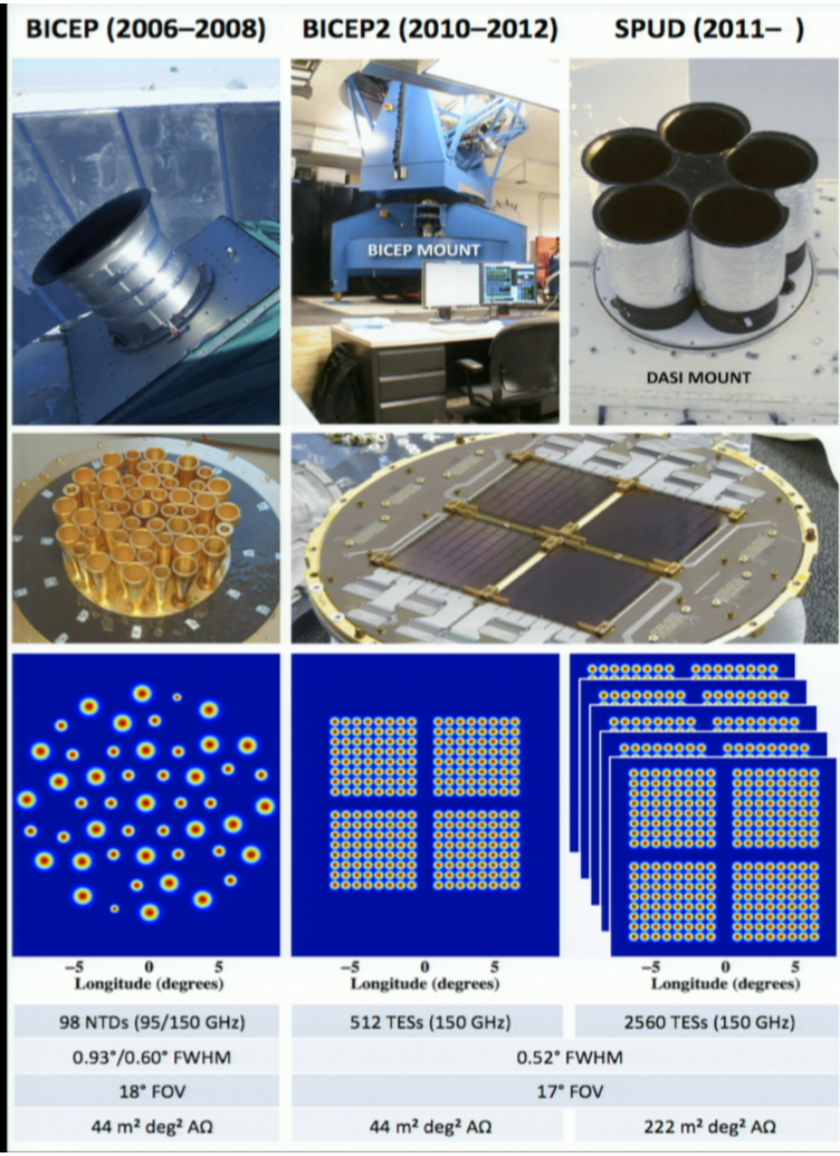


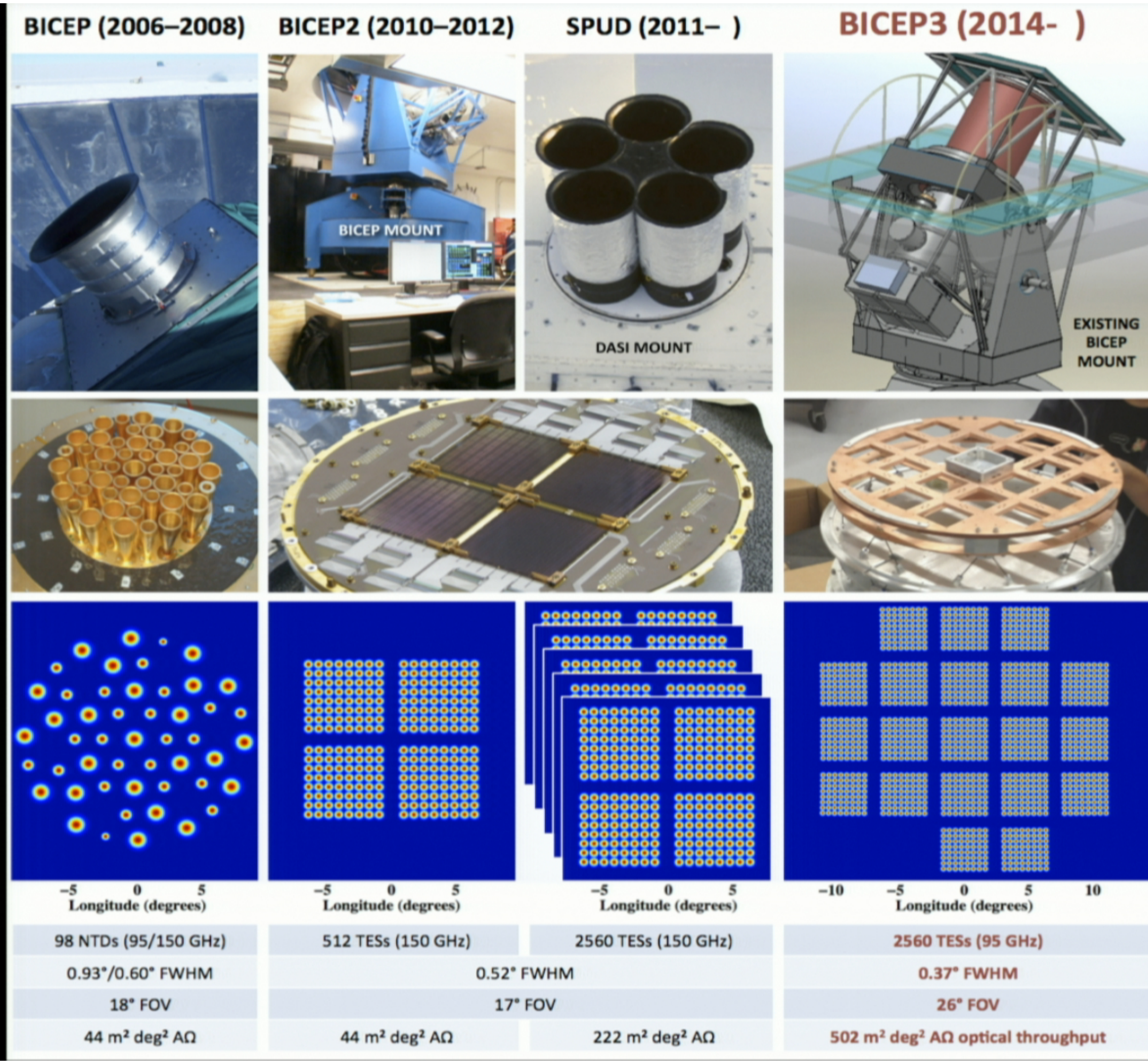
98 NTDs (95/150 GHz)

0.93°/0.60° FWHM

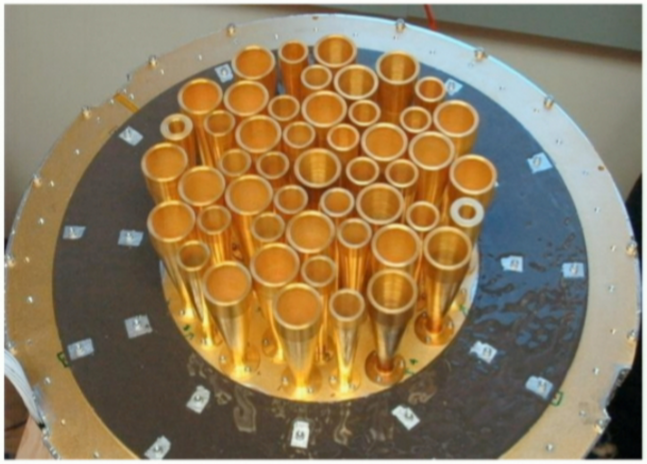
18° FOV

44 m² deg² AΩ


BICEP (2006–2008)
BICEP2 (2010–2012)
SPUD (2011–)
BICEP MOUNT
DASI MOUNT
−5 0 5
Longitude (degrees)
−5 0 5
Longitude (degrees)
−5 0 5
Longitude (degrees)
98 NTDs (95/150 GHz)
512 TESs (150 GHz)
2560 TESs (150 GHz)
0.93°/0.60° FWHM
0.52° FWHM
18° FOV
17° FOV
44 m² deg² AΩ
44 m² deg² AΩ
222 m² deg² AΩ


BICEP (2006–2008)
BICEP2 (2010–2012)
SPUD (2011–)
BICEP3 (2014-)
BICEP MOUNT
DASI MOUNT
EXISTING BICEP MOUNT
−5 0 5
Longitude (degrees)
−10 −5 0 5 10
98 NTDs (95/150 GHz)
512 TESs (150 GHz)
2560 TESs (150 GHz)
2560 TESs (95 GHz)
0.93°/0.60° FWHM
0.52° FWHM
0.37° FWHM
18° FOV
17° FOV
26° FOV
44 m² deg² AΩ
44 m² deg² AΩ
222 m² deg² AΩ
502 m² deg² AΩ optical throughput

BICEP2: 10-fold increase in mapping speed:



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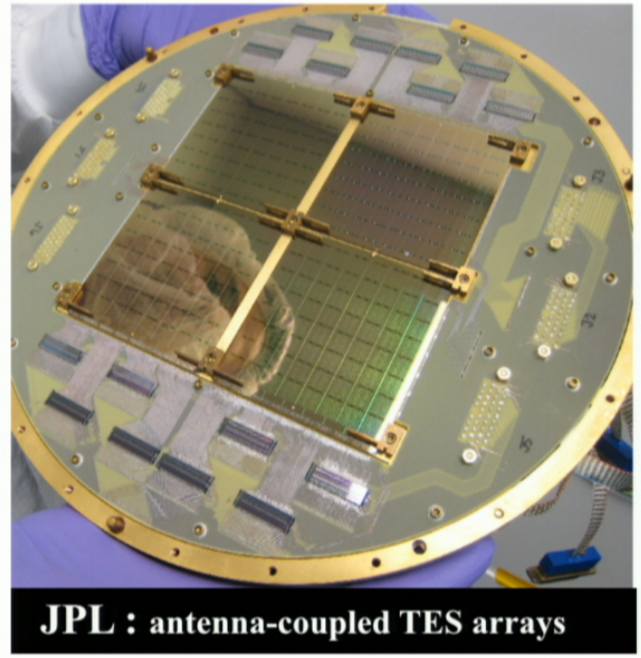
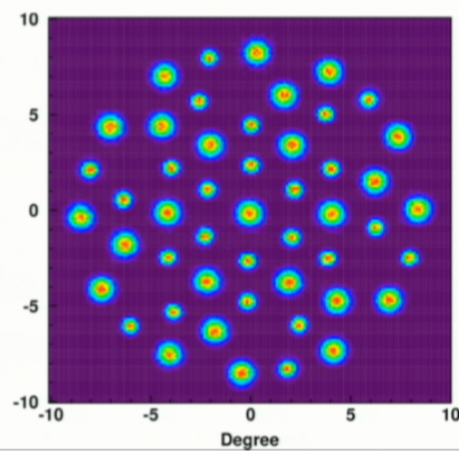


BICEP1

48
150 GHz
detectors



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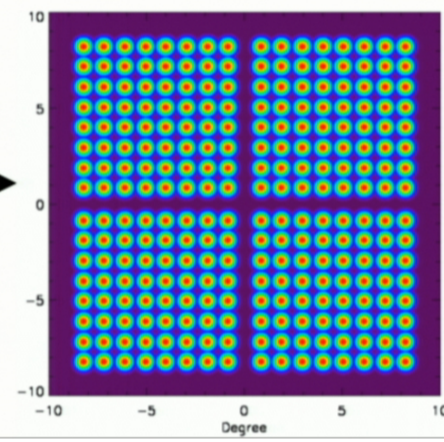
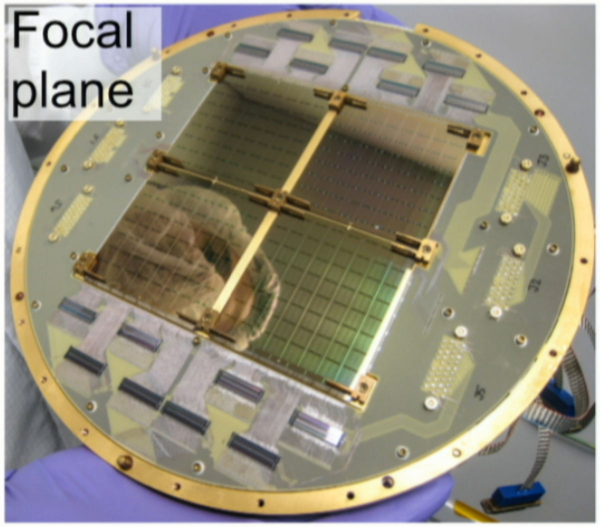


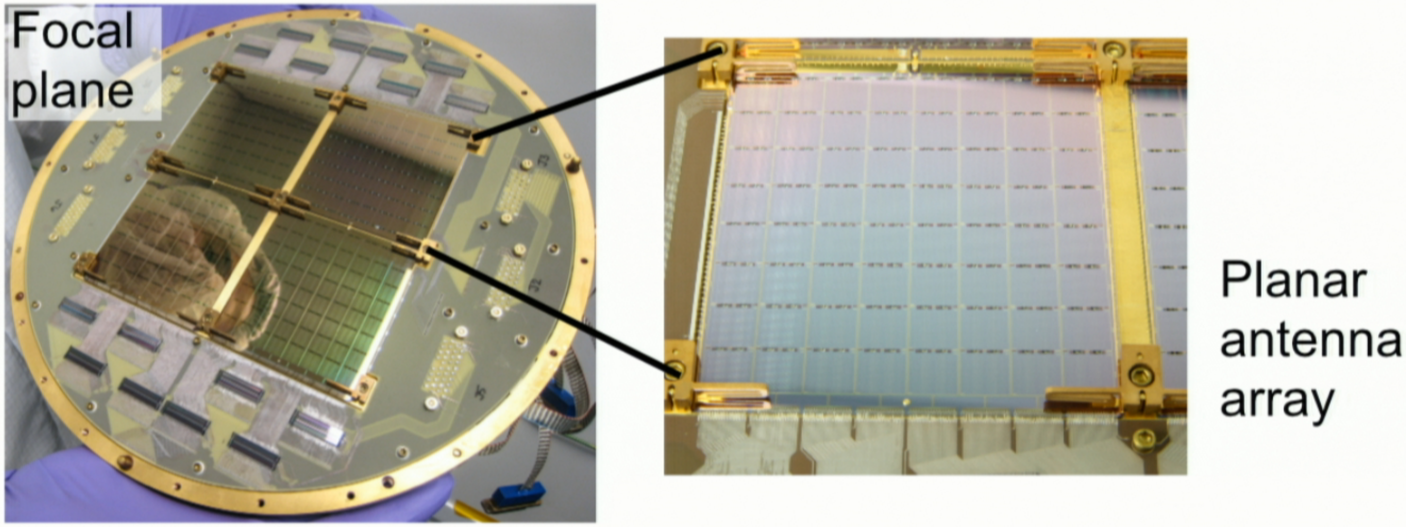
BICEP2

512
150 GHz
detectors

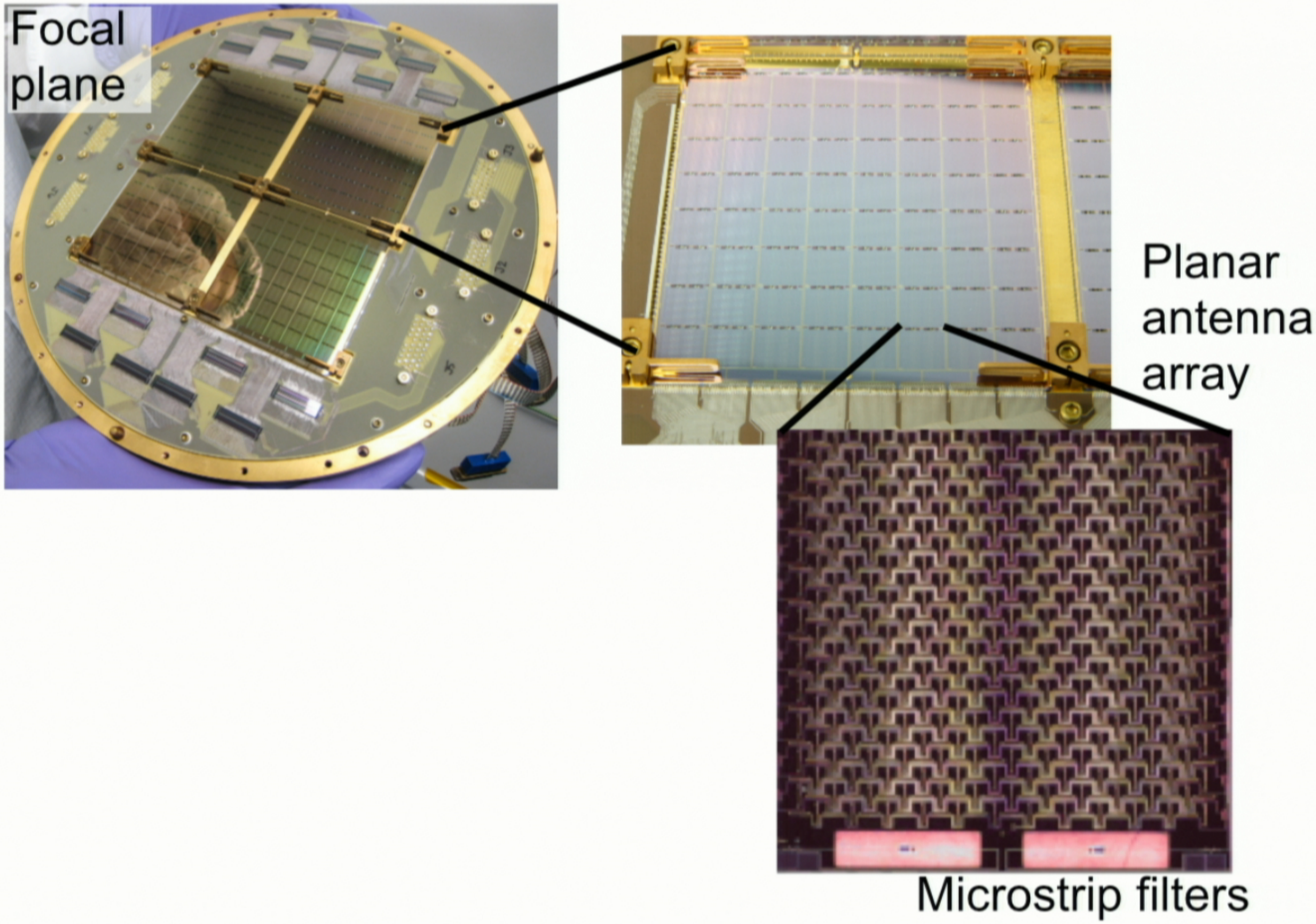
Mass-produced Superconducting Detectors



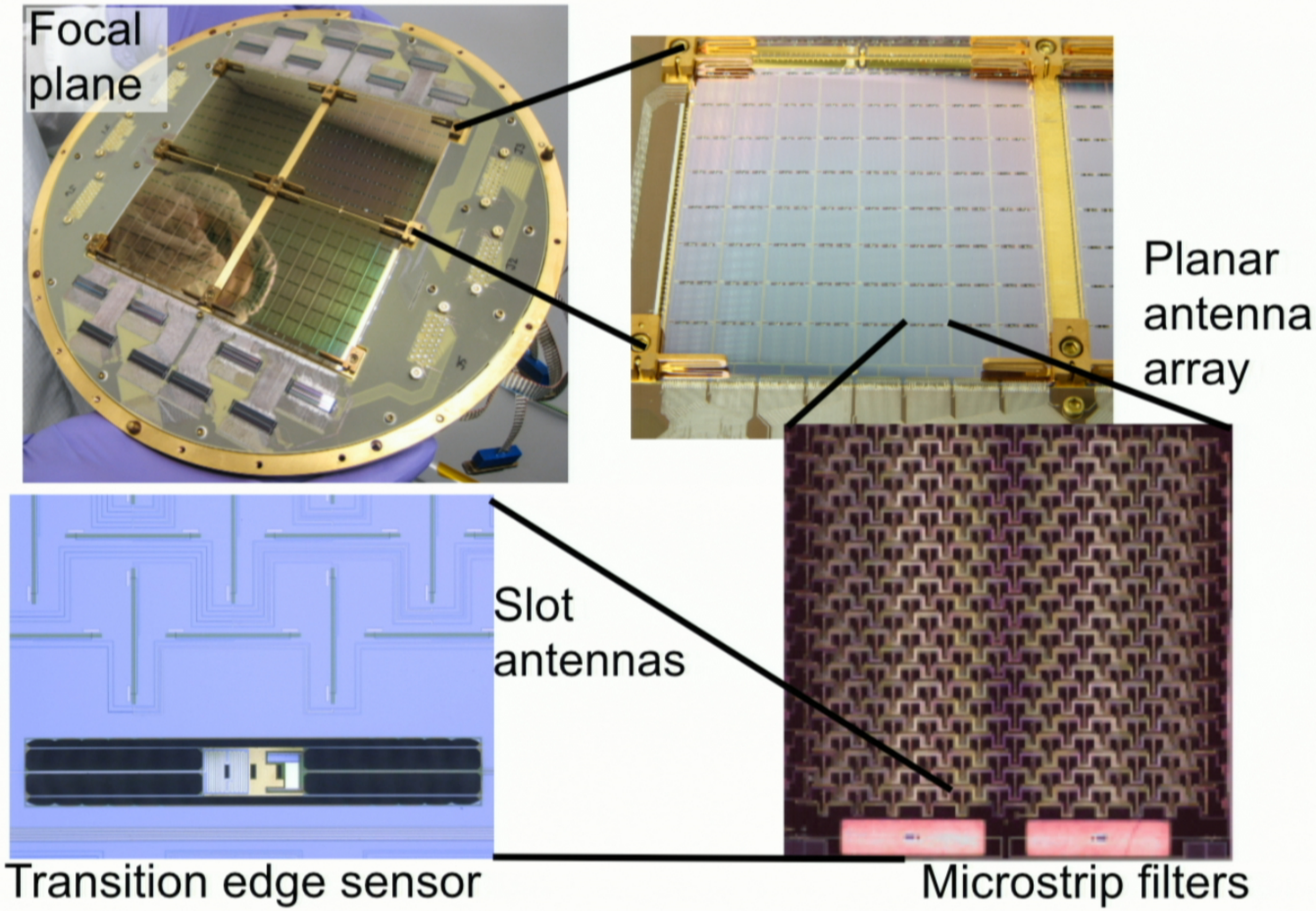
Mass-produced Superconducting Detectors



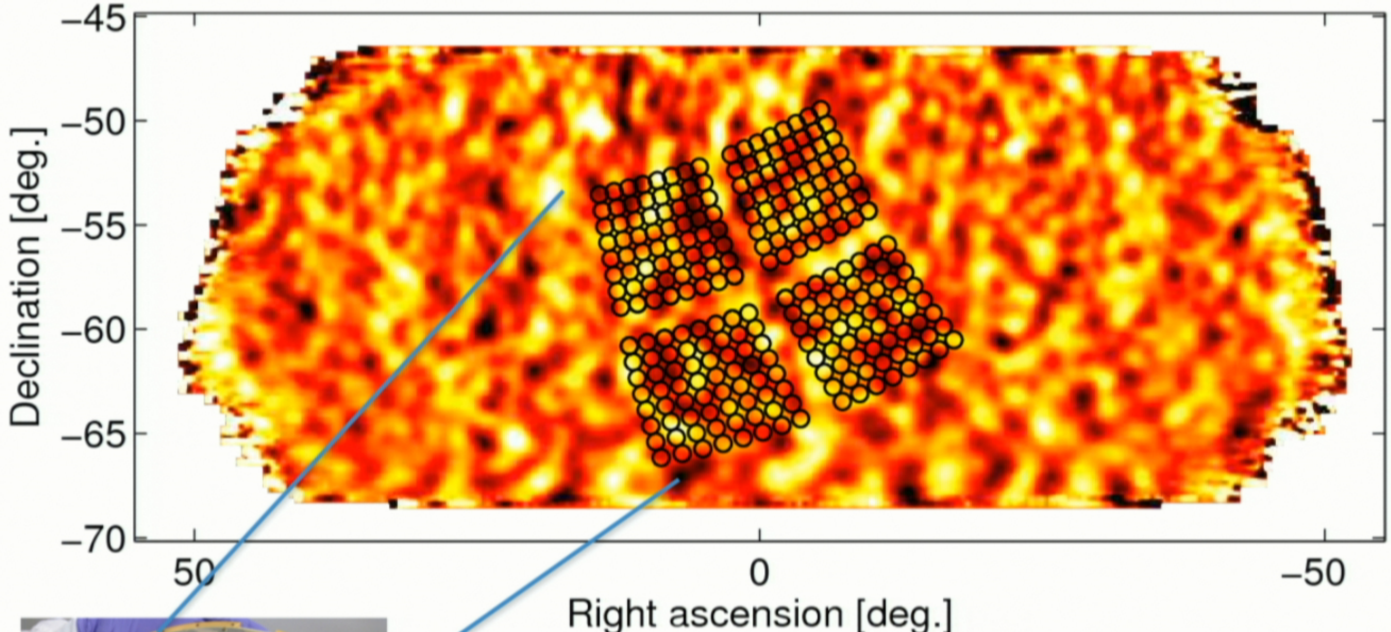
Mass-produced Superconducting Detectors

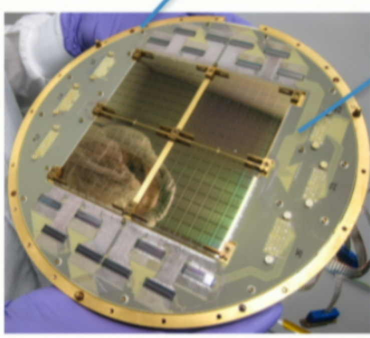


Mass-produced Superconducting Detectors



BICEP2 on the Sky





Projection of the BICEP2 focal plane on the sky!

(Background is the CMB temperature map as measured with BICEP2)

Christopher Sheehy for the Bicep2 Collaboration

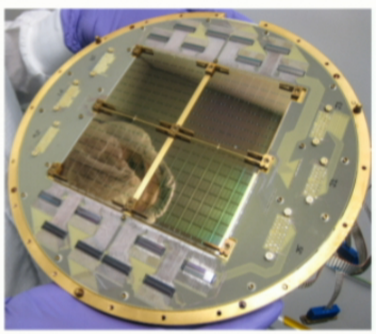
BICEP2 on the sky

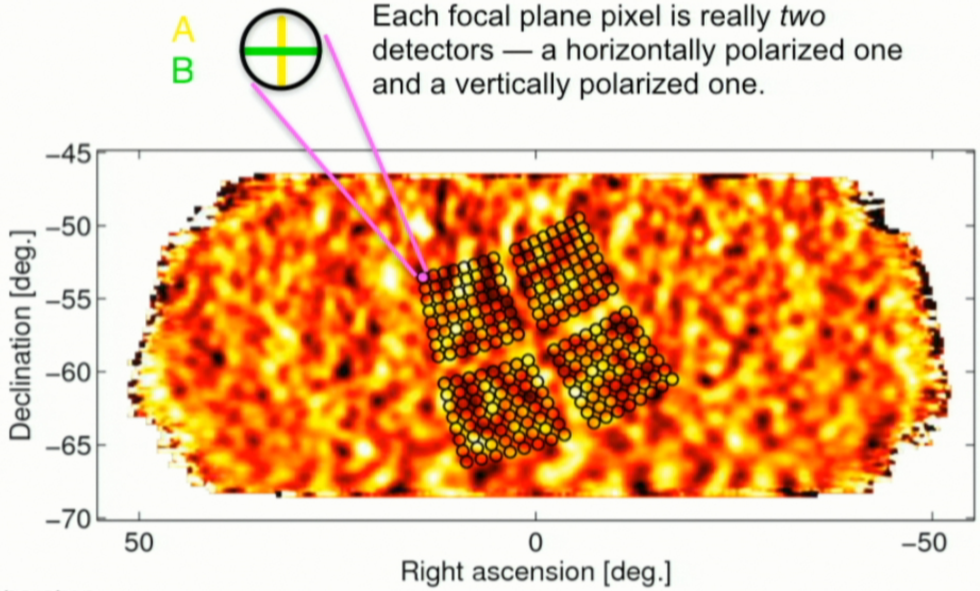
Scan the telescope back and forth on the sky.

Measure CMB T by summing the signal from orthogonally polarized detector pairs.

Measure CMB polarization by differencing the signal.

Each focal plane pixel is really *two* detectors — a horizontally polarized one and a vertically polarized one.





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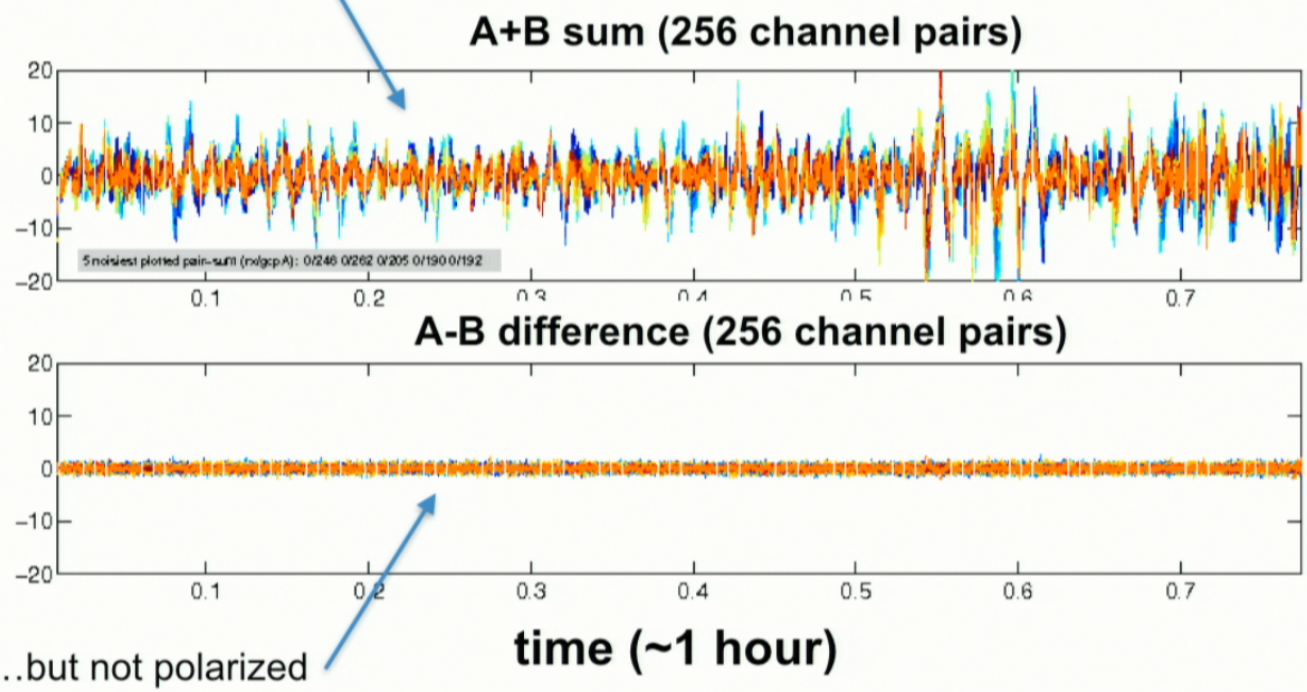
BICEP2 on the sky

Atmosphere is bright!



…but not polarized

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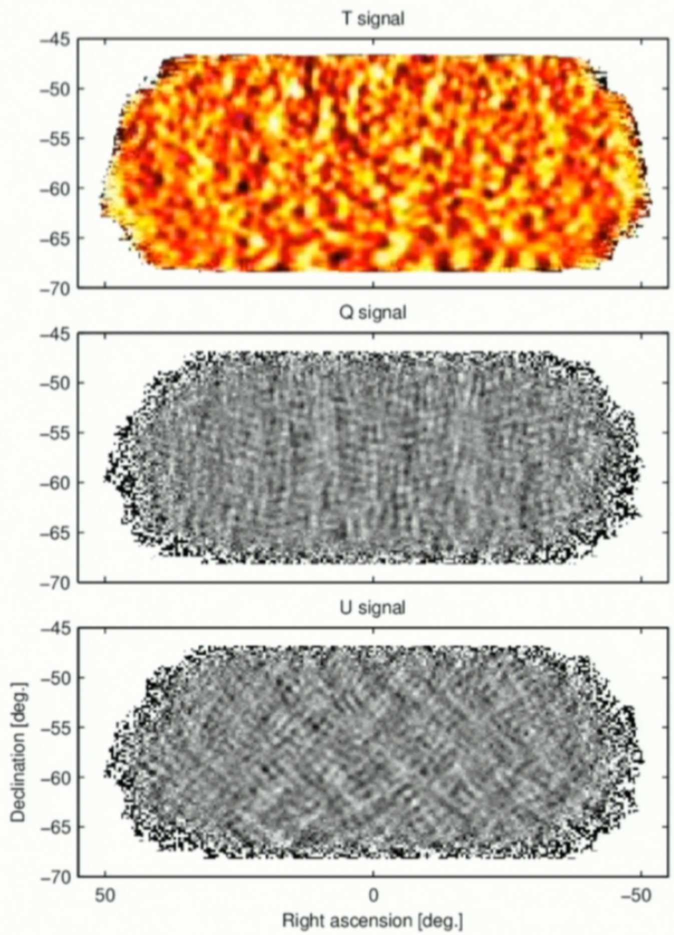
BICEP2 T and Stokes Q/U Maps



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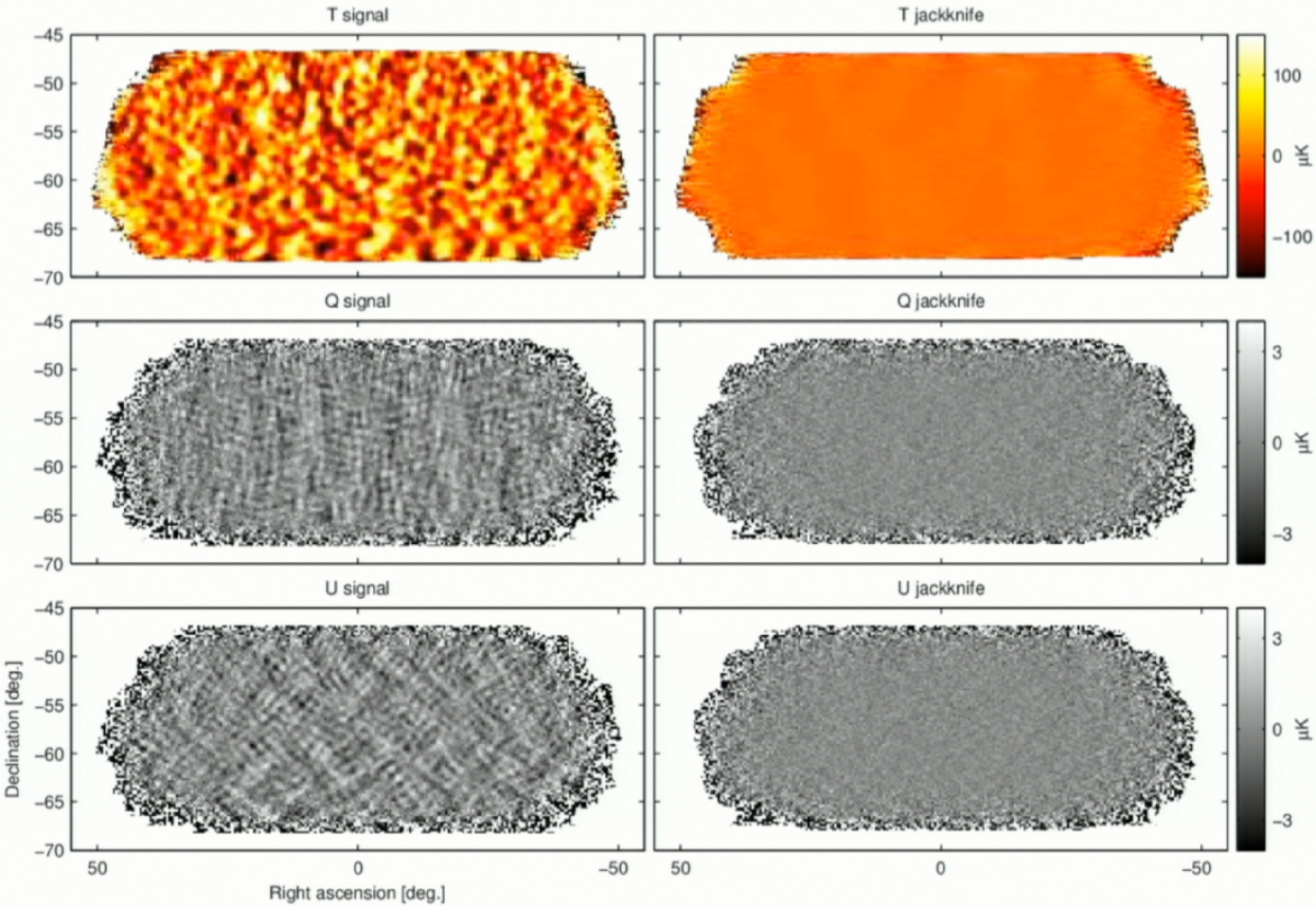
BICEP2 T and Stokes Q/U Maps



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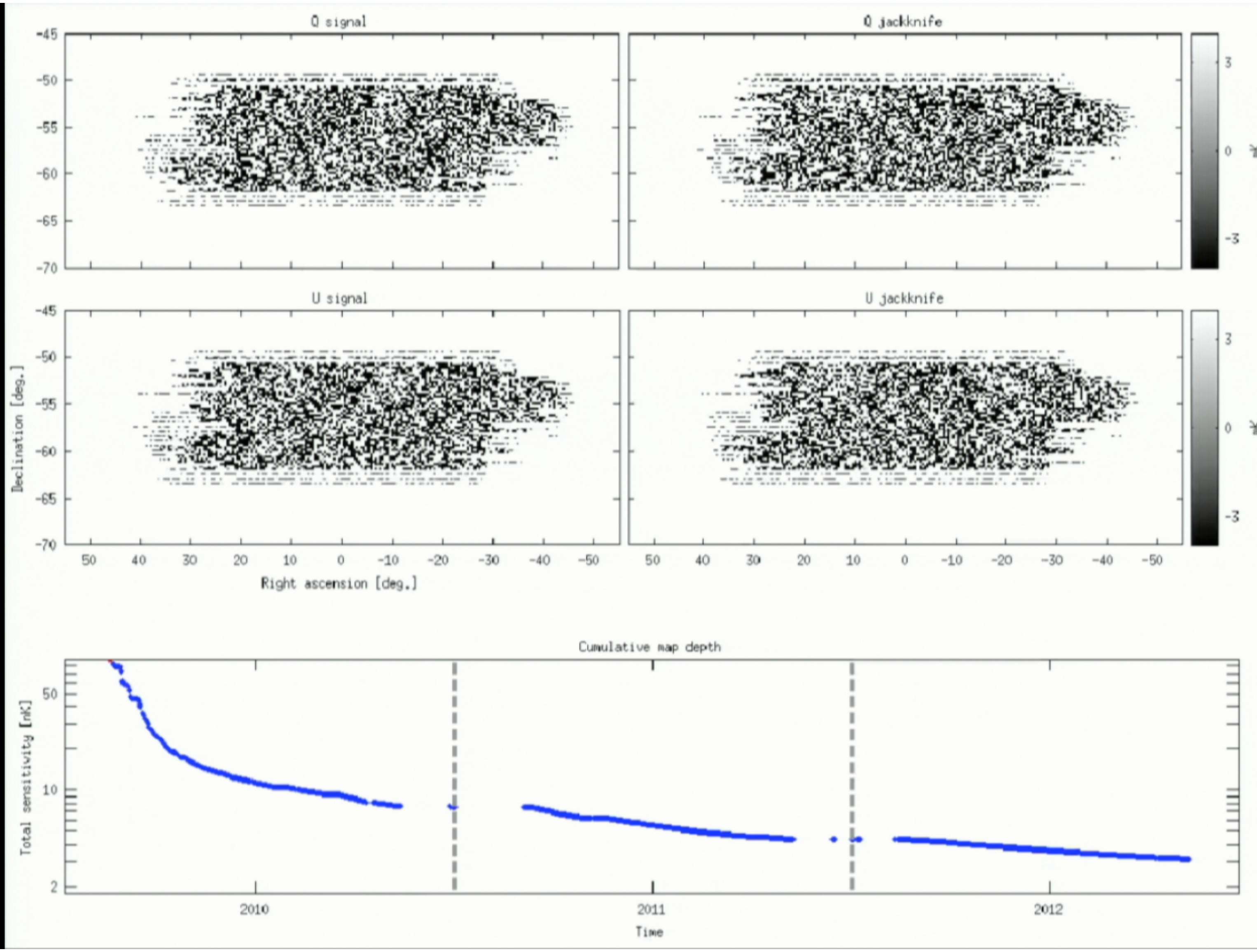
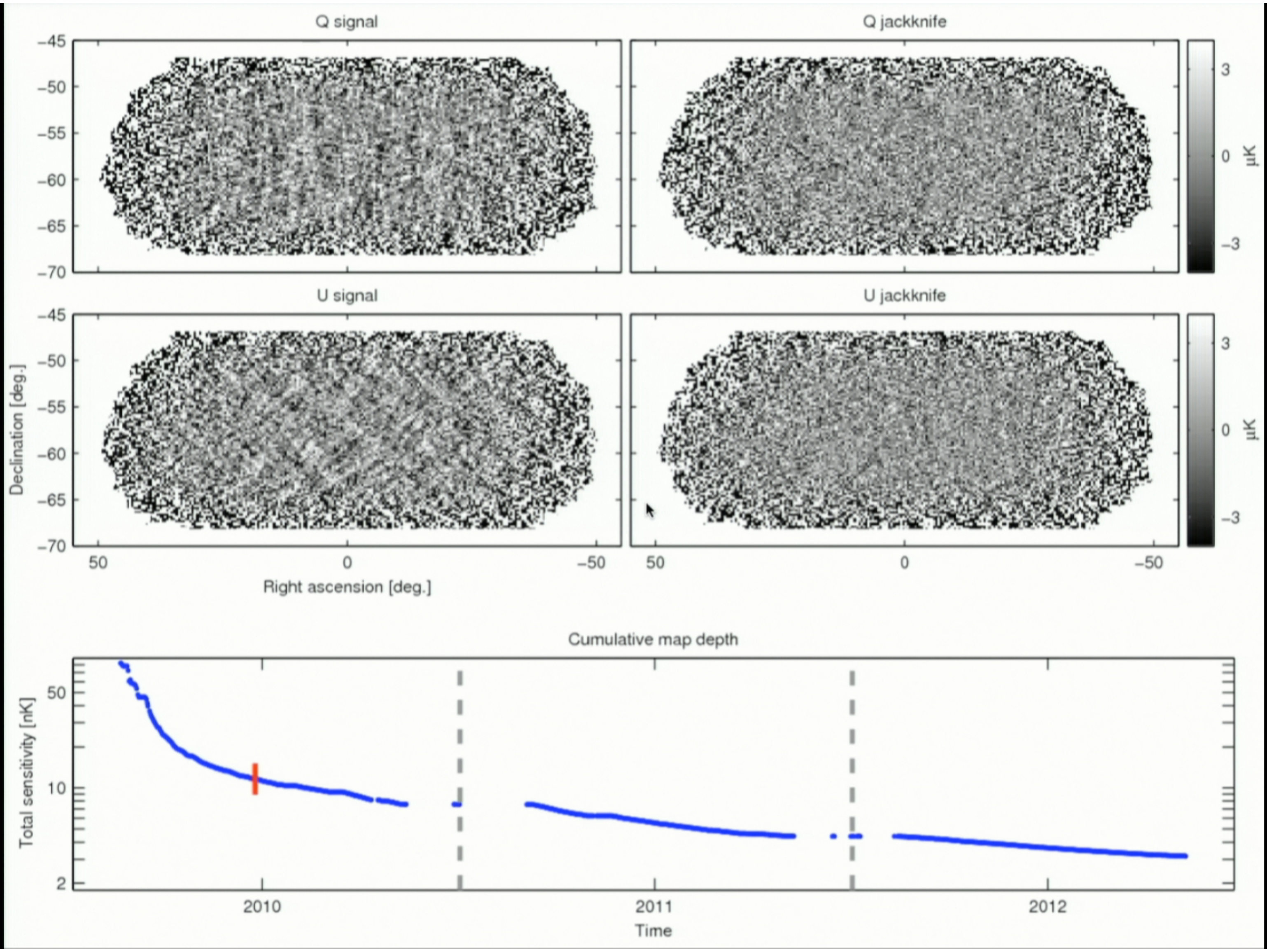
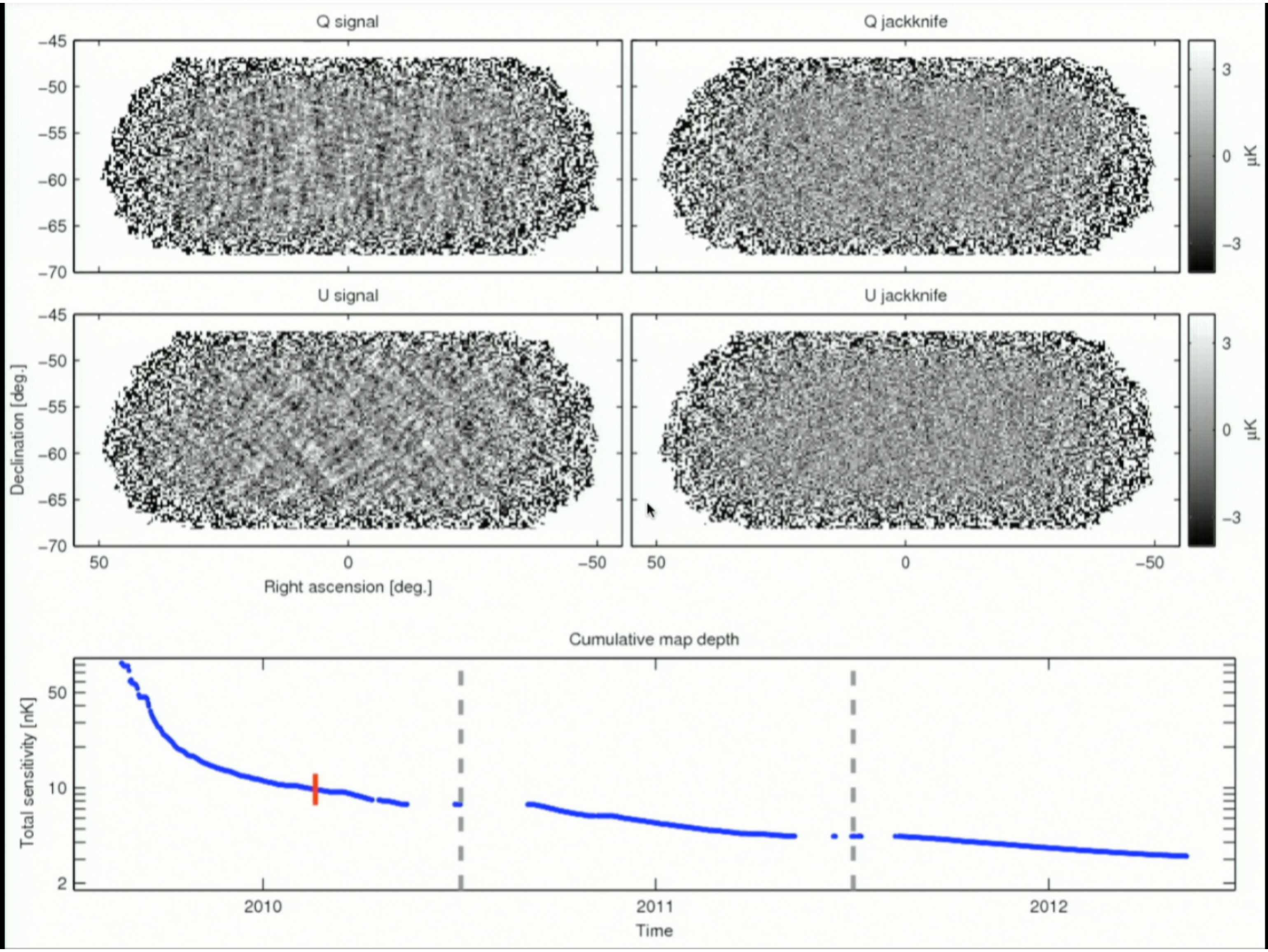
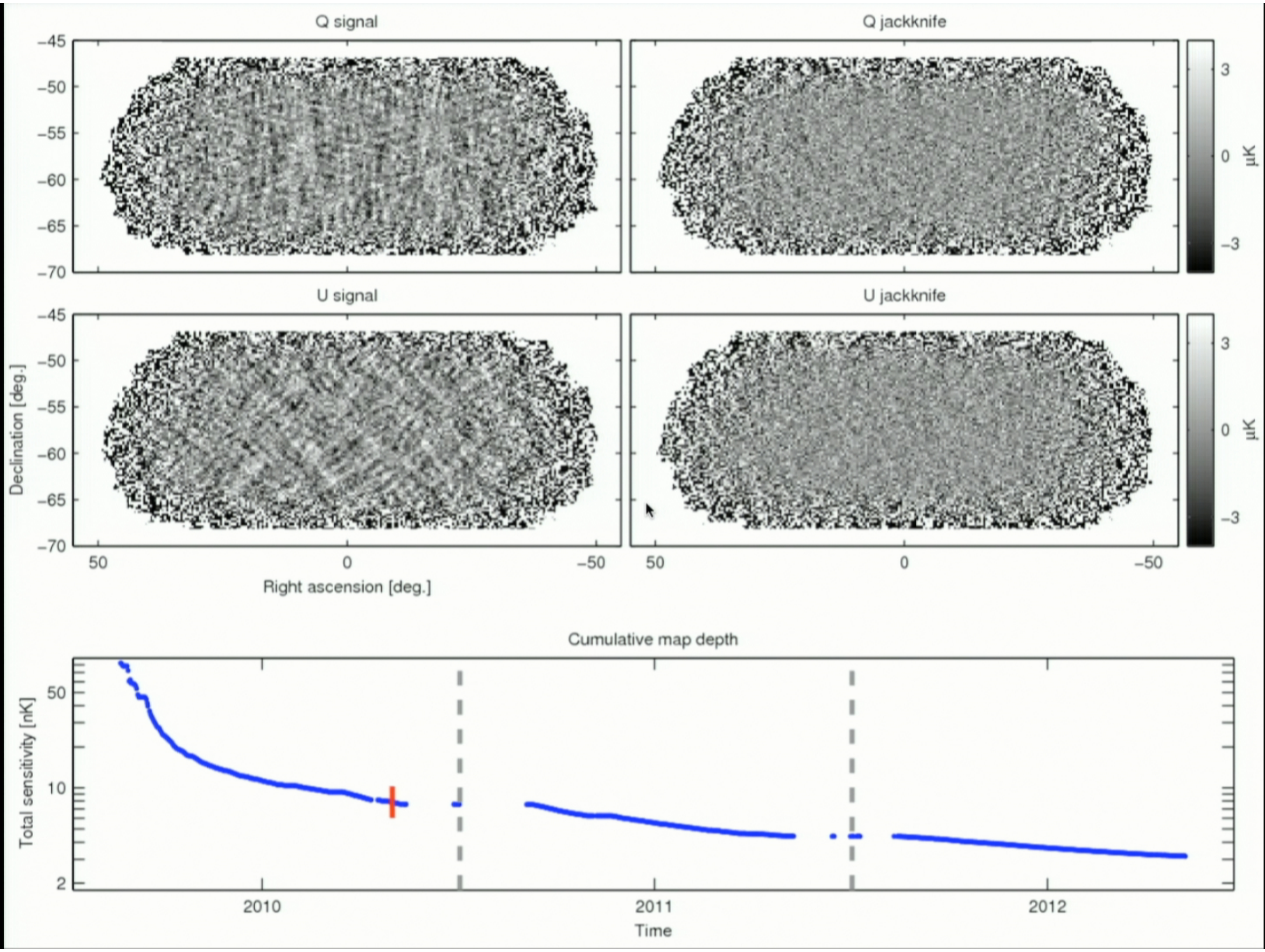


Q signal
Q jackknife
U signal
U jackknife
Declination [deg.]
Right ascension [deg.]
Cumulative map depth
Total sensitivity [nK]
Time



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


Q signal
Q jackknife
U signal
U jackknife
μK
3
0
−3
−45
−50
−55
−60
−65
−70
Declination [deg.]
50
0
−50
Right ascension [deg.]
Cumulative map depth
Total sensitivity [nK]
50
10
2
2010
2011
2012
Time



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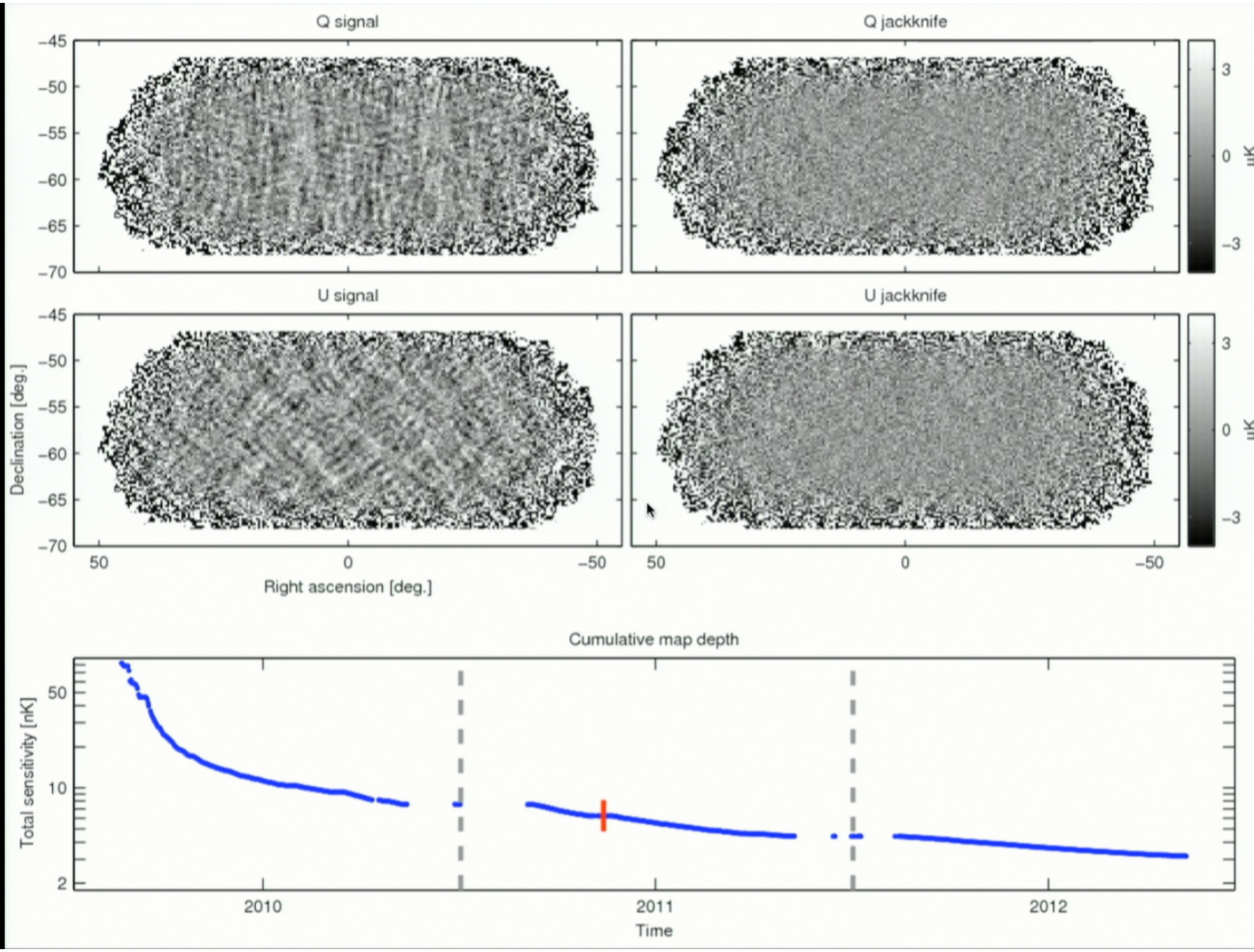
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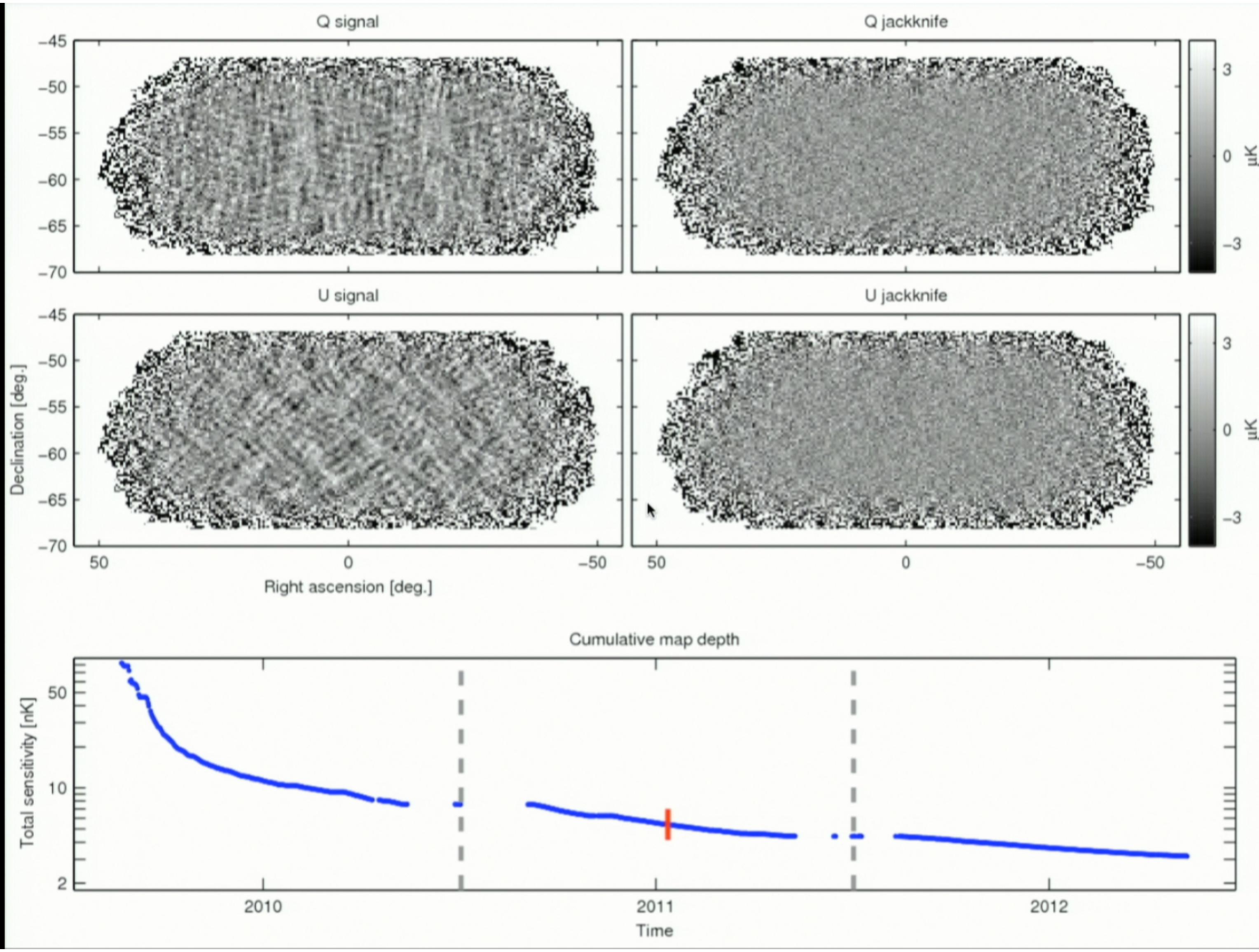
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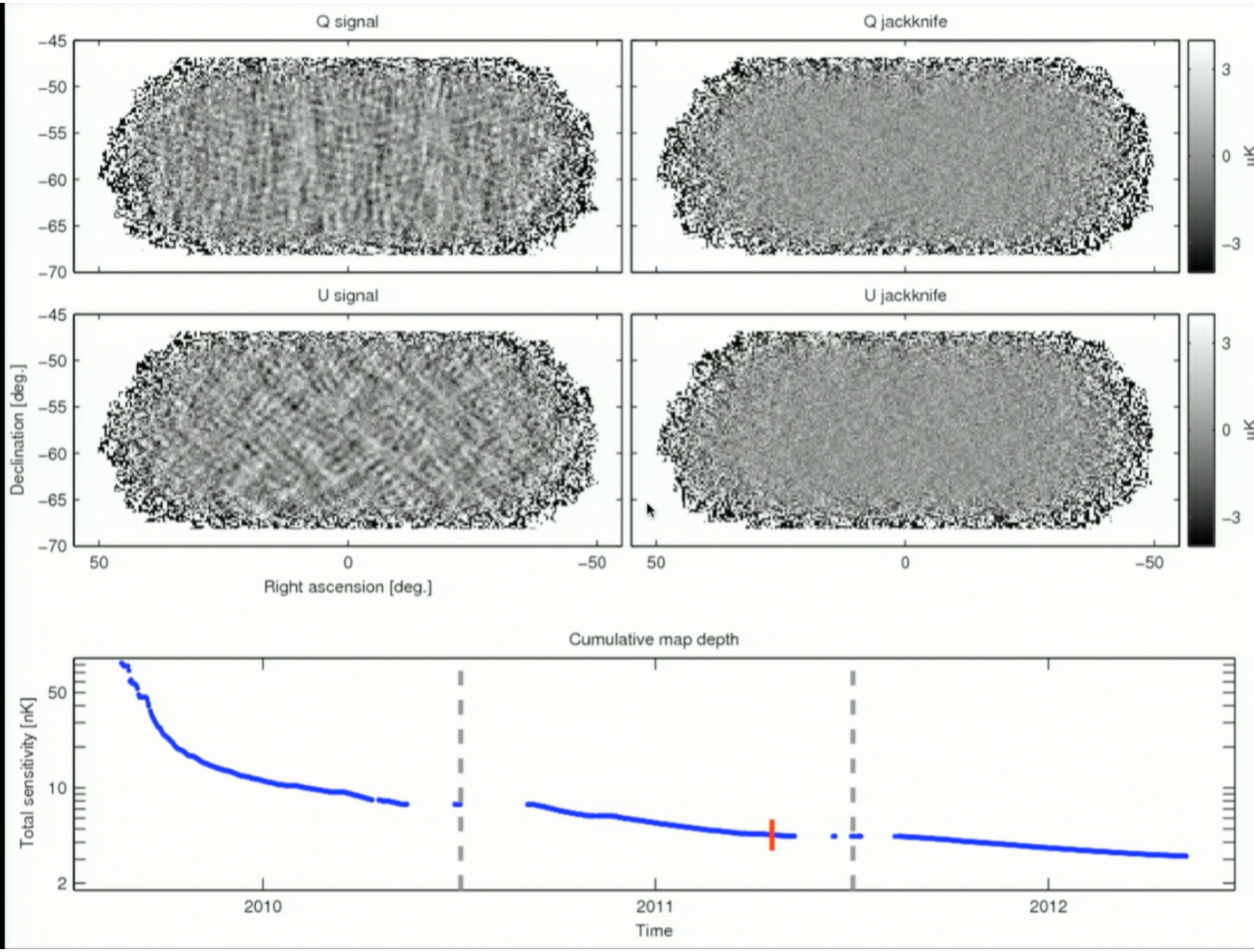
Q signal
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U signal
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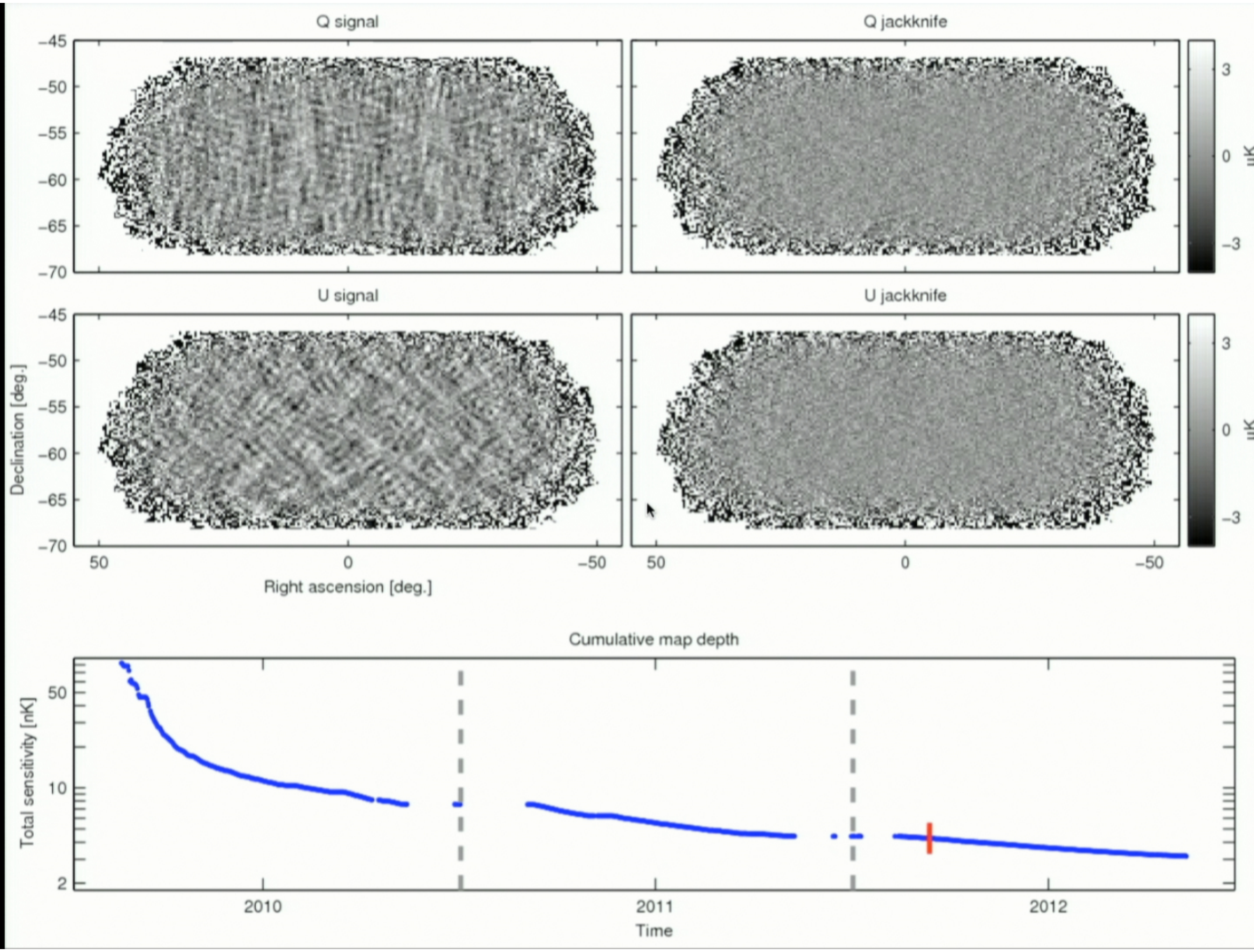
Declination [deg.]
Right ascension [deg.]
μK
Cumulative map depth
Total sensitivity [nK]
Time
2010
2011
2012



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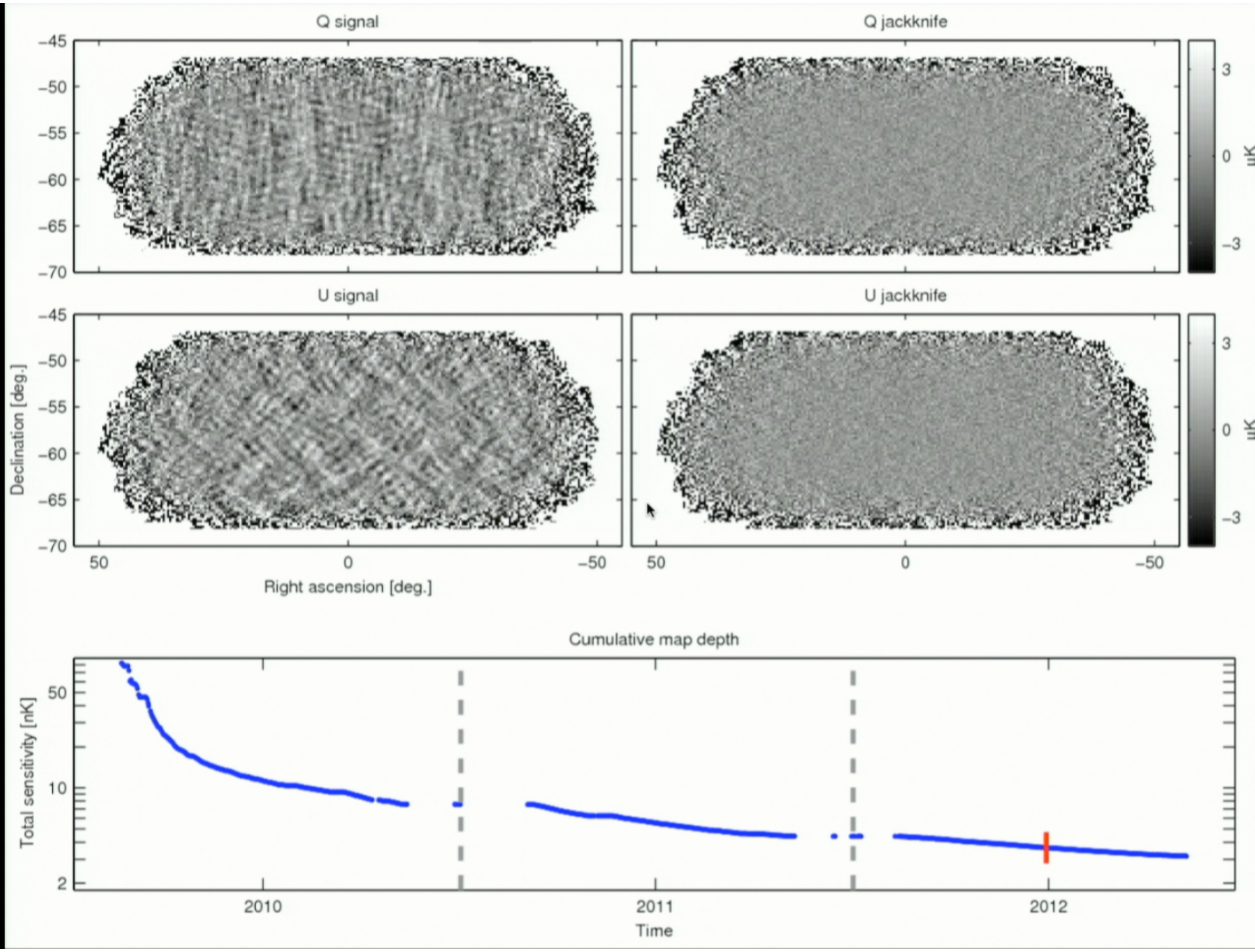
Q jackknife
U signal
U jackknife
Declination [deg.]
Right ascension [deg.]
μK
Cumulative map depth
Total sensitivity [nK]
Time
2010
2011
2012



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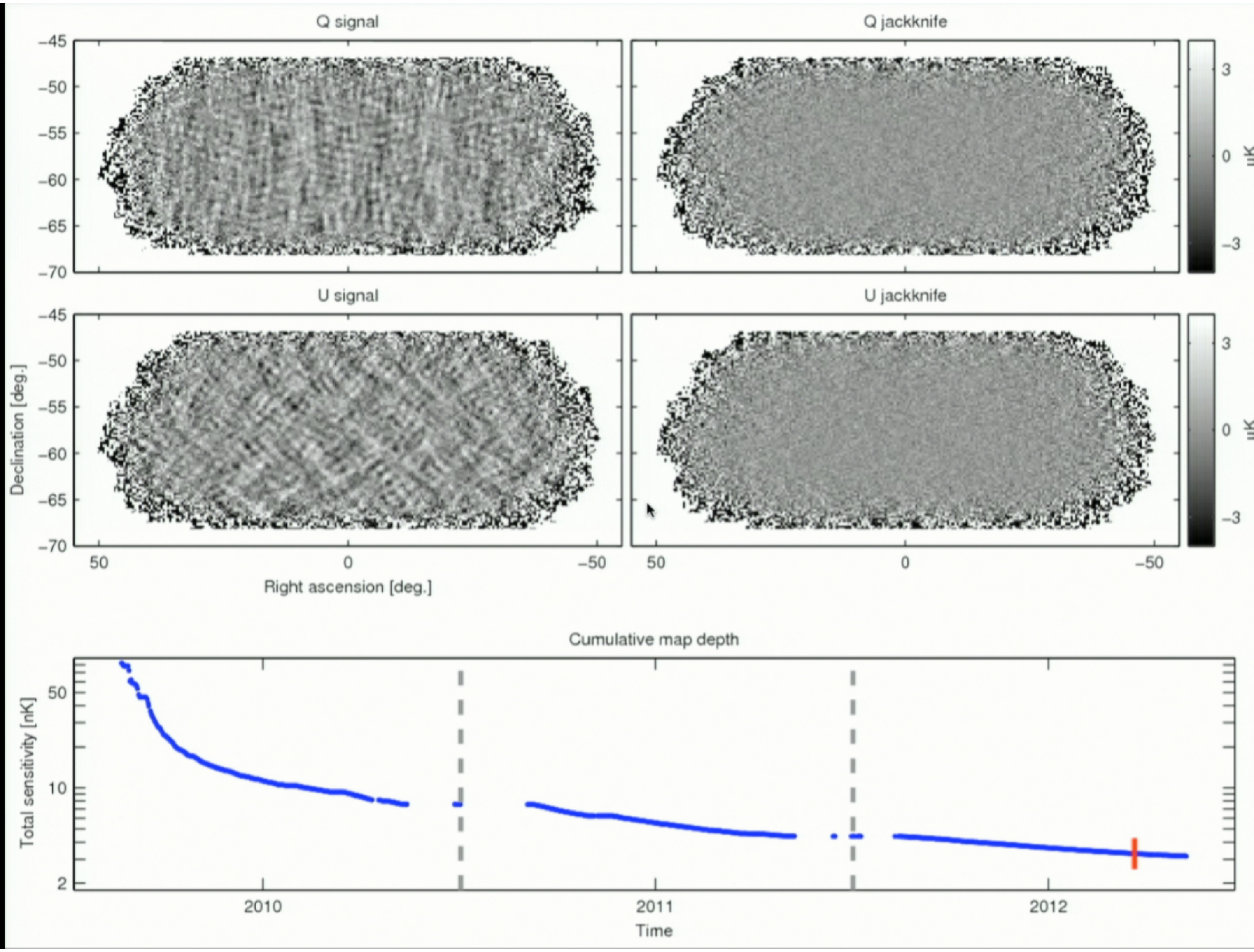
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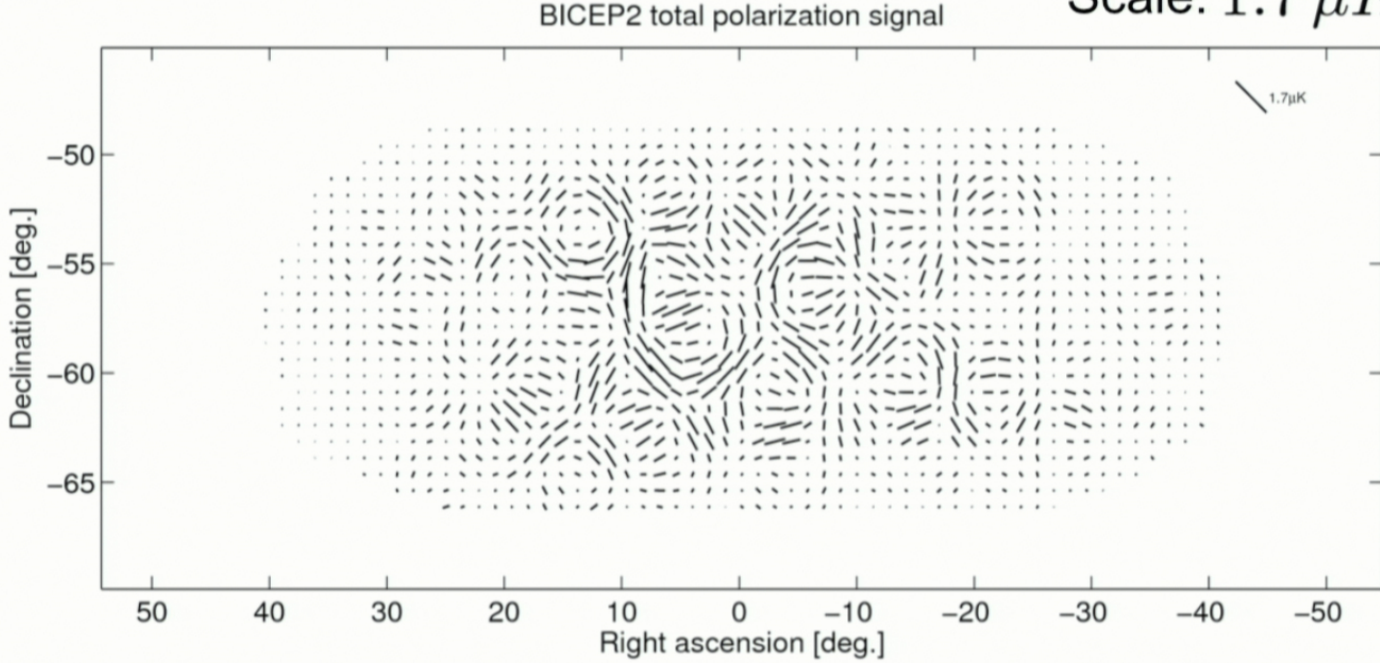
Q jackknife
U signal
U jackknife
Declination [deg.]
Right ascension [deg.]
μK
−45
−50
−55
−60
−65
−70
50
0
−50
3
0
−3
Cumulative map depth
Total sensitivity [nK]
Time
50
10
2
2010
2011
2012

Total Polarization

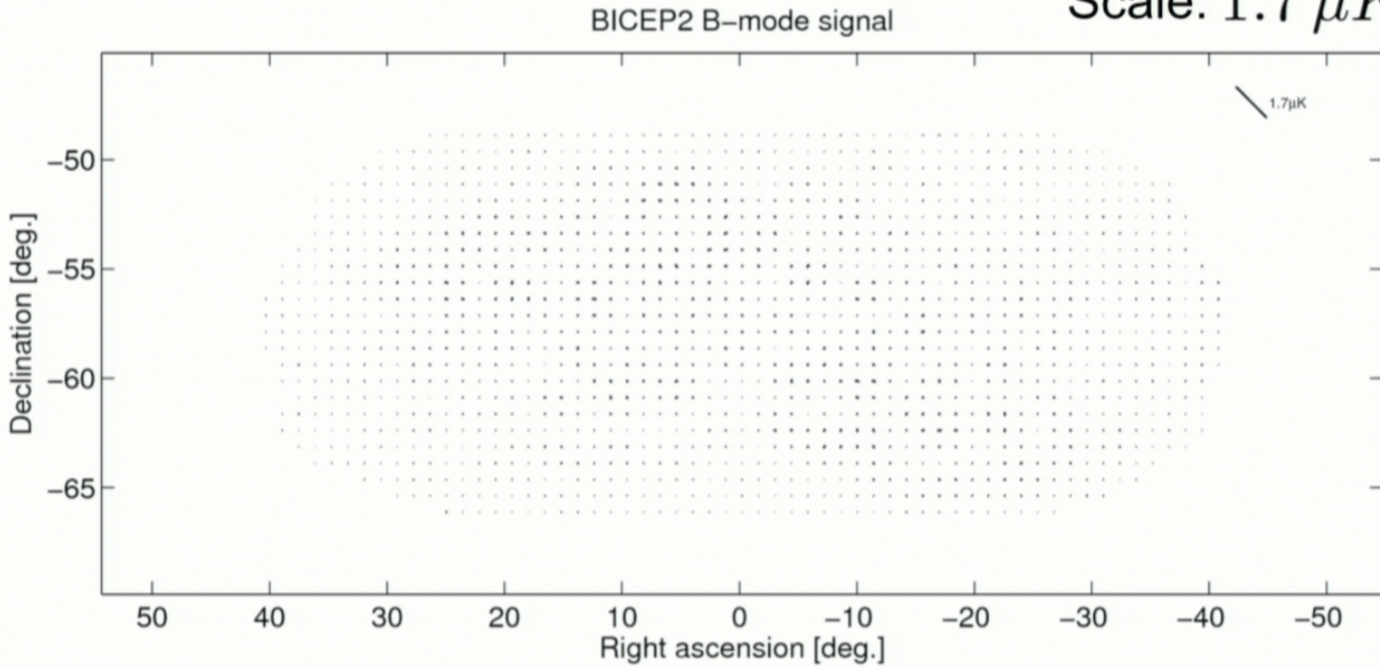
Scale: $1.7\,\mu K$



Christopher Sheehy for the Bicep2 Collaboration

B-mode Contribution

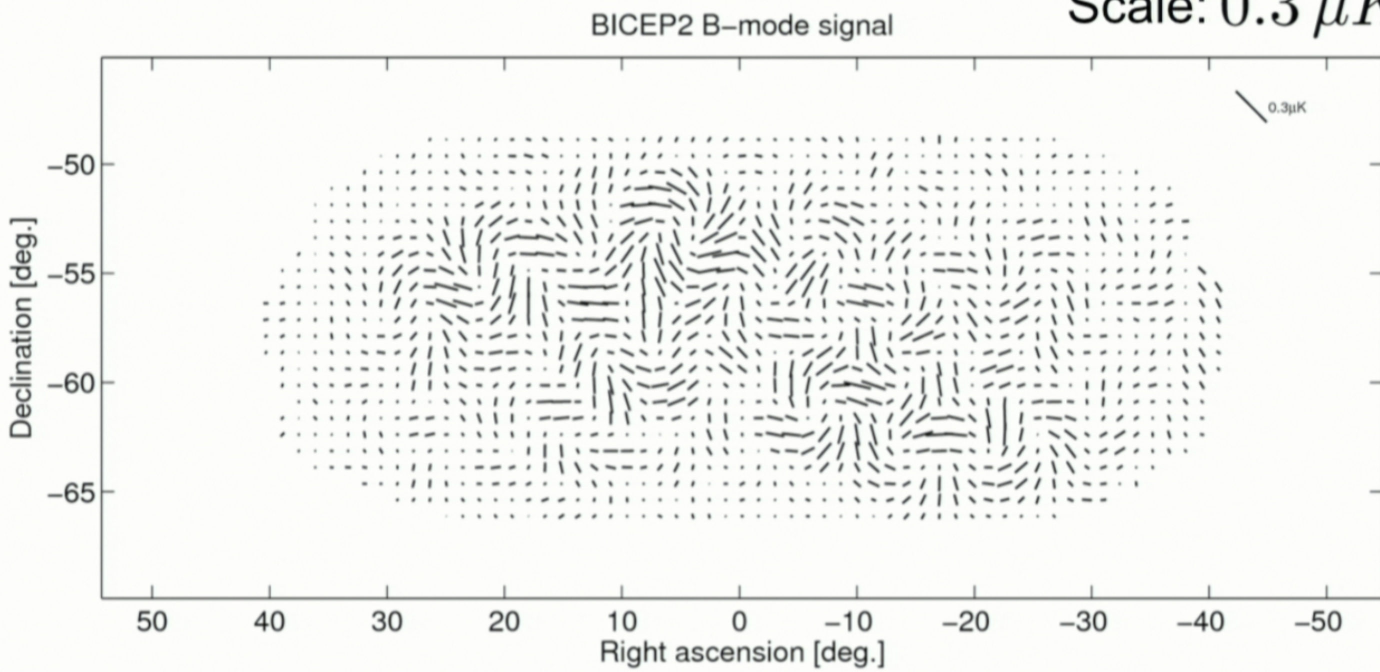
Scale: $1.7\,\mu K$



Christopher Sheehy for the Bicep2 Collaboration

B-mode Contribution

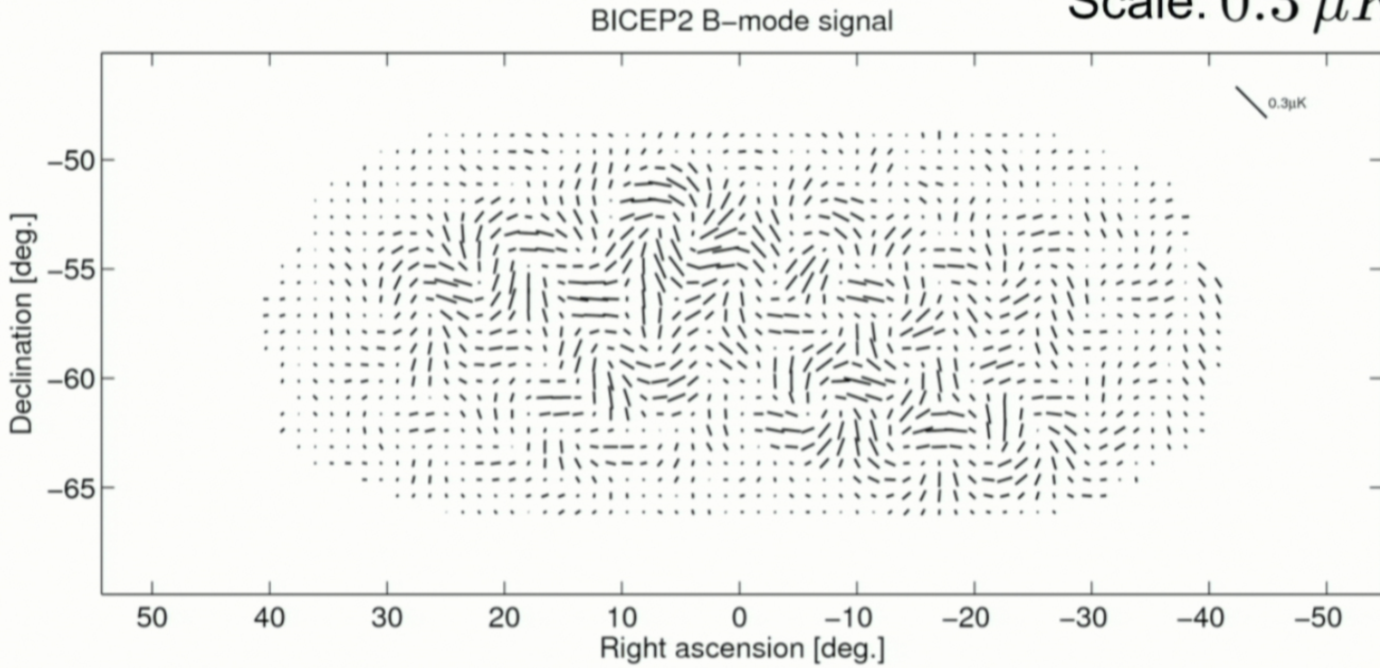
Scale: $0.3\,\mu K$



Christopher Sheehy for the Bicep2 Collaboration

B-mode Contribution

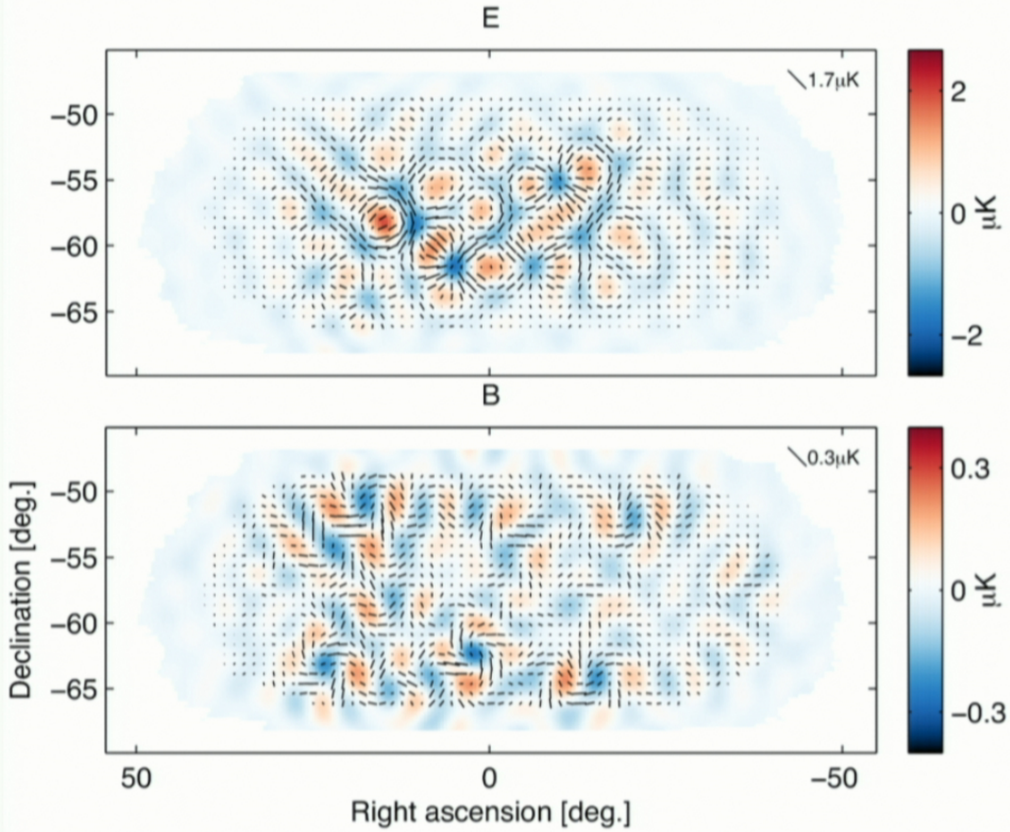
Scale: $0.3\,\mu K$



Christopher Sheehy for the Bicep2 Collaboration

Map-based E - B purification:

Simulation : LCDM (w/o lensing), no noise
filtered to 20< l <150



E-mode signal is converted into B-mode power through sky cut and filtering operations

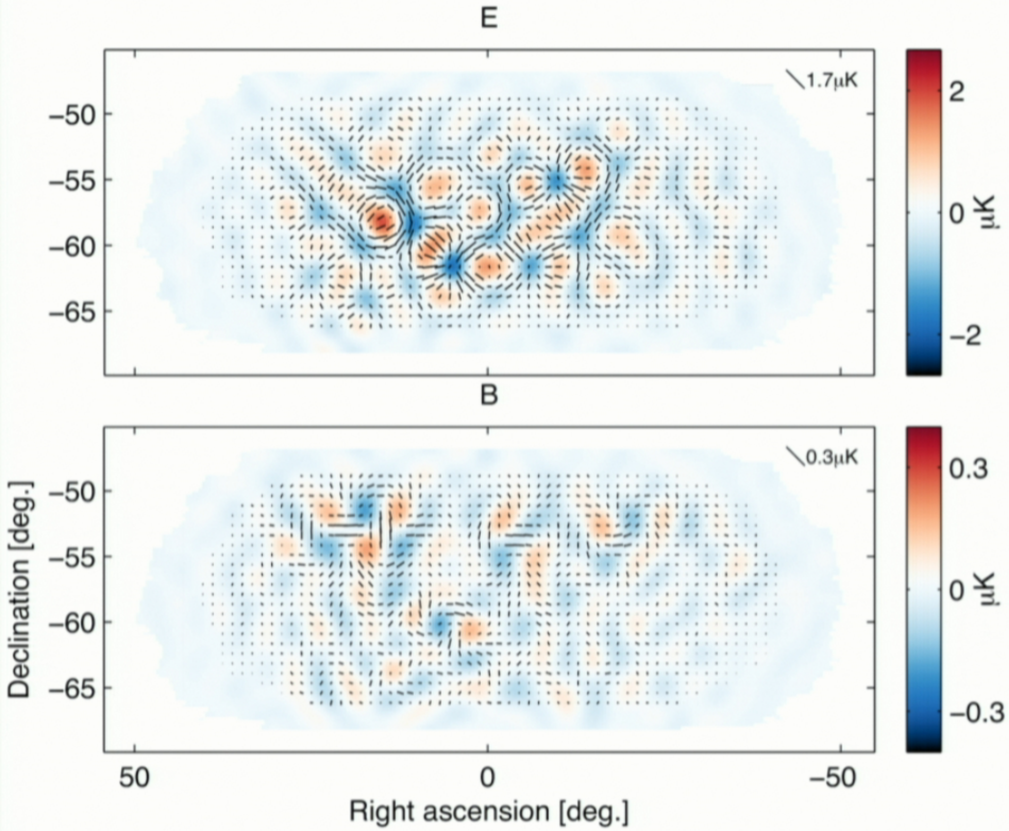
E to B leakage **without** purification is unacceptably high

Christopher Sheehy for the Bicep2 Collaboration

Map-based E - B purification:

Simulation : LCDM (w/o lensing), no noise

filtered to 20< l <150



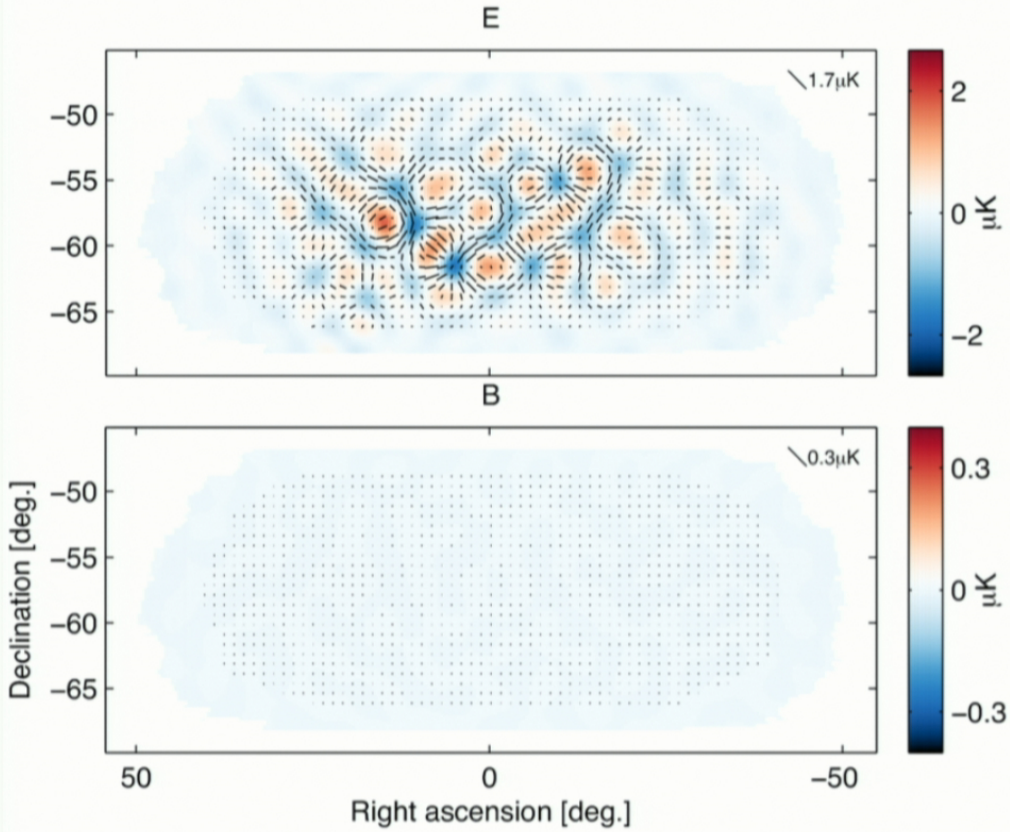
E-mode signal is converted into B-mode power through sky cut and filtering operations

E to B leakage **<u>with Smith et al 2006</u>** method works well, but contamination is still high due to filtering operations

Christopher Sheehy for the Bicep2 Collaboration

Map-based E - B purification:

Simulation : LCDM (w/o lensing), no noise
filtered to 20< **l** <150

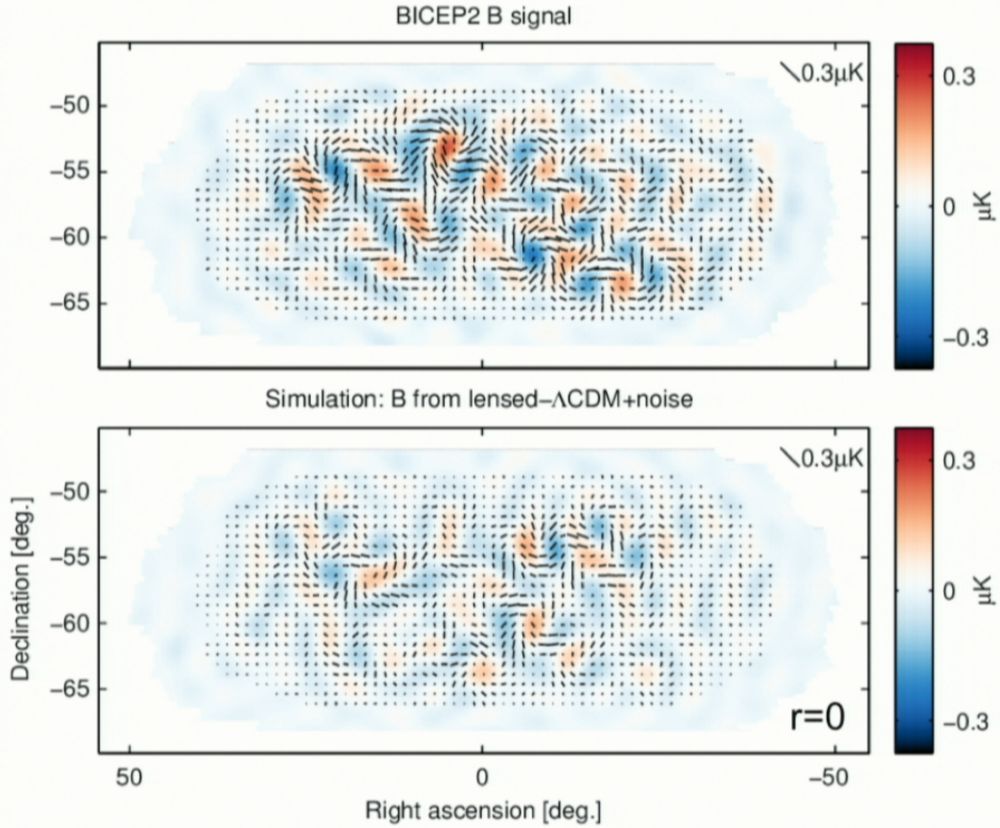


Pure E is very similar to the raw E, since B to E leakage is comparatively small

E to B leakage **with** purification is orders of magnitude smaller

Christopher Sheehy for the Bicep2 Collaboration

B-mode Map vs. Simulation



Analysis calibrated by 500 lensed-ΛCDM+noise simulations.

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

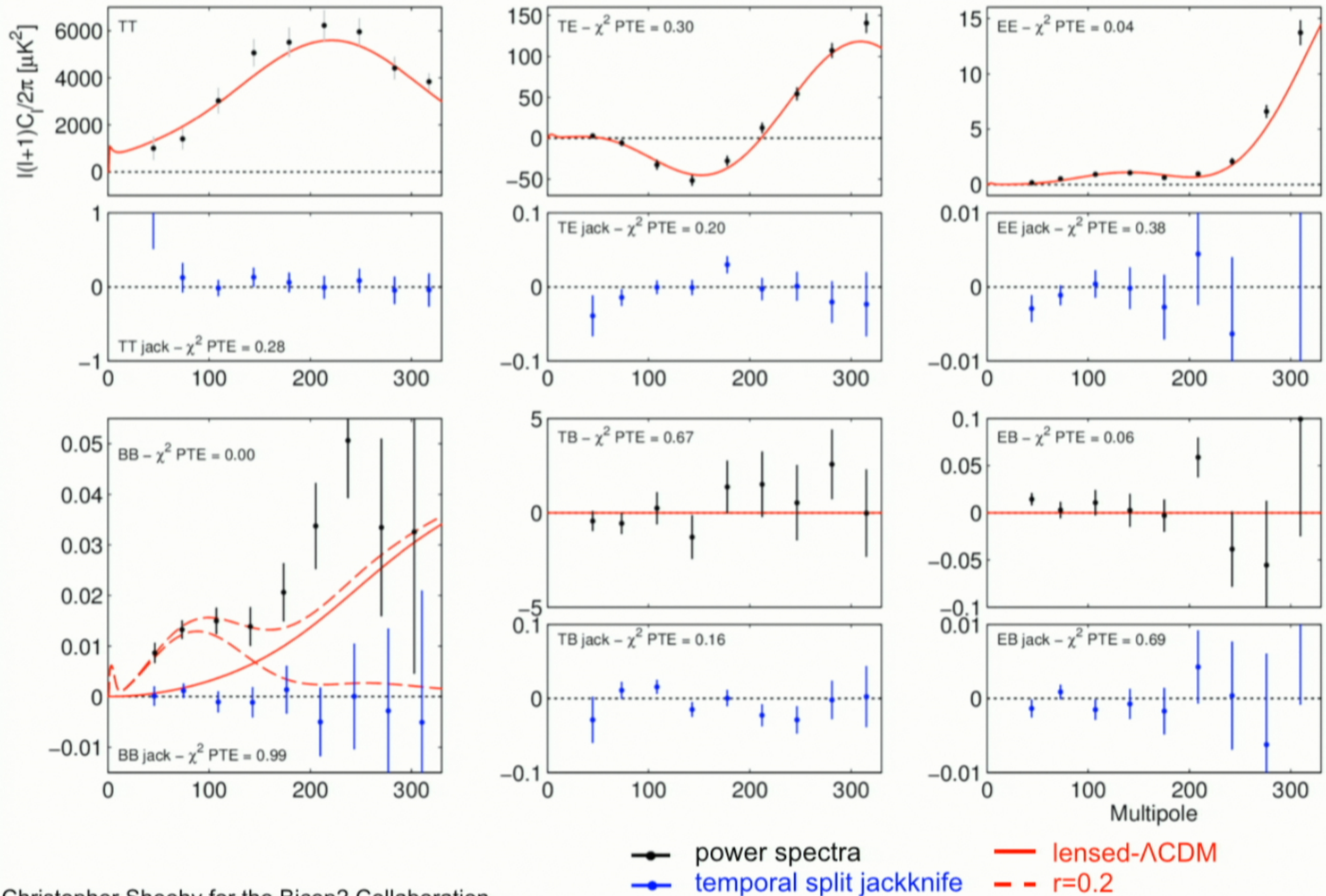
Allows us to perform arbitrary filtering operations.

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

From the simulations we derive the uncertainties on our measurements.

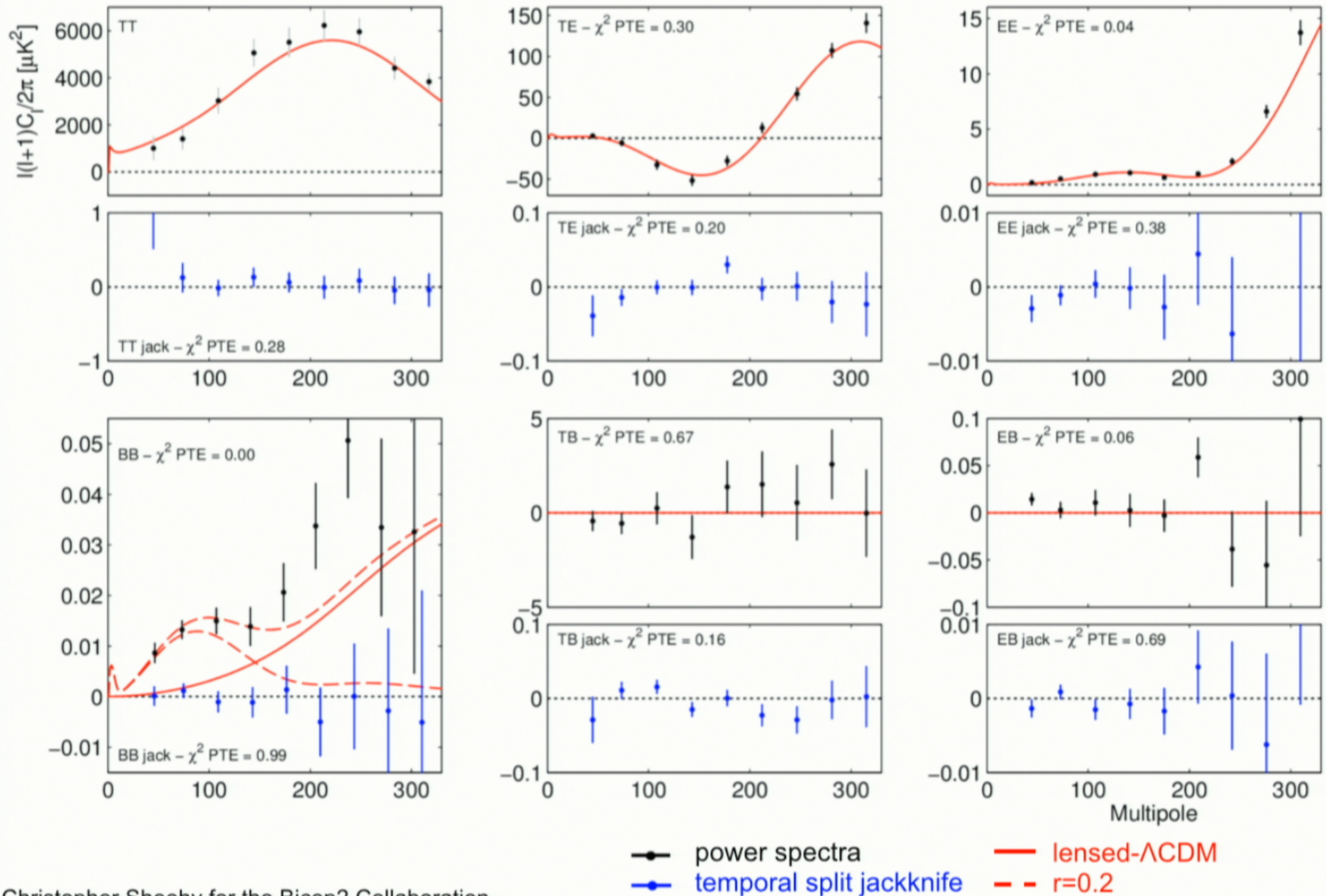
Christopher Sheehy for the Bicep2 Collaboration

Temperature and Polarization Spectra



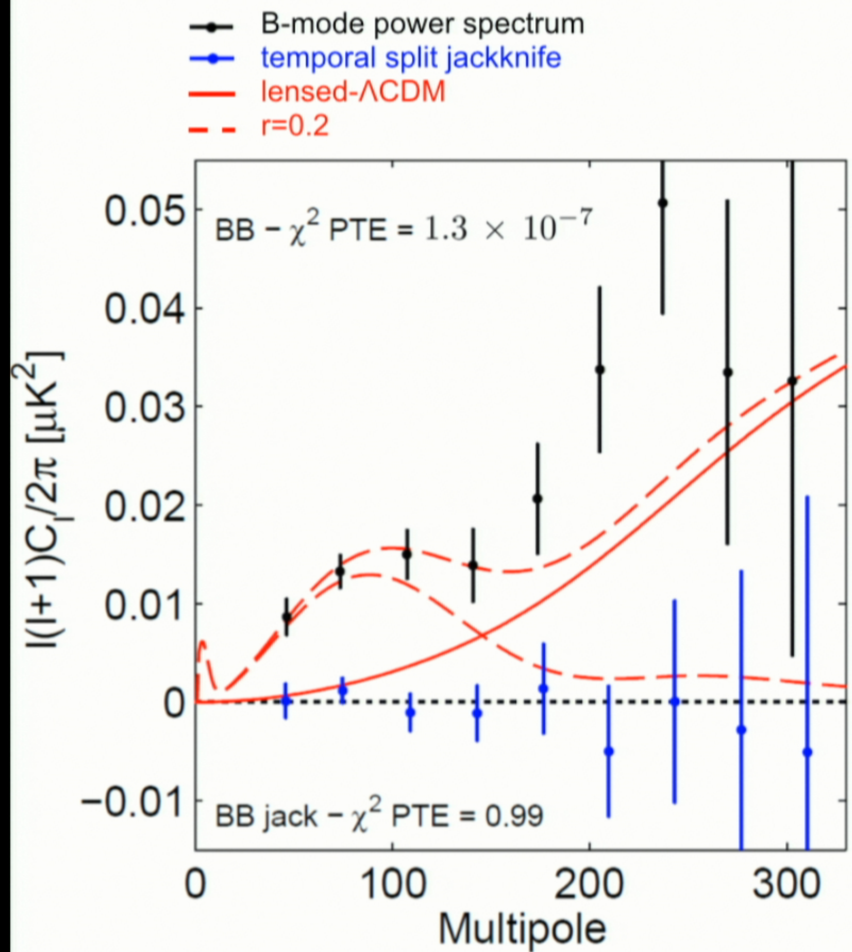
Christopher Sheehy for the Bicep2 Collaboration

Temperature and Polarization Spectra



Christopher Sheehy for the Bicep2 Collaboration

BICEP2 B-mode Power Spectrum



Consistent with lensing expectation at higher l.

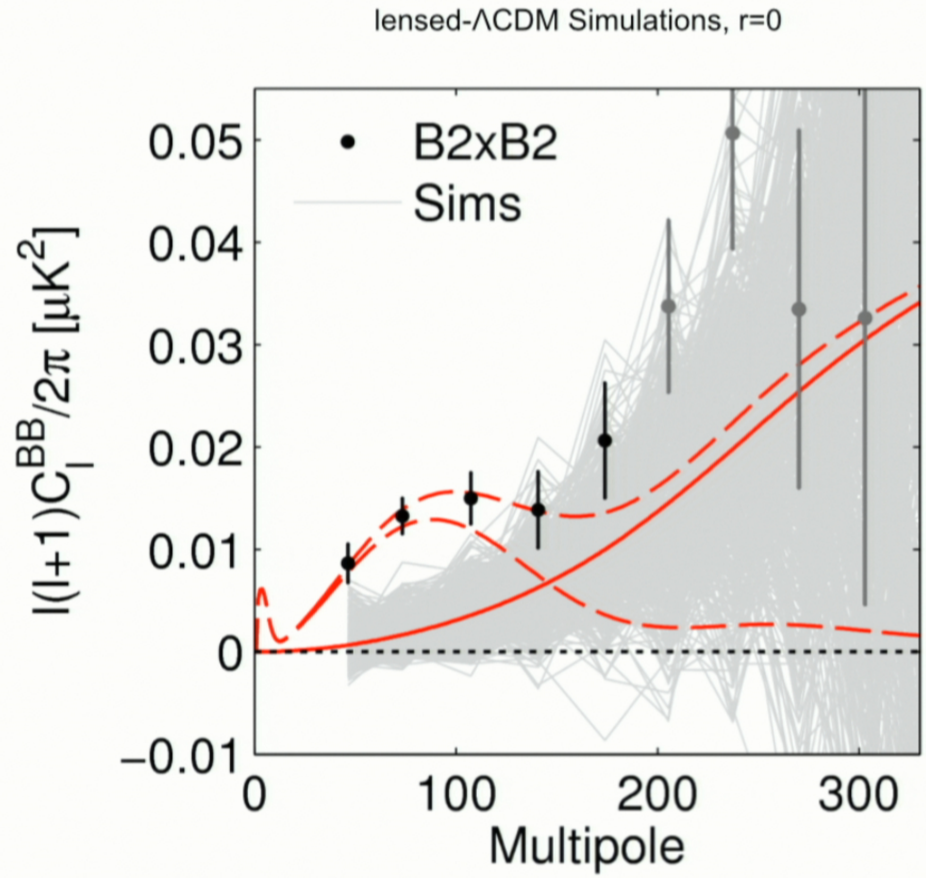
At low l excesses over lensed-ΛCDM at high signal-to-noise.

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

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

Christopher Sheehy for the Bicep2 Collaboration

B-mode Bandpowers and Simulations



What could it be?
Part I: Instrumental systematics?

Christopher Sheehy for the Bicep2 Collaboration

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
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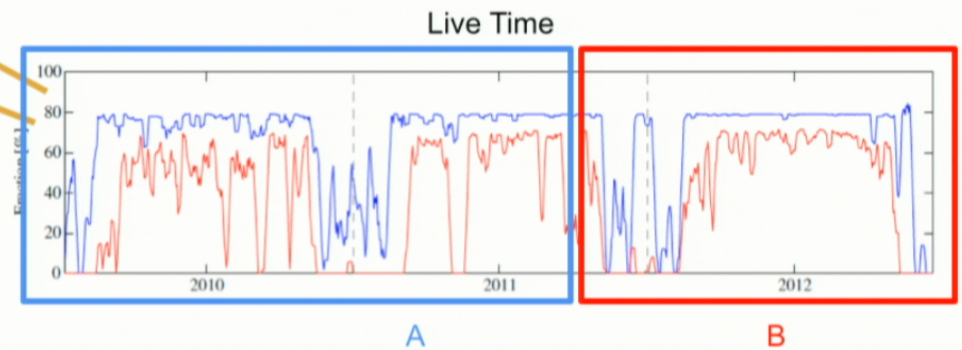

Splits by time

Christopher Sheehy for the Bicep2 Collaboration

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				
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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
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EE	0.812	0.587	0.196	0.204
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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
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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
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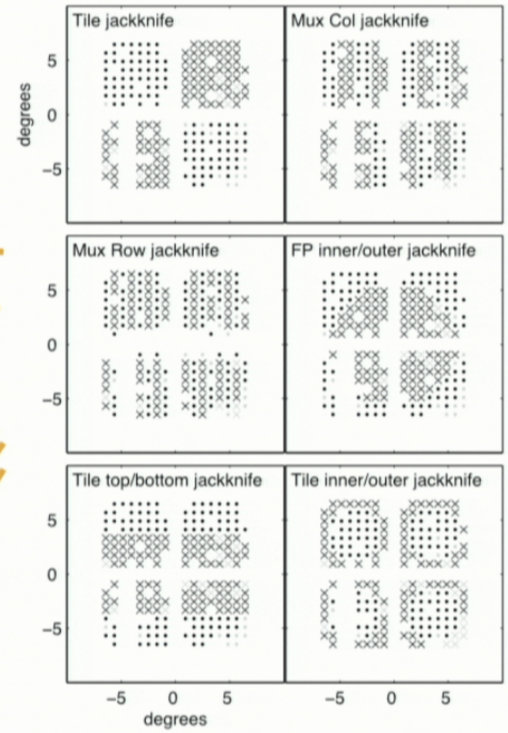
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.790

Maps of BICEP2 focal plane



Splits by channel selection

Christopher Sheehy for the Bicep2 Collaboration

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
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EE	0.483	0.762	0.978	0.938
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EB	0.529	0.577	0.840	0.659
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EE	0.812	0.587	0.196	0.204
BB	0.826	0.972	0.293	0.283
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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
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EE	0.052	0.178	0.653	0.739
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EB	0.529	0.226	0.024	0.048
Tile/Deck jackknife				
EE	0.048	0.088	0.144	0.132
BB	0.908	0.840	0.629	0.269
EB	0.050	0.154	0.591	0.591
Focal Plane inner/outer jackknife				
EE	0.230	0.597	0.022	0.090
BB	0.216	0.531	0.046	0.092
EB	0.036	0.042	0.850	0.838
Tile top/bottom jackknife				
EE	0.289	0.347	0.459	0.599
BB	0.293	0.236	0.154	0.028
EB	0.545	0.683	0.902	0.932
Tile inner/outer jackknife				
EE	0.727	0.533	0.128	0.485
BB	0.255	0.086	0.421	0.036
EB	0.465	0.737	0.208	0.168
Moon jackknife				
EE	0.499	0.689	0.481	0.679
BB	0.144	0.287	0.898	0.858
EB	0.289	0.359	0.531	0.307
A/B offset best/worst				
EE	0.317	0.311	0.868	0.709
BB	0.114	0.064	0.307	0.094
EB	0.589	0.872	0.599	0.790

Splits by boresight orientation

Christopher Sheehy for the Bicep2 Collaboration

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
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EE	0.541	0.377	0.916	0.938
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BB	0.826	0.972	0.293	0.283
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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
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Moon jackknife				
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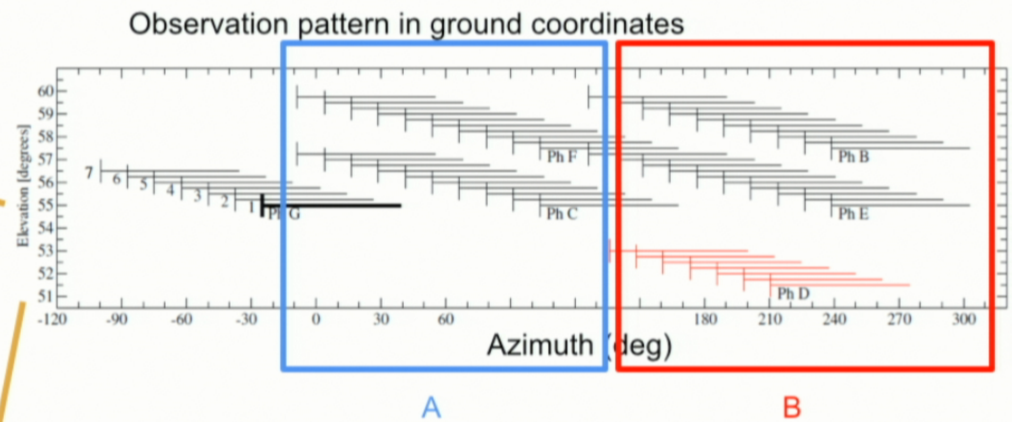

Splits by possible external contamination

Christopher Sheehy for the Bicep2 Collaboration

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
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EE	0.004	0.004	0.070	0.236
BB	0.397	0.176	0.381	0.086
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EB	0.036	0.042	0.850	0.838
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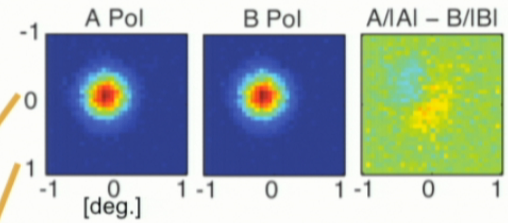
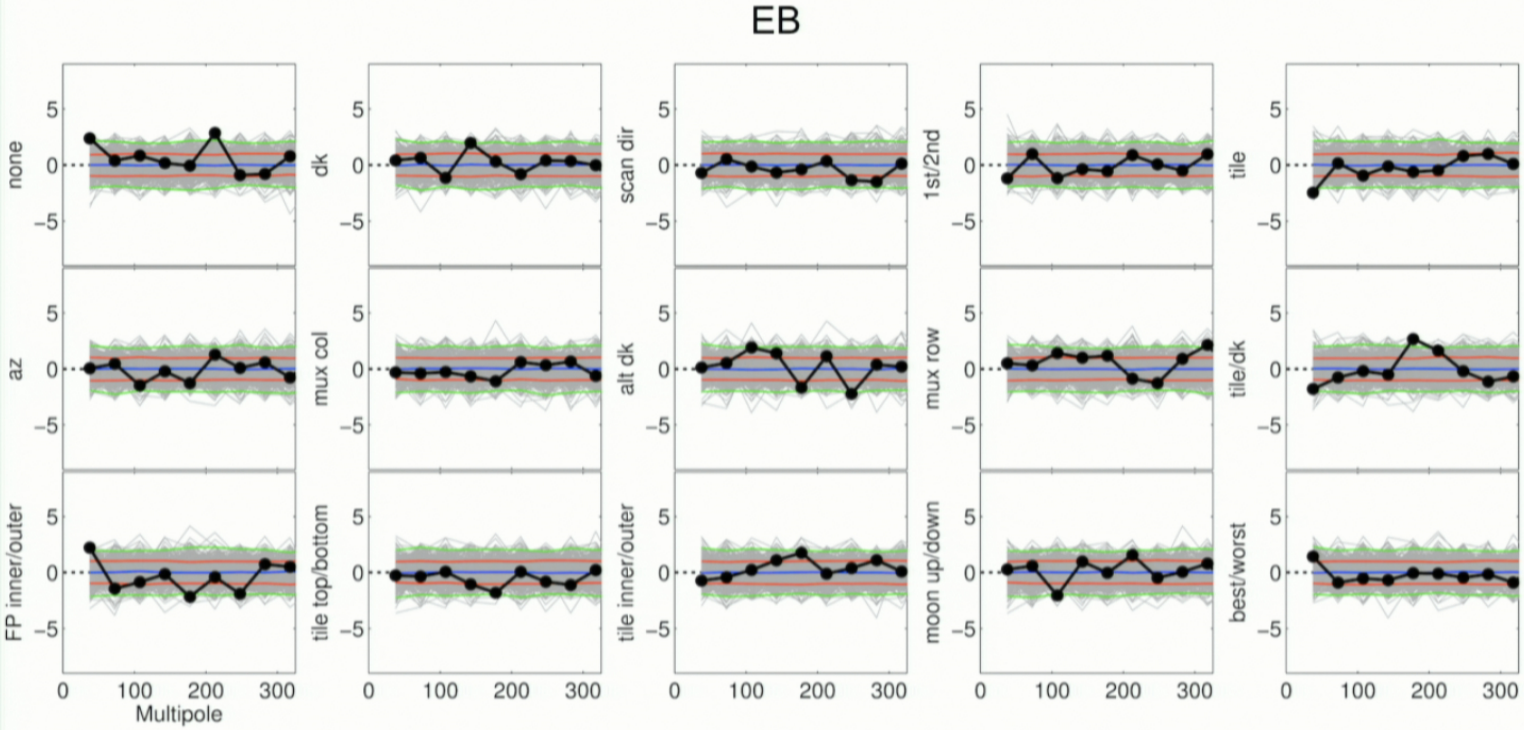


Splits by intrinsic detector properties

Christopher Sheehy for the Bicep2 Collaboration

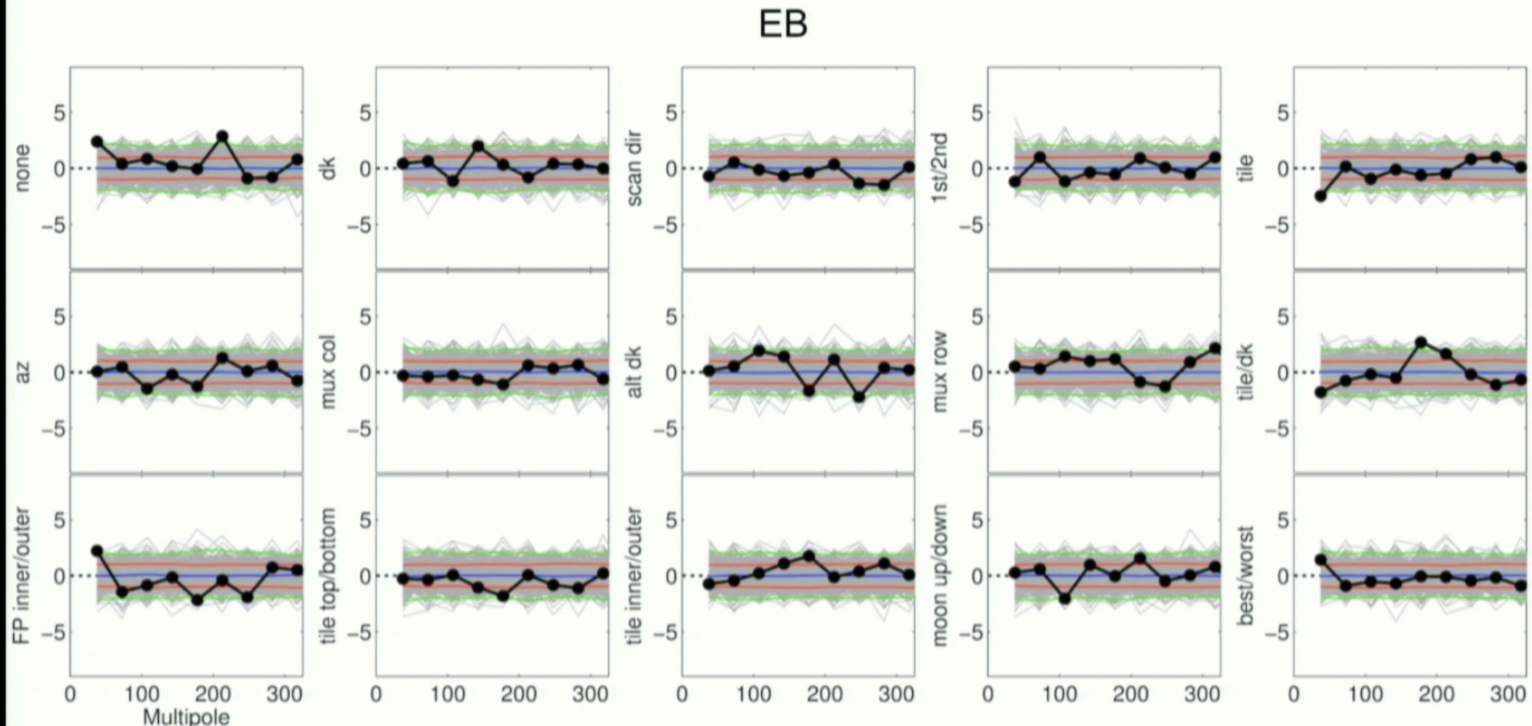
Jackknife Bandpower Deviations



Bandpower deviations of real data vs. signal plus noise simulations (w/ lensing)

John Q Public for the Bicep2 Collaboration

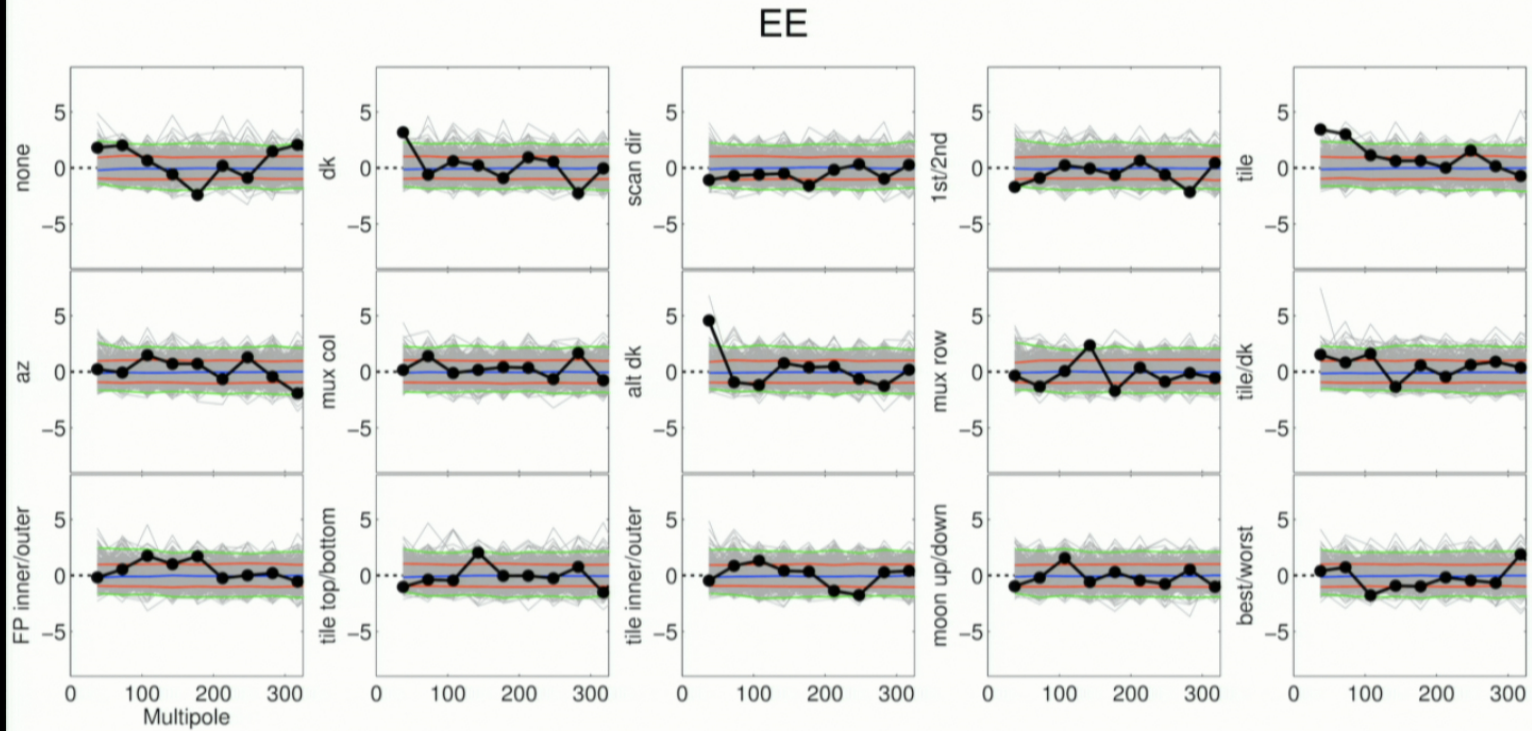
Jackknife Bandpower Deviations



Bandpower deviations of real data vs. signal plus noise simulations (w/ lensing)

John Q Public for the Bicep2 Collaboration

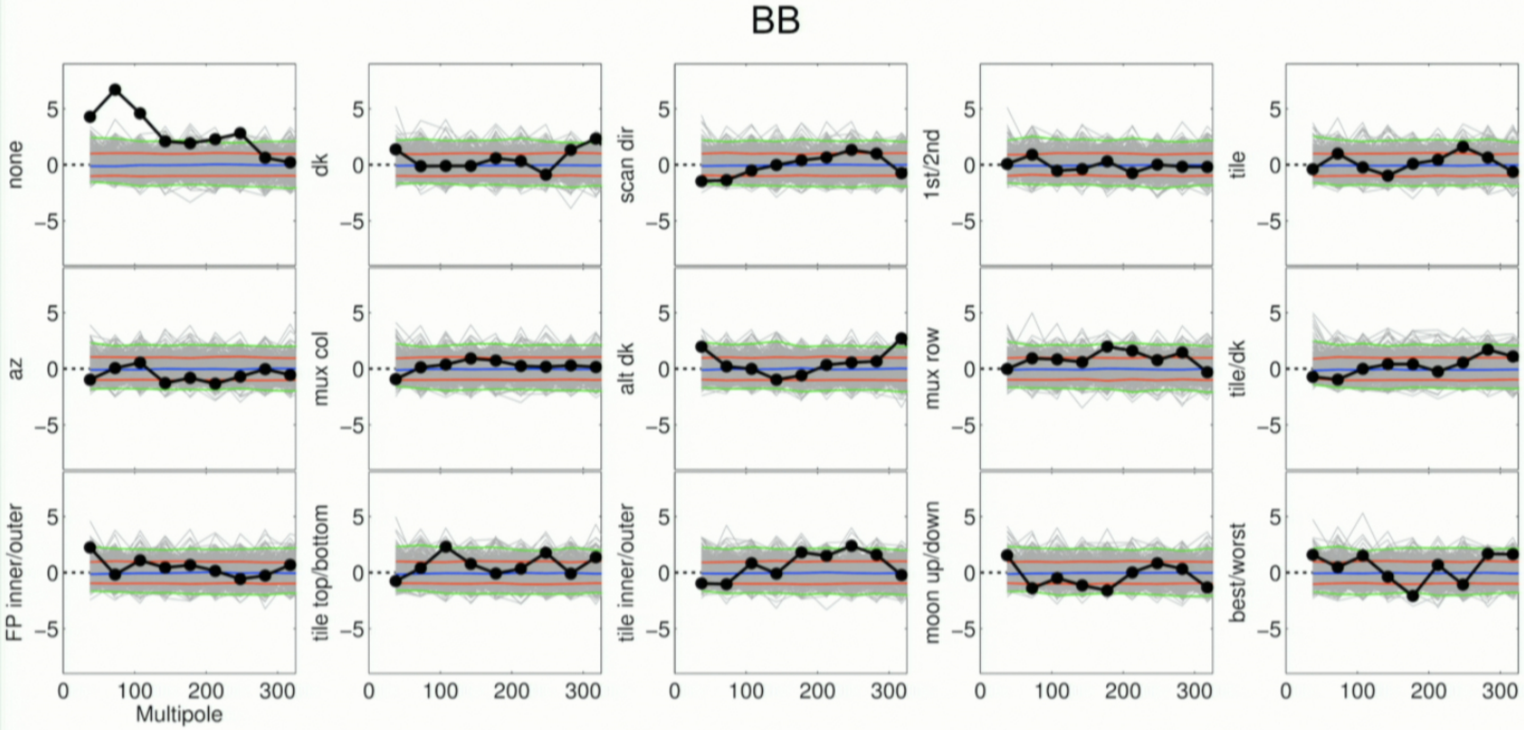
Jackknife Bandpower Deviations



Bandpower deviations of real data vs. signal plus noise simulations (w/ lensing)

Christopher Sheehy for the Bicep2 Collaboration

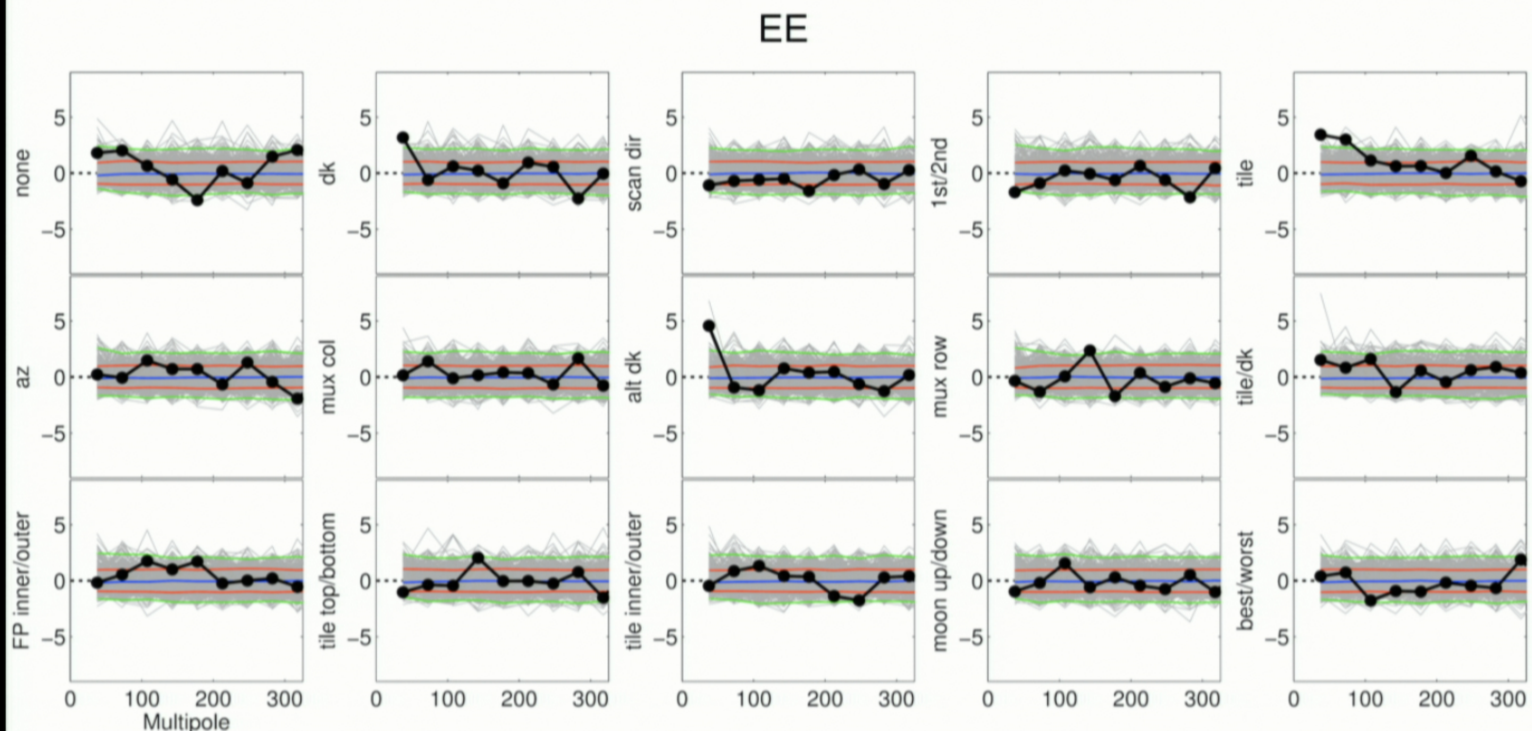
Jackknife Bandpower Deviations



Bandpower deviations of real data vs. signal plus noise simulations (w/ lensing)

Christopher Sheehy for the Bicep2 Collaboration

Jackknife Bandpower Deviations



Bandpower deviations of real data vs. signal plus noise simulations (w/ lensing)

Christopher Sheehy for the Bicep2 Collaboration

Check Systematics: Jackknifes

TABLE 1
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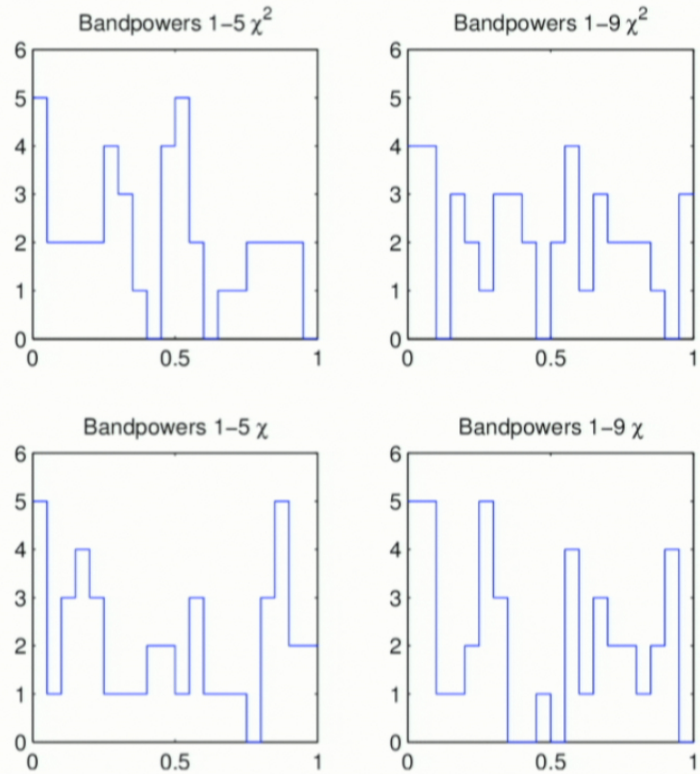
BB	0.293	0.236	0.154	0.028
EB	0.545	0.683	0.902	0.932
Tile inner/outer jackknife				
EE	0.727	0.533	0.128	0.485
BB	0.255	0.086	0.421	0.036
EB	0.465	0.737	0.208	0.168
Moon jackknife				
EE	0.499	0.689	0.481	0.679
BB	0.144	0.287	0.898	0.858
EB	0.289	0.359	0.531	0.307
A/B offset best/worst				
EE	0.317	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 statistics defined from the jackknife tests result in uniform probability to exceed (PTE) distributions:



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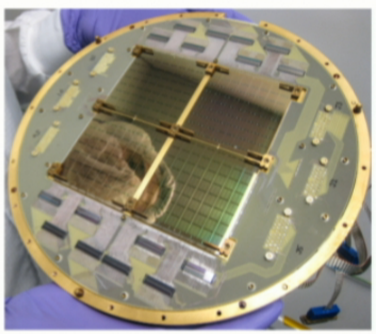
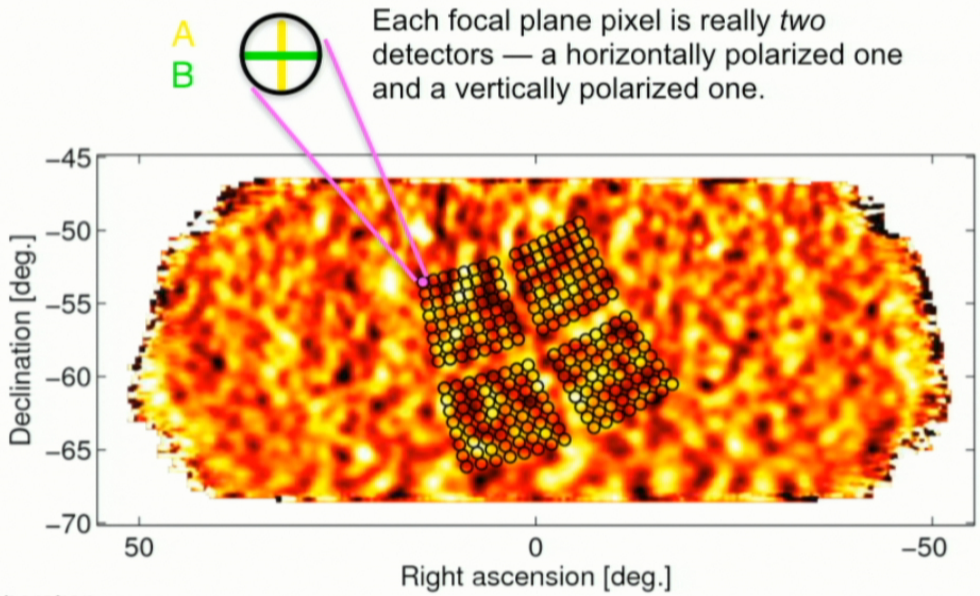
Beam systematics

Each focal plane pixel is really two orthogonally polarized detectors

Call these detectors “A” and “B”. They nominally point to the same location on the sky and have identical response to the CMB, i.e. have the same “beam”.





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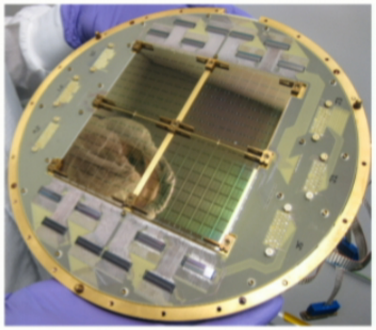
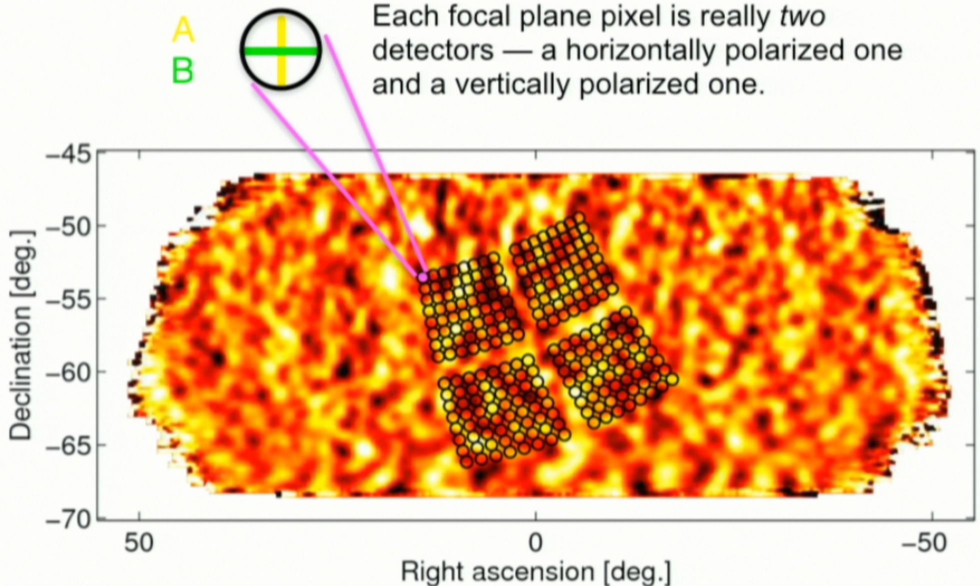
Beam systematics

If the CMB is unpolarized, the “pair difference” should be zero

If the response to the CMB is different for A and B, then even if the CMB is unpolarized, the pair difference is non-zero. This is contaminates polarization!





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Beam systematics
example: pointing center mismatch

"A" and B" beams

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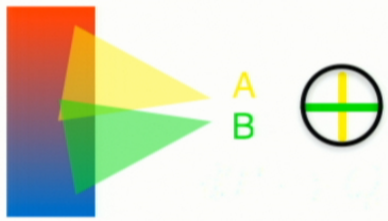
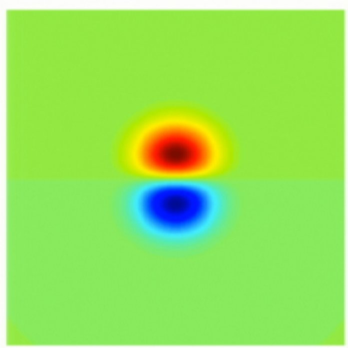
Beam systematics

example: pointing center mismatch

"A" and B" beams



A-B difference beam



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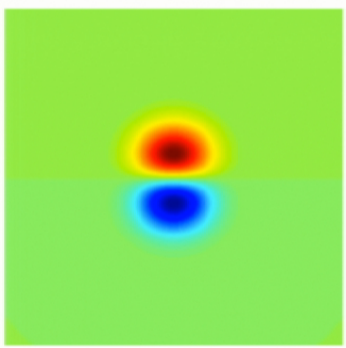
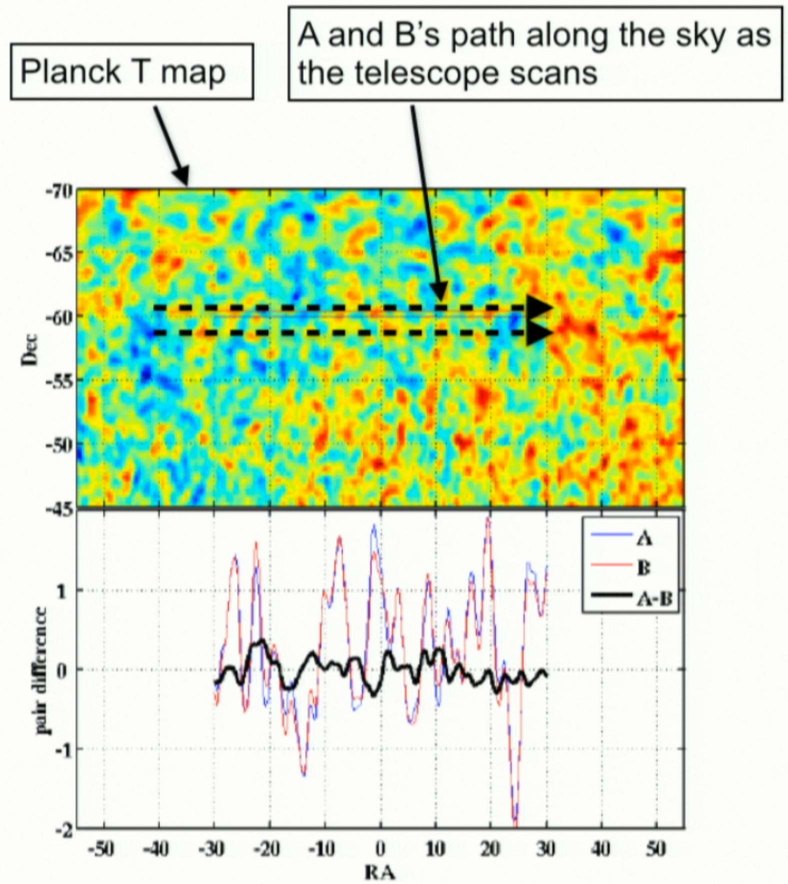
Beam systematics
example: pointing center mismatch

"A" and B" beams

A-B difference beam





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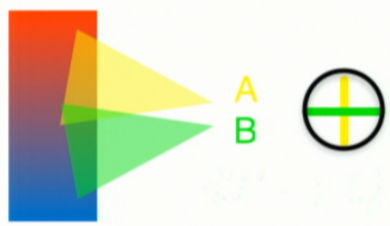
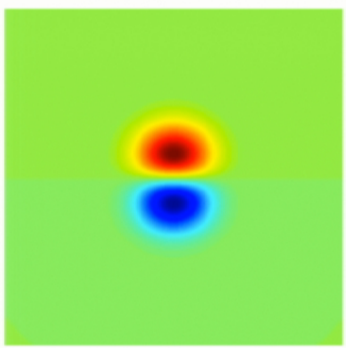
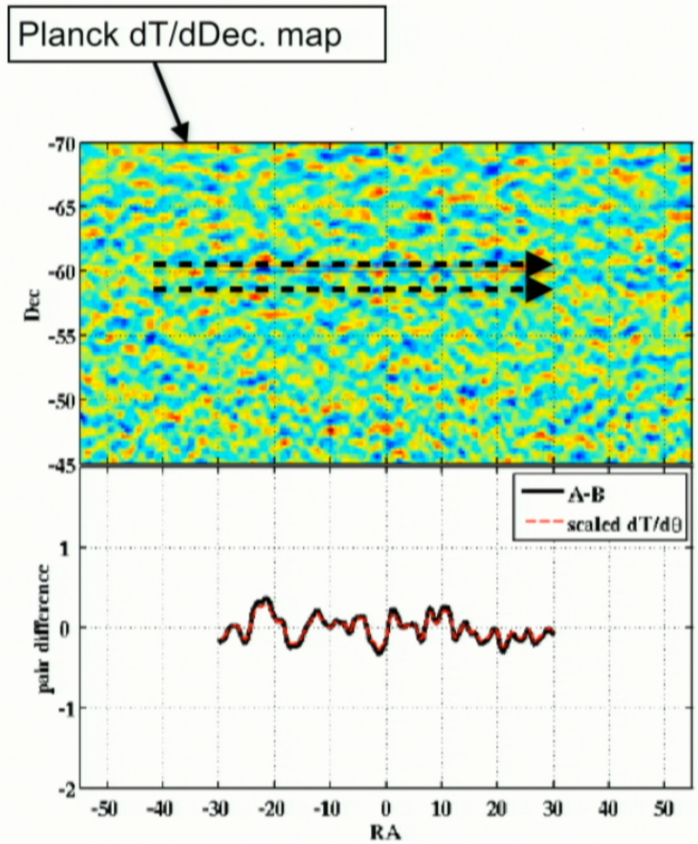
Systematics removal: deprojection
example: pointing center mismatch

"A" and B" beams



A-B difference beam





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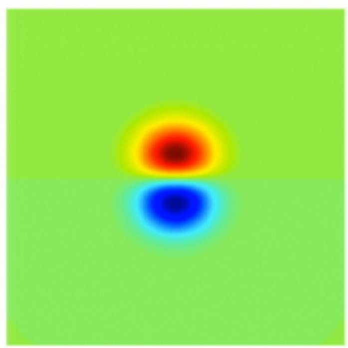
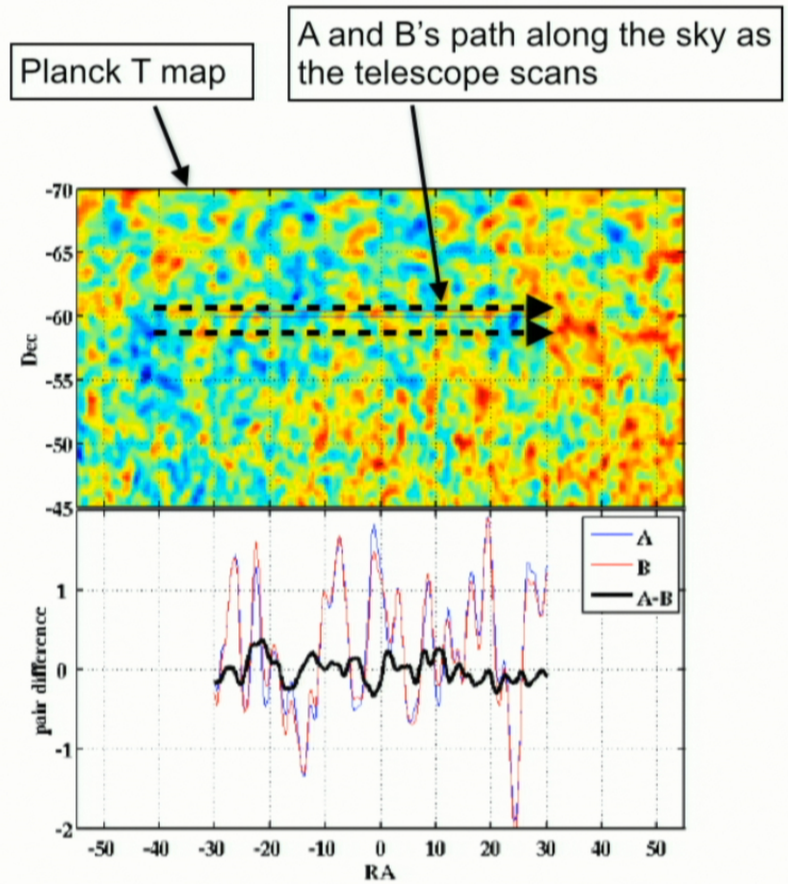
Beam systematics

example: pointing center mismatch

"A" and B" beams

A-B difference beam





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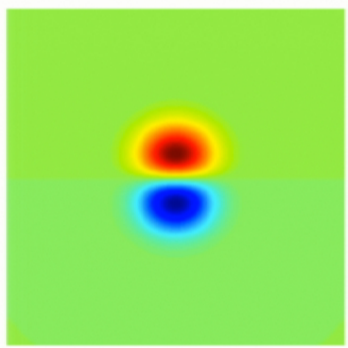
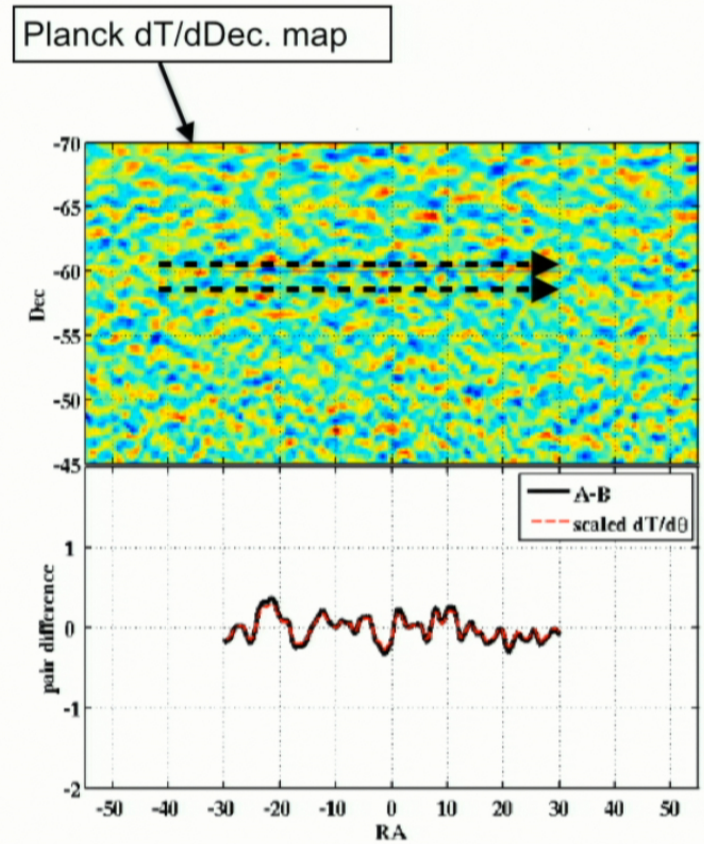
Systematics removal: deprojection

example: pointing center mismatch

"A" and B" beams

A-B difference beam





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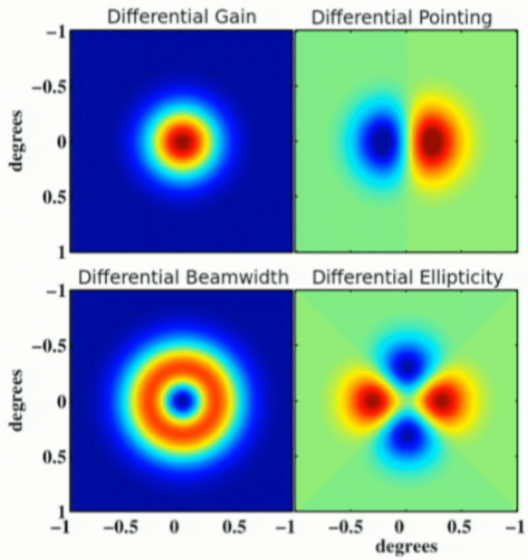
Systematics removal: deprojection

Differences of elliptical Gaussians



Use the Planck 143 GHz map to form templates of leakage from mismatched elliptical Gaussian beams.

Fit these templates to the data and subtract.

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

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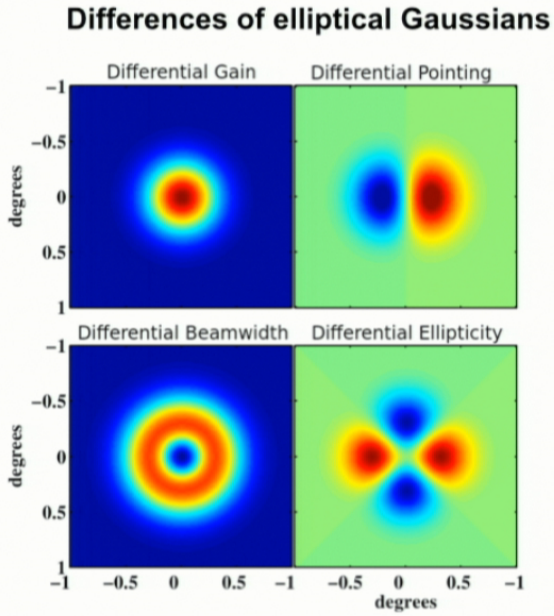
Systematics removal: deprojection



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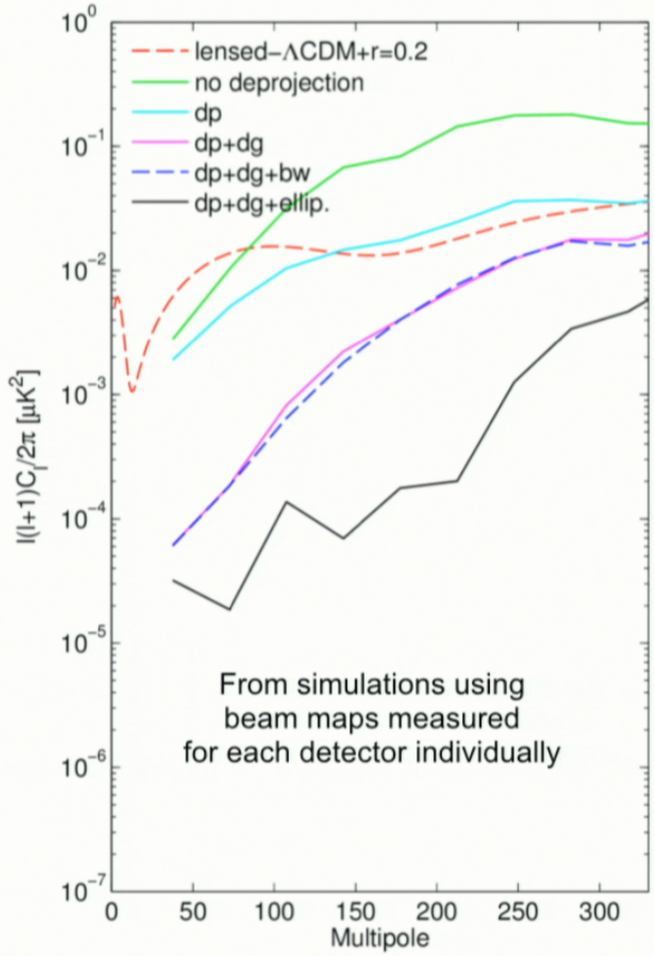

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We know our beam shapes

Far field beam mapping:
microwave source mounted here

Detailed description in companion Instrument Paper

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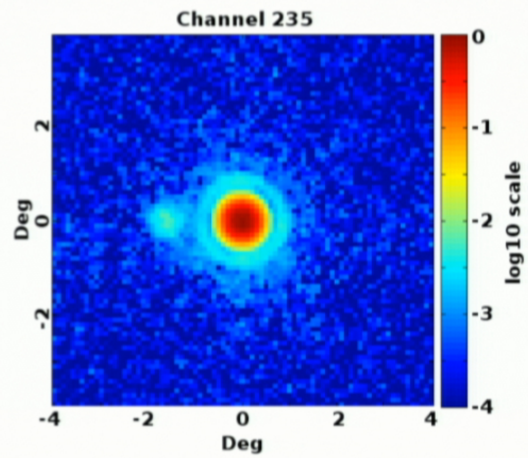
We know our beam shapes

Far field beam mapping:
microwave source mounted here

High fidelity beam maps of individual detectors



Detailed description in companion Instrument Paper

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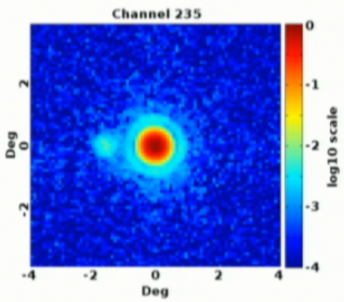
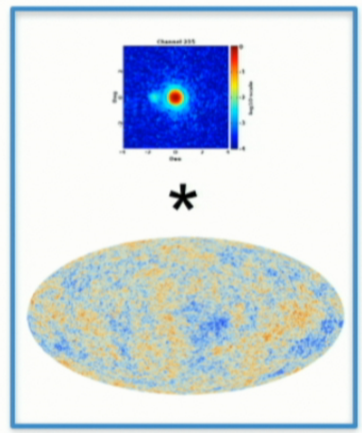
We know our beam shapes

Because contamination from beam shape mismatch is entirely deterministic, we can both remove it (deprojection) **and** predict it in simulation using calibration data as input.

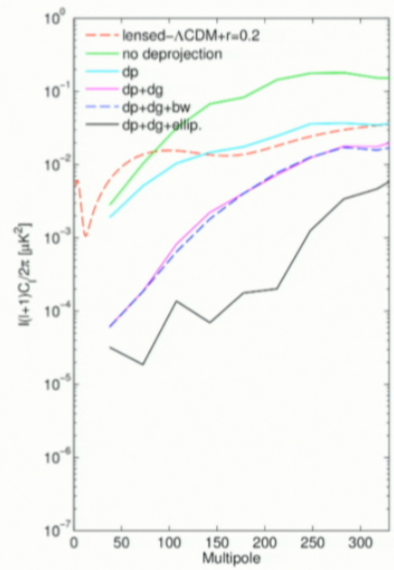
Calibration data for each channel



Simulation
(explicit convolution with Planck T map)



Predictions of contamination



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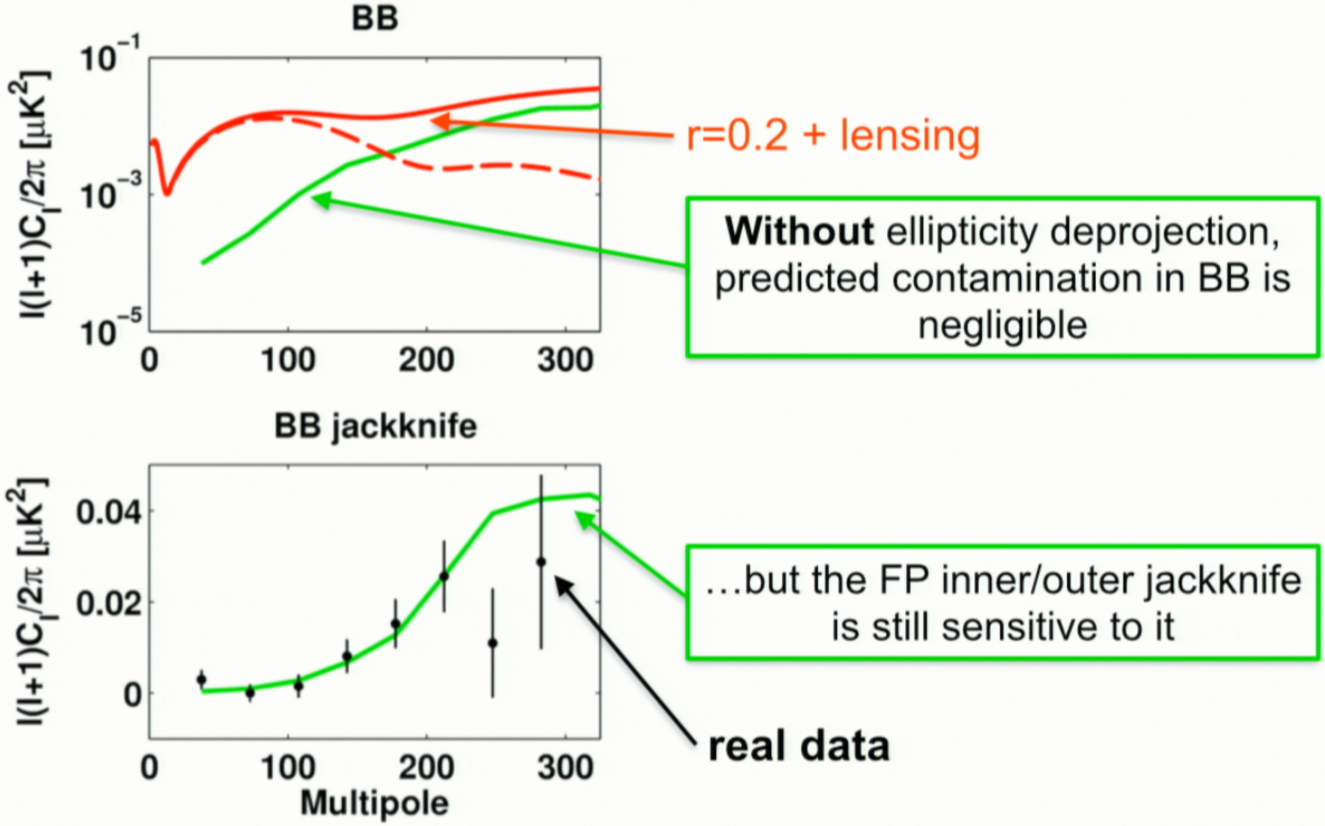
We know our beam shapes

example: slightly elliptical beams



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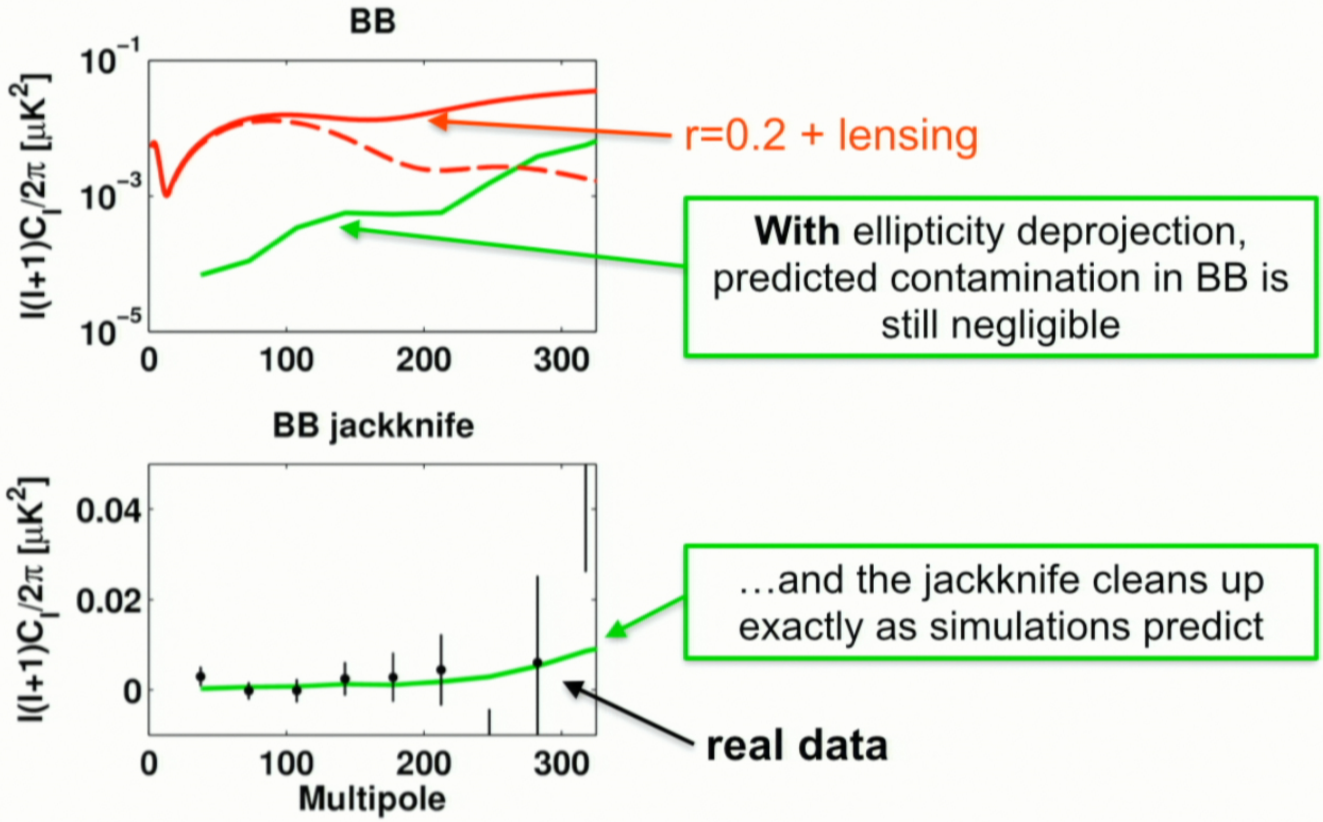

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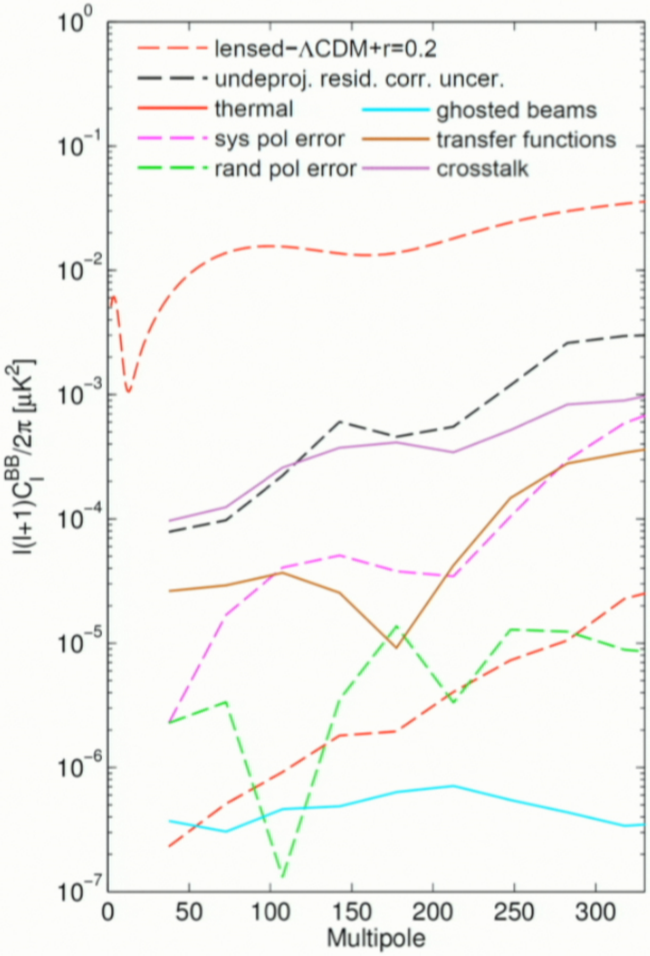
Systematics beyond beam imperfections



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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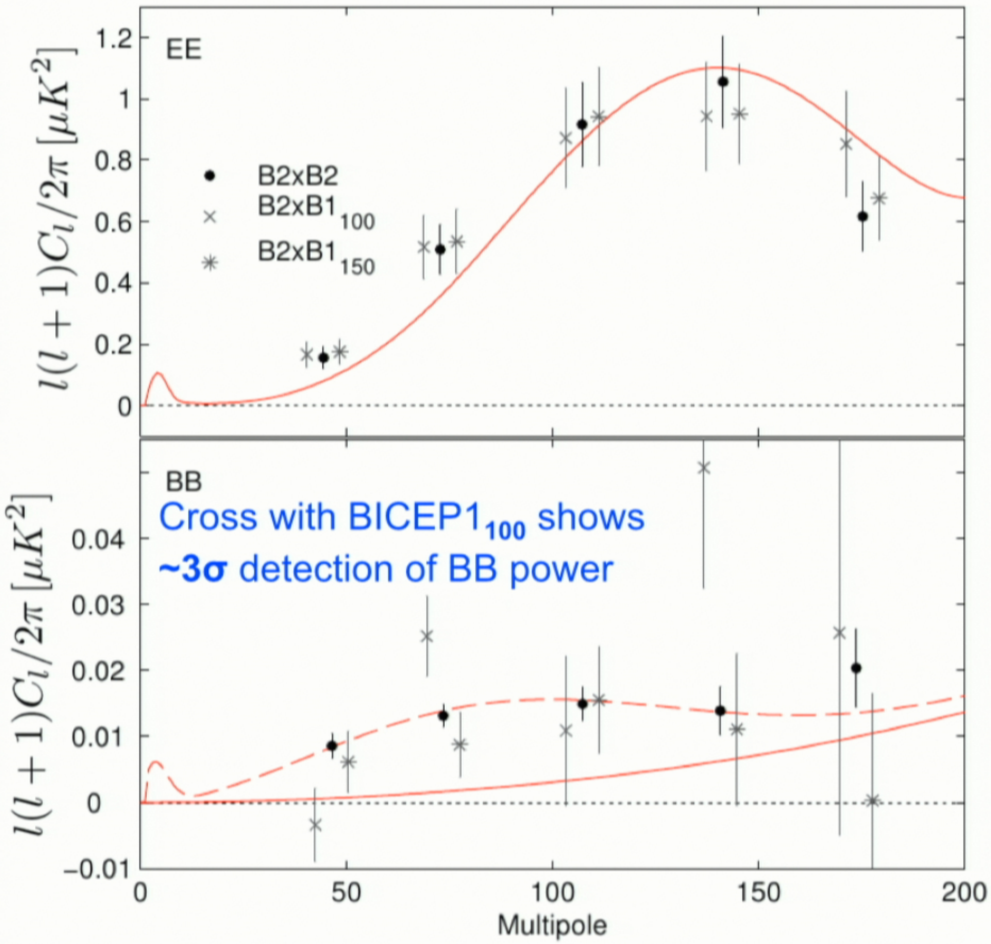
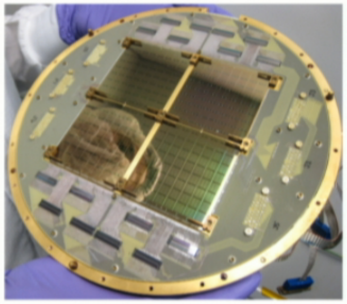
BICEP2 auto and Cross Spectra with BICEP1



BICEP2: Phased antenna array and TES readout, all at150 GHz



BICEP1: Feedhorns and NTD readout, at 150 and 100 GHz

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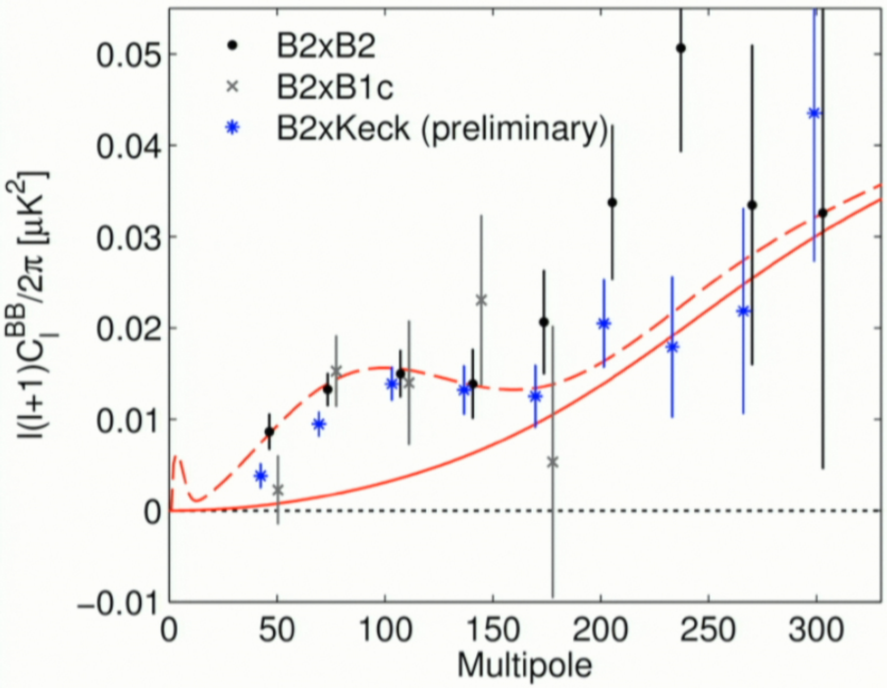
Cross spectra between three experiments

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



BICEP2 auto spectrum compatible with B2xB1 frequency combined 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

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Cross spectra between three experiments

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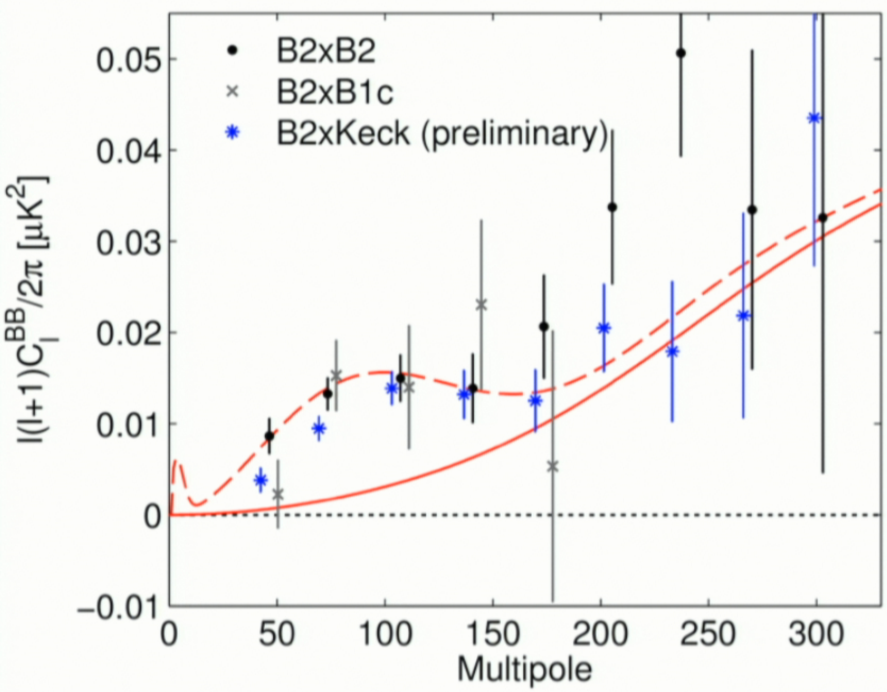

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What could it be?
Part II: Galactic foregrounds?

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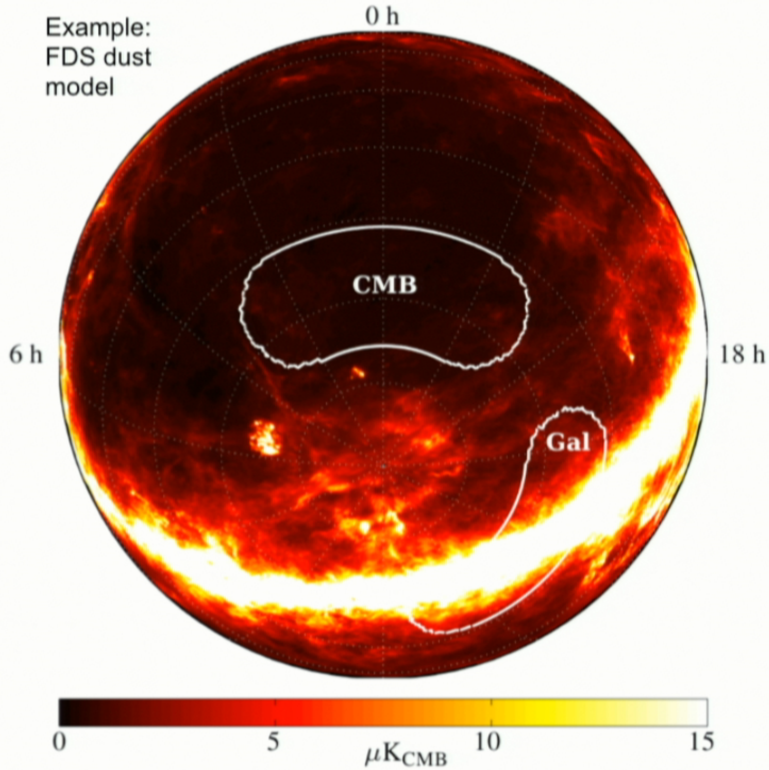
Observational Strategy

Example:
FDS dust
model



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

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

Expected foreground contamination of the B-mode power: r ≤ ~0.01.

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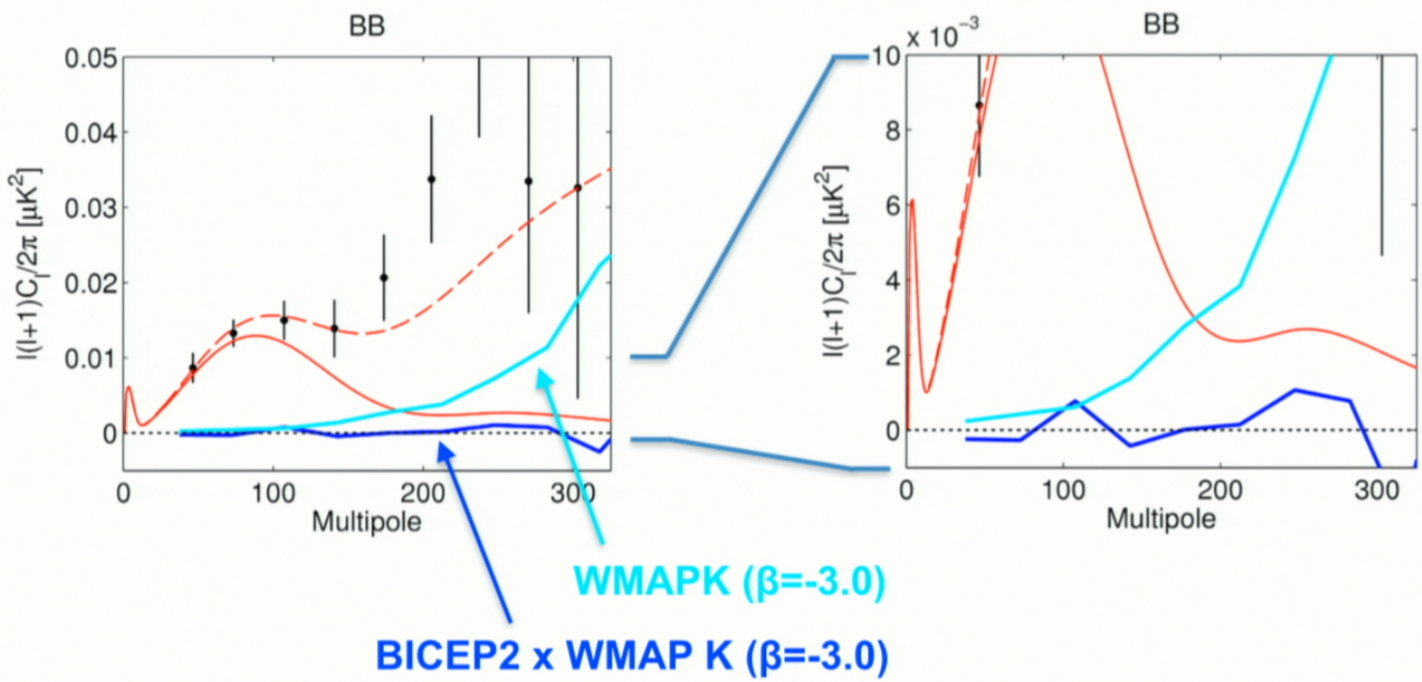
Synchrotron?

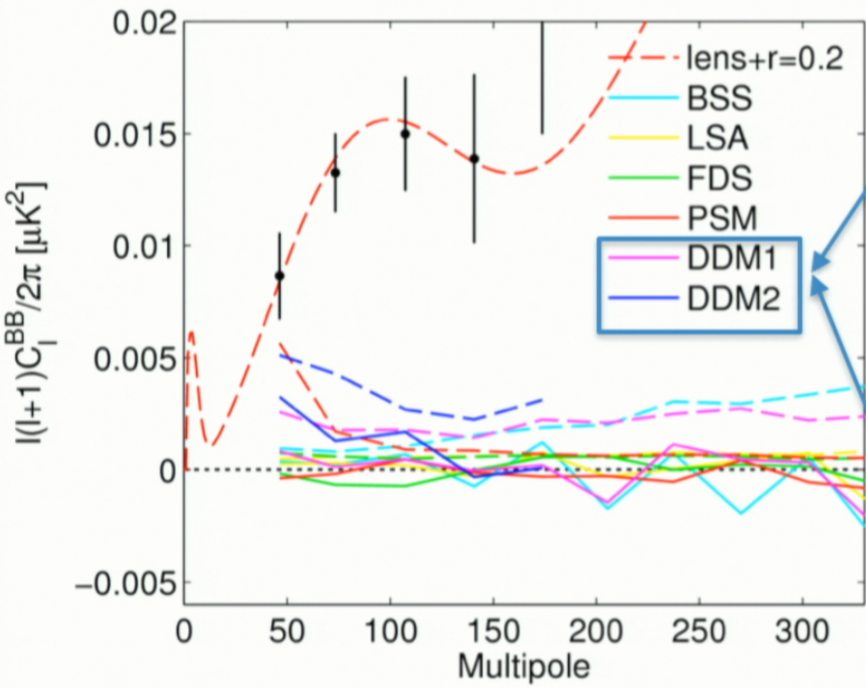
BICEP2 x WMAP 22 GHz polarization (extrapolated to 150 GHz with beta=-3.3) is noise dominated but limits synchrotron to r<.0003.

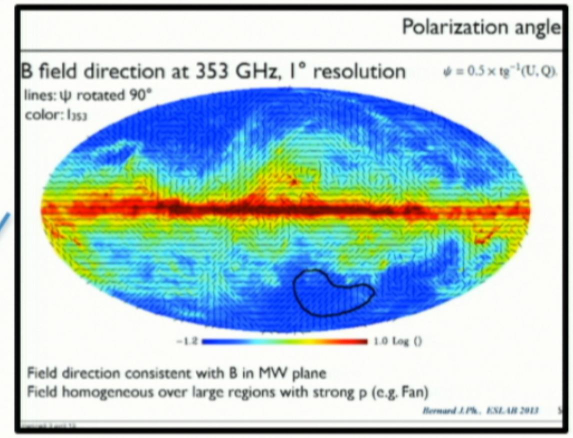


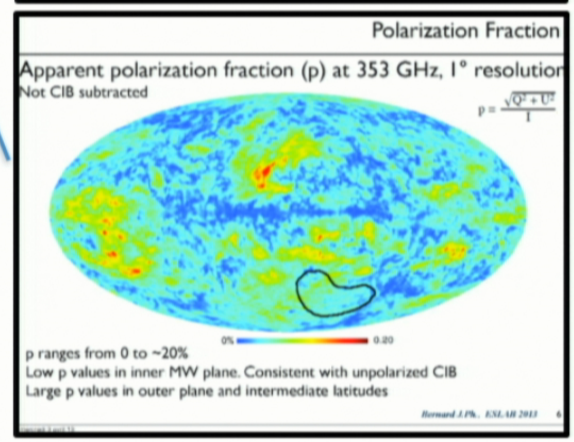
Dust?

Data driven models (DDM) use Planck dust model (2013) and 47ESLAB (2013)

Dashed: Dust auto spectra
Solid: BICEP2xDust cross spectra







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http://www.rssd.esa.int/SA/PLANCK/docs/eslab47/Session07_Galactic_Science/47ESLAB_April_04_11_25_Bernard.pdf

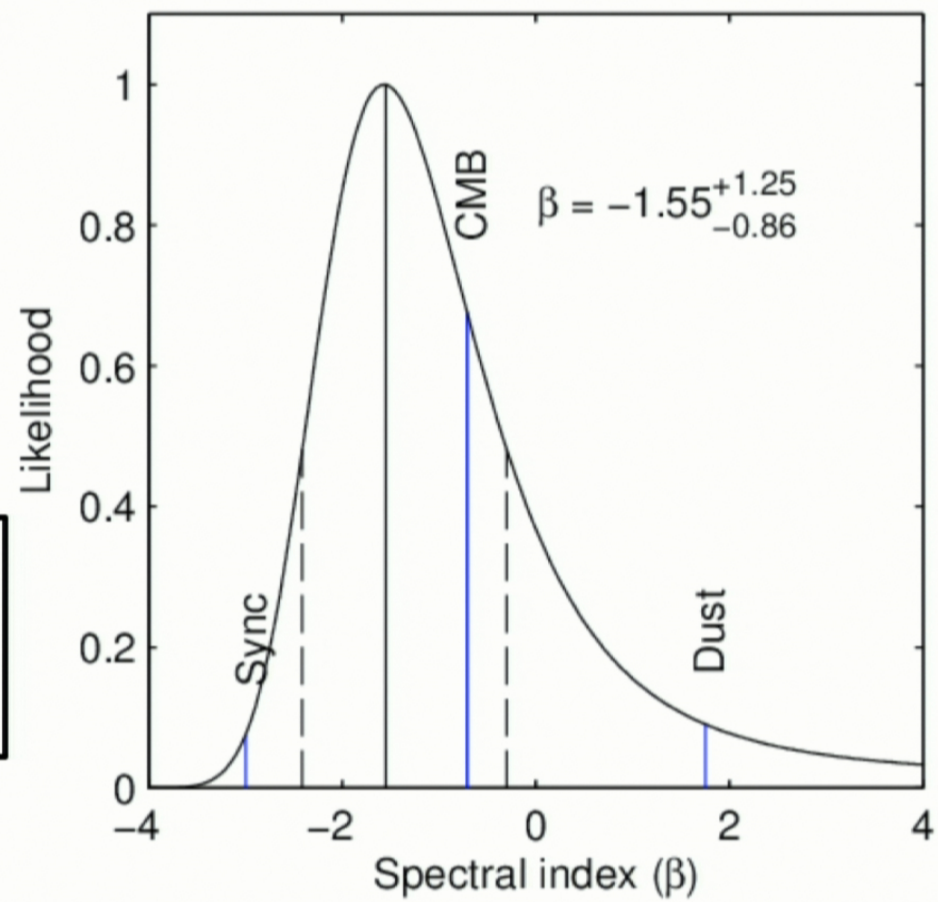
Spectral Index of the B-mode Signal

Using BICEP1, comparison of B2 auto with $B2_{150} \times B1_{100}$ constrains signal frequency dependence, independent of foreground projections

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

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

Likelihood ratio test: consistent with CMB spectrum, disfavor dust/sync spectral indices +1.75/-3.0 at **2.2/2.3σ**



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What could it be?
Part III: Cosmology

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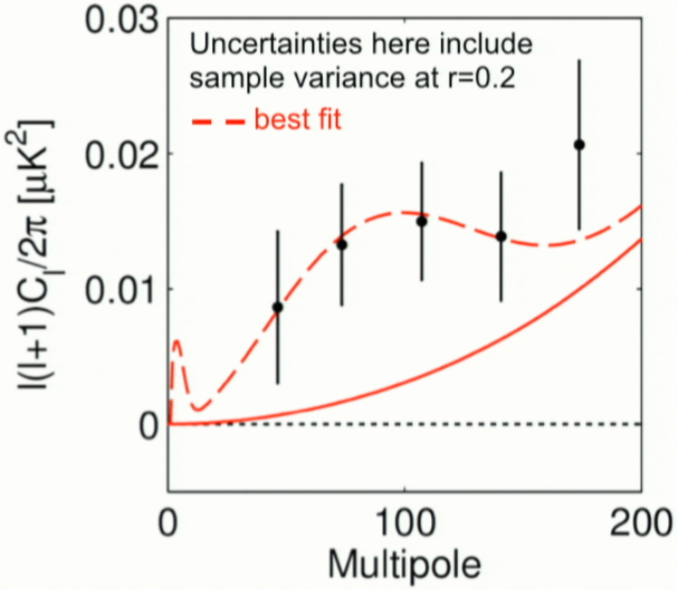
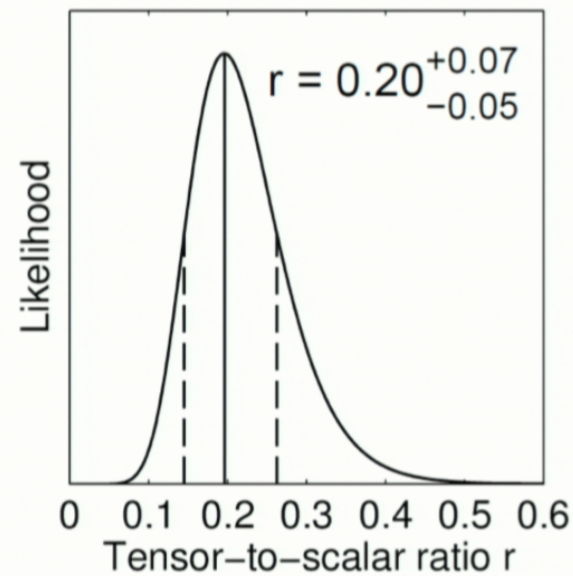
Constraint on Tensor-to-scalar Ratio r





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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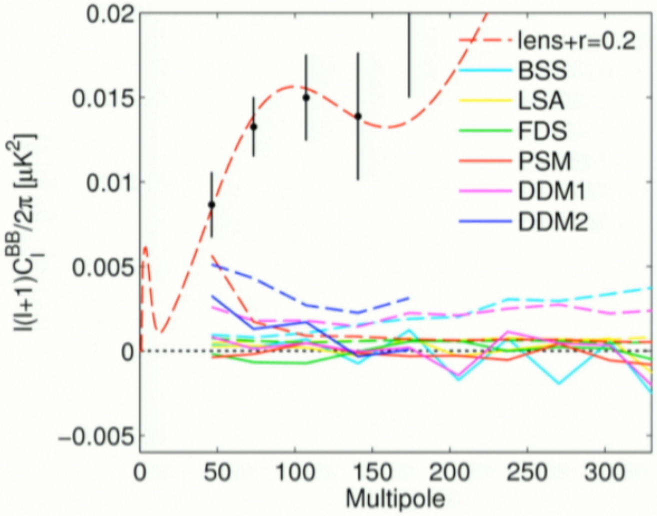
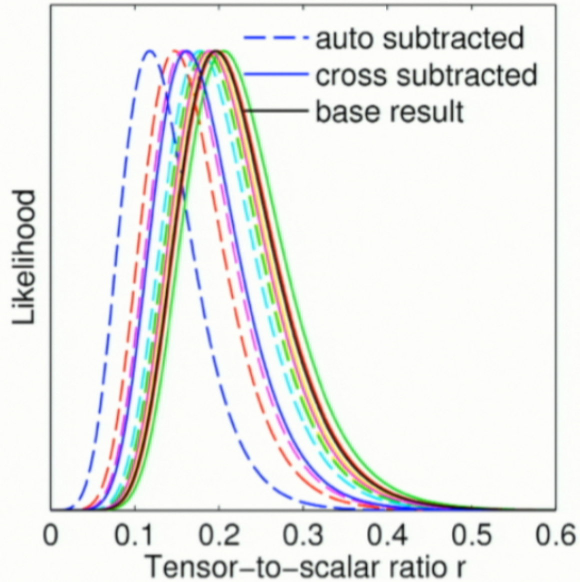
Constraint on r under Foreground Projections



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 still ruled out at 5.9σ

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

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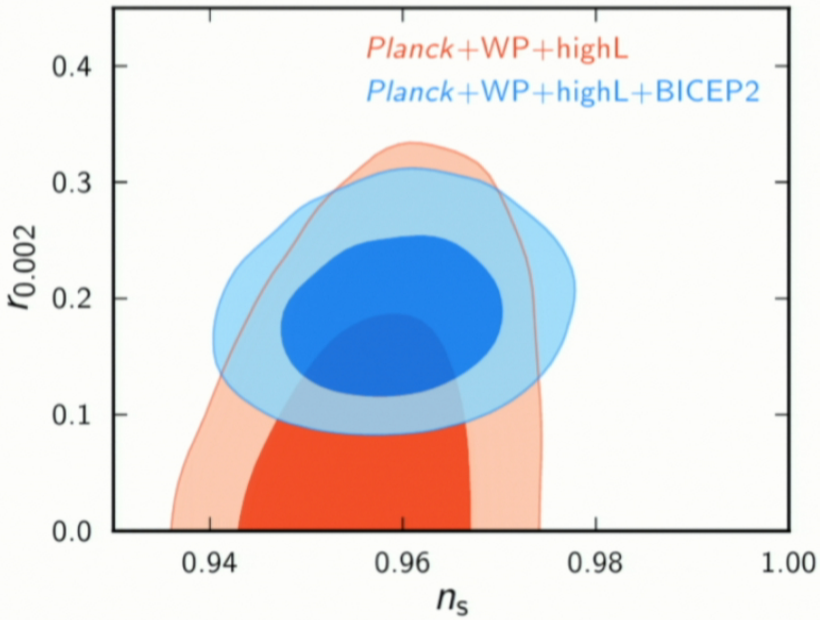
Tension?

Indirect limit on r from combination of *temperature* data over a wide range of angular scales:

SPT+WMAP+BAO+H_0	: r < 0.11
Planck+SPT+ACT+$WMAP_{pol}$	: r < 0.11



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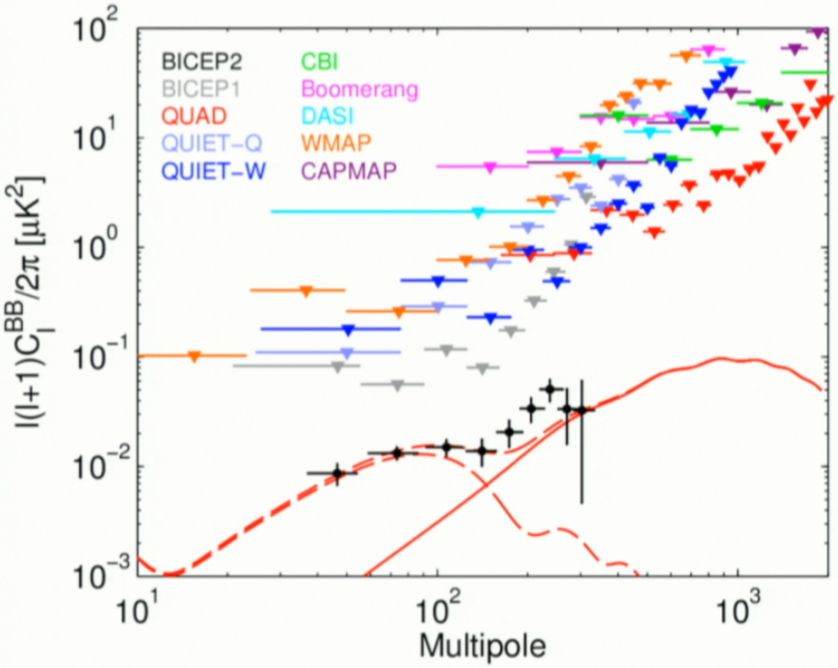
Constraint on r *with running allowed*:
(dn_s/dk -> -.028 +/- 0.009)

Simply an illustration of a simple LCDM extension that could in principle resolve tension

Obviously, the specific resolution remains to be seen.

Conclusions

BICEP2 and upper limits from other experiments:



http://www.bicepkeck.org/bicep2_2014_release

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 gravity wave model:

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

With r=0 is ruled out at 7.0σ.

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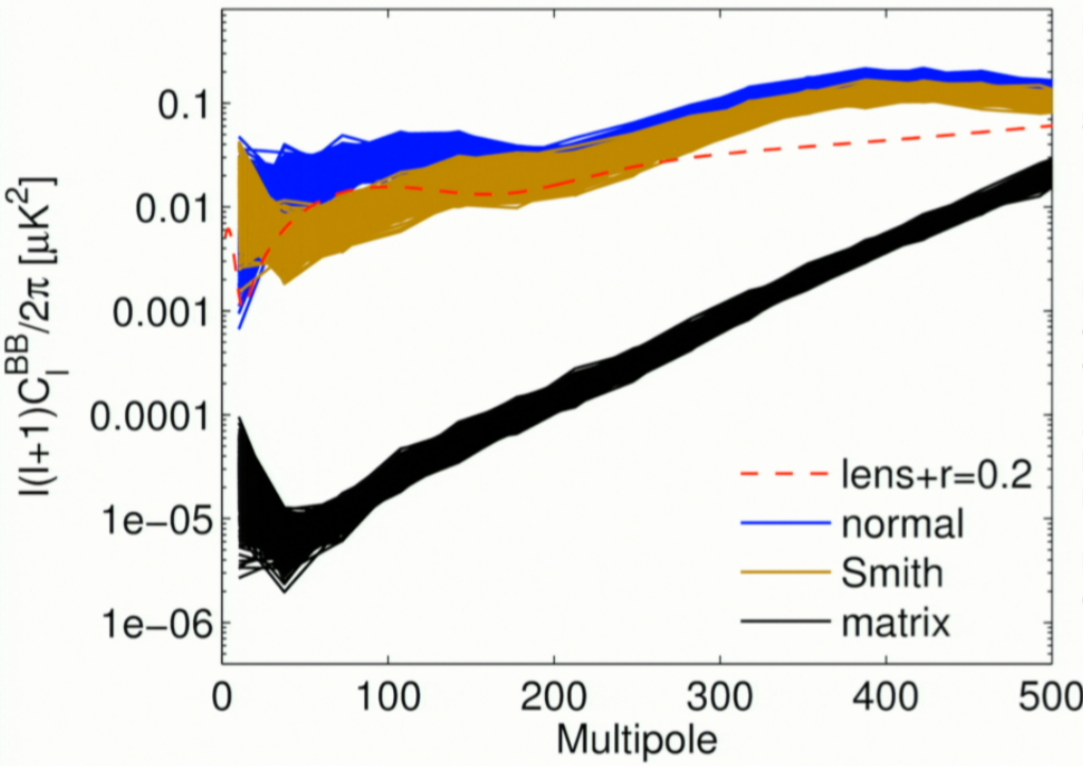
Map-based E - B purification:

BB autospectra comparison for three estimators



Curves show 500 LCDM signal only simulations - all the BB power is a result of E to B leakage

Normal estimator does not attempt to correct for filtering and sky cut

Smith estimator fixes sky cut leakage, but filtering leakage remains (Smith 2006)

Matrix purification reduces contamination to $r<10^{-4}$

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