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.
The South Pole Telescope – Cosmology, Detectors, and Life at the Pole
UCSC Physics Colloquium, 11-Jun-2009

**History of the universe**

- **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 $\sim 10^{-5}$

Angular distribution

Angular Scale $\Delta \Theta \approx 180/\ell$
Angular structure depends on cosmological parameters

For example, geometry:
  dominant angular scale $\sim 1^\circ$
  $\Rightarrow$ universe is flat

Angular Scale $\Delta \Theta \approx 180/\ell$
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

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

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

- $3^{rd}$ peak > $2^{nd}$ 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 $\Omega_m$ 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 $\Rightarrow \omega$, $\Omega_m$ (gravity vs. “dark energy”)

Inverse Compton scattering: Hot gas bound to clusters of galaxies scatters CMB $\Rightarrow$ distorts black-body spectrum – shifts to higher frequencies:

At 150 GHz clusters appear as dark spots
The SZ signal is independent of redshift $z$.

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

$w$ 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 \( l > 2500 \)

Good measurement of \( \sigma_8 \) – amplitude of initial density perturbations.

Figure by Tom Crawford
DETECTORS
Detected Signal

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

$\text{REGION OF SKY AT TEMPERATURE } T$

$\text{PRIMARY REFLECTOR}$

$\text{SECONDARY REFLECTOR}$

POWER DELIVERED TO DETECTOR $\sim kTB$
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 3rd 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

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| LBNL                  |                                               |                                             |
| Helmuth Spieler       |                                               |                                             |

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| Univ. of Illinois Urbana       |                                               |                                             |
| John Mohr                      |                                              | Joe Dick                                   |
|                                  |                                              |                                             |
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|                                 |                                              |                                             |
|                                 |                                              |                                             |
|                                 |                                              |                                             |
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 ($T = 2.7$K):

$$P = kT B = 2.2 \cdot 10^{-15} \, B \, \text{erg/Hz} \, \text{or} \, 2.3 \cdot 10^{-4} \, B \, \text{eV/Hz}$$

$B = \text{Bandwidth}$

Cluster signal $< 1$ mK
Signal Spectrum in Galaxy Cluster Search

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

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

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 + $^4\text{He}/^3\text{He}/^3\text{He}$ 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
  \[ \Rightarrow \] 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 \( \mu V \)
current of order \( \mu A \)

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:

\[
\frac{\Delta I}{\Delta P} = \frac{1}{V_{bias}}
\]
Close-up of spiderweb bolometer
Focal Plane Design for APEX-SZ and SPT

Disk with machined conical horns positioned above bolometer array.

Horns match optics to bolometer plane.
READOUT
• Constant voltage bias requires that readout impedance $\ll$ bolometer resistance
  
bolometer resistance $\approx 1 \ \Omega$
  
bias resistance $\approx 20 \ \text{m}\Omega$
  
amplifier input impedance $\approx 10 \ \text{m}\Omega$

  1\textsuperscript{st} 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 $\mu$W

• Heat conduction through wires to 4K stage acceptable up to $\sim$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

$$(\omega_0 t + \omega_m t) \text{ and } (\omega_0 t - \omega_m t)$$

symmetrically positioned above and below the carrier frequency $\omega_0$.

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-feedback 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)
   \[ \Rightarrow \] High loop gain-bandwidth product of 10s of MHz required
   \[ \Rightarrow \] Limits wiring length to maintain phase margin for stability

3. In-situ characterization of individual SQUIDs required to determine operating point.
   \[ \Rightarrow \] Digitally controlled bias scan and bias point

4. SQUIDs extremely sensitive to high-frequency RF pickup
   \[ \Rightarrow \] 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

COLD ELECTRONICS ————> WARM ELECTRONICS

MULTIPLEXER CIRCUITRY
CHANNEL 1
CHANNEL n

SQUID CONTROLLER

OSCILLATOR - DEMODULATOR BOARD

SUMMED BIAS CARRIERS
CHANNEL 1
CHANNEL n

SUMMED NULLING CARRIERS

SQUID INPUT AMPLIFIER

DDS OSC

FPGA: CONTROL AND READOUT

TO / FROM ONLINE COMPUTER

The South Pole Telescope – Cosmology, Detectors, and Life at the Pole
UCSC Physics Colloquium, 11-Jun-2009

Helmuth Spieler
LBNL
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)
The South Pole Telescope – Cosmology, Detectors, and Life at the Pole
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Helmuth Spieler
LBNL

Measured Noise Spectrum in 8-Channel MUX System

- Sensor noise
- Demodulator noise floor

Sensor noise white above 0.2 Hz

(Trevor Lanting)
Cross-Talk < 1%

Optical/Dark Demodulated Spectra (LED on, 84Hz)

- demodulator noise floor
- optical channel (ch. 2; 396.0kHz)
- dark channel (ch. 3; 452.5kHz)

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 \( \Rightarrow \) Balloon-borne experiments (e.g. EBEX)
Satellite mission (CMBPOL?)
Life at the Pole
The South Pole Telescope – Cosmology, Detectors, and Life at the Pole
UCSC Physics Colloquium, 11-Jun-2009
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
The optics cryostat (white) and receiver cryostat (red) removed from rcvr cabin
Disassembled focal plane for upgrades

Sometimes some fine tuning is required

Wirebonding replacement SQUIDs
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)
The Annual Race Around the World
The House Science Committee Playing Golf at the Pole
Takeoff for McMurdo

On the Ross Ice Shelf
... sometimes there’s a special reception party
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