QUIET

The Search for B-Mode Polarization in the Cosmic Microwave Background Using Coherent HEMT Detectors

A Proposed New Initiative for Fermilab

August 7th 2009

DOE/NSF Briefing on FCPA Activities

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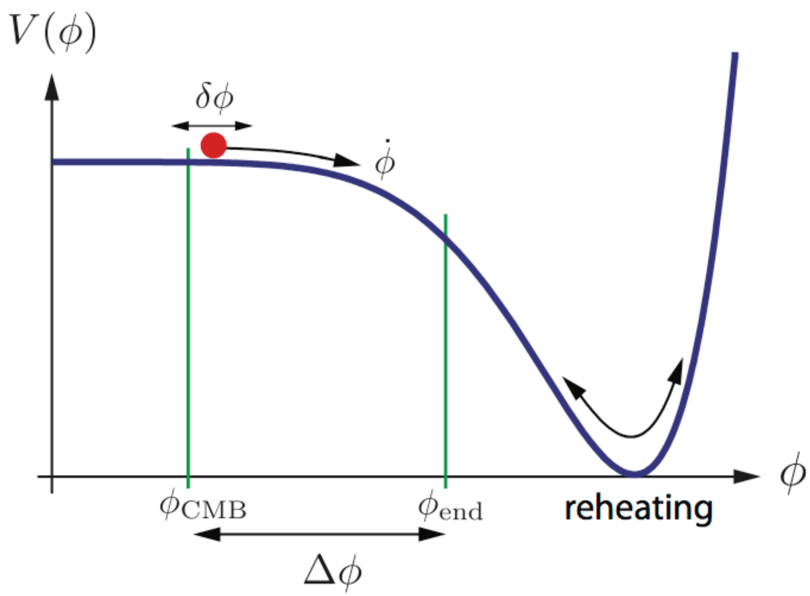
Hogan Nguyen, Albert Stebbins

Outline

- The Science of CMB Polarization
- The QUIET Experiment
- Fermilab Involvement in QUIET Phase I
- Our proposal for QUIET Phase II involvement
- Summary

Probing the Inflationary Potential

Tensor fluctuations of the metric (ie. gravity waves) in the inflationary era are ***encoded*** in the polarization of the CMB.   A ***curl*** (or B-mode) is generated.



$r \equiv$ T/S tells us

- The energy scale of inflation
  (this is an HEP experiment)

-The field displacement $\Delta\phi$ during the inflationary era

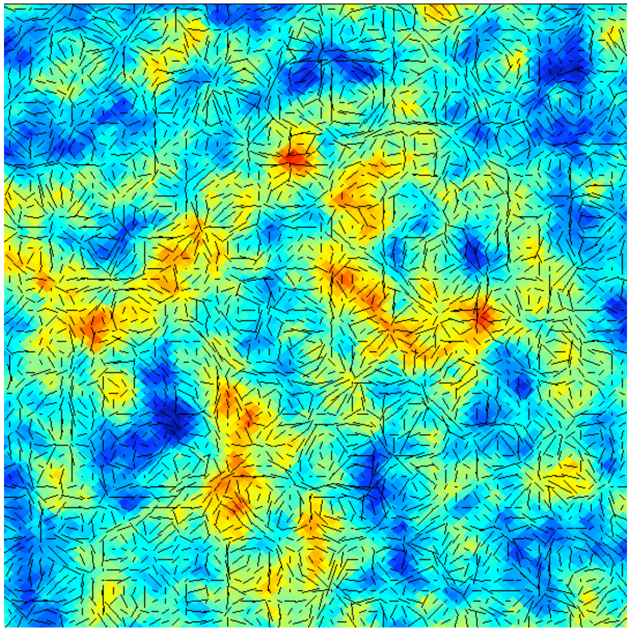
$$V^{1/4} = 3.3 \times 10^{16} \times r^{1/4} \text{ GeV}$$

$$\frac{\Delta\phi}{M_{\rm pl}} \gtrsim \left(\frac{r}{0.01}\right)^{1/2}$$

A Difficult Measurement !

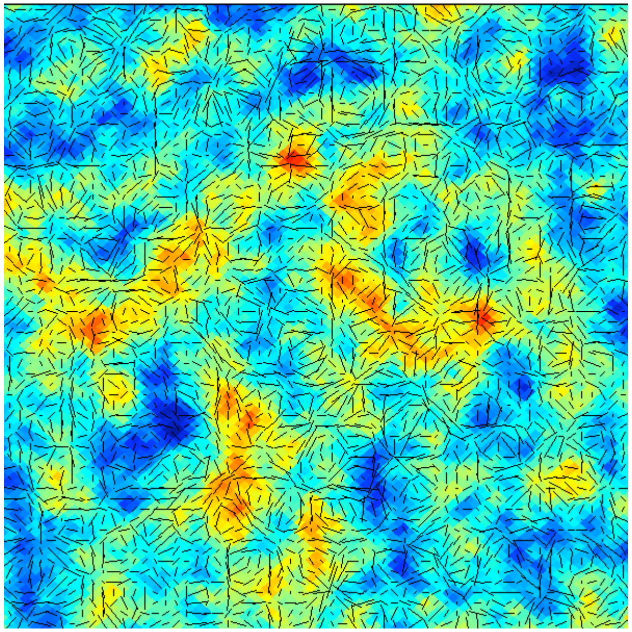
Simulated

$r = 0$

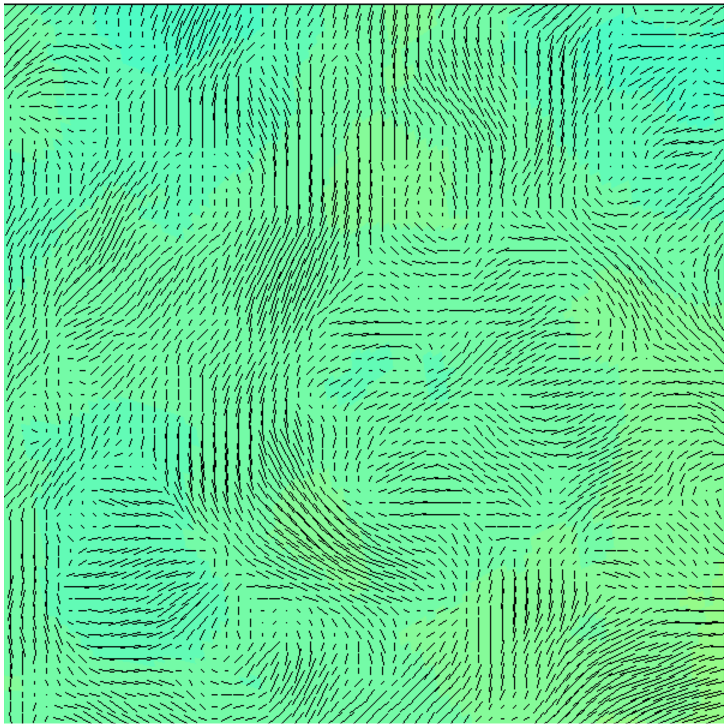


Simulated

$r = 0.2$



Difference between
$r = 0.2$ and $r = 0$
(magnified by 500)



Gravitational Lensing of the CMB generates a B-mode (W. Hu et al.)

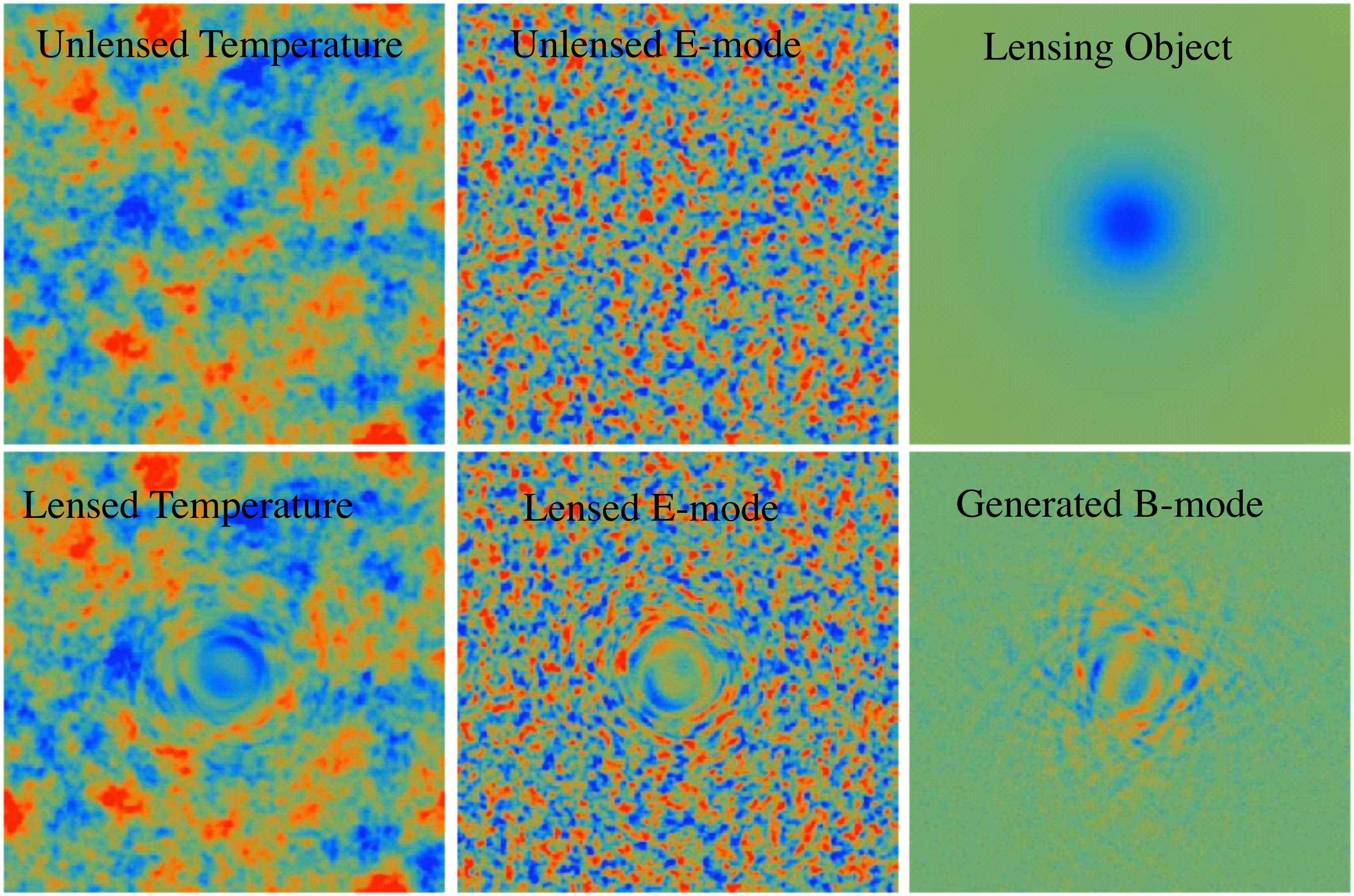
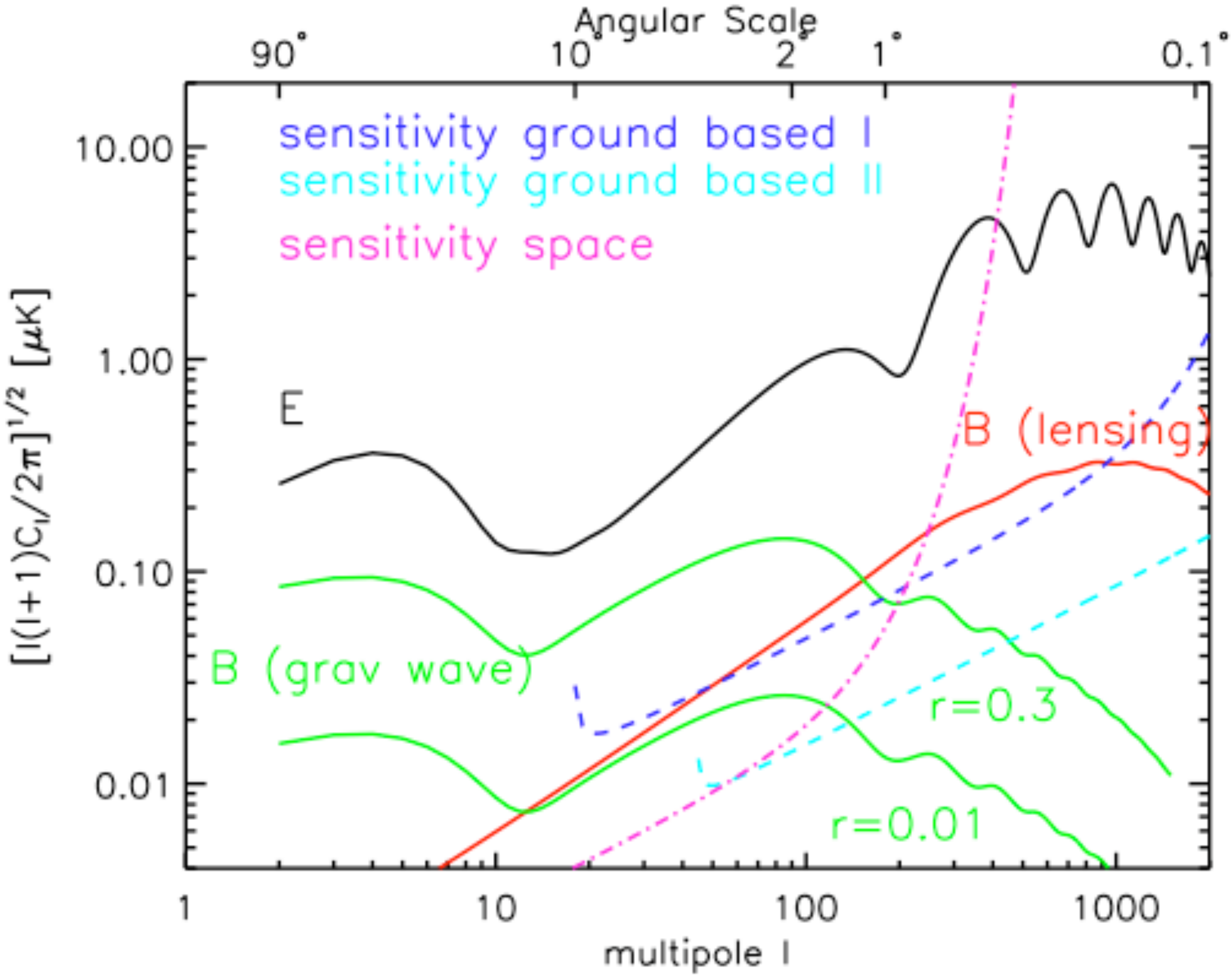


FIG. 1.— An exaggerated example of the lensing effect on a $10° \times 10°$ field. Top: (left-to-right) unlensed temperature field, unlensed E-polarization field, spherically symmetric deflection field $d(\mathrm{n})$. Bottom: (left-to-right) lensed temperature field, lensed E-polarization field, lensed B-polarization field. The scale for the polarization and temperature fields differ by a factor of 10.

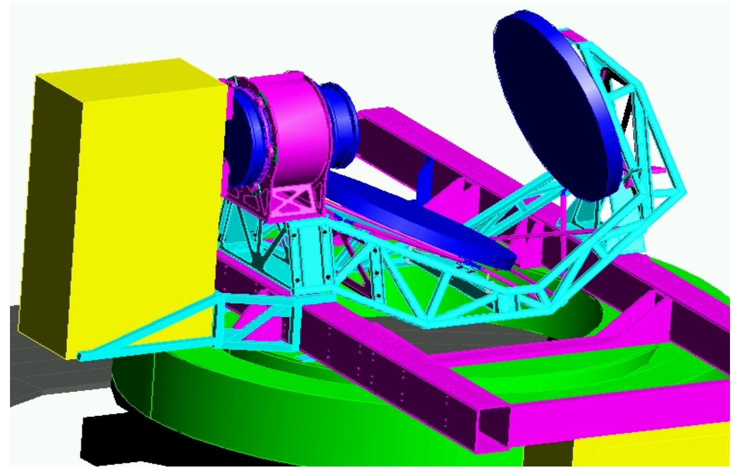
$V^{1/4} = 3.3 \times 10^{16} \ (T/S)^{1/4} \text{GeV}$

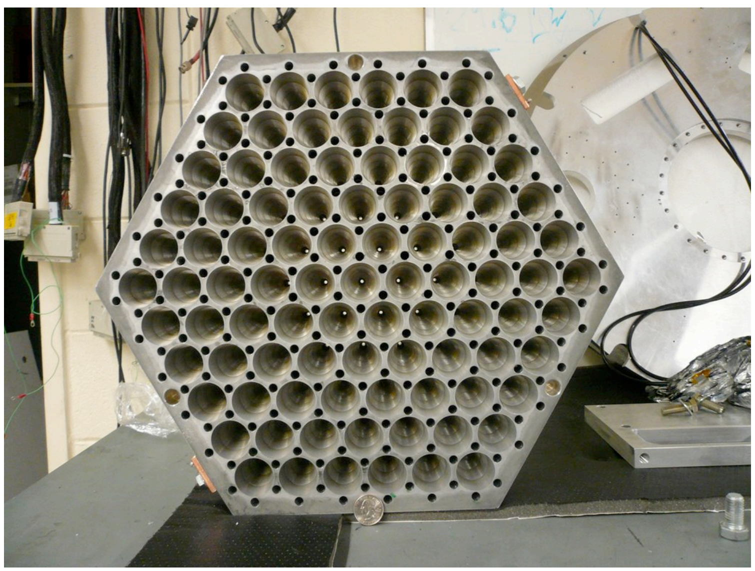


The QUIET Experiment

Caltech, Chicago, Columbia, Fermilab, KEK, JPL, Manchester, Miami, MPI, Oslo, Oxford, Princeton, Stanford

Chajnantor Plateau (5612 m ASL), Chile

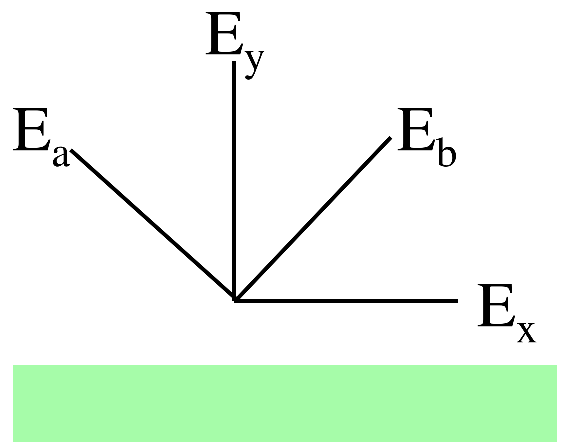


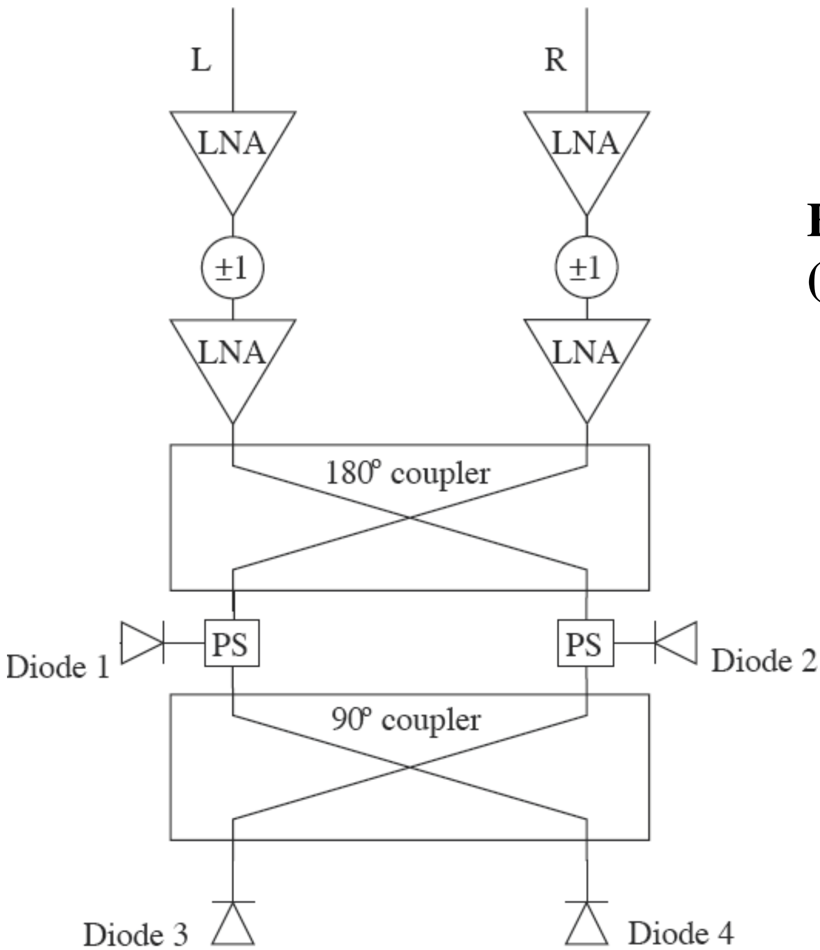


91-element W-band array
currently deployed at Site

Currently the only experiment to employ HEMT-based technology on this scale

Simultaneous Q/U measurements in a single HEMT-based module operating at 20 Kelvin





Fundamentally very different than TES (bolometric) technology

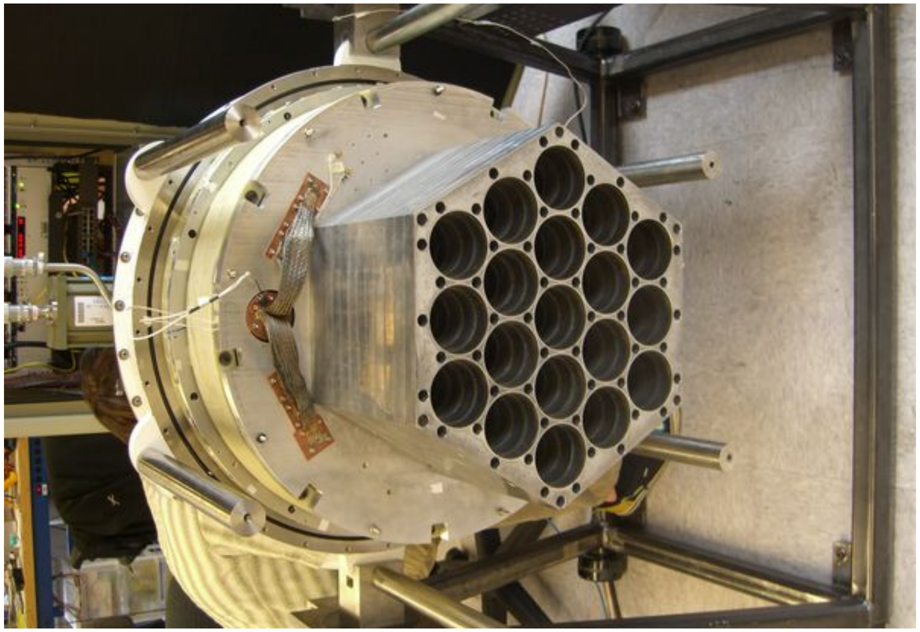
$$|L \pm R|^2 = \left|\left(E_x + iE_y\right) \pm \left(E_x - iE_y\right)\right|^2 = \underline{4E_x^2, 4E_y^2}$$

Q

$$\left|(L \pm R) + i(L \mp R)\right|^2 = |L \mp iR|^2 = |L|^2 + |R|^2 \mp 2\,\mathrm{Im}\left(RL^*\right)$$

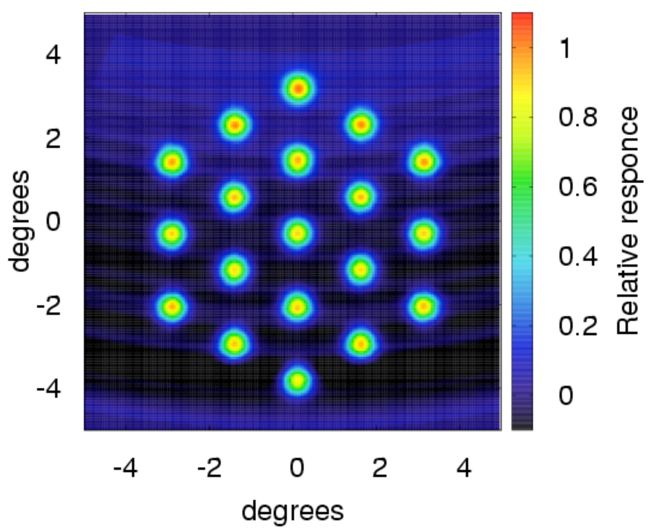
$$\mathrm{Im}\left(RL^*\right) = \mathrm{Im}\left(E_x + iE_y\right)^2 = 2E_xE_y = \underline{E_a^2 - E_b^2}$$

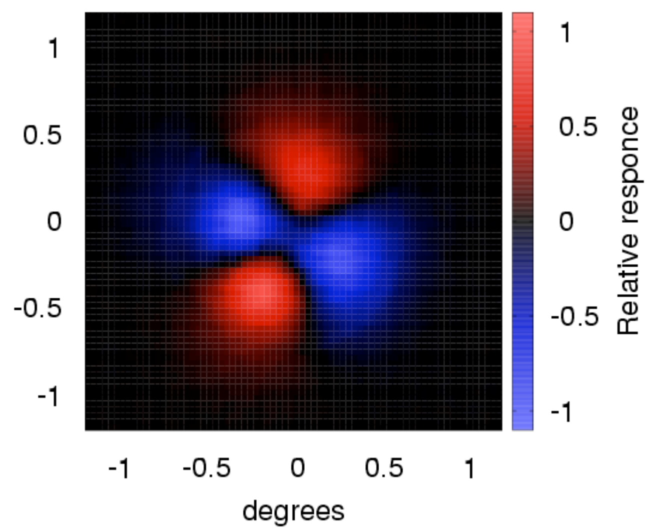
U



Completed ~ 9 months of observations using the 19-element Q-band

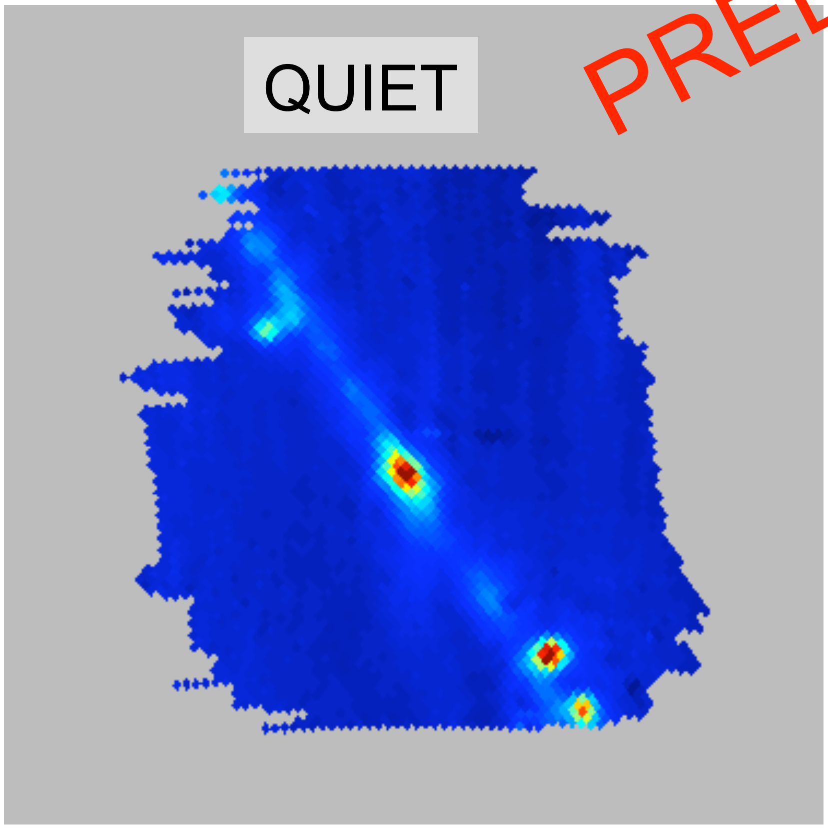
Moon exposure over each element (preliminary)



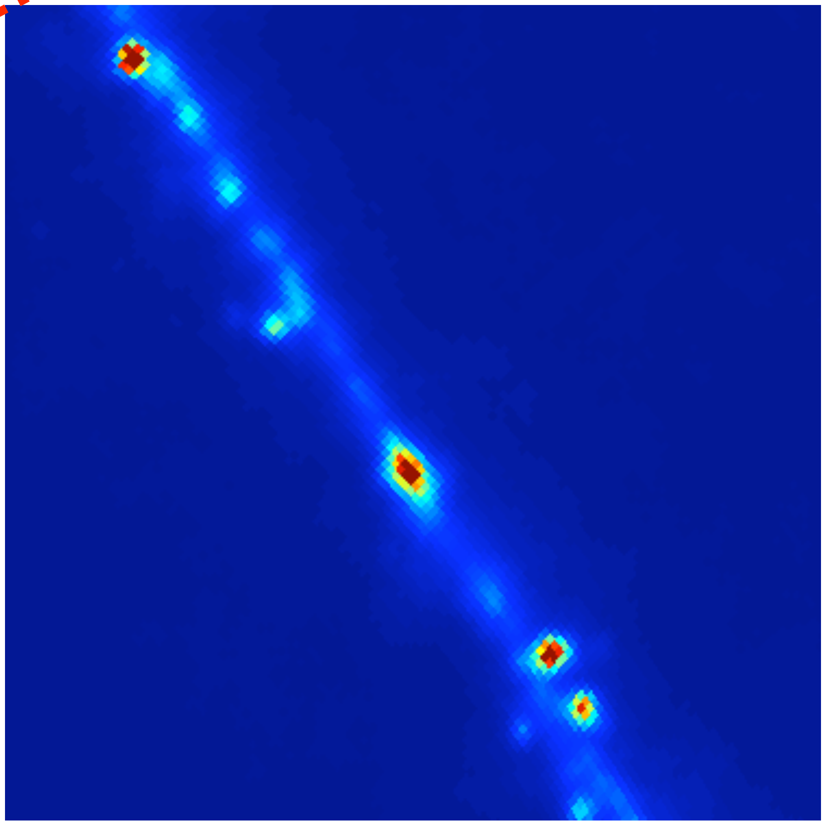


Preliminary Data

Galaxy
(TT, <100 hrs)

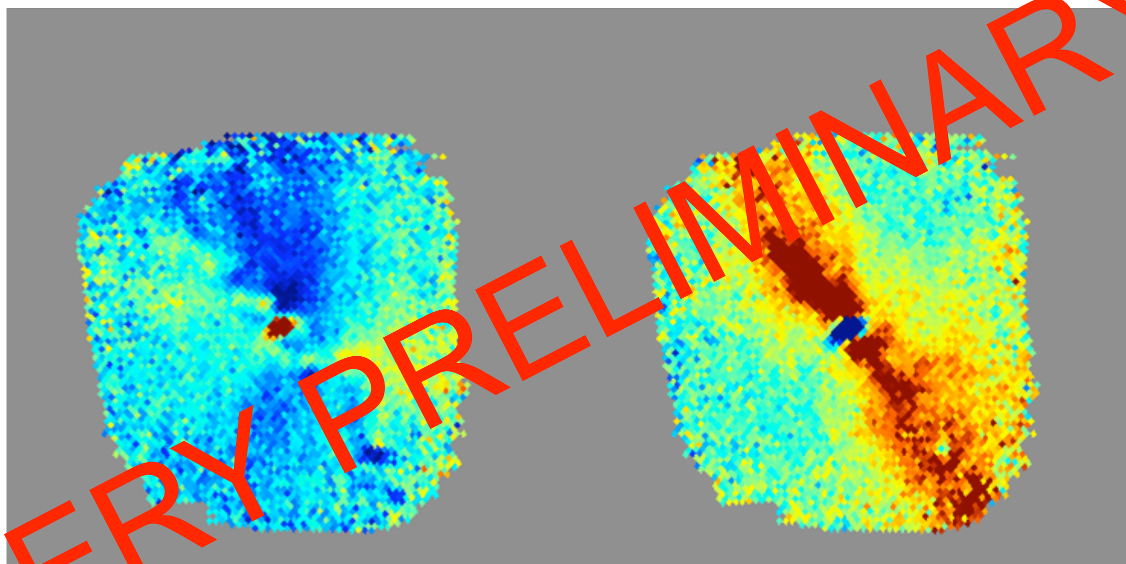


WMAP

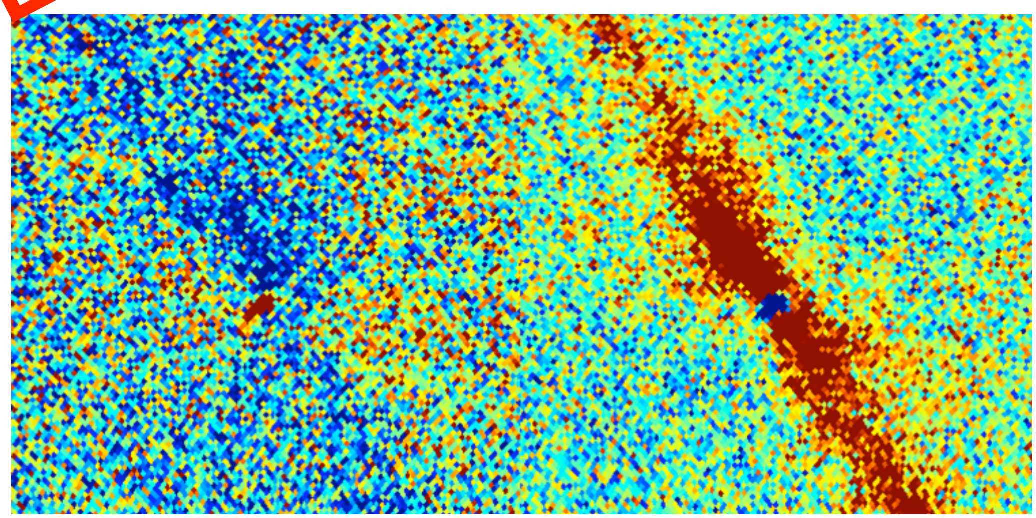


Preliminary Data (Cont'd)

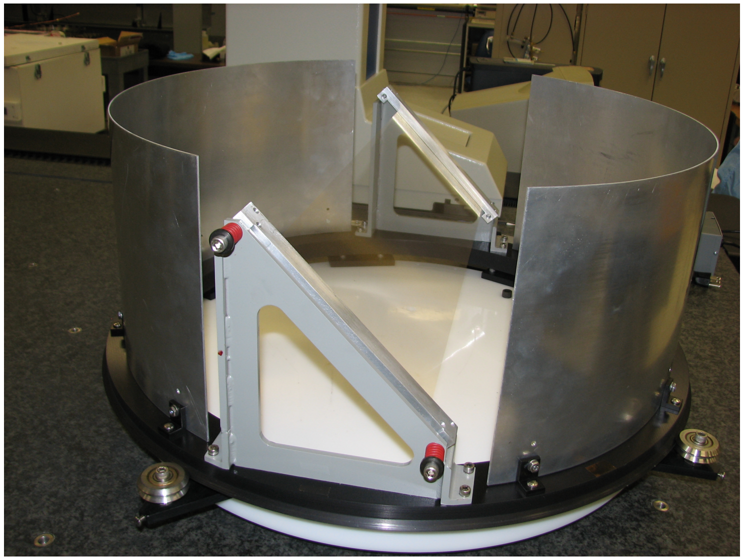
Galaxy
(Pol., <100 hrs)
systematic efects
not considered yet



WMAP



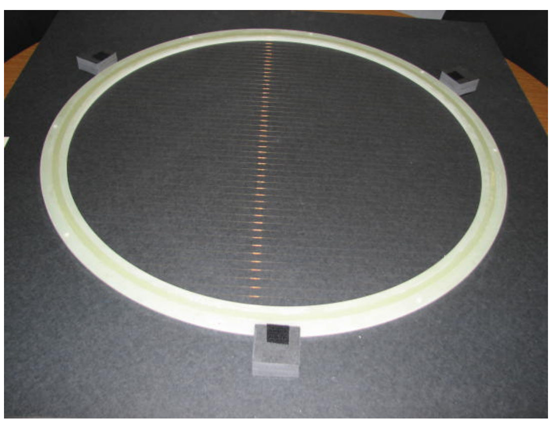
QUIET Phase 1 R&D at Fermilab



Large and accurate rotatable wire grids to produce and modulate polarized microwaves

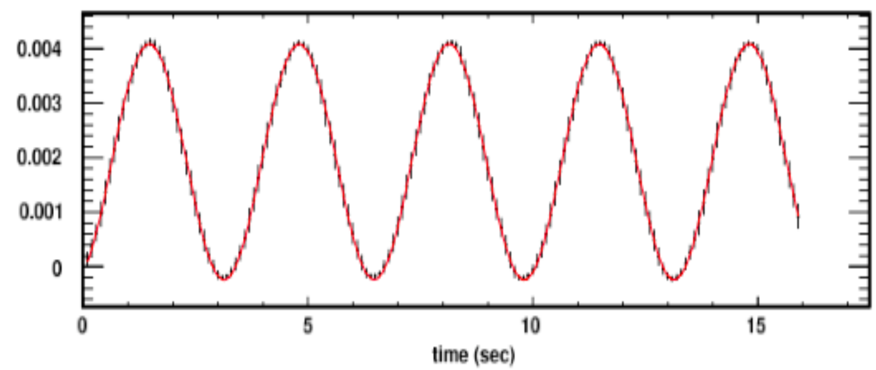
Made by PPD chamber winding group using HEP techniques

In use at KICP lab in Chicago since Feb 09 to optimize detector settings, calibrate relative "angles" of all modules, and provide absolute response to known input polarization signal



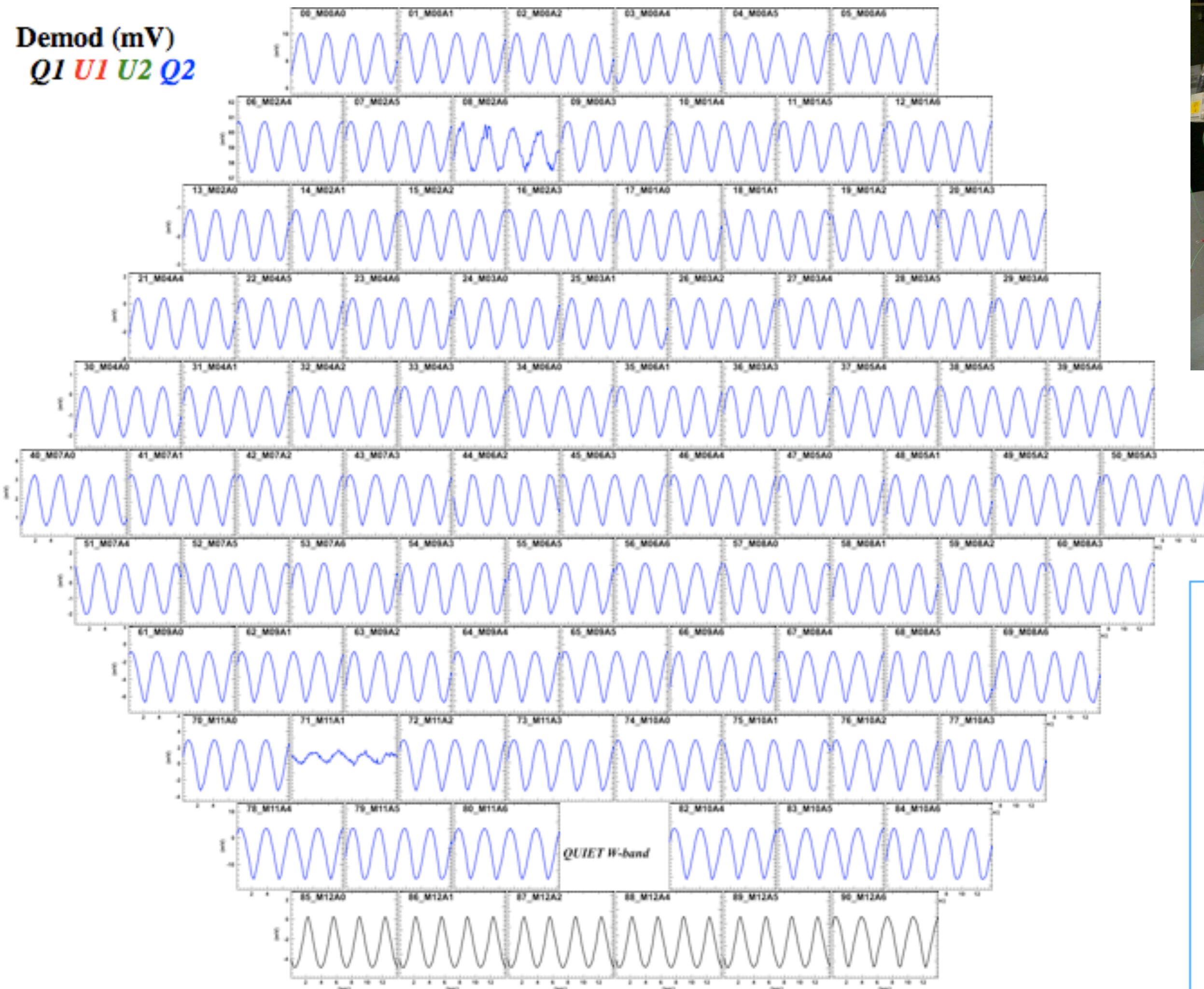
Grid rotates to modulate the polarization

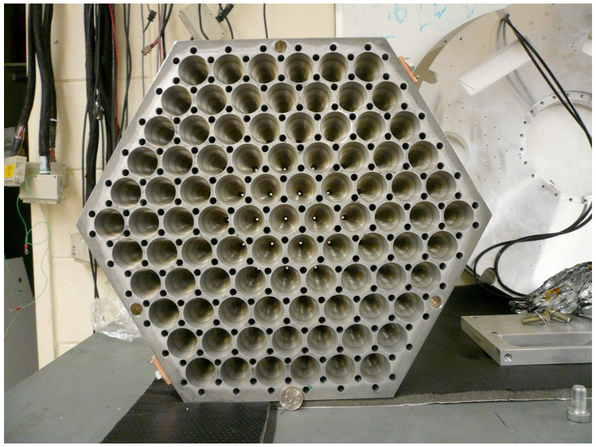
Typical Stokes-Q Response from a W-band Module

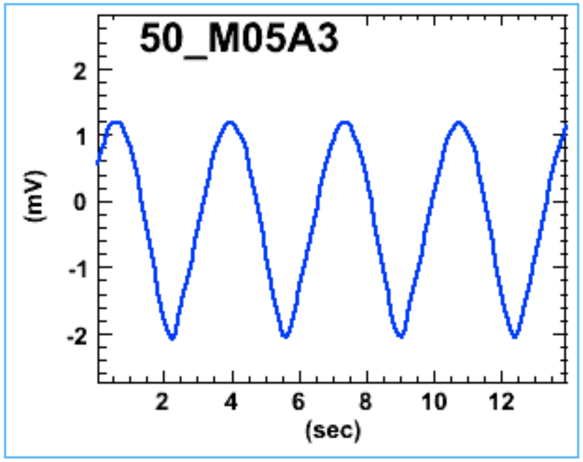


Deployed in Chile in June 09

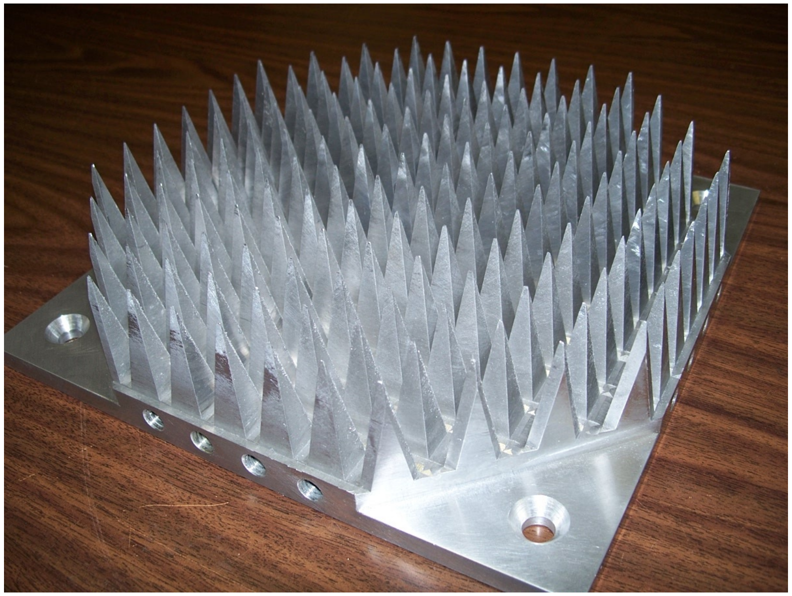
91 Element W-band Optimized by Wiregrid and Ready for Observation







D. Butler, J. Korienek, C. Lindenmeyer, W. Newby, J. Wilson. Not pictured: J. Montes, R. Rucinski, K. Schultz



QUIET Phase 1 R&D at Fermilab

20 Kelvin Black Body Microwave Source For Full-System Characterization

A significant job carried out primarily by PPD Technical Staff:

- A vacuum tank with a high-strength microwave-transparent vacuum window with anti-reflective coating.
- A Microwave-absorbing epoxy cast over an aluminum core
- A Commercial 5W@20K Cryocooler

Useful for characterizing large arrays of detectors of ANY technology.

Mimics the sky noise in Chile, while in a laboratory setting

Our Proposed Involvement in QUIET Phase II

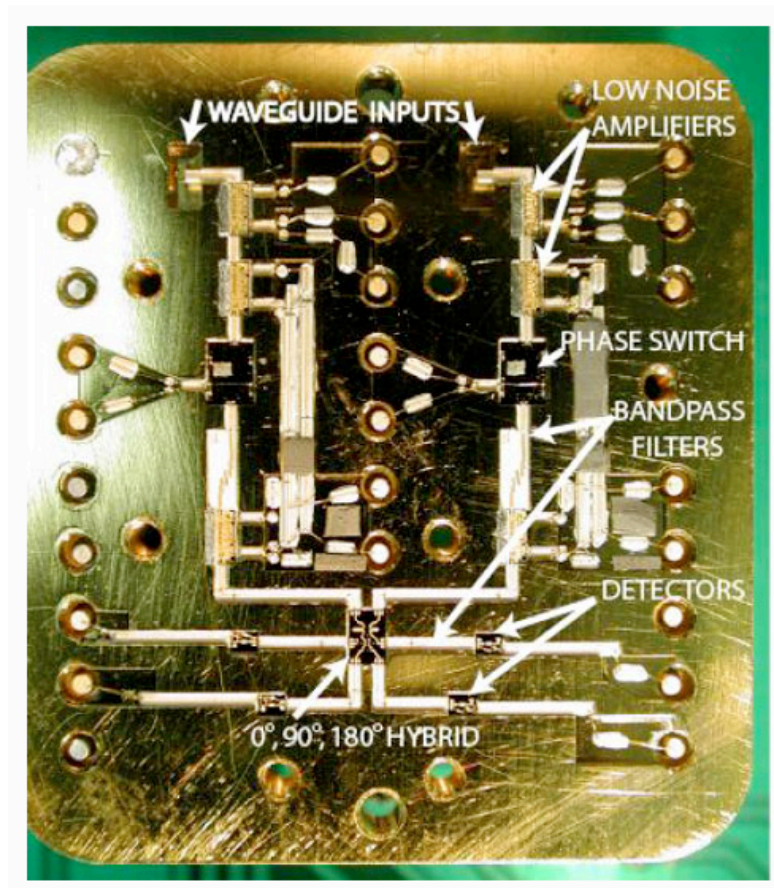
Robotic Assembly of ~1500 W-band Polarization Modules

The collaboration invited us to take on this role.

A critical need within QUIET.

Involvement is Commensurate with our role as a National Laboratory.

1” W-band HEMT module



Technical Challenges for W-Band Assembly

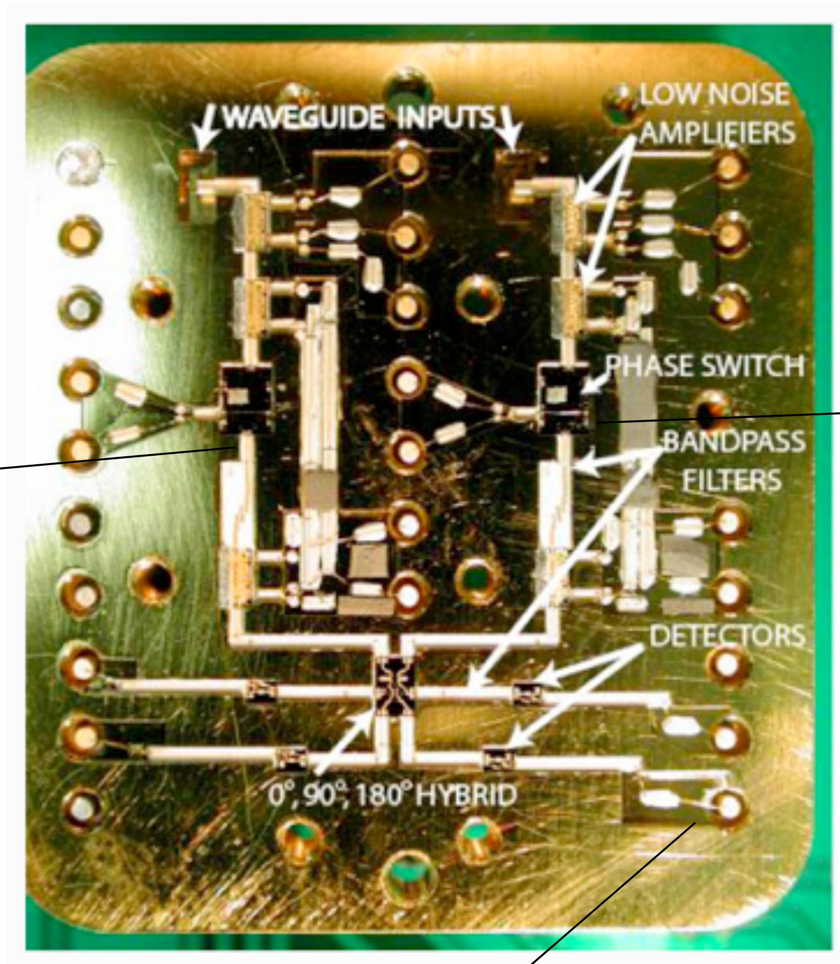
Precision Placement of 106 components (12.5 microns to 50 microns accuracy)

Components as small as 0.2 mm x 0.2 mm

ESD-sensitive active components

Control of silver epoxy deposition at the 100 micron level

Wirebonds and Epoxy adhesion survives repeated cycling between room T and 20K



Phase difference between the two paths less than 20 degrees

MMIC HEMT components have "air bridges" on top surface. Pickup tool cannot touch top surface.

Intermediate probing of components, needed for QA.

Systems Testing of Fully Assembled Modules and making Repairs

Automated Assembly to guarantee timely delivery of ~1500 working modules

Ribbon Bonding for making electrical connections (some require "deep-access" bonder)

Meeting the Production Goals

Retrofit Coordinate Measurement Machines (CMMs) to Perform Automated Pick-and-Place Assembly

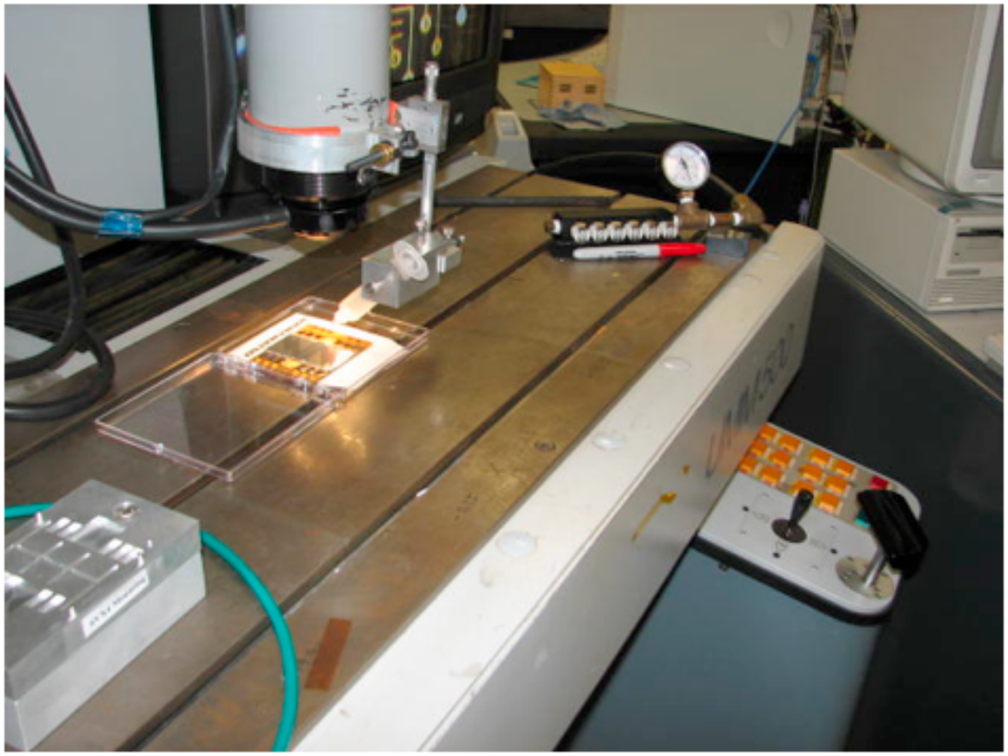
- **Performs a single Pick-and-Place Operation in 15 seconds (more than adequate)**
- **Will be interfaced with powerful Labview and Vision System Software**

Robotic assembly techniques are critical for the the LHC silicon detector upgrades.

O(10000) modules needed for CMS and ATLAS

Strong interests from ATLAS and CMS in using robotic assembly tools at Fermilab

A natural synergy between QUIET and Fermilab/HEP



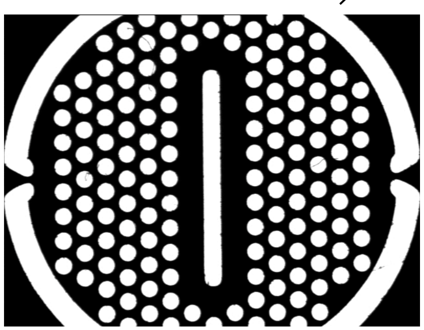
Zeiss 500 fitted with glue dispenser.
Used for the CDF Run-IIb silicon R&D

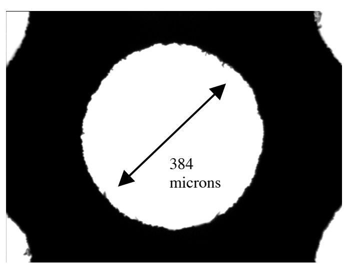
Handling of Very Small Parts

Smallest parts are the 200 micron x 200 micron capacitors

Can purchase tool from semi-conductor industry

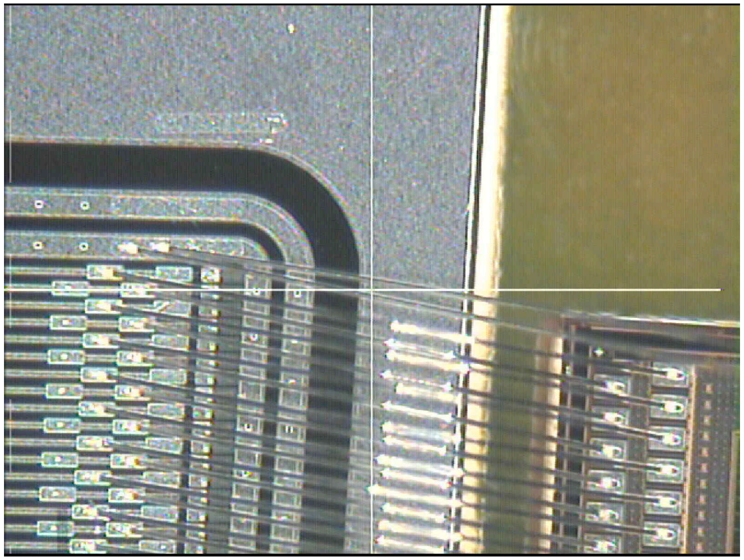
Can fabricate tool via photochemical milling





200 micron wide silicon strip handled by vacuum pick-up tool

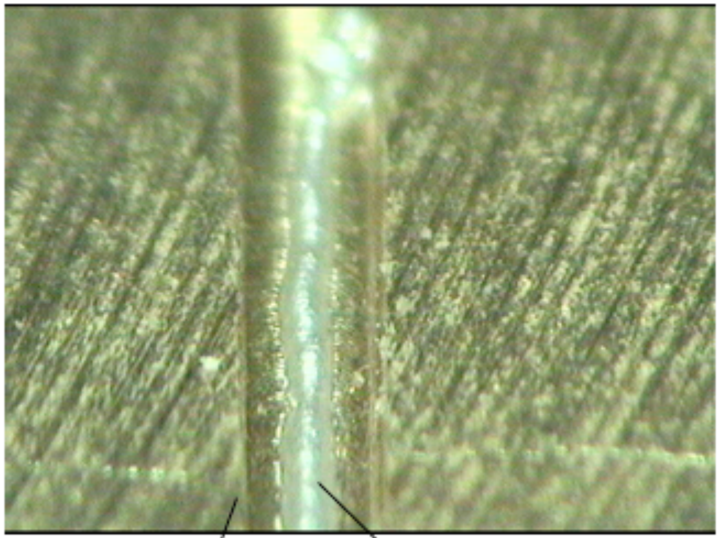
Demonstrated Technical Competence



Superb Wirebonding Expertise

Precision Glue Dispensing

We were able to dispense silver epoxy through a 100 micron diameter syringe.

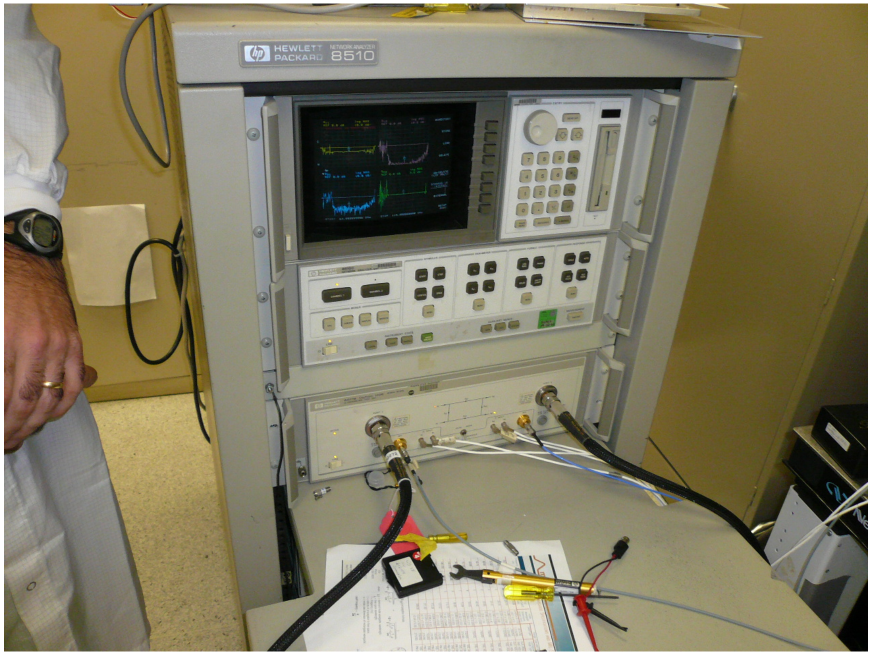


500 micron channel cut into brass

200 micron Ag Epoxy glue bead

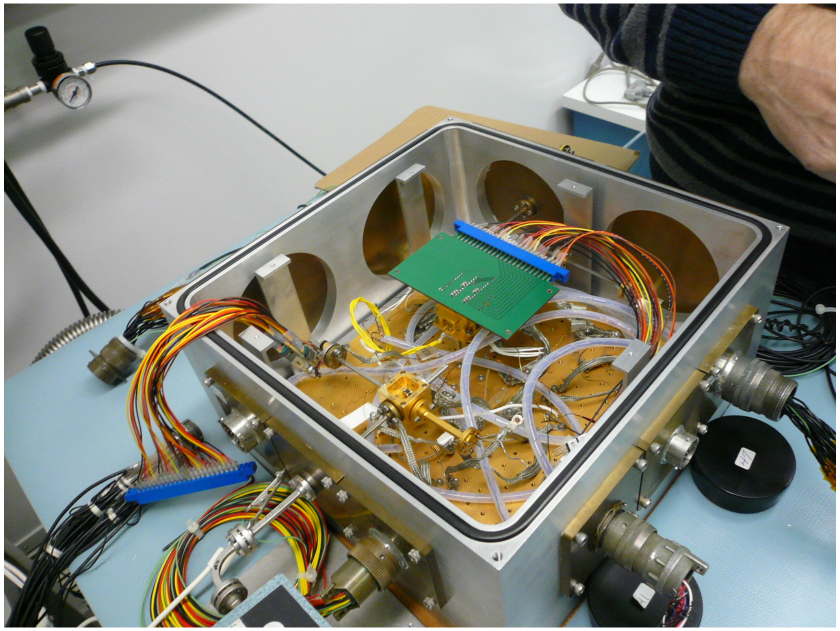
Automated Wirebonding Machine at the Fermilab Silicon Detector Facility

Quality Assurance is Critical



Inspection
Production Testing
Documentation
Management
Environment, Safety, and Health (ES&H)

We accounted for these in the time-and-effort estimate



VNA Teststands at NASA-JPL used for production testing and debugging of modules

We will replicate these stations at Fermilab.

We will utilize RF expertise at Fermilab.

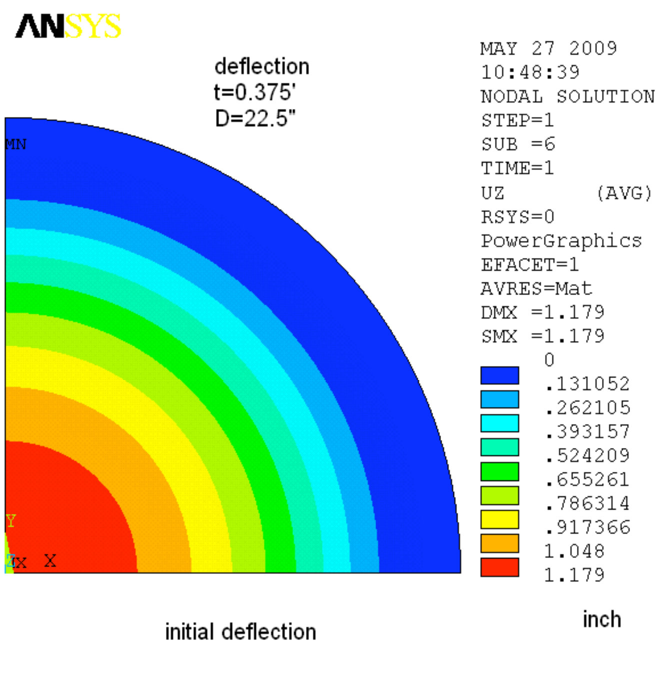
Our Proposed Involvement in QUIET Phase II

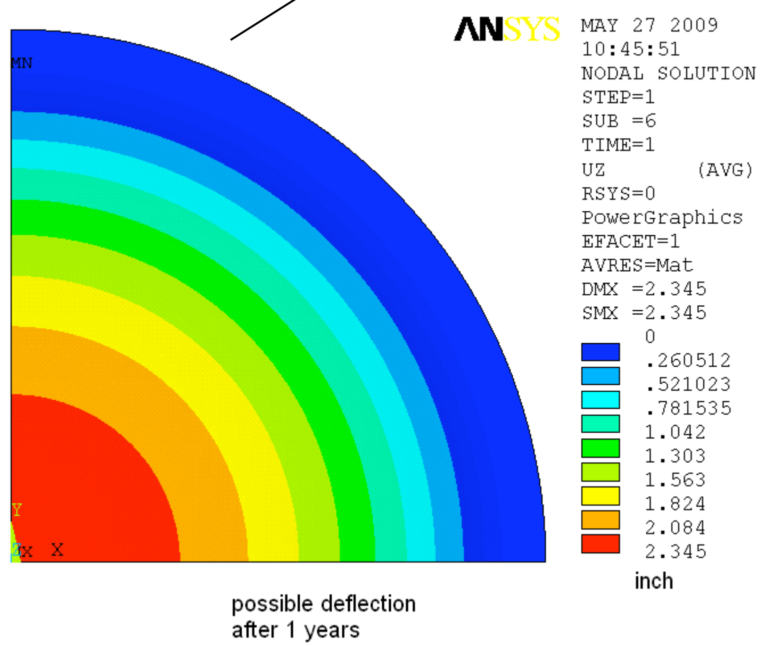
Wire Grid Assembly and Finite Element Analysis of Cryostat Vacuum Window.

Modest but really important contribution !

Mechanical Strength impacts the cryostat size
Distortion of the waves (window acts as a lens)
Thermal noise from the window

FEA of a QUIET Phase 1 Window,
done by Fermilab PPD Engineering Group





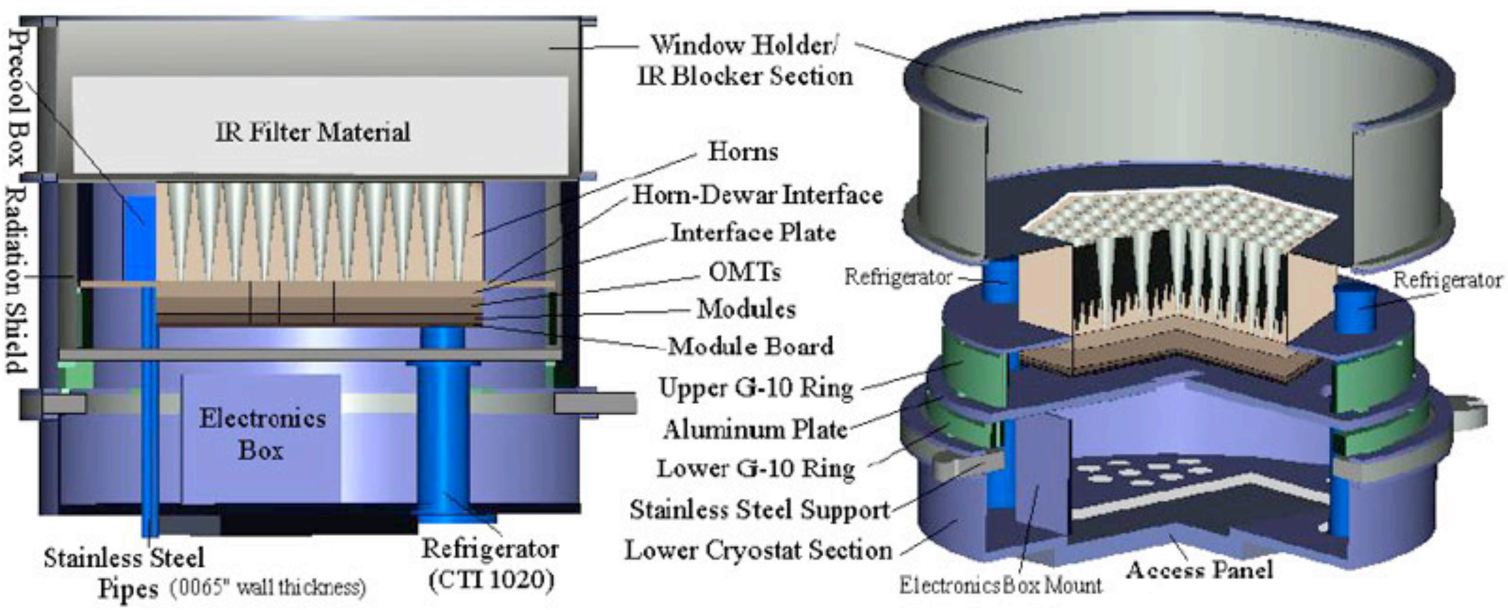
quiet, ,Tivar 1000uv,t=0.375,p=15 psi,22.5 inch

Our Proposed Involvement in QUIET Phase II

Final Cryostat Assembly and Characterization at Fermilab before deployment.

An exciting possibility !

Key to attracting other scientists to the project, and enabling the staff to be at the center of the scientific activities



Time line of QUIET R&D at Fermilab

- DeJongh and Nguyen visited JPL in Dec 08, entered discussions with Winstein and JPL staff on QUIET.
- Rotatable Wire Grid delivered to collaboration in Feb 09
- Received W-band module fabrication notes from JPL in April 09
- Nguyen to take shifts in Atacama, Chile in May 09
- **Hosted a QUIET Collaboration and Phase II meeting at Fermilab in June 09**
- **B. Winstein presentation to PASAG in July 09**
- Fritz Dejongh visited JPL and SLAC in July 09 to discuss production module testing

Completed

- **Joint PPD/FCPA review of QUIET in August 09**
- **QUIET Collaboration submits Phase II proposal to NSF in mid August**

Our next Steps

- **Presentation to the laboratory PAC**
- **Recognition as a DOE project**

Our hope

Summary

We'd like to propose a Fermilab/DOE partnership with QUIET

Project Construction Tasks

Assembly and QA of ~ 1500 W-band modules
Final assembly and commissioning of a cryostat
Calibration tools and window engineering analysis

Request to Fermilab/DOE:

Technical, Engineering, and Scientific Effort

Production tooling material costs
(NSF would provide funds for detector material costs)

Contribution to Chile site operations cost (~60 K$/year/institution)

Funds for Travel to Chile for Shifts and Installation

Fermilab W-band Module Assembly Labor and Tooling Costs

	Base (K$)	Contingency (K$)
Assembly Tooling Purchases	40.3	12.1
Assembly Tooling Fabrication Labor	23.6	23.6
Robotic Assembly Software Development	72.0	72.0
Parts Pick-and-Place Labor	23.3	11.7
Wirebonding Labor	70.9	21.2
Module Inspection, Supervision, Organization	131.0	65.4
Total	361	206

Assembly duration of ~1.2 years

Fermilab W-band Module Production Testing and Cryostat Commissioning Costs

	Base (K$)	Contingency (K$)
Production Testing Equipment	100	30
Production Testing Labor	169.8	84.9
Cryostat Assembly Labor, ES&H	149.3	74.7
Total	419.1	189.6

Though there are details to be worked out, we don't see any technical showstoppers

These costs will be internally reviewed by Fermilab in August 2009

Summary

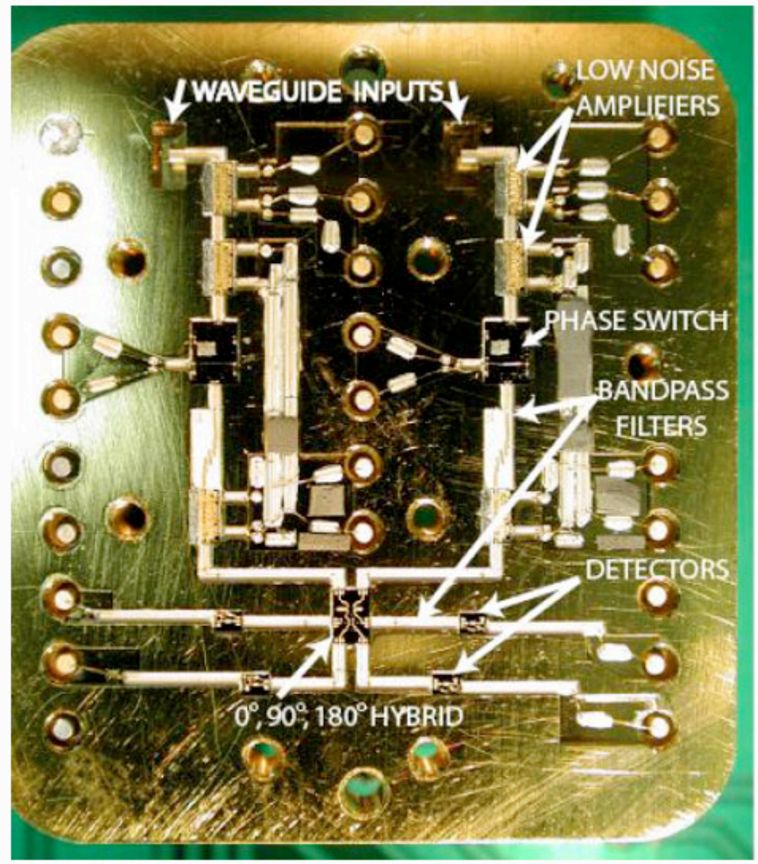
History and Strong Tradition of Intellectual Leadership

Dodelson and Stebbins were among the first to understand the importance of primordial CMB polarization.

A core for a strong Fermilab scientific team

Dodelson, Stebbins:	theory, analysis, scan strategy
DeJongh, Nguyen:	Detector fabrication, cryogenics
McGinnis:	RF/microwave circuit design and technology

The QUIET Collaboration is inviting us to take a central role.

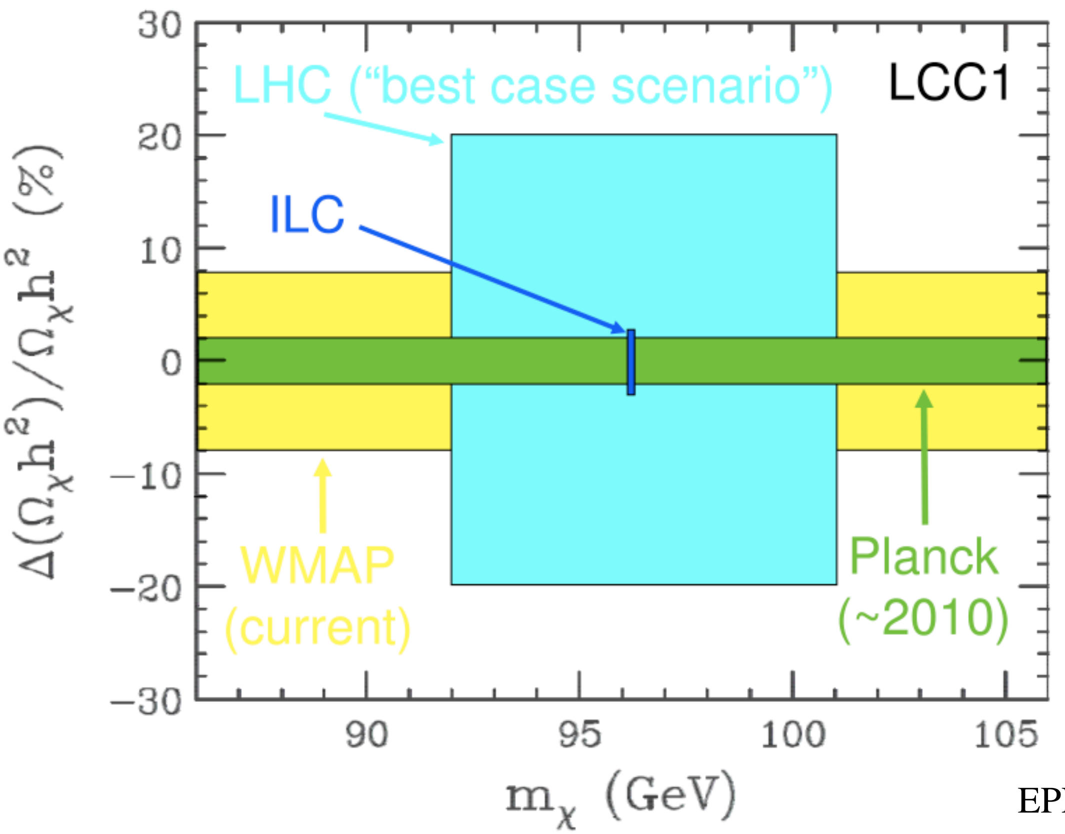


Backup Slides

Cost to Retrofit the 4 Zeiss 500 machines into Robotic Assembly Machines						
Material Costs	**Cost Per**	**Number Of Items**	**Extended Cost**	**Contingency**	**Contigency ($)**	
Rotary Stage	1411	4	5644	**30%**	**1693.2**	
Linear Stage	1471	8	11768	**30%**	**3530.4**	
Motor Controller	800	12	9600	**30%**	**2880**	
Vacuum Pickup Tools	100	23	2300	**30%**	**690**	
Custom Carriage Trays	100	10	1000	**30%**	**300**	
Miscellaneous Tooling	10000	1	10000	**30%**	**3000**	
Module Testing Hardware	100000	1	100000	**30%**	**30000**	
Sum			140312		42093.6	
Labor Cost for Developing Tooling	**Number of Weeks**	**Personnel**	**Extended Cost**	**Hr Rate**	**Contingency**	**Contingency (dollars)**
Labview Programming	20	Computing Professional	62,624	**78.28**	**100%**	62624
Zeiss Programming	4	Senior Technician	9448	**59.05**	**100%**	9448
Labor to build tooling	10	Senior Technician	23,620	**59.05**	**100%**	23,620
Sum			95,692			95692
Labor Cost for W-band Assembly	**Labor Type**	**Number of Hours**	**Extended Cost**	**Hr Rate**	**Contingency**	**Contingency (dollars)**
Wirebonding	Sr. Tech	1200	70860	**59.05**	**30%**	21258
Assembly	Technician-II	500	23375	**46.75**	**50%**	11687.5
Inspection and Organization	Technical Supervisor	1600	130880	**81.8**	**50%**	65440
Sum			225115			98385.5
Other non-scientist Labor	**Labor Type**	**Number of FTE-years**	**Extended Cost**	**Hr Rate**	**Contingency**	**(dollars)**
Electrical Testing	EP-II or Electrical Engineer Equivalent	1	169790.4	**81.63**	**50%**	84,895
Cryostat assembly and ES&H	Tech Specialist	1	149323.2	**71.79**	**50%**	74661.6
sum			319113.6			159,557
		Total Labor	639,921		**Total Labor Contingency**	353634

Time Estimate for W-band Module Assembly of 1600 Modules						
Parts Placement utilizing 4 Tech-II Full time						
Time to Place One Part (minutes)	Number of Parts Per module	Modules Per Hour	Number of Zeiss machines	Total Number Per hour	Number of Modules	Total Number of hours
0.75	100	0.8	4	3.2	1600	500
Inspection time, setup, organization (Tech Supervisor)						
Time per module (hours)	Number of Modules	Total Time (hours)				
1	1600	1600				
Wirebonding Time (Sr. Tech)						
Time Per Module (hours)	Number of modules	Total Time (hours)				
0.75	1600	1200				
Actual Calendar Time Estimate	**Total assembly time (hours)**	**Total inspection/org time (hours)**	**Total Wirebonding Time (hours)**			
	500	1600	1200			
Number of days (5-hour work day)	100	320	240			
Number of Personnel	4	1	1			
Number of days	25	320	240			
Number of years	0.096153846	1.230769231	0.923076923			
(260 work days/year)						

CMB & Collider DM Constraints

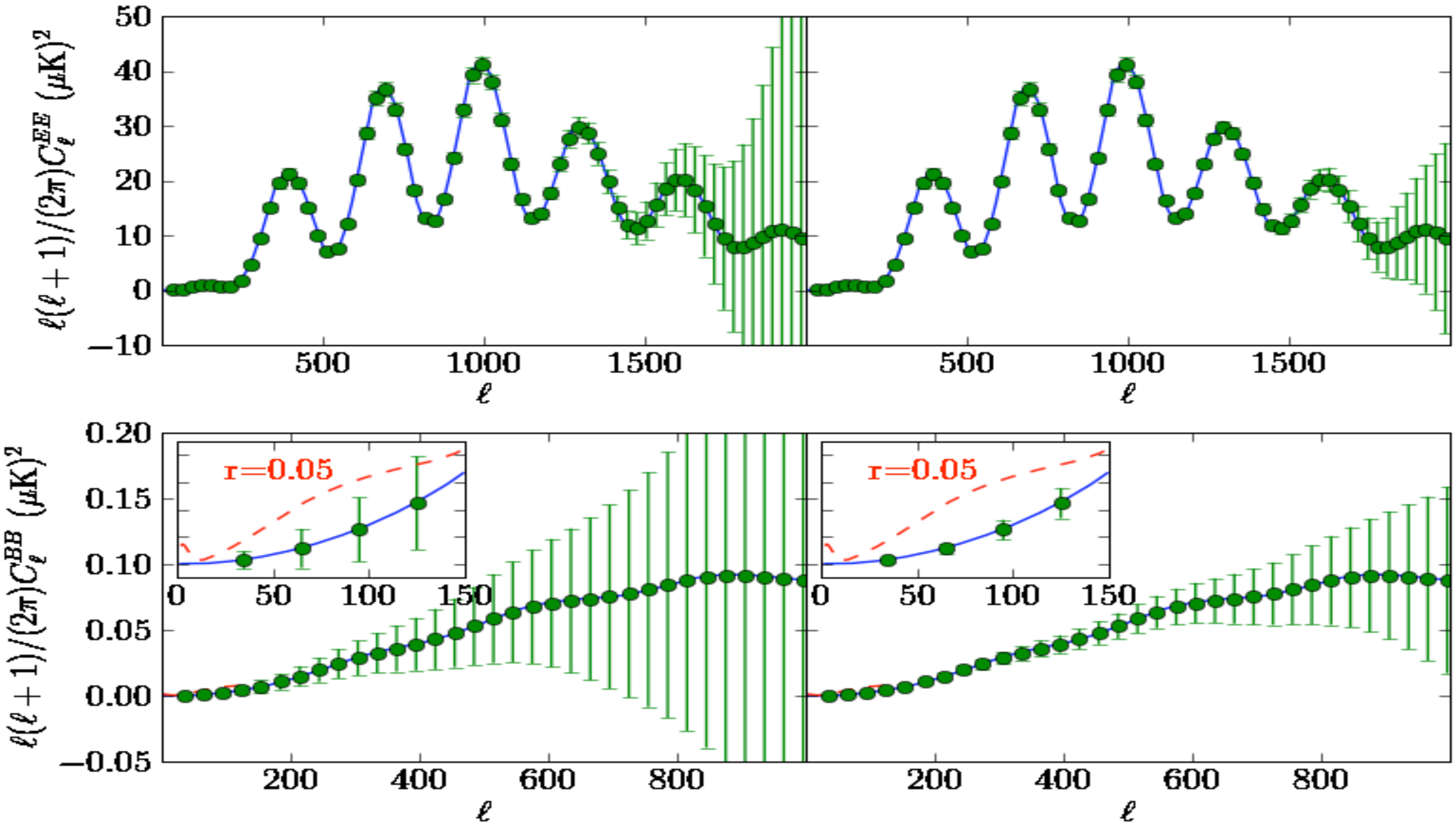


EPP2010

QUIET Phase-II (1600 pixels)

Current Performance
(noise, duty cycle, 1/f)

Likely Improvements



0.018	Δr	0.005
10σ	lensing	35σ