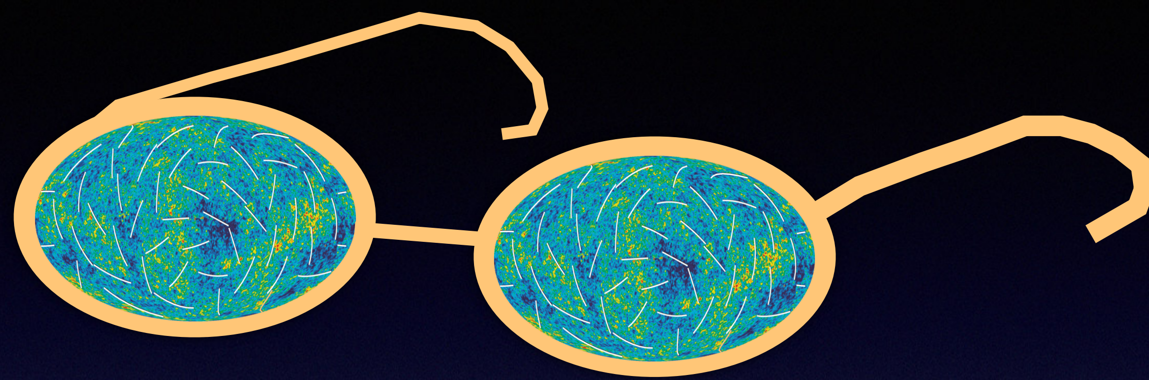
The Twisted Universe



Fundamental physics through the CMB's lenses

Brian Keating

Aspen

12 January 2016

http://cosmology.ucsd.edu/

@CMB3K

@BICEPTWO

@BrianUCSD

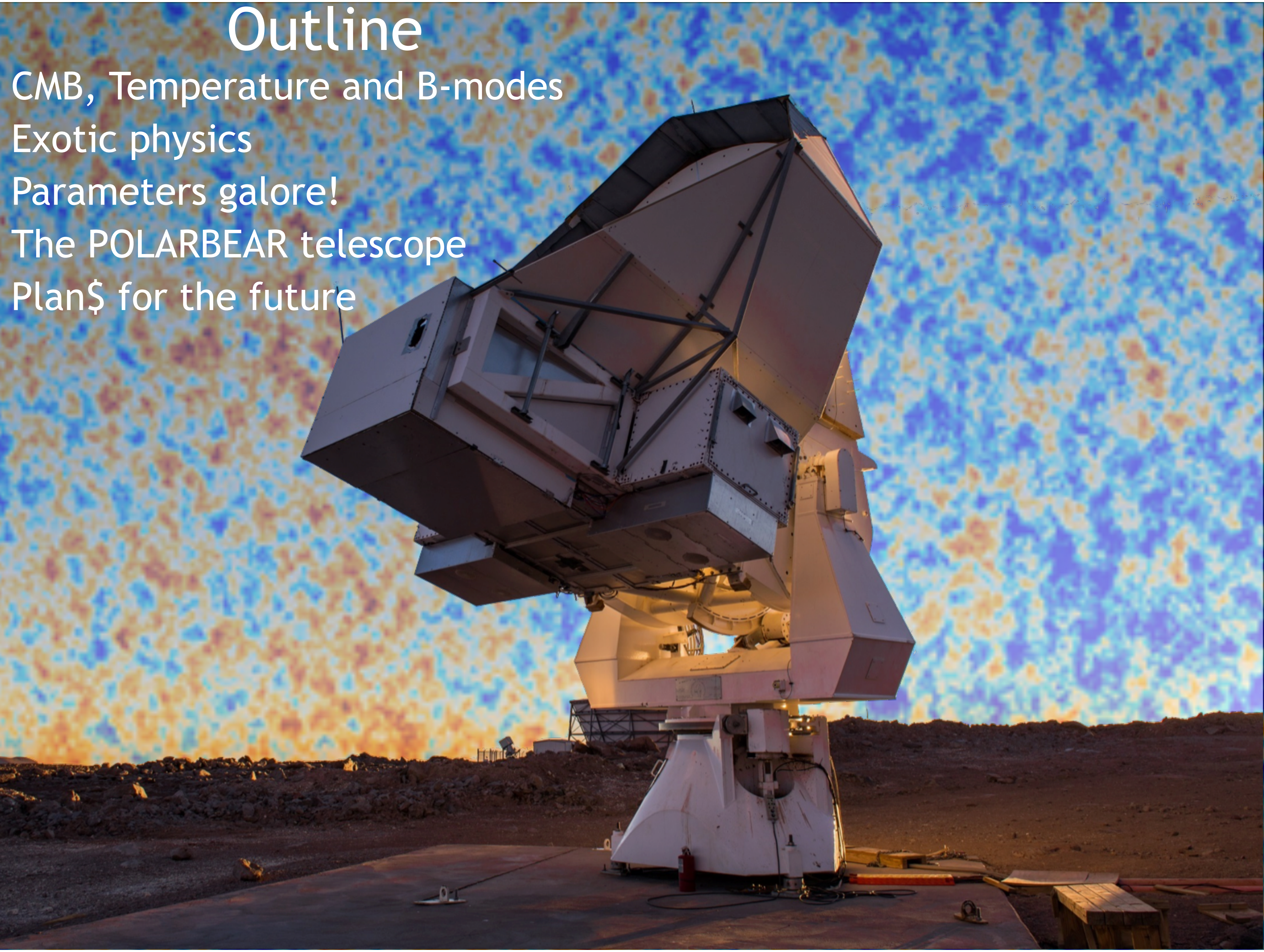
UNIVERSITY OF CALIFORNIA · SAN DIEGO · LET THERE BE LIGHT

ACEC

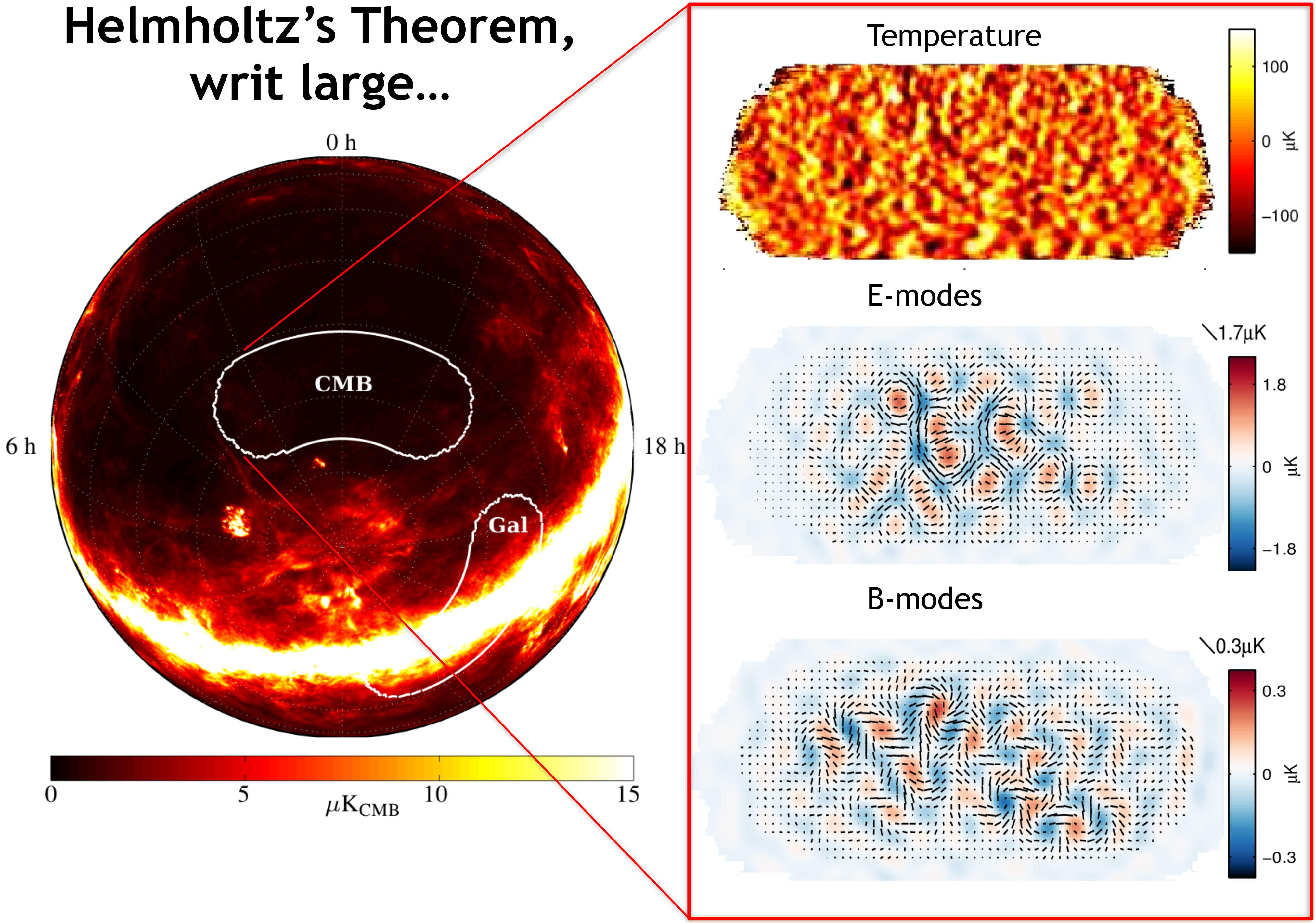
AX CENTER *for* EXPERIMENTAL COSMOLOGY

Outline

CMB, Temperature and B-modes
Exotic physics
Parameters galore!
The POLARBEAR telescope
Plan$ for the future

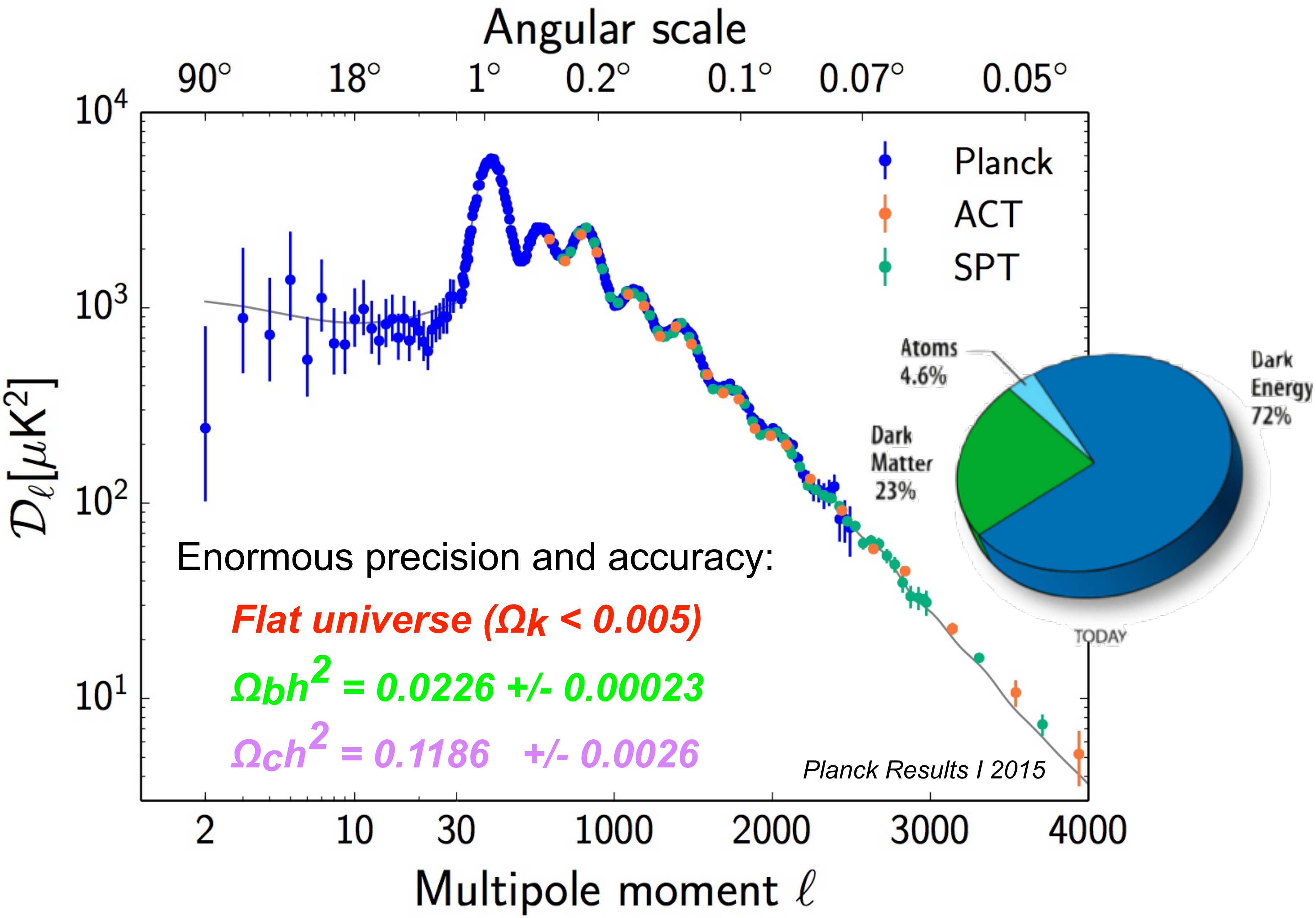


Helmholtz’s Theorem, writ large…



Images: BICEP2 collaboration

Parameters, Parameters, Parameters!



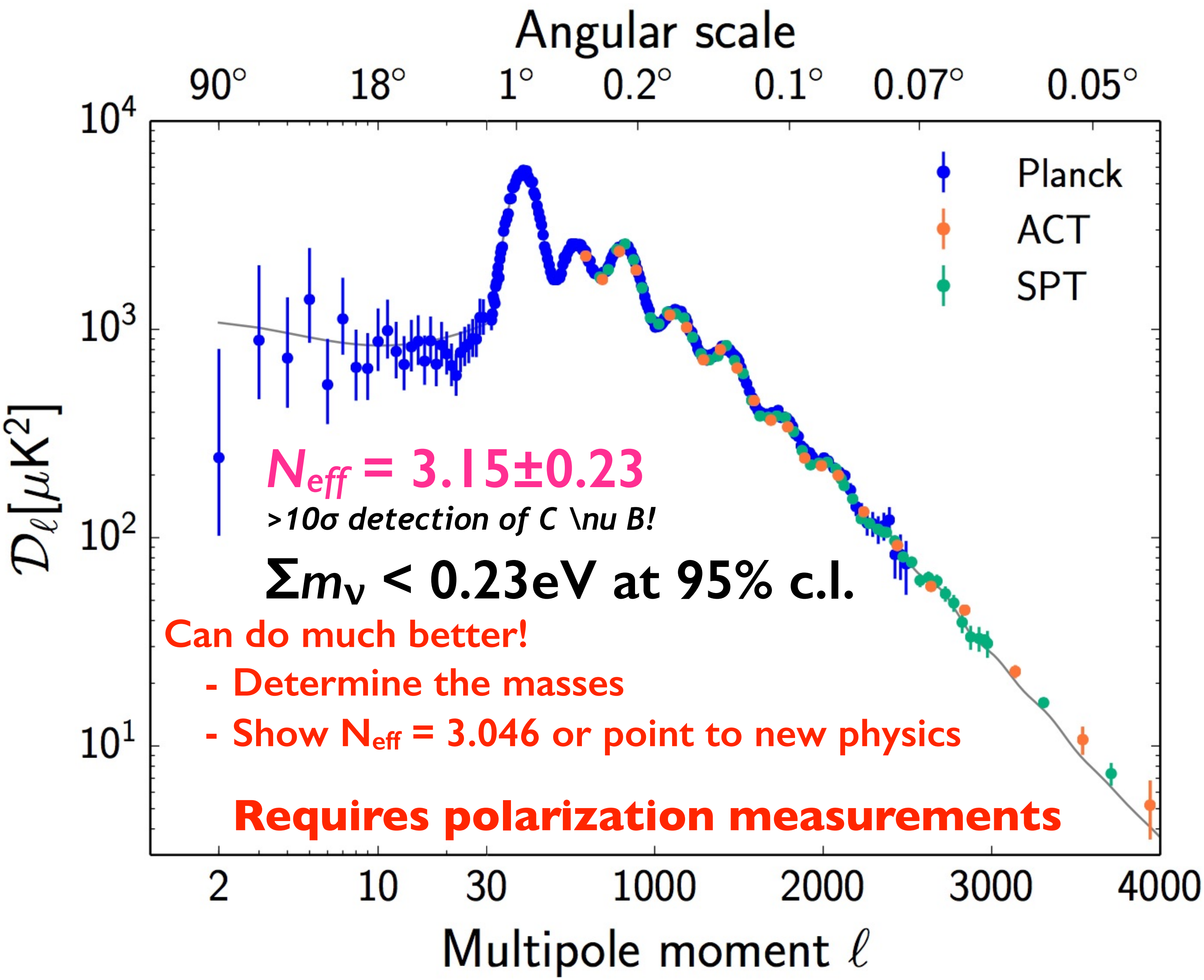
Enormous precision and accuracy:

Flat universe ($\Omega_k < 0.005$)

$\Omega_b h^2 = 0.0226 \pm 0.00023$

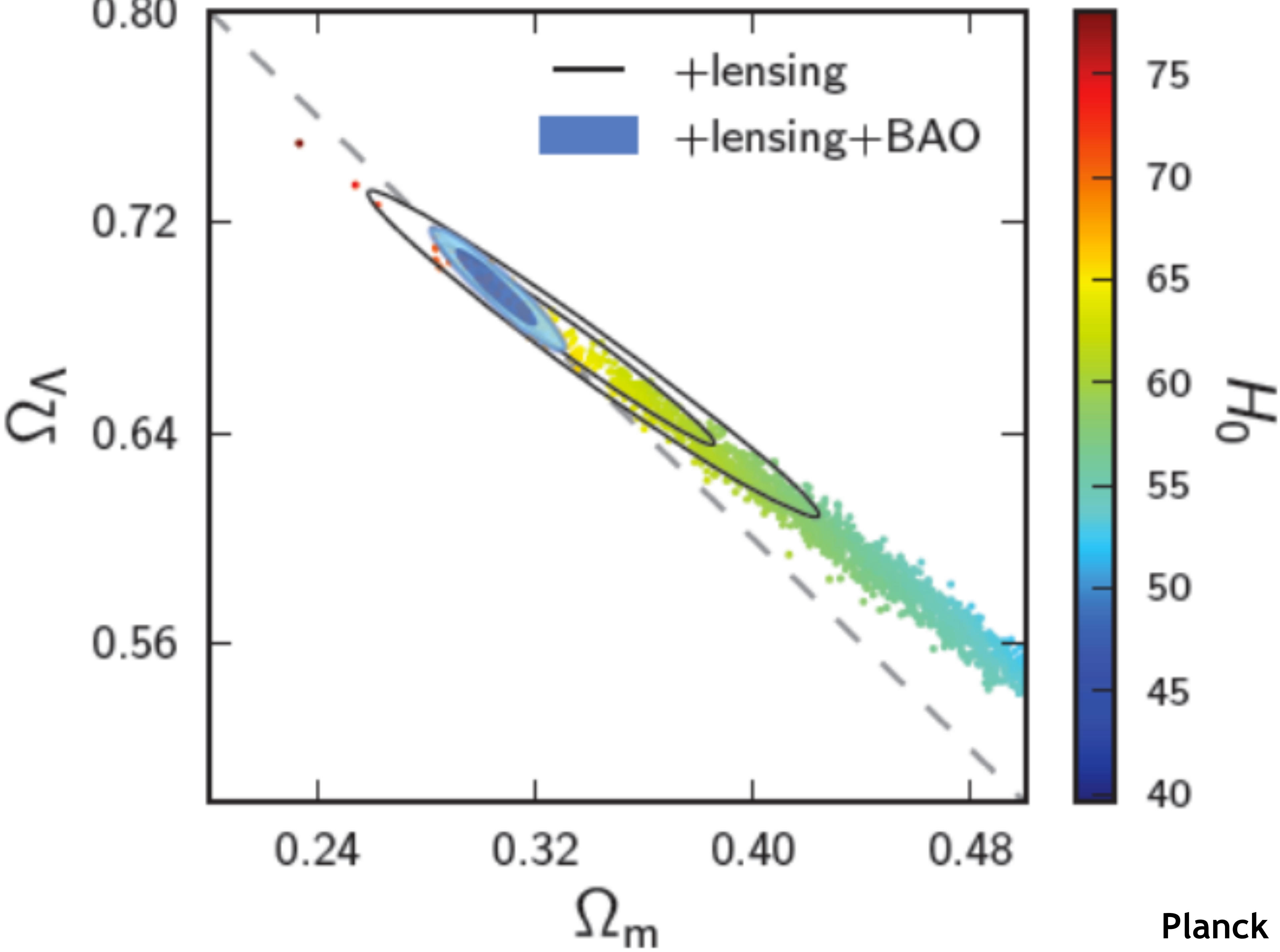
$\Omega_c h^2 = 0.1186 \pm 0.0026$

What about physics constraints - Neutrinos?



N_{eff} is the effective number of light relativistic species, for std model N_{eff} = 3.046

Dark Energy

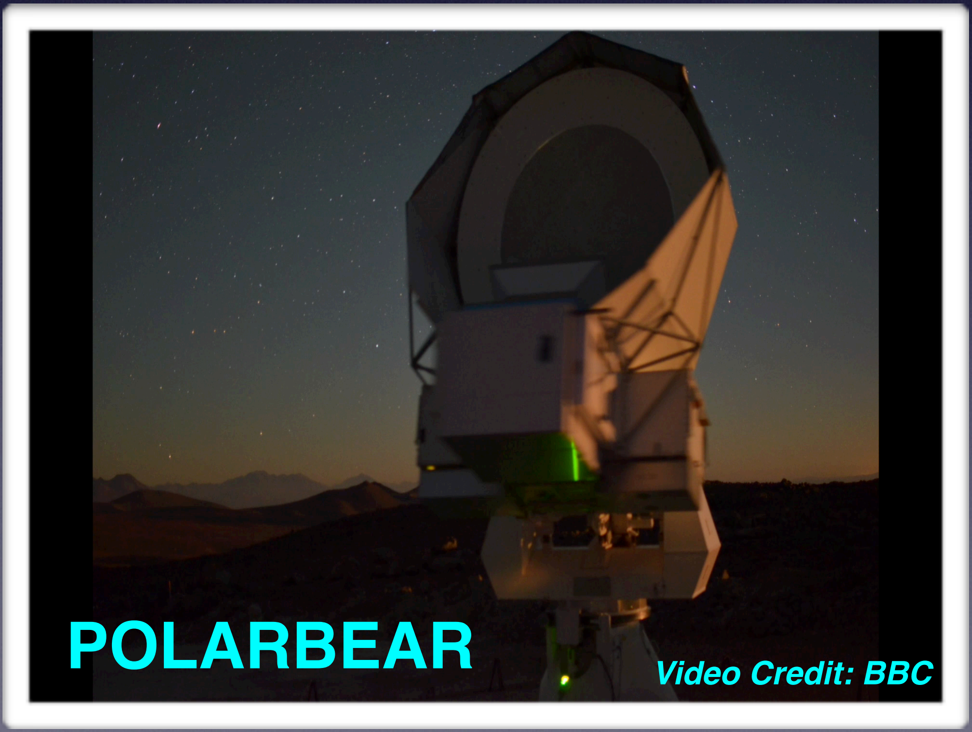


Planck 2015

Focus on *<u>Fun</u>*damental Physics

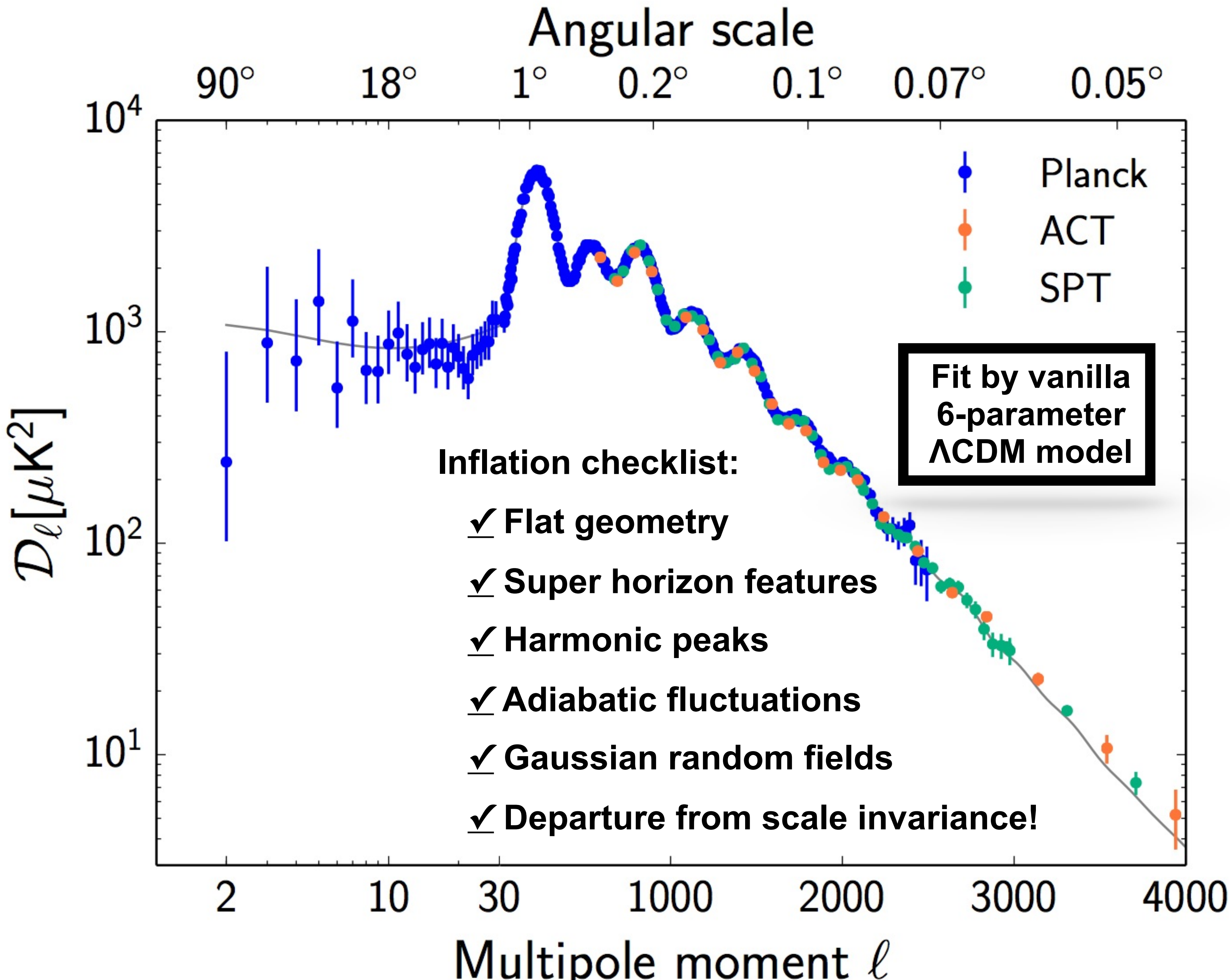
CMB polarization experiments can reveal:

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).

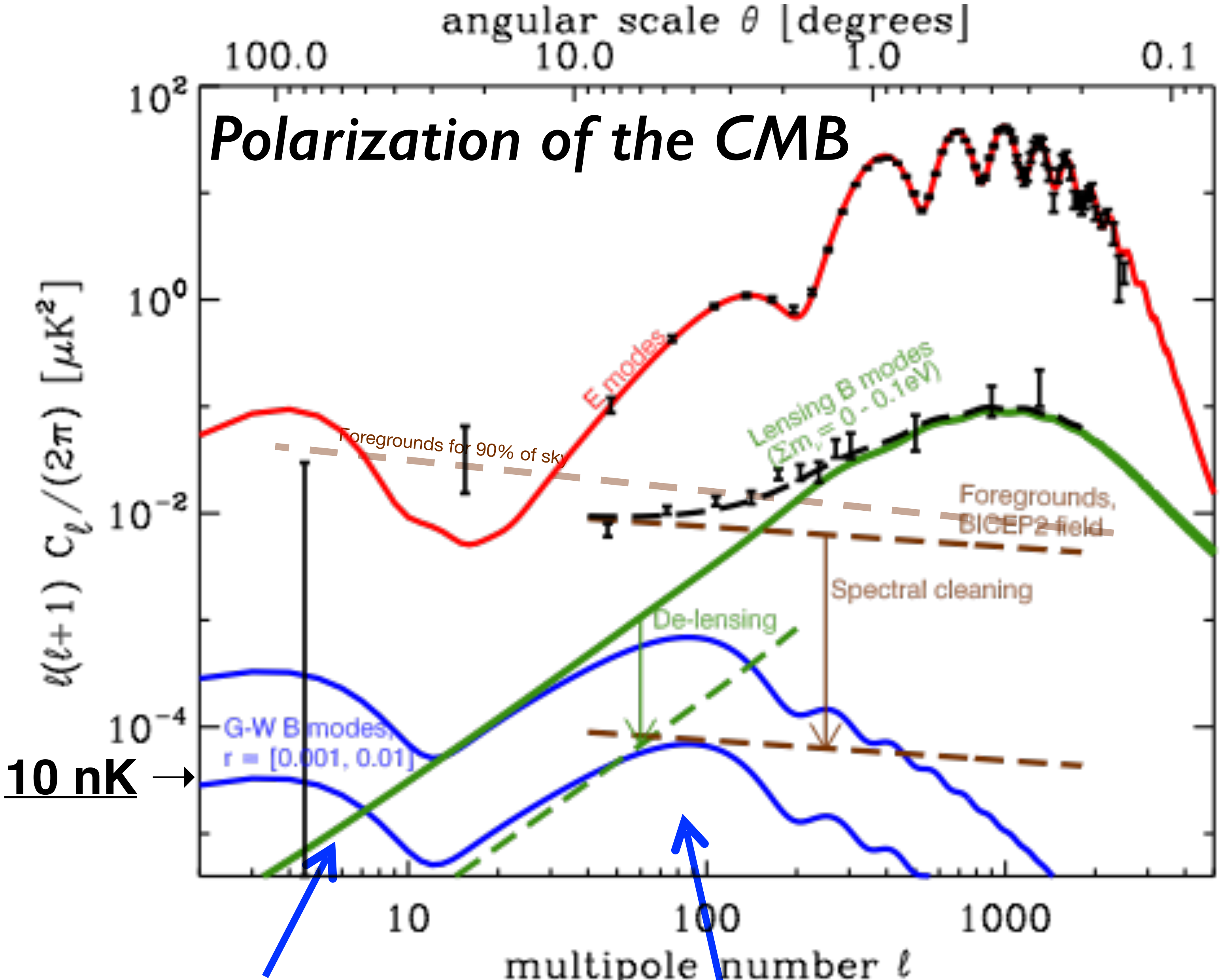


- Further Fundamental Physics:
- Neutrino masses
- Helium abundance
- Neutrino chemical potentials
- Equivalence Principle Tests
- Primordial magnetic fields
- **Exotic physics, such as cosmic polarization rotation!**

What about physics constraints - Inflation?



_X_ Inflationary gravitational waves (tensors)! Requires polarization measurements



Incredible progress over last 2 years!

NANOKELVIN parts-per-billion polarimetry!!

B-modes detected!!

reionization bump
exploring if possible
from the ground, i.e., CLASS

recombination bump
key target of CMB-S4
for r > 0.001

inflationary
gravity wave
B modes

Incredible progress, but still a long long way to go!

Recent & upcoming Atacama CMB experiments

Photo: Rahul Datta & Alessandro Schillaci

Recent South Pole CMB experiments

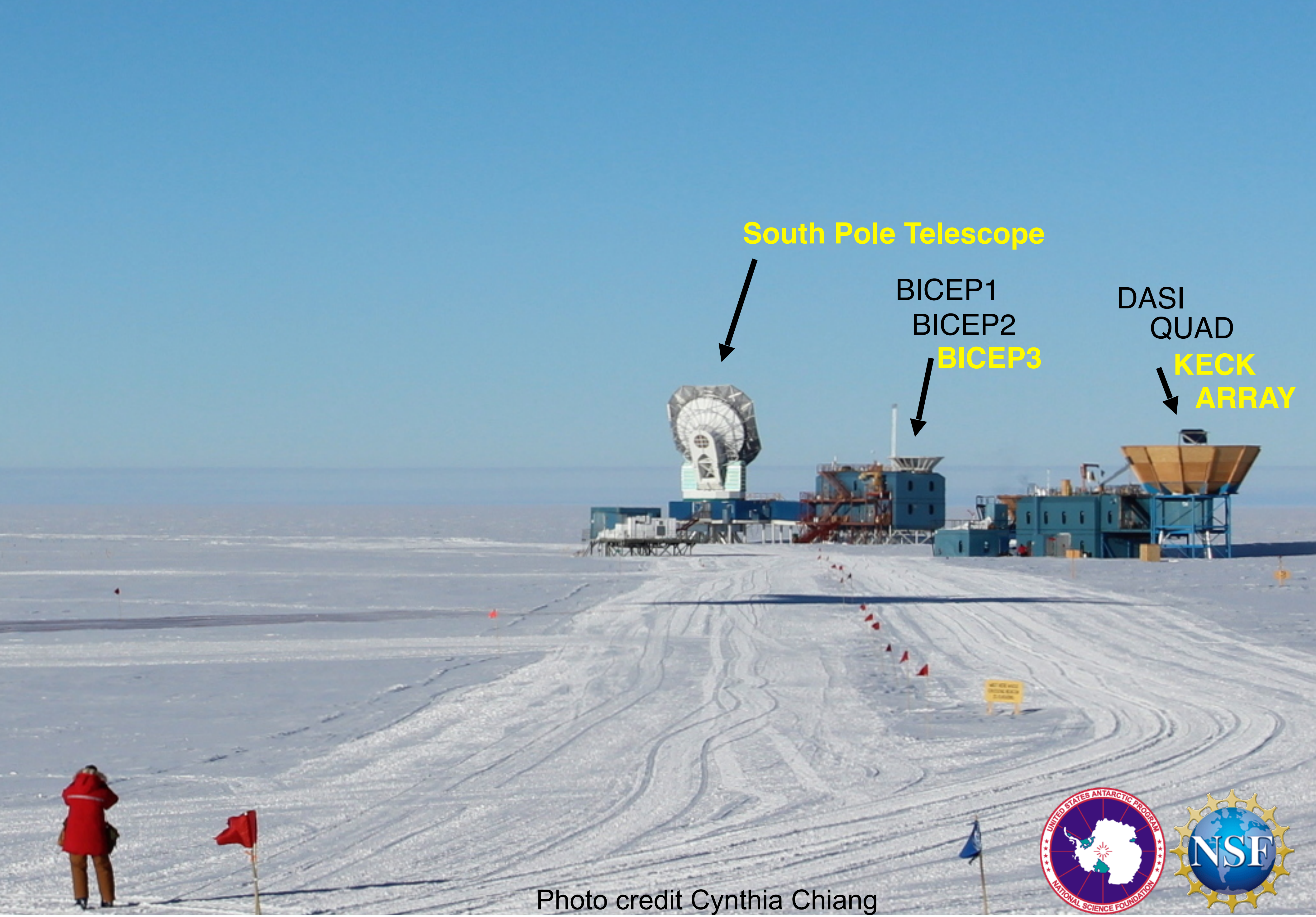


Photo credit Cynthia Chiang

BICEP/Keck first 95 GHz results

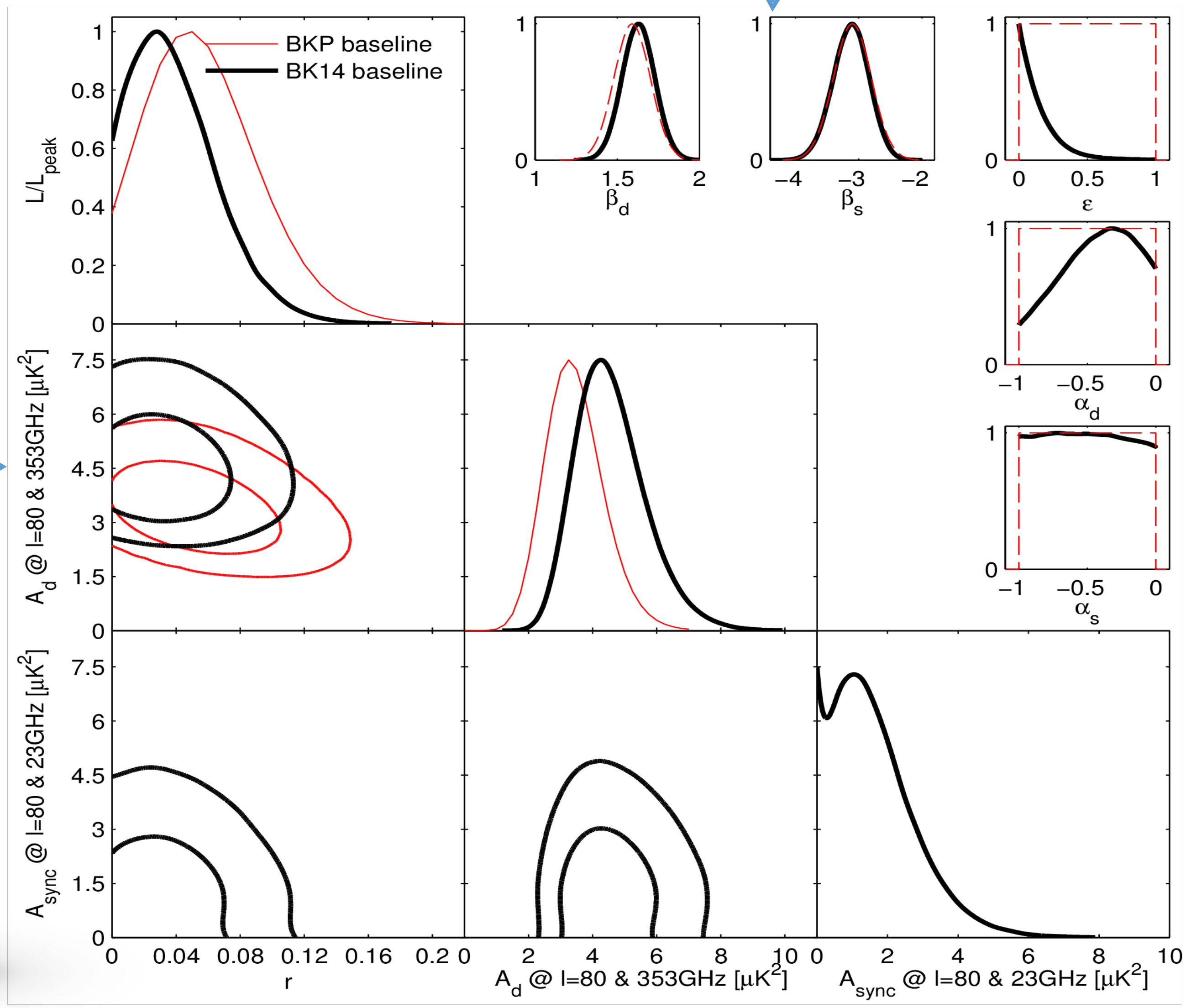
BICEP/Keck 150 GHz + Keck Array 2014 95 GHz
arXiv:1510.09217 [astro-ph.CO]

Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation

Joint likelihood of all spectra vs. lensing+dust +sync+r model:

dust vs. r degeneracy lifted



Marginalize over generous ranges in spatial spectral indices

r < 0.09 (95% CL) ***from polarization only;***
Now stronger than constraints from CMB temperature!

CMB & Lorentz Violation

Add a Chern-Simons Interaction to E&M

$$\mathcal{L}_{\rm EM} = -\frac{1}{4}F_{\nu\lambda}F^{\nu\lambda}$$

$$\mathcal{L}_{\rm CS} = -\frac{1}{2}p_\alpha A_\beta \tilde{F}^{\alpha\beta}$$

$$\begin{aligned} \vec{\nabla}\cdot\vec{E} &= 4\pi\rho - \vec{p}\cdot\vec{B} \\ -\partial_t\vec{E} + \vec{\nabla}\times\vec{B} &= 4\pi J - p_0\vec{B} + p\times\vec{E} \\ \vec{\nabla}\cdot\vec{B} &= 0 \\ \partial_t\vec{B} + \vec{\nabla}\times\vec{E} &= 0. \end{aligned}$$

Carroll, Field, Jackiw 1990

"Cosmic birefringence"

$$\omega = ck \quad \rightarrow \quad \omega = \begin{cases} ck & \text{LCP} \\ c(1-\epsilon)k & \text{RCP} \end{cases}$$

- **Violates Lorentz Invariance & parity symmetry in EM.**
- **Rotates the polarization plane of photons.**

Crazy?

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

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

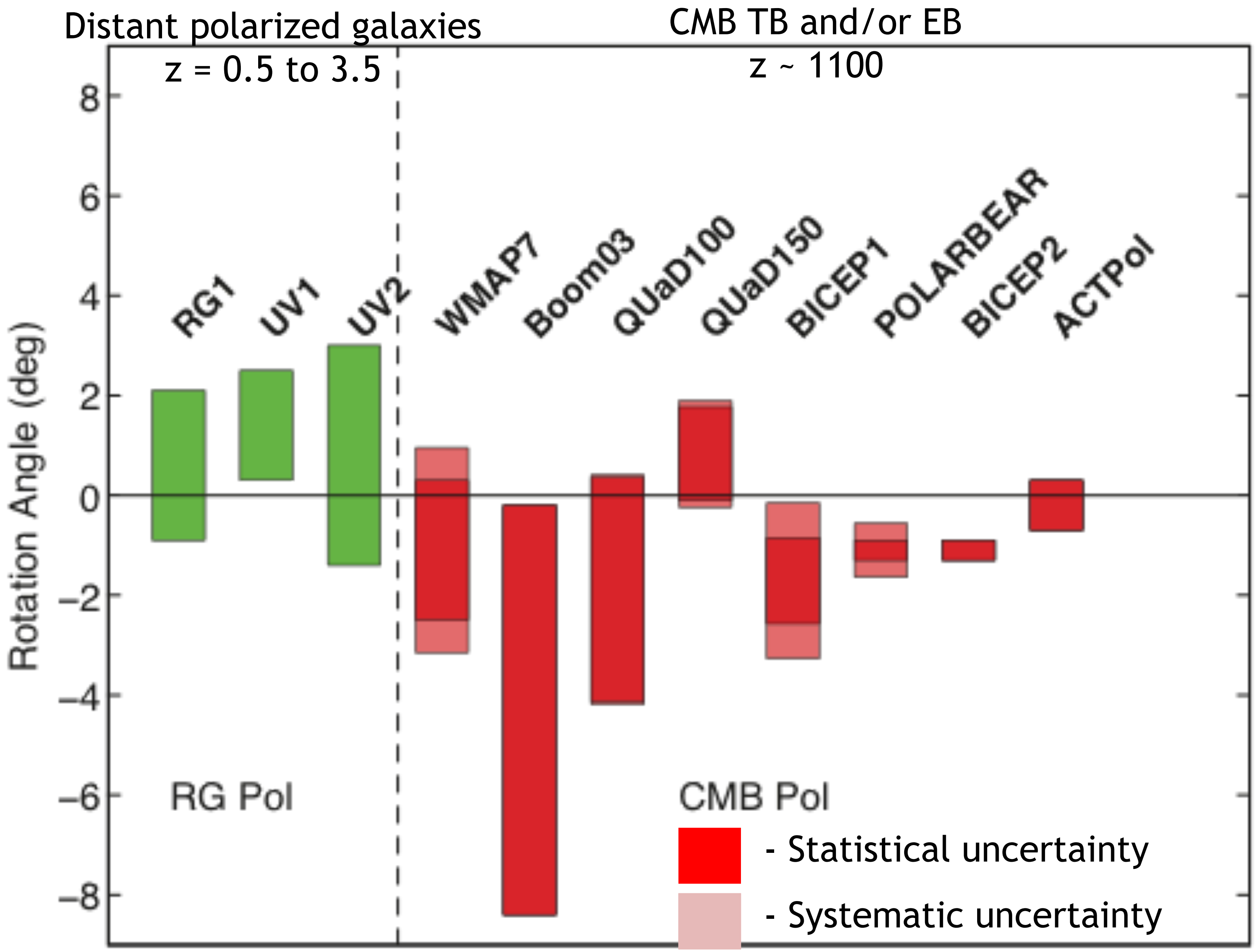
(5) Birefringence and Dark Matter detection http://arxiv.org/pdf/astro-ph/0611684v3.pdf
Susan Gardner

(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
Contaldi

(8) Kolb & Turner (1990): Bounds on PMF from BBN

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



Kaufman, Keating, Johnson 2014

Magnetic Motivation

- Magnetic fields detected in >100 galaxies & clusters.
- Upper *and* Lower limits exist on ***primordial magnetic fields*** (PMF).
- U.L. are10-100x below galactic & cluster fields
- Magnetic fields are amplified, or created, in structure formation.
- No detections of purely cosmological fields (i.e., not bound struct.)
- BBN: $t \simeq 1$ s, $T \simeq 1$ MeV, energy density of the Universe is 10^{25} erg cm^{-3} comparable to the energy density in a 10^{13} G magnetic field. The PMF must be lower to not spoil BBN predictions.
- This implies PMF: $B < 10^{-6}$ G. (Kolb & Turner astro-ph/0207240)

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

Cosmic Magnetic Fields

- Seen in galaxies and clusters
- Origin unknown
  - astrophysical?
  - primordial?

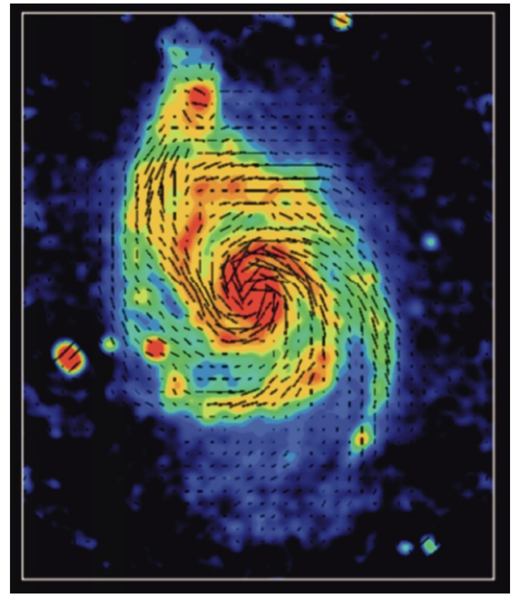


Image courtesy of NRAO/AUI

- Generated in the early universe:
- Inflationary mechanism?
- Phase transitions?
- Not “if”, but “how much?”

A distinct CMB signature would prove their primordial origin

Science 2 April 2010:
Vol. 328 no. 5974 pp. 73–75
DOI: 10.1126/science.1184192

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REPORT

Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars

Andrii Neronov*, Ievgen Vovk

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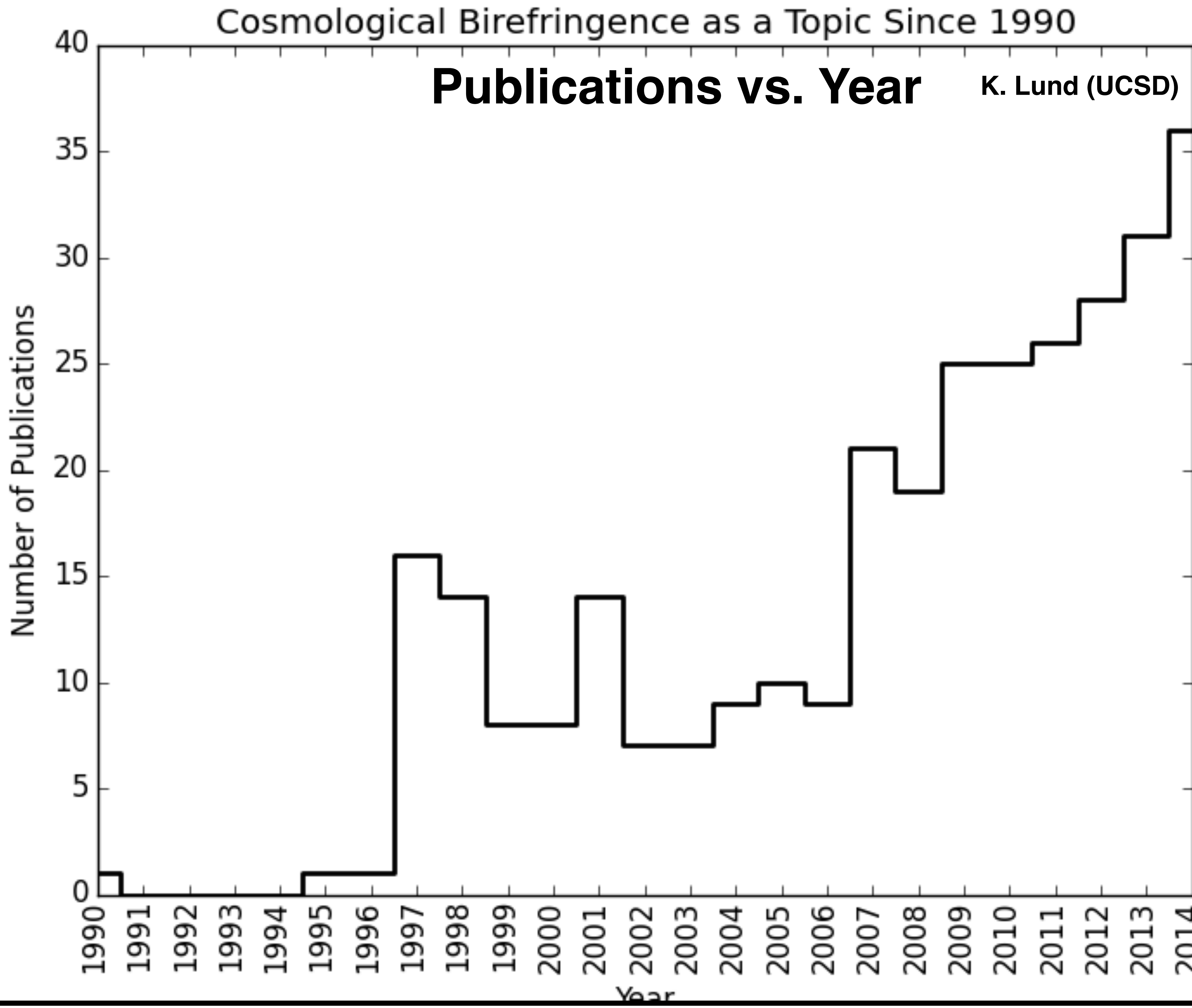
*To whom correspondence should be addressed. E-mail: Andrii.Neronov@unige.ch

ABSTRACT

Magnetic fields in galaxies are produced via the amplification of seed magnetic fields of unknown nature. The seed fields, which might exist in their initial form in the intergalactic medium, were never detected. We report a lower bound $B \geq 3 \times 10^{-16}$ gauss on the strength of intergalactic magnetic fields, which stems from the nonobservation of GeV gamma-ray emission from electromagnetic cascade initiated by tera-electron volt gamma rays in intergalactic medium. The bound improves as $\lambda_B^{-1/2}$ if magnetic field correlation length, λ_B, is much smaller than a megaparsec. This lower bound constrains models for the origin of cosmic magnetic fields.


Cosmological Birefringence as a Topic Since 1990
Publications vs. Year
K. Lund (UCSD)
Number of Publications
0
5
10
15
20
25
30
35
40
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year

CMB & CPT

Probing CPT Violation with CMB Polarization Measurements

Jun-Qing Xia[1], Hong Li[2,3], and Xinmin Zhang[2,3]
[1] *Scuola Internazionale Superiore di Studi Avanzati, Via Beirut 2-4, I-34014 Trieste, Italy*
[2] *Institute of High Energy Physics, Chinese Academy of Science, P. O. Box 918-4, Beijing 100049, P. R. China and*
[3] *Theoretical Physics Center for Science Facilities (TPCSF), Chinese Academy of Science, P. R. China*

The electrodynamics modified by the Chern-Simons term $\mathcal{L}_{cs} \sim p_\mu A_\nu \tilde{F}^{\mu\nu}$ with a non-vanishing p_μ violates the *Charge-Parity-Time Reversal* symmetry (CPT) and rotates the linear polarizations of the propagating *Cosmic Microwave Background* (CMB) photons. In this paper we measure the rotation angle $\Delta\alpha$ by performing a global analysis on the current CMB polarization measurements from the *seven-year Wilkinson Microwave Anisotropy Probe* (WMAP7), *BOOMERanG 2003* (B03), BICEP and QUaD using a Markov Chain Monte Carlo method. Neglecting the systematic errors of these experiments, we find that the results from WMAP7, B03 and BICEP all are consistent and their combination gives $\Delta\alpha = -2.33 \pm 0.72$ deg (68% *C.L.*), indicating a $3\,\sigma$ detection of the CPT violation. The QUaD data alone gives $\Delta\alpha = 0.59 \pm 0.42$ deg (68% *C.L.*) which has an opposite sign for the central value and smaller error bar compared to that obtained from WMAP7, B03 and BICEP. When combining all the polarization data together, we find $\Delta\alpha = -0.04 \pm 0.35$ deg (68% *C.L.*) which significantly improves the previous constraint on $\Delta\alpha$ and test the validity of the fundamental CPT symmetry at a higher level.

Physics Letters B, Vol. 687, Issue 2-3, p.129-132.

Xia claimed BICEP1 (w/ others) had a 3 sigma detection of CPT violating polarization rotation!

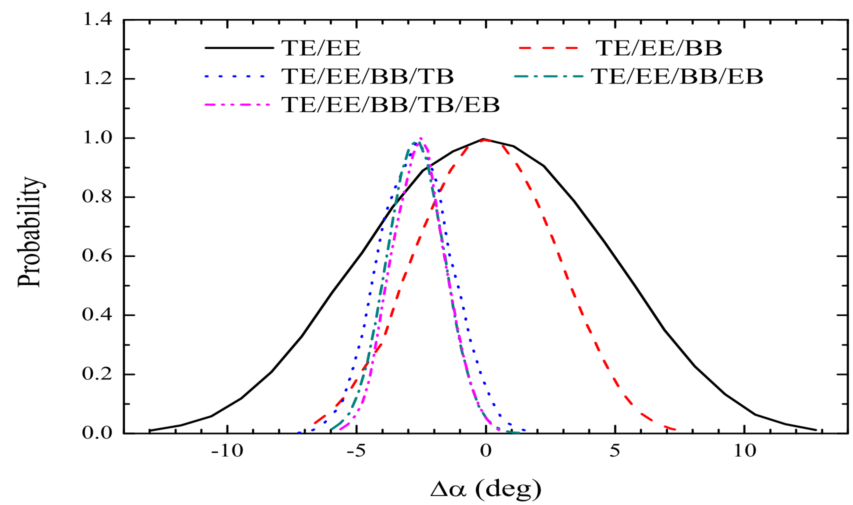


FIG. 3: The one-dimensional posterior distributions of the rotation angle derived from the BICEP polarization data.

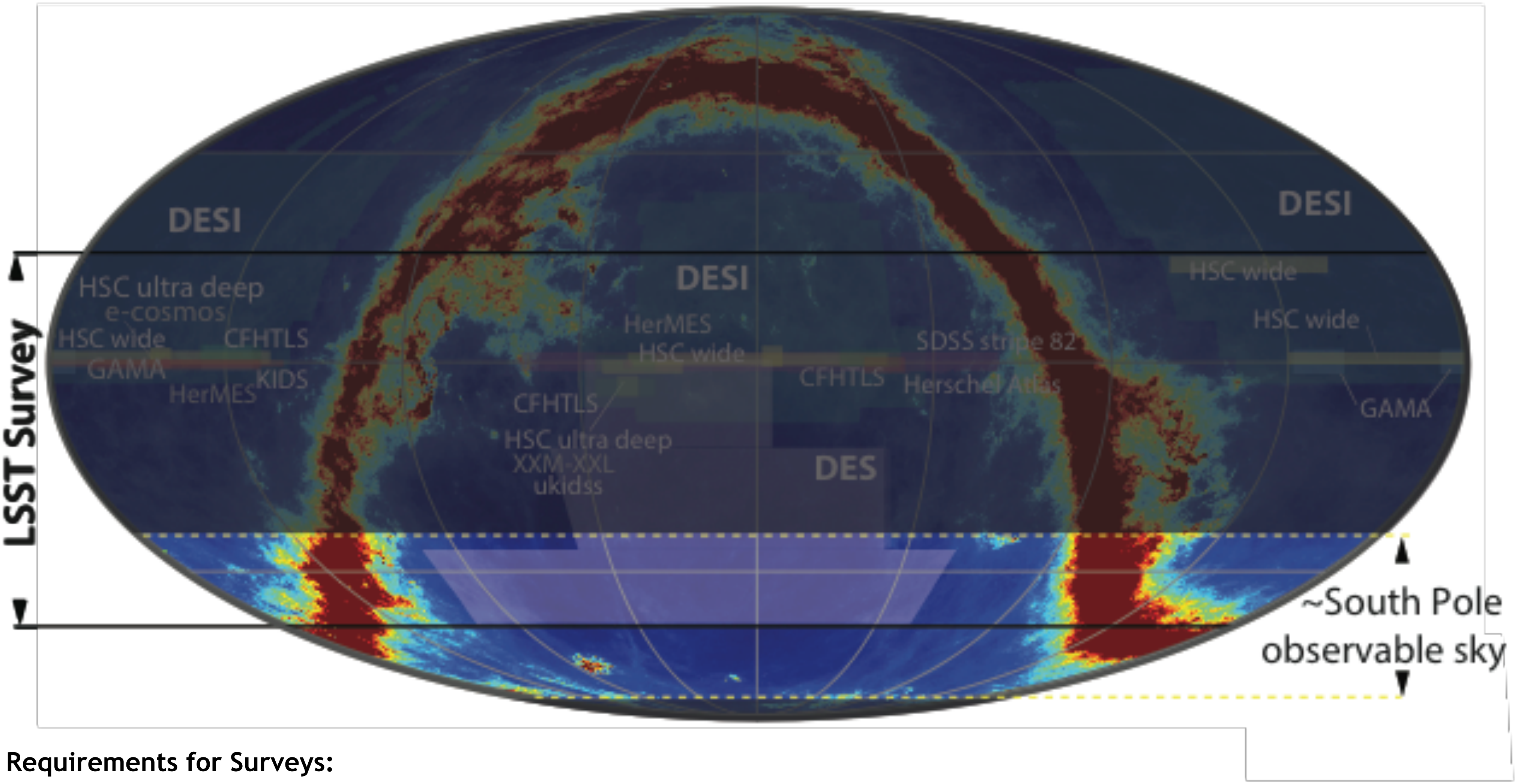
So how to make the definitive measurement?

1. Build the lowest possible systematic telescope!
2. Modulate the polarization signal: fast and far away!
3. Calibrate in as many ways as possible.
4. Observe the cleanest possible regions of sky.
5. Analyze your data in least biased way possible. Check for biases via “null tests”.

Comparison of CMB Sites: Modulation & Foregrounds

Steps 2 & 4

Foreground + optical survey coverage map



Requirements for Surveys:

(1) **Low foreground regions** for Inflation and Lensing

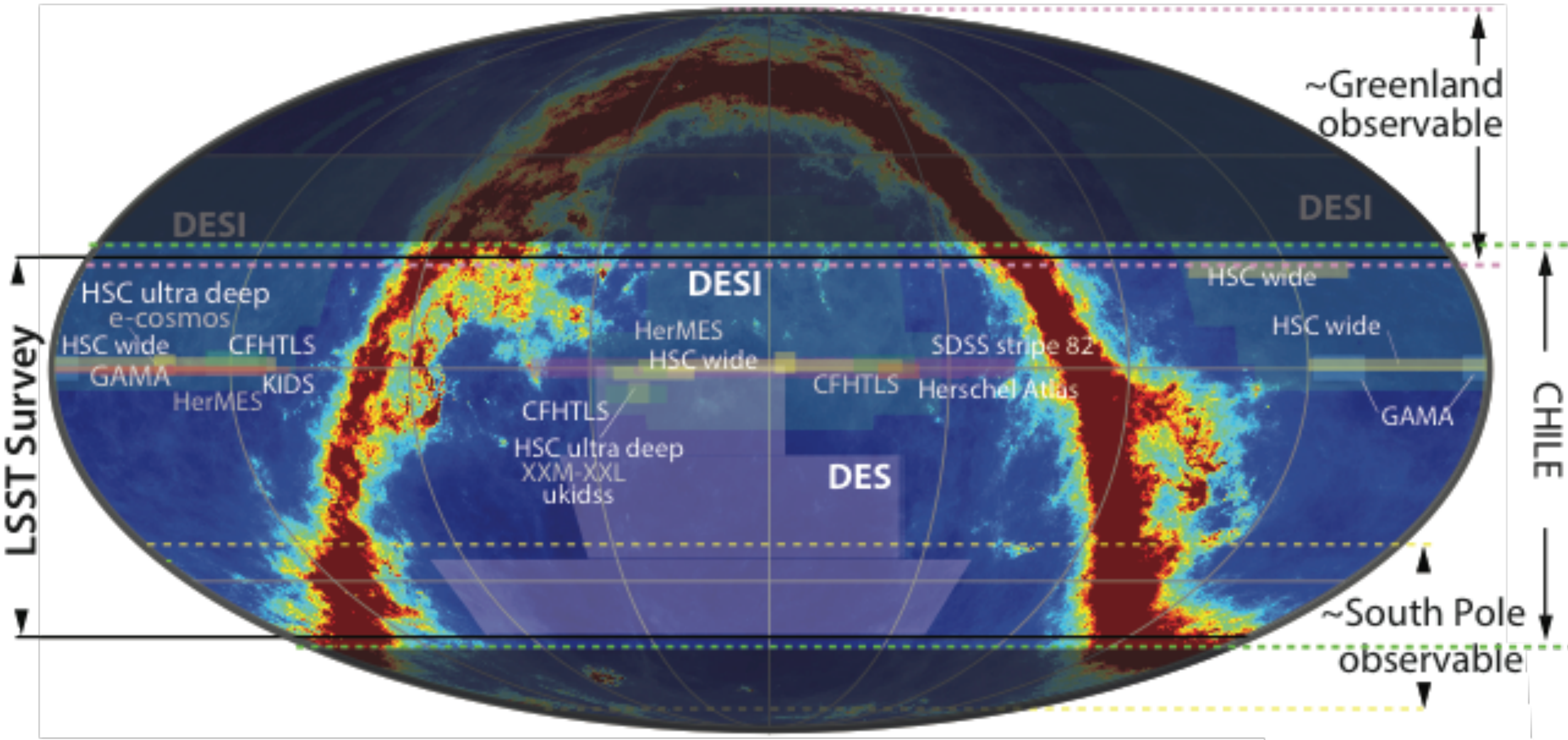
(2) Overlap with optical surveys to maximize impact of LSS measurements for neutrinos, dark energy, dark matter, and astrophysics.

M. Devlin

Comparison of CMB Sites: Modulation & Foregrounds

Steps 2 & 4

Foreground + optical survey coverage map



Requirements for Surveys:

(1) **Low foreground regions** for Inflation and Lensing

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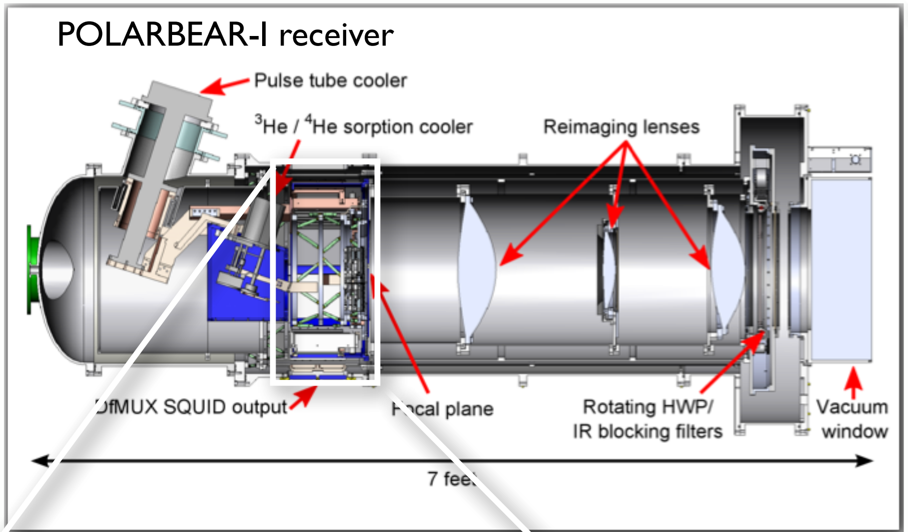
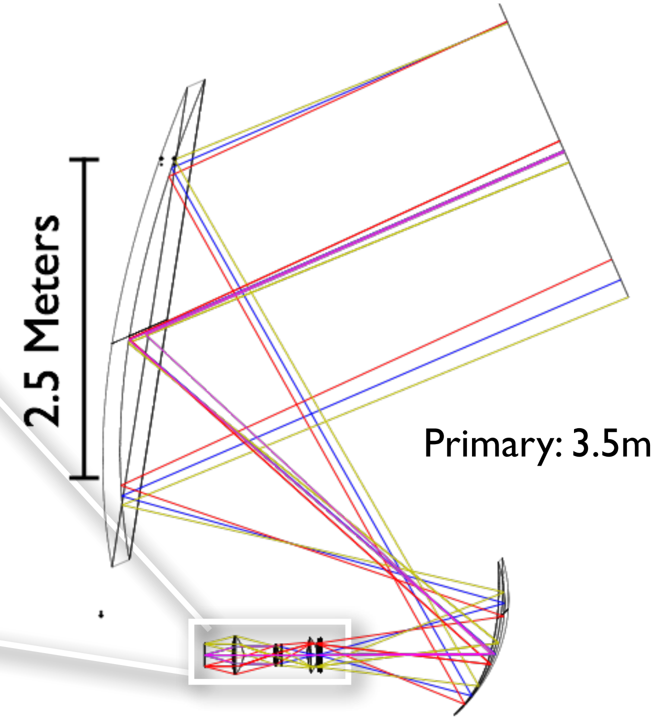
M. Devlin

The POLARBEAR Experiment

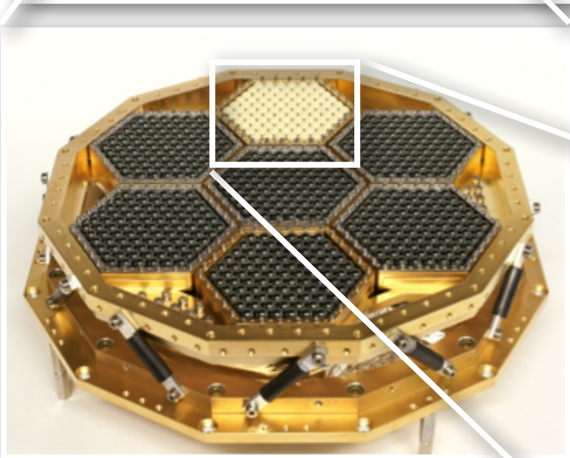
Instrument design





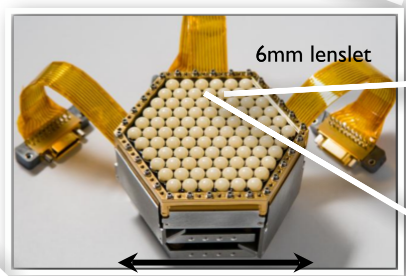
Huan Tran Telescope

Focal plane

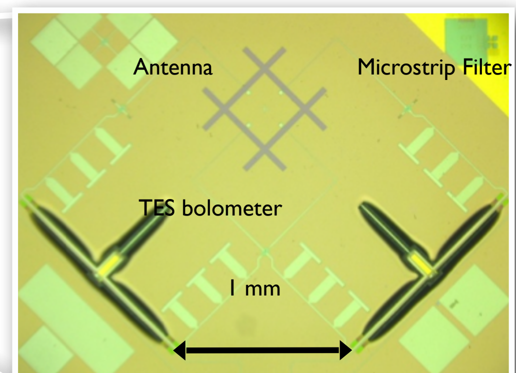


1274 bolometers @ 150 GHz
Cooled to 25 mK

Hex Module



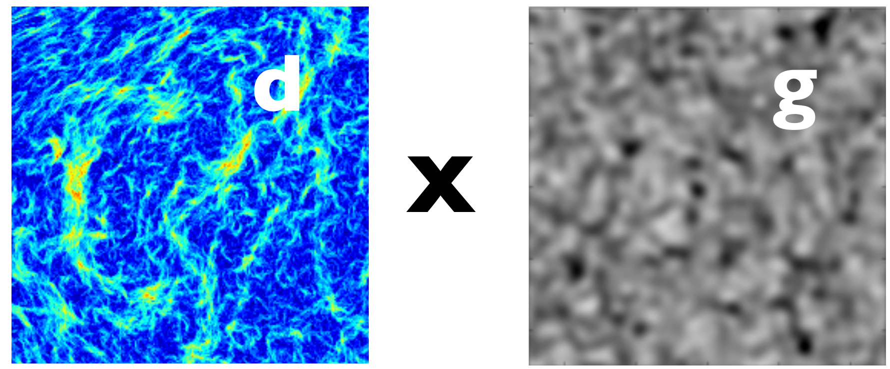
8cm



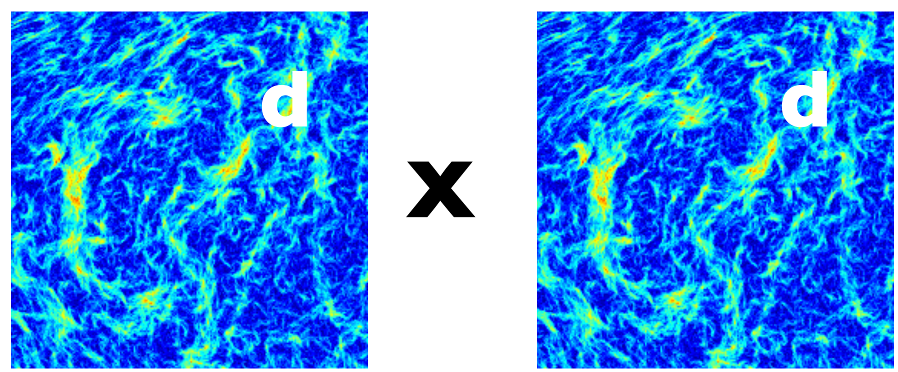
POLARBEAR evidence for B-modes…4.3\sigma from CMB alone

- 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



New PRD "Editors' Suggestion" arXiv 1509.02461

POLARBEAR Constraints on Cosmic Birefringence and Primordial Magnetic Fields

Polarbear Collaboratio

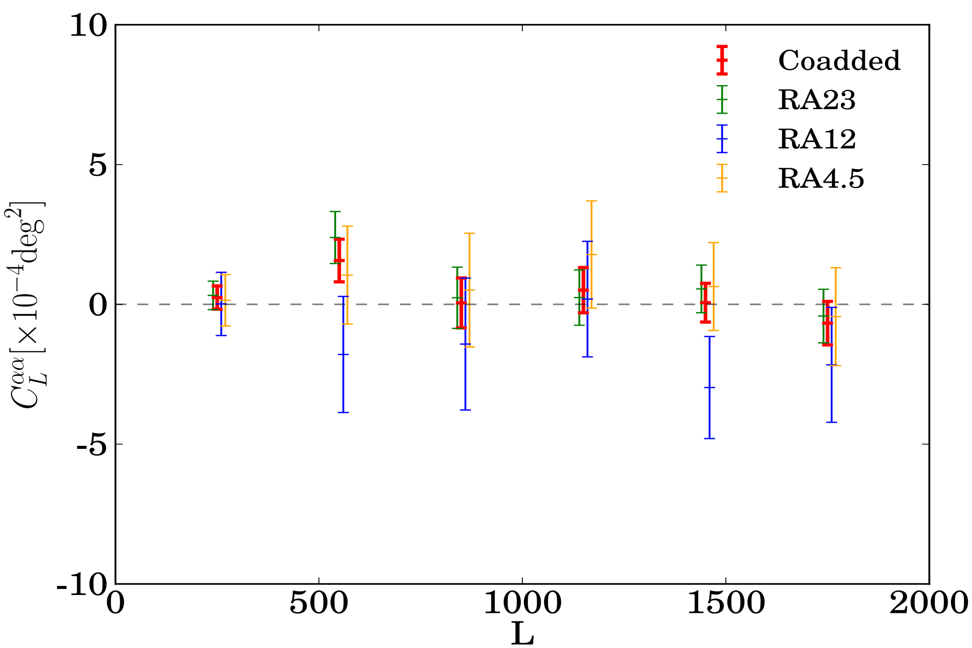


FIG. 2: The anisotropic cosmic rotation power spectra from POLARBEAR 's first-season data in three patches. The spectrum of an individual patch is indicated by the green (RA23), blue (RA12) and orange (RA4.5) colors. The coadded (red) power spectrum is consistent with zero.

PMF < 3.9 nG — **POLARBEAR**

PMF < 4.5 nG — **Planck**

POLARBEAR Constraints on Cosmic Birefringence and Primordial Magnetic Fields

POLARBEAR Collaboration, Peter A.R. Ade,[1] Kam Arnold,[2] Matt Atlas,[2] Carlo Baccigalupi,[3] Darcy Barron,[4] Amy Bender,[5] David Boettger,[6] Julian Borrill,[7,8] Scott Chapman,[9] Yuji Chinone,[4] Ari Cukierman,[4] Matt Dobbs,[10] Anne Ducout,[11] Rolando Dunner,[6] Tucker Elleflot,[2] Josquin Errard,[8,7] Giulio Fabbian,[3] Stephen Feeney,[11] Chang Feng,[12] Adam Gilbert,[10] Neil Goeckner-Wald,[4] John Groh,[4] Grantland Hall,[4] Nils W. Halverson,[13,14,15] Masaya Hasegawa,[16,17] Kaori Hattori,[16] Masashi Hazumi,[16,18,17] Charles Hill,[4] William L. Holzapfel,[4] Yasuto Hori,[4] Logan Howe,[2] Yuki Inoue,[17,16] Gregory C. Jaehnig,[13,15] Andrew H. Jaffe,[11] Oliver Jeong,[4] Nobuhiko Katayama,[18] Jonathan P. Kaufman,[2] Brian Keating,[2] Zigmund Kermish,[19] Reijo Keskitalo,[7,8] Theodore Kisner,[7,8] Akito Kusaka,[20] Maude Le Jeune,[21] Adrian T. Lee,[4,20] Erik M. Leitch,[22,23] David Leon,[2] Yun Li,[24] Eric Linder,[20] Lindsay Lowry,[2] Frederick Matsuda,[2] Tomotake Matsumura,[25] Nathan Miller,[26] Josh Montgomery,[10] Michael J. Myers,[4] Martin Navaroli,[2] Haruki Nishino,[16] Takahiro Okamura,[16] Hans Paar,[2] Julien Peloton,[21] Levon Pogosian,[24] Davide Poletti,[21] Giuseppe Puglisi,[3] Christopher Raum,[4] Gabriel Rebeiz,[27] Christian L. Reichardt,[28] Paul L. Richards,[4] Colin Ross,[9] Kaja M. Rotermund,[9] David E. Schenck,[13,14] Blake D. Sherwin,[4,29] Meir Shimon,[30] Ian Shirley,[4] Praween Siritanasak,[2] Graeme Smecher,[10] Nathan Stebor,[2] Bryan Steinbach,[4] Radek Stompor,[21] Aritoki Suzuki,[31] Jun-ichi Suzuki,[16] Osamu Tajima,[16,17] Satoru Takakura,[32,16] Alexei Tikhomirov,[9] Takayuki Tomaru,[16] Nathan Whitehorn,[4] Brandon Wilson,[2] Amit Yadav,[2] Alex Zahn,[2] and Oliver Zahn[4]

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[5]*Argonne National Laboratory, Argonne, IL 60439*
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[24]*Department of Physics, Simon Fraser University, Burnaby, BC, V5A 1S6, Canada*
[25]*Institute of Space and Astronautical Studies (ISAS), Japan Aerospace Exploration Agency (JAXA), Sagamihara, Kanagawa 252-5210, Japan*
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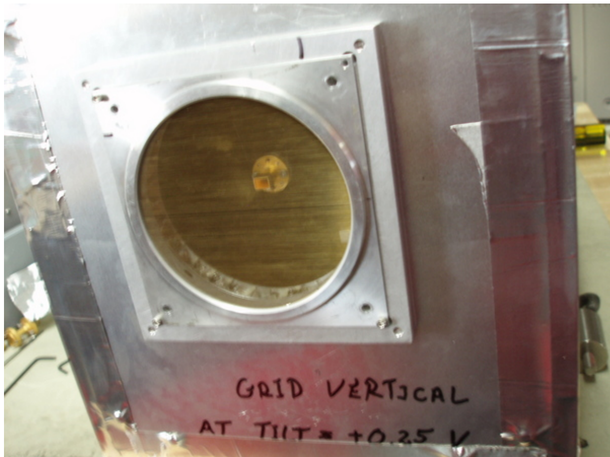
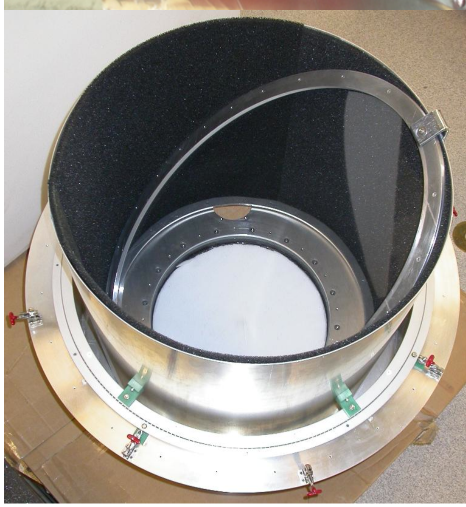
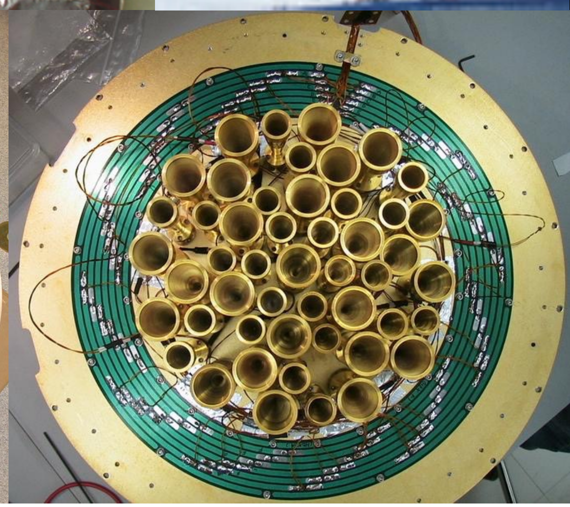
[29]*Miller Institute for Basic Research in Science, University of California, Berkeley, CA 94720, USA*
[30]*School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel*
[31]*Radio Astronomy Laboratory, University of California, Berkeley, CA 94720, USA*

Calibrating Polarization Orientation







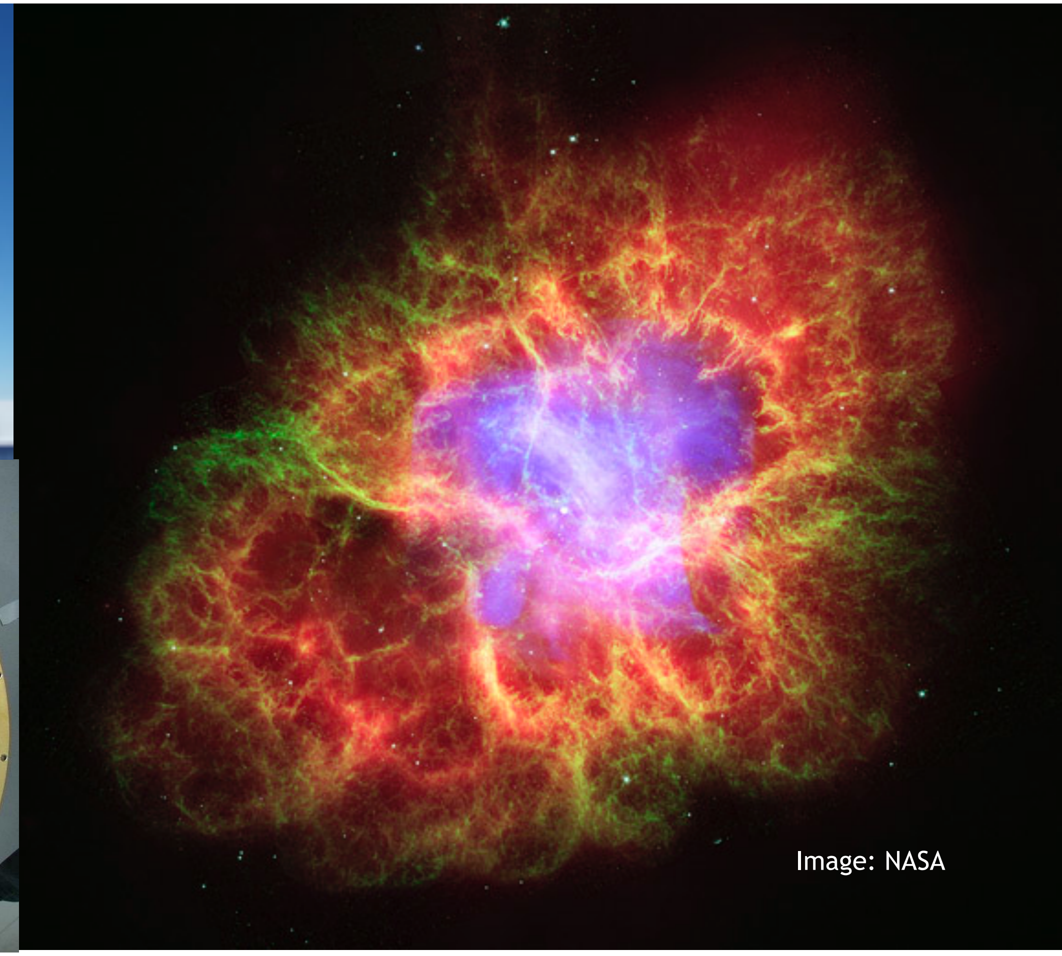
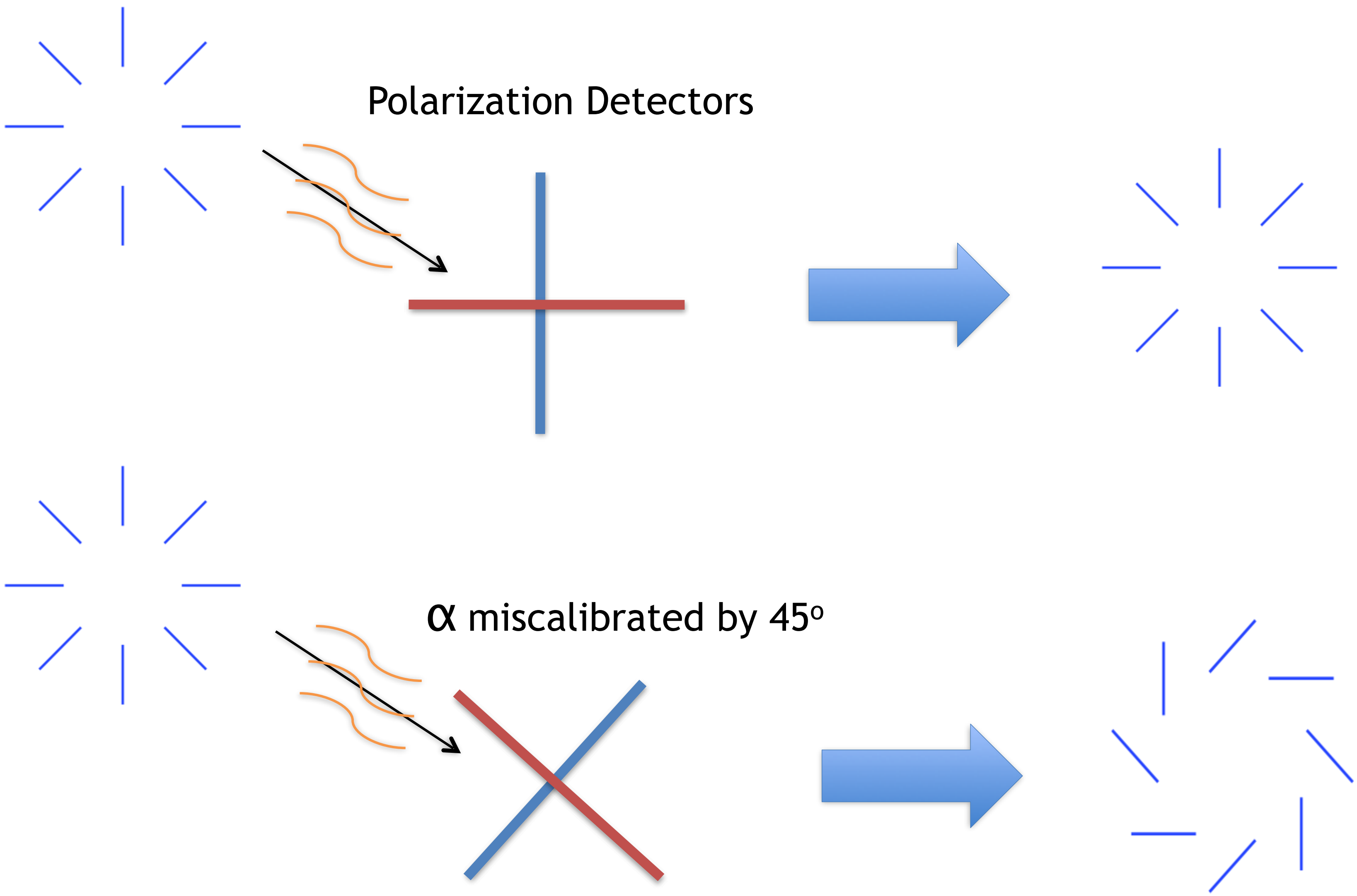


Table 3: Current calibration methods and their precision.

Hardware Method	Precision	Celestial Source	Precision
dielectric sheet	1.3° [12]	Tau A	0.5° [14]
near-field wire grid	1.7° [51]	Cen A	$1.7^{\circ a}$ [58]
as-designed	0.5° [48]		
rotating far-field source	$< 1^\circ$ [50]		

Polarization Orientation Calibration Error



Birefringence & Systematics

Leakage of temperature to polarization causes:

$$B \propto \omega T, \text{ with } \omega \ll 1$$

$$C_\ell^{BB} \propto \omega^2 C_\ell^{TT}$$

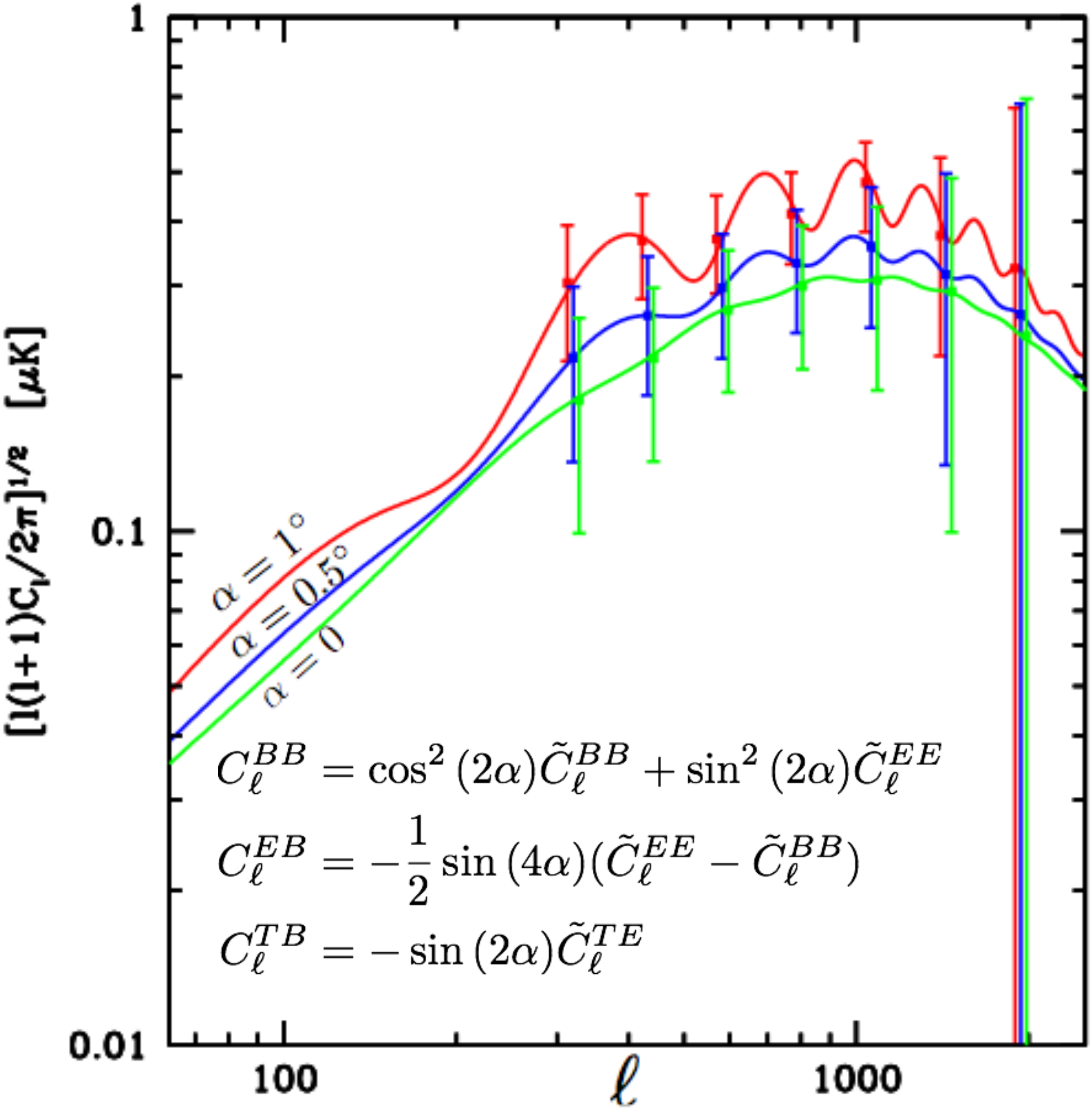
$$C_\ell^{TB} \propto \omega C_\ell^{TT}$$

Therefore systematics that are low enough for B-modes are not necessarily sufficient to measure EB & TB

But, can use to "self-calibrate" polarization angle better than with any calibrator (Keating, Shimon & Yadav (2012)

Note: foregrounds less of a problem: http://arxiv.org/abs/1512.06834

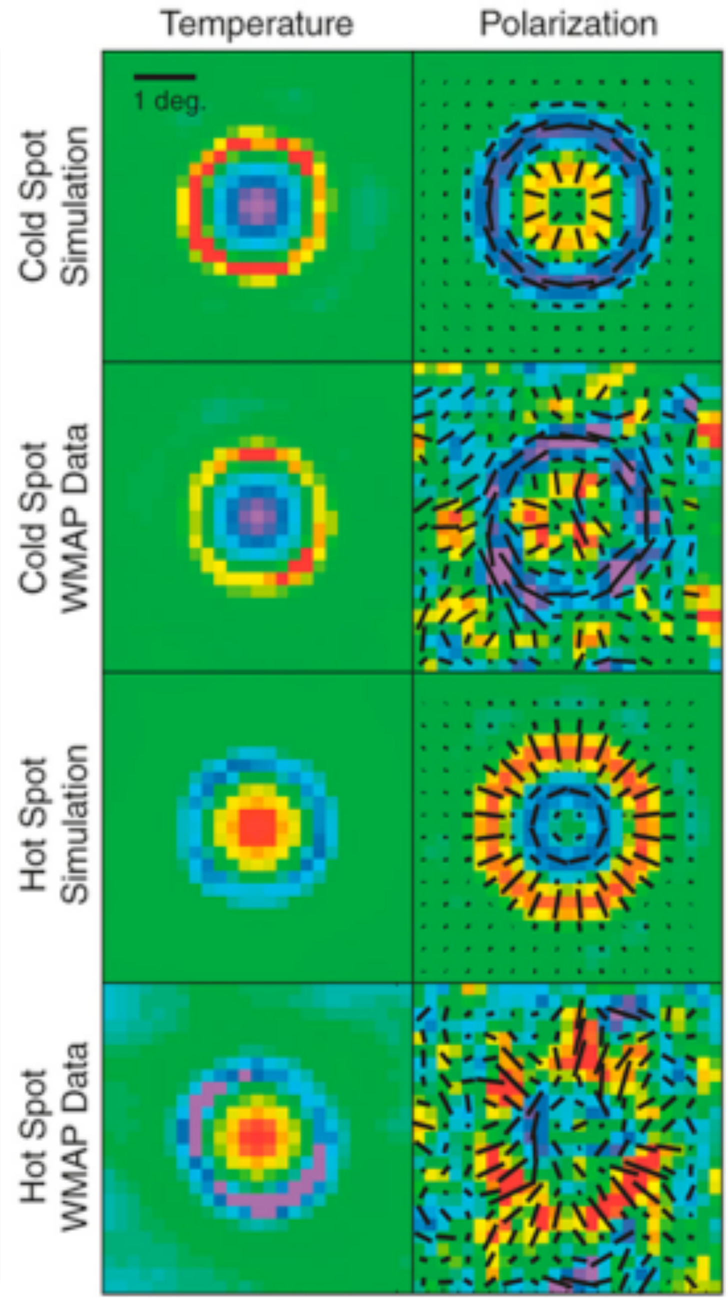
BB Predictions for various levels of α



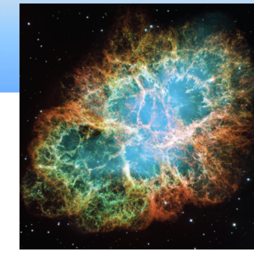
$$C_\ell^{BB} = \cos^2(2\alpha)\tilde{C}_\ell^{BB} + \sin^2(2\alpha)\tilde{C}_\ell^{EE}$$

$$C_\ell^{EB} = -\frac{1}{2}\sin(4\alpha)(\tilde{C}_\ell^{EE} - \tilde{C}_\ell^{BB})$$

$$C_\ell^{TB} = -\sin(2\alpha)\tilde{C}_\ell^{TE}$$

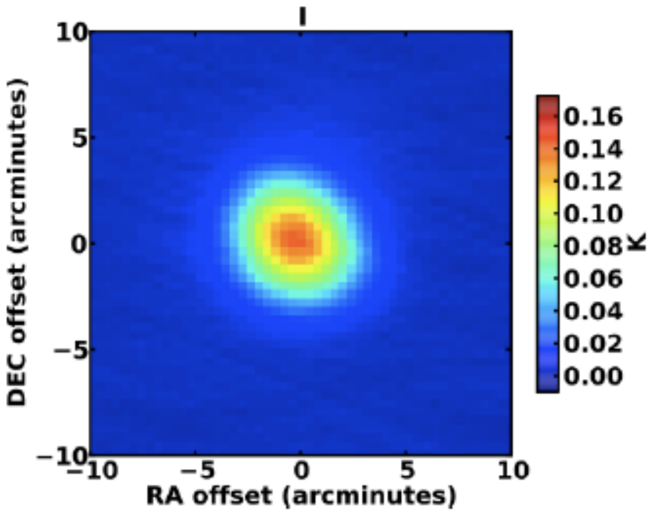


Polarization Map: Calibrate

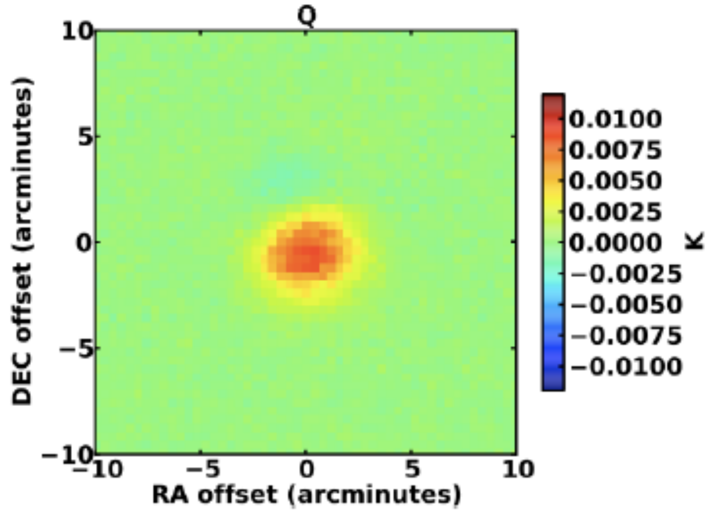


TauA (Crab nebula)

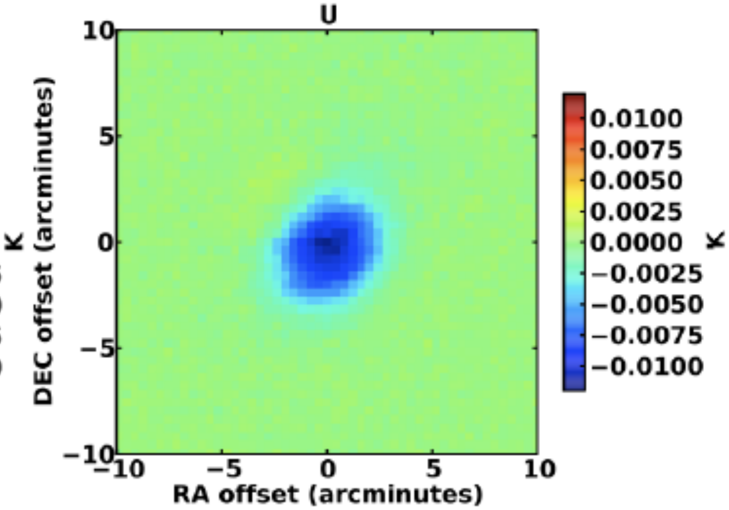
Temperature



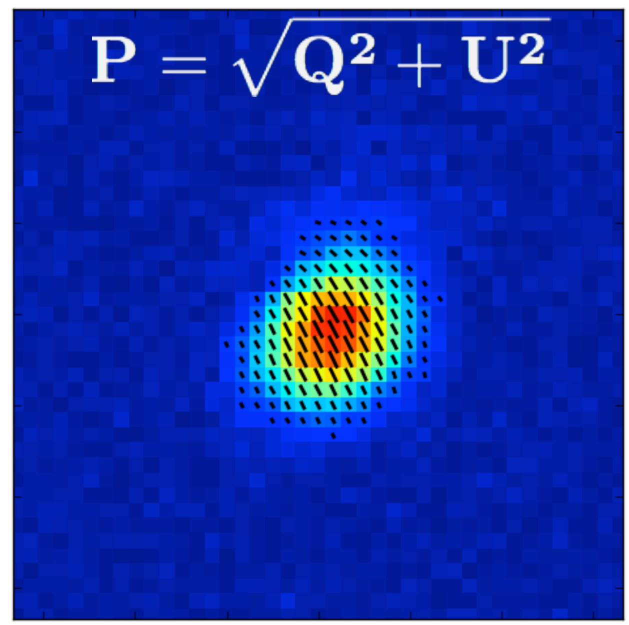
Stokes Q

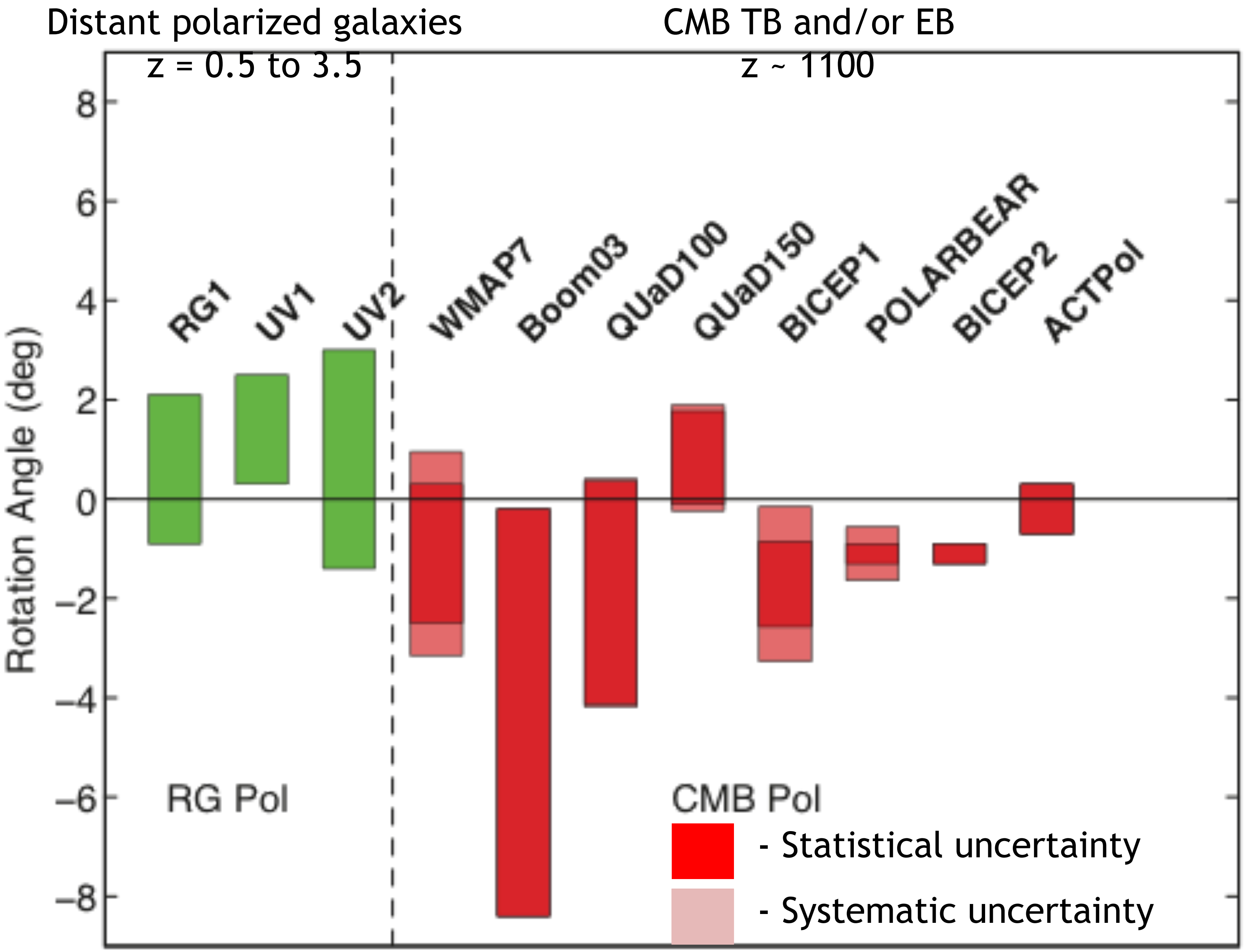


Stokes U



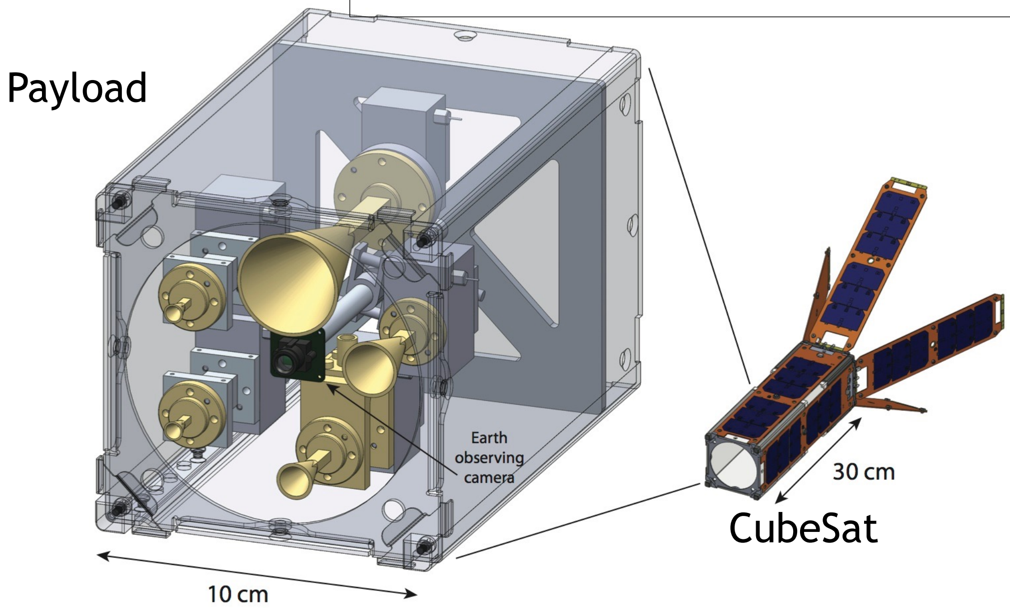
- Cross-check with other experiments (WMAP, QUIET, IRAM, PLANCK)
- Measure TauA every 36 hour obs. cycle
- Used TauA as calibrator for self-consistency; used EB self-calibration for final results

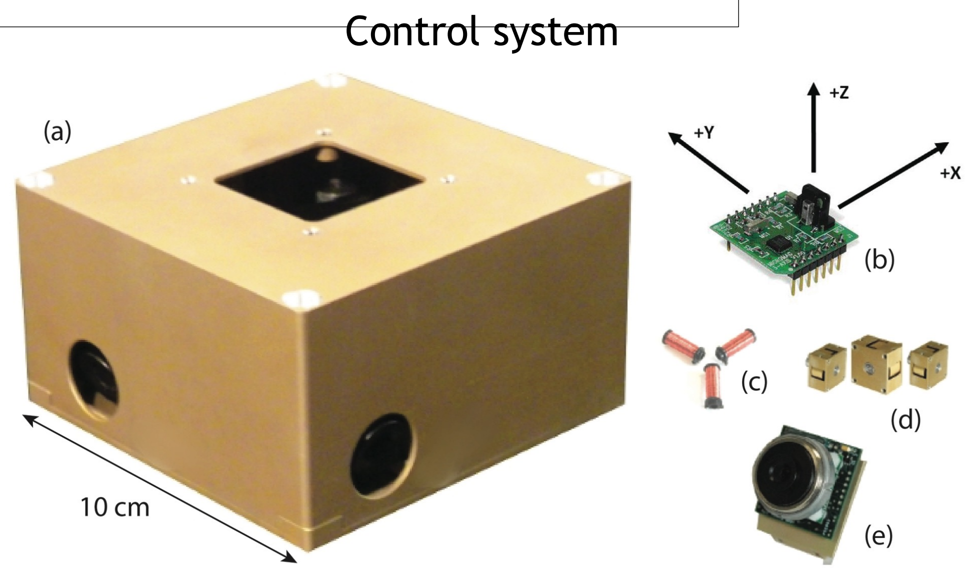


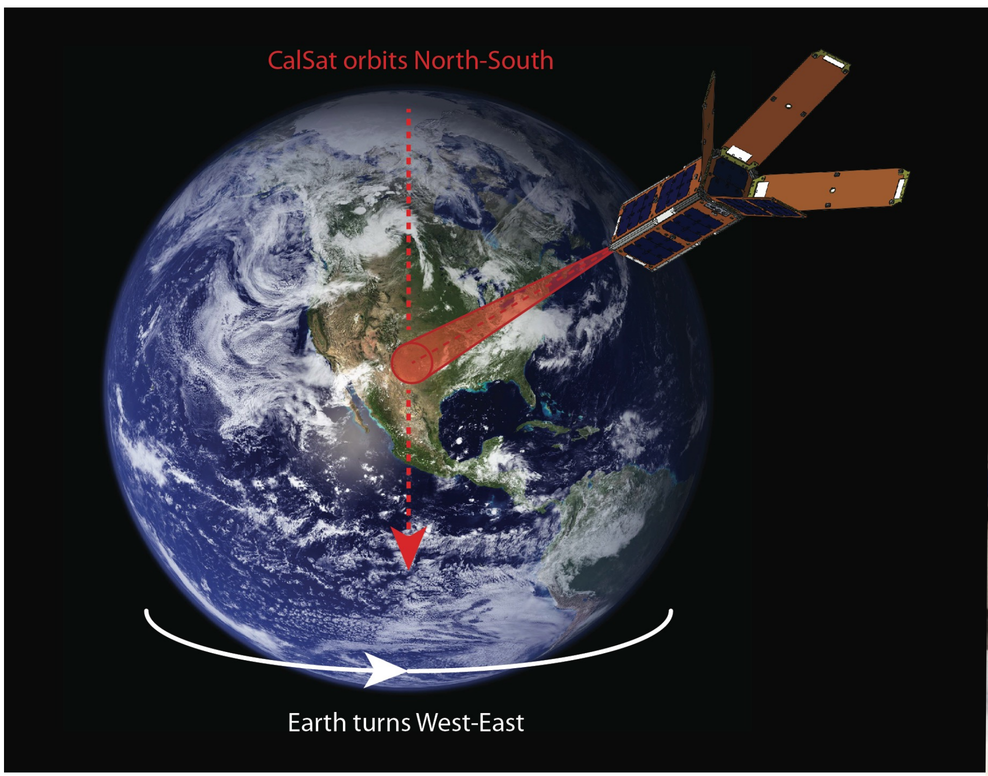


Kaufman, Keating, Johnson 2014

CalSat: Invited for NSF MSIP

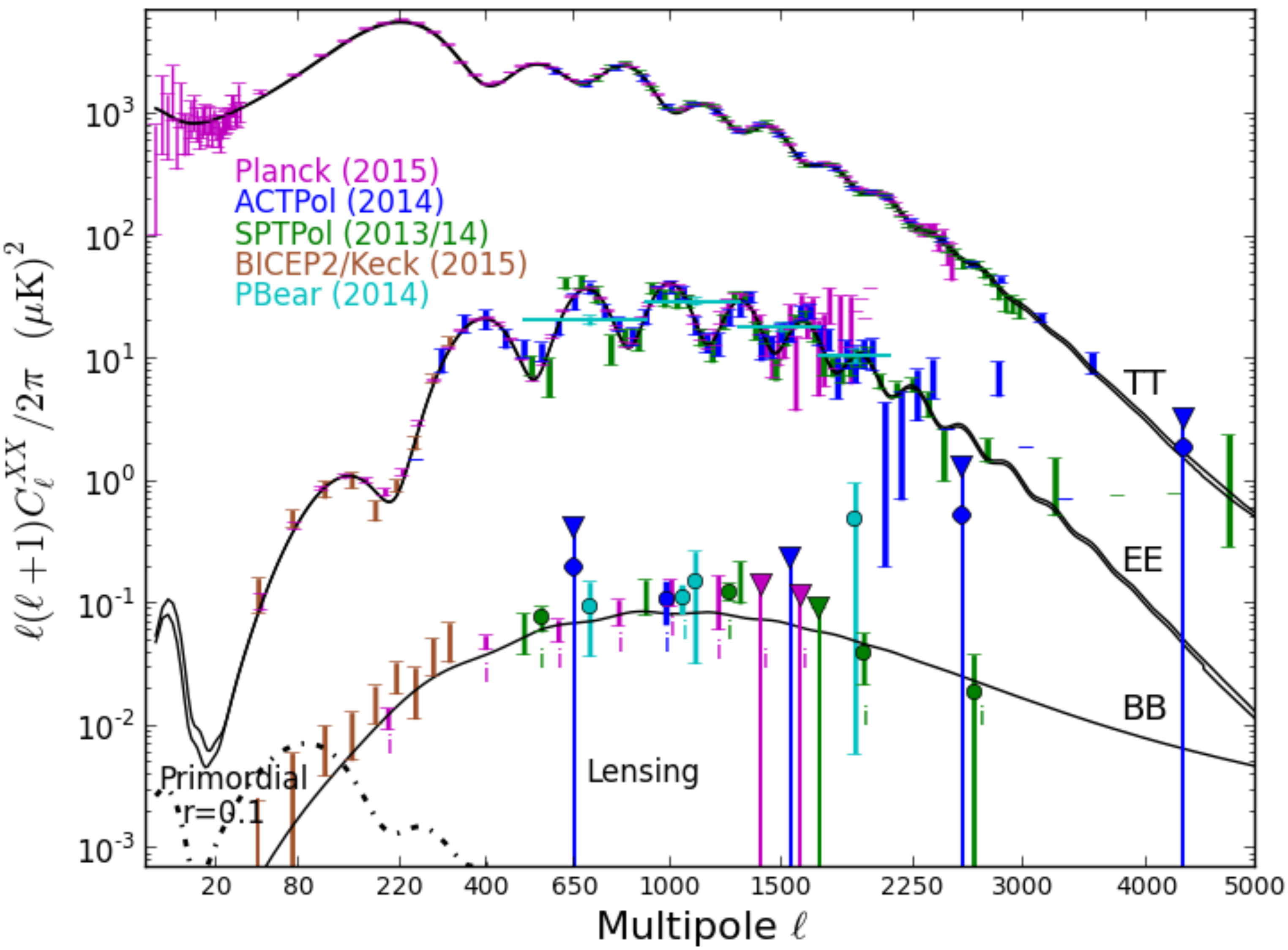






- Operates in the primary CMB bands (47, 80, 140, 249, 309 GHz)
- Commercial microwave components
- Pure polarized signal
- CubeSat platform in Polar low Earth orbit, visible from every observatory
- Star pointing cameras provide 0.05° polarization angle precision
- Use with current and future telescopes like Simons Array

Today's Challenge: Foregrounds



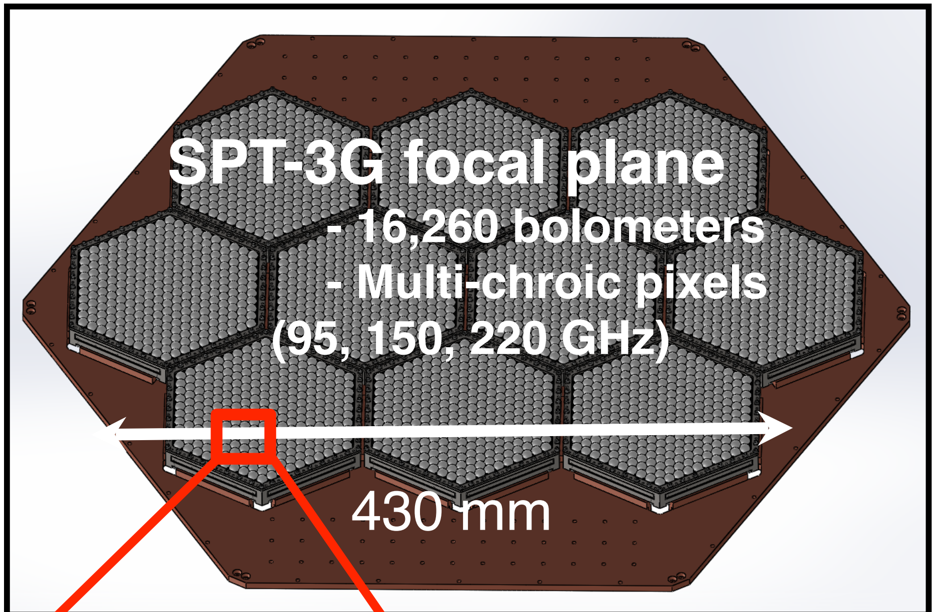
BICEP2
March 2014

BICEP2
After foreground
Removal from Planck

Broad frequency coverage and resolution are required to detect and remove foregrounds

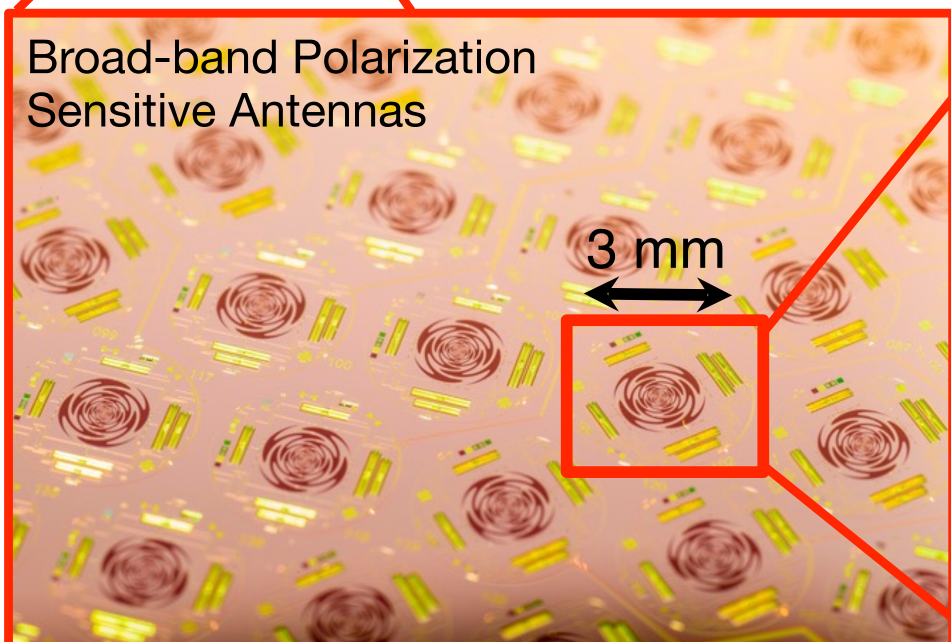
L. Page

SPT-3G and Simons Array: Dust Buster Detectors

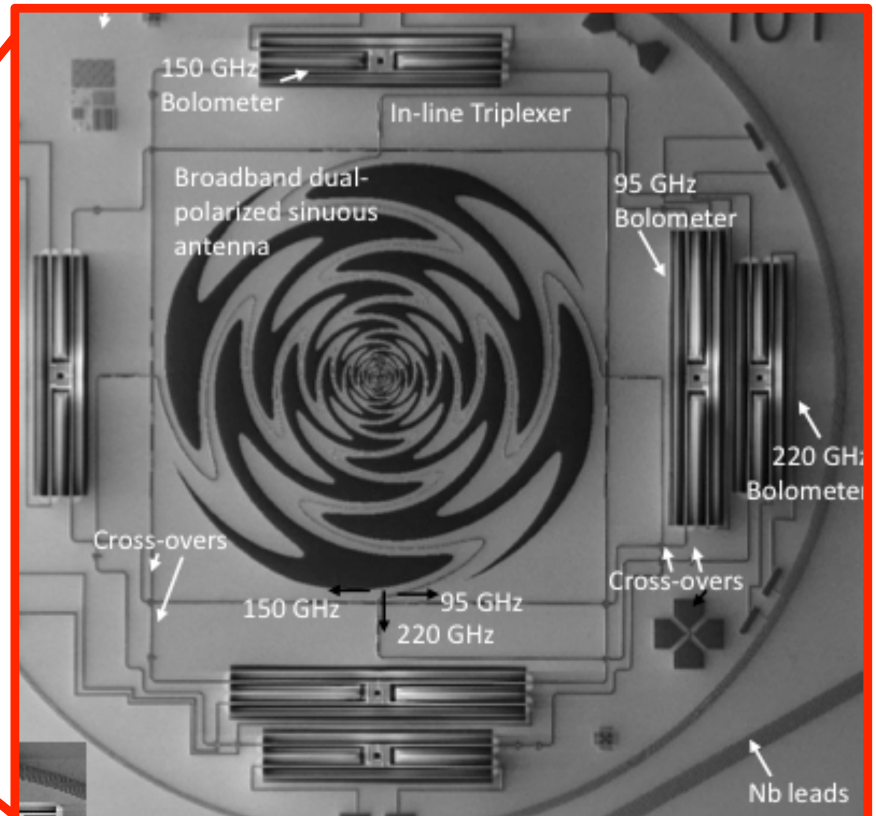


Sinuous detectors: multiple bands in one spatial pixel.

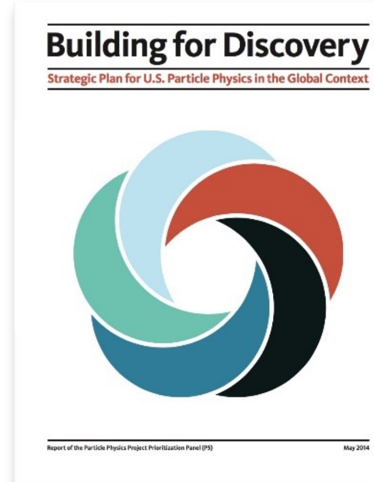
DOE Labs (ANL, FNAL, LBNL, SLAC) building up fabrication capabilities & infrastructure.



Fabricated at Argonne National Lab (ANL)



Stage IV CMB experiment: CMB-S4



Recommended by the DOE Particle Physics Project Prioritization Panel (P5) report for funding under all budget scenarios. Also, by the National Resource Council's Antarctic Reports

CMB-S4 achieves critical thresholds in r, N_{eff} and Σm_ν

Years	Stage	Sensitivity (μK^2)	$r_{u.lim}$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy FoM
2015–2016	Stage 2 1000 detectors	$\gtrsim 10^{-5}$	$r \lesssim 0.1$	0.14	0.15eV (BOSS BAO prior)	~130 (Stage-3 DE (CMB+BAO+SN+WL))
2017–2020	Stage 3 10,000 detectors	10^{-6}	$r \lesssim 0.01$ $E_{inf} < 10^{16}$ GeV	0.06	0.06eV (BOSS BAO prior)	~350 (Stage-3 DE +DESI-BAO)
2021–2024	Stage 4 CMB-S4 ~500,000 detectors	10^{-8}	$r \lesssim 0.001$	0.02	0.015eV (DESI BAO prior)	~1250 (Stage-4 DE (CMB+BAO+SN+WL+CL))

Community coming together to define the science goals

Next workshop March 7-8, 2016 at Berkeley LBNL

Take away

- Decade of the B-mode has begun!
- Fascinating physics beyond "just" the B-modes.
- Can't combine experiments…they are highly correlated.
- No standard polarized candle…must make our own!
- Foregrounds for other physics may be less important than for gravitational waves.
- Exciting era of "big science" with CMB-S4!

NSF

CONICYT
Ministerio de Educación
Gobierno de Chile

MEXT

NASA

Thank you!

SIMONS FOUNDATION
Advancing Research in Basic Science and Mathematics