QUIET

A Cosmic Microwave Background Probe of Inflation

using

Coherent Detectors

Food For Thought Seminar
Hogan Nguyen, EPP
Sept. 14th 2010

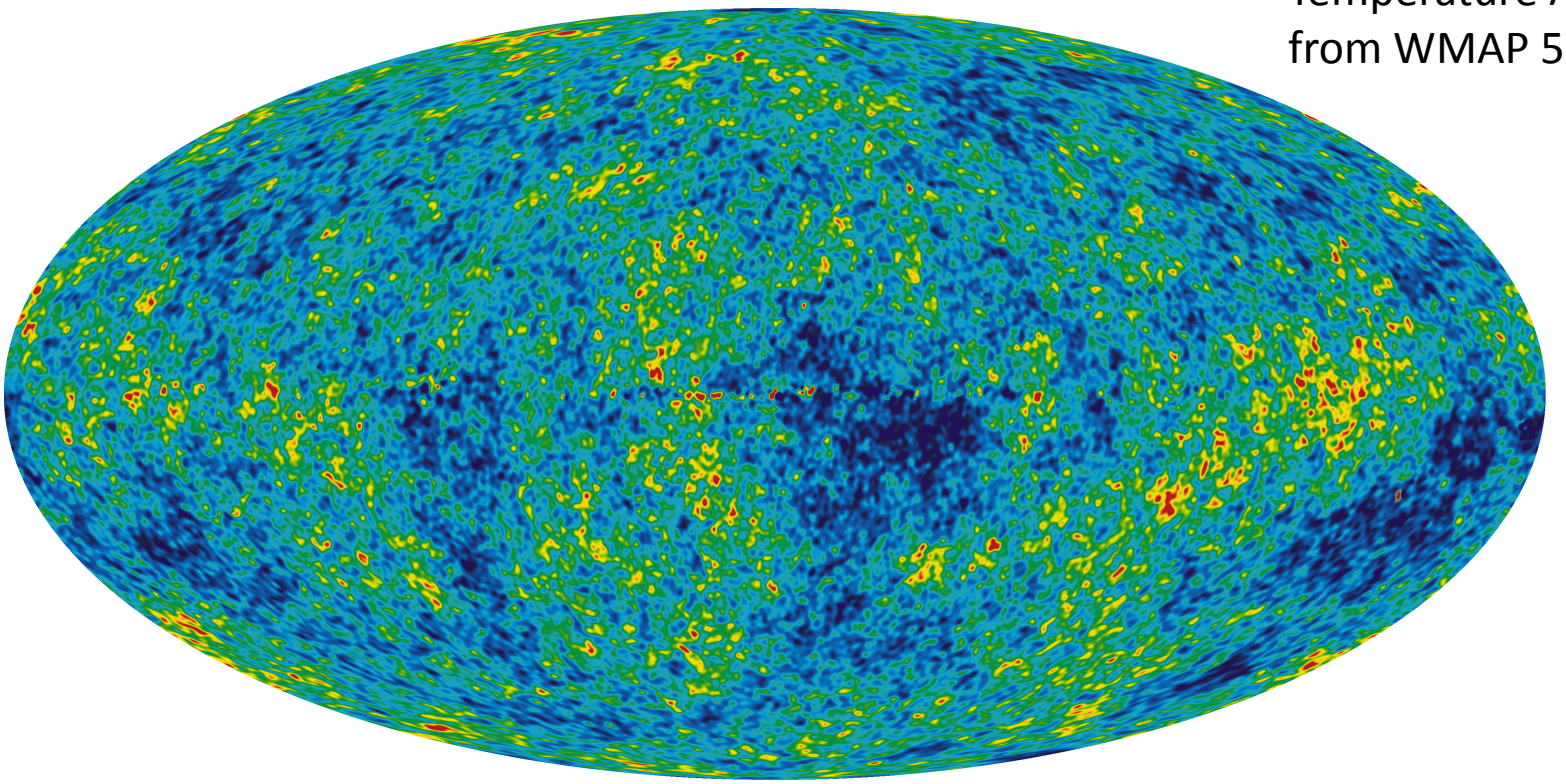
Outline

Fun Facts about the Cosmic Microwave Background

Fun Facts about Inflation

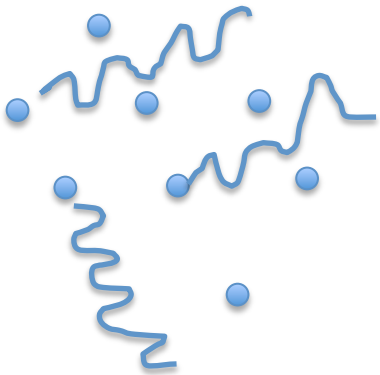
Cool Experimental Details

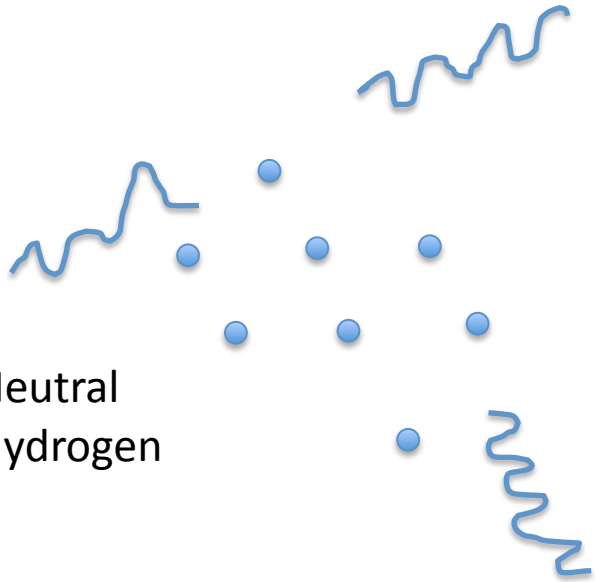
Temperature Anisotropy
from WMAP 5-year Survey



The Cosmic Microwave Background

Primordial
Plasma





Neutral
Hydrogen

Acoustic Oscillations of Baryonic Matter
in the Primordial Plasma

Attractive force: Self Gravity from baryonic matter,
non-baryonic matter, and photons

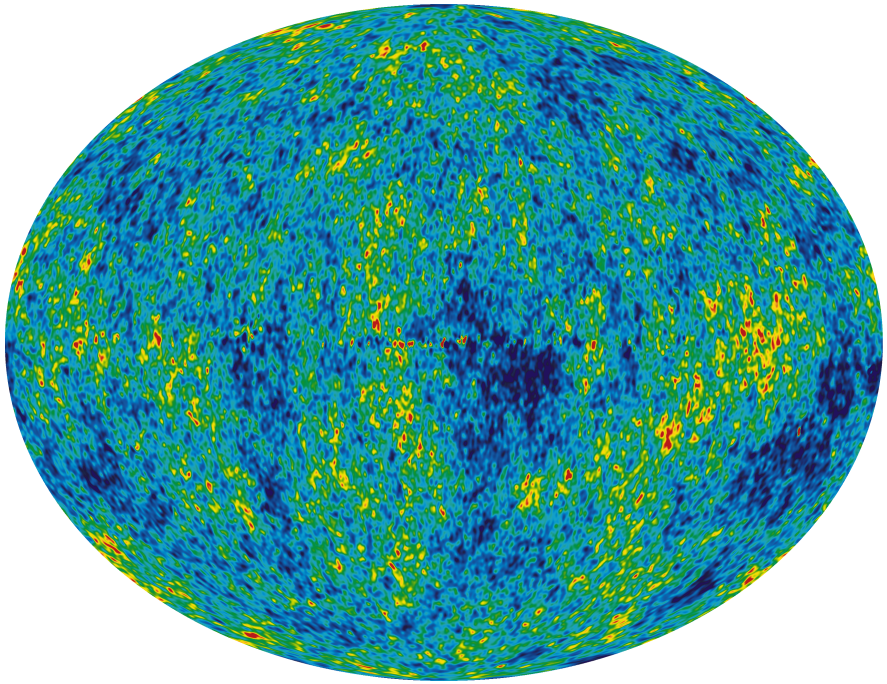
Repulsive force: Photons

Note: **No Acoustic Oscillation of Non-baryonic matter**

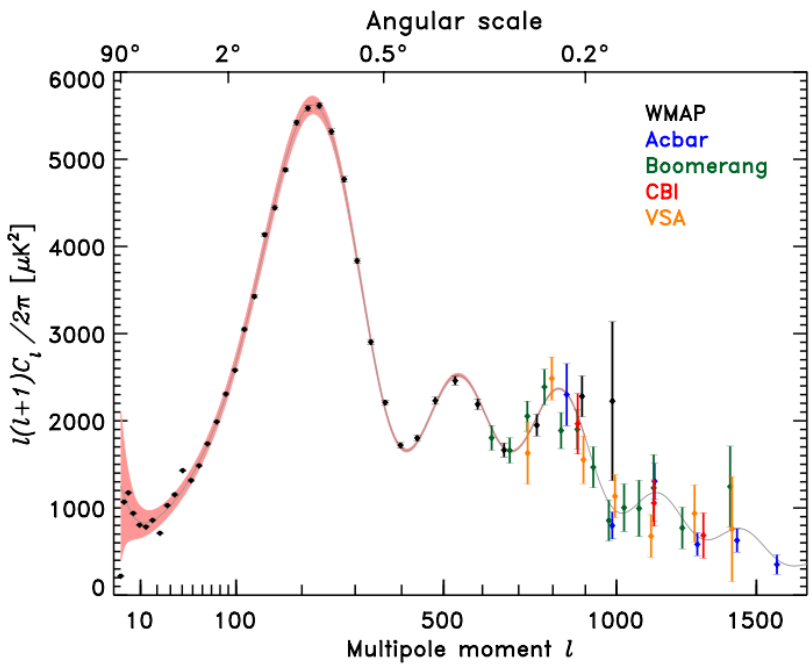
The CMB was released at the time Neutral Hydrogen was formed ('Decoupling')

A 'Snapshot' of 400K years after the Big Bang

Cosmic Microwave Background Amazing Fun Facts



Temperature correlation between two separated points in sky



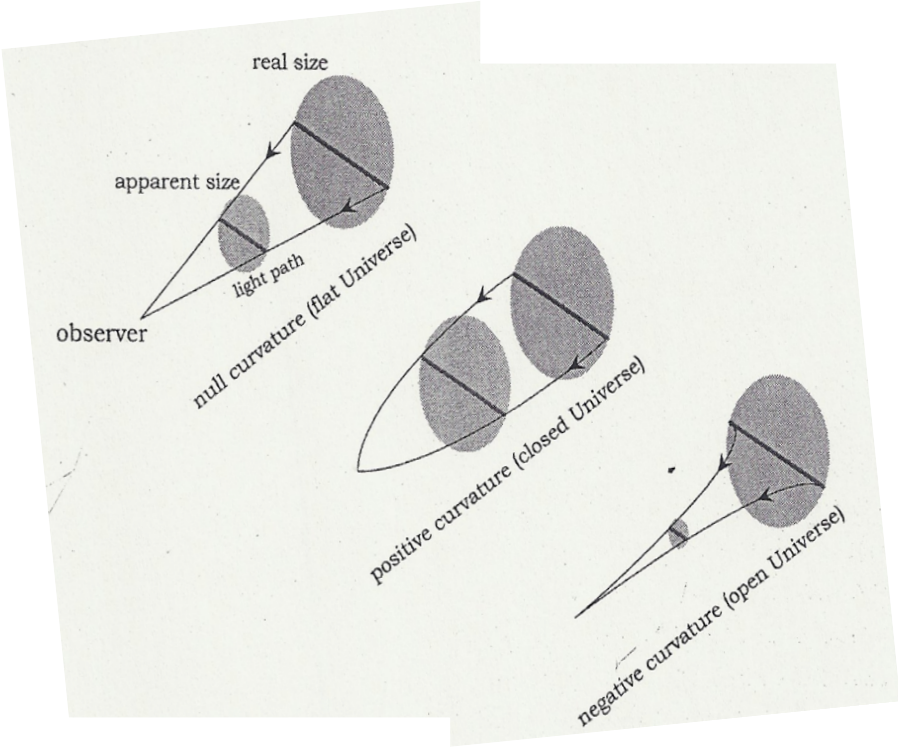
Oscillations of the same FREQUENCY are in Phase

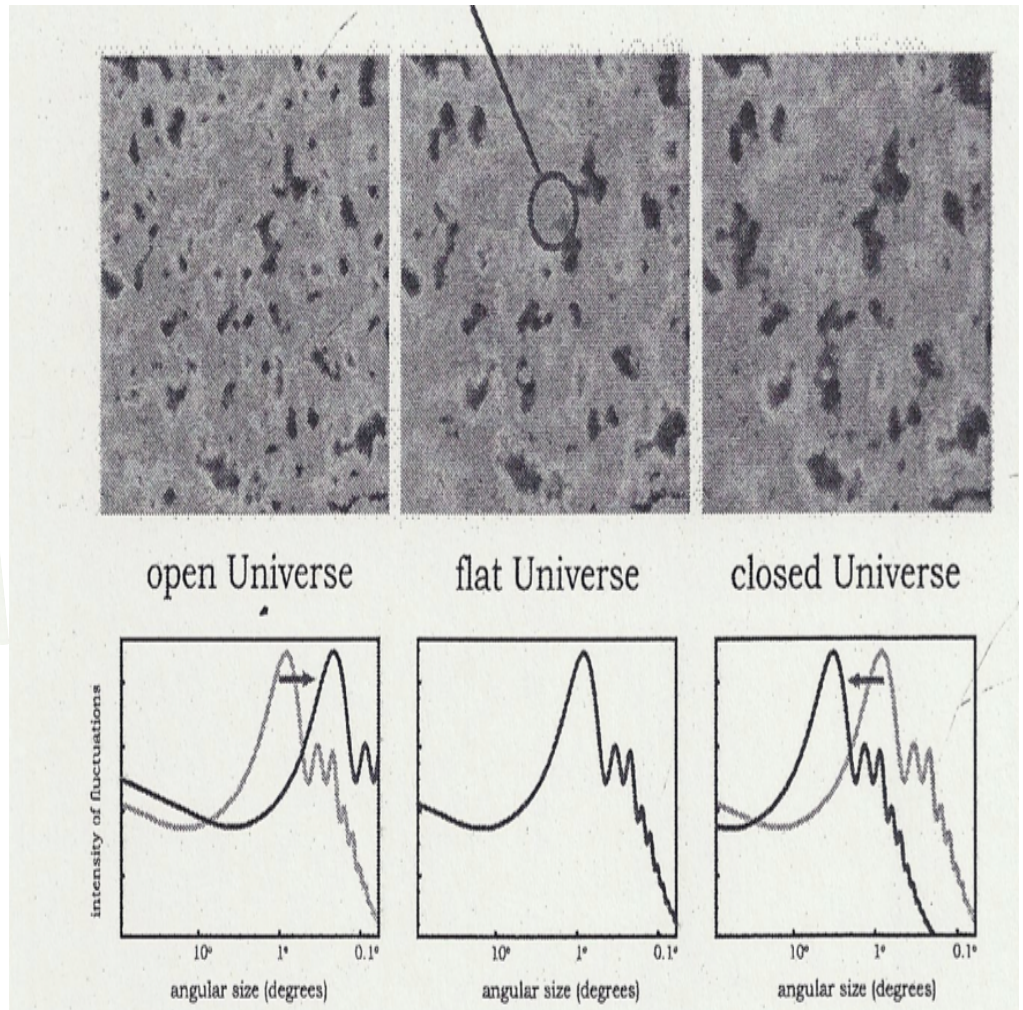
Height of oscillation determine AMOUNT of Non-Baryonic Matter

Location of 1st peak says that universe is FLAT

The Universe is Geometrically Flat

Location of 1st peak says that Universe is FLAT

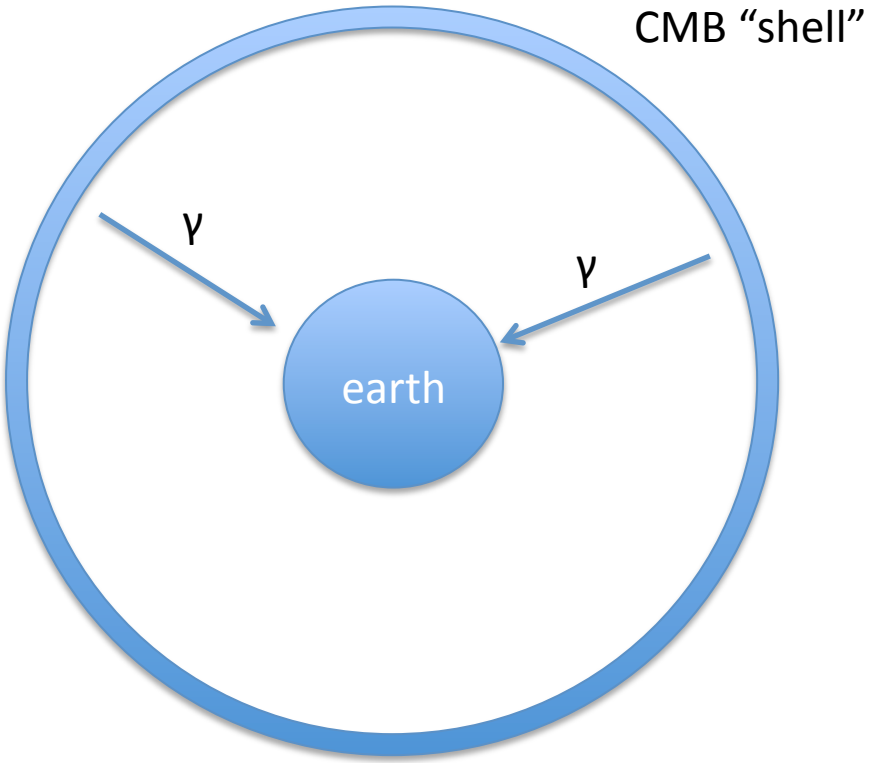




Theory Predicts Intrinsic Spot Size

Geometry of Space can
enlarge or diminish Spot size

Inflation Allows You to Travel Faster Than Light ... Sort of

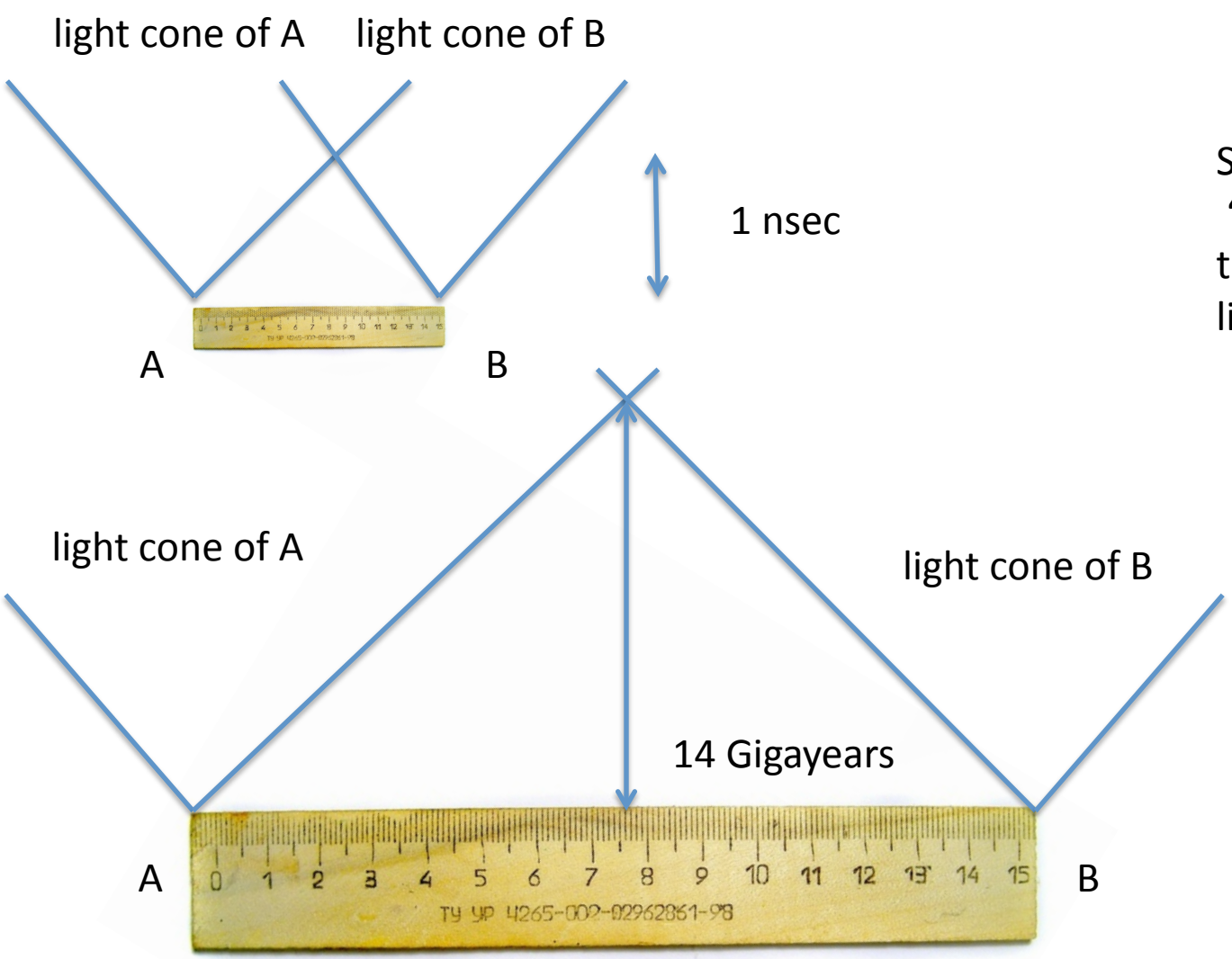


CMB photons emitted 13.6 billion years ago are meeting at Earth for the FIRST time.

AMAZING coincidence that temperatures agree to within 80 μK

Some mechanism for disconnected space-time points to have been in causal contact in the past.

Inflation Allows You to Travel Faster Than Light ... Sort of

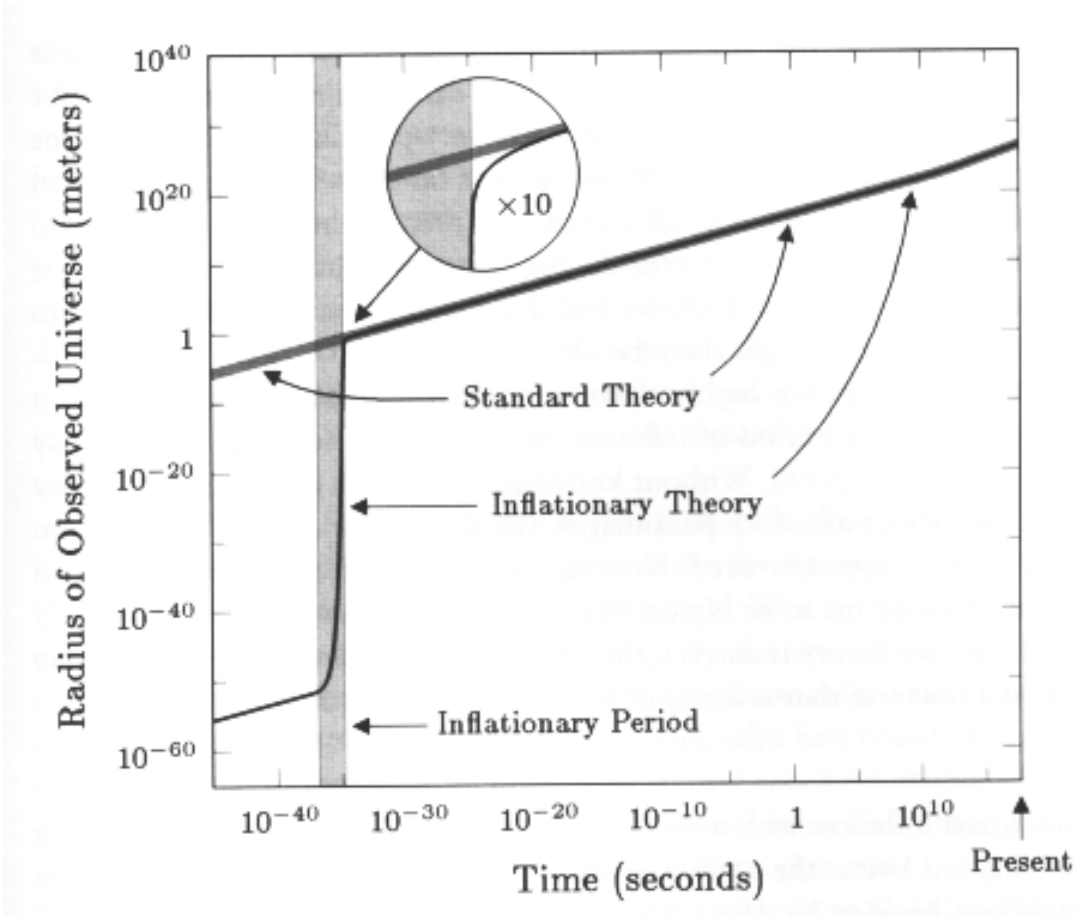


Space expanded 'faster than the speed of light'

Allowed by the laws of physics

Inflation Allows You to Travel Faster Than Light ... Sort of

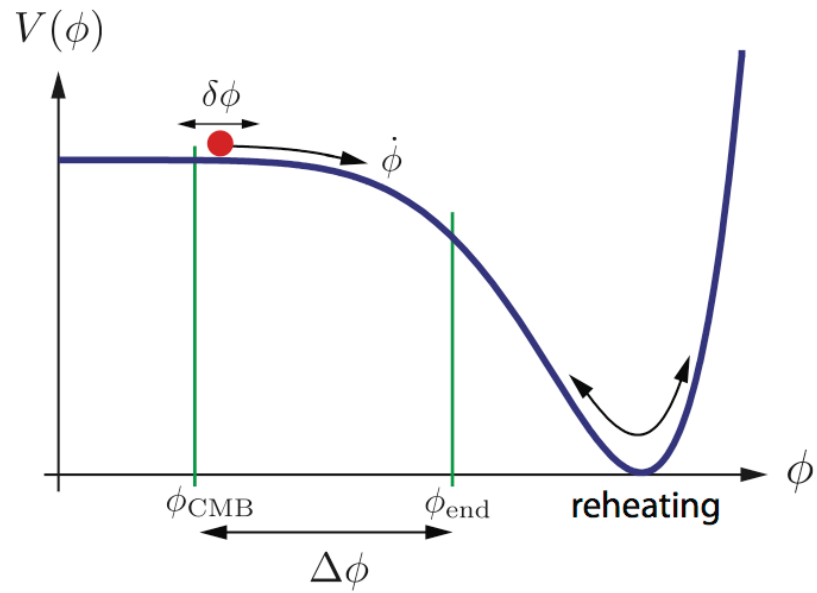
Observable Universe grew by 10^{50} in 10^{-35} seconds (model dependent)



From Guth, the Inflationary Universe

Inflation is High Energy Physics at the GUT Scale !

Scalar Field Φ describes the vacuum energy to expand space during Inflation



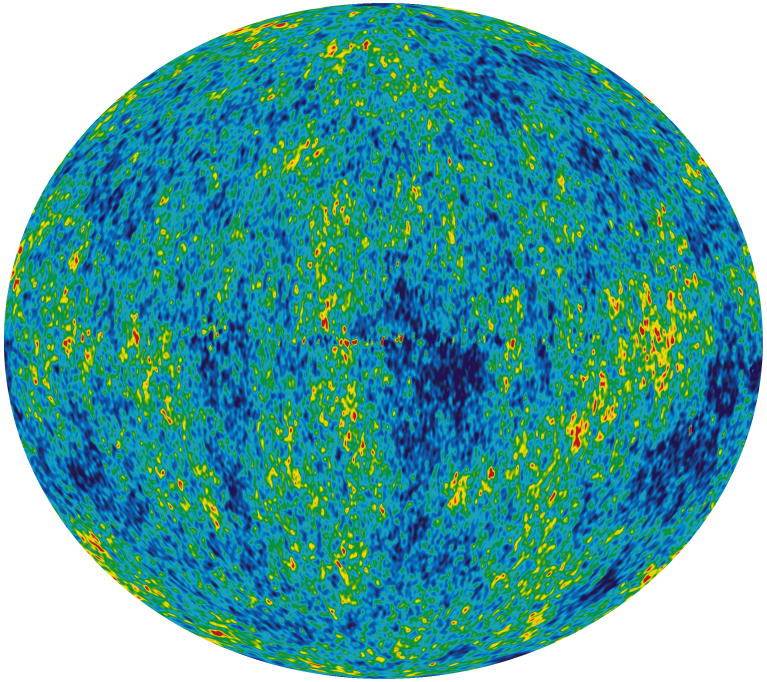
Freidman equation from GR

$$H^2 = (8\pi/3)\, G\, V(\Phi)$$

$V(\Phi)^{1/4}$ is of order 10^{16} GeV

H = Hubble's constant during inflation
G = Newton's constant

Inflation ... The Ultimate Amplifier of Quantum Phenomenon



Universe size (before Inflation) ~ 10^{-50} meters

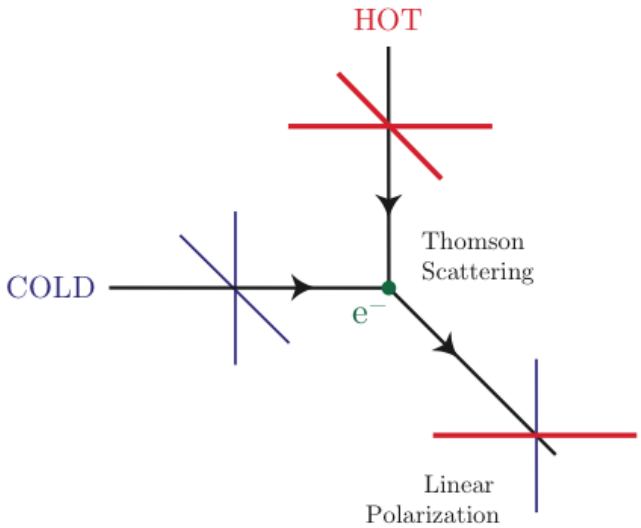
Universe size (after Inflation) ~ 1 meter

Inflation magnified Quantum Fluctuations
to large scales:

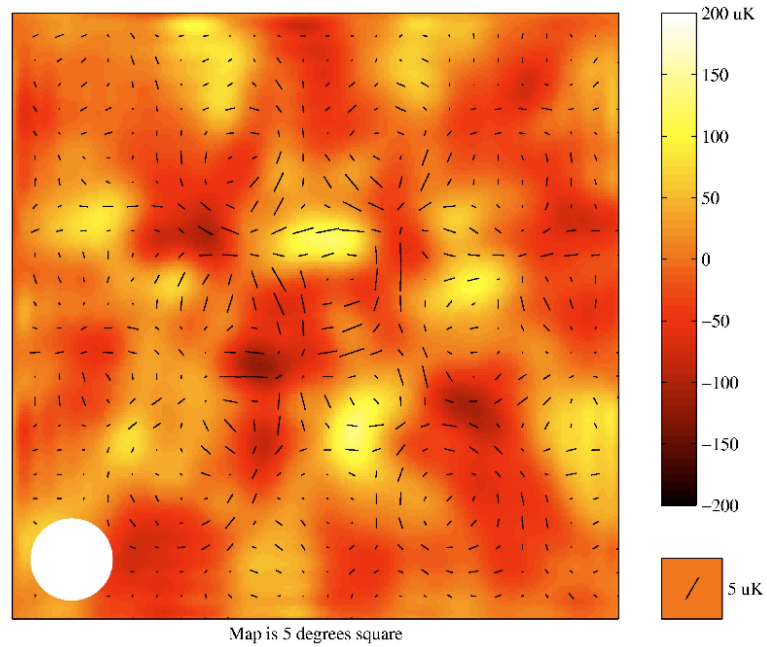
Matter Density QM Fluctuations	→	Temperature Anisotropy in the CMB
Space-time Metric QM Fluctuations (primordial gravity waves)	→	***B-mode polarization in the CMB***

CMB Polarization: The Next Frontier

Temperature Anisotropy (Scalar Field)
Polarizes the CMB

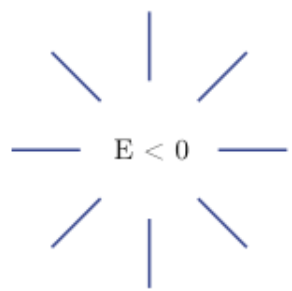


Observed by DASI in 2002

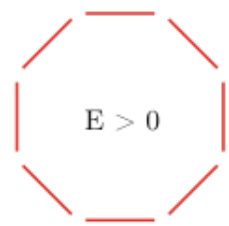


Generated at the BOUNDARY between Hot and Cold Spot.

Since Scalar Field has NO handedness, Generates a 'curl-free' (E-mode) Polarization Pattern.



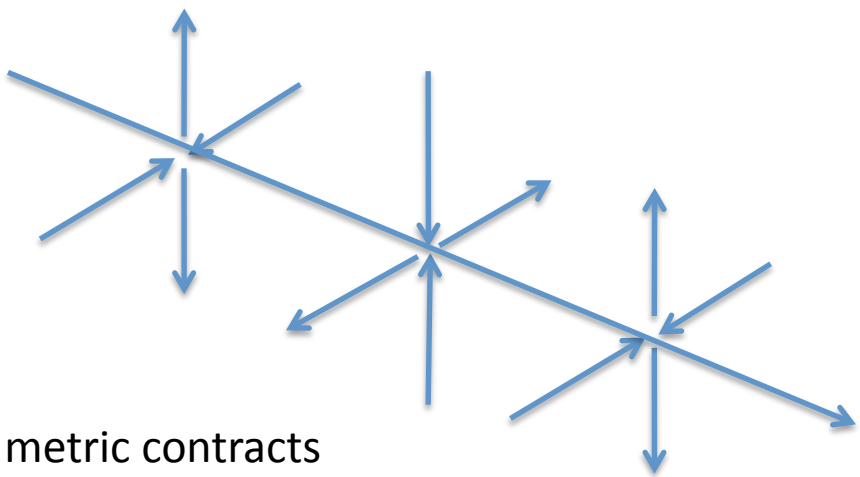
cold spot



hot spot

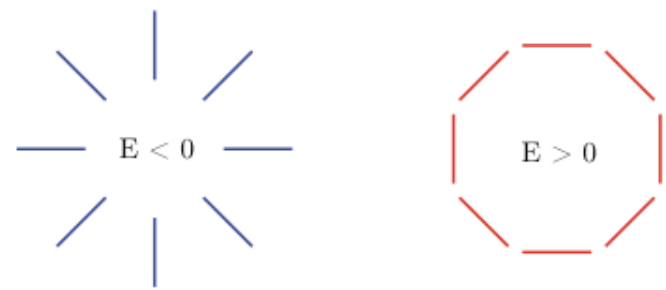
CMB Polarization: The Next Frontier

The Presence of Gravitational Waves MODIFIES the E-mode of the CMB Polarization !



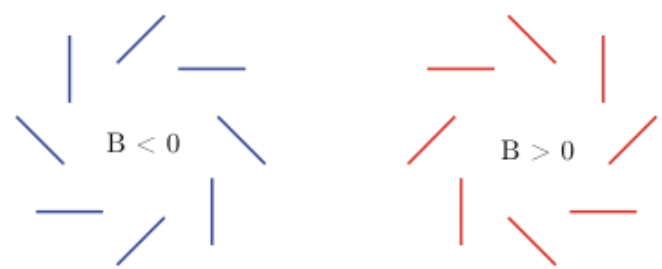
metric contracts and expands

GW propagation



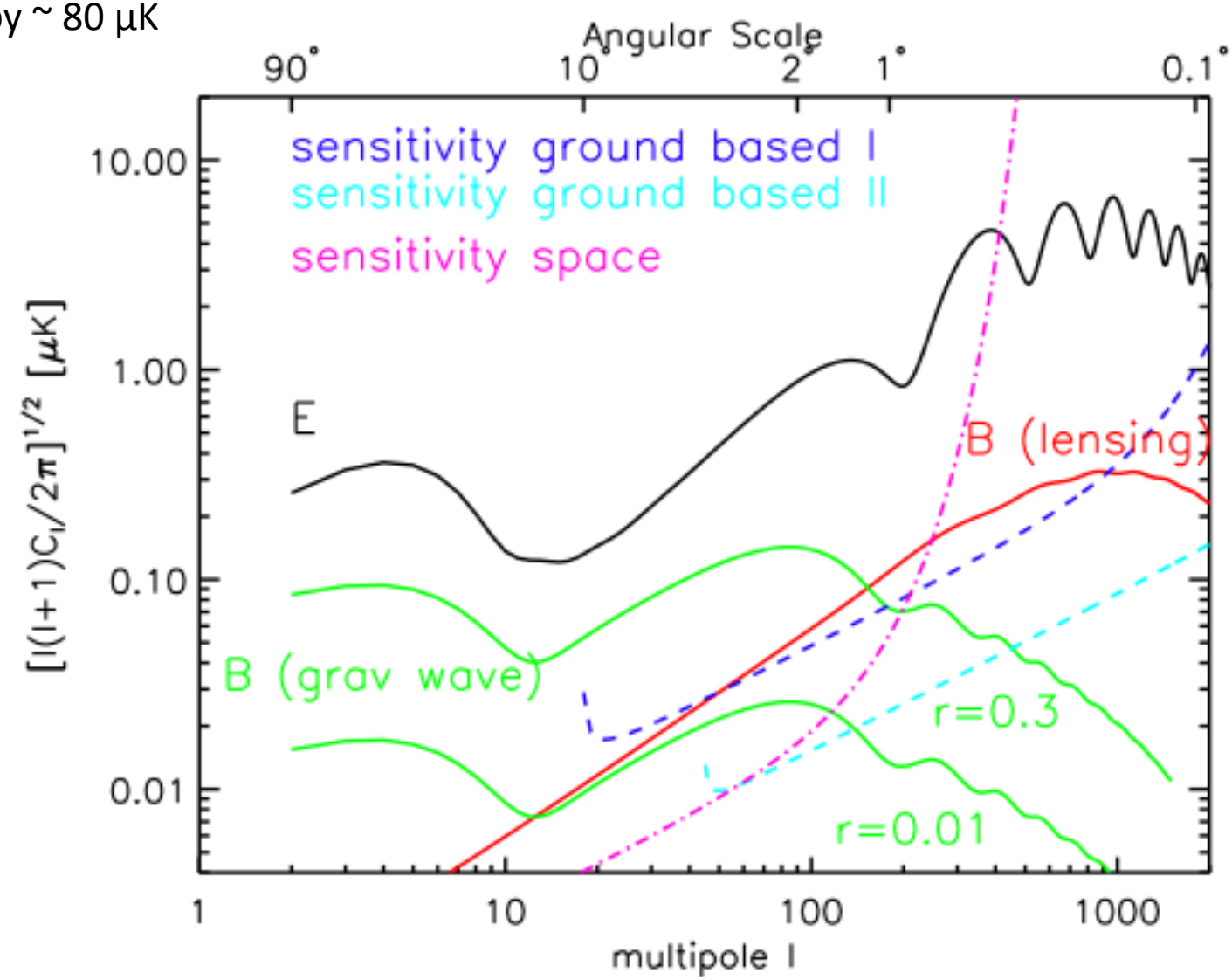
tensor field (GW) modifies E-mode

Polarization gains a handedness (B-mode)



CMB Polarization is Small

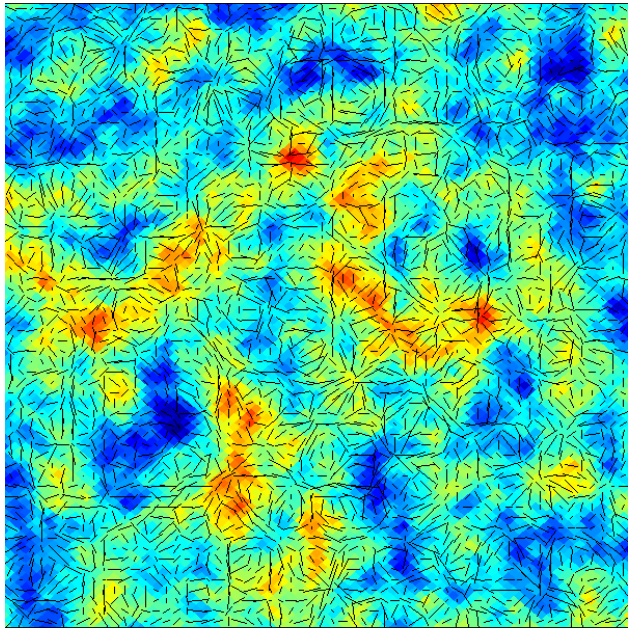
Temperature
Anisotropy ~ 80 µK



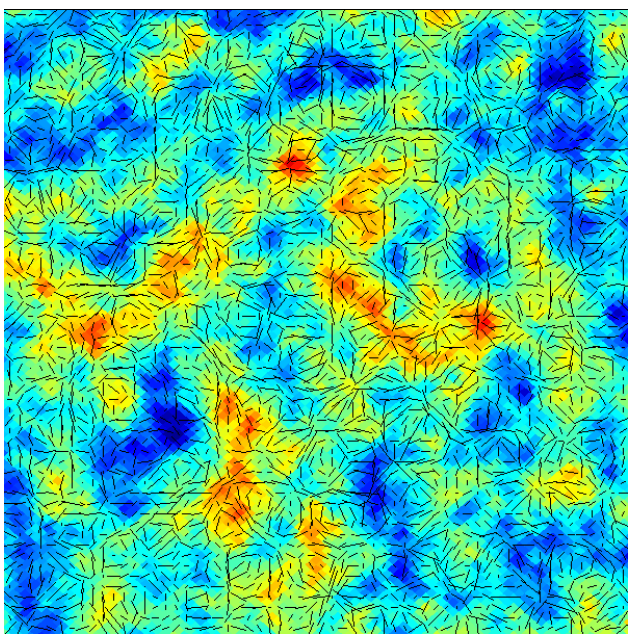
Simulation

A Difficult Measurement !

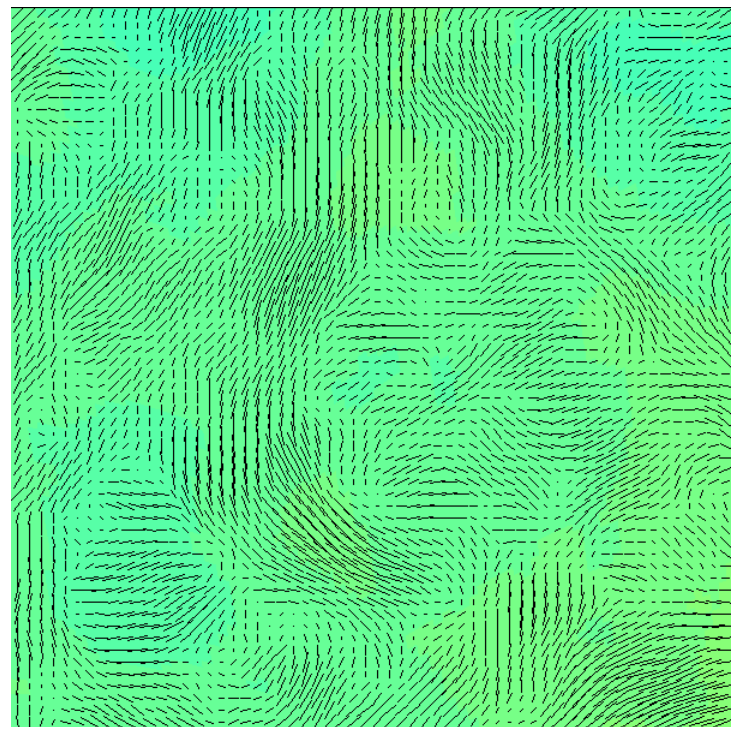
No Tensor fields



Tensor/Scalar = 0.2



Difference between *T/S* = 0.2 and *T/S* = 0 (magnified by 500)



Another Tool: Gravitational Lensing of the CMB

Since the CMB is the oldest light in the universe, can even see before the birth of first stars

Temperature Anisotropy

E-mode

Unlensed

Lensed

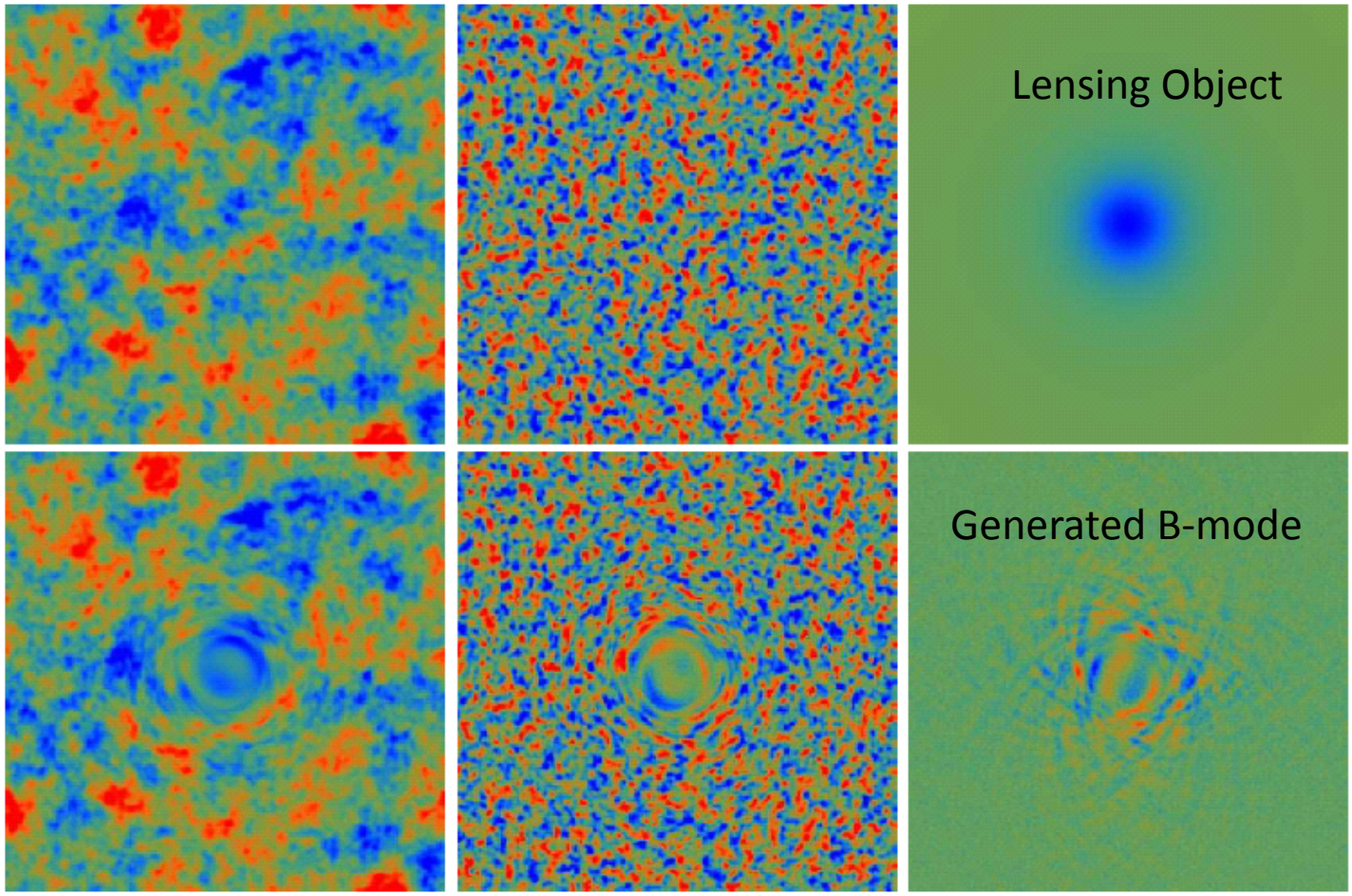


FIG. 1.— An exaggerated example of the lensing effect on a $10^\circ \times 10^\circ$ field. Top: (left-to-right) unlensed temperature field, unlensed E-polarization field, spherically symmetric deflection field $d(\mathrm{n})$. Bottom: (left-to-right) lensed temperature field, lensed E-polarization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

The QUIET Experiment

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

Chajnantor Plateau (5612 m ASL),
Atacama Desert, Chile

Very Dry (PWV < 5 mm year round)

Area is hotbed of millimeter wave astronomy
ALMA, ACT, ABS

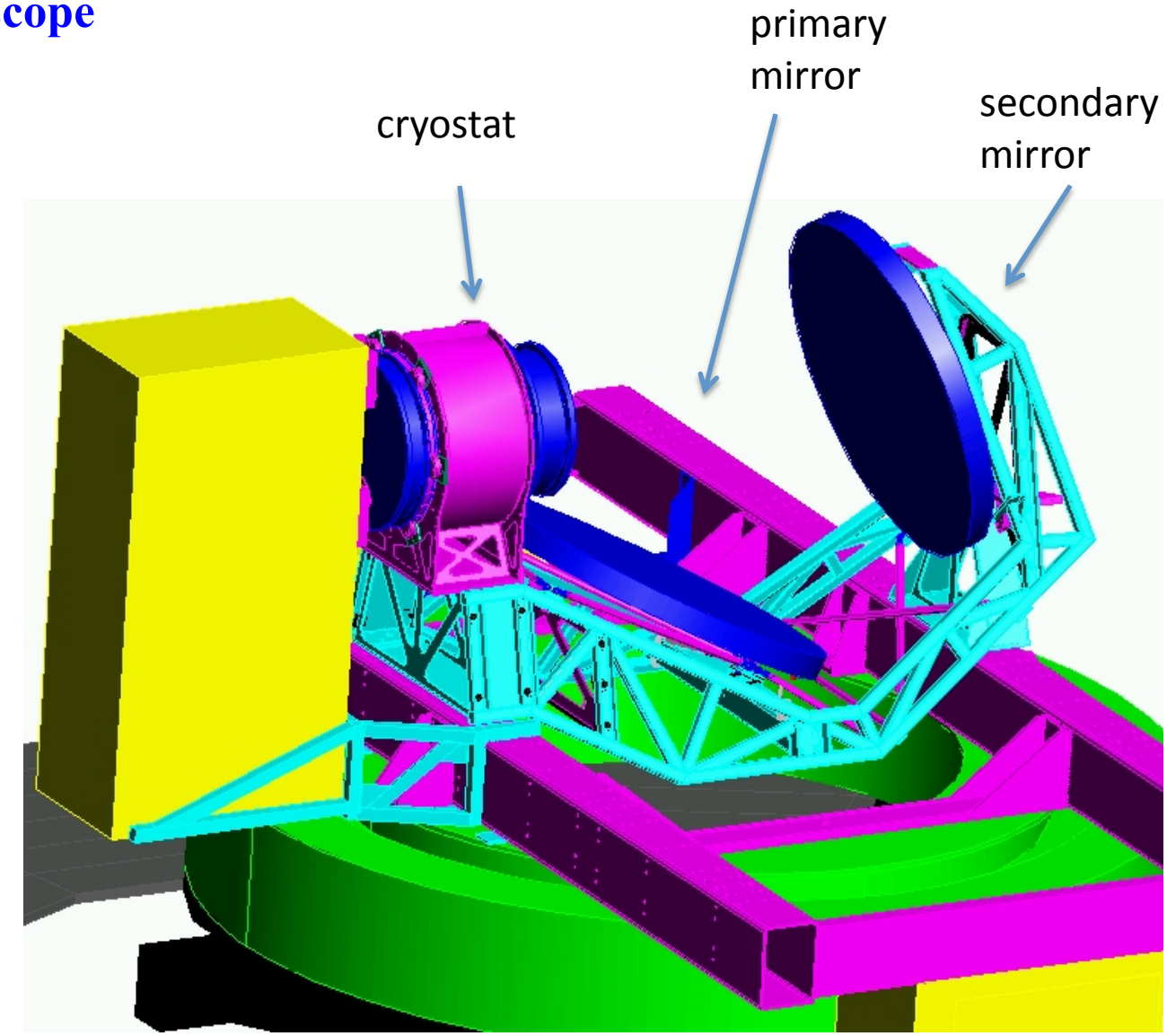
Phase 1 (Taking data NOW!)

Phase 2 (Awaiting NSF Approval for construction)

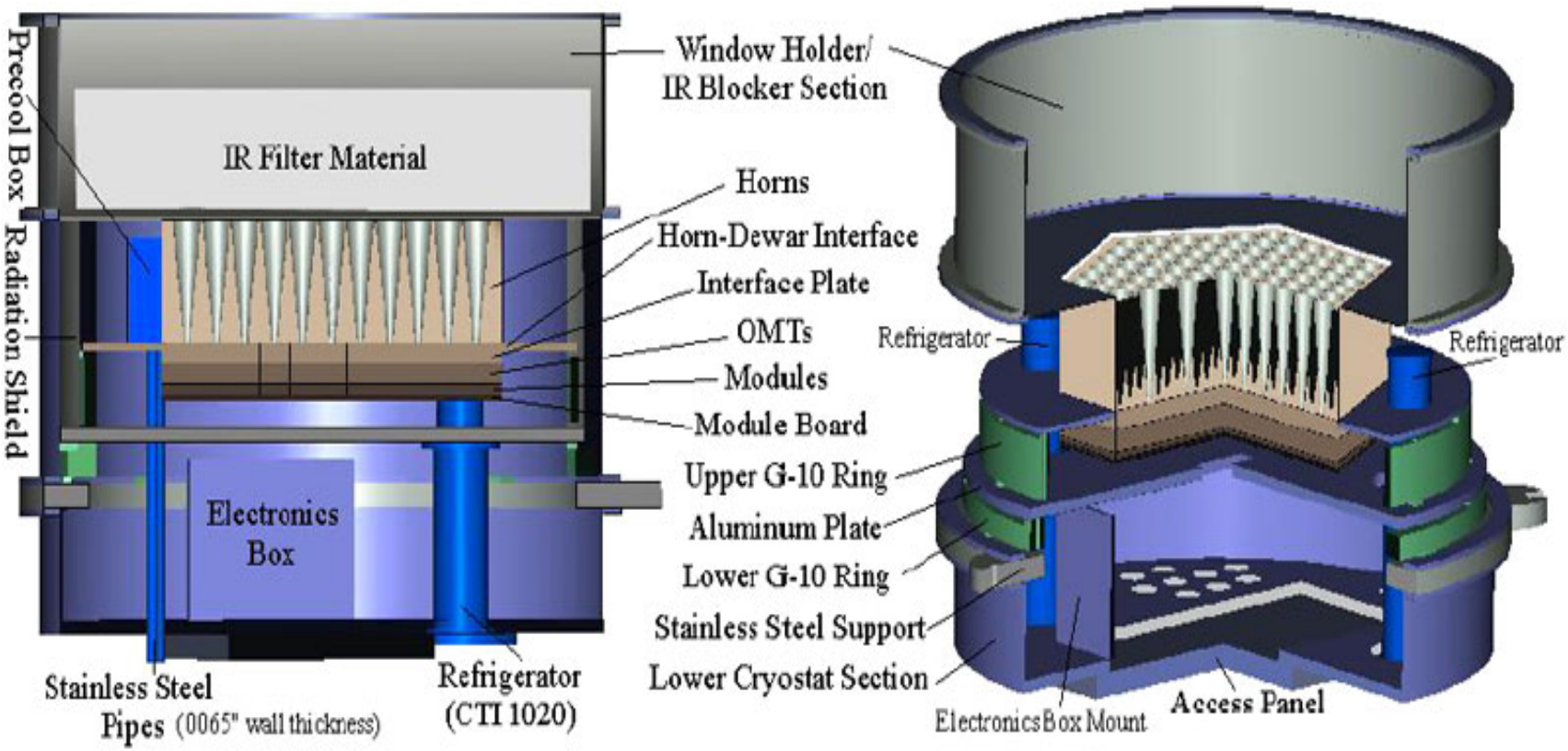
The Phase 1 Telescope

3 axes are needed

- Azimuth
- Elevation
- Boresight Rotation (for polarization systematics)

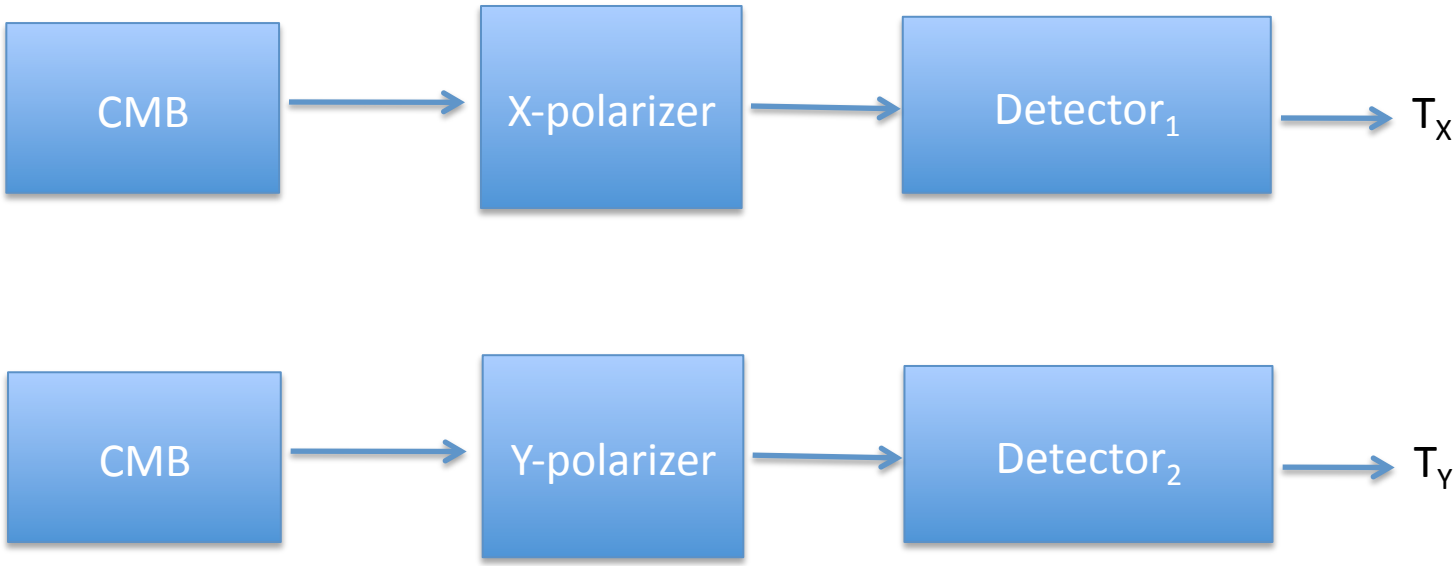


The 20 Kelvin Cryostat (Phase 1)



22”

Basic Concept of Measuring Polarization

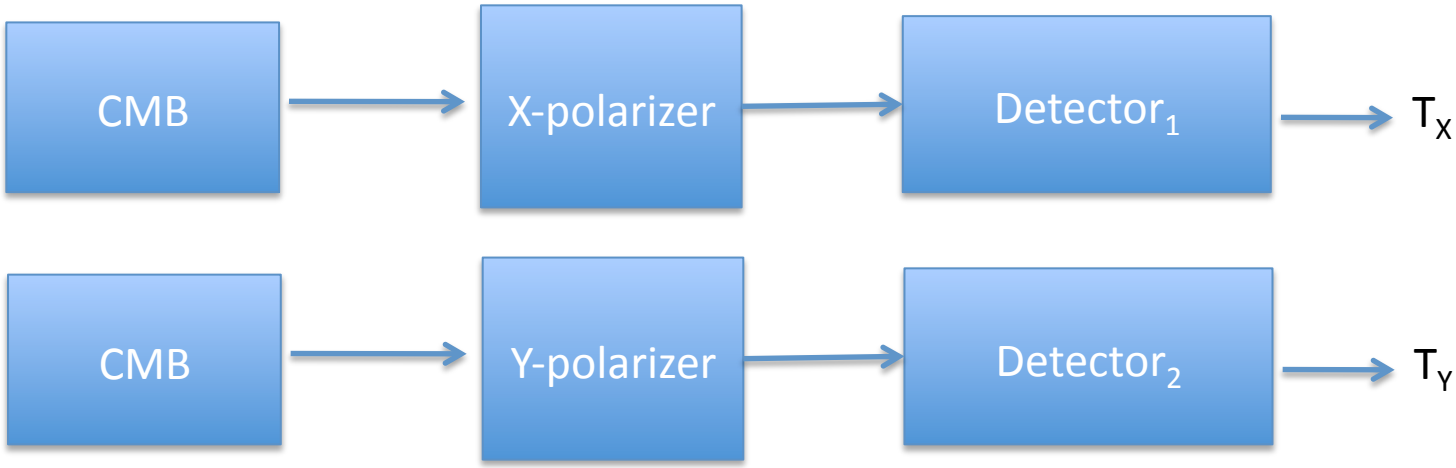


T_X ~ 3 Kelvin
T_Y ~ 3 Kelvin

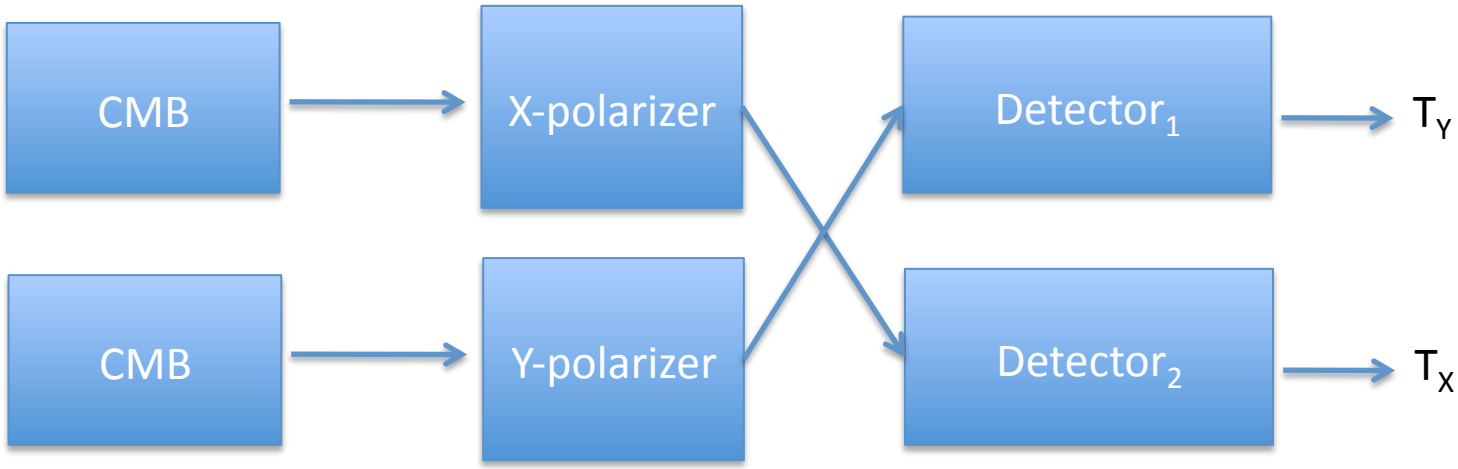
$T_X - T_Y$ ~ 80 μK

If Detectors 1 and 2 don't have equal gain, then can FAKE a polarization

High Speed Switching To Cancel Detector Systematics

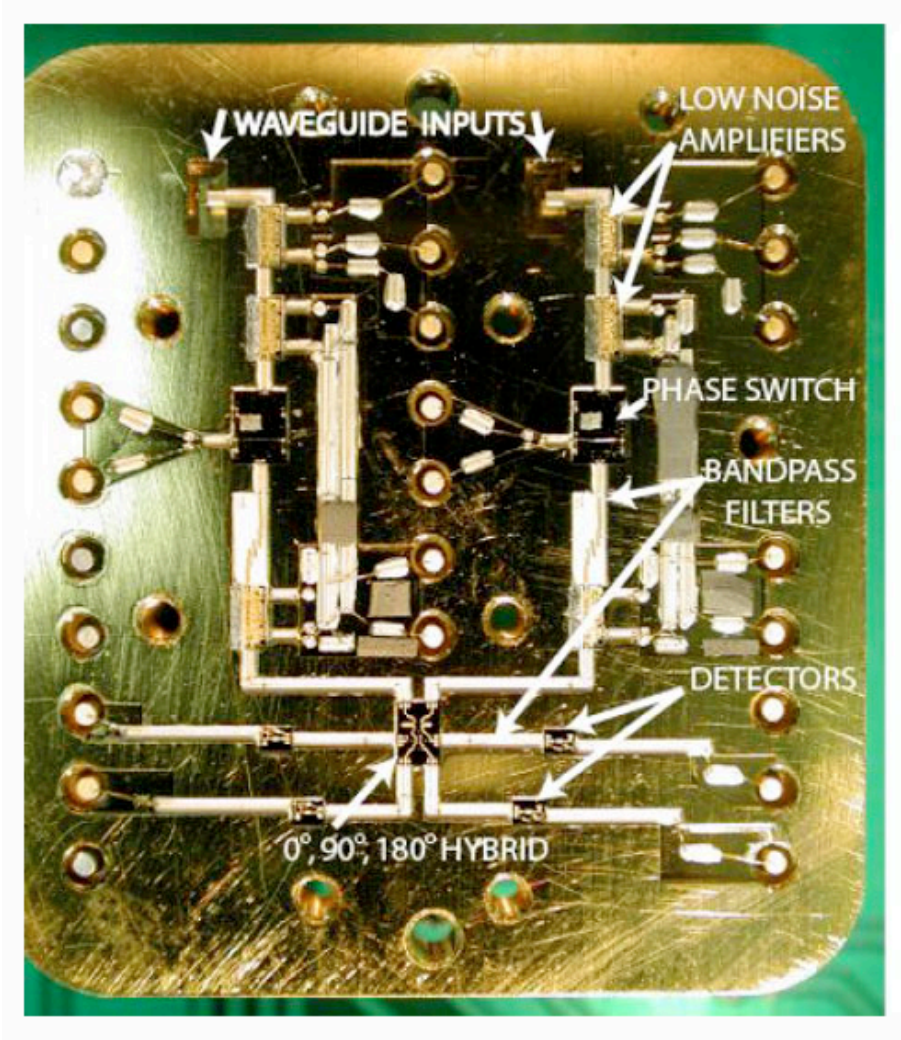


Rapidly Switch back and forth



QUIET Uses Coherent Detectors

1 "



90 GHz detector developed at JPL

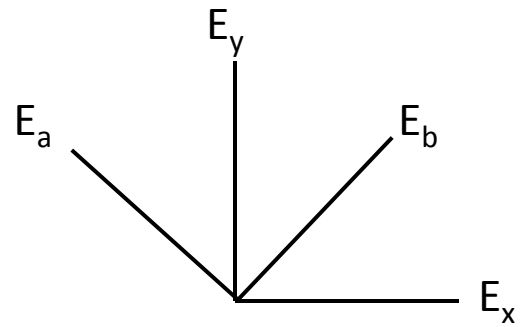
Single Microwaves
Photons are amplified
by ~ 90 dB (10^9)

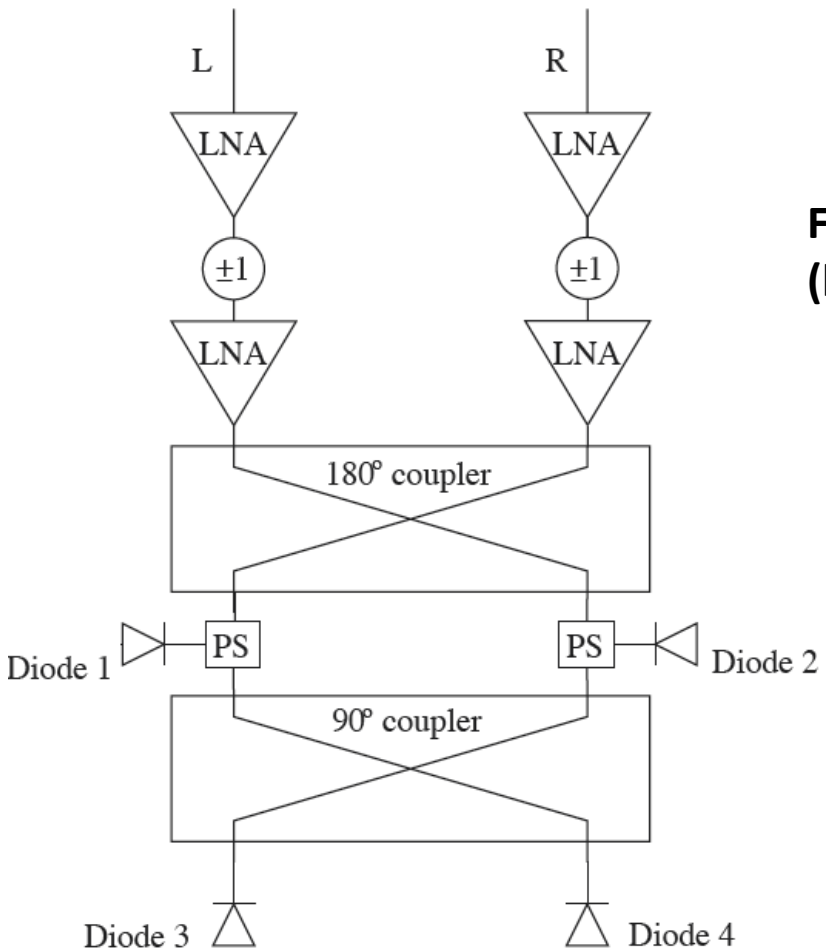
Pay a noise penalty from the amplifiers

Use High Speed Microwave Circuitry to Manipulate the Macroscopic EM fields

Typical Gain: 2 Kelvin → 1 mV

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



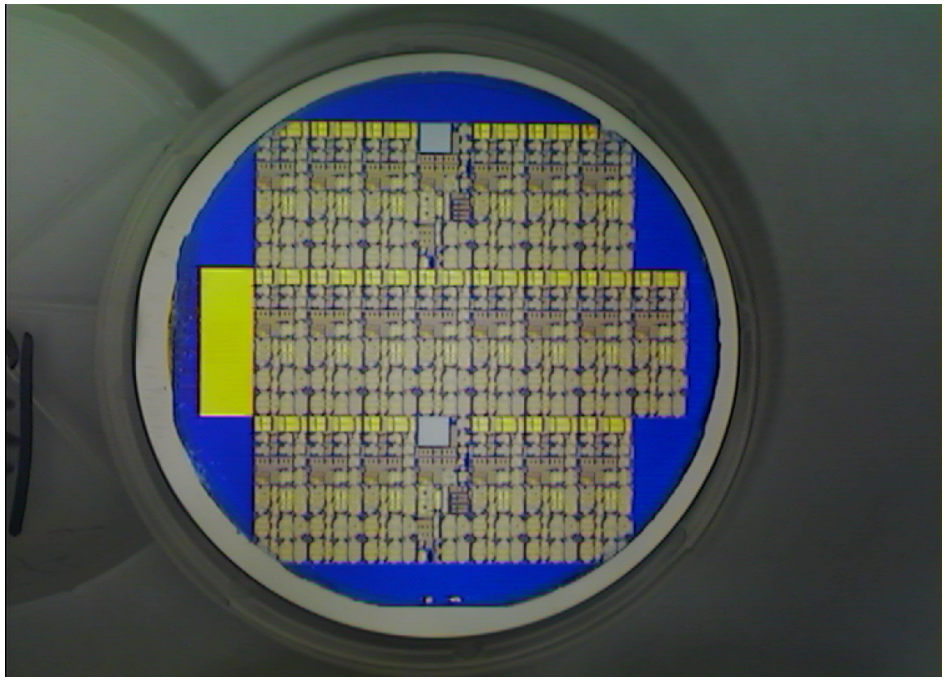


Fundamentally very different than TES (bolometric) technology

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

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

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

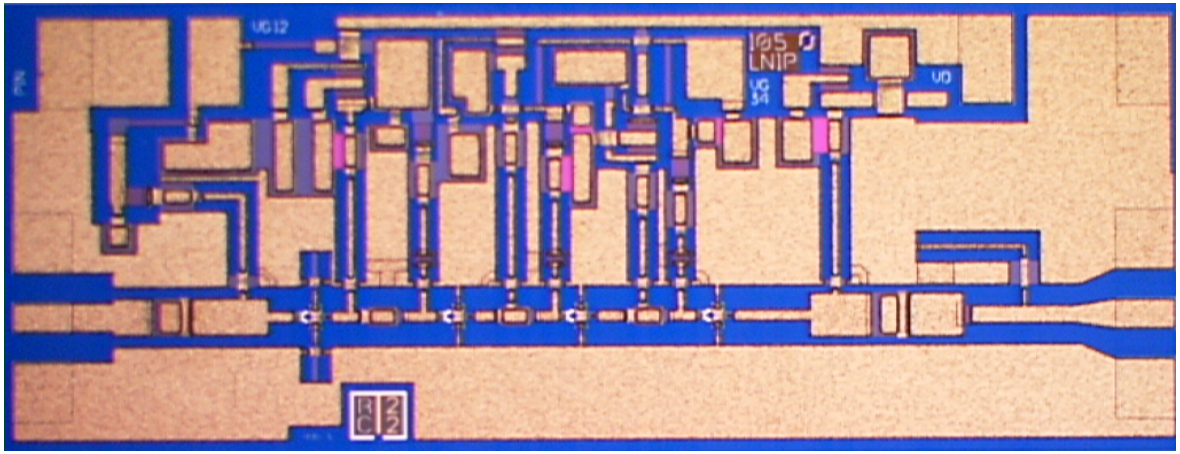


High Electron Mobility Transistors using Indium Phosphide

Northrop Grumman Transistor Design

Low Noise Amplifier Design from JPL (4 transistors)

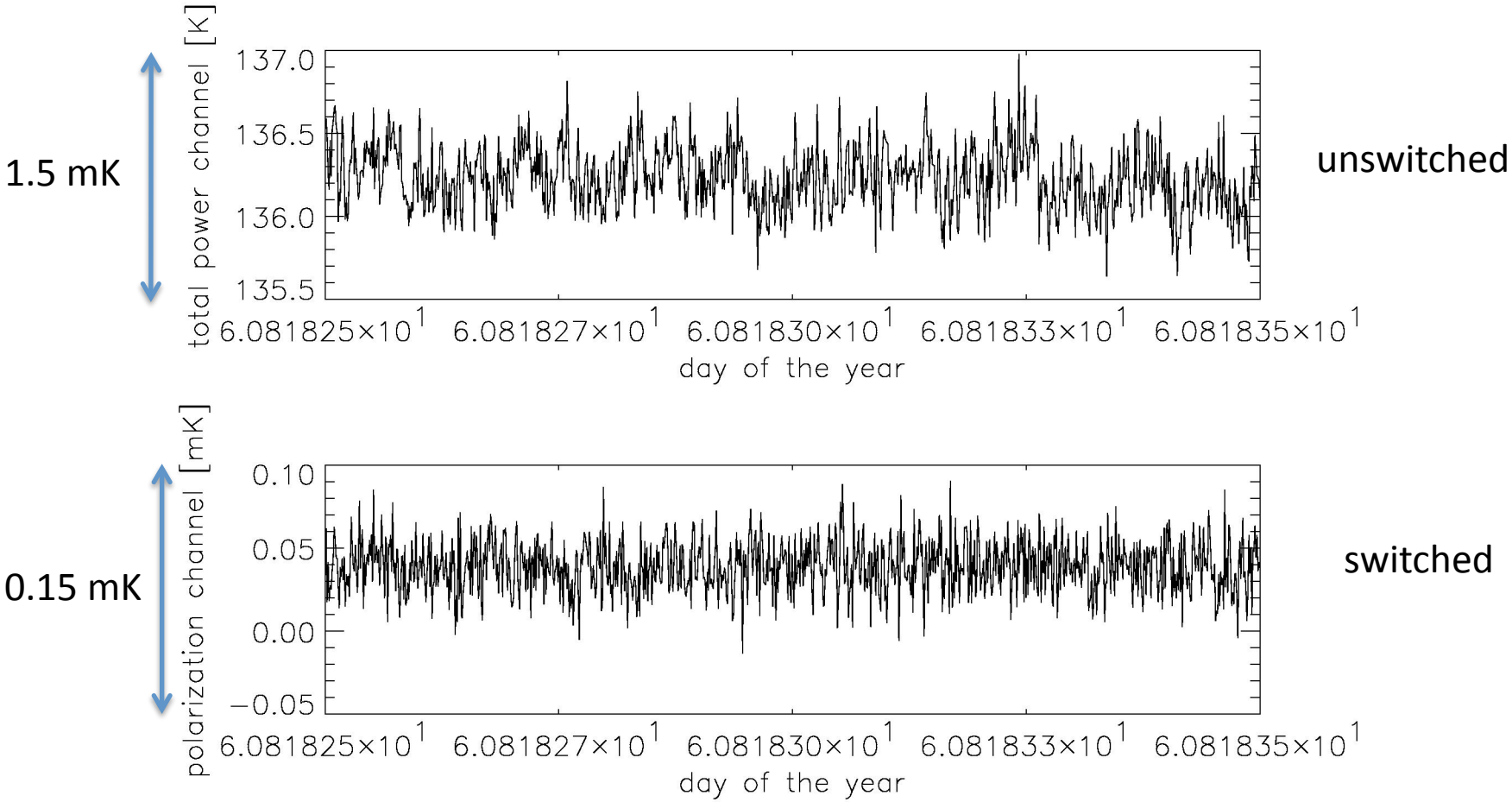
0.75 mm



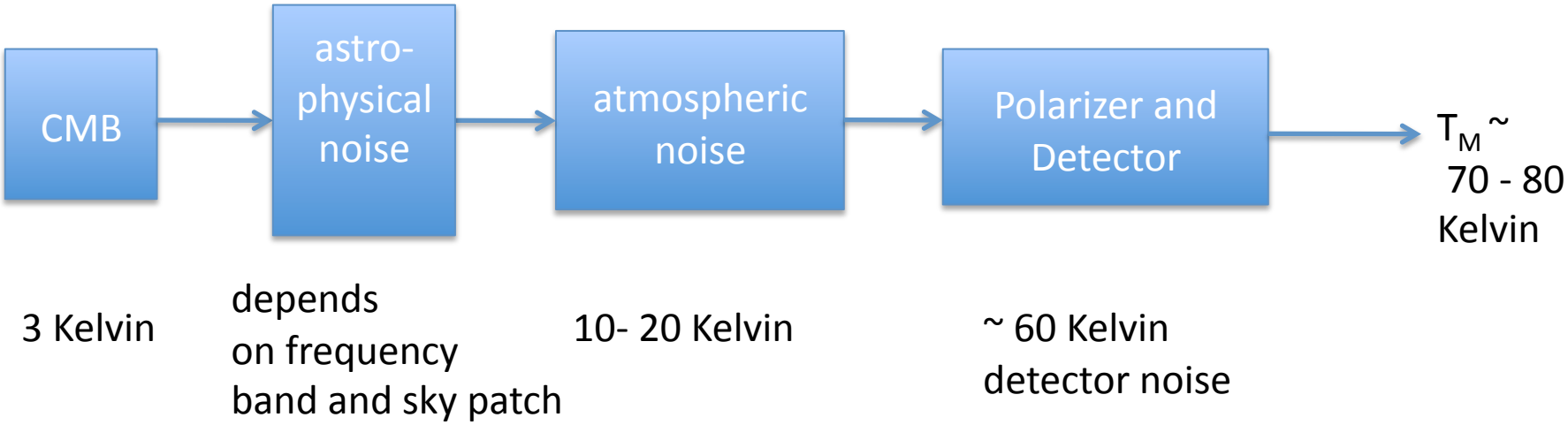
~2.5 mm

High Speed Switching to Suppress Noise

Temperature vs. time, 10 ms bins



Other Important Effects



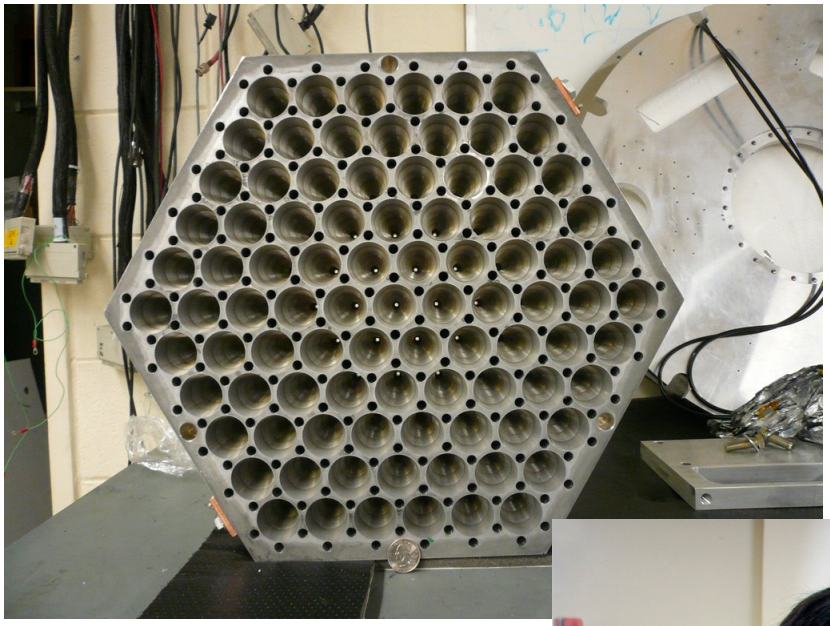
Tricks to Reduce Temperature Measurement Error

Use an array of Detectors to reduce noise by 1/sqrt(N)

Observe for a LONG time

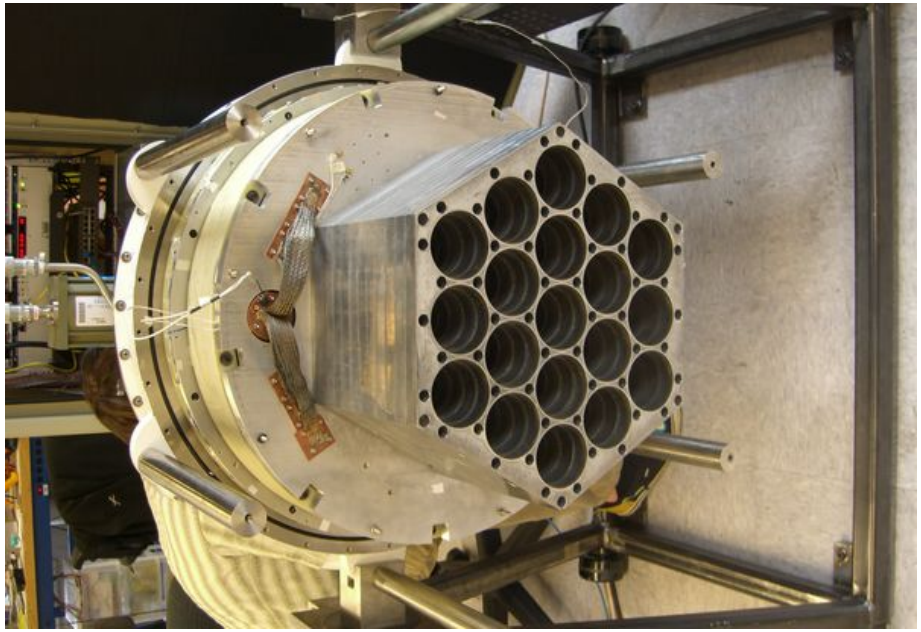
Vary Atmospheric Path Length

Use theory and other tricks to remove astro physical noise



Assembly of 91 W-band detectors at Chicago

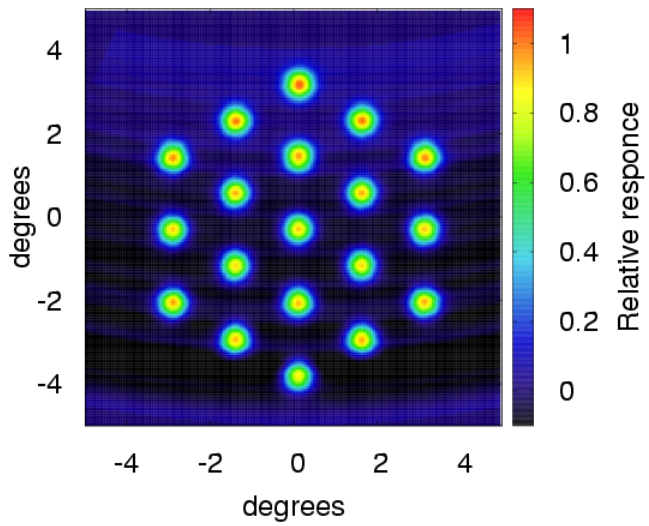
(Spring 2009)

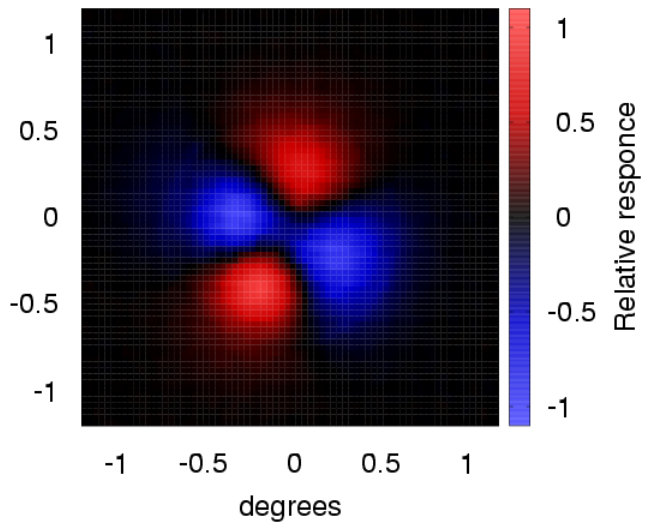


Completed ~ 9 months of observations using the 19-element Q-band in June 2009

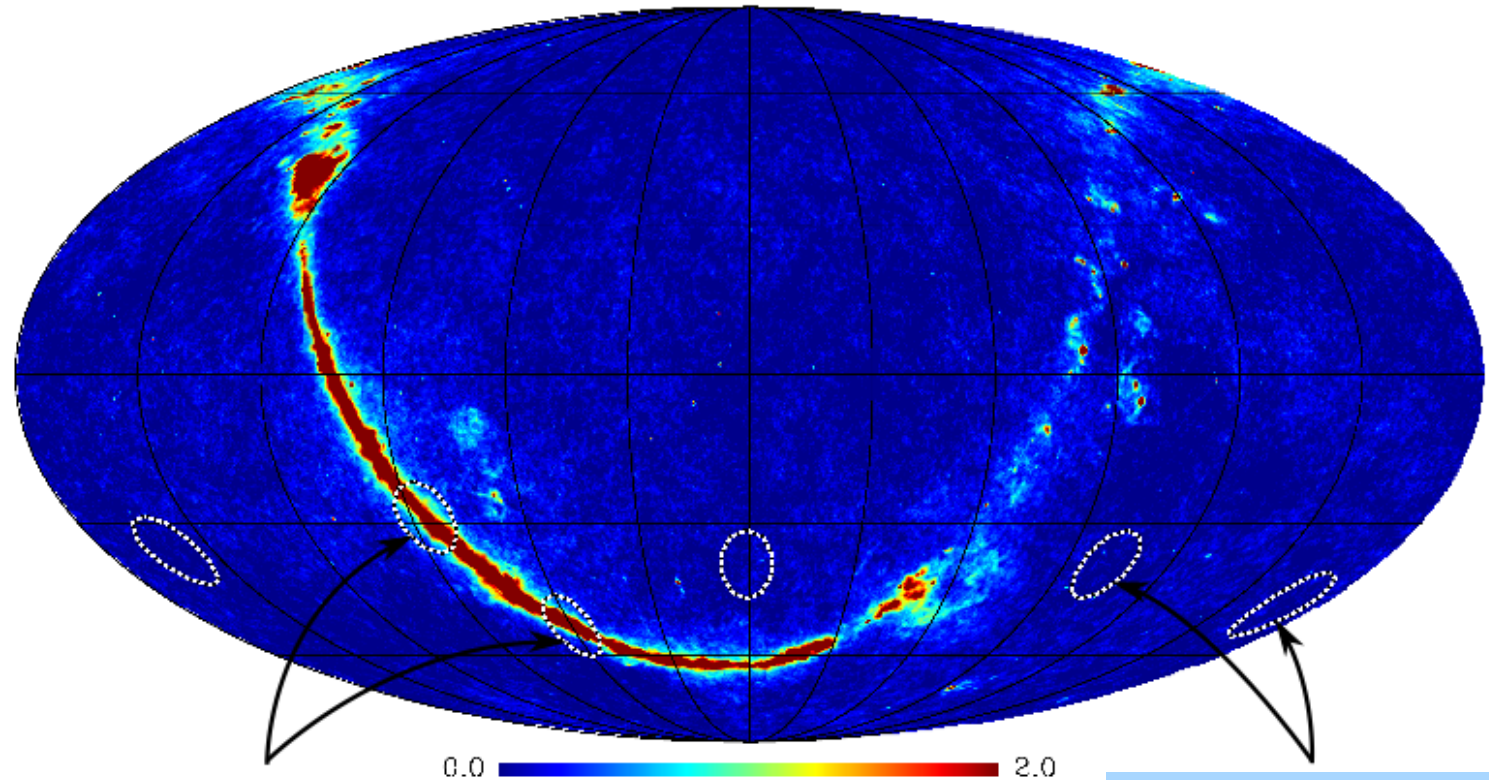
Very near to release of Q-band result.

Moon exposure over each element





QUIET Observing Patches



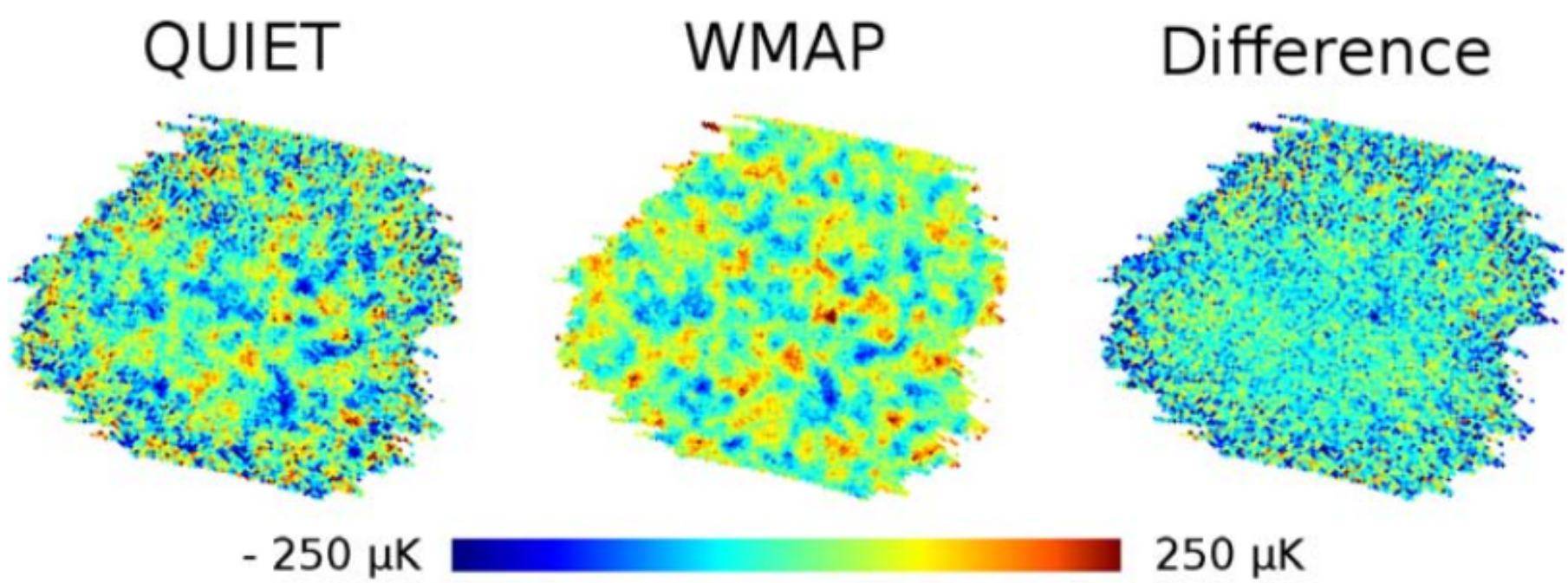
galactic patches

Map precision on 1x1 degree pixel:

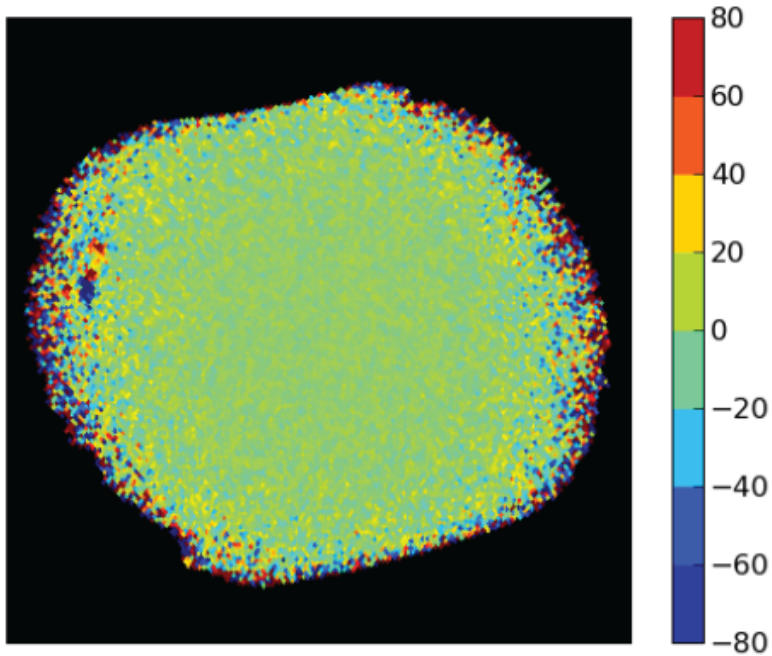
Planck: 1 μK (100 GHz)
QUIET: 10^{-1} μK (90 GHz)

QUIET CMB Temperature Map

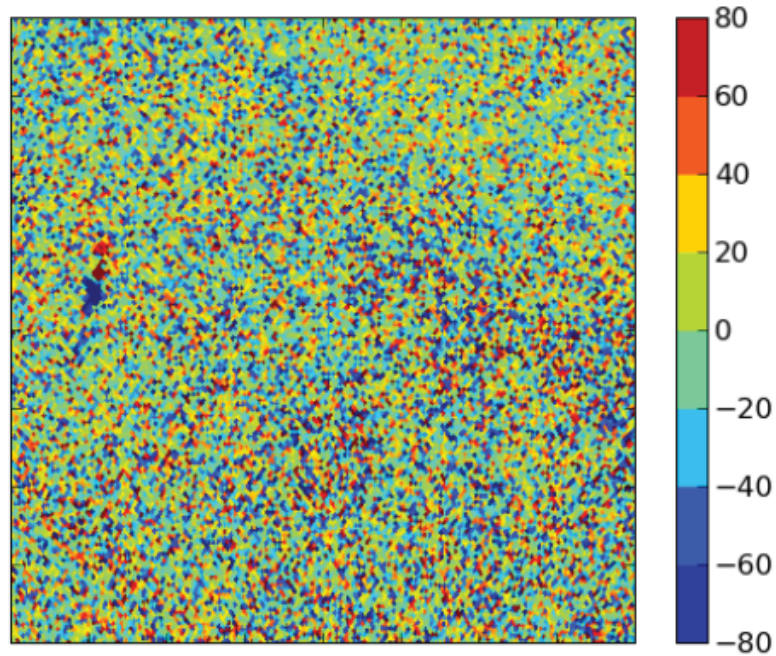
(1 detector, 1 month vs. 5 years)



QUIET ~ 600 hrs



WMAP 5 years



QUIET-I Stokes Q map of one patch:
Already deeper than Planck forecasts

Dejongh, Dodelson, Kubik Nguyen, and Stebbins (with help from McGinnis for RF stuff !)

~15x more detectors than Phase-1

Robotic Assembly of ~1500 W-band Polarization Modules at Sidet

Commissioning 1 cryostat at Sidet Lab A

Calibration Tools

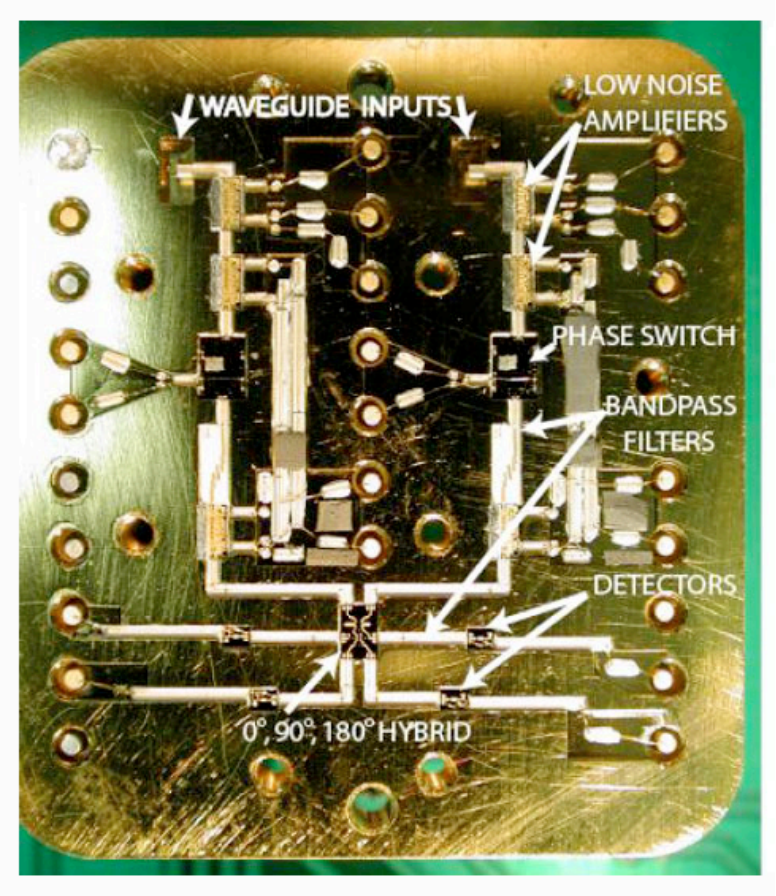
Vacuum Window Engineering

Work on Improved Modules

Phase II Awaiting Word from NSF

Fermilab Proposed Involvement in QUIET Phase II

1" W-band HEMT module



1600 detectors
for Phase-II

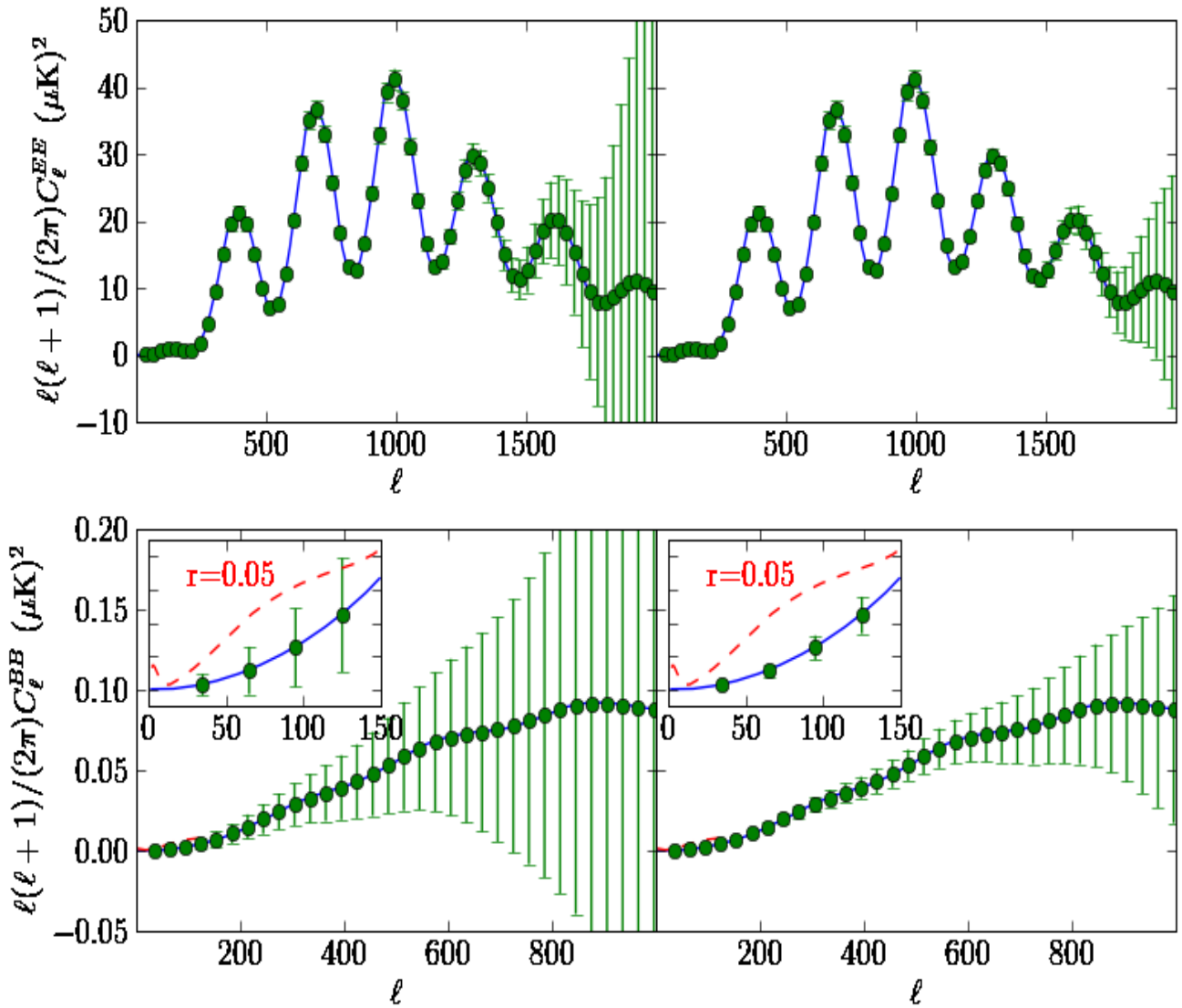
Same detectors:
10σ for T/S = 0.018

Improved detectors:
35σ for T/S = 0.005

From B-mode lensing:

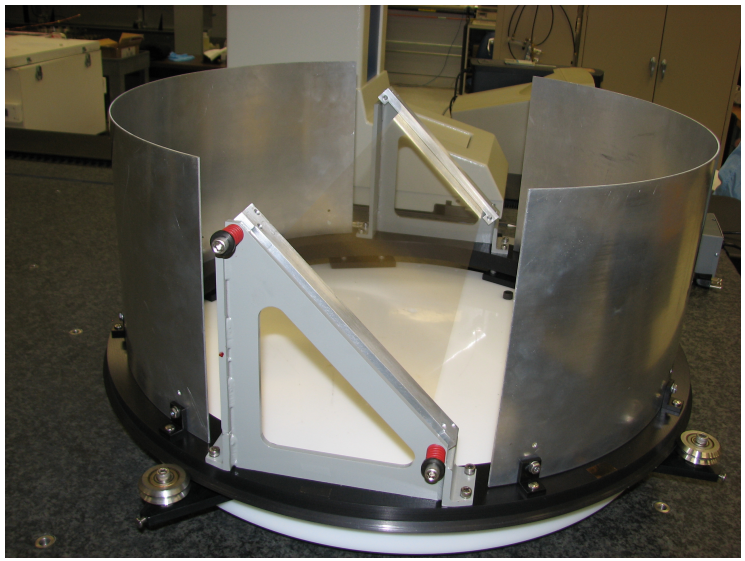
sum of all neutrino
mass < 0.3 eV

Current* Performance Likely Improvements



* already better!

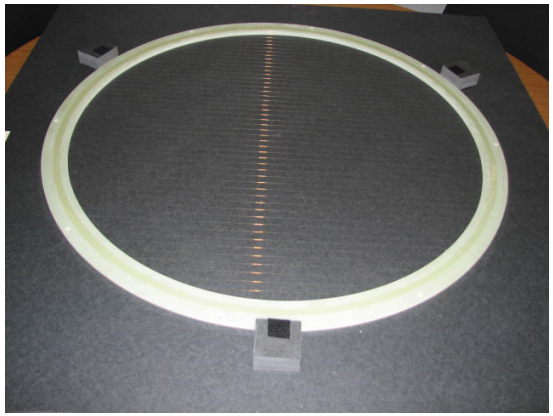
Wiregrid Polarizer and Modulator



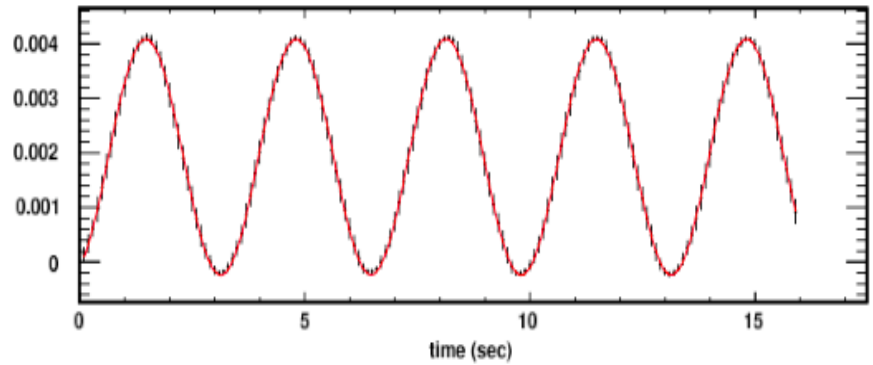
Large and accurate rotatable wire grids to produce and modulate polarized microwaves

Made by PPD chamber winding group using HEP techniques

Grid rotates to modulate the polarization



Typical Stokes-Q Response from a W-band Module



Deployed in Chile in July 09

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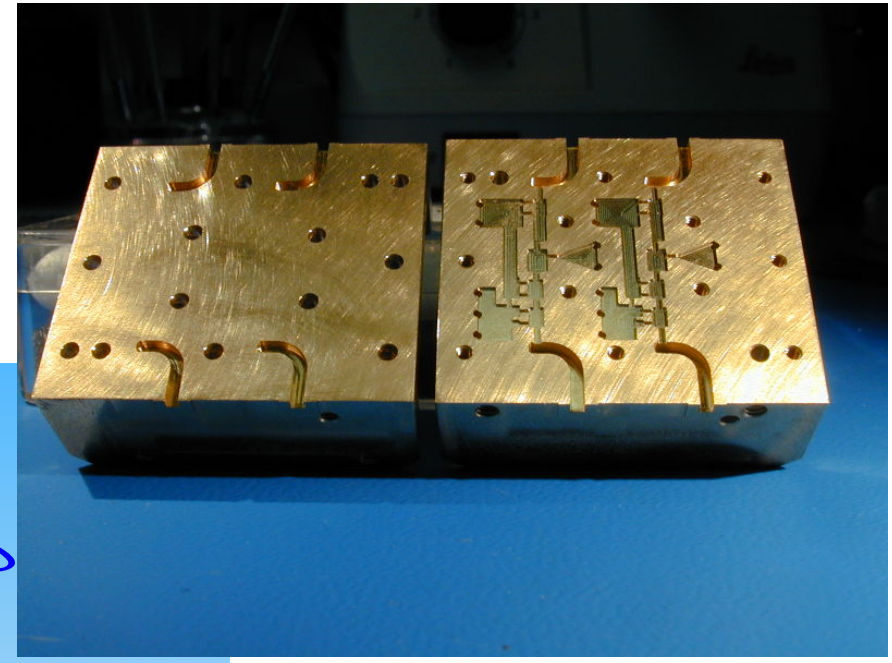
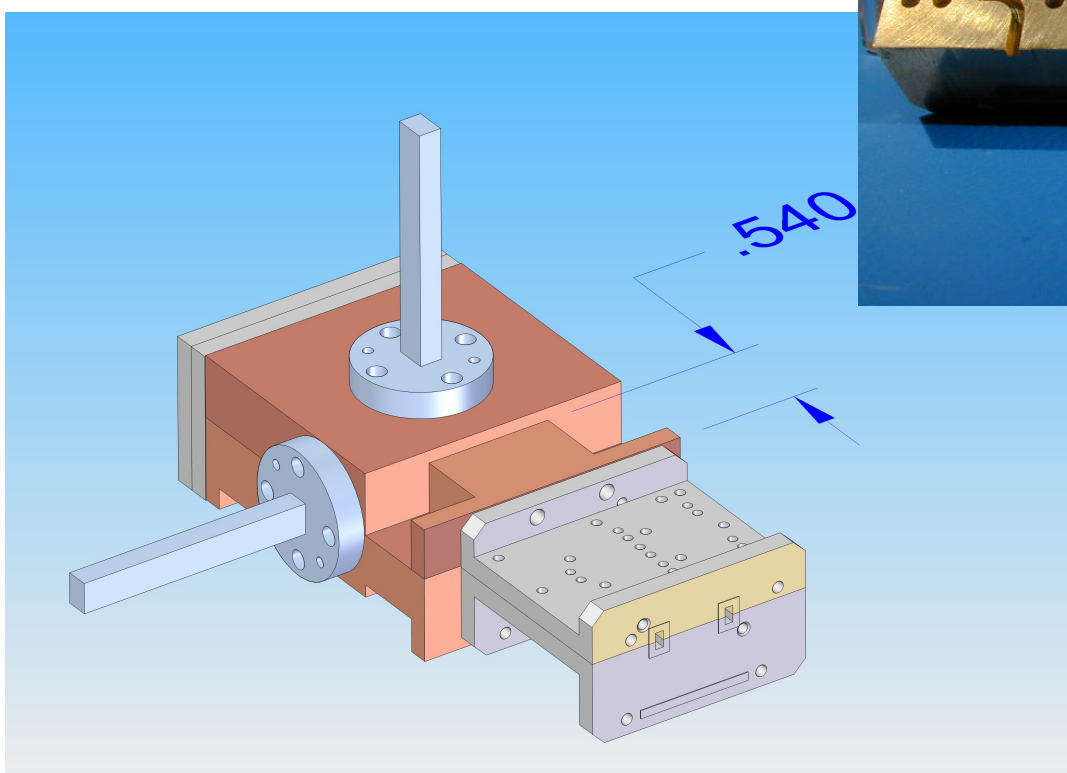
Fermilab Wiregrid in Chile in July 2009

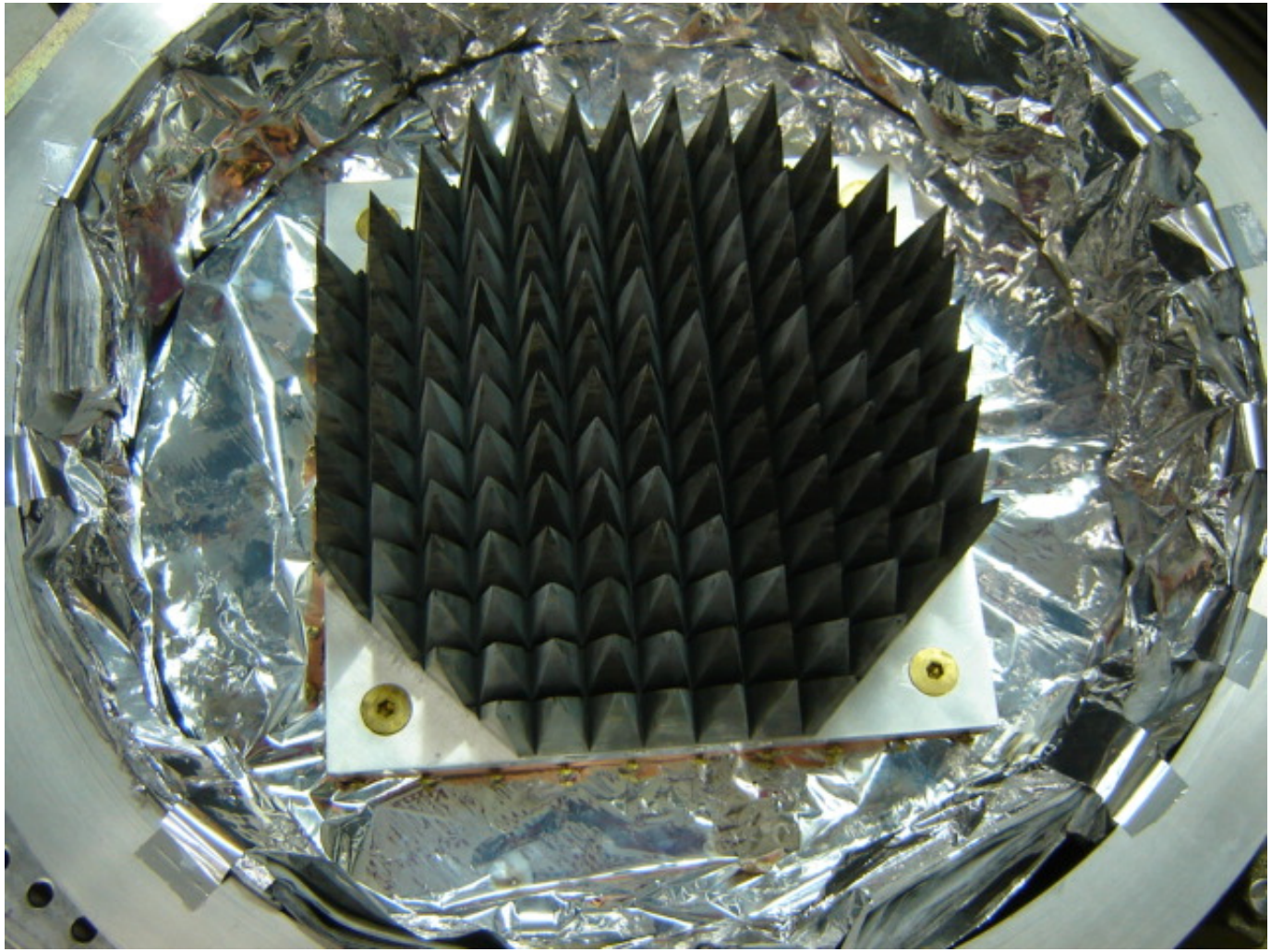
Machining, Assembly, and Testing of Improved Modules

New Modules
will be tested here
at Lab 3 in the Fall 2010



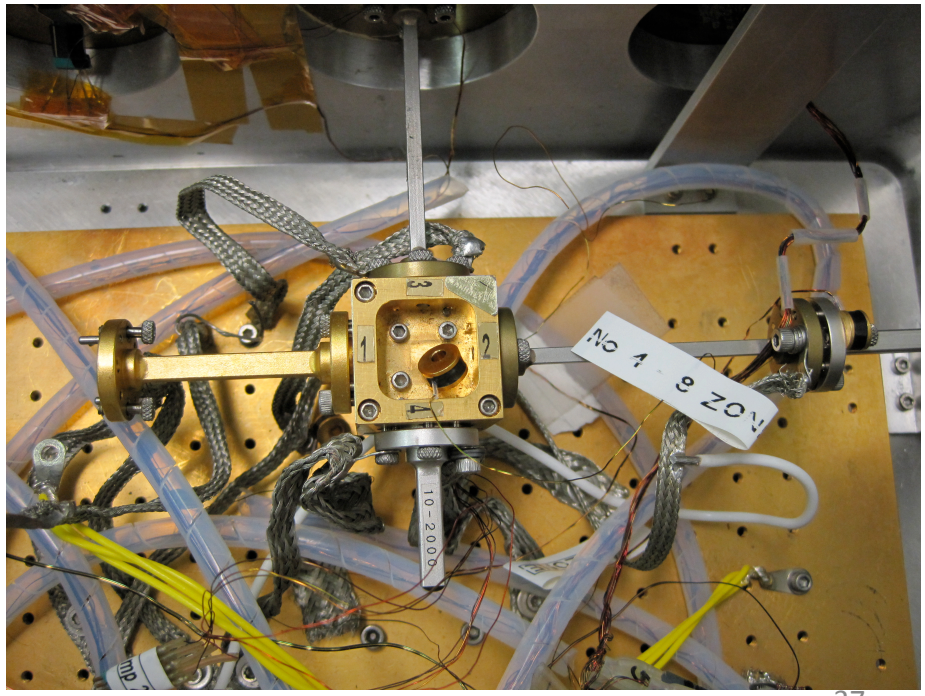


20 Kelvin Black Body Calibrator



Summary ... It's FUN

We're trying to start a new experiment at Fermilab

Fermilab Scientists were among the first to understand the profound nature of CMB Polarization (Dodelson, Stebbins)

Inflation is HEP at the GUT Scale