The South Pole Telescope – Cosmology, Detectors, and Life at the Pole

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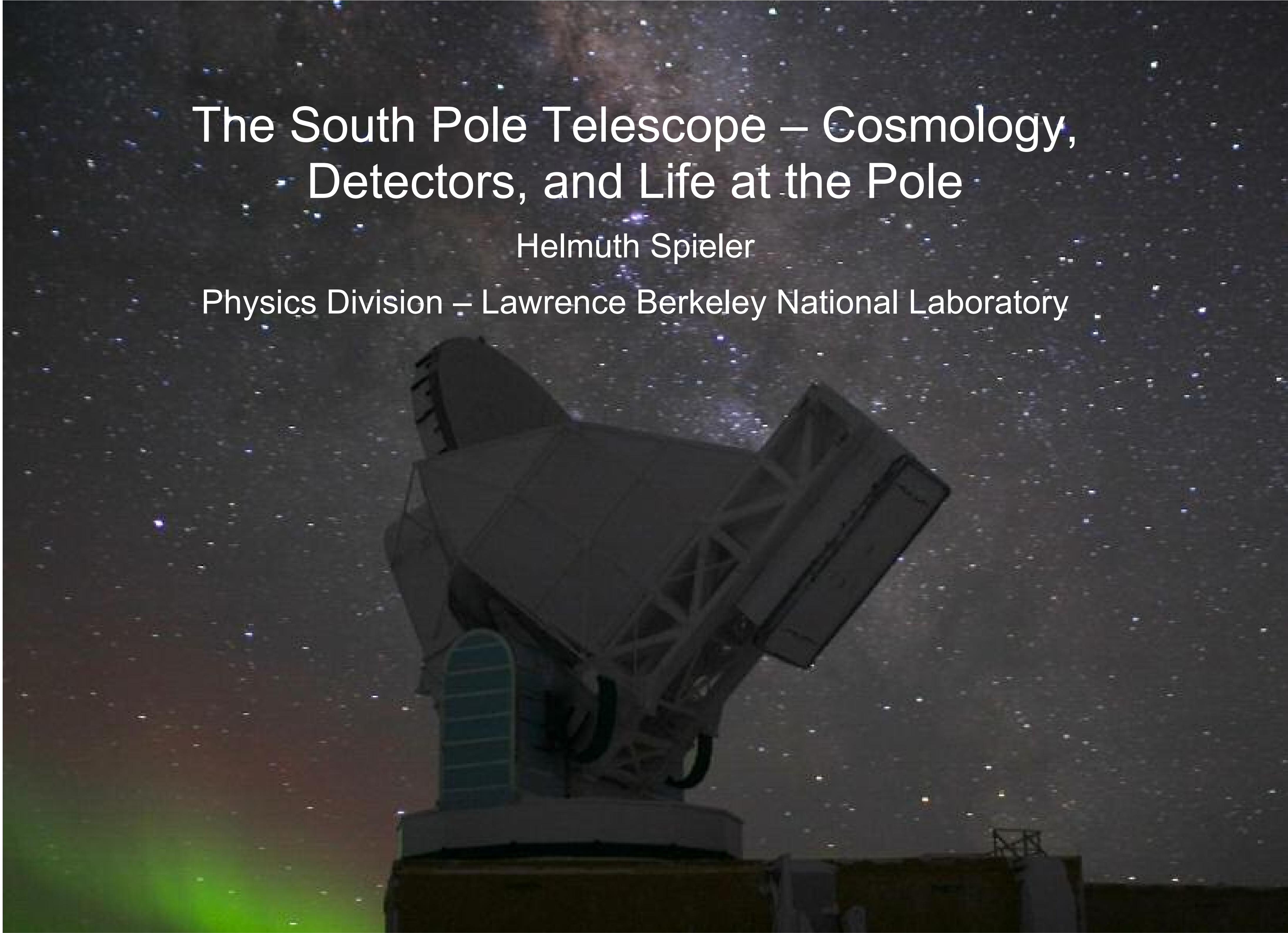


Outline

1. Physics Introduction

   Brief Overview of Physics Goals

2. Measurement Techniques

   Cosmic Microwave Background as a Tool

3. Detectors

   Superconducting Transition Edge Sensors
   + Multiplexed Readout at 0.25K

4. Life at the Pole

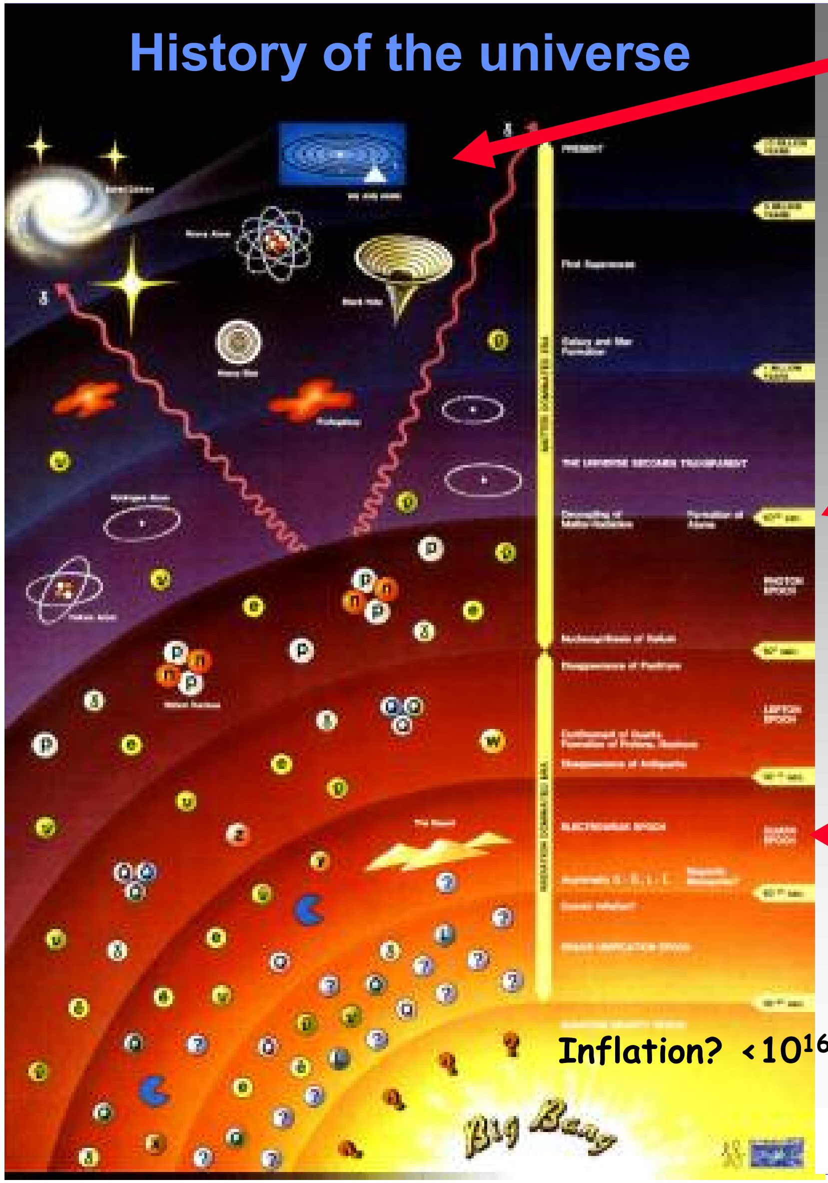
   It’s a nice place to work

More information at spt.uchicago.edu

and

www-physics.LBL.gov/~spieler.

History of the universe



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)

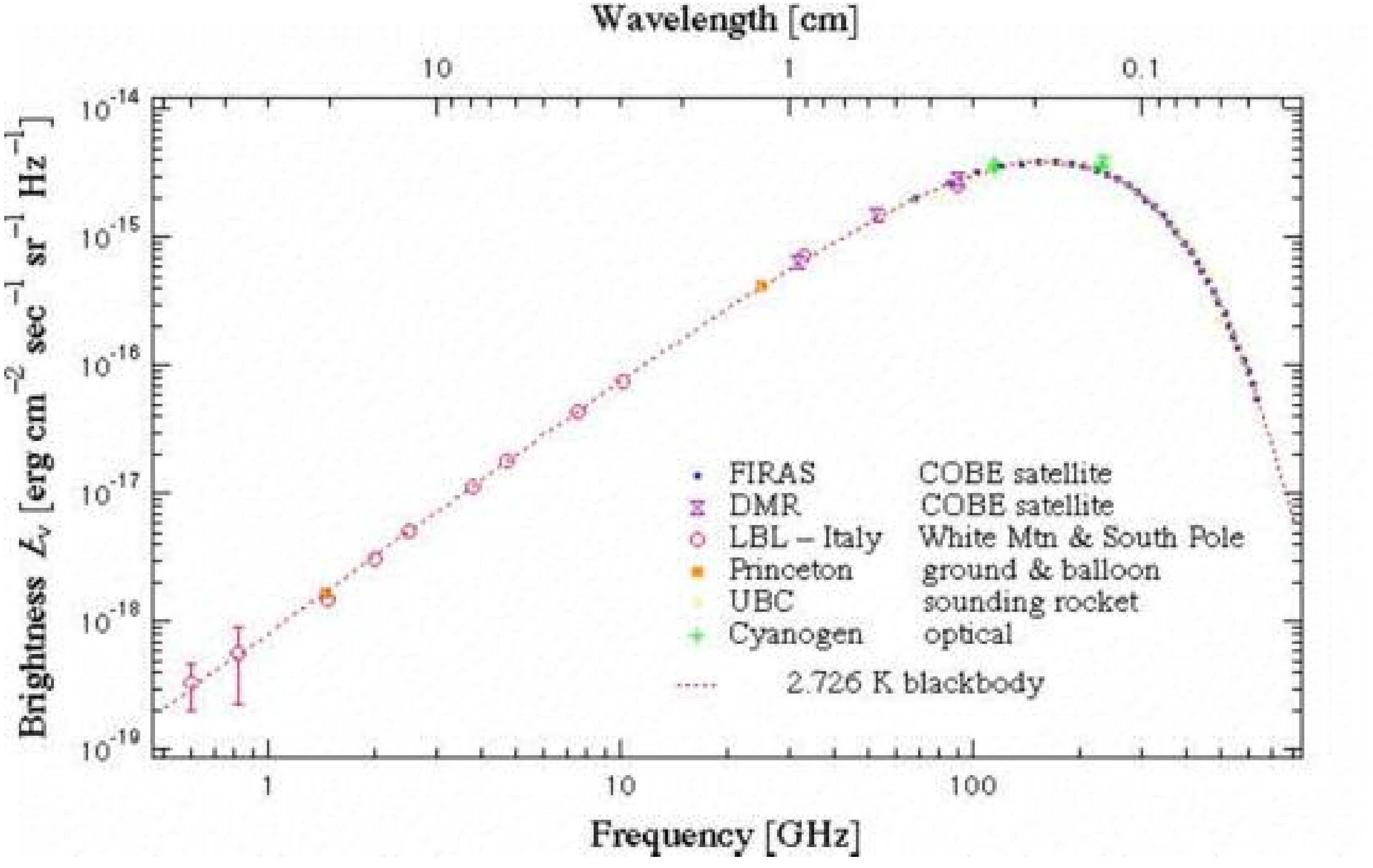
🡐Protons and Neutrons Form (10^{-10} sec)

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

Inflation? $<10^{16}$ GeV

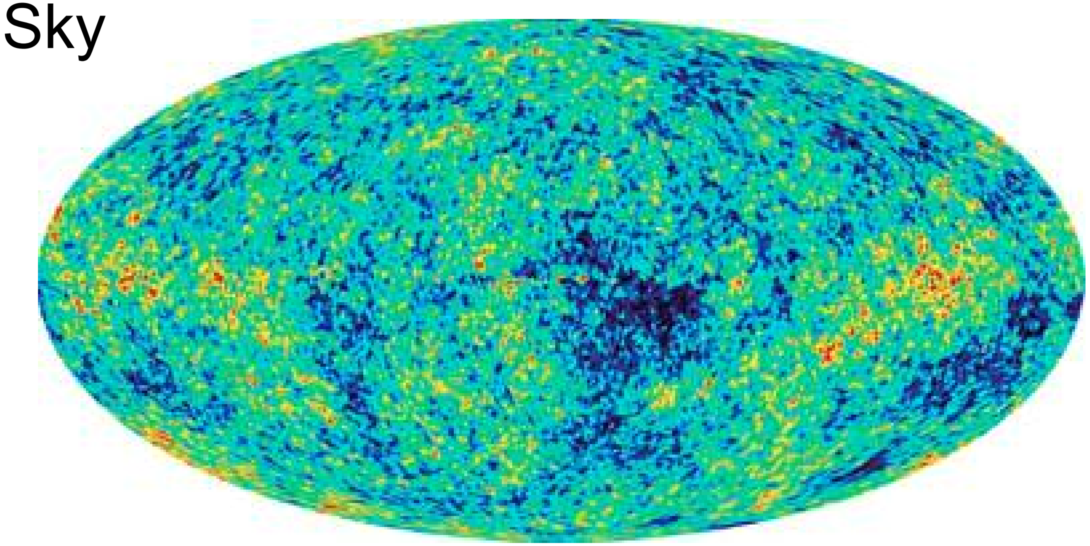
LHC probes physics relevant to the universe at age 10^{-14} sec.

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.

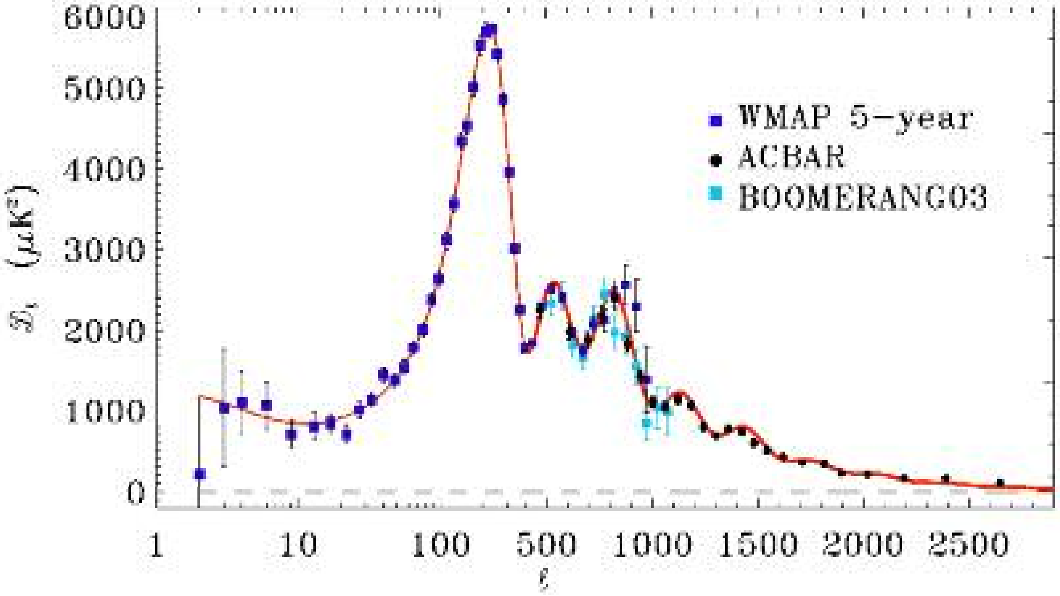
Map Temperature of Sky



Data from WMAP

Temperature anisotropy ~10^{-5}

Angular distribution

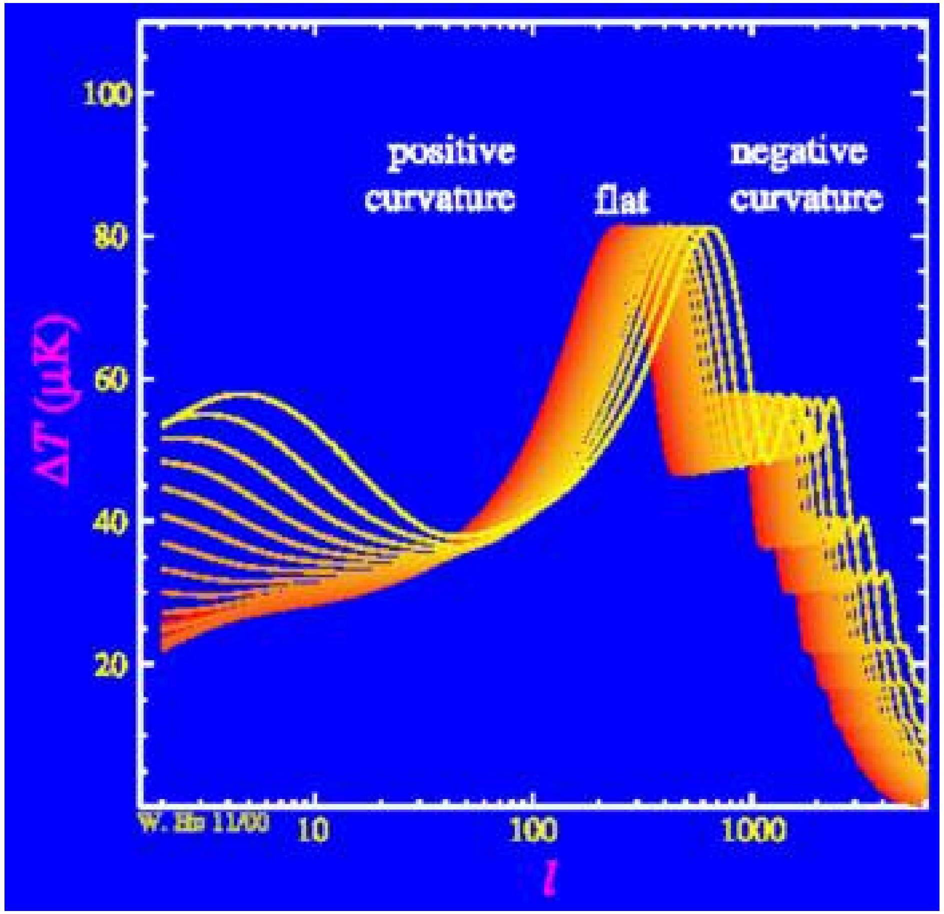


Angular Scale $\Delta\Theta \approx 180/\,l$

Angular structure depends on cosmological parameters

For example, geometry:
dominant angular scale ~1°

$\Rightarrow$ universe is flat



Angular Scale $\Delta\Theta \approx 180/\,l$

Analyzing the power spectrum:

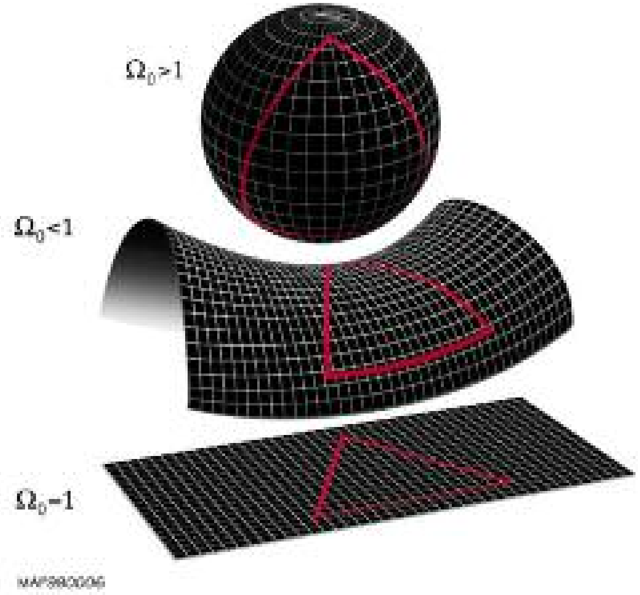
Normalization set by the total amount of matter $\Omega_M = \Omega_b + \Omega_{CDM}$

Position of 1st peak:
geometry of universe

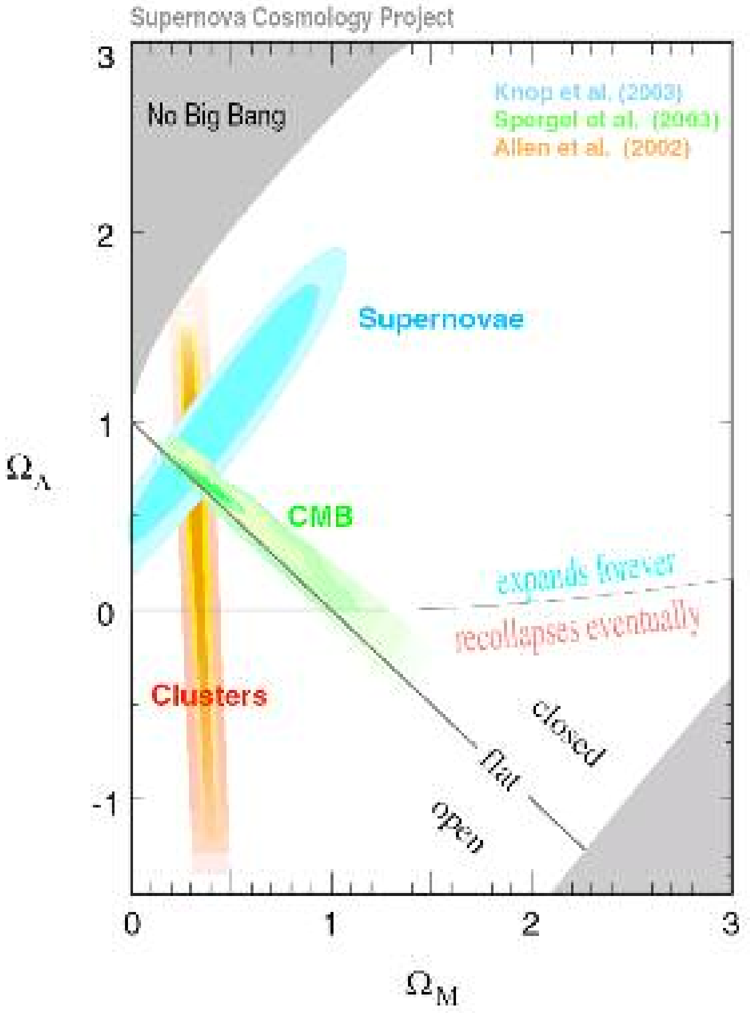
$l > 200$	$\Omega_0 > 1$	pos. curv.
$l \approx 200$	$\Omega_0 = 1$	flat
$l < 200$	$\Omega_0 < 1$	neg. curv.

Ratio of 1st to 2nd peak: amount of baryonic matter

3rd peak > 2nd peak: presence of cold dark matter



- CMB measurements provide constraints on fundamental cosmological parameters
- CMB spatial distribution largely unaffected since
  300k yrs after Big Bang
- Supernova and CMB data *together* give best constraints on mass and energy density of the universe
- Also consistent with Ω_m from Large Scale Structure data



Cosmology relies on combined data from different techniques

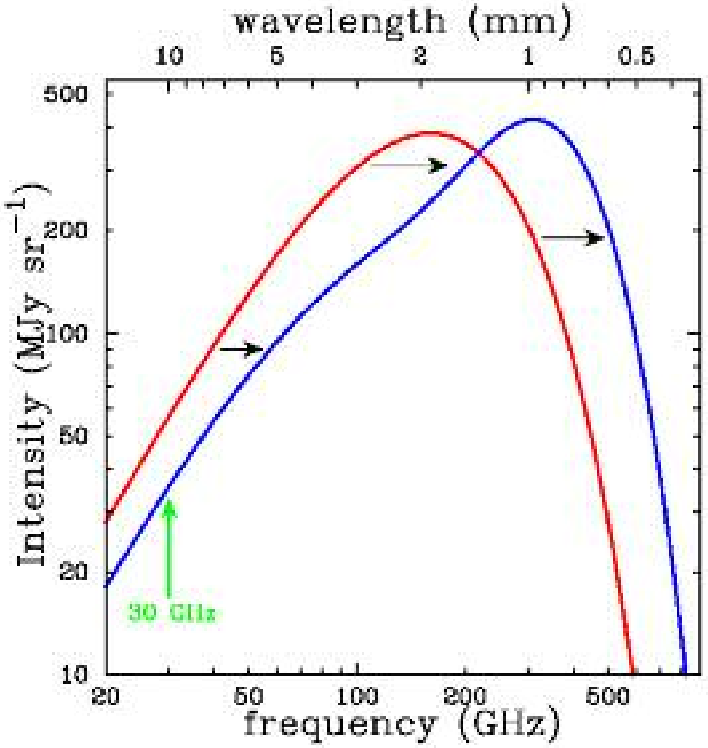
Today we use CMB as a tool:

Example: Map large-scale structure using Sunyaev-Zel'dovich Effect to measure density of galaxy clusters vs red shift ⇒ w, Ω_m (gravity vs. "dark energy")

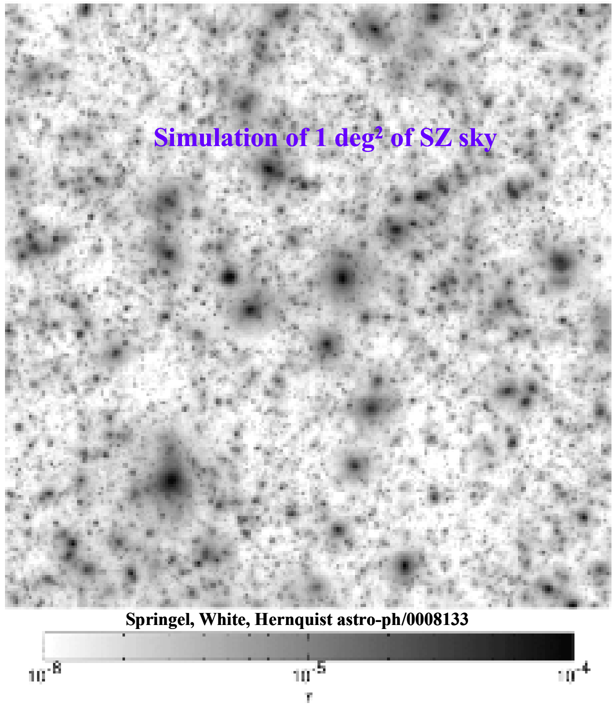
Inverse Compton scattering: Hot gas bound to clusters of galaxies scatters CMB

⇒ distorts black-body spectrum – shifts to higher frequencies:

At 150 GHz clusters appear as dark spots

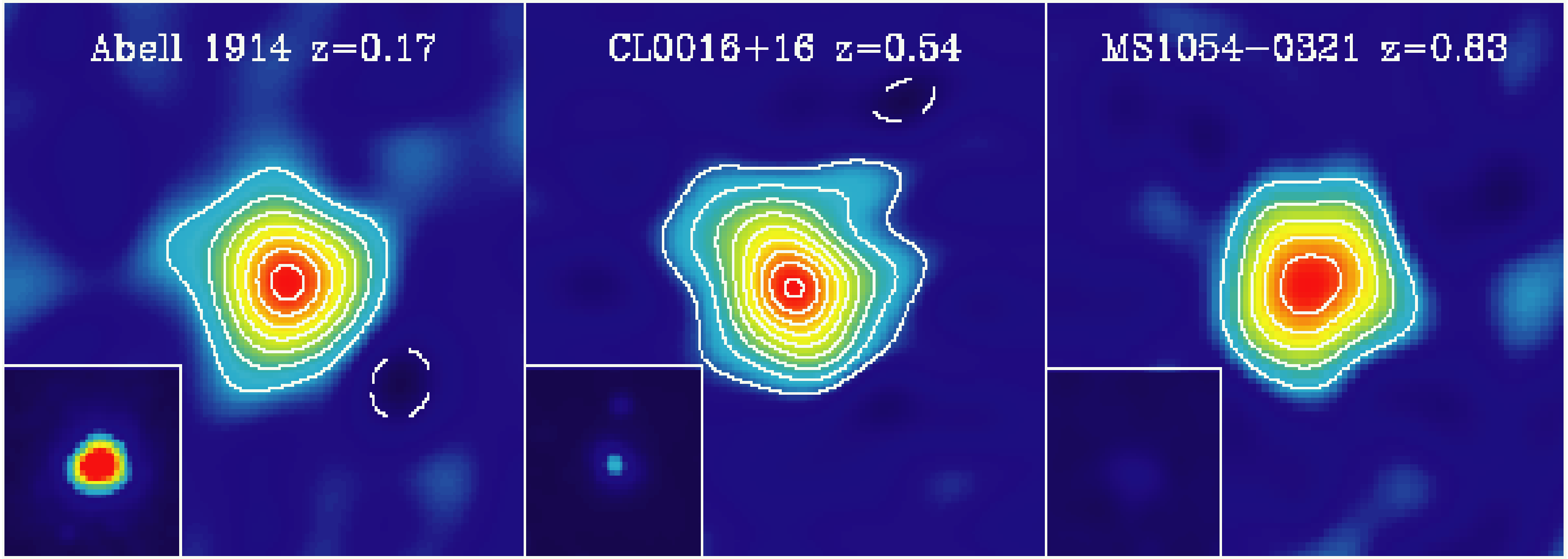


Galaxy cluster searches



Springel, White, Hernquist astro-ph/0008133

SZ signal independent of redshift z



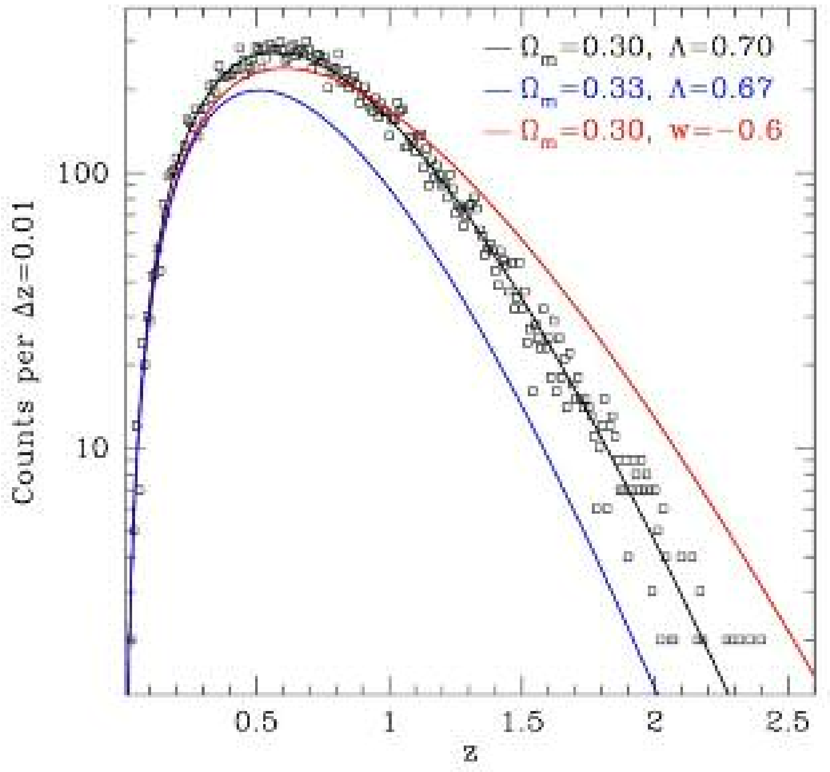
(Holzapfel et al.)

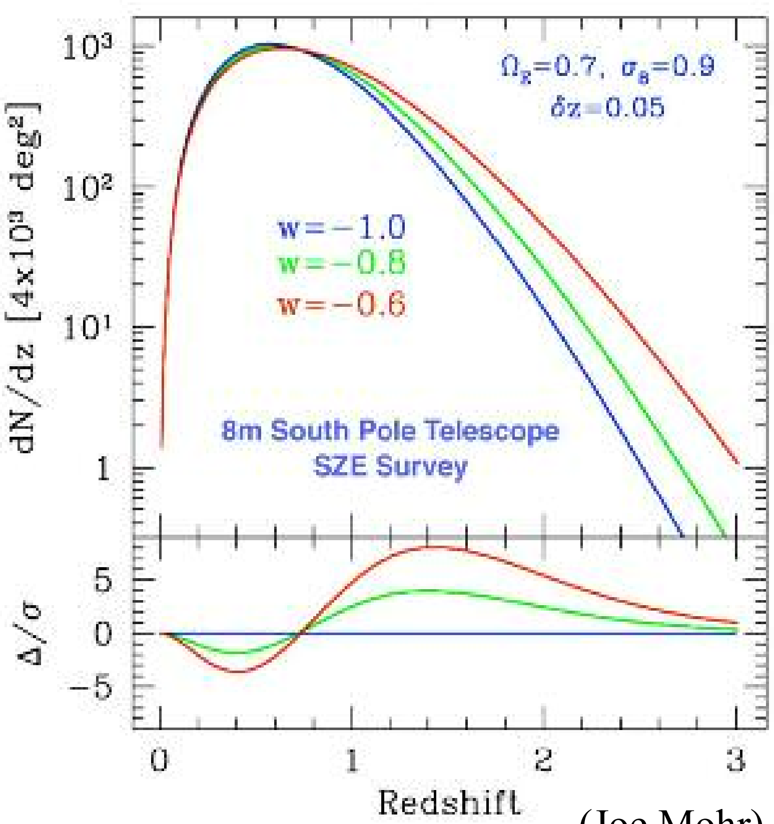
In contrast to x-rays (insets), SZ surface brightness is independent of redshift, so clusters can be seen at any distance.

However, optical data needed to determine redshift (collaboration with DES and others)

Technique that requires arrays with high sensitivity to achieve efficiency in random searches.

Cluster densities at z > 1 sensitive to cosmological parameters





(Joe Mohr)

w is the equation of state parameter for Dark Energy

Other SPT Cosmology Studies

1. Foregrounds / Point Sources

Foregrounds include active galactic nuclei (AGN) and dust emission from galaxies

2. Thermal Sunyaev-Zel'dovich Effect

CMB spectrum can be distorted by scattering off of free electrons

⇒ "Energy kick" in galaxy clusters dominates power spectrum at 150 GHz for $l > 2500$

Projections for a 100-sq. deg survey, 150GHz (red), 220 GHz (blue)

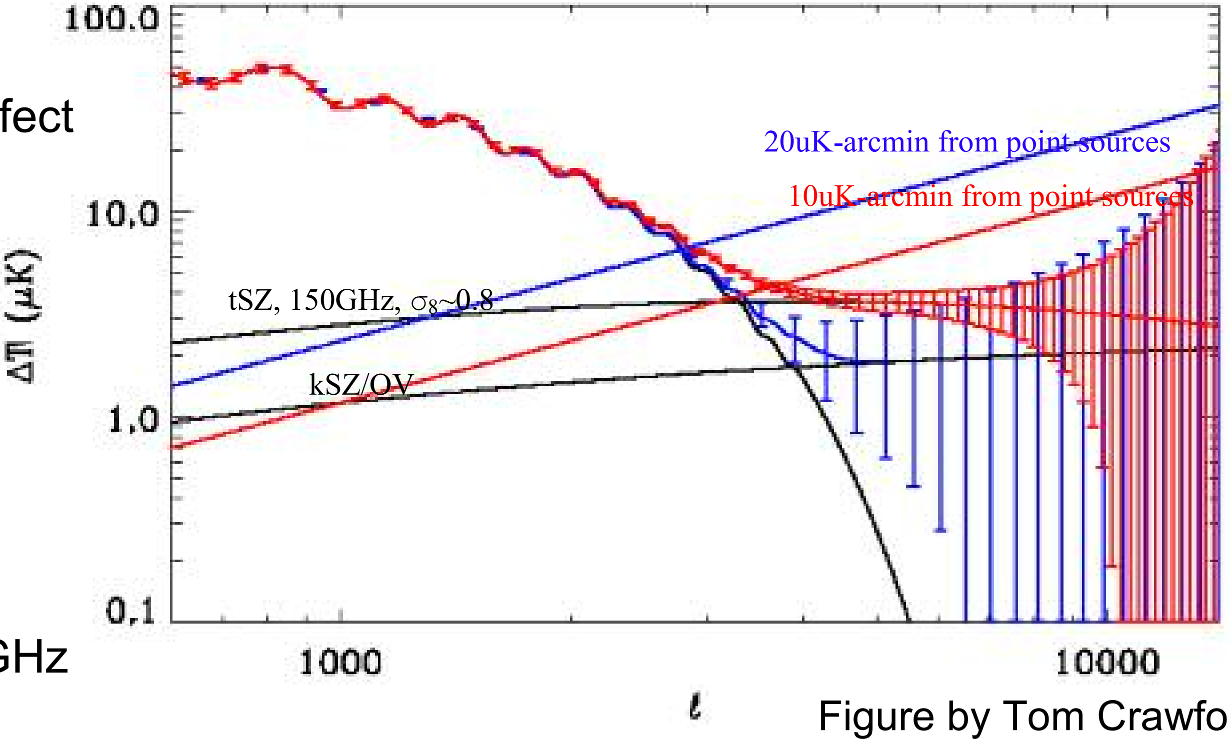
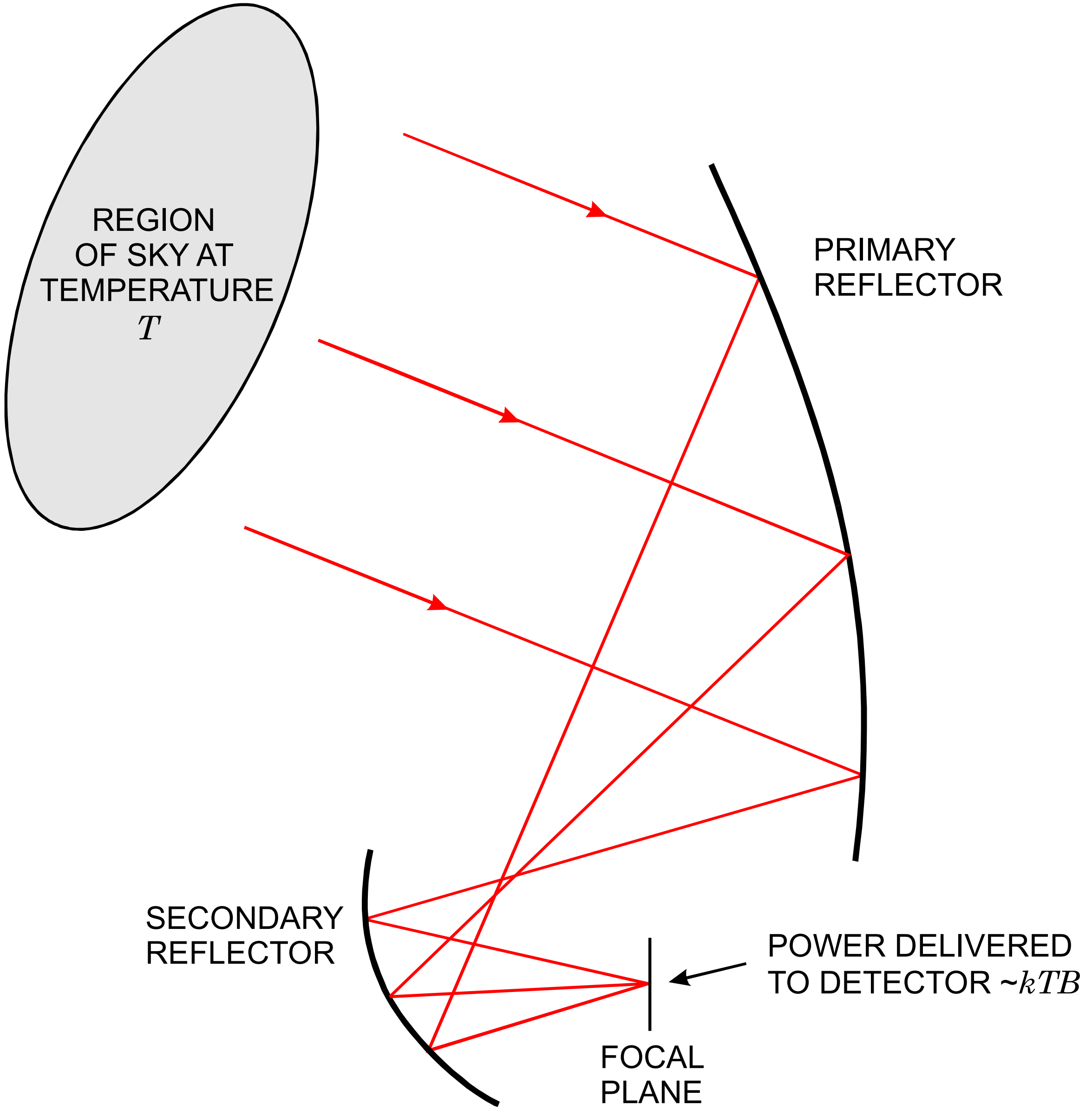


Figure by Tom Crawford

Good measurement of σ_8 – amplitude of initial density perturbations.

DETECTORS

Detected Signal



- View region of sky with temperature T (CMB: $T \approx$ 3K)
- Measured signal proportional to kTB (B = bandwidth)

South Pole Telescope

10m diameter parabolic reflector with off-axis feed

~25 micron surface accuracy

Beamwidth: 1.3 arcmin

1 deg field of view

Maximum scan speed: 4 deg/s

100% observing time

9300 ft altitude

Funded by NSF Polar Programs

First light 2007 – currently in 3^{rd} year of observations

Why go the South Pole?

High altitude to reduce atmospheric absorption

Atmospheric absorption at the relevant frequencies depends strongly on water content

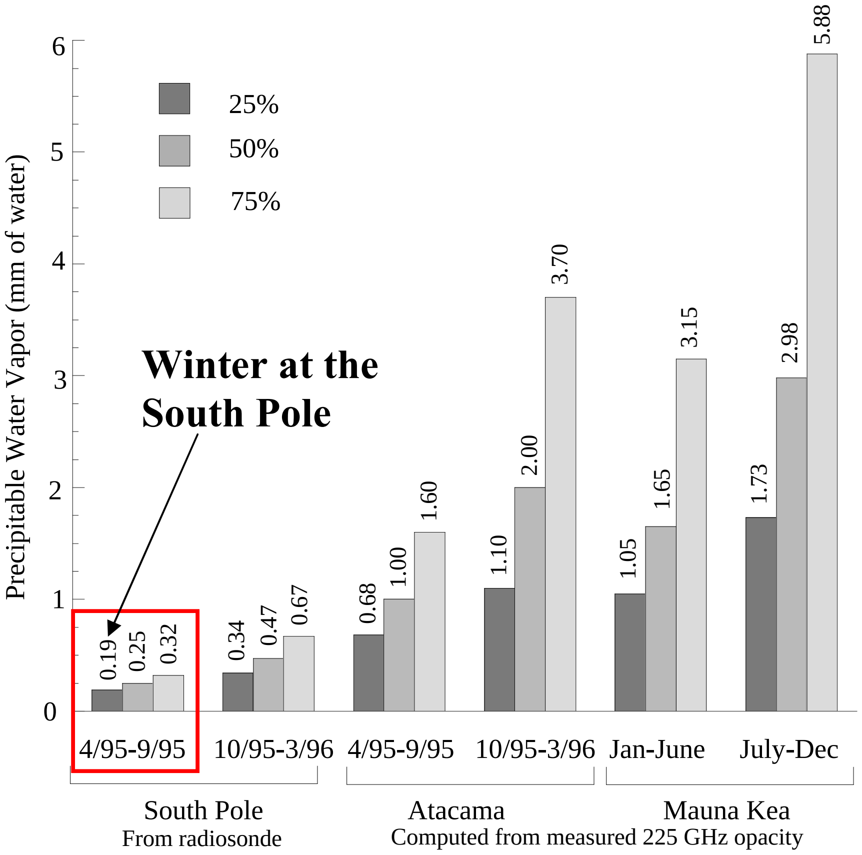
⇒ Site must be high and dry

Atmospheric stability:
Antarctic winds go around the Pole

Good place to work

Other sites, e.g. Atacama Plateau in Chile are also good.

Although precipitation is higher and more atmospheric variations, there is greater flexibility in scanning strategies.



To reduce systematic errors, scans of a given portion of the sky should be performed with various scan orientations.

SPT Collaboration

UC Berkeley

William Holzapfel
Adrian Lee
Christian Reichardt
Bradford Benson
Martin Lueker
Jared Mehl
Tom Plagge
Dan Schwan
Erik Shirokoff

LBNL

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Joaquin Vieira
Ryan Keisler
Lindsey Bleem
Abigail Crites
Erik Leitch

Harvard-Smithsonian Center for Astrophysics

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University of Colorado

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NIST

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McGill

Matt Dobbs
Gil Holder

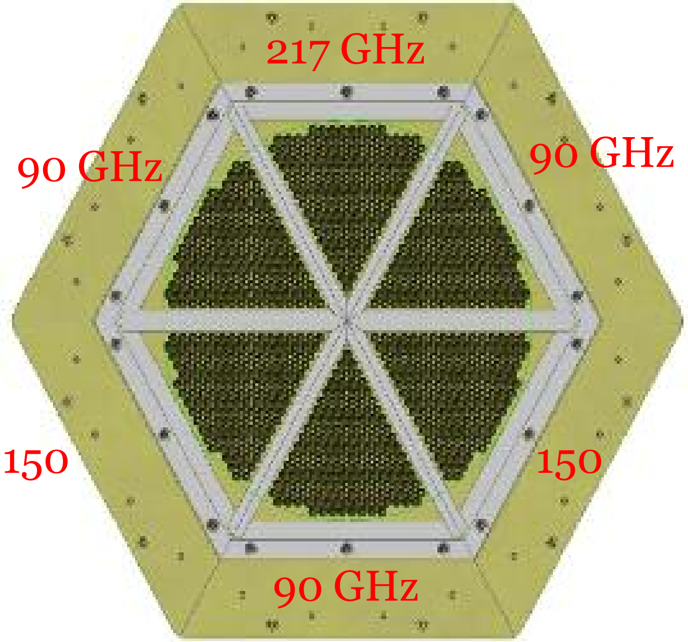
Univ. of Illinois Urbana

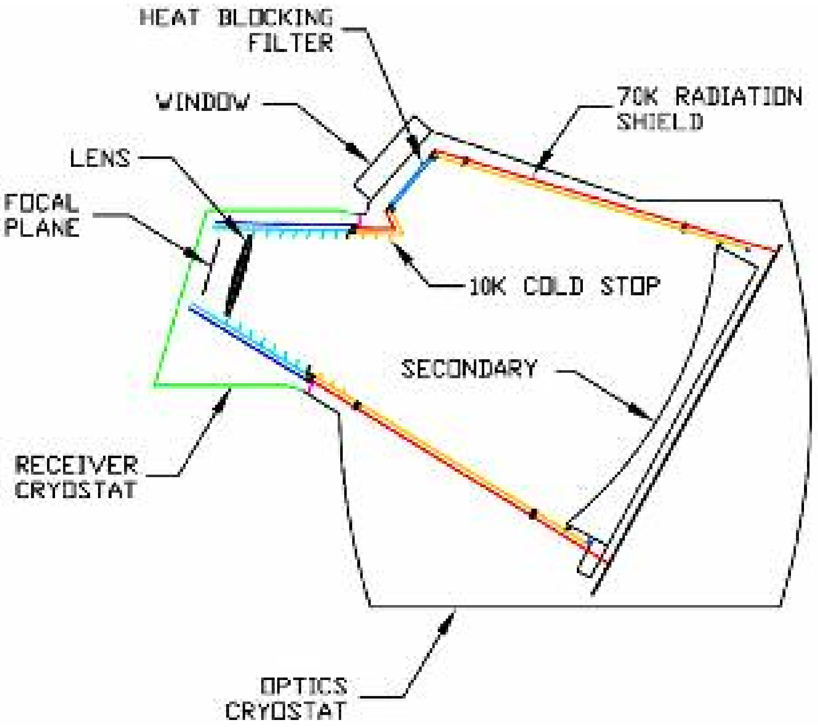
Joe Mohr

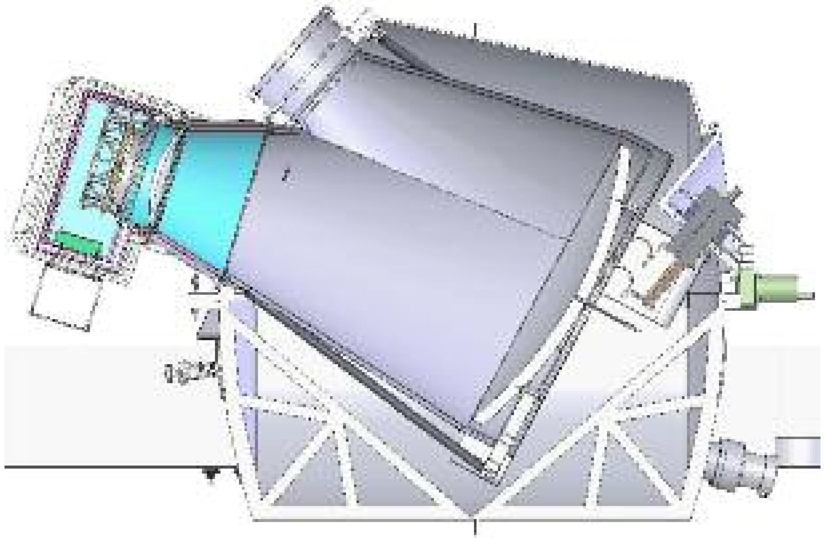
UC Davis

Lloyd Knox
Jason Dick

Optics and Focal Plane







Current configuration:

4 wedges at 150 GHz
1 ea. at 90 and 220 GHz

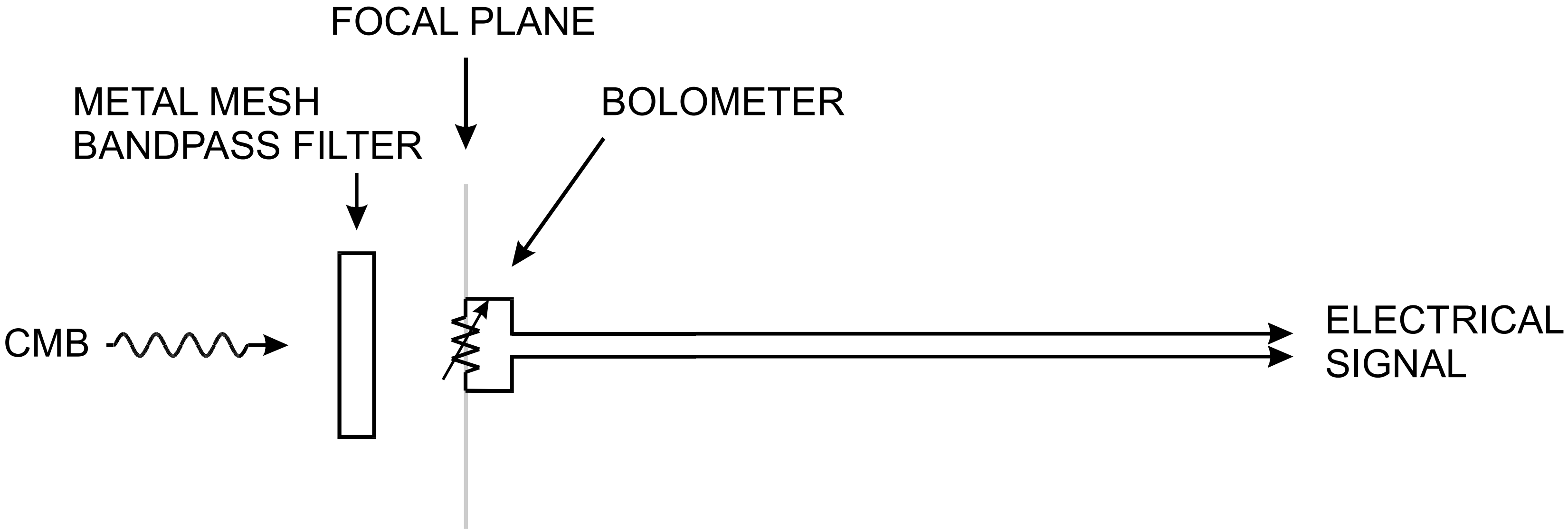
Signals are measured with bolometers

The signal is thermal noise (T = 2.7K):

$$P = kTB = 2.2 \cdot 10^{-15} B \text{ erg/Hz} \quad (\text{or } 2.3 \cdot 10^{-4} B \text{ eV/Hz})$$

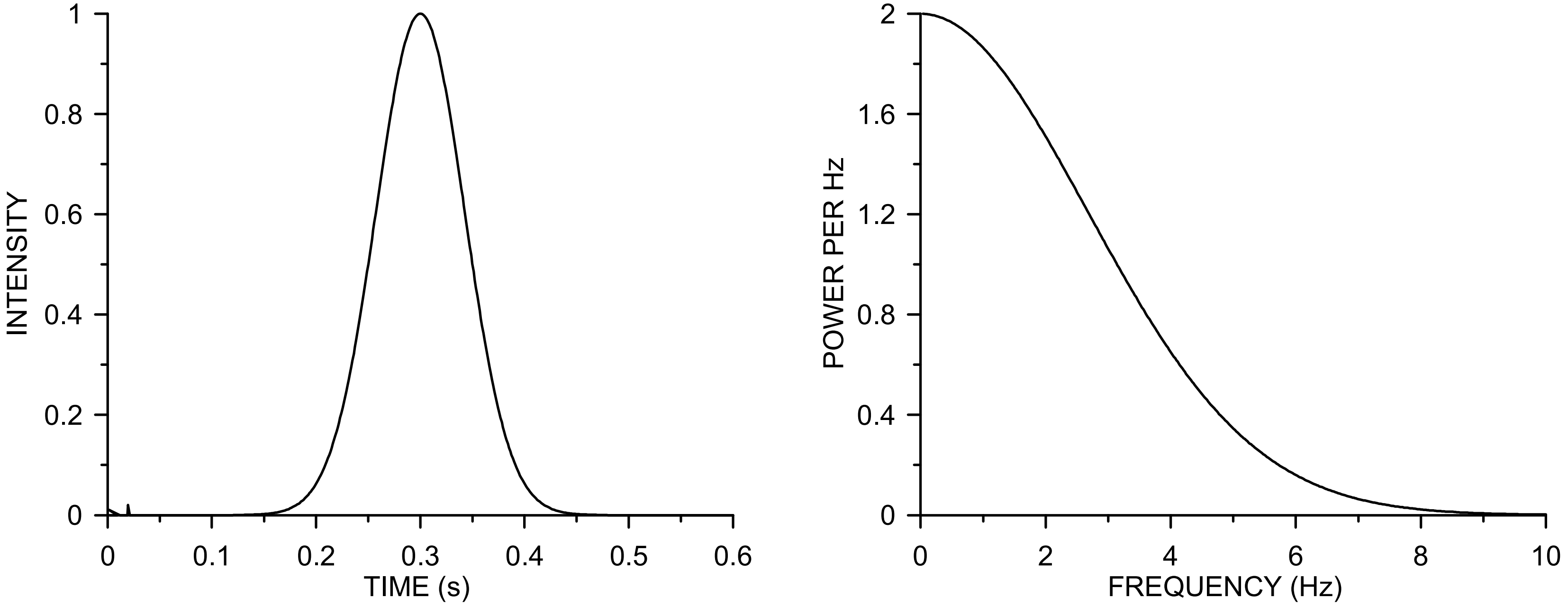
B = Bandwidth

Cluster signal < 1 mK



Signal Spectrum in Galaxy Cluster Search

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

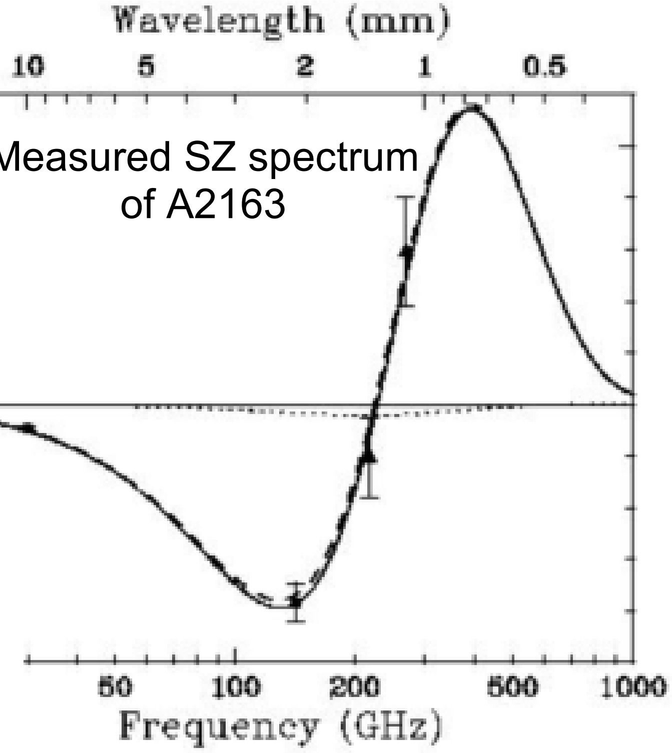


(W. Lu, CWRU)

Typical observations: scan back and forth in azimuth at 0.25 degrees/s, step in elevation

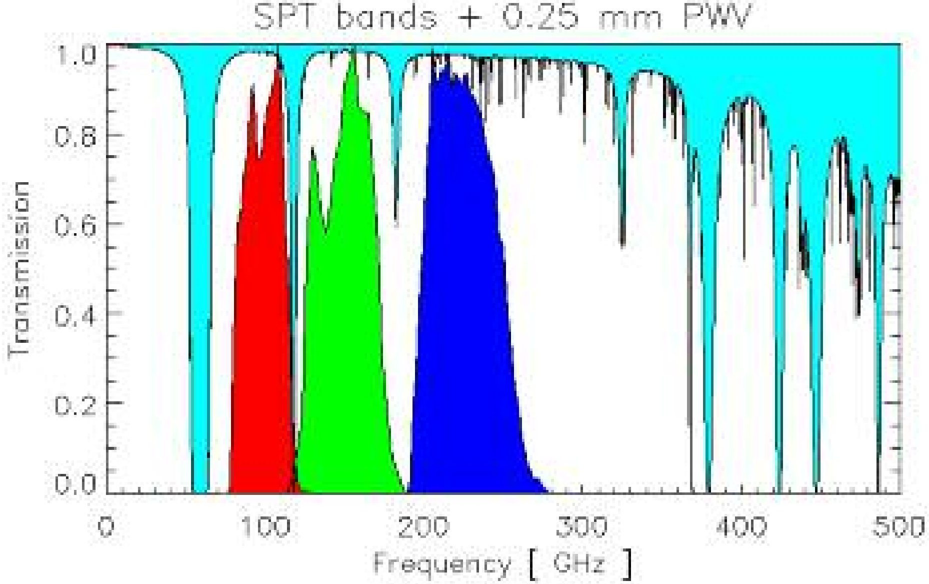
⇒ Maintain Gain Stability + Noise Level down to ~0.1 Hz

SZ Effect



Measured SZ spectrum of A2163

Observing Bands:
90, 150, 220 GHz



New 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

⇒ bolometer arrays (100s to 1000s)

extending observation time

⇒ 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 + ^{4}He/^{3}He/^{3}He 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)

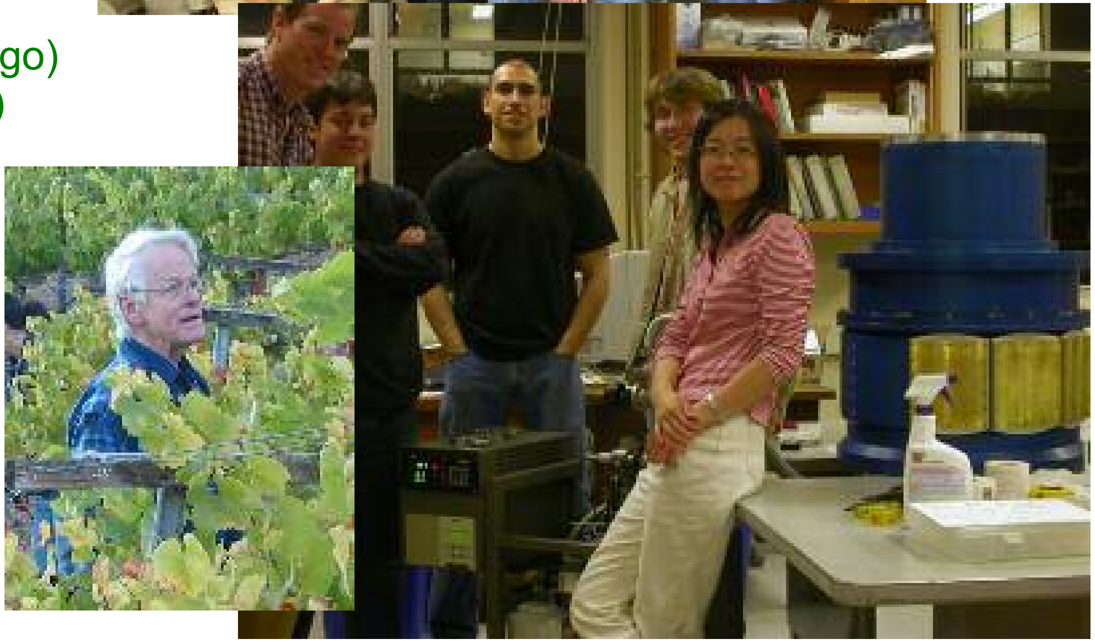
John Clarke (LBNL,UCB) SQUIDs

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

Brad Benson (UCB – now Univ. Chicago)
H.-M. "Sherry" Cho (UCB – now NIST)
Matt Dobbs (LBNL
– now McGill Univ.)
Nils Halverson (UCB
– now Univ. Colorado)
Huan Tran (UCB)

+ 15 graduate students

Support: NSF, NASA, DoE

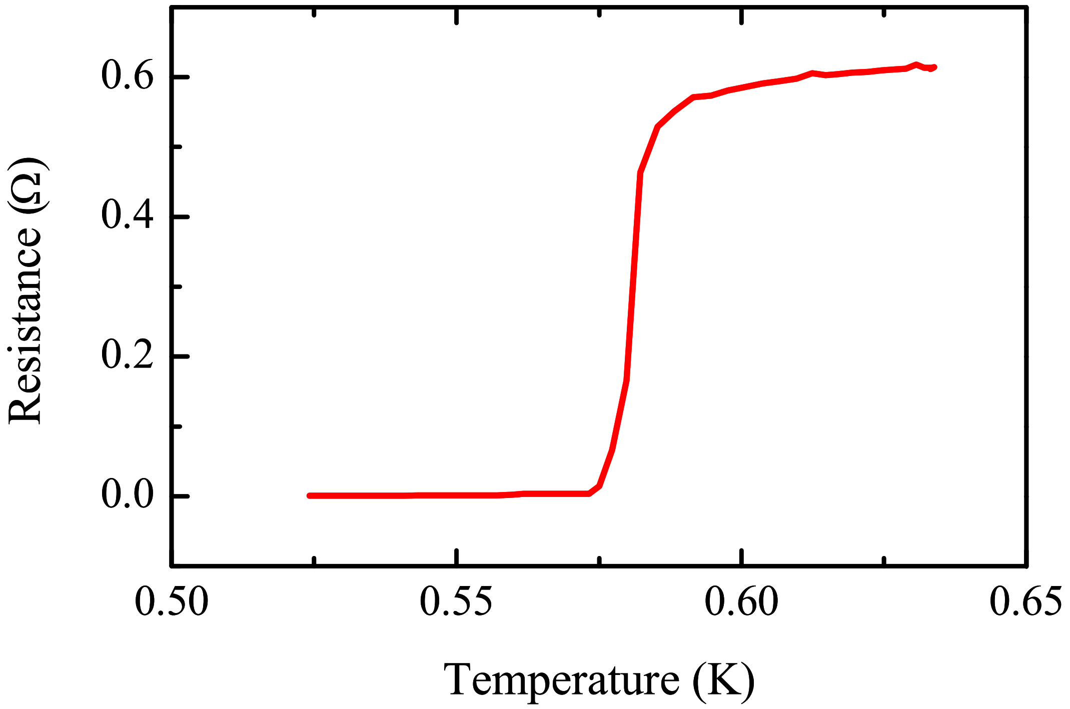


Bolometers

Superconducting transition edge sensors:

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

⇒ Large change in resistance with absorbed power



- Thin bi-layers (e.g. Al – Ti) allow tuning of transition temperature

Why Bolometers?

Amplifiers (phase coherent systems) subject to quantum noise limit.

Minimum spectral noise power density: $$\frac{dP}{d\omega} = \hbar\omega$$

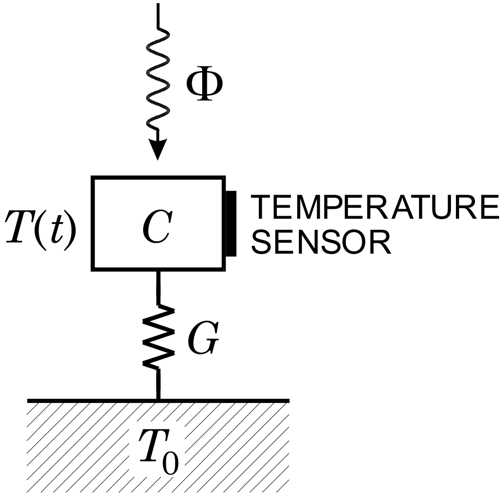
Follows from uncertainty principle.

(H.A. Haus and J.A. Mullen, Phys. Rev. 128 (1962) 2407-2413)

For a simple derivation see Spieler, *Semiconductor Detector Systems*, pp. 132-133

Bolometers do not preserve phase, so not subject to quantum noise limit.

Thermal Detectors



Basic principle:

Assume thermal equilibrium:

If all absorbed Energy $E = \Phi \Delta t$ is converted into phonons, the temperature of the sample will increase by

$$\Delta T = \frac{E}{C} \ ,$$

where C is the heat capacity of the sample (specific heat x mass).

After absorption of an energy packet E the heat flows through the thermal conductance G and the bolometer temperature decays as

$$T - T_0 = \frac{E}{C} e^{-t/\tau}$$

with the thermal time constant $\tau = \frac{C}{G} \ ,$

analogous to a capacitor discharged through a resistance.

Voltage-Biased Transition-Edge Sensors

Required power is of order pW, i.e.   voltage of order µV
current of order µA

Simplest to bias device with a constant current and measure change in voltage

Problem: power dissipated in sensor $P = I^2 R$

Increasing $R \Rightarrow$ Increasing $P \Rightarrow$ Increasing $R \Rightarrow$ Increasing P

$\Rightarrow$ thermal runaway

When biased with a constant voltage $P = \frac{V_b^2}{R}$

Increasing $R \Rightarrow$ Decreasing $P \Rightarrow$ Decreasing $T \Rightarrow$ Decreasing R

$\Rightarrow$ negative feedback $\Rightarrow$ stabilizes operating point

Analogous to op-amp: Bolometer time constant corresponds to amplifier cutoff frequency.

However, subject to constraints of feedback theory and possible instability!

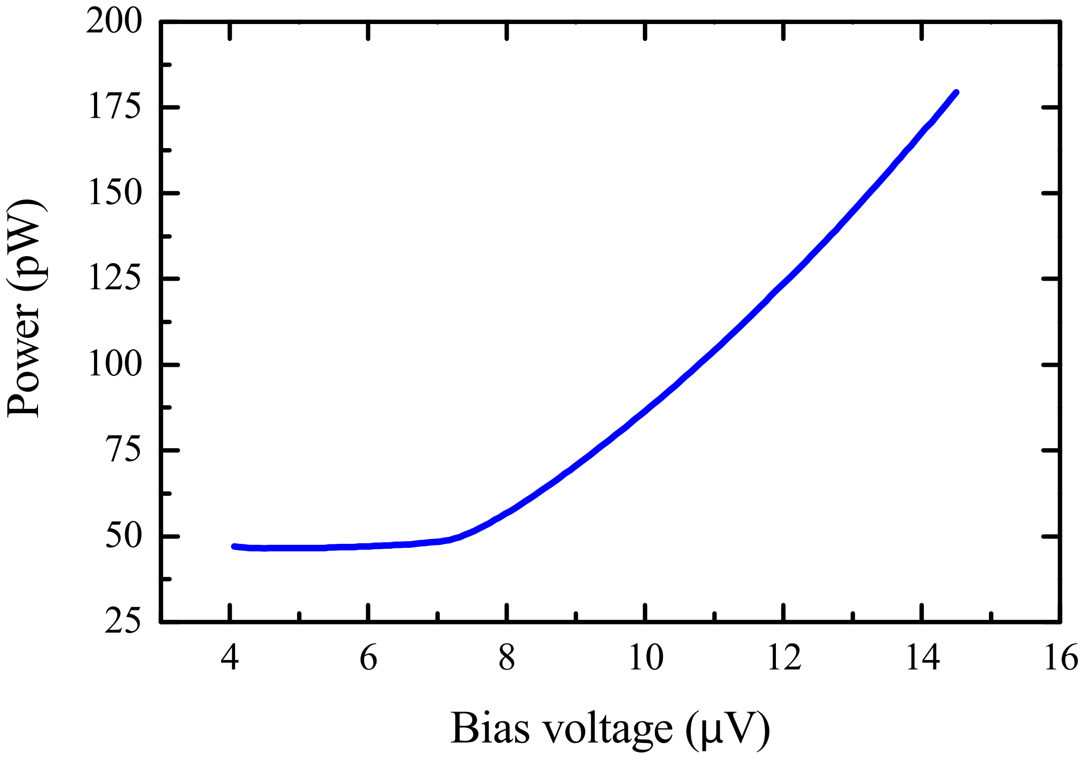
- Operate with constant voltage bias

⇒ Electrothermal negative feedback

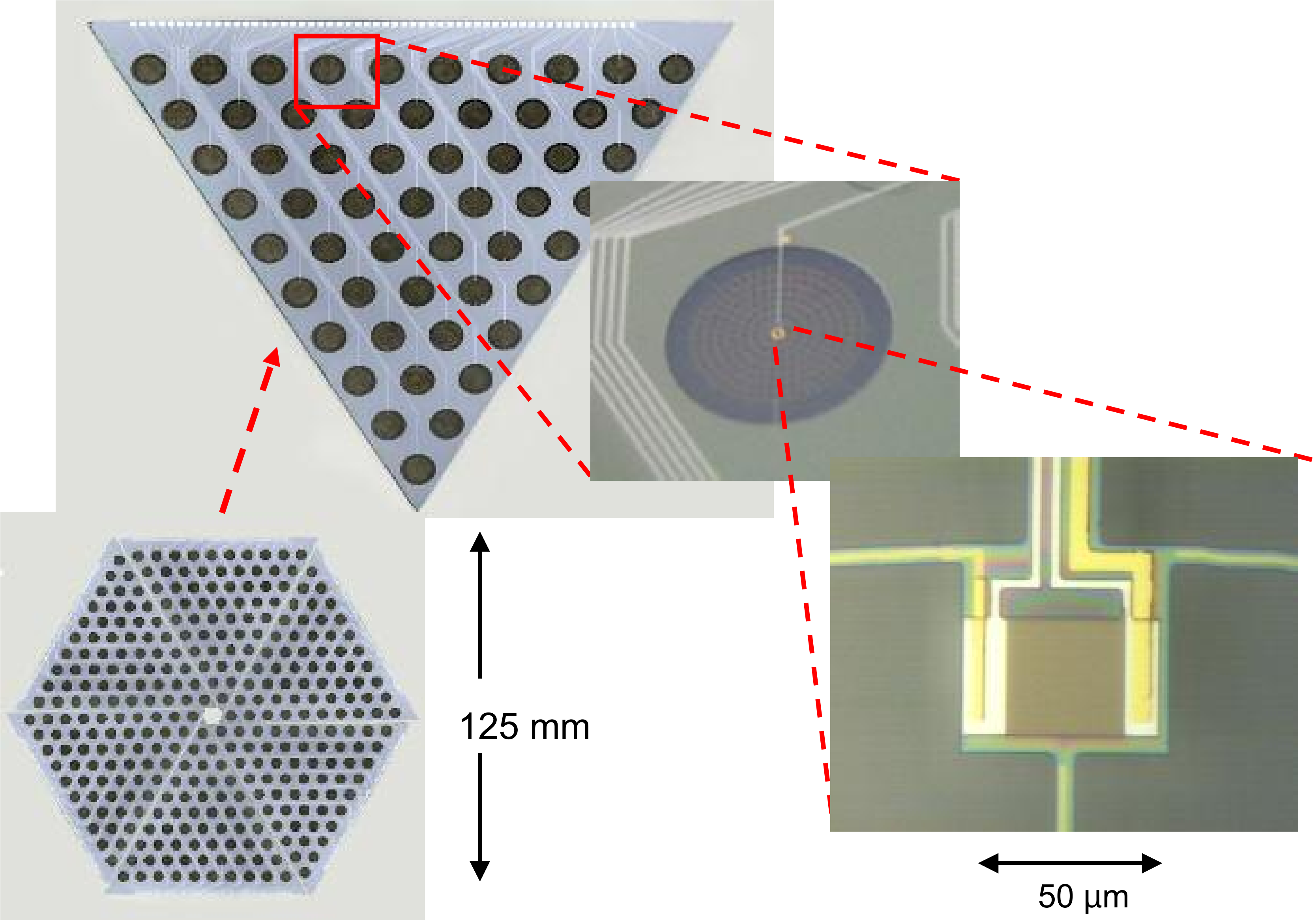
⇒ Stabilize operating point + predictable response

⇒ "Constant power operation":
Change in absorbed power is balanced by change in electrical power:

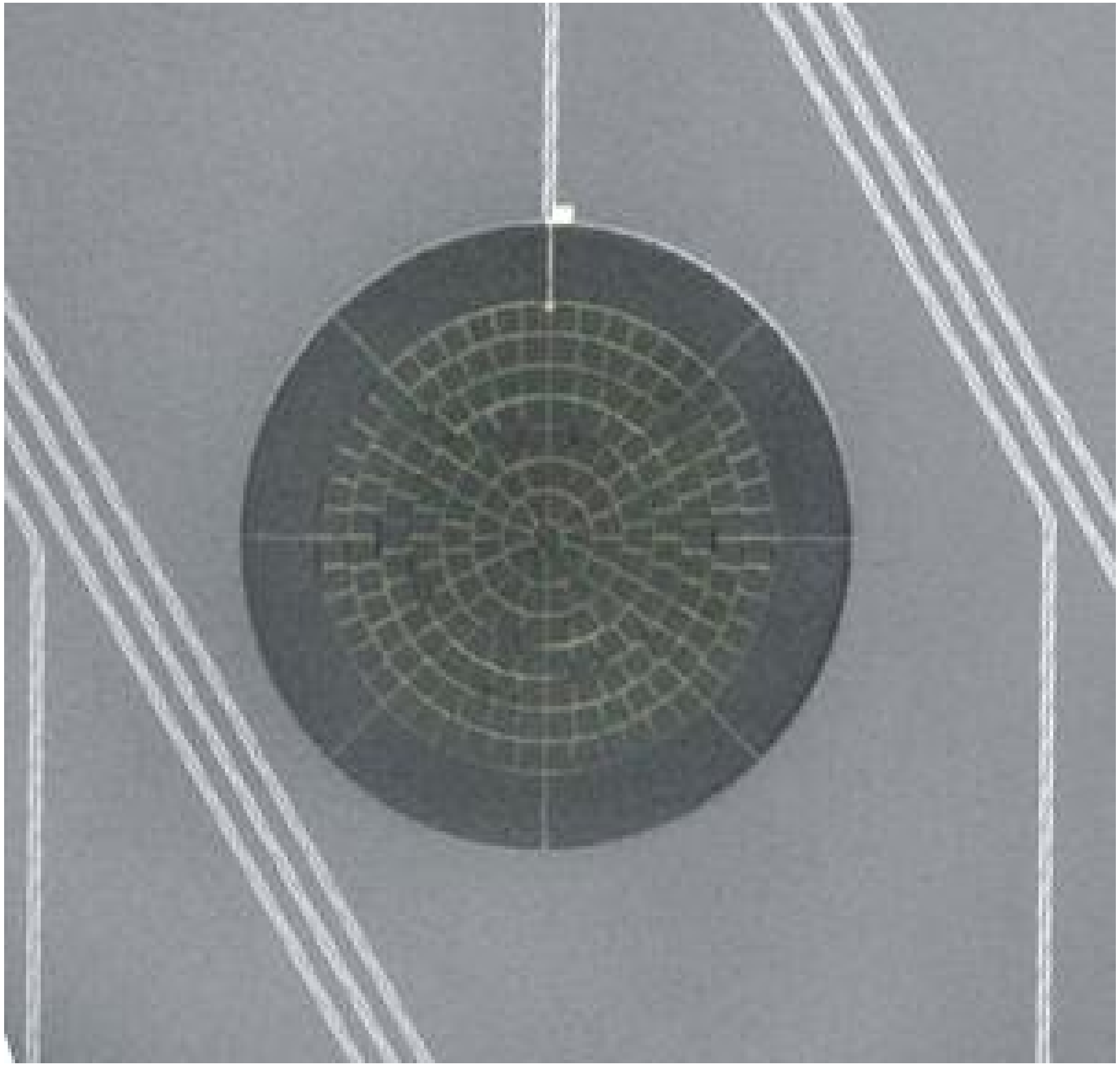
$$\Delta I / \Delta P = 1 / V_{bias}$$



APEX Focal Plane (Jared Mehl)



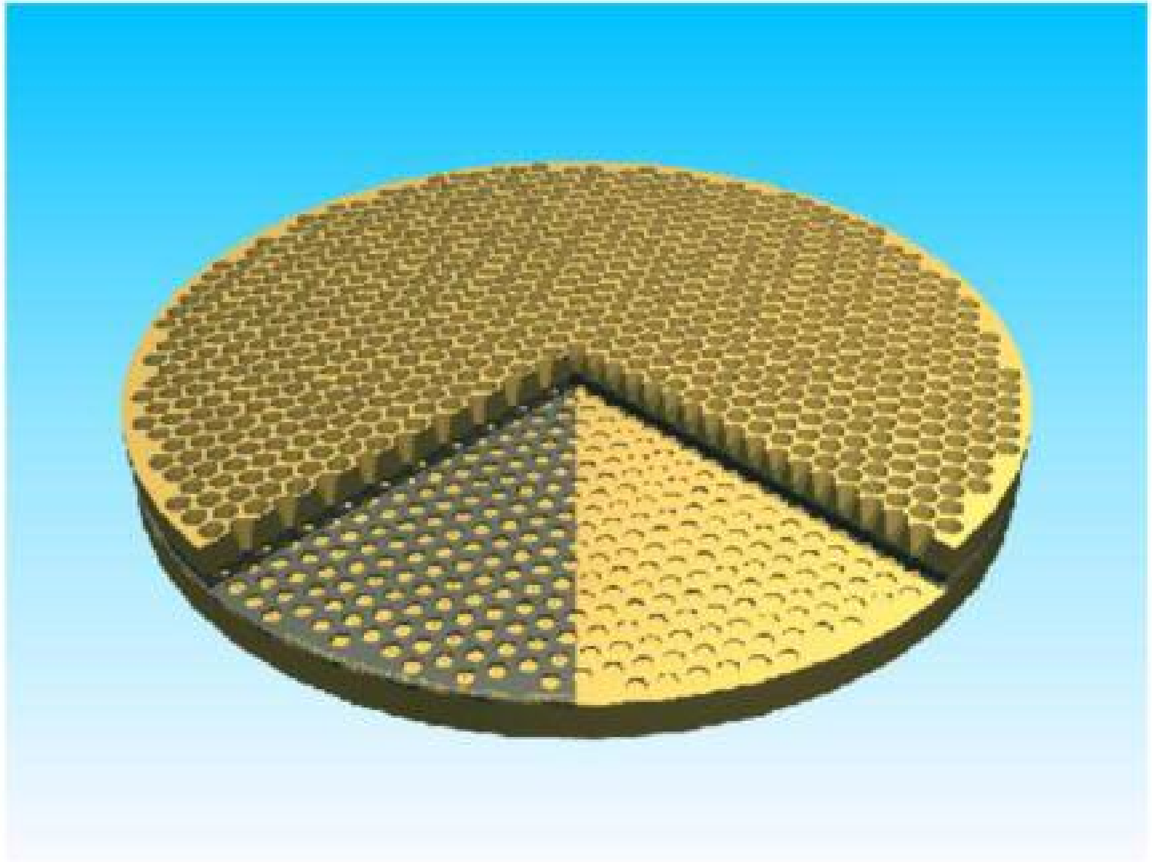
Close-up of spiderweb bolometer



Focal Plane Design for APEX-SZ and SPT

Disk with machined conical horns positioned above bolometer arrray.

Horns match optics to bolometer plane.



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

  (orders of magnitude greater than signal)

- 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

  + no noise degradation

Principle of Frequency-Domain Multiplexing

1. High-frequency bias (~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

⇒ High-frequency bias greatly reduces sensitivity to microphonics!

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

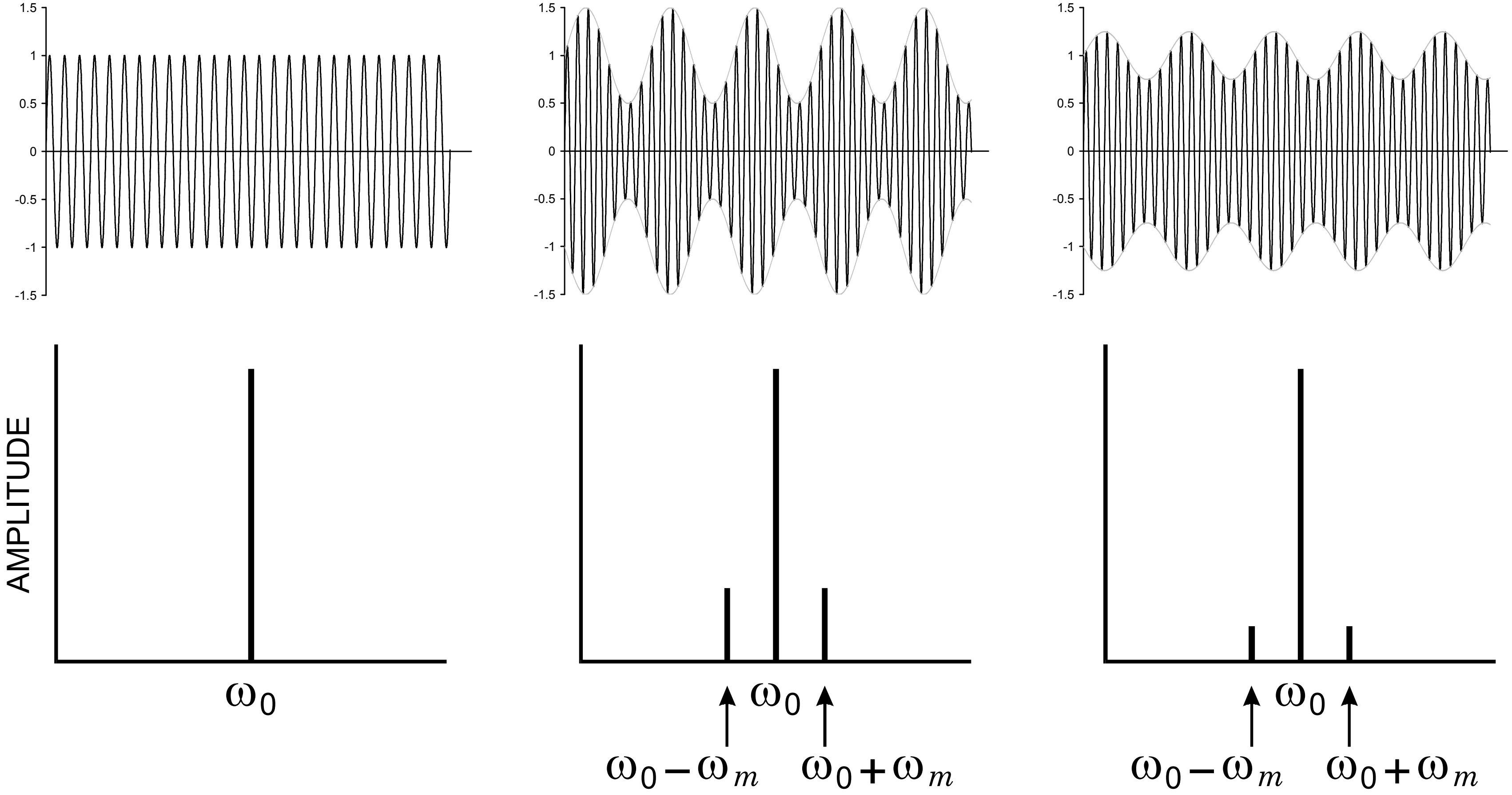
$(\omega_0 t + \omega_m t)$ and $(\omega_0 t - \omega_m t)$

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.

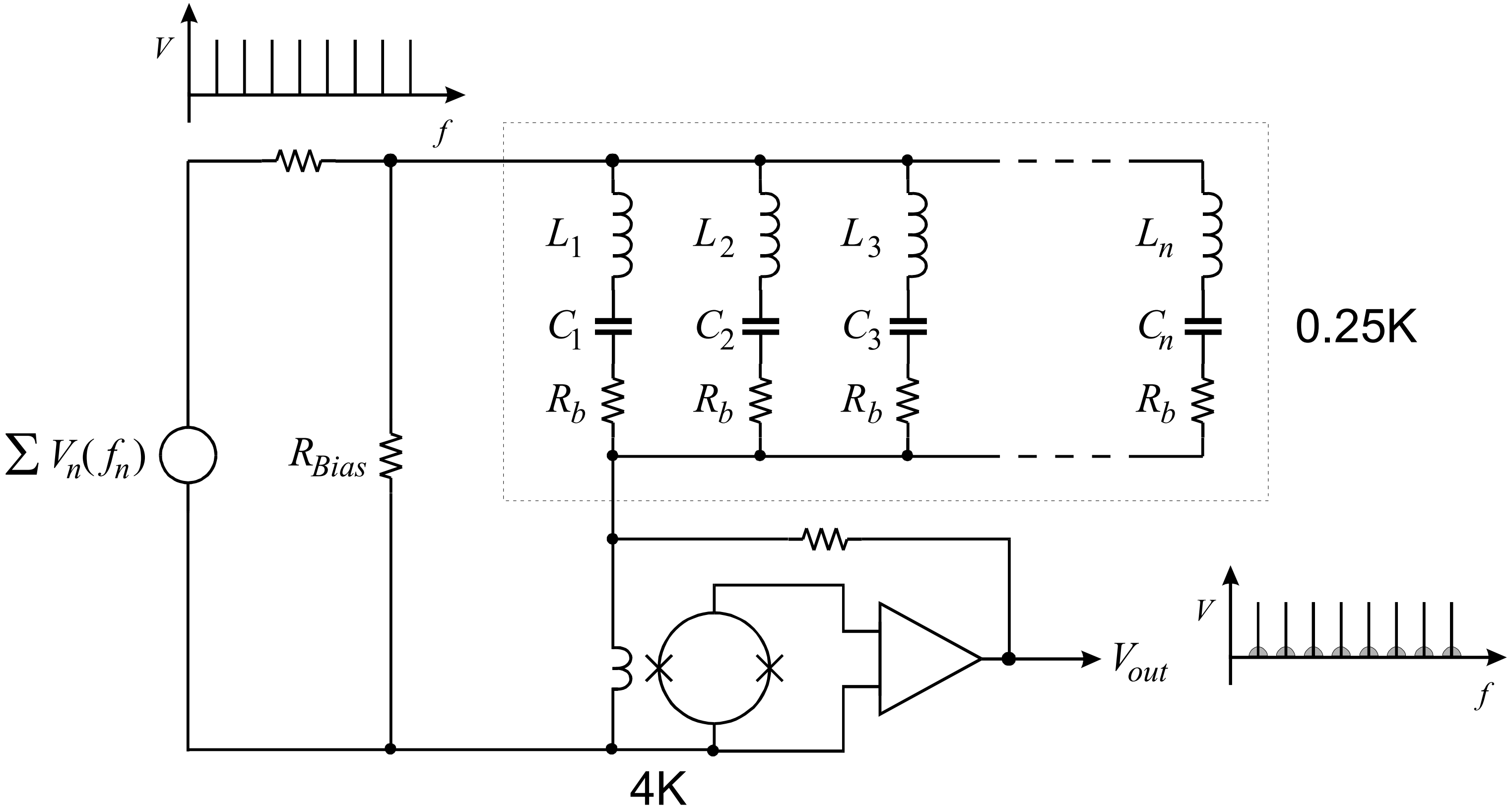
The power contained in the sidebands is equal to the modulation power, distributed equally between both sidebands.

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).

SQUIDs have limited signal range!

1. SQUIDs have periodic output

Maximum signals must remain within monotonic range

Dynamic range extended by

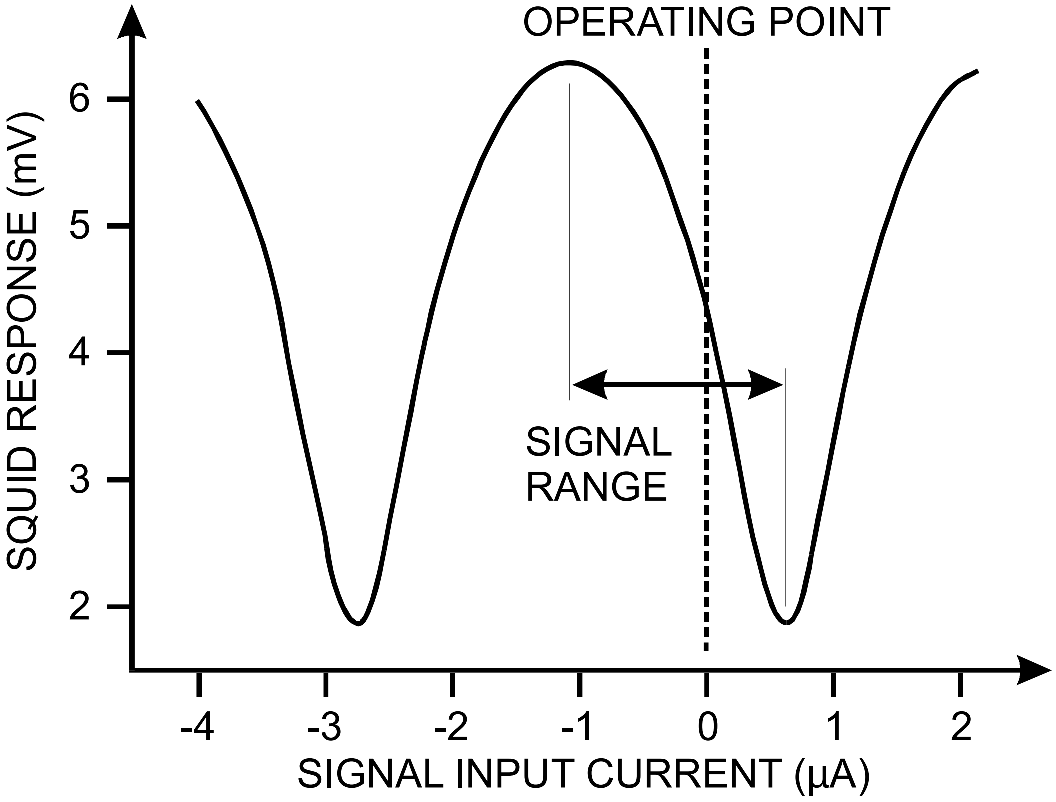
SQUID array
(100 SQUIDs in series)

Shunt feedback

2. Feedback must be active to maximum bias frequency (~MHz)

⇒ High loop gain-bandwidth product of 10s of MHz required

⇒ Limits wiring length to maintain phase margin for stability



3. In-situ characterization of individual SQUIDs required to determine operating point.

⇒ Digitally controlled bias scan and bias point

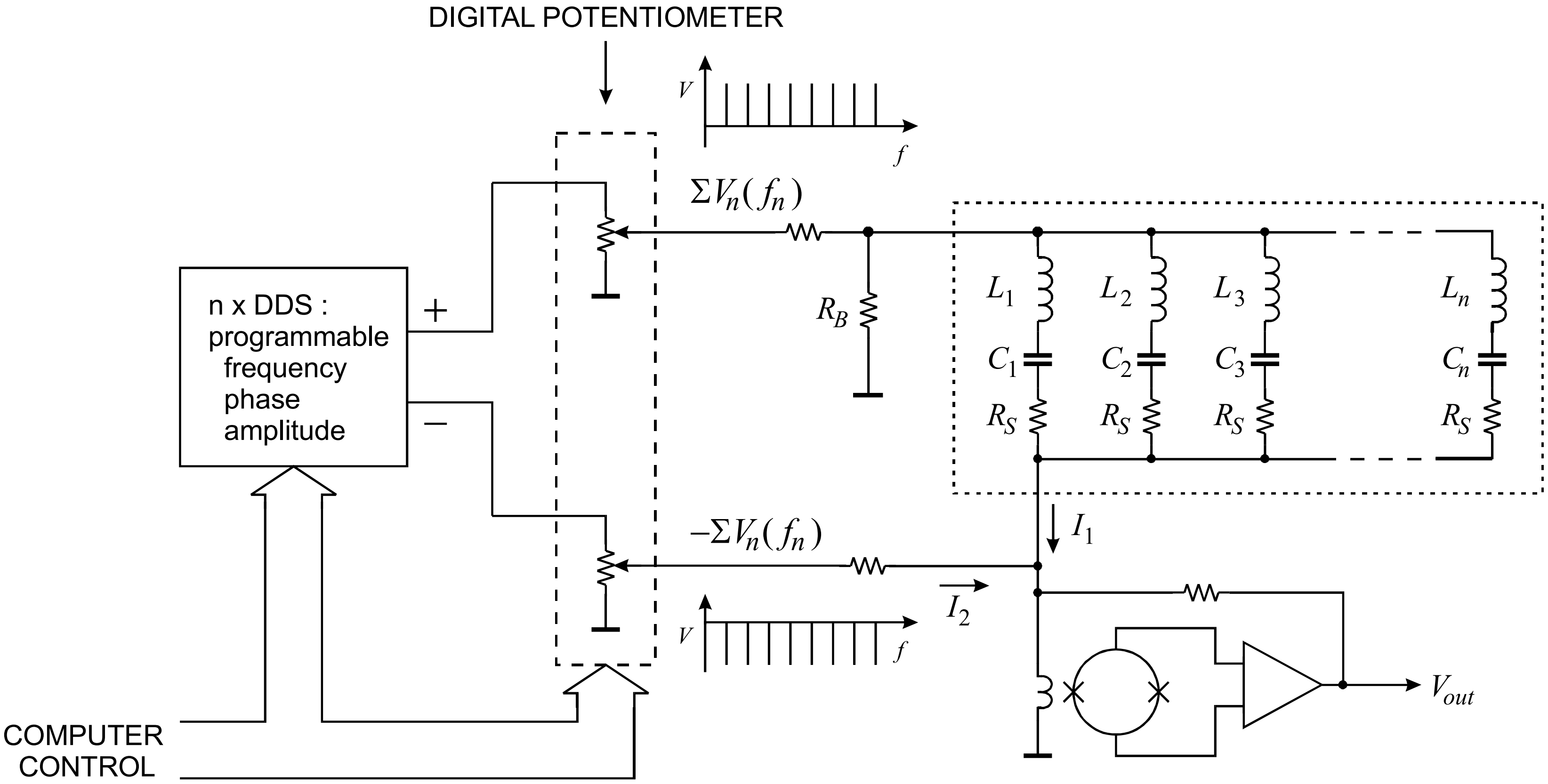
4. SQUIDs extremely sensitive to high-frequency RF pickup

⇒ Digital crosstalk big problem as wide bandwidth connections to SQUID required.

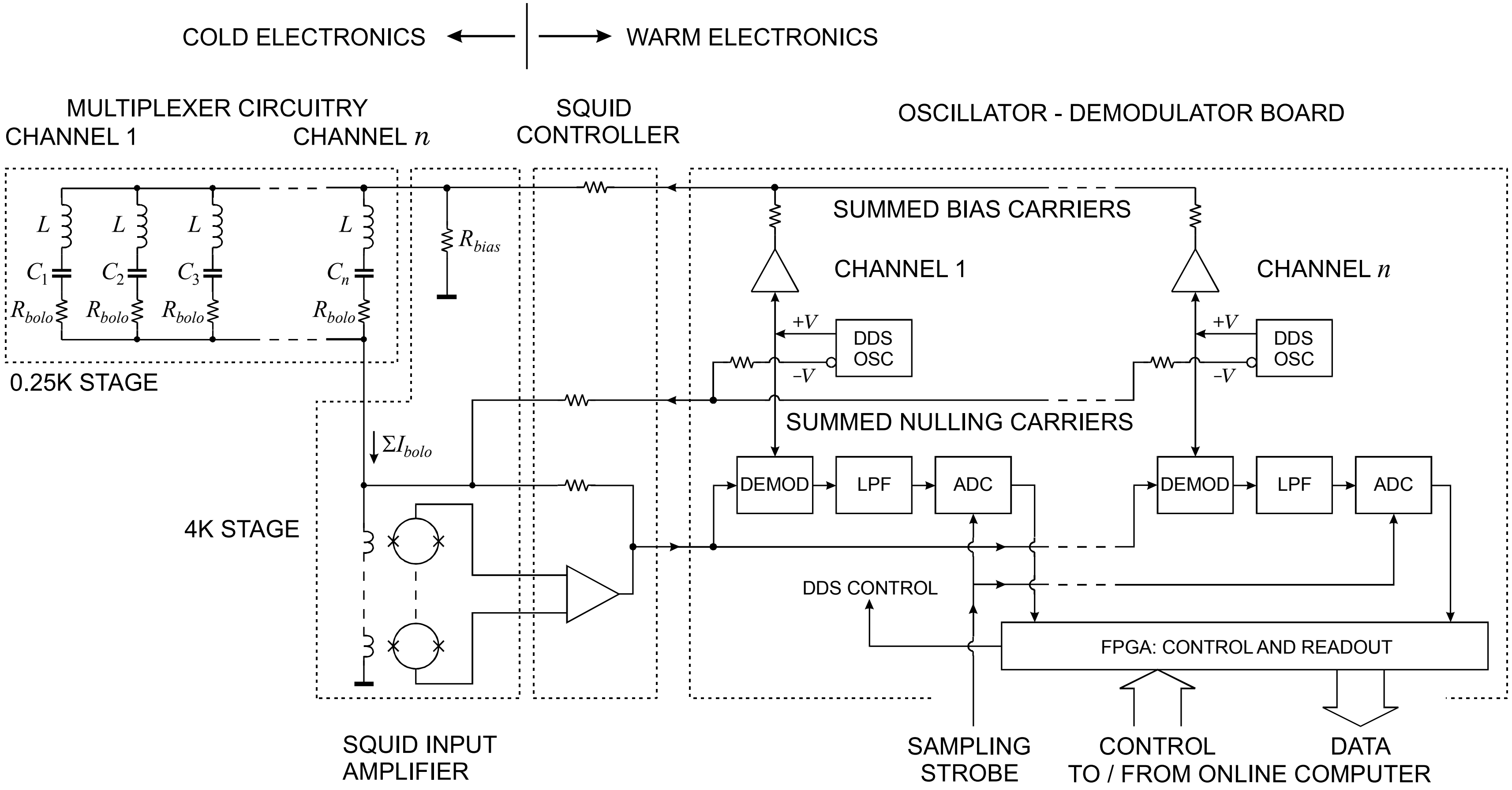
Carrier Nulling

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.



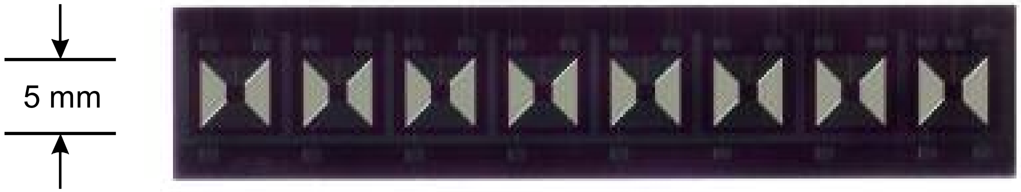
System Block Diagram



MUX chip (0.25K stage)

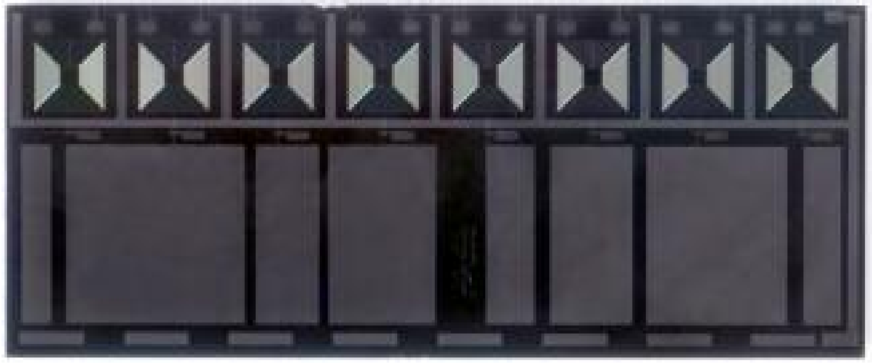
Superconducting spiral inductors integrated on a chip

(fabbed by Northrup-Grumman)



Capacitors can be integrated with inductors, but external chip capacitors require less space.

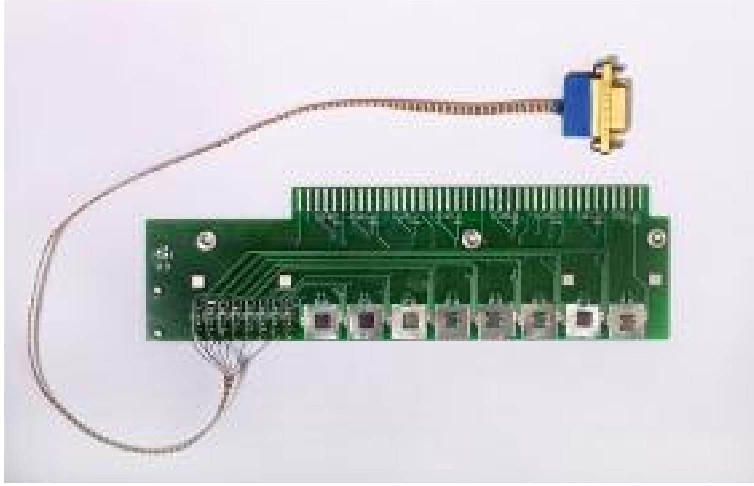
NP0 capacitors perform well at 4K



SQUIDs mounted as arrays of eight in magnetic shield (4K stage)

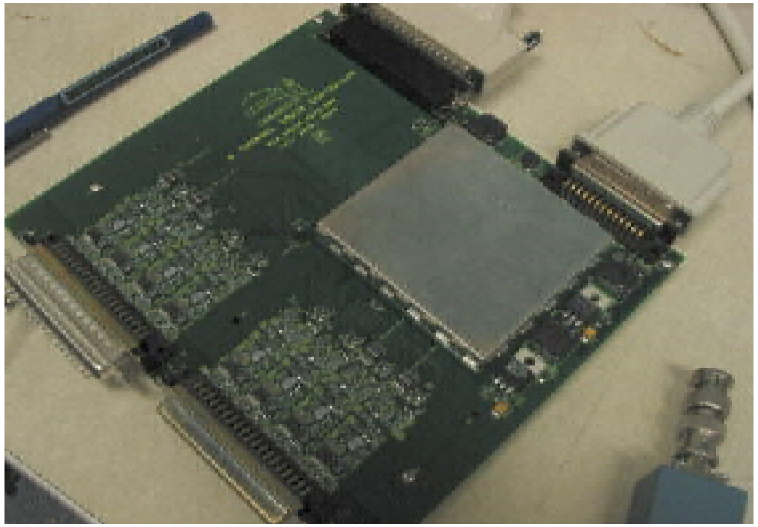
SQUID mounting board

SQUIDs mounted on Nb pads
to pin magnetic flux



Magnetic Shield
(M. Lueker)

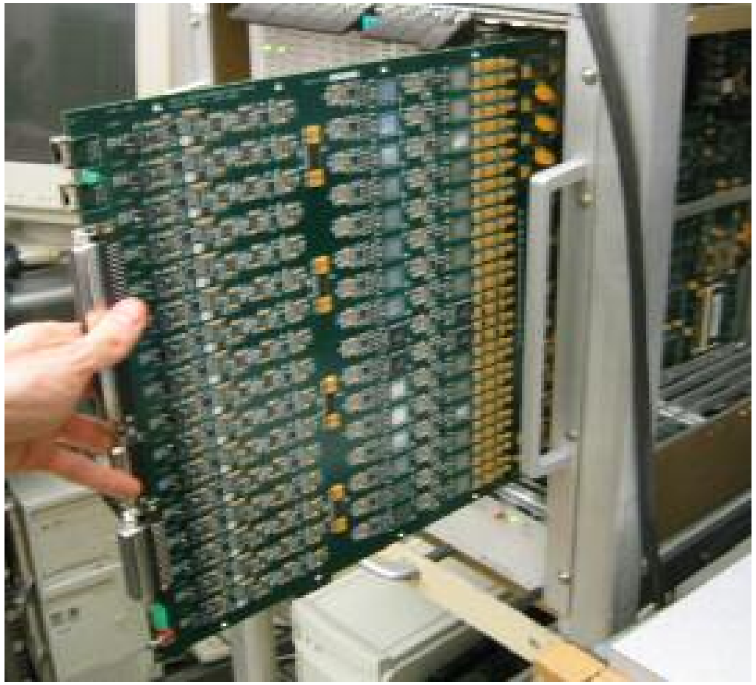
8-channel SQUID Controller



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

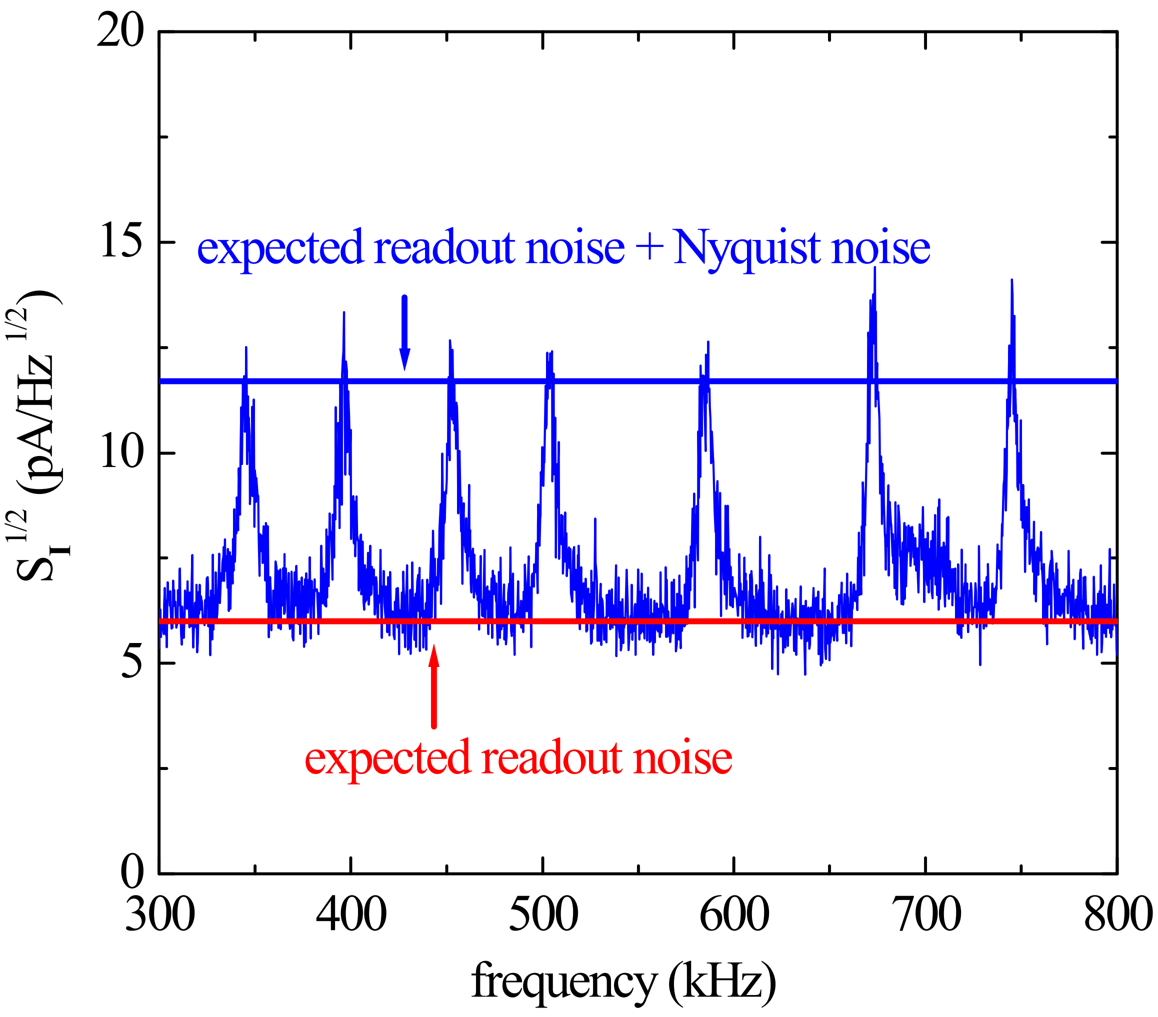


16 individual demodulator channels
1 DDS freq. generator per channel
On-board A/D
Opto-isolated computer interface

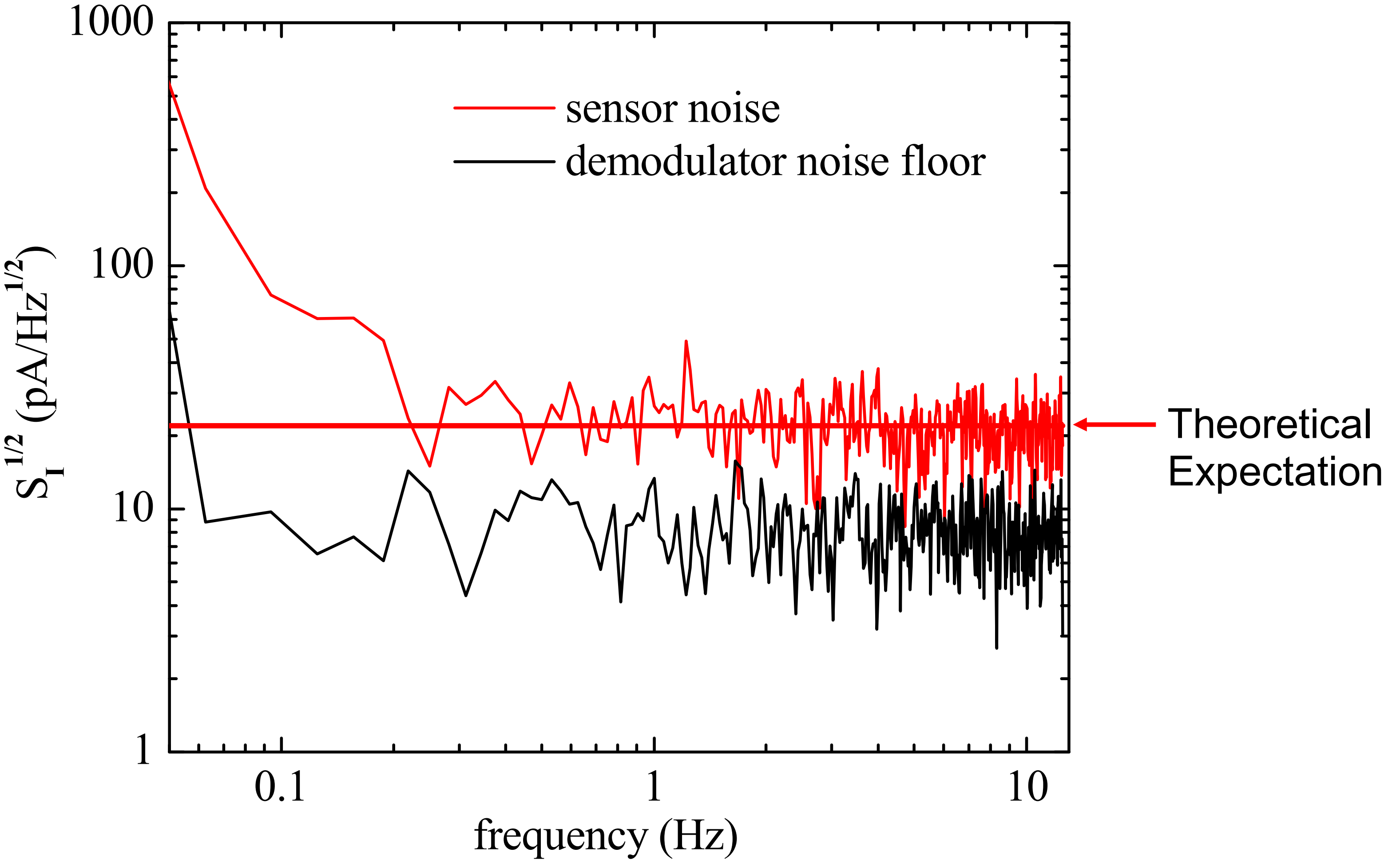
Design at LBNL
(M. Dobbs, J. Joseph, M. Lueker, C. Vu)

High Energy Physics experience essential!

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



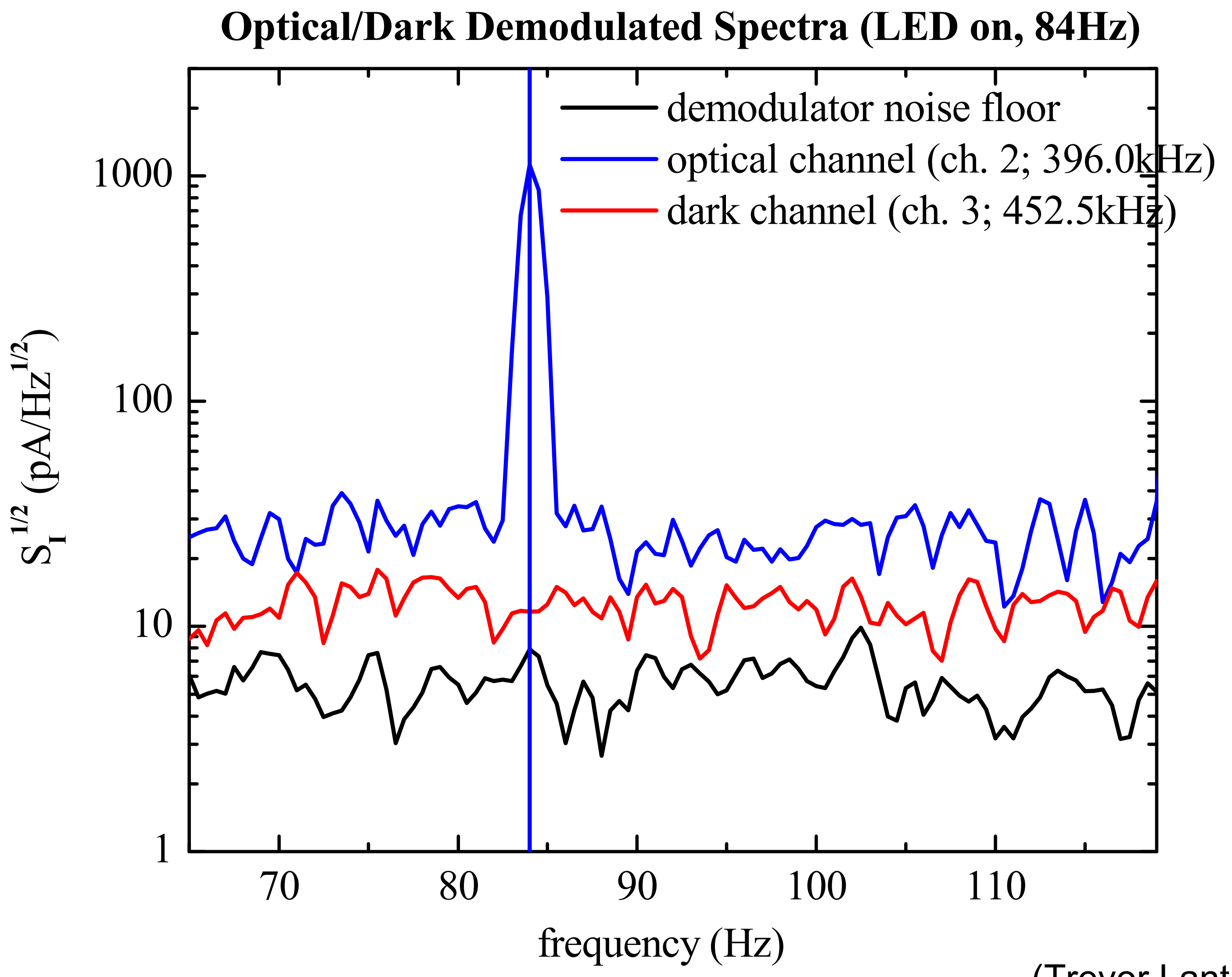
Measured Noise Spectrum in 8-Channel MUX System



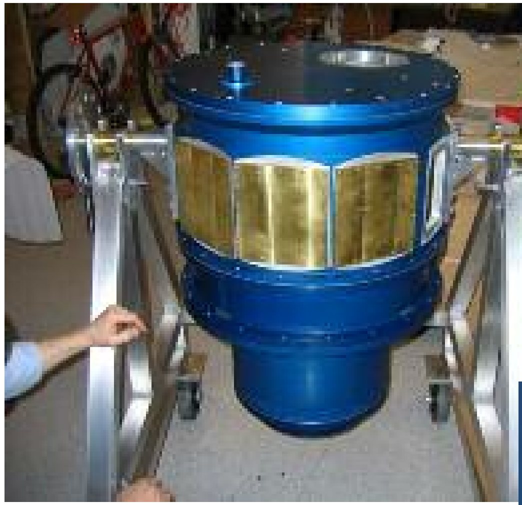
Sensor noise white above 0.2 Hz

(Trevor Lanting)

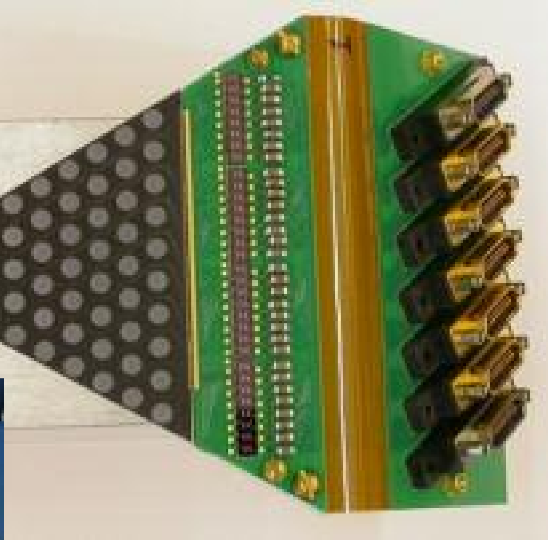
Cross-Talk < 1%

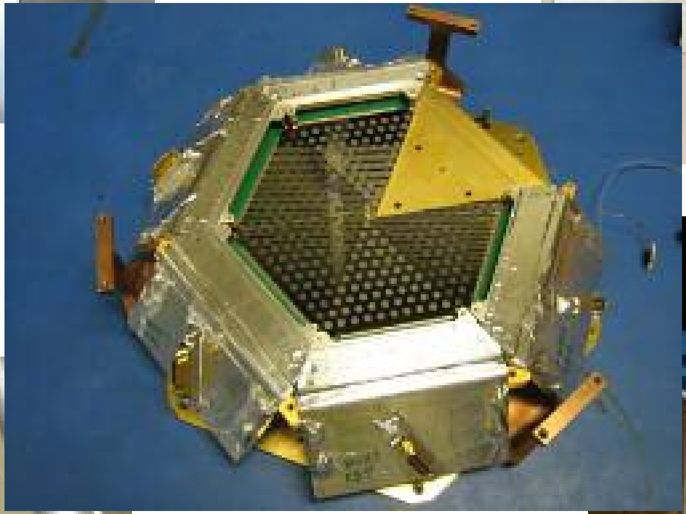


(Trevor Lanting)

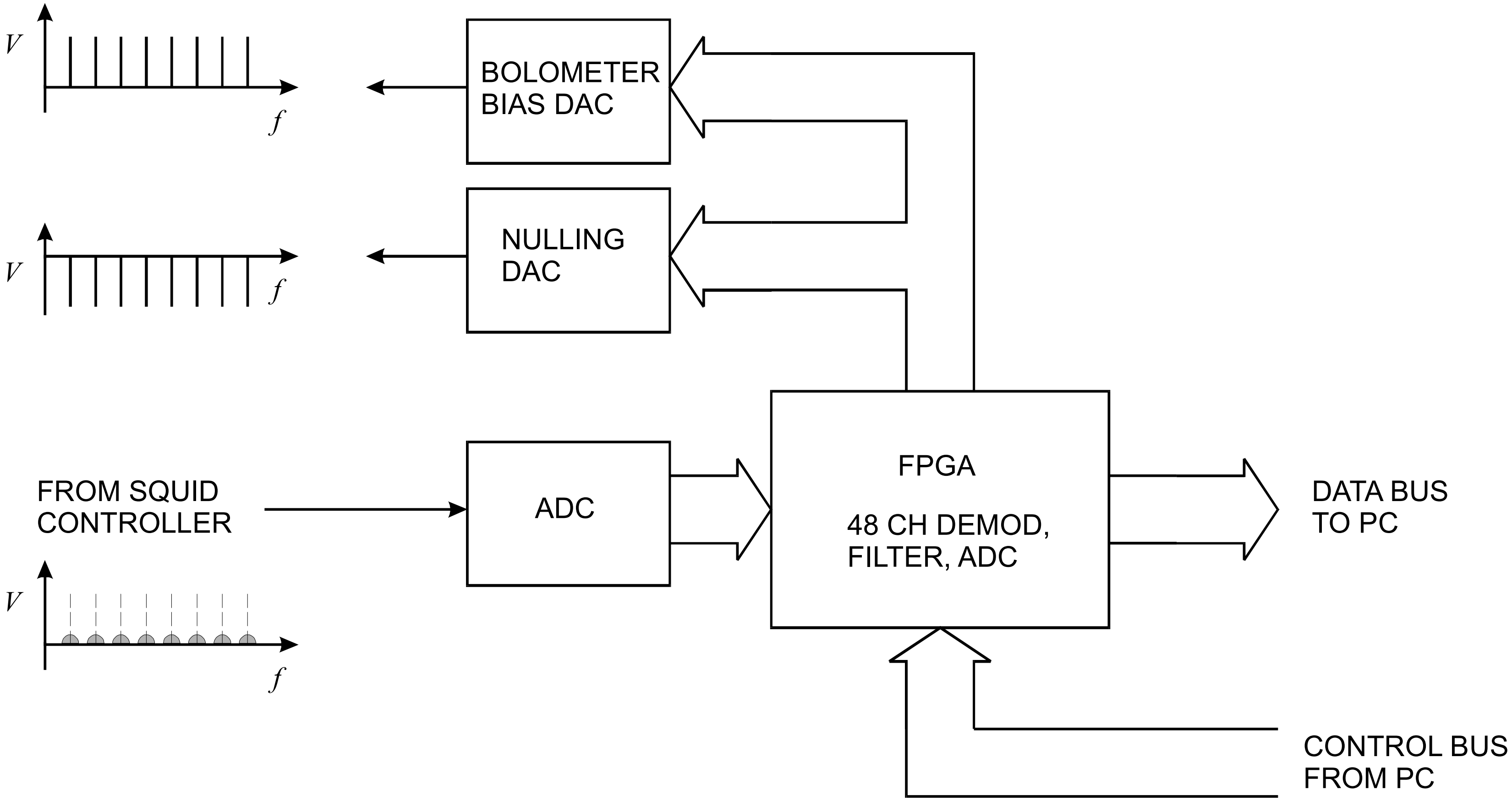


APEX-SZ MUXed Array (SPT prototype)



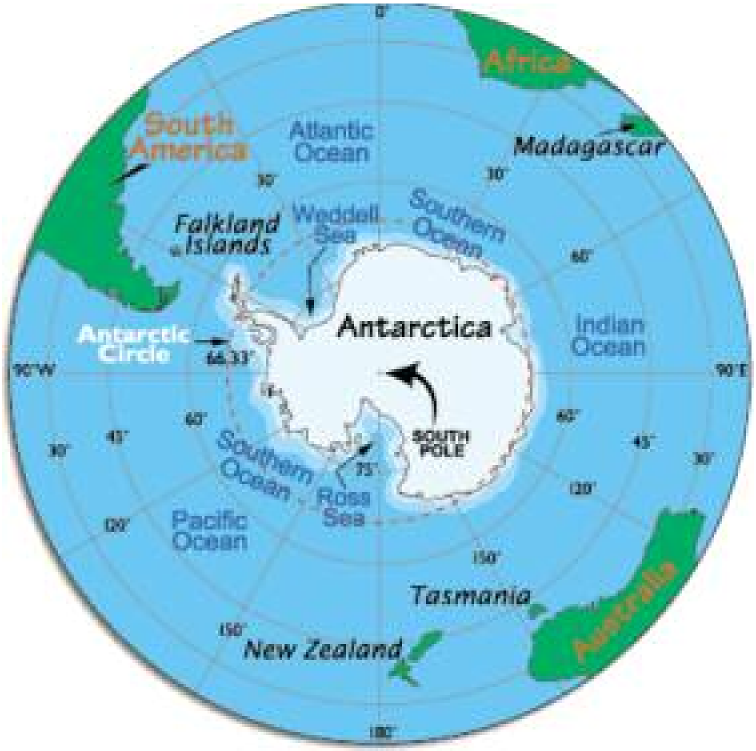


New Development: “Fully Digital” Demodulator (Matt Dobbs, LBNL/McGill)



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

Life at the Pole


0°
Africa
South America
Atlantic Ocean
Madagascar
30°
30°
Falkland Islands
Weddell Sea
Southern Ocean
60°
Antarctica
Indian Ocean
Antarctic Circle
66.33°
90°W
90°E
60°
60°
45°
45°
30°
30°
75°
SOUTH POLE
Southern Ocean
Ross Sea
120°
120°
Pacific Ocean
150°
150°
Tasmania
New Zealand
Australia
180°


Satellite Image Map of Antarctica
AVHRR Mosaic Color Composite
South Atlantic Ocean
Fimbull I.S.
Antarctic Peninsula
Weddell Sea
Filchner I.S.
Indian Ocean
Ronne I.S.
Amery I.S.
Ellsworth Mountains
Bellingshausen Sea
West I.S.
Transantarctic Mountains
Shakleton I.S.
Amundsen Sea
Ross I.S.
South Pacific Ocean
Ross Sea
McMurdo Sound
USGS
http://TerraWeb.wr.usgs.gov/TRS/projects/Antarctica/AVHRR.html
I.S. = Ice Shelf


TRANSPORTING MATERIALS TO THE SOUTH POLE
1
Port Hueneme
CA, USA
Vessel travels West through Pacific
2
Christchurch
NZ
3
All materials
must fit inside
Herc LC-130
4
McMurdo
5
South Pole
17 days
8,000 miles
7 days
2,400 miles
3 hrs.
900 m.
S.Pole season:
100 days
SEP
DEC
JAN
FEB
MID-NOV
MID-FEB

Flights from Christchurch to McMurdo in C-17

Landing on the Ross Ice Shelf

Mt. Erebus – Active Volcano

Take the bus to McMurdo

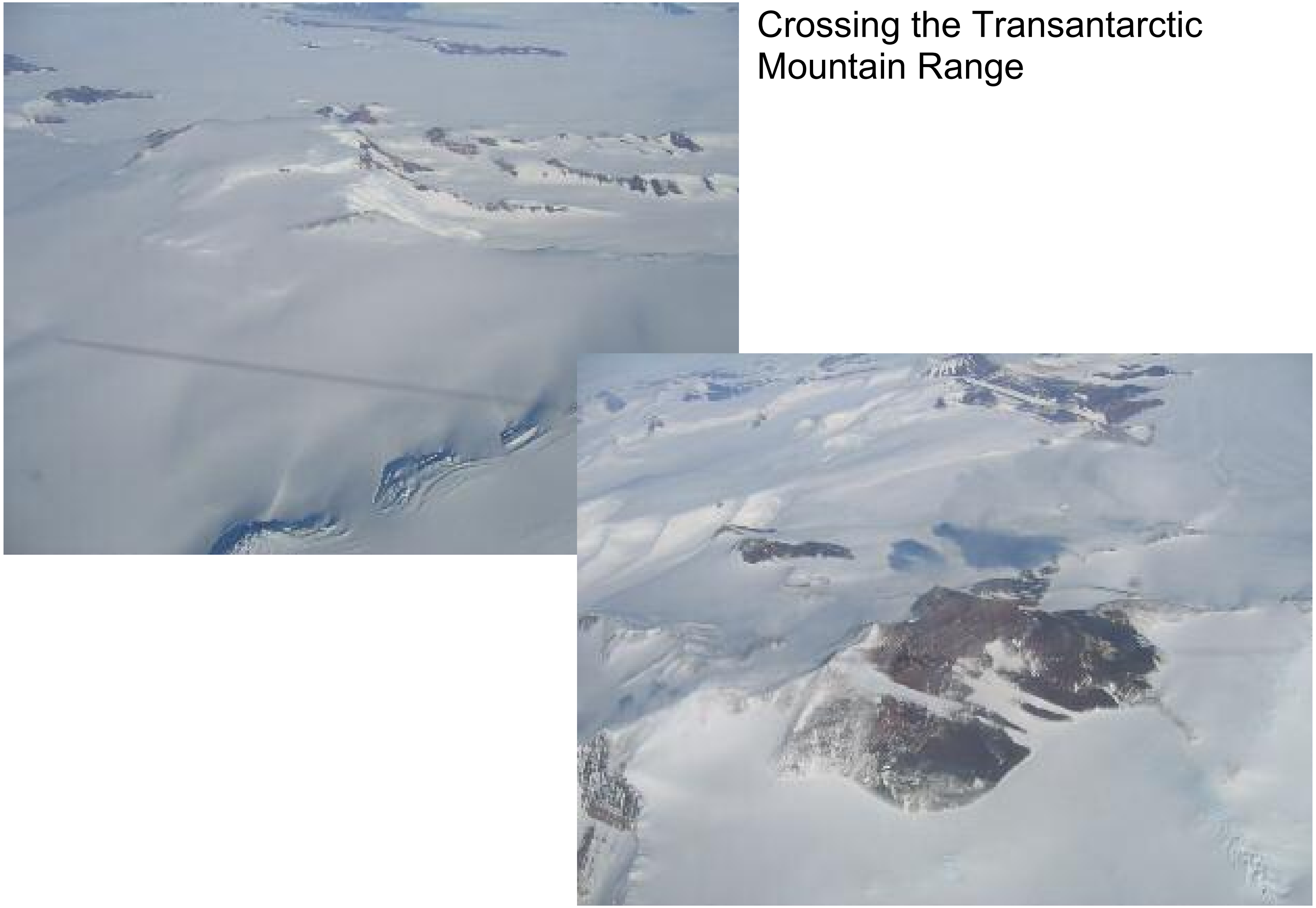
Summer in McMurdo

Flight to the Pole

All flights to the Pole are on C-130 cargo planes.

Flights are cancelled if weather either at the Pole or for return landing at McMurdo is uncertain

Crossing the Transantarctic Mountain Range



The Geographical South Pole

The “Ceremonial South Pole”

Altitude 9300 ft. It’s flat – the Pole is on 9000 ft of ice.

Another View: Drilling Holes for Ice Cube

South Pole Telescope and the Dark Sector Lab

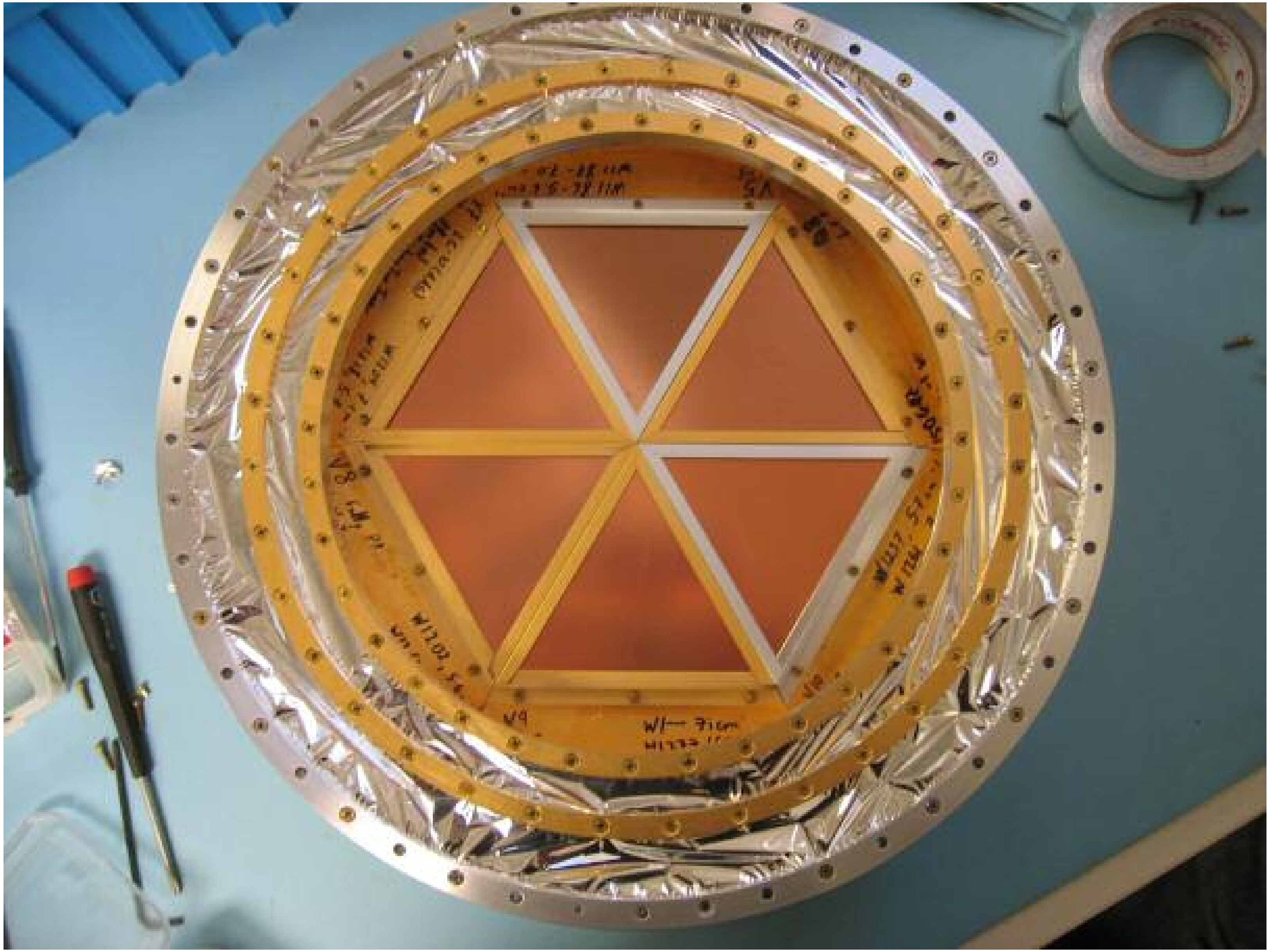
The optics cryostat (white) and receiver cryostat (red) removed from rcvr cabin

Disassembled focal plane for upgrades

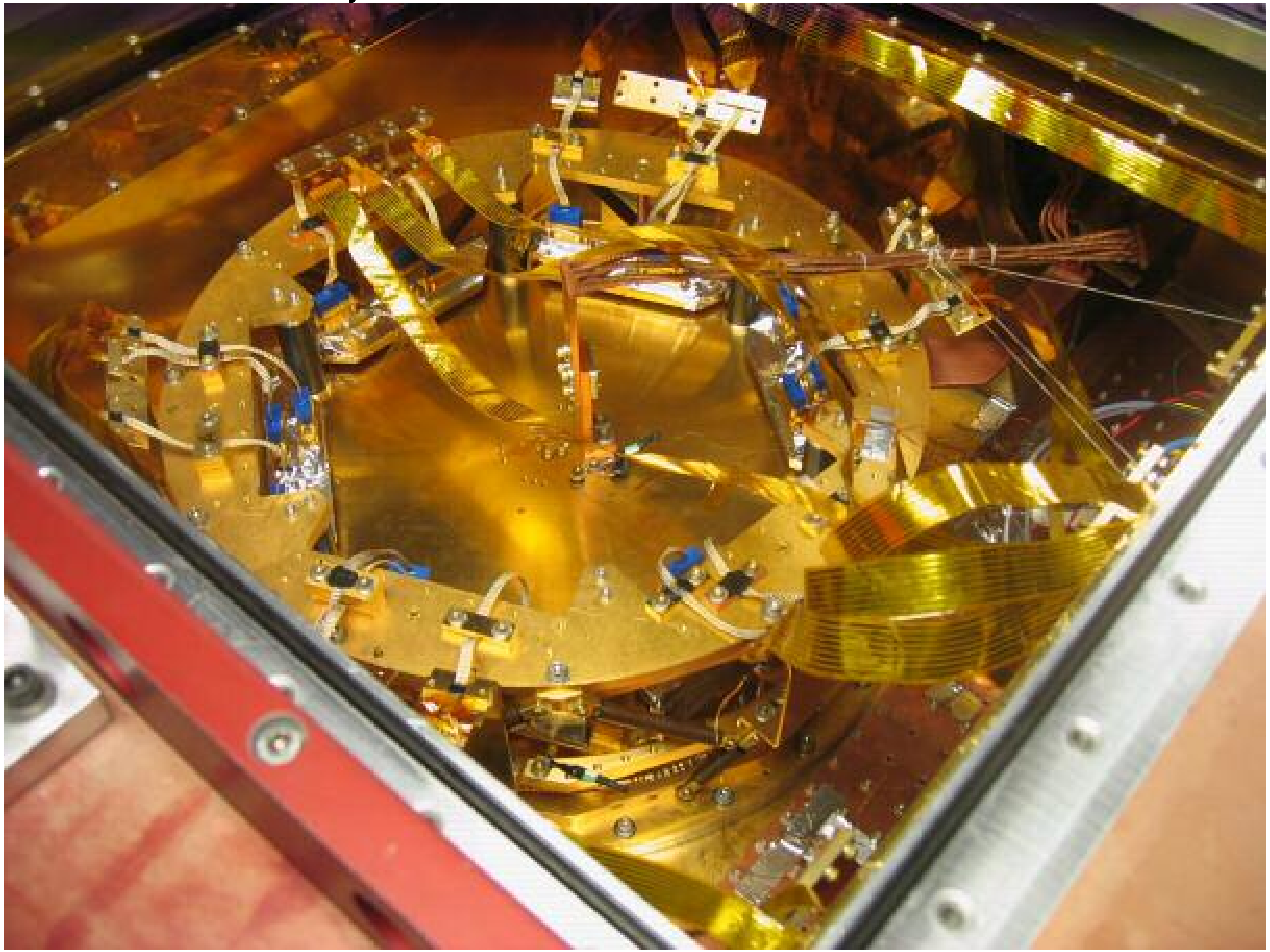
Wirebonding replacement SQUIDs

Sometimes some fine tuning is required

Assembled focal plane



Innards of receiver cryostat



Assembly area

Assembled cryostat beneath the open receiver cabin

Weather: Sun is up 24 hrs a day at about 23° above the horizon

Typical temperatures (2007-8): -40°C with -55°C wind chill
in winter typ. -70°C

Full gear for cold days, ...

but sometimes its “balmy”
(-20°C with little wind)

Visibility can change quickly

When it gets worse, follow the flags
(... better follow the right ones)

The main station
Summer population ~250
Winter ~60

The galley (food available 24 hrs)

Food is stored outside (at the Pole it's always well below freezing)


MERRY CHRISTMAS
FROM THE
SOUTH POLE

The Annual Race Around the World

The House Science Committee Playing Golf at the Pole

Takeoff for McMurdo

On the Ross Ice Shelf

2009 Flight McMurdo to Christchurch – 8 hrs “business class” in a Royal New Zealand Air Force C-130 (fuel economy much better than C-17)

Summary

- South Pole Telescope in its 3rd year of operation, taking data efficiently
- Current CMB experiments achieve 10^2 – 10^3 fold improved sensitivity
- Monolithic fabrication technology provides wafer-scale TES kilopixel arrays
- 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
- System incorporates techniques from
  - Cryogenics and superconductivity
  - RF communications (old and new)
  - Low noise analog electronics
  - High Energy Physics
- Collaboration between University and National Lab was essential, although not supported by funding agencies (NSF – DOE)

Enough Talk – the End