BICEP2 Results, Implications, and the Future of *Tensor Cosmology*

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Amazing combination of

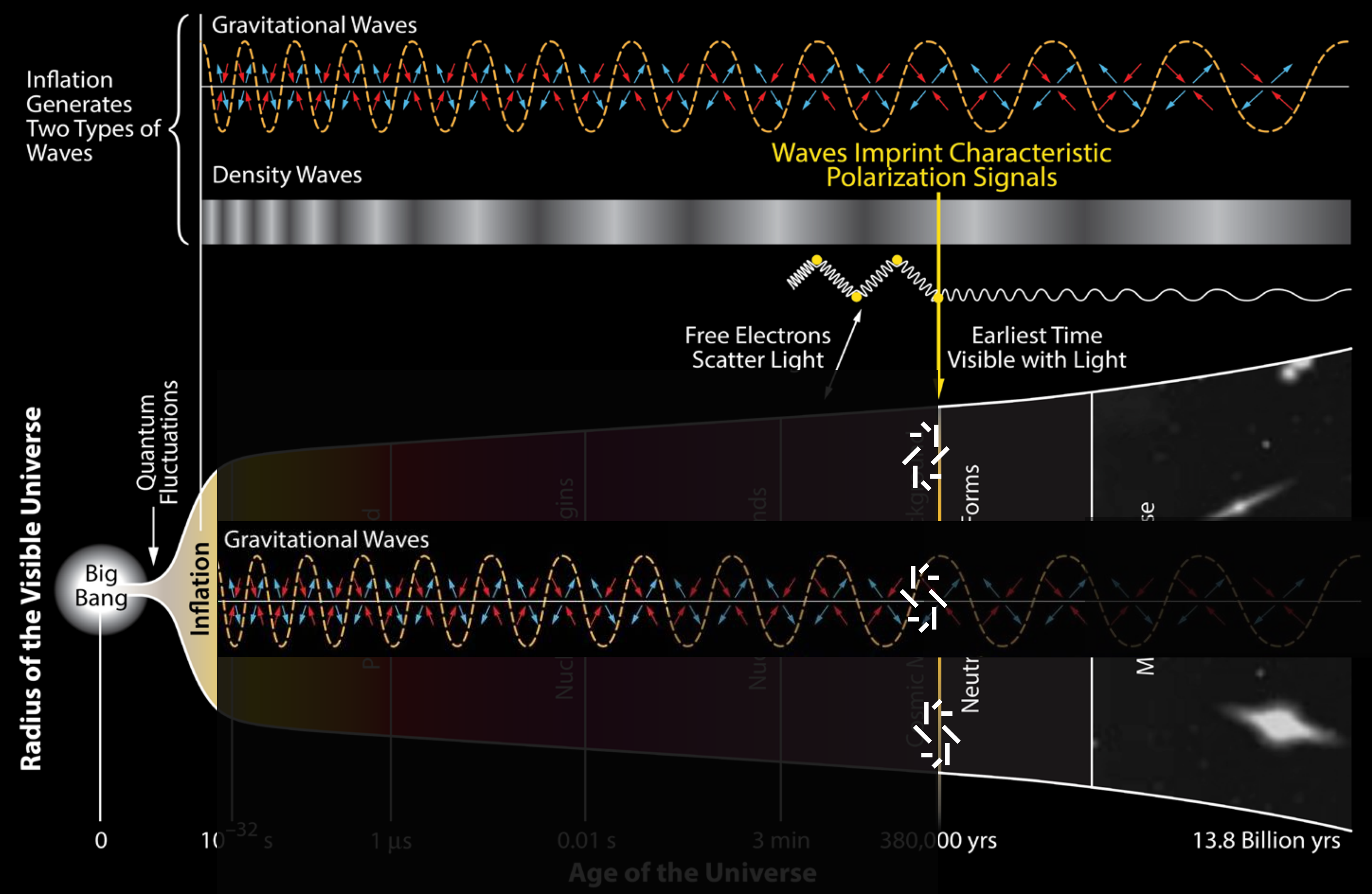
Theoretical ideas :

- **Inflation**
- **Inflation generates gravitational waves**
- **Gravitational waves generate B-modes**

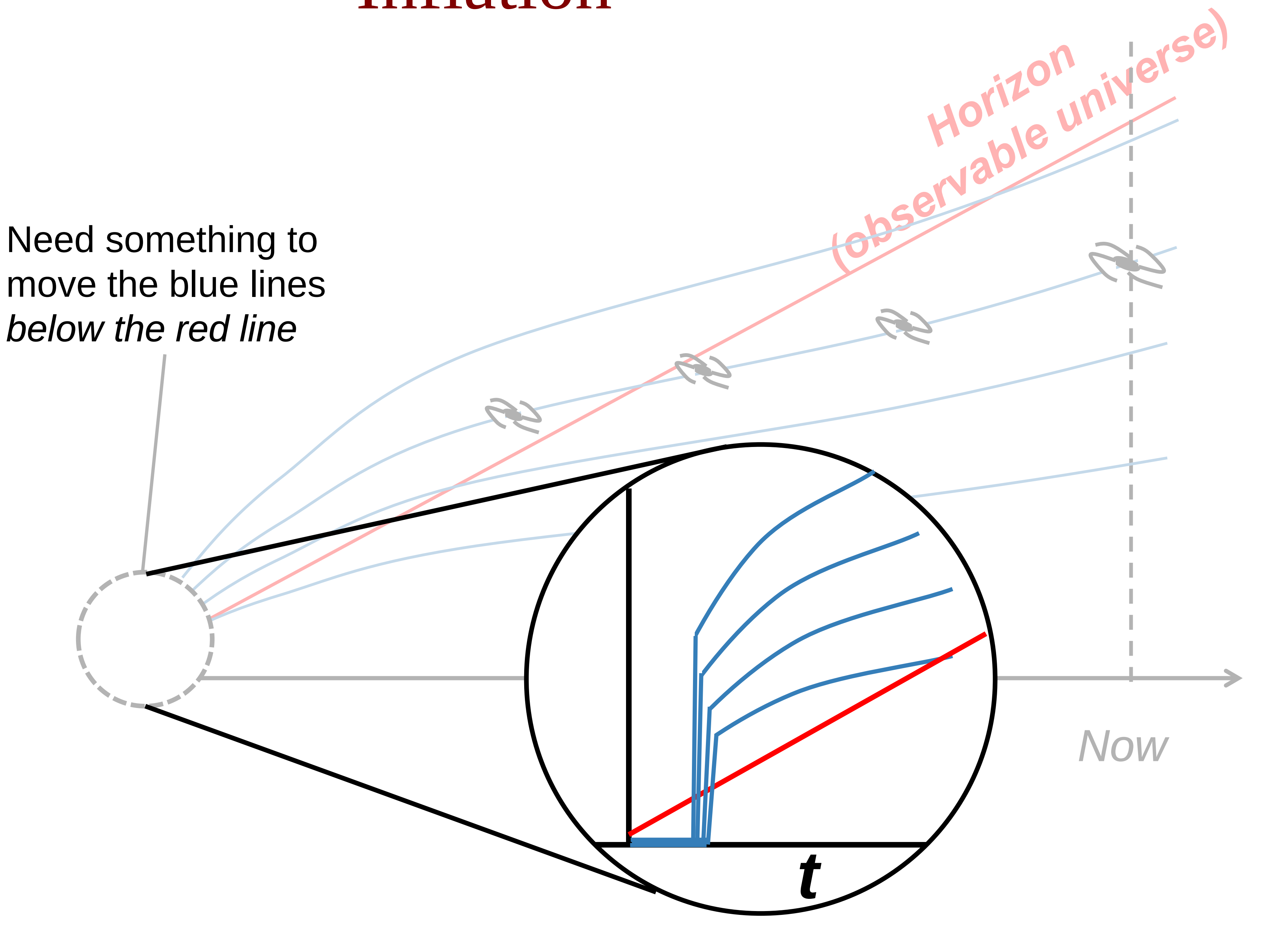
Technology :

- Refractor in a cryostat
- Polarimeters on a chip
- TES and SQUIDs
- *and focus, hard work , faith, etc..*

History of the Universe



Inflation



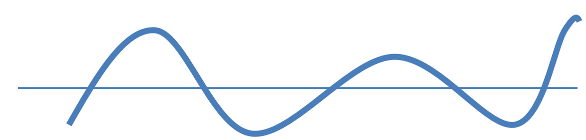
Need something to
move the blue lines
below the red line
Horizon
(observable universe)
Now
t

How does Inflation work?

- Solved the horizon and flatness problems
- How is it achieved ? Exponential expansion.

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} \quad \longleftrightarrow \quad \nabla^2 \Phi = 4\pi G \rho$$

$$T_{\mu\nu} = \partial_\mu \varphi \partial_\nu \varphi - \frac{1}{2} g_{\mu\nu} \partial^\sigma \varphi \partial_\sigma \varphi - g_{\mu\nu} V(\varphi)$$



$$H^2 = \frac{8\pi G}{3} V(\varphi)$$

Slow roll, ~ const. Hubble

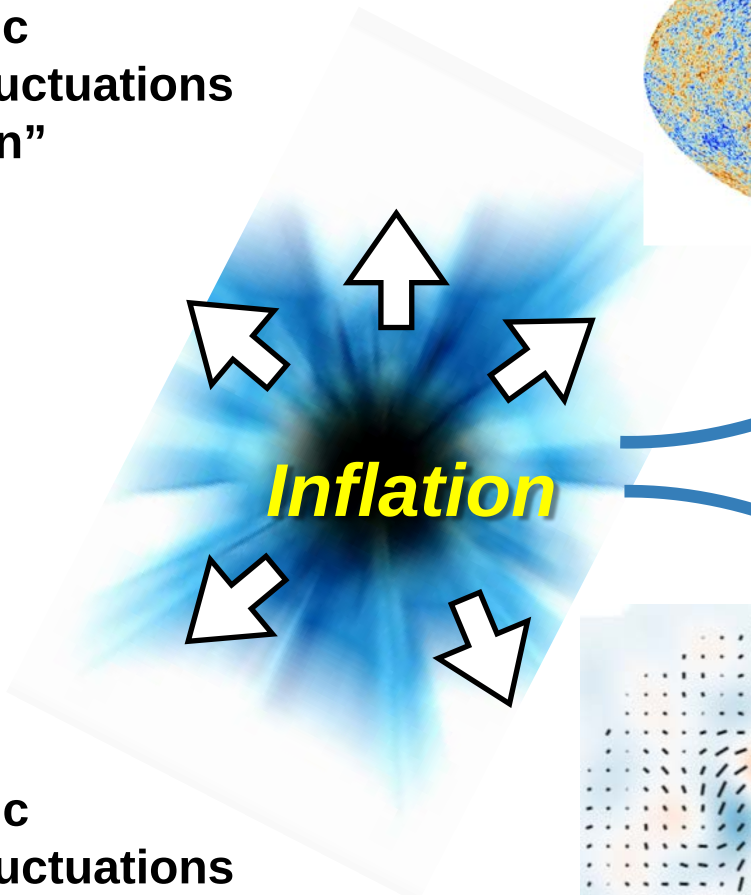
~ exponential expansion (inflation)

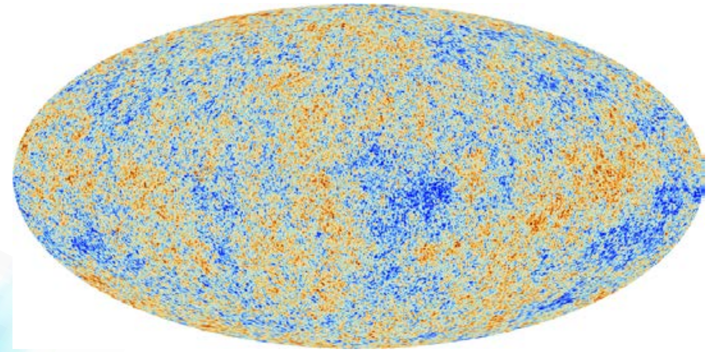
Generation of perturbations

- *This is the part that connects* **quantum** *w/* **cosmos**
- Prior to BICEP2, the properties of the scalar perturbations have become the strongest evidence for inflation
  - Adiabatic (1 D.o.F. , related to inflaton field φ)
  - Gaussian (vacuum state of φ)
  - Spectral index n_s <~ 1

Density perturbations and gravitational waves

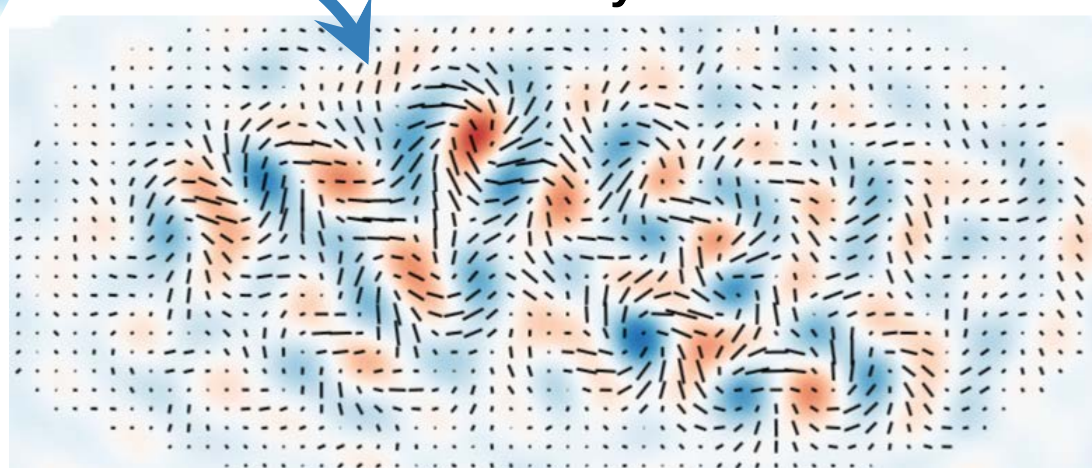
Sub-atomic vacuum fluctuations of “inflaton”





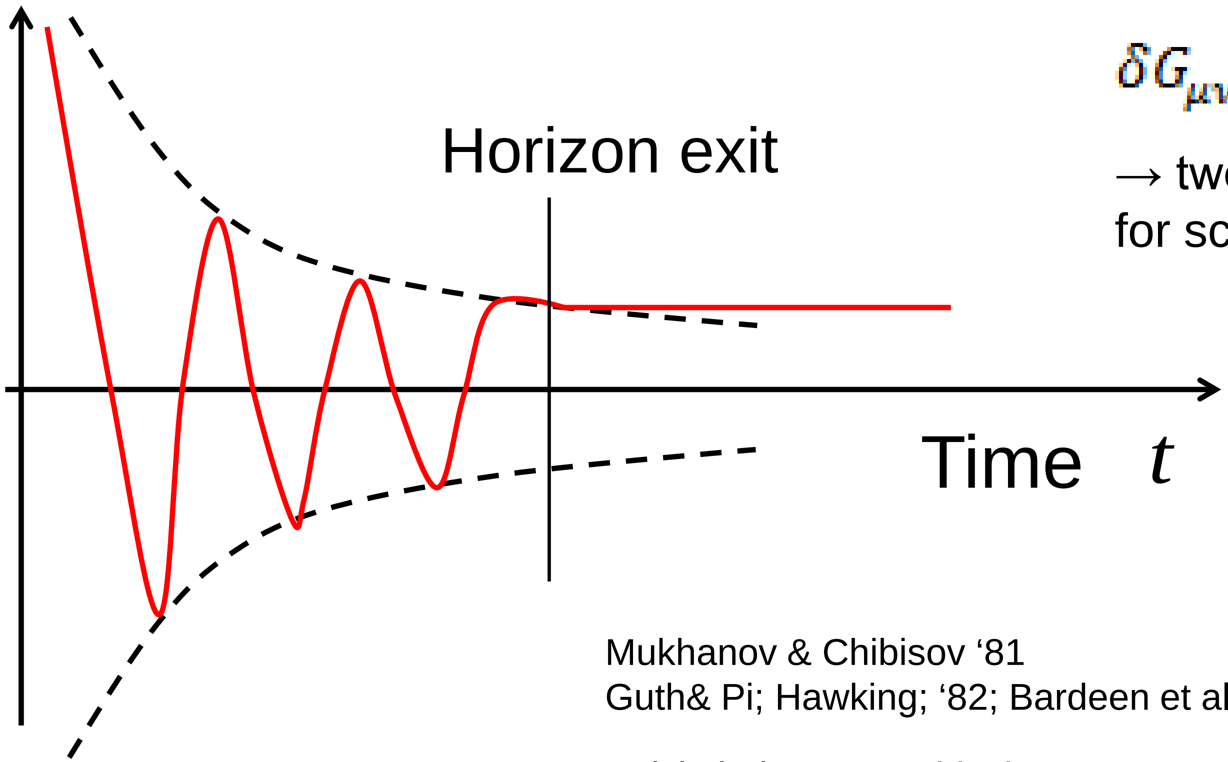
Density perturbations *studied* by Planck, WMAP, SPT, etc.

Gravitational waves detected by BICEP2



Sub-atomic vacuum fluctuations of *graviton* (quanta of gravity)

Generation of ***scalar/tensor*** perturbations



$$\delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu}$$

→ two linear wave equations for scalar /tensor

Mukhanov & Chibisov '81
Guth& Pi; Hawking; '82; Bardeen et al., '83; Sasaki '83

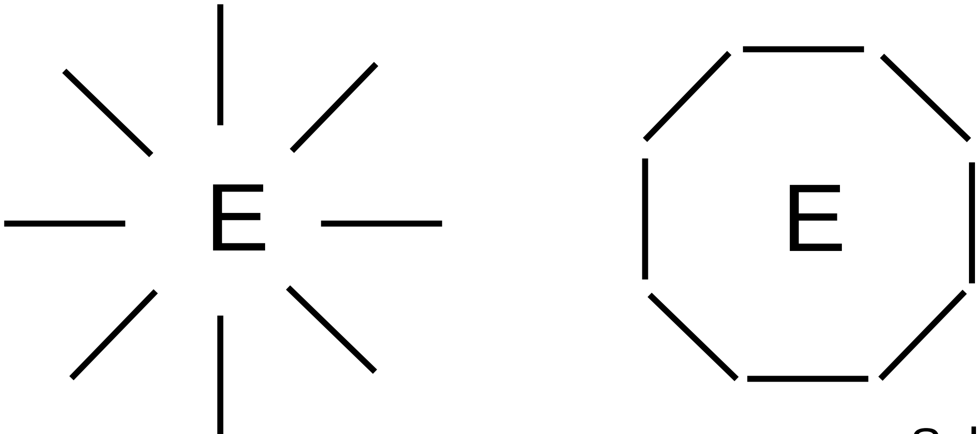
Grishchuk 74; Starobinsky 79
Rubakov et al, 82; Frabri & Pollock , 82

Quantum fluctuations in the vacuum state of the *inflaton*/*graviton* fixes the r.m.s of the linear solutions

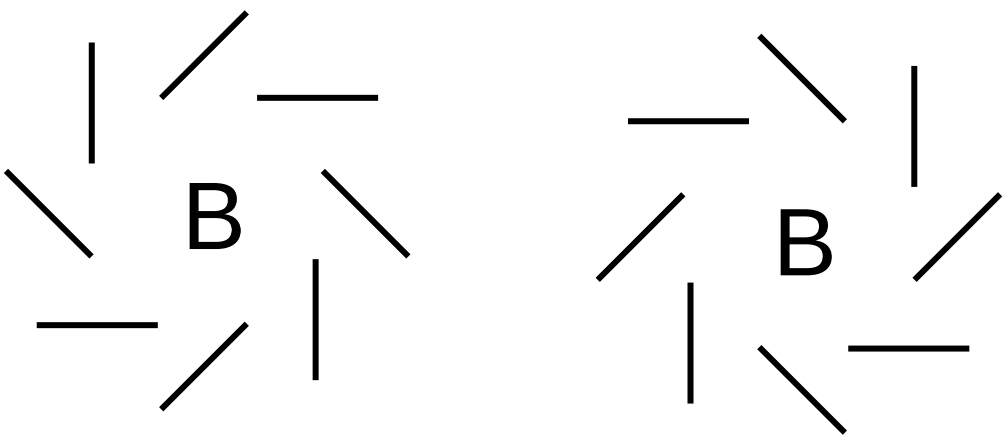
Inflationary B-modes, known as the "Holy Grail" of cosmology

- Started out as *graviton* vacuum fluctuations
- Energy scale of inflation ~ expansion rate ~ GW amplitude
- Alternative models generate no GW
- *Field range and "UV" completeness*

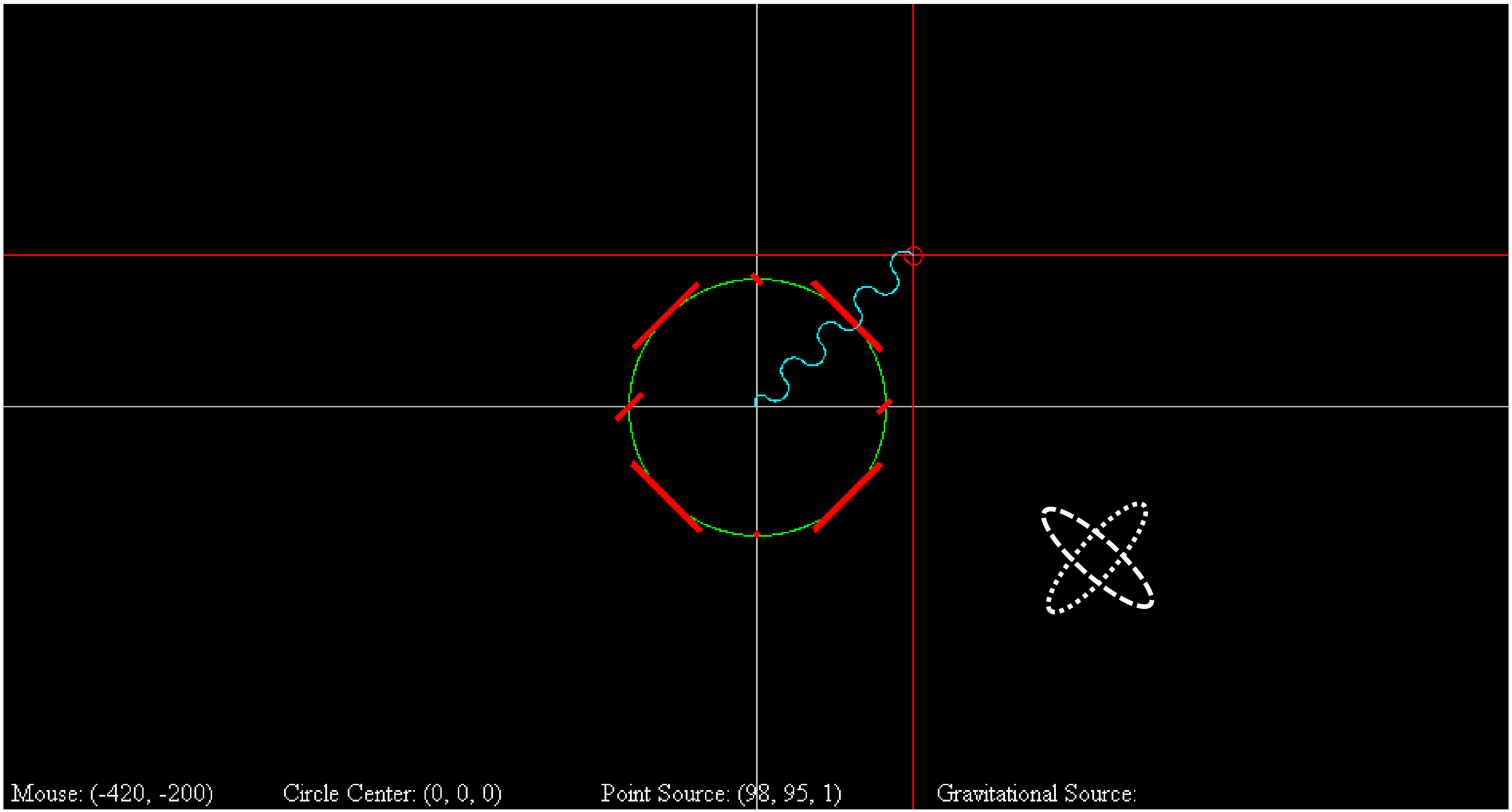
Only gravitational waves can generate B-modes



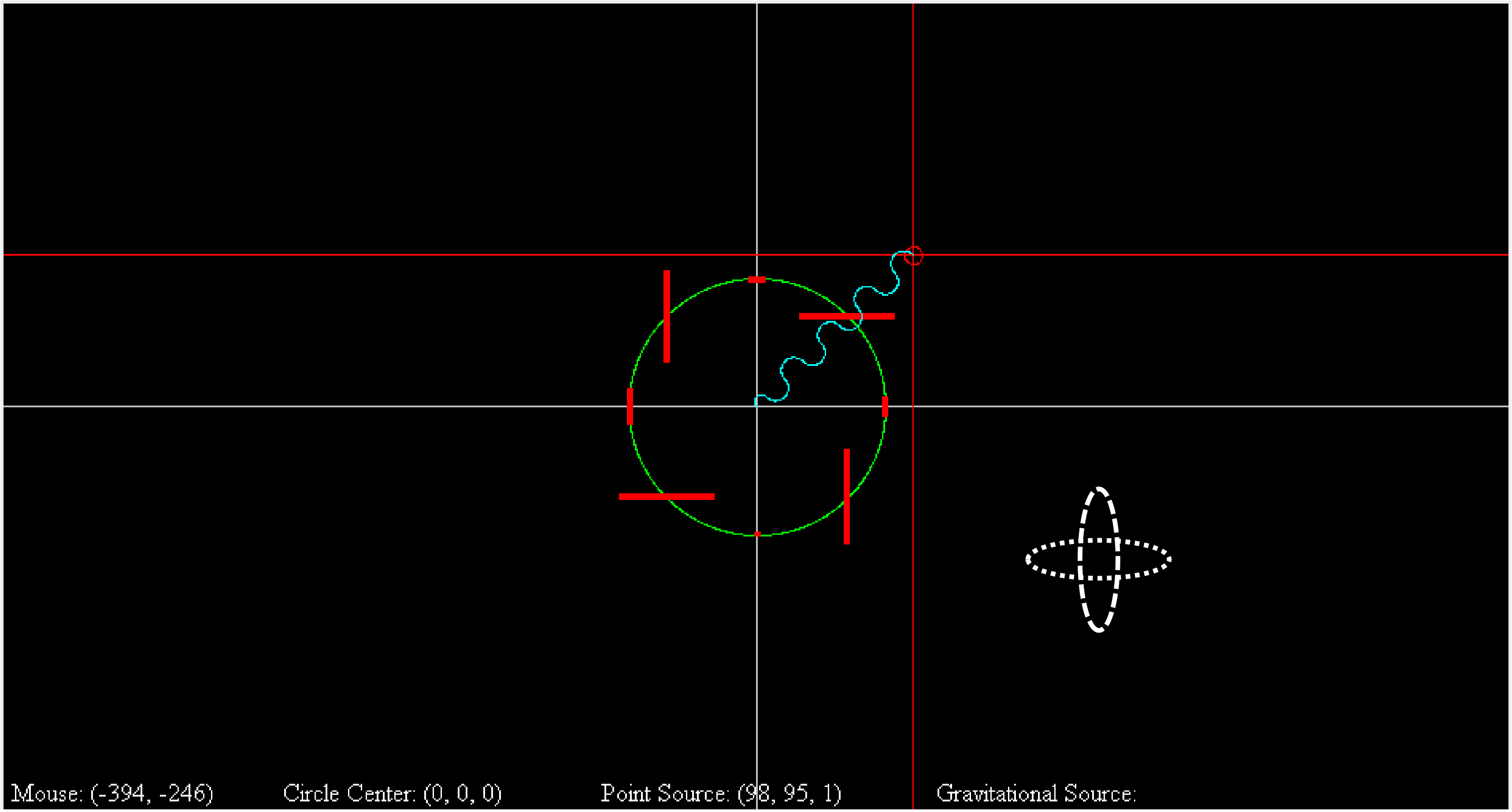
Seljak & Zaldarriaga '97
Kamionkowski, Kosowsky, Stebbins '97



Gravitational waves generate *E*-mode polarization



Gravitational waves generate *B*-mode polarization



!!!

The polarization pattern is unique, but small

Vertical / Horizontal differ by 1 part in 30,000,000

Amazing combination of

Theoretical ideas :

- Inflation
- Inflation generates gravitational waves
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Technology :

- **Refractor in a cryostat**
- **Polarimeters on a chip**
- **TES and SQUIDs**
- ***and focus, hard work , faith, etc..***

South Pole is the Mecca of CMB research (BICEP1, BICEP2, Keck Array, BICEP3)

- High, dry, cold, low water vapor in the atmosphere
- Stable climate for continuous 6 months
- Great logistical support (US NSF-Office of Polar Program)

VE RI TAS
HARVARD

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891

cea

UCSD

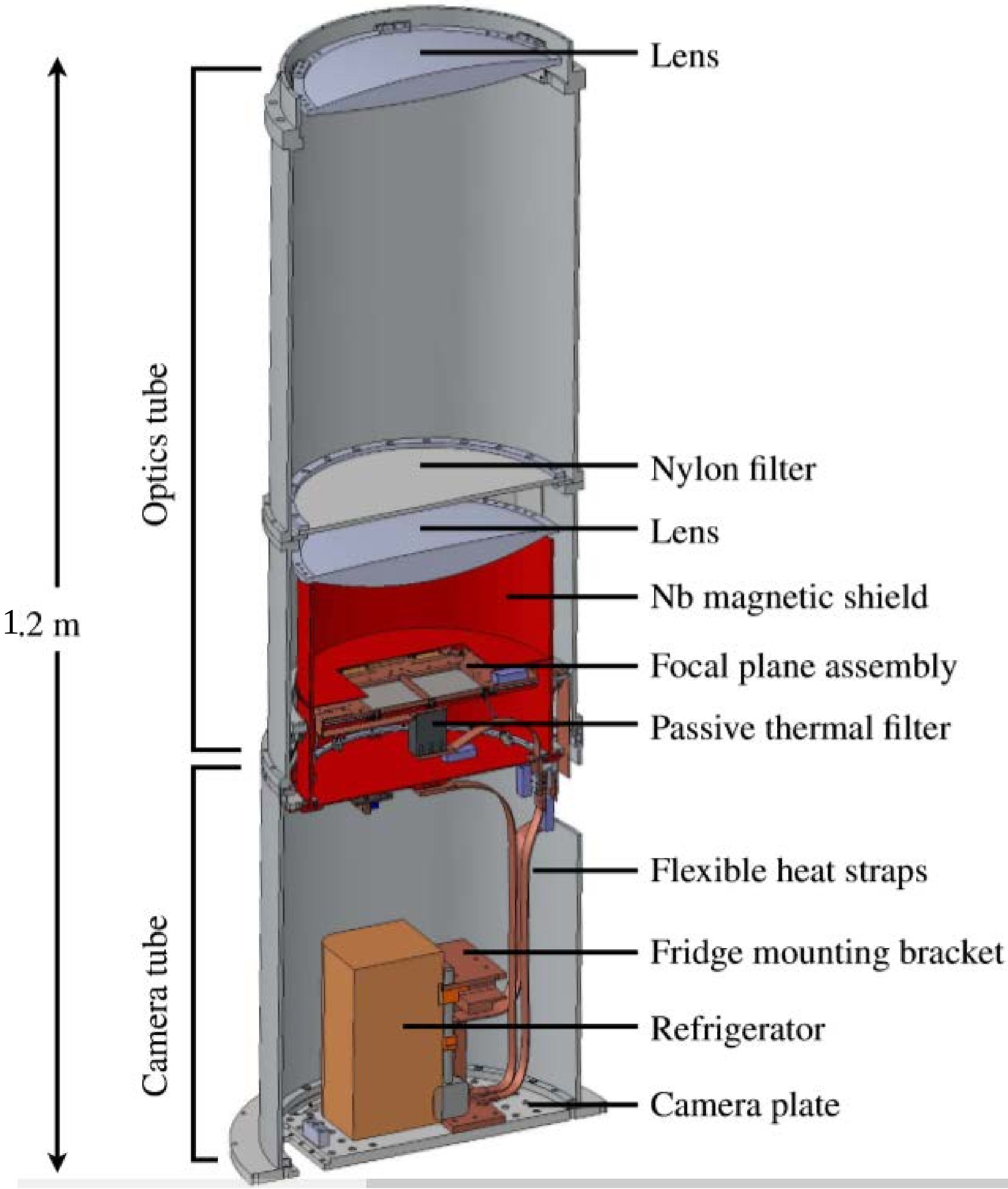
JPL

NIST

CARDIFF
UNIVERSITY

UNIVERSITY OF
TORONTO

UBC



BICEP/Keck series
BICEP1/2/3
Keck Array

microwave (95/150 GHz)
Superconducting sensors
Low temperature physics
(0.25K)

Lithographic detectors
High packing density
Mass production

A very focused program on B-modes

BICEP1: 2006, 2007, 2008

BICEP2: 2010, 2011, 2012

Keck Array: 2011, 2012, 2013, …

BICEP3: 2015…

A very focused program on B-modes

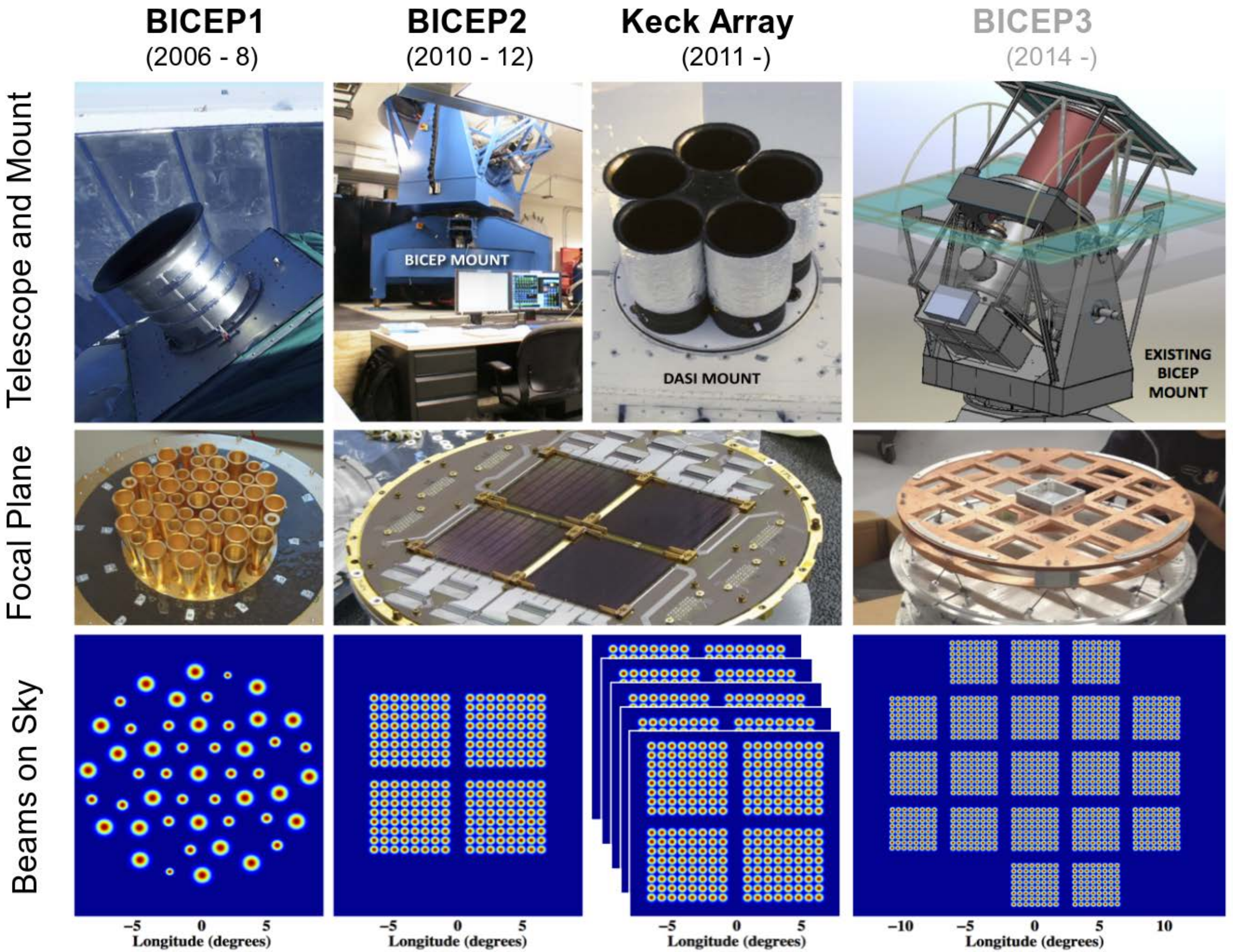
BICEP1: 2006, 2007, 2008

BICEP2: 2010, 2011, 2012

Keck Array: 2011, 2012, 2013, …

BICEP3: 2015…

More and more detectors ..



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)

A very focused program on B-modes

A very focused program on B-modes

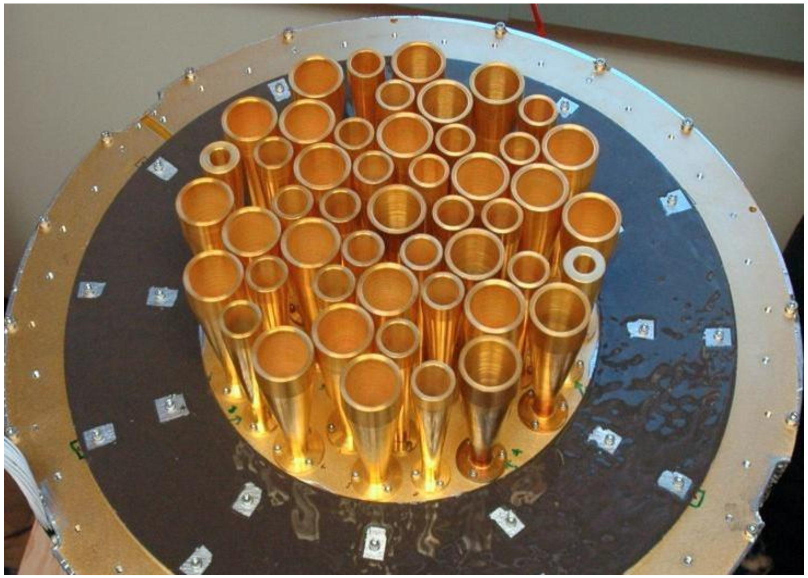
BICEP1: 2006, 2007, 2008 (*r*<0.70; 95%)

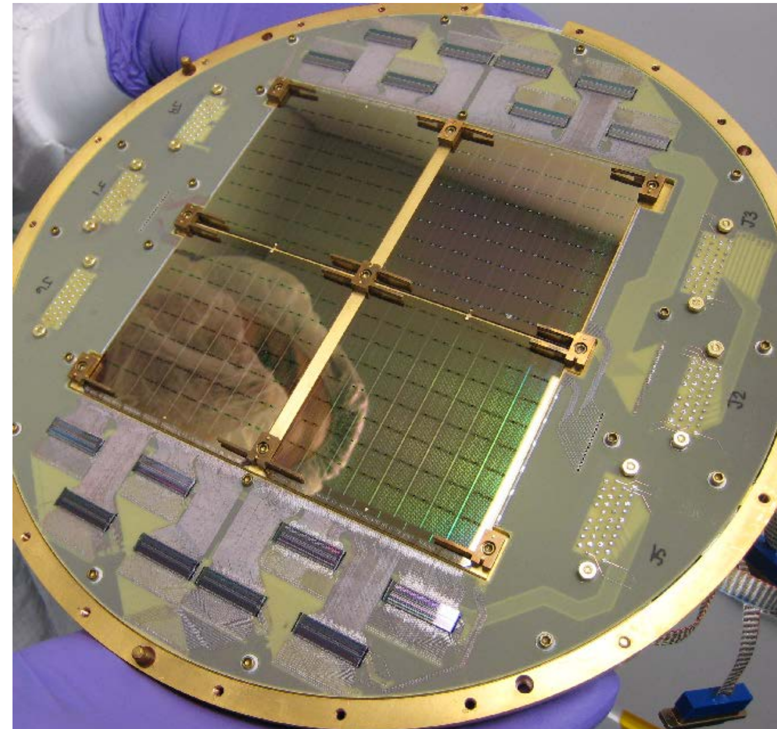
BICEP2: 2010, 2011, 2012

Keck Array: 2011, 2012, 2013, …

BICEP3: 2015…

3 BICEP2 year = 30 BICEP1 years!

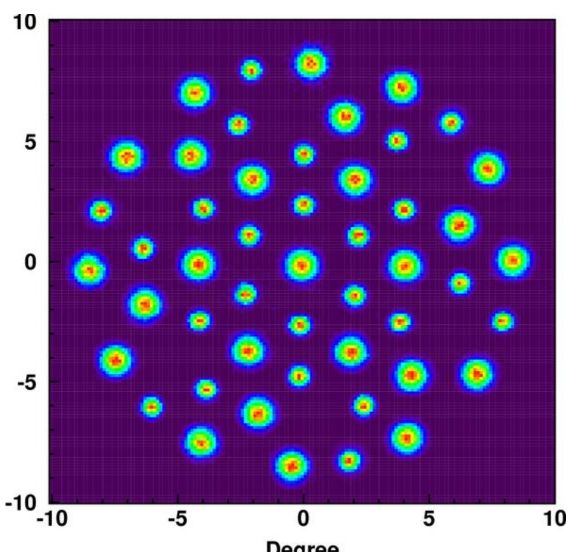


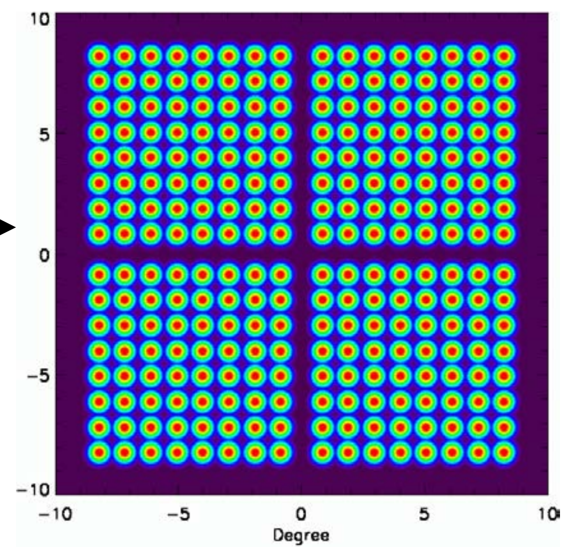


JPL : antenna-coupled TES arrays

BICEP1

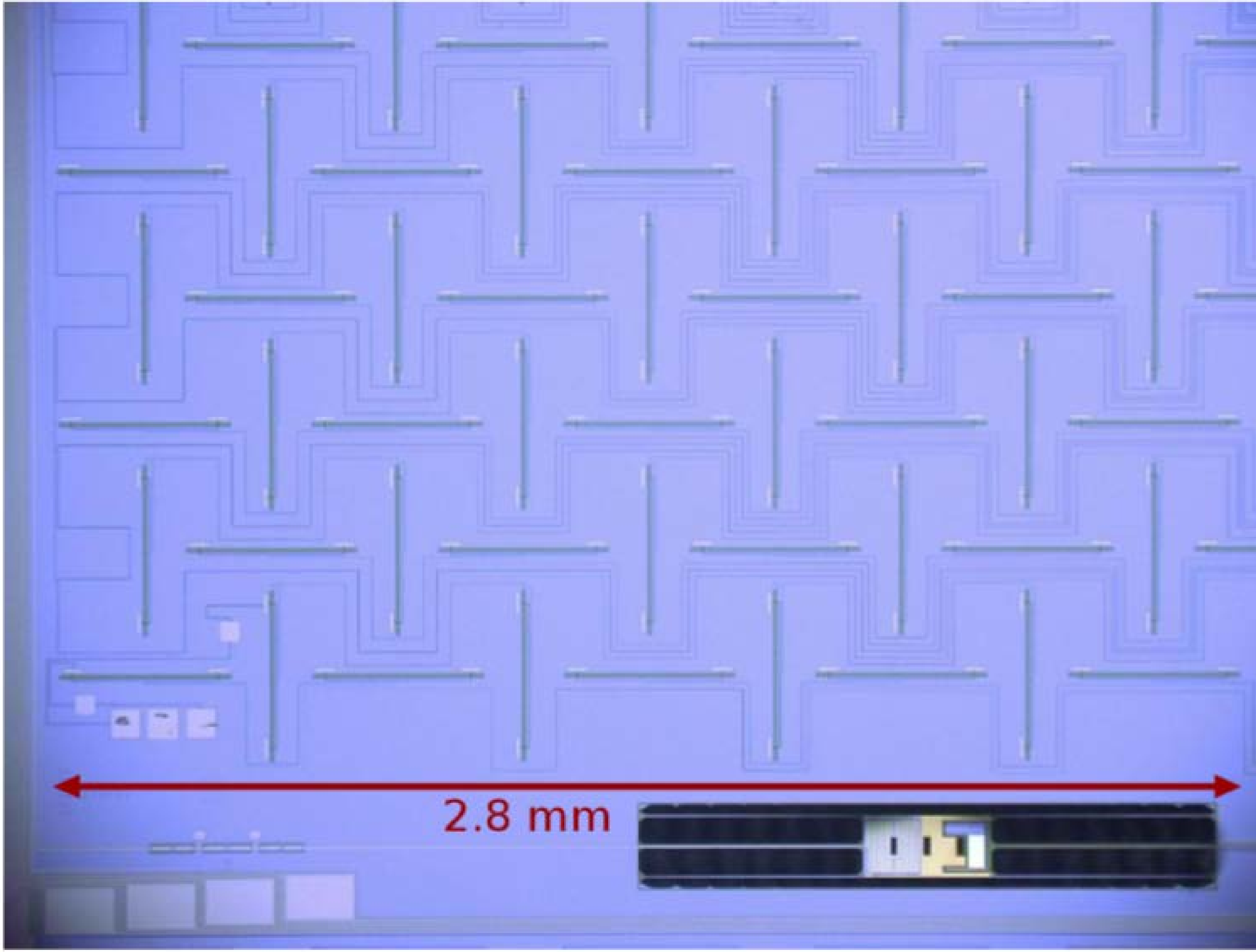
48
150 GHz
detectors





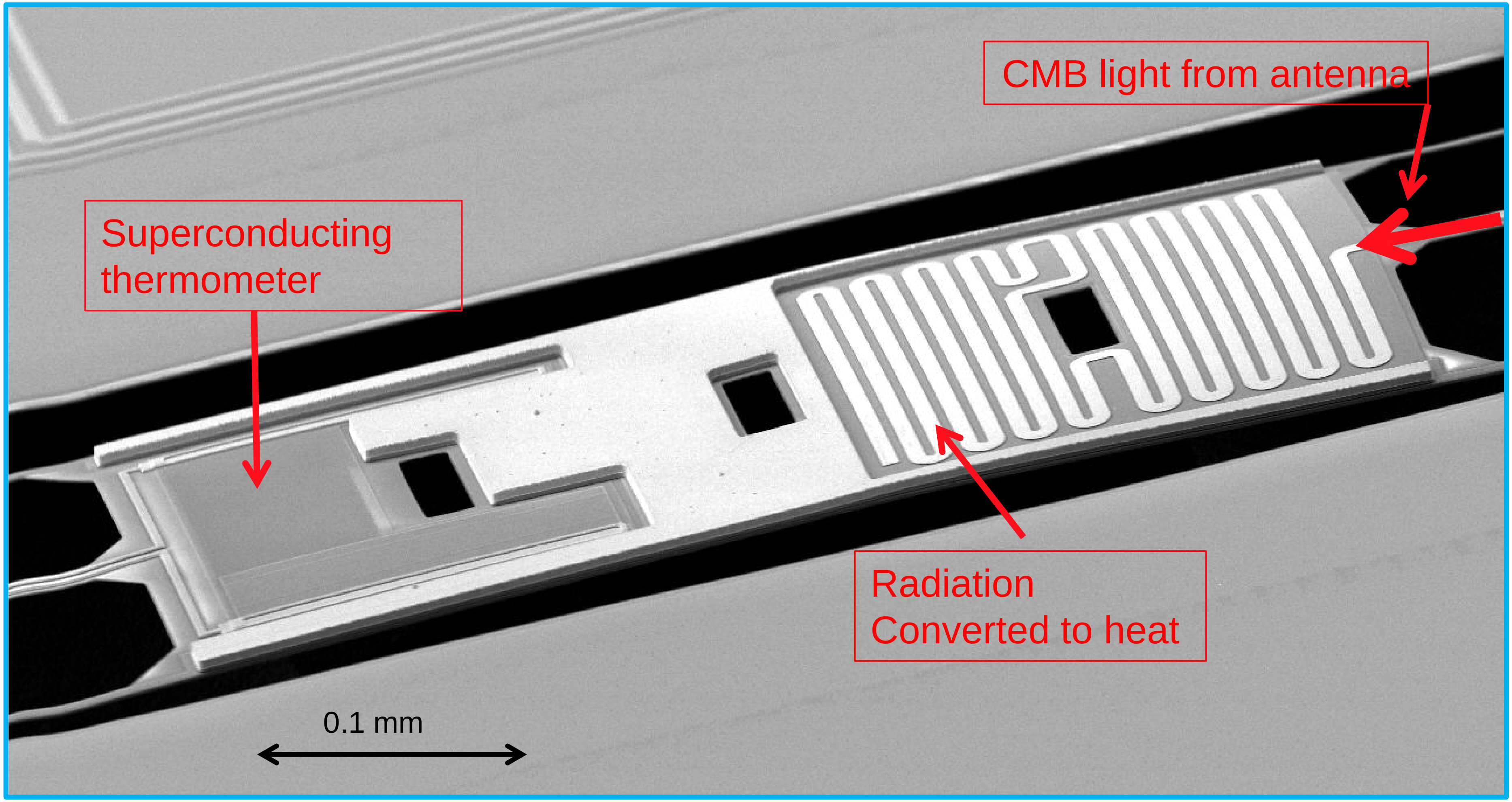
BICEP2

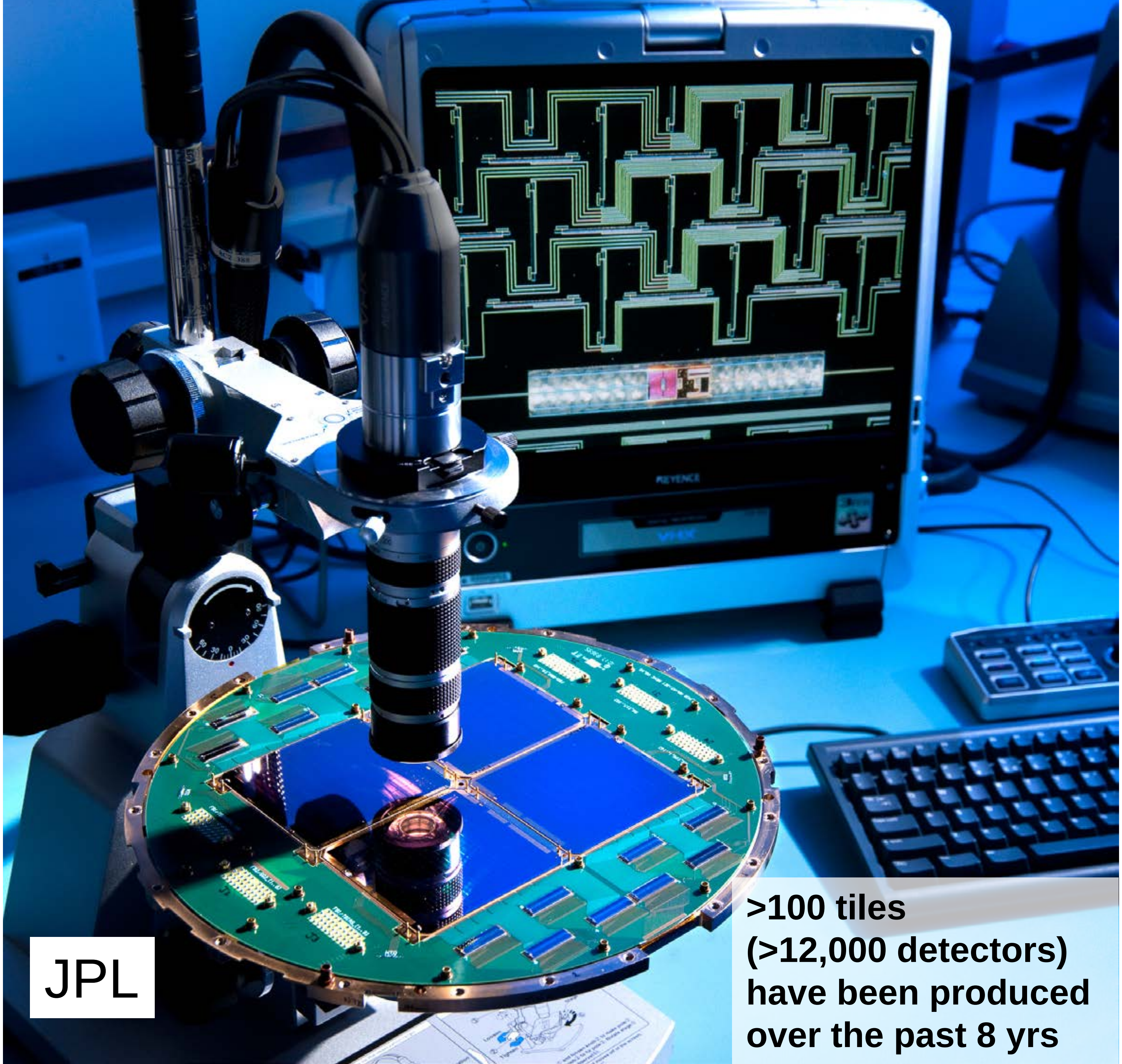
512
150 GHz
detectors


2.8 mm

Detecting the CMB radiation

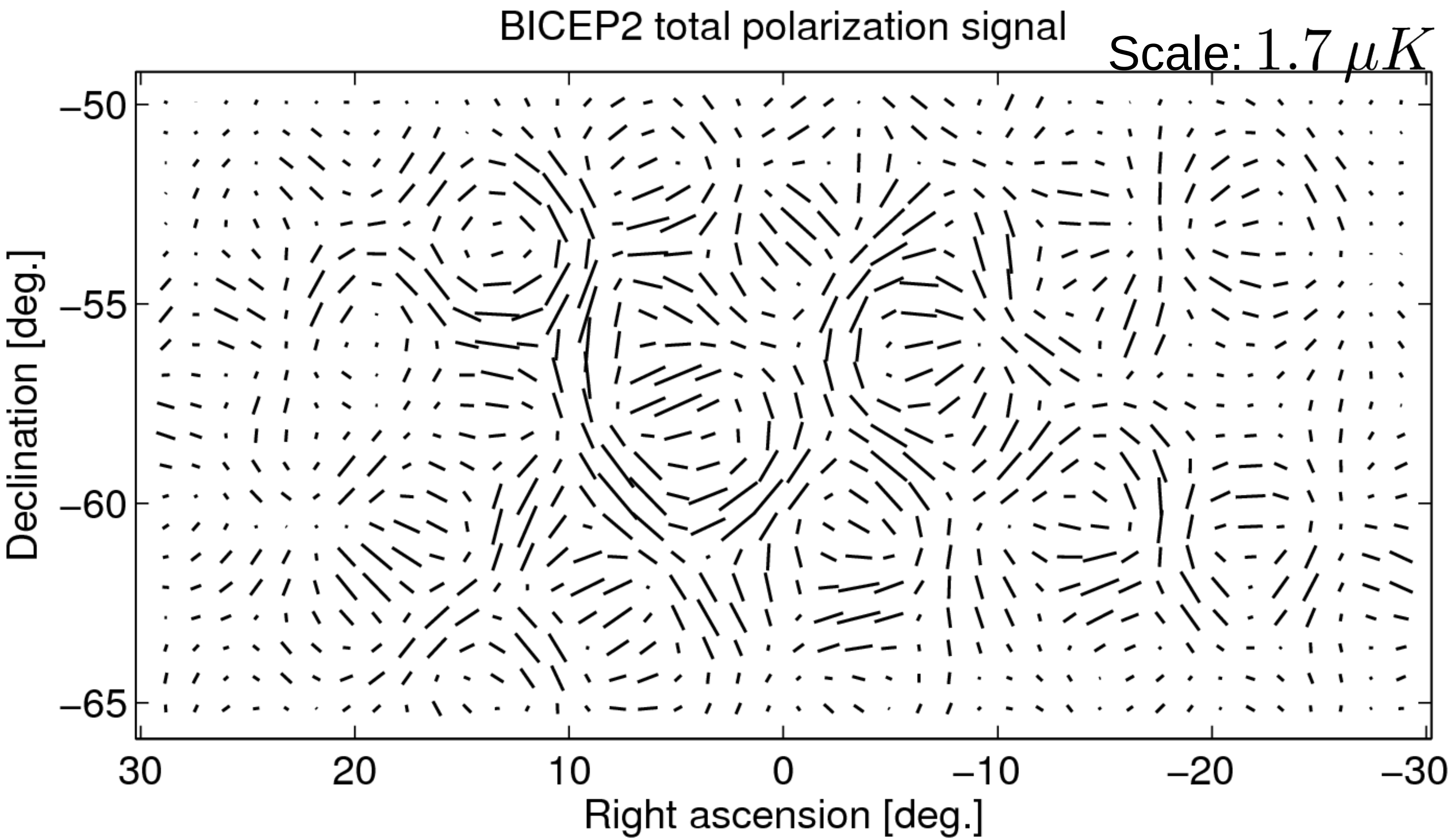
BICEP2 Detector: Transition-Edge Superconductor



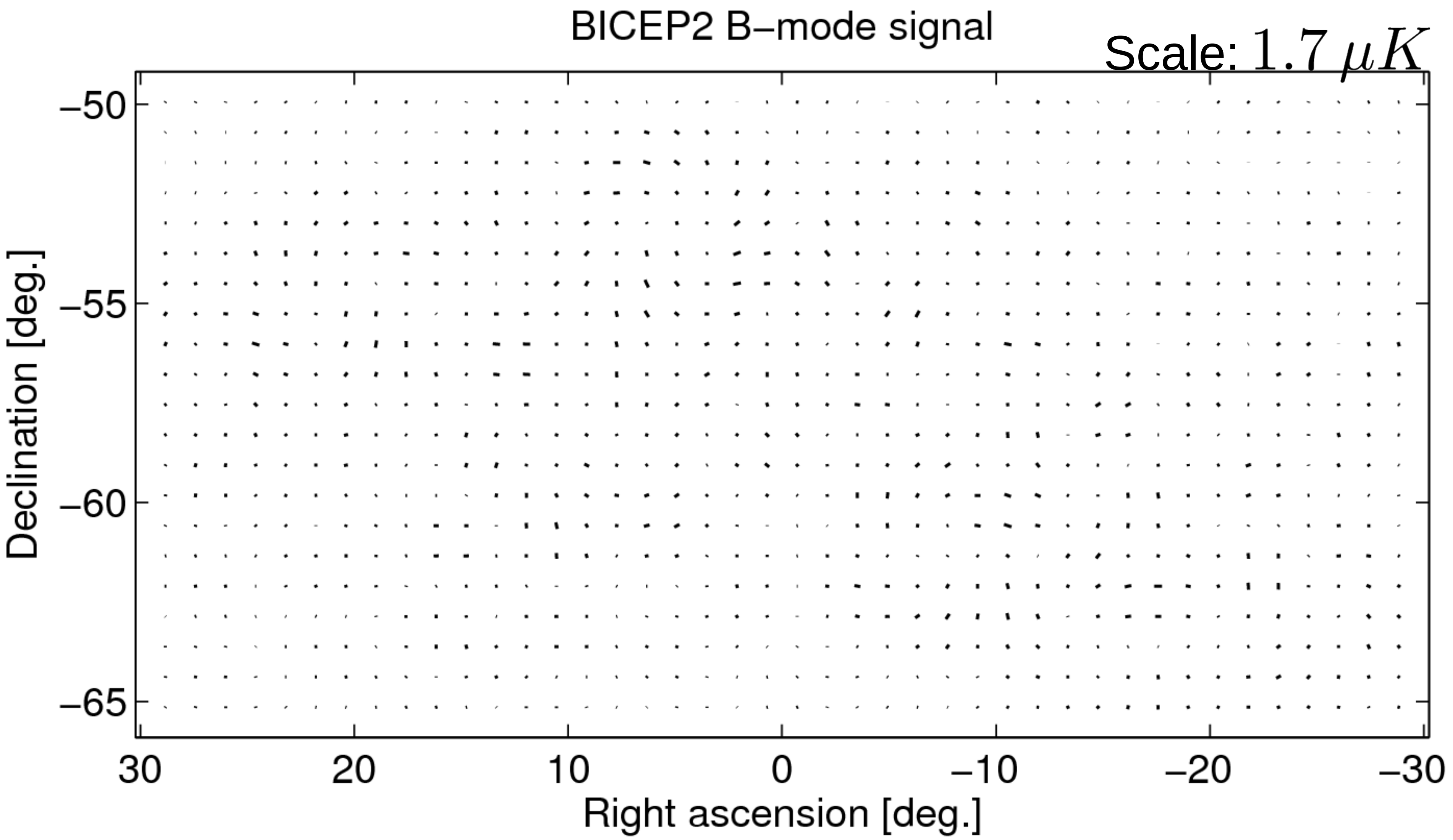


>100 tiles (>12,000 detectors) have been produced over the past 8 yrs

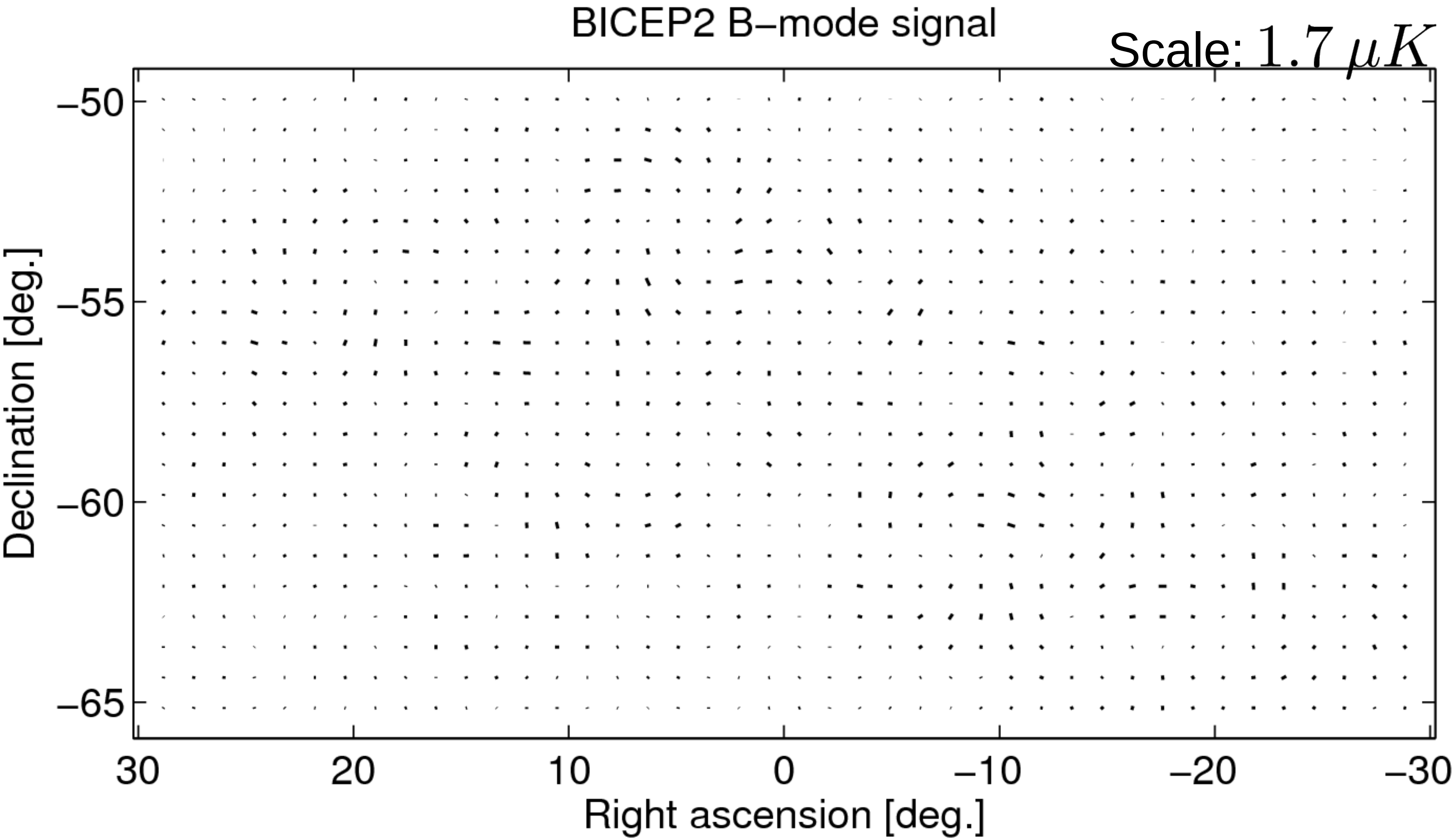
Total polarization (3 yrs of data)



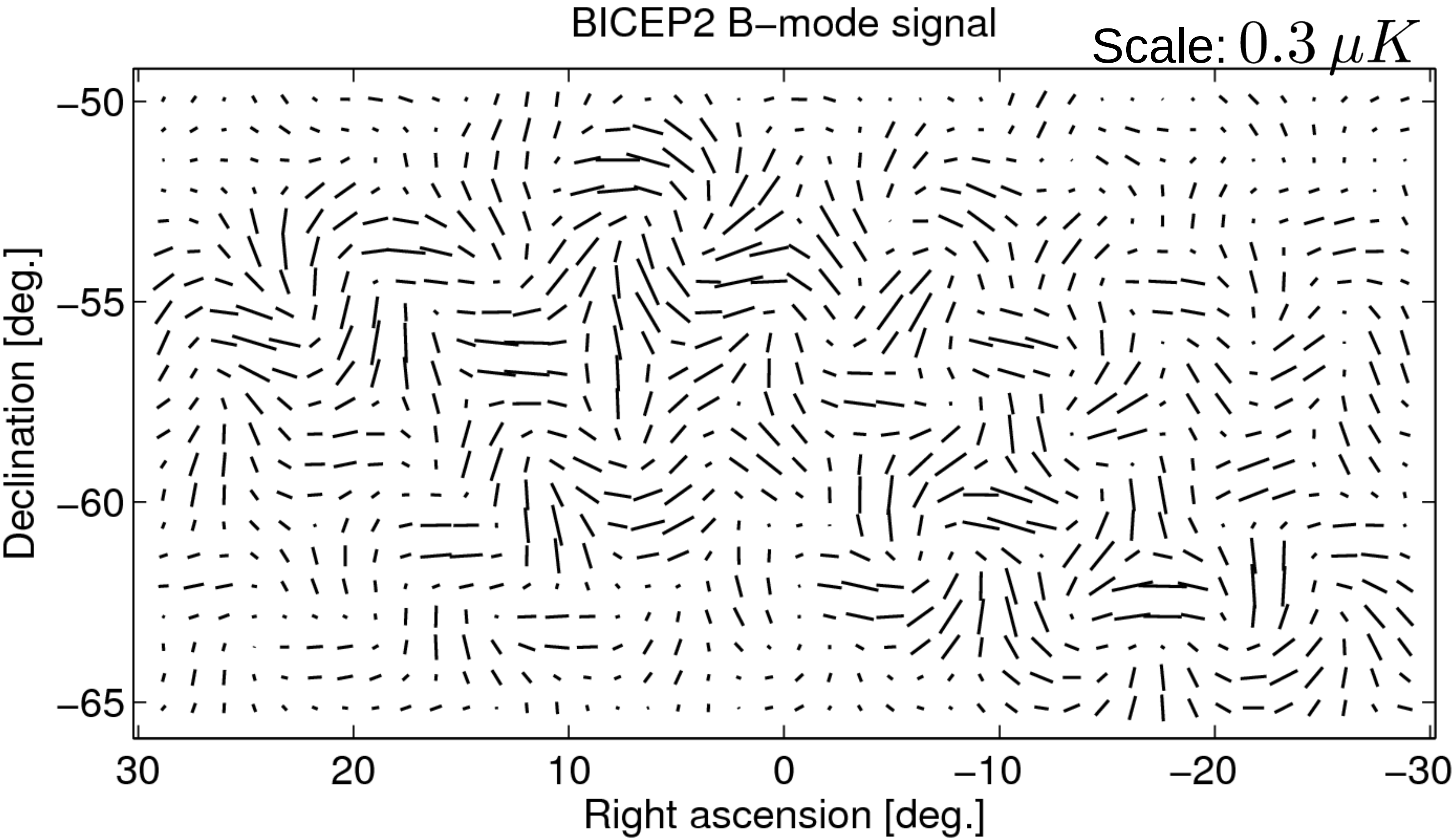
B-mode contribution



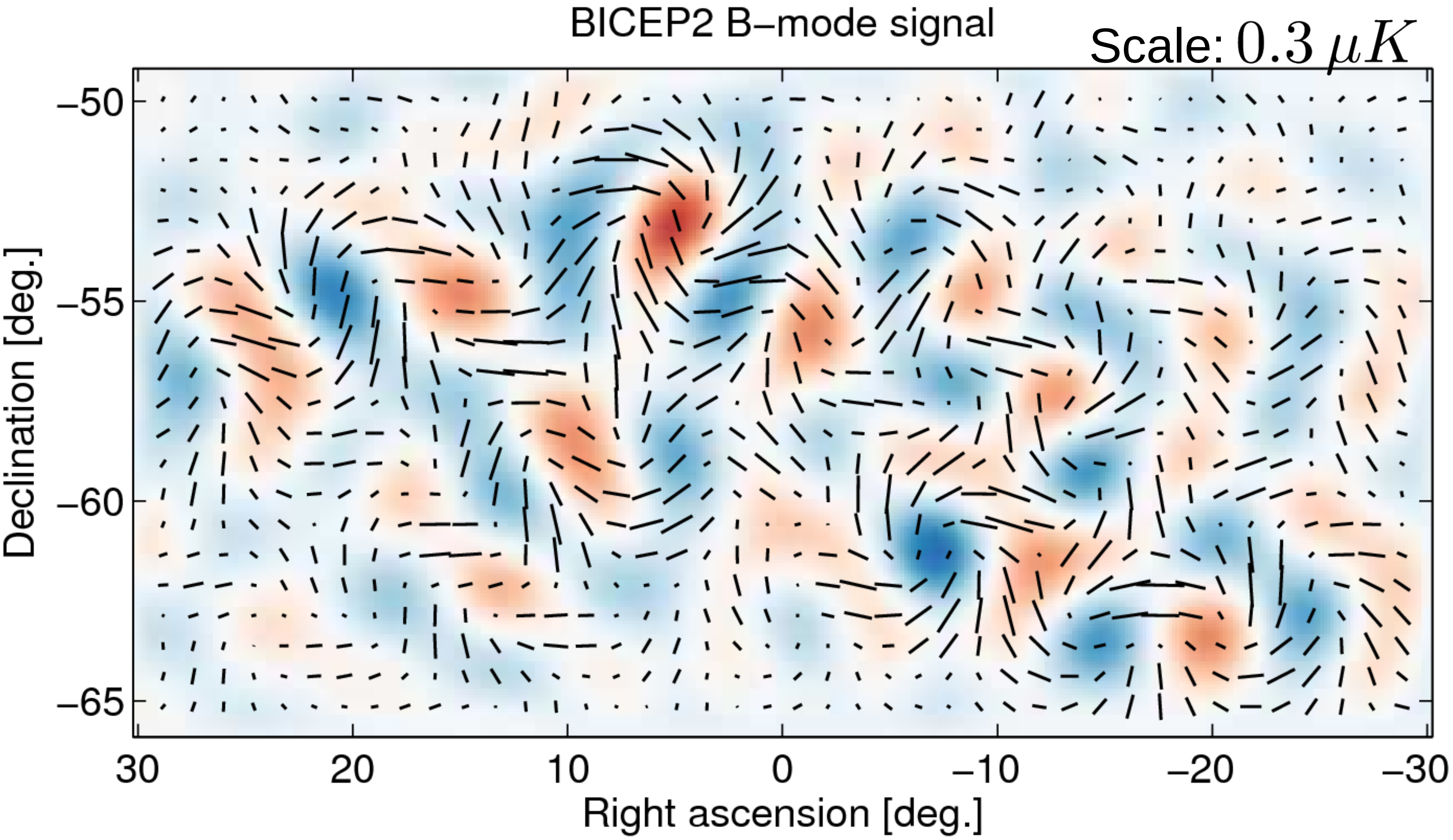
B-mode contribution



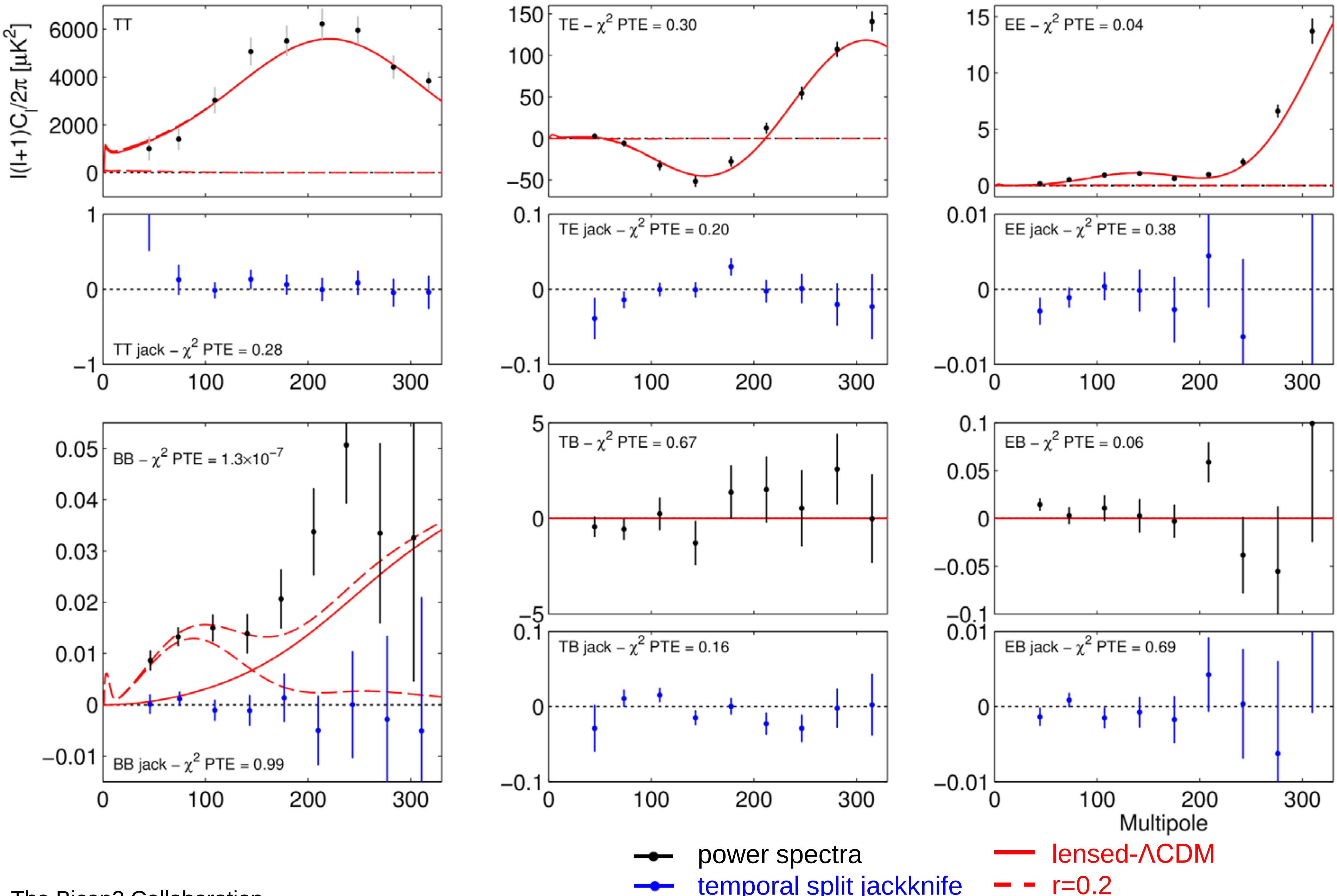
B-mode contribution



B-mode contribution



Temperature and Polarization Spectra



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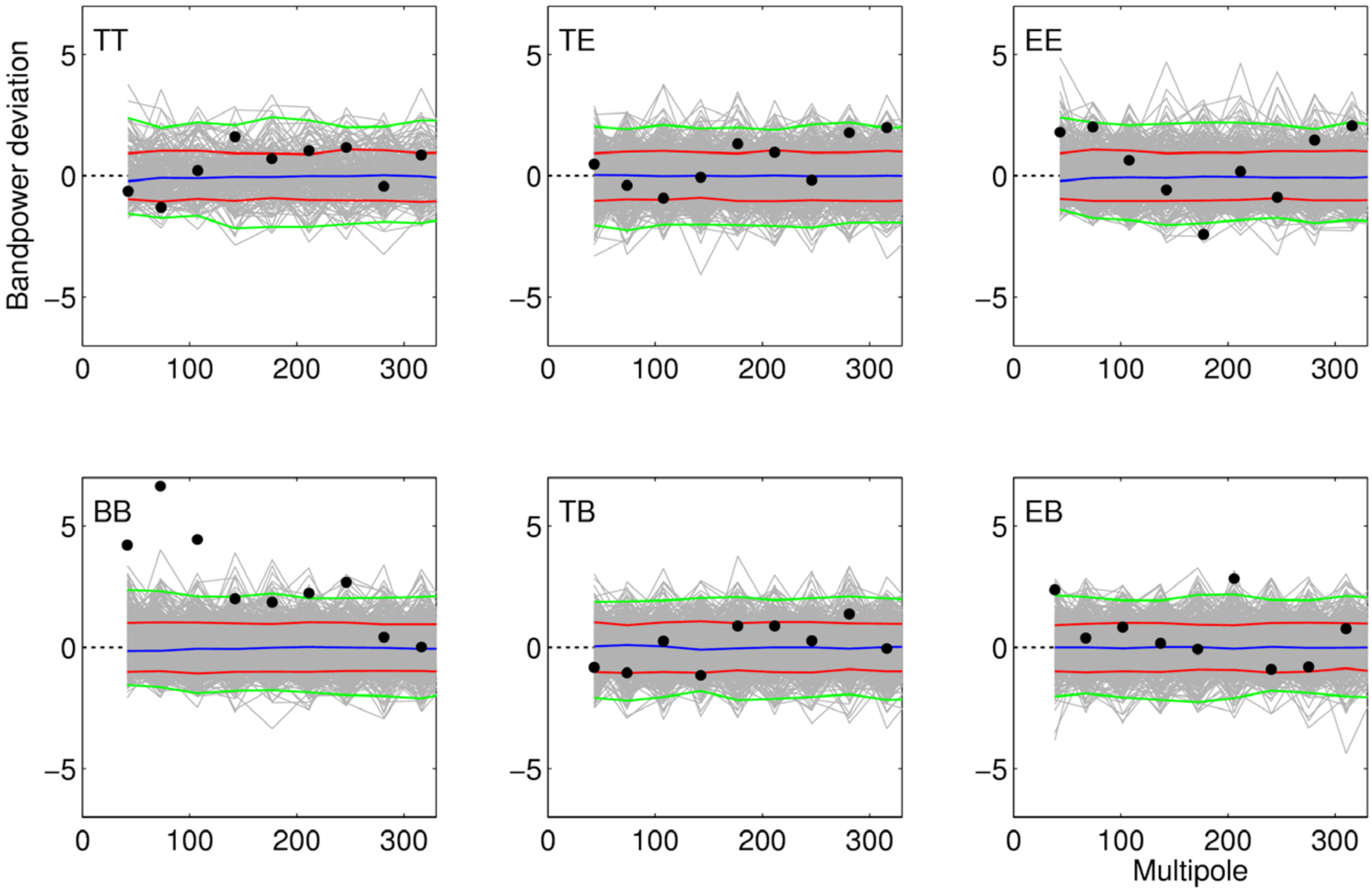
Bandpower Deviations



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

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

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Check Systematics: Jackknifes

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

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

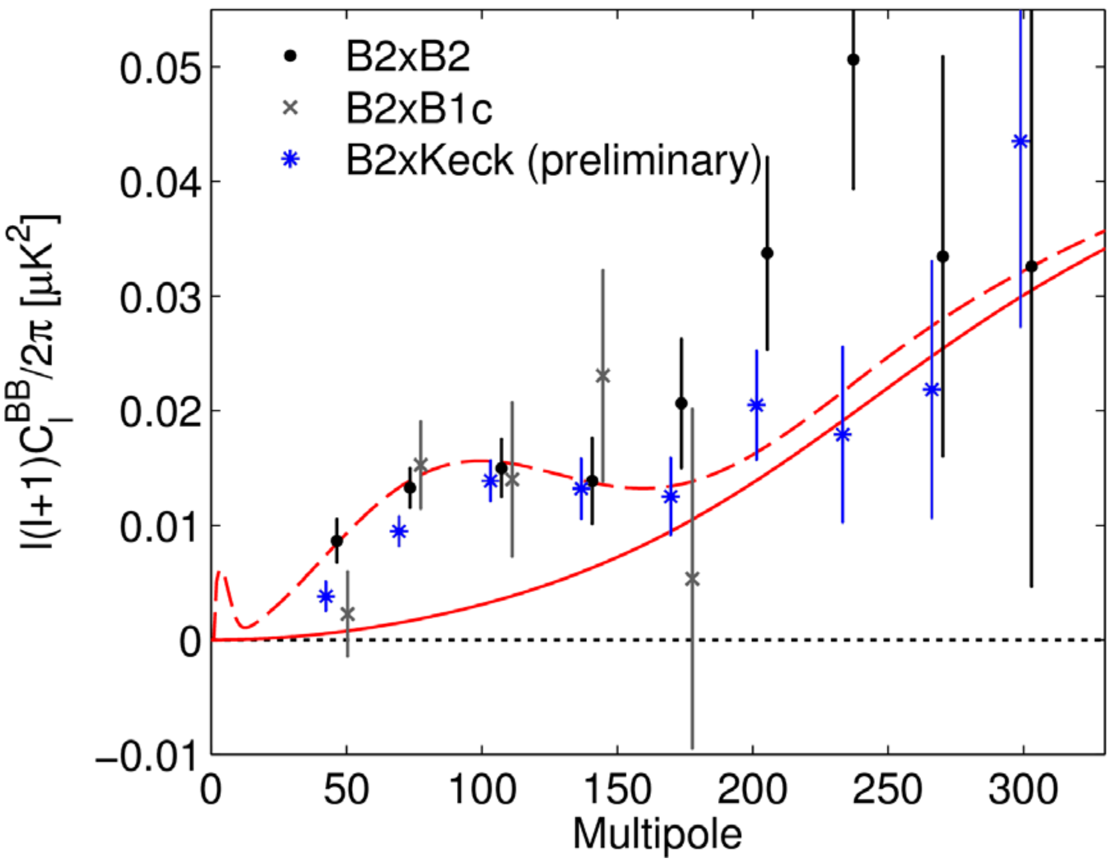
Checks for contamination from ground-fixed signals, such as polarized sky or magnetic fields, or the moon

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.

Additional Cross Spectra

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

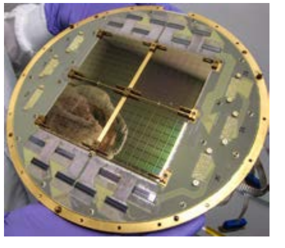


BICEP2 auto spectrum compatible with B2xB1c cross spectrum

~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

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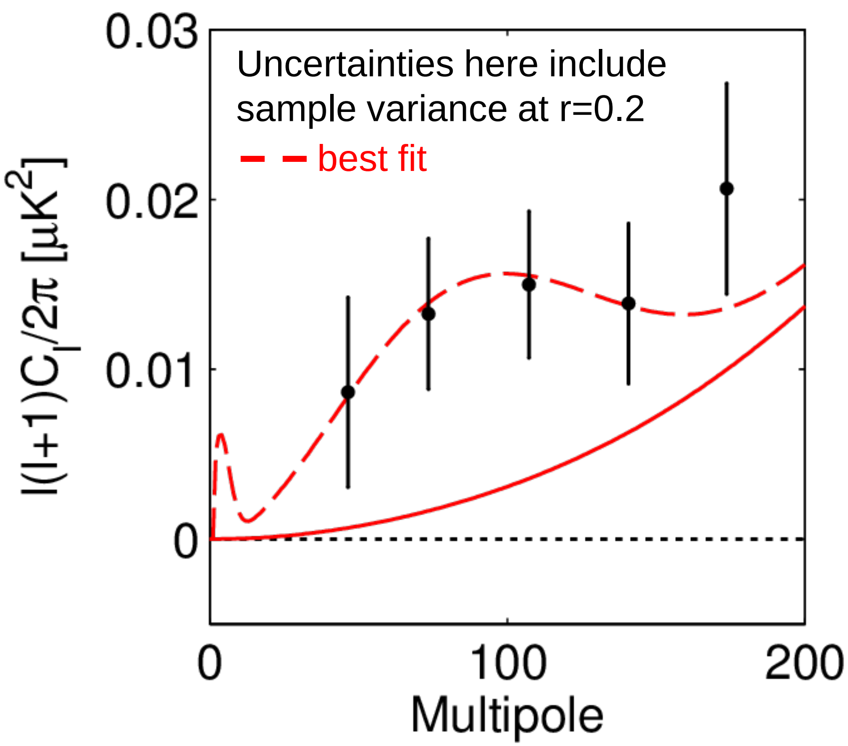
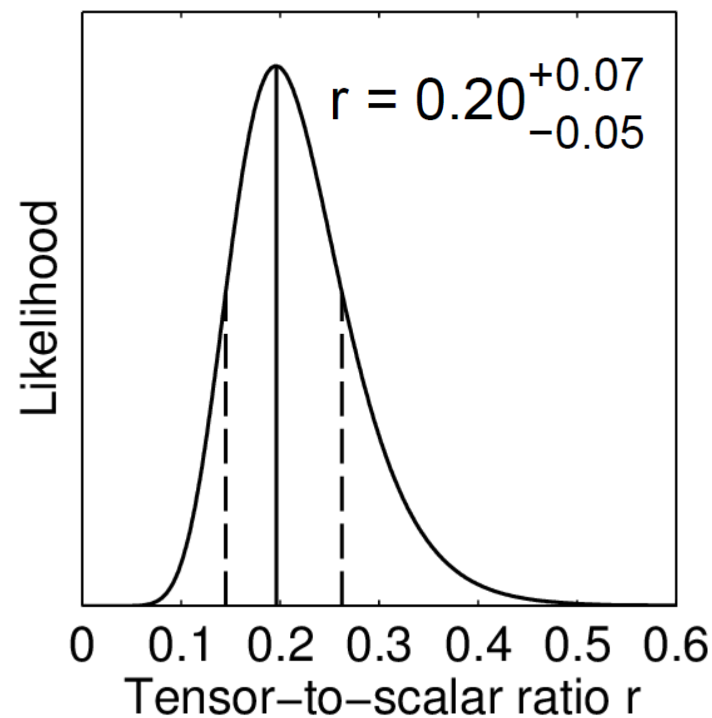
Constraint on Tensor-to-scalar Ratio r



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

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

Apply “direct likelihood” method, uses:
→ lensed-ΛCDM + noise simulations
→ weighted version of the 5 bandpowers
→ B-mode sims scaled to various levels of r
(n_T=0)



Within this simplistic model we find:

r = 0.2 with uncertainties dominated by sample variance

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

r=0 ruled out at 7.0σ

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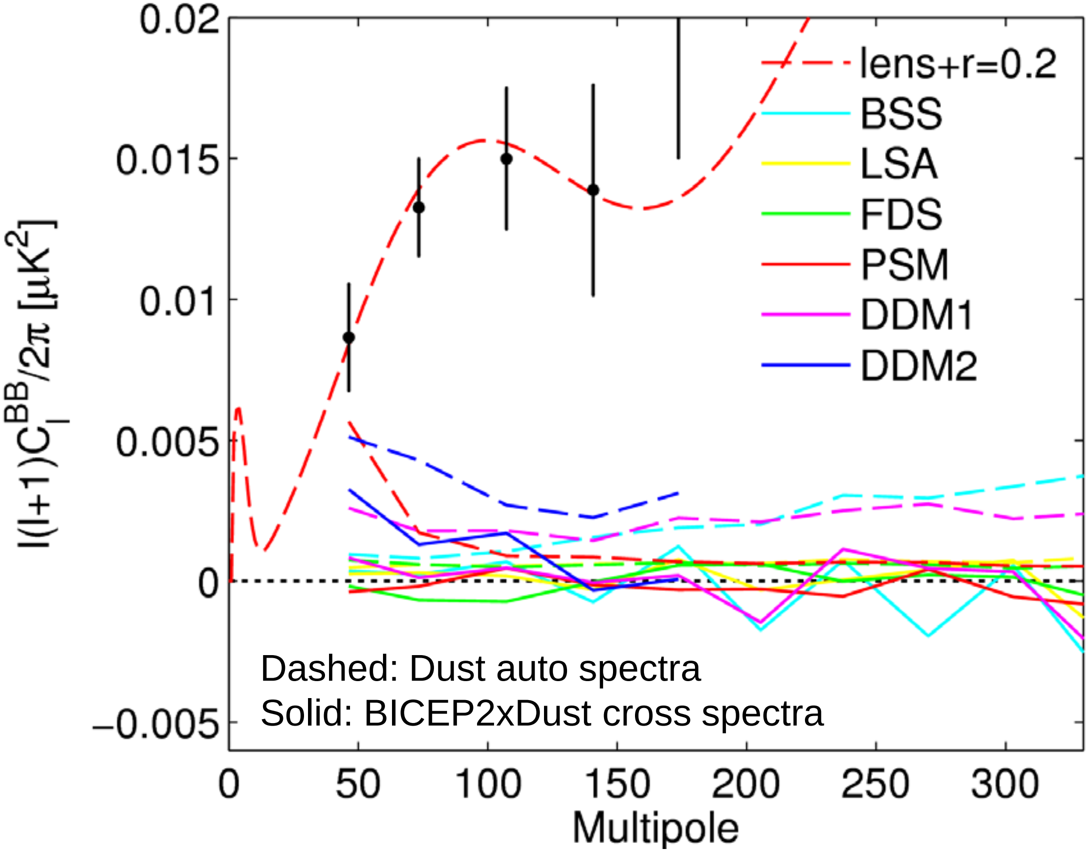
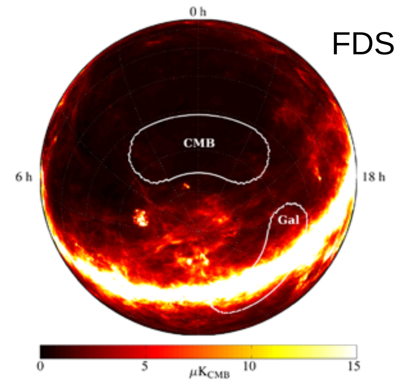
Polarized Dust Foreground Projections





FDS Model

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

Use various models of polarized dust emission to estimate foregrounds.

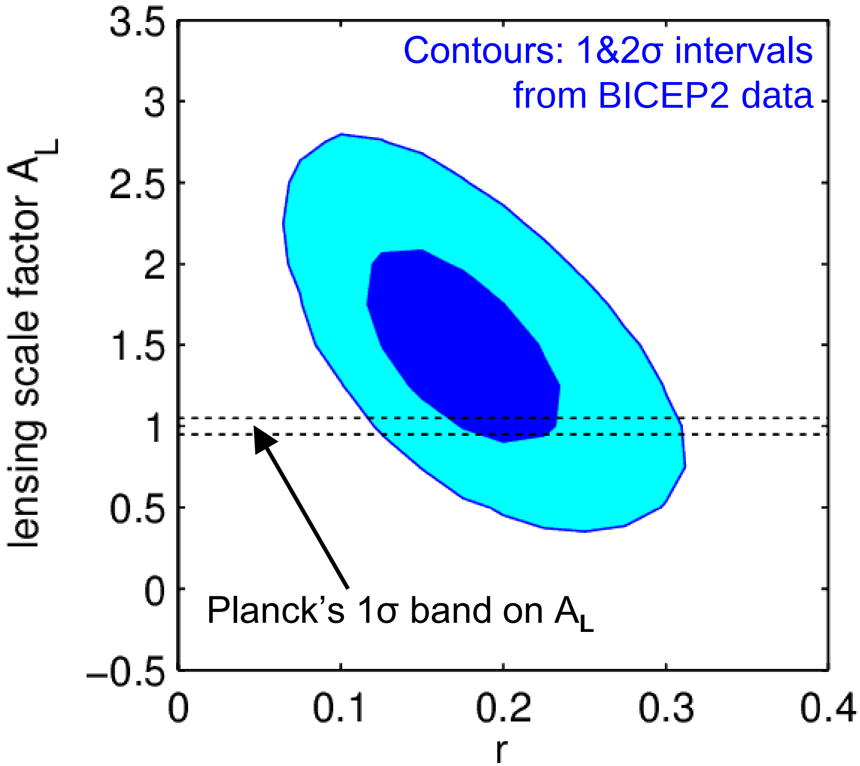
All dust auto spectra well below observed signal level.

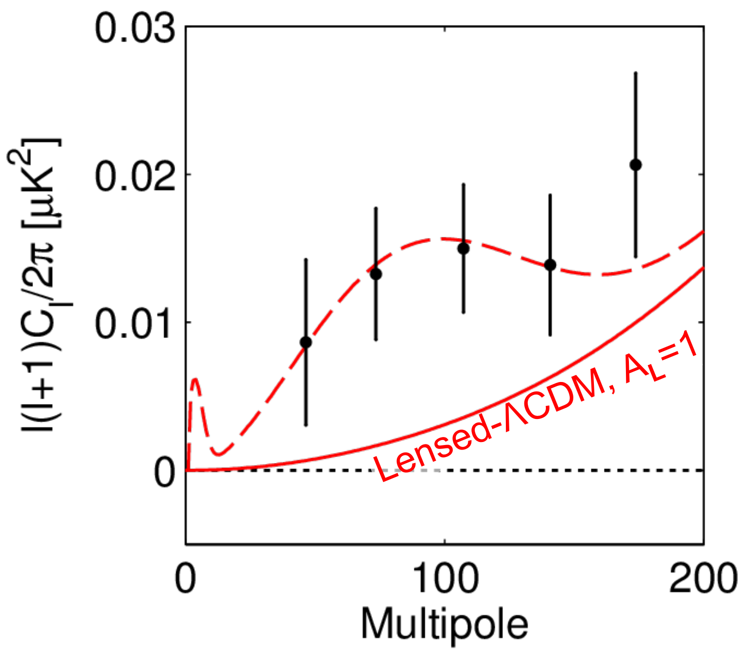
Cross spectra consistent with zero.

Joint Constraint on r and Lensing Scale Factor

Lensing deflects CMB photons, slightly mixing the dominant E-modes into B-modes -- dominant at high multipoles

Planck data constrain the amplitude of the lensing effect to $A_L = 0.99 \pm 0.05$.





In the joint constraint on r and A_L we find:

BICEP2 data is perfectly compatible with a lensing amplitude of A = 1.

Marginalizing over r, we detect lensing B-modes at 2.7σ

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Compatibility with Indirect Limits on r

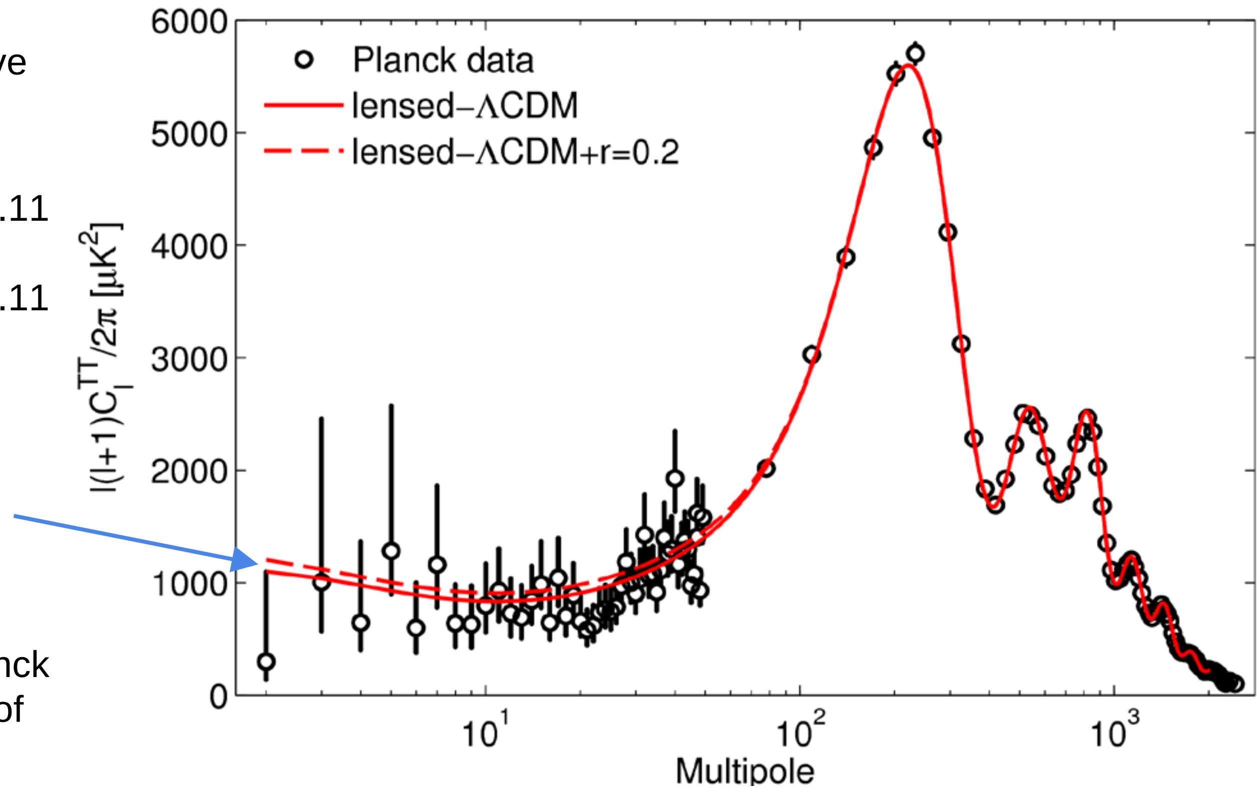
Using temperature data over a wide range of angular scales limits on r have been set:

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

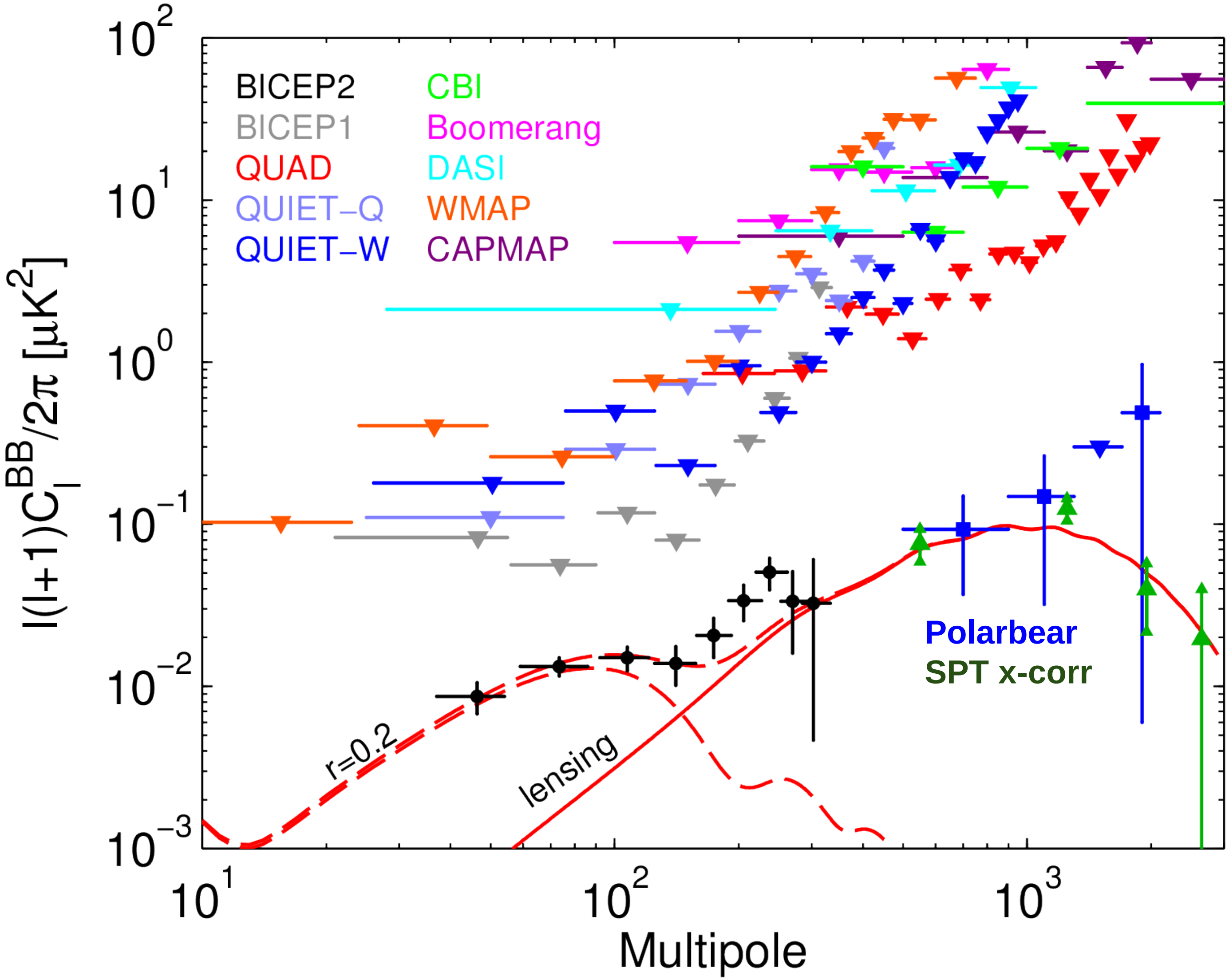
Planck+SPT+ACT+$WMAP_{pol}$: $r < 0.11$

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

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



BICEP2 and upper limits from other experiments:



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(Standard) implications

- Inflation happened
- Gravity is quantized
- Inflation happened at the GUT scale
- Chaotic Inflation models are favored
- Many string-motivated models have been ruled out
- Inflation field moves over Super Planckian range → needs shift symmetry in Q.G.
- Half of axion parameter space is ruled out
- Low ell anomaly becomes worse
- …..

Prospects

BICEP1: 2006, 2007, 2008 ($r<0.70$; 95%)

BICEP2: 2010, 2011, 2012 ($r=0.2$ +0.07-0.05)

Keck Array: 2011, 2012, 2013,

2014 (576 100GHz detectors)…

BICEP3: 2015…

Prospects

BICEP1: 2006, 2007, 2008

BICEP2: 2010, 2011, 2012

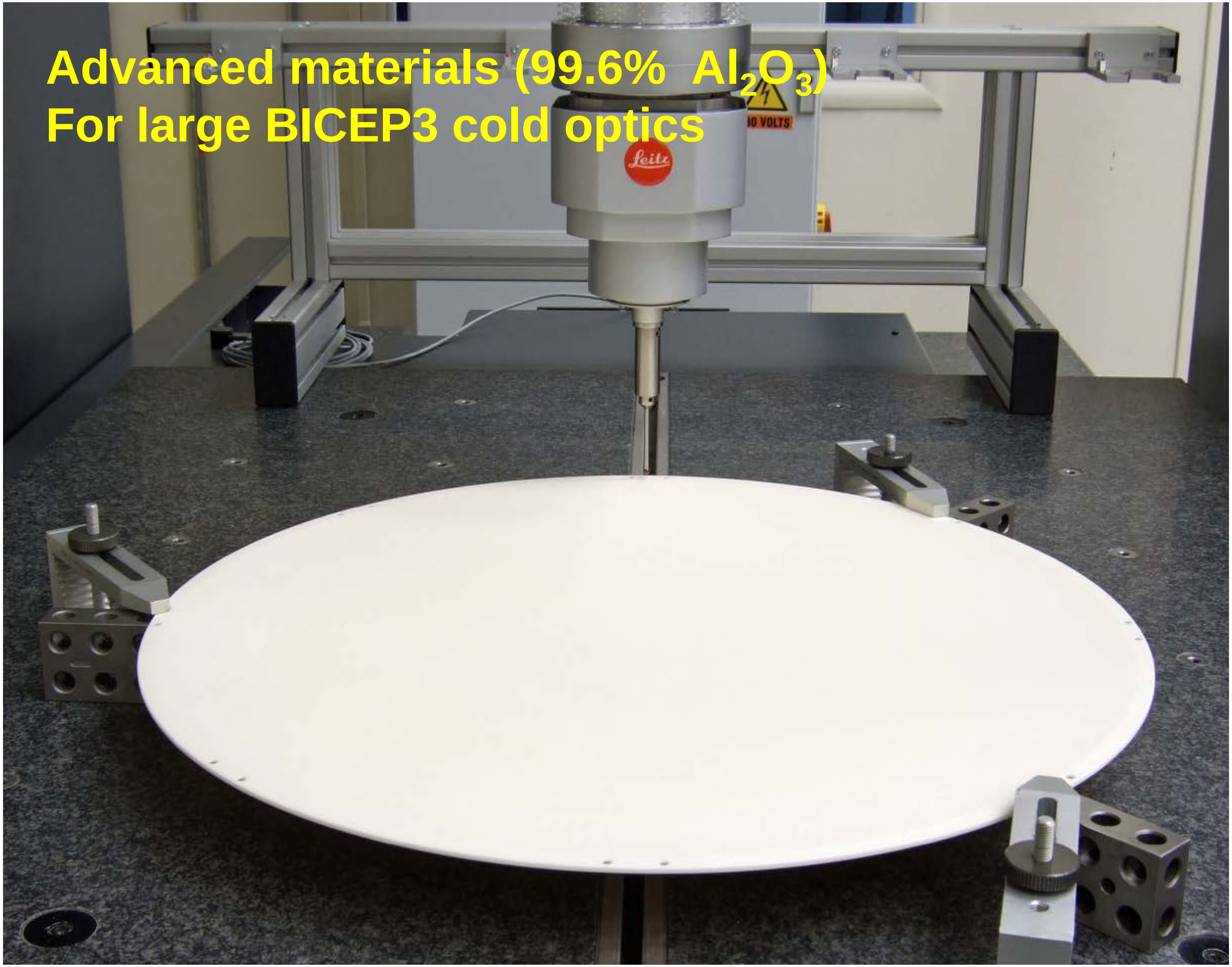
Keck Array: 2011, 2012, 2013,

2014 (576 100GHz detectors)…

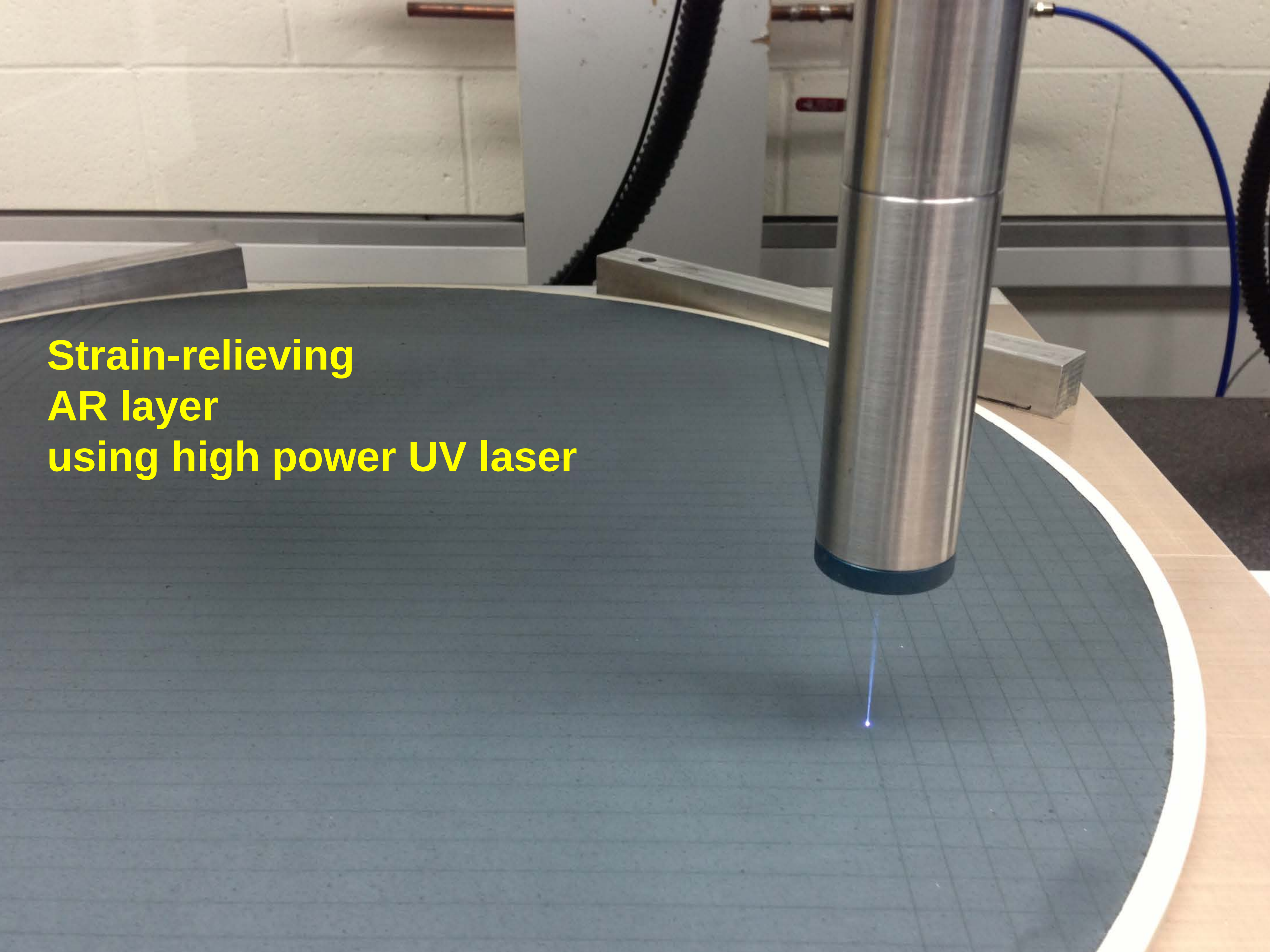
BICEP3: 2015 –

(another 2560 100GHz detectors)

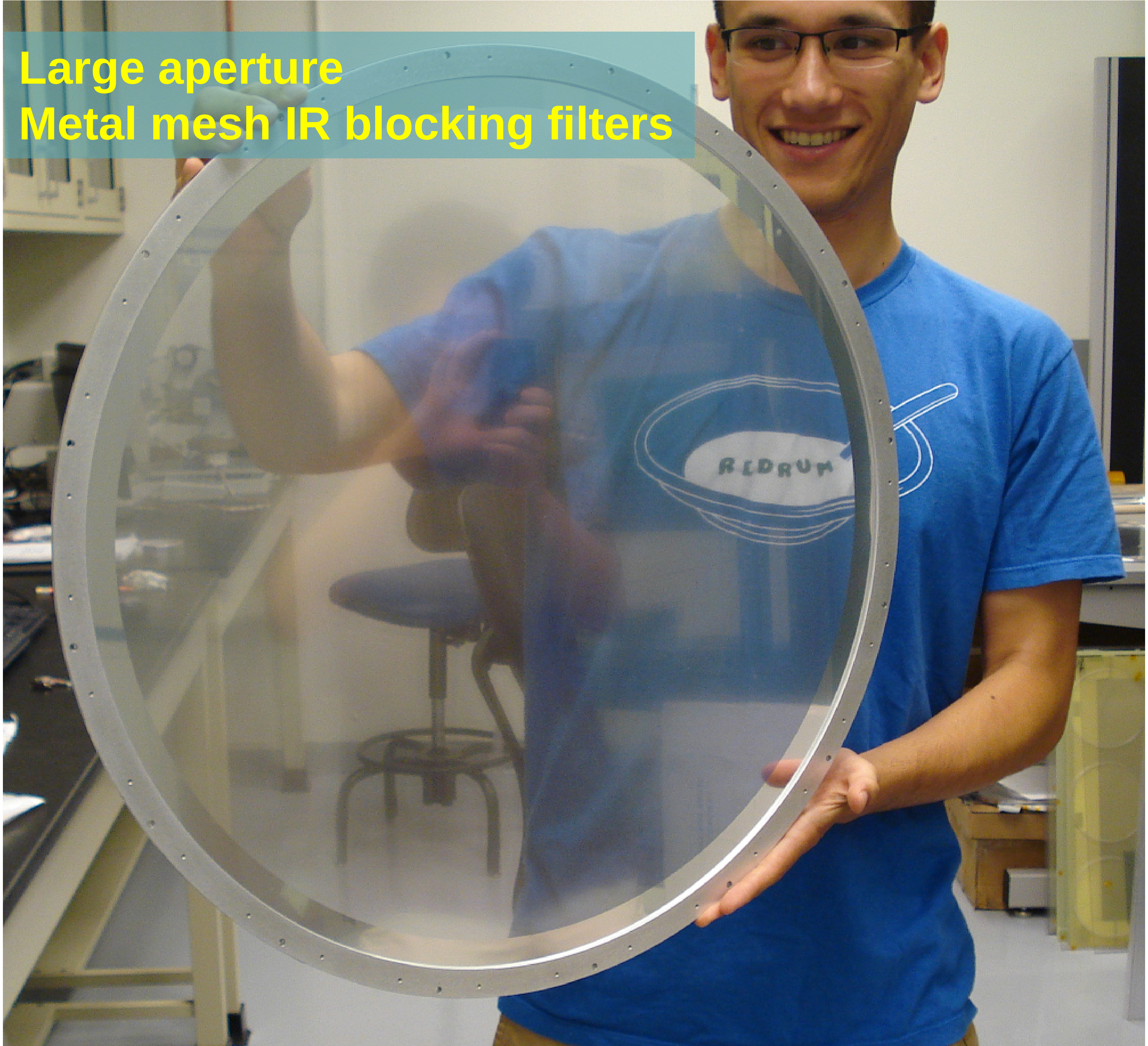
Advanced materials (99.6% Al_2O_3)
For large BICEP3 cold optics



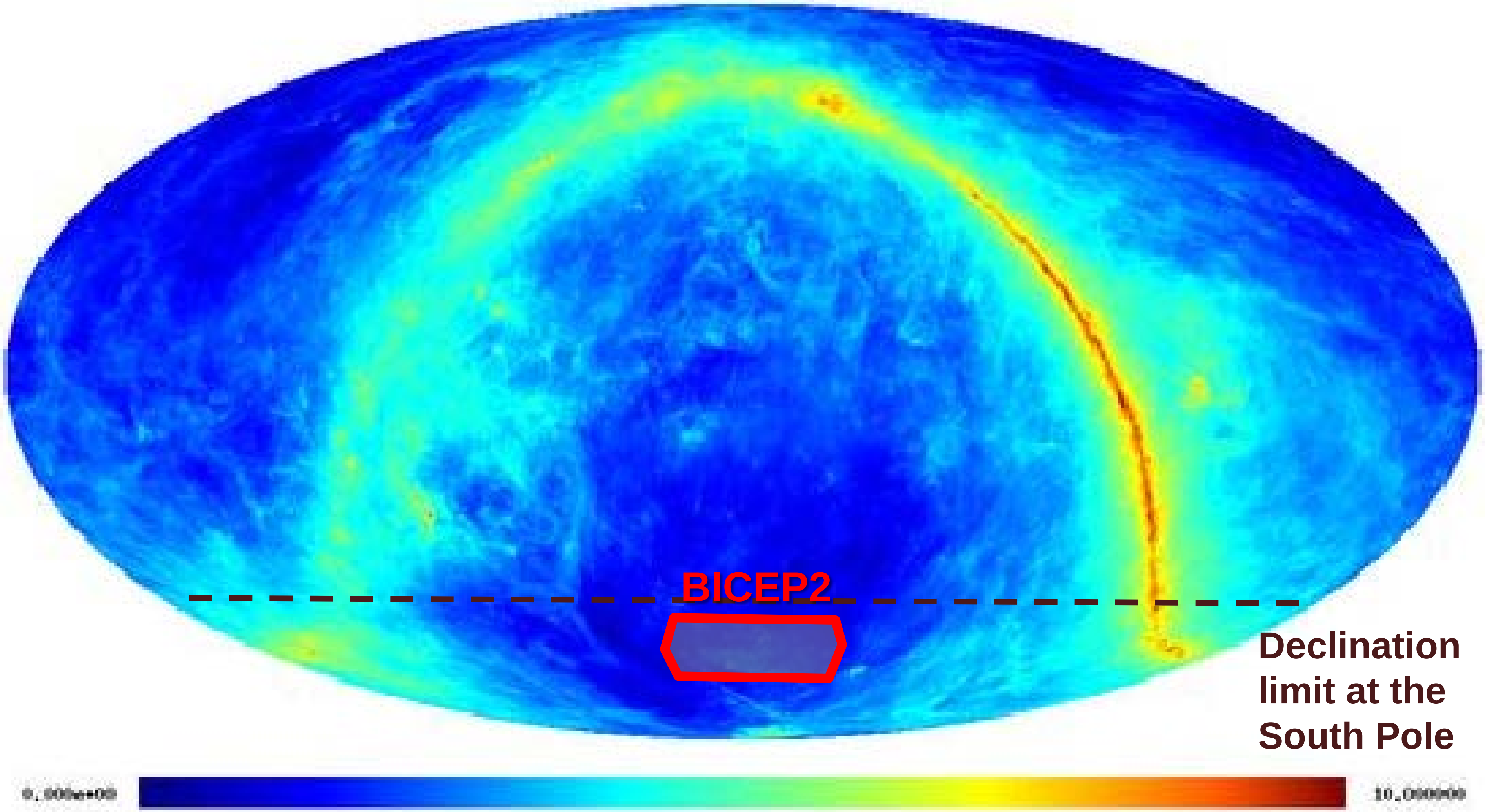

Epoxy-based
AR-coating
On curved lens


Strain-relieving
AR layer
using high power UV laser

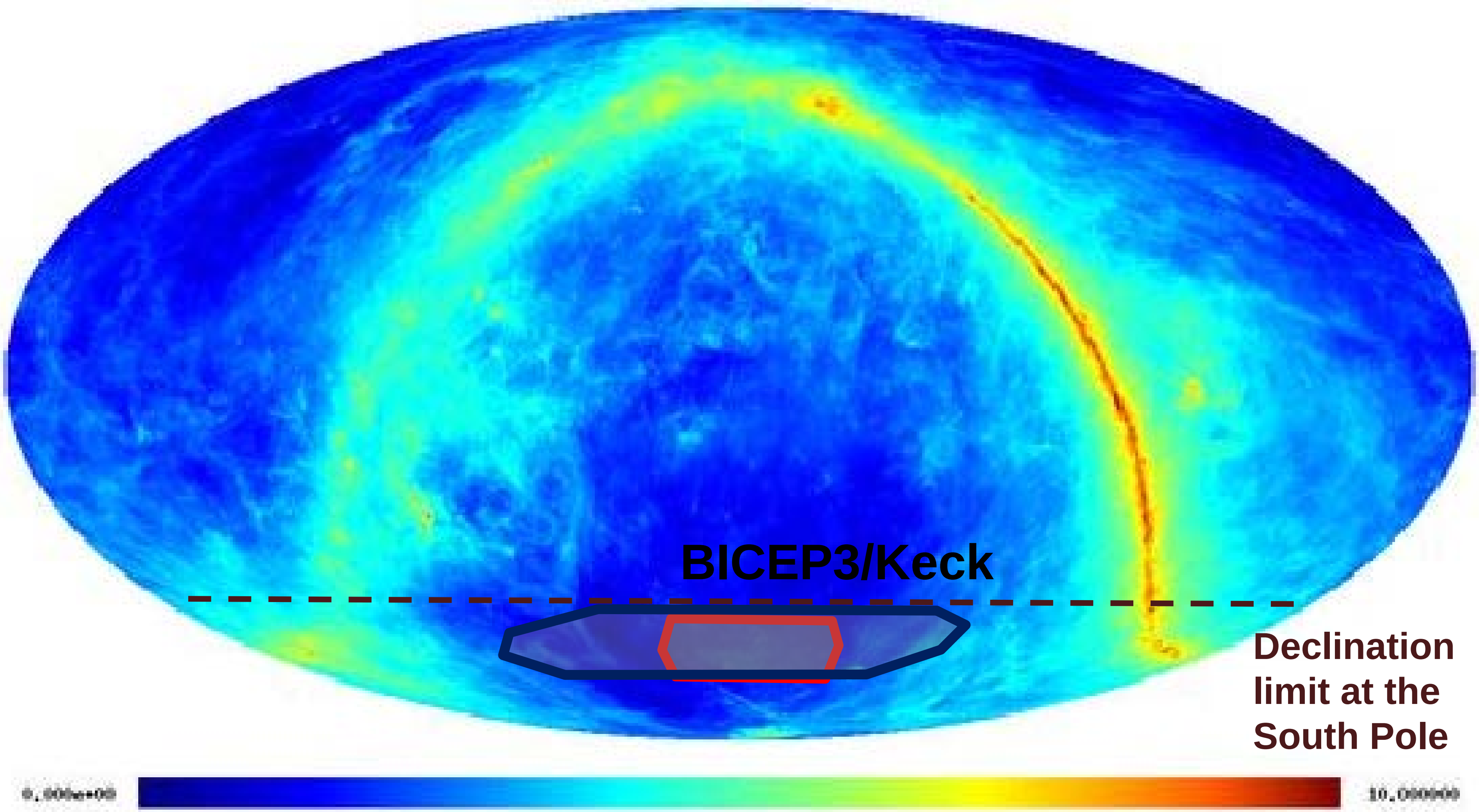
Large aperture
Metal mesh IR blocking filters



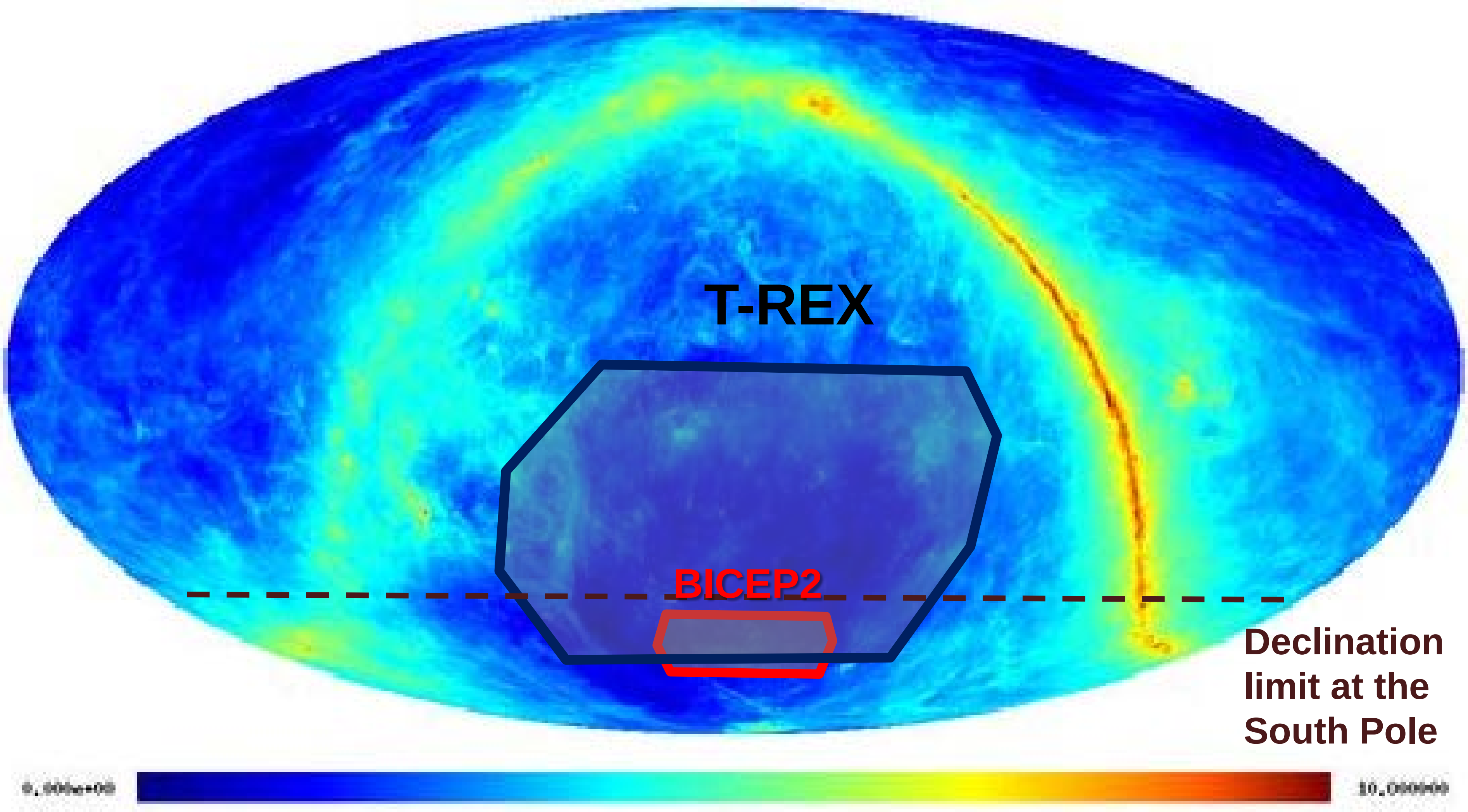
After B2? Increasing the sky coverage



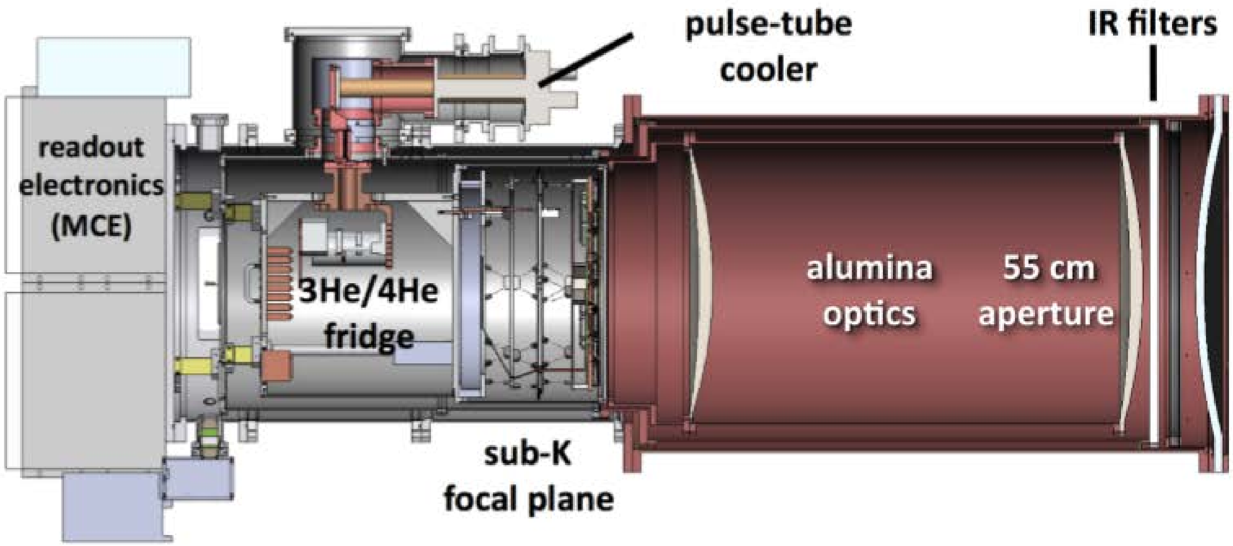
After B2? Increasing the sky coverage

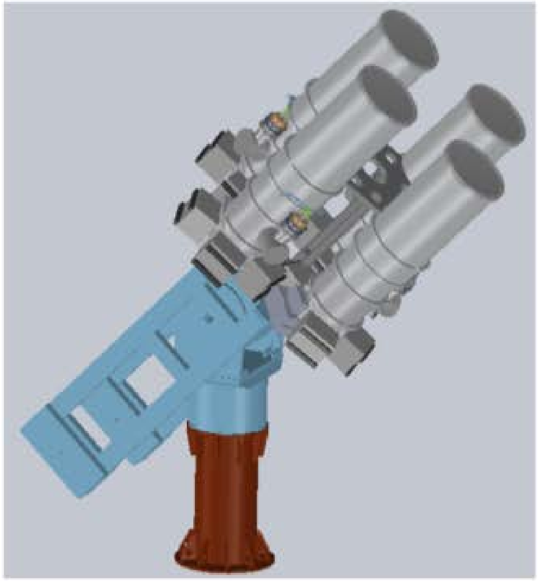


After B3? Increasing the sky coverage



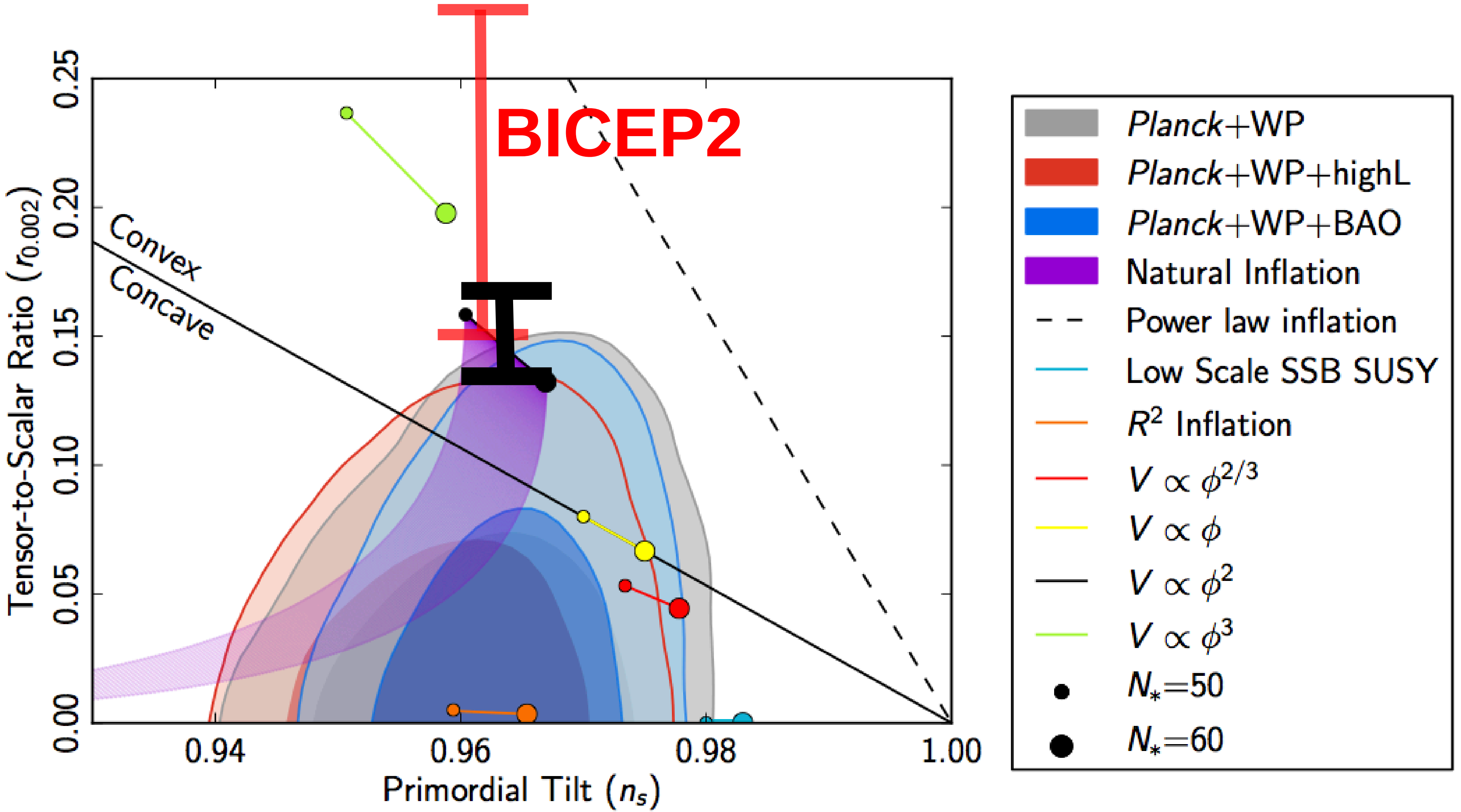
T-REX (TensoR EXperiment):
Straight duplication of BICEP3



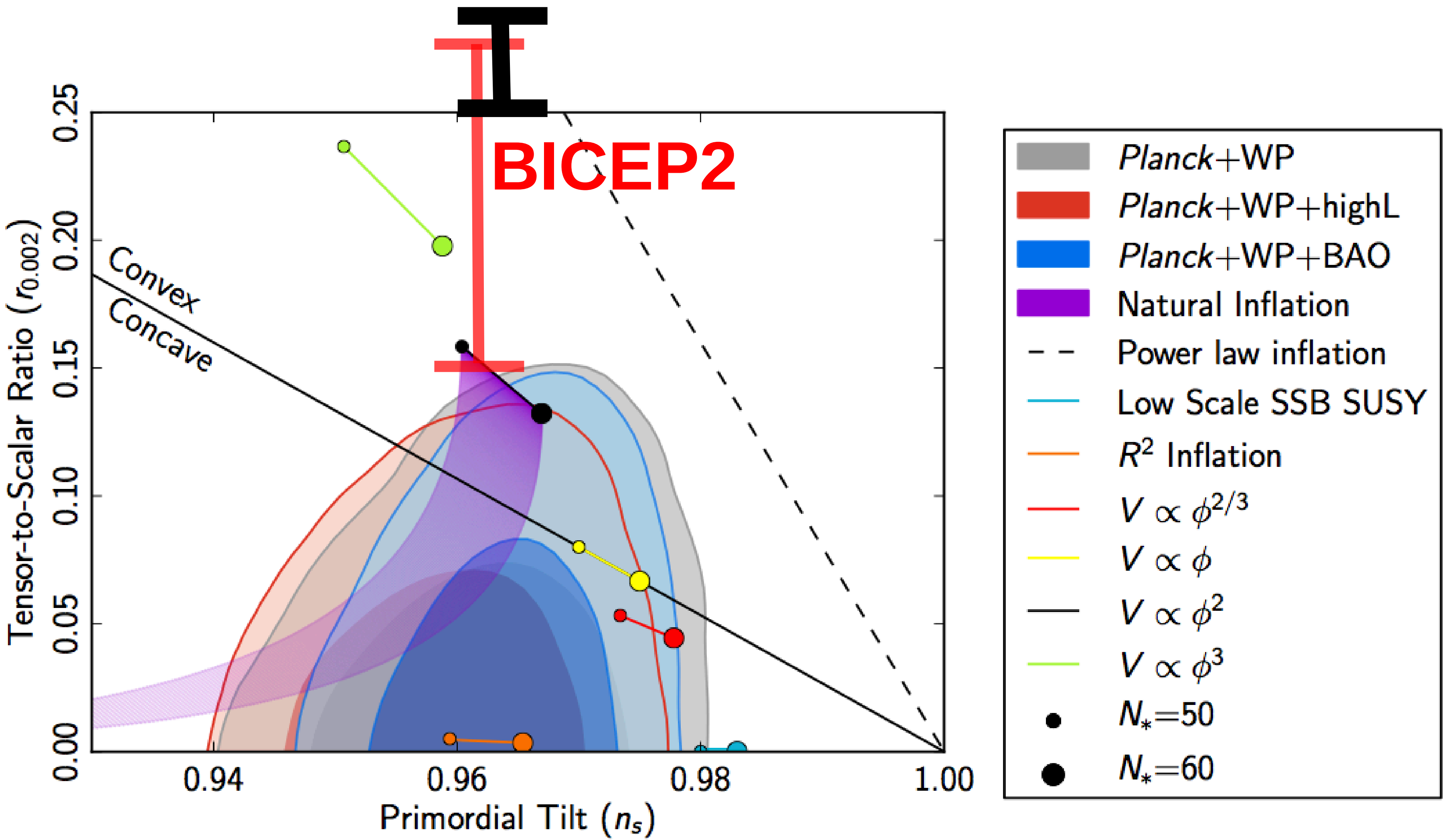


A project that is “shovel-ready”

Where will T-REX land?

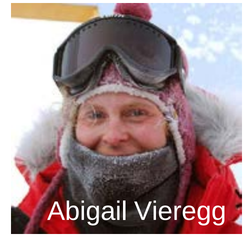


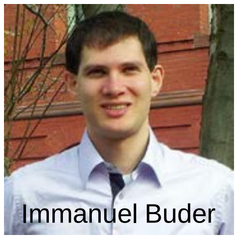
Where will T-REX land?




Thank you !
Keith Vanderlinde

BICEP2 Postdocs





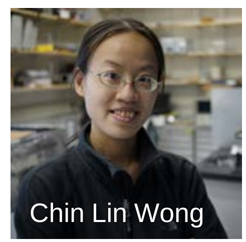
BICEP2 Winterovers

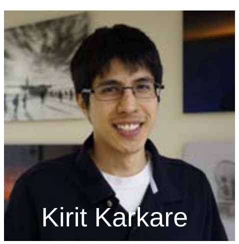
2010

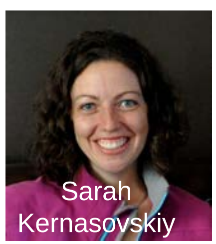
2011

2012

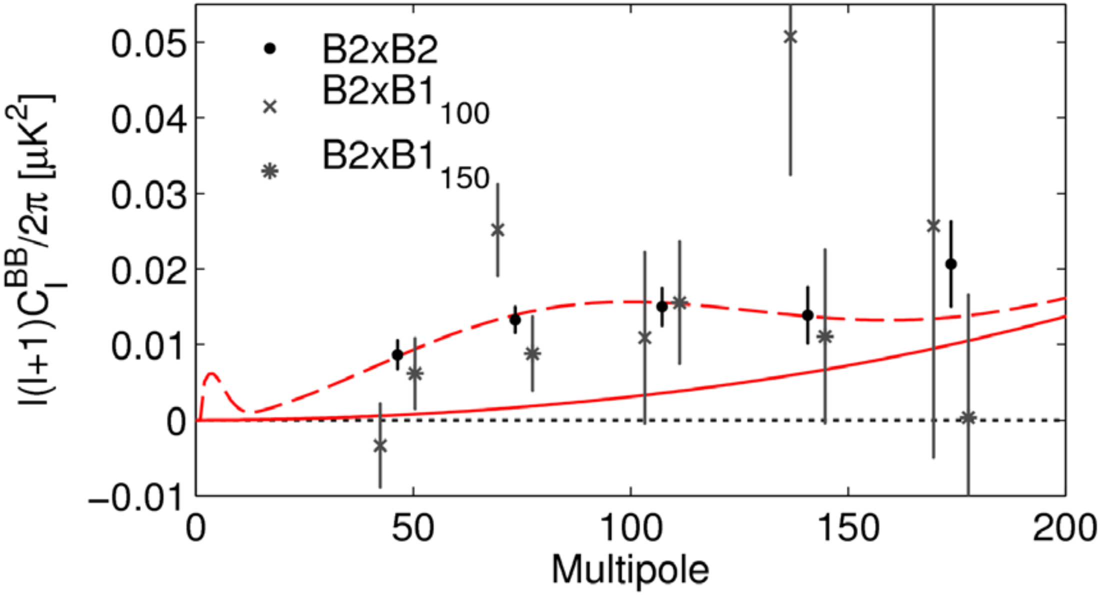
BICEP2 Graduate Students







Spectral Index of the B-mode Signal

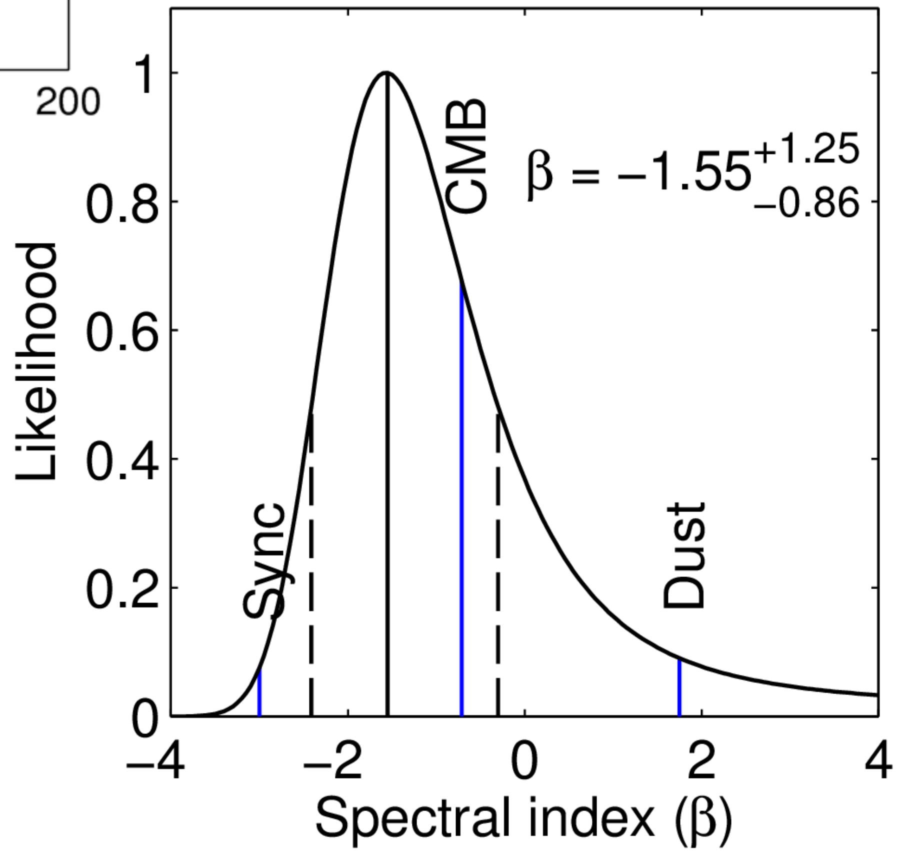


Likelihood ratio test: consistent with CMB spectrum, disfavor pure dust/sync at **2.2/2.3σ**

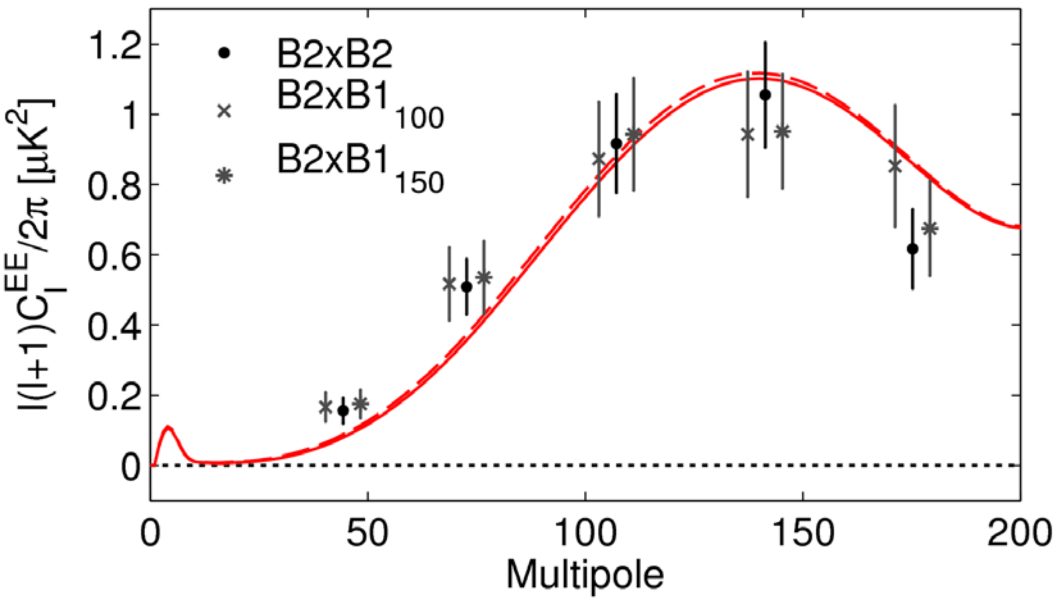
Comparison of B2 auto with $B2_{150}$ x $B1_{100}$ constrains signal frequency dependence, independent of foreground projections

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

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



Spectral Index of the E-mode Signal

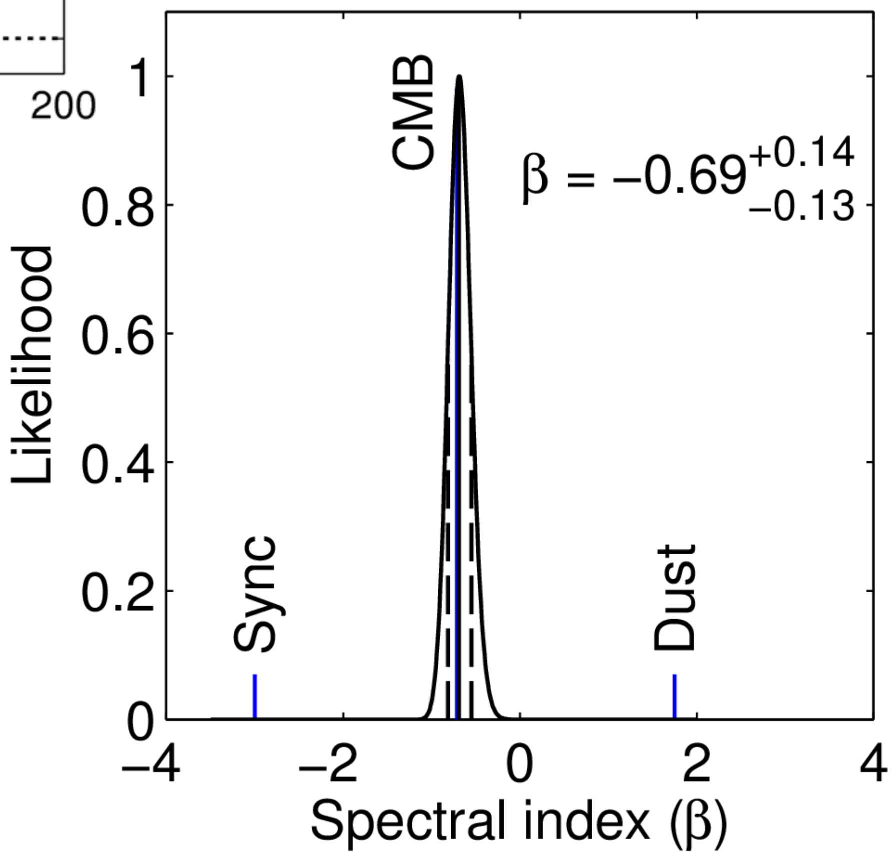


Likelihood ratio test: consistent with CMB spectrum, disfavor pure dust/sync at **11/30σ**

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

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

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

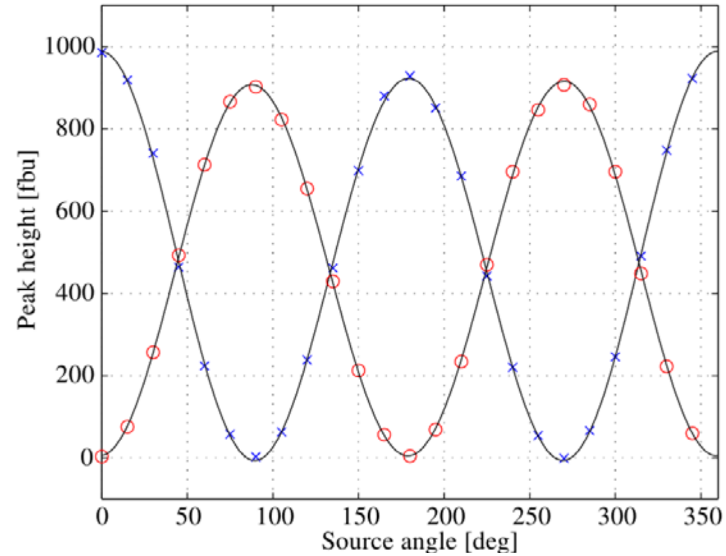


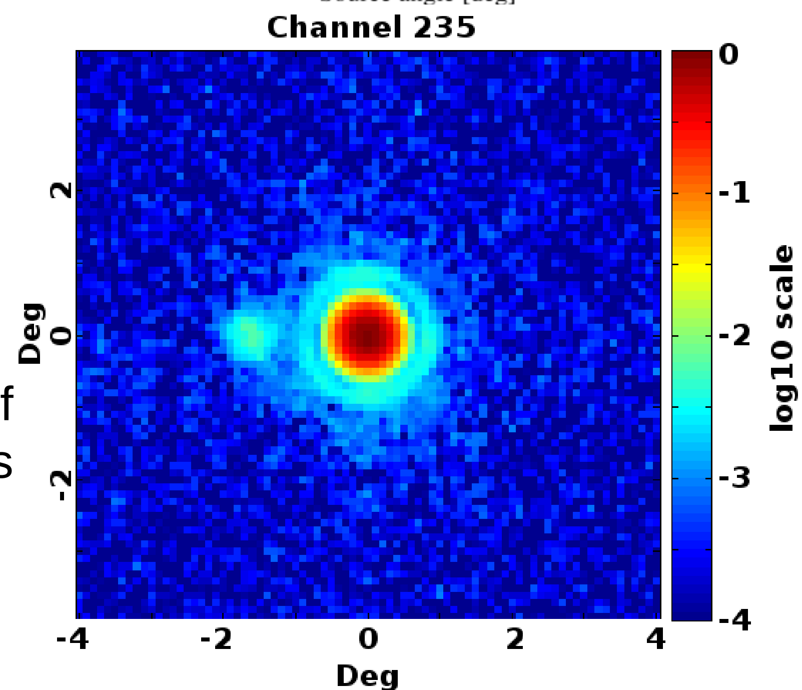
Calibration Measurements

For instance...

Far field beam mapping

Detector Polarization Calibration

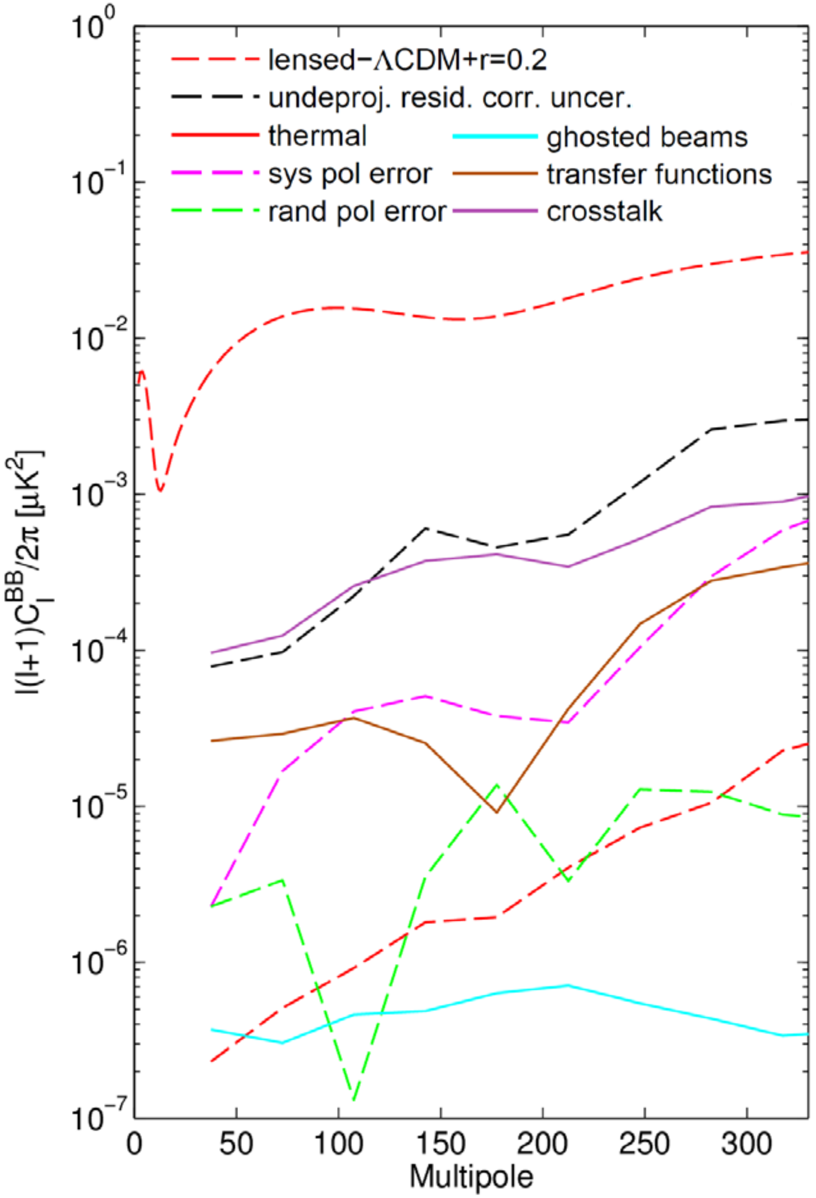




Hi-Fi beam maps of individual detectors

Detailed description in companion Instrument Paper

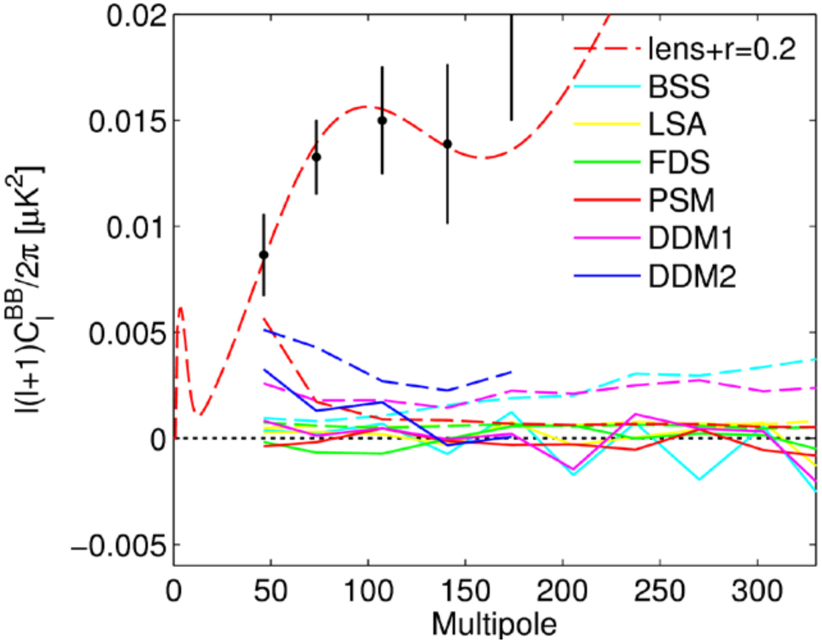
Systematics beyond Beam imperfections



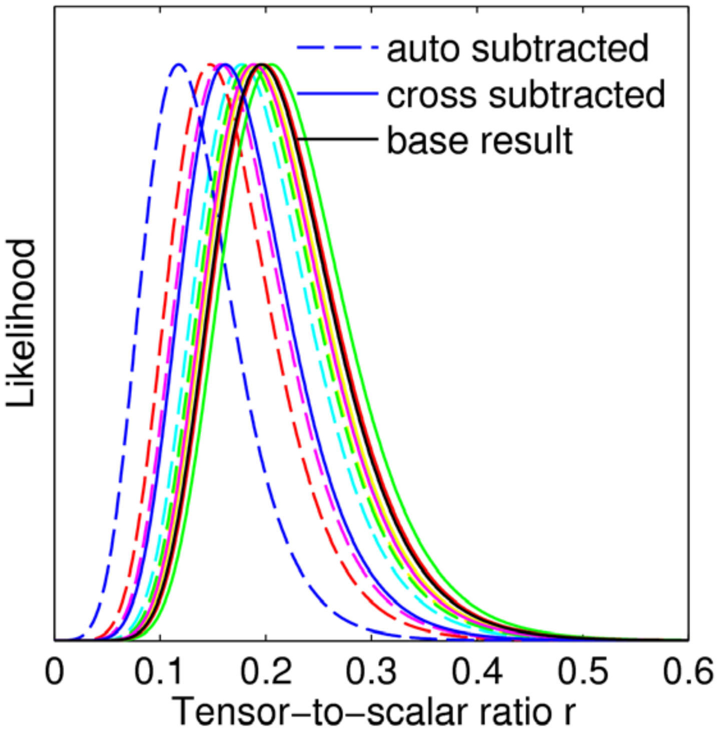
All systematic effects that we could imagine were investigated!

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

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.