QUIET Experiment and HEMT receiver array

SLAC Advanced Instrumentation Seminar
October 14th, 2009

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Outline

- Introduction
  - Physics of CMB Polarization
  - QUIET Project Overview
- QUIET Instrumentation
  - HEMT Array Receiver
  - Optics and Mount
  - Data Acquisition and electronics
- Summary and Future Plan

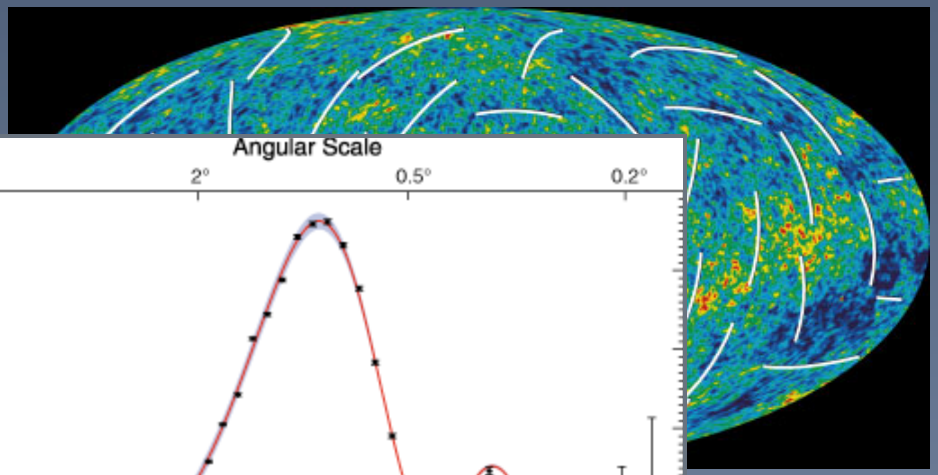
Introduction

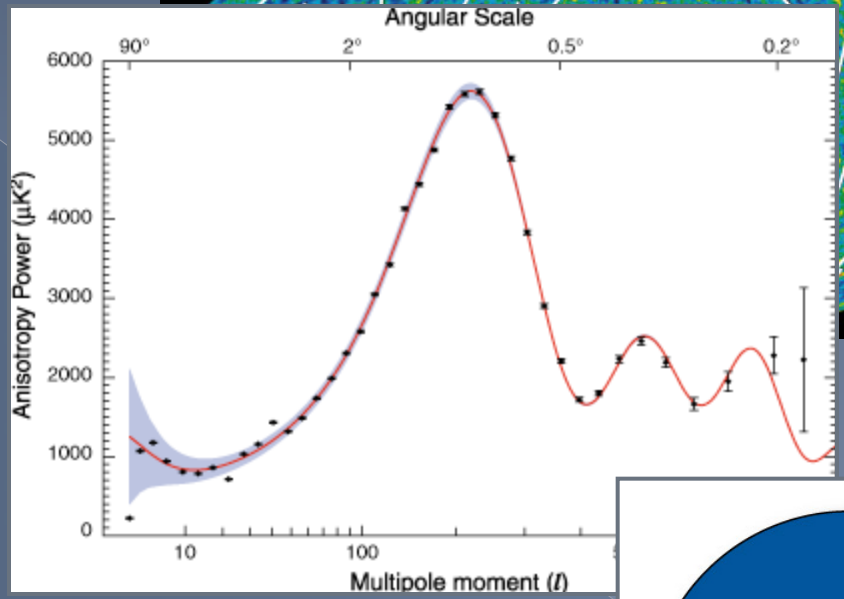
Cosmology After WMAP

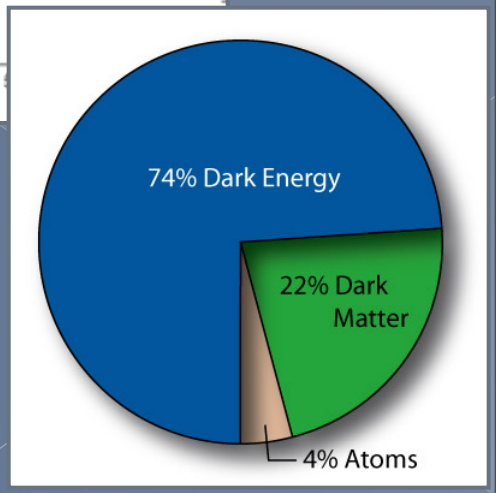
NASA/WMAP Science Team

WMAP + Others

- Flat ΛCDM
  - $\Omega_{all} \sim 1$
  - $\Omega_{\Lambda} = 0.74 \pm 0.06$
  - $\Omega_m h^2 = 0.13 \pm 0.01$

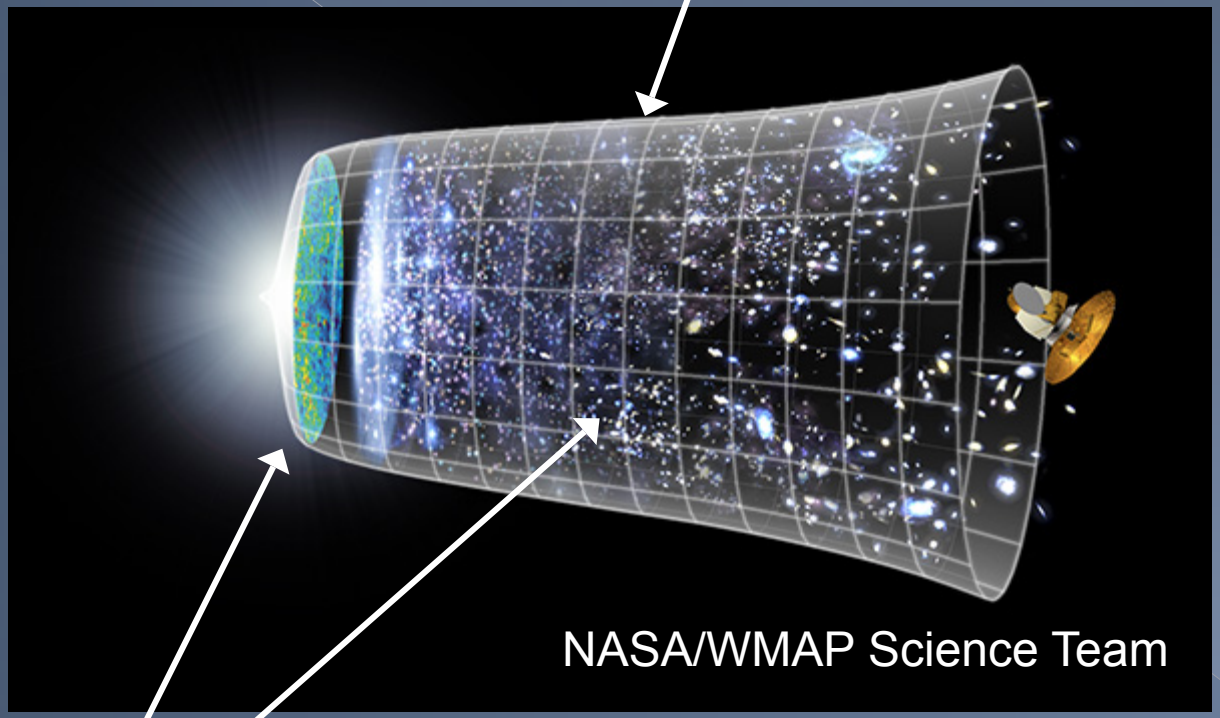






Solved and Unsolved Problems

Solved: Time Evolution of the Universe



Unsolved: Physics of the Beginning (Inflation)
Source of the Evolution (Dark Energy, Dark Matter)

Unsolved Problems

- Inflation
  - Did it happen?
  - What's the correct model?
  - Shape of potential: Physics at GUT Scale?
  - Signature: Primordial Gravitational-Wave (CGB?)
  - Detectable via CMB Polarization

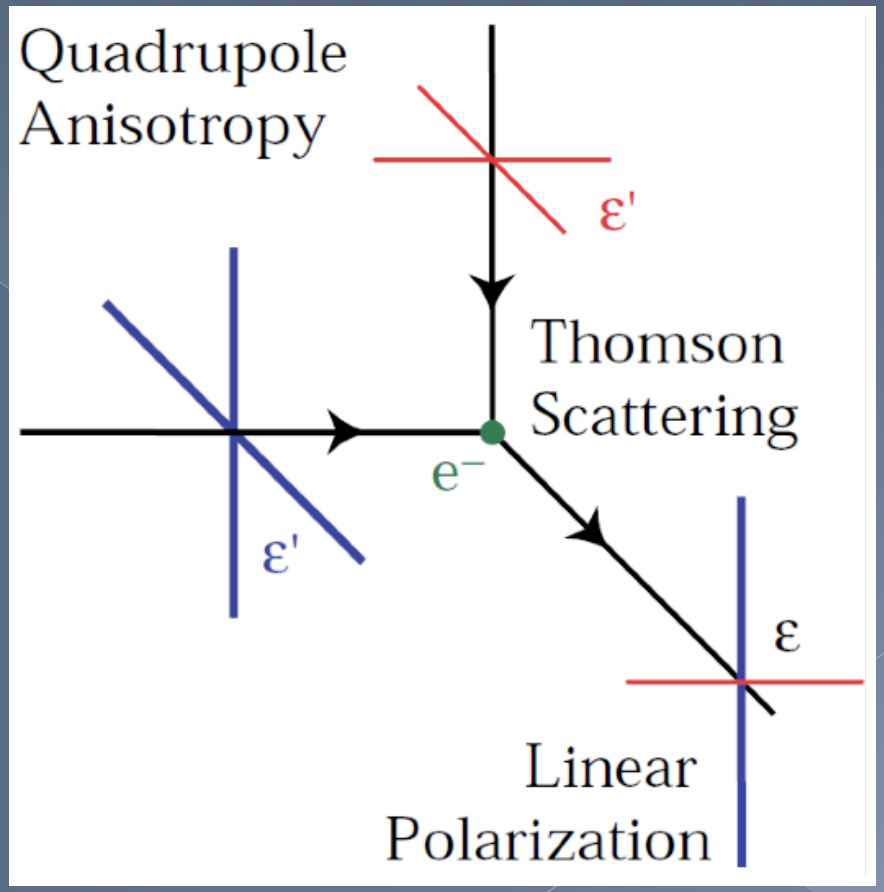
- Dark Energy
  - Equation of State: $w = p/\rho$
  - Dark Energy = Cosmological Constant? (i.e., $w = -1$?)

Cluster, Weak Lensing, BAO, SNe Ia, etc...

CMB Polarization

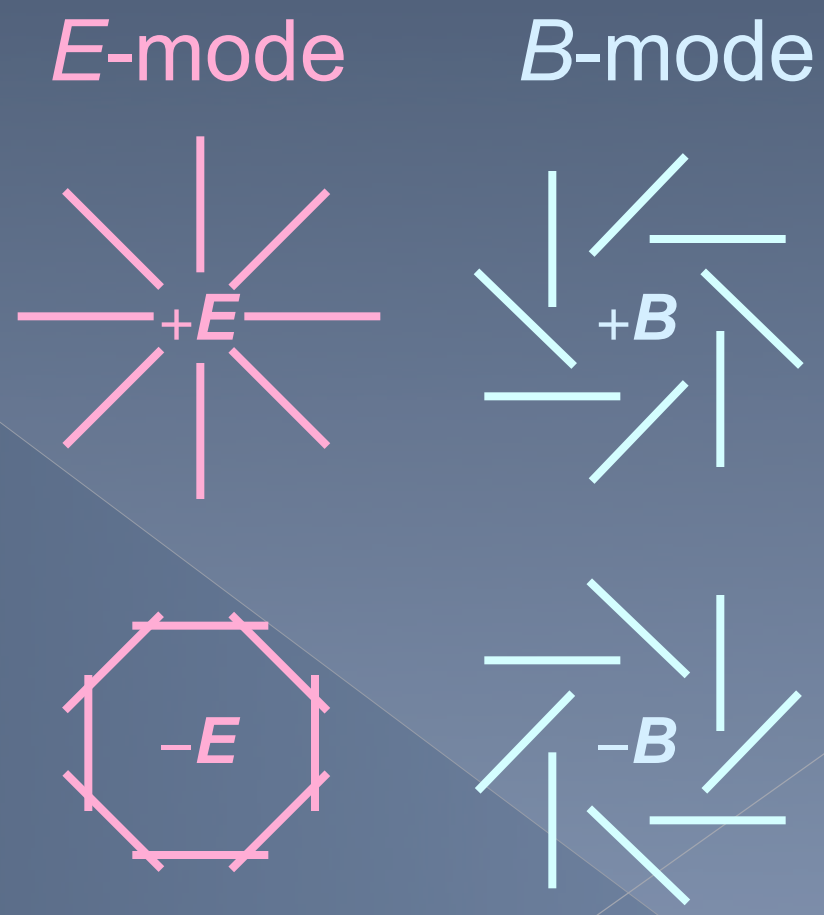
- CMB is from last (Thomson) scattering
  - →Linearly polarized
- Anisotropy
  - →Non-zero overall polarization

A CMB Polarization Primer (Hu & White)



E-mode and *B*-mode

- Polarization: Tensor-field
  - Tensor = "Bar" without direction
  - c.f. Vector = "Bar" with direction
- Decomposable into *E*-mode and *B*-mode
  - Analogous to the vector field decomposition to (rot. free mode) + (div. free mode)

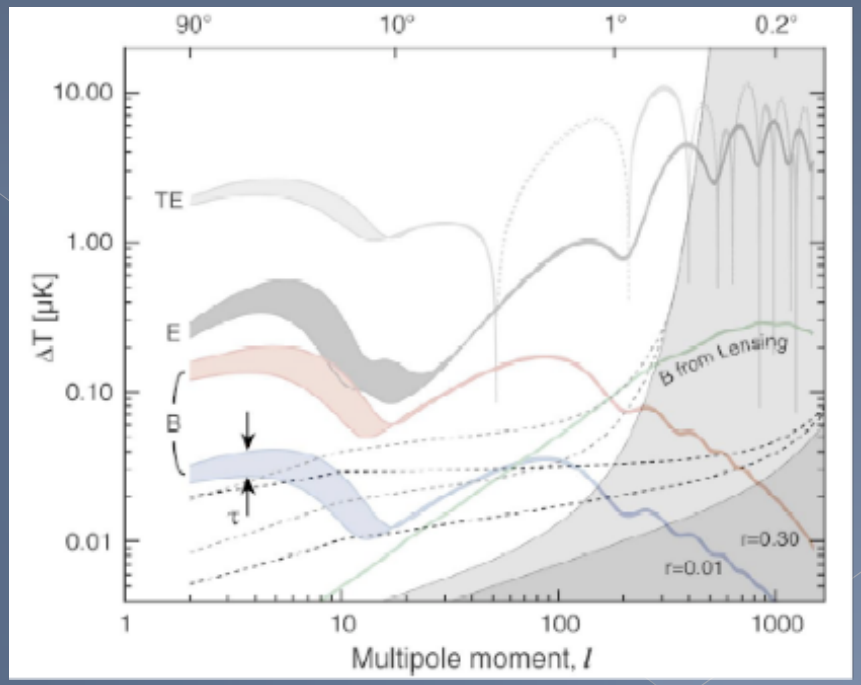


B-mode Polarization

- Gravitational wave from Inflation
  - Tensor perturbation of metric
    → Gravitational wave
    → B-mode
  - Unique signal of Inflation
  - Size of *B*-mode
    → Tensor/Scalar ∝ V
  - V: Inflation potential, GUT scale ?

TT is around here (~$10^2 \mu$K)

CMB Task Force



r = T/S

T/S~0.1 if V~GUT scale

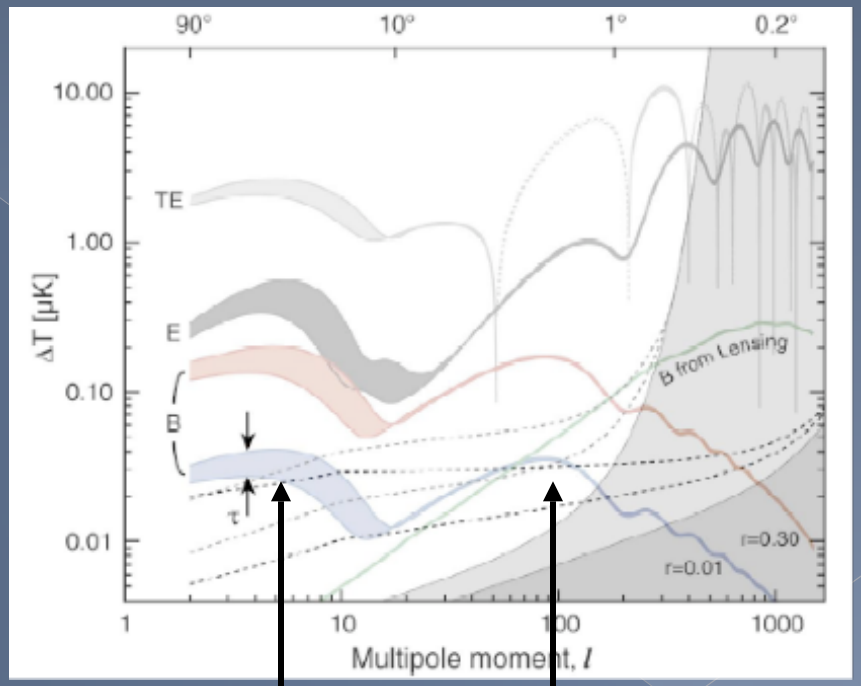
B-mode measurement

Two possible targets

- Large ℓ (ℓ~100: ~2°)
  - Ground based is competitive
  - Could be lensing *B* dominant (subtract?)
- Small ℓ (ℓ~5: ~50°)
  - Originates from reionization
  - Advantageous to Satellite
  - Free from lensing *B*

TT is around here (~$10^2 \mu$K)

CMB Task Force



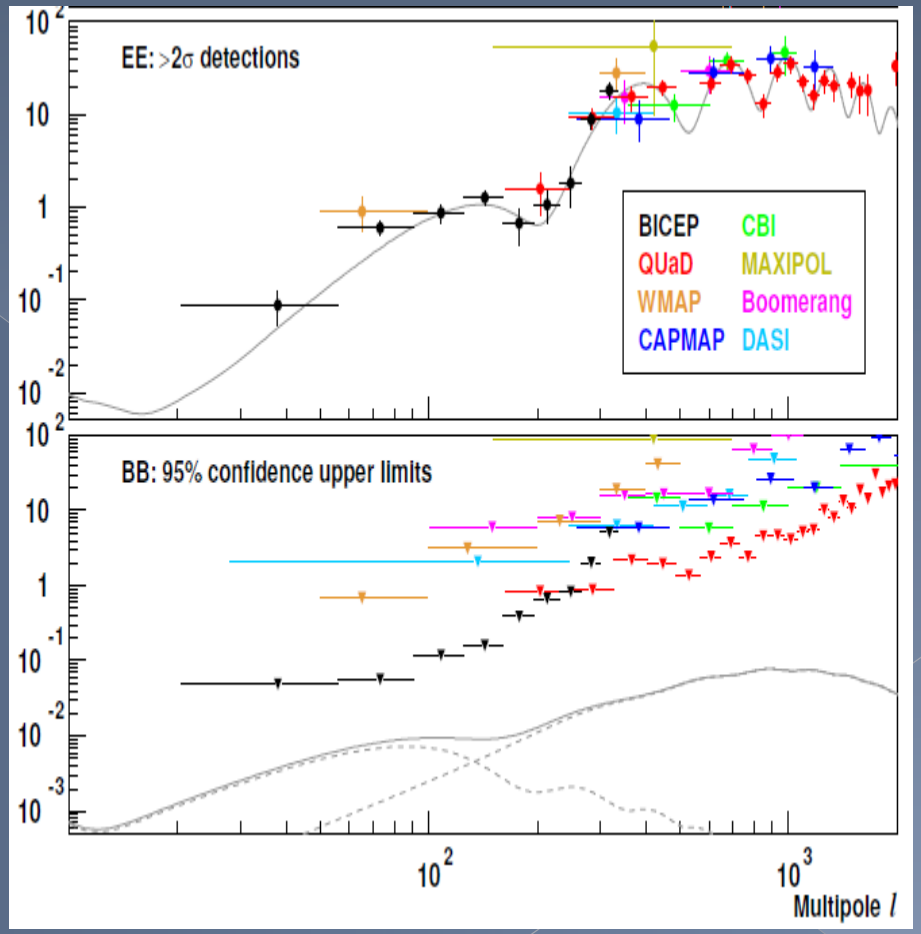
ℓ~5 ℓ~100

NOTE: atmosphere is not polarized

Current Status

- Significantly non-zero *EE* correlation is found
  - WMAP, DASI, CBI, BOOMERanG, CAPMAP, QuaD, BICEP
- No significant *BB* measurement, yet

Plot from Chiang et al (2009)



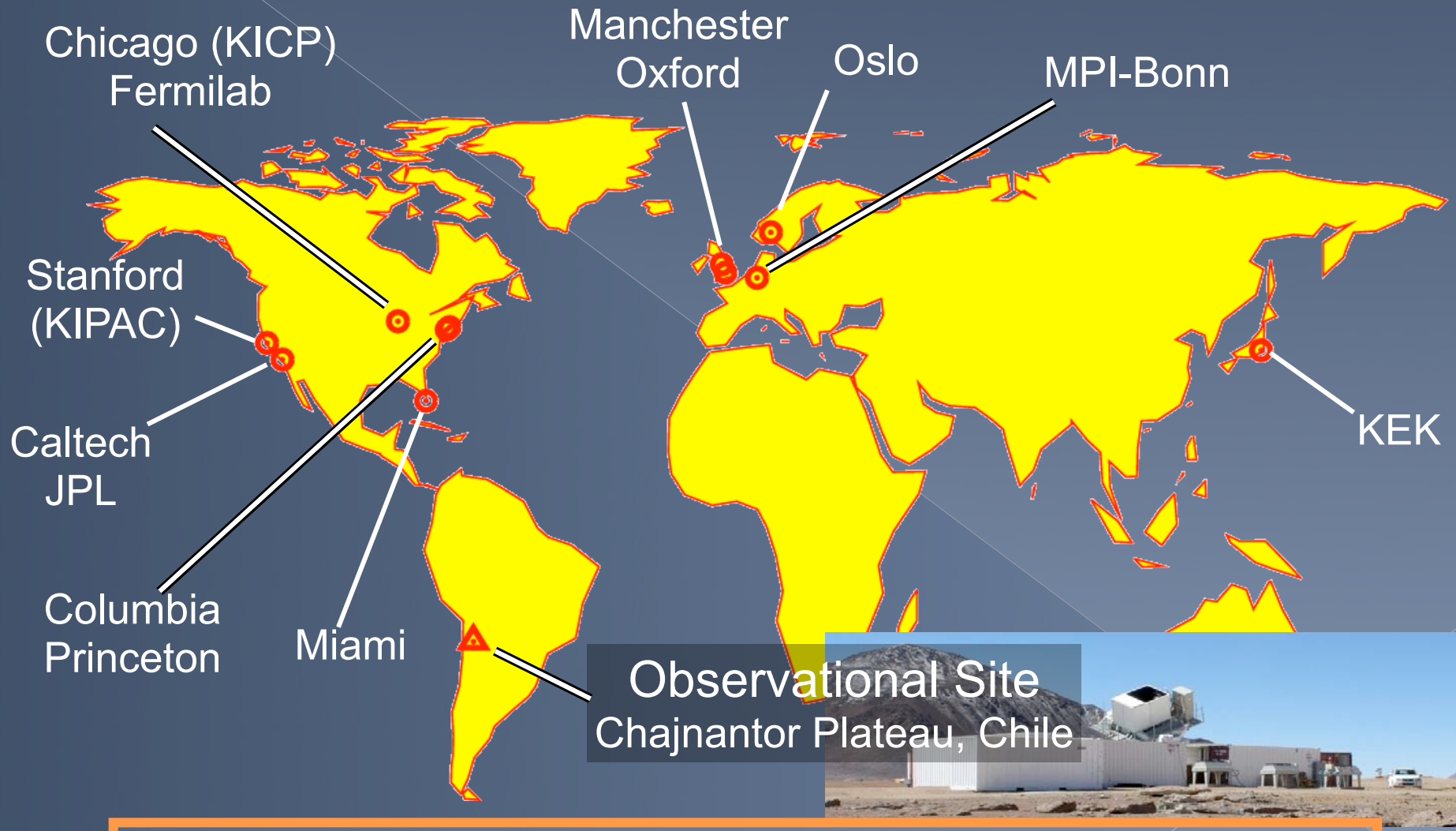
QUIET Experiment

- CMB polarization measurement
- At two frequencies
  - W-band (90GHz)
  - Q-band (44GHz)
  - [At phase-II: Ka-band (30GHz)]
- First large HEMT polarimeter array
  - State-of-the-art packaged MMIC technology
  - Competitive sensitivity
- Targeted ℓ~50-1000 (1°~0.05°)
- Located at Chajnantor, Chile

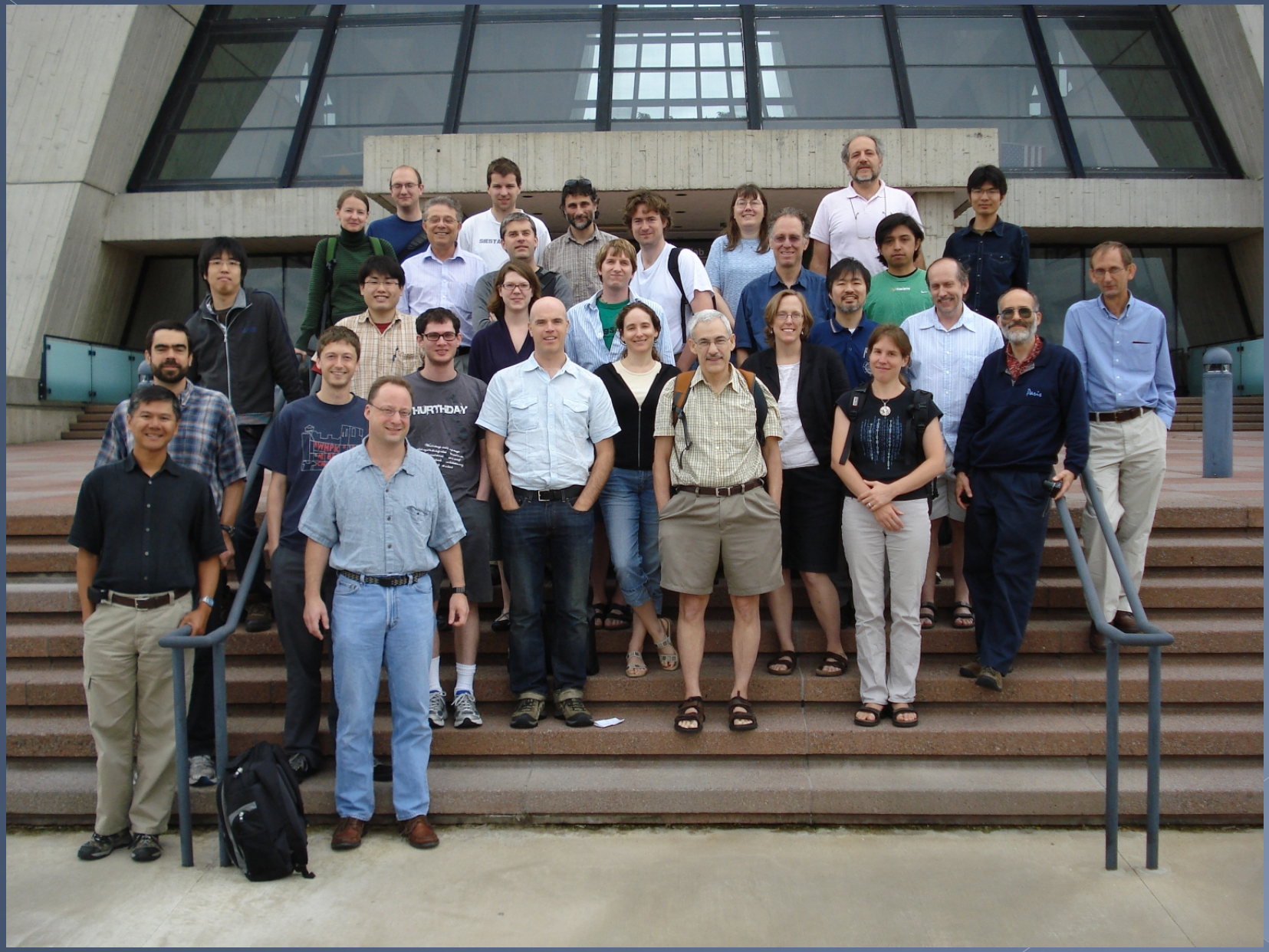
The QUIET Observing Site

- Chajnantor Plateau, Chile
  - 17,000'
  - Extremely low moisture
  - ~1 hour drive from San Pedro de Atacama
  - Year-round access
  - Observing throughout the year (day and night)

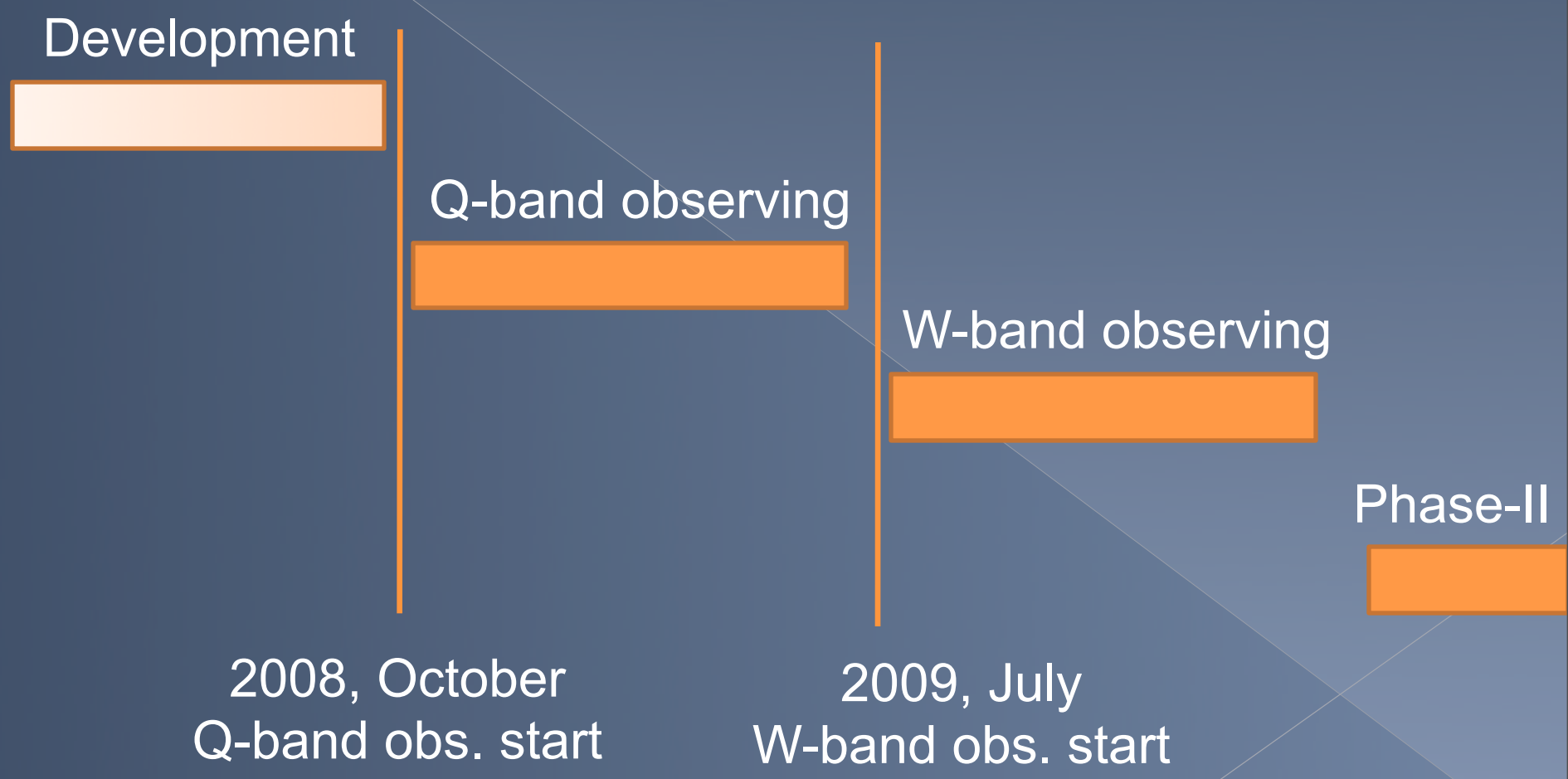
QUIET collaboration



5 countries, 13 institutes, ~35 scientists

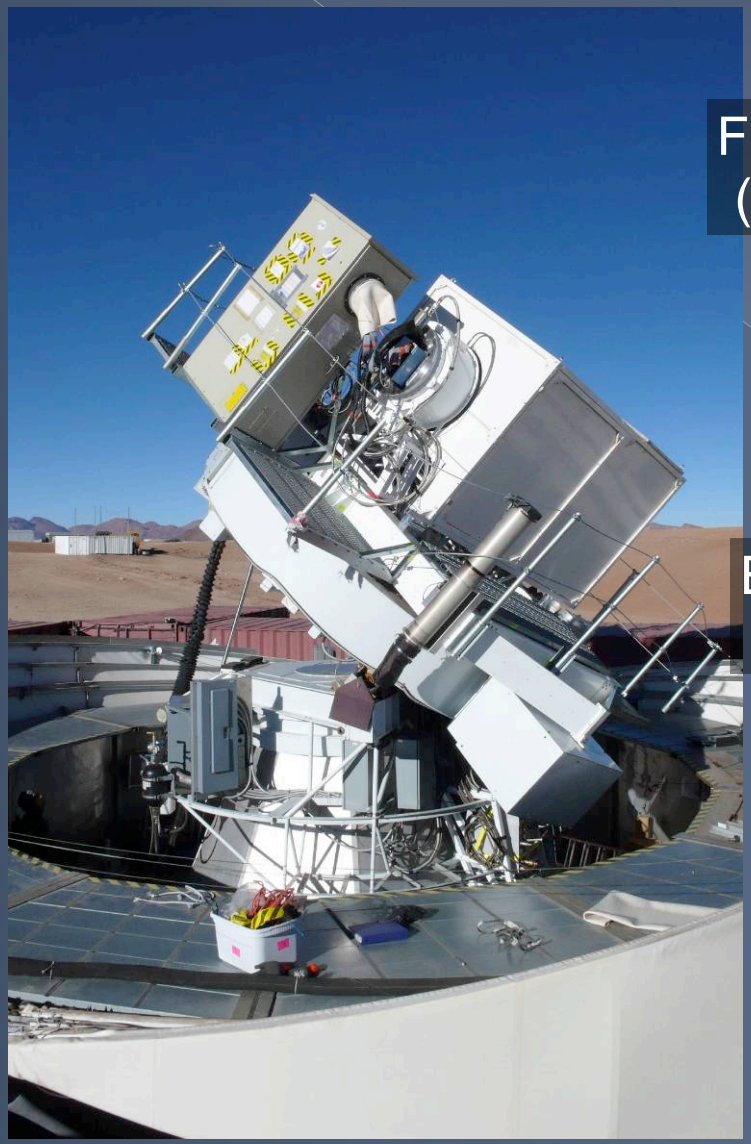

HURTHDAY

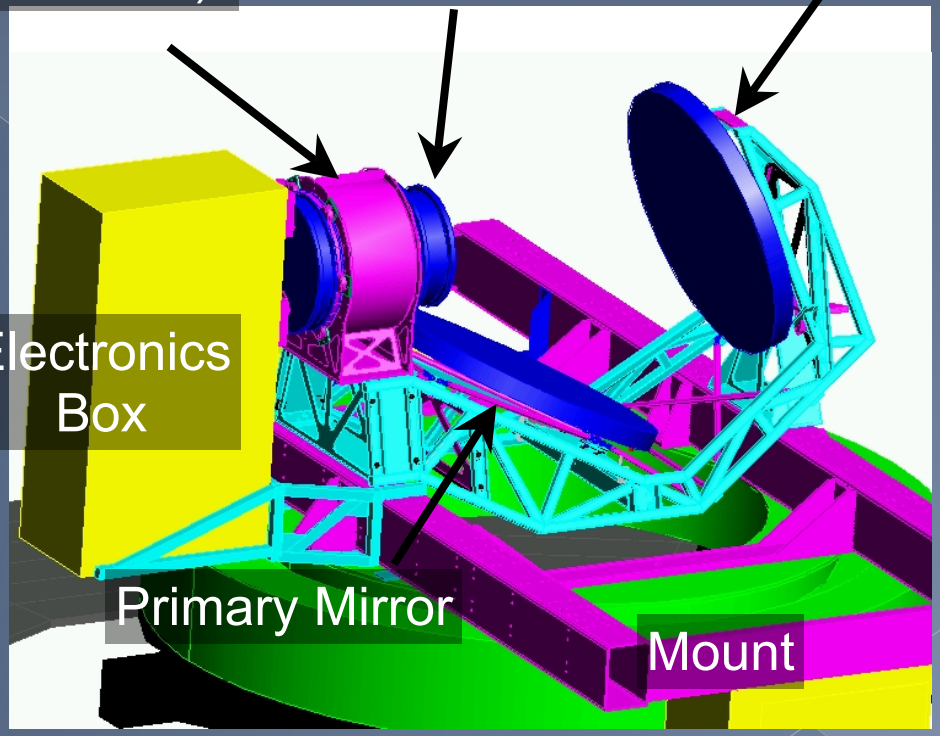
QUIET Time Schedule



Instrumentation

QUIET – a big picture



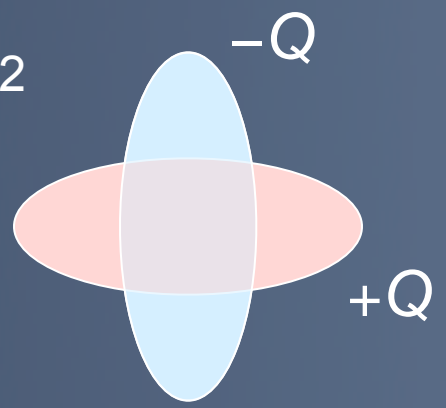


Receiver

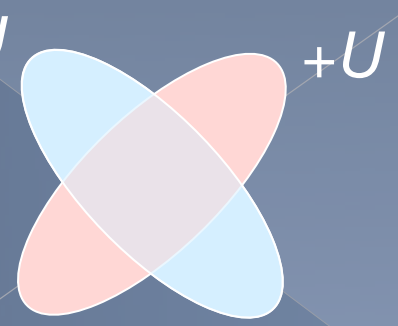
Basics of Polarization

- Stokes parameters (I, Q, U, V)
  - A set of parameters fully characterizing intensity and polarization of radio wave.
  - I: Intensity (→ T in CMB)
  - Q, U: Two linear polarization (→ E, B in CMB)
  - V: Circular polarization (zero in CMB)

$Q = E_x^2 - E_y^2$



$U = 2E_xE_y$

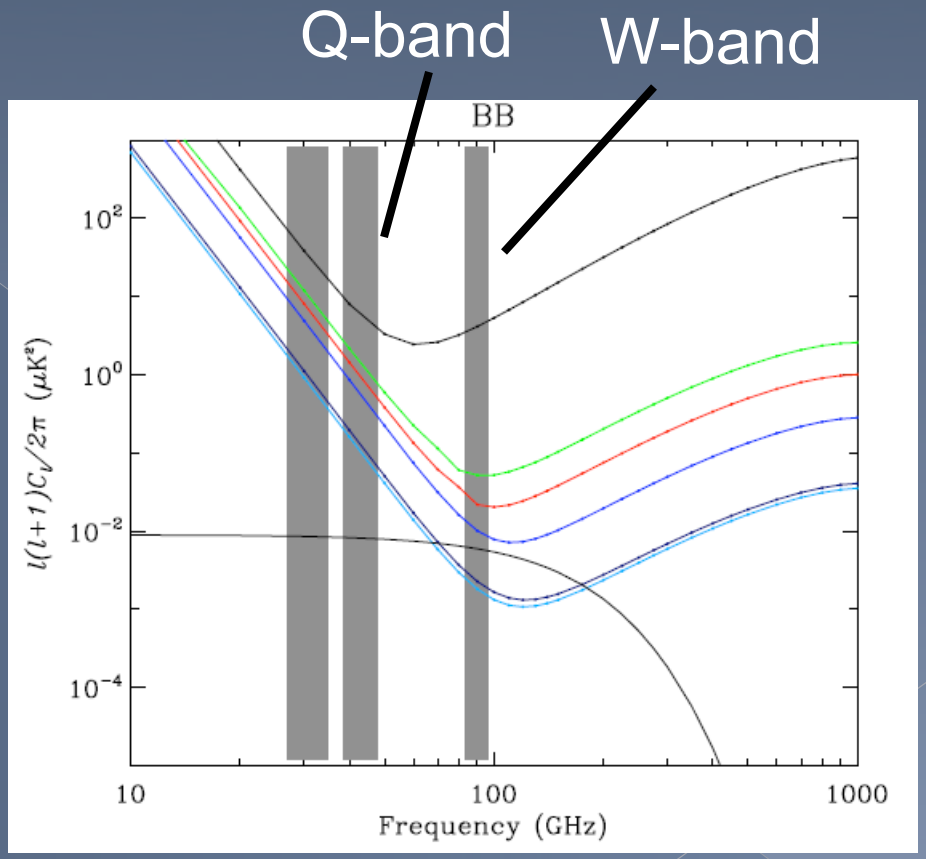


Choice of Technology

- HEMT
  - Good at ν<100GHz
  - Established (used in WMAP etc.)
  - MMIC + packaging technology for array
  - (Pseudo-)correlation polarimeter
  - Quantum noise limit: $T_{\mathrm{det}} \sim h\nu/k_{\mathrm{B}}$
    - Not significant for ground based.
- Bolometer
  - Good at ν>100GHz
  - Suitable for array
  - "Brute force" polarimeter
  - No quantum noise limit

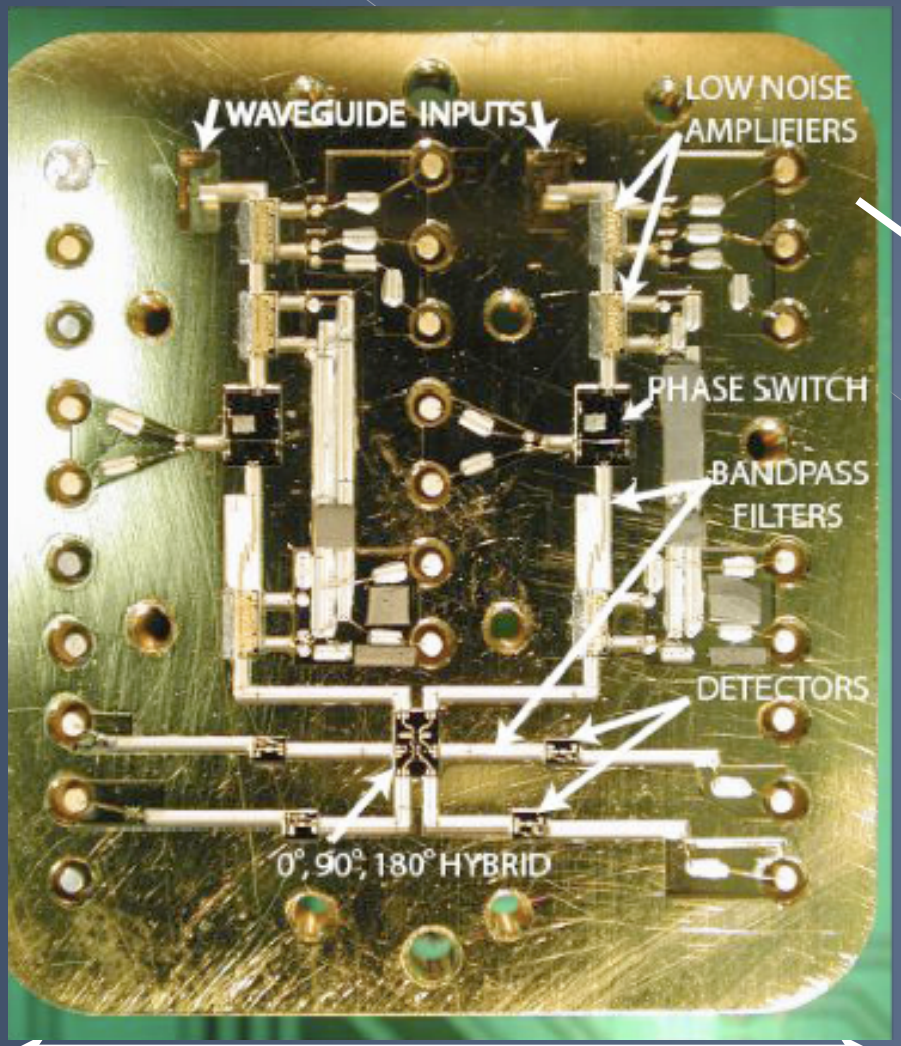
Choice of ν and "Foreground"

- Contamination for "Background" measurement: "Foreground"
- Primary, inevitable systematic error
- Two large sources
  - Synchrotron radiation from cosmic ray
  - Dust emission (dust aligned in *B* field)
- QUIET (W) is around minimum



Spectra of CMB and foreground sources

Key Technology: Polarimeter on Chip

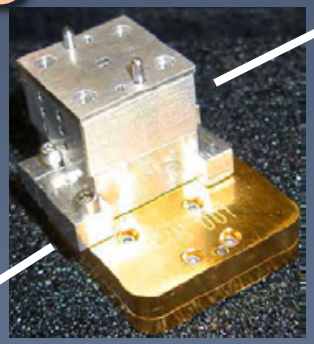


~3cm

L-R decomposition

OMT

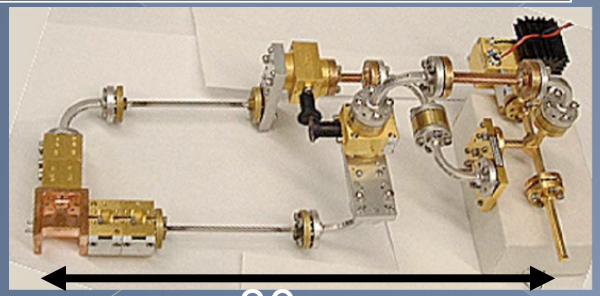
(Princeton)



HEMT Module

"Polarimeter On Chip"
Key technology for large array
(JPL)

c.f. CAPMAP polarimeter



~30cm

Radiometer Equation

- Performance of radiometer:
  - Receiver temperature T_{rec}
  - Band width *BW*
  - Type-dependent pre-factor (1 per diode at QUIET)

Per-diode noise level

$$\Delta T = \frac{T_{rec}}{\sqrt{BW \cdot \tau}}$$

Noise level per Fourier mode

Integration time

Effective number of Fourier modes / sec

$$BW = \frac{\left[\int g(f)\,df\right]^2}{\int g^2(f)\,df}$$

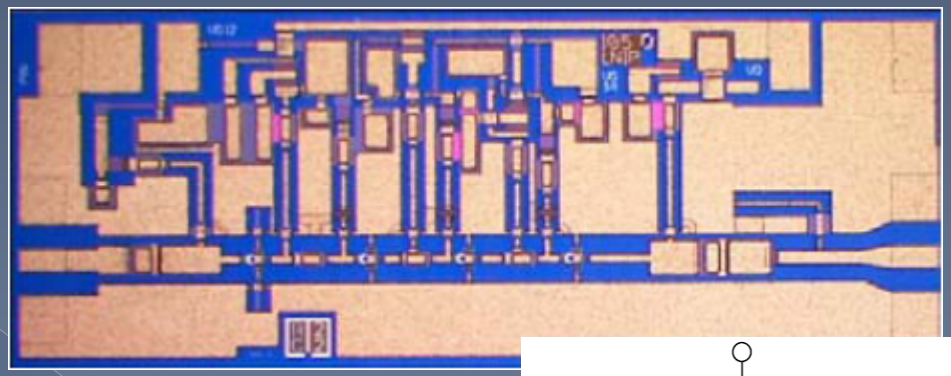
g(*f*): gain

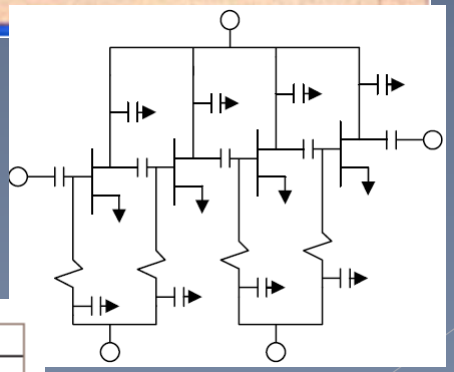
Flat & Wide

→ Large *BW*

HEMT MMIC Amplifier

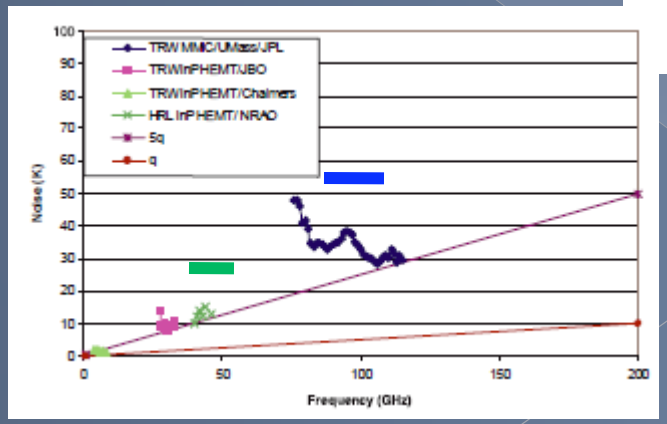
InP HEMT Amp. (for W-band)



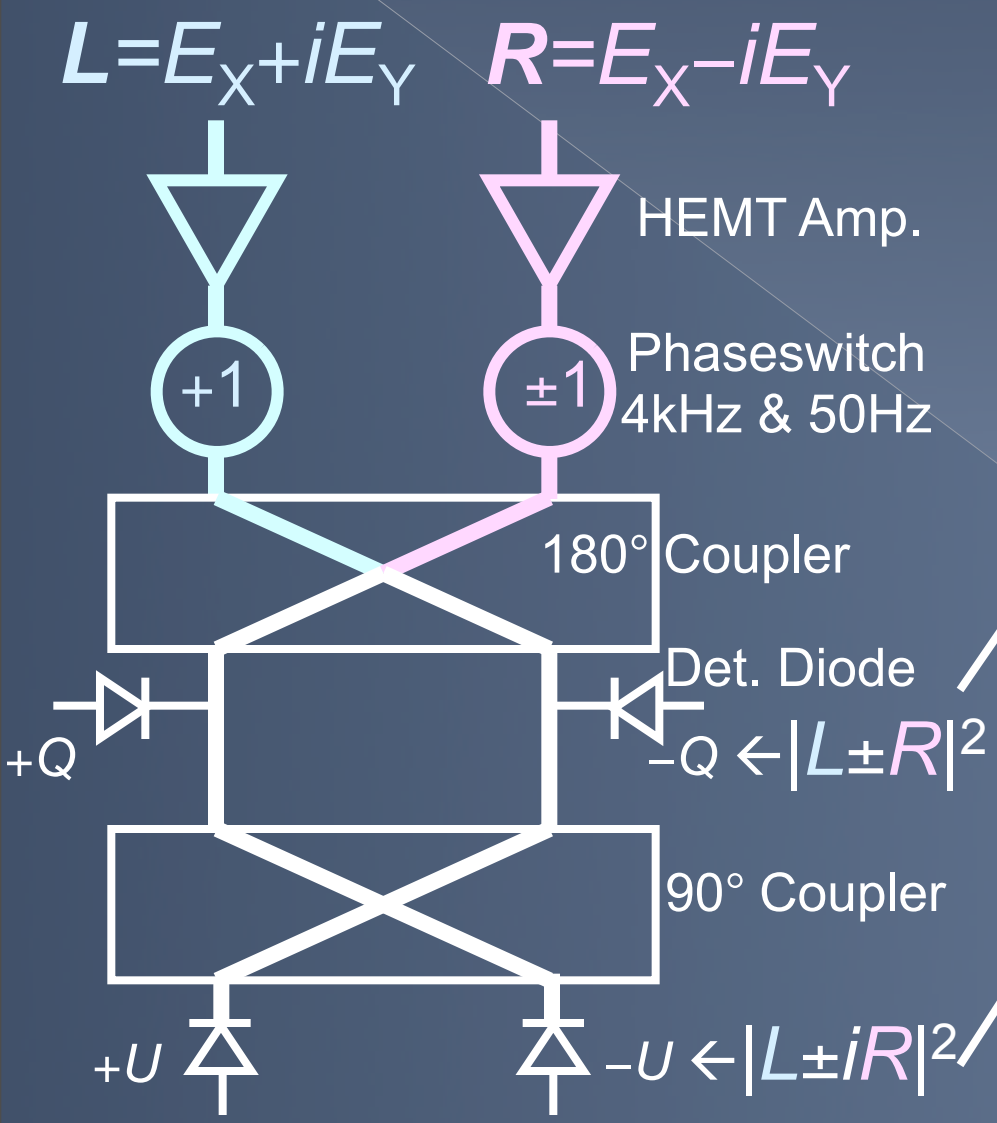


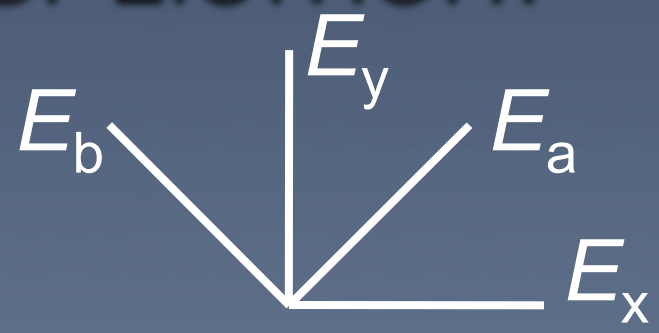
- Amplification "with phase info"
  - Intrinsic adv.: Q/U simultaneous meas
  - Fundamental limit: $\Delta n \cdot \Delta\phi \geq 1/2 \rightarrow \Delta T \geq h\nu/k_B$
- Noise level:
  - ~55K@90GHz
  - ~25K@45GHz

Well above quantum limit
Further degradation in modules



Principle of Receiver Element



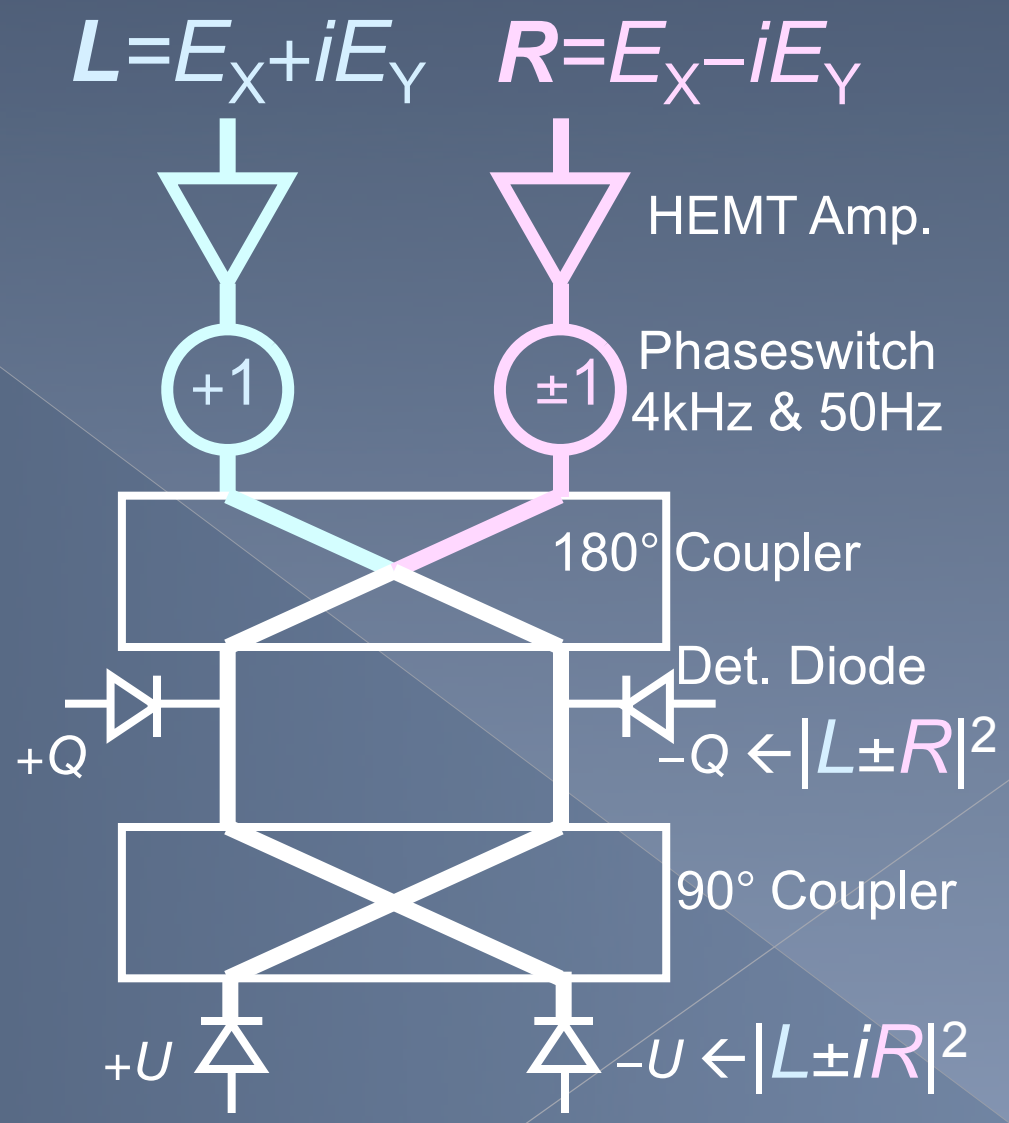


$$|L \pm R|^2 = 2E_x^{\,2} + 2E_y^{\,2} \pm 2\underbrace{\left(E_x^{\,2} - E_y^{\,2}\right)}_{Q}$$

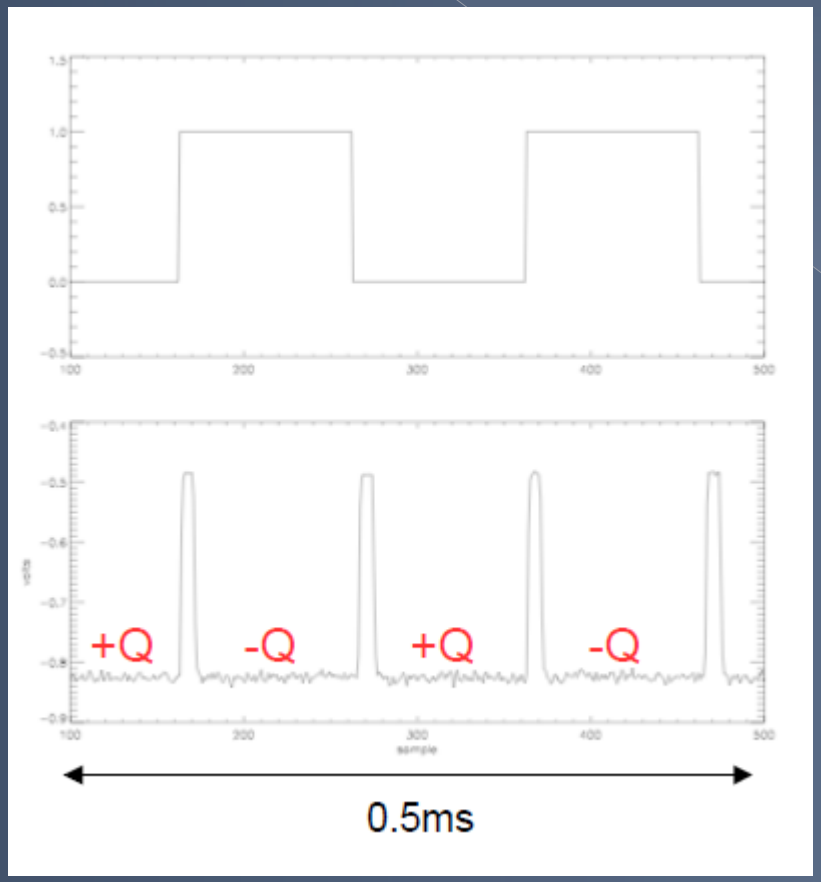
$$|L \pm iR|^2 = 2E_x^{\,2} + 2E_y^{\,2} \mp 4E_xE_y = 2E_a^{\,2} + 2E_b^{\,2} \mp 2\underbrace{\left(E_a^{\,2} - E_b^{\,2}\right)}_{U}$$

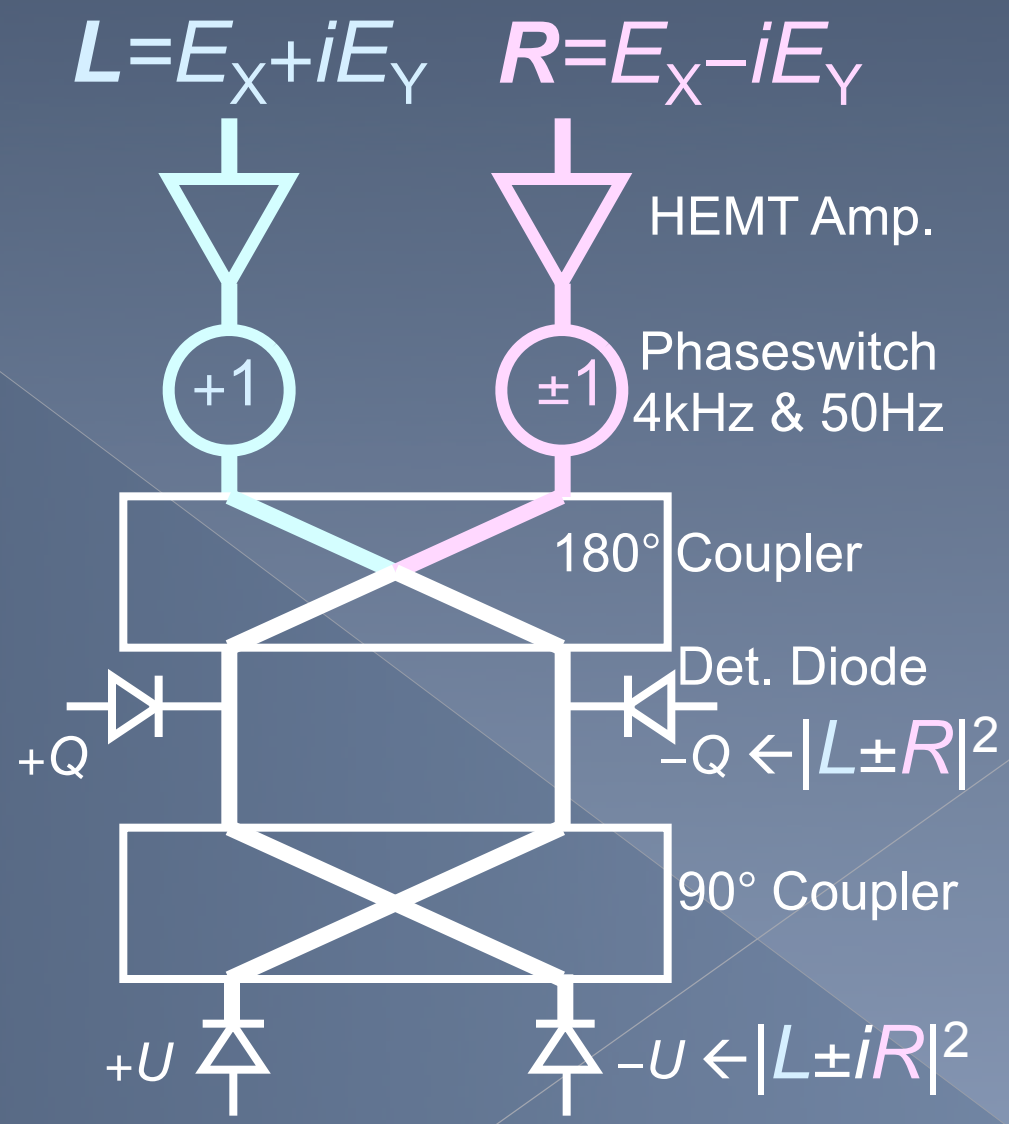
Principle of Receiver Element

- *Q*-*U* simultaneous measurement
- Use of *L*-*R* (not E_X-E_Y)
  - No fake signal from gain difference
- Demodulation
  - $1/f$ noise reduction



Why demodulation?



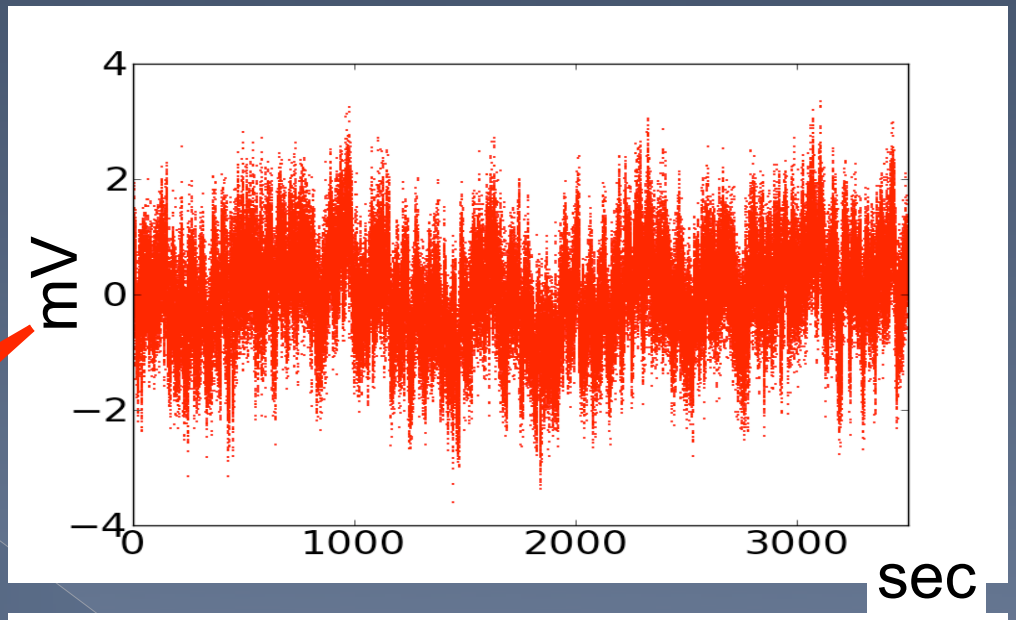


Time Stream

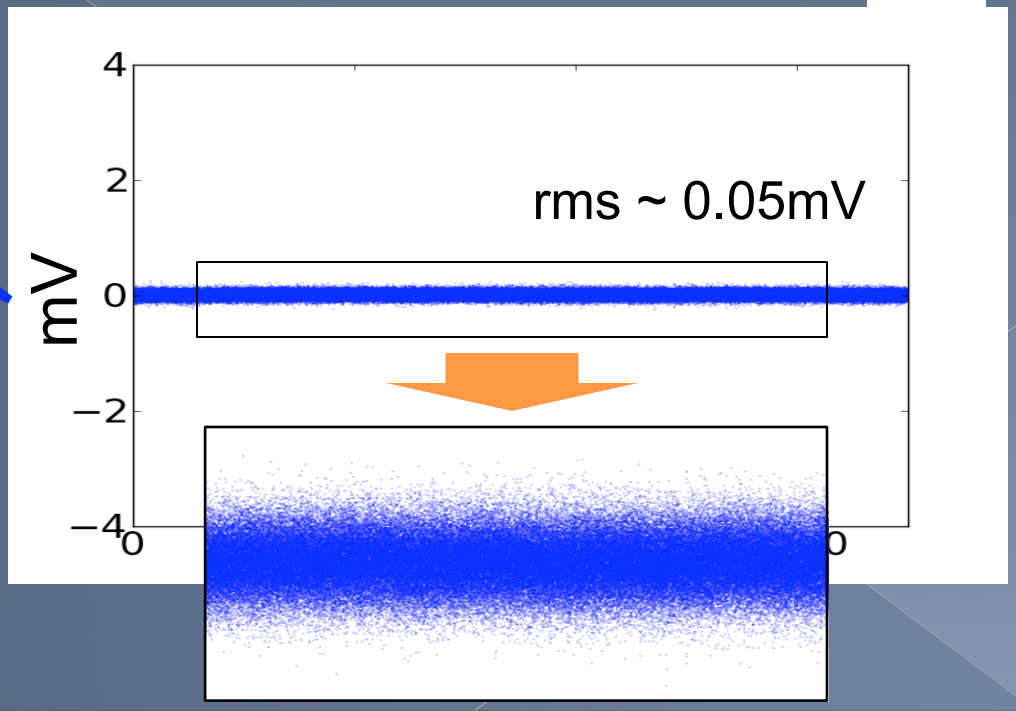
50Hz timestream

Addition

800kHz timestream



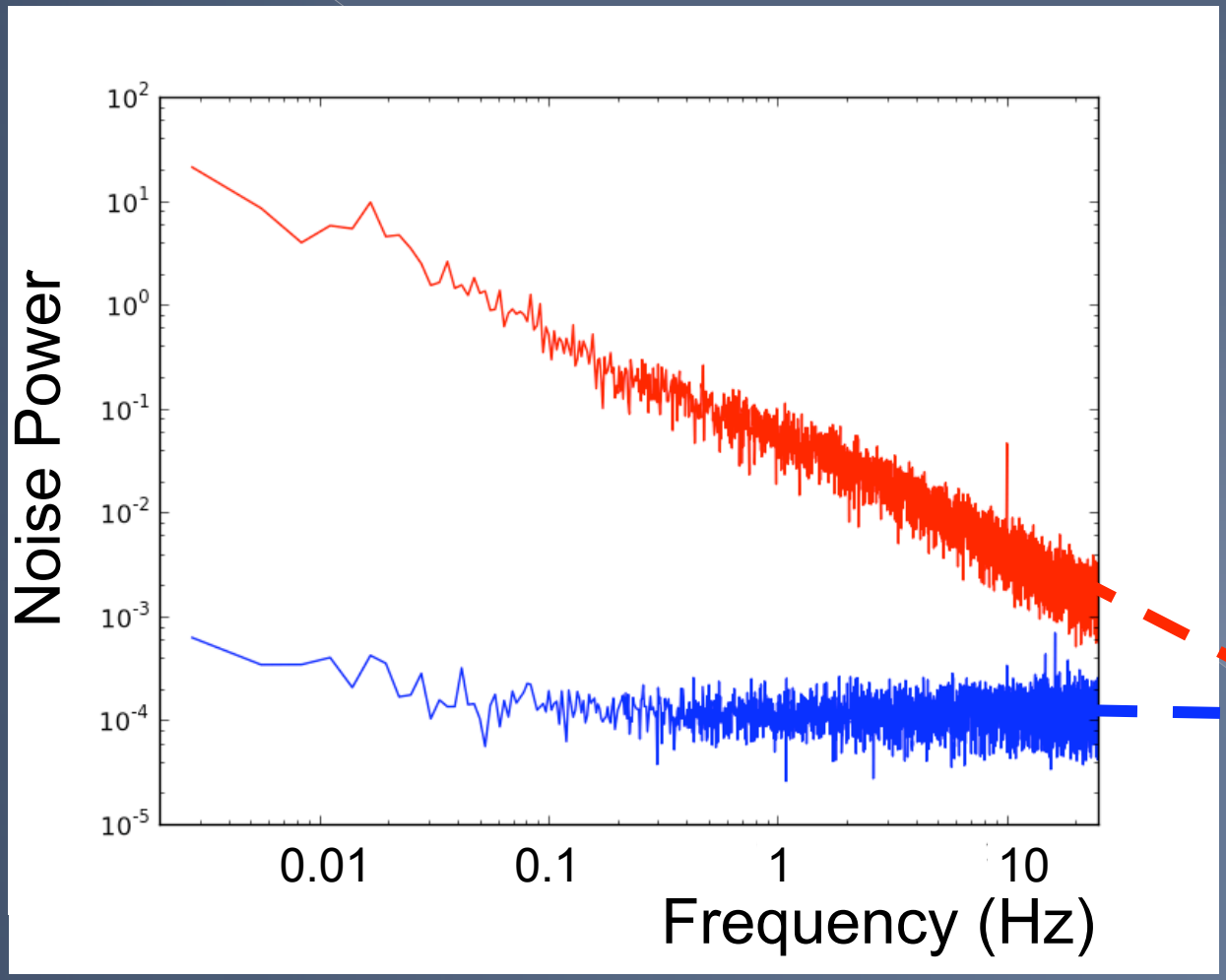
Subtraction



Tiny tiny signal
on top of huge offset

CMB polarization (E-mode)
~ 0.00002 mV

Noise spectrum



Switching frequency 4kHz

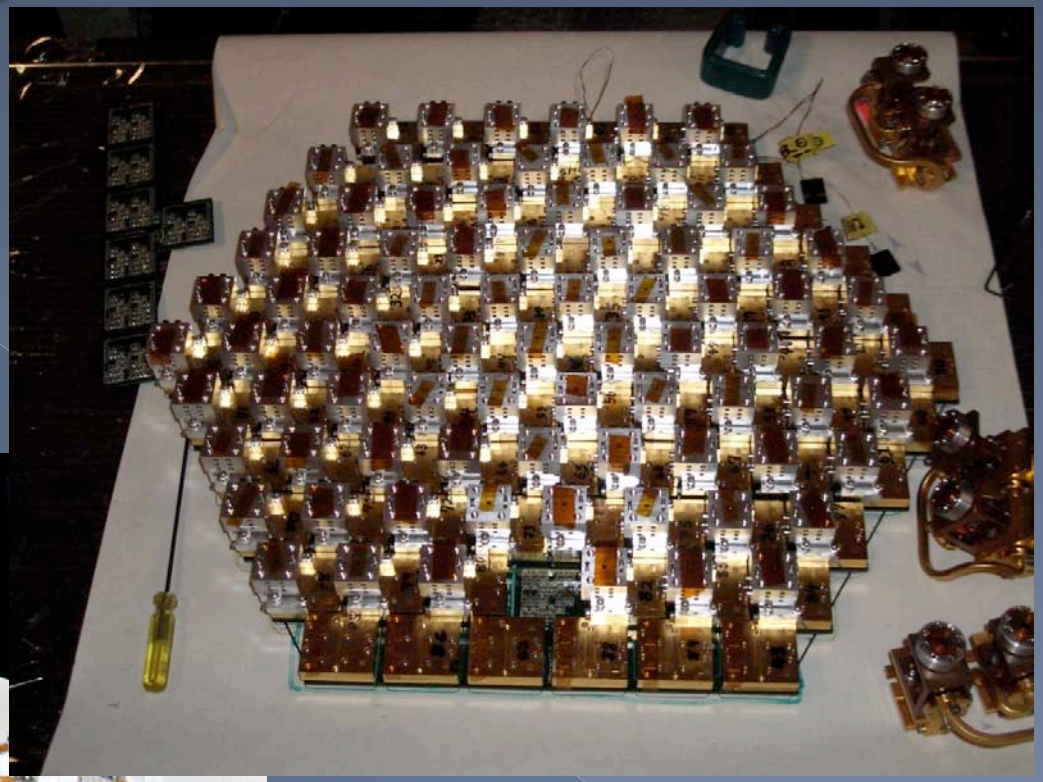
Q-band Array

Array sensitivity
~70 μK·√s

Integrated at Columbia

W-band Array

Array sensitivity
~60 μK·√s

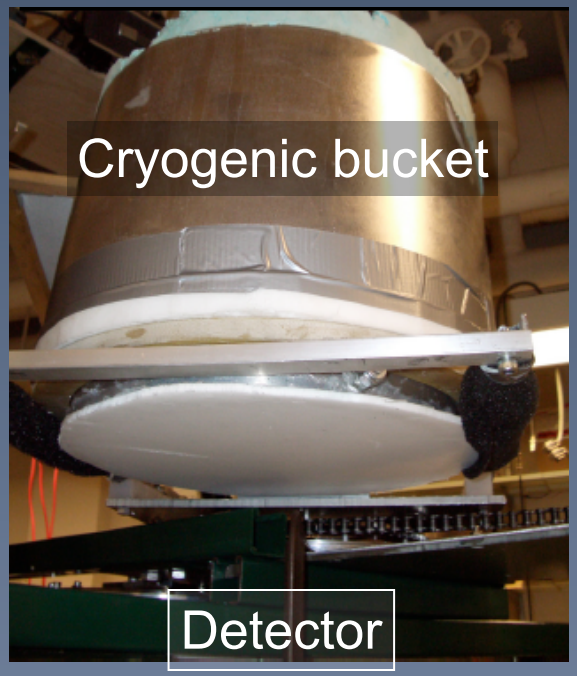


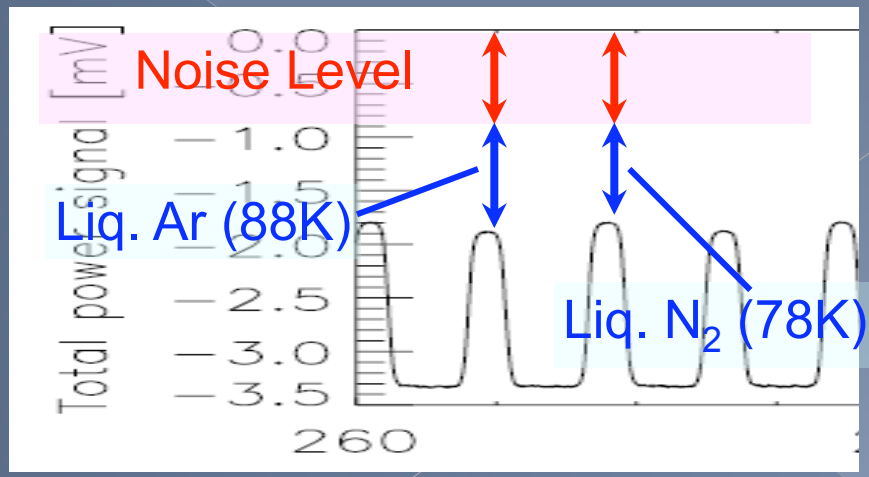
Integrated at Chicago

The world largest HEMT array polarimeter

Lab. Measurements

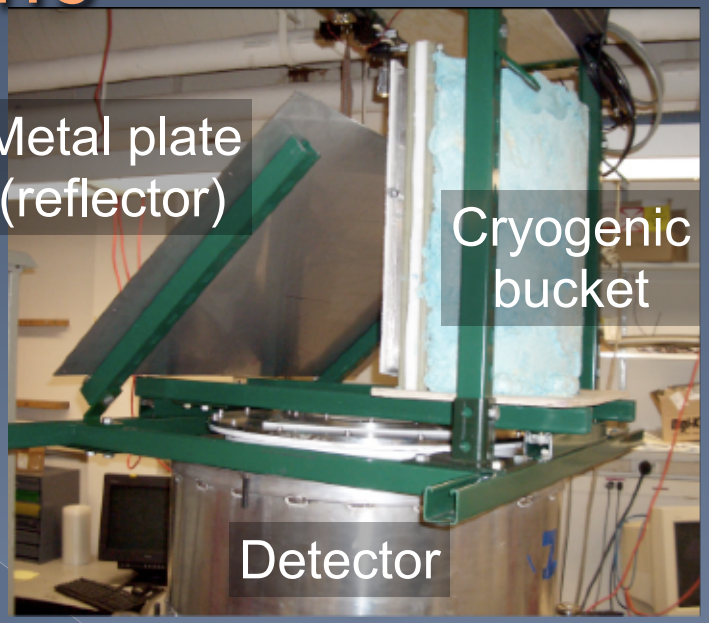
- Difficulty: everything emits microwave
  - Things around us ~300K
  - Impossible to input zero-signal
- Our signal is Gaussian noise
  - How to distinguish from detector noise?

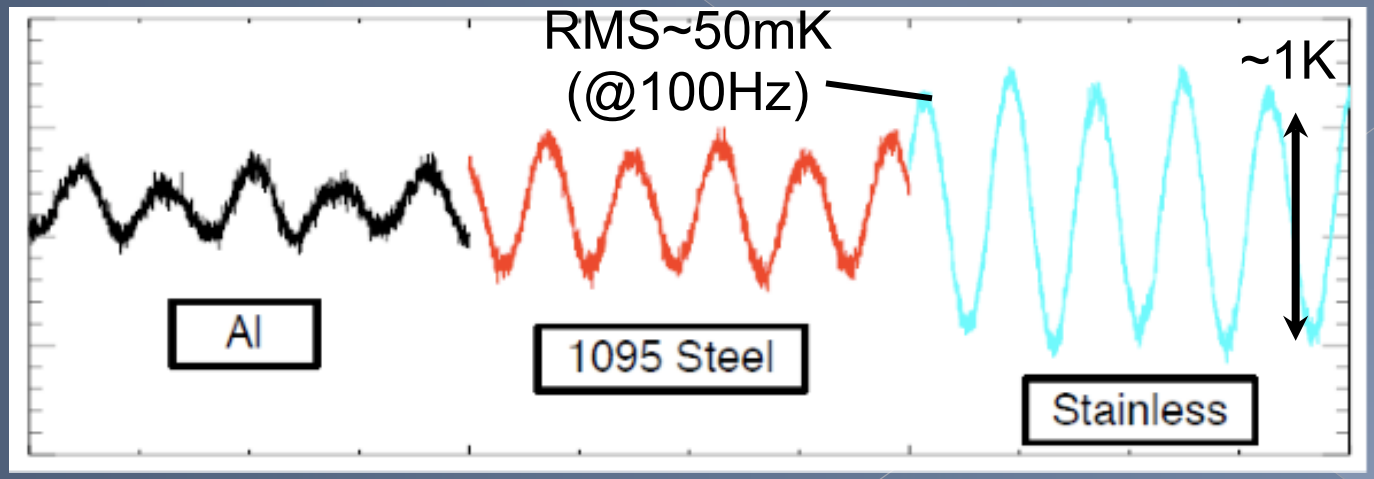




Lab. Measurements

- Reflection by metal plate
  - Known polarization
- Direct measures of
  - Responsivity
  - Noise level





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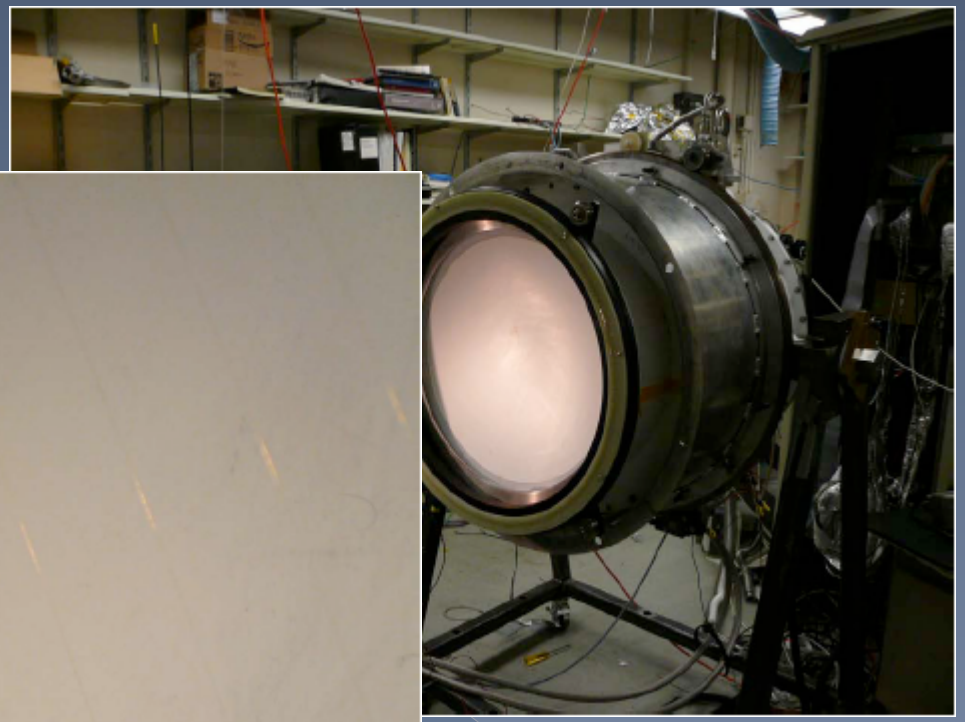
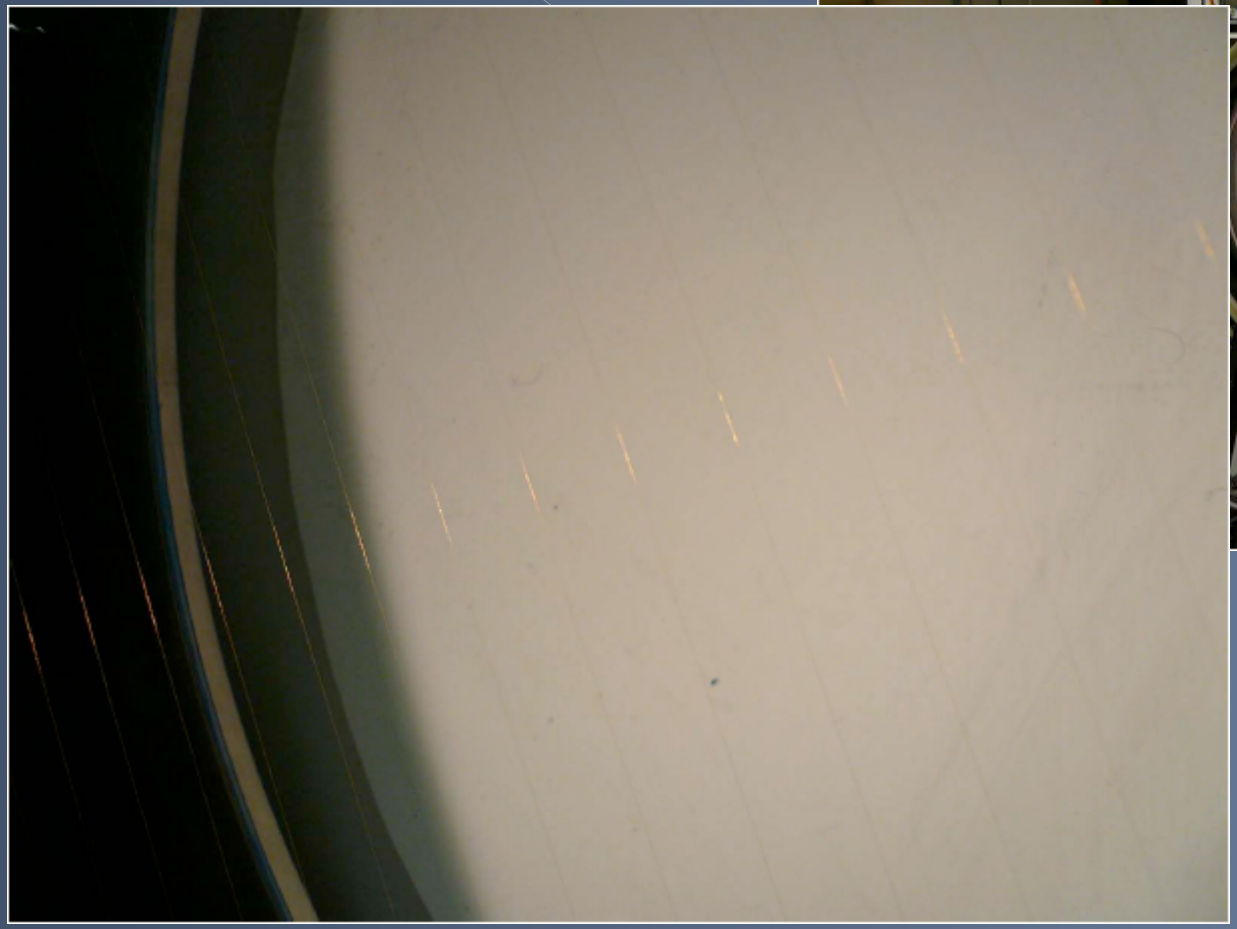
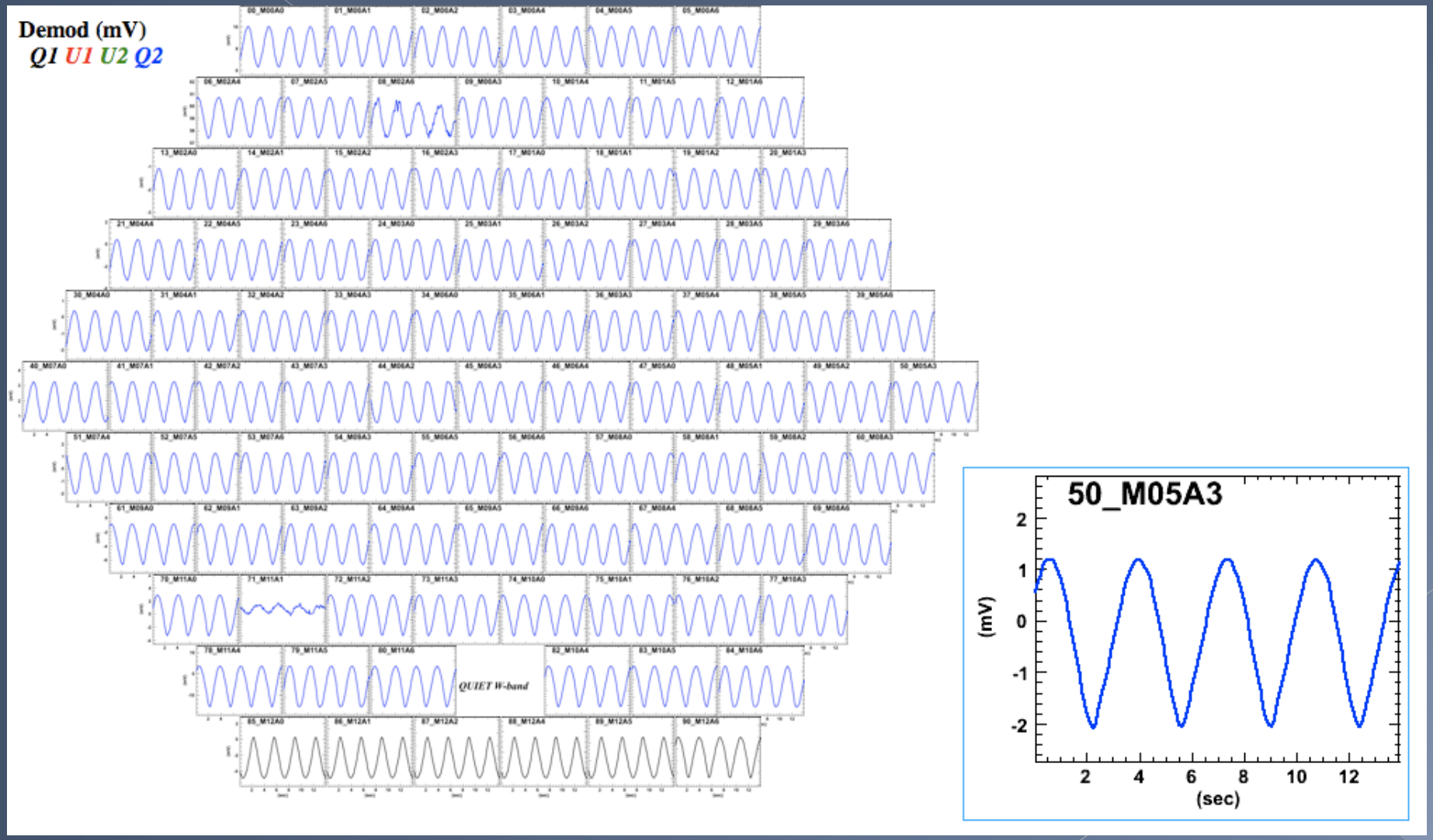


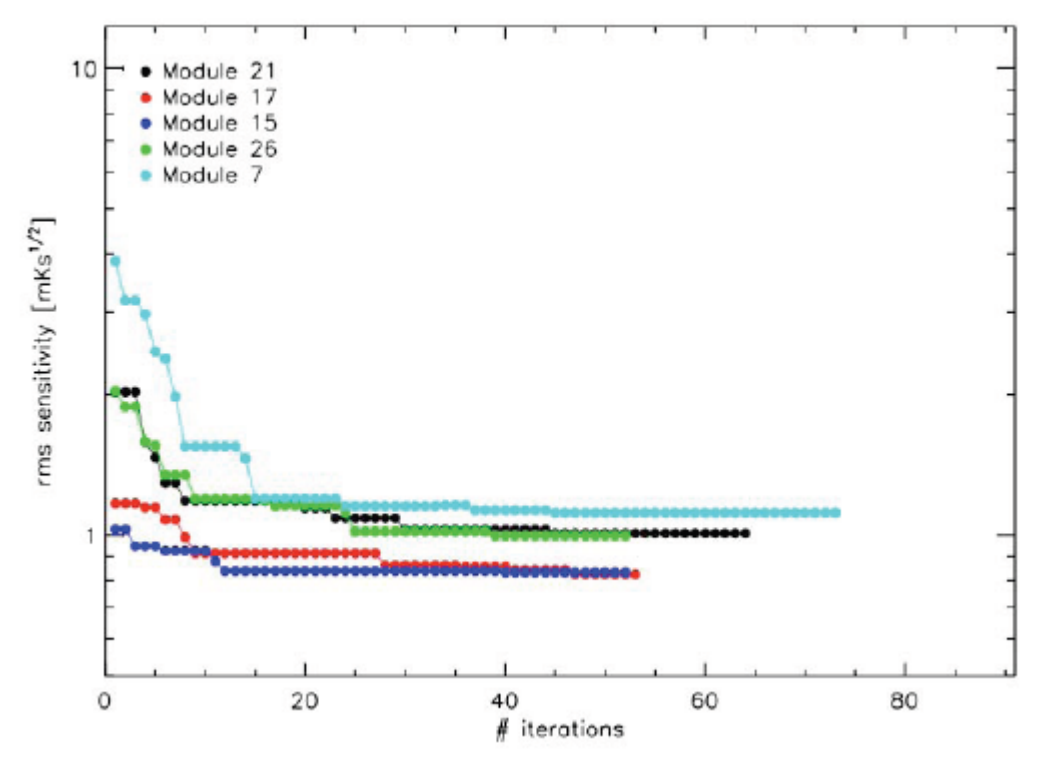


Lab. Measurements



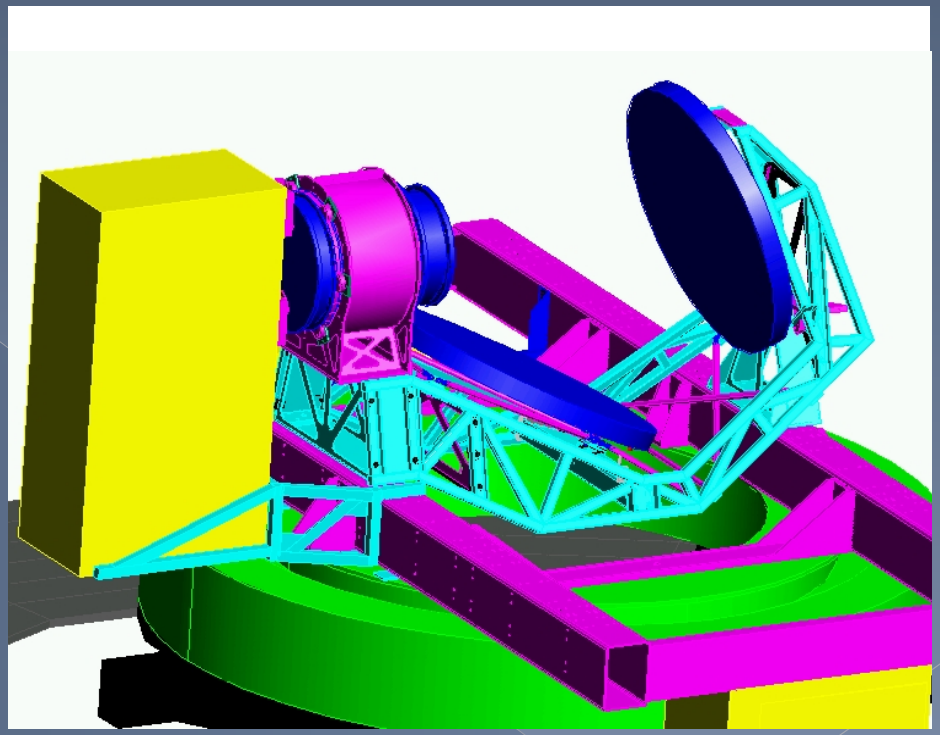
Optimization Procedure

- To exploit best performance, especially BW, bias needs to be optimized
  - 10 bias/module (drain & gate)
  - Simultaneous optimization of many modules



Telescope and Mount

Optics: Telescope

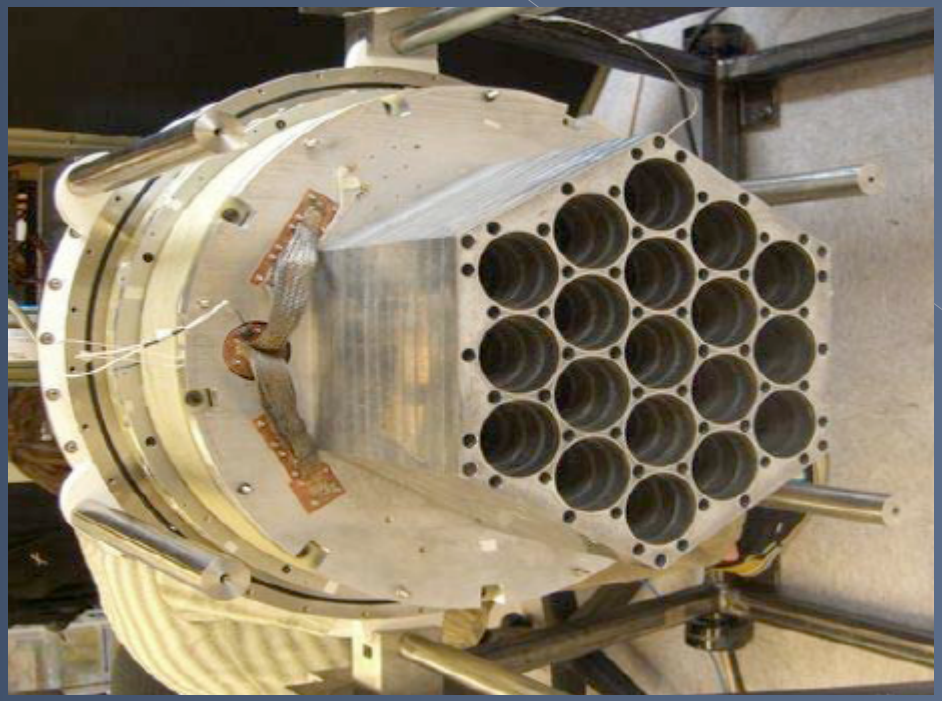


1.4m Primary mirror
FWHM ~ 28arcmin @ Q-band
FWHM ~ 13arcmin @ W-band

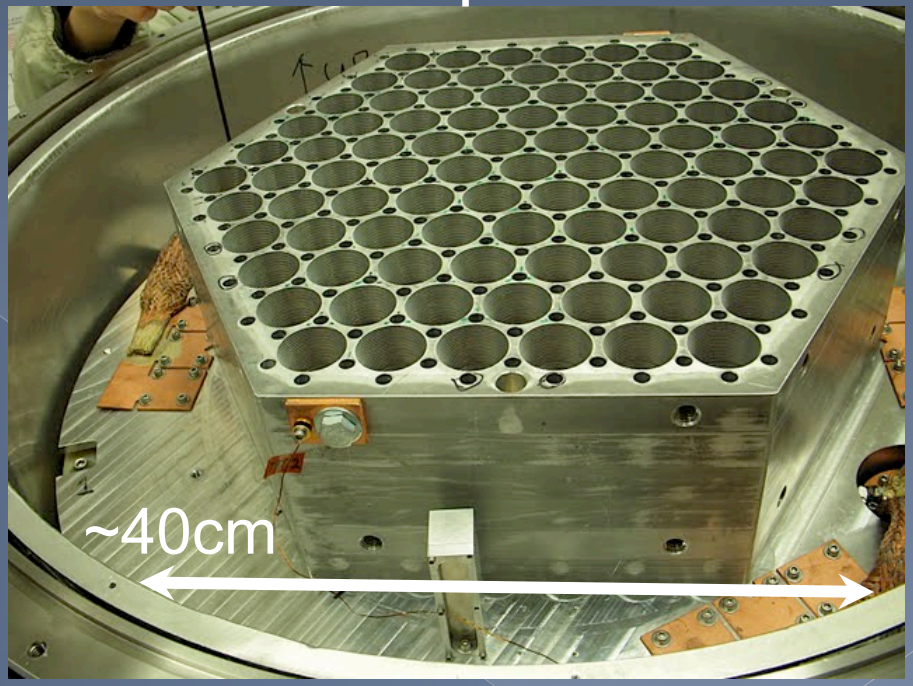
Stanford
Caltech/JPL

Optics: Platelet Array

Q-band platelet



W-band platelet

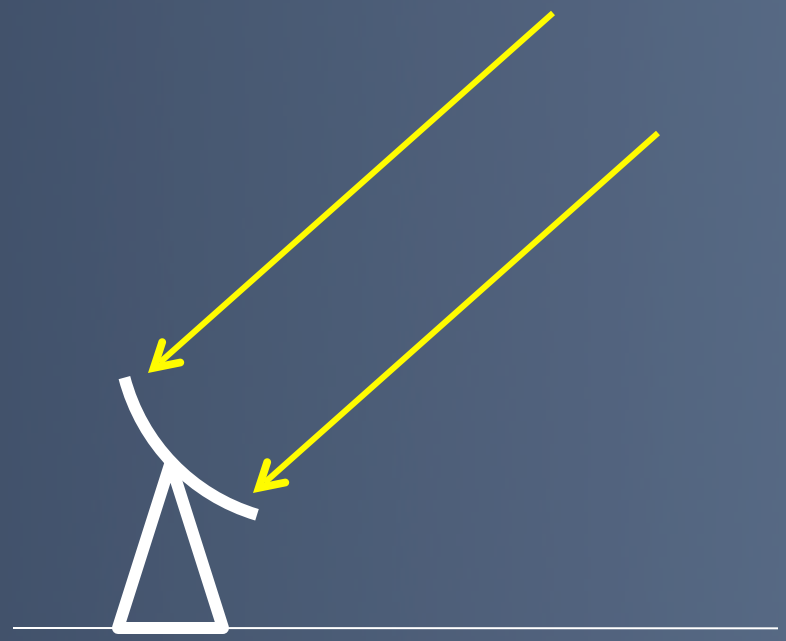


Miami

Horn array to couple to modules
Created by diffusion bonding

Digression: bigger telescope?

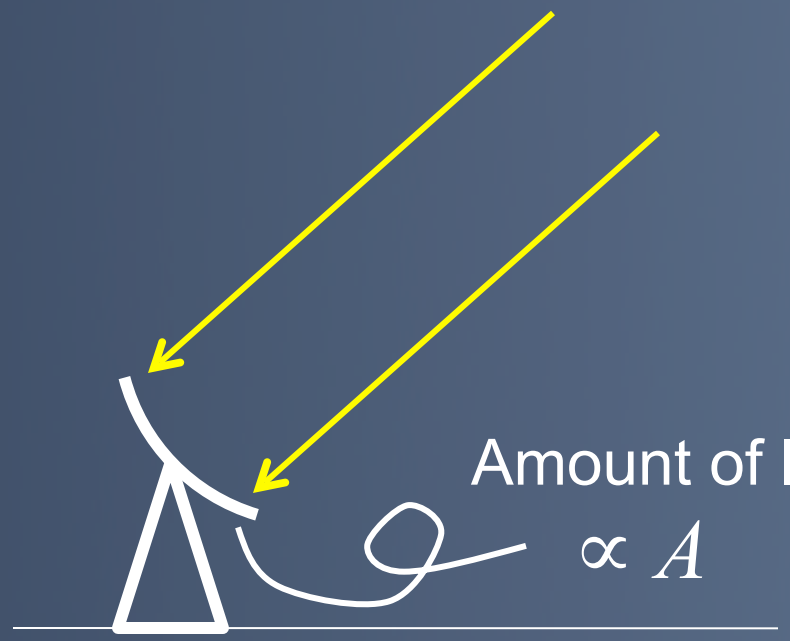
You may think bigger telescope collects more light and thus reduces noise. NO!



A: Area of the primary mirror

Digression: bigger telescope?

You may think bigger telescope collects more light and thus reduces noise. NO!



Amount of light collected

$\propto A$

A: Area of the primary mirror

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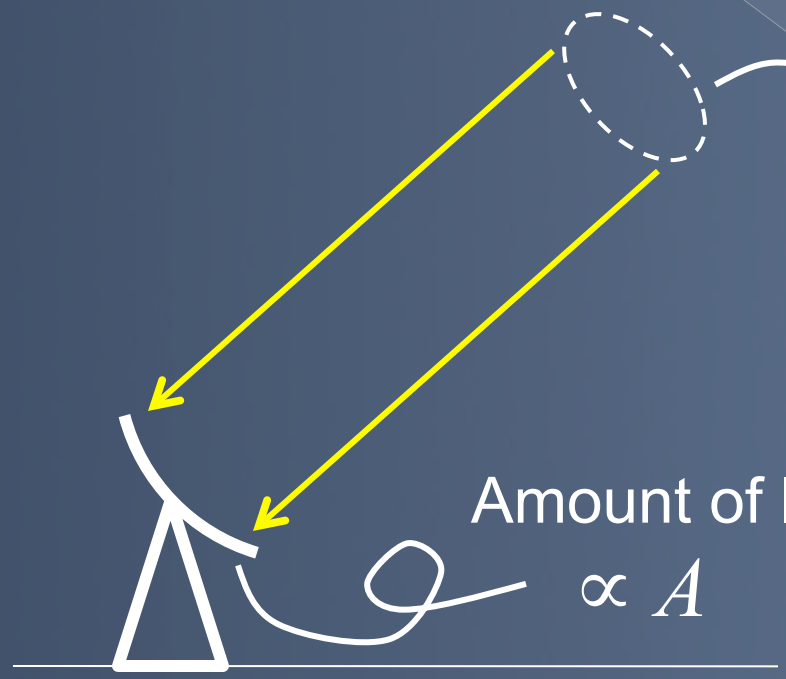

Size of the image on the sky
(=Area of integration)
$\propto 1/A$ (diffraction limit)

Amount of light collected
$\propto A$

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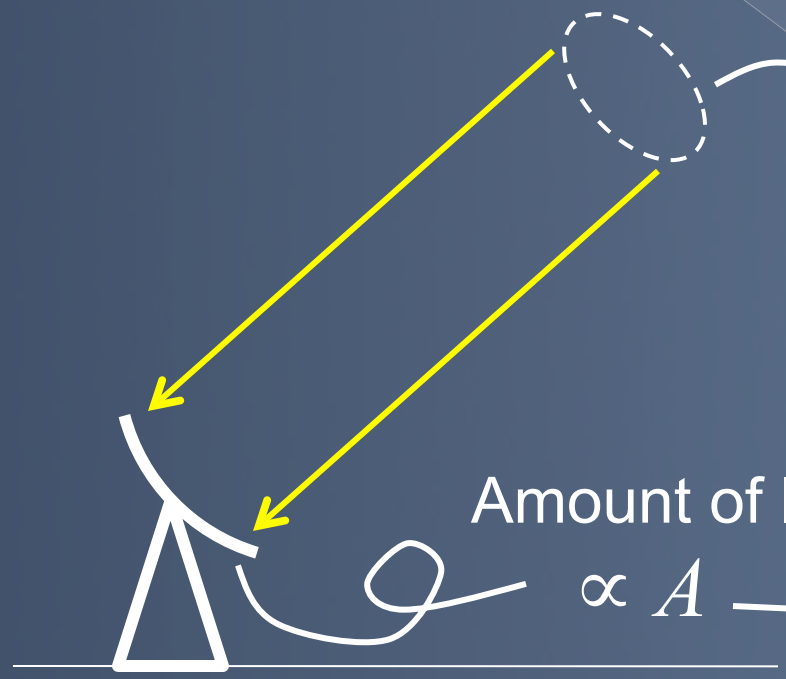


Size of the image on the sky
(=Area of integration)
$\propto 1/A$ (diffraction limit)

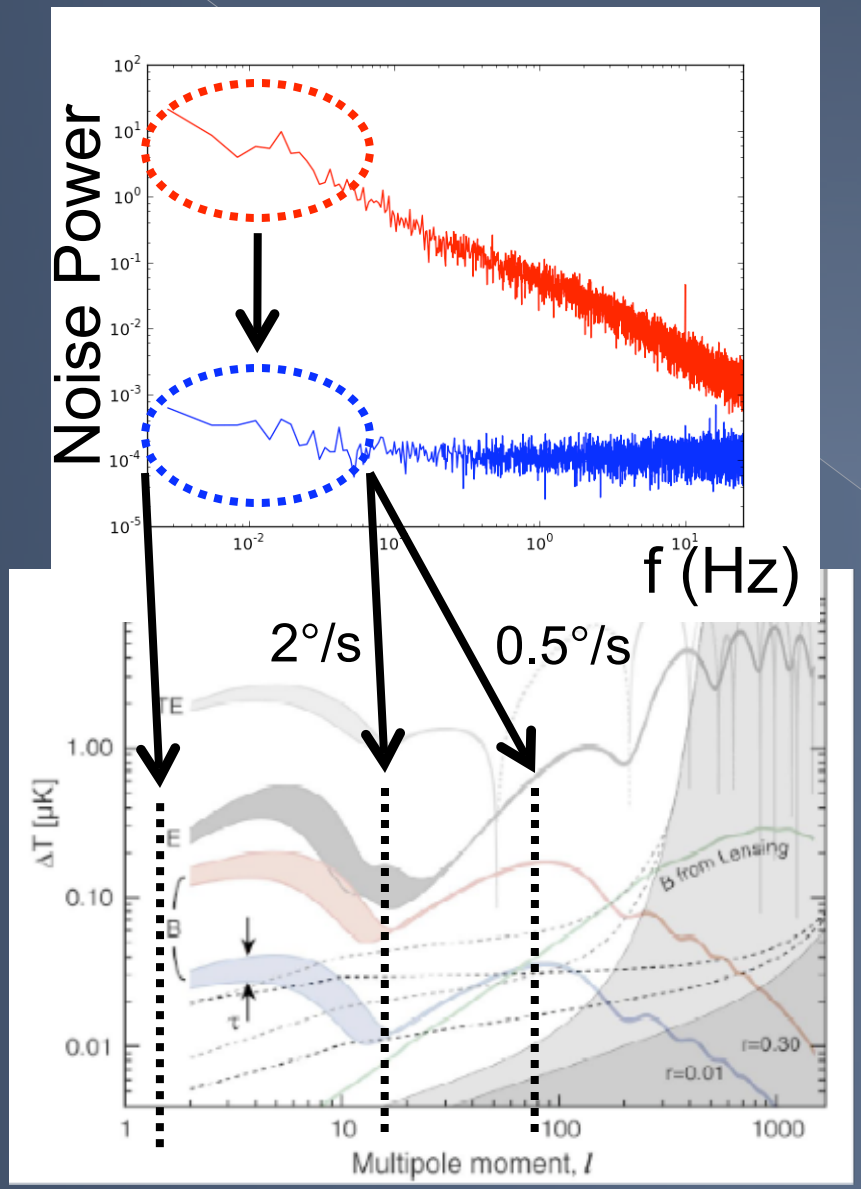
Amount of light collected
$\propto A$

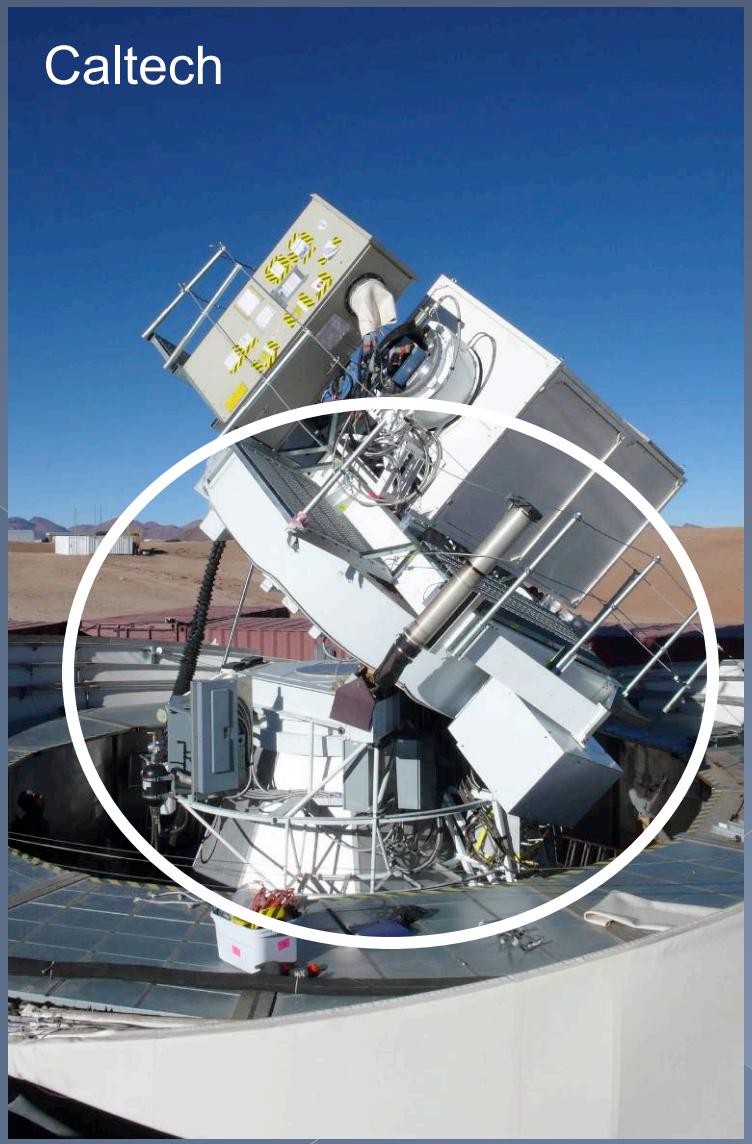
Cancels out for
"surface like" target

A: Area of the primary mirror

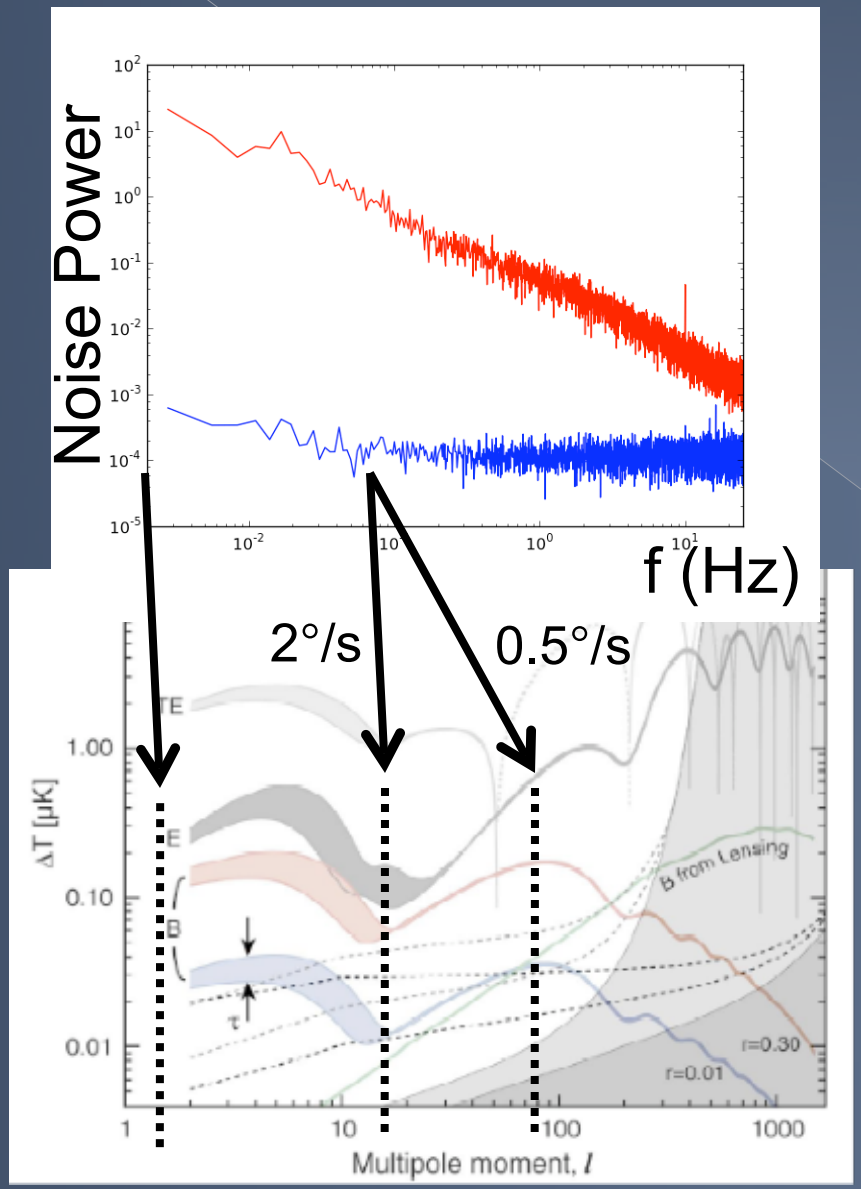
Mount

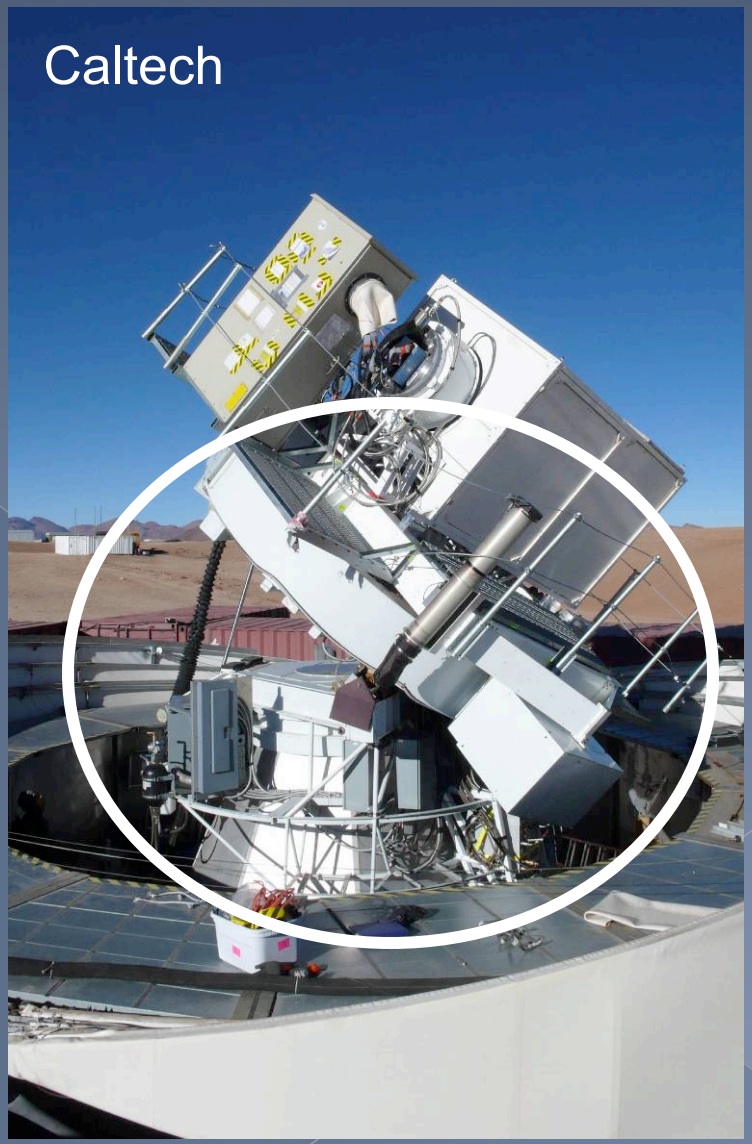
Mount: Importance of Speed



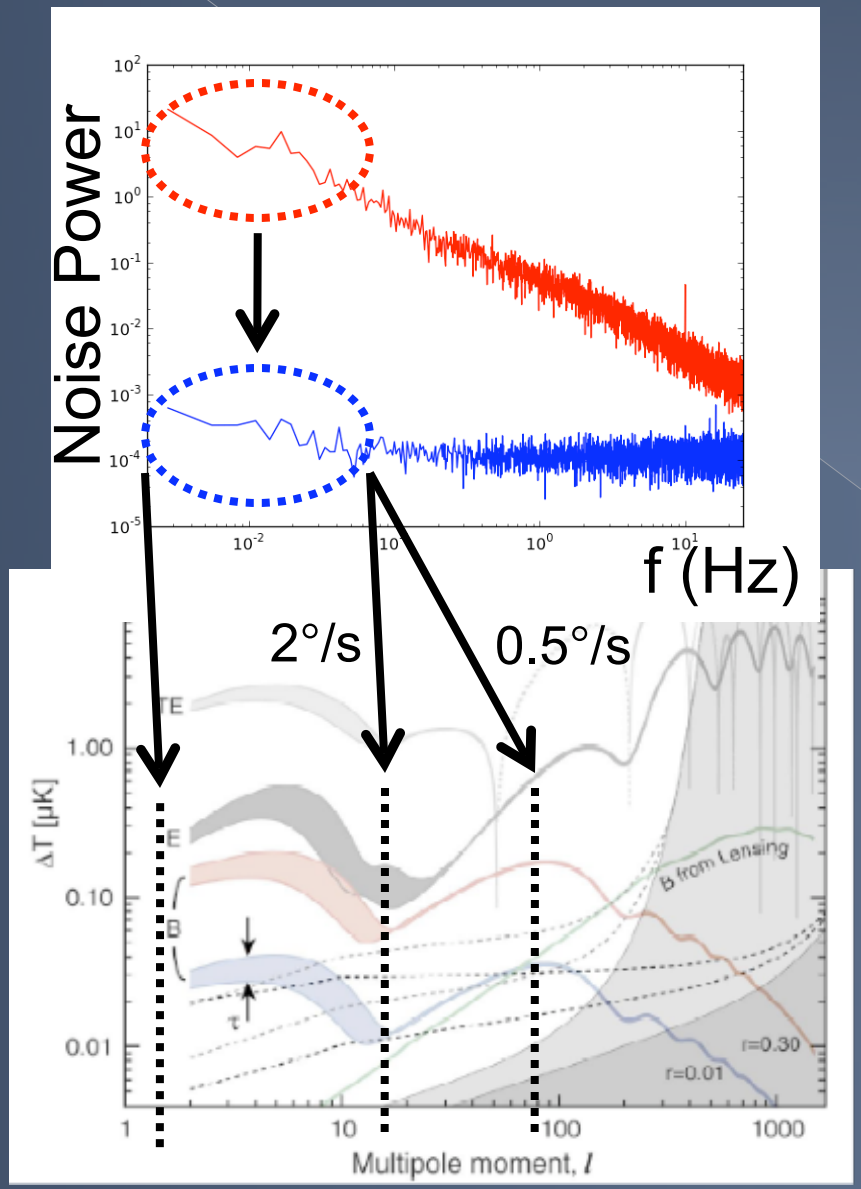


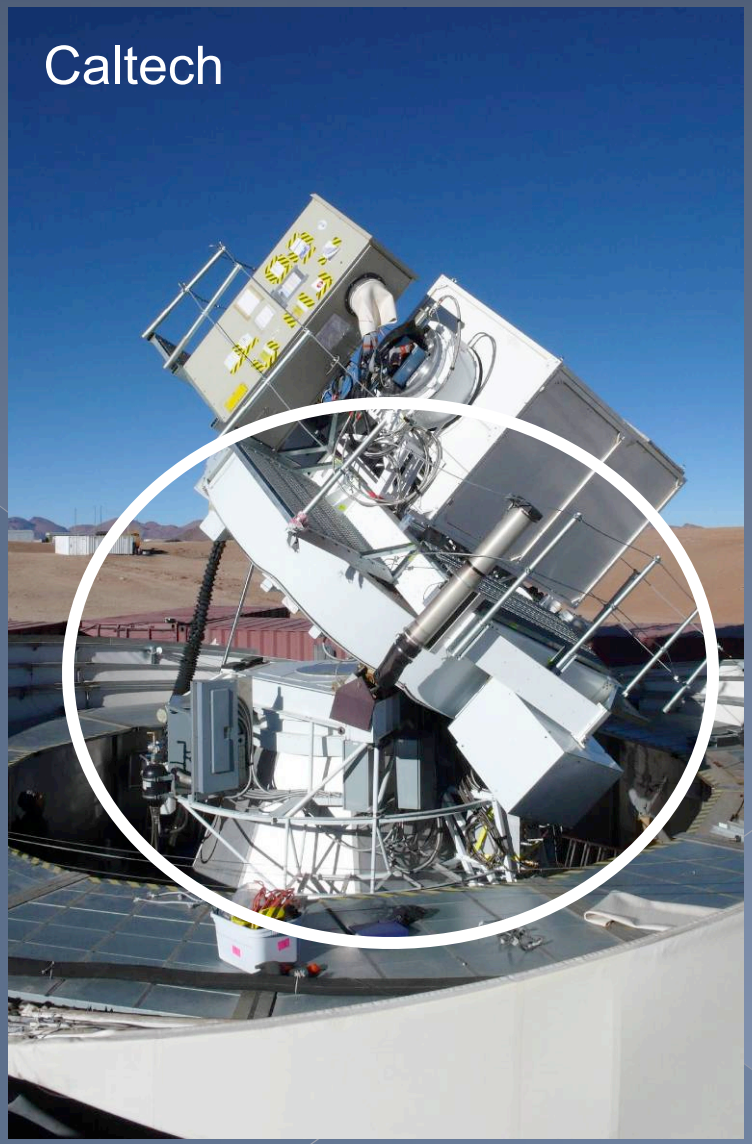
Mount: Importance of Speed





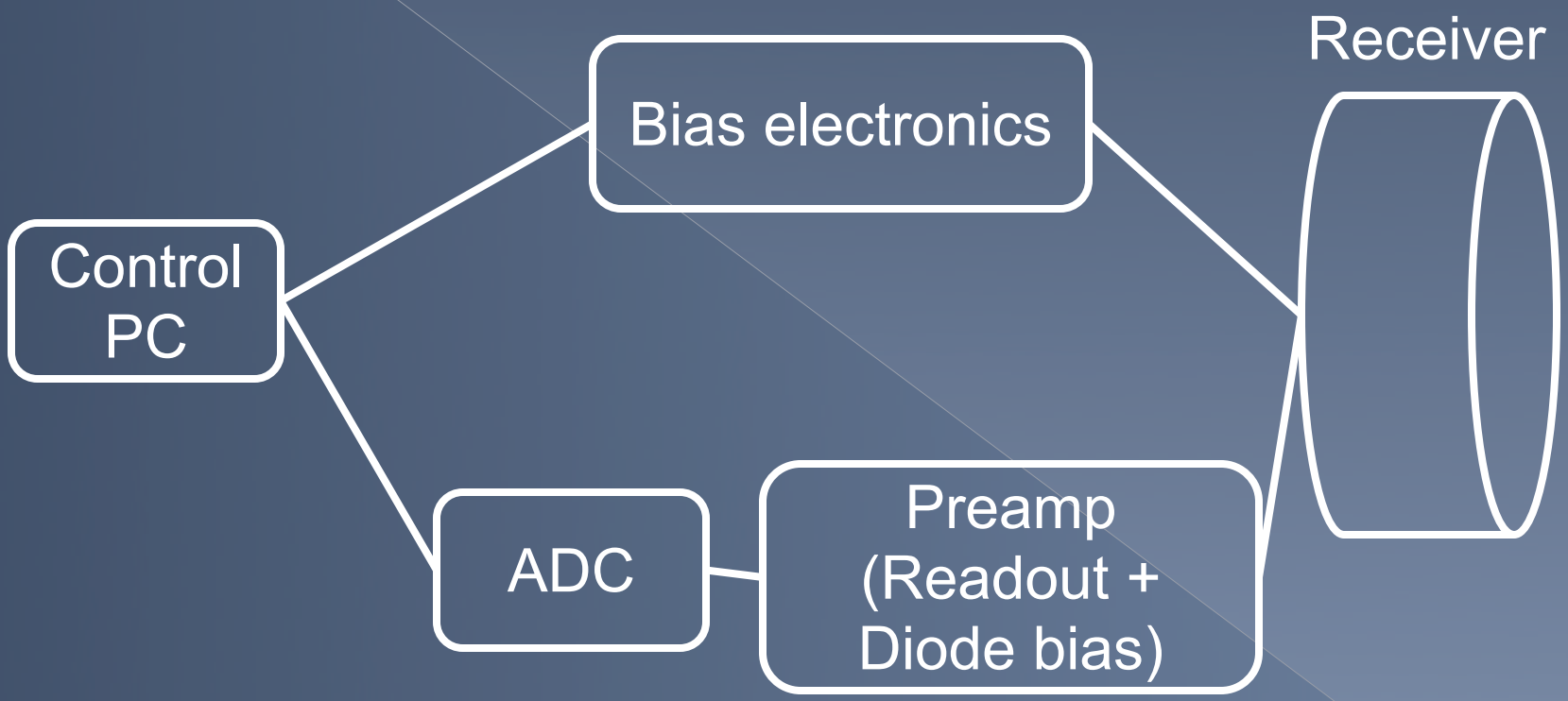
Mount: Importance of Speed





Data Acquisition and Electronics

Electronics Schematic

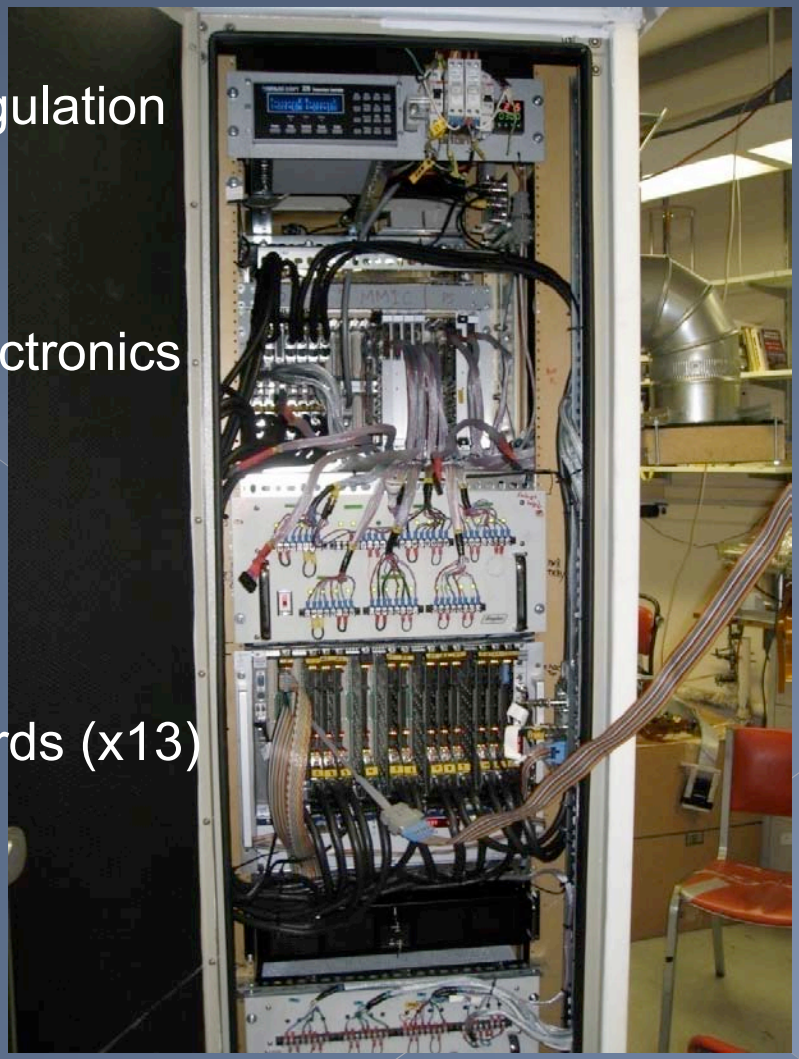


Enclosure (on the mount)

Cryo. regulation

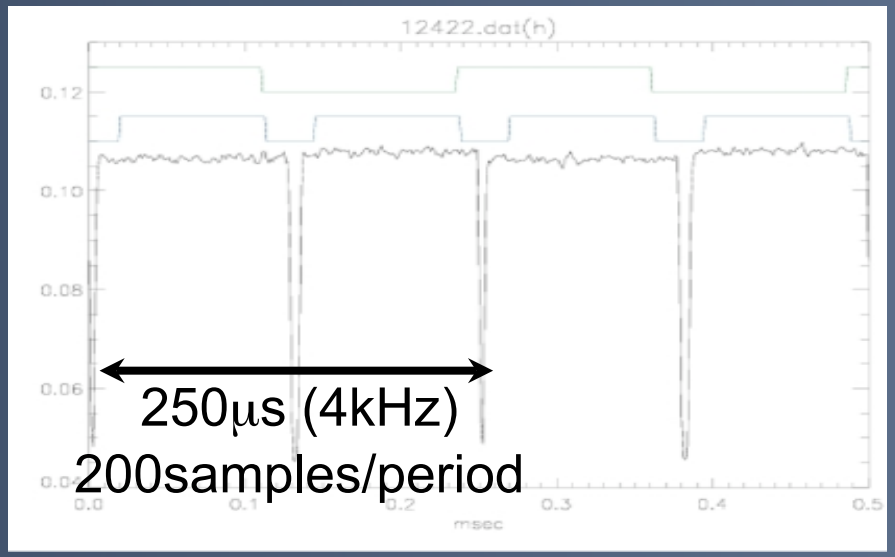
Bias Electronics

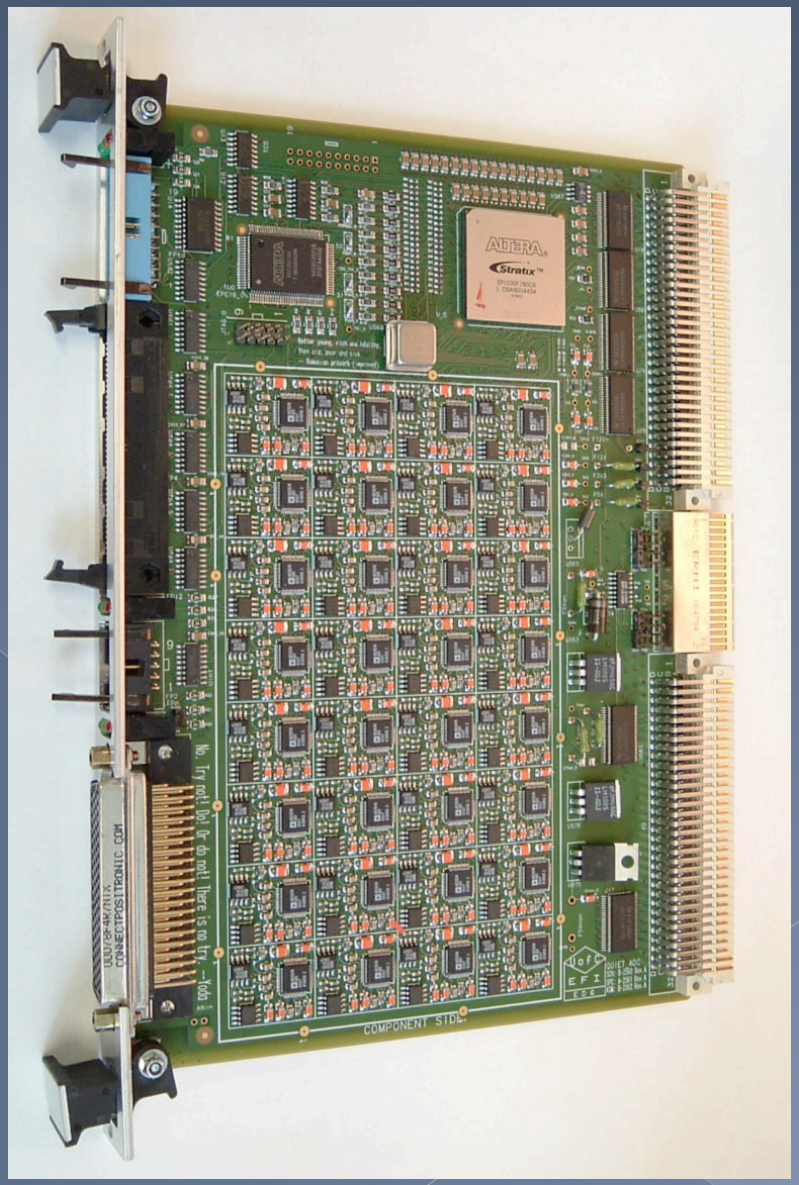
ADC boards (x13)



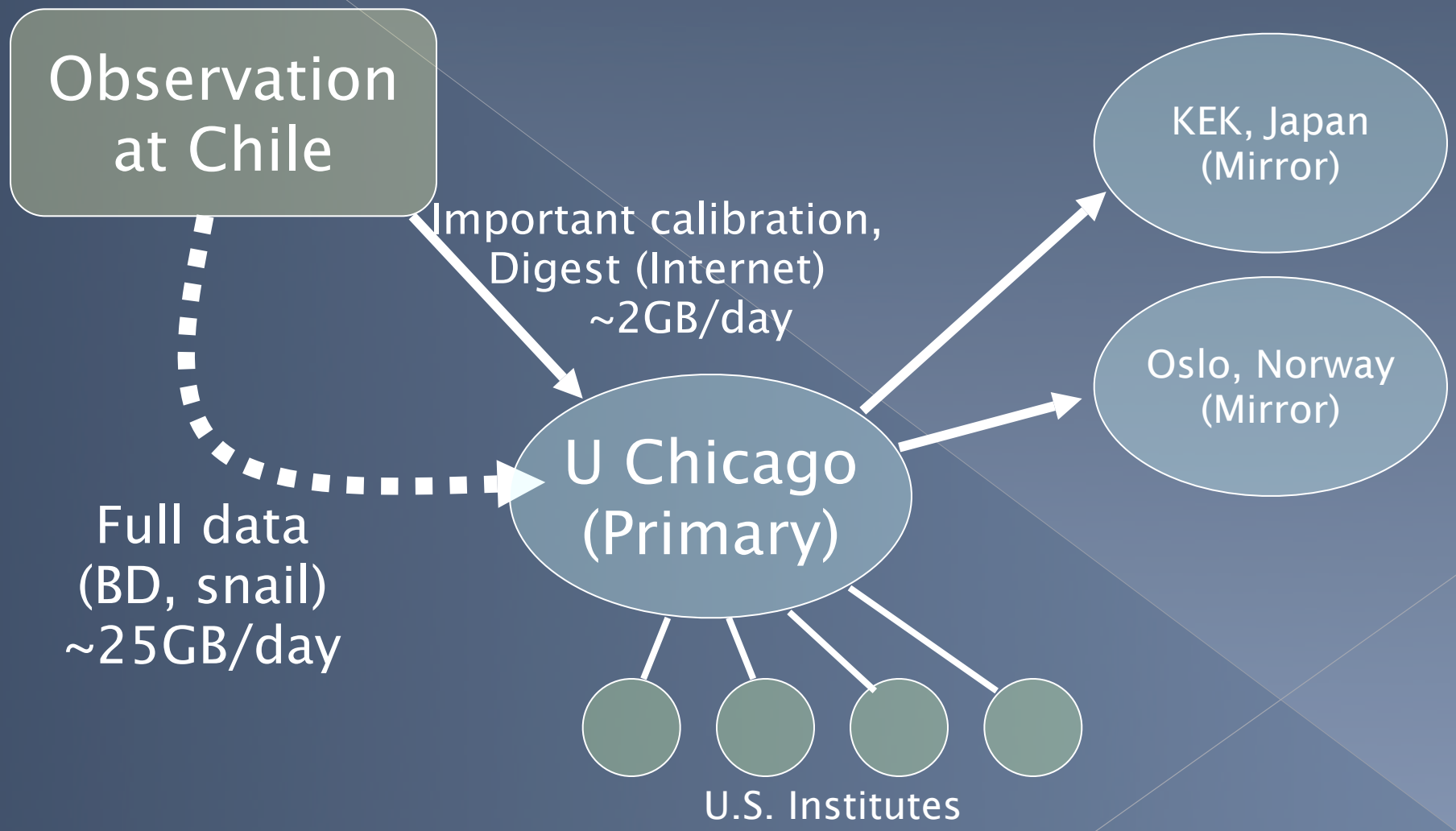
DAQ

- 18-bit, 800kHz ADC (Chicago)
  - Based on the one used at CDF
- Control and down sample (average) by FPGA



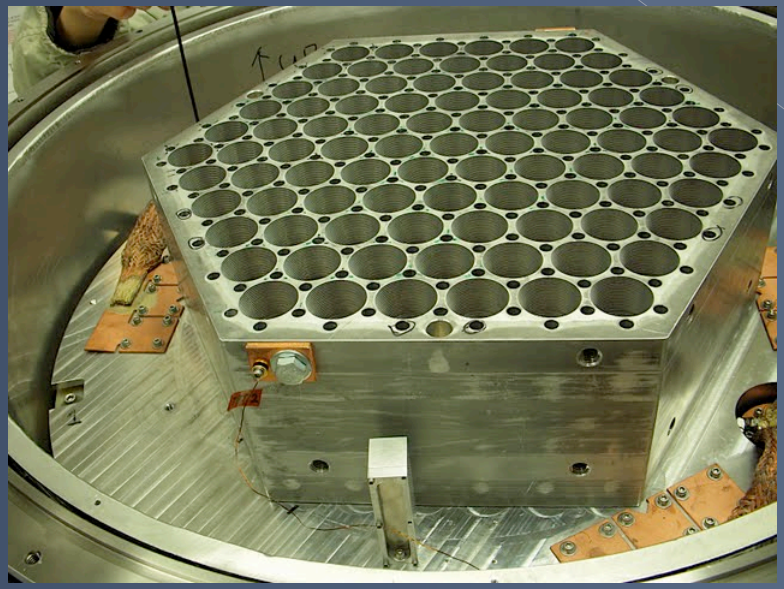


Data Management: Bring it off of the mountain!!

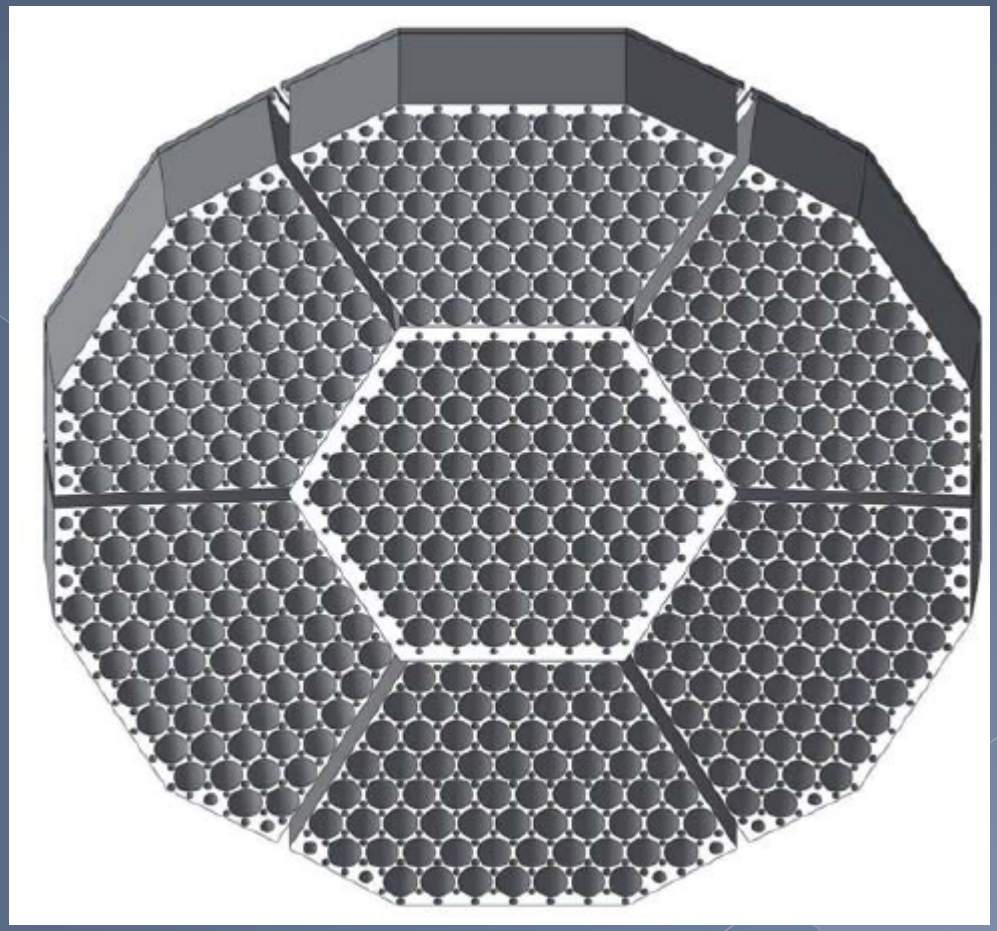


(Near) Future

QUIET Phase-II (x16 scale up!)

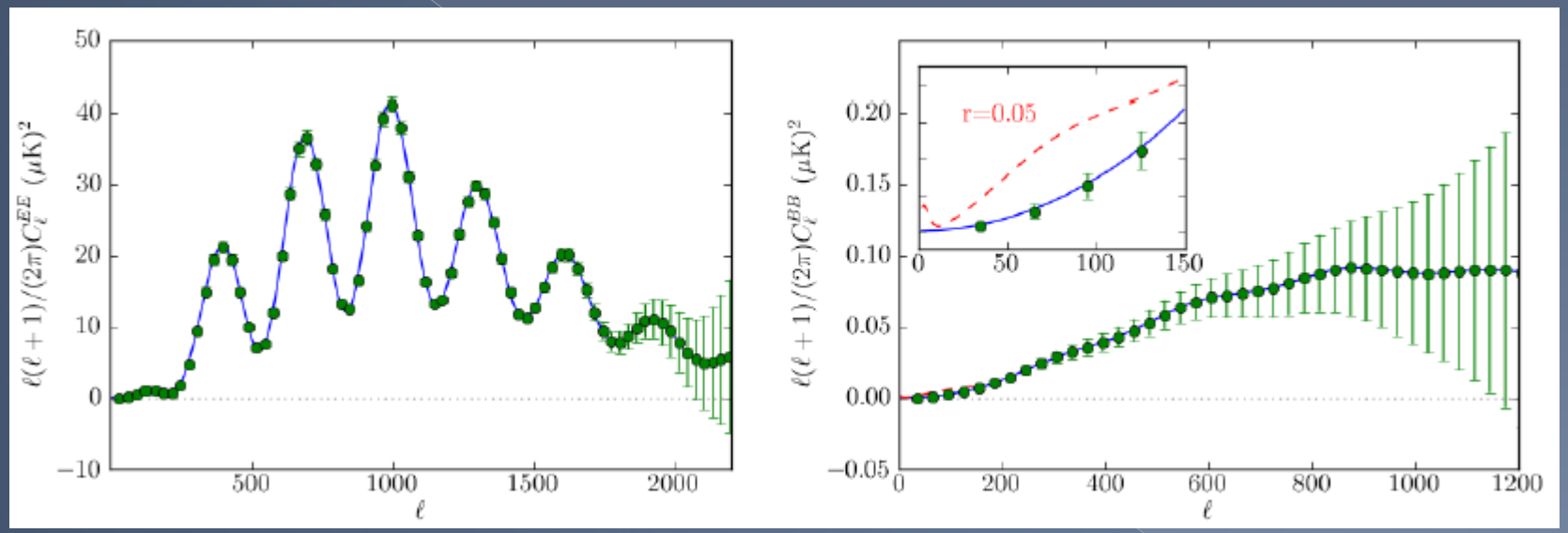


Phase-I W-band
91-element array



499-element array (x3)

Expected Sensitivity



E-mode: High S/N measurement up to ℓ~2000

B-mode: Detection or significant limit on r, detection of lensing

Summary

- CMB polarization
  - A unique opportunity to access fundamental physics
  - A field where new technologies are growing
- QUIET experiment
  - HEMT receiver array experiment using state-of-the-art MMIC packaging technique
    - Demodulation, Q/U simultaneous meas.
  - Competitive sensitivity
  - Phase-I observing, proposing phase-II

Phase switch

- Switch between two paths with 180° different phases
- One of the fundamental limitations to BW