SQUIDs: Then and Now

Josephson Semicentennial Celebration
Cambridge
23 June 2012

Prologue

Royal Society Mond Laboratory

Free School Lane

Cambridge

New research student 1 October 1964

Eric Gill 1933

Why "Free School Lane"?

The "Free School" was founded in 1615 by Dr Stephen Perse who left money in his will to educate 100 boys from Cambridge, Barnwell, Chesterton and Trumpington . The PERSE SCHOOL occupied this site until 1890, and the Whipple Museum is situated in the original school hall—100 m south of the Mond.

Free School Lane100 m North of the Mond

SQUIDs Then…

First Week at the Mond

- Thesis advisor: Brian Pippard

- Thesis research required measuring voltages of 10^{-12} to 10^{-13} volts

A Superconducting Galvanometer

By A. B. Pippard and G. T. Pullan

Received 21 June 1951

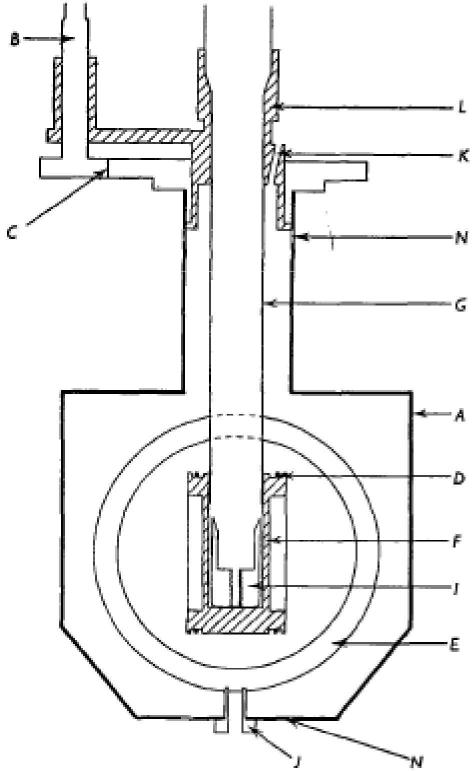
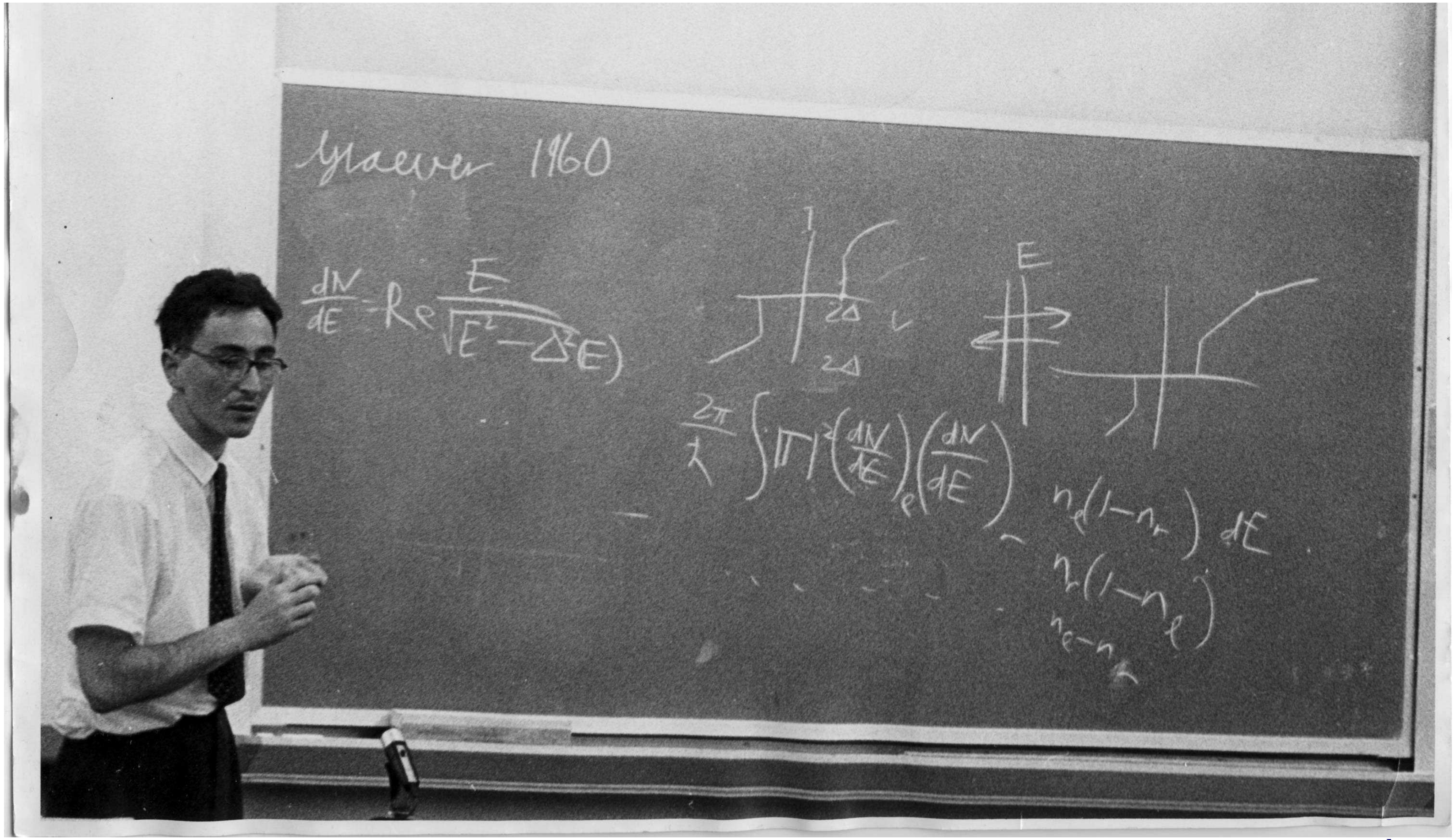


Fig. 2. The galvanometer coil assembly.

- Tangent magnetometer
- Magnet and mirror suspended from a long quartz fiber at the centre of a Helmholtz pair
- Current in the coil caused a deflection of a reflected light beam

Brian Josephson Explains Tunneling

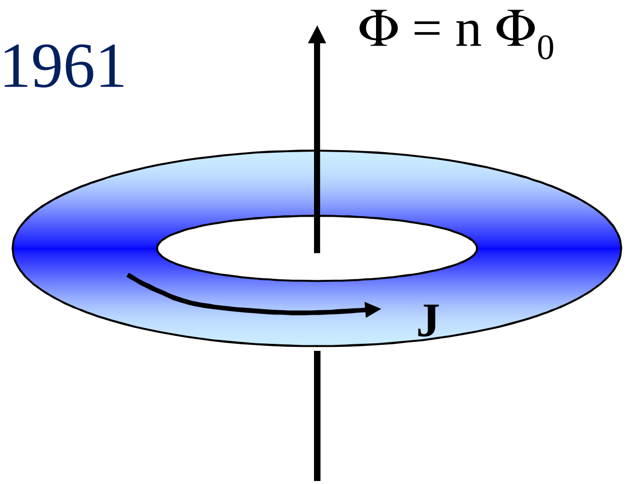


Courtesy Brian Josephson

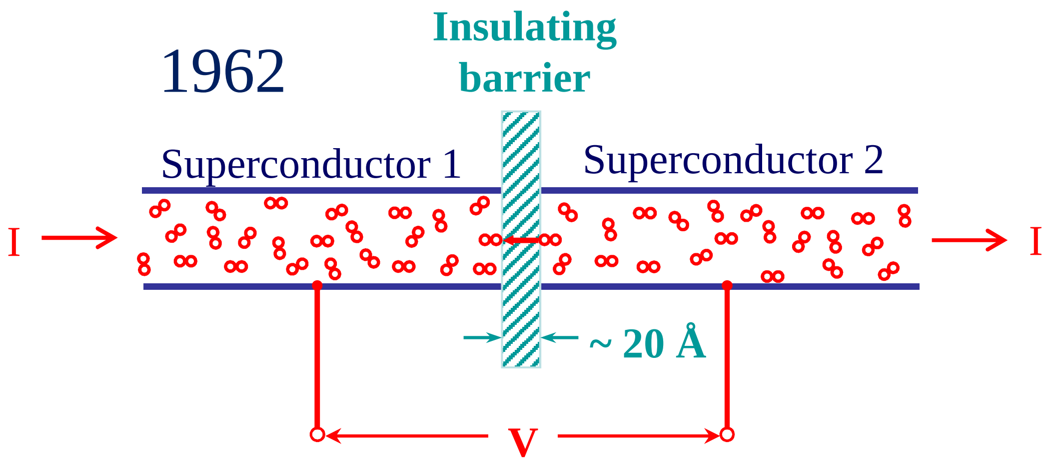
November 1964

1961 to 1964

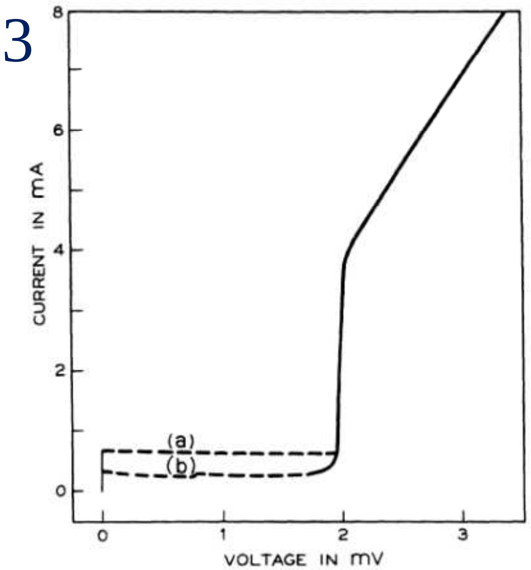
1961



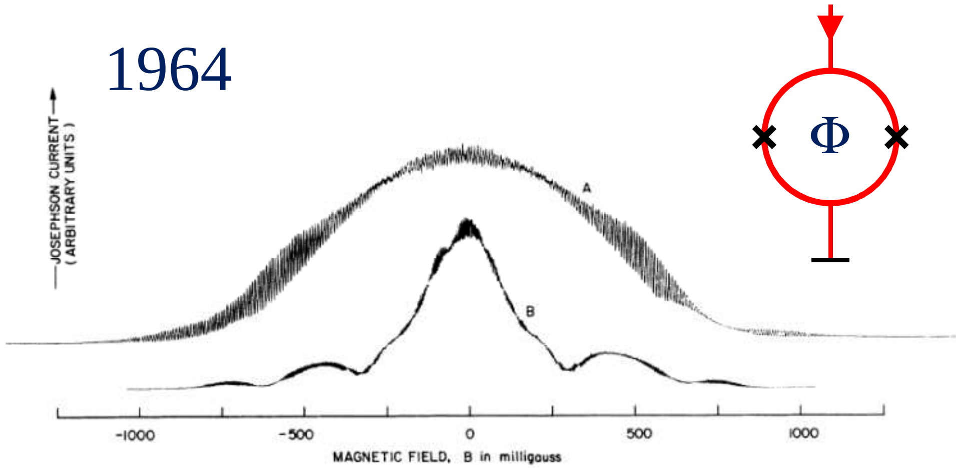
1962



1963



1964



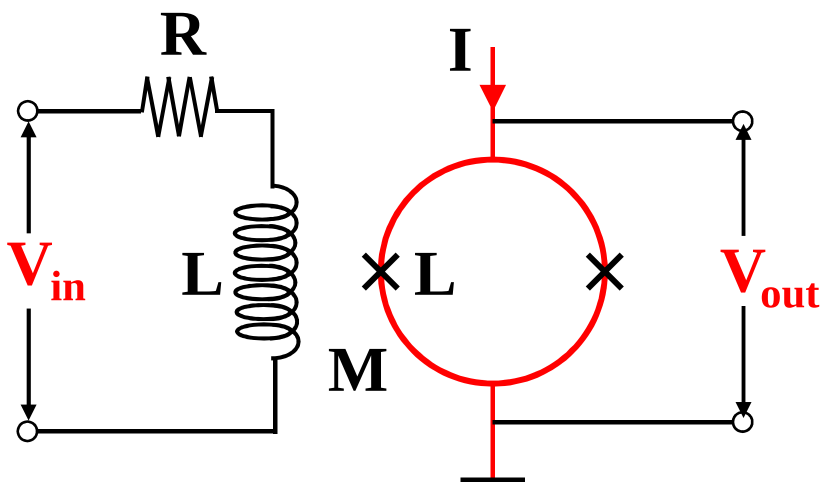
The Very Next Day—November 1964

Brian Pippard:

"John, How would you like a voltmeter with a resolution of 2×10^{-15} V in 1 second?"

Courtesy Kelvin Fagan

Brian's Idea



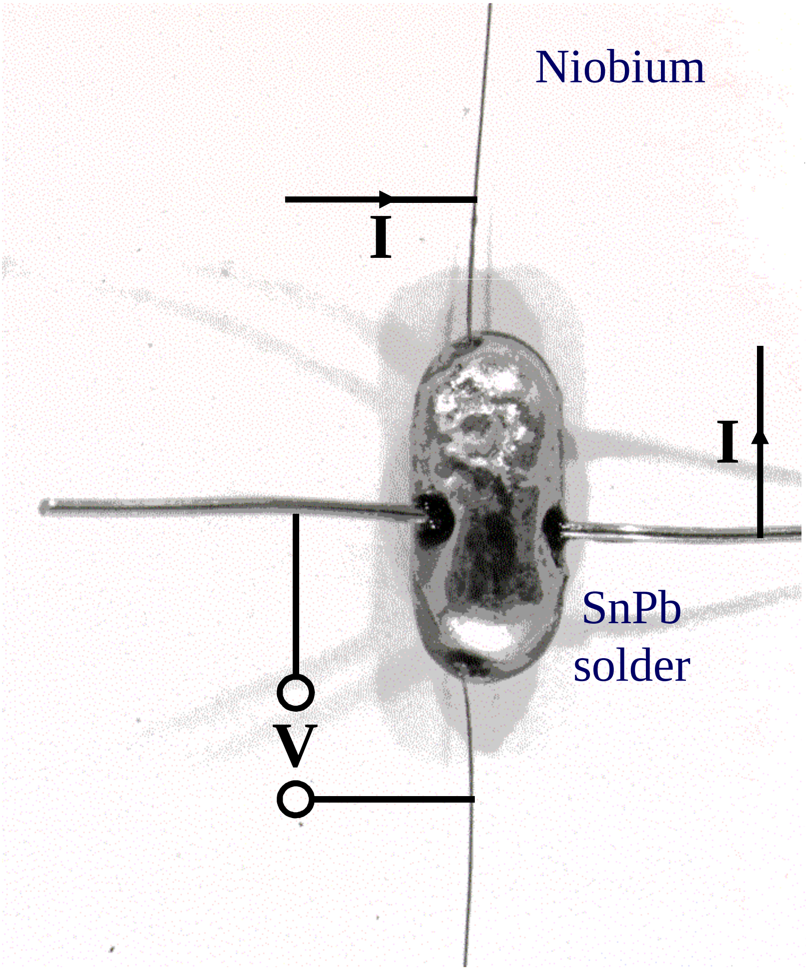
$M = L$
$\tau = L/R$

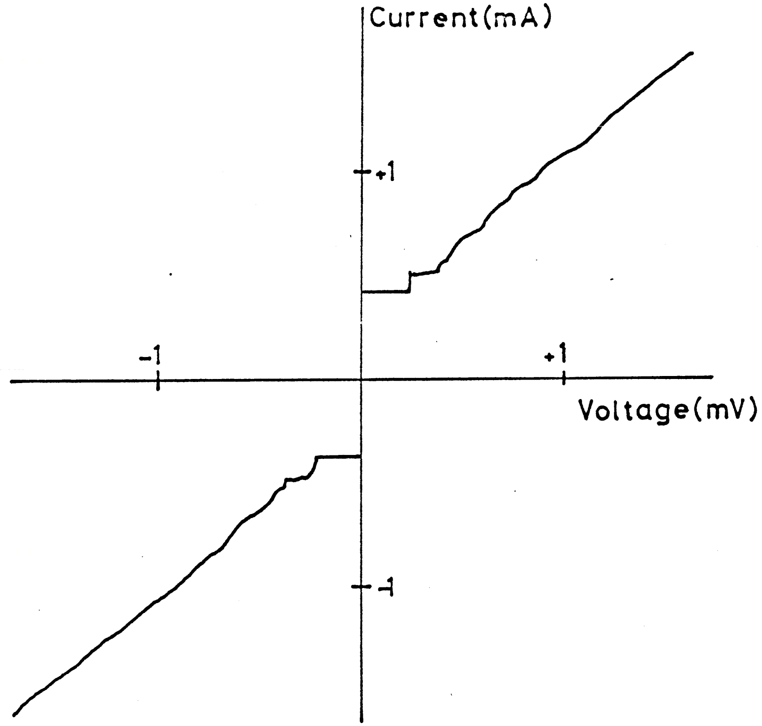
Digital voltmeter: $I_{\Phi 0} = \Phi_0/M = \Phi_0/L$

Voltage resolution: $V_{in} = I_{\Phi 0}R = \Phi_0/\tau = 2 \times 10^{-15}$ V
for $\tau = 1$ s

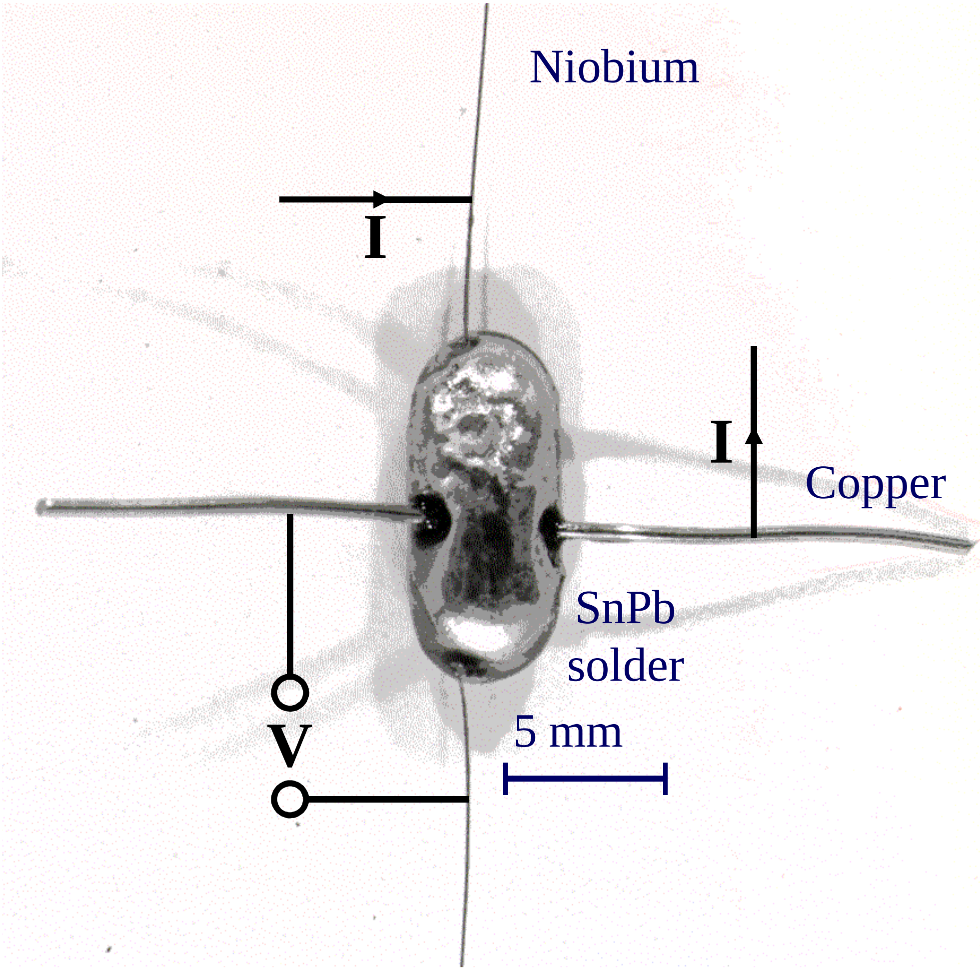
At Tea

• Paul Wraight pointed out that Nb has a surface oxide layer and PbSn solder is a superconductor (February 1965)





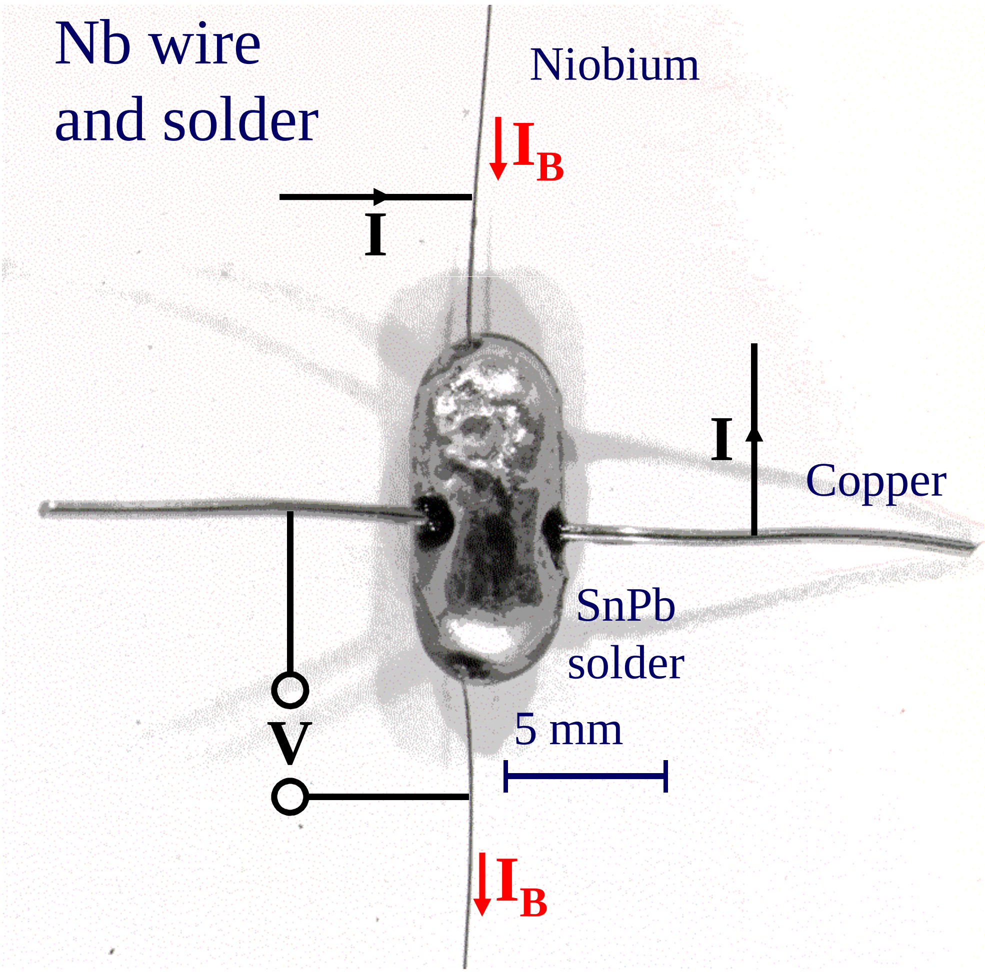
The Very Next Day

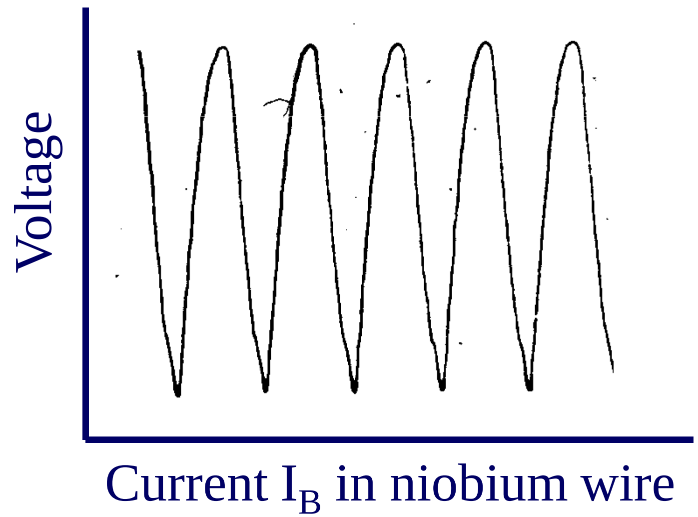


Brian Pippard:
It looks as though a slug crawled through the window last night and expired on your desk!”

The SLUG

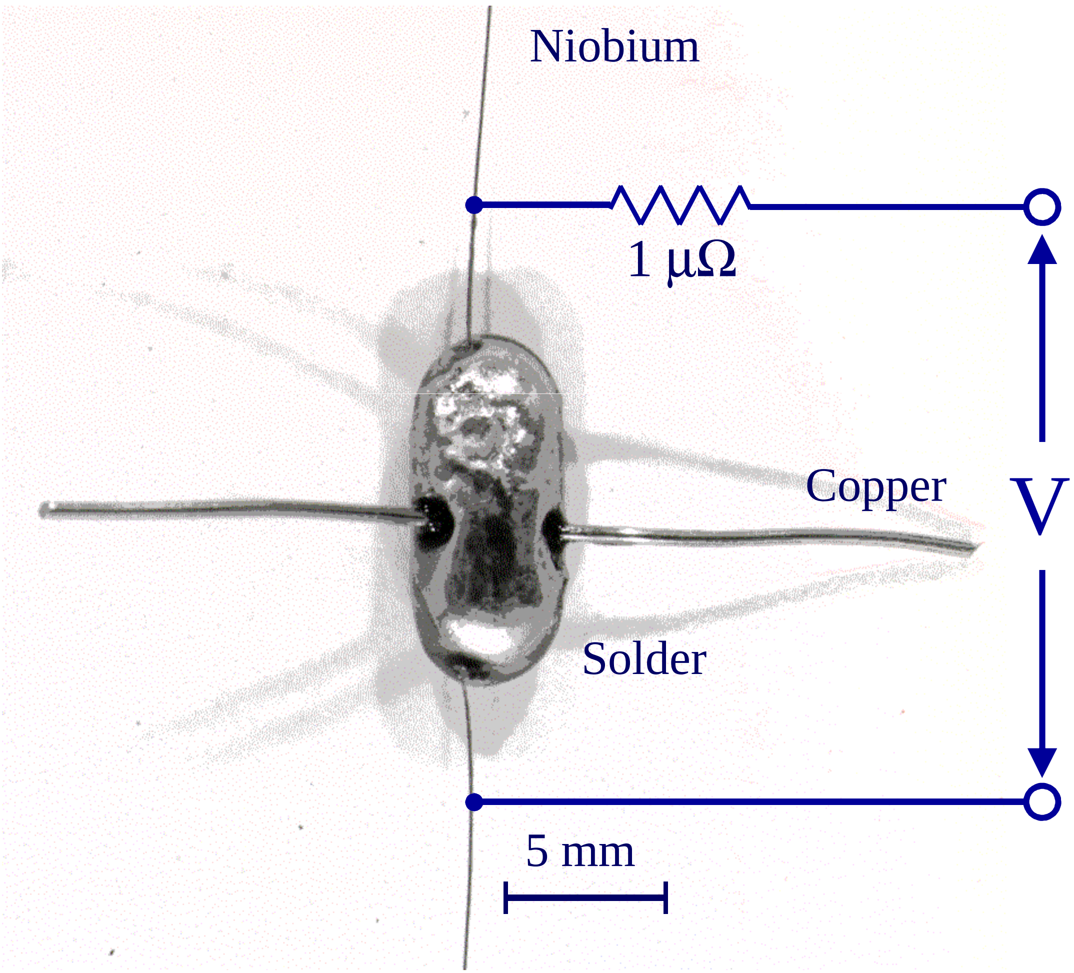
(Superconducting Low-Inductance Undulatory Galvanometer)

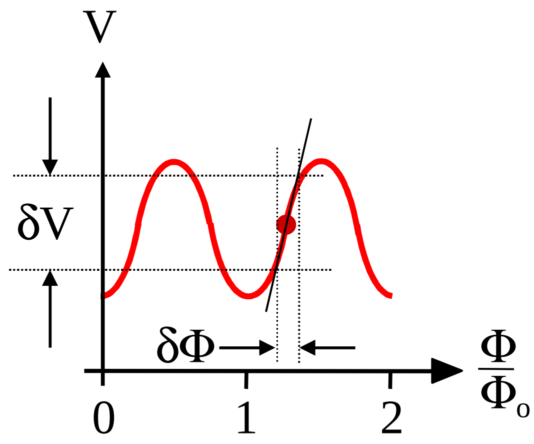




February 1965

The SLUG as a Voltmeter





Analog voltmeter

Voltage noise at 4.2 K

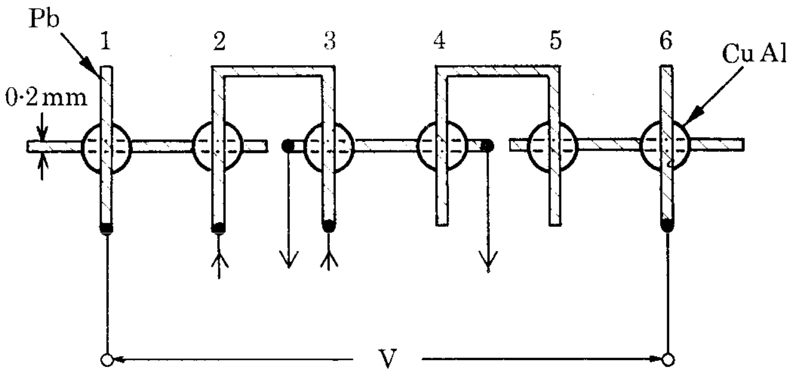
10 $fVHz^{-1/2}$

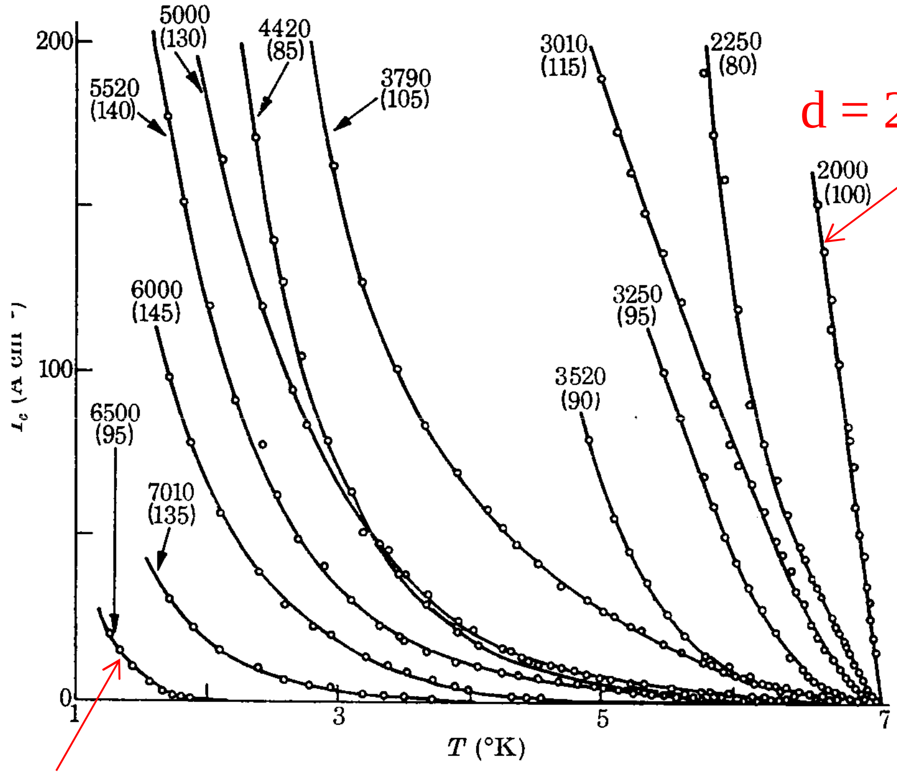
(10^{-14} $VHz^{-1/2}$)

Wiring Up a SLUG

Courtesy Gordon Donaldson

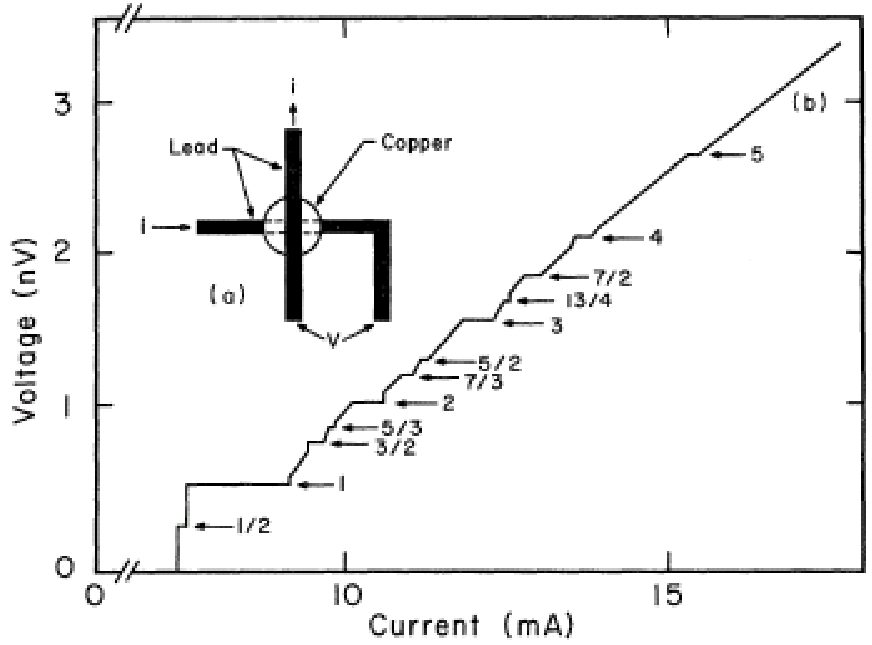
Josephson Tunnelling in SNS Junctions

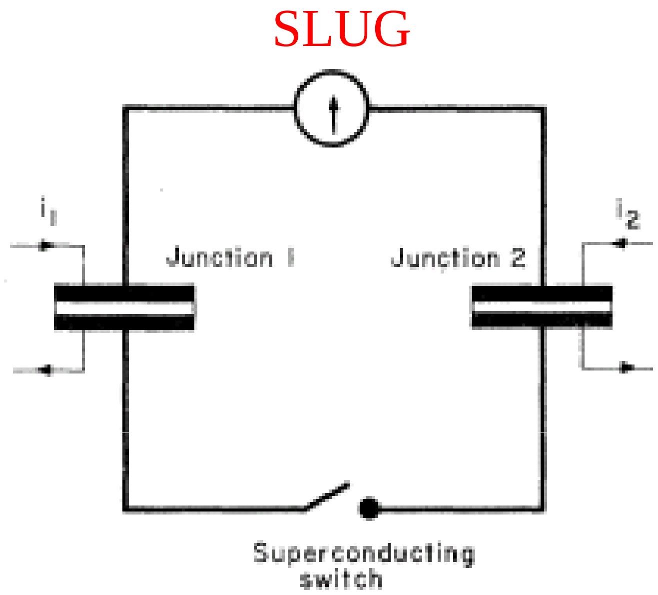




Near T_c: $I_c(T) \propto (T_c - T)^2 \exp(-d/\xi_N)$, where ξ_N is the pair decay length in the normal metal (DeGennes)

Universality of the Josephson Voltage-Frequency Relation

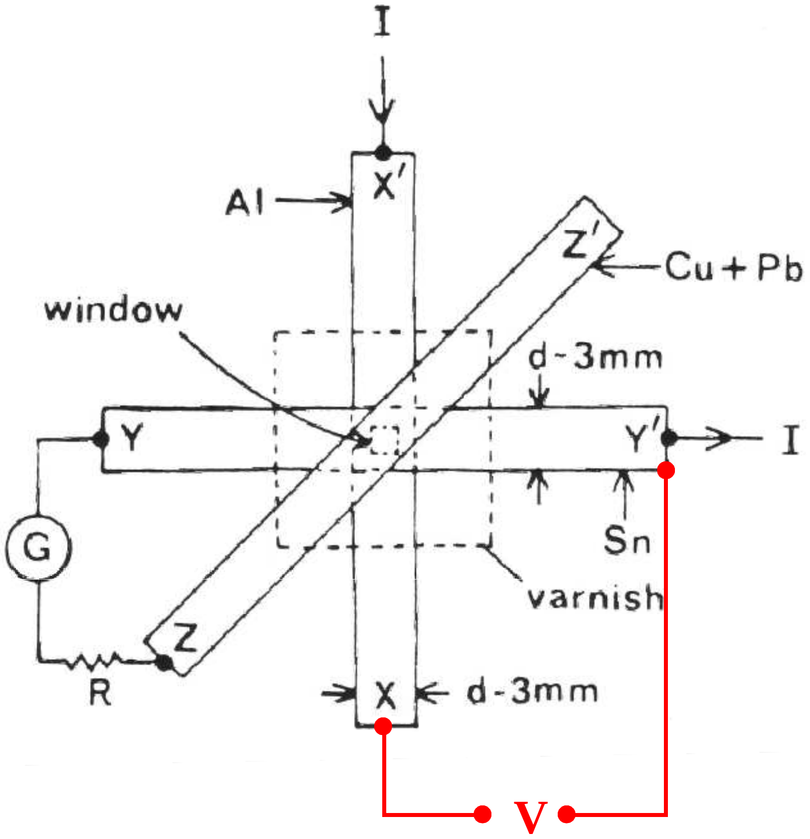


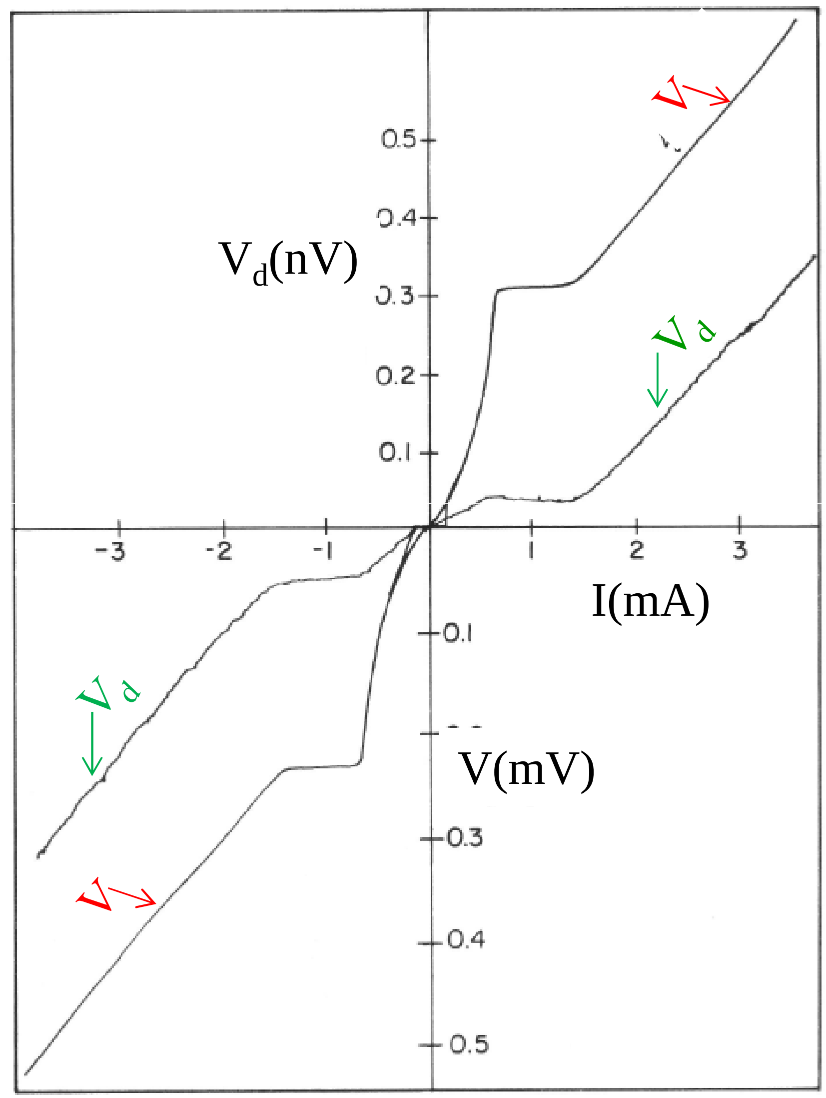


- Steps induced on current-voltage characteristic by 250 kHz radiation: $hf = (m/n)2eV$

- Both junctions biased on the same step generated by the same oscillator.
- Close switch: upper bound on current.
- Found $2e/h$ the same to 1 part in 10^8.
- Subsequently, Tsai *et al*. measured an upper bound of 2 parts in 10^{16}.

Charge Imbalance: Observation





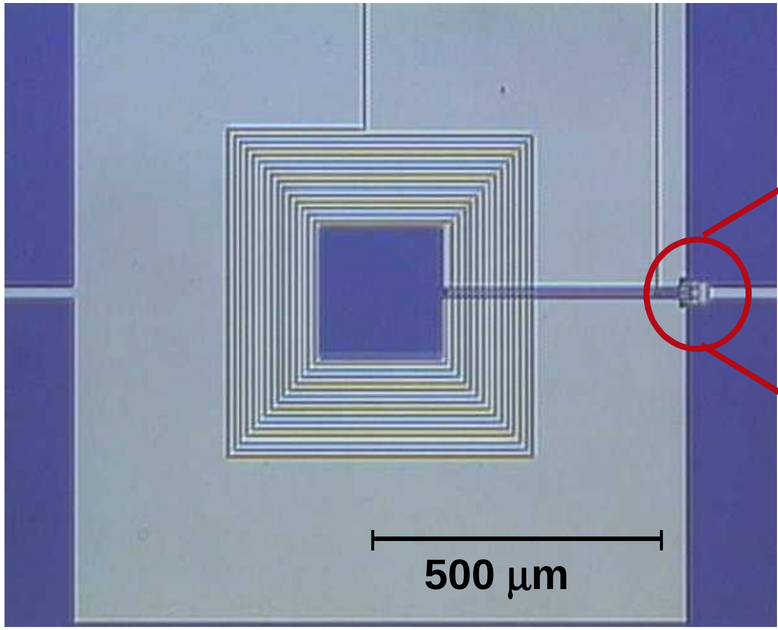
- Current injected through the Al-AlOx-Sn junction creates a charge imbalance between the electron-like and hole-like quasiparticle branches in the superconducting Sn film.
- This imbalance establishes a potential difference across the Sn-SnOx-Cu junction.
- Detailed investigation of nonequilibrium superconductivity.

…and Now

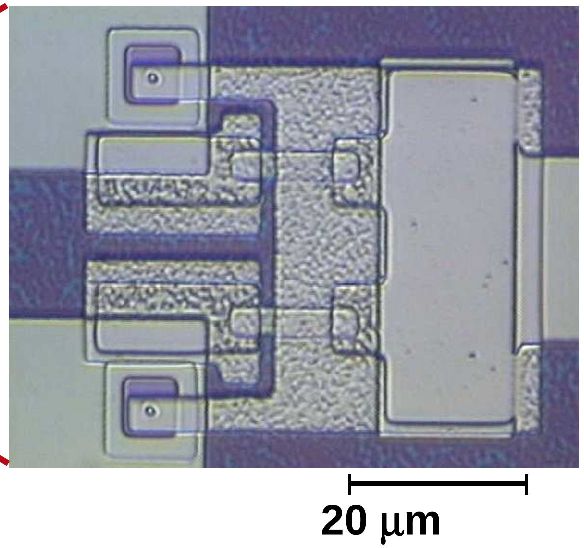
Thin-Film, Square Washer DC SQUID

Ketchen and Jaycox (1981)

SQUID with input coil



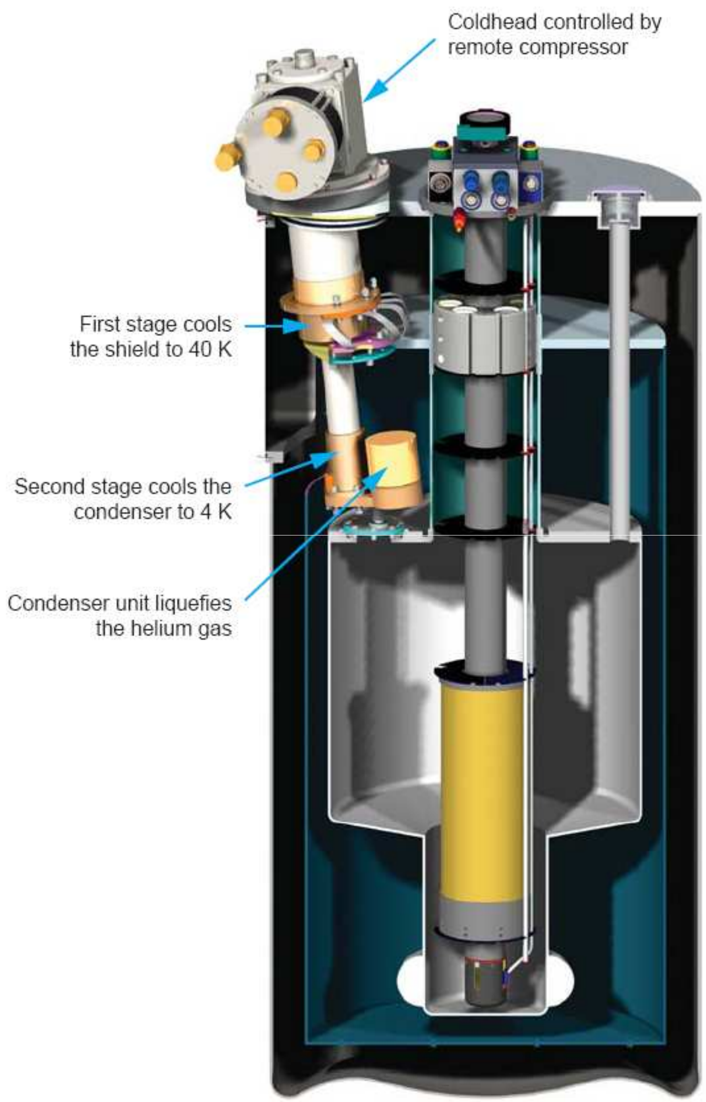
Josephson junctions



At 4.2 K
Flux noise: 1 – 2 $\mu\Phi_0/Hz^{-1/2}$
~ Φ_0/1,000,000 in 1 second

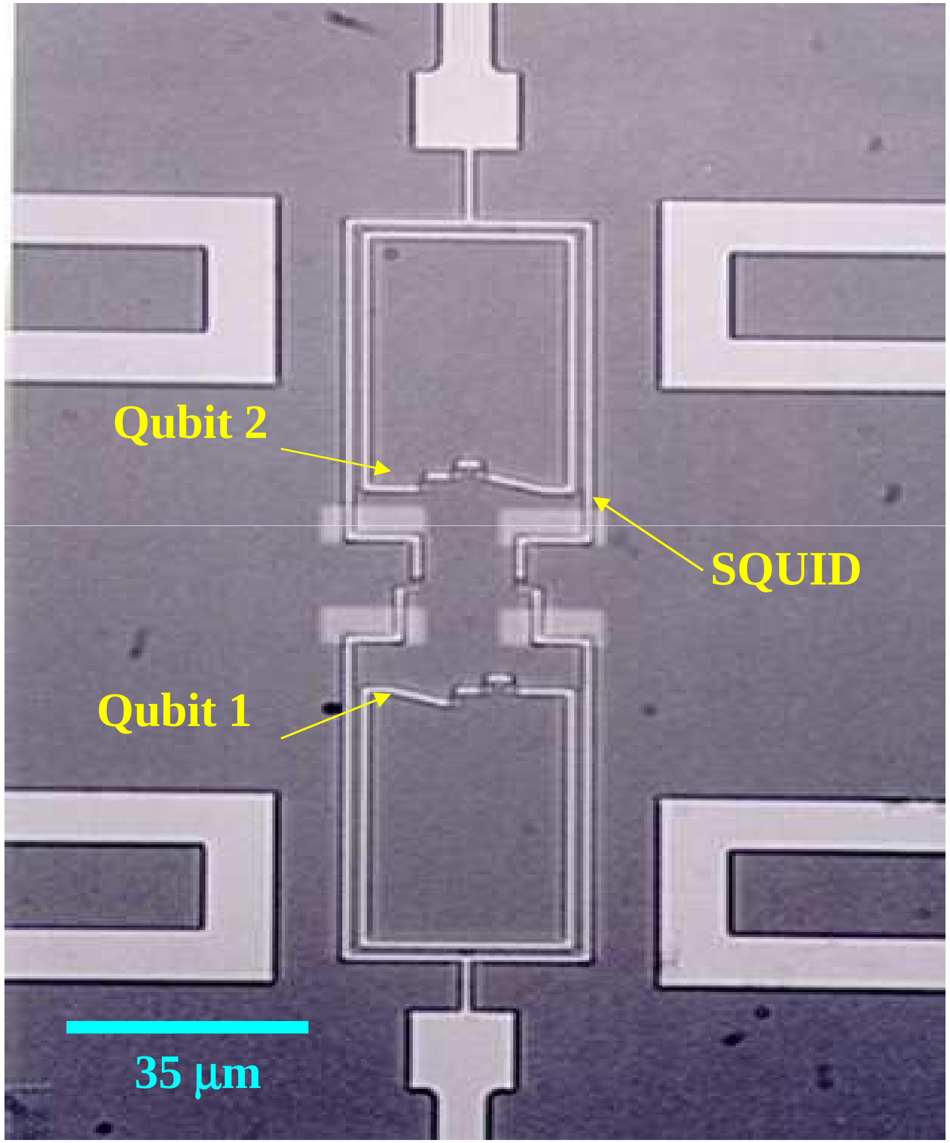
- Wafer scale process
- Photolithographic patterning
- Nb-AlOx-Nb Josephson junctions (John Rowell)

Quantum Design "Evercool"



Cut-away Dewar View

UC Berkeley Flux Qubits



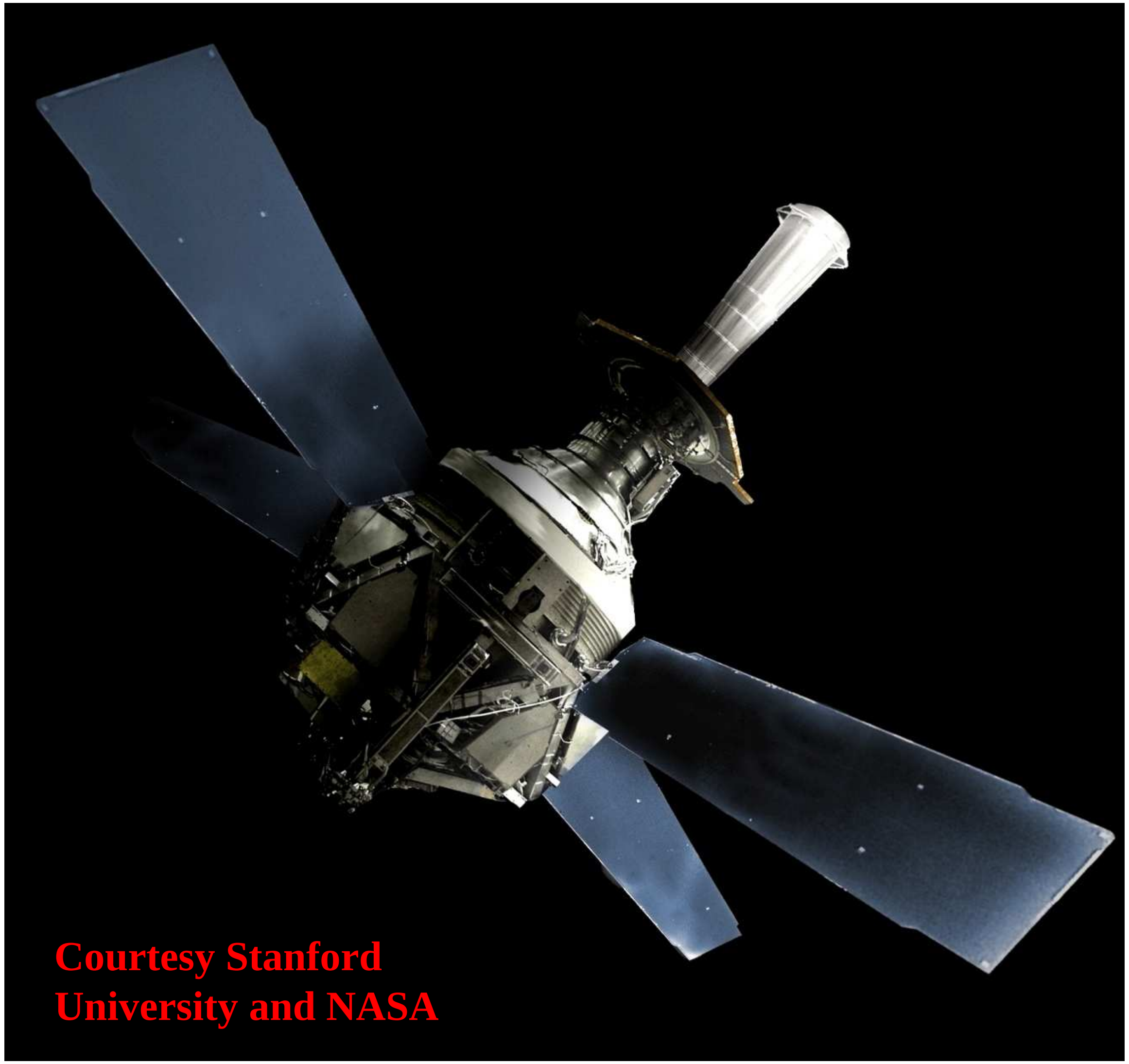
UC Berkeley

High-T_c SQUIDs Prospecting for Mineral Deposits

Courtesy Cathy Foley, CSIRO

Gravity Probe-B

Tests of General Relativity



- Geodetic effect—curved space-time due to the presence of the Earth

- Lense-Thirring effect—dragging of the local space-time frame due to rotation

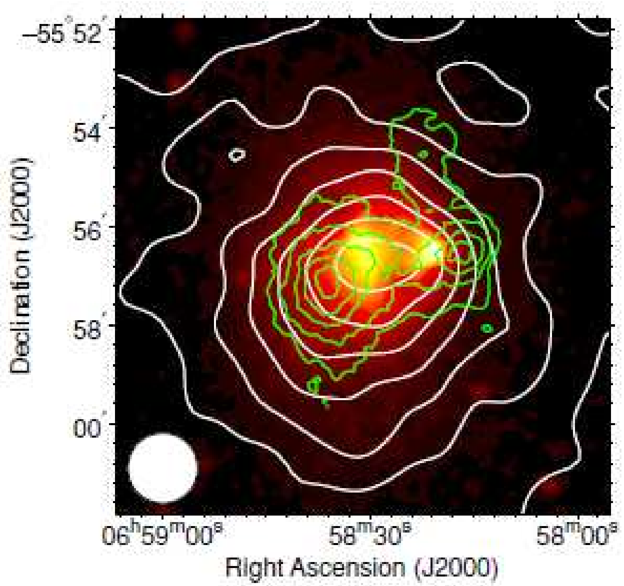
- Gyroscopes: Spinning, niobium-coated sapphire sphere develops magnetic dipole moment, read out by a SQUID

South Pole Telescope: Searching for galaxy clusters

UC Berkeley + Many other groups

- Antarctica 9,500 feet
- 960 transition edge sensors with multiplexed SQUID readout
- 12,000 SQUIDs

The "Bullet Cluster"



300-Channel SQUID Systems for Magnetoencephalography (MEG)

Magnetic Resonance Imaging at 132 μT

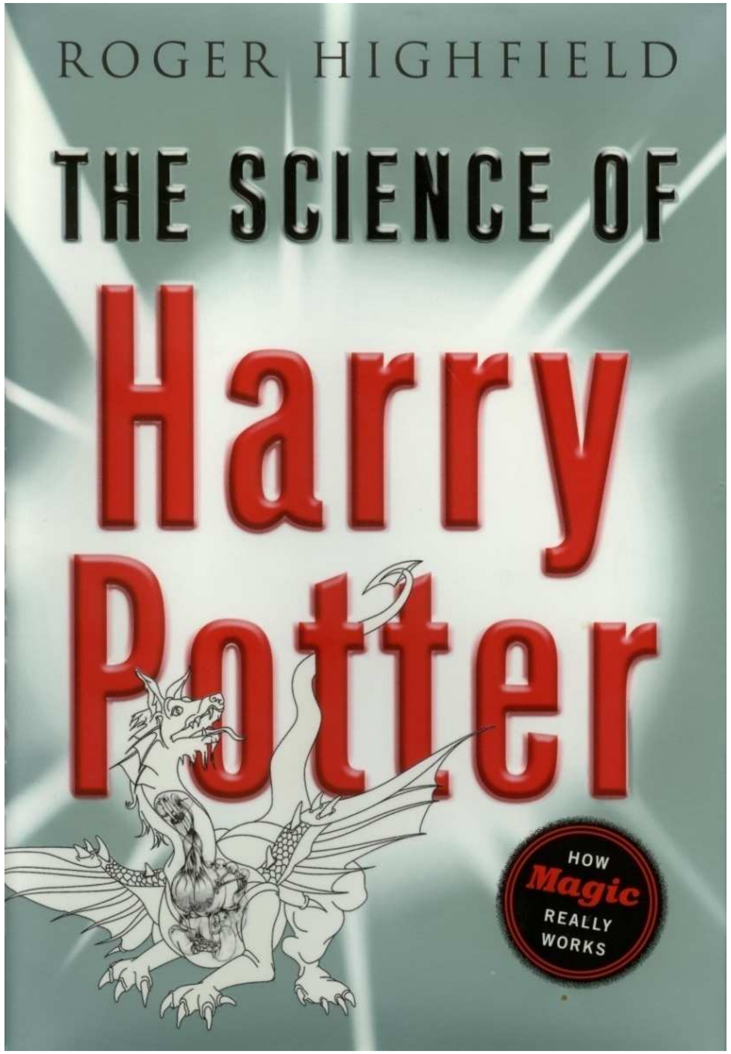
UC Berkeley

Harry Potter: The Sorting Hat

"There is nothing hidden in your head
The Sorting Hat can't see,
So try me on and I will tell you
Where you ought to be."

The Science of Harry Potter

Roger Highfield, 2002



"The magnetic fields sprouting from Harry's head influence the electron pairs circulating in the SQUIDs in the Sorting Hat. Because quantum mechanics says that all the electron pairs in each SQUID act in concert (in the jargon, all the electrons are in the same "quantum state"), they convert a tiny change in his brain's magnetic field into a detectable change in voltage with a sensitivity unmatched by any other device."

Cold Dark Matter: The Hunt for the Axion

S.J. Asztalos
G. Carosi
C. Hagmann
D. Kinion,
K. van Bibber
M. Hotz
L.J. Rosenberg
G. Rybka,
J. Hoskins
J. Hwang
P. Sikivie
D. B. Tanner
R. Bradley
JC

Cosmic Microwave Background (CMB)

Neutrinos	0.6%
Baryons (ordinary matter)	4.6%
Dark Energy (DE)	73%
Cold Dark Matter (CDM)	*22%*

Cold Dark Matter

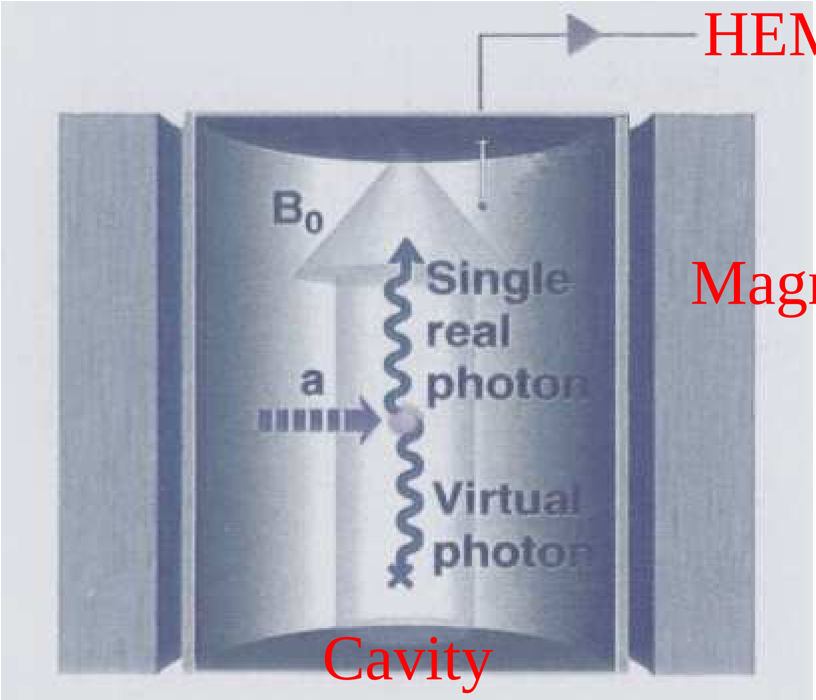
A candidate particle is the axion, proposed in 1978 to explain the absence of a measurable electric dipole moment on the neutron

- Density of CDM: $\rho_{\mathbf{CDM}} \approx 0.45$ GeV cm^{-3}
- Predicted axion mass: $m_a \approx 1$ μeV – 1 meV (0.24 - 240 GHz)
- For $m_a = 1$ μeV: $n_a \approx 4.5 \times 10^{14}$ cm^{-3}

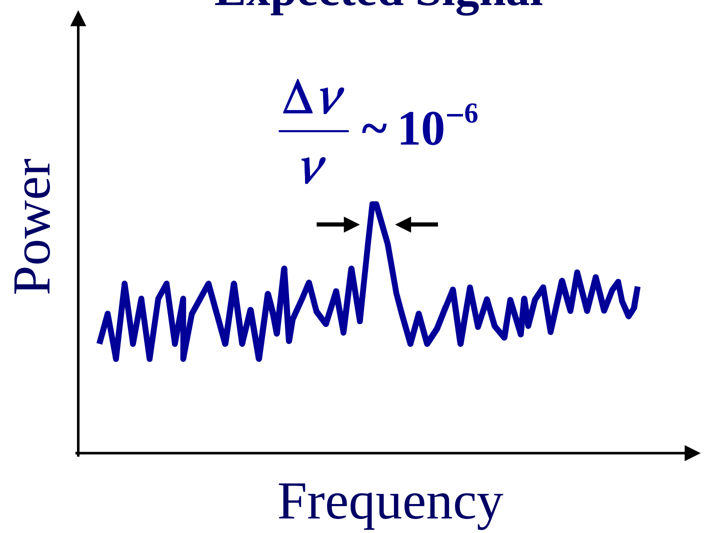
Resonant Conversion of Axions into Photons

Pierre Sikivie (1983)

Primakoff Conversion



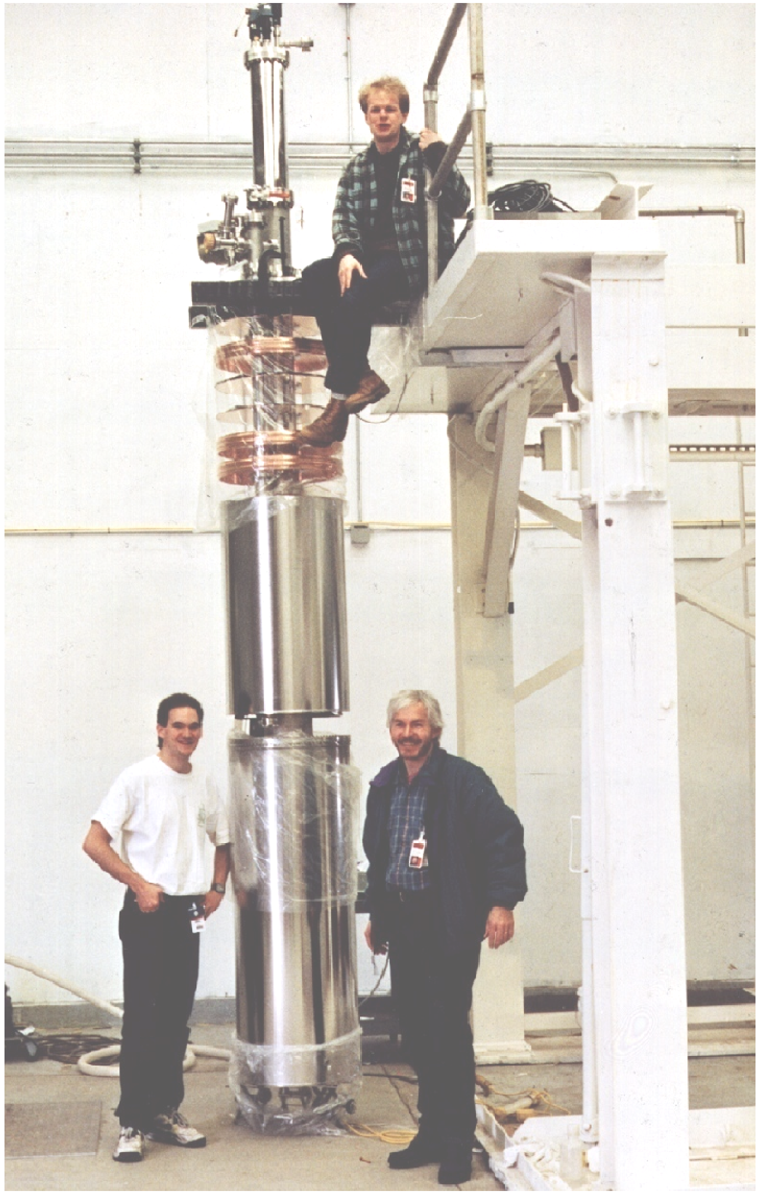
Expected Signal



*High Electron Mobility Transistor

Need to scan frequency

Axion Dark Matter eXperiment (ADMX)

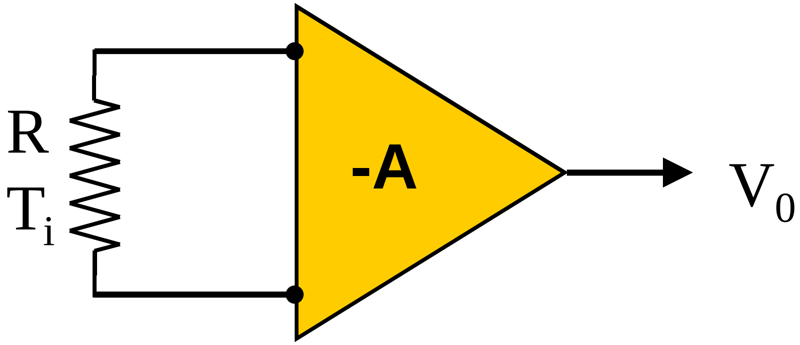


Originally: Lawrence Livermore National Laboratory

Now: University of Washington, Seattle

- Cooled to 1.5K
- 7 tesla magnet

Amplifier Noise Temperature



$$S_V^0(f) = A^2 \cdot 4k_B\left[T_i + T_N(R)\right]R$$

Quantum limit: $\boldsymbol{T_{QL} = hf/k_B}$

LLNL Axion Detector

- Original system noise temperature: $T_S = T + T_N \approx 3.2$ K

  Cavity temperature: $T \approx 1.5$ K

  Amplifier noise temperature: $T_N \approx 1.7$ K

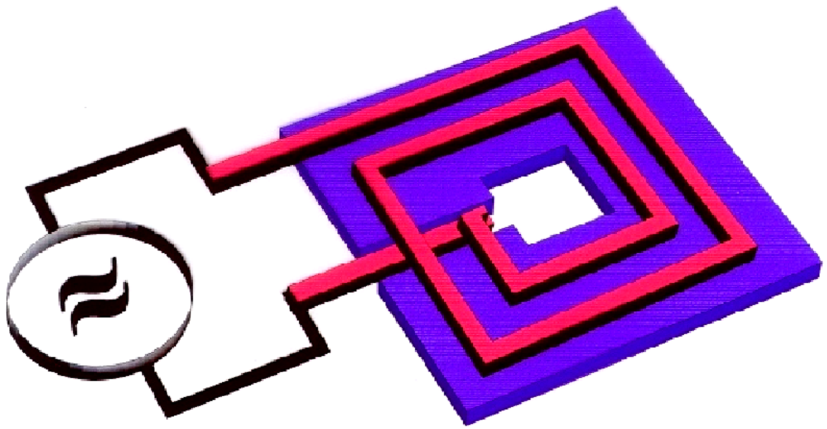
- Time to scan the frequency range from $f_1 = 0.24$ to $f_2 = 0.48$ GHz:

$$\tau(f_1, f_2) \approx 4 \text{ x } 10^{17}(T_S/1\text{ K})^2(1/f_1 - 1/f_2) \text{ sec}$$

$\approx$ **270 years**

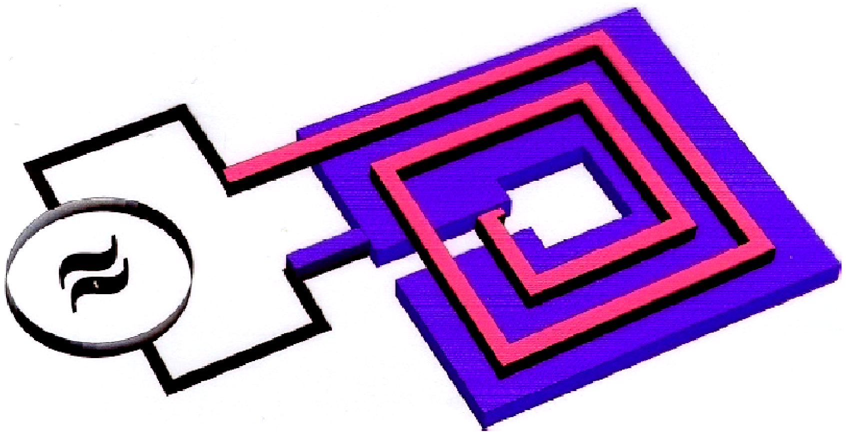
Microstrip SQUID Amplifier (MSA)

Conventional SQUID Amplifier



- Source connected to both ends of coil

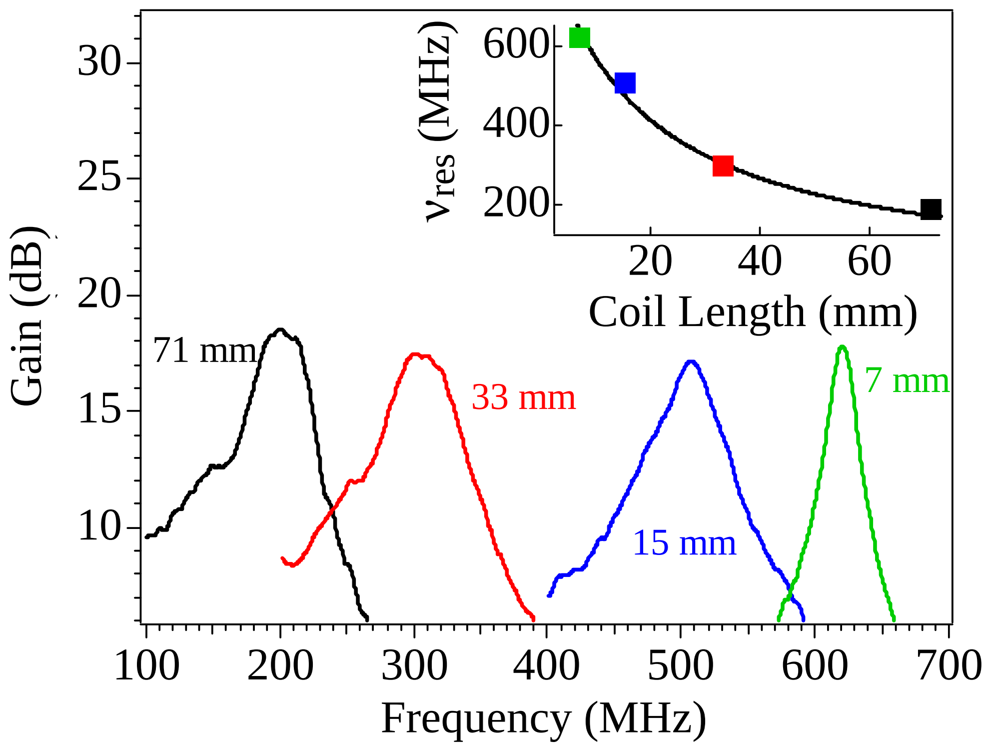
Microstrip SQUID Amplifier



- Source connected to one end of the coil and SQUID washer; the other end of the coil is left open

MSA Gain Measurements

Gain for four coil length



M. Mück, J. Gail, C. Heiden[†], M-O André , JC

Near the Quantum Limit

Frequency = 620 MHz

T_{bath} = 50 mK

T_N^{opt} = 48 ± 5 mK

T_Q = 30 mK

MSA:Impact on Axion Detector

- Original LLNL axion detector: $T_S \approx 3.2$ K
- Microstrip SQUID amplifier: $T_N \approx 50$ mK
- Next generation: Cool system in a dilution refrigerator to 50 mK
- For $T \approx T_N \approx 50$ mK: $T_S \approx T + T_N \approx 0.1$ K

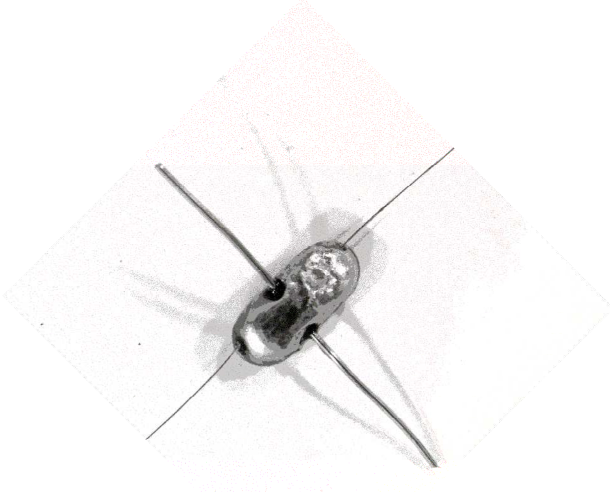
- Scan time $\propto T_s^2$:

$$\tau(0.24 \text{ GHz}, 0.48 \text{ GHz}) \approx 270 \text{ years x } (0.1/3.2)^2$$

≈ 100 days

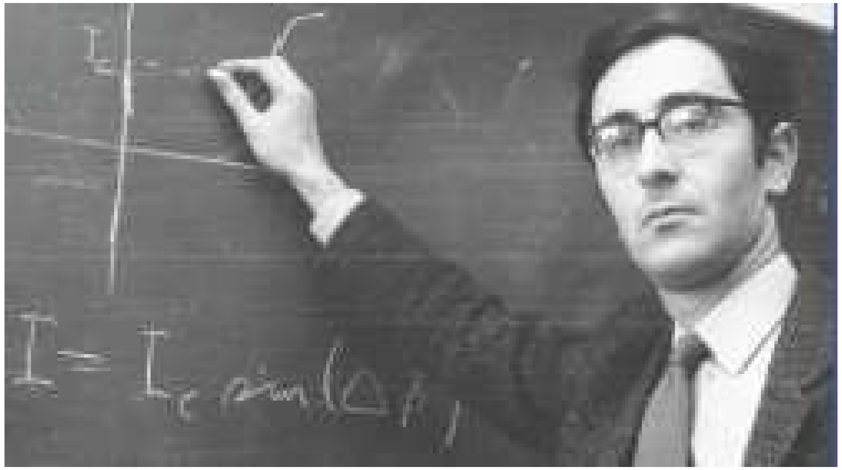
Outlook for the Axion Detector

- During 2009-10, an MSA was operated on the axion detector at 1.5 K to demonstrate proof-of-principle.
- 88,370, 80-sec data sets were acquired.
- Next: cavity and MSA cooled to 50 mK with a dilution refrigerator.
- This will enable an effective axion search over the energy range 1 – 10 μeV.



Epilogue

- SQUIDs are amazingly diverse, with applications in physics, chemistry, biology, medicine, materials science, geophysics, cosmology, quantum information,……..
- SQUIDs are remarkably broadband: 10^{-4} Hz (geophysics) to 10^{9} Hz (axion detectors).
- At low temperatures, the resolution of SQUID amplifiers is essentially limited by Heisenberg's Uncertainty Principle.
- The applications of SQUIDs are many and varied—and exist only because of its extraordinarily low noise.



Then…

Congratulations Brian!

…and Now