QUIET

THE Q/U IMAGING EXPERIMENT

MEASURING CMB POLARIZATION
WITH
MASSIVE ARRAYS OF COHERENT DETECTORS

C. R. Lawrence, JPL

& the QUIET Collaboration

Zel'dovich-90
SPACE RESEARCHINSTITUTE, 2004 DECEMBER 21

Overview

The QUIET experiment is a 5-year program to measure the polarization of the CMB with accuracy near the limit of what is possible from the ground

- Large arrays of coherent (i.e., phase preserving) detectors
- Two frequencies (40 and 90 GHz)
- Multiple telescopes (3 × 2 m + 7 m) at 5,080 m in the Atacama desert
- Angular scales from a few arcminutes to a few degrees

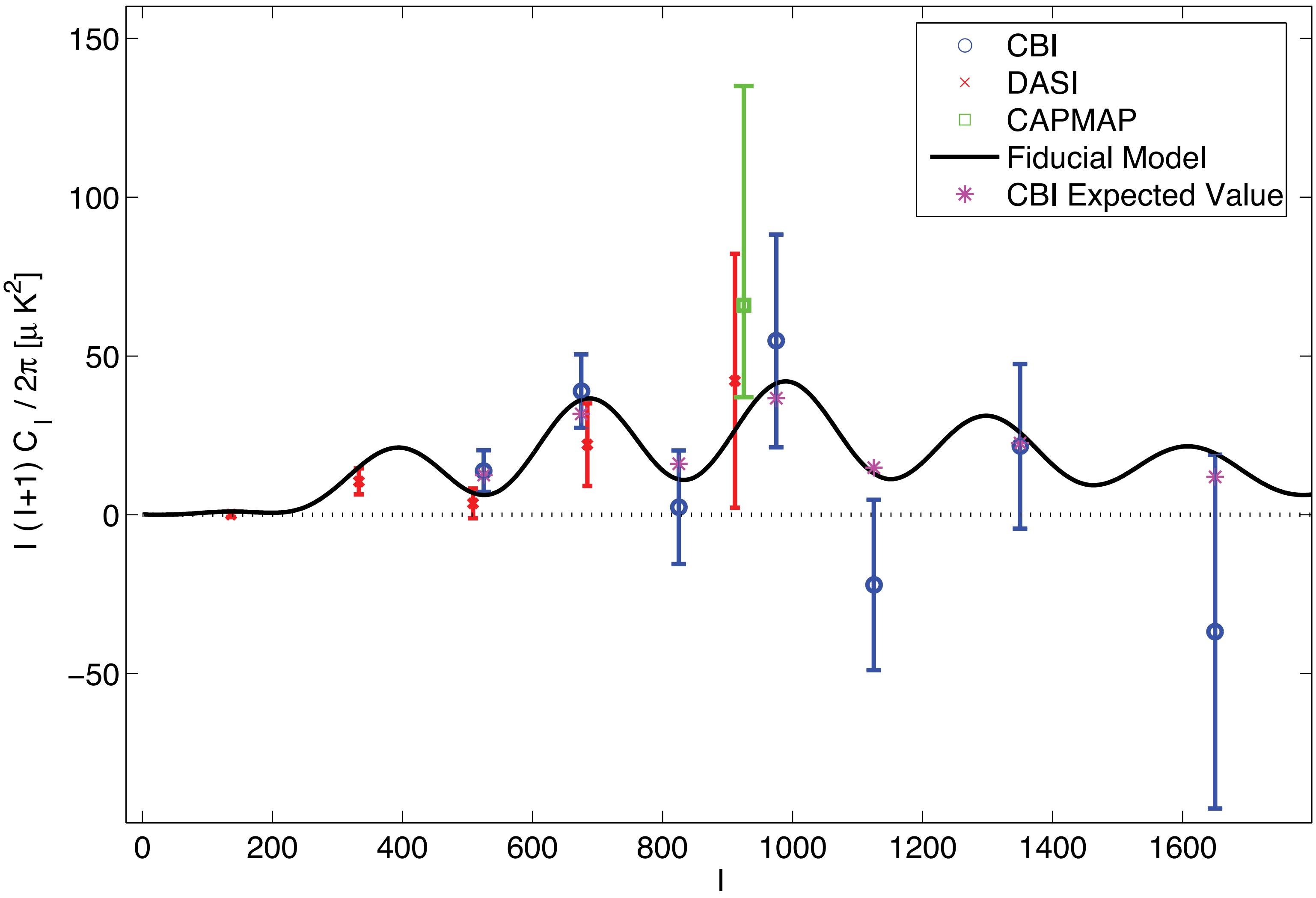
- Collaboration involving JPL, Berkeley, Caltech, Chicago, Columbia, GSFC, Harvard SAO, Miami, and Princeton

- Two phases
  - $\sim$100 feeds in Phase I
  - $\sim$1000 feeds in Phase II

CMB Polarization

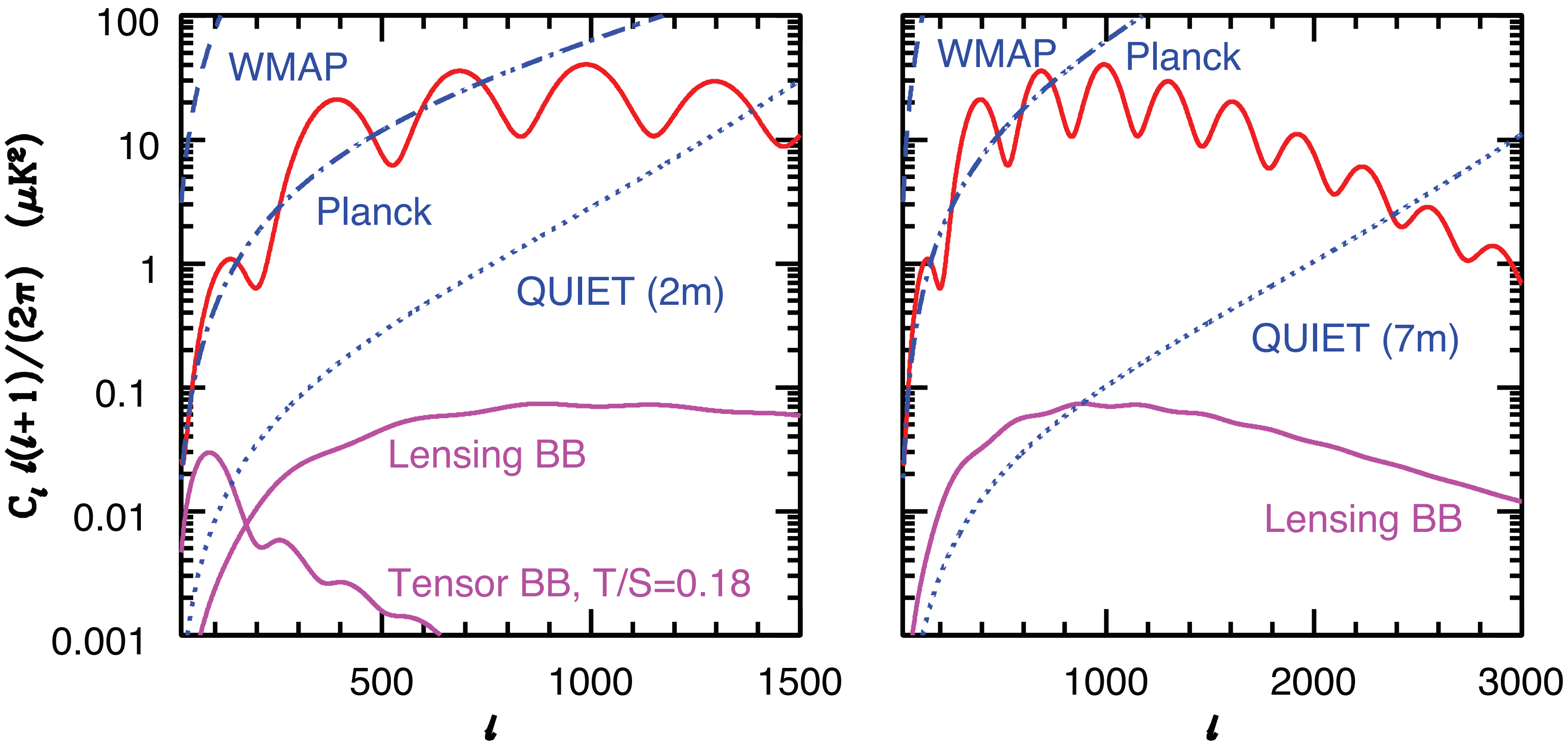
- For 40 years, the cosmic microwave background has been our most important source of information about the geometry and contents of the Universe
- CMB polarization comes from Thomson scattering of quadrupole anisotropies in the surface of last scattering
- E-mode (“gradient”) polarization results from density perturbations
  - Encodes information about the Universe not contained in intensity variations
  - Different constraints on cosmological parameters
    - Slope of the primordial spectrum
    - Reionization
- B-mode (“curl”) polarization results from vector or tensor perturbations or higher order effects such as gravitational lensing
  - Gravitational waves produced by inflation
    - Amplitude constrains expansion rate—directly related to energy scale of inflation
    - Probe of Unification Physics—well beyond the reach of accelerators
  - Gravitational lensing
    - Mass distributed in the Universe converts primordial E-modes into B-modes
    - Unique constraints on massive neutrinos, dark matter velocity dispersion, running of the spectral index

E-mode Measurements To Date



Readhead et al. 2004

Fluctuation Levels and Expected QUIET Noise Levels



- E-mode fluctuations are a few percent the level of intensity fluctuations
- B-mode fluctuations from lensing are smaller still
- B-mode fluctuations from gravitational waves are likely smaller still—could be zero!

Important Facts—#1

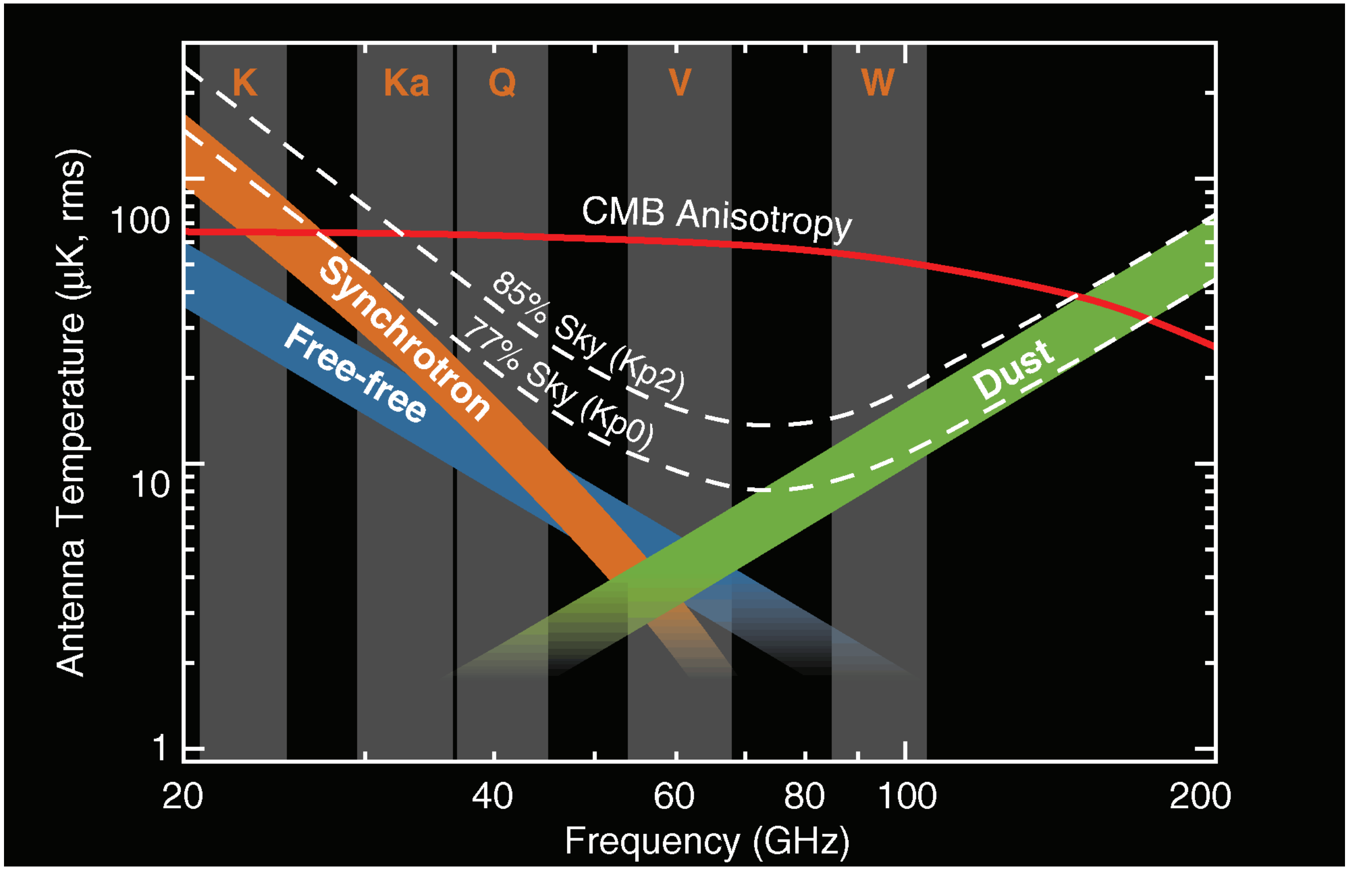
- Individual detectors are approaching fundamental physical limits to noise
  - Photon statistics of background itself
  - Quantum limit for coherent systems ($q \approx h\nu/k$)

The only way to achieve lower noise is to increase N detectors × Integration Time

$$\boxed{\text{N must be large!}}$$

Important Facts—# 2

- Temperature foreground minimum on ∼1° angular scales is at 70 GHz



- Determination of polarized foreground minimum not published yet
- Let's assume the minimum frequency isn't very different

Much of critical frequency range accessible from ground!

Important Facts—# 3

- Polarized atmospheric fluctuations are dramatically lower than atmospheric intensity fluctuations
  - CBI has not detected atmospheric noise in polarization

Therefore...

- Observations of CMB polarization from the ground with
  - A large number of detectors
  - In the frequency range 30–150 GHz
  - From a high, dry site

offer spectacular promise!

Key Ingredient

- Ten years of technology development in cryogenic mm-wave amplifiers

+

- A recent breakthrough in packaging technology for mm-wave circuits

enable

- Huge, affordable arrays of high performance, coherent polarimeters

MMICs

Monolithic Micro/millimeterwave Integrated Circuits offer the:

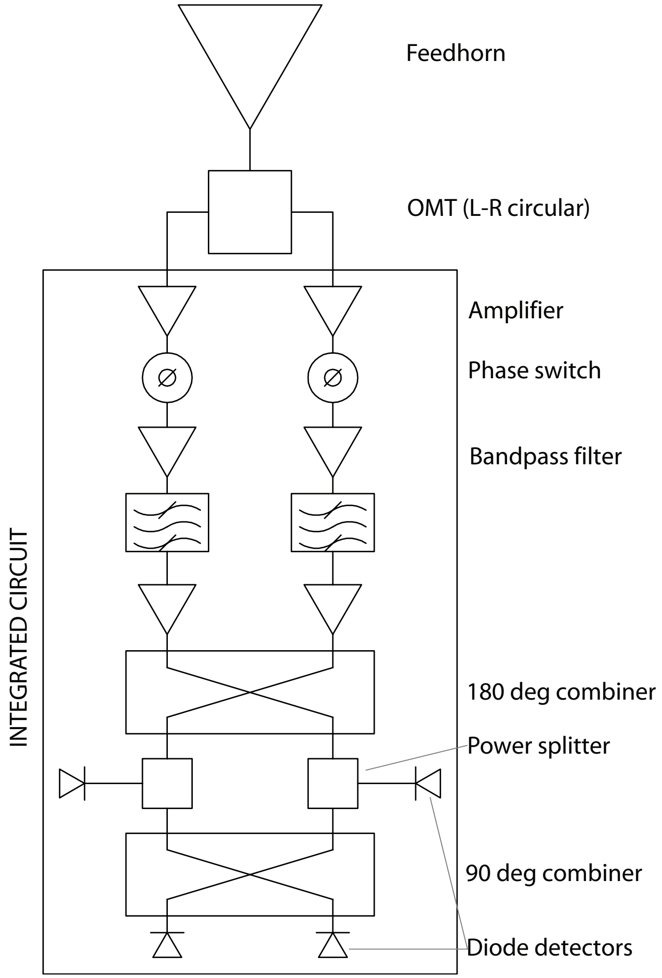
- Best performance at frequencies above 30–40 GHz
- Highly repeatable performance
- Easy integration
  - A 90 GHz WMAP amplifier, made from discrete transistors, took 2 weeks to build
  - A Planck 100 GHz prototype MMIC amplifier took 2 hours to build

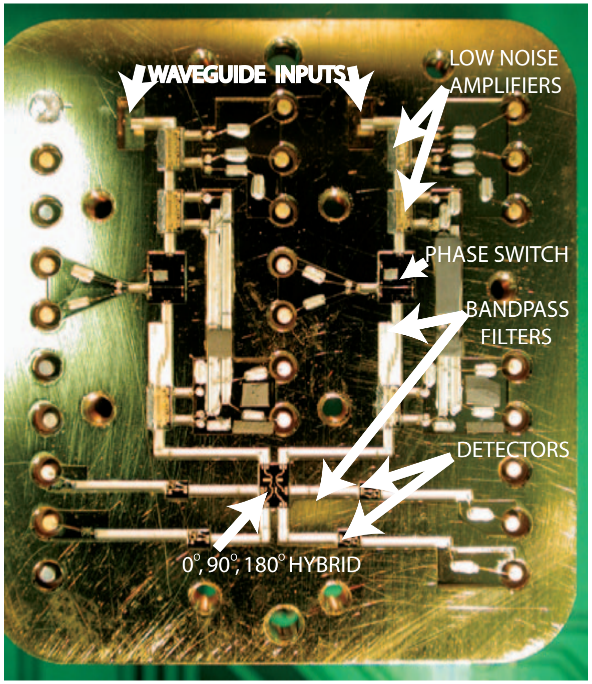
Recent Breakthrough

- New approach, based on breakthrough in packaging developed by Todd Gaier and Mike Seiffert at JPL
  - Low cost packages with minimal DC functionality
  - Completely automated assembly
  - Automated testing and bias tuning
  - Modules Reside on a "motherboard" which provides all DC functions (e.g., bias, A/D, readout)

No radio frequency cables or connectors!

Q/U Polarimeter Schematic





$$\Longrightarrow \quad \frac{E_x+iE_y}{\sqrt{2}} \quad \frac{E_x-iE_y}{\sqrt{2}}$$

$$\frac{A+B}{\sqrt{2}} = E_x \qquad \frac{A-B}{\sqrt{2}} = iE_y \qquad \text{with } \phi = 0^\circ$$

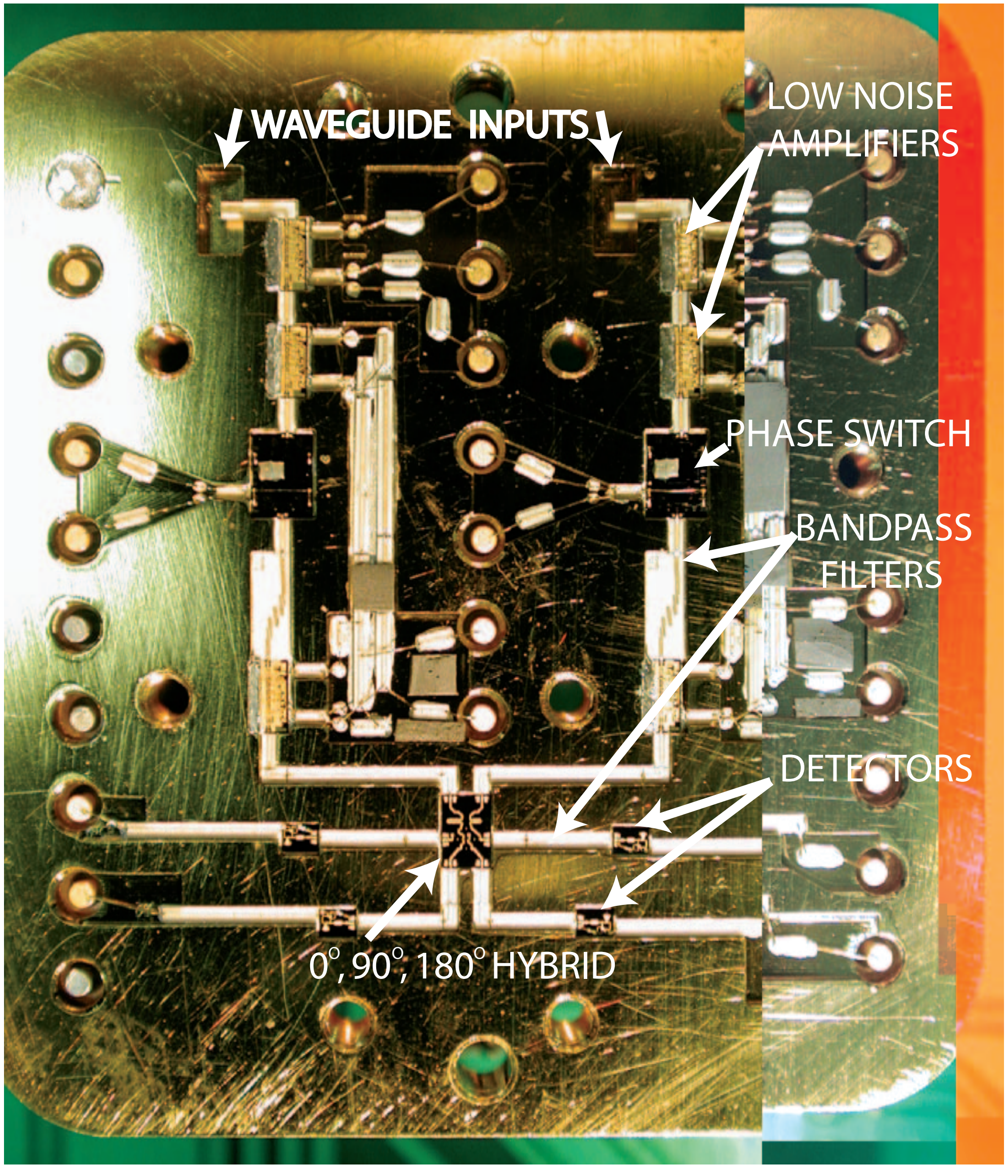
$$\Longrightarrow \quad \frac{A+B}{\sqrt{2}} = iE_y \qquad \frac{A-B}{\sqrt{2}} = E_x \qquad \text{with } \phi = 180^\circ$$

$$\Longrightarrow \quad VV^* = E_x^2 \qquad E_y^2 \quad \Longrightarrow \qquad E_x^2 - E_y^2 \equiv \text{ “}Q\text{”}$$

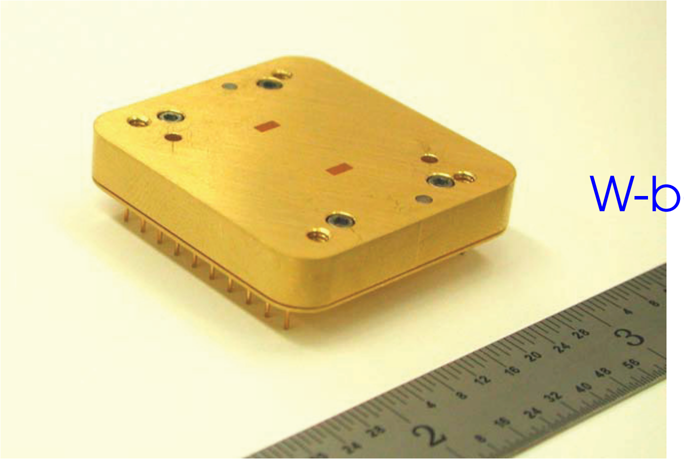
$$\frac{A+iB}{\sqrt{2}} = E_x - E_y \qquad \frac{B+iA}{\sqrt{2}} = i(E_x + E_y) \qquad \text{with } \phi = 0^\circ$$

$$\Longrightarrow \quad VV^* = -E_xE_y \qquad E_xE_y \quad \Longrightarrow \qquad E_xE_y \equiv \text{“}U\text{”}$$

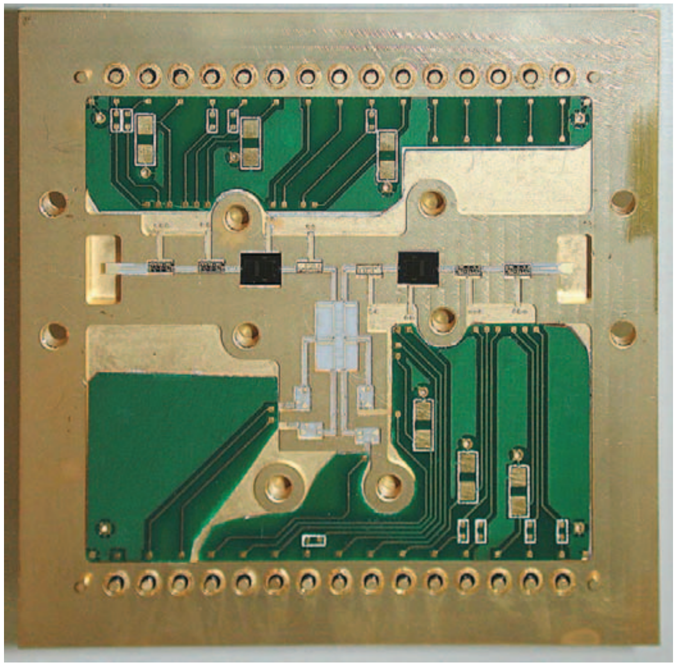
Modules



W-band, 1.″25 × 1″

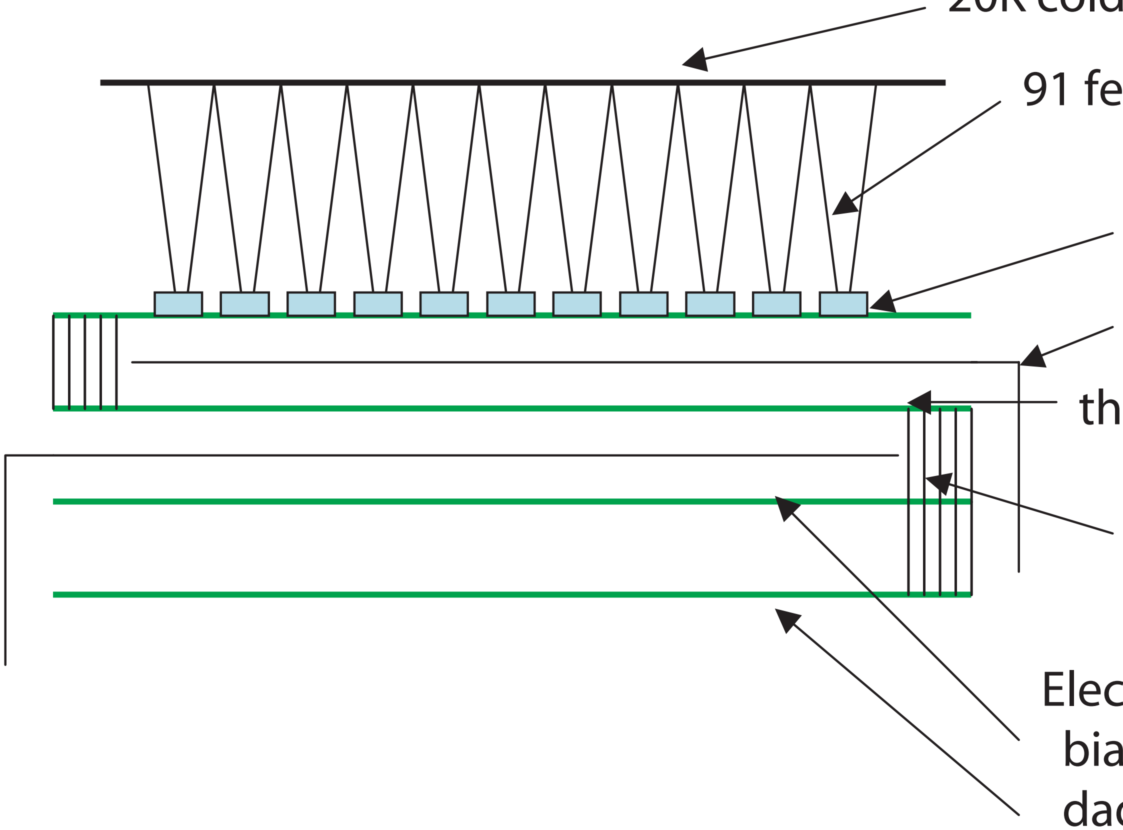


W-band



Q-band, 2″ × 2″

Modules & Circuit Boards



20K cold stage and feed horn support*

91 feeds + OMTs, hex close pack

module board

80K shield

thermal interconnect board

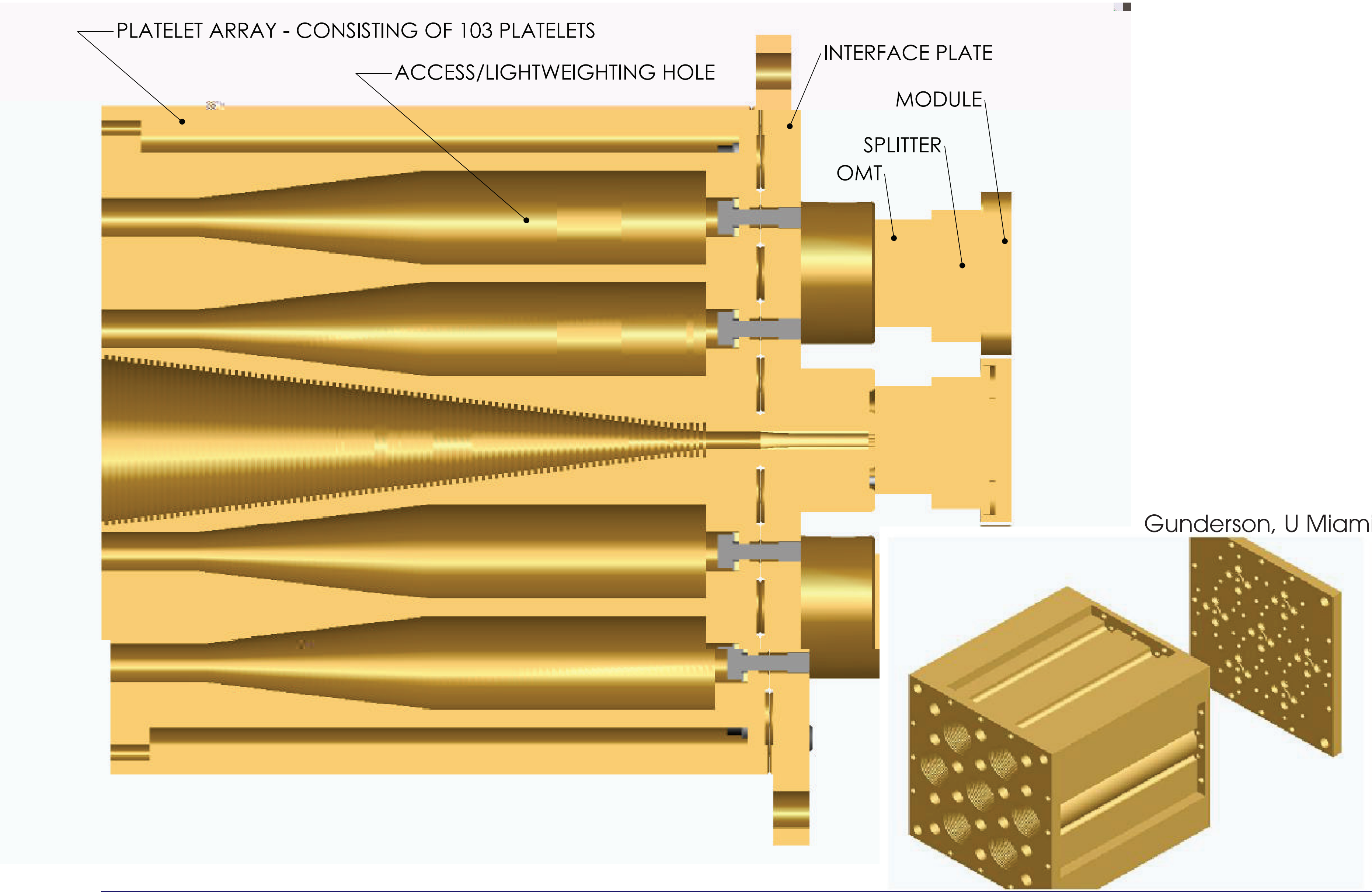
boards plug together!

Electronics stack:
bias (91 x 16)
daq (91 x 4)

Key Points

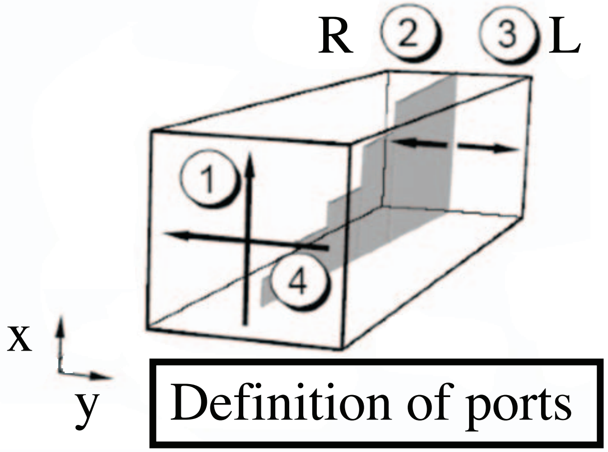
- Complete correlation polarimeter, RF in, DC out
  - Can just as easily be configured to measure differential intensity from two feeds
- Simultaneous measurement of Stokes Q and U
  - Once the “quantum tax” is paid in the first amplification, the full phase-coherent signal can be used multiple times
  - Cannot be done with direct detectors
- No cables, no connectors on module
- Large number of pins allows independent optimization of bias for all transistors
  - Tuning can be done under computer control for multiple modules simultaneously
- Bias and readout circuitry all on silicon boards
- All parts can be mass produced inexpensively
- Scalable to thousands of elements

Feed Array—7-element Prototype

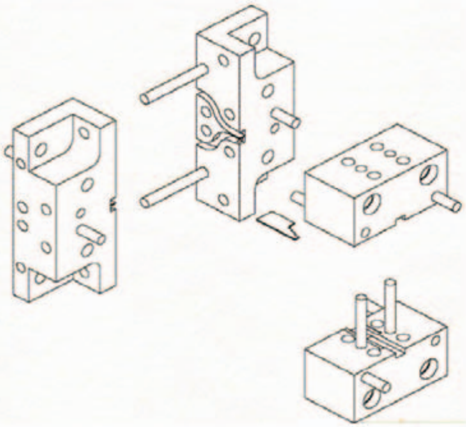


Gunderson, U Miami

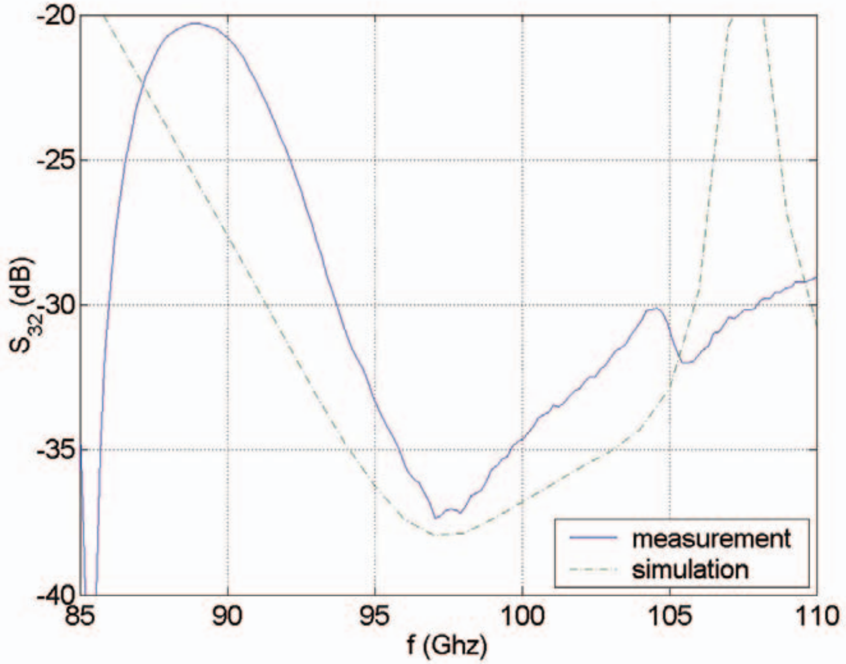
Polarizers



Definition of ports



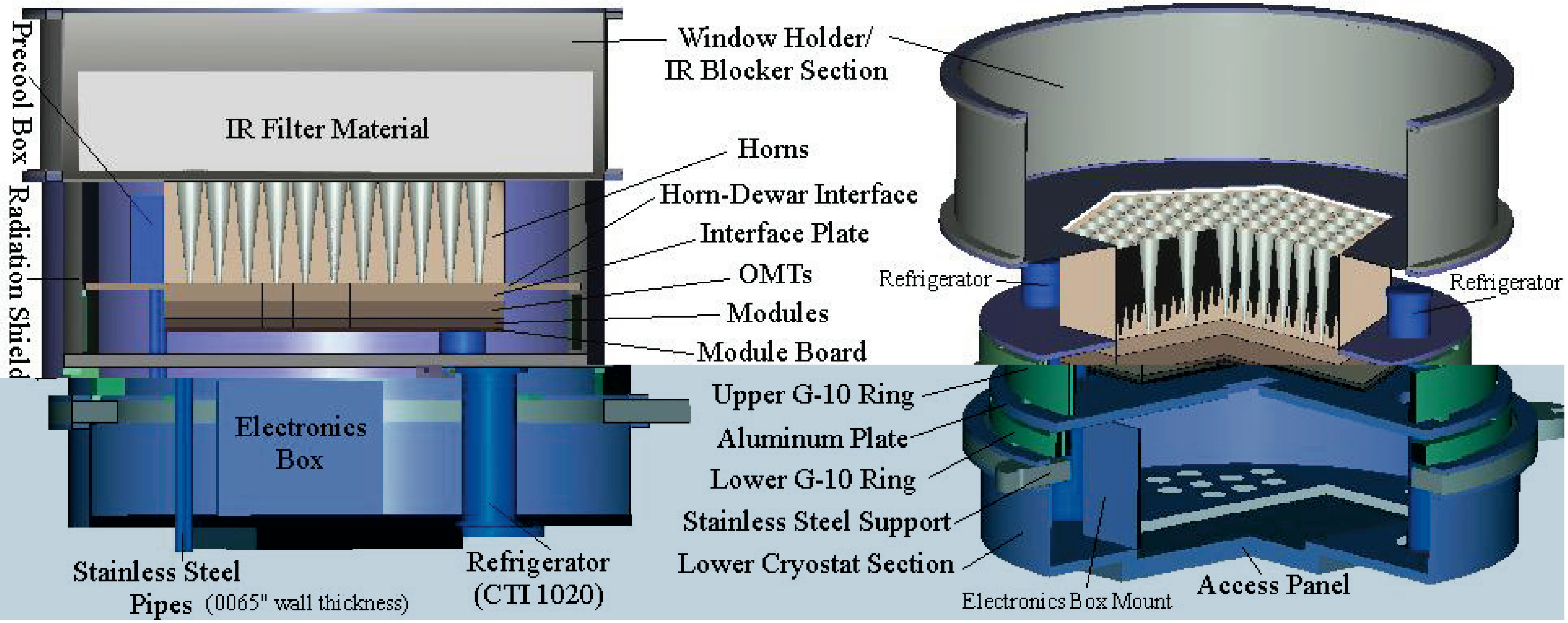
Assembly of split blocks



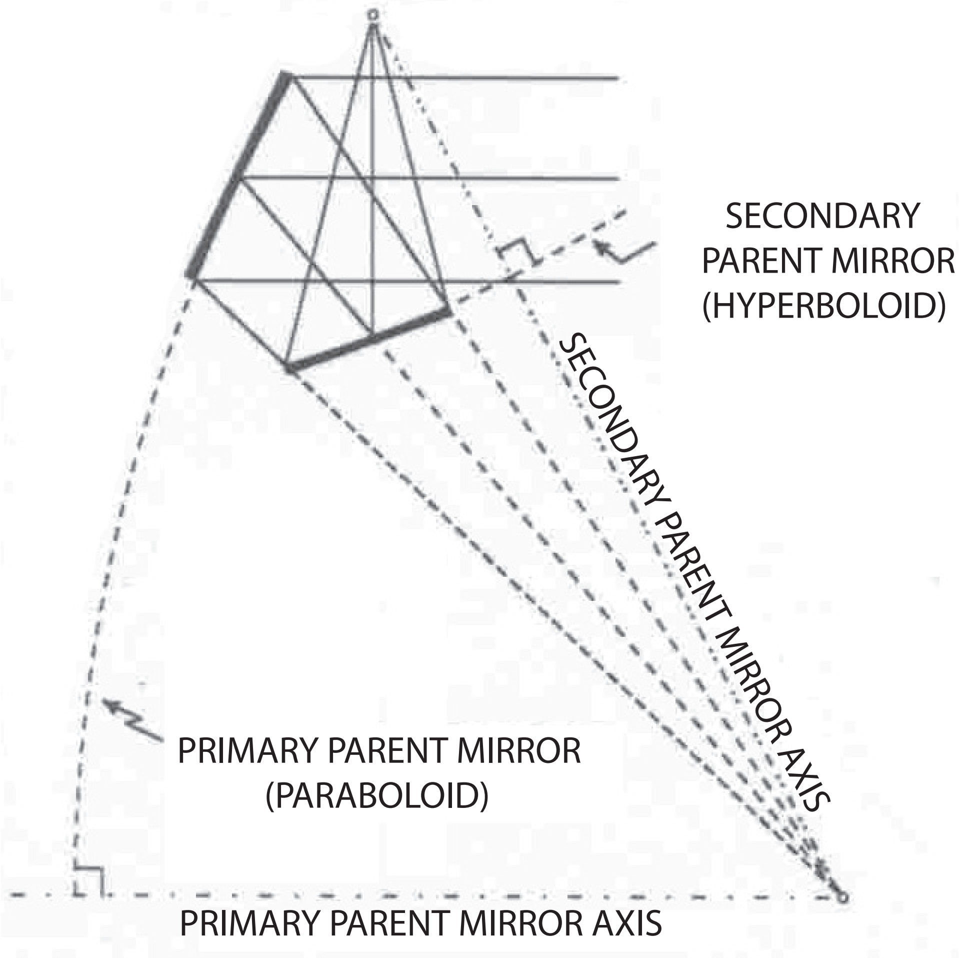
W-band prototype

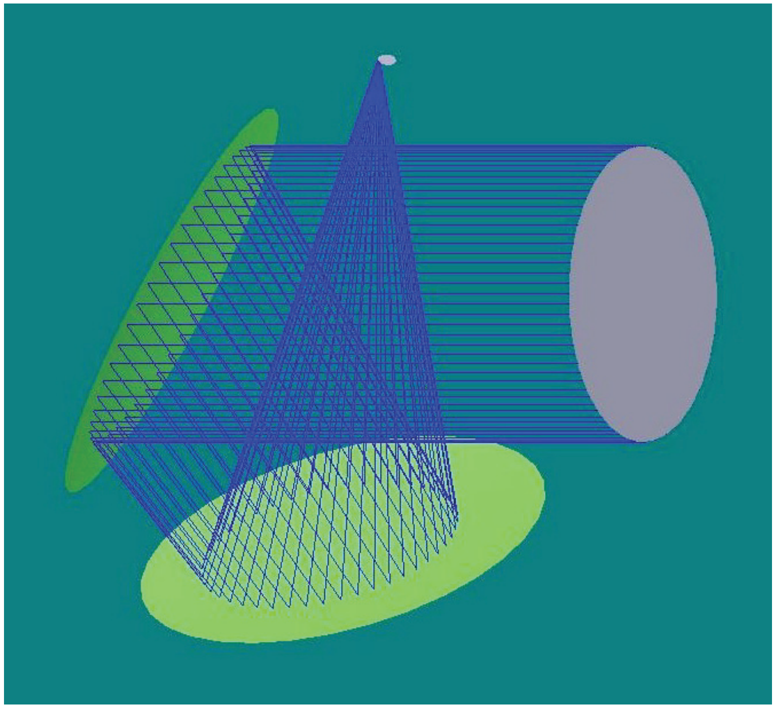
Staggs, Princeton

Cryostat—91-element Phase I

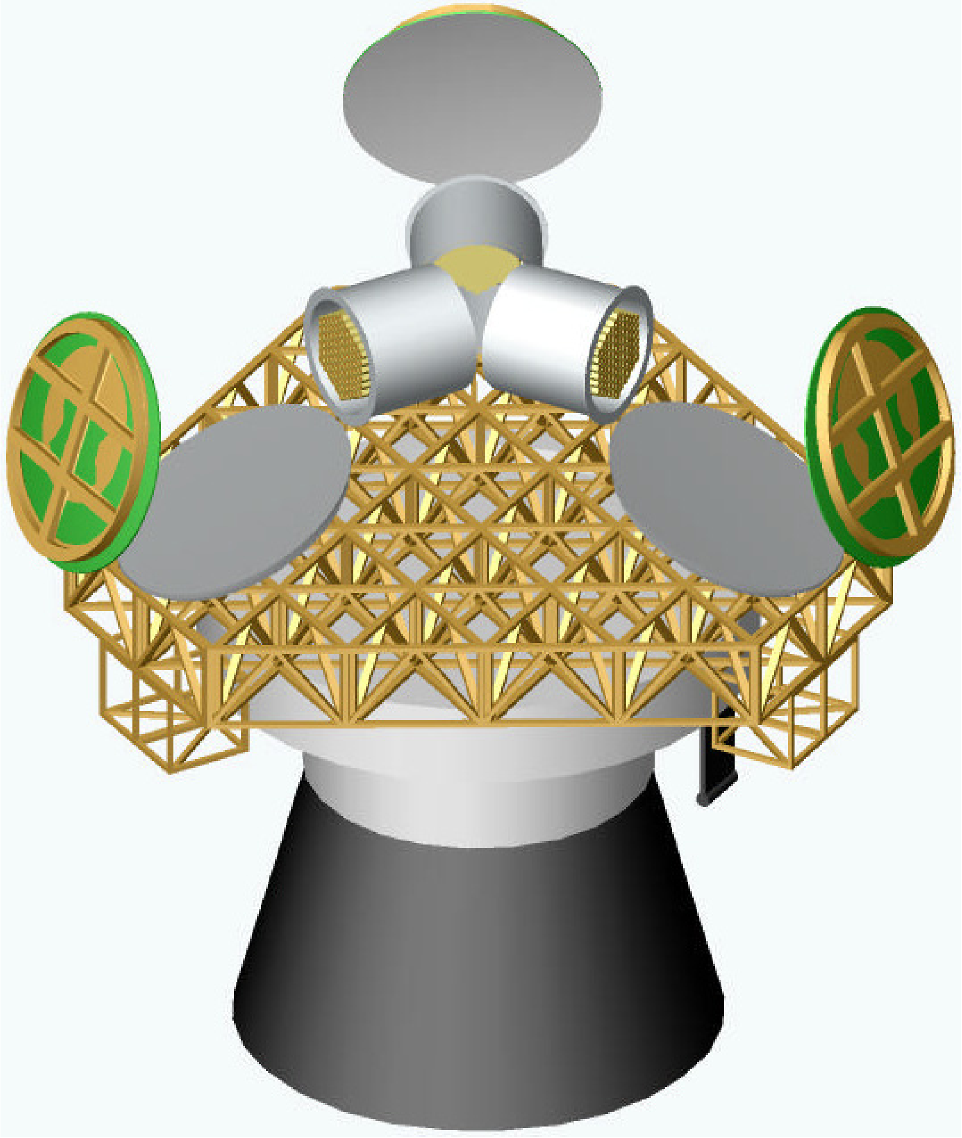


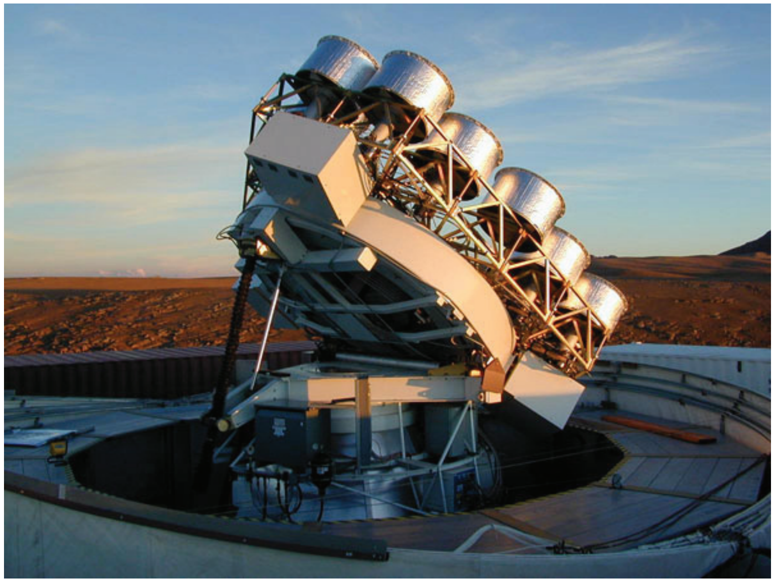
2-m Telescope



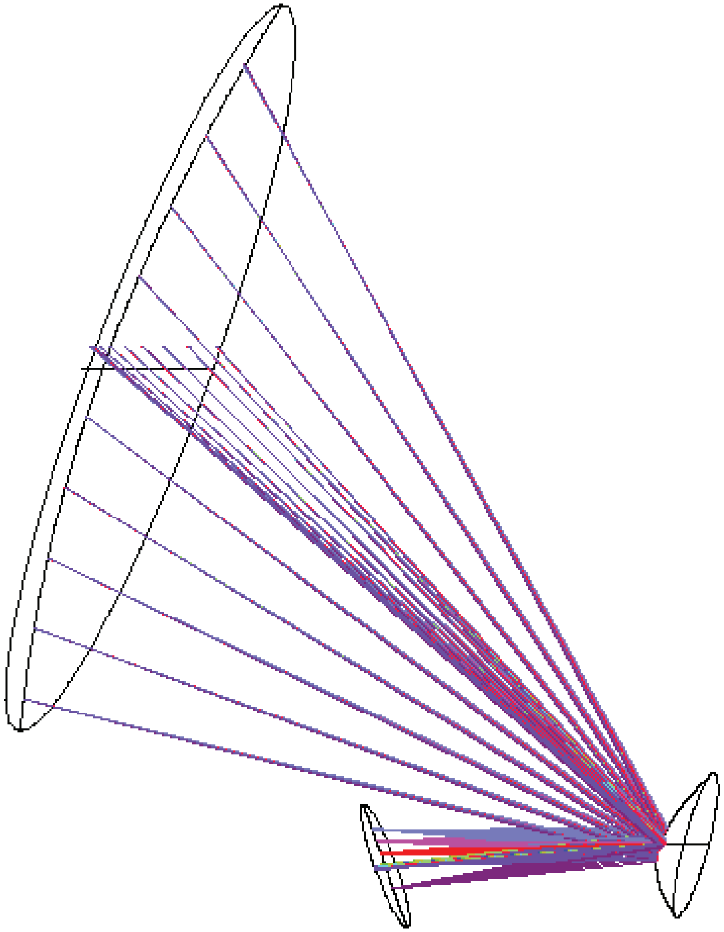


"side-fed Cassegrain" design

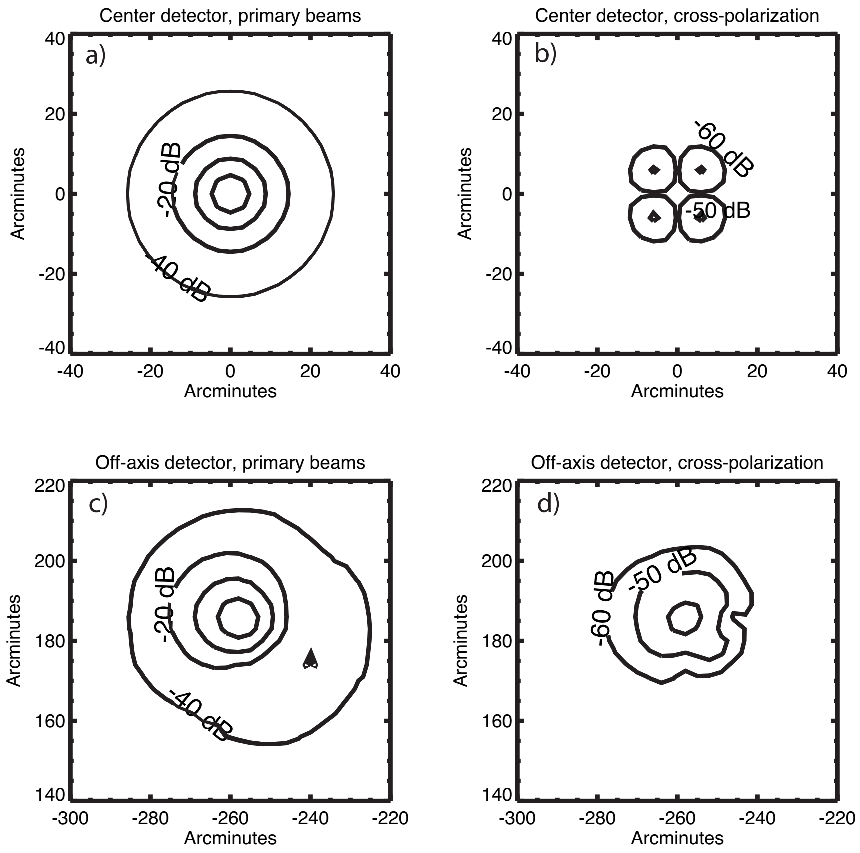




7-M Telescope

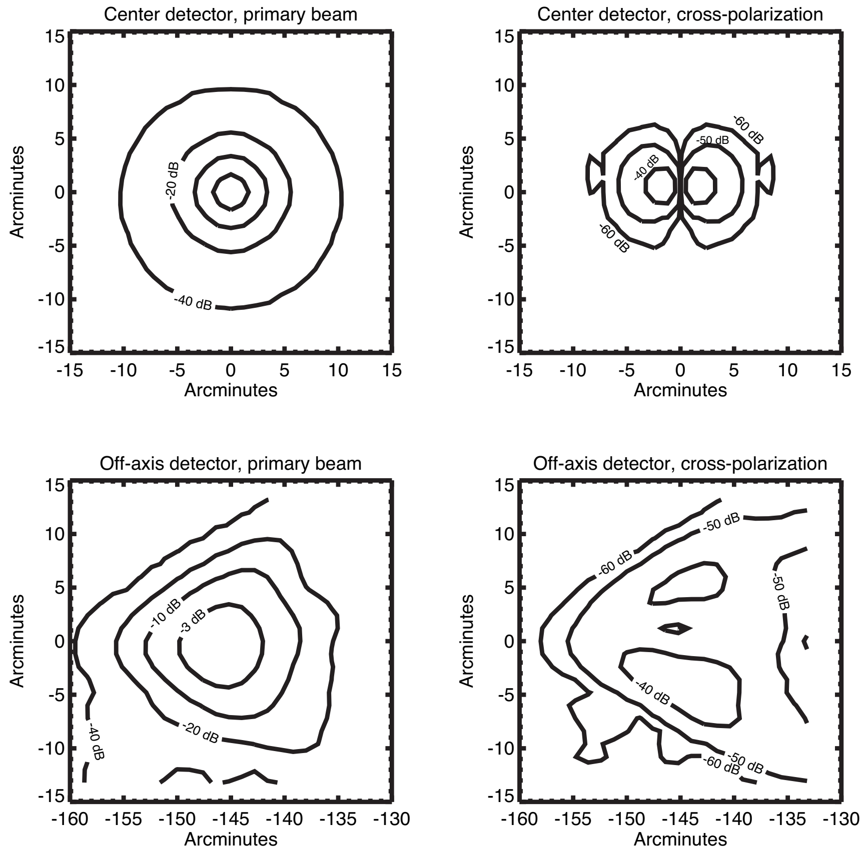


Optical Performance



2-m beams

Primary (left) and cross-polar (right) beams for center (top) and extreme off-axis (right) feeds.



7-m beams

Primary (left) and cross-polar (right) beams for center (top) and extreme off-axis (right) feeds.

- Only corrugated feeds provide such a low level of cross-polar response.

The CBI Site

The QUIET Collaboration

- QUIET (Q/U Imaging ExperimenT) Institutions and Senior Members:
  - Berkeley (White)
  - Caltech (Pearson, Readhead)
  - Chicago (Winstein)
  - Columbia (Miller)
  - GSFC (Wollack)
  - Harvard Smithsonian (Wilson)
  - JPL (Dragovan, Gaier, Gorski, Lawrence, Seiffert),
  - Miami (Gundersen)
  - Princeton (Staggs)
- Many postdocs and graduate students also involved.

QUIET Hardware Schedule

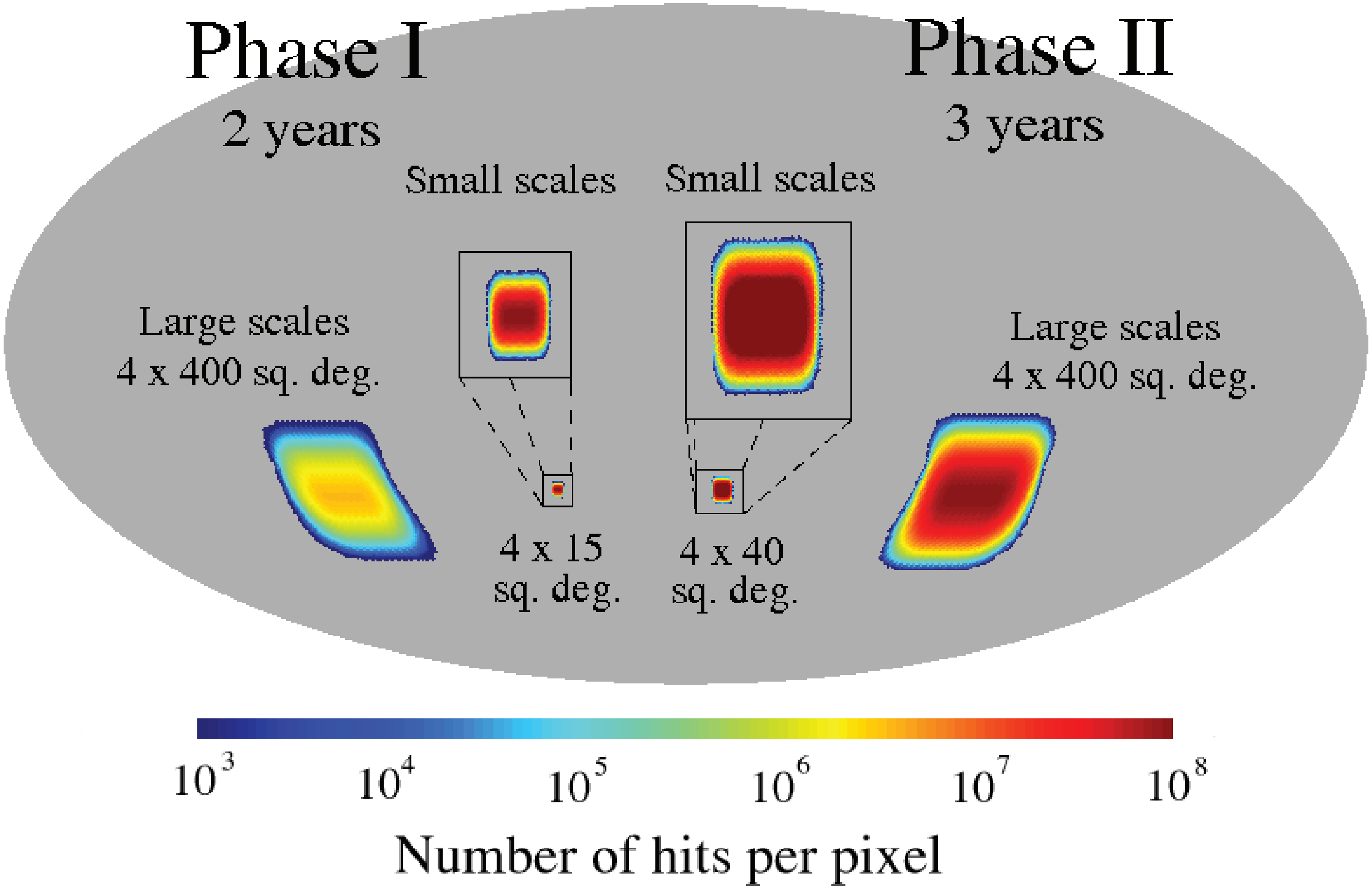
- Phase I (funded)
  - 7-element Demonstrator Array (DA, April 2005)
  - 1-m telescope mounted on CBI platform (June 2005)

    Same optical design as 2-m telescopes
  - 91-element camera at 90 GHz (W1, December 2005)
  - 19-element camera at 40 GHz (Q1, April 2006)
- Phase II (proposal pending; dates contingent on funding)
  - 1-m DA observations (July 2005)
  - 1-m W1 observations (January 2006)
  - 2-m telescope (1) & new CBI top platform (March 2006)
  - 7-m telescope move to Chile complete (December 2006)
  - 397-element camera at 90 GHz (W2, June 2007)
  - 91-element camera at 40 GHz (Q2, June 2008)
  - 2-m telescope (2) (March 2008)
  - 91-element camera at 40 GHz (Q3, November 2008)
  - 2-m telescope (3) (December 2008)
  - 397-element camera at 90 GHz (W3, January 2009)

Observing Strategies

- We want
  - A spatially uniform distribution of integration time (maximizes sensitivity for a given integration time)
  - Scan paths to cross a given pixel from many directions ("cross-linking" provides stability against time-dependent systematics)
  - Convex regions (best for separating E and B modes)
  - To scan at constant elevation (minimizes atmospheric elevation-angle effects)
  - To observe at relatively high elevation (minimize ground and atmospheric pickup)
  - Fast scanning (reduces effects of $1/f$ noise)
  - Wide distribution of parallactic angles at a given pixel (reduces polarization systematics)
  - Deep observations of small regions for B-mode sensitivity
  - To observe regions with low foreground levels
- To achieve these characteristics, we will use
  - Periodic scans in azimuth at $\sim 1^\circ$/s at high elevation
  - Re-point and change elevations every 20–60 minutes
  - Observe larger patches with 2-m optics

Sky Regions and Hits Per Pixel



In each case, just one of four observed patches is depicted.
Patch sizes are shown to scale. Small-scale regions are also enlarged for visibility.

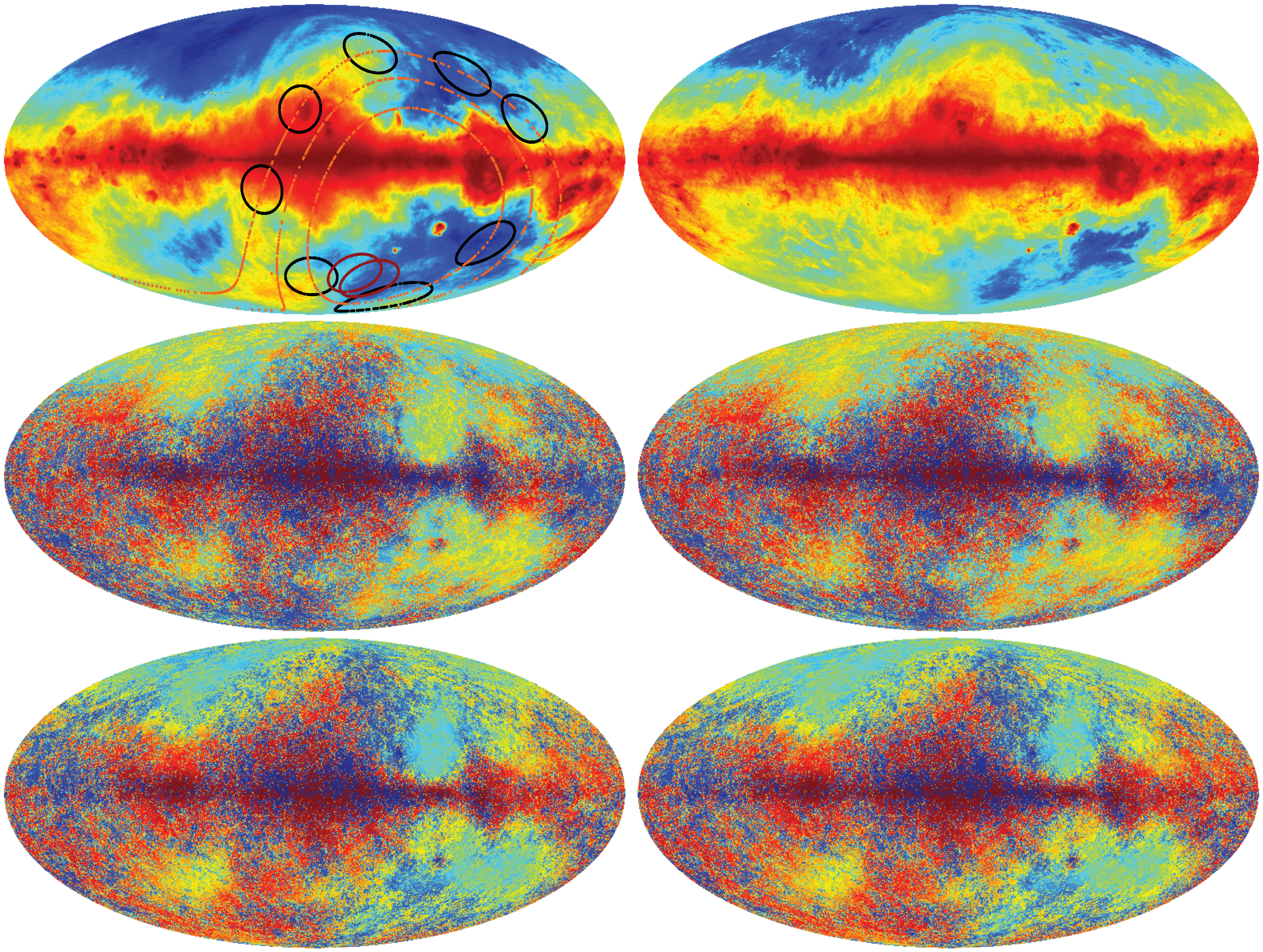
Observation Plan

Phase	Scale	Region [deg^2]	Noise/Pixel[a] [nK]
I	Large	4 × 400	400
I	Small	4 × 15	775
II	Large	4 × 400	85
II	Small	4 × 40	290

[a] W band. “Pixel” size is 1° for large scale, 0°.1 for small scale.

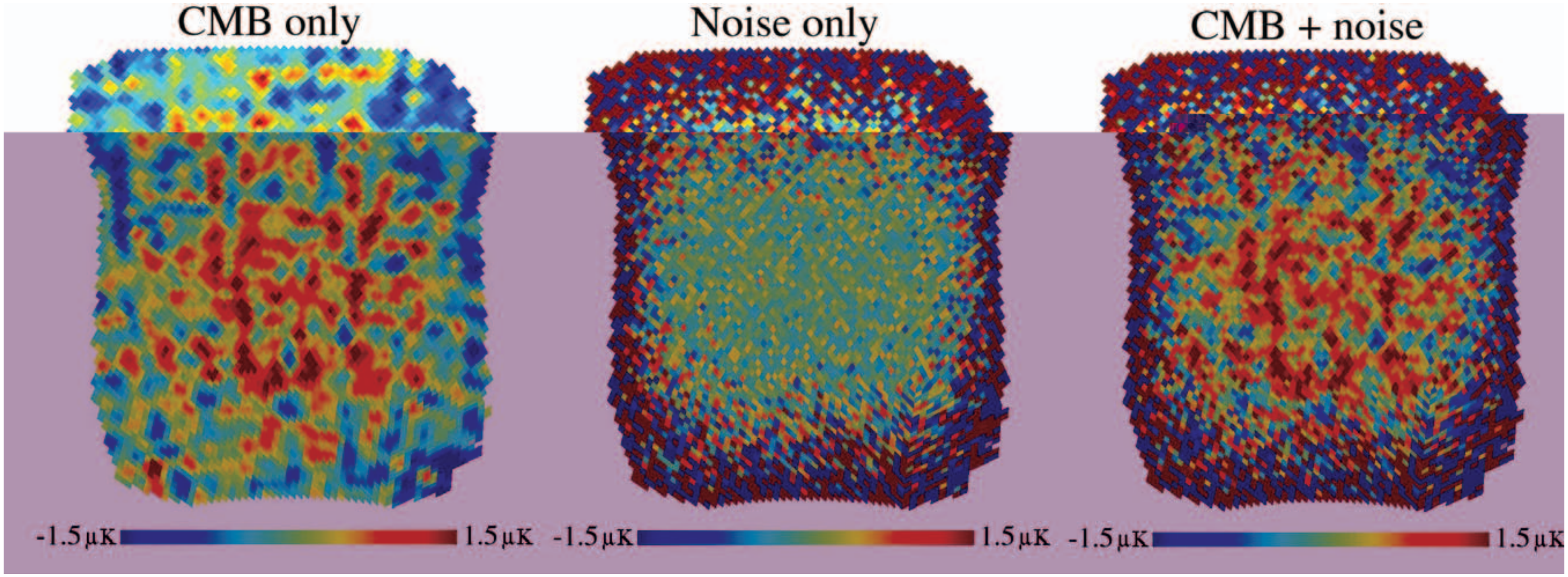
[b] Q band noise comparable on large scales, where a higher level of foregrounds is likely, and much lower on small scales, for 2.5 × larger pixels.

Selection of Sky Regions



Models of diffuse Galactic synchrotron, free-free, and dust emission in I, Q, and U (top, middle, bottom, respectively) at 40 GHz (left) and 90 GHz (right), from the Planck Component Separation Working Group. Regions of sky considered for QUIET are overlaid on the top left sky.

Simulated Map



Simulated field (Stokes Q) for the large-scale experiment, Phase II. Patch size = 400 square degrees. Illustrates the superb SNR that QUIET will obtain in the spatial domain.

QUIET Characteristics

								Q+U SENSITIVITY[b]	
	$\nu_{\rm center}$	FWHM	FOV	$N_{\rm feeds}$		$T_{\rm sys}^{\rm a}$	$\Delta\nu$	Per Feed	Array
COMPONENT	[GHz]	[′]	[°]	Pol	Temp	[K]	[GHz]	[μK s$^{1/2}$]	[μK s$^{1/2}$]
QUIET Phase I									
1 m	40	41	11	17	2	27	8	159	39
1 m	90	18	12	83	8	54	18	248	27
QUIET Phase II									
2 m	40	23	13	166	16	27	8	159	12
7 m	40	9	6	83	8	27	8	159	17
2 m	90	10	12	714	80	54	18	248	9
7 m	90	3–8	5	357	40	54	18	248	13

[a] Antenna temperature units, based on field-tested MMIC amplifier noise + 2.73 K + NRAO model atmosphere at 45° elevation.

[b] Thermodynamic units, including both Q and U from correlation polarimeter, with normalization Q $= (T_x + T_y)/2$

QUIET II has 3–4 times better polarization sensitivity than Planck at 100 GHz!

Systematics

- Gain fluctuations can induce spurious polarization
  - Common-mode in correlation polarimeter design, subtract out

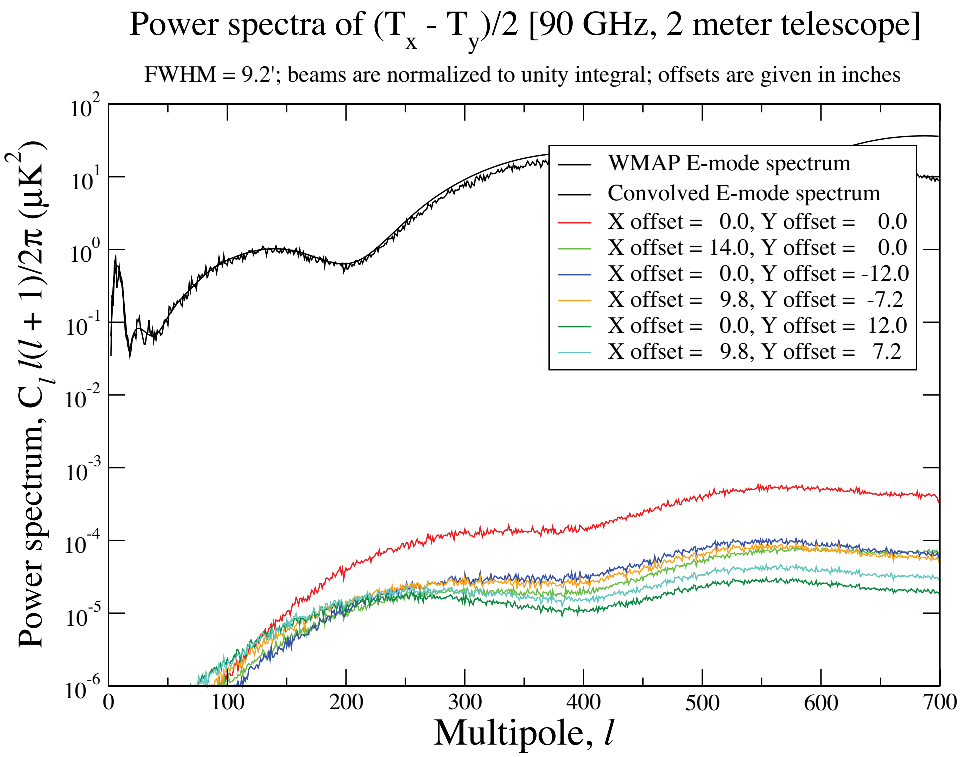
    $1/f$ knee frequency expected to a few mHz
- Phase errors between the two arms of the polarimeter rotate polarization axes
  - Can be calibrated out with essentially no loss of information
- I to Q/U leakage
  - Non-zero return loss of amplifiers coupled with non-zero isolation of OMTs causes a spurious correlated signal (roughly a 1% effect)

    Sets requirements on isolation. Broad parallactic angle distribution minimizes some effects.

    10% of channels set up to measure I to monitor/protect against atmospheric fluctuations, ground pickup, and unpolarized unresolved sources
- Pointing errors of telescope lead to spurious B-mode signal
  - Expected pointing error below 0.03 beam leads to 0.07 (0.007) muK error for large (small) scale experiment, well below noise levels

Systematics—cont'd

- Differing ellipticities of two polarized beams generates a spurious polarization signal.
  - Optics design minimizes this. Full-sky simulations show effect will be well below the noise.



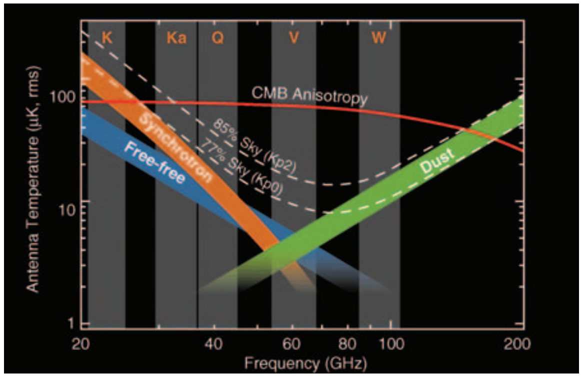
Power spectra of $(T_x - T_y)/2$ [90 GHz, 2 meter telescope]

FWHM = 9.2'; beams are normalized to unity integral; offsets are given in inches

- Ground pickup
  - Ground screens plus the fact that our scanning strategy permits frequent removal of structure from ground

Foregrounds

- At the very least, it will take 4 parameters to describe polarized foregrounds
  - Two for synchrotron
  - Two for dust

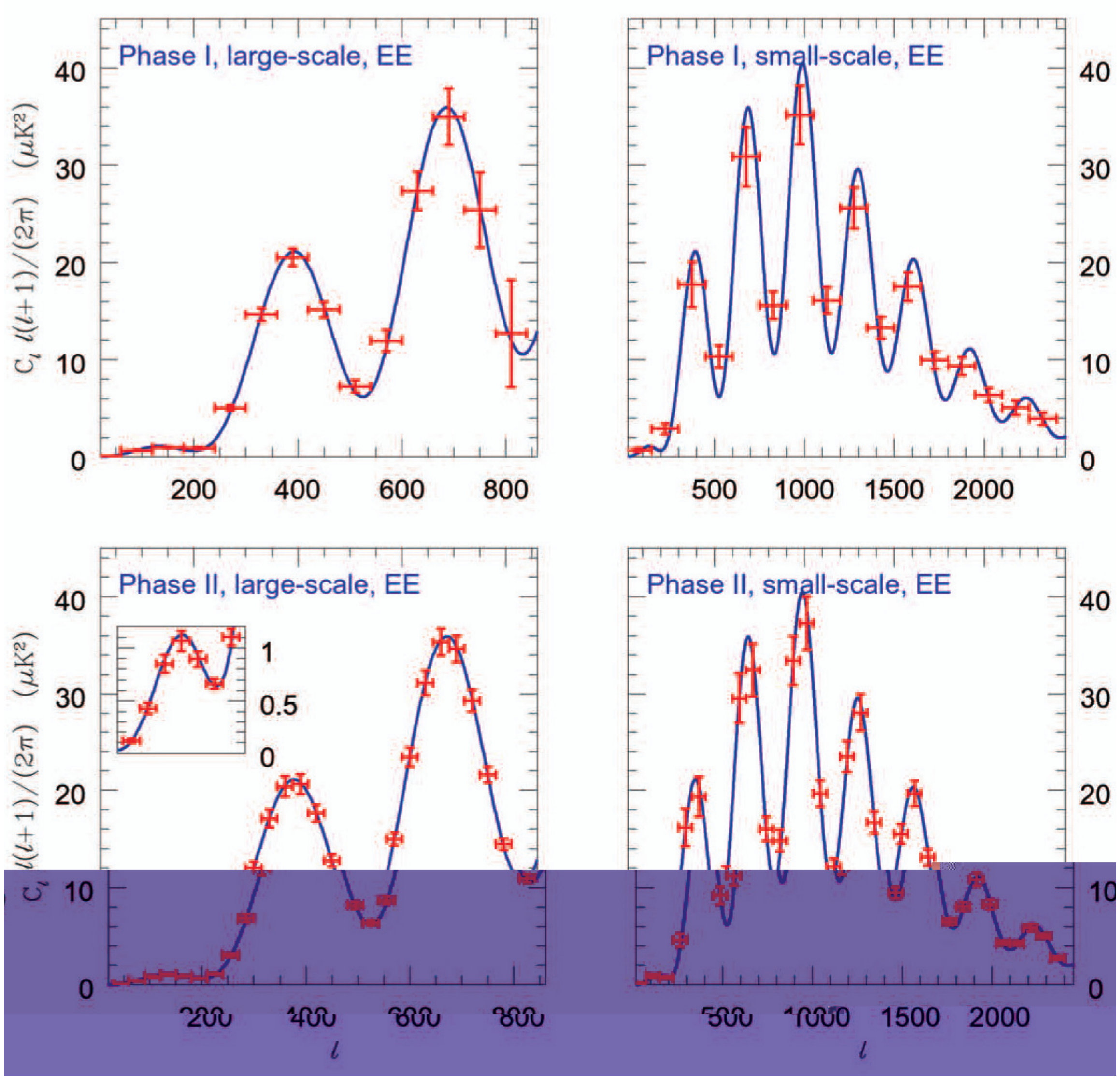


- Plus 1 for the CMB, separation of CMB and foregrounds on the basis of spectrum will require $\geq (5+1)$ frequencies between, say, 40 GHz and 150 GHz
- QUIET cannot do this (no ground experiment can!)
- But little is known about polarized foregrounds, and WMAP doesn't have the sensitivity to say much except on large angular scales
- QUIET foreground strategy
  - Observe low foreground regions
  - Learn a lot about foregrounds!

Expected Results, EE

- Simulations take into account:
  - Removal of ground-synchronous mode from time stream
  - Removal of best-fit quadratic polynomial in each scan period, horn by horn
  - E-B leakage

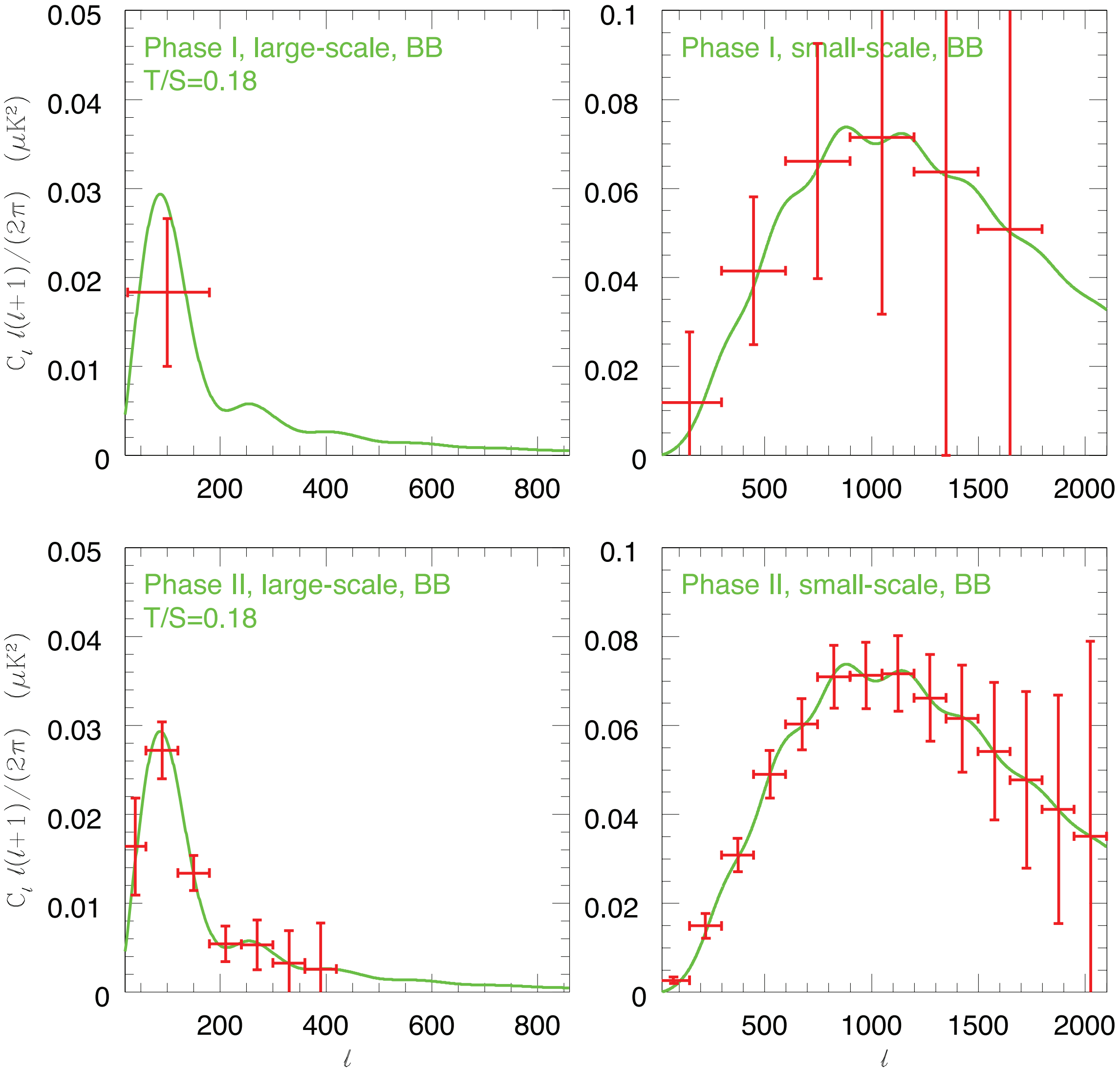
    Pixel-pixel noise covariance matrix used in computing associated band-power Fisher matrix
  - Band-power correlations are $<10\%$



Expected Results, BB

- Left panels show gravitational wave spectrum with $T/S = 0.18$
- Right panels show lensing spectrum
- 5σ detection of GW at
  - $T/S = 0.16$ in Phase I
  - $T/S = 0.009$ in Phase II

    Assuming lensing can be separated out



Amplifiers and Bolometers

- For CMB polarimetry, amplifier arrays
  - Are more sensitive from the ground than bolometer arrays up to 100 GHz
    - Bolometers on the ground have sensitivity per feed of $\geq$250 μK $\mathrm{s}^{1/2}$
    - We expect sensitivity per feed of 250 μK $\mathrm{s}^{1/2}$ at 100 GHz, 160 μK $\mathrm{s}^{1/2}$ at 40 GHz
  - Have significant advantages in controlling systematics
    - Easy integration with corrugated feeds
    - Inherently differential polarimetry, rather than “subtract two big numbers” polarimetry
    - Simultaneous measurement of Q and U
  - Have significant operational advantages
    - 20 K operation, vs. 0.1–0.3 K operation
    - Room temperature circuit board readouts, vs. cryogenic multiplexers
    - Simultaneous measurement of Q and U, vs. Q *OR* U for bolometers

The QUIET arrays offer the best detector technology for ground-based CMB observations at 100 GHz or below.

Summary

- Breakthrough in millimeterwave packaging/mass production technology enables arbitrarily large arrays at modest cost
- Adaptable for polarimetry, intensity radiometry, and spectroscopy
- Will revolutionize many areas of radio astronomy and Earth remote sensing
- For CMB polarimetry, amplifier arrays offer the best technology for ground-based observations up to 100 GHz
- QUIET will
  - Measure CMB polarization with high SNR for $50 \leq \ell \leq 2500$
  - Learn essential information about polarized foregrounds, which are likely to be the ultimate limit to how well CMB polarization can be measured
- Watch for QUIET!