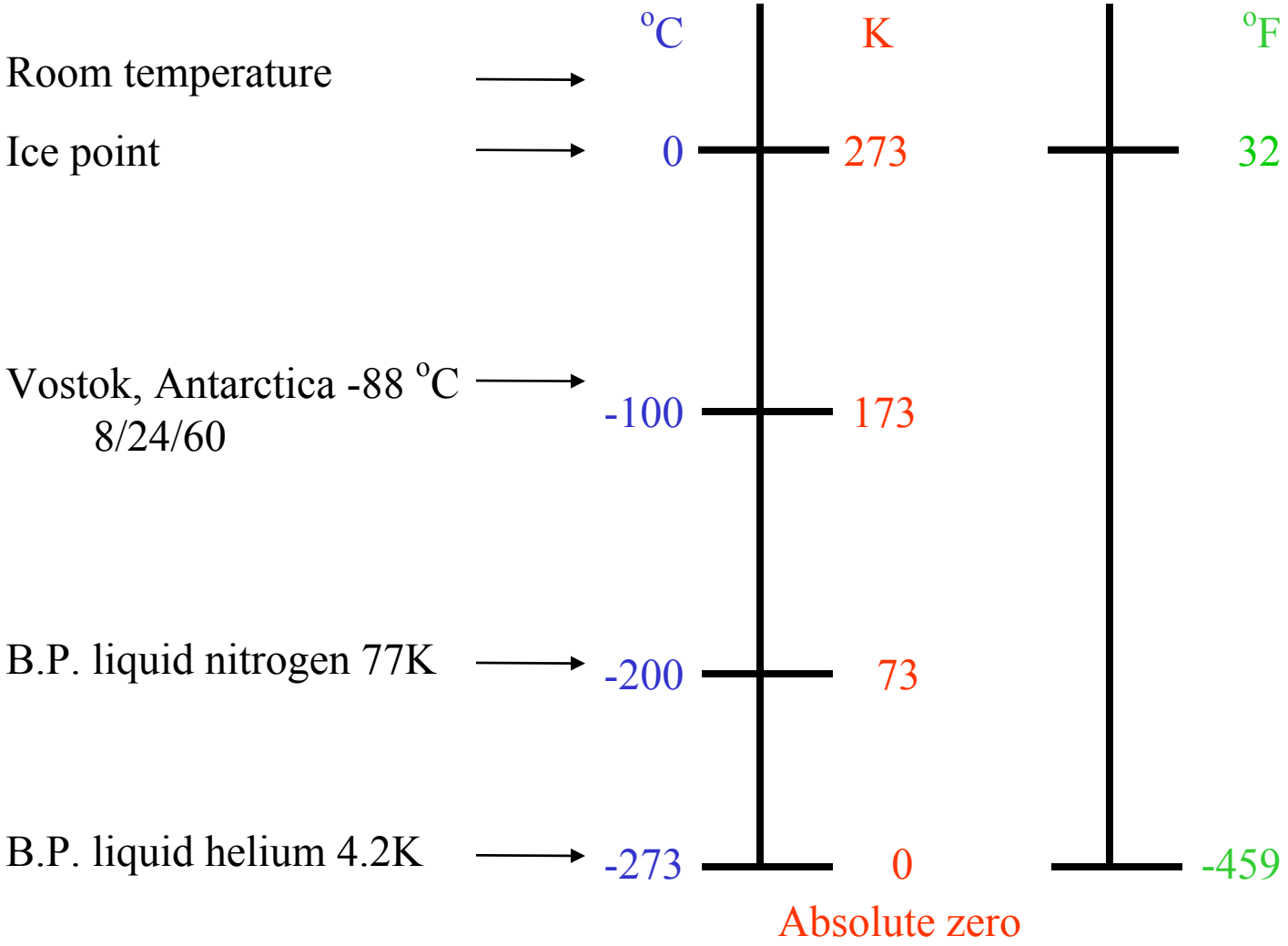
SQUIDs: From Cosmology to Magnetic Resonance Imaging in Microtesla Fields

- Milestones in superconductivity
- The SQUID
- Applications of SQUIDs: an overview
- Searching for cold dark matter with a SQUID
- Magnetic resonance imaging with a SQUID

The Finnish Academy

8 November 2004

Centigrade/Kelvin/Fahrenheit Temperature Scales



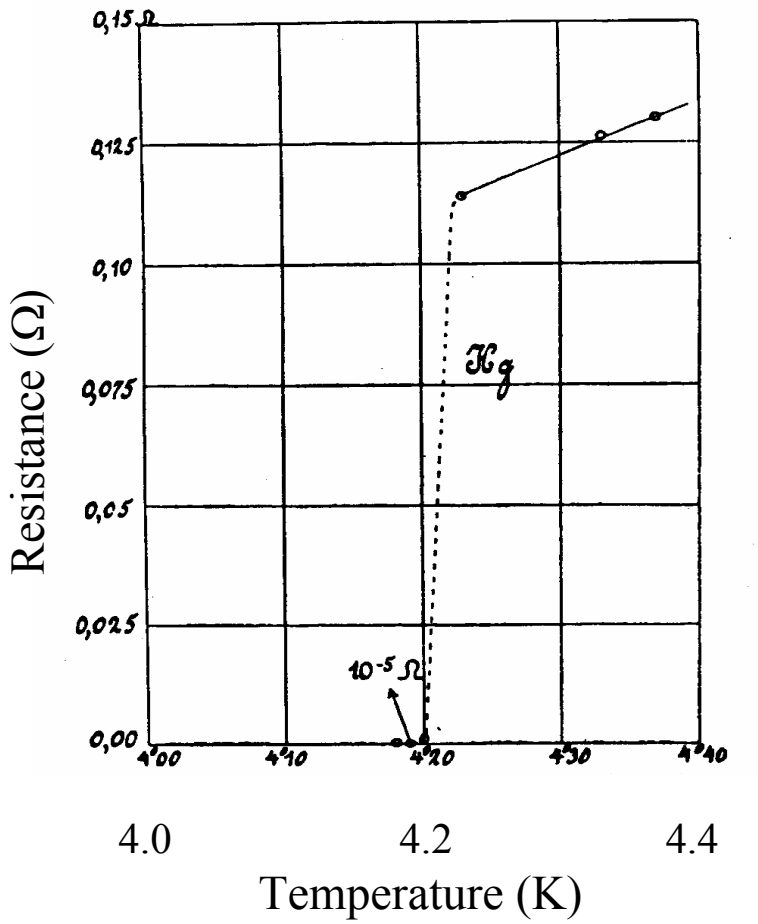
Milestones in Superconductivity

1911 Kamerlingh Onnes discovers zero resistance

Heike Kamerlingh Onnes

Courtesy Kamerlingh Onnes Laboratory, University of Leiden

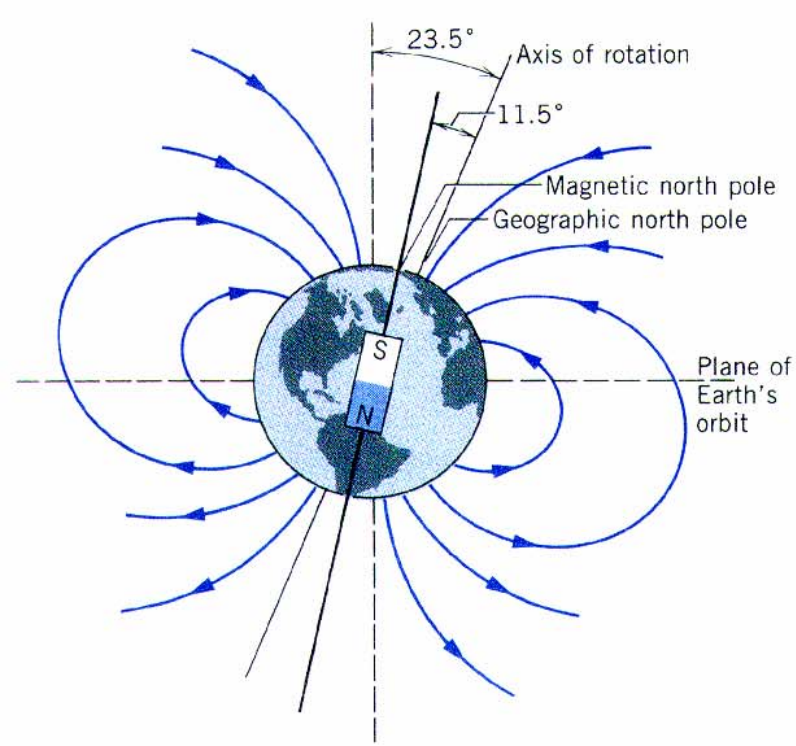
The Discovery of Superconductivity



Resistance vanishes below the transition (or critical) temperature T_c

Magnetic Fields

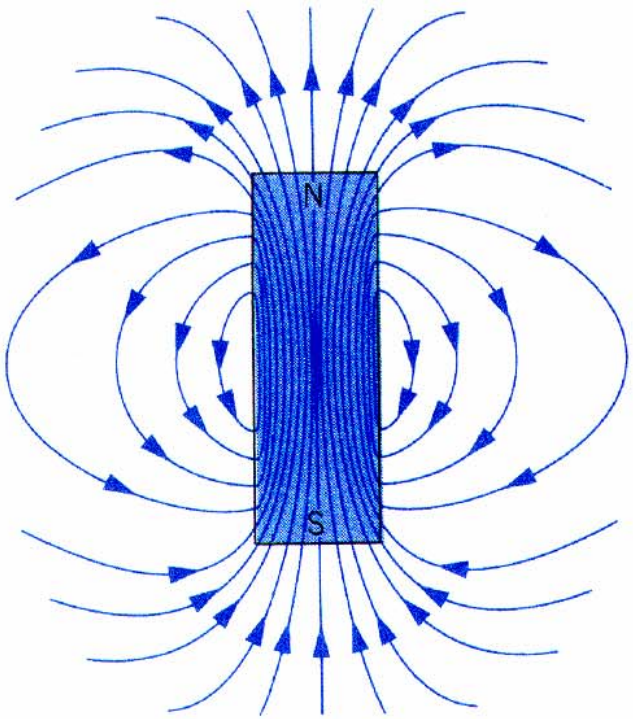
The earth



~1 gauss

10^{-4} tesla

Bar magnet

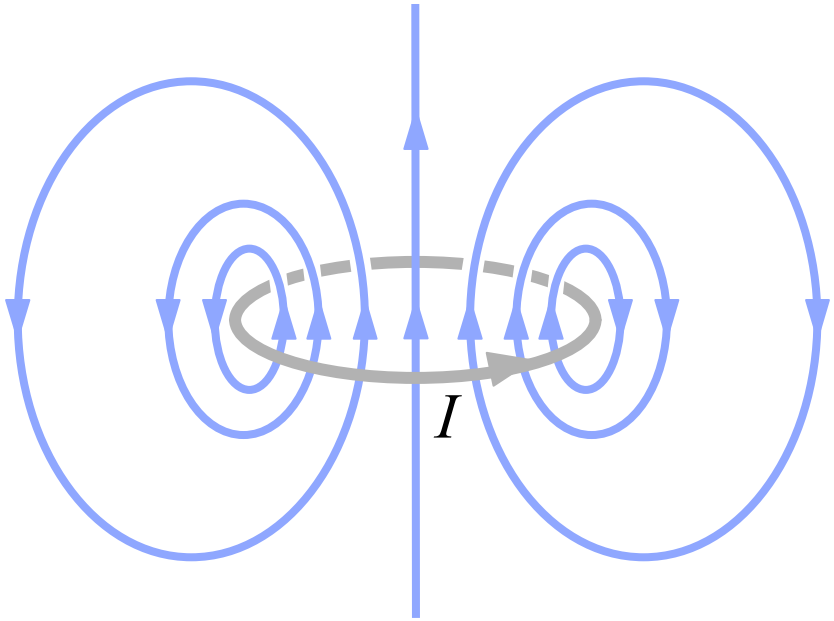


~1000 gauss

0.1 tesla

Zero Resistance

Magnetic field



- Current persists forever
- Resistance at least one billion billion times less than copper
- **Basis of superconducting magnets**

A Few Other Superconductors

Element	T_c
Aluminum	1.2 K
Indium	3.4 K
Tin	3.7 K
Lead	7.2 K
Niobium	9.2 K

- "Type I" superconductors
- Driven normal by magnetic fields less than 2000 gauss

Milestones in Superconductivity

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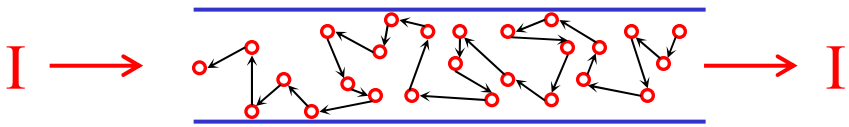
1957 Bardeen, Cooper and Schrieffer develop “BCS” theory

Normal Metals vs. Superconductors

Normal Metals

Electron has charge -e

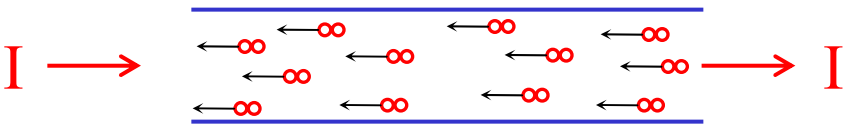


Scattering of electrons produces resistance.

A current generates a voltage, and hence causes dissipation.

Superconductors : BCS Theory

Electrons are paired together :
these Cooper pairs have charges -2e



Cooper pairs carry a supercurrent which encounters no resistance.

A supercurrent generates no voltage, and hence causes no dissipation.

Milestones in Superconductivity

1911 Kamerlingh Onnes discovers zero resistance

1957 Bardeen, Cooper and Schrieffer develop “BCS” theory

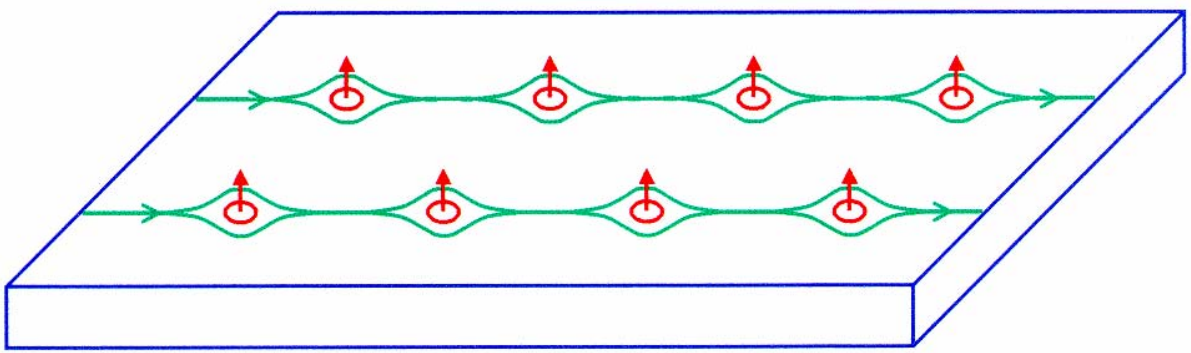
1957 Alexei Abrikosov predicts Type II superconductors

Large-scale applications are made possible

Type II Superconductors

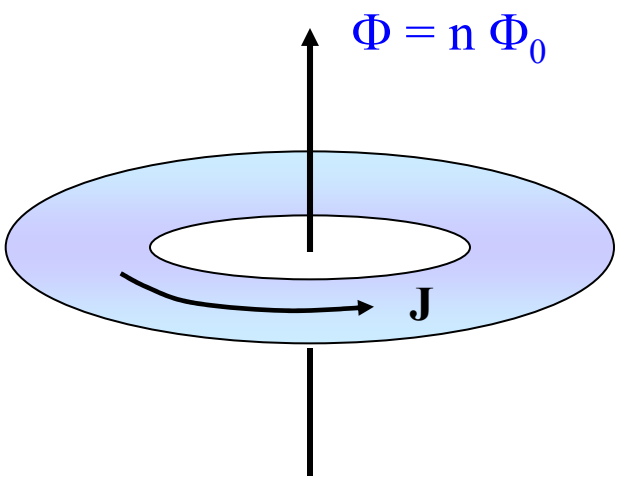
Alloys: ~2000 known

The secret of their success: Type II materials admit "vortices" of magnetic field, and the supercurrents flow around them.



High field magnets made possible.

Flux Quantization



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

Milestones in Superconductivity

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Large-scale applications are made possible

1960 Ivar Giaever invents tunnel junctions

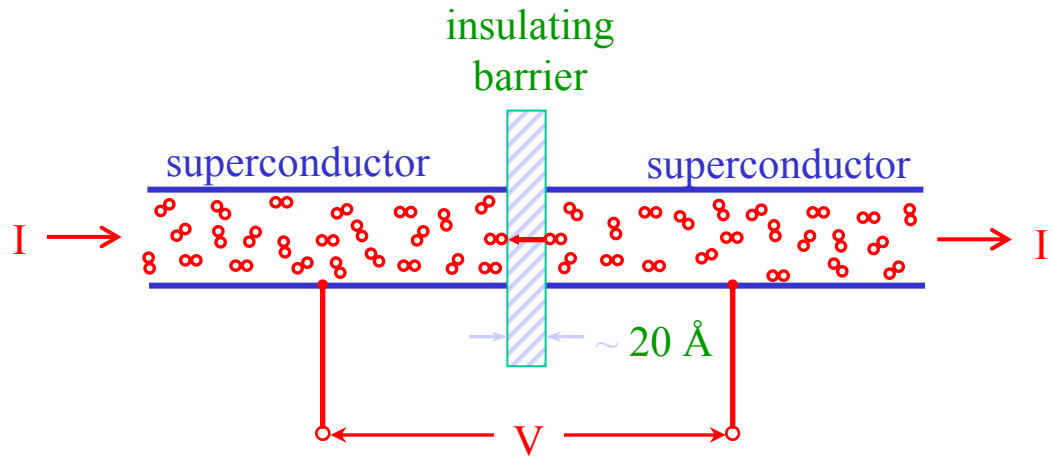
1962 Brian Josephson invents “Josephson Tunneling”

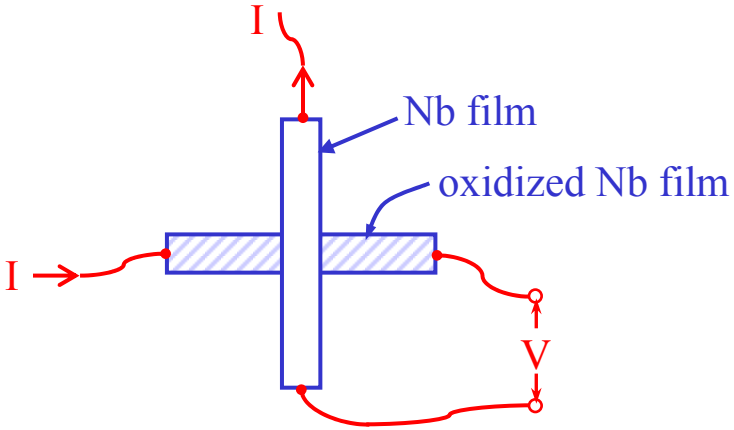
Superconducting electronics is born

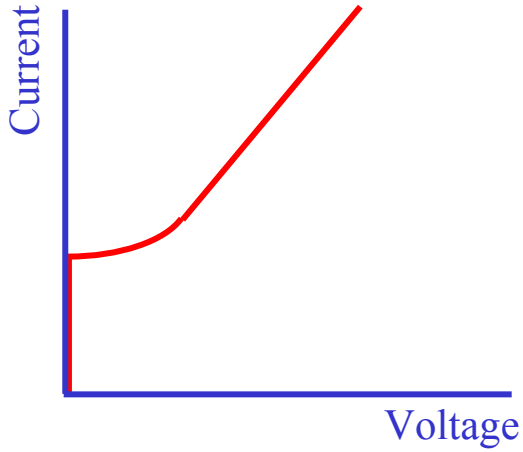
Josephson Tunneling

- Cooper pairs tunnel through barrier

Brian Josephson 1962







Created the field of superconducting electronics

Milestones in Superconductivity

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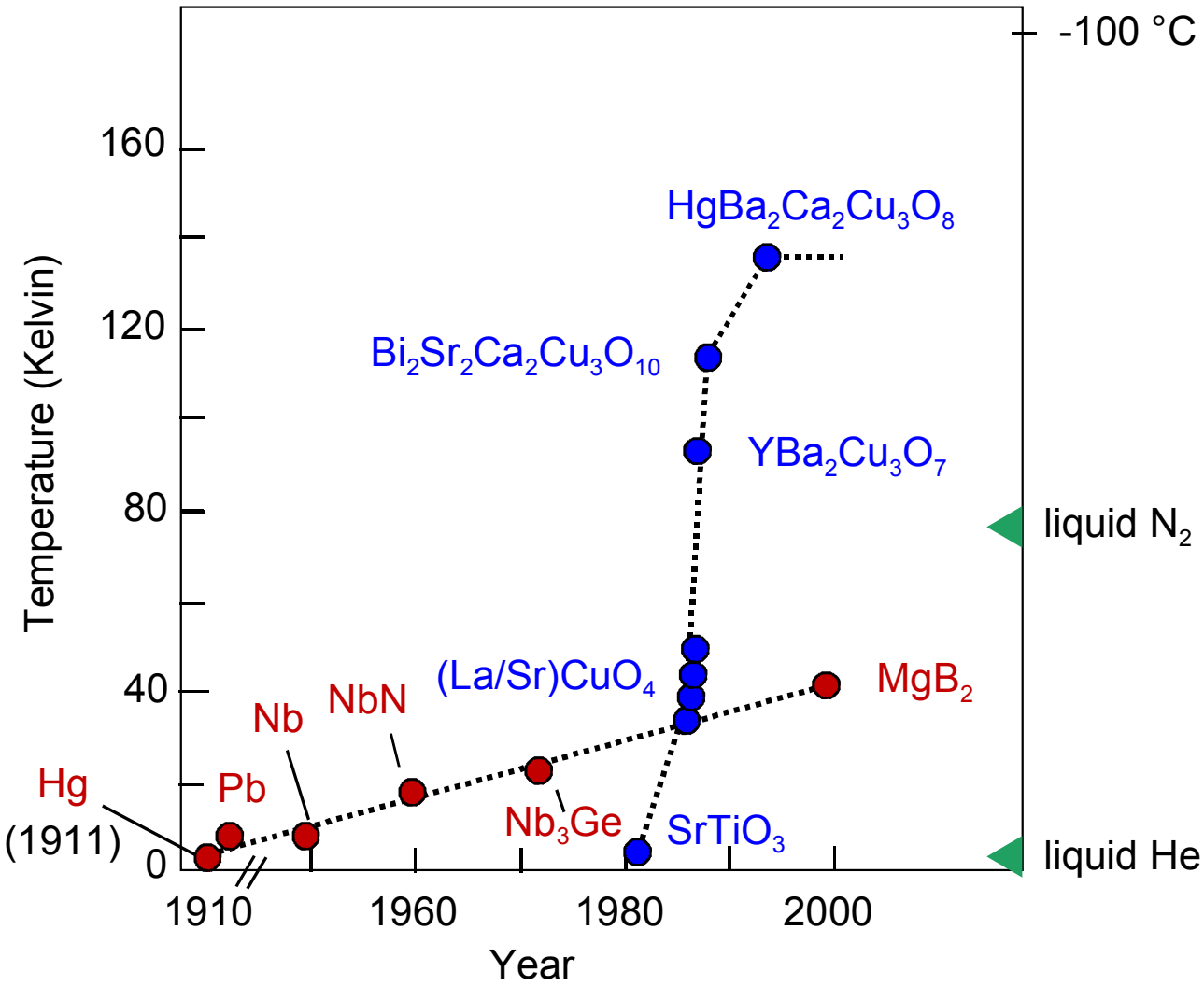
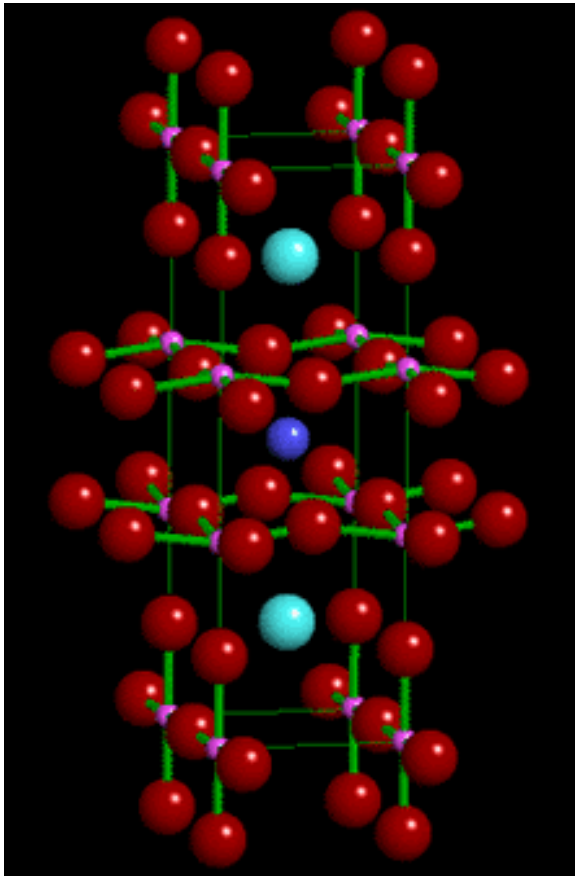
Superconducting electronics is born

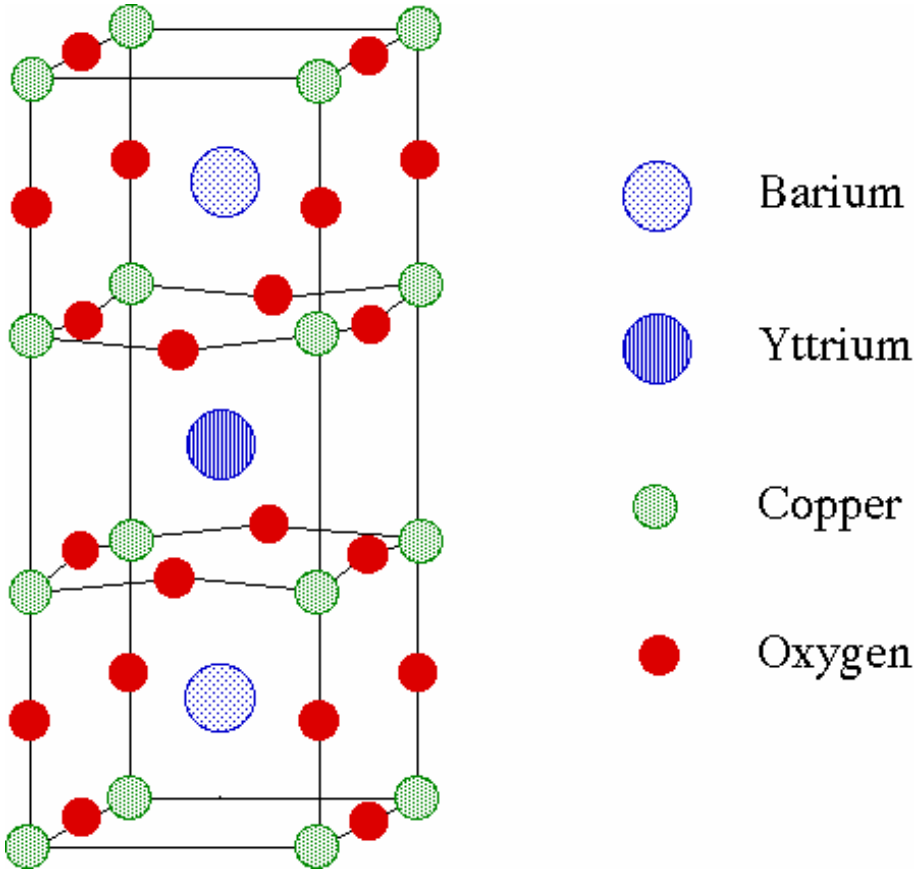
1986 Bednorz and Muller discover high-T_c superconductivity

Transition Temperature Over the Years



YBCO





Milestones in Superconductivity

1911 Kamerlingh Onnes discovers zero resistance
Nobel Prize 1913

1957 Bardeen, Cooper and Schrieffer develop "BCS" theory
Nobel Prize 1972

1957 Alexei Abrikosov predicts Type II superconductors
Nobel Prize 2003

Large-scale applications are made possible

1960 Ivar Giaever invents tunnel junctions
Nobel Prize 1973

1962 Brian Josephson invents "Josephson Tunneling"
Nobel Prize 1973

Superconducting electronics is born

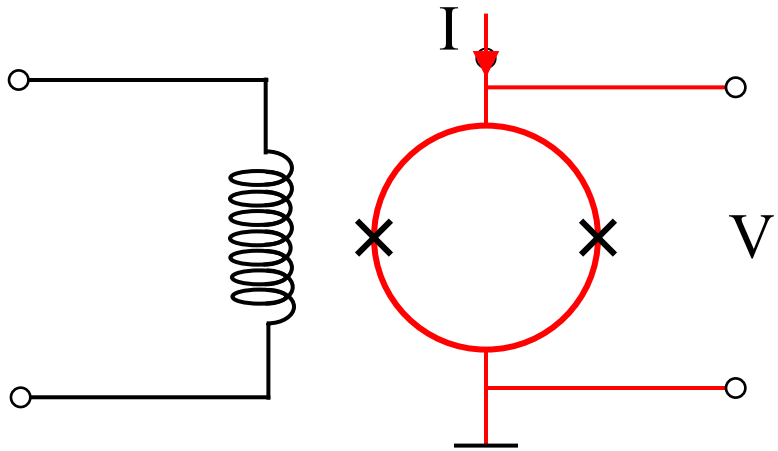
1986 Bednorz and Muller discover high-T_c superconductivity
Nobel Prize 1987

The SQUID

The dc Superconducting Quantum Interference Device

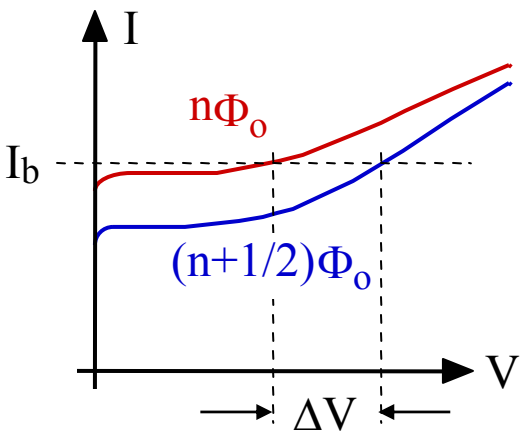
- **dc SQUID**

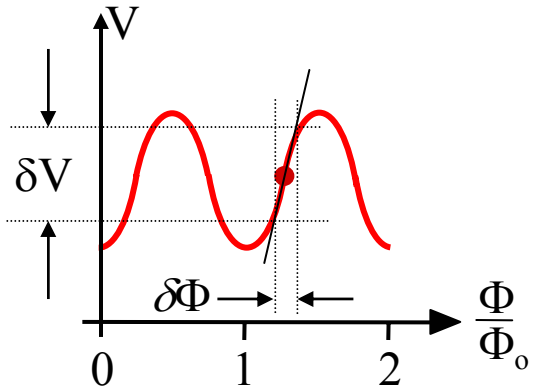
  Two Josephson junctions on a superconducting ring



- **Current-voltage (I-V) characteristic modulated by magnetic flux Φ:**

  Period one flux quantum $\Phi_o = h/2e = 2 \times 10^{-15}$ T m^2

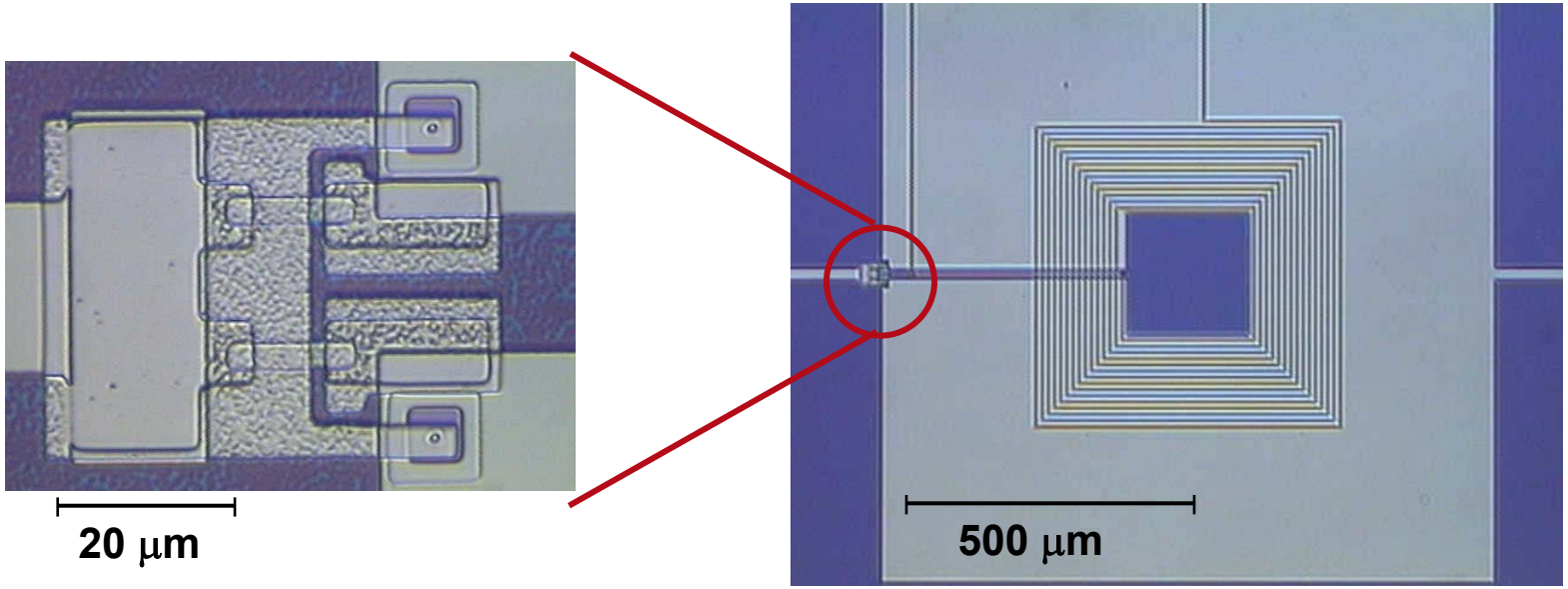




Low-T_c SQUID

Operating temperature = 4.2 K

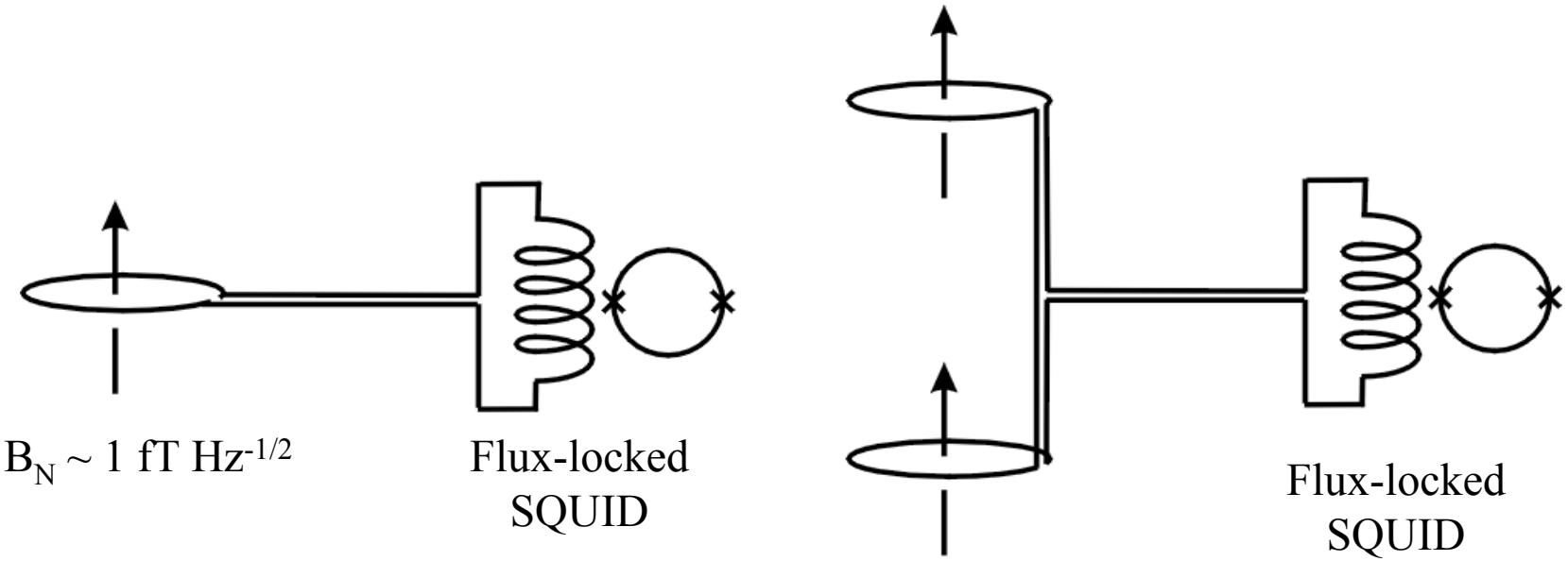
Multilayer device: niobium - aluminum oxide - niobium



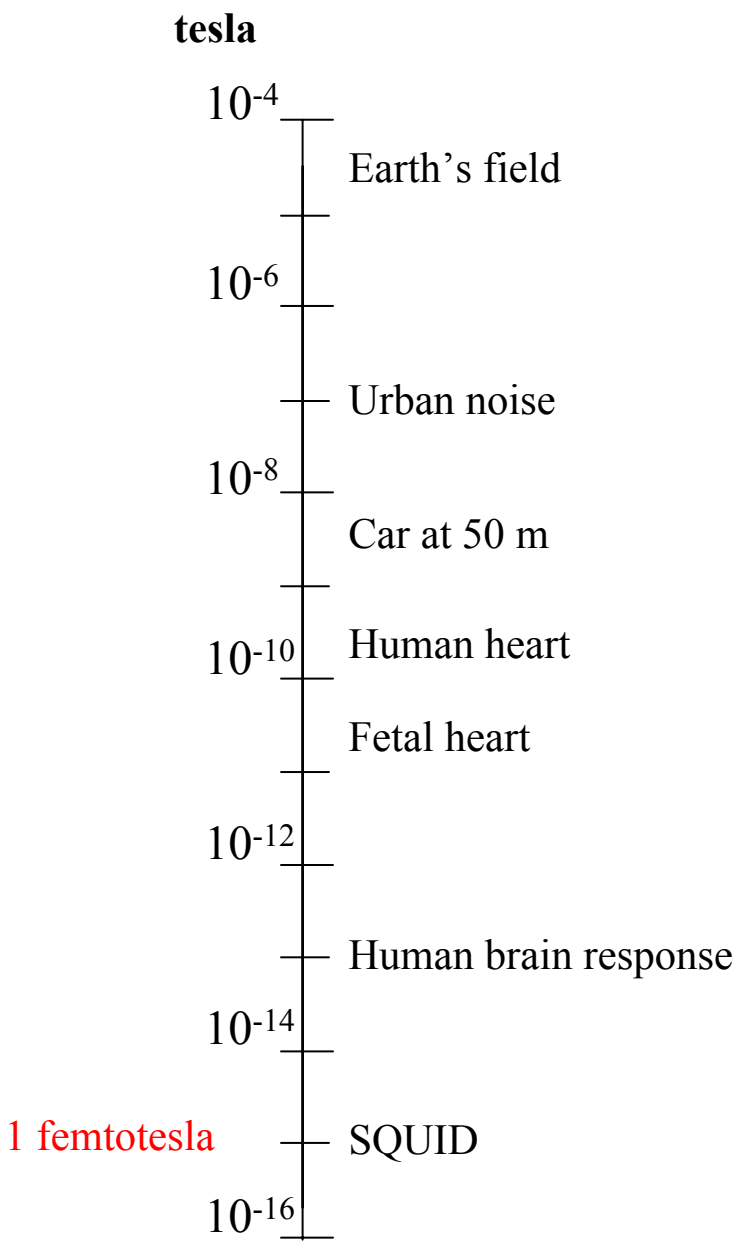
Josephson junctions

Nb-AlOx-Nb SQUID with input coil

Superconducting Flux Transformer: Magnetometer and Gradiometer



Magnetic Fields



Applications of SQUIDs:

An Overview

Olli Lounasmaa

Olli was did much to bring SQUIDs to Finland, and greatly encouraged their application to Magnetoencephalography (MEG). MEG is the single biggest consumer of SQUIDs, and has important applications in both brain research and clinical diagnosis. Neuromag is a leading supplier of MEG systems around the world. Olli was also deeply involved with the use of SQUIDs to study nuclear ordering in copper and silver at ultralow temperatures.

Neuromag® 306-Channel SQUID System for Magnetoencephalography

Applications of Magnetoencephalography

Clinical (Reimbursable in the United States)

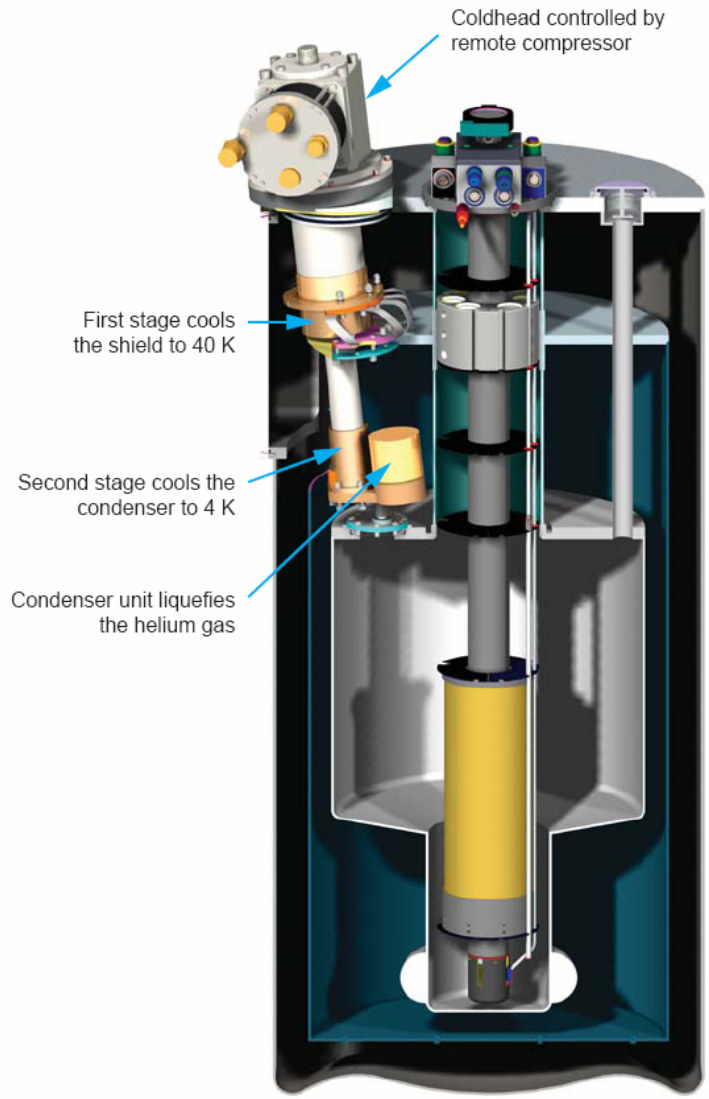
- Presurgical screening of brain tumors (evoked response)
- Location of epileptic foci (spontaneous signals)

Research

- Language mapping in the brain
- Identification of patients with schizophrenia
- Identification of patients with dyslexia
- Alzheimer's disease
- Parkinson's disease
- Neurological recovery following stroke or hemorrhage

CardioMag Imaging System for Magnetocardiography

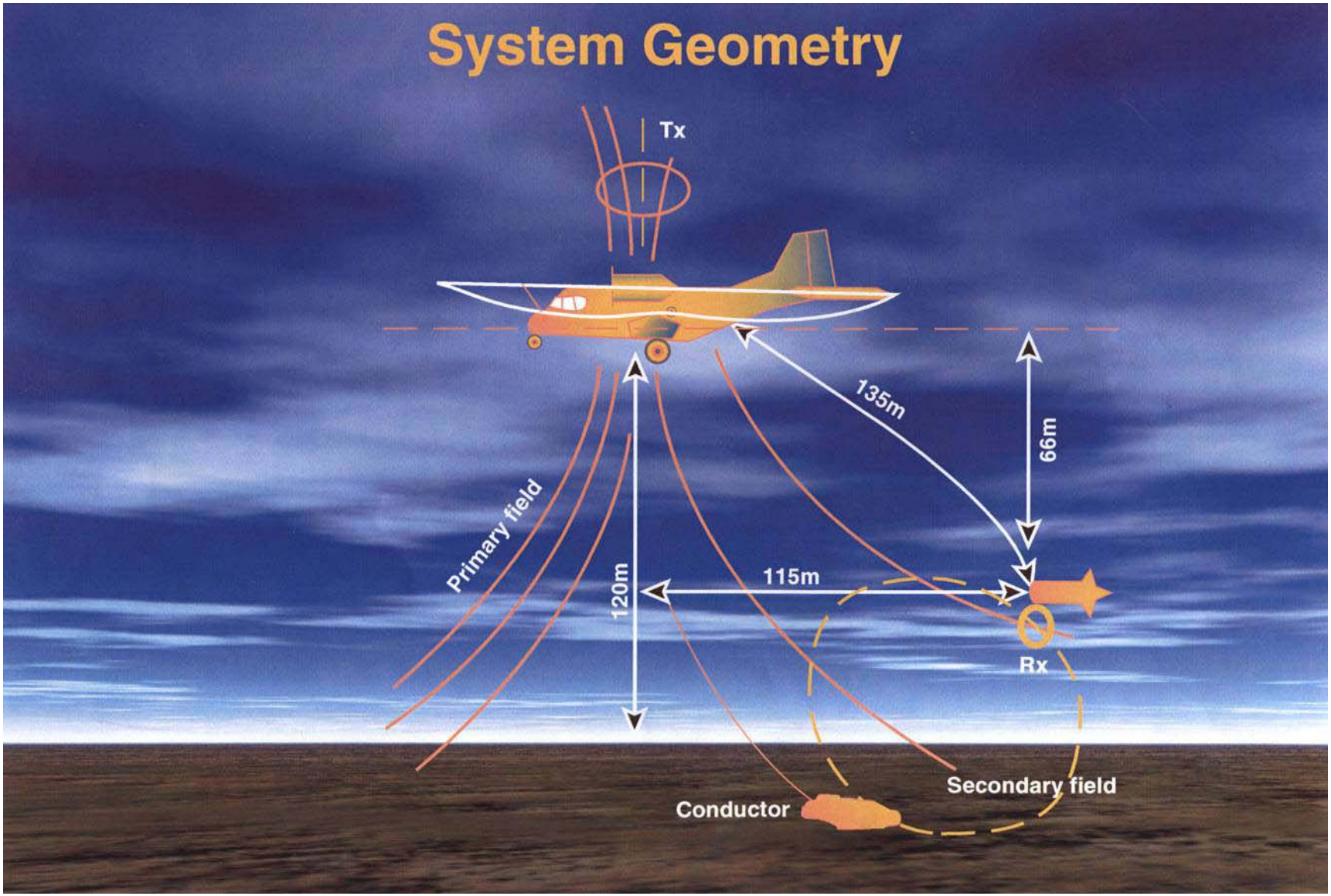
Quantum Design "Evercool"



Cut-away Dewar View

2G Superconducting Rock Magnetometer

SQUID Surveying for Minerals

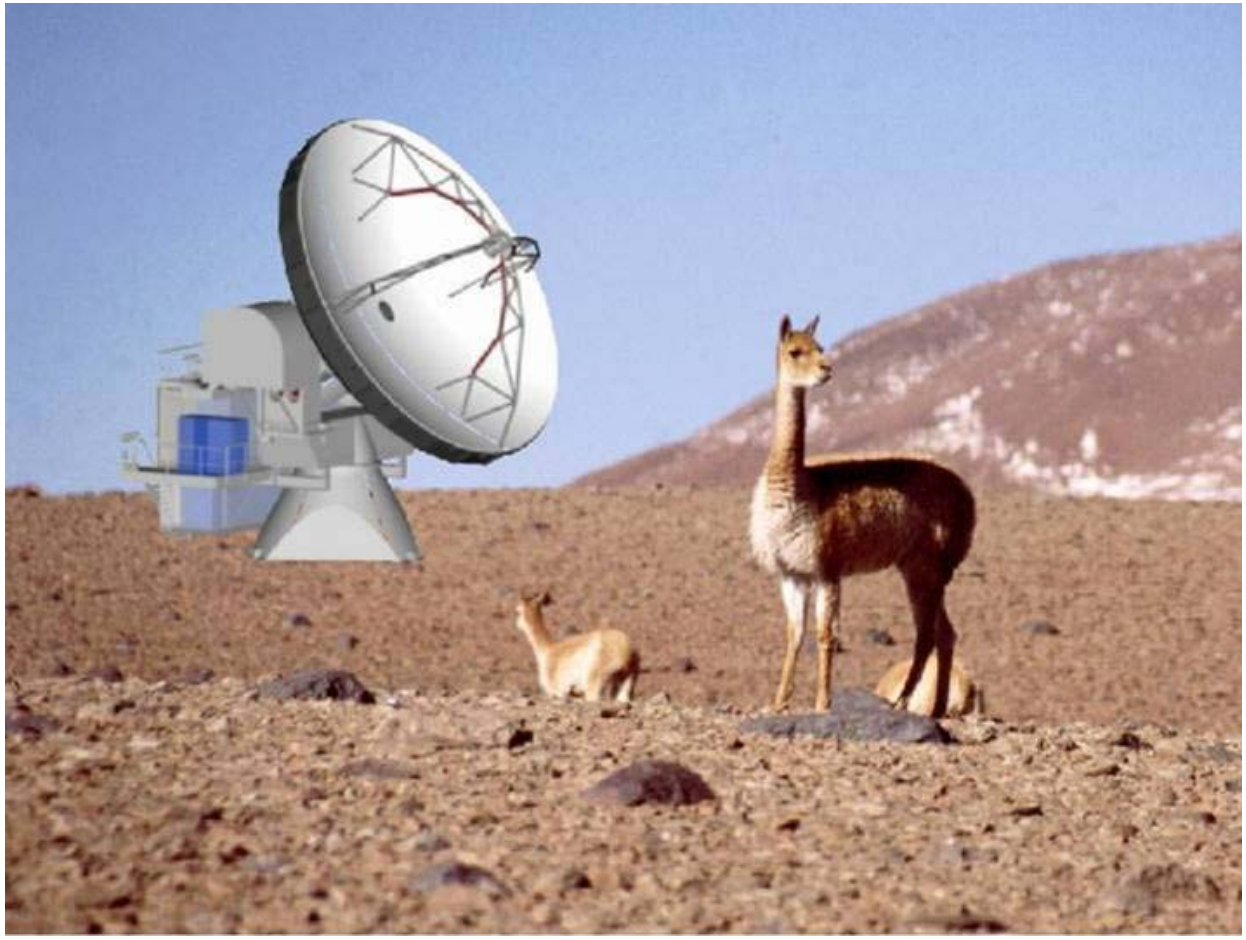


Courtesy Cathey Foley (CSIRO)

MAGMA-C1 Scanning SQUID Microscope
Neocera, Inc.

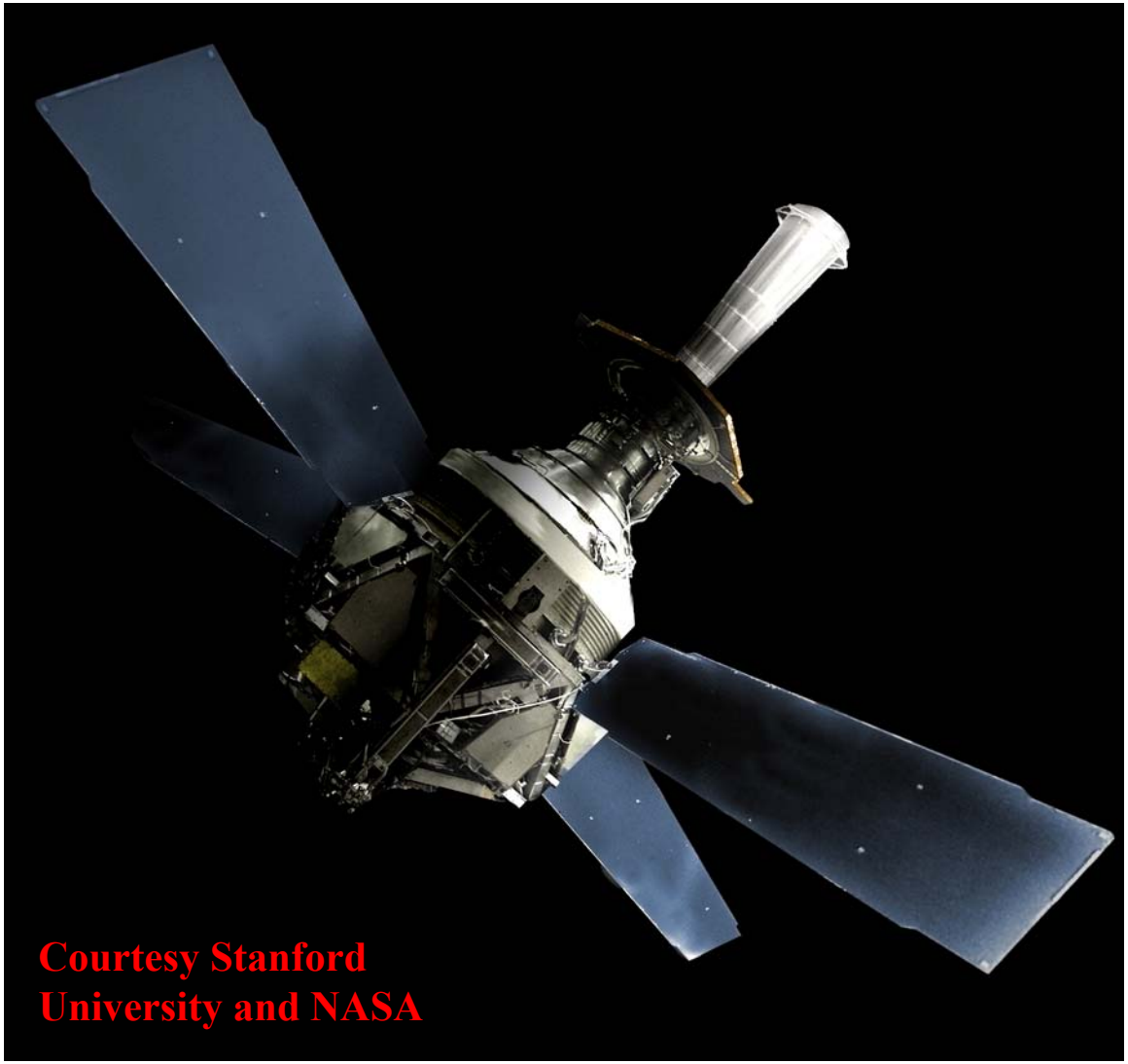
A Non-Contact, Non-Destructive Next Generation Imaging tool for the Semiconductor Industry's complex devices, advanced packages, and full assemblies

Atacama Pathfinder EXperiment

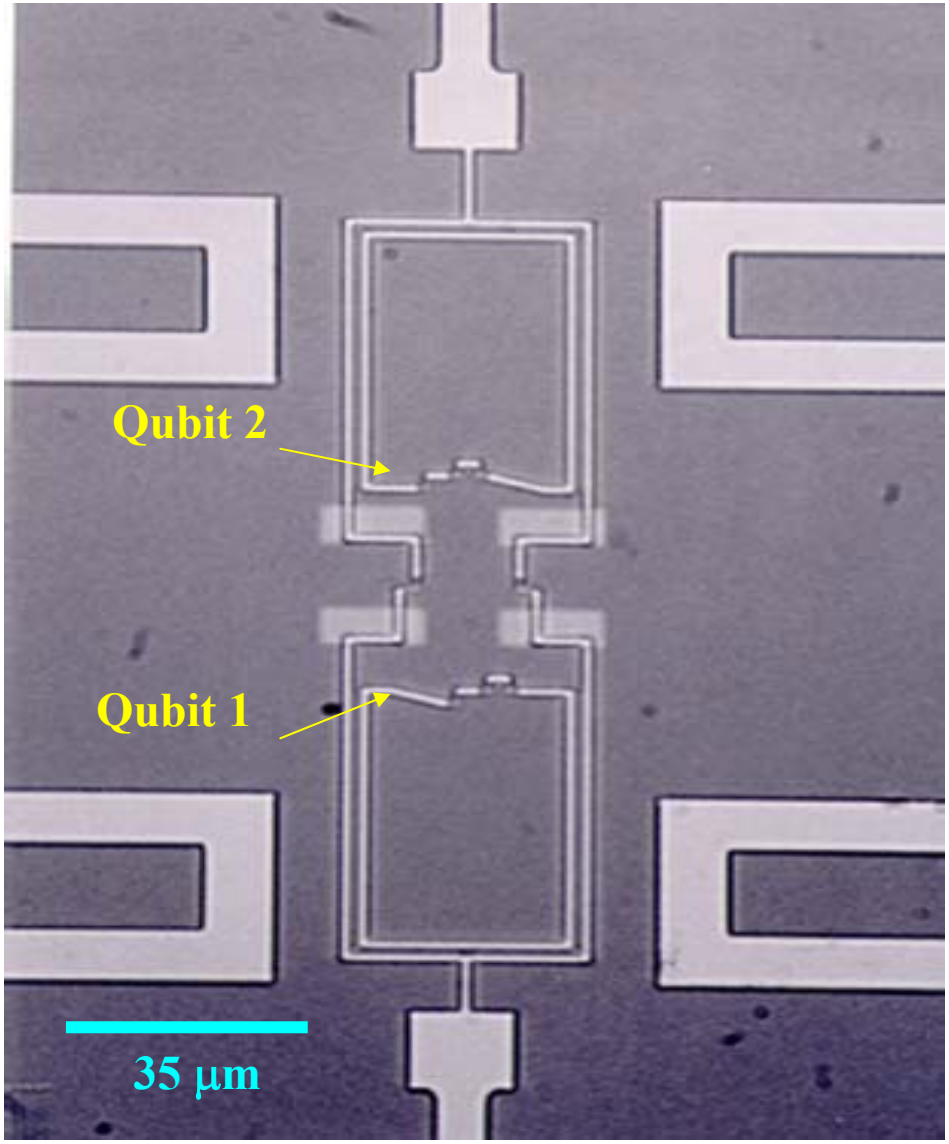


Gravity Probe-B

Tests of General Relativity



UC Berkeley Flux Qubits



Searching for Axions: The Microstrip SQUID Amplifier

University of Gießen
Michael Mück
Jost Gail
Christoph Heiden†

UCB, LBNL and LLNL
Marc-Olivier André
Darin Kinion
Jan Kycia

Support: DOE/BES
DOE/HEP
NSF

Cold Dark Matter

- Recent cosmic microwave background measurements indicate that ~25% of the mass of the universe is cold dark matter (CDM).

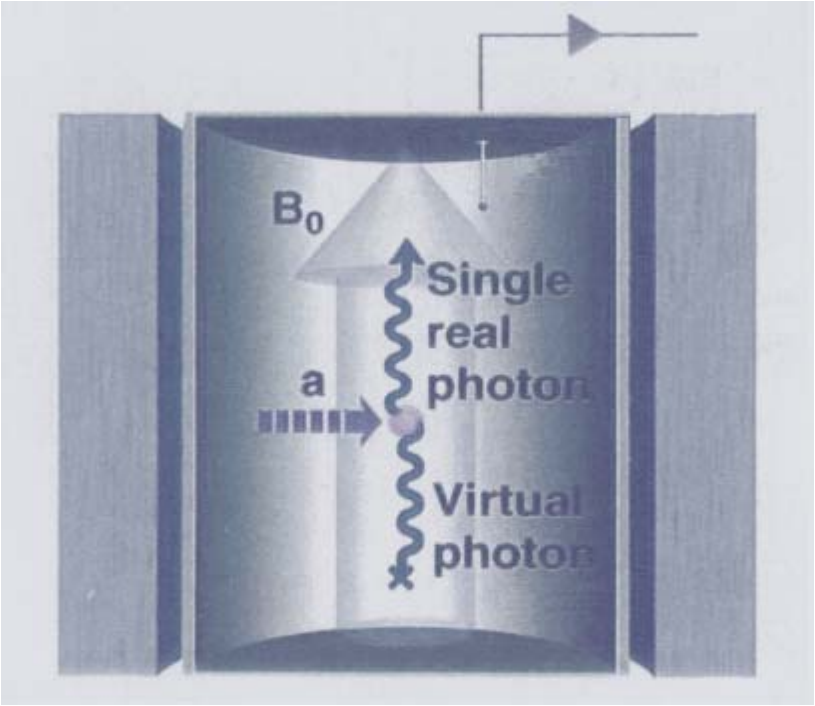
- A candidate particle is the axion, proposed in 1978 to explain the absence of a measurable neutron electric dipole moment.

- The axion is predicted to be a very light particle with no charge or spin.

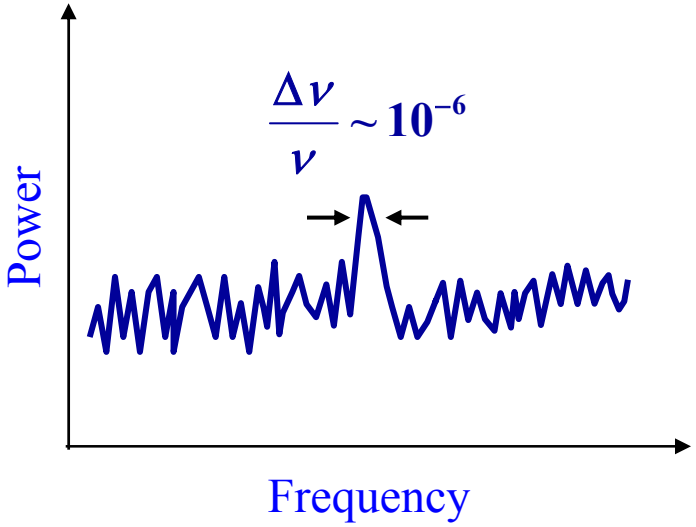
Resonant Conversion of Axions into Photons

Pierre Sikivie (1983)

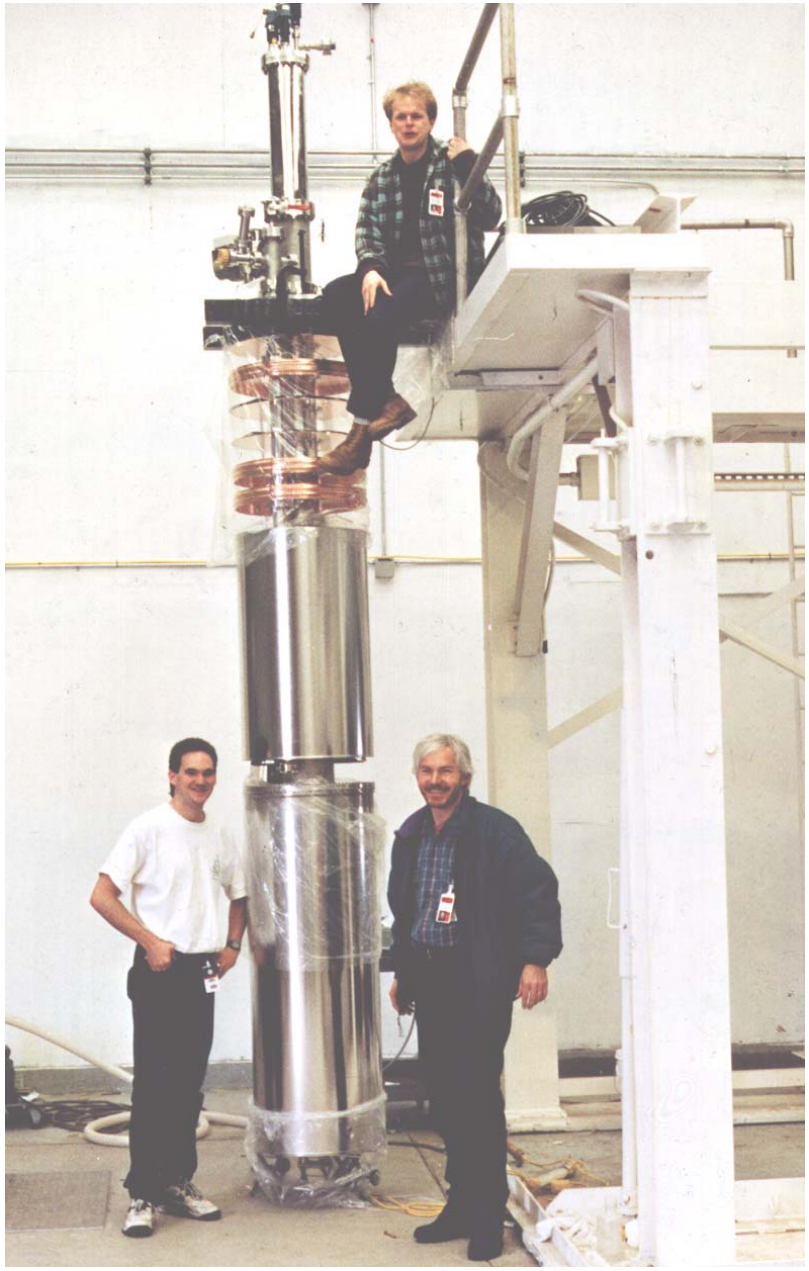
Primakoff Conversion



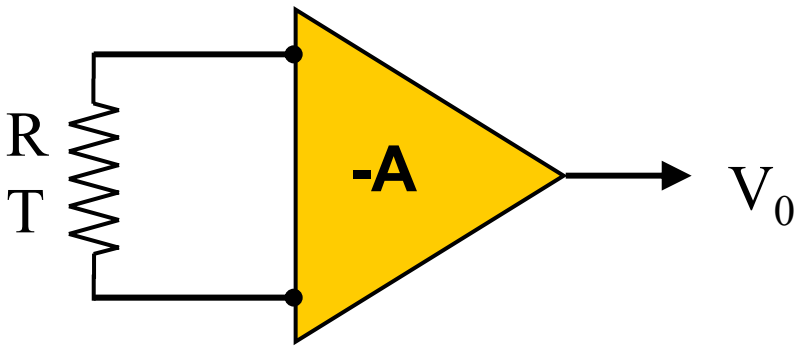
Expected Signal



Axion Detector at
Lawrence Livermore
National Laboratory



Noise Temperature



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

LLNL Axion Detector

- Current 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 range of frequencies from f_1 to f_2:

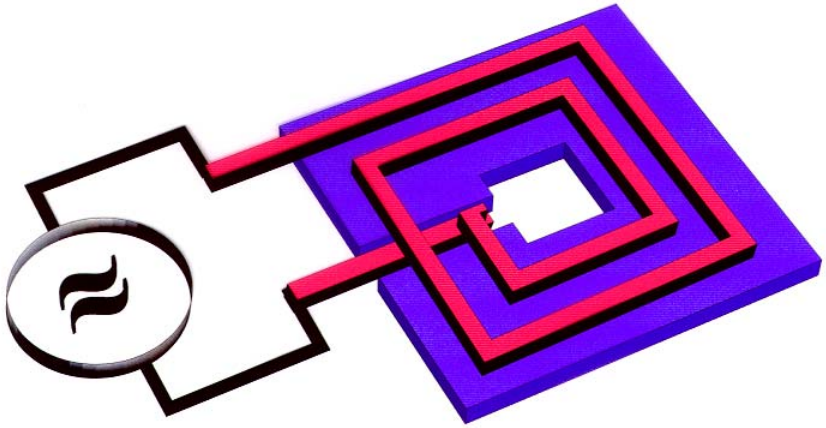
  $\tau(f_1, f_2) \approx 4 \times 10^{16}(T_S/1\text{ K})^2(1/f_1 - 1/f_2)$ sec

  For $f_1 = 0.24$ GHz, $f_2 = 2.4$ GHz: $\tau \approx 45$ years

- Note: There is only a factor of 2 to be gained in T_S by reducing T unless T_N is also reduced.

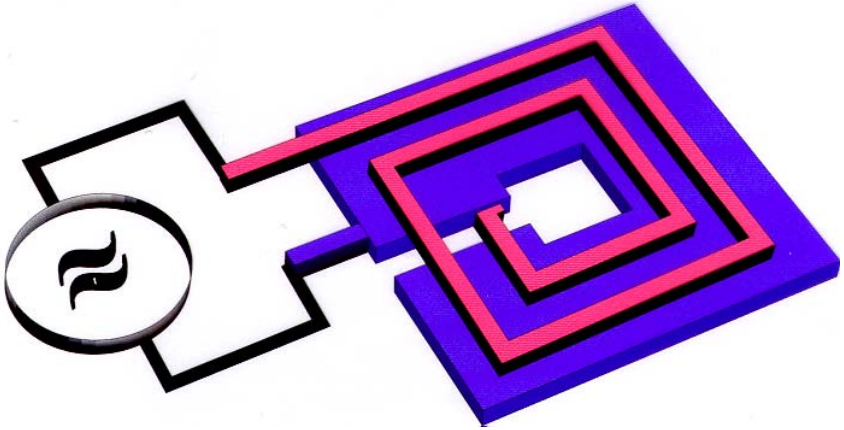
Microstrip SQUID Amplifier

Conventional SQUID Amplifier



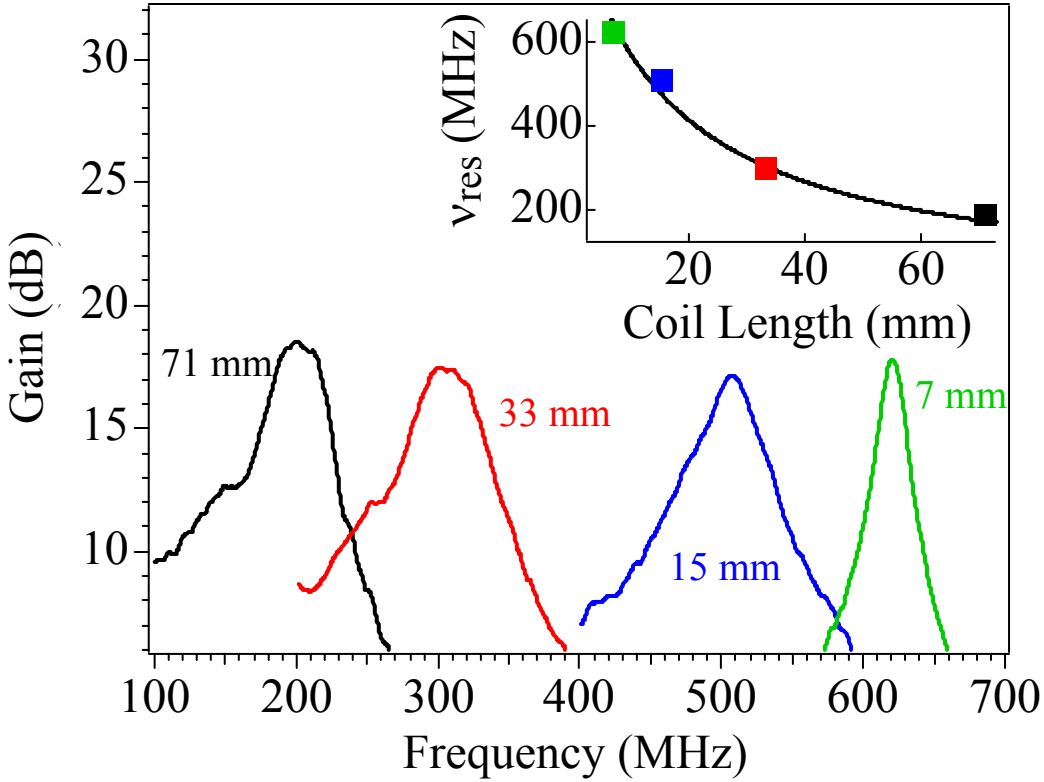
- Source connected to both ends of coil

Microstrip SQUID Amplifier



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

Gain vs. Coil Length



Noise Temperature of Microstrip Amplifier

At 20 mK the noise temperature is 50mK, about 40 times lower than that of the current semiconductor amplifier

Microstrip SQUID Amplifier: Impact on Axion Detector

- Current LLNL axion detector: $T_S \approx 3.2$ K
- For $T \approx T_N \approx 50$ mK: $T_S \approx T + T_N \approx 100$ mK

$\tau \approx 45$ years x $(0.1/3.2)^2$

≈ 18 days

Summary

- Gain ≥ 20 dB for frequencies ≤ 1 GHz
- Cooled to 20 mK, T_N is within a factor of 2 of the quantum limit
- Noise temperature 40 times lower than state-of-the-art cooled semiconductor amplifiers

Future directions

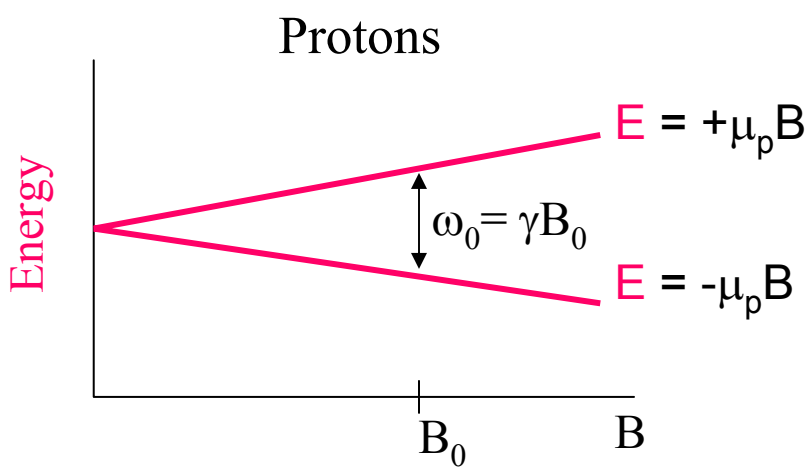
- Implement second-generation axion detector: expected to increase scan rate by three orders of magnitude
- Post-amplifier for radio-frequency single-electron transistor: should enable quantum-limited charge amplifier

Microtesla Nuclear Magnetic Resonance and Magnetic Resonance Imaging

- Nuclear magnetic resonance
- Magnetic resonance imaging

Michael Hatridge
Nathan Kelso
SeungKyun Lee
Robert McDermott
Michael Mössle
Michael Mück
Whit Myers
Bennie ten Haken
Andreas Trabesinger
Erwin Hahn
Alex Pines

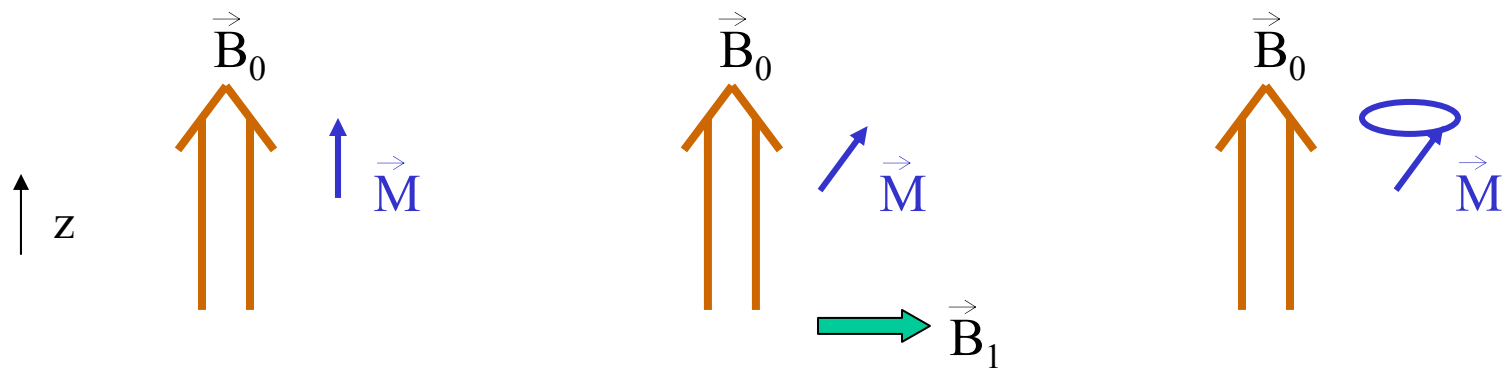
Nuclear Magnetic Resonance



$\nu_0 = 42.58$ MHz/tesla

Magnetic moment ($\mu_p B_0 << k_B T$)

$$M = N\mu_p \frac{N_\uparrow - N_\downarrow}{N_\uparrow - N_\downarrow} = \frac{N\mu_p^2 B_0}{k_B T}$$



Equilibrium RF pulse Precession


BRUKER
900
UltraStabilized™
BRUKER

High Field MRI

3T MRI scanner (GE)

1.5T MRI scanner (GE)

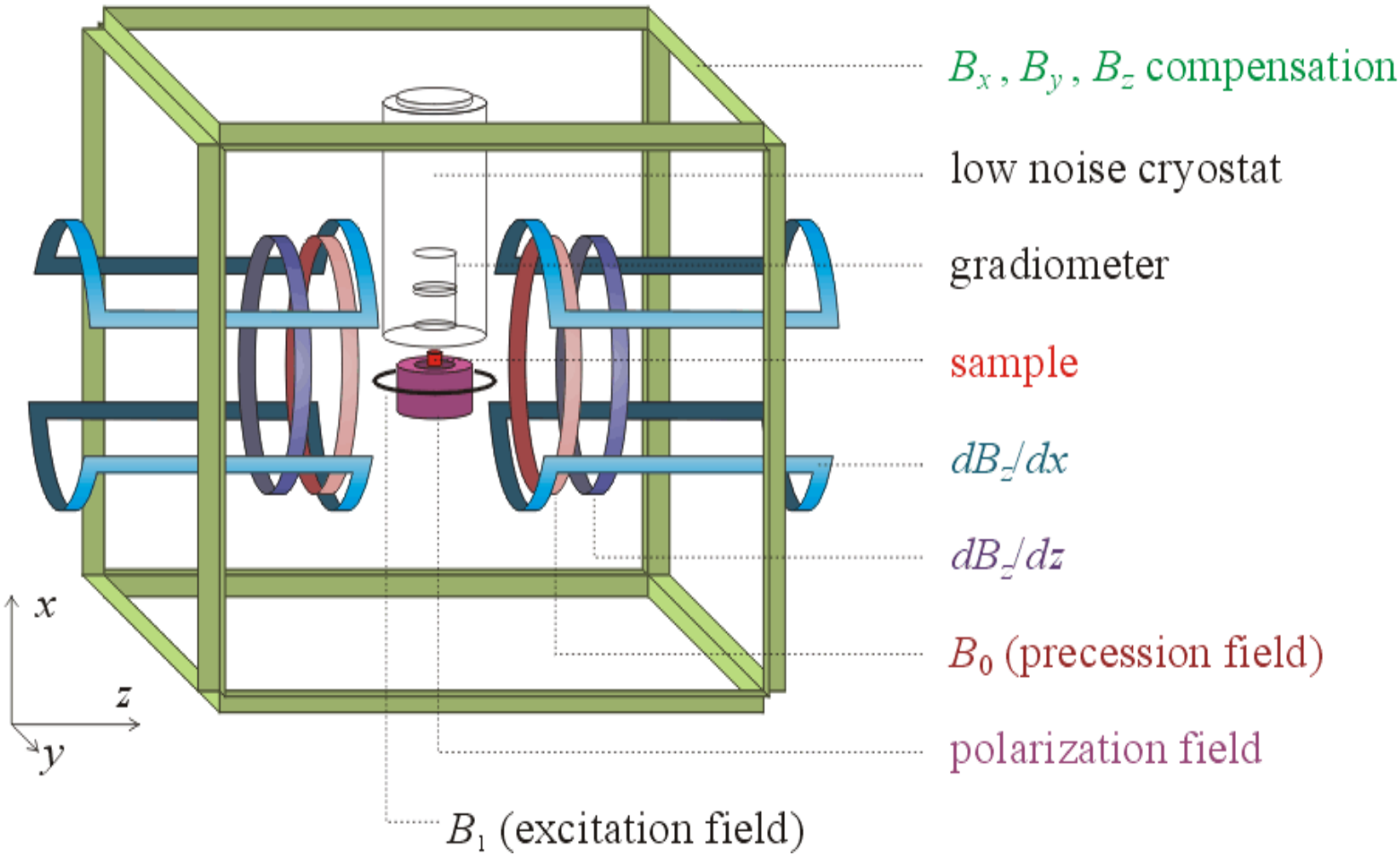
Timeline

Michael Crichton, 1999

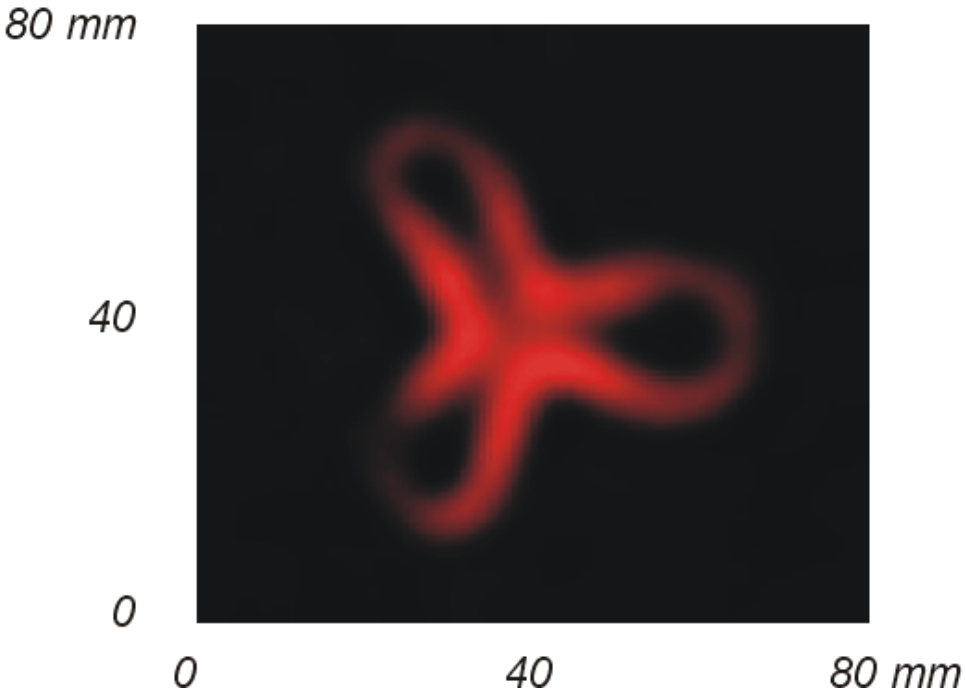
"Most people", Gordon said, "don't realize that the ordinary hospital MRI works by changing the quantum state of atoms in your body ... But the ordinary MRI does this with a very powerful magnetic field - say 1.5 tesla, about twenty-five thousand times as strong as the earth's magnetic field. We don't need that. We use Superconducting QUantum Interference Devices, or SQUIDs, that are so sensitive they can measure resonance just from the earth's magnetic field. We don't have any magnets in there".

The “Cube”

MRI Coils

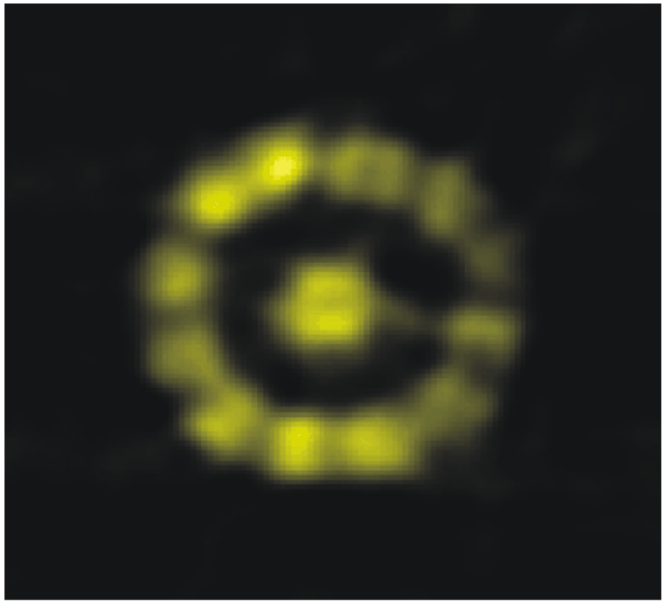

B_x , B_y , B_z compensation
low noise cryostat
gradiometer
sample
dB_z/dx
dB_z/dz
B_0 (precession field)
polarization field
B_1 (excitation field)
x
z
y

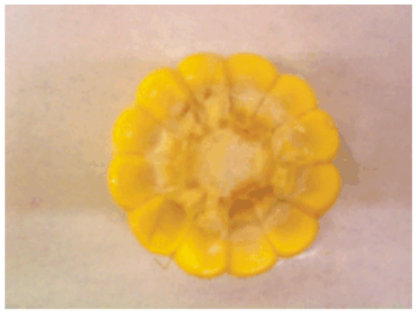
Red Pepper



B0 = 132μT
G = 100μT/m
48 projections
1.5 min. acquisition

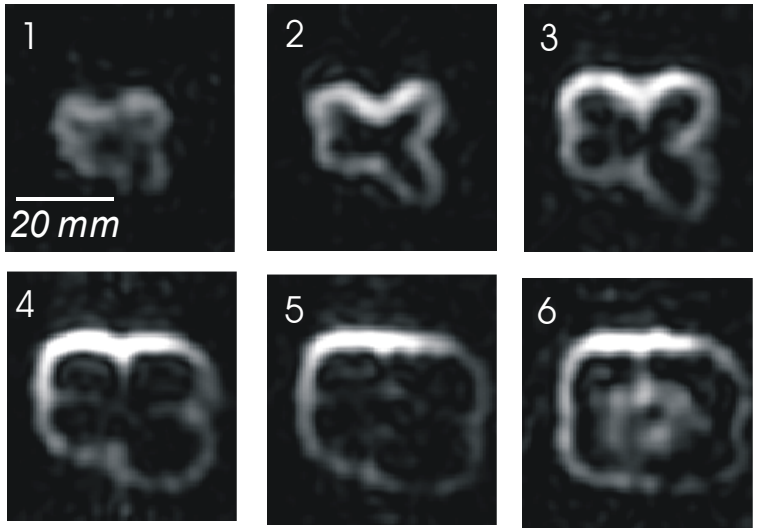
Corn

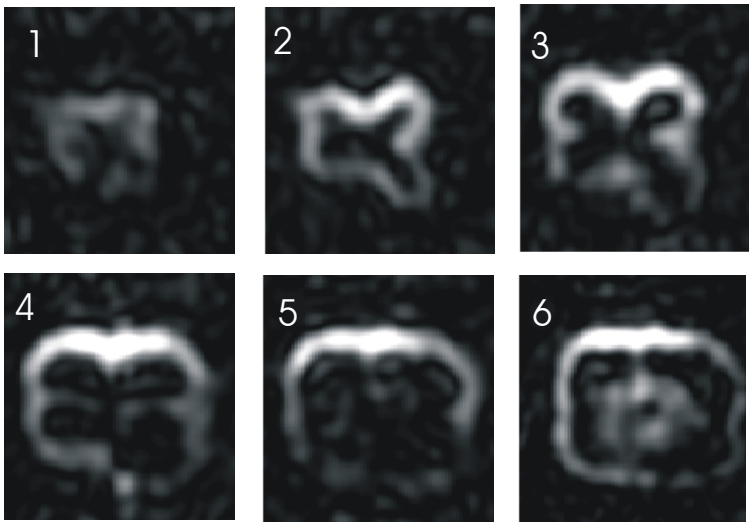


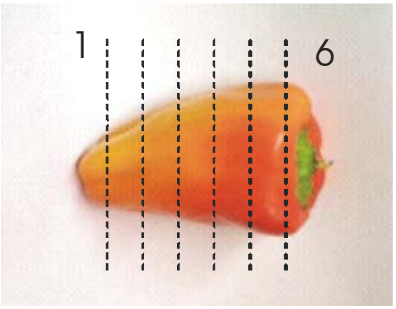


B0 = 132μT
G = 100μT/m
48 projections
3 min. acquisition

Three dimensional images of pepper



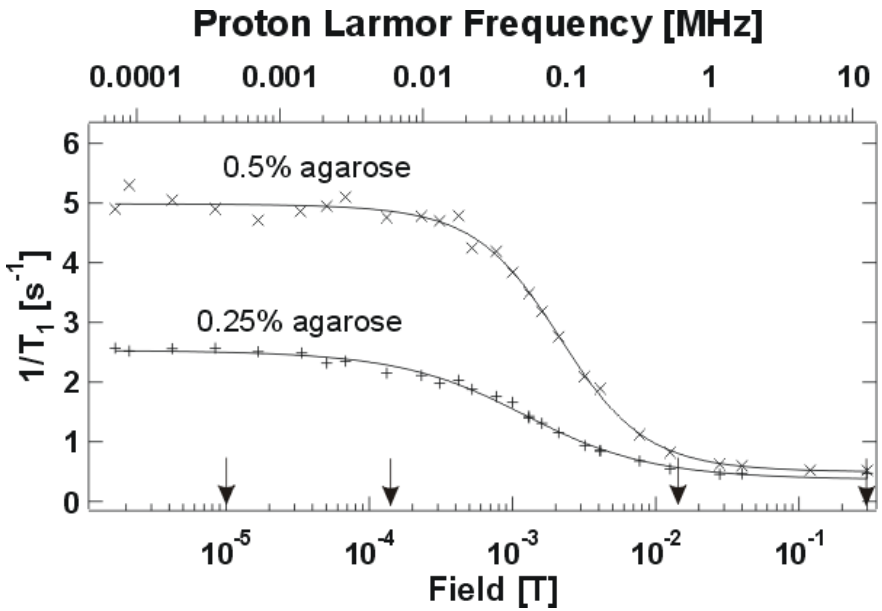


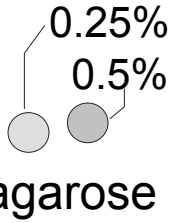


T_1-weighted Contrast Imaging

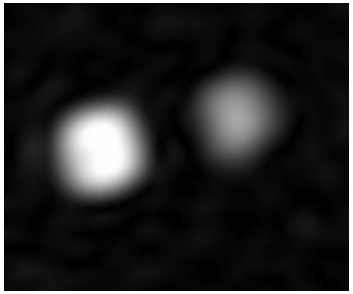
- T_1 is the relaxation time of the proton spins
- T_1 depends strongly on the environment of the protons
- T_1-weighted contrast imaging is widely used in conventional MRI to distinguish different types of tissue
- T_1 (malignant tissue) > T_1 (normal tissue)
- T_1-contrast can be much higher in low fields

T_1 contrast images of agarose gel

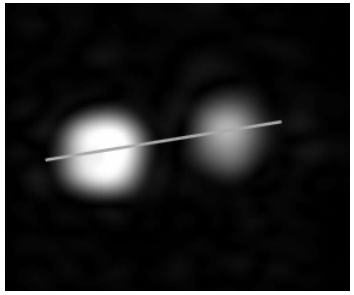


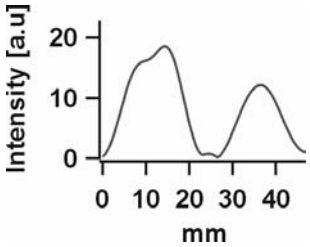


B_{int} = 10 μT

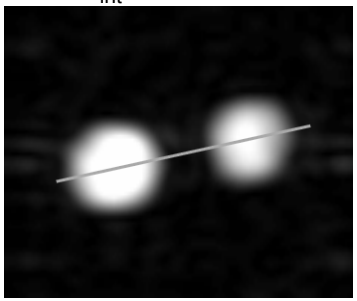


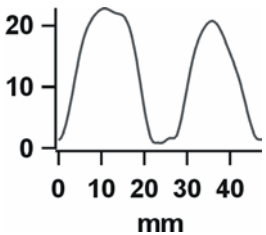
B_{int} = 132 μT



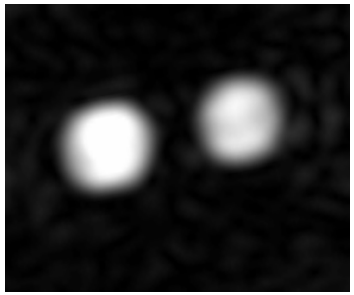


B_{int} = 13.2 mT

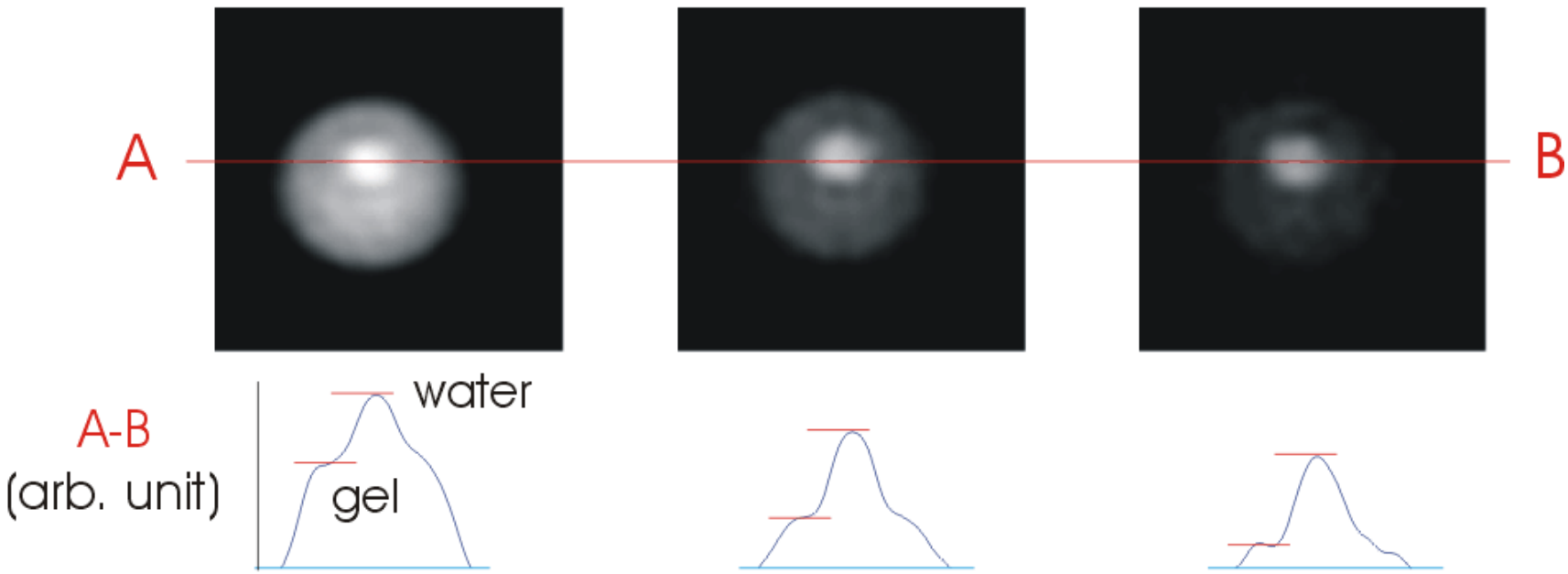




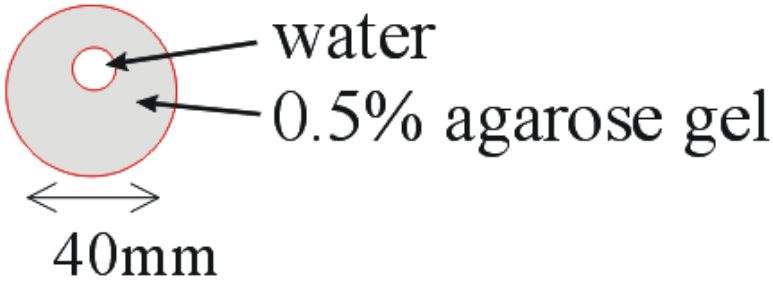
B_{int} = 300 mT



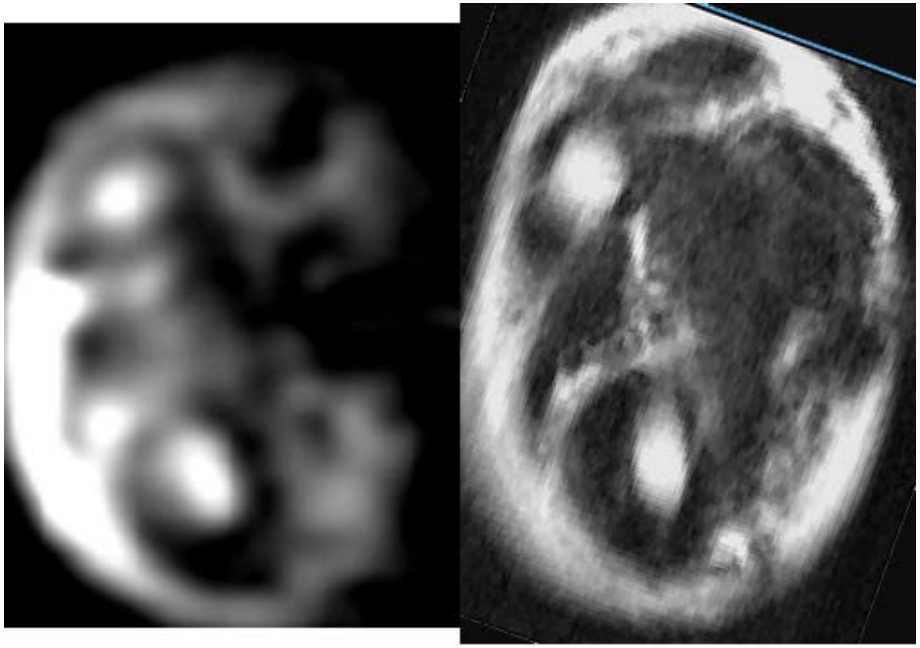
T_1 contrast in 132 μT : water vs. gel



t_d = 20 ms t_d = 200 ms t_d = 400 ms



Forearm (20 mm slice)



$B_p \sim 40$ mT
$B_0 = 132$ μT

$B_0 = 4$ T

4T image:
Courtesy of Ben Inglis,
Henry H. Wheeler, Jr.
Brain Imaging Center,
UC Berkeley

Future directions for low-field MRI

- Reduce system noise
  - Increased signal-to-noise ratio
  - Reduced acquisition time
- Multichannel system
  - Increased signal-to-noise ratio
  - Improved spatial resolution
  - Increased coverage
- Combine low-field MRI with existing technology for magnetoencephalography (MEG)
- Low-cost “open” MRI system
  - Screening for tumors (with T_1-weighted contrast)
  - Imaging knee, foot, elbow, wrist ...
  - Monitoring T_1 in bone marrow