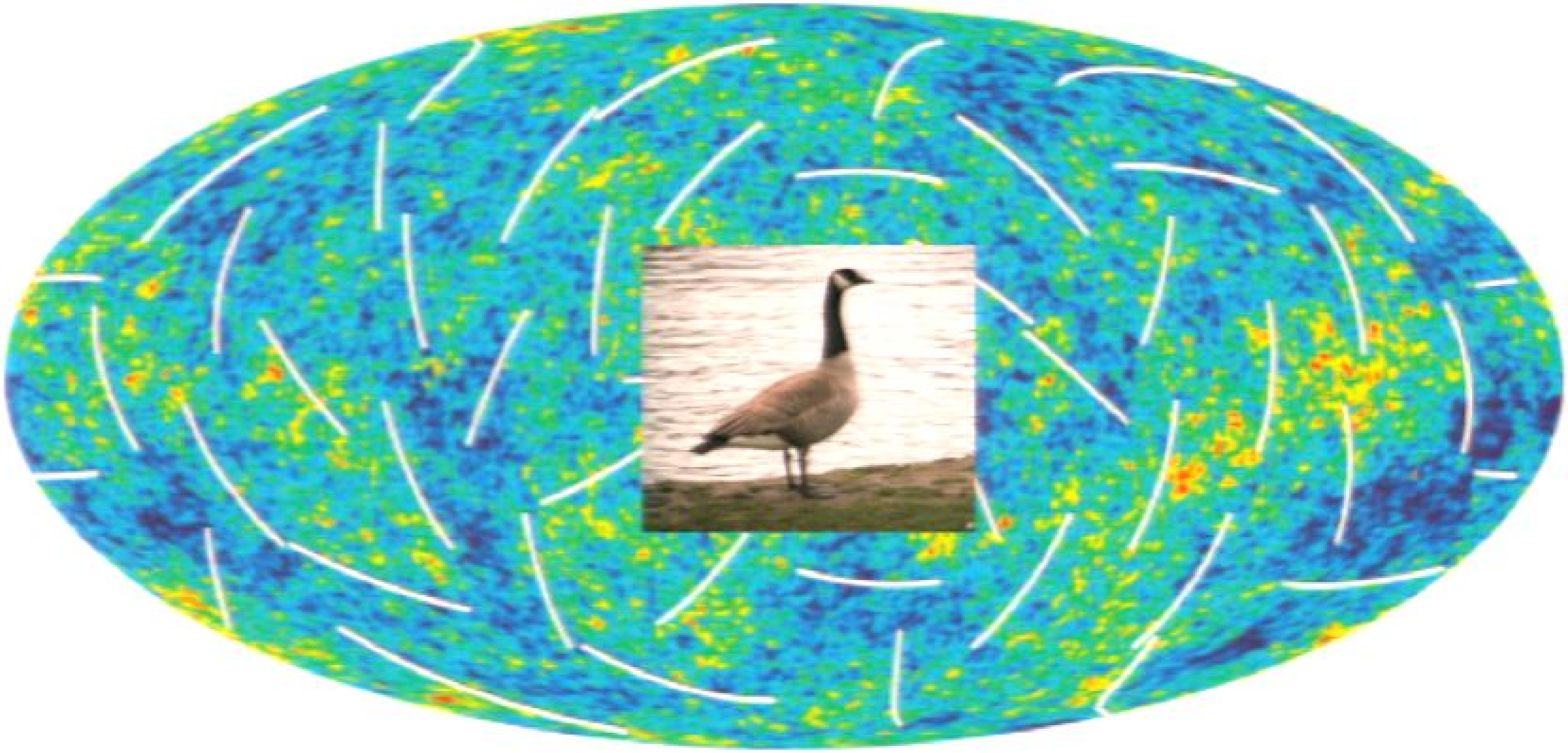
Title: Prospects for Detecting Primordial B-modes from Sub-Orbital Experiments

Date: Jun 04, 2008 10:10 AM

URL: http://pirsa.org/07060078

Abstract:

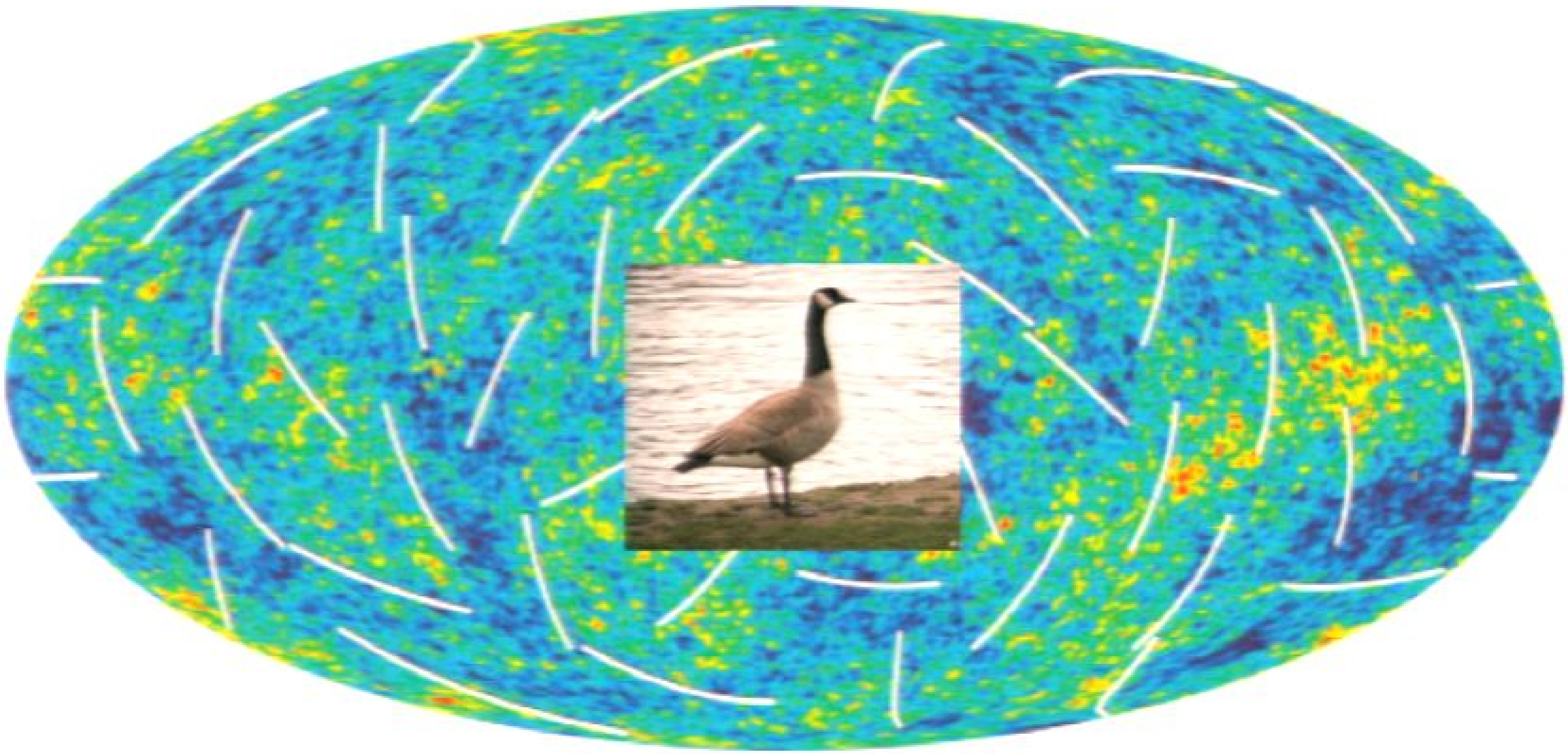
Prospects for Detecting Primordial Gravitational Radiation via the CMB



Andrew Lange

Caltech

Prospects for Detecting Primordial B-modes with Sub-Orbital Experiments

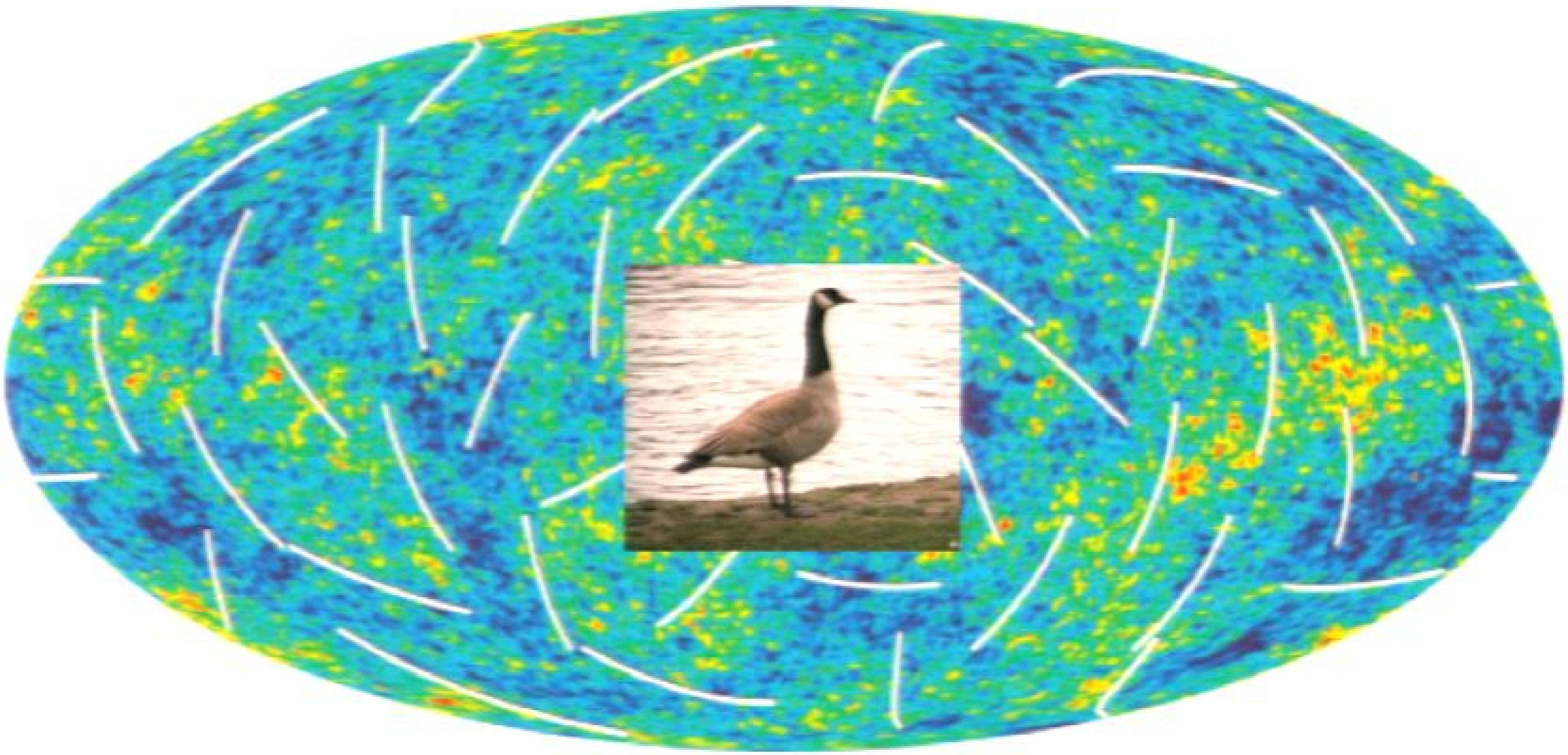


Andrew Lange

PASCOS 2008

Why it is desperately important that the

Prospects for Detecting Primordial B-modes with Sub-Orbital Experiments



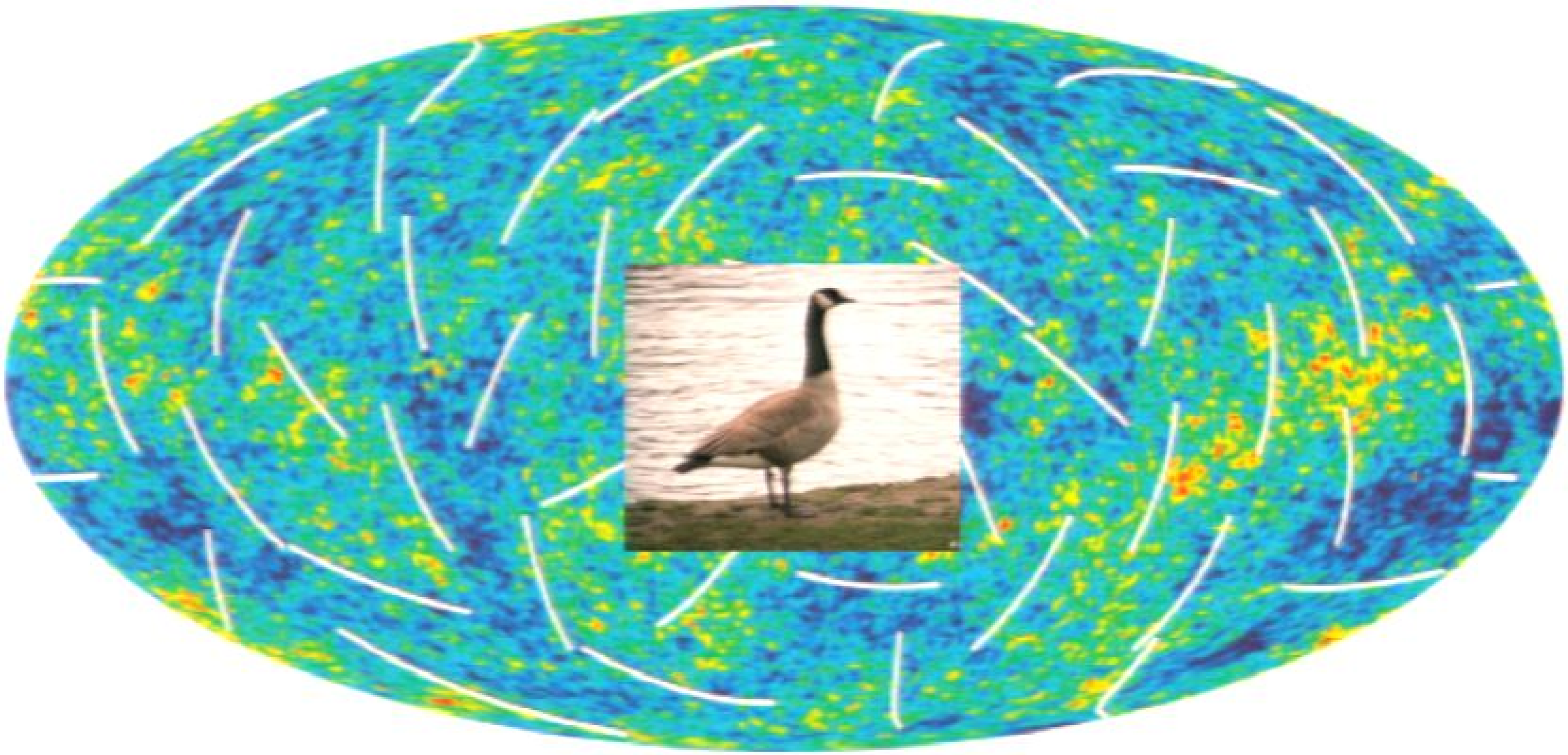
Andrew Lange

PASCOS 2008

Why it is desperately important that the

Prospects for Detecting Primordial B-modes with Sub-Orbital Experiments

are excellent.



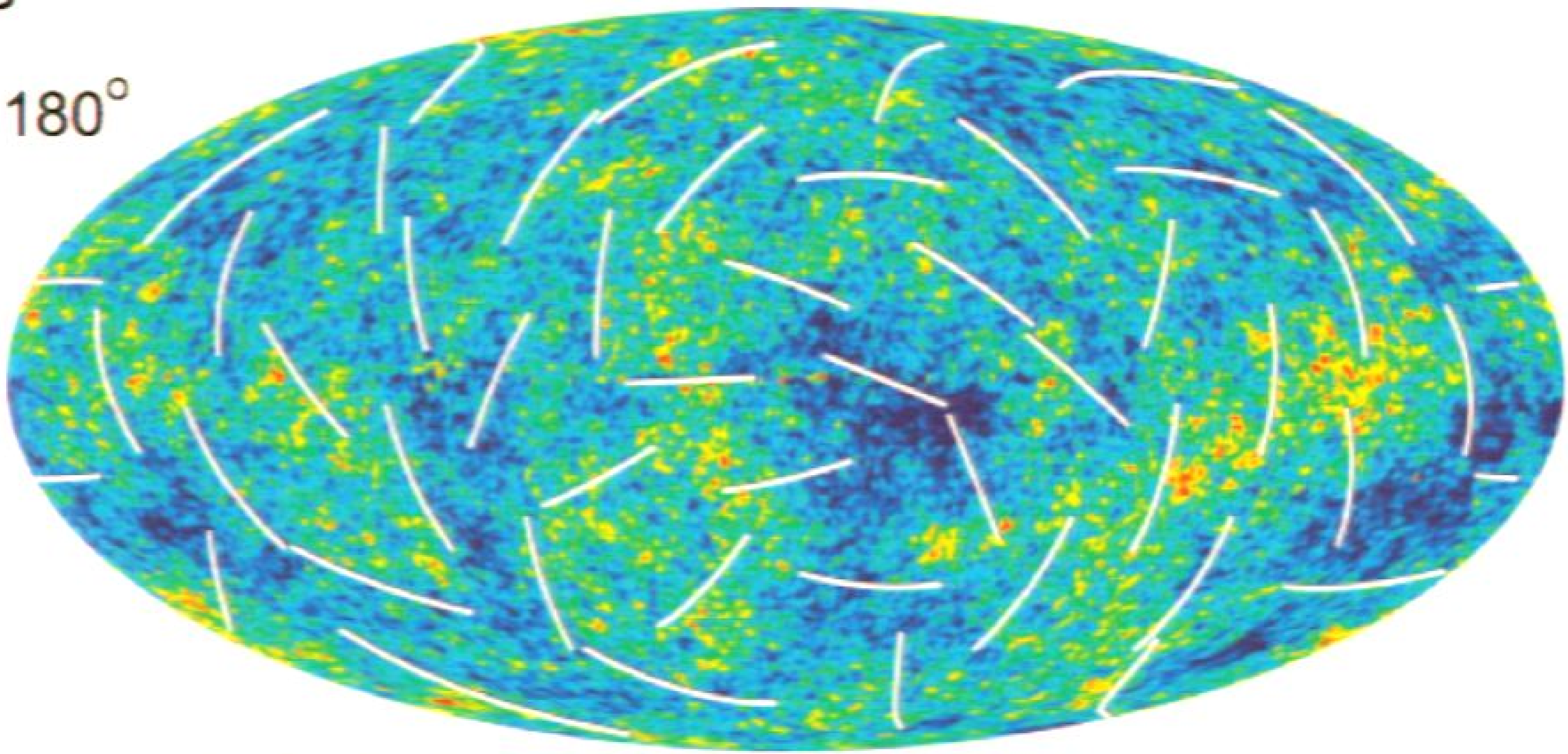
Andrew Lange
PASCOS 2008

A Physicist's History of the Universe:

14 billion yr	400,000 yr	1 hour	<< 1 s
telescopes	atoms	nuclei	????

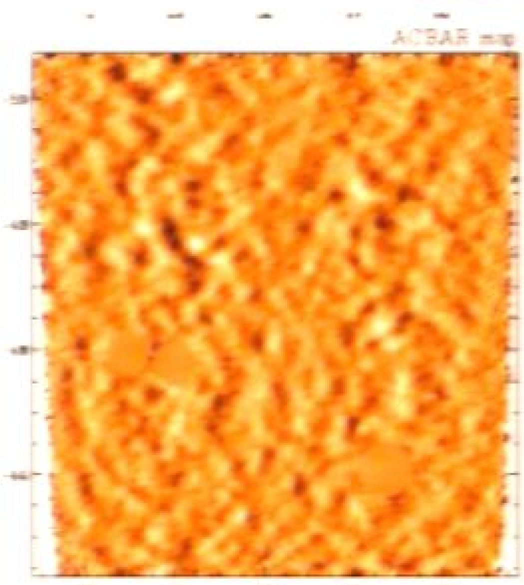
WMAP

14' -> 180°

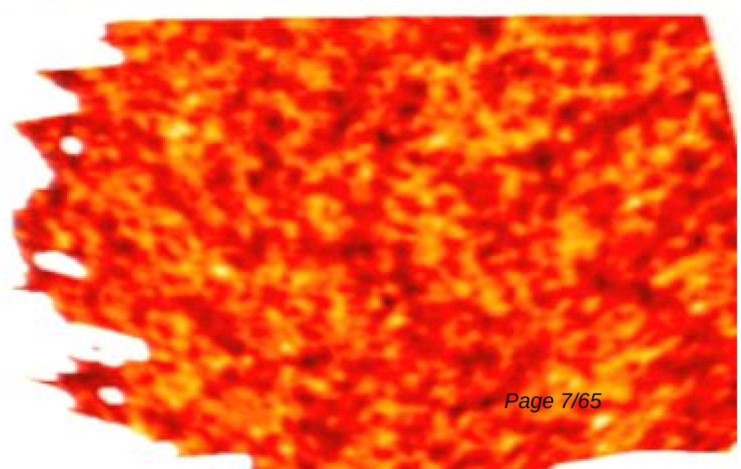


ACBAR

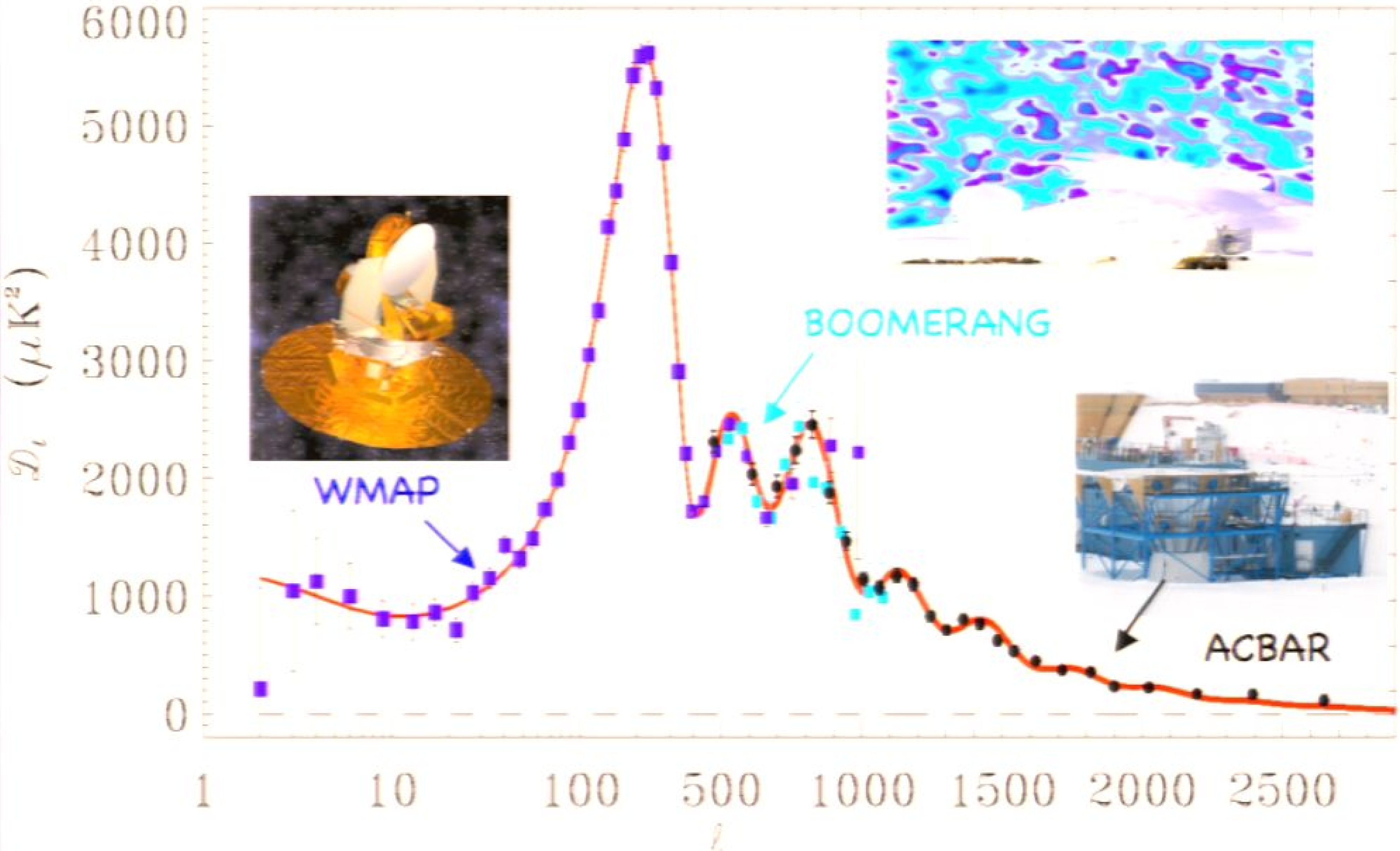
5' -> 0.5°



BOOMERanG 10' -> 10°



The basic temperature features have been mappec



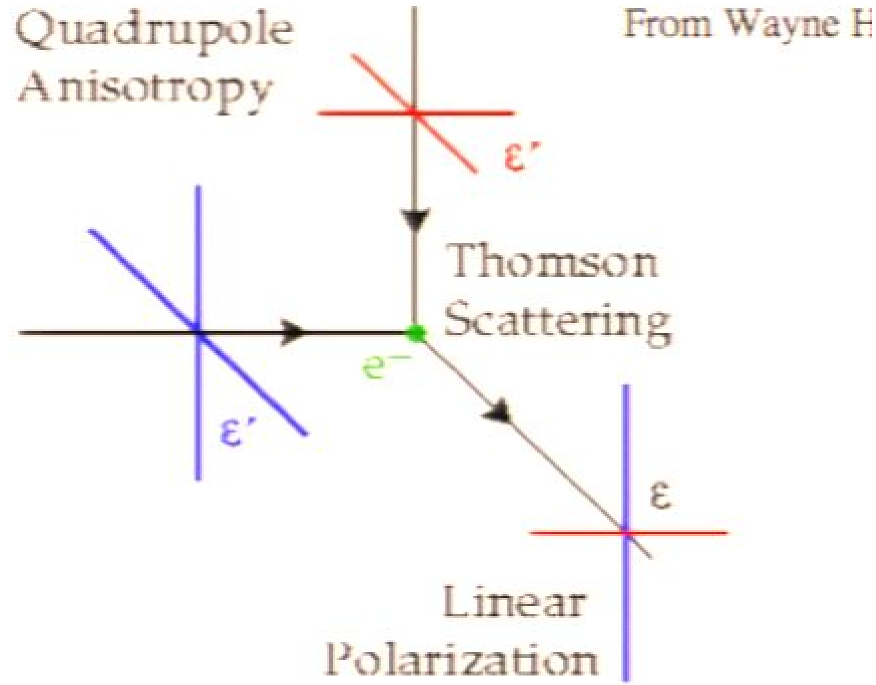
Reichardt et al. astro-ph 0801.1491

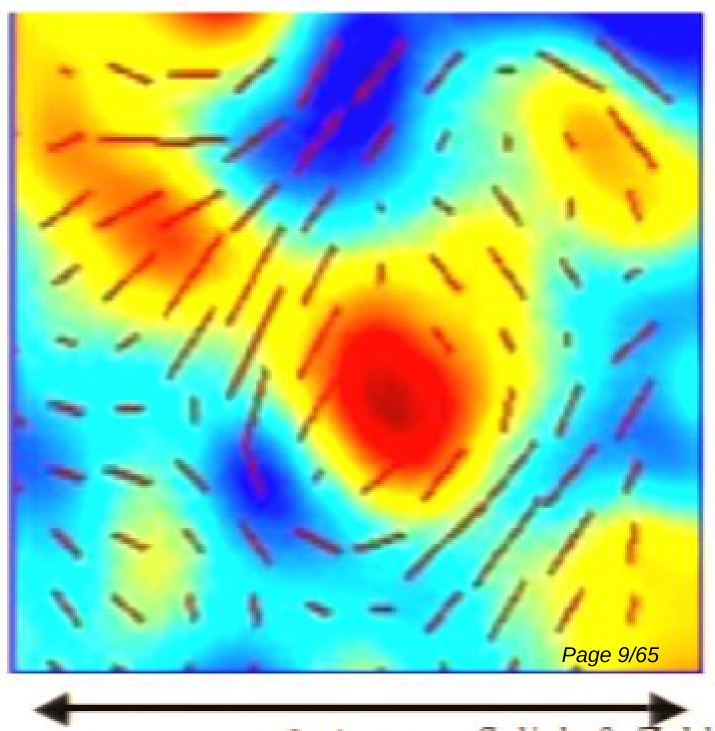
CMB Polarization

- Polarization of the CMB is produced by Thompson scattering of a quadrupolar radiation pattern.

- A component of the polarization is correlated with the temperature anisotropy.

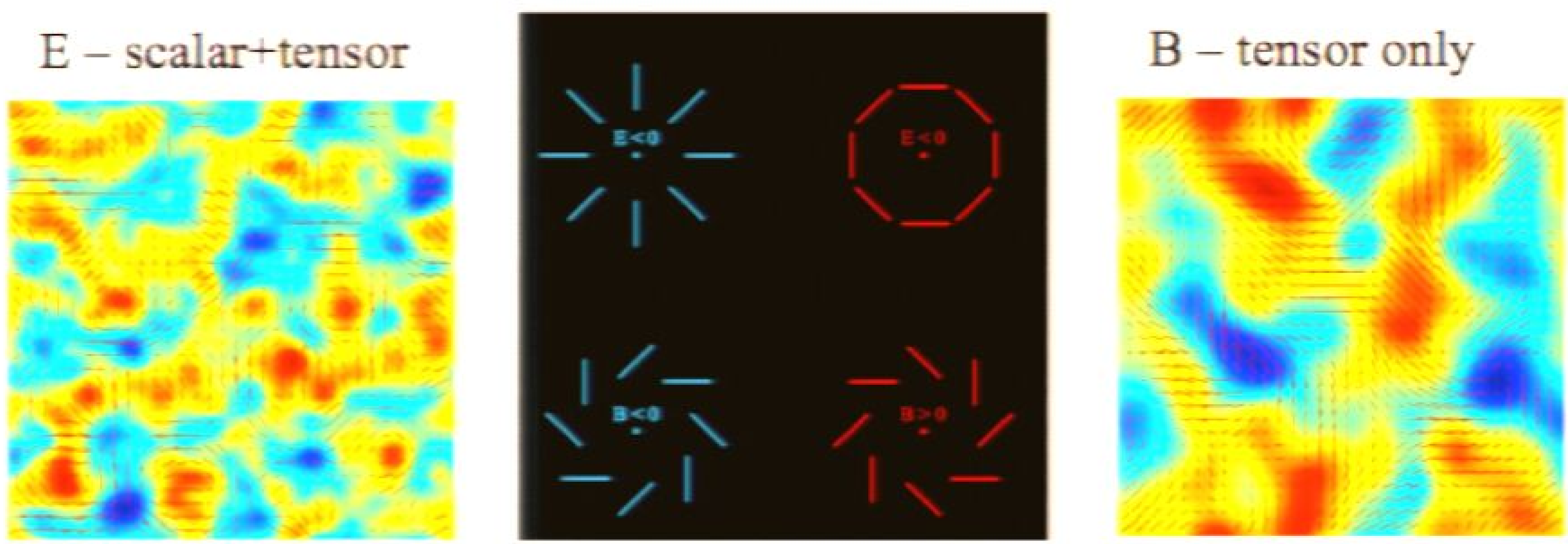
- Whenever there are free electrons, the CMB is polarized.



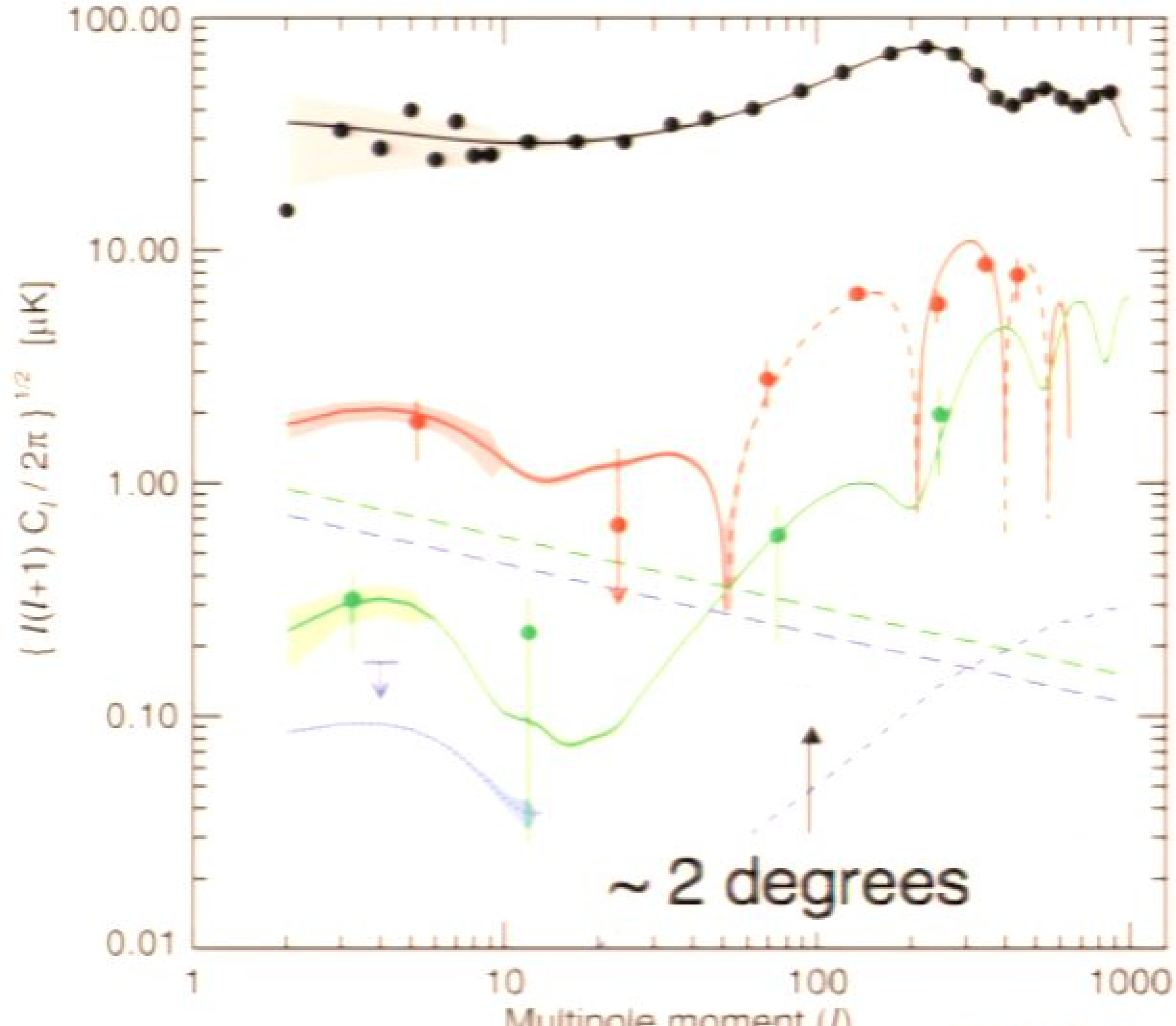


Inflation and CMB Polarization

- Both types of fluctuations contribute to CMB polarization anisotropy.
  - Scalar modes produce only "E-mode" or gradient-like polarization patterns.
  - Tensor modes produce both E-mode and B-mode (curl-like) polarization patterns.
- The observation of B-mode polarization uniquely separates scalar and tensor modes from inflation and measures the energy scale of inflation.
- *Only* known probe of E ~ 10^{16} GeV… 10^{12} *higher than planned accelerators!*



What does the signature look like?



TT – temperature anisotropy

TE – temperature – polarization correlation

EE – E-mode polarization

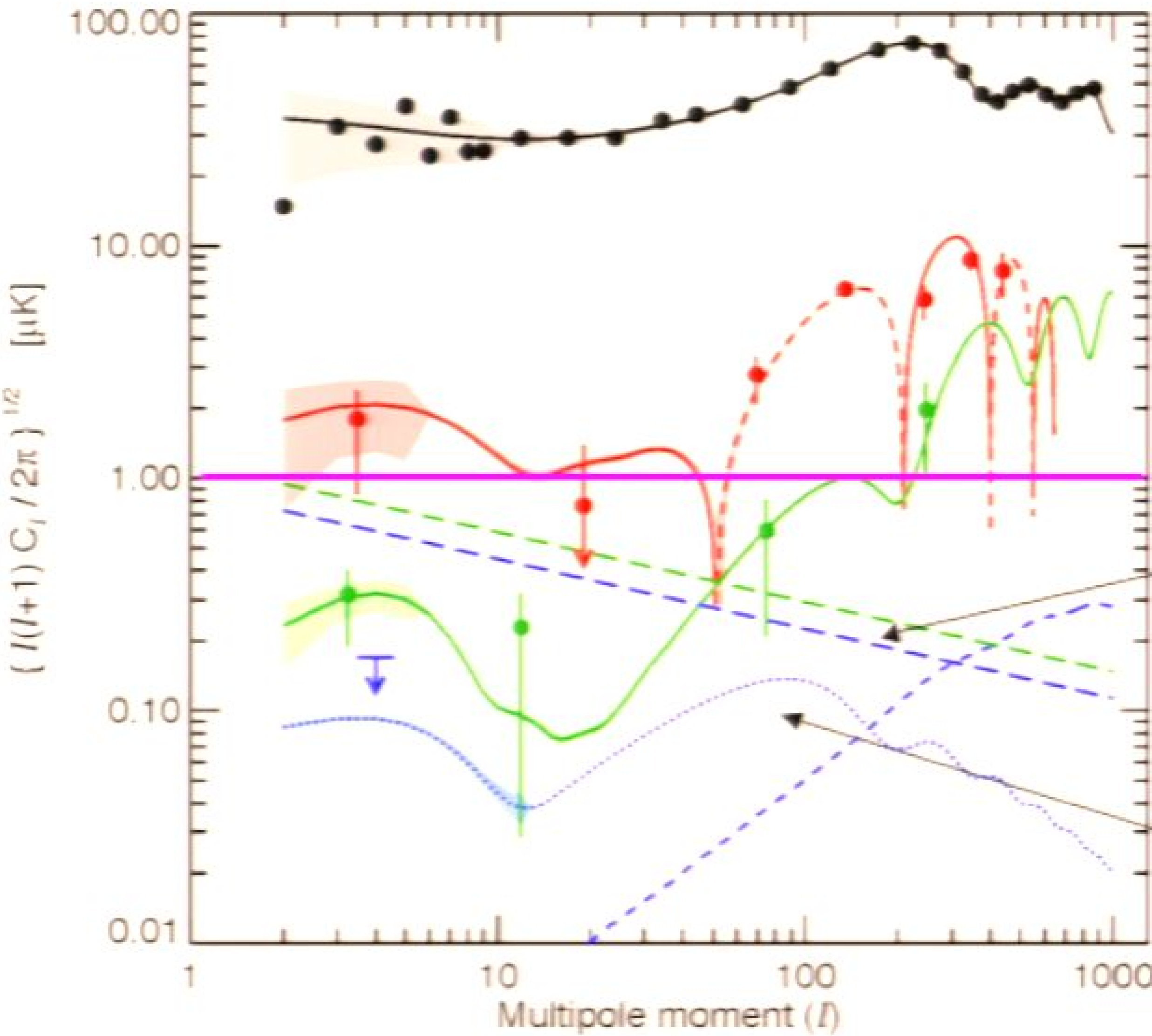
BB – B-mode polarization

→ gravity wave amplitude

→ test of inflation

WMAP: Page et al. 2006

Galactic confusion will limit the search



1 μK (300 ppb)

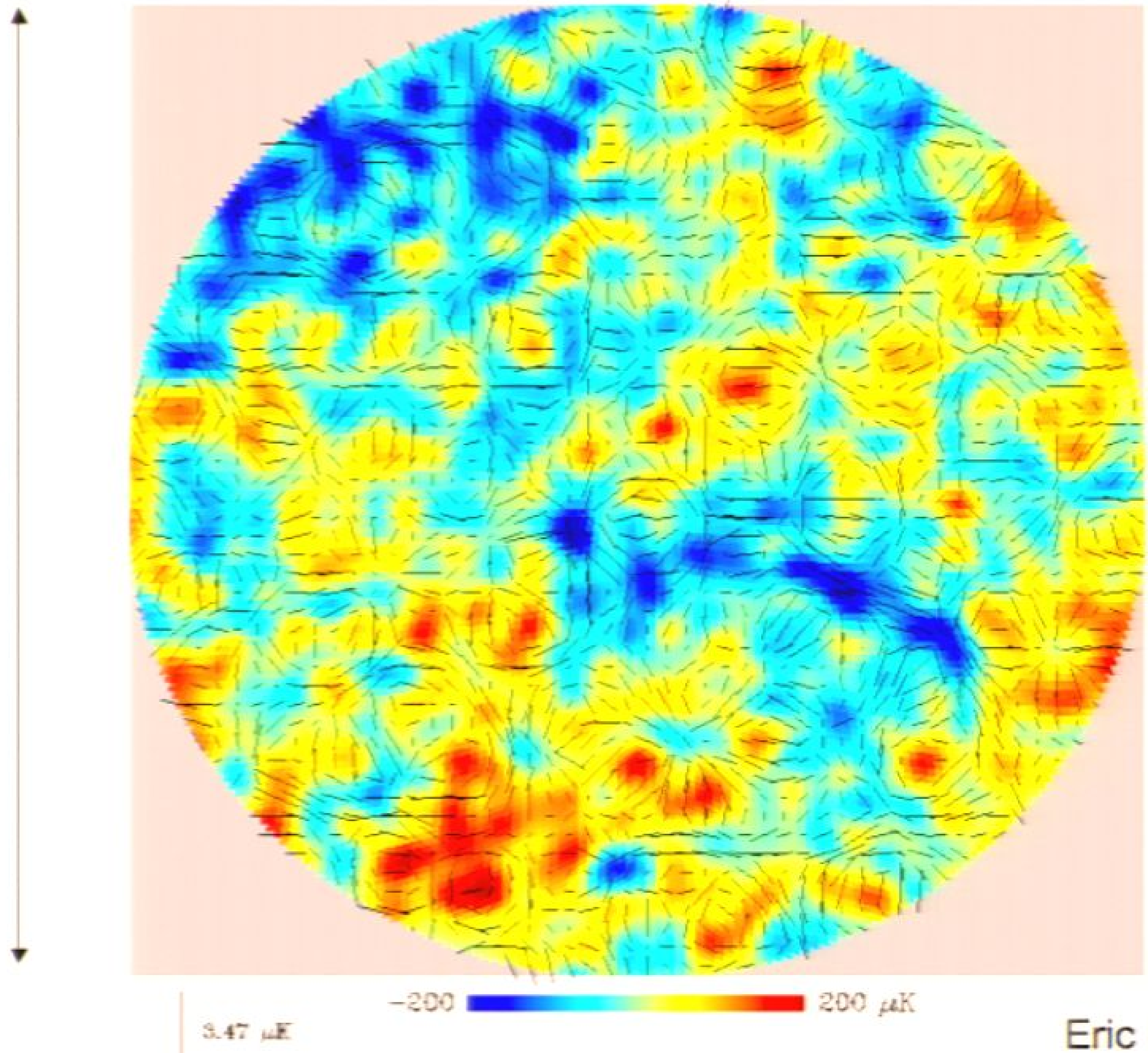
Galactic Confusion (**65** GHz)

r= **0.3 (!)**

(r = 0.01 is P = 1 ppb)

No gravitational waves (r = 0)

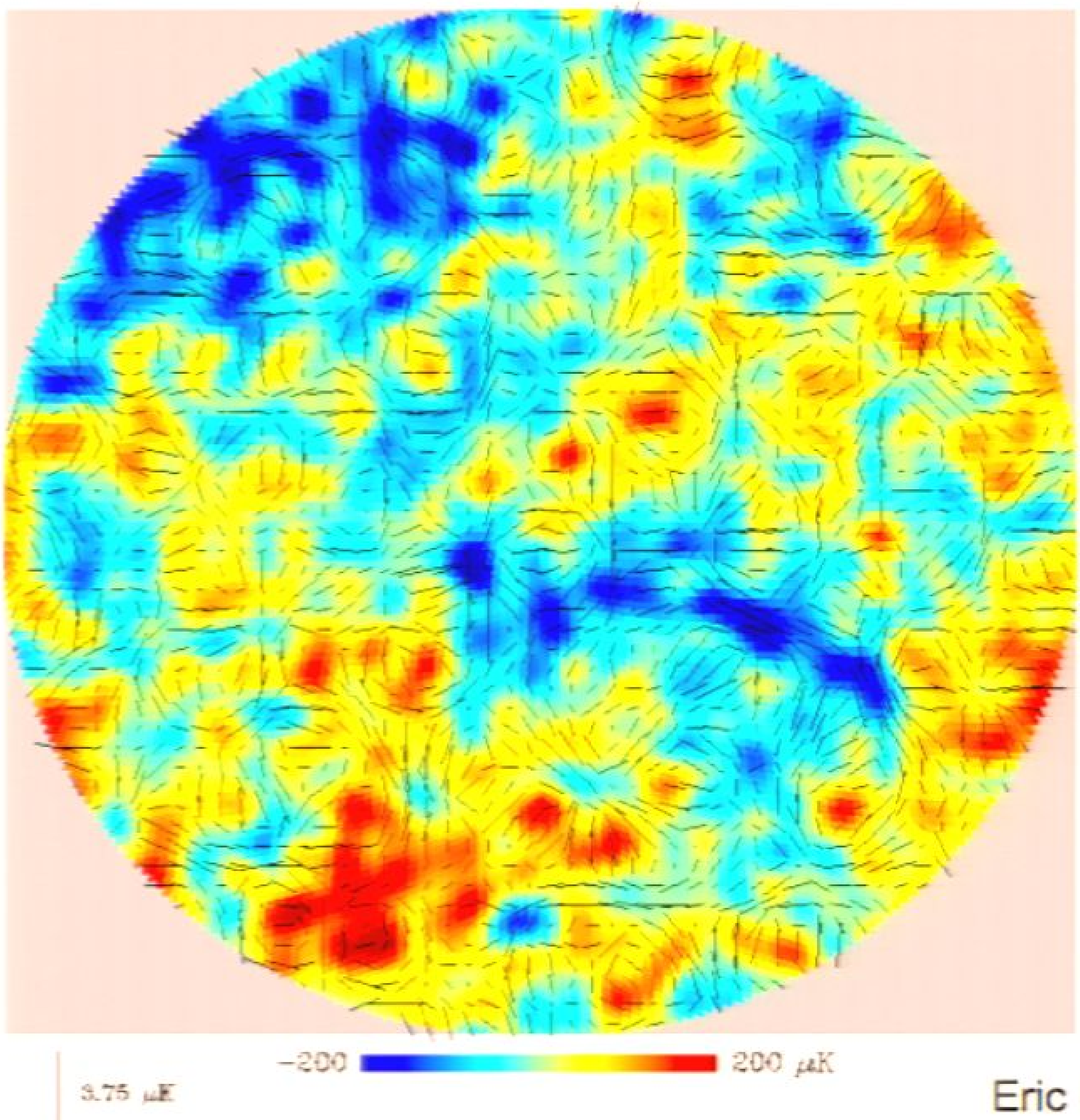
30
degrees



Eric Hivon

Gravitational waves (r = 0.3)

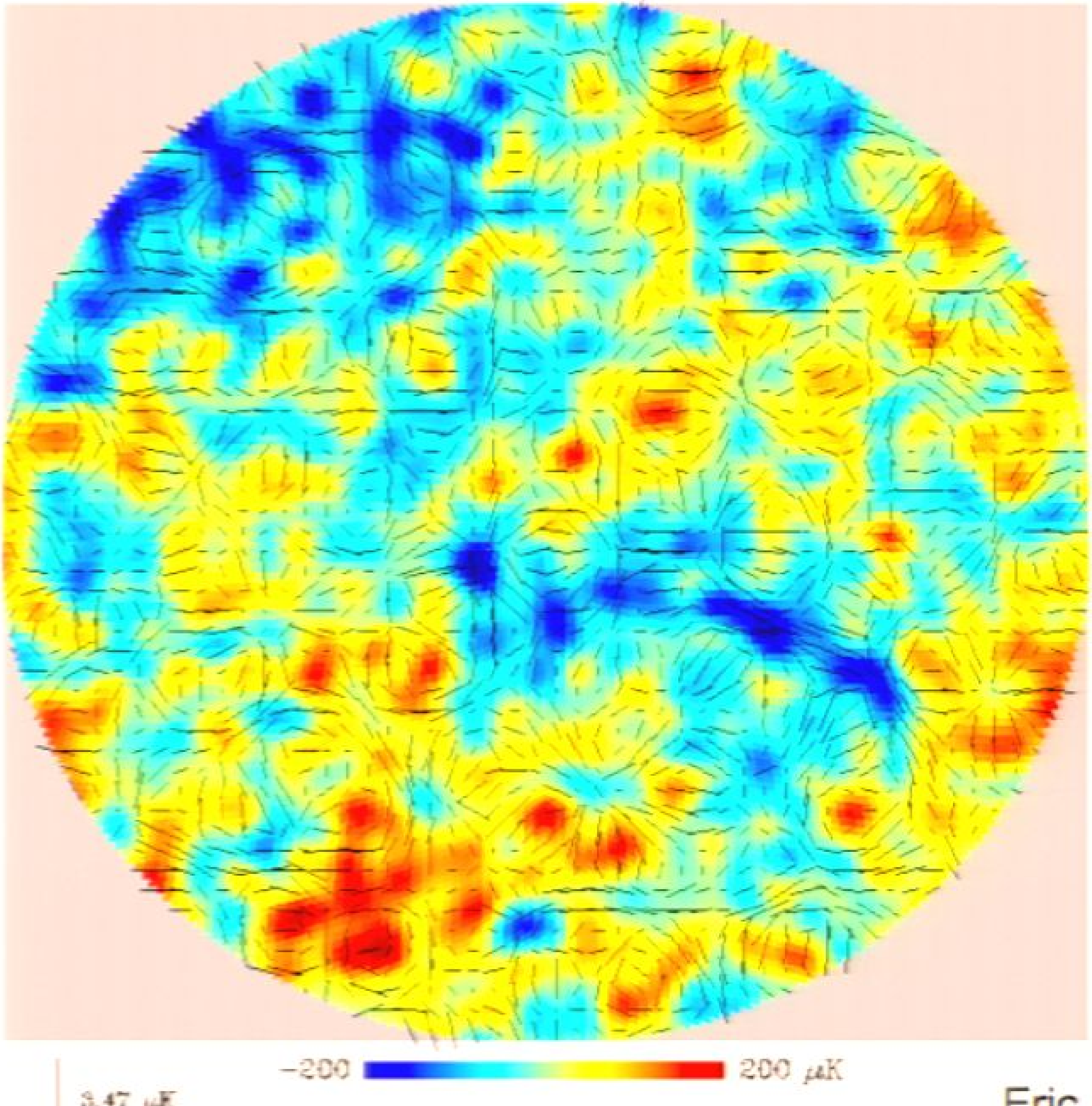
30
degrees



Eric Hivon

No gravitational waves (r = 0)

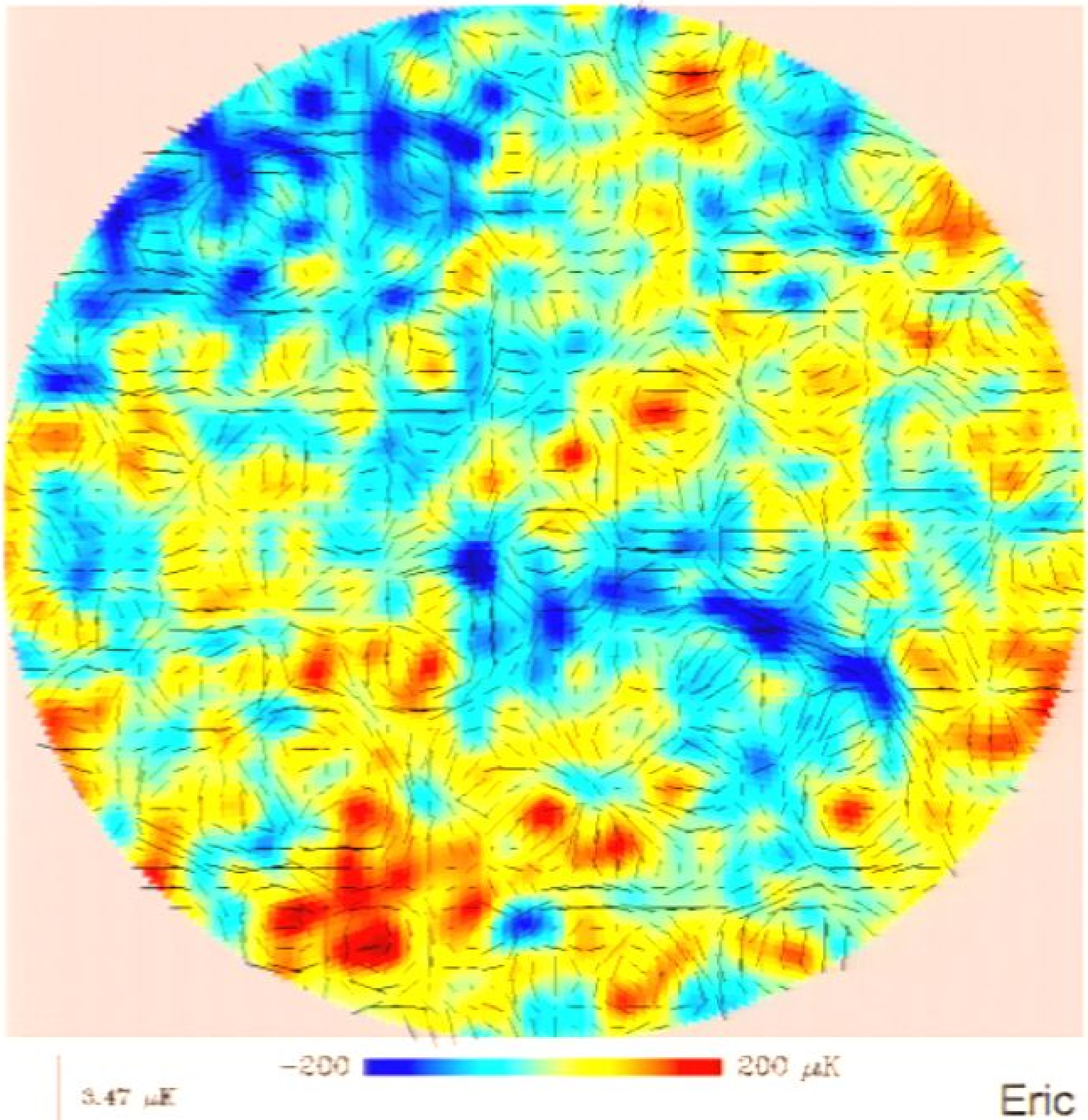
30
degrees



Eric Hivon

No gravitational waves (r = 0)

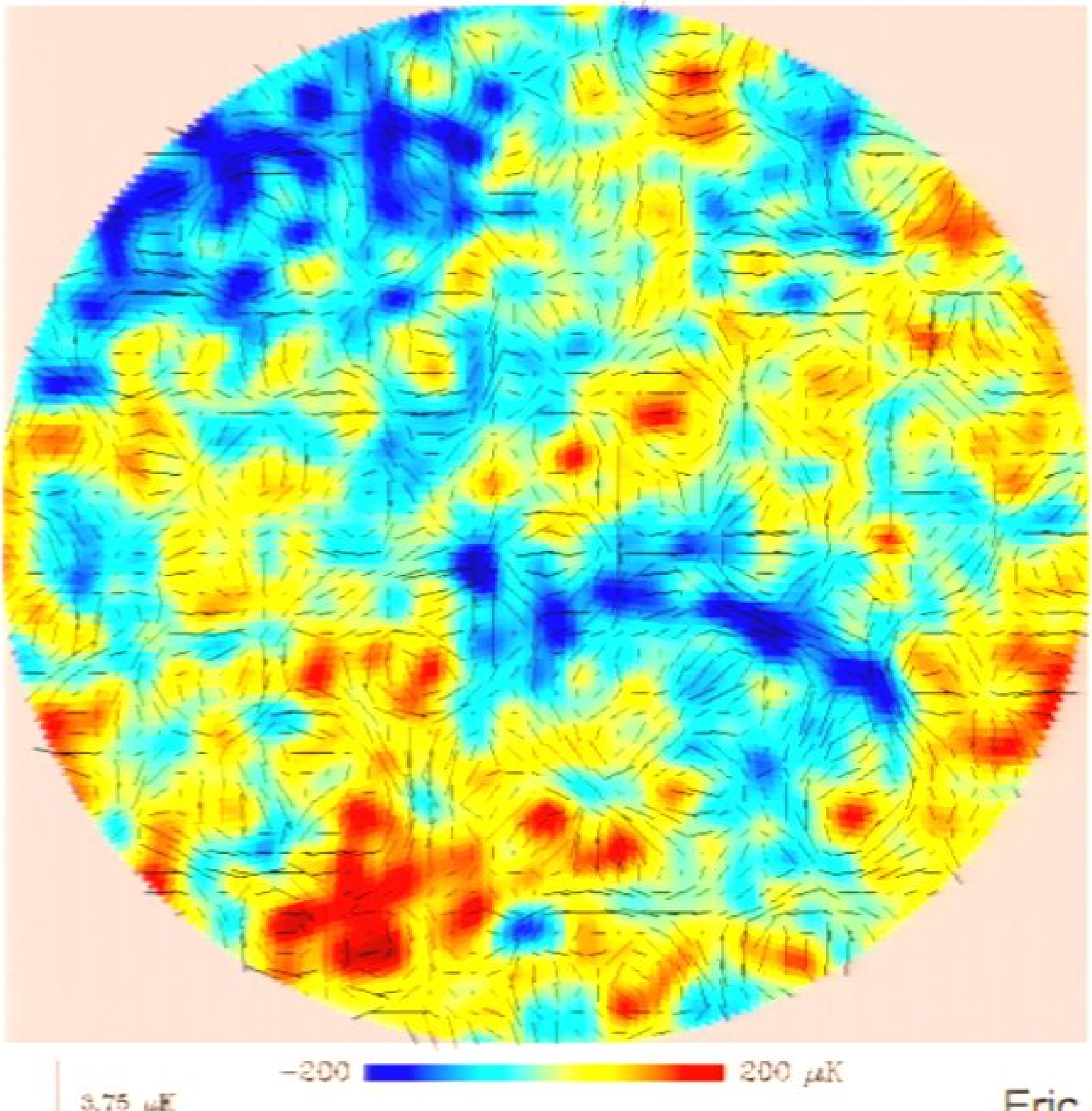
30
degrees



Eric Hivon

Gravitational waves (r = 0.3)

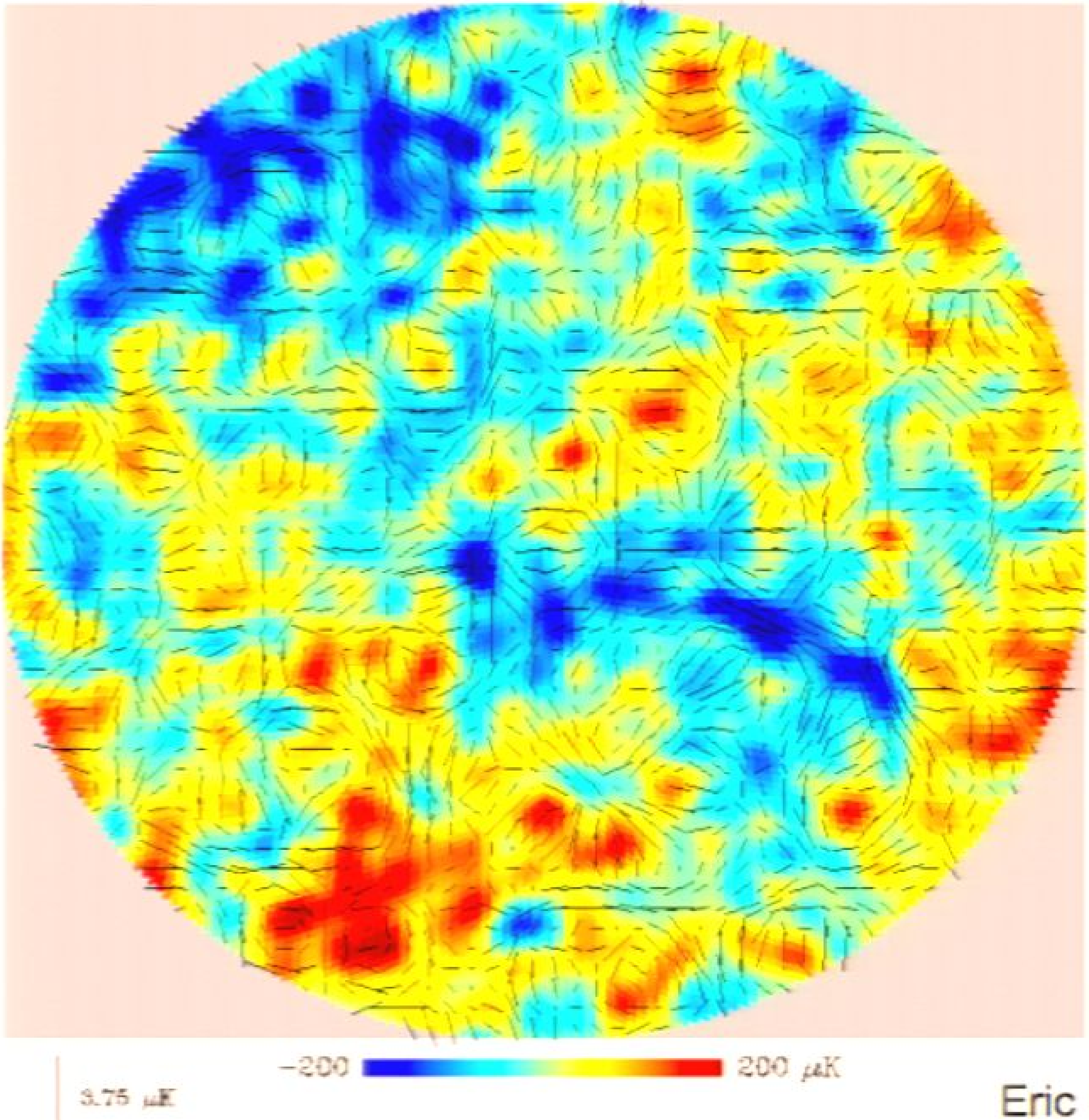
30 degrees



Eric Hivon

Gravitational waves (r = 0.3)

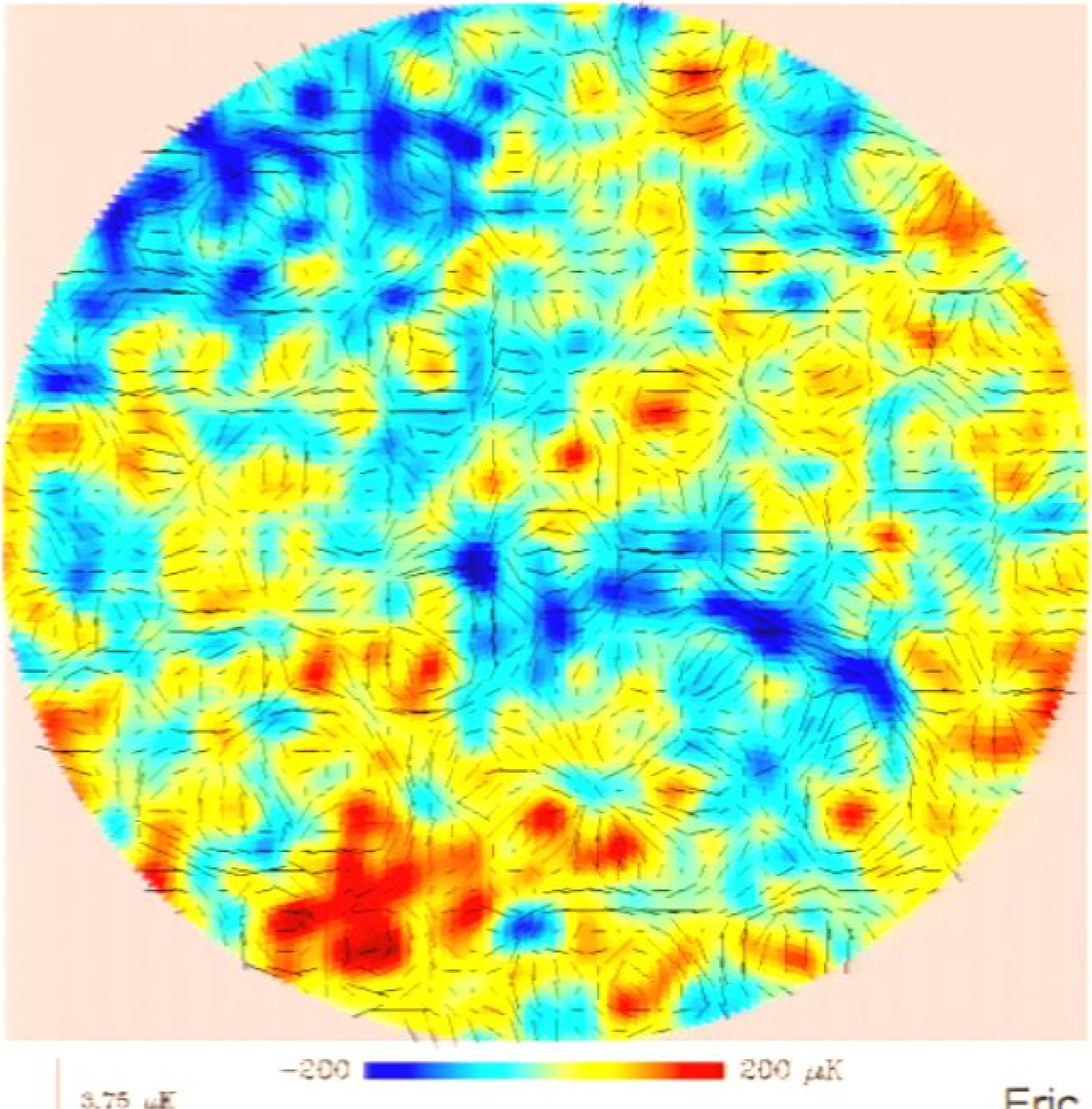
30 degrees



Eric Hivon

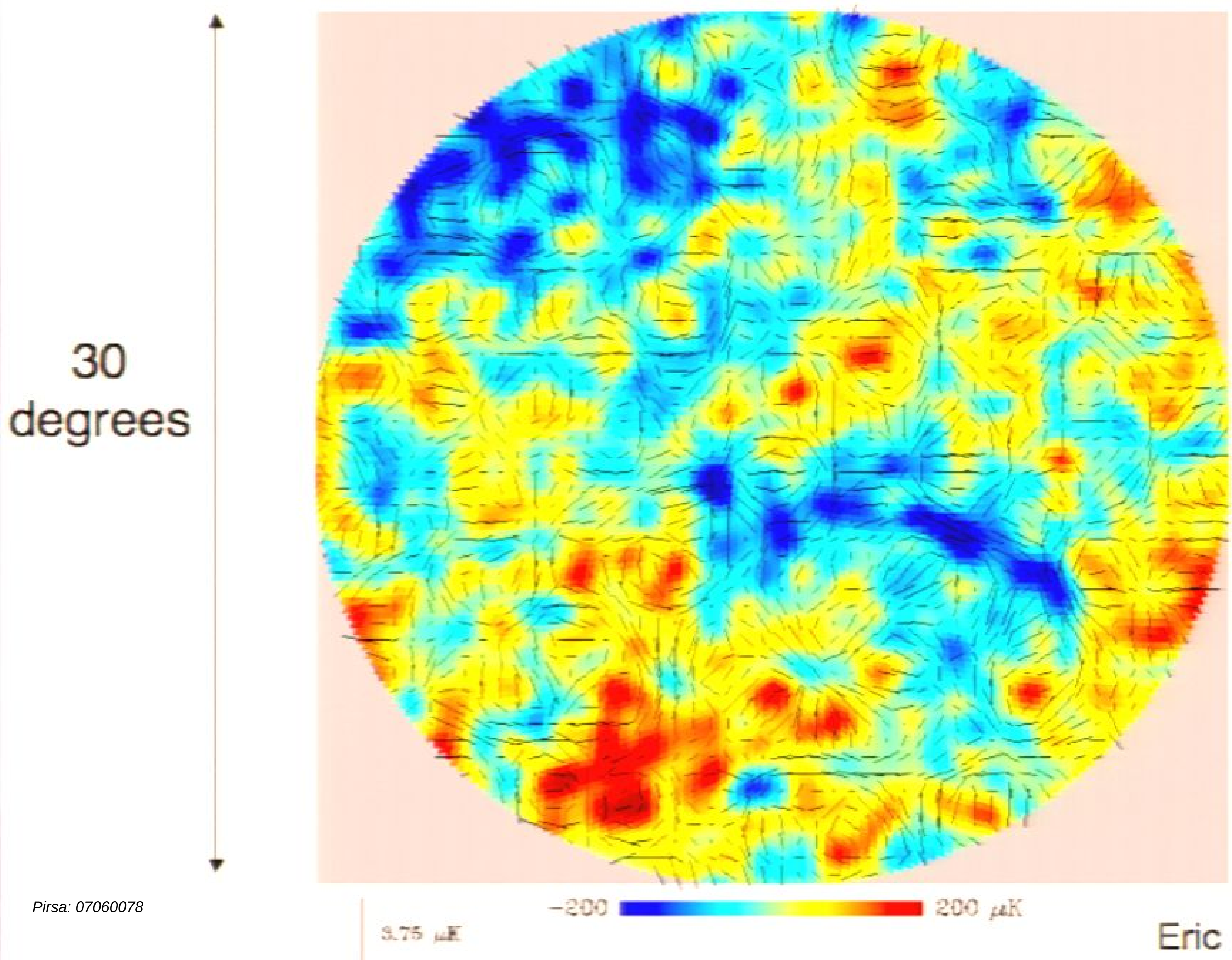
No gravitational waves (r = 0)

30 degrees



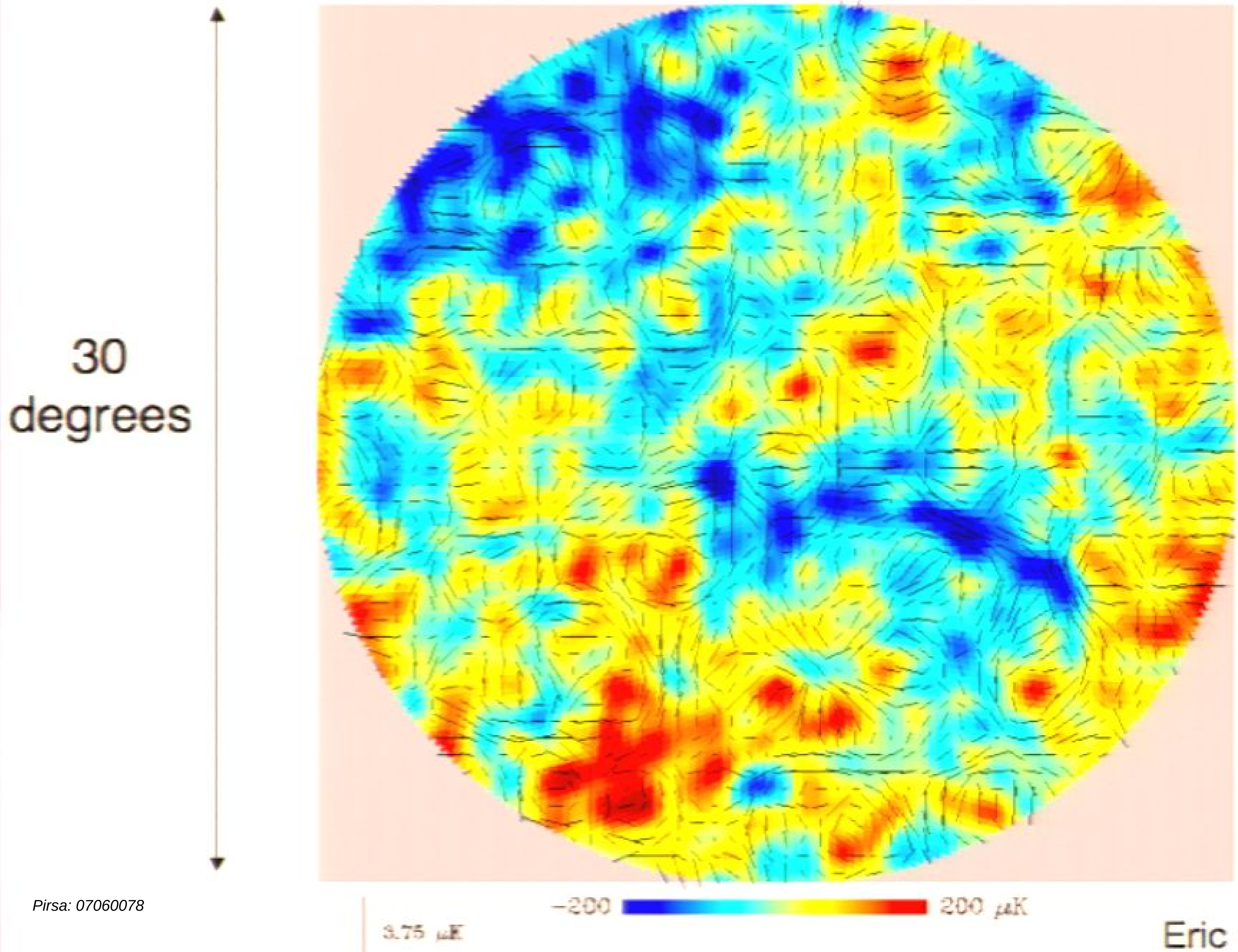
Eric Hivon

Gravitational waves (r = 0.3)



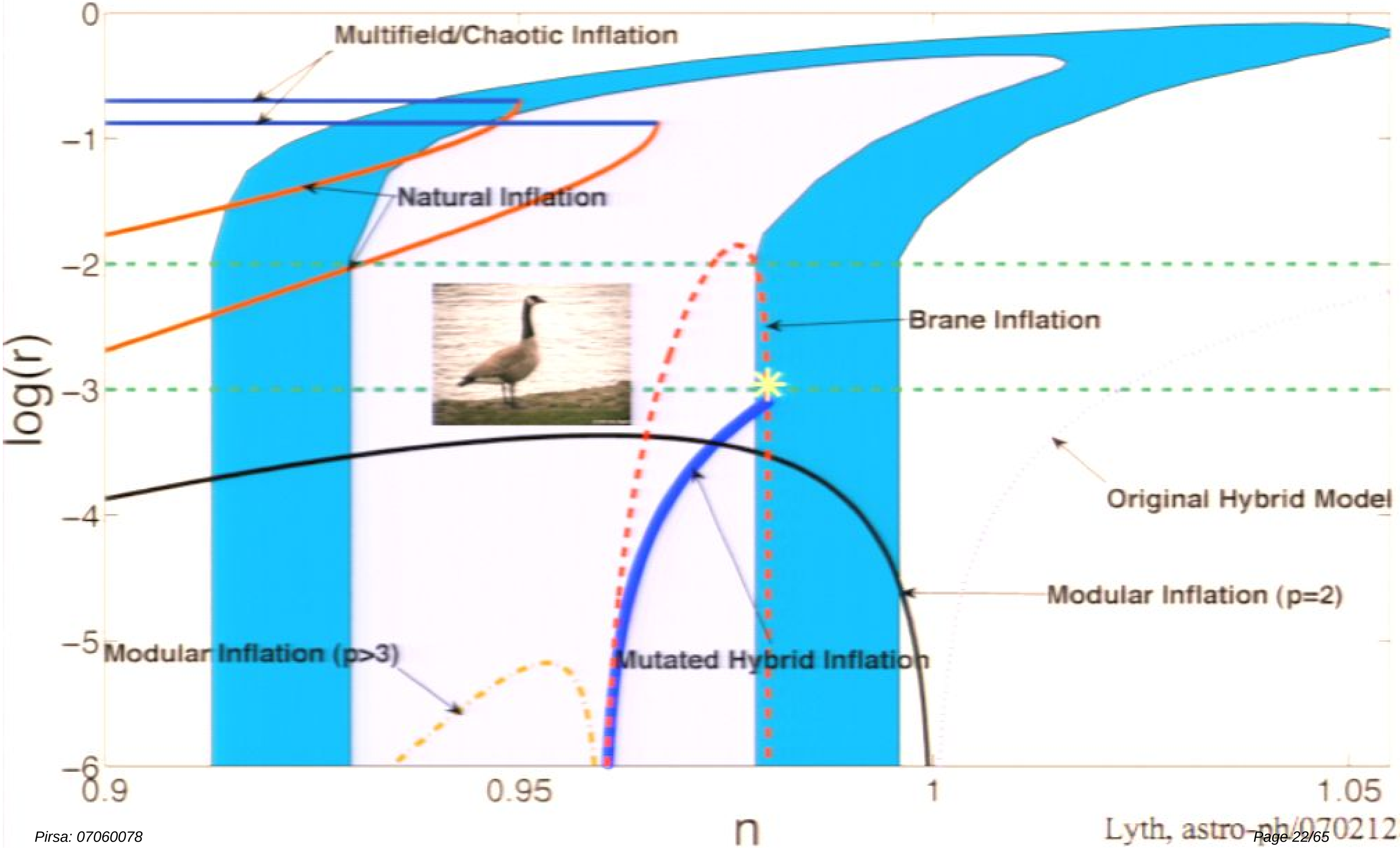
Eric Hivon

Gravitational waves (r = 0.3)



Eric Hivon

Inflationary parameters: n_s, r



Lyth, astro-ph/0702128

WILD GOOSE CHASE -- "Englishmen in the late 16th century invented a new kind of horse race called the wild-goose chase in which **the lead horse could go off in any direction and the succeeding horses had to follow accurately the course of the leader at precise intervals**, like wild geese following the leader in formation. At first the phrase 'wild-goose chase' figuratively meant an erratic course taken by one person and followed by another; Shakespeare used it in this sense. But later the common term's origins were forgotten and a 'wild-goose chase' came to mean **'a pursuit of anything as unlikely to be caught as a wild goose,' any foolish, fruitless, or hopeless quest."** From the "Encyclopedia of Word and Phrase Origins" by Robert Hendrickson (Facts on File, New York, 1997).

Task Force on CMB Research

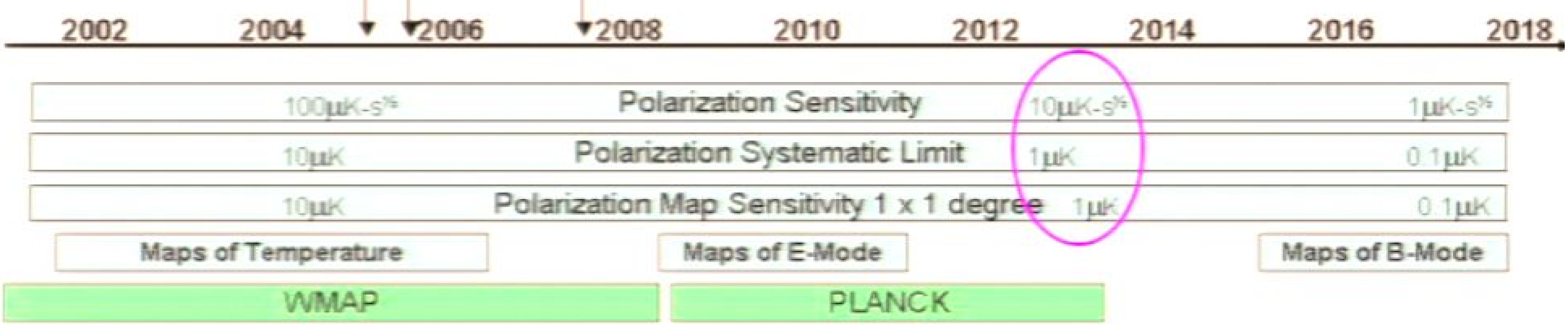
- Google: "cmb task force"
- Convened by NASA/NSF/DOE in 2003
- 14 members (3 from our Project Team)
- Final Report July 2005
- Findings & Recommendations:
  - "A unique CMB polarization signal directly tests inflation. As our highest priority, we recommend a phased program to measure this signal to the limit set by astrophysical foregrounds."
- Envisioned a satellite launched in 2018 (now > 2025, based on the state of NASA).

3 years later: progress has been much faster than expected!

CMB Task Force Report July 2005

BICEP deployed November 2005

2013 goals achieved in 2007 (2 yrs vs. 8 yrs)



CMB Task Force Report , Fig. 10.2

Past & Current CMB Polarization Experiments

DASI	South Pole	1998	30	NRAO HEMT Int.
CBI	Atacama	1999	30	NRAO HEMT Int.
BOOM 2003	Antarctic Balloon	2003	150	JPL PSB
WMAP	L2	2003	22, 30, 45, 70	NRAO HEMT
QUAD	South Pole	2005	100, 150	JPL PSB
BICEP	South Pole	2006	100, 150	JPL PSB

Experiments in Development

QUIET	Atacama	2008	45, 90	JPL MMIC HEMT
BICEP2	South Pole	2009	150 (+100, 220)	JPL ACB
Planck	L2	2009	30 - 350	JPL Polarized Bolometer
EBEX	Antarctic Balloon	2010	150 - 300	UCB Bolo. + Wire Grid
SPIDER	Australia	2010	100, 150, 220	JPL ACB
Polar Bear	Atacama	2010	100, 150, 220	UCB ACB
Clover	Atacama	2010	100, 150, 220	UK ACB

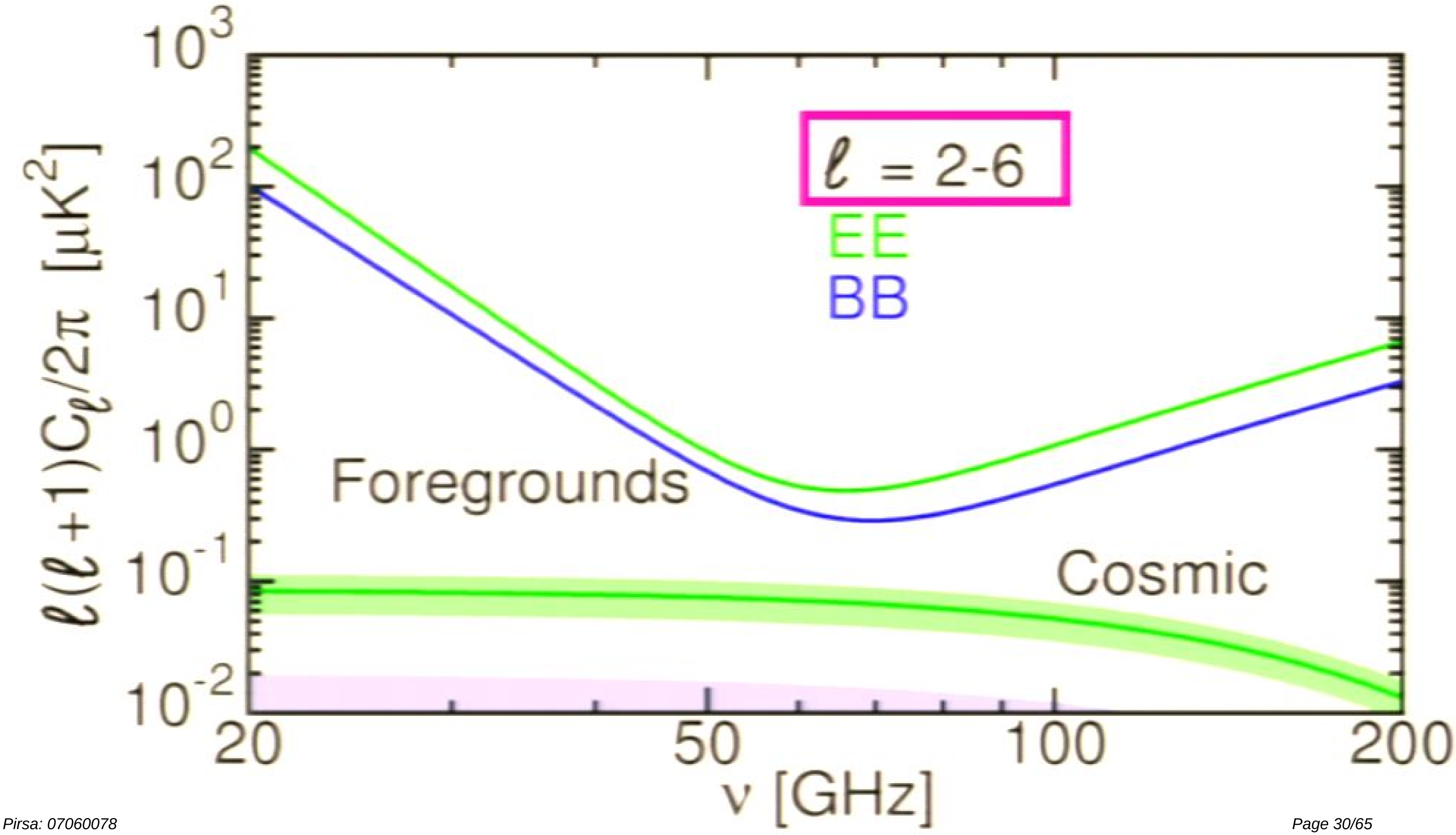
Much time and money is being spent on goose traps, in the hopes of measuring how big the goose is.

It would be very valuable to know as quickly as possible if there is, in fact, a goose.

How to flush out the goose?

- Foregrounds: 150 GHz
  small, clean patch
- Systematics: Small, cold telescope
- Sensitivity: Lots! (New technology)
- Site: South Pole

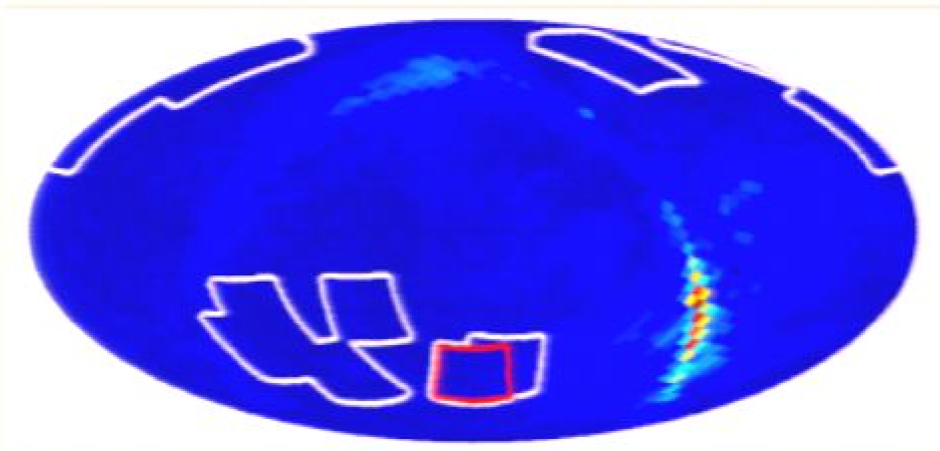
Foreground minimum near 70 GHz



Ned Wright, Aspen 2008

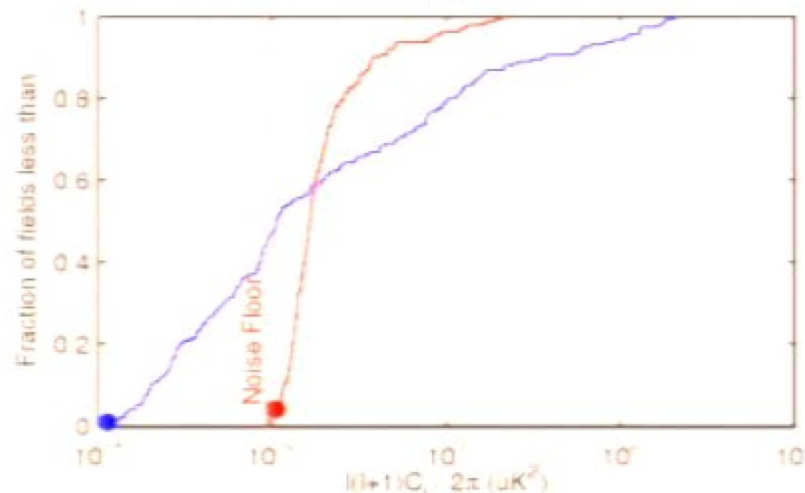
So why 150 GHz?

WMAP K-band P @ 150GHz (assuming index -3.0)

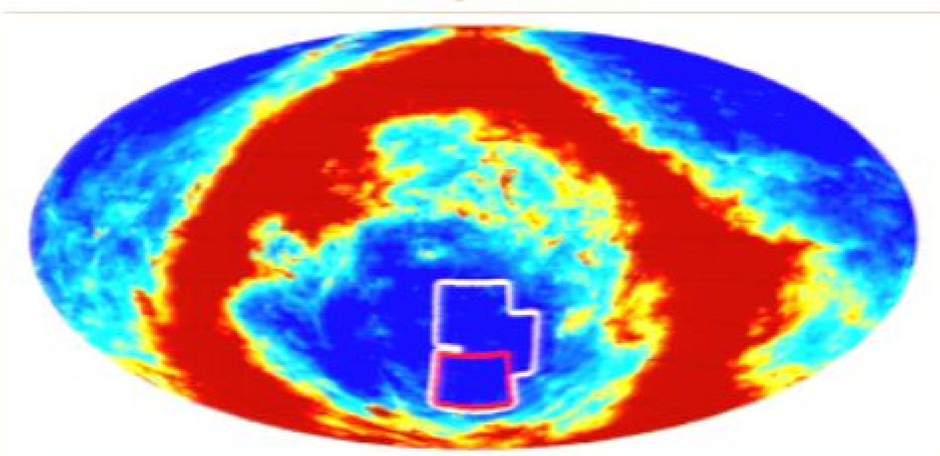


Color range 0 to 4uK

100GHz

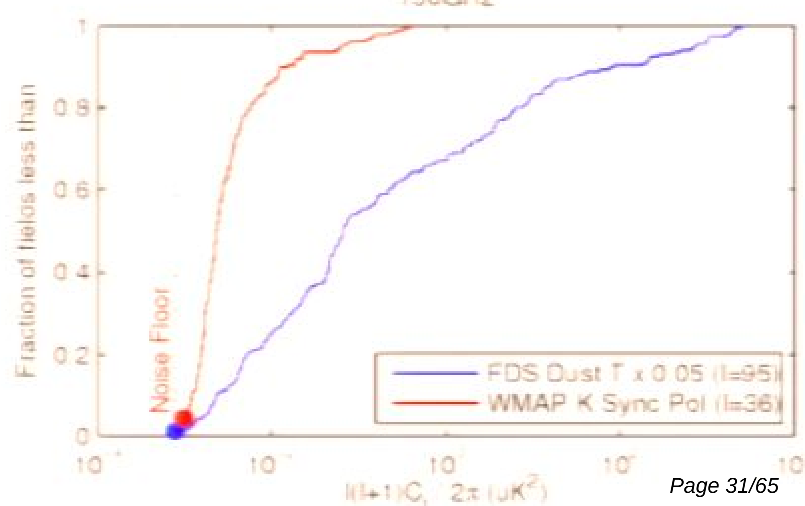


FDS Dust T @ 150GHz x 0.05



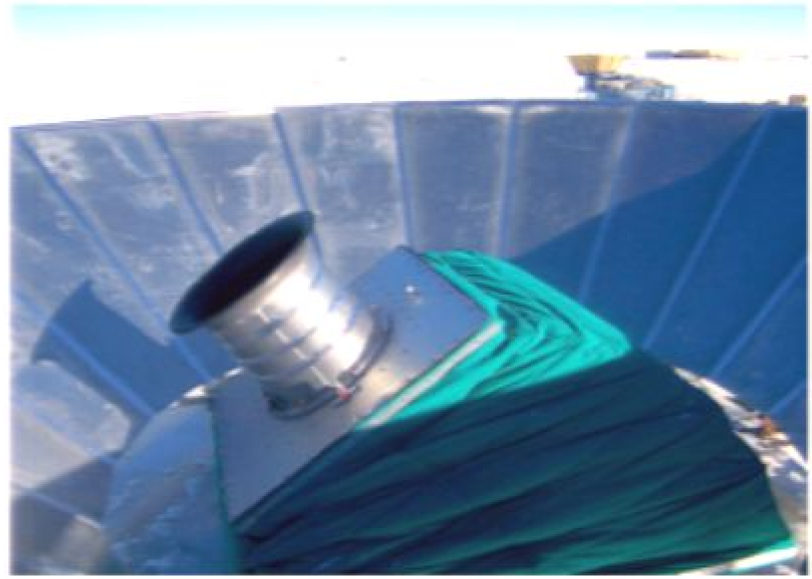
Color range 0 to 4uK

150GHz



Clem Pryke

Why a small aperture?



- ➢Aperture filling waveplate
- ➢Aperture filling calibration
- ➢Stability of (4K) telescope & beams
- ➢Superior sidelobe suppression

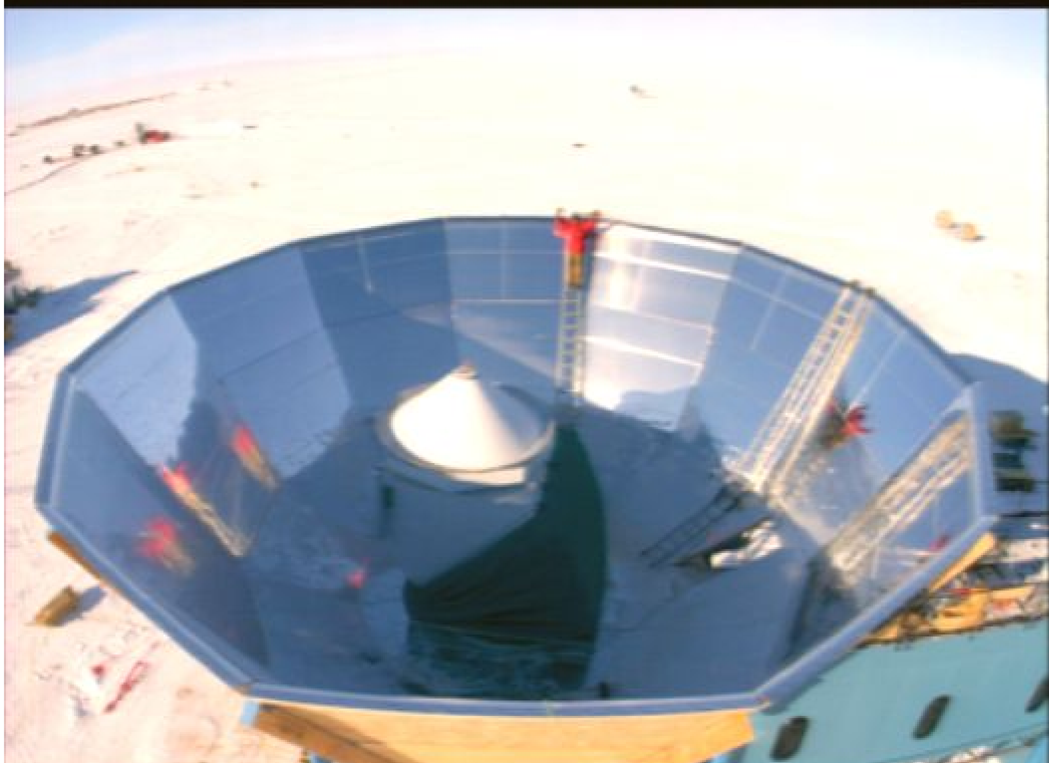
Why the South Pole?

- Best target region observable 24/7, 10 months per year.
- Altitude ~ 10,500 feet.
- Sun below horizon for 6 months
- Extremely stable, dry atmosphere
- Easy access to telescope (!?)
- Simple, low-cost logistics (!?)

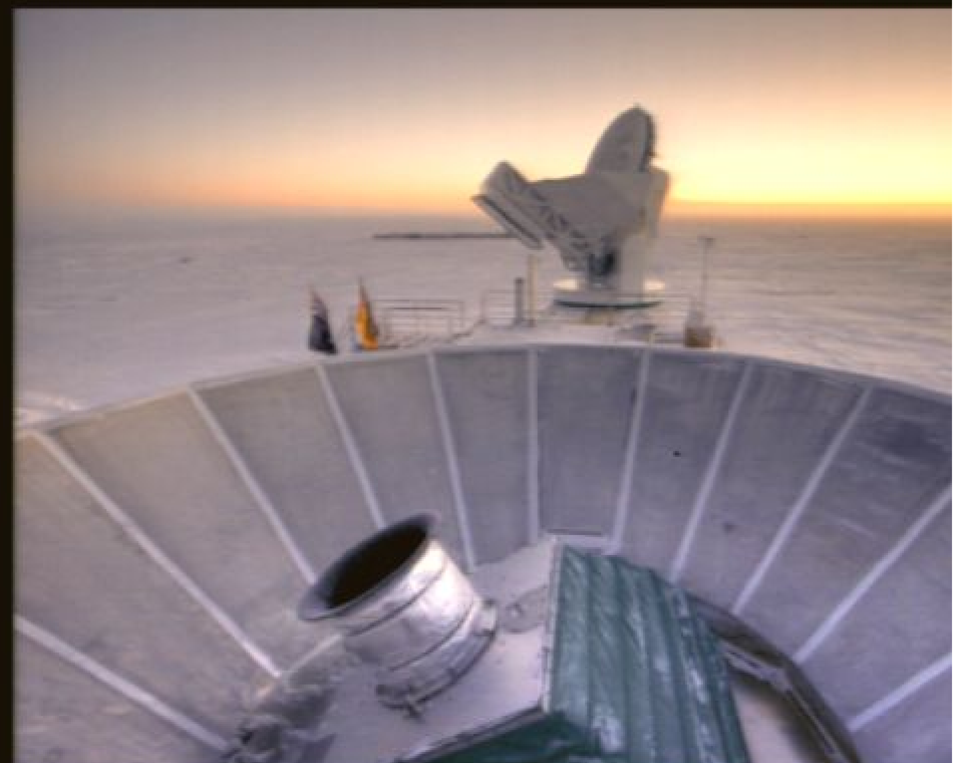
Paradise for CMB Experimentalists

The newly completed station includes a greenhouse, library, saunas, and a basketball court. All that plus *all* of our logistical needs at no charge to our grant.

CMB polarization machines…an update



QUAD



BICEP

TO APPEAR IN THE ASTROPHYSICAL JOURNAL
Preprint typeset using LaTeX style emulateapj

QUAD: A HIGH-RESOLUTION COSMIC MICROWAVE BACKGROUND POLARIMETER

J. HINDERKS, P. ADE, J. BOCK, M. BOWDEN, M. L. BROWN, G. CAHILL, J. E. CARLSTROM, P. G. CASTRO, S. CHURCH, T. CULVERHOUSE, R. FRIEDMAN, K. GANGA, W. K. GEAR, S. GUPTA, J. HARRIS, V. HAYNES, J. KOVAC, E. KIRBY, A. E. LANGE, E. LEITCH, O. E. MA[...] L. PICCIRILLO, C. PRYKE, N. RAJG[...]

arXiv:0805.1990v1 [astro-ph] 14 May 2008

We describe the QUaD expe[...] crowave Background (CMB) [...] scope equipped with a cryoge[...] ters. The focal plane contain[...] resolutions of 5′ and 3.5′, res[...] and polarization anisotropies [...] and collected science data du[...]

Subject headings: cosmic mic[...]

1. INTRODUCTION

The Cosmic Microwave Background [...] tool for understanding the origin and [...] verse. Thompson scattering from qu[...] at the surface of last scattering polar[...] level of 10%. The resulting polari[...] sky can be mathematically decompo[...] E modes and odd-parity B modes [...] 1997). The E mode signal, which ha[...] number of experiments (Readhead et [...] 2005; Montroy et al. 2006; Page et al. [...] CAPMAP Collaboration: C. Bischoff e[...] nated by scalar perturbations (density fl[...] universe. The B-mode signal has yet to [...] be generated by gravitational waves in [...] lensing of E-modes by intervening stru[...]

[1] Kavli Institute for Particle Astrophysics and [...] of Physics, Stanford University, 382 Via Pueblo [...] USA.
[2] Current address: NASA Goddard Space Fl[...] Road, Greenbelt, Maryland 20771, USA.
[3] School of Physics and Astronomy, Cardiff [...] ings, The Parade, Cardiff CF24 3AA, UK.
[4] Jet Propulsion Laboratory, 4800 Oak Grove [...]

SUBMITTED TO ApJ
Preprint typeset using LaTeX style emulateapj

SECOND AND THIRD SEASON QUAD CMB TEMPERATURE AND POLARIZATION POWER SPECTRA

QUAD COLLABORATION – C. PRYKE, P. ADE, J. BOCK, M. BOWDEN, M. L. BROWN, G. CAHILL, P. G. CASTRO, S. CHURCH, T. CULVERHOUSE, R. FRIEDMAN, K. GANGA, W. K. GEAR, S. GUPTA, J. HINDERKS, J. KOVAC, A. E. LANGE, E. LEITCH, S. J. MELHUISH, Y. MEMARI, J. A. MURPHY, A. ORLANDO, R. SCHWARZ, C. O'SULLIVAN, L. PICCIRILLO, N. RAJGURU, B. RUSHOLME, A. N. TAYLOR, K. L. THOMPSON, A. H. TURNER, E. Y. S. WU AND M. ZEMCOV

Submitted to ApJ

arXiv:0805.1944v2 [astro-ph] 14 May 2008

ABSTRACT

We report results from the second and third seasons of observation with the QUaD experiment. Angular power spectra of the Cosmic Microwave Background are derived for both temperature and polarization at both 100 GHz and 150 GHz, and as cross frequency spectra. All spectra are subjected to an extensive set of jackknife tests to probe for possible systematic contamination. For the implemented data cuts and processing technique such contamination is undetectable. We analyze the difference map formed between the 100 and 150 GHz bands and find no evidence of foreground contamination in polarization. The spectra are then combined to form a single set of results which are shown to be consistent with the prevailing LCDM model. The sensitivity of the polarization results is considerably better than that of any previous experiment — for the first time multiple acoustic peaks are detected in the E-mode power spectrum at high significance.

Subject headings: CMB, anisotropy, polarization, cosmology

1. INTRODUCTION

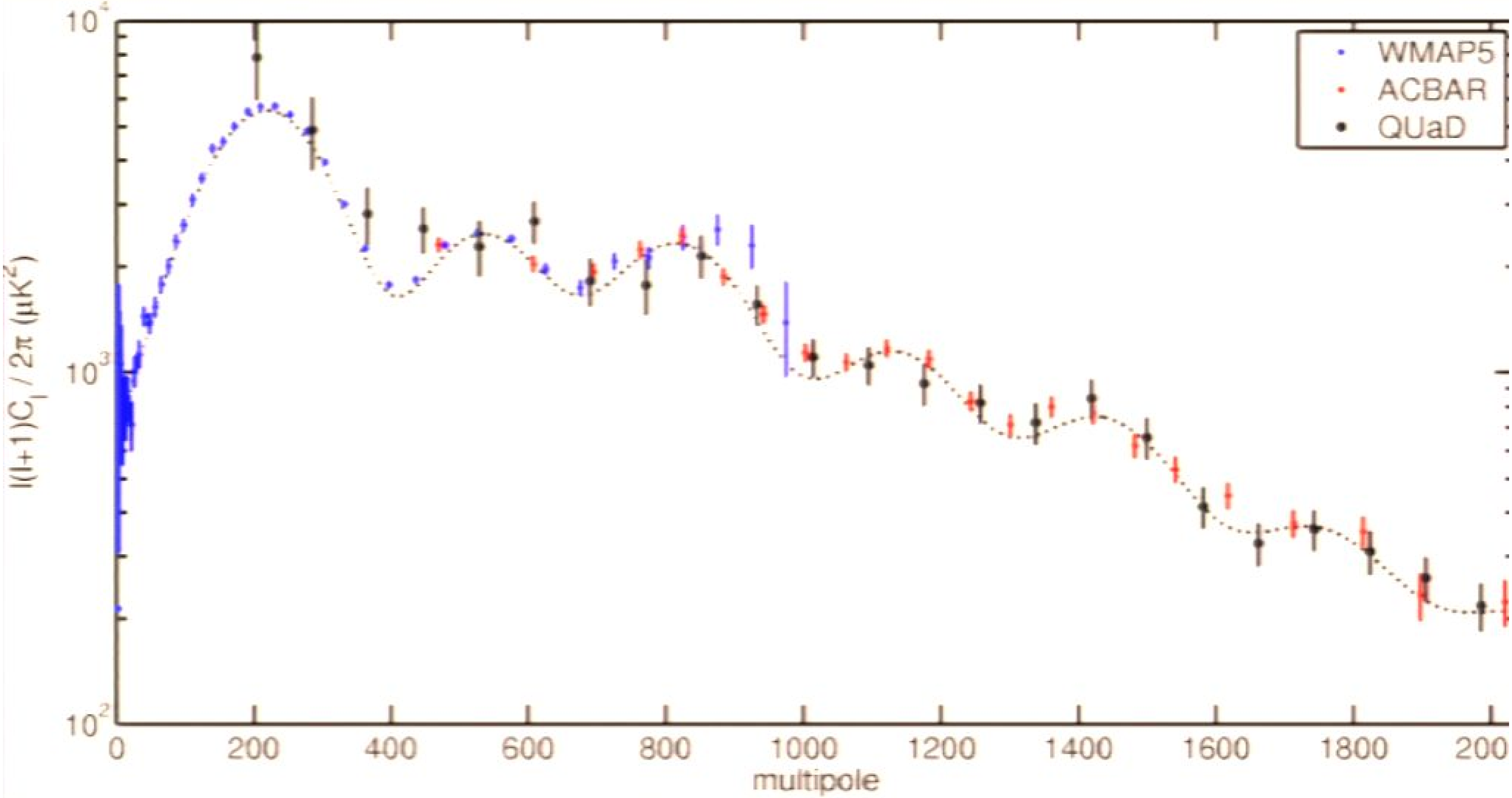
The anisotropy of the Cosmic Microwave Background (CMB) gives us direct insight into the structure of the Universe when it was a tiny fraction of its current age, and is one of the central pillars of the enormously successful standard cosmological model. The temperature anisotropy power spectrum has now been measured to good precision from the largest angular scales down to a small fraction of a degree (e.g. Reichardt et al. (2008)) — the expected series of acoustic peaks is present and fitting the spectrum yields tight constraints on the basic parameters of the cosmological model (e.g. Dunkley et al. (2008)).

The CMB is expected to be polarized at the ~ 10% level principally because of motions in the material at the time of last scattering. Since the plasma flows along gradients in the density field the resulting observable polarization pattern has gradients (E-modes), but zero curl (B-modes) (e.g. Hu & White (1997)). Given a standard cosmologica[l] model fit to the temperature spectrum (TT), the E-mode spec[trum] (EE), and temperature-E-mode cross spectrum (TE) are nearly deterministically predicted — only at the largest angular scales is there additional information. It is important to remember that, although very successful, the standard cosmological model (which we will refer to throughout as LCDM) contains several components which we have only circumstantial evidence for (dark matter and dark energy). Measuring the EE and TE spectra is thus a crucial test of the overal[l] theoretical paradigm.

As the CMB travels to us through the [...]ing large scale structure subtle deflections due to gravitational lensing occu[r] (e.g. Hu (2003)). This converts some fraction of the E-mod[...]

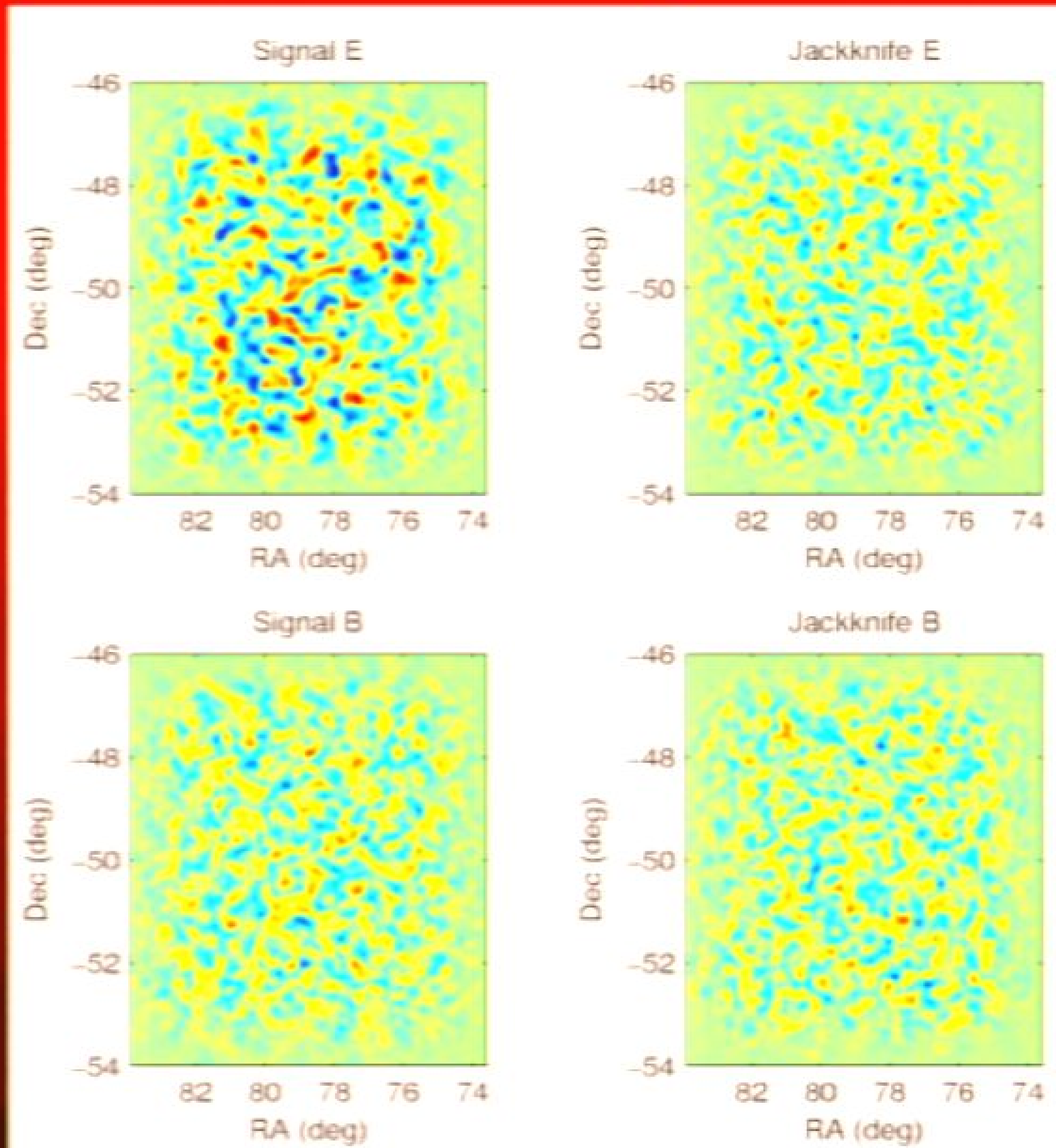
[1] Kavli Institute for Cosmological Physics, Department of Astronomy & Astrophysics, Enrico Fermi Institute, University of Chicago, 5640 South El-

TT Compared to Other Experiments

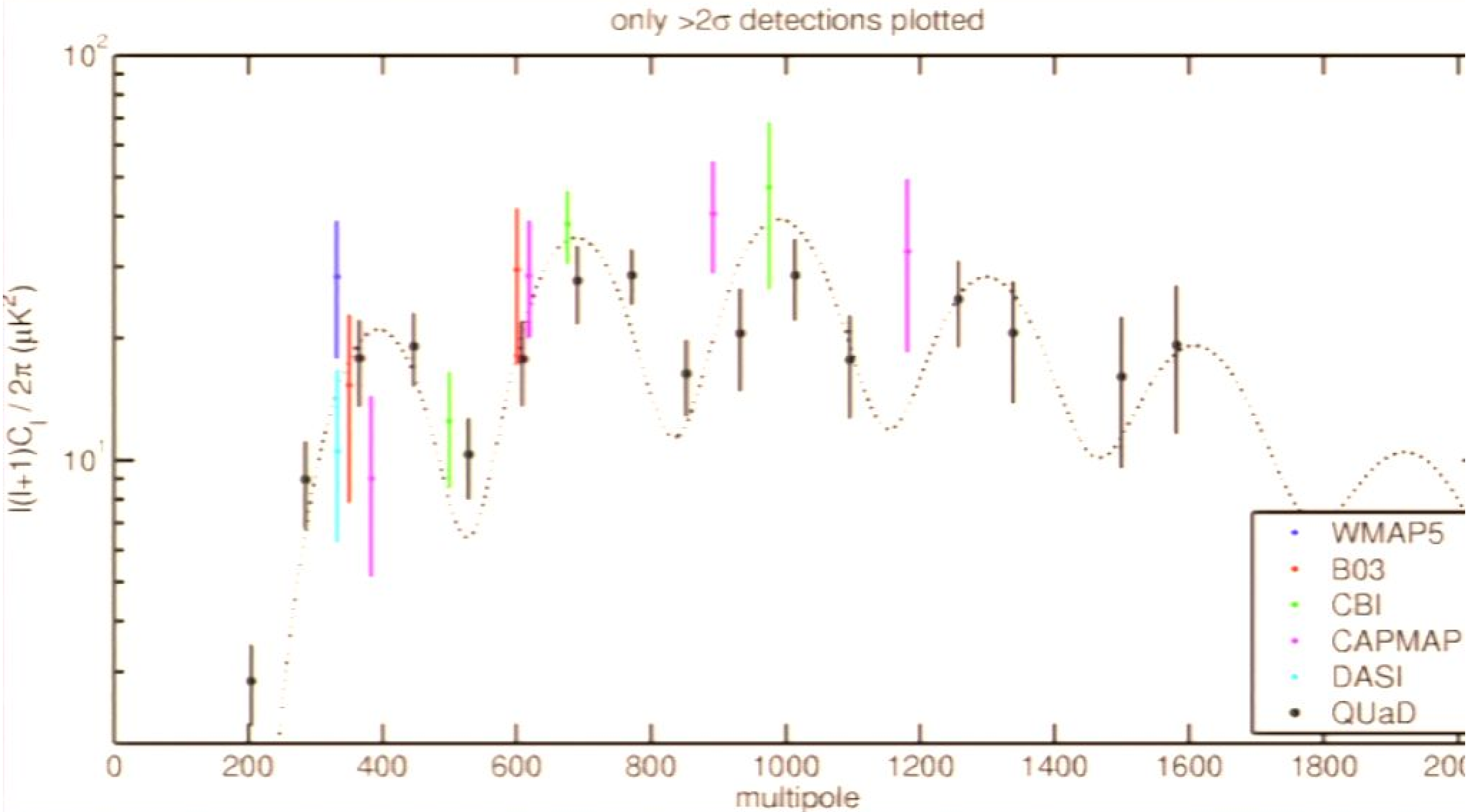


QUaD breaks no new ground in this release - will improve on ACBAR above multipole 2000 (UC grad. student Robert Friedman)

E/B Maps

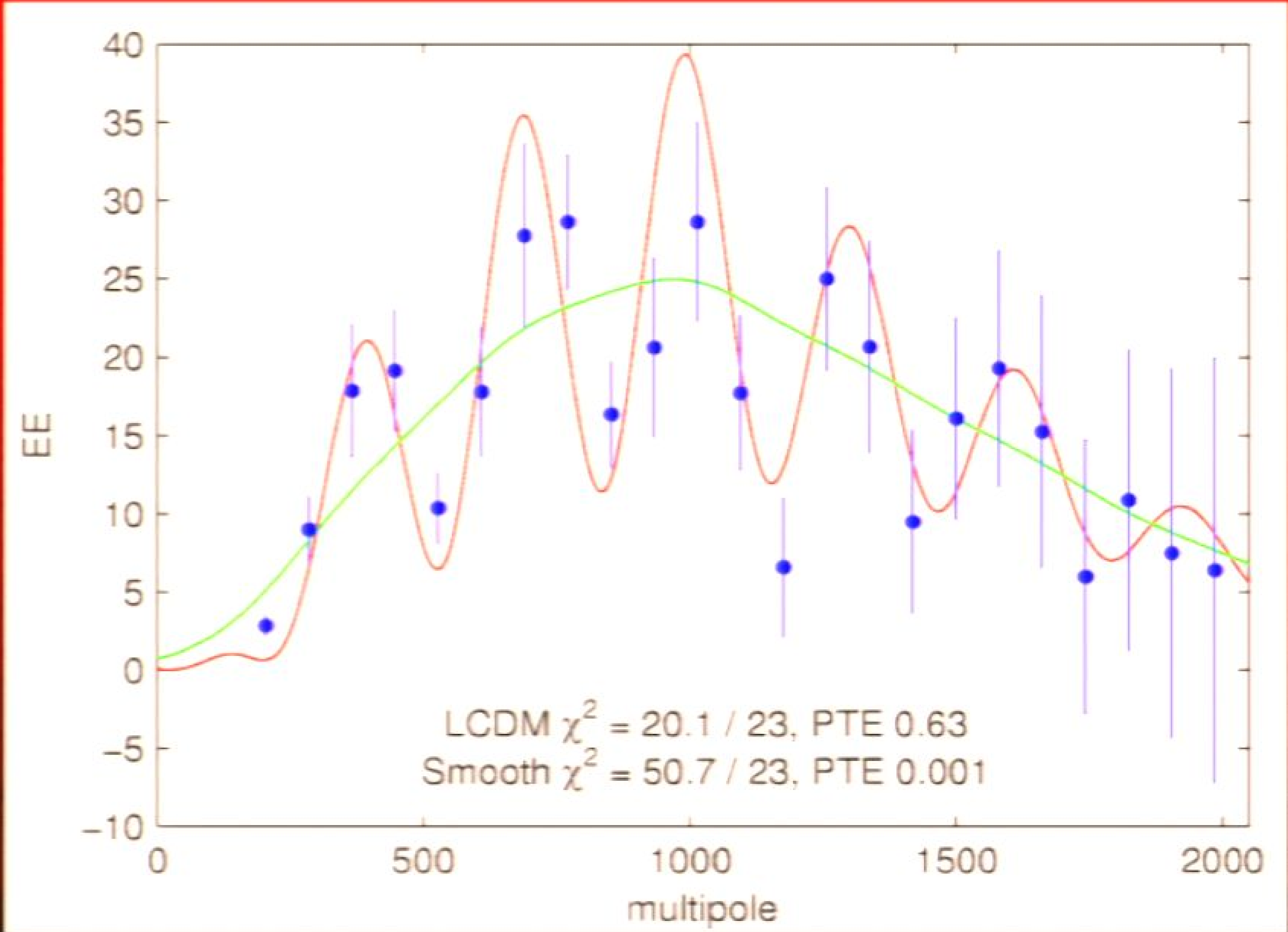

Signal E
Jackknife E
Signal B
Jackknife B
Dec (deg)
RA (deg)
-46
-48
-50
-52
-54
82
80
78
76
74

EE Compared to Other Experiments

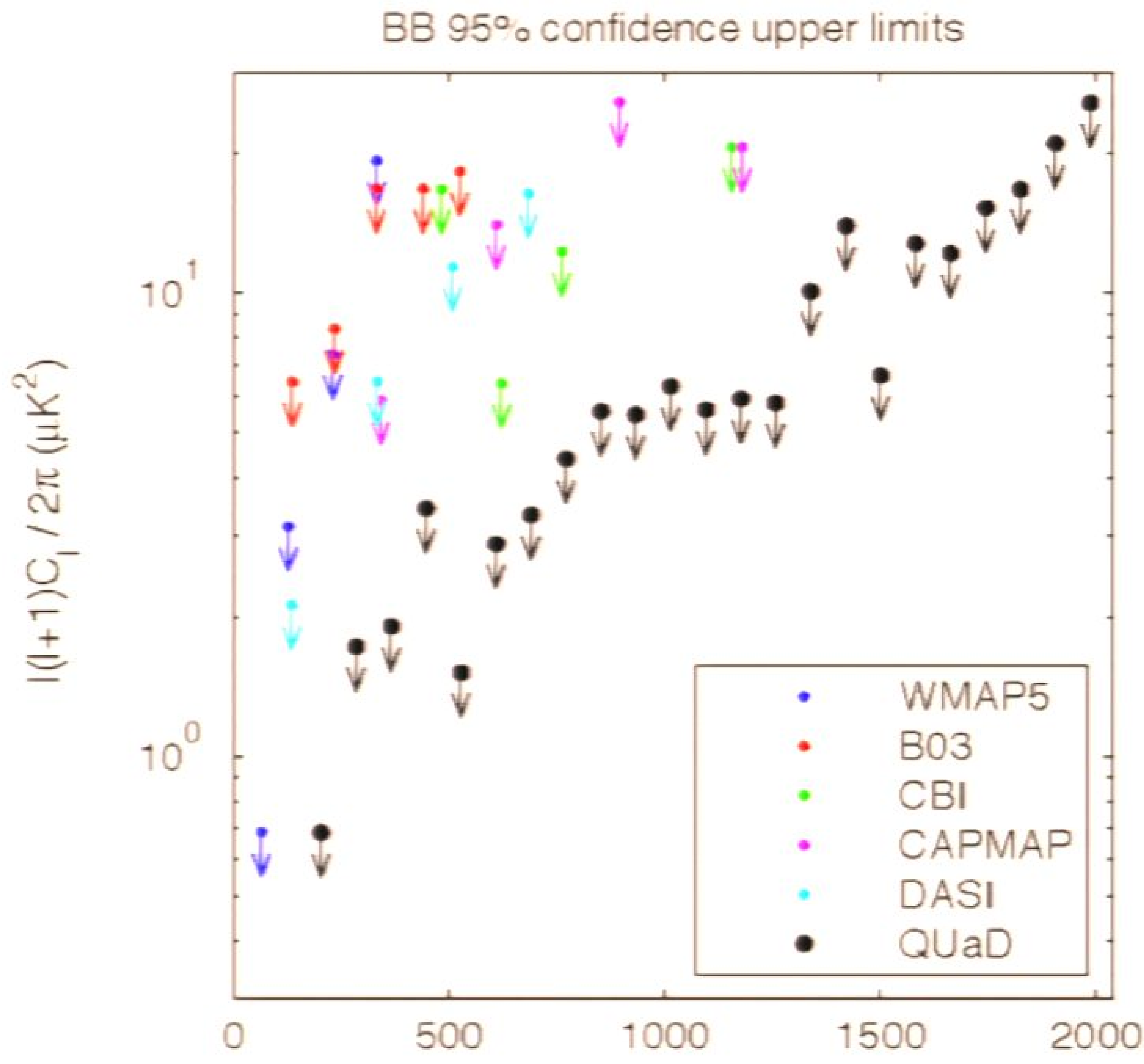


QUaD detects a series of peaks for the first time...

Does the EE Spectrum Have Peaks?

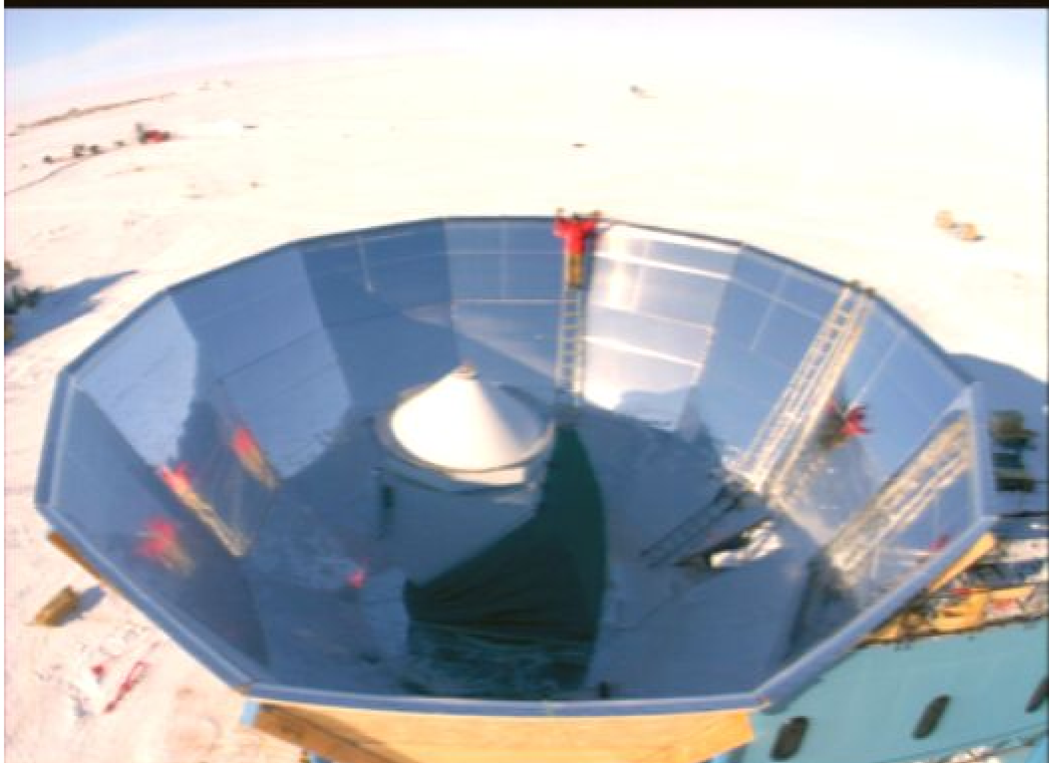


Chance that true spectrum is smooth is 1 in a 1000

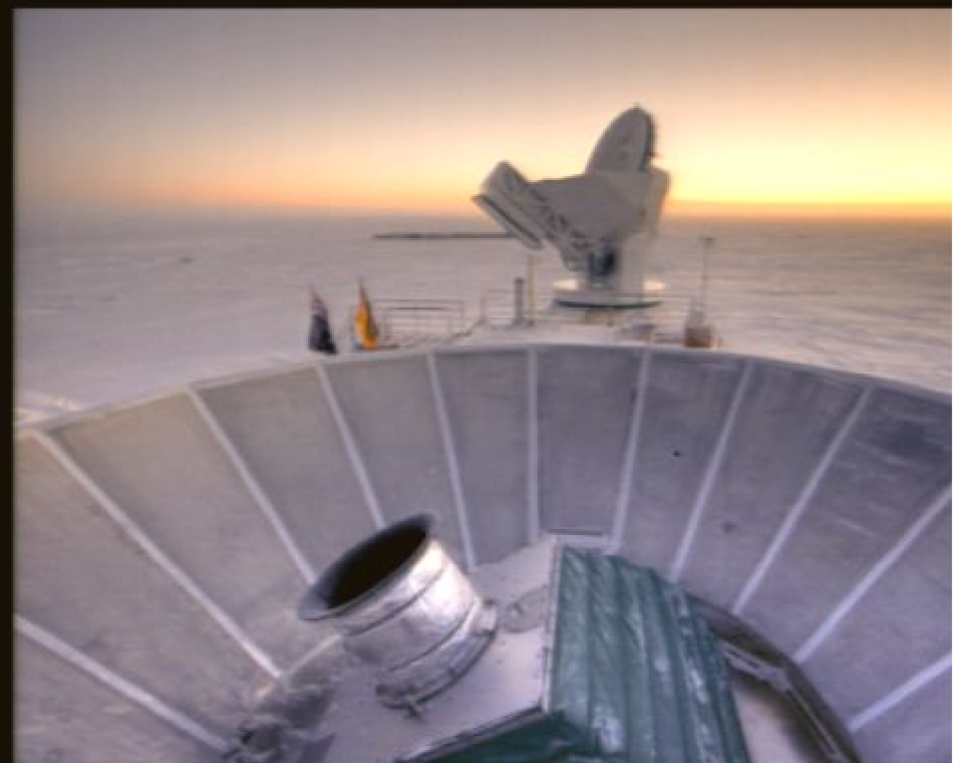


BB 95% confidence upper limits
$l(l+1)C_l\,/\,2\pi\ (\mu K^2)$
10^1
10^0
0
500
1000
1500
2000
WMAP5
B03
CBI
CAPMAP
DASI
QUaD

CMB polarization machines…an update



QUAD



BICEP

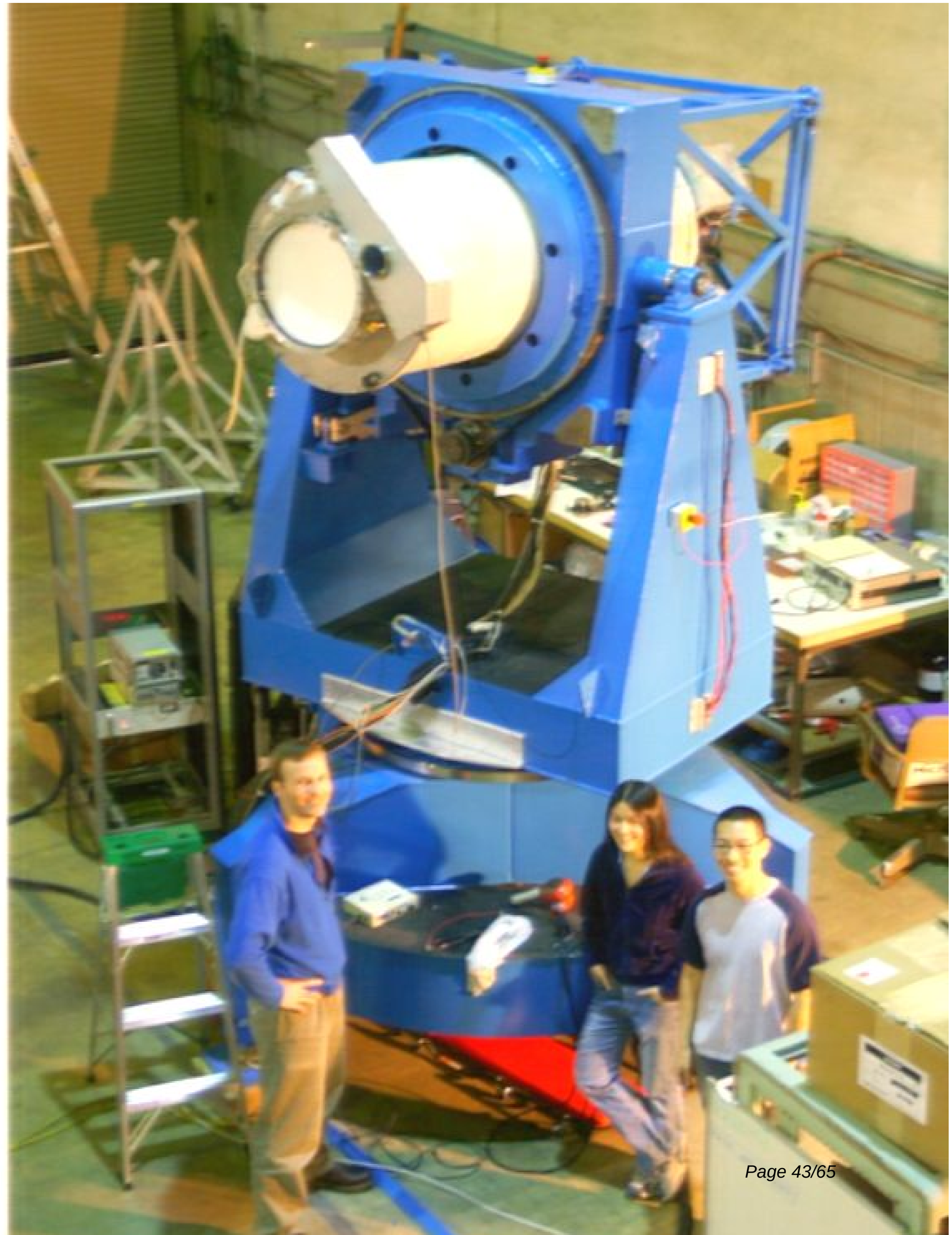
BICEP

first telescope designed to detect the "echo" of creation

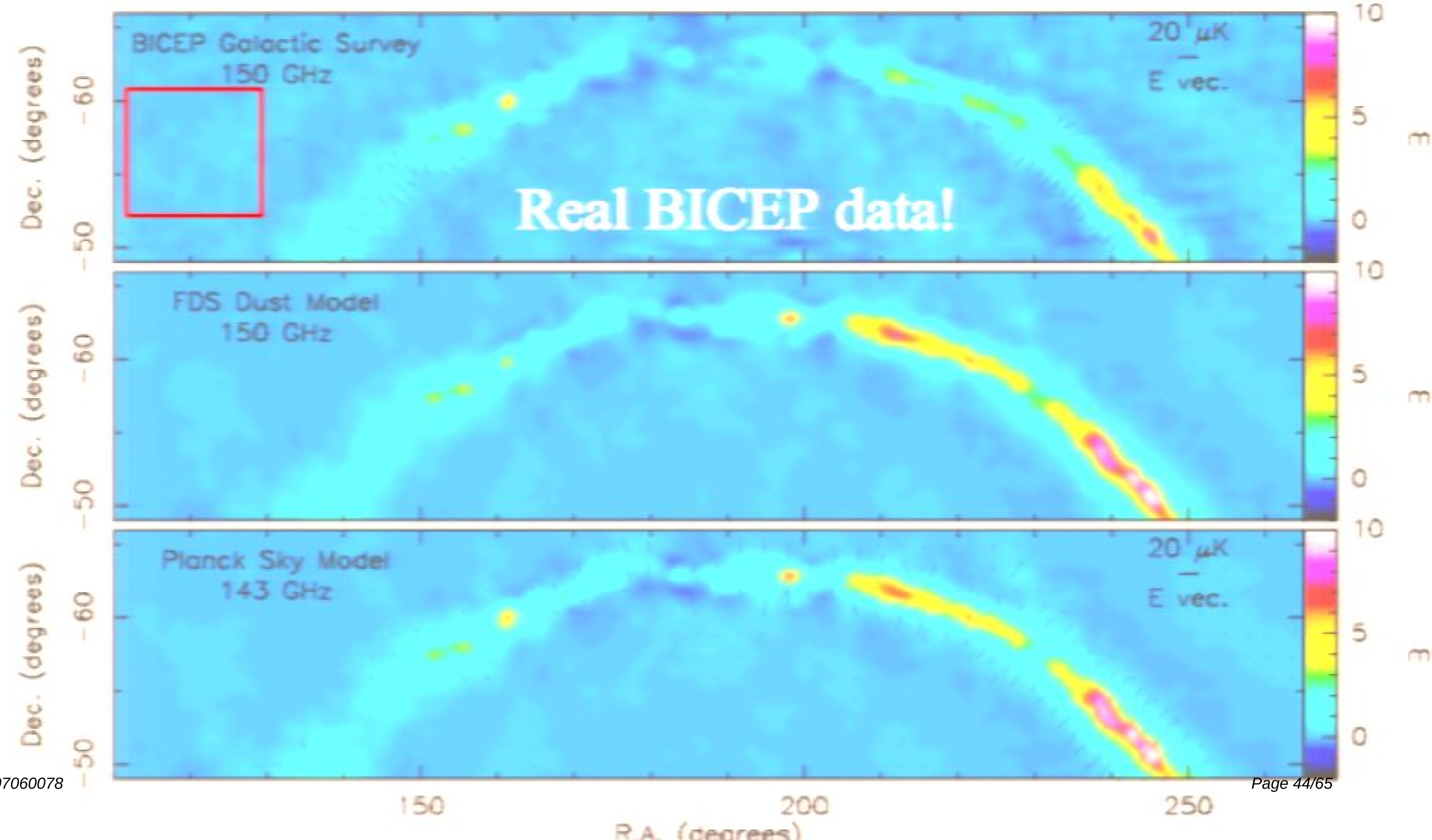
25 cm aperture!

~ $3M, 3 years

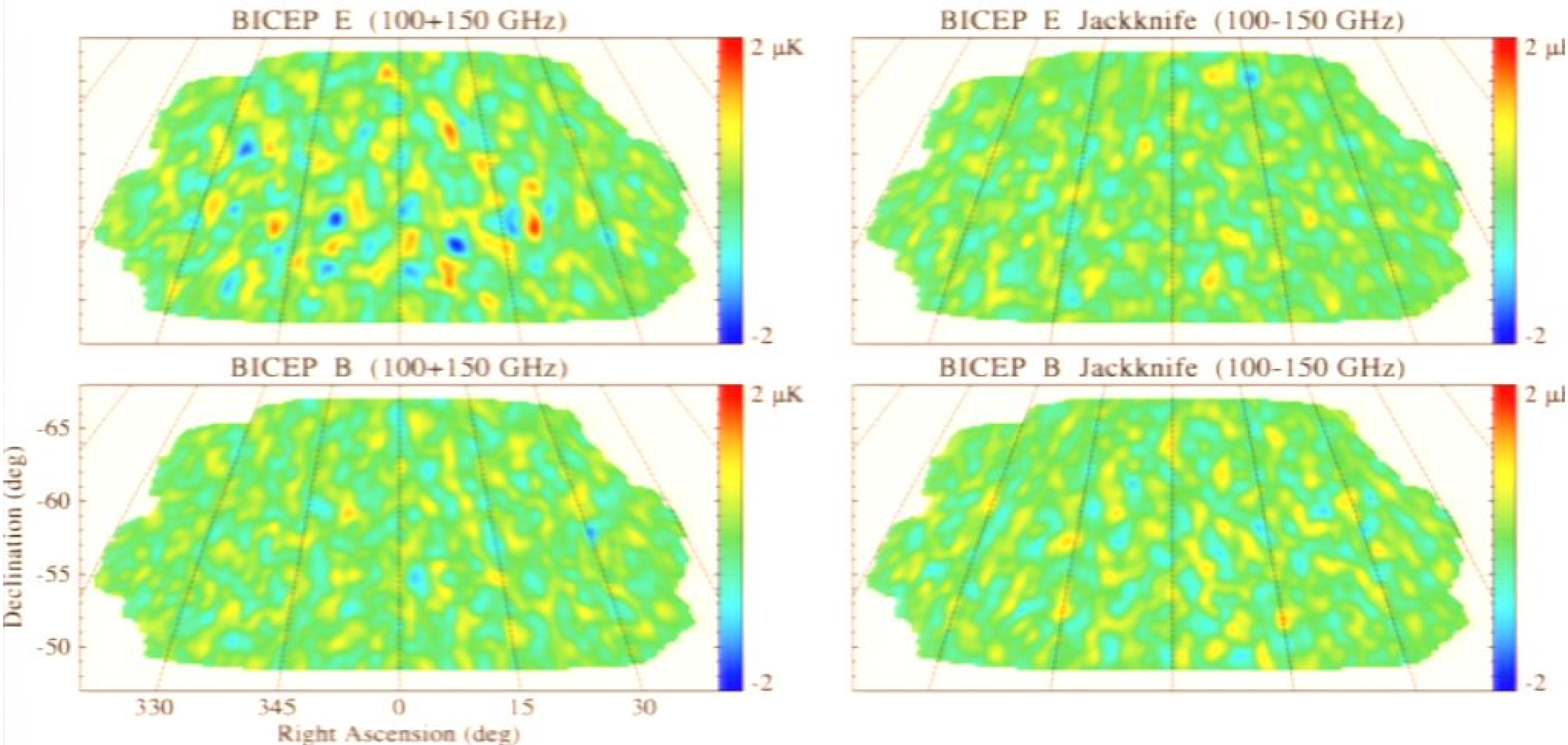
sited at South Pole



Polarization in the plane of the Galaxy is at or below expected levels

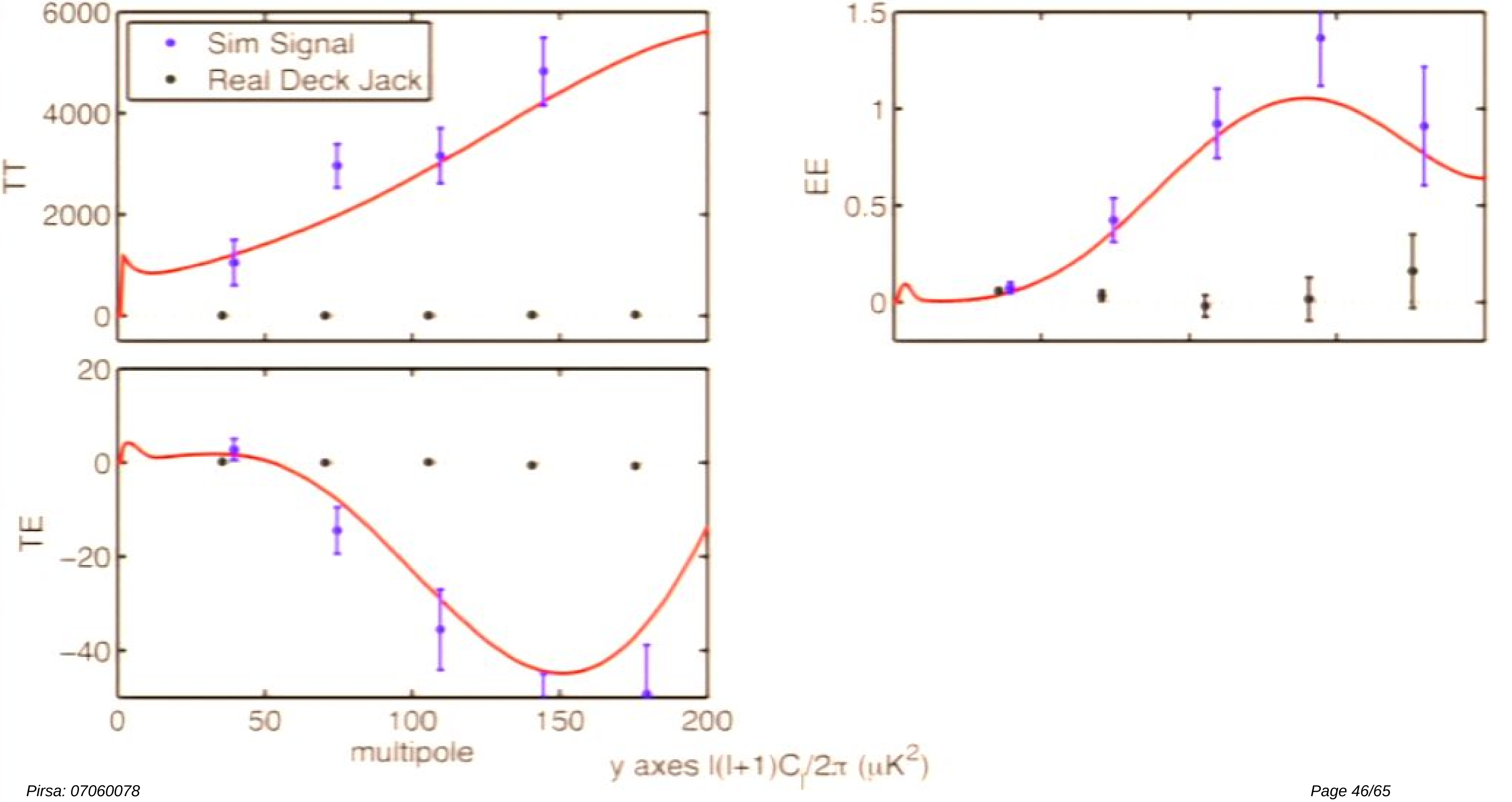


BICEP E/B polarization



Kiwon Yoon, Cynthia Chiang

BICEP T, TE, E spectra



Denis Barkats

We can do better (with better detectors)….

Parameter	Definition	BICEP1 Req't (r=0.1)	BICEP1 Meas.[1]	BICEP2/SPUD Req't (r=0.01) w/o HWP	BICEP2/SPUD Req't (r=0.01) w/ HWP	BICEP2/SPUD Calculated[2]
Gain mismatch (I-pol)	$(g_1 - g_2)/g$	$< 1.5 \times 10^{-2}$	$< 5 \times 10^{-3}$	$< 2.5 \times 10^{-3}$	negl.	4×10^{-4}
Differential FWHM	$(\sigma_1 - \sigma_2)/\sigma$	$< 4 \times 10^{-2}$	$< 2 \times 10^{-3}$	$< 7 \times 10^{-3}$	negl.	2×10^{-4}
Differential pointing	$\Delta\theta/\sigma$	$< 3 \times 10^{-2}$	1×10^{-2}	$< 5 \times 10^{-3}$	negl.	9×10^{-5}
Differential ellipticity	$(e_1 - e_2)/2$	$< 9 \times 10^{-2}$	$< 1 \times 10^{-3}$	$< 1.6 \times 10^{-2}$	negl.	7×10^{-5}
Cross-polarization	$\Delta\phi$ (rad)	$< 1.4 \times 10^{-2}$	5×10^{-3}	$< 2.4 \times 10^{-2}$	negl.	5×10^{-6}
Pol. sidelobes to Galaxy[3]	(dBi)	< -13	< -38	< -18		< -38
Pol. sidelobes to ground[3]	(dBi)	< -24	< -38	< -29		< -38
Optics temperature[4]	ΔT_{RJ} (μK)	<3.5	<0.7	<1	<3	<0.7
Cold-stage temperature[4]	ΔT (nK)	<3	<2.7	<1	<3	<1

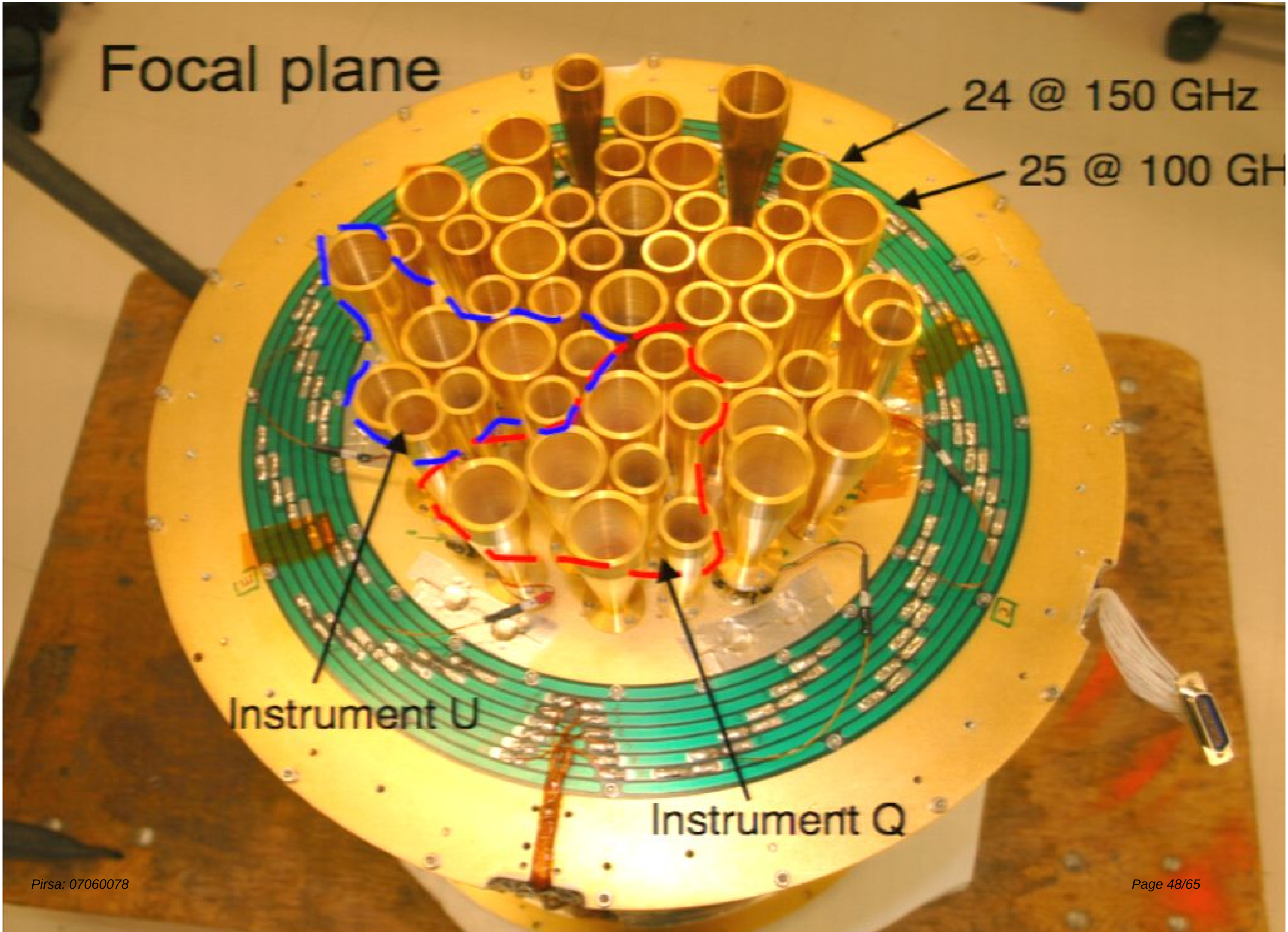
[1] Typical value measured from an end-to-end beam test of the entire BICEP1 optics.

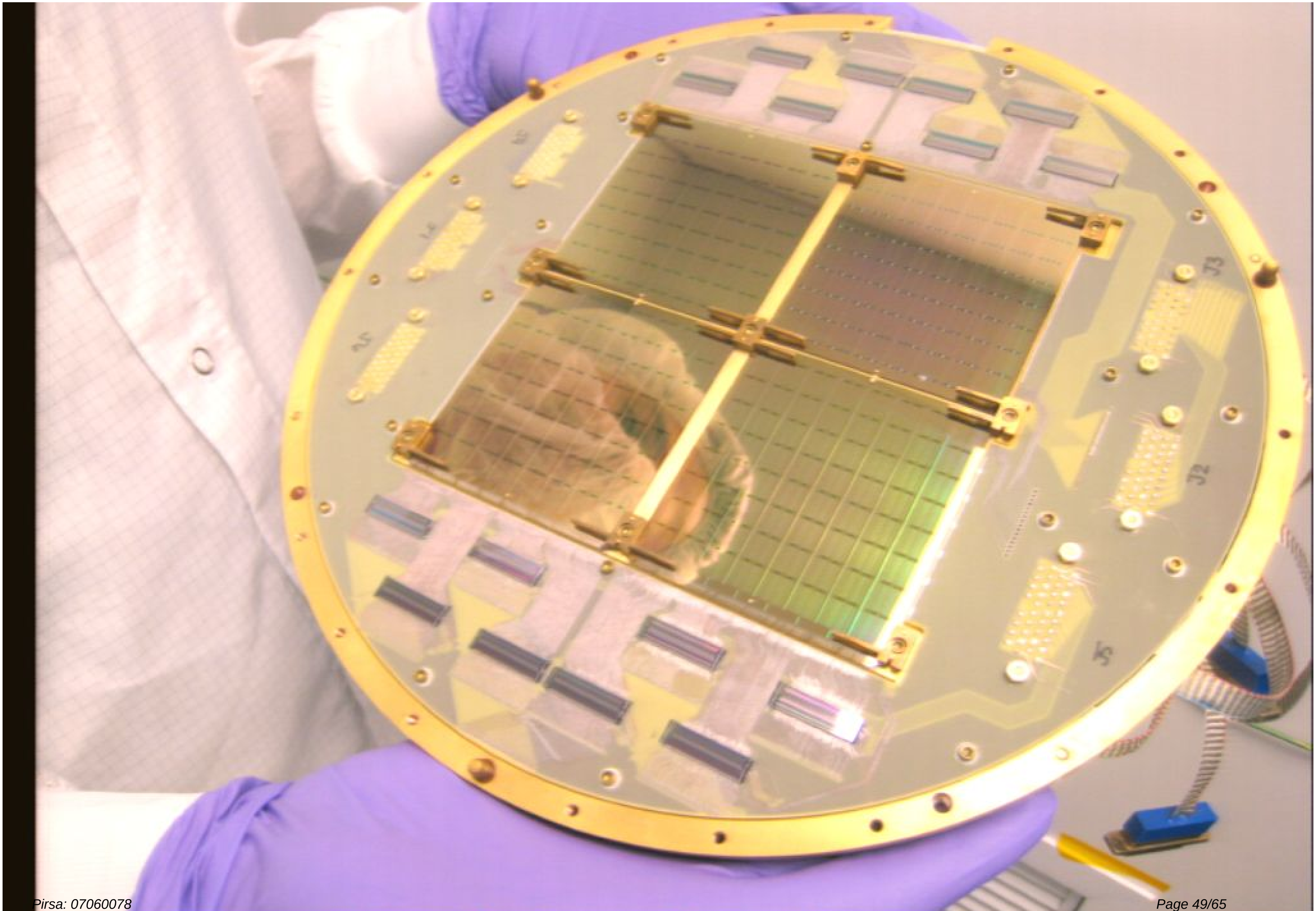
[2] BICEP2/SPUD estimates for main beam effects based on a physical optics calculation of the refracting optics (worst case over the entire FOV), sidelobe and temperature levels based on BICEP1 performance.

[3] Following Page et al. (2003), defined here as $G_0(\theta, \phi) = (4\pi/\Omega)Pg(\theta, \phi)$, where P is the polarization.

[4] Scan-synchronous, over $\ell = 30 - 300$, assuming no reduction from varying the scan pattern.

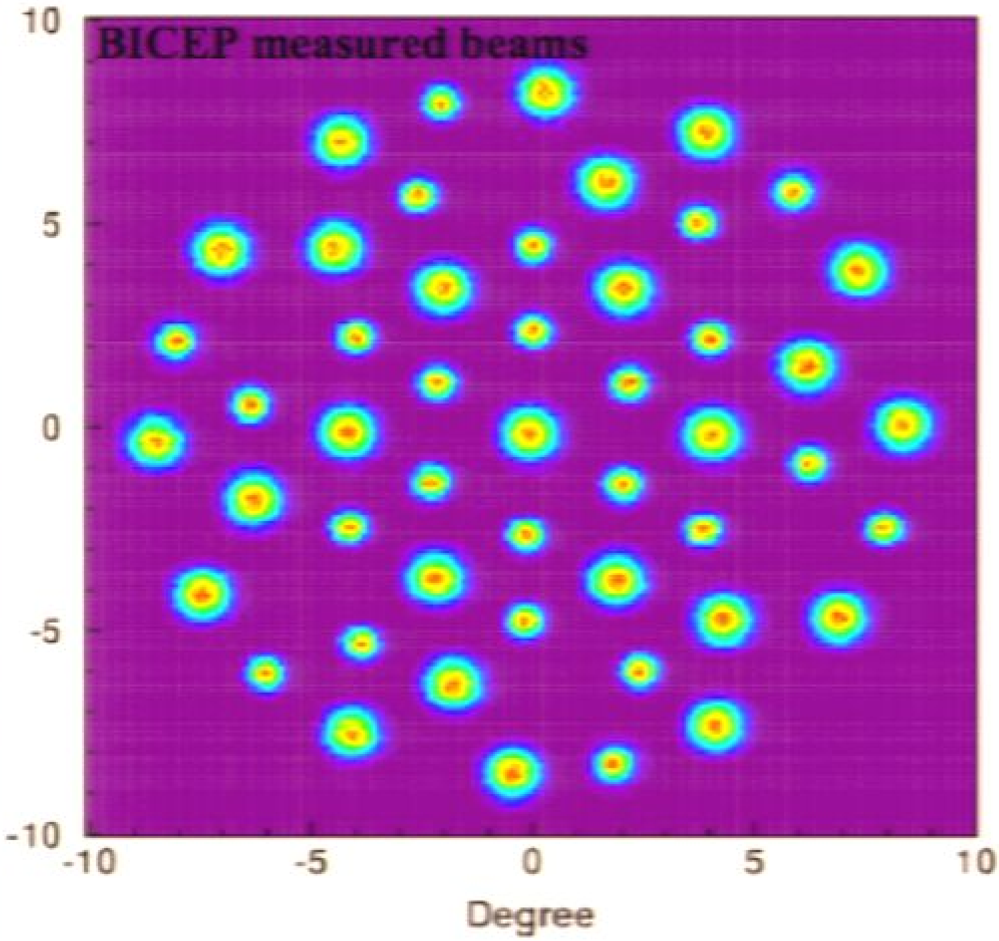
Table 2: Potential Systematic Errors for BICEP and SPUD.

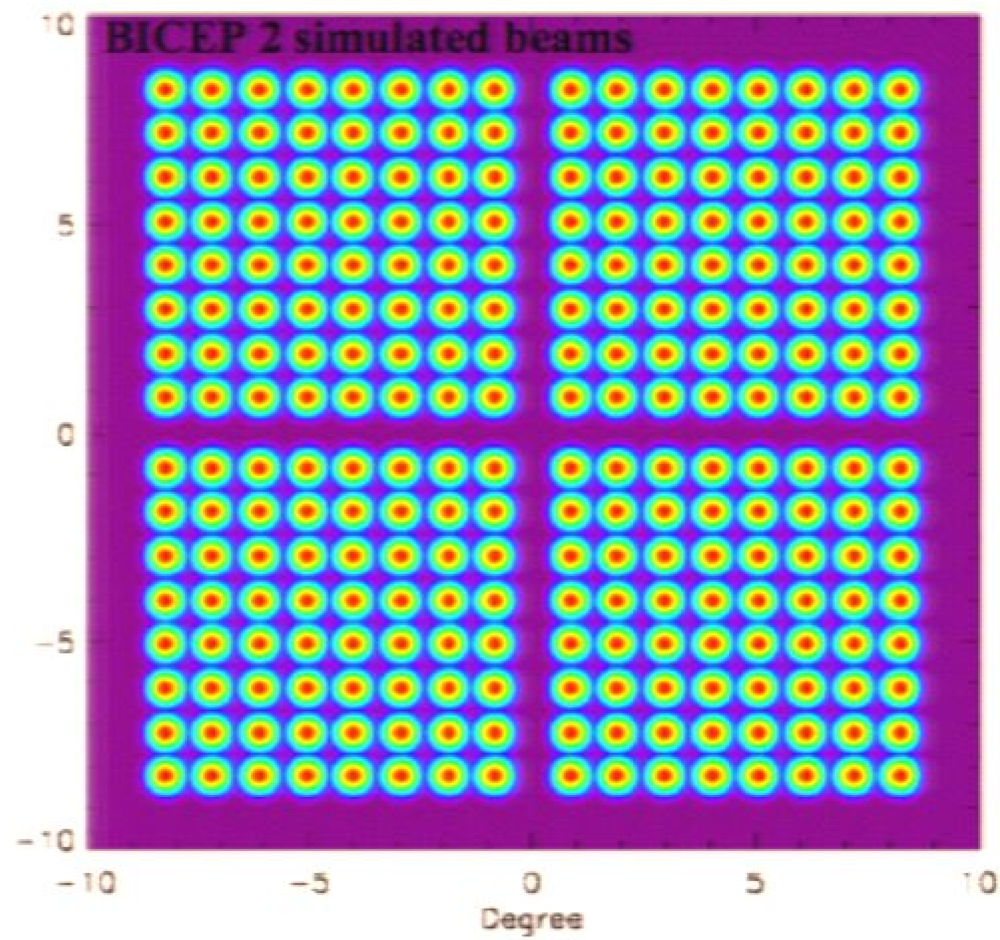

Focal plane
24 @ 150 GHz
25 @ 100 GH
Instrument U
Instrument Q

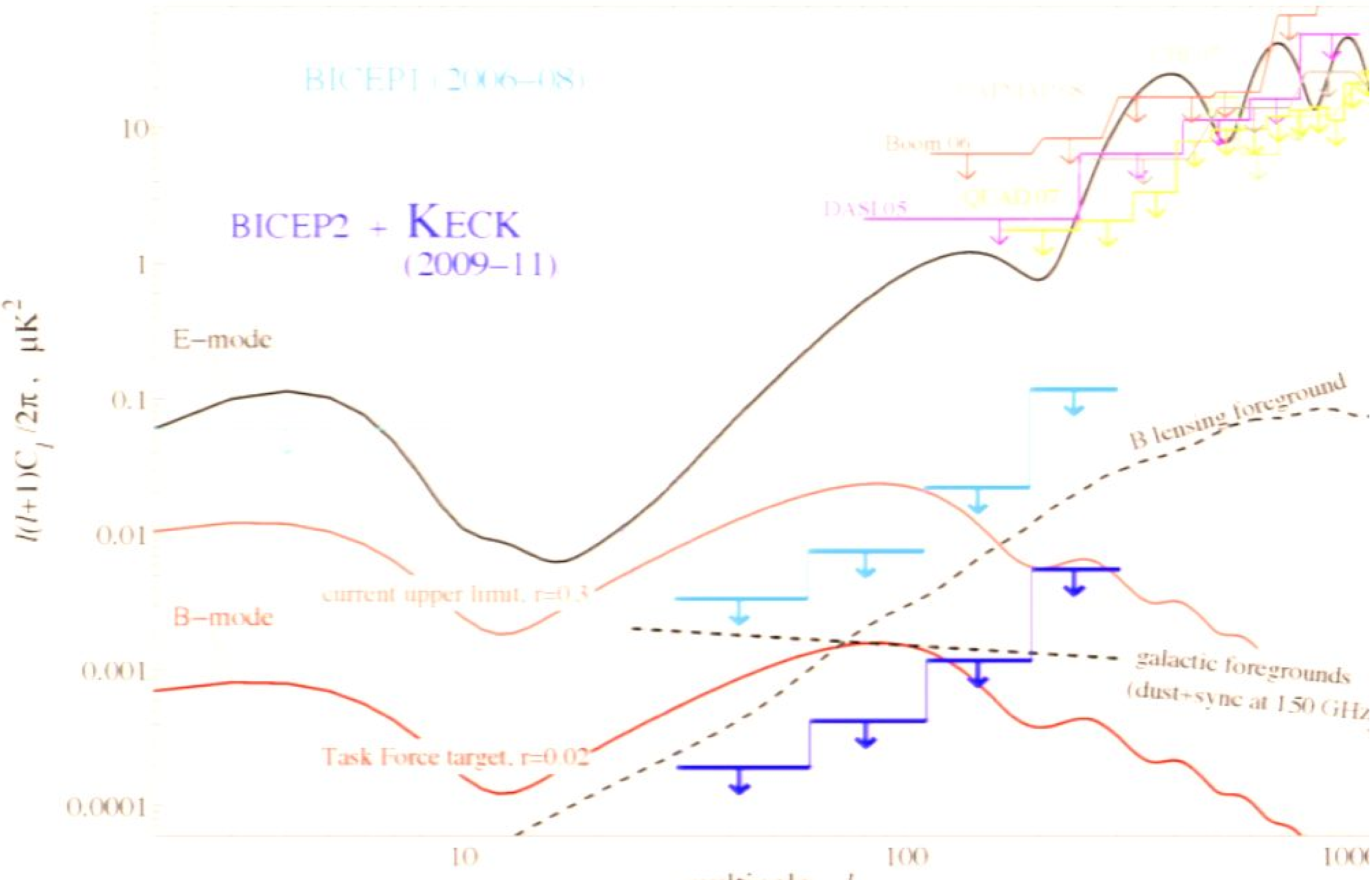


BICEP2 focal plane, May 2009

Getting more pixels on the sky …







BICEP1 (2006–08)
BICEP2 + KECK
(2009–11)
Boom 06
QUAD 07
DASI 05
E–mode
B–mode
current upper limit, r=0.3
Task Force target, r=0.02
B lensing foreground
galactic foregrounds
(dust+sync at 150 GHz
10
1
0.1
0.01
0.001
0.0001
$l(l+1)C_l/2\pi$, μK^2
multipole, l

What comes next?

What comes next?

The next step requires a larger team….

Caltech (Lange)

Chicago (Pryke)

CWRU (Ruhl)

Harvard (Kovac)

JPL(Bock)

NIST (Irwin)

Stanford (Kuo)

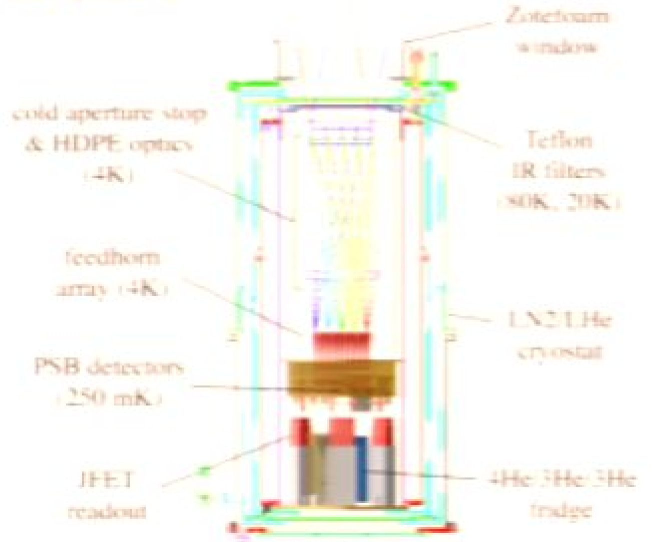
UBC (Halpern)

UCSD (Keating)

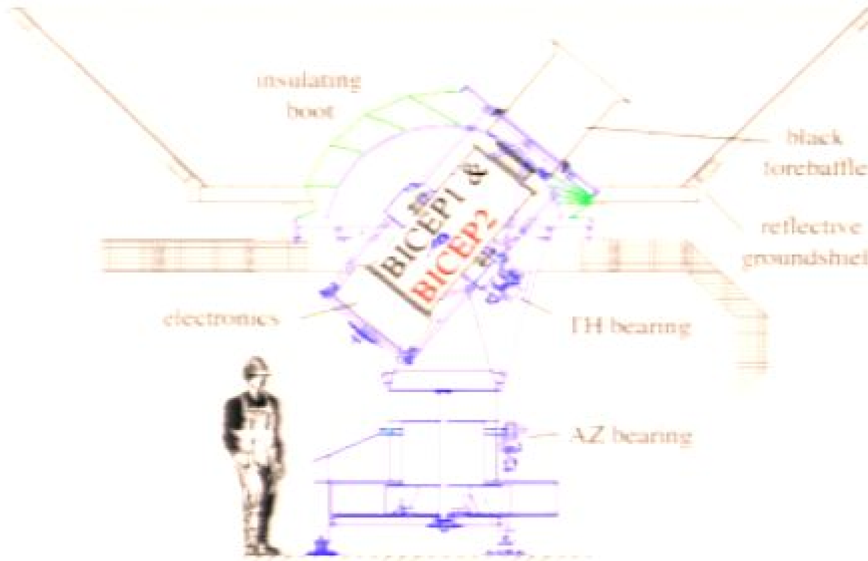
UT (Netterfield)

more telescopes (small ones!): SPUD (2010)

BICEP:

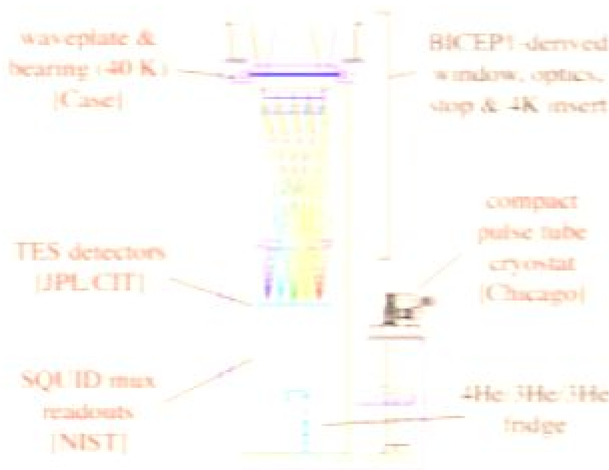


BICEP1

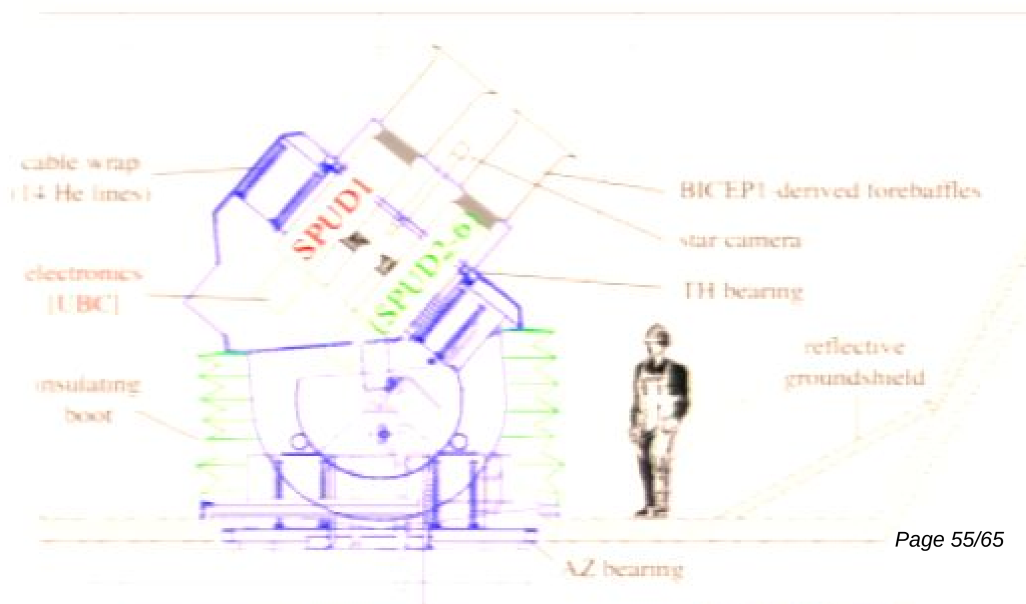


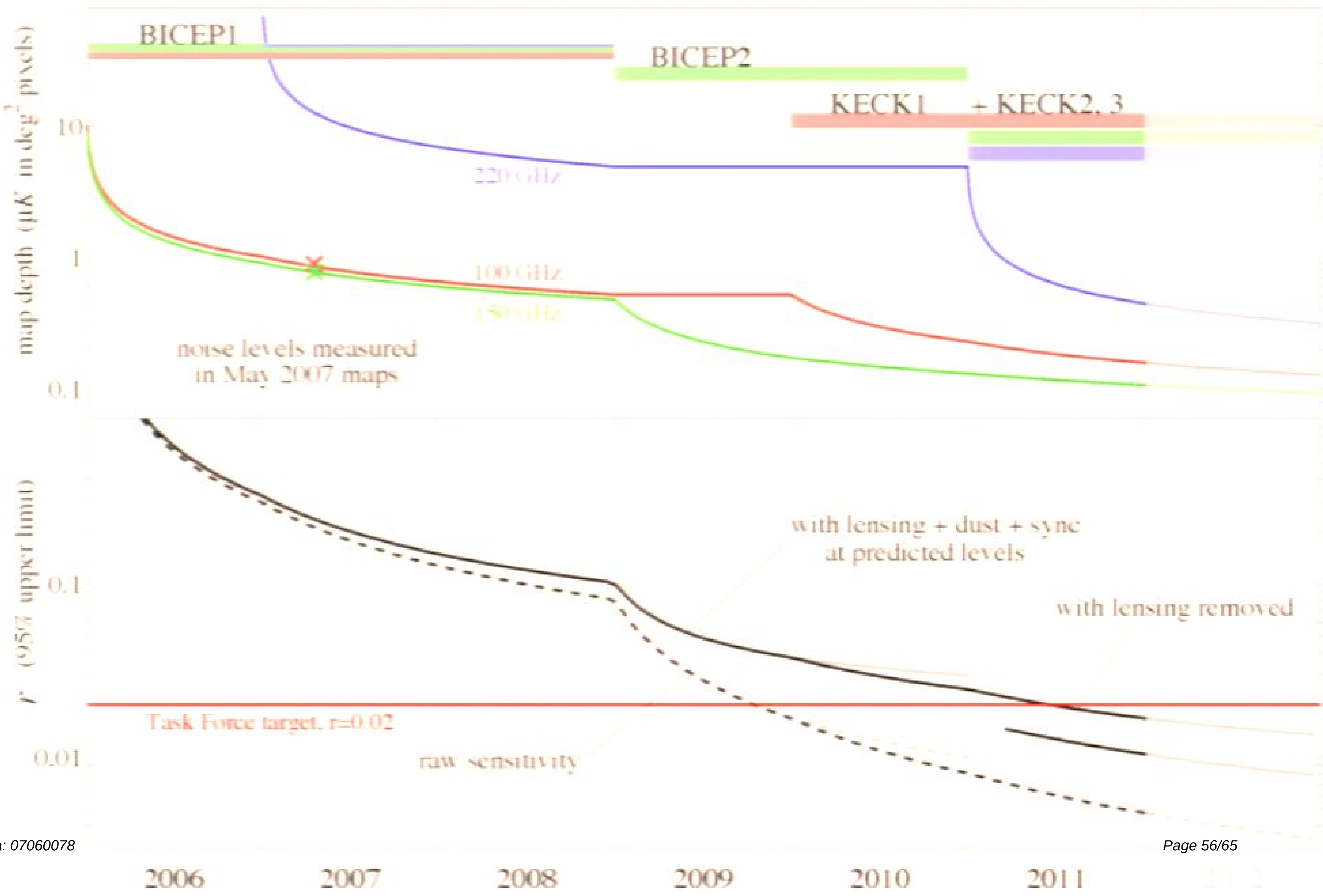
DSL BICEP platform (7500 lbs cap)

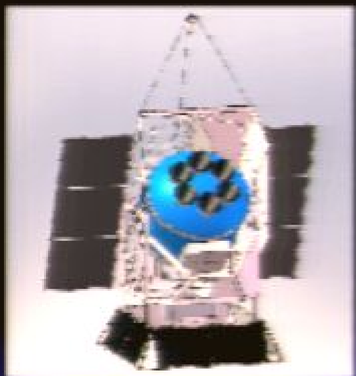
SPUD:



SPUD1




BICEP1
BICEP2
KECK1
+ KECK2, 3
map depth (μK in deg² pixels)
10
1
0.1
220 GHz
100 GHz
150 GHz
noise levels measured
in May 2007 maps
r (95% upper limit)
0.1
0.01
with lensing + dust + sync
at predicted levels
with lensing removed
Task Force target, r=0.02
raw sensitivity
2006
2007
2008
2009
2010
2011



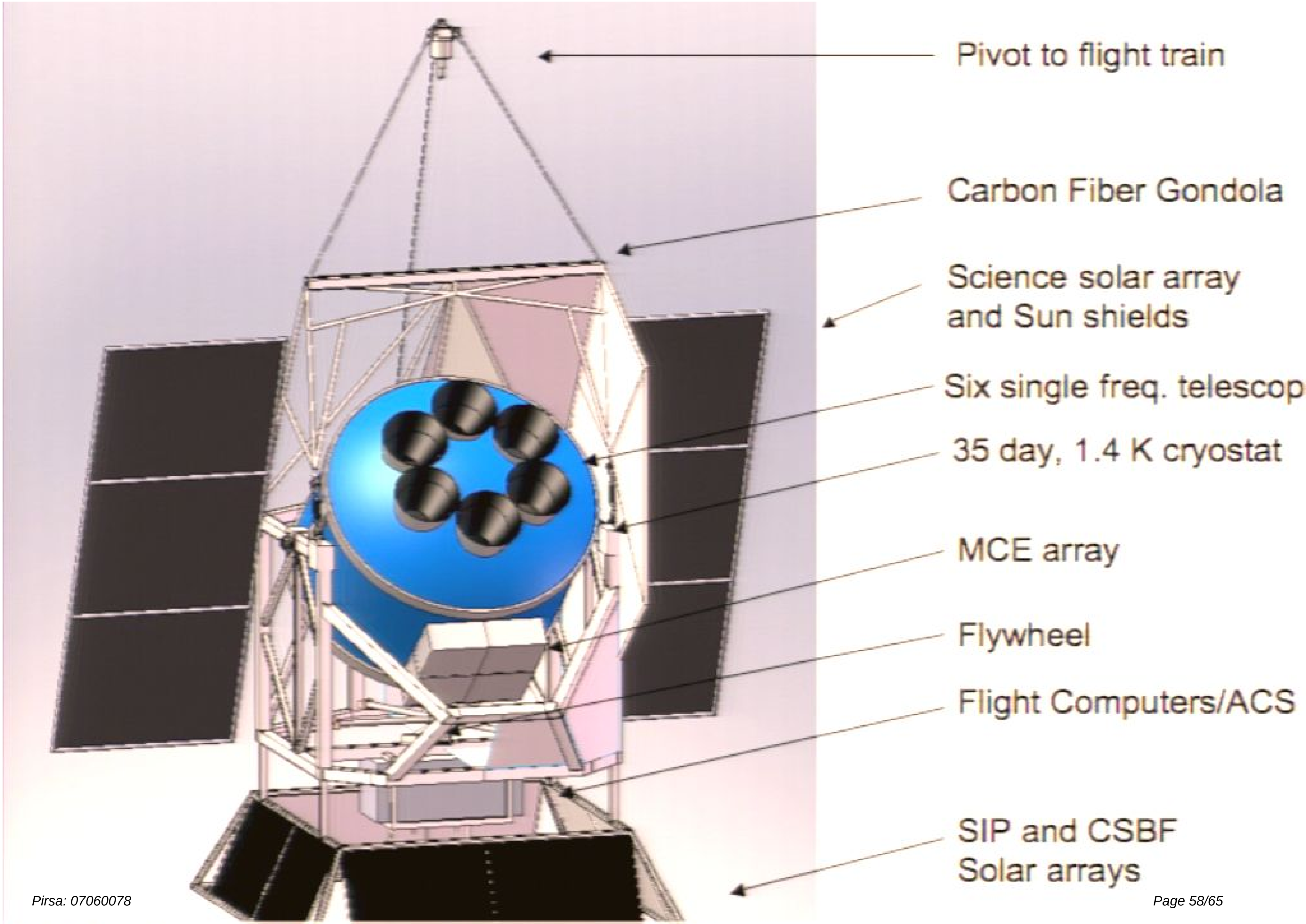
Spider:
Searching for the Echoes of Inflatio

alice springs, australia

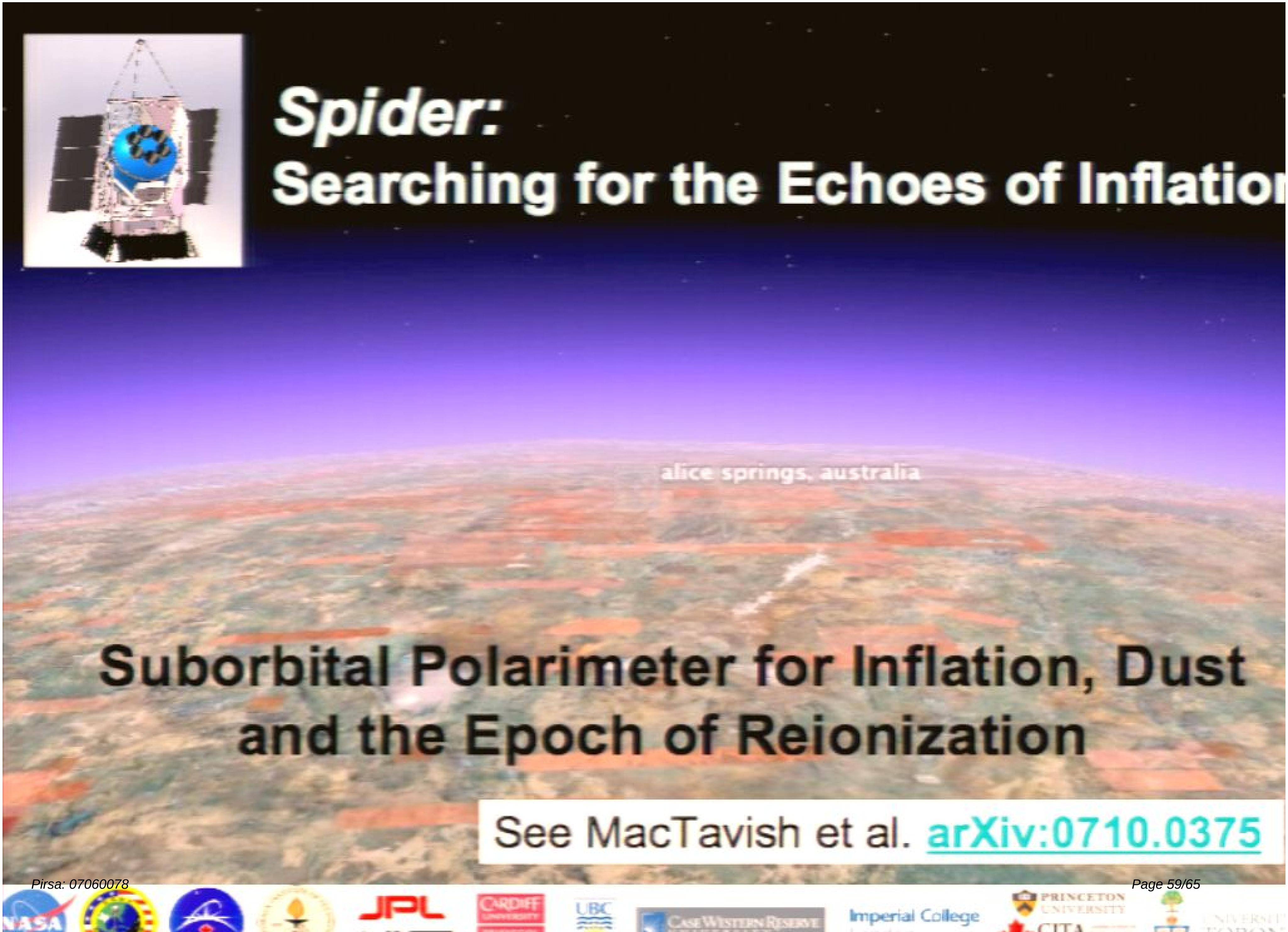
Suborbital Polarimeter for Inflation, Dust and the Epoch of Reionization

See MacTavish et al. arXiv:0710.0375

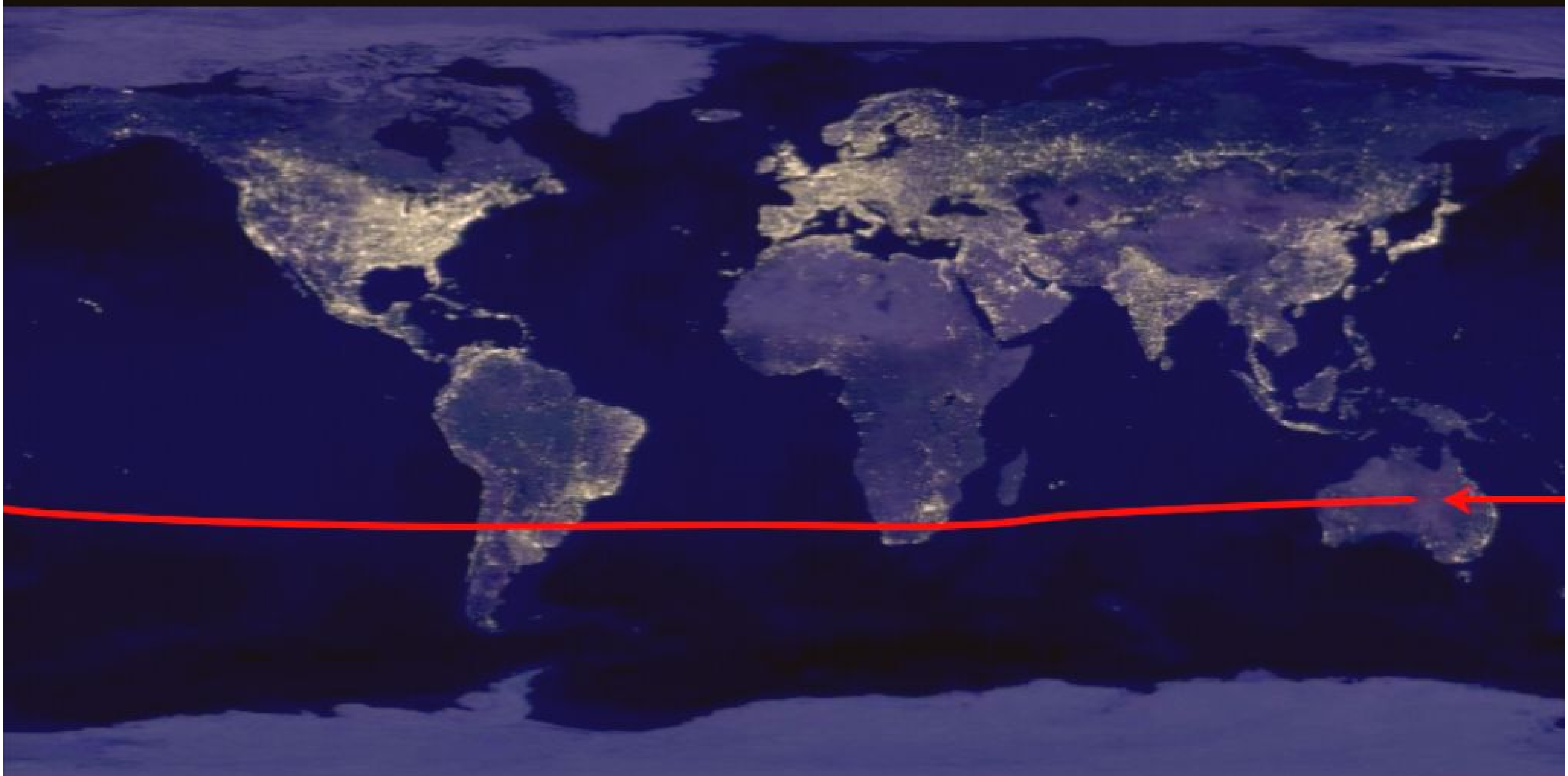
Imperial College
PRINCETON UNIVERSITY



***Spider:* Searching for the Echoes of Inflation**


Spider:
Searching for the Echoes of Inflatio
alice springs, australia
Suborbital Polarimeter for Inflation, Dust
and the Epoch of Reionization
See MacTavish et al. arXiv:0710.0375

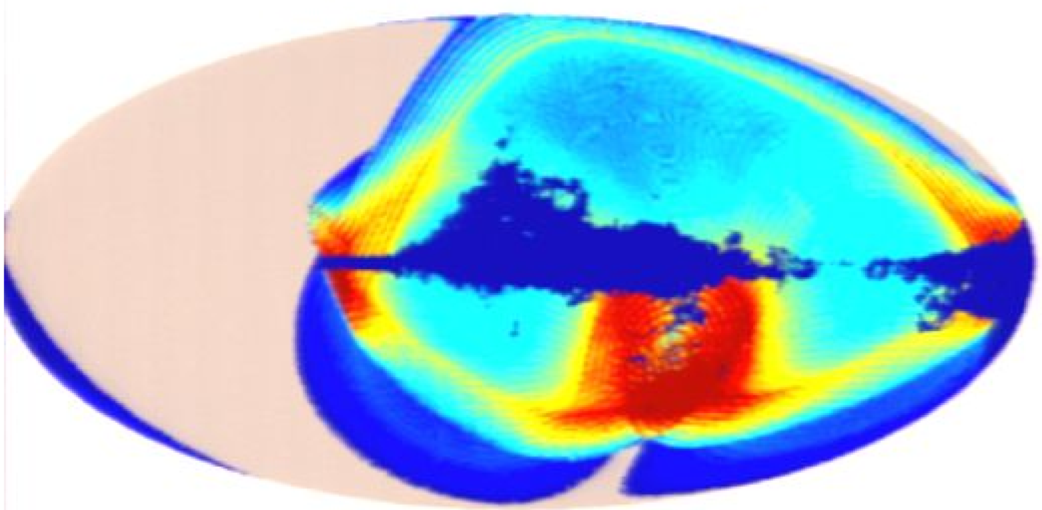
Spider's ULDB Flight Plan

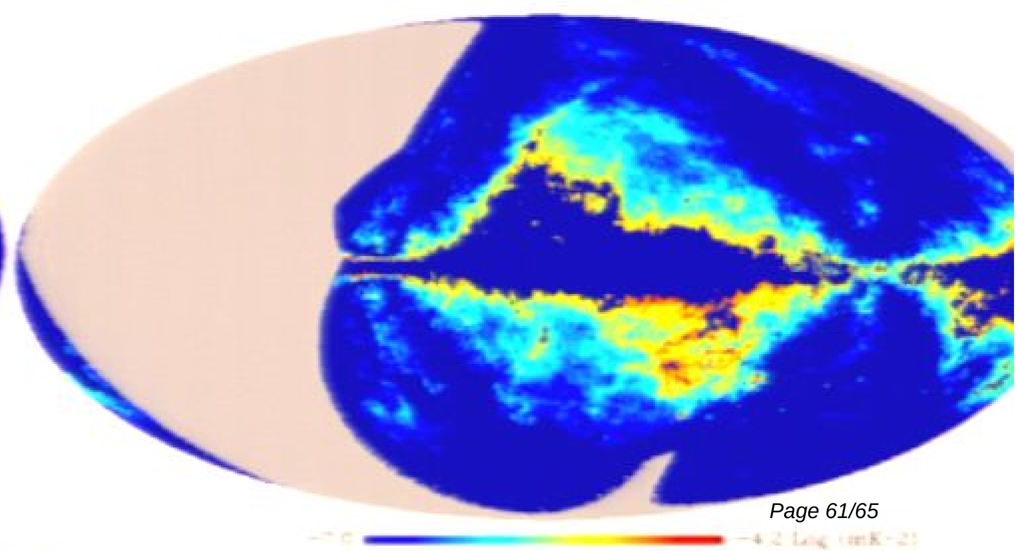


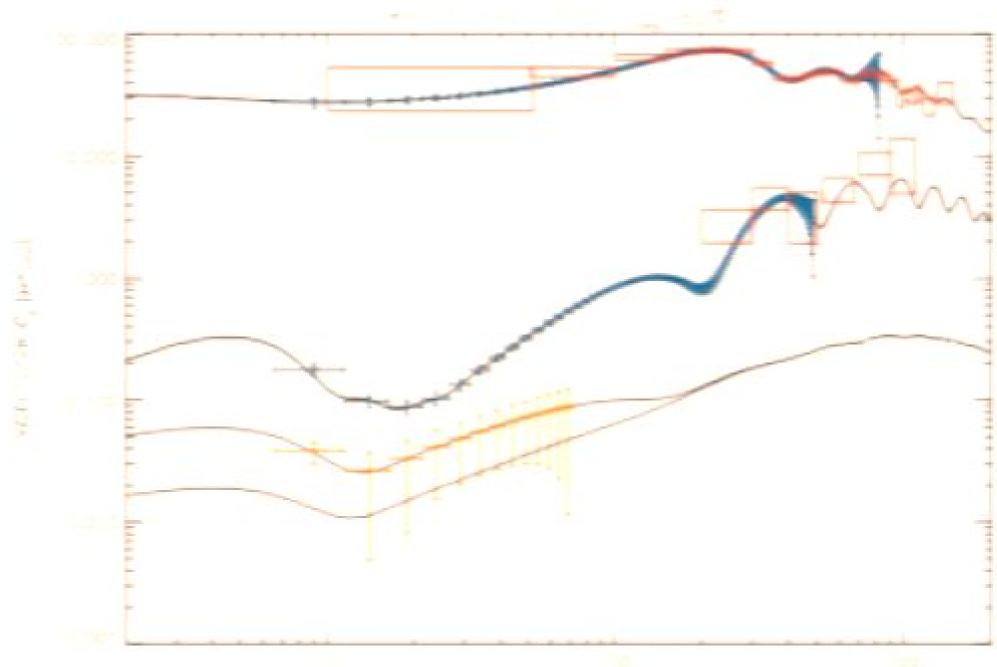
Spider: Searching for the Echoes of Inflation

Spider's Flight Schedule:

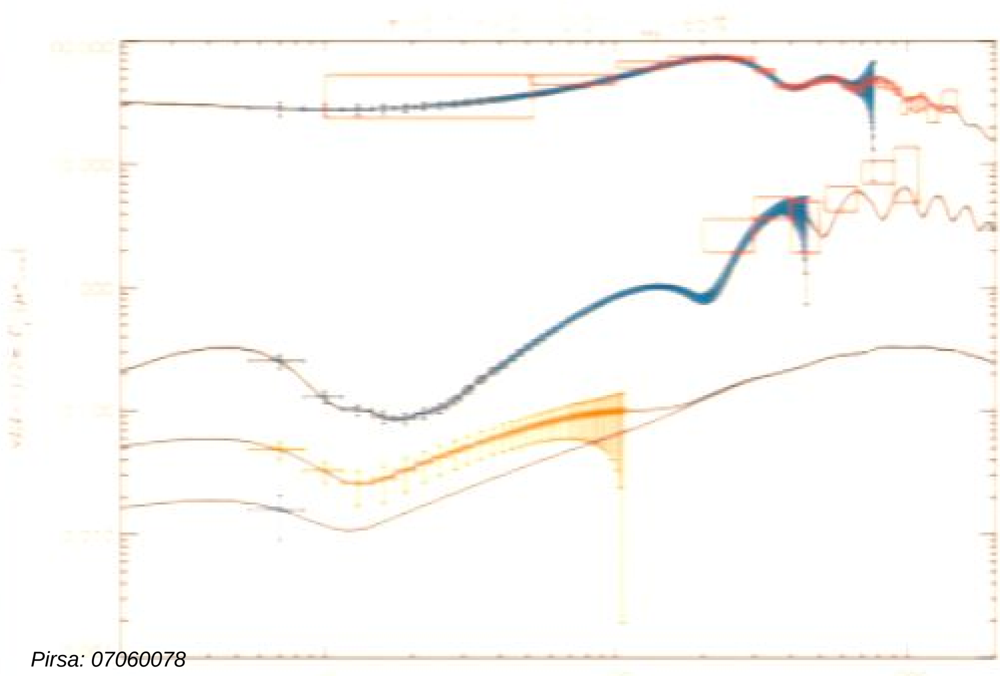
- Spring 2010: Alice Springs 5-day turnaround flight
  - Achieve E-mode science goals
  - Establish competitive limits on scalar to tensor ratio
- 20+ day ULDB flight the following season
  - Characterize the B-mode spectrum
  - Map the Galactic polarized emission







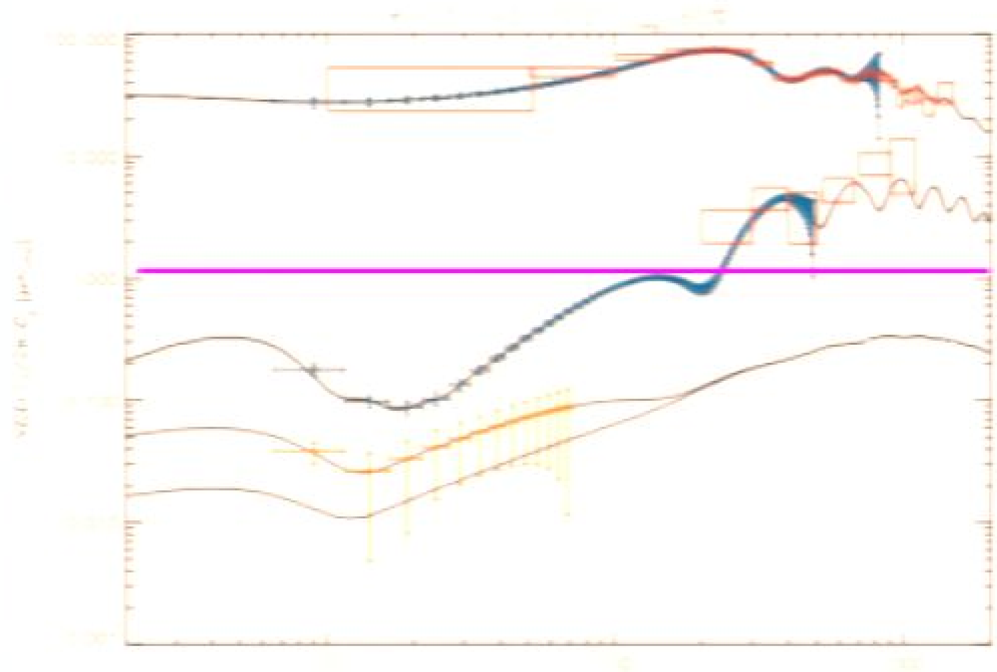
Spider Turnaround Flight
Spring 2010



Spider ULDB Flight
Fall 2011

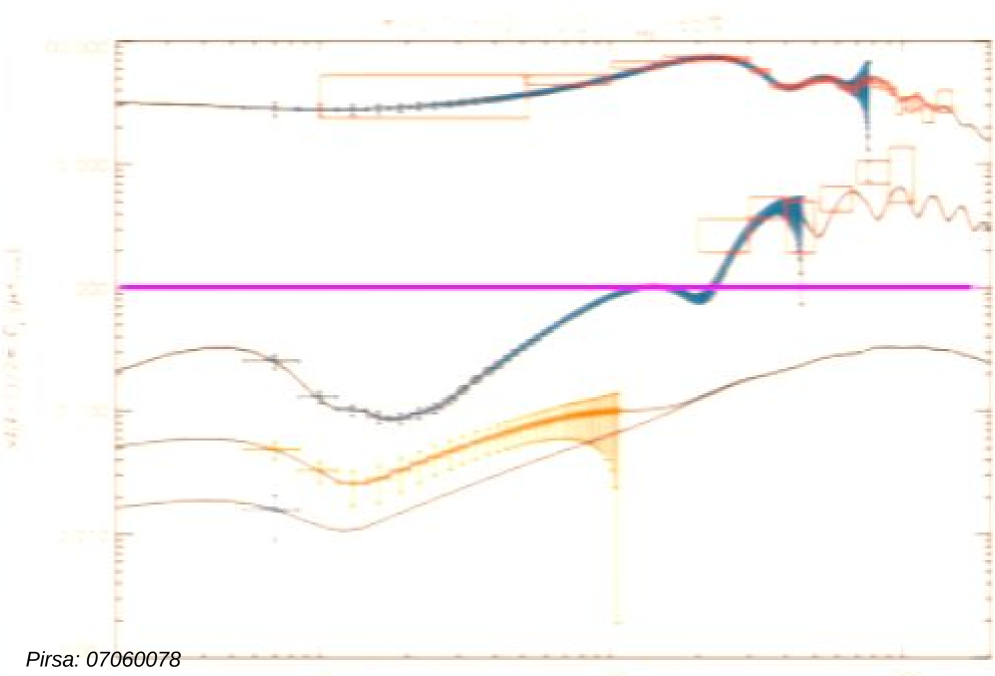
Sensitivity similar to Planck, with advantage of being a true polarimeter

Spider: **Searching for the Echoes of Inflation**



Spider Turnaround Flight

Spring 2010



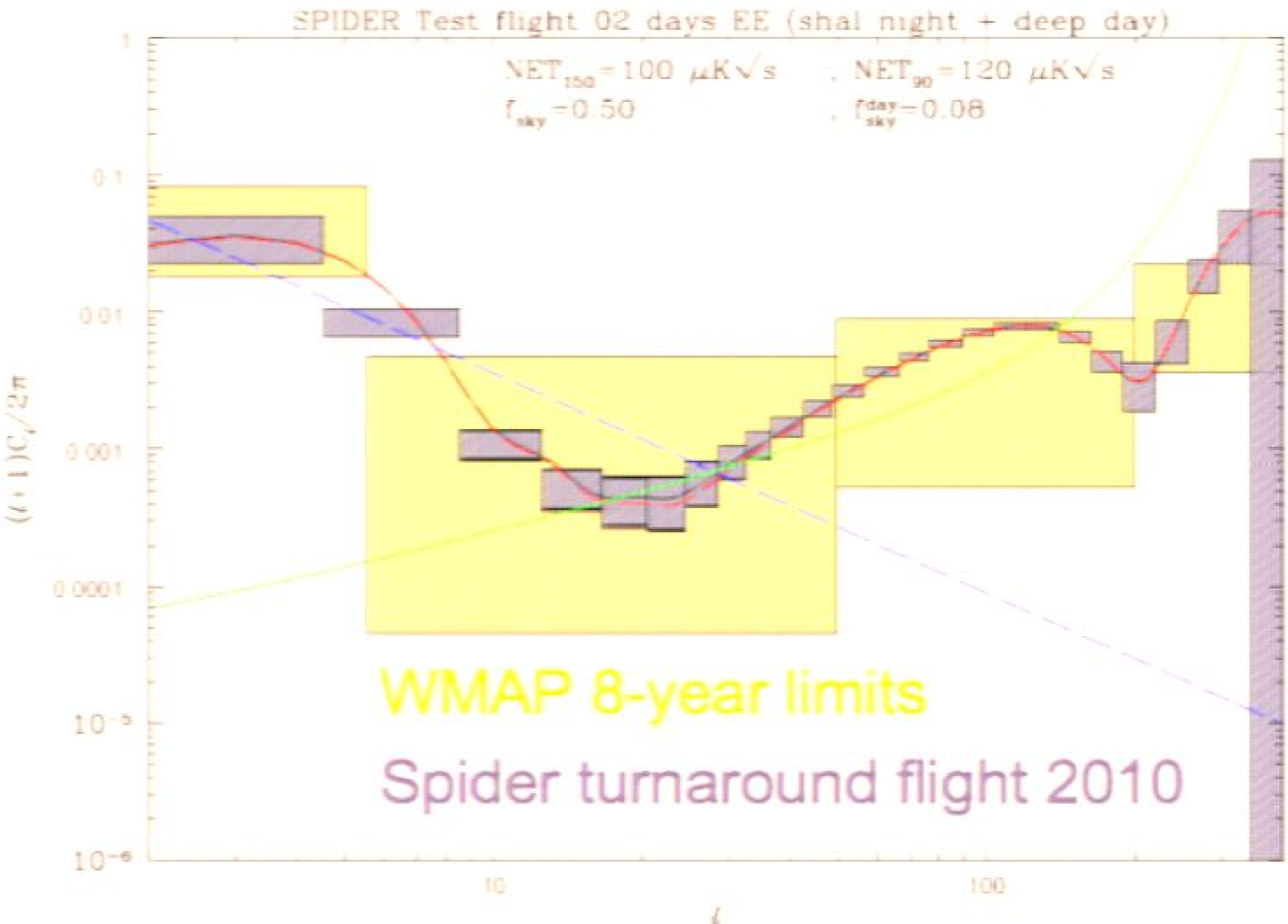
Spider ULDB Flight

Fall 2011

Sensitivity similar to Planck, with advantage of being a true polarimeter

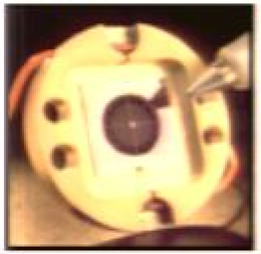
Spider: Searching for the Echoes of Inflation

EE Science from 2010 "Test" Flight

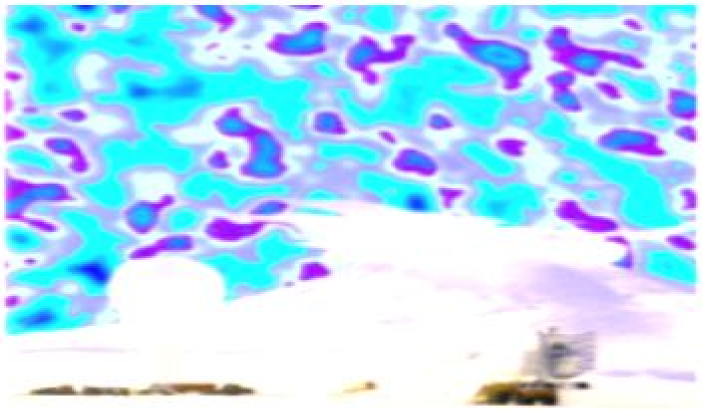


Spider: Searching for the Echoes of Inflation

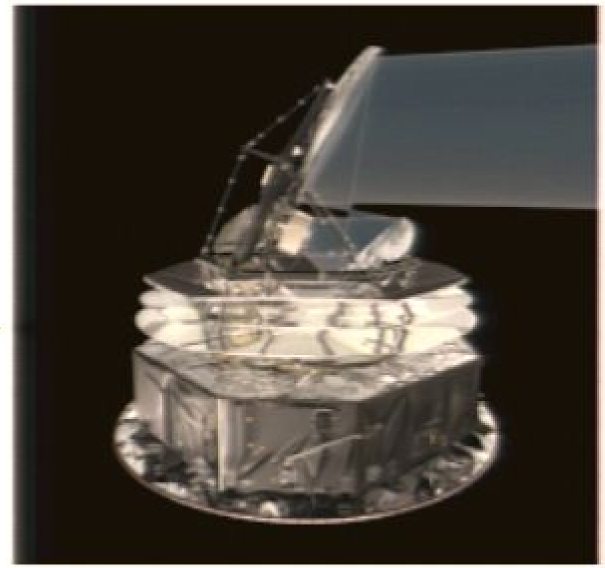
Spider web Bolometer



1995

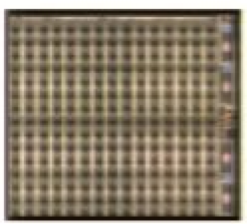


BOOMERanG 1998 (2000)

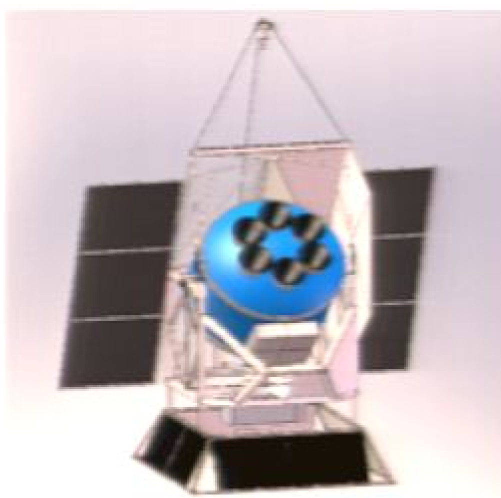


PLANK 2008 (2012

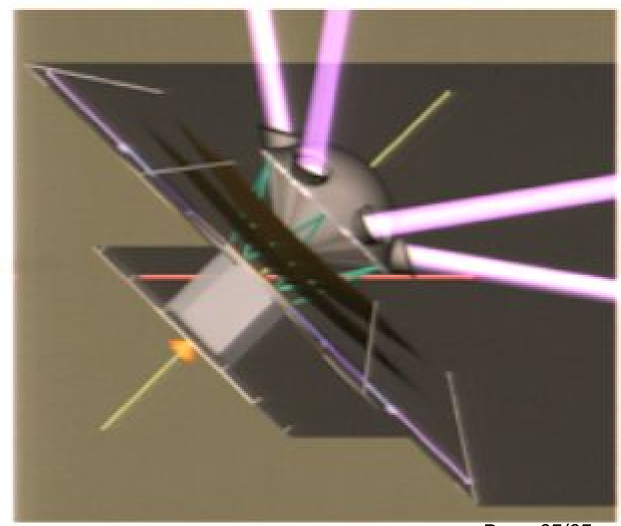
Antenna-coupled TES



2007



SPIDER 2010 (2012)



EPIC 2020 (2024)