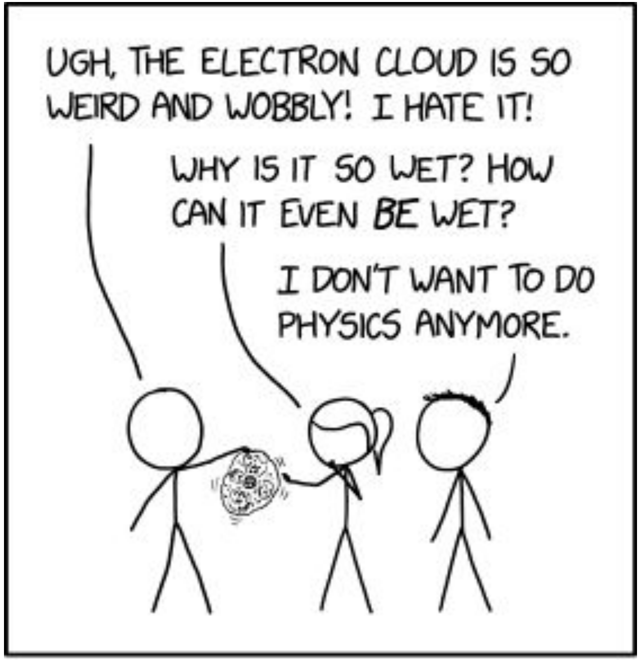
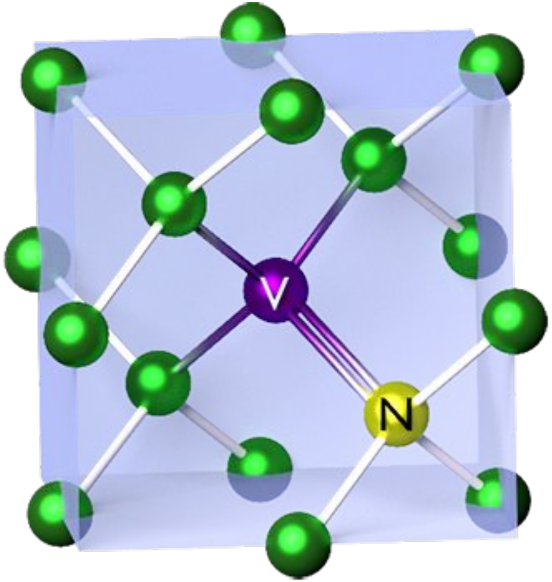
More Examples of Quantum Sensors



WHEN OUR LAB WAS BUILDING THE QUANTUM EXPANDER DEVICE, WE DIDN'T EXPECT OUR FIRST DISCOVERY TO BE "ATOMS ARE REALLY GROSS."

Single Spin Sensors

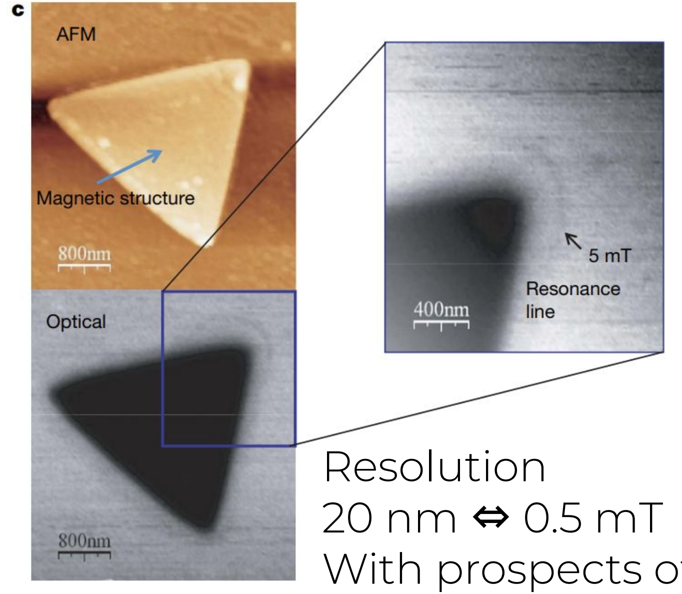
Single NV center



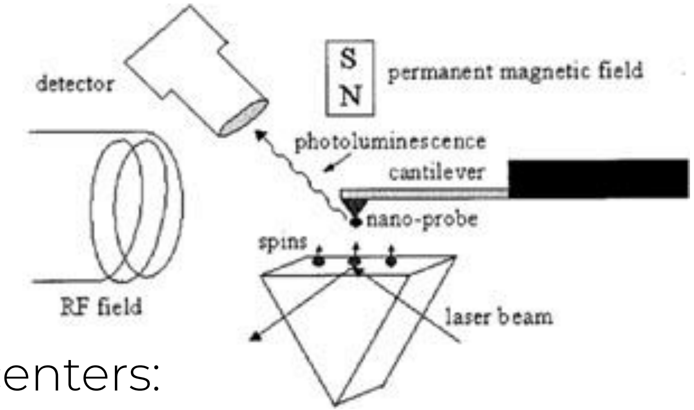
Among all solid state spins, Nitrogen-Vacancy centers in diamonds are the most prominent because of:

1. Room temperature optical detection
2. Possibility to use in nanostructures
3. Long lived ground state spin coherence
4. Measurable response to
   a. Magnetic field (Zeeman effect),
   b. Electric field (Stark effect),
   c. Temperature and Pressure

Single Spin Sensors



Resolution
20 nm ⇔ 0.5 mT
With prospects of
Sub-nm ⇔ ~μT

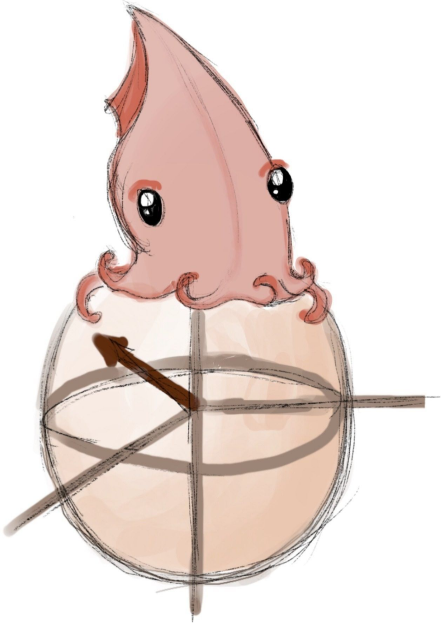


Applications of NV centers:

- ➔ Nanoscale imaging magnetometry
- ➔ Biomarkers within living organisms
  - ◆ Tracking
  - ◆ in vivo temperature measurements
  - ○ (potentially) monitoring of metabolic processes
- ➔ in situ pressure measurements

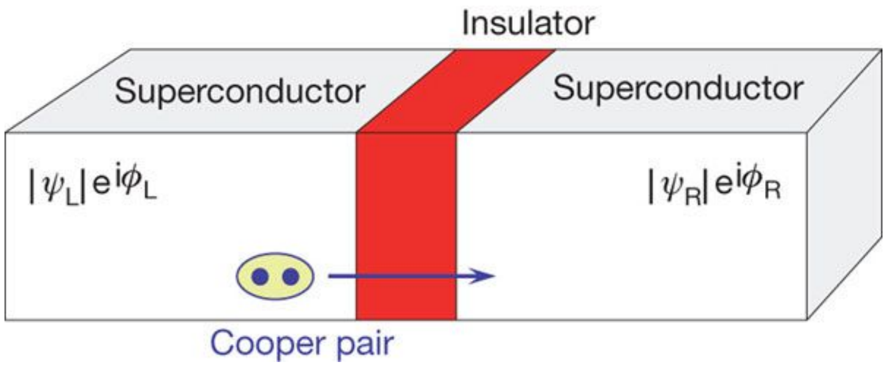
SQUID

Superconducting Quantum Interference Device



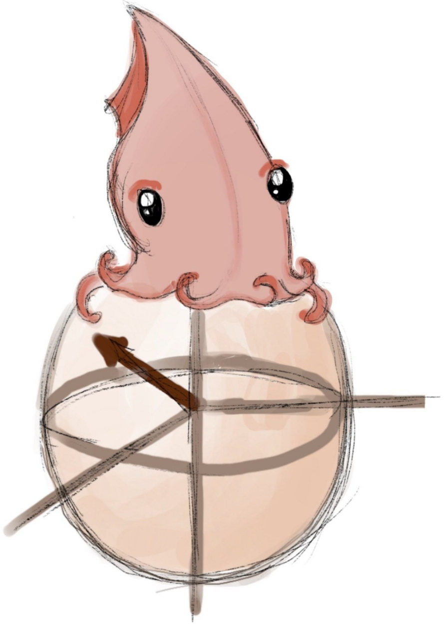
How it works?
Oversimplified explanation:

If we make a sandwich superconductor-insulator-superconductor, we would get the Josephson Junction



SQUID

Superconducting Quantum Interference Device



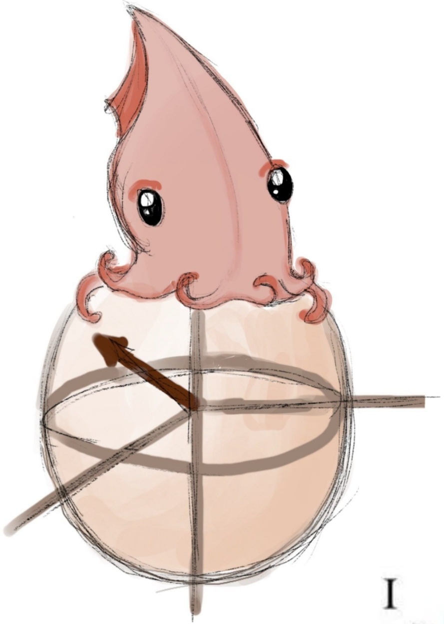
How it works?
Oversimplified explanation:

If we also consider that superconductors actively adjusts its shielding currents to maintain magnetic flux quantization,
We can get to brilliant designs of SQUIDs — Josephson Junction loop.

Magnetic flux through a closed superconducting loop is quantized in discrete units called flux quanta:
$\Phi_0 \approx 2.07 \times 10^{-15}$ Weber.

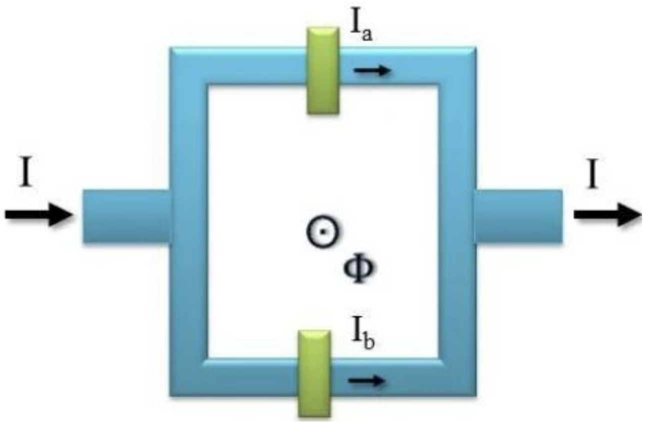
SQUID

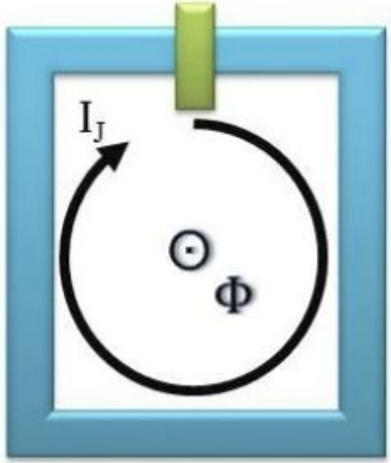
Superconducting Quantum Interference Device



How it works?

- DC SQUID: two Josephson junctions in parallel forming a loop
- RF SQUID: one Josephson junction in a loop

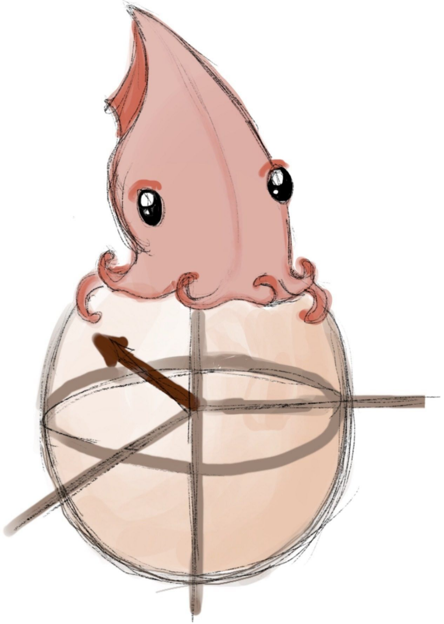




SQUID

Superconducting Quantum Interference Device

$$\text{sensitivity} \propto \frac{1}{\gamma\sqrt{T_\chi}}$$



Key points:

- measure magnetic fields with a sensitivity down to 10 aT/√Hz
- Wide range of applications
  - materials characterization in solid state physics
  - clinical magnetoencephalography
  - Geology
  - gyroscopes in the Gravity Probe B
- Requires cryogenic temperatures

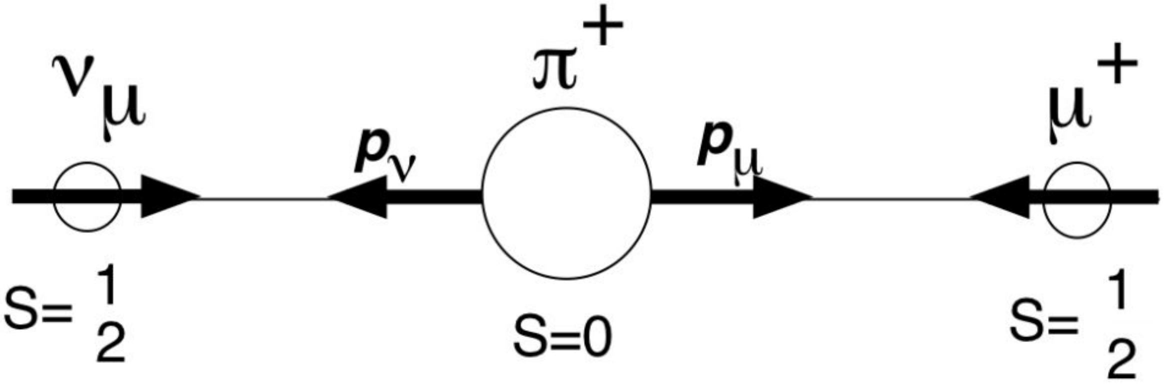
Available for SQUIDs:	10^{-18} T
Magnetic field of heart:	10^{-10} T
Magnetic field of brain:	10^{-13} T

Elementary Particles

Muons

Muons are excellent spin detectors as we can get them 100% polarized with ease in (p + …→)$\pi\to\mu\nu$!

EASY setup!



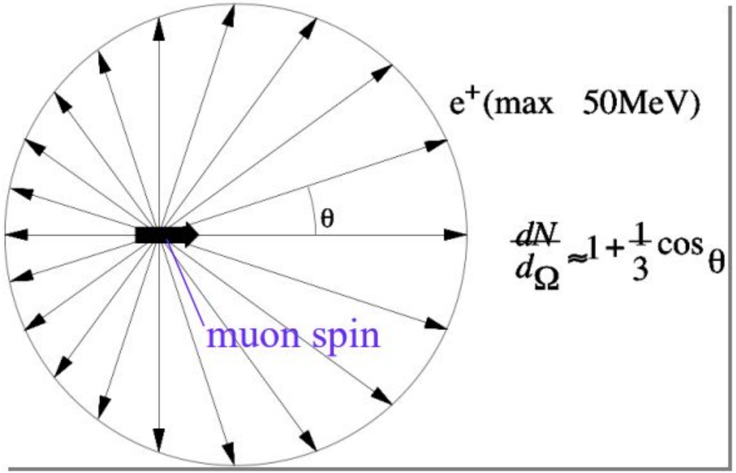
μ^+ is 100% spin-polarized along the direction of motion.

Elementary Particles

Muons

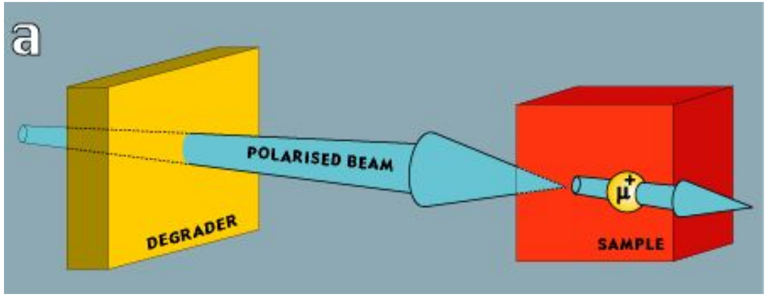
Muon decays also can tell a lot about spin direction as positrons from $\mu \rightarrow e\nu\nu$ are preferably emitted along muon spin!

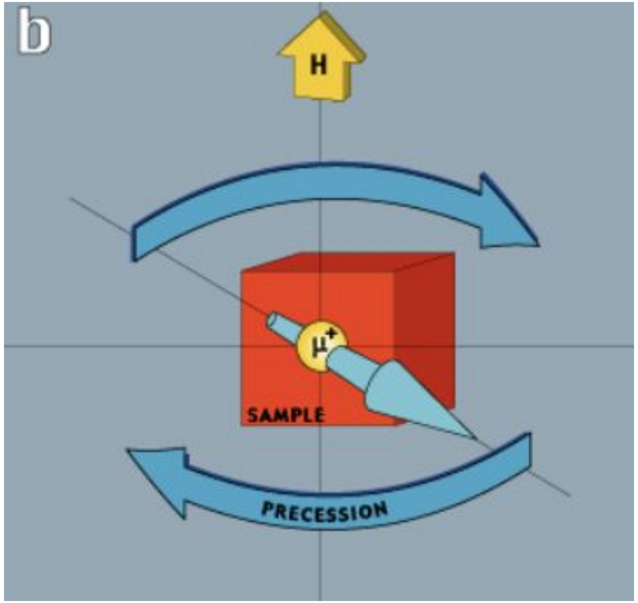
Not so EASY but fairly simple readout!

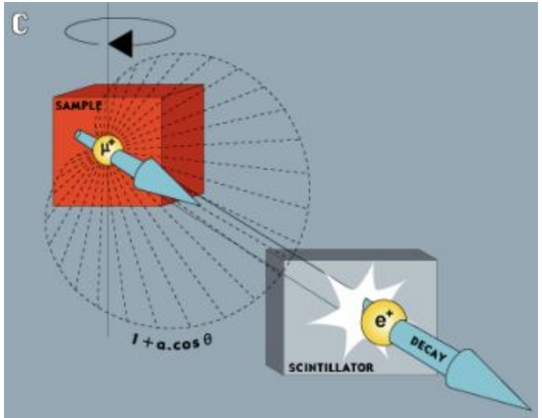


Elementary Particles

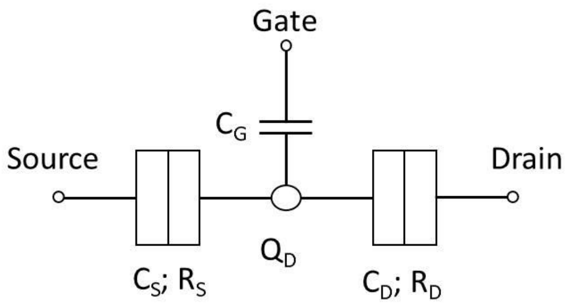
Muons and
muon Spin Rotation = μSR







Other sensors



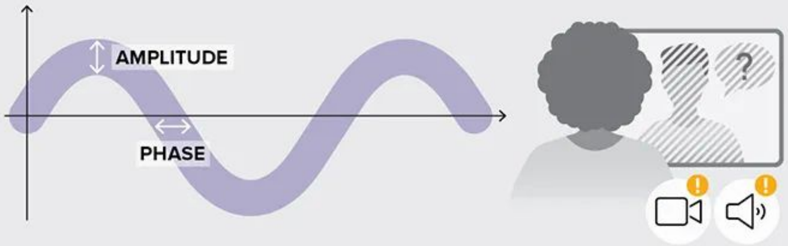
- Single electron transistors (SET's) sense electric fields by measuring the tunneling current across a submicron conducting island sandwiched between tunneling source and drain contacts
- Phonons as single particle sensors are promising in mechanical measurements
- LIGO and Virgo employ "squeezed" laser light to go beyond quantum limits (sometimes)
    - Squeezing of light – the creation of partially-entangled states with phase or amplitude fluctuations below those of a classical coherent state of the light field .

QUANTUM SQUEEZING

A technique for measuring signals with greater precision

Argonne NATIONAL LABORATORY

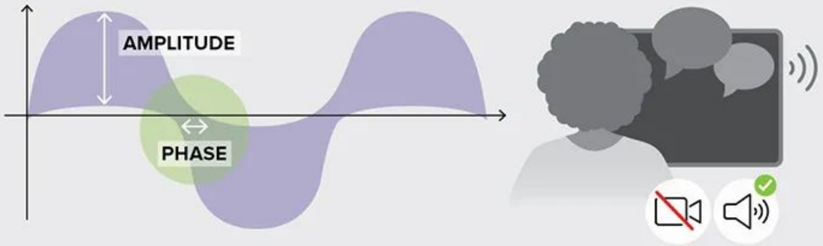
A system has **uncertainty** of amplitude and phase.



The thickness of the line in this wave function indicates **uncertainty for both phase and amplitude.** To better understand what's happening in this system, we pick which metric matters more to us and sacrifice the other.

For example, in a poor-quality video call, we may decide that audio is more important than video and that we need to sacrifice video in order to hear others clearly.

Increased uncertainty of amplitude yields a **decreased uncertainty** of phase.



In quantum squeezing, scientists increase the uncertainty of either amplitude or phase to decrease the uncertainty (increase the precision) of the other variable. Here, the amplitude uncertainty is increased in order to **decrease the phase uncertainty.**

Even though we're now less sure of the system's amplitude, we can get **a more precise reading of the wave function's phase.** This is akin to tuning out or eliminating a call's video feed in order to increase the clarity (decrease the uncertainty) of the audio feed.

U.S. DEPARTMENT OF ENERGY

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