Title: Experimental Quantum Cosmology with the BICEP CMB Polarimeter

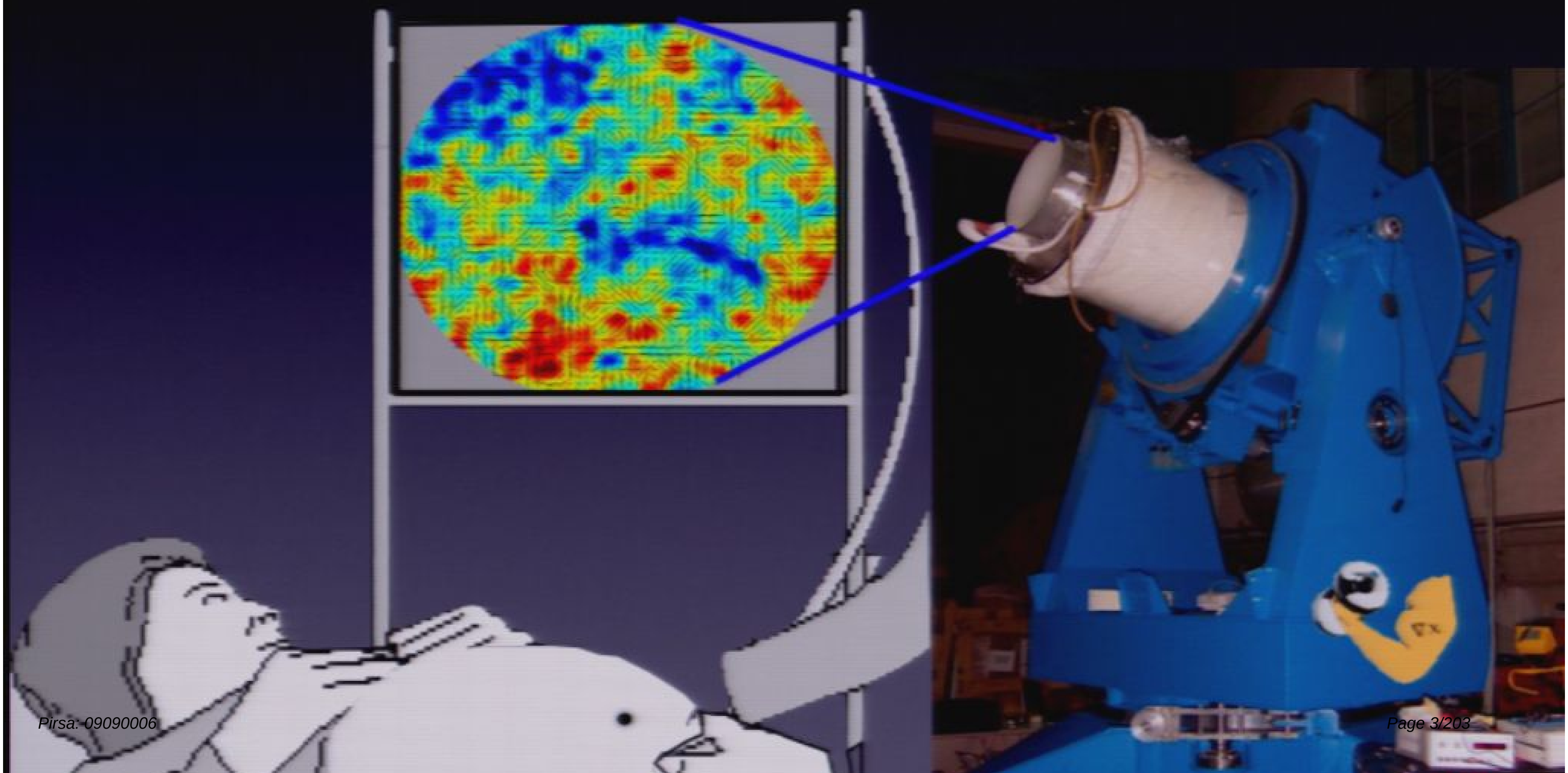
Date: Sep 23, 2009 02:00 PM

URL: http://pirsa.org/09090006

Abstract: The Background Imager of Cosmic Extragalactic Polarization (BICEP) experiment is the first polarimeter developed to measure the inflationary B-mode polarization of the CMB. During three seasons of observing at the South Pole, Antarctica beginning in 2006, BICEP mapped 2% of the sky chosen to be clean of polarized foreground emission, with sub-degree resolution. In this colloquium I will present initial results derived from a subset of the data acquired during the first two years of data and discuss the unique design features of BICEP which led to the first meaningful limits on the tensor-to-scalar ratio to come from B-mode polarization. Recently, Xia, Li & Zhang (2009) have claimed a detection of parity-violating "cosmic birefringence" effects using publicly available BICEP data. I will discuss polarimetric fidelity in the light of systematic errors and how such effects are particularly pernicious for probes of cosmic parity violation. I will conclude with a discussion demonstrating how BICEP, and its successor "BICEP2" will inform future measurements of the inflationary gravitational wave background and cosmic birefringence.


Experimental Quantum Cosmology with the BICEP CMB Polarimeter
Brian Keating
http://cosmology.ucsd.edu/

“The Birth Pangs of the Big Bang”



Outline

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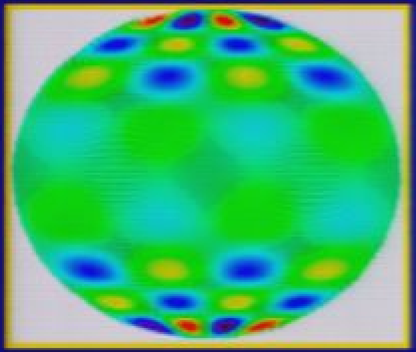
- **Brief Introduction to theory**



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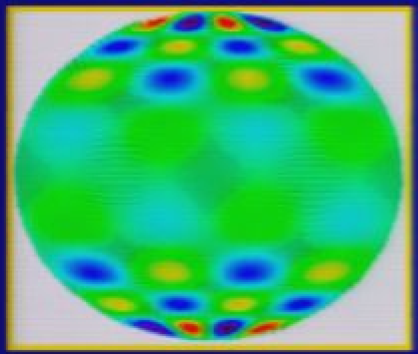

- **Details of the Instrument**

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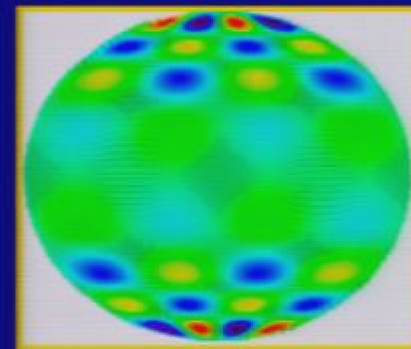
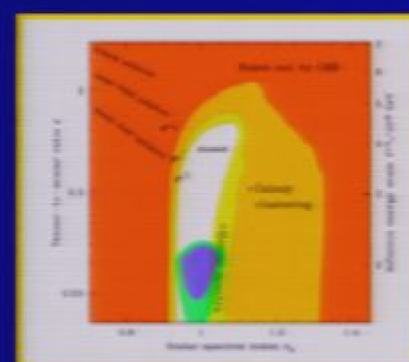
- Brief Introduction to theory



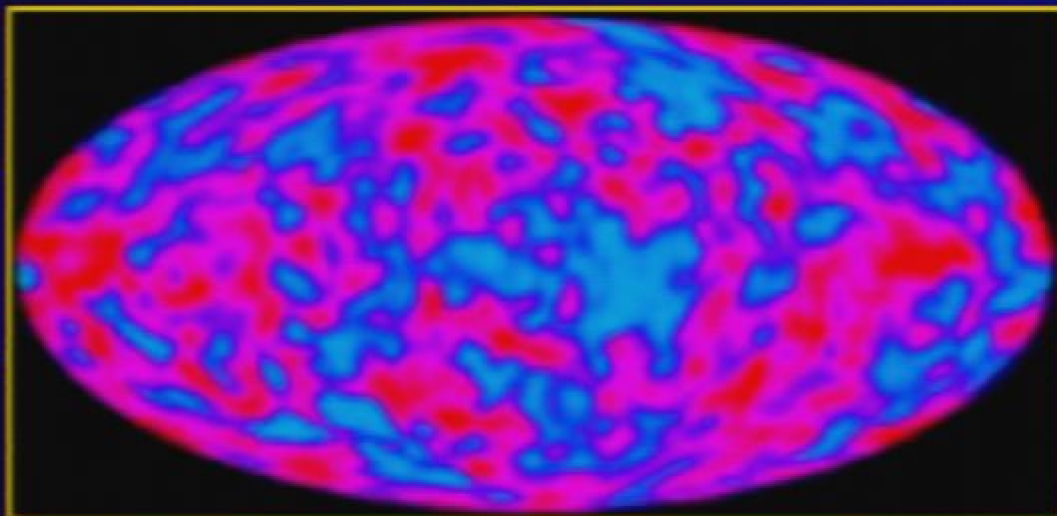
- Details of the Instrument

- Expected results



Inflation: Quantum Fluctuations in Space Time

Age:
10^{13} sec



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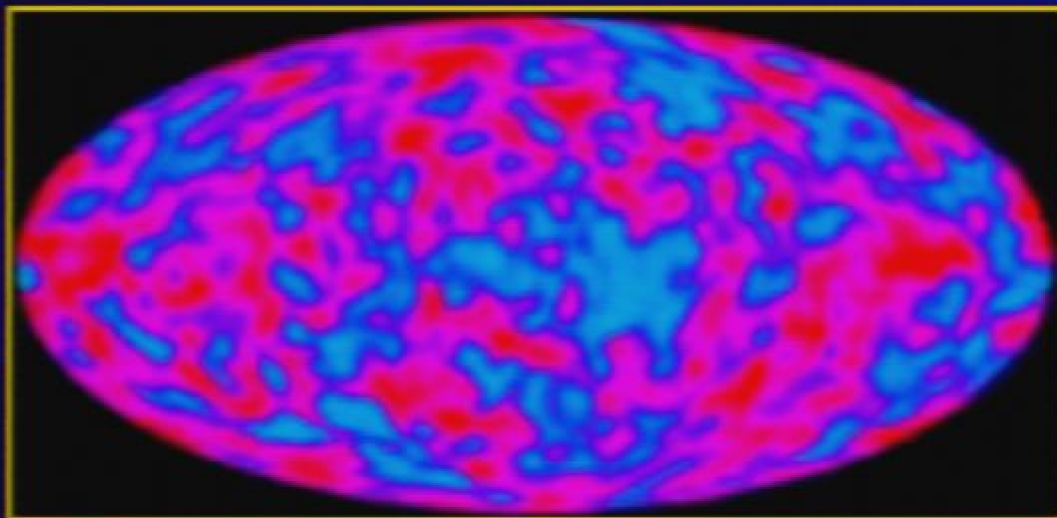

Age:
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Age:
10^{-36} sec

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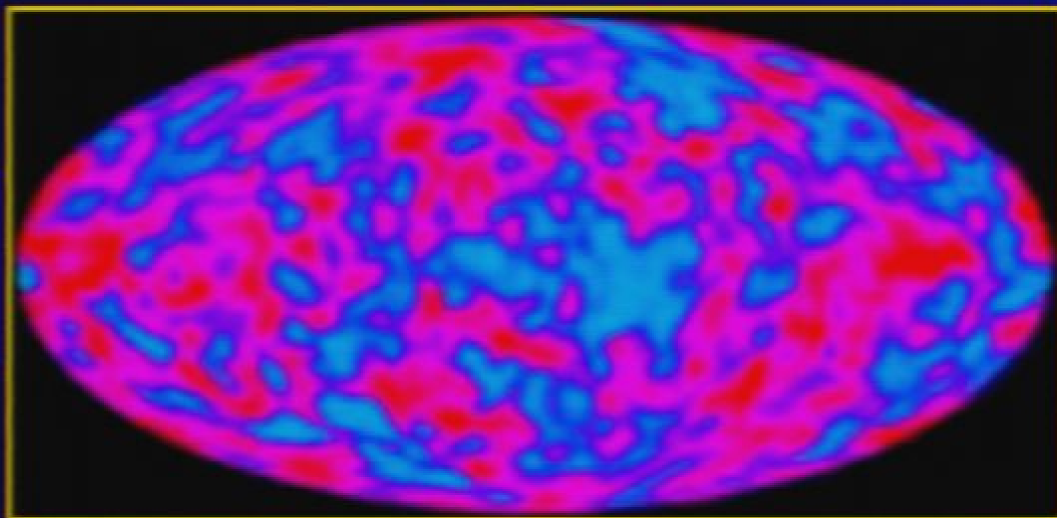

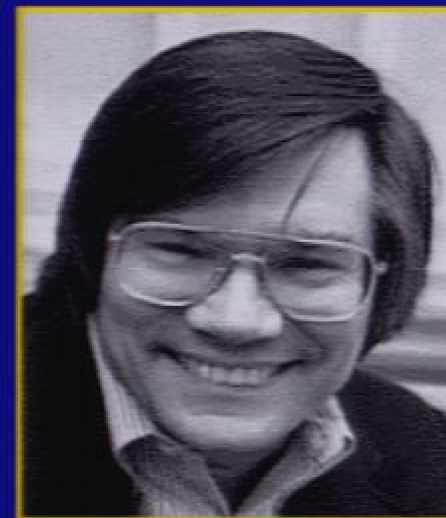

Age:
2×10^{9}
sec

Alan Guth Inflation 1981

Age:
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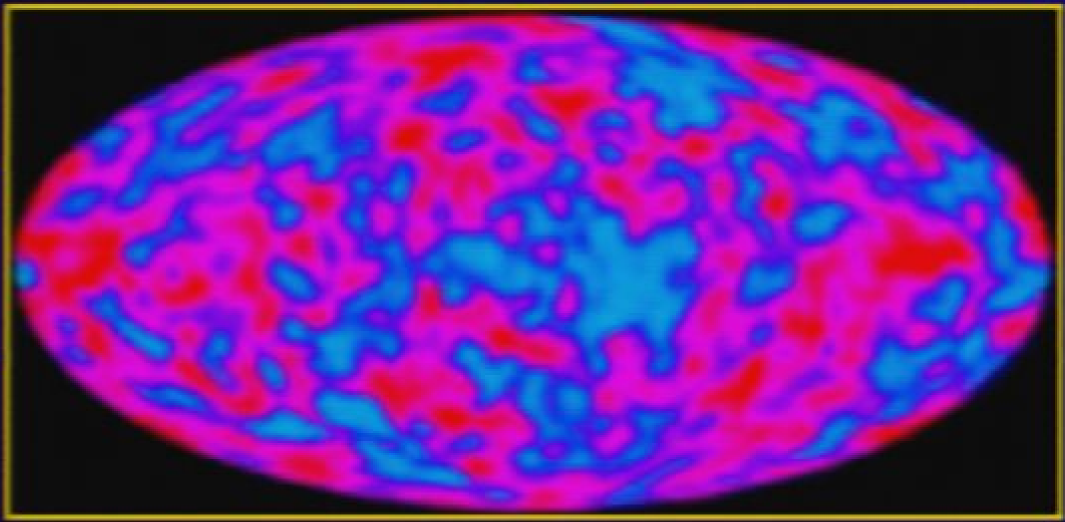

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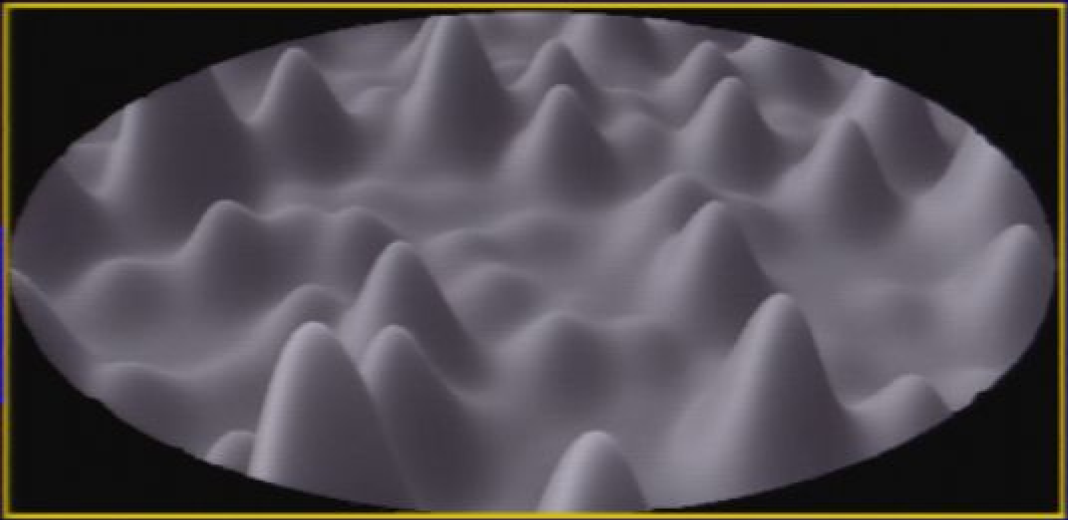

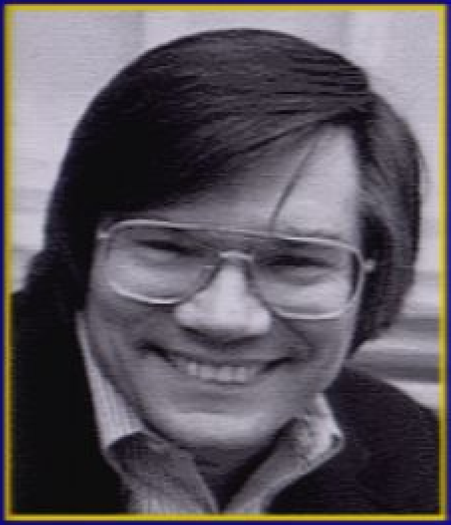

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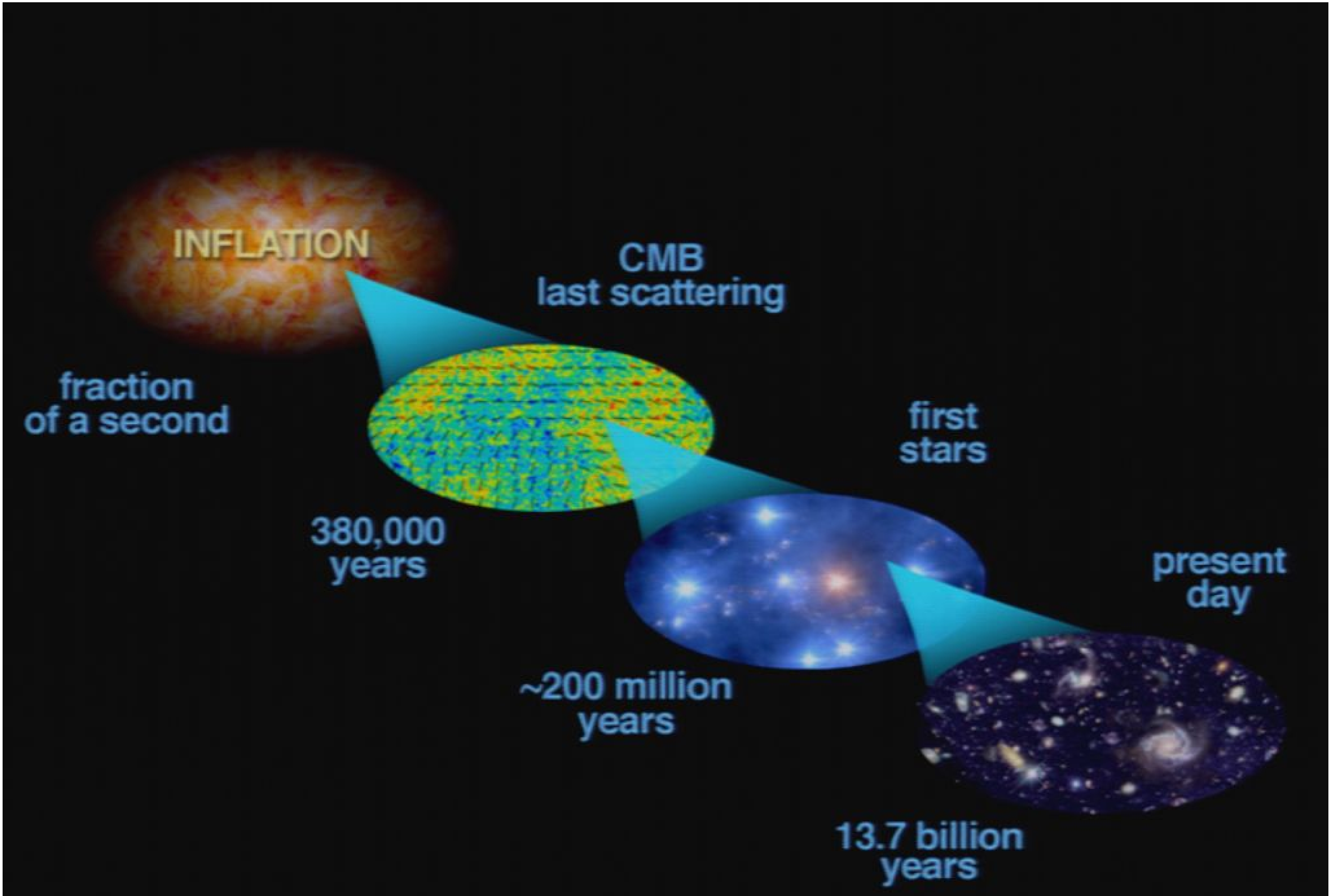
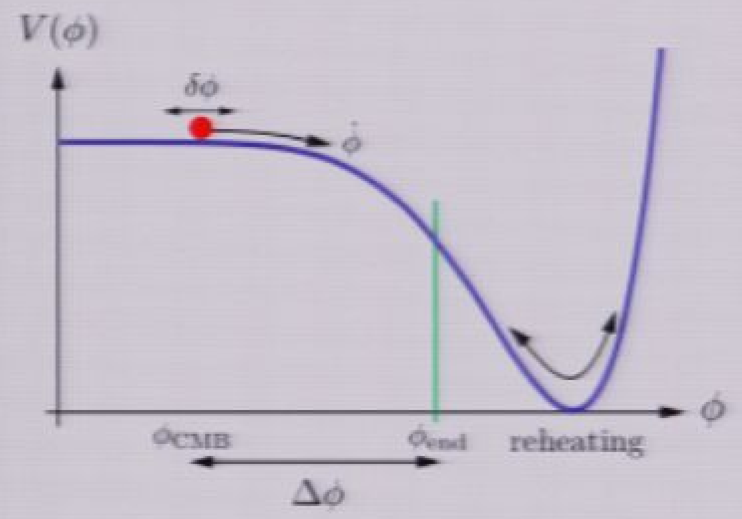
Age: 2×10^{9} sec

Age: 10
sec


INFLATION
CMB
last scattering
fraction
of a second
first
stars
380,000
years
present
day
~200 million
years
13.7 billion
years

Cartoon Guide



inflaton fluctuations $\delta\phi$

↓

curvature perturbations ζ

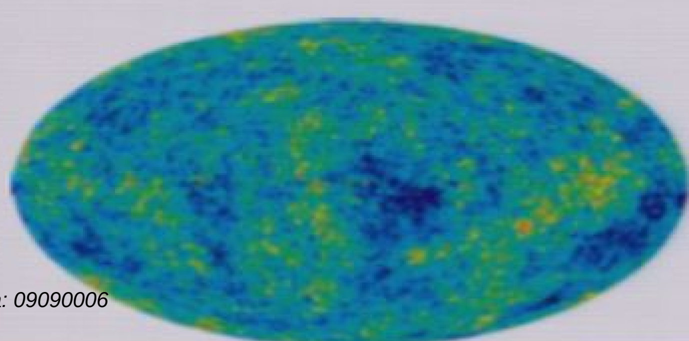
on uniform density hypersurfaces

↓

density perturbations $\delta\rho$

↓

CMB anisotropies ΔT



D. Baumann

Tensors

Besides scalar fluctuations inflation produces **tensor fluctuations**:

$$ds^2 = dt^2 - a^2(t)(1 + h_{ij})dx^i dx^j$$

gravitational waves

massless gravitons

$$\Delta_{\rm t}^2(k) = \frac{8}{M_{\rm pl}^2}\left(\frac{H}{2\pi}\right)^2$$

de Sitter fluctuations of any light field

robust prediction of inflation!

Tensors

The tensor-to-scalar ratio

$$r \equiv \frac{\Delta_t^2}{\Delta_s^2}$$

$$\epsilon \equiv \frac{M_{pl}^2}{2}\left(\frac{V'}{V}\right)^2$$

$$\eta \equiv M_{pl}^2 \frac{V''}{V}$$

is model-dependent because scalars are!

In contrast,

The prediction for tensors is *simple* and *the same* in all models!

$$\Delta_t^2 \propto H^2$$

scale-dependence

e.g. slow-roll inflation

$$\Delta_s^2 = A_s k^{n_s - 1}$$

$$n_s - 1 = 2\eta - 6\epsilon$$

Observational Evidence

Scalar Fluctuations

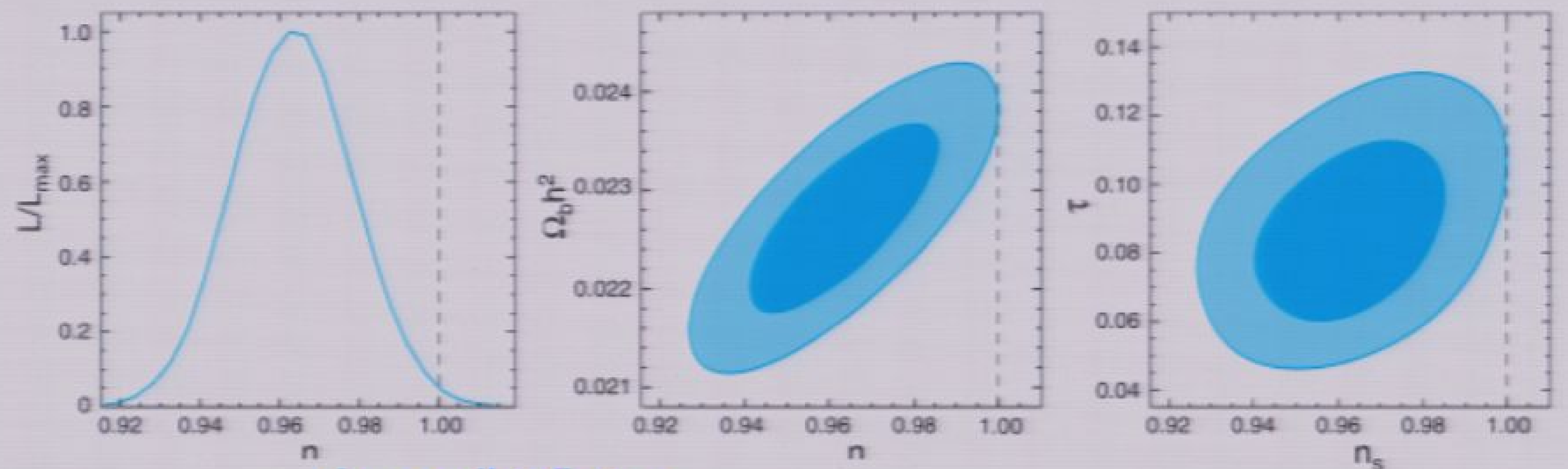
Inflation predicts

percent-level deviations from $n_s = 1$

WMAP sees

$$n_s = 0.963^{+0.014}_{-0.015}$$

2.5σ away from $n_s = 1$



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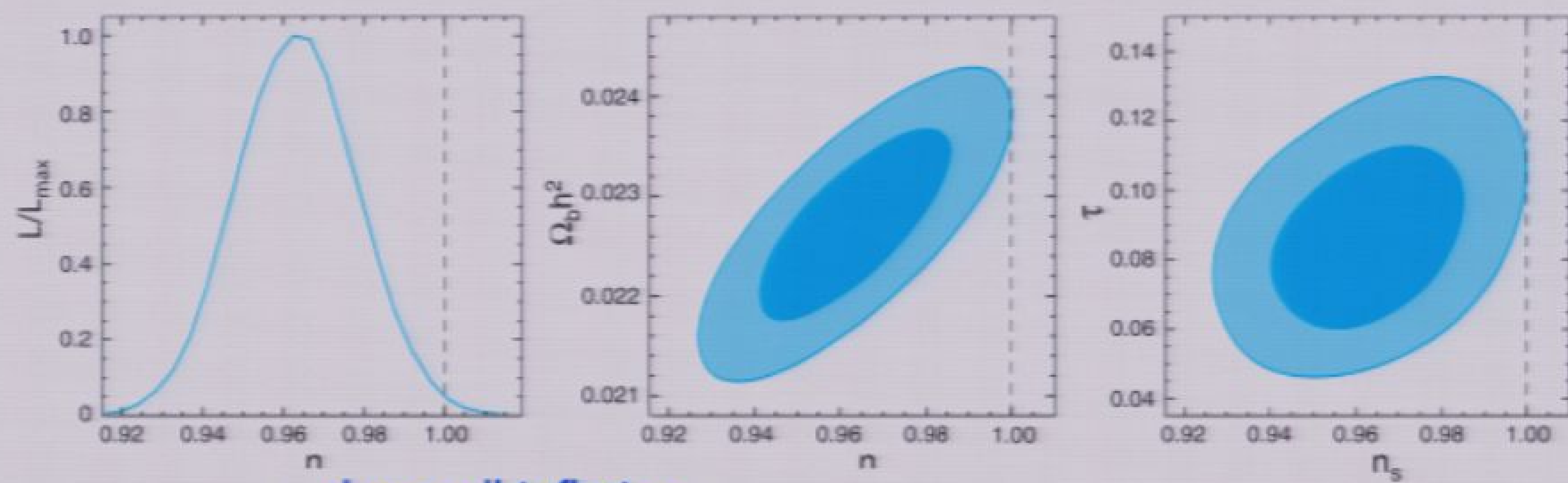

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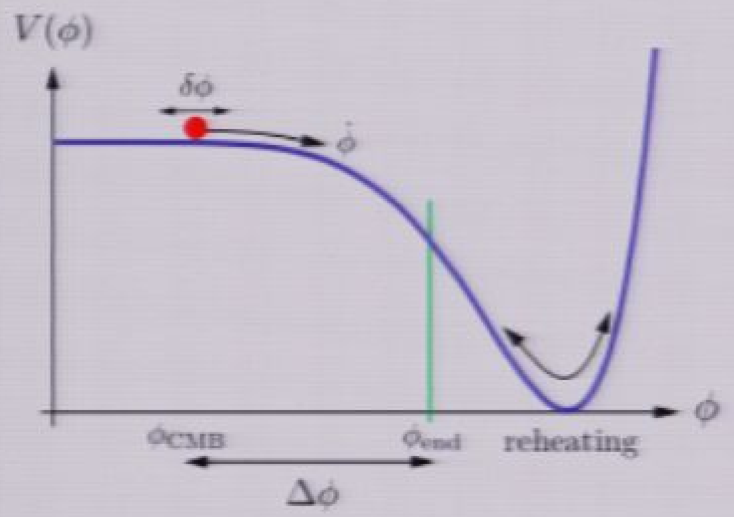

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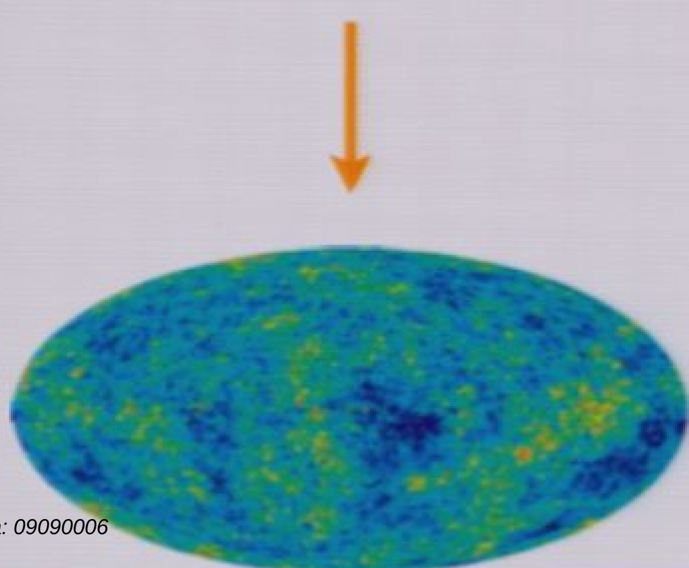

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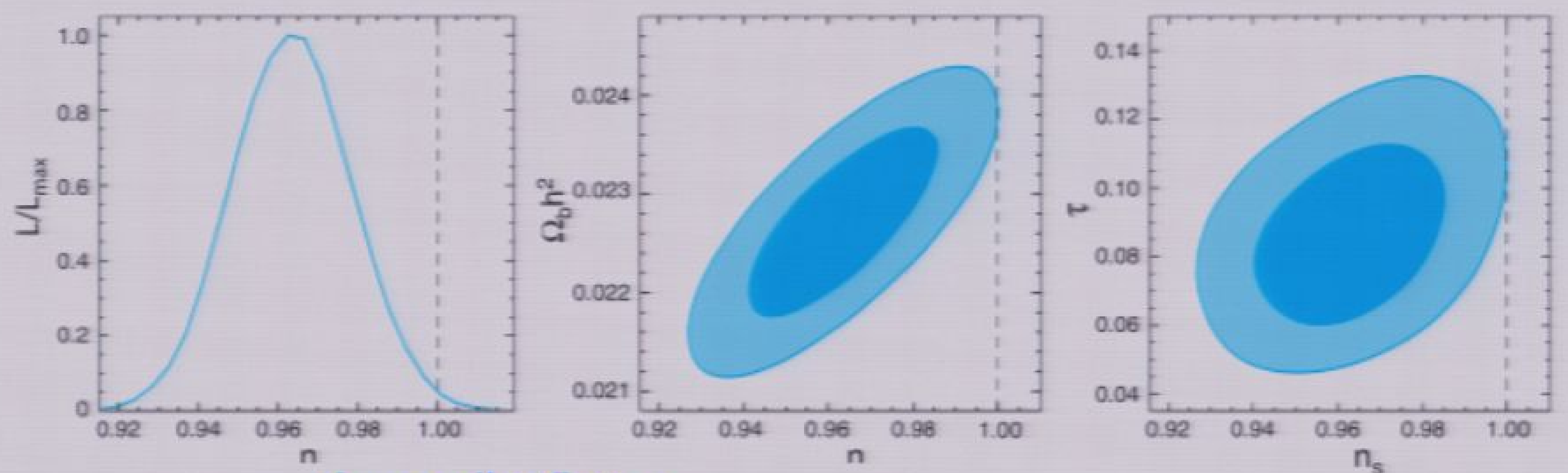

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i.e. ***flatness and homogeneity*** of the universe and a primordial spectrum of ***nearly scale-invariant, Gaussian and adiabatic scalar fluctuations.***

(Thought we knew the universe was homogeneous and had small density fluctuations since Zeldovich)

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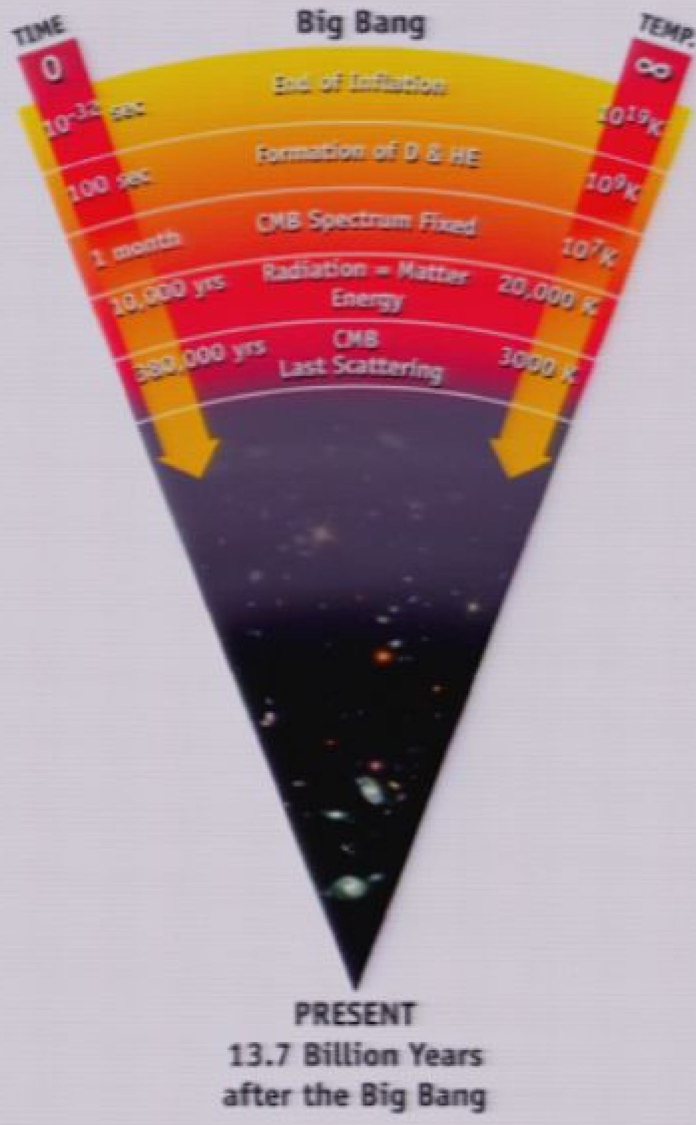
Energy Scale of Inflation

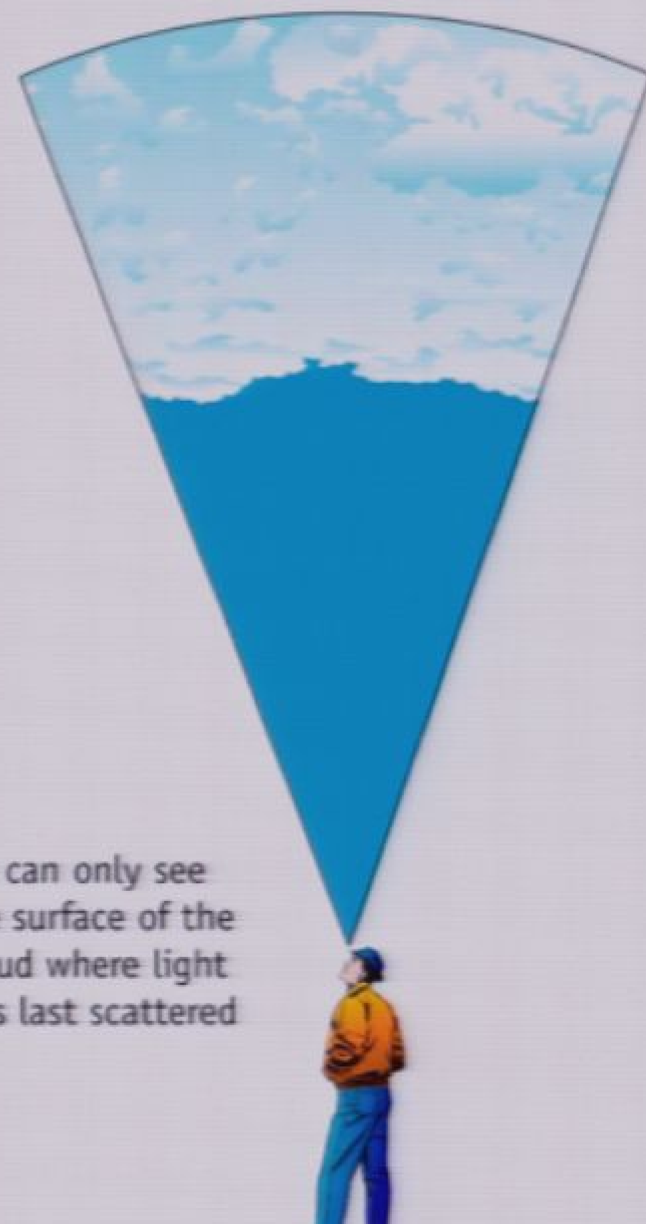
Tensors measure the energy scale of inflation

$$E_{\rm inf} \equiv V^{1/4} = 10^{16}{\rm GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

Single most important data point about inflation!

Last Scattering Surfaces

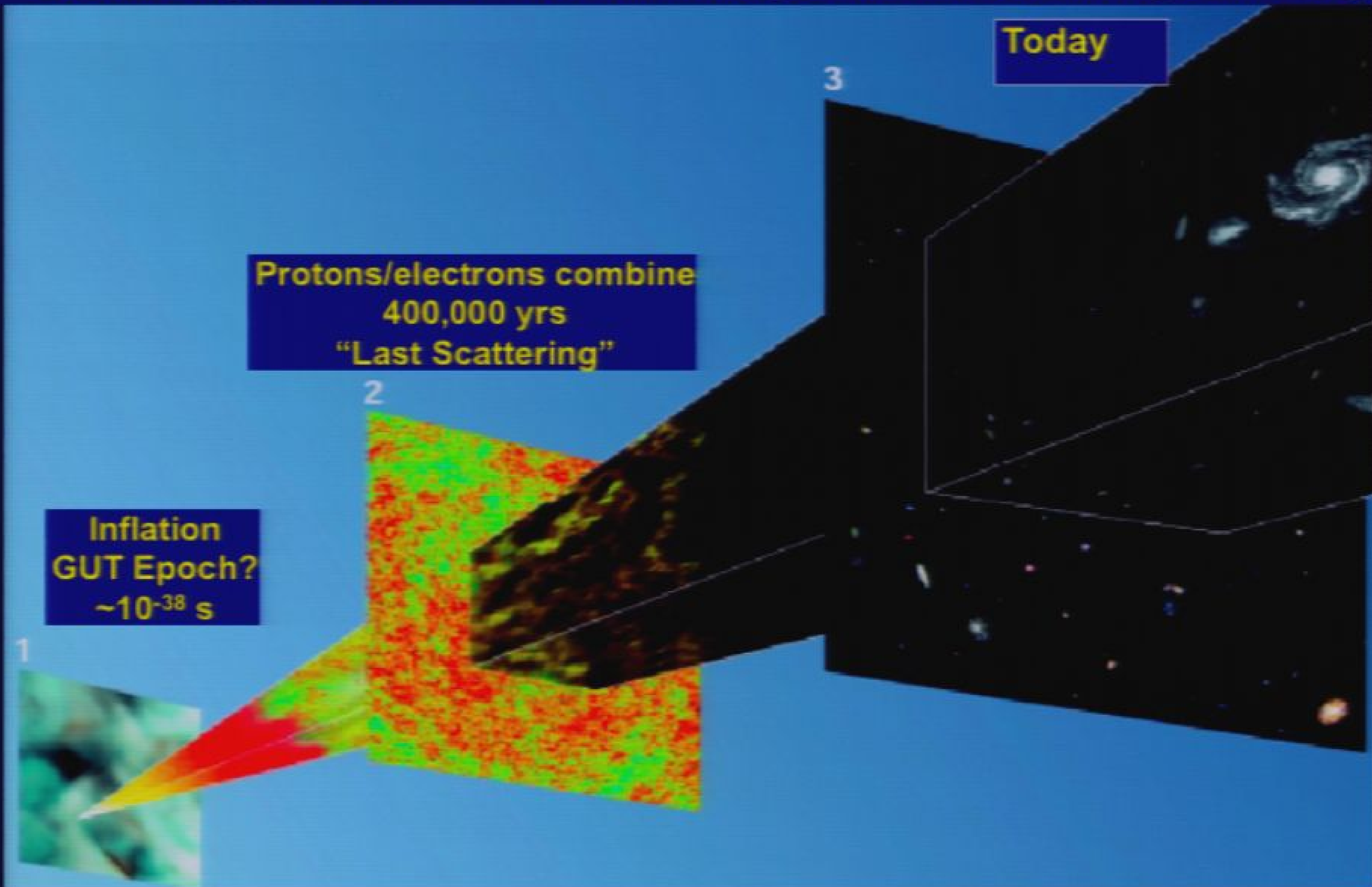




We can only see the surface of the cloud where light was last scattered

Somewhere, beyond the C…MB

GWB Energy Density ~ $a^4 \rightarrow 10^{12}$ times higher at Last Scattering than today



$z=e^{60}$ $z=1000$ $z=0$

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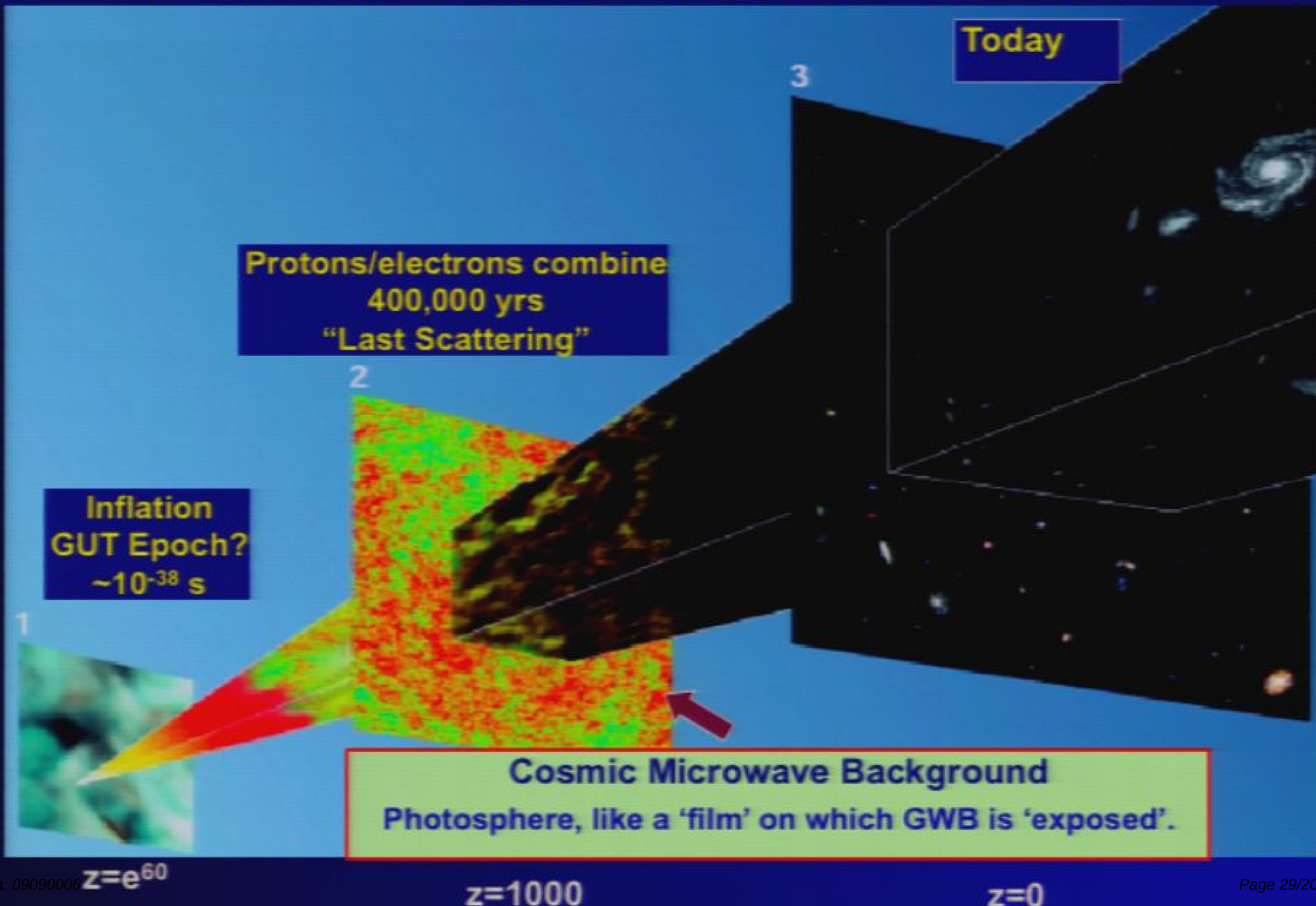

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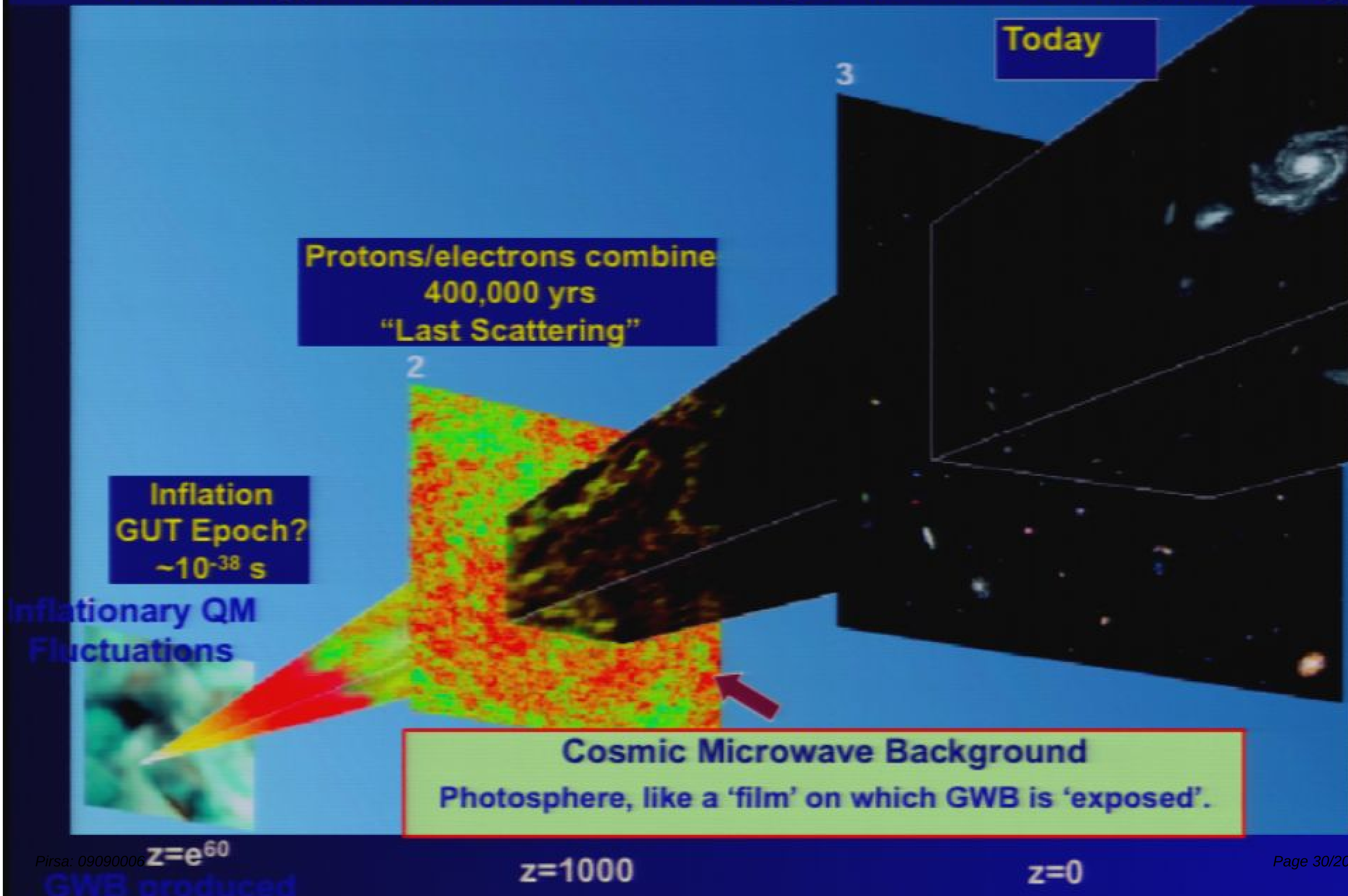

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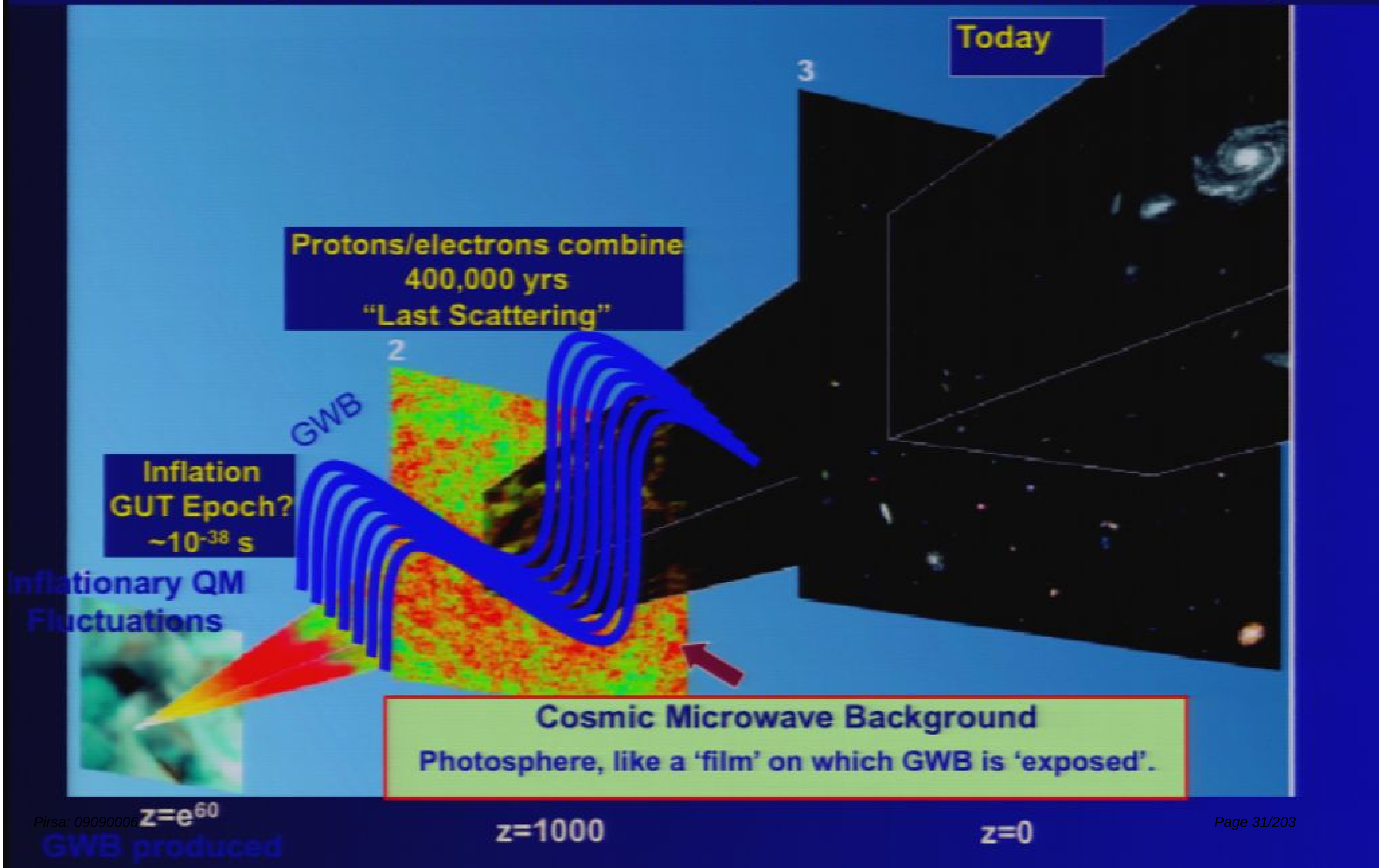
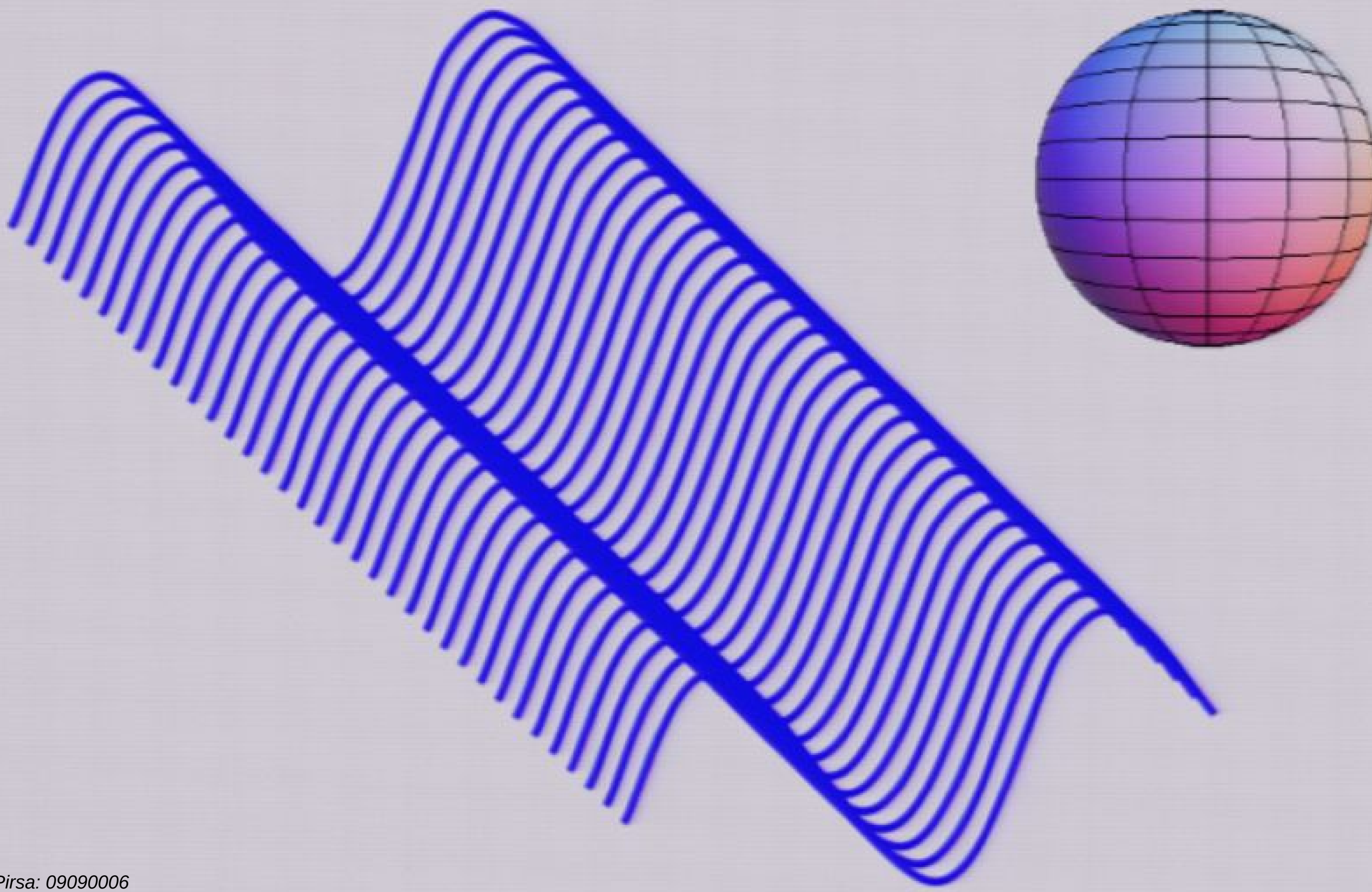


Gravitational Waves "Squeeze" Spacetime



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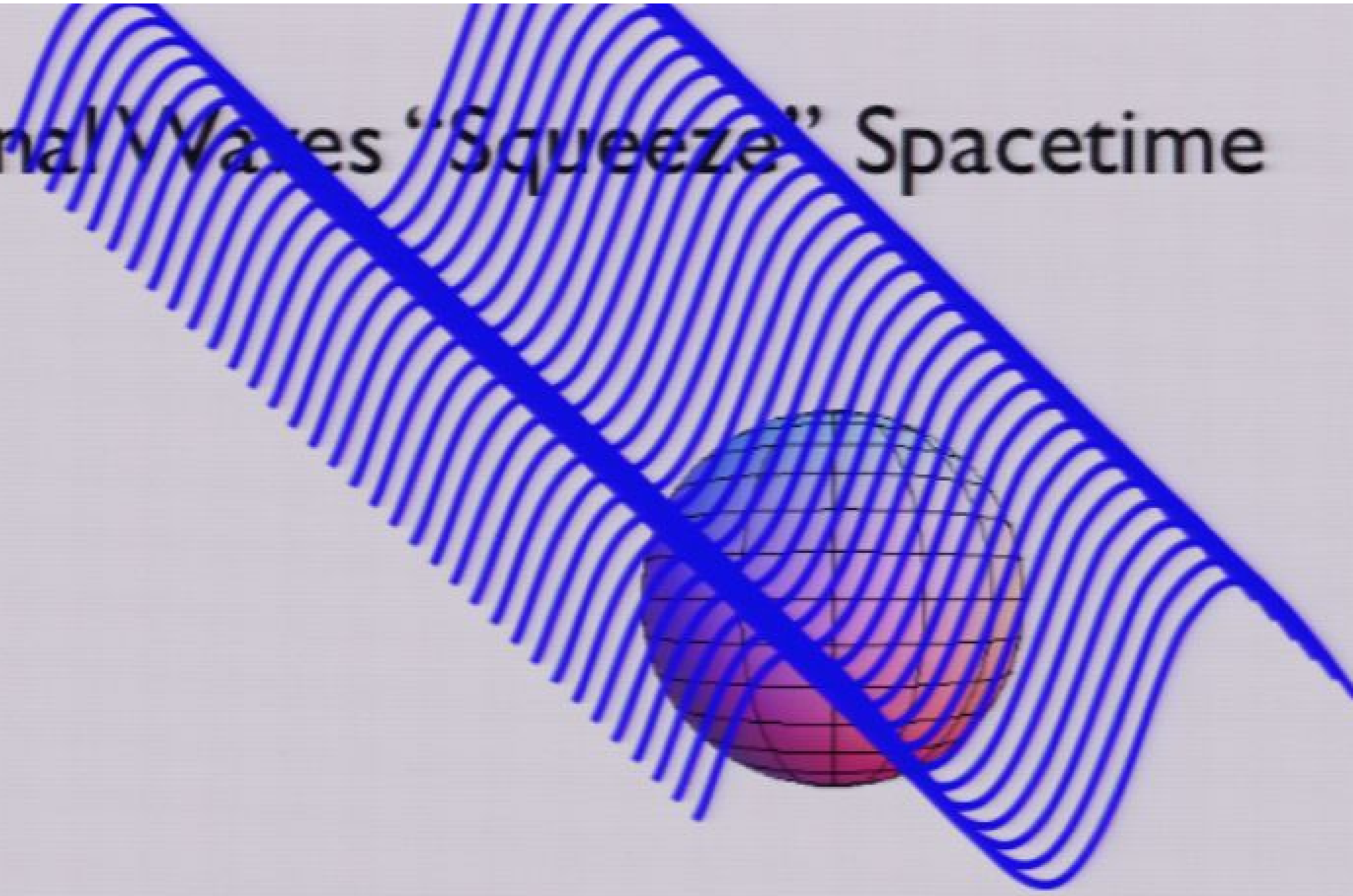

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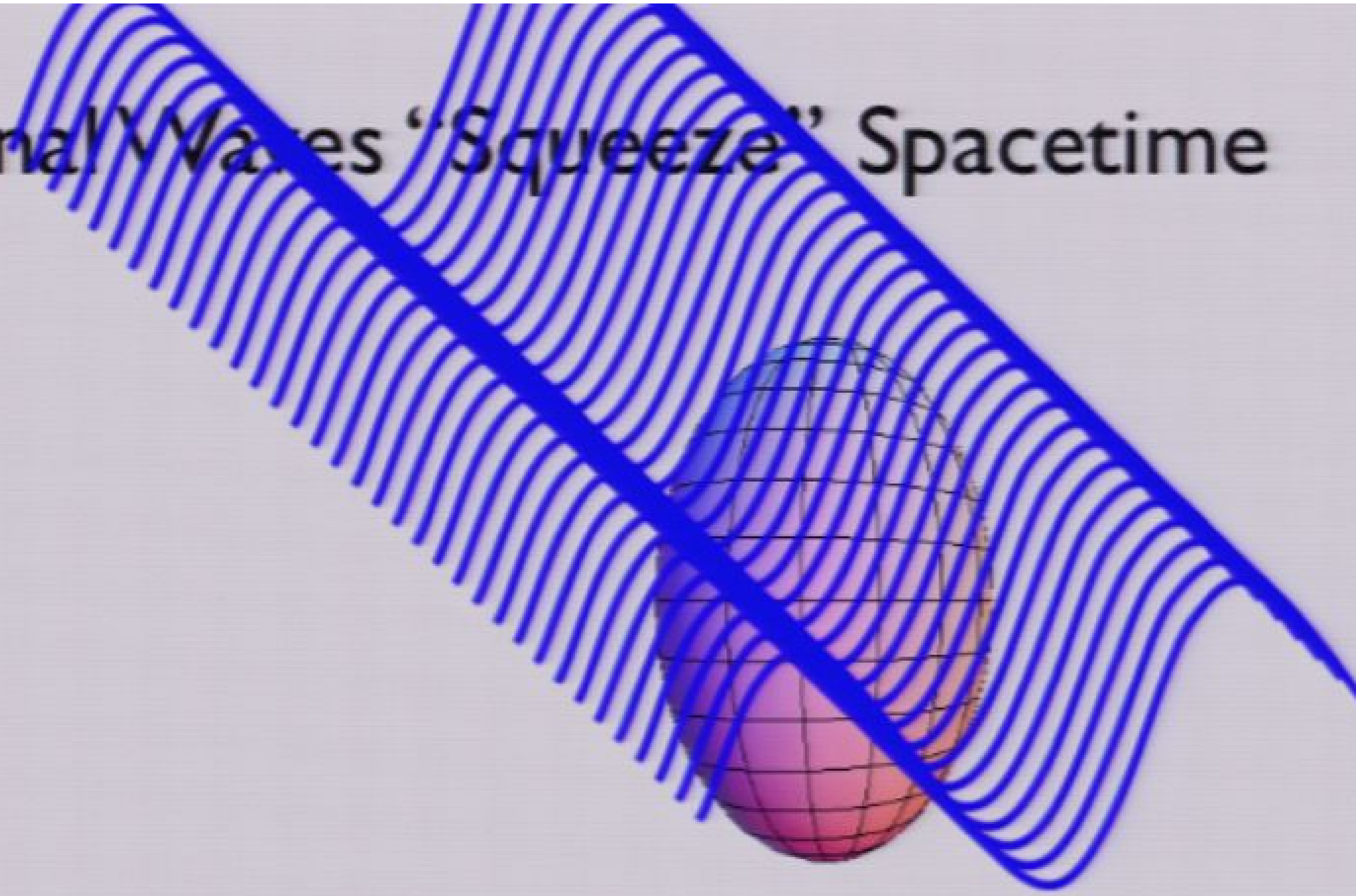

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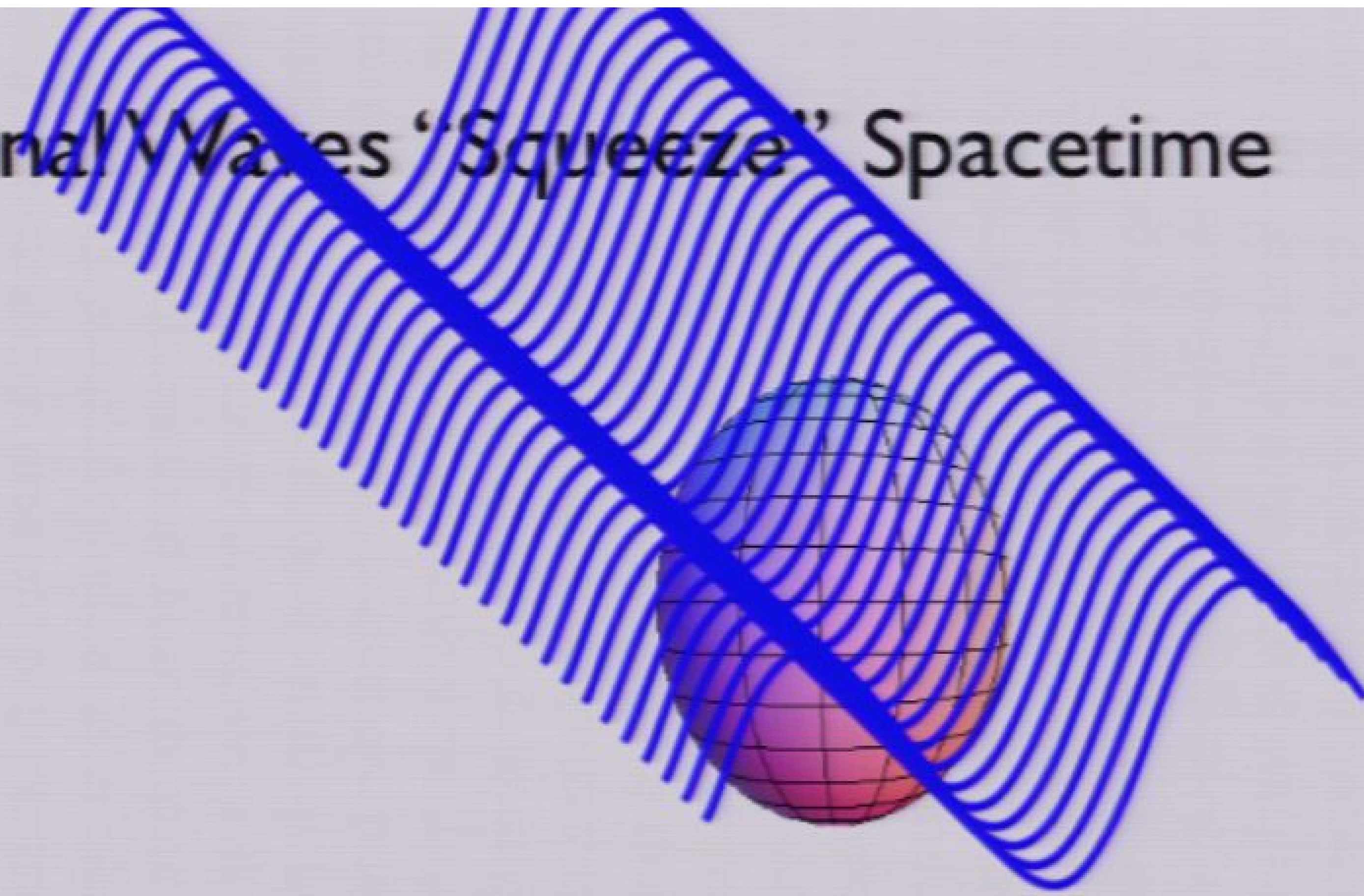

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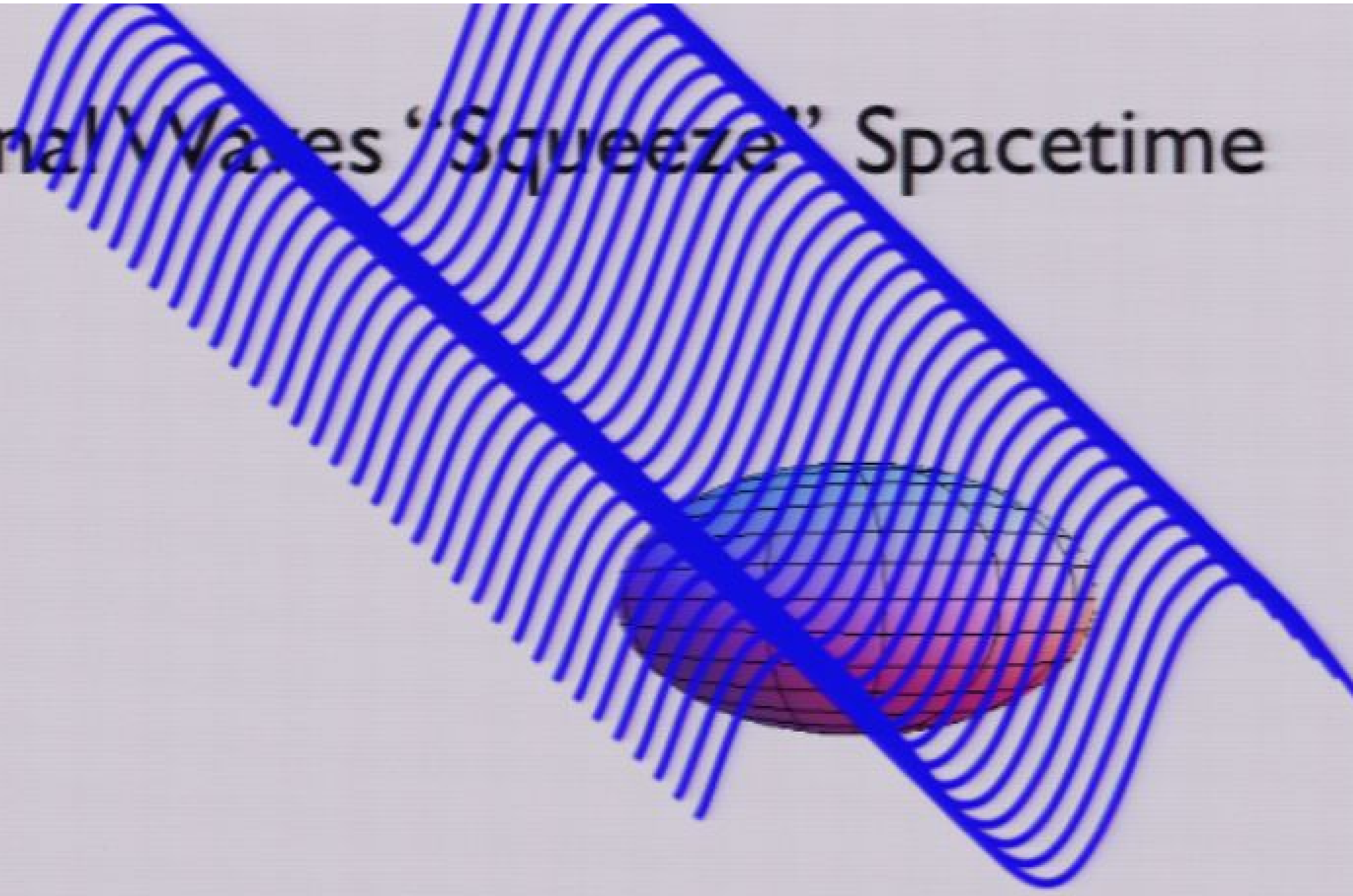

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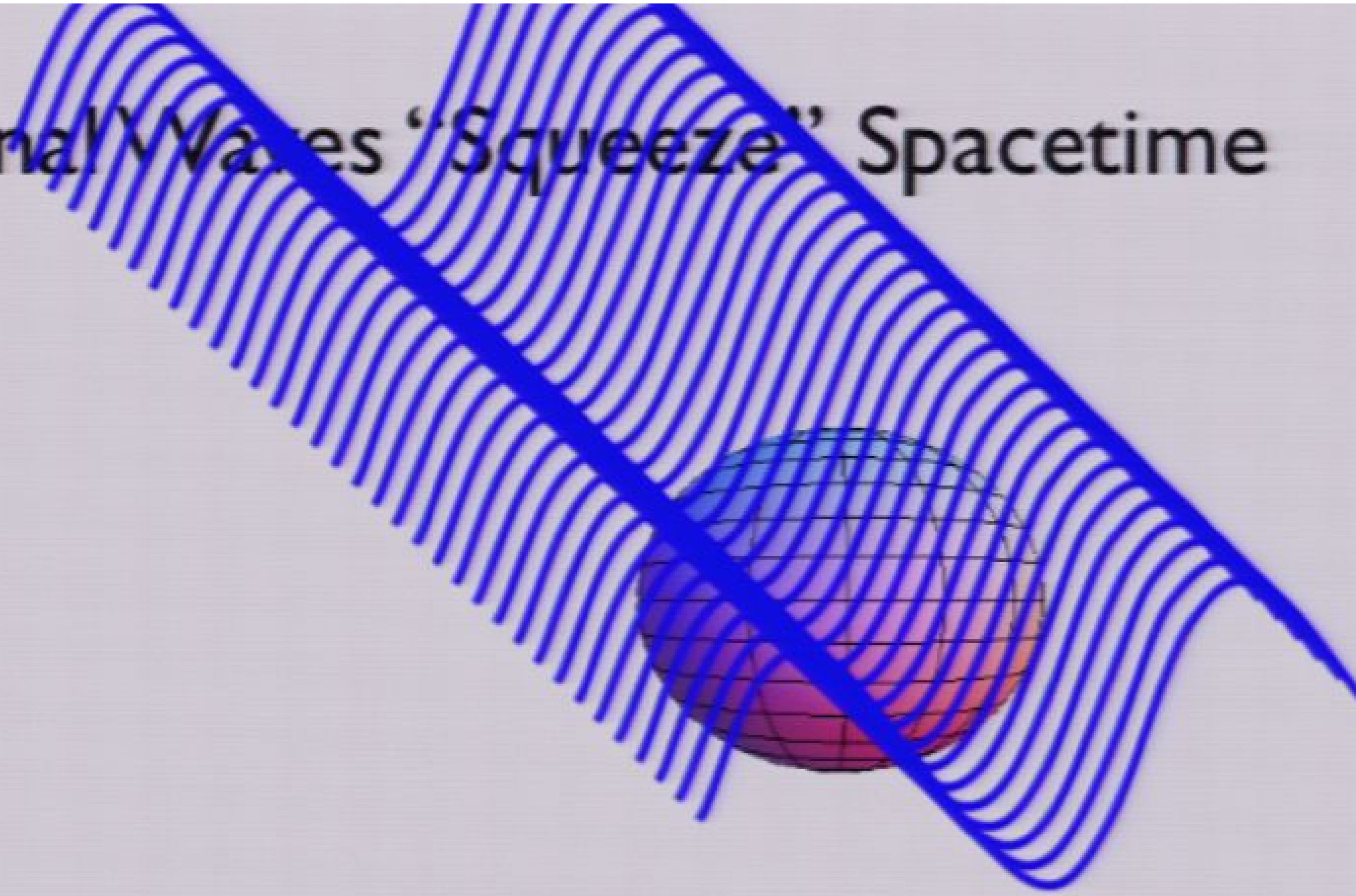
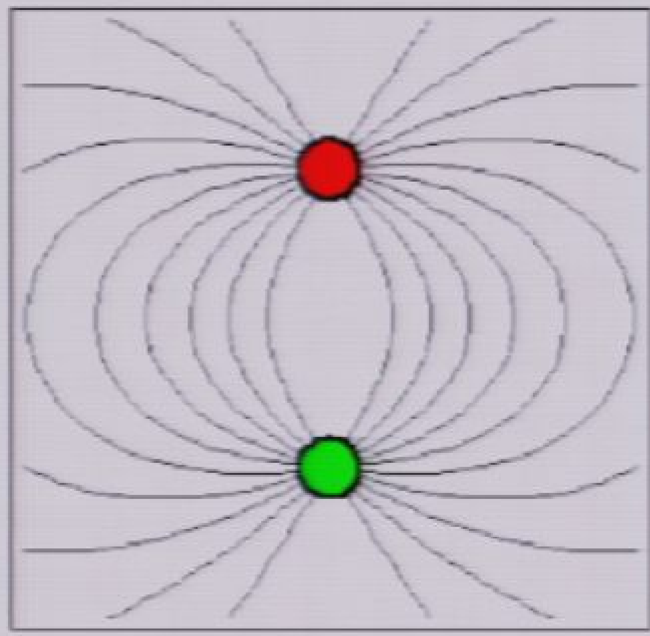
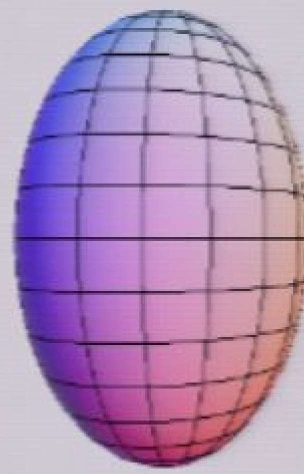


Gravitational Waves are Analogous to Electromagnetic Waves

EM Waves arise from the periodic motion of charges

Gravitational Waves arise from the periodic motion of ST.





redicted by Maxwell in 1873. Predicted by Einstein in 1915

EM waves would also be produced if the charges were "stationary" and space time "moved" periodically.

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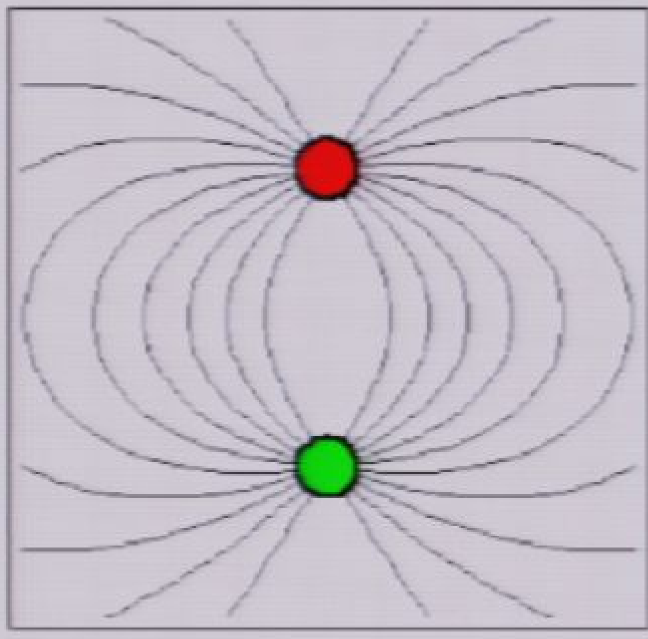

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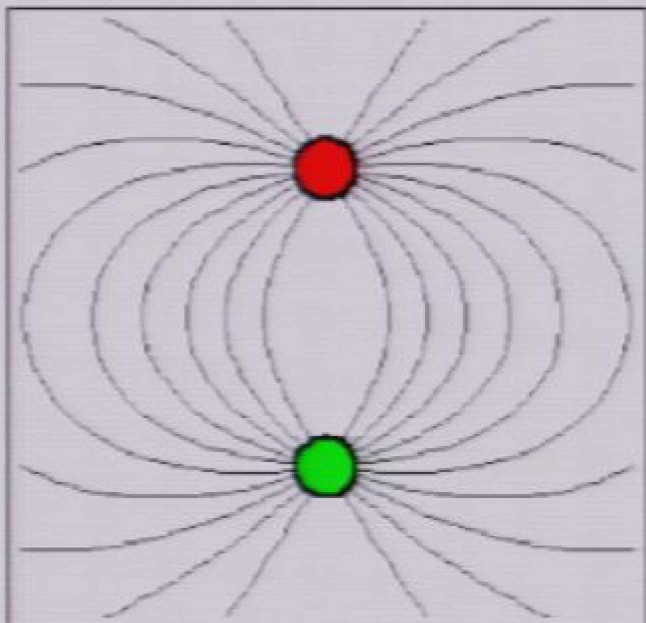

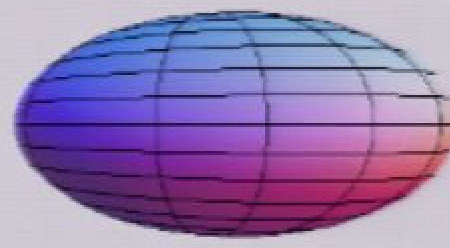

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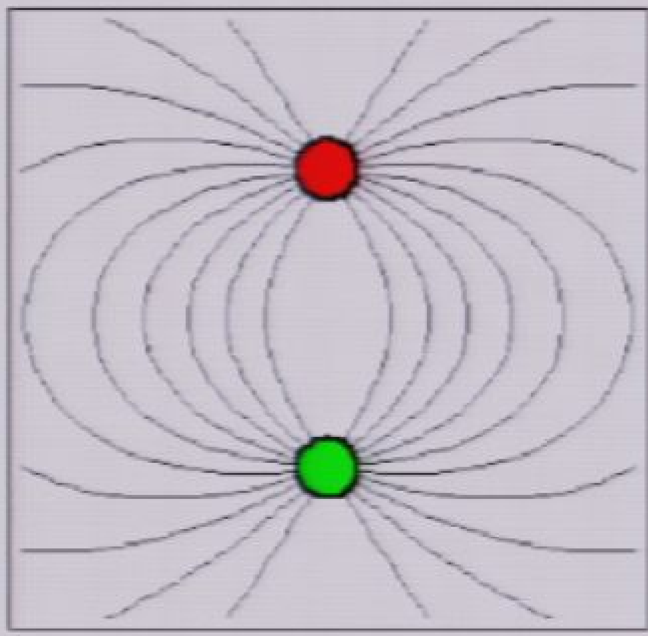

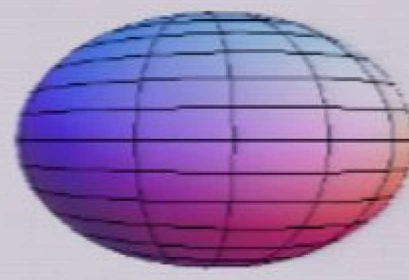

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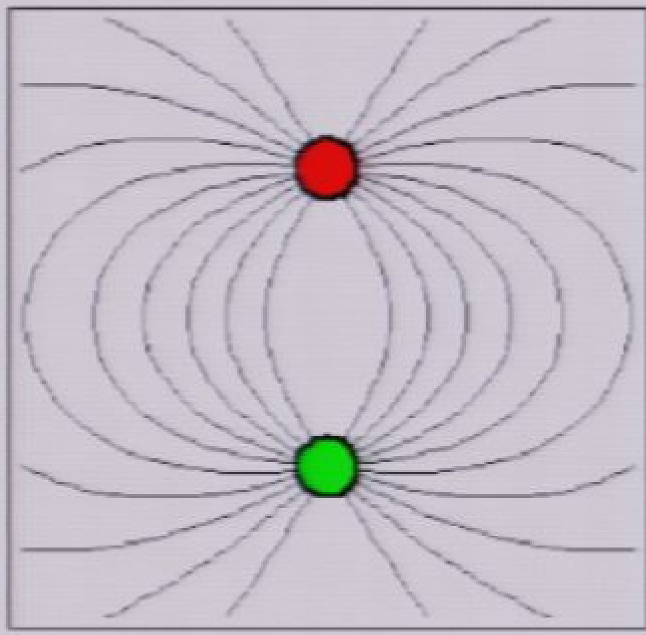

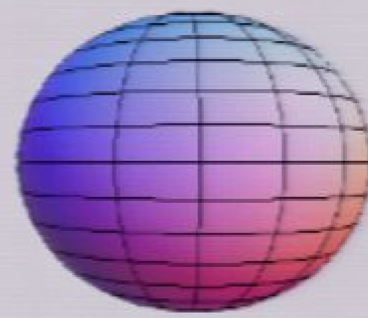

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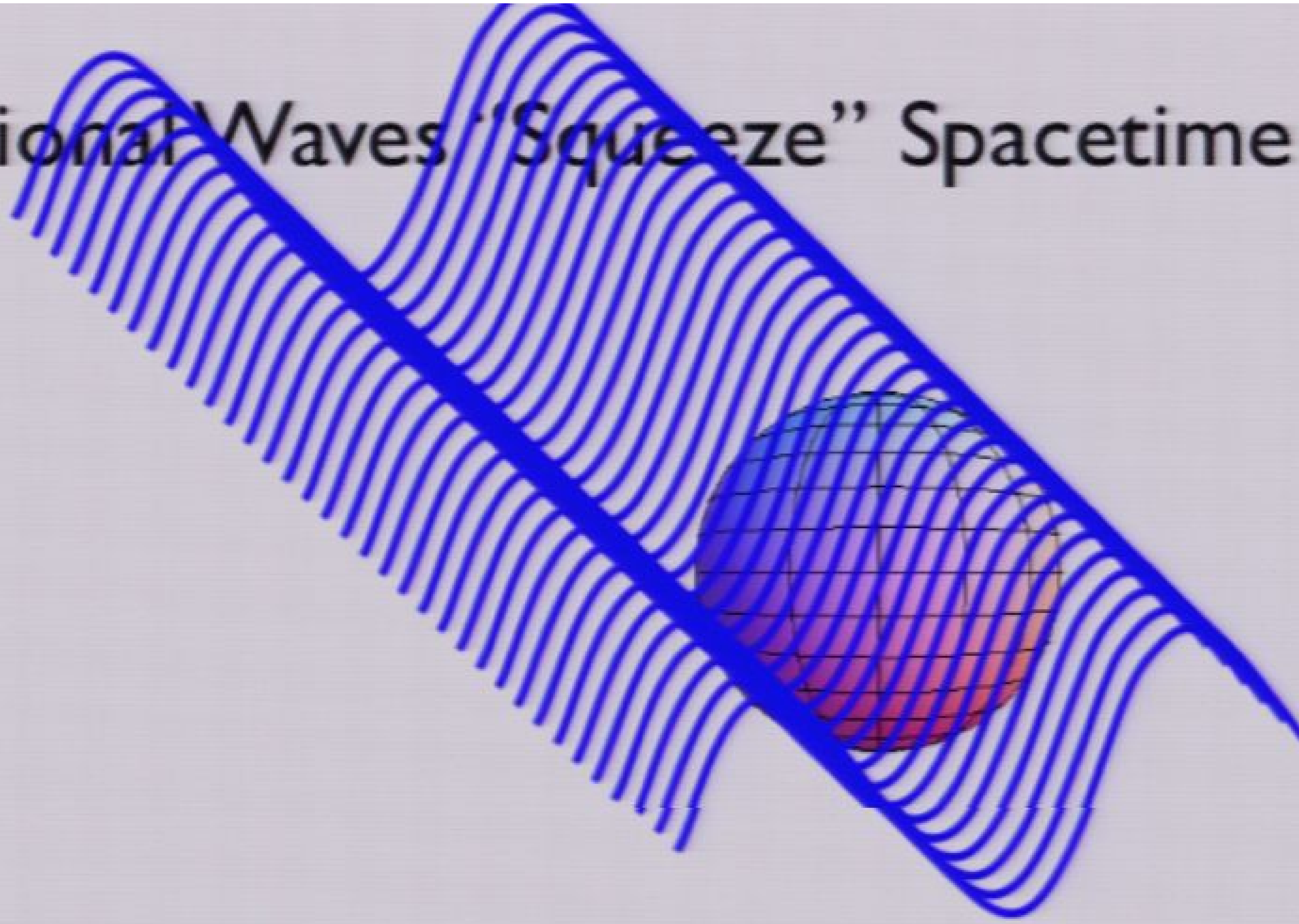

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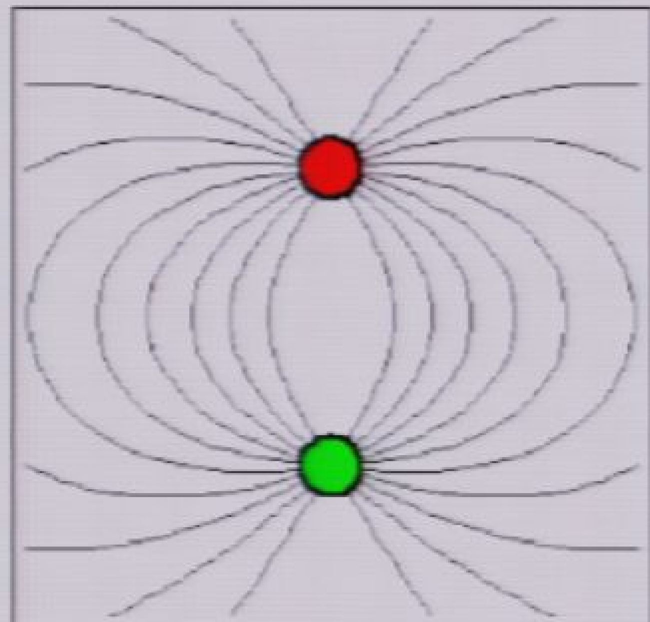

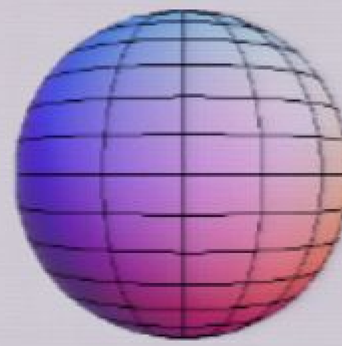

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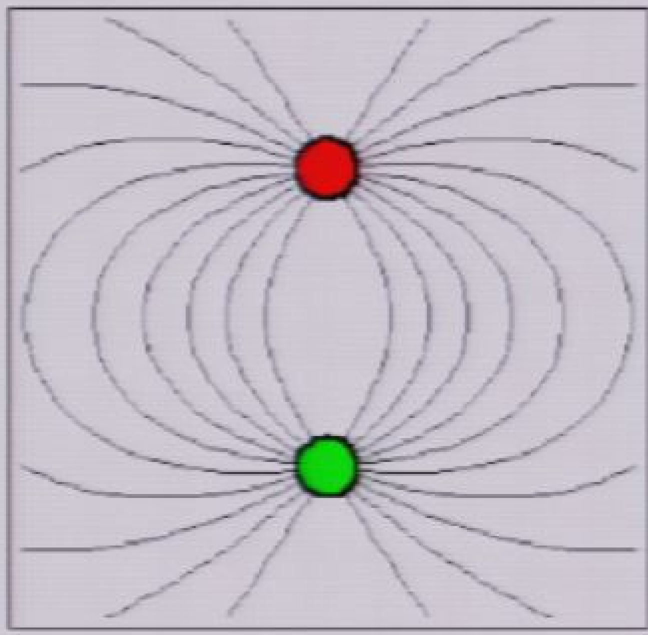

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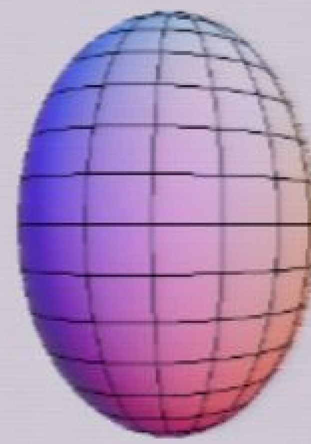

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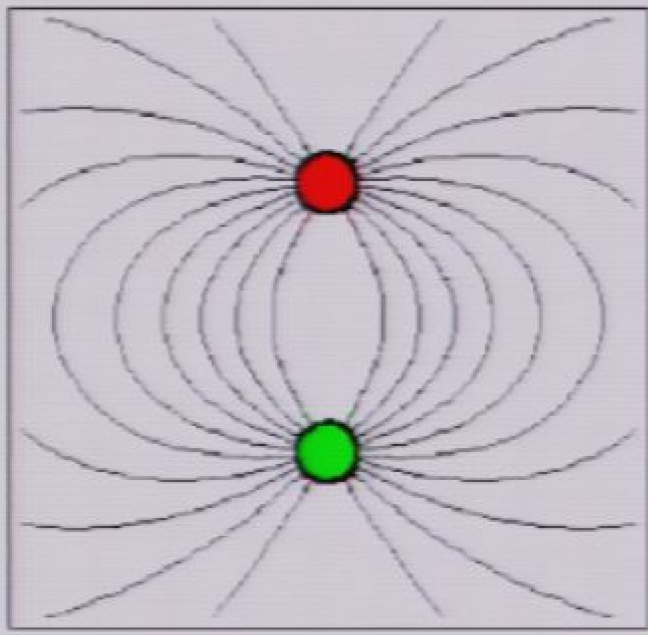

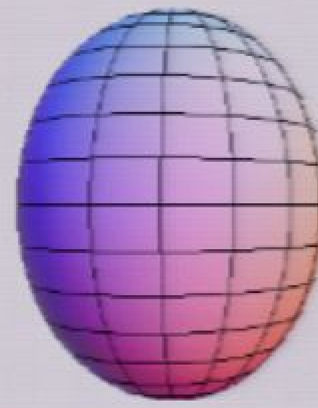

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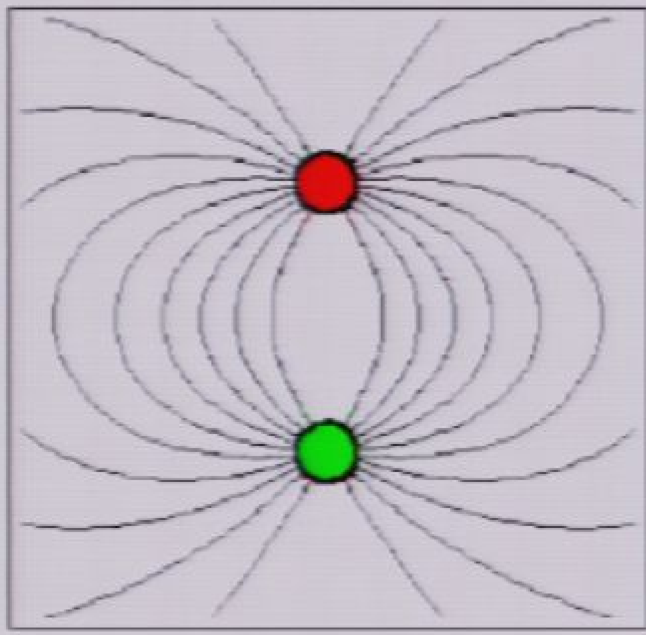

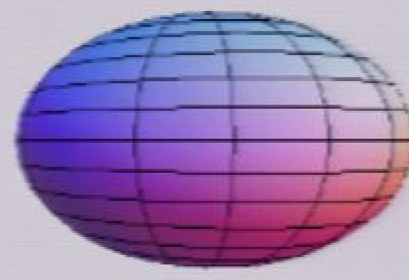

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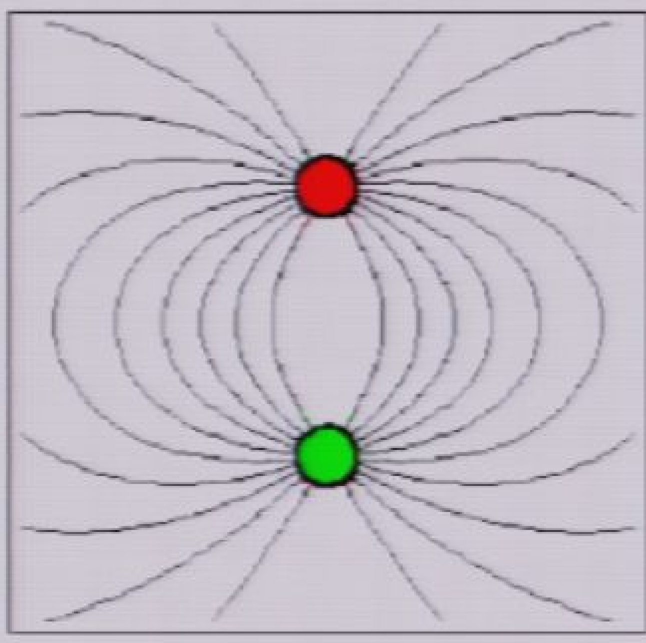

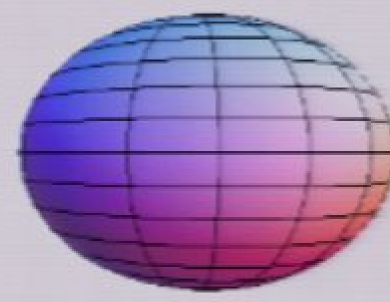

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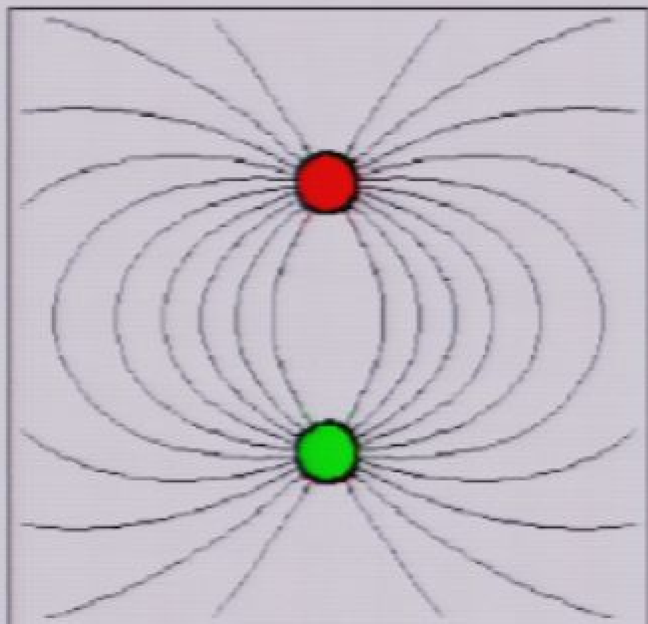

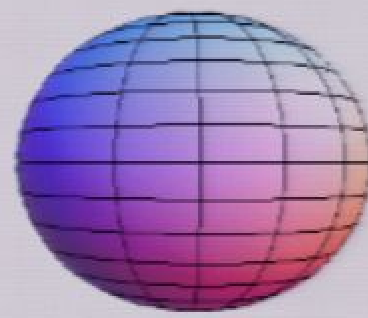

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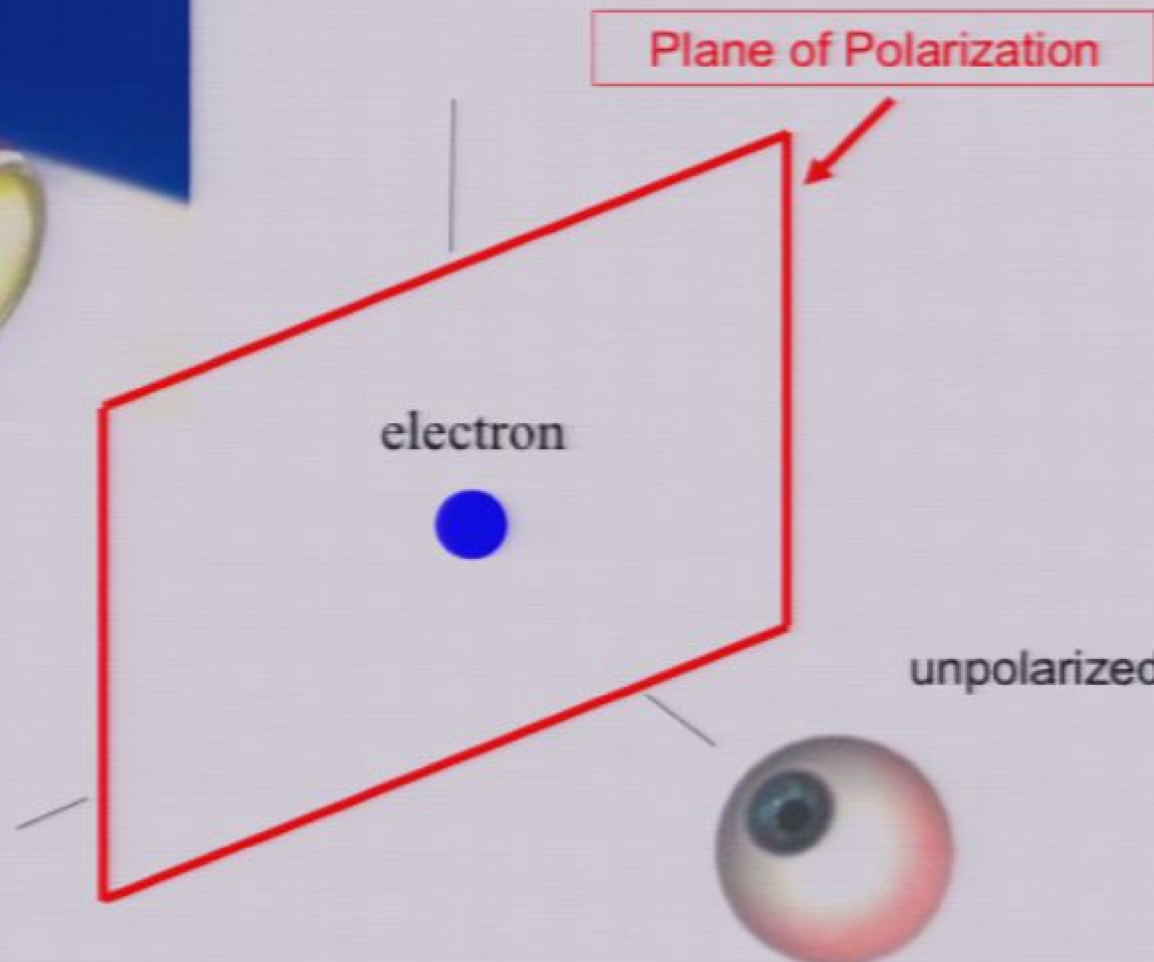

Polarization ~ $\cos^2\Theta$ – *Quadrupole Scattering*

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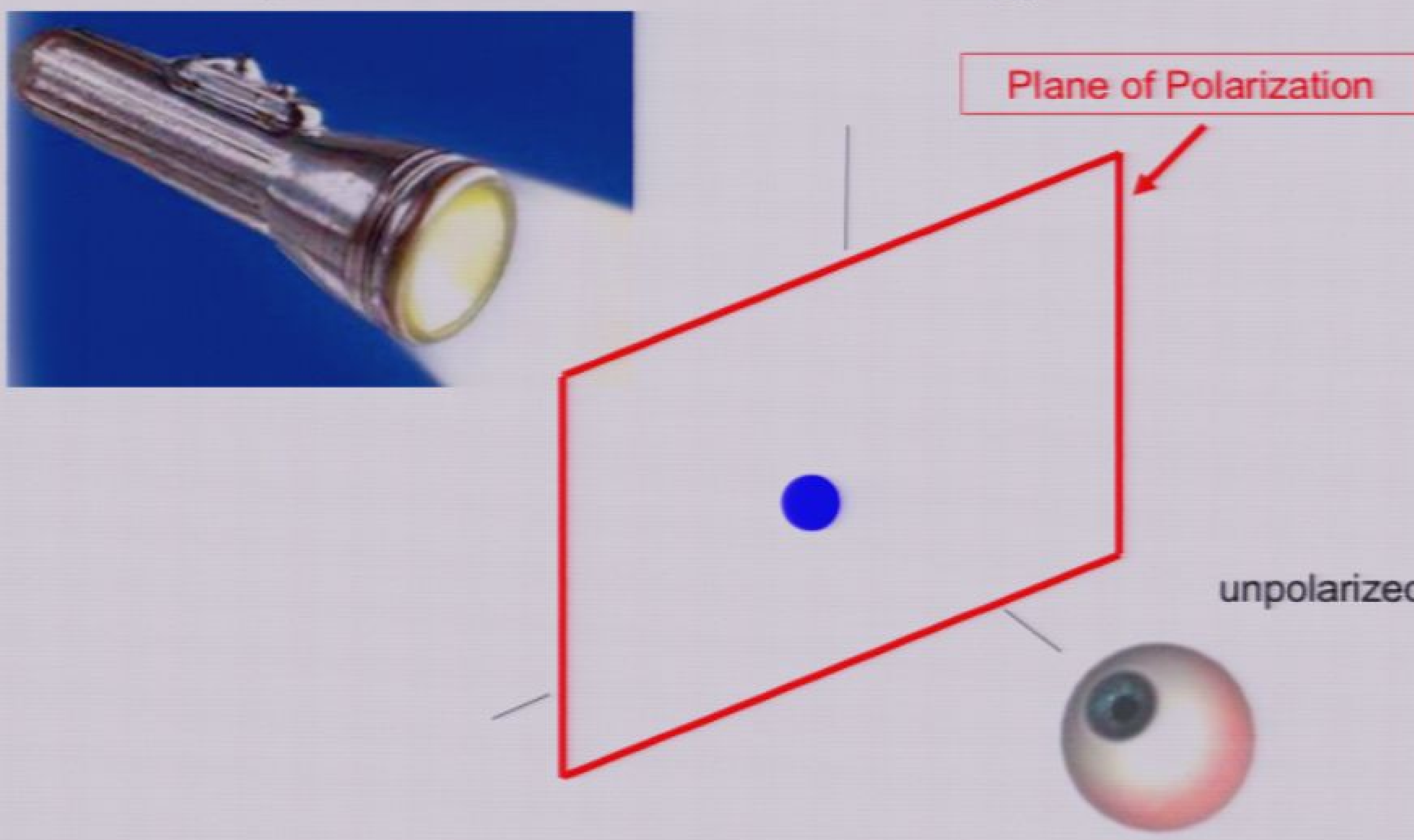

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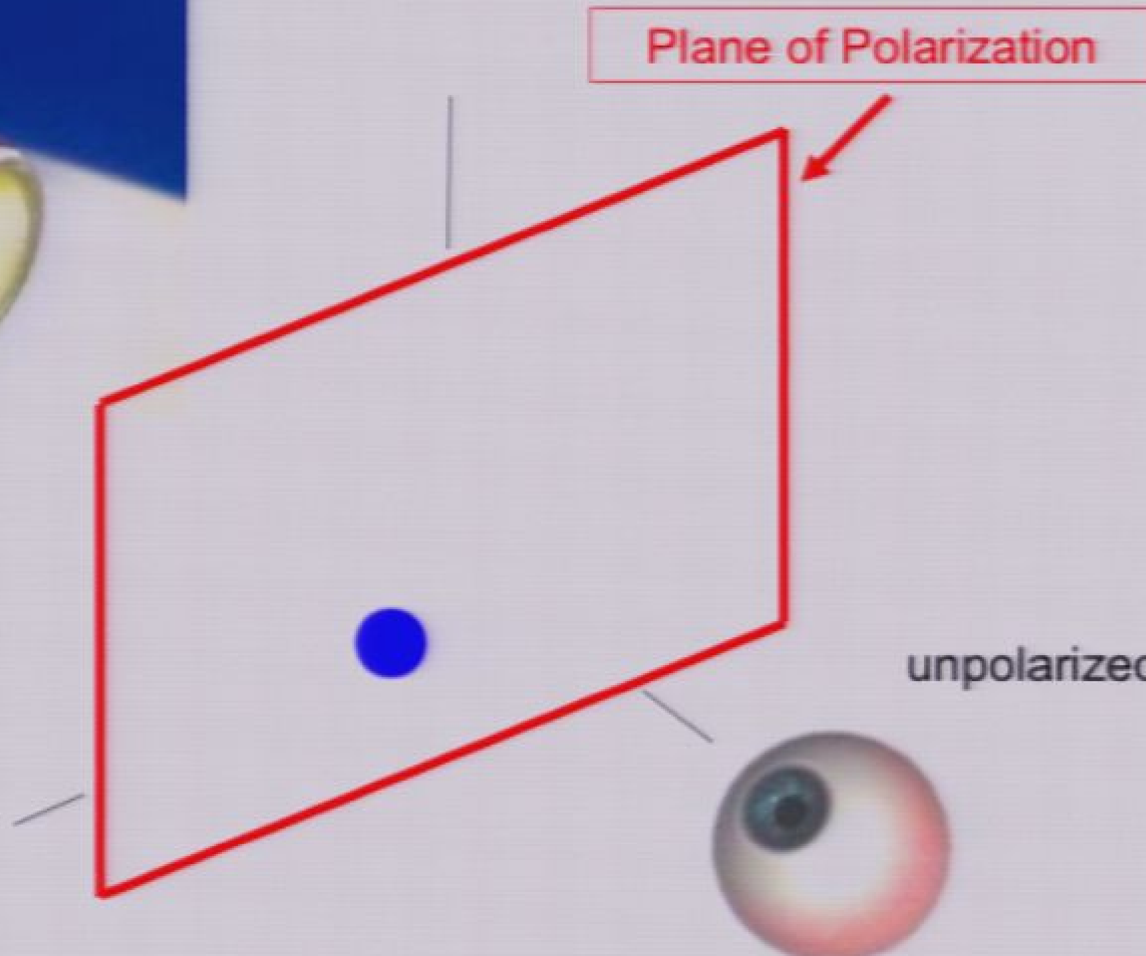

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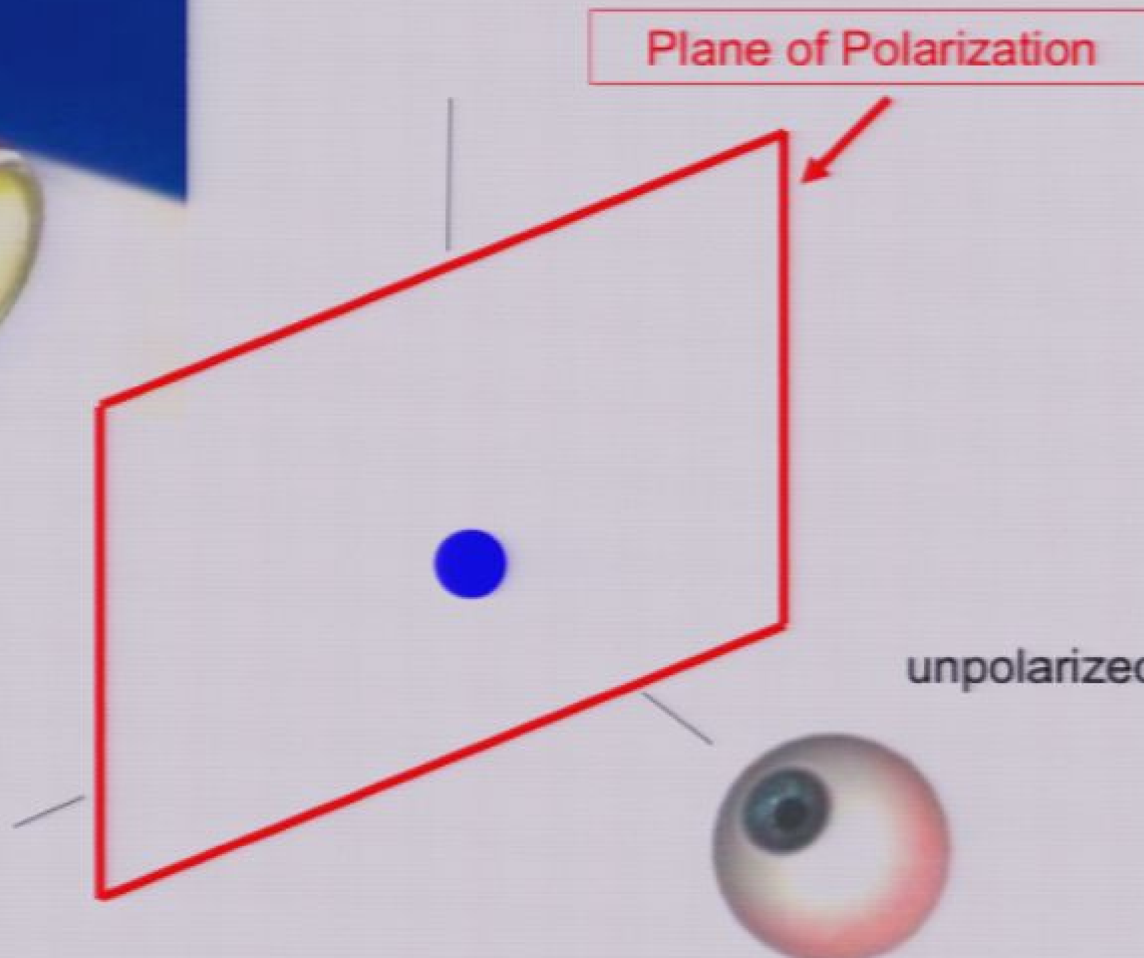

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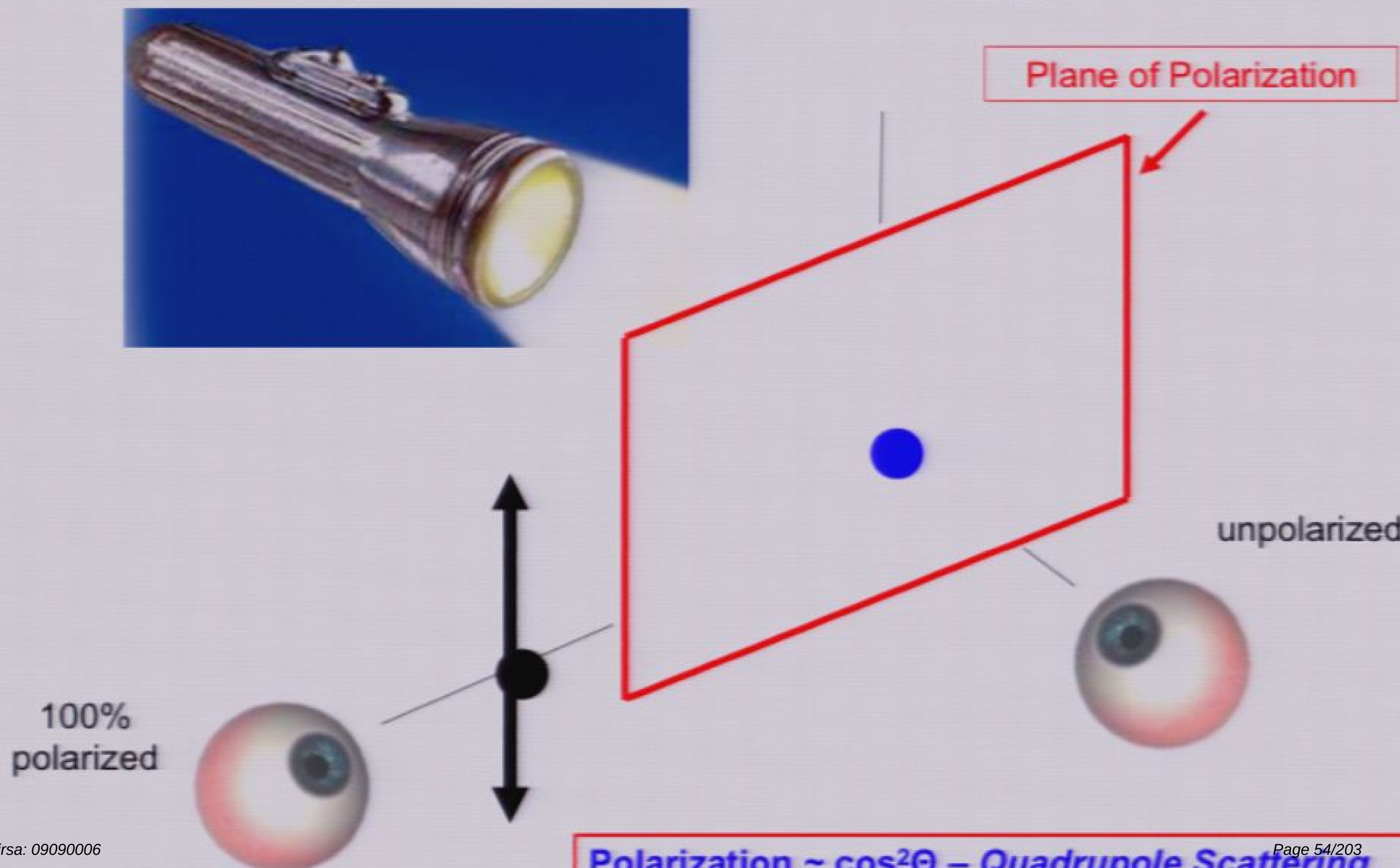

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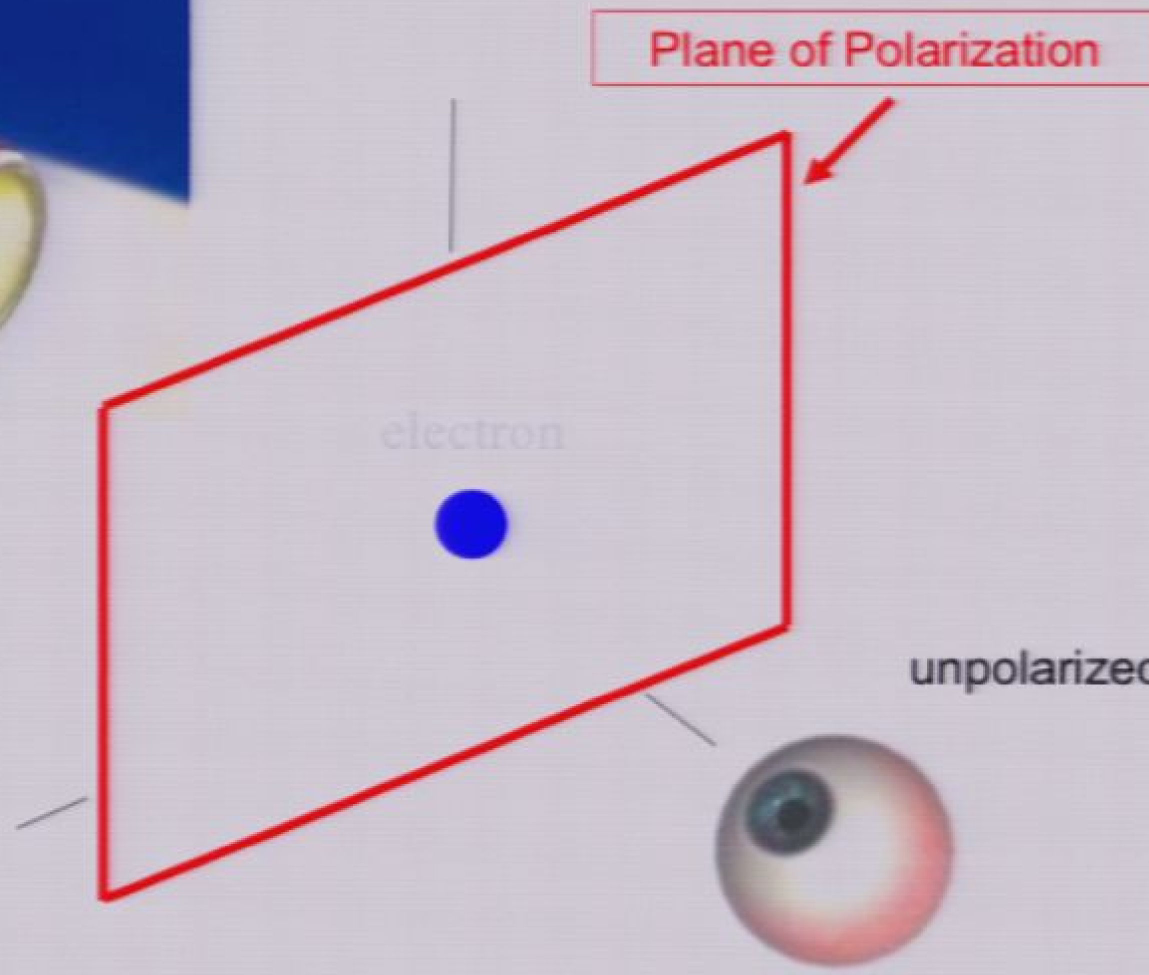

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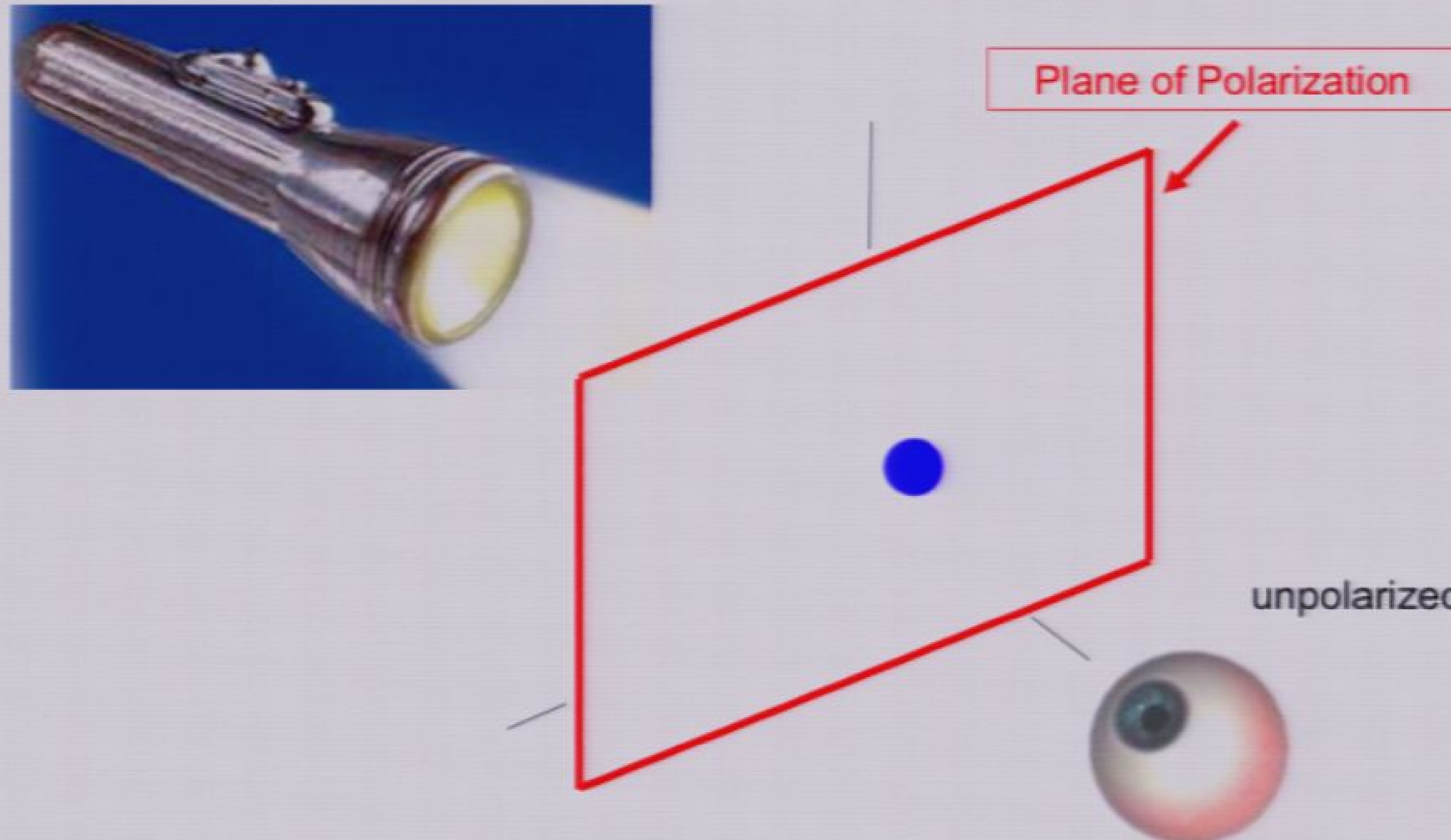

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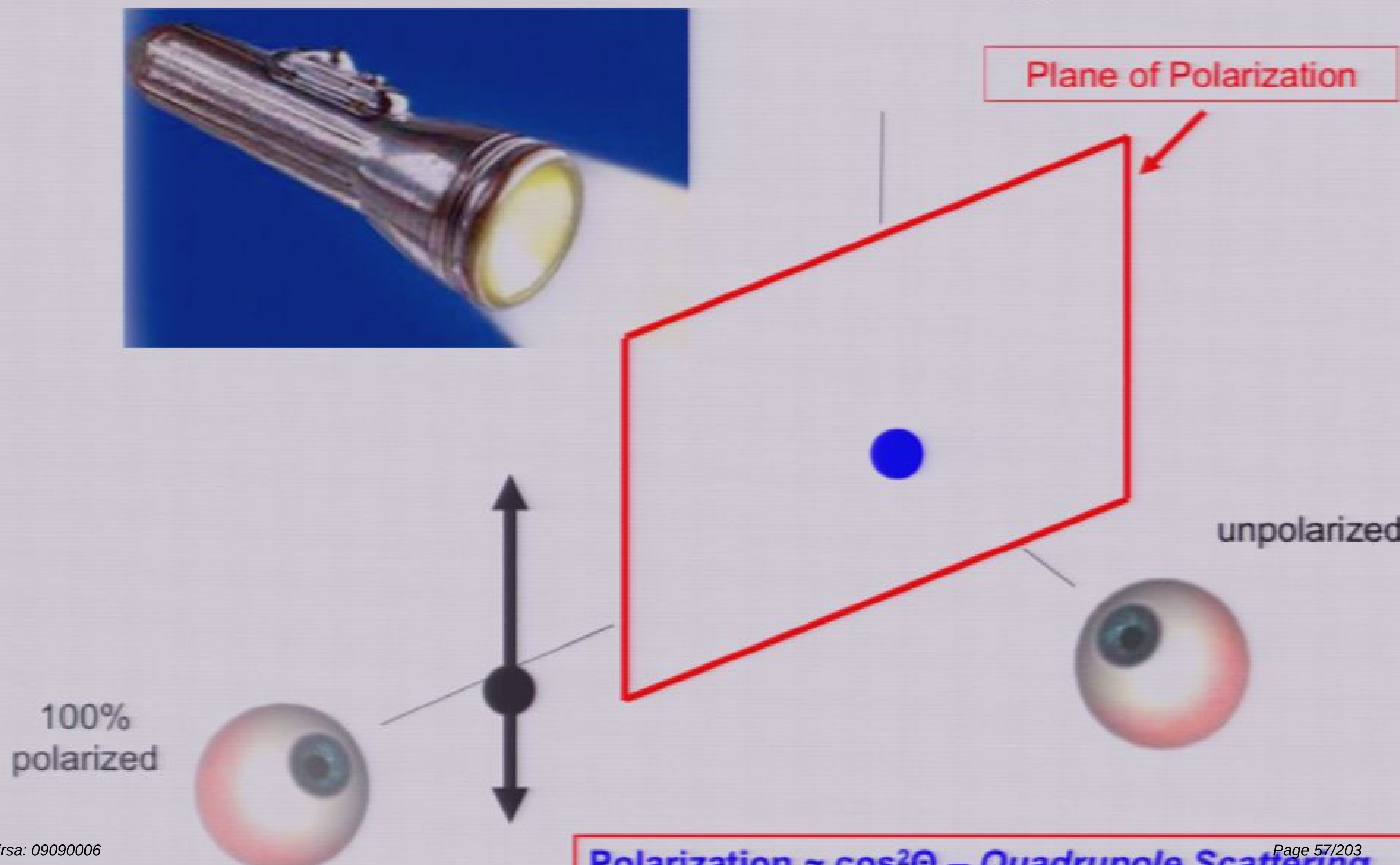

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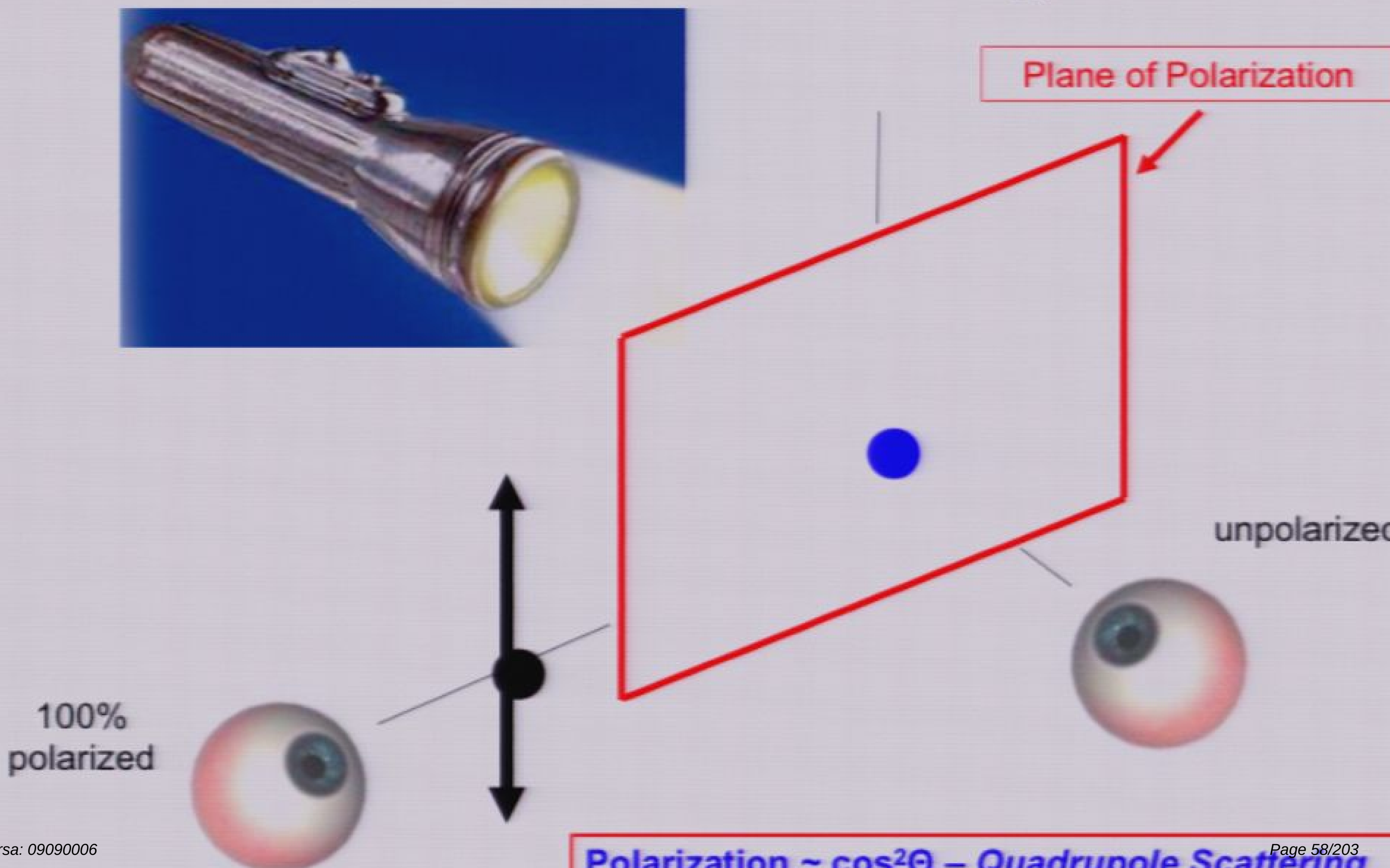

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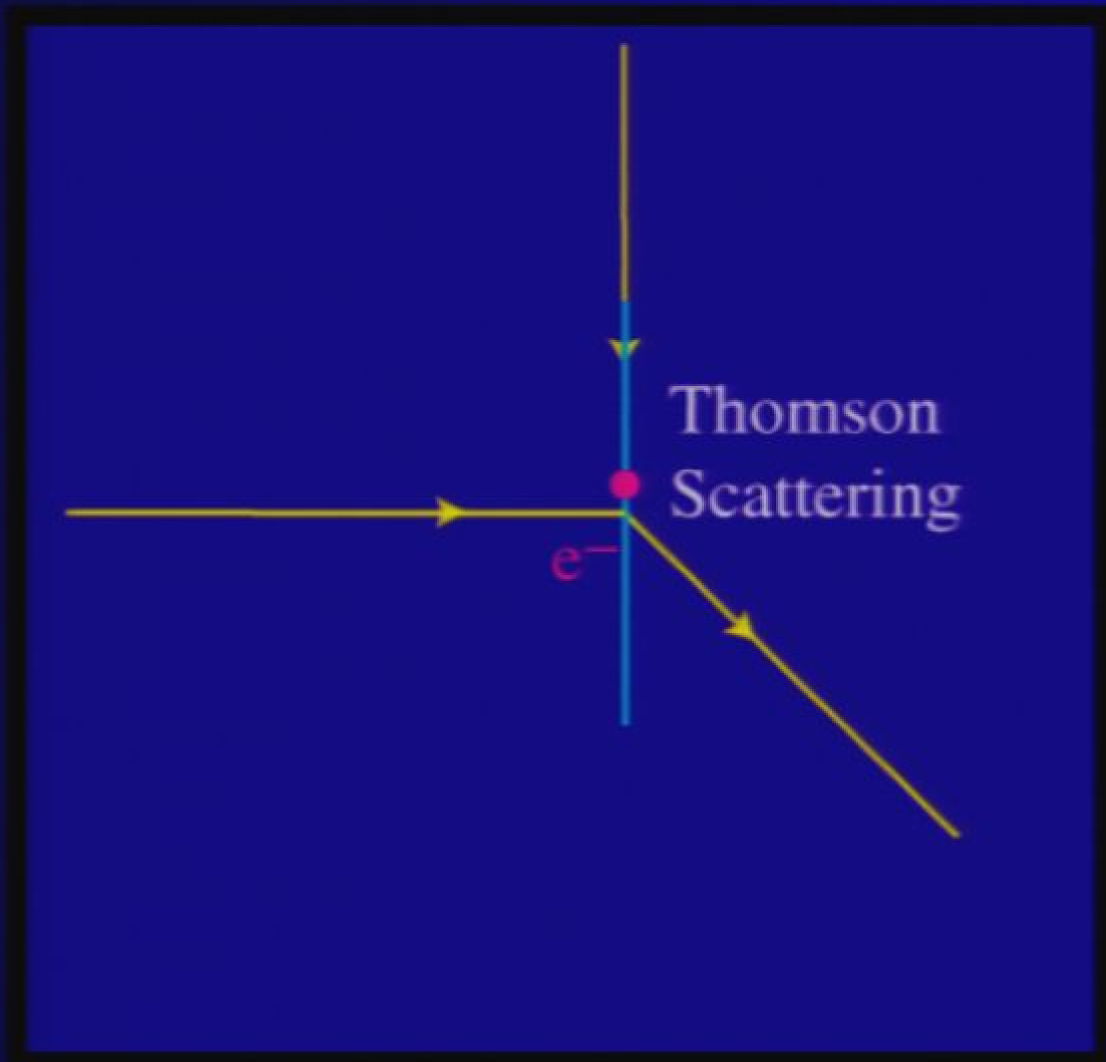

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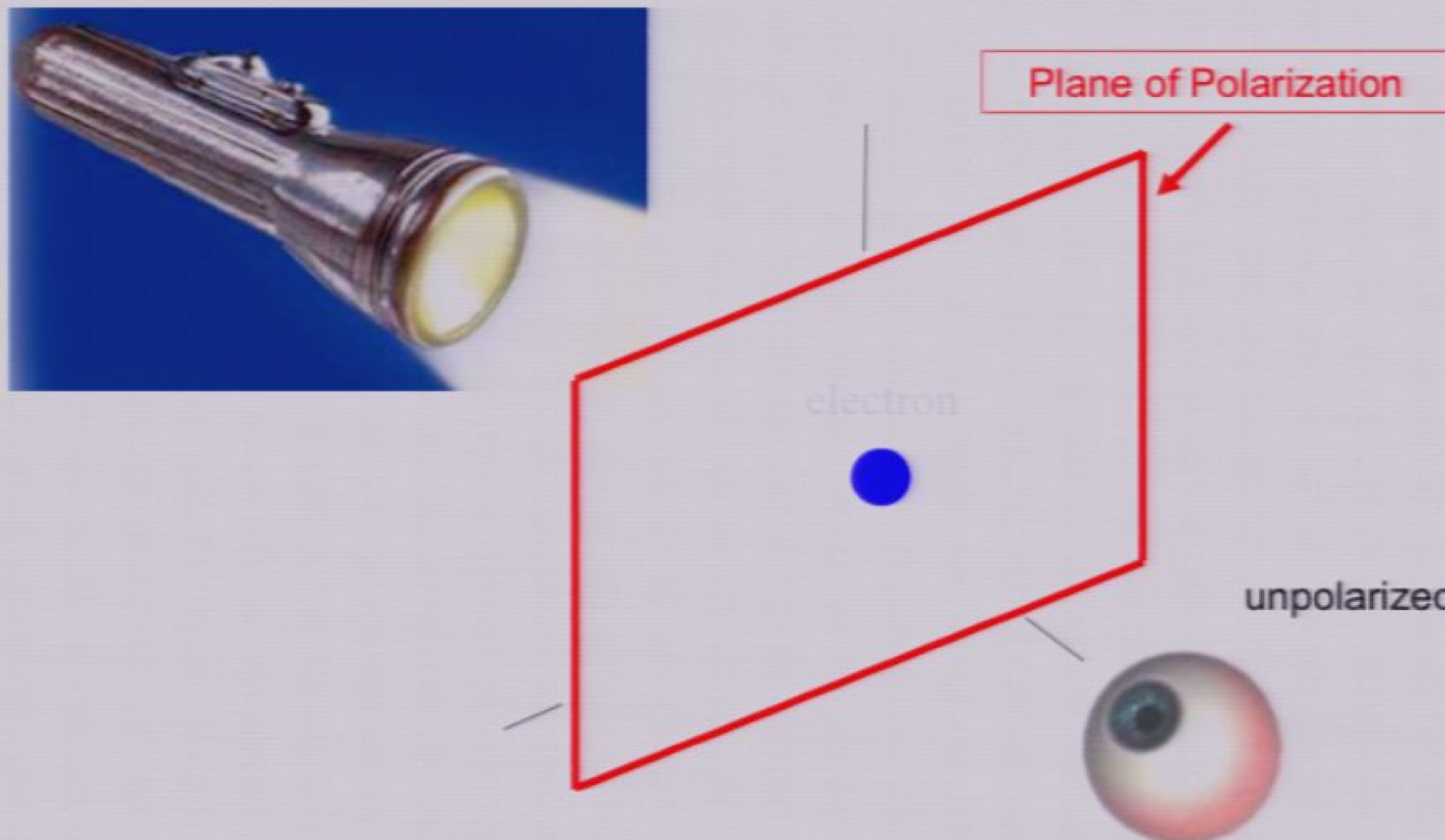

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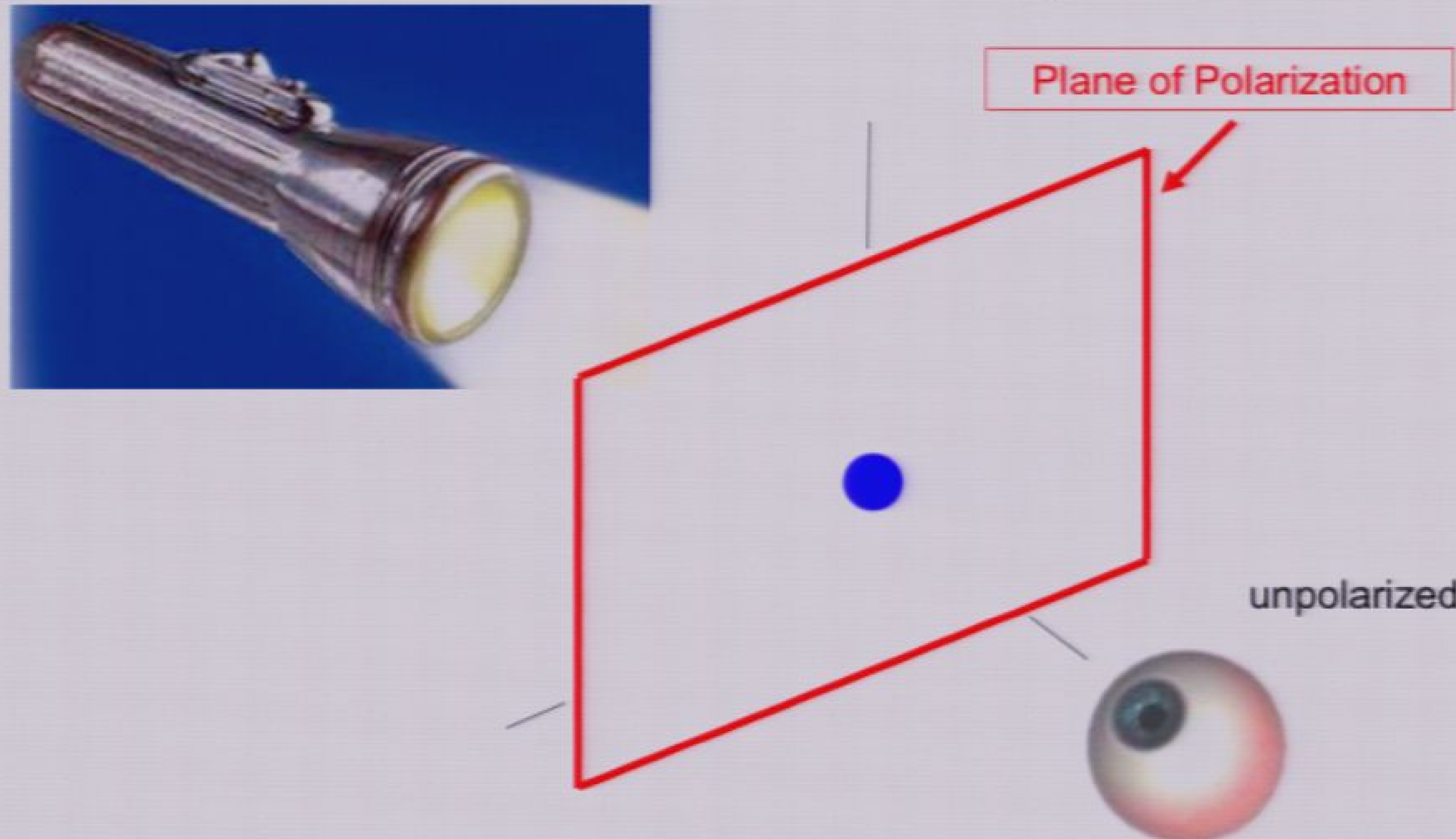

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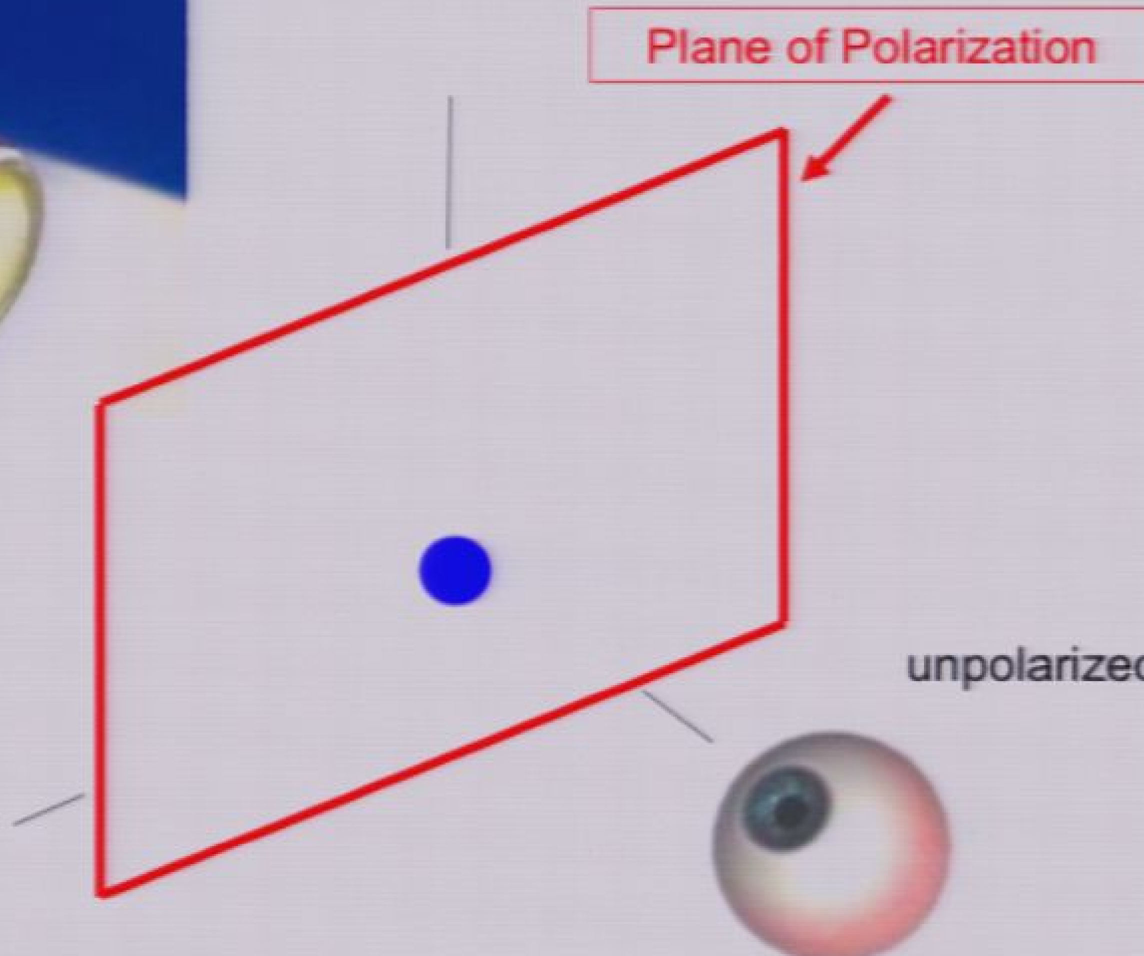

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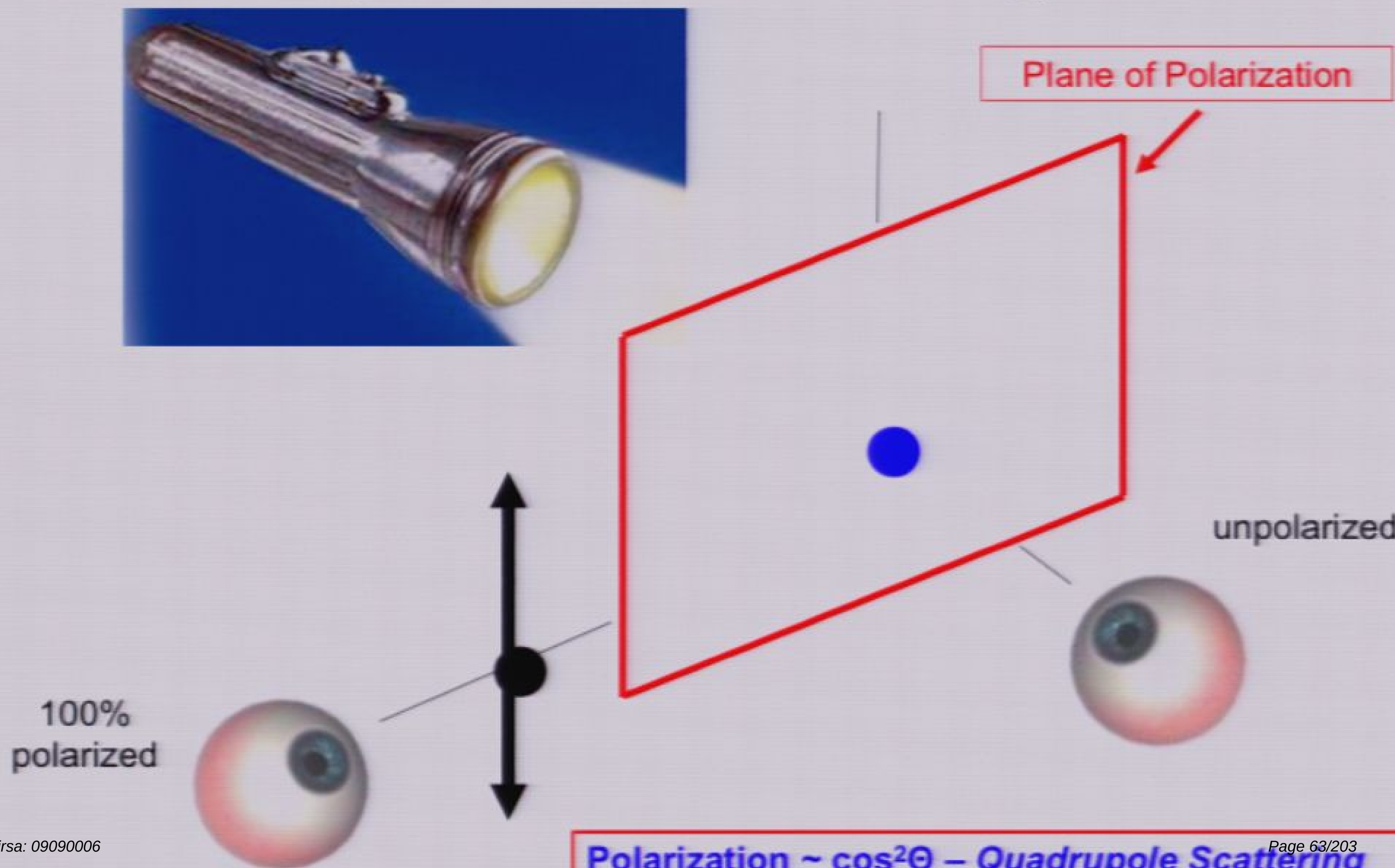

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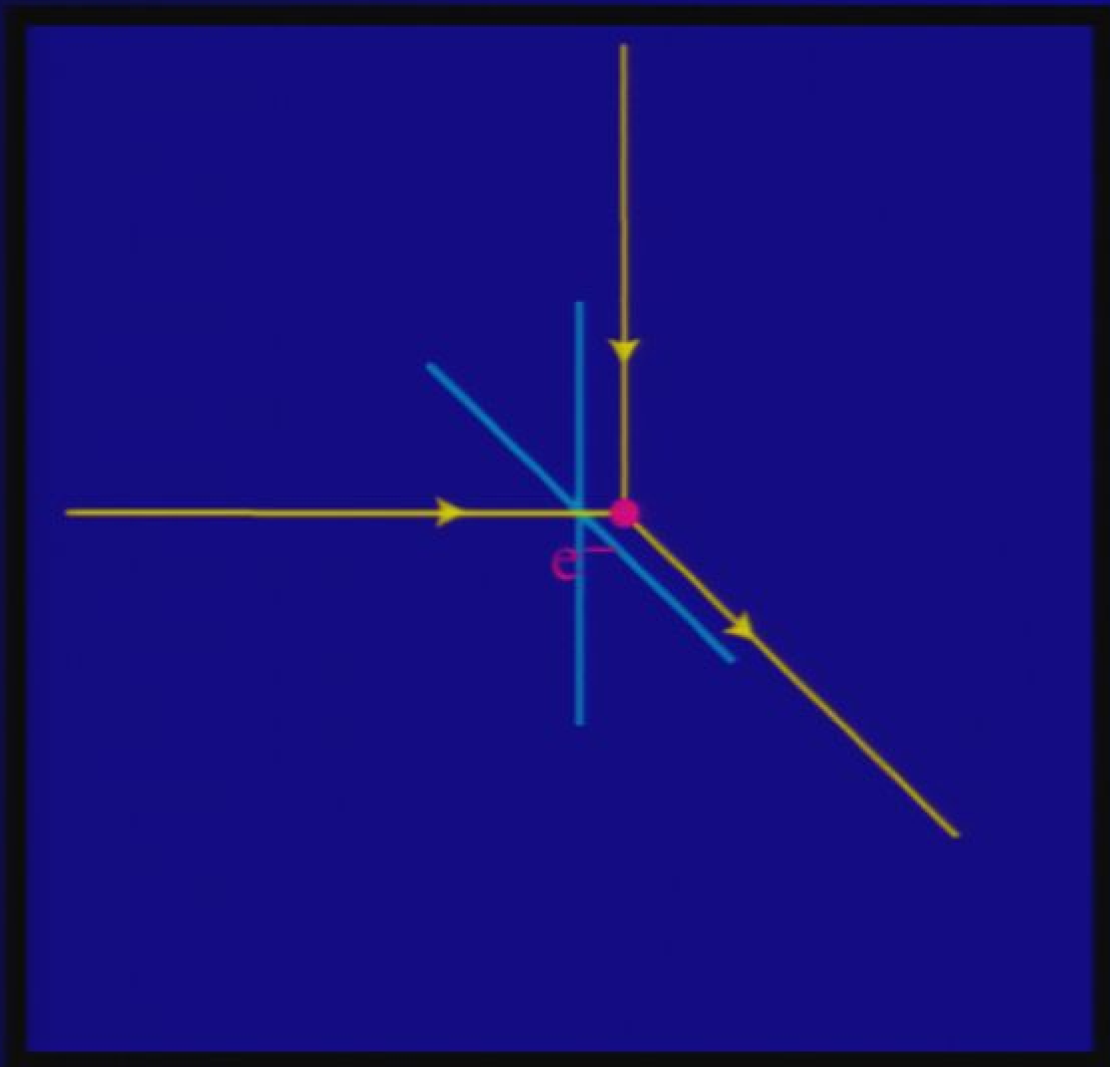

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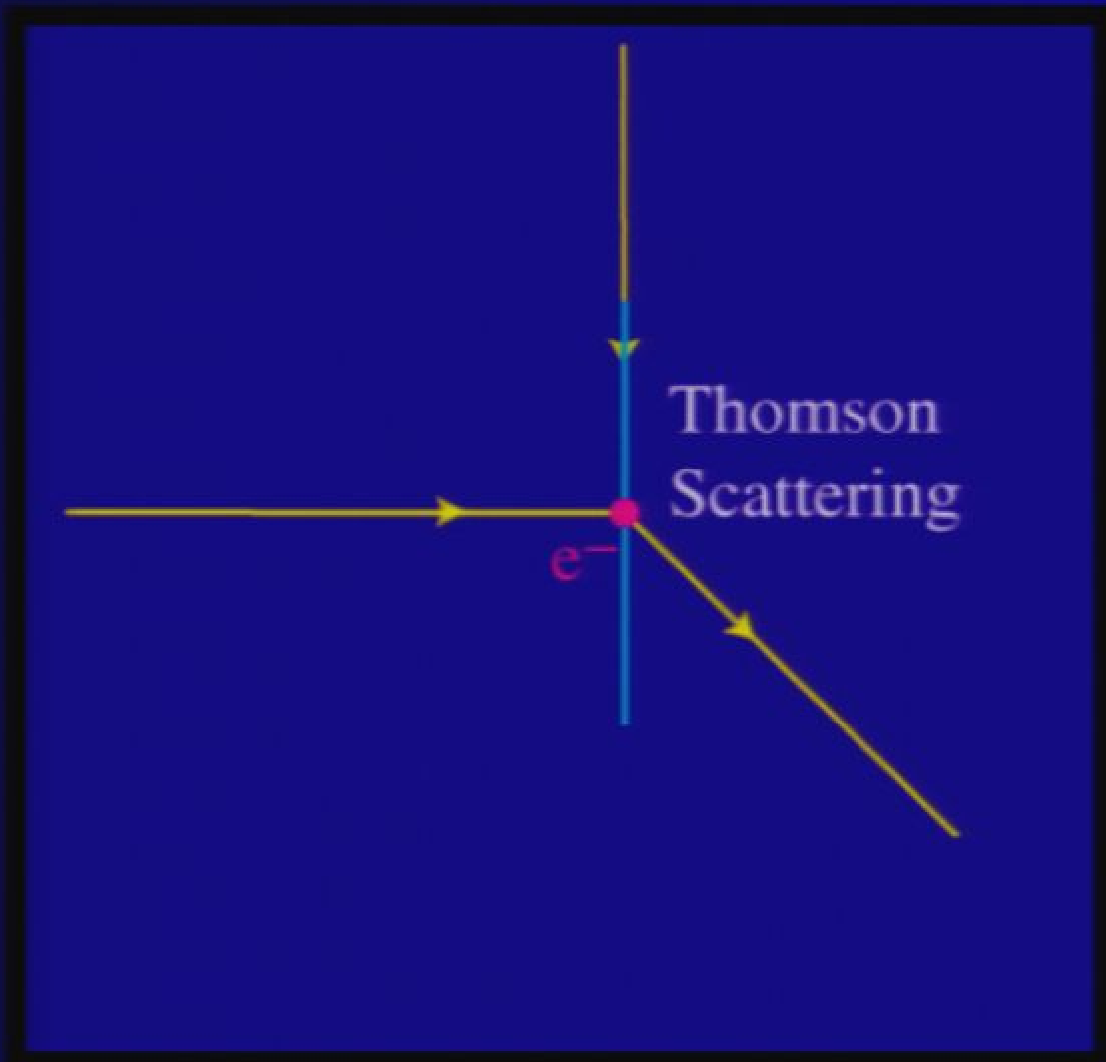

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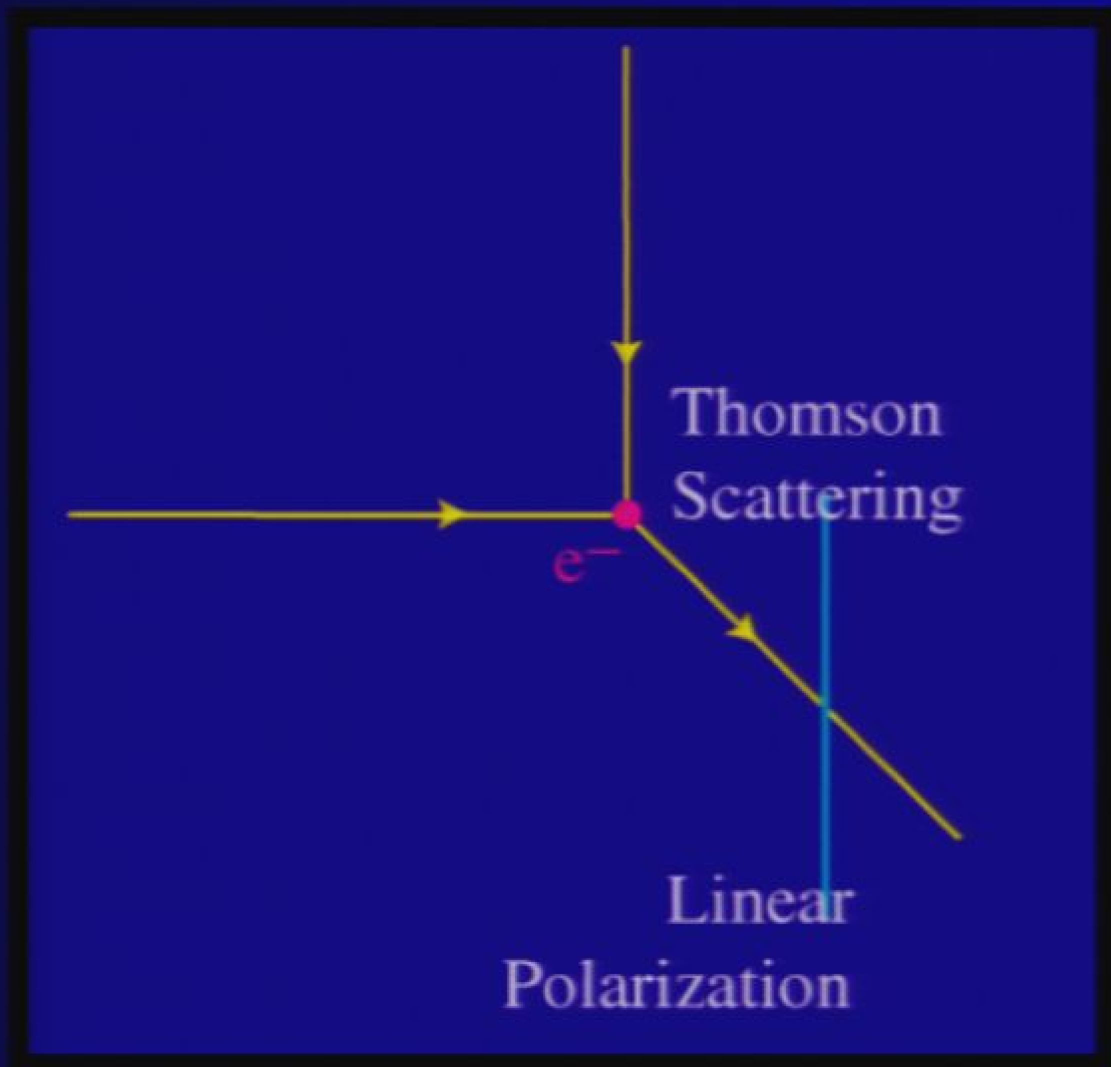
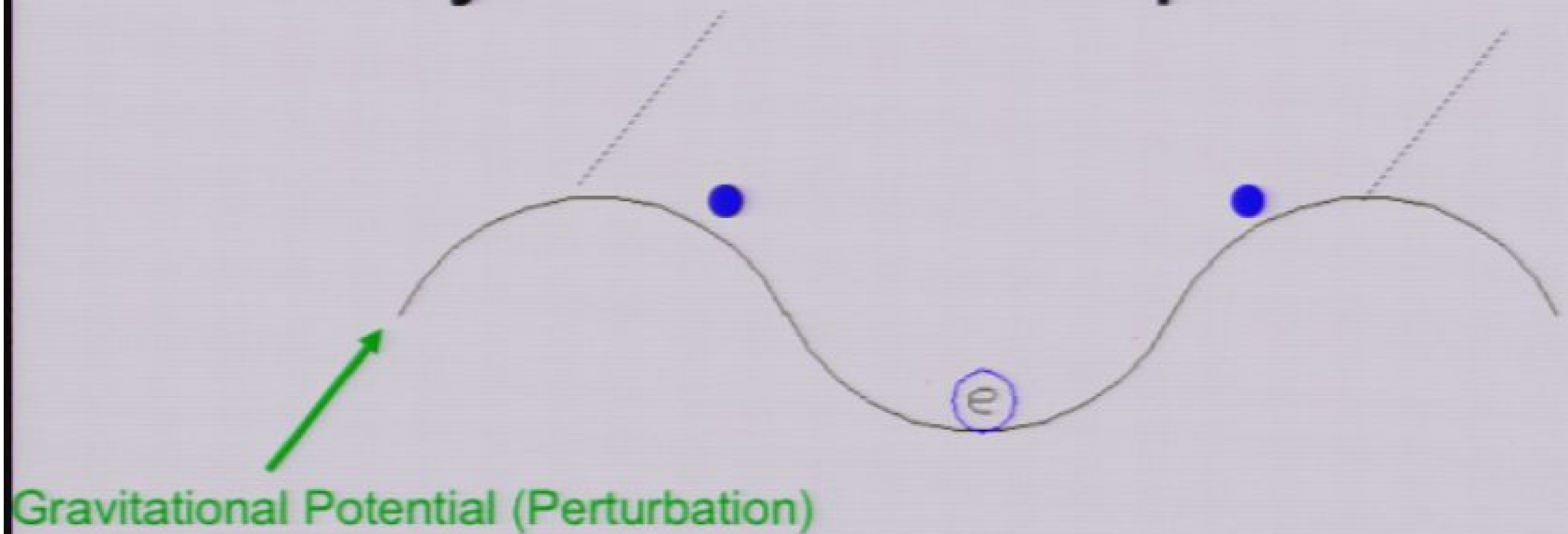


Why is the CMB polarized?



Tightly coupled regime: photons and matter flow as one fluid

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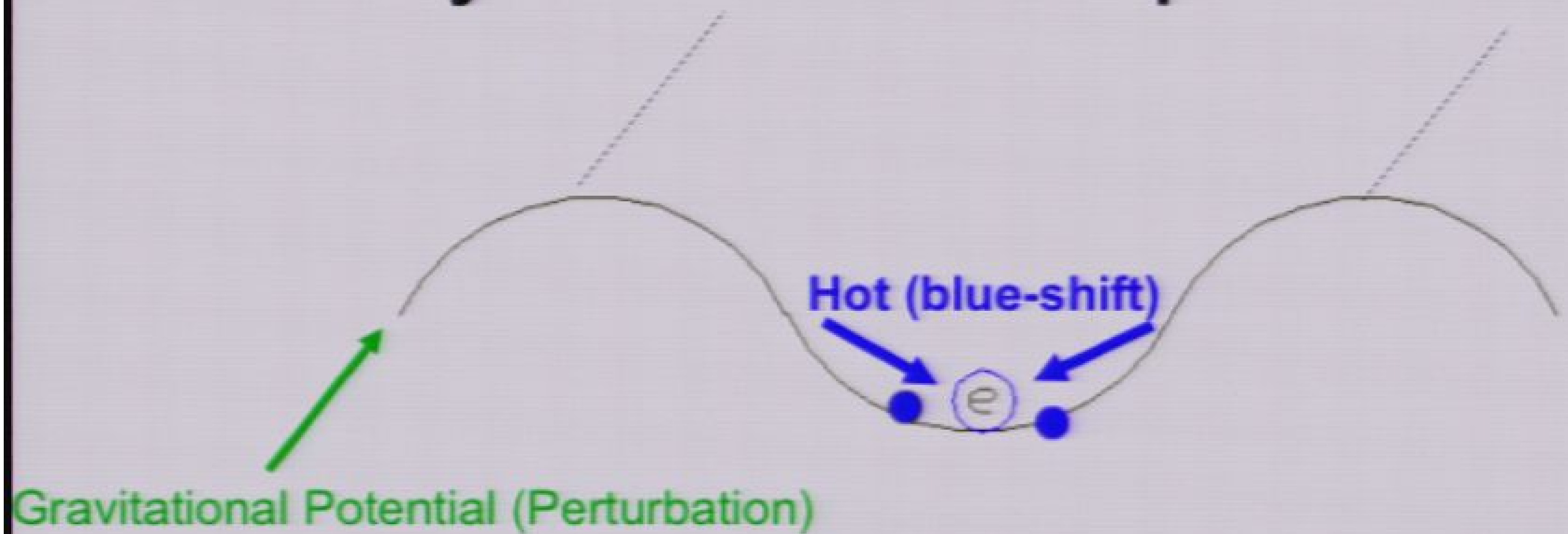

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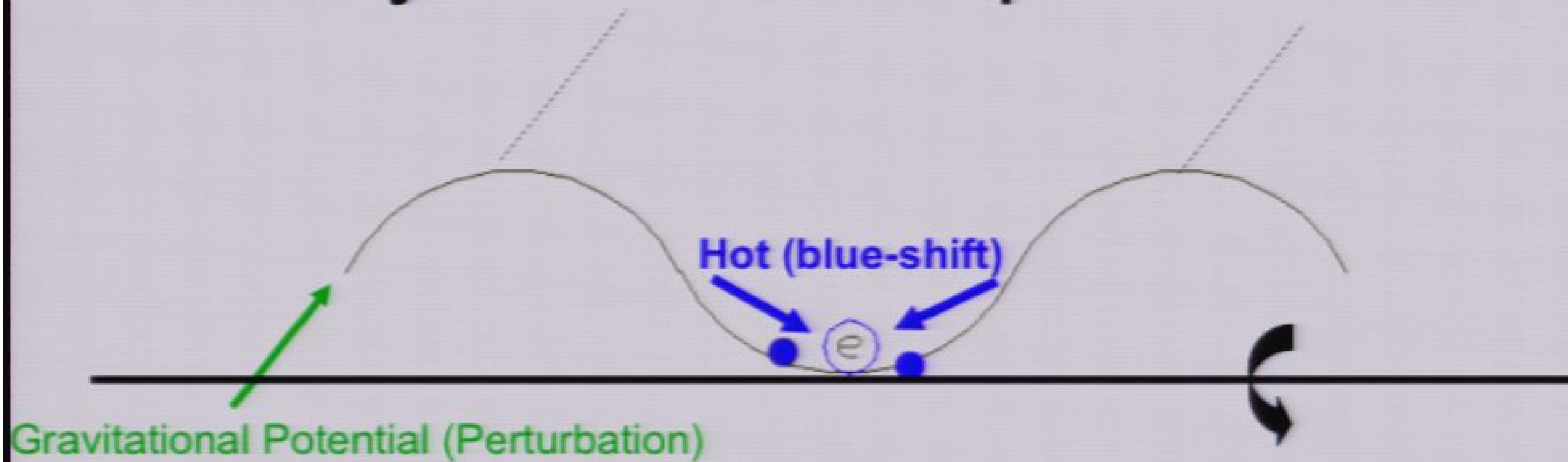

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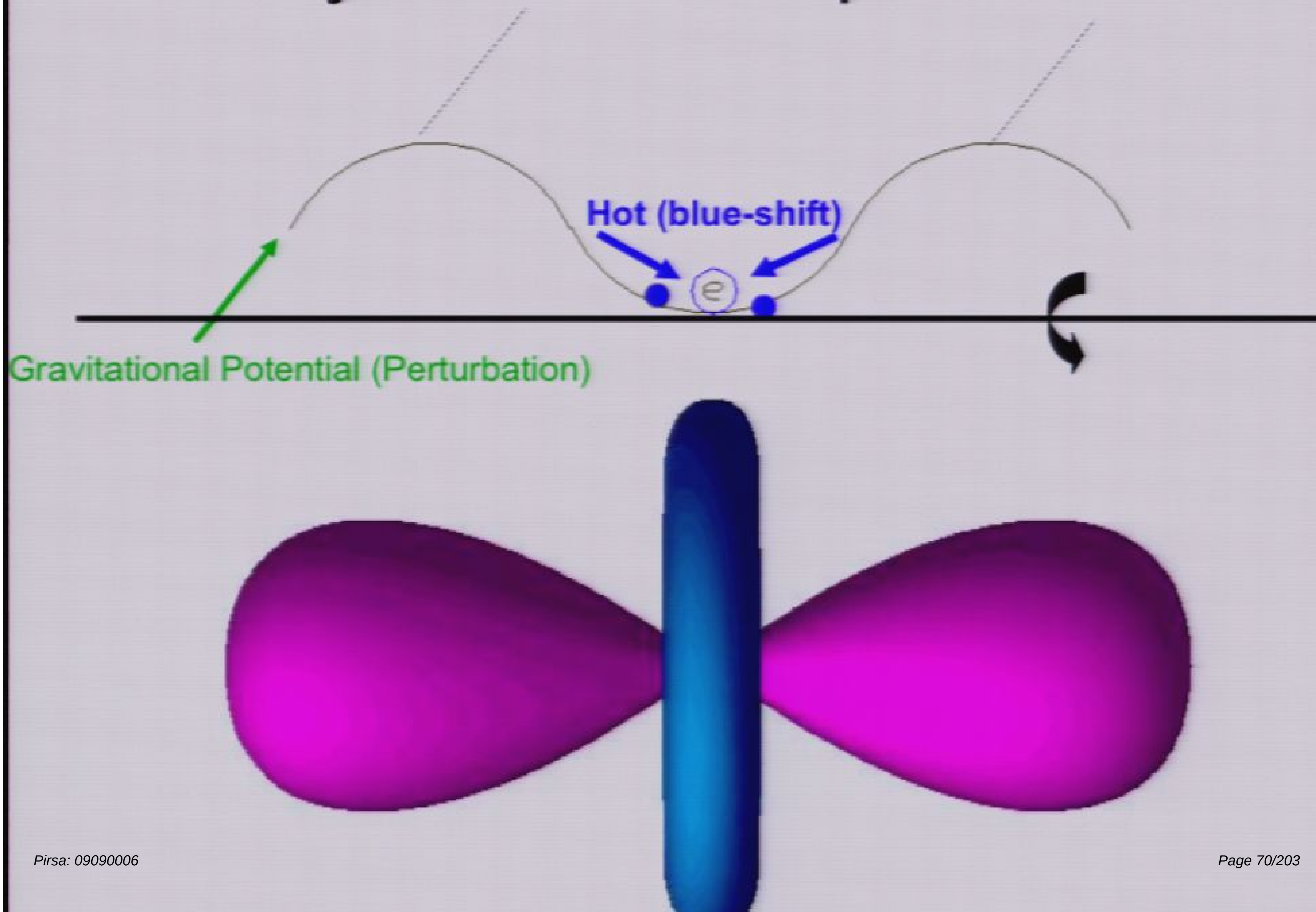

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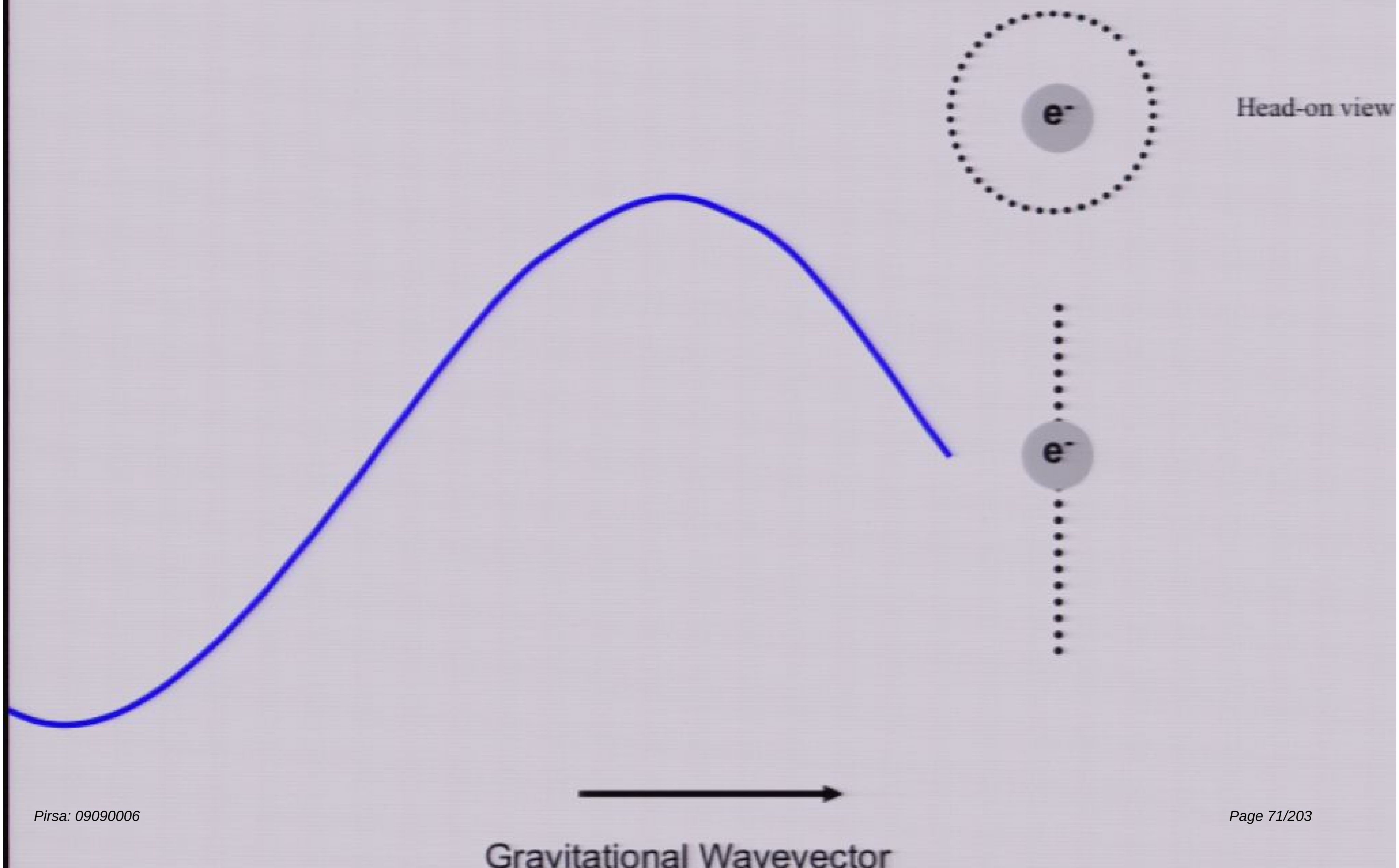

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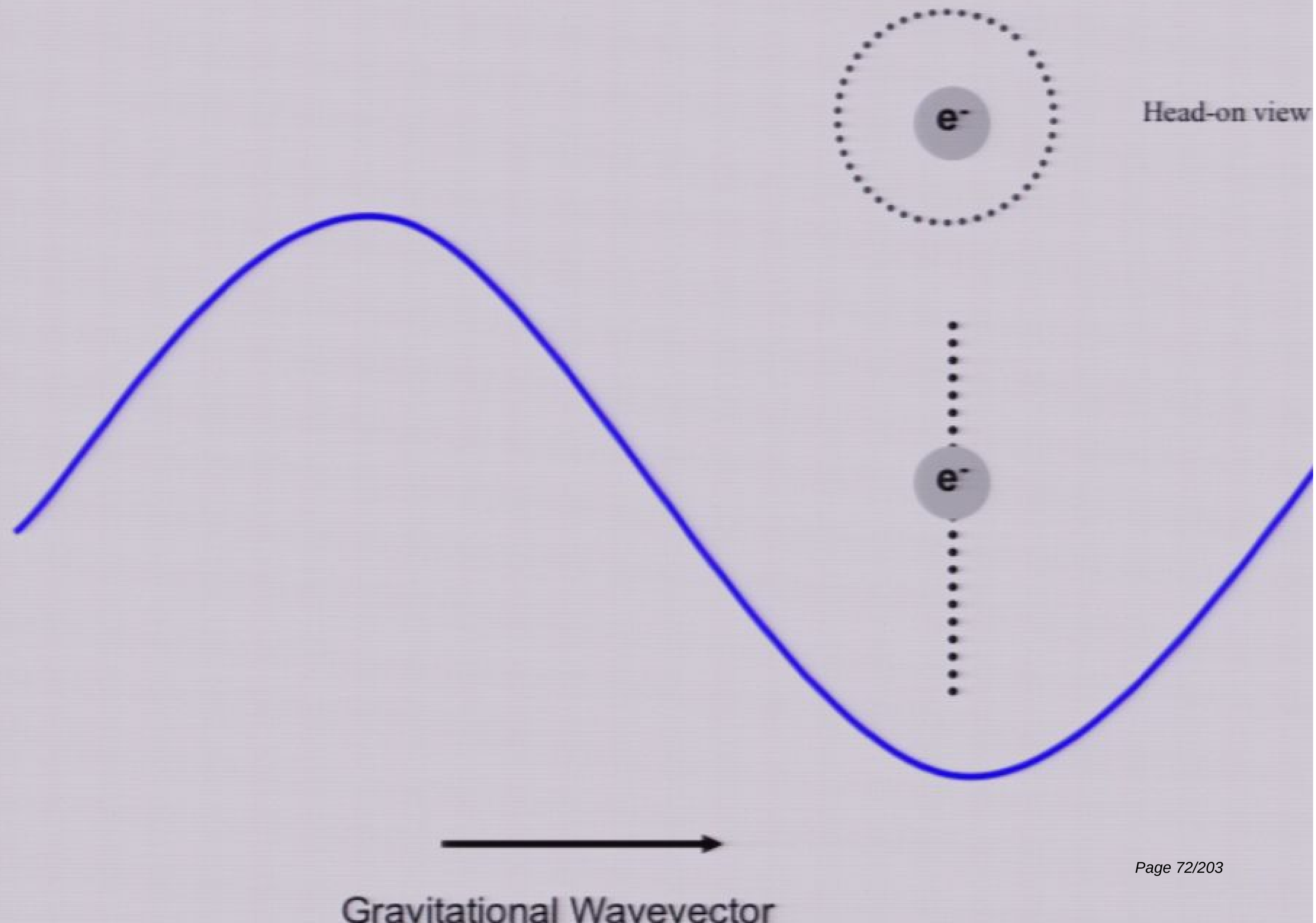

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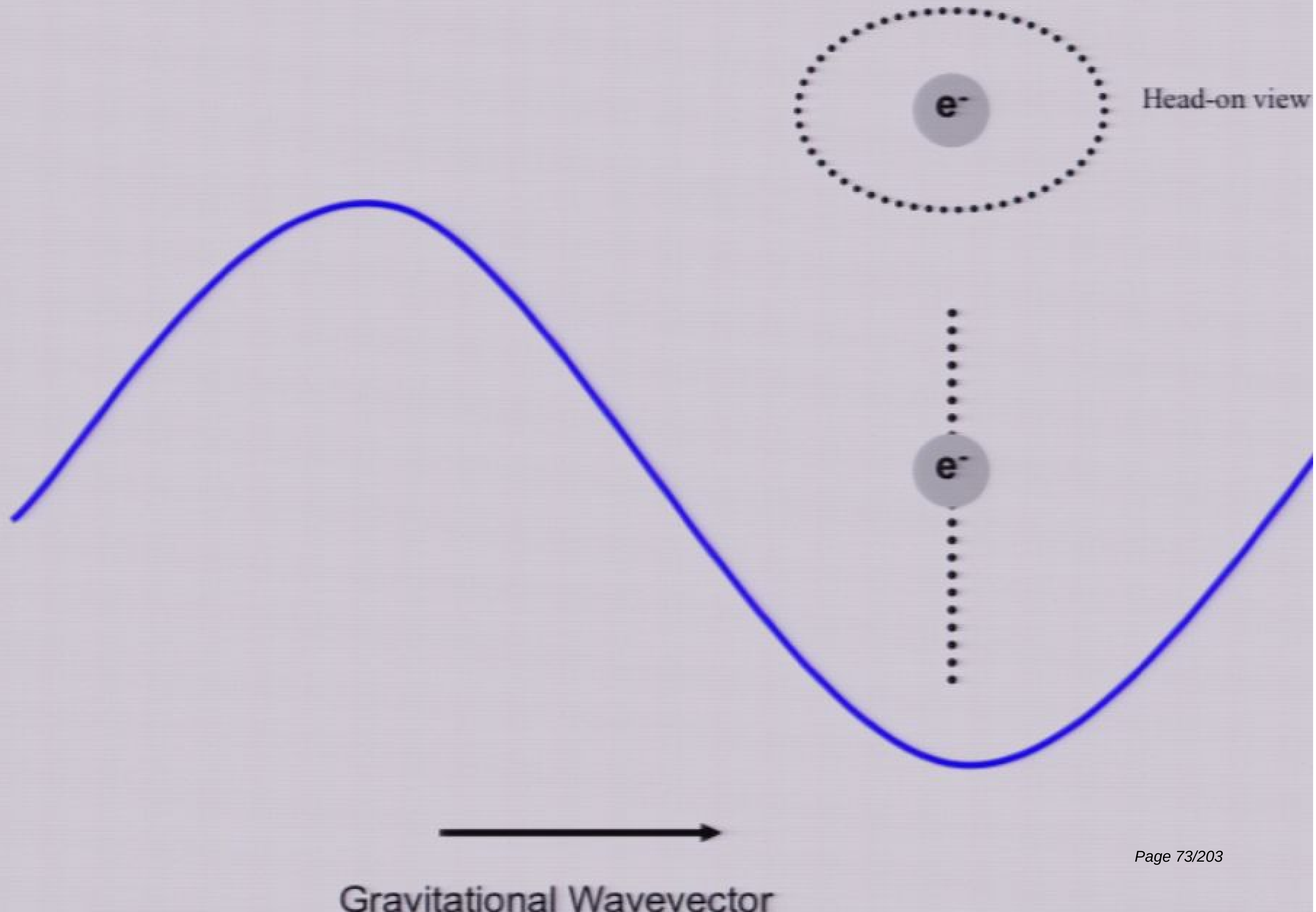

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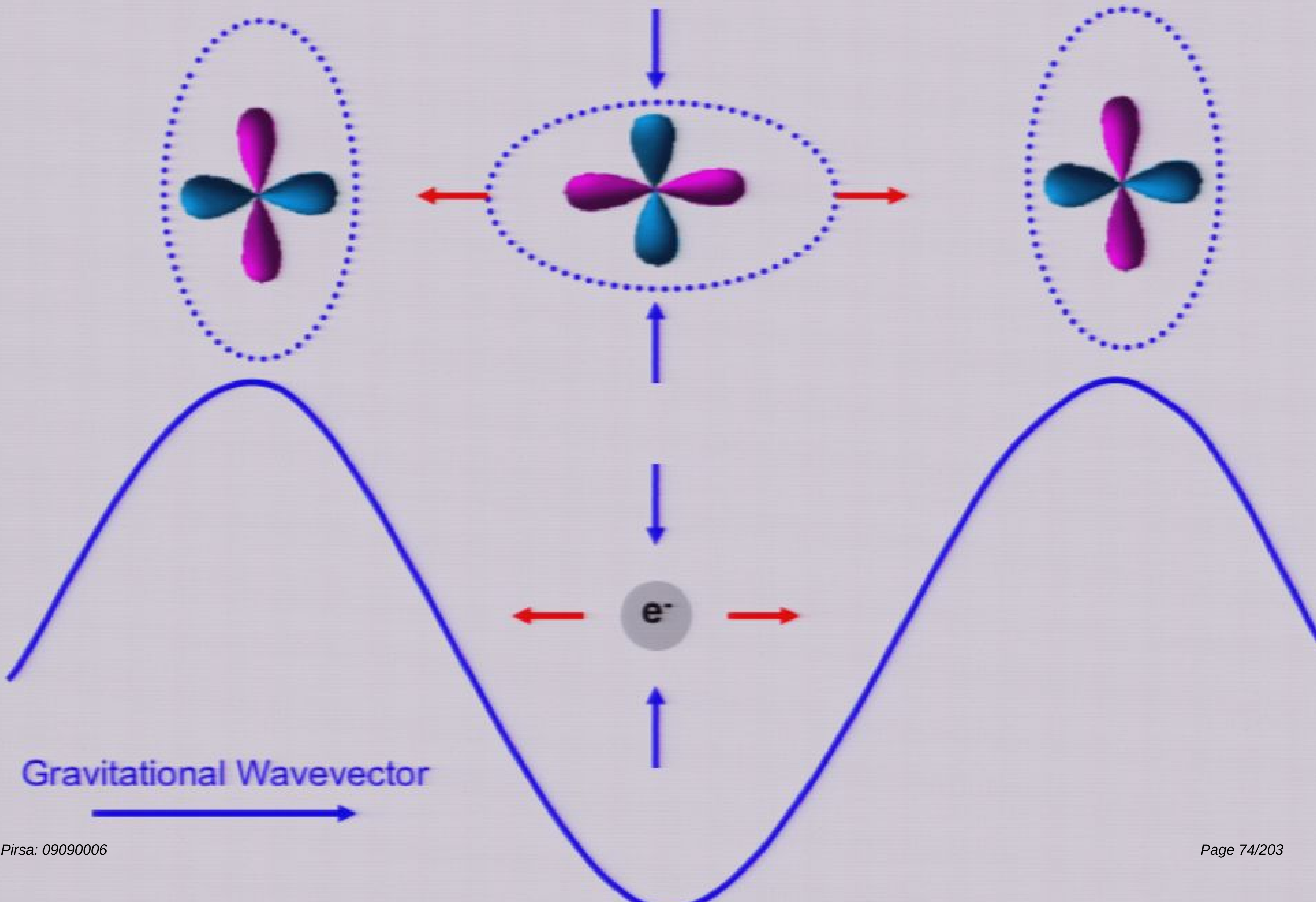
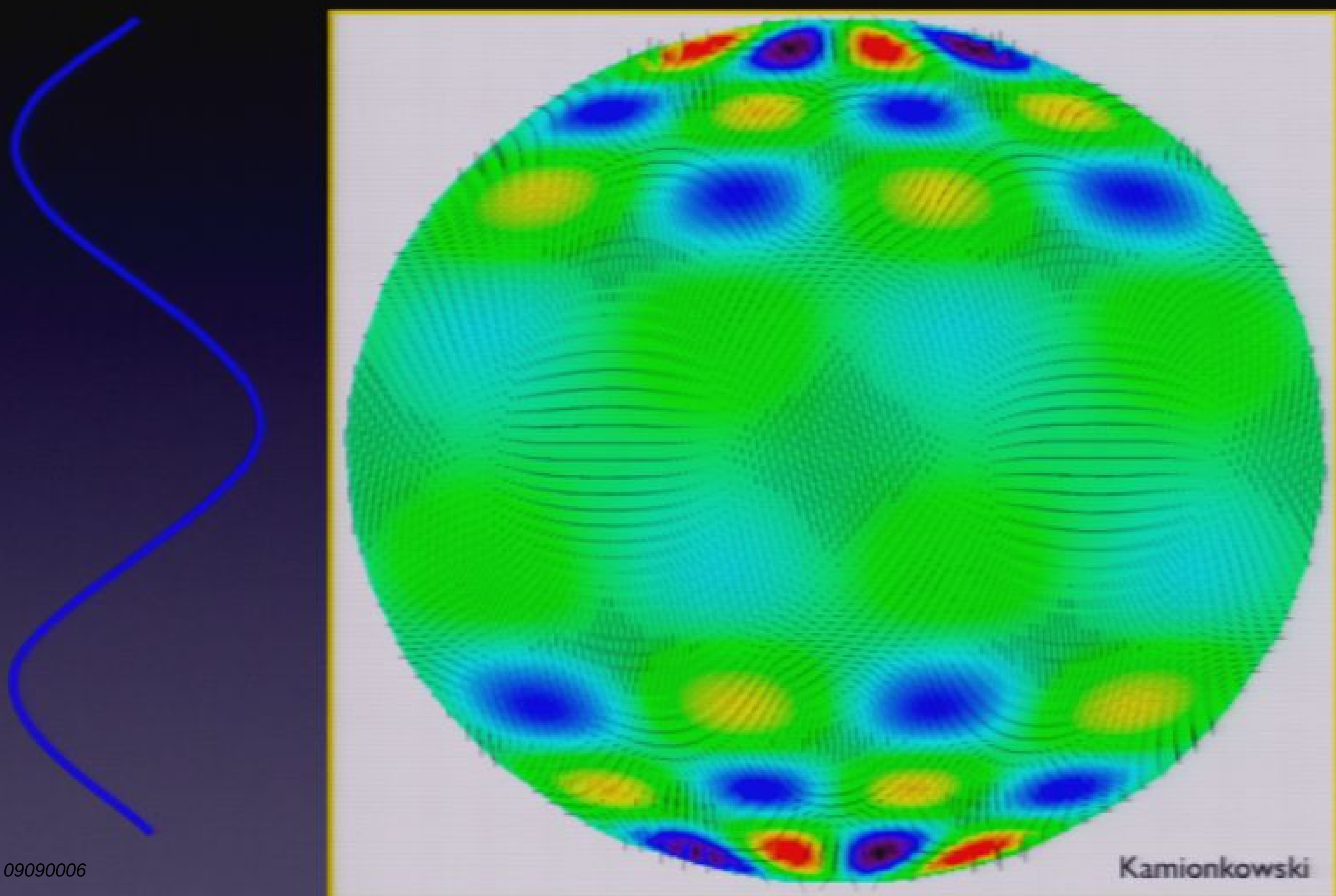


Polarization from a Single GW

First studied by Alexander Polnarev, 1985



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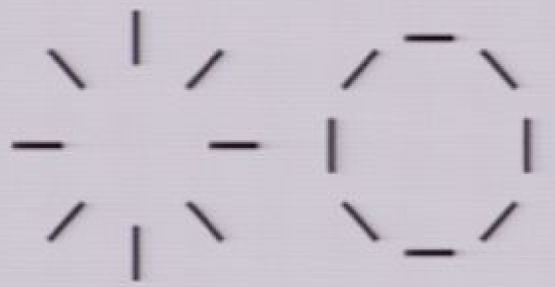
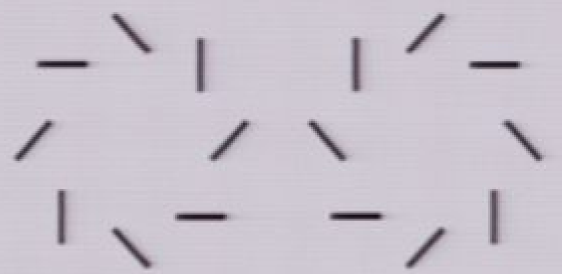
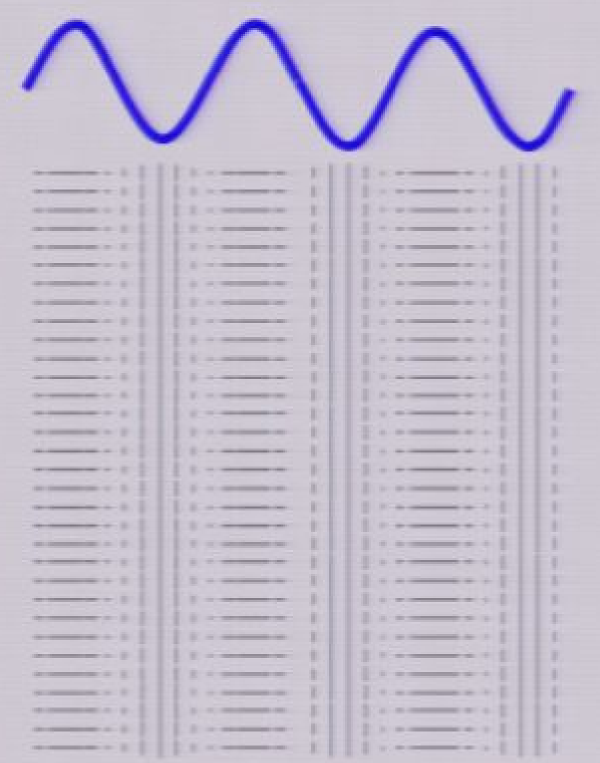


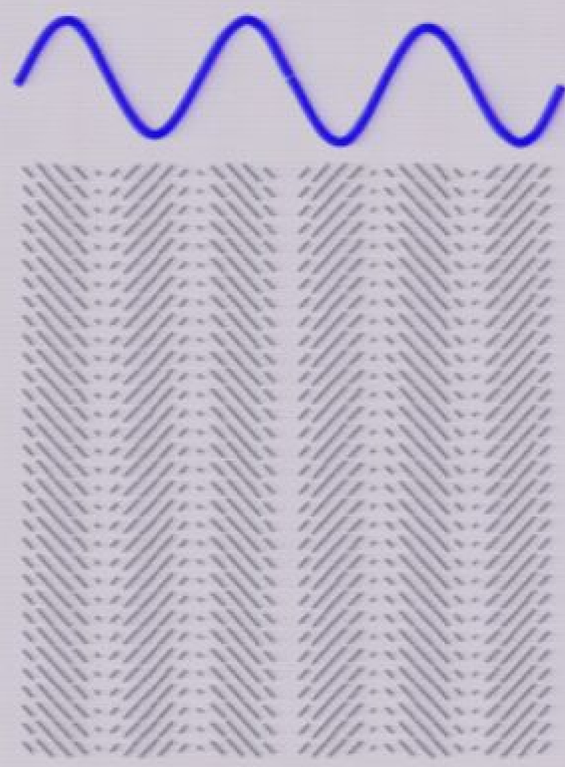
E "Hot Spot"



B "Hot Spot"



E Fourier Mode



B Fourier Mode

- Maps of Q and U can be decomposed into coordinate-independent patterns
- Modes retain their rotational invaricance upon rotation of the local coordinate system - analogous to

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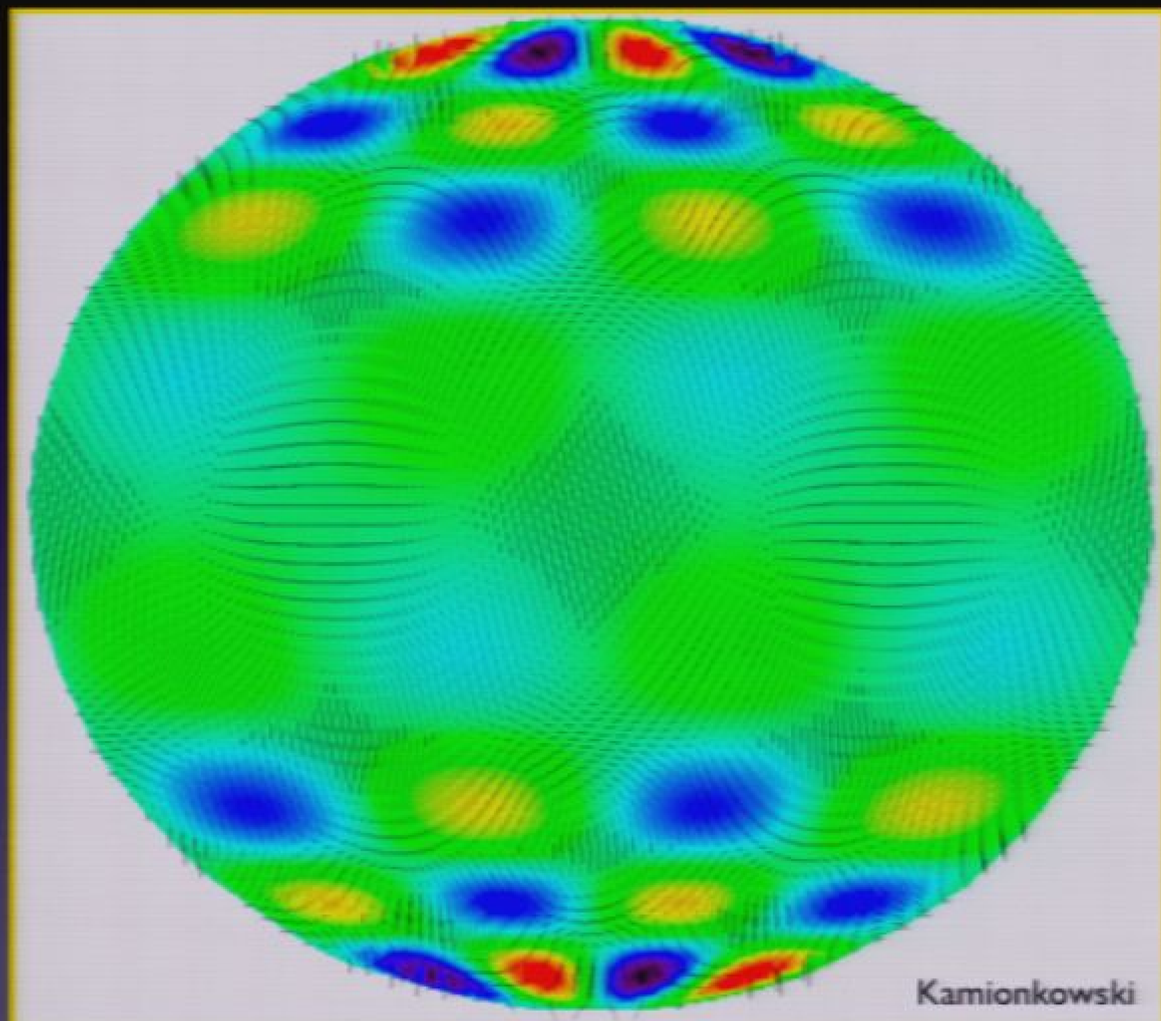

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Kamionkowski

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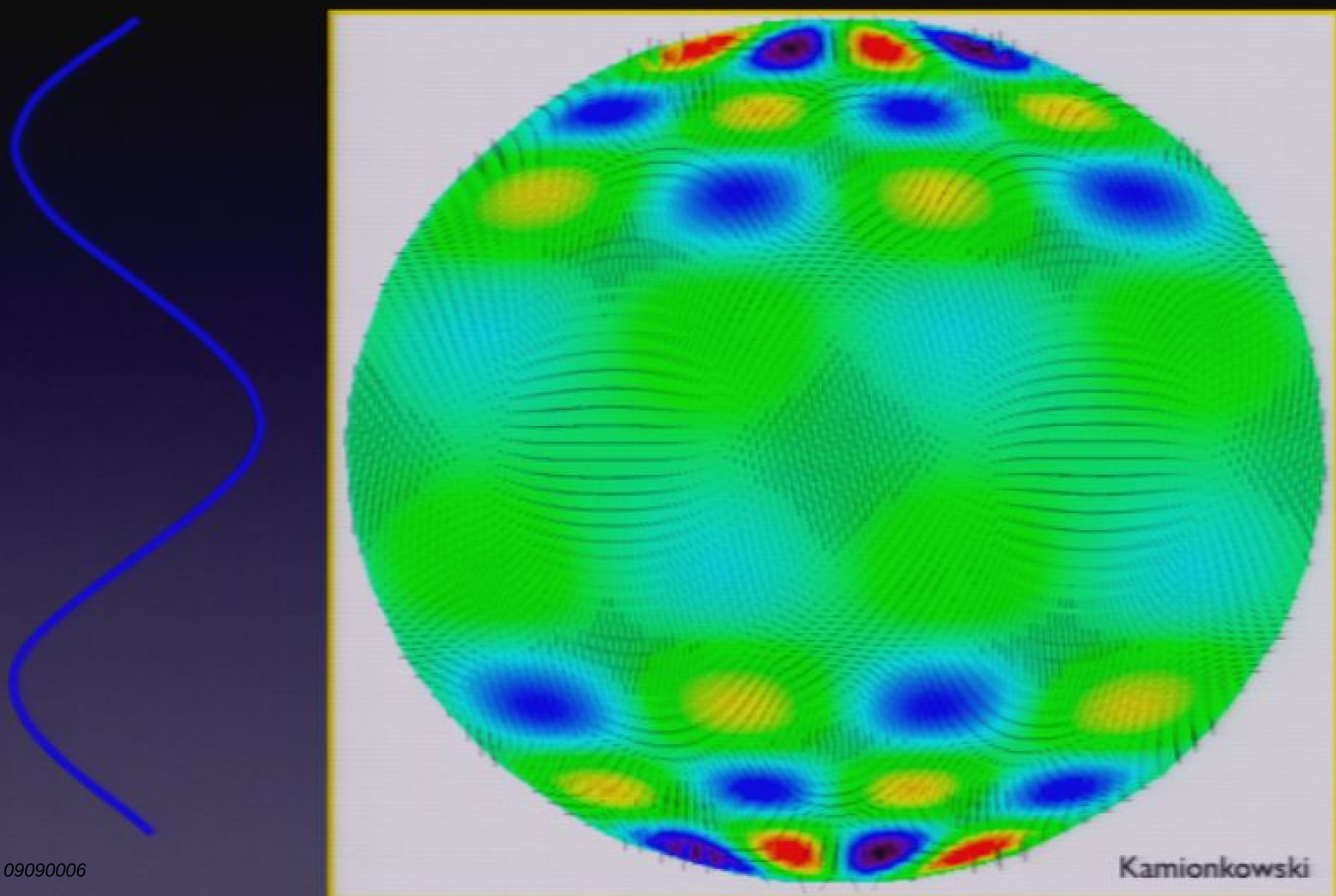

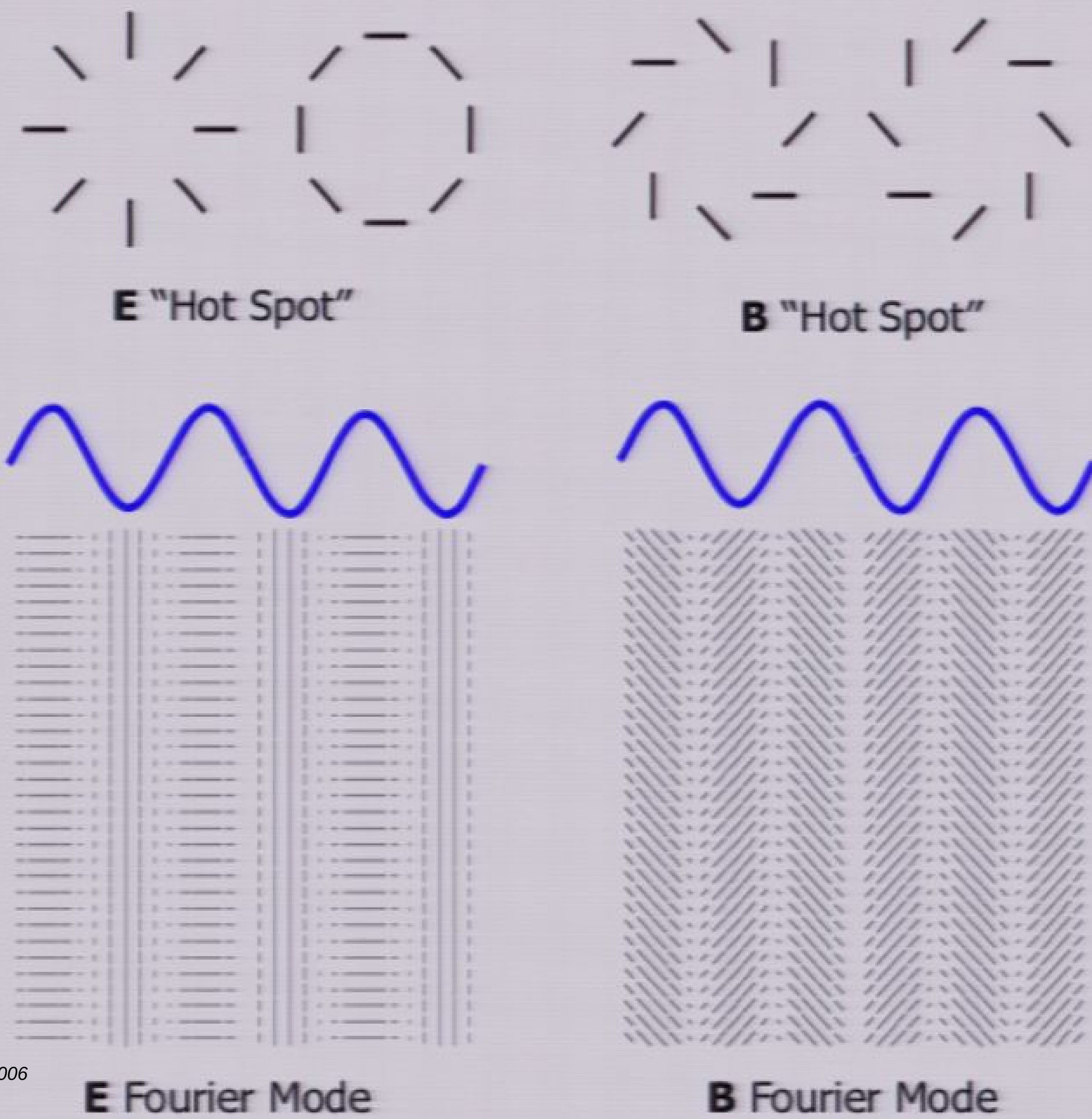

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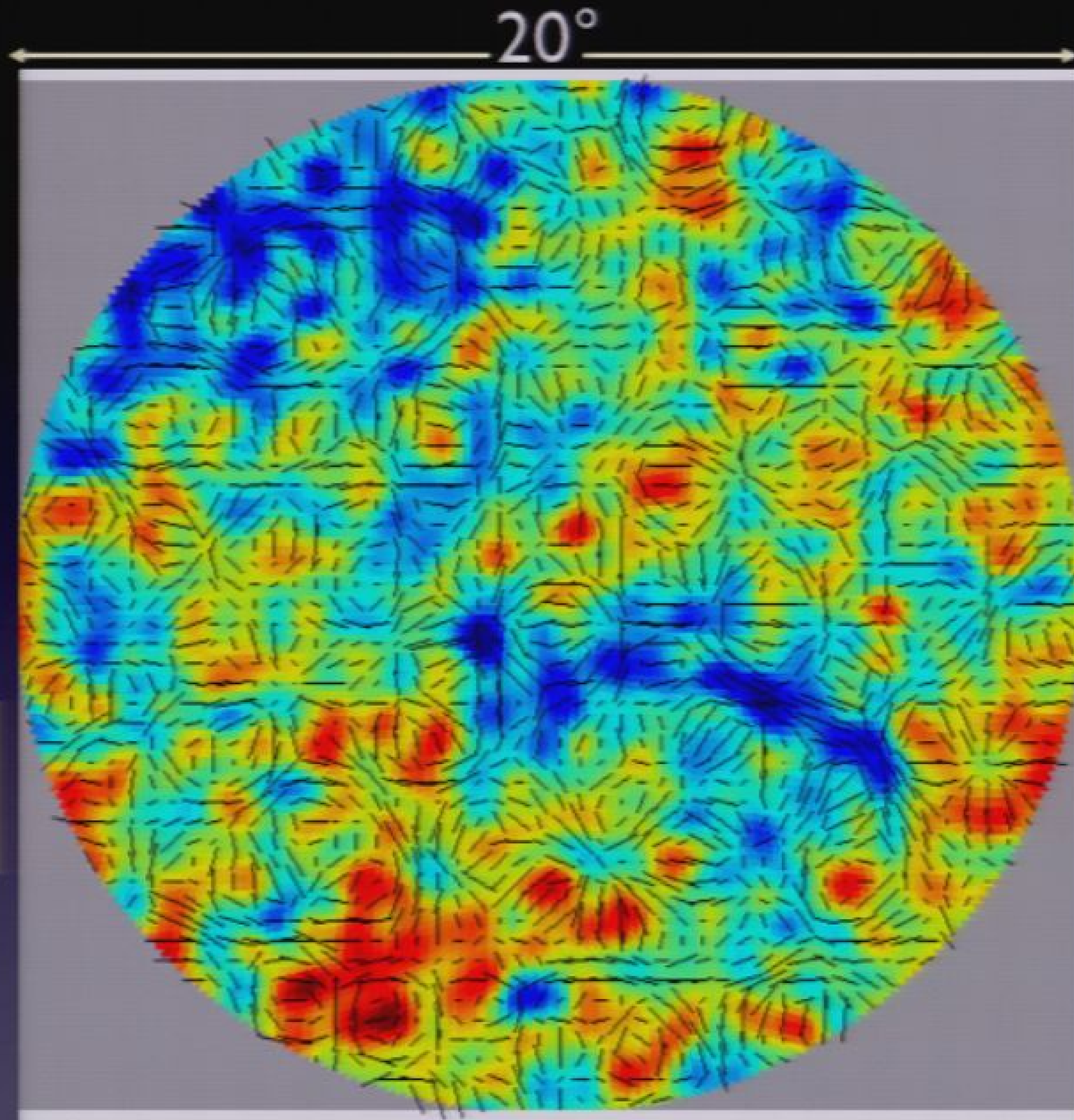
Div, Grad, Curl and All That

Simulated BICEP CMB Map

GWB: > 1° scales

Helmholtz's Thm:
"grad": even parity
"curl": odd parity



Without Gravitational Waves

Div, Grad, Curl and All That

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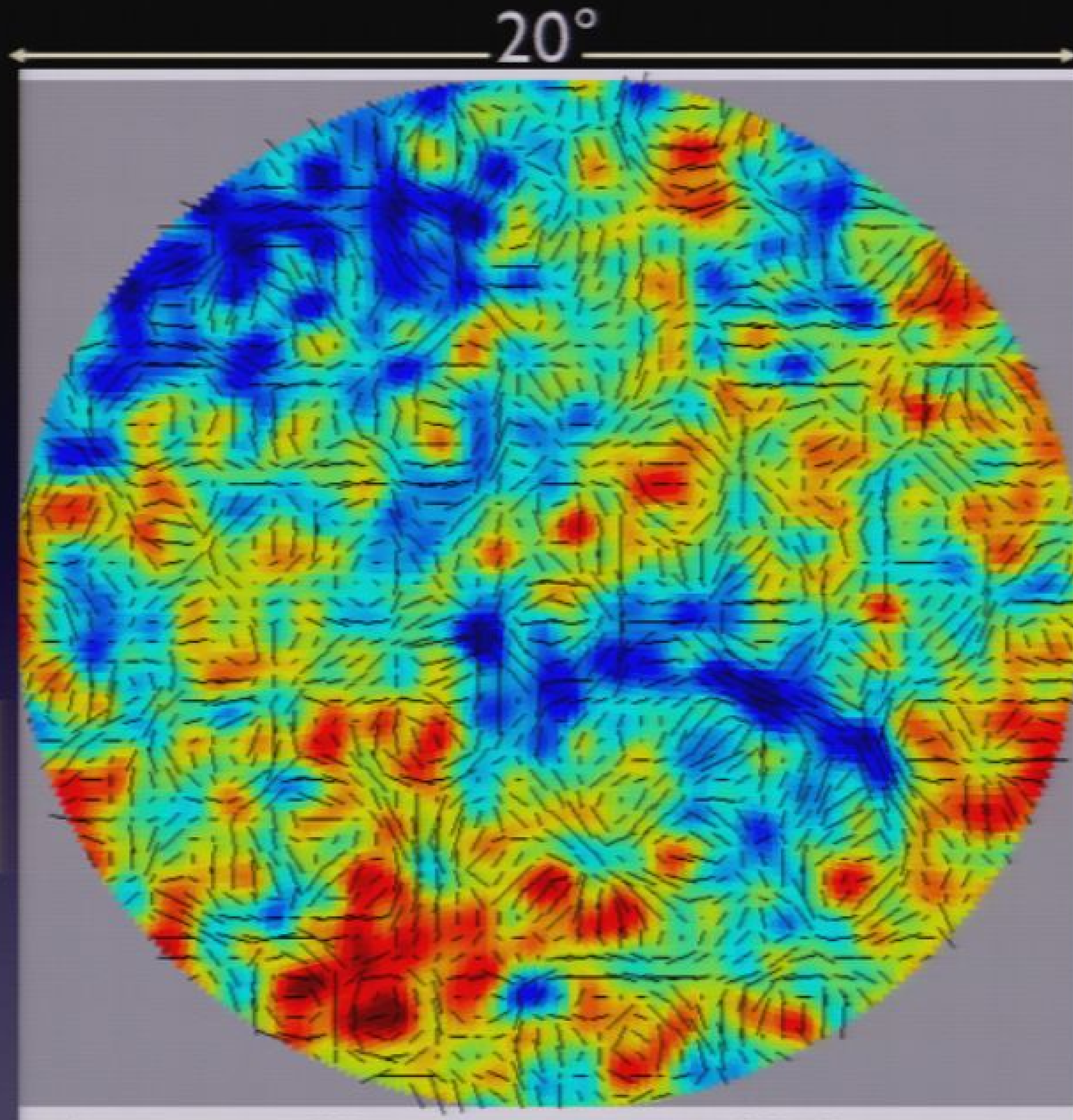

With *30 nK* Gravitational Waves!

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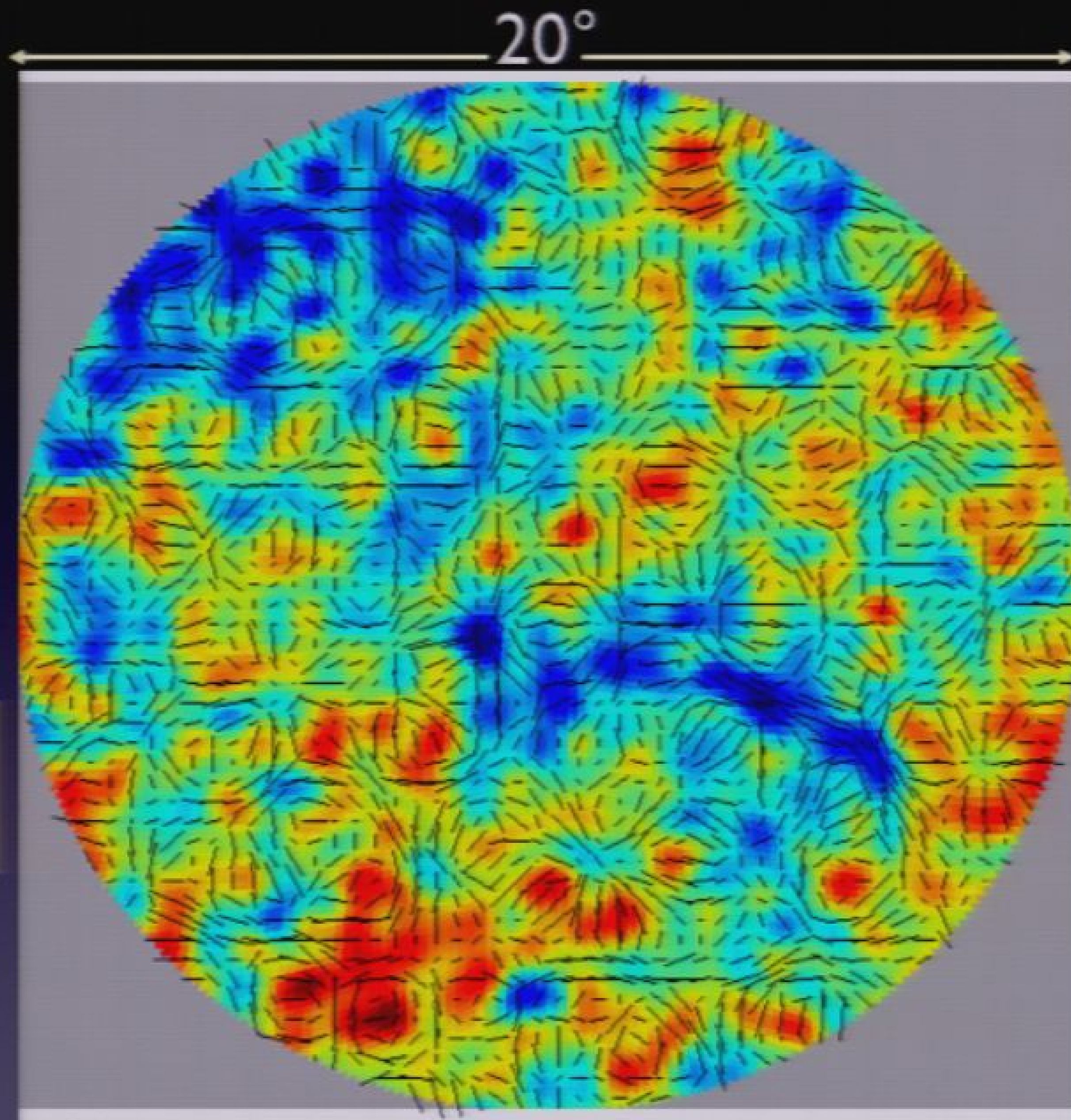

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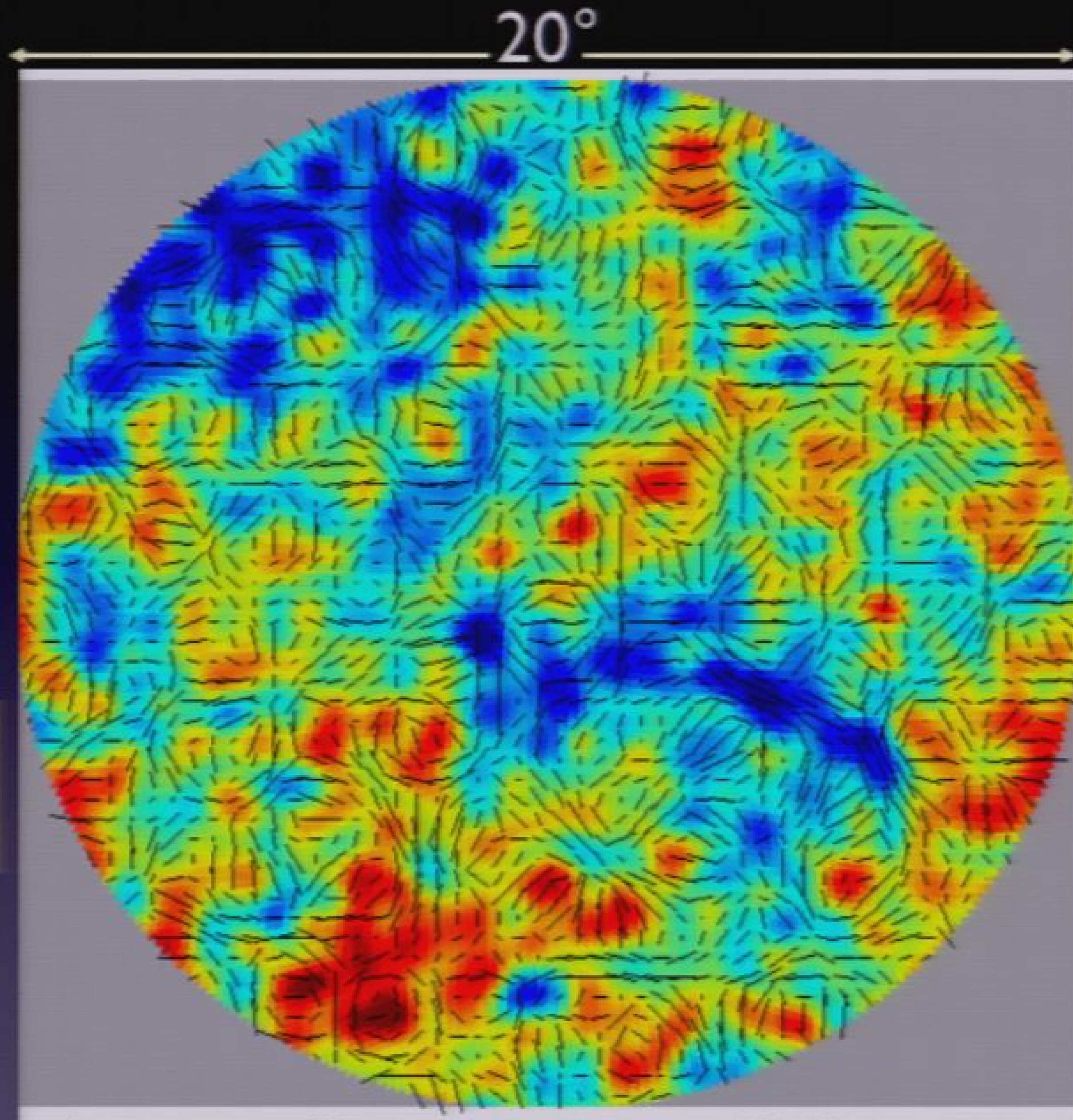
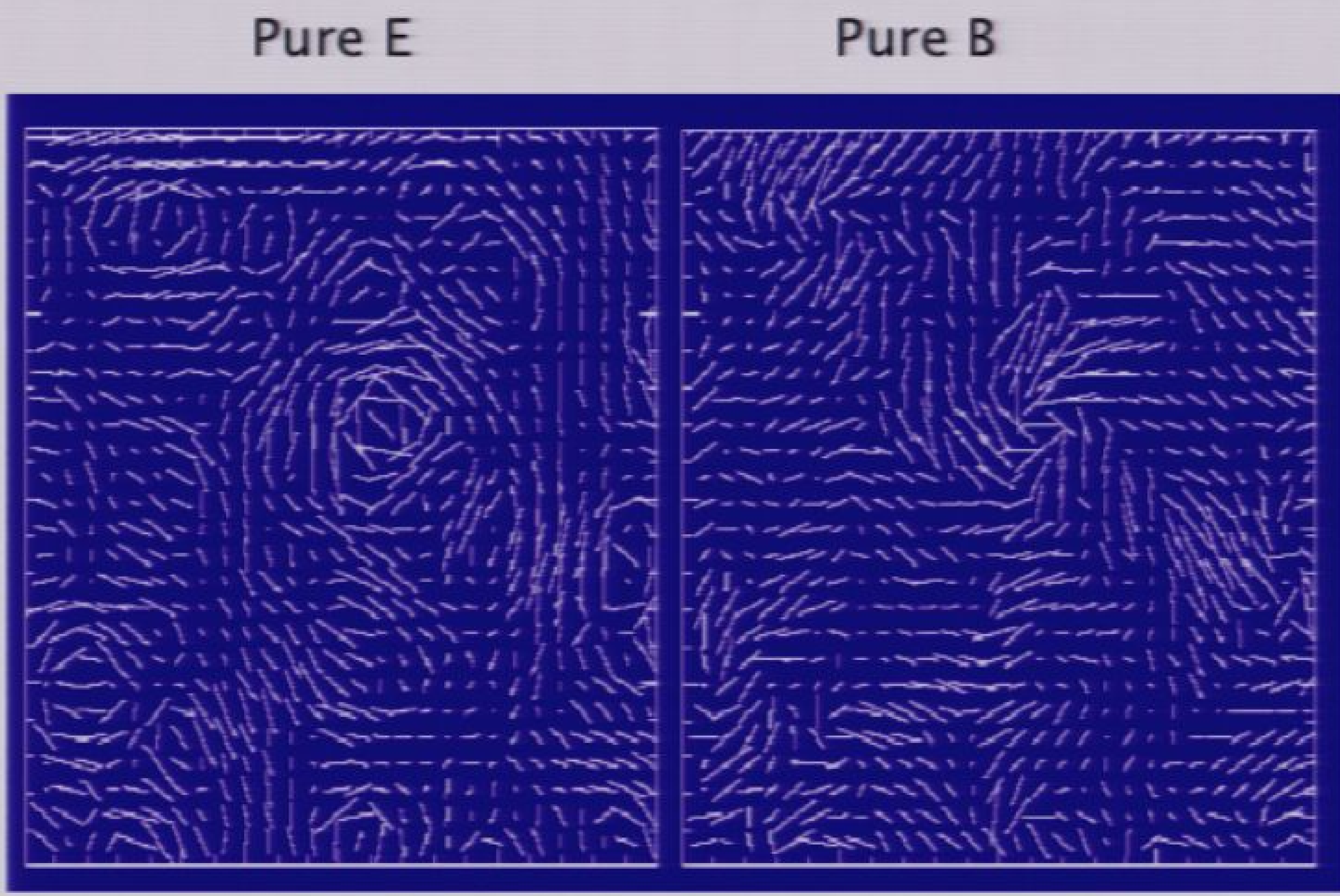


With *30 nK* Gravitational Waves!

It's clearly impossible to "see" curl effects in map space, so we resolve map into E/B

Superimposing Many Fourier Modes:



Picture by Wayne Hu

BICEP!

Bolometric Imaging of Cosmic Extragalactic Polarization

Jamie Bock*
Darren Dowell
Hien Nguyen
Eric Hivon
Denis Barkats

Andrew Lange**
Cynthia Chiang
John Kovac
Bill Jones
Chao-Lin Kuo
Tomotake Matsumura
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JPL / IPAC / Caltech

Brian Keating*
Evan Bierman
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Peter Ade
U. Cardiff

Bill Holzapfel*
Yuki Takahashi
U.C. Berkeley

Lionel Duband
CEA, Grenoble

** = PI
* = Co-I

"The Muscle Behind Curls"

Brian G. Keating (UCSD)

Background Imaging of Cosmic Extragalactic Polarization

Caltech / JPL

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U Chicago

Clem Pryke, Chris Sheehy

Princeton

Bill Jones, Cynthia Chiang

Stanford

Chao-Lin Kuo, Jamie Tolan

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Cardiff

Peter Ade

IAP, Paris

Eric Hivon*

IAS, Orsay

Nicolas Ponthieu*

CEA Grenoble

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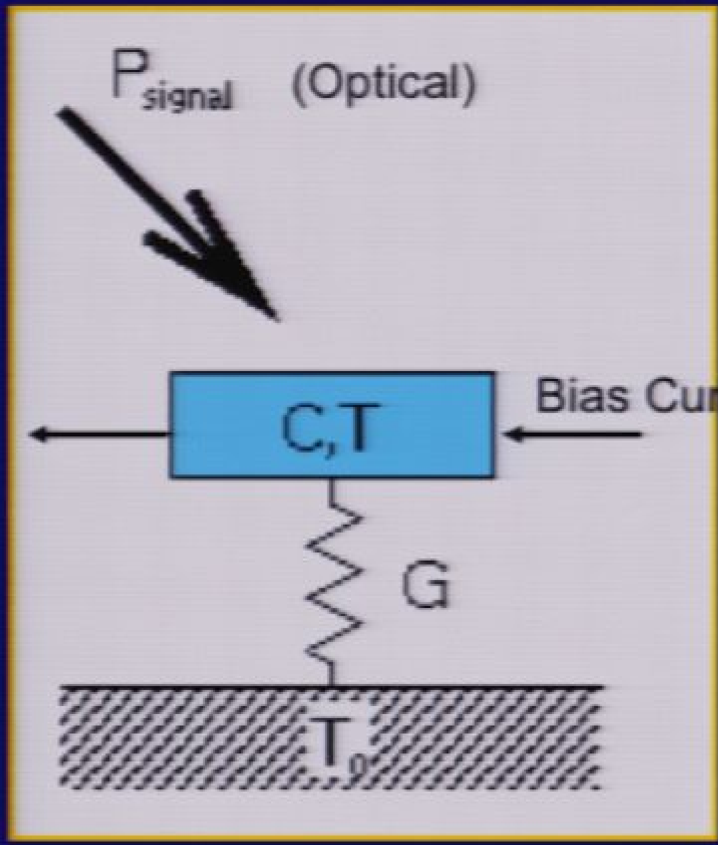
NRAO

Denis Barkats*

Bolometers

- Temperature dependent resistor
- Most sensitive detectors in frequency range 60 – 1000 GHz

(λ = 5mm – 300 μm)



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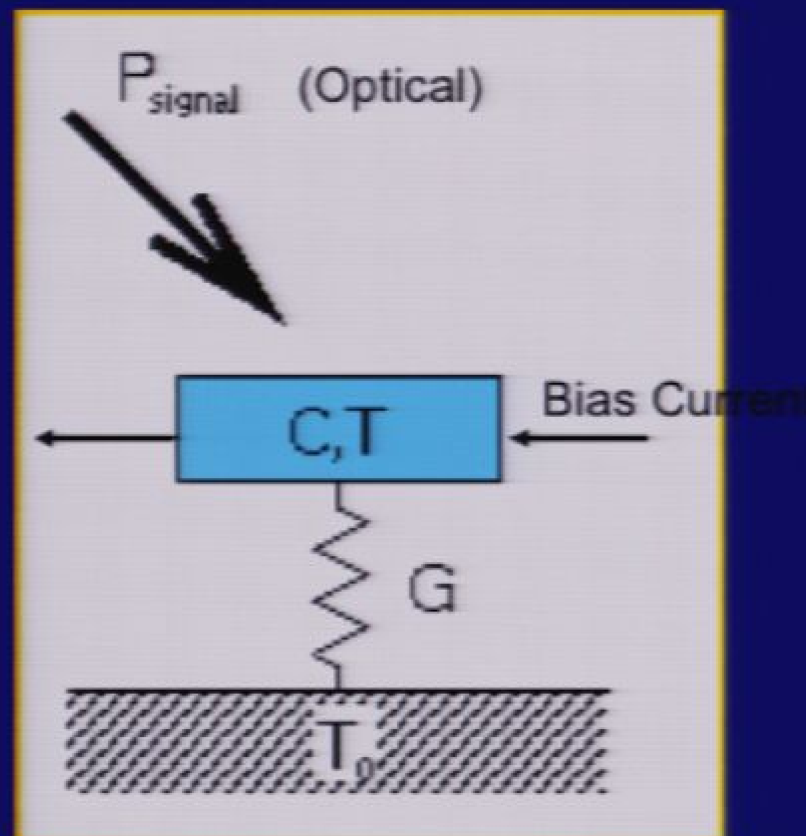
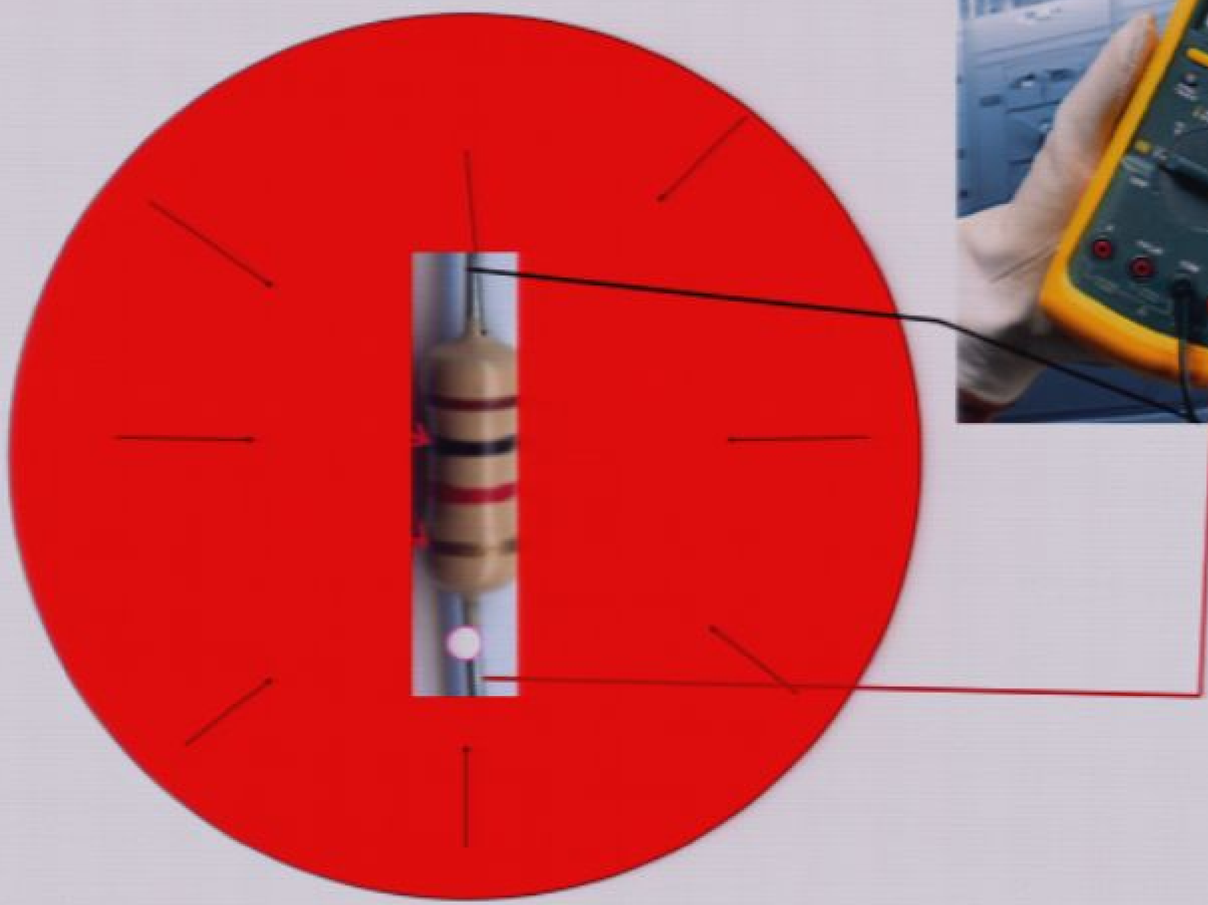


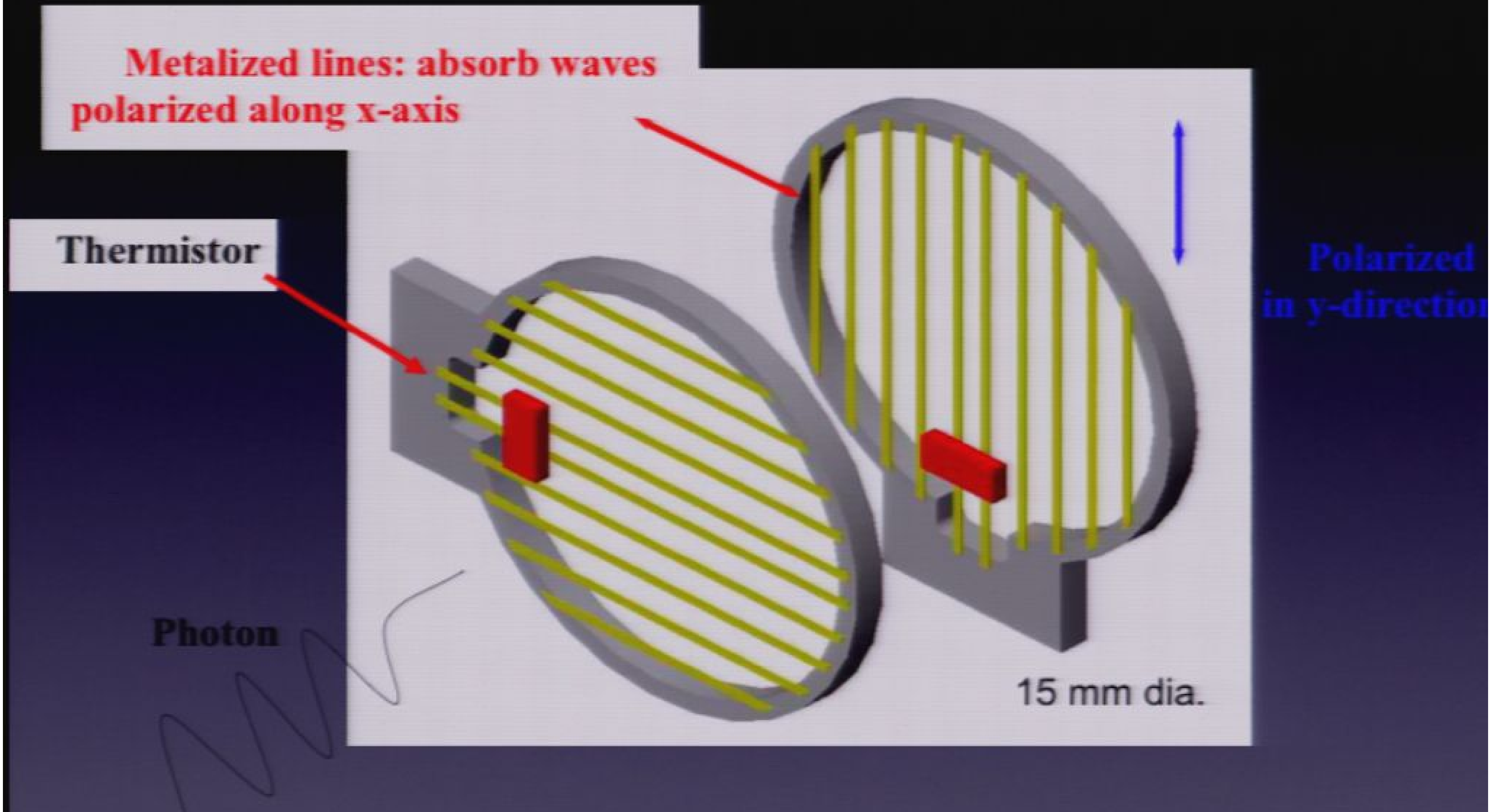
Bolometers: Resistor in an oven



•Random motion of electrons produces alternating current/voltage

•Higher temperature, higher AC voltage .

Enabling Technology: Polarization Sensitive Bolometers



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

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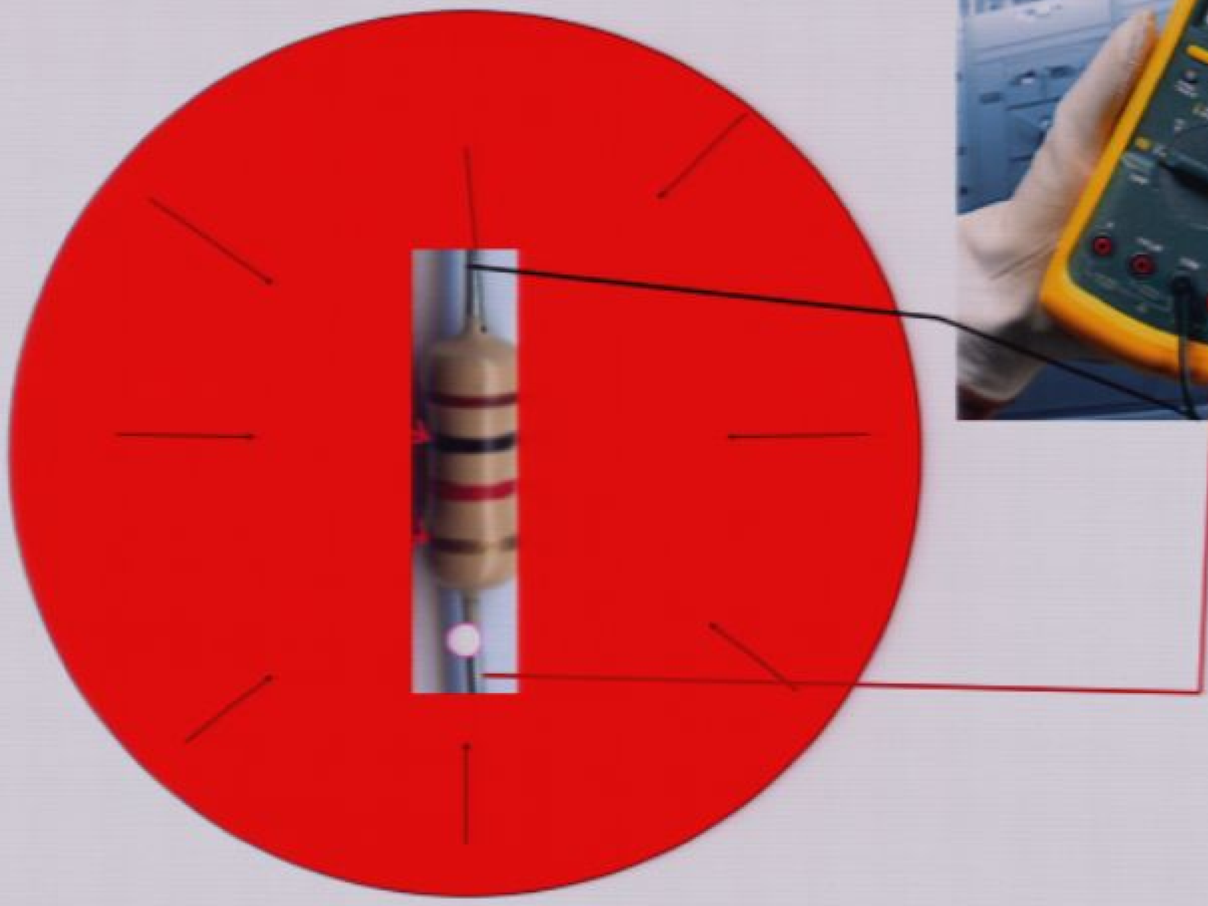

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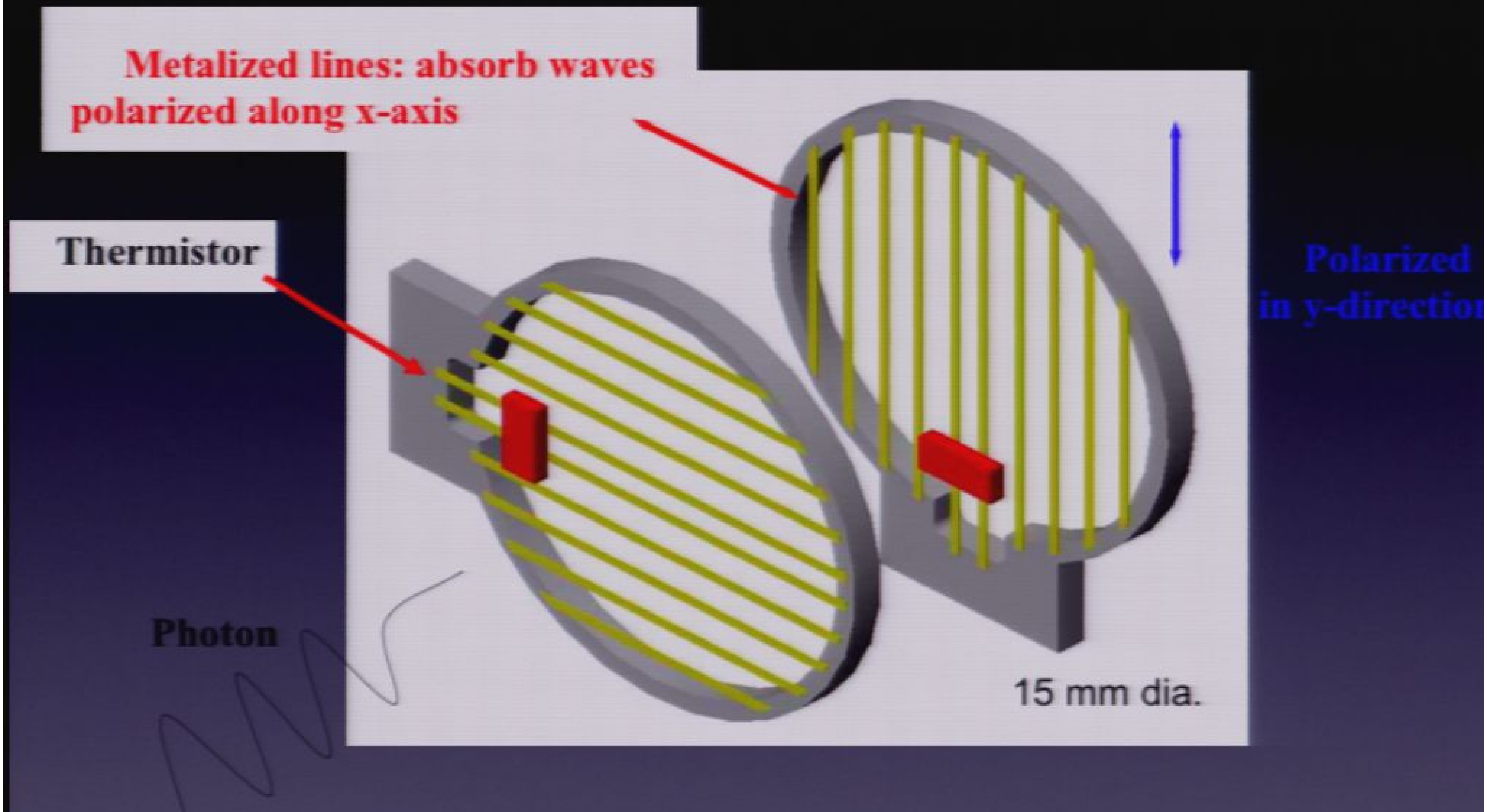

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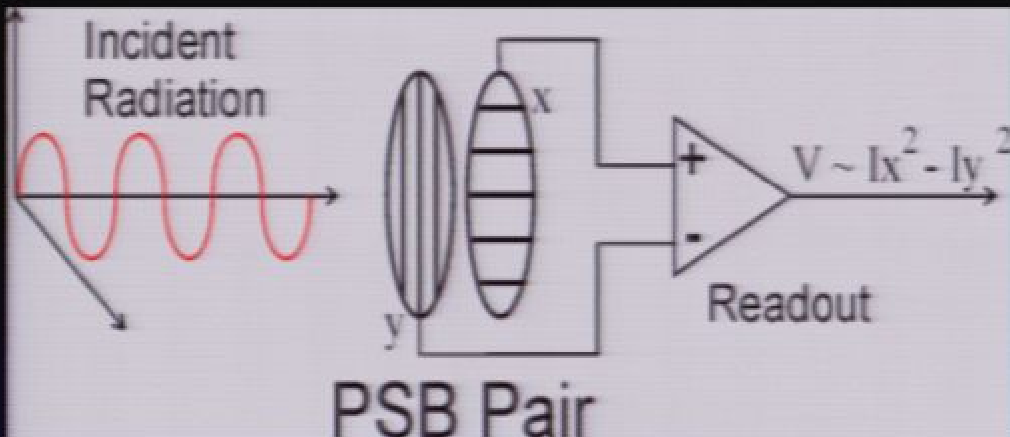
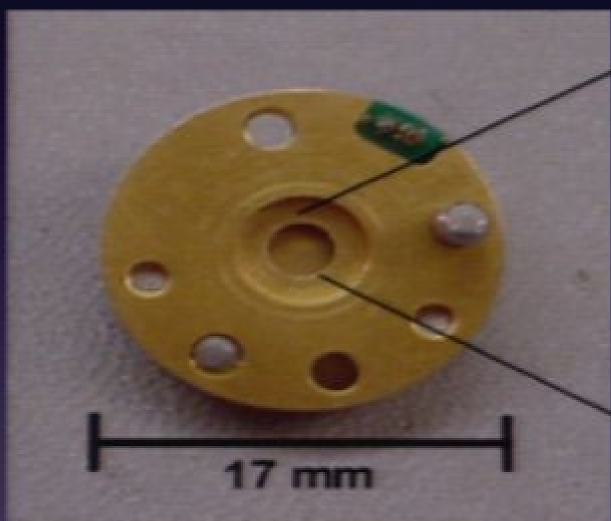
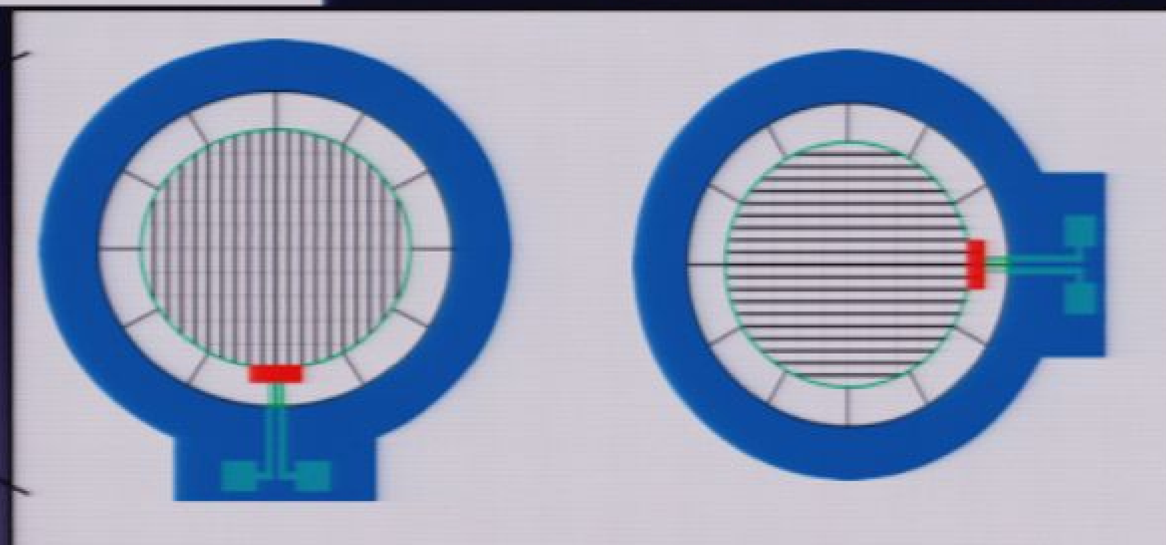


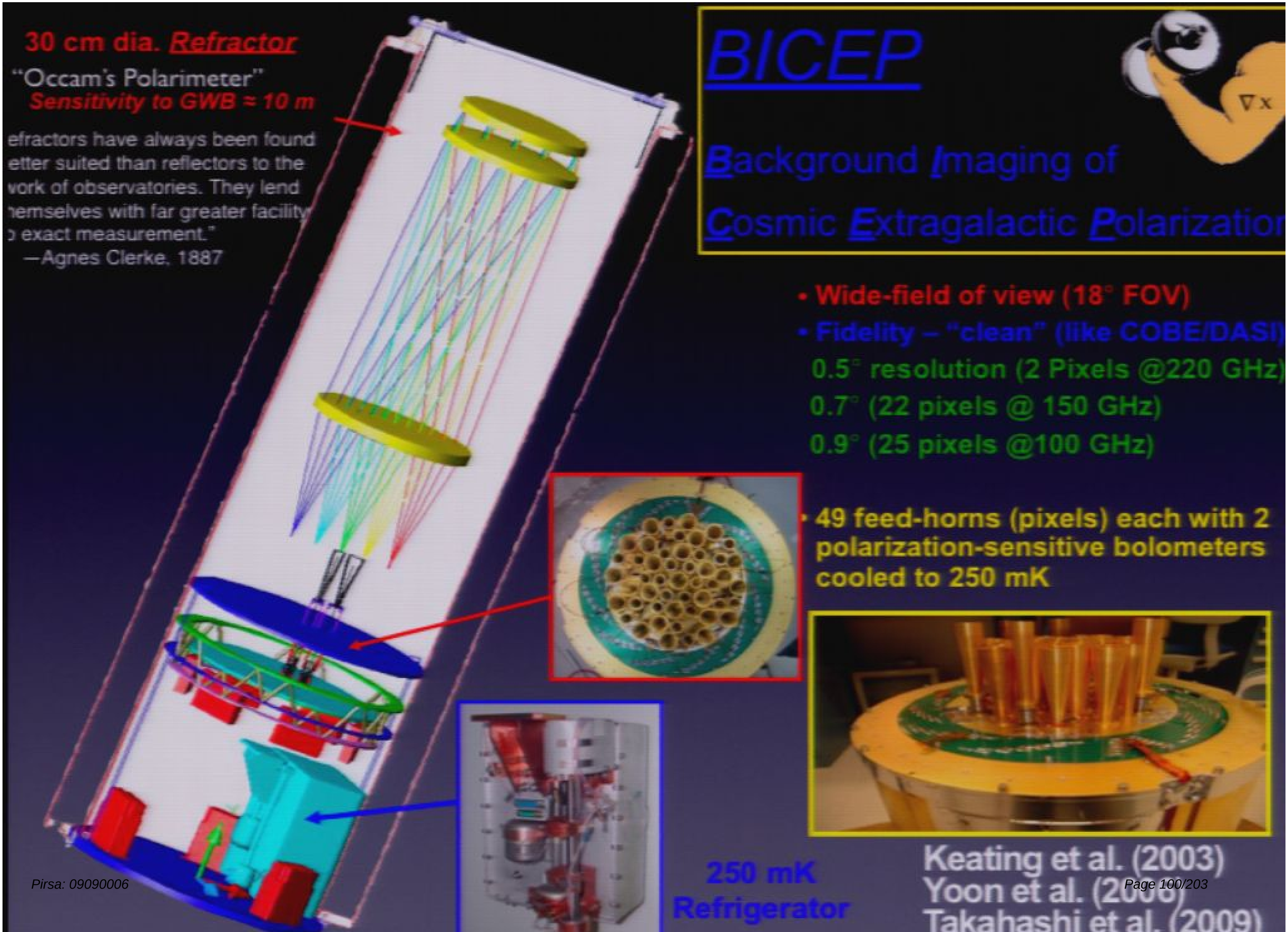




PSB Pair = Two ORTHOGONAL PSBs

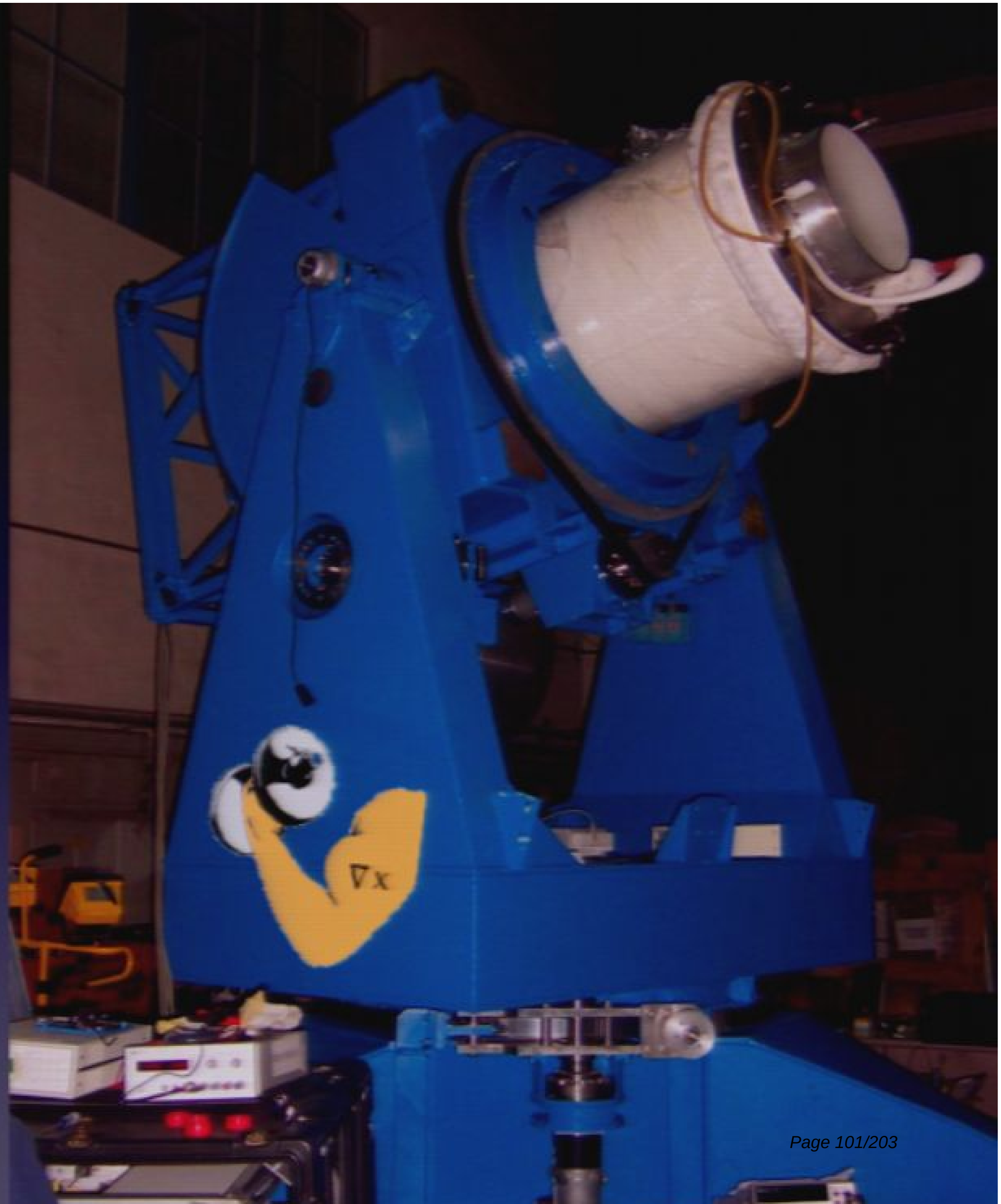
Orthogonal polarization mode detectors share same feed, filter & optics stack.

Devices achieve 35% end-to-end optical efficiency and ~5% cross polarization.

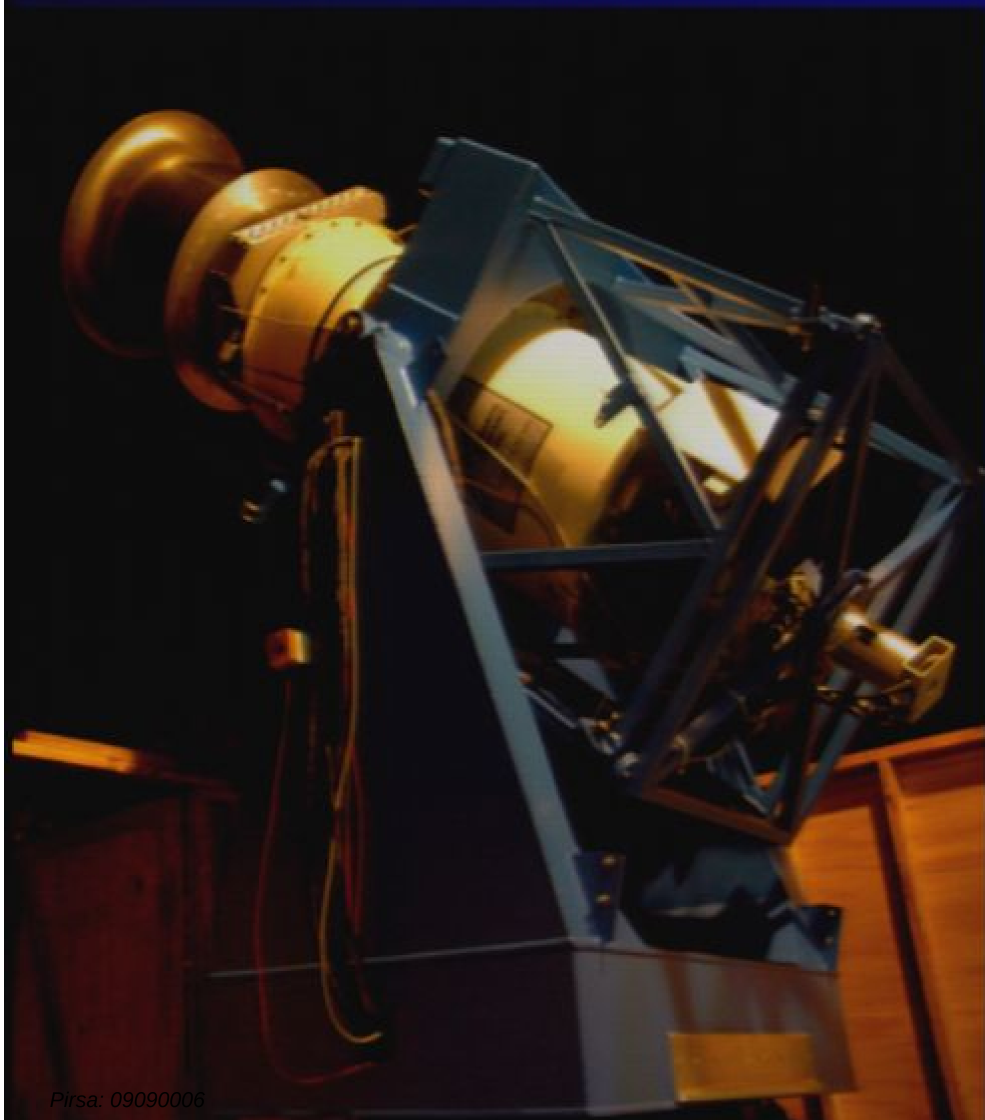

30 cm dia. Refractor
"Occam's Polarimeter"
Sensitivity to GWB ≈ 10 m
efractors have always been found
etter suited than reflectors to the
vork of observatories. They lend
hemselves with far greater facility
o exact measurement."
—Agnes Clerke, 1887
BICEP
∇x
Background Imaging of
Cosmic Extragalactic Polarizatio
• Wide-field of view (18° FOV)
• Fidelity – "clean" (like COBE/DASI)
0.5° resolution (2 Pixels @220 GHz)
0.7° (22 pixels @ 150 GHz)
0.9° (25 pixels @100 GHz)
• 49 feed-horns (pixels) each with 2
polarization-sensitive bolometers
cooled to 250 mK
250 mK
Refrigerator
Keating et al. (2003)
Yoon et al. (2006)
Takahashi et al. (2009)

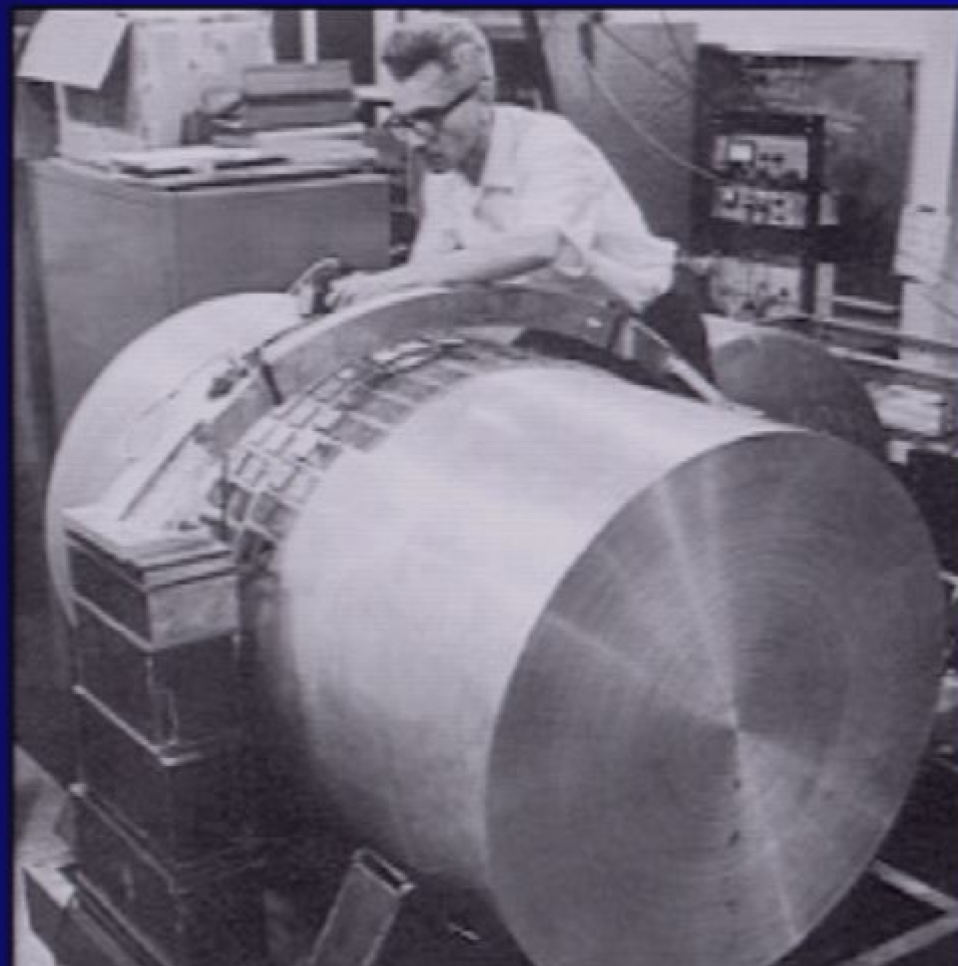
BICEP:
First dedicated B-mode experiment. Also, the first entirely cooled telescope for CMB (temperature ***or*** polarization).

Since BICEP, many similar concepts for large angular scale polarimeters (in the US, France, and England)!



Choose Your Gravitational Wave Detector!





JOSEPH WEBER WITH GRAVITATIONAL WAVE DETECTOR

Choose Your Gravitational Wave Detector!

Despite unfriendly natives, Antarctica is the world's *premier* CMB site.

Despite unfriendly natives, Antarctica is the world's *premier* CMB site.

Despite unfriendly natives, Antarctica is the world's *premier* CMB site.

Despite unfriendly natives, Antarctica is the world's *premier* CMB site.

It's the highest, driest, coldest, and darkest continent


BOARDING
PASS
47


U.S. AIR FORCE
1104
62ND AW
446TH AW


From my window seat


Catch a taxi into town
FOREMOST


No traffic or construction delays on local freeways

Pickup some local currency


No traffic or construction delays on local freeways

Pickup some local currency

Hit the local non-smoking bar


or, hit the local smoking bar!

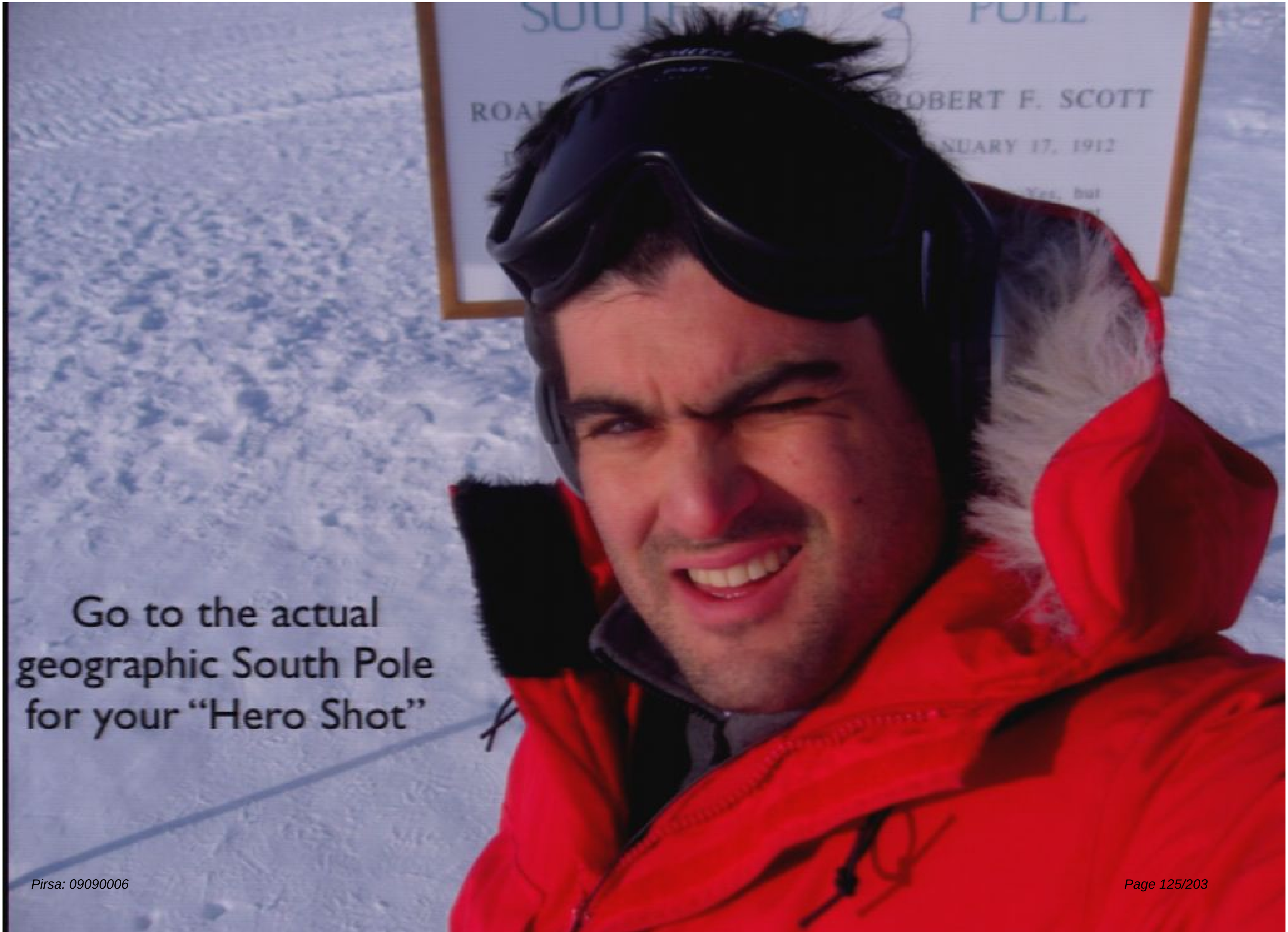
Next day hop a flight for the Pole...

Land at the Airport

“Great God this is an *awesome* place!”

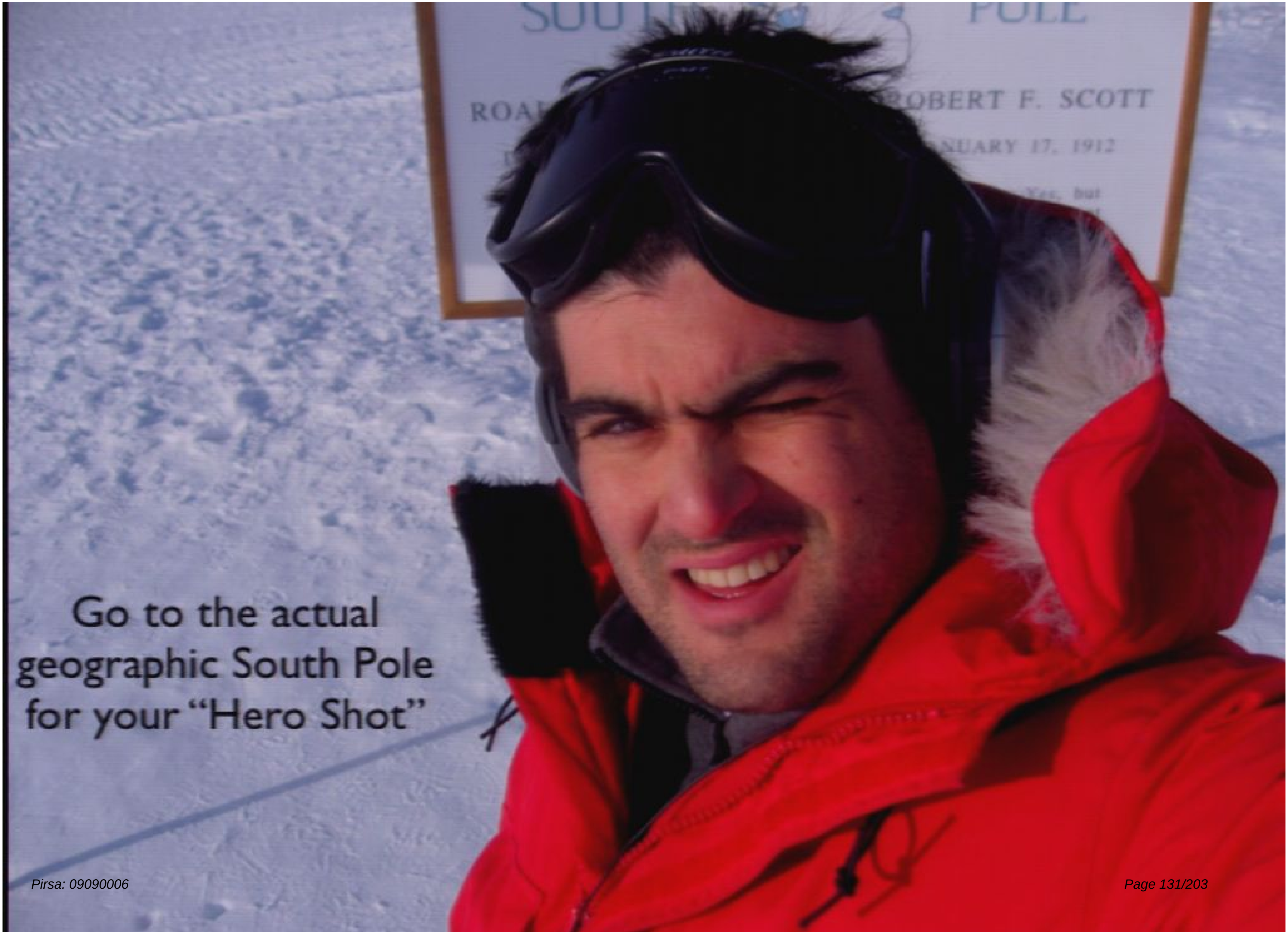
“Great God this is an *awesome* place!”

“Great God this is an *awesome* place!”



Go to the actual geographic South Pole for your "Hero Shot"


Then start walking to work…

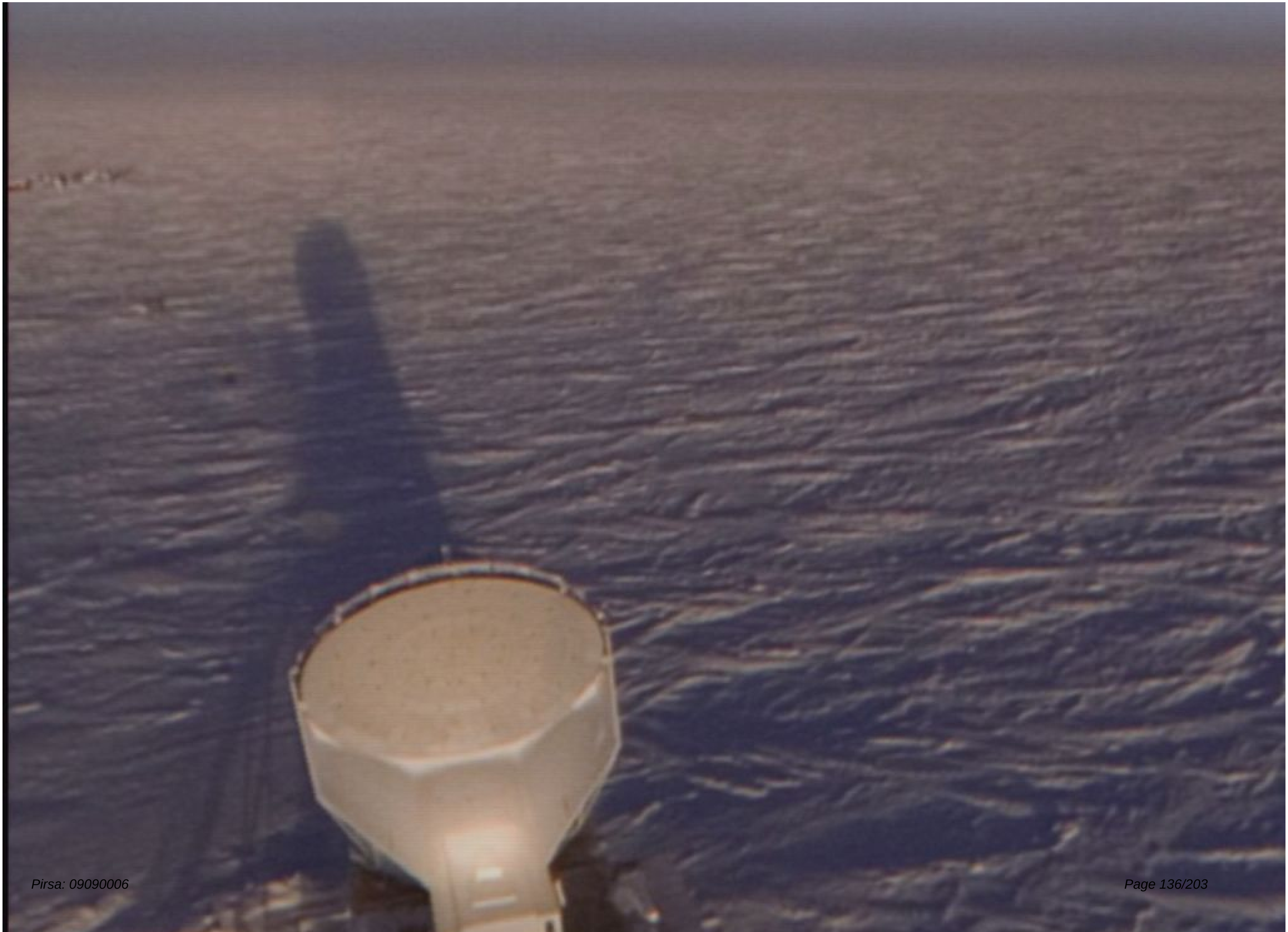


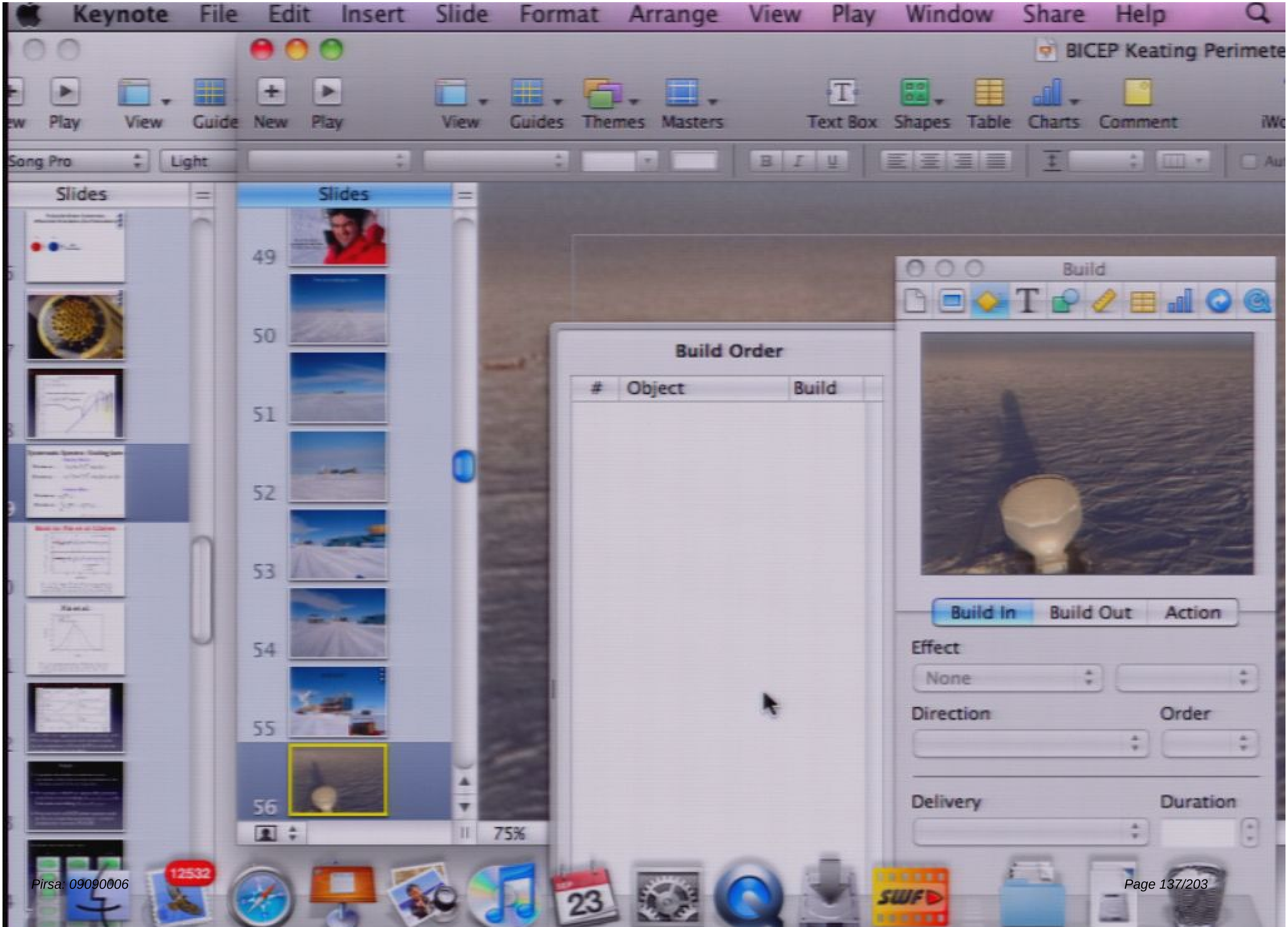
Go to the actual geographic South Pole for your "Hero Shot"

Land at the Airport

BICEP & SPT


BICEP & SPT
Outhouse
Ummm....looks familiar!!!




Keynote File Edit Insert Slide Format Arrange View Play Window Share Help
BICEP Keating Perimete
New Play View Guides Themes Masters Text Box Shapes Table Charts Comment
Light
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49
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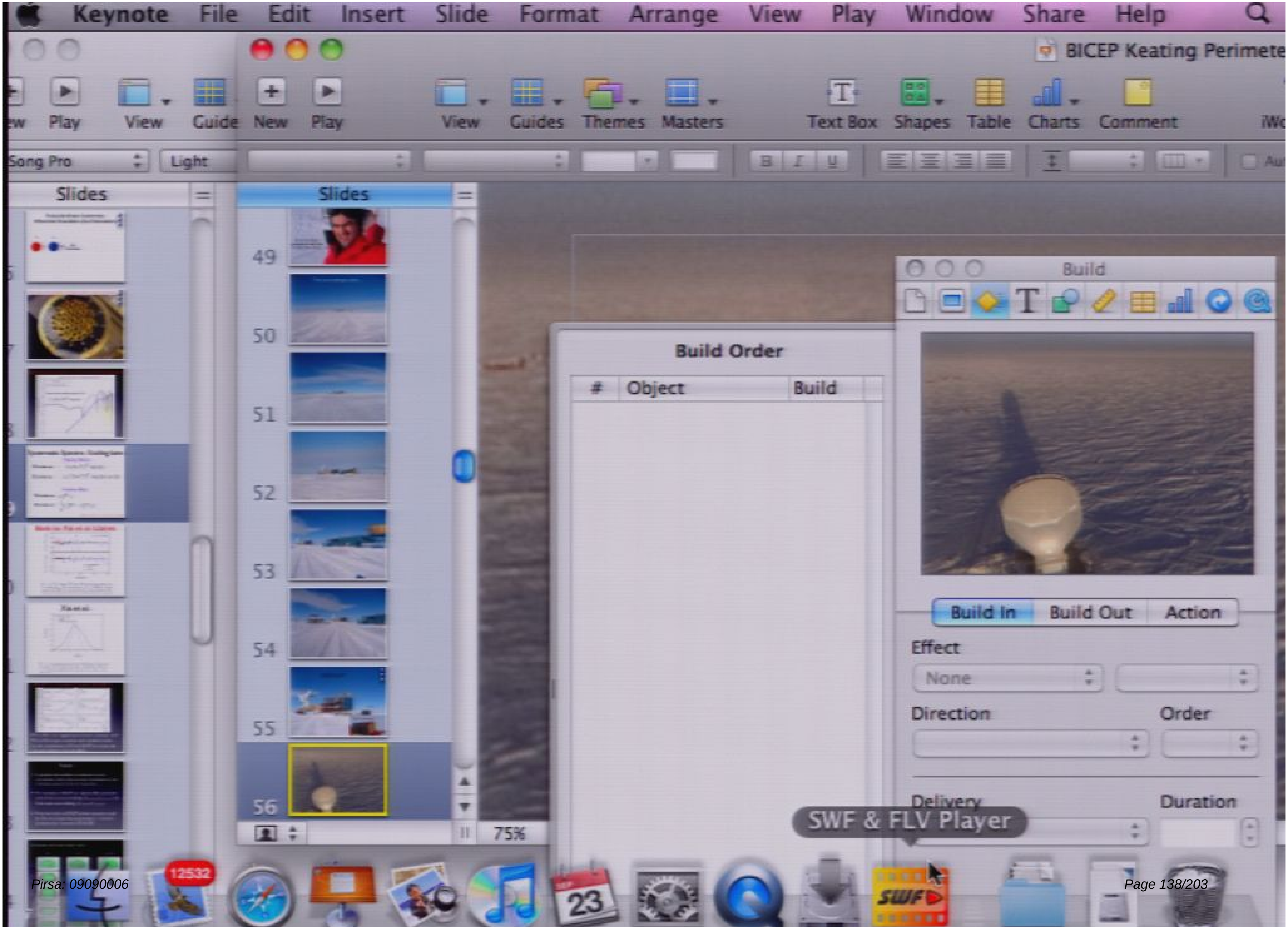
23


Keynote File Edit Insert Slide Format Arrange View Play Window Share Help
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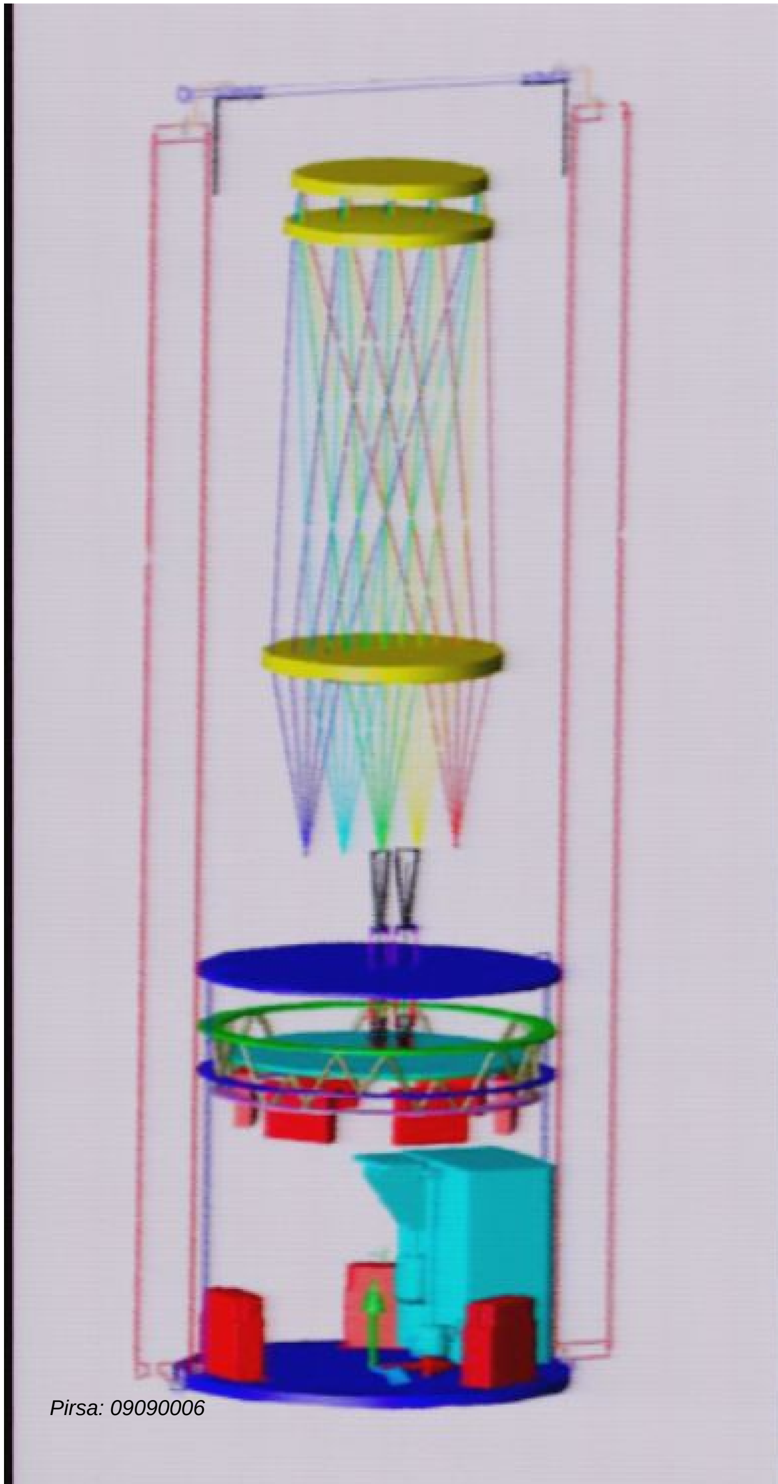
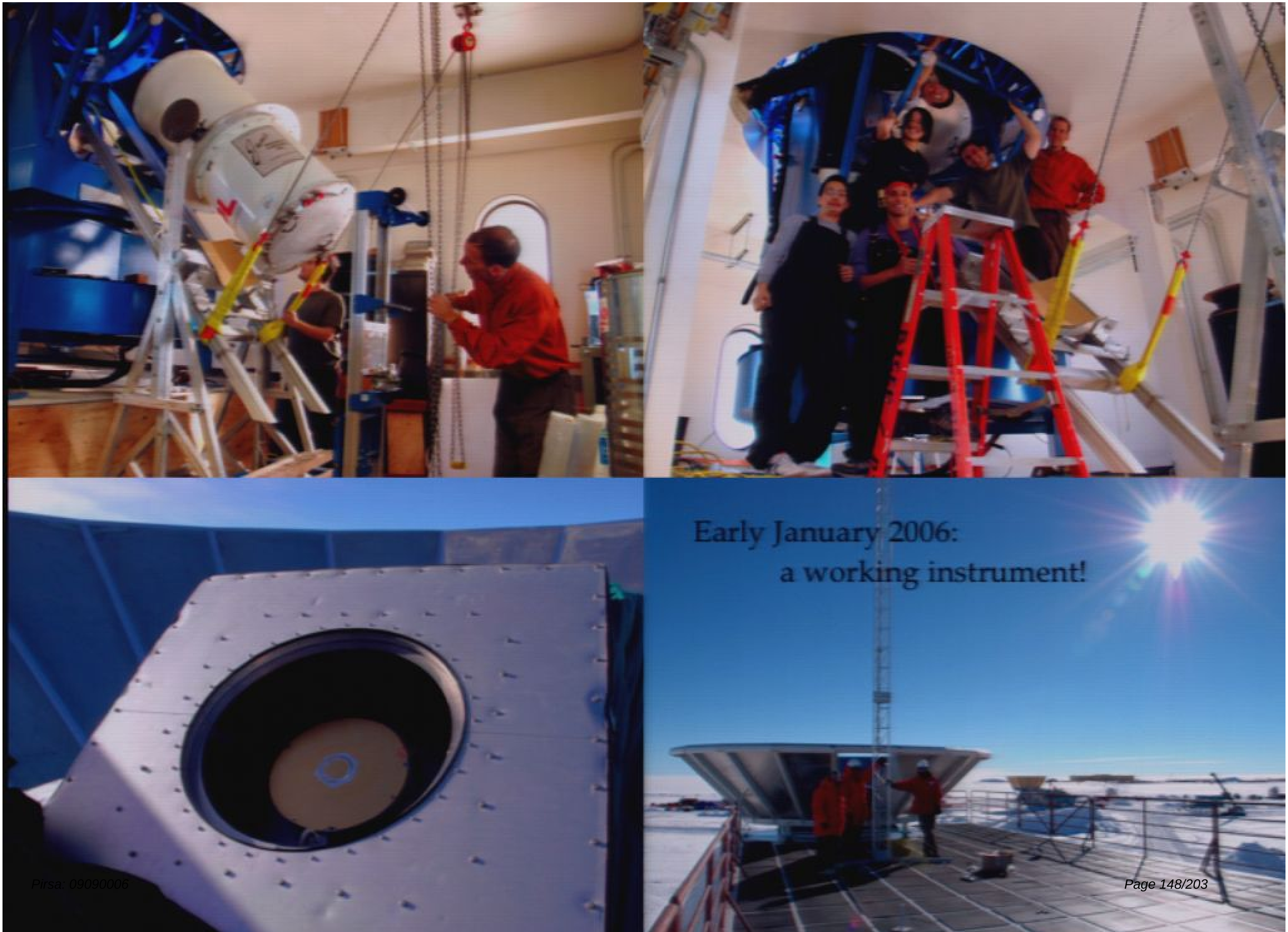
Dark Sector Laboratory
late 2005...



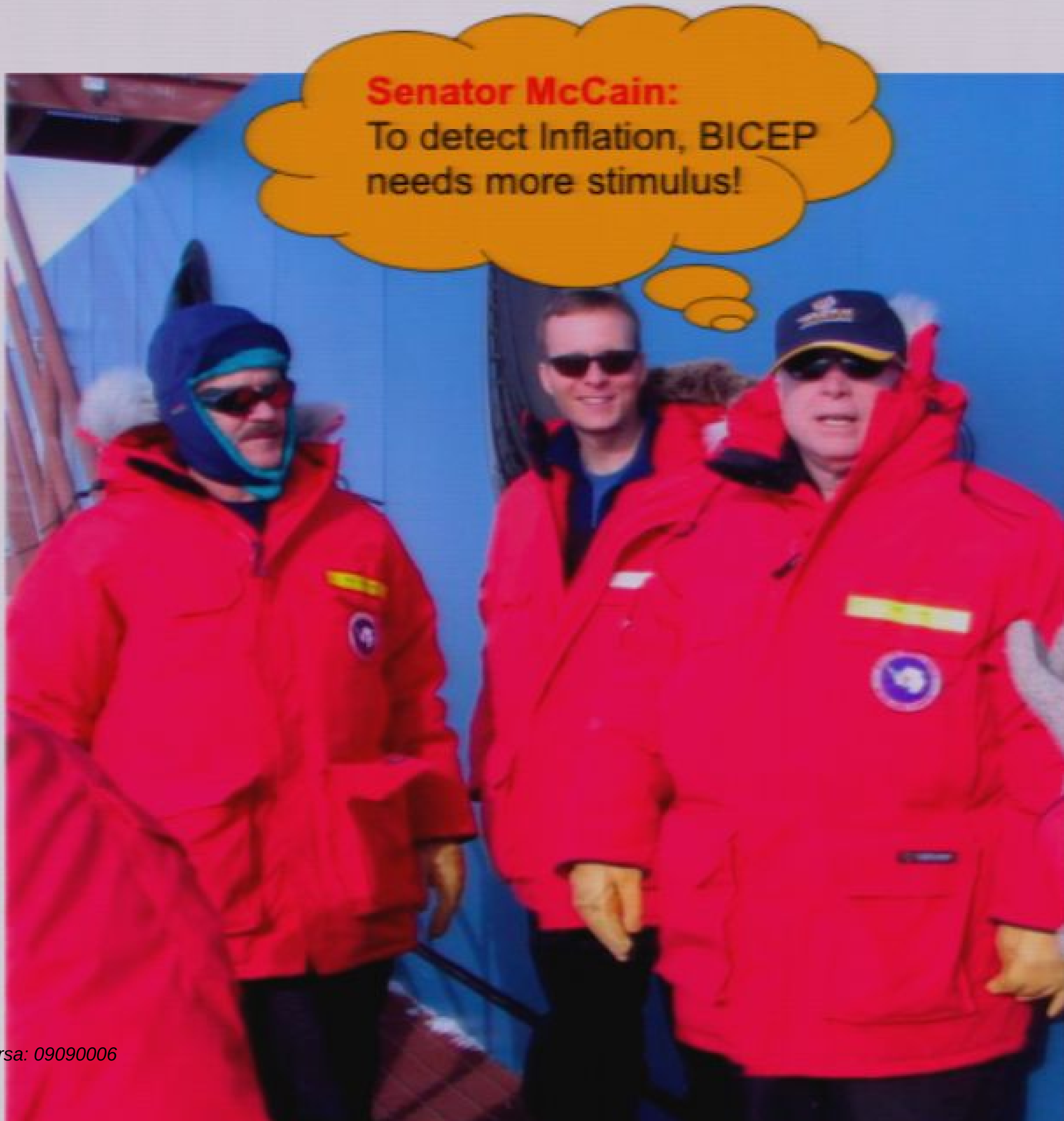

Early January 2006:
a working instrument!

The smell of *cold cash* attracts the dignitaries

25 congressmen/women, senators, and other VIPs visit South Pole and BICEP

January 12, 2006

The smell of *cold cash* attracts the dignitaries



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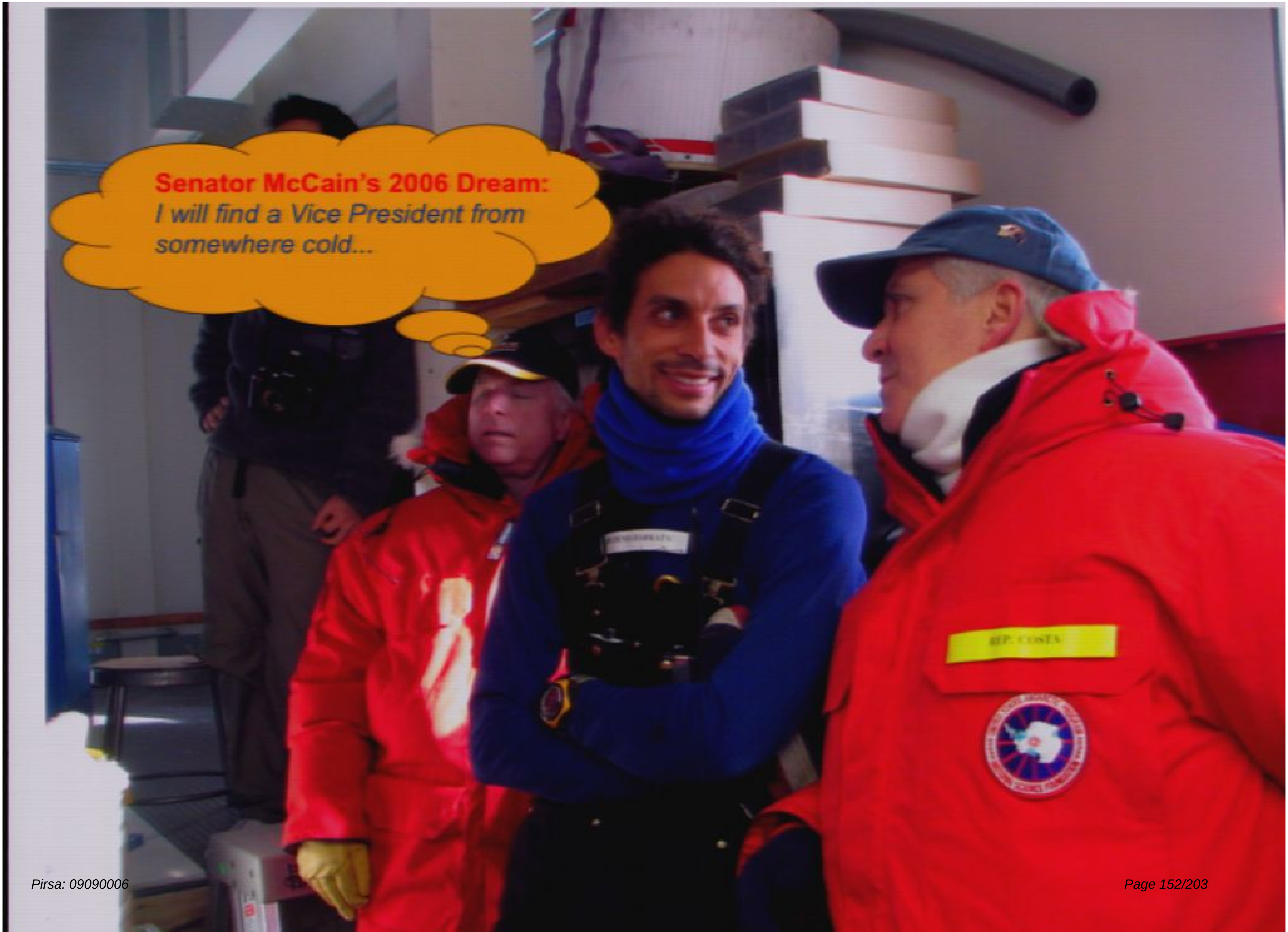
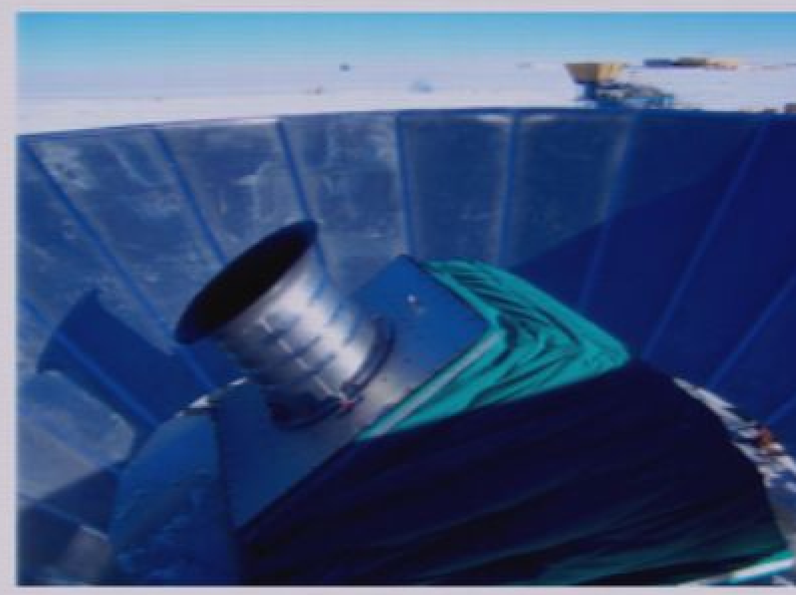
January 12, 2006

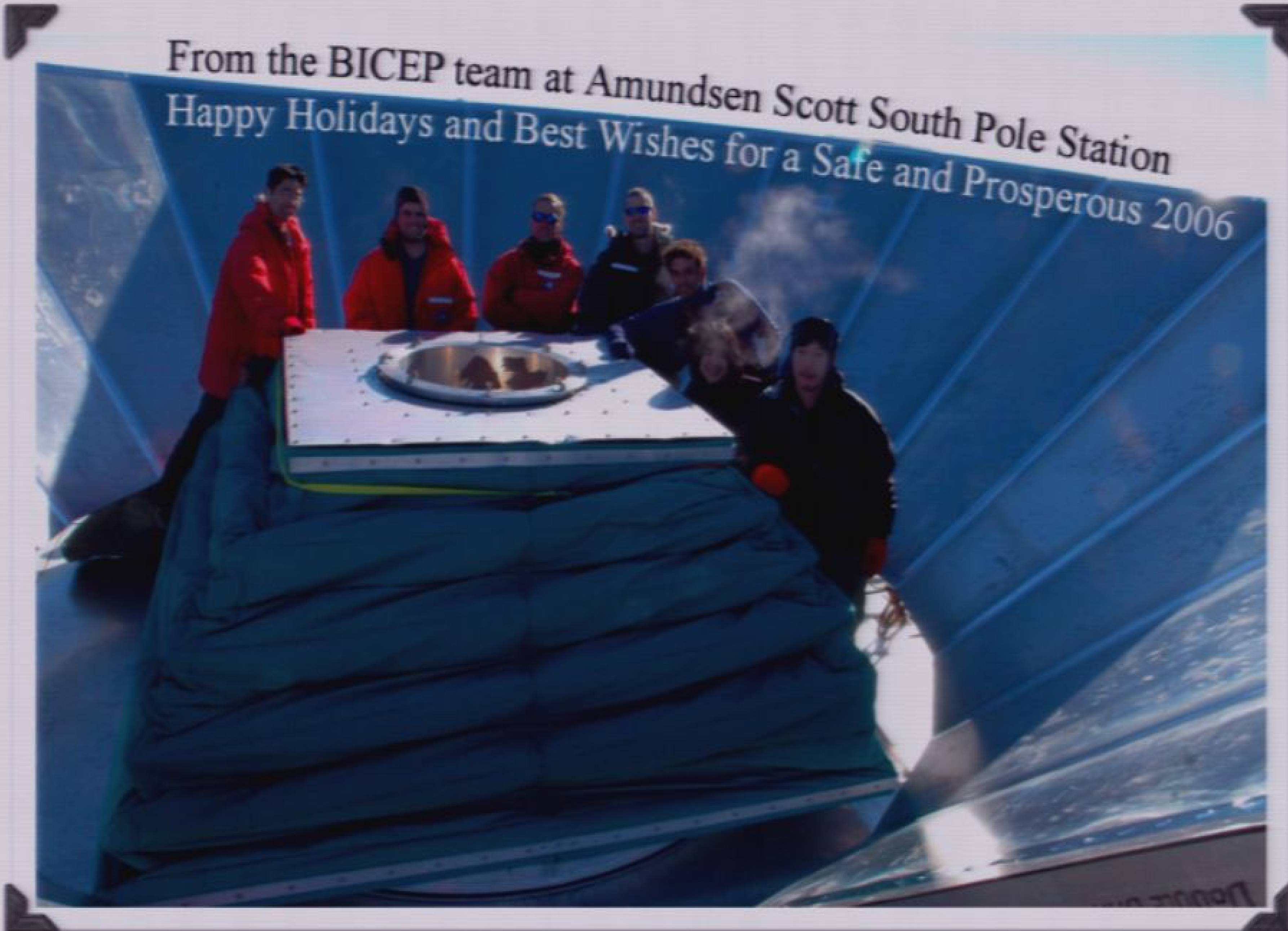

REP. COSTA


Senator McCain's 2006 Dream:
I will find a Vice President from somewhere cold...

Why a small aperture?



- Cost effective
- Easy calibration
- Simple cold (4K) telescope
- Superior contamination suppression



“First Microwave” Postcard December 31, 2005

Overview of the BICEP telescope and DSL Observatory

Minimize polarization systematics

Azimuthal symmetry

Simple refractor, no mirrors

)ptimized for $30 < \ell < 300$

Beam sizes ~ 0.9°, 0.6°

Field of view ~ 18°

Observed sky fraction ~ 2%

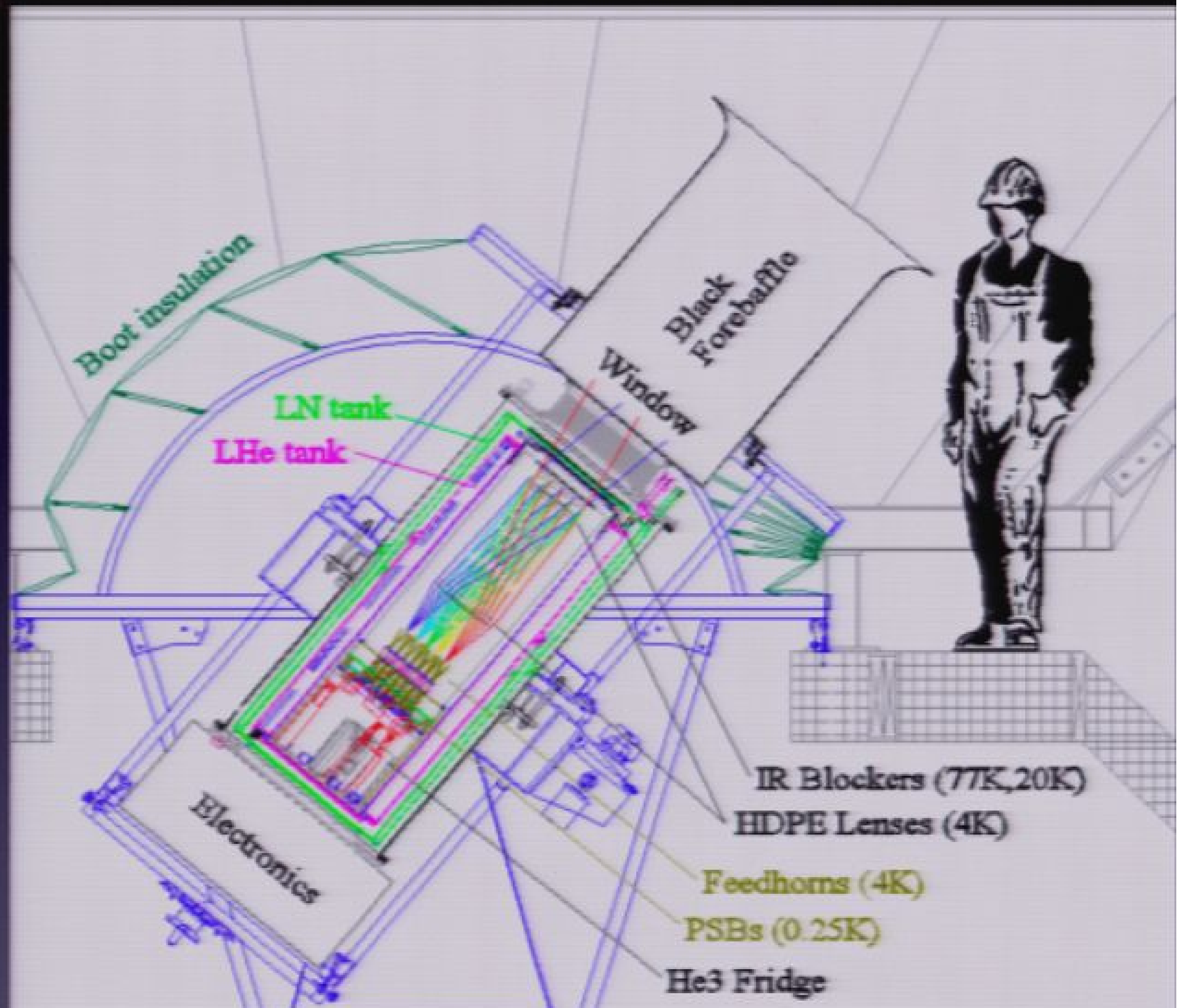
Frequency coverage

100 GHz: 25 pixels
150 GHz: 22 pixels
220 GHz: 2 pixels

Signal-to-noise considerations

PSB differencing

South Pole: long integration over contiguous patch of sky, reduced atmospheric loading



(Yoon et al., astro-ph/0606278)

Target field and scan strategy

Primary CMB field:
"Southern Hole"

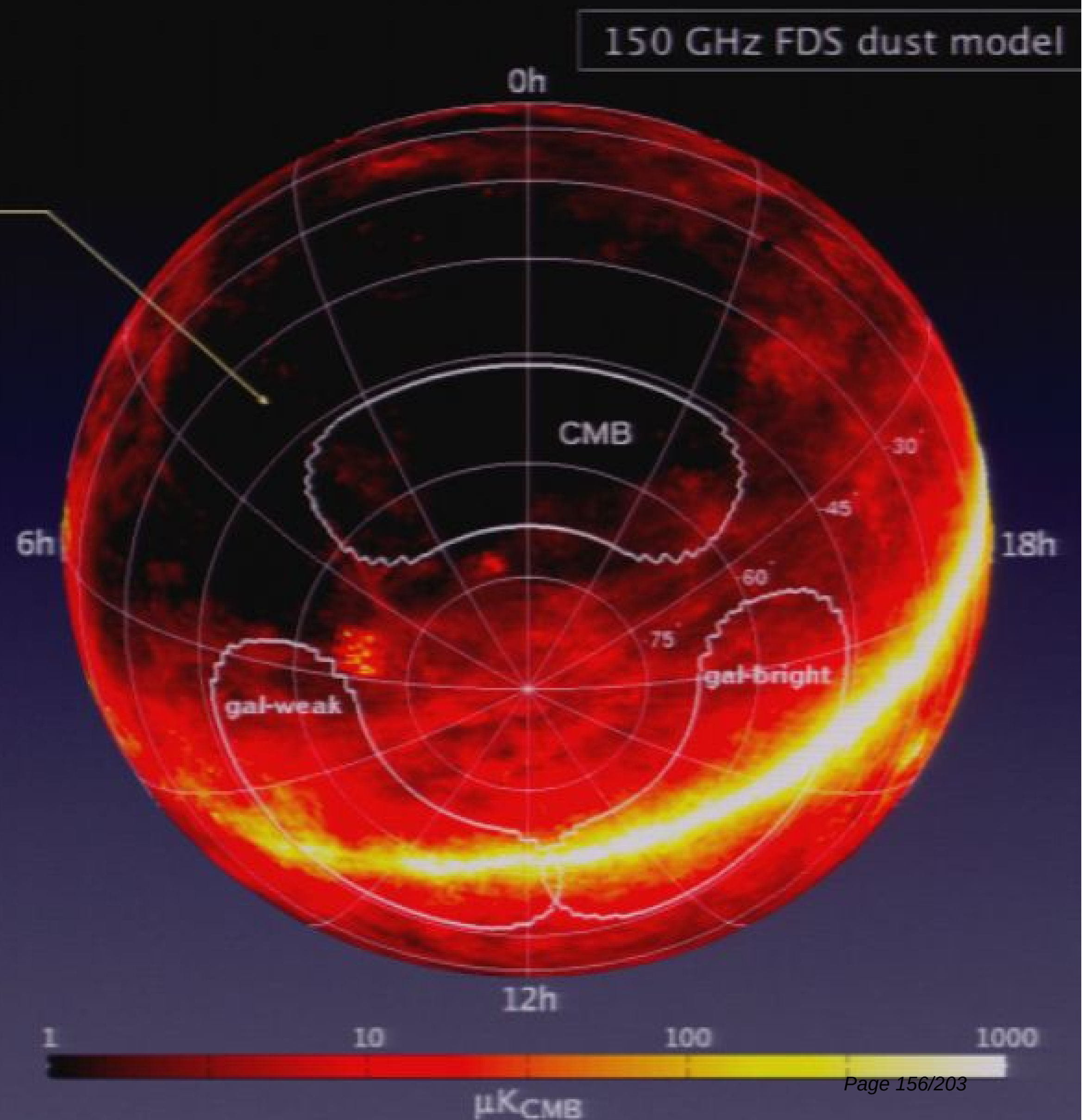
- Dust emission 100x lower than median
- Total emission minimized at 150 GHz

48–hour observing cycles

- 4 x 9–hour CMB observations
- Az / el raster scans
- Fixed boresight angle {-45°, 0°, 135°, 180°}

Three years of data: 2006 to 2008

- Initial analysis: first two years
- Conservative data cuts

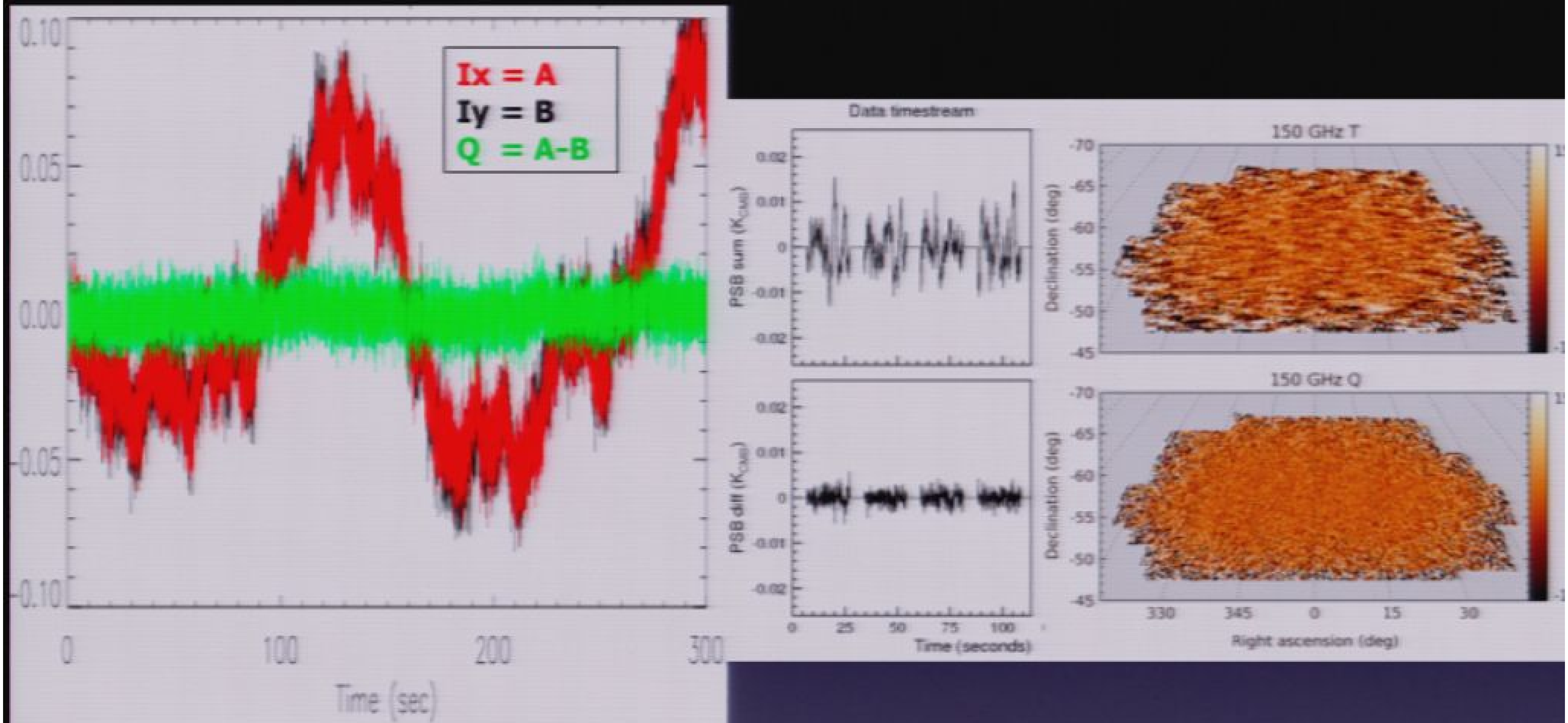


Sunset 3:13 AM March 23, 2009
Sunrise 6:04 AM: September 21, 2009

Best data occurs during these months, though we obtain data nearly year round

Photo: D. Barkats, Winterover

Detector and Atmospheric Noise

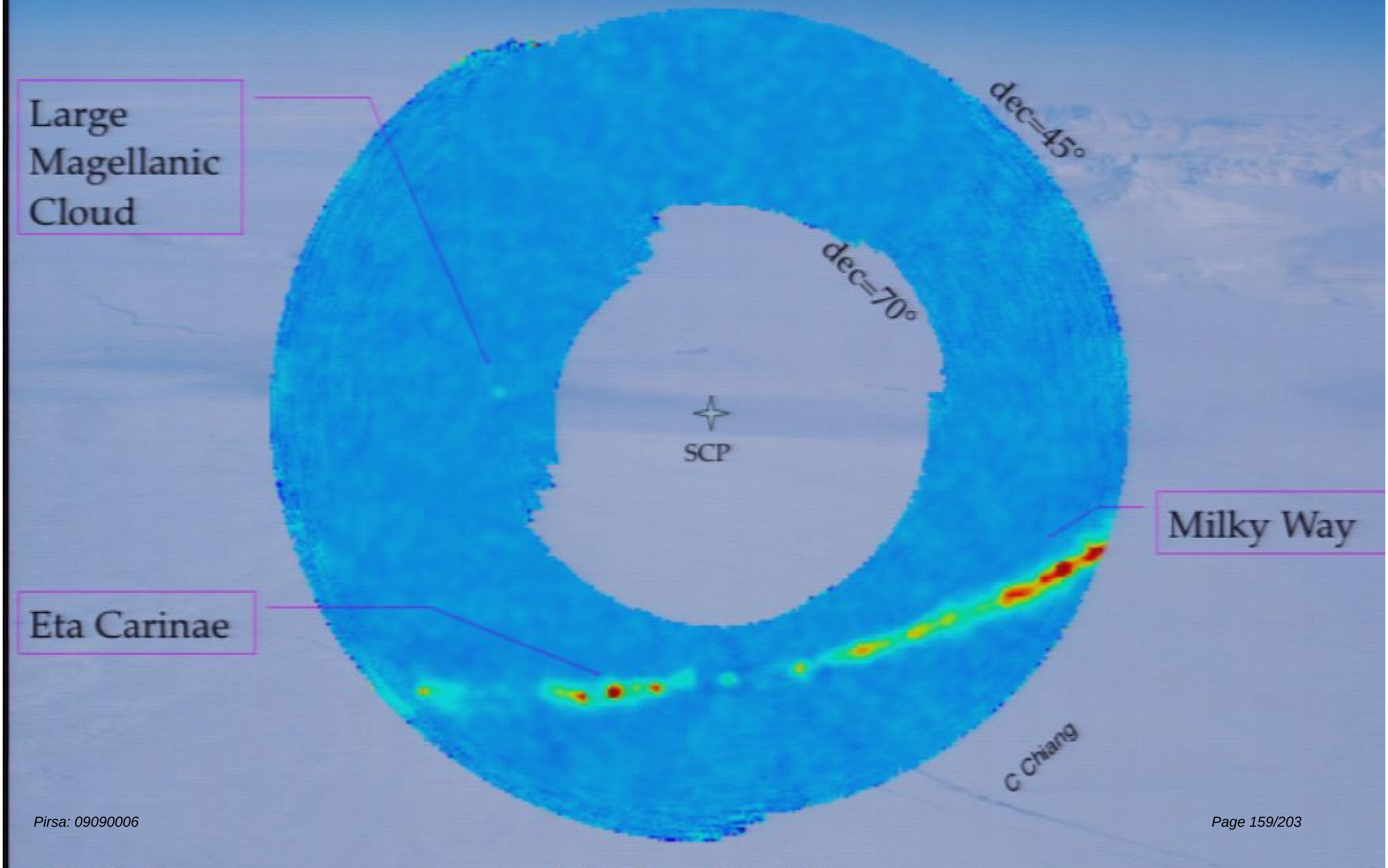


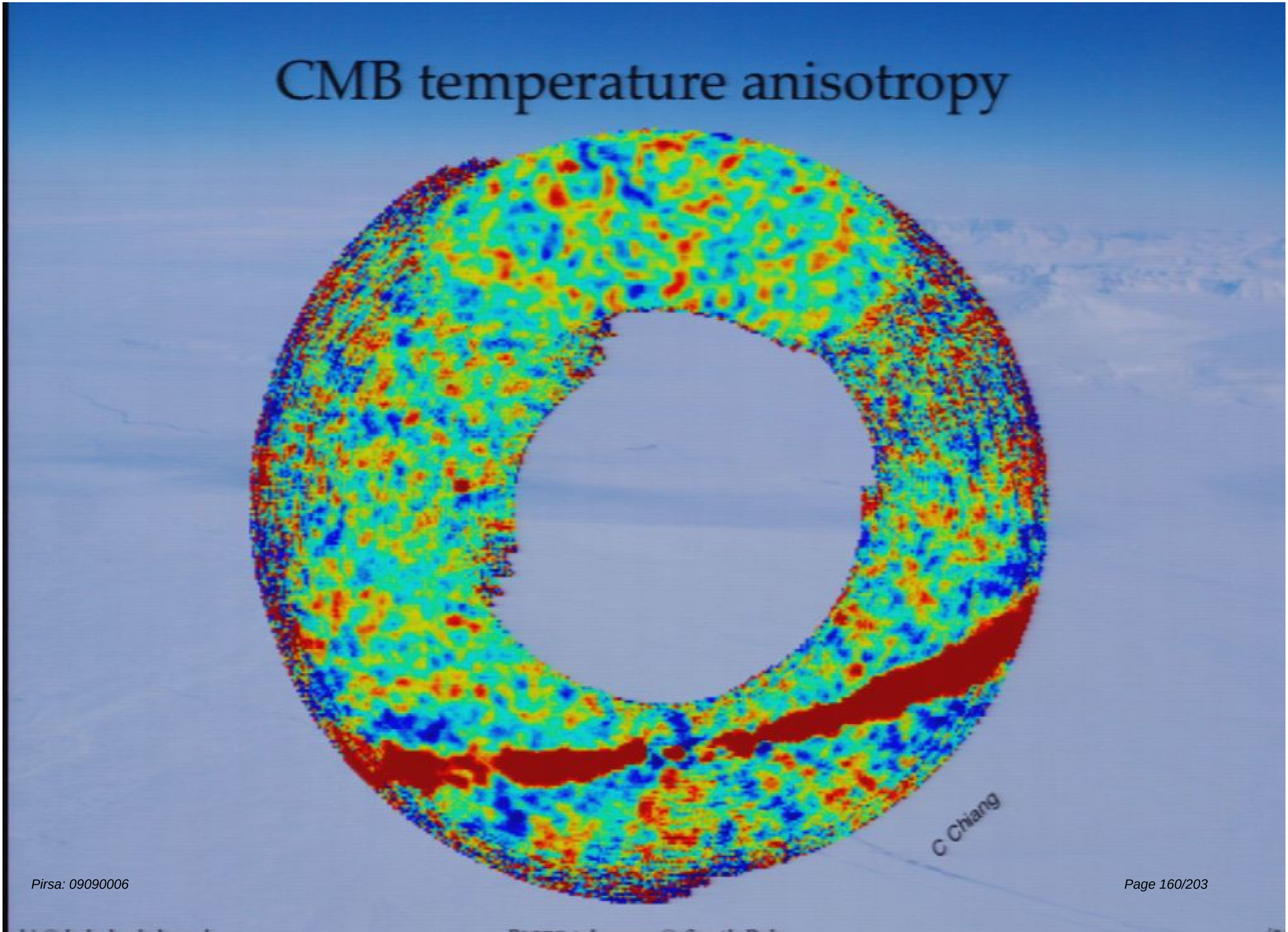
Atmospheric noise contaminates single channel data.

Effect worse at 150 GHz due to water line.

PSB difference signal is much more stable.

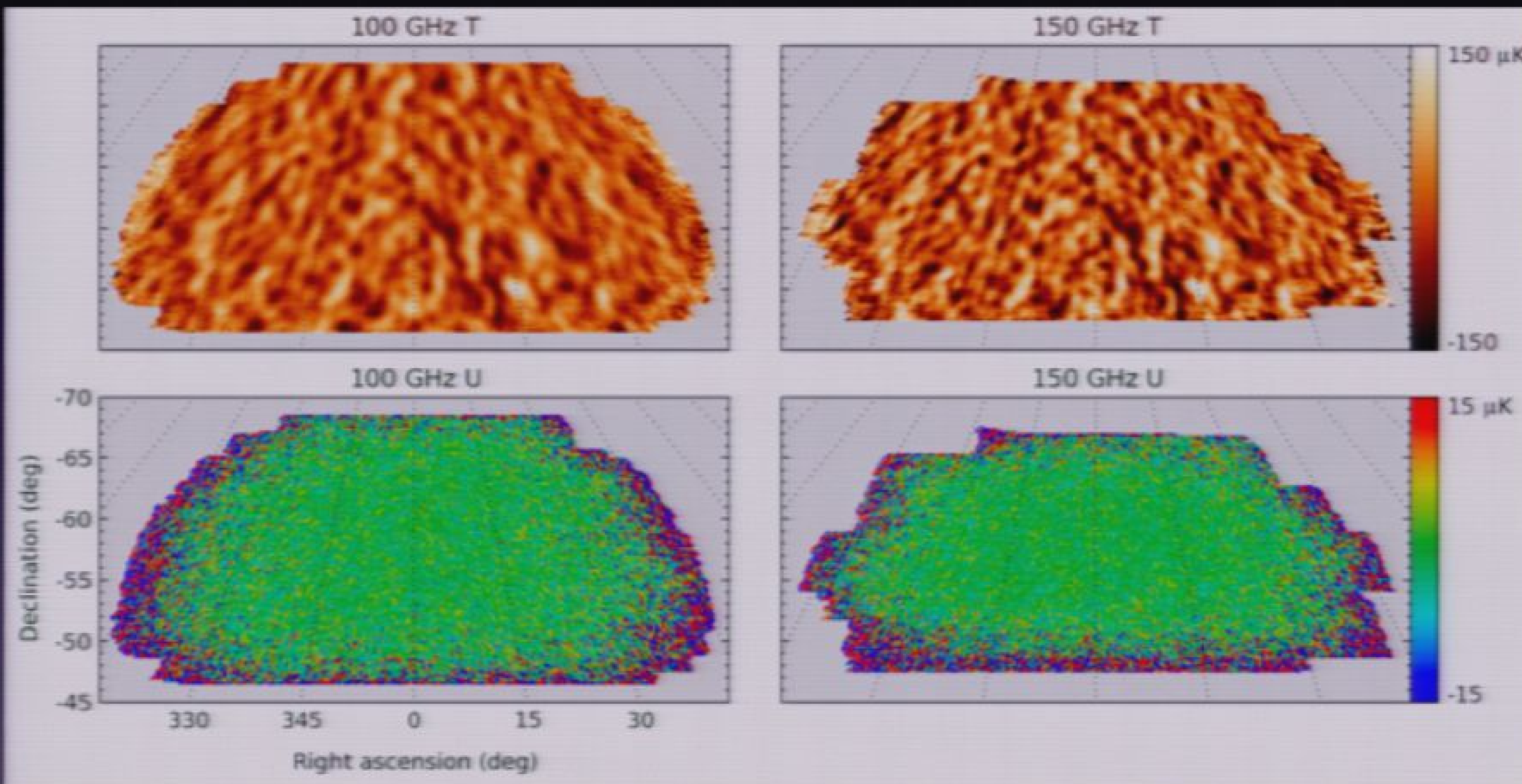
BICEP Polarization Map



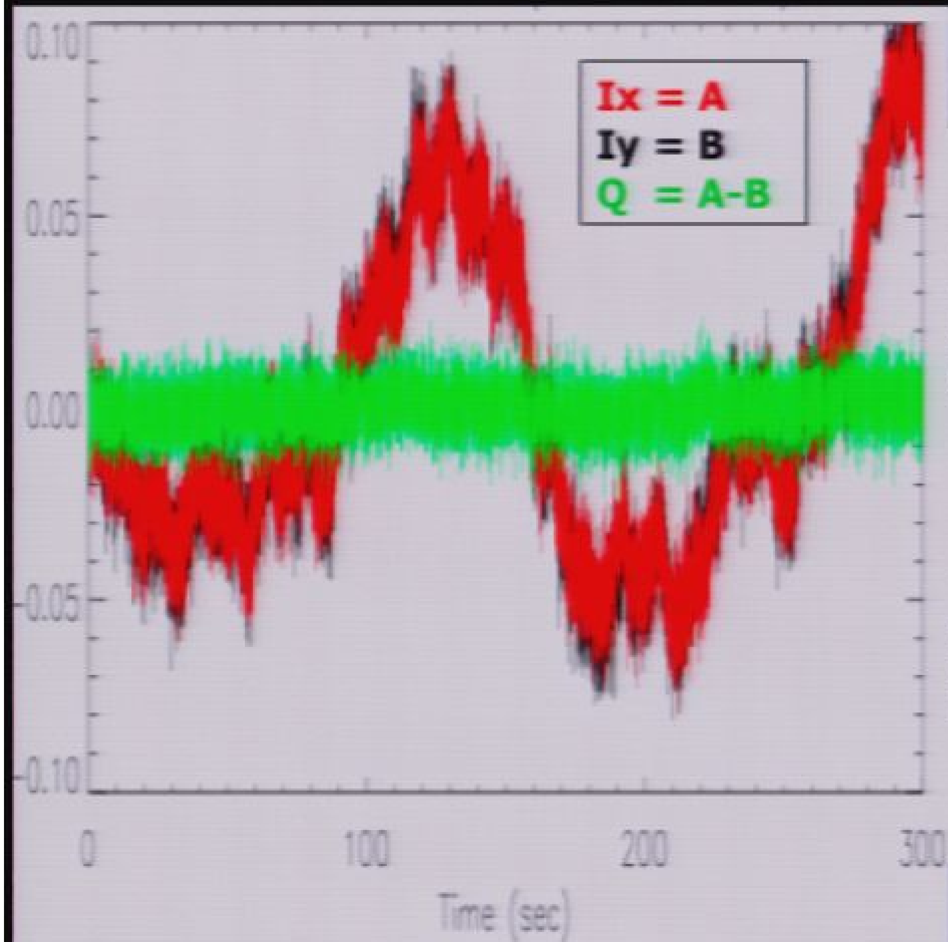

CMB temperature anisotropy
C Chiang

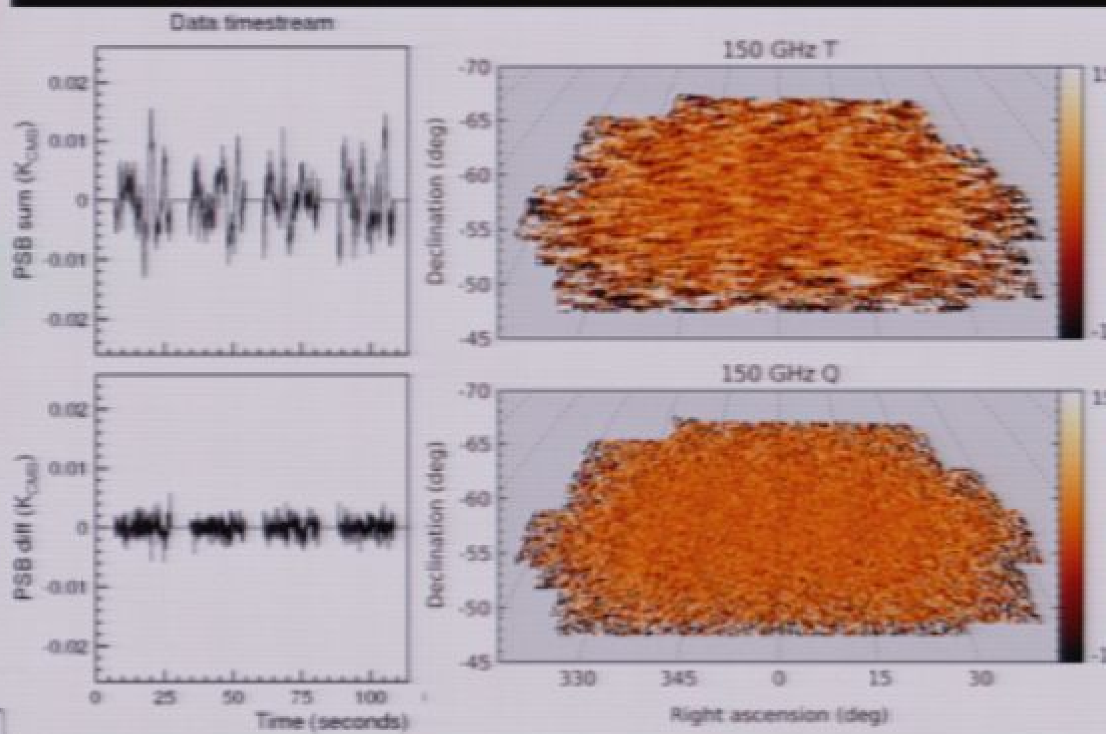
Timestreams to maps

- Form gain-adjusted sum/diff PSB timestreams, polynomial filter + azimuth template subtractio
- Noise in two-year polarization maps: 0.81 μK and 0.64 μK per sq. deg. at 100 and 150 GHz



Detector and Atmospheric Noise





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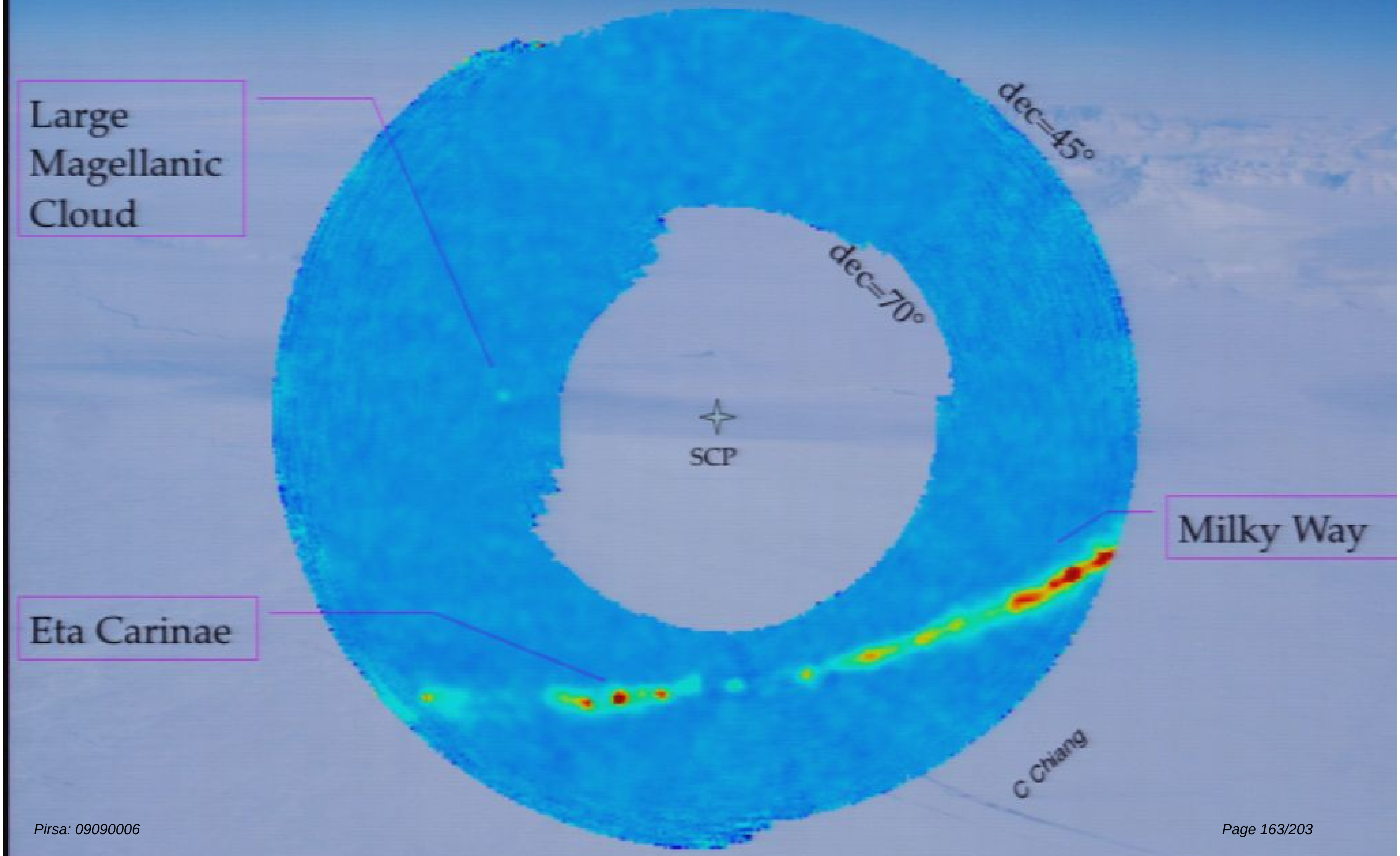
BICEP Polarization Map



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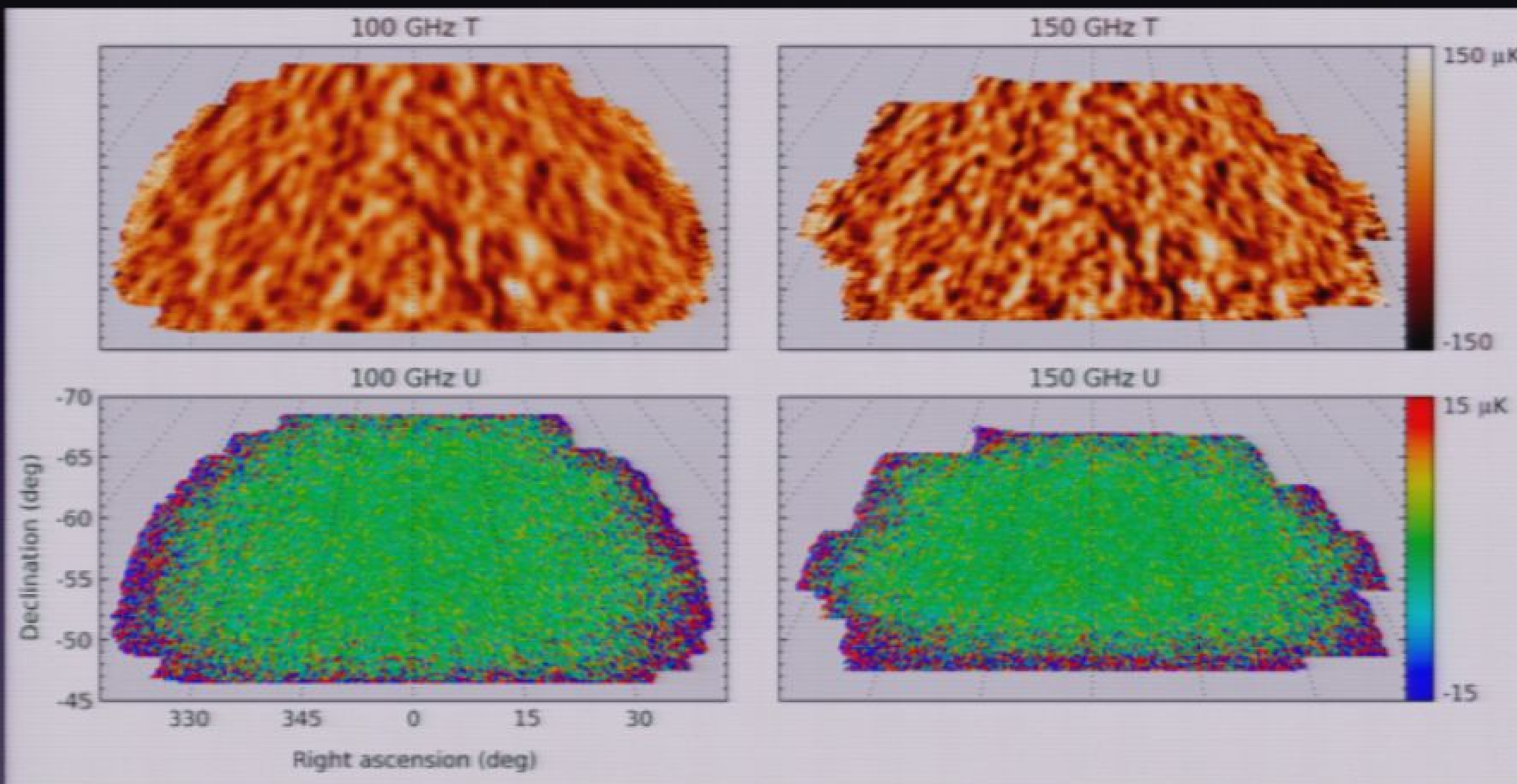
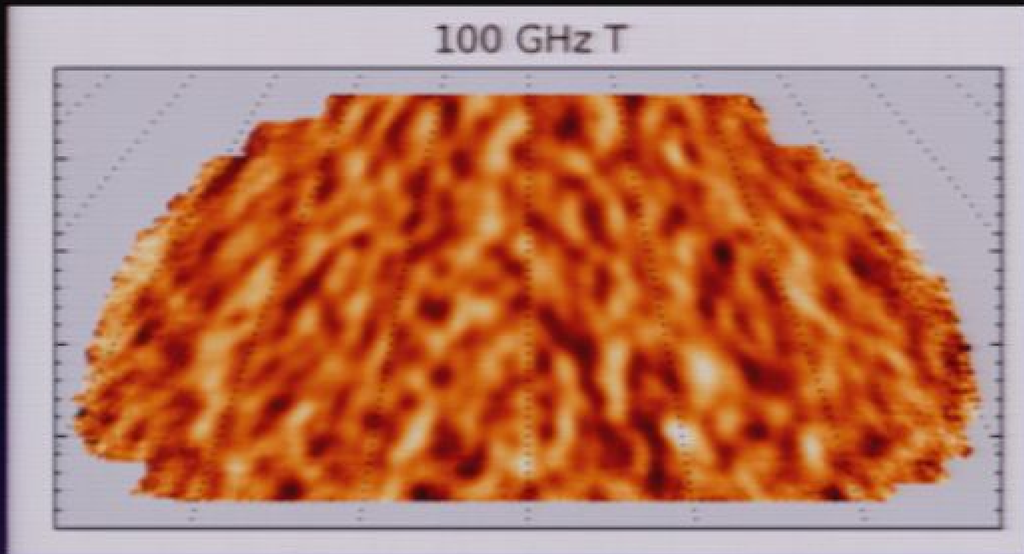
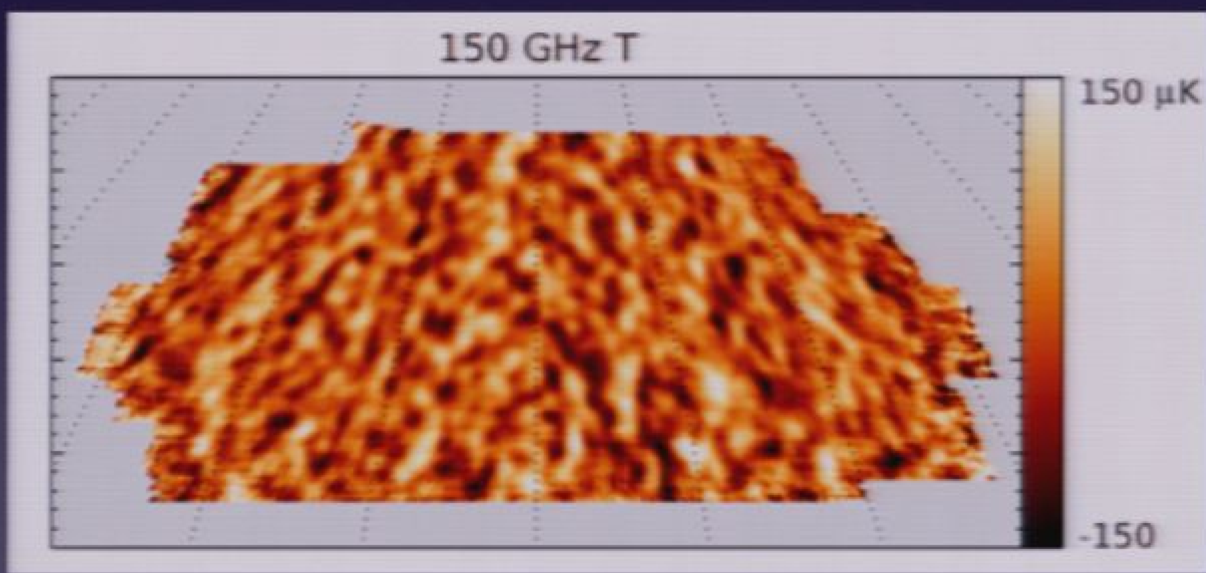
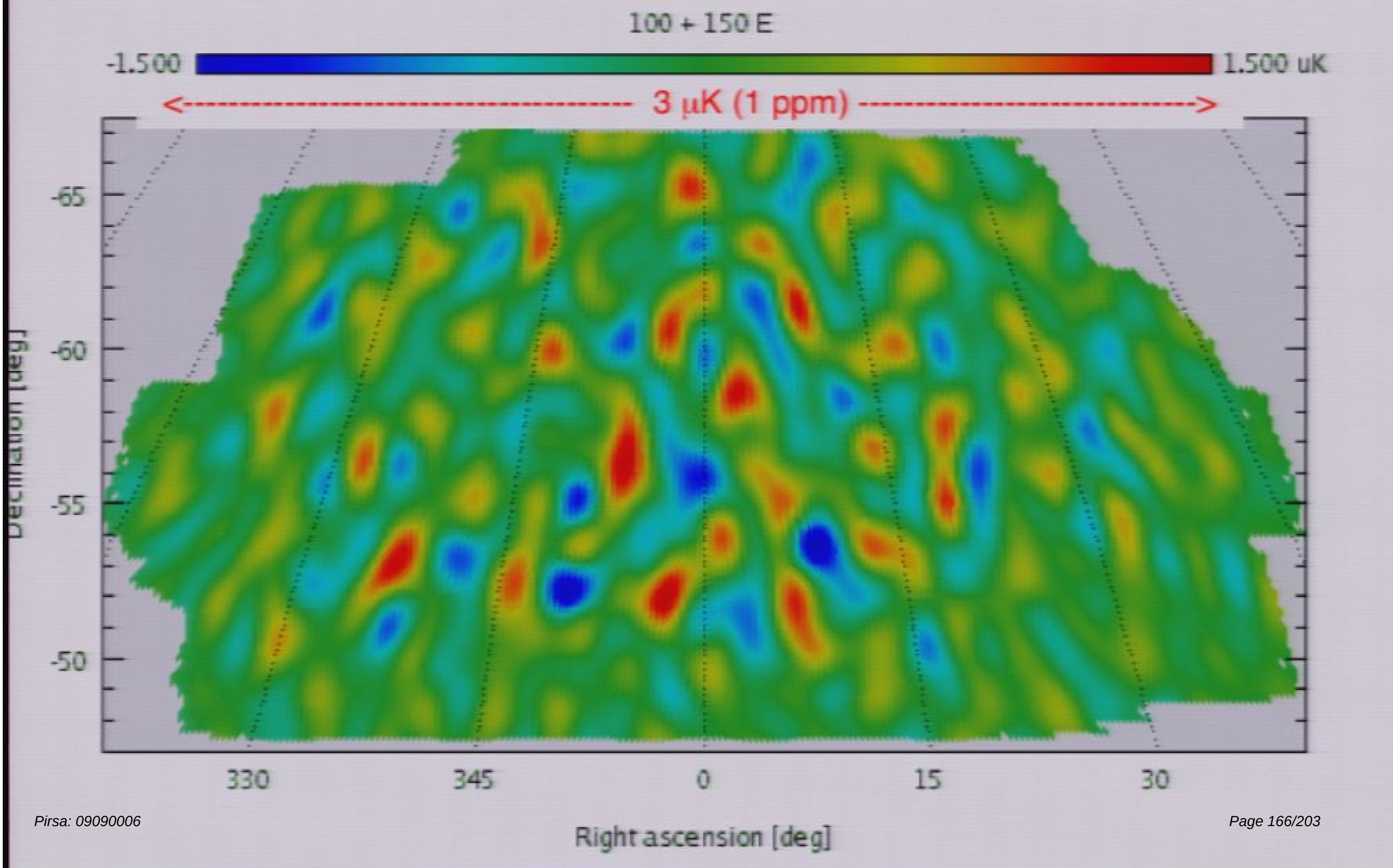


The most sensitive CMB Maps Ever Made

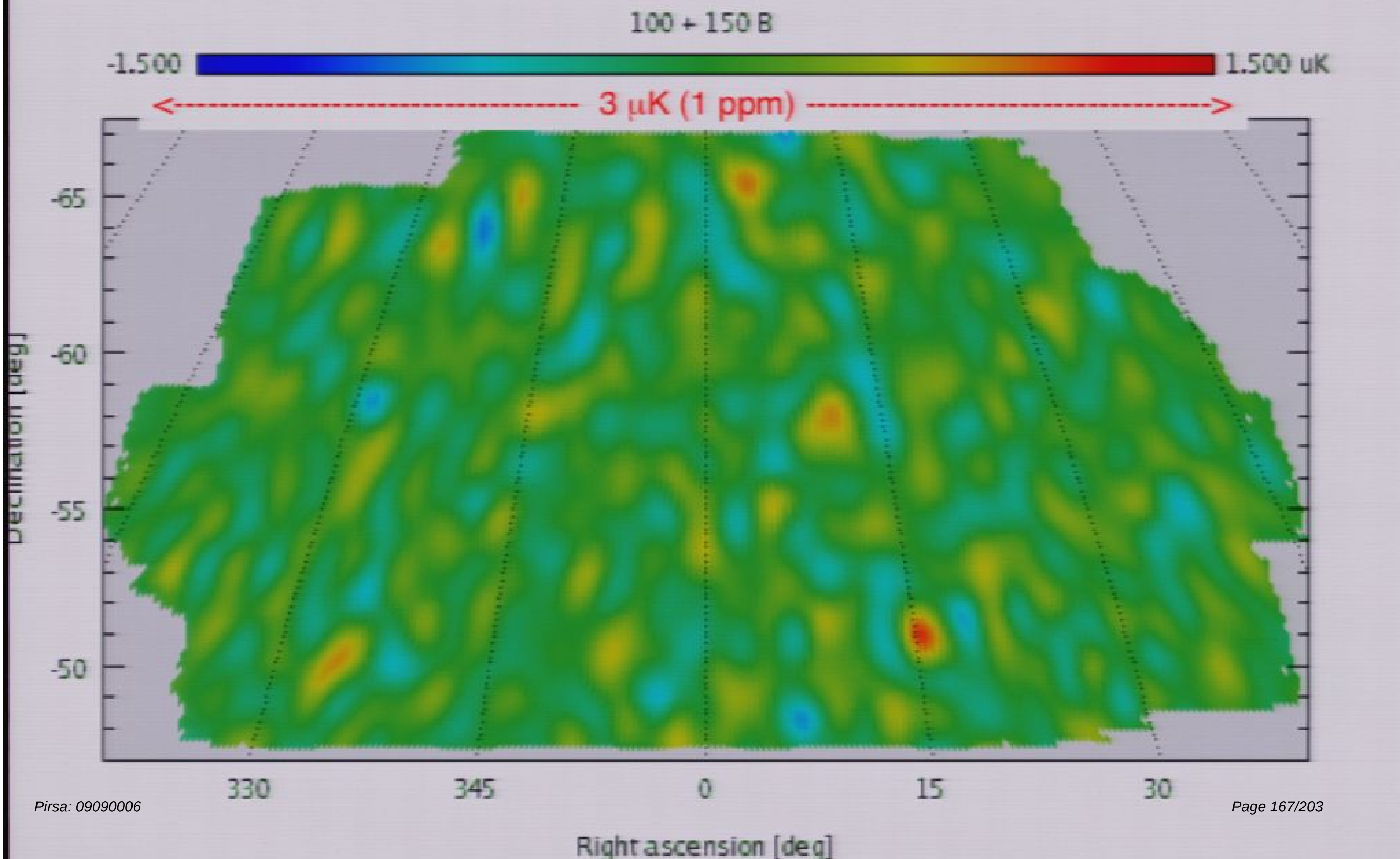




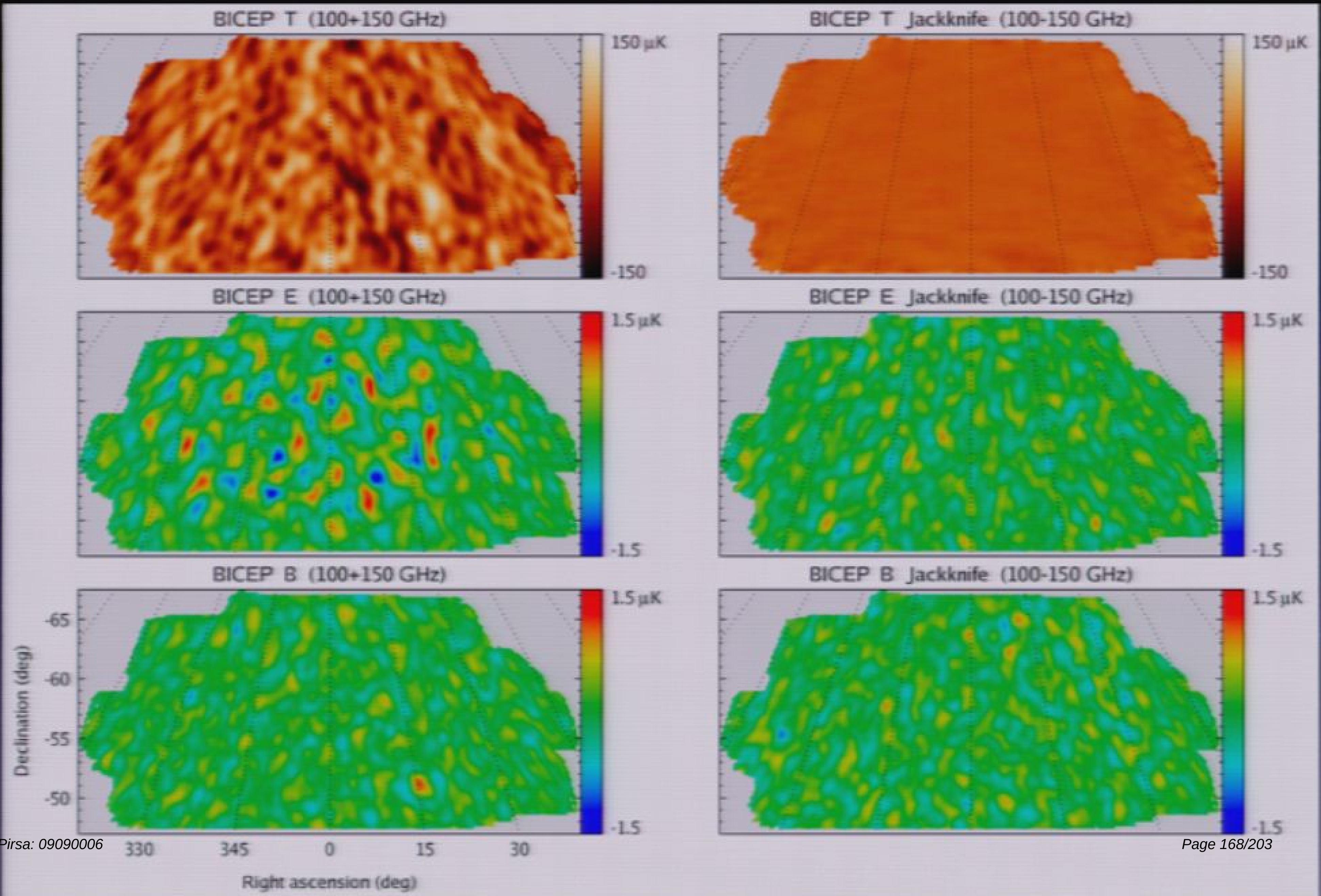
E-mode Maps


100 + 150 E
-1.500
1.500 uK
3 μK (1 ppm)
-65
-60
-55
-50
Declination [deg]
330
345
0
15
30
Right ascension [deg]

B-mode 100 &150 GHz



Manufacturing Statistics: Double your data; split your data in half!

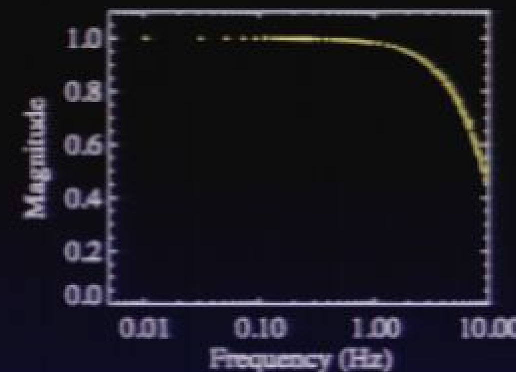


Instrument characterization

Bolometer transfer functions

Method: Gunn or noise diode source, analyze response to transitions

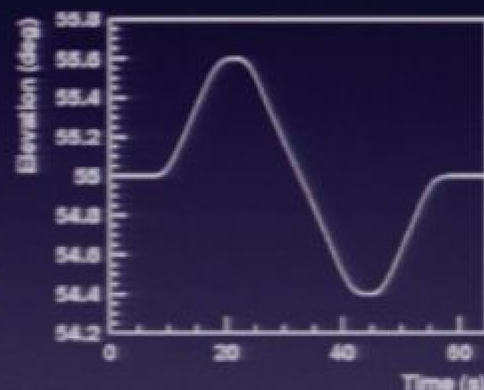
Result: relative gain uncertainty < 0.3% over 0.1 – 1 Hz after deconvolution

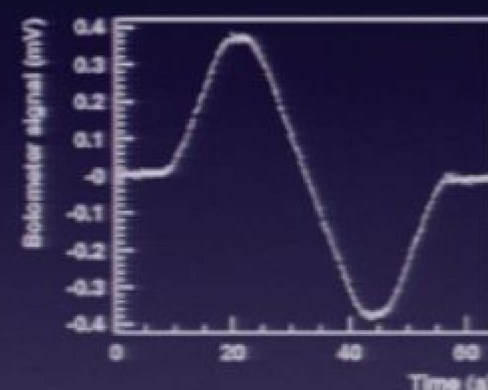


Relative gains

Method: atmospheric signal from “elevation nods”

Result: common mode rejection > 98.9%

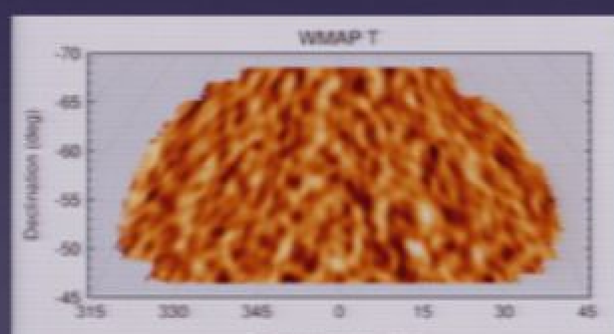


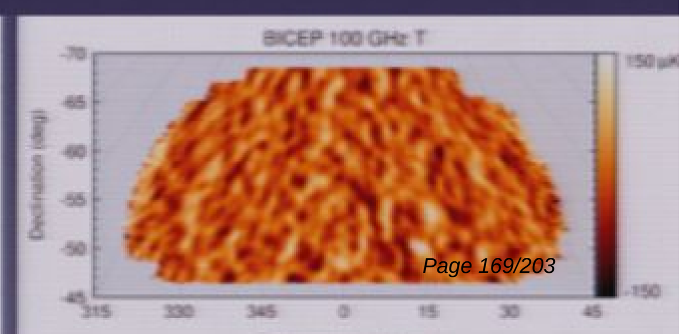


Absolute gains and detector pointing

Method: cross-correlate BICEP and WMAP temperature maps

Result: gain uncertainty ~2%, centroid uncertainty 0.03° rms



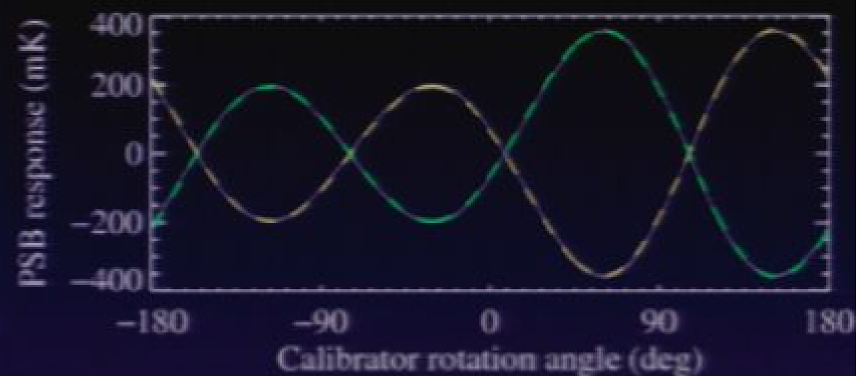


Instrument characterization

Cross-polar leakage and polarization orientation angle

Method: rotating polarized sources (dielectric sheet, wire grid, etc.)

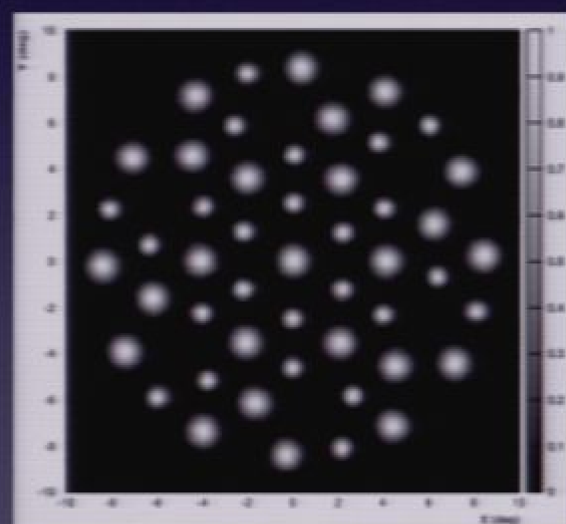
Result: cross-polar leakage uncertainty ±0.01, orientation angle uncertainty ±0.7°

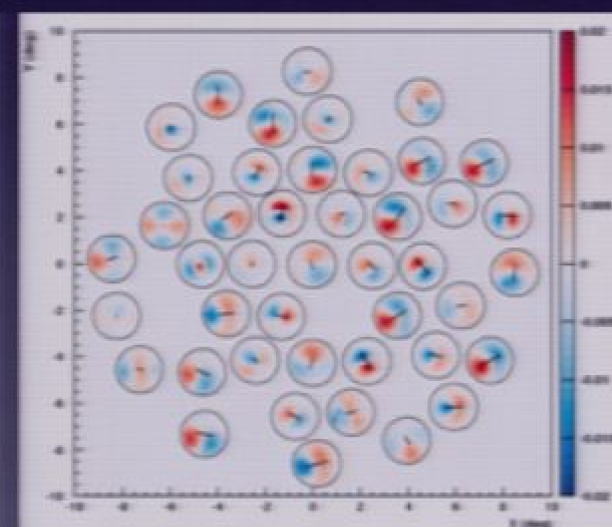


Main beam shapes

Method: map far-field sources (thermal source and noise diode)

Result: average FWHM 0.93°, 0.60° at 100, 150 GHz





More details: Takahashi et al., arXiv:0906:4069

From maps to power spectra (Chiang et al 2009)

Output of Spice estimator

Spice kernel

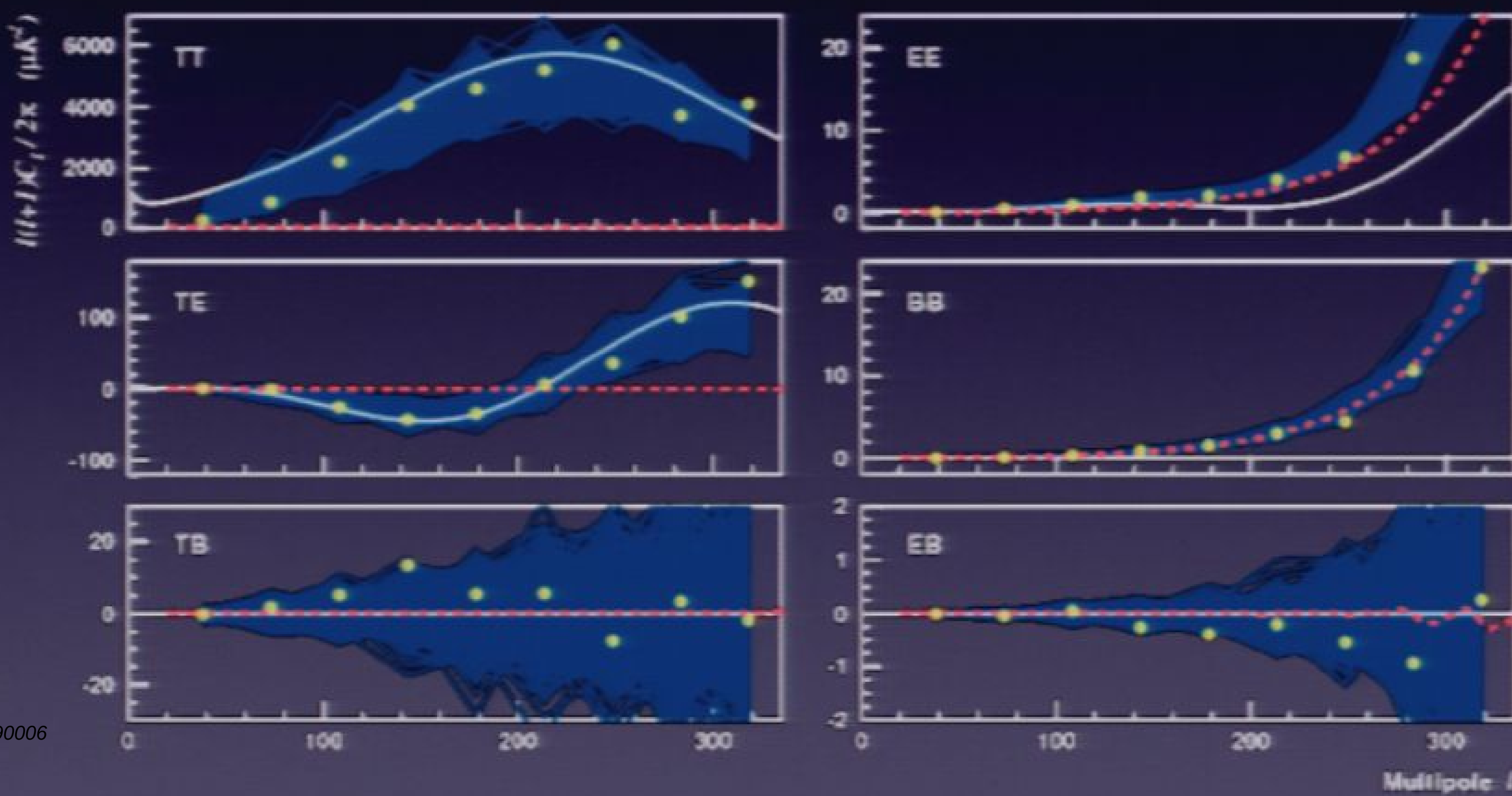
Ell space filter function

$$\hat{C}_\ell = \sum_{\ell'} \kappa_{\ell\ell'} F_{\ell'} \mathcal{B}^2_{\ell'} C_{\ell'} + \hat{N}_\ell$$

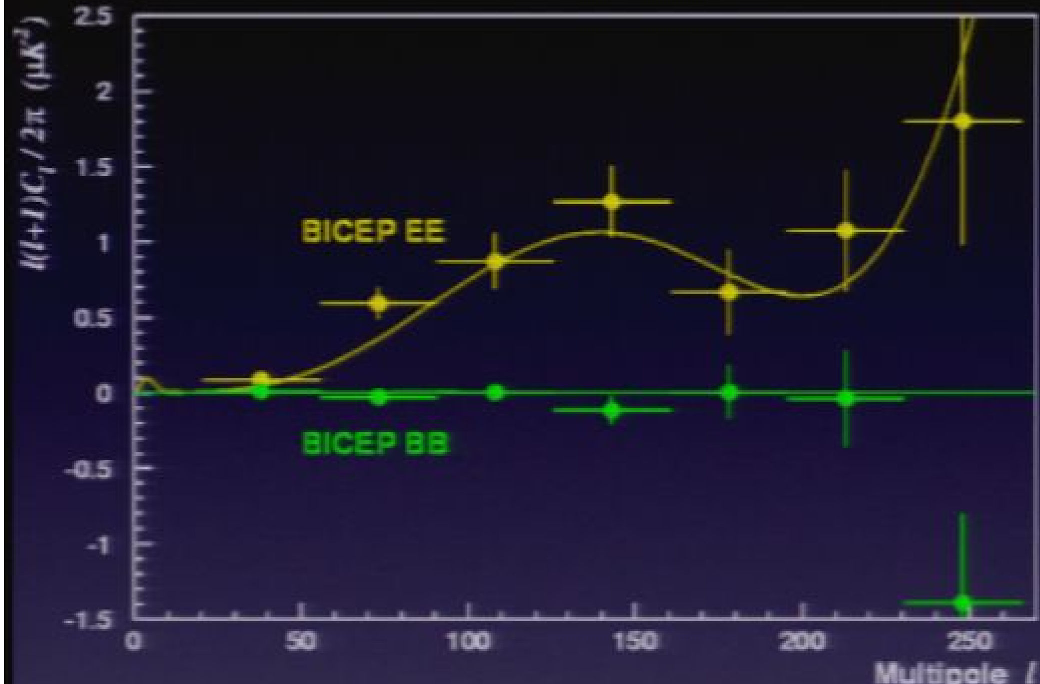
Noise power spectrum

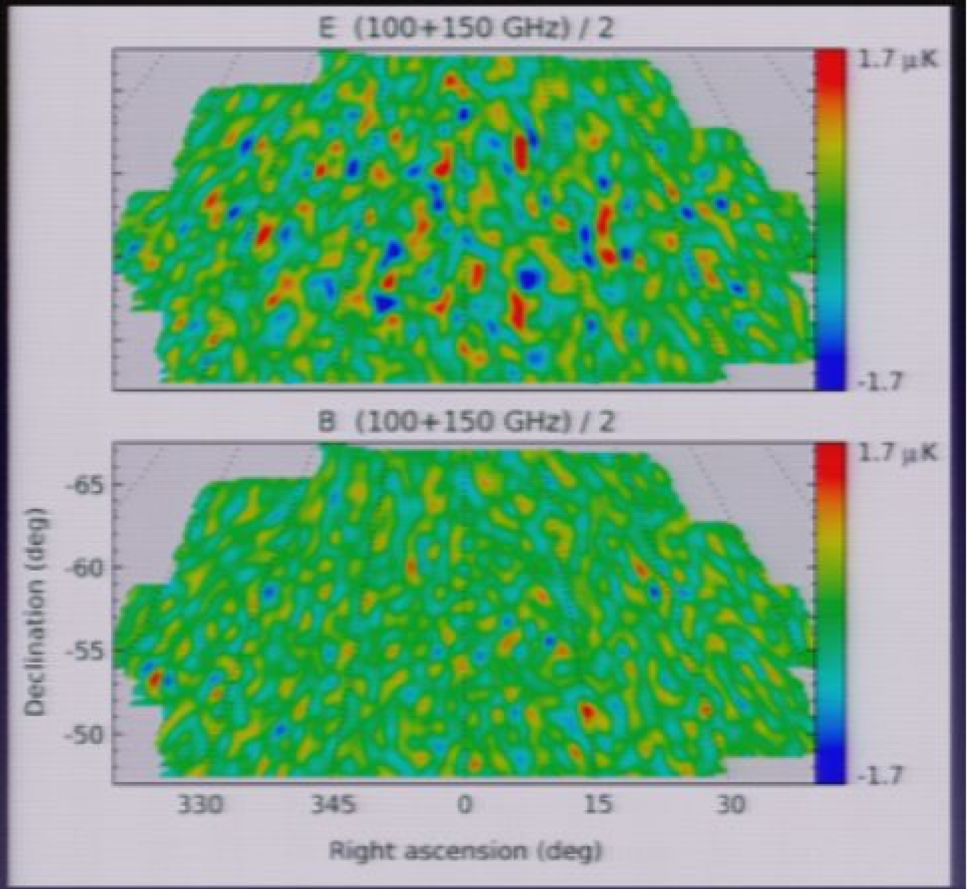
Beam / pixel factor

The answer: underlying C_ℓ



Polarization Power Spectra from BICEP

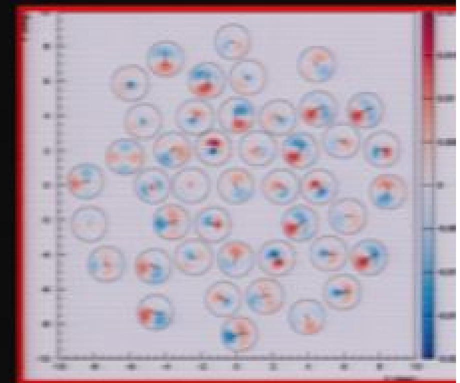




- For the first time, BICEP detects EE peak at ell ~ 140 with high S/N
- BB spectrum is consistent with zero, other spectra consistent with LCDM
- Polarization data pass jackknife consistency tests

Only Observations of the G.W.B. on November 1, 2007

Potential systematics

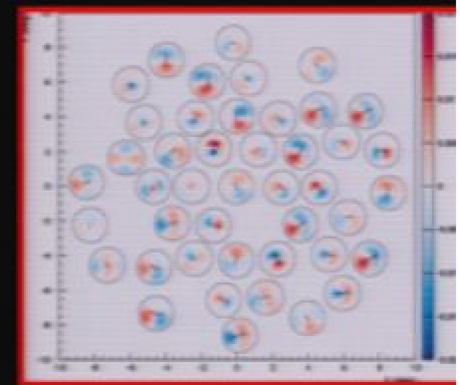


- Uncertainties in calibration and beams can leak T, E into B
- We set r = 0.1 benchmark for systematics: false BB < 0.007 μK^2 $\ell \sim 100$
- Used signal simulations to calculate false BB from systematic errors

Instrument property	Benchmark (r = 0.1)	Measured
Relative gain uncertainty	0.9%	<1.1%
Differential beam size	3.6%	< 0.3%
Differential pointing	1.9%	1.3 ± 0.4%
Differential ellipticity	1.5%	< 0.2%
Polarization orientation uncertainty	2.3°	< 0.7°
Telescope pointing uncertainty	5 arcmin	0.2 arcmin
Polarized sidelobes (100, 150 GHz)	−9, −4 dBi	−26, −17 dBi
Focal plane temperature stability	3 nK	1 nK
Optics temperature stability	4 μK	0.7 μK

More details: Takahashi et al., arXiv:0906:4069

Potential systematics



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Many of these are adequate for **r=0.01!**

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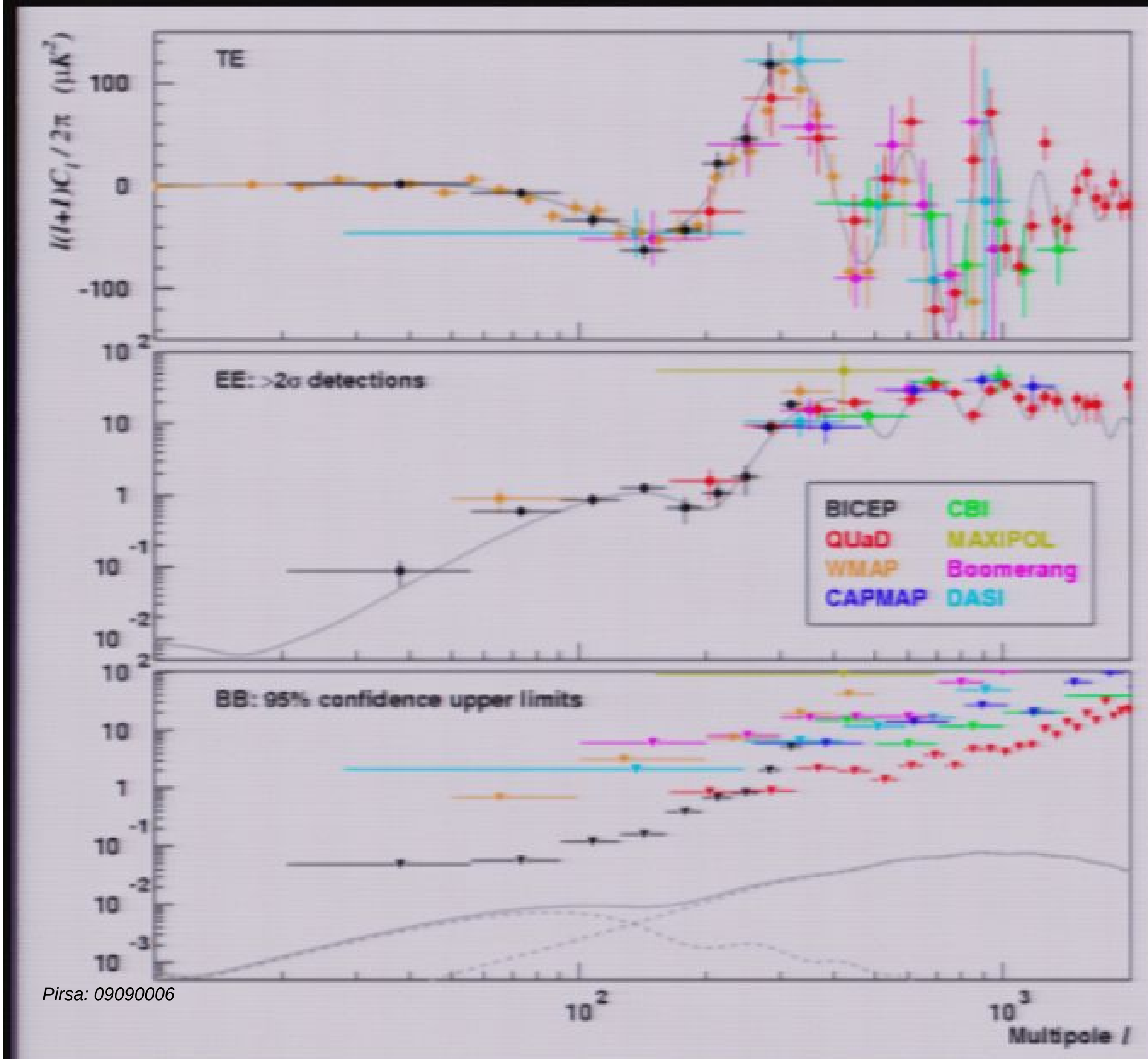
The state of the field



BICEP contributes highest S/N polarization measurements at ell ~ 100

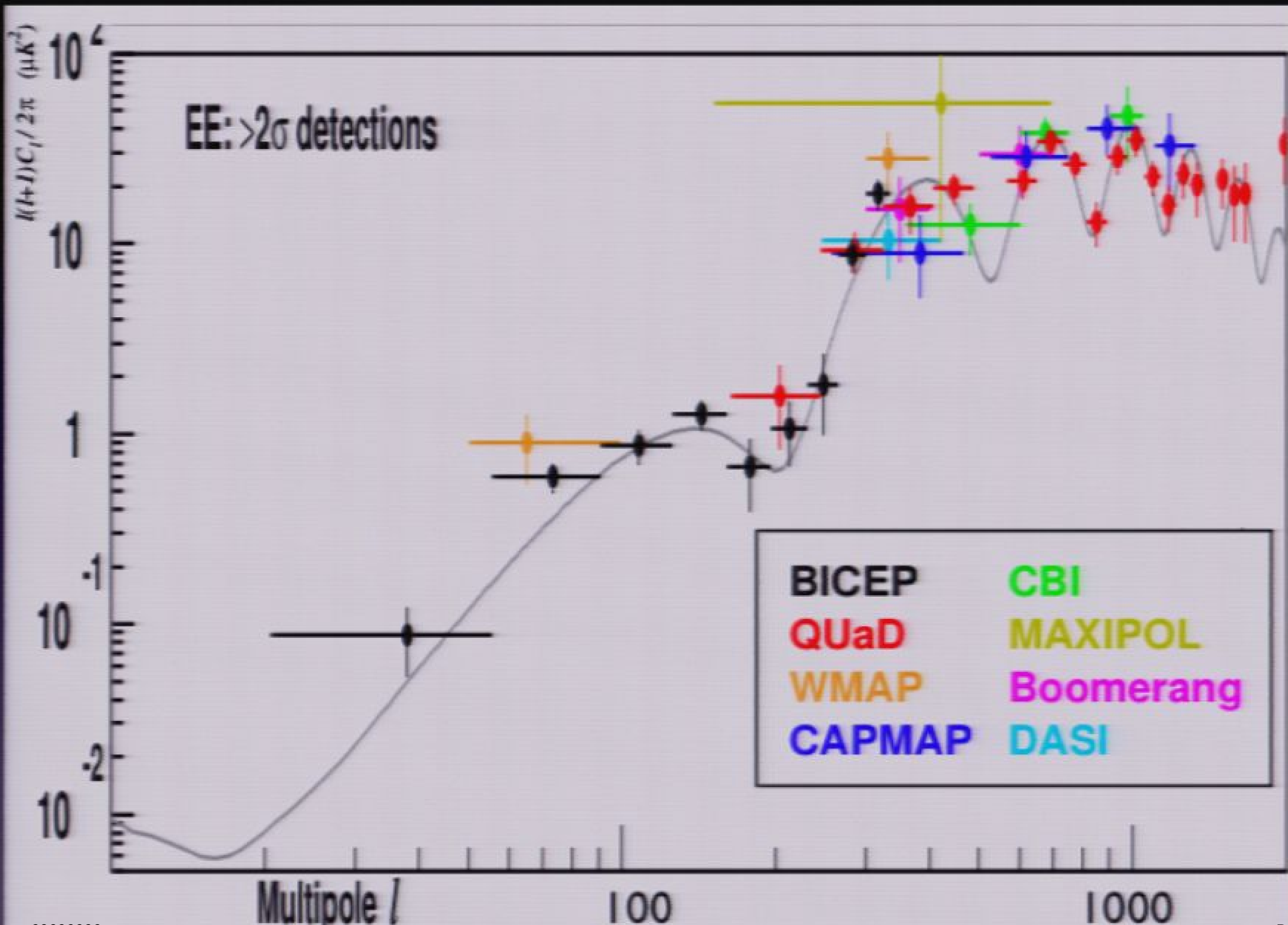
BB upper limits are the most powerful to date

Upcoming analysis will use full data set, relaxed data cuts...

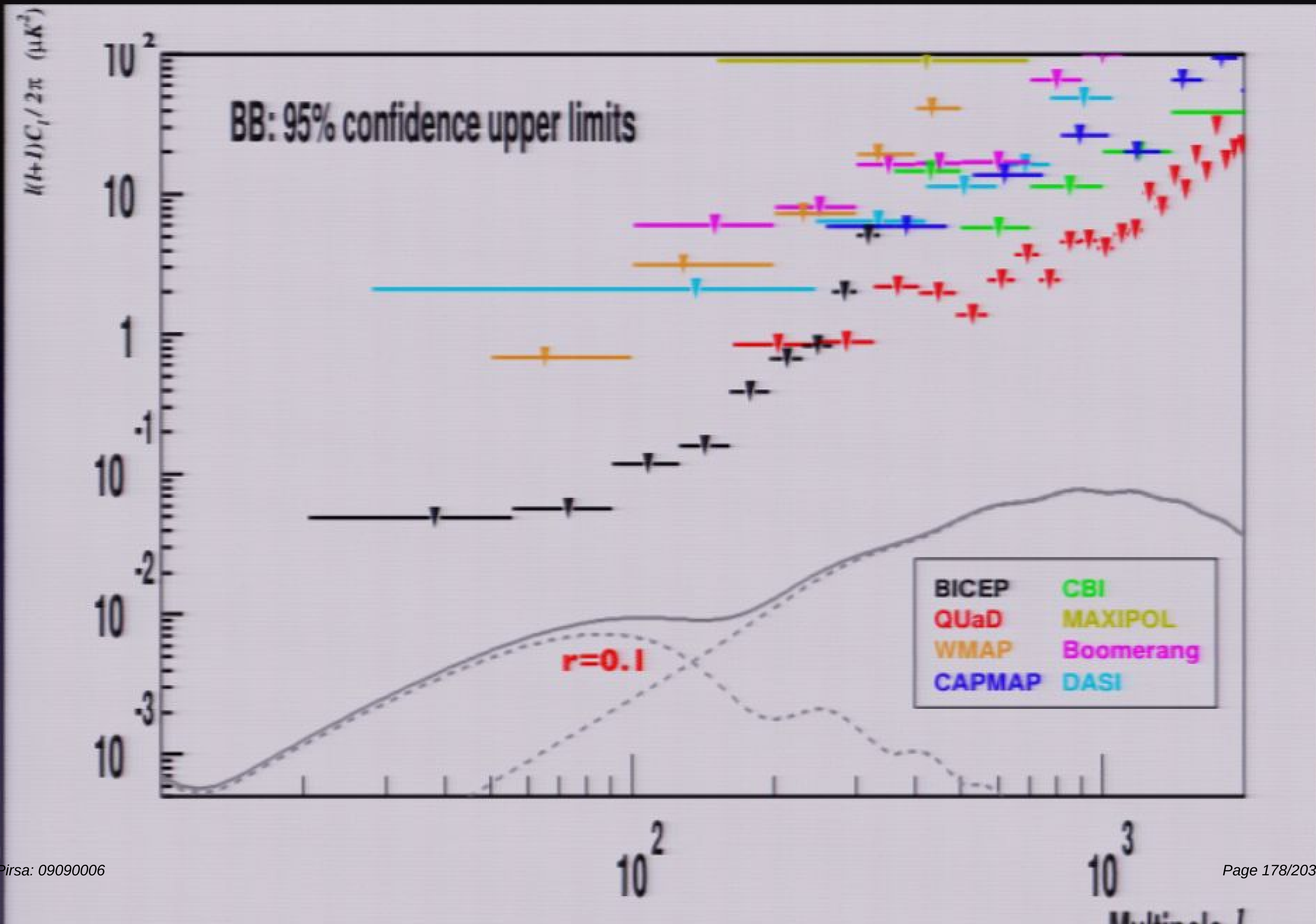
BICEP two-year results: arXiv:0906.1181

BICEP data: http://bicep.caltech.edu

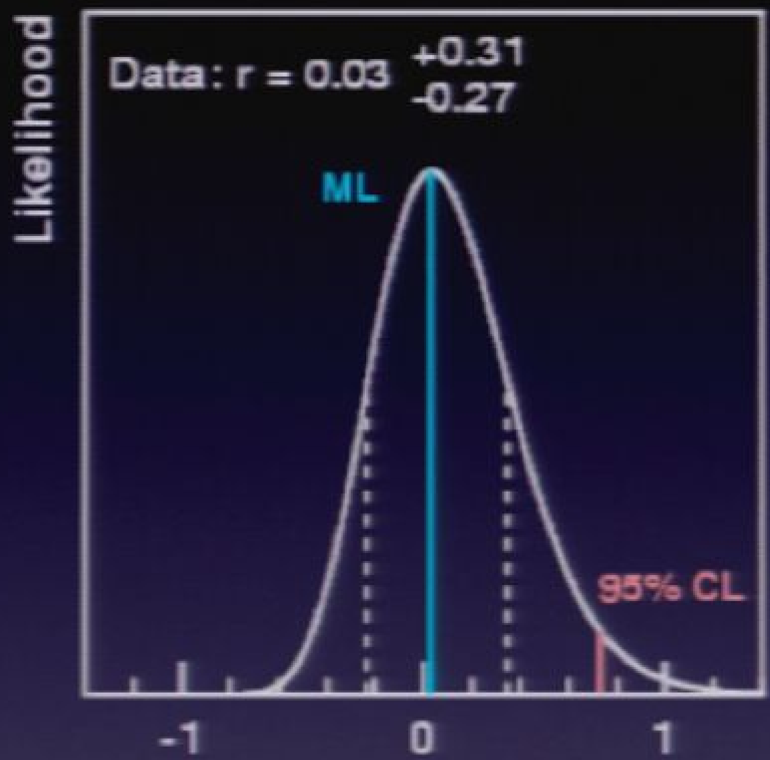
The state of the field

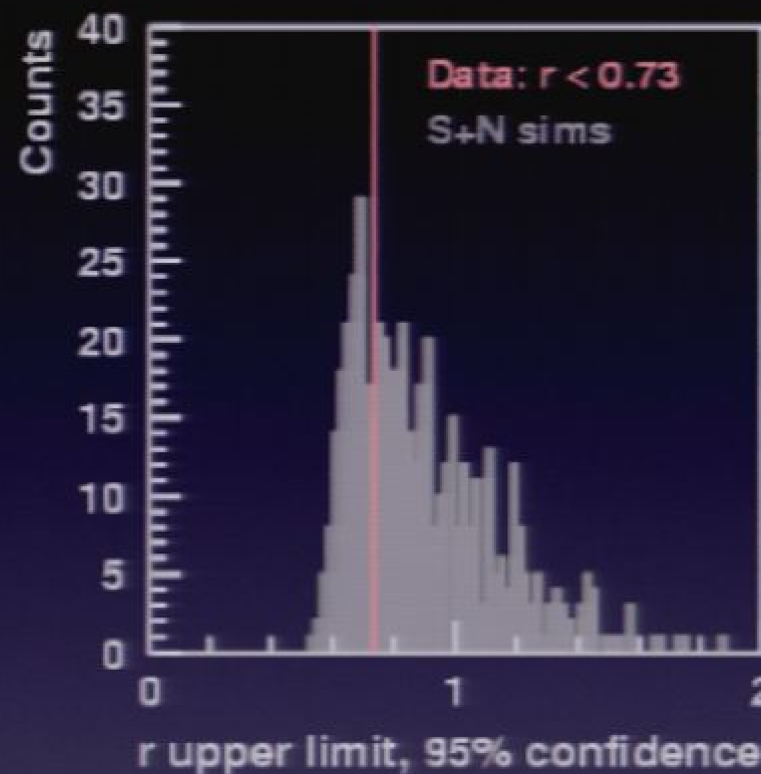


B-mode Polarization Limits compared to r=0.1



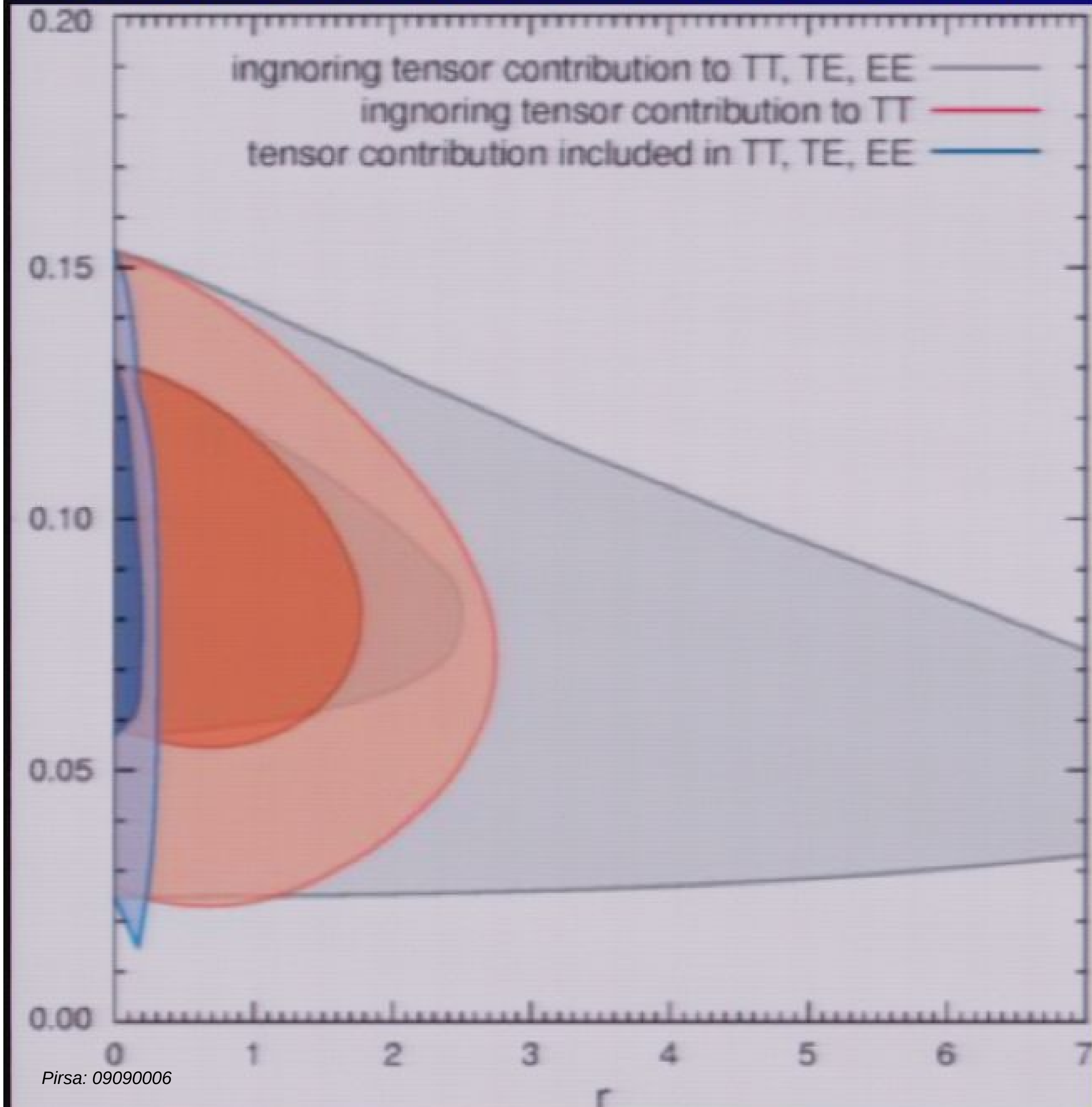
Constraint on r from BICEP BB





- Assume fixed LCDM parameters, calculate template BB, vary r
- Calculate chi-squared and likelihood as function of r
- BICEP BB: r = 0.03, +0.31, −0.27, upper limit is r < 0.73 at 95% confidence

Constraints on GW



- Our ability to constrain the amplitude of gravity waves is still coming mostly from the temperature spectrum.
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- ***WMAP would have to integrate for ~ 100 years to achieve BICEP's sensitivity!***
- ***(And BICEP's cost is <5% of WMAP)***

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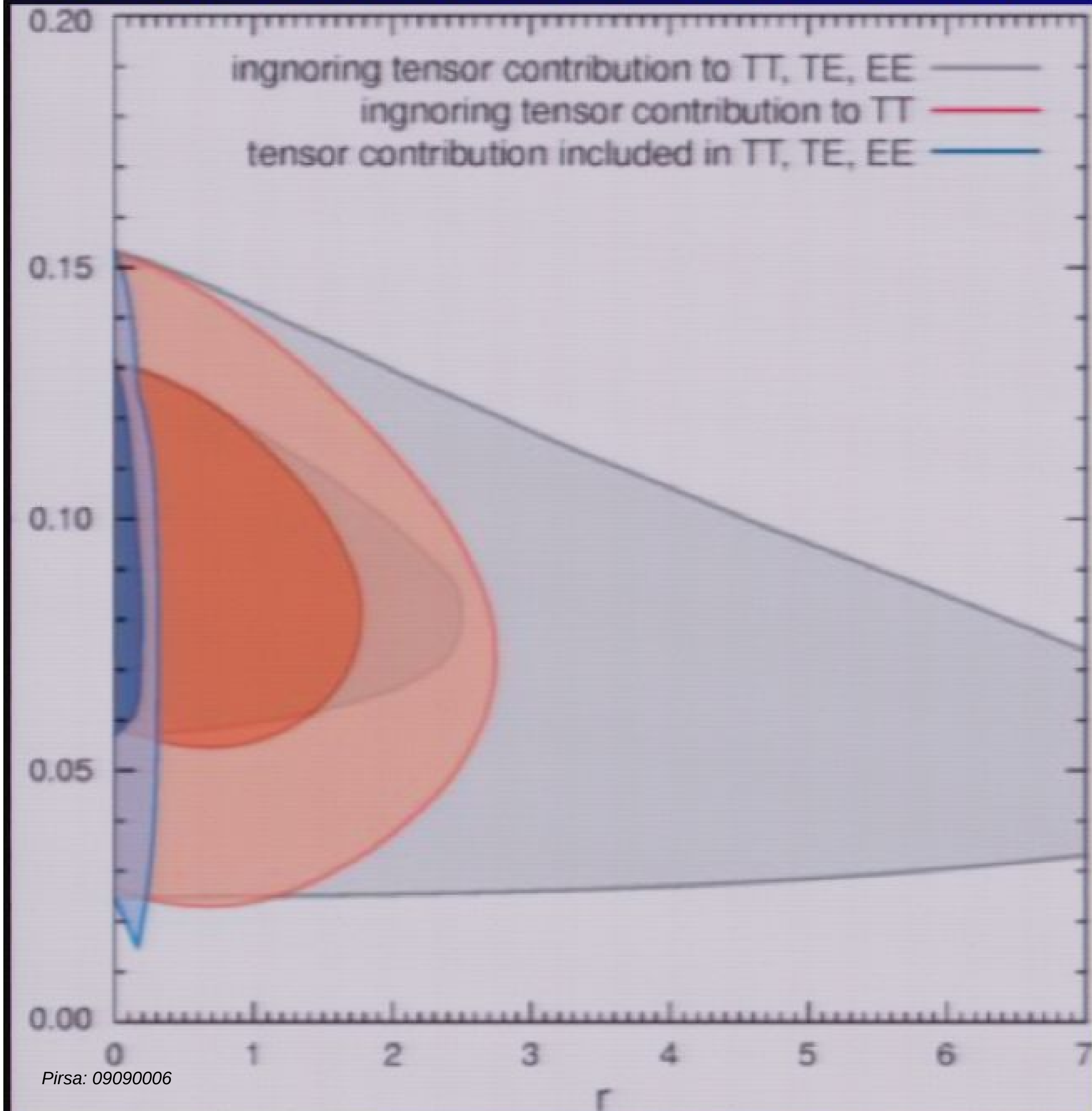

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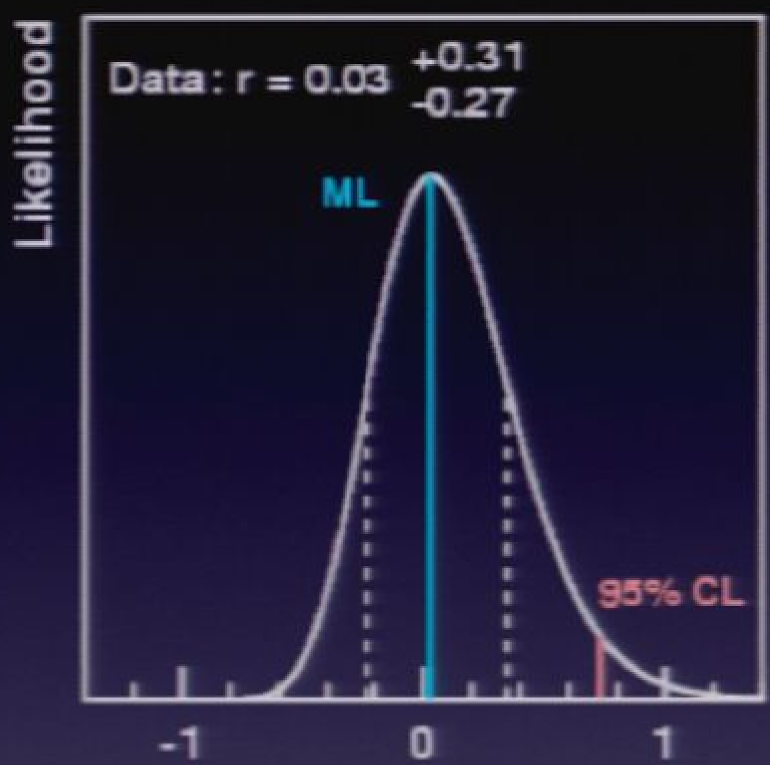

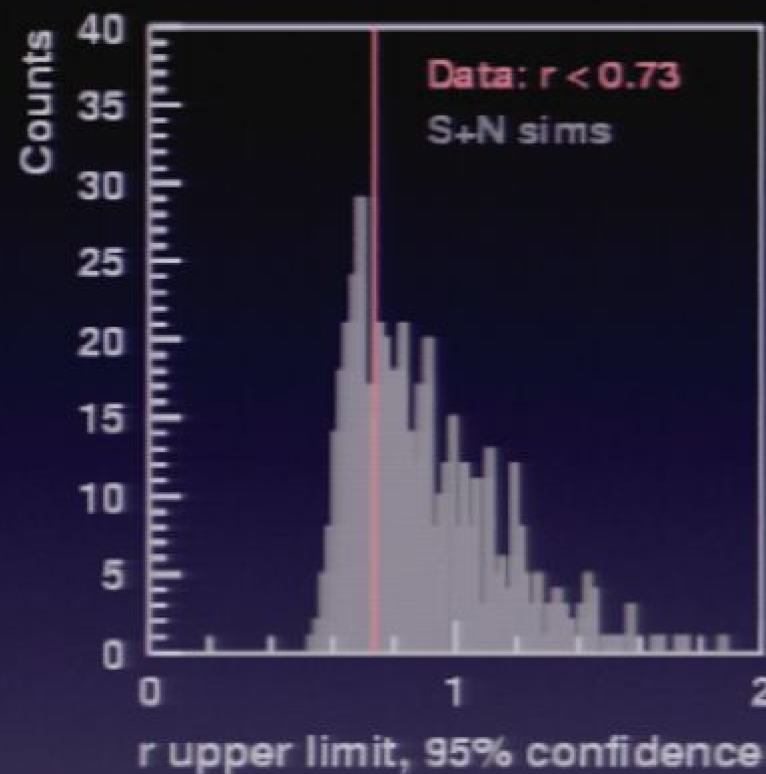

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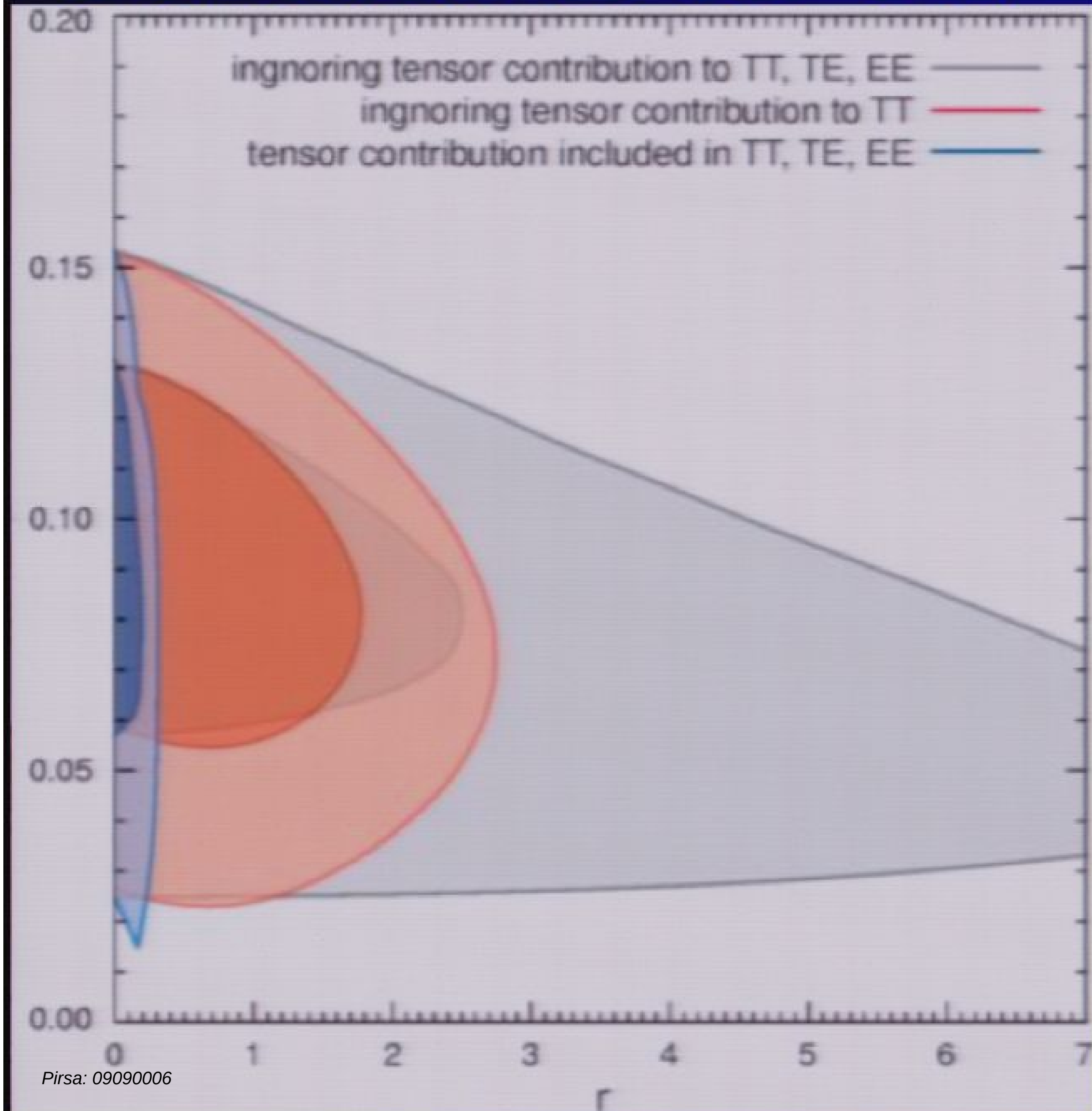

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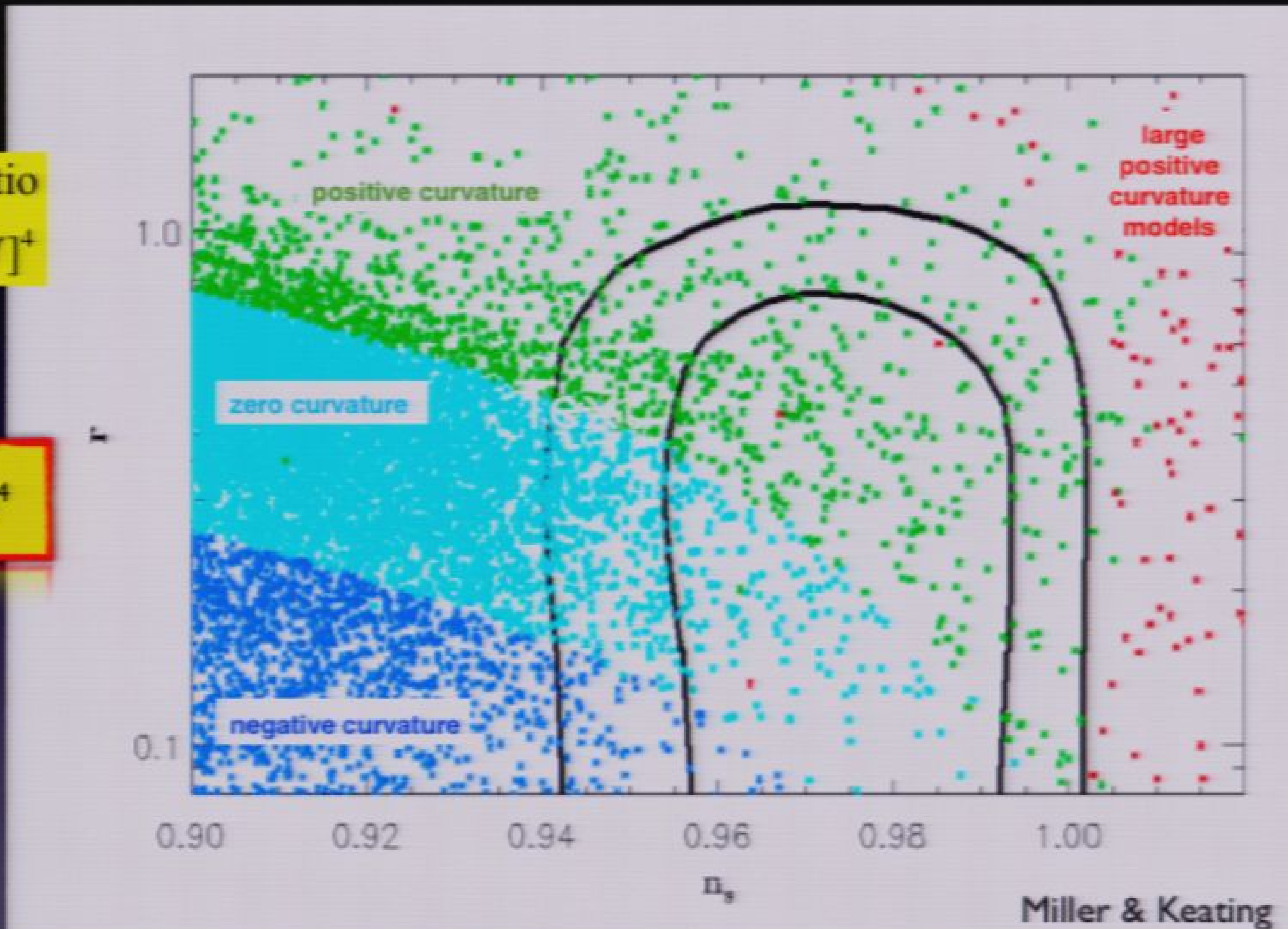
What can we say about the Taxonomy of the Inflationary "Zoo"

tensor - to - scalar ratio

$r \approx V/[3.8\times10^{16}\,\mathrm{GeV}]^4$

$V < [3.5\times10^{16}\,\mathrm{GeV}]^4$



WMAP BB only gives r < 6

WMAP priors on n_s, BICEP BB limits

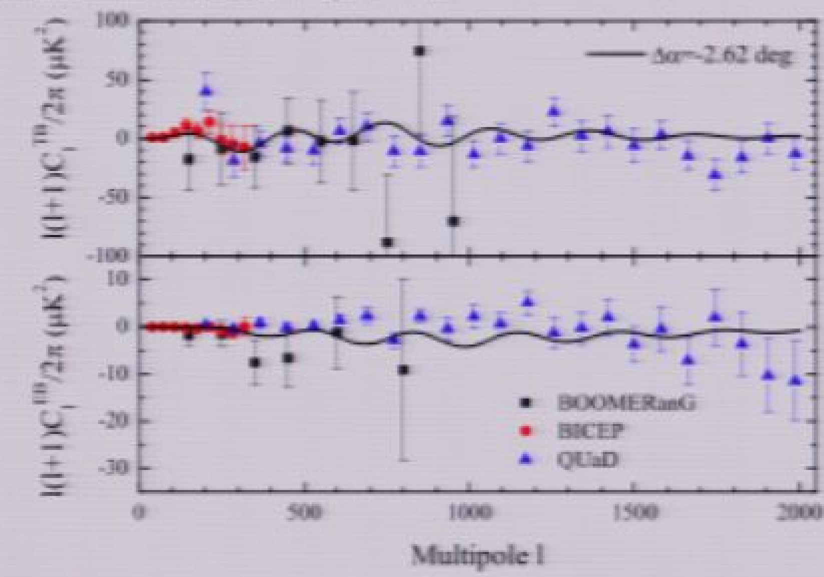
Probing CPT Violation with CMB Polarization Measurements

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
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



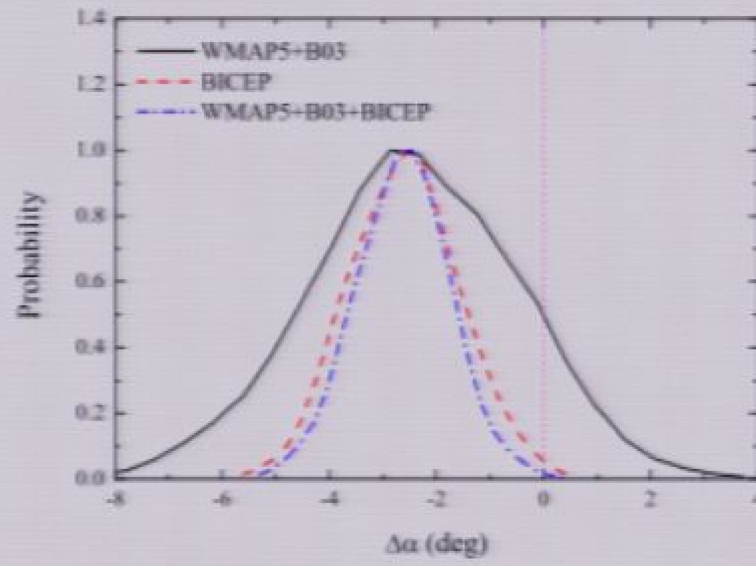


FIG. 1: The binned TB and EB spectra measured by the small-scale CMB experiments of BOOMERanG (black squares), BICEP (red circles) and QUaD (blue triangles). The black solid curves show the theoretical prediction of a model

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

Parity Violating Interactions

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

Caroll & Field (1990)

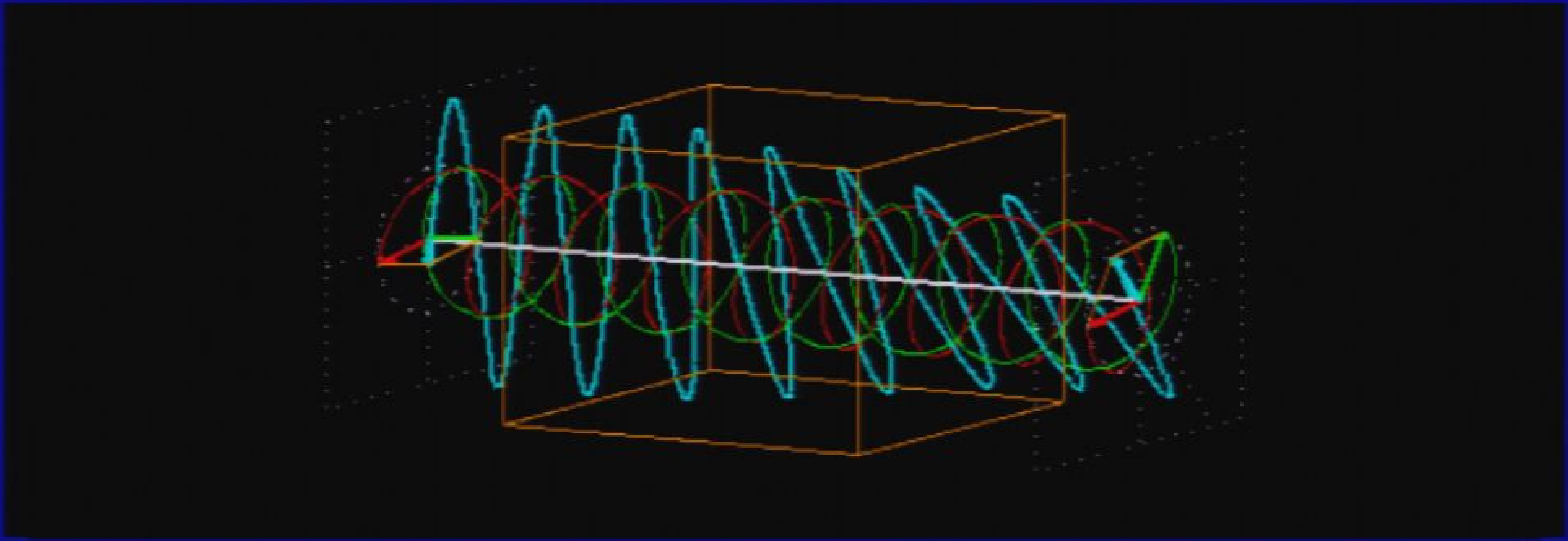
Modified Lagrangian

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

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

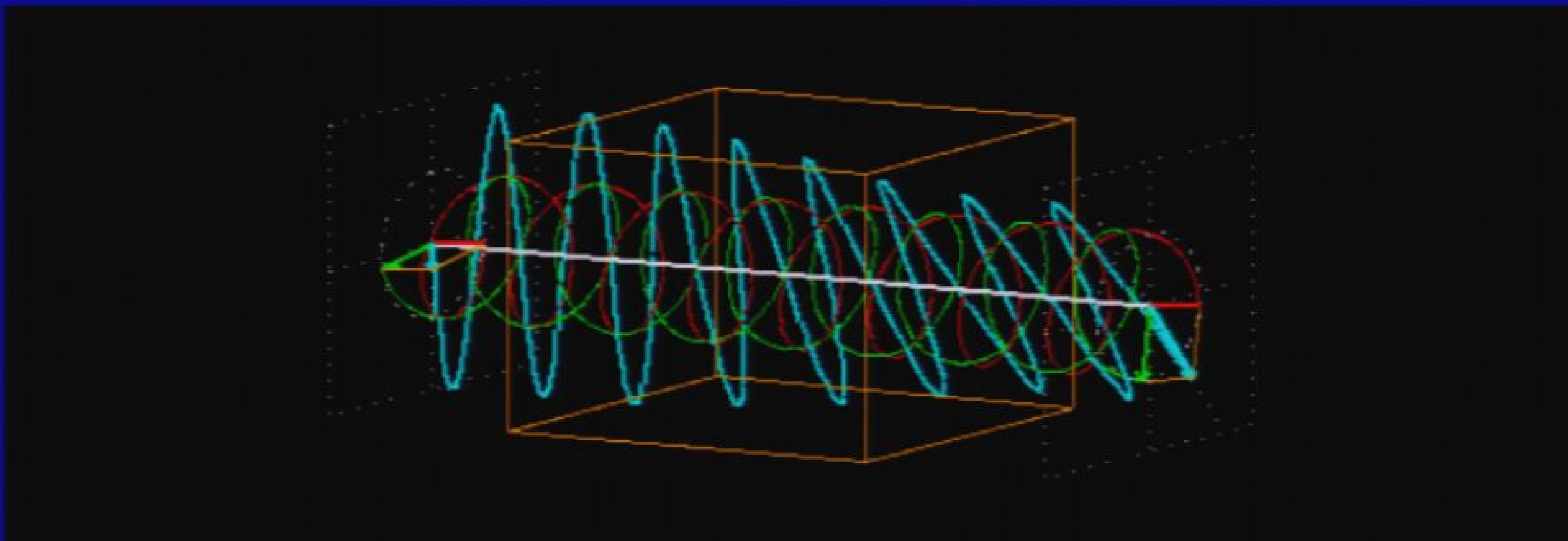


Rotation of the polarization plane $\Rightarrow$
mixing Q and U $\Rightarrow$
converting $E \rightarrow B \Rightarrow$
inducing `forbidden' TB and EB

Couples to CMB lensing ?

Shimon et al. 2009

Rotation of Polarization Plane



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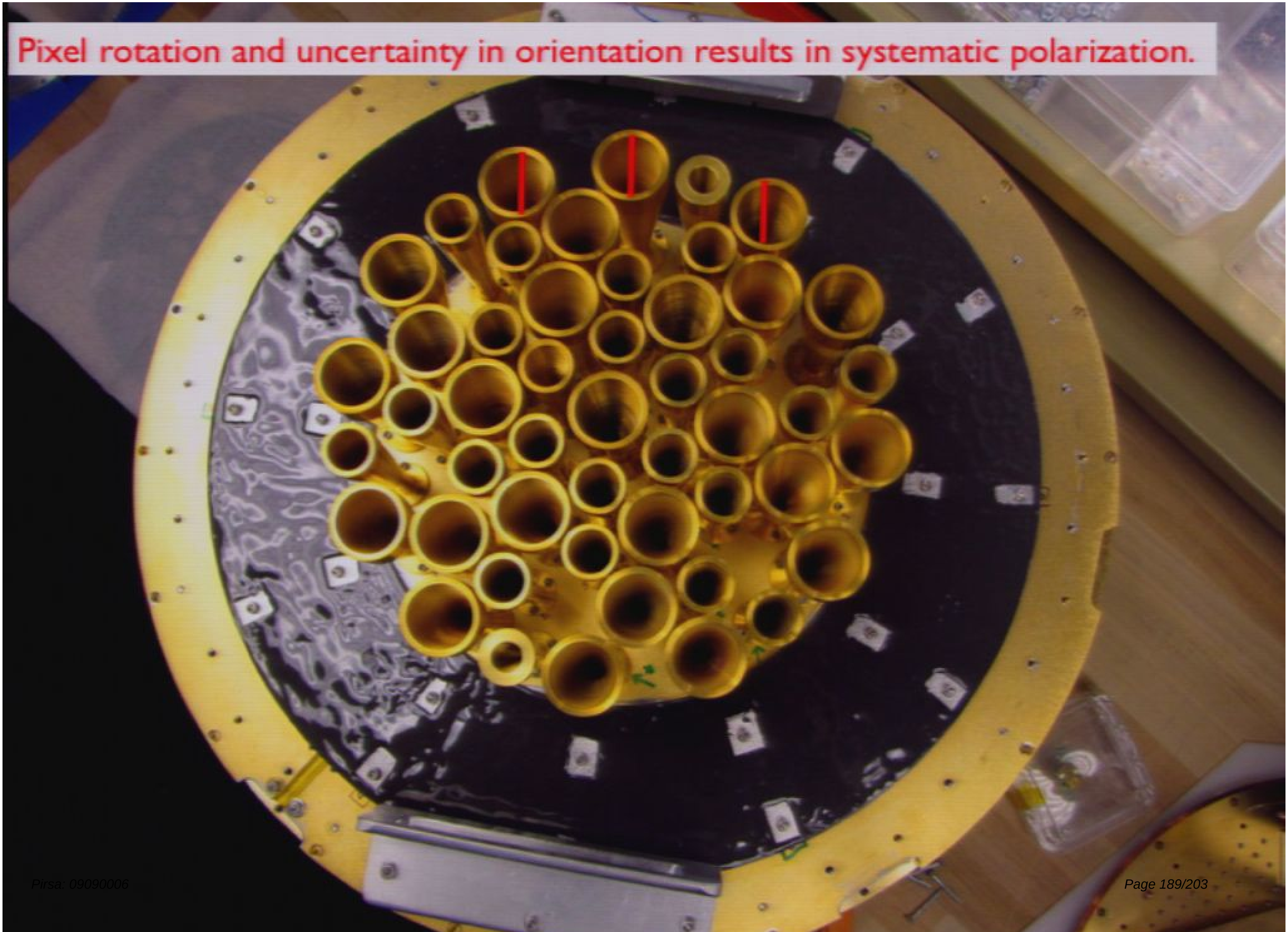

Pixel rotation and uncertainty in orientation results in systematic polarization.

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

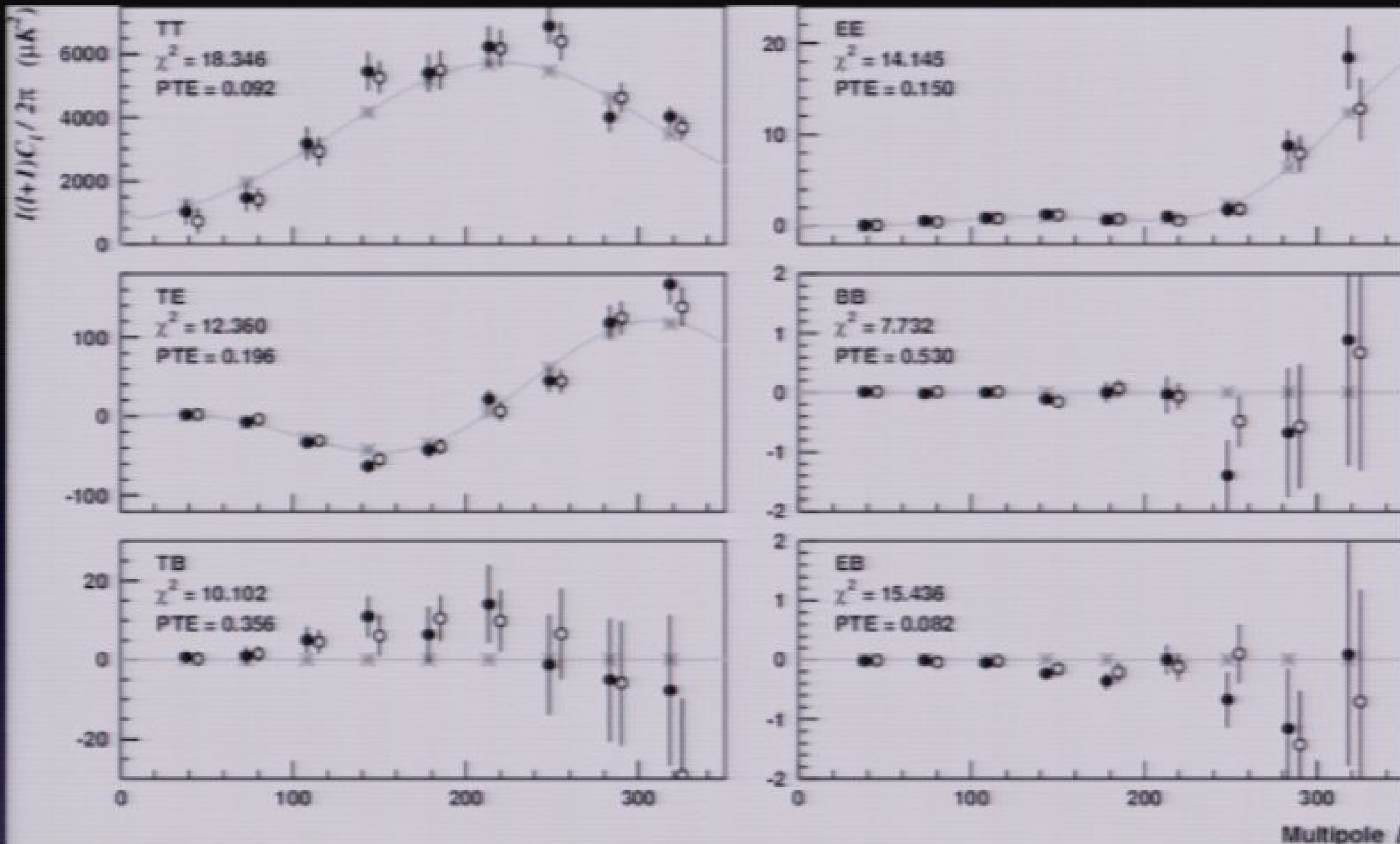
Notes

- 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?

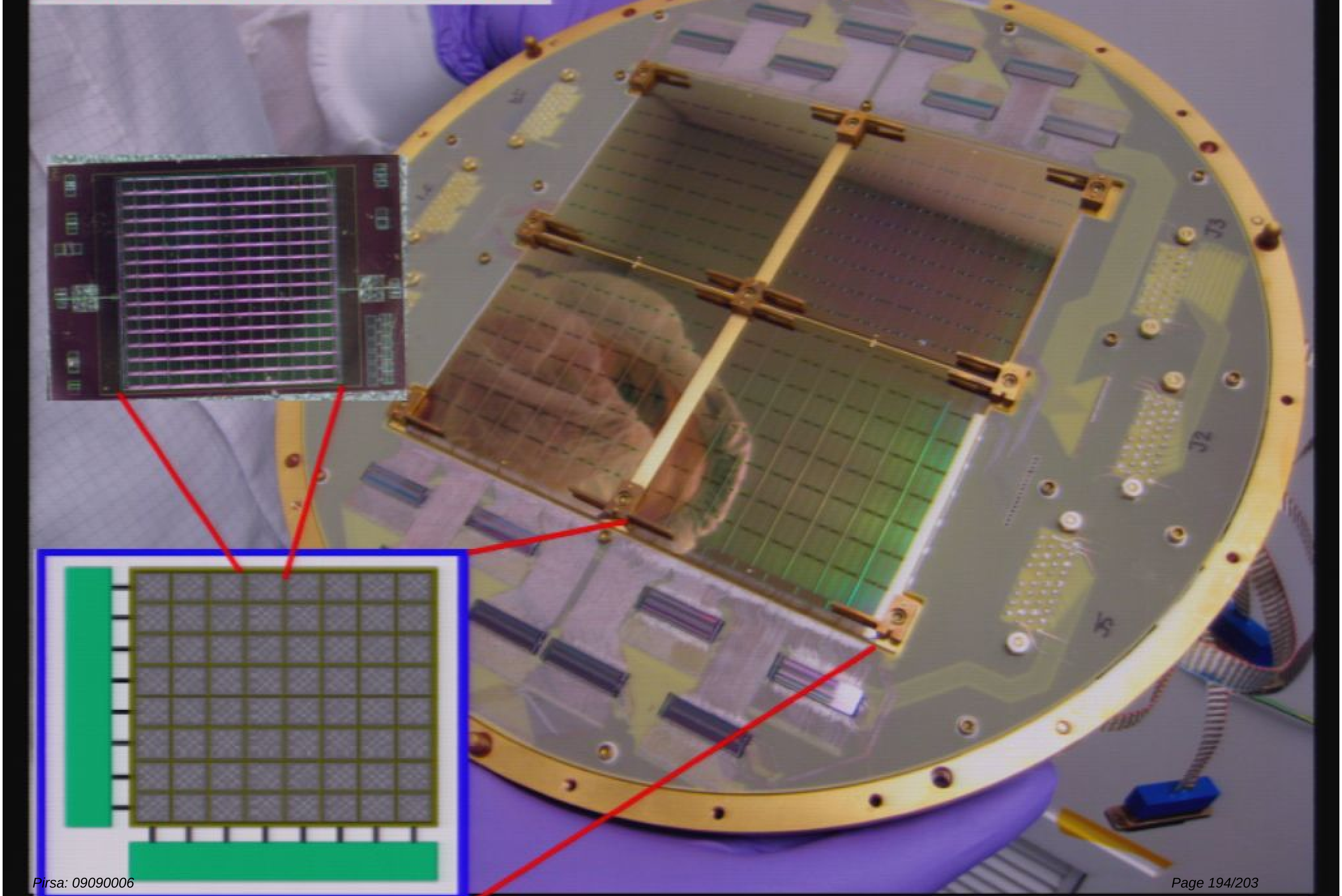
BICEP vs. Standard model: TB=EB=0



- 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'

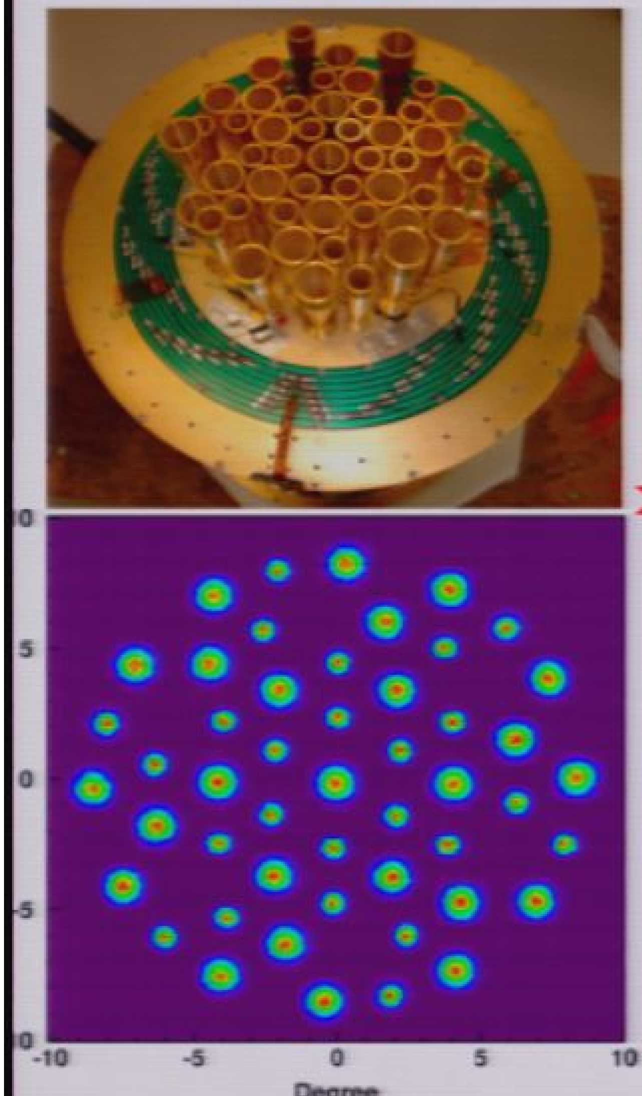

More results to come...with ≈2x more data
http://cosmology.ucsd.edu/

After BICEP comes BICEP2

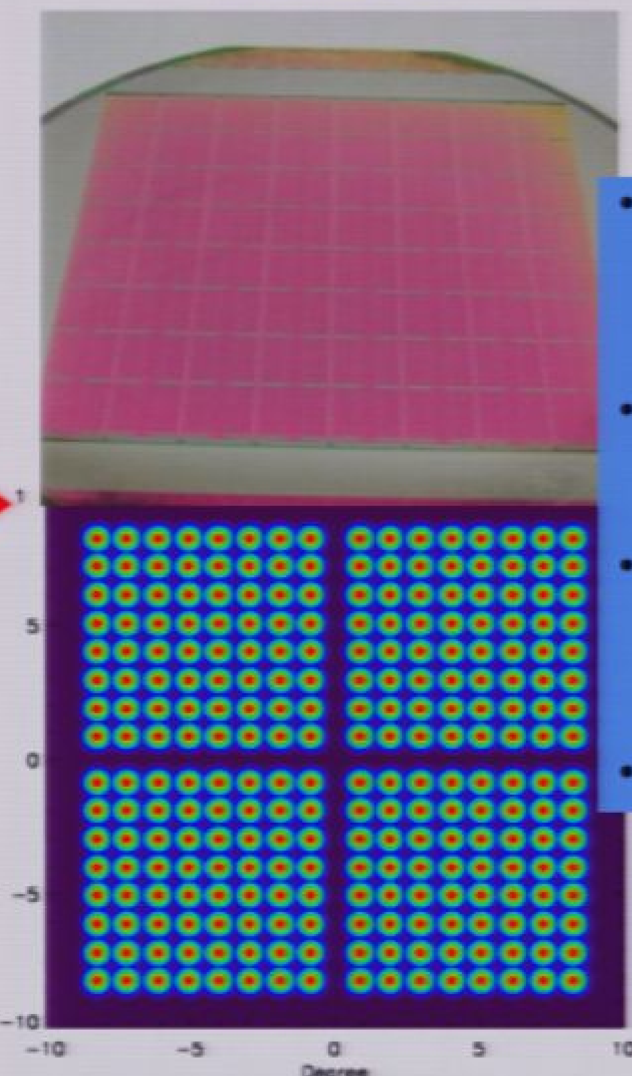


BICEP2 focal plane, May 2009. Fully Lithographed Focal Plane

BICEP1

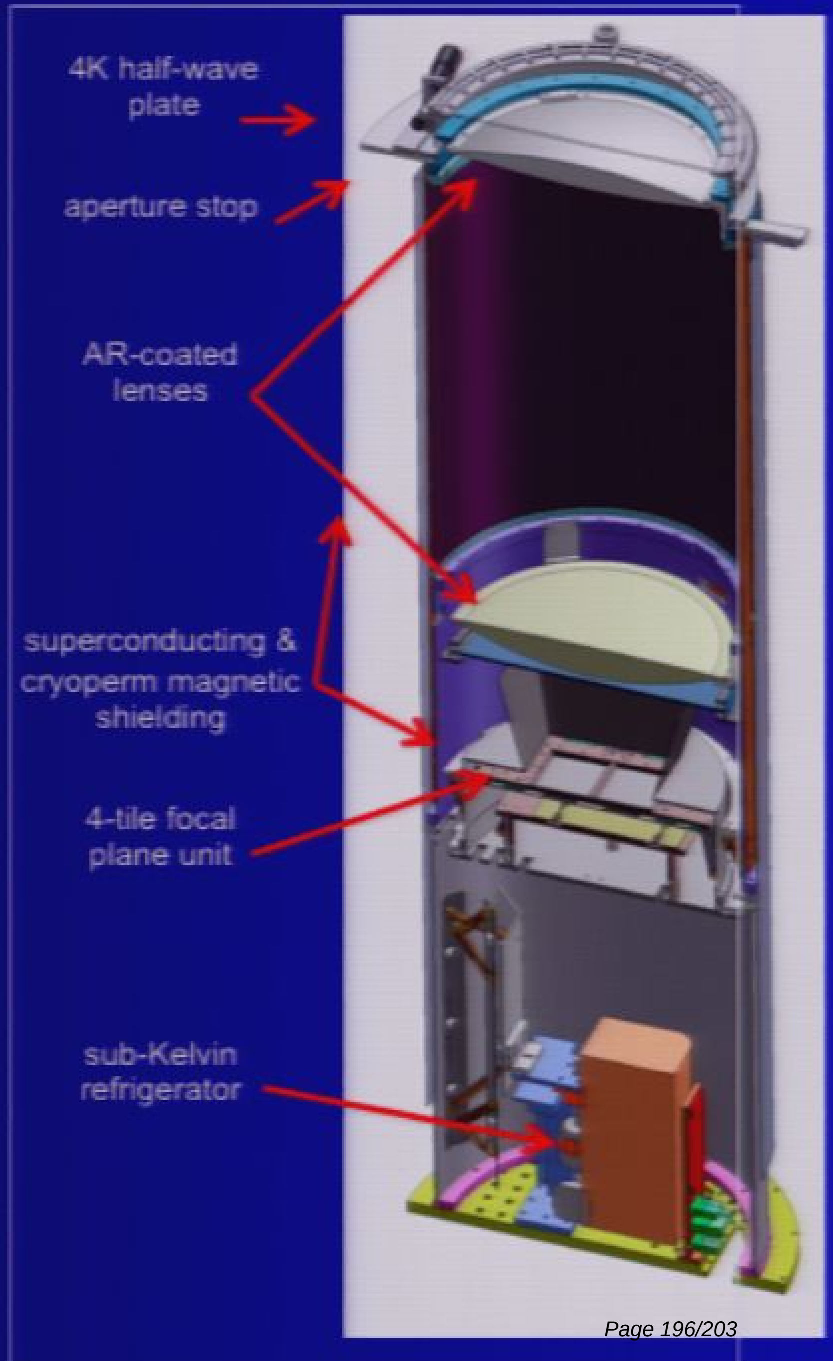


BICEP2



- **Integrate all these component on a Si wafer -> mass production**
- **Compact, inexpensive, photolithographic**
- **TES enables SQUID multiplexed read-out (NIST/ UBC)**
- **Higher packing density**

This is BICEP 2….
It will be 5x "stronger" than the original BICEP



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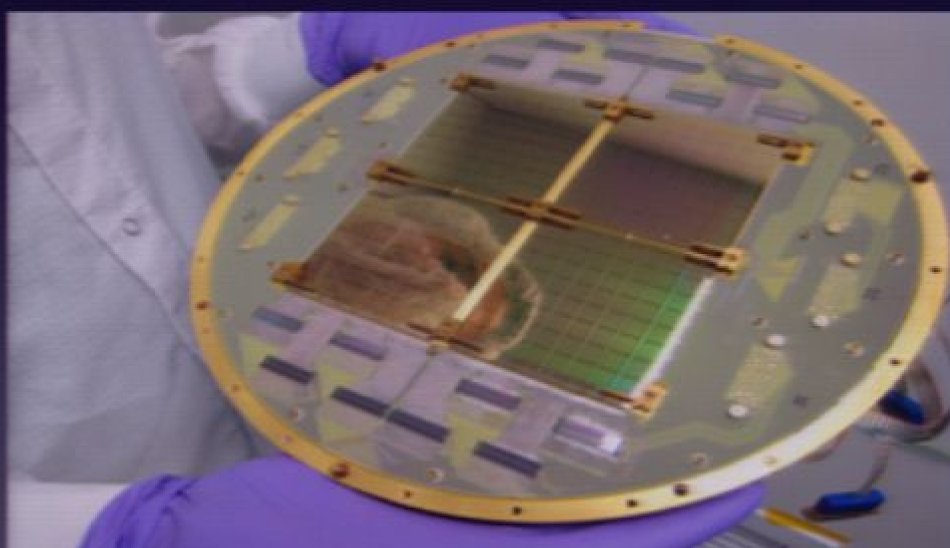
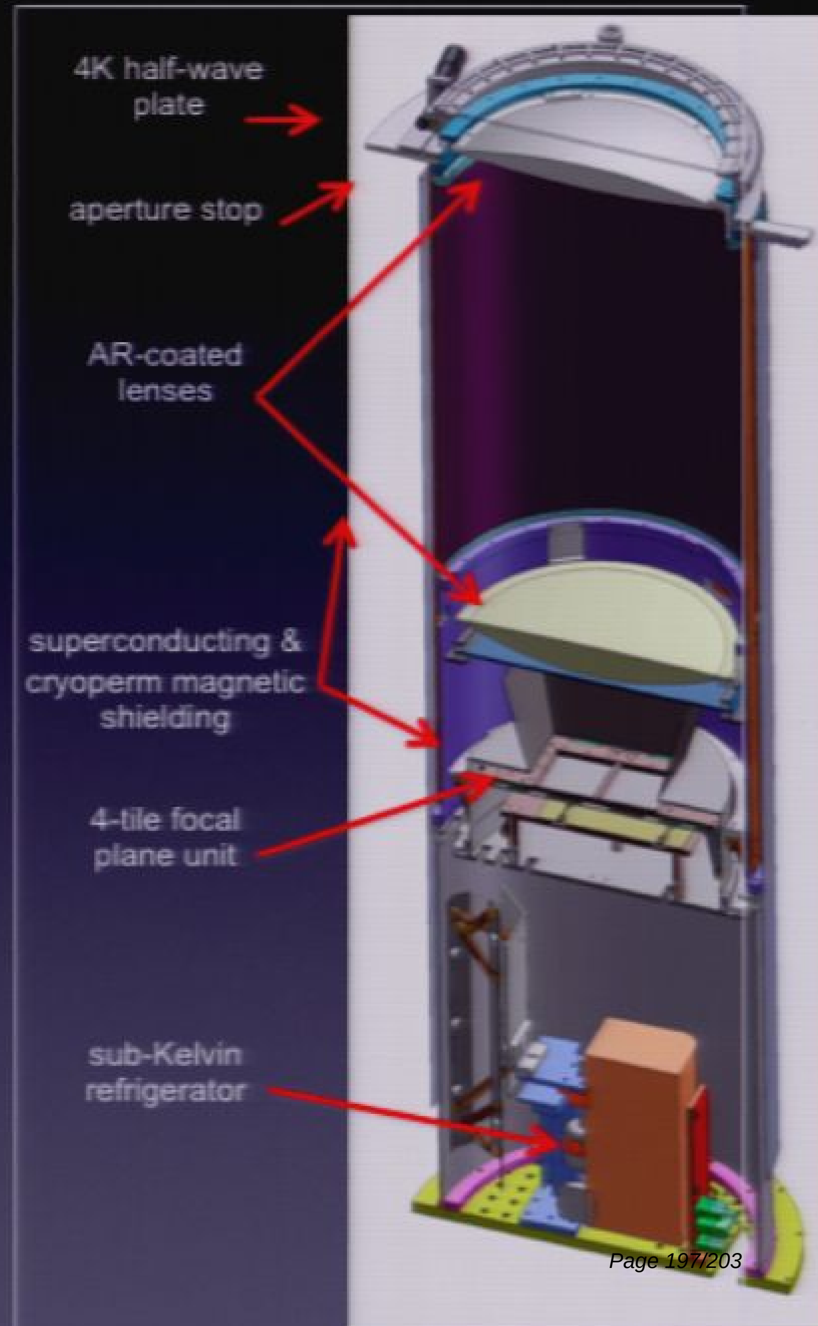
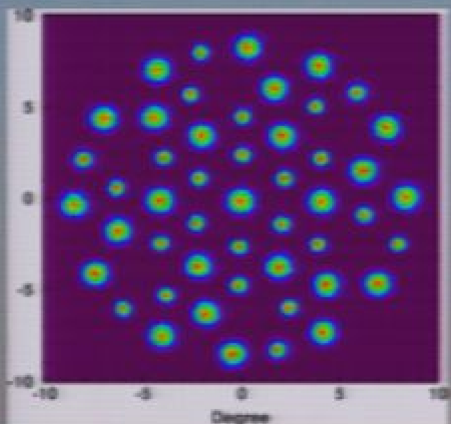
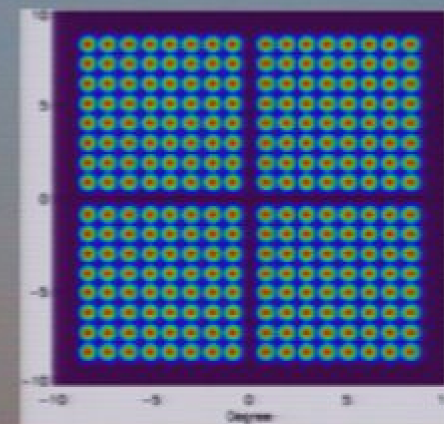


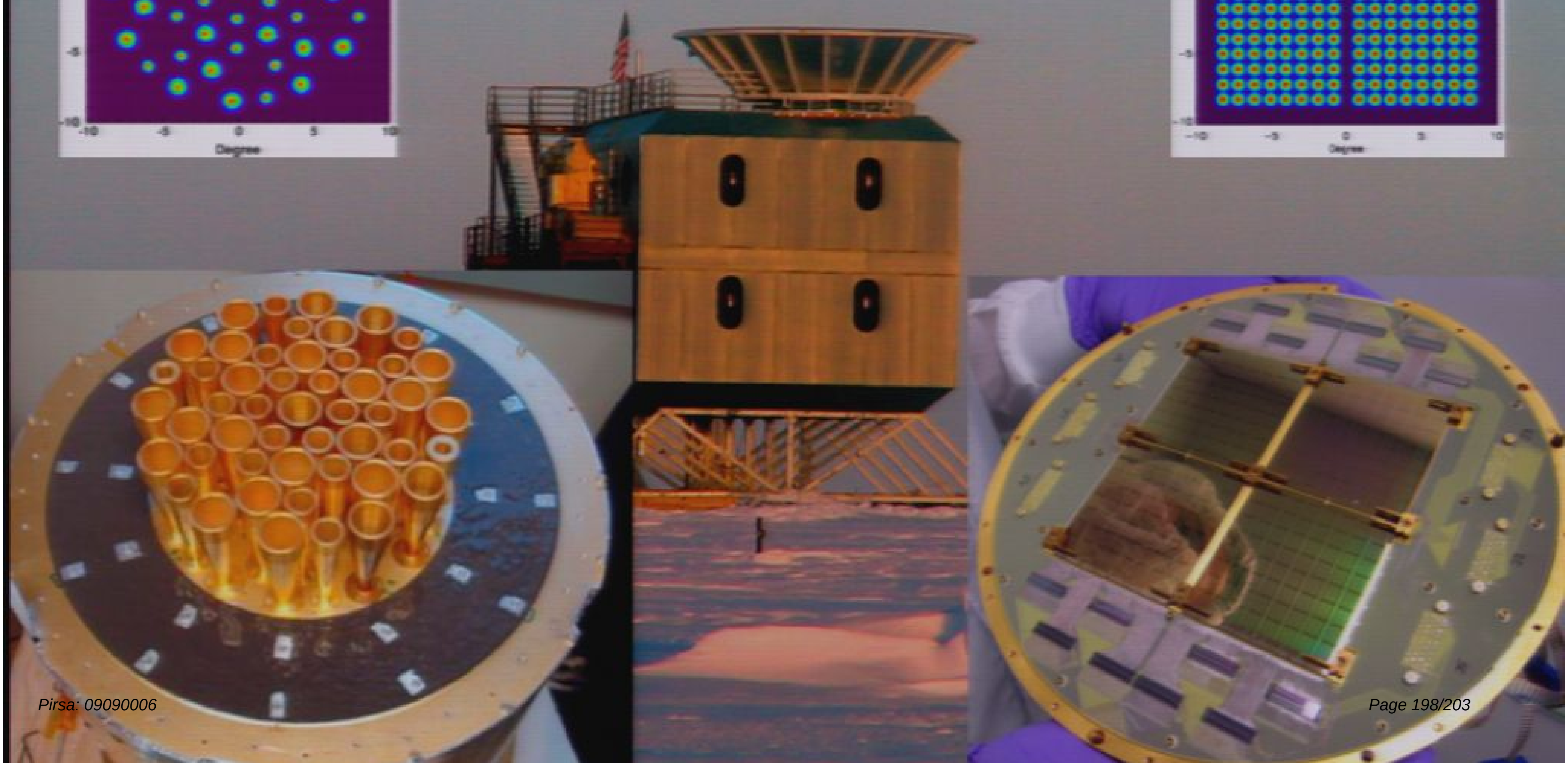


BICEP2 will take over: 2010-2011

~5x mapping speed







D. Barkats

Conclusions

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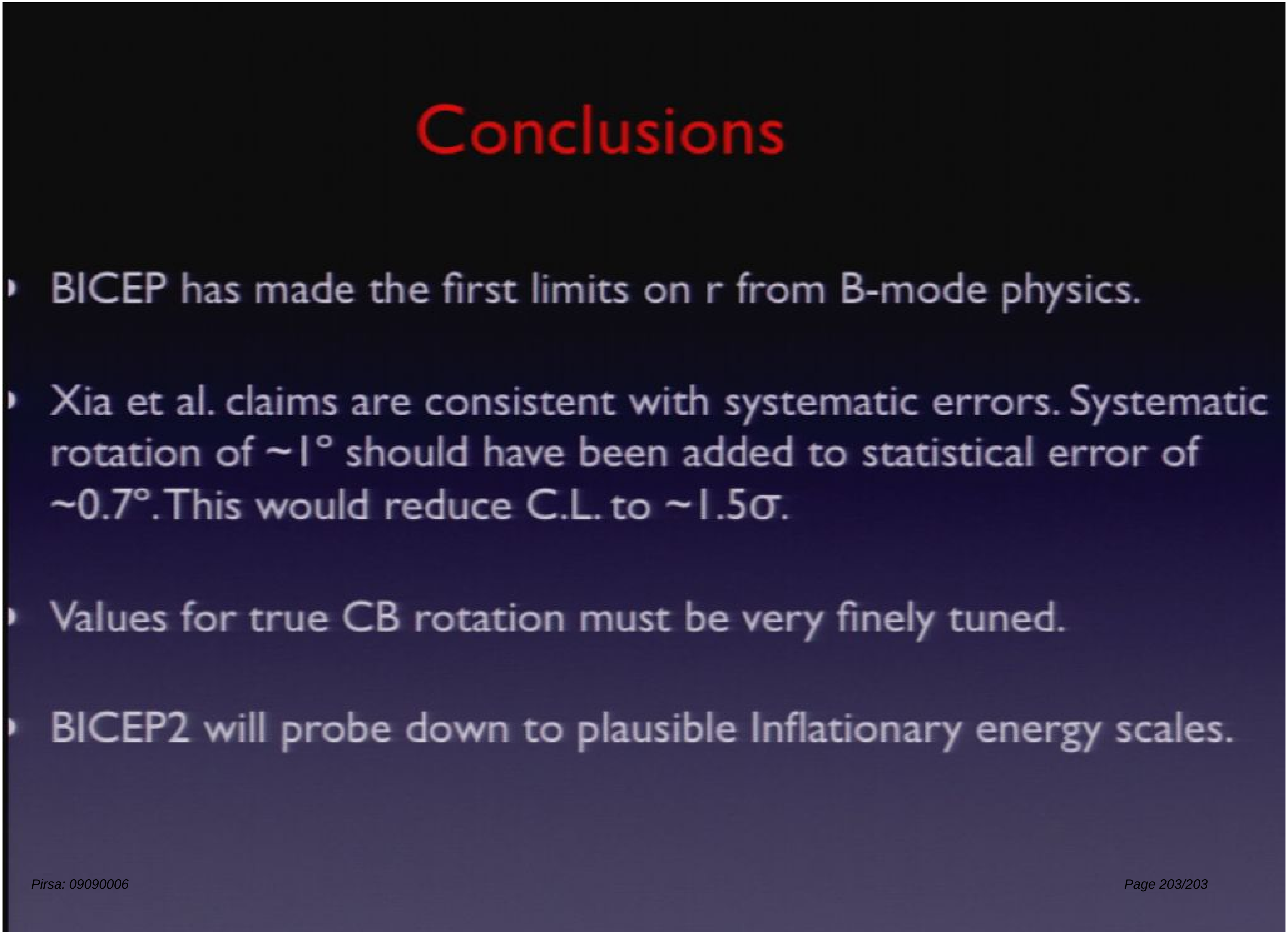
- Values for true CB rotation must be very finely tuned.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BICEP2 will probe down to plausible Inflationary energy scales.