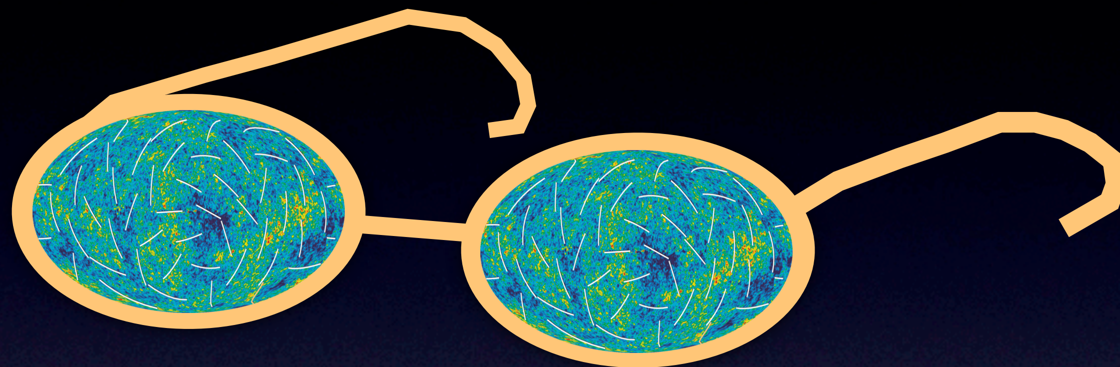
Fundamental Physics



Through the CMB's Lenses

Brian Keating

http://cosmology.ucsd.edu/

9 September 2013 TAUP

UNIVERSITY OF CALIFORNIA SAN DIEGO

LET THERE BE LIGHT

ACEC

AX CENTER *for* EXPERIMENTAL COSMOLOGY

Focus on *Fun*damental Physics

Cosmic Microwave Background (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). Also, a form of GW indirect detection.

Further Fundamental Physics:

Neutrino masses

Helium abundance

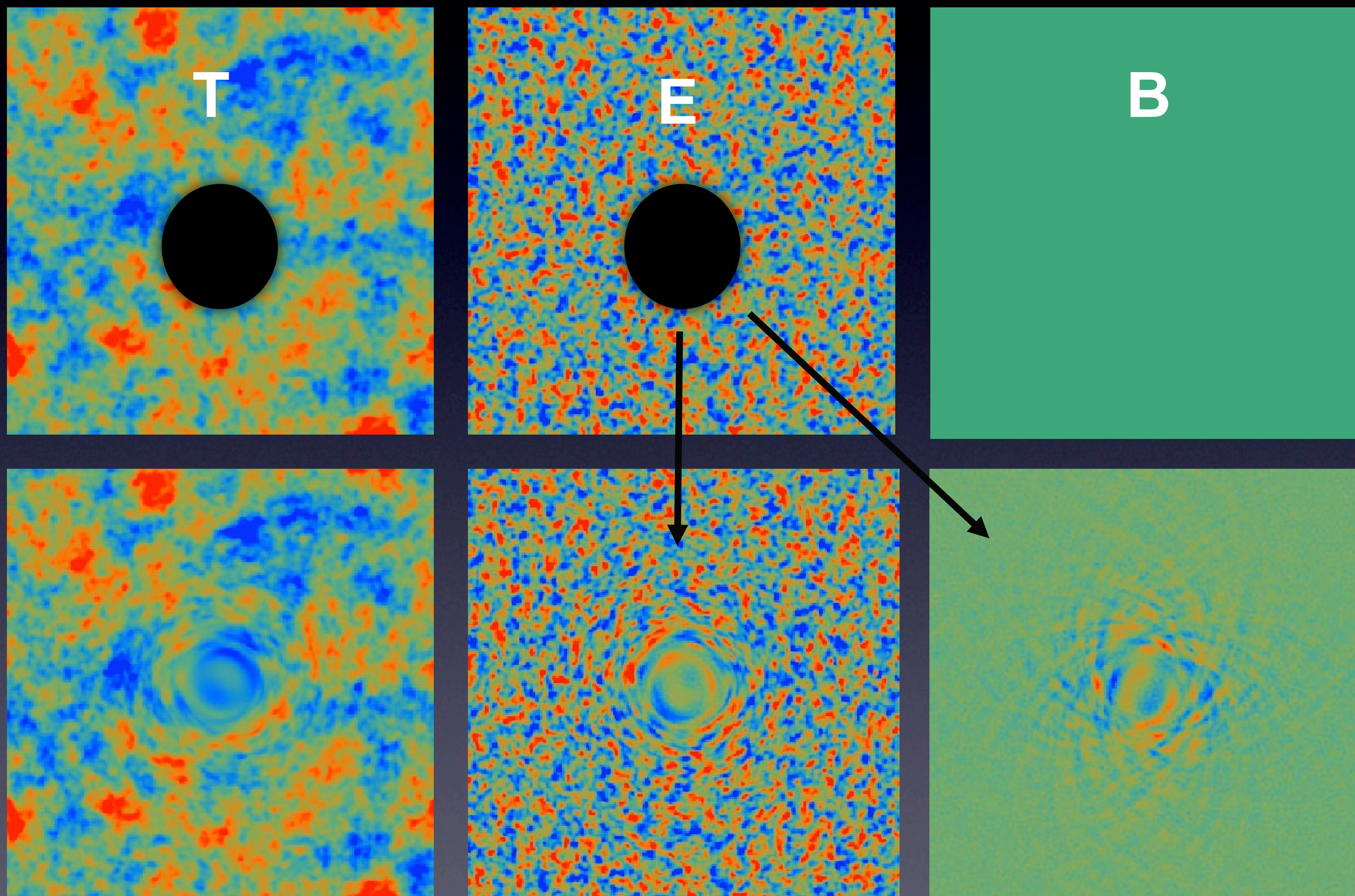
Neutrino chemical potentials

Interstellar magnetic fields

Primordial magnetic fields

Exotic physics, such as cosmic birefringence

“Is this Better or Worse?” Before & After Lensing Maps



Hu & Okamoto 2002

“Blink and You’ll Miss It!”

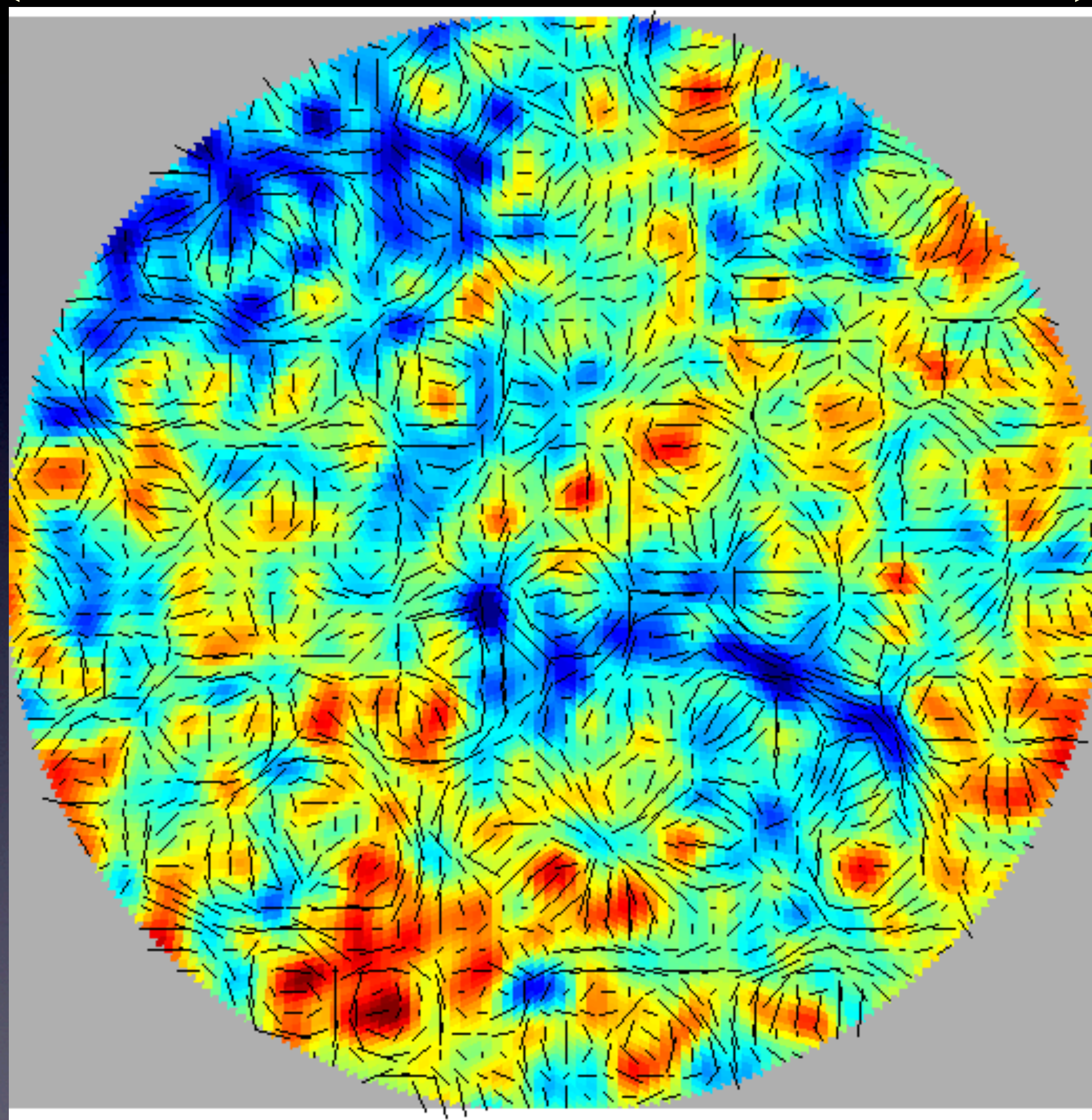
CMB Map

GWB: > 2° scales

Lensing, m_ν < 0.1°

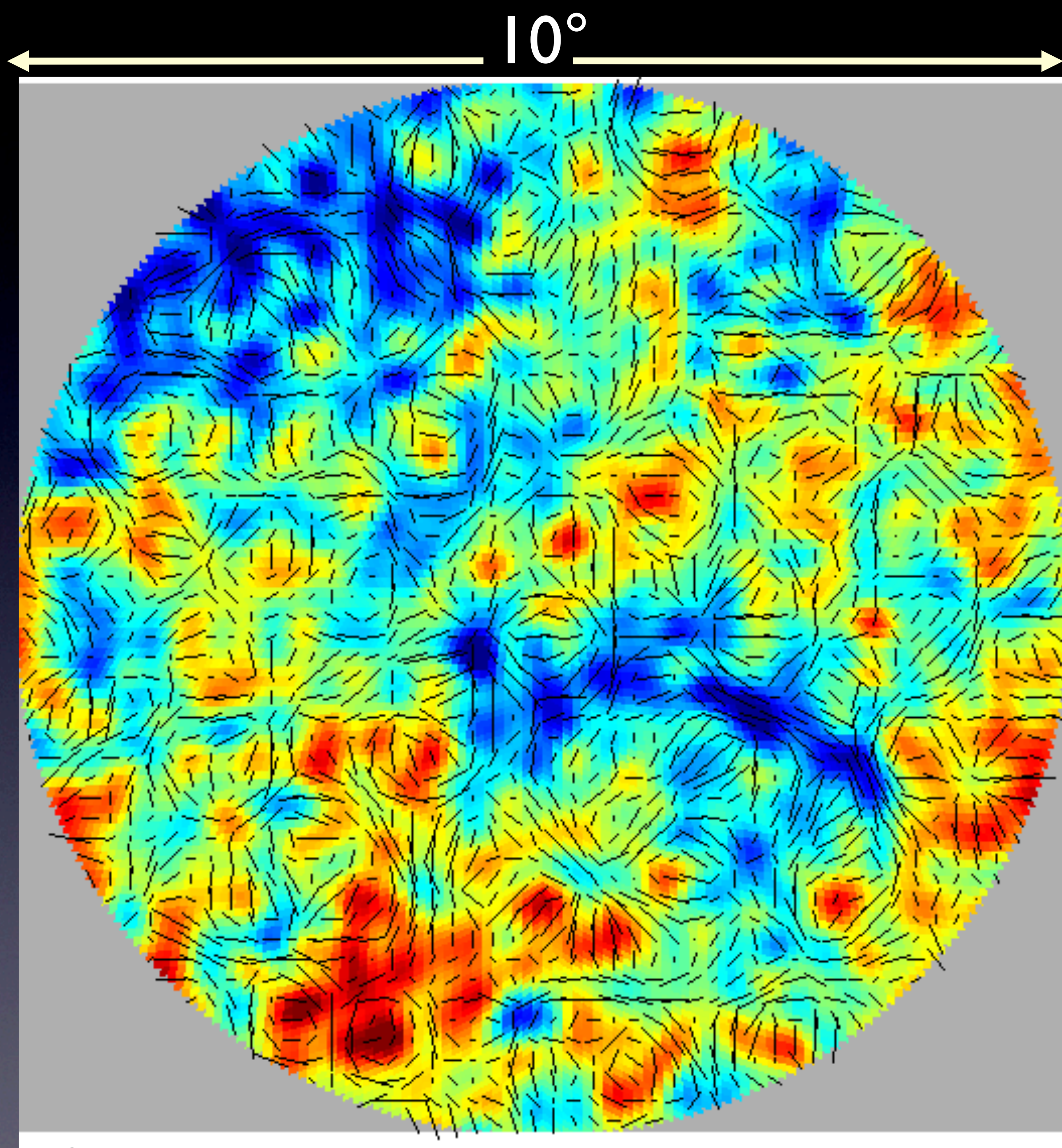
Helmholtz’sThm:
“grad”: even parity
“curl”: odd parity

10°



Without B-modes

“Blink and You’ll Miss It!”



CMB Map

GWB: > 2° scales

Lensing, m_ν < 0.1°

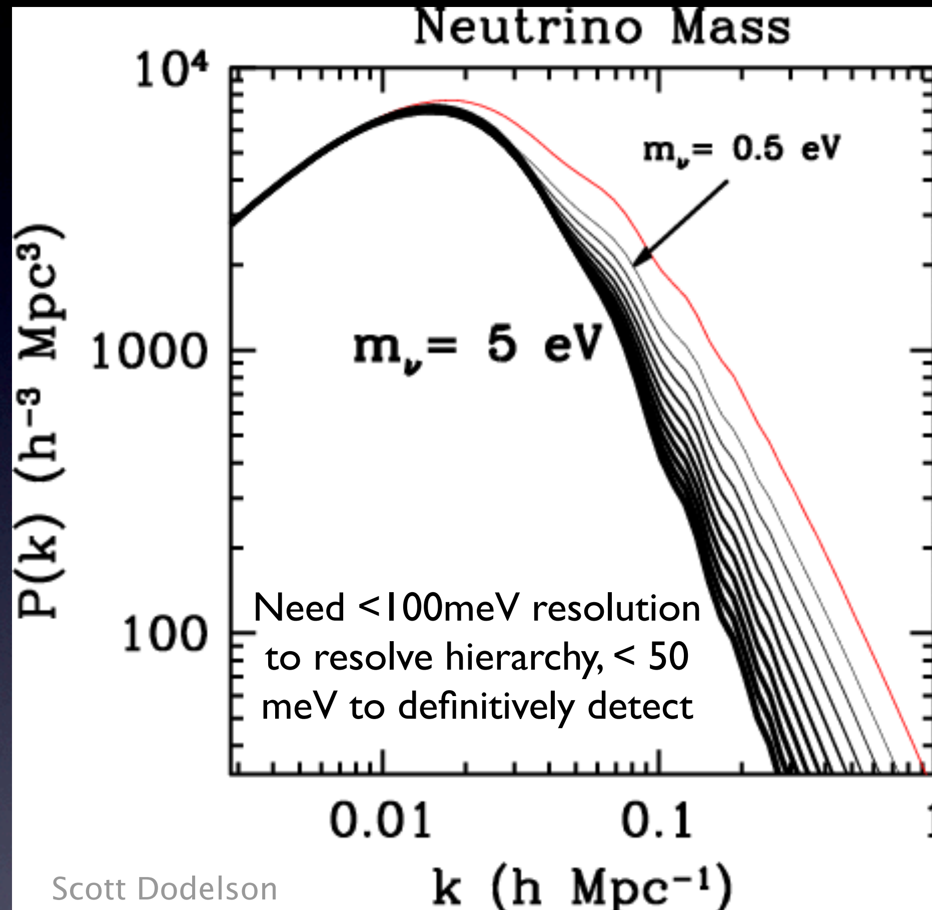
Helmholtz’sThm:
“grad”: even parity
“curl”: odd parity

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

With B-modes From Gravitational Lensing!

Neutrinos

- We now 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.

Why is Polarization Sensitive to Lensing?

- B-mode polarization is *extremely* sensitive since it is a whole new signal (at small angular scales).
- EB correlations are *forbidden* without lensing, so EB is the *most sensitive* to the deflection angle (Hu & Okamoto,), and to neutrino physics: M_ν (Kaplinghat et al) and degeneracy, ξ (Shimon et al.) .
- As an additional bonus, EB is cleaner than TT.

Magnetic Motivation

- Magnetic fields detected in >100 galaxies, galaxy clusters, including Coma.
- Only upper 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).
- Constraints on PMF can be derived by considering using BBN, the CMB and polarized extragalactic sources.
- BBN: at $t \simeq 1$ s, $T \simeq 1$ MeV, the energy density of the Universe is 2×10^{25} erg cm−3 which is comparable to the energy density in a 6×10^{12} G magnetic field. The PMF must be lower to not spoil BBN predictions.
- This implies PMF: $B < 10^{-6}$ G. (Kolb & Turner, http://arxiv.org/pdf/astro-ph/0207240v1.pdf)

Exotic: Primordial Magnetic Fields 𝔹

Perhaps the magnetic fields we see in the structure around us, originated from seed magnetic fields imprinted in the "early universe"

Galaxies	B~ few μG,	~Kpc
Galaxy clusters	B~ 1-10 μG,	~10-100 Kpc
Objects at z~2	B~10 μG	

The physics responsible for generating the seed magnetic fields is largely unknown.

- Phase transitions- QCD, Electroweak, GUT
- Cosmic strings

$$\alpha = \frac{3}{16\pi^2 e}\lambda_0^2 \int \dot{\tau}\, \mathbf{B} \cdot d\mathbf{l}$$

c.f.: Temperature signal $C_\ell^{TT} \propto B^{\frac{1}{4}}$

- We would like to detect the presence of primordial magnetic field (PMF) and to know the physics responsible for generating PMF

Anisotropic stress, charges creates magnetic fields which, via Faraday rotation, converts E to B

𝔹 —— Magnetic helicity and Magnetic flux are almost conserved during the evolution of the universe ——→ CMB

Yadav & Pogosian (2011)
Yadav, Shimon, & Keating (2012)

Helium Abundance: As good as astrophysical bounds

High-\ell E-modes enter the horizon before the helium fully recombines

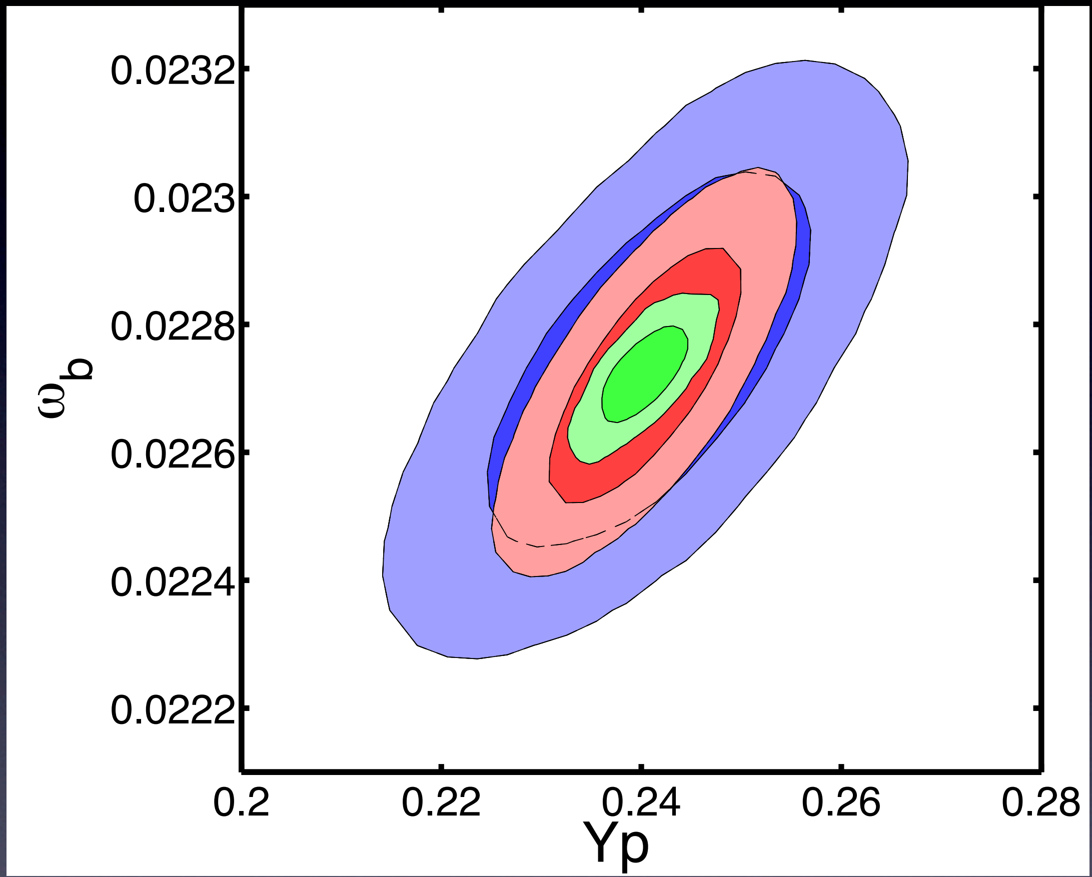
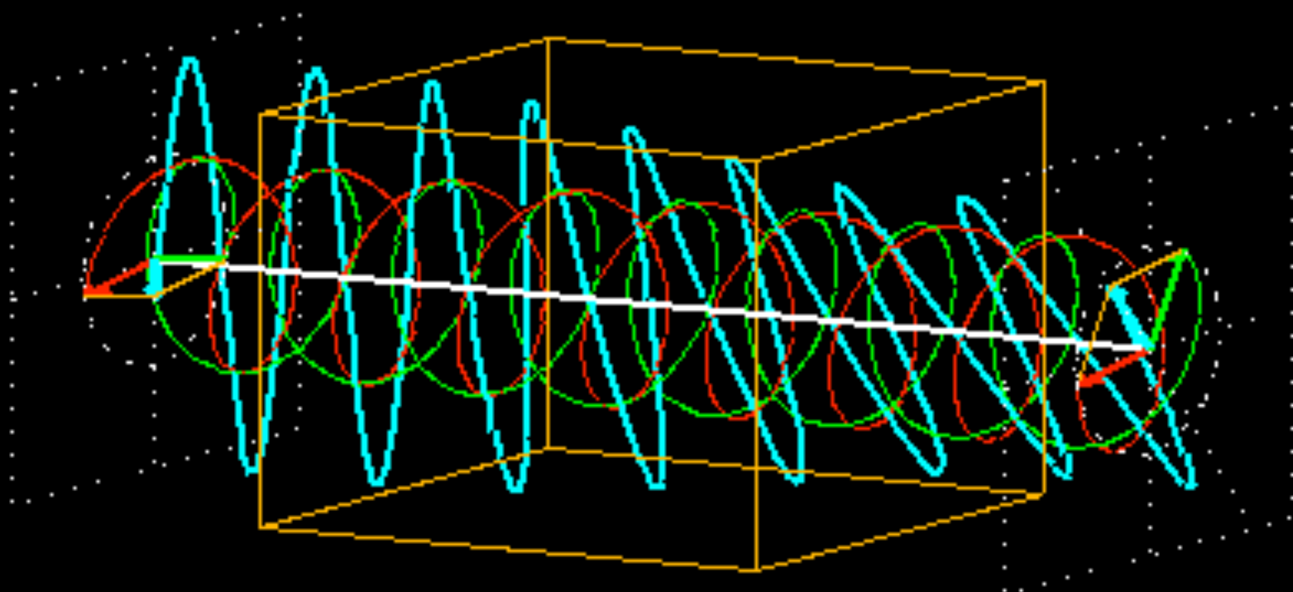


FIG. 8. 68% and 95% likelihood contour plots on the Y_{He} - ω_b plane for Planck (blue), Planck+ACTPol (red) and CMBPol (green).

Galli et al. *arXiv* 1005:3808

Cosmic Birefringence



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

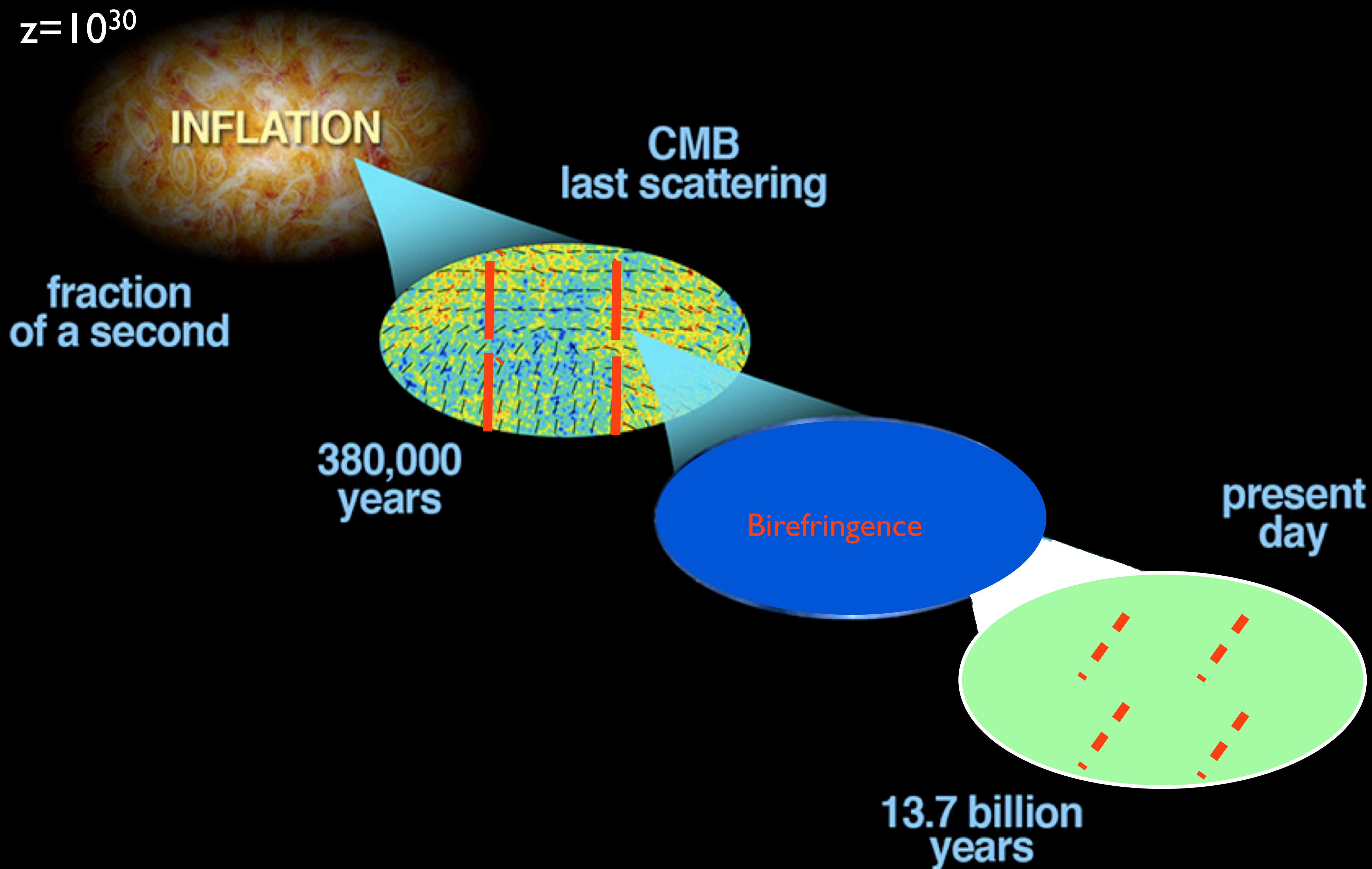
Komatsu et al. (2009)

Wu et al. (2009)

Miller, Shimon & BK (2009)

Alexander & Yunes (2009)

Birefringence



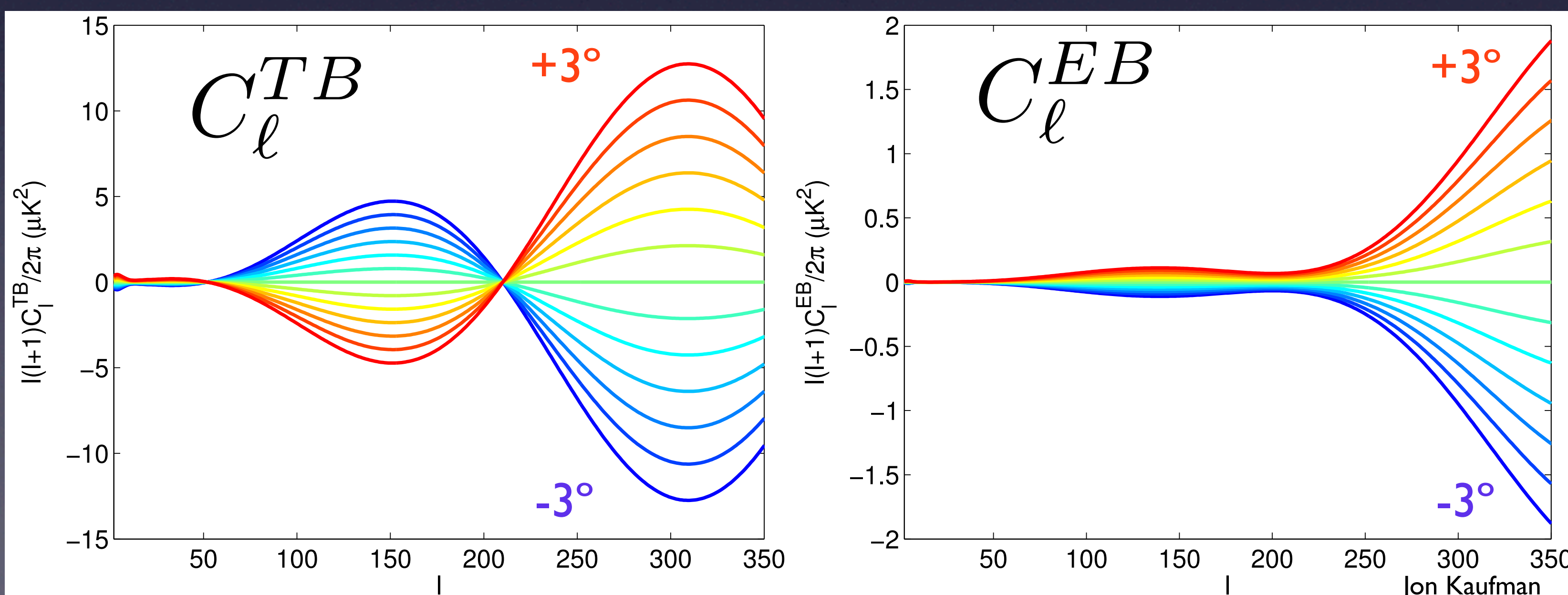
Exotic: Parity Violating Interactions

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

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

Produces two different phase velocities; one for LCP, on for RCP: $\omega^2 = k^2 \pm (4\pi g_\chi \dot{\chi} k)$

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



(a) TB (b) EB

August 2009

Probing CPT Violation with CMB Polarization Measurements

Jun-Qing Xia[1], Hong Li[2,3], and Xinmin Zhang[2,3]
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[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 *five-year Wilkinson Microwave Anisotropy Probe* (WMAP5), *BOOMERanG 2003* (B03), BICEP and QUaD using a Markov Chain Monte Carlo method. We find that the results from WMAP5, B03 and BICEP all are consistent and their combination gives $\Delta\alpha = -2.62 \pm 0.87$ deg (68% *C.L.*), indicating a $3\,\sigma$ detection of the CPT violation for the first time. 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 WMAP5, B03 and BICEP. When combining all the polarization data together, we find $\Delta\alpha = 0.09 \pm 0.36$ 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.

PACS numbers: 98.80.Es, 11.30.Cp, 11.30.Er

Xia et al. claim a *first* detection of CPT violation!?! Parameterized by Chern-Simons rotation angle α

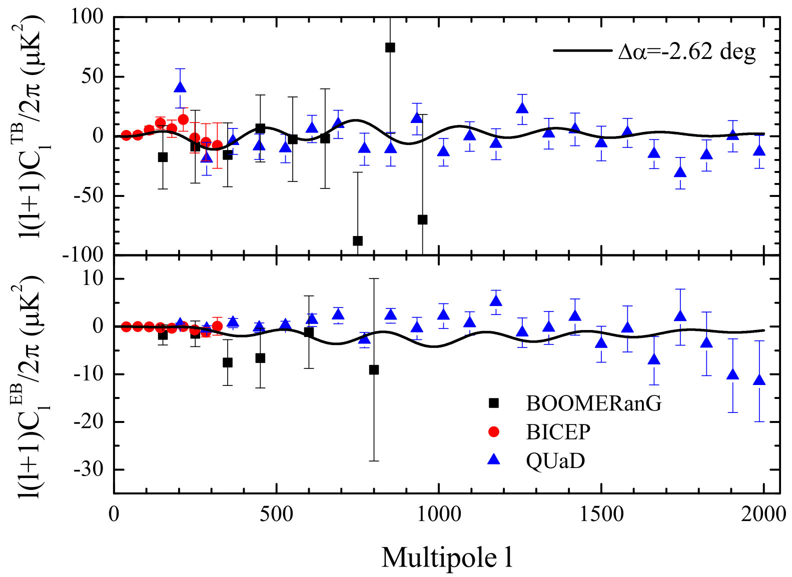


FIG. 1: The binned TB and EB spectra measured by the small-scale CMB experiments of BOOMERanG (black squares), BICEP (red circles) and QUaD (blue triangles). The black solid curves show the theoretical prediction of a model with $\Delta\alpha = -2.62$ deg.

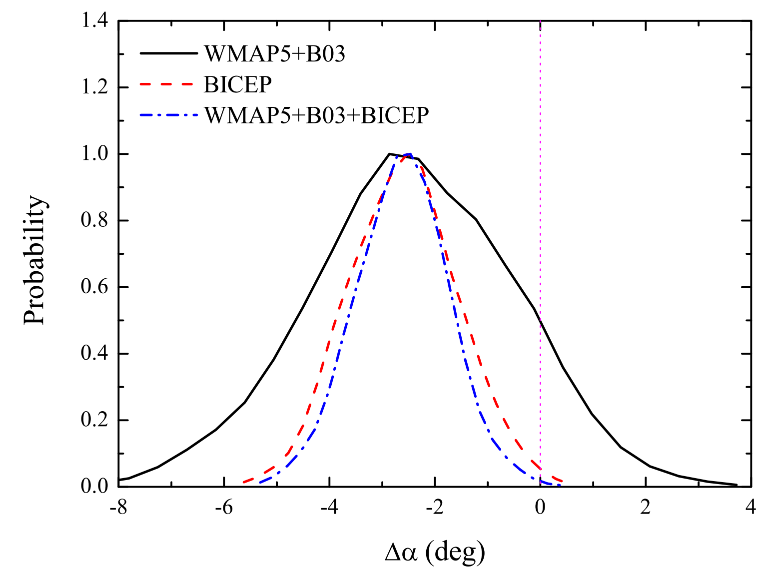


FIG. 2: One-dimensional posterior distributions of the rotation angle derived from various data combinations. The dotted vertical line illustrates the unrotated case ($\Delta\alpha = 0$) to guide eyes.

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)

Current measurements of α

Method	CB rotation	Distance	Direction	
RG radio pol.	$\lvert\theta\rvert < 6^o$	$0.4 < z < 1.5$	all-sky (uniformity ass.)	
RG radio pol.	$\theta = -0.6^o \pm 1.5^o$	$\langle z \rangle = 0.78$	all-sky (uniformity ass.)	
RG UV pol.	$\theta = -1.4^o \pm 1.1^o$	$z = 0.811$	$RA: 176.37^o, Dec: 31.56^o$	
RG UV pol.	$\theta = -0.8^o \pm 2.2^o$	$\langle z \rangle = 2.80$	all-sky (uniformity ass.)	
RG UV pol.	$\langle \theta^2 \rangle \leq (3.7^o)^2$	$\langle z \rangle = 2.80$	all-sky (stoch. var.)	
WMAP7	33+41+61	$2-23$	$-3.8 \pm 5.2 \pm 1.5$	[1]
WMAP7	**41+61+94**	**24-800**	$\mathbf{-0.9 \pm 1.4 \pm 1.5}$	[1]
WMAP7	33+41+61+94 [1]	$2-800$	$-1.1 \pm 1.4 \pm 1.5$	[1]
WMAP7	33+41+61	$2-23$	$-3.0^{+2.6}_{-2.5}$ [2]	[18]
WMAP7	33+41+61	$2-47$	-1.6 ± 1.7	[18]
WMAP7	33+41+61	$2-30$	$-4.2^{+1.9+10.2}_{-3.1-7.5}$	[19]
WMAP7	33+41+61	$2-800$	$-1.3^{+0.6+2.3}_{-0.7-2.3}$	[19]
BOOM03	**145**	**150-1000**	$\mathbf{-4.3 \pm 4.1}$ [3]	[20]
QUAD	**100**	**200-2000**	$\mathbf{-1.89 \pm 2.24 \pm 0.5}$	[21]
QUAD	**150**	**200-2000**	$\mathbf{0.83 \pm 0.94 \pm 0.5}$	[21]
QUAD	100+150	$200-2000$	$0.64 \pm 0.5 \pm 0.5$	[22]
BICEP	**100+150**	**21-335**	$\mathbf{-2.60 \pm 1.02 \pm 0.7}$	[13] [4]

http://arxiv.org/pdf/1211.3321v2.pdf

Birefringence & Systematics

Birefringence & Systematics

Leakage of temperature to polarization causes:

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

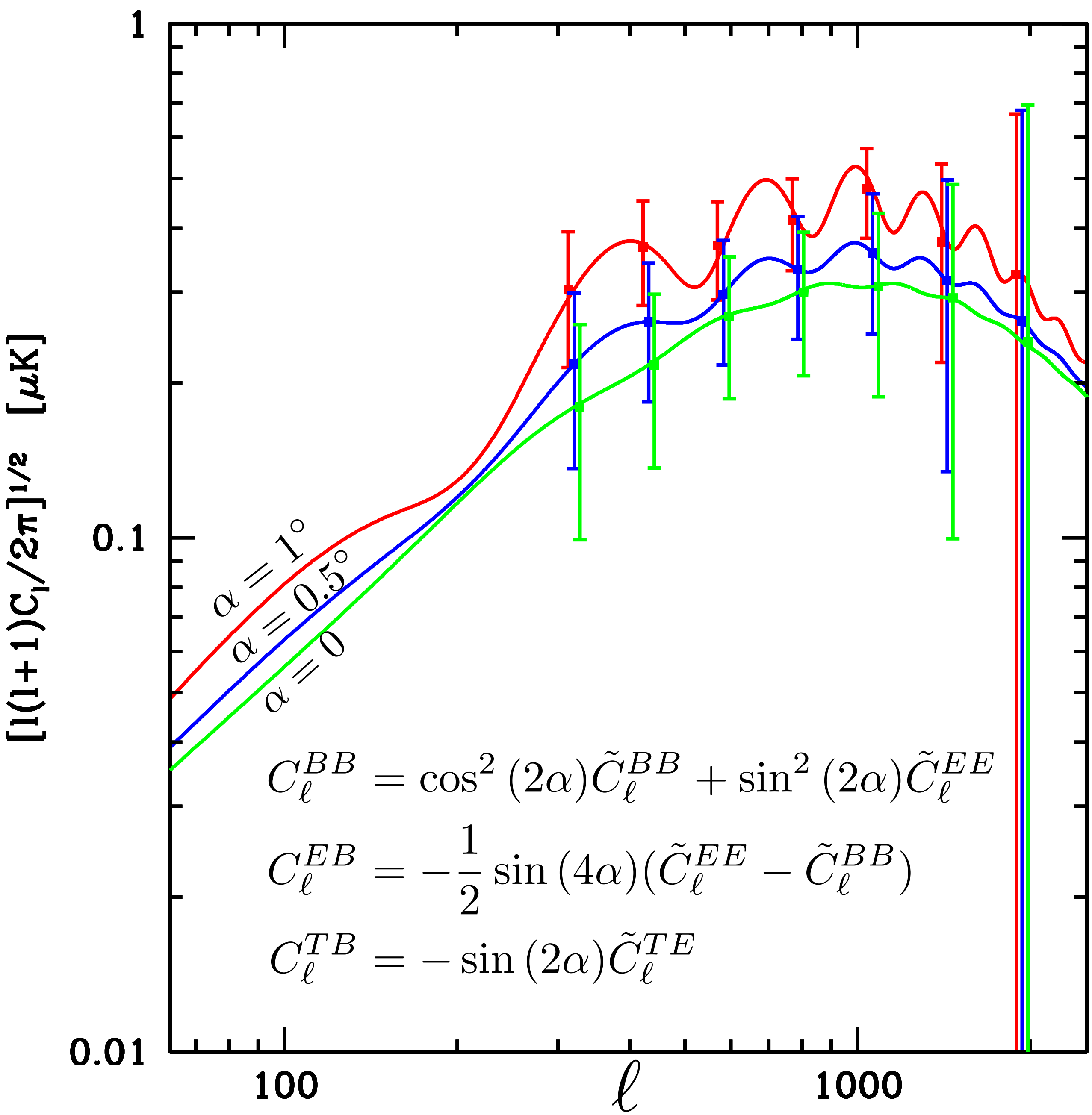
$$C_\ell^{BB} \propto \omega^2 C_\ell^{TT}$$

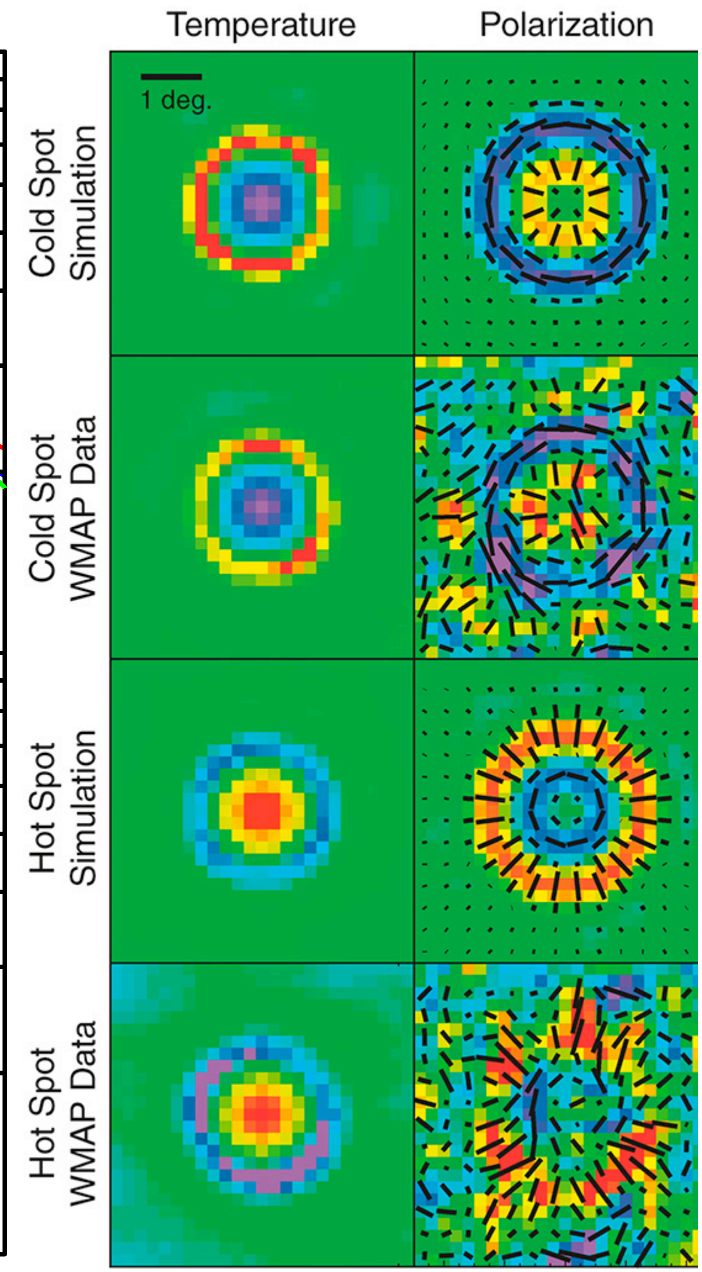
$$C_\ell^{TB} \propto \omega C_\ell^{TT}$$

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 (2013)

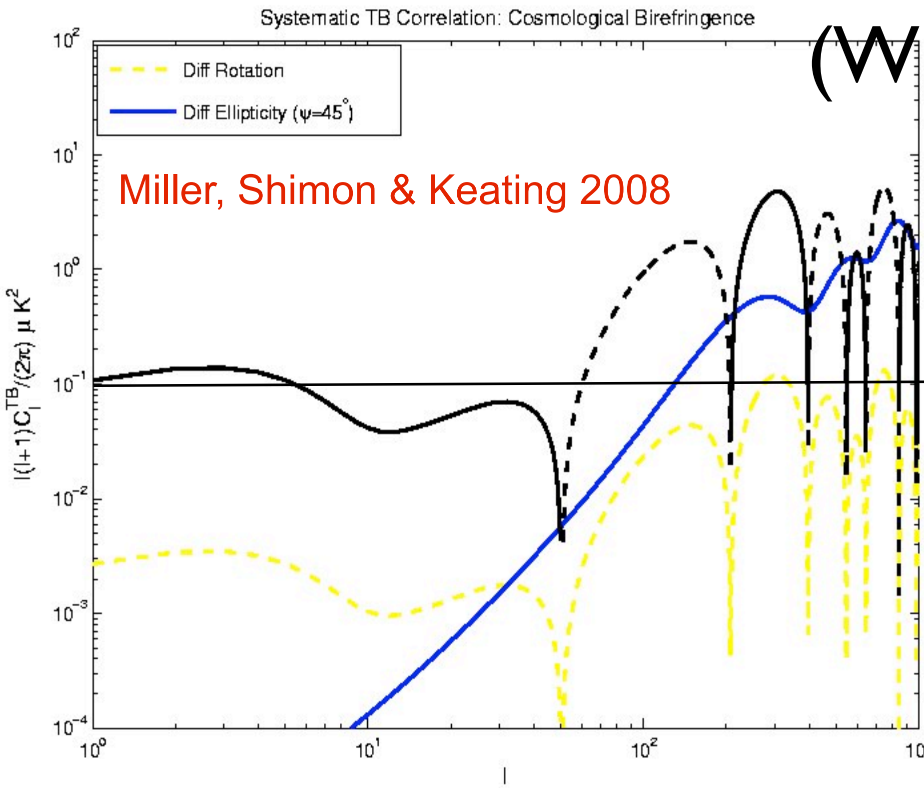
BB Predictions for various levels of α

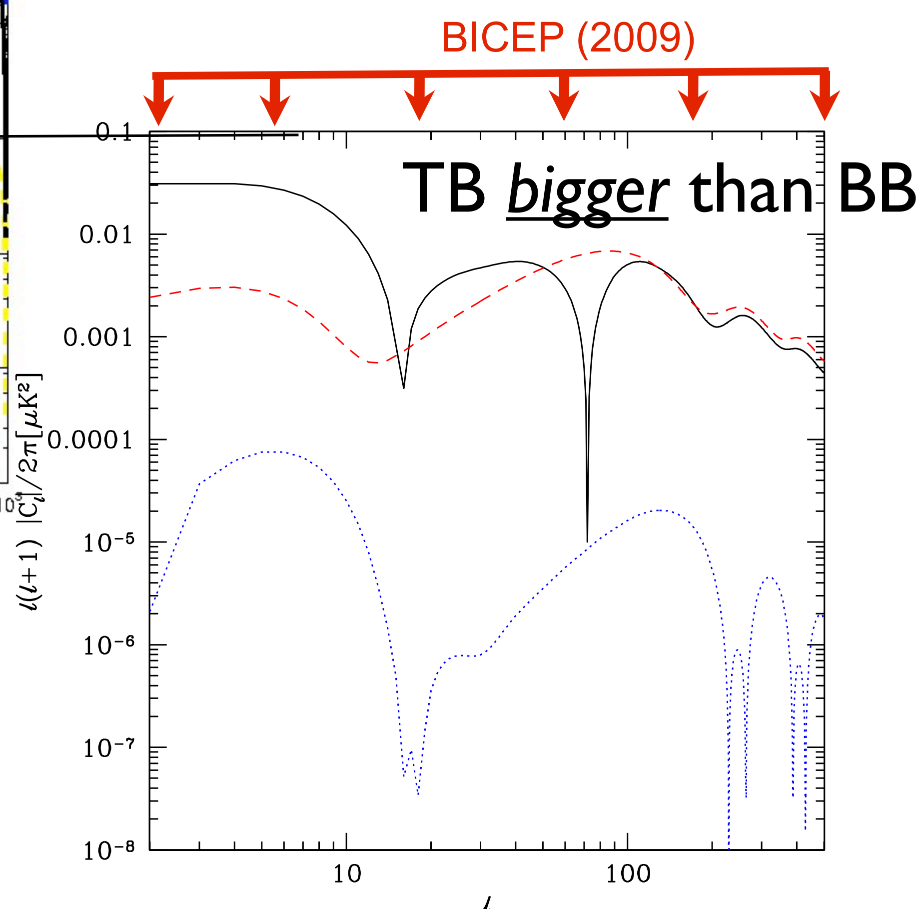




Contaldi, Magueijo & Smolin (2008)

(Why not let gravity violate parity?)



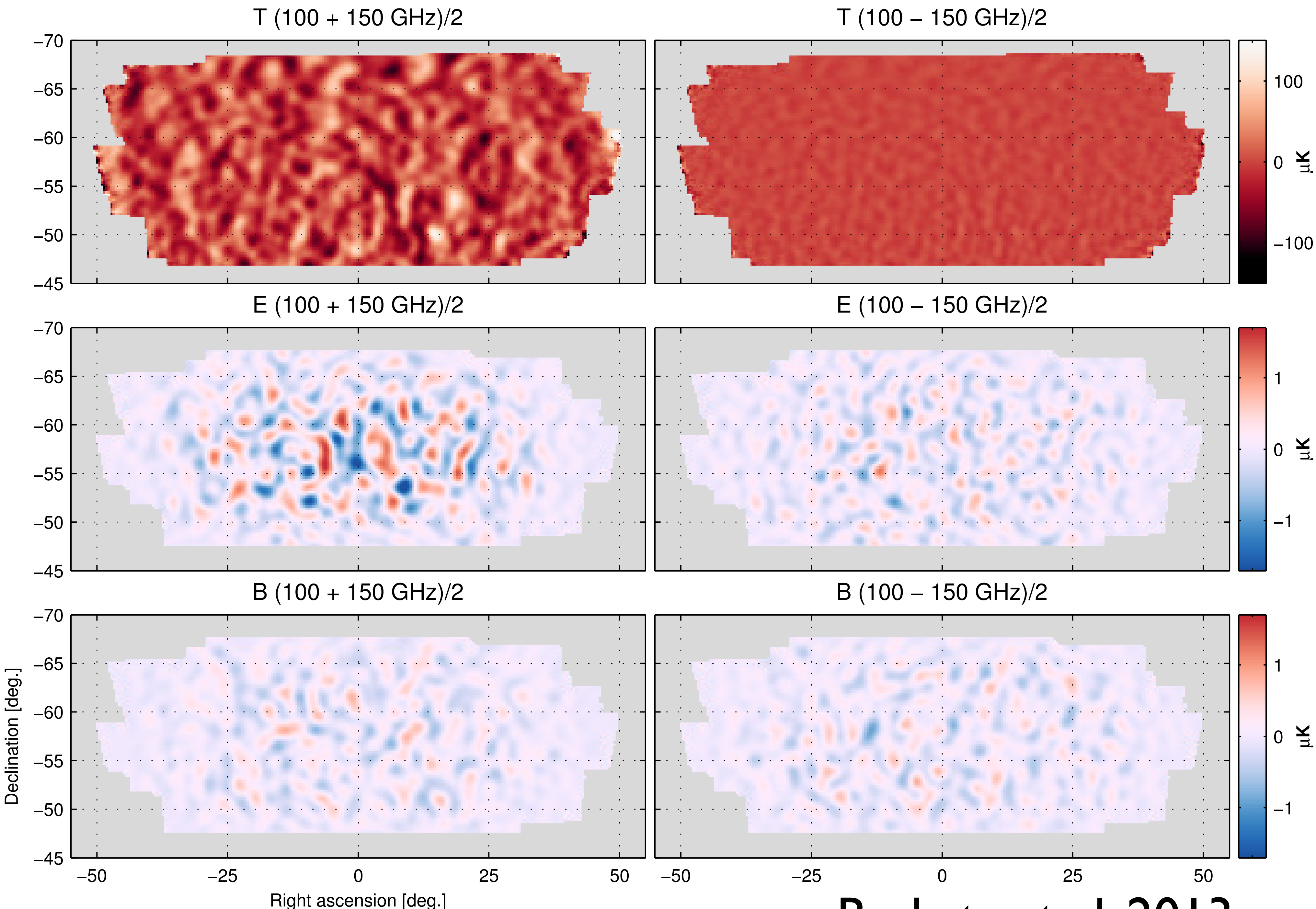


Systematics should be manageable for TB!

FIG. 1: Tensor contribution to the TB (solid, black), BB (dashed, red), and EB (dotted, blue) spectra for a standard ΛCDM model with tensor to scalar ratio $r = 0.1$ and chirality parameter $\gamma = 10$.

BICEP1 3-yr results

Next week, hopefully...



Barkats et al. 2013

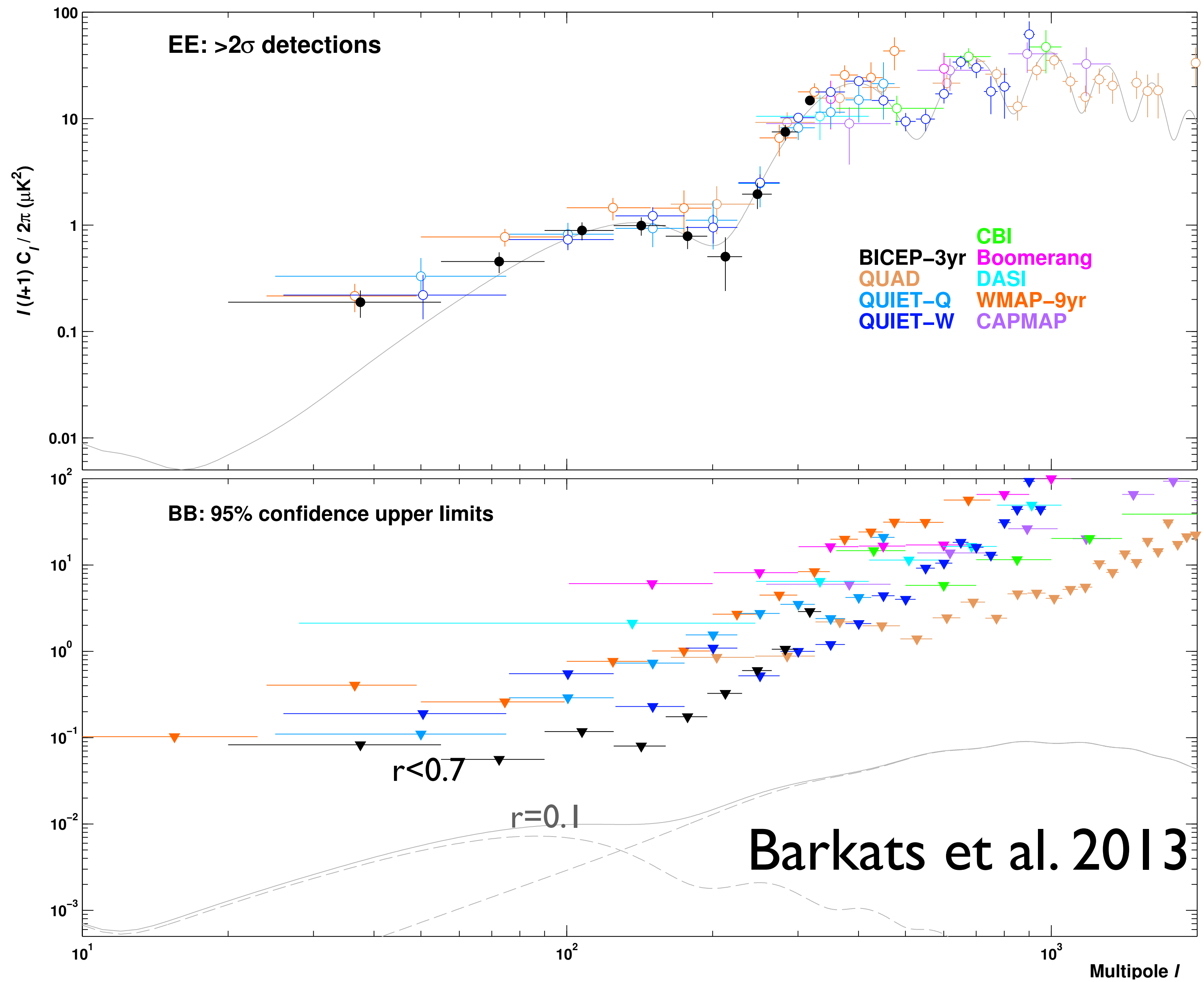
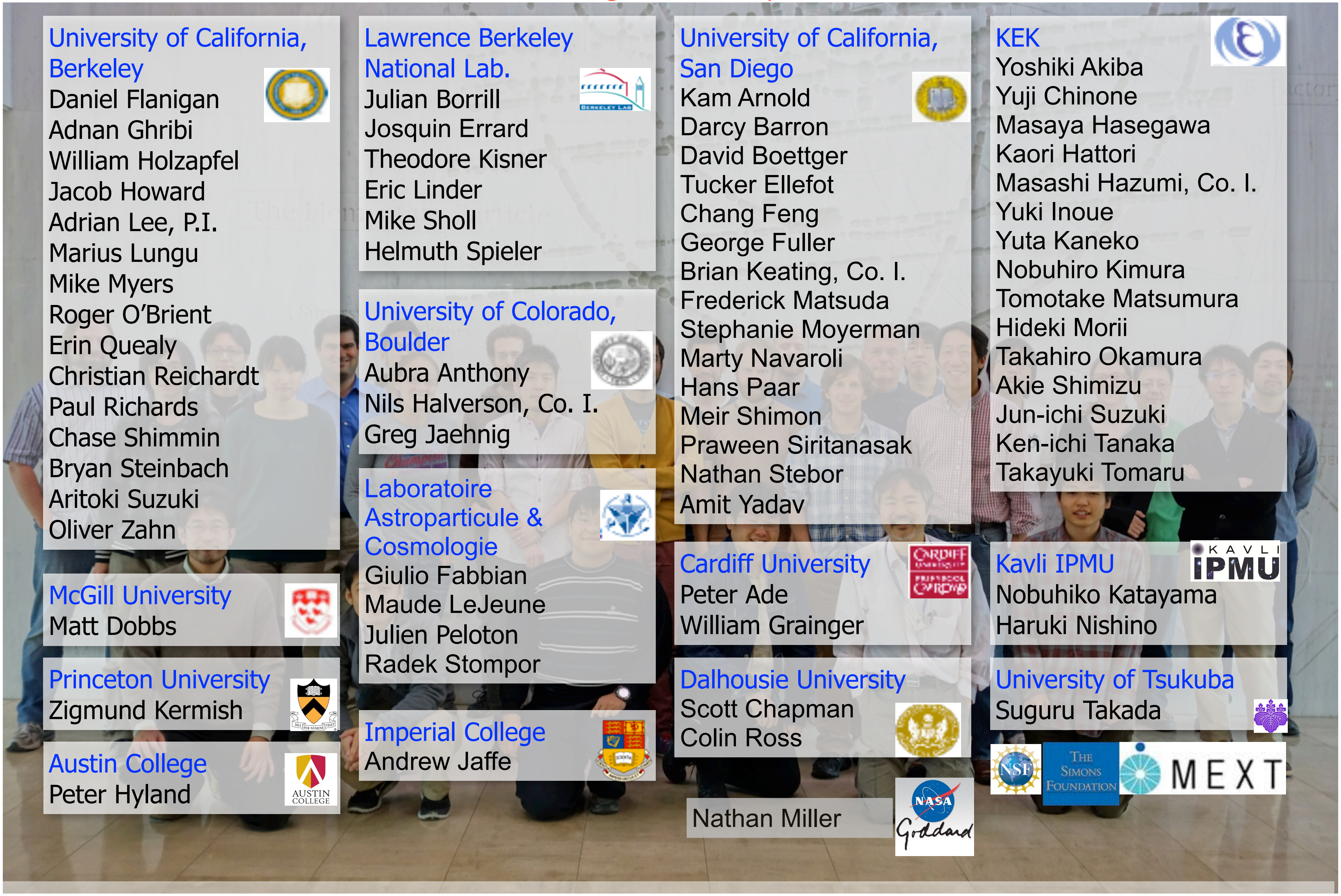


FIG. 12.— BICEP1's *EE* and *BB* power spectra complement existing data from other CMB polarization experiments (Leitch et al. 2005; Montroy et al. 2006; Sievers et al. 2007; Bischoff et al. 2008; Brown et al. 2009; QUIET Collaboration et al. 2011; Bennett et al. 2012; QUIET Collaboration et al. 2012). Theoretical spectra from a ΛCDM model with $r = 0.1$ are shown for comparison; the *BB* curve is the sum of the inflationary and gravitational lensing components. At degree angular scales, BICEP1's constraints on *BB* are the most powerful to date.

The POLARBEAR Experiment

POLARBEAR Collaboration

POLARBEAR Collaboration Meeting @ KEK, Japan, Mar. 24-28, 2013



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Ken-ichi Tanaka
Takayuki Tomaru

Kavli IPMU
Nobuhiko Katayama
Haruki Nishino

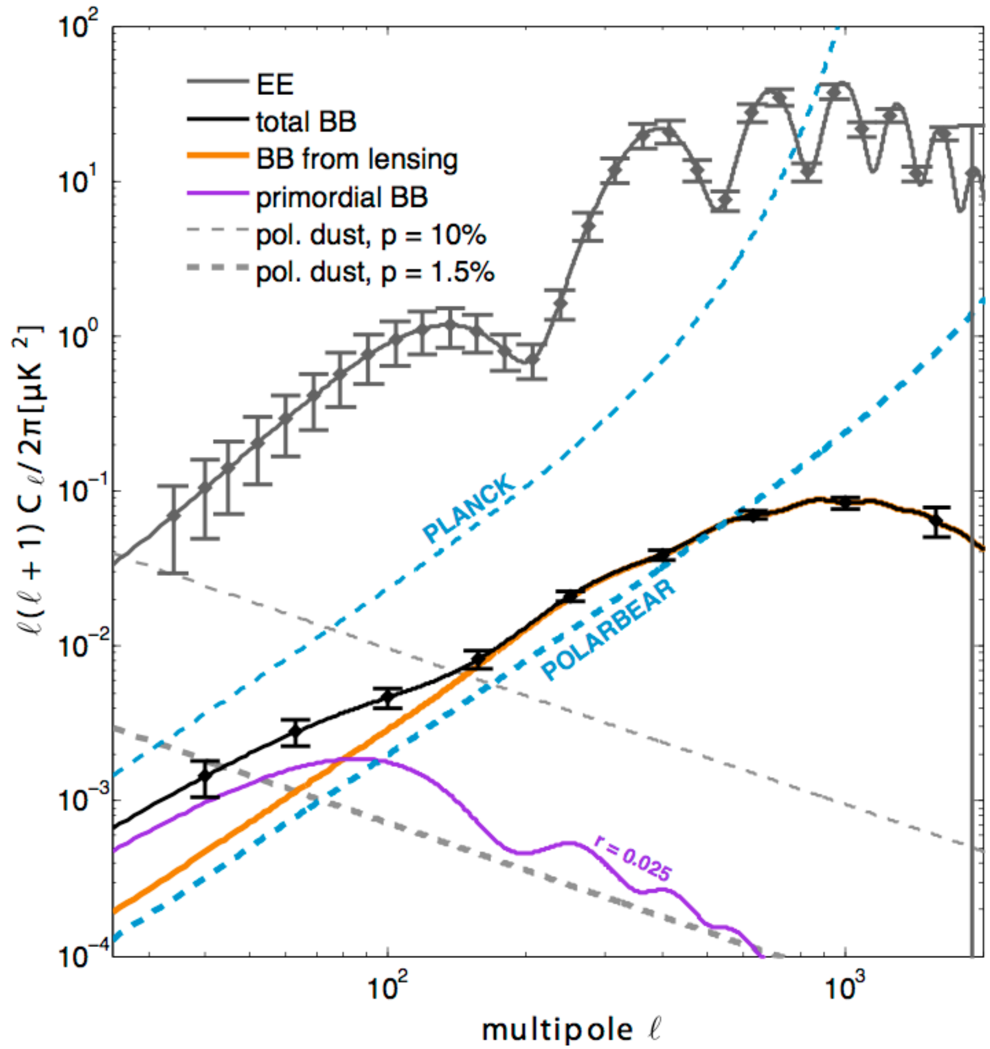
University of Tsukuba
Suguru Takada

International Collaboration from 5 countries, 14 institutes, ~70 members

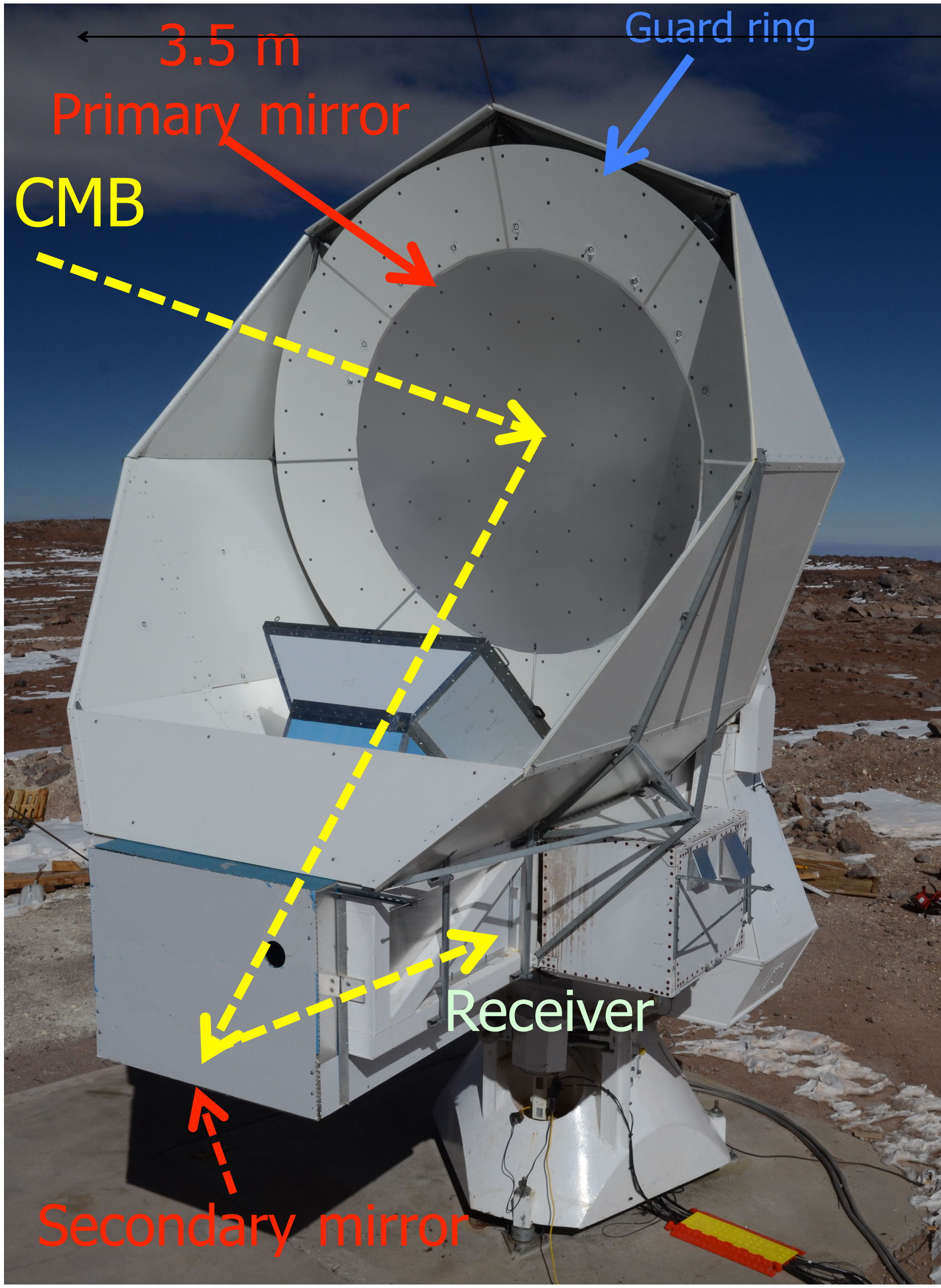
Goals of POLARBEAR

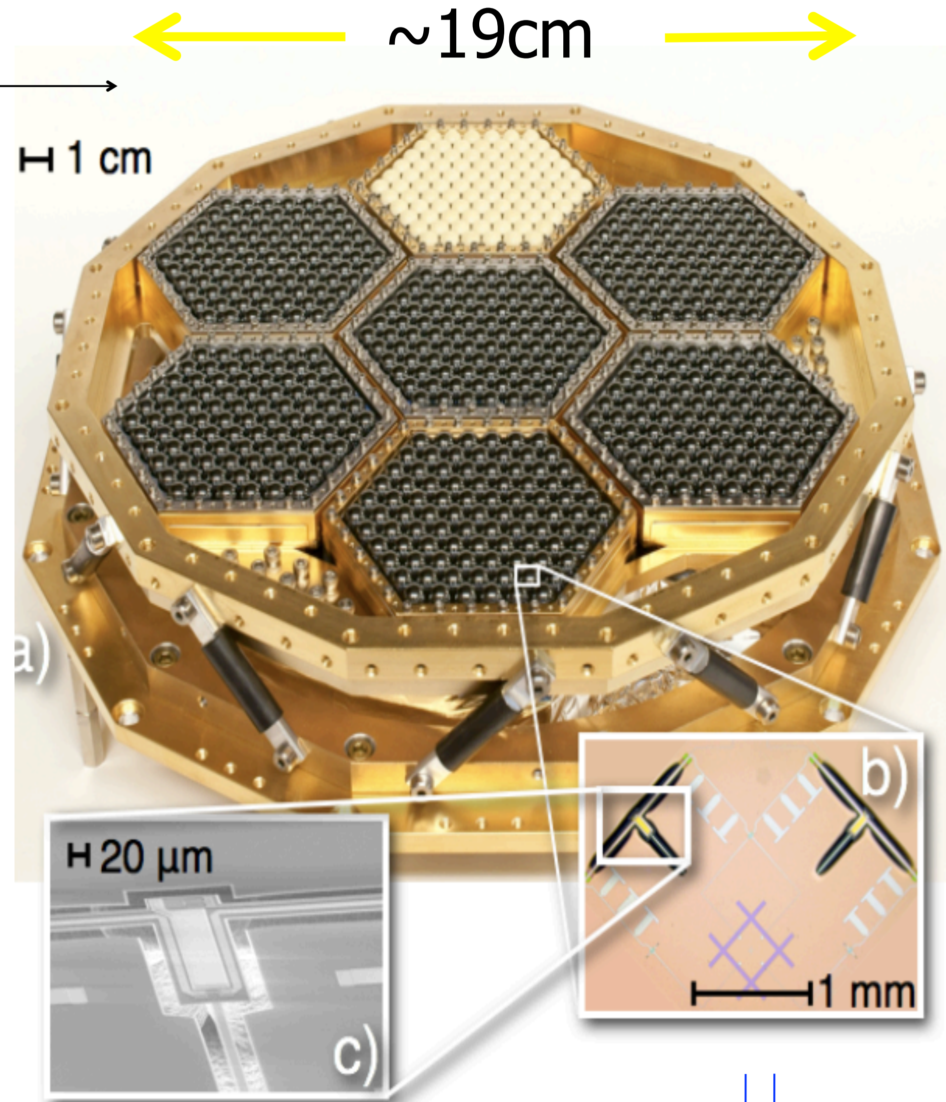
2yrs observation

- Search for inflationary B-modes to r=0.025 (95% CL) & detect gravitational lensing B-modes.
- Set first constraints on neutrino parameters from CMB polarization alone.
- Look for "beyond the standard model", such as Cosmic Birefringence, primordial magnetic fields.

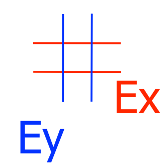


Huan Tran Telescope (HTT) @ the James Ax Observatory



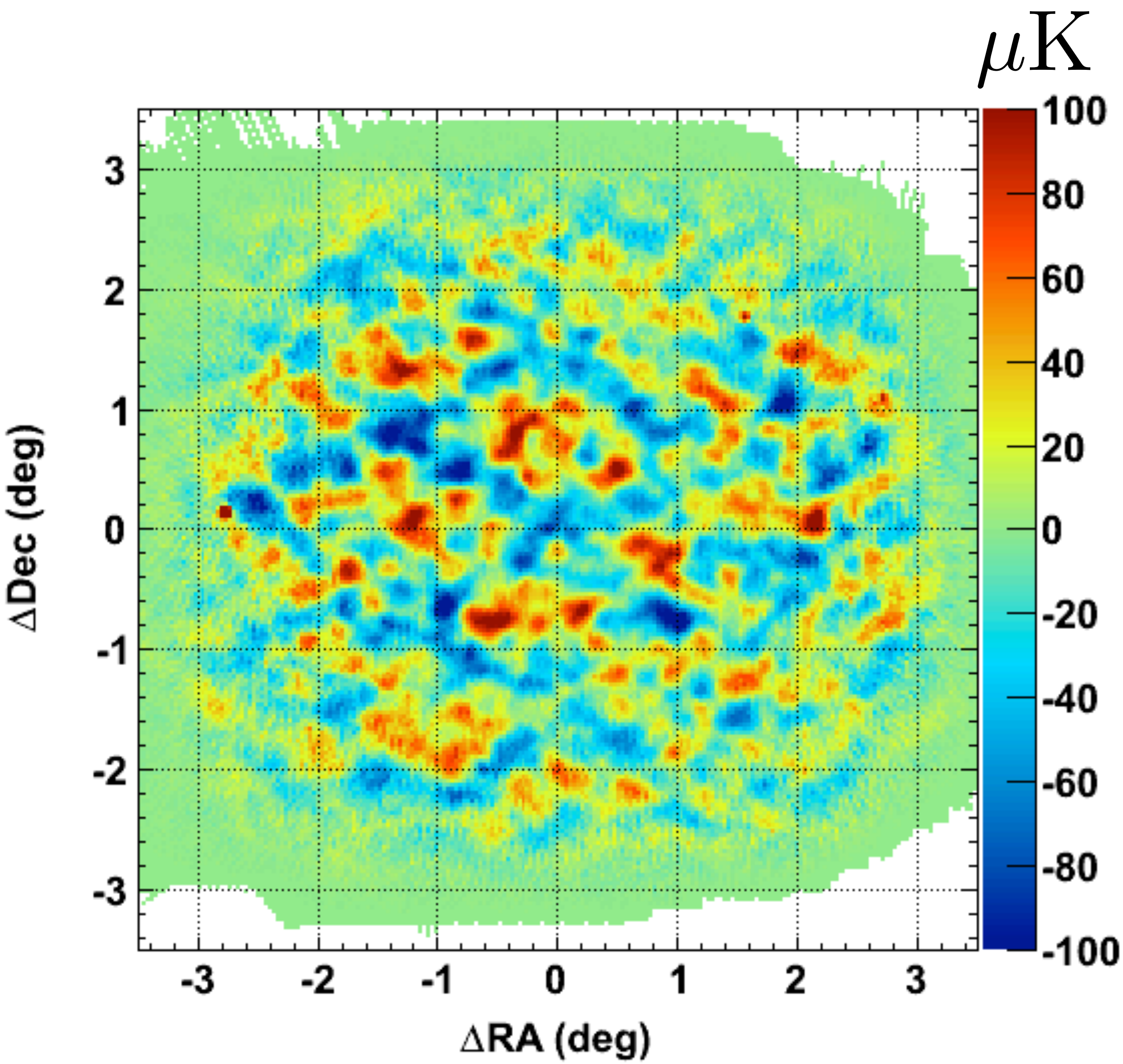


Lenslet



dual dipole antenna

Temperature Anisotropy Map



- Roughly 10 times deeper than Planck (@143GHz)
- Our analysis pipeline works well
- One of three patches


Eclipse from the
EDGE OF SPACE p. 66
See Sirius B: The Nearest
WHITE DWARF p. 30
Spot the Other
BLUE PLANETS p. 50
THE ESSENTIAL GUIDE TO ASTRONOMY
SKY
& TELESCOPE
What Put the Bang in the Big Bang p. 22
Telescope Alignment Made Easy p. 64
Explore the Nearby Milky Way p. 32
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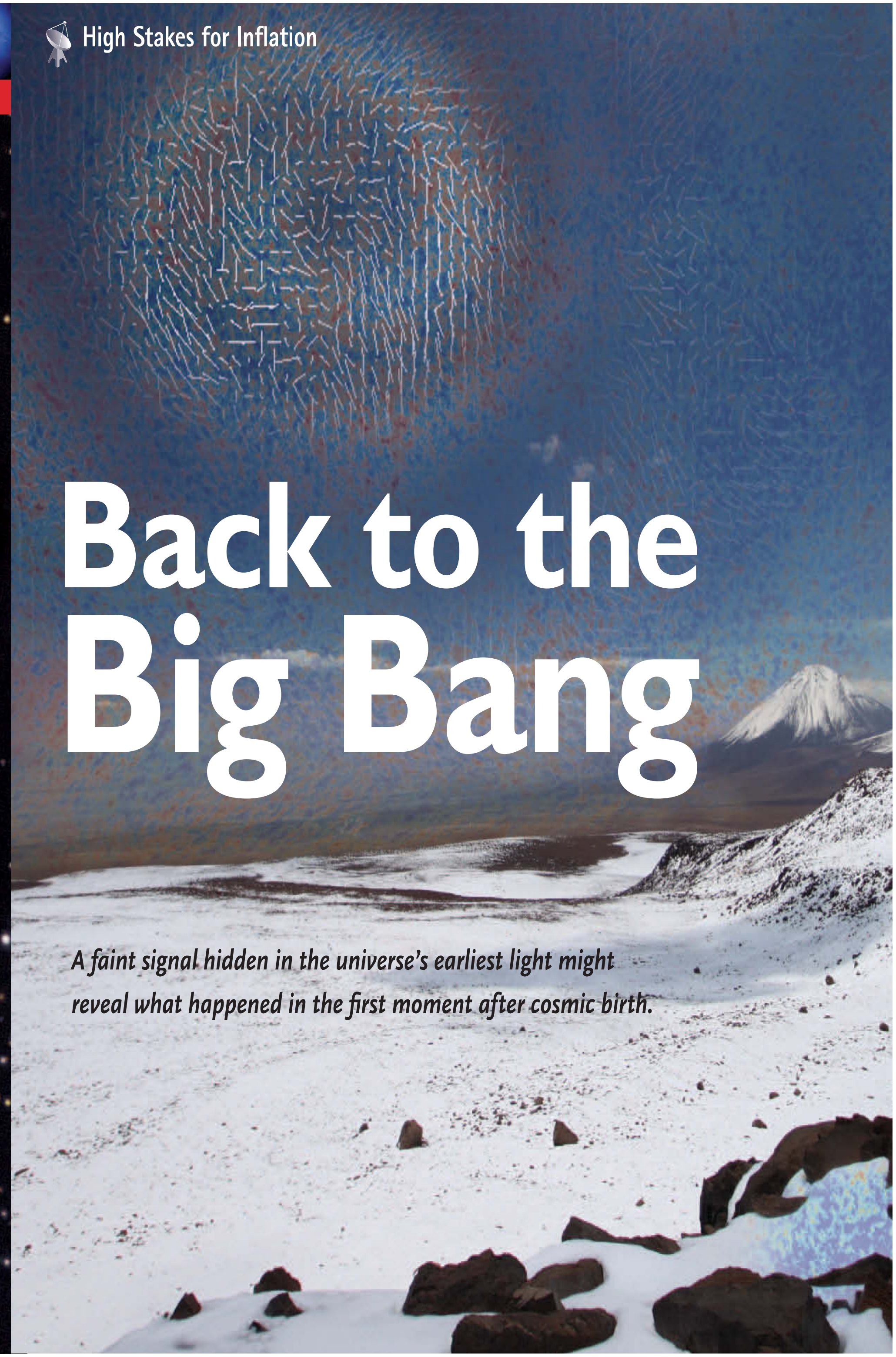
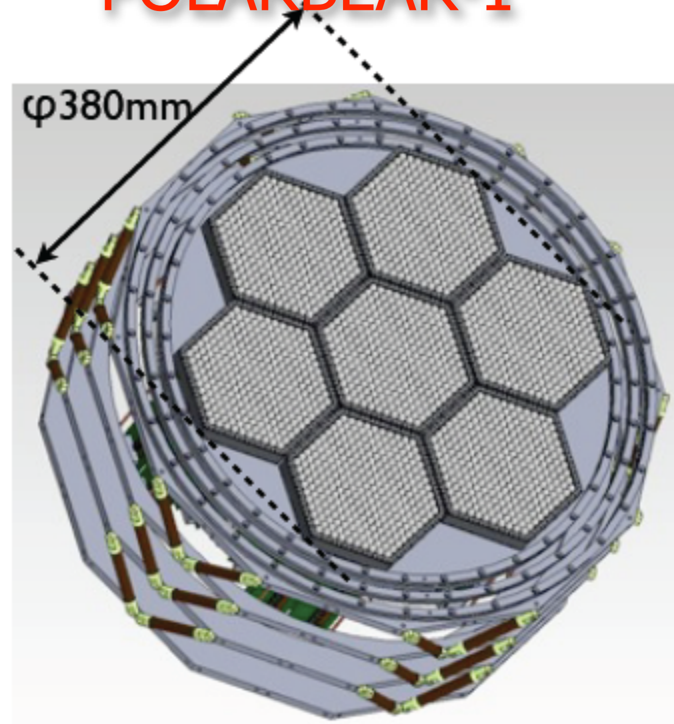
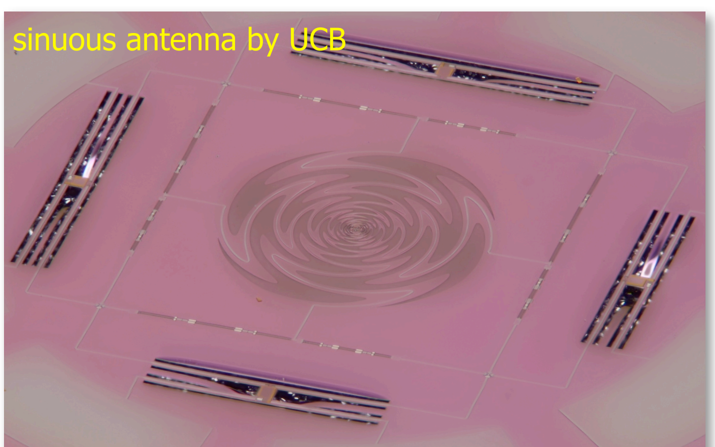

High Stakes for Inflation
Back to the
Big Bang
A faint signal hidden in the universe's earliest light might
reveal what happened in the first moment after cosmic birth.

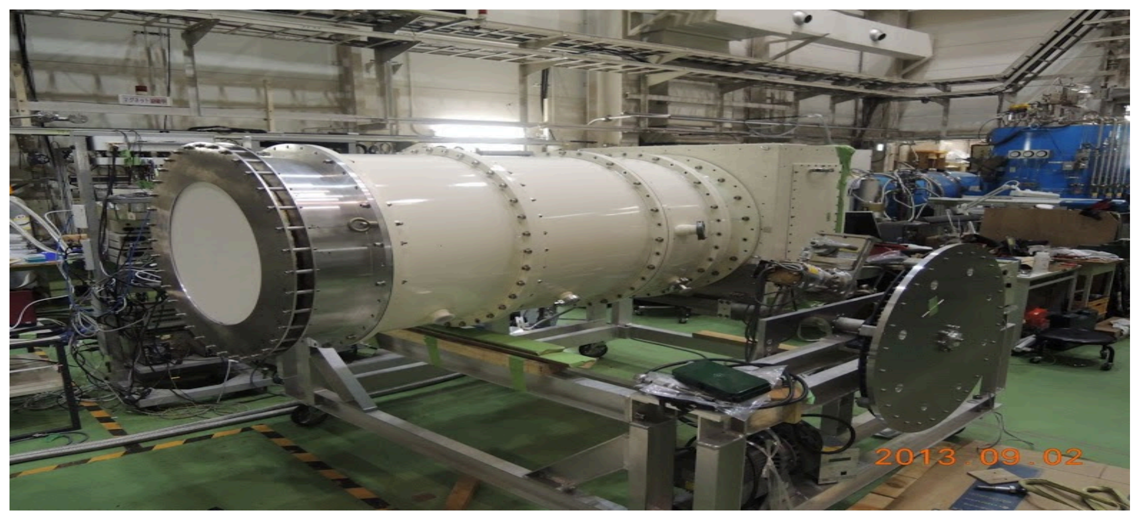
POLARBEAR Roadmap

- POLARBEAR-2 (2014+)
  - 3.5′ beam & 7,588 bolometers
  - 90/150 GHz dual-band pixels
  - r ~ 0.01 (95% C.L.)
  - 90 meV neutrino mass (68% C.L.)
  - “Stage 3”

6 times more than POLARBEAR-1







Simons Array (2016)

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

80% of ... ble from Chile

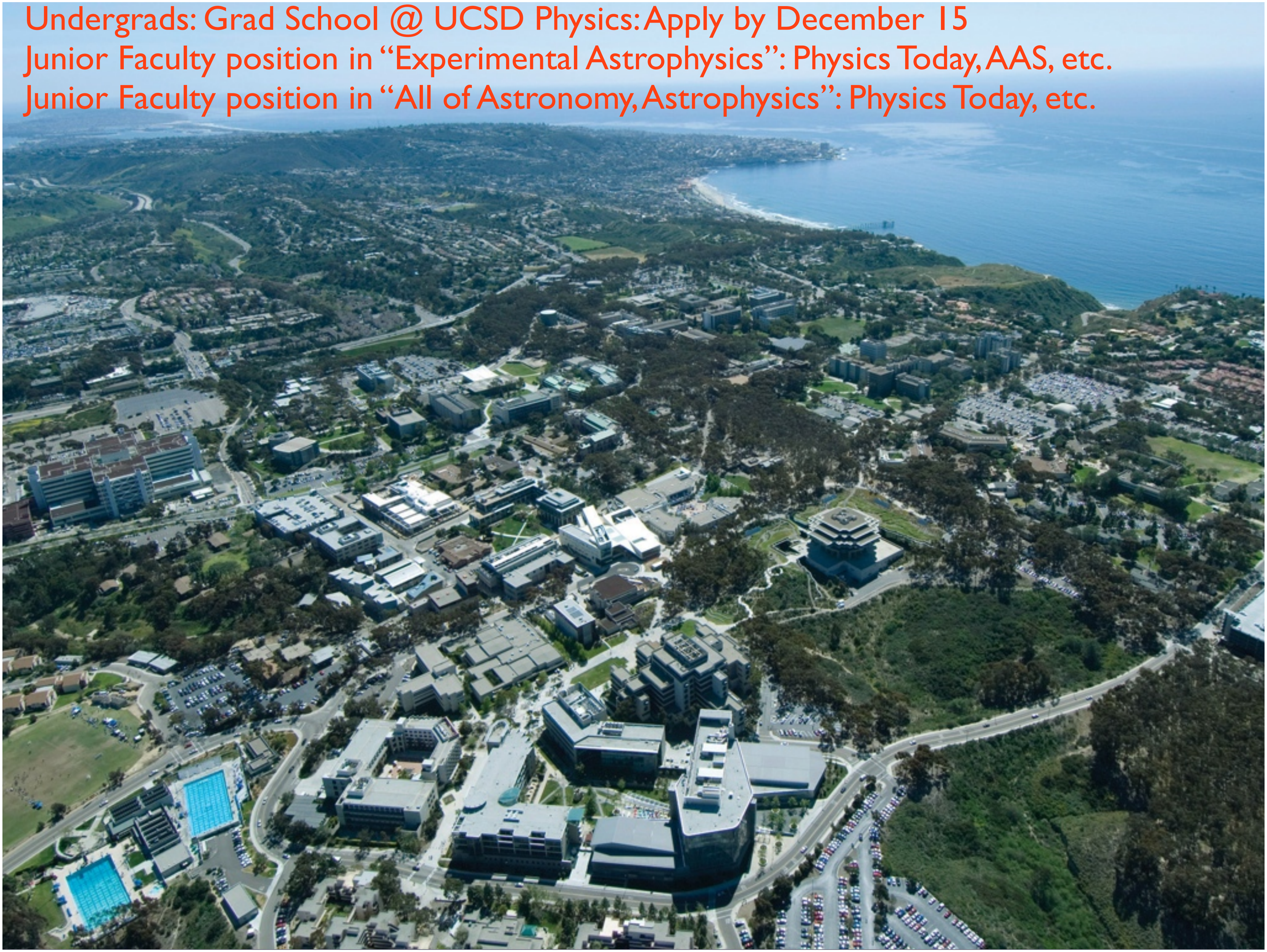
- 3 x Te ... 3 x ... UCB)
  > 22,0 ...
- 90/15 ... pixels

HELP WANTED

Student, Postdoc & Fab Tech Positions at UCSD & UCB

funded by Simons Foundation

Undergrads: Grad School @ UCSD Physics: Apply by December 15
Junior Faculty position in “Experimental Astrophysics”: Physics Today, AAS, etc.
Junior Faculty position in “All of Astronomy, Astrophysics”: Physics Today, etc.



POLARBEAR Roadmap

- current POLARBEAR (POLARBEAR-1)
  - 3.5′ beam & 1,274 bolometers
  - Array NET = 21 uK√s
  - r ~ 0.025 (95% C.L.)
- POLARBEAR-2
  - 3.5′ beam & 7,588 bolometers
  - 90/150 GHz dual-band pixels
  - r ~ 0.01 (95% C.L.)
- Simons Array
  - 3 Telescopes, > 22,000 bolometers)
  - 90/150/220 GHz dual-band pixels
  - r ~ 0.007 (95% CL)
  - Scalable: more telescopes or 3-band pixels