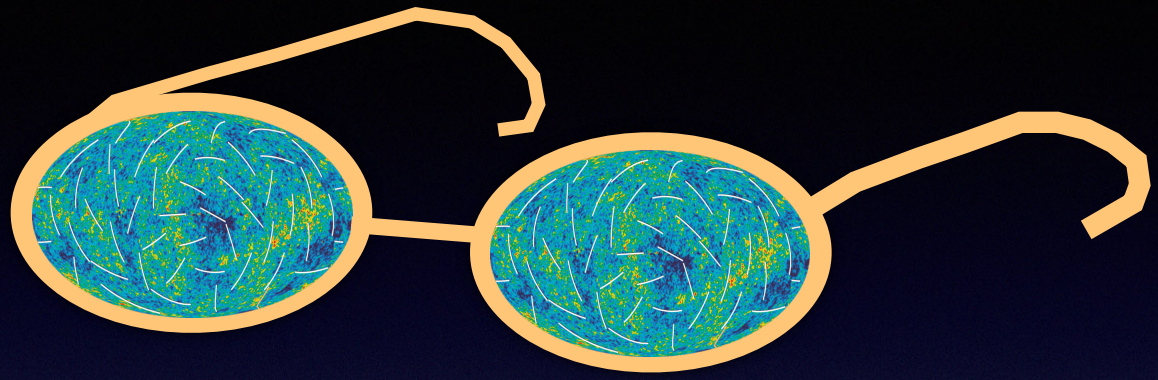
Fundamental Physics



Through the CMB's Lenses

Brian Keating

16 January 2015

http://cosmology.ucsd.edu/

@CMB3K
@BICEPTWO
@BrianUCSD

ACEC
AX CENTER *for* EXPERIMENTAL COSMOLOGY

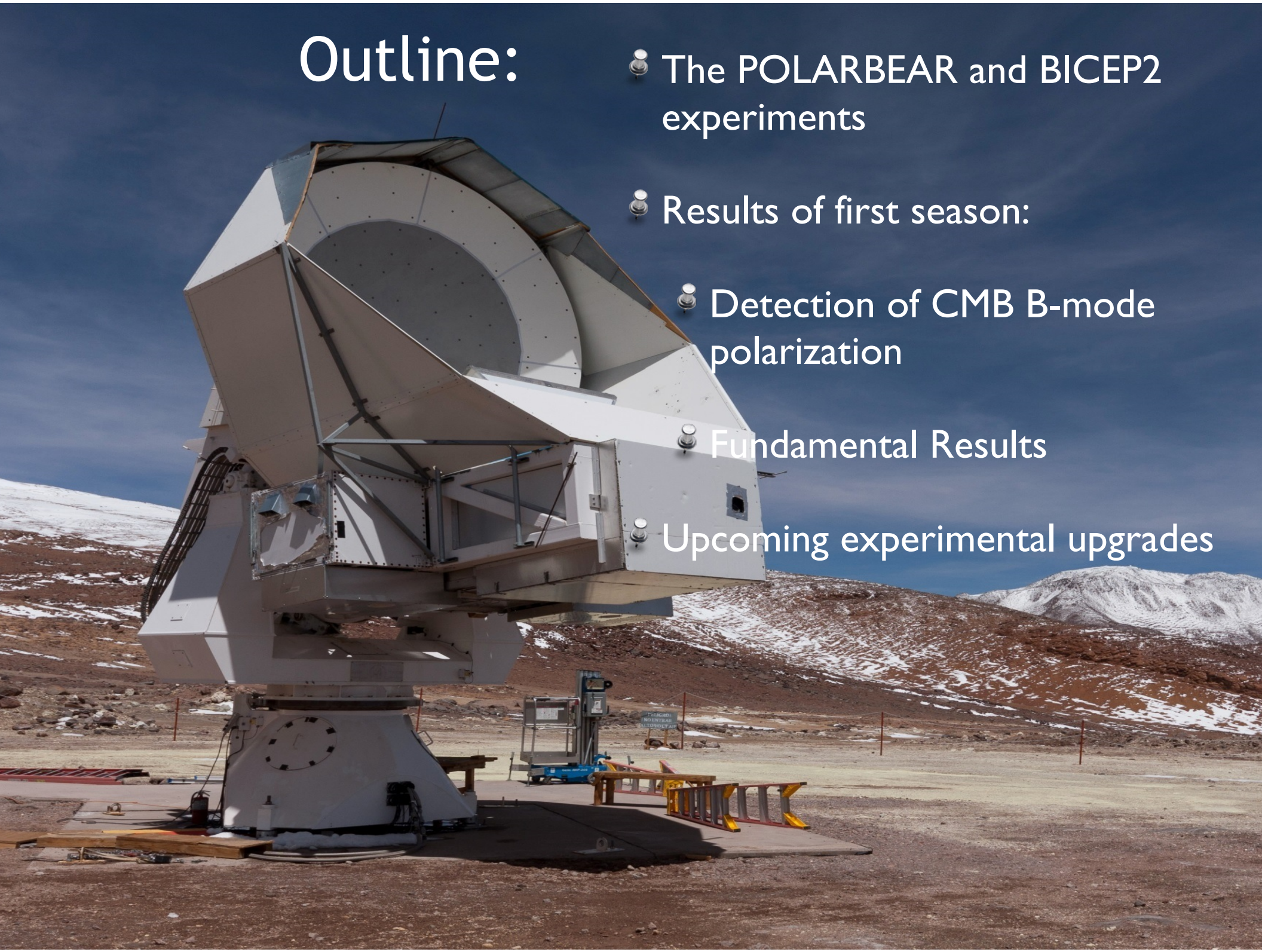
Focus on *Fun*damental Physics

CMB polarization experiments can reveal:

Evidence for the universe's initial conditions via a detection of the CMB's large-scale B-mode polarization pattern, providing constraints on inflationary gravitational waves (at E~10^{16} GeV).

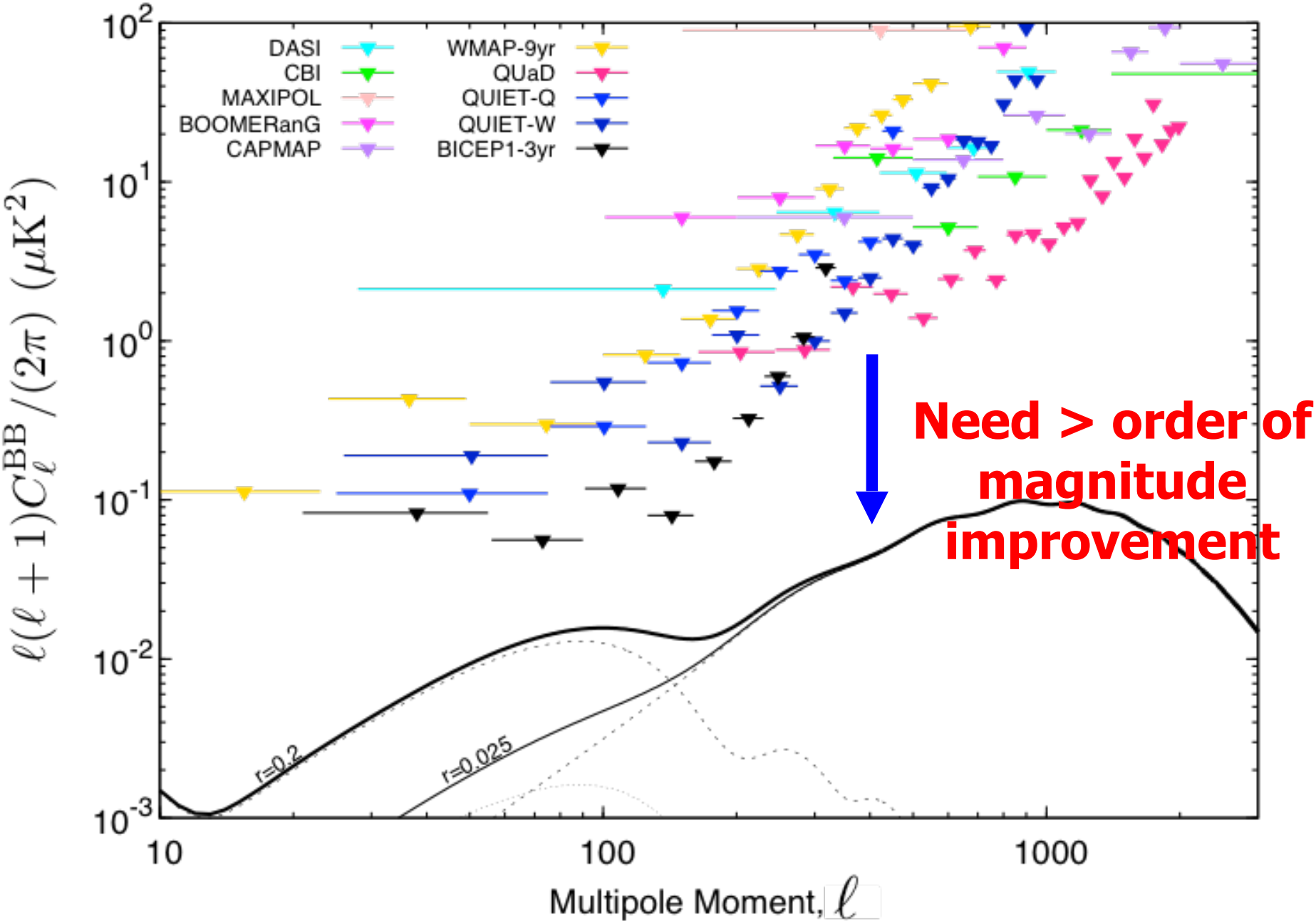
- Further Fundamental Physics:
- Neutrino masses
- Helium abundance
- Neutrino chemical potentials
- Equivalence Principle Tests
- Primordial magnetic fields
- Exotic physics, such as cosmic birefringence

Outline:

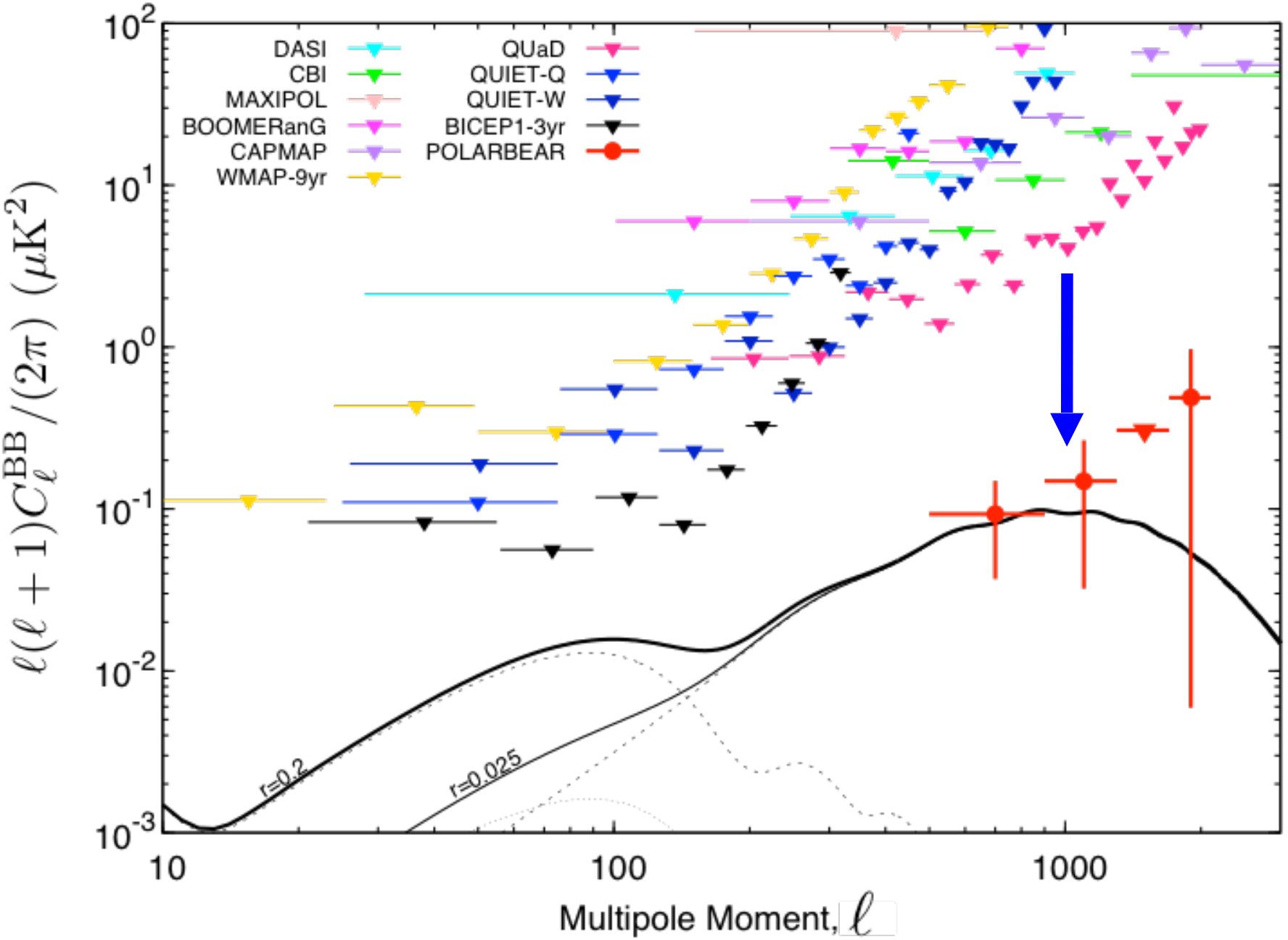


- The POLARBEAR and BICEP2 experiments
- Results of first season:
  - Detection of CMB B-mode polarization
  - Fundamental Results
- Upcoming experimental upgrades

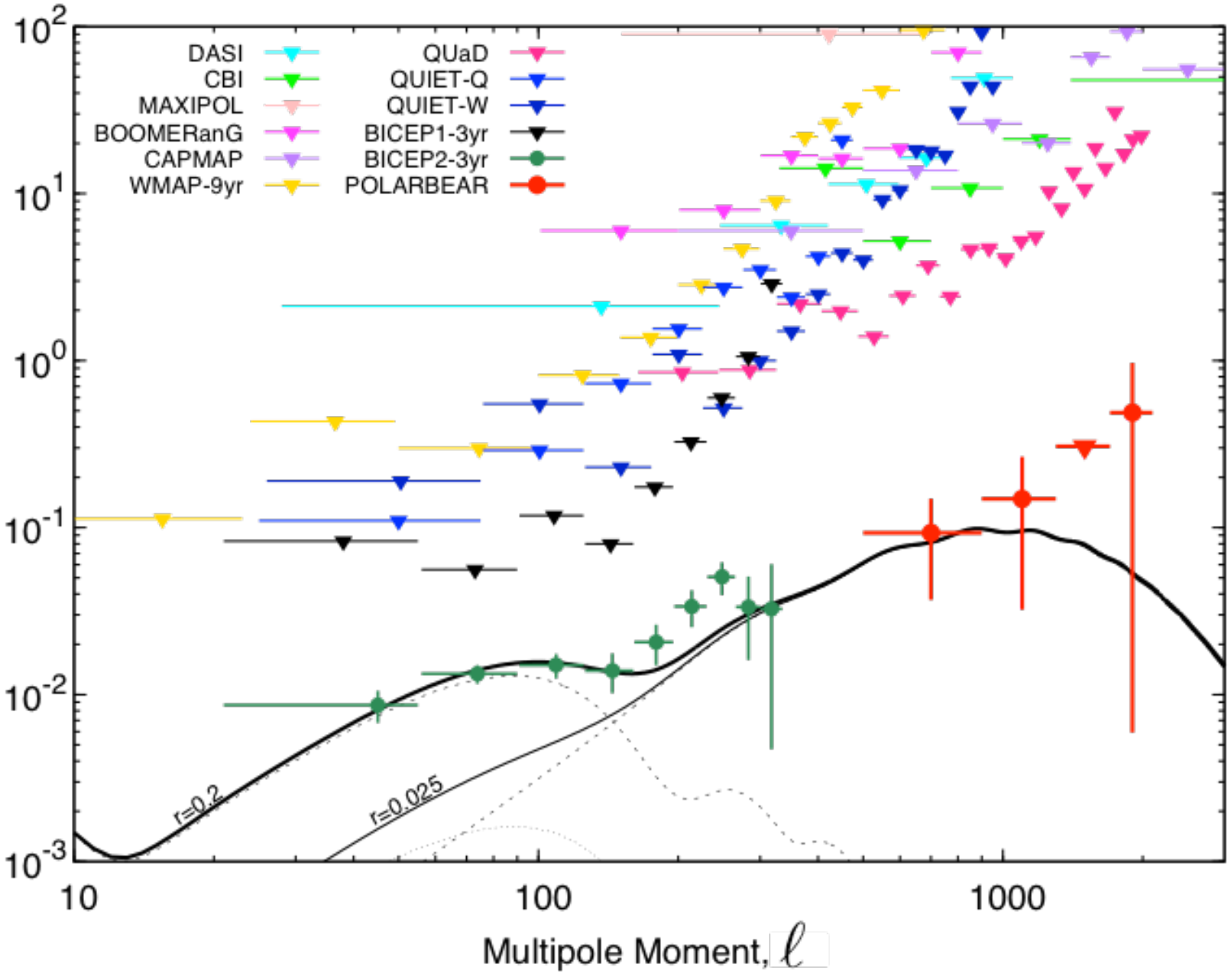
B-mode Power Spectrum (<10 March 2014)

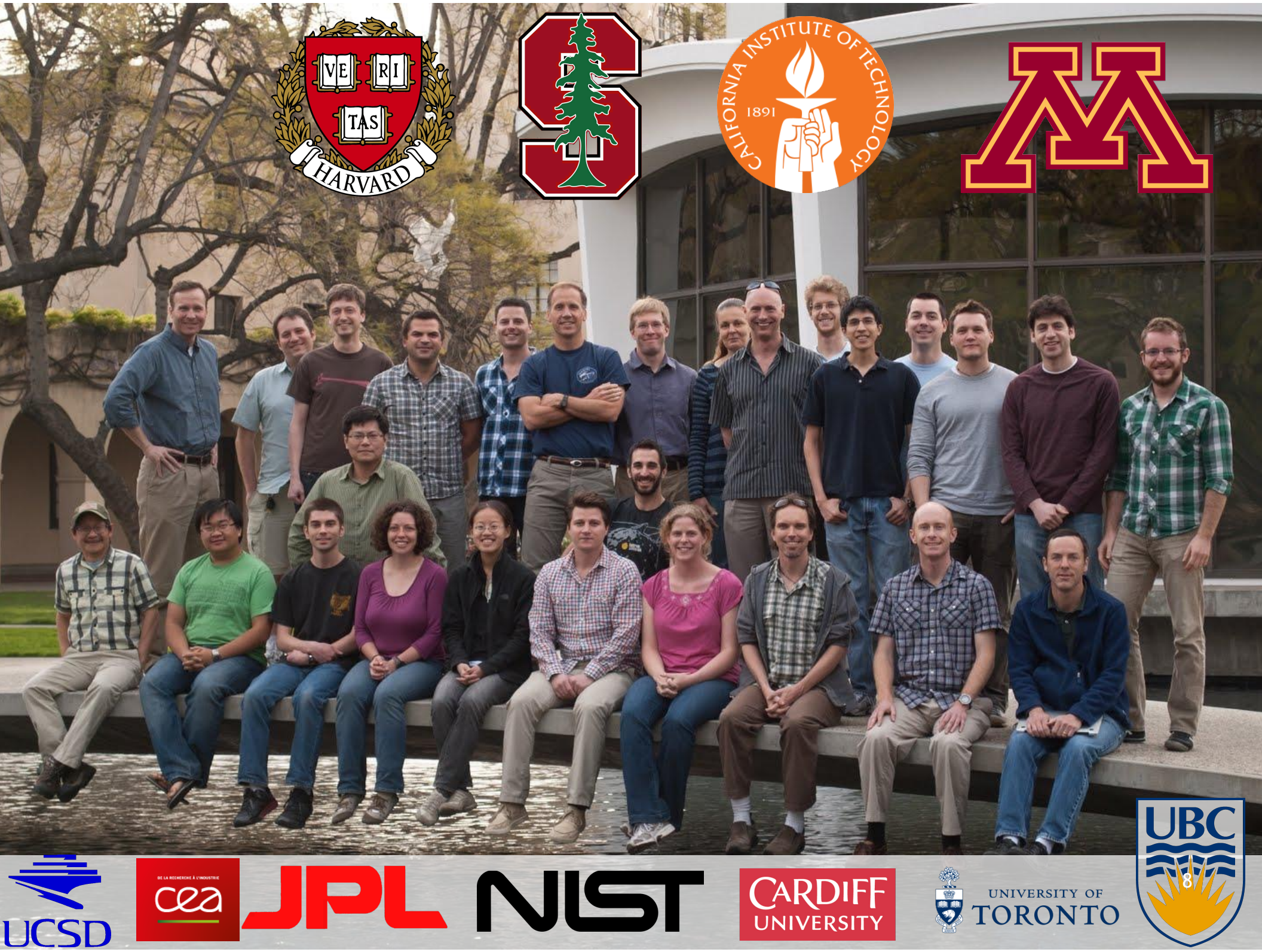


B-mode Power Spectrum on March 10, 2014

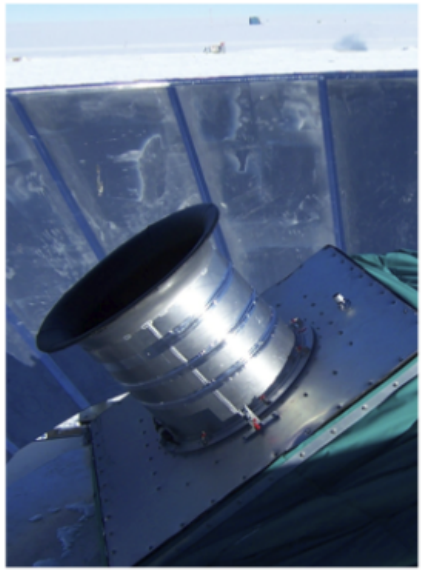


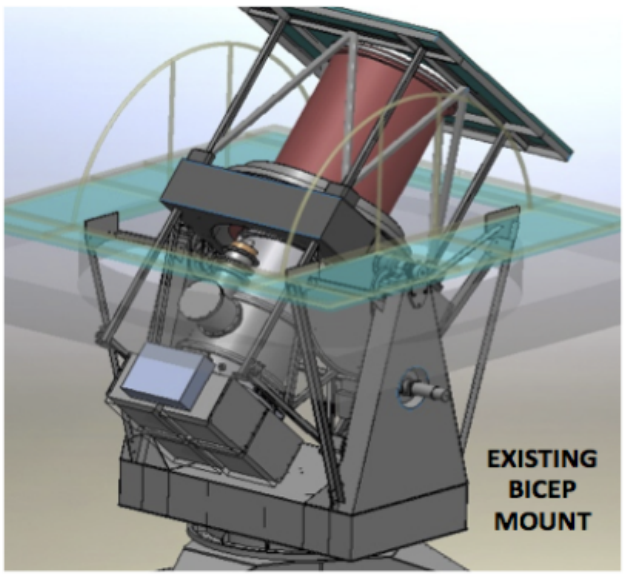
B-mode Power Spectrum on 17 March 2014

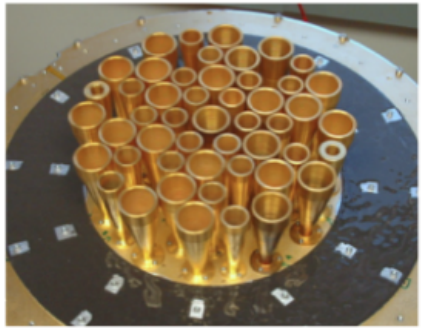


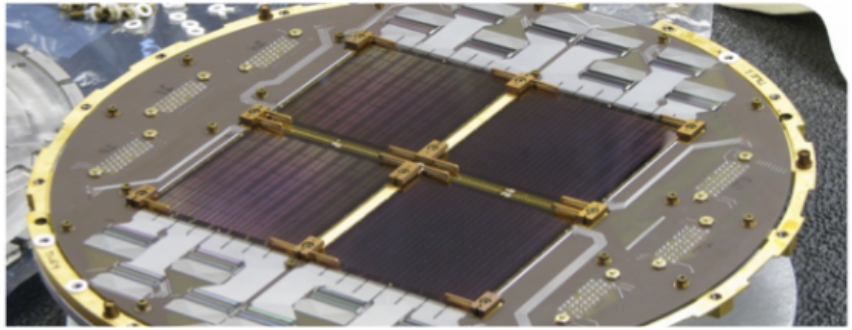

VE RI TAS
HARVARD
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
UCSD
cea
DE LA RECHERCHE À L'INDUSTRIE
JPL
NIST
CARDIFF UNIVERSITY
UNIVERSITY OF TORONTO
UBC

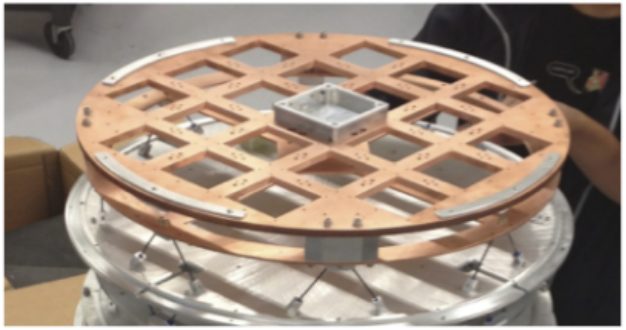
BICEP1 (2006 - 8)	BICEP2 (2010 - 12)	Keck Array (2011 -)	BICEP3 (2014 -)

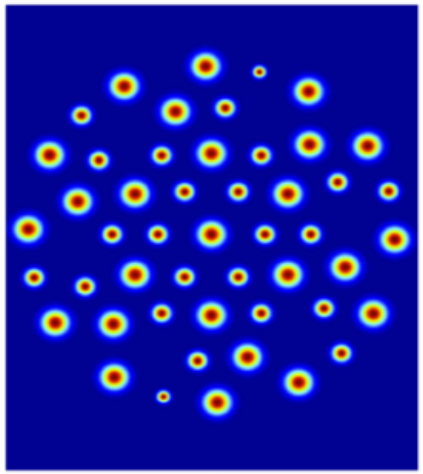


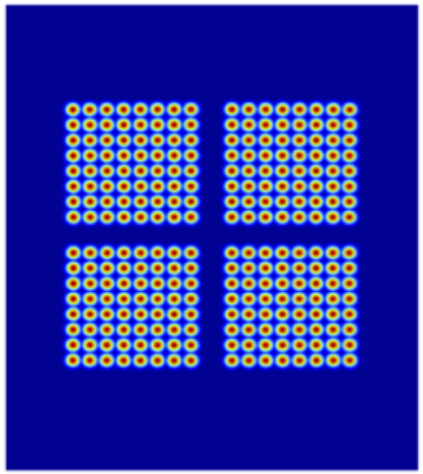


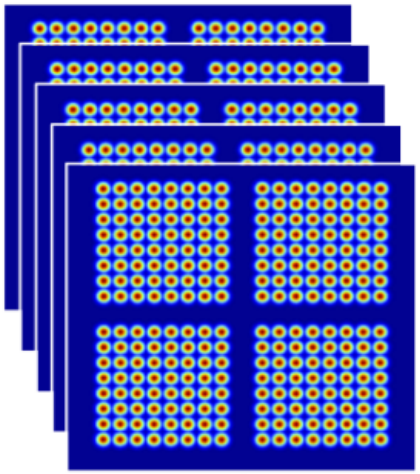


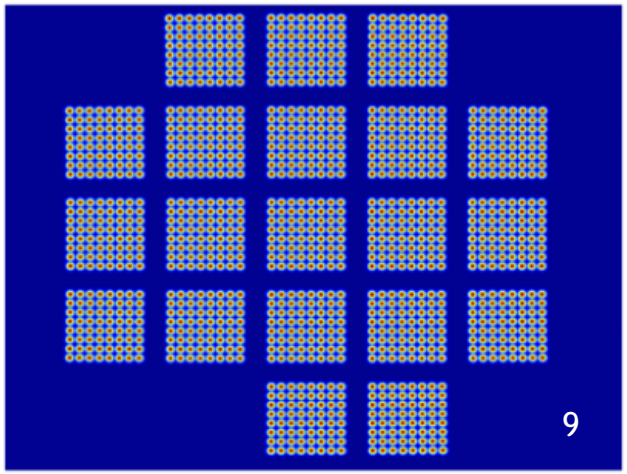












POLARBEAR Collaboration

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Yasuto Hori
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Suguru Takada

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Peter Ade

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David Boettger
Rolando Dunner

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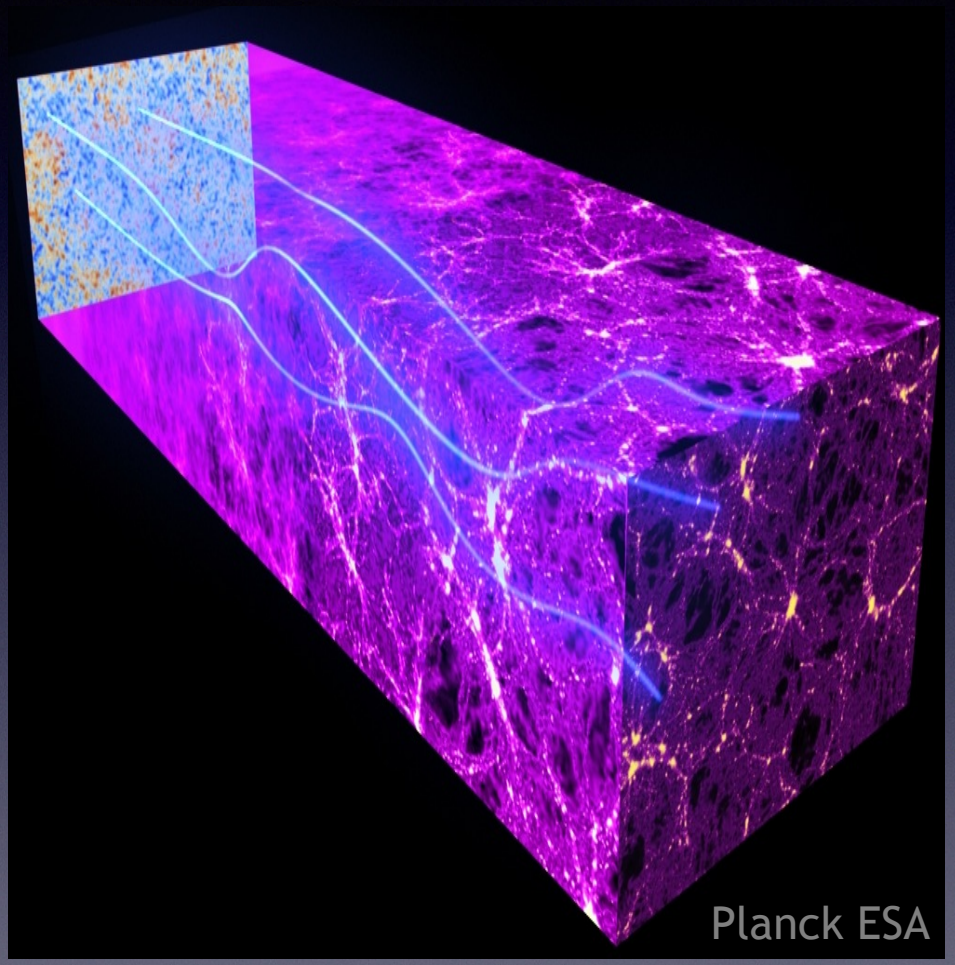
Lensing

- CMB photons are gravitationally lensed by large scale structure.
- Many small deflections deflect the CMB.
- Converts some E-modes into small scale B-modes.

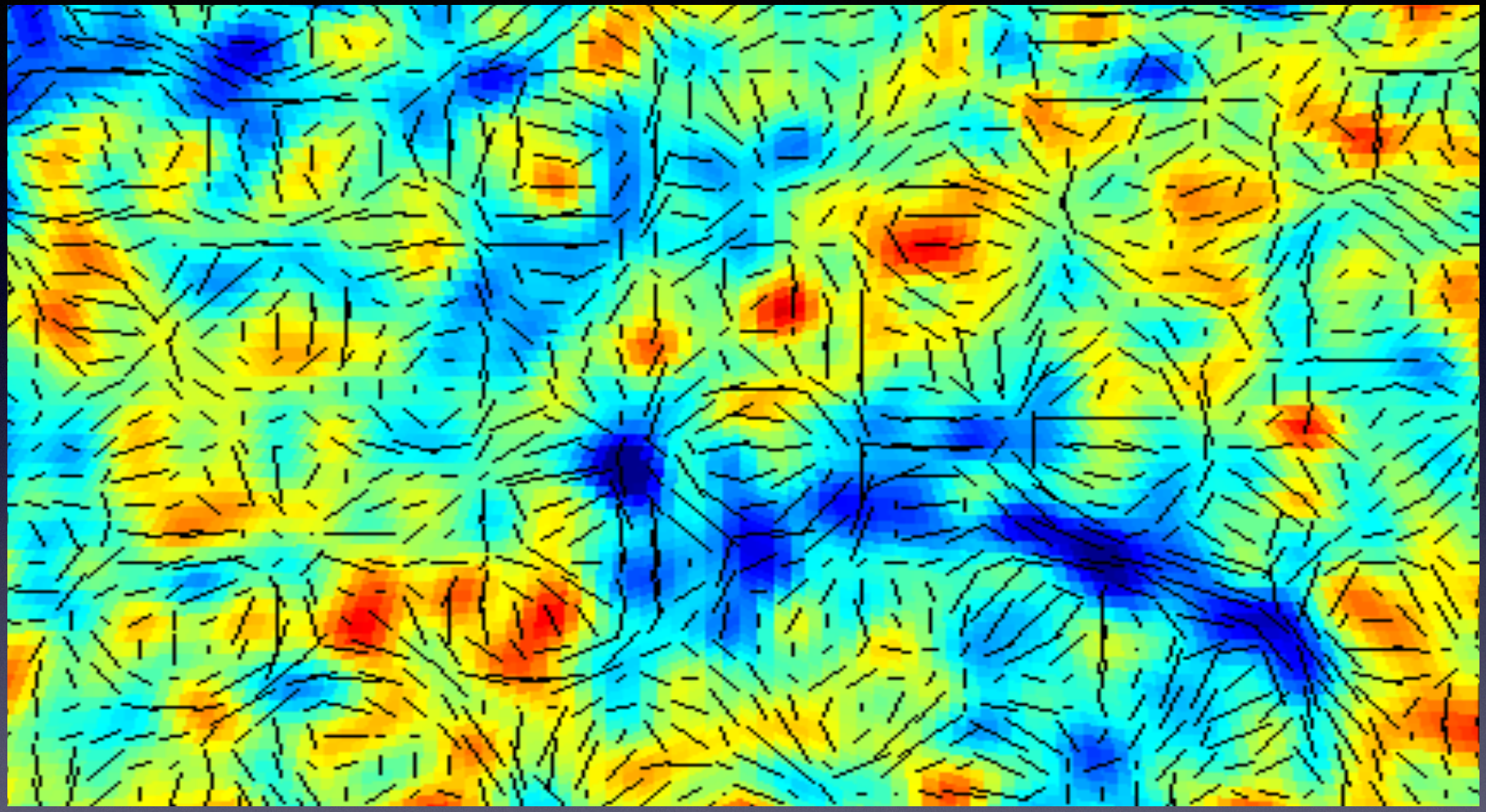


$$B(\mathbf{l}) = \int d\mathbf{l}'[\mathbf{l}' \cdot (\mathbf{l}' \hat{-} \mathbf{l}) \cos(2\phi_{\mathbf{l},\mathbf{l}'})] E(\mathbf{l}') d(\mathbf{l}' - \mathbf{l})$$

Seljak 1996

“Blink and You’ll Miss It!”

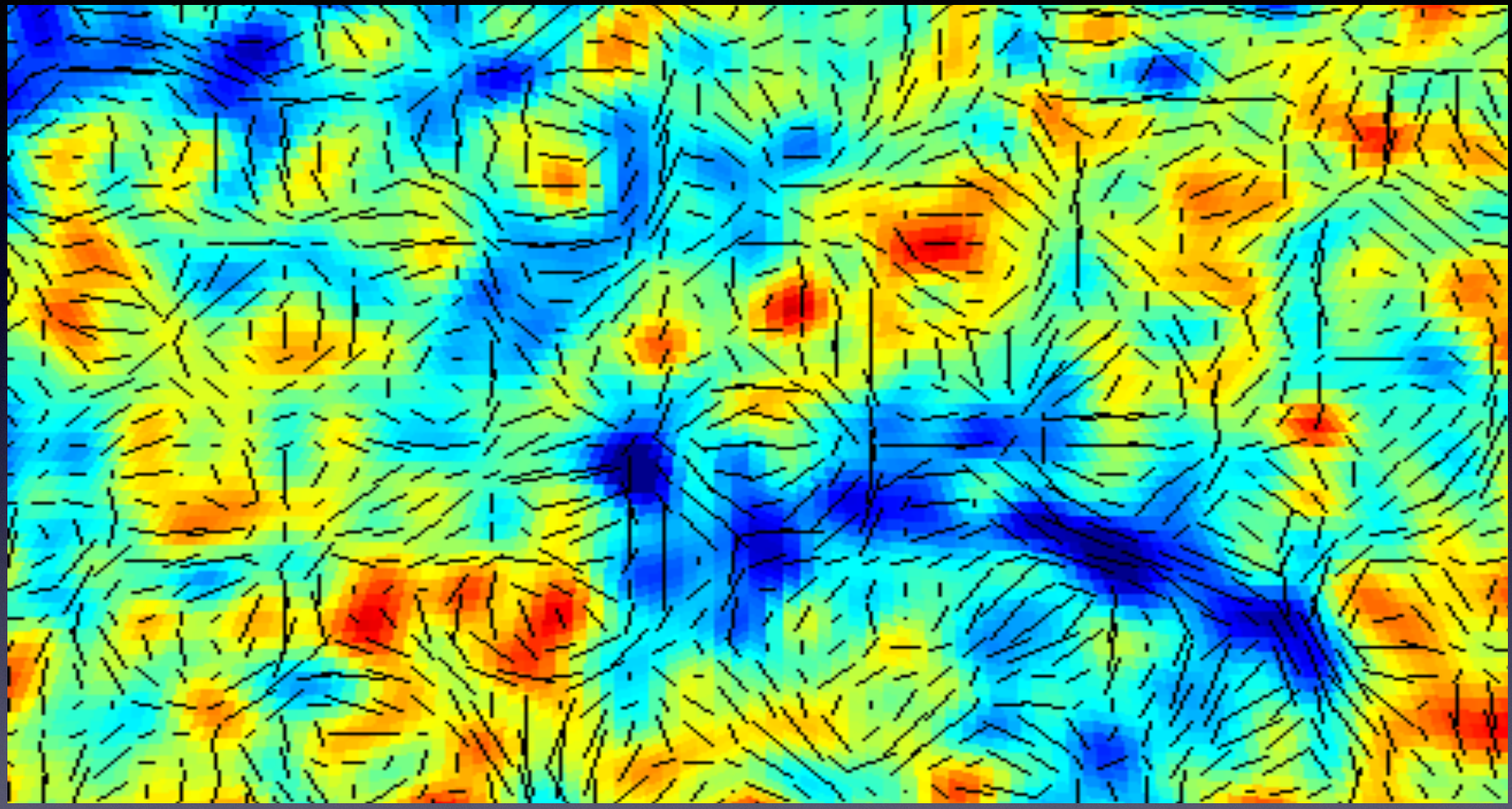
10°



Without B-modes

“Blink and You’ll Miss It!”

10°

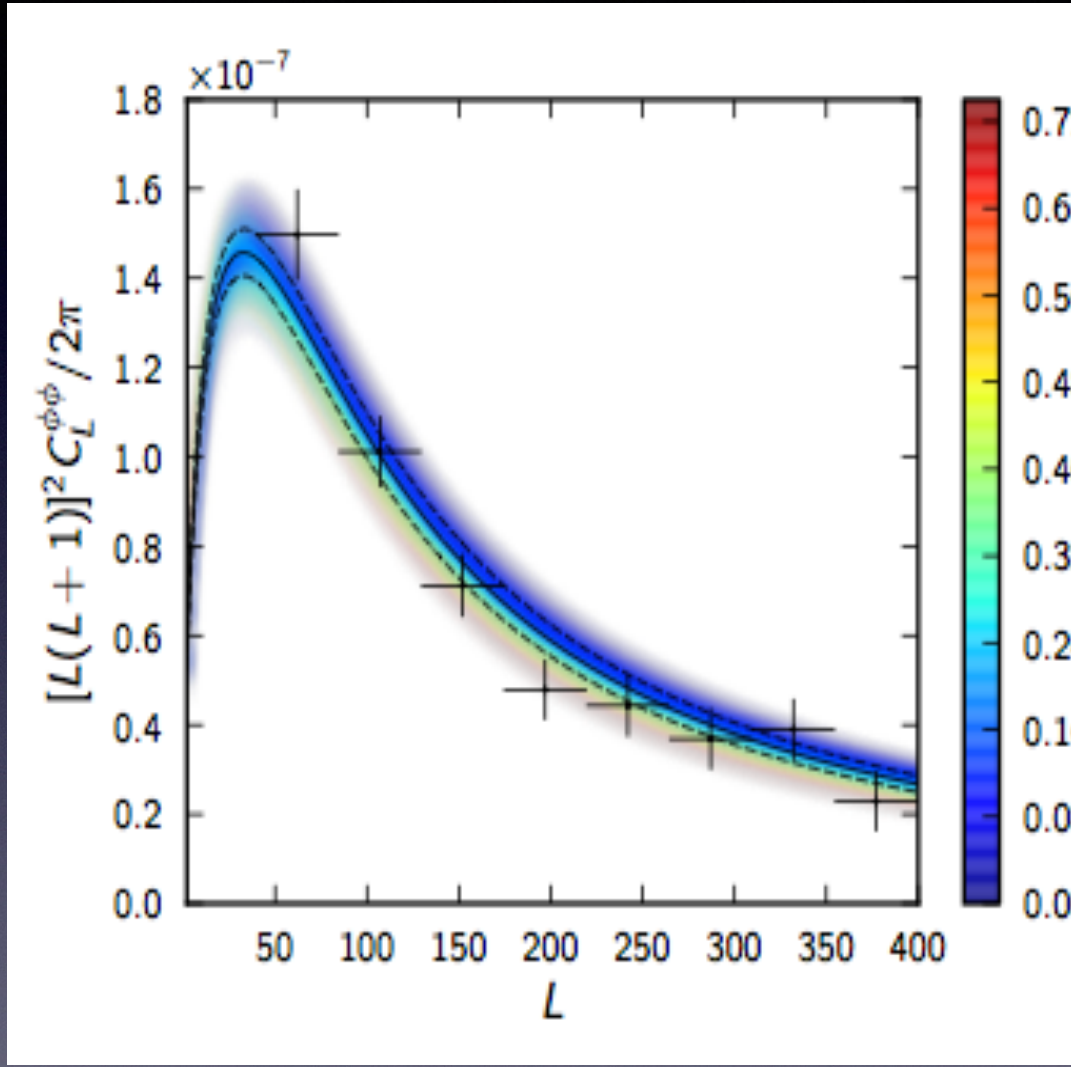


Each photon is deflected by a few arcminutes but the structures responsible for lensing are coherent over ~3º scales.

With B-modes From Gravitational Lensing!

Neutrinos

- We know there are only ~3 relativistic Fermions which are cosmologically relevant.
- At least one of the three neutrinos has mass (from neutrino oscillation experiments).
- Oscillation experiments are only sensitive to the square of the mass differences.
- Cosmological probes are sensitive to the sum of all three masses. The more massive the neutrinos are, the larger the suppression at small angular scales.



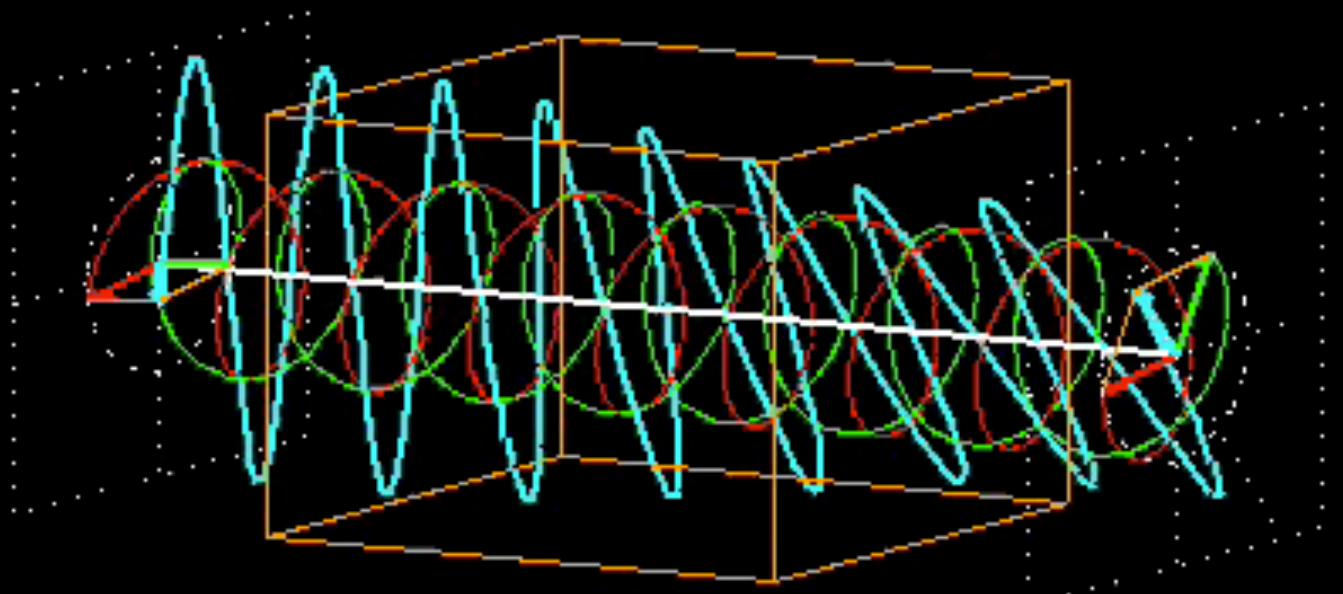
Neutrino mass and (possible) chemical potential affect structure formation.

Magnetic Motivation

- Magnetic fields detected in >100 galaxies & clusters.
- Upper and Lower limits exist on cosmological, primordial magnetic fields (PMF).
- Limits are10-100x below galactic & cluster fields, suggesting that magnetic fields are amplified, if not created, in structure formation.
- There are no detections of purely cosmological fields (i.e., fields not associated with gravitationally bound or collapsing structures)

Pogosian (2009)
Yadav, Shimon, & Keating (2012)

Cosmic Birefringence



Rotation of the polarization plane $\Rightarrow$
mixing Q and U $\Rightarrow$
converting $E \rightarrow B \Rightarrow$
inducing `forbidden' TB and EB

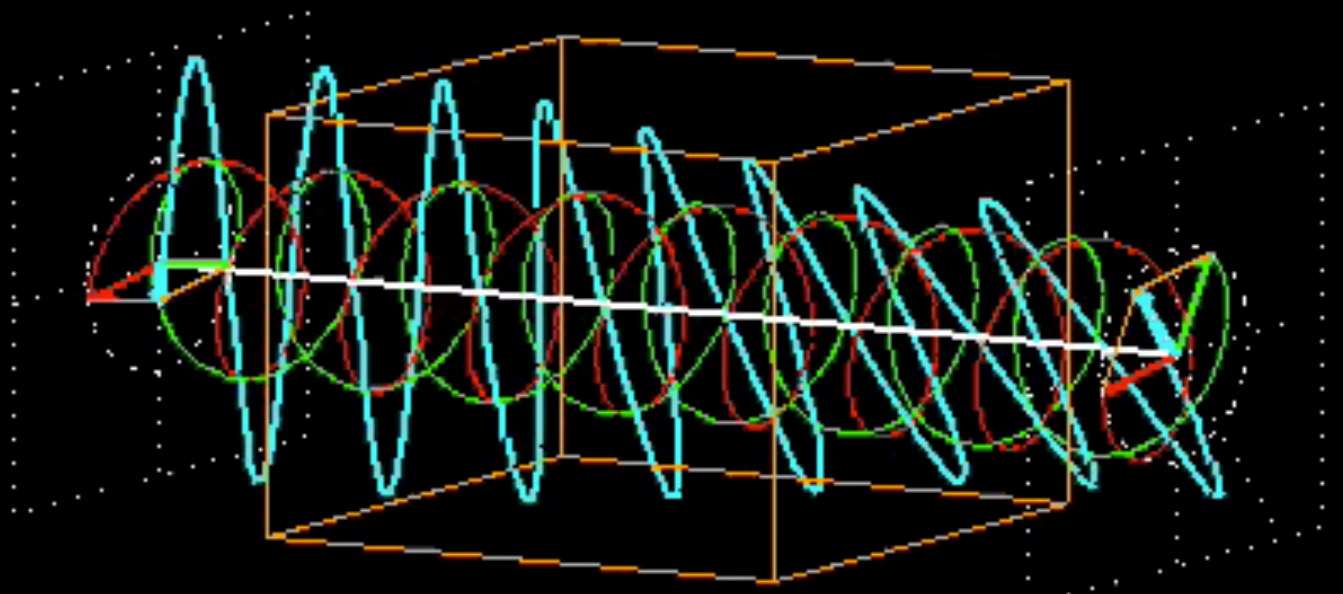
Komatsu et al. (2009)

Wu et al. (2009)

Miller, Shimon & BK (2009)
Alexander & Yunes (2009)

Kaufman et al. BICEP1 (2014)
Kaufman, Keating, & Johnson (2014)

Cosmic Birefringence



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Kaufman, Keating, & Johnson (2014)

Exotic: Parity Violating Interactions

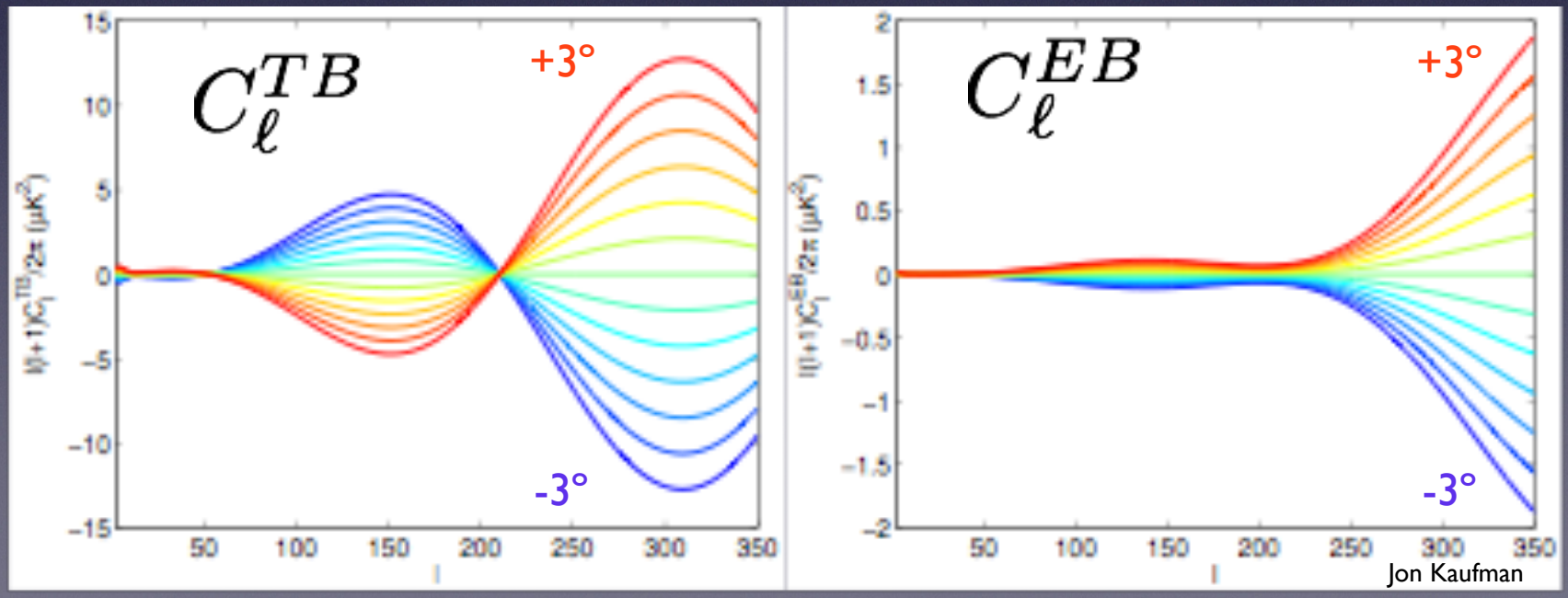
Modify the Electromagnetic Lagrangian (Carroll, Field & Jackiw 1990)

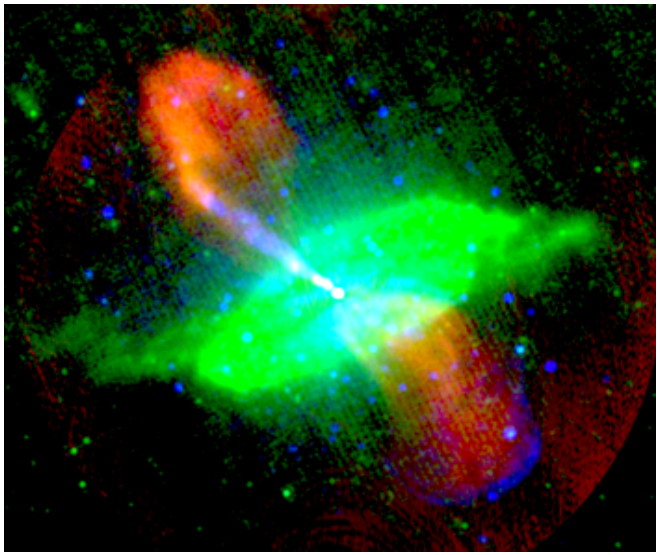
$$\mathcal{L} \propto E^2 - B^2 \rightarrow E^2 - B^2 + g\vec{E} \cdot \vec{B}$$

$$\omega^2 = k^2 \pm (4\pi g_\chi \dot{\chi} k)$$

Produces two different phase velocities; one for LCP, on for RCP:

The superposition of the two circular polarizations causes rotation of the plane of linear polarization. Produces "forbidden" spectra!





Radio galaxy polarization

- Polarized via synchrotron emission
- If spatial geometry is known, we can infer the expected polarization axis
- Must be corrected for Faraday rotation
- Only a statistical relationship

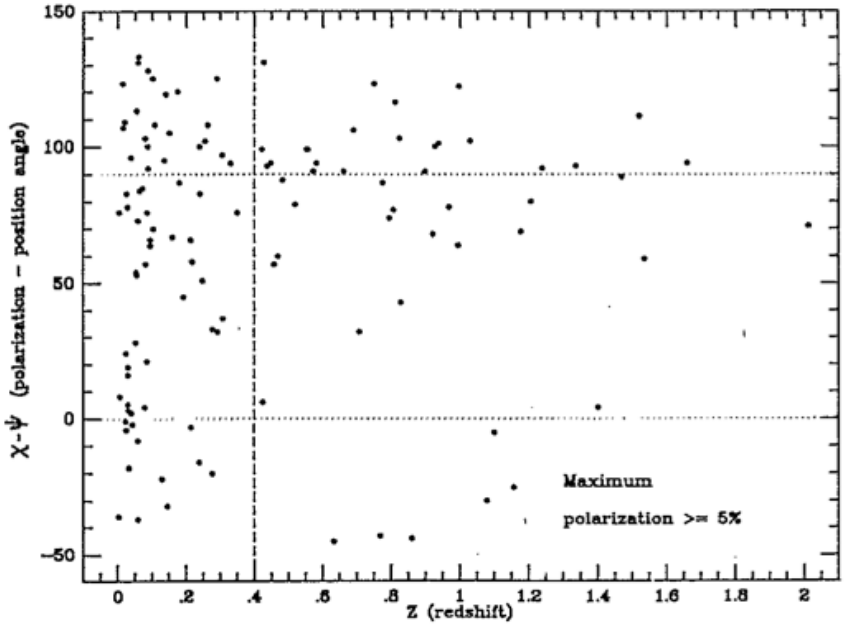


FIG. 1. The polarization angle χ minus the position angle ψ of the galaxies with maximum polarizations $p_{max} = 5\%$, plotted vs redshift z. It is clear that the data are grouped around the horizontal lines at 0° and 90°, even at large redshift. The vertical line at $z = 0.4$ indicates the point beyond which we searched for deviation from these values.

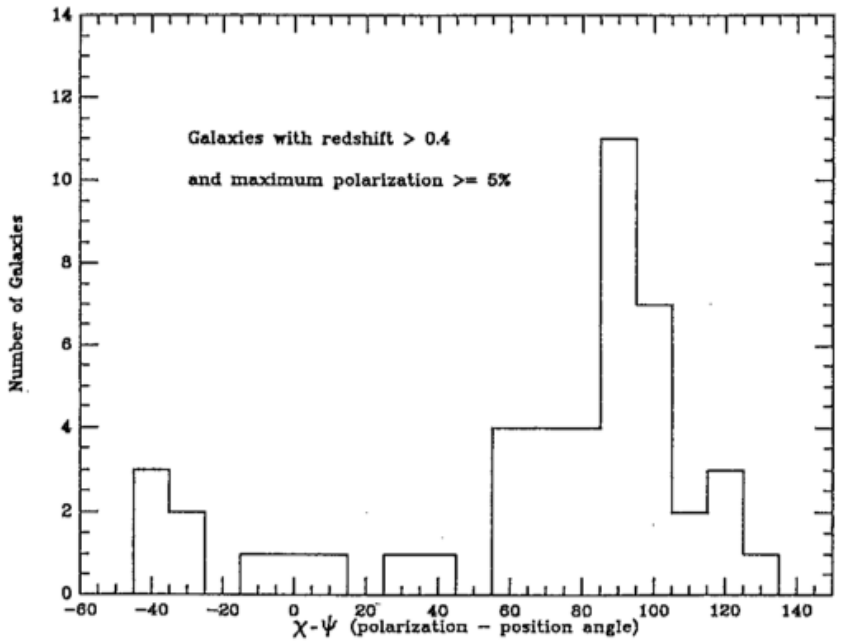


FIG. 2. A histogram of number of galaxies vs $\chi - \psi$, in bins of 10°, for those sources with $p_{max} >= 5\%$ and $z > 0.4$. The peak near 90° is obvious.

Crazy?

(1) Birefringence and Lorentz-violation: http://prd.aps.org/abstract/PRD/v41/i4/p1231_1
Jackiw, Field, & Carroll

(2) Birefringence, Inflation and Matter-Antimatter asymmetry: http://arxiv.org/pdf/hep-th/0403069.pdf
Michael Peskin, Stephon Alexander

(3) Chern-Simons Inflation and Baryogenesis http://arxiv.org/pdf/1107.0318.pdf
David Spergel, Stephon Alexander

(4) Birefringence and Dark Energy: http://arxiv.org/pdf/1104.1634.pdf
Marc Kamionkowski

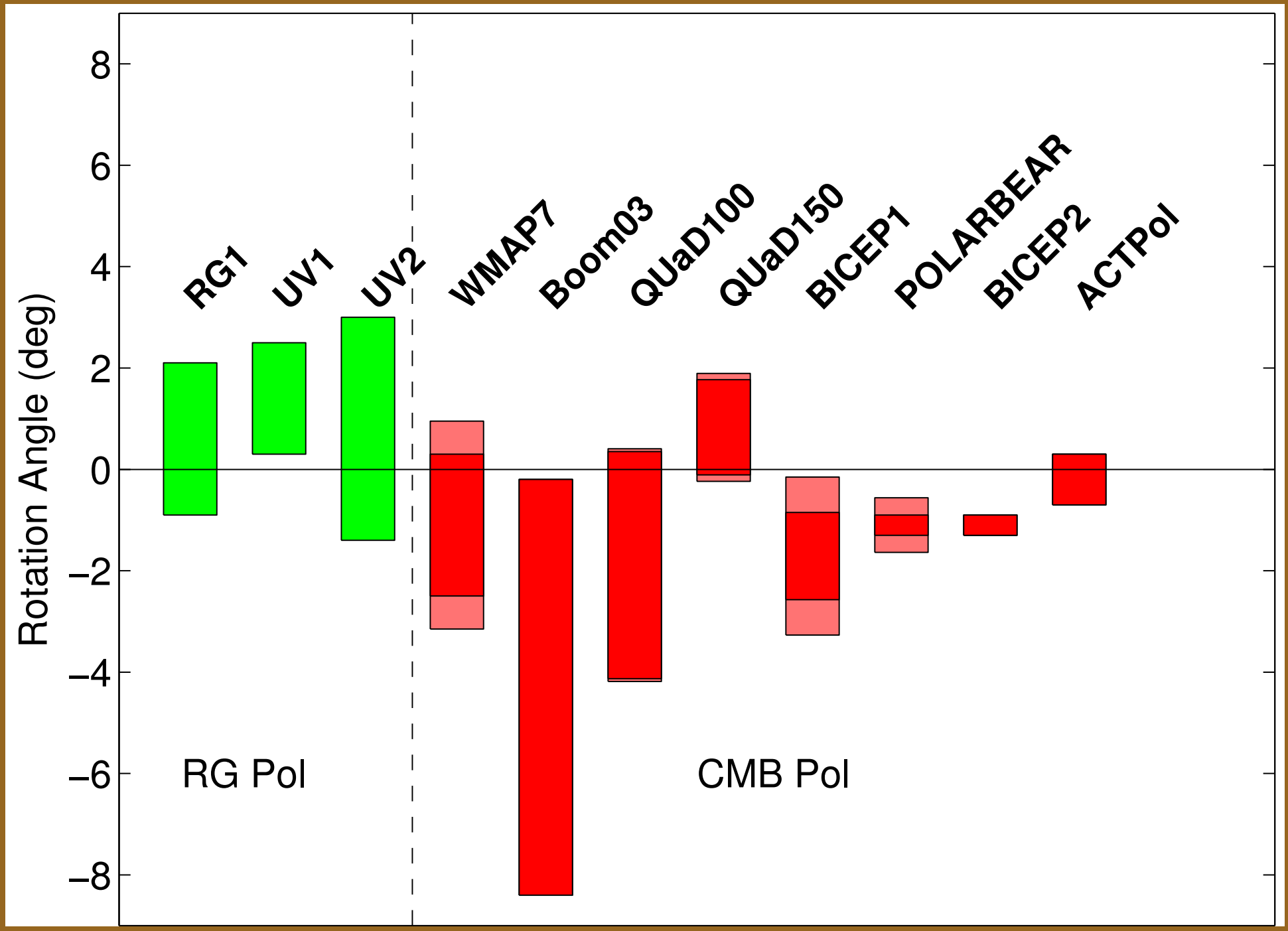
(5) Birefringence and Dark Matter detection http://arxiv.org/pdf/astro-ph/0611684v3.pdf
Susan Gardner

(6) Chern-Simons birefriencence and quantum gravity: http://ccdb5fs.kek.jp/cgi-bin/img/allpdf?198402145 ***Edward Witten***

(7) Anomalous CMB polarization and gravitational chirality: http://lanl.arxiv.org/abs/0806.3082
Lee Smolin

(8) Kolb & Turner (1990)

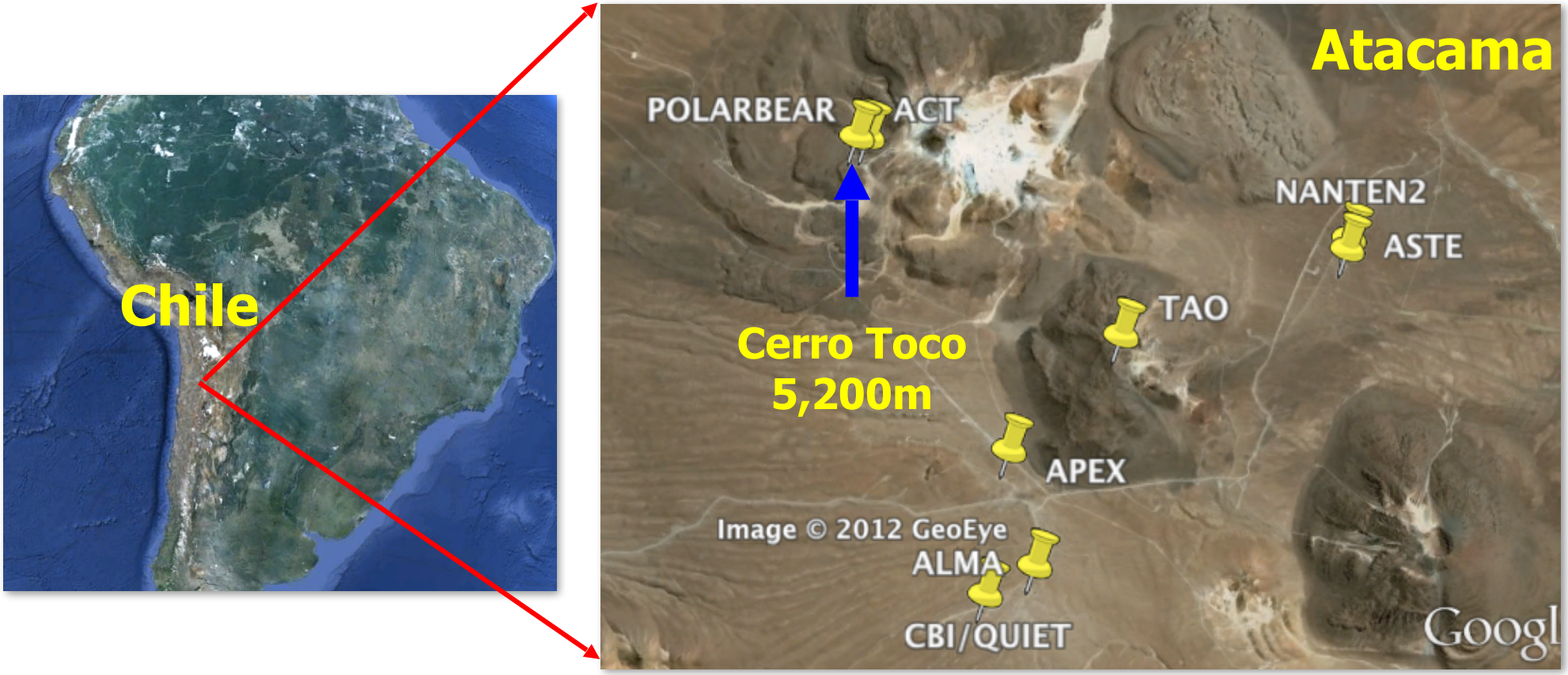
(9) Kaufman, Keating, Johnson: Precision Tests of Parity Violation Over Cosmological Distances (http://arxiv.org/abs/1409.8242**)**



arXiv 1409.8242

POLARBEAR Experiment

- Observing from the James Ax Observatory in the Atacama desert in Northern Chile on Cerro Toco (altitude 5,200m) since January 2012



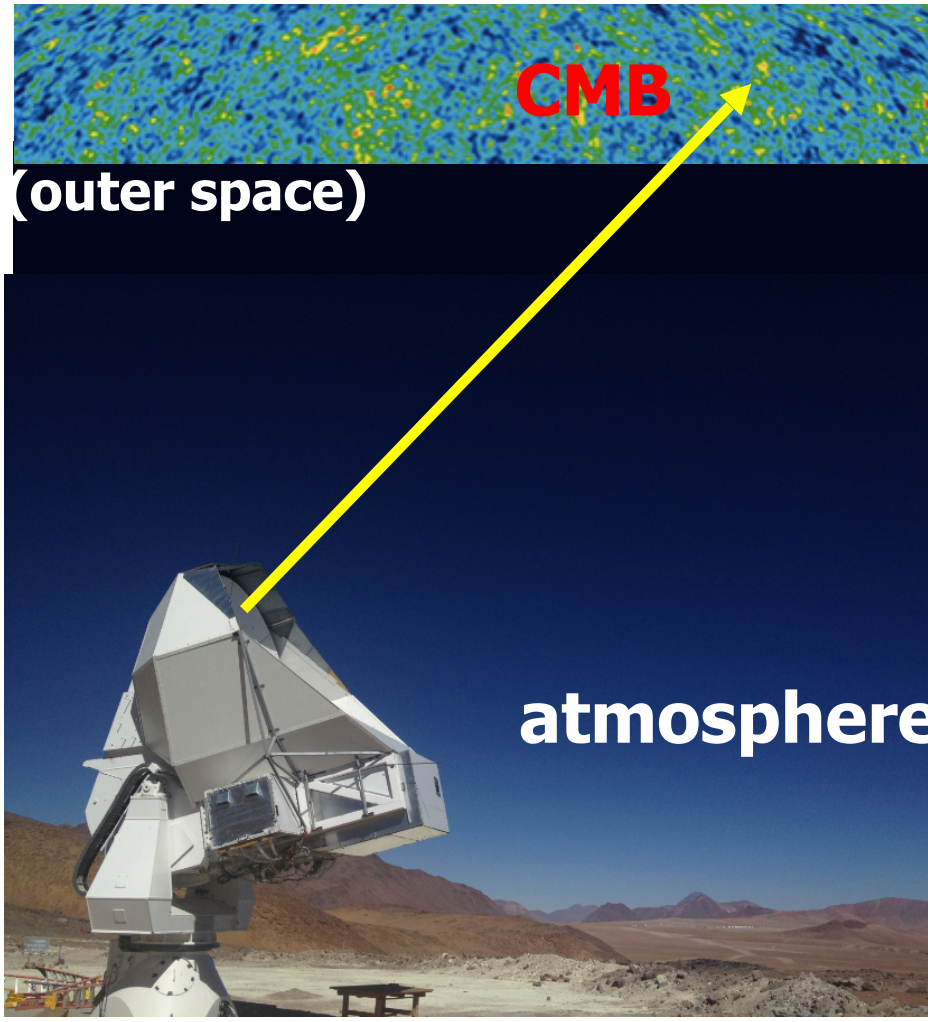
The James Ax Observatory in the Atacama desert

- Low pressure
- Very dry (usually) all year
- Good weather (almost) all year

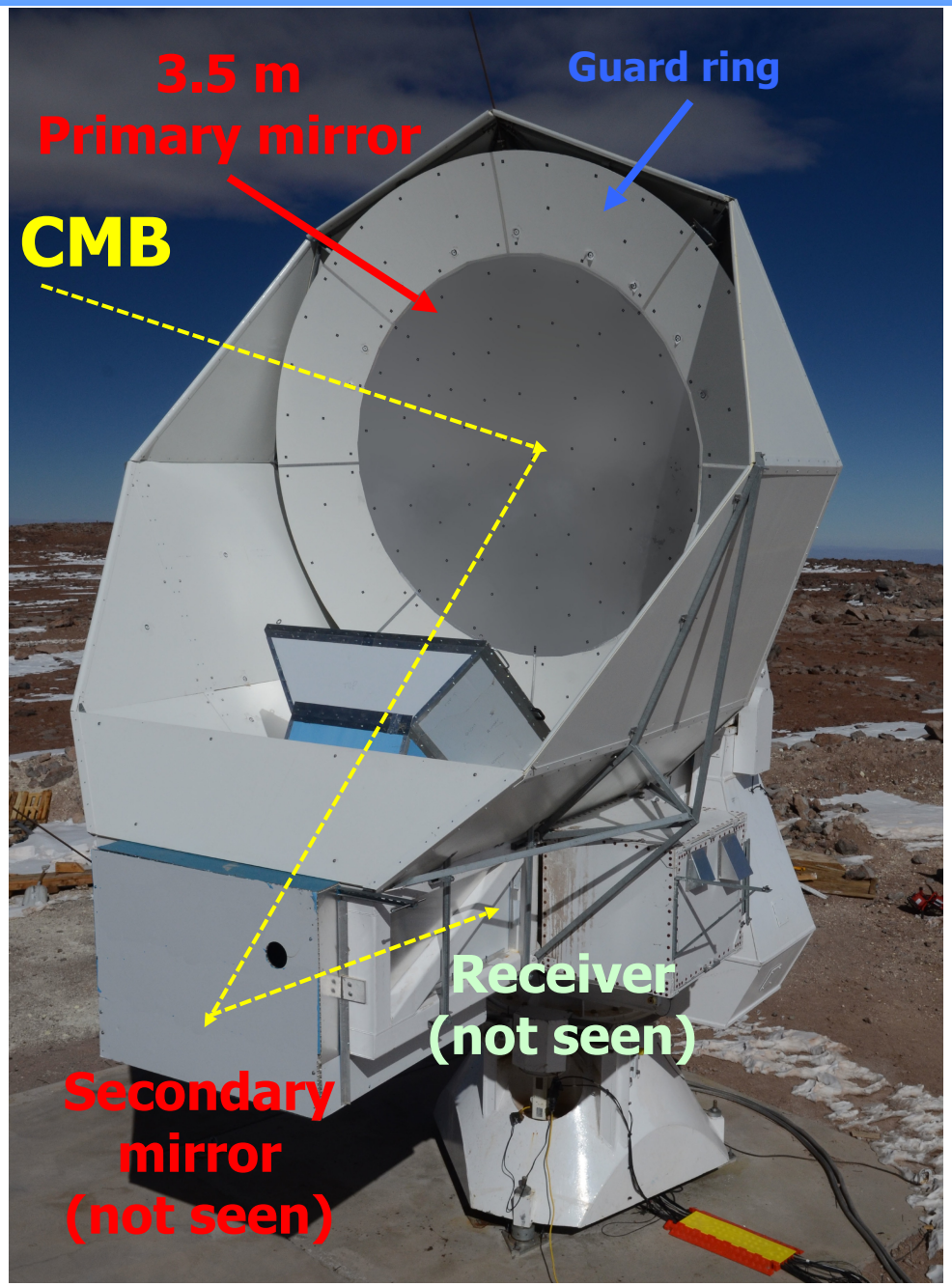
Low atmospheric noise

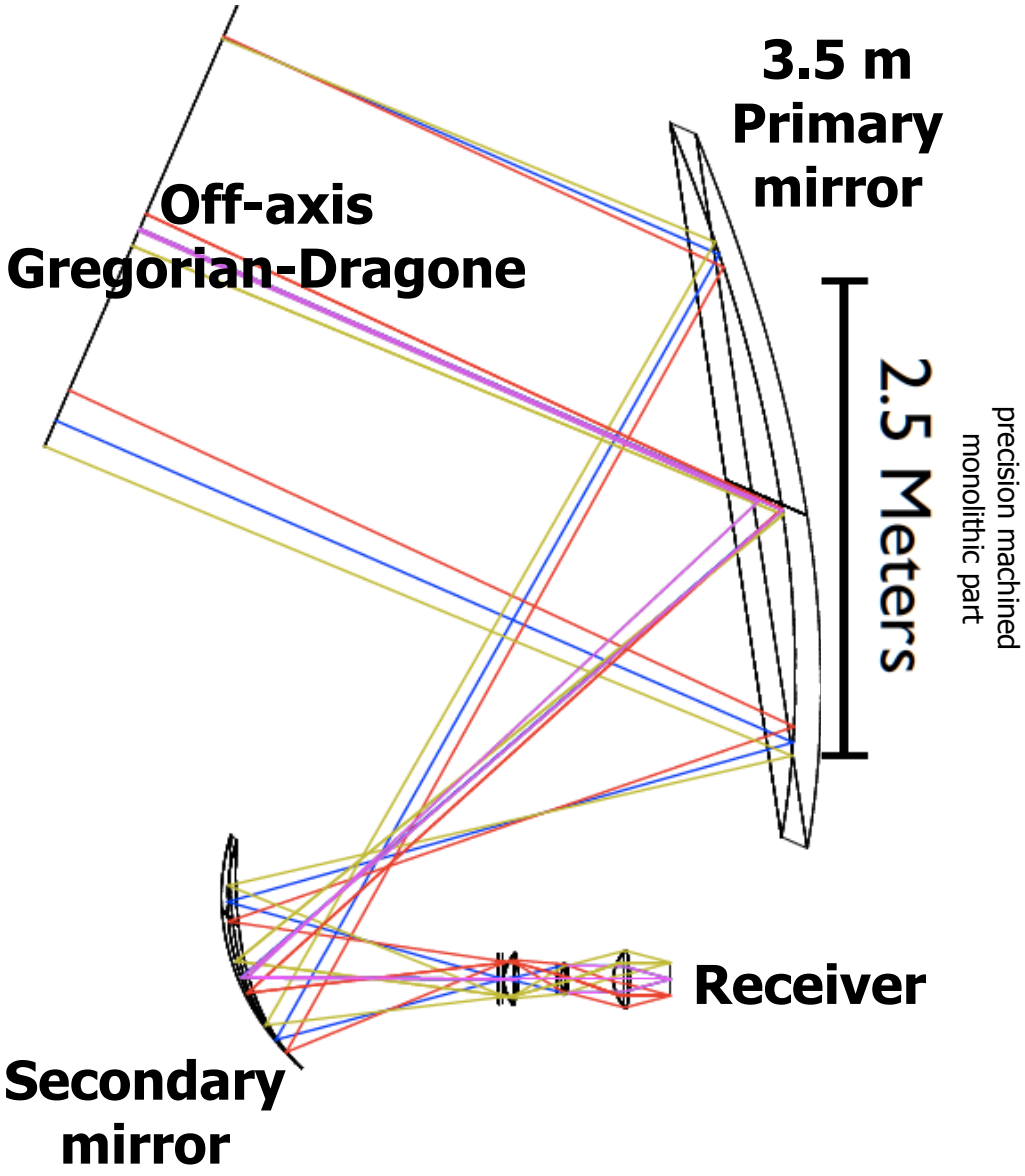
- ~1 hour drive from San Pedro de Atacama (nearest town)
- Observe throughout the year (as well as day & night)

Necessary because we needed >1000 hrs integration time to detect B-mode

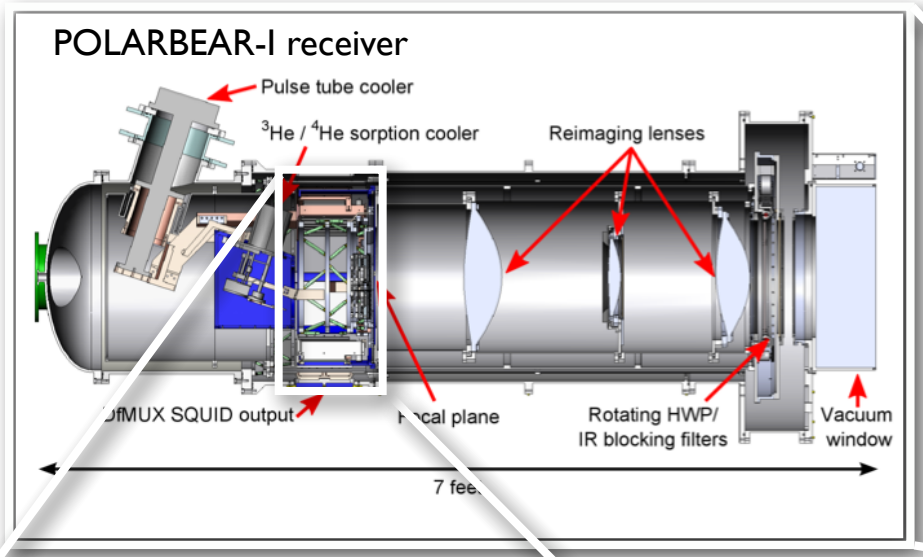


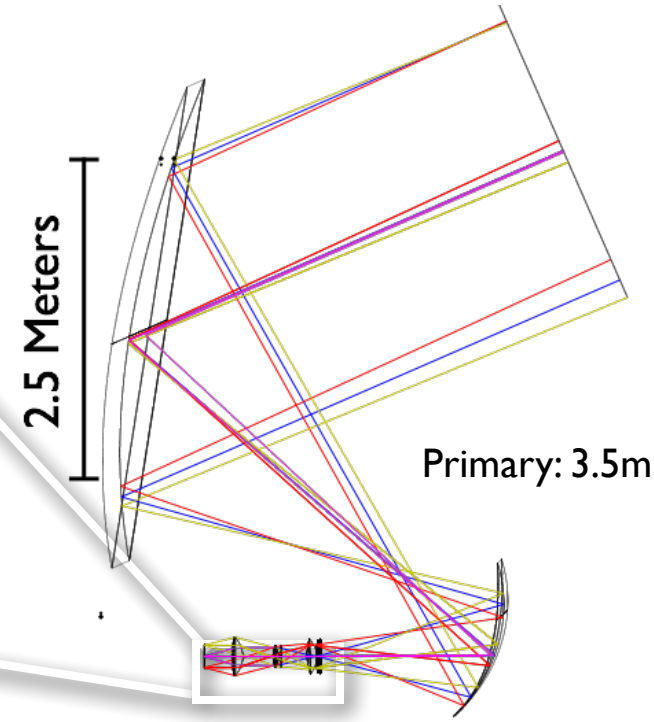
Telescope（Huan Tran Telescope）





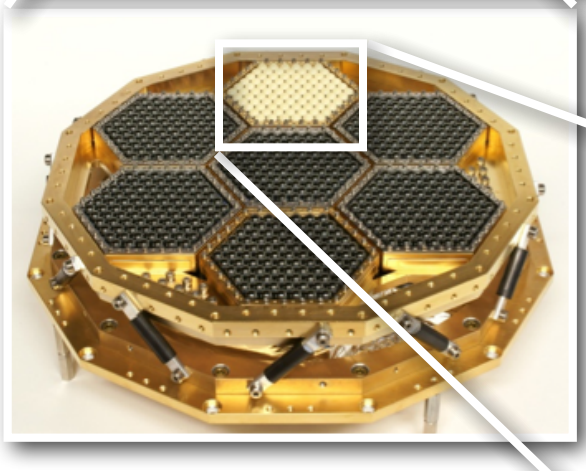
Instrument design





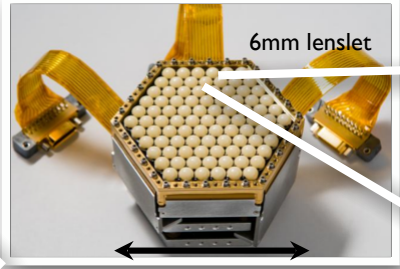
Huan Tran Telescope

Focal plane

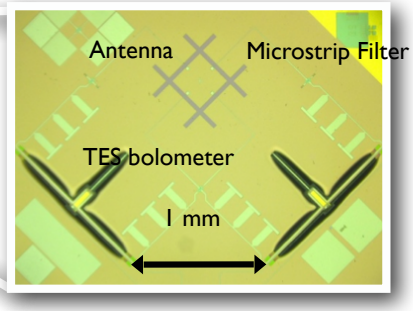


1274 bolometers @ 150 GHz
Cooled to 25 mK

Hex Module

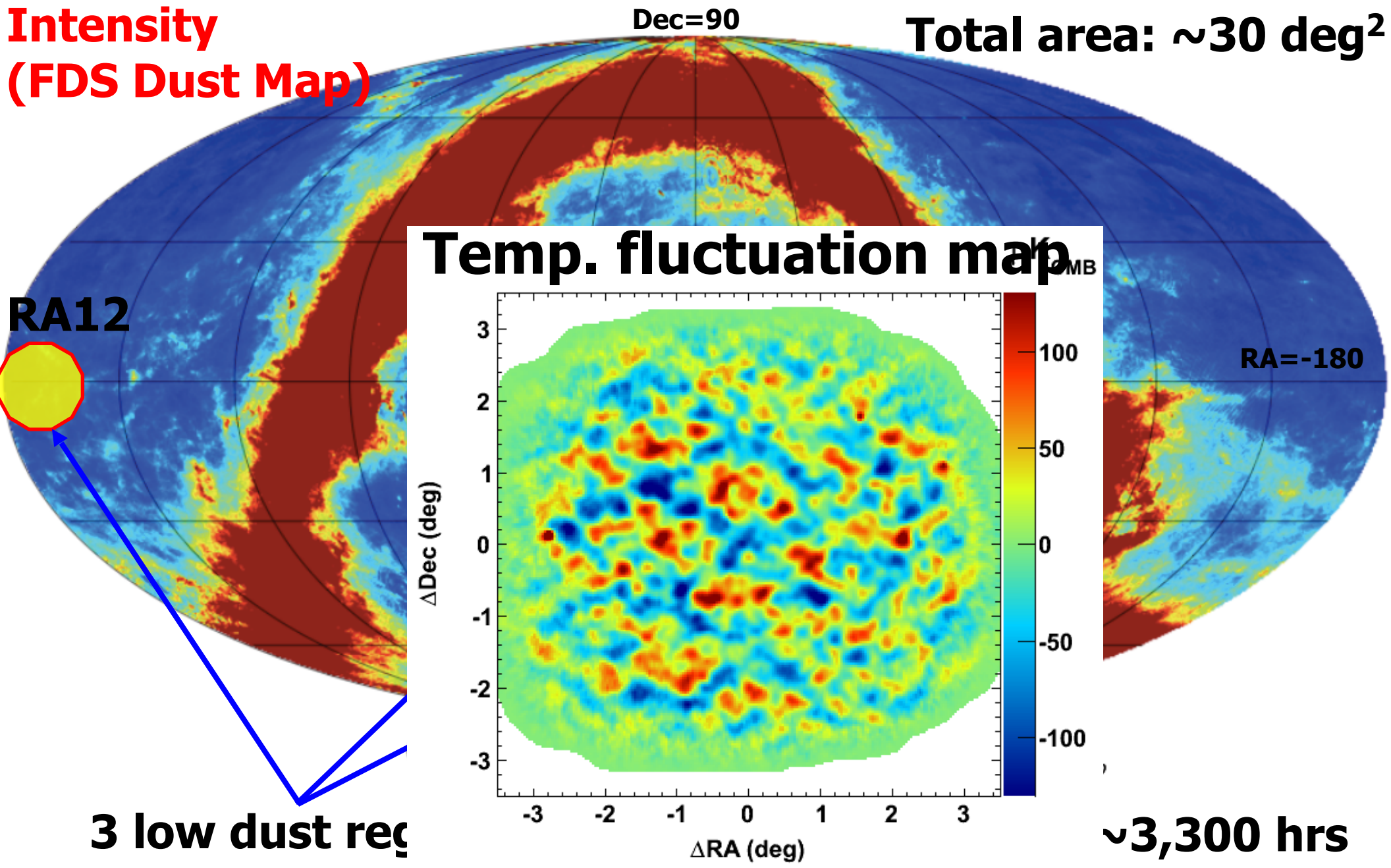


8cm



Observations in 2012 & 2013

Intensity (FDS Dust Map)

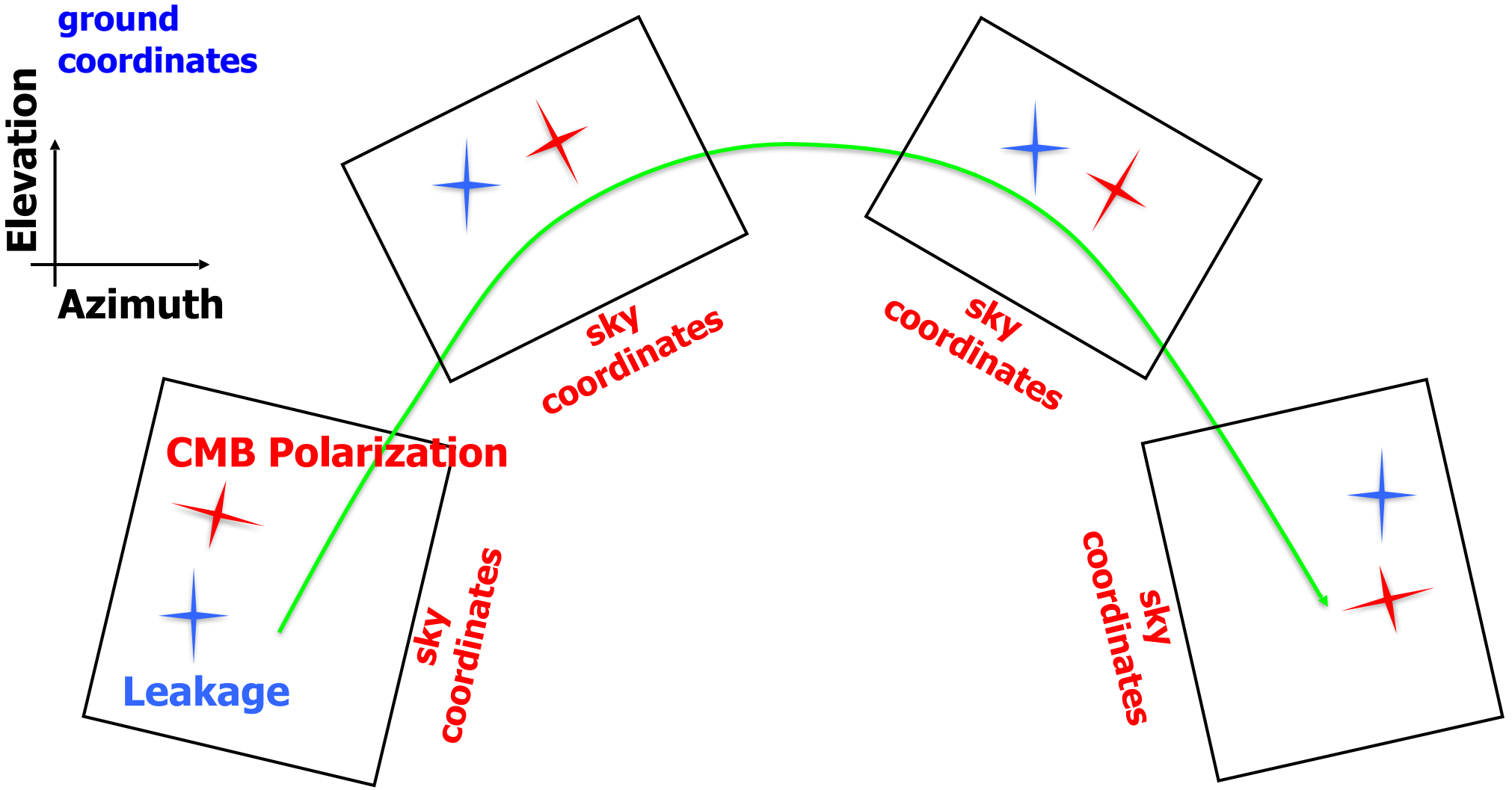


Total area: ~30 deg^2

3 low dust reg

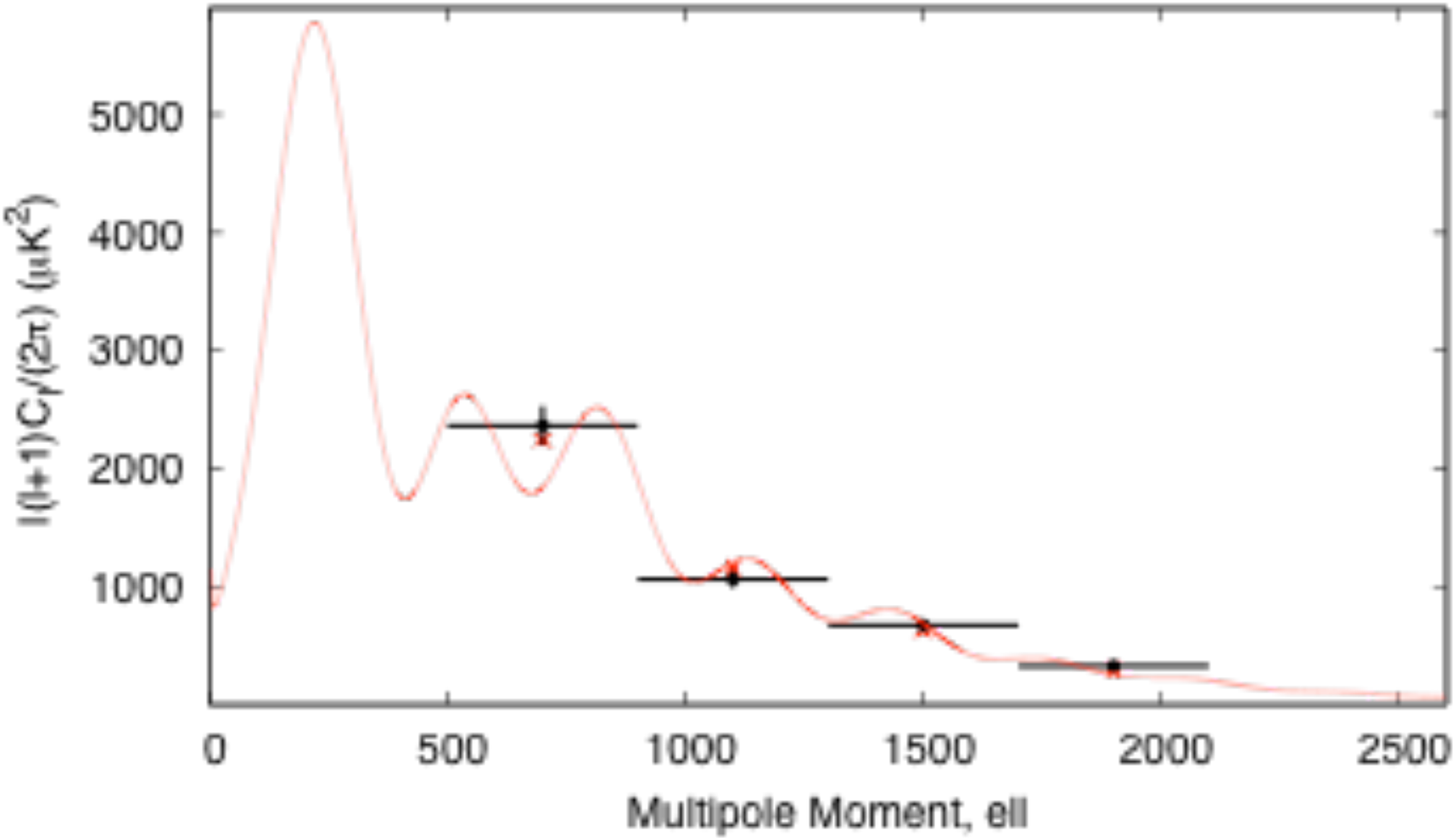
~3,300 hrs

Leakage Suppression by Sky Rotation



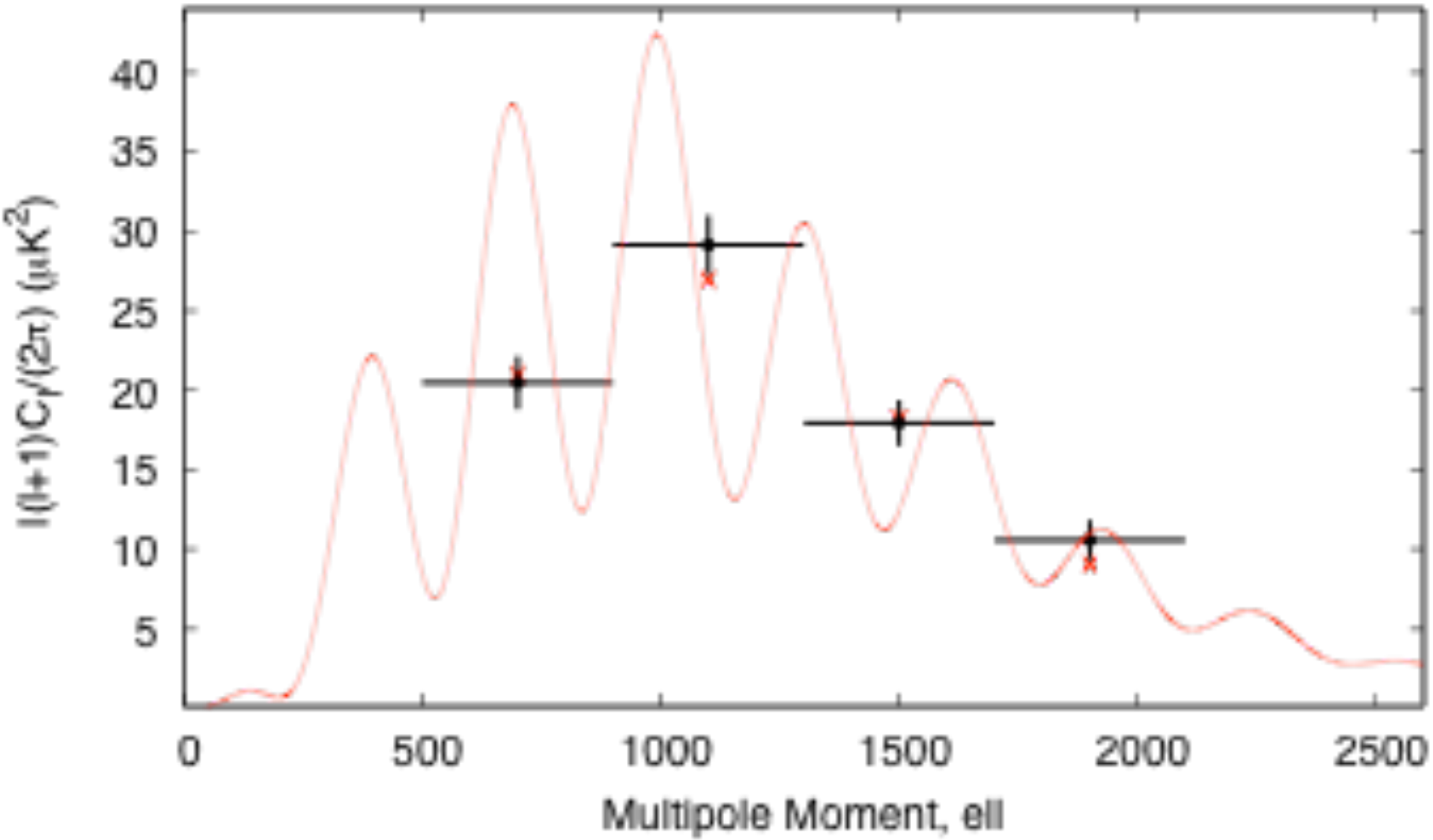
- CMB signal is fixed with respect to the sky (doesn't rotate)
- Leakage signal is NOT fixed with respect to sky coordinates, but fixed with respect to ground coordinates: leakage is reduced due to sky rotation.

Temperature Power Spectrum (TT)



consistent w/ LCDM model

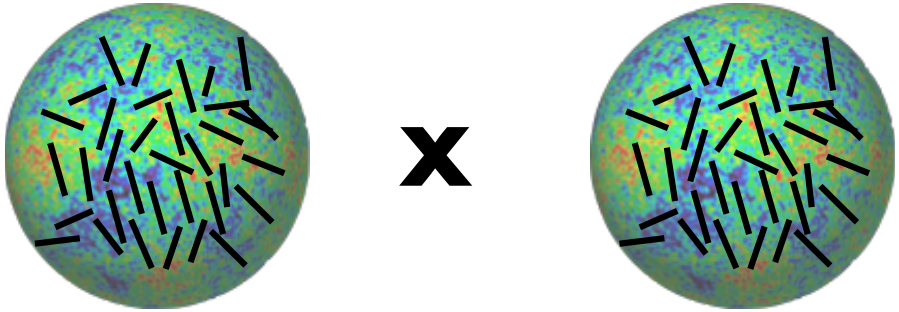
E-mode Power Spectrum (EE)



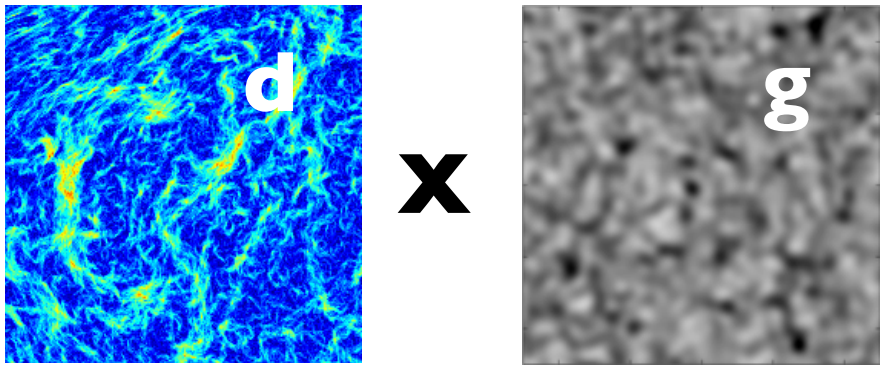
consistent w/ LCDM model

Three-fold evidence for B-modes…4.3\sigma from CMB alone

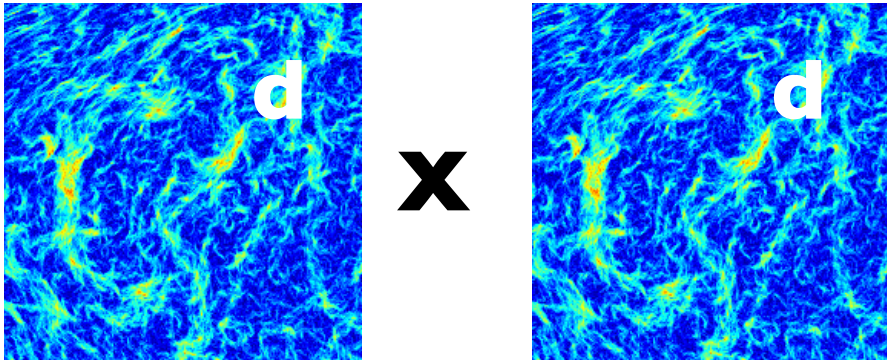
- 2-point correlation:
  CMB BB power spectrum
  (ApJ October 2014)
  arXiv:1403.2369



- 3-point correlation:
  CMB cross correlation with biased tracers of dark matter halos
  (PRL vol. 112, "Editors' Suggestion")
  arXiv:1312.6646



- 4-point correlation: polarized lensing reconstruction (PRL vol. 113, "Editors' Suggestion")
  arXiv:1312.6645



B-mode derived lensing cross-power spectrum
Polarization Lensing × Infrared Background (CIB)

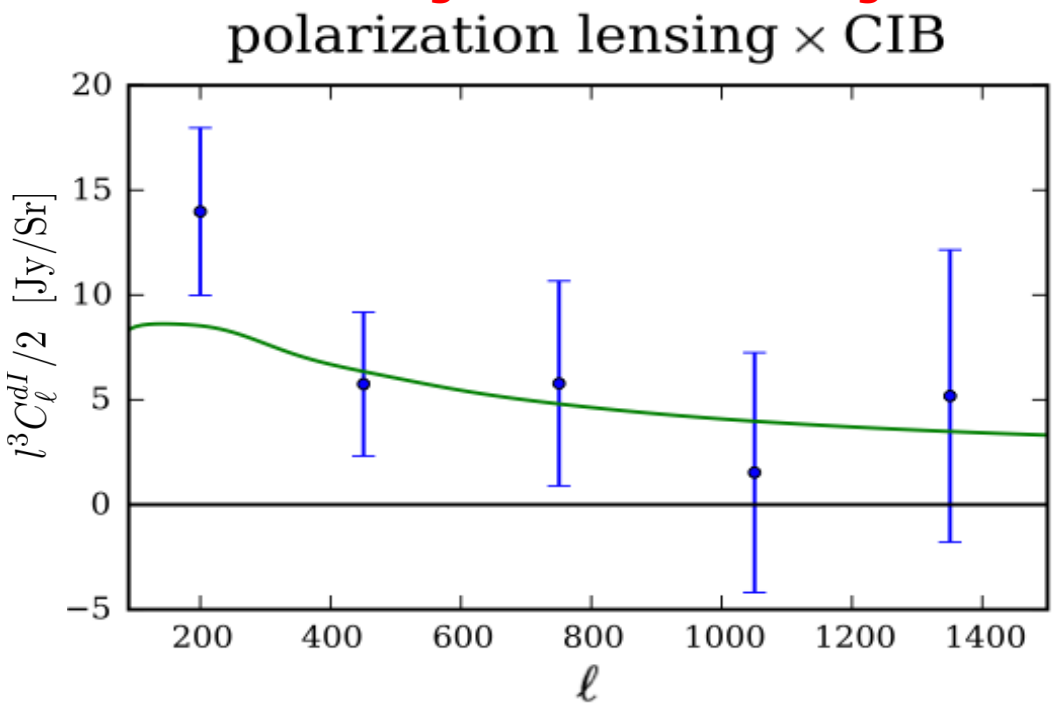
by POLARBEAR

- 4 sigma detection: early measurement of polarization lensing / B-modes (with Hanson et al. 2013)
  - 2.3 sigma if only EB

- Robust: systematics don't correlate because CIB by Herschel satellite & lensing B-mode by POLARBEAR are completely different measurements

by Herschel satellite

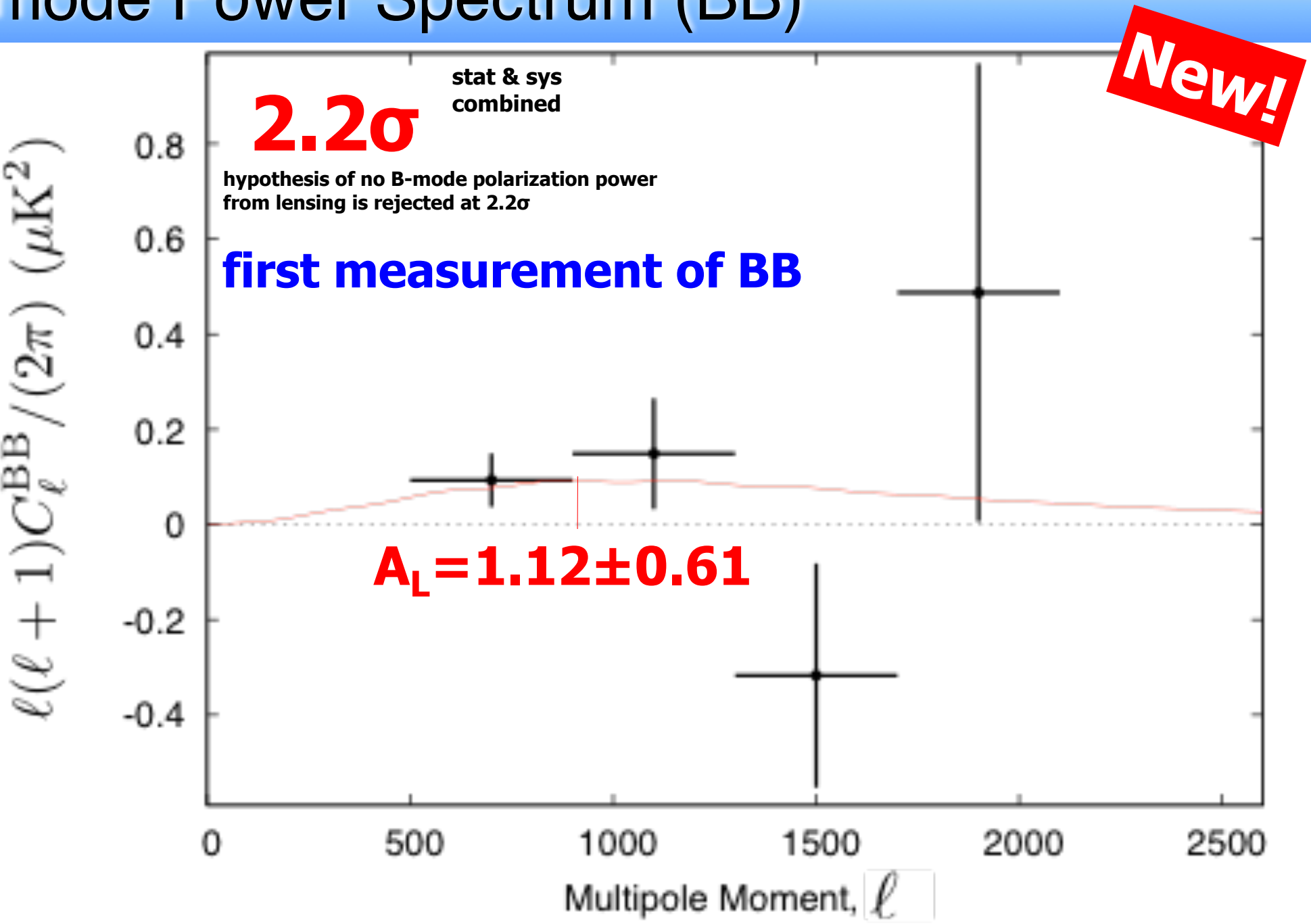
CIB is a good tracer of lensing



[POLARBEAR Collaboration 2013]

First detected by SPTpol Collaboration (2013)

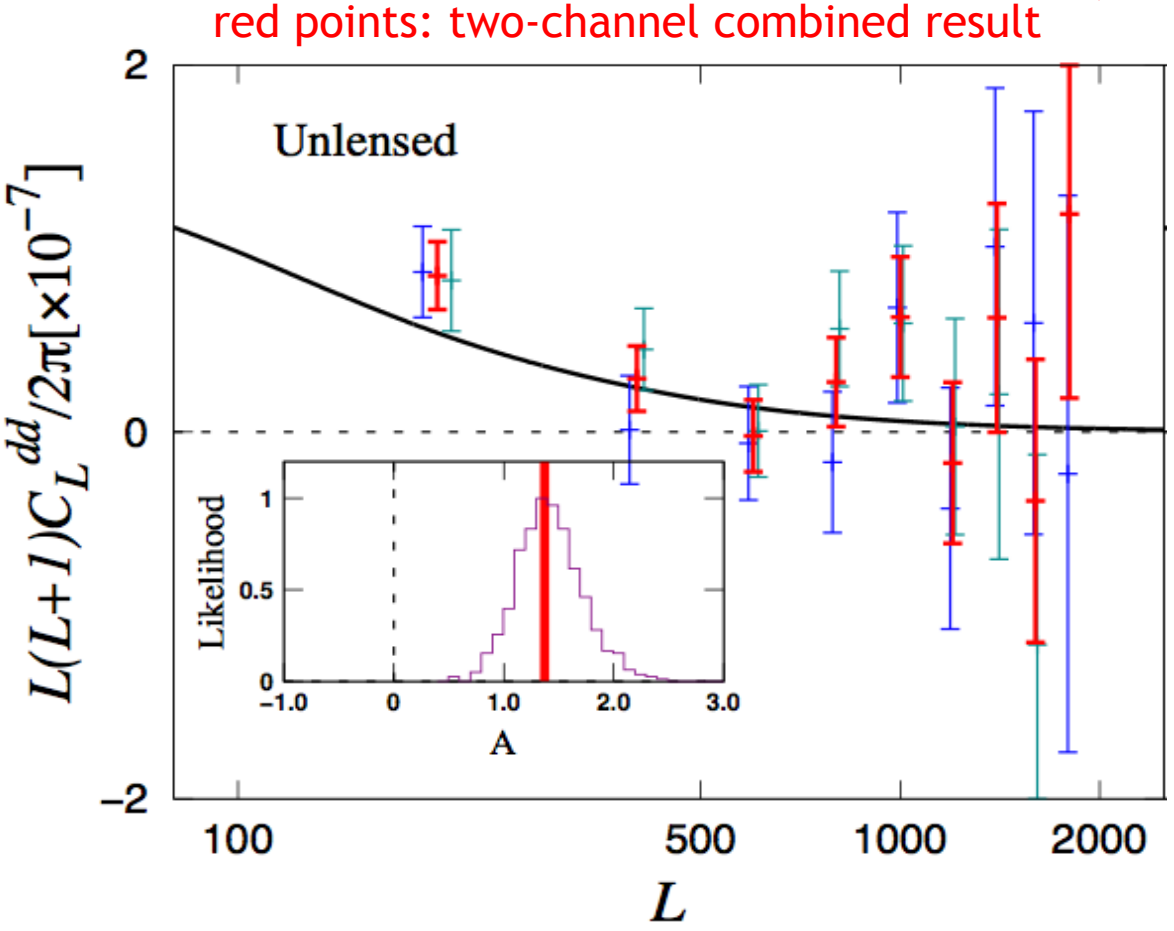
B-mode Power Spectrum (BB)



B-mode derived lensing power spectrum

New!

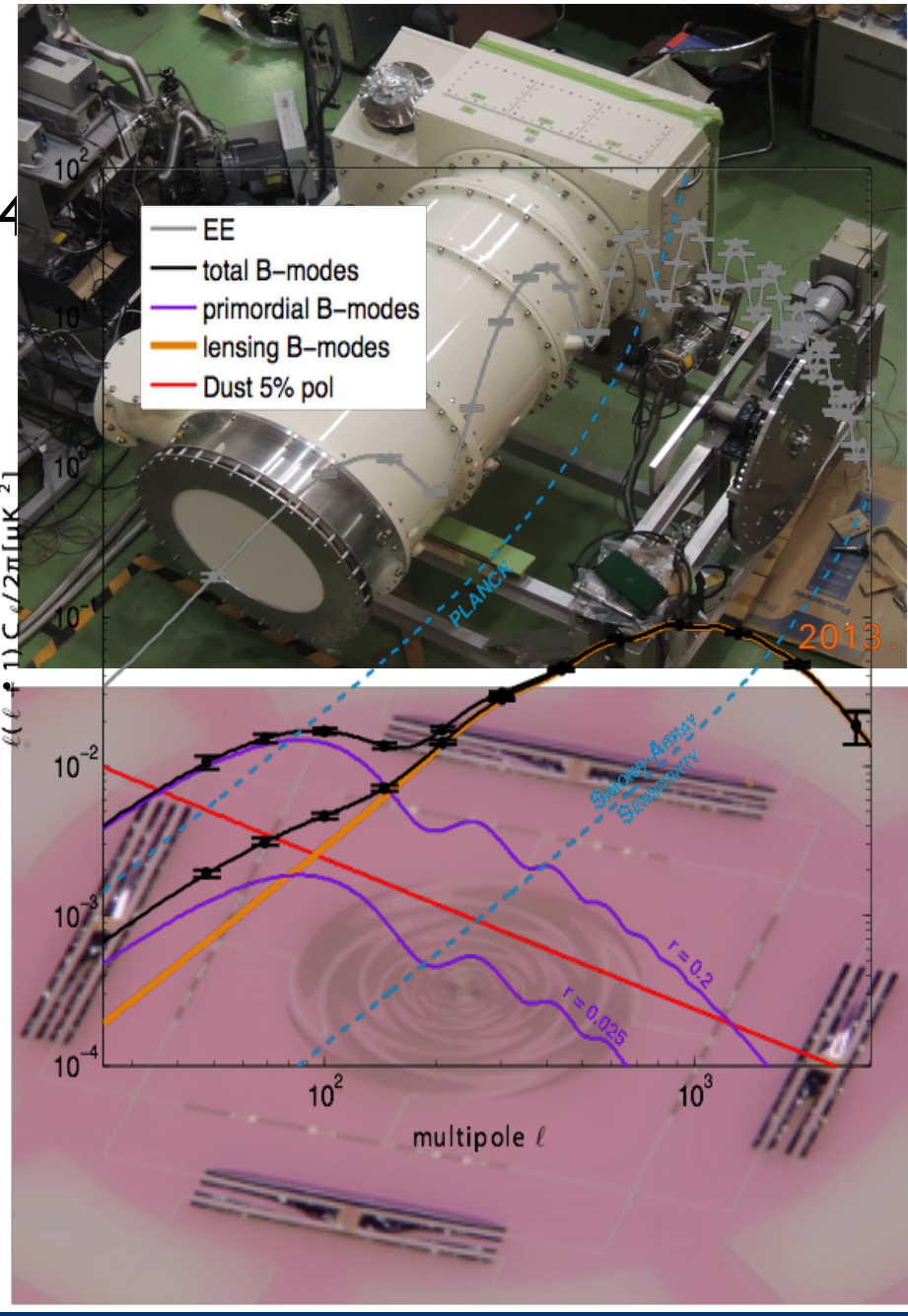
- 4.2 sigma result – first CMB-only detection of pol. lensing and lensing B-modes
- Novel measurement: proof of concept and test of polarization lensing – for future with >>10 x S/N!

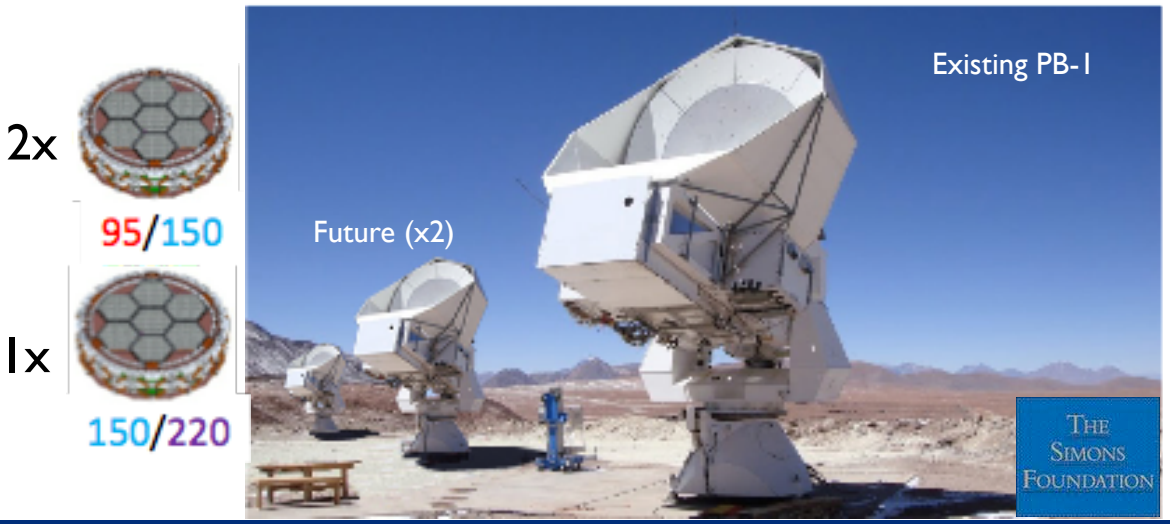


[POLARBEAR Collaboration 2013]

The future of the POLARBEAR experiment

- Multichroic pixels receiver in 2015: 7,588 detectors, 90/150 GHz
- Simons Array (2017): 3 telescopes, 22,764 detectors, 90/150/220 GHz
- High sensitivity: for B-modes characterization, r, de-lesning, n_T
- Constrain neutrino mass to 19 meV, hierarchy, primordial magnetism & more…

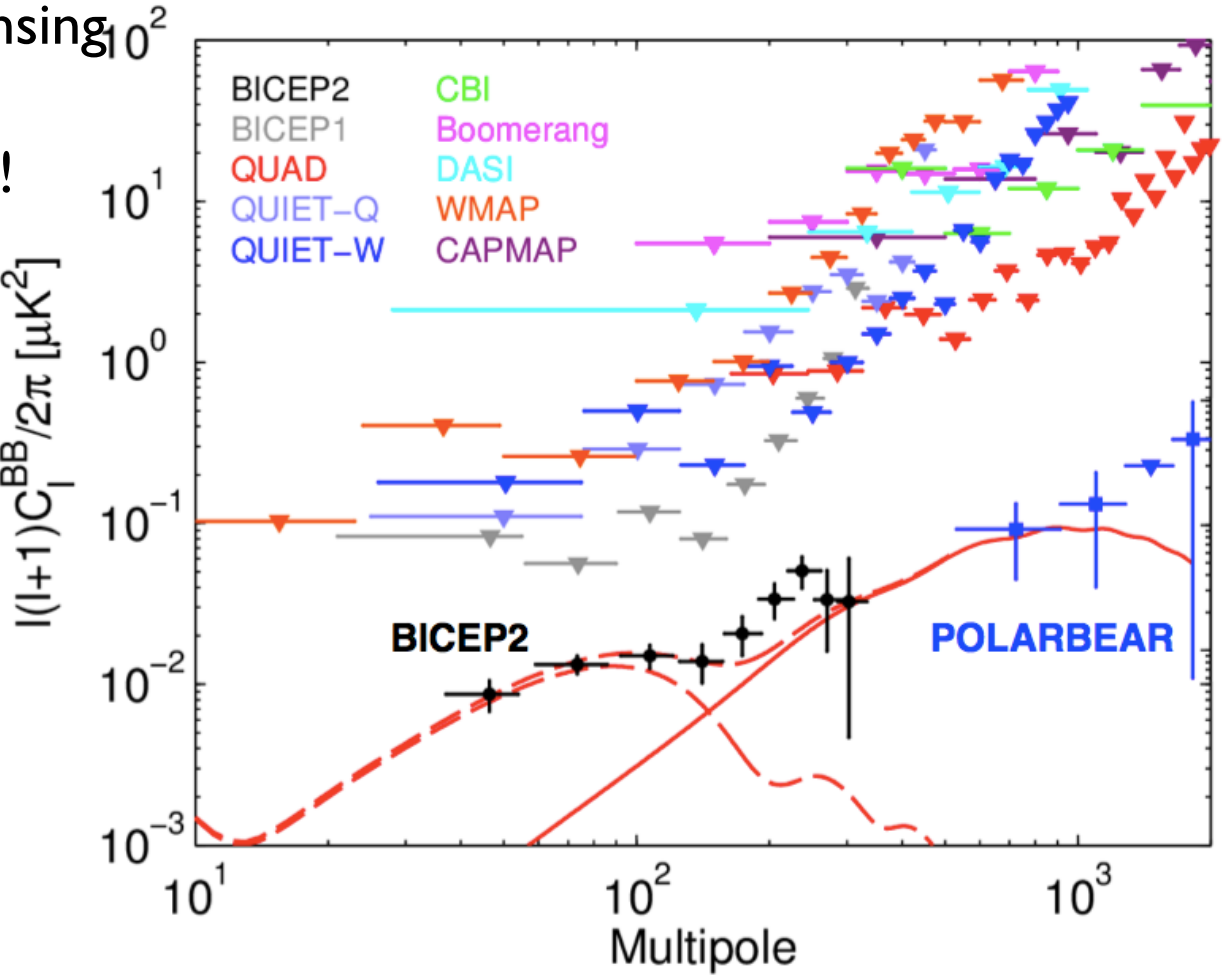




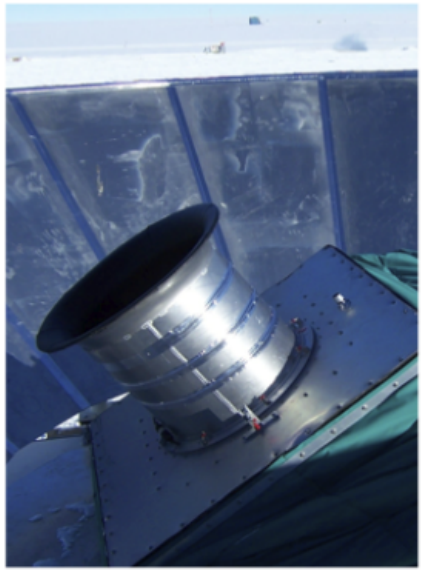
Conclusions

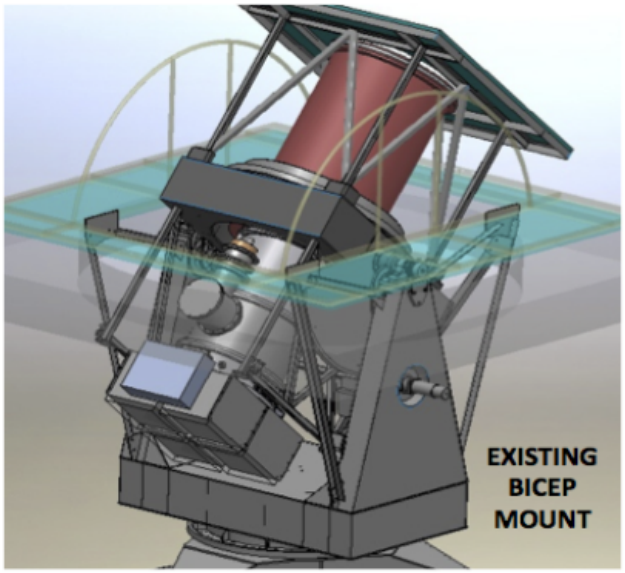
- POLARBEAR: first direct detection of lensing of CMB polarization (validated with CIB cross-correlation.
- Exciting March 2014: measurements of B-modes by POLARBEAR and BICEP2.
- Last months: ACTpol EE & pol. lensing
- Decade of the B-mode has begun!

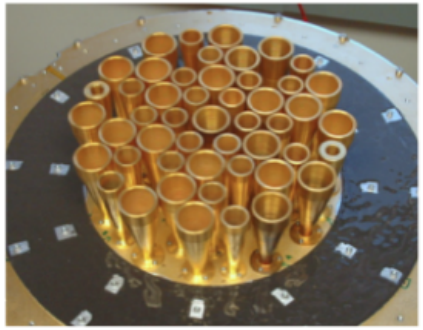
http://cosmology.ucsd.edu/BICEP2

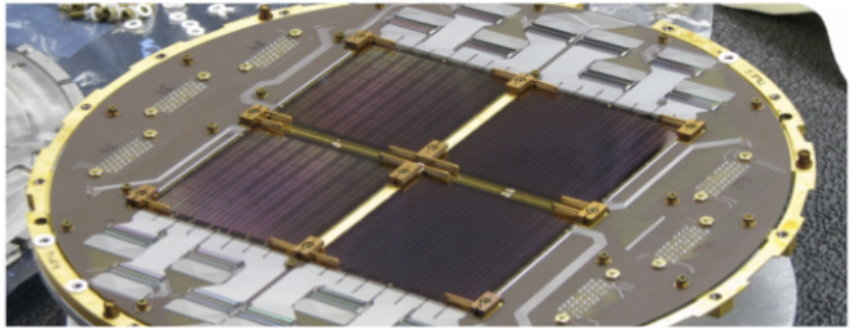


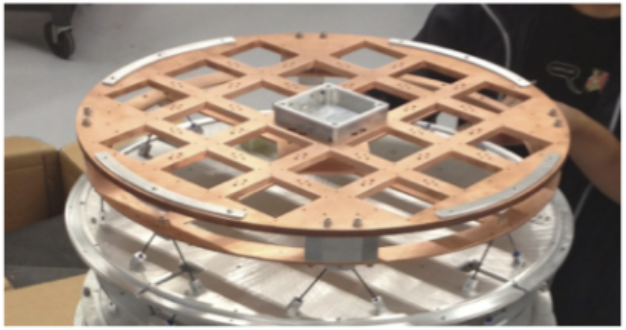
BICEP1 (2006 - 8)	BICEP2 (2010 - 12)	Keck Array (2011 -)	BICEP3 (2014 -)

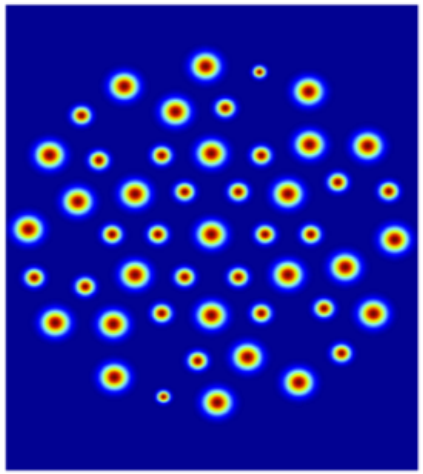


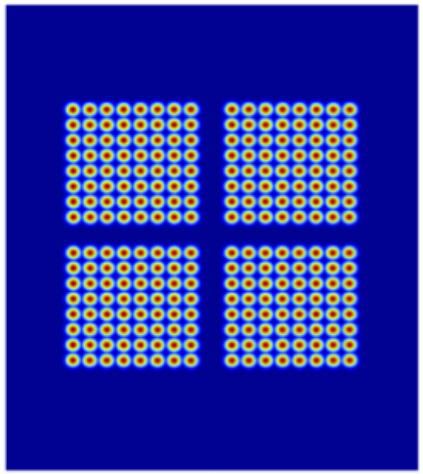


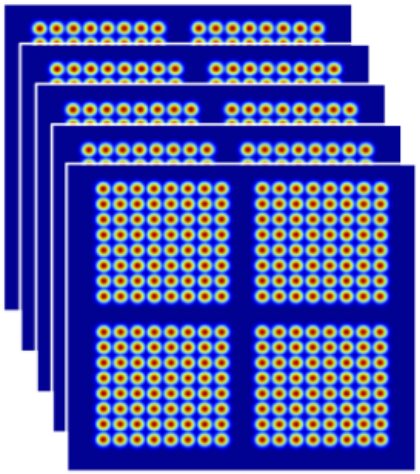


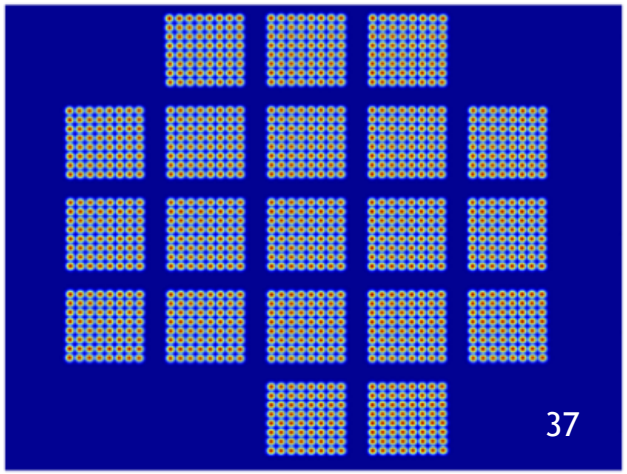






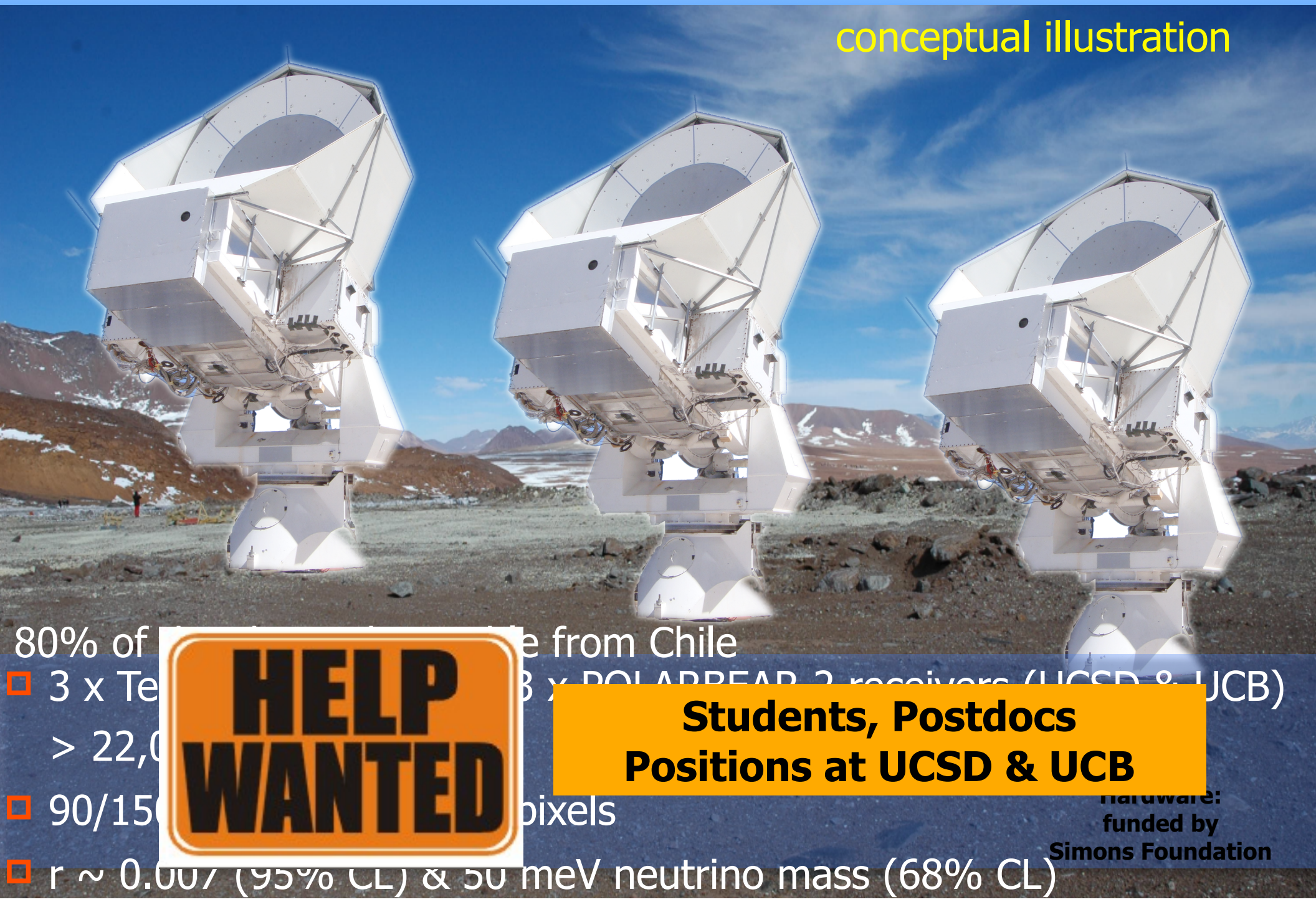






Simons Array (2016)

Brian Keating (PI), Adrian Lee (co-PI)
Kam Arnold (PM)



80% of [illegible] from Chile

- 3 x Te[illegible] x POLARBEAR-2 receivers (UCSD & UCB)
  > 22,0[illegible]
- 90/15[illegible] pixels
- r ~ 0.007 (95% CL) & 50 meV neutrino mass (68% CL)

Students, Postdocs
Positions at UCSD & UCB

Hardware:
funded by
Simons Foundation


NSF


CONICYT
Ministerio de
Educación
Gobierno de Chile


MEXT


NASA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