Title: You Can't Spell BICEP without "CP": the Real-World Flip-Side of CMB Polarization Parity Predictions

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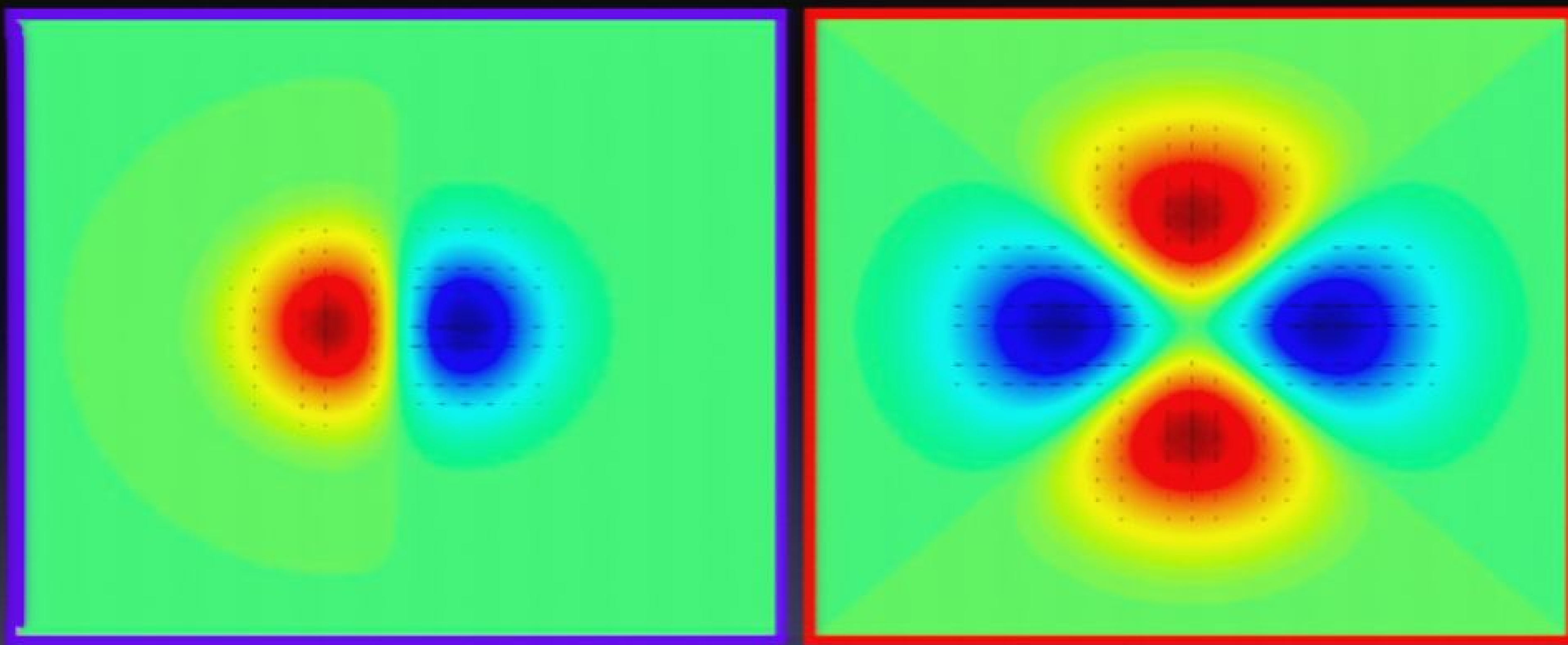
Abstract: In addition to its ability to probe Inflation, CMB polarization offers the intriguing possibility to detect CP-symmetry violation. In some sense these predictions, if true, would be more surprising than confirmation of the inflationary paradigm -- for which ample, albeit circumstantial, evidence already exists. Moreover, recent theoretical predictions imply that, not only are parity violating CMB polarization effects possible, but that they have already been detected at 3\sigma confidence levels in existing polarization data. I will present a worked example showing the impact of experimental systematic effects on such measurements, and present a robust test to help determine the veracity of the theoretical predictions. I will show that the CP-symmetry violating observables are more susceptible to certain systematic effects, and discuss the future prospects for such CMB polarization probes of fundamental physics.

You Can't Spell BICEP without "CP":
The Real-World Flip-Side of CMB Polarization Parity Predictions



Brian Keating

Perimeter Institute

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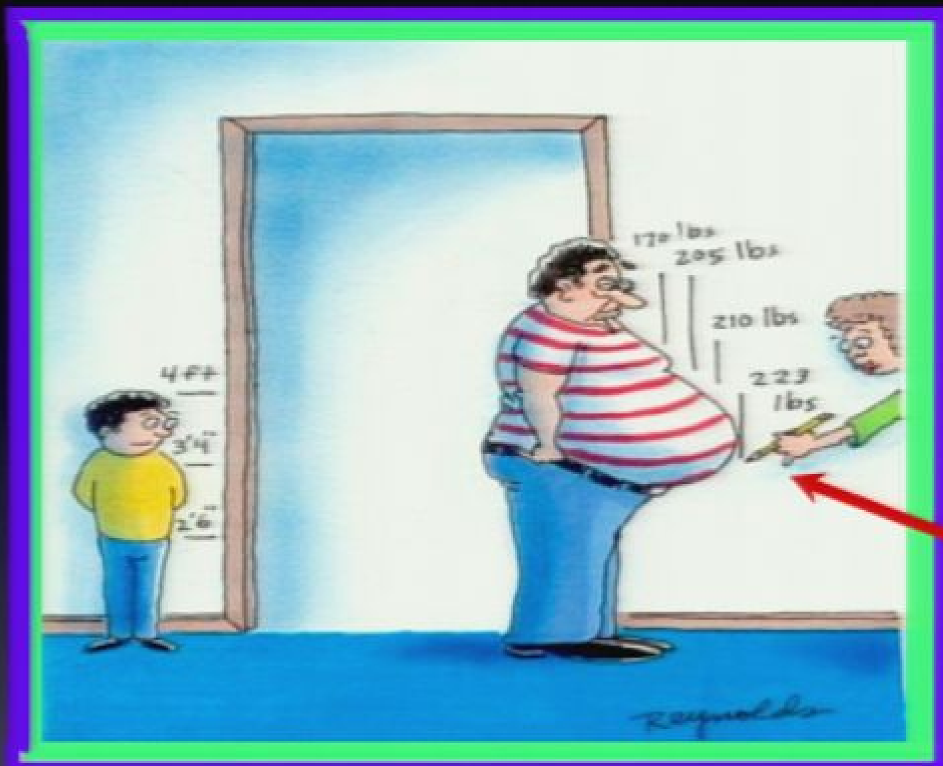

Physics beyond the GUT Scale

Brian Keating
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August 2009: BICEP gets flipped off by Xia et al

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*

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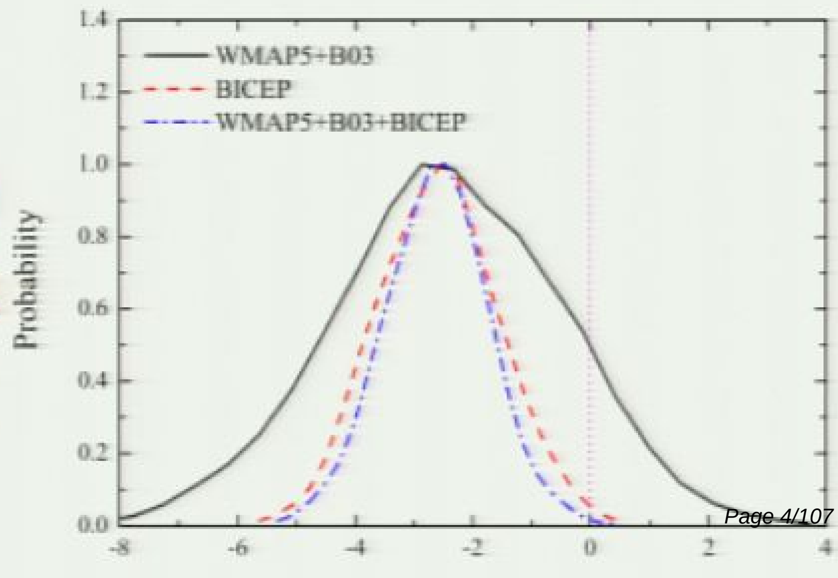

Outline

- Brief review of CMB polarization effects, spectra, and Cosmic Birefringence.
- Xia et al. claims and implications.
- BICEP instrument, data and systematics.
- Future prospects.

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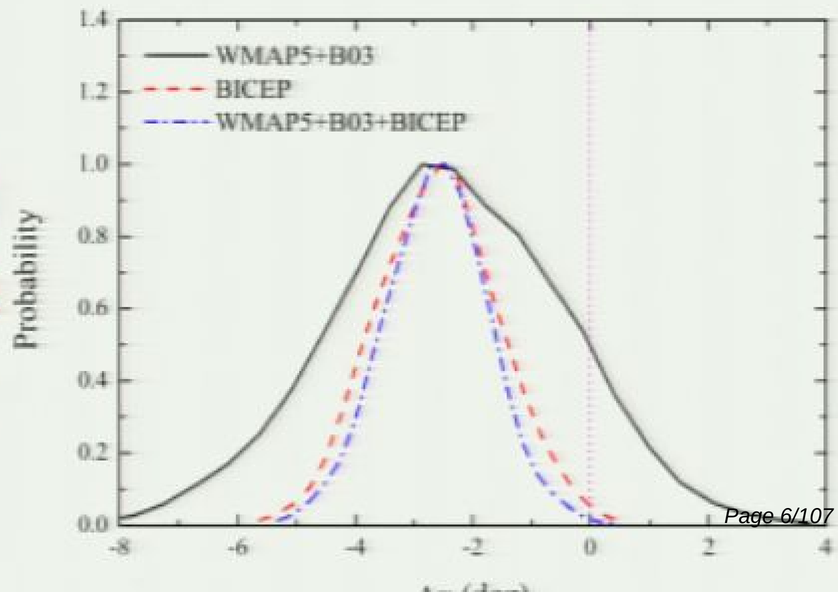

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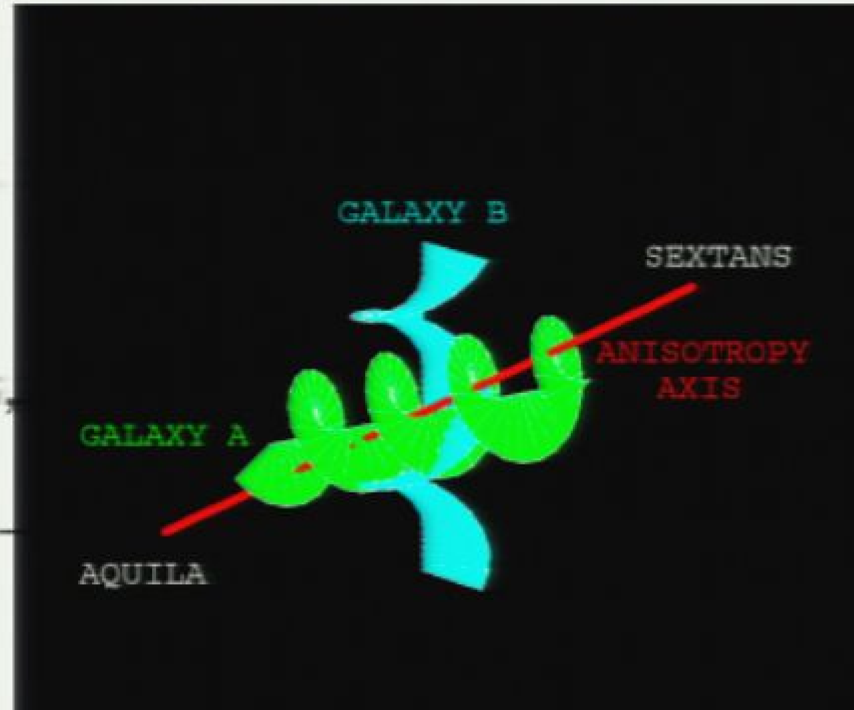

Ralston & Nodland 1997

Let us now turn to modifications. In the most obvious departure from the standard formulas, we add a "photon mass term" by supplementing $\mathcal{L}$ with $\frac{\mu^2}{2}A^\mu A_\mu = \frac{\mu^2}{2}\phi^2 - \frac{\mu^2}{2}\mathbf{A}^2$ where μ has dimension of inverse length. In the new equations of motion $-\mu^2 A^\mu$ is added to j^μ, so that when the wave *Ansatz* $e^{ik_\alpha x^\alpha} = e^{i(\omega t - \mathbf{k}\cdot\mathbf{r})}$, $k^\alpha = (\omega/c, \mathbf{k})$, $k \equiv |\mathbf{k}|$ is taken for fields in the source-free case ($j^\mu = 0$), the dispersion law reads

$$k^\alpha k_\alpha = \mu^2 \,, \qquad \omega = c\sqrt{k^2 + \mu^2}\,.$$

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Parity Violating Interactions

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

Modified Lagrangian
due to CS terms

Caroll & Field (1990)

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

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The new term is charge - blind and parity violating :

$\mathrm{E} \rightarrow \mathrm{E}$

$\mathrm{B} \rightarrow \mathrm{-B}$

Parity reversal symmetry is violated as is
Lorentz invariance

g is χ, ϕ ?

Let us examine wave solutions in the absence of sources. ($\rho = \mathbf{j} = 0, j^\mu = 0$). We again make the *Ansatz* that fields behave as exponentials of phases, $e^{i(\omega t - \mathbf{k}\cdot\mathbf{r})} = e^{ik_\alpha x^\alpha}$, $k^\alpha = (\omega/c, \mathbf{k})$, $k \equiv |\mathbf{k}|$, and find the dispersion law

$$(k^\alpha k_\alpha)^2 + (k^a k_\alpha)(p^\beta p_\beta) = (k^a p_a)^2 .$$

We get two values for group velocity:

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Instead of $\int (E^2 + B^2)\, dV$ being conserved we get:

$$\mathcal{E} = \tfrac{1}{2}\int \mathrm{d}^3 r \left[\mathbf{E}^2 + \left(\mathbf{B} + \frac{m}{2}\mathbf{A}\right)^2\right] - \frac{m^2}{8}\int \mathrm{d}^3 r\, \mathbf{A}^2 .$$

Polarized Radiation Fields: Stokes Parameters

With the modified EM fields we can calculate polarization properties.

$$E_x(t) = a_x(t)\cos(\omega_0 t + \phi_x), \quad E_y(t) = a_y(t)\sin(\omega_0 t + \phi_y)$$

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- Modified Spectra

Standard Model spectra rescaled:

$$C_\ell^{\prime\,\mathrm{TE}} = C_\ell^{\mathrm{TE}} \cos(2\Delta\alpha)\ ,$$
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- Note: EE & BB have no sensitivity to sign of α

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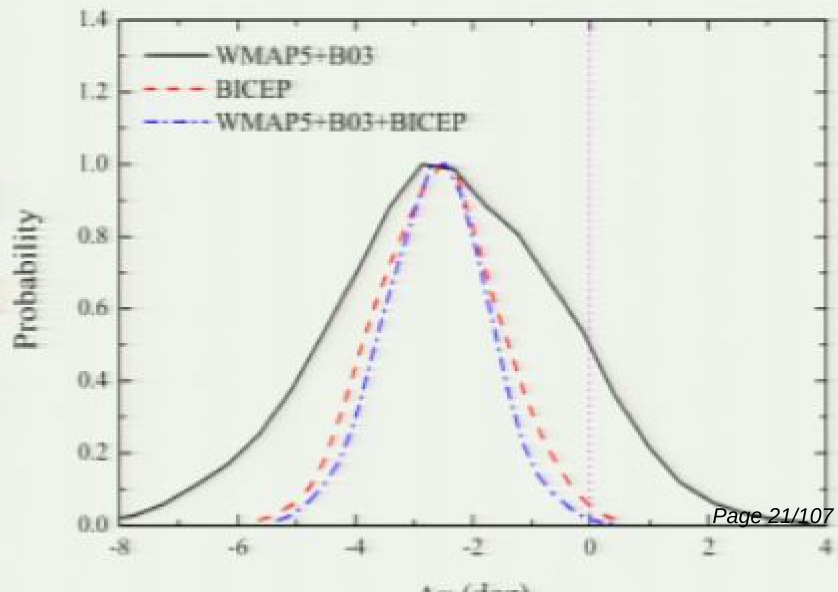

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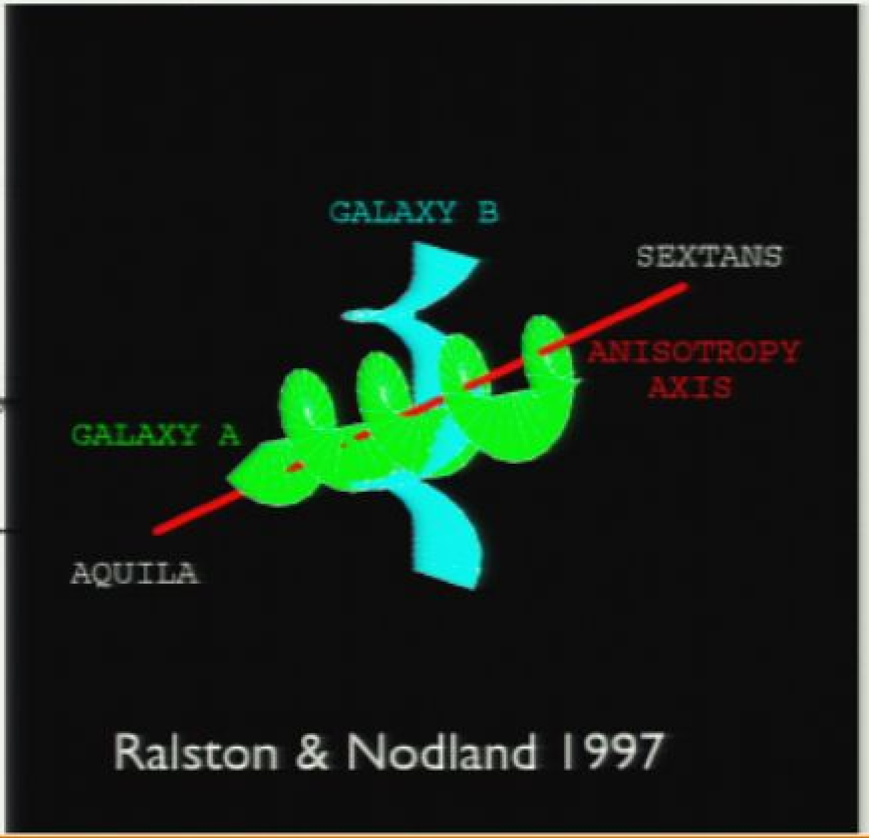

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Modified Lagrangian

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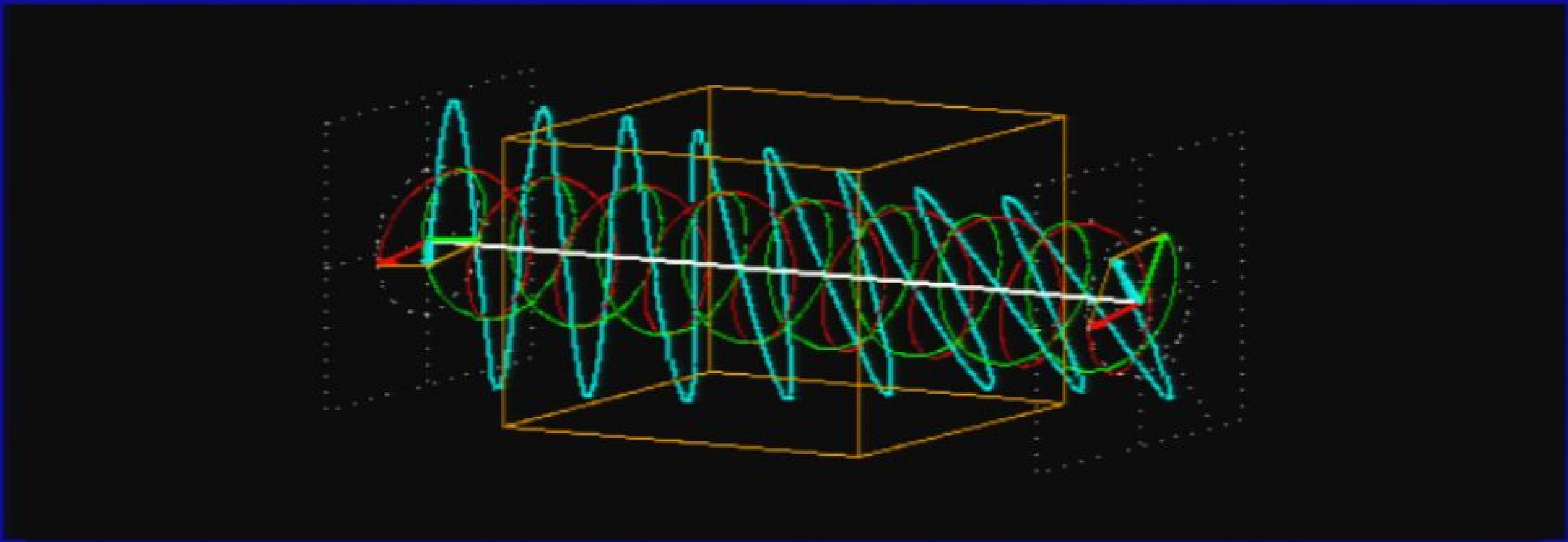
We have two different phase velocities; one for left-circular polarization, the other for right circular polarization.

The superposition of the two circular polarizations causes rotation of the plane of linear polarization!

Rotation of Polarization Plane



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

Couples to CMB lensing ?

Shimon et al. 2009

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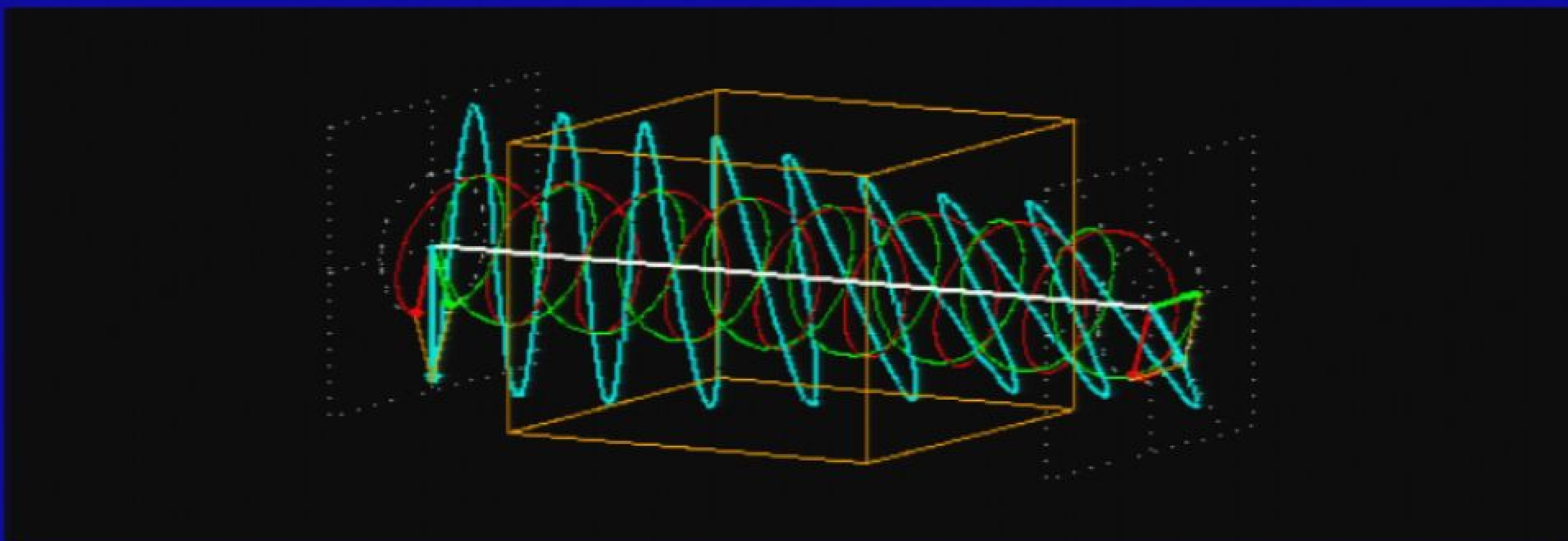

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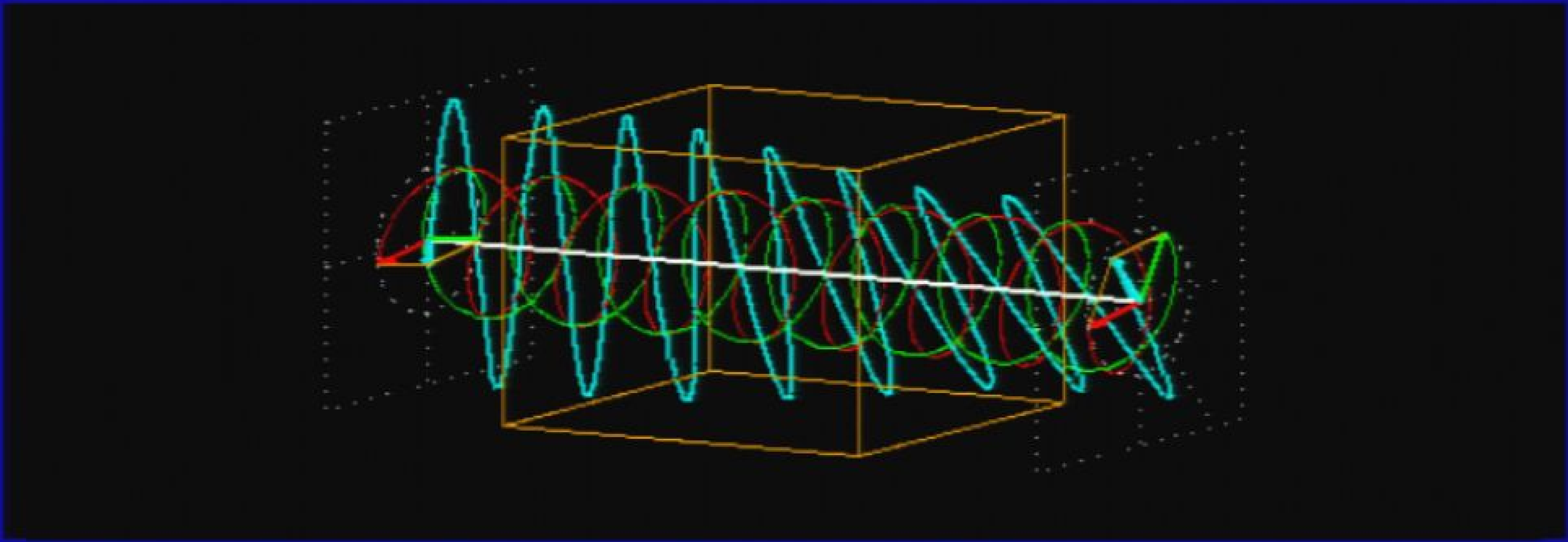

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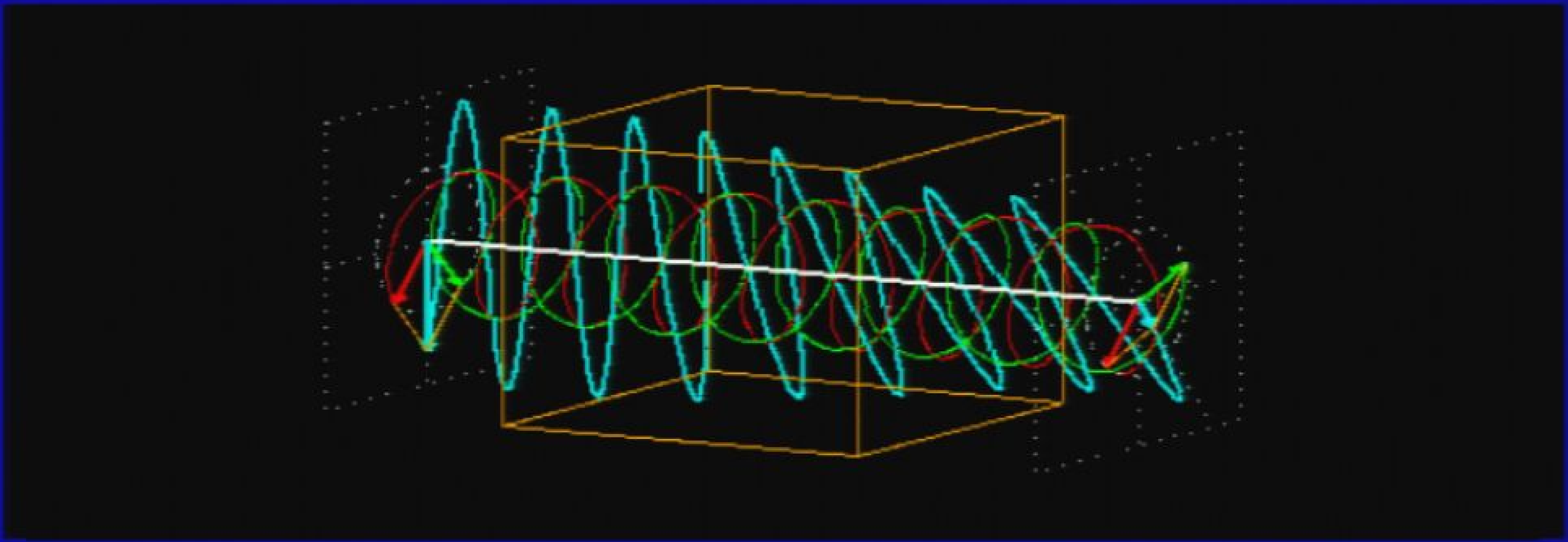

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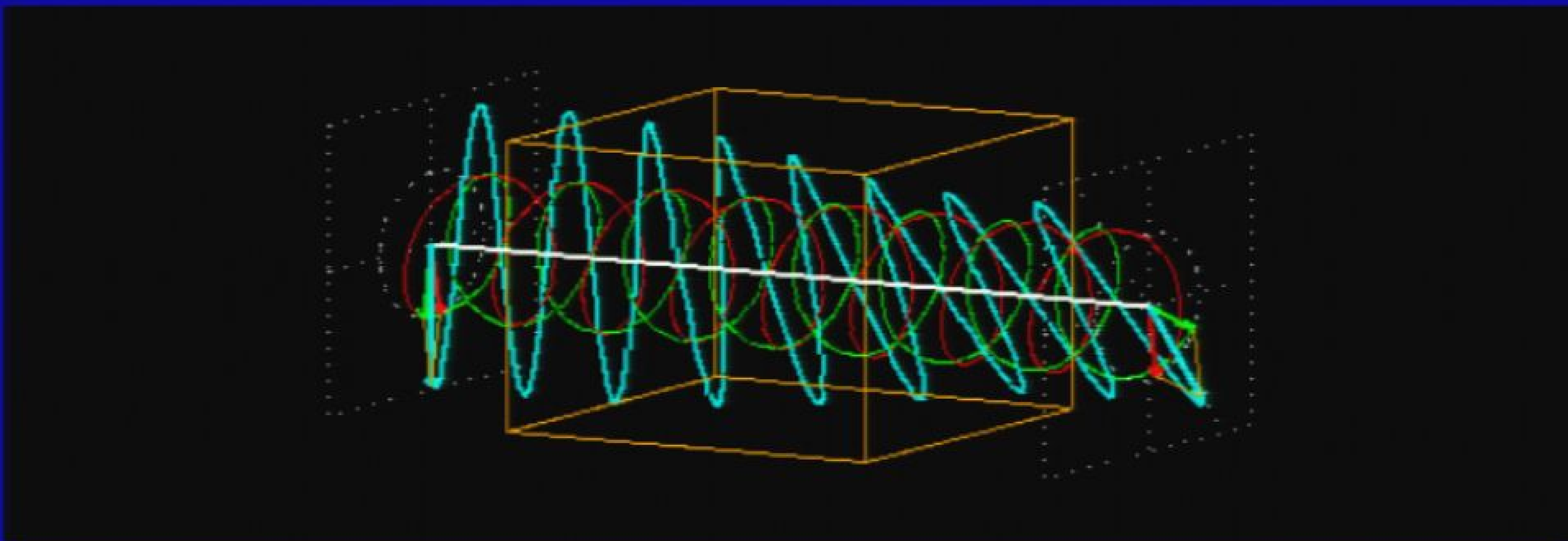

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[3]*Theoretical Physics Center for Science Facilities (TPCSF), Chinese Academy of Science, P. R. China*

Xia et al. claim a *first* detection of CB, parameterized by rotation angle α

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 3σ 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

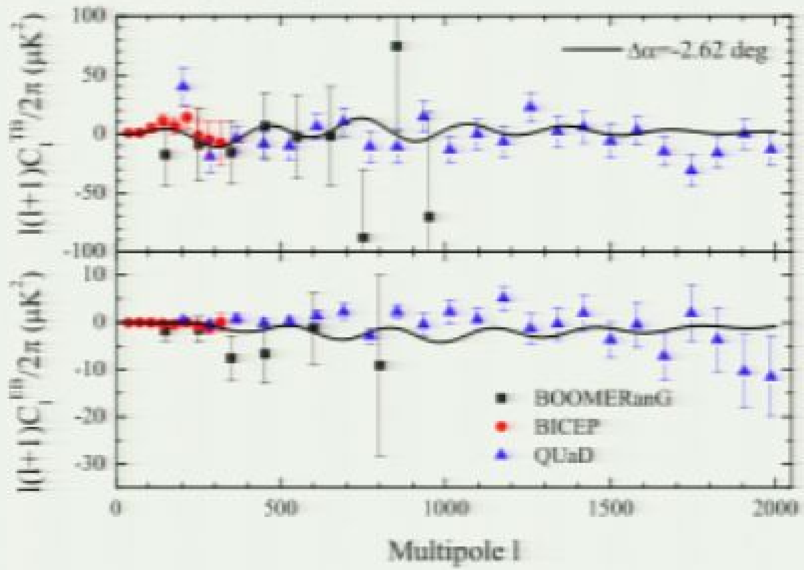

FIG. 1: The binned TB and EB spectra measured by the small-scale CMB experiments of BOOMERanG (black squares), BICEP (red circles) and QUaD (blue triangles). The

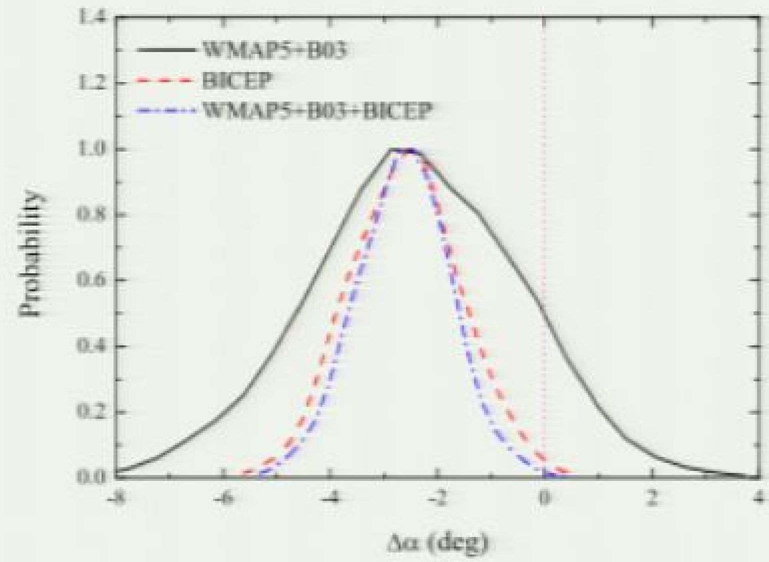

FIG. 2: One-dimensional posterior distribut[...] the rotation angle derived from various data combinations. The dotted vertical line illustrates the unrotated case ($\Delta\alpha = 0$) to

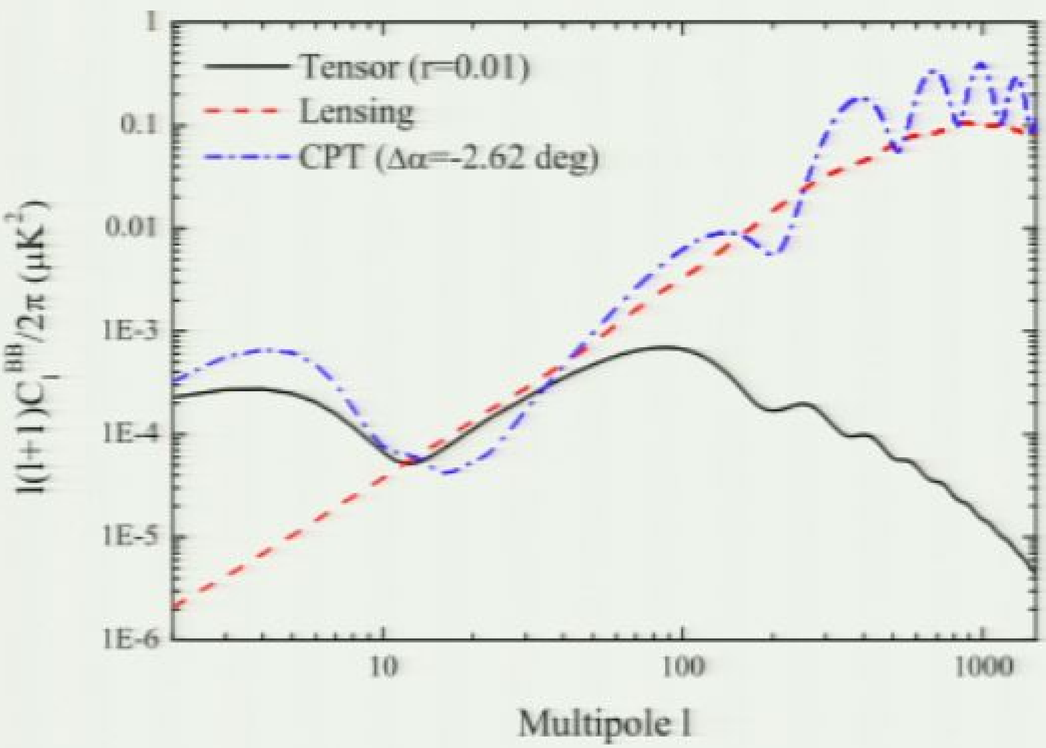

FIG. 3: The theoretical predictions of the BB power spectra from three different sources: primordial tensor B-mode with $r = 0.01$ (black solid line); lensing-induced (red dashed line) and rotation-induced (blue dash-dot line). The cosmological parameters used here are $\Omega_b h^2 = 0.022$, $\Omega_c h^2 = 0.12$, $\tau = 0.084$, $n_s = 1$, $A_s = 2.3 \times 10^{-9}$, and $h = 0.70$.

With α as claimed, what BB spectra result? Answer: scaled version of EE

TABLE I: Constraints on the rotation angle from v CMB data sets. The Mean values and 68% $C.L.$ erro are shown.

Data	$\Delta\alpha$ (deg)	Referen
WMAP5+B03+BICEP	-2.62 ± 0.87	This wo
BICEP	-2.60 ± 1.02	This wo
WMAP5+B03	-2.6 ± 1.9	Ref.[8
WMAP5	-1.7 ± 2.1	Ref.[1
WMAP3+B03	-6.2 ± 3.8	Ref.[1
WMAP3	-2.5 ± 3.0	Ref.[1
WMAP3+B03	-6.0 ± 4.0	Ref.[6

UCSD

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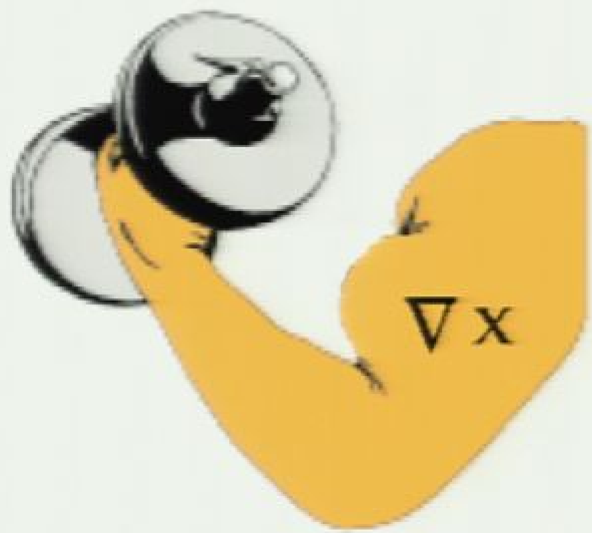
Yuki Takahashi
U.C. Berkeley

Lionel Duband
CEA, Grenoble

** = PI
* = Co-I



UCSD

BICEP!

Bolometric Imaging of Cosmic Extragalactic Polarization

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Darren Dowell
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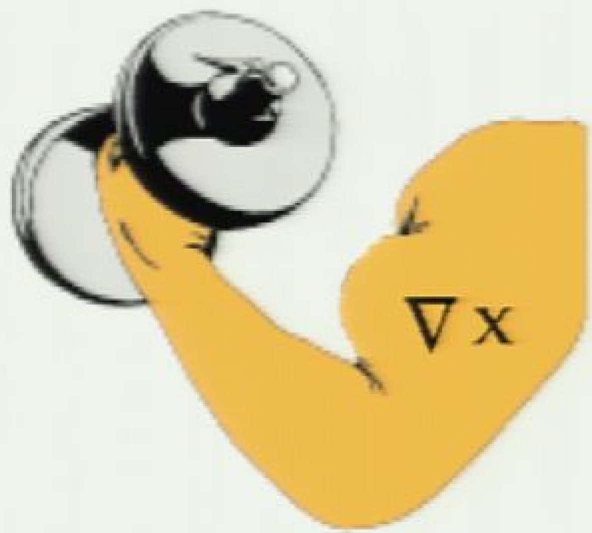
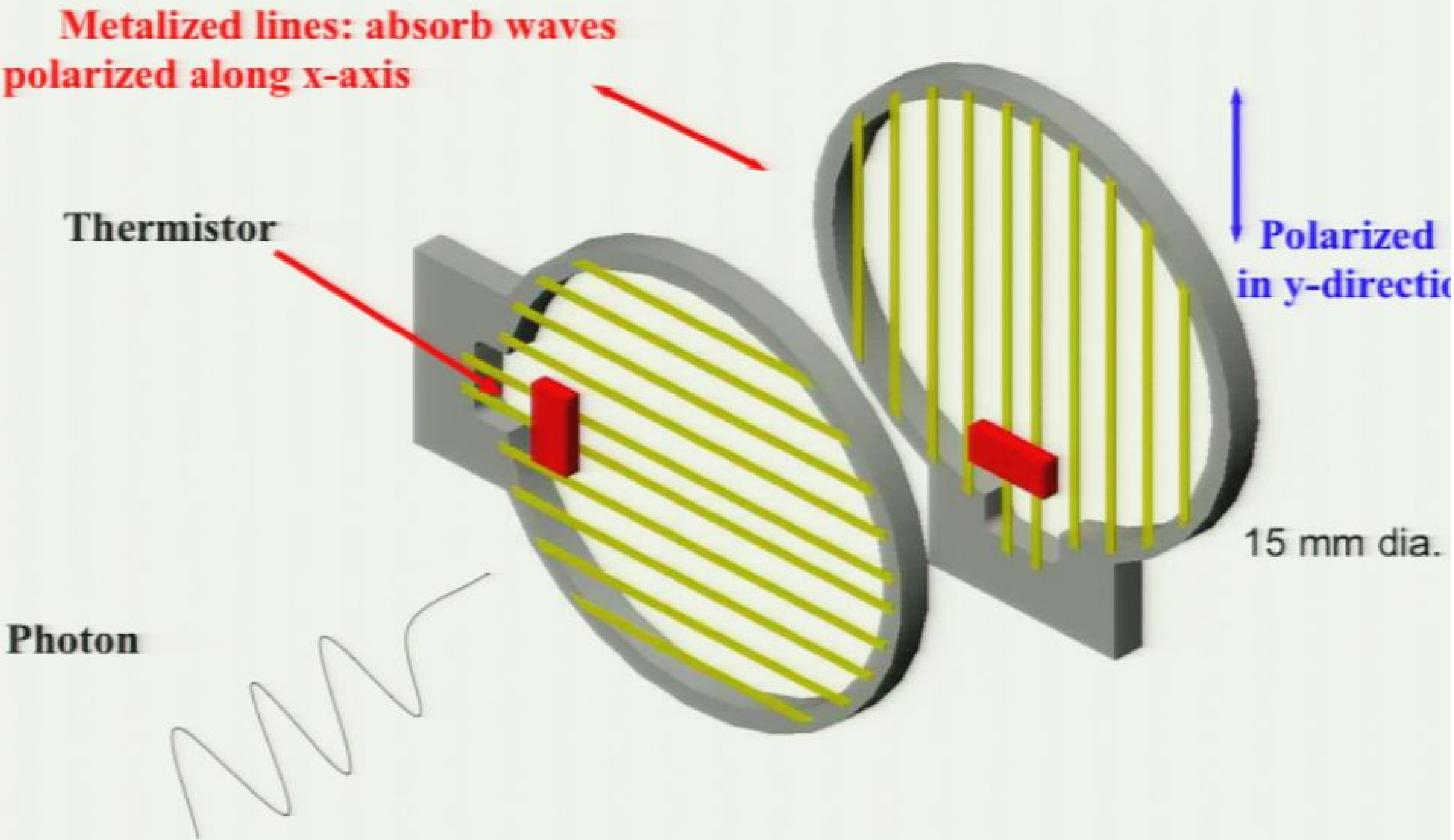


Brian G. Keating (UCSD)


BICEP: Much more tomorrow....
http://cosmology.ucsd.edu/

BICEP:
First telescope dedicated to discovering the GWB.
Since BICEP, many imitators (in the US, France, and England)!

Polarization Sensitive Bolometers

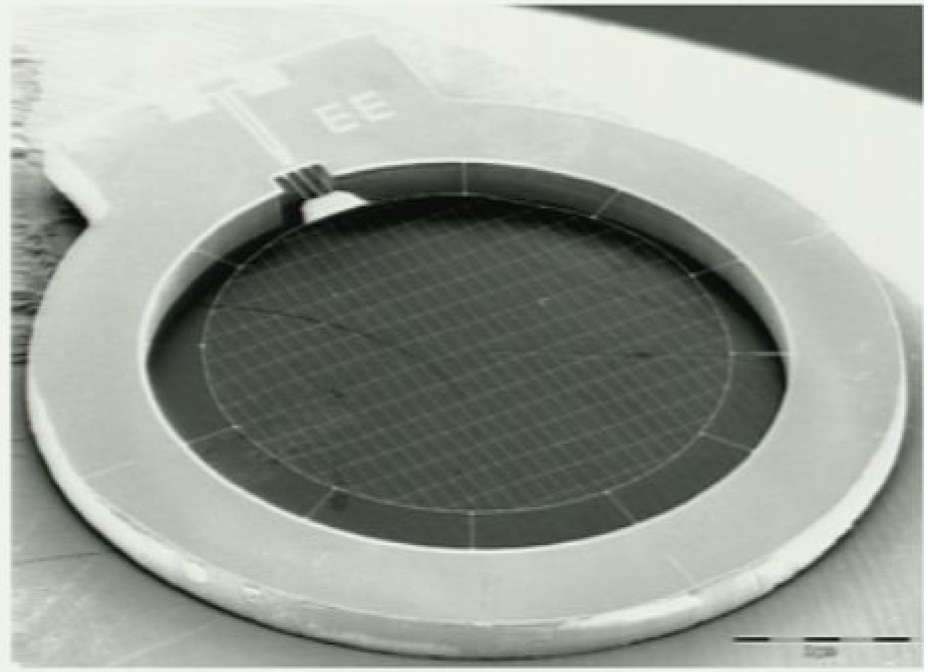


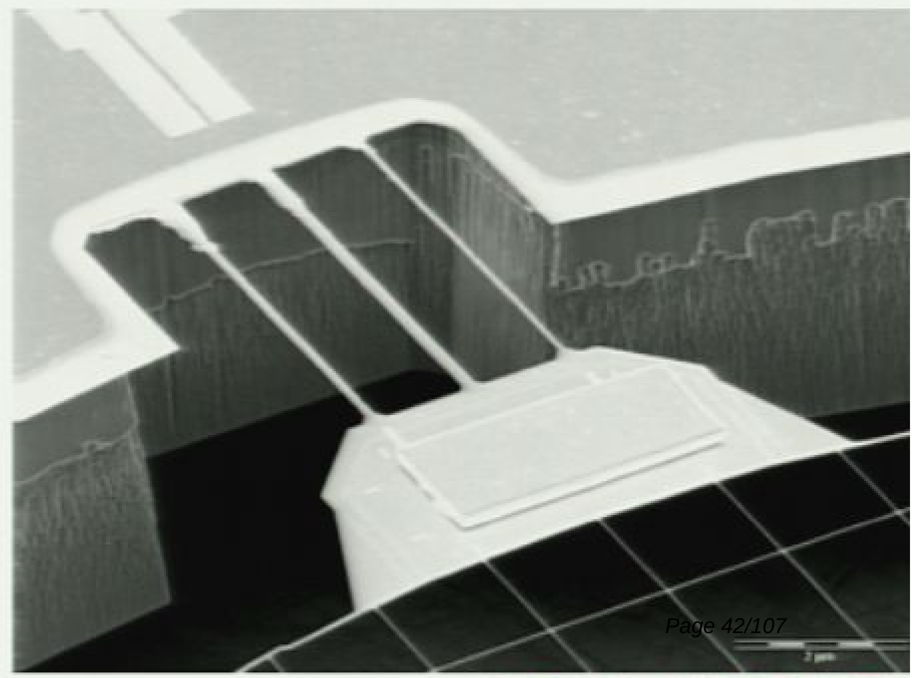
• A bolometer is a temperature dependent resistor coupled to a photon absorber

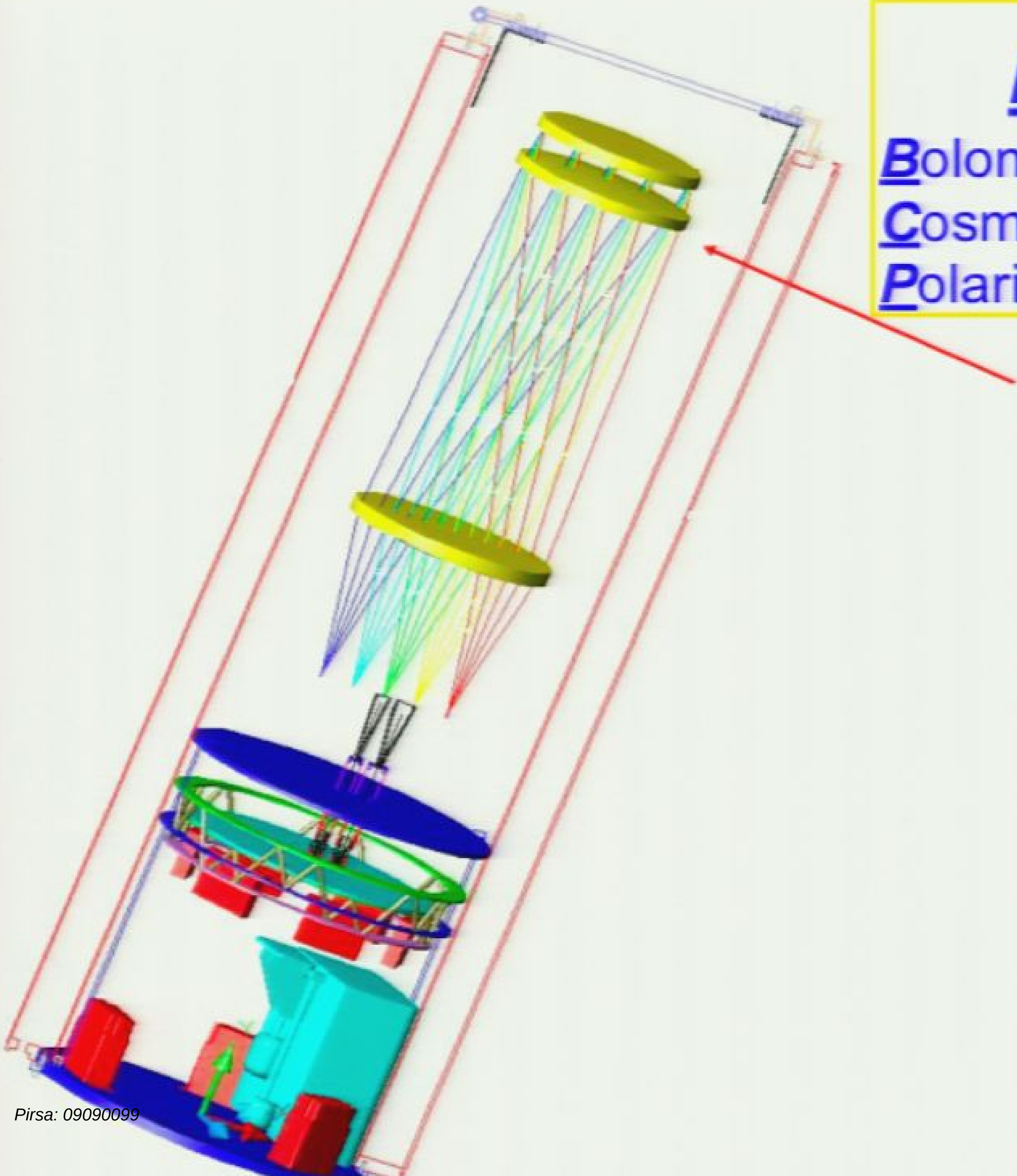
Polarization Sensitive Bolometers

- Orthogonal polarization mode detectors share same feed/filter stack

- Current Boomerang devices achieve 35% end-to-end optical efficiency and ~5% cross polarization. The PSB modules themselves achieve >95% absorption efficiency and 1.5% cross polarization.



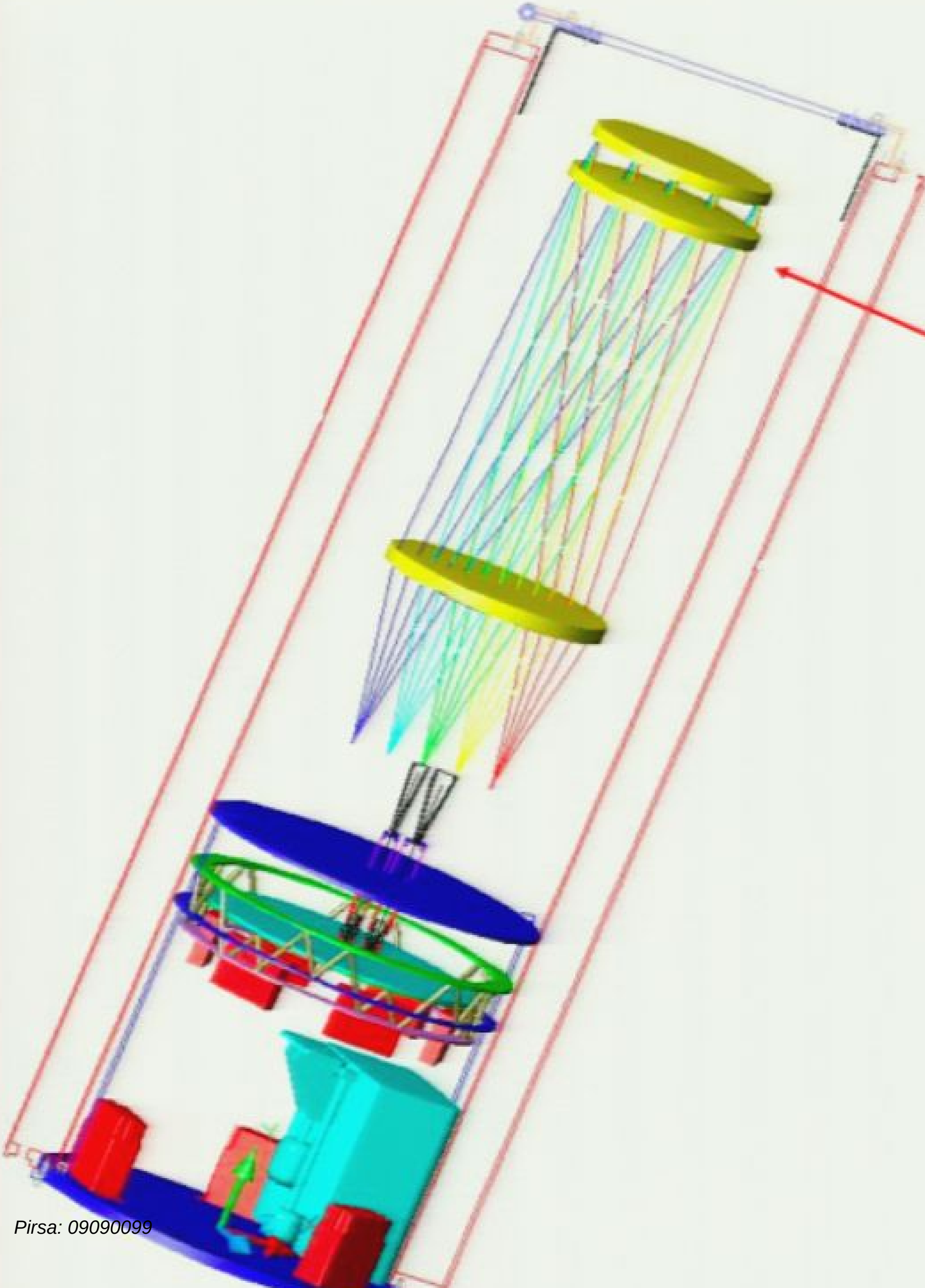




BICEP

Bolometric **I**maging of
Cosmic **E**xtragalactic
Polarization

Keating et al. (2003)



BICEP

Bolometric **I**maging of
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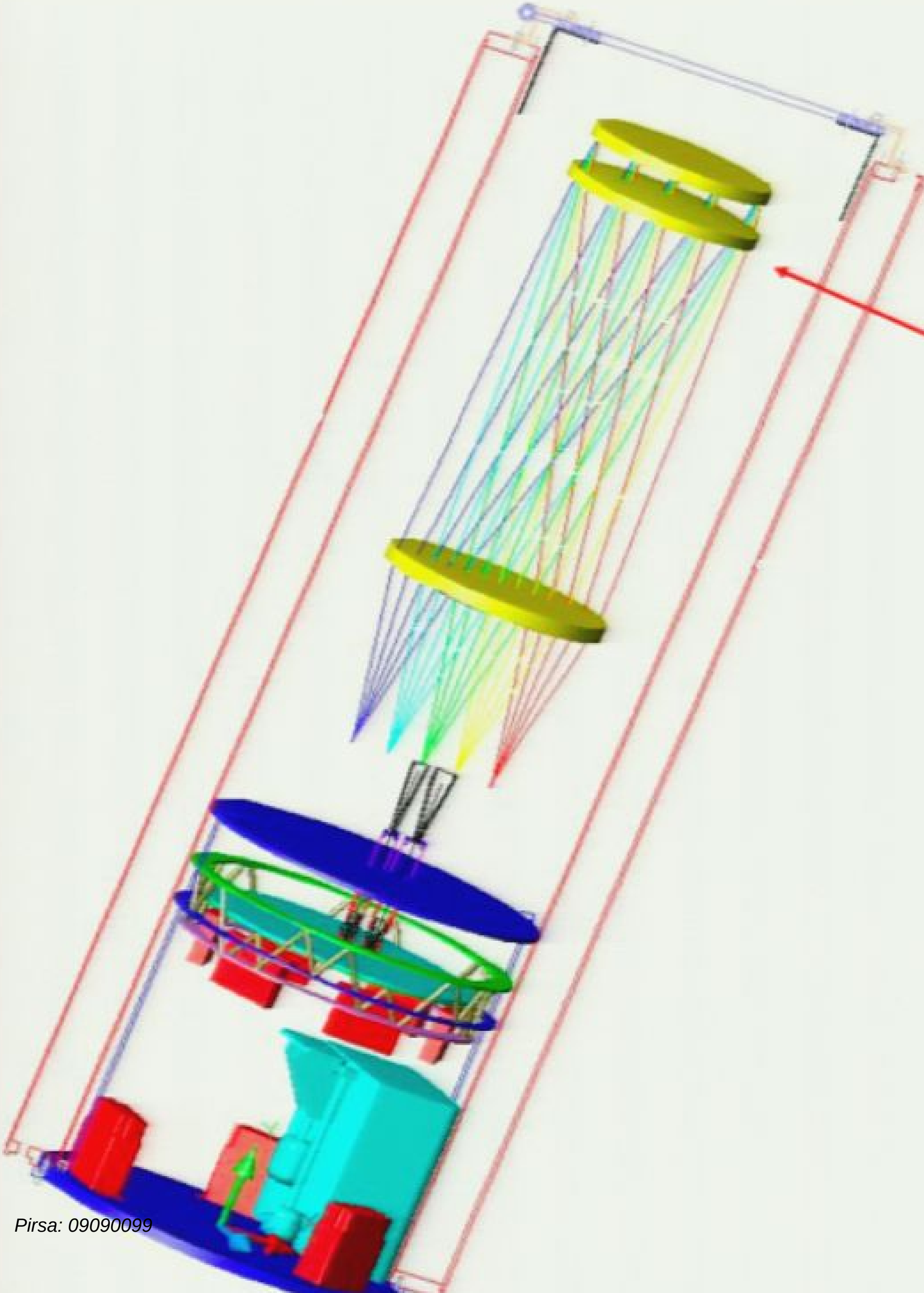
Polarization

- **30 cm dia. *Refractor***
- ***~ same sensitivity to GWB as a 10 m diameter telescope!***

Keating et al. (2003)



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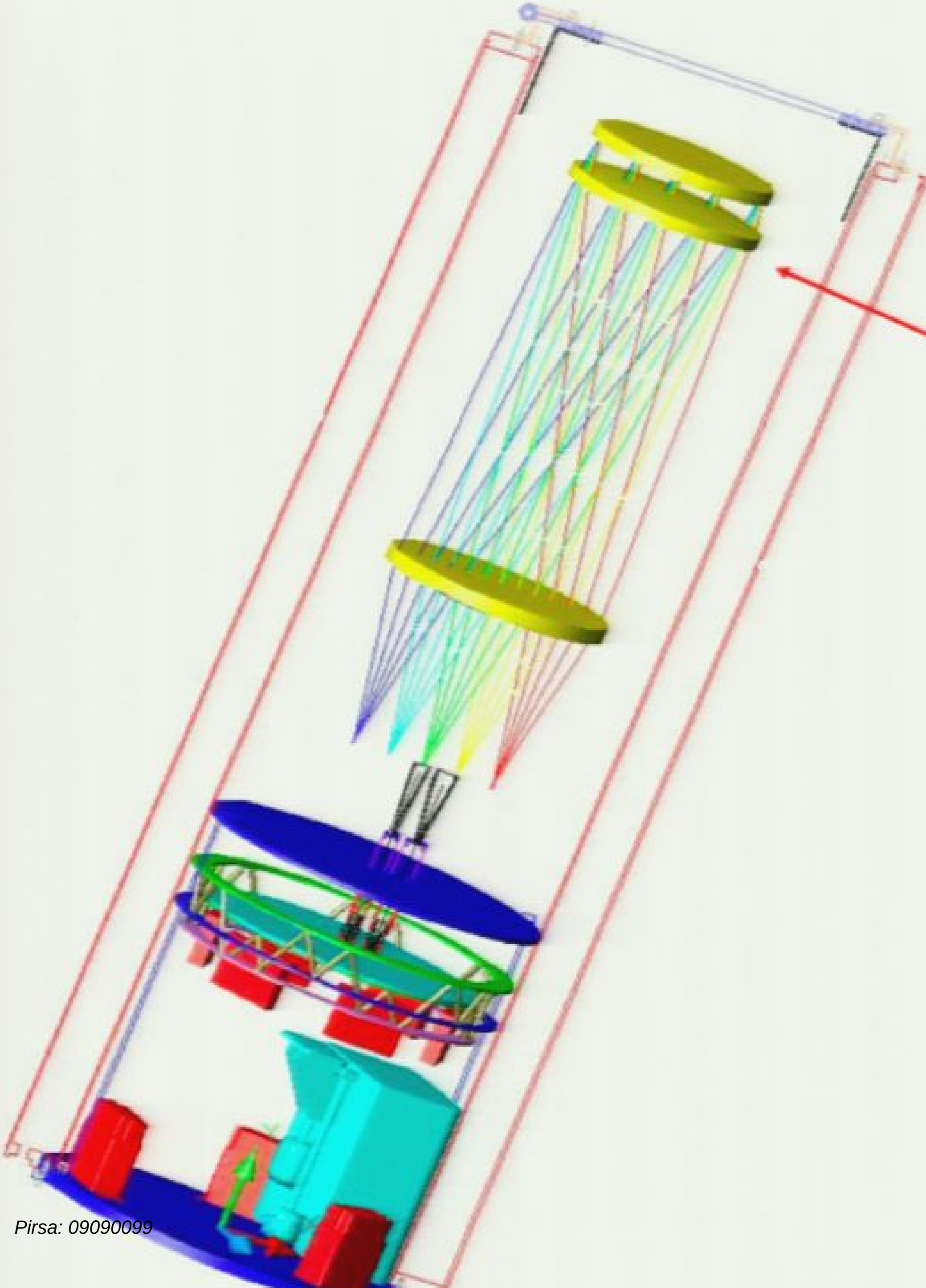
- **Fidelity – systematically "clean" (like COBE/DASI)**

Keating et al. (2003)



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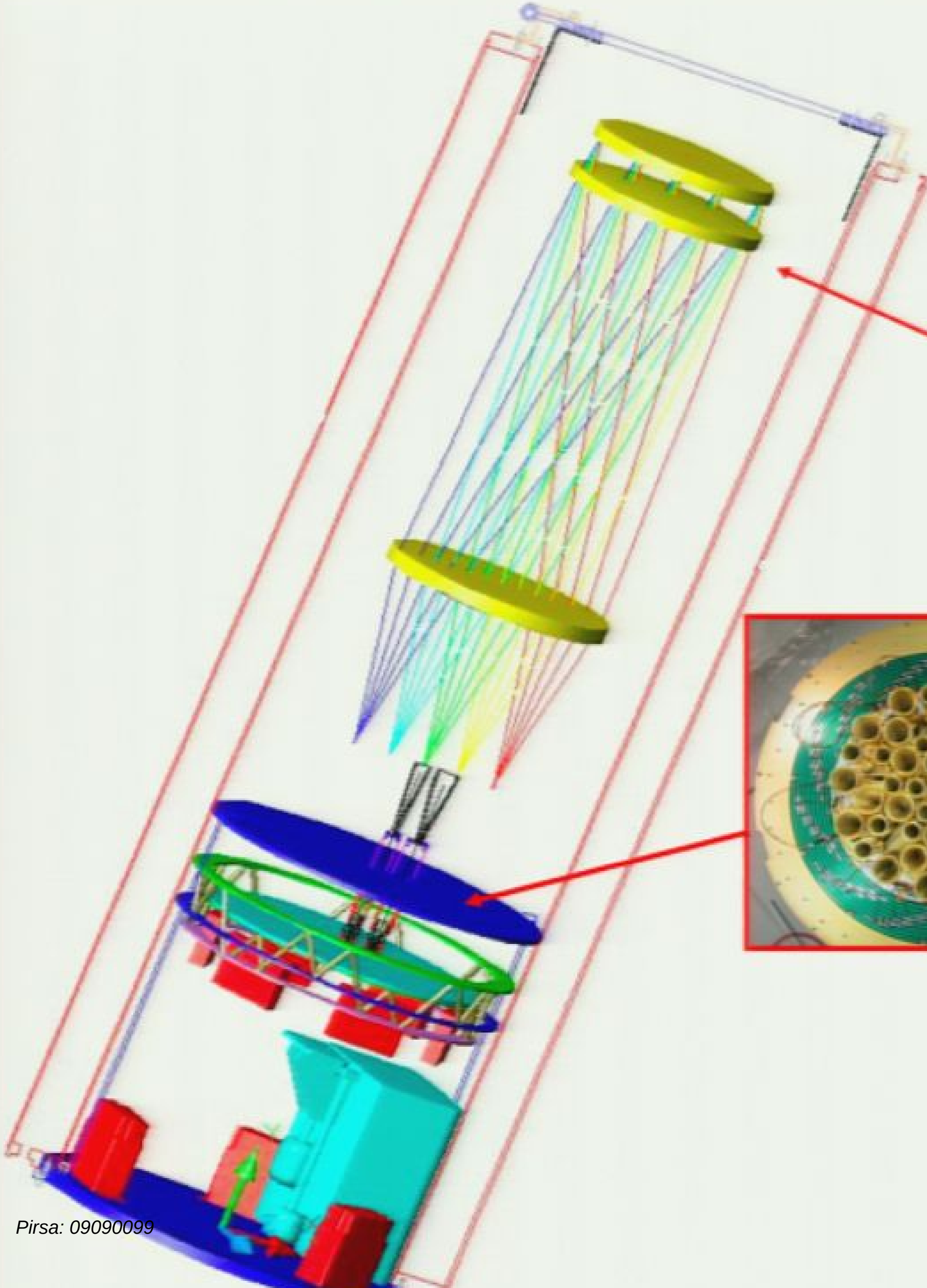

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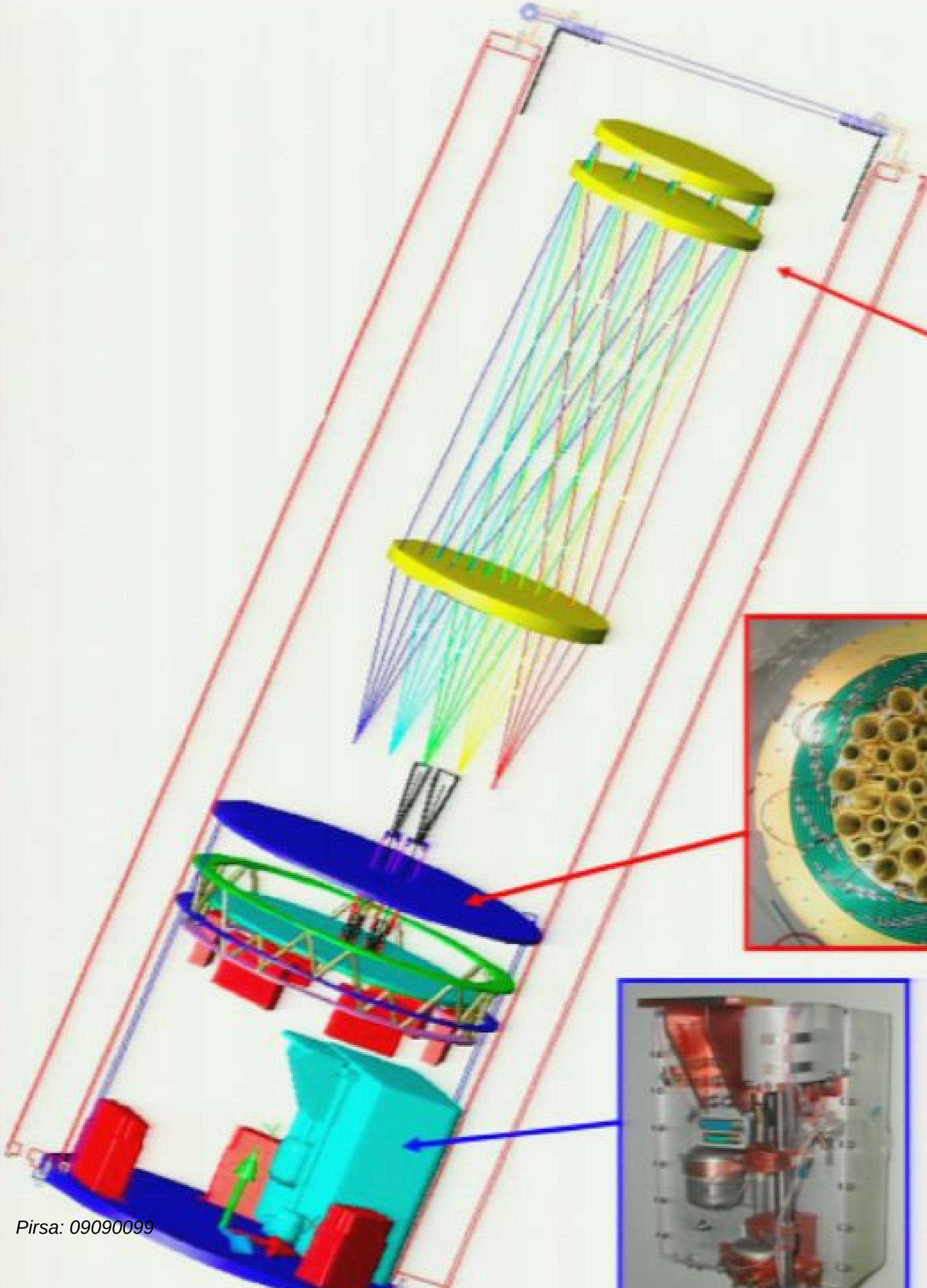
- 49 feed-horns (pixels) each with polarization-sensitive bolometers cooled to 250 mK

Keating et al. (2003)



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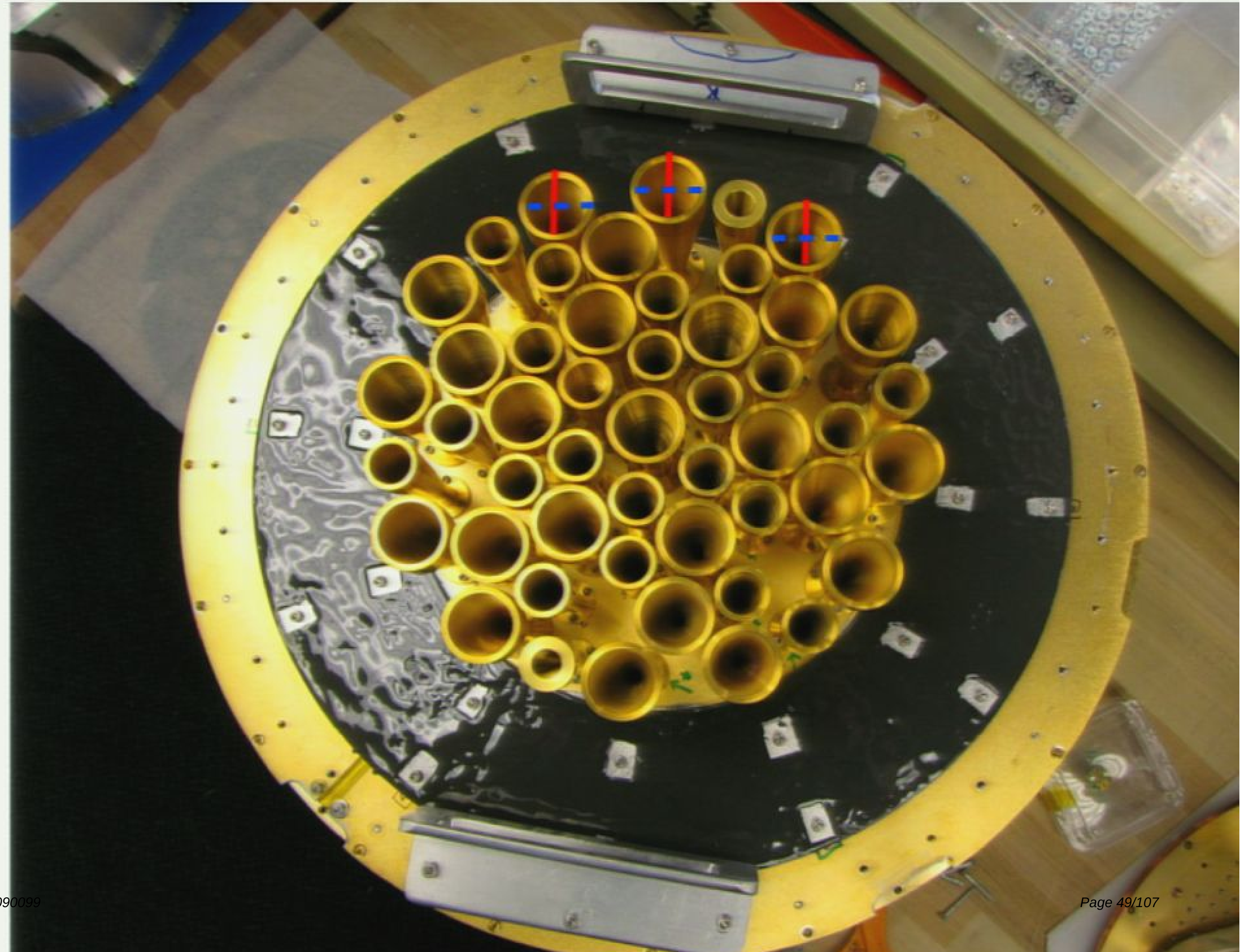
250 mK

Refrigerator

Keating et al. (2003)



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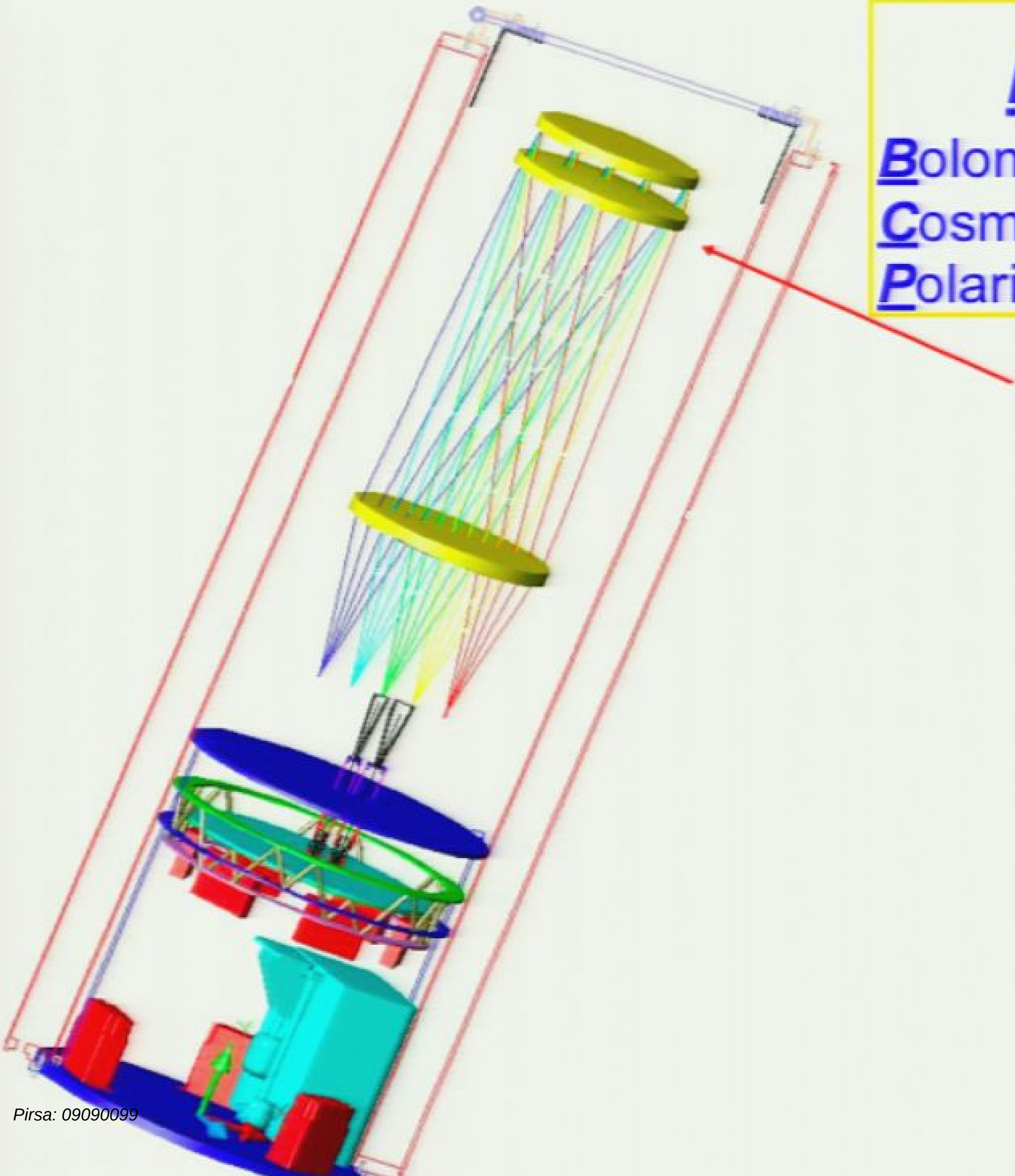
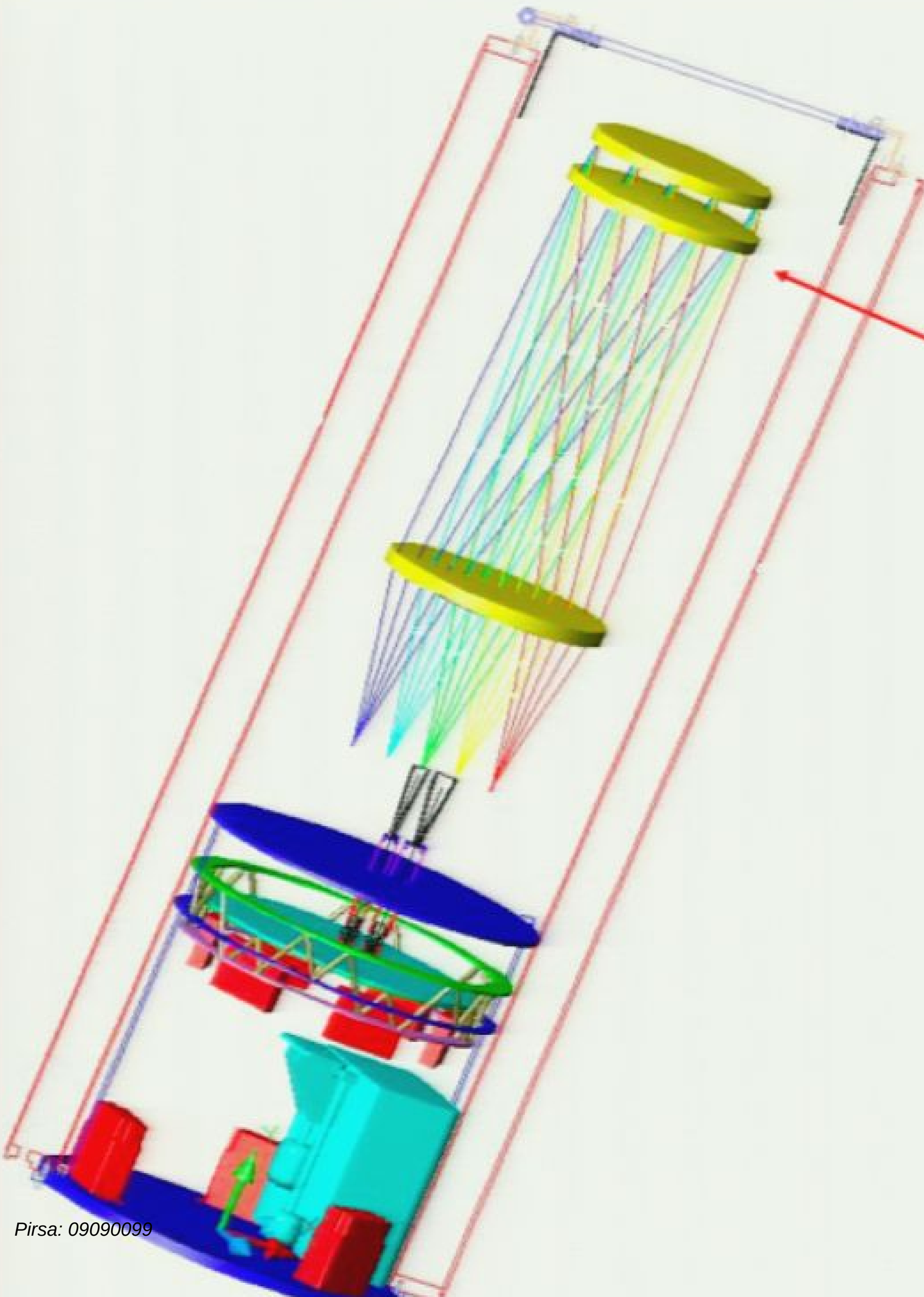


Keating et al. (2003)



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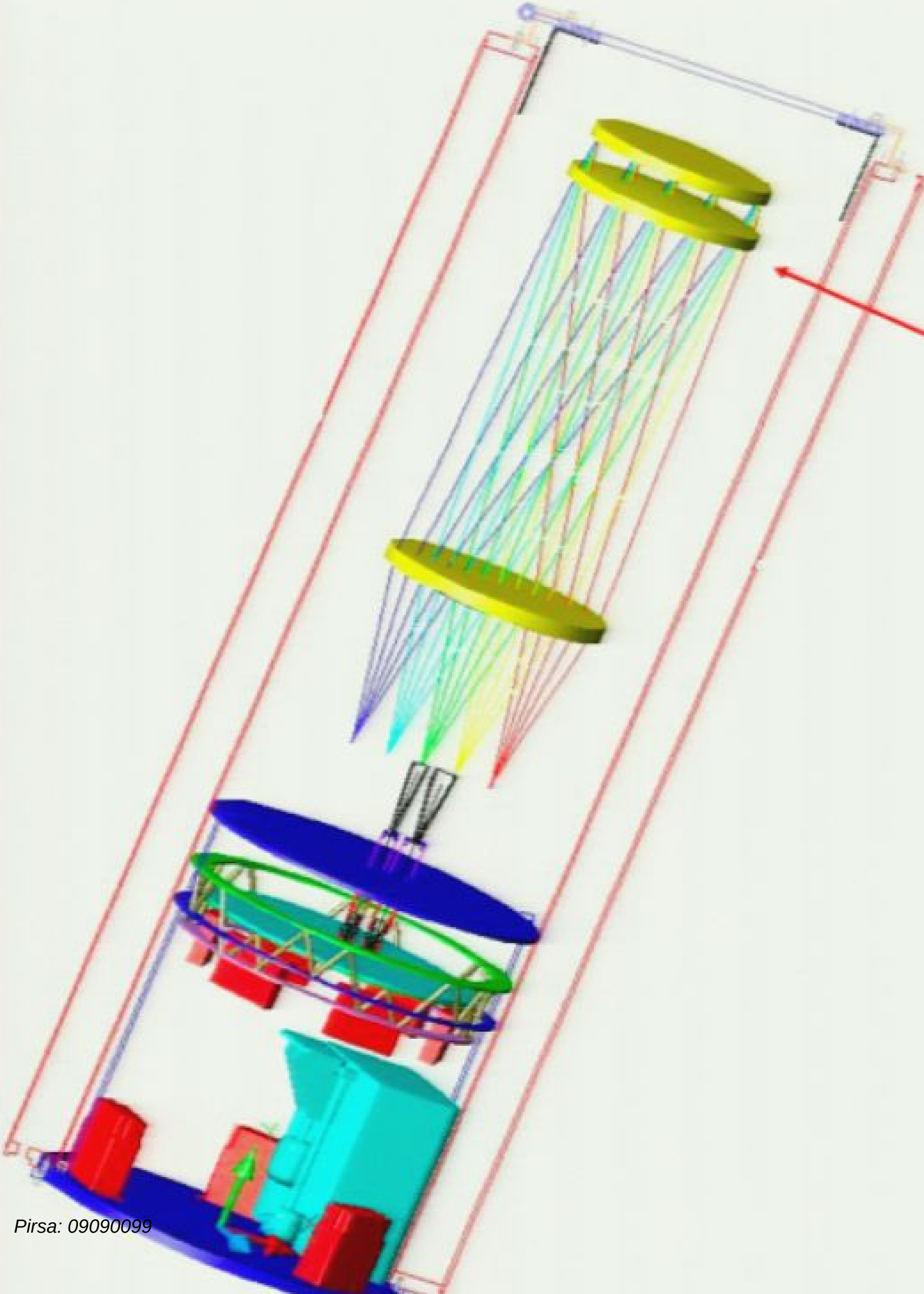

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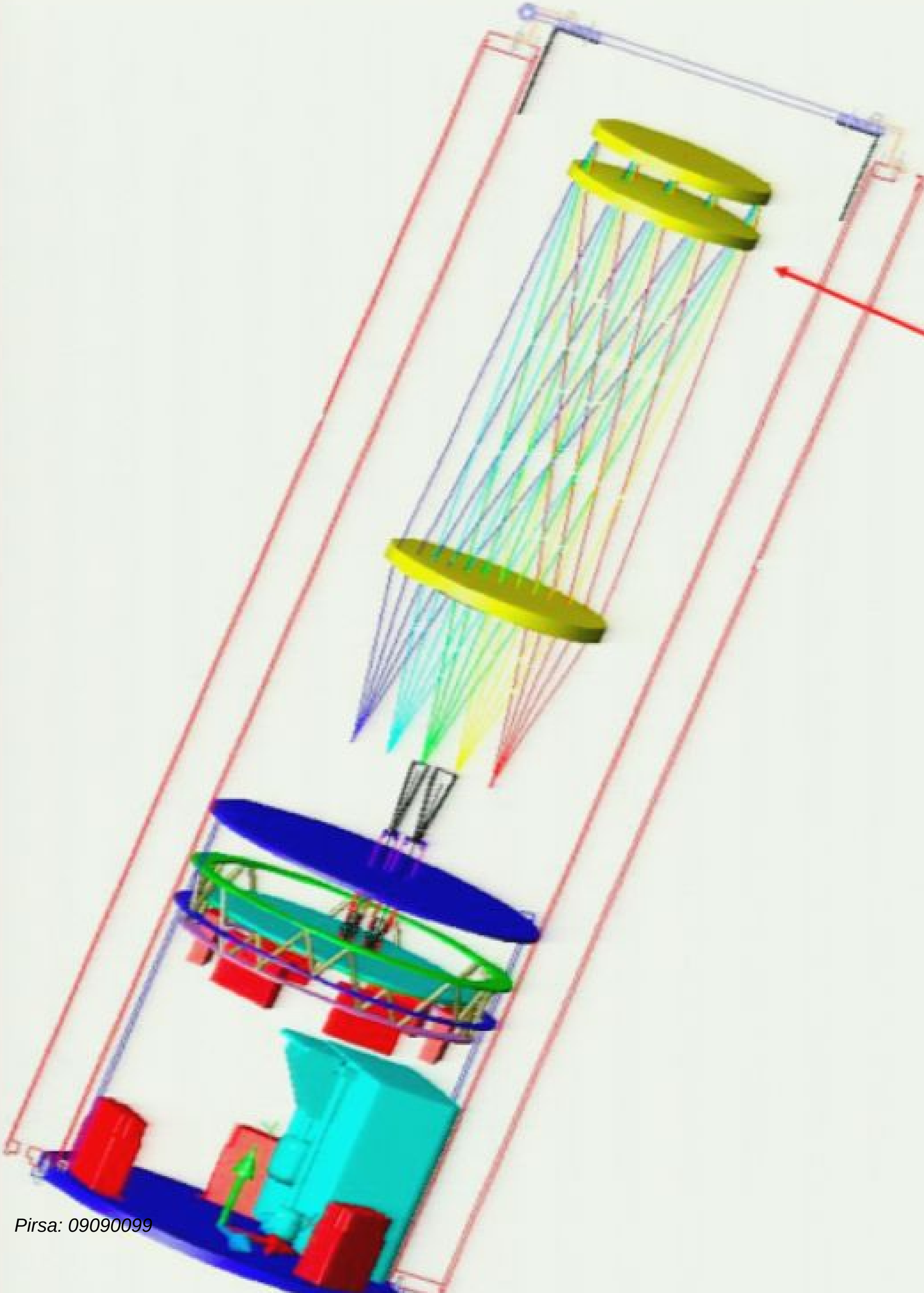

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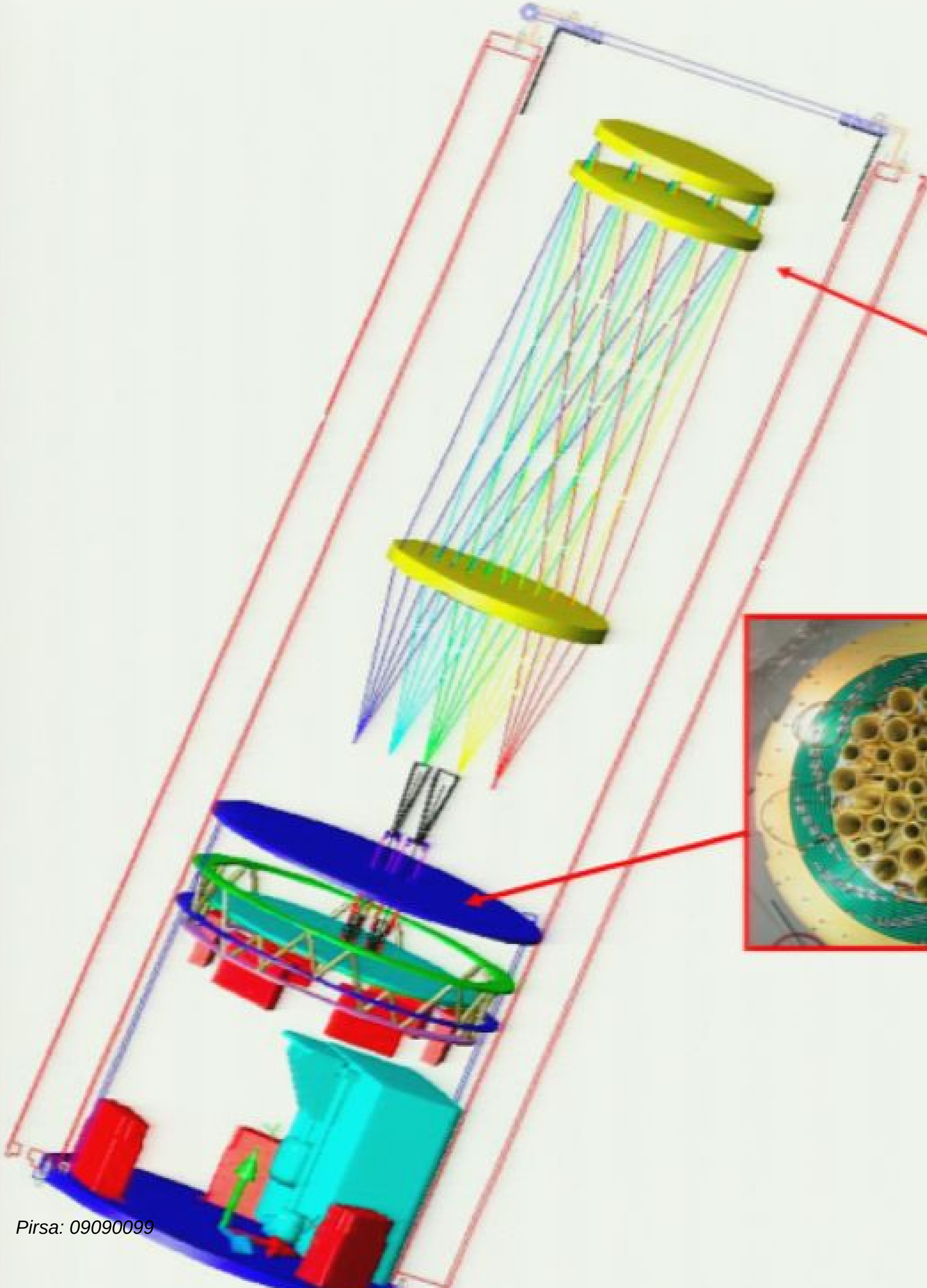

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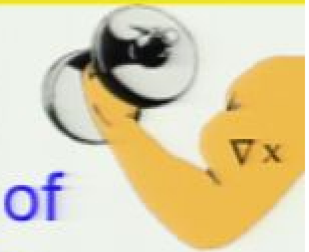

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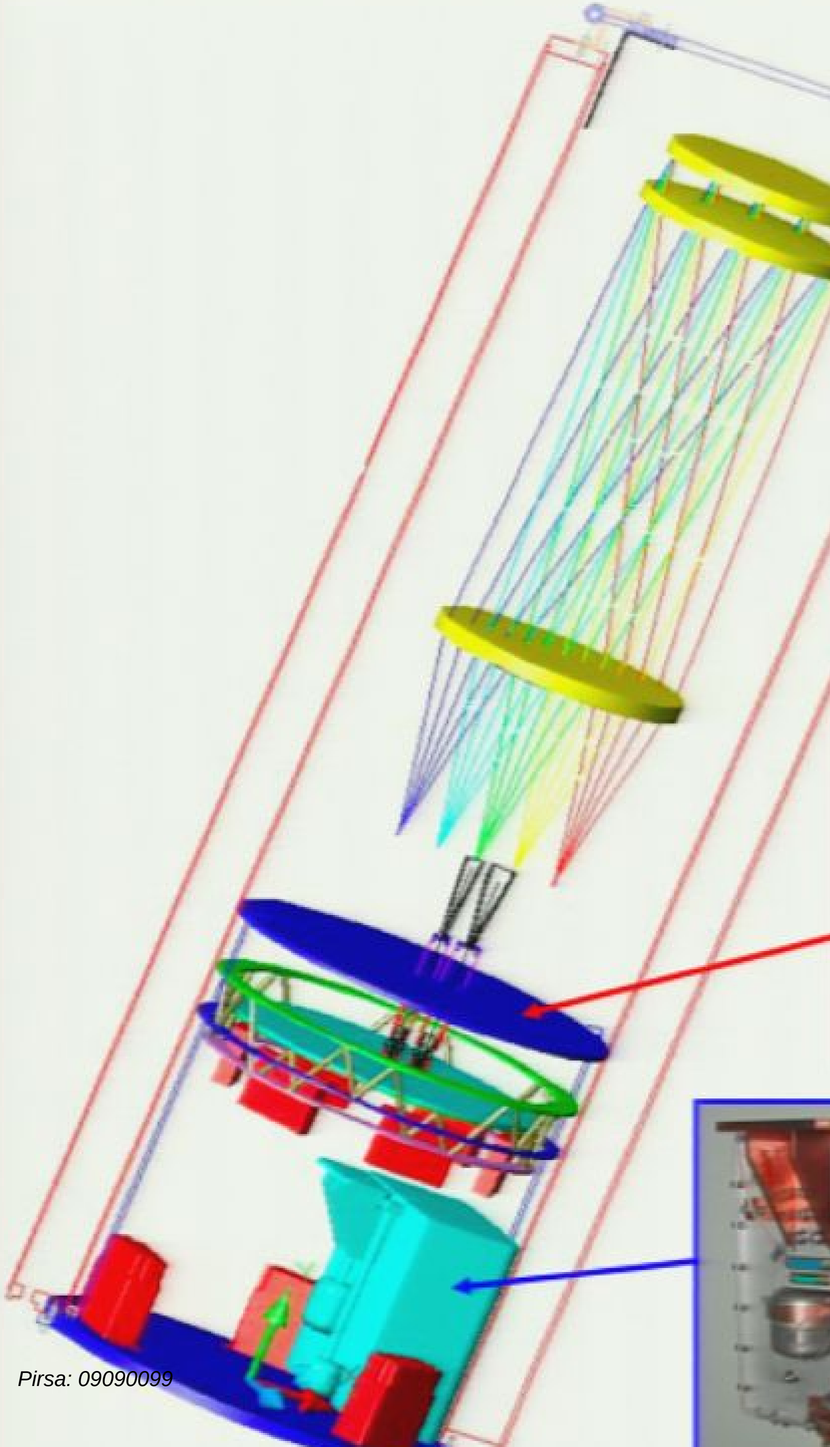

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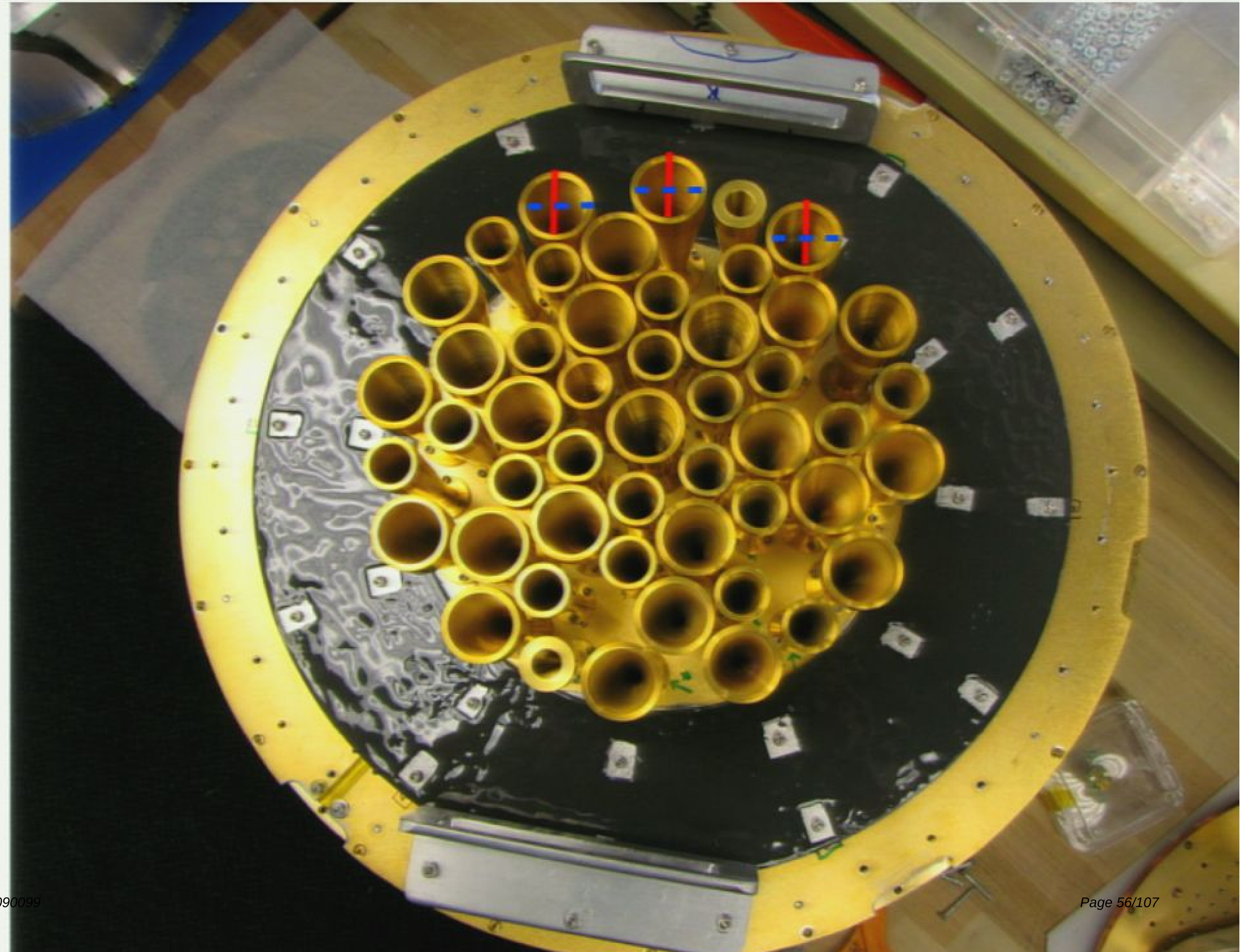
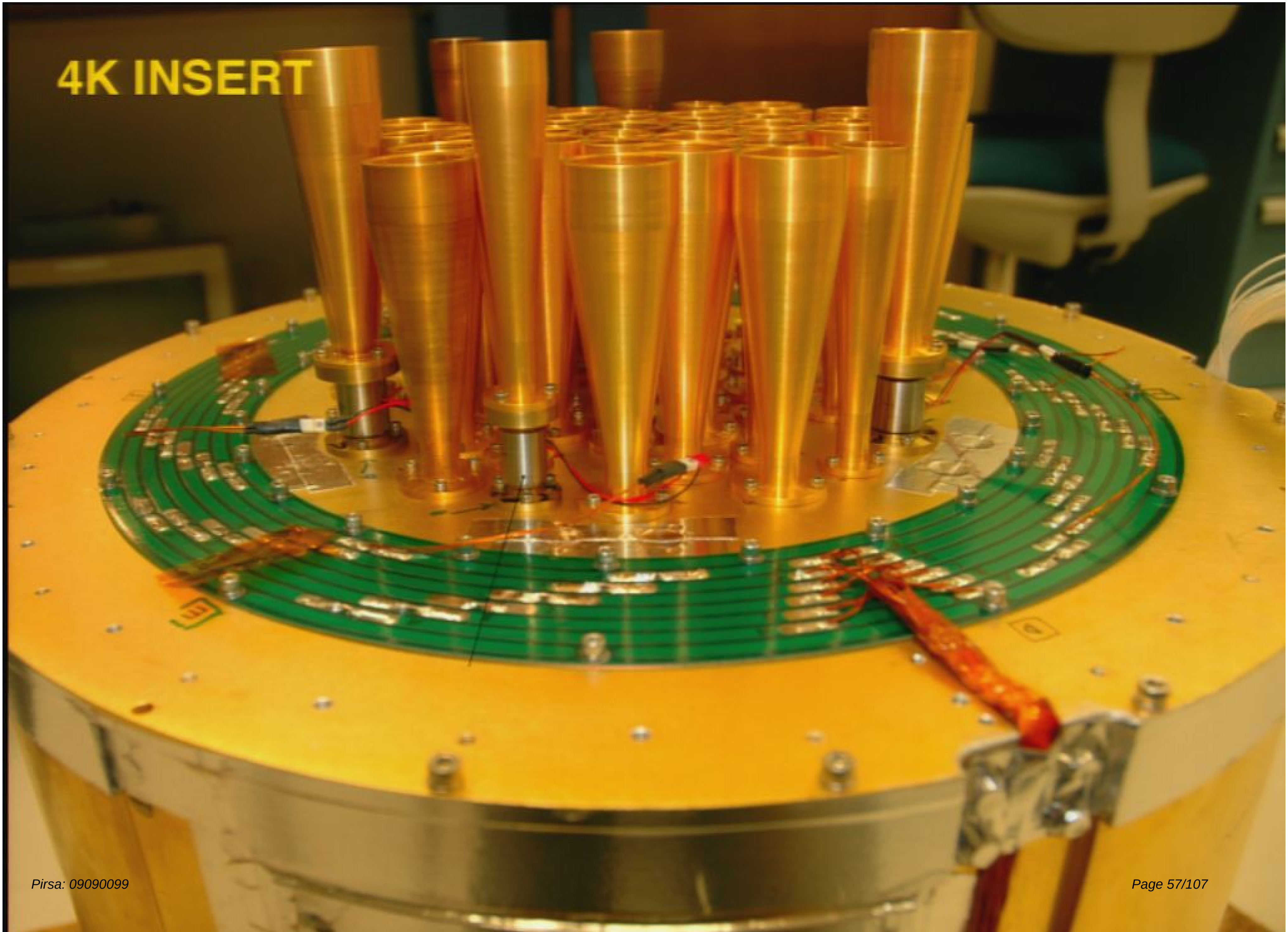
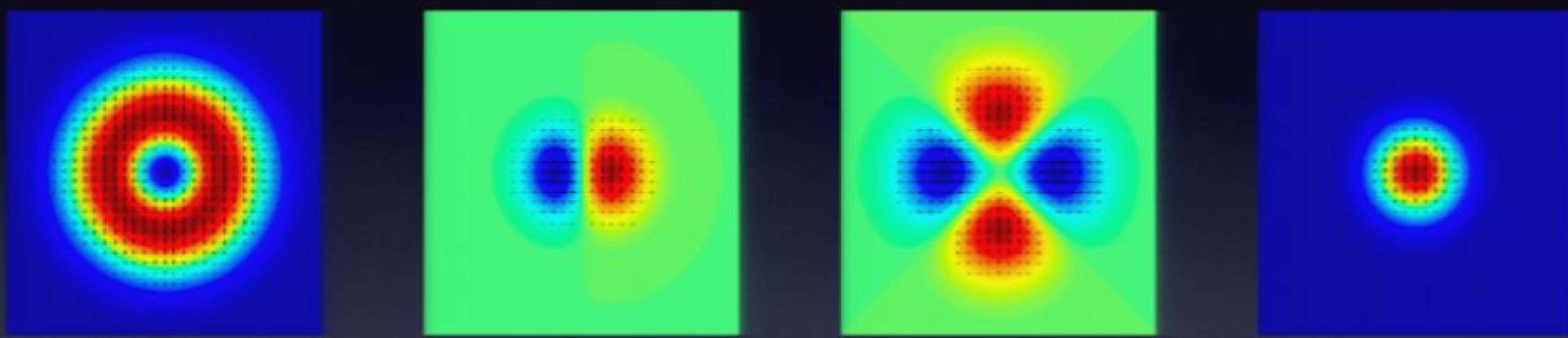
- **49 feed-horns (pixels) each with 2 polarization-sensitive bolometers cooled to 250 mK**

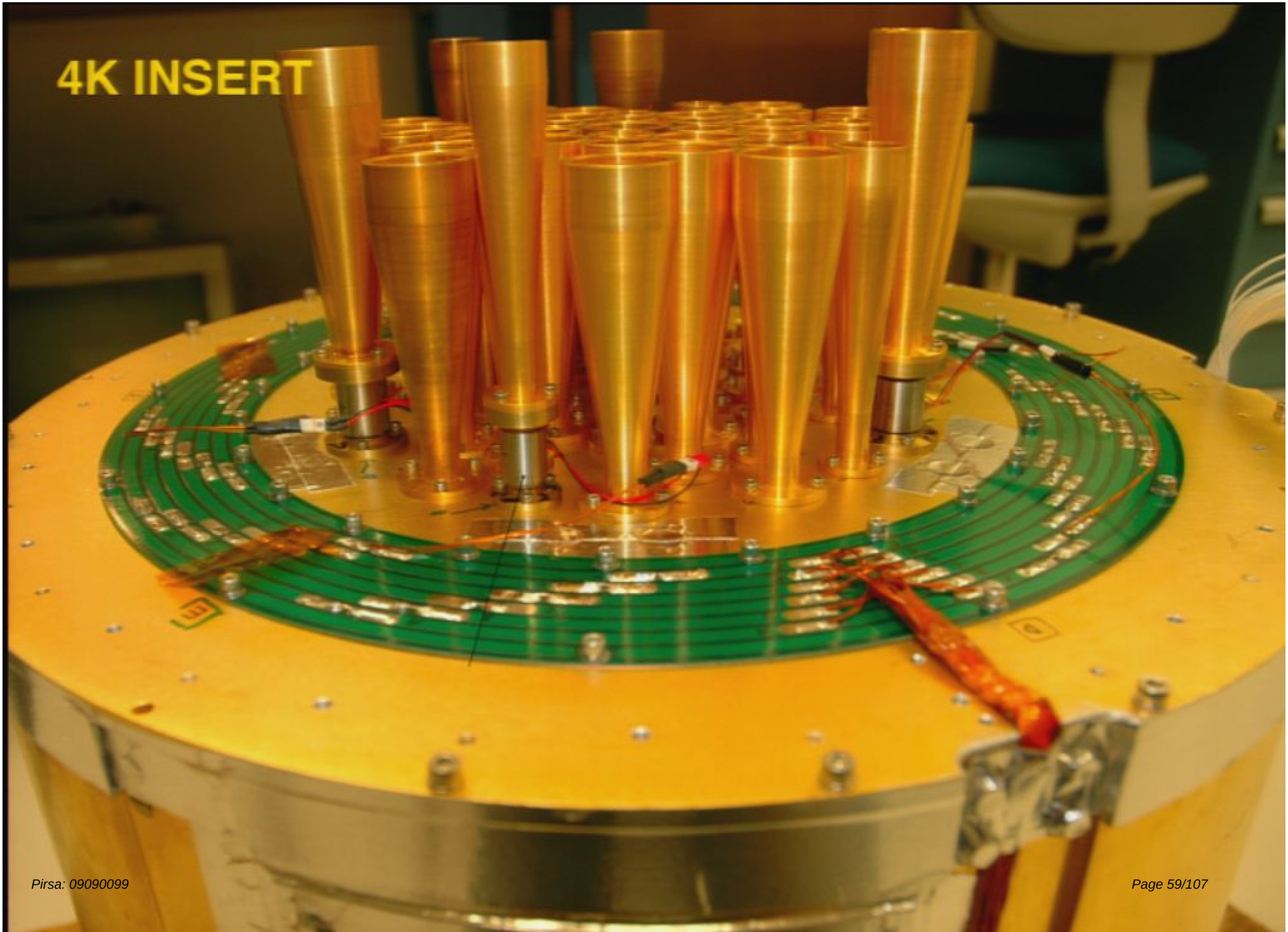
Keating et al. (2003)




4K INSERT

However, all is not perfect!
Systematic Beam Effects in Real Space

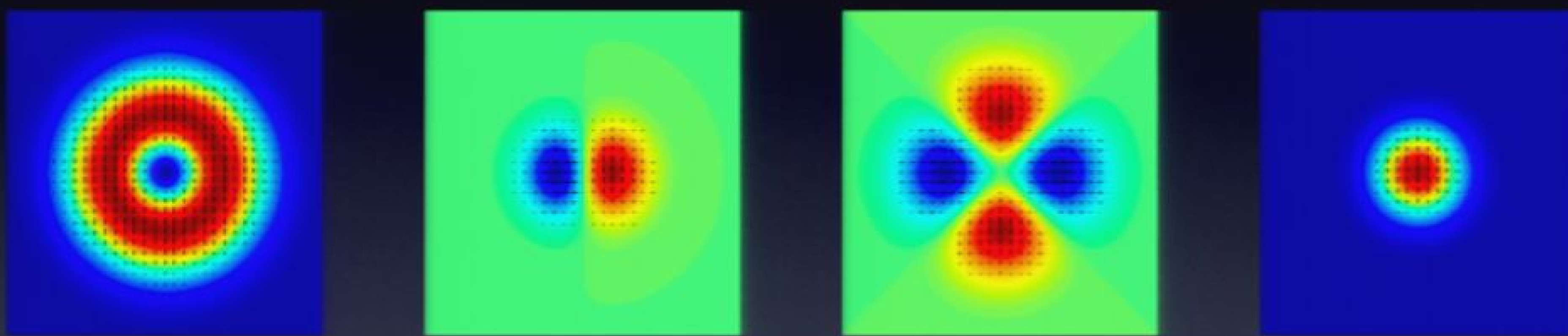



4K INSERT

However, all is not perfect! Systematic Beam Effects in Real Space

differential beam offset (dipole IP effect)

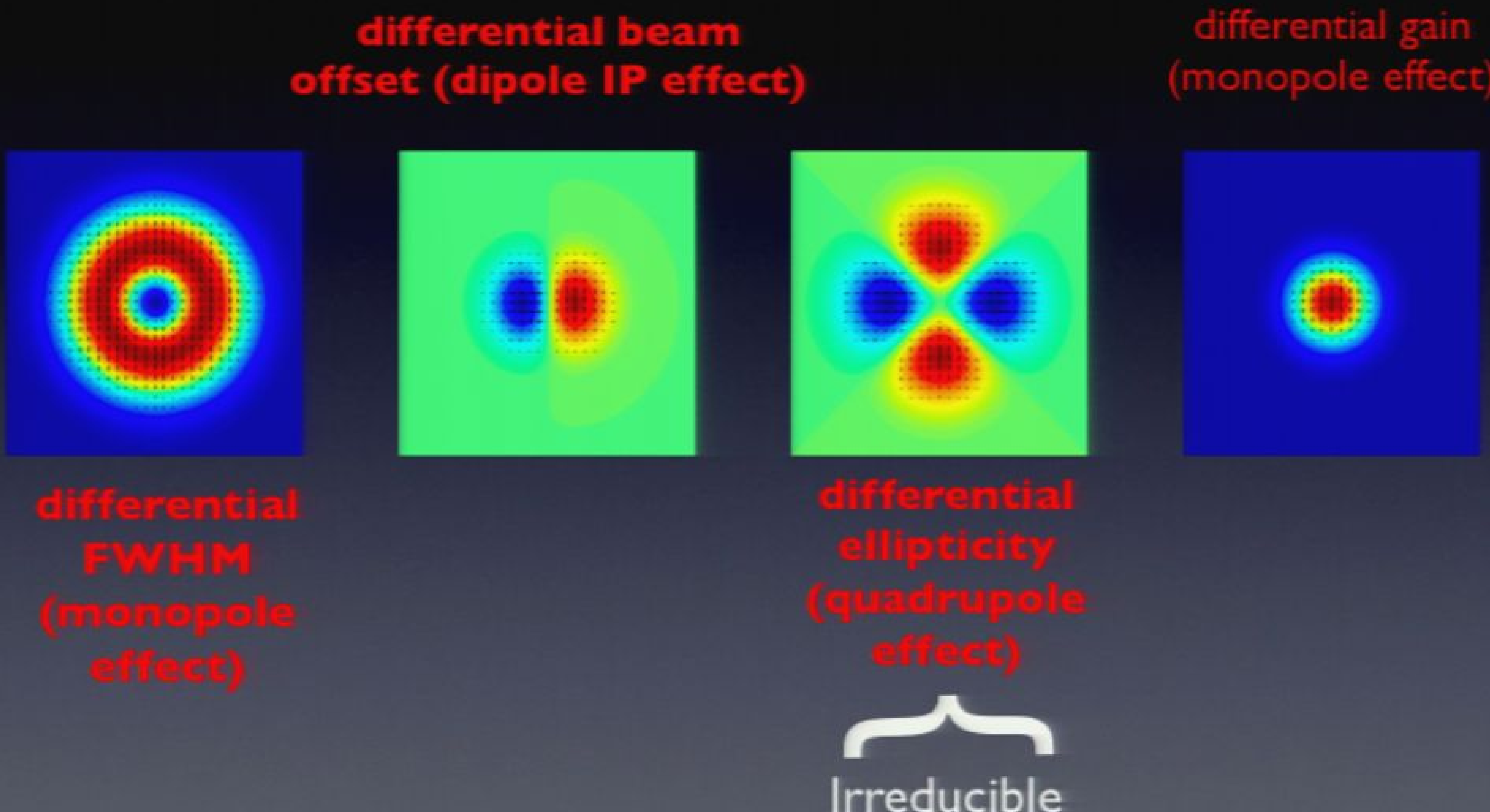
differential gain (monopole effect)



differential FWHM (monopole effect)

differential ellipticity (quadrupole effect)

However, all is not perfect!
Systematic Beam Effects in Real Space



Beam Systematics Impact on Cosmological Birefringence

- Intensity leakage to polarization: T→E,B

$$B \propto \omega T, \quad \omega << 1$$

$$C_l^{BB} \propto \omega^2 C_l^{TT}$$

$$C_l^{TB} \propto \omega C_l^{TT}$$

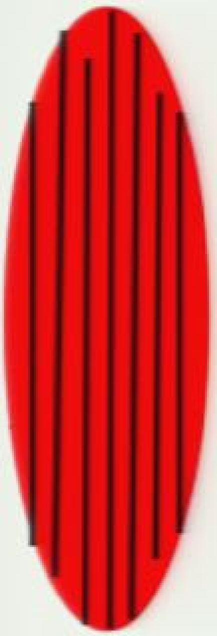
Therefore, keeping C_l^{BB} low does not necessarily guarantee low C_l^{TB}

We measure pixel orientations numerous times per season, but in th

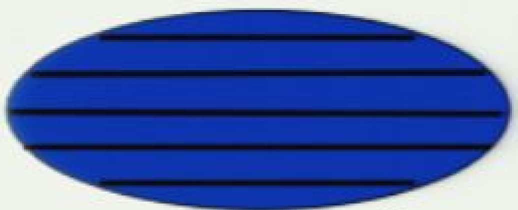
end we optimized for BB modes (T/S ratio.)

Irreducible Beam Systematic: Differential Ellipticity

T_y



T_x



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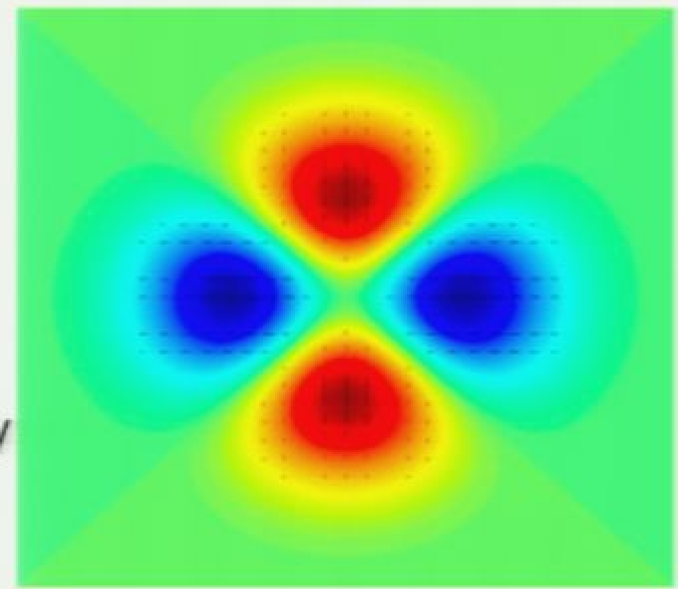
For an unpolarized point source

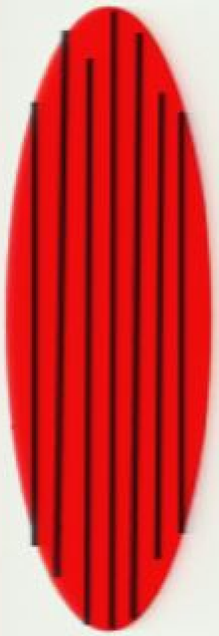


$$Q \propto \frac{\partial^2 T}{\partial x^2} - \frac{\partial^2 T}{\partial y^2} \; = \; \text{Diff. ellipticity}$$

$$\left\langle \frac{\partial^2 T}{\partial \theta^2} \right\rangle \approx 0.1 \mu K / arc\,\min^2$$

Irreducible Beam Systematic: Differential Ellipticity

T_y $\qquad$ T_x



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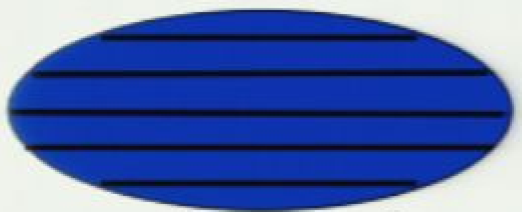

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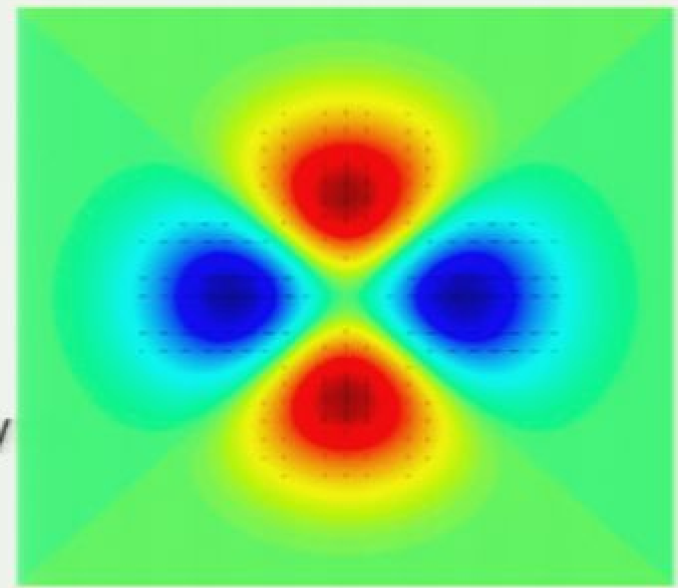
For an unpolarized point source

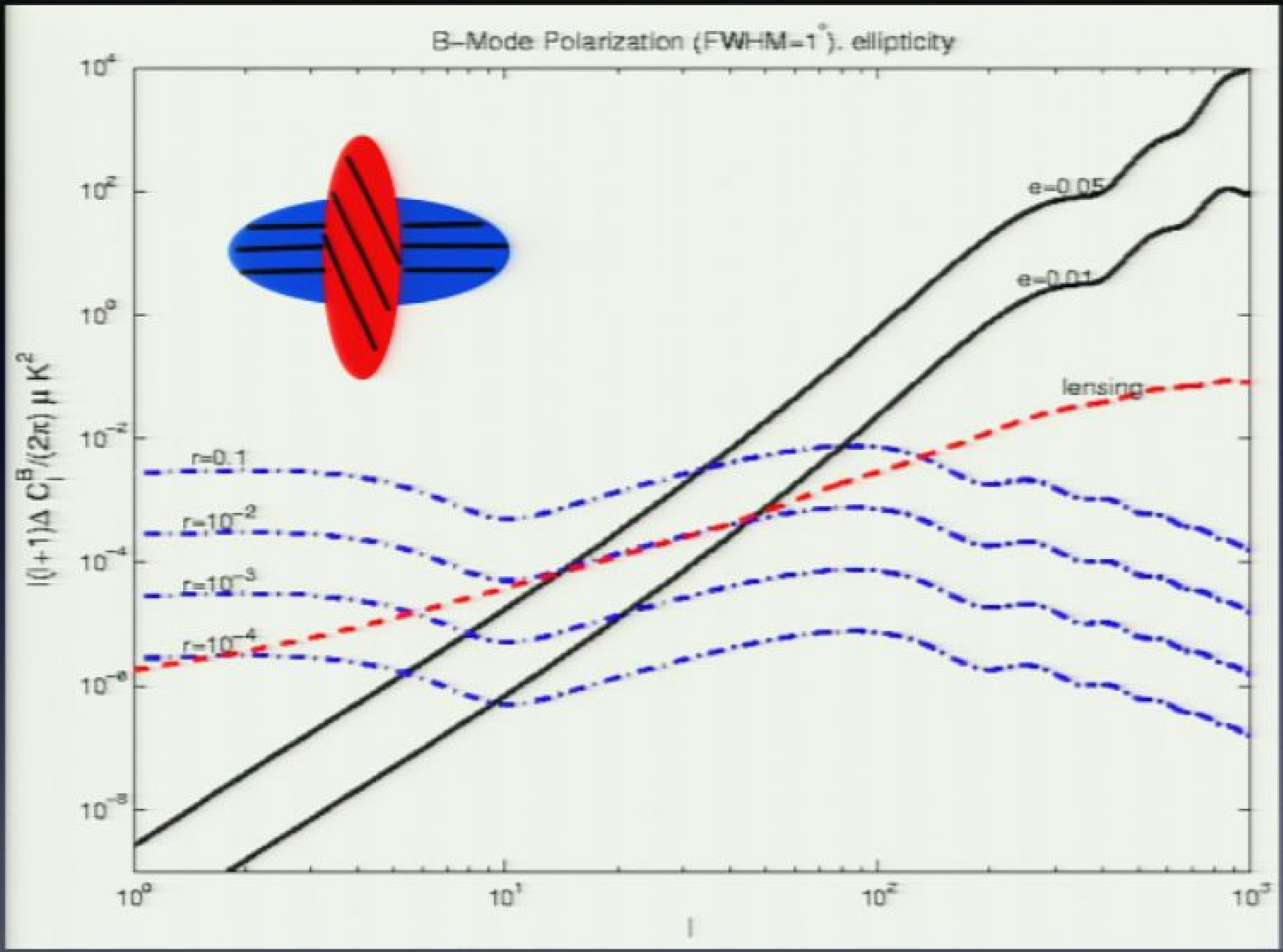


$$Q \propto \frac{\partial^2 T}{\partial x^2} - \frac{\partial^2 T}{\partial y^2}$$ = Diff. ellipticity

$$\left\langle \frac{\partial^2 T}{\partial \theta^2} \right\rangle \approx 0.1 \mu K / arc\min^2$$

BICEP: Differential ellipticity is well understood

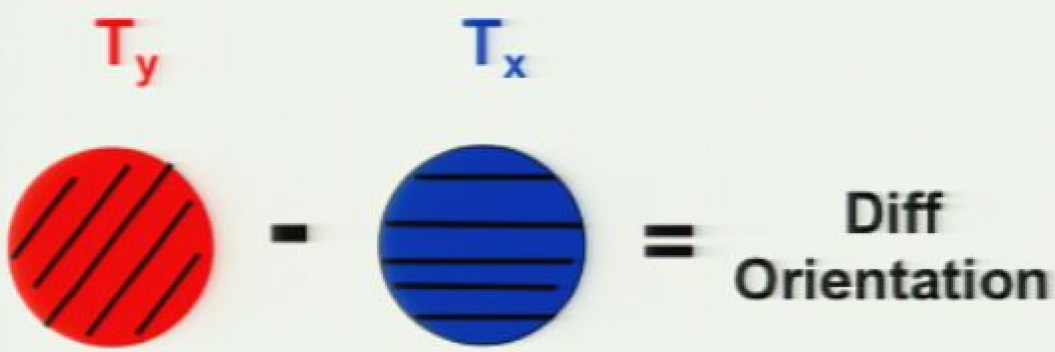
B-mode Differential Ellipticity (Inst. Polarization)



Differential Ellipticity effect is **not** reducible.

As shown here, would produce *both* E & B modes.

Reducible Beam Systematic
Differential Orientation (De-Polarization)



Reducible Beam Systematic
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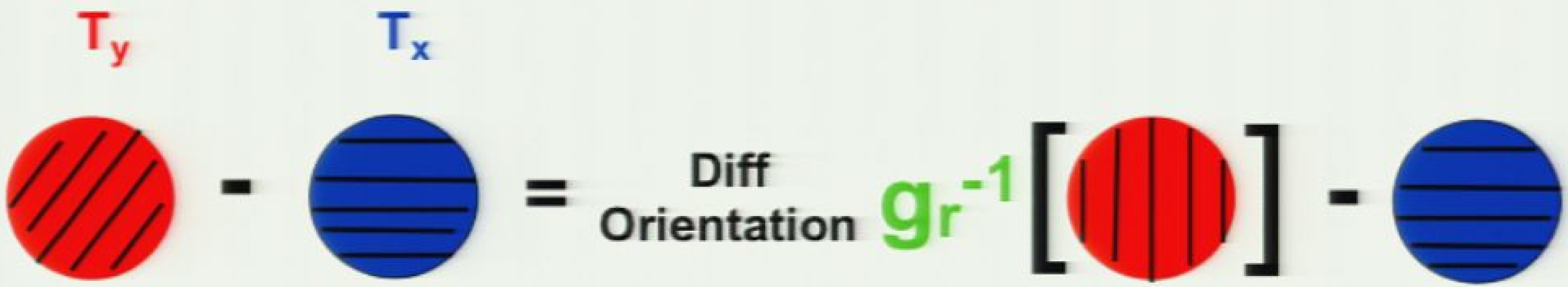

Reducible Beam Systematic
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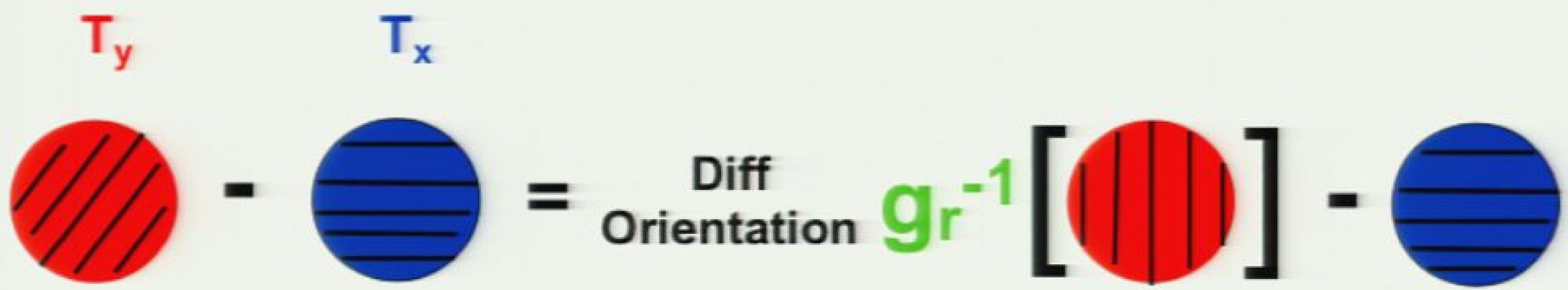
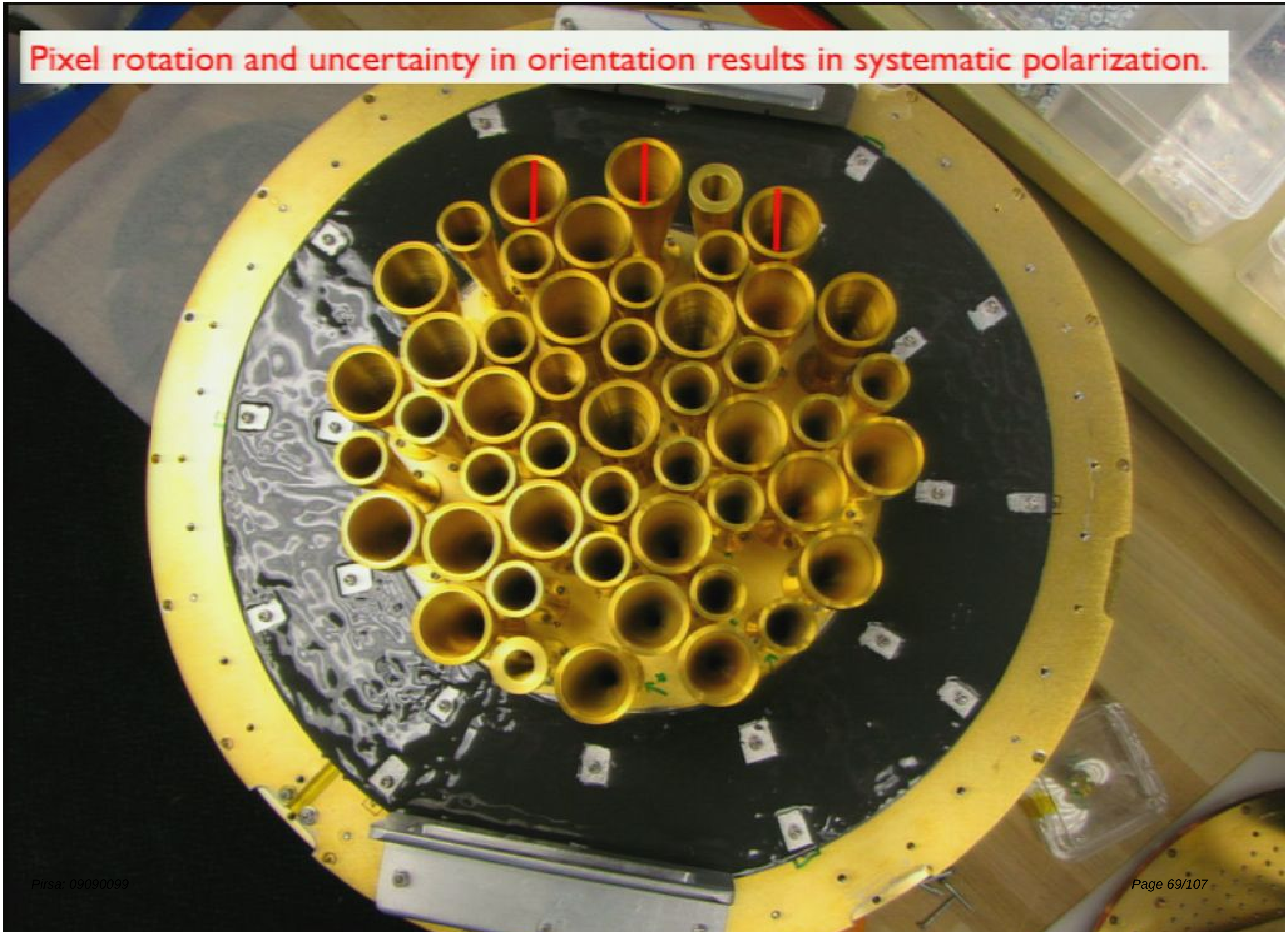
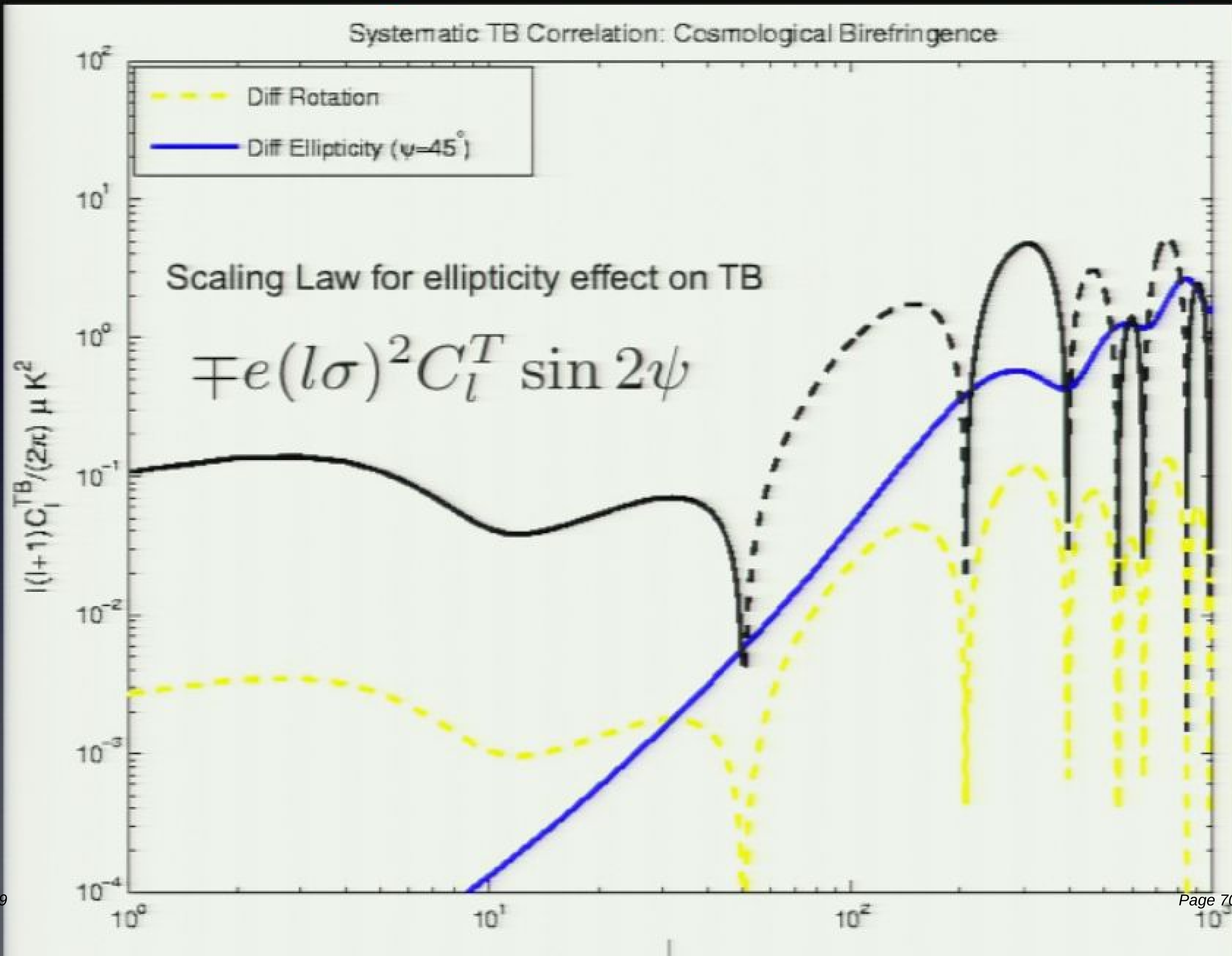


Differential Orientation does not produce cross polarization.
It is merely a differential relative gain effect and can be removed by calib.


Pixel rotation and uncertainty in orientation results in systematic polarization.

Systematics Impact on Cosmic Birefringence:



Systematic Spectra : Scaling laws

Ellipticity Effects

TB scales as: $\mp e(l\sigma)^2 C_l^T \sin 2\psi$

EB scales as: $\pm e^2 (l\sigma)^4 C_l^T \sin 2\psi \cos 2\psi$

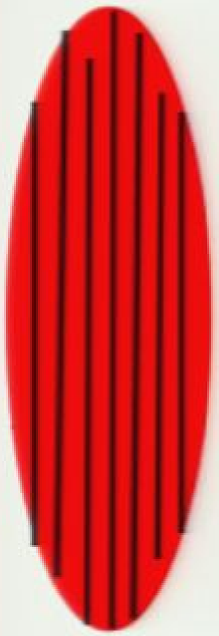
Rotation Effect

TB scales as: $C_\ell^{\mathrm{TE}}\ \varepsilon$

EB scales as: $\frac{1}{2}(C_\ell^{\mathrm{EE}} - C_\ell^{\mathrm{BB}})\,\varepsilon$

Irreducible Beam Systematic: Differential Ellipticity

T_y



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T_x

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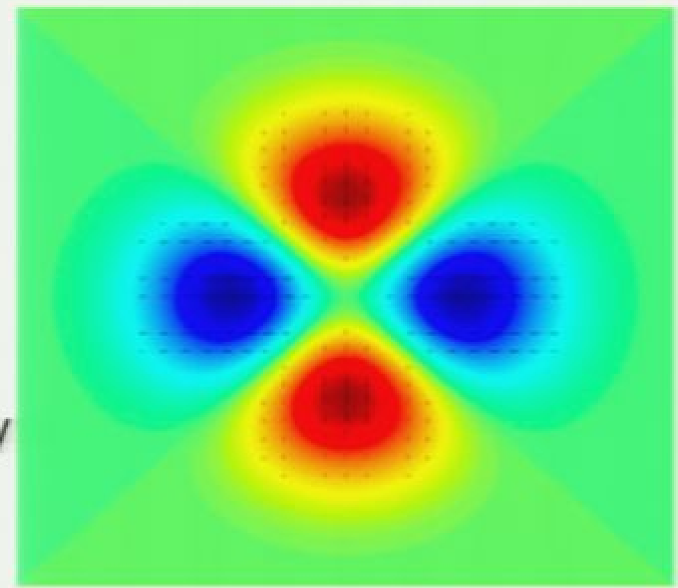
For an unpolarized point source



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Irreducible Beam Systematic: Differential Ellipticity

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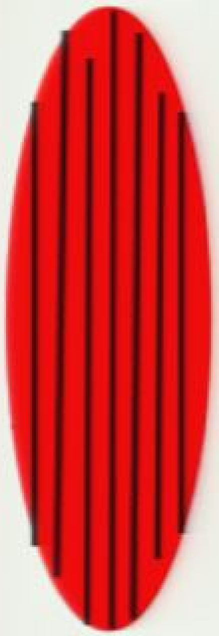
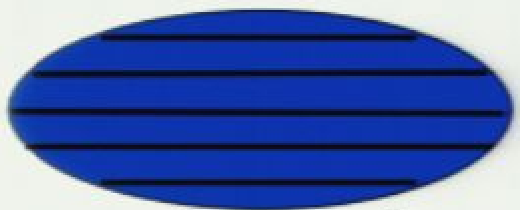
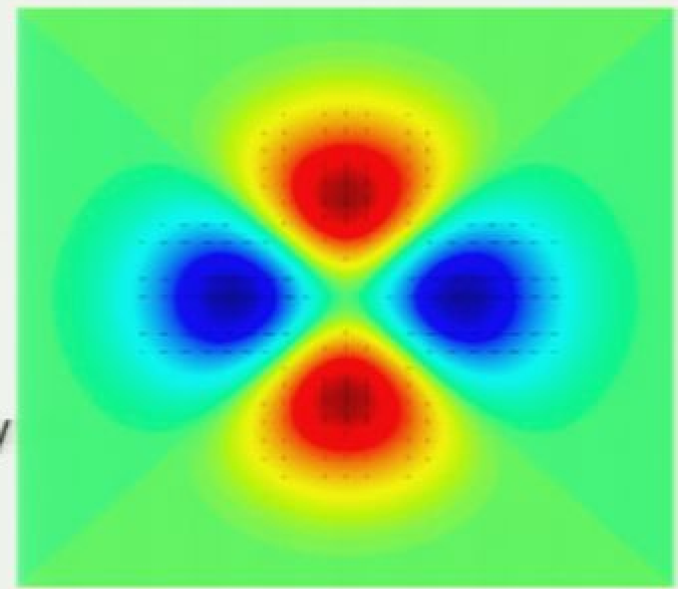


T_x



For an unpolarized point source

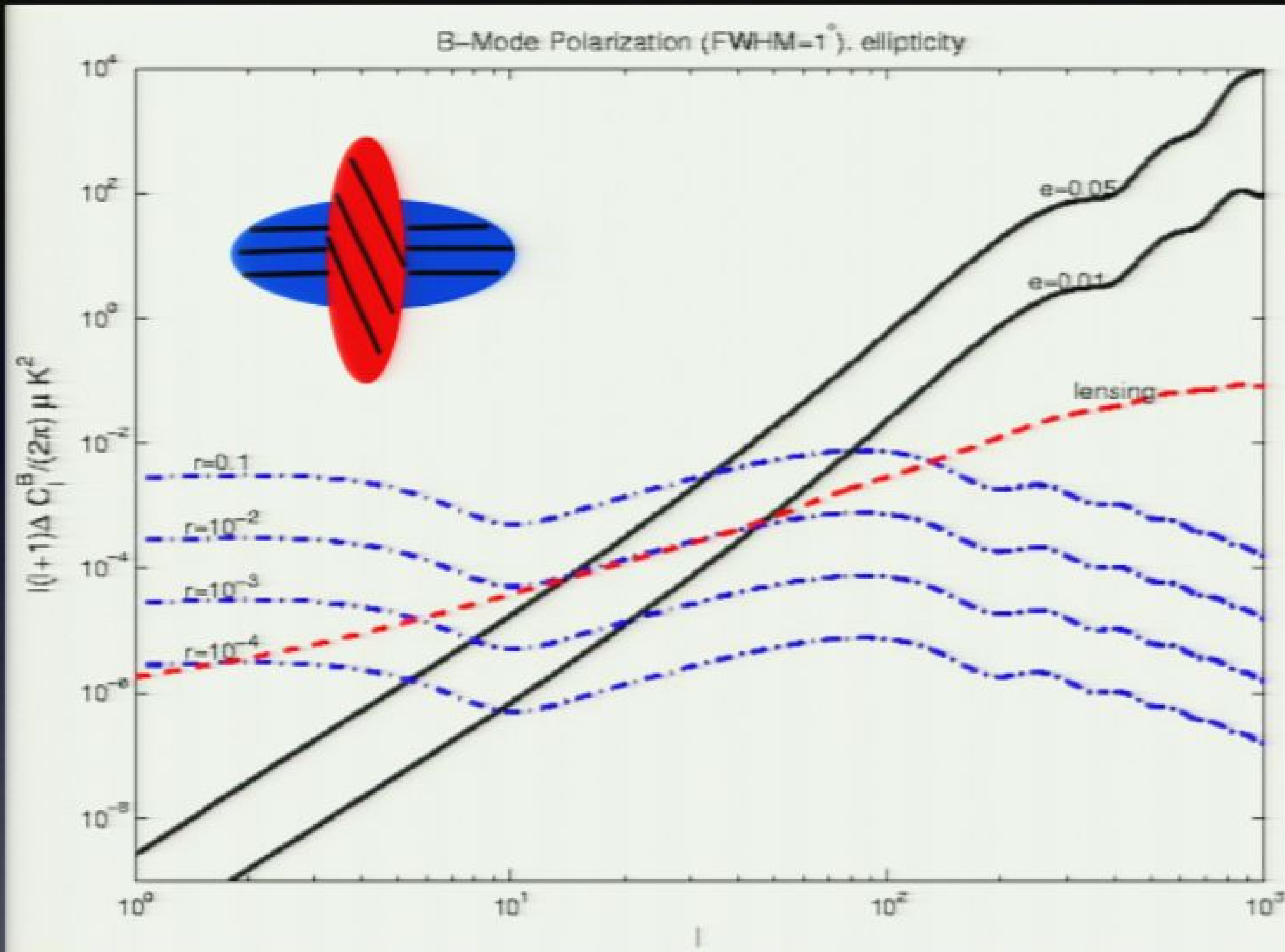


$$Q \propto \frac{\partial^2 T}{\partial x^2} - \frac{\partial^2 T}{\partial y^2} = \text{Diff. ellipticity}$$

$$\left\langle \frac{\partial^2 T}{\partial \theta^2} \right\rangle \approx 0.1 \mu K / arc\,\min^2$$

BICEP: Differential ellipticity is well understood

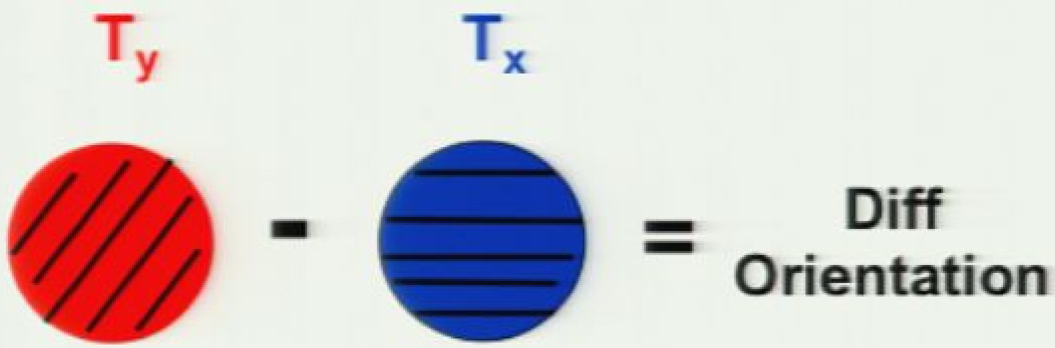
B-mode Differential Ellipticity (Inst. Polarization)



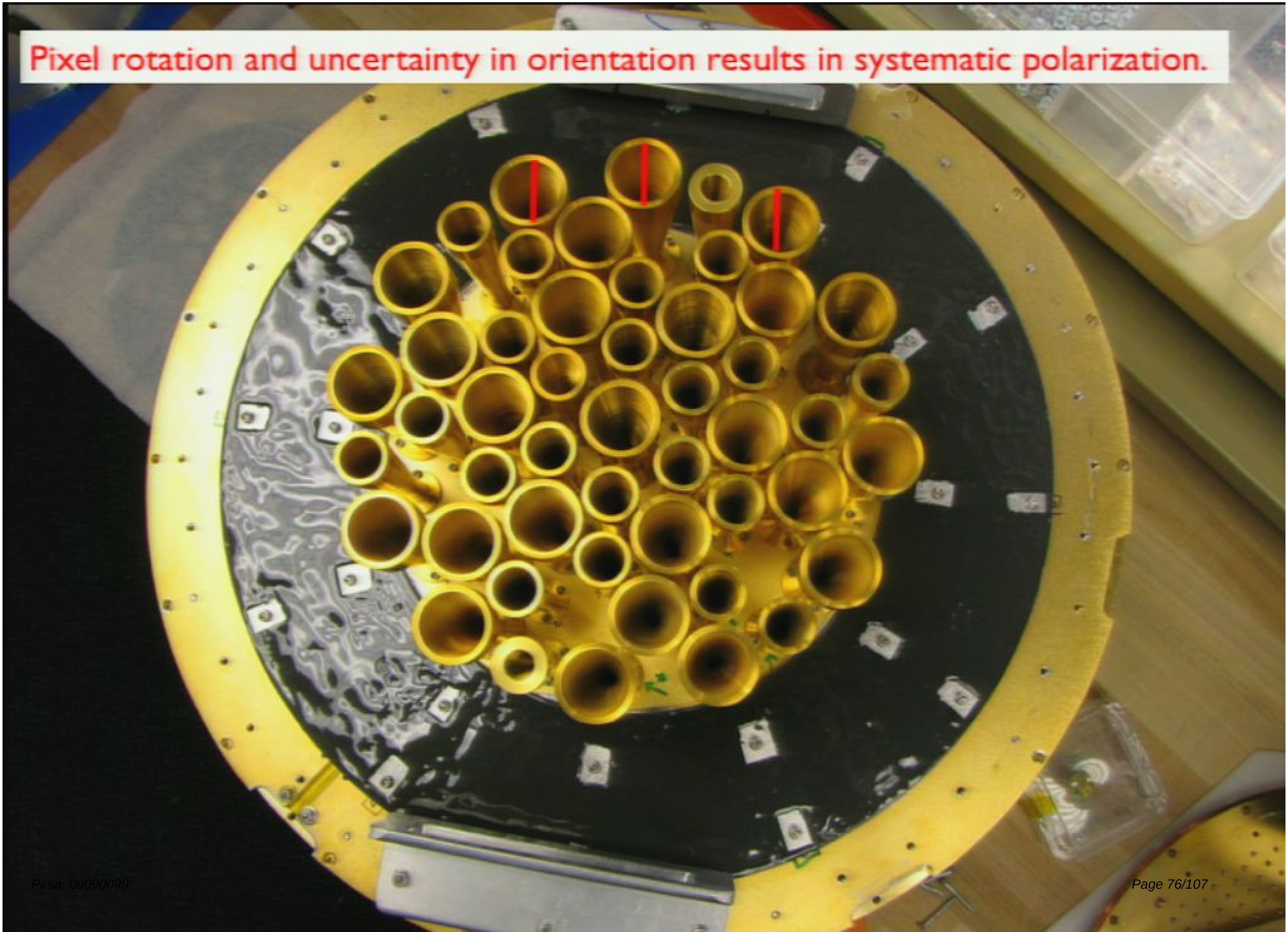
Differential Ellipticity effect is **not** reducible.

As shown here, would produce *both* E & B modes.

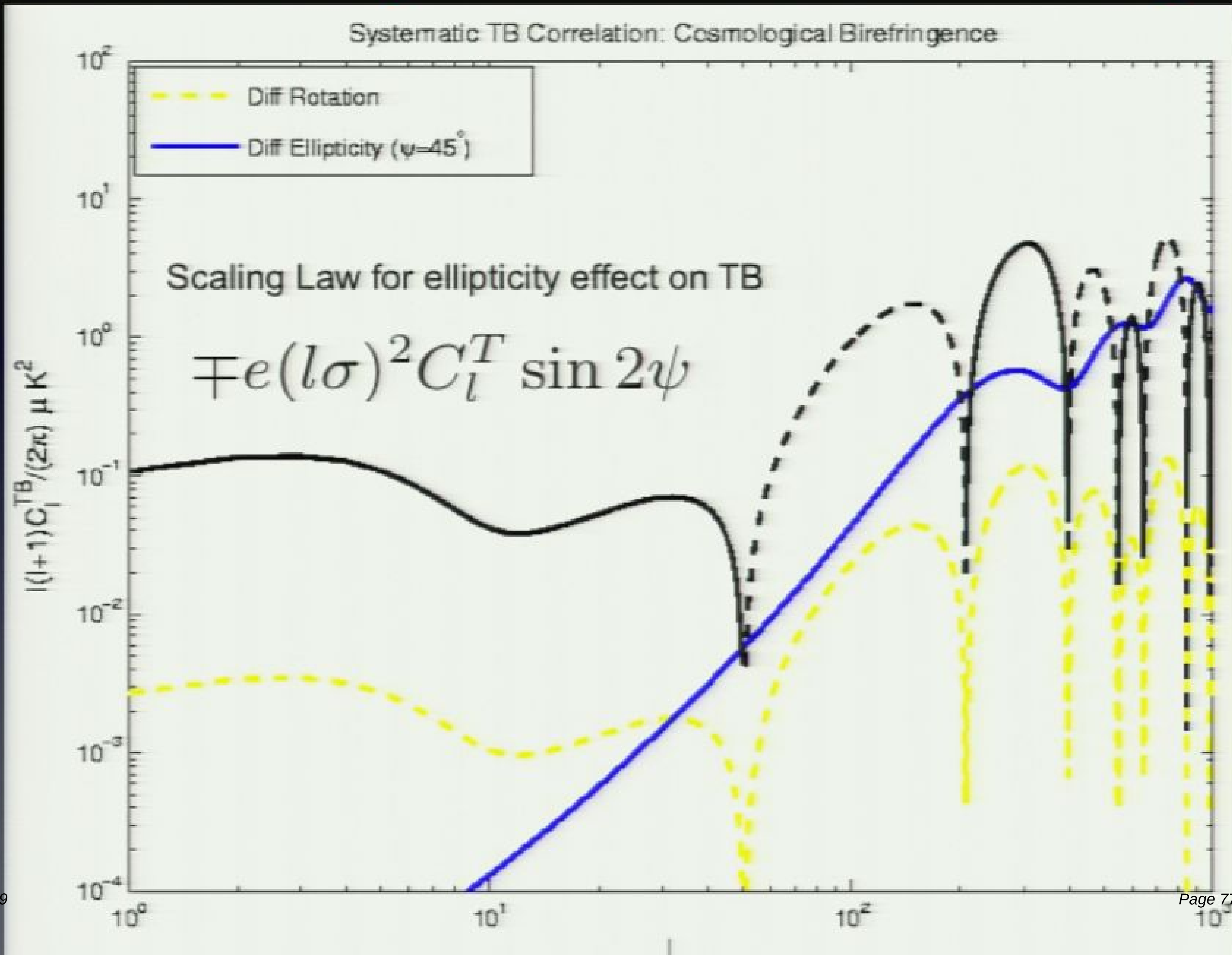
Reducible Beam Systematic
Differential Orientation (De-Polarization)



Pixel rotation and uncertainty in orientation results in systematic polarization.



Systematics Impact on Cosmic Birefringence:



Systematic Spectra : Scaling laws

Ellipticity Effects

TB scales as: $\mp e(l\sigma)^2 C_l^T \sin 2\psi$

EB scales as: $\pm e^2(l\sigma)^4 C_l^T \sin 2\psi \cos 2\psi$

Rotation Effect

TB scales as: $C_\ell^{\mathrm{TE}}\ \varepsilon$

EB scales as: $\frac{1}{2}(C_\ell^{\mathrm{EE}} - C_\ell^{\mathrm{BB}})\,\varepsilon$

Back to Xia et al. Claims

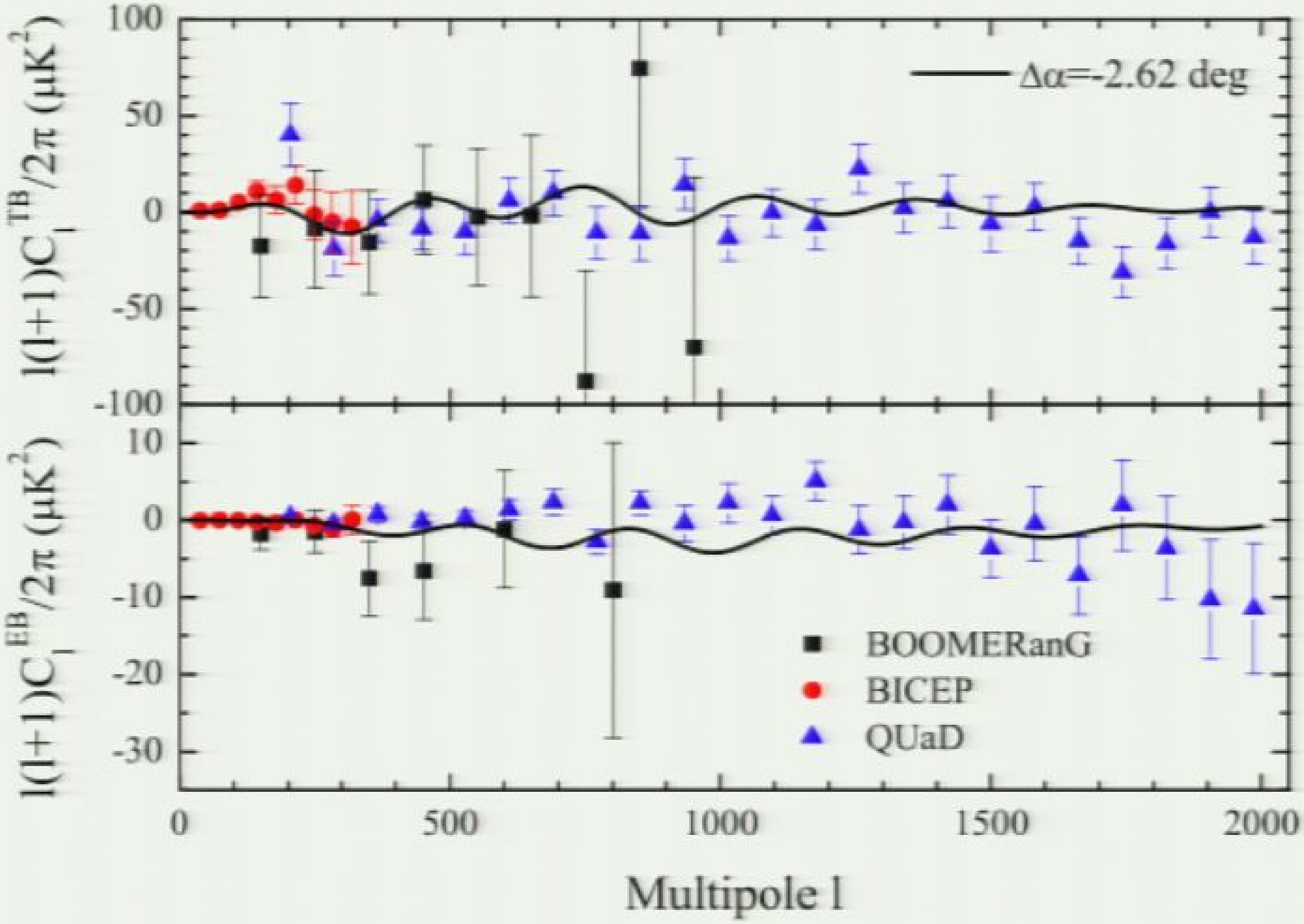


FIG. 1: The binned TB and EB spectra measured by the small-scale CMB experiments of BOOMERanG (black squares), BICEP (red circles) and QUaD (blue triangles). The black solid curves show the theoretical prediction of a model

Xia et al.

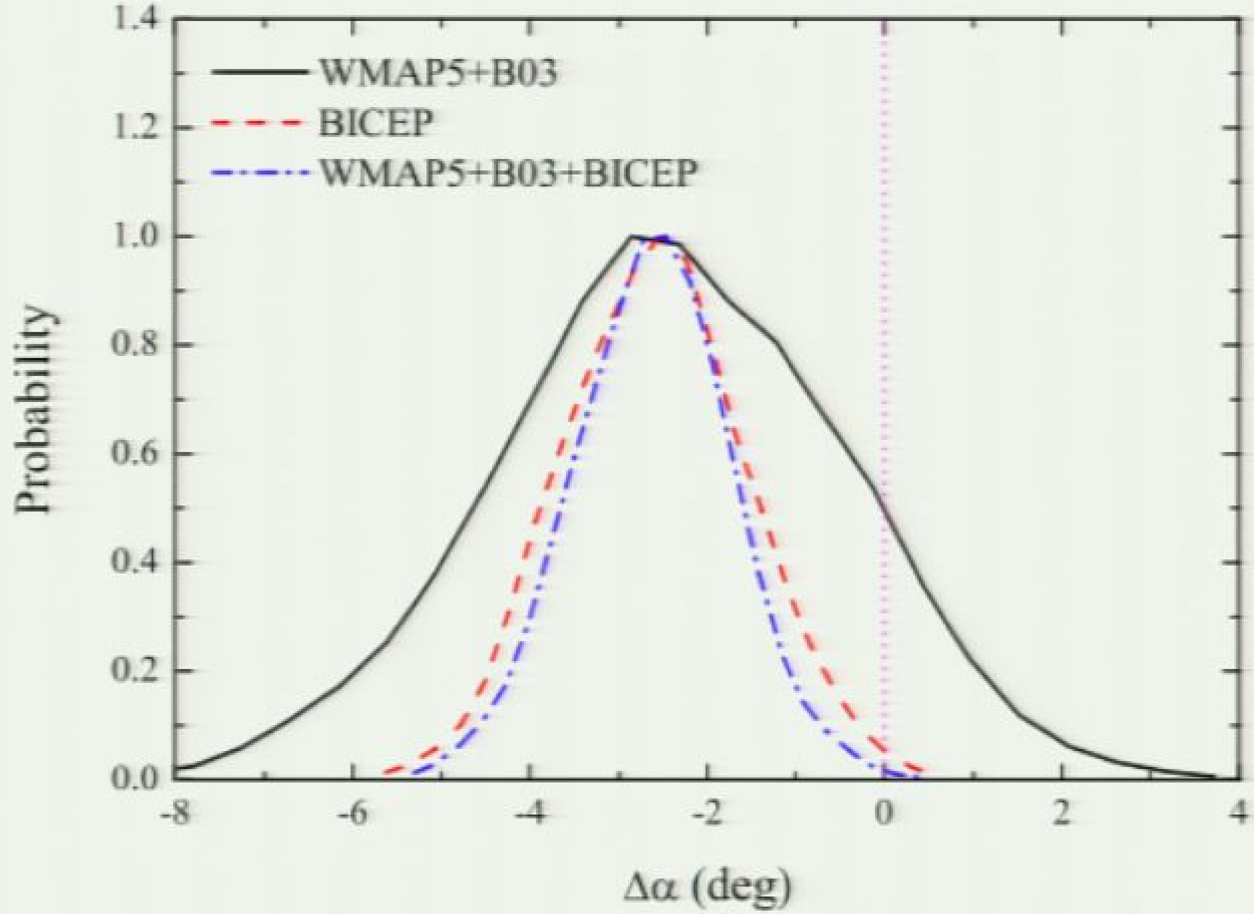
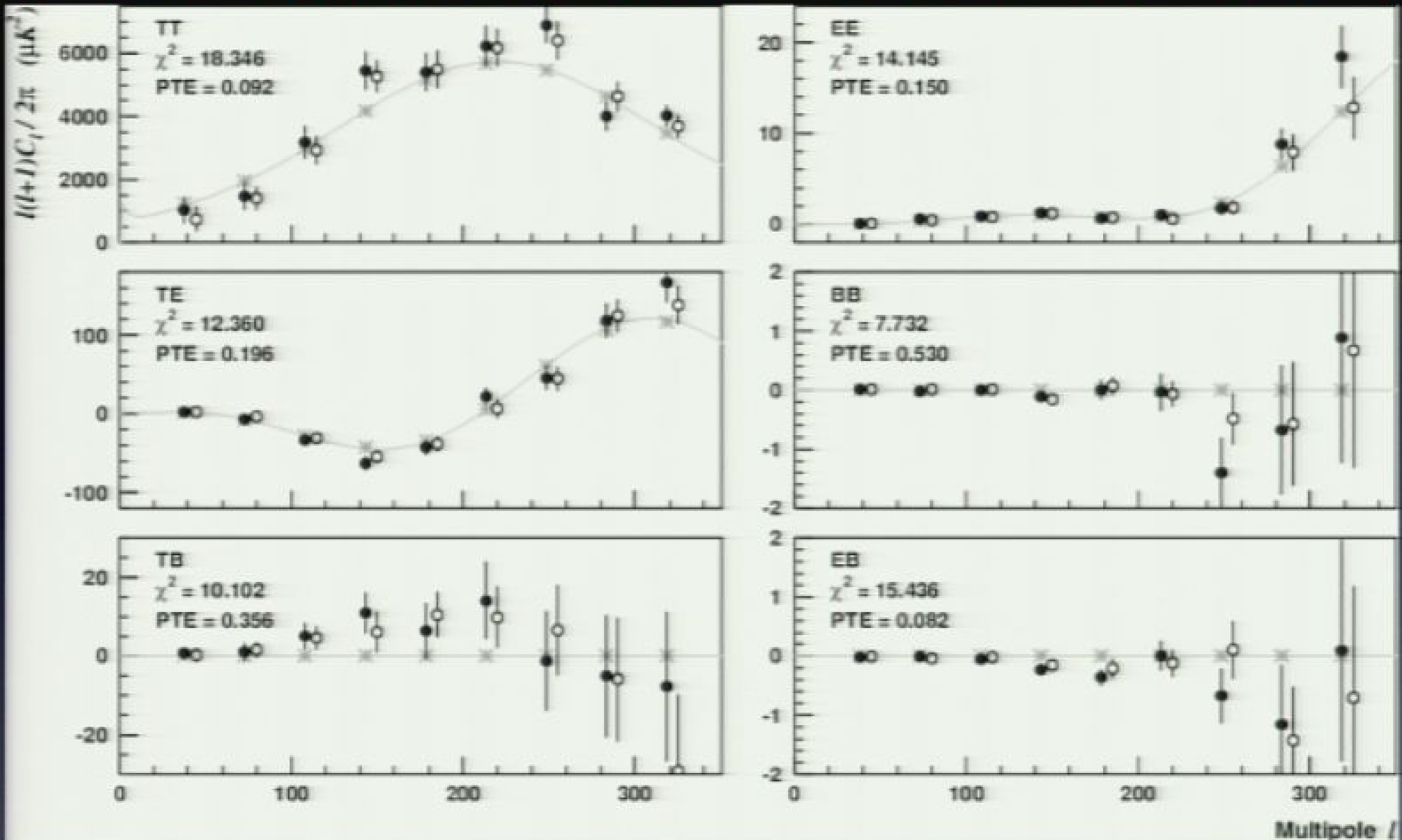


FIG. 2: One-dimensional posterior distributions of the rotation angle derived from various data combinations. The dotted vertical line illustrates the unrotated case ($\Delta\alpha = 0$) to guide eyes.

BICEP vs. Standard model: TB=EB=0



- PTE on EB is low suggesting systematics playing a role?
- PTE on TB is large; consistent with standard model.
- Use the combination of TB and EB PTE to isolate the systematic effect vs. the 'real effect'

Notes

- In general, one prefers to measure a cross-correlation rather than an auto-correlation as this minimizes several forms of noise bias.
- For example, in BICEP our tightest BB constraints come from cross-correlating $\langle C_{L,100GHz}\ C_{L,150\ GHz}\rangle$ not from auto-correlating $\langle C_{L,150GHz}\ C_{L,150\ GHz}\rangle$.
- First, we look at BICEP power spectra used by Xia et al, ignoring systematics - is there evidence for non-zero TB & EB?

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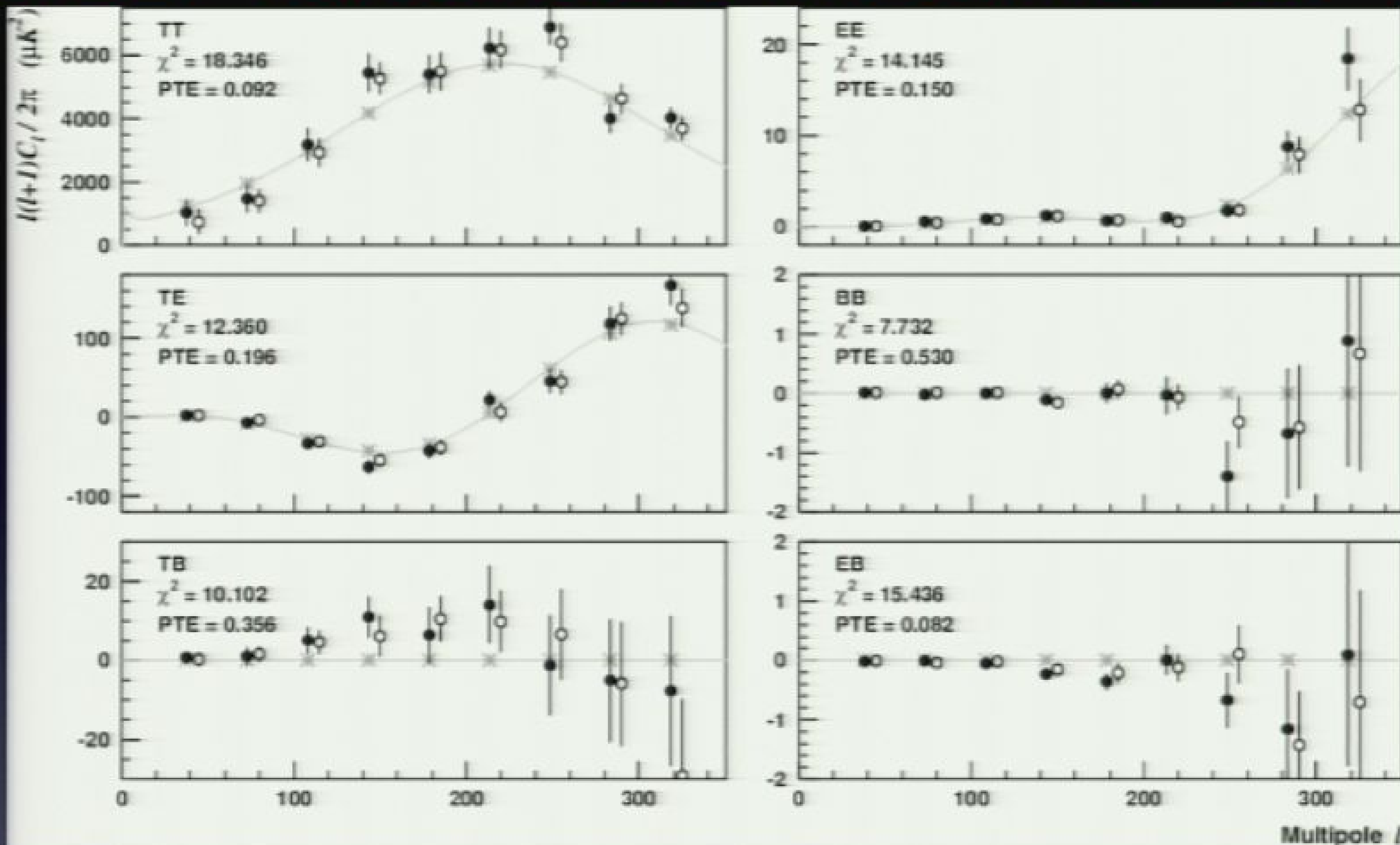

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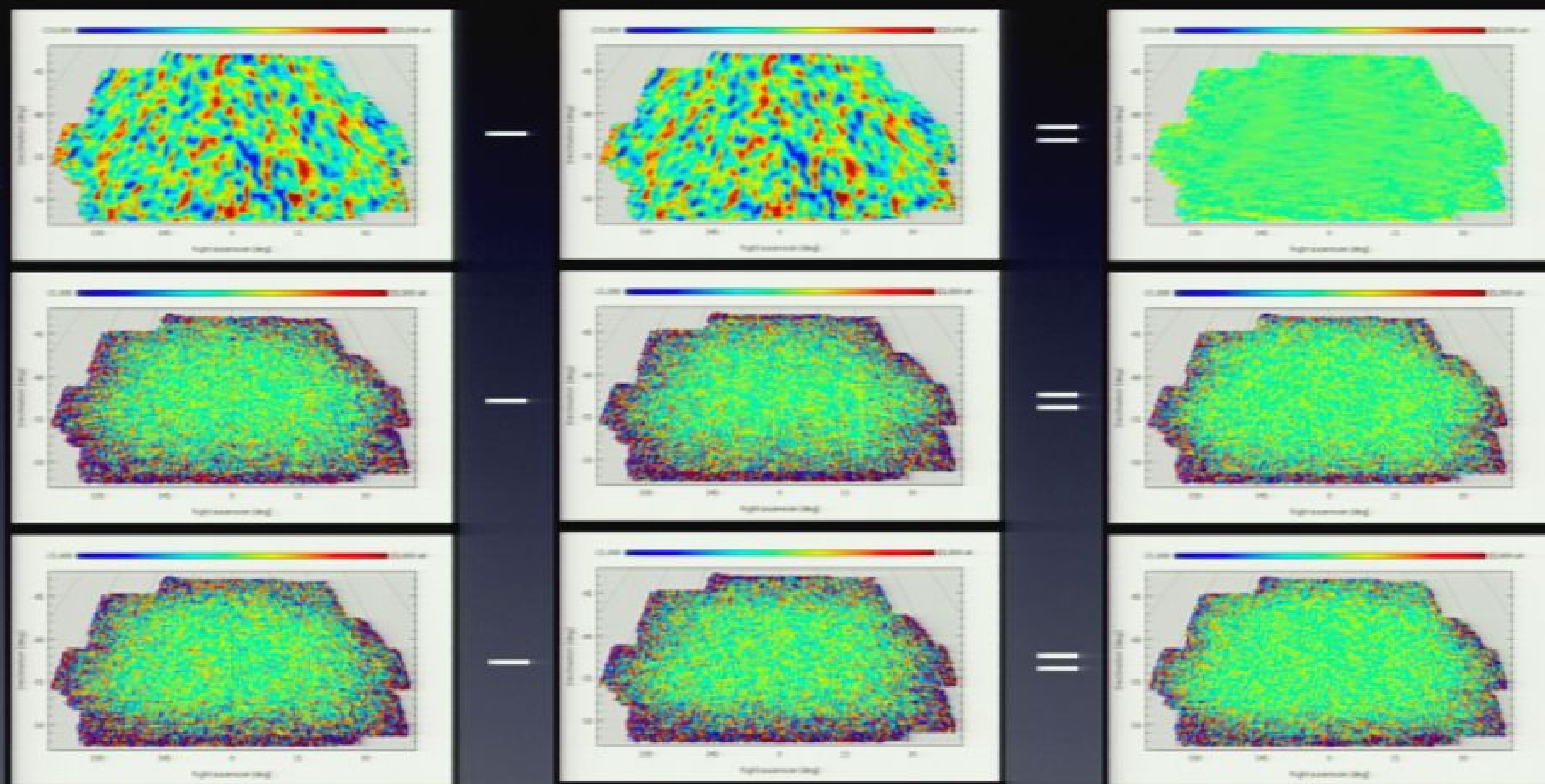
Jackknives and consistency tests



Diff spectra should be close to zero

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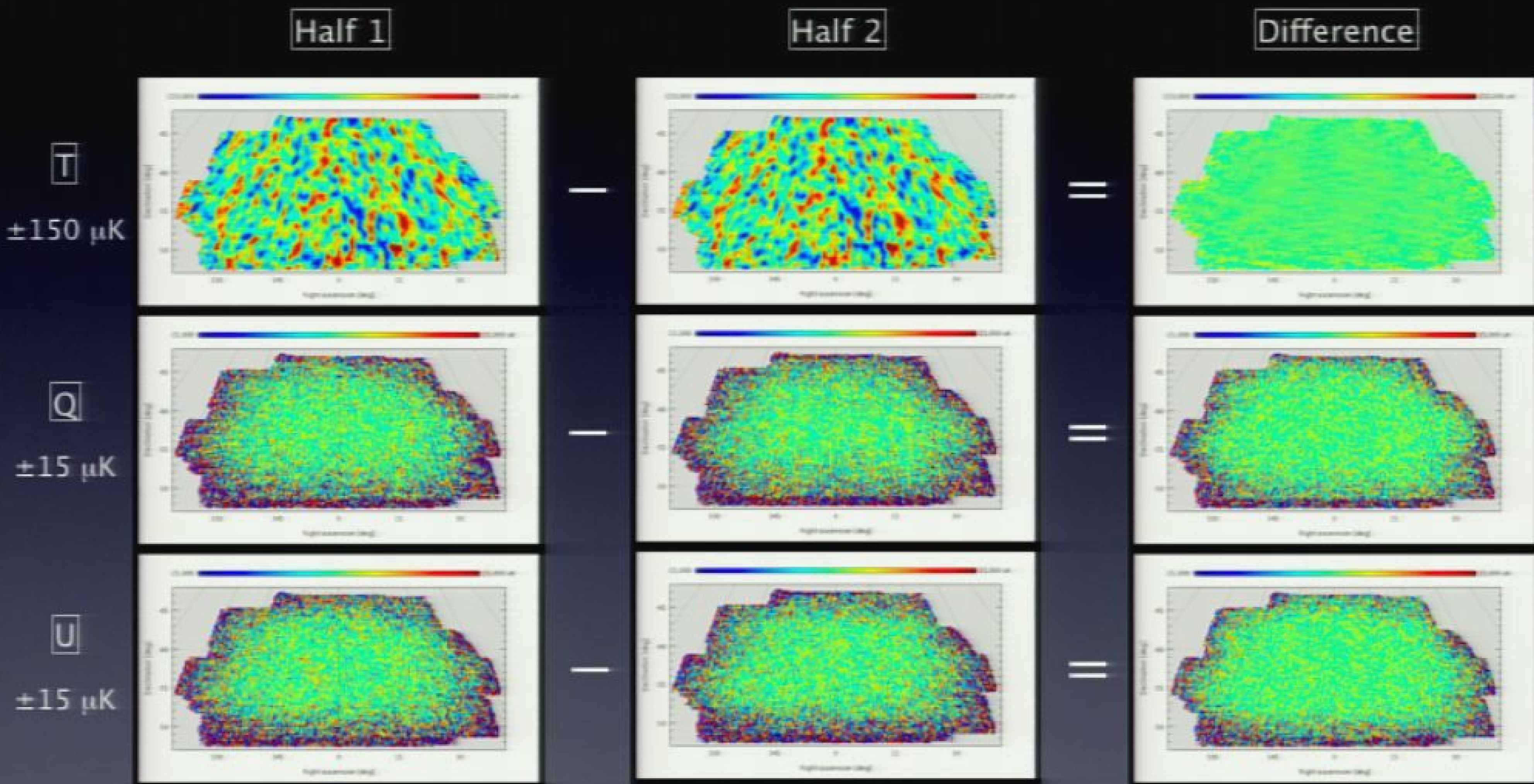
Jackknives and consistency tests

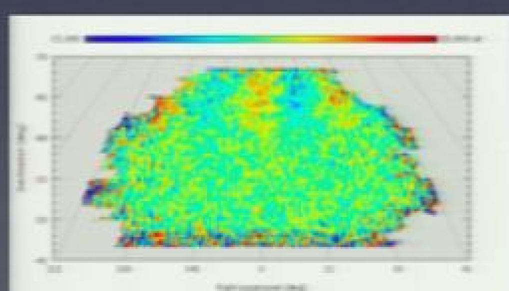


Diff spectra should be close to zero

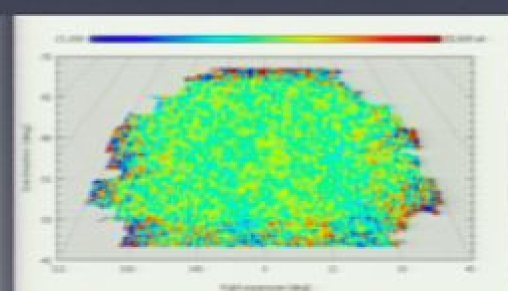
BICEP's jackknives

Jackknife type	What it tells you
0) Data vs. LCDM	Is LCDM a good model?
1) Left vs. right scan direction	Transfer function errors
2) Elevation coverage order	Ground pickup
3) Boresight angle pairs	Everything.
4) Focal plane Q/U	Instrumental polarization
5) 8-day temporal split	Not much (this is a "nice" jackknife)
6) 2006 vs. 2007 observing seasons	Anything different between the two years
7) 100 vs. 150 GHz	Foreground contamination

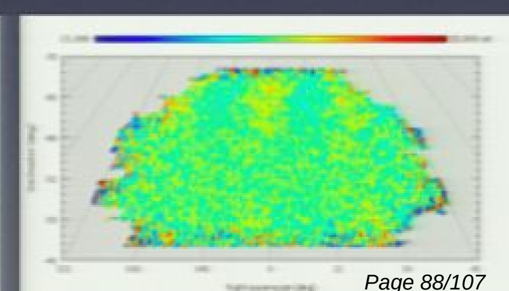
An example (extreme) jackknife failure



Half 1



Half 2



Difference

Spectra with statistical errors used to obtain error bars

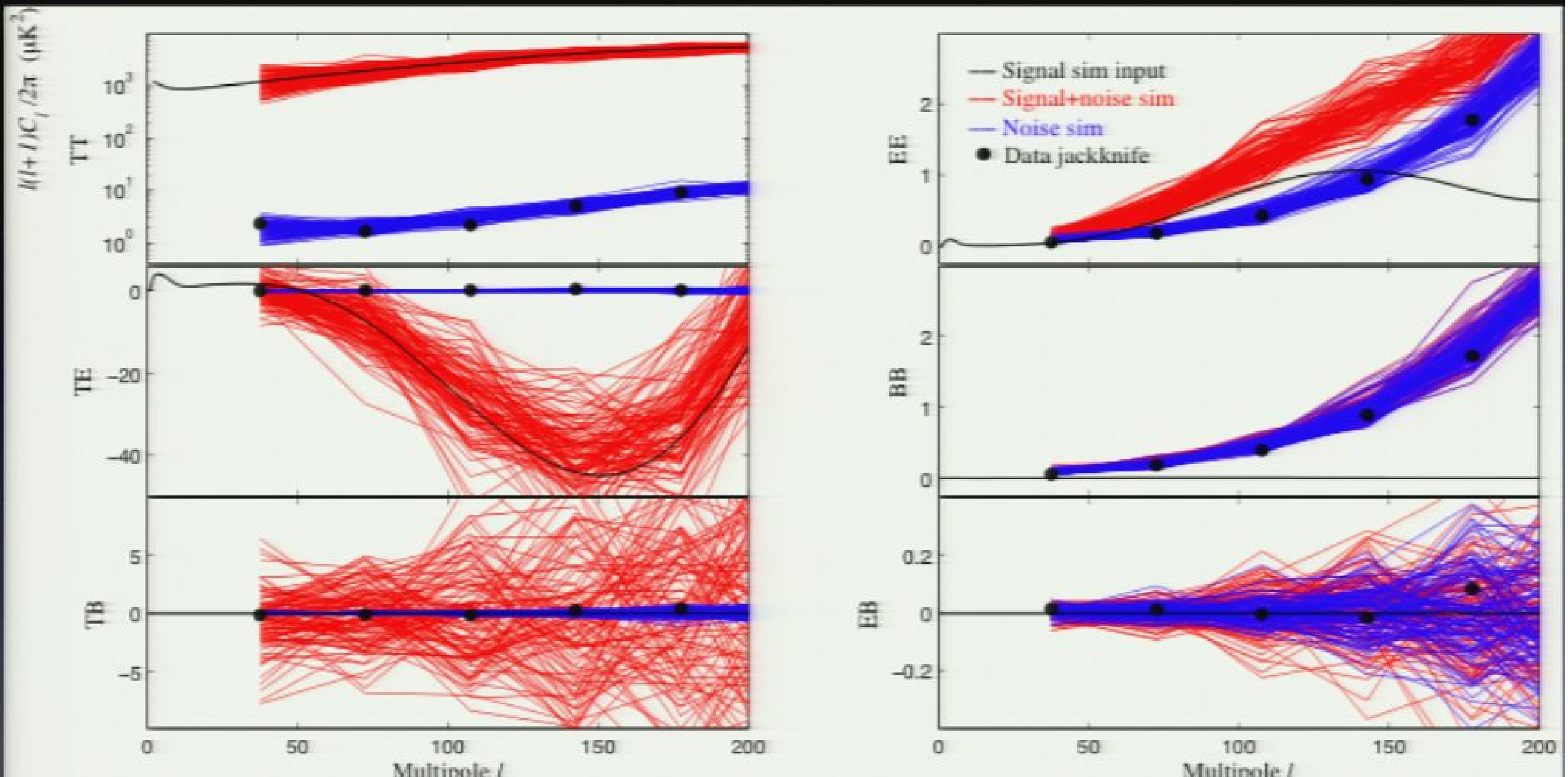
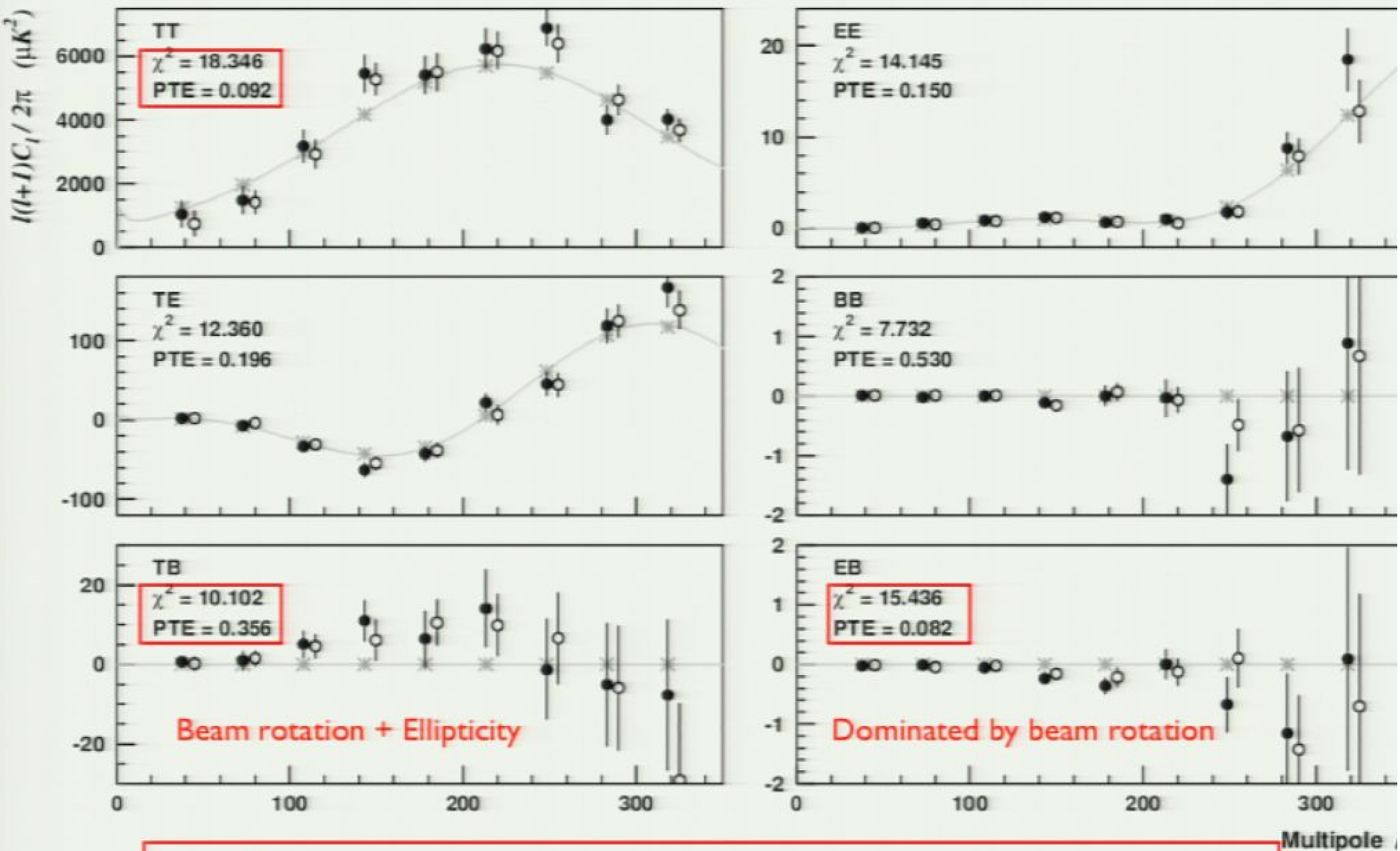


FIG. 22.— 150 GHz power spectra of 100 realizations of simulated signal+noise and noise only, compared to the scan-direction jackknife spectra from the actual data. The distributions of simulated noise spectra are consistent with the data jackknife spectra, which are expected to be signal-free and a good representation of noise in the data. The CMB signal simulation uses the input spectra shown. Error bars in the final spectra are determined by thee scatter in the signal+noise spectra, which is noise-dominated for *BB* and *EB* and largely cosmic variance limited for other spectra.

Final spectra at 150 GHz

Final Spectra, Systematics not subtracted!



χ^2 for Standard Model, i.e. with $\alpha = 0$

Issues with BICEP's TB & EB data

- Systematics in real space can't be ignored.
- EB from rotation, ε ,TB from diff ellipticity
- For T data in TB BICEP used :

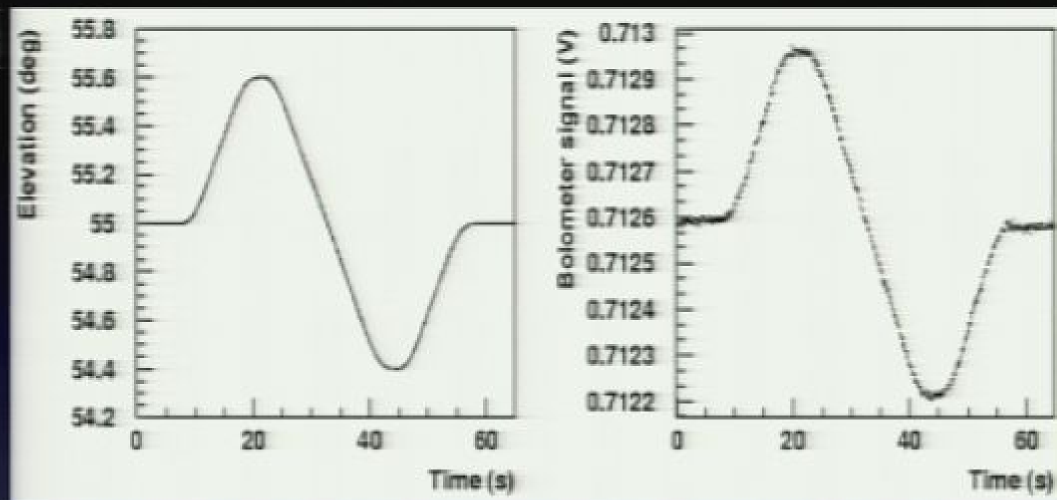
<WMAP T x BICEP B>

Calibration checklist: Crucial for T

Relative detector gains

Atmospheric signal from "elevation nods"

Fit PSB timestreams to airmass model, csc(el)



Median common mode rejection after gain correction 99.6%

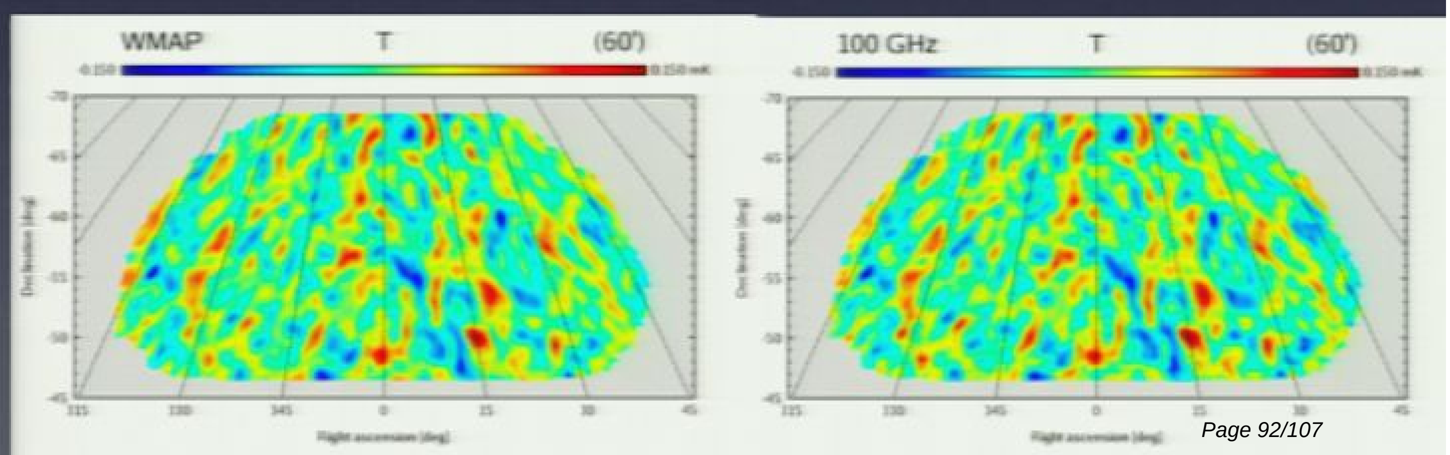
Absolute V/K scaling

Cross-correlate WMAP and BICEP temperature maps to get V/K factor

(also use CMB to derive pixel centroids!)

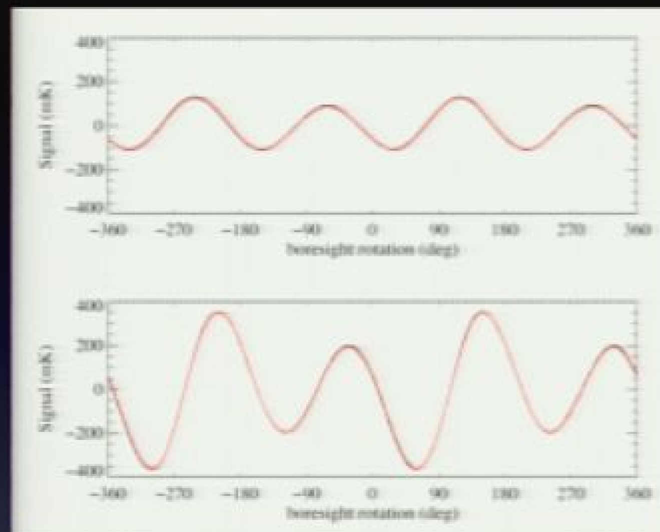
WMAP

BICEP



Calibration checklist: Crucial for E & B

Polarization orientation angles



Angles repeatable within 0.3°

Absolute orientation uncertainty: 0.7°

Calibration checklist: Crucial for E & B

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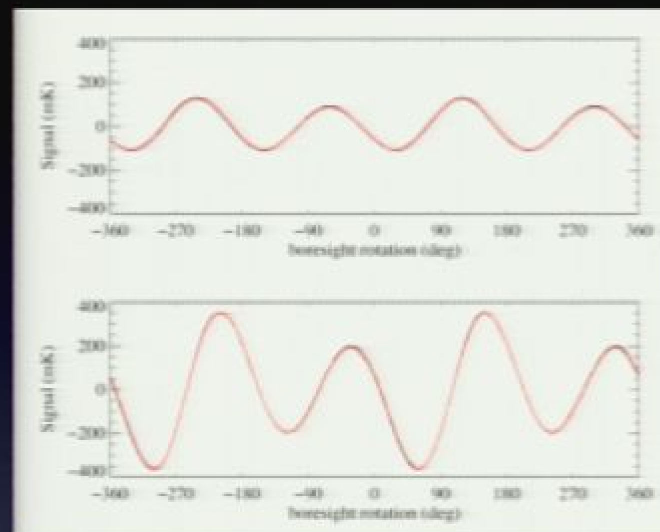

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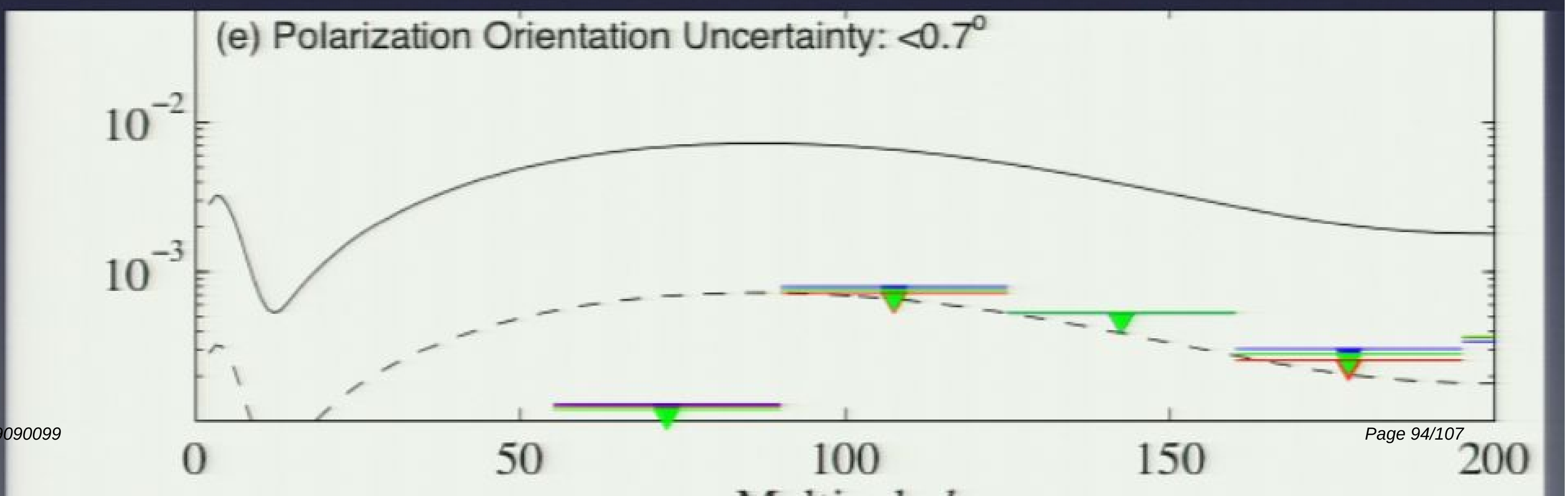
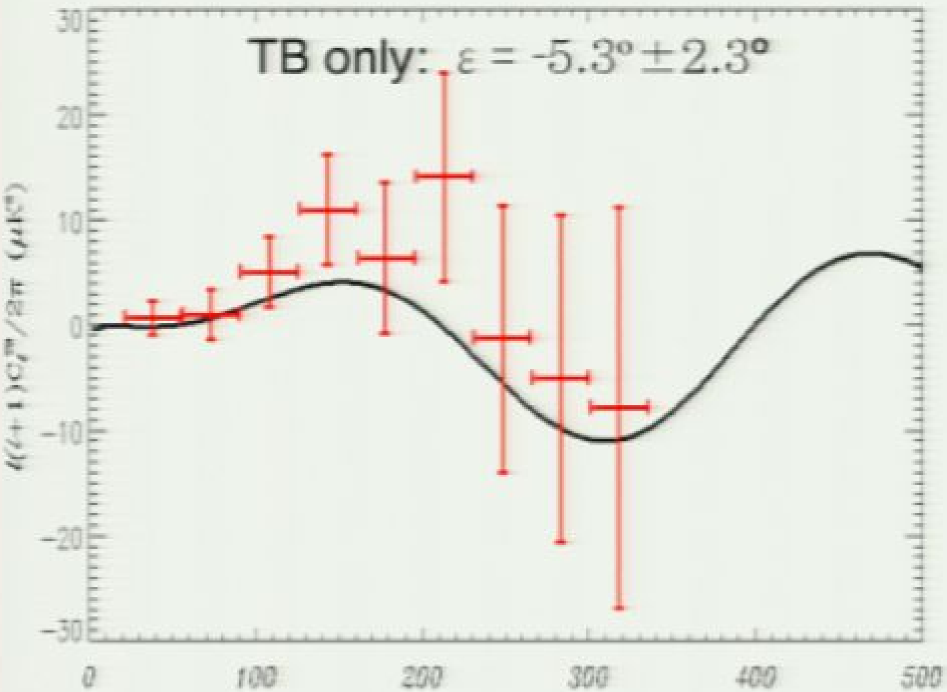
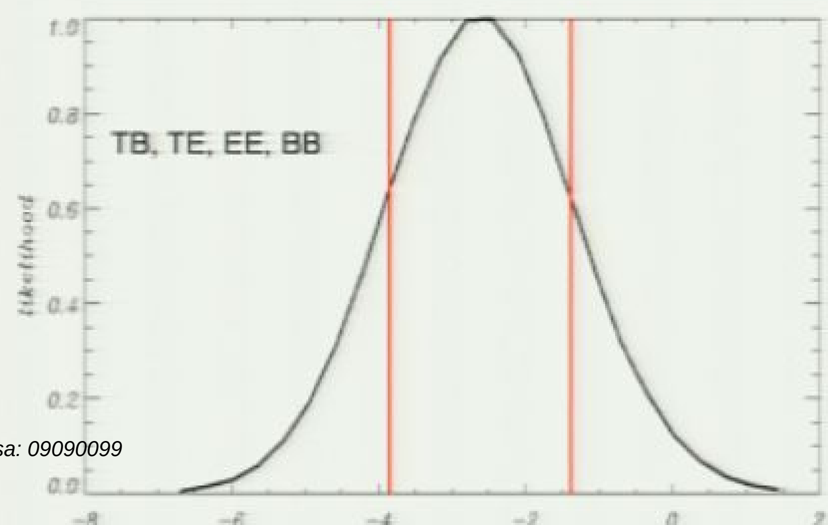


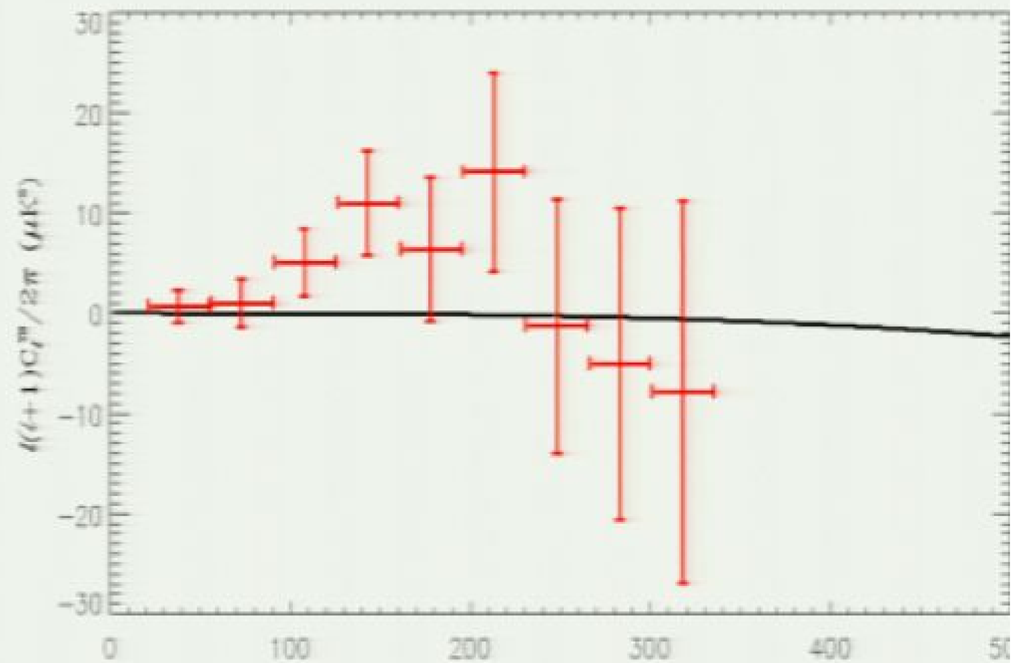
BICEP Data & Best Fit Systematics Spectra:

Differential Rotation

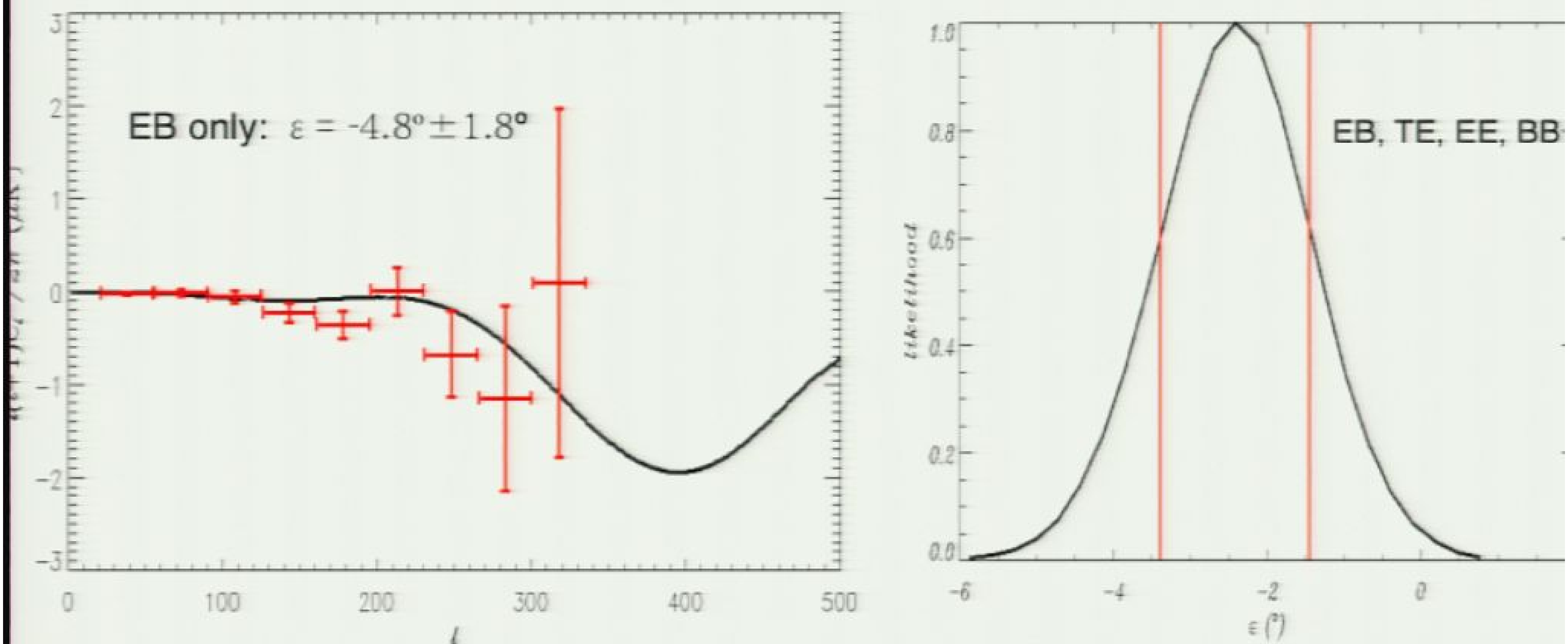




Differential Ellipticity

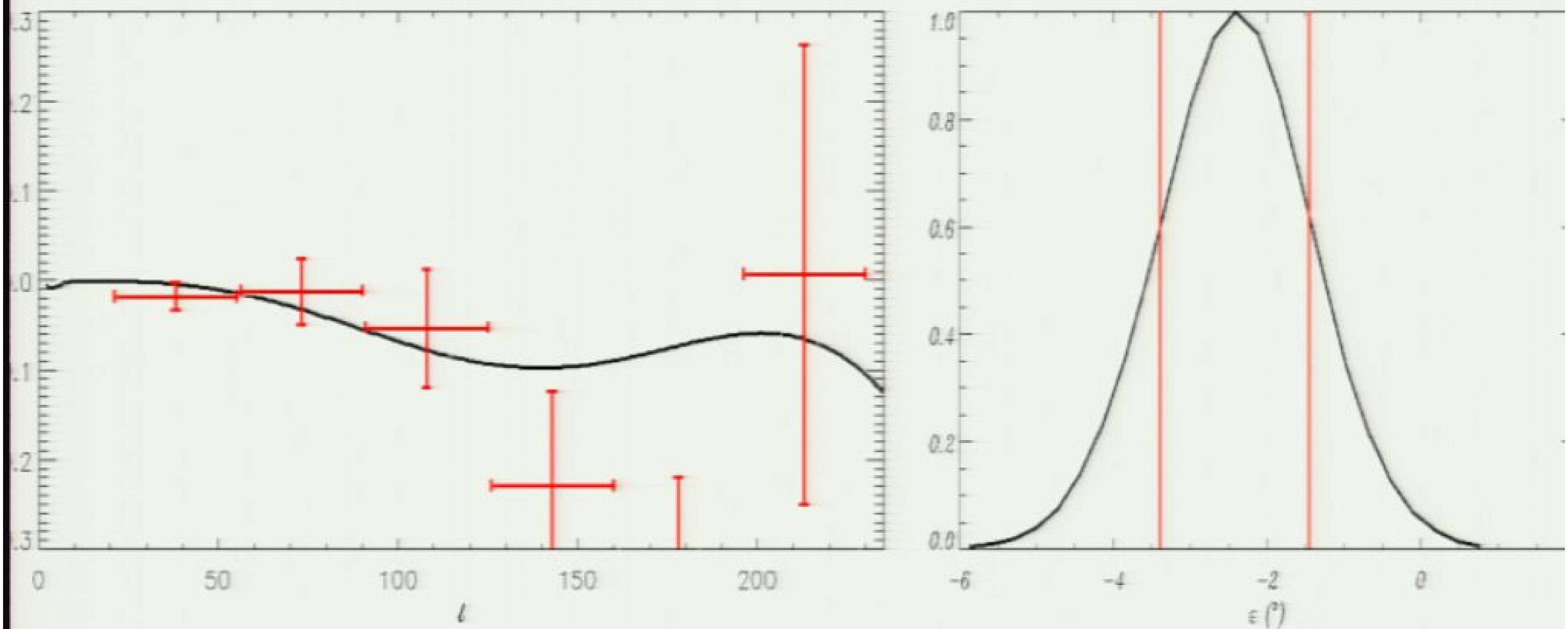


BICEP EB From Differential Rotation



Ellipticity constraint comes from TB

BICEP EB From Differential Rotation



Ellipticity constraint comes from TB

Other sources of tension for Xia et al.

➡ QUaD

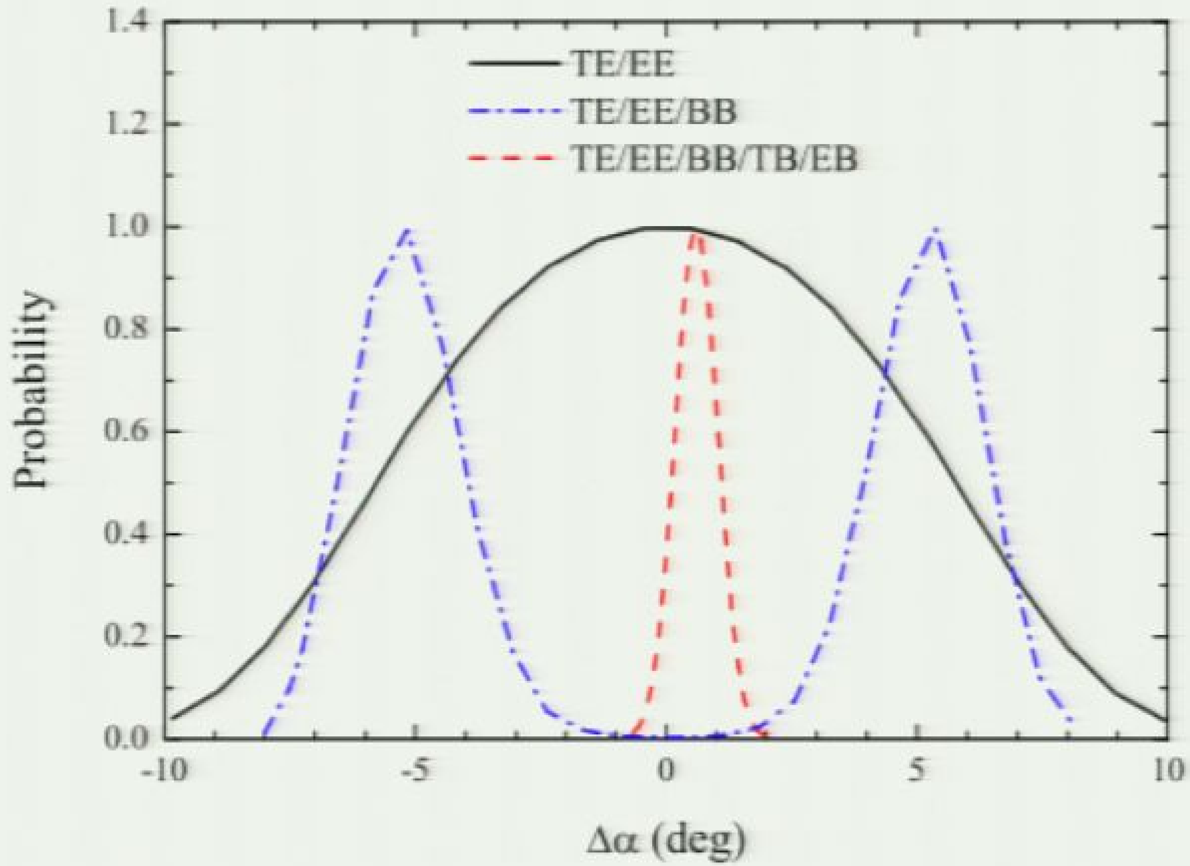


FIG. 4: The one-dimensional posterior distributions of the rotation angle derived from the QUaD polarization data.

Other sources of tension for Xia et al.

➡ WMAP

Komatsu et al. 2008

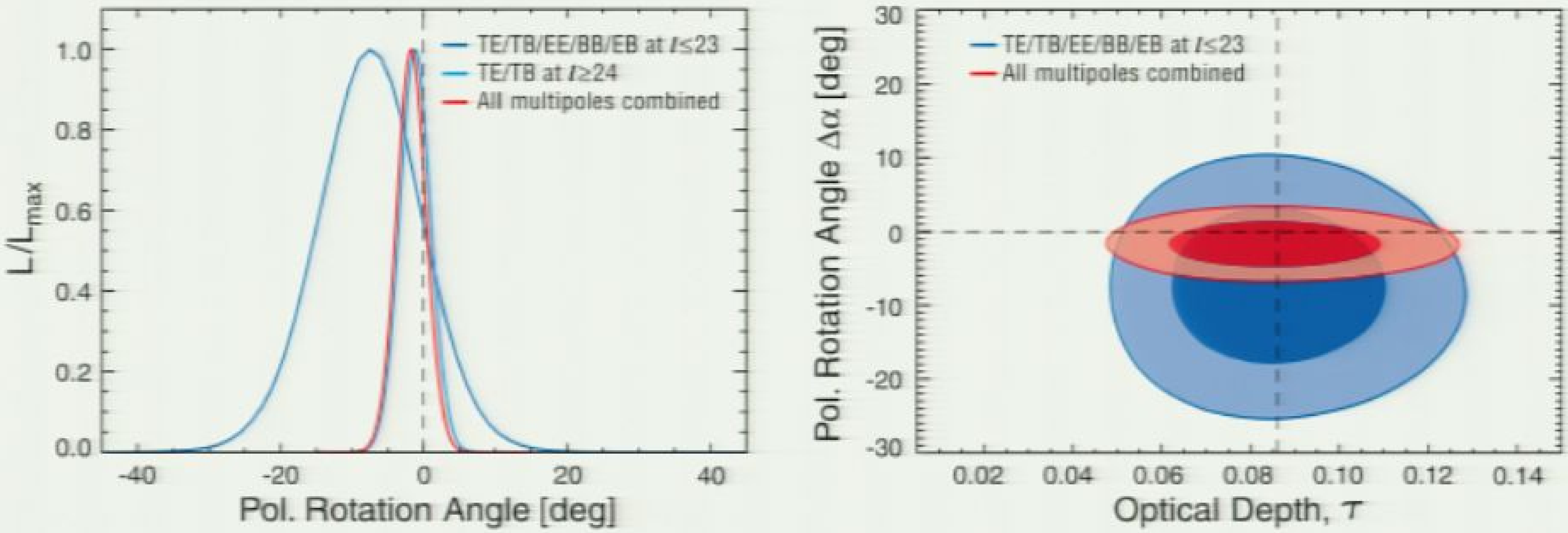


FIG. 10.— Constraint on the polarization rotation angle, $\Delta\alpha$, due to a parity-violating interaction that rotates the polarization angle of CMB (§ 4.3). We have used the polarization spectra (TE/TB/EE/BB/EB at $l \le 23$, and TE/TB at $l \ge 24$), and did not use the TT power spectrum. (*Left*) One-dimensional marginalized constraint on $\Delta\alpha$ in units of degrees. The dark blue, light blue, and red curves show the limits from the low-l ($2 \le l \le 23$), high-l ($24 \le l \le 450$), and combined ($2 \le l \le 450$) analysis of the polarization data, respectively. (*Right*) Joint two-dimensional marginalized constraint on τ and $\Delta\alpha$ (68% and 95% CL). The bigger contours are from the low-l analysis, while the smaller ones are from the combined analysis. The vertical dotted line shows the best-fitting optical depth in the absence of parity violation ($\tau = 0.086$), whereas the horizontal dotted line shows $\Delta\alpha = 0$ to guide eyes.

Contaldi, Magueijo & Smolin (2008)

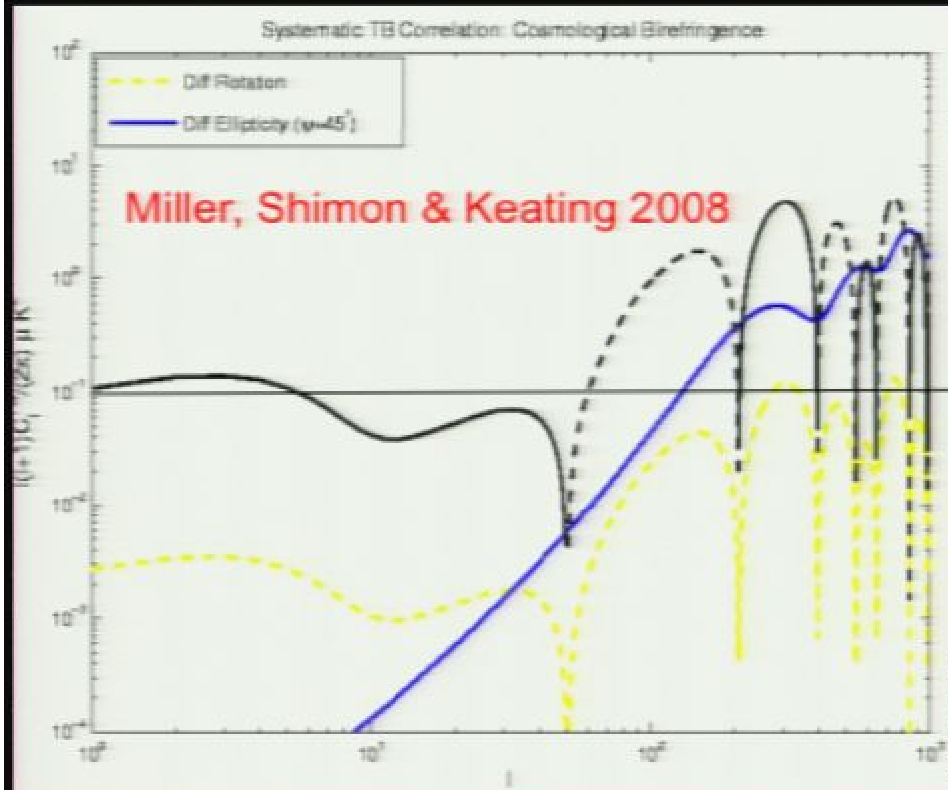
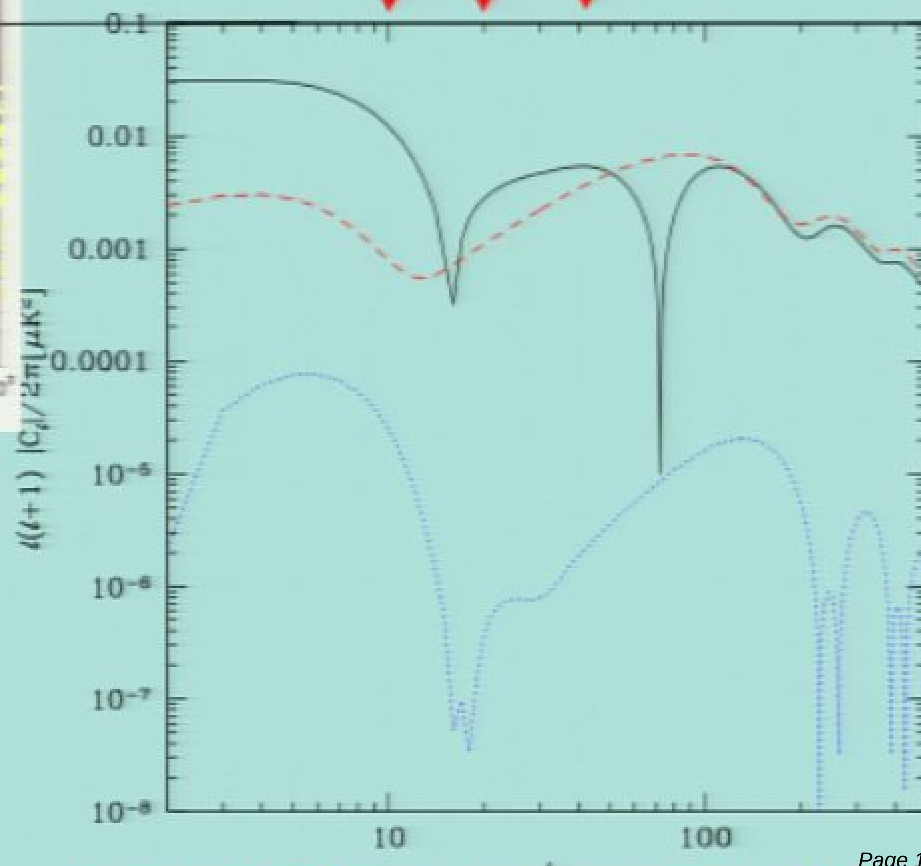


FIG. 1: Tensor contribution to the TB (solid, black), BI (dashed, red), and EB (dotted, blue) spectra for a standar ΛCDM model with tensor to scalar ratio $r = 0.1$ and chiralit parameter $\gamma = 10$.

BICEP Initial data release



Systematics should be manageable for TB!

Conclusions

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- See you tomorrow for a discussion of BICEP's Inflationary