LARGE-SCALE BOLOMETER ARRAYS AND READOUT FOR NEXT-GENERATION CMB EXPERIMENTS

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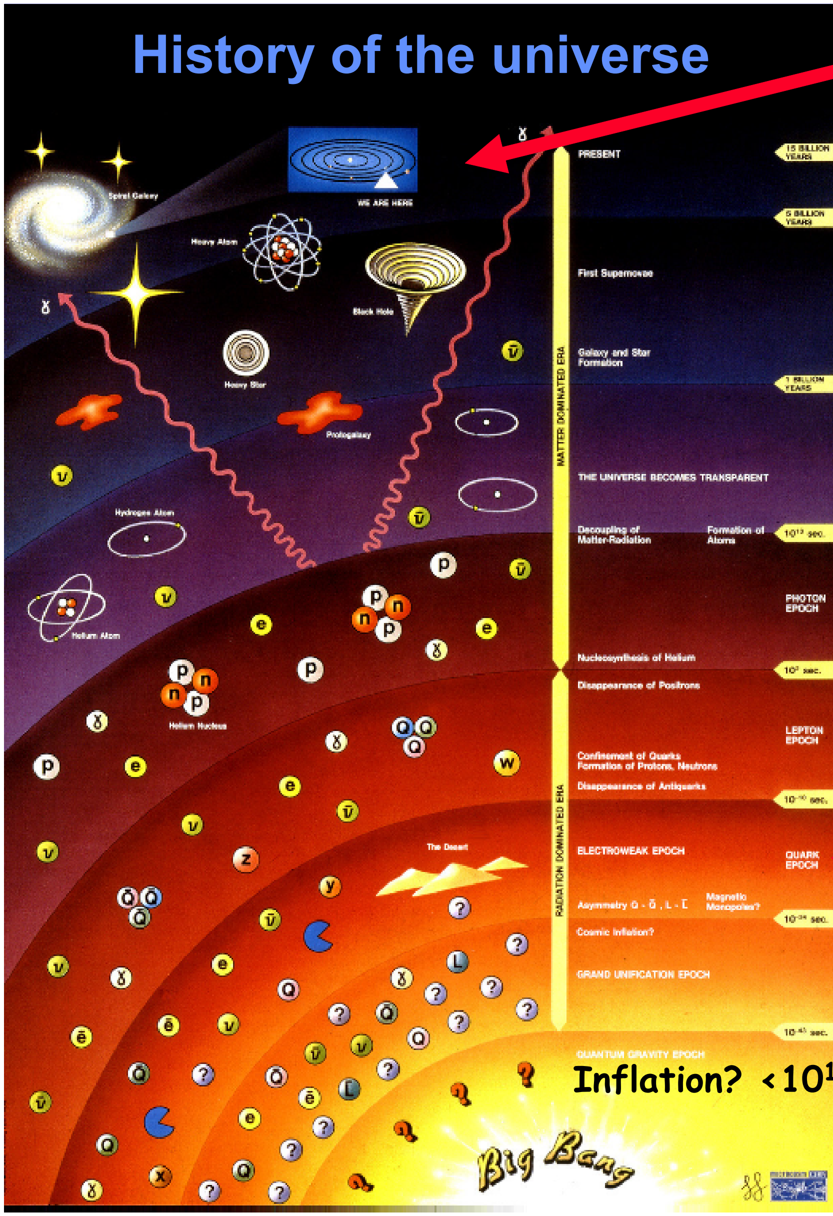
Outline:

1. CMB Physics and Experiments
2. Measurement Techniques and Requirements
3. Bolometer Arrays
4. Frequency-Multiplexed Readout
5. System results

Slides at www-physics.LBL.gov/~spieler. Also see my 2005 Heidelberg Lectures.



Inflation? $<10^{16}$ GeV

You are here

← NOW (12.7 Billion years)

← Stars form (1 Billion years)

CMB Structure Imprinted

← Atoms Form (300 000 years)

← Nuclei Form (180 seconds)

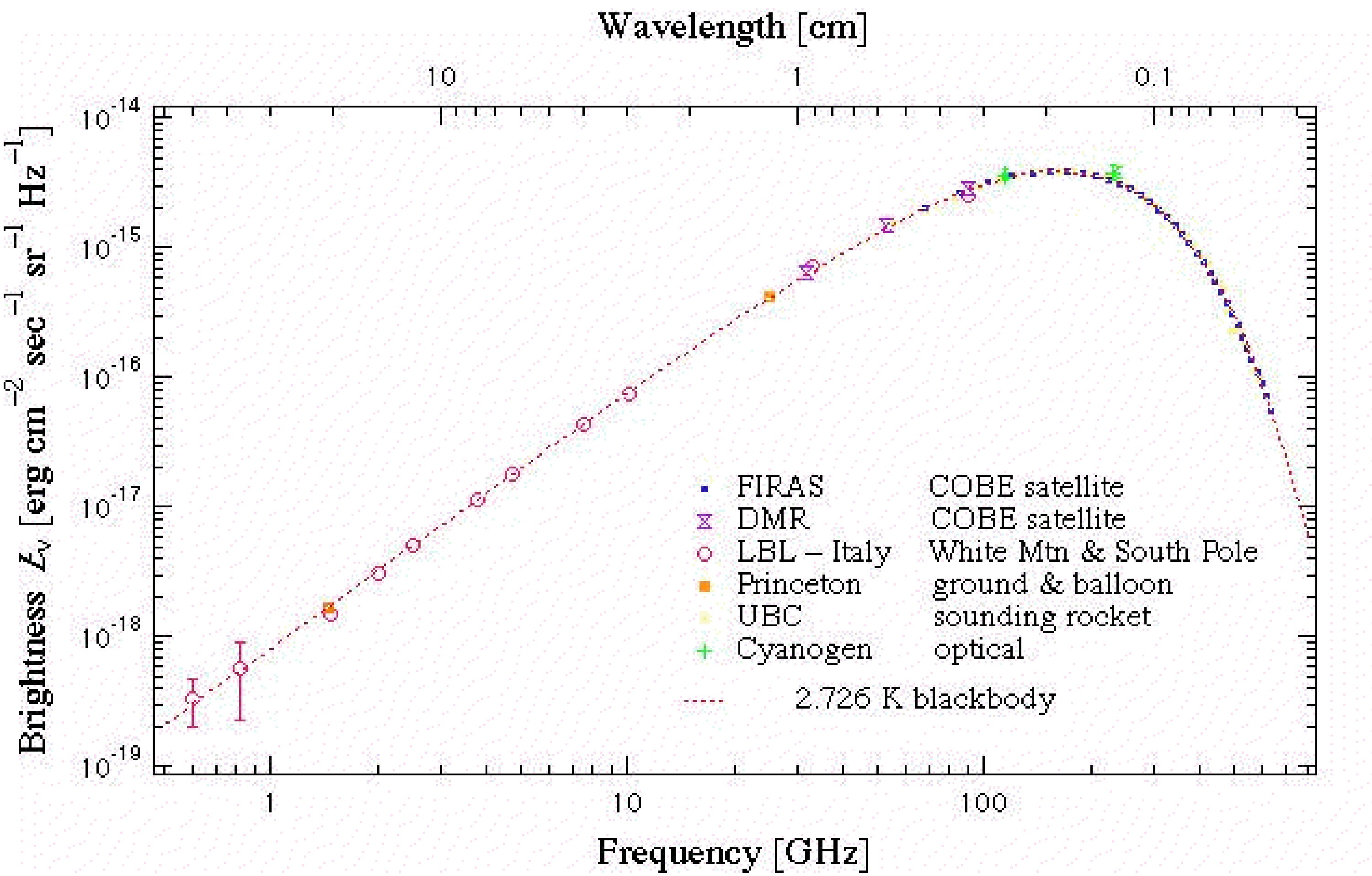
← Protons and Neutrons Form (10^{-10} sec)

← Quarks Differentiate (10^{-34} sec ?)

LHC probes physics relevant to the universe at age 10^{-14} sec.

CMB has a near perfect black body spectrum (T = 2.7K)

– measurements within 1% of theoretical spectrum



CMB very well understood – has provided precision data on key cosmological parameters.

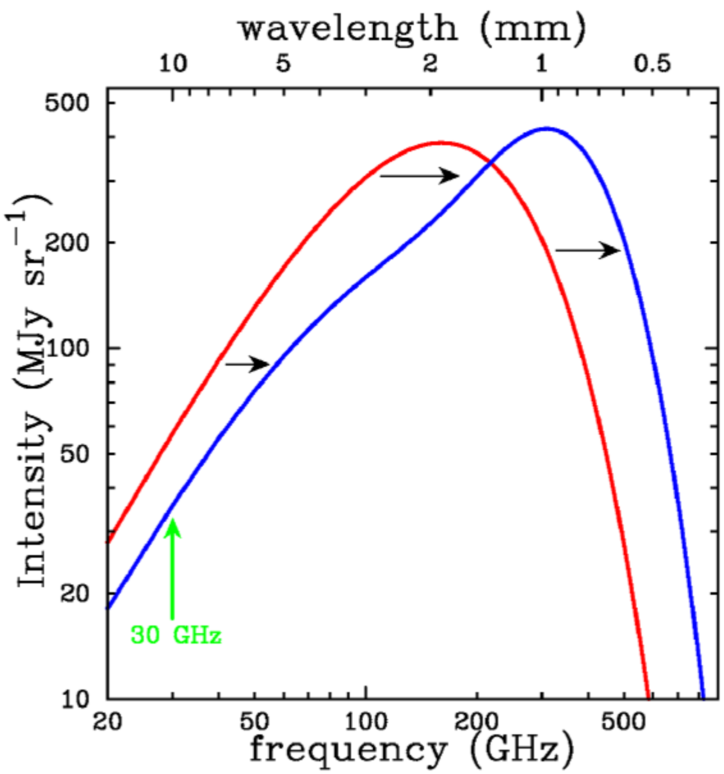
Today we use CMB as a tool:

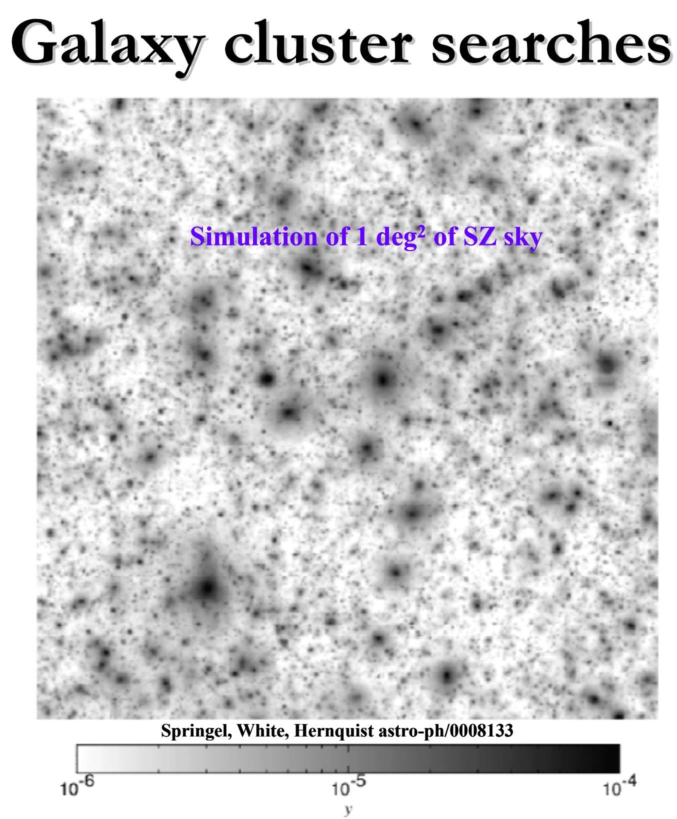
1. Map large-scale structure: use Sunyaev-Zel'dovich Effect in galaxy cluster search $\Rightarrow\ w,\ \Omega_m$

Inverse Compton scattering: Hot gas bound to clusters of galaxies scatters CMB

$\Rightarrow$ distorts black-body spectrum – shifts to higher frequencies:

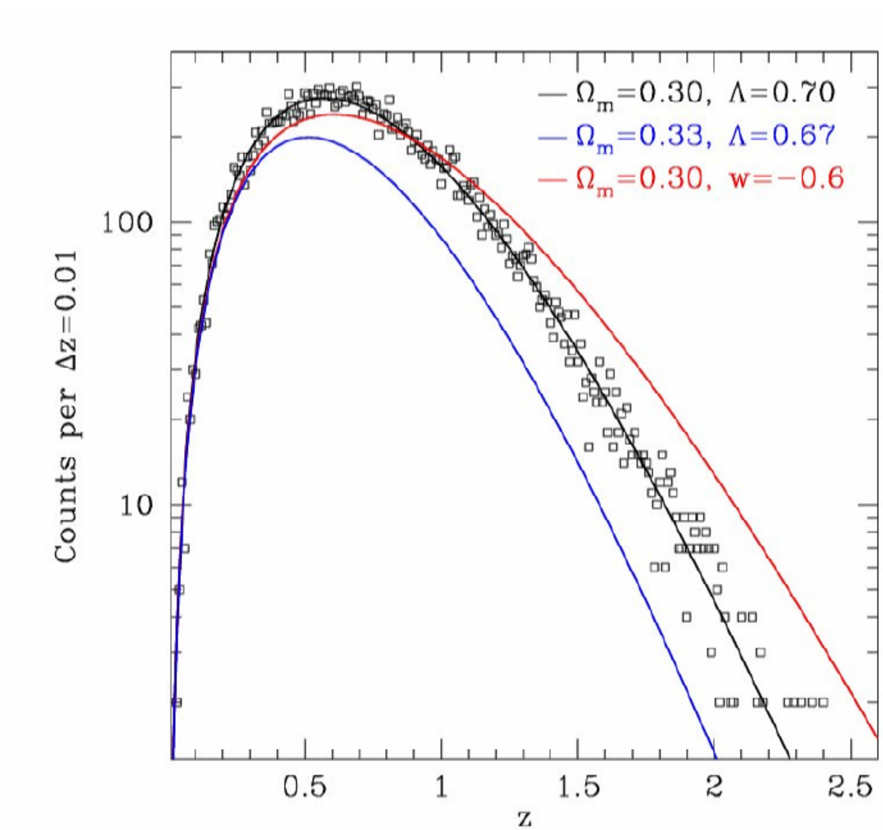
Clusters appear as dark spots in CMB sky

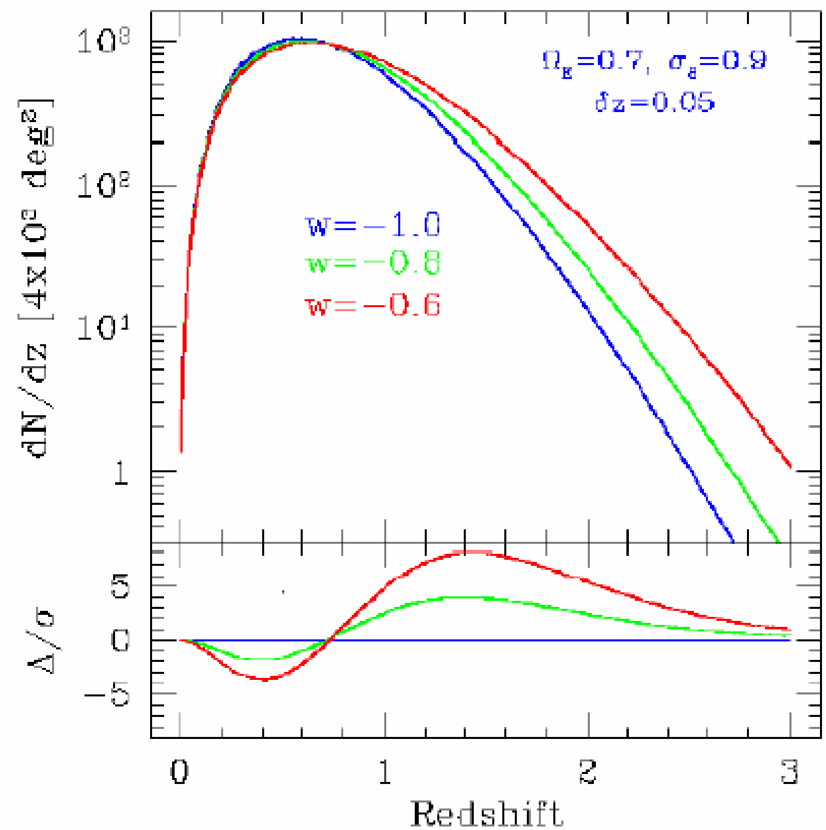




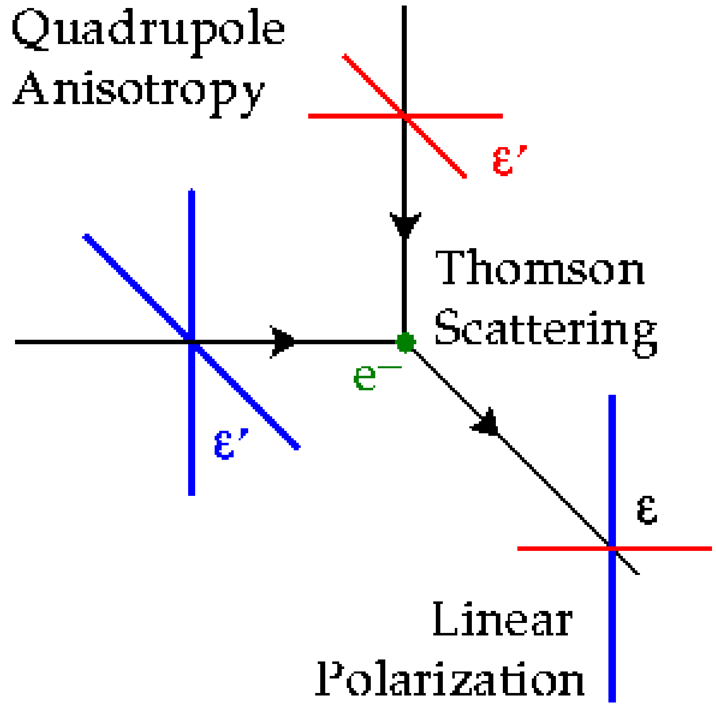
SZ Signal independent of redshift z!

Cluster densities at z > 1 sensitive to cosmological parameters





2. CMB Polarization



Thomson scattering ⇒ Polarization

If CMB were perfectly isotropic, all polarizations would occur equally

⇒ no net polarization.

However, CMB is anisotropic:

Quadrupole anisotropy yields net polarization.

⇒ patterns with no preferential handedness in polarization field ("E modes")

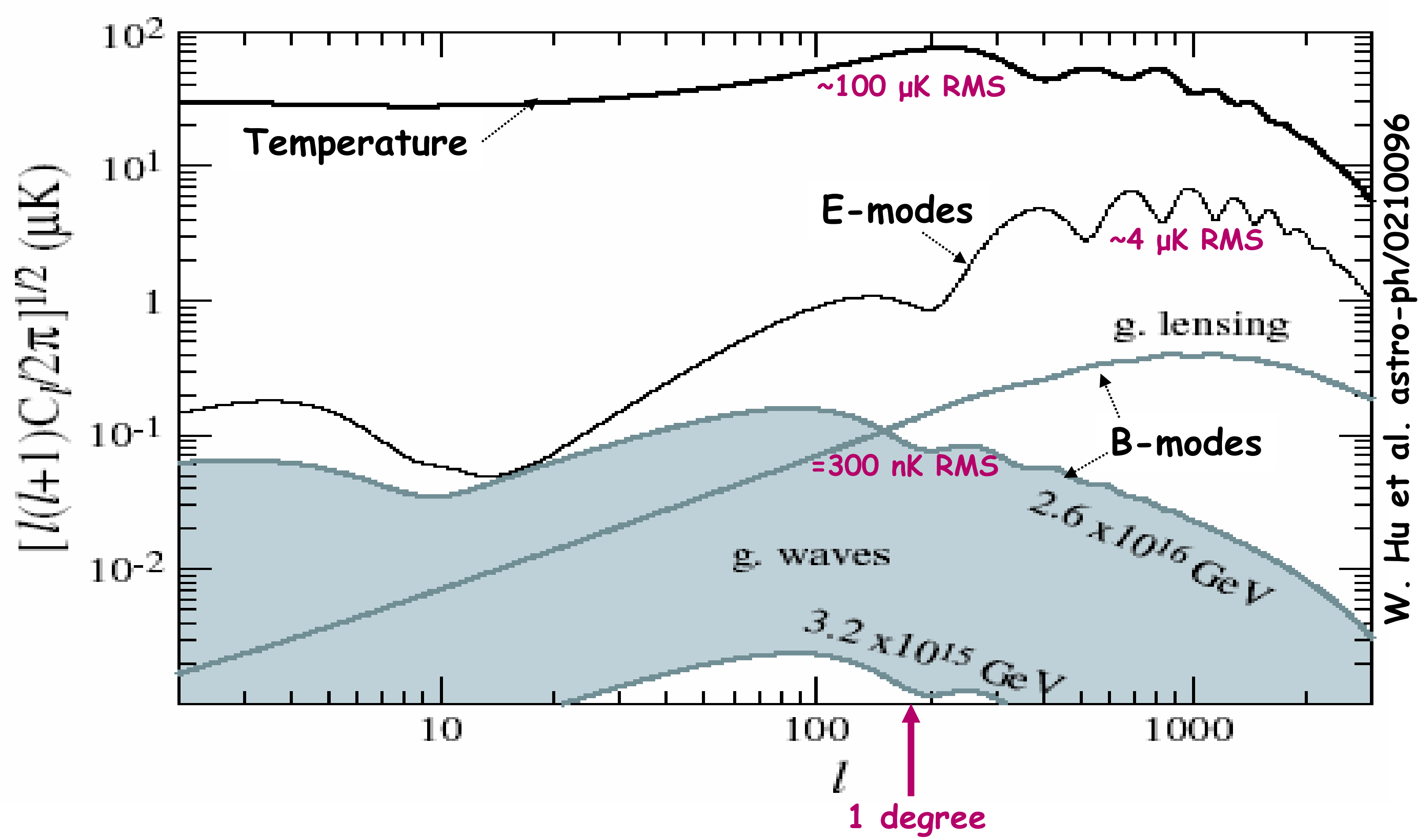
CMB Polarization allows us to look beyond the time of last scattering:

Gravity waves emitted during inflation (~10^{-38} s after Big Bang) interact with matter and leave imprint on surface of last scattering.

CMB temperature is image of matter distribution.

Gravity waves: tensor interaction ⇒ net curl in polarization field ("B-modes")
("smoking gun" of inflation)

Required Sensitivity



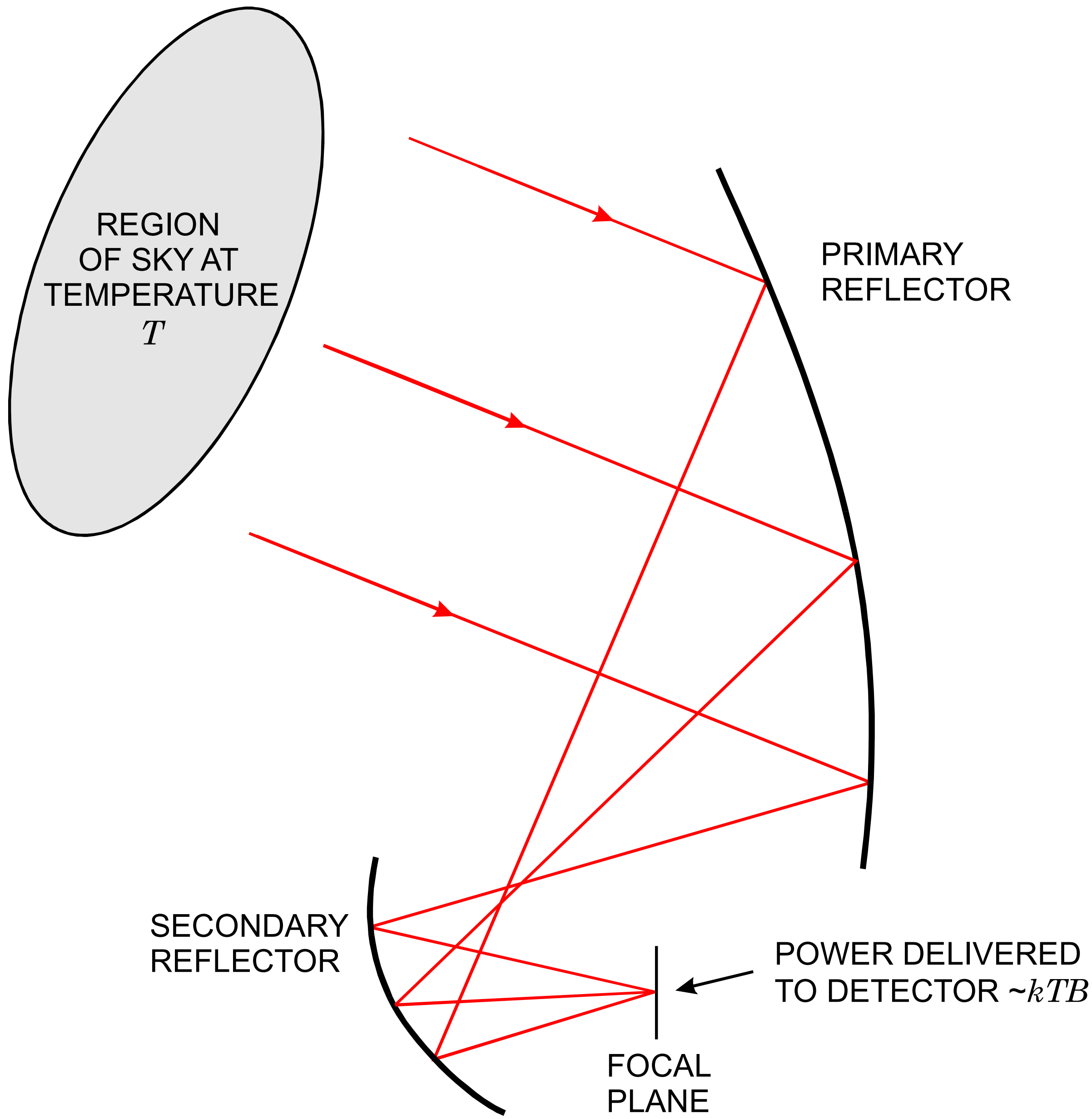
Magnitude of gravity wave signal set by **energy scale of inflation**

B-modes are also generated by weak lensing of E-mode polarization

Gravity wave signature and lensing have different angular scales

Requires 3m reflector to provide angular resolution.

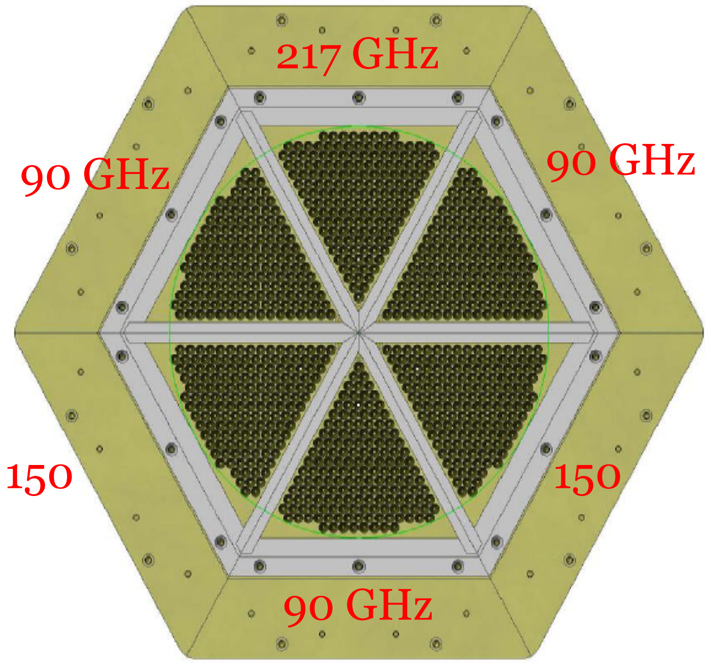
DETECTED SIGNAL

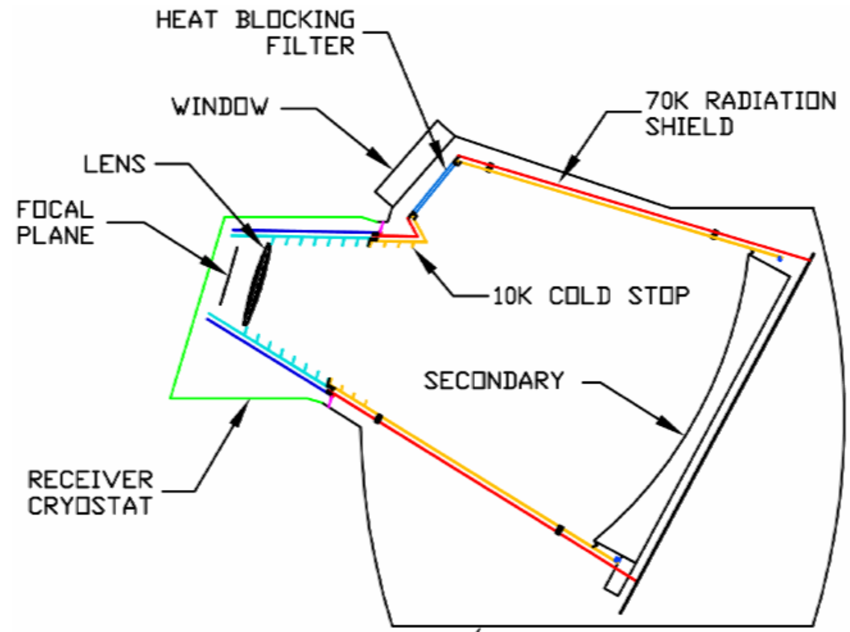


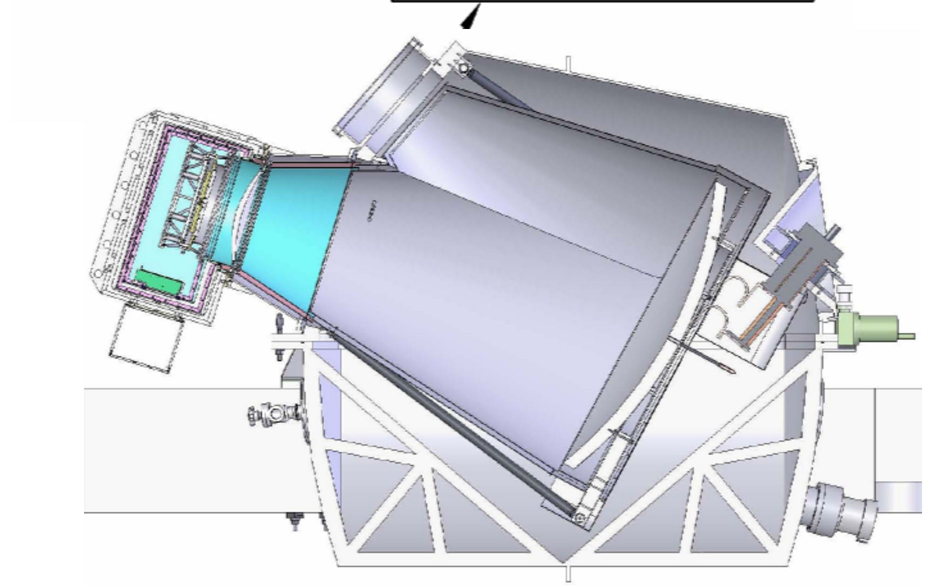
- View region of sky with temperature T
  (CMB: $T \approx$ 3K)

- Measured signal proportional to kTB
  (B = bandwidth)

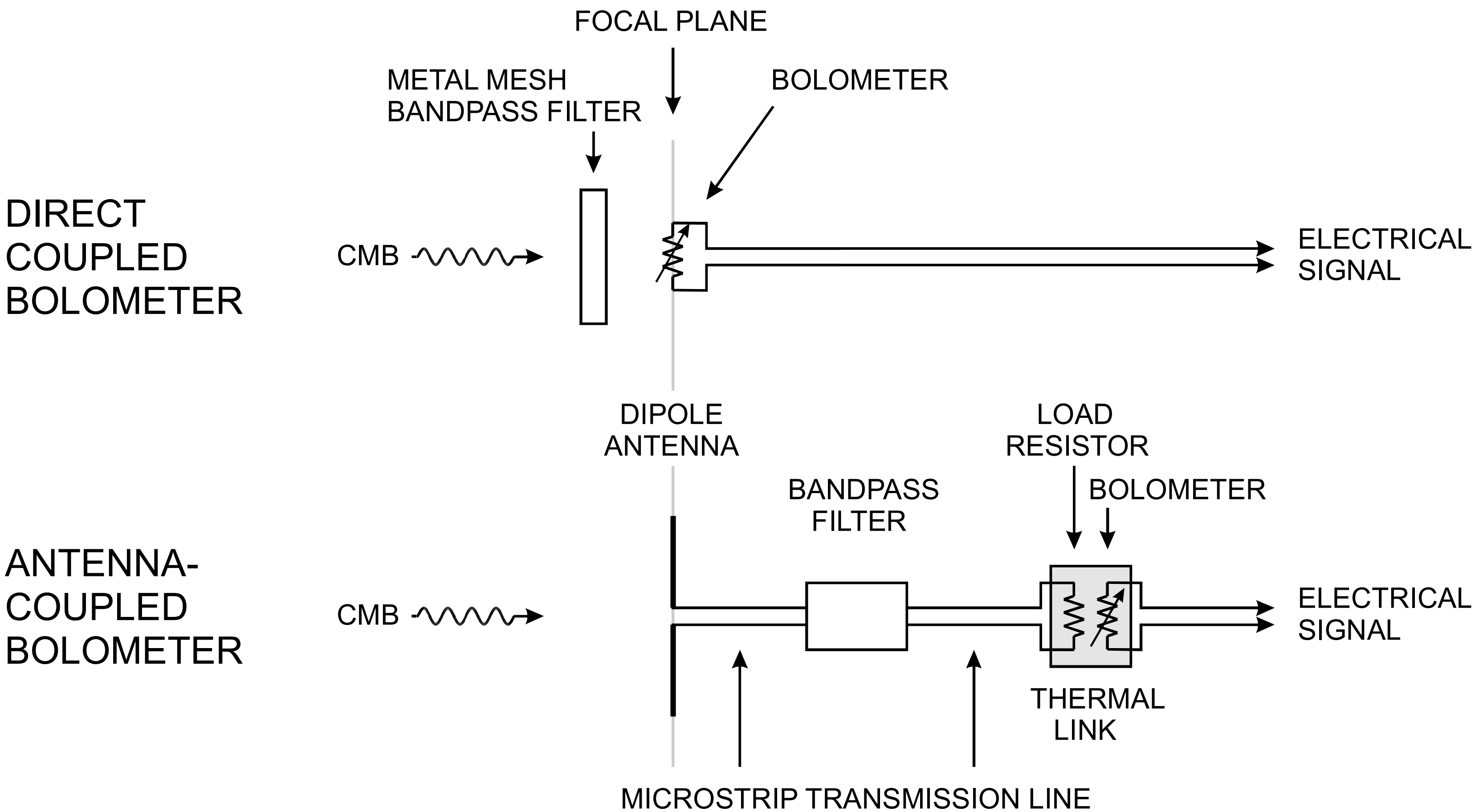
Example Optics and Focal Plane (South Pole Telescope)







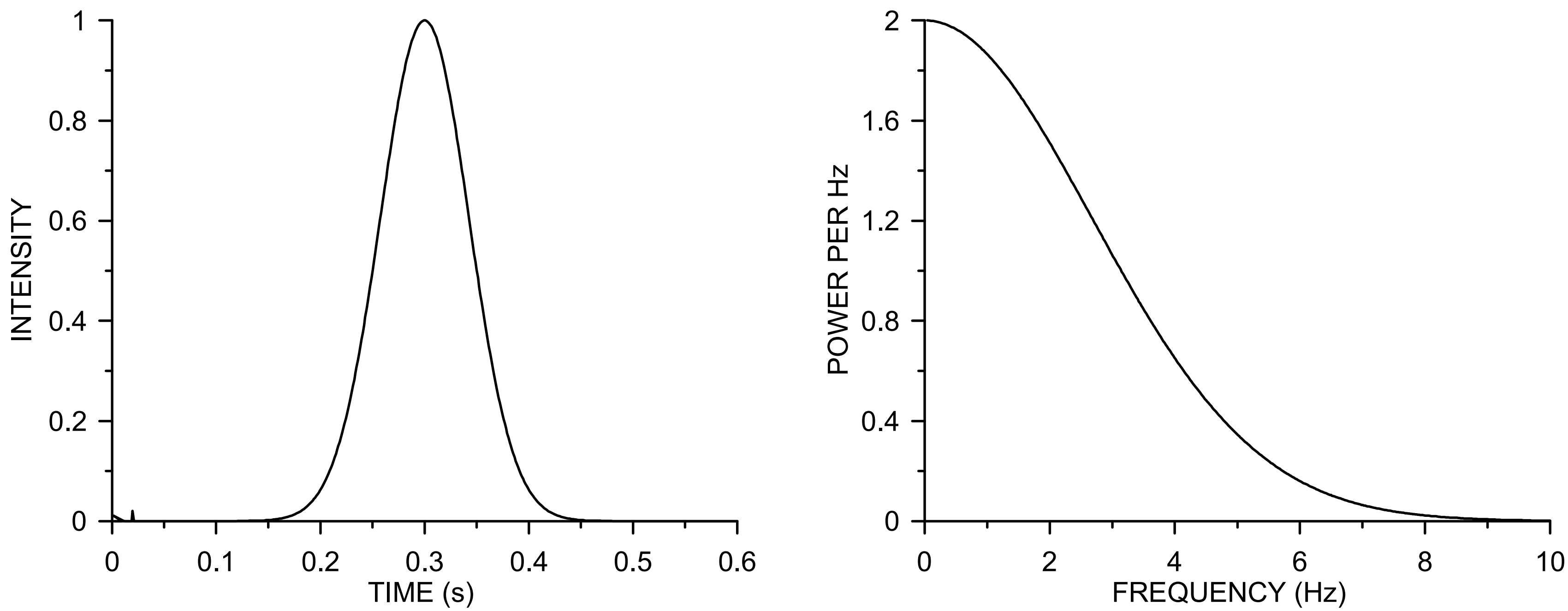
COUPLING TO BOLOMETER



Antenna-coupling provides inherent polarization sensitivity.

Signal Spectrum in Galaxy Cluster Search

Antenna beam width: 1' FWHM Scan speed: 10'/s



(W. Lu, CWRU)

$\Rightarrow$ Maintain Gain Stability + Noise Level down to ~0.1 Hz

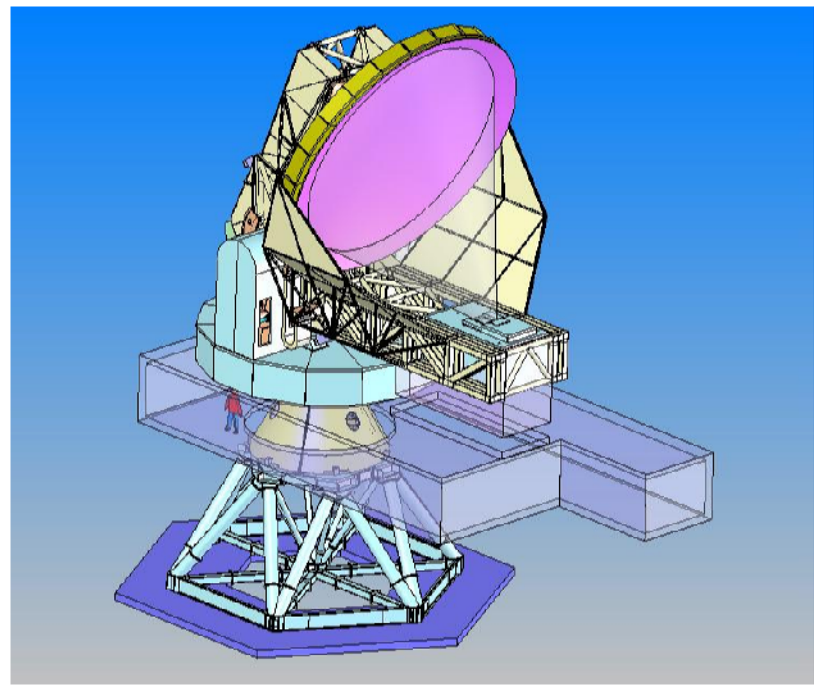
Some Next Generation Experiments:

1. Cluster Searches: APEX-SZ UCB, LBNL, MPIfR, Colorado, McGill

South Pole Telescope Univ. Chicago, UCB, LBNL, CWRU, CfA, Colorado, McGill, Univ. Illinois

APEX
(Atacama Plateau, Chile, 5000m)
~300 pixels

South Pole Telescope
(Installation: 2006-2007)
~1000 pixels



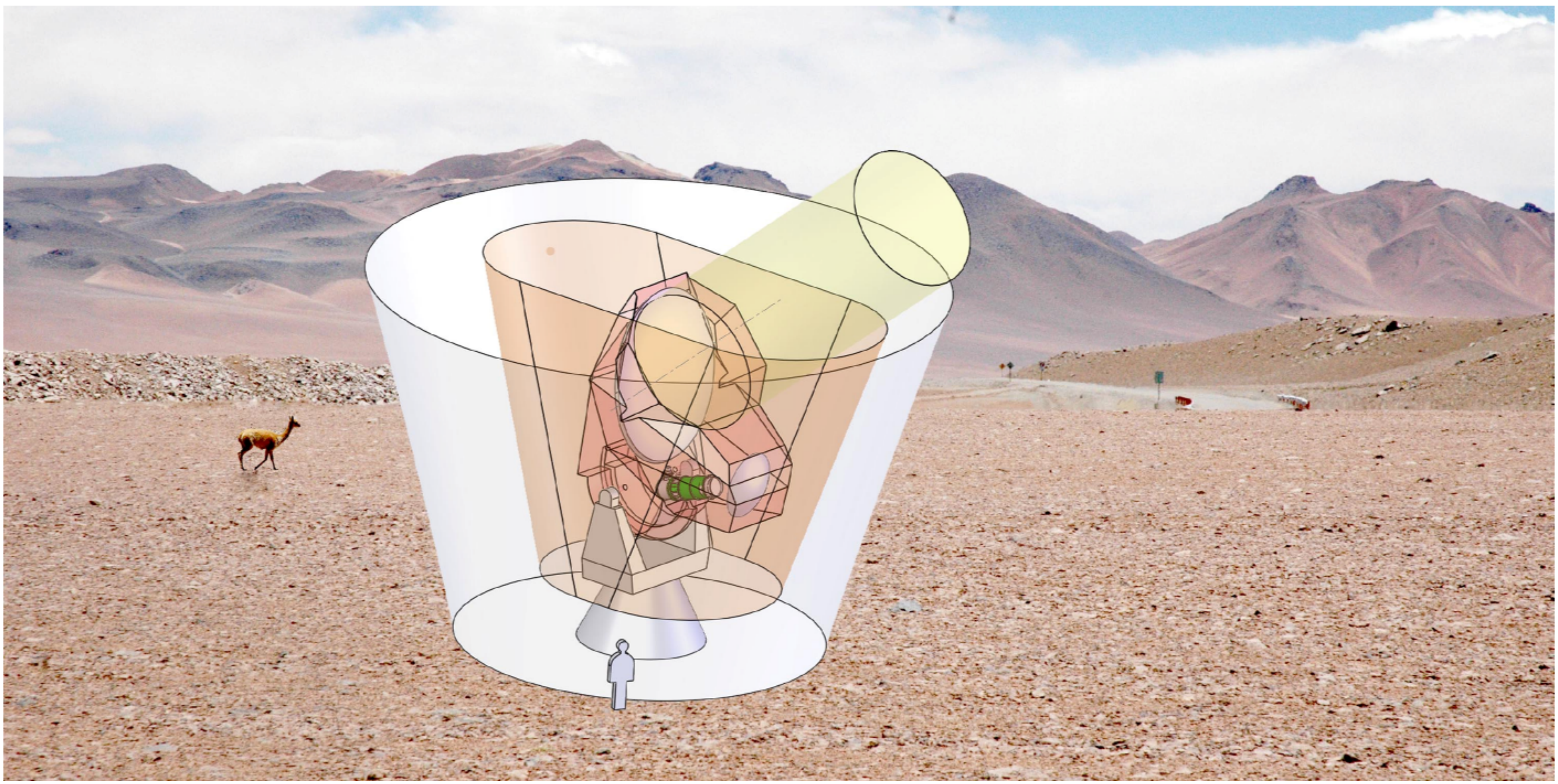
2. Polarization & Inflation: PolarBear (UCB, LBNL, UCSD, Colorado, McGill)

Reviewed by SAGENAP, proposal to DoE and NSF

Atacama plateau (Chilean Andes, 5000 m altitude)

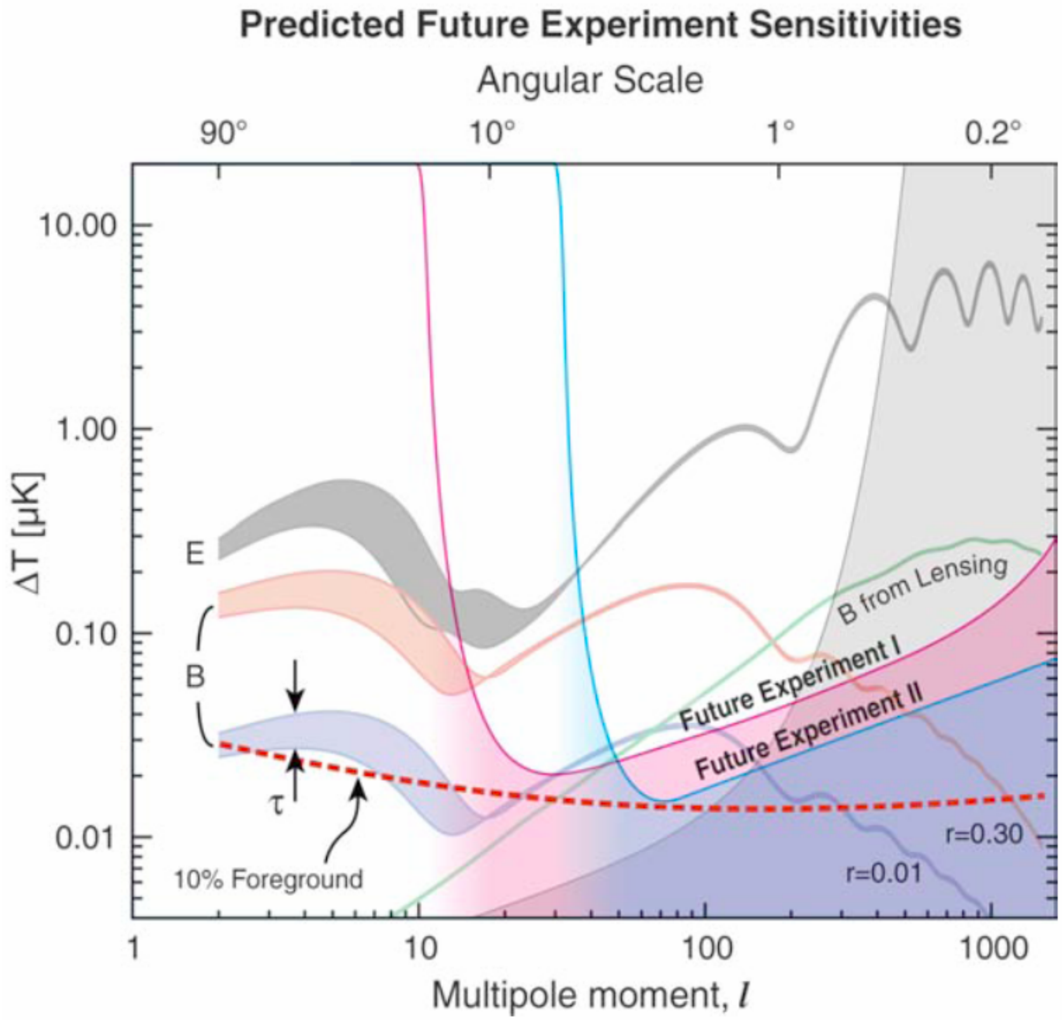
~1000 dual polarization pixels

3m telescope: angular resolution to separate gravitational from lensing B-modes



PolarBear designed from ground up to optimize polarization measurements

⇒ Minimize cross-polarization and instrumental polarization
Sensitivity and resolution to separate E and B modes



PolarBear performance similar to Experiment I

from Interagency Task Force on CMB Research ("Weiss Committee")

All of these experiments require a major step up in sensitivity

Bolometers today are so sensitive that we are limited by the shot noise of the CMB photons

Increase sensitivity by

performing many measurements simultaneously

$\Rightarrow$ bolometer arrays (100s to 1000s)

extending observation time

$\Rightarrow$ ground-based experiments
eventually space-based

Bolometer array technology:

Wafer-scale monolithic fabrication ("radiometer on a chip")

Cold multiplexing on 0.25K stage (reduce heat leaks through wiring)

Cryogen free system: pulse tube cooler + $^4He/^3He/^3He$ sorption fridge
(remote operation with minimal on-site staff)

Berkeley Bolometer Group

William Holzapfel (UCB)
Adrian Lee (LBNL,UCB)
Paul Richards (UCB)
Helmuth Spieler (LBNL)

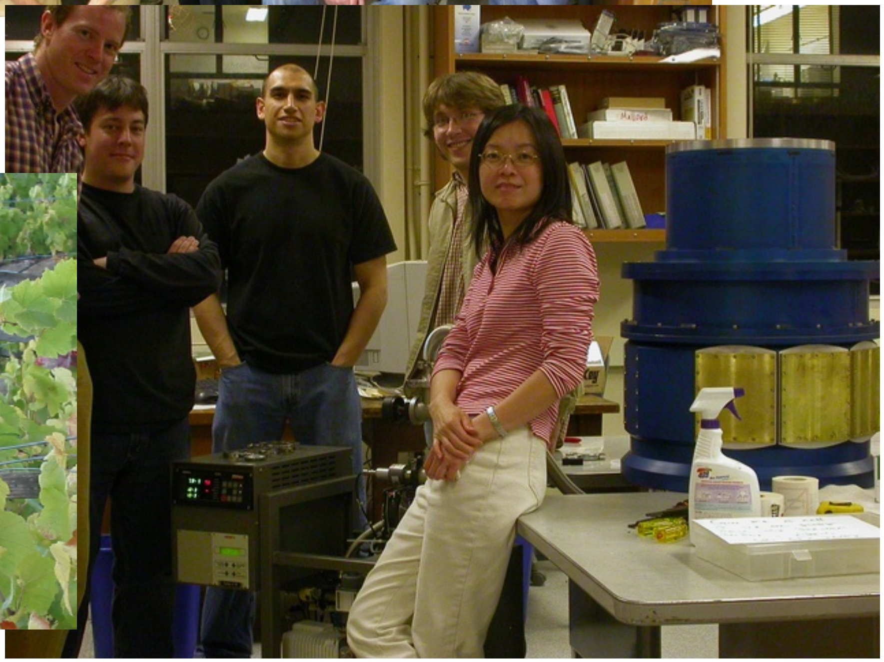
John Clarke (LBNL,UCB) SQUIDs

Greg Engargiola (UCB RAL)
John Joseph (Eng. Div. LBNL)
Chinh Vu (Eng. Div. LBNL)

Brad Benford (UCB)
H.-M. “Sherry” Cho (UCB)
Matt Dobbs (LBNL – now McGill Univ.)
Nils Halverson (UCB – now Univ. Colorado)
Huan Tran (UCB SSL)

+ 15 graduate students

Funding: NSF, NASA, DoE



Bolometers

Superconducting transition edge sensors:

- Bias thin film superconductor at transition from super- to normal conducting

⇒ Large change in resistance with absorbed power

- Operate with constant voltage bias

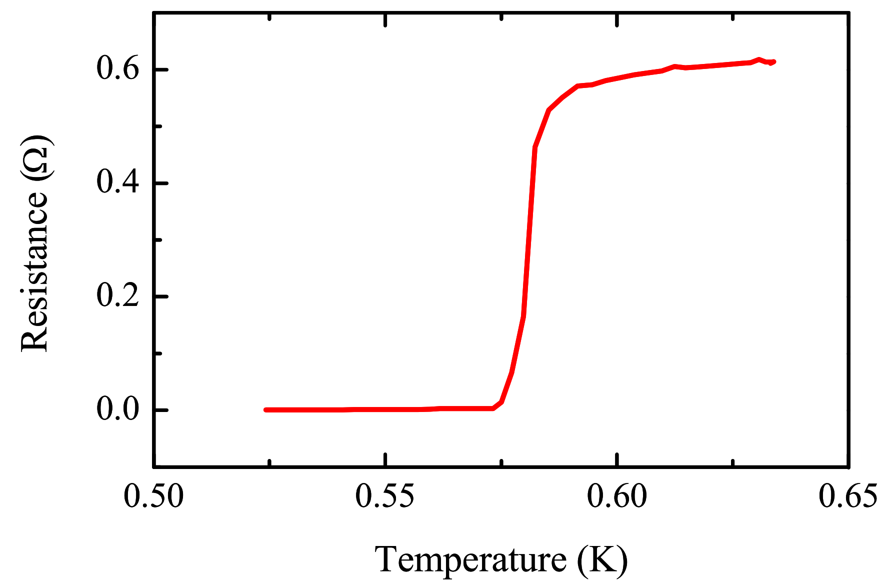
⇒ Electrothermal negative feedback

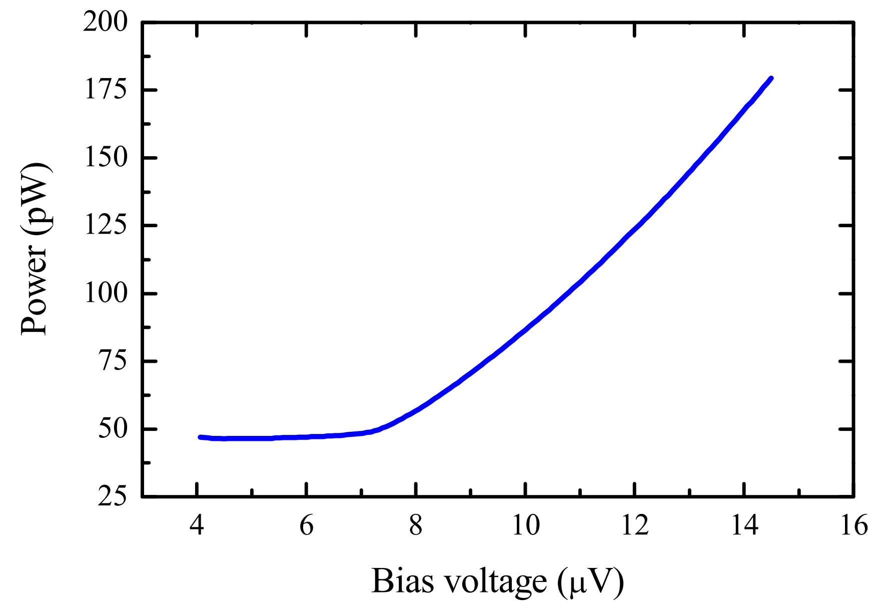
⇒ Stabilize operating point + predictable response

⇒ "Constant power operation": Change in absorbed power is balanced by change in electrical power: $\Delta I / \Delta P = 1 / V_{bias}$

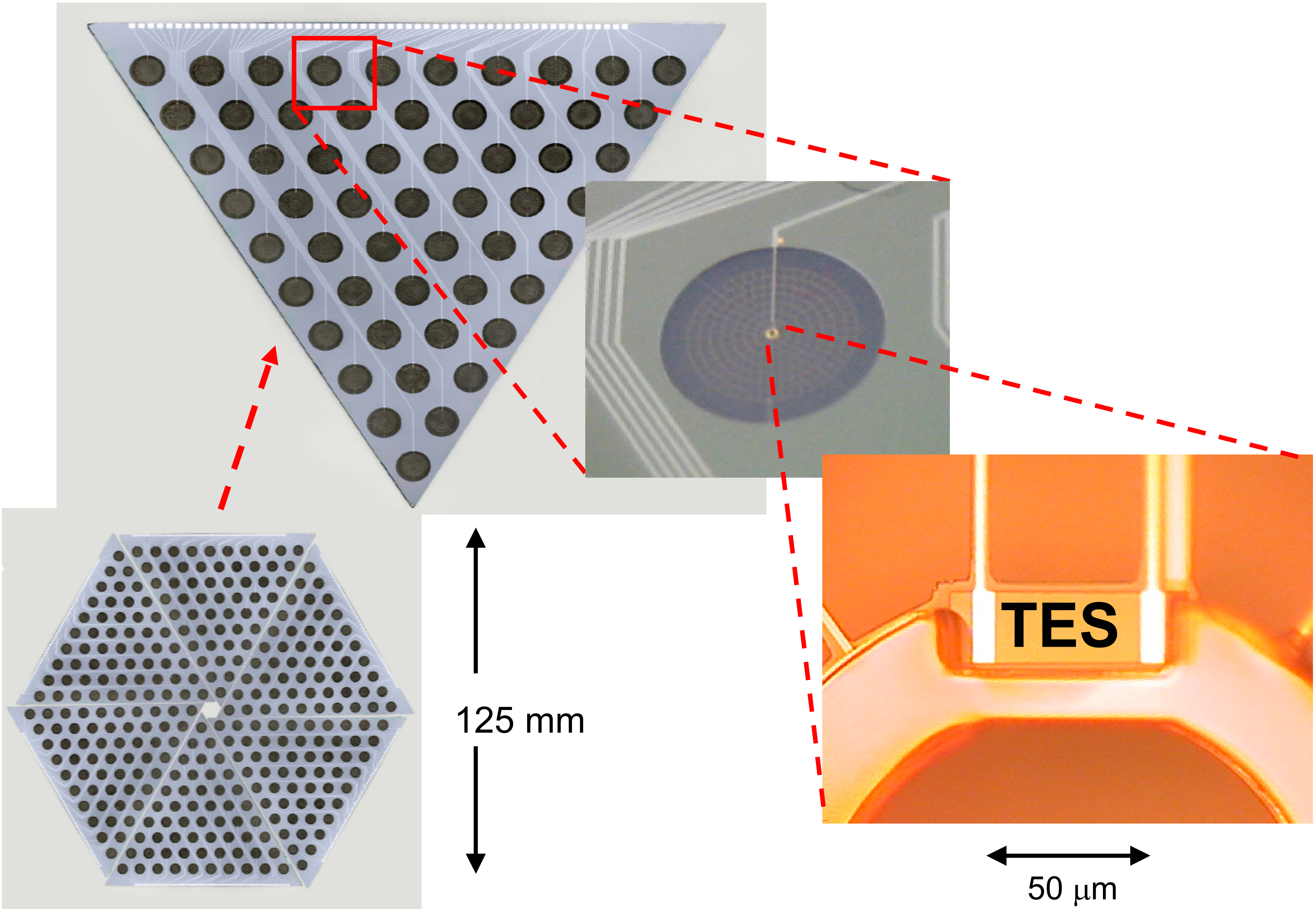
- High-frequency bias

⇒ Greatly reduced sensitivity to microphonics

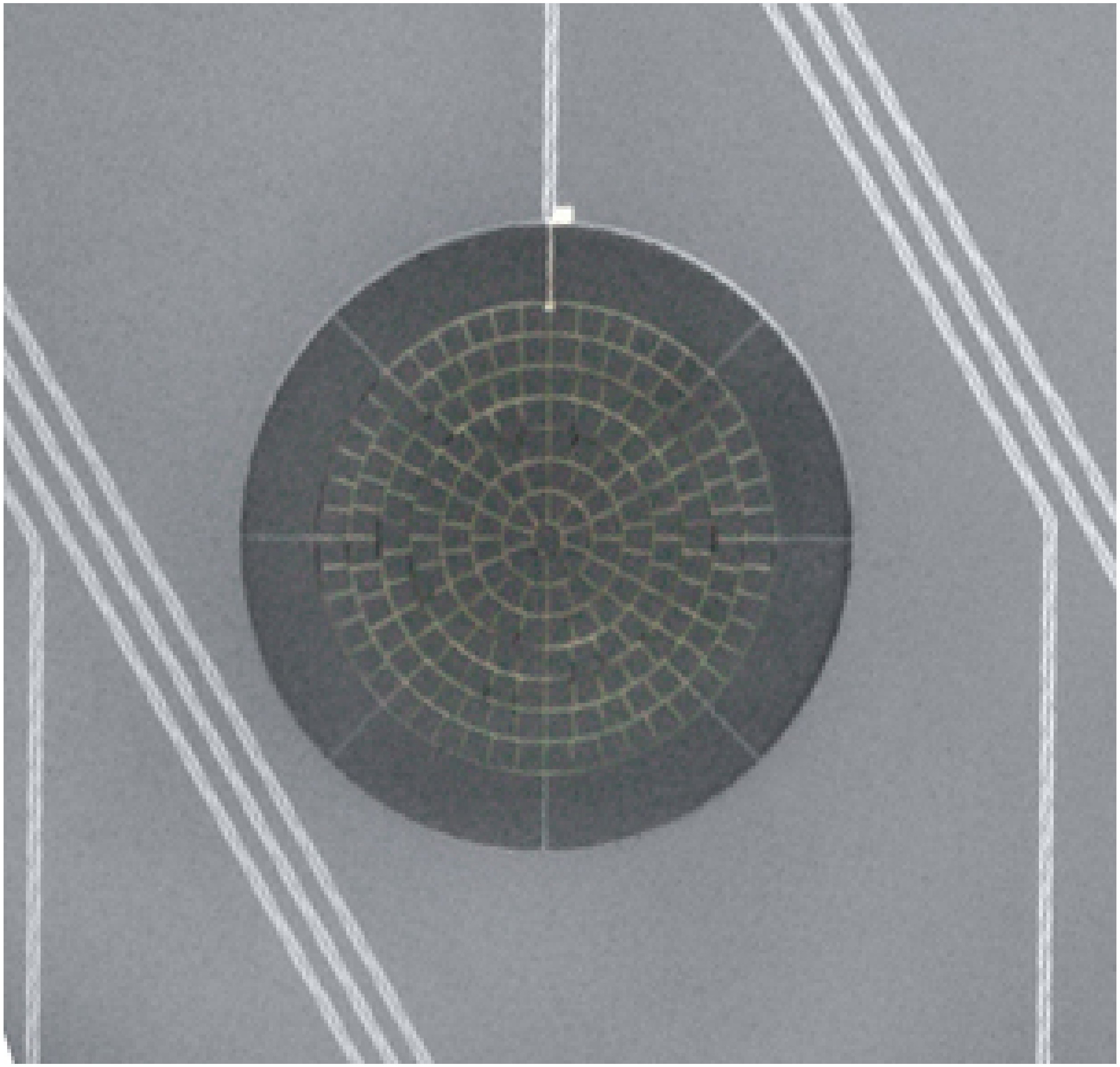




APEX Focal Plane



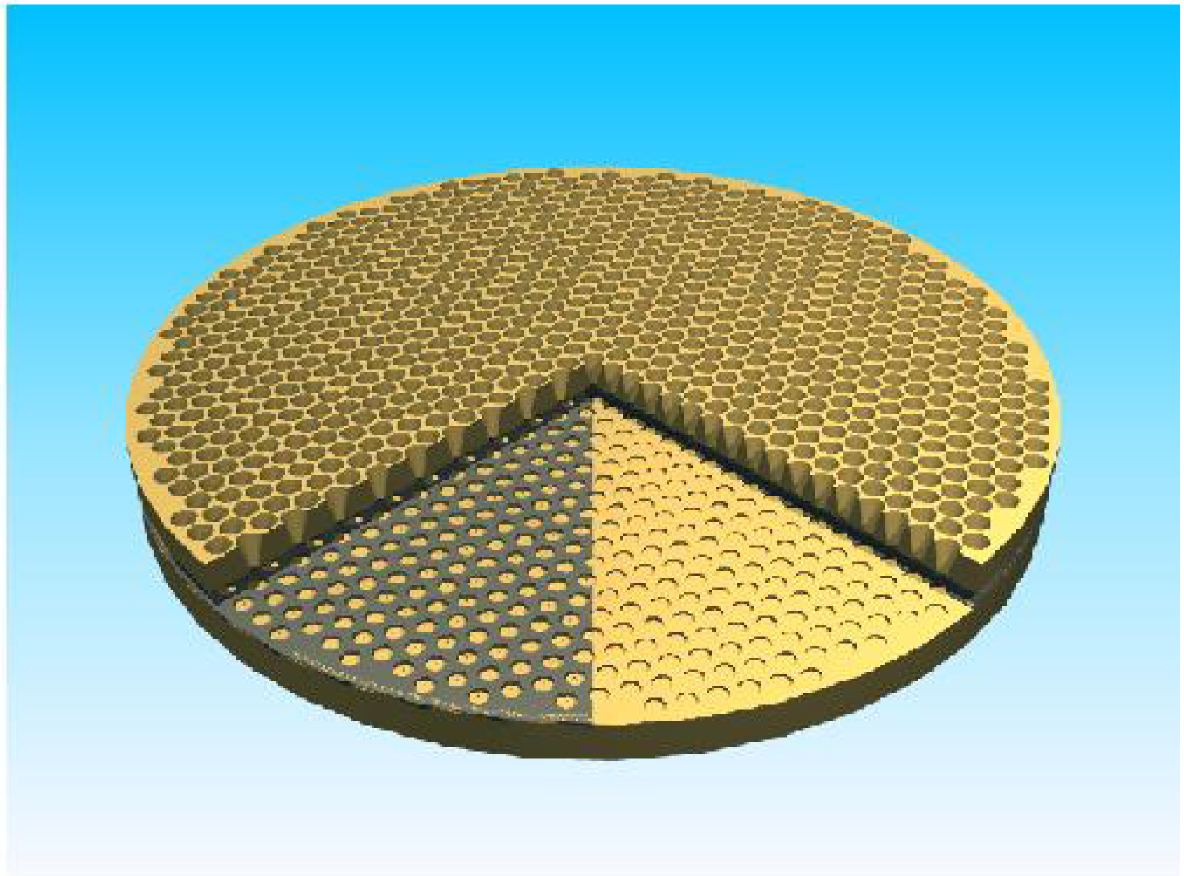
Close-up of spiderweb bolometer



Focal Plane Design for APEX-SZ and SPT

Disk with machined conical horns positioned above bolometer arrray.

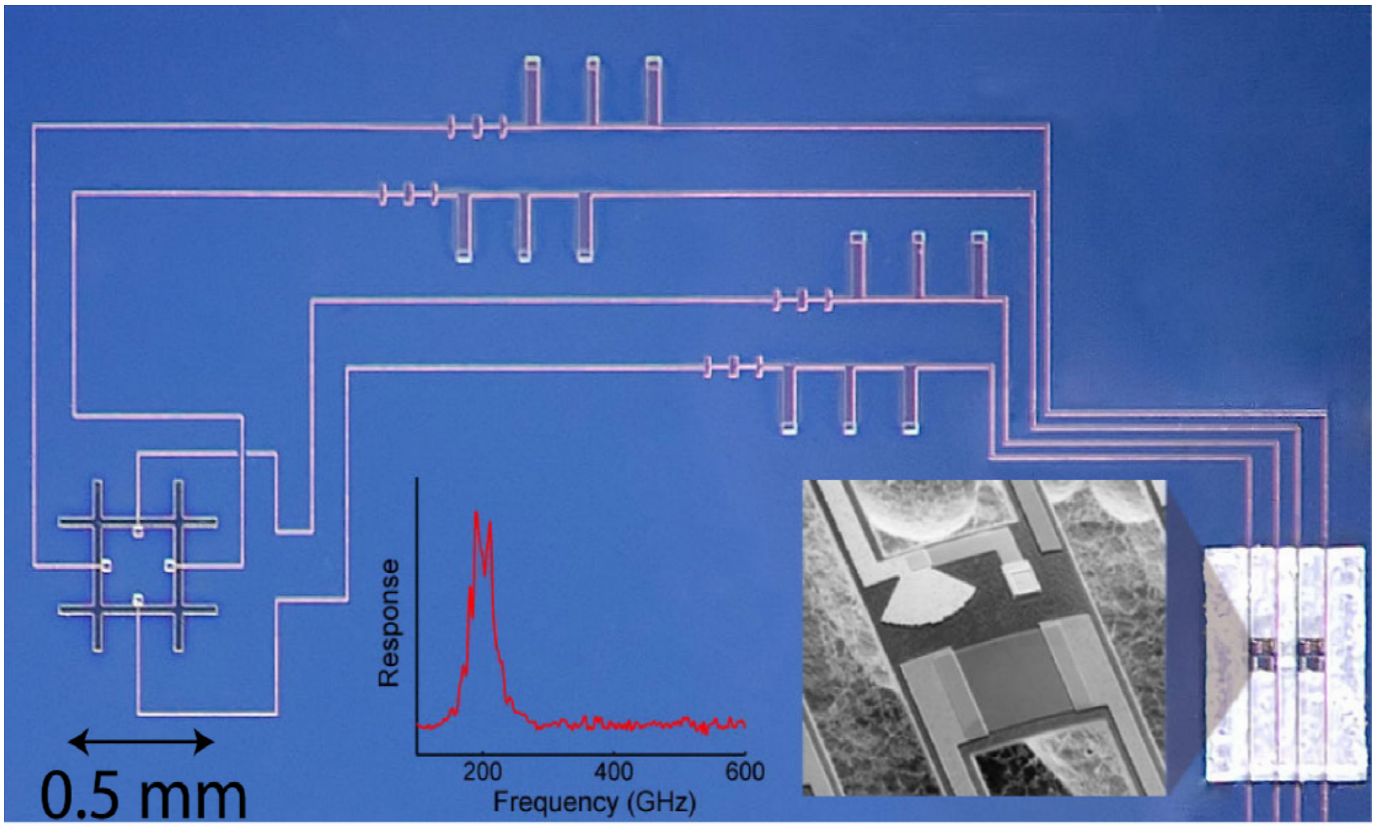
Horns match optics to bolometer plane.



Antenna-Coupled Prototype Pixel (Mike Myers)

Microstrip
Transmission Lines

Bandpass Filters (217 GHz, 40% BW)

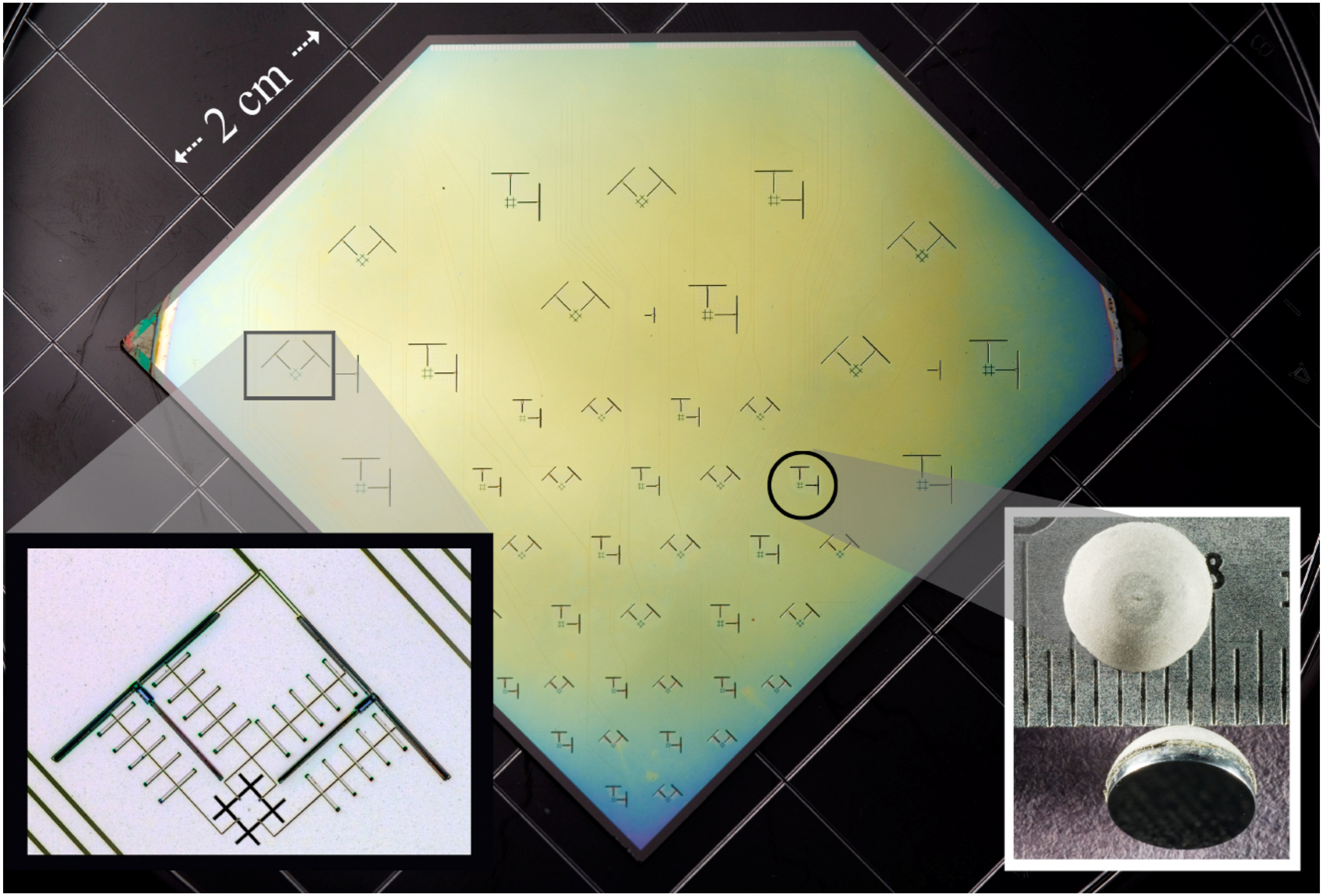


Microstrip terminated on a Si-nitride suspension.

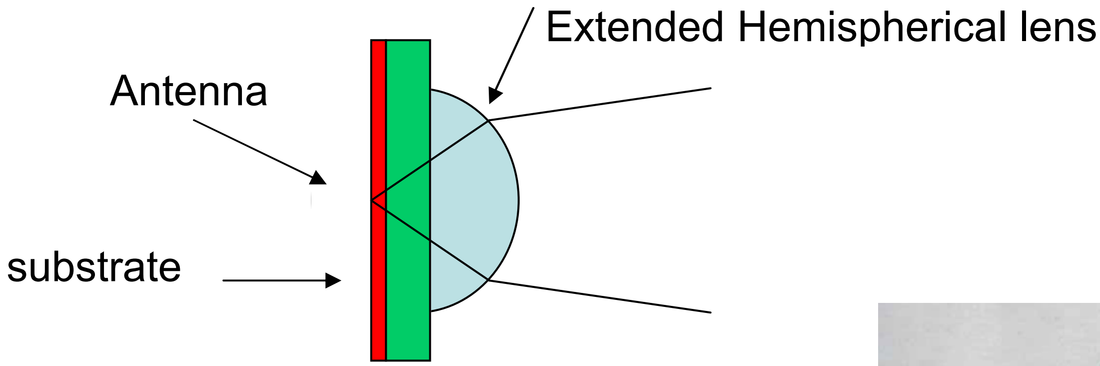
Power measured with TES

Double-Slot Dipole Antenna

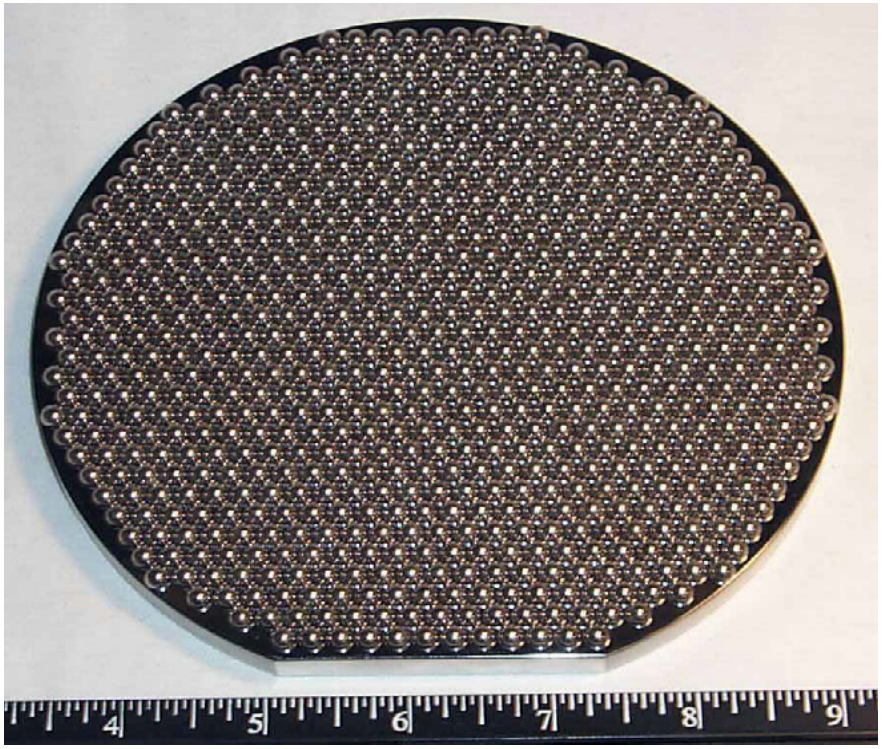
PolarBear Array Segment (Kam Arnold) – 90, 150, 220 GHz bands



Antenna Coupling to Optics by Dielectric (Si) Lenses

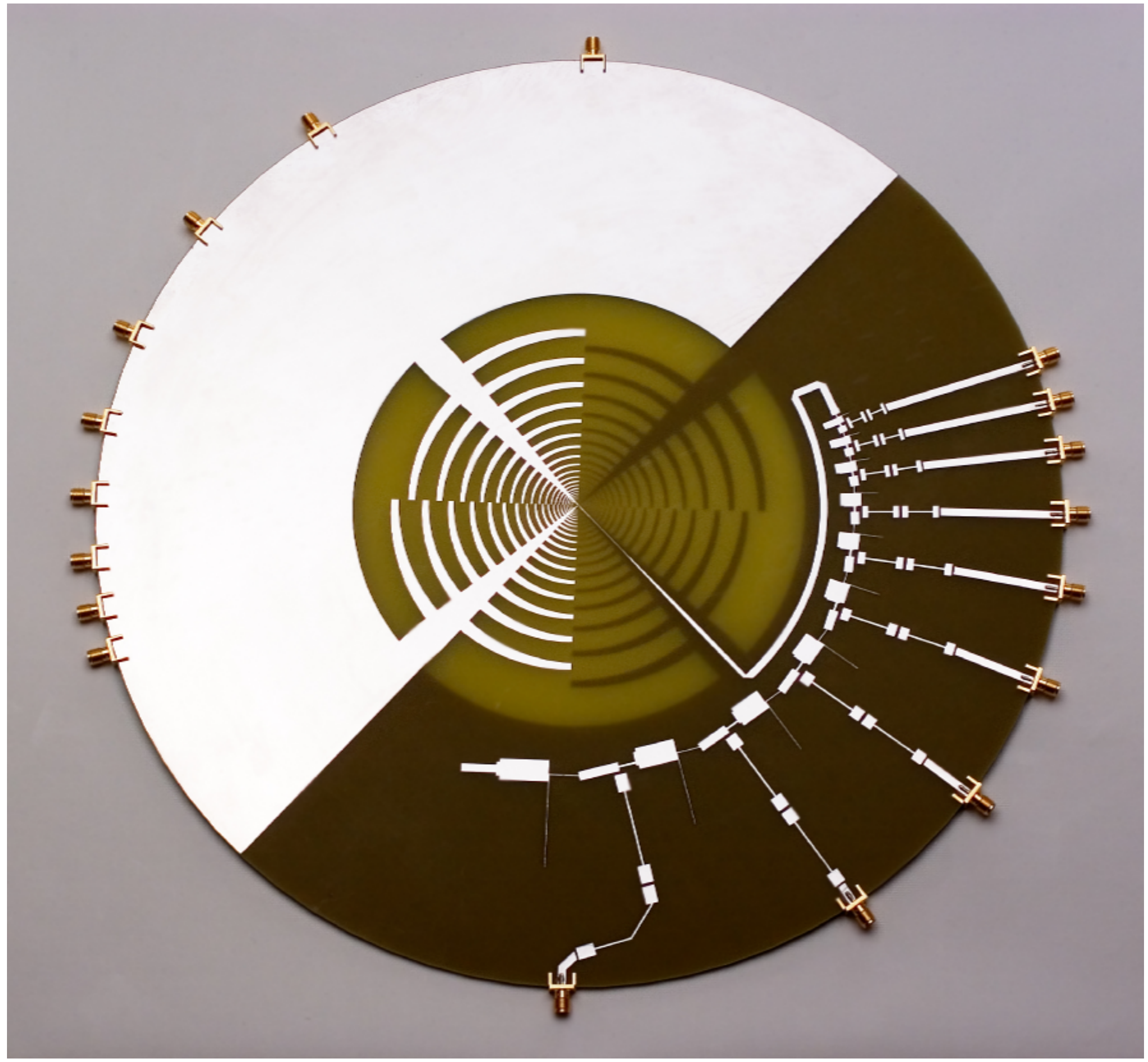


- Well developed (SIS mixers, etc.)
- High antenna gain, symmetric beam
- Forward radiation pattern
- Efficient coupling to telescope
  (similar to scalar horn)
- Complete pixel fits beneath lens
- Stycast AR coating
- Broadband for multichroic pixels



Future Development: Wideband Polarization-Sensitive Antenna + "Channelizer"
$\Rightarrow$ Multi-Frequency Pixel

GHz Scale Model:



THz pixel with 3 bands currently in fab

(Roger O'Brient + Greg Engargiola)

Readout

- Constant voltage bias requires that readout impedance $\ll$ bolometer resistance

  bolometer resistance $\approx 1\ \Omega$

  bias resistance $\approx 20\ \mathrm{m}\Omega$

  amplifier input impedance $\approx 10\ \mathrm{m}\Omega$

  1st amplifier stage: SQUID at 4K in shunt feedback configuration.
  High-frequency feedback loop includes SQUID +
  warm electronics (300K).

- Typical bolometer bias power: 10 – 40 pW
- Power Budget on 0.25K stage: <10 μW
- Heat conduction through wires to 4K stage acceptable up to ~300 bolometers

  $\Rightarrow$ Larger arrays require multiplexing

- Novel development:

  Frequency-Domain MUX with ZERO additional power on cold stage

Principle of Frequency-Domain Multiplexing

1. AC bias bolometers (~100 kHz – 1 MHz)

   Each bolometer biased at different frequency

2. Signals change sensor resistance

   ⇒ Modulate current

   ⇒ Transfer signal spectrum to sidebands adjacent to bias frequency

   ⇒ Each sensor signal translated to unique frequency band

3. Combine all signals in common readout line

4. Retrieve individual signals in bank of frequency-selective demodulators

Modulation Basics

If a sinusoidal current $I_0 \sin\omega_0 t$ is amplitude modulated by a second sine wave $I_m \sin\omega_m t$

$$I(t) = (I_0 + I_m \sin\omega_m t)\sin\omega_0 t$$
$$I(t) = I_0 \sin\omega_0 t + I_m \sin\omega_m t \sin\omega_0 t$$

Using the trigonometric identity $2\sin\alpha\sin\beta = \cos(\alpha-\beta) - \cos(\alpha+\beta)$ this can be rewritten

$$I(t) = I_0 \sin\omega_0 t + \frac{I_m}{2}\cos(\omega_0 t - \omega_m t) - \frac{I_m}{2}\cos(\omega_0 t + \omega_m t)$$

The modulation frequency is translated into two sideband frequencies

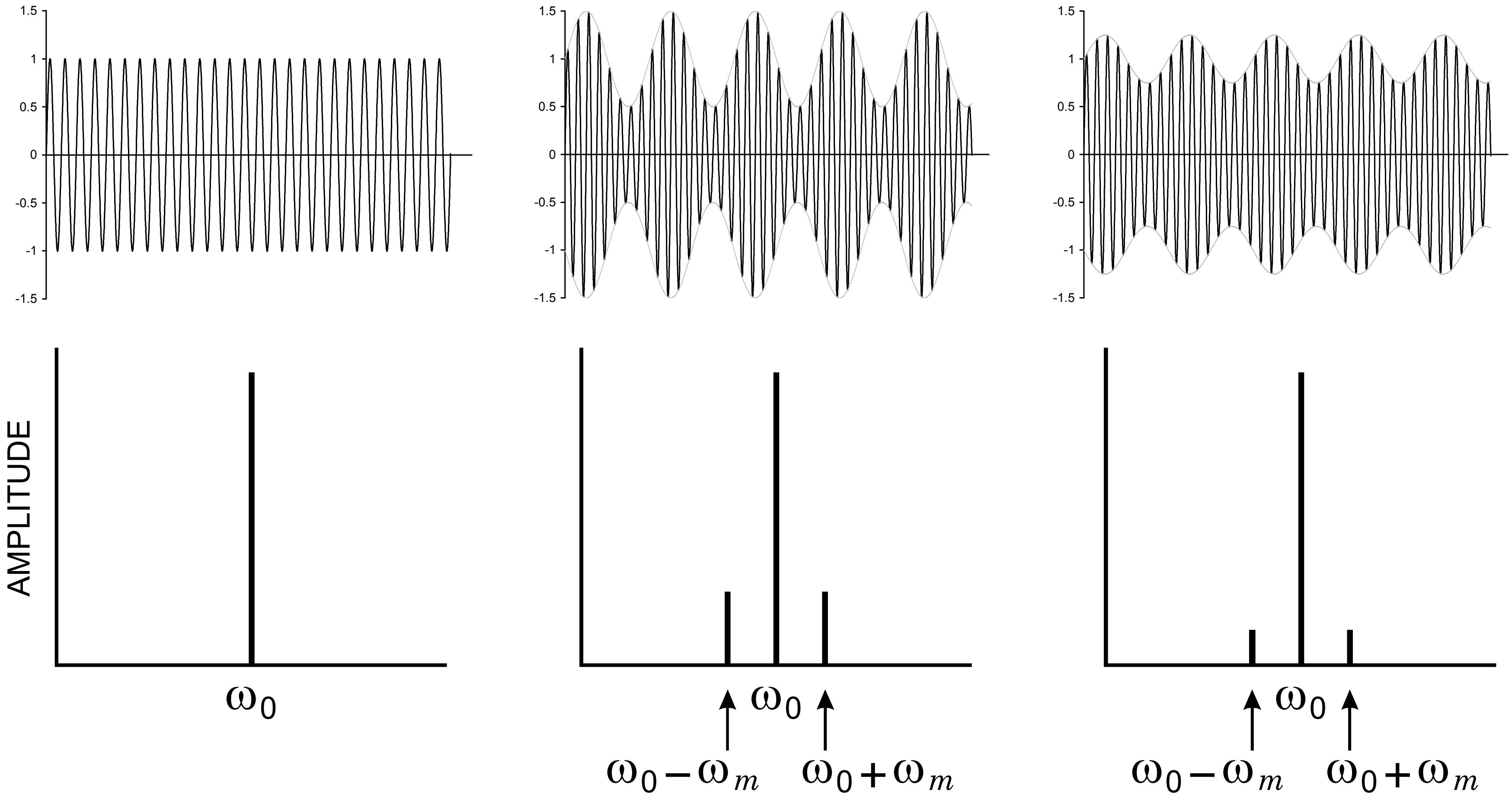
$(\omega_0 t + \omega_m t)$ and $(\omega_0 t - \omega_m t)$

symmetrically positioned above and below the carrier frequency ω_0.

All of the information contained in the modulation signal appears in the sidebands; the carrier does not carry any information whatsoever.

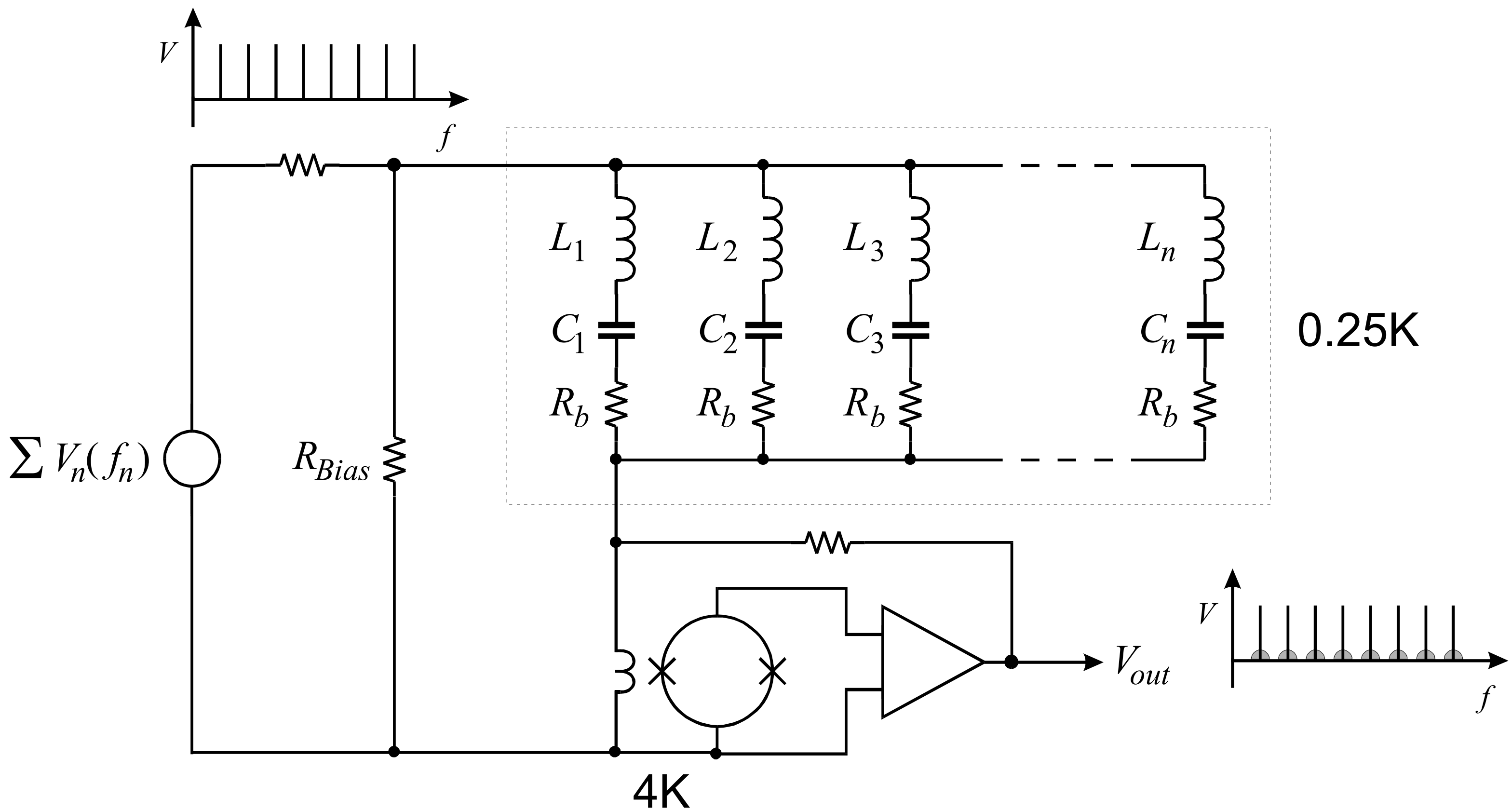
The power contained in the sidebands is equal to the modulation power, distributed equally between both sidebands.

Modulation Waveforms and Spectra



Carrier amplitude remains constant! All signal information in the sidebands.

MUX circuit on cold stage



- "Comb" of all bias frequencies fed through single wire.
- Tuned circuits "steer" appropriate frequencies to bolometers and limit noise bandwidth.
- Wiring inductance tuned out at resonance to reduce impedance.
- Current return through shunt-fedback SQUID amplifier (low input impedance).
- No additional power dissipation on cold stage (only bolometer bias power).

Demodulation

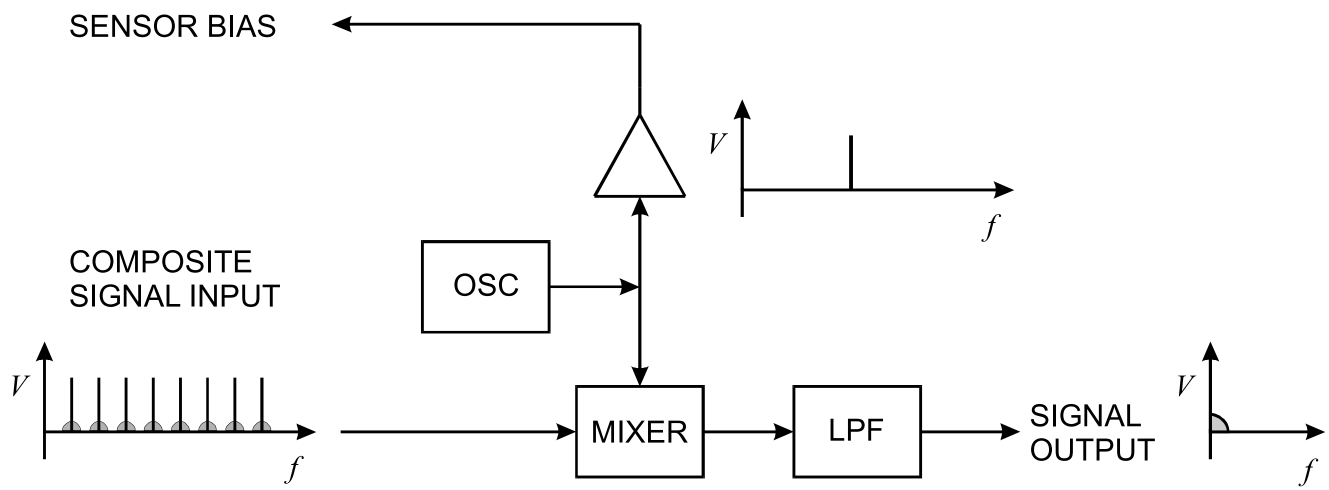
The same carrier signal that biases the sensor is used to translate the sideband information to baseband.

The mixer acts analogously to a modulator, where the input signal modulates the carrier, forming both sum and difference frequencies.

In the difference spectrum the sidebands at $f_n \pm \Delta f_S$ are translated to a frequency band

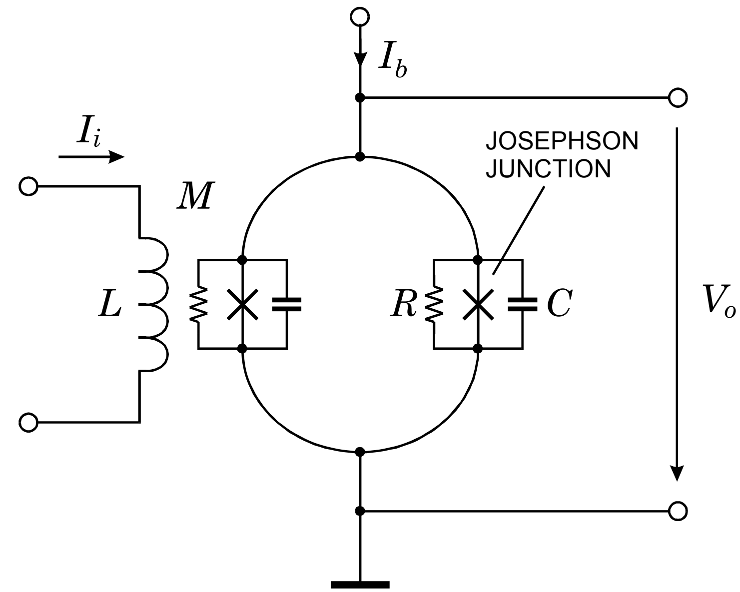
$$f_n - (f_n \pm \Delta f_S) = 0 \pm \Delta f_S .$$

A post-detection low-pass filter attenuates all higher frequencies and determines the ultimate signal and noise bandwidth.

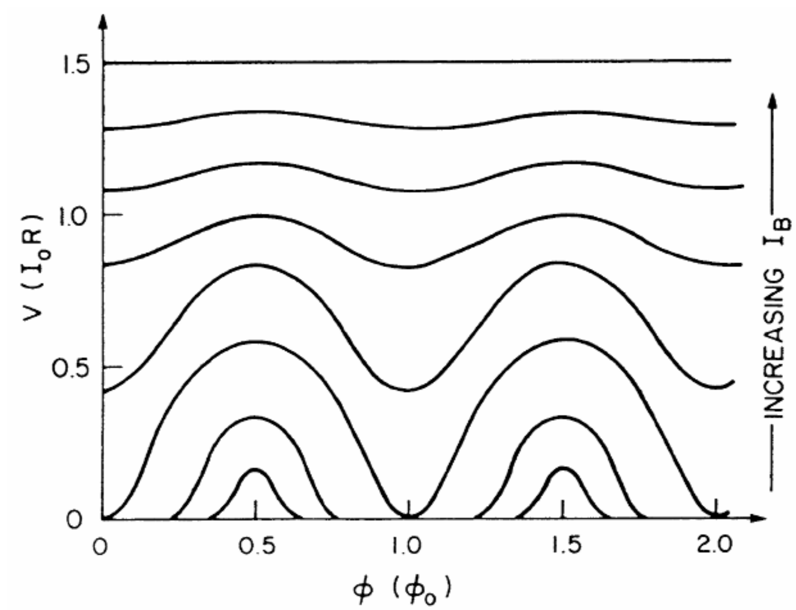


- We use a highly linear sampling demodulator that aliases the high-frequency signal to baseband.

SQUIDs used as current amplifiers



SQUID output periodic in magnetic flux through SQUID loop, i.e. input current, so input signal must be constrained to ¼ period.



⇒ Negative feedback required to
- extend dynamic range,
- reduce distortion

⇒ Shunt feedback provides low input impedance

We use 100-SQUID arrays from NIST.

Intermodulation

SQUID output voltage approx. sinusoidal function of flux

$\Rightarrow$ non-linear: $$\sin x \approx x - \frac{x^3}{3!} + \frac{x^5}{5!} \ \ldots$$

Non-linear terms lead to mixing products.

For two input frequencies f_1 and f_2: 3rd order distortion $\Rightarrow$

$3f_1$

$3f_2$

$2f_1 \pm f_2$

$2f_2 \pm f_1$

What levels are of concern?

Bolometer noise current:	10 pA/Hz$^{1/2}$
Bandwidth:	1 kHz
Total noise current:	320 pA
Bolometer bias current:	10 μA
i_{noise} / i_{bias} =	$3.2 \cdot 10^{-5}$ (-90 dBC)

Depends on ratio of signal to maximum optical loading

System must be designed for very low distortion – choose appropriate technology

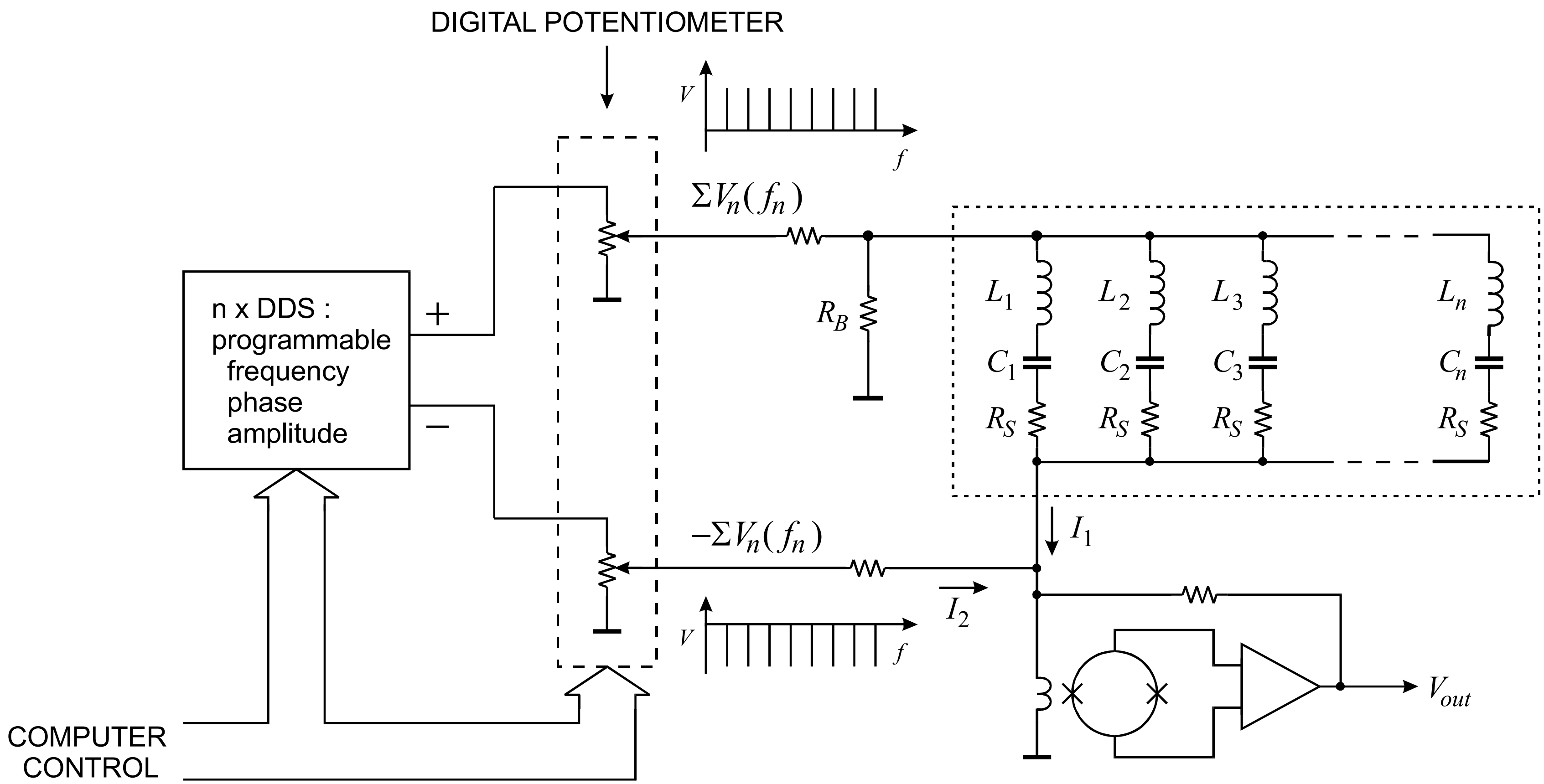
Similar constraint applies to all frequency multiplexing schemes

Carrier Nulling

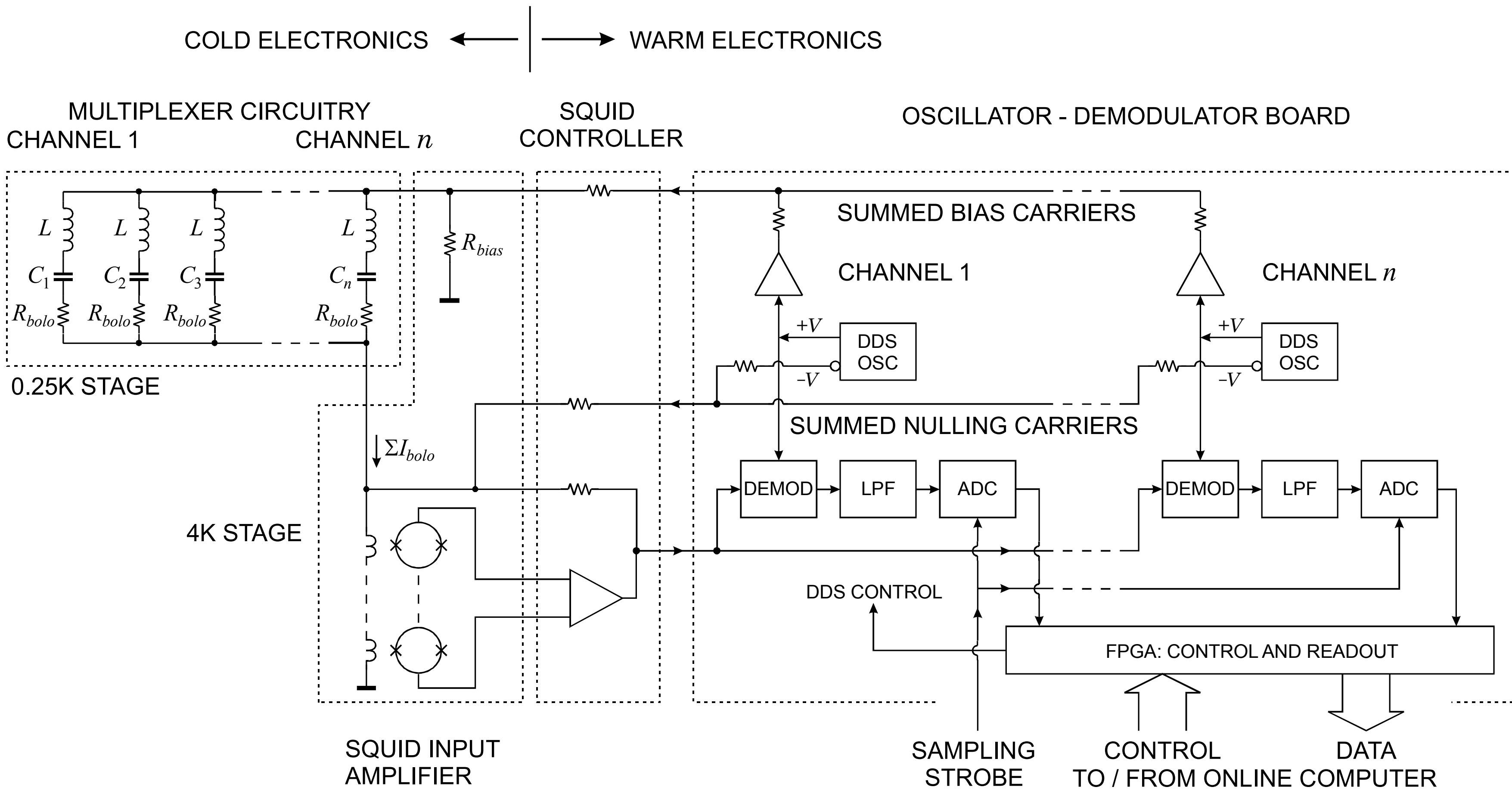
Maximum input signal to SQUID is limited, even with feedback ("flux jumping")

All of the information is in the sidebands, so the carrier can be suppressed to reduce dynamic range requirements.

Low-frequency sideband noise associated with carriers cancels (-110 dBc at 10 Hz)



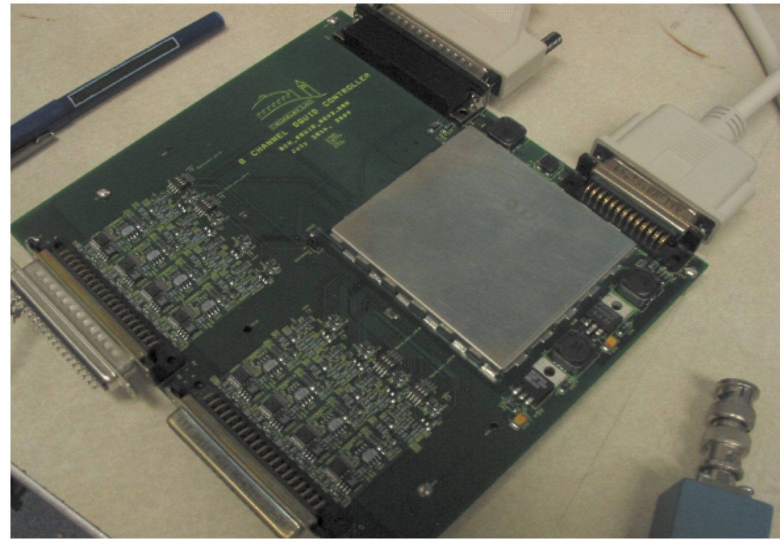
System Block Diagram



8-channel SQUID Controller

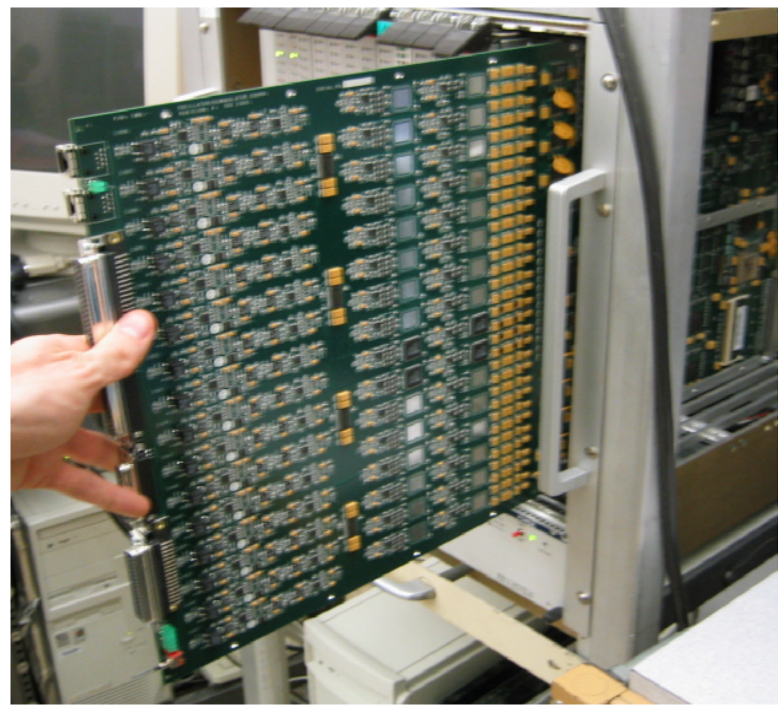
Computer-controlled (FPGA)
SQUID diagnostics
Open/closed loop
Switchable gain

SQUIDs VERY sensitive to pickup (up to GHz), so local shielding of digital circuitry is crucial.



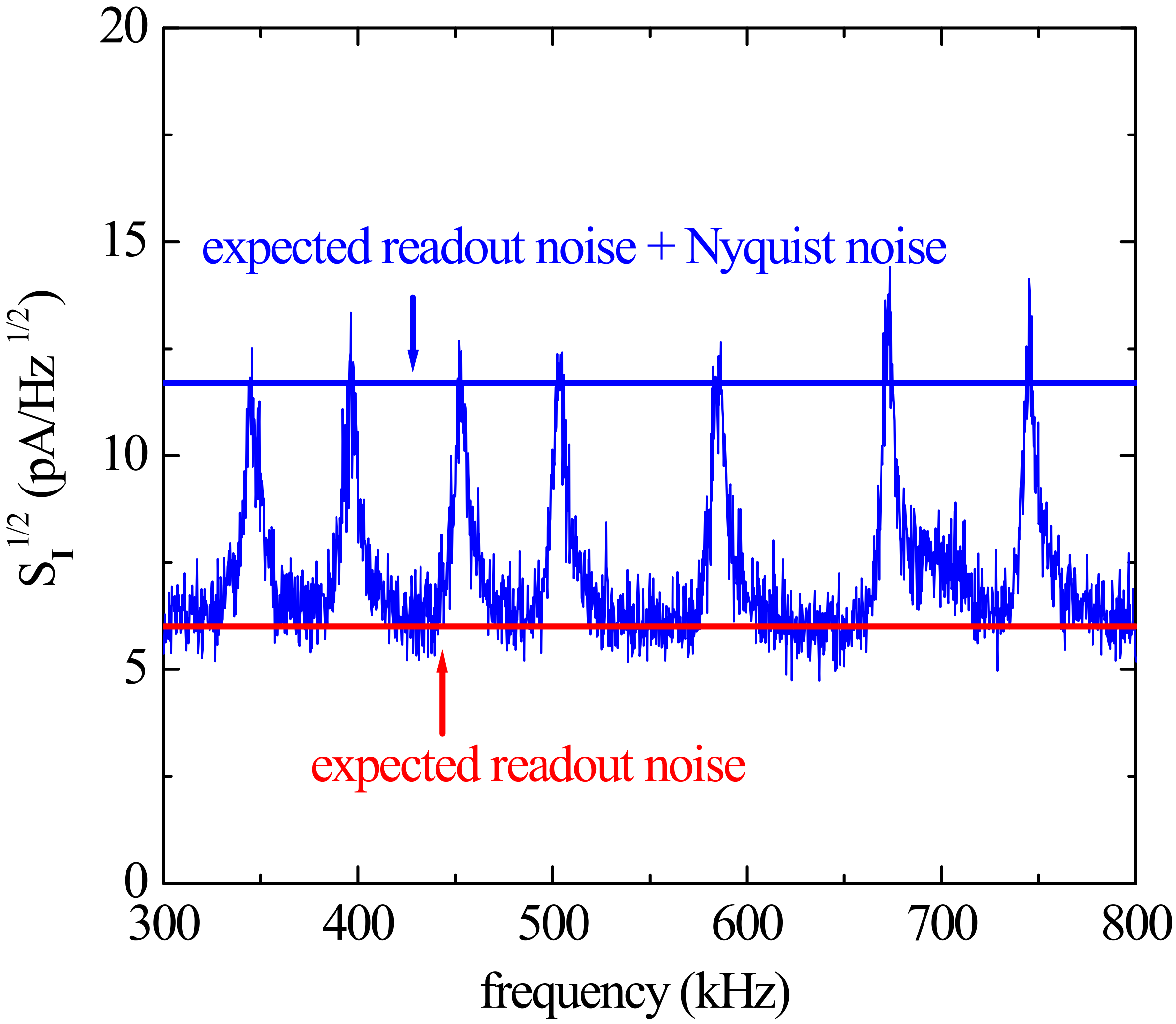
16-channel Demodulator Board

16 individual demodulator channels
1 DDS freq. generator per channel
On-board A/D
Opto-isolated computer interface

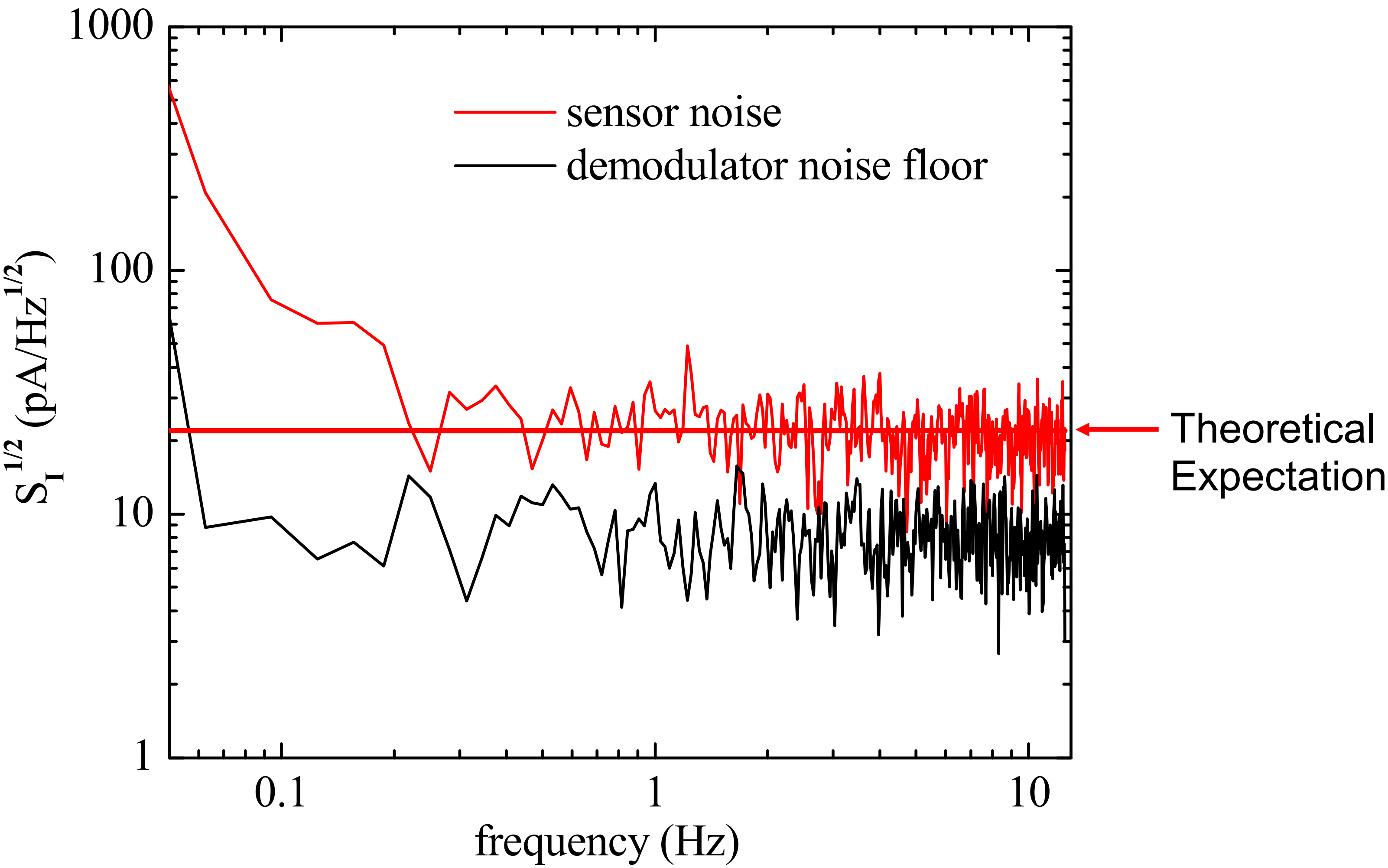


Design and prototyping at LBNL
(M. Dobbs, J. Joseph, M. Lueker, C. Vu)

Measured MUX Noise Spectrum at SQUID Amplifier Output
(Trevor Lanting)



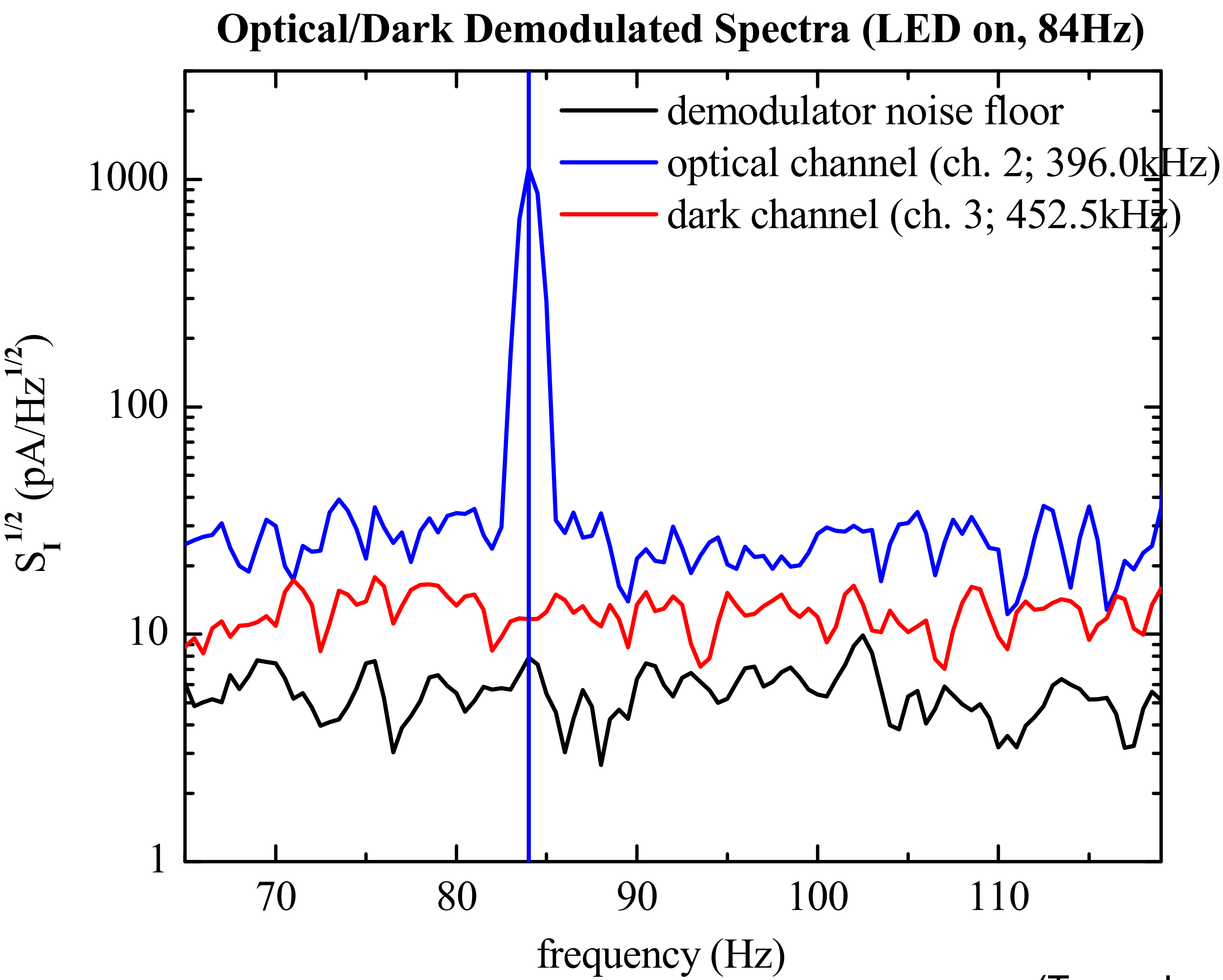
Measured Noise Spectrum in 8-Channel MUX System



Sensor noise white above 0.2 Hz

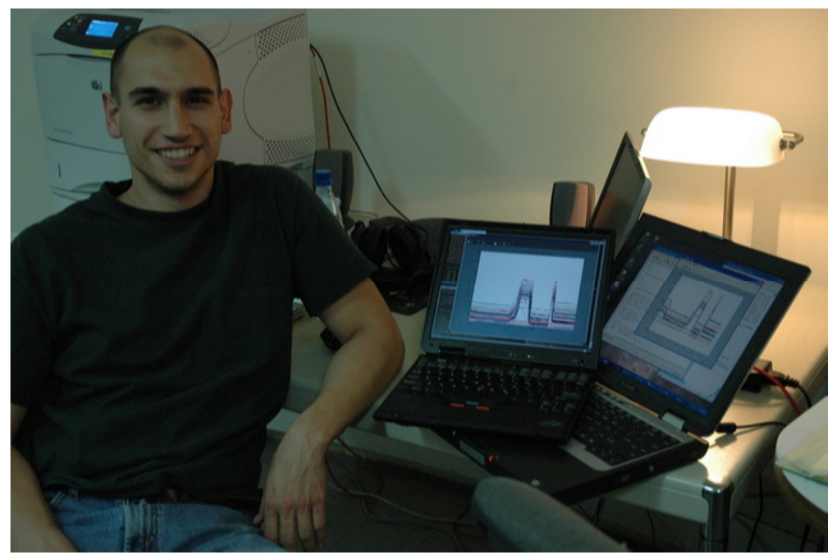
(Trevor Lanting)

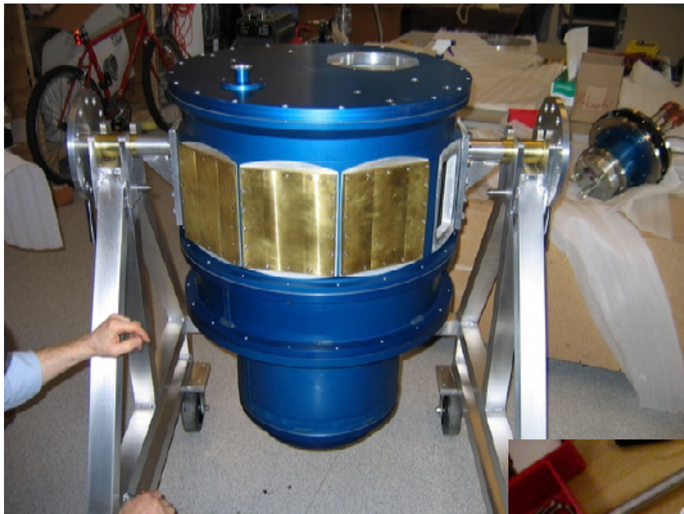
Cross-Talk < 1%

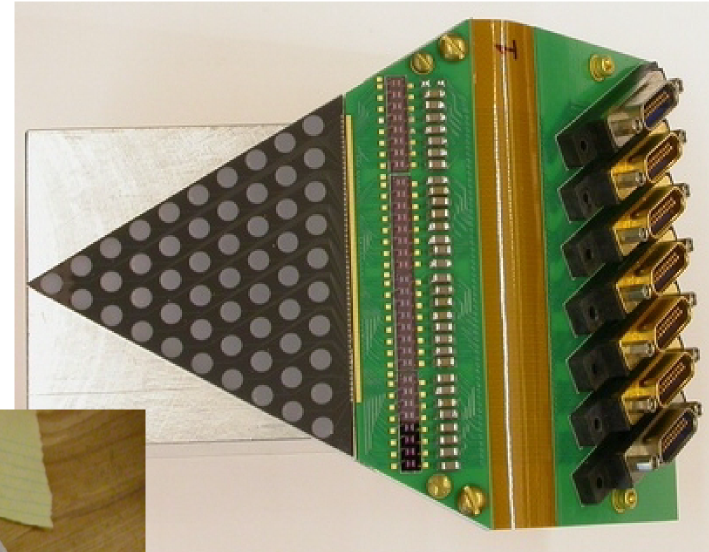


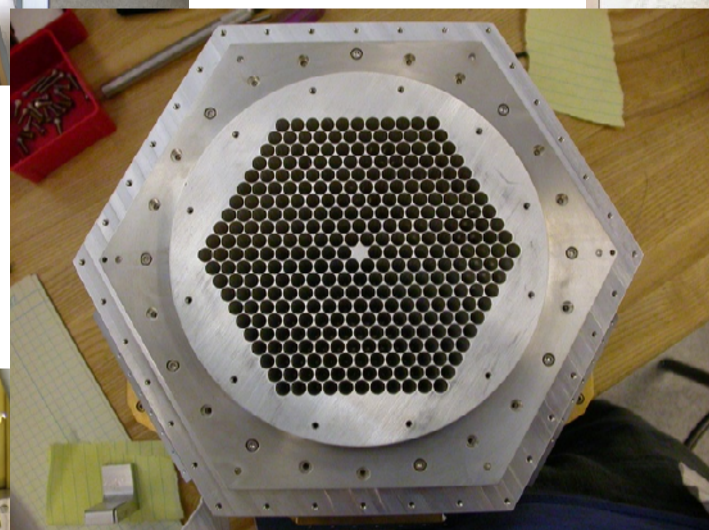
(Trevor Lanting)

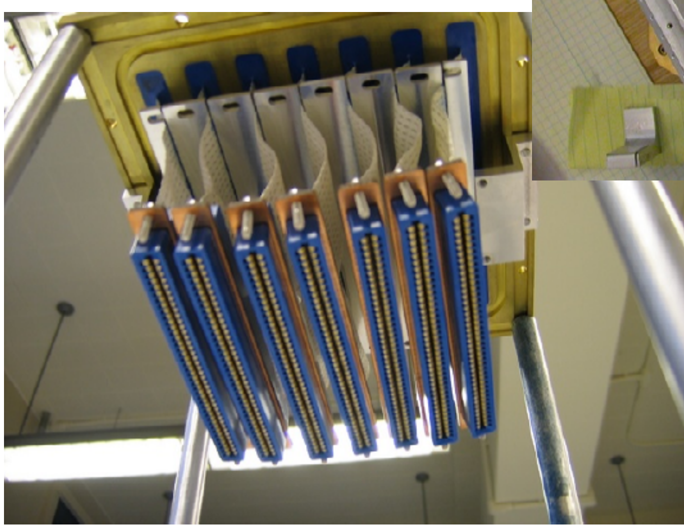
TES Array at Atacama





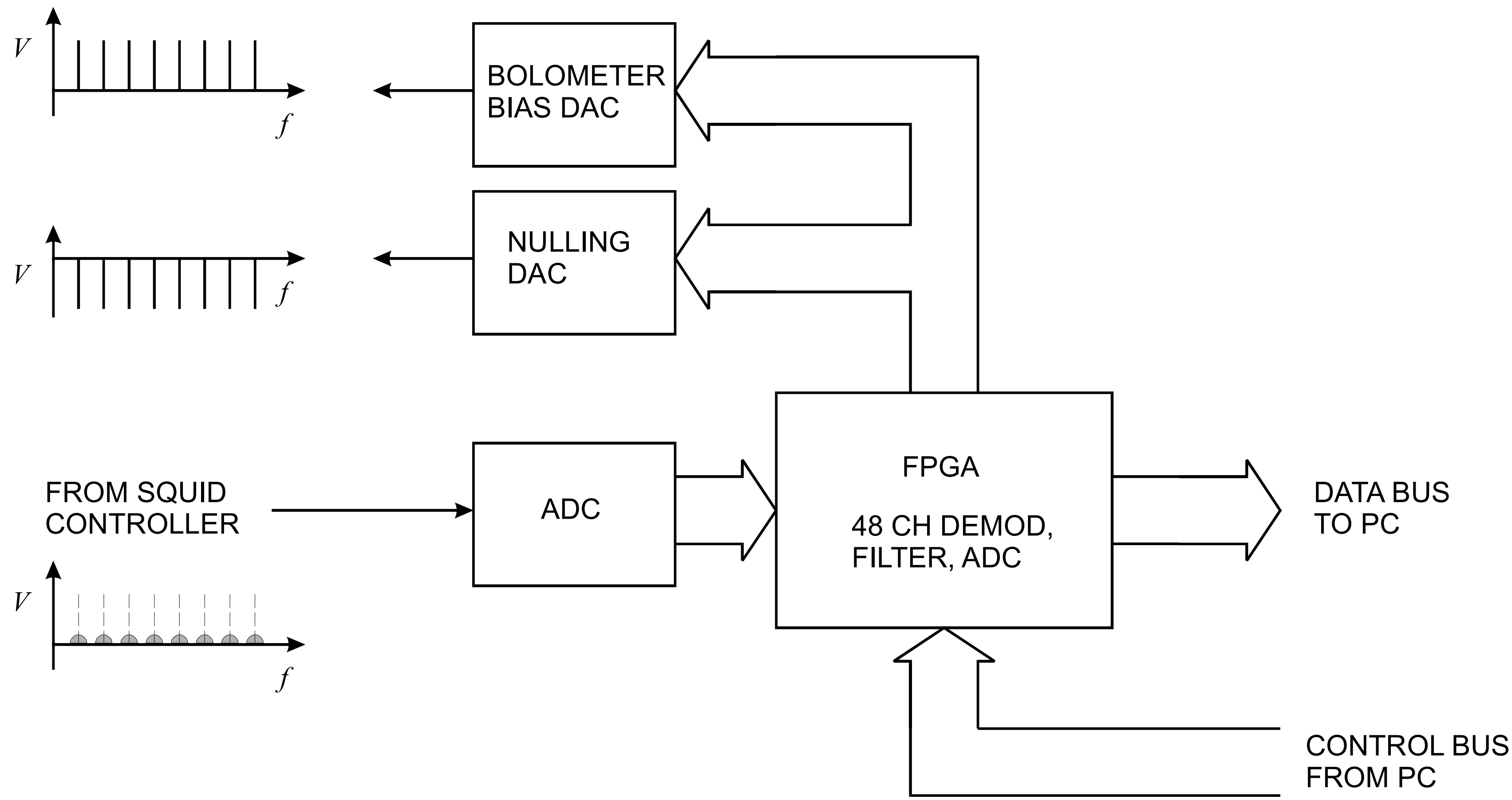







100 EA

New Development: "Fully Digital" Demodulator (Matt Dobbs, LBNL/McGill)



- Prototypes of key components tested
- Substantial reduction in power $\Rightarrow$ Balloon-borne experiments (e.g. EBEX)
  Satellite mission (CMBPOL?)

How many bolometers can (or should) be MUXed?

Lower bounds set by

Acceptable thermal leaks in wiring (~ 300 single channels OK)

Cost (SQUIDs + wiring assemblies)

e.g. for 8-fold MUXing SQUIDs no longer major cost driver.

Upper bounds

Overall bandwidth
– determined by wiring length in SQUID feedback loop.

Single-point failure modes

Failure in a MUX module should lead to negligible loss in number of signal channels.

Baseline design for APEX-SZ and SPT: 8-fold MUXing

32-fold MUXing practical (extend max. frequency from 1 MHz to 3 MHz)
Appears adequate for 10^4 bolometers.

Technical limits to MUXing

1. Frequency spacing of bias carriers depends on selectivity of tuned circuits.

2. Minimum LC bandwidth (Q) set by bolometer time constant.

3. Channel spacing set by allowable cross-talk and noise leakage from other channels.

4. Minimum frequency set by bolometer thermal time constant
   (typ. min. 100 kHz)

5. Maximum frequency set by large-signal bandwidth of SQUID feedback loop.

   Loop gain-bandwidth product: set by a) required dynamic range (no. and magnitude of carriers)
   b) distortion in SQUID

   Limited by total wiring length of feedback loop

   Example: round trip wiring length of 20 cm limits loop gain-bandwidth product to ~100 MHz (at 1 MHz extend dynamic range x100)

H. Spieler, Frequency Domain Multiplexing for Large-Scale Bolometer Arrays, in Proceedings Far-IR, Sub-mm & mm Detector Technology Workshop, J. Wolf, J. Farhoomand and C. McCreight (eds.), NASA/CP-211408, 2002 and LBNL-49993, www-physics.LBL.gov/~spieler.

Solutions

1. Maximize dynamic range of SQUID

SQUID is limited by flux, so reducing the mutual input inductance allows larger input current.

Smaller input mutual inductance
increases input noise current
reduces SQUID transresistance (gain)

Limited by bolometer noise and noise of warm amplifier

$\Rightarrow$ SQUID arrays (many SQUIDs connected in series)

We use 100-SQUID arrays from NIST

2. Cold local feedback loop

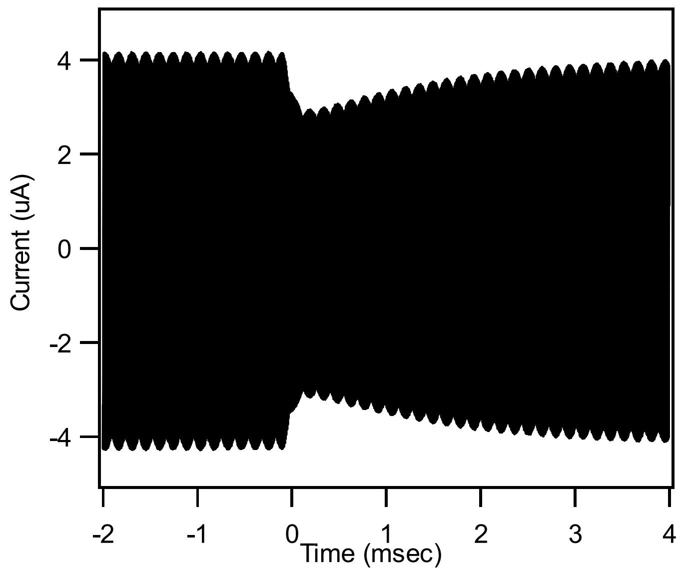
Use local feedback around 300-SQUID array.
Reduced wire length increases maximum frequency.
In addition: External warm feedback loop with reduced gain-bandwidth
$\Rightarrow$ larger bandwidth for given wire length

- With SQUID array and cold/warm feedback loop ~30 channels per readout line practical.

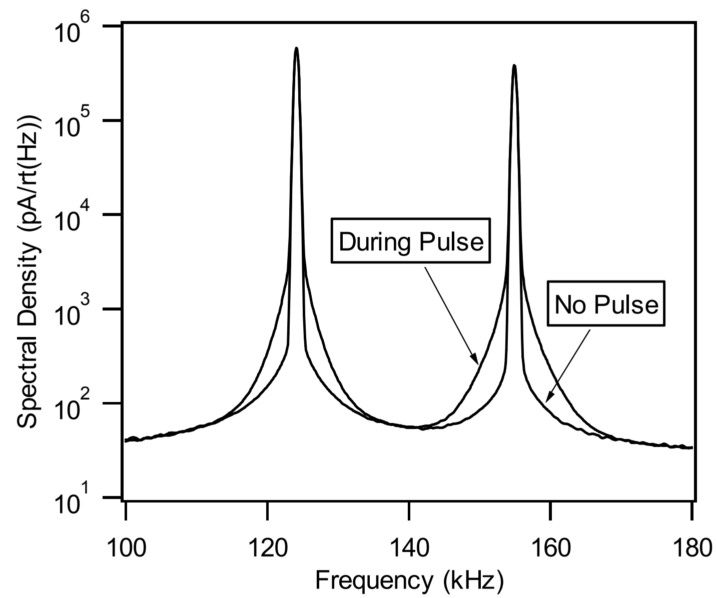
Frequency-Domain MUX Demonstrated with Gamma-Ray Micro-Calorimeters

LLNL/UCB/LBNL collaboration

Time domain



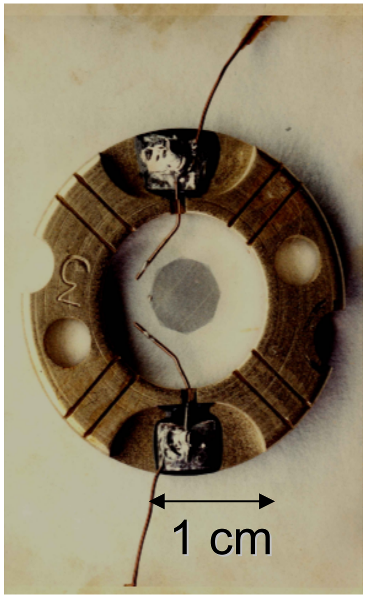
Frequency Domain

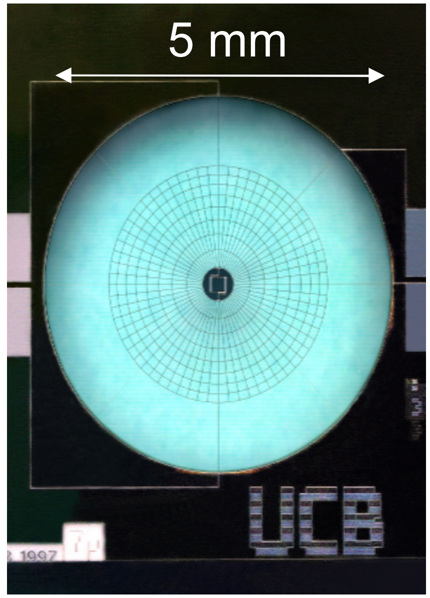


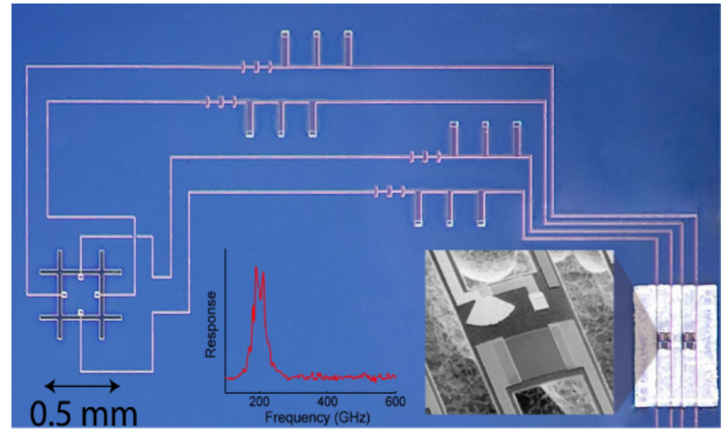
Energy resolution of 60 eV FWHM at 60 keV unaffected by multiplexer.

MUXing $\Rightarrow$ increase active area, overall rate capability

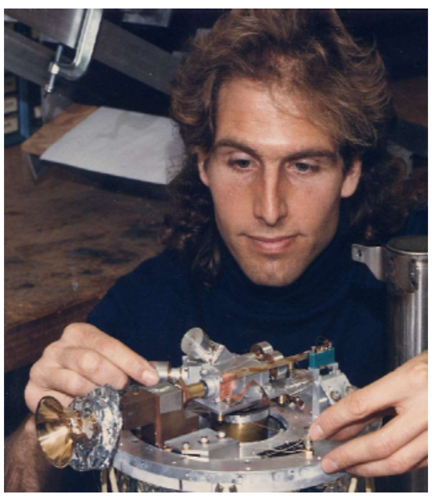
Major Transition in CMB Instrumentation

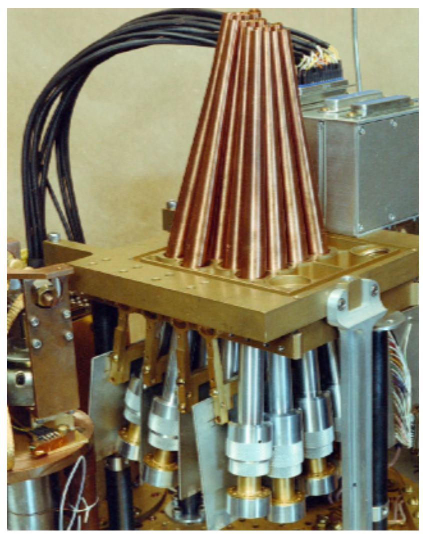




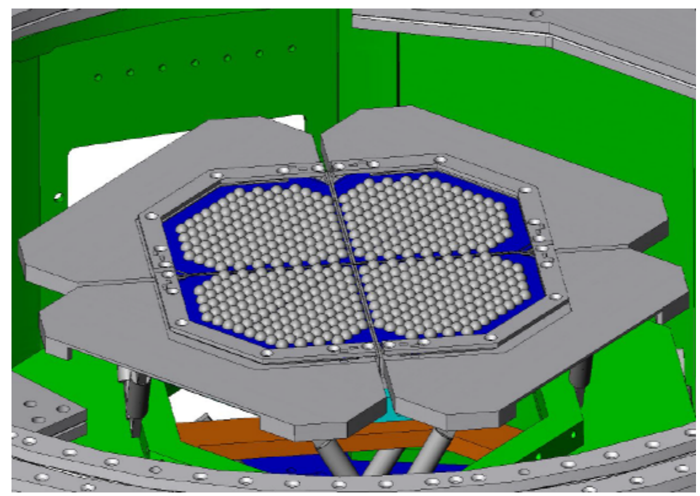


10 cm





10 cm



1980s 1990s 2000s

Summary

- Next-generation CMB experiments require $10^2 - 10^3$ fold improved sensitivity
- Monolithic fabrication technology provides wafer-scale TES kilopixel arrays
- Antenna-coupled arrays provide polarization discrimination
- Frequency-domain MUXing demonstrated

  Zero power dissipation at 0.25K focal plane

  <1% cross-talk

  Very insensitive to vibration

  Negligible increase in noise

  Conceptually simple, but many crucial details

- Systems demonstrated in APEX test run (despite sleet and snow)
- Bolometer arrays and readout in production for APEX and SPT