CMB B-mode Polarization Experiments: First Results from POLARBEAR (and BICEP2)

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“Major discovery!” by BICEP2

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[5,17], 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[9,7,17], 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.

You might already know well the BICEP2 result…
Any progress so far after then?

Just a week before the BICEP2 paper…

A MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND *B*-MODE POLARIZATION POWER SPECTRUM AT SUB-DEGREE SCALES WITH POLARBEAR

THE POLARBEAR COLLABORATION: P.A.R. ADE[29], Y. AKIBA[32], A.E. ANTHONY[2,5], K. ARNOLD[14], M. ATLAS[14], D. BARRON[14], D. BOETTGER[14], J. BORRILL[3,31], S. CHAPMAN[9], Y. CHINONE[17,13], M. DOBBS[25], T. ELLEFLOT[14], J. ERRARD[31,3], G. FABBIAN[1,18], C. FENG[14], D. FLANIGAN[13,10], A. GILBERT[25], W. GRAINGER[28], N.W. HALVERSON[2,5,15], M. HASEGAWA[17,32], K. HATTORI[17], M. HAZUMI[17,32,20], W.L. HOLZAPFEL[13], Y. HORI[17], J. HOWARD[13,16], P. HYLAND[24], Y. INOUE[32], G.C. JAEHNIG[2,15], A.H. JAFFE[11], B. KEATING[14], Z. KERMISH[12], R. KESKITALO[3], T. KISNER[3,31], M. LE JEUNE[1], A.T. LEE[13,27], E.M. LEITCH[4,19], E. LINDER[27], M. LUNGU[13,8], F. MATSUDA[14], T. MATSUMURA[17], X. MENG[13], N.J. MILLER[22], H. MORII[17], S. MOYERMAN[14], M.J. MYERS[13], M. NAVAROLI[14], H. NISHINO[20], H. PAAR[14], J. PELOTON[1], D. POLETTI[1], E. QUEALY[13,26], G. REBEIZ[6], C.L. REICHARDT[13], P.L. RICHARDS[13], C. ROSS[9], I. SCHANNING[14], D.E. SCHENCK[2,5], B.D. SHERWIN[13,21], A. SHIMIZU[32], C. SHIMMIN[13,7], M. SHIMON[30,14], P. SIRITANASAK[14], G. SMECHER[33], H. SPIELER[27], N. STEBOR[14], B. STEINBACH[13], R. STOMPOR[1], A. SUZUKI[13], S. TAKAKURA[23,17], T. TOMARU[17], B. WILSON[14], A. YADAV[14], O. ZAHN[27]

Draft version March 10, 2014

ABSTRACT

We report a measurement of the *B*-mode polarization power spectrum in the cosmic microwave background (CMB) using the POLARBEAR experiment in Chile. The faint *B*-mode polarization signature carries information about the Universe's entire history of gravitational structure formation, and the cosmic inflation that may have occurred in the very early Universe. Our measurement covers the angular multipole range $500 < \ell < 2100$ and is based on observations of $30\,\mathrm{deg}^2$ with $3.5'$ resolution at 150 GHz. On these angular scales, gravitational lensing of the CMB by intervening structure in the Universe is expected to be the dominant source of *B*-mode polarization. Including both systematic and statistical uncertainties, the hypothesis of no *B*-mode polarization power from gravitational lensing is rejected at 97.5% confidence. The band powers are consistent with the standard cosmological model. Fitting a single lensing amplitude parameter A_{BB} to the measured band powers, $A_{BB} = 1.12 \pm 0.61(\mathrm{stat})^{+0.04}_{-0.10}(\mathrm{sys}) \pm 0.07(\mathrm{multi})$, where $A_{BB} = 1$ is the fiducial WMAP-9 ΛCDM value. In this expression, "stat" refers to the statistical uncertainty, "sys" to the systematic uncertainty associated with possible biases from the instrument and astrophysical foregrounds, and "multi" to the calibration uncertainties that have a multiplicative effect on the measured amplitude A_{BB}.

- POLARBEAR published the best B-mode measurement at sub-degree scale!

First result from ACTpol is out too.

THE ATACAMA COSMOLOGY TELESCOPE: CMB POLARIZATION AT $200 < \ell < 9000$

Sigurd Naess[1], Matthew Hasselfield[2,3], Jeff McMahon[4], Michael D. Niemack[5], Graeme E. Addison[3], Peter A. R. Ade[6], Rupert Allison[1], Mandana Amiri[3], Andrew Baker[7], Nick Battaglia[8], James A. Beall[9], Francesco de Bernardis[5], J Richard Bond[10], Joe Britton[9], Erminia Calabrese[1], Hsiao-mei Cho[9], Kevin Coughlin[4], Devin Crichton[11], Sudeep Das[12], Rahul Datta[4], Mark J. Devlin[13], Simon R. Dicker[13], Joanna Dunkley[1], Rolando Dünner[14], Joseph W. Fowler[9], Anna E. Fox[9], Patricio Gallardo[5,14], Emily Grace[15], Megan Gralla[11], Amir Hajian[10], Mark Halpern[3], Shawn Henderson[5], J. Colin Hill[2], Gene C. Hilton[9], Matt Hilton[16], Adam D. Hincks[3], Renée Hlozek[2], Patty Ho[15], Johannes Hubmayr[9], Kevin M. Huffenberger[17], John P. Hughes[7], Leopoldo Infante[14], Kent Irwin[18], Rebecca Jackson[4,19], Jeff Klein[13], Brian Koopman[5], Arthur Kosowsky[20], Dale Li[9], Thibaut Louis[1], Marius Lungu[13], Mathew Madhavacheril[21], Tobias A. Marriage[11], Loïc Maurin[14], Felipe Menanteau[22,23], Kavilan Moodley[16], Charles Munson[4], Laura Newburgh[15], John Nibarger[9], Michael R. Nolta[10], Lyman A. Page[15], Christine Pappas[15], Bruce Partridge[24], Felipe Rojas[14], Benjamin Schmitt[13], Neelima Sehgal[21], Blake D. Sherwin[25], Jon Sievers[26,10], Sara Simon[15], David N. Spergel[2], Suzanne T. Staggs[15], Eric R. Switzer[27,10], Robert Thornton[28,13], Hy Trac[8], Carole Tucker[6], Alexander Van Engelen[21], Jon Ward[13], Edward J. Wollack[27]

Draft: May 22, 2014

ABSTRACT

We report on measurements of the cosmic microwave background (CMB) and celestial polarization at 146 GHz made with the Atacama Cosmology Telescope Polarimeter (ACTPol) in its first three months of observing. Four regions of sky covering a total of 270 square degrees were mapped with an angular resolution of $1.3'$. The map noise levels in the four regions are between 11 and 17 μK-arcmin. We present TT, TE, EE, TB, EB, and BB power spectra from three of these regions. The observed E-mode polarization power spectrum, displaying six acoustic peaks in the range $200 < \ell < 3000$, is an excellent fit to the prediction of the best-fit cosmological models from WMAP9+ACT and *Planck* data. The polarization power spectrum, which mainly reflects primordial plasma velocity perturbations, provides an independent determination of cosmological parameters consistent with those based on the temperature power spectrum, which results mostly from primordial density perturbations. We find that without masking any point sources in the EE data at $\ell < 9000$, the Poisson tail of the EE power spectrum due to polarized point sources has an amplitude less than 2.4 μK^2 at $\ell = 3000$ at 95% confidence. Finally, we report that the Crab Nebula, an important polarization calibration source at microwave frequencies, has 8.7% polarization with an angle of $150.9° \pm 0.5°$ when smoothed with a $5'$ Gaussian beam.

- Only three months of data.
- High-ell E-mode power spectrum measurement
  - B-mode power spectrum is null consistent.

First Results from POLARBEAR

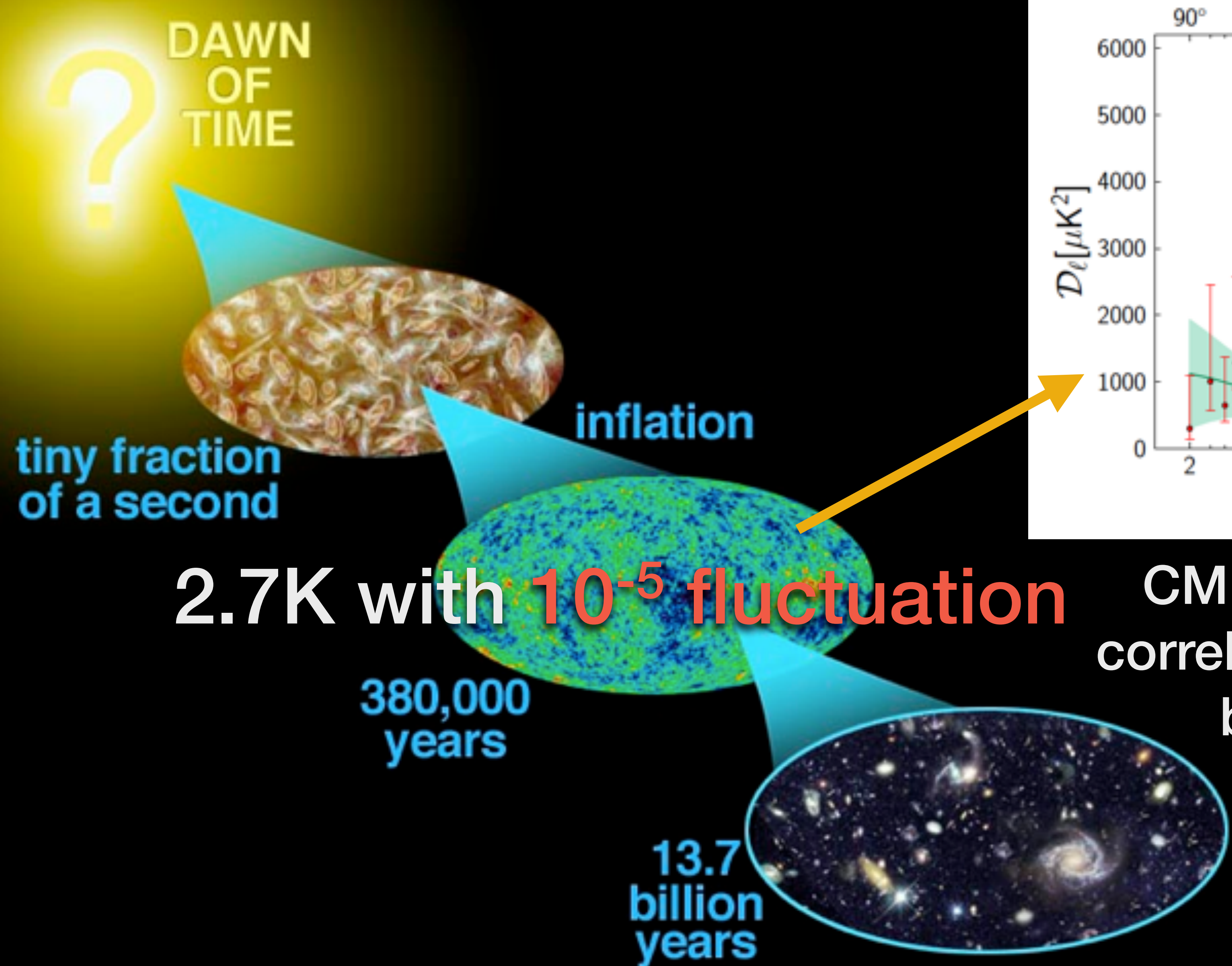
- "A Measurement of the Cosmic Microwave Background B-Mode Polarization Power Spectrum at Sub-Degree Scales with POLARBEAR" (http://arxiv.org/abs/1403.2369)
  - Best measurement of B-mode auto-power spectrum in sub-degree angular scale
- "Gravitational Lensing of Cosmic Microwave Background Polarization" (http://arxiv.org/abs/1312.6646, accepted at PRL)
  - First evidence for gravitational lensing with CMB polarization data alone
- "Evidence for Gravitational Lensing of the Cosmic Microwave Background Polarization from Cross-correlation with the Cosmic Infrared Background" (PRL 112, 131302 (2014))
  - Cross-correlation with CIB, confirmation of SPTpol result

Measurement of lensing B-modes with three independent methods

Cosmology with CMB B-modes

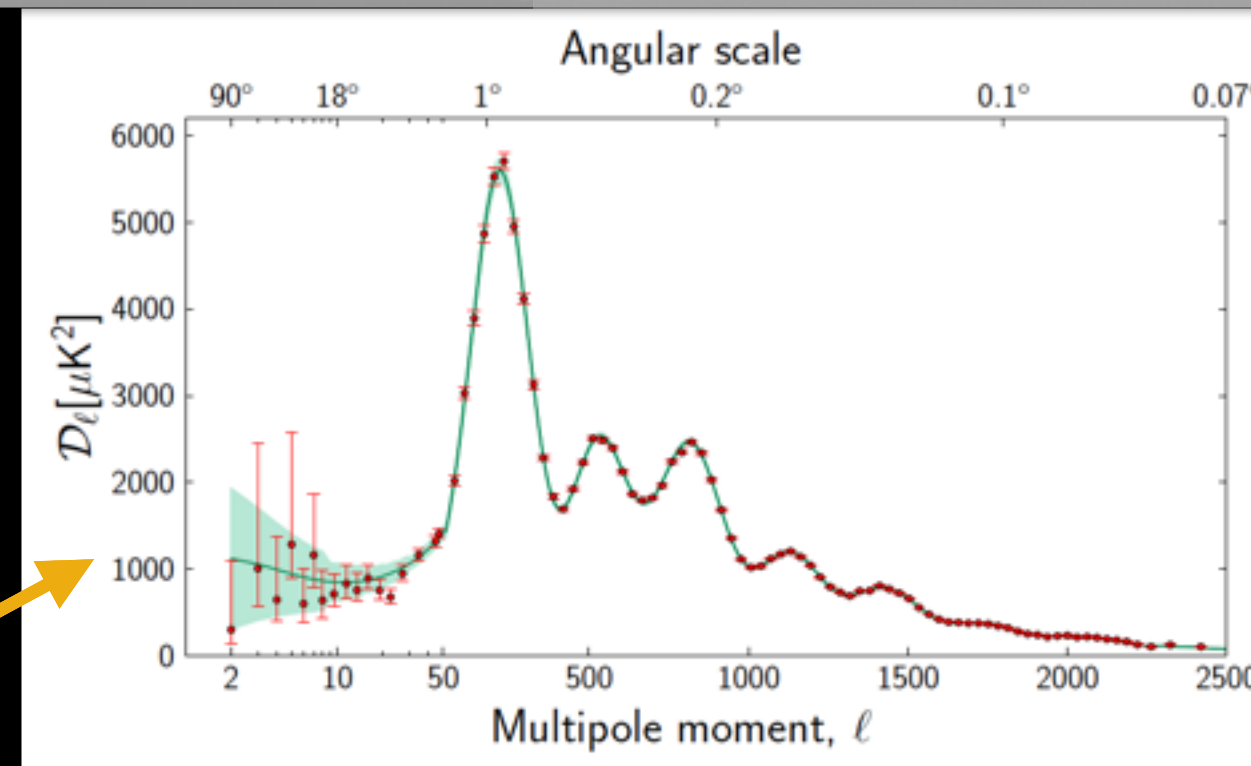
- Primordial Gravitational Wave from Inflation
  - GUT-scale ultra high energy physics
- Weak Gravitational Lensing from Large Scale Structure
  - Sum of neutrino mass

Cosmic Microwave Background



2.7K with 10^{-5} fluctuation

CMB Temperature Power Spectrum by Planck

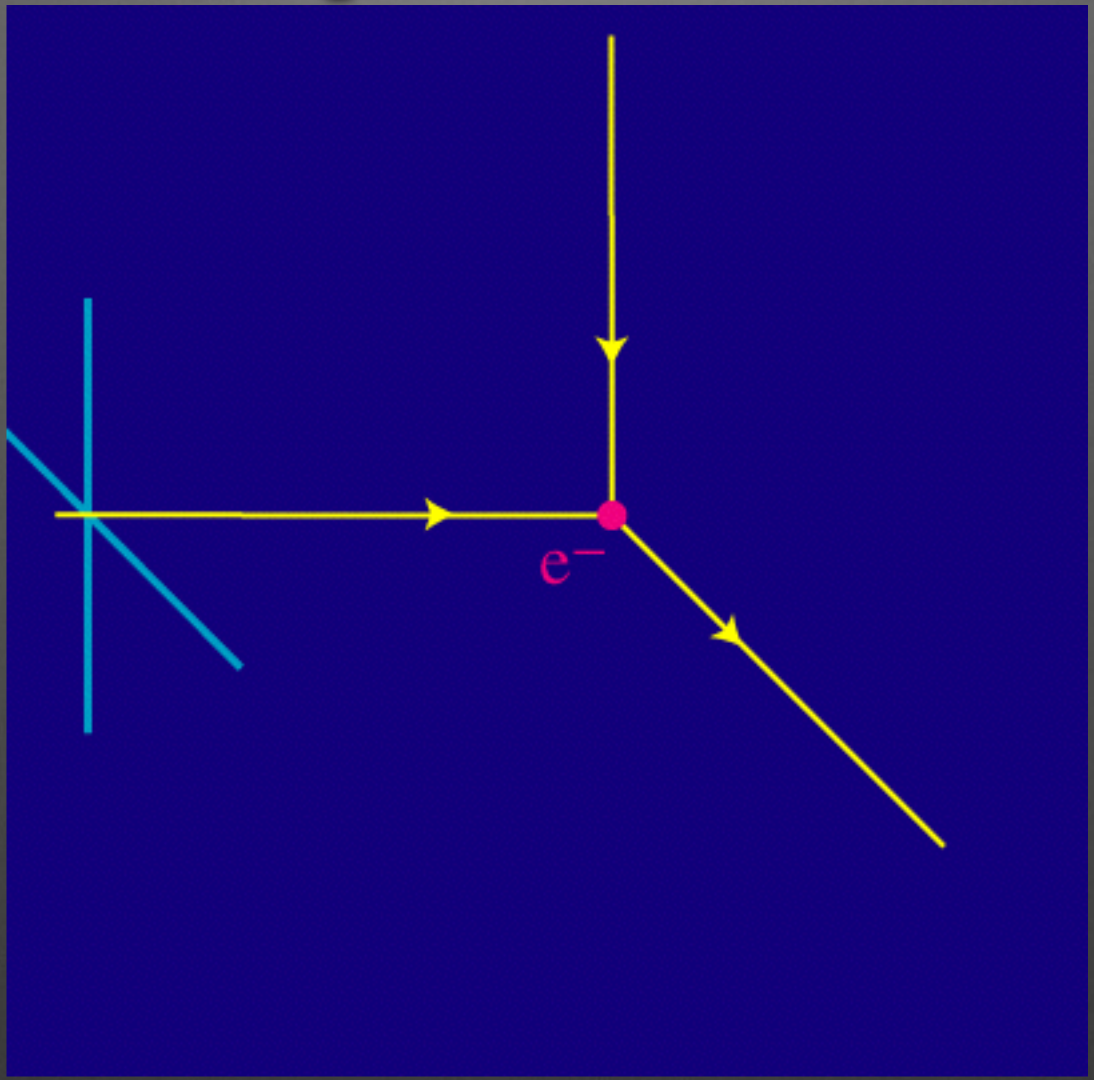


CMB can be described by 2-point correlation function (power spectrum) because of the Gaussianity.

$$C_l = \frac{1}{2l+1}\sum_m \langle a_{lm} a_{lm}^* \rangle$$

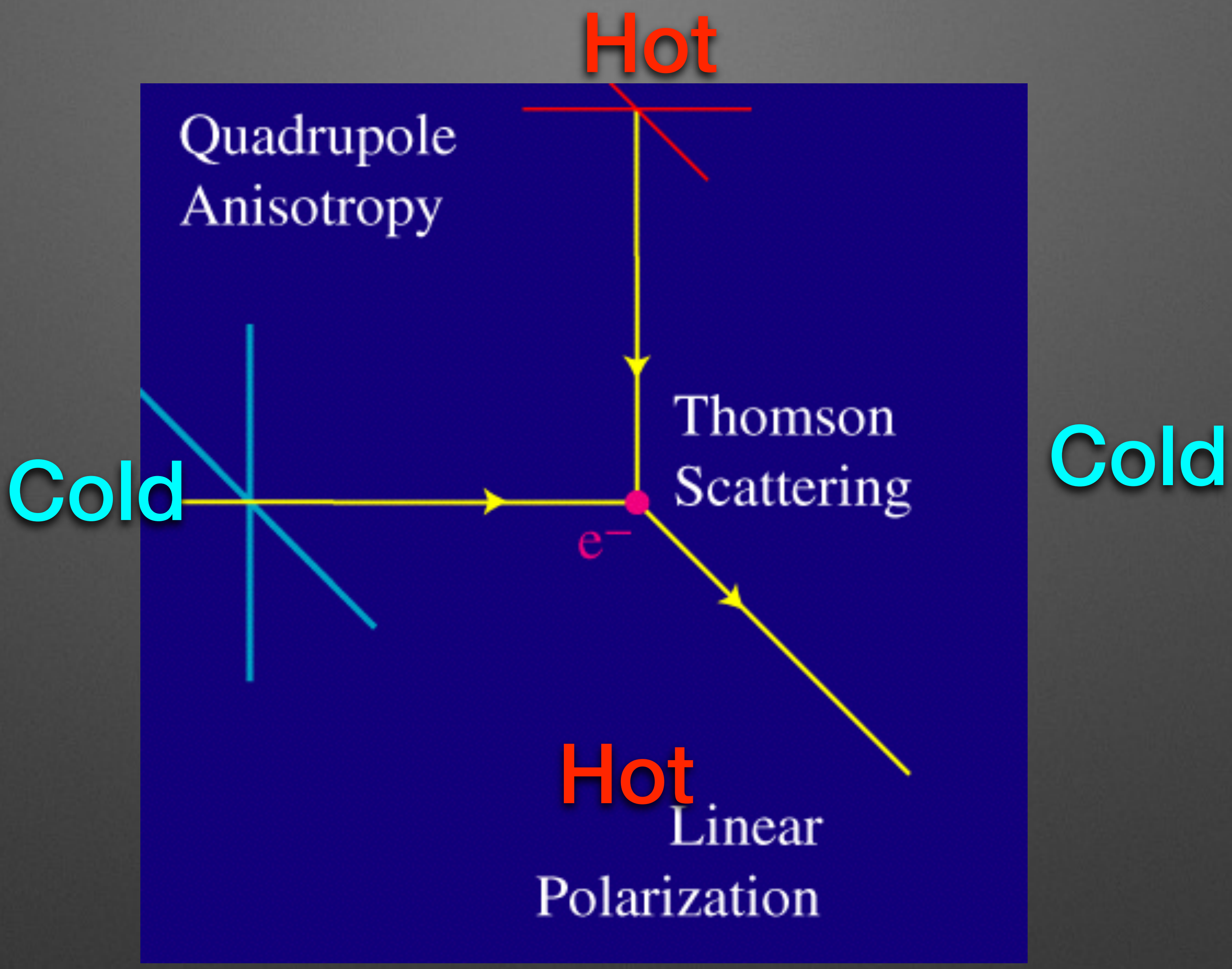
Physics in the early universe is imprinted in CMB.

Thomson scattering makes linear polarization



Wayne Hu (http://background.uchicago.edu/~whu/intermediate/Polarization/polar1.html)

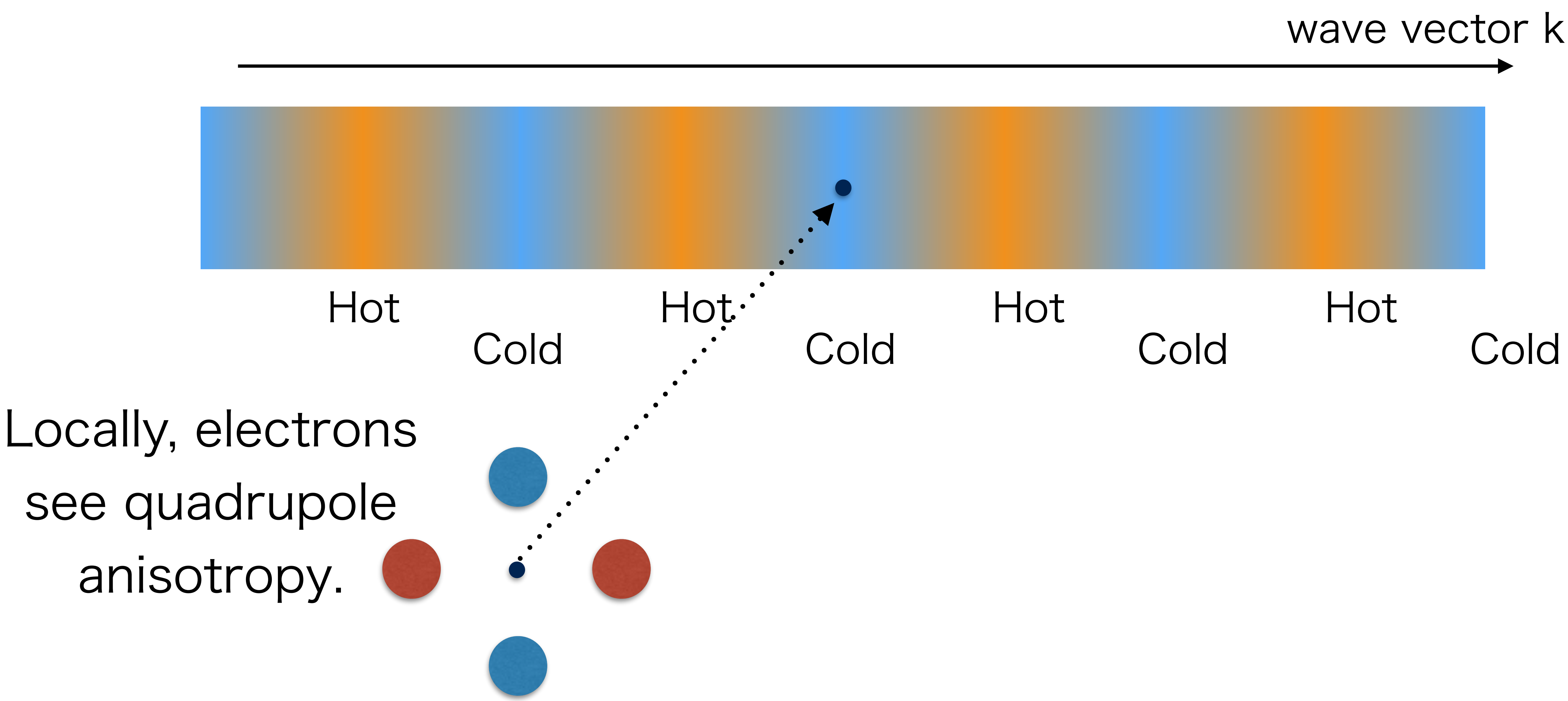
Local quadrupole anisotropy+Thomson scattering induced CMB polarization



Wayne Hu (http://background.uchicago.edu/~whu/intermediate/Polarization/polar1.html)

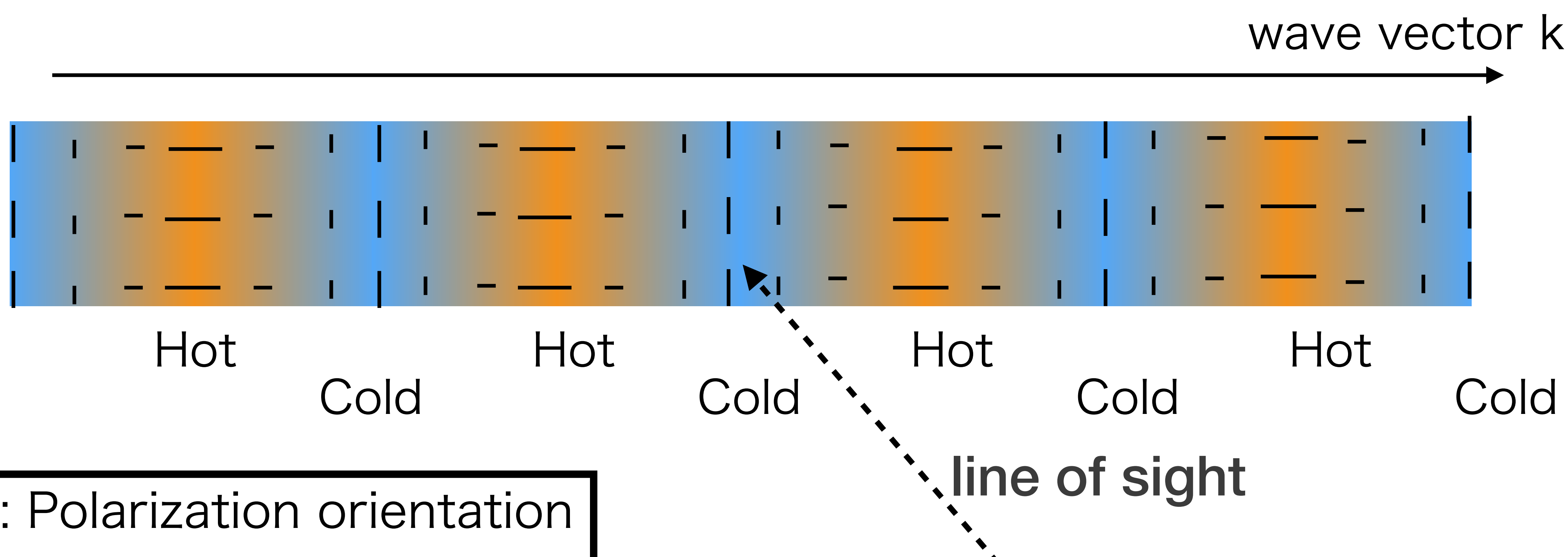
Density-wave (scalar perturbation)

A density wave produces temperature anisotropy.



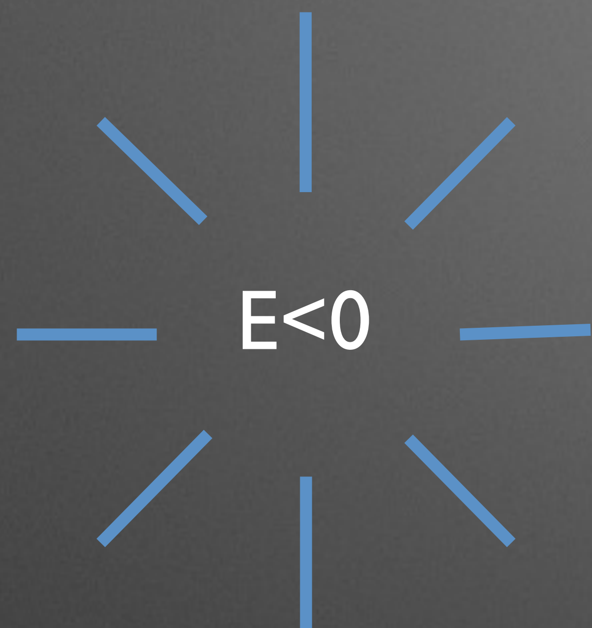
Density-wave (scalar perturbation)

Polarization pattern produced by the density wave



E-mode: Polarization orientation is parallel or perpendicular to the wave vector, k.
No polarization change by the sign flip of k.

E-mode and B-mode

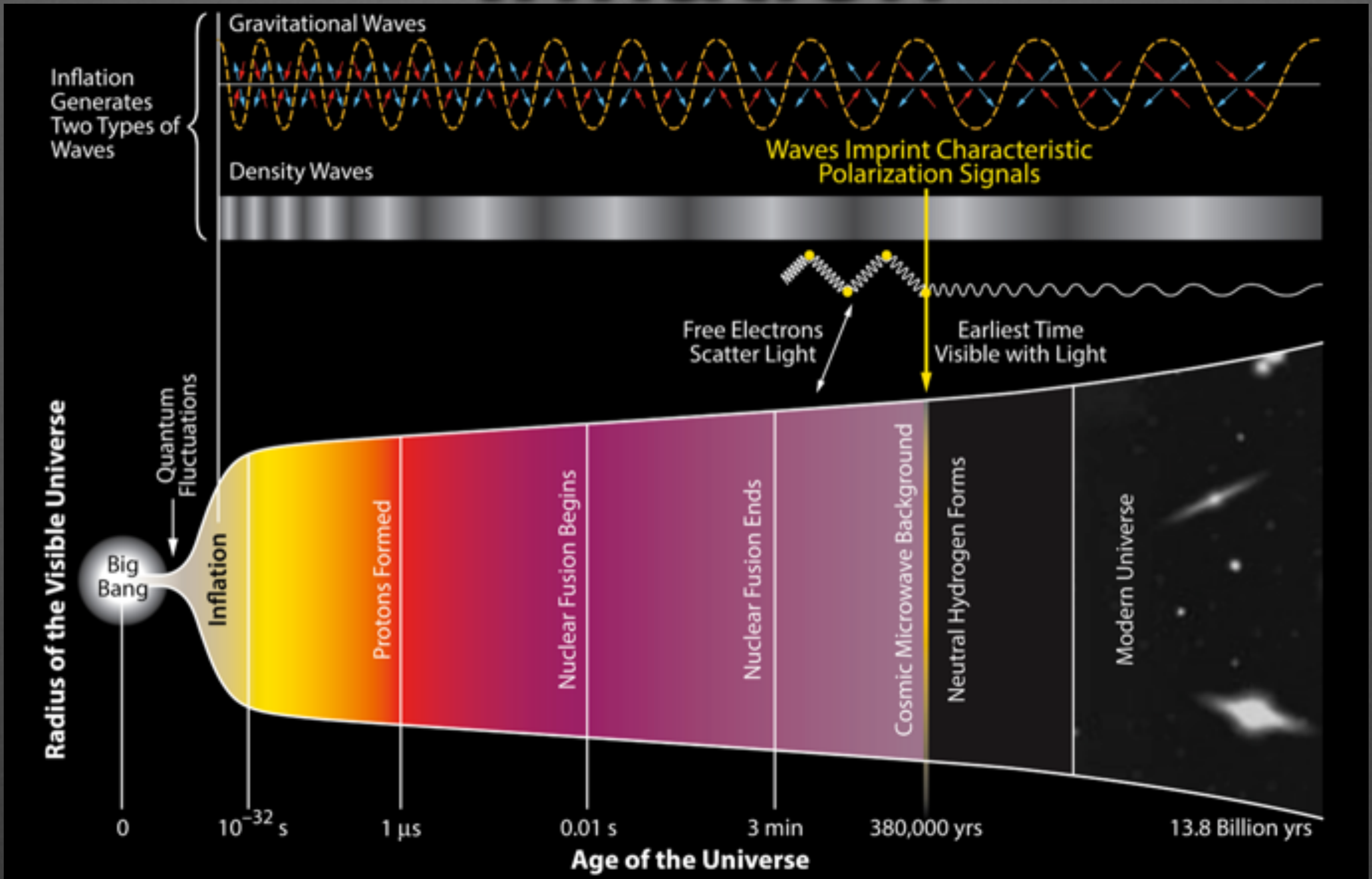


E-mode (grad):
even parity

B-mode (curl):
odd parity

- Polarization fields can be decomposed into two orthogonal fields of E- and B-modes
  - Density perturbations (which have been seen as temperature fluctuation) can only create E-mode.

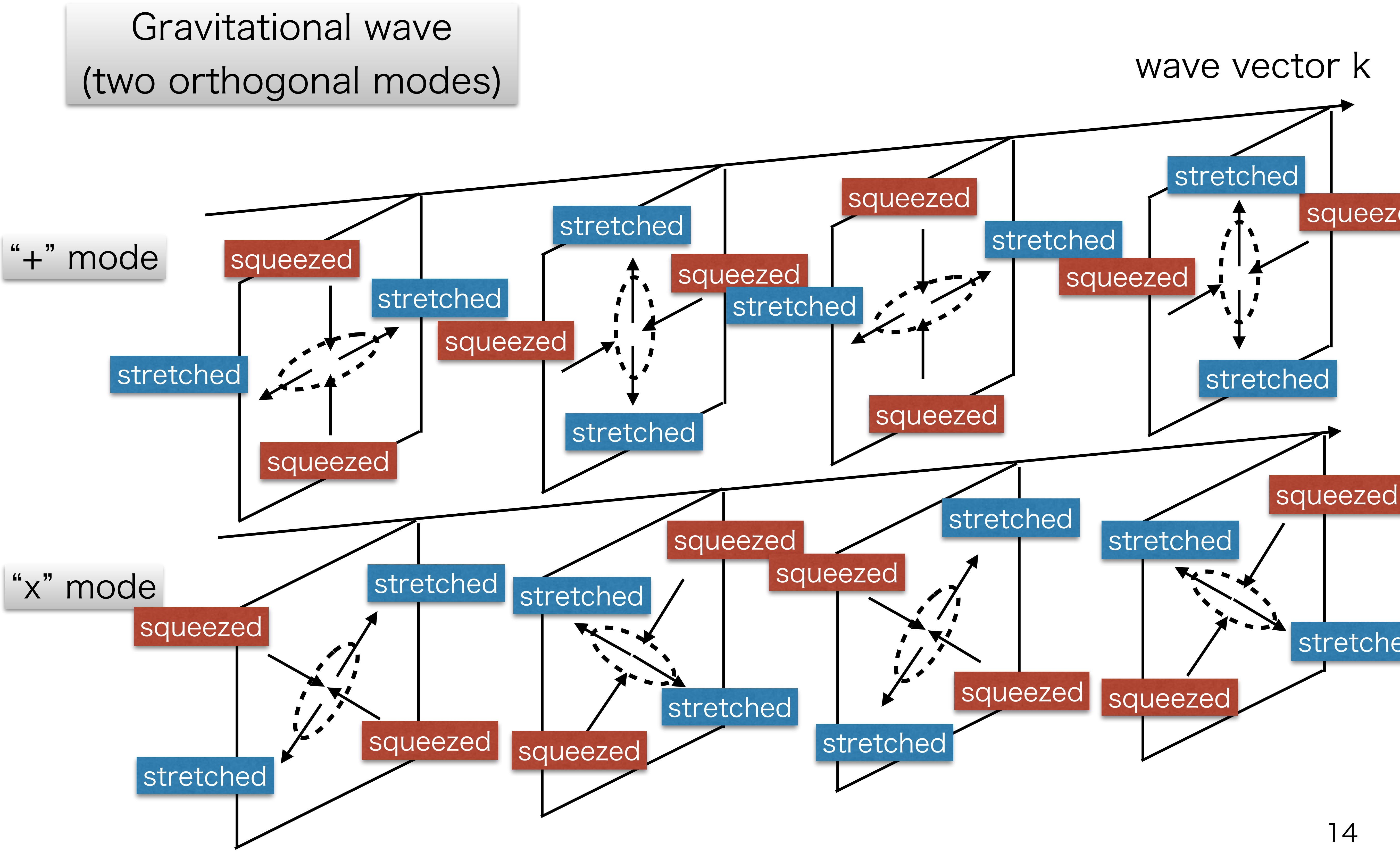
Inflation



(Fig. from BICEP2 team)

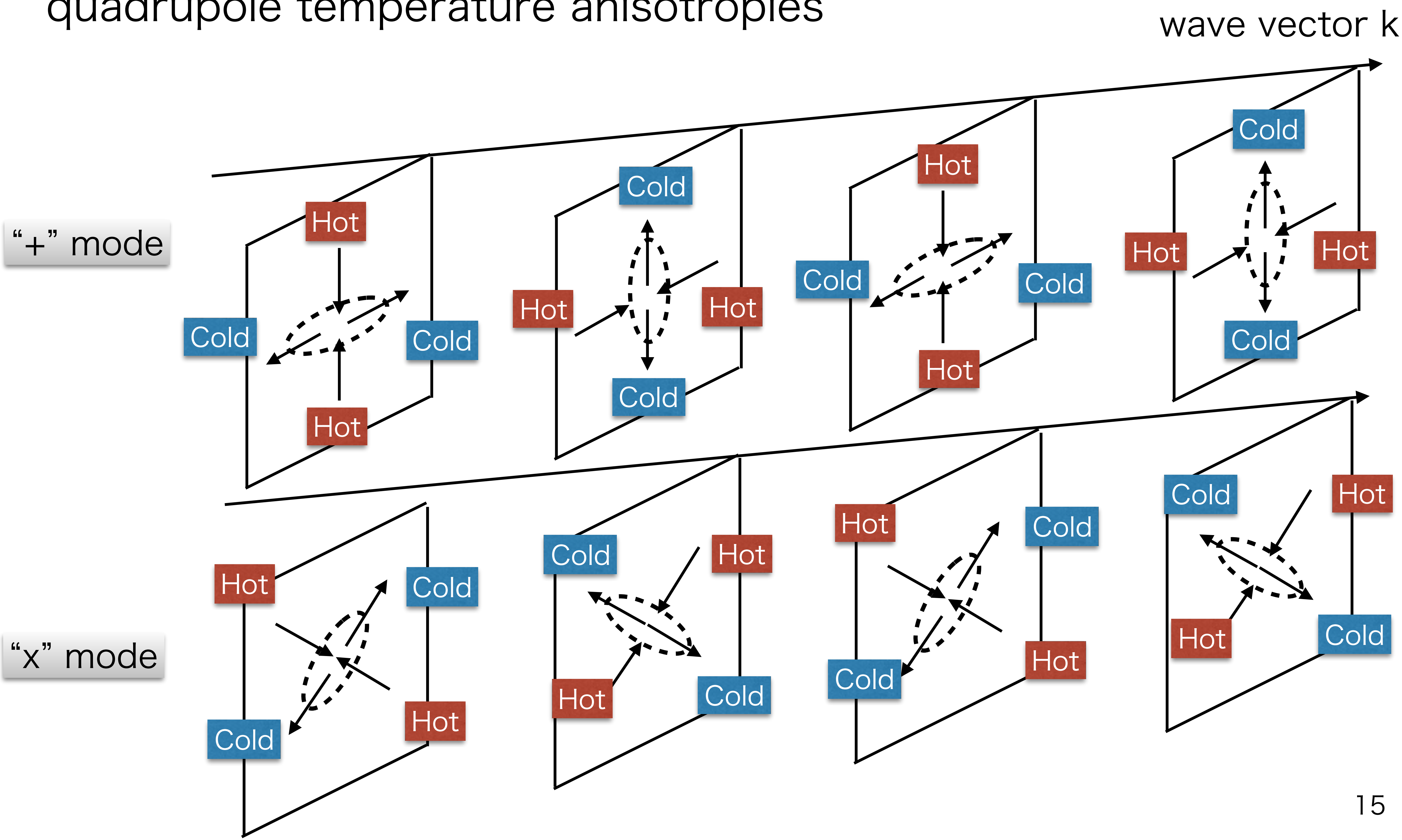
- Accelerating expansion (~e^{60}) in 10^{-35} seconds
- Two types of perturbations were generated during inflation from quantum fluctuations
  - Scalar (density) perturbations
  - Tensor perturbations = Gravitational wave

Gravitational wave (tensor perturbations)



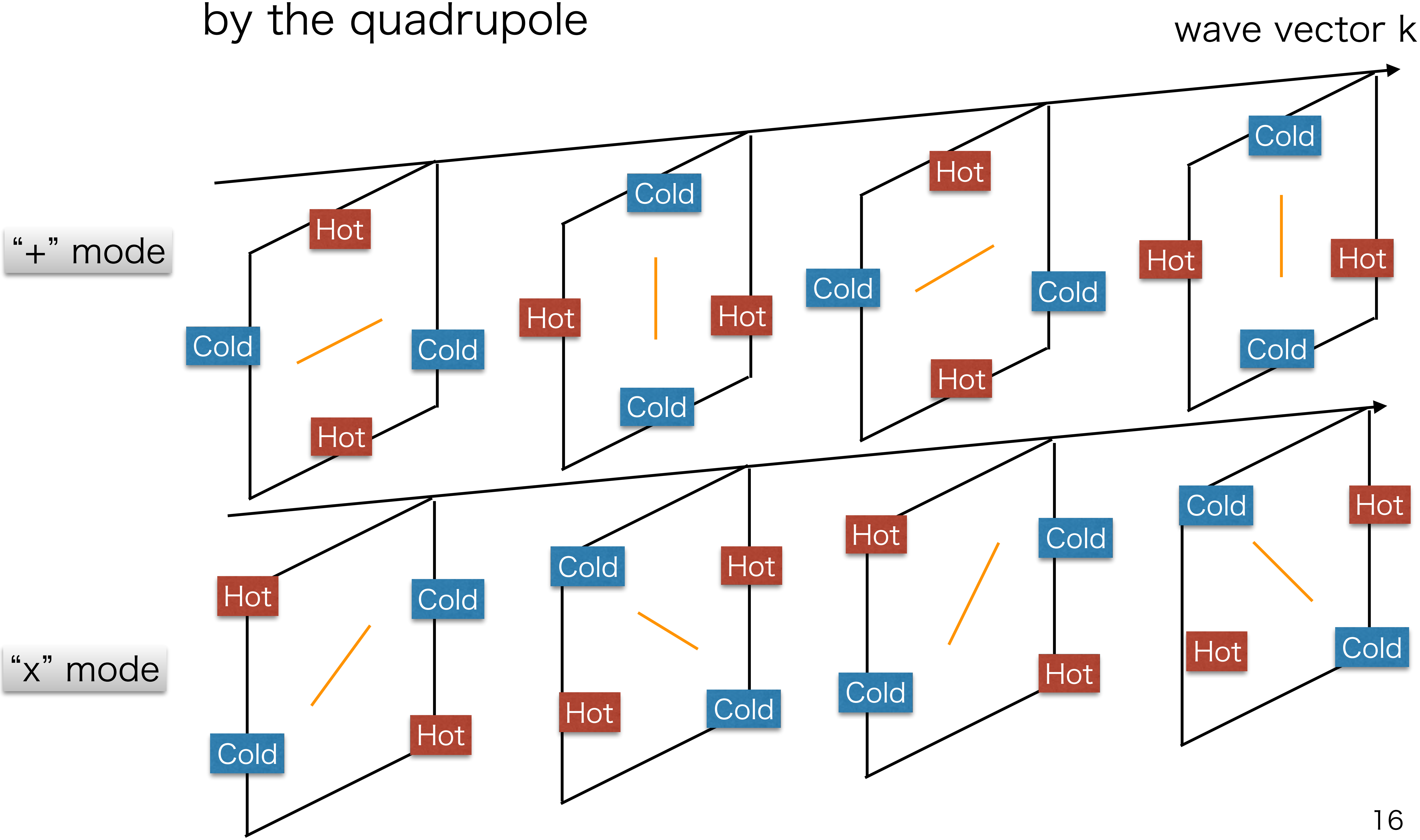
Local quadrupole from gravitational wave

Gravitational wave produces local quadrupole temperature anisotropies



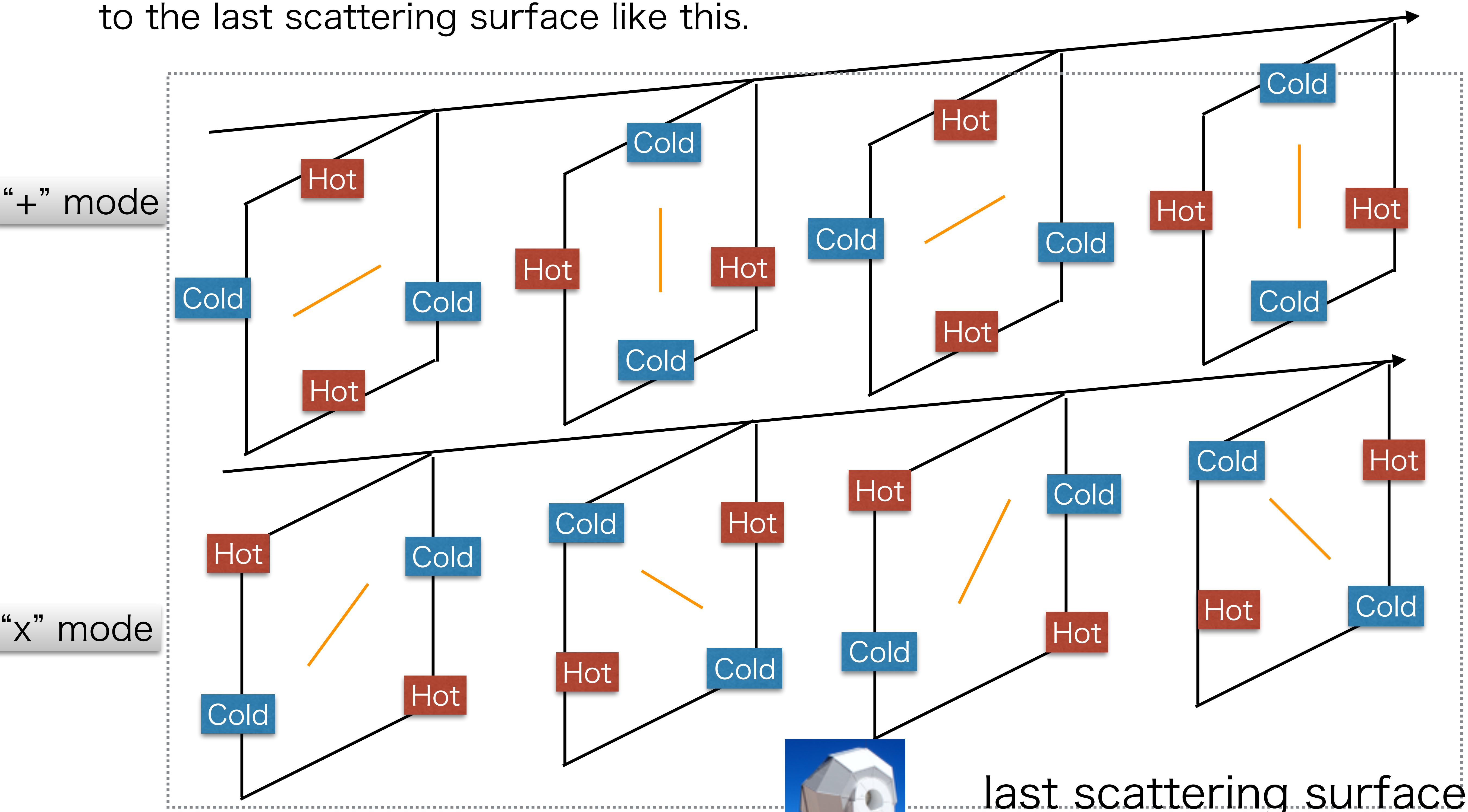
Polarization pattern by gravitational wave

Polarization pattern generated by the quadrupole



Polarization pattern by gravitational wave

Let's consider the polarization projection on to the last scattering surface like this.

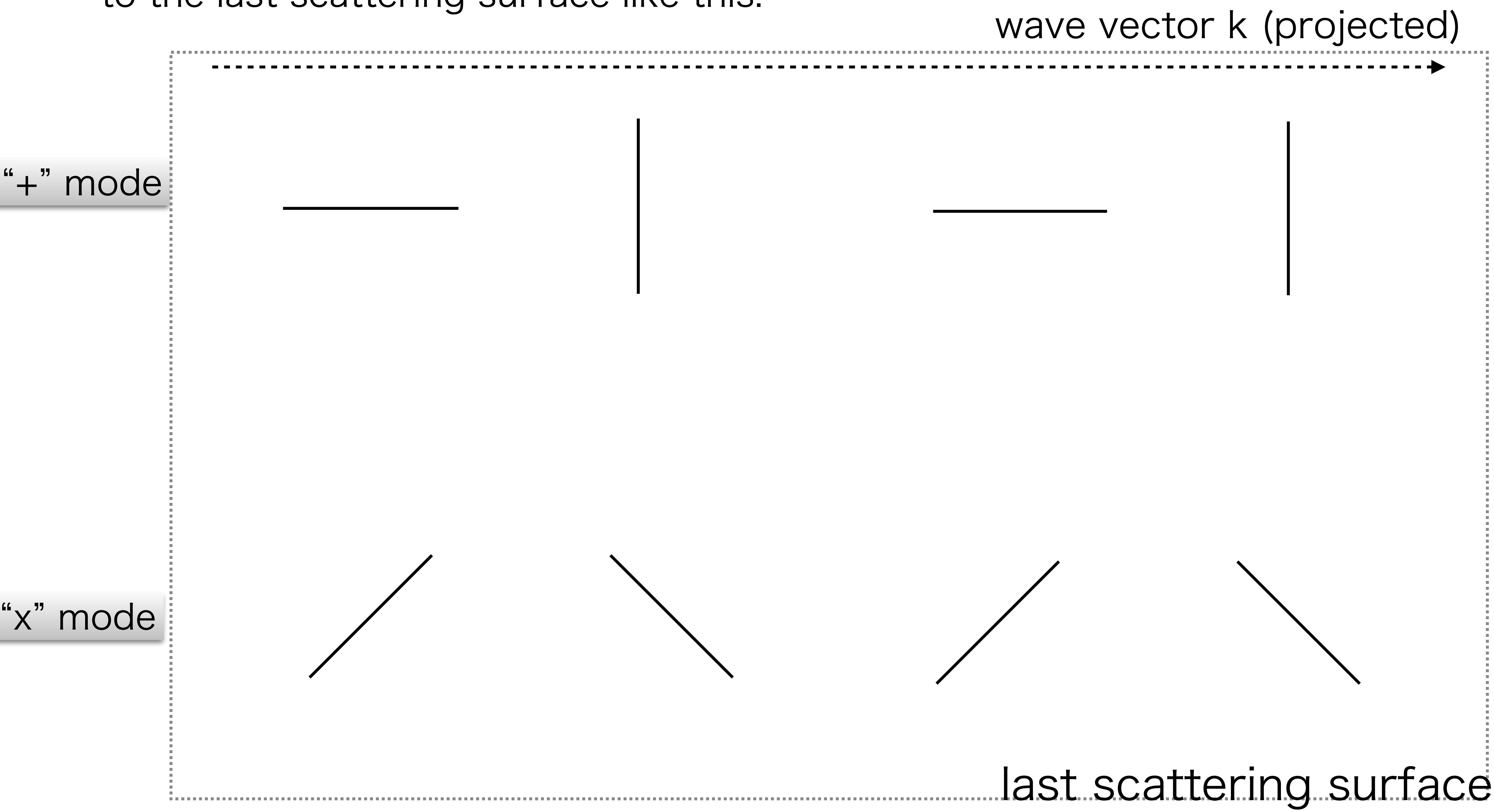


line of sight
= normal to the display

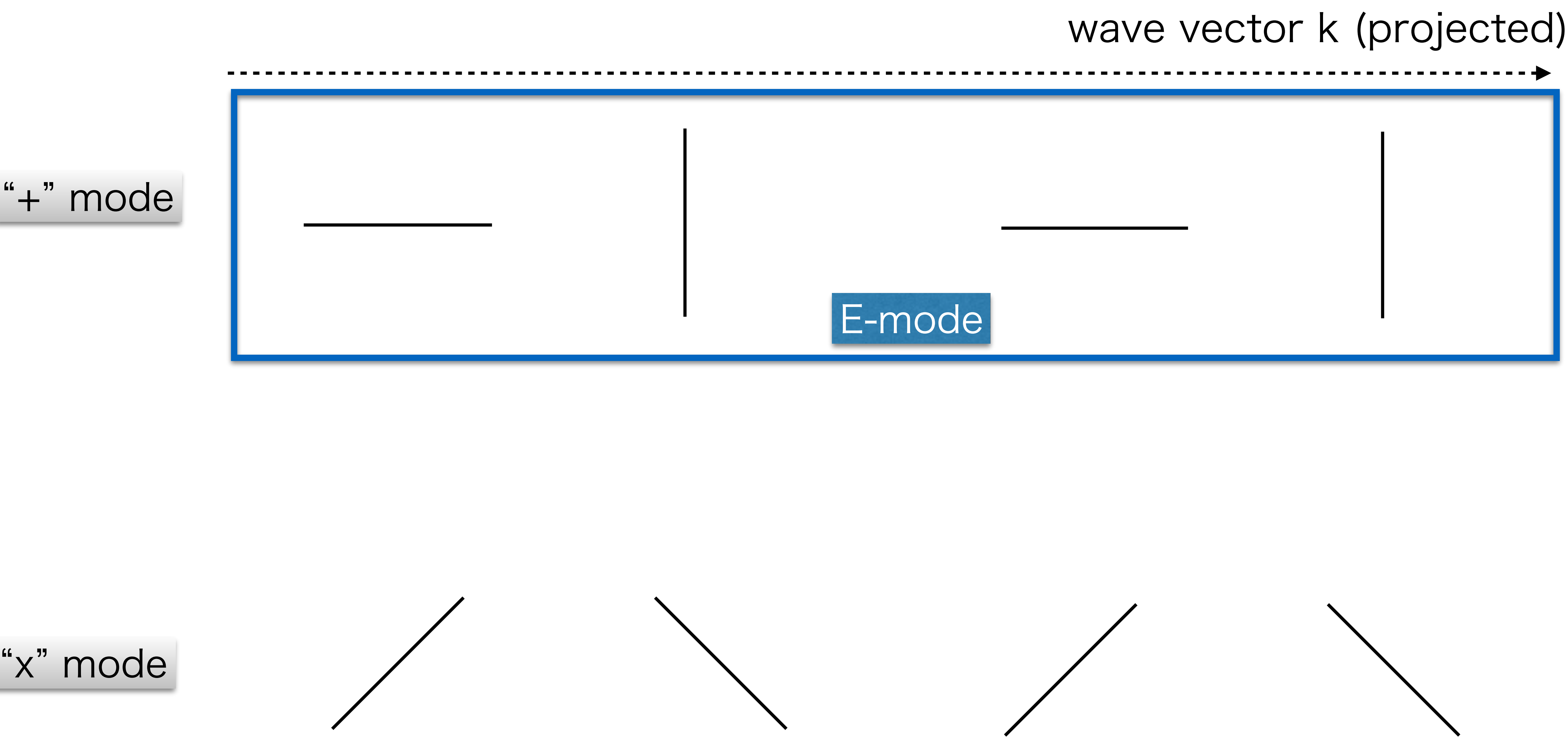
observer

Polarization pattern by gravitational wave

Let's consider the polarization projection on
to the last scattering surface like this.



E-mode from gravitational wave



B-mode from gravitational wave

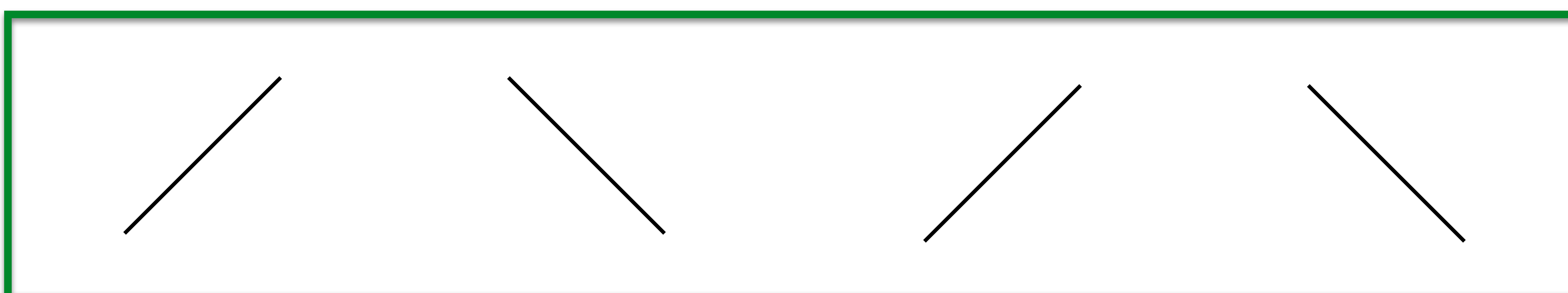
wave vector k (projected)

Polarization orientations can be changed by the sign flip of k.

B-mode: Polarization orientation is 45 or 135 rotated to the wave vector, k.

B-mode

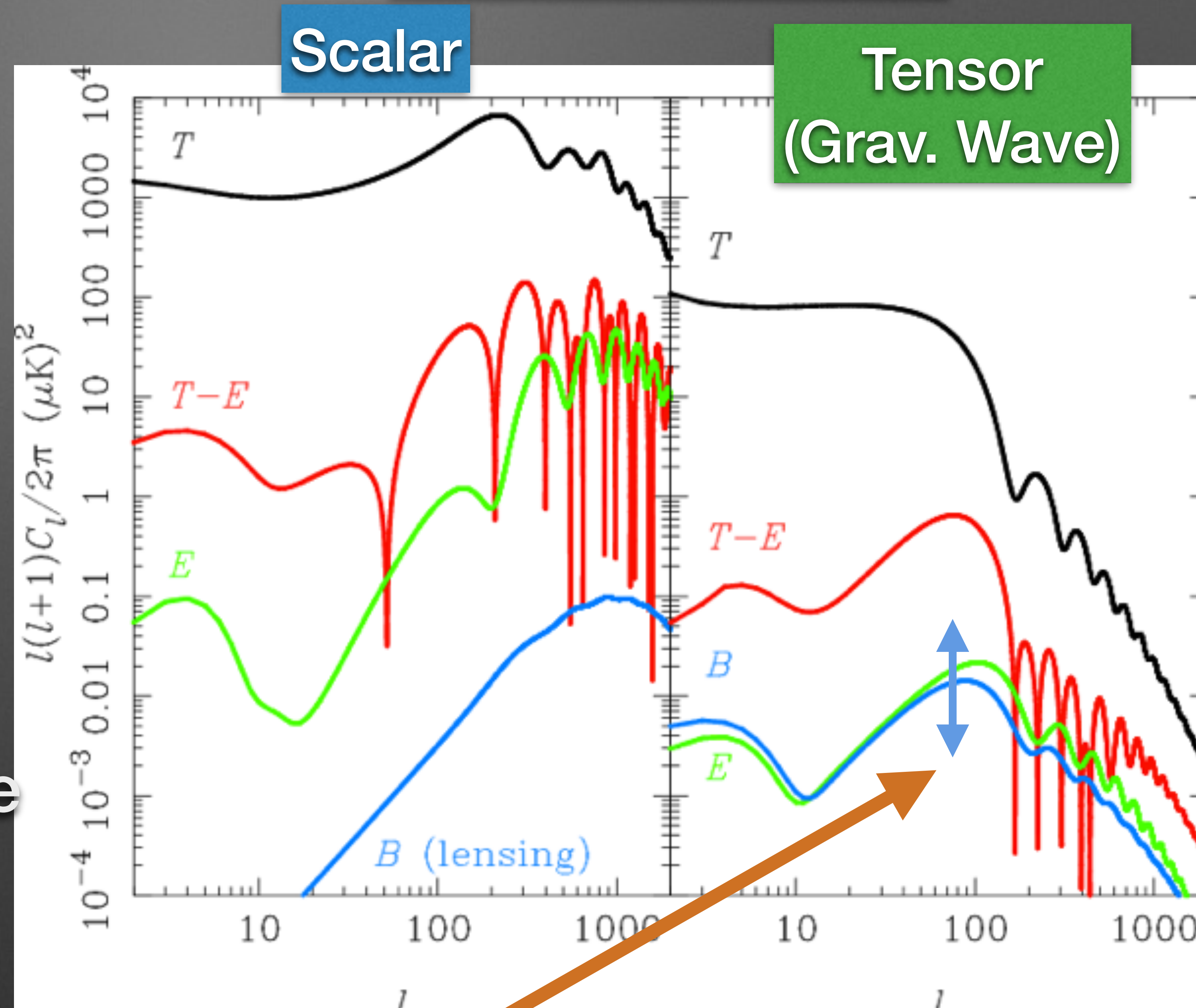
“x” mode



Scalar/Tensor Perturbations

- Scalar perturbations:
  - Produces CMB Temperature fluctuation (and E-mode polarization)
- Tensor perturbations: Gravitational Wave
  - Tiny effect in T or E
  - But produces B-mode polarization too
  - Unique prediction from inflation!

CMB power spectra



arXiv:1210.6008

scaled by “r” (tensor-to-scalar ratio)

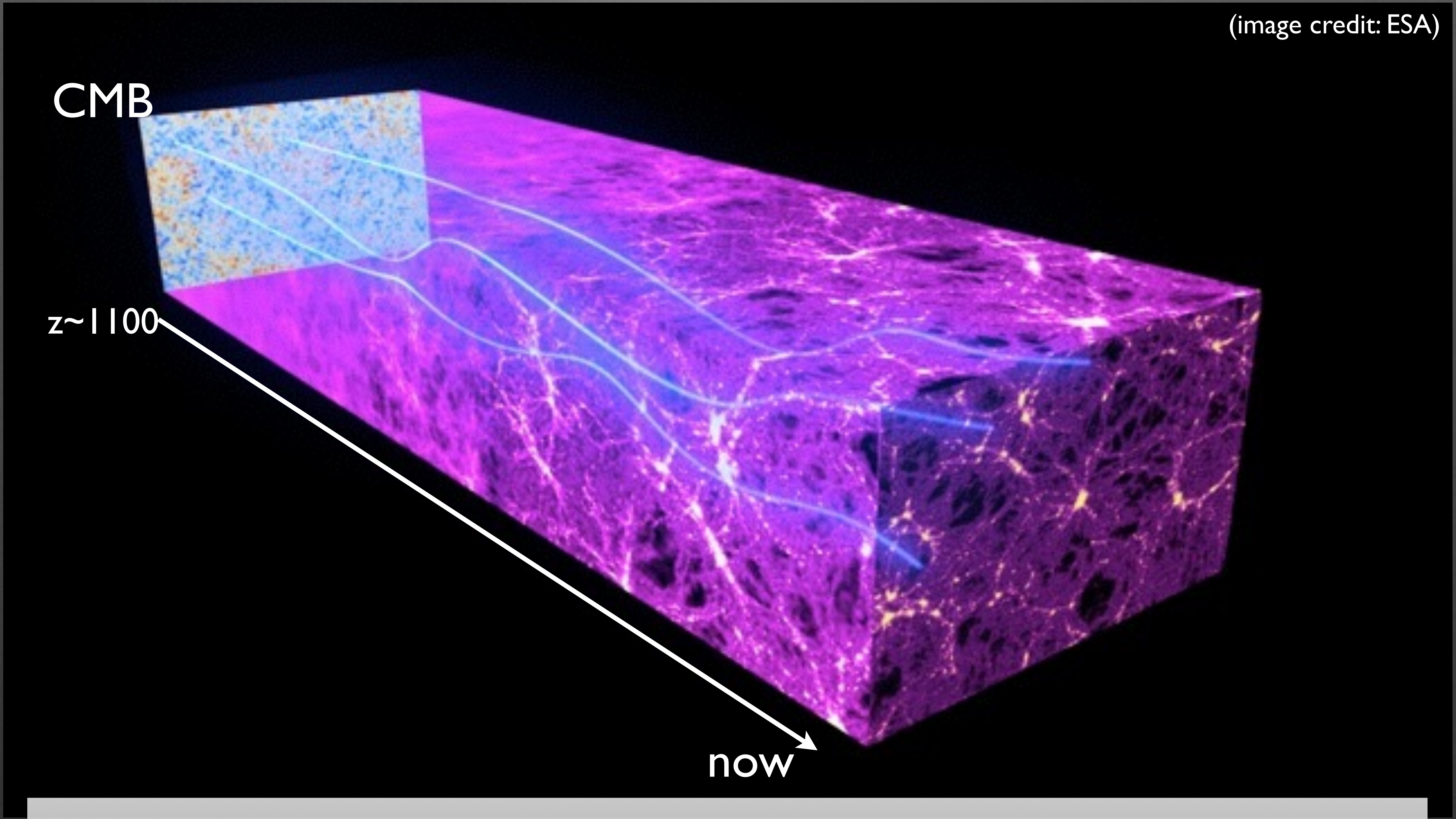
Quantitative Study of Inflation w/ B-mode

- Energy scale of inflation directly relates to the ratio of tensor and scalar perturbations
  - Tensor-to-scalar ratio:

$$r \equiv \frac{A_t}{A_s} \quad P_s = A_s\left(\frac{k}{k_0}\right)^{n_s-1} \quad P_t = A_t\left(\frac{k}{k_0}\right)^{n_t}$$

    - Proportional to B-mode power spectrum
  - Inflation potential: $V^{1/4} \sim (r/0.01)^{1/4} \times 10^{16}$ GeV
- Detecting B-mode in large angular scales proves inflation and enables quantitative study of models of inflation.
  - Also a probe of physics of ultra high energy scale (~GUT scale)
  - r=0.2 → energy scale of inflation: 2×10^{16} GeV

Another B-mode source: Gravitational Weak Lensing



Observed CMB has been deflected by gravitational potentials of Large Scale Structure from z~1100 up to now.

CMB Polarization and Weak Lensing

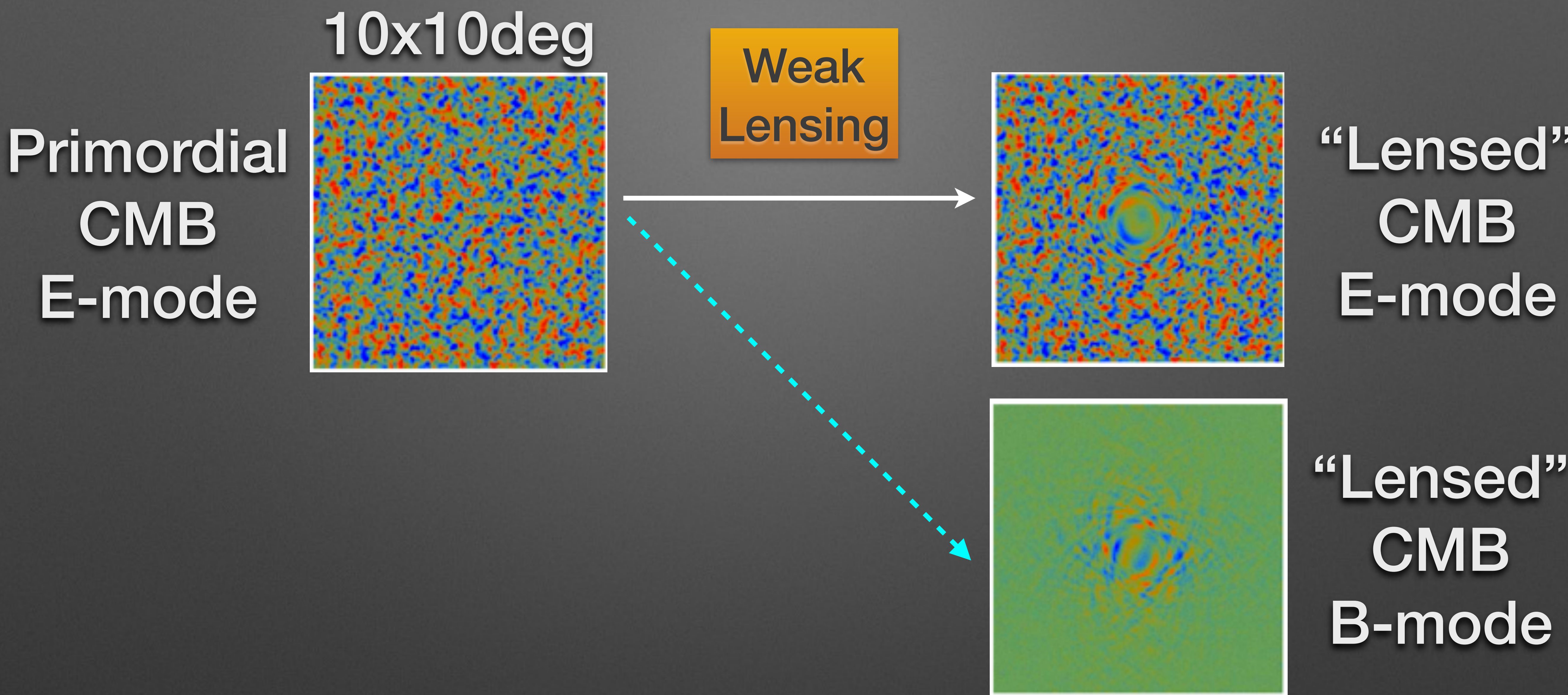


Fig. from astro-ph/0111606

- Gravitational lensing mixes E-mode and B-mode.
- Primary B-mode source in small angular scale (sub-degree).

CMB Polarization and Weak Lensing

Observed CMB polarization

$$(Q+iU)(\hat{\mathbf{n}}) = (\tilde{Q}+i\tilde{U})(\hat{\mathbf{n}}+\mathbf{d}(\hat{\mathbf{n}}))$$

~: primordial CMB

deflection angle (weak lensing effect)

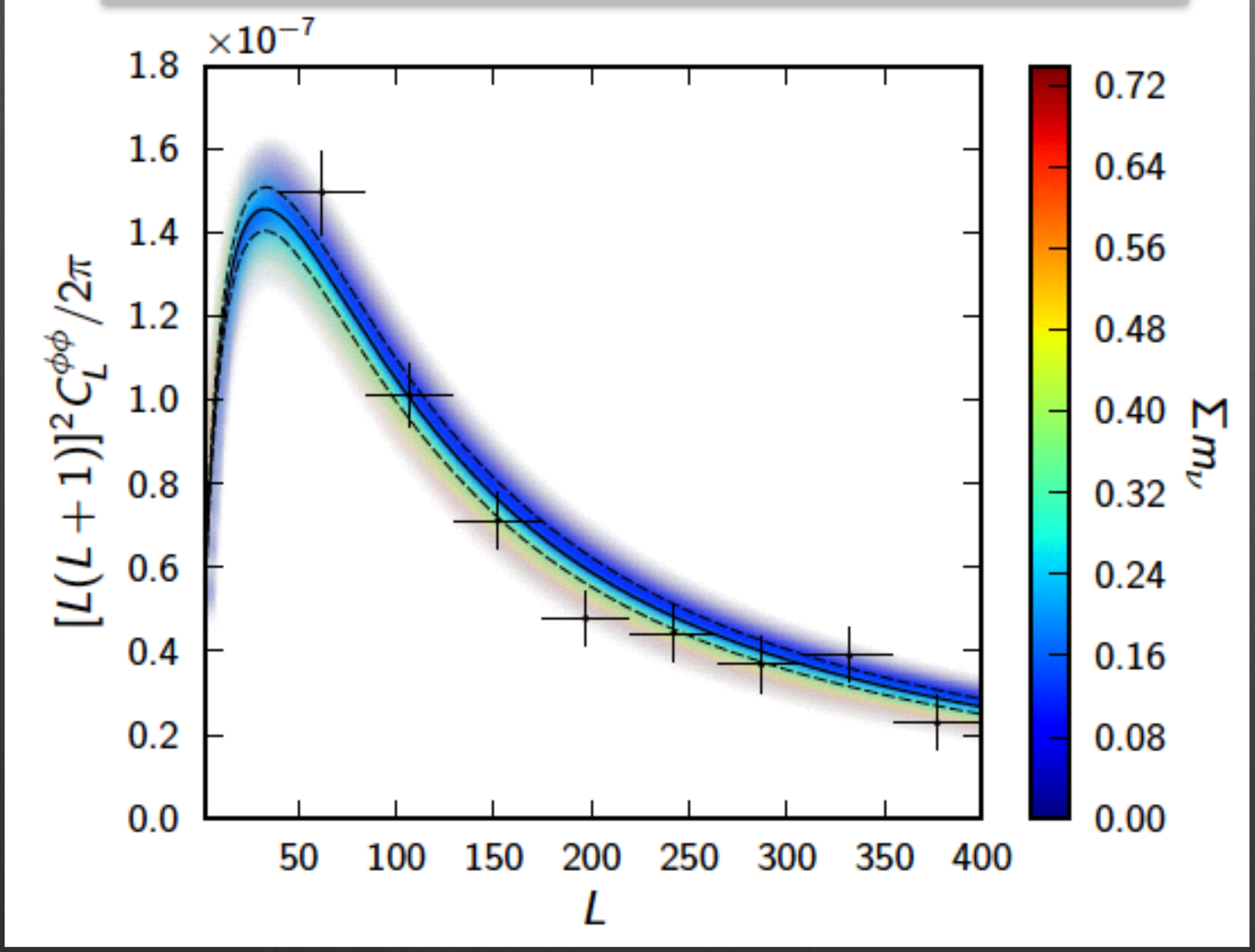
- Typical deflection angle: a few arcmin
- Coherent over ~2 deg. scale

Requires degree-scale observation with a telescope of arc minute resolution

Weak Lensing and Neutrino Mass

- Massive neutrinos suppress the evolution of large scale structures.

Lensing potential power spectrum



arXiv:1303.5077

Higher neutrino mass

↓

Less large-scale structure

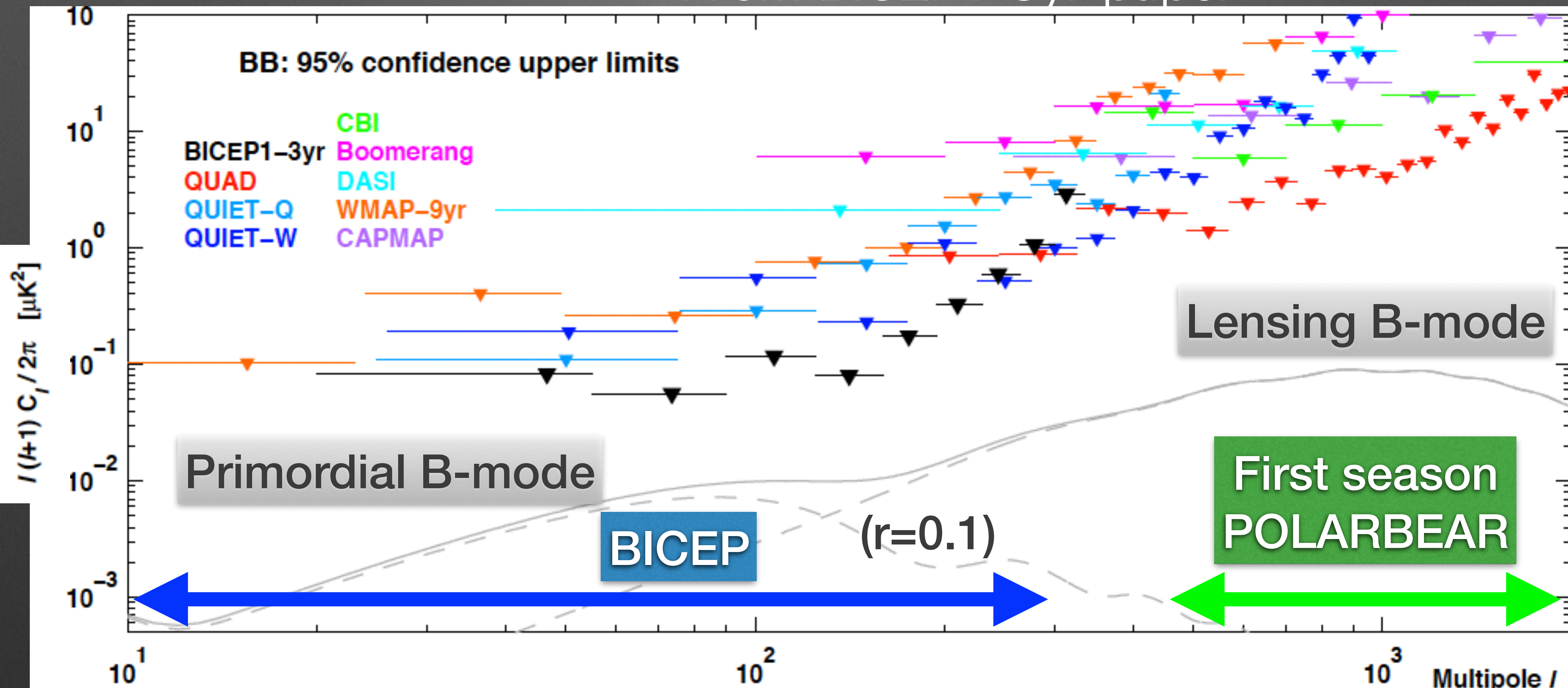
↓

Smaller lensing effect

Planck 2013 (lensing)
w/ WMAP pol.+SPT+ACT
$\Sigma(m_\nu) < 0.85$ eV (95%CL)

Upper limits of B-mode power spectrum before March 2014

From BICEP1-3yr paper arXiv:1310.1422



Large angular scale ⟷ Small angular scale

- SPTpol claimed the "detection of B-mode" by the cross-correlation with galaxy, but BB auto-correlation spectrum from SPTpol is not published yet.

CMB polarization experiments

CMB polarization experiments

- Satellite: PLANCK
- Balloon-borne: EBEX, SPIDER
- South Pole
  - BICEP and Keck Array
  - SPTpol
- Atacama Desert, Chile
  - POLARBEAR
  - ACTpol
  - Atacama B-mode Search (ABS)

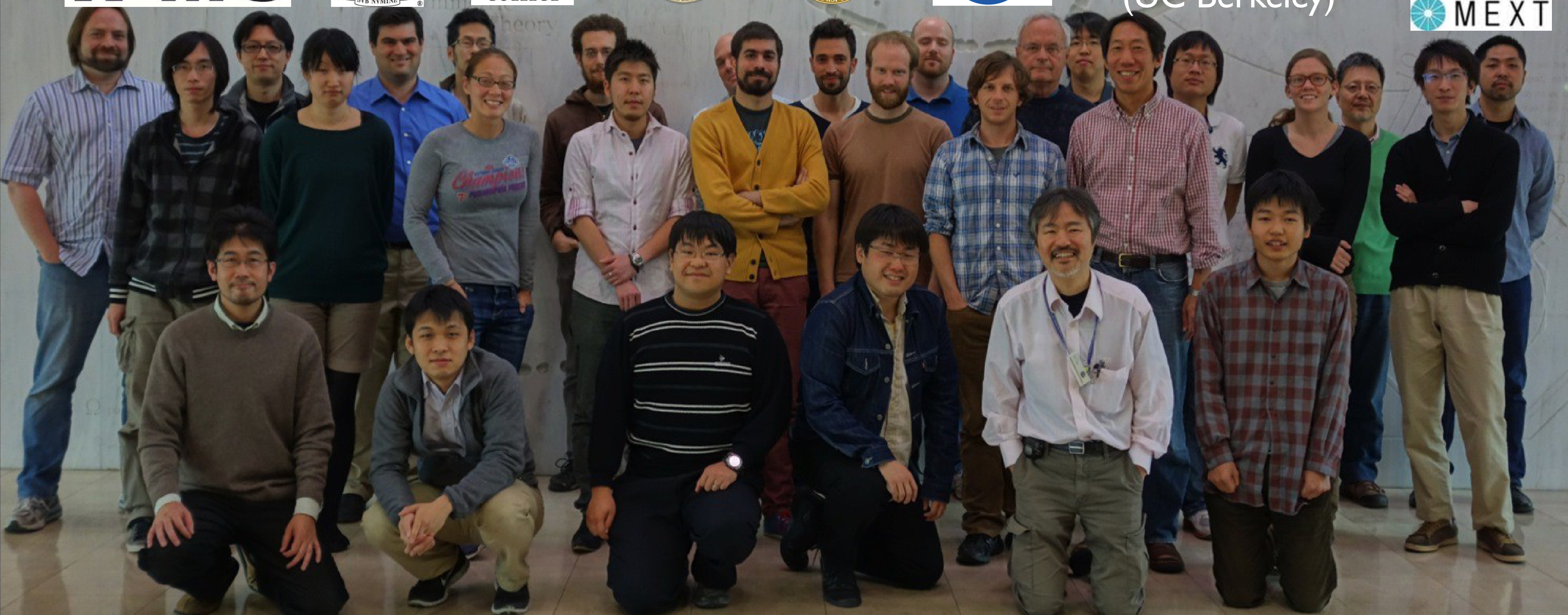
Need thin and dry atmosphere

POLARBEAR

- Ground-based CMB polarization experiment in the Atacama desert
  - 5,200m altitude
  - Thin and dry atmosphere
- Started observation since early 2012

POLARBEAR Collaboration

PI: Adrian T. Lee
(UC Berkeley)



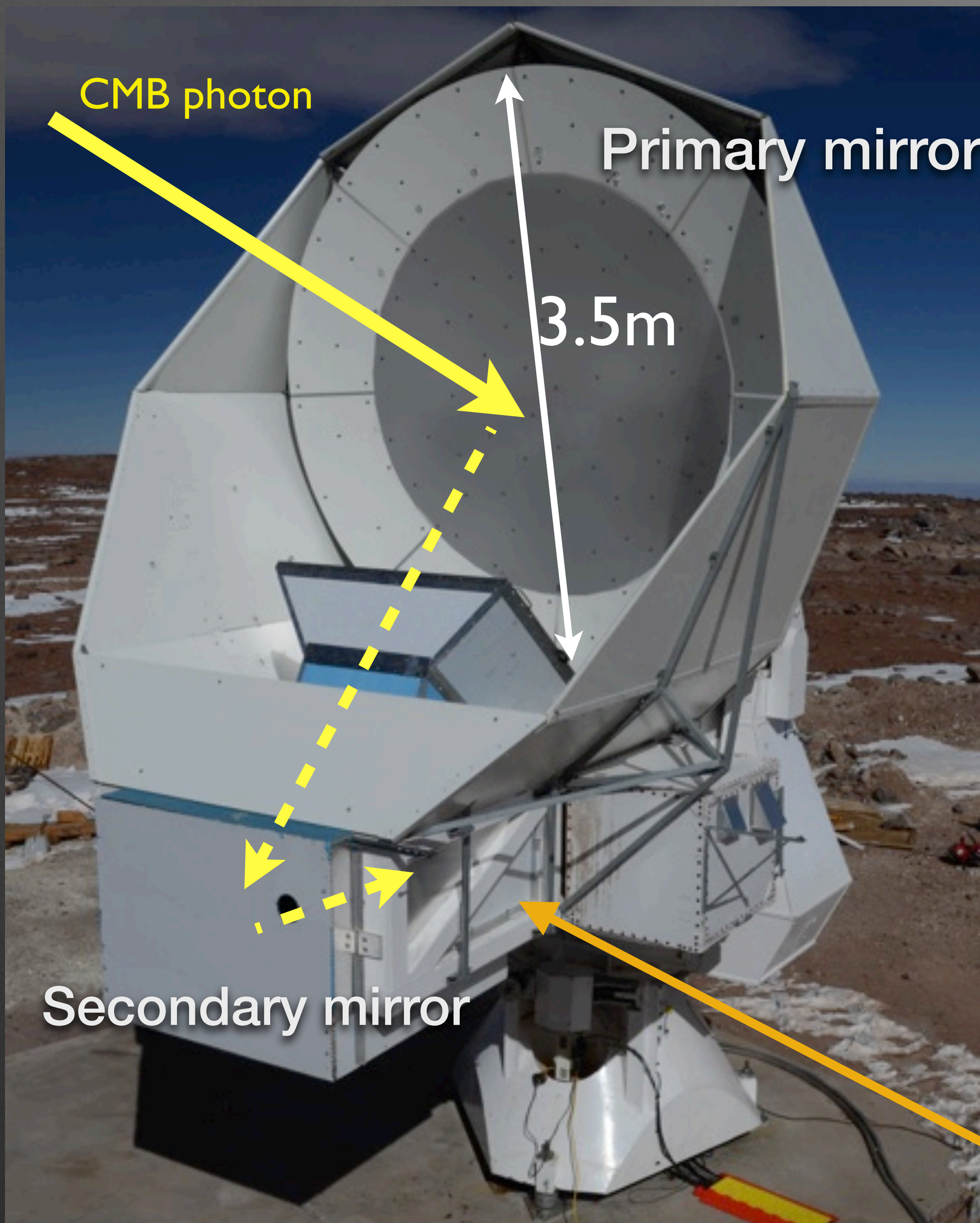
International collaboration from 5countries, ~70 researchers

POLARBEAR site

POLARBEAR site

Atacama desert

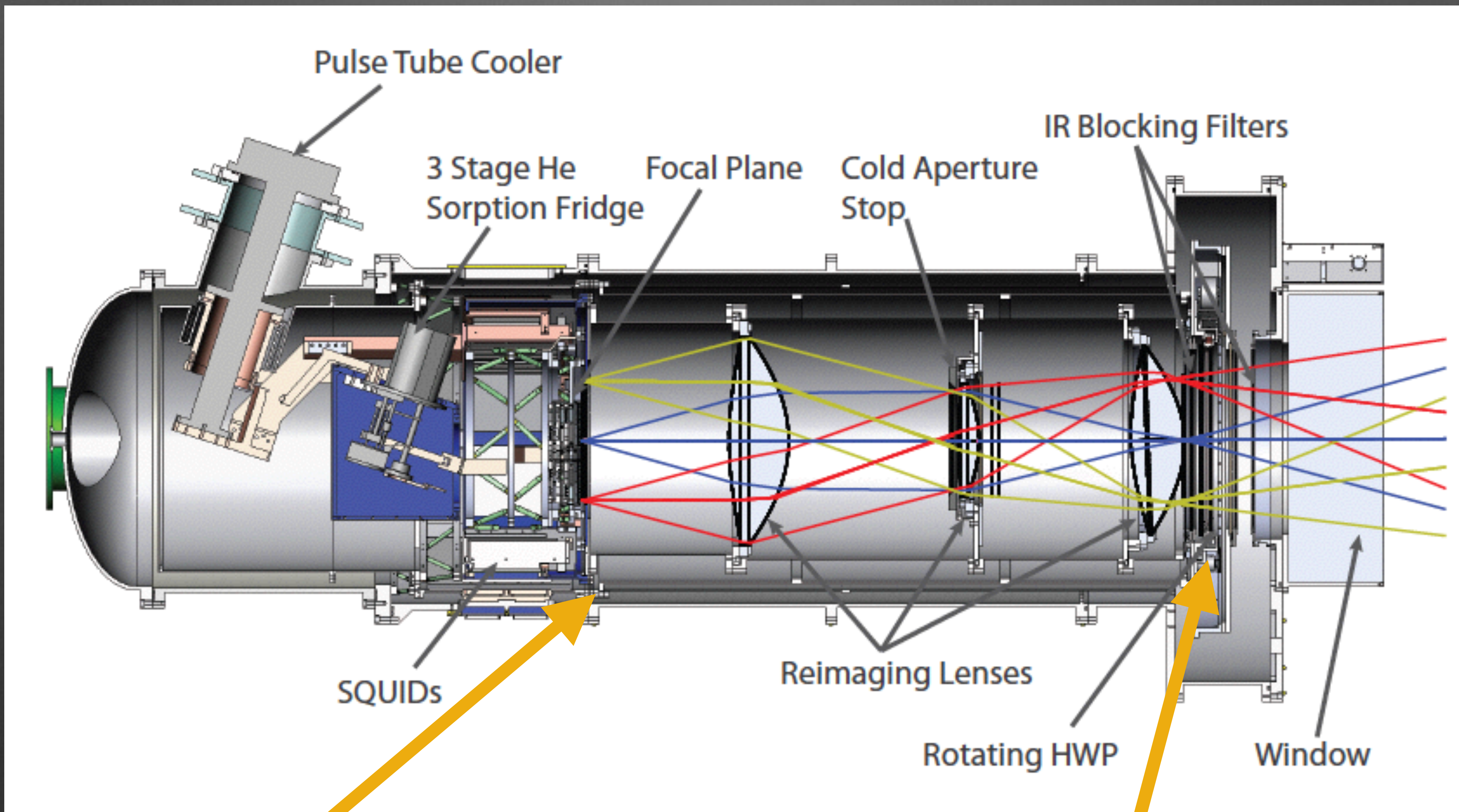
Huan Tran Telescope



- Off-axis Gregoriane Dragone
- 3.5m Primary mirror
    - 3.5 arcmin (FWHM) resolution
    - designed to measure both primordial and lensing B-modes

Receiver cryostat

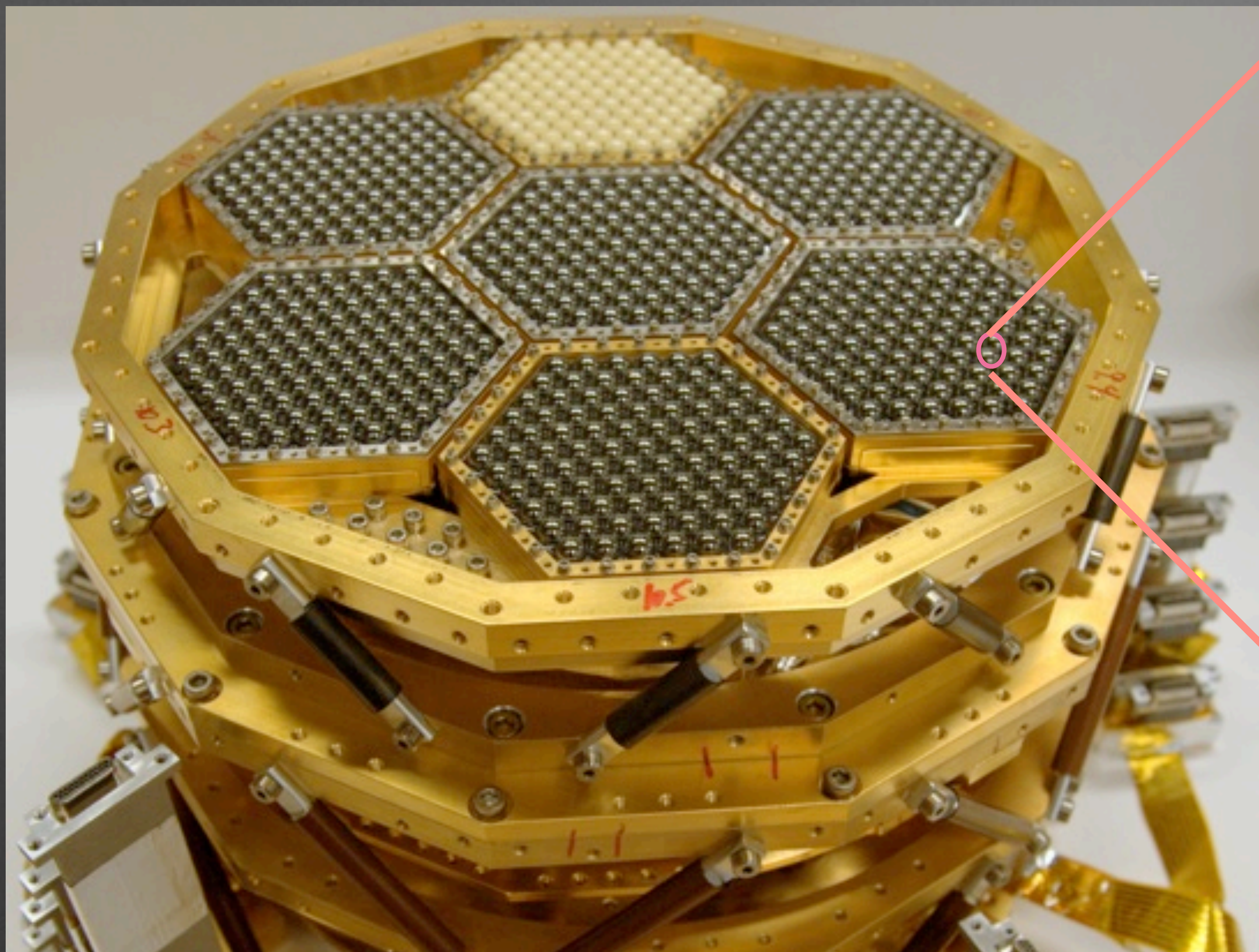
POLARBEAR Receiver

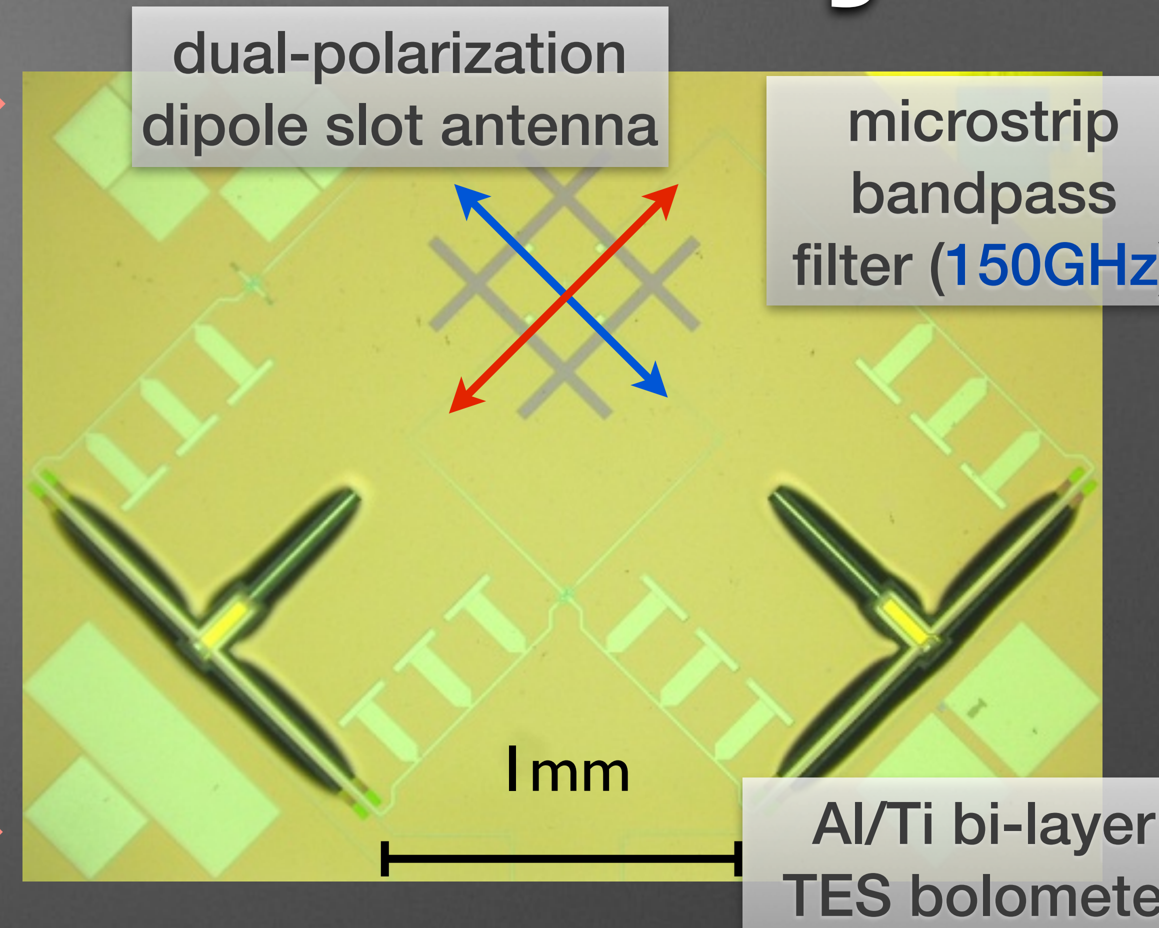


Focal Plane (cooled to 0.25K)

HWP (polarization modulation)

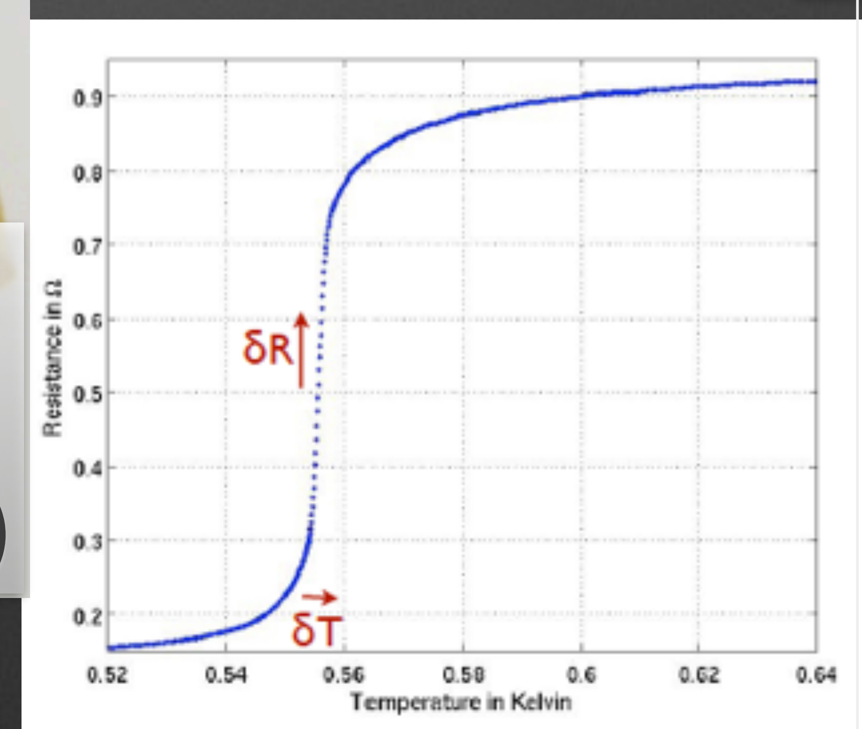
Focal Plane Detector Array





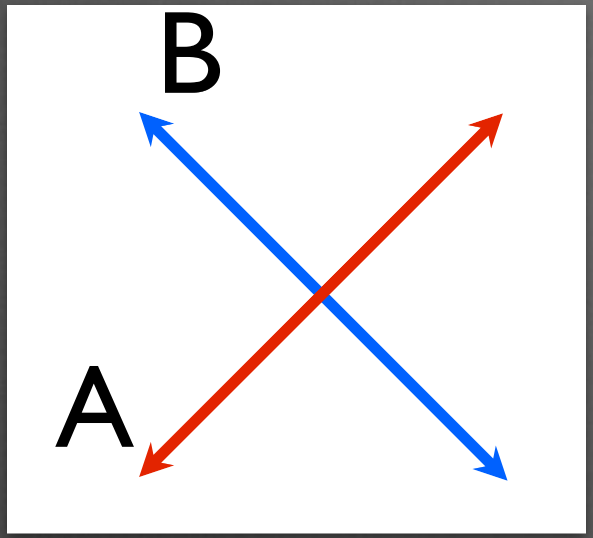
- 2 bolometers in a pixel
- 637 pixels in a array
- 1274 bolometers (~80% yield)

Noise level: 550 $uKs^{1/2}$ /bolo
23 $uKs^{1/2}$ /array



photon
↓
Temp ↑
↓
R ↑
↓
current ↓
(V-biased)

Polarization measurement by pair-differencing

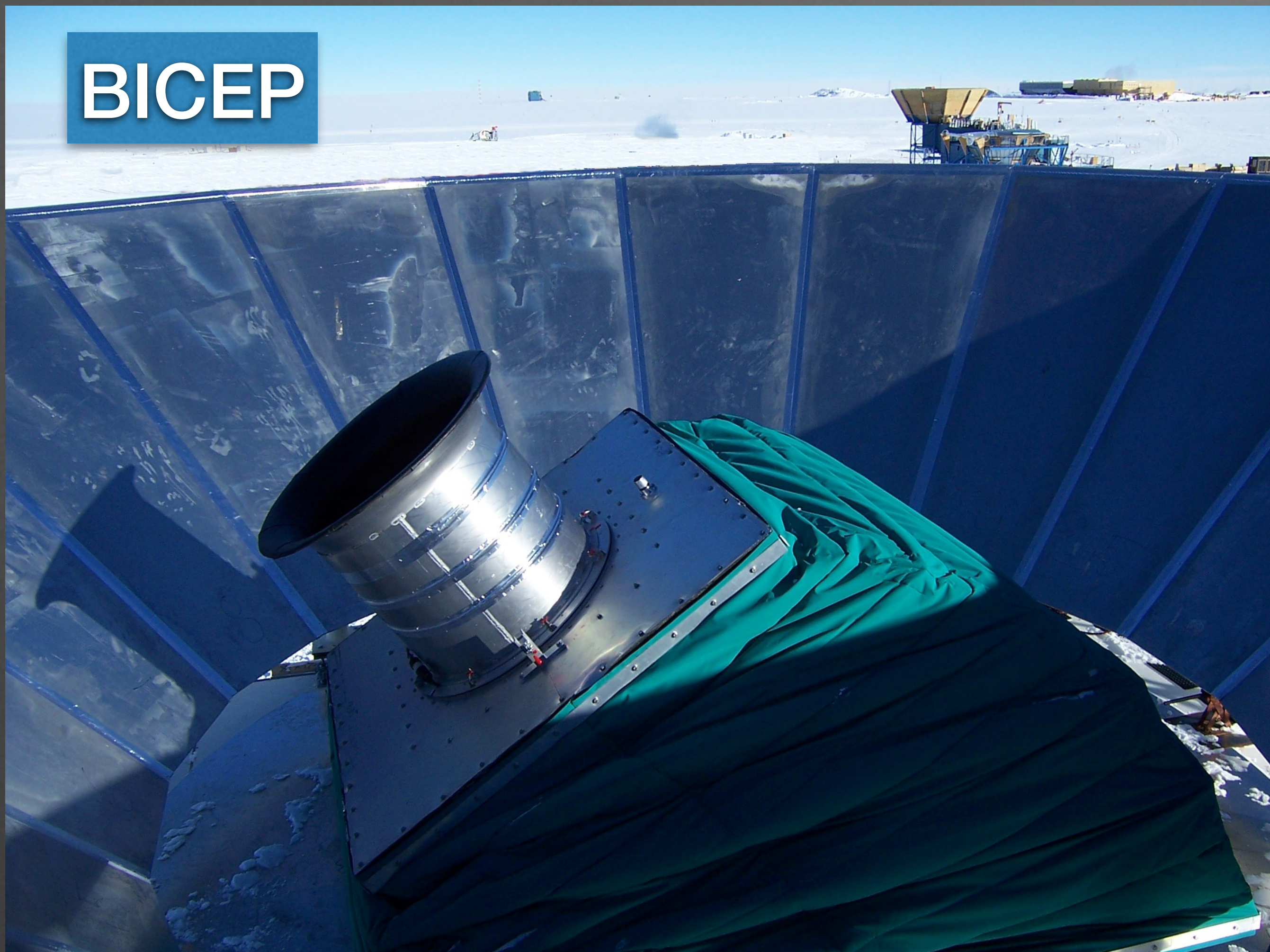


Pair bolometers in a single pixel are sensitive to linear polarizations, which are perpendicular to each other.

Pixel differencing gives us a polarization information of incident light.
It is also effective for common mode noise rejection.

Good beam (and gain) matching between pair detectors is crucial because the mismatch can potentially cause leakage from T->P.

BICEP/Keck Array



- CMB polarization experiments at South Pole
  - Target large angular scales, i.e. the primordial gravitational wave B-modes

Spec. Summary of BICEP/Keck

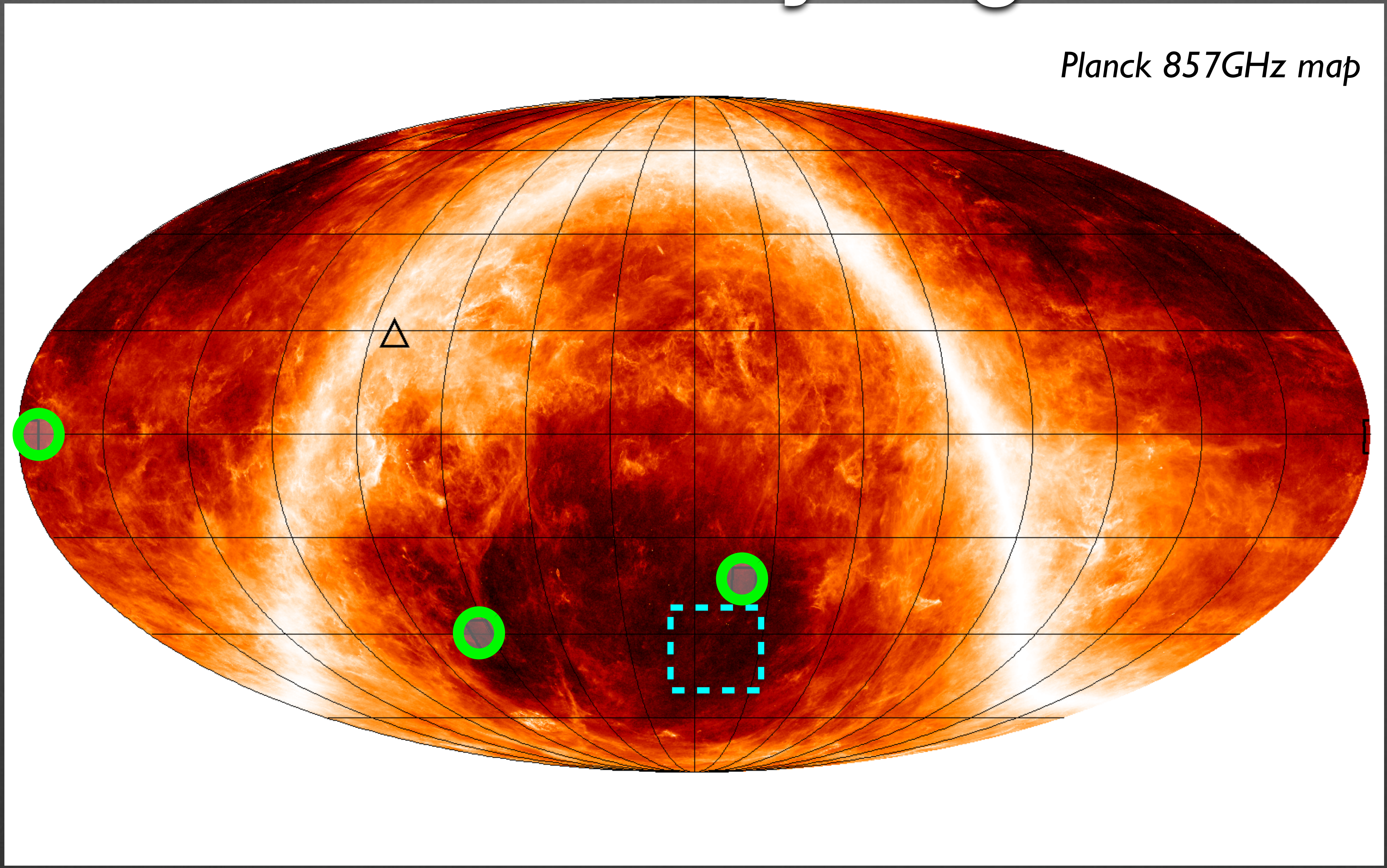
	BICEP1	BICEP2	Keck Array ≒	BICEP3
Operation Time	2006-2008	2010-2012	2011-	2014
Frequency	100/150 GHz	150 GHz	150GHz (100GHz)	100GHz
Detectors	98 NTD Ge	512 TES bolometers	2560 TES bolometers	2560 TES bolometers
Noise level (uK s	54 (/array)	16 (/array)	~10 (/array)	
Beam (Resolution)	0.93°/0.60° FWHM	0.52° FWHM	0.52° FWHM	0.37° FWHM

comparable to SPTpol, POLARBEAR, etc

optimized for large angular scale

BICEP/Keck also empolys similar detector technique (TES bolometers + pair-differencing).

Observed Sky Region



- Choose low astrophysical "foreground" regions
- POLARBEAR: 3 small sky regions (3°x3°): ~30 deg^2
- BICEP: ~380 deg^2, fsky~2%

Telescope scan

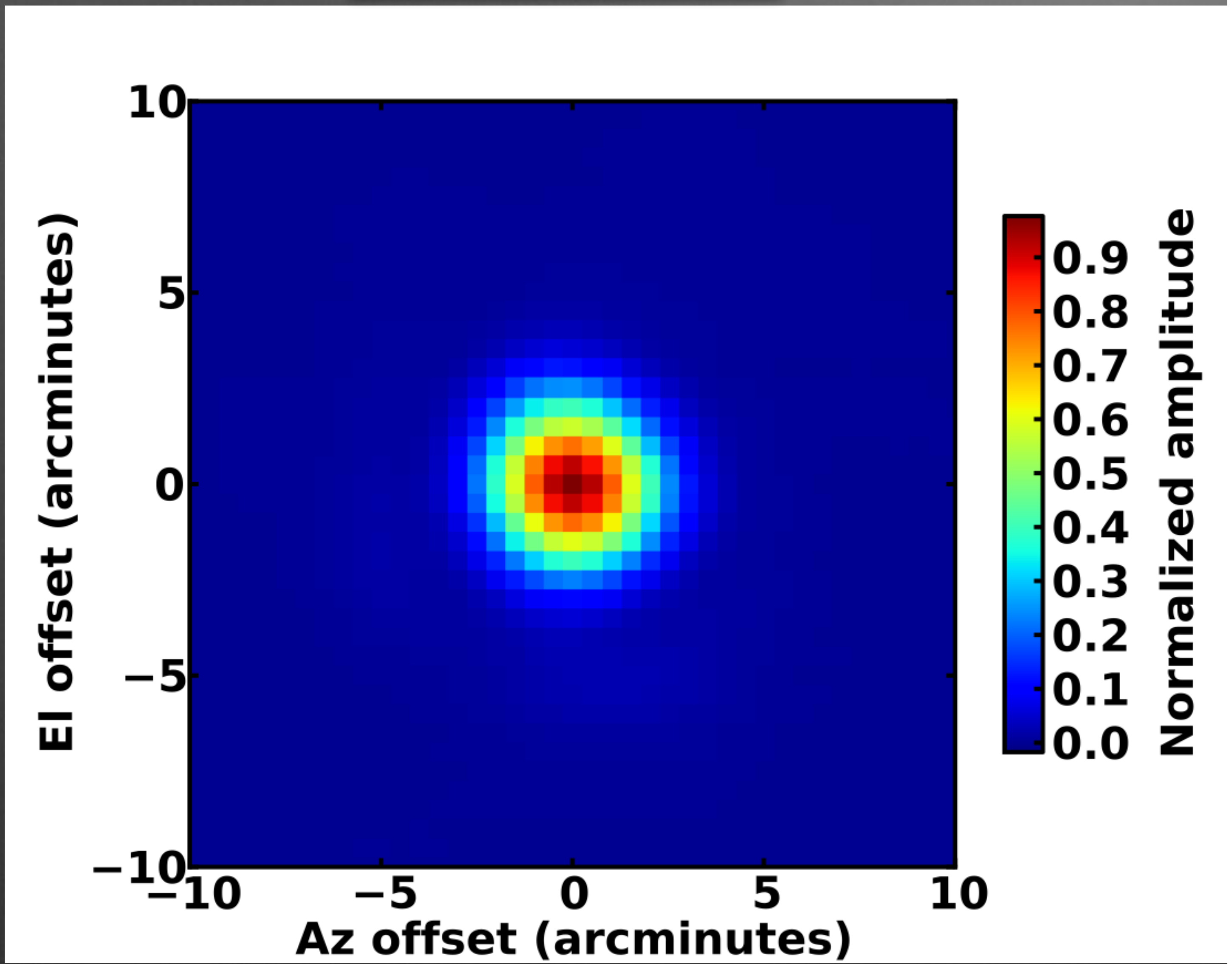
- Always scanning in azimuth (horizontally) at each constant elevation
  - To see the modes before detector gain drifting.

CMB Data Analysis

- Calibration: Gain, Pointing, Beam, Polarization angle…
- Data Selection: Bad weather, Badly tuned detectors…
- Map-making: I, Q, U maps of each field (for each day)
- Power spectrum: Cross-spectrum with each-day-maps
- Null Tests (Jackknife): data validation, systematics check
- Systematic Error: Estimate leakage from T, E → B

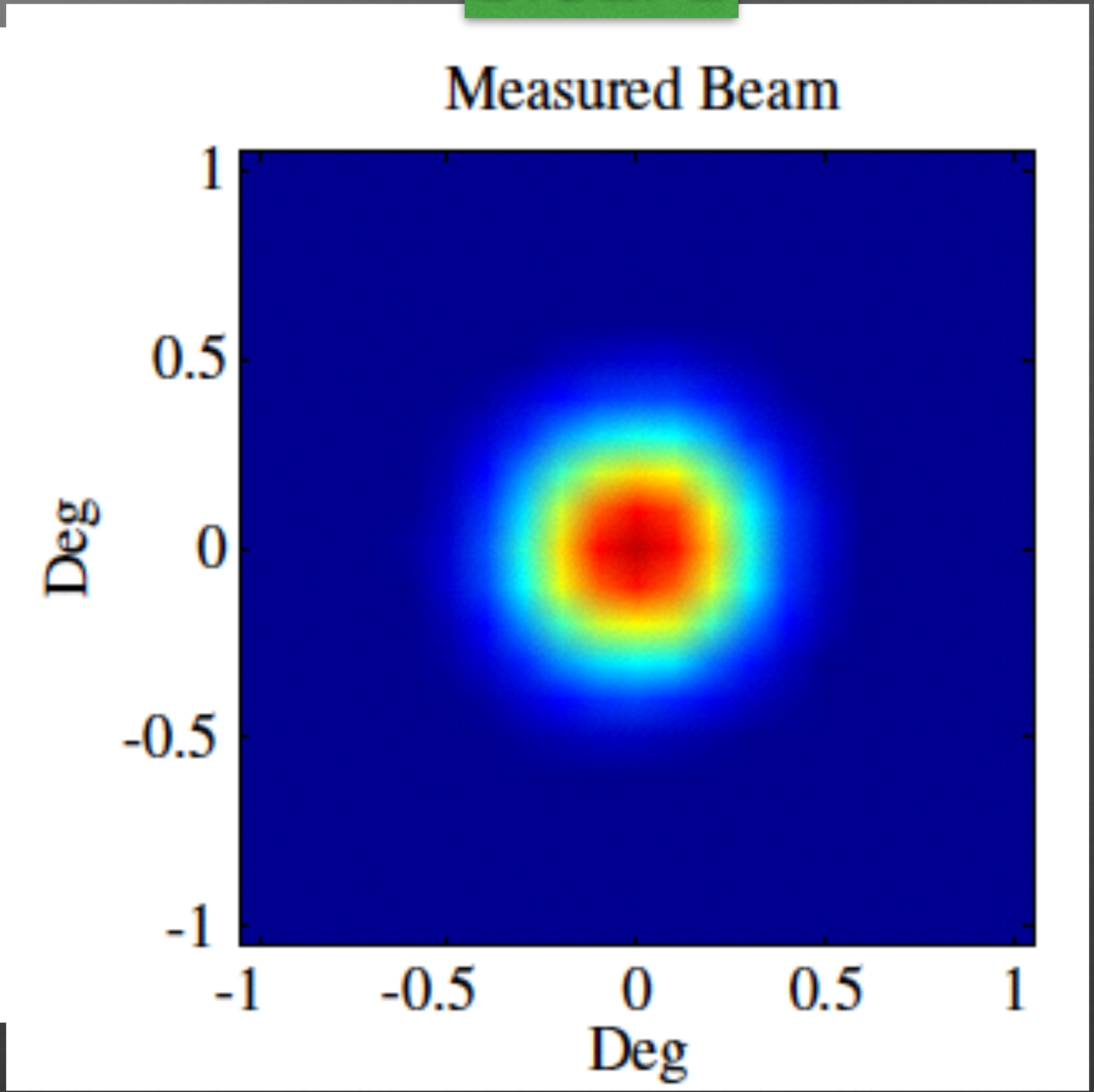
Beam Measurement

POLARBEAR



(coadded map of Saturn)

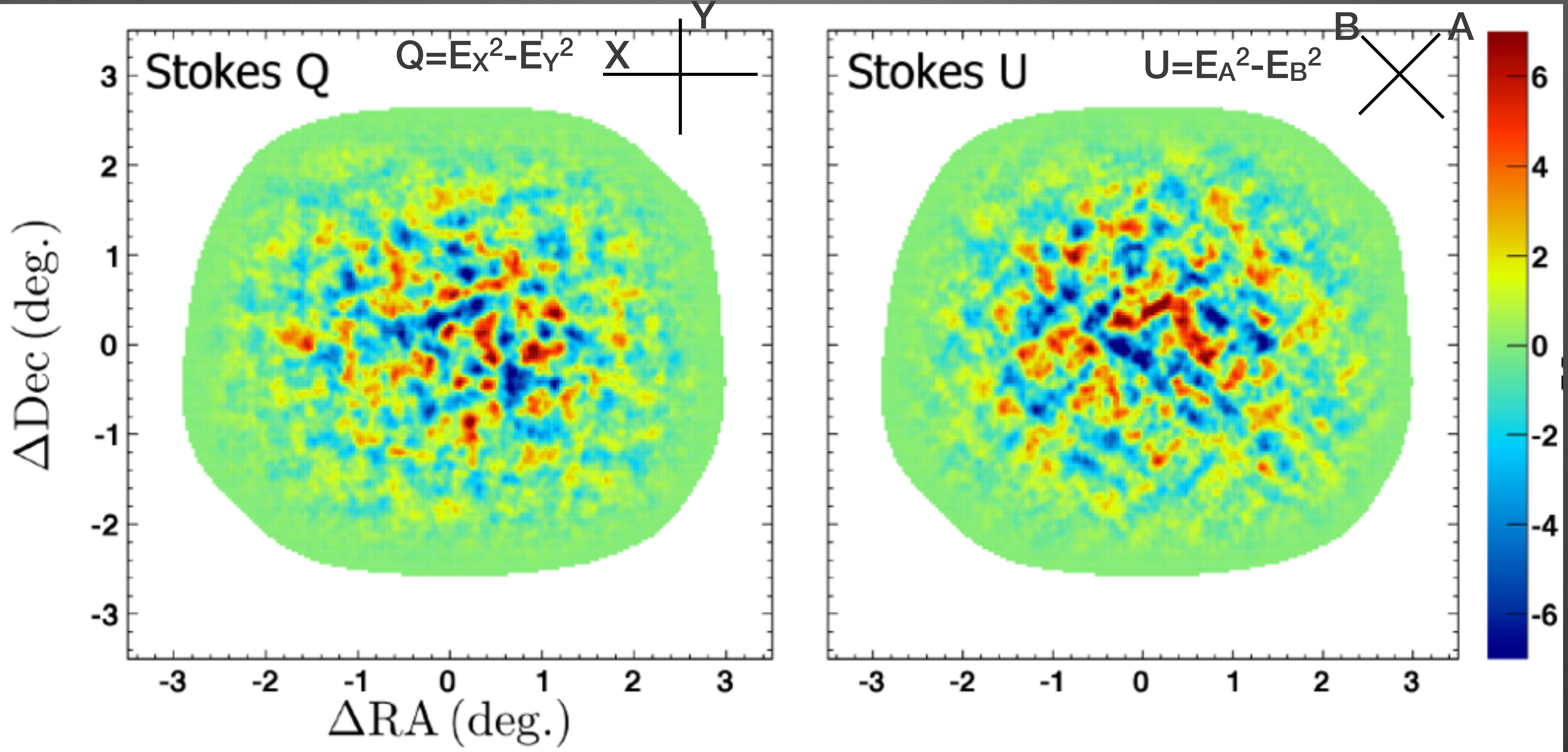
BICEP2



Circular beam with 3.5’ FWHM

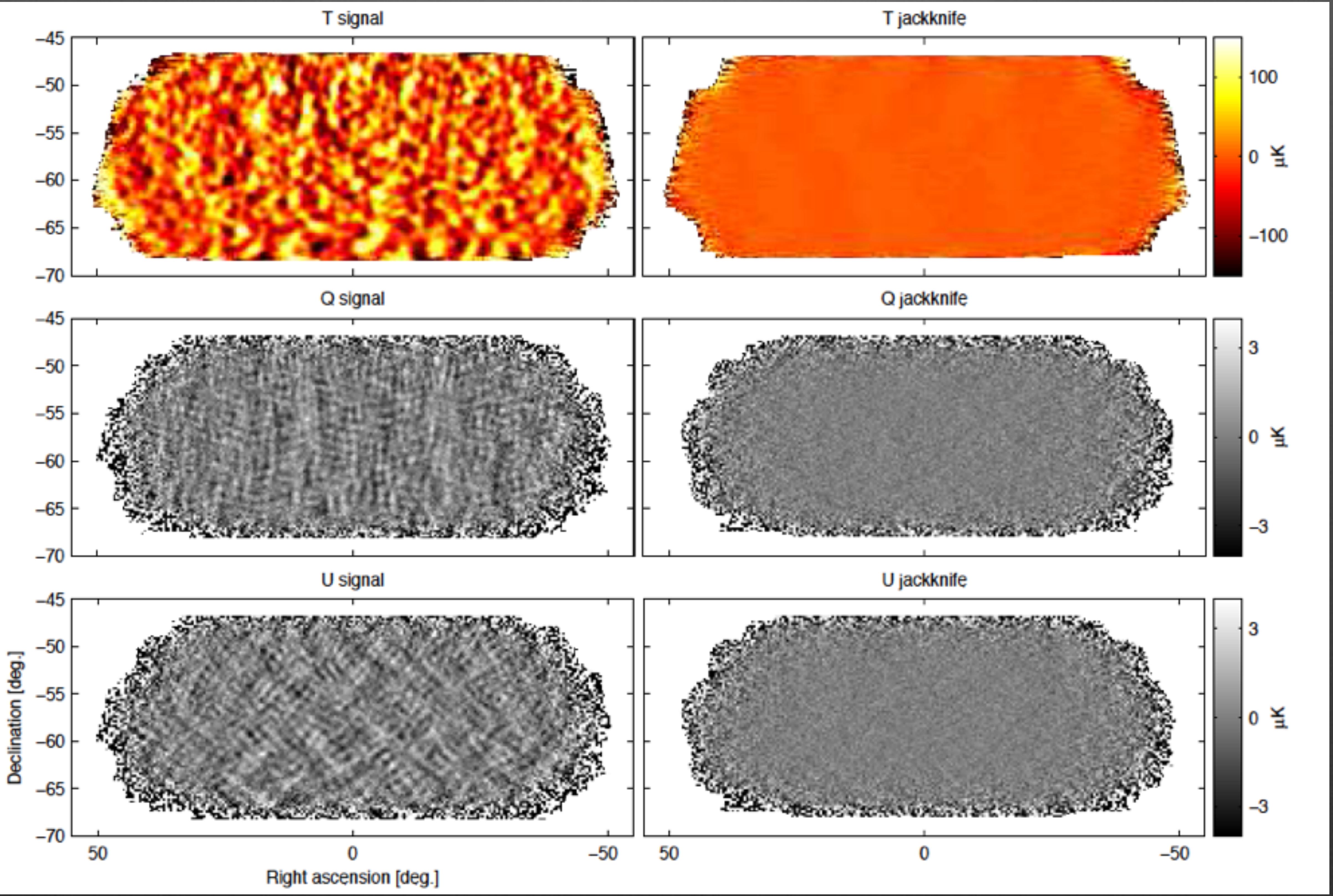
0.52° FWHM

CMB Polarization Maps (POLARBEAR)



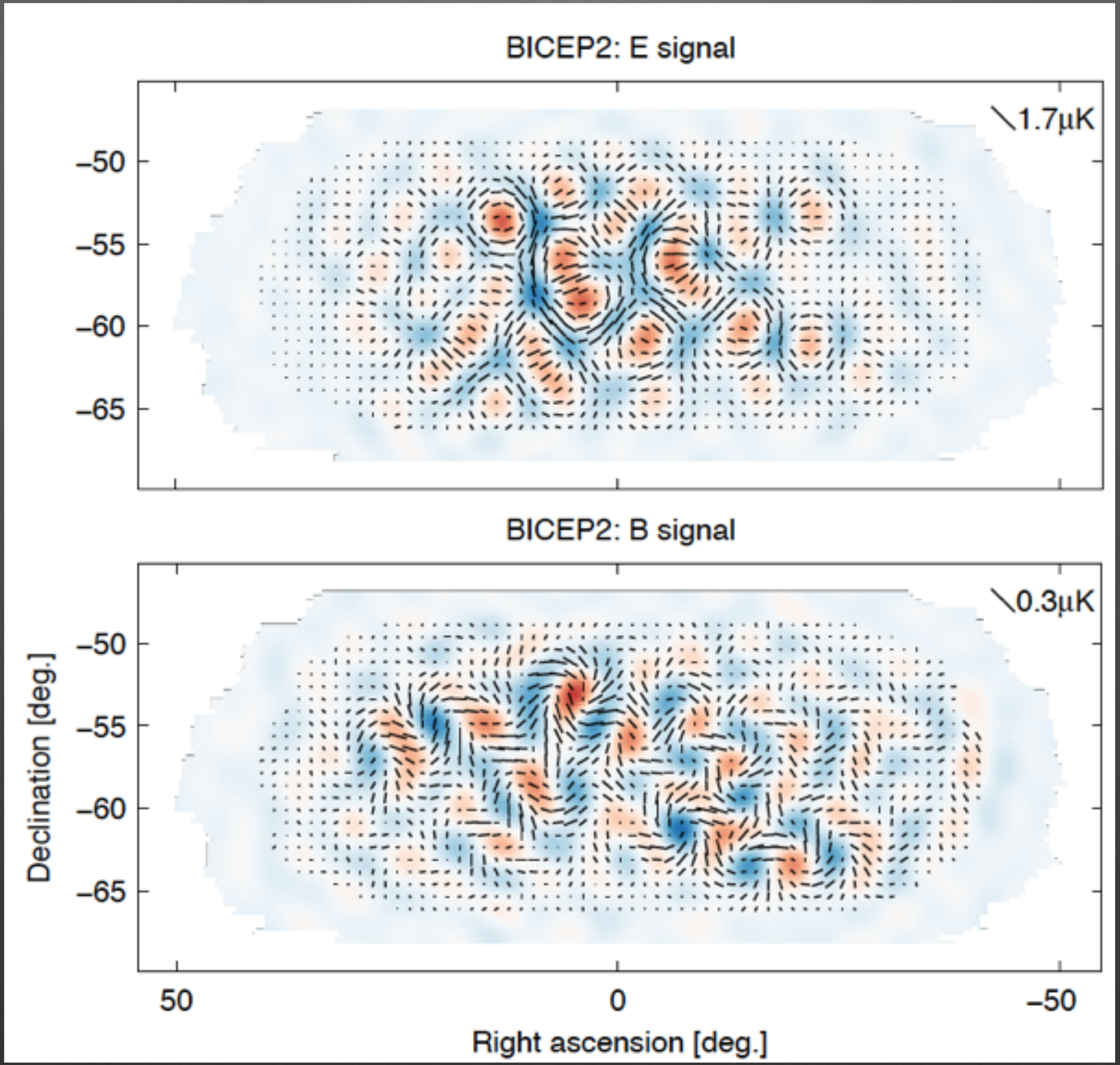
- (Filtered) map noise level: 5 uK-arcmin
- ~10 times deeper than Planck
  - Deepest map in this scale ~ BICEP2

BICEP2 CMB Maps



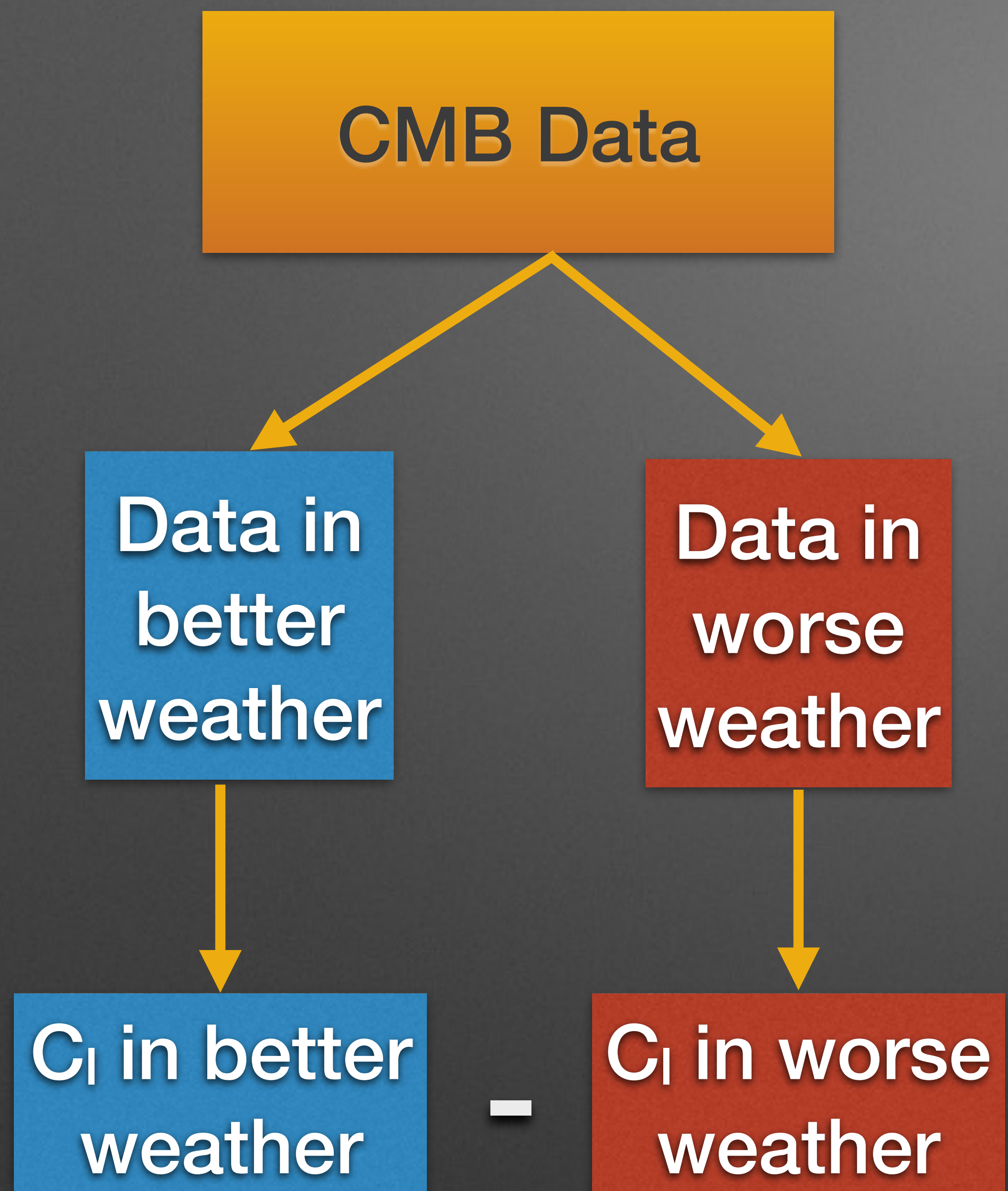
RMS noise level of 87 nK in 1° x 1° pixel

BICEP2 E-mode & B-mode maps



Impressive demonstration of E and B modes.
We can see B-modes in map space.

Null Tests (Jackknife)



= Null?

Split the data into two with some criteria to illuminate some possible systematic effect

Subtract spectra with each other and Check if the residual spectrum is null or not.

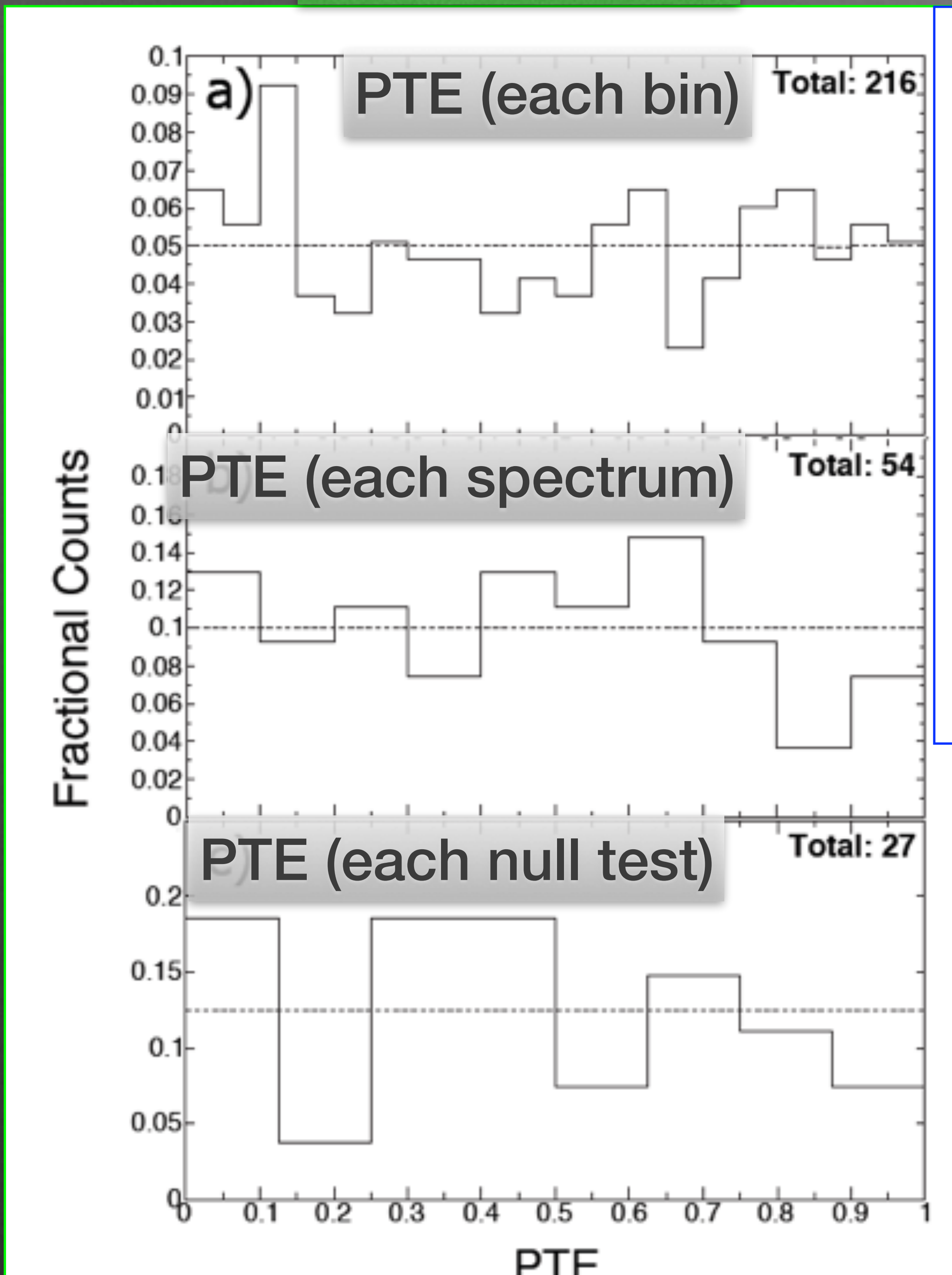
- If there is a systematic bias between the two data set, the difference spectrum would not be null.
- BICEP2 did this in a map space.

Null Tests (POLARBEAR)

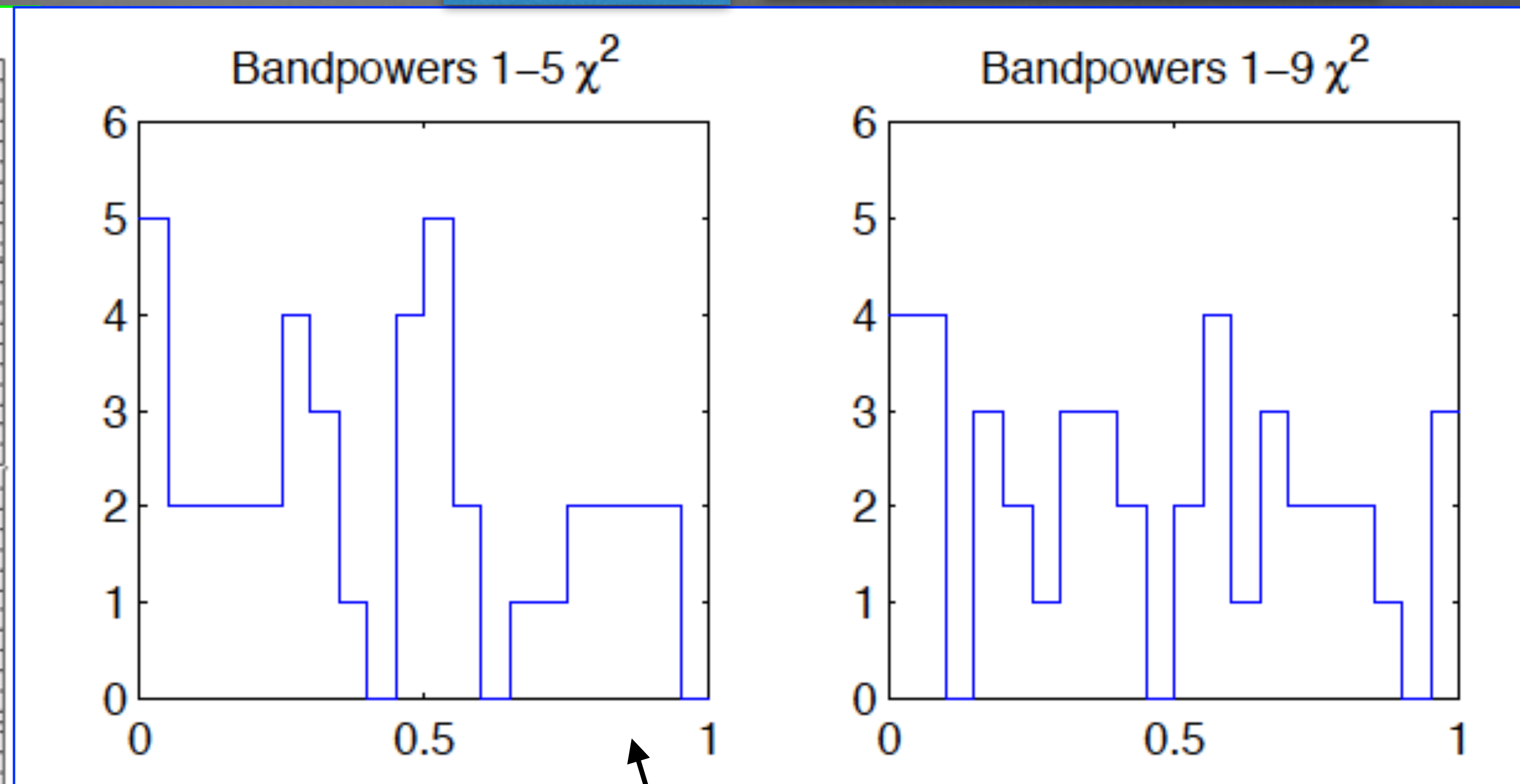
- First half vs. Second half
- Rising vs. Setting
- High vs. Low elevation
- High vs. Low gain
- Good vs. Bad weather
- Pixel polarization angle orientation type
- Left vs Right side detectors
- Left vs. right-going scan
- Moon distance

Null Test PTEs

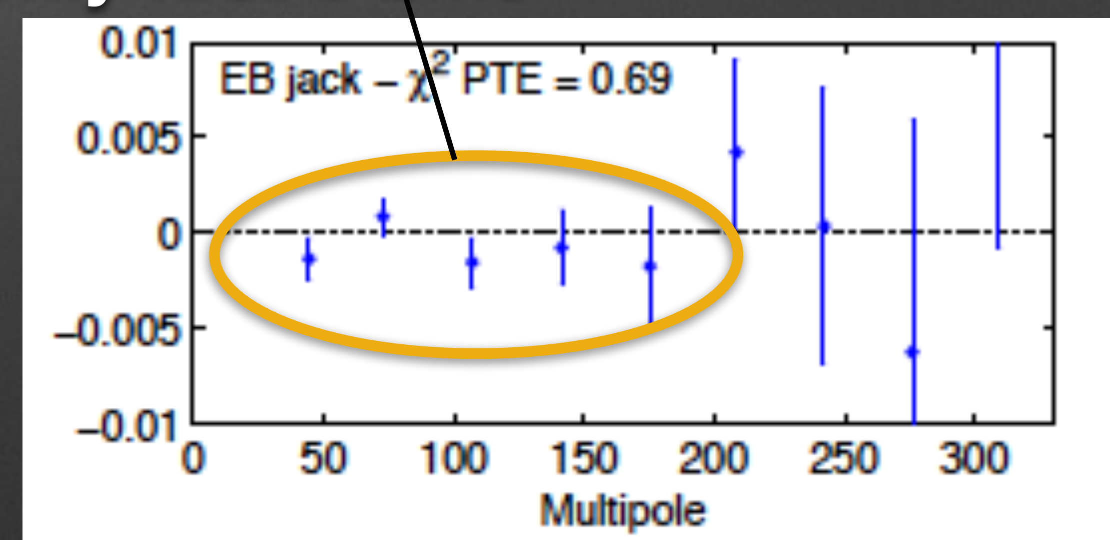
POLARBEAR



BICEP2 PTE (each spectrum)



using only first 5 bins

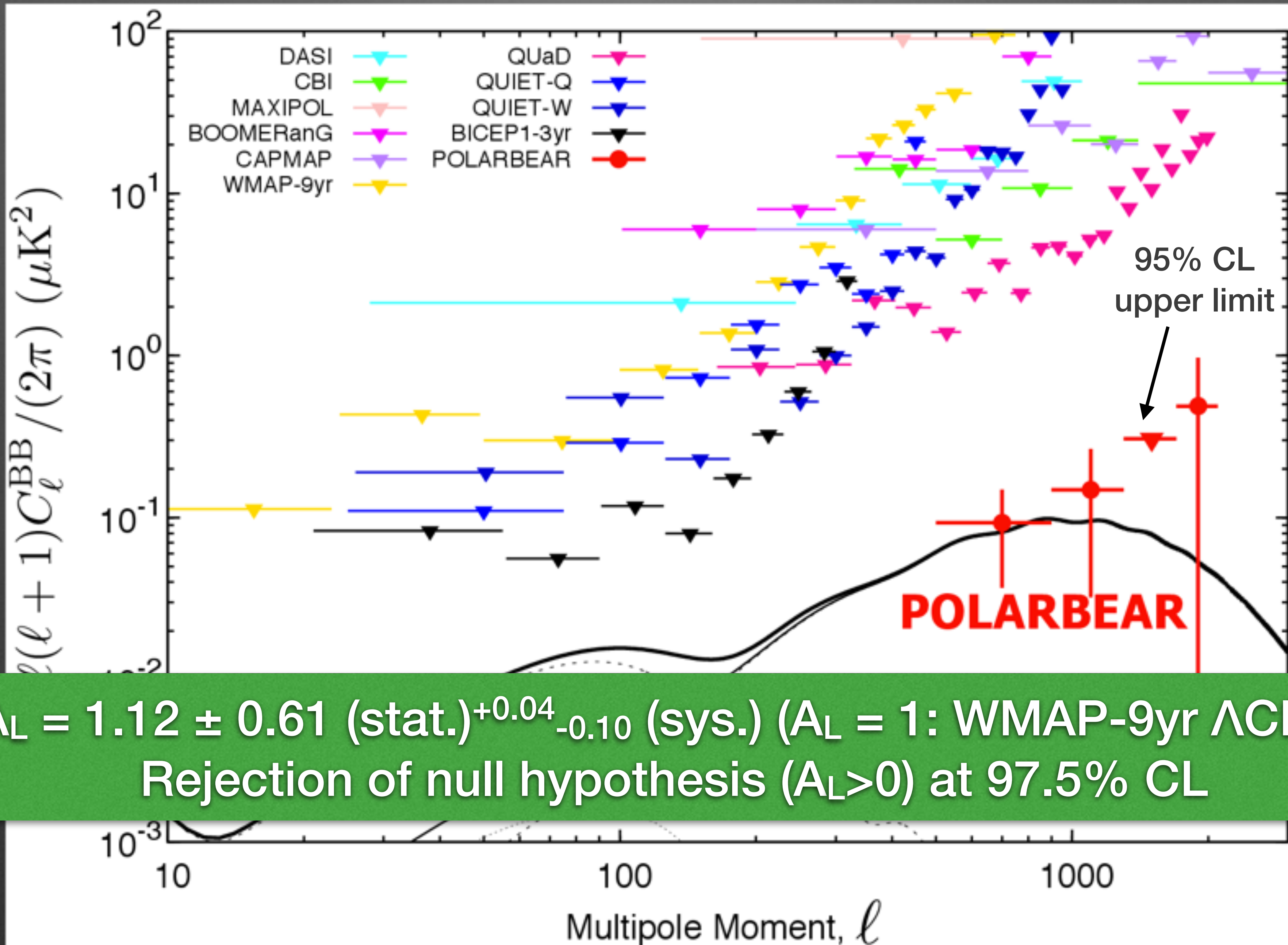


No significant systematics found

(After passing all the null tests…)
B-mode power spectra

(BB power spectrum was blinded for POLARBEAR.)

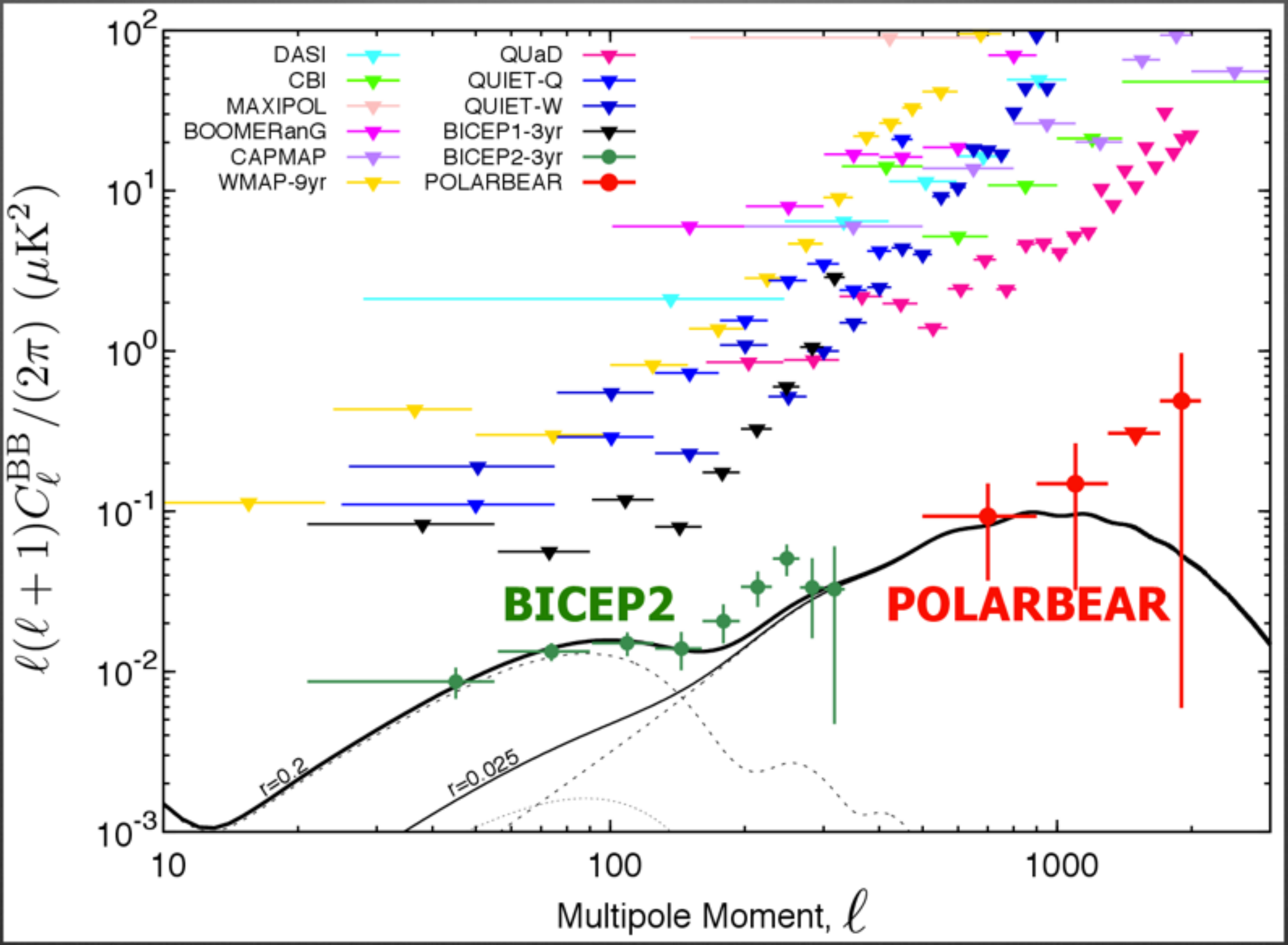
Comparison with other upper limits (3/10)



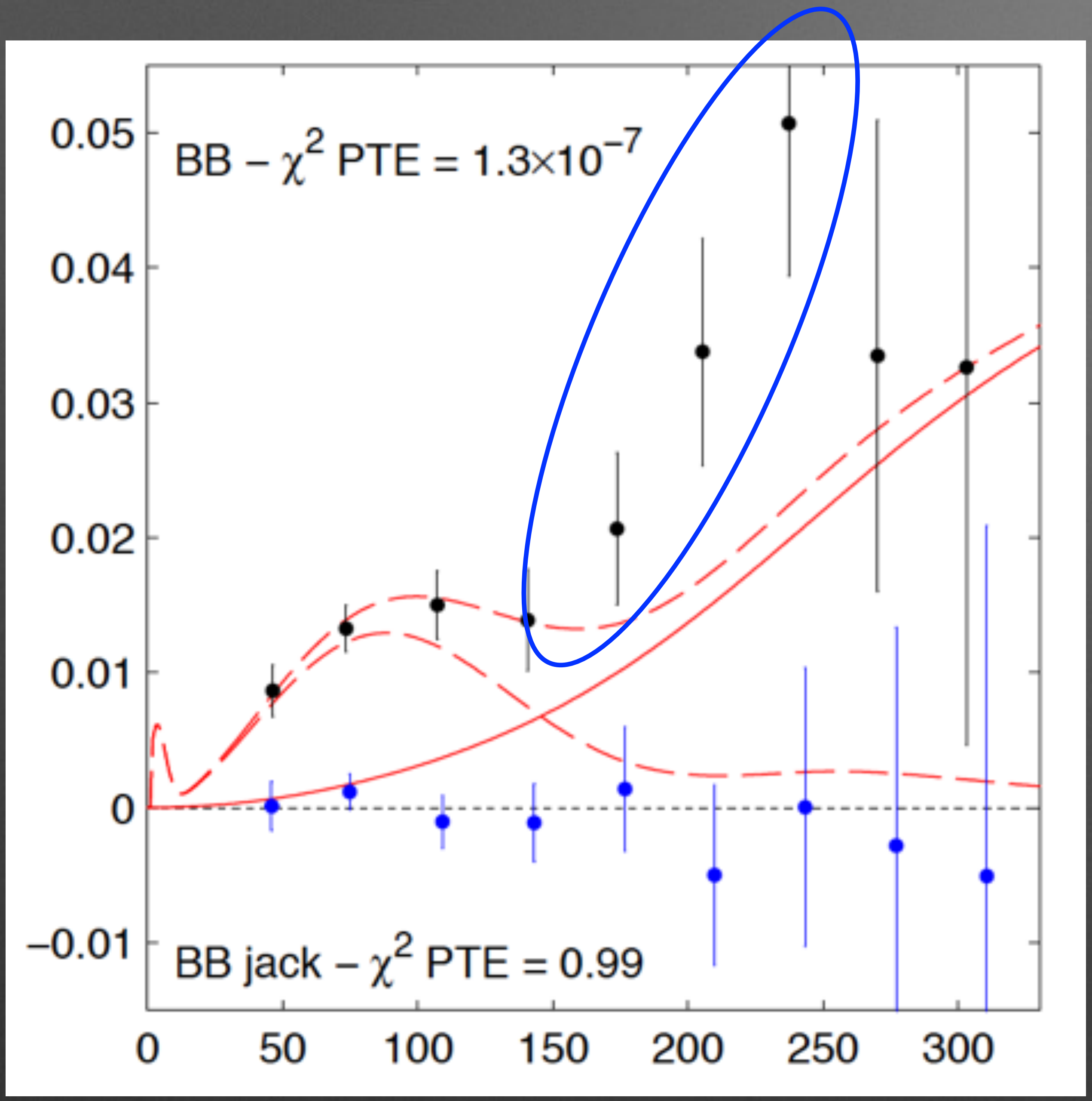
$A_L = 1.12 \pm 0.61$ (stat.)$^{+0.04}_{-0.10}$ (sys.) ($A_L = 1$: WMAP-9yr ΛCDM)

Rejection of null hypothesis ($A_L>0$) at 97.5% CL

Comparison with other upper limits (3/17)



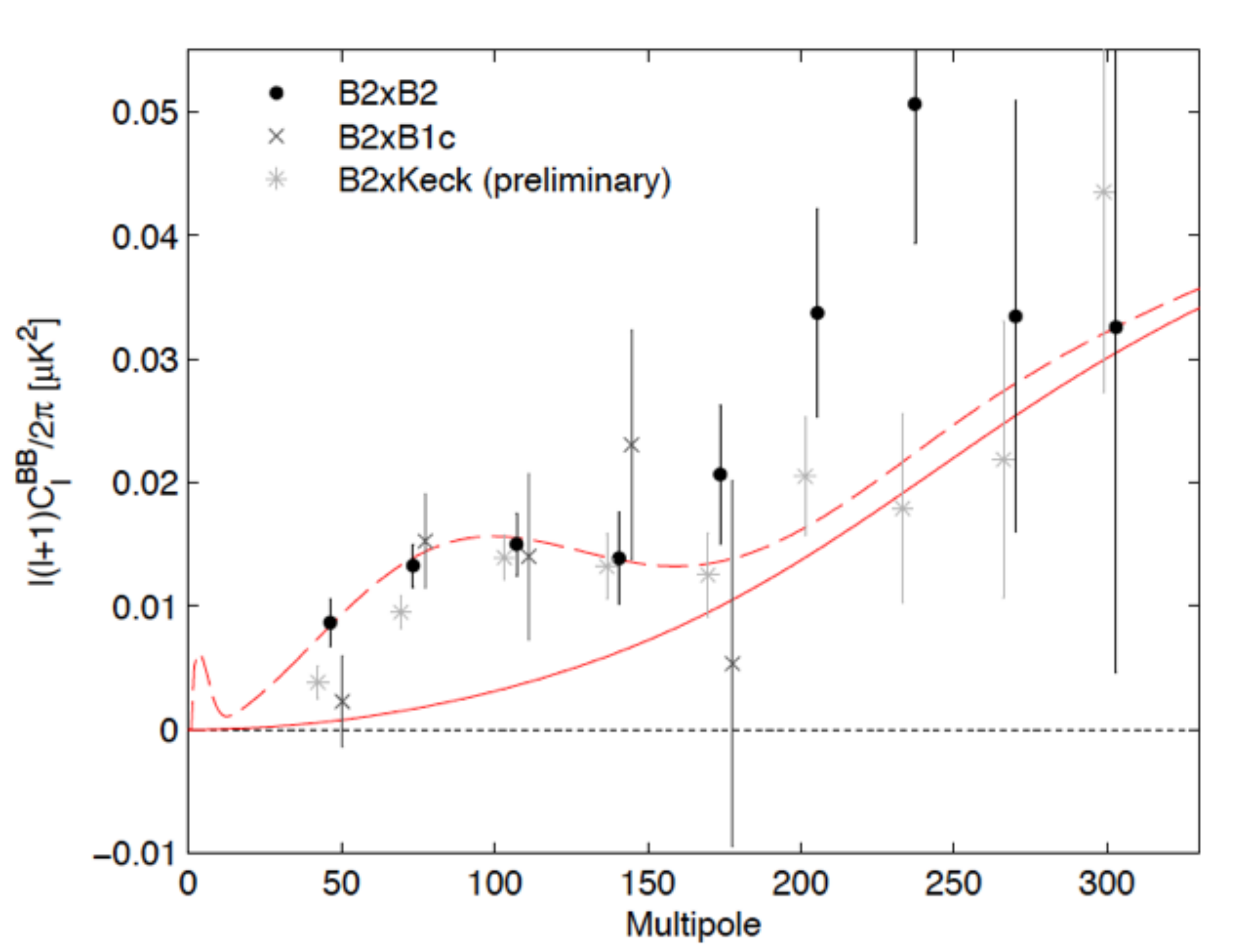
BICEP2 BB spectrum



- Very low PTE with the solid line (lensed ΛCDM)
  - 5.3σ detection of the excess power at low-ell
- What about the excess around ell~200?
  - "We caution against over interpretation of the two high band powers at ell~220 — their joint significance is less than 3σ"

These might be just statistical fluctuations, or might be an indication for unknown systematics?

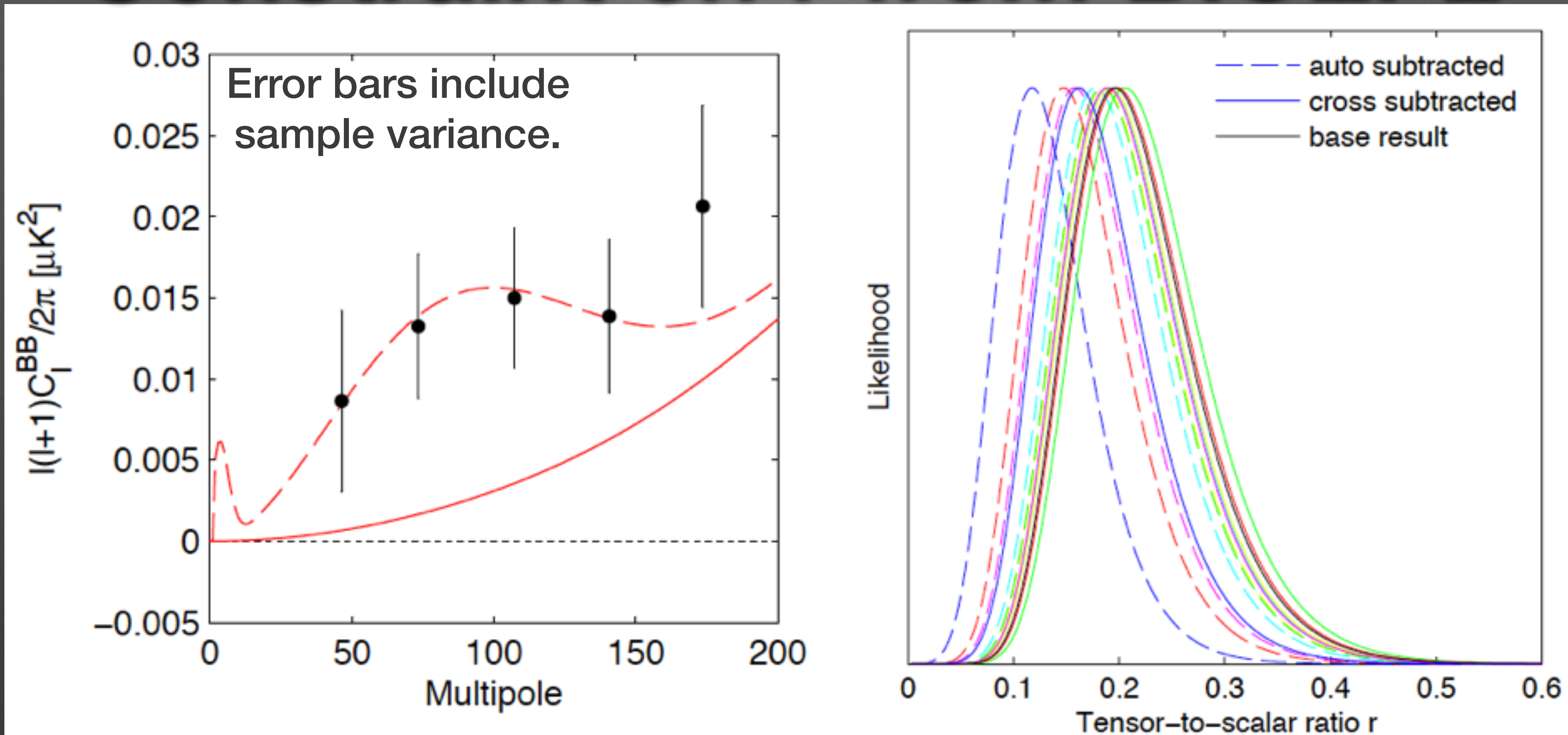
Cross-spectrum w/ Keck Array



If there are any systematics only in BICEP2 data, the cross correlation of BICEP2xKeck should show significantly different result.

- The cross-spectrum with Keck Array shows better fit with lensed ΛCDM+r>0 although it looks significantly different from the BICEP2 auto-spectrum.
  - This adds some confidence for non-zero r detection.
  - But this might also indicate unknown systematic contamination of BICEP2.

Constraint on r from BICEP2



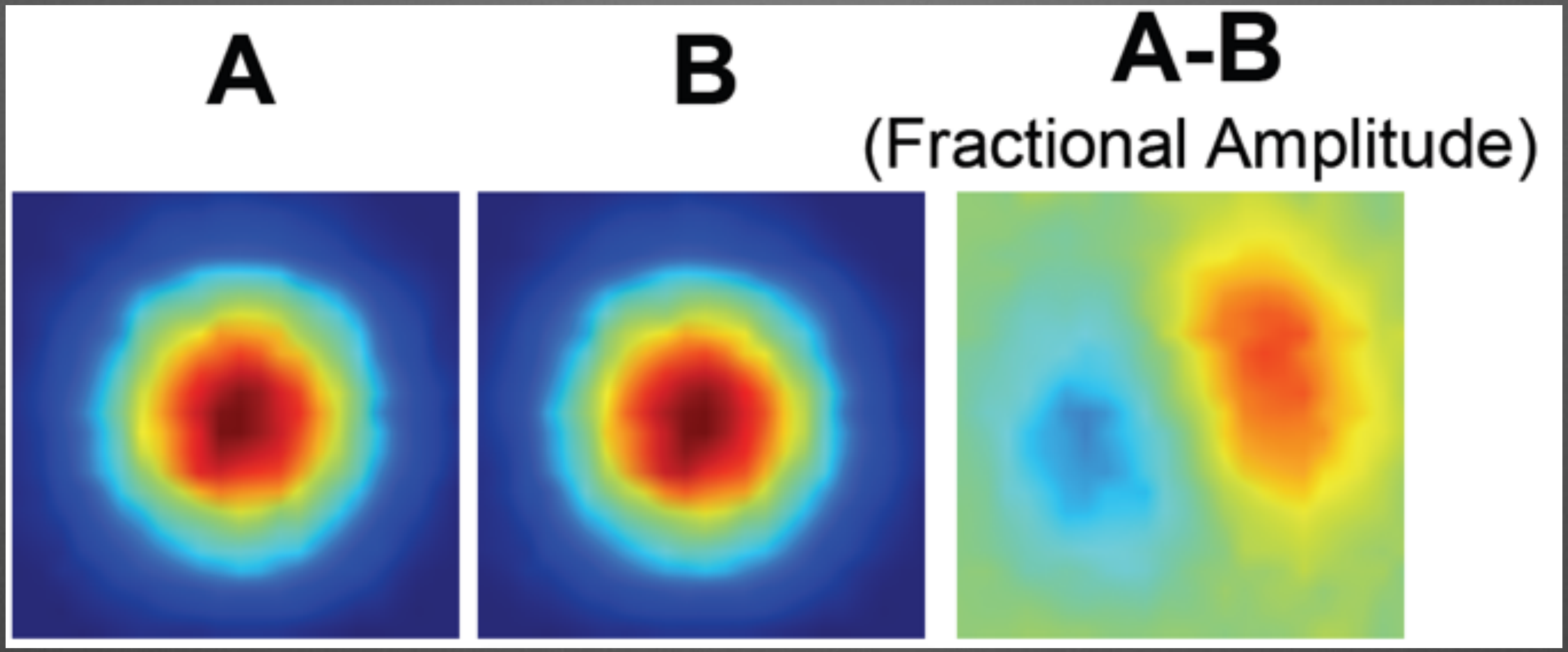
- $r=0.20^{+0.07}_{-0.05}$, 7.0σ r>0 detection
  - w/ foreground subtraction (DDM2): $r=0.16^{+0.06}_{-0.05}$, 5.9σ detection
  - (Best-fit r ranges between 0.12 ~ 0.21 depending on the model or the treatment of foreground)

Then, what is going on now?

Some worrying systematics

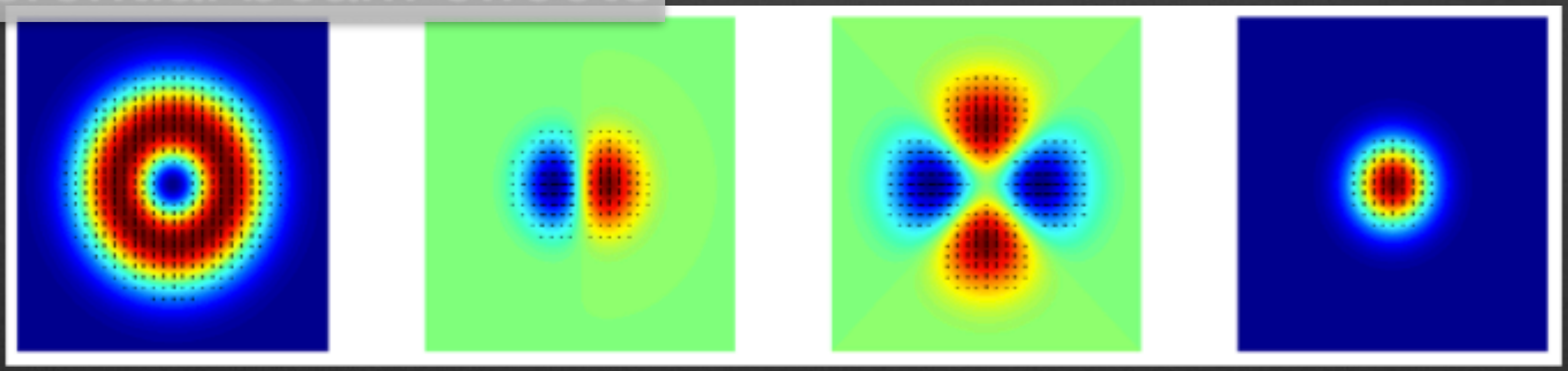
- Instrumental systematics
- Foreground contamination

Most worrying (instrumental) systematics for BICEP2: Differential Beam Systematics

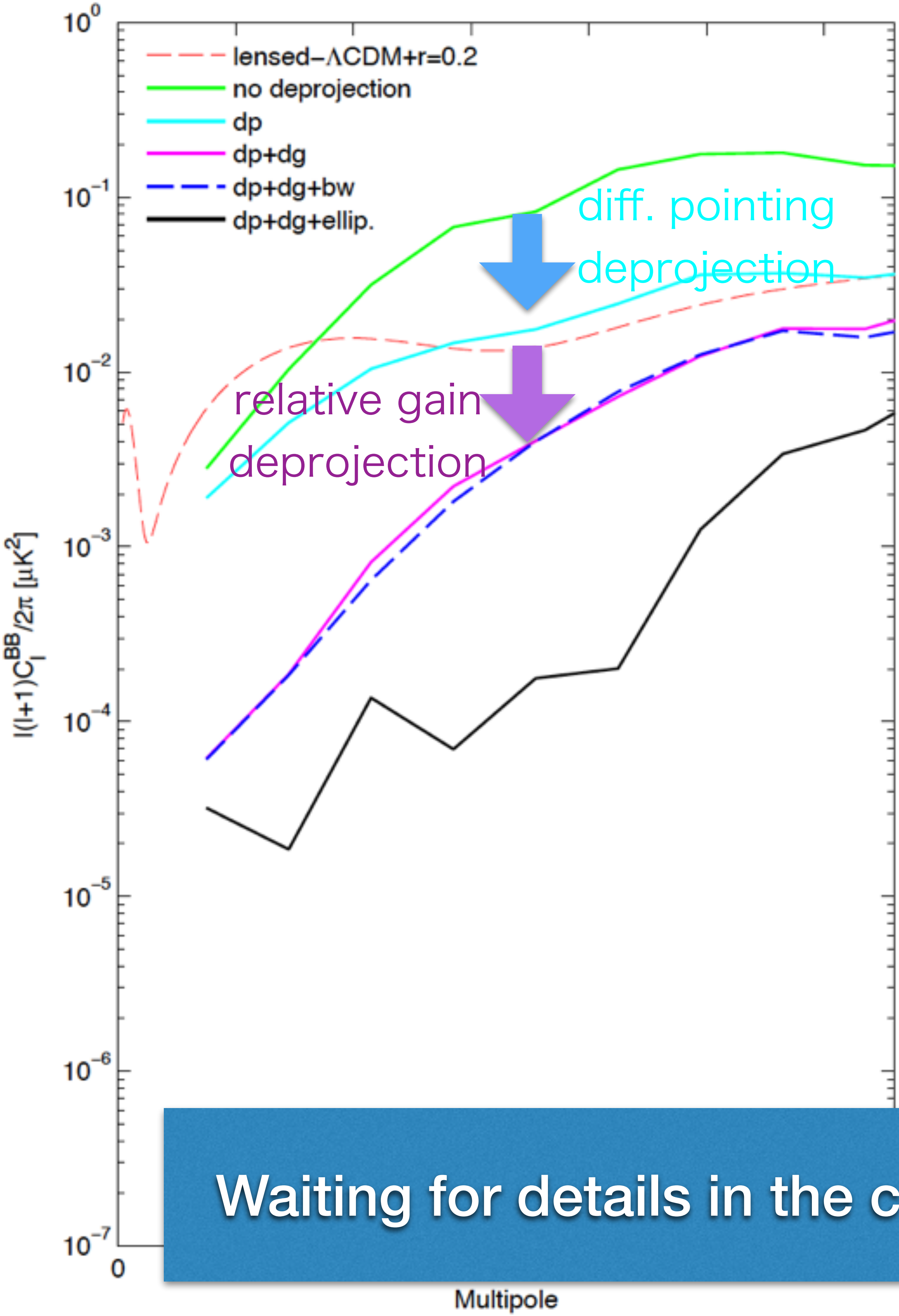


- Pointing mismatch: Differential pointing can cause a serious leakage from temperature fluctuation to B-mode polarization.

Other differential beam effects



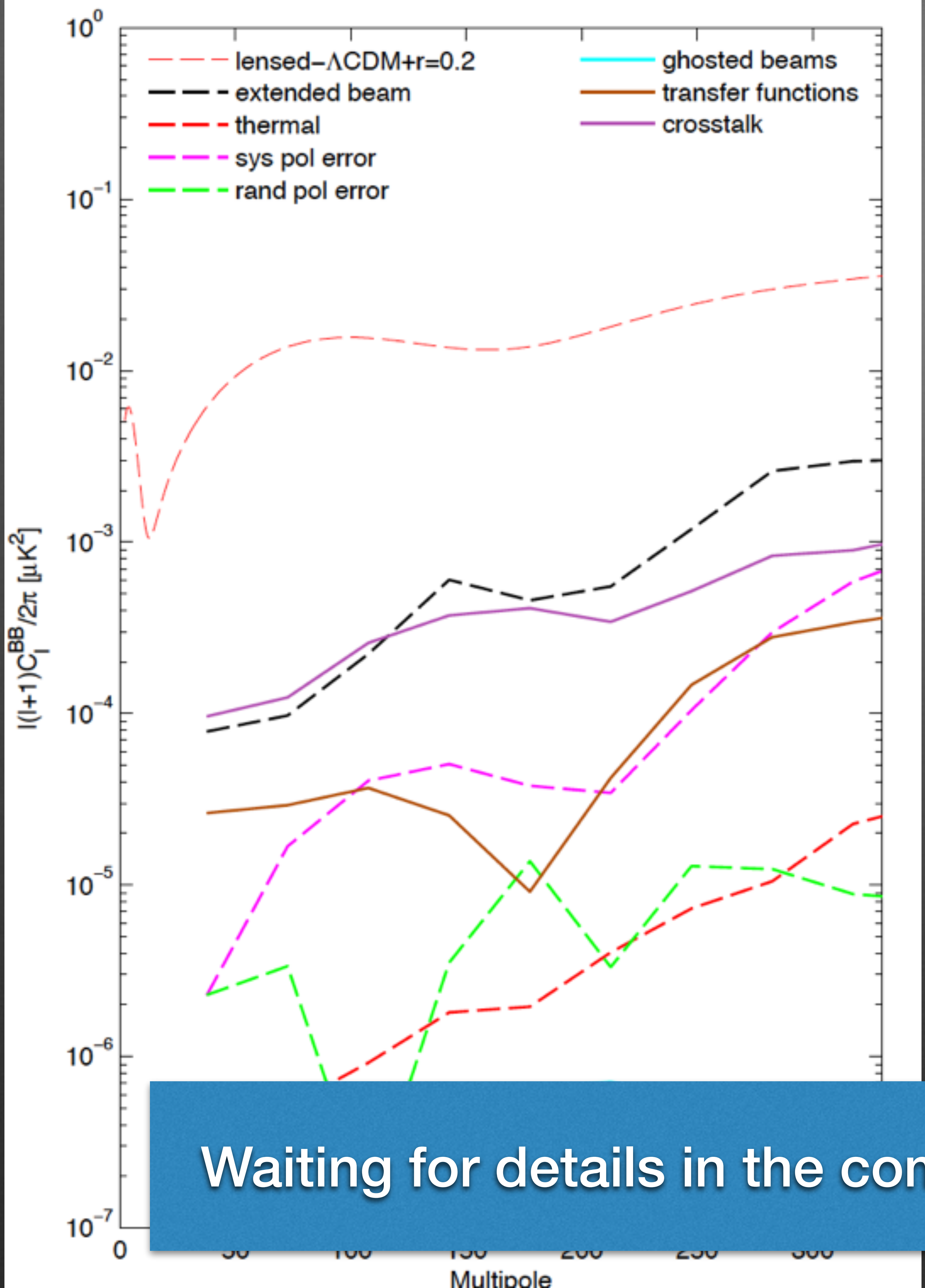
beam size pointing ellipticity gain



Differential beam systematics and “deprojection”

- Differential beam effect can be mitigated by “deprojection” technique in the BICEP2 data analysis using Planck T map.
- Without the deprojection, observed ClBB would be dominated by the leakage from ClTT by differential pointing and relative gain mismatch.

Waiting for details in the coming systematics paper…

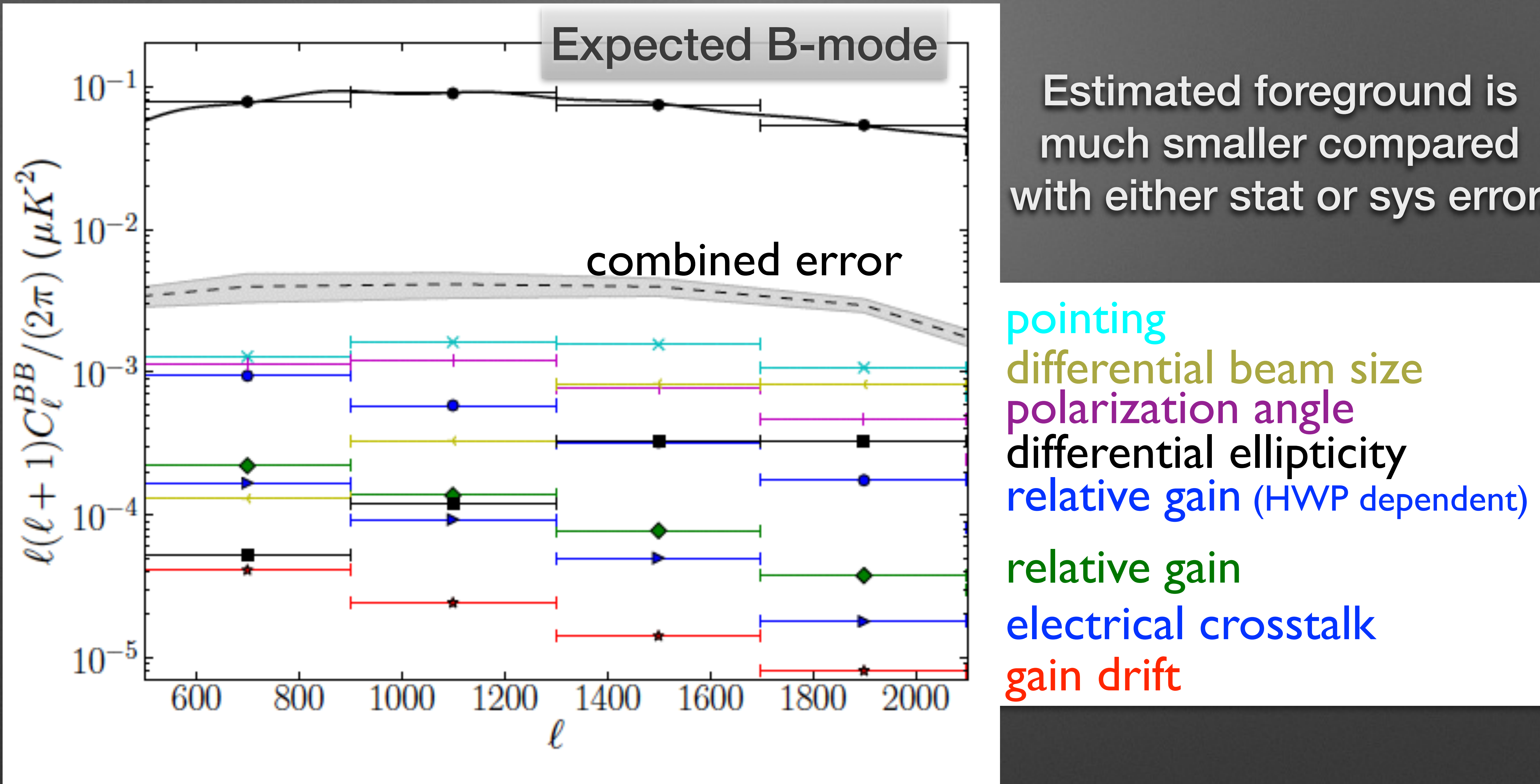


Systematic uncertainty (BICEP2)

- Every systematic uncertainty is estimated to be negligible.

Waiting for details in the coming systematics paper…

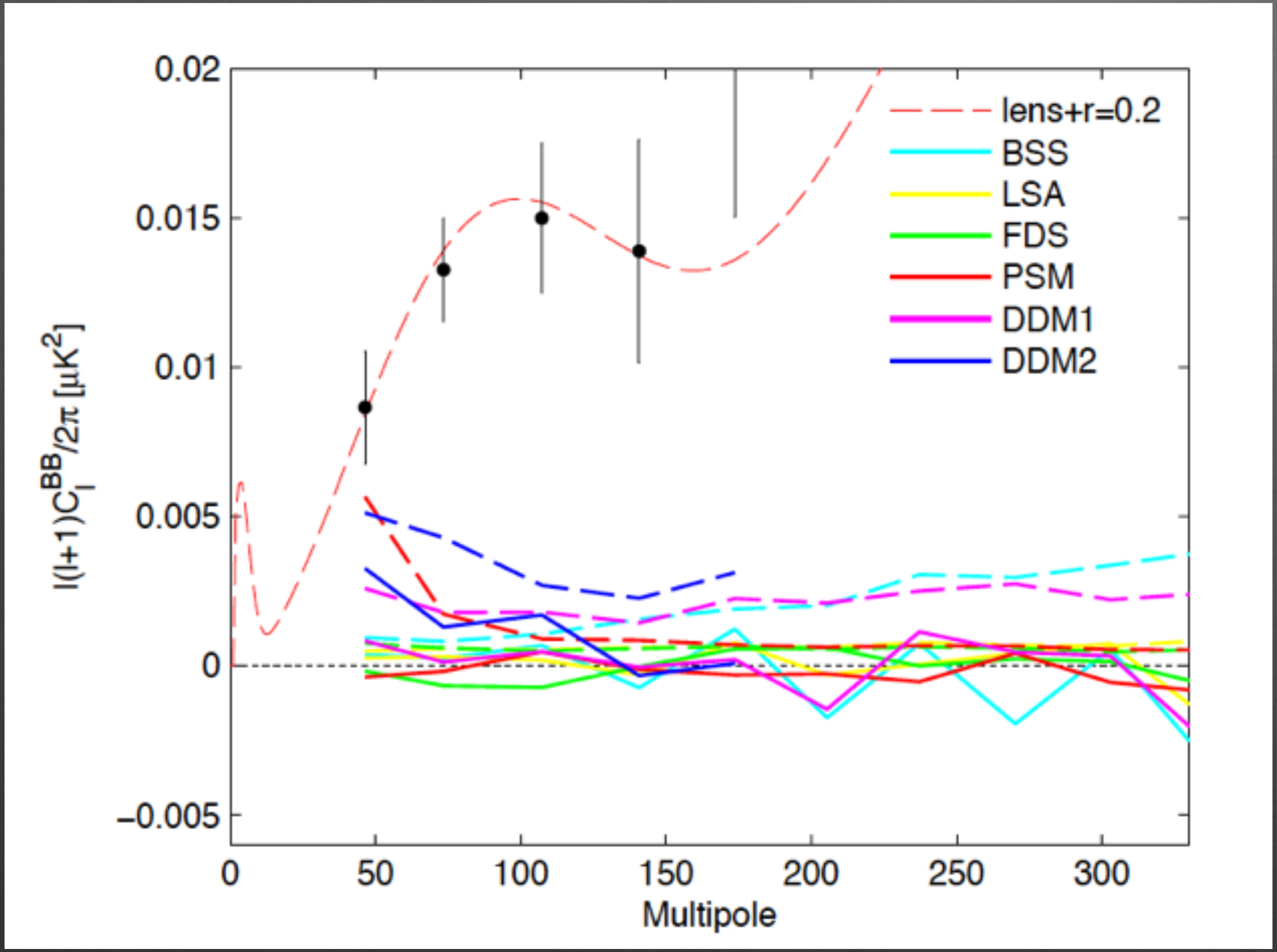
Systematic uncertainty (POLARBEAR)



Estimated foreground is much smaller compared with either stat or sys error.

Negligible leakage without deprojection

Astrophysical foregrounds (BICEP2)



- Dashed lines: auto-spectra of models
- Solid lines: cross-spectra with BICEP2 maps

- DDM: "Data Driven Model" constructed from publicly available Planck data products. The Planck dust model map at 353GHz is scaled to 150 GHz.

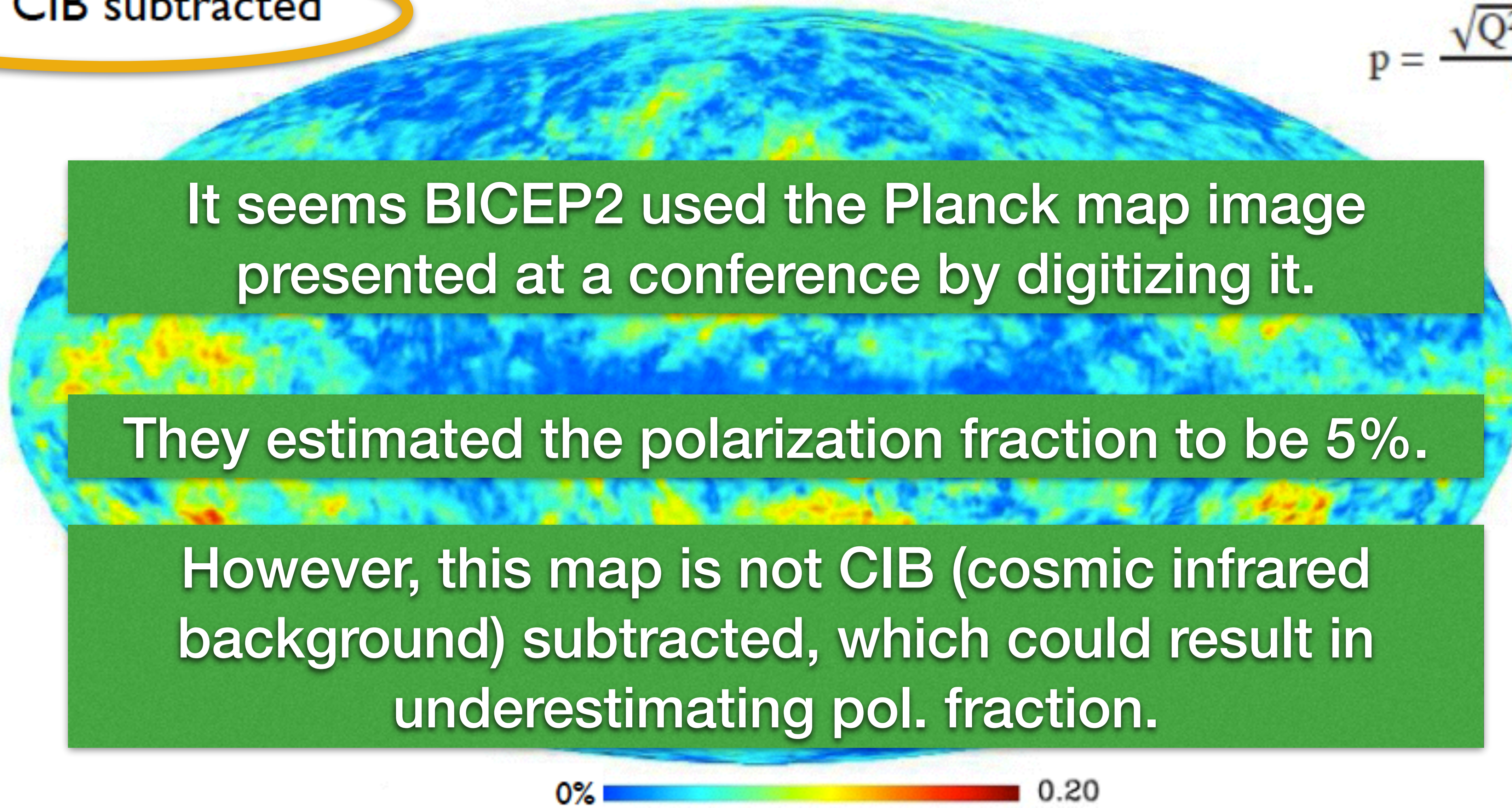
What is wrong with this?

Polarization Fraction

Apparent polarization fraction (p) at 353 GHz, 1° resolution

Not CIB subtracted

$$p = \frac{\sqrt{Q^2 + U^2}}{I}$$



It seems BICEP2 used the Planck map image presented at a conference by digitizing it.

They estimated the polarization fraction to be 5%.

However, this map is not CIB (cosmic infrared background) subtracted, which could result in underestimating pol. fraction.

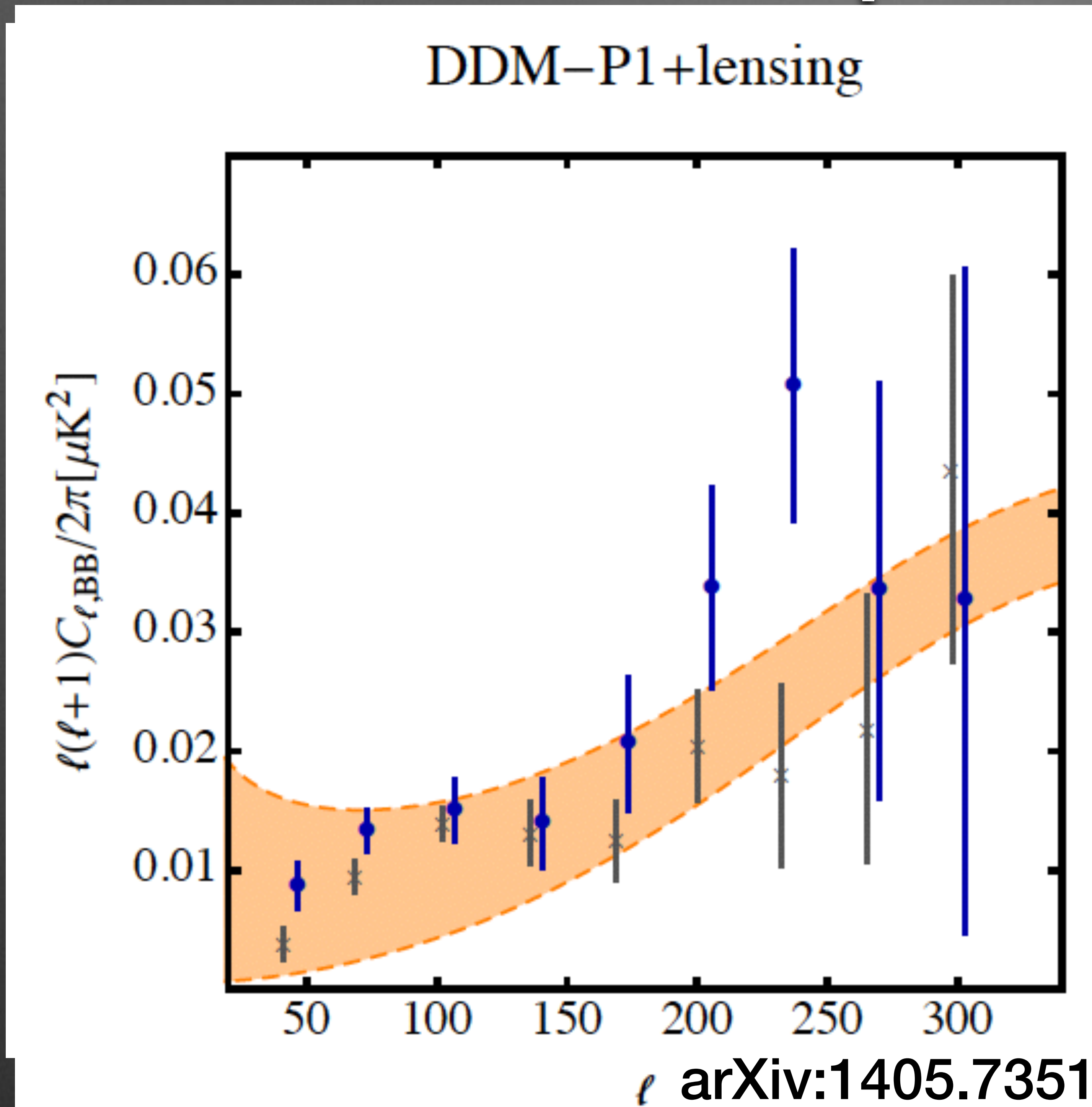
p ranges from 0 to ~20%

Low p values in inner MW plane. Consistent with unpolarized CIB

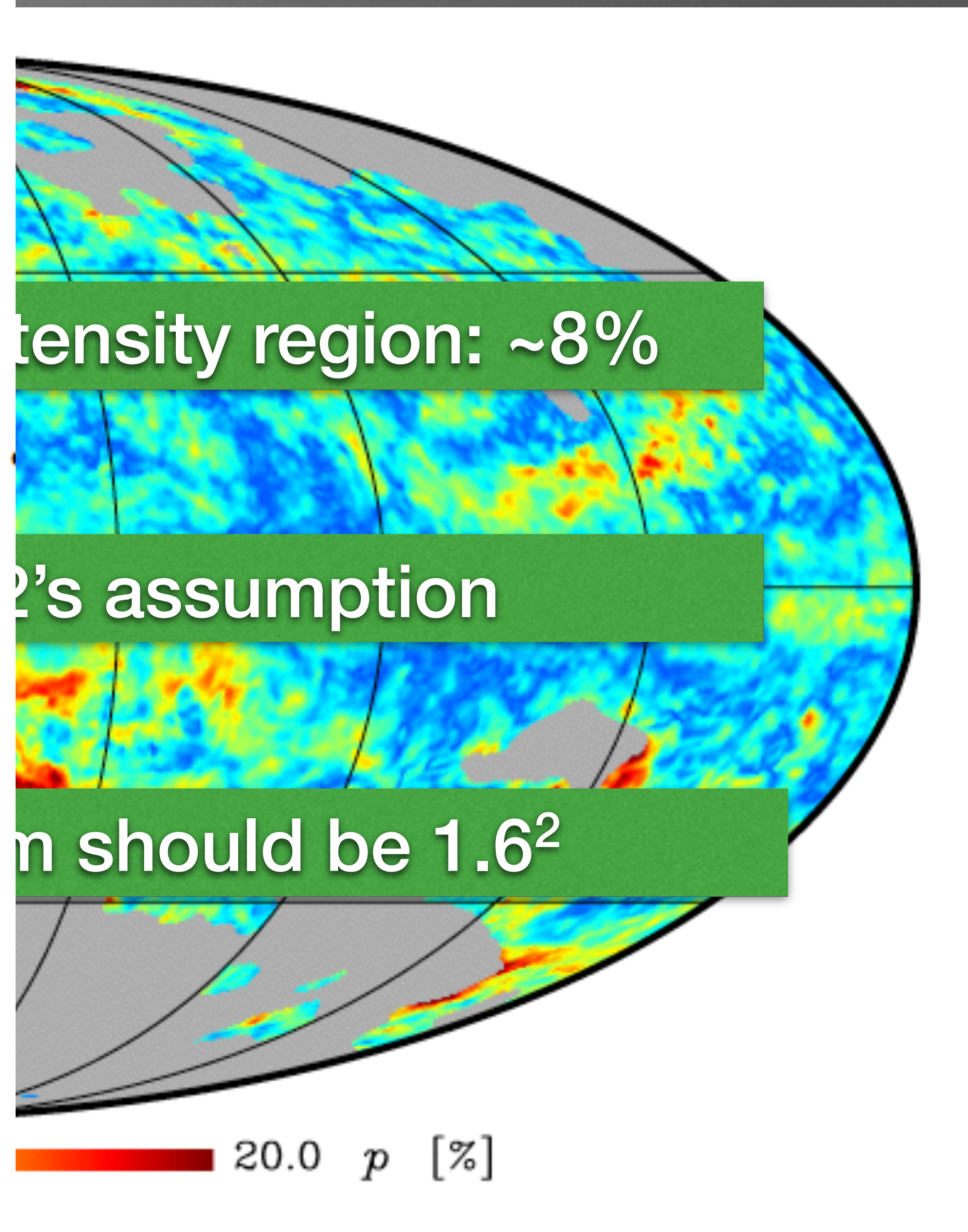
Large p values in outer plane and intermediate latitudes

Bernard J.Ph., ESLAB 2013 6

Recent Planck dust polarization fraction map



arXiv:1405.7351



tensity region: ~8%

2's assumption

n should be 1.6^2

arXiv:1405.0871

No one knows the answer… Wait for Planck's next release.

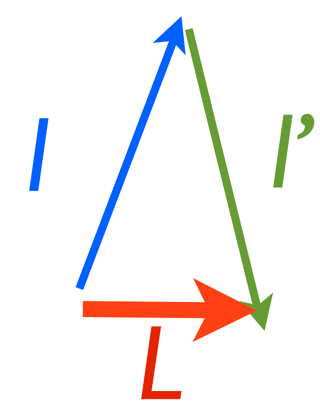
Other analysis results from POLARBEAR

Optimal Estimator for Gravitational Lensing

- Gravitational lensing induces correlation between different multipoles (*l* and *l*’) of E-mode and B-mode.
  - We can make use of the correlation to estimate the lensing deflection field, d(L).

$$d_{EE}(\mathbf{L}) \propto \sum_{\mathbf{l}} E(\mathbf{l})E(\mathbf{l}')$$

$$d_{EB}(\mathbf{L}) \propto \sum_{\mathbf{l}} E(\mathbf{l})B(\mathbf{l}')$$



(Hu, Okamoto, 2002)

arXiv:1312.6646

C_L^{dd} = <dxdx’*>

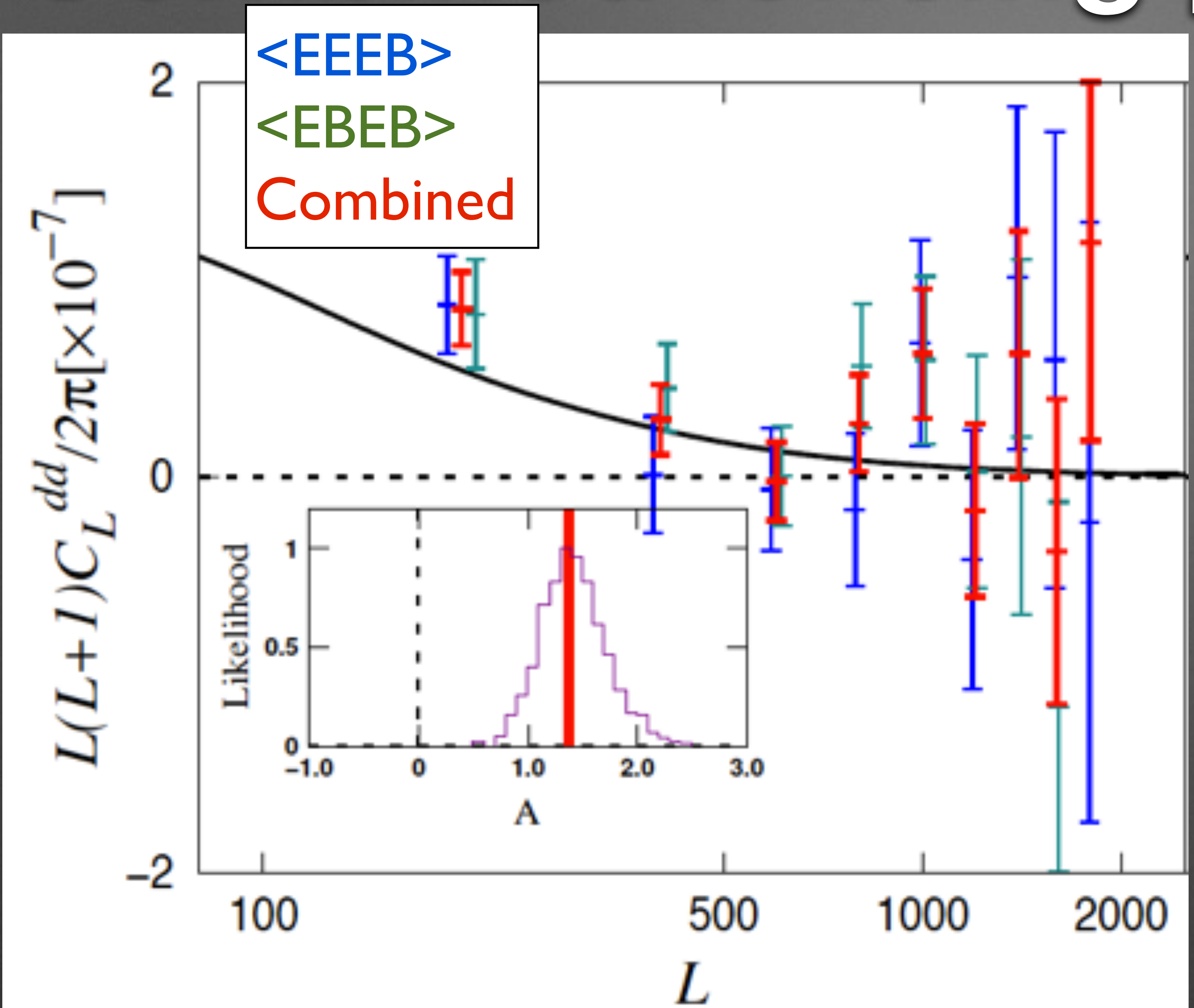
“4-point correlation” with only CMB polarization data alone

PRL 113, 131302 (2014)

C_L^{dI} = <dx, CIB>

Cross-correlation with CIB (biased tracer of dark matter halos)

Combined lensing power spectra

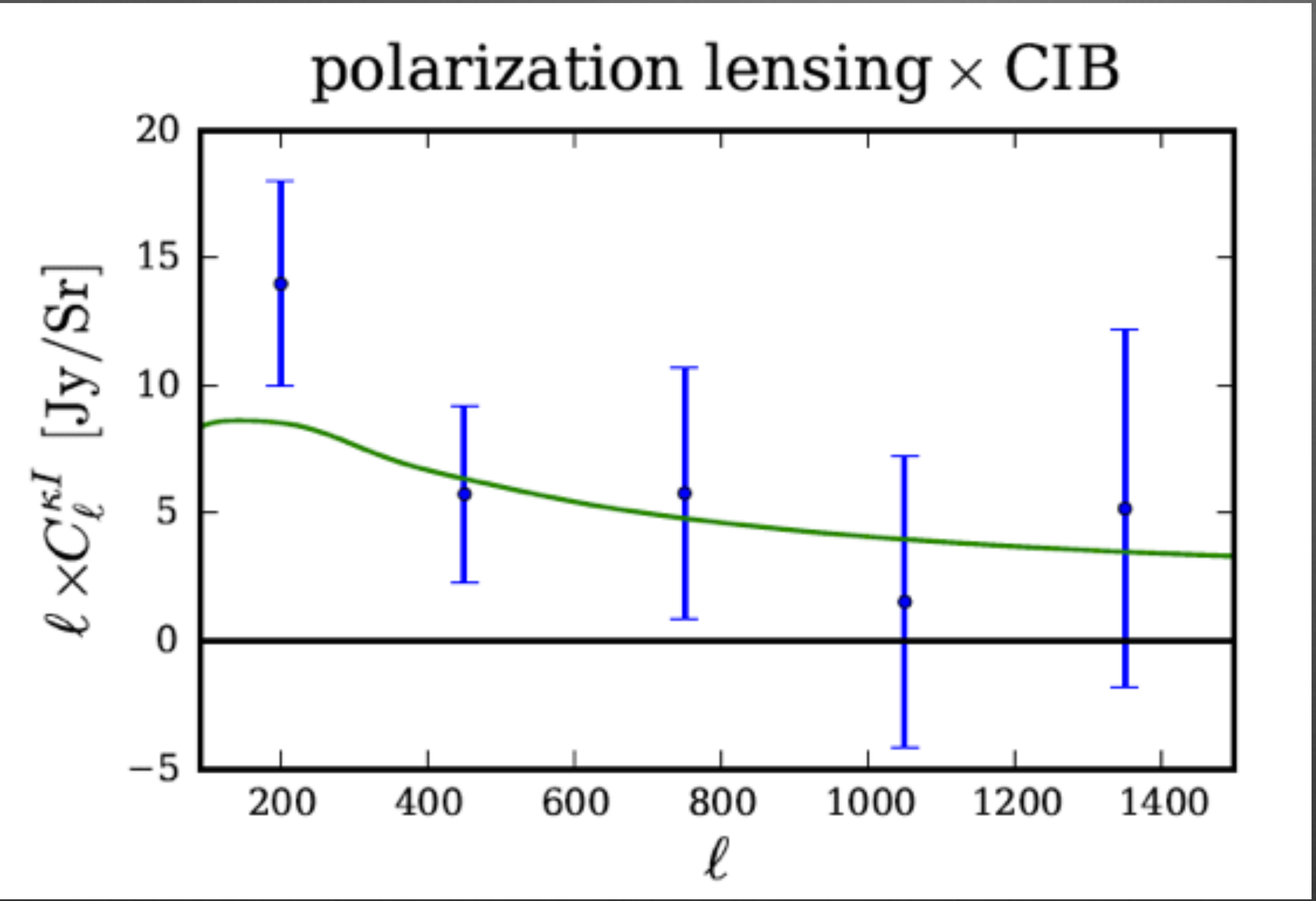


A_L=1.37+/-0.30 (stat.)
+/-0.13 (sys.)
(A_L=1: ΛCDM w/ WMAP9)

A_L: Lensing amplitude

- Consistent between <EEEB> and <EBEB>.
- 4.2 σ rejection of null hypothesis
- First detection (evidence) for gravitational lensing with CMB polarization alone

Cross-correlation with CIB



d_{EB}
d_{EE} x CIB

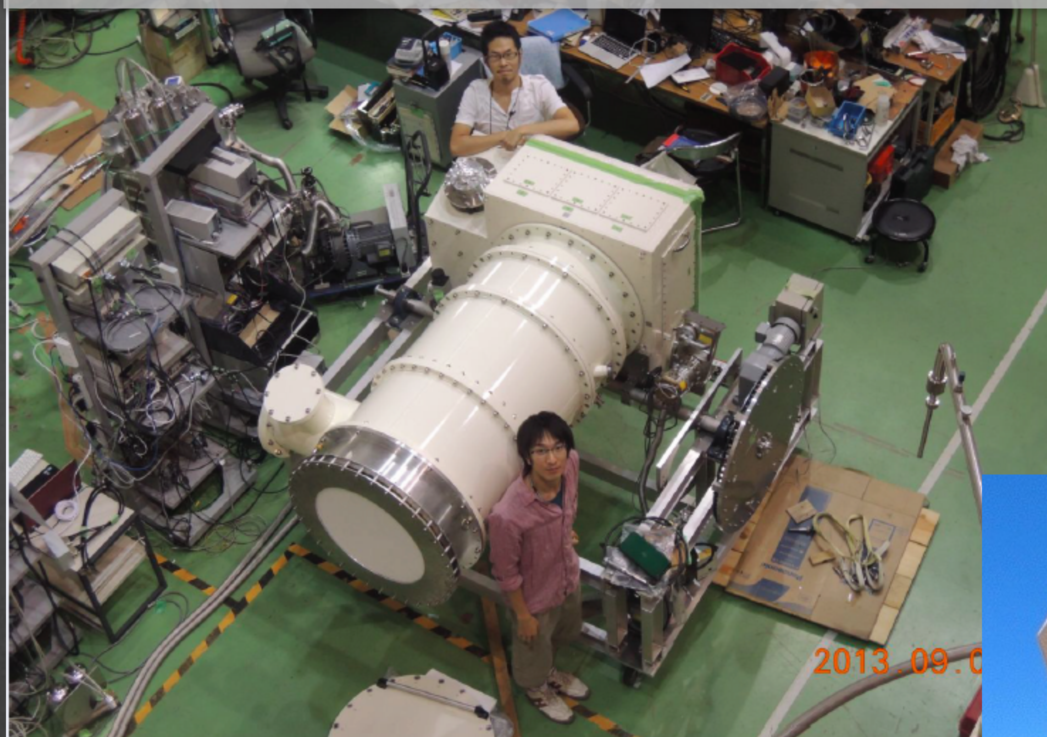
CIB: Herschel/SPIRE ~500um

CIB is a good tracer for the matter distribution in z=1~3.
→ Should correlate with CMB lensing.

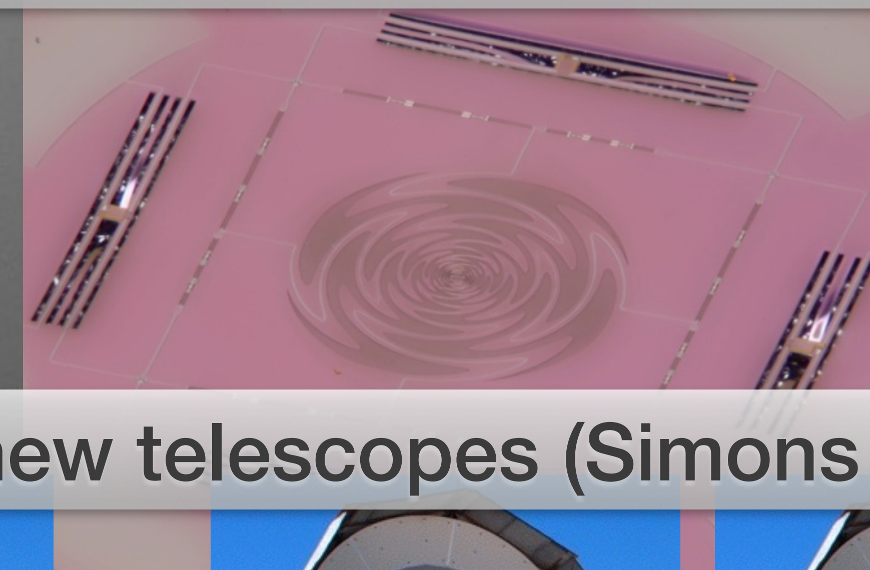
- Reject null hypothesis at 4.0 σ
- Consitent with SPTpol (Hanson et al, 2013)

POLARBEAR-2 & Simons Array

New POLARBEAR-2 receiver developed by KEK



Multichroic antenna(90+150GHz) +TES bolometer



Two new telescopes (Simons Array)

+

- POLARBEAR-2 will be deployed in 2015
- Confirm and measure r. Characterize B-mode better
- Constrain sum of neutrino mass: σ ~ 20 meV (w/o sys.)

Summary

- **BICEP2 detected B-mode power at degree angular scale**
  - Detection of non-zero r at > 5 σ, r=0.1~0.2
  - Recent discussions on foreground suggest that the detection of the cosmological signal is not conclusive.
    - Needs confirmations from other experiments!
- **POLARBEAR measured B-mode power spectrum with the best sensitivity at sub-degree angular scale.**
  - Detected gravitational lensing with three independent methods (at > 4σ)
  - POLARBEAR is starting large angular scale observations.

"New era of B-mode cosmology has begun."