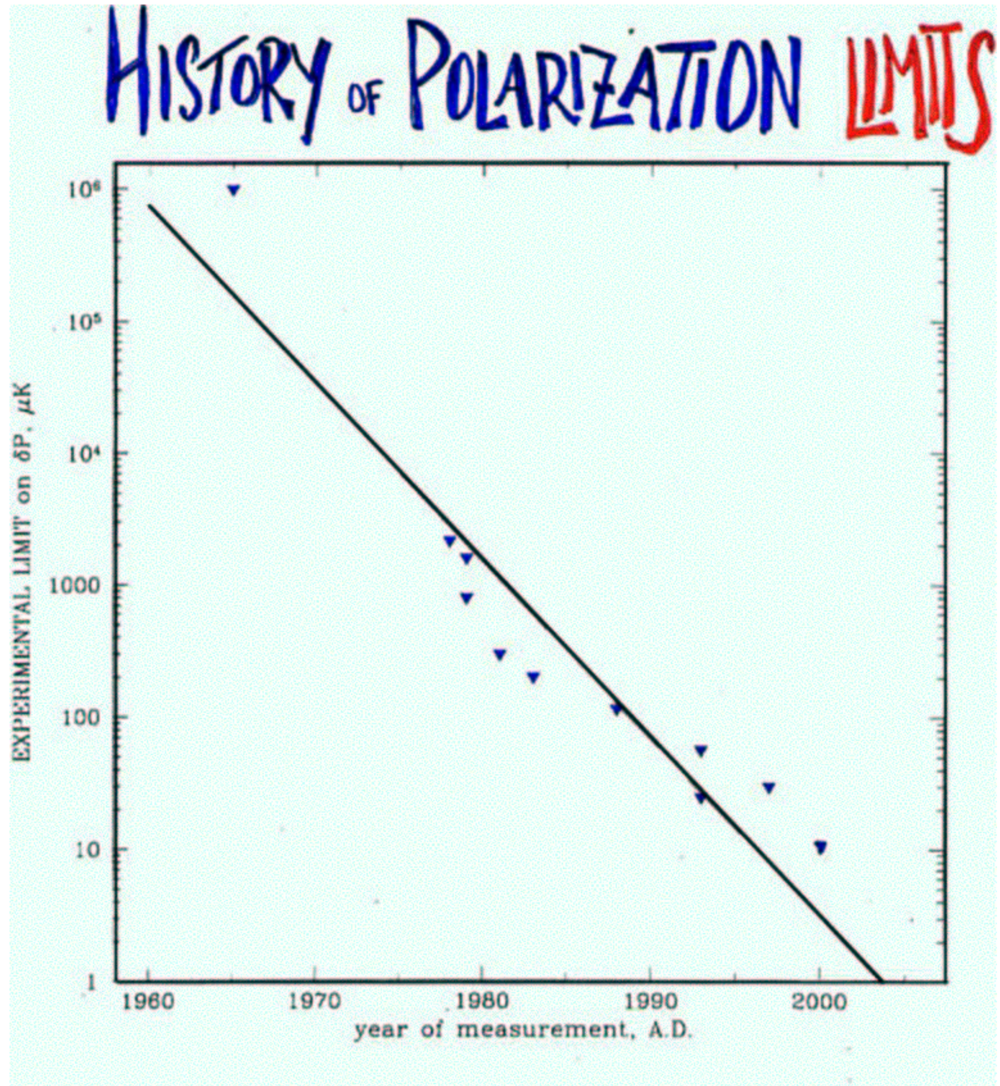
CMB Polariztion

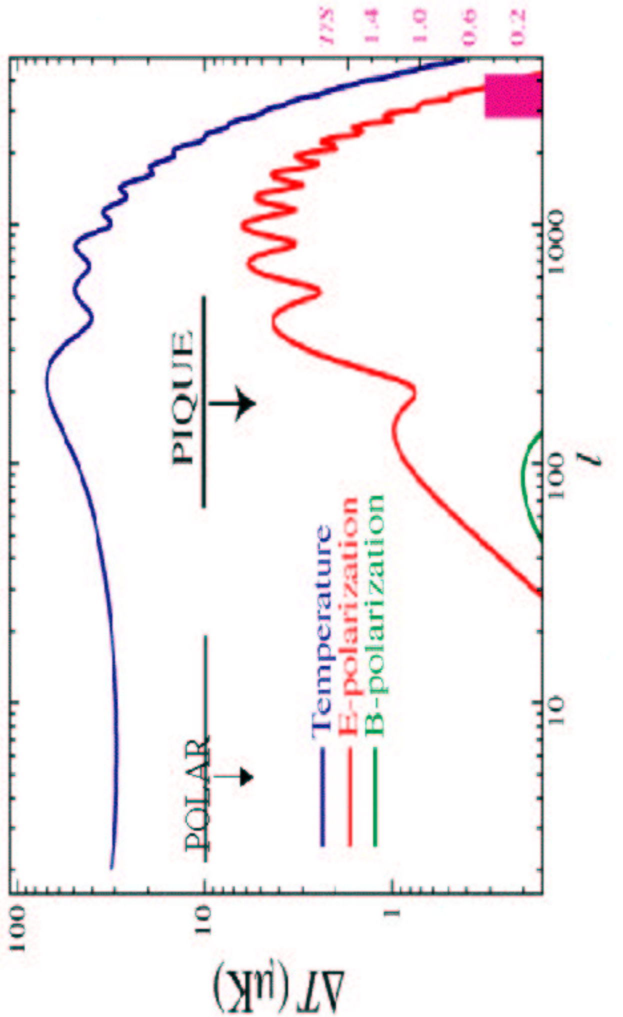
B. Winstein

Chicago, CfCP

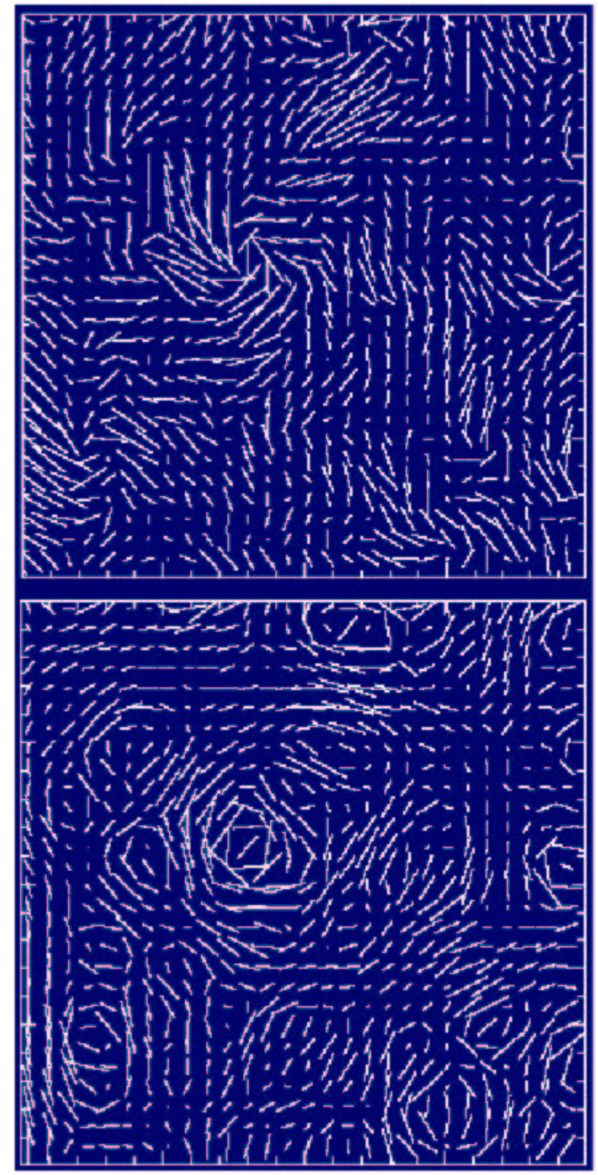
- General Introduction to the Problem
- The CAPMAP Solution



CMB Power Spectra



E/B Modes



Energy of Inflation?

- Scale of Inflation < 2 x 10^{16} GeV (COBE)
- Ultimate goal of the field
  - No guarantee of a detection
  - Analogous to proton decay searches
    - Neutrino physics important "byproduct"
    - Lensing case needs development
- Ultimate limit (from lensing) appears to be ? 3 x 10^{15} GeV (Knox and Song)

Signal Levels, Sensitivities

- Fine Scale Anisotropies
  - T: 40 μK
  - E: 4 μK
  - B: ? 0.2 μK
- Pixel Sensitivities (approx. statistical errors only!)
  - Map: ? 70 μK
  - Planck: ? 10 μK
  - Planck sensitivity concentrated (3^0 x 3^0): ? 0.2 μK
  - Polarbear (3^0 x 3^0): ? 0.1 μK

Considerations for Detecting Polarization

- HEMT/Bolometer?
- Frequency Coverage
- Ground, Balloon, Space based?
- Scanning Strategy, Coverage?
- Foregrounds
  - More attention needed
  - CfCP Workshop?

4 1. Radio Astronomical Fundamentals

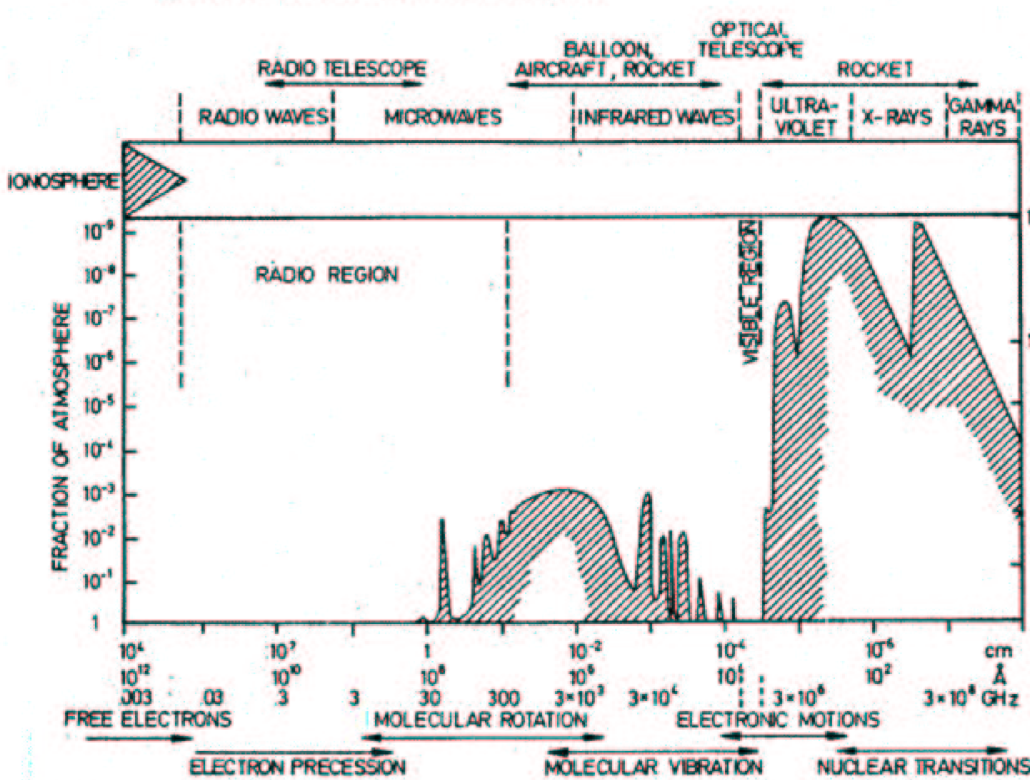


Fig. 1.1. The transmission of the earth's atmosphere for electromagnetic radiation. The diagram gives the height in the atmosphere at which the radiation is attenuated by a factor 1/2

Foregrounds

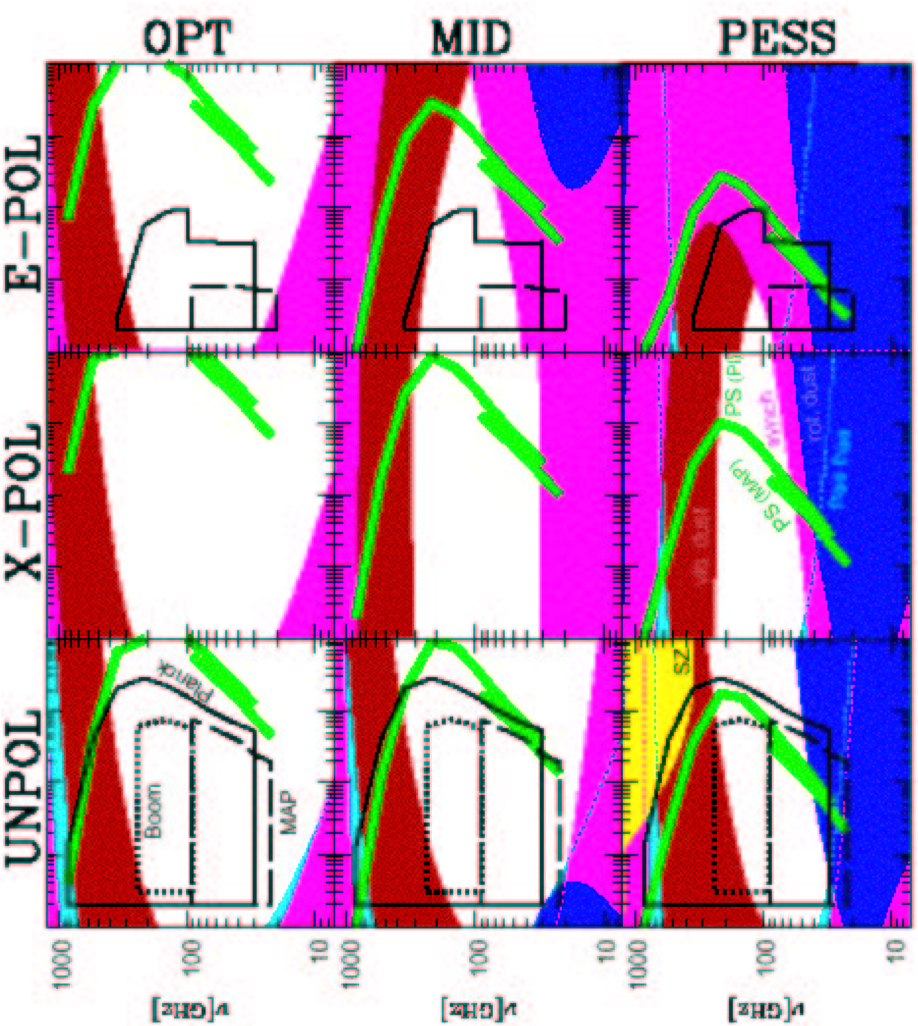
- Dust
- Synchrotron
- Bremsstrahlung
- S-Z from clusters
- Point sources
- Gravitational-lensing
  - (non Gaussian)
- ????

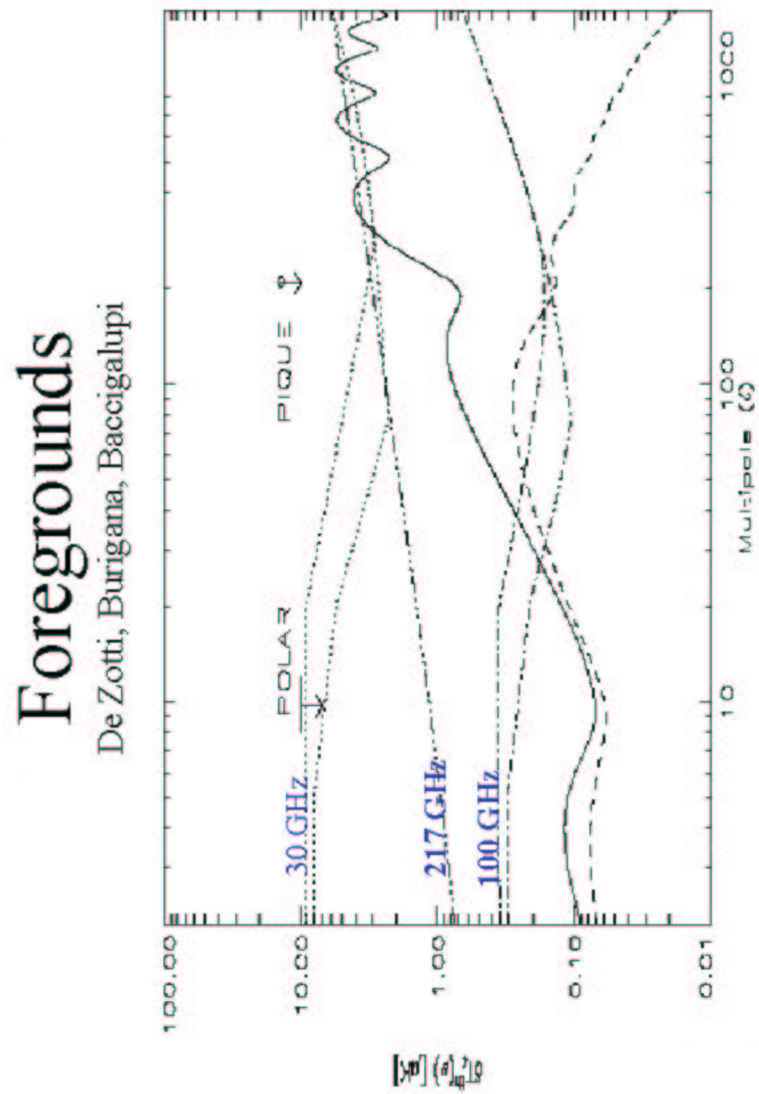
Foregrounds, continued

- Much more important for polarization
- None has been fully characterized
- Many free parameters to be determined
- Excellent studies by a few groups

  e.g. Tegmark, Eisenstein, Hu, Oliveira-Costa, astro-ph/9905257

Note: small patch studies can take advantage of especially clean regions


OPT
MID
PESS
E-POL
X-POL
UNPOL
Multipole l
ν[GHz]
Planck
MAP
Boom
SZ


Foregrounds
De Zotti, Burigana, Baccigalupi
POLAR
PIQUE
30 GHz
217 GHz
100 GHz
Multipole (ℓ)

Radiometers a la Dicke

Antenna Noise as a pulse train:

$1/\Delta\nu$

$\Delta\nu$ is receiver bandwidth

- T_{system} = 100 K
- T_{signal} = 1 μK = 10^{-8} of system Temp.
  - ➤need 10^{16} pulses
- Take $\Delta\nu$ = 10 GHz
  - ➤Count for 10^{6} seconds for 1σ
- Challenge to keep systematics (amplifier drifts, atmospheric noise, etc.) under control during this large integration time.

Want to measure a Variance

⇒ multiple spots

$$\mathcal{L}(\sigma_s) = \prod_{i=1}^{N} \frac{1}{\sqrt{\sigma_{N_i}^2 + \sigma_s^2}} e^{-Q_i^2/2(\sigma_{N_i}^2 + \sigma_s^2)}$$

Essence of Analysis

σ_{N_i} = detector noise at i'th pixel { must be understood!

σ_s = signal "noise"

Q_i = measured temperature at i'th pixel

ℓ-space coverage determined by pixel geometry, beam size

Detector Technology

- Bolometer
  - Incoherent
  - Very low system temp
  - Stable
  - Systematics
    - Several clever schemes look promising
  - No doubt the only way to the B-modes
- HEMT
  - Coherent
  - Higher system temp.
  - Systematics
    - Most (all) limits today come from HEMT systems

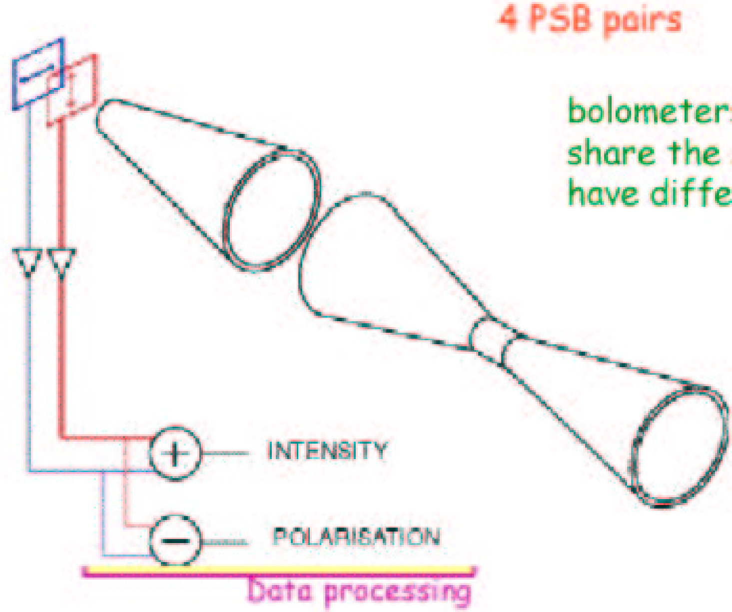
Polarisation Measurement with the Planck HFI

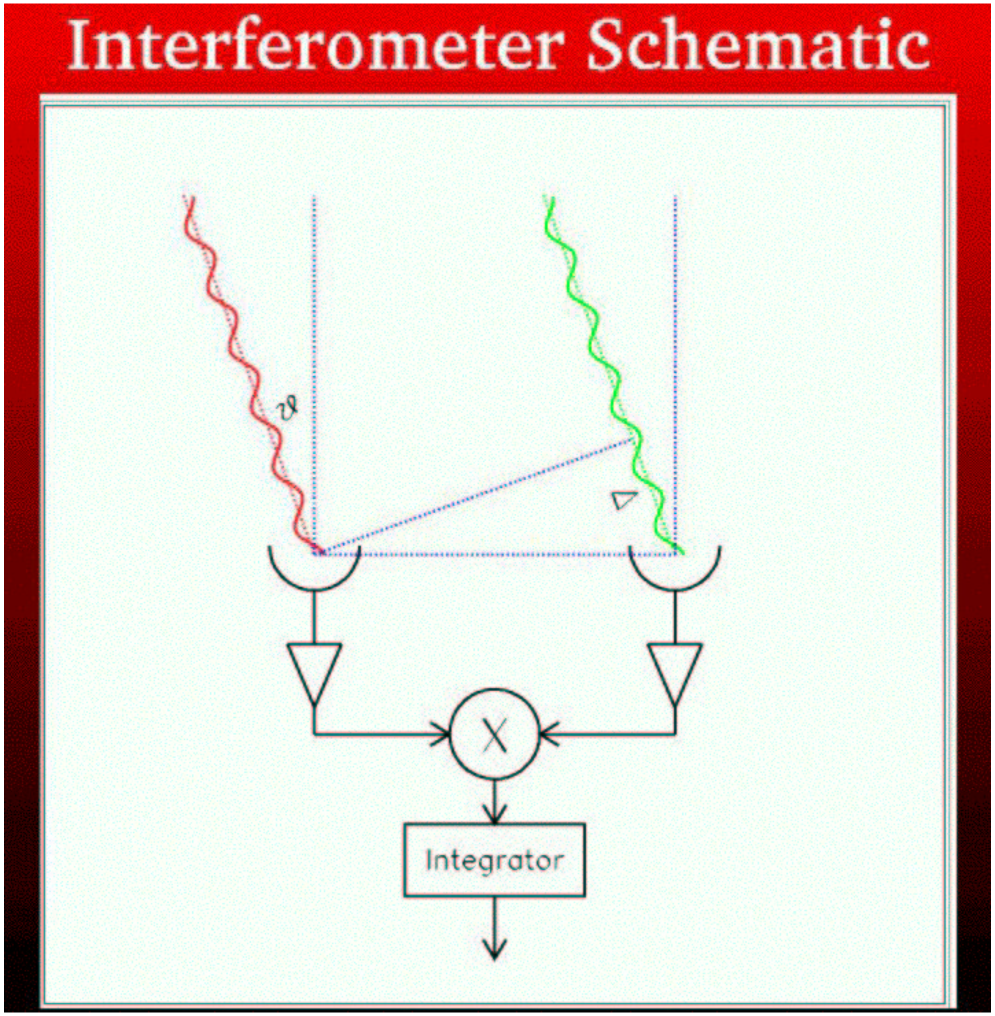
- Polarisation sensitive bolometers (PSB)
  - 143 GHz, 217 GHz, 353 GHz

4 unpolarised bolometers

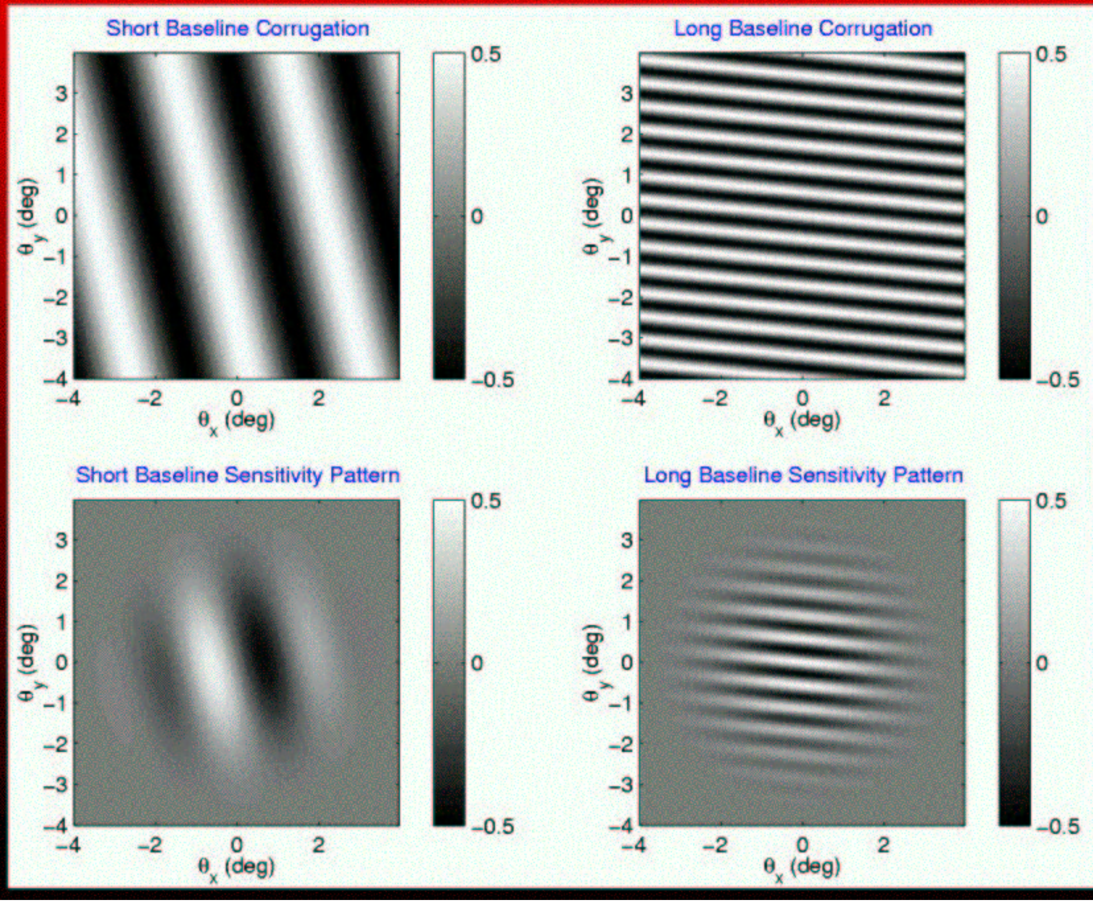
4 PSB pairs

bolometers from a PSB pair share the same optics but have different readouts.




Interferometer Schematic
Integrator

Sensitivity Patterns



Circular Polarized Visibilities

- Polarization state of rxA:

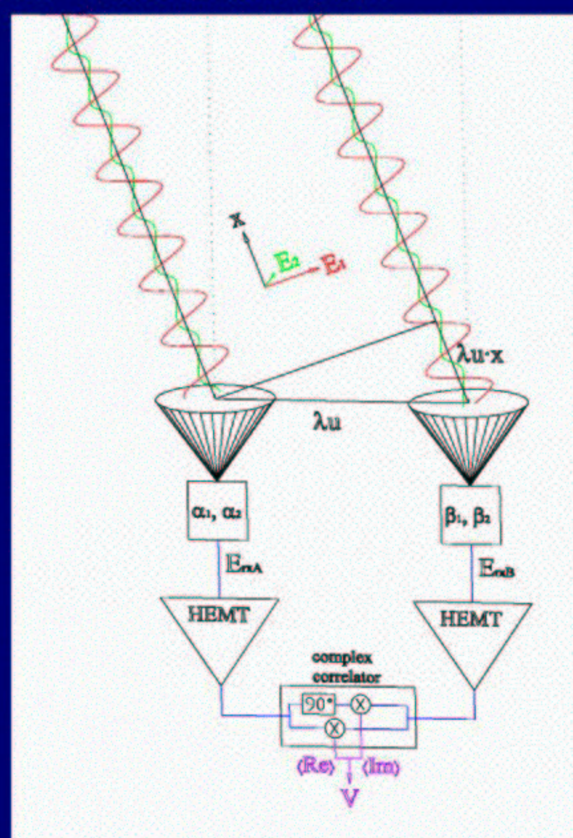
$$E_{\text{rxA}} = (\alpha_1 E_1 + \alpha_2 E_2)$$

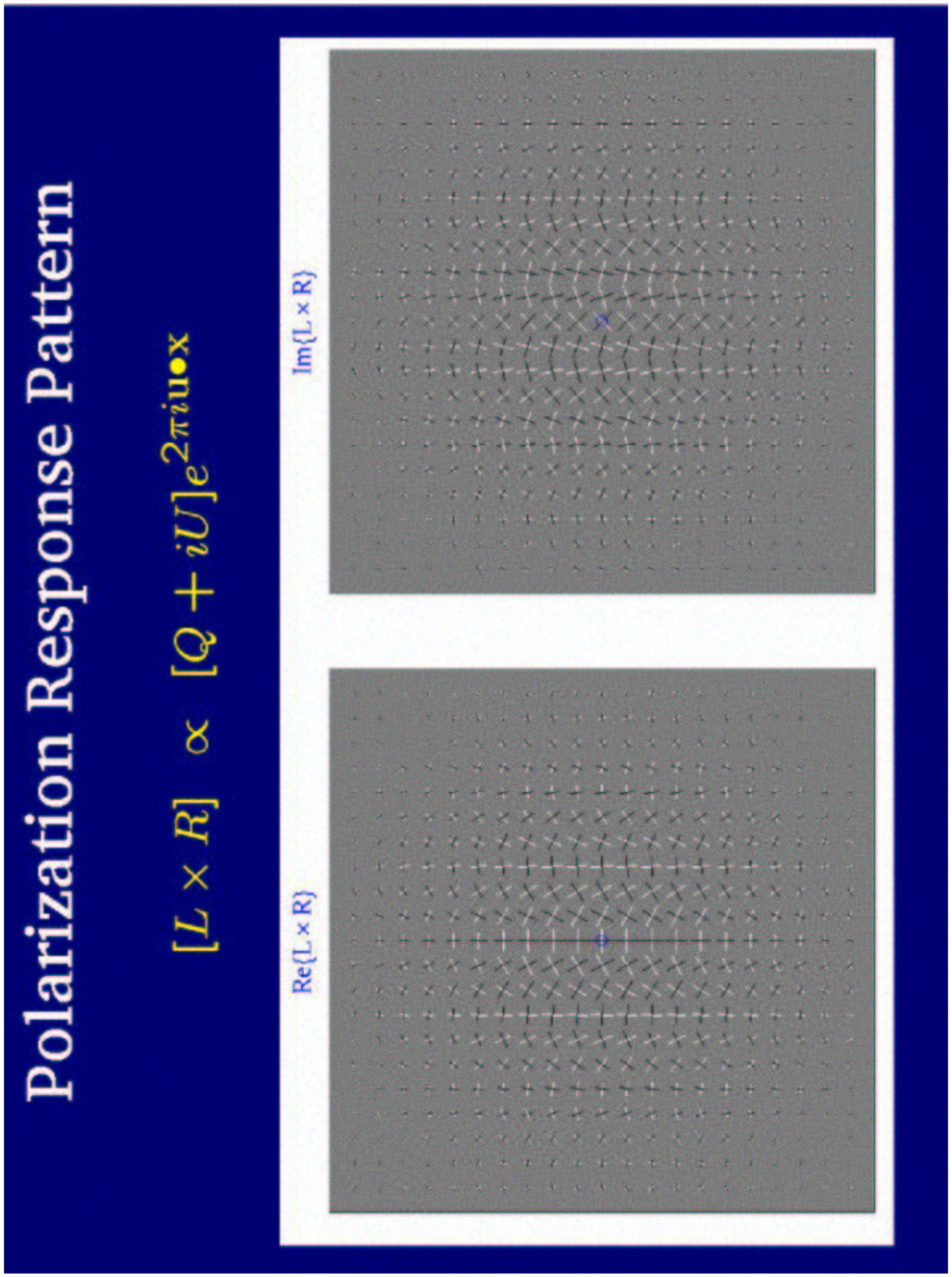
- rxA in state $\{L\} \Rightarrow \alpha_1/\alpha_2 = e^{i\pi/2}$.
- rxA in state $\{R\} \Rightarrow \alpha_1/\alpha_2 = e^{-i\pi/2}$.
- Output of correlator:

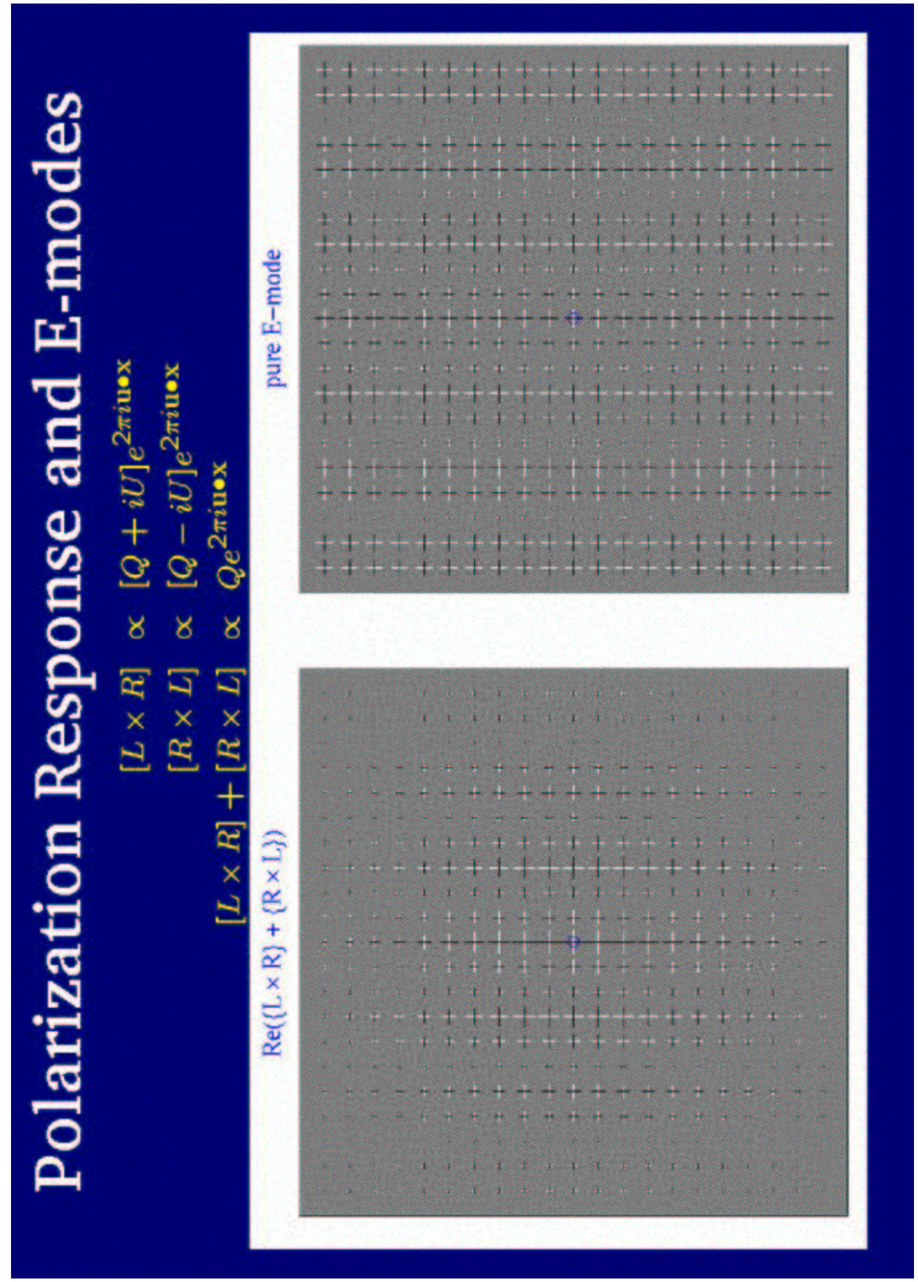
$$V \propto \begin{bmatrix} \left(\alpha_1\beta_1^* + \alpha_2\beta_2^*\right) I \\ + \left(\alpha_1\beta_1^* - \alpha_2\beta_2^*\right) Q \\ + \left(\alpha_1\beta_2^* + \alpha_2\beta_1^*\right) U \\ +i \left(\alpha_1\beta_2^* - \alpha_2\beta_1^*\right) V \end{bmatrix} e^{2\pi i \mathbf{u} \bullet \mathbf{x}}$$

so...

$$\begin{aligned} [L \times L] &\propto [I + V] e^{2\pi i \mathbf{u} \bullet \mathbf{x}} \\ [R \times R] &\propto [I - V] e^{2\pi i \mathbf{u} \bullet \mathbf{x}} \\ [L \times R] &\propto [Q + iU] e^{2\pi i \mathbf{u} \bullet \mathbf{x}} \\ [R \times L] &\propto [Q - iU] e^{2\pi i \mathbf{u} \bullet \mathbf{x}} \end{aligned}$$

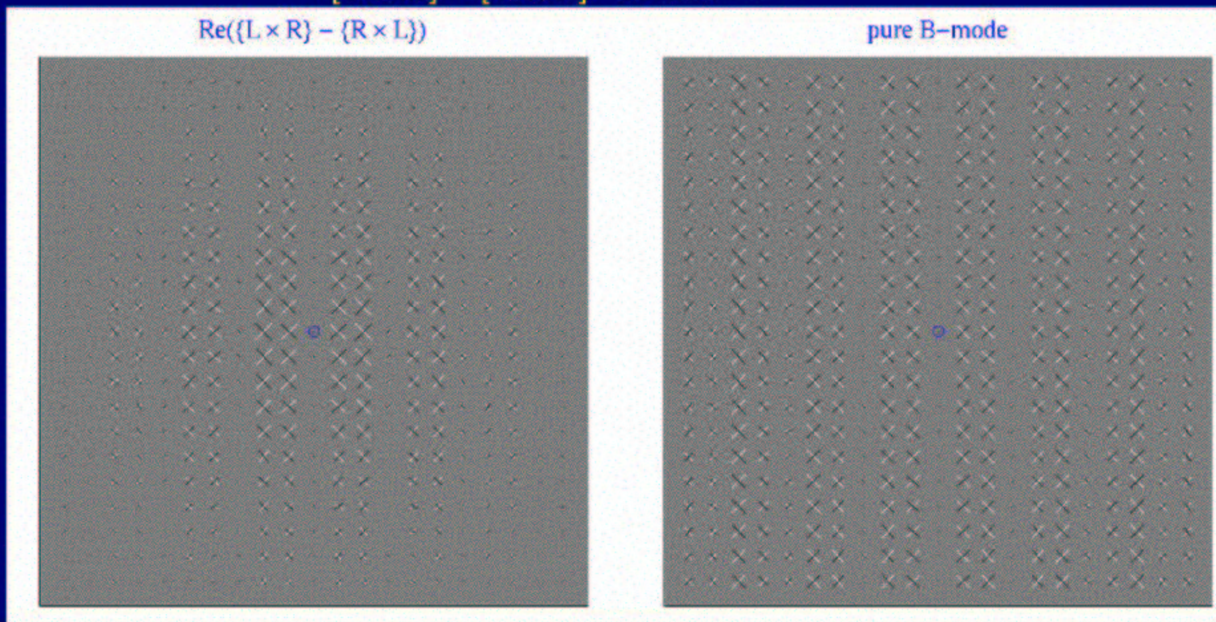



Polarization Response Pattern
$[L \times R] \propto [Q + iU]e^{2\pi i \mathbf{u} \bullet \mathbf{x}}$
Re{L × R}
Im{L × R}


Polarization Response and E-modes
$[L \times R] \propto [Q + iU]e^{2\pi i \mathbf{u} \bullet \mathbf{x}}$
$[R \times L] \propto [Q - iU]e^{2\pi i \mathbf{u} \bullet \mathbf{x}}$
$[L \times R] + [R \times L] \propto Qe^{2\pi i \mathbf{u} \bullet \mathbf{x}}$
Re({L × R} + {R × L})
pure E–mode

Polarization Response and B-modes

$$[L \times R] \;\propto\; [Q + iU]e^{2\pi i \mathbf{u}\bullet\mathbf{x}}$$
$$[R \times L] \;\propto\; [Q - iU]e^{2\pi i \mathbf{u}\bullet\mathbf{x}}$$
$$[L \times R] - [R \times L] \;\propto\; iUe^{2\pi i \mathbf{u}\bullet\mathbf{x}}$$



Current Polarization Experiments

(representative sample)

- HEMT based: coherent, low sensitivity
  - PIQUE/CAPMAP
  - Polar/Compass
  - DASIPOL
  - MAP
- Bolometer based: incoherent, high sensitivity
  - Boomerang 2001
  - Maxipol
  - Planck

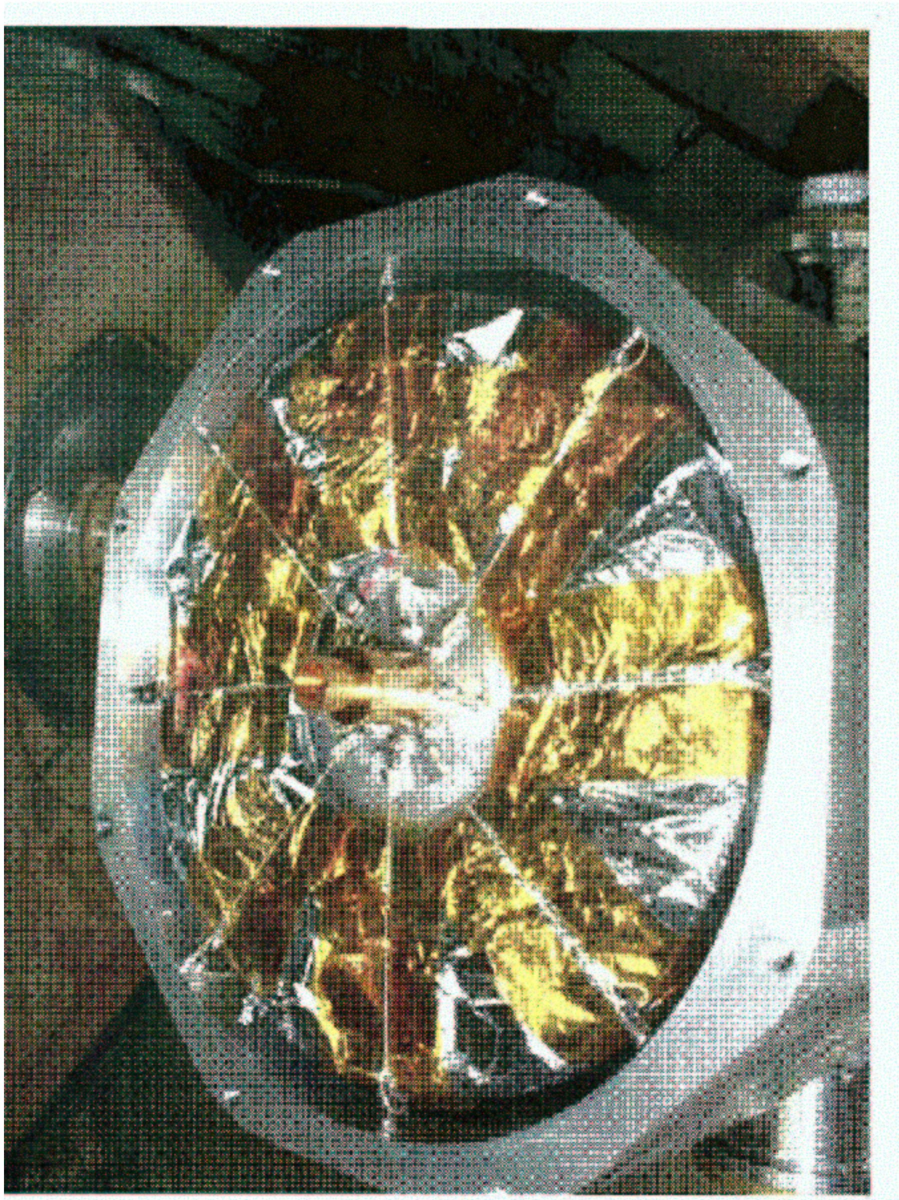
Experiments distinguished by
•Frequency coverage
•Sensitivity
•Scanning strategy
•Systematic controls

	Frequencies (#)	Beam	Site	Technique
POLAR	30 (1)	7°	WI	Correl. Rad., axial spin
COMPASS	30 (1), 90 (1)	20', 7'	WI	Correl. Rad., NCP scan
PIQUE	40 (1), 90 (1)	30', 15'	NJ	Correl. Rad., NCP chop
CAPMAP	40 , 90	13', 6'	NJ?	Correl. Rad. Array
DASI	30 (13)	20', 7'	S. Pole	Interferometer
CBI	30 (13), 90 (13)?	3'	Atacama	Interferometer
VLA	8.4	6"	Socorro	Interferometer
Polatron	90 (1)	2'	OVRO	Bolo,1/2 λ plate
QUEST	150 , 225 (~30)	4', 3'	Chile?	Bolo Array, 1/2 λ plate
* POLARBEAR	150 … (3000 dt'rs)	10'	S. Pole or M. Kea	Bolo Array
BOOM2K	150 (4), 240 (4), 340 (4)	10'	Antarctic LDB	Bolo Array
MAXIPOL	150 (12), 420 (4)	10'	US-Balloon	Bolo Array,cold 1/2 λ plate
BaR-SPOrt	32, 90	30', 12'	Antarctic LDB	Correl. Rad. Array
MAP	22, 30, 40(2), 60(2), 90(4)	13'	L2, full-sky	Correl. Rad. Array*
SPOrt	22, 32, 60, 90	7°	ISS, full-sky	Correl. Rad. Array
PLANCK-LFI	30(4), 44(6), 70(12),100(34)	33',23',13', 10'	L2, full-sky	Correl. Rad. Array
PLANCK-HFI	100(4), 143(12), 217(12), 353(6), 545(8), 857(6)	11', 8, 6', 5', 5', 5'		Bolo Array

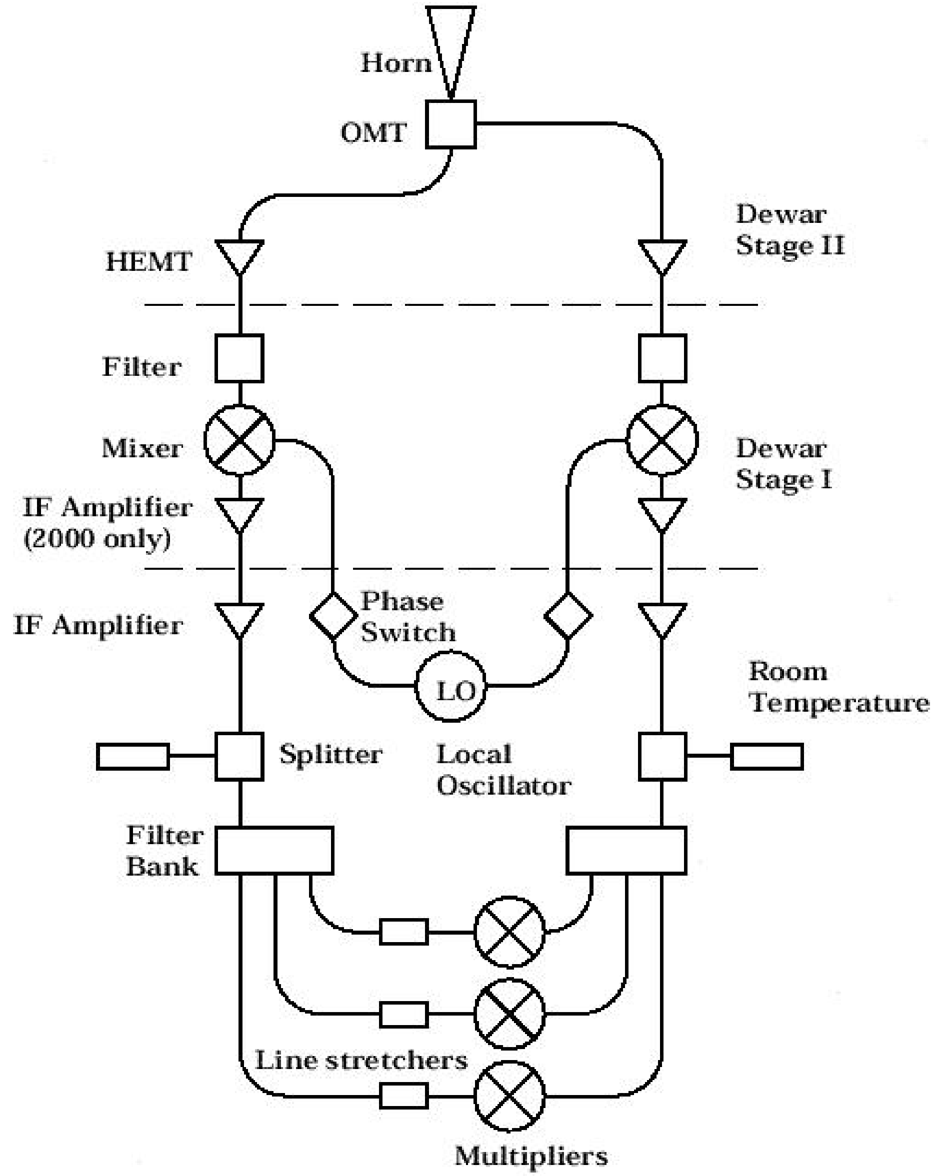
Compilation by Peter Timbie

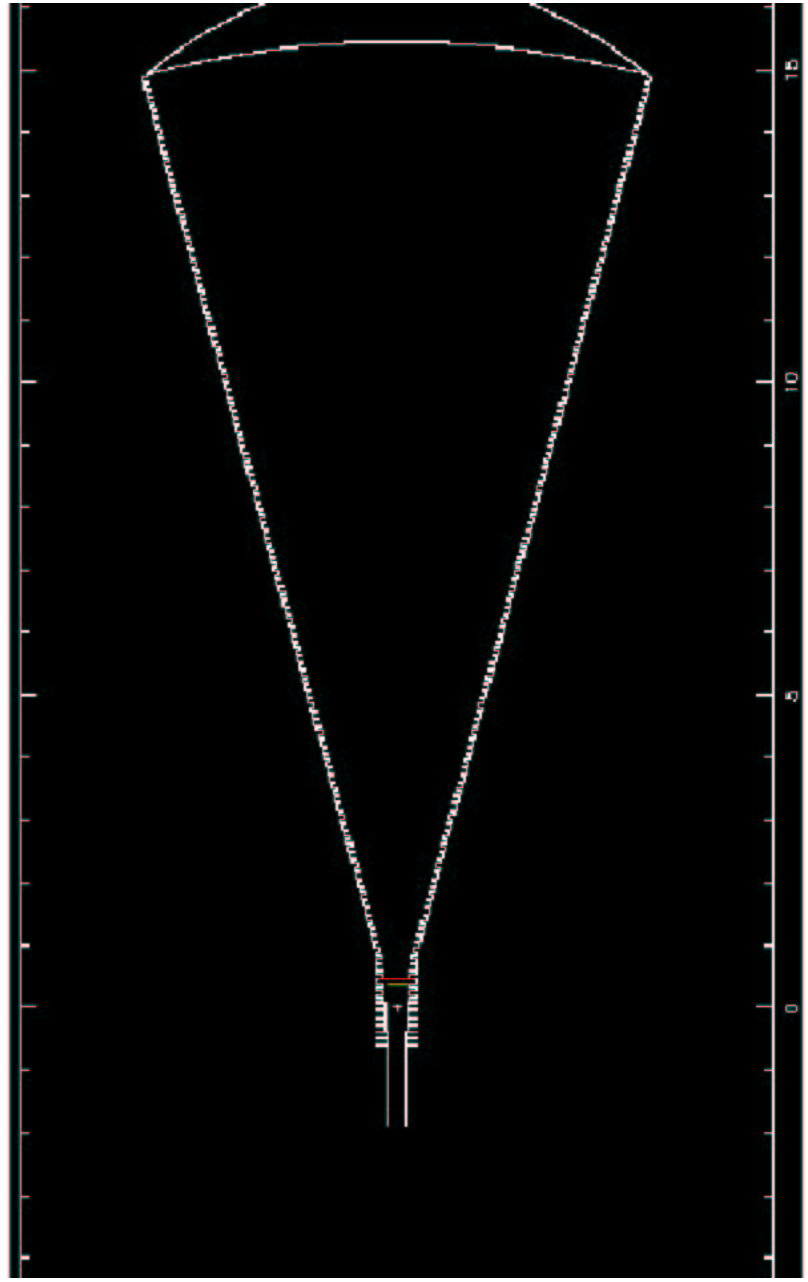
CAPMAP

- Chicago
  - M. Hedman, D. Sharaf, D. Samtleben, B. Winstein + 4 undergraduates
- Miami
  - J. Gundersen, E. Stefanescu + undergraduates
- Princeton
  - D. Barkats, P. Farese, J. Mcmahon, S. Staggs + lots of undergraduates
- Todd Gaier (JPL)

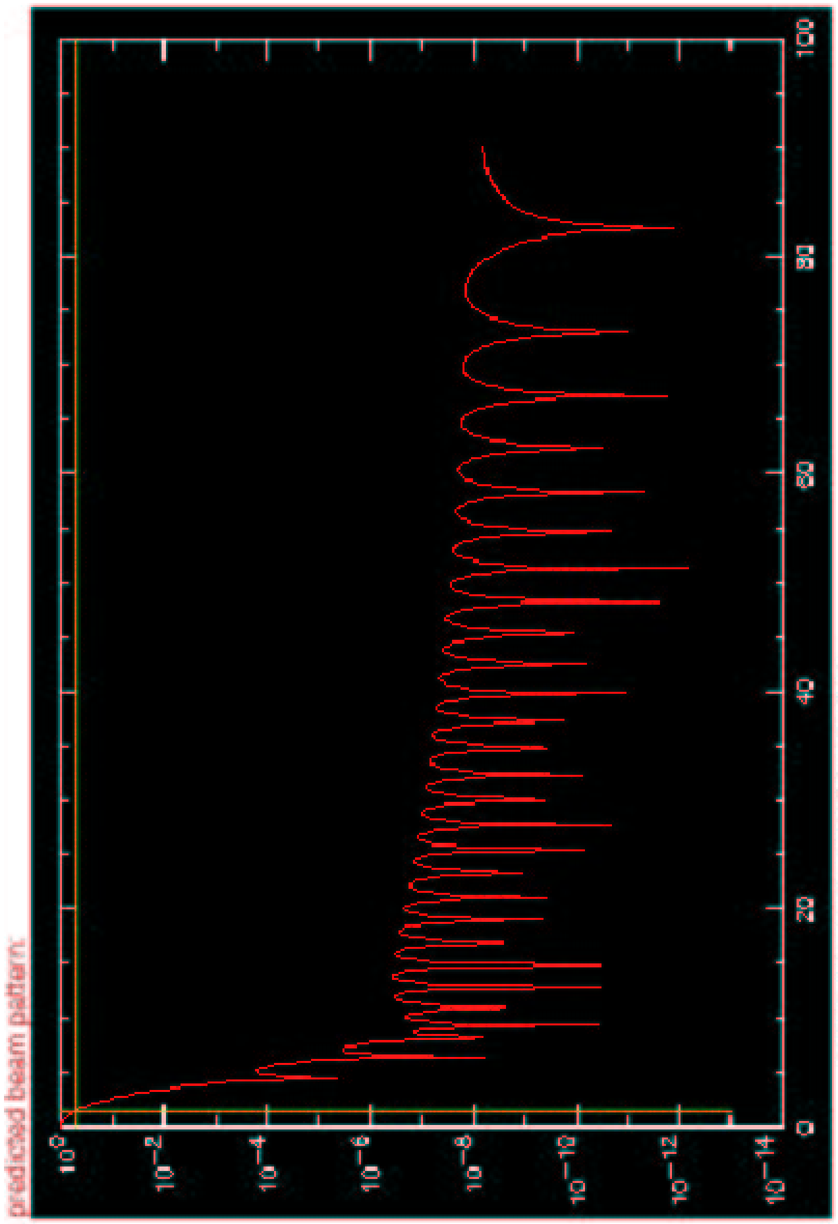


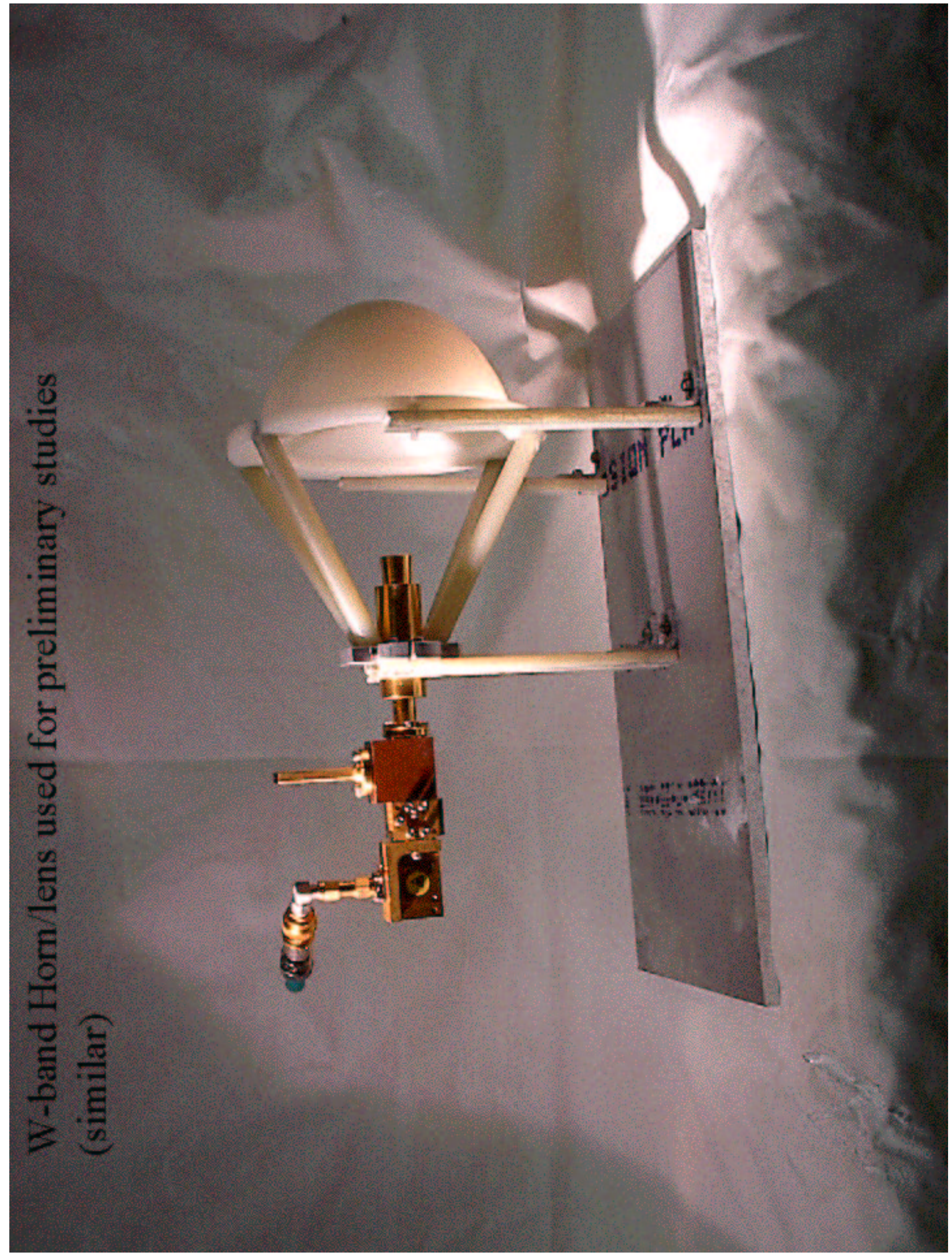
PIQUE 90 GHz Dewar



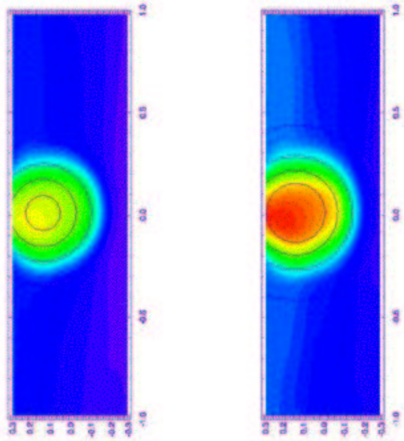


CAPMAP horn/lens design

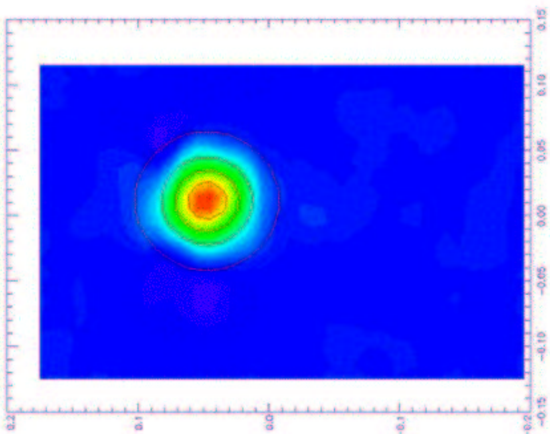

predicted beam pattern:
horn beam pattern: (15deg hwhp)
0
20
40
60
80
100
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}


W-band Horn/lens used for preliminary studies
(similar)

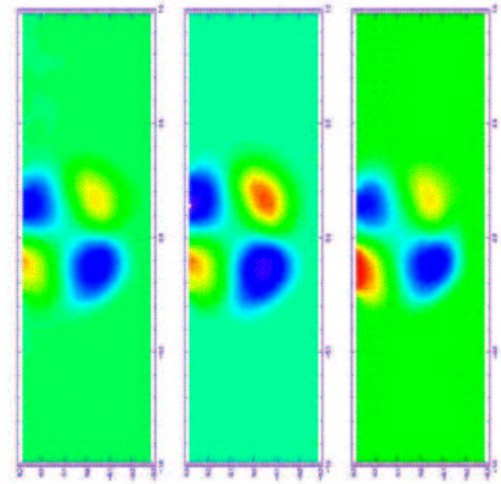
Moon
(total power)



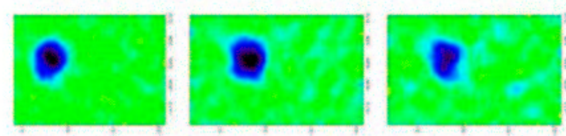
Jupiter
(total power)

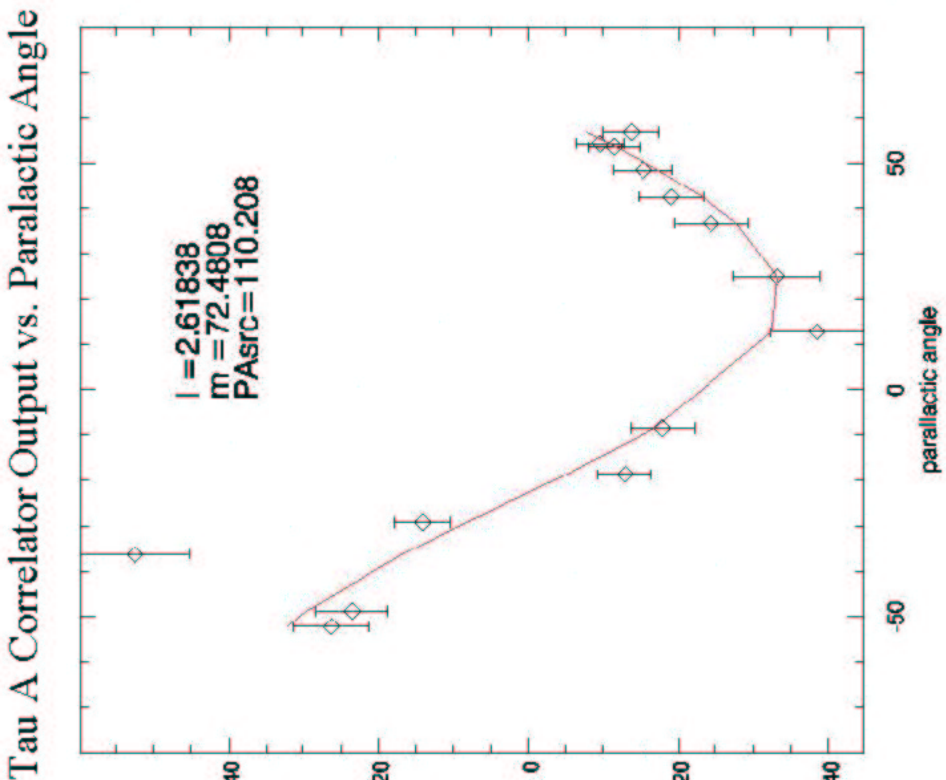


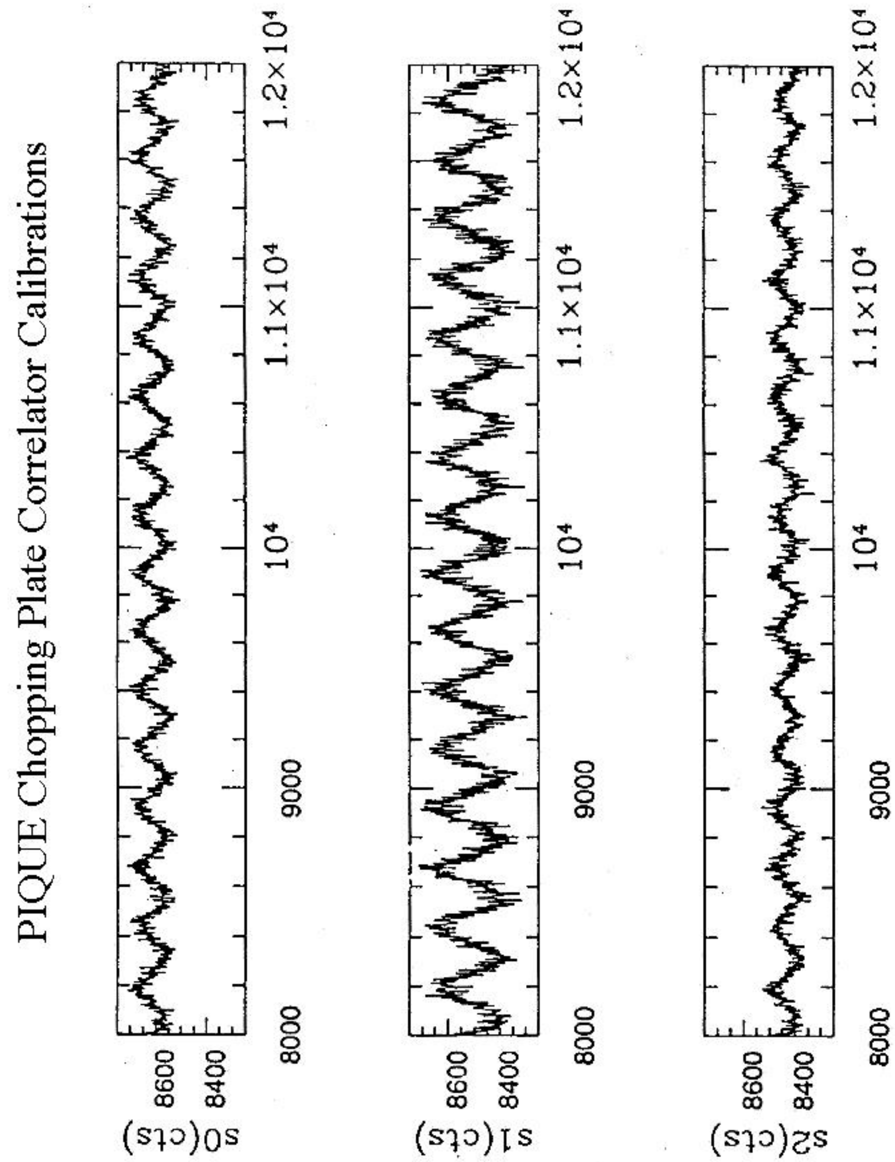
Moon
(three polarization channels)



Tau A
(three polarization channels)




Tau A Correlator Output vs. Paralactic Angle
I =2.61838
m =72.4808
PAsrc=110.208
parallactic angle


PIQUE Chopping Plate Correlator Calibrations
s0(cts)
s1(cts)
s2(cts)

CAPMAP Strategy

- Concentrate at the best angular scale
  - 3' beam
- Map a small cap around the NCP
  - High sensitivity
- Try a ring scan, like TOPHAT (Dale Fixen)
  - May fallback on an az-scan

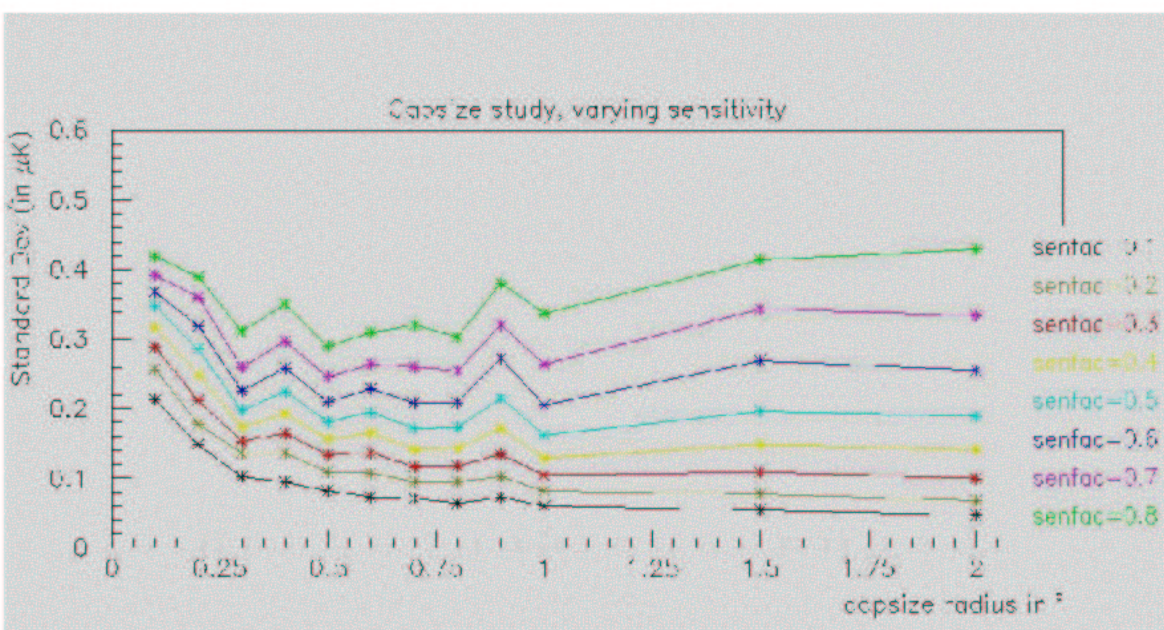
Single Horn Improvements

	PIQUE	CAPMAP	Factor
Hours	250	250	1.0
T_{sys}	130	90	1.44
BW	12 GHz	15 GHz	1.12
Modes	Half	All	1.41
Signal (expected)	2 μK	5 μK	2.5

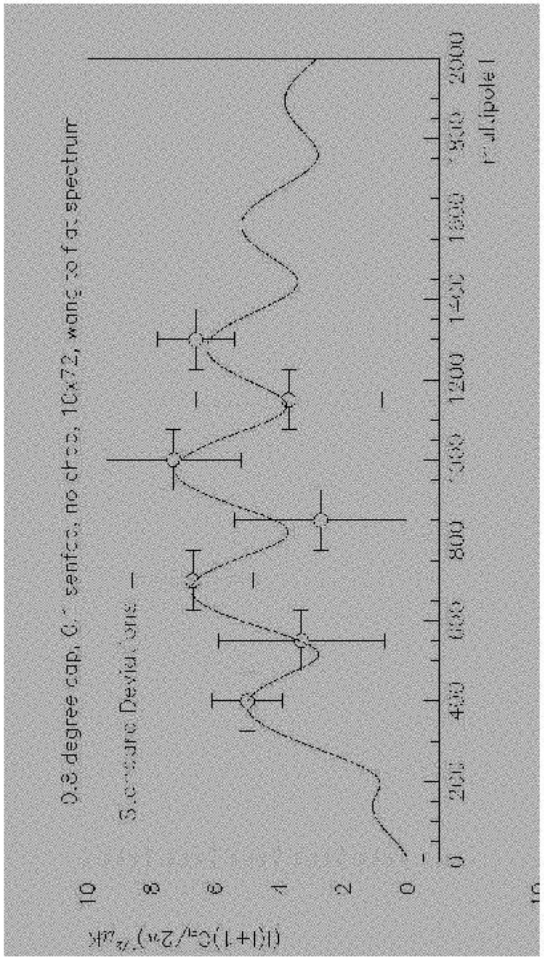
Over Factor = 5.7

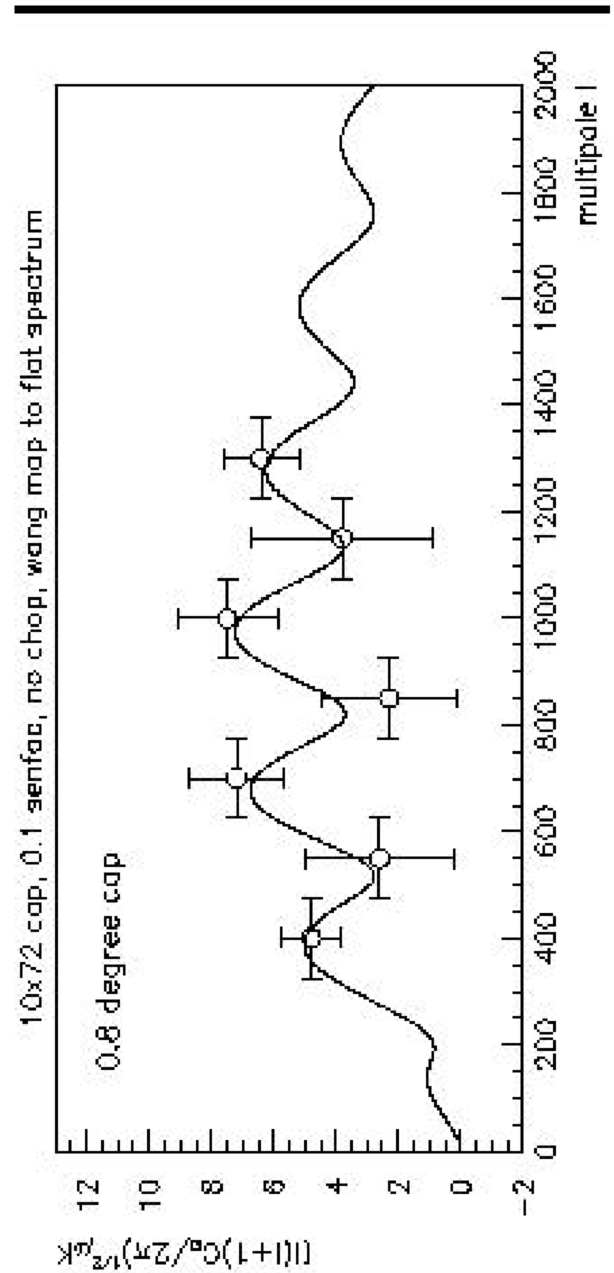
Senfac = 0.8 μK, W-band

SENSITIVITY SIMULATIONS
(using CfCP 32-node cluster)

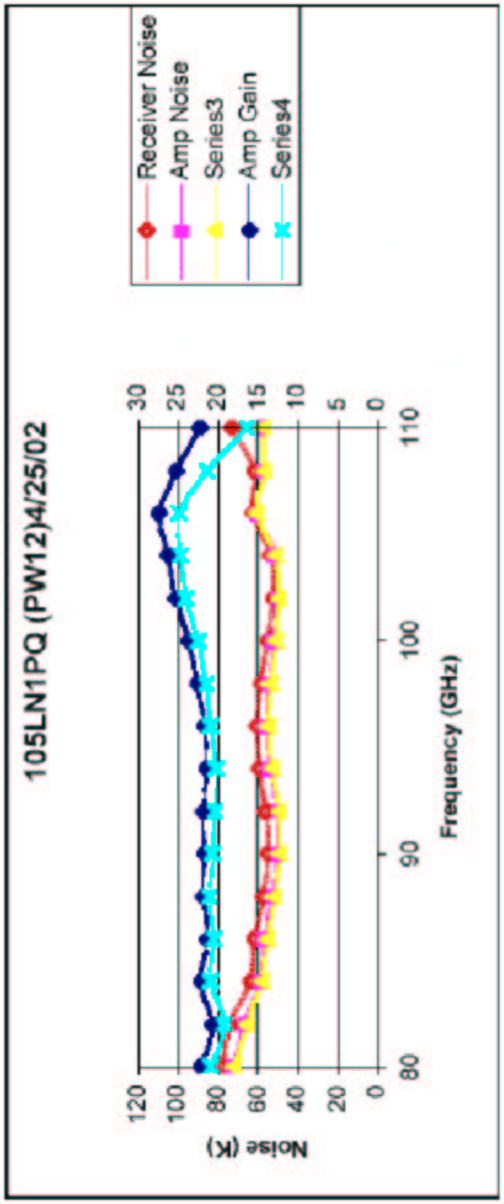


CAPMAP Multi-band Sensitivity





"Typical" CAPMAP HEMT Performance



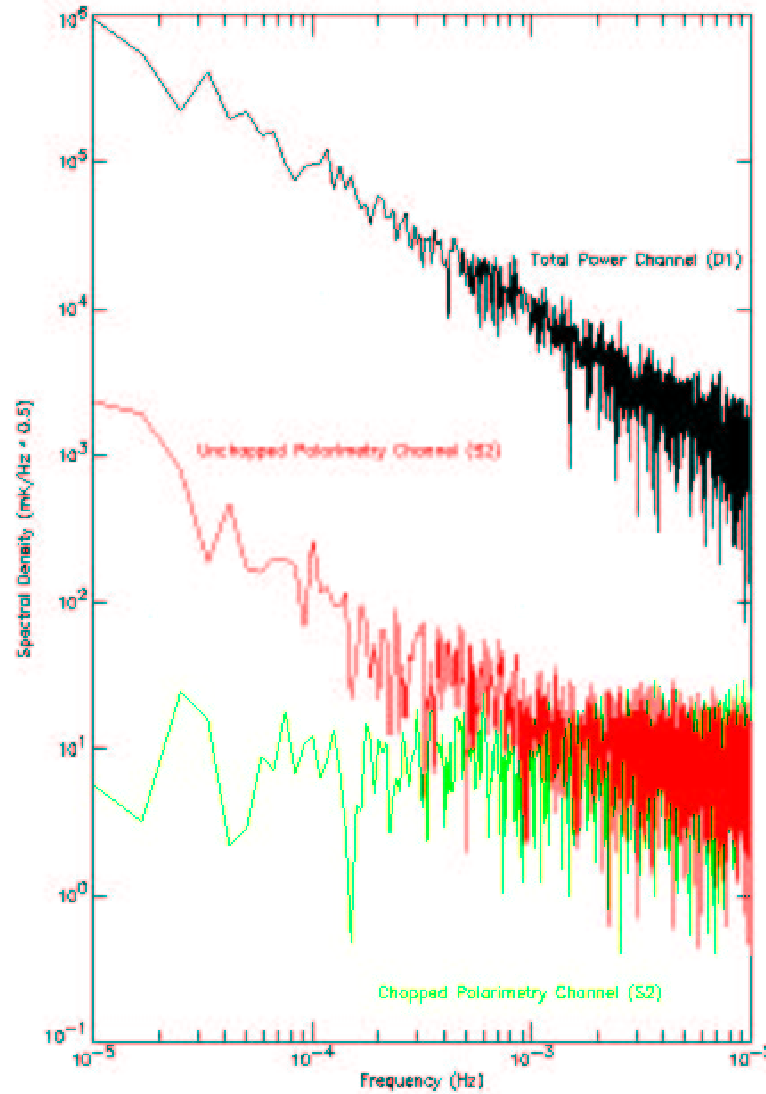
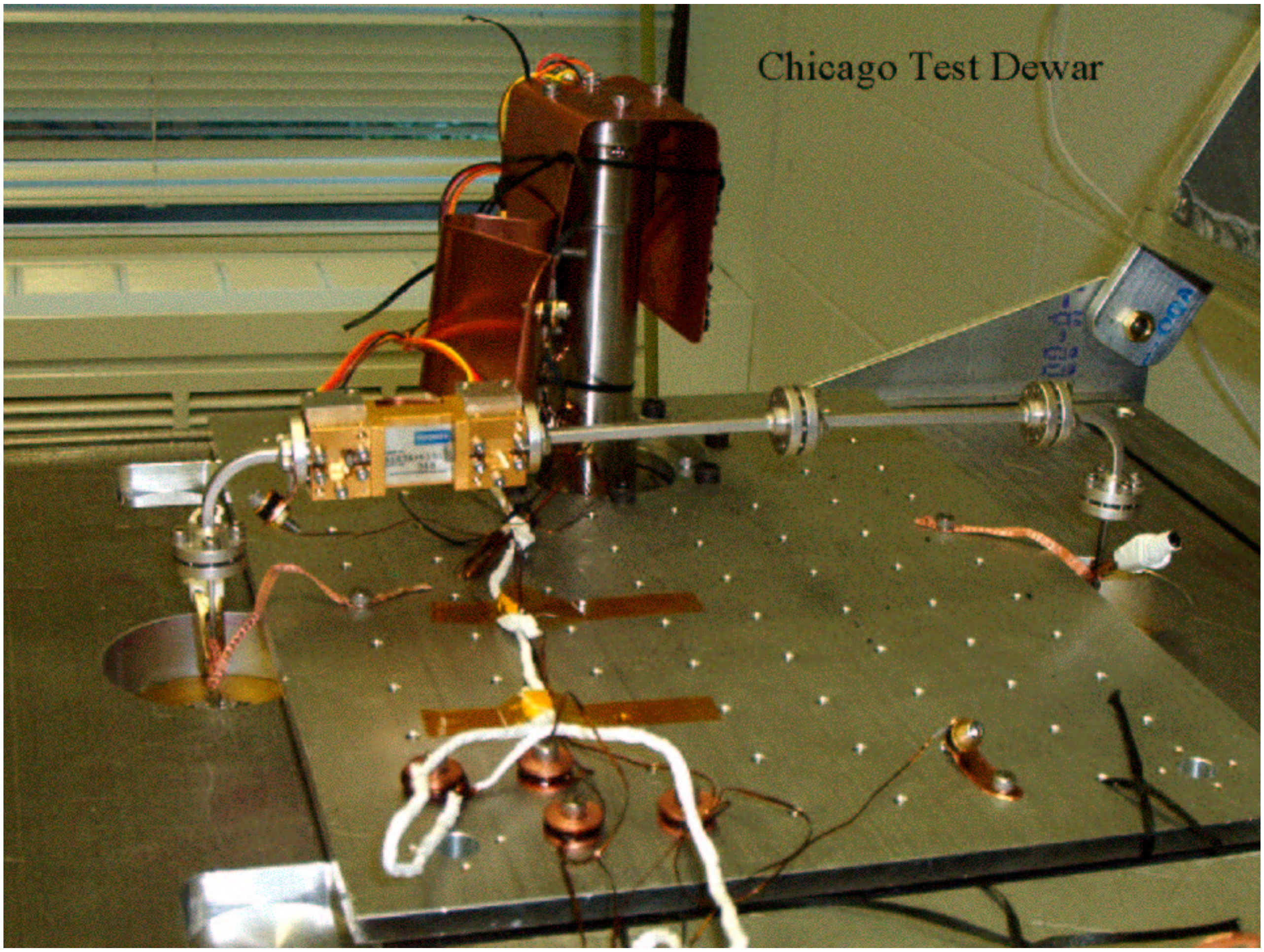
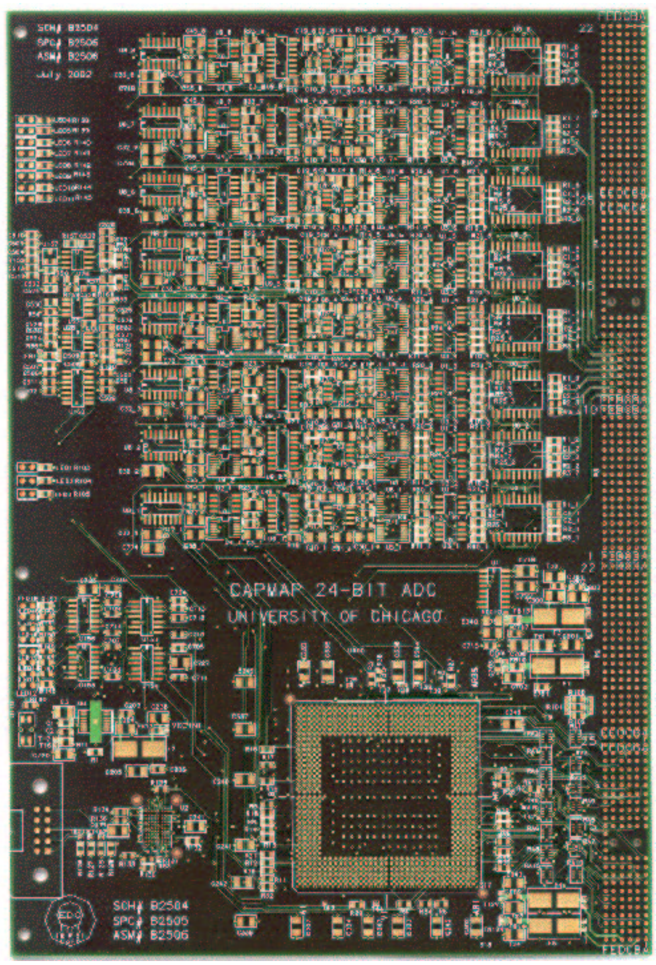


Figure 7.2: Power spectra from a day (February 22, 2000) during the first observing season. The power spectra of a total power channel, an unchopped multiplier channel, and a chopped multiplier channel are shown



CAPMAP DAQ

- cPCI card
- Gain/filtering/offsets
- Sigma-delta 32 kHz
- 24 bit resolution
- Coadding in FPGA
  - Digital demodulation
  - 250 Hz
- 7 GB per day



Conclusions

- Polarization is the next frontier in the CMB
- We hope that CAPMAP will contribute
  - Sensitivity at the most interesting scales (l=1000)
  - SENFAC=0.4 μK, this winter (4 horns)
  - SENFAC<0.2 μK, after 3 seasons (10 horns)
  - Q-band sensitivity a bonus (KUPID)
  - Polarized offsets must be handeled

KUPID-

Ku-band Polarization Identifier

University of Miami – J. Gundersen
University of Chicago – B. Winstein
Princeton University – S. Staggs

SCIENCE GOALS
- Survey polarized galactic synchrotron at 12-18 GHz
- Characterize anomalous (spinning dust?) foreground
- Measure CMB polarization in low foreground regions
- Follow-up observations of interesting regions identified by MAP and other CMB experiments

RECEIVER SYSTEM
- Phase switched, homodyne correlation polarimeter
- Multiplexed into three, 2-GHz bands between 12-18 GHz
- Incorporates low noise (5 K) NRAO HEMT amplifiers
- Designed for simultaneous measurement of Q and U Stokes parameters – also measures T with degraded sensitivity

ANTENNA SYSTEM
- Crawford Hill 7 meter off-axis cassegrain (shown at left)
- FWHM=0.2° at 15 GHz – well matched to MAP, PIQUE and COMPASS

FIRST LIGHT - Late Spring 2003