SQUIDs: Then and Now

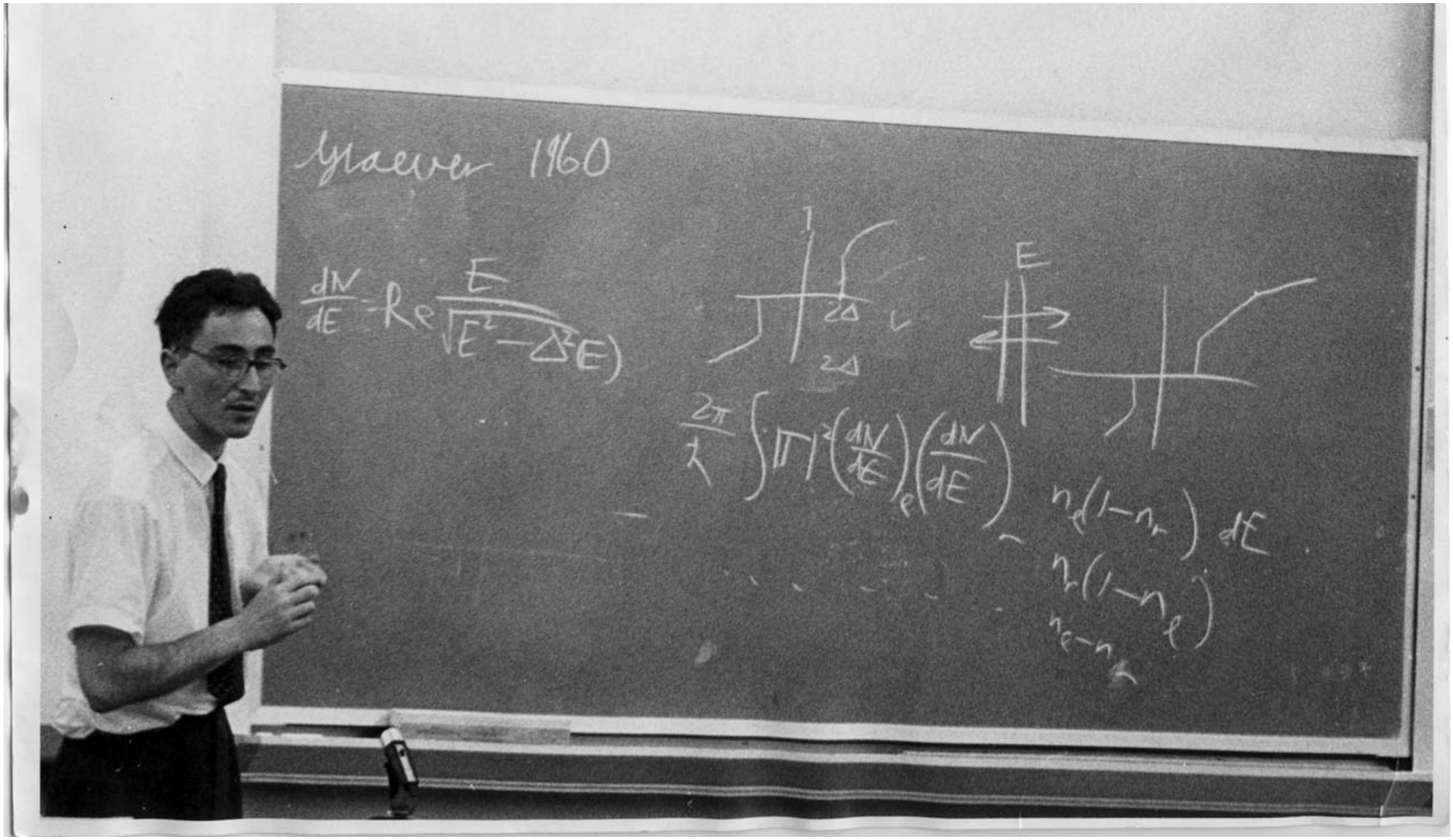
- SQUIDs: Then
- SQUIDs: Now
- The diversity of SQUIDs
  - Ultralow field magnetic resonance imaging
  - Cold dark matter: The hunt for the axion

History Day
Superconductivity Centennial Conference
Den Haag
The Netherlands
September 21, 2011

Support:
DOE Basic Energy Sciences
DOE High Energy Physics
National Institutes of Health
BBN Technologies

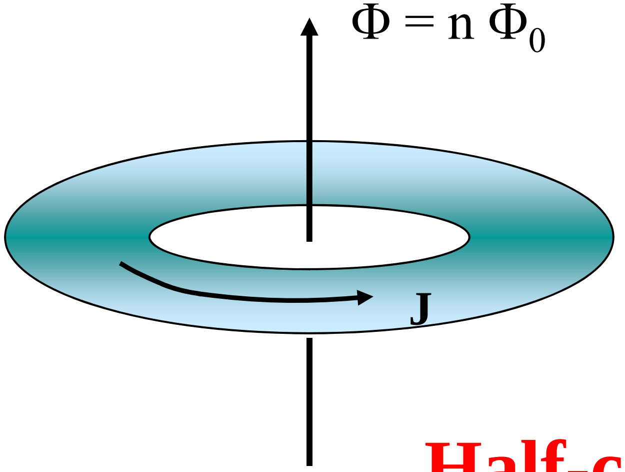
SQUIDs Then

Brian Josephson Explains Tunneling



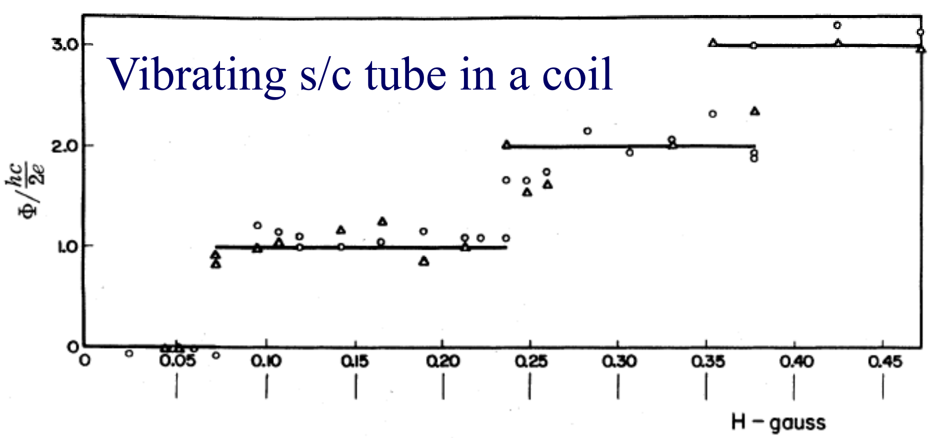
Courtesy Brian Josephson

Flux Quantization

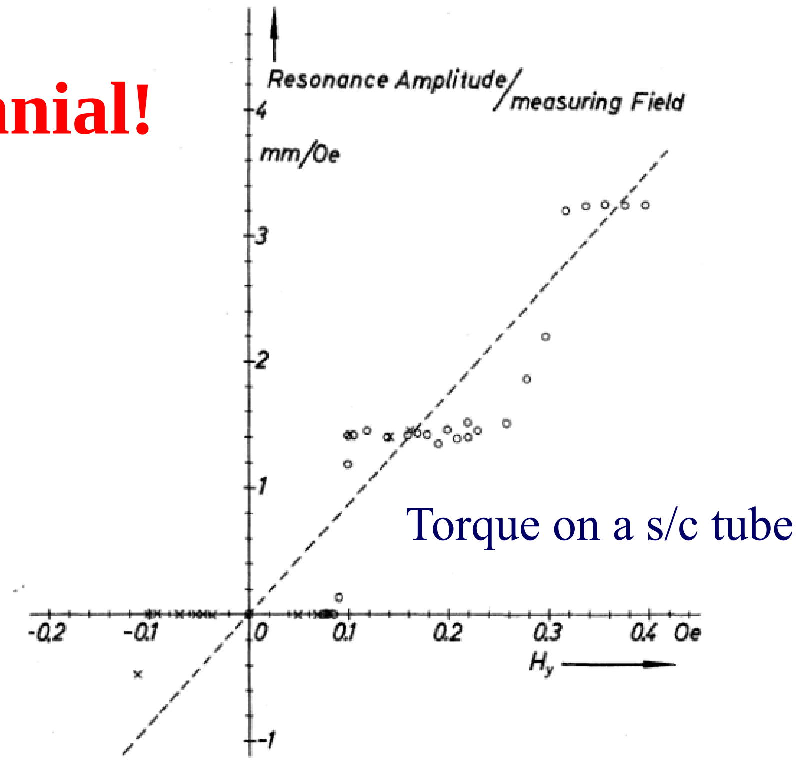


$\Phi = n\Phi_0$ (n = 0, ±1, ±2, ...)
where
$\Phi_0 \equiv h/2e \approx 2 \times 10^{-15}$ Tm^2
is the flux quantum

Half-centennial!

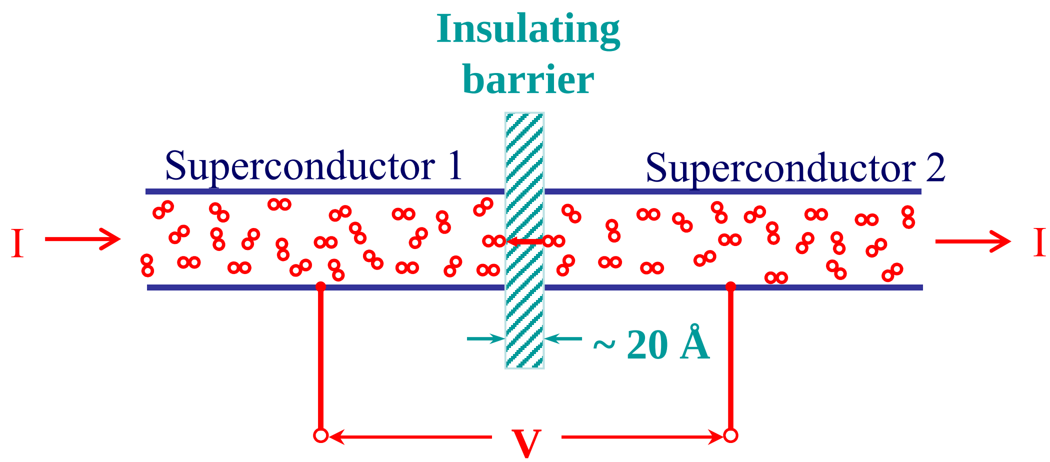


Deaver and Fairbank 1961

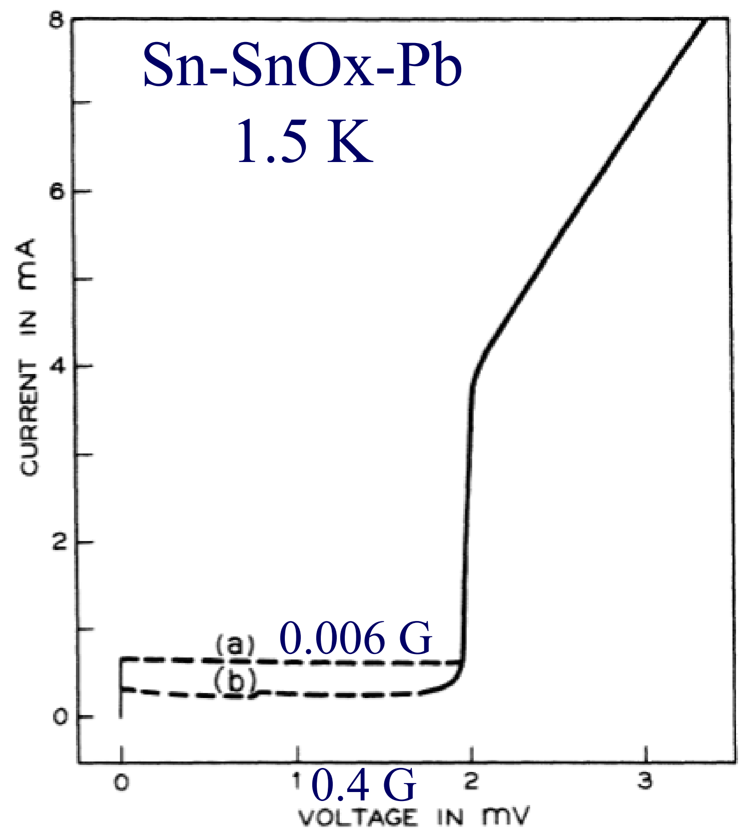


Doll and Näbauer 1961

Josephson Tunneling



$$I = I_0 \sin\delta$$
$$\delta = \phi_1 - \phi_2$$
$$d\delta/dt = 2eV/\hbar$$
$$= 2\pi V/\Phi_0$$

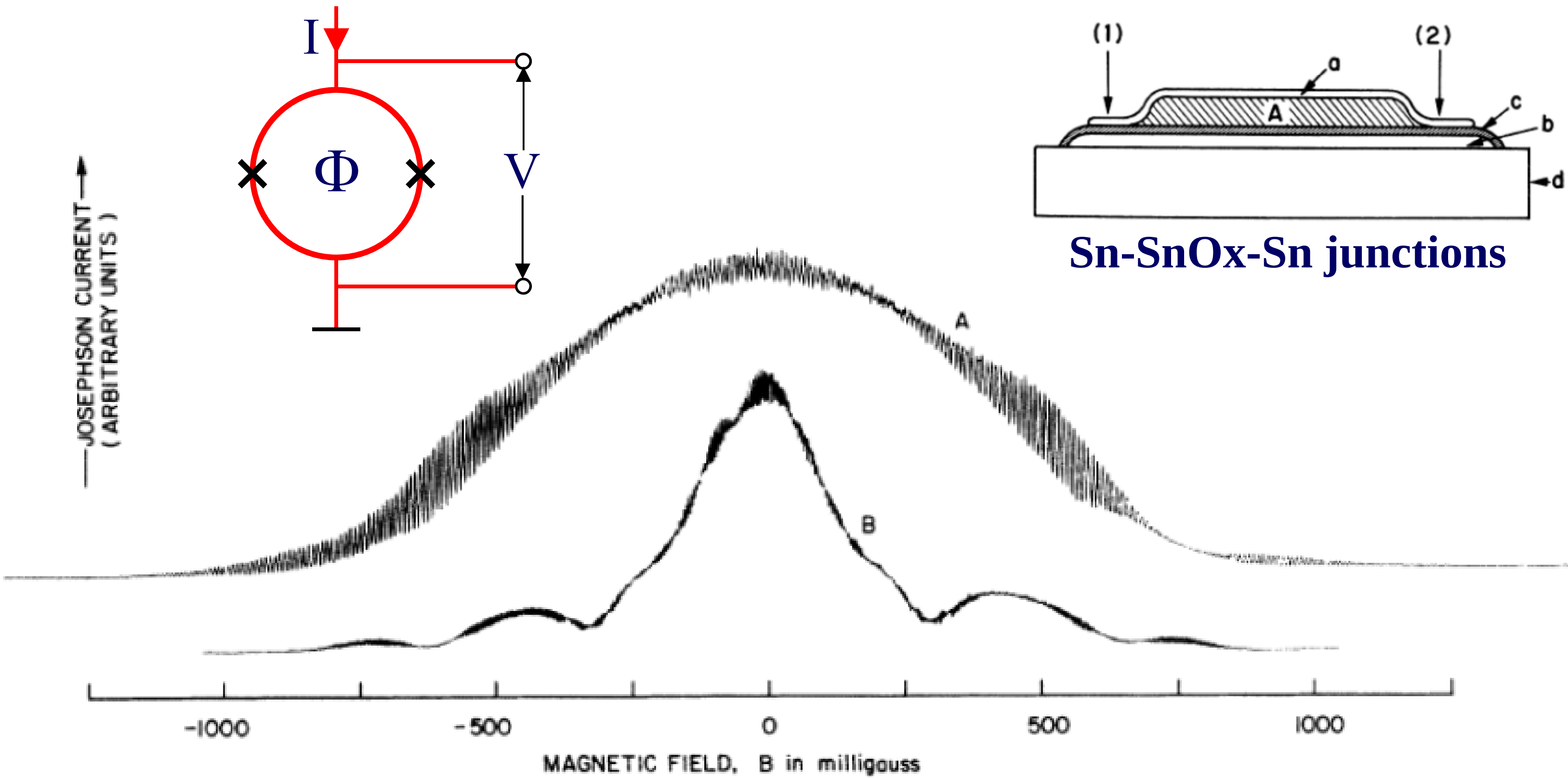


Josephson 1962

Half-Centennial Next Year!

Anderson and Rowell 1963

Birth of the Superconducting Quantum Interference Device (SQUID)



Sn-SnOx-Sn junctions

- Critical current versus applied magnetic field for two different junction spacings
- Rapid oscillations due to interference, slow oscillations due to diffraction
- Essential physics analogous to two-slit interference in optics

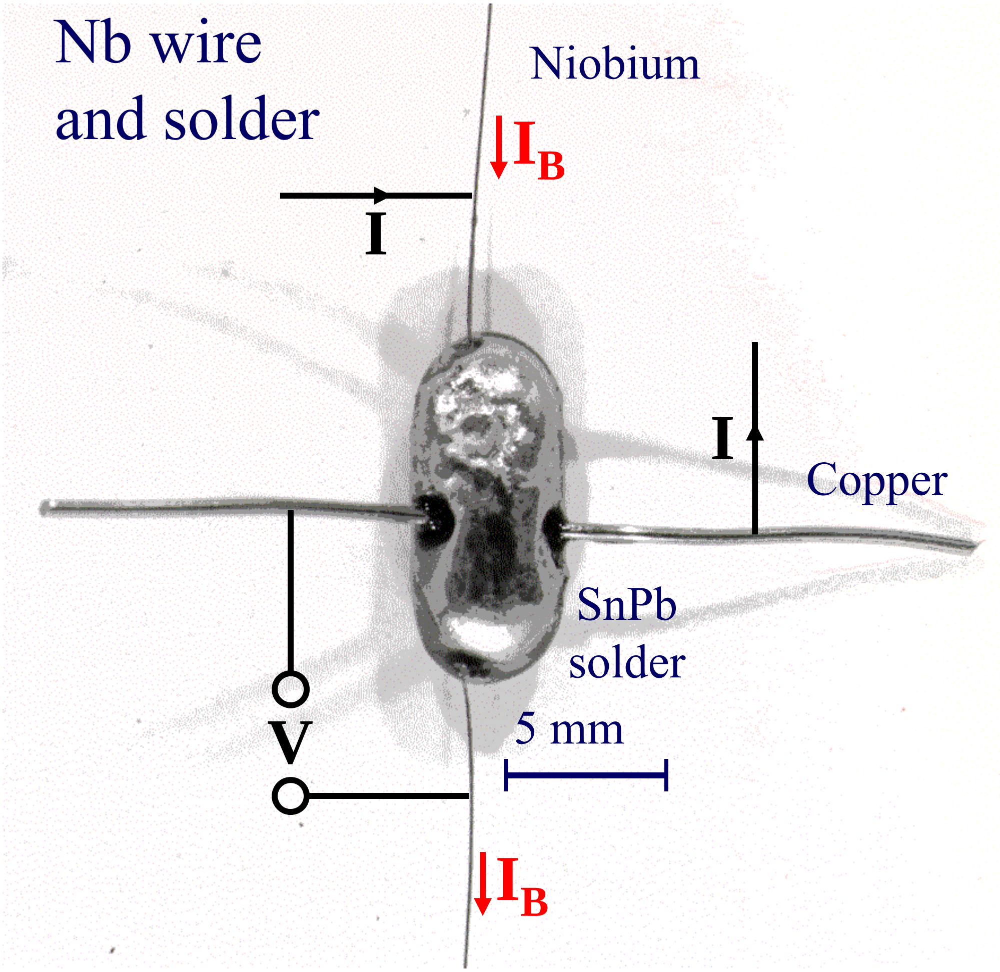
Jaklevic, Lambe, Silver and Mercereau 1964

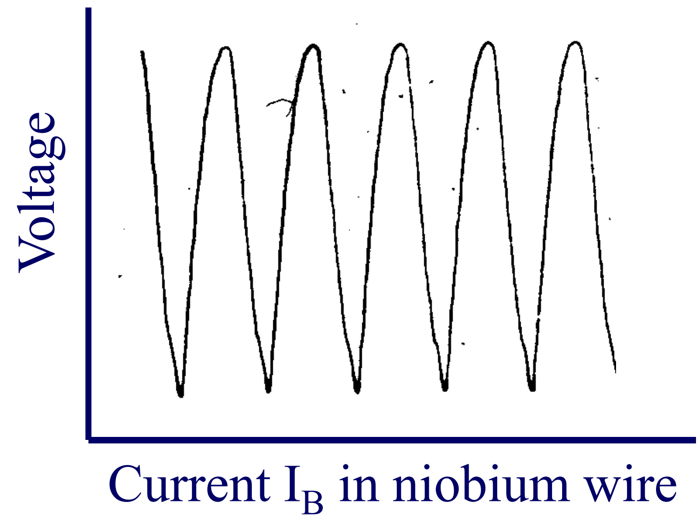
Sir Brian Pippard Serves Tea to Lady Bragg

Courtesy Cavendish Laboratory

The SLUG

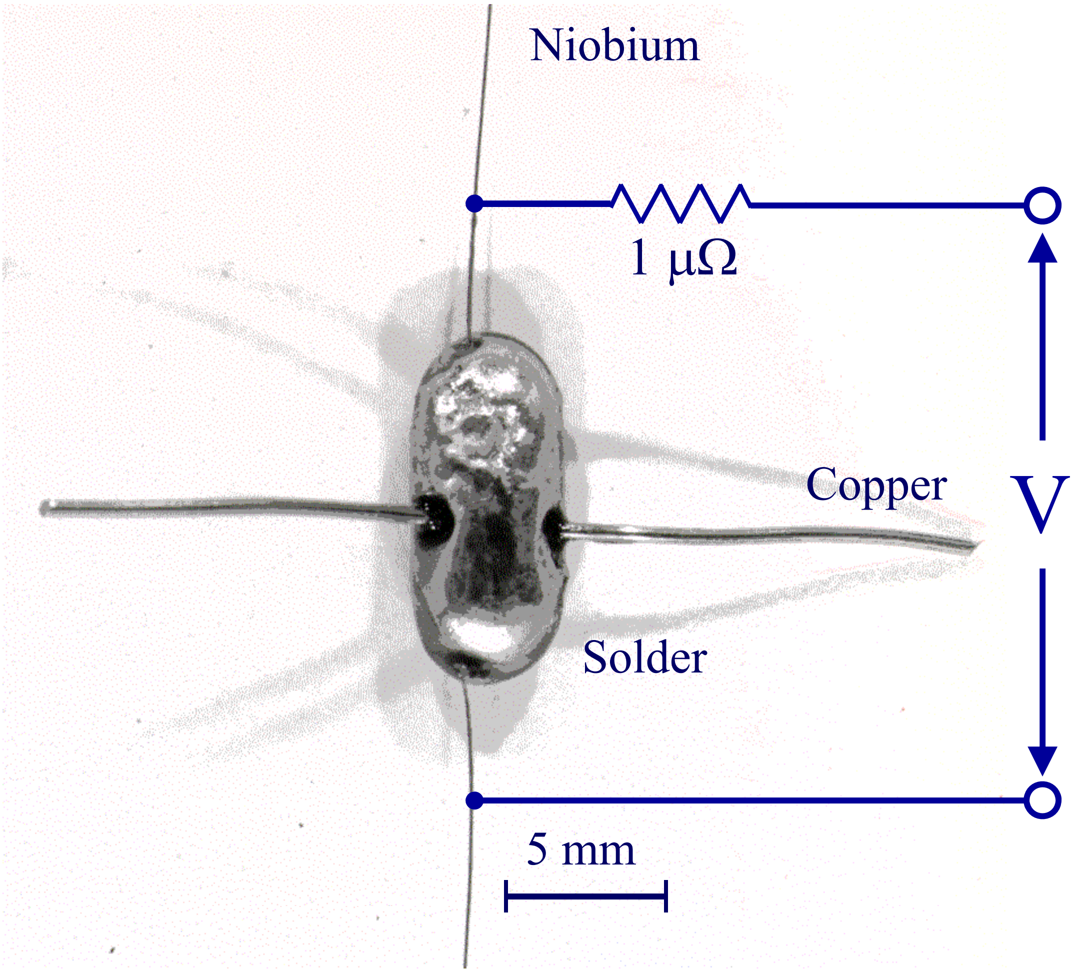
(Superconducting Low-Inductance Undulatory Galvanometer)





JC February 1965

The SLUG as a Voltmeter



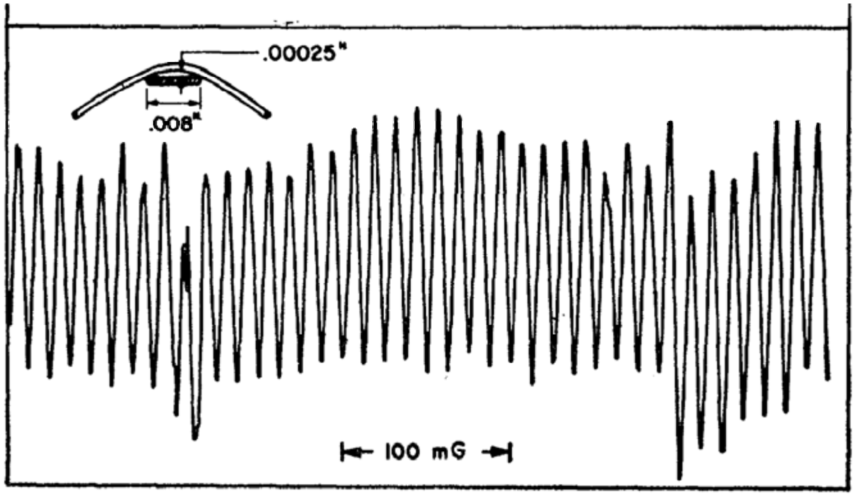
Voltage noise
10 $fVHz^{-1/2}$

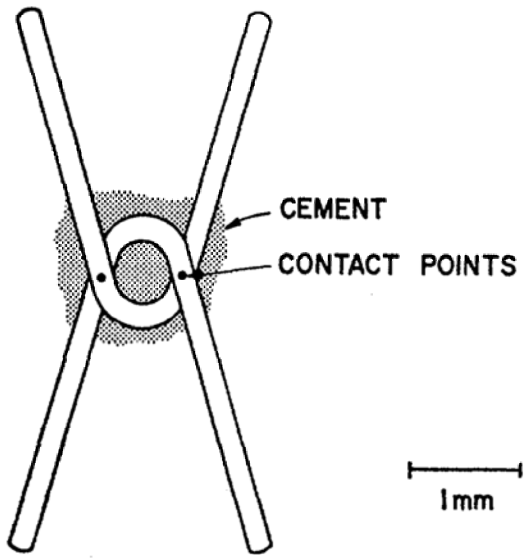
John Wires up a SLUG

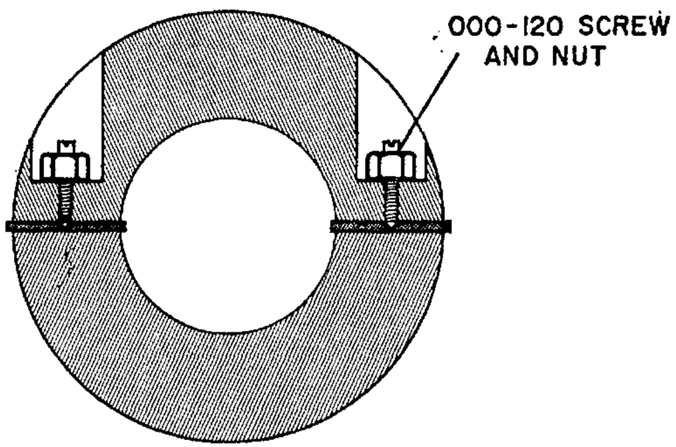
Courtesy Gordon Donaldson

Other SQUID Designs

Niobium structures



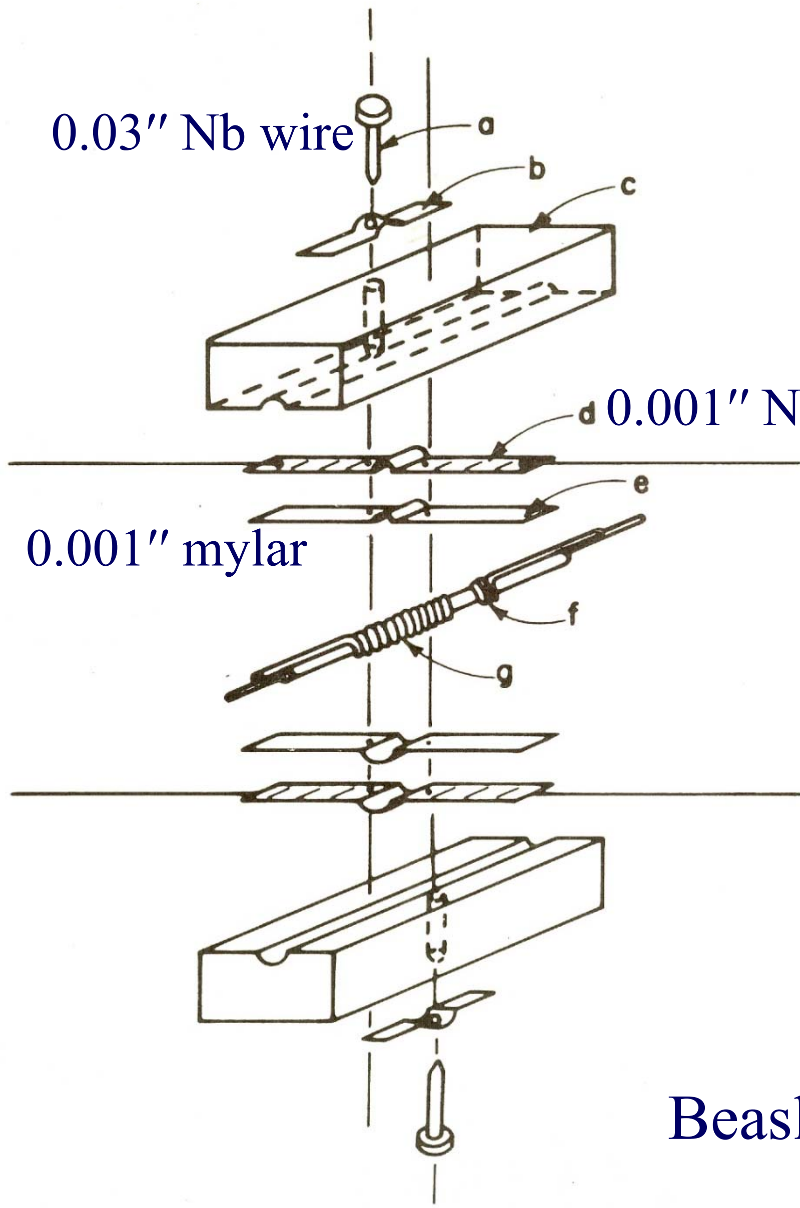




Zimmerman and Silver 1966

Adjustable Niobium SQUID

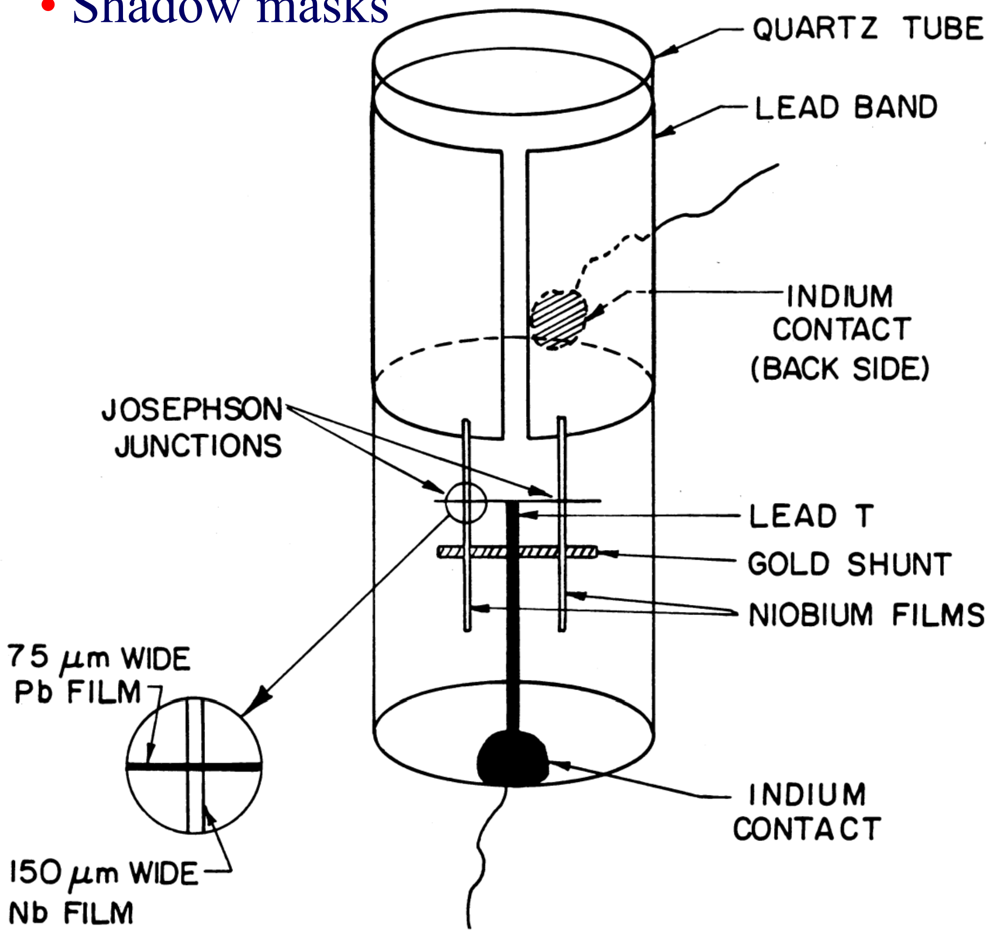
Nb wire
and foil



Beasley and Webb 1967

Thin-Film Cylindrical SQUID

- Nb-NbOx-PbIn junctions
- Shadow masks



10^{-14} tesla $Hz^{-1/2}$ (10 $fTHz^{-1/2}$)

Goubau, Ketchen, JC 1974

SQUIDs Now

Nb-AlOx-Nb Tunnel Junctions

Trilayer process

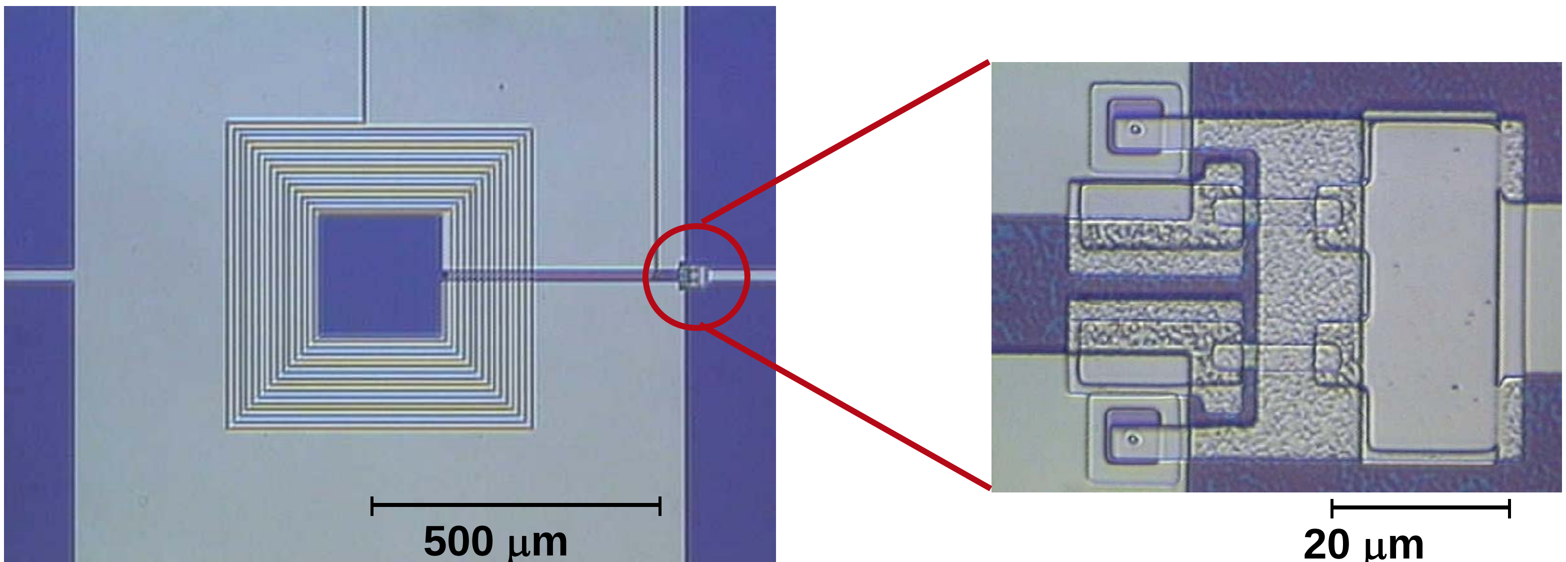
- Deposit Nb film as base electrode
- Deposit Al film
- Grow AlOx layer thermally in O_2
- Deposit Nb film as counter electrode

Standard process for all low-T_c electronics

Rowell *et al*. 1981

Thin-Film, Square Washer DC SQUID

- Wafer scale process
- Photolithographic patterning

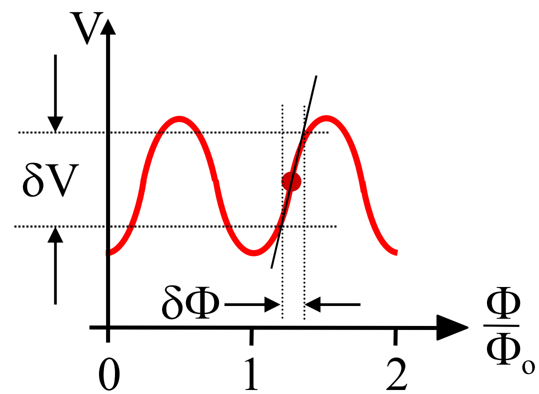


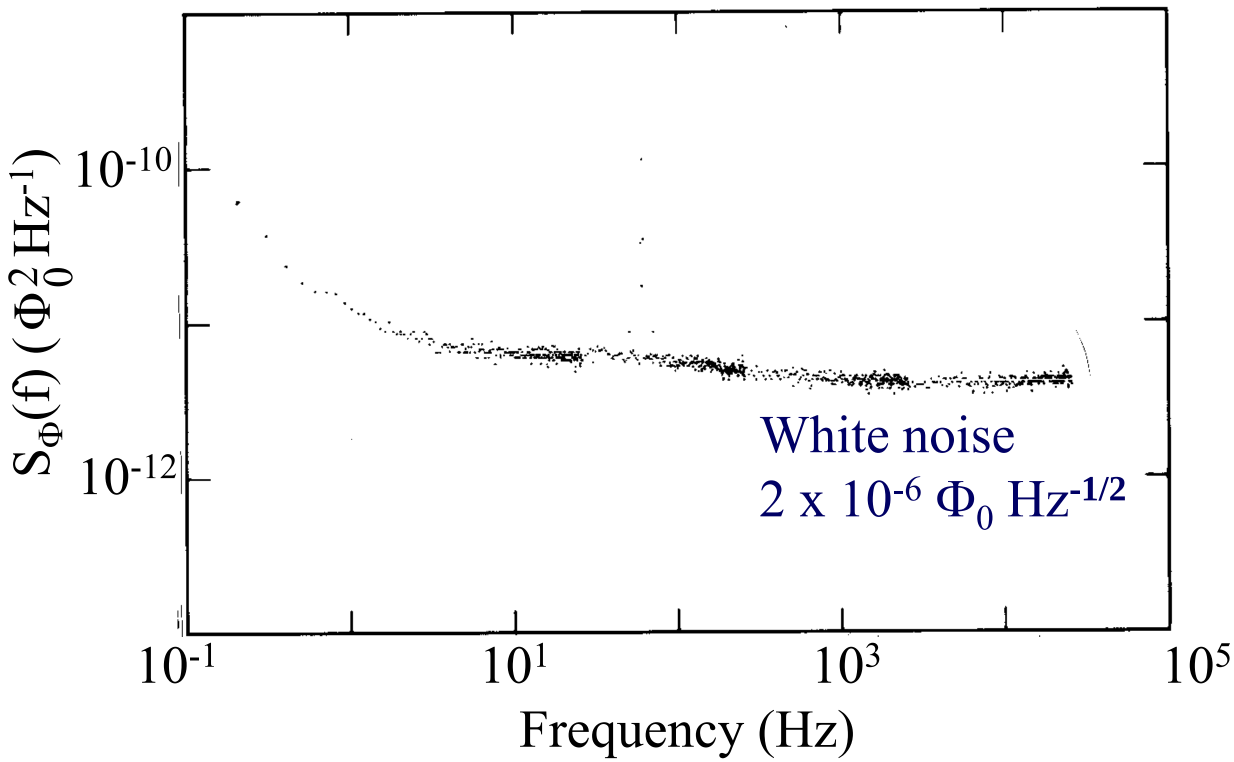
SQUID with input coil

Josephson junctions

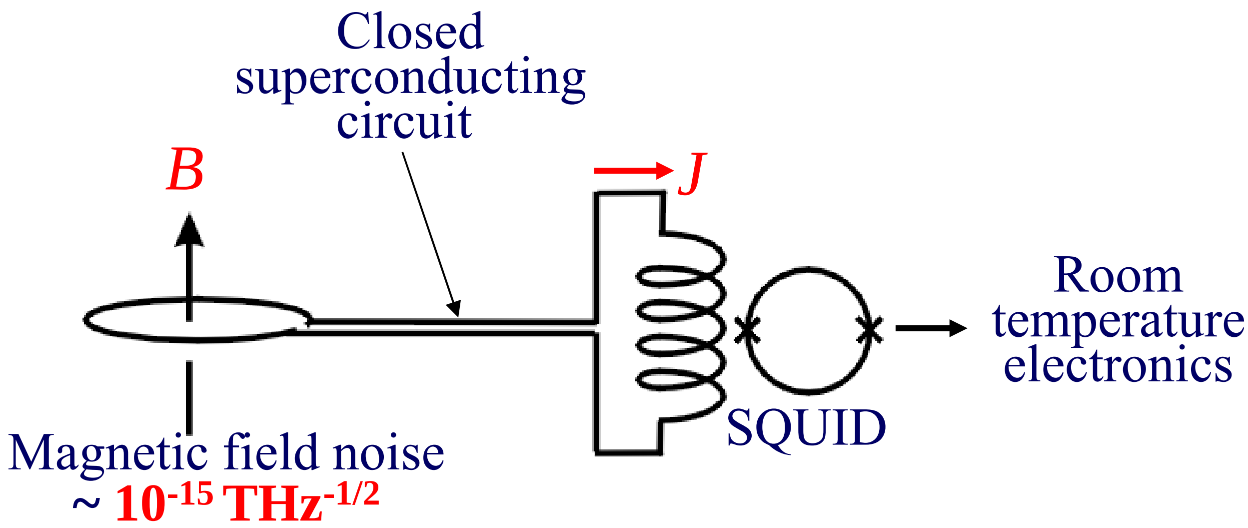
Ketchen, Jaycox (1981)

Flux Noise in the SQUID

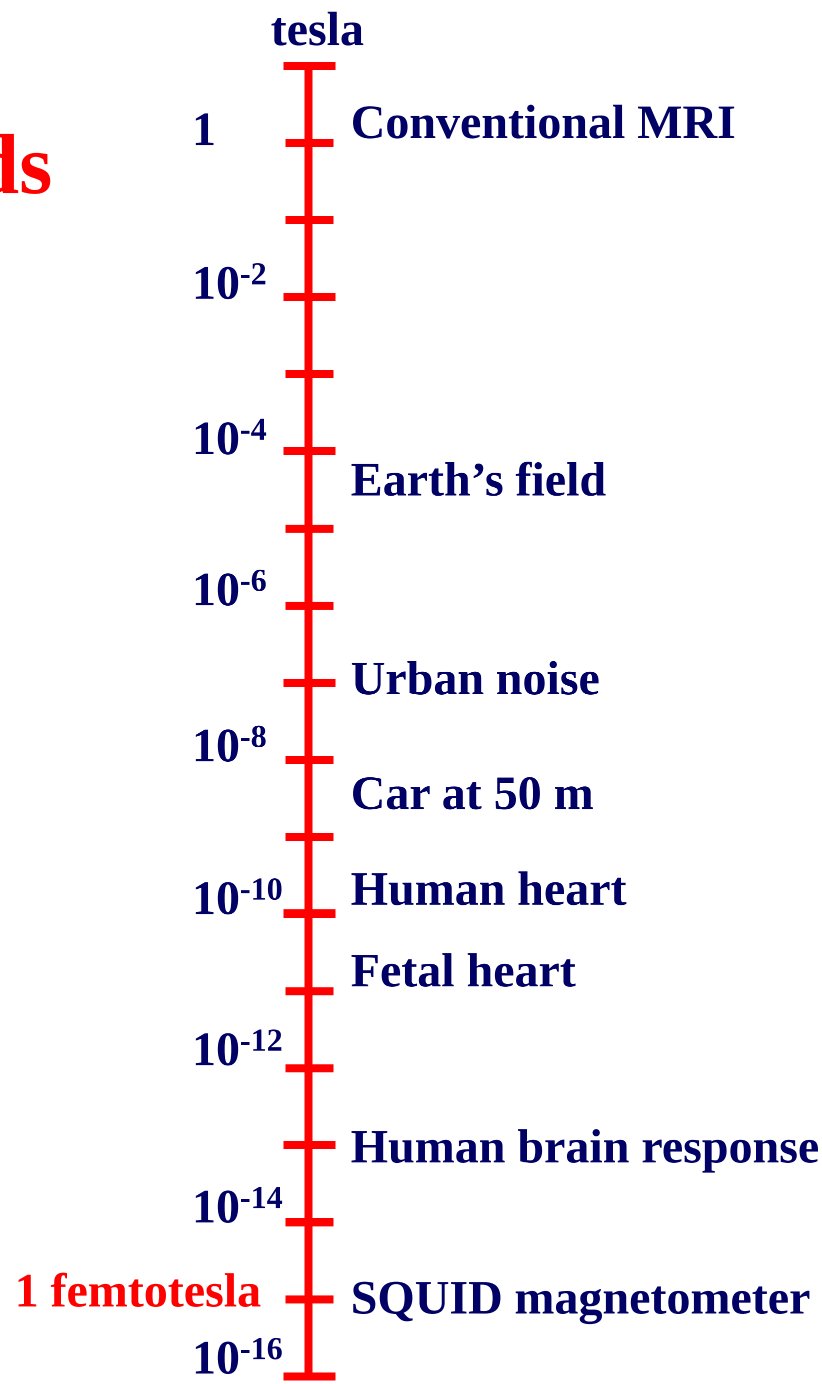




Superconducting Flux Transformer: Magnetometer

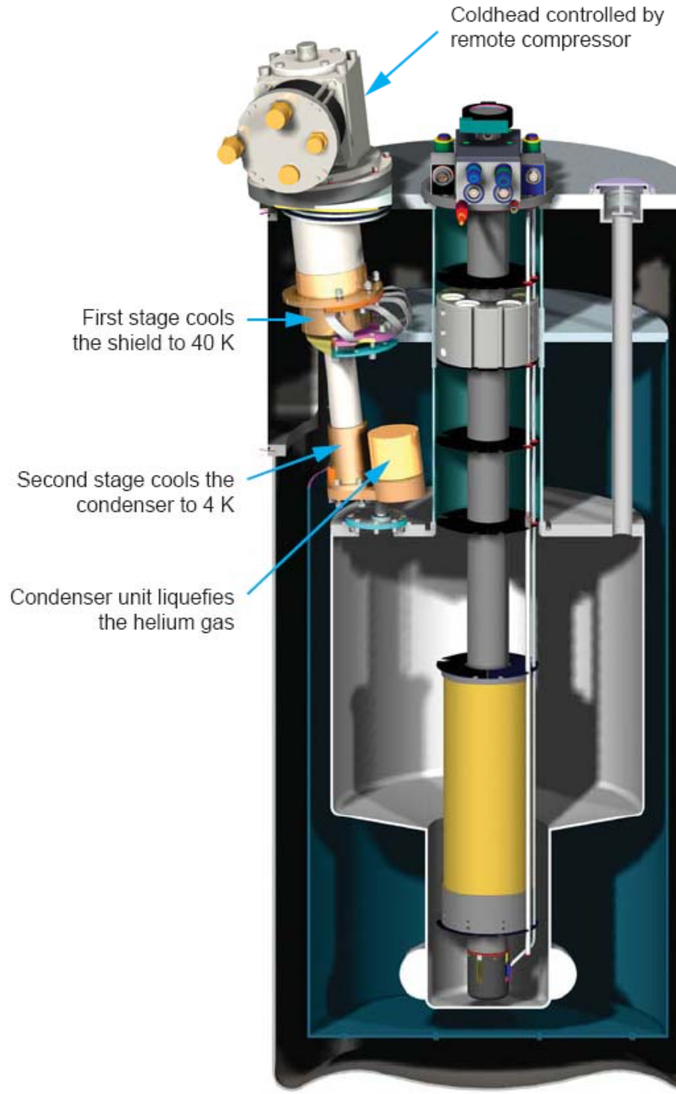


Magnetic Fields



The Diversity of SQUIDs

Quantum Design "Evercool"



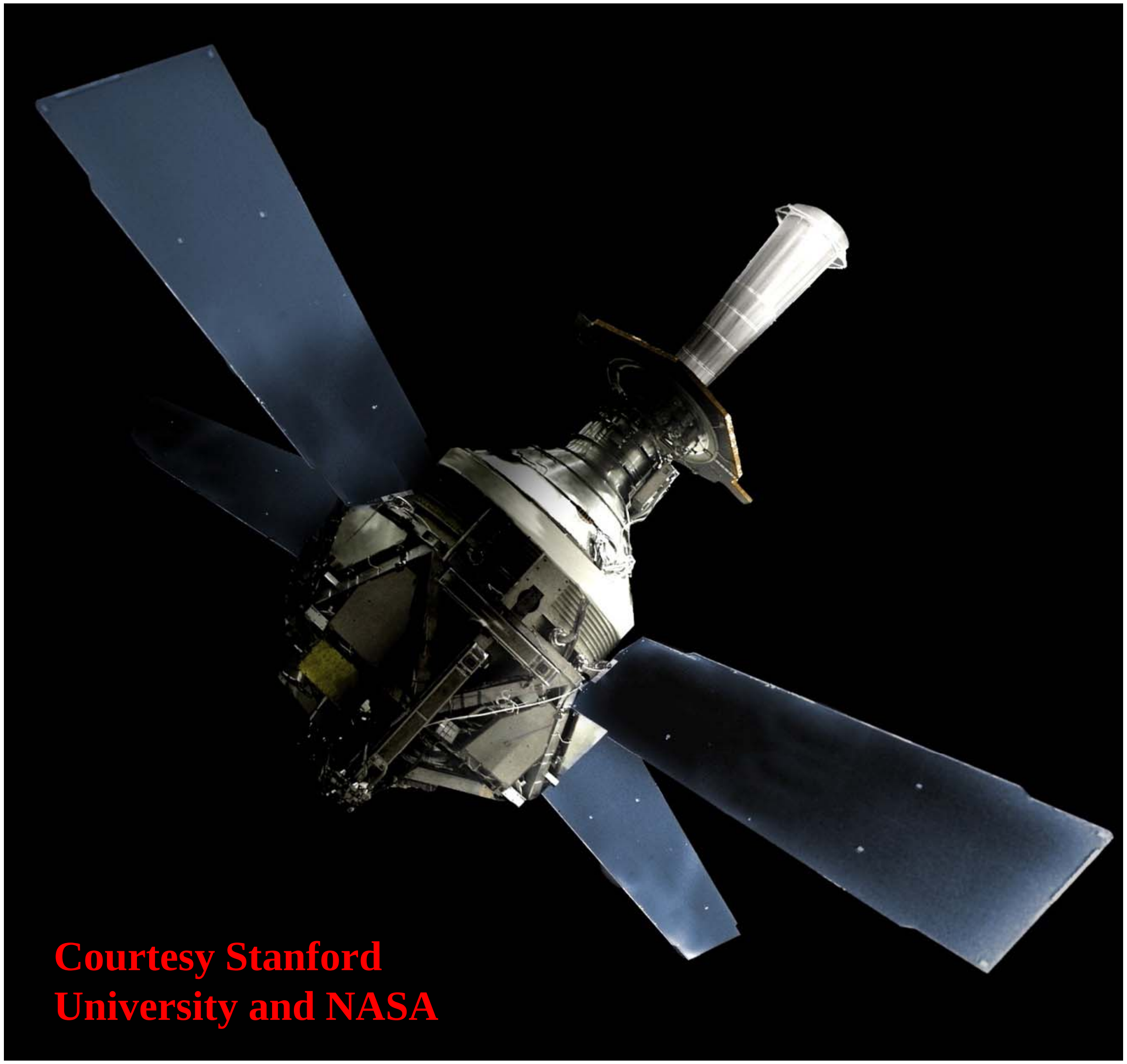
Cut-away Dewar View

High-T_c SQUIDs Prospecting for Mineral Deposits

Courtesy Cathy Foley, CSIRO

Gravity Probe-B

Tests of General Relativity

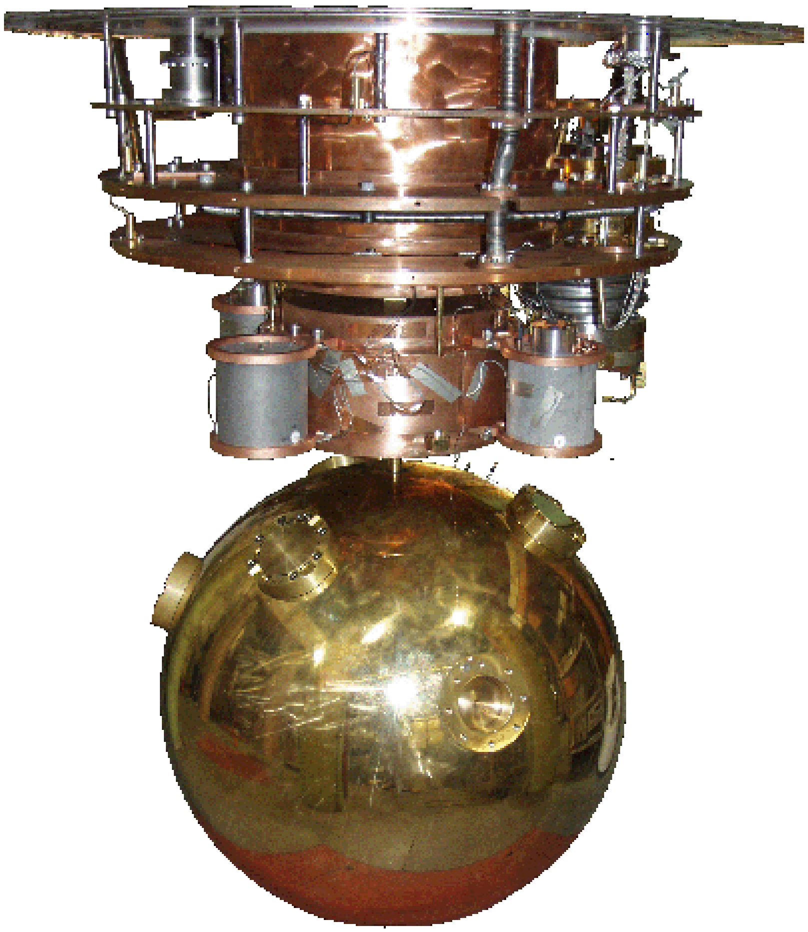


- Geodetic effect—curved space-time due to the presence of the Earth

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

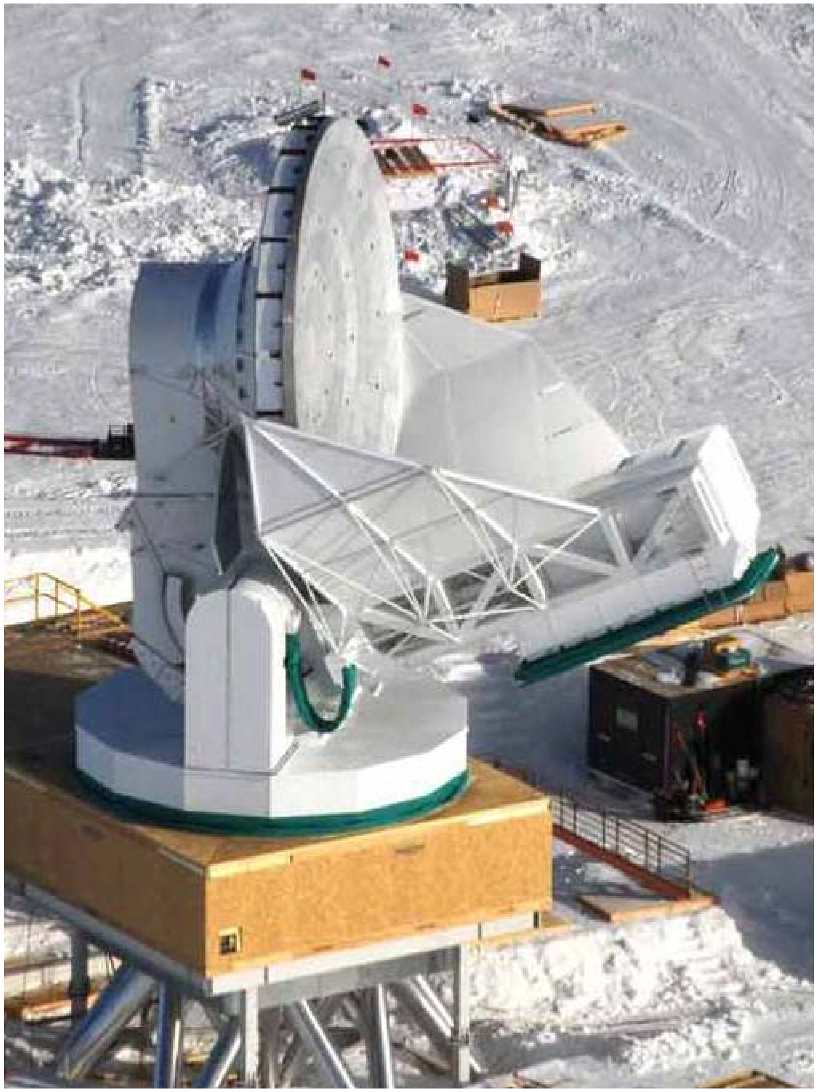
MiniGRAIL: Gravitational Wave Antenna

Leiden University

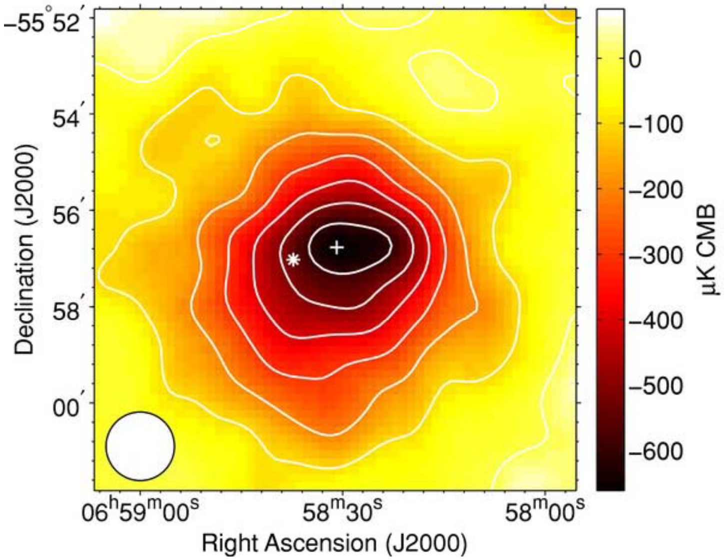


- Spherical gravitational wave detector
- Temperature: 20 mK
- Diameter: 650 mm
- Resonance frequency: 3160 Hz
- Motion coupled to a transducer that amplifies the motion, and couples flux into a dc SQUID
- Quantum limited strain sensitivity: $dL/L \sim 4 \times 10^{-21}$

SPT: South Pole Telescope



- Antarctica 9,500 feet
- 10 meter dish
- 960 Transition Edges Sensors with multiplexed SQUID readout
- SPT will survey 4,000 square degrees of sky in the next two years, and is expected to find large numbers of galaxy clusters.



The Bullet Cluster

CardioMag Imaging System for Magnetocardiography

300-Channel SQUID Systems for Magnetoencephalography (MEG)

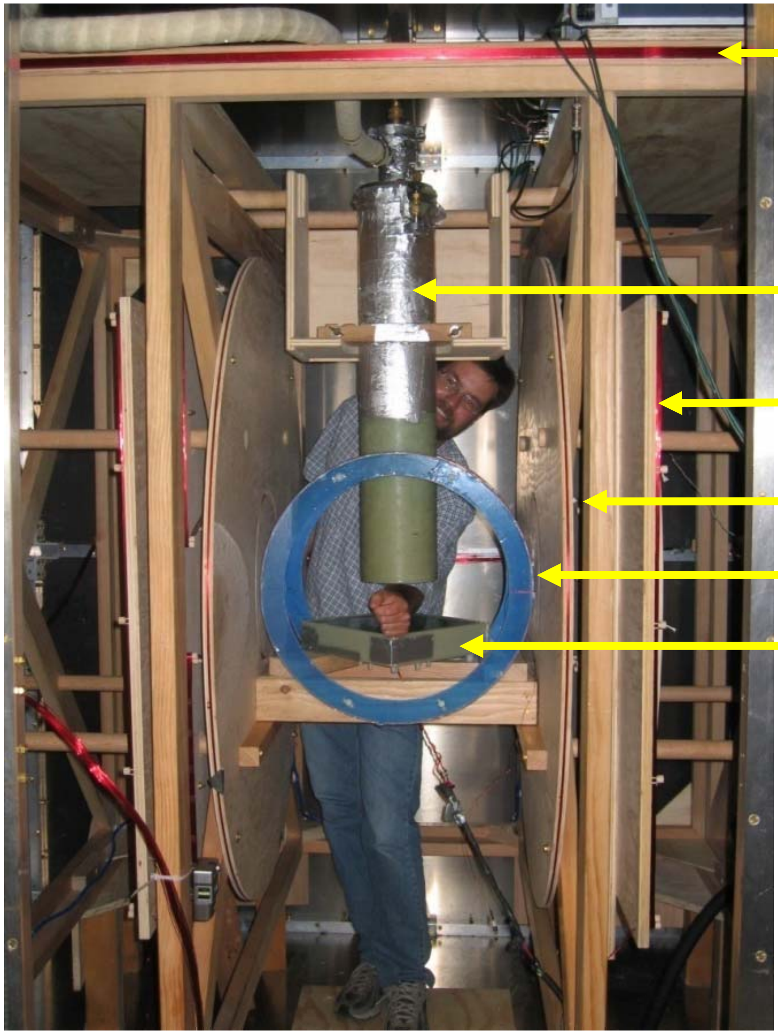
Ultralow Field
Magnetic Resonance Imaging

High-Field Magnetic Resonance Imaging


Courtesy GE, Inc.

- Magnetic field $B_0 = 1.5$ T
- Proton NMR frequency $\nu_0 \approx 64$ MHz
- What if we were to lower the magnetic field and NMR frequency by a factor of 10^4?

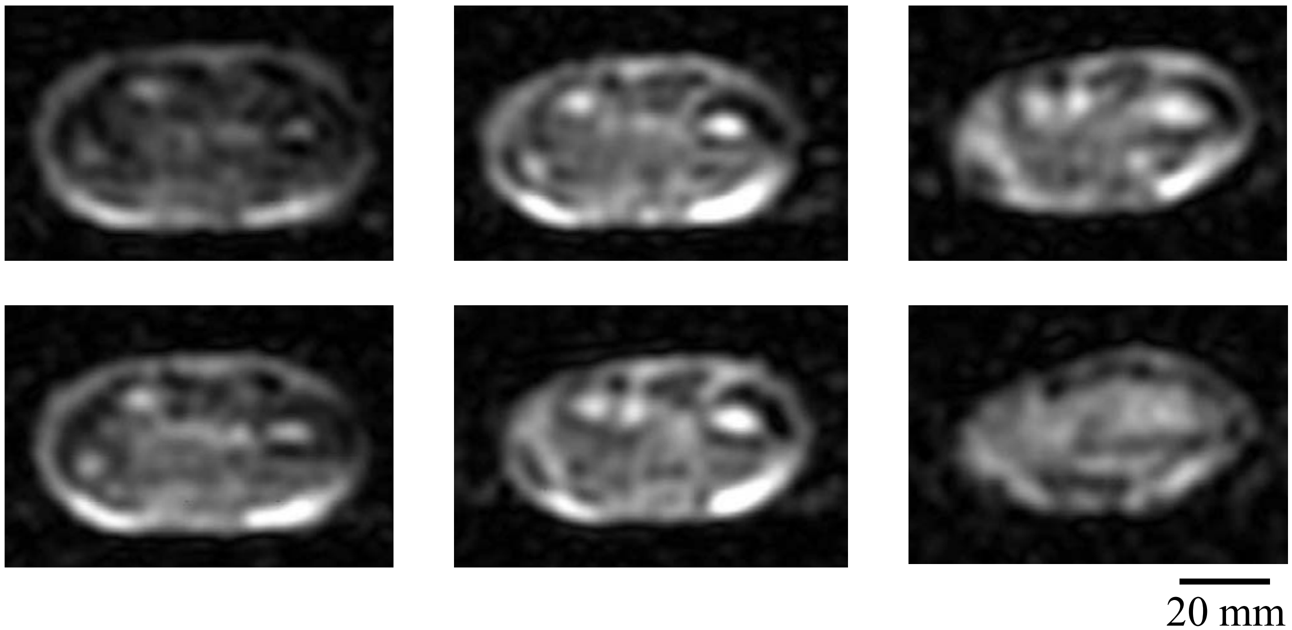
ULF MRI Coil Geometry



$B_0 = 132\ \mu T$
$\nu_0 = 5600$ Hz

- Gradient fields define voxels in space in the same way as in high-field MRI

Three-Dimensional *In Vivo* Images of the Arm



T_1-Weighted Contrast Imaging

- If two different types of tissue have the same proton density, a conventional MRI pulse sequence may not distinguish them.

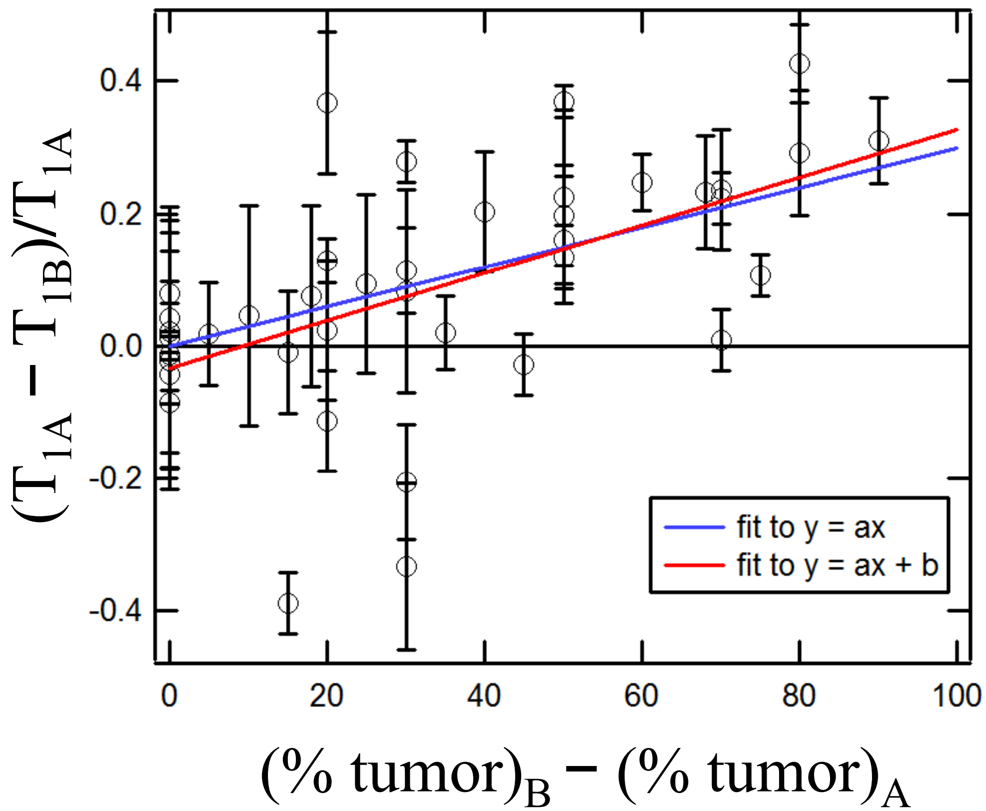
- T_1 depends strongly on the environment, and can be used to differentiate tissues types using a T_1-contrast pulse sequence.

- T_1 contrast can be much higher in low fields than in high fields.

Measurements on *Ex Vivo* Prostate Tissue

- Malignant prostate removed surgically at UCSF hospital.
- Pathologist cuts two small tissue samples, one healthy and one cancerous (Blind: we do not know which is which).
- Samples rushed to Berkeley in a biohazard bag placed on ice.
- T_1s measured: $T_{1A} > T_{1B}$
- Specimens are returned to UCSF where the pathologist characterizes a thin slice of each specimen.

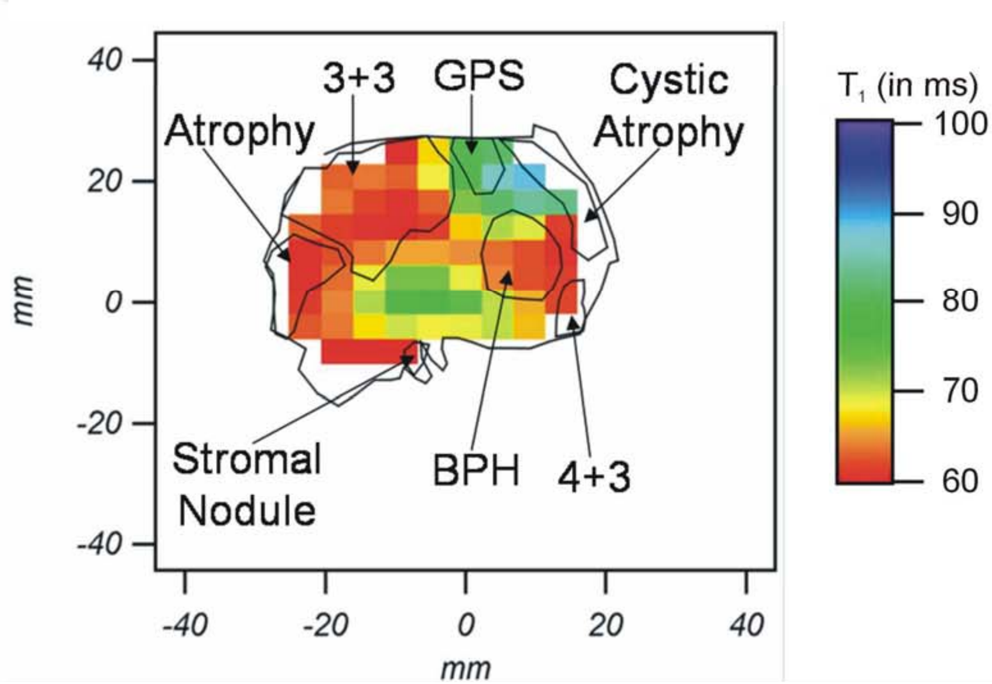
Contrast $(T_{1A} - T_{1B})/T_{1A}$ vs. % Difference in Tumor Content for each Specimen Pair



35 patients

- T_1(100% normal) = (1.43 ± 0.10) T_1(100% tumor)
- Sufficient for *in vivo* T_1-wighted contrast imaging

T_1-Map of Prostate Slice



- Dark lines indicate histology, which is performed on a thin slice.
- T_1 map is averaged over the entire thickness.
- Map clearly shows T_1 contrast

- Tissue identified through histological mapping
- Tissue is *healthy* unless labeled otherwise
- X + Y: Gleason score of tumors; 5 is the most advanced
- BPH: Benign Prostatic Hyperplasia
- GPS: Gland Poor Stroma

Outlook

• Microtesla MRI has the advantage of significantly higher T_1 contrast than high-field MRI.

• Other kinds of cancer: Do other types of tumors show T_1 contrast similar to that of prostate tumors?

• New funding to study *ex vivo* breast cancer

• National Institutes of Health provided funding to build a prototype system for *in vivo* imaging of prostate cancer.

• Next step: *in vivo* imaging

Cold Dark Matter:
The Hunt for the Axion

Cosmic Microwave Background: "The Cosmic Rosetta Stone"

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

- Thus 95% of the universe is unknown!

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

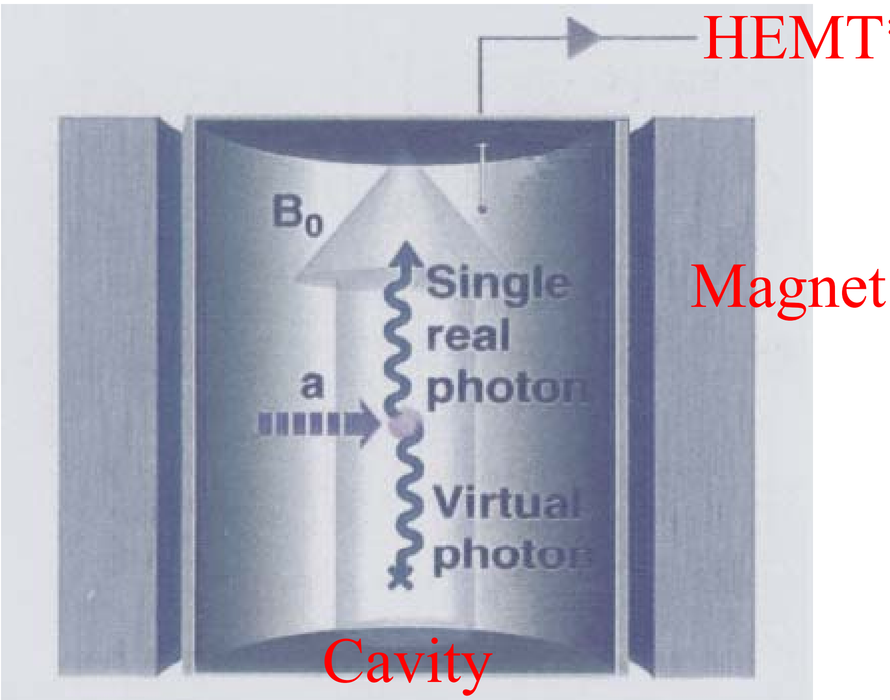
Predicted mass:

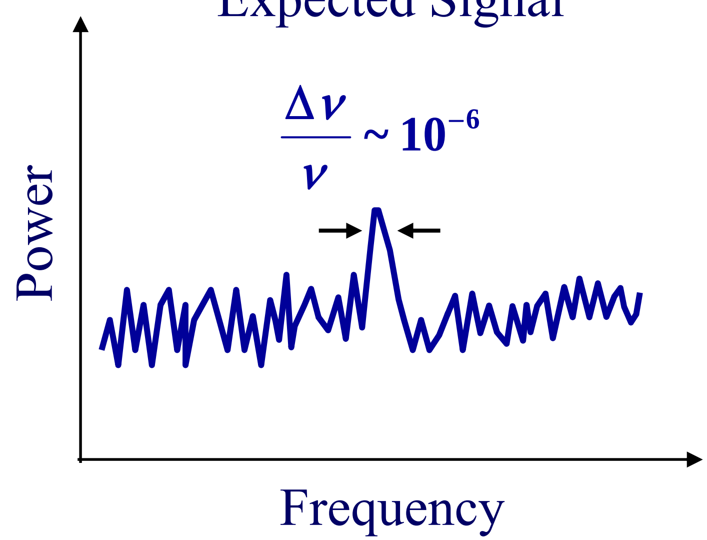
$m_a \approx 1\ \mu eV - 1\ meV$ (0.24 - 240 GHz)

Resonant Conversion of Axions into Photons

Pierre Sikivie (1983)

Primakoff Conversion





*High Electron Mobility Transistor

Need to scan frequency

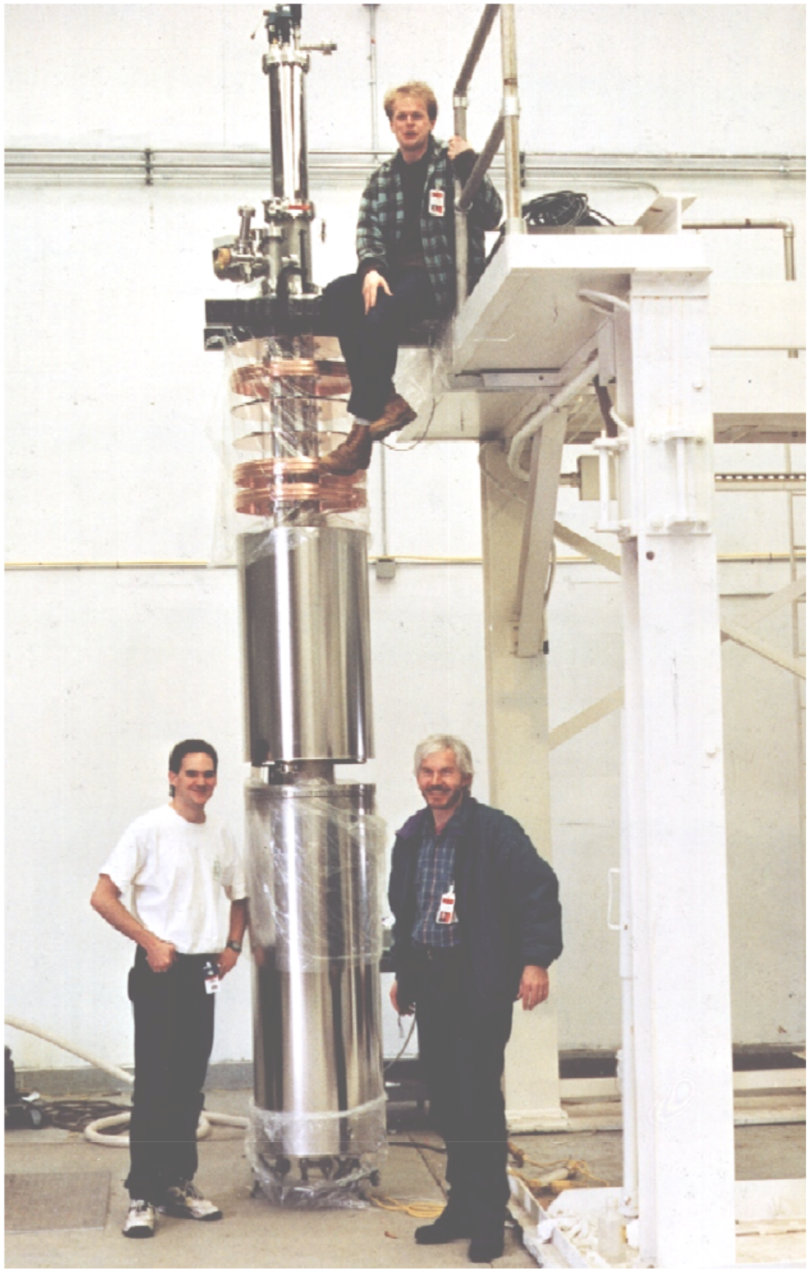
Axion Detector at Lawrence Livermore National Laboratory

- Cooled to 1.5K
- 7 tesla magnet

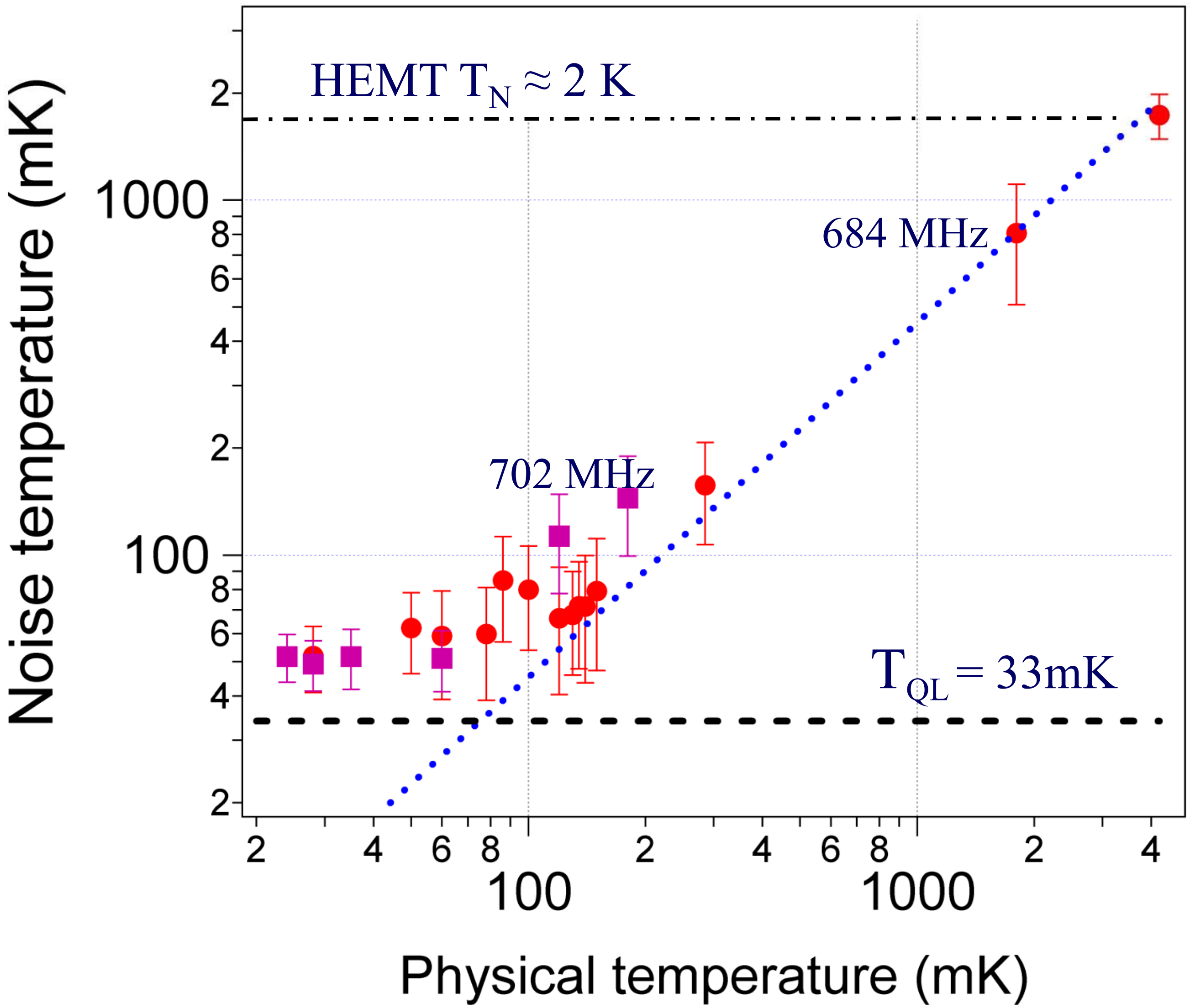
Scan Time

Using a HEMT amplifier, time to scan the frequency range from

0.24 to 0.48 GHz: 270 years



Noise Temperatures of Two SQUID Amplifiers



- In the classical limit theory predicts $T_N \propto T$
- In the quantum limit: $T_{QL} = hf/k_B$
- Closest approach to quantum limit: At 799 MHz $T_N = 47 \pm 5$ mK $T_{QL} = 38$ mK

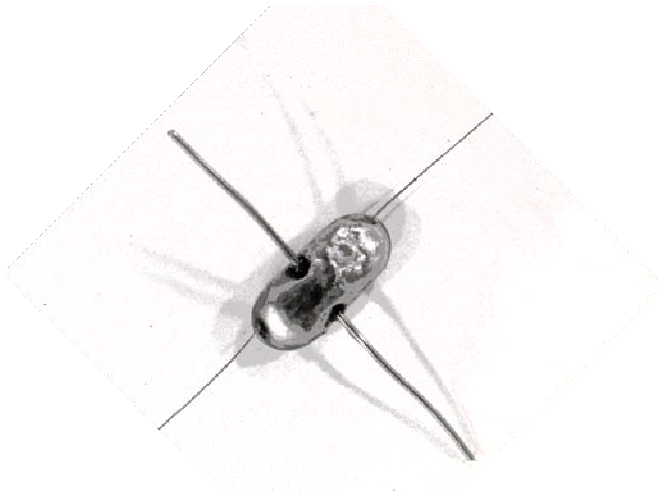
Scan Time

- Using a HEMT amplifier, time to scan the frequency range from 0.24 to 0.48 GHz ≈ 270 years.

- The HEMT has been replaced with a SQUID amplifier. With the system cooled to 50 mK with a dilution refrigerator, time to scan the frequency range from 0.24 to 0.48 GHz ≈ 100 days.

- A SQUID amplifier was successfully operated on the axion detector at 1.5 K to demonstrate proof-of-principle.

- Given the success of this trial run, the Department of Energy has funded the installation of a dilution refrigerator to cool the cavity and SQUID to 50 mK. This will enable an effective search for the axion 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).
- The resolution of SQUID amplifiers is essentially limited by Heisenberg's Uncertainty Principle.
- Microtesla MRI, the axion search, and a host of other applications, exist only because of the extraordinarily low noise of the SQUID—which in itself seems to be a very tiny part of the whole system.

Thank You!

ULFMRI

Sarah Busch
Erwin Hahn
Michael Hatridge
Nathan Kelso
SeungKyun Lee
Robert McDermott
Michael Mössle
Michael Mück
Whit Myers
Fredrik Öisjöen
Alex Pines
Dan Slichter
Paul SanGiorgio
Bennie ten Haken
Andreas Trabesinger
Travis Wong
Koos Zevenhoven
High Precision Devices

Axion Detector

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