Inflation and CMB Polarization Observations

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University of California at Berkeley

Introduction and Motivation

- Original Motivation for Inflation to solve cosmological problems: Horizon, Flatness, relics, etc.
- CMB/COBE –> Primordial Power Spectrum –> prediction of near scale invariant spectrum –> borne out by succeeding experiments and codified by WMAP
- Prediction of correlation between TE-pol –> WMAP detects such correlation (Kogut et al.)
- Prediction of B-mode polarization from Inflation-produced tensor modes

Testing Inflation

- Universe is flat; $\Omega_{tot} = 1 \pm 10^{-5}$:
  $\Omega_{tot} = 1.01 \pm 0.02$
- Fluctuations nearly scale invariant; $0.96 < n_s < 1$, $n_T \cong r/8 \sim 0$: $n_s = 0.98 \pm 0.02$, $n_T \sim$ unconstrained
- Ratio of Gravitational Waves to Scalars; $r \lesssim 0.15$:
  $r < 0.36$
- Running of Spectral Index; $\alpha <\sim 0$: $|\alpha| <\sim 0.01$
- Fluctuations are adiabatic: apparently
- Fluctuation Level Q: $Q/T \cong (2 \pm 0.2)\ x\ 10^{-5}$
- No evidence for non-Gaussianity: $-58 < f_{NL} < 134$
- Large scale TE correlations: yes, see observations

Historical Side Note

- At time of COBE discovery of Anisotropy - 1992 - clear Inflation was strong candidate theory
  - I talked with Alan Guth, Paul Steinhardt, Dick Bond to learn about Inflation and related quantities
  - Week after visited Cambridge & S. Hawking asking about predictions on spectrum and sources
  - Next days teaching Journees Relativistes with Paul Steinhardt in Amsterdam - 45 min walks together along canals between hotel and school with arguments about the gravitational wave contribution to CMB fluctuations. This lead to three papers - my main theory papers-
    - Davis, Hodges, Smoot, Steinhardt, & Turner PRL 1992
    - Smoot & Steinhardt Classical and Quantum Gravity 1992, Grav. Essay

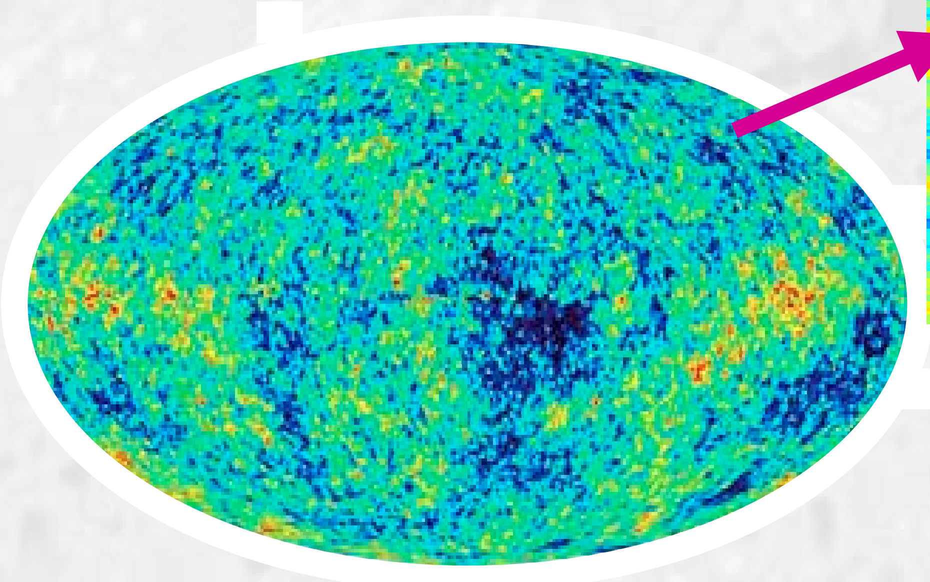
B-mode Physics

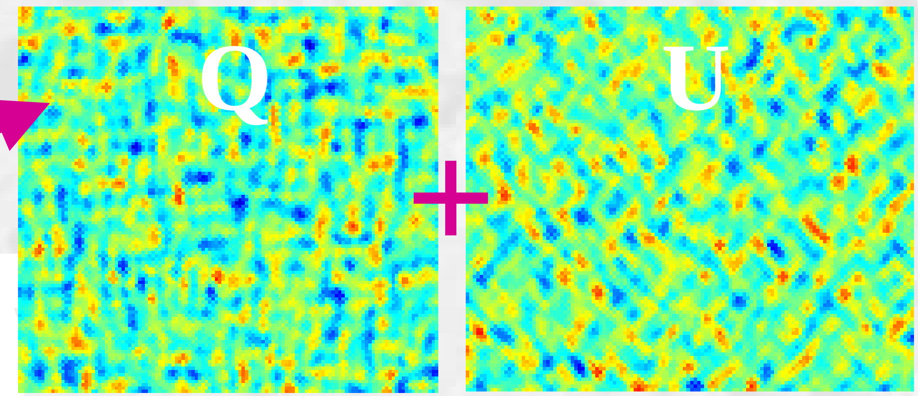
- Large-scale Gaussian B-modes from primordial gravitational waves:
  - energy scale of inflation
    level selects field vs brane/extradimensions
  - rule out most ekpyrotic and pure curvaton/ inhomogeneous reheating models and others

- non-Gaussian B-modes on small and large scales:
  - expected signal from lensing of CMB
  - other small second order signals
  - defects, magnetic fields, primordial vectors
  - foregrounds, systematics, etc.

Polarisation of the CMB

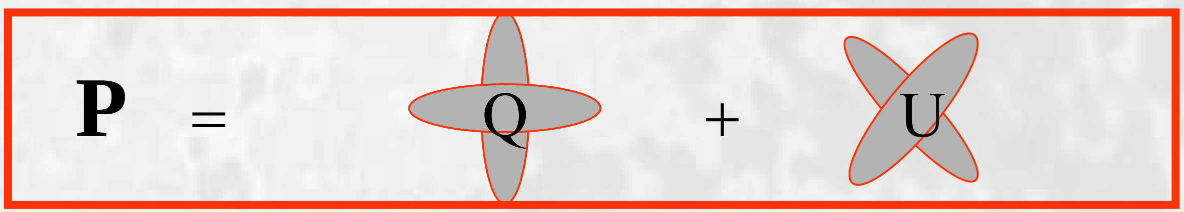
Temperature





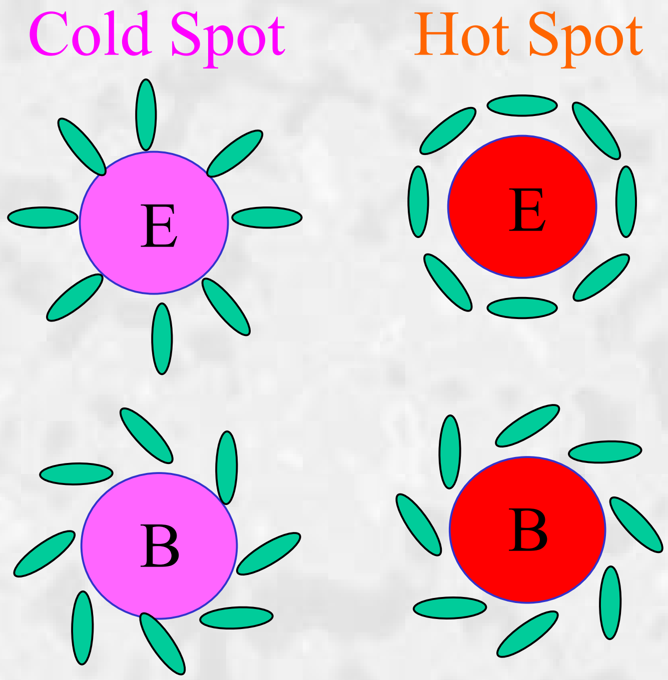
- Generated by Thompson scattering off electrons by quadrupolar anisotropy.

Polarisation Matrix:



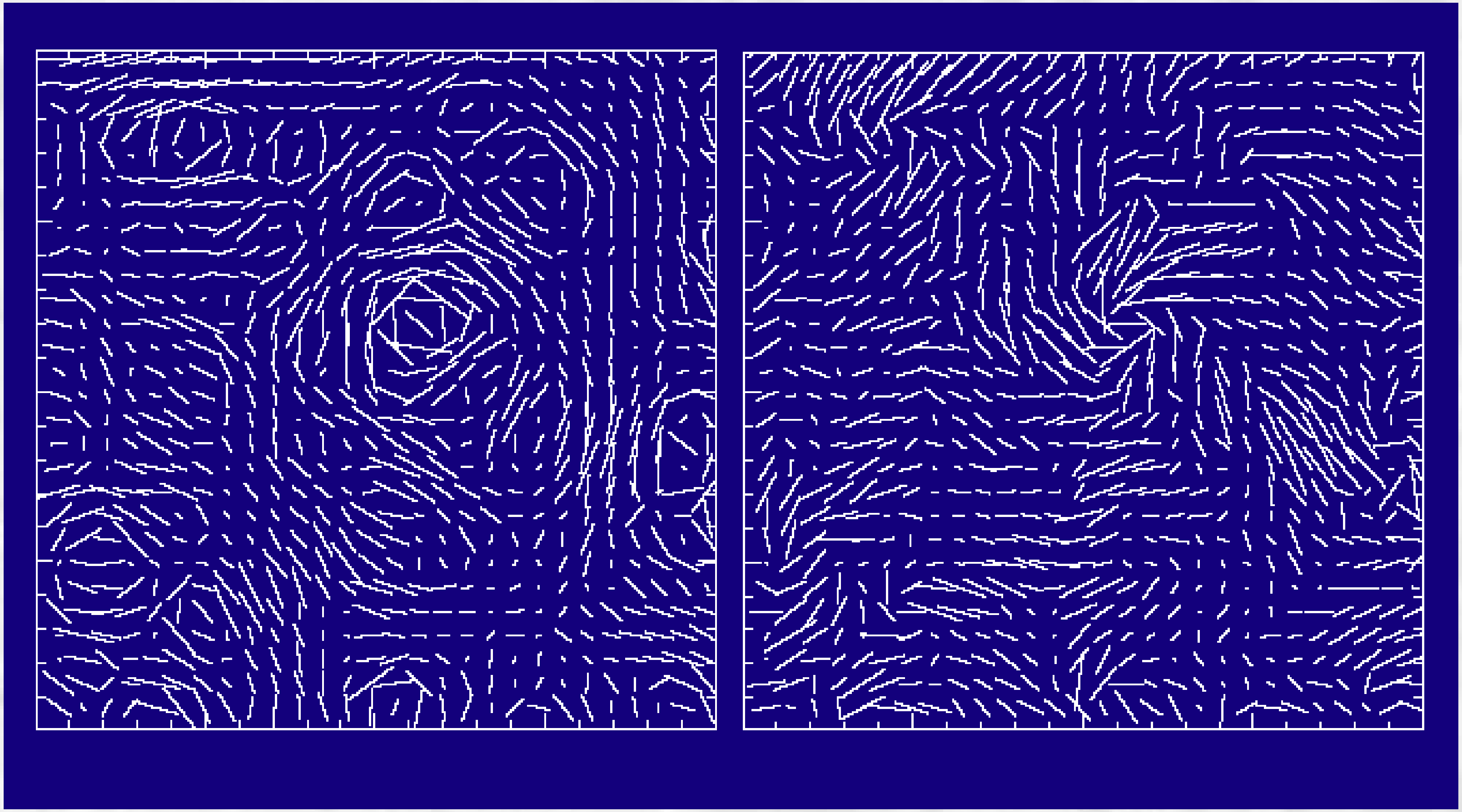
E/B Decomposition

- Can decompose Q,U into:
  - E-modes (even-parity):
  - B-modes (odd-parity):



- E-modes generated by scalar & tensor perturbations.
- B-modes generated by tensors & grav. lensing.

Pure E(left) & B(right)



Initial Limits on CMB Polarization

A Measurement of Excess Antenna Temperature at 4080 Mc/s

A.A. Penzias & R.W. Wilson

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value of about 3.5 K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964 - April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

ApJ, 142: 419-421

Next Limits on Polarization

- Caderni et al., 1978
- Nanos, 1979
- Lubin and Smoot, 1979/81
- Lubin, Melese & Smoot, 1983
- COBE 1995
- Sironi et al., 1997
- Partridge et al., 1997
- Subrahmanyan et al. 2000
- Saskatoon
- Archeops

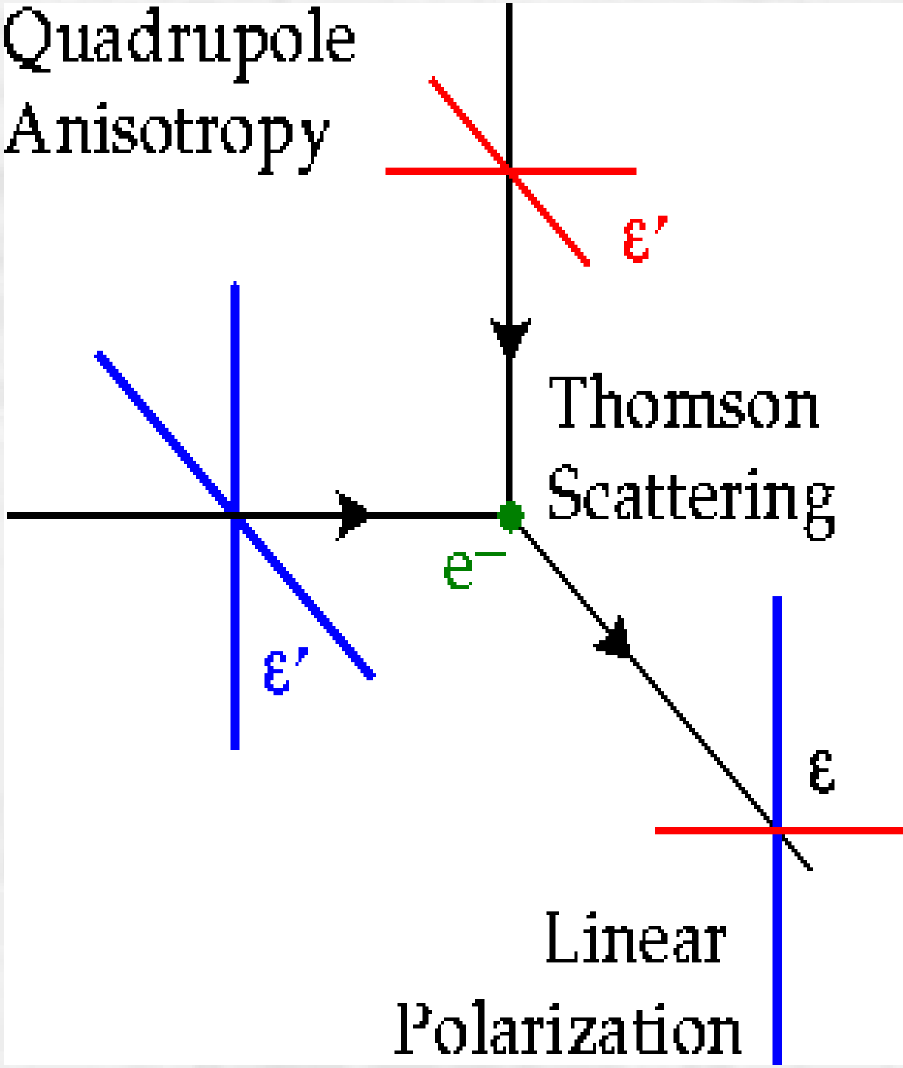
- COLD
- POLAR
- PIQUE
- COMPASS
- CBI
- DASI
- CBI?

Additional Polarization Observations

- WMAP and Company (now – 2005)
- Near-Term Experiments (2005 – 2008)
- Mid-Term Experiments (2007-?)
- Future Experiments (2017+?)

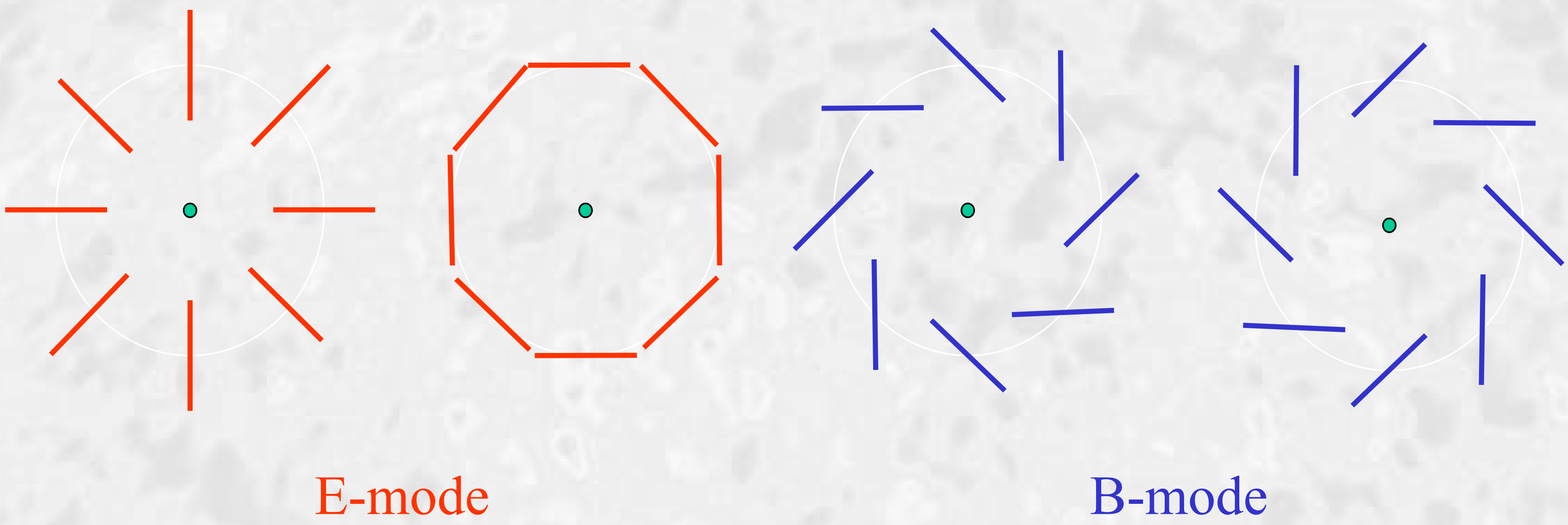
Generation of CMB Polarization

$$\frac{d\sigma_T}{d\Omega} \propto |\hat{\epsilon} \cdot \hat{\epsilon}'|^2$$



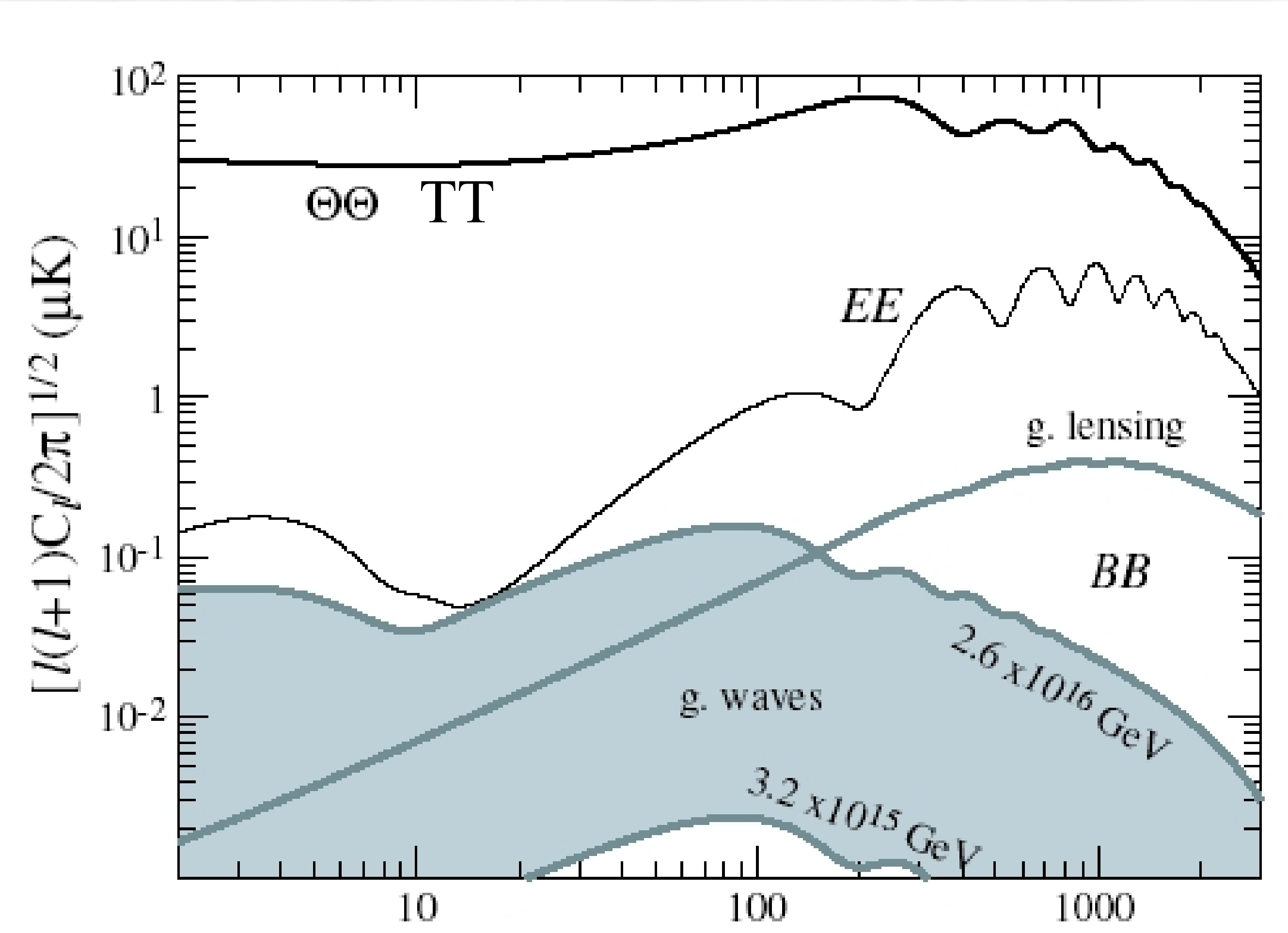
from Wayne Hu

E-modes and B-modes



- Density Fluctuations → E-mode
- Gravitational Waves → B, E modes

Polarization Power Spectra

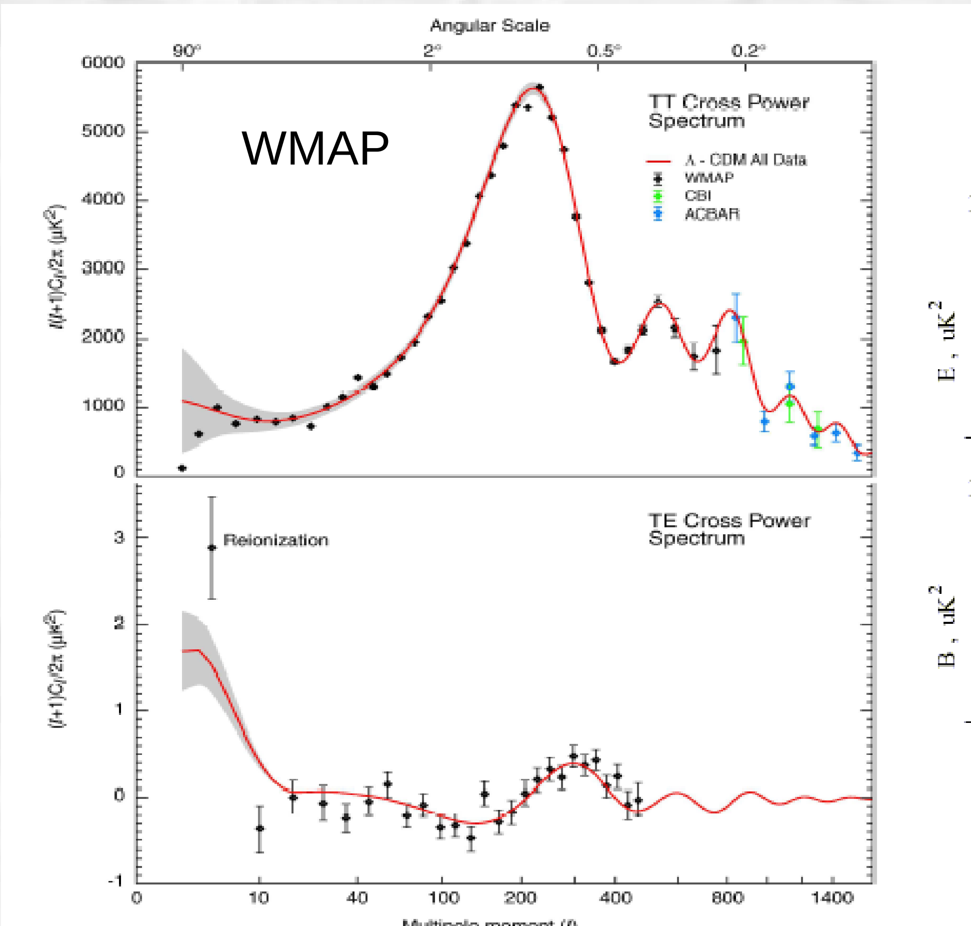


from Hu, Hedman, and Zaldarriaga

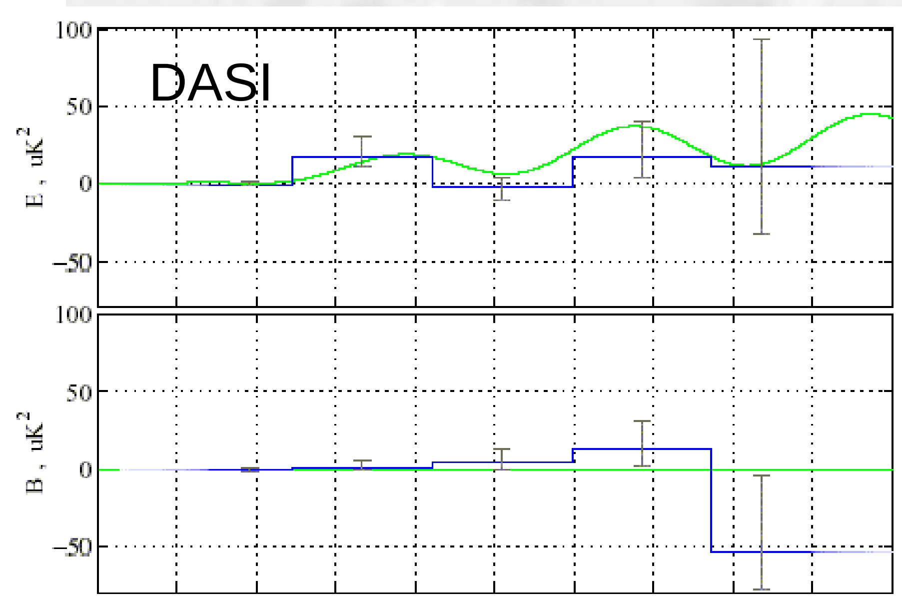
E-Mode Peaks→ Signature of Inflation

B-Mode Amplitude → Energy Scale of Inflation

Significant Current CMB Polarization Data

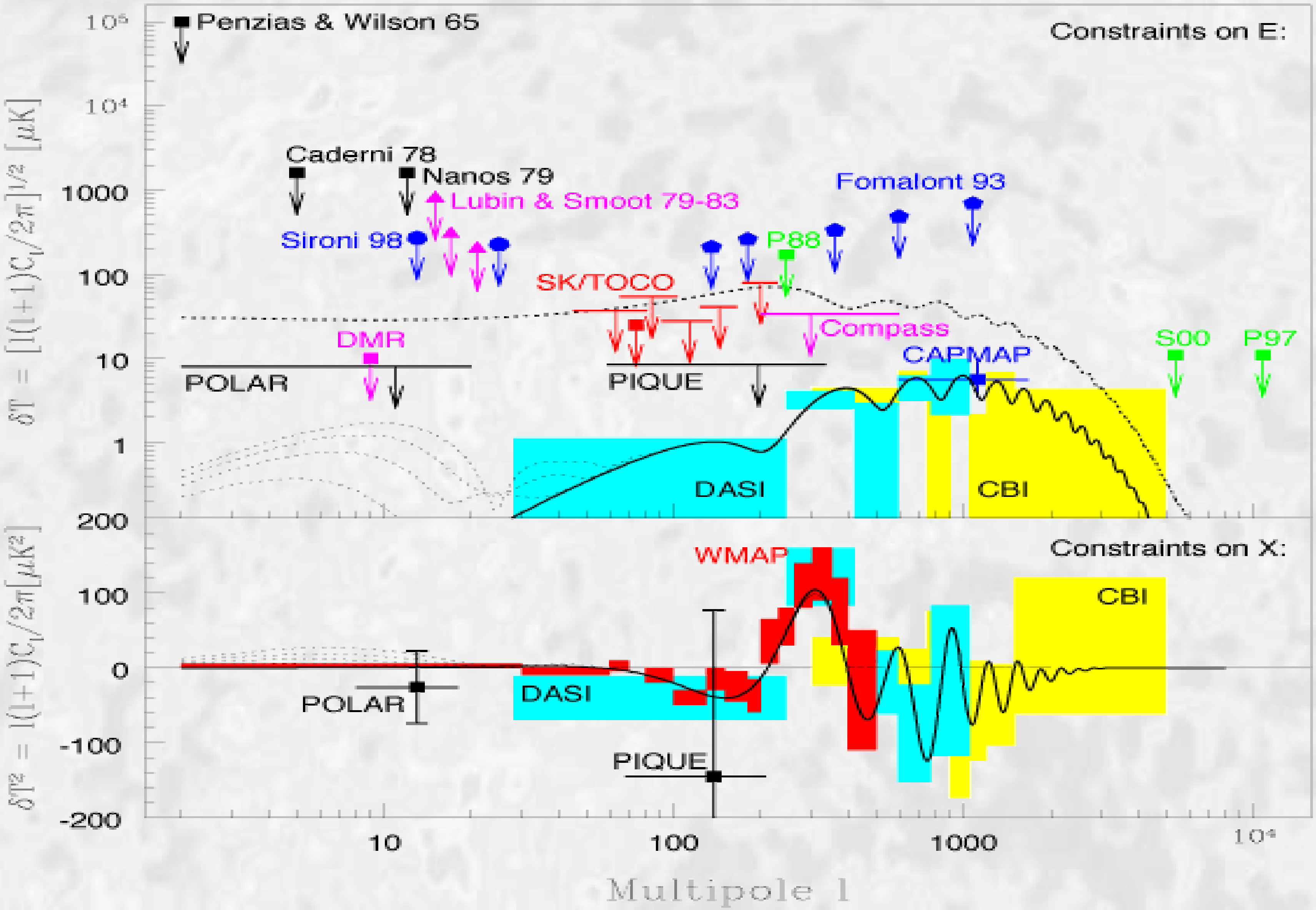


from Kogut et. al



from Kovac et al.

Summary of Polarization Observations



WMAP Information

Wilkinson Microwave Anisotropy Probe

Technology : HEMT	Platform : Satellite
Frequencies : 23, 33, 41, 61, 94 GHz	Telescope : 1.4 x 1.5m back-to-back Gregor.
NET/Detector :0.8,0.8,1.0,1.2,1.6 mK√s	Location : 2nd Sun-Earth Lagrange Pt
# of Detectors : 4, 4, 8, 8, 16	Start Date : October 2001
Beam Size (′) : 56, 40, 31, 21, 13	Duration : 4 years (?)
Multipoles :	Sky Fraction : 1.0 (Full Sky)
	Efficiency : 100%

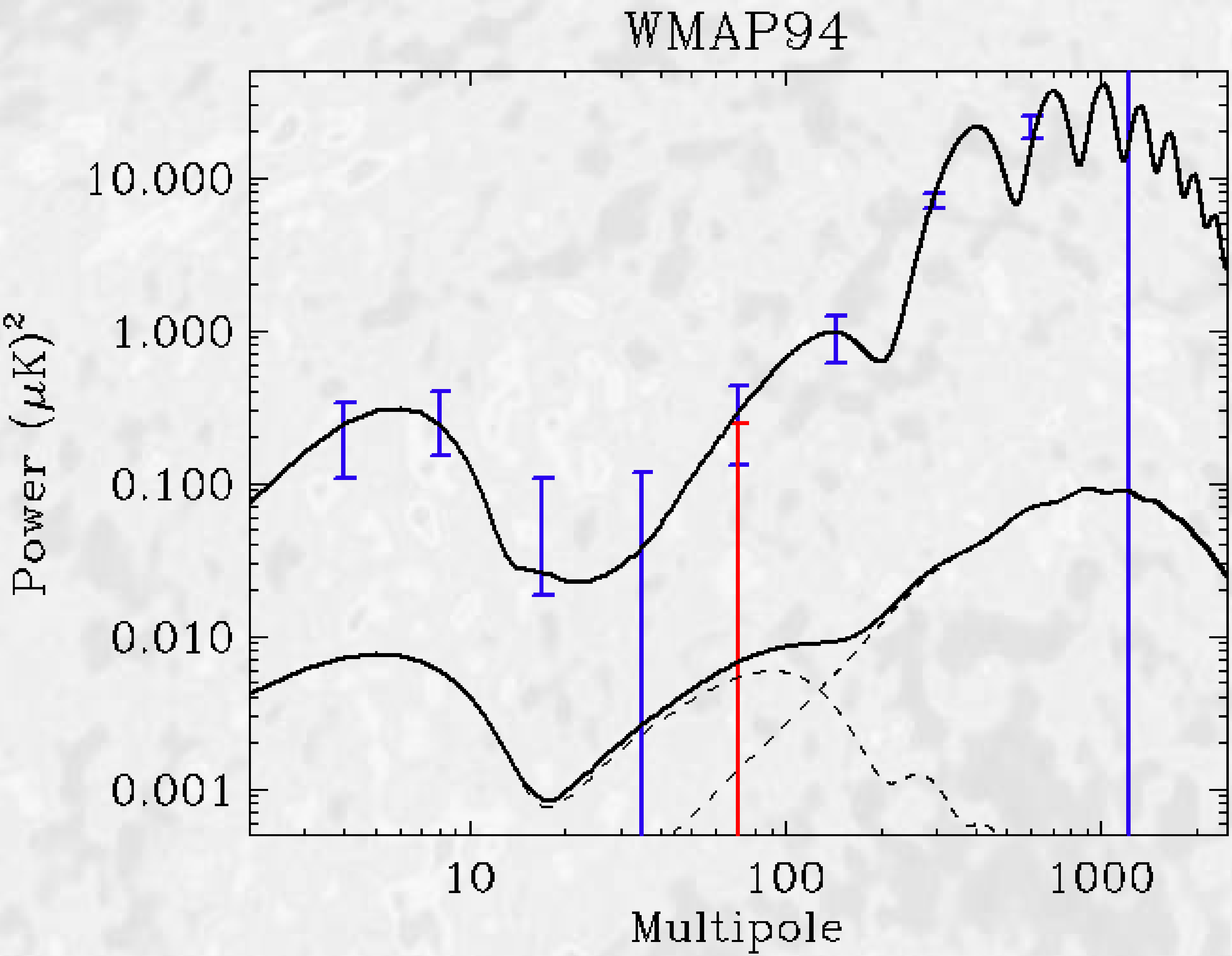
PI(s) : Chuck Bennett (GSFC)

Reference : Wilkinson Microwave Anisotropy Probe (WMAP): Explanatory Suppl.

Web Page : lambda.gsfc.nasa.gov

See talks by Peiris & Doré

Ken Ganga's Estimate of Expected Errors



SPOrt Information

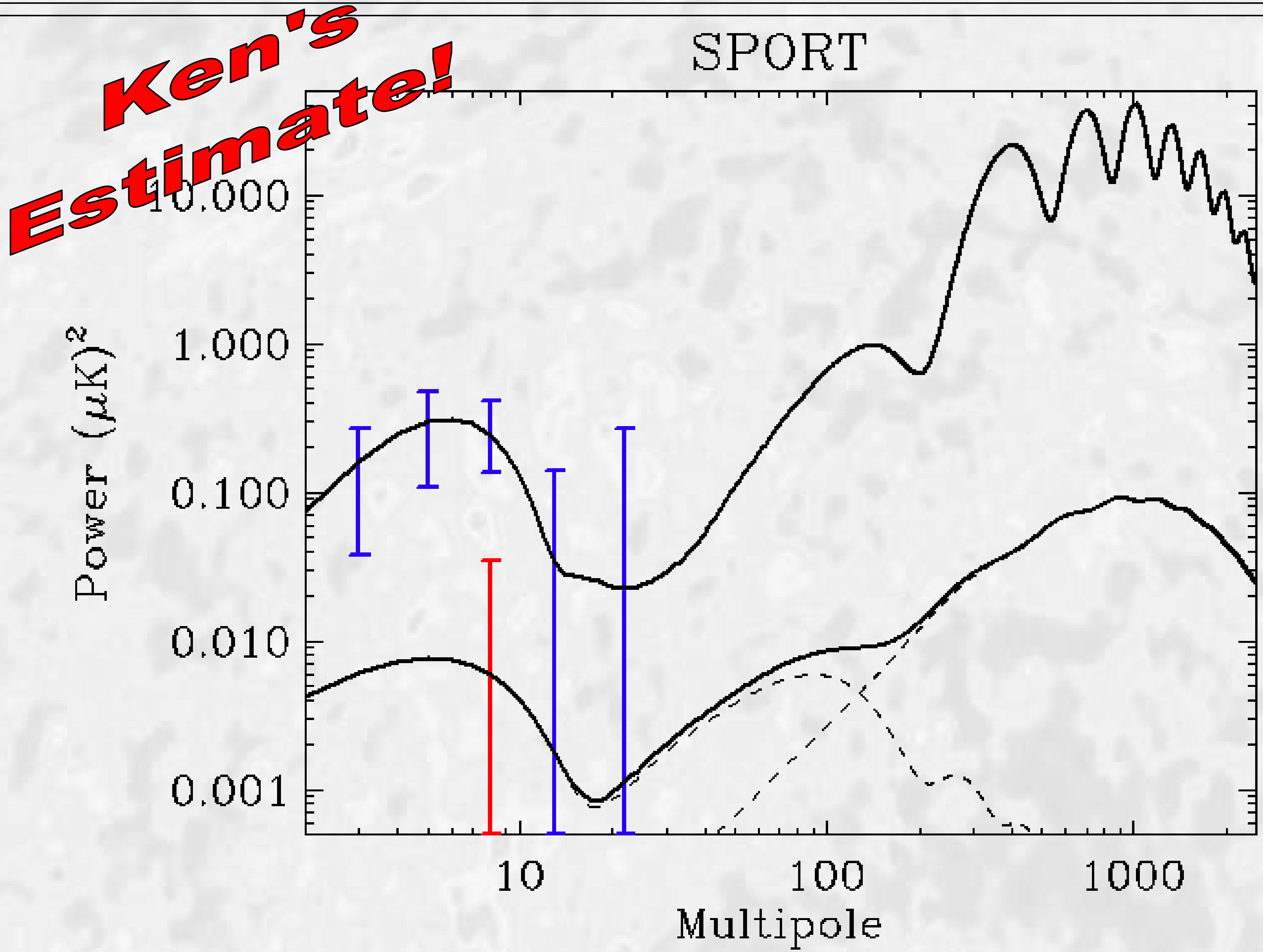
Sky Polarization Observatory

Technology : Correlation Polarimeters	Platform : Space
Frequencies : 22, 32, 90 GHz	Telescope : Corrugated feed horns
NET/Det. : - , - , 530 $\mu K_{CMB} s^{1/2}$	Location : International Space Stat'n
# of Det. : 2, 2, 4	Start Date : 2007?
Beam Size (') : 420 (7°)	Duration : 1.5 years
Multipoles : 2—30	Sky Fraction : 0.8
	Efficiency : 100%

PI(s) : Stefano Cortiglioni

Reference : New Astronomy, **9**, 297-327 (2004)

Web Page : http://sp0rt.bo.iasf.cnr.it:8080/index.php


Ken's Estimate!
SPORT
Power $(\mu K)^2$
10.000
1.000
0.100
0.010
0.001
10
100
1000
Multipole

CAPMAP

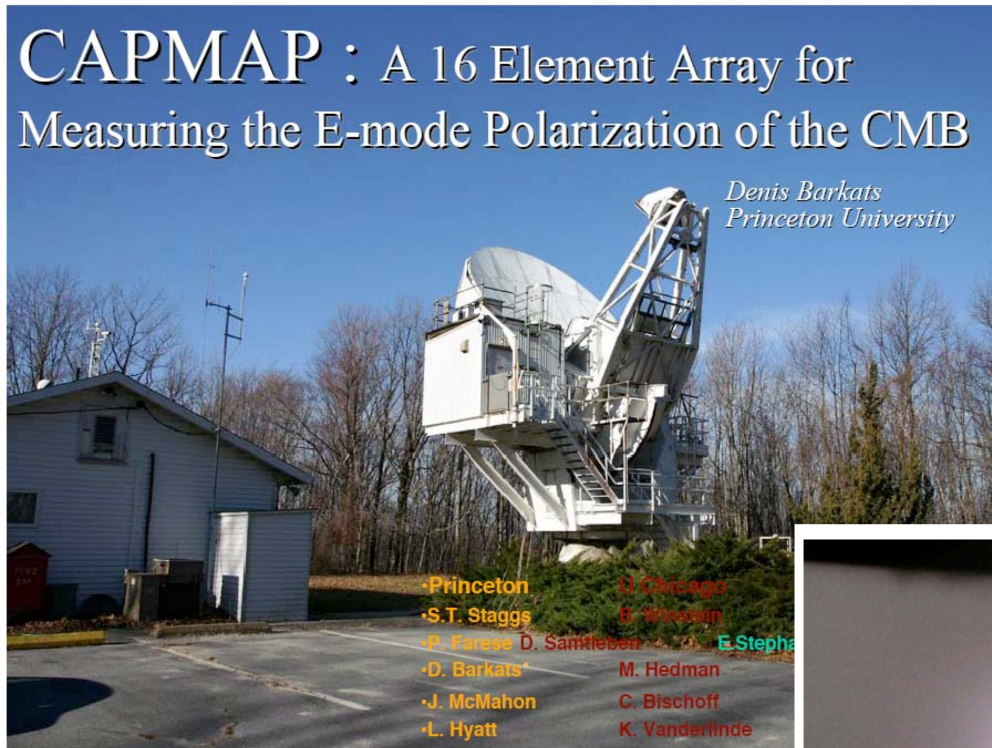
Cosmic Anisotropy Polarization MAPper

Technology	: Hetero. Corr. Pol.	Platform	: Ground-based
Frequencies	: 40, 90 GHz	Telescope	: 7 m, Off-Ax., Cas.
NET/Array	: 200 $\mu K_{CMB} s^{1/2}$	Location	: Crawford Hill, NJ
# of Det.	: 4, 12	Start Date	: 50% deployed
Beam Size (’)	: 6, 4	Duration	: 2 years
Multipoles	: 500-1500	Sky Fraction	: $2 \cdot 10^{-5}$ (1° cap)
		Efficiency	:

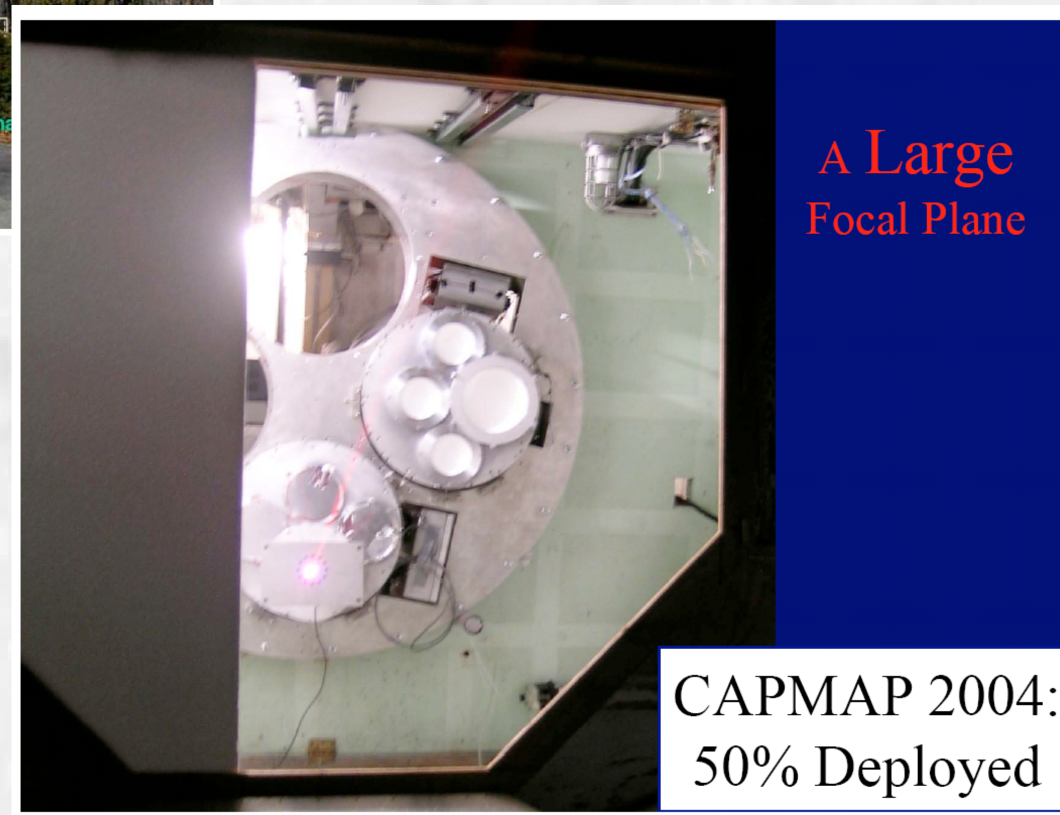
PI(s) : Suzanne Staggs (Princeton)

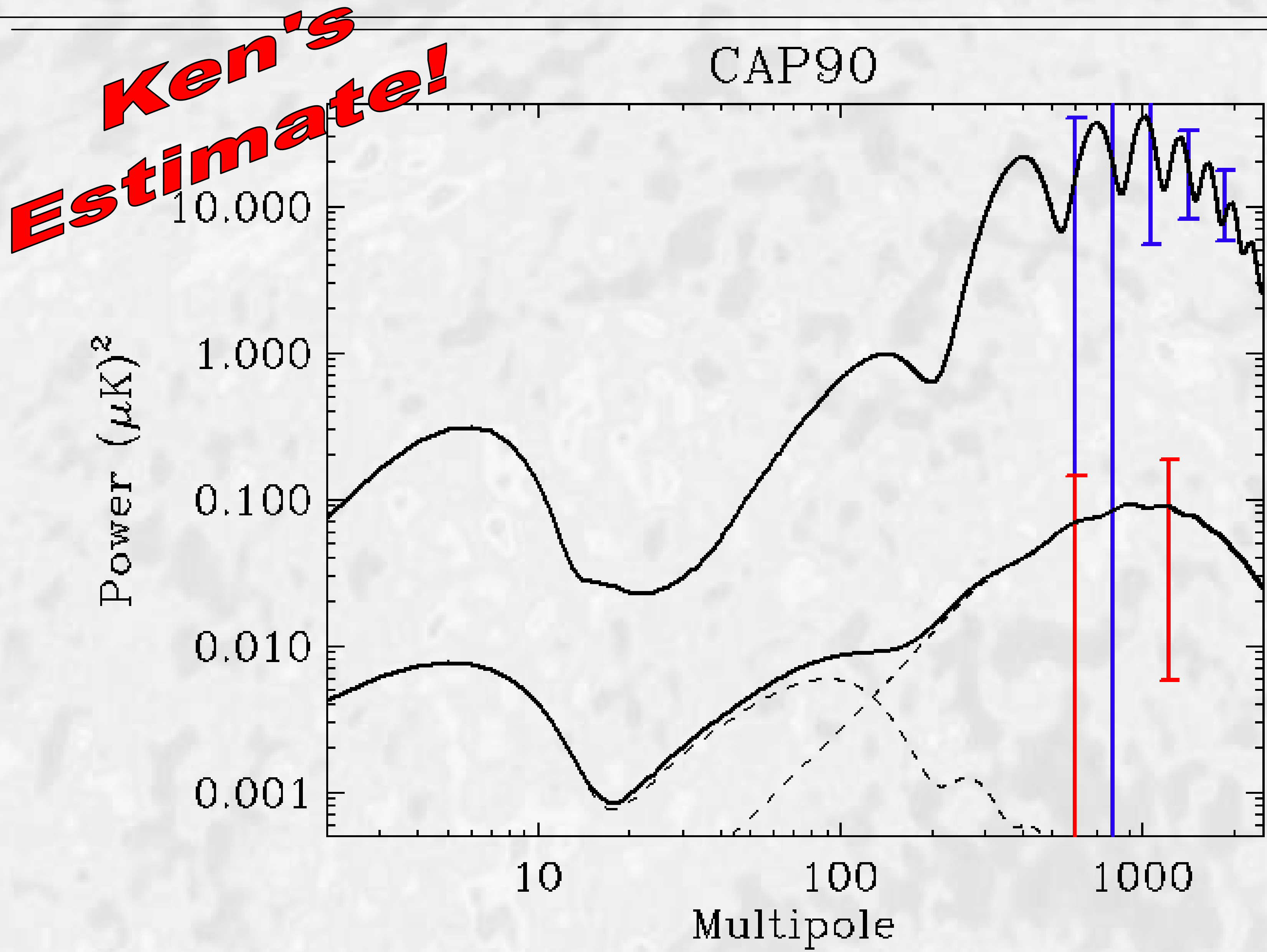
Reference : Barkats, 2003, New Ast. Rev. **47**, 1077–1081.

Web Page : http://cosmology.princeton.edu/capmap/webpage/homepg.html



from
Denis Barkats
Jan. 2004




Ken's Estimate!
CAP90
10.000
1.000
0.100
0.010
0.001
10
100
1000
Multipole
Power (μK)^2

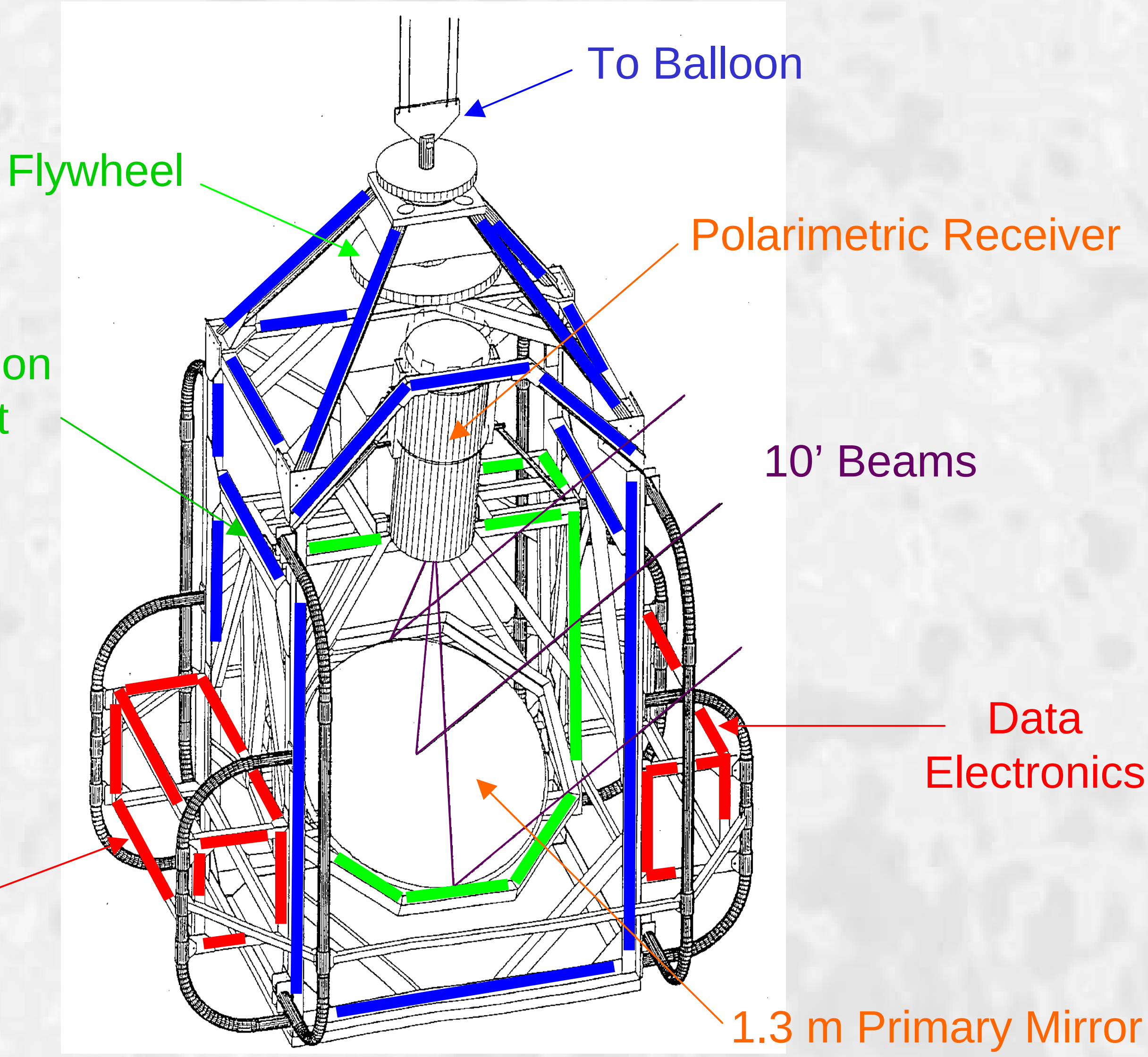
MAXIPOL

Matt Abroe[2] Peter Ade[3] Jamie Bock[4] Julian Borrill[1,6] Jeff Collins[1] Pedro Ferreira[5] Shaul Hanany[2] Andrew Jaffe[9] Brad Johnson[2] Trevor Lanting[1] Adrian Lee[1] Tomotake Matsumura[2] Bahman Rabii[1] Tom Renbarger[2] Paul Richards[1] George Smoot[1,6,7] Radek Stompor[1,7,8] Huan Tran[1] Celeste Winant[1] Proty Wu[10]

1) University of California 2) University of Minnesota 3) Queen Mary and Westfield College 4) Jet Propulsion Laboratory 5) University of Oxford 6) Division of Physics, LBNL 7) Space Sciences Laboratory, UCB 8) Copernicus Astronomical Center 9) Imperial College 10) Taiwan University

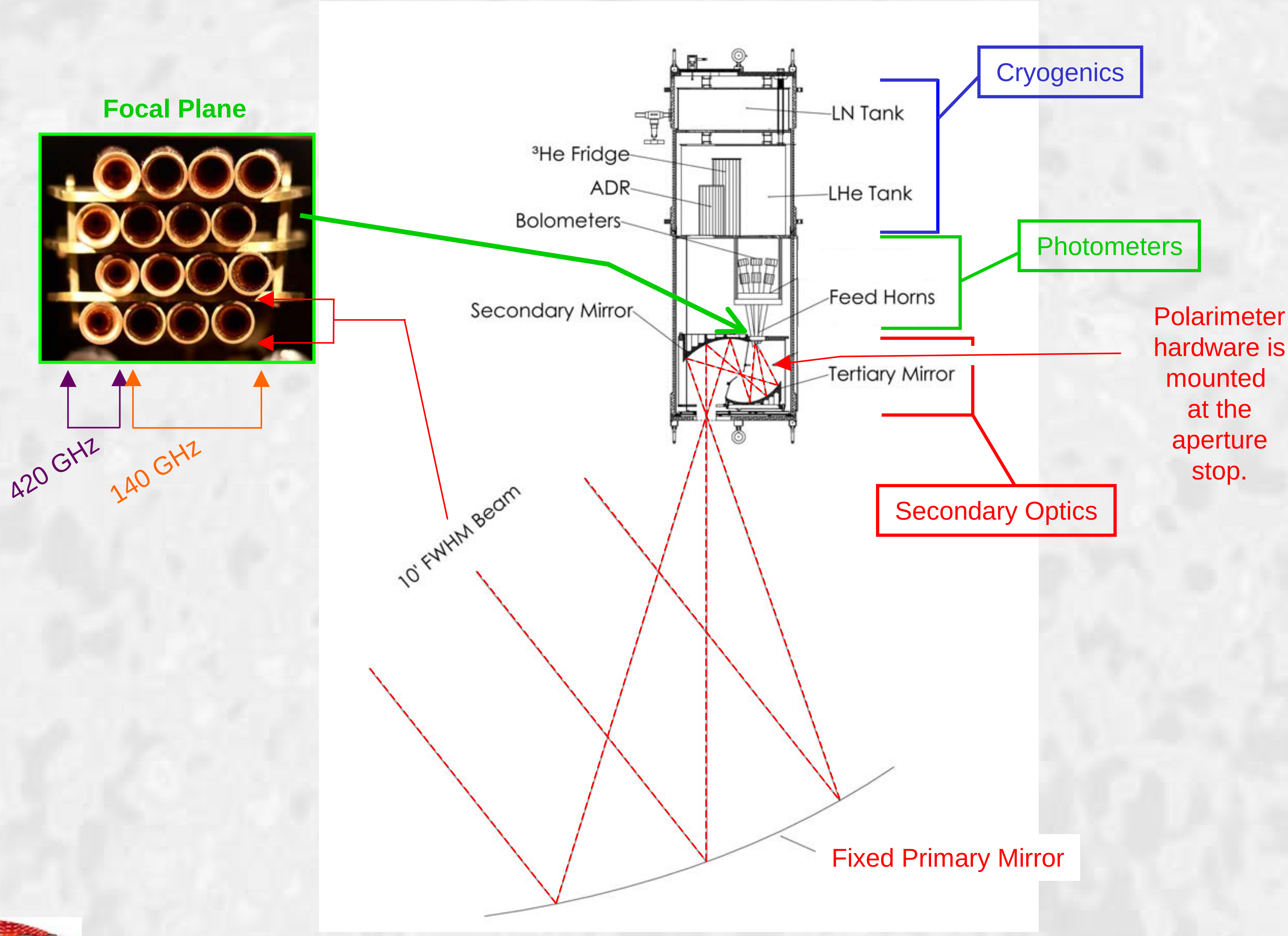
MAXIPOL Instrument

- ✓ Flight Proven MAXIMA Hardware
- ✓ Extensive baffling is added for flight.

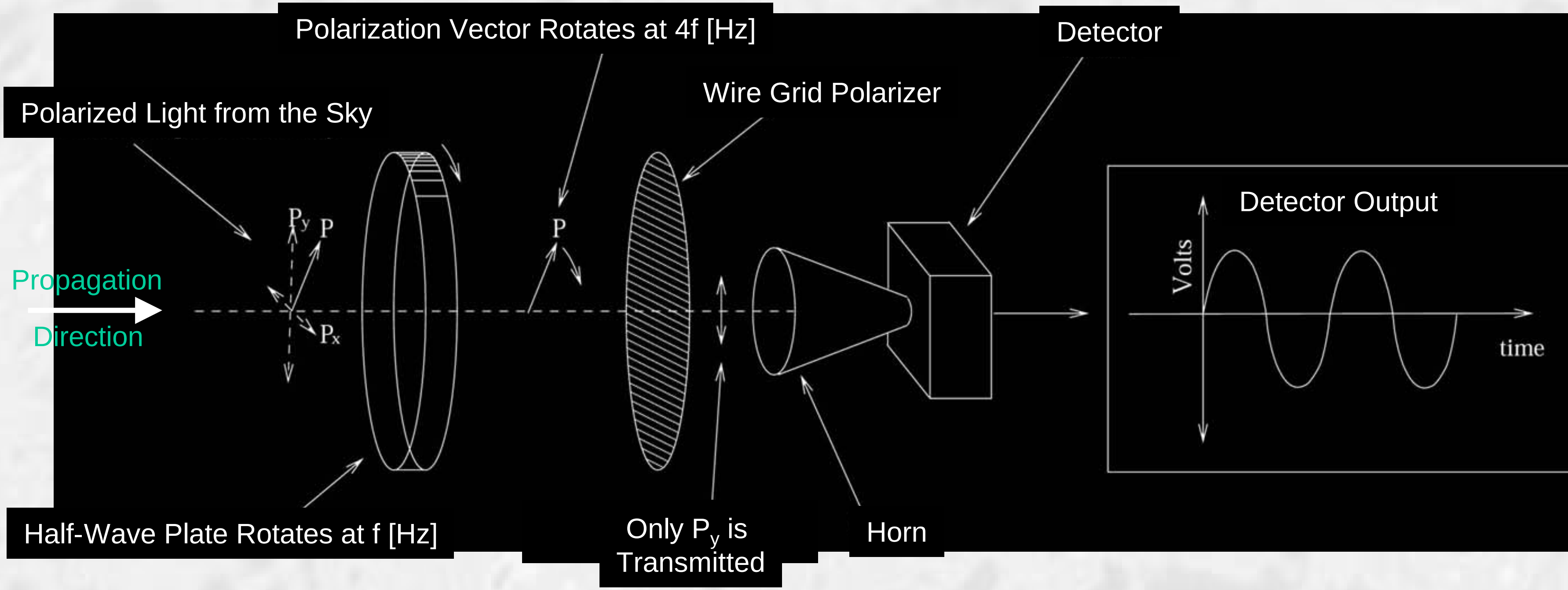


MAXIPOL Polarimetric Receiver

Focal Plane



Polarimeter Strategy: Rotating Half-Wave Plate



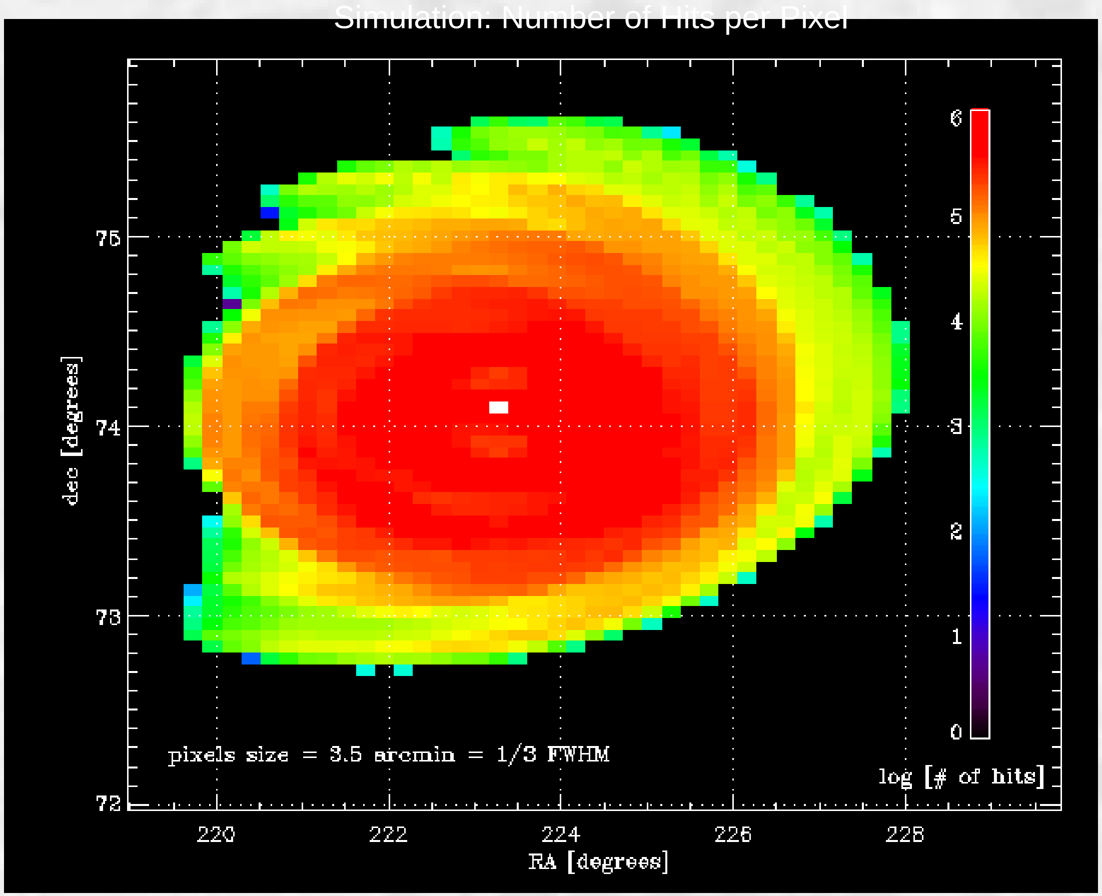
✓ Standard astronomical technique –
First implementation in a CMB experiment

✓ Method provides strong rejection of systematic errors

✓ I, Q and U maps from ONE detector –
no bolometer cross calibration

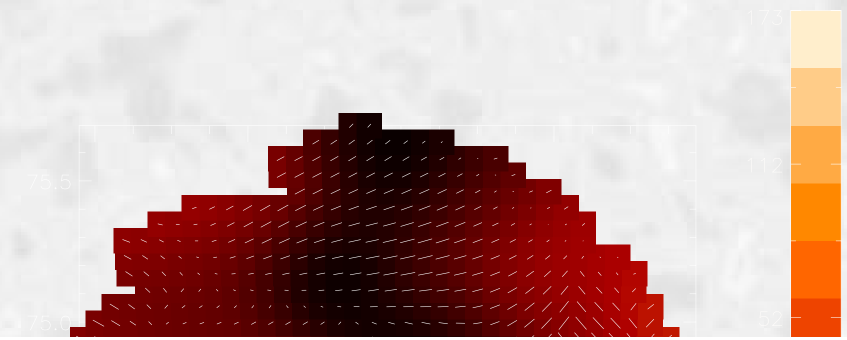
MAXIPOL-1 Sky Coverage,

- ✓ Combined Coverage for Twelve 140 GHz Channels
- ✓ 13 Hours of Integration on Single Patch of Sky
- ✓ 2º peak-to-peak Bowtie Scan
- ✓ guide star = Beta Ursae Minoris
- ✓ 1380 3.5' pixels



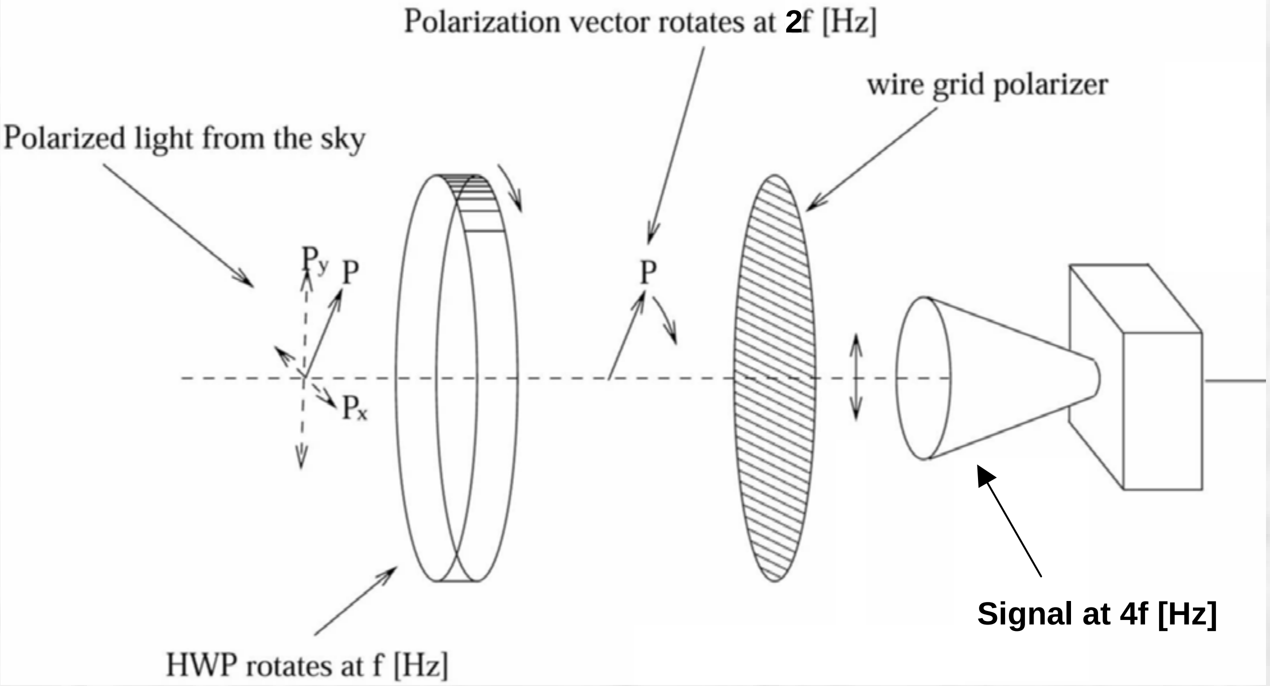
Expected MAXIPOL-1 Sky Signal Given WMAP Data

- ✓Weiner filtered WMAP data for MAXIPOL-1 BUM scan
- ✓ TE correlations only



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

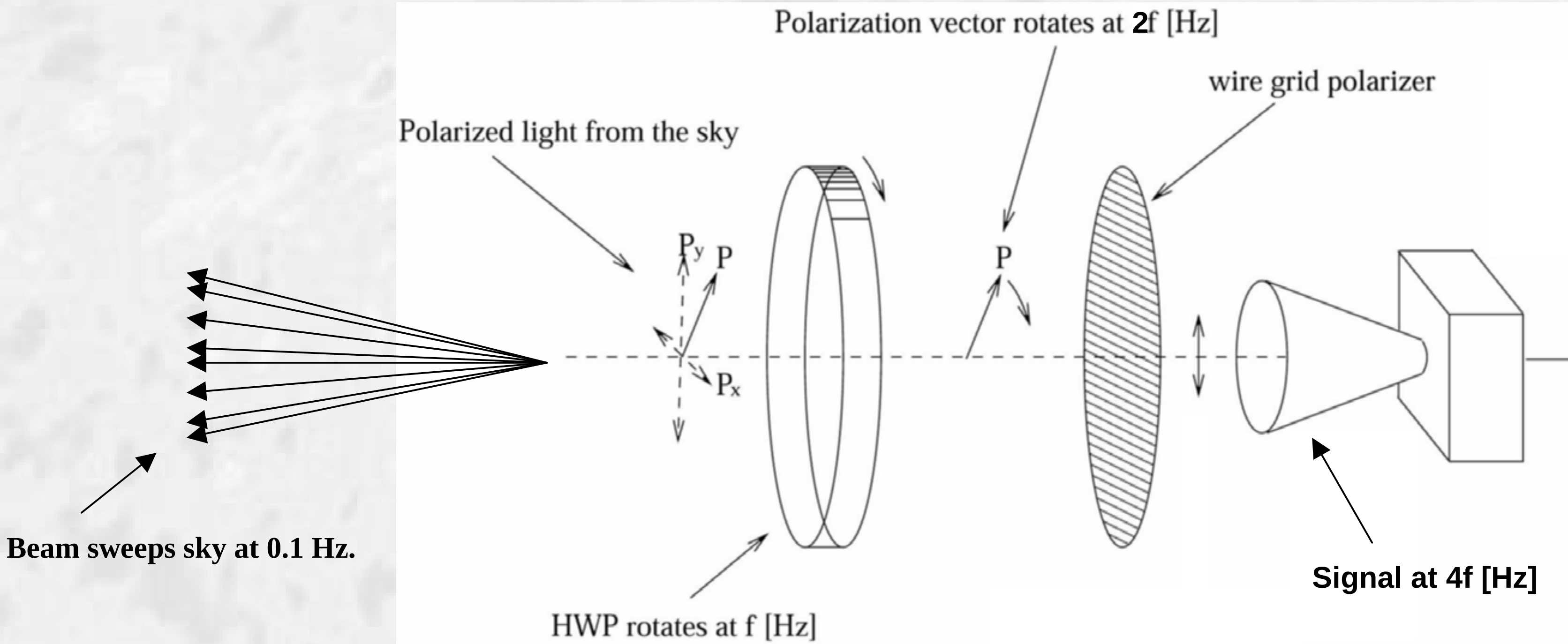
MAXIPOL Polarization Detection Scheme



Rotating Half Wave Plate (No Differencing)

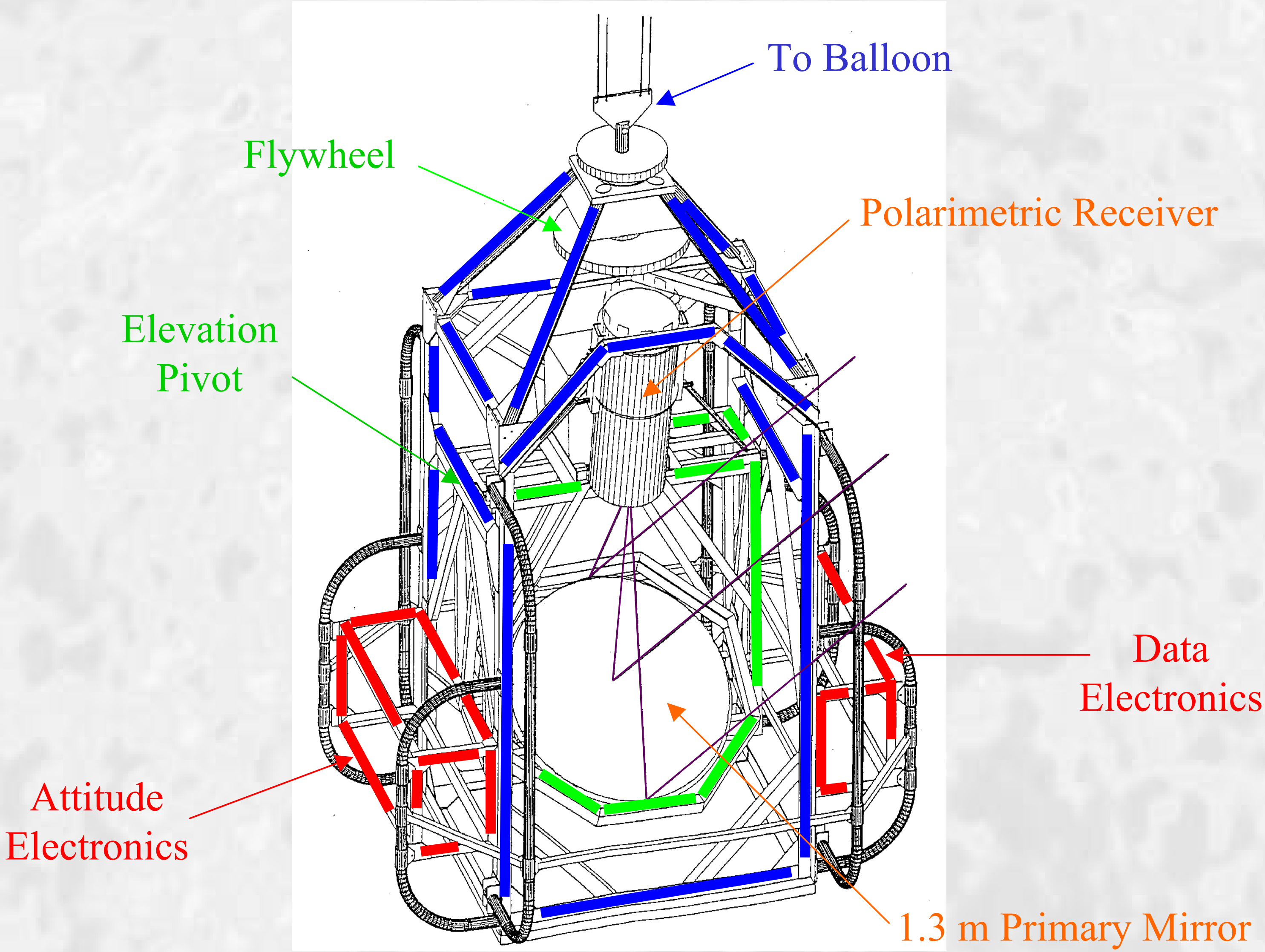
- -√2 gain in sensitivity
- -Responsivity enters as overall calibration
- -CMB signal → white detector noise region (avoid systematics?)

MAXIPOL Polarization Detection Scheme

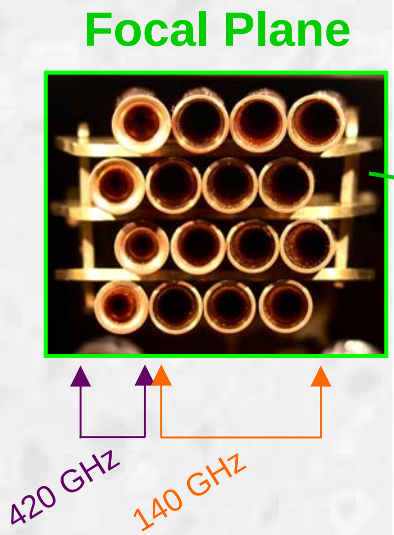


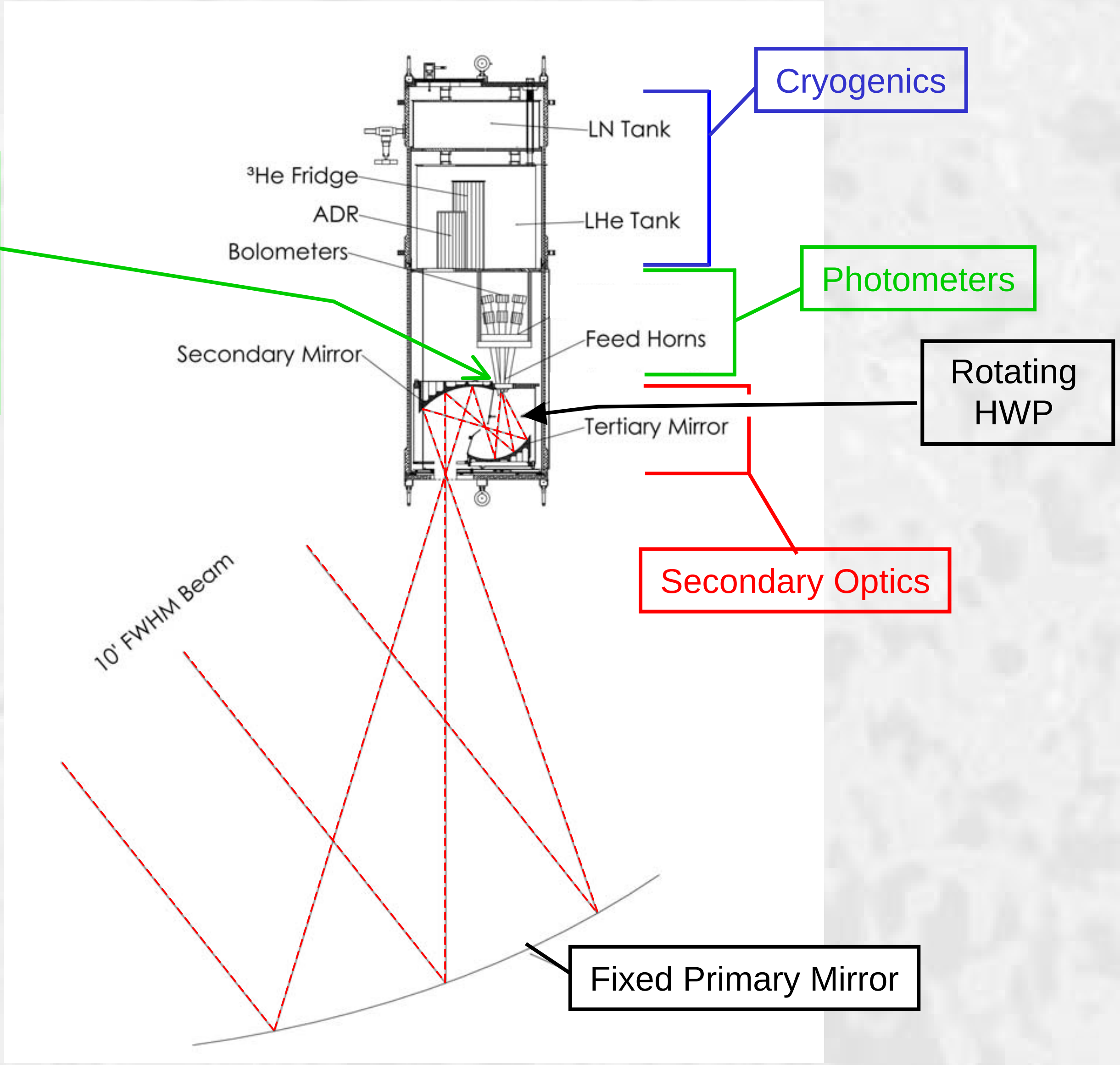
- Telescope Sky Scan
  - -Azimuth Modulation
  - -Sky Rotation
  - (avoid atmosphere,1/f noise)
- Rotating HWP (No Differencing)
  - -√2 gain in sensitivity
  - -Responsivity enters as overall calibration
  - -CMB signal → white detector noise region (avoid systematics?)

MAXIPOL Instrument



MAXIPOL Polarimetric Receiver





BOOMERaNG Information

Balloon Observations of Millimetric Extragalactic Radiation aNd Geomagnetics

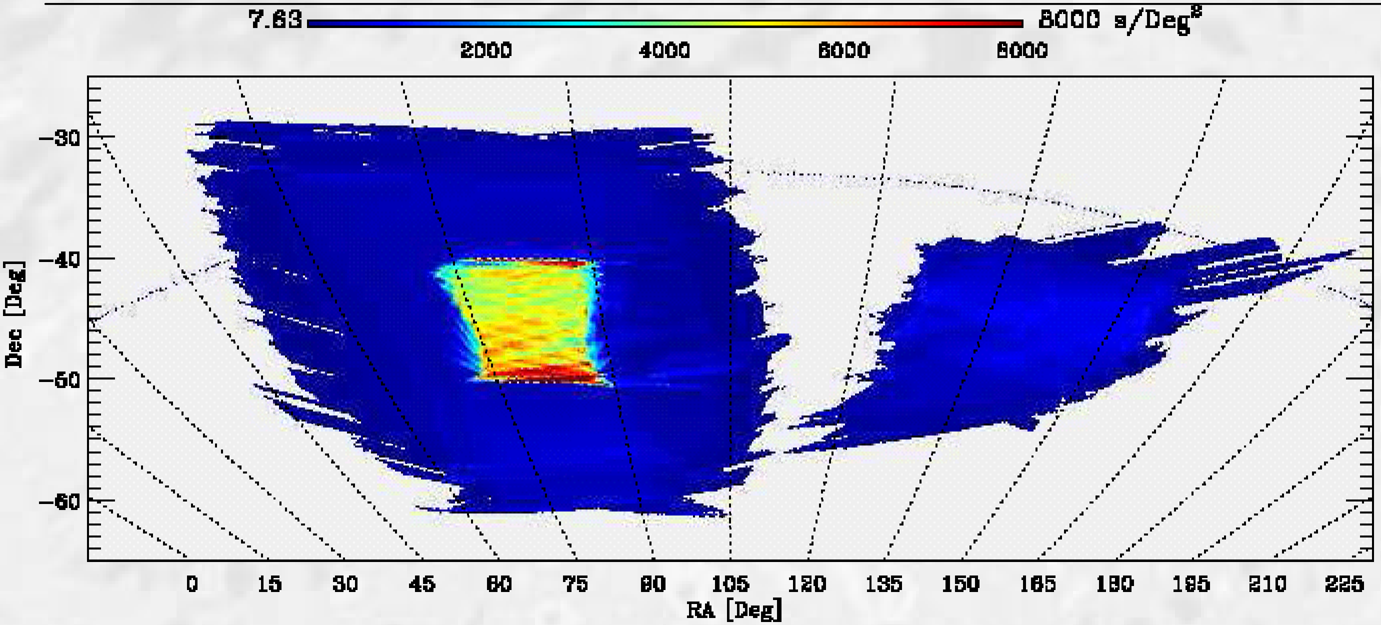
Technology : Bolometers	Platform : Balloon
Frequencies : 145, 245, 345 GHz	Telescope : 1.3 m off-axis Cassegrain
NET/Det. : 150, 350, 800 $\mu K_{CMB} s^{1/2}$	Location : Antarctica
# of Det. : 8, 4, 4	Start Date : January, 2003
Beam Size (’) : 9.5, 6.5, 7	Duration : 12 days
Multipoles :	Sky Fraction : 0.003 (123 deg.^{2})
	Efficiency :

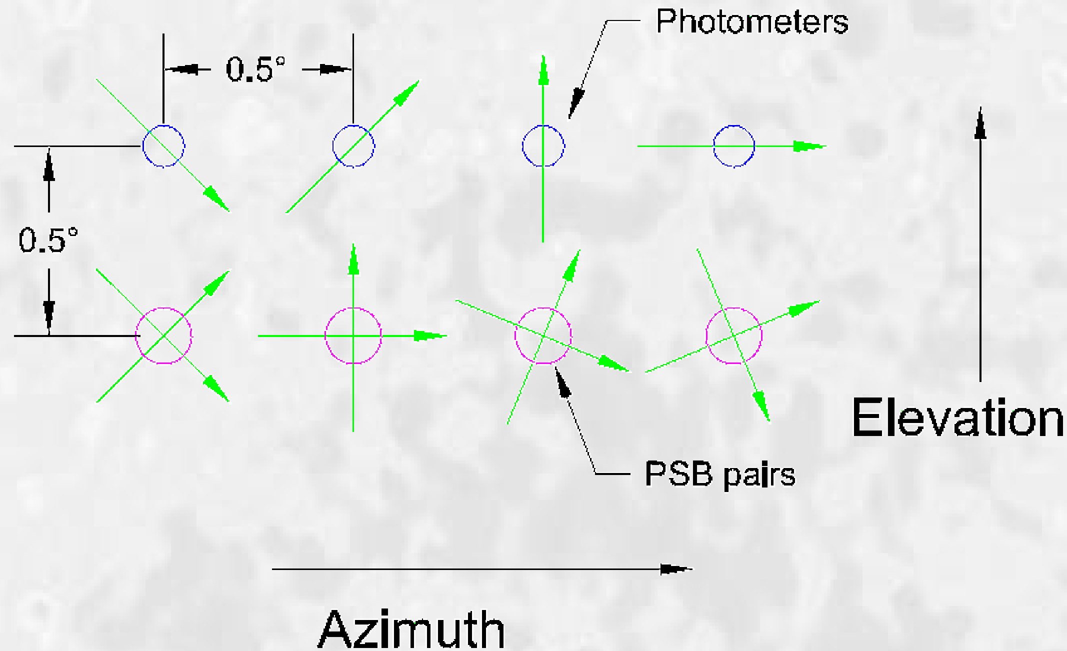
PI(s) : John Ruhl (CWRU); Paolo DeBernardis (Rome)

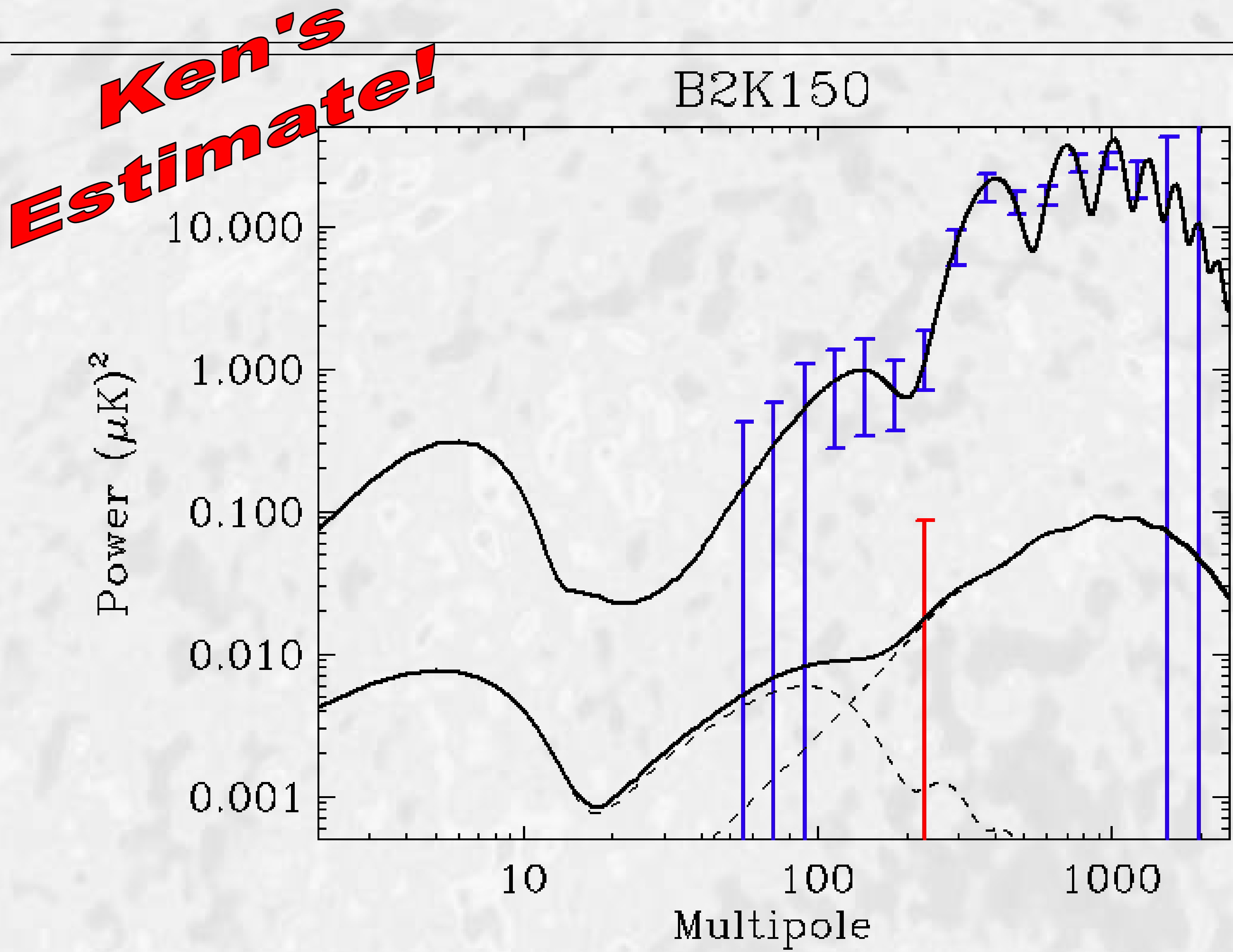
Reference : http://www.astro.caltech.edu/~lgg/boomerang_instr.htm

Web Page : http://www.astro.caltech.edu/~lgg/boomerang_front.htm

B2K


7.63
8000 s/Deg²
2000
4000
6000
8000
-30
-40
-50
-60
Dec [Deg]
0
15
30
45
60
75
90
105
120
135
150
165
180
195
210
225
RA [Deg]


Photometers
0.5°
0.5°
PSB pairs
Elevation
Azimuth


Ken's Estimate!
B2K150
Power $(\mu K)^2$
10.000
1.000
0.100
0.010
0.001
10
100
1000
Multipole

2005

- Should have multiple detections of the E-E power spectrum
- Should have upper limits on the B-B spectrum
- Should have a much better understanding of how difficult it will be to make out the features in the polarization spectra

Near Term

AMiBA Information

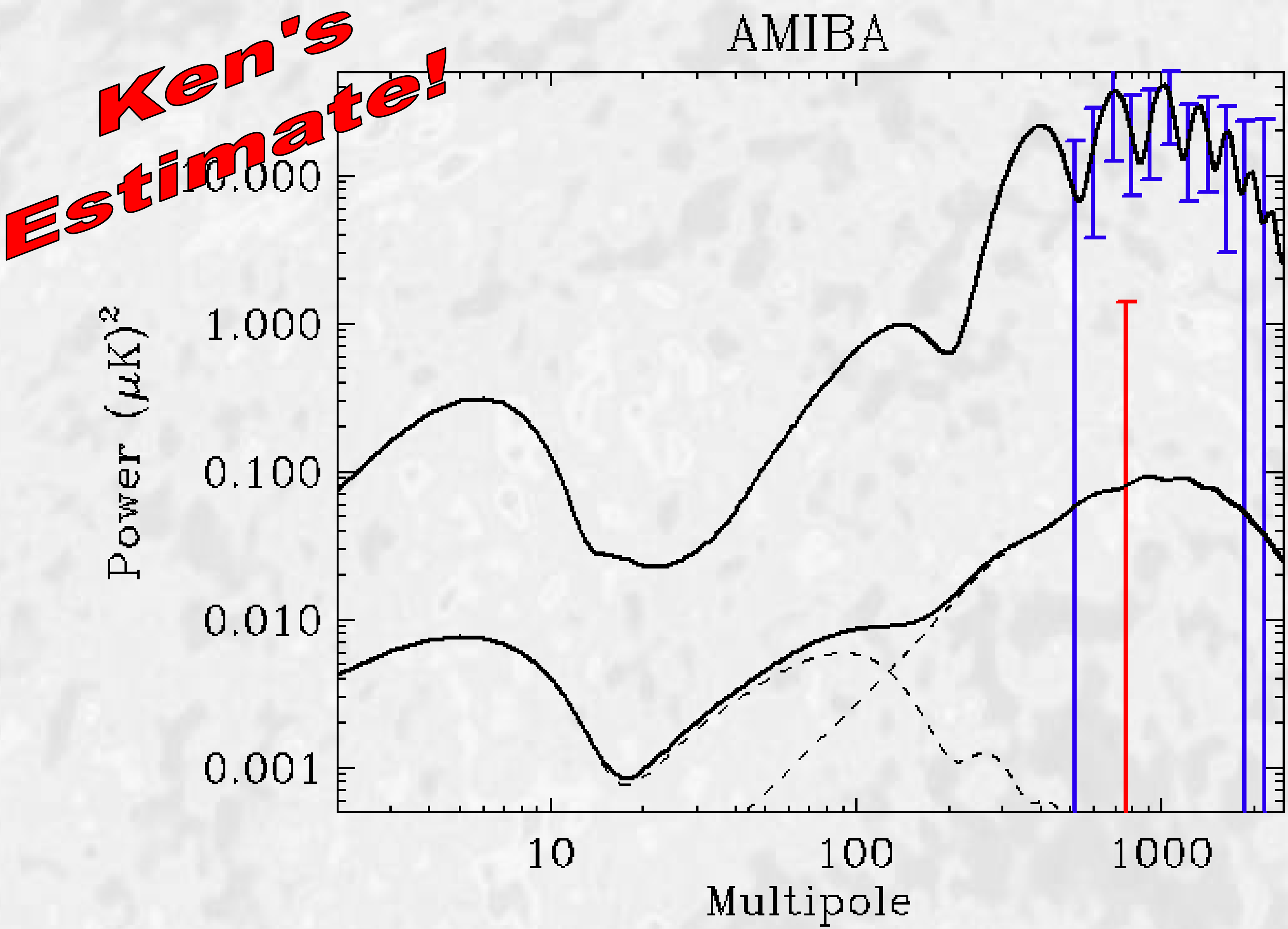
Array for Microwave Background Anisotropy

Technology : HEMT	Platform : Ground-based
Frequencies : 90 GHz	Telescope : Interferometer
NET/ARRAY : 100 $\mu K_{CMB}(hr)^{1/2}$	Location : Mauna LOA, HI; USA
# of Det. : 19	Start Date :
Beam Size (’) : 2	Duration : 100 nights
Multipoles : 700 – 2000	Sky Fraction : 0.0002 (2.9°×2.9°)
	Efficiency :

PI(s) : Dr. Sun Kwok

Reference :

Web Page : http://amiba.asiaa.sinica.edu.tw/


Ken's Estimate!
AMIBA
10.000
1.000
0.100
0.010
0.001
Power $(\mu K)^2$
10
100
1000
Multipole

QUaD

QUEST (Q/U Extragalactic Submillimeter Telescope) and DASI	
Technology : PS Bolometers	Platform : Ground-Based
Frequencies : 100, 150 GHz	Telescope : On-Axis
NET/Det. : 270, 300 μK_{CMB}	Location : South Pole
# of Det. : 24, 38	Start Date : February, 2005
Beam Size (’) : 4.2, 6.0	Duration : 2 Austral Winters
Multipoles :	Sky Fraction : 0.0073 (300 deg.^{2})
	Efficiency :

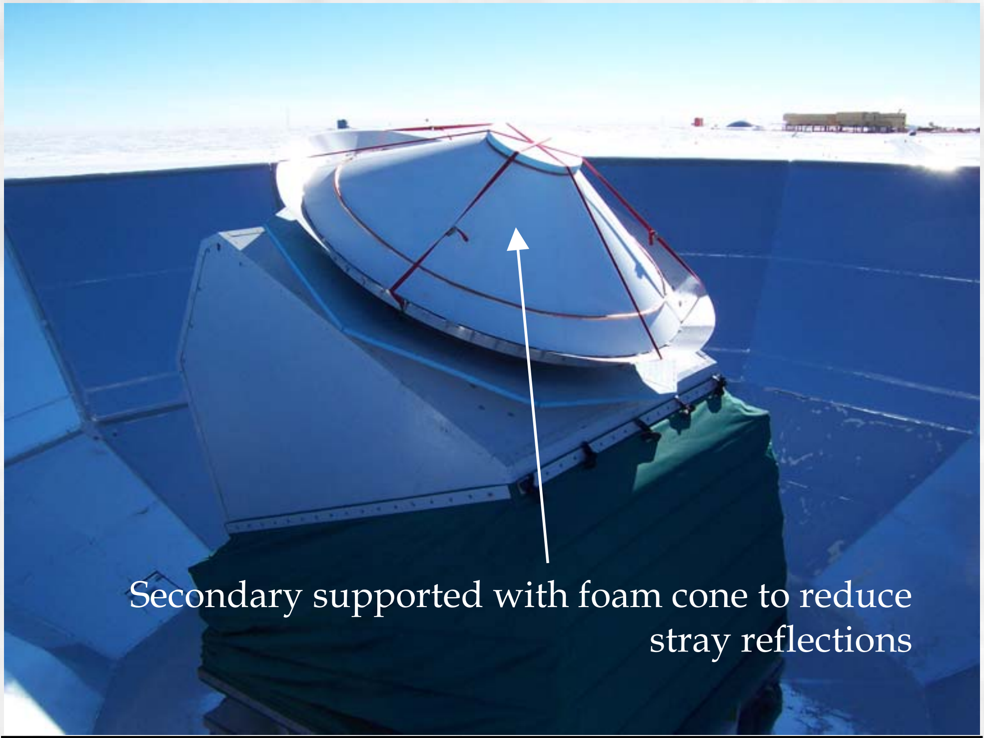
PI(s) : Church (Stanford); Gear (Cardiff)

Reference : Church *et al.* (2003), New Ast. Rev., **47**, Issue 11-12, 1083

Web Page : http://www.astro.cf.ac.uk/groups/instrumentation/projects/quest/

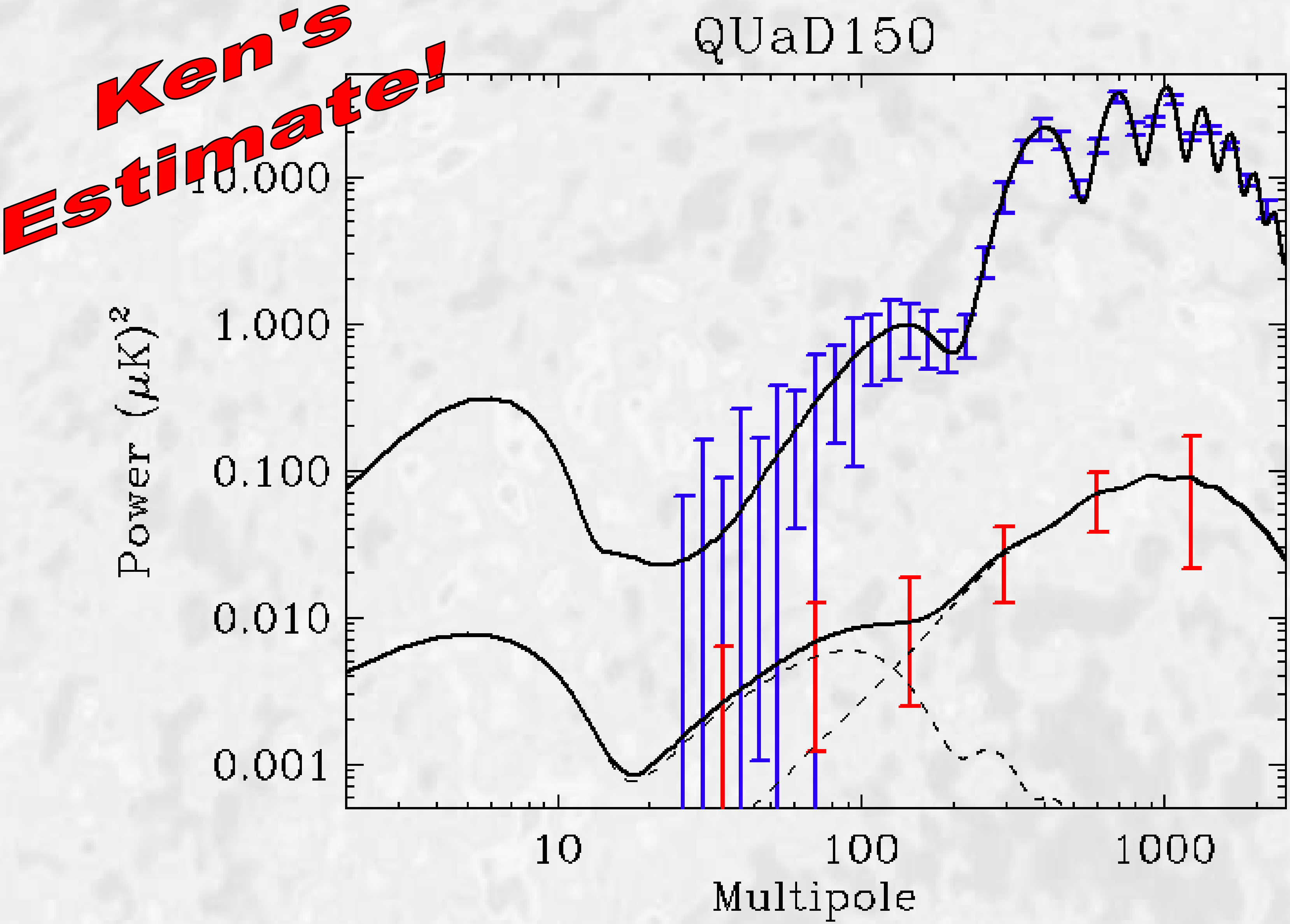
Quick QUaD Facts

- Designed specifically for polarization measurements
  - 100 and 150 GHz
  - Angular resolution of 4-6′
  - 300 square degrees of sky
  - Bolometric array receiver mounted on a 2.6 m telescope
- Comprises the QUEST experiment mounted on the DASI platform at the South Pole (QUEST at DASI – QUaD)
- Extremely stable environment with very low water vapor emission – ideally suited for CMB astronomy

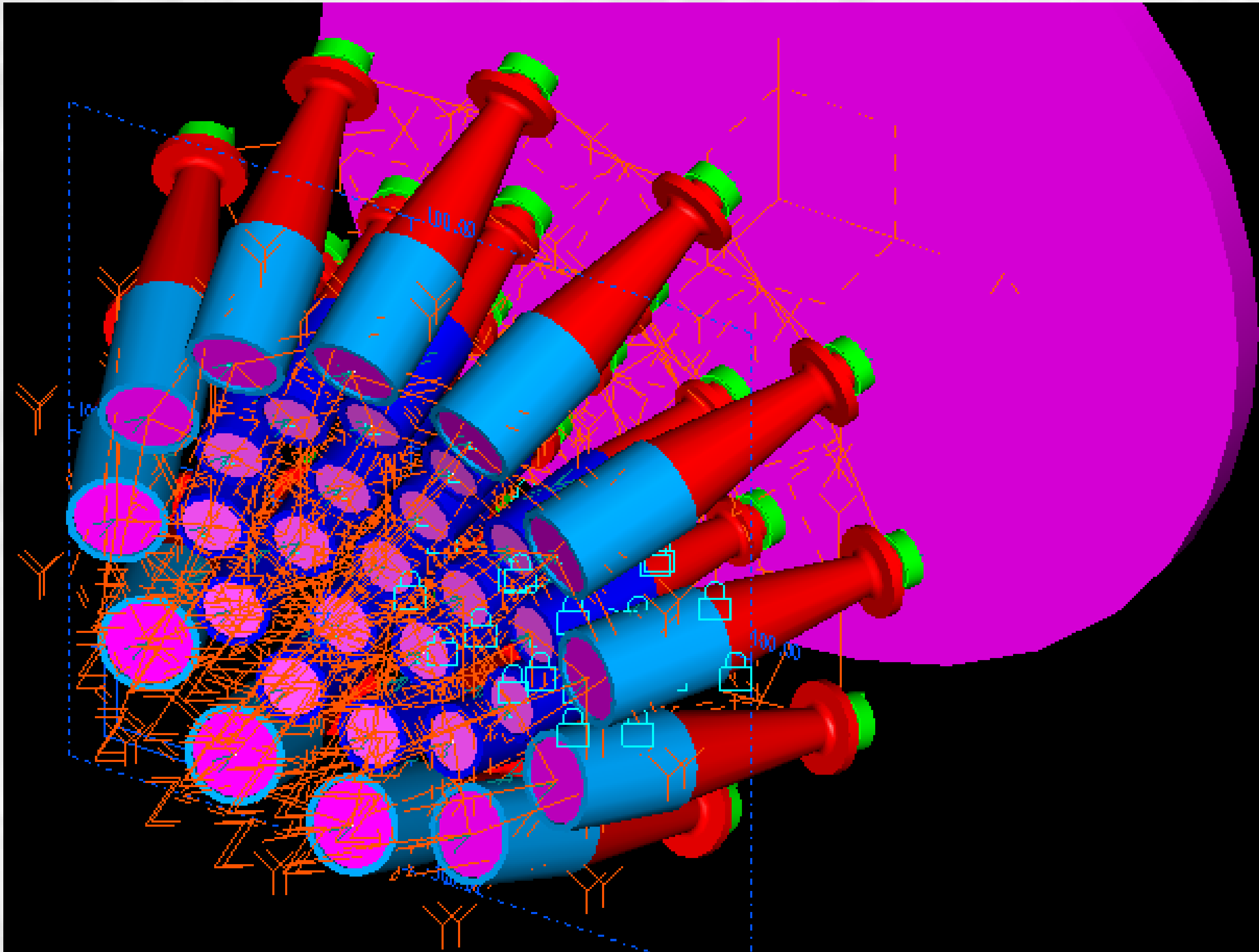


Freq (GHz)	Beam (‘)	# Feeds	% Bandwidth	NET/bolo. ($\mu K \cdot s^{1/2}$)
100	6.3	12	25	270
150	4.2	19	25	300

Predicted QUaD Spectra



QUaD Focal Plane



BICEP Information

Technology : Pol. Sens. Bolometers	Platform : Ground Based
Frequencies : 100, 150 GHz	Telescope :
NET/Det. : 280, 280 $\mu K_{CMB} s^{1/2}$	Location : South Pole
# of Det. : 48, 48	Start Date : February, 2005
Beam Size (’) : 60, 40	Duration : 2 austral winters
Multipoles :	Sky Fraction : 0.08
	Efficiency :

PI(s) : Andrew Lange (Caltech)

Reference :

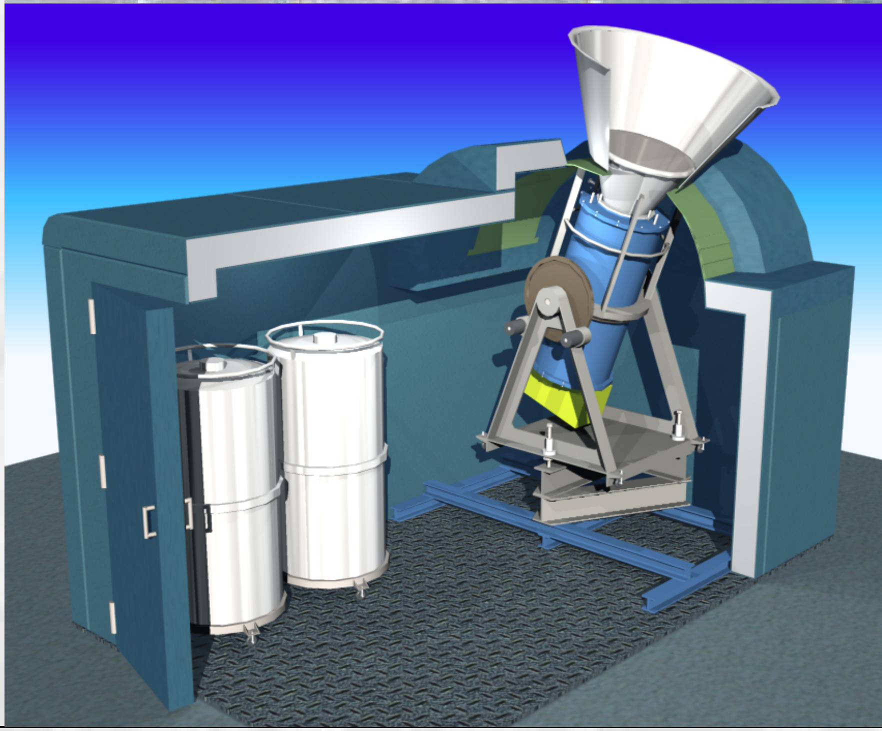
Web Page :

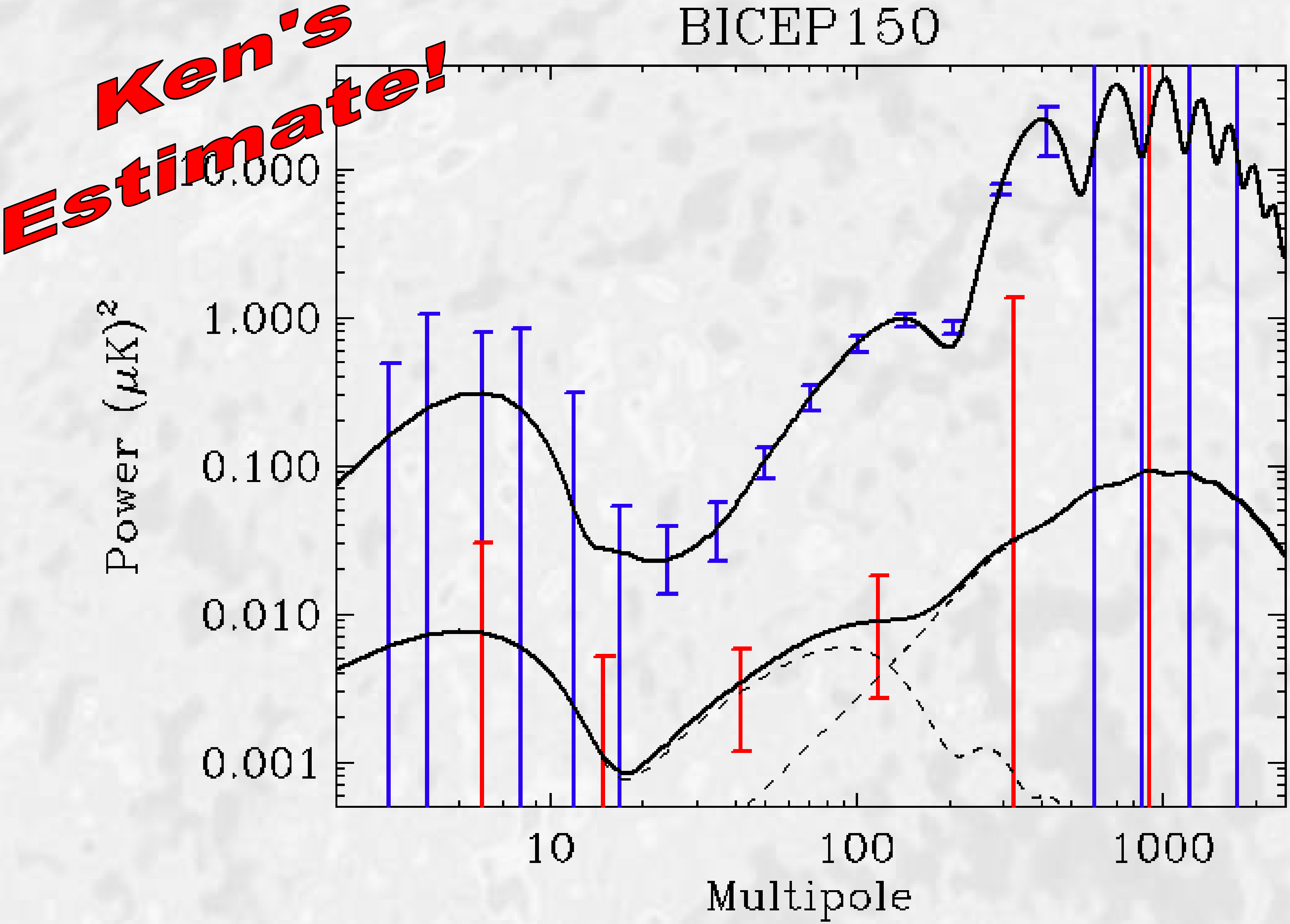
- South Pole site allows for a continuous observation of a contiguous region on the sky – ideal for measuring B-modes

- The BICEP mount will have the capability to tilt from vertical as well as continuous rotation about the dewar boresight at ~1 RPM

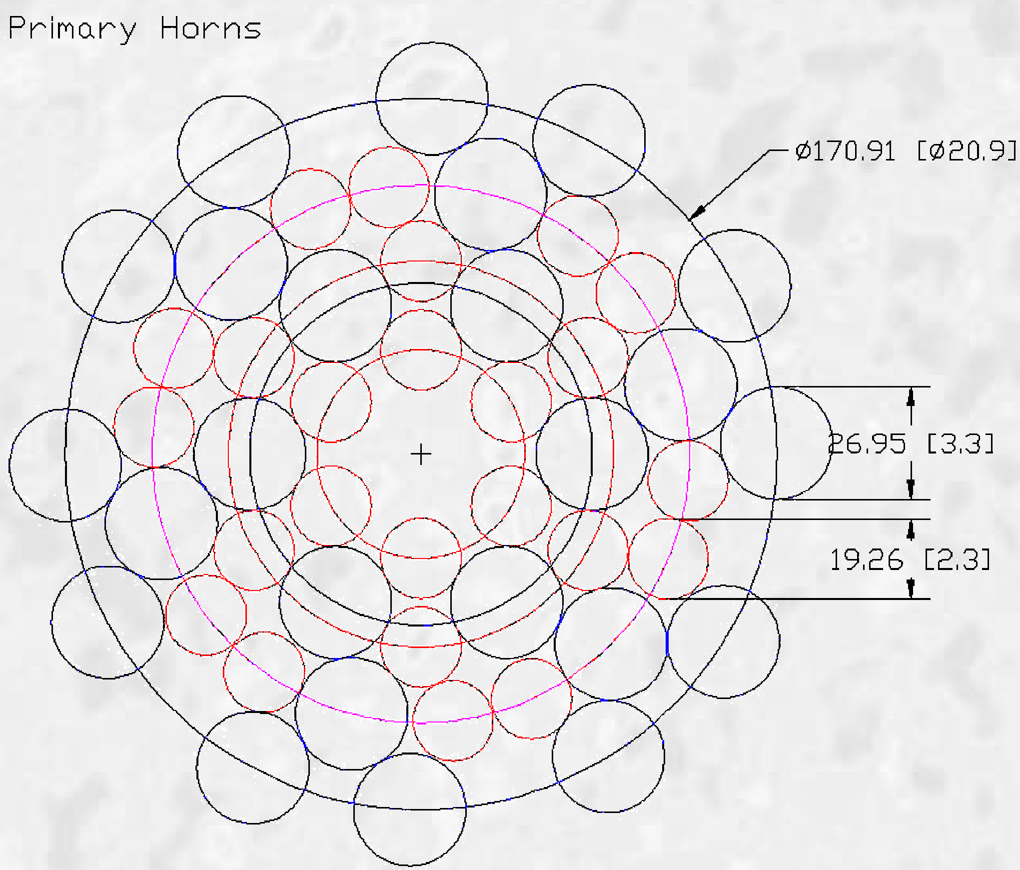
- Drift scanning will be combined with continuous boresight rotation for a well-connected and modulated map

- Drift-scanning and boresight rotation are combined with frequent calibrations, faraday modulation, and PSB pair differencing to achieve five levels of differencing




Ken's Estimate!
BICEP150
Power $(\mu K)^2$
10.000
1.000
0.100
0.010
0.001
10
100
1000
Multipole

BICEP Focal Plane



- 24 horns / 48 detectors at each frequency
- Pixels arranged in circular rings to take advantage of boresight rotation

~2008

- We will have mapped features in the E-E spectrum
- We should have a detection of B-B lensing spectrum, IGWs if nature is forthcoming…
- A number of initial version of the experiments discussed later will also be coming out with results similar to those discussed previously, if funded…
- Planck should be flying…

Mid Term

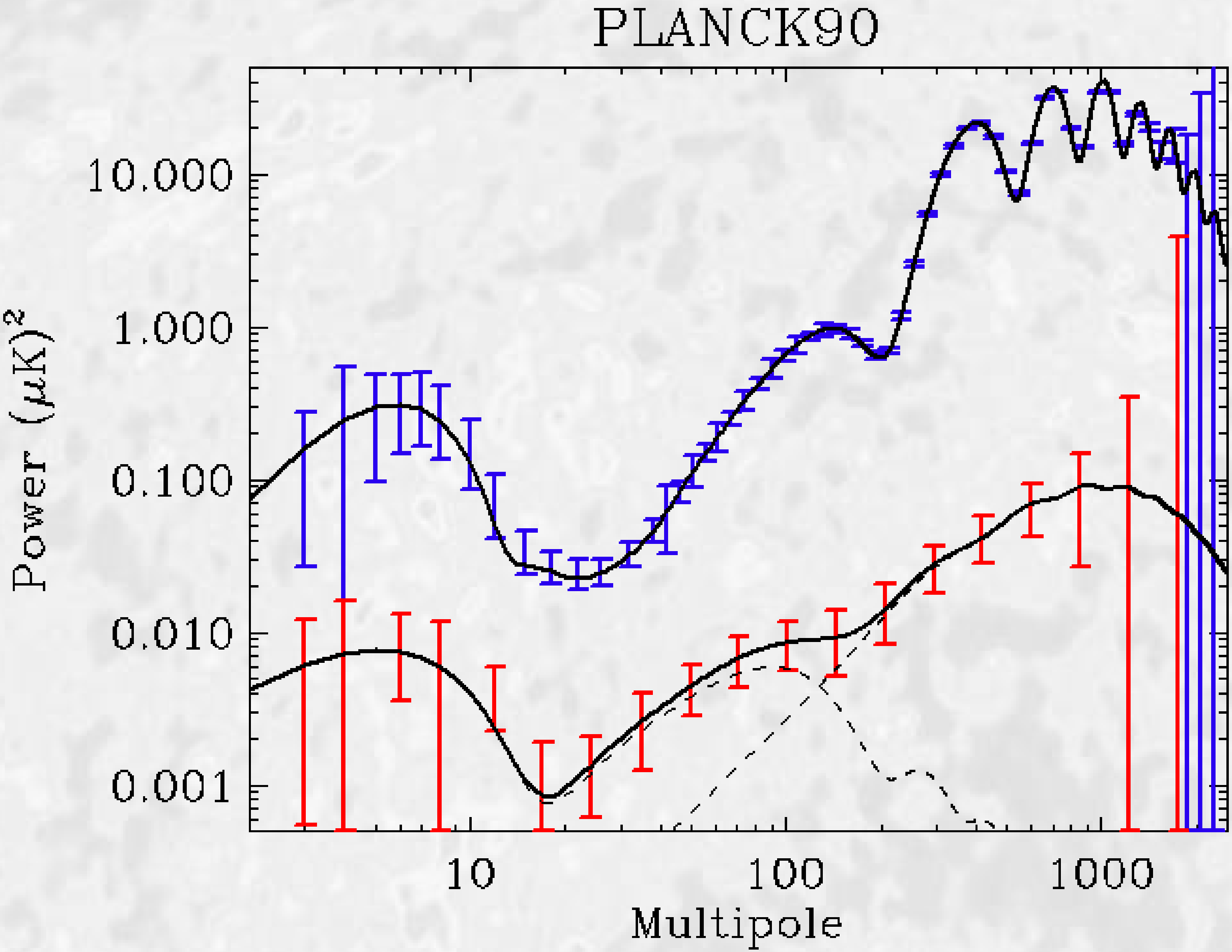
Planck Information

Technology : HEMTs and Bolometers	Platform : Satellite
Freq.s (GHz): 30, 44, 70,100,143,220,353	Telescope :
NET/det. :170,200,270, 51 , 56 , 81 ,253	Location : Sun-Earth 2nd Lagrange Pt.
# of Det. : 4 , 6 , 12 , 8 ,12/8,12/8,12/8	Start Date : 2007
Beam Size : 33,24, 14,9.2, 7.1, 5 , 5	Duration : 14 months
Multipoles :	Sky Fraction : 0.6
	Efficiency : 0.9

PI(s) : Jean-Loup Puget (IAS); Nazzareno Mandolesi (Bologna)

Reference :

Web Page : http://sci.esa.int/science-e/www/area/index.cfm?fareaid=17


PLANCK90
Power $(\mu K)^2$
10.000
1.000
0.100
0.010
0.001
10
100
1000
Multipole

PolarBear Statistics

POLARization of the Background millimEter wAve Radiation

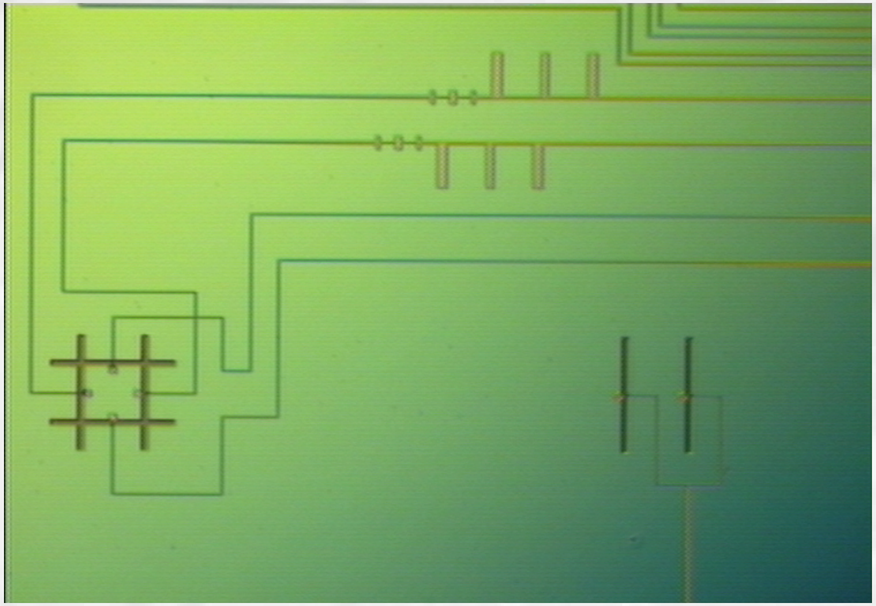
Technology : Antenna-coupled Bolos	Platform : Ground-based
Frequencies : 90, 150, 220 GHz	Telescope : 3m off-axis Dragone
NET/Det. : 310, 345, 640 $\mu K_{CMB} s^{1/2}$	Location : White Mountain, CA
# of Det. : 400, 600, 200	Start Date : (Mid-2006) 2007-8
Beam Size (') : 6.7, 4 , 2.7	Duration : (1-year) 1.5 years
Multipoles :	Sky Fraction : 0.0054 (225 deg.^{2})
	Efficiency : 30% (60% of night time)

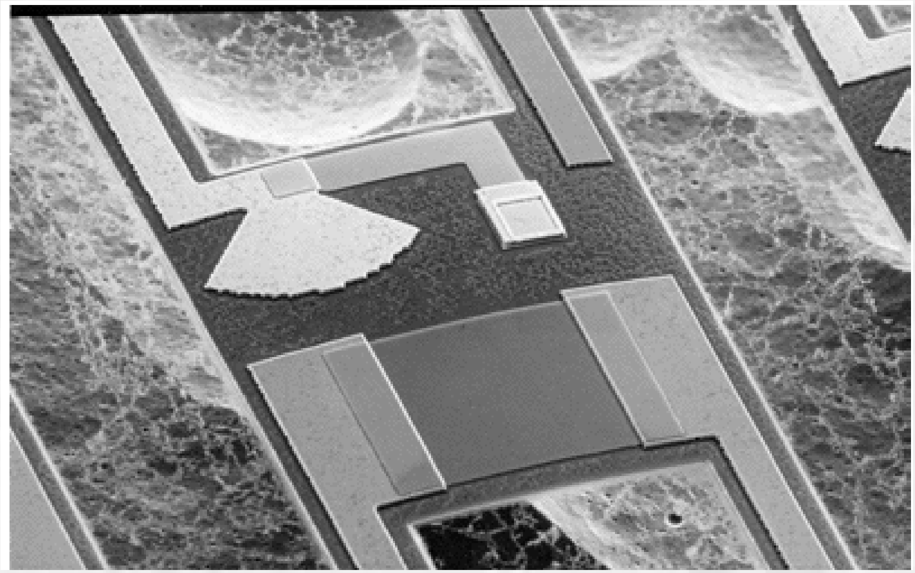
PI(s) : Adrian Lee (Berkeley/LBL)

Reference : Adrian Lee

Web Page :

New Detector Technology: **Radiometer on a Chip**

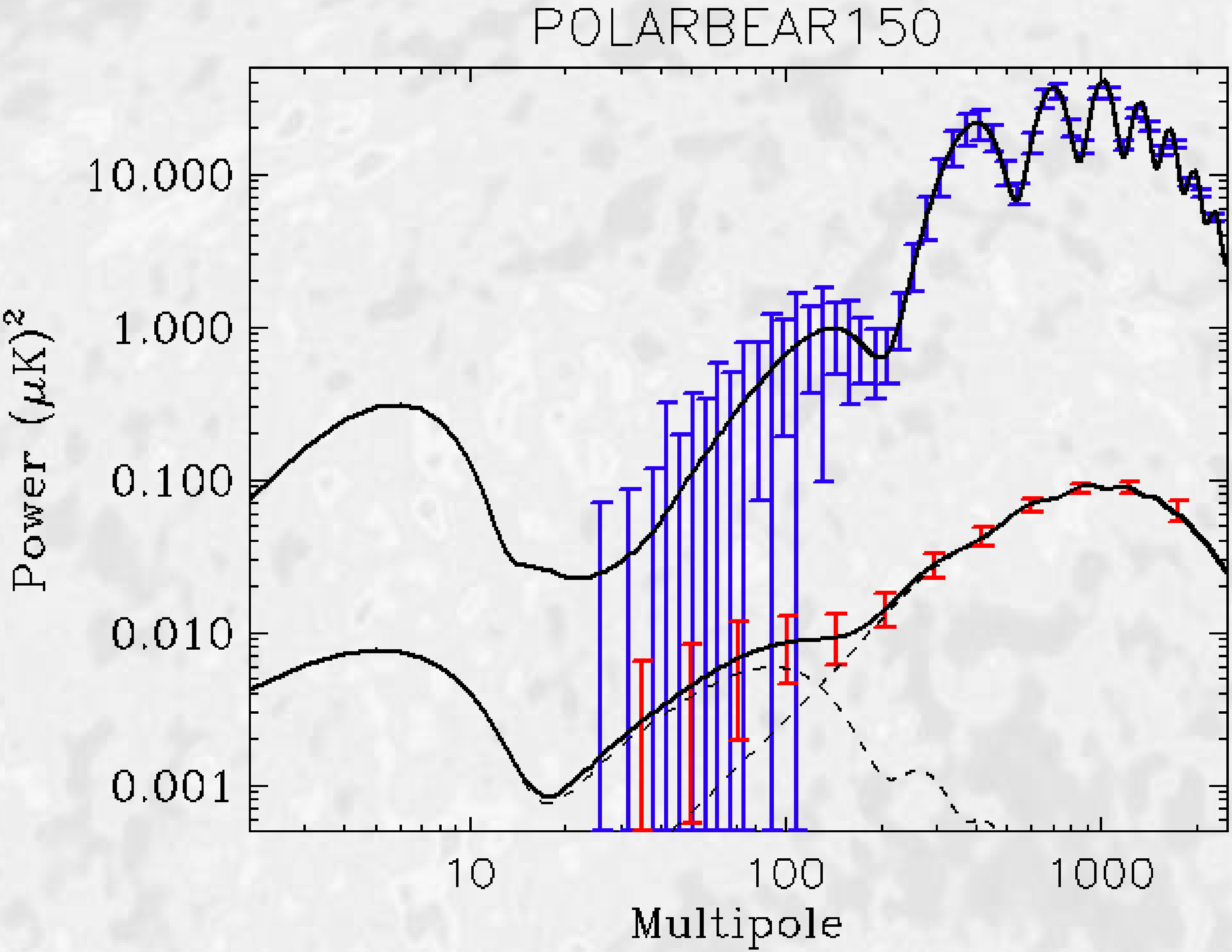




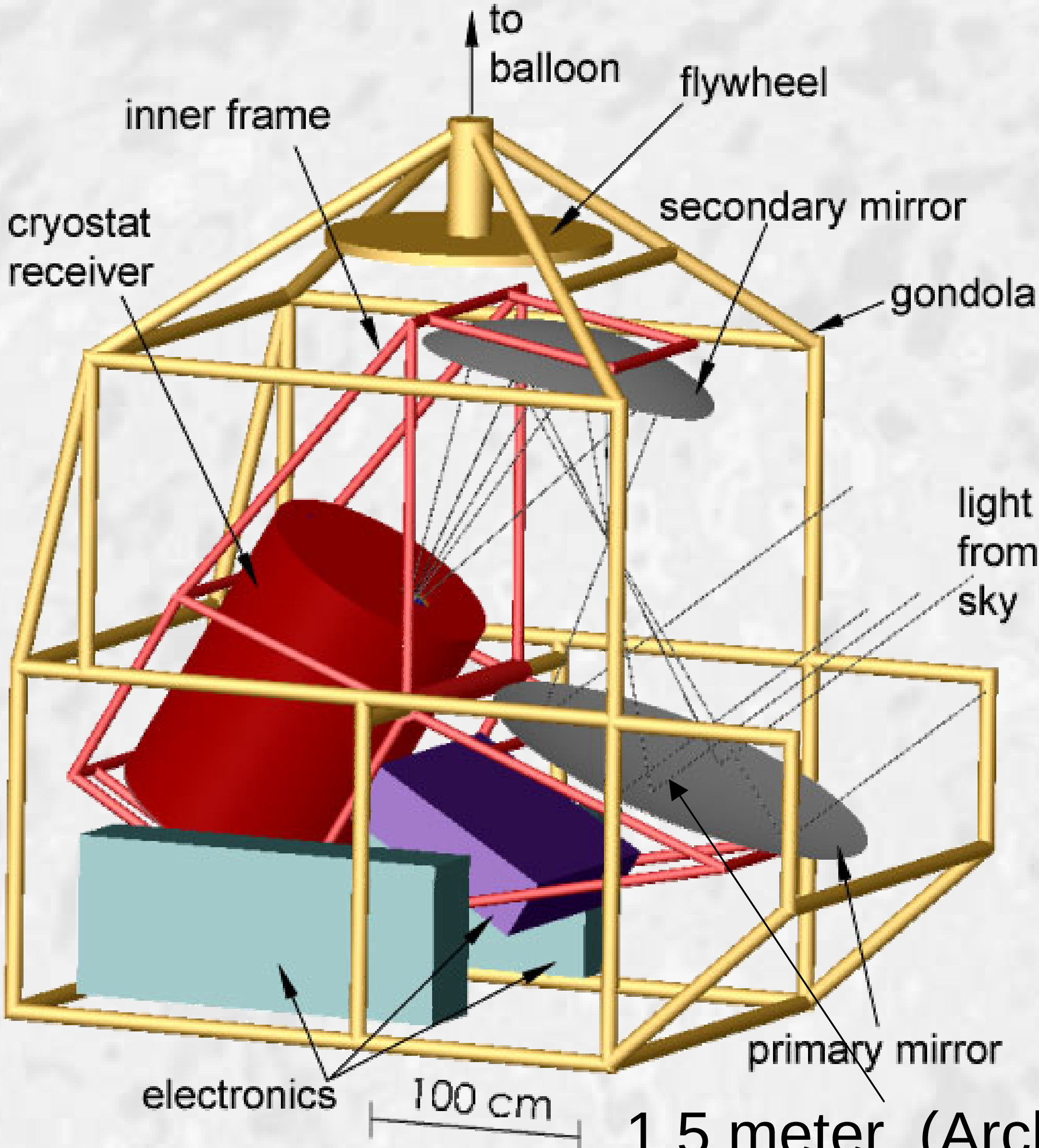
1 mm

50 micron

- Bolometer Detector at 300 mK
  - Required Sensitivity Achieved
- Large Arrays possible using photolithography (scalable technology)
- Berkeley Plays Pioneer Role -- Initial Investigation with NSF grant

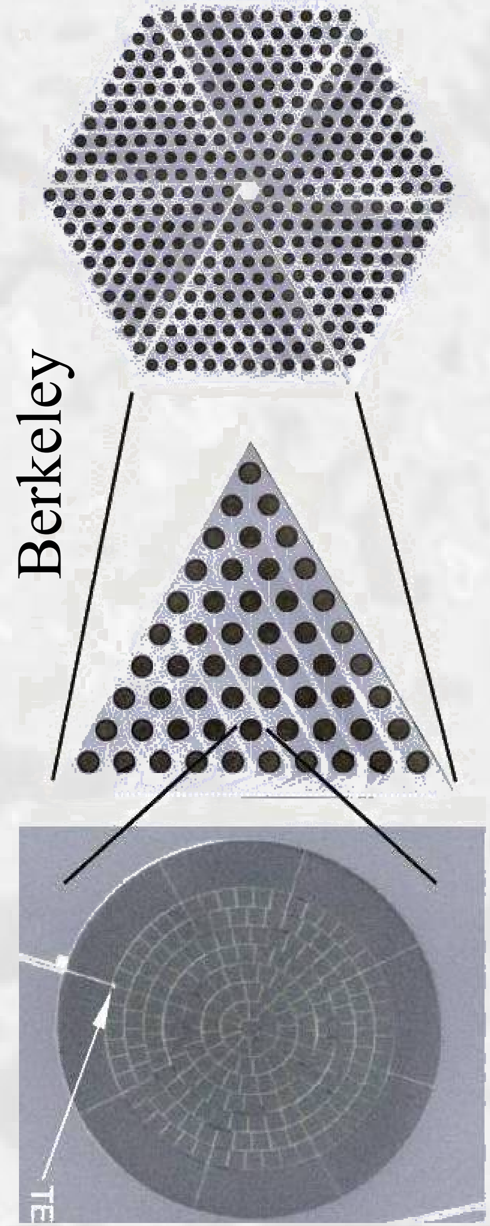

POLARBEAR150
10.000
1.000
0.100
0.010
0.001
Power $(\mu K)^2$
10
100
1000
Multipole

EBEX



1.5 meter (Archeops)

TES Bolometers from Berkeley



EBEX Information

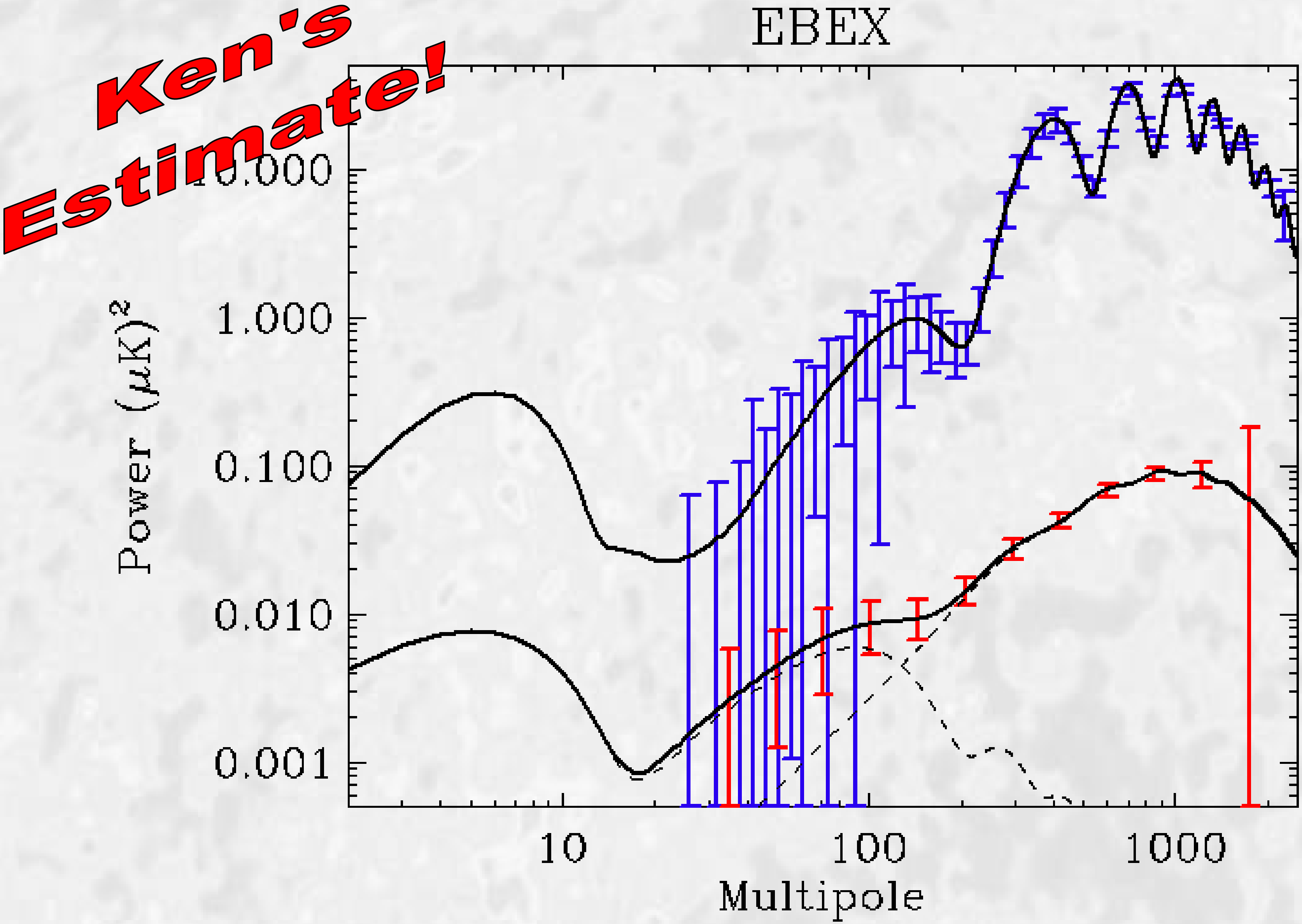
E/B mode EXperiment

Technology : TES Bolometers	Platform : Long-Duration Balloon
Frequencies : 150, 250, 350, 450 GHz	Telescope :
Sensitivity : 0.5 μK_{CMB}/8' pixel@150	Location :
# of Det.* : 605, 55, 30, 25	Start Date : 2007-8
Beam Size (') : 8, -, -, 3	Duration : 14 days
Multipoles : 25-2000	Sky Fraction : 0.008 (350 square deg.)
	Efficiency :

PI(s) : Shaul Hanany (Minn.)

Reference :

Web Page : http://groups.physics.umn.edu/cosmology/maxipol/


Ken's Estimate!
EBEX
10.000
1.000
0.100
0.010
0.001
Power $(\mu K)^2$
10
100
1000
Multipole

ClOver

C_l ObserVER

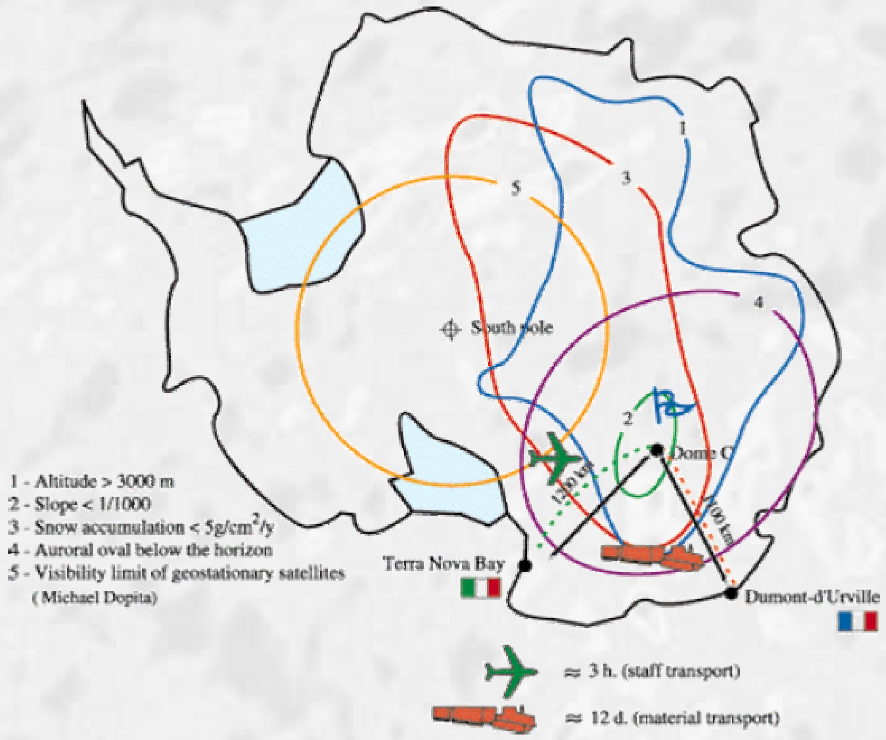
Technology : TES Bolometers	Platform : Ground-Based
Frequencies : 90, 150, 220 GHz	Telescope : 3 assemblies with 4 te.
NET/Det. : 170, 215, 455 μK_{CMB}	Location : Dome C (Antarctica)
# of Det. : 256, 256, 256	Start Date : 2008
Beam Size (’) : 15’, 15’, 15’	Duration : 4500 hours
Multipoles : 20-1000	Sky Fraction : 15 deg. dia. ring
	Efficiency :

PI(s) : Walter Gear

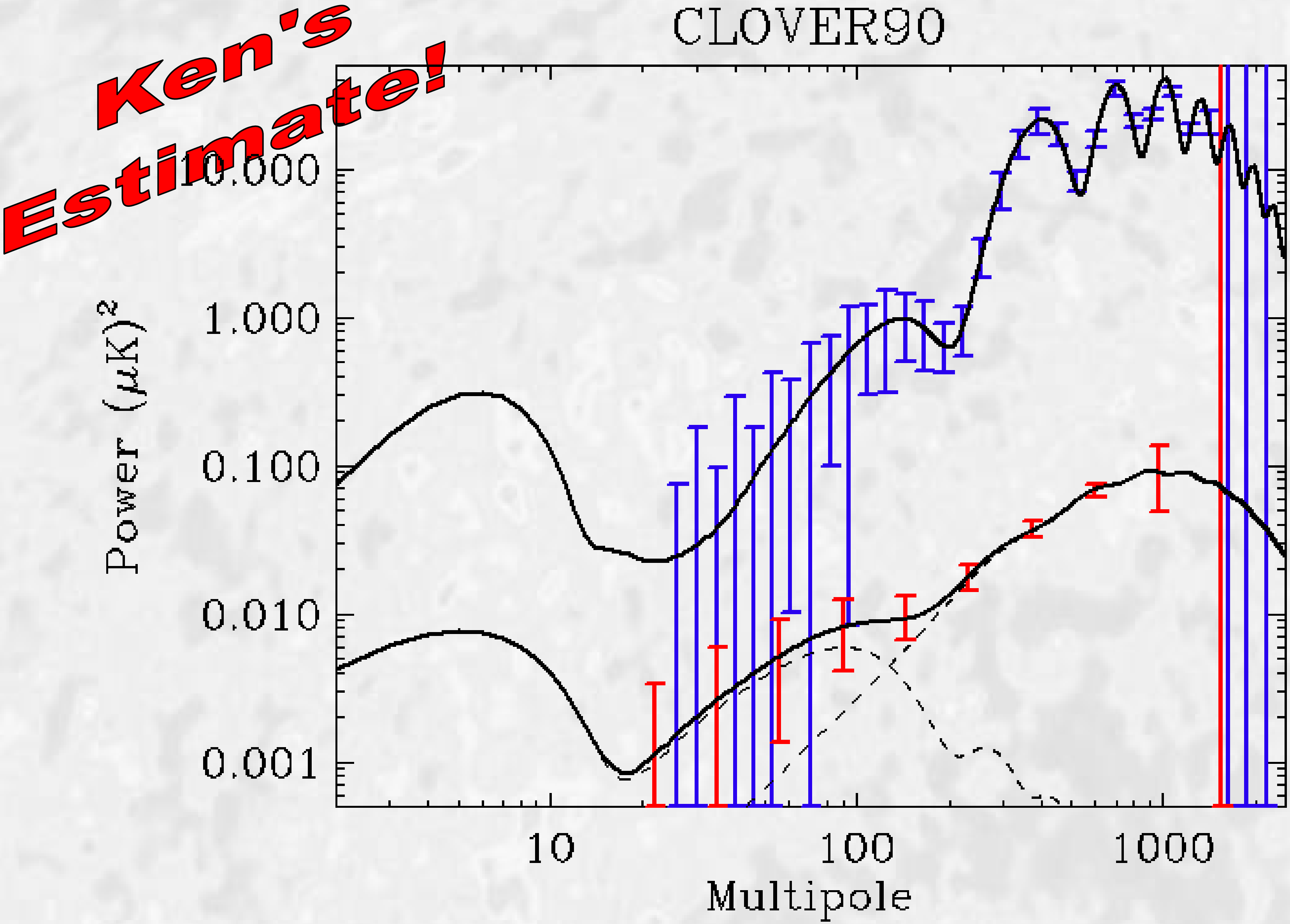
Reference :

Web Page :

Dome Concordia



Also the site for BRAIN, a bolometric interferometer, using some of the same technology as CLOVER. A 4-element array is planned for late 2005, with a 256 element planned on these "mid-term" time scales.


Ken's Estimate!
CLOVER90
Power $(\mu K)^2$
10.000
1.000
0.100
0.010
0.001
10
100
1000
Multipole

QUIET Information

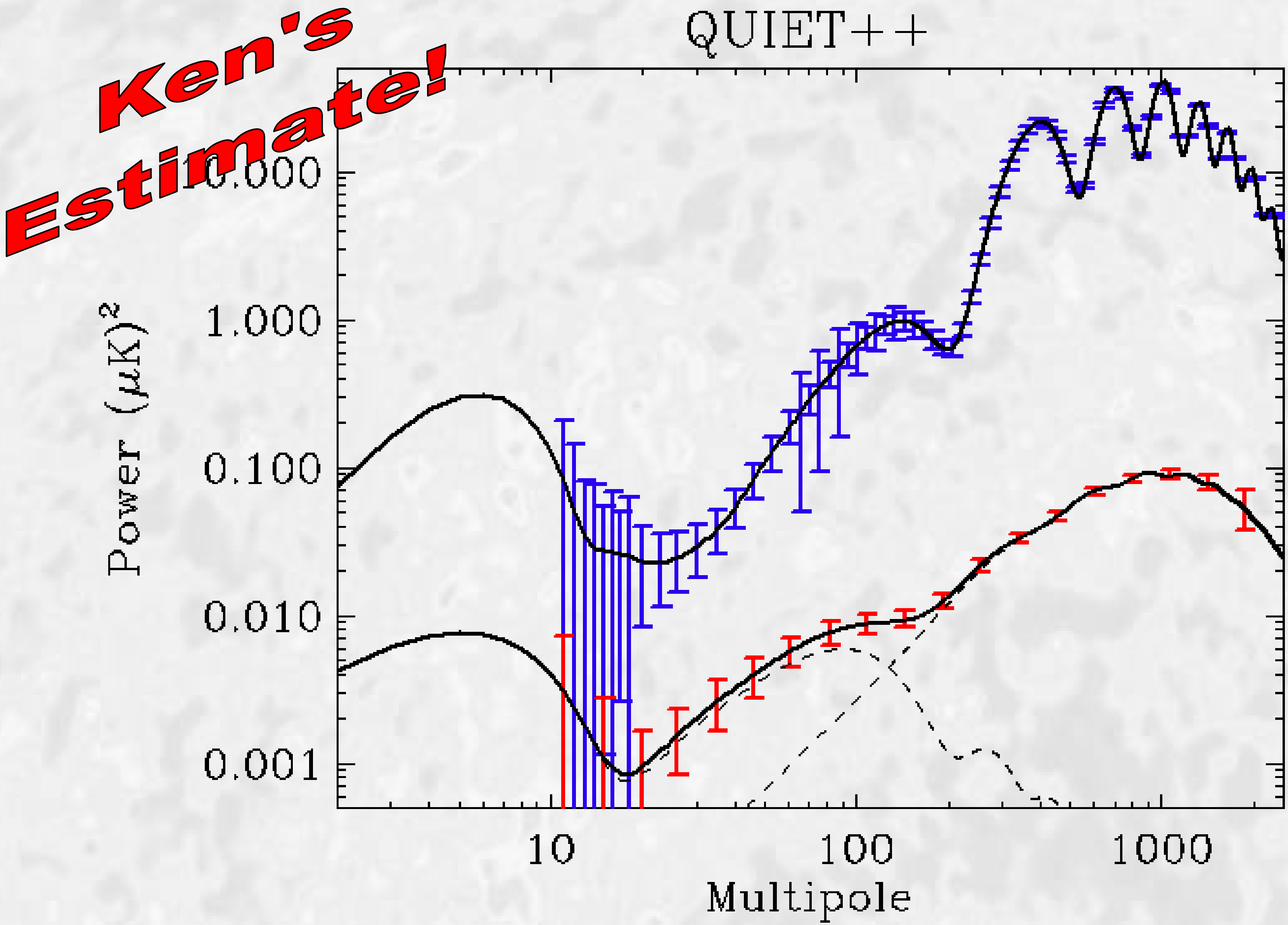
Q/U Imaging ExperimenT

Technology :	Platform : Ground Based
Frequencies : 90 GHz	Telescope :
NET/Det. : 315 $\mu K_{CMB} s^{1/2}$	Location : Chile
# of Det. : 1000	Start Date : 2006 (for 1000 feeds)
Beam Size (’) : 4	Duration : 360 nights
Multipoles :	Sky Fraction : 0.1 (4000 deg.^{2})
	Efficiency :

PI(s) :

Reference :

Web Page : http://cfcp.uchicago.edu/~peterh/polarimetry/quiet3.html


Ken's Estimate!
QUIET++
Power $(\mu K)^2$
10.000
1.000
0.100
0.010
0.001
10
100
1000
Multipole

Current Context

- We will have begun to reconstruct the B-B spectrum with high quality maps of the polarized microwave sky of area ~300 square degrees (i.e., less than a percent of the sky) and perhaps 10%.

- All of the previous are also sold as preparatory experiments for the “next” satellite mission (post-Planck), CMBPol…

Long Term

NASA's Inflation Probe Studies

- Imaging Cosmic Microwave Background Polarization with EPIC
  - Bock, James (NASA Jet Propulsion Laboratory)
- A Mission Concept Study for the Einstein Inflation Probe
  - Hinshaw, Gary (NASA/GSFC)
- Mission Concept Study for the Einstein Polarization Interferometer for Cosmology (EPIC)
  - Timbie, Peter (University of Wisconsin-Madison)

- The possibility of a European Inflation Probe is being discussed as well.

Inflation Probe Guesses

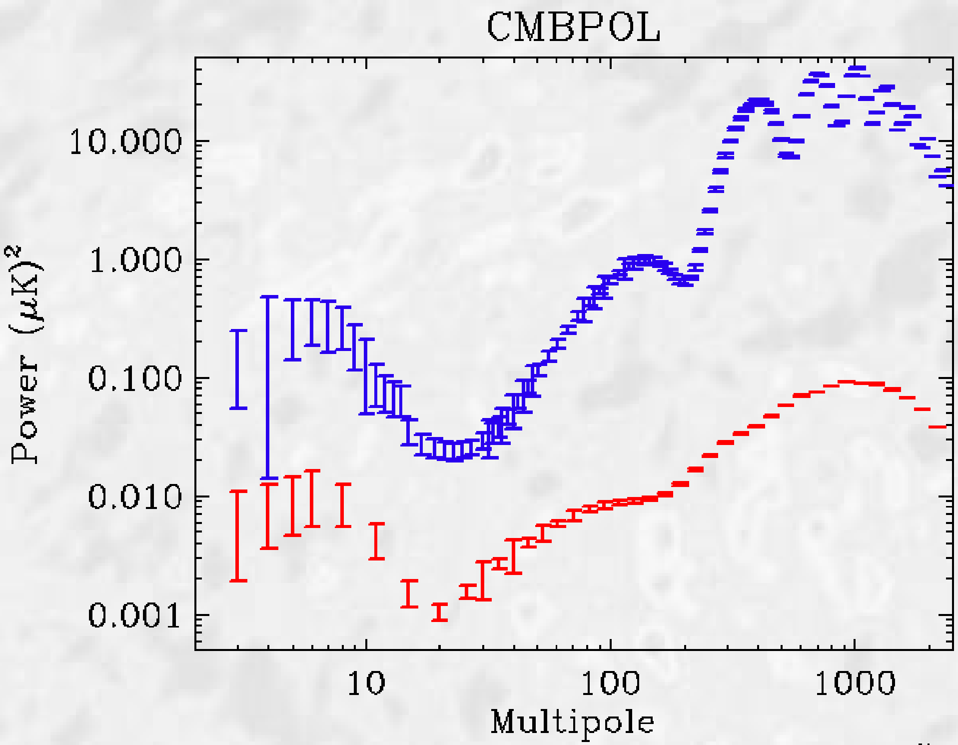
Technology :	Platform : Satellite
Frequencies : …, …, …, 90, …, … GHz	Telescope : ~ 3m
NET/Det. : 35 $\mu K_{CMB} s^{1/2}$?	Location : L2 ?
# of Det. : 10000 ?	Start Date : 2017 ?
Beam Size : 4' (?)	Duration : 2 years ?
Multipoles : 2-2500	Sky Fraction : Full Sky
	Efficiency : 100% ?

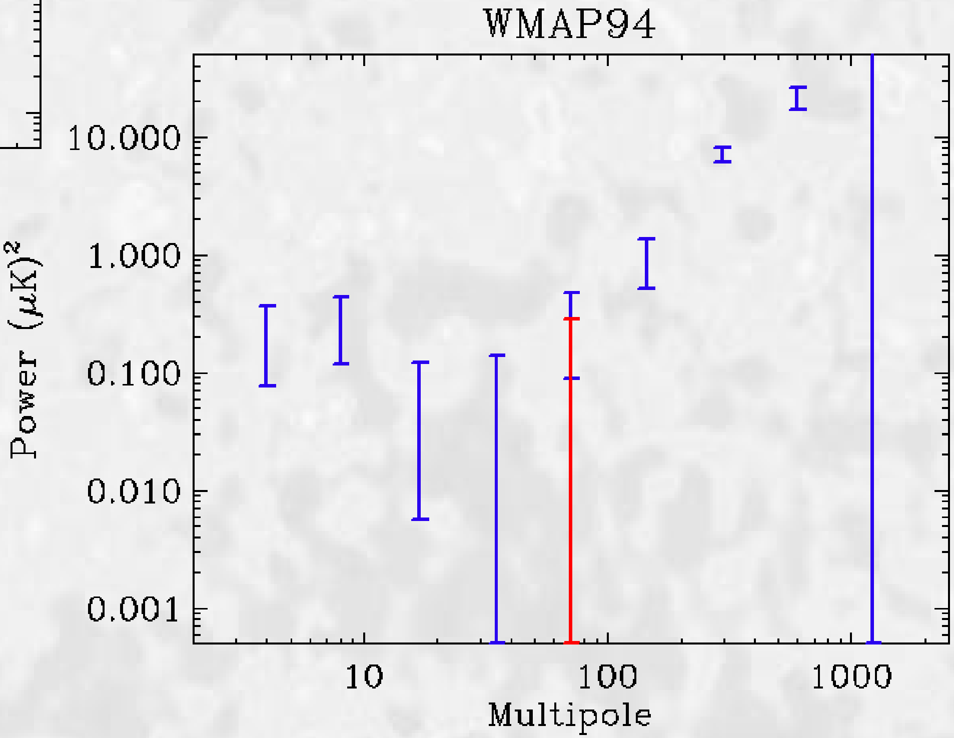
PI(s) :

Reference :

Web Page :

Estimate of CMBPOL Sensitivity vs WMAP





Ken's Estimates

Conclusions

- We are on a strong, steady program to observe the CMB polarization both E & B modes
- We can expect to probe inflation to $\sim 10^{15}$ GeV level
- Many versions of Inflation predict lower level but a significant faction may be probed by gravity waves from string kinks - LIGO, LISA
- Still a strong test of the predictions of Inflation