Inflationary cosmology with BICEPs

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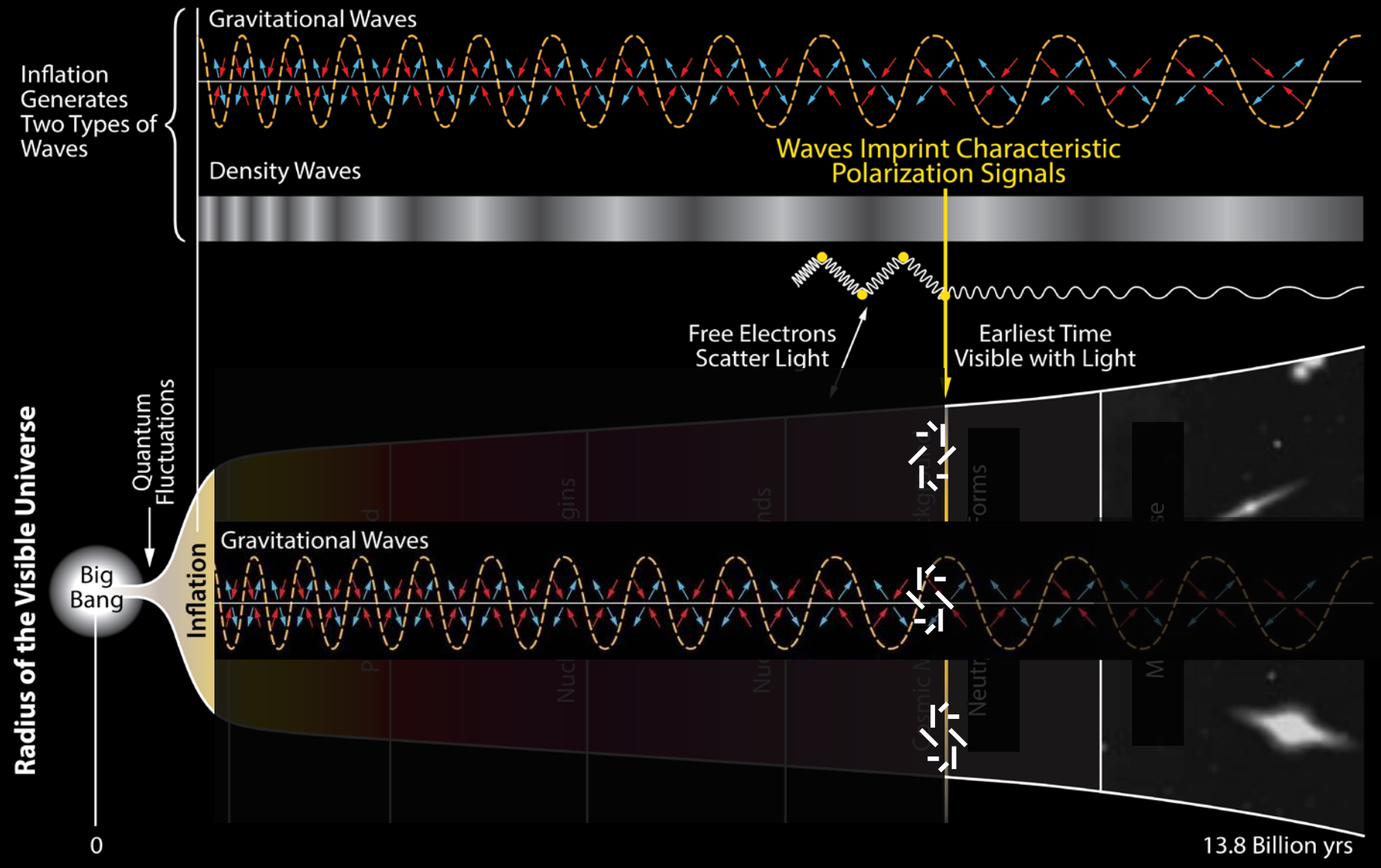
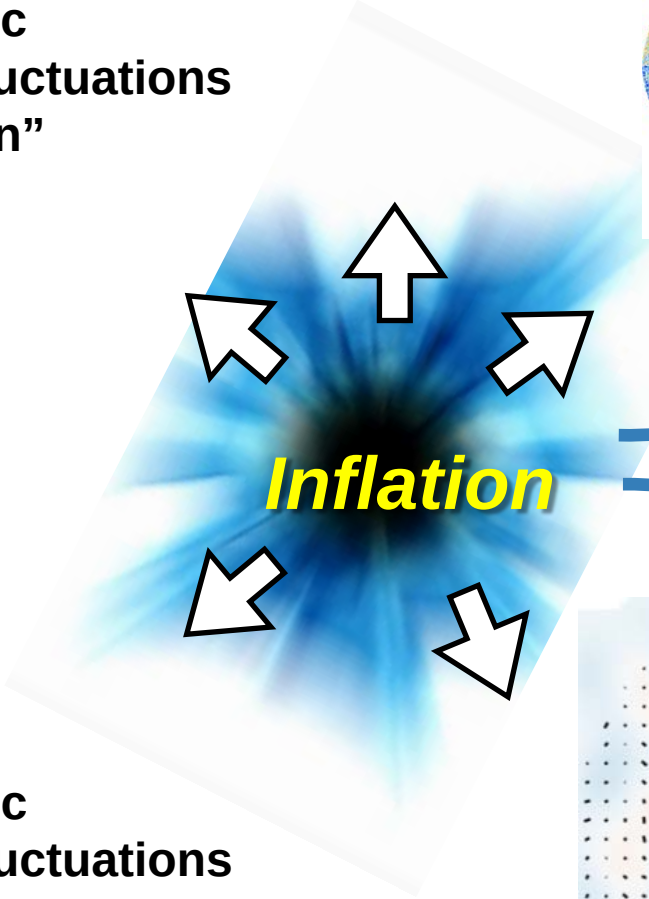
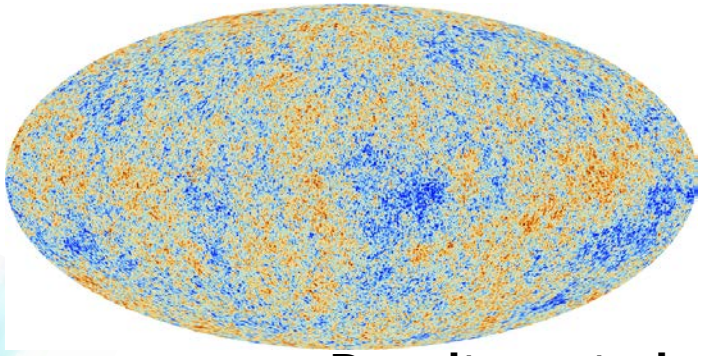
History of the Universe



Density perturbations and gravitational waves

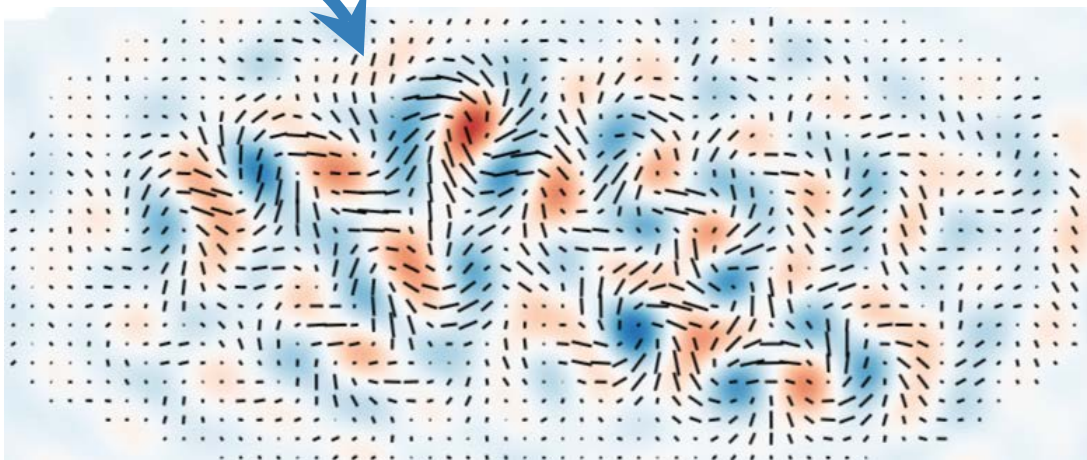
Sub-atomic vacuum fluctuations of "inflaton"





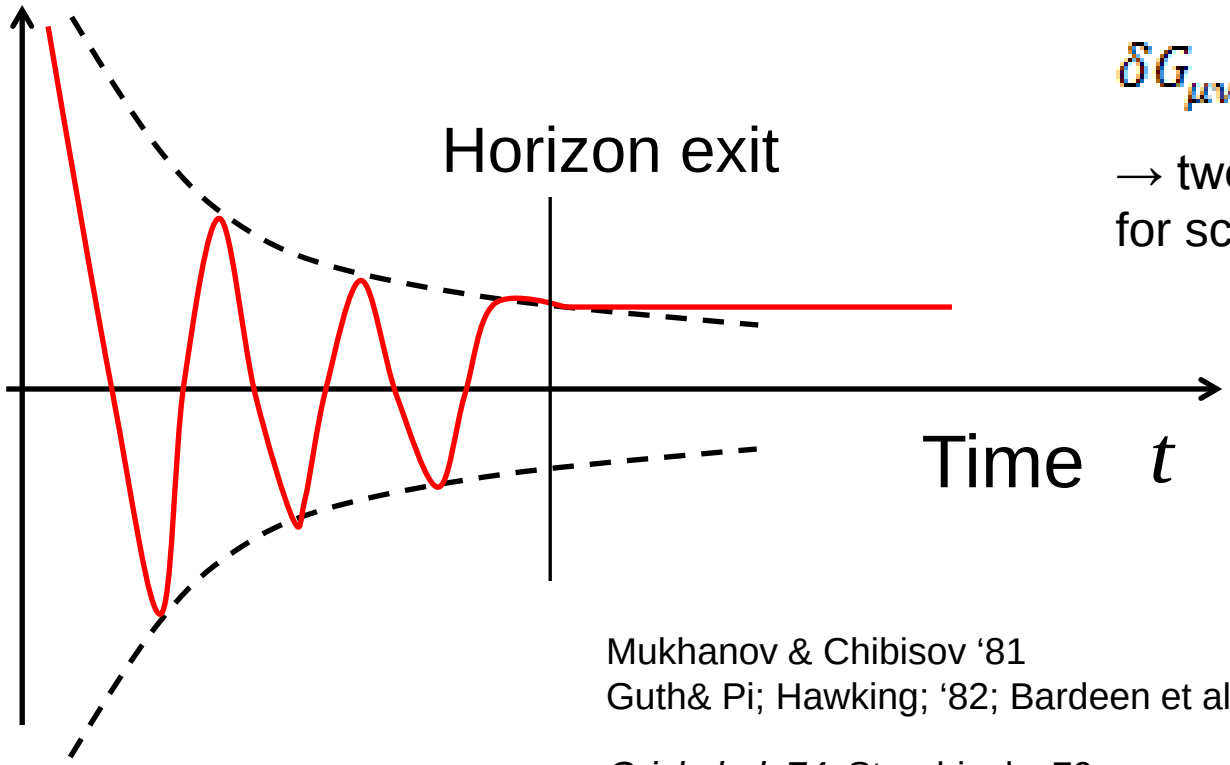
Density perturbations *studied* by Planck, WMAP, SPT, etc.

Gravitational waves



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

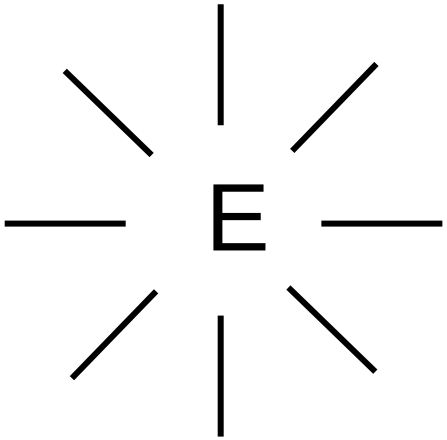
Grishchuk 74; Starobinsky 79
Rubakov et al, 82; Frabri & Pollock , 82

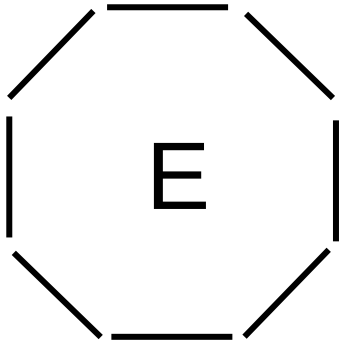
Quantum fluctuations in the vacuum state of the *inflaton/graviton* fixes the r.m.s of the linear solutions

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

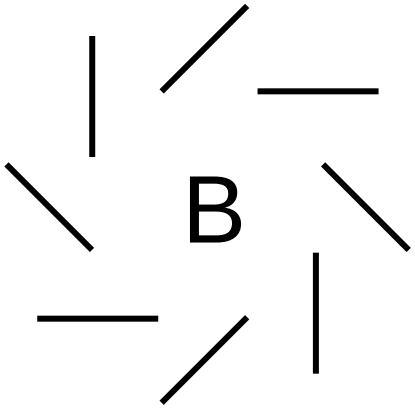
- Started out as *graviton* vacuum fluctuations
- Energy scale of inflation ~ expansion rate ~ GW amplitude
- Alternative models generate no GW
- *Field range and "UV" completeness*

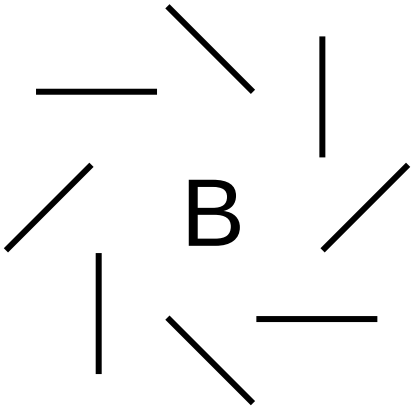
Only gravitational waves can generate B-modes

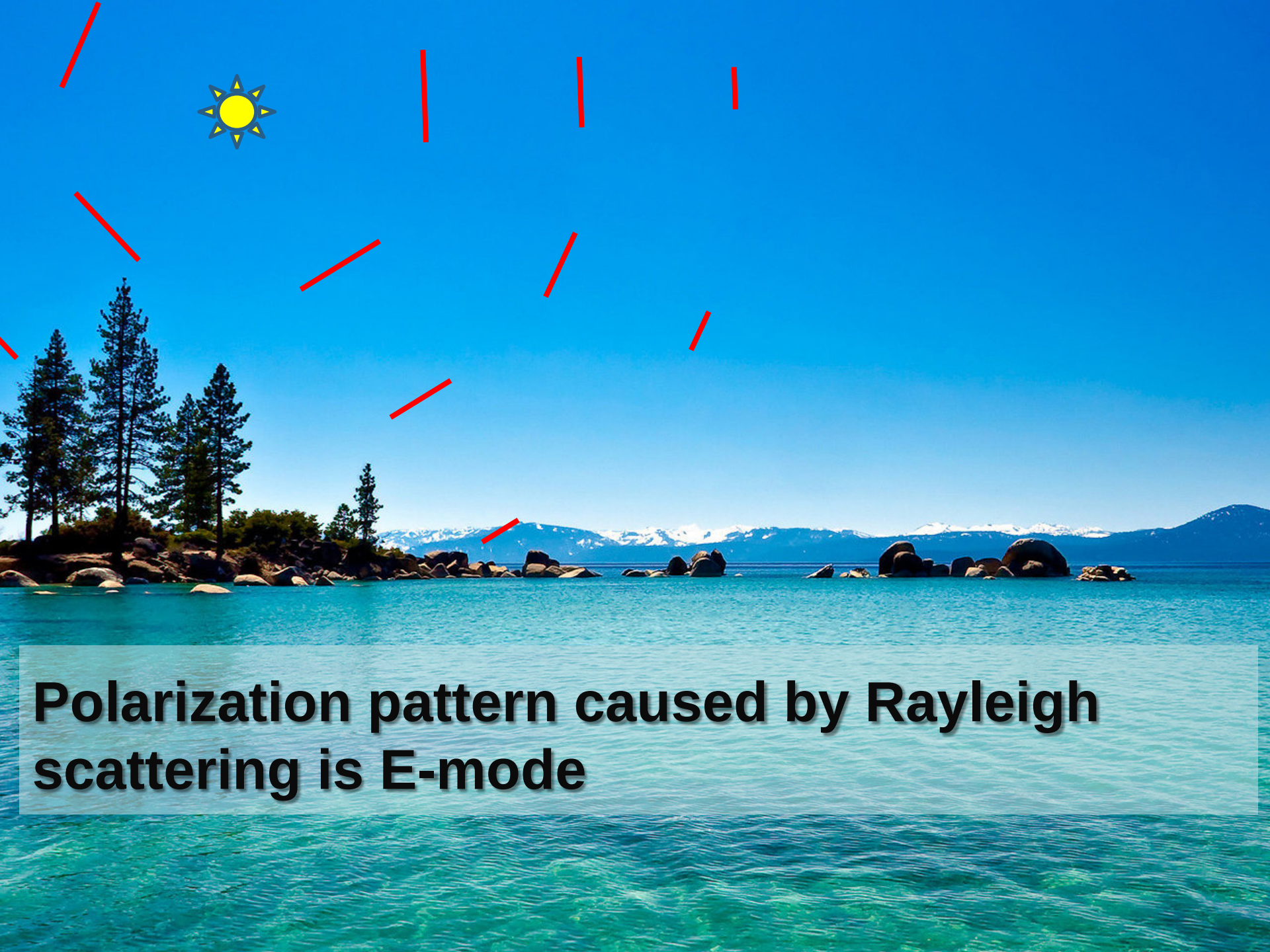




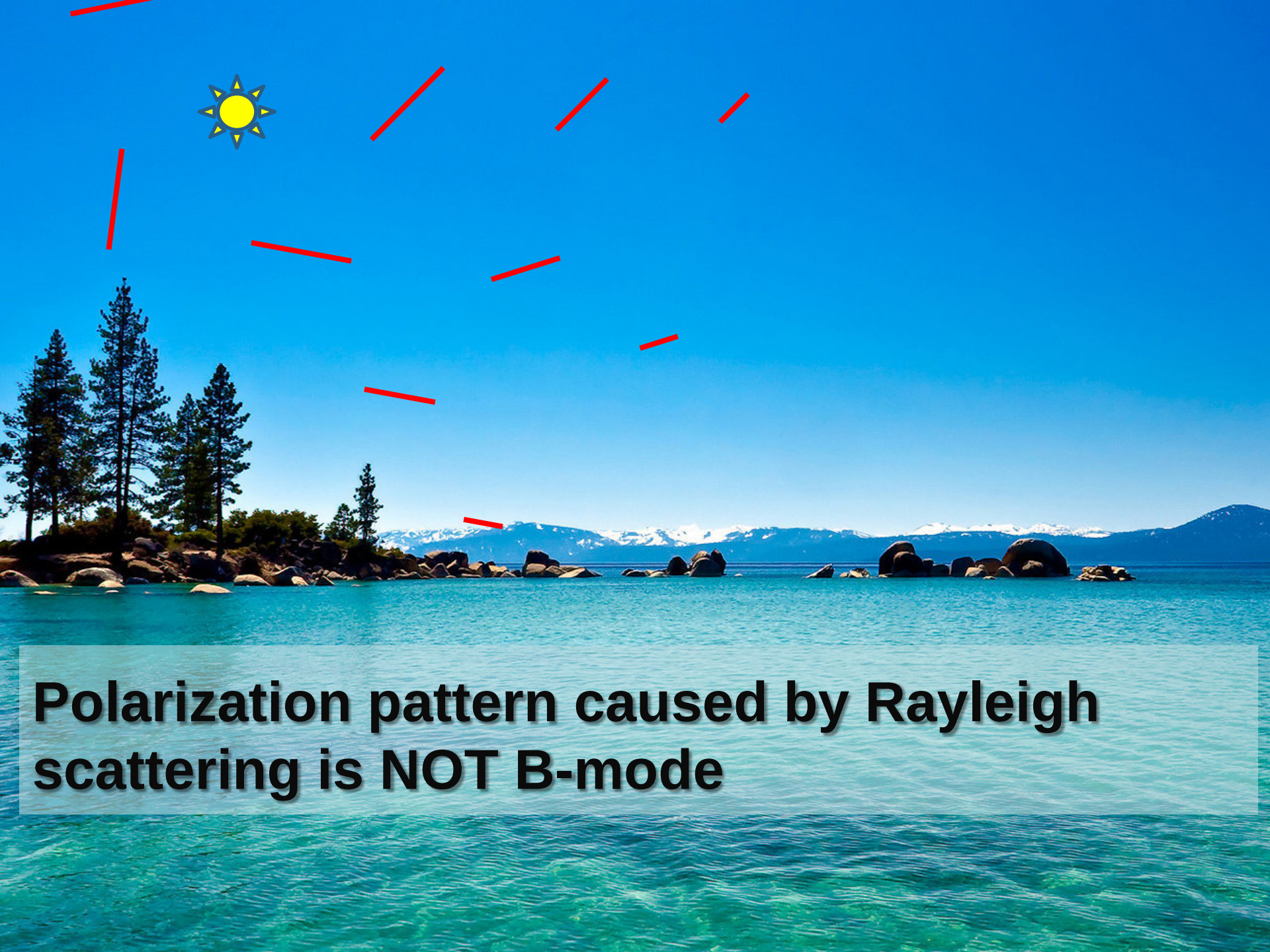
Seljak & Zaldarriaga ‘97
Kamionkowski, Kosowsky, Stebbins ‘97





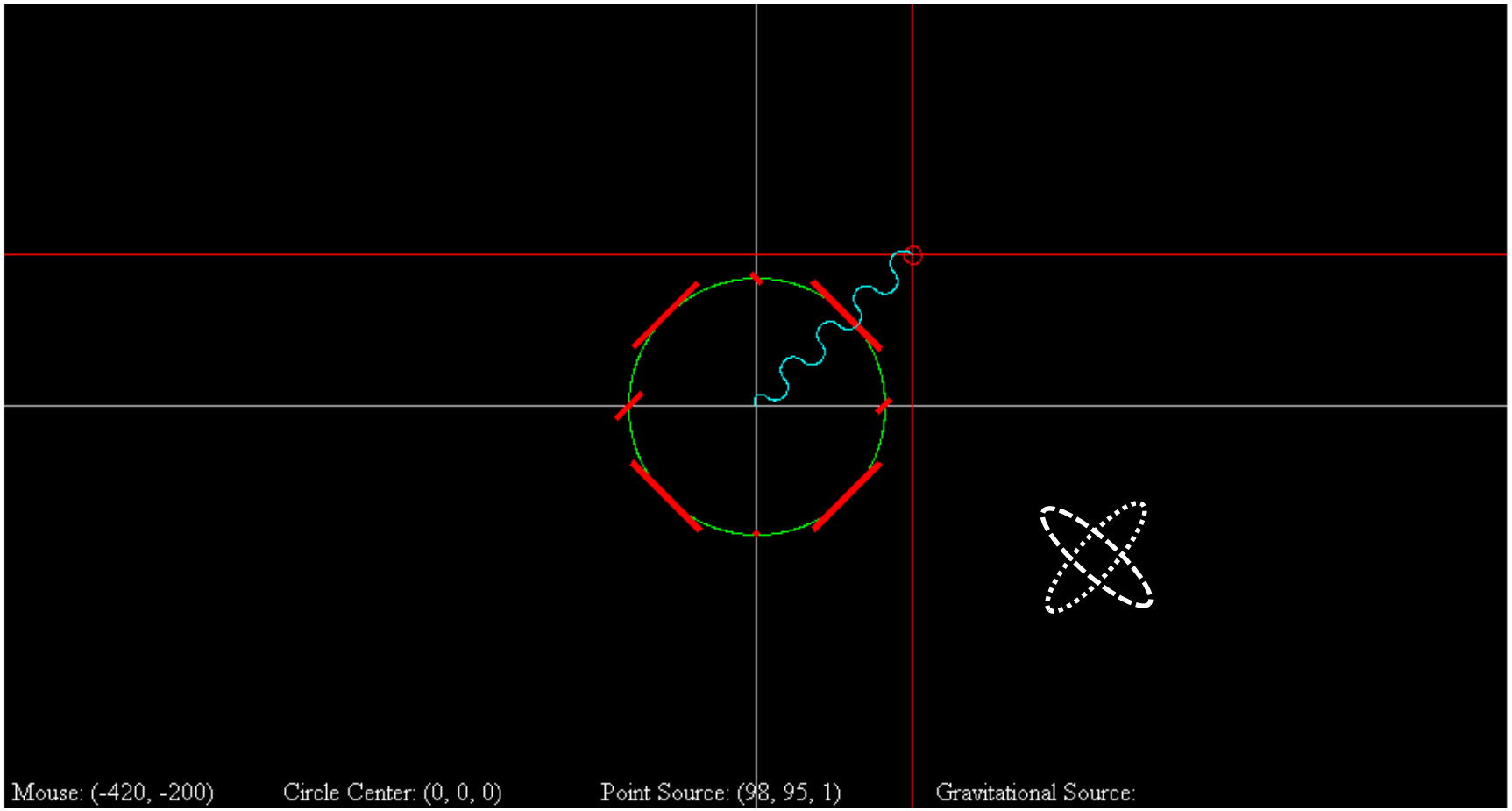


Polarization pattern caused by Rayleigh scattering is E-mode

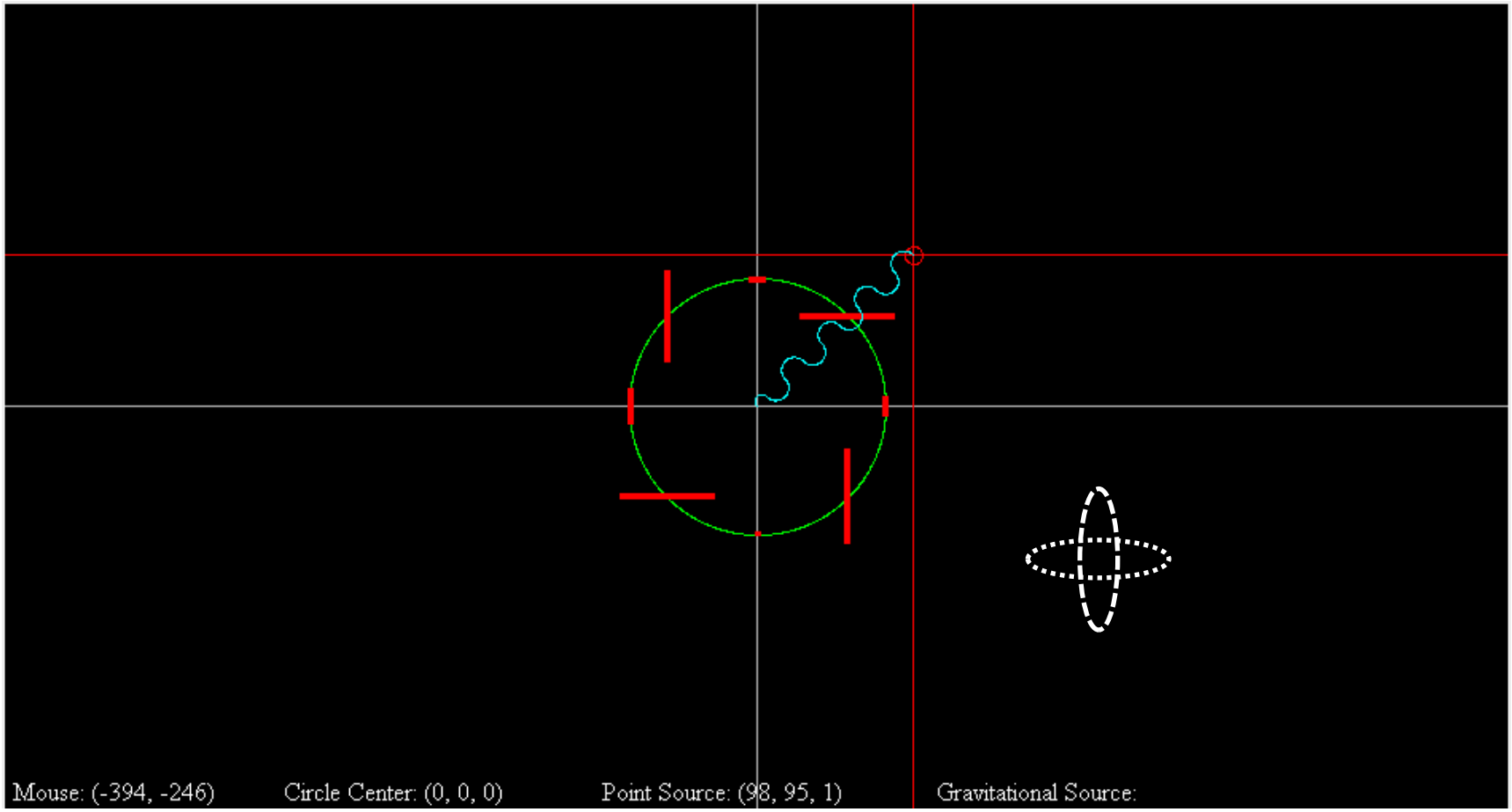


Polarization pattern caused by Rayleigh scattering is NOT B-mode

Gravitational waves generate *E*-mode polarization



Gravitational waves generate *B*-mode polarization



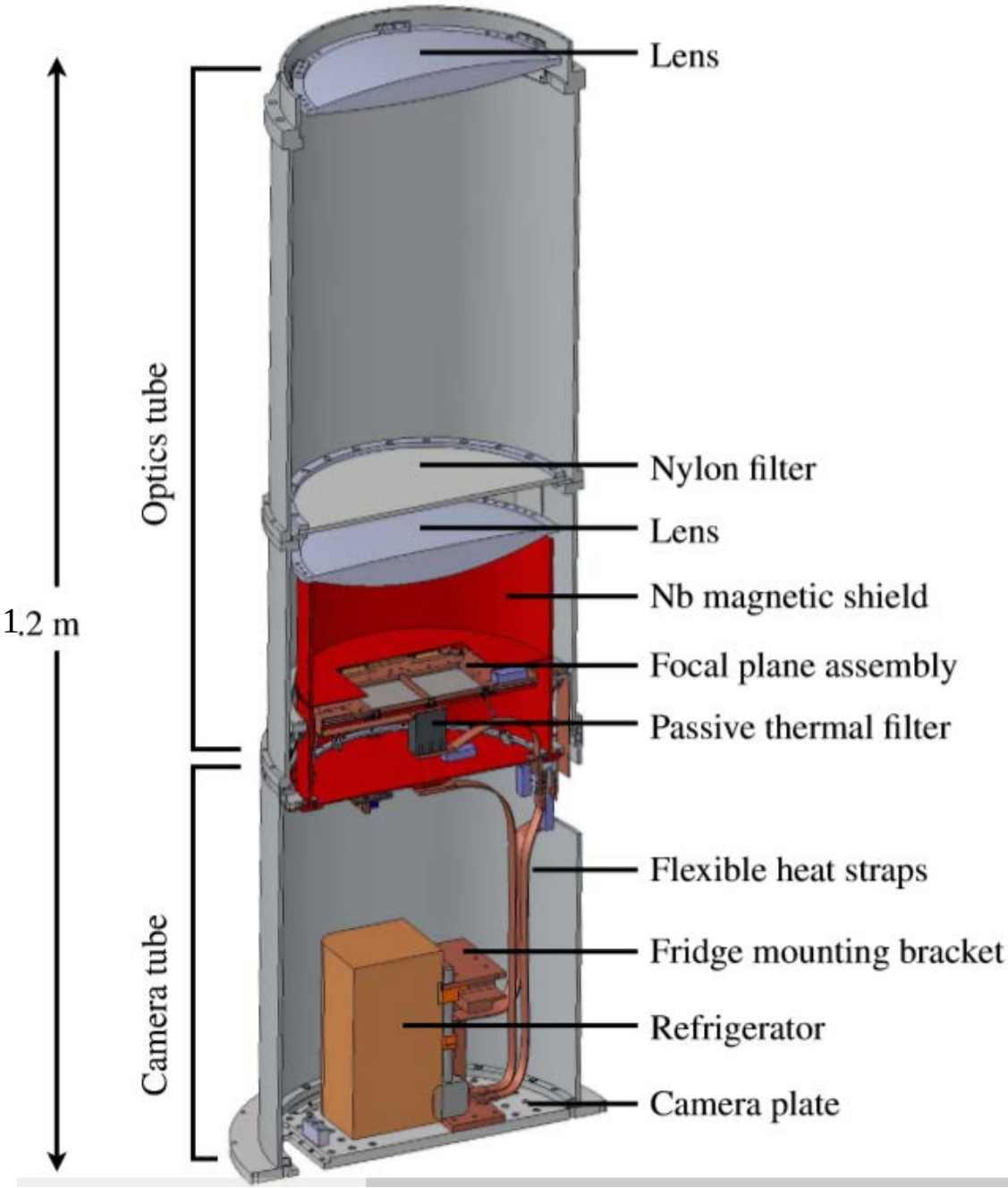
!!!

The polarization pattern is unique, but small

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

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 (NSF-Office of Polar Program+ Lockheed)



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

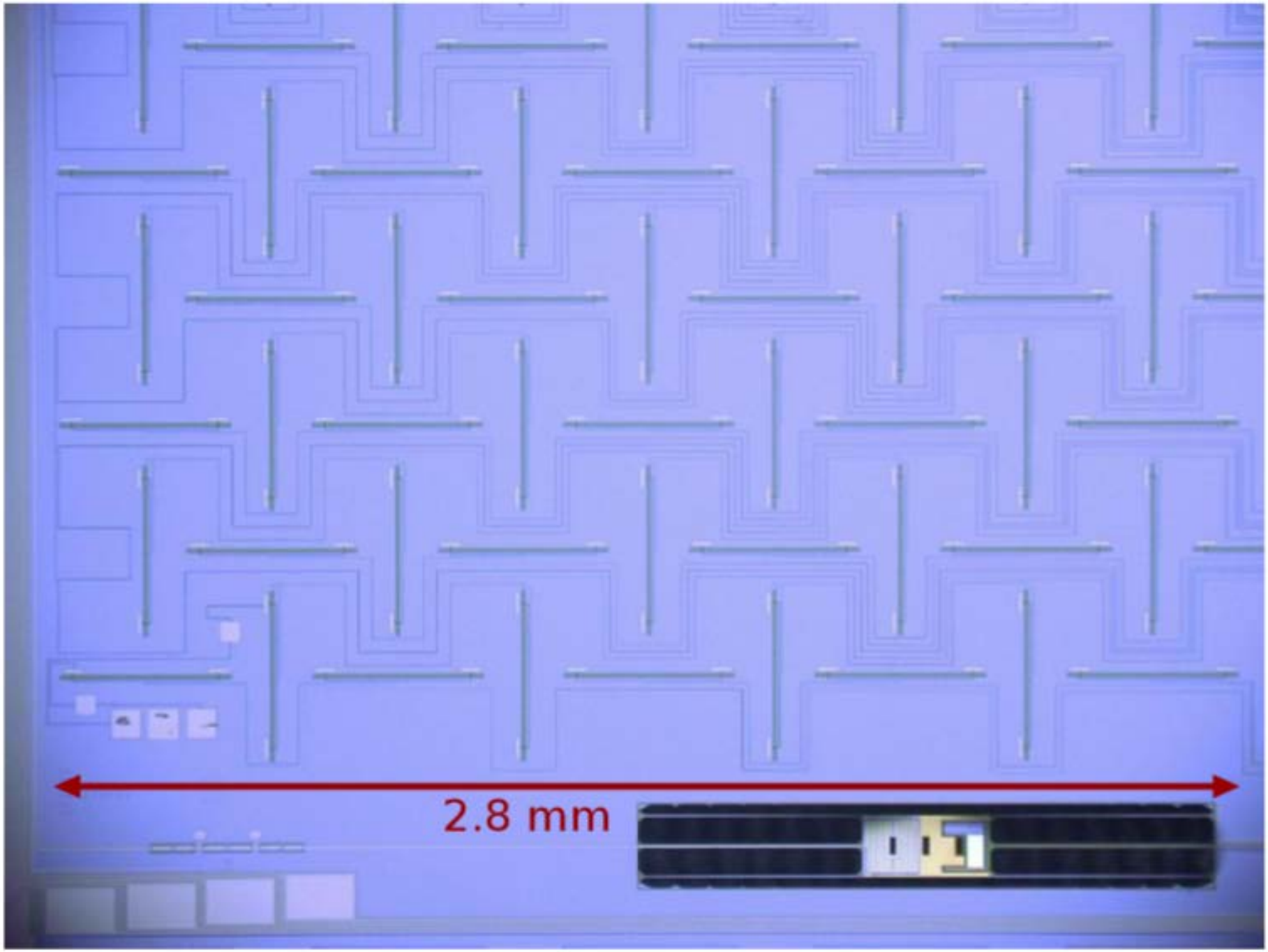
On going program + R&D for the future

BICEP1: 2006, 2007, 2008

BICEP2: 2010, 2011, 2012

Keck Array: 2011, 2012, 2013, …

BICEP3: 2015…

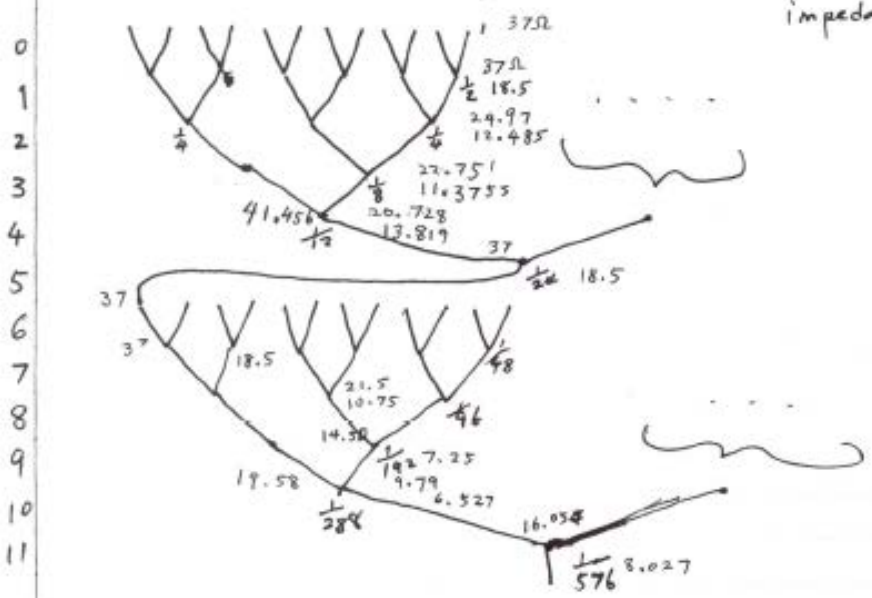

2.8 mm

9/21/06

Dual pol H - antenna

Peter "3"

impedance : 37 + 15j Ω



170 μm
500
500 x 2
500 x 2
500 x 6
500 x 12
170
300
300 x 2
300 x 2
300 x 6

CLK notebook
a design was found
after 3 years
9/21/2006

~clkuo/polarimeter/feednetwork/taper>

Maximum reflectivity ~ 1% inband taper_sll_H_antenna_peter3

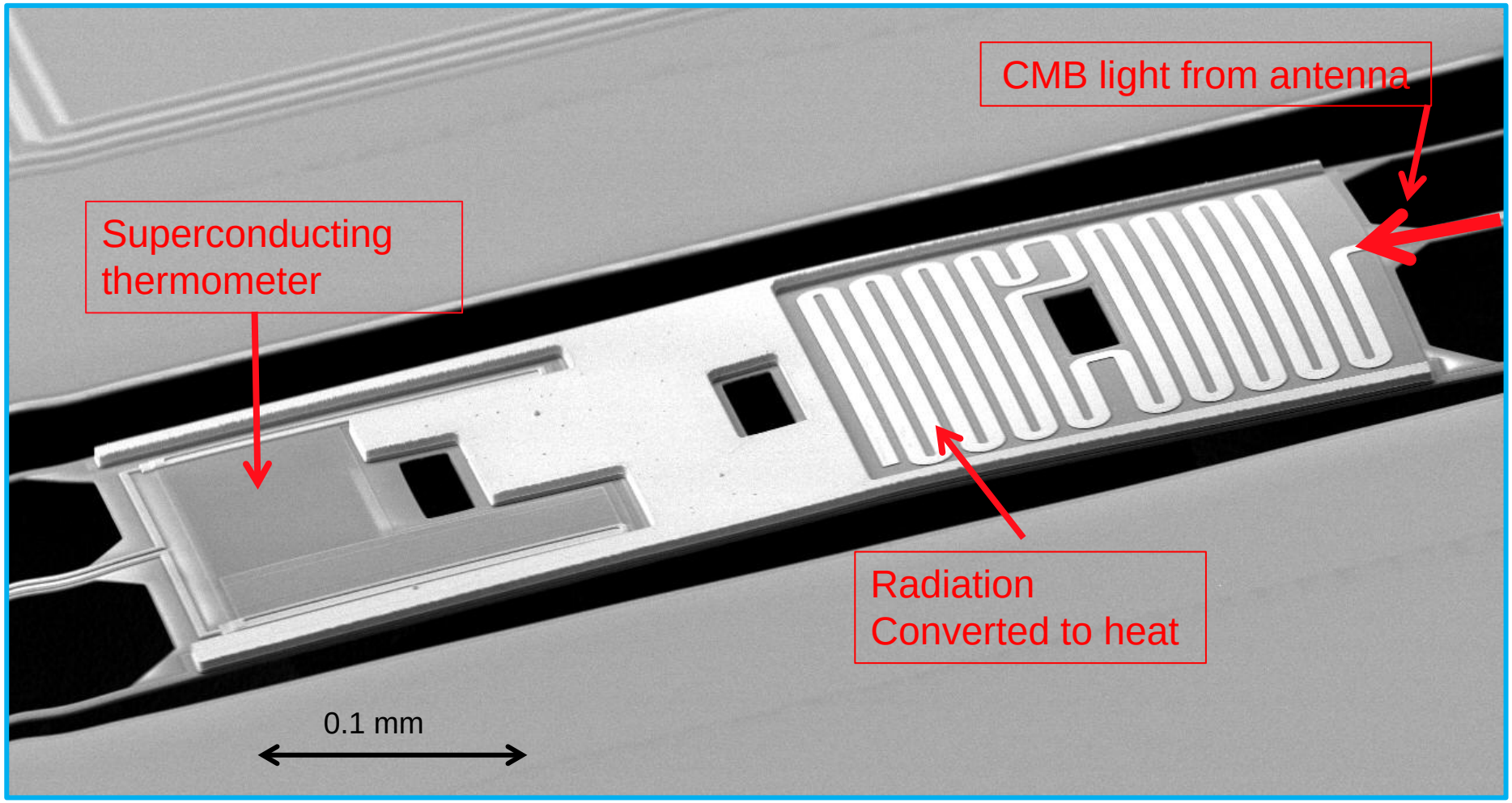
2nd level | ε = 4.5, thickness = 3000 Å supermix 1st level

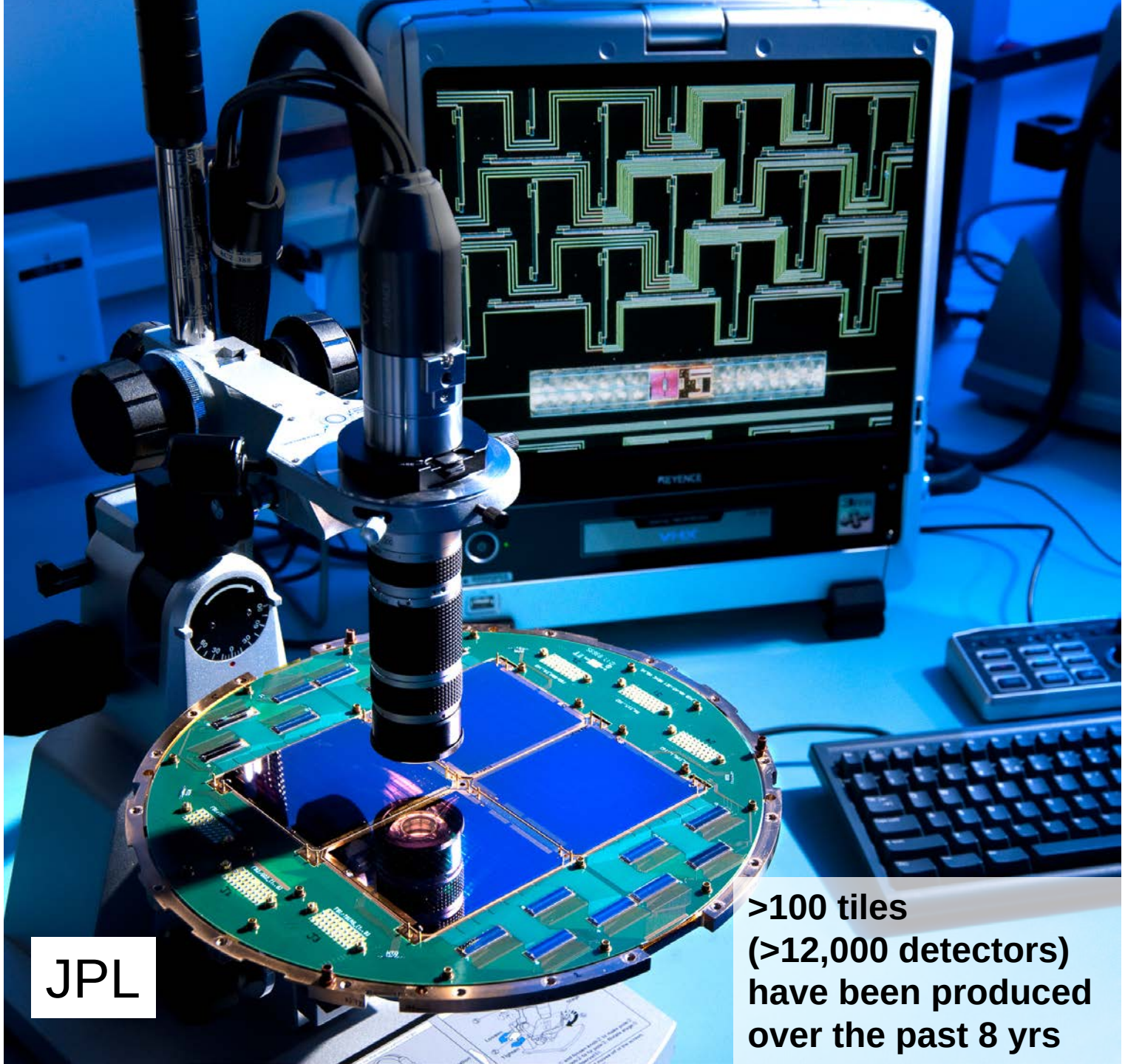
Z(Ω)	W(μm)
37	0.931
18.5	2.53
21.5	2.083
10.75	4.87
14.5	3.42
7.25	7.605
9.79	5.42

Z (Ω)	W (μm)
24.97	1.706
12.485	4.09
22.751	1.933
11.3755	4.562
20.728	2.185 ?
13.819	3.625
41.456	0.765

Detecting the CMB radiation

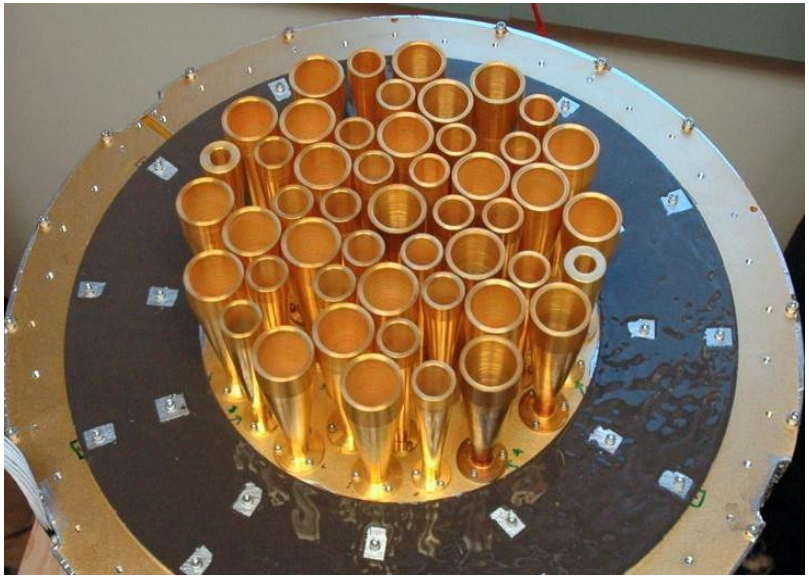
BICEP2 Detector: Transition-Edge Superconductor

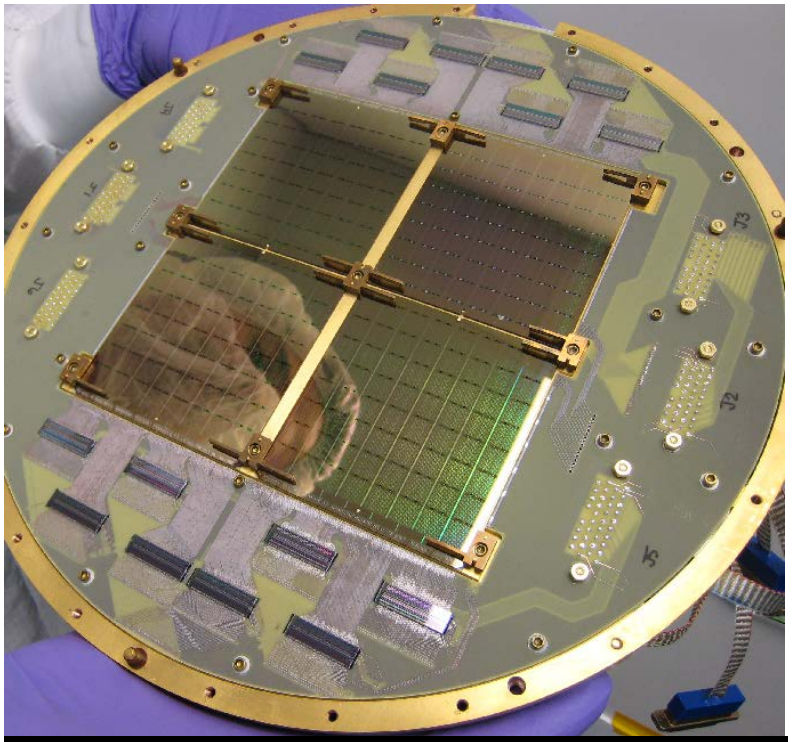




>100 tiles (>12,000 detectors) have been produced over the past 8 yrs

3 BICEP2 year = 30 BICEP1 years!

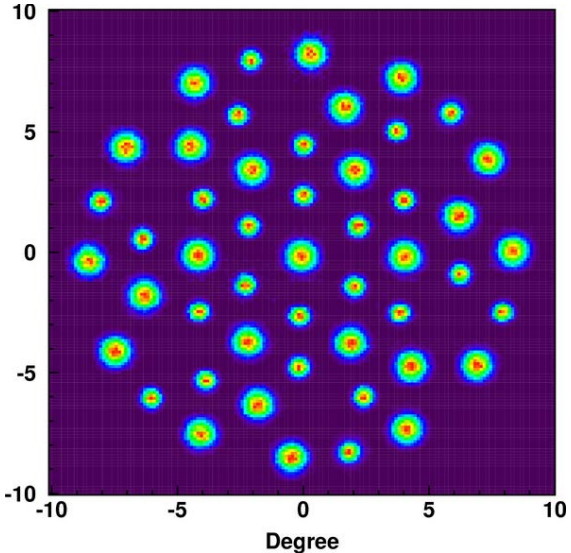


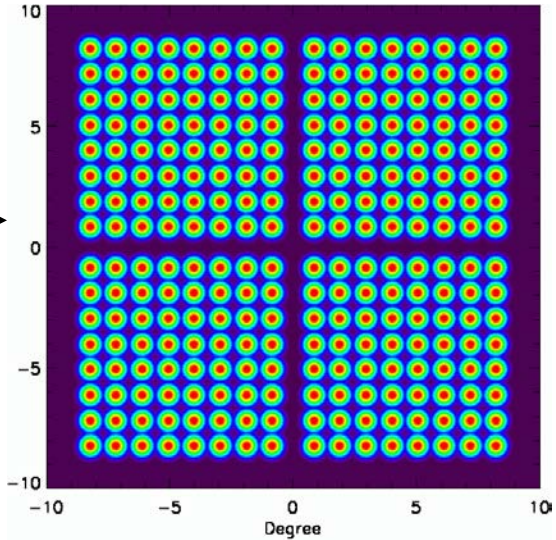


JPL : antenna-coupled TES arrays

BICEP1

48
150 GHz
detectors





BICEP2

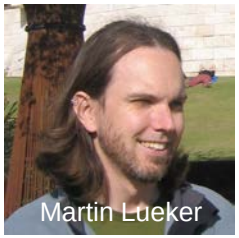
512
150 GHz
detectors

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

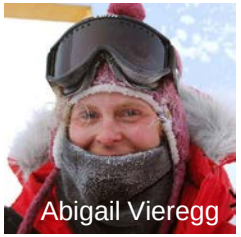
BICEP2 Postdocs

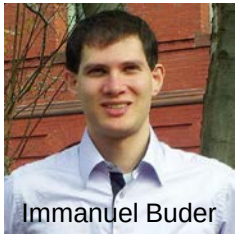
Colin Bischoff

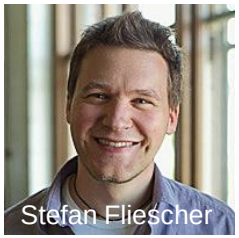
Jeff Filippini


Martin Lueker

Walt Ogburn


Abigail Vieregg


Immanuel Buder


Stefan Fliescher

Roger O'Brient

Angiola Orlando

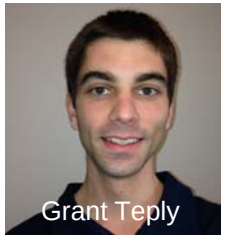
Zak Staniszewski

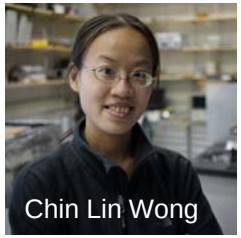
BICEP2 Graduate Students

Randol Aikin

Justus Brevik

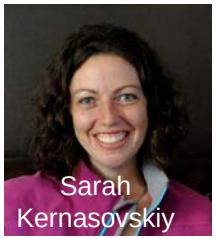
Chris Sheehy


Grant Teply


Chin Lin Wong

Kirit Karkare

Jon Kaufman


Sarah Kernasovskiy

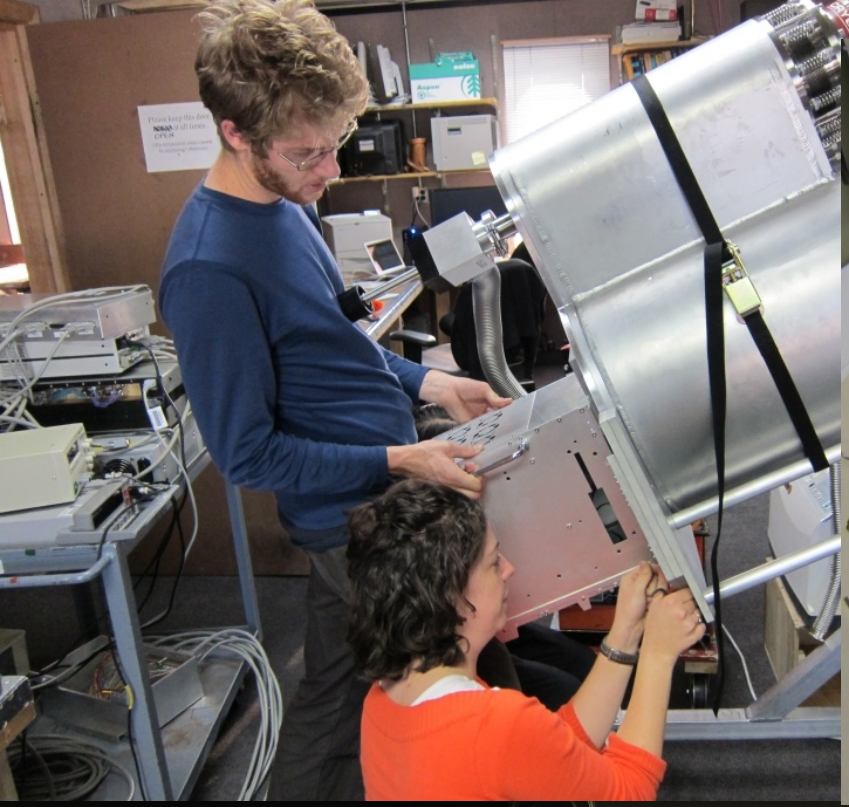
Jamie Tolan

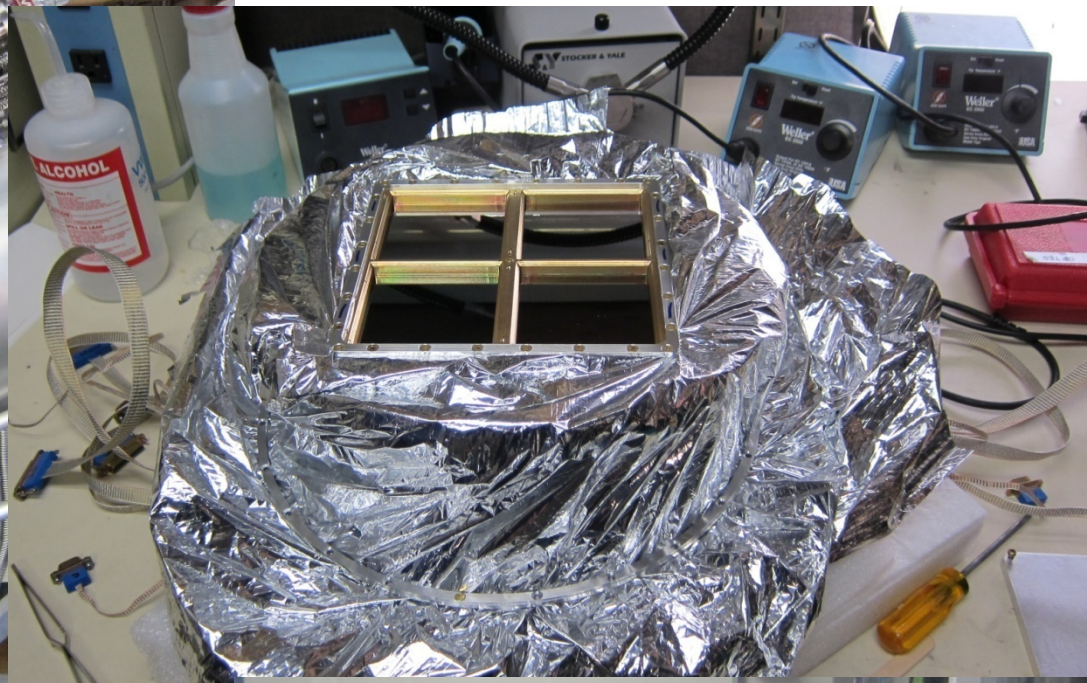
BICEP2 Winterovers

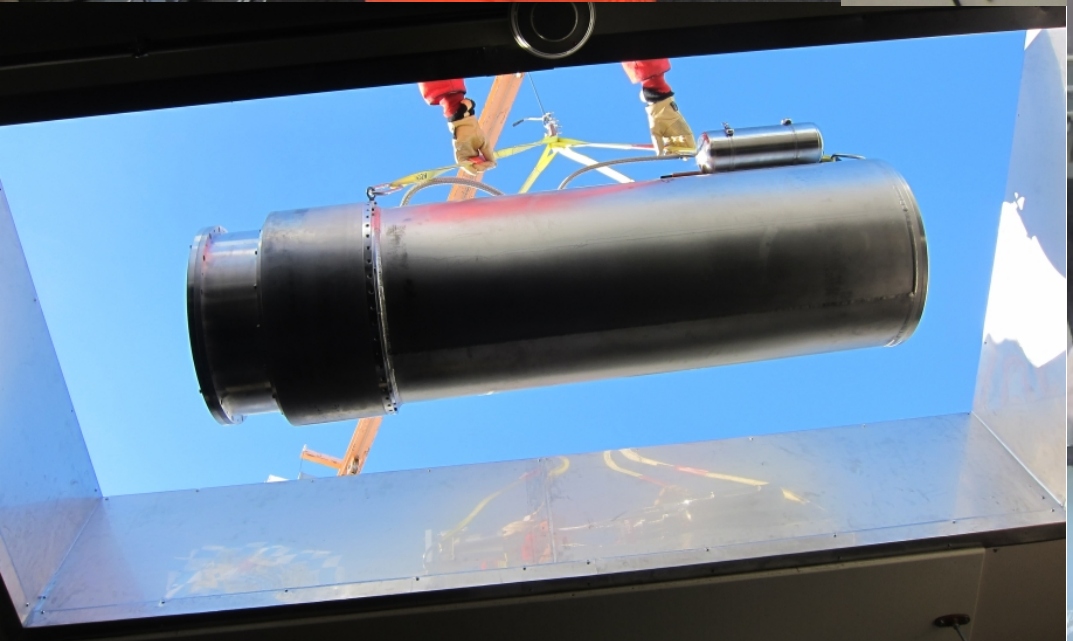
Steffen Richter 2010

Steffen Richter 2011

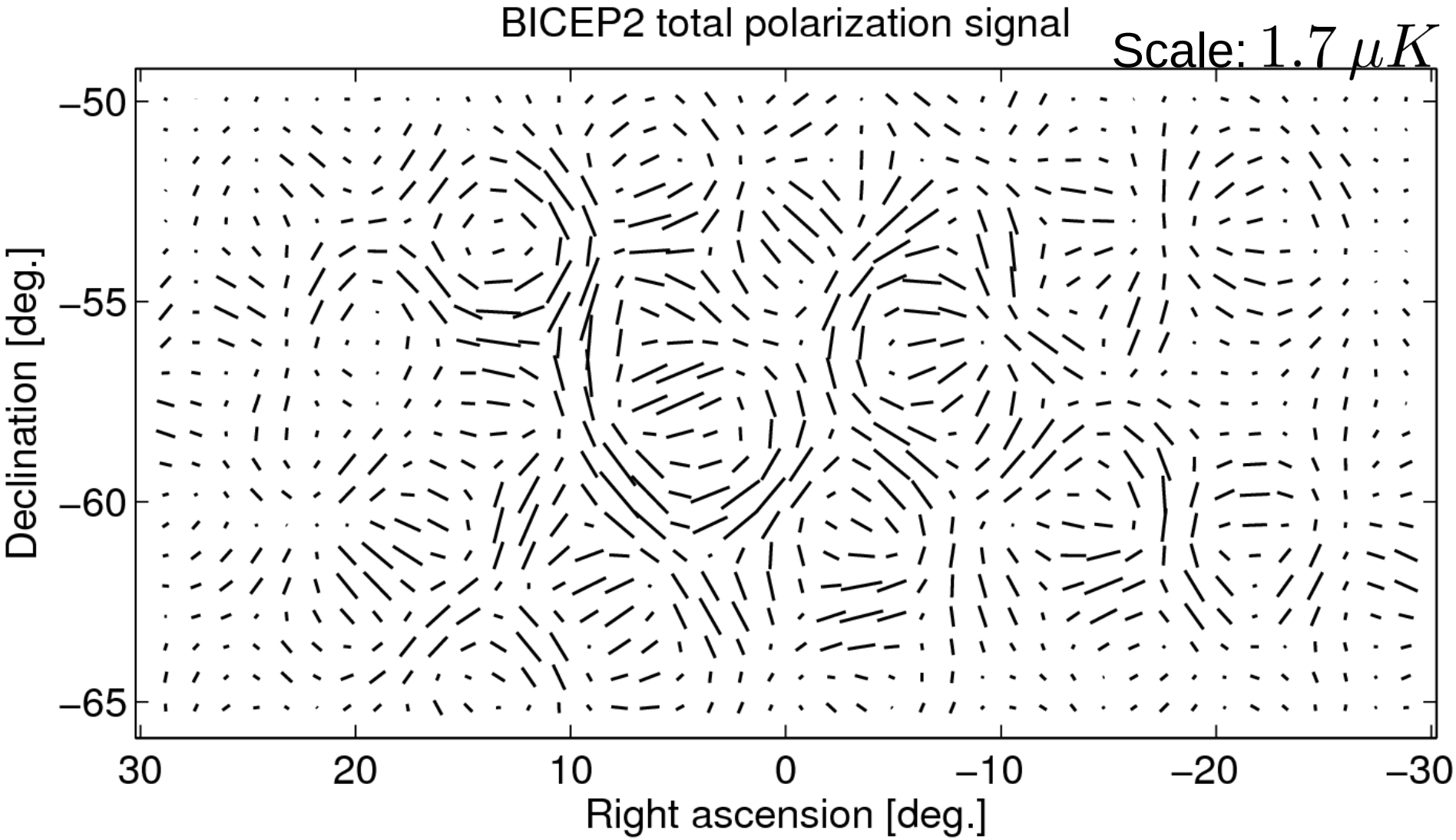
Steffen Richter 2012



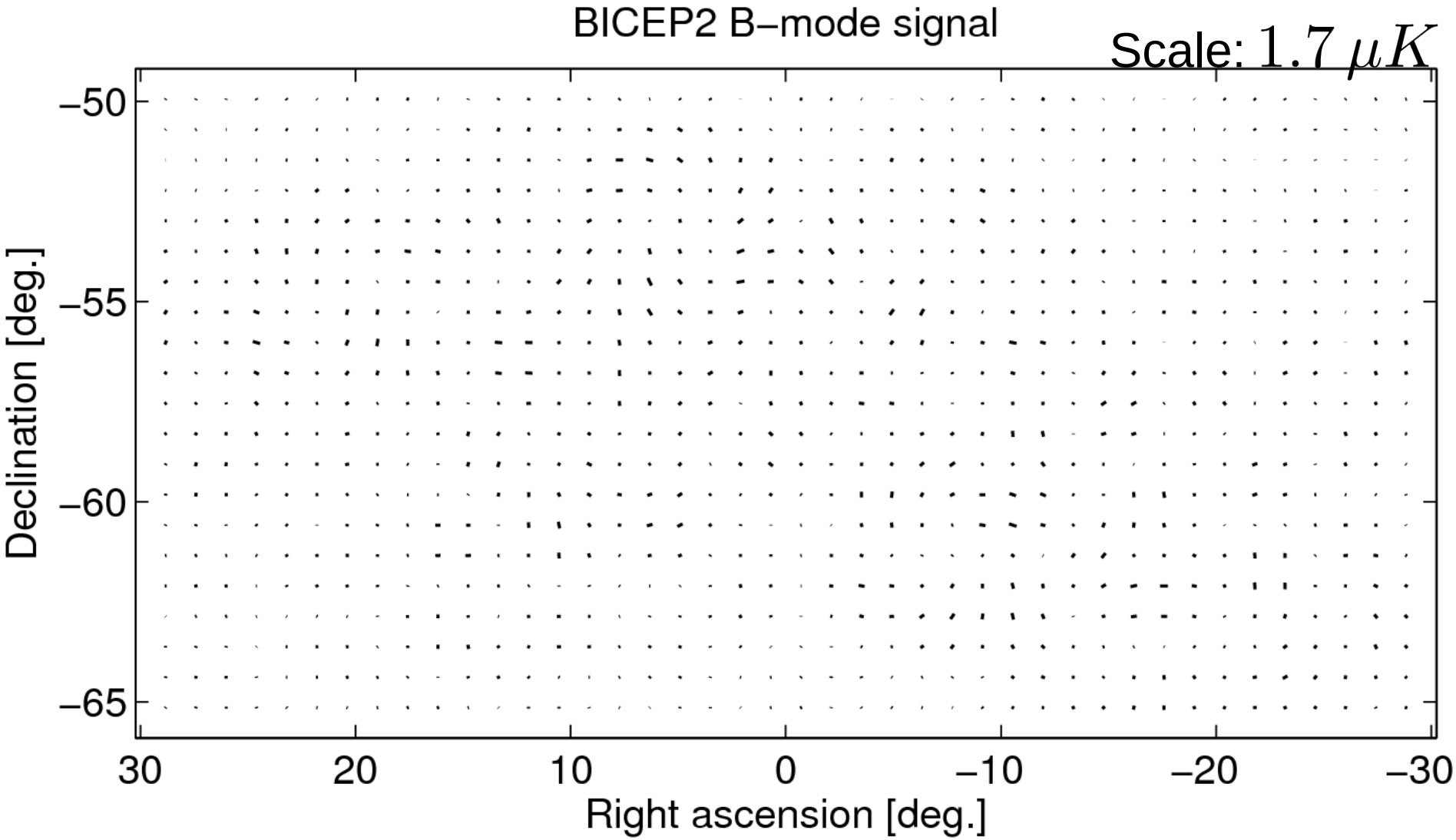

ALCOHOL
STOCKER & YALE
Weller



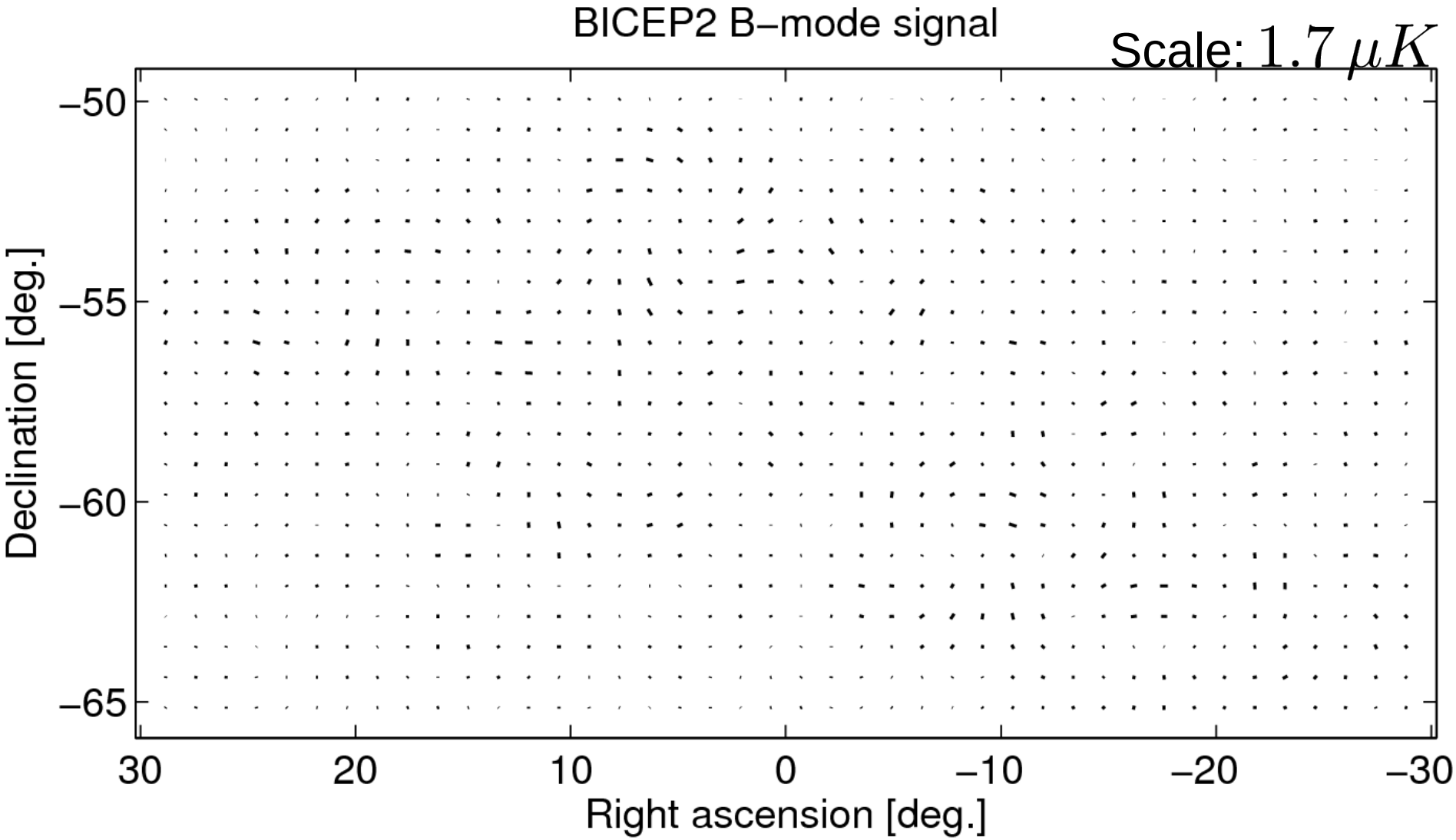
Total polarization



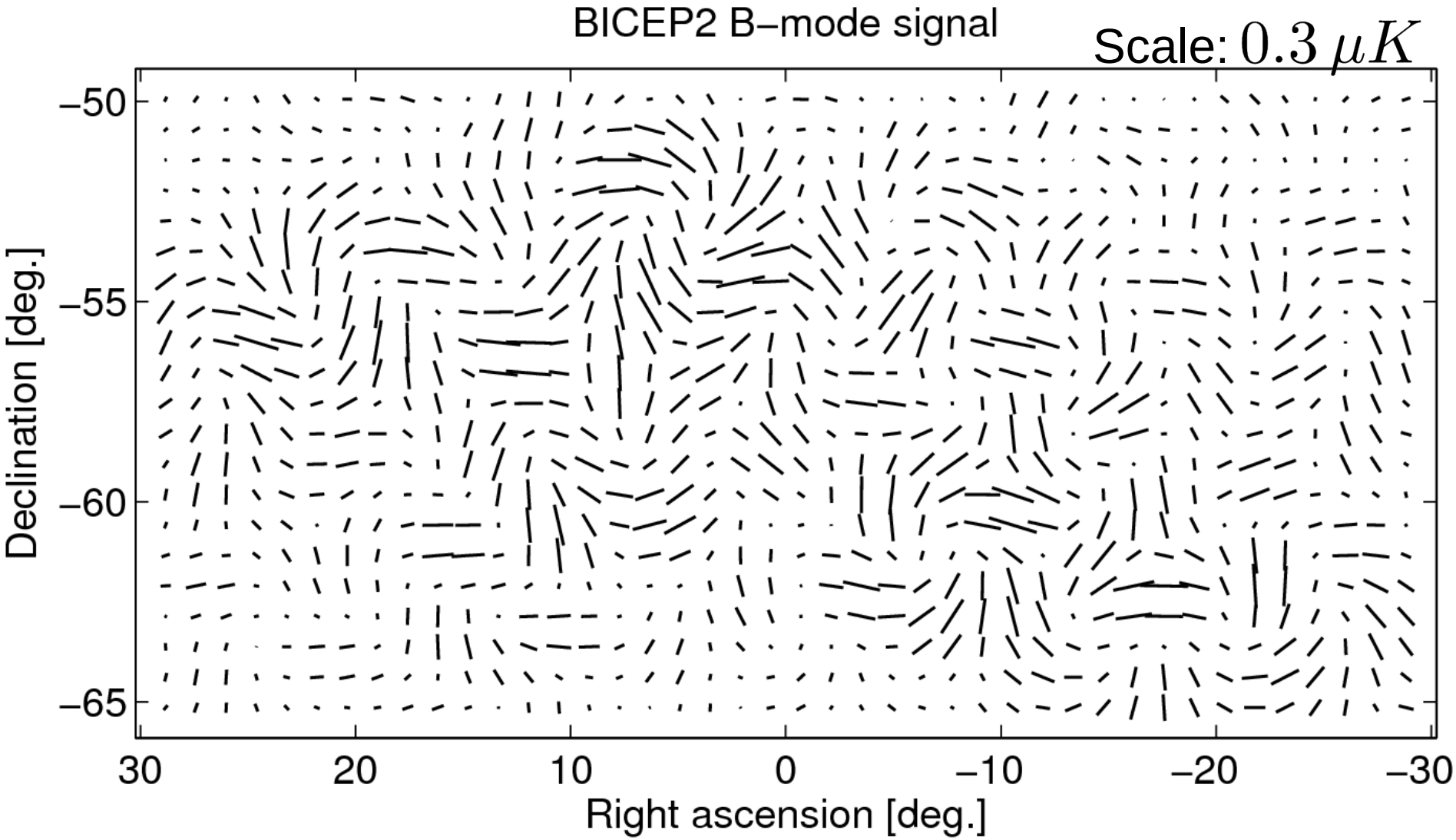
B-mode contribution



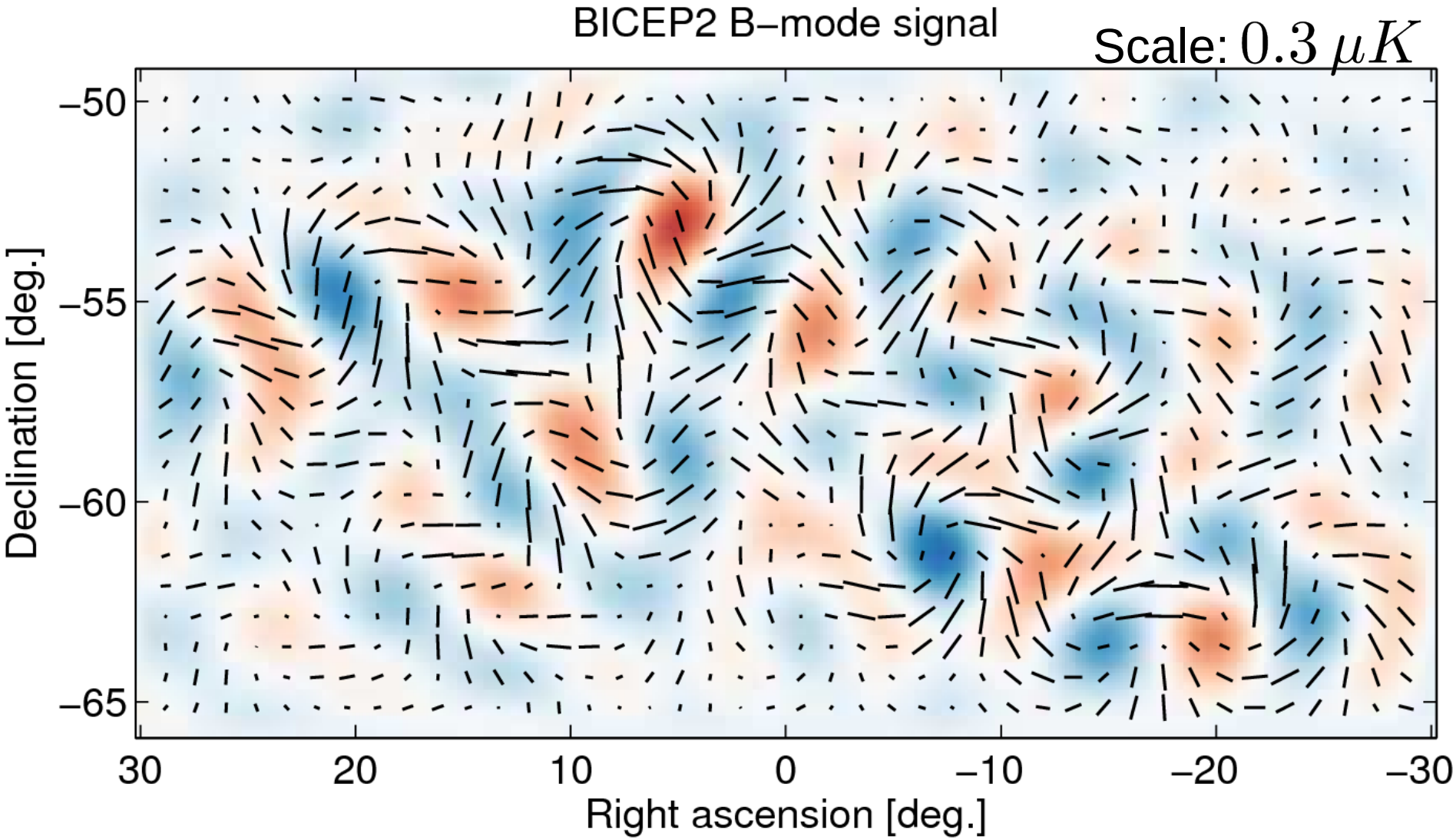
B-mode contribution



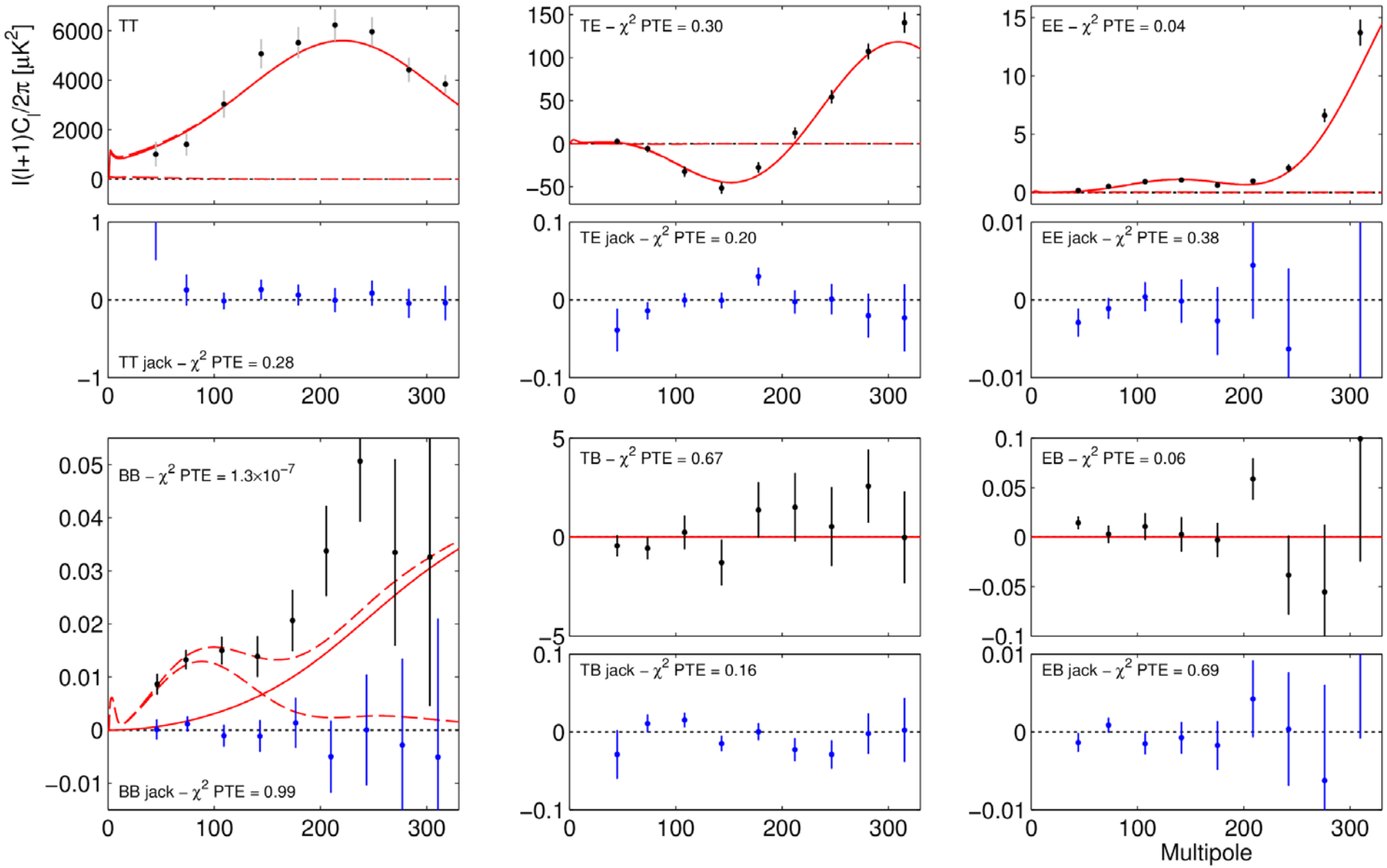
B-mode contribution



B-mode contribution

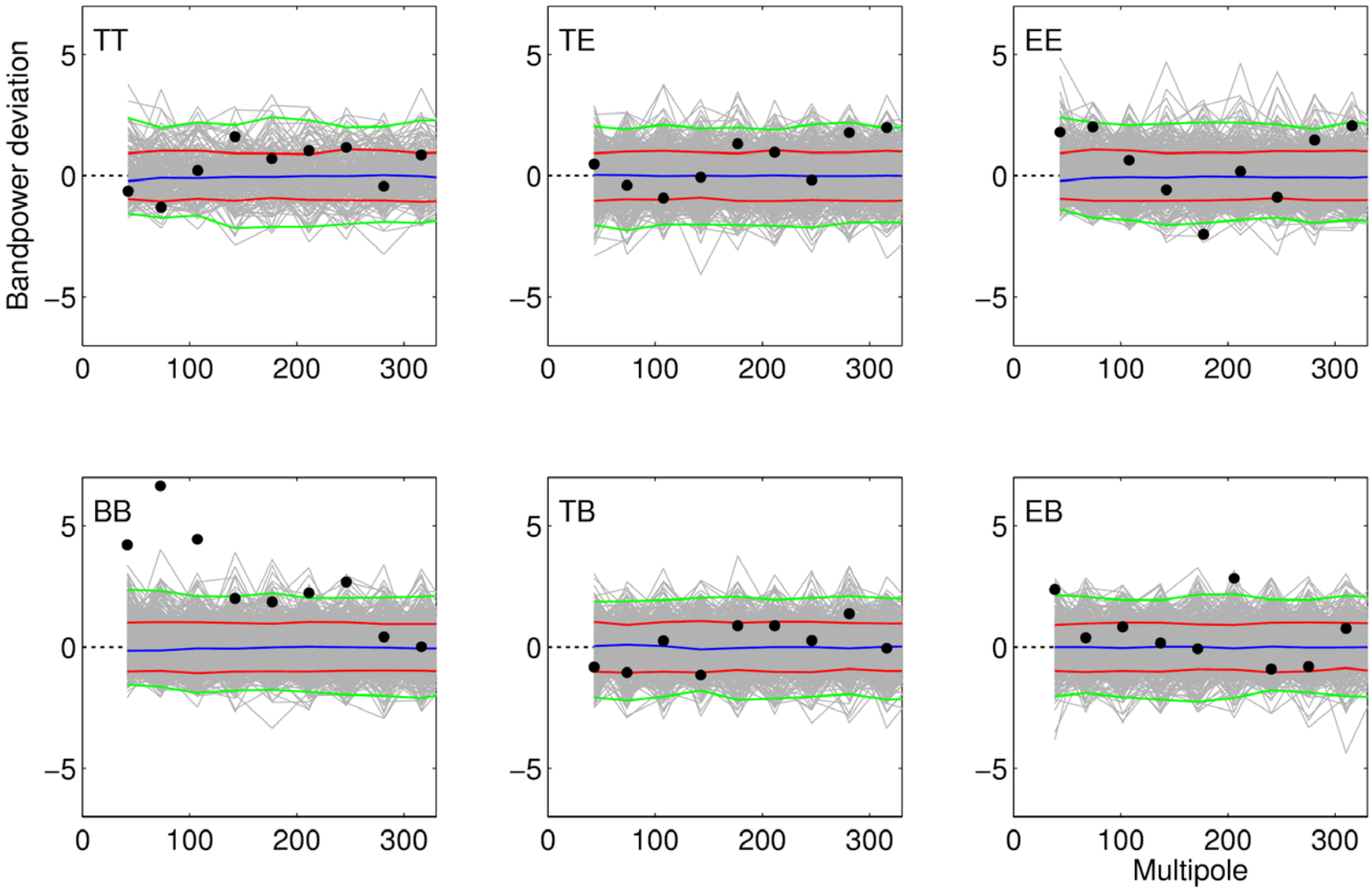


Temperature and Polarization Spectra



The Bicep2 Collaboration

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

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
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

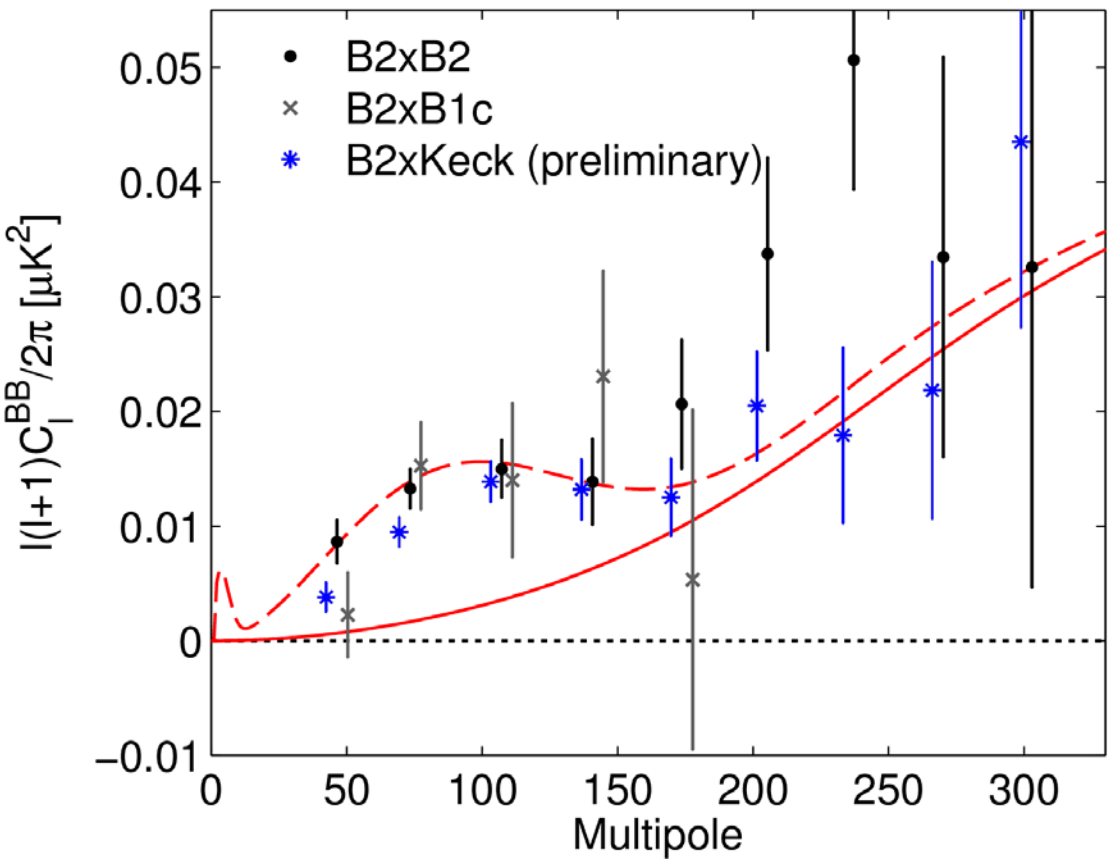
Checks for contamination from ground-fixed signals, such as polarized sky or magnetic fields, or the moon

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):

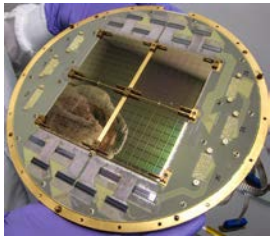


BICEP2 auto spectrum compatible with B2xB1c cross spectrum

~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



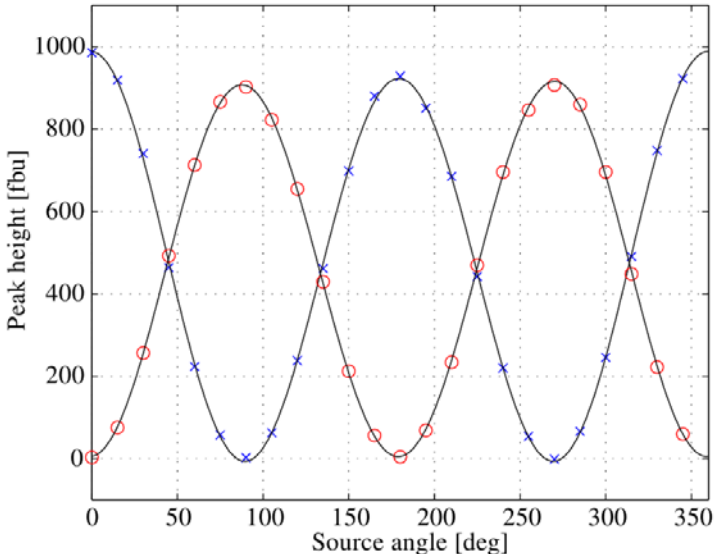
Cross spectra:
Powerful additional evidence against a systematic origin of the apparent signal

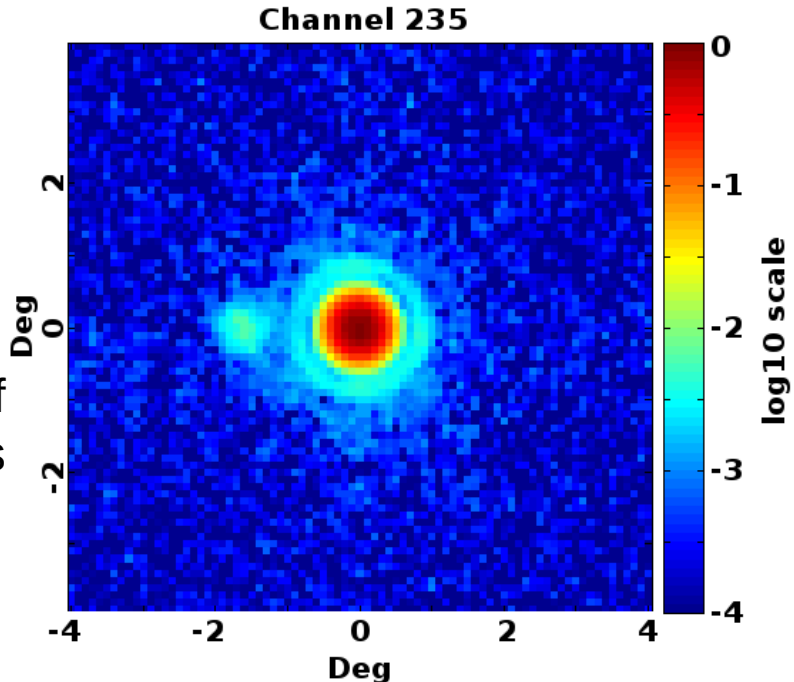
Calibration Measurements

For instance...

Far field beam mapping

Detector Polarization Calibration

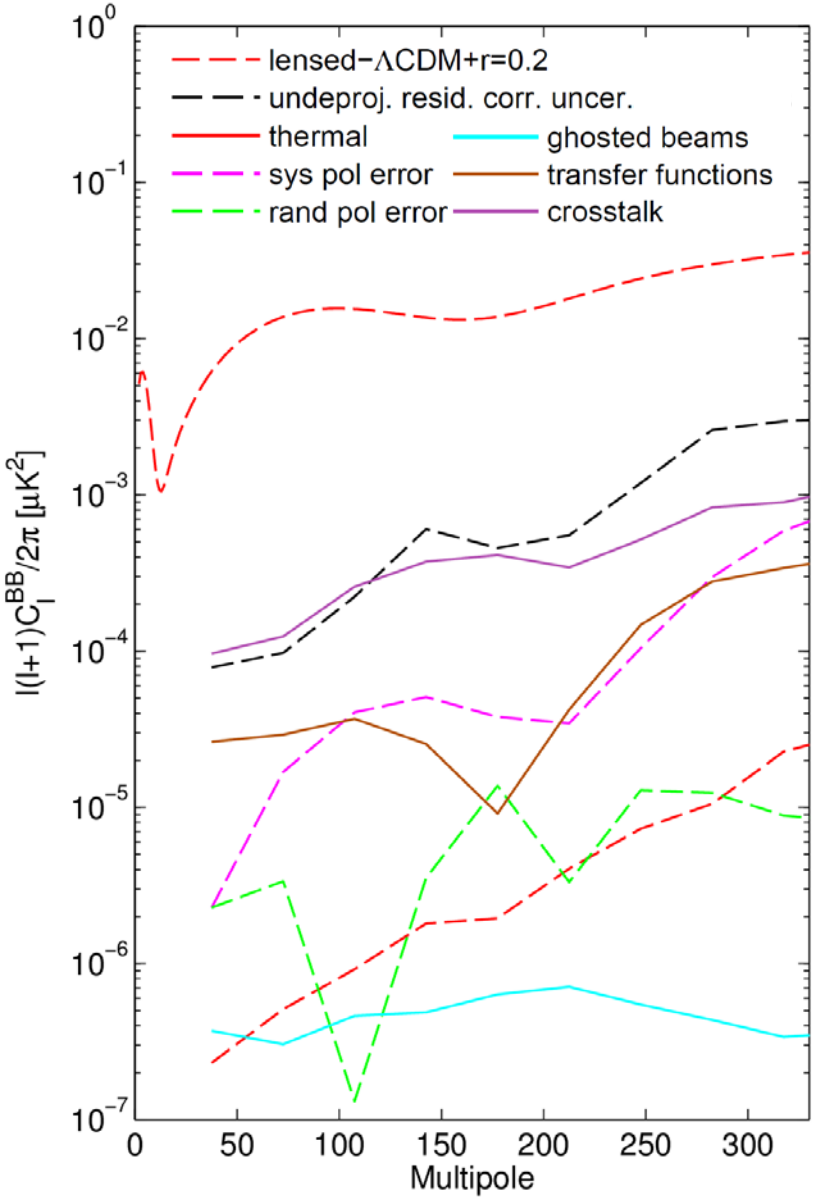




Hi-Fi beam maps of individual detectors

Detailed description in companion Instrument Paper

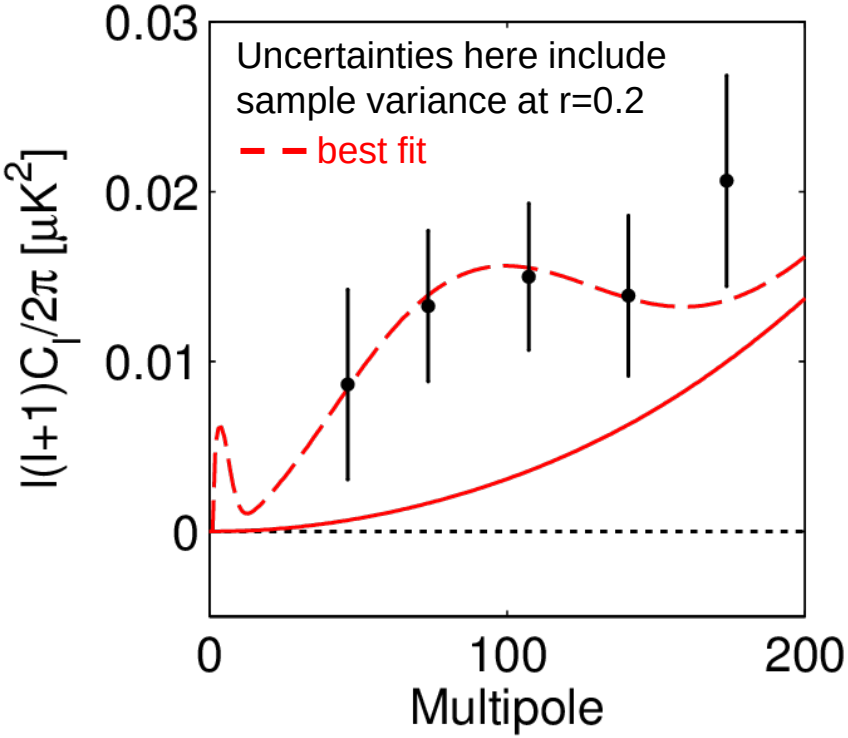
Systematics beyond Beam imperfections



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 Tensor-to-scalar Ratio r



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

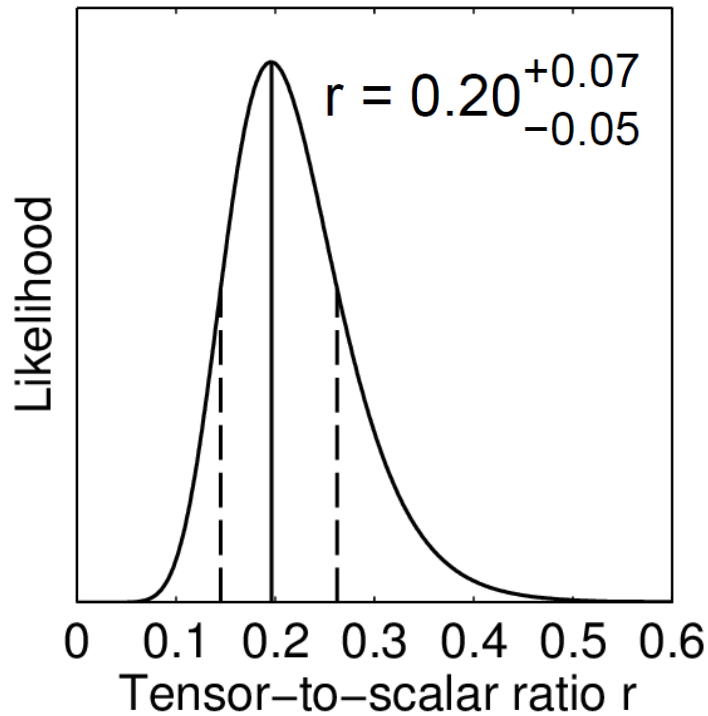
Find the most likely value of the tensor-to-scalar ratio r

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:

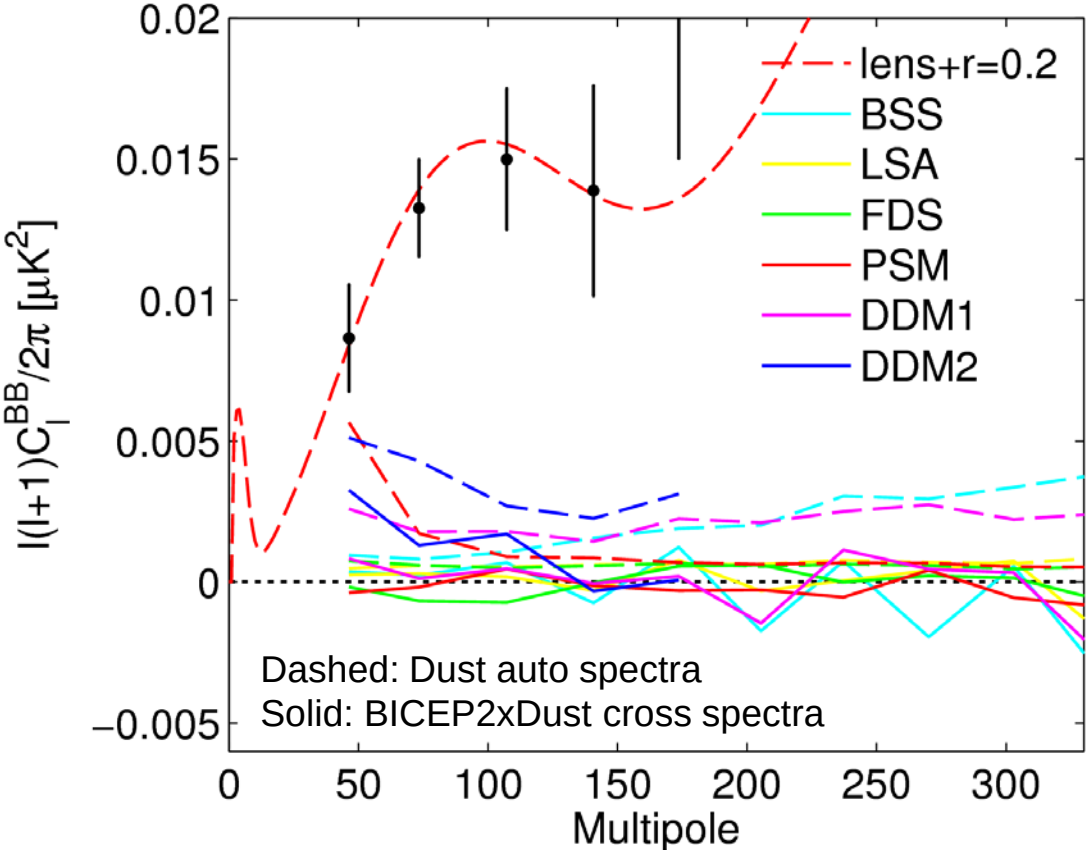
r = 0.2 with uncertainties dominated by sample variance

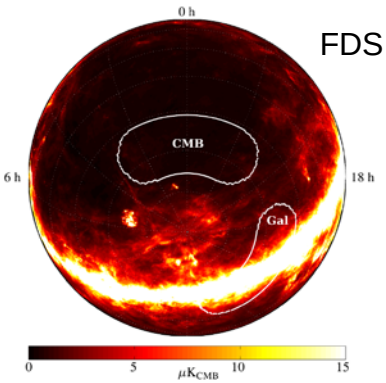
PTE of fit to data: 0.9
→ model is perfectly acceptable fit to the data

r=0 ruled out at 7.0σ

The Bicep2 Collaboration

Polarized Dust Foreground Projections





FDS Model

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

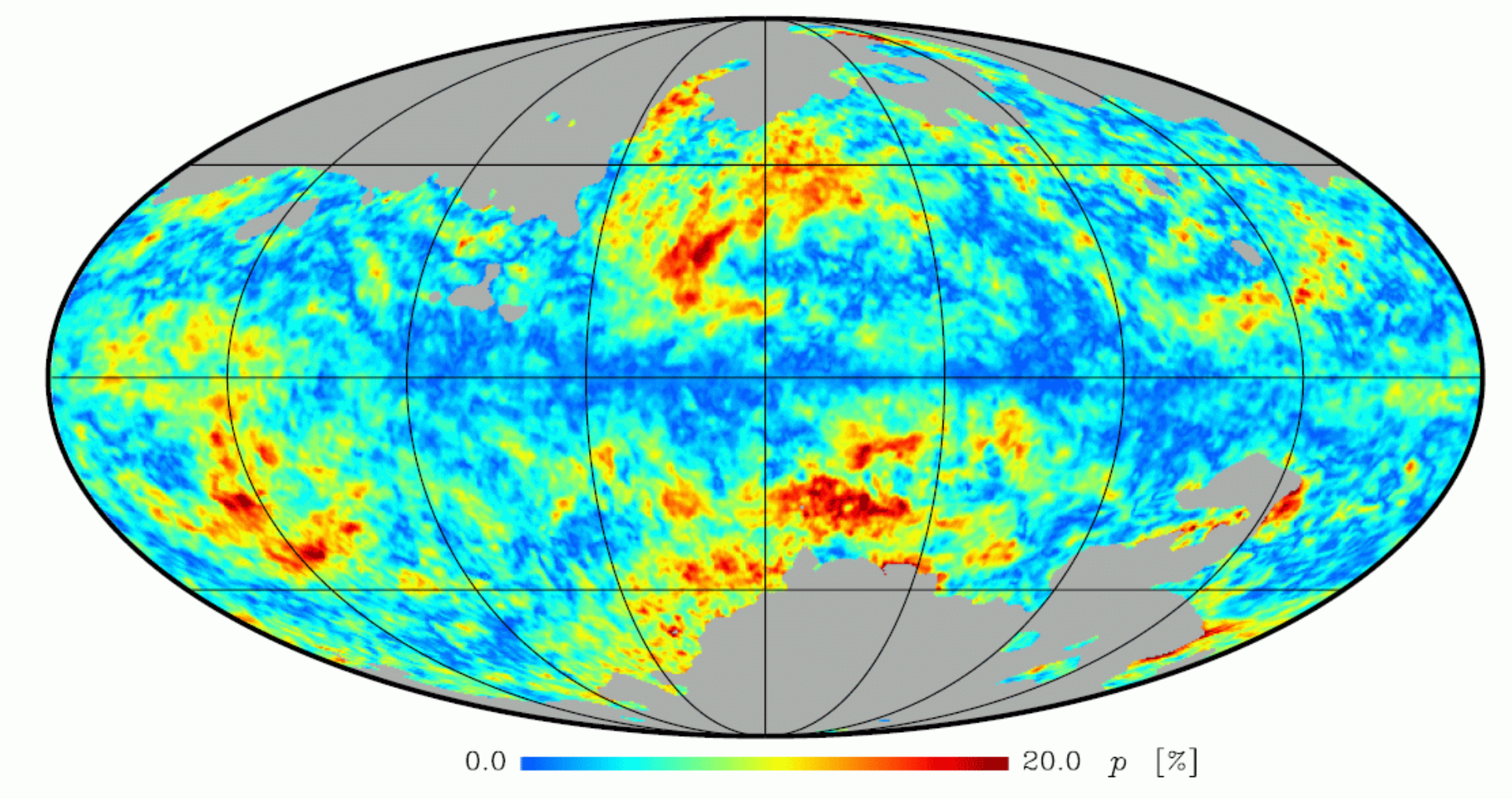
Use various models of polarized dust emission to estimate foregrounds.

All dust auto spectra well below observed signal level.

Cross spectra consistent with zero.

The Bicep2 Collaboration

Polarization fraction from *Planck XIX* (May 6)



The Bicep2 Collaboration

Polarization fraction from *Planck XIX* (May 6)

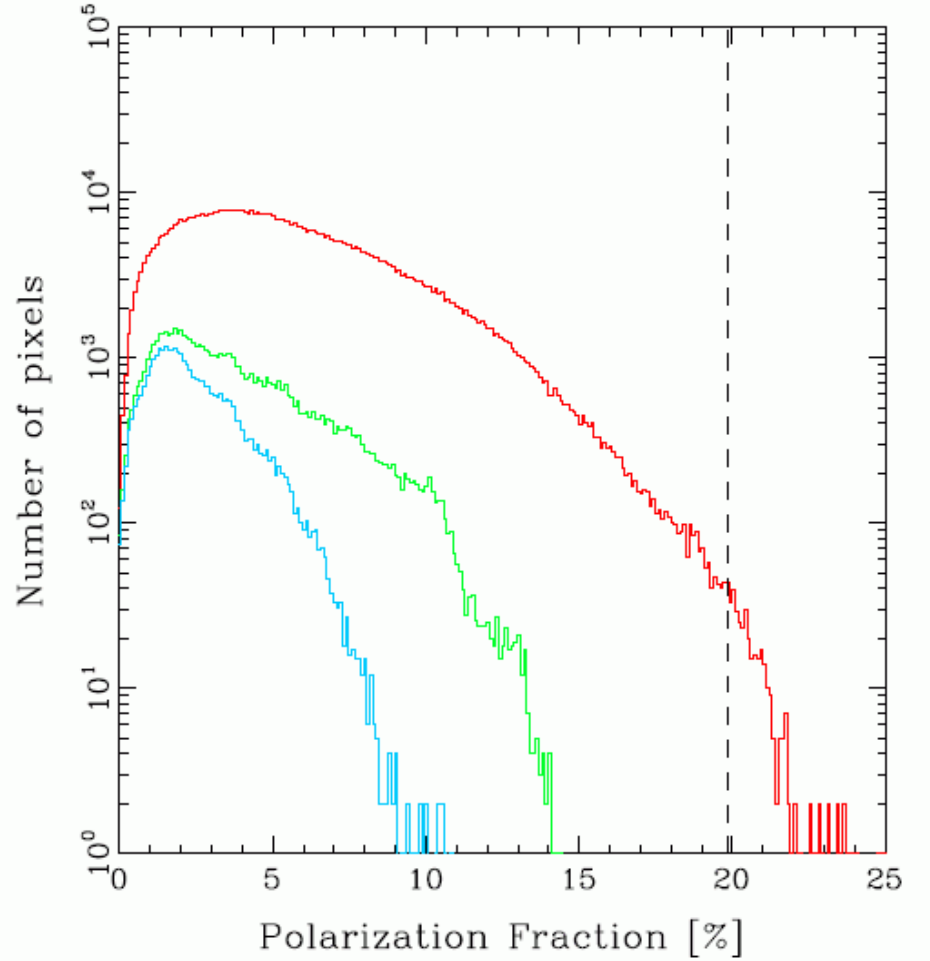
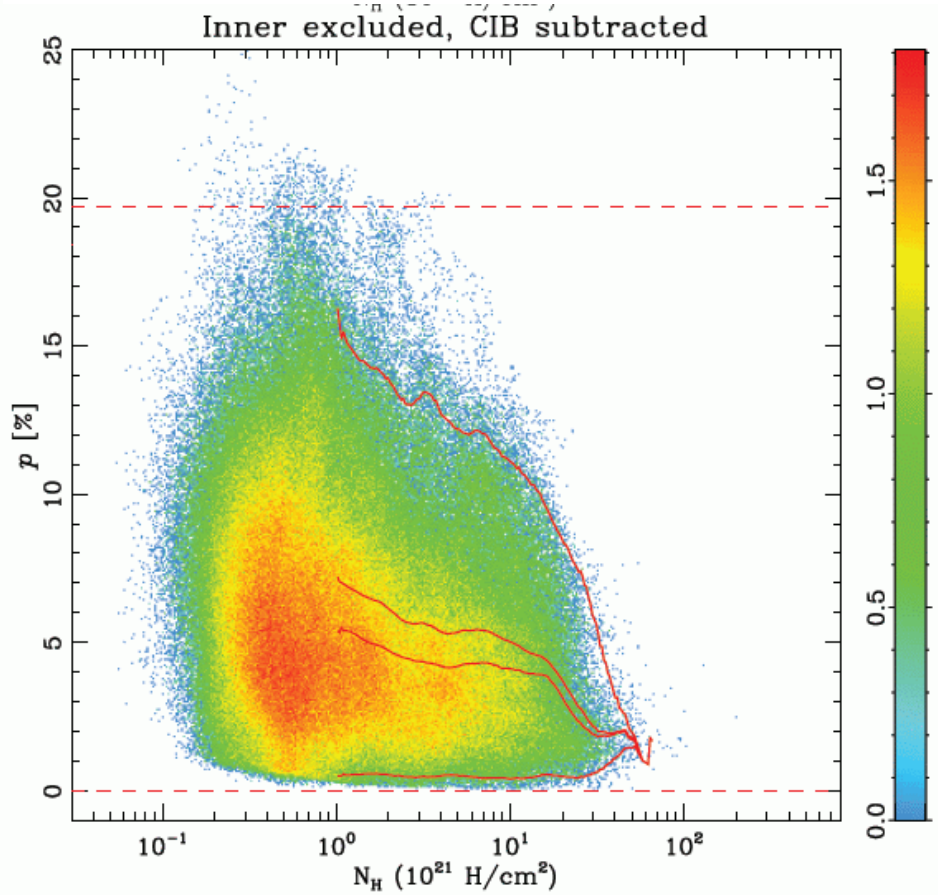


Fig. 7. Histograms of the observed polarization fraction at 1° resolution for the whole sky shown in Fig. 1 (*red*), the Galactic plane within $|b_{II}| < 5°$ (*green*) and the inner Galactic plane within $|b_{II}| < 5°$ and $|\ell_{II}| < 90°$ (*blue*).

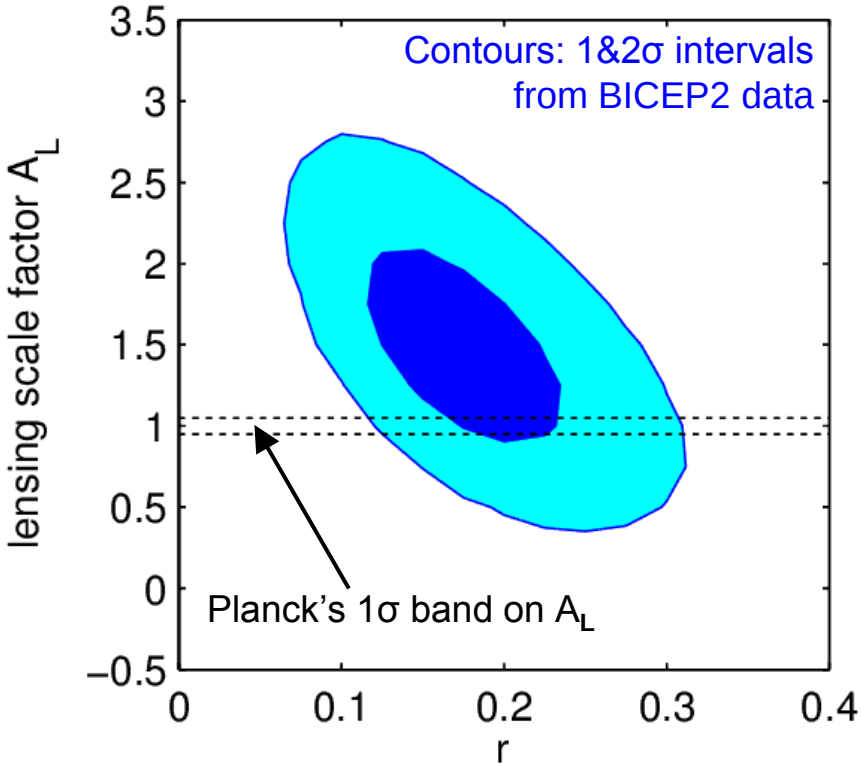


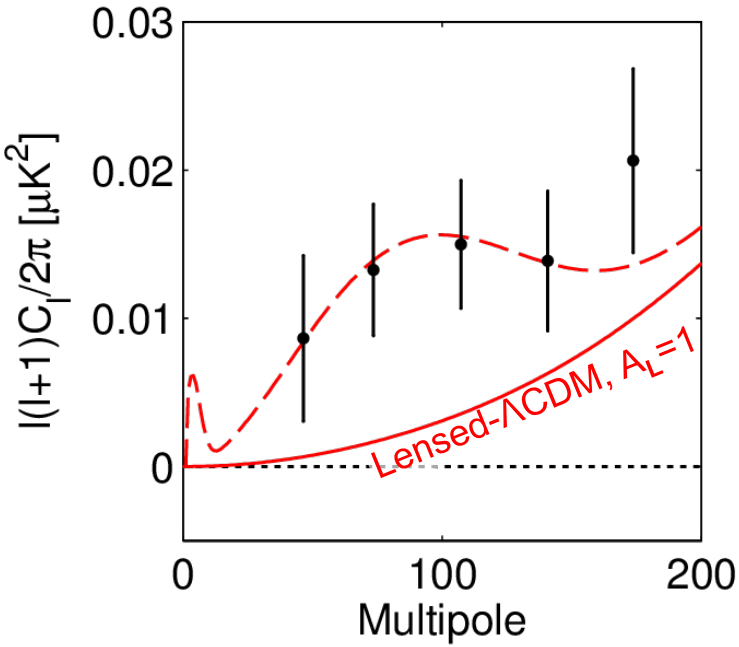
The Bicep2 Collaboration

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

Compatibility with Indirect Limits on r

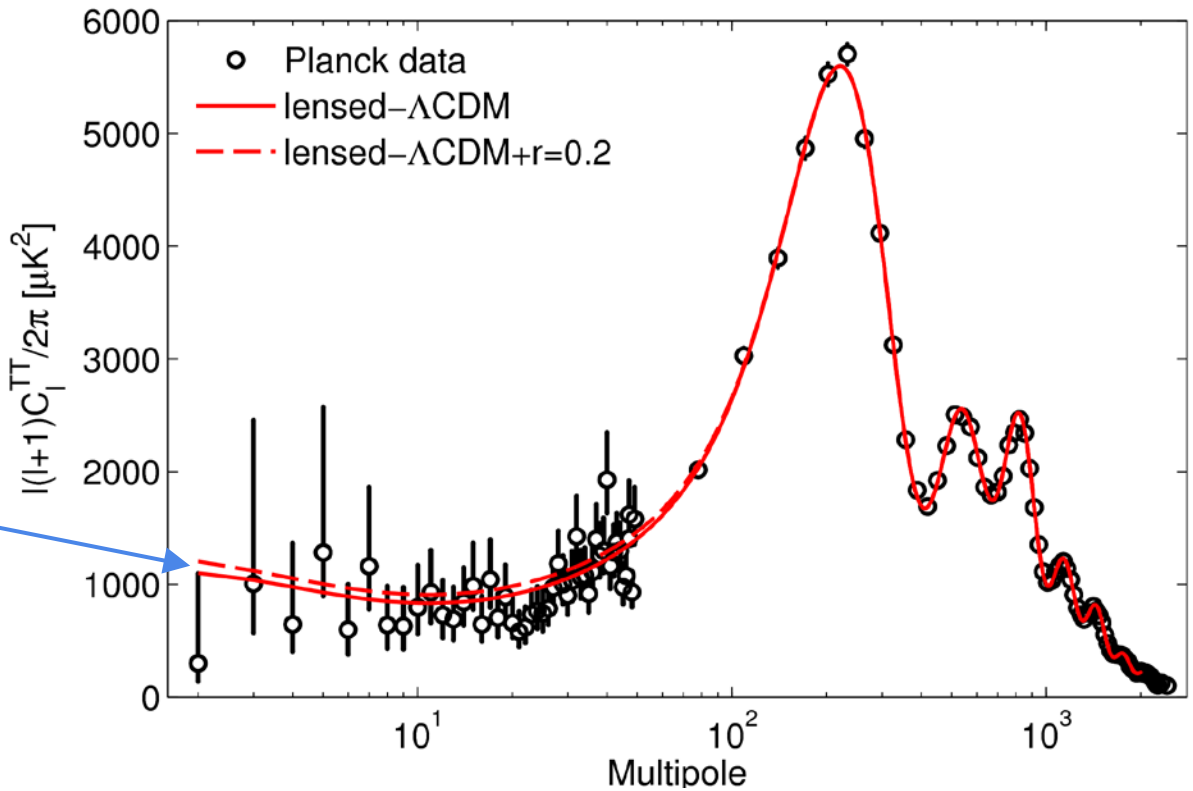
Using temperature data over a wide range of angular scales limits on r have been set:

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

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

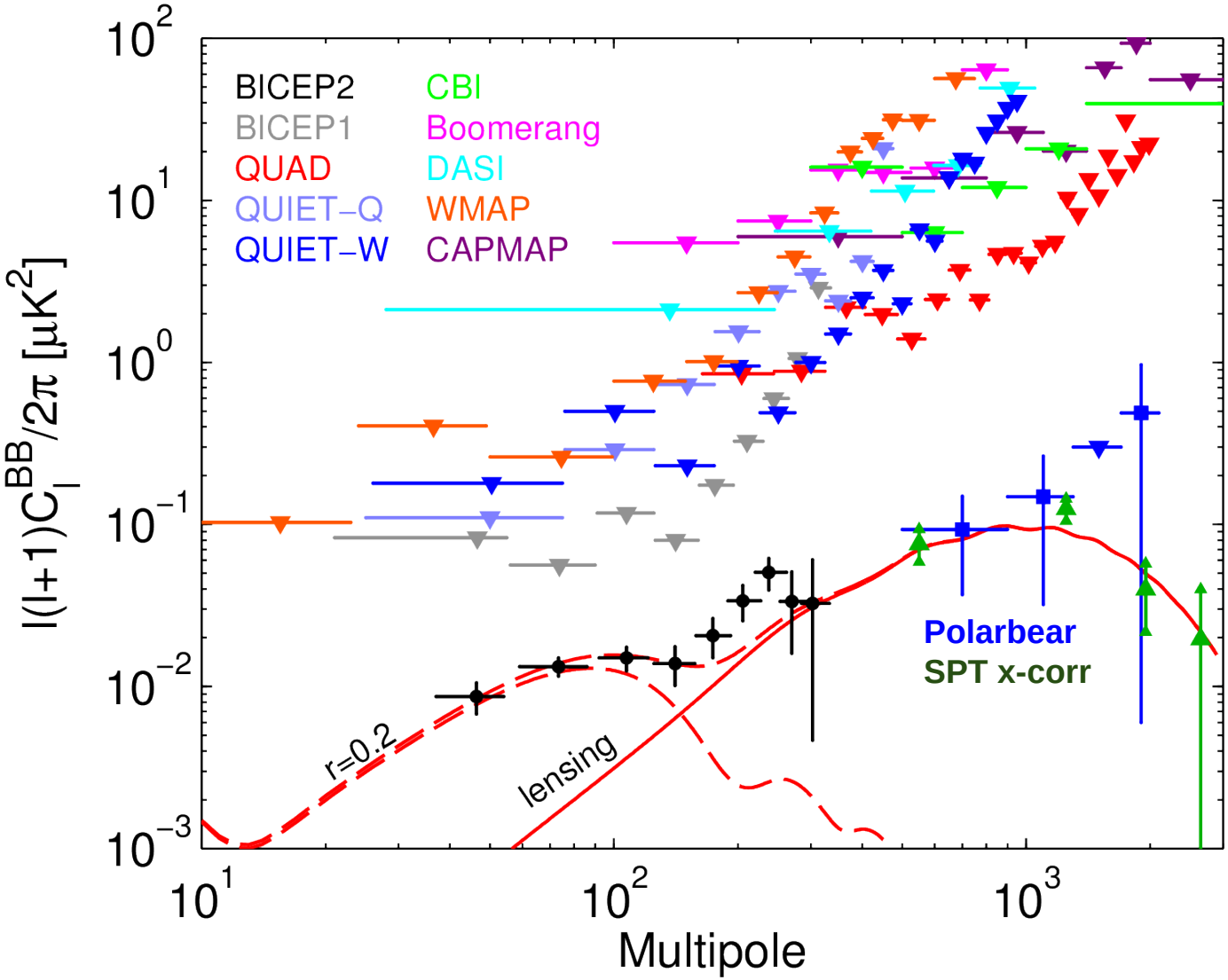
r=0.2 makes a small change to the temperature spectrum.

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



The Bicep2 Collaboration

BICEP2 and upper limits from other experiments:



The Bicep2 Collaboration

Future

- We really want to confirm the signal (Keck-100, BICEP3, SPTpol, Planck, …)
- Increase the frequency and sky coverage
- Test the scale invariance of B-modes (n_T)
  - All sky survey
  - delensing with large aperture telescopes
- Test the Gaussianity of B-modes
- Search for the (tensor) reionization bump
- Can we fit tensor into TT spectrum ?

Prospects

BICEP1: 2006, 2007, 2008

BICEP2: 2010, 2011, 2012

Keck Array: 2011, 2012, 2013,

2014 (576 100GHz detectors)…

BICEP3: 2015…

Prospects

BICEP1: 2006, 2007, 2008

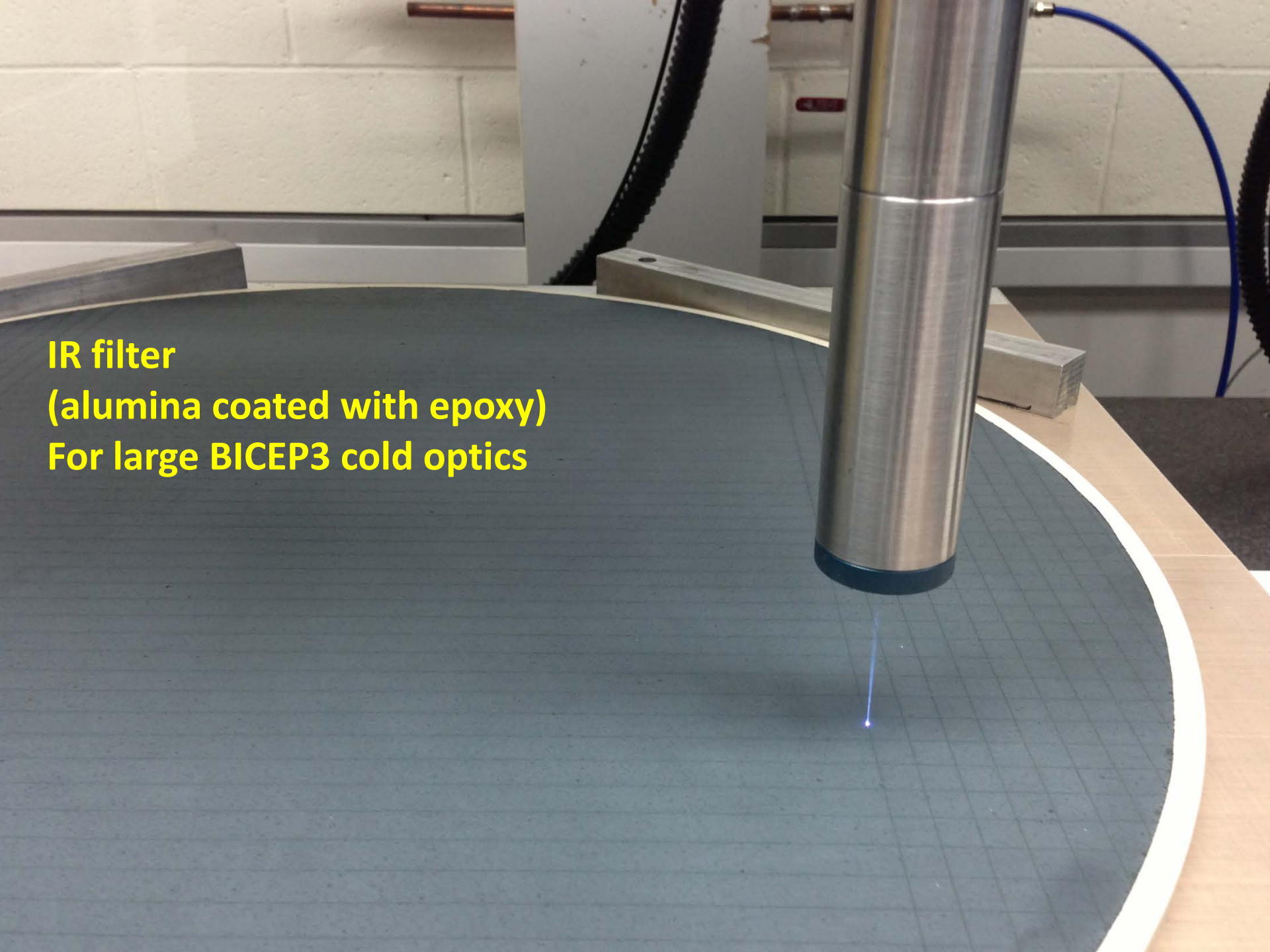
BICEP2: 2010, 2011, 2012

Keck Array: 2011, 2012, 2013,

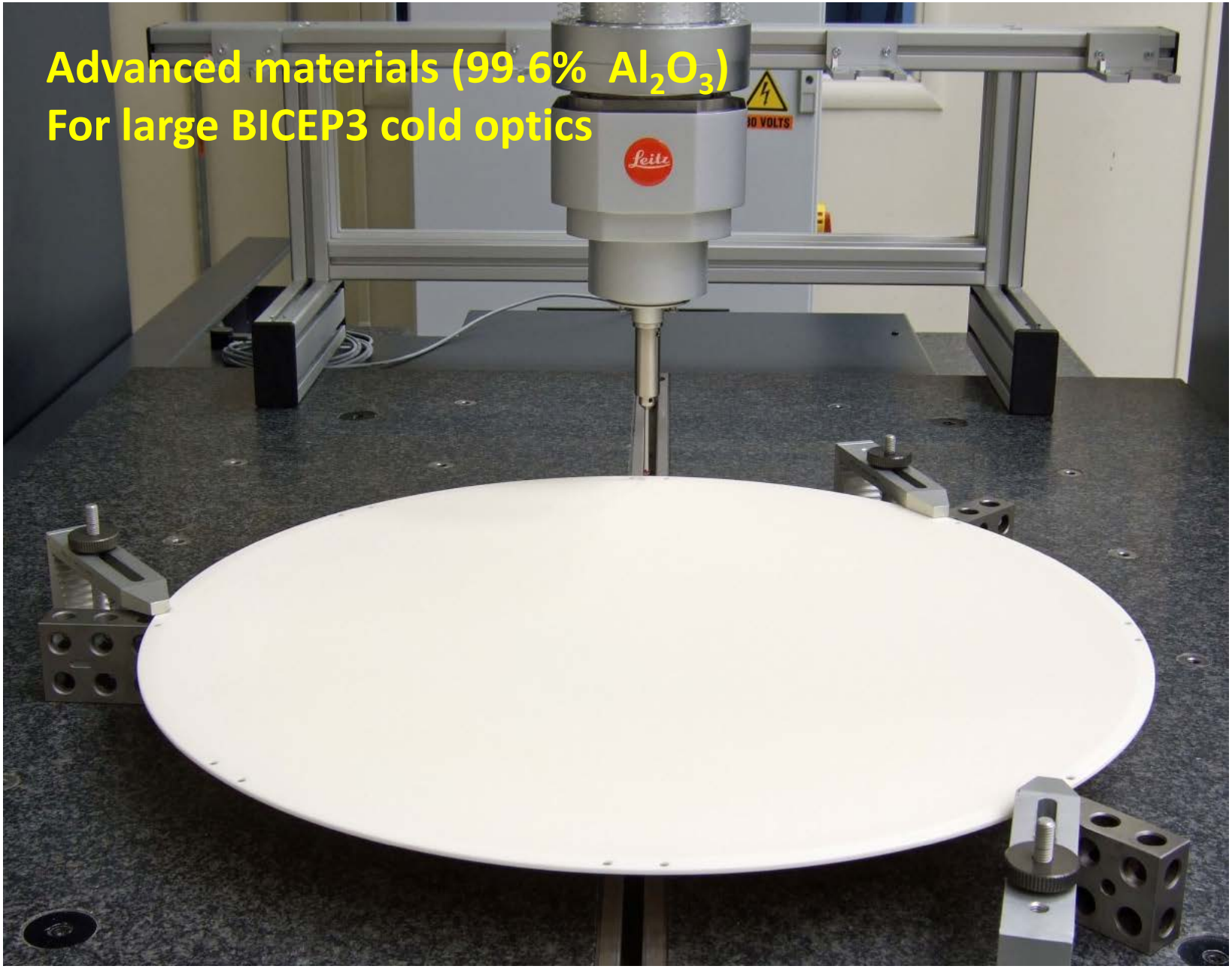
2014 (576 100GHz detectors)…

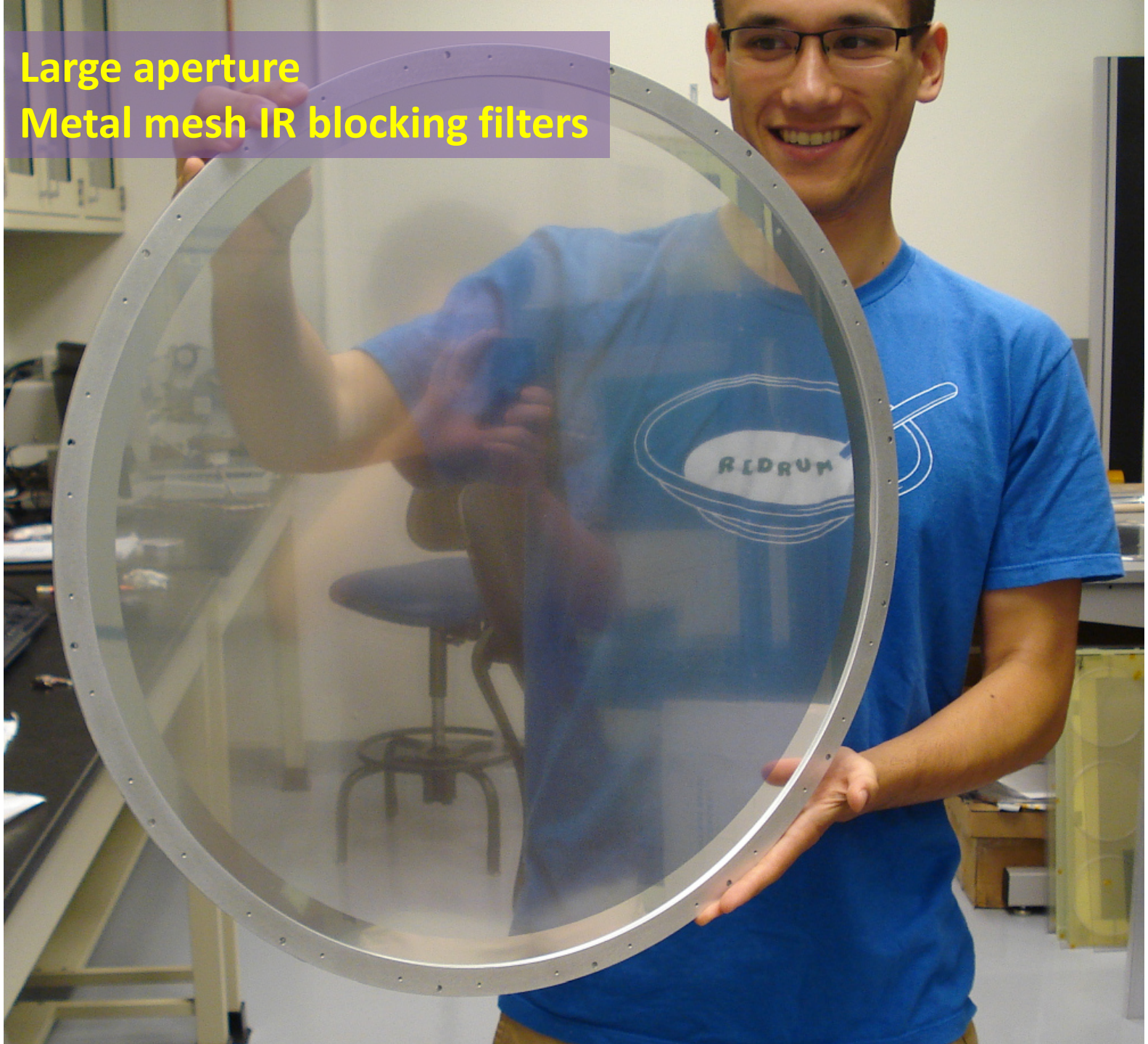
BICEP3: 2015 –

(another 2560 100GHz detectors)


IR filter
(alumina coated with epoxy)
For large BICEP3 cold optics

Epoxy-based
AR-coating
On curved lens


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

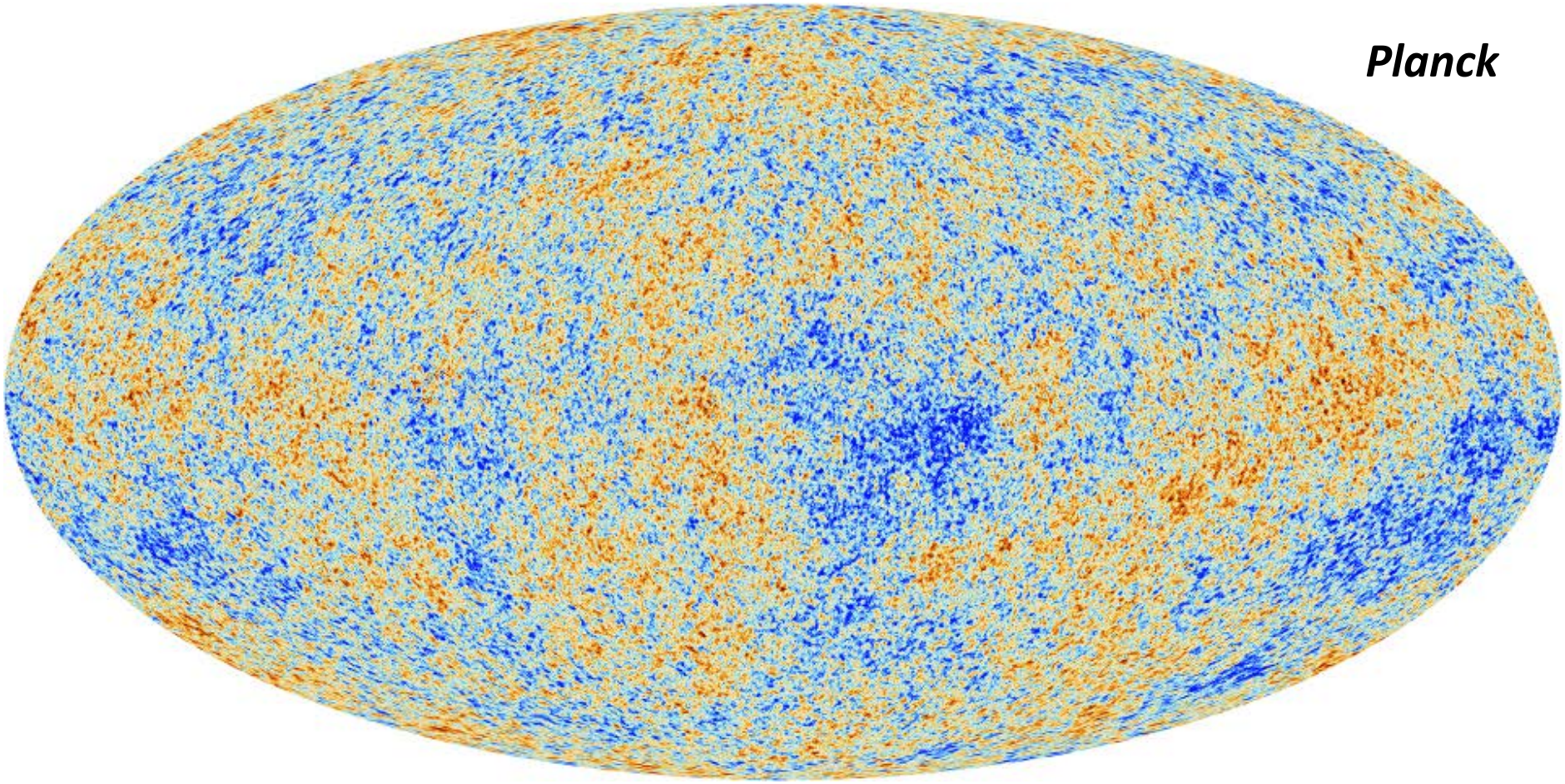

Large aperture
Metal mesh IR blocking filters

CMB after

Planck, ACT, SPT, POLARBEAR, BICEP3?

Three fundamental *maps* of our Universe

Map # 1
(scalar perturbations)

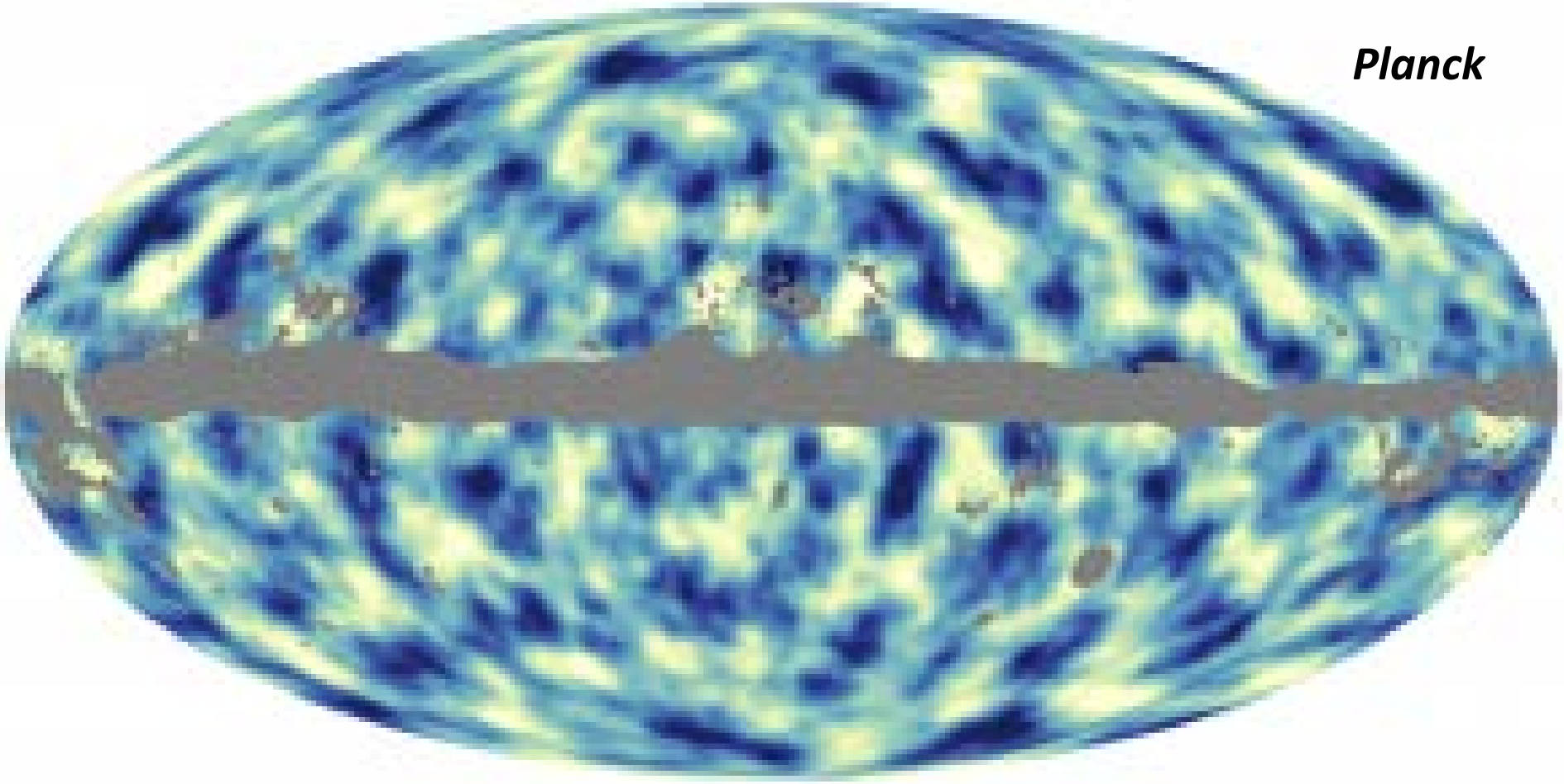


Three fundamental *maps* of our Universe

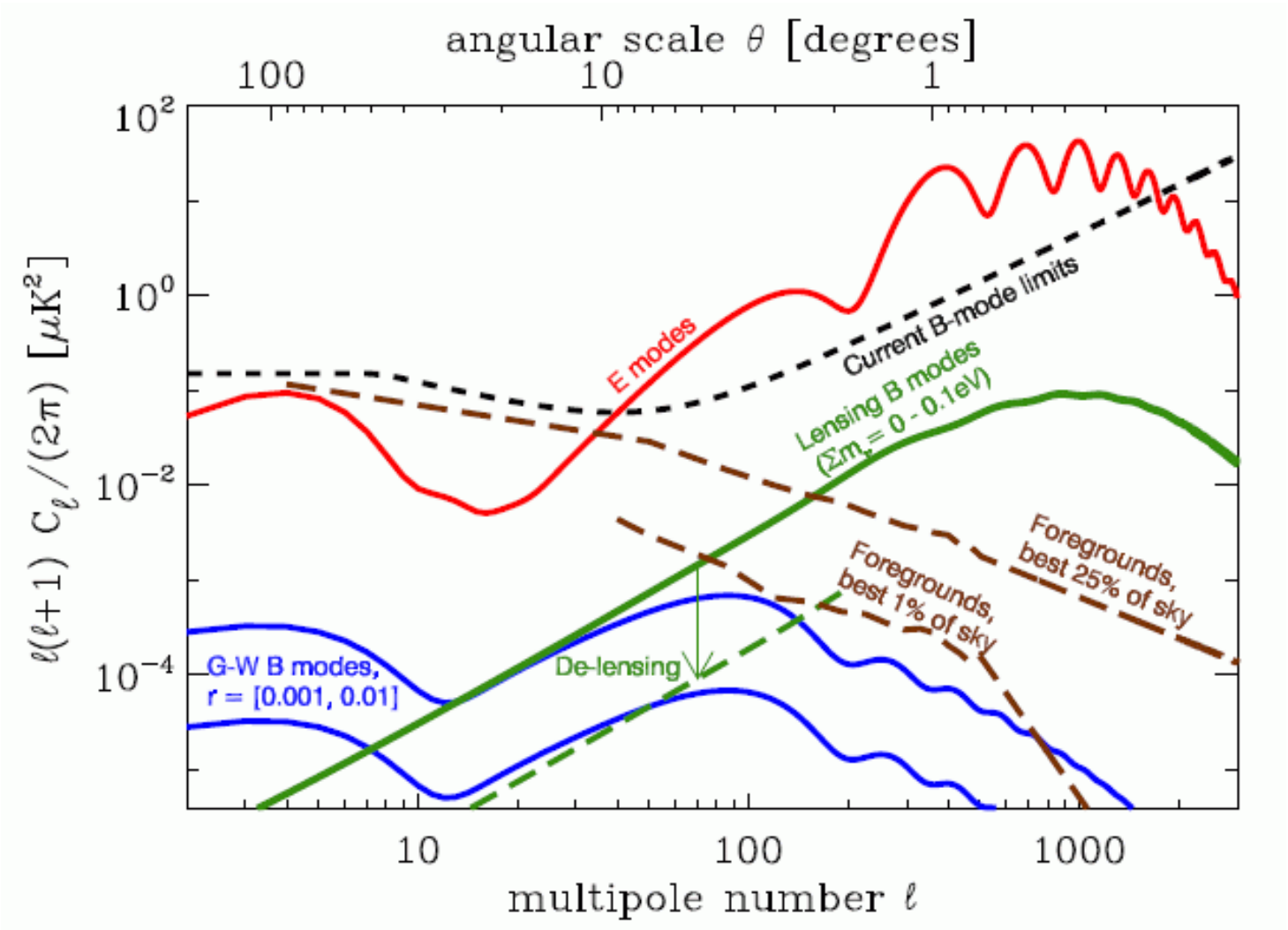
Map # 2
(tensor perturbations)

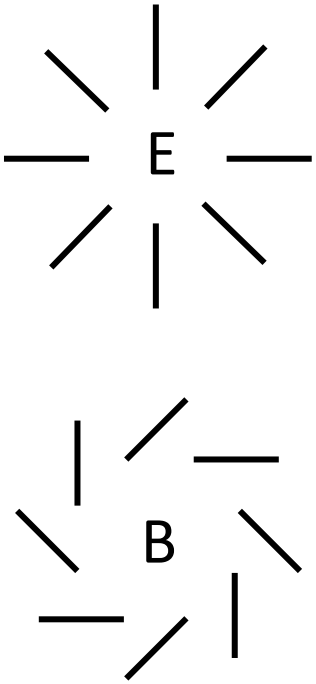
Three fundamental *maps* of our Universe

Map # 3
(lensing deflection field)



CMB B-mode polarization





Snowmass Process (HEP community summer study)

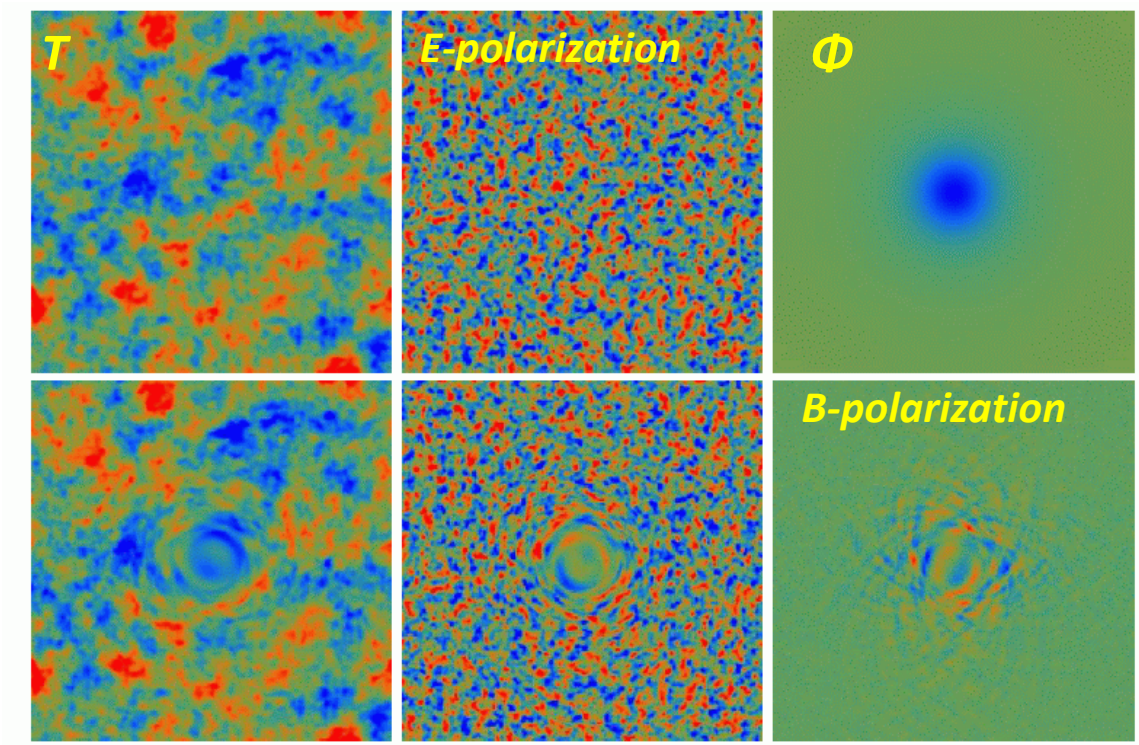
- **P5 = US Particle Physics Projects Prioritization Panel**

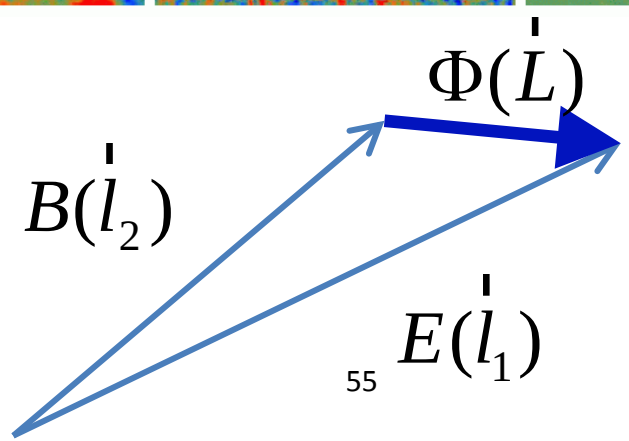
May 23, 2014:

"Recommendation 18: Support CMB experiments as part of the core particle physics program. The multidisciplinary nature of the science warrants continued multiagency support."

Budget for CMB-S4 project is included under all three budget scenarios considered.

Lensing reconstruction

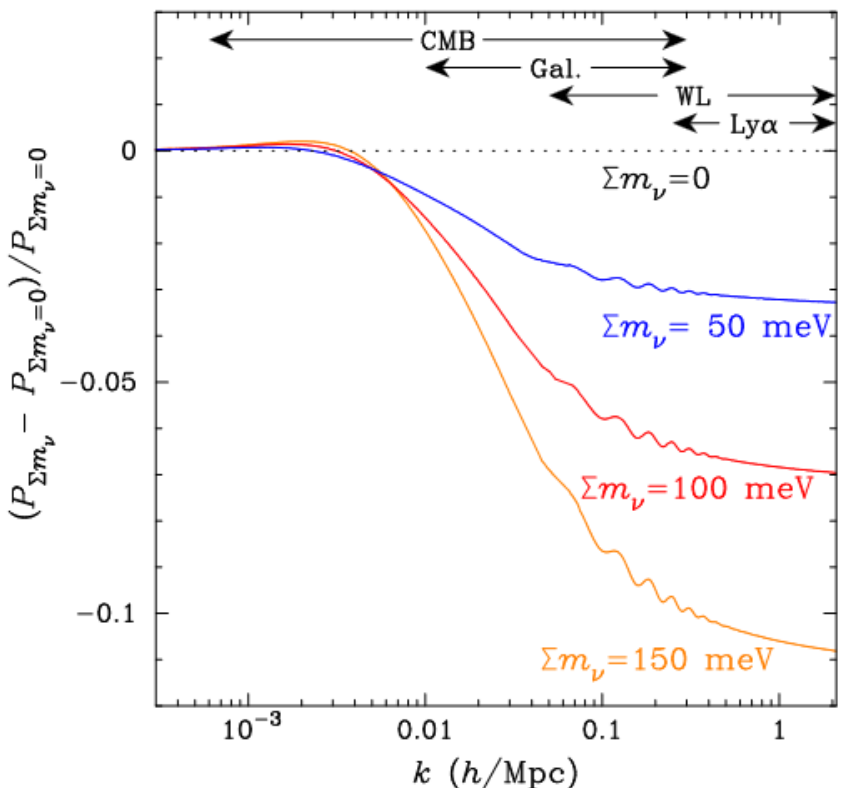


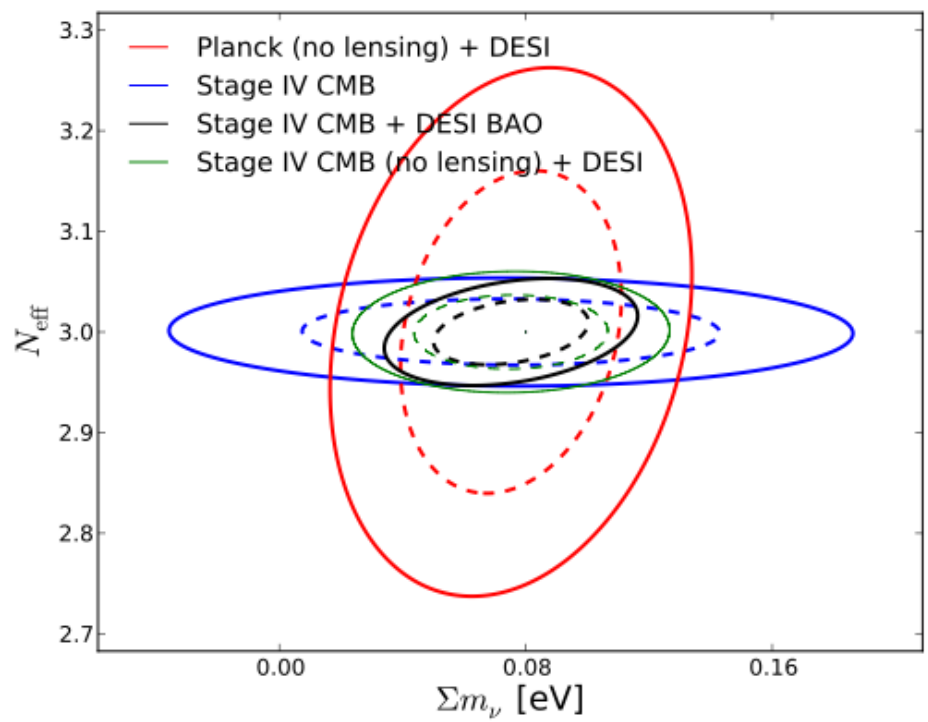


CMB as a probe of neutrinos

Arcminute-measurements of CMB polarization is a probe of cosmic neutrinos

- Number of relativistic species N_{eff} (CMB "damping tail" in polarization)
- Sum of neutrino masses ($\sum m_\nu$) suppresses structures *(*lensing *B*-modes*)*





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SLAC

A Guide to Designing Future Ground-based CMB Experiments

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[6] *Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA*
[7] *Brookhaven National Laboratory, Upton, NY 11973, USA*
[8] *Berkeley Center for Cosmological Physics, Department of Physics, University of California, and Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

(Dated: February 18, 2014)

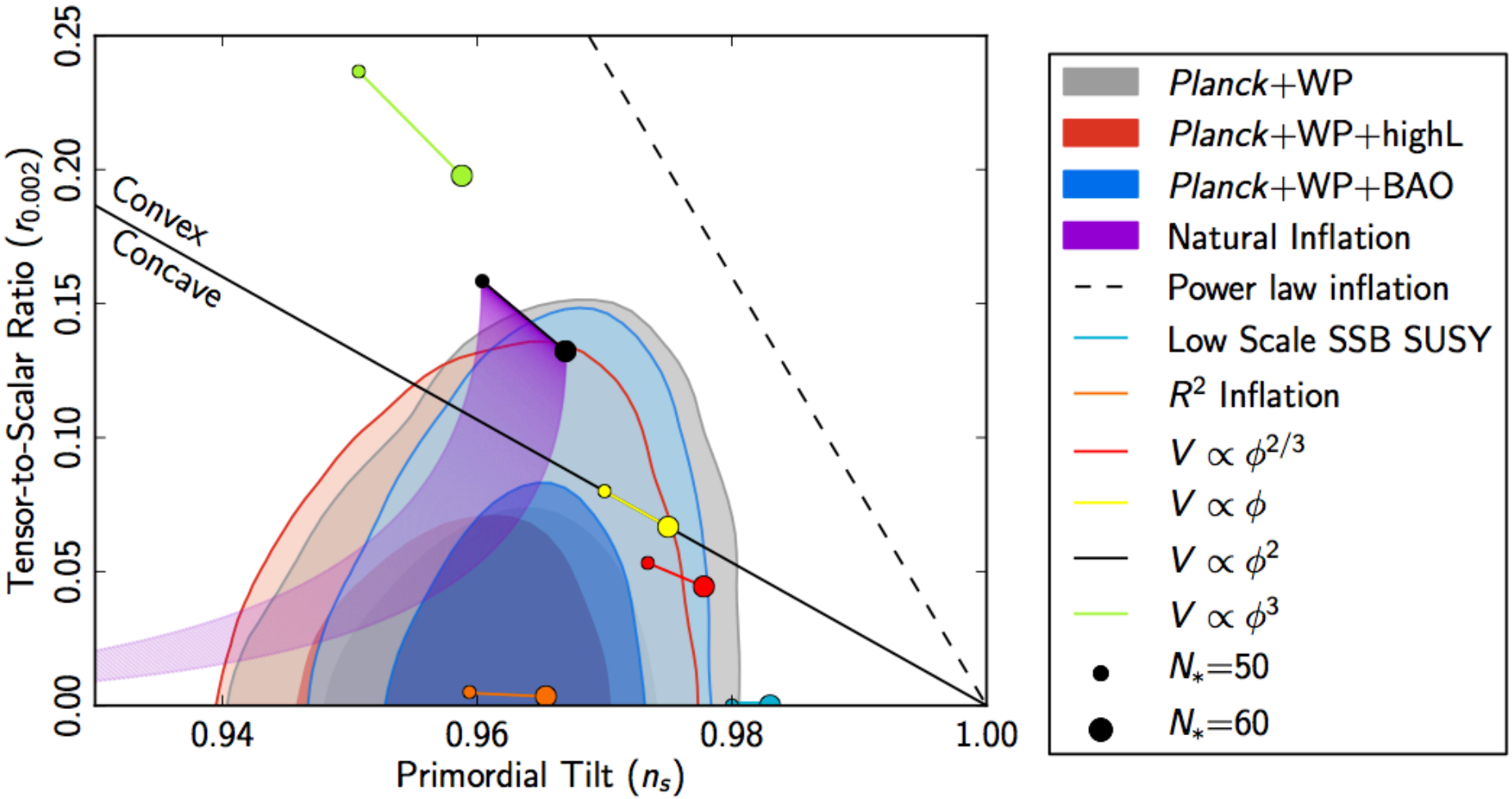
In this follow-up work to the High Energy Physics Community Summer Study 2013 (HEP CSS 2013, a.k.a. SNOWMASS), we explore the scientific capabilities of a future Stage-IV Cosmic Microwave Background polarization experiment (CMB-S4) under various assumptions on detector count, resolution, and sky coverage. We use the Fisher matrix technique to calculate the expected uncertainties in cosmological parameters in $\nu\Lambda$CDM that are especially relevant to the physics of fundamental interactions, including neutrino masses, effective number of relativistic species, dark-energy equation of state, dark-matter annihilation, and inflationary parameters. To further chart the landscape of future cosmology probes, we include forecasted results from the Baryon Acoustic Oscillation (BAO) signal as measured by DESI to constrain parameters that would benefit from low redshift information. We find the following best 1-σ constraints: $\sigma(M_\nu) = 15$ meV, $\sigma(N_{\rm eff}) = 0.0156$, Dark energy Figure of Merit $= 303$, $\sigma(p_{ann}) = 0.00588 \times 3 \times 10^{-26}$ cm^3/s/GeV, $\sigma(\Omega_K) = 0.00074$, $\sigma(n_s) = 0.00110$, $\sigma(\alpha_s) = 0.00145$, and $\sigma(r) = 0.00009$. We also detail the dependences of the parameter constraints on detector count, resolution, and sky coverage.

Inflation: spectral index

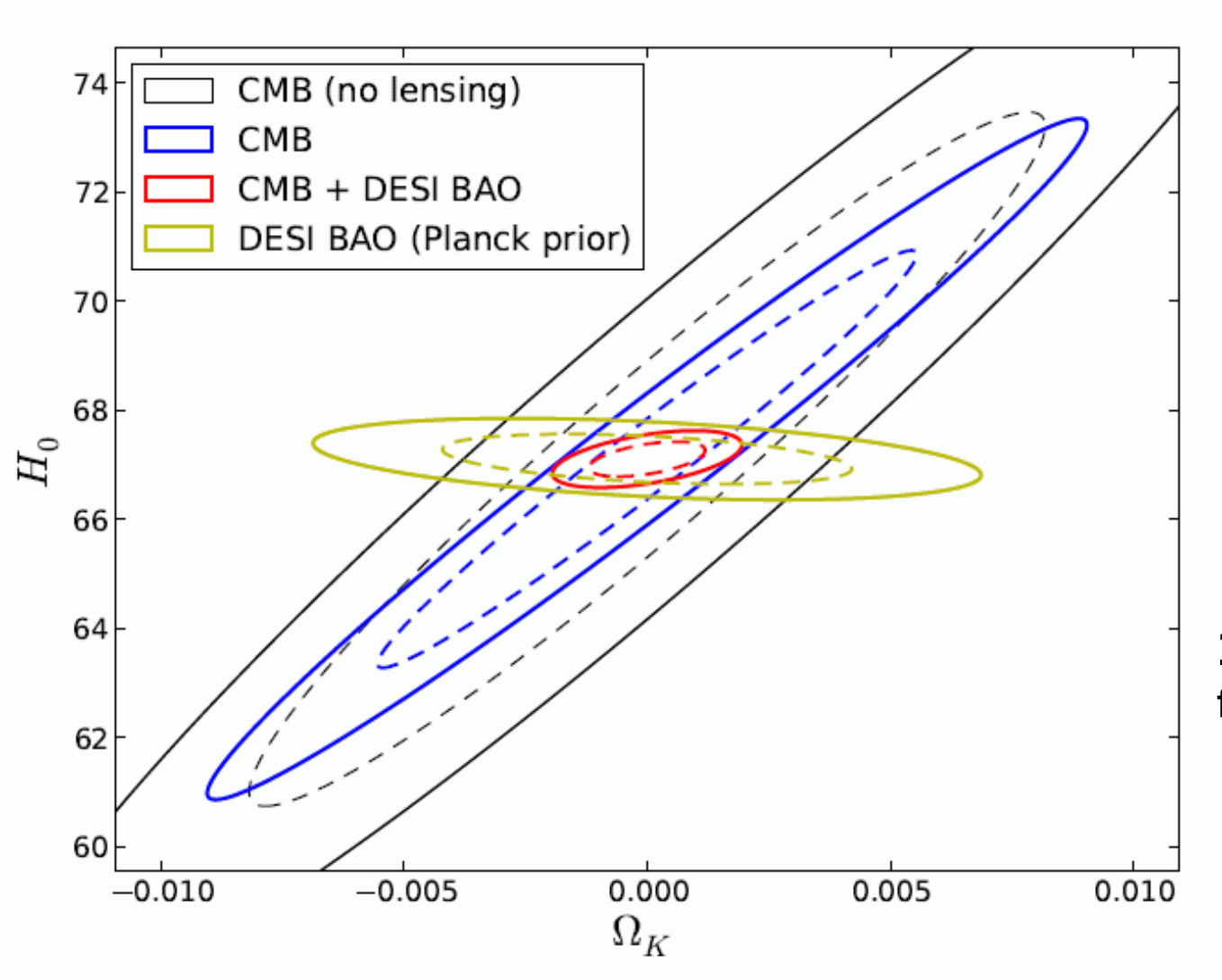
	CMB				CMB+BAO			
	$1'$	$2'$	$3'$	$4'$	$1'$	$2'$	$3'$	$4'$
10^4 detectors								
$f_{sky} = 0.25$	2.91	2.94	2.98	3.04	2.19	2.23	2.29	2.36
$f_{sky} = 0.50$	2.11	2.13	2.16	2.21	1.64	1.67	1.71	1.75
$f_{sky} = 0.75$	1.76	1.77	1.80	1.83	1.39	1.42	1.45	1.48
10^5 detectors								
$f_{sky} = 0.25$	2.66	2.73	2.80	2.86	1.93	1.98	2.04	2.12
$f_{sky} = 0.50$	1.94	1.97	2.01	2.06	1.44	1.47	1.51	1.56
$f_{sky} = 0.75$	1.60	1.63	1.66	1.70	1.22	1.24	1.28	1.32
10^6 detectors								
$f_{sky} = 0.25$	2.38	2.48	2.62	2.73	1.70	1.76	1.83	1.92
$f_{sky} = 0.50$	1.75	1.81	1.90	1.96	1.28	1.32	1.37	1.43
$f_{sky} = 0.75$	1.45	1.51	1.57	1.61	1.10	1.12	1.16	1.20

Table V: n_s 1-σ constraints in units of 10^{-3} from CMB and from CMB+BAO. "CMB" includes lensing.

Inflation: spectral index



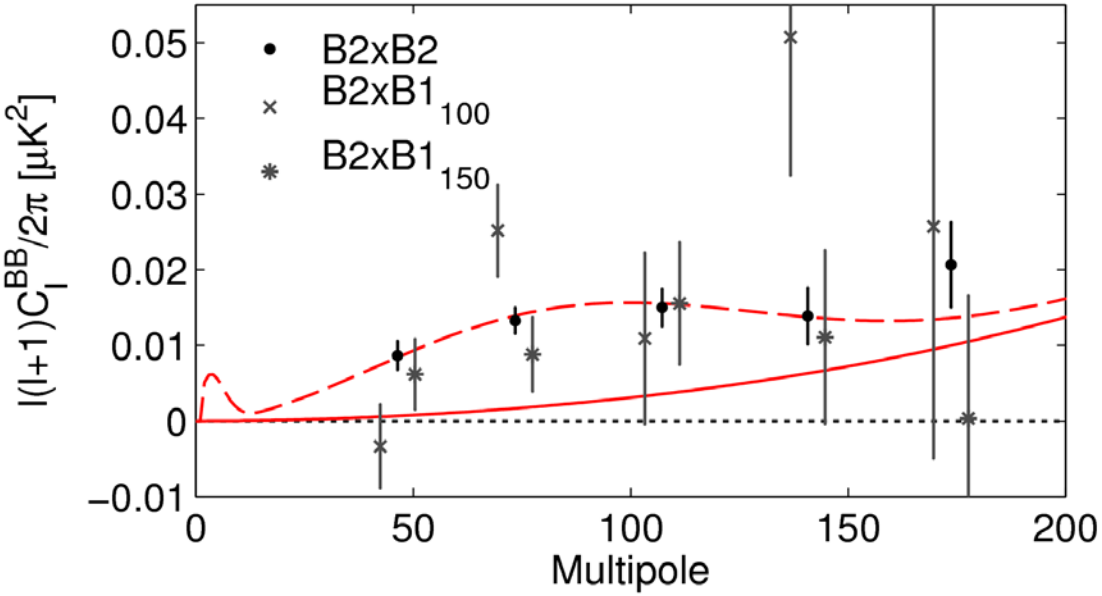
Inflation: Mean spatial curvature



1σ ~
few x 10^{-3}

Thank you !
Keith Vanderlinde

Spectral Index of the B-mode Signal

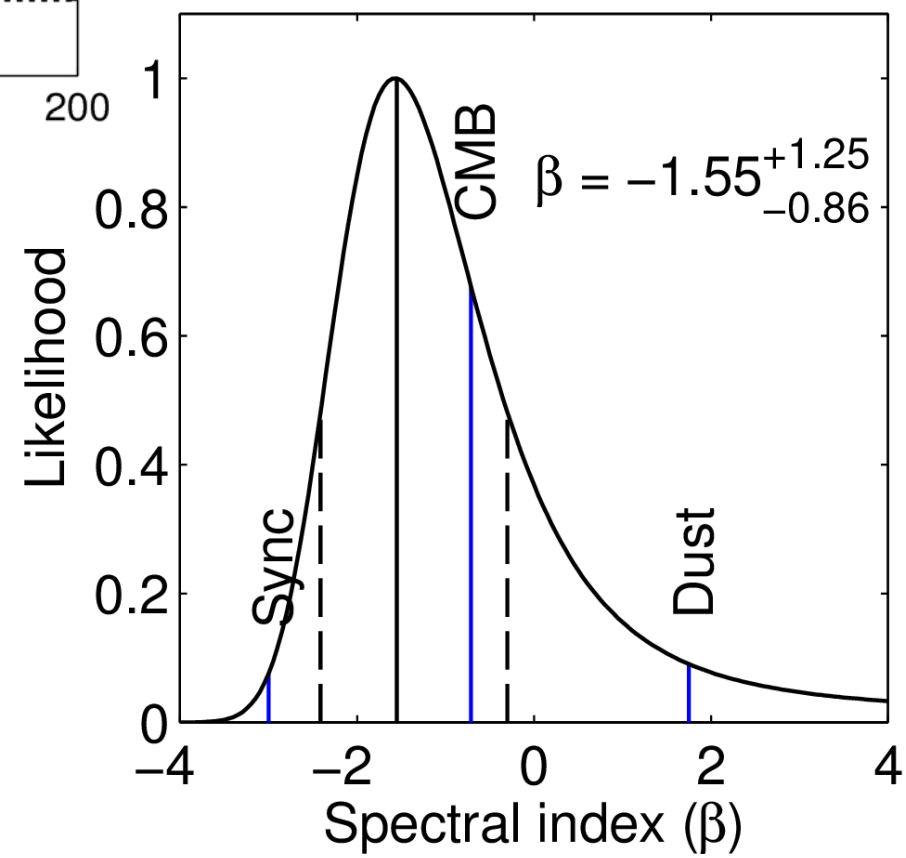


Likelihood ratio test: consistent with CMB spectrum, disfavor pure dust/sync at **2.2/2.3σ**

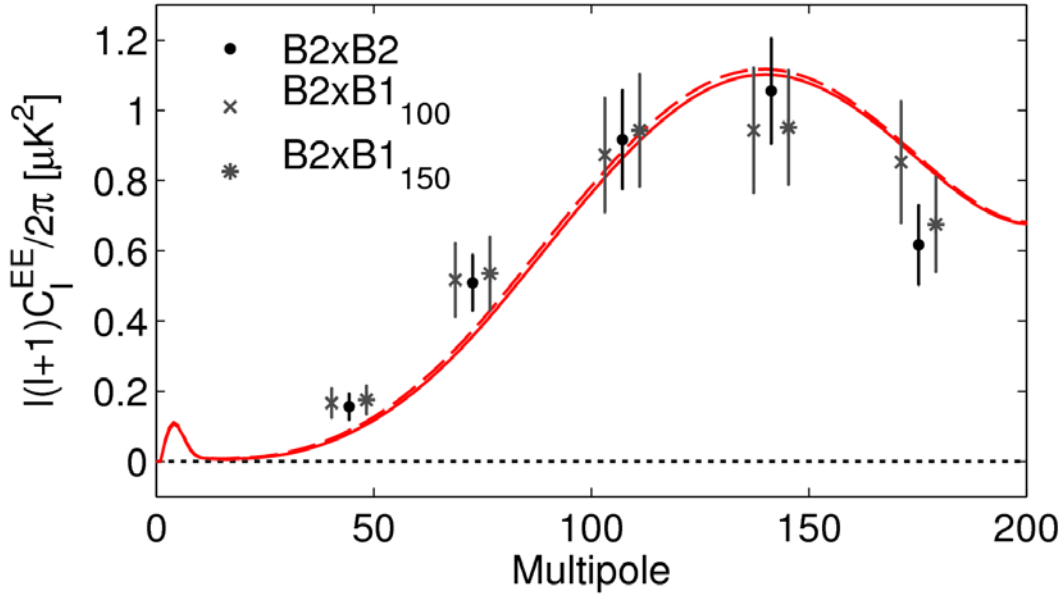
Comparison of B2 auto with $B2_{150}$ x $B1_{100}$ constrains signal frequency dependence, independent of foreground projections

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

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

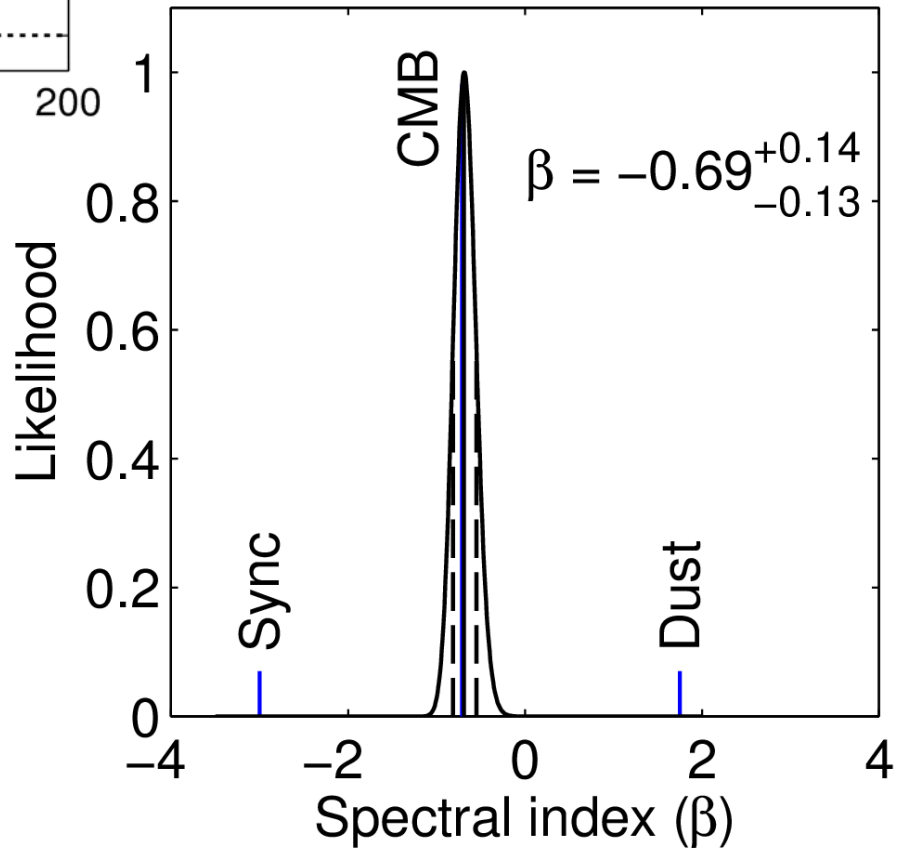


Spectral Index of the E-mode Signal



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