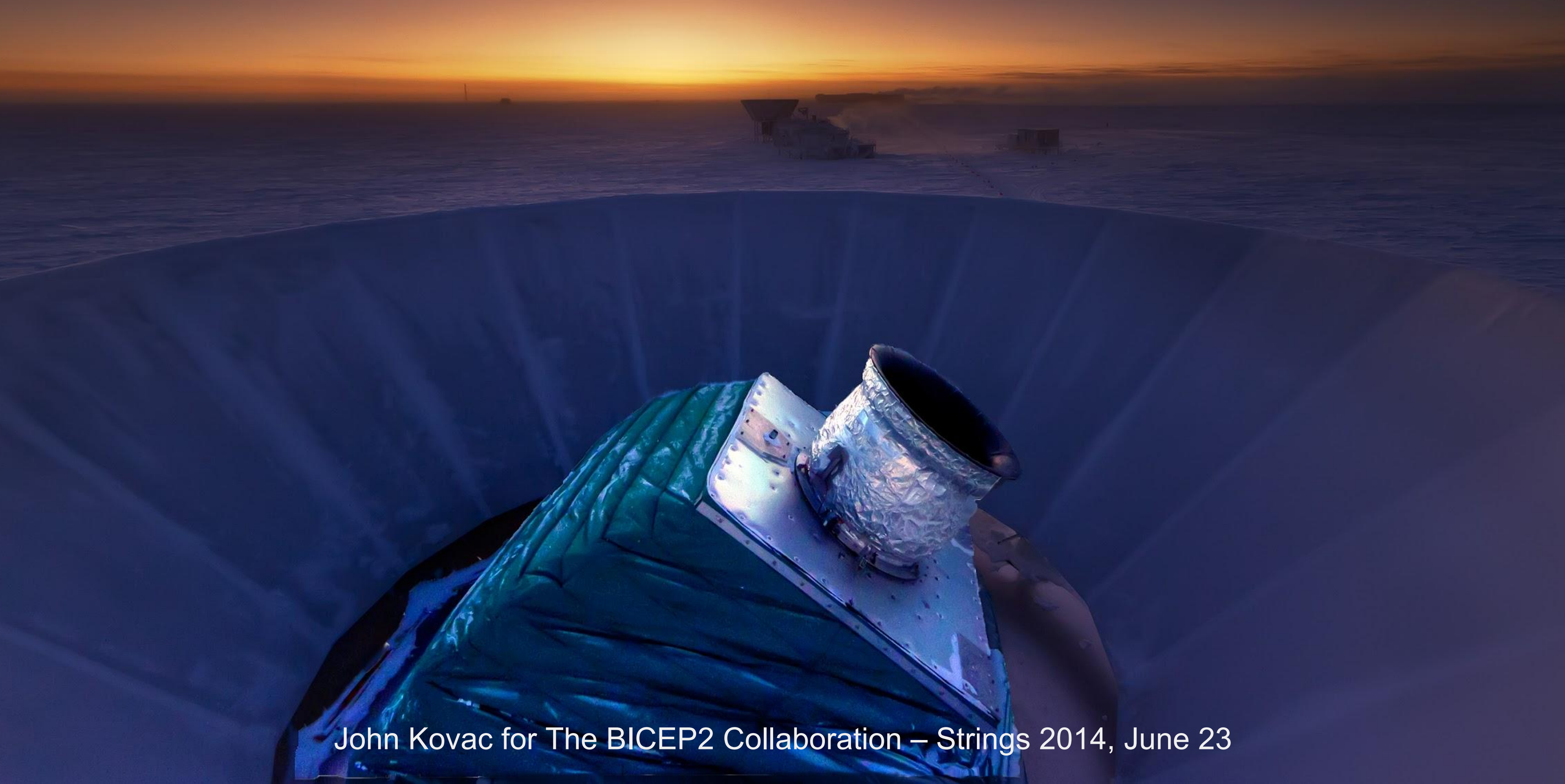
Detection of B-mode Polarization at Degree Scales using BICEP2



John Kovac for The BICEP2 Collaboration – Strings 2014, June 23

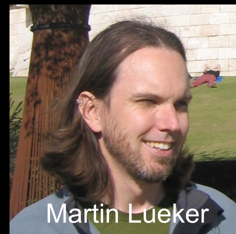
BICEP2 I: Detection of B-mode Polarization at Degree Angular Scales

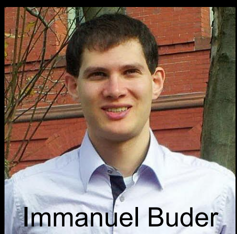
BICEP2 Collaboration - P. A. R. Ade,[1] R. W. Aikin,[2] D. Barkats,[3] S. J. Benton,[4] C. A. Bischoff,[5] J. J. Bock,[2,6] J. A. Brevik,[2] I. Buder,[5] E. Bullock,[7] C. D. Dowell,[6] L. Duband,[8] J. P. Filippini,[2] S. Fliescher,[9] S. R. Golwala,[2] M. Halpern,[10] M. Hasselfield,[10] S. R. Hildebrandt,[2,6] 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,[4,16] 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]

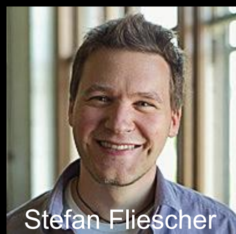
We report results from the BICEP2 experiment, a Cosmic Microwave Background (CMB) polarimeter specifically designed to search for the signal of inflationary gravitational waves in the B-mode power spectrum around $\ell \sim 80$. The telescope comprised a 26 cm aperture all-cold refracting optical system equipped with a focal plane of 512 antenna coupled transition edge sensor (TES) 150 GHz bolometers each with temperature sensitivity of $\approx 300\ \mu\mathrm{K}_{\mathrm{CMB}}\sqrt{\mathrm{s}}$. BICEP2 observed from the South Pole for three seasons from 2010 to 2012. A low-foreground region of sky with an effective area of 380 square degrees was observed to a depth of 87 nK-degrees in Stokes Q and U. In this paper we describe the observations, data reduction, maps, simulations and results. We find an excess of B-mode power over the base lensed-ΛCDM expectation in the range $30 < \ell < 150$, inconsistent with the null hypothesis at a significance of $> 5\sigma$. Through jackknife tests and simulations based on detailed calibration measurements we show that systematic contamination is much smaller than the observed excess. Cross correlating against WMAP 23 GHz maps we find that Galactic synchrotron makes a negligible contribution to the observed signal. We also examine a number of available models of polarized dust emission and find that at their default parameter values they predict power $\sim 5 - 10\times$ smaller than the observed excess signal (with no significant cross-correlation with our maps). However, these models are not sufficiently constrained by external public data to exclude the possibility of dust emission bright enough to explain the entire excess signal. 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 dust at 1.7σ. 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. Accounting for the contribution of foreground dust will shift this value downward by an amount which will be better constrained with upcoming datasets.

arXiv:1403.3985 / published PRL June 19

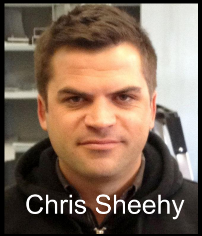
The BICEP2 Postdocs

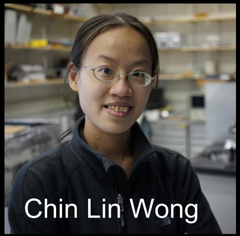


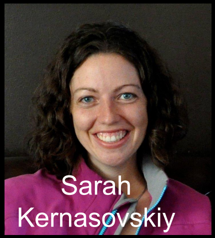




The BICEP2 Graduate Students







BICEP2 Winterovers

2010

2011

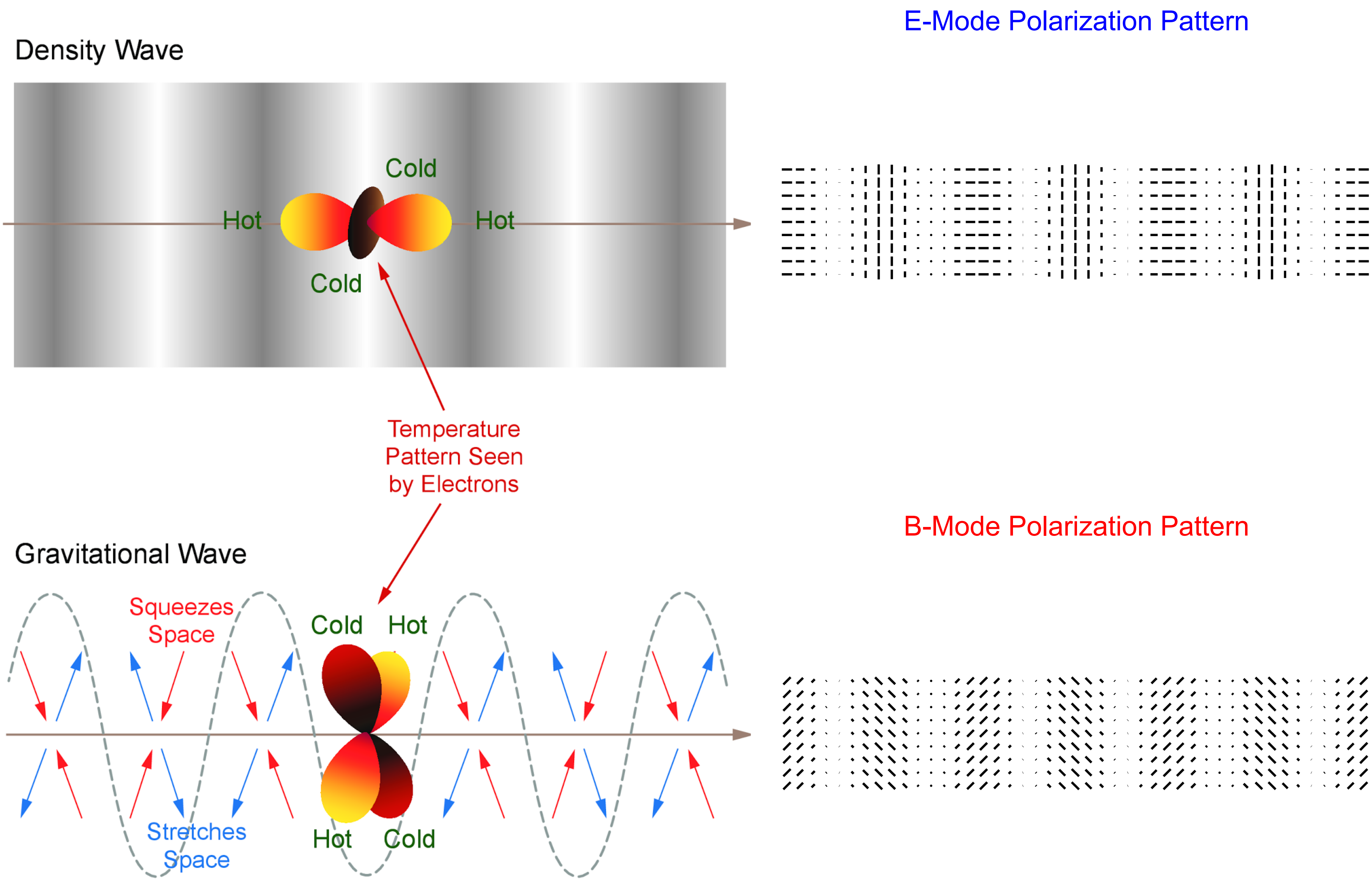
2012

launching Cosmology's greatest wild goose chase

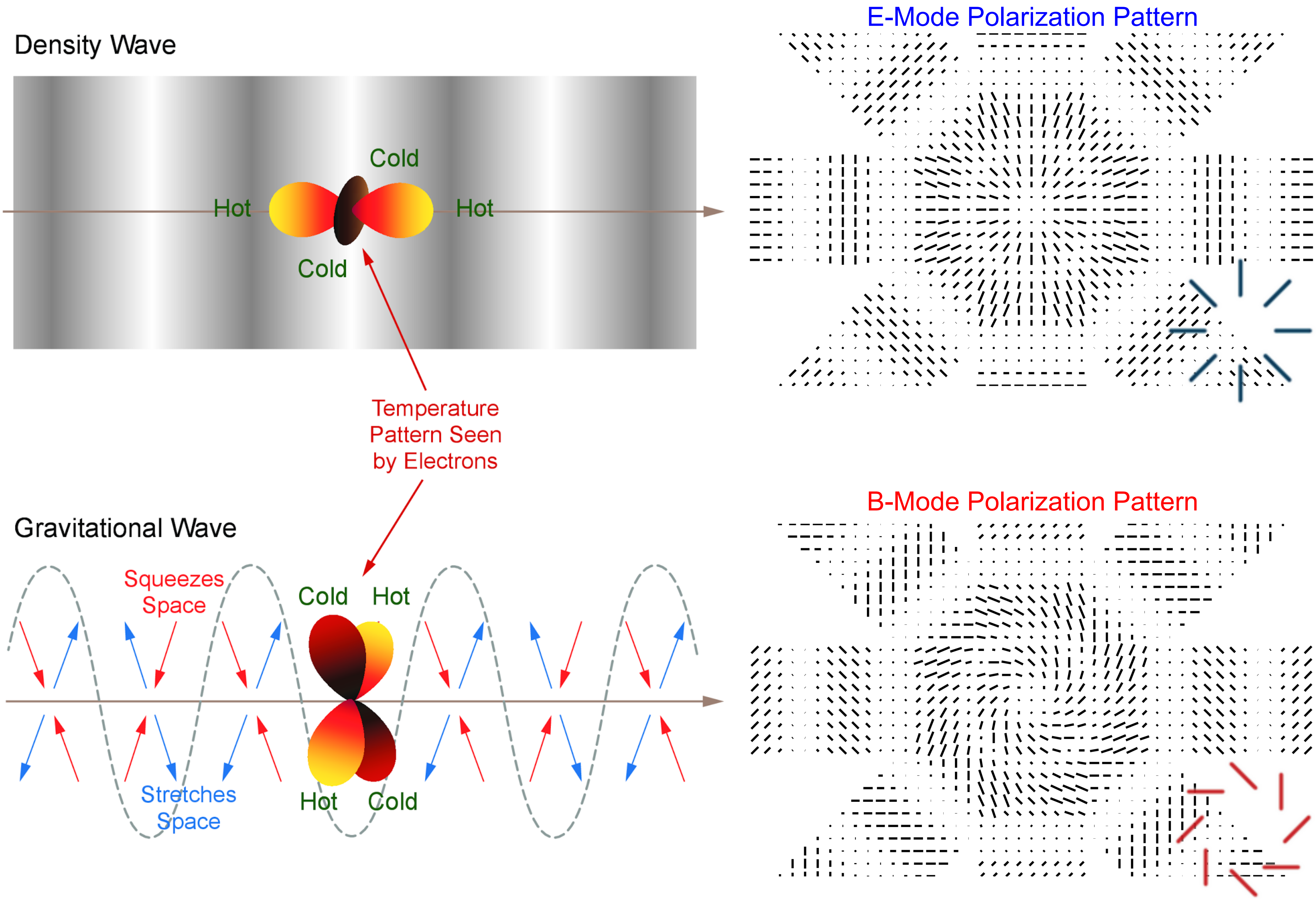
The Search for Inflationary B-Modes

Andrew Lange
Caltech Marvin L. Goldberger Professor of Physics
1957 - 2010

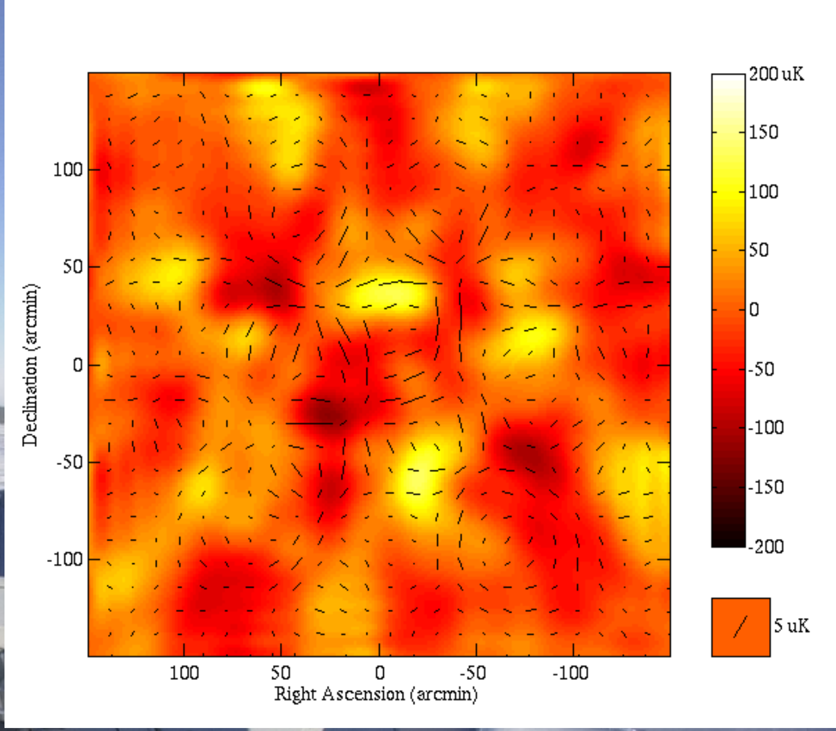
CMB Polarization



CMB Polarization



E-modes COSMO 2002: DASI first detects polarization of CMB



E-modes from the ground

- Deep, Concentrated coverage (few modes)
- Foreground avoidance (limited frequencies)
- Systematic control with (repeated) in-situ calibration
- Large detector count, rapid technology cycle
- Relentless observing – large number of null tests

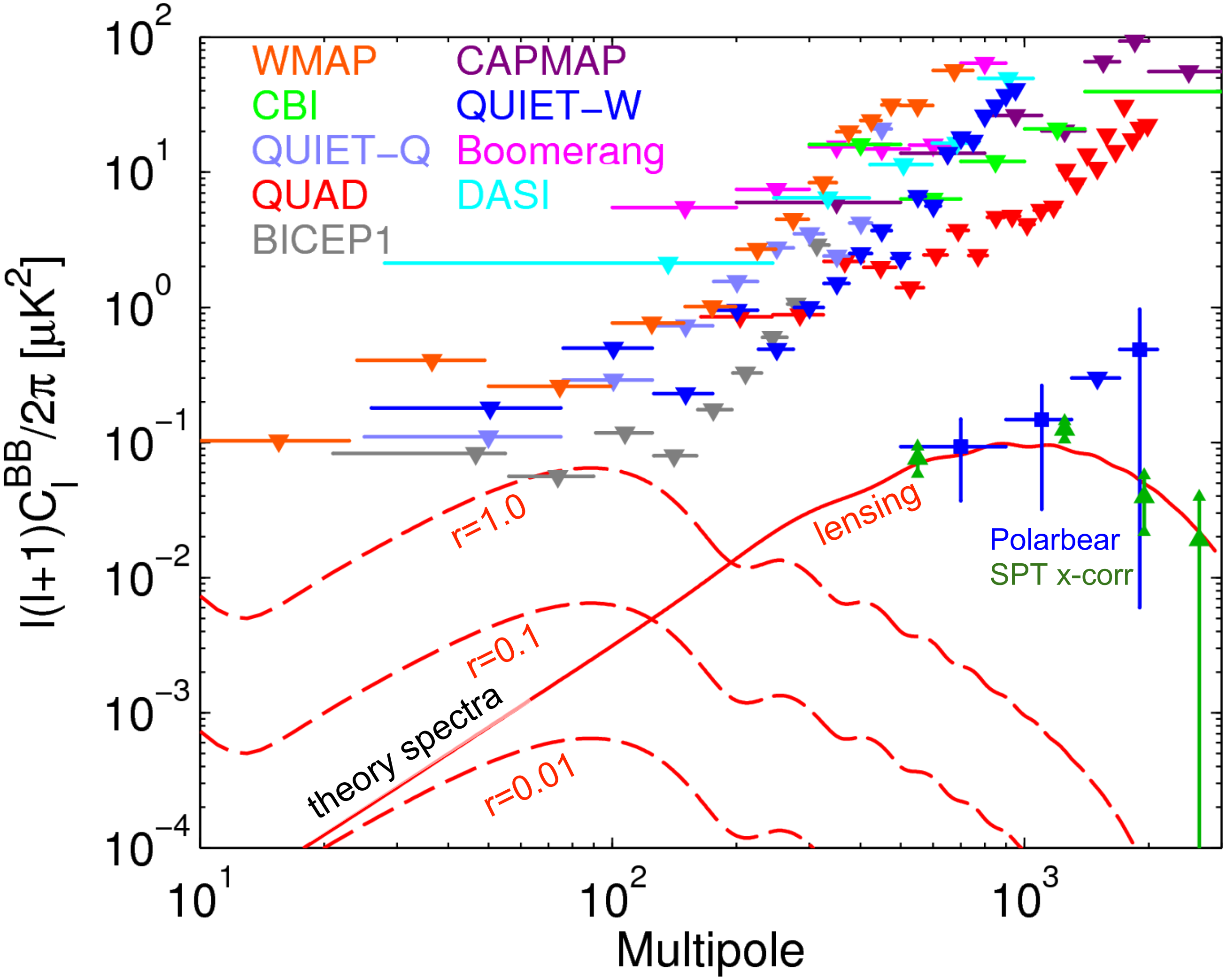
→ powerful recipe for high-confidence initial discovery

B-modes from the ground

- Deep, Concentrated coverage (few modes)
- Foreground avoidance (limited frequencies)
- Systematic control with (repeated) in-situ calibration
- Large detector count, rapid technology cycle
- Relentless observing – large number of null tests

→ powerful recipe for high-confidence initial discovery

The long search for Inflationary B-modes



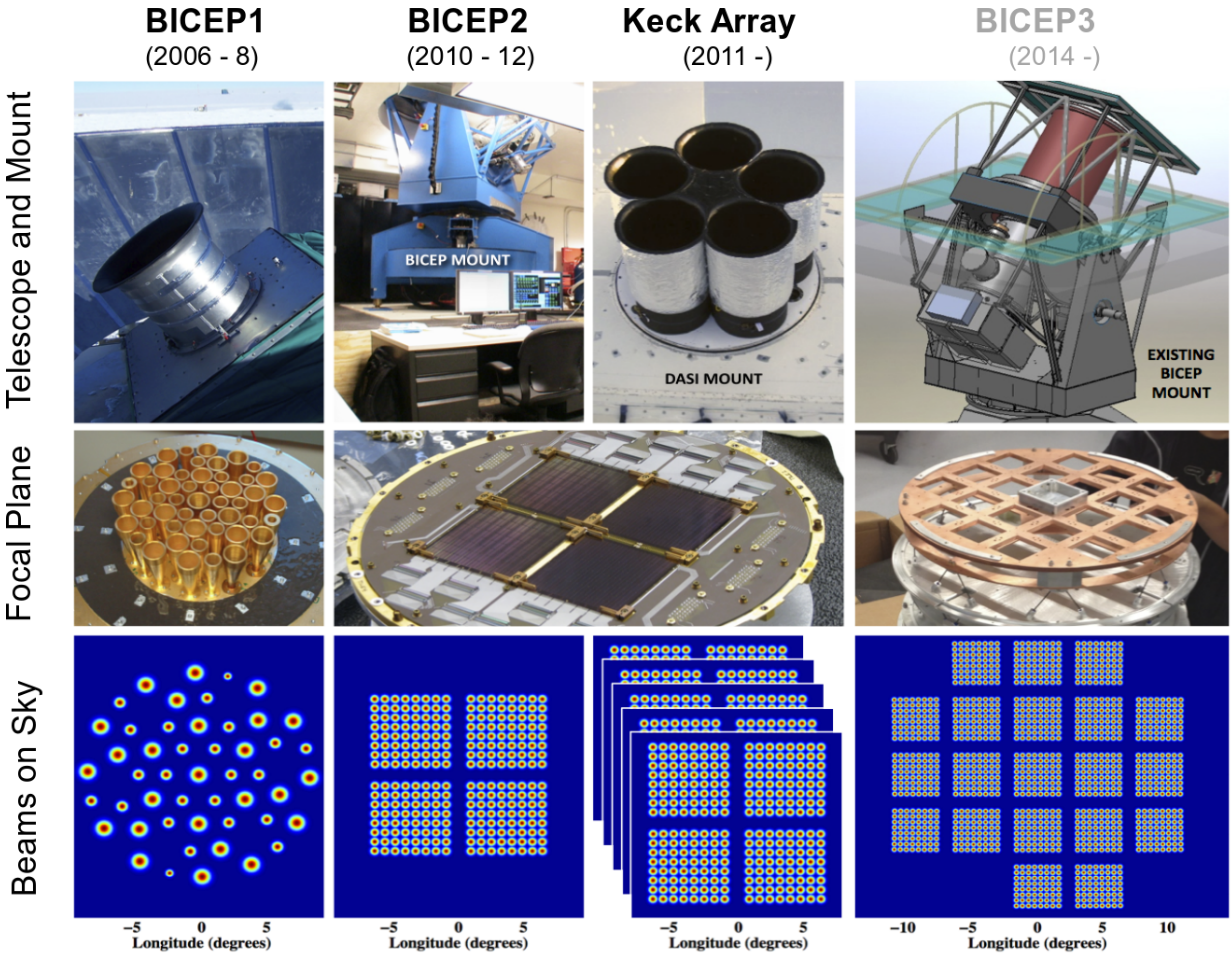
Best previous limit on r from BICEP1:

r < 0.7 (95% CL)

Note at high multipoles lensing B-mode dominant.

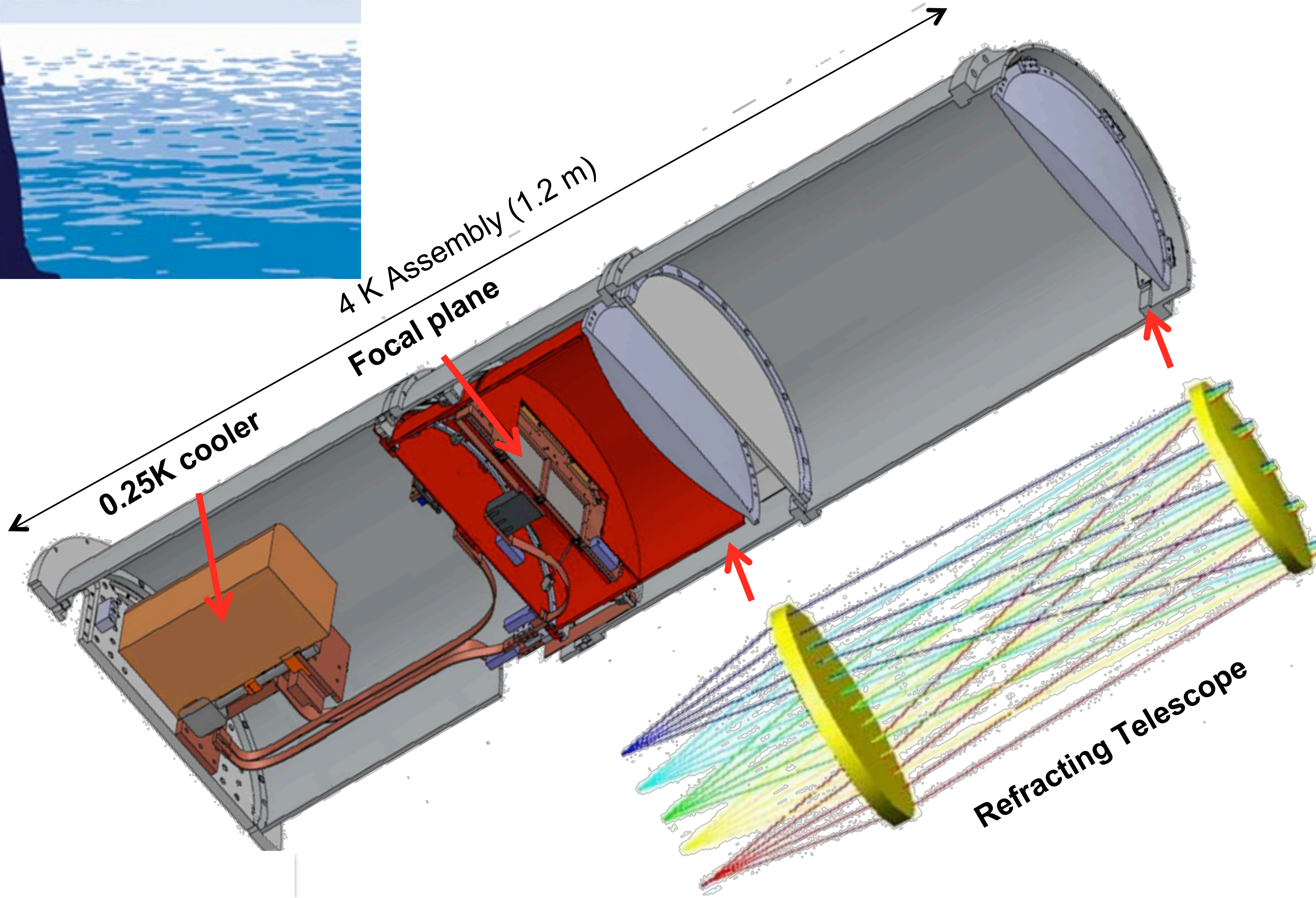
John Kovac for The Bicep2 Collaboration

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

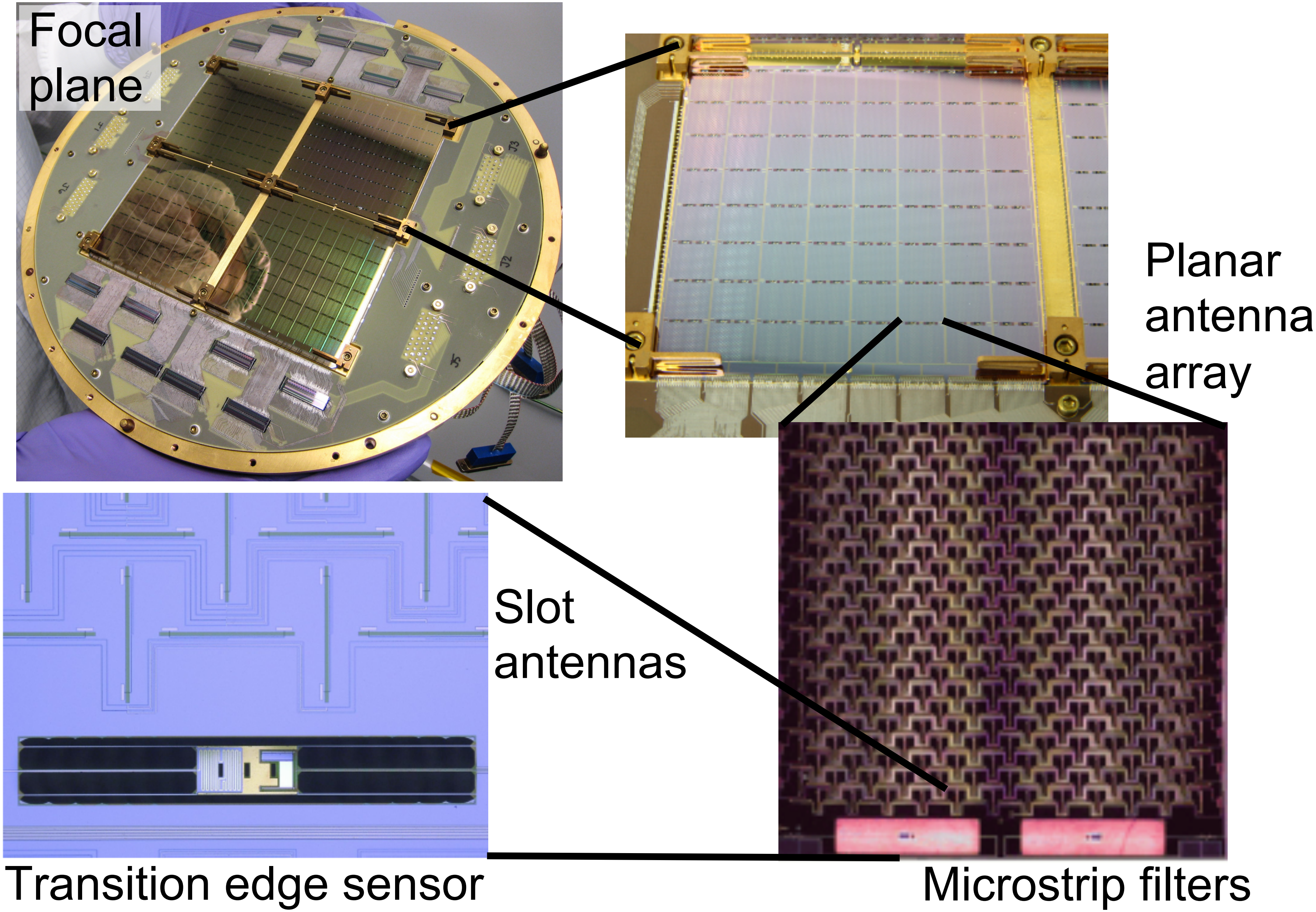

BICEP1
(2006 - 8)
BICEP2
(2010 - 12)
Keck Array
(2011 -)
BICEP3
(2014 -)
Telescope and Mount
BICEP MOUNT
DASI MOUNT
EXISTING
BICEP
MOUNT
Focal Plane
Beams on Sky
−5 0 5
Longitude (degrees)
−5 0 5
Longitude (degrees)
−5 0 5
Longitude (degrees)
−10 −5 0 5 10
Longitude (degrees)

BICEP2 Experimental Concept

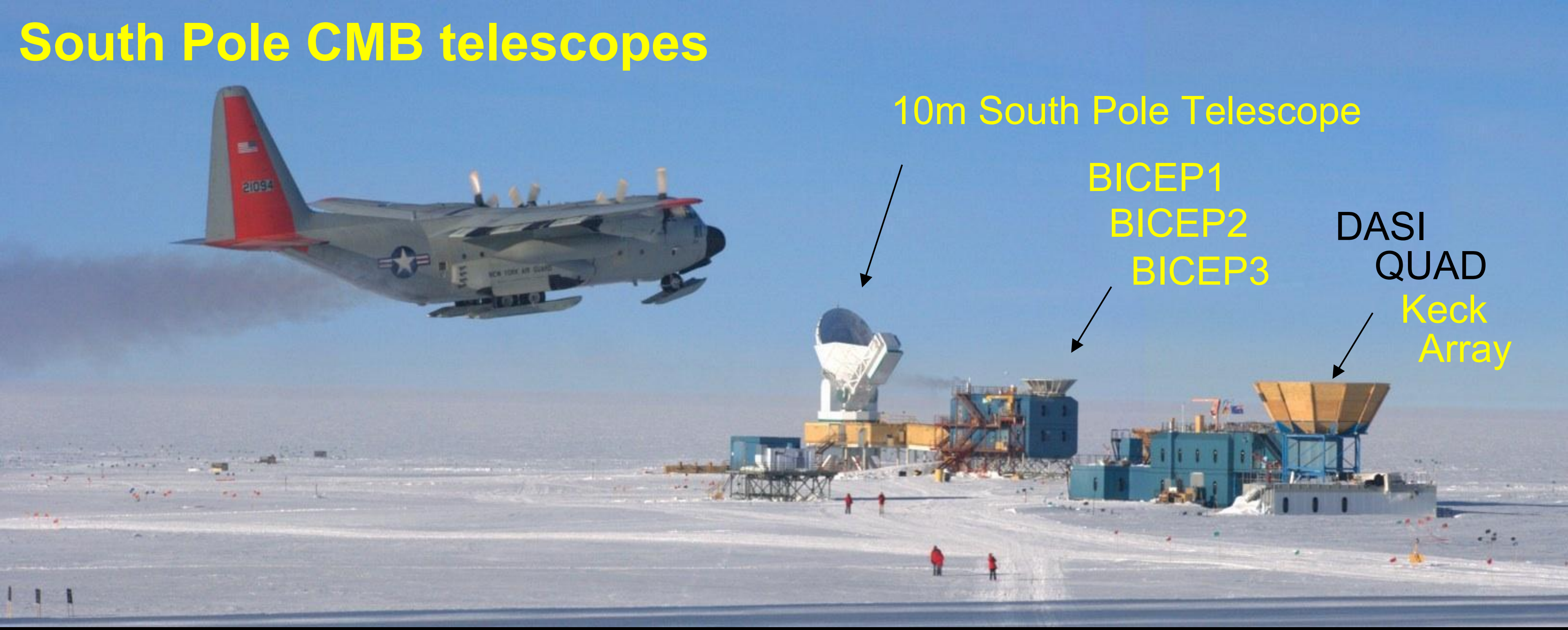
- Small aperture
- Wide field of view
- Cold refractor



Mass-produced superconducting detectors from JPL



South Pole CMB telescopes



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

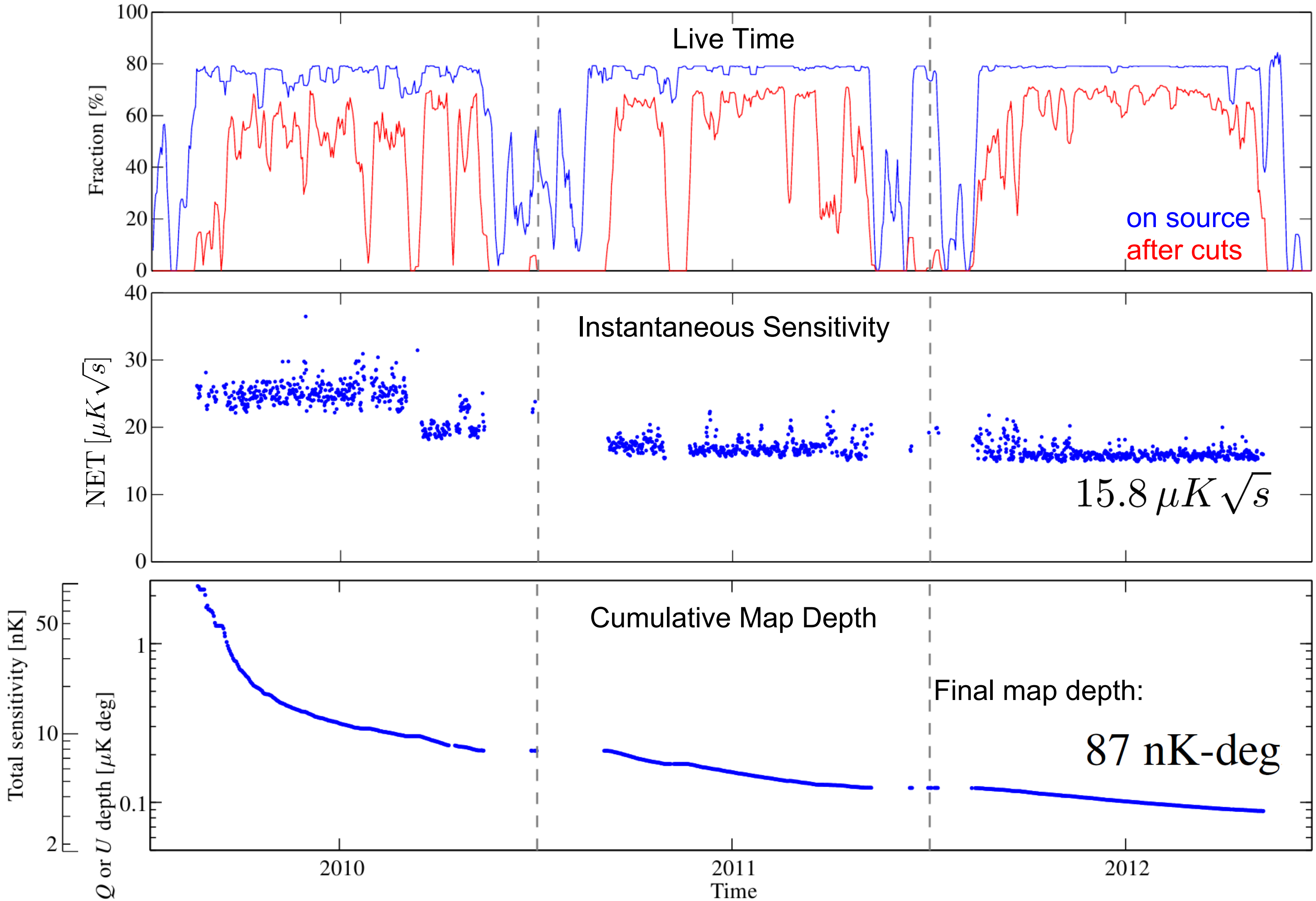
Dry, stable atmosphere and 24h coverage of "Southern Hole".

Atacama, Greenland(?) excellent alternatives offering different coverage

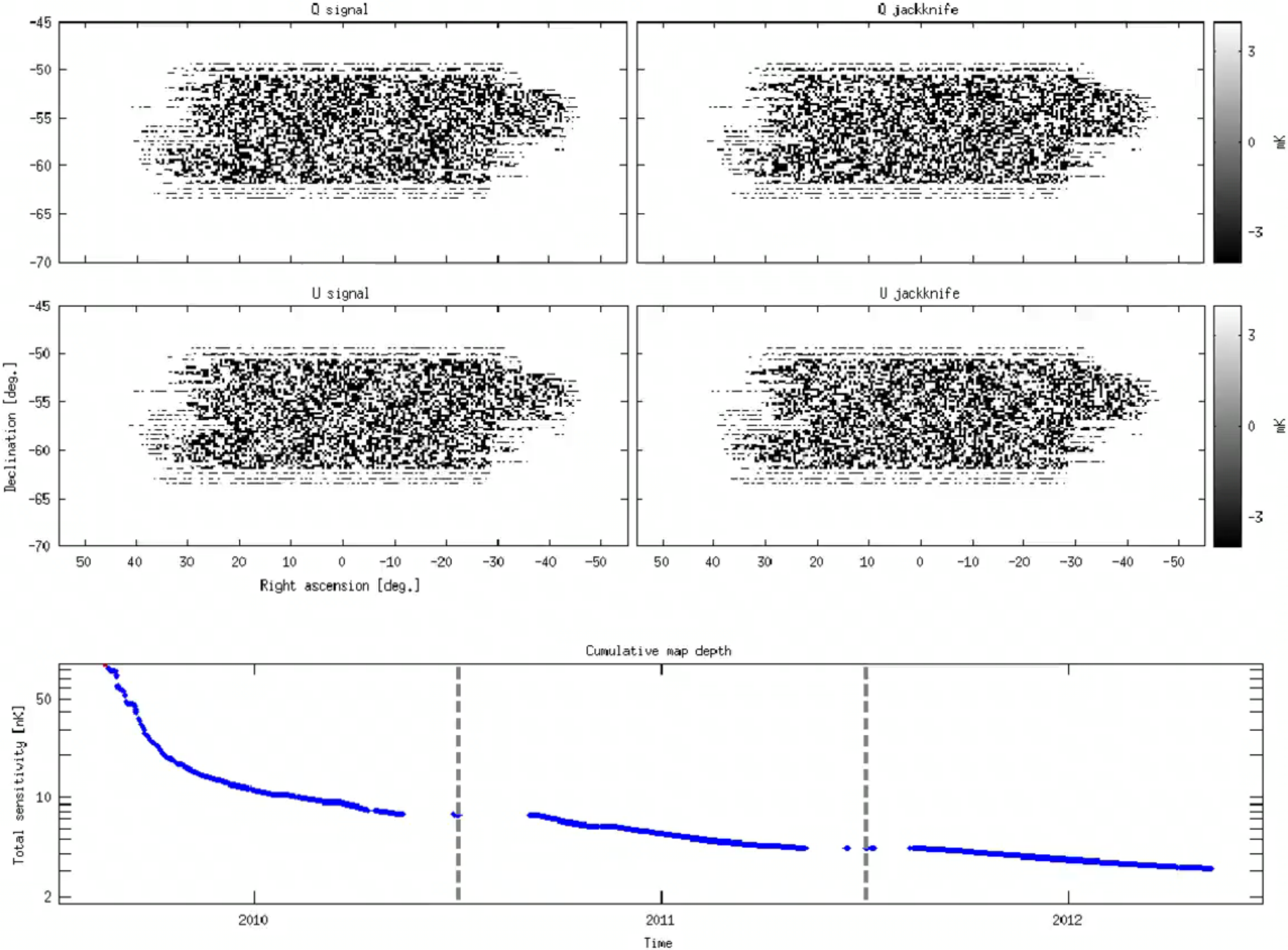
South Pole: “Relentless Observing”


photo: Keith Vanderlinde

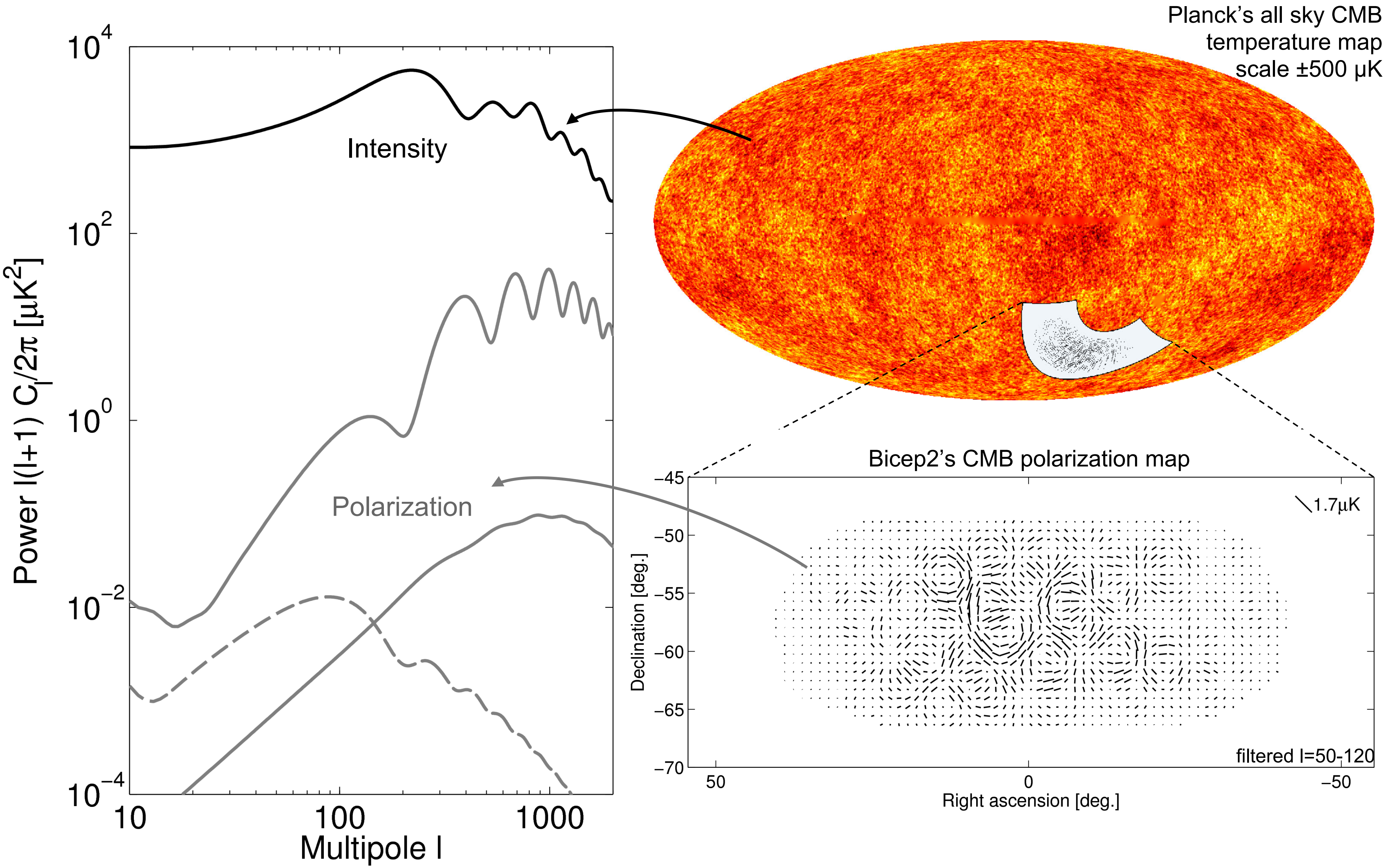
BICEP2 3-year Data Set



John Kovac for The Bicep2 Collaboration

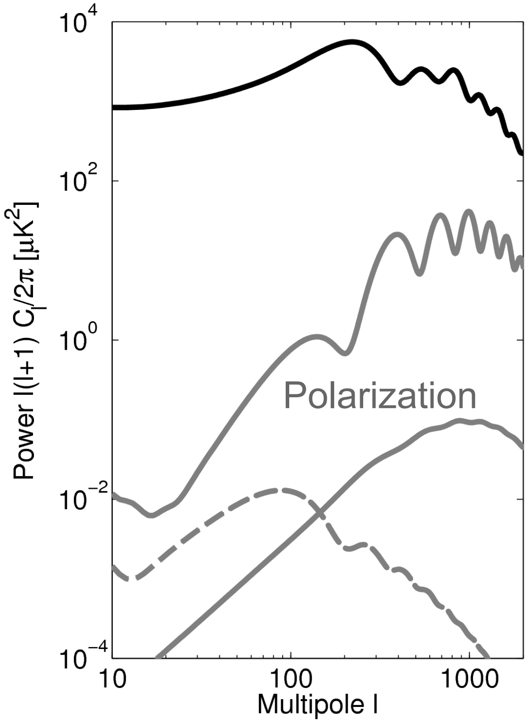

Q signal
Q jackknife
U signal
U jackknife
Declination [deg.]
Right ascension [deg.]
mK
Cumulative map depth
Total sensitivity [nK]
Time
2010
2011
2012

Cosmic Microwave Background

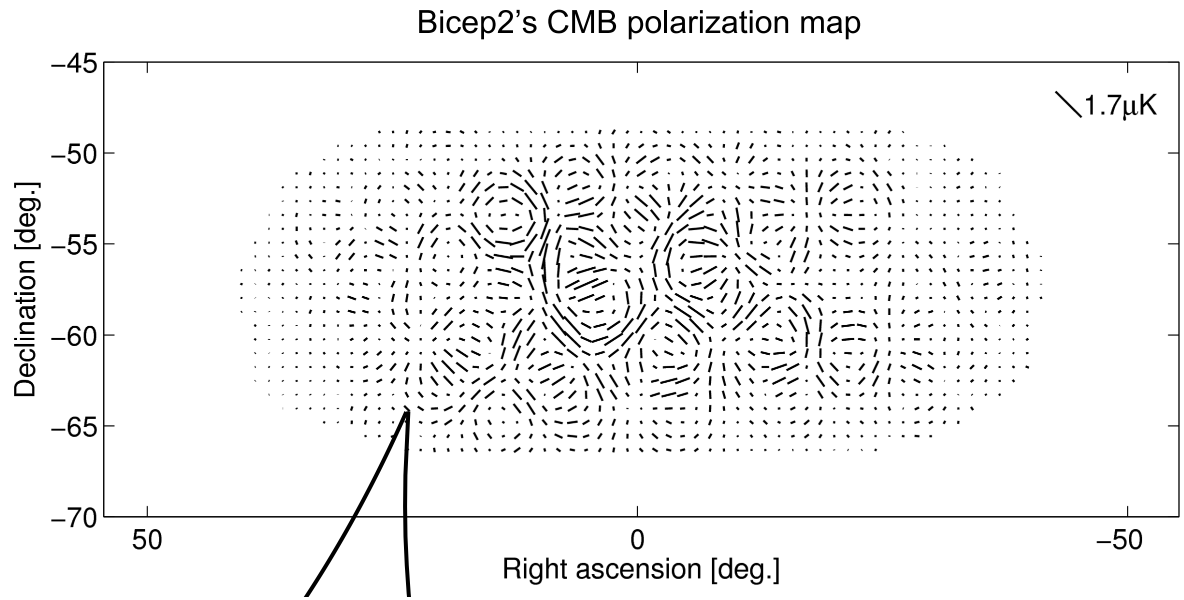


The Bicep2 Collaboration

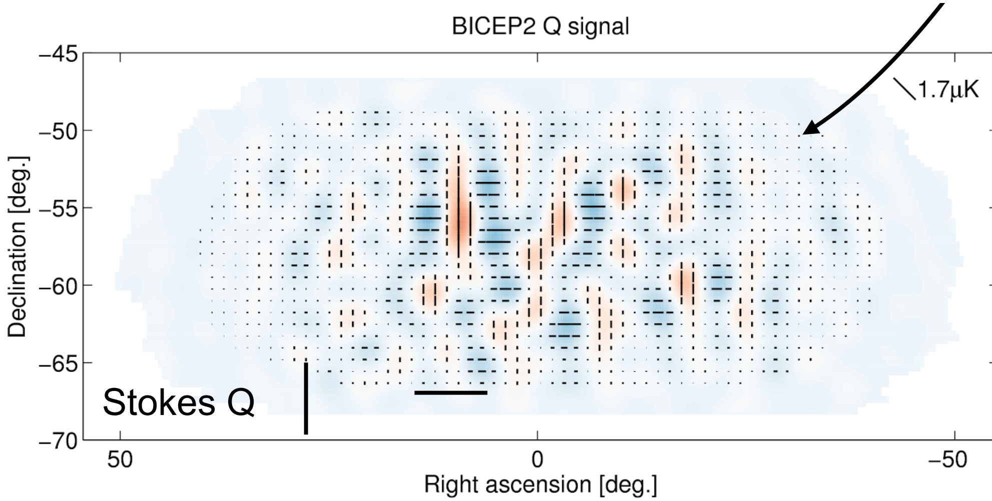
CMB Polarization

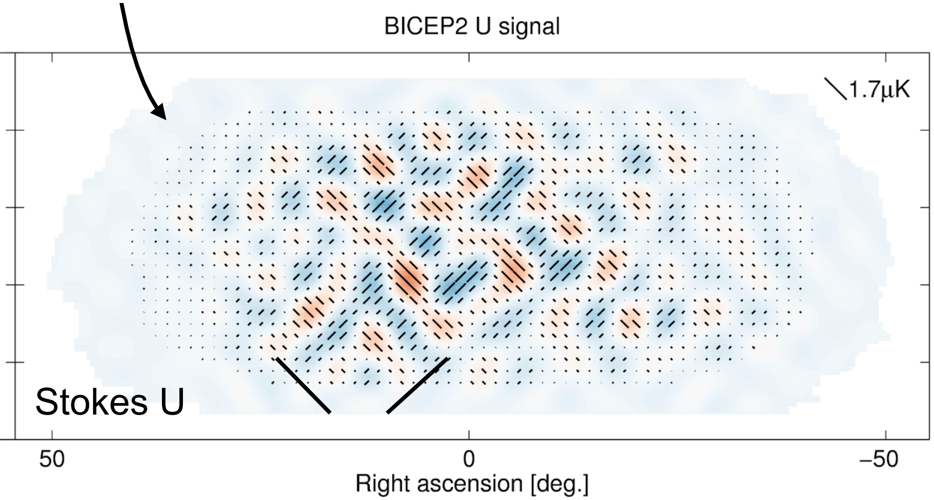


Need 2D basis to describe polarization map...



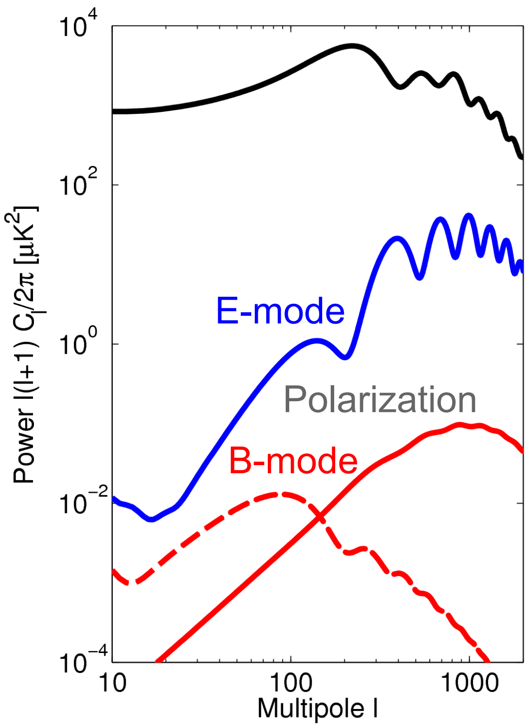
...familiar choice: Stokes Parameters Q&U



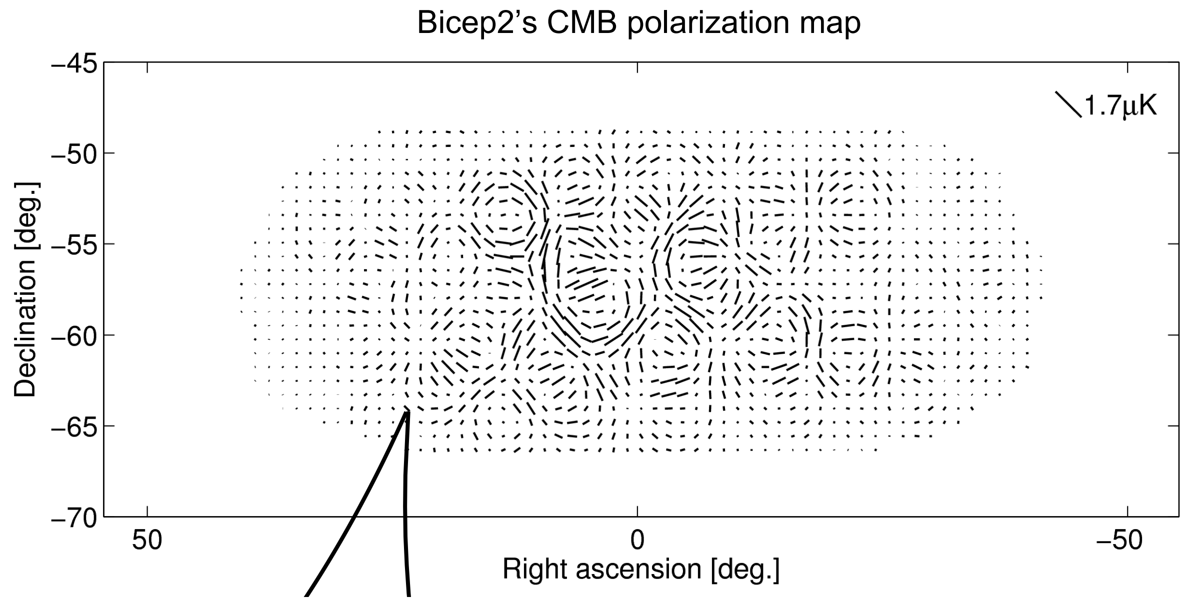


The Bicep2 Collaboration

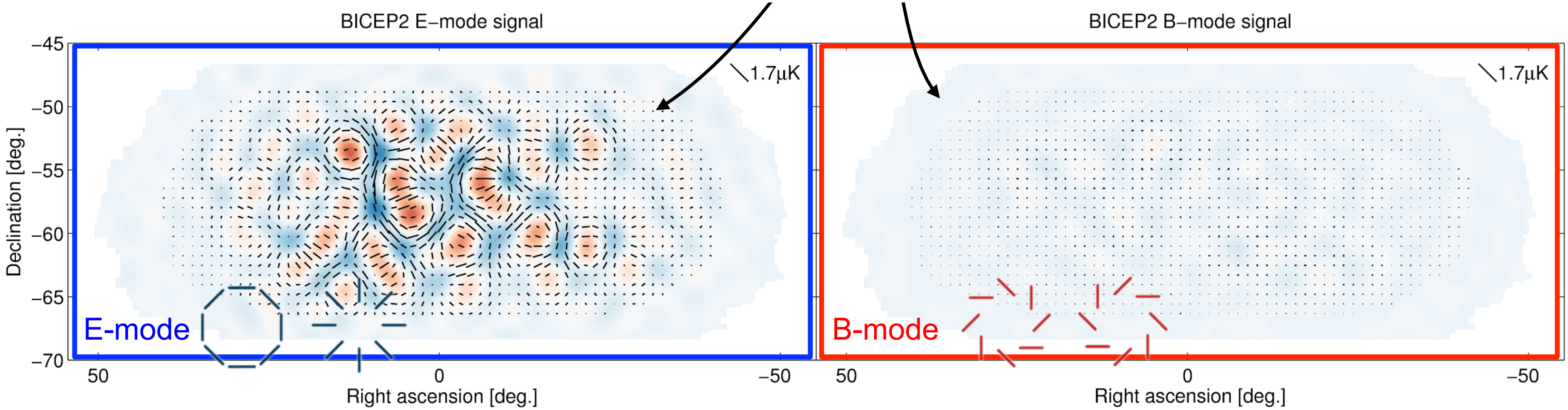
CMB Polarization



Need 2D basis to describe polarization map...

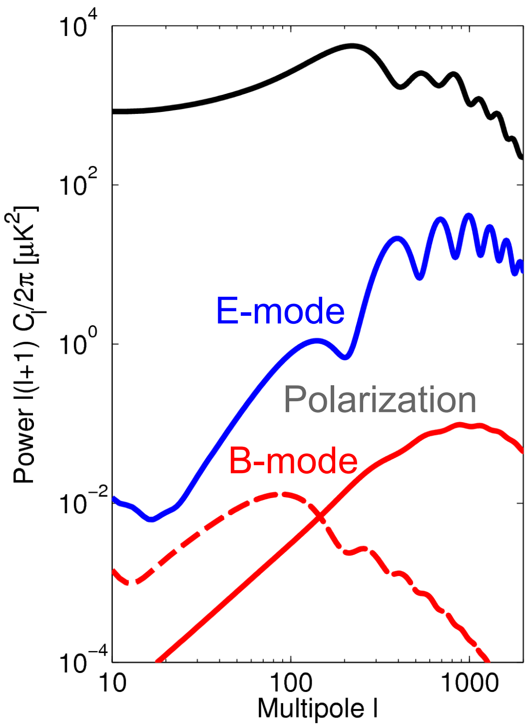


...clever choice in this case: E&B-modes

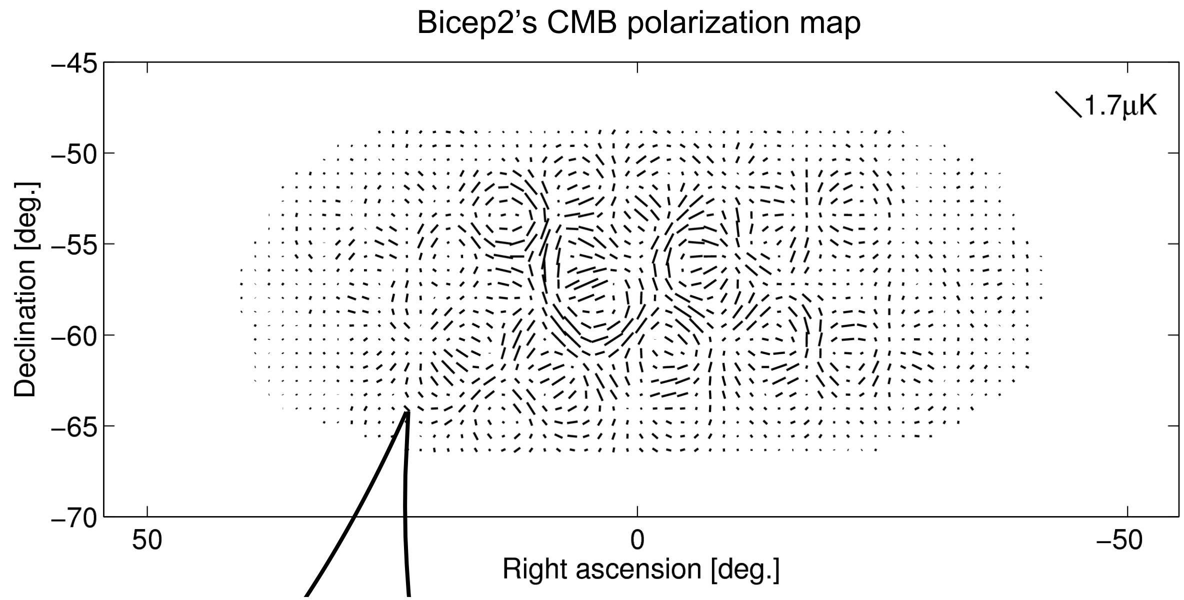


The Bicep2 Collaboration

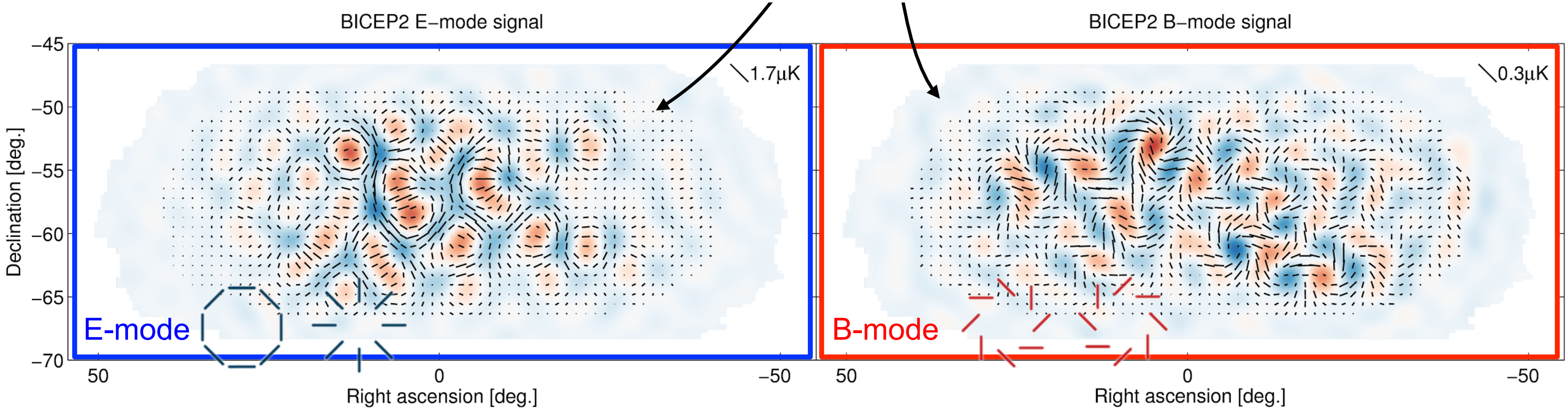
CMB Polarization



Need 2D basis to describe polarization map...

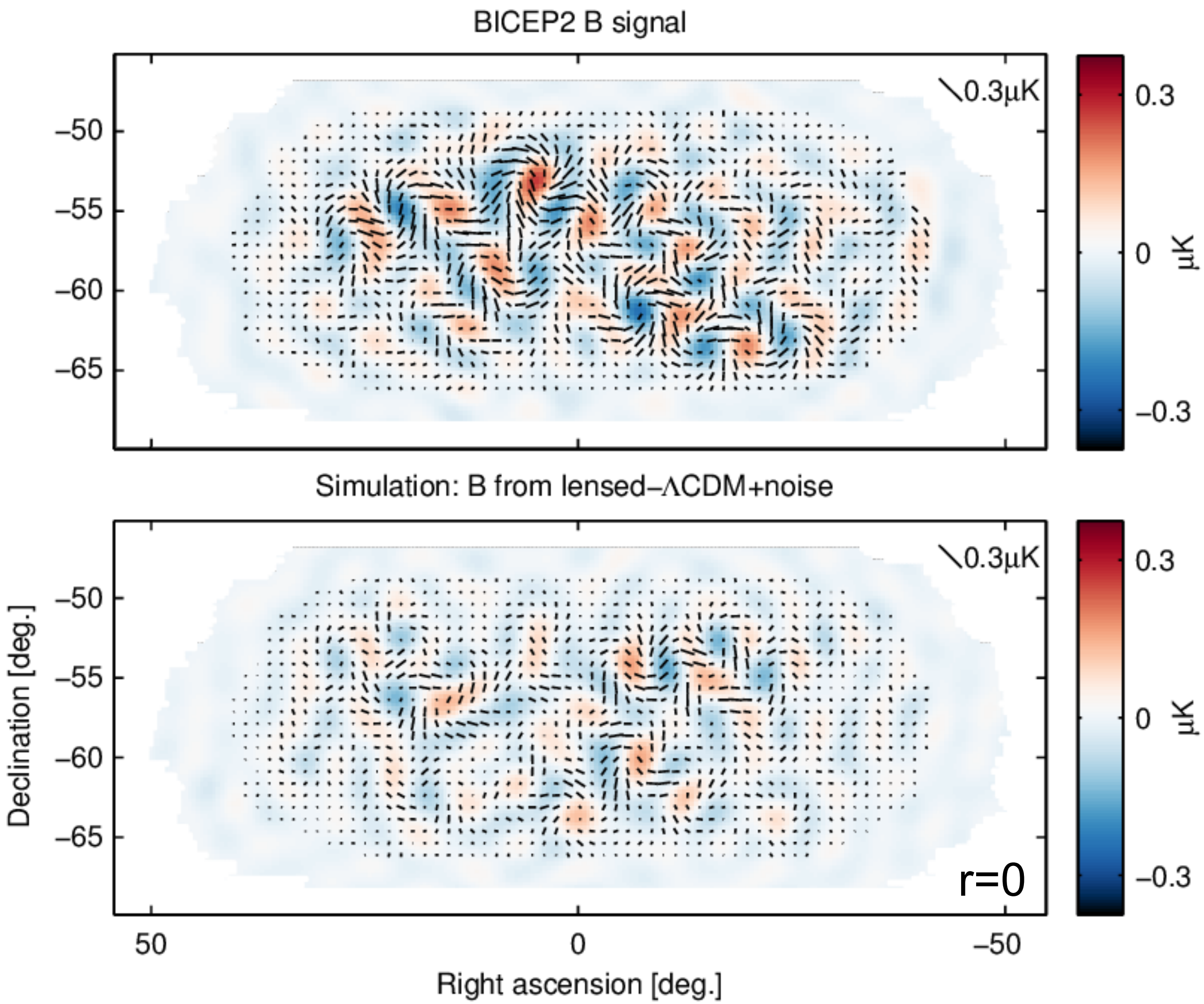


...clever choice in this case: E&B-modes



The Bicep2 Collaboration

B-mode Map vs. Simulation



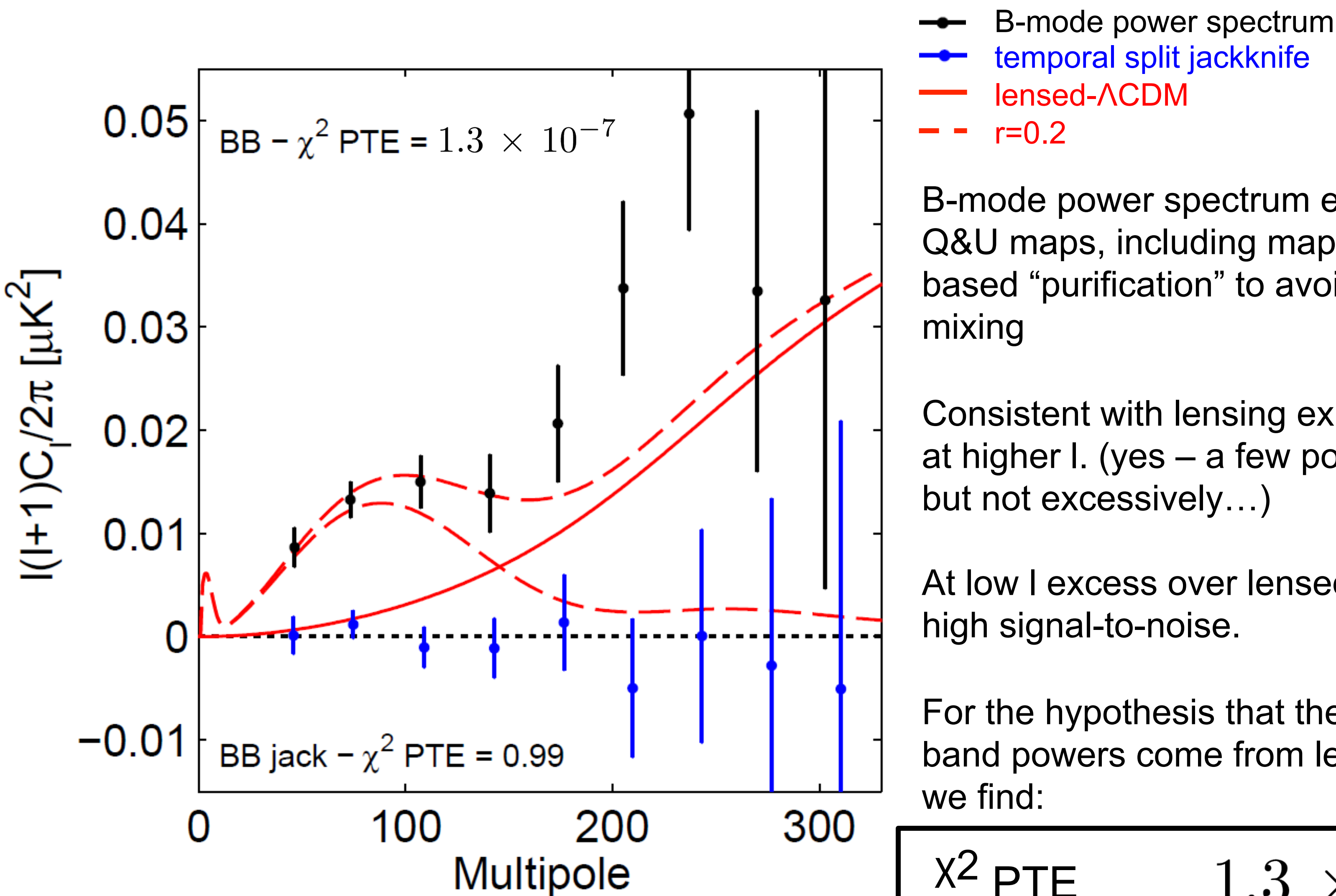
Analysis "calibrated" using lensed-ΛCDM+noise simulations.

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

We perform various filtering operations: Use the sims to correct for these

Also use the sims to derive the final uncertainties (error bars)

BICEP2 B-mode Power Spectrum



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

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

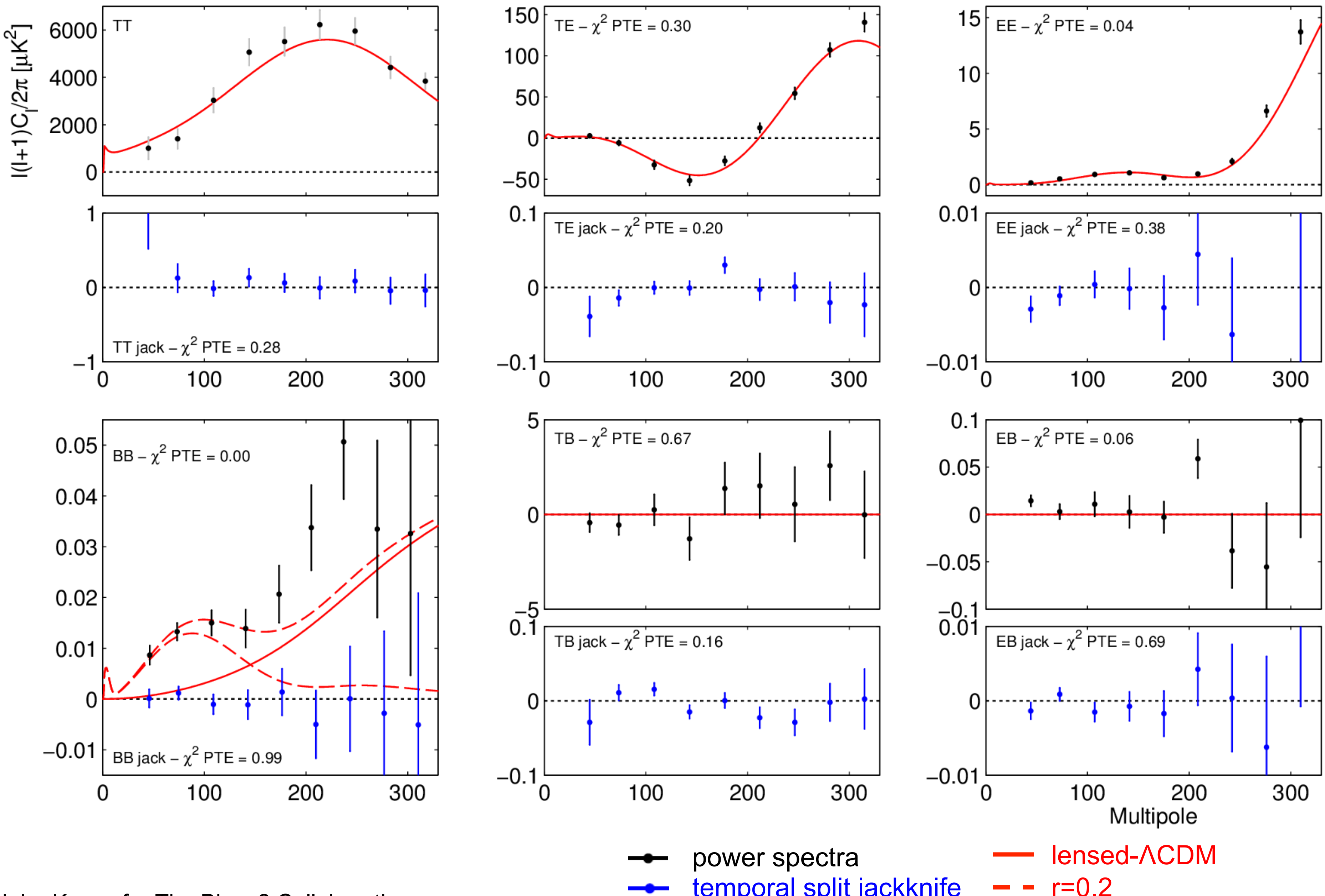
At low l excess over lensed-ΛCDM with high signal-to-noise.

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

χ^2 PTE	1.3×10^{-7}
significance	$5.3\,\sigma$

John Kovac for The Bicep2 Collaboration

Temperature and Polarization Spectra



John Kovac for The Bicep2 Collaboration

Check Systematics: Jackknifes

14 jackknife tests applied to 3 spectra, 4 statistics

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. 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.

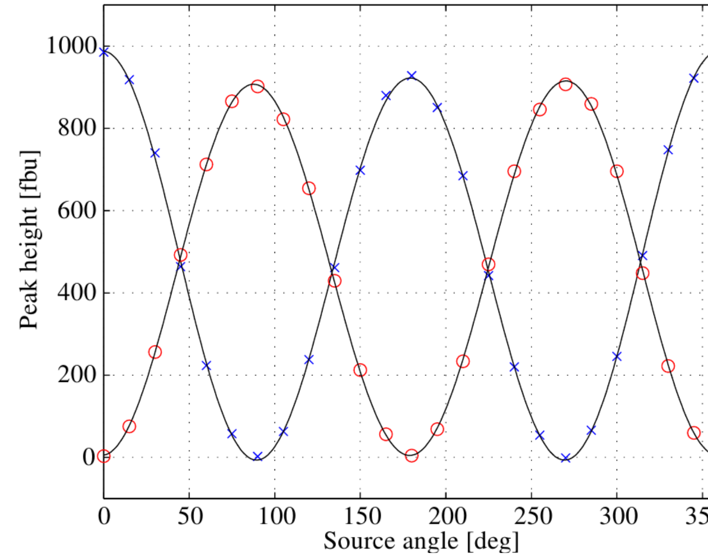
See parallel session talk by Chris Sheehy

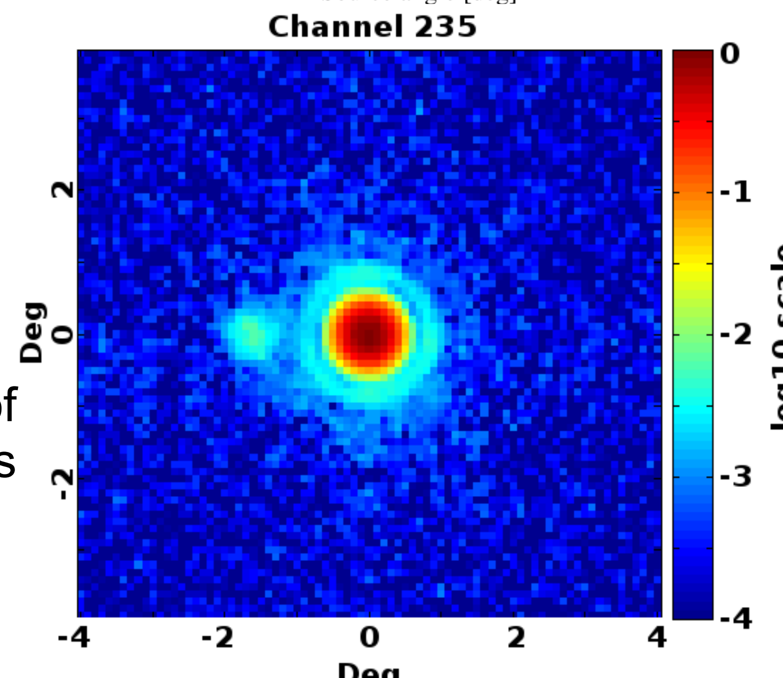
Calibration Measurements

For instance...

Far field beam mapping

Detector Polarization Calibration





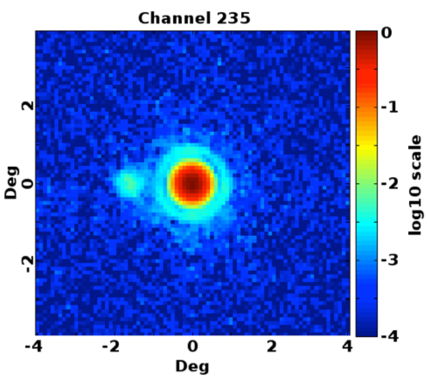
Hi-Fi beam maps of individual detectors

Detailed description in companion Instrument Paper

We know our Beam Shapes

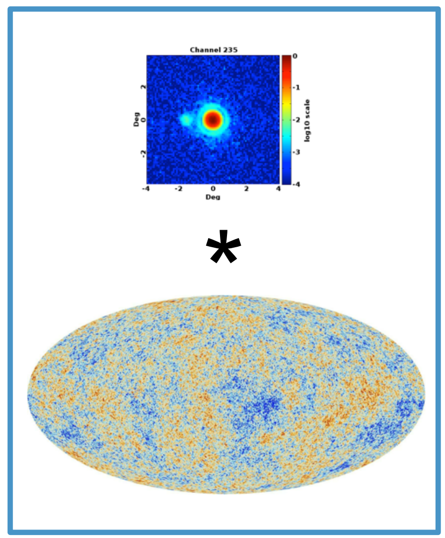
Because contamination from beam shape mismatch is entirely deterministic, we can both remove it (deprojection) **and** predict it in simulation using calibration data as input.

Calibration data for each channel

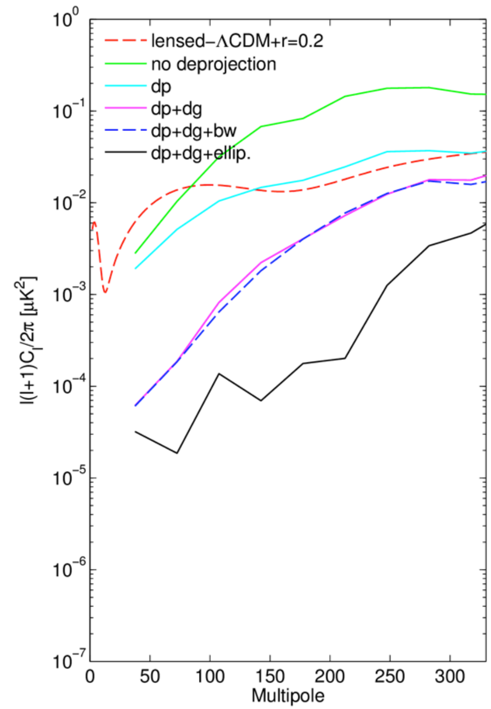


Simulation

(explicit convolution with Planck T map)



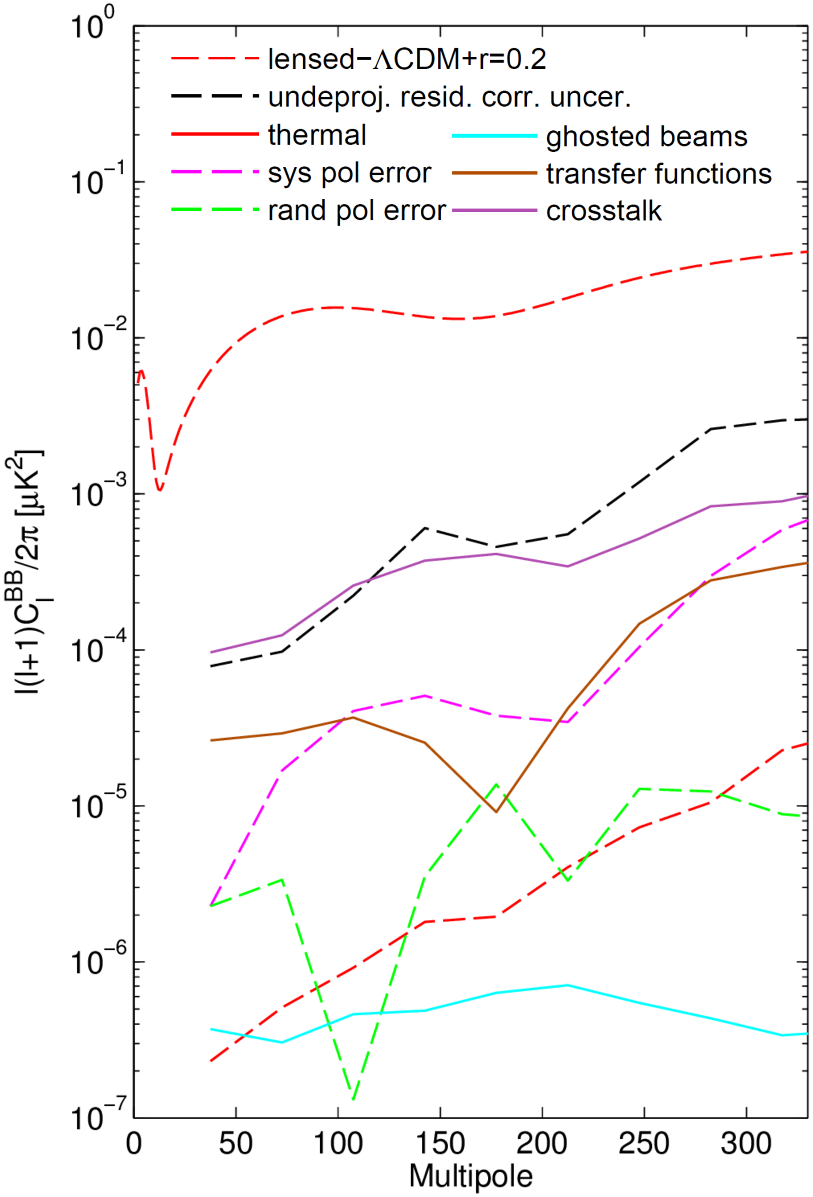
Predictions of contamination



See parallel session talk by Chris Sheehy

John Kovac for The Bicep2 Collaboration

Systematics beyond Beam imperfections



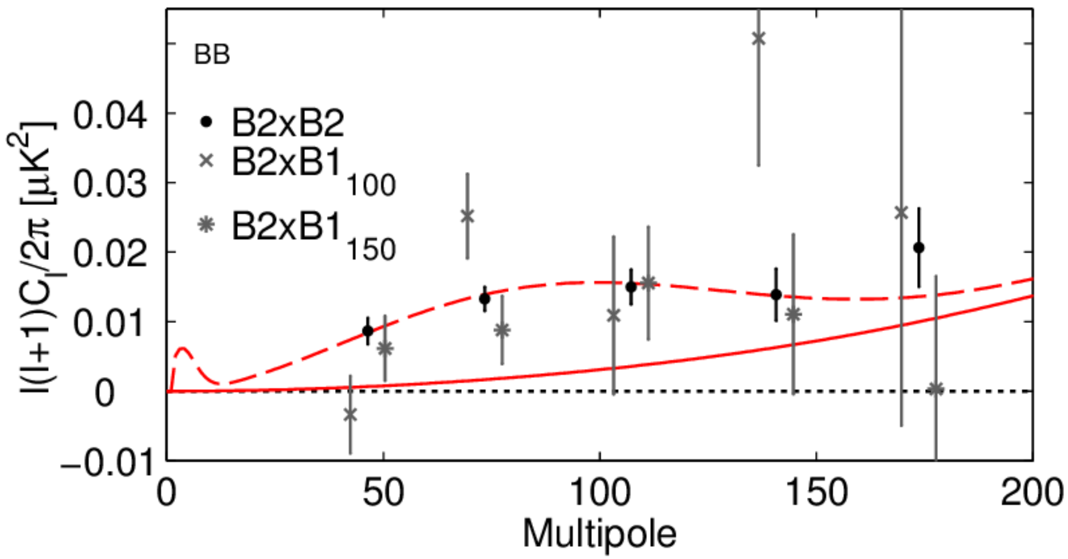
All systematic effects that we could imagine were investigated!

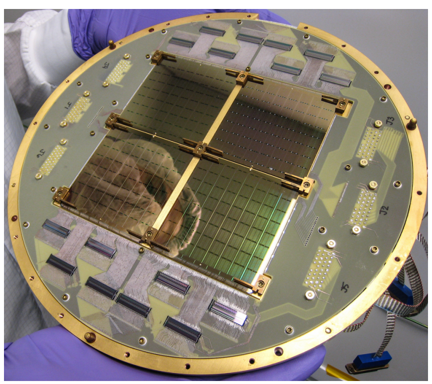
We find with high confidence that the apparent signal *cannot be explained* by instrumental systematics!

See parallel session talk by Chris Sheehy

John Kovac for The Bicep2 Collaboration

Cross Correlation with BICEP1





BICEP2: Phased antenna array and TES readout 150 GHz

BICEP1: Feedhorns and NTD readout 150 and 100 GHz

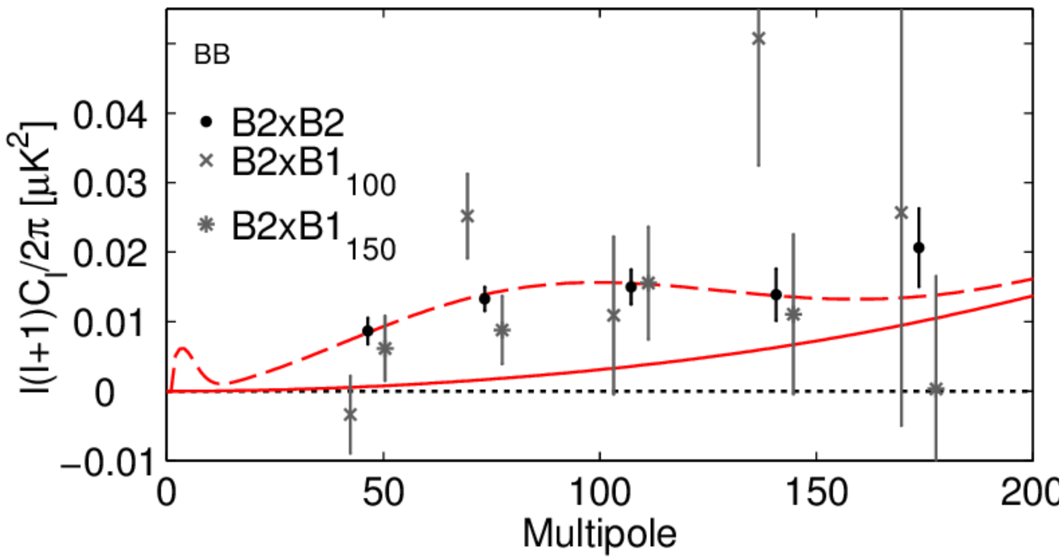
Though less sensitive, BICEP1 applied **different technology** (systematics control) and **multiple colors** (foreground control) to the **same sky**.

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

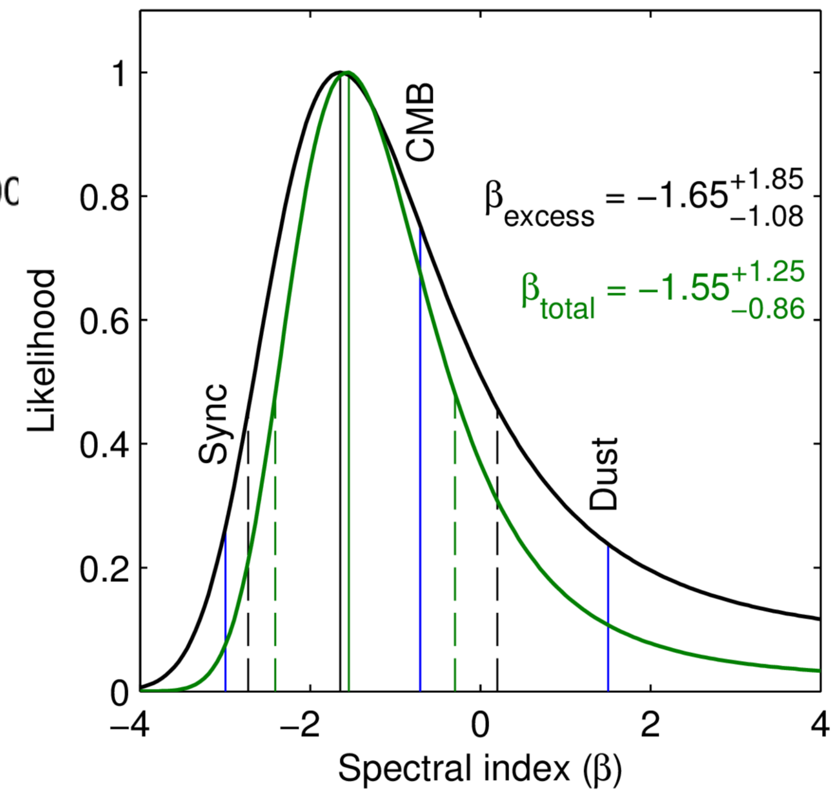
Cross with BICEP1_{100} shows **~3σ** detection of BB power

John Kovac for The Bicep2 Collaboration

Spectral Index of the B-mode Signal



Likelihood ratio test: consistent with CMB spectrum, disfavor pure dust for excess at **1.7σ**



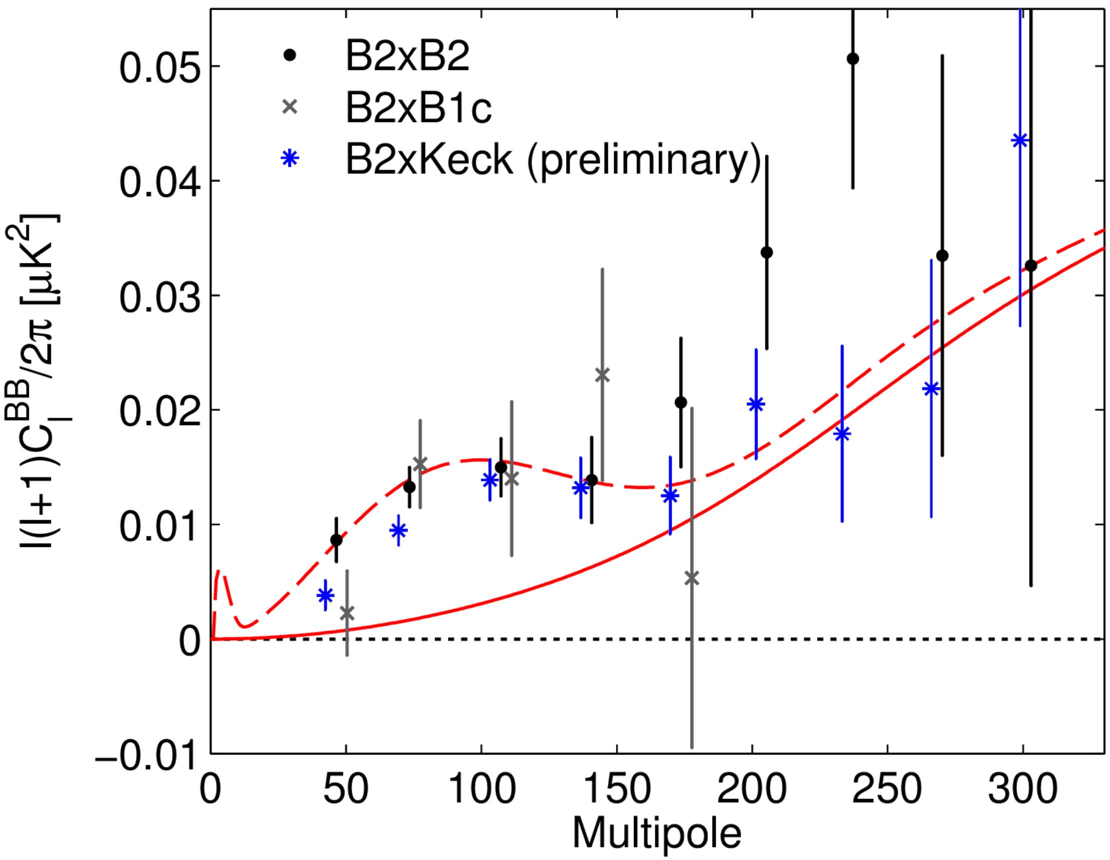
Comparison of B2 auto with $B2_{\mathbf{150}}$ x $B1_{\mathbf{100}}$ constrains signal frequency dependence, independent of foreground projections

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):

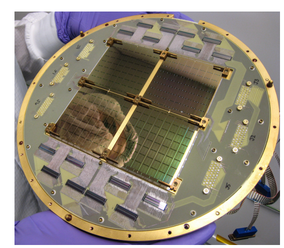


BICEP2 auto spectrum compatible with B2xB1c cross spectrum

~3σ evidence of excess power in the cross spectrum

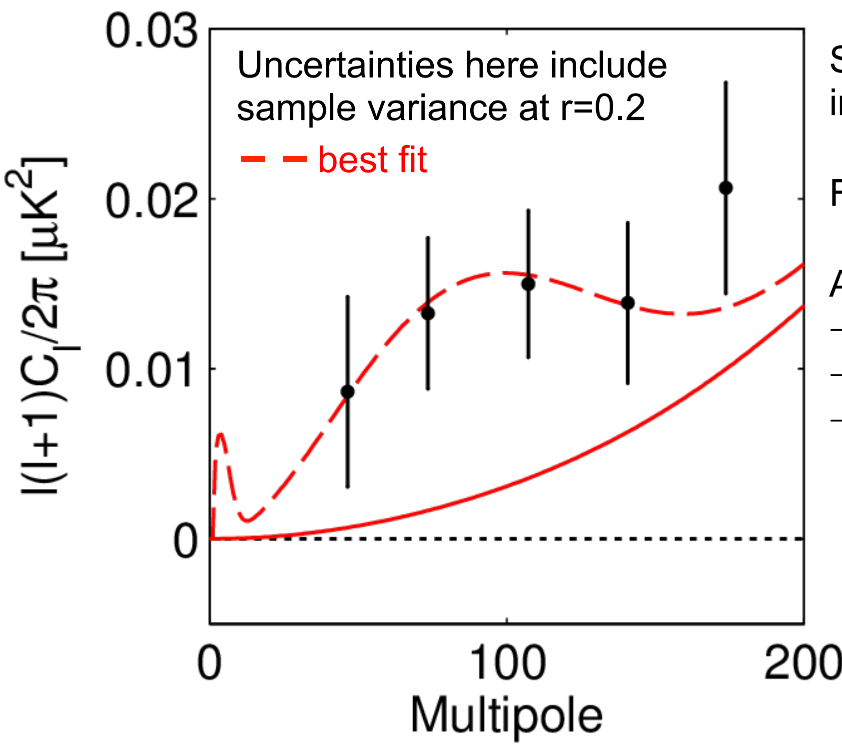
Additionally form cross spectrum with 2 years of data from *Keck Array*, the successor to BICEP2

Excess power is also evident in the B2xKeck cross spectrum



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

Formal constraint on r

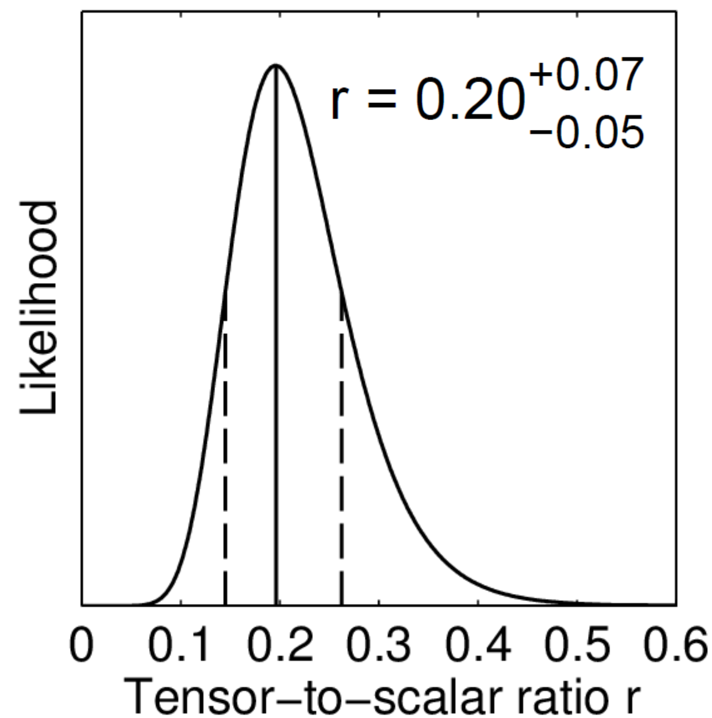


Substantial excess power in the region where the inflationary gravitational wave signal is expected to peak

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)



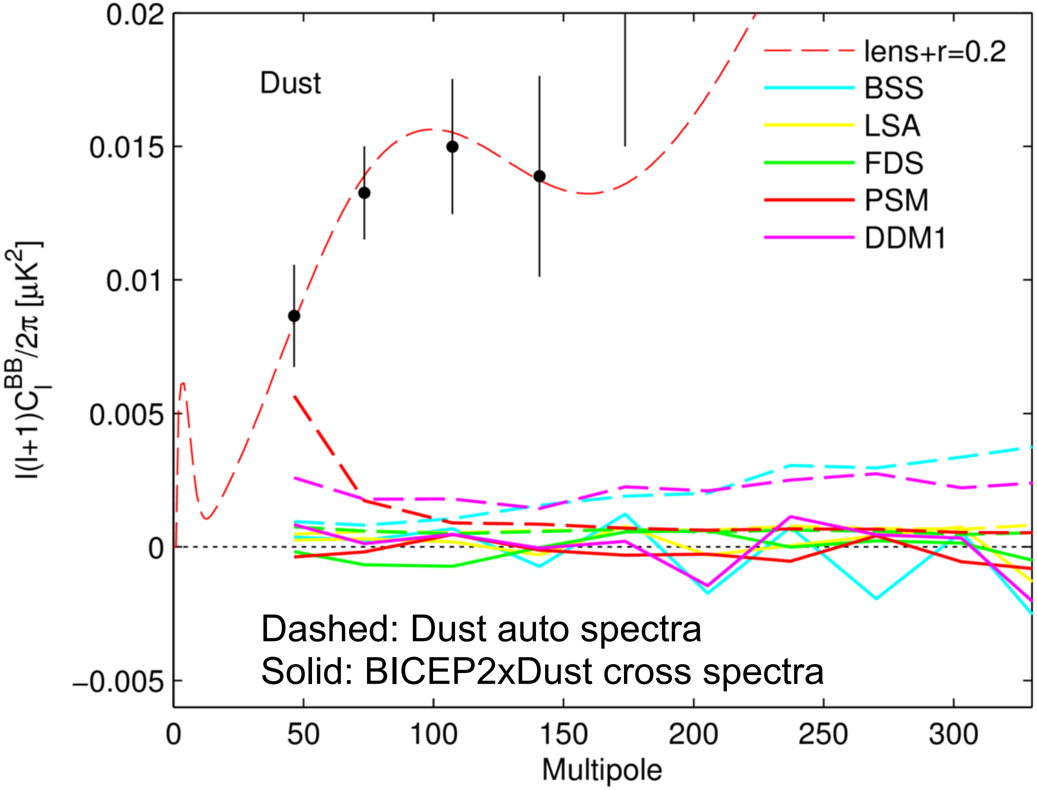
Within this simplistic model we find:

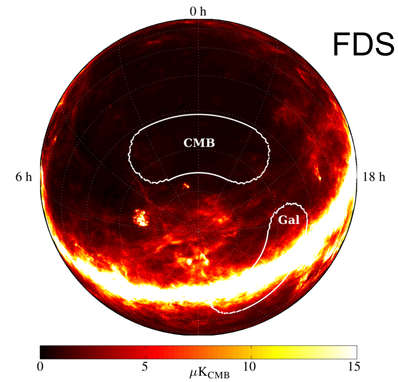
r = 0.2 with uncertainties dominated by sample variance

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

r = 0 ruled out at 7.0σ

Polarized Dust Foreground Projections





FDS Model

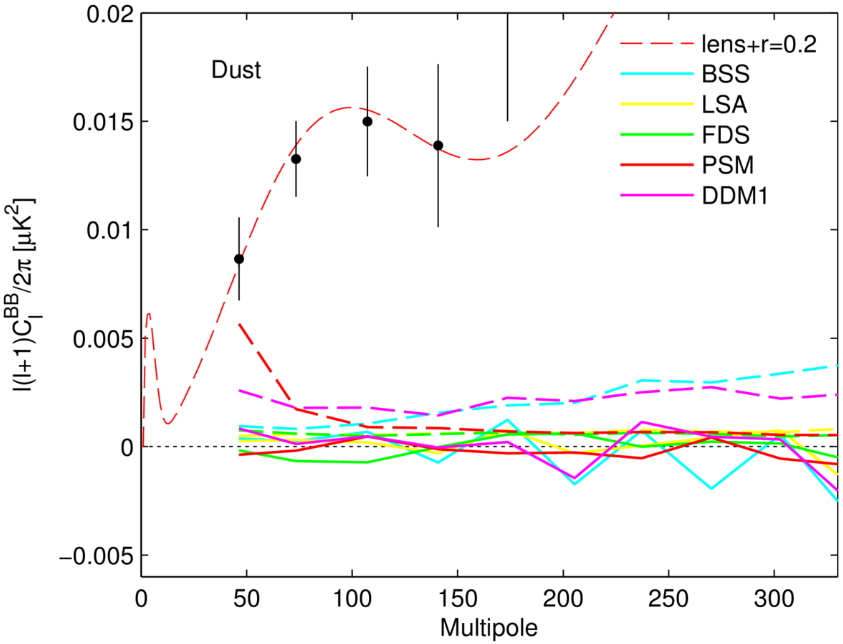
The BICEP2 region is chosen to have lowest foreground emission based on available pre-Planck models.

Use models of polarized dust emission to estimate foregrounds. **(default parameter values)**

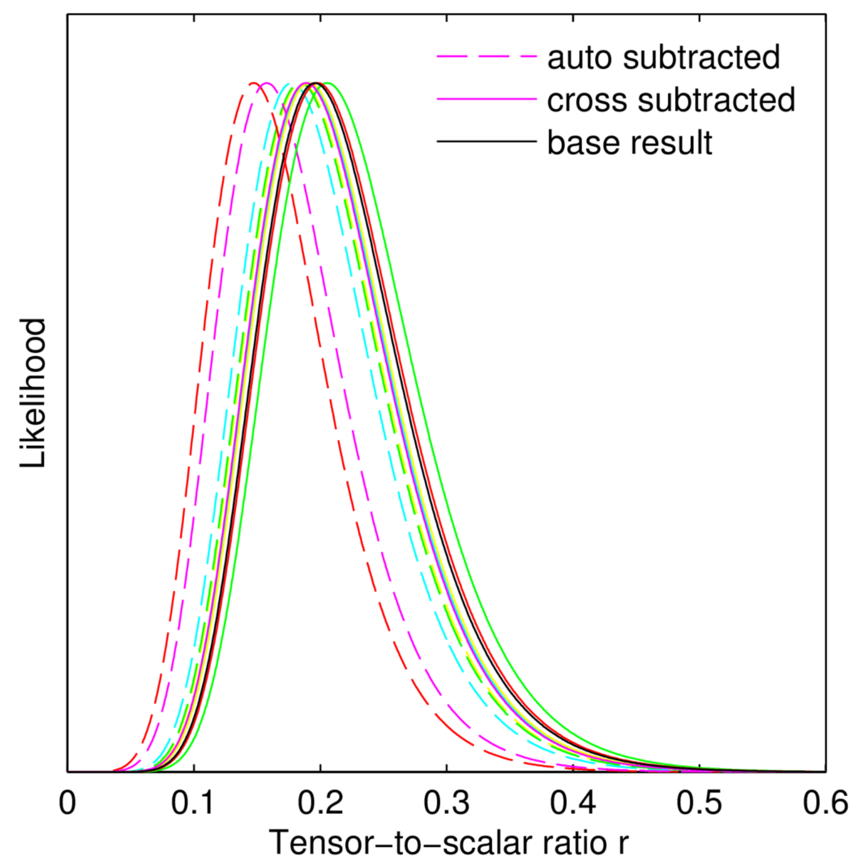
Dust model auto spectra are well below observed signal level.

Cross spectra are lower, though this could indicate limitations of models.

Constraint on r under Foreground Projections



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



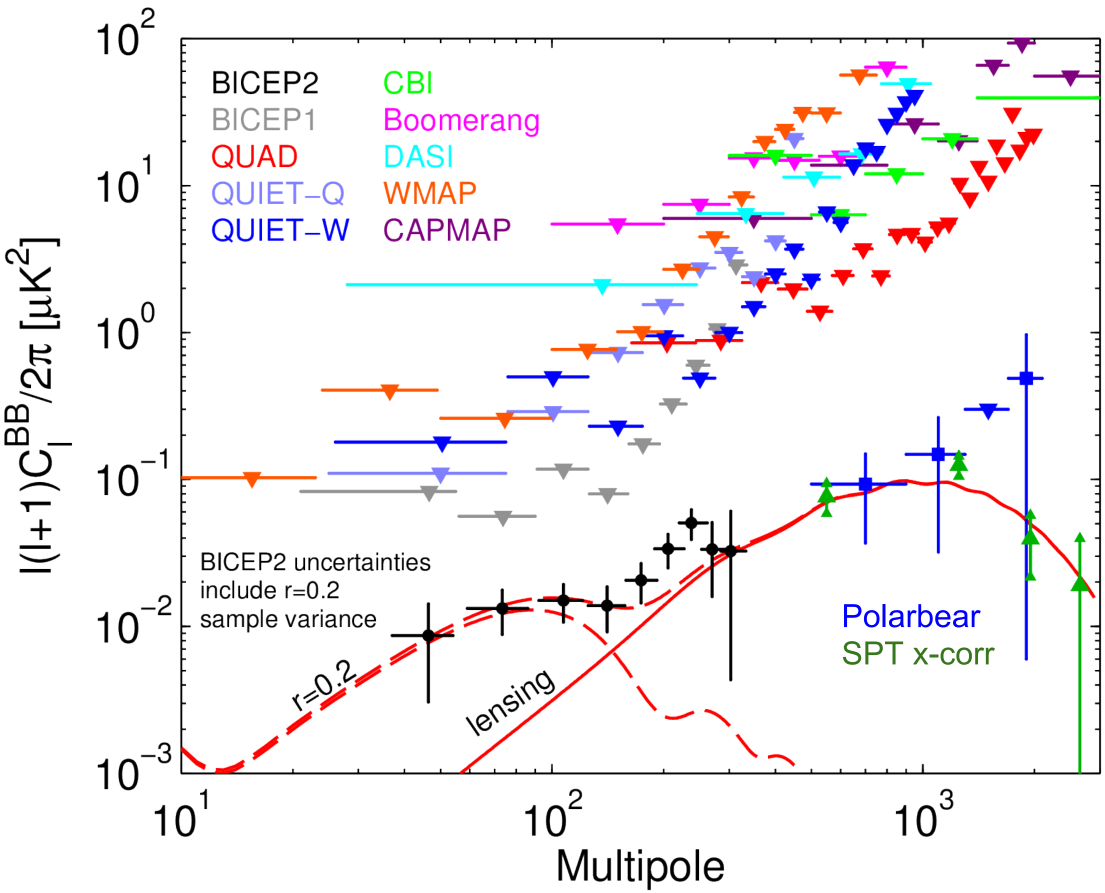
"Probability that each of these models reflect reality hard to assess" – uncertainties could go in either direction, but large enough to equal entire signal.

r = 0.15 to 0.19 based on models at default values.

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

Conclusions circa March 17th

BICEP2 and limits from other experiments:



http://www.bicepkeck.org

Deepest polarization maps yet made:
87nK-deg / 3nK total

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
→ B-mode distribution / spectrum

With no foreground subtraction, constraint on tensor-to-scalar ratio r in simple inflationary gravitational wave model:

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

r = 0 is ruled out at 7.0σ. **This shifts down depending on foreground level.**

John Kovac for The Bicep2 Collaboration

Developments Since March…

- Intense media and science community interest (!)
- Many early instrumental / stat queries… mostly seem to have faded
- Concerns seem to have boiled down to:

  Polarized dust foreground may be stronger than previously projected…

- In May, 4 new papers on dust polarization appeared from Planck
  - These specifically mask out low foreground regions like ours (due to "non small systematics and not dust dominated")
  - Trend to higher polarization in low dust regions. 4% mode, but > 10% in some regions
- PRL final version of paper published June:

  B-mode detection + analysis are secure.

  Uncertainty on interpretation has increased.

  "Is it all dust?"

  BICEP2(+1) internal constraints are weak. Dust models may not be reliable.

  Getting new data more important than ever.

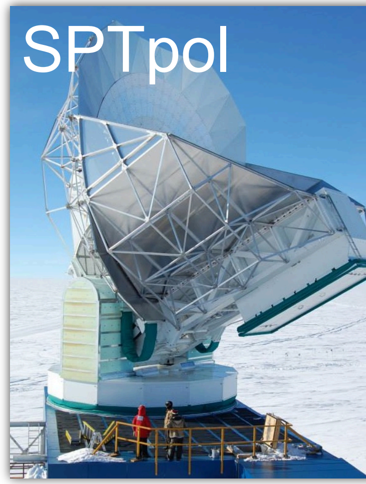
- Joint Analysis underway with Planck, combining maps to cross spectra

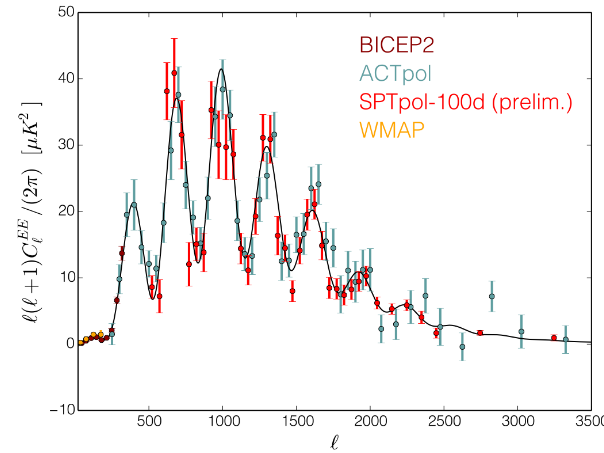
  →Most powerful way to overcome limitations of noise/systematics in Planck maps of polarized dust in our region.

Coming Next

Many other experiments are making rapid progress!

- SPTpol has data in the can over same sky patch at 100 and 150 GHz
  - Should be able to see signal alone and/or in cross correlation with BICEP2/Keck – analysis started
- Polarbear, ACTpol have exciting results
  - pushing toward degree-scales



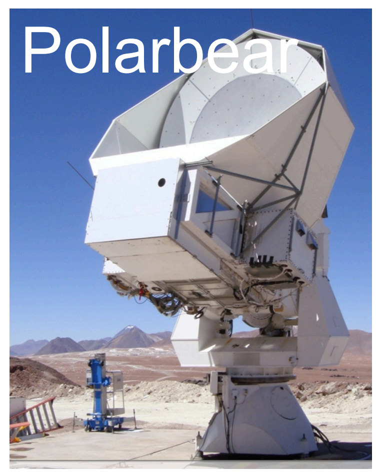


- ABS running, CLASS soon…
- Balloons:

EBEX has data in the can (220?)

Spider will fly later this year.

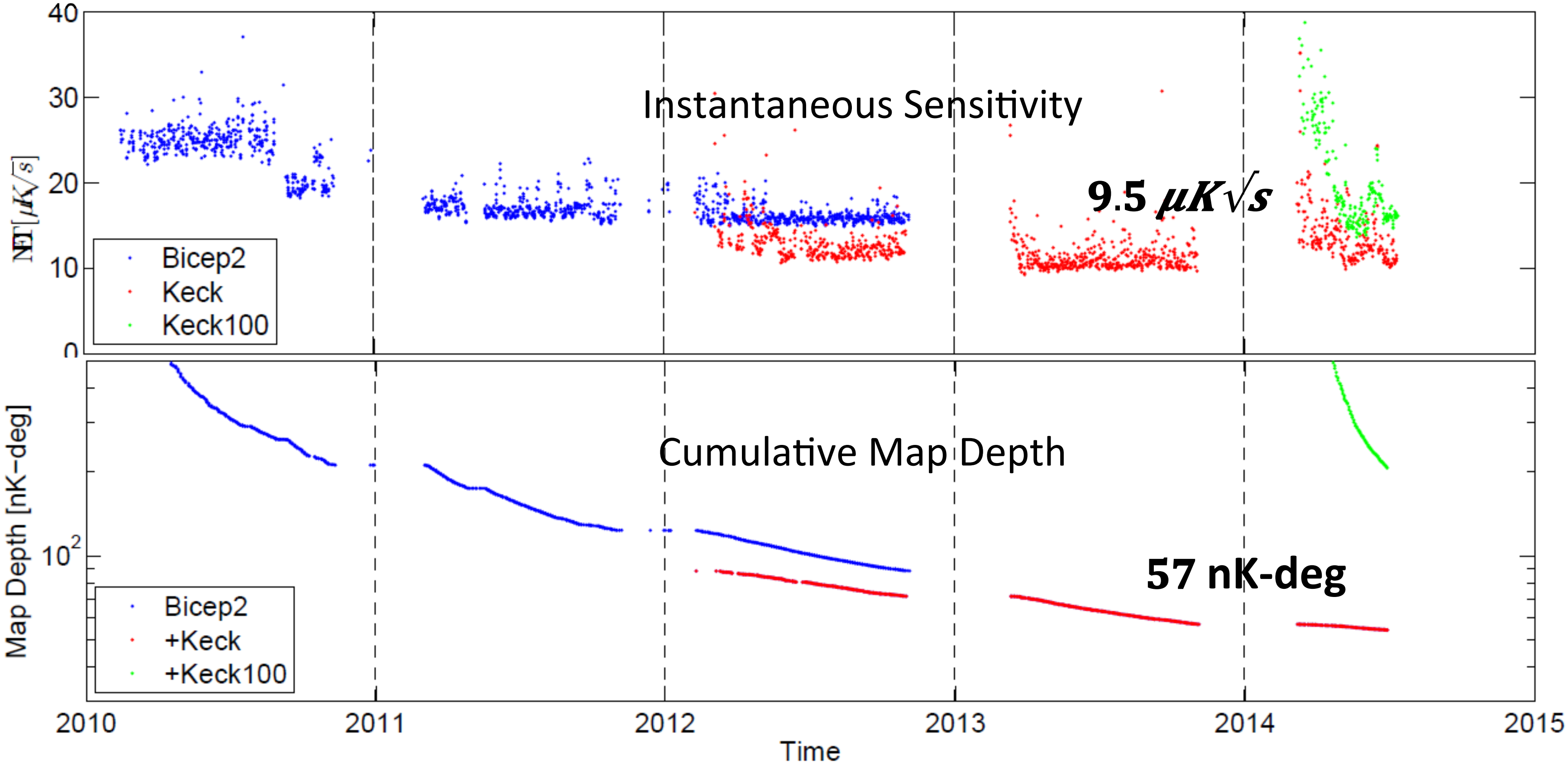
PIPER will fly sometime soon.



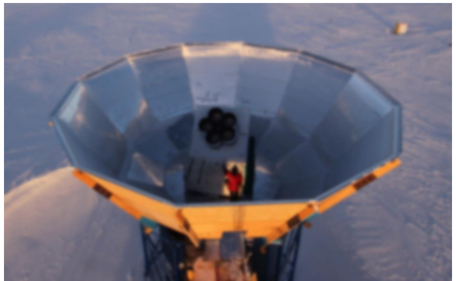
See parallel session talks by Ryan Keisler and Blake Sherwin

Coming Next

Keck Array + BICEP3: new data @ 100 + 220



Sarah Kernasovskiy



Keck 2014 is running right now with 2 receivers at 100GHz

BICEP3 to deploy this October!

Coming Next (summary)

- Keck 2014 is running right now with 2 receivers at 100GHz
  - Sensitivity of BICEP1 already surpassed, soon will **tighten foreground constraint**
  - **BICEP3** deploys in 3 months, doubles Keck's power, all at 100 GHz

- Planck will weigh in soon
  - hints already of higher dust, but limited by noise/systematics
  - Joint BICEP2 + Planck map-based analysis should offer best constraints

- Ground based efforts are moving VERY FAST:
  - SPTpol, Polarbear, ACTpol, ABS, Spider, EBEX, CLASS, PIPER…

Most powerful way to advance the science **is more data, all used together**.