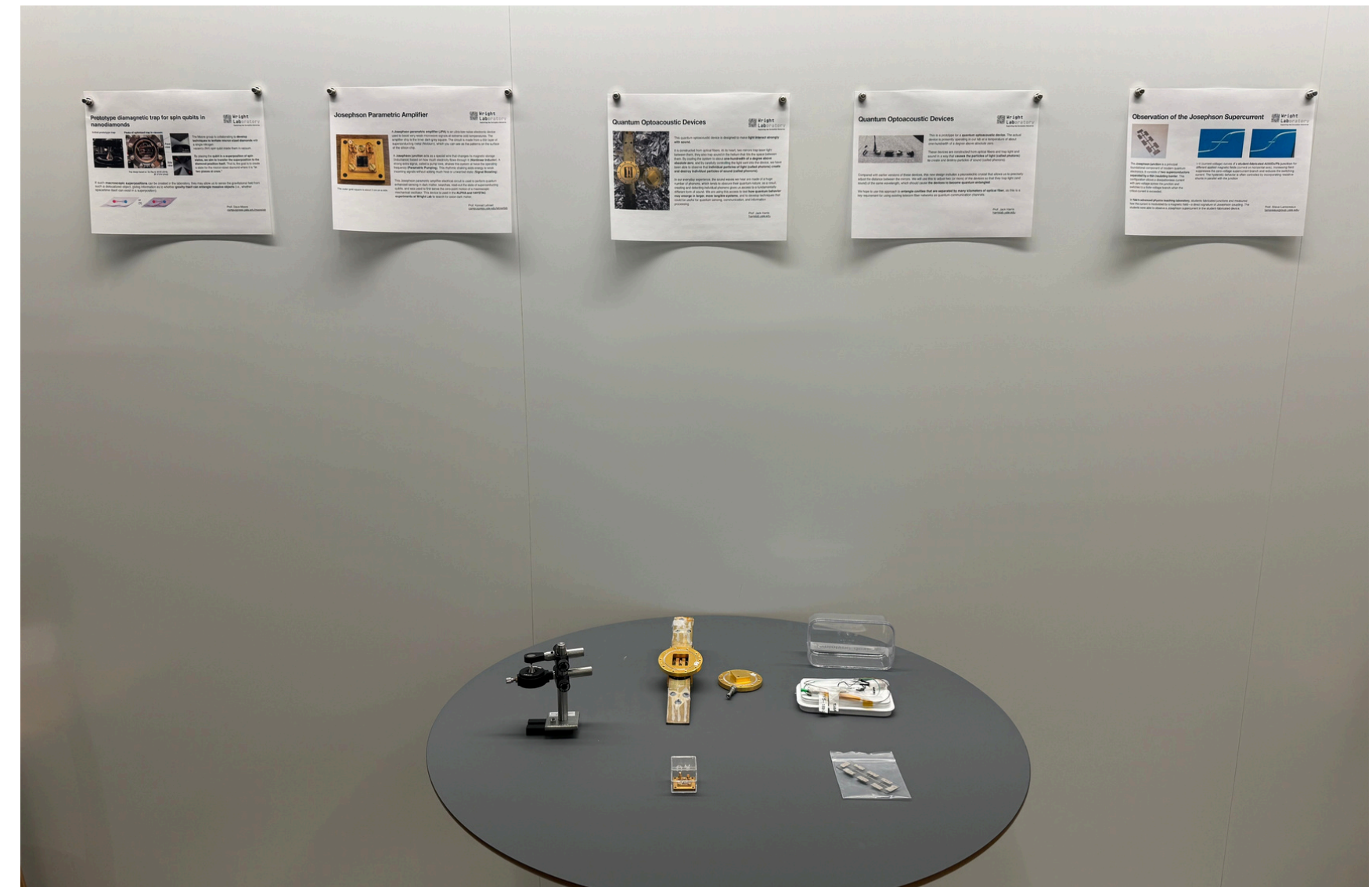
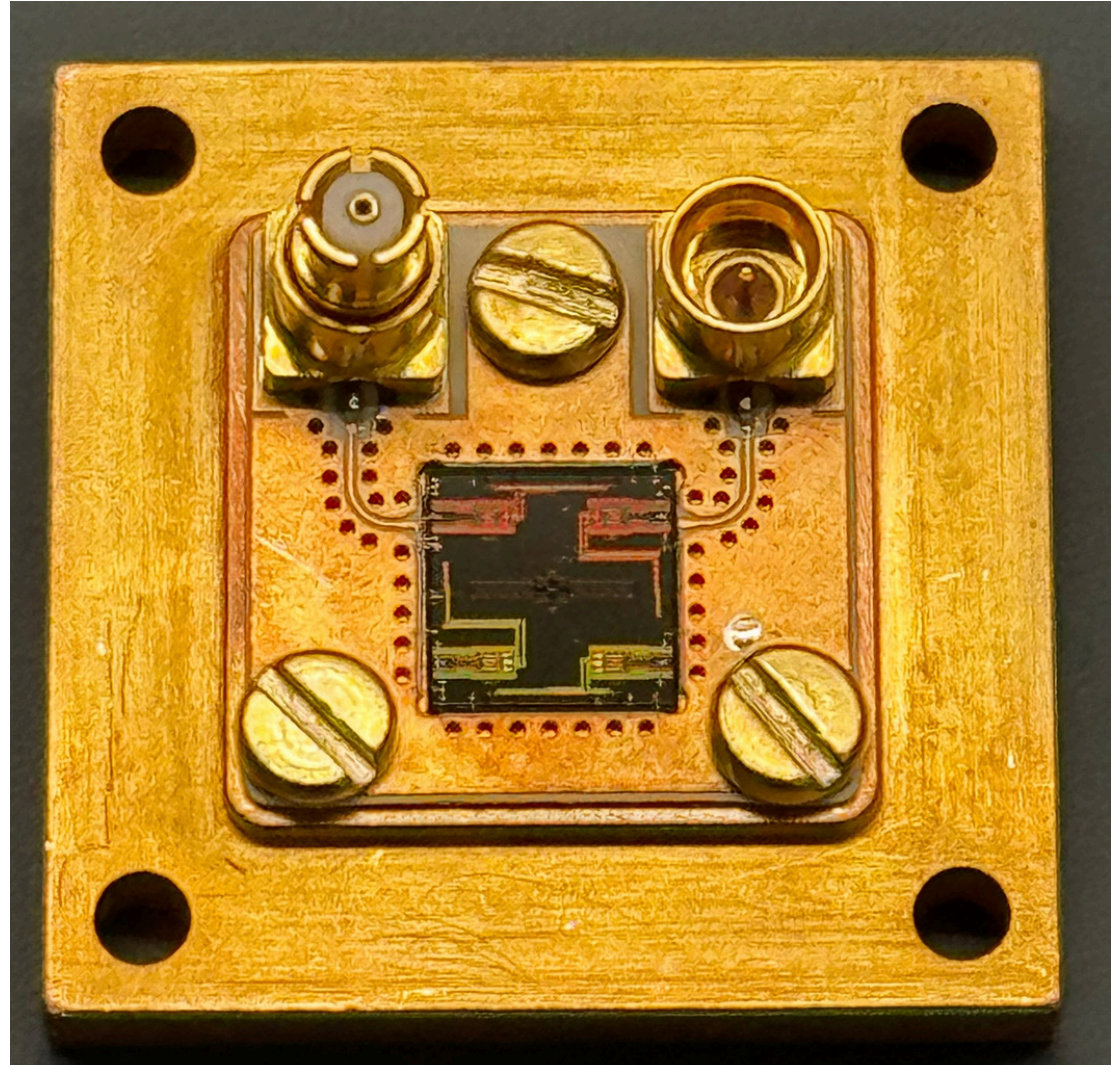


Quantum Sensors for Discovery and Applied Science



Josephson Parametric Amplifier



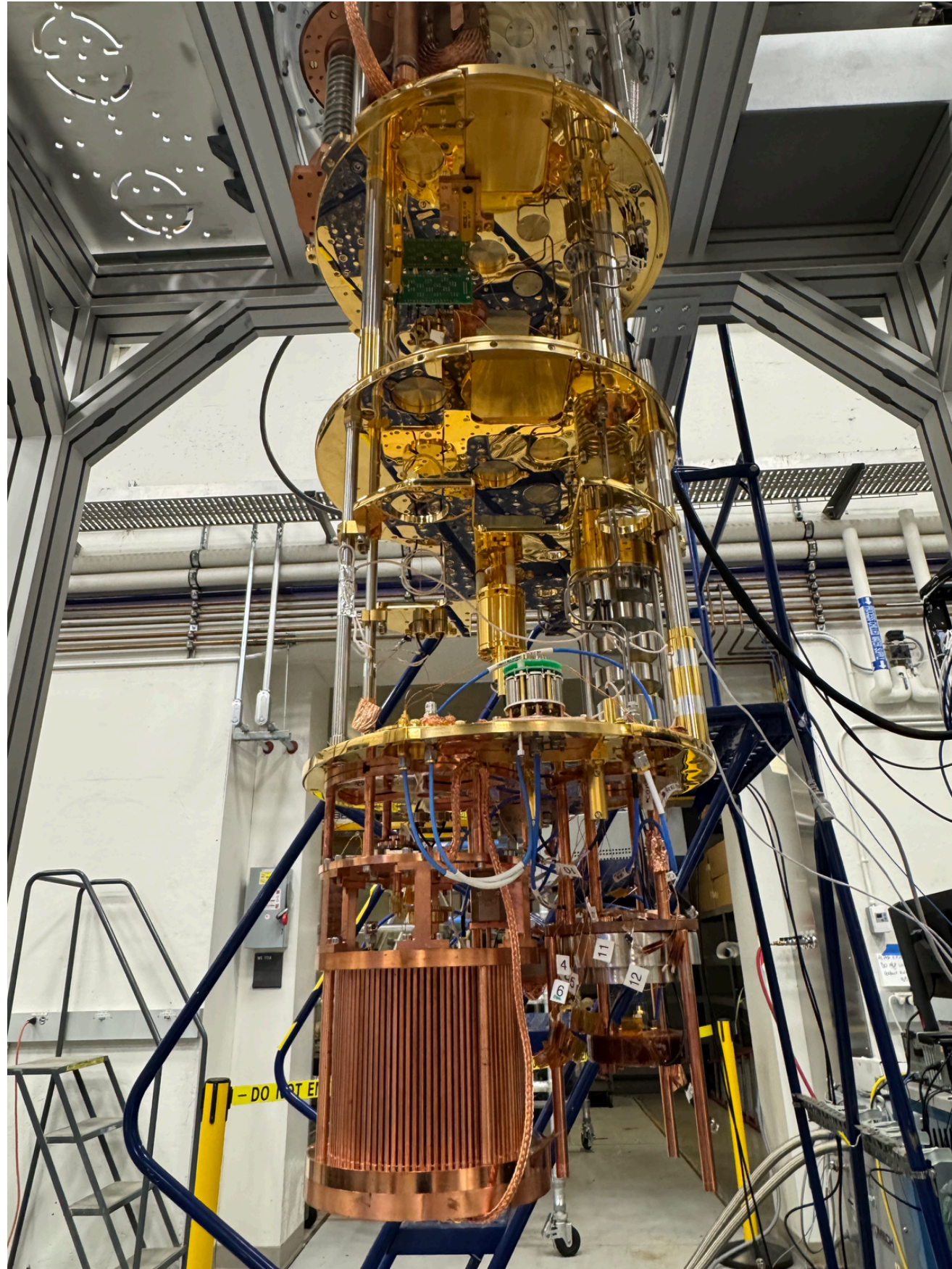
The outer gold square is about 2 cm on a side.

A **Josephson parametric amplifier (JPA)** is an ultra-low-noise electronic device used to boost very weak microwave signals at extreme cold temperatures. The amplifier chip is the inner dark grey square. The circuit is made from a thin layer of superconducting metal (Niobium), which you can see as the patterns on the surface of the silicon chip.

A **Josephson junction** acts as a special wire that changes its magnetic storage (inductance) based on how much electricity flows through it (**Nonlinear Inductor**). A strong extra signal, called a pump tone, shakes this system at twice the operating frequency (**Parametric Pumping**). This rhythmic shaking adds energy to weak incoming signals without adding much heat or unwanted static (**Signal Boosting**).

This Josephson parametric amplifier electrical circuit is used to perform quantum enhanced sensing in dark matter, searches, read-out the state of superconducting qubits, and was used to first sense the zero-point motion of a macroscopic mechanical oscillator. This device is used in the **ALPHA and HAYSTAC experiments at Wright Lab** to search for axion dark matter.

ALPHA - Axion Longitudinal Plasma HAloscope



The nature of **dark matter** is one of the longest enduring cosmological mysteries. The axion is one of the few candidates for dark matter that would not only explain most of the matter in the universe, but another outstanding problem in physics: why is the strong force time-symmetric?

The **ALPHA (Axion Longitudinal Plasma HAloscope)** Consortium is working to detect the **axion** and help explain the underlying structure of the universe. By using a wire metamaterial to create an artificial plasma with designer properties, ALPHA will create a kind of “radio” capable of picking up axion dark matter.



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<https://axion-dm.yale.edu/alpha-experiment>

Prototype diamagnetic trap for spin qubits in nanodiamonds

Initial prototype trap

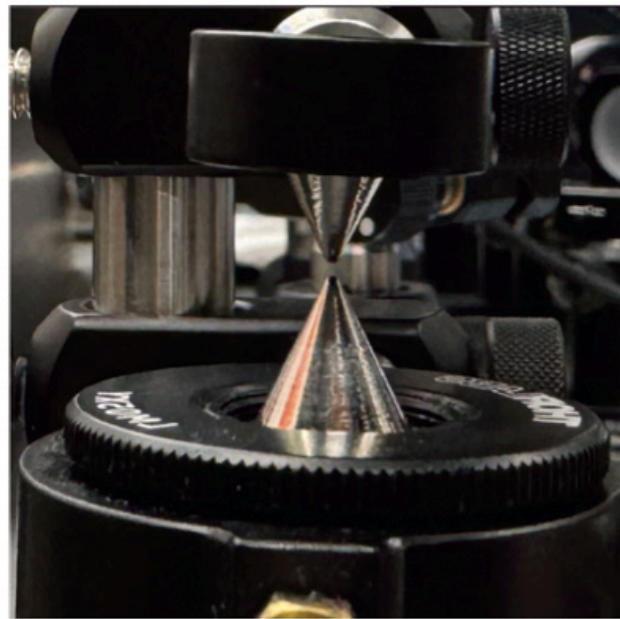
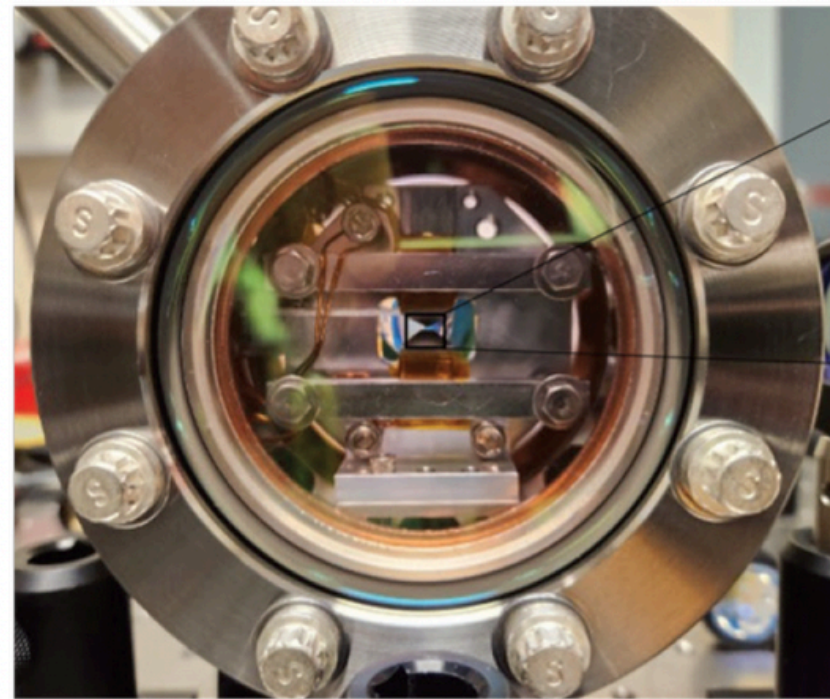
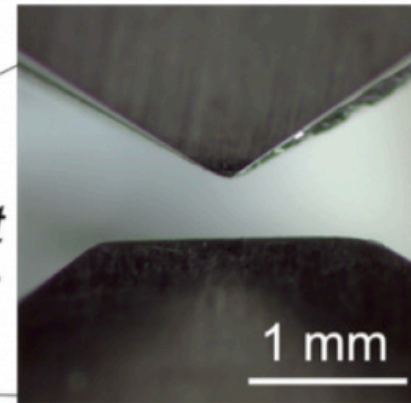


Photo of optimized trap in vacuum:

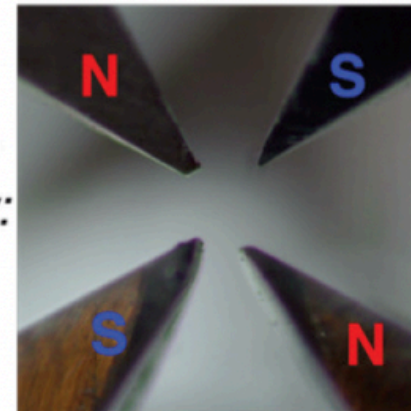


Trap design based on: *Sci Rep* 6, 30125 (2016),
[B. D'Urso group]

Front
view:



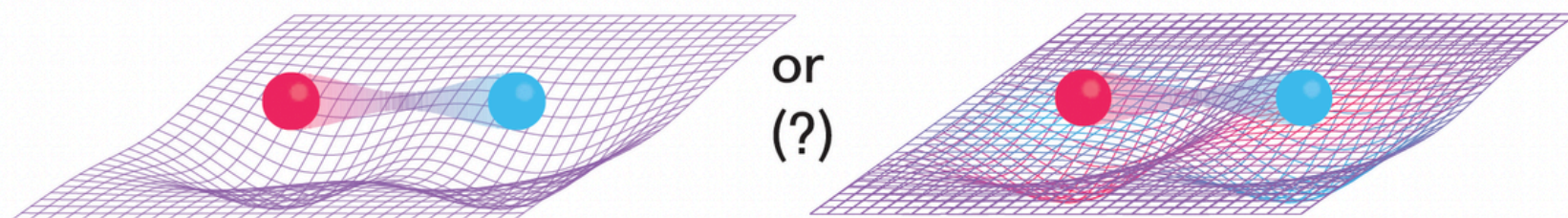
Side
view:



The Moore group is collaborating to **develop techniques to levitate micron sized diamonds** with a single nitrogen vacancy (NV) spin qubit inside them in vacuum.

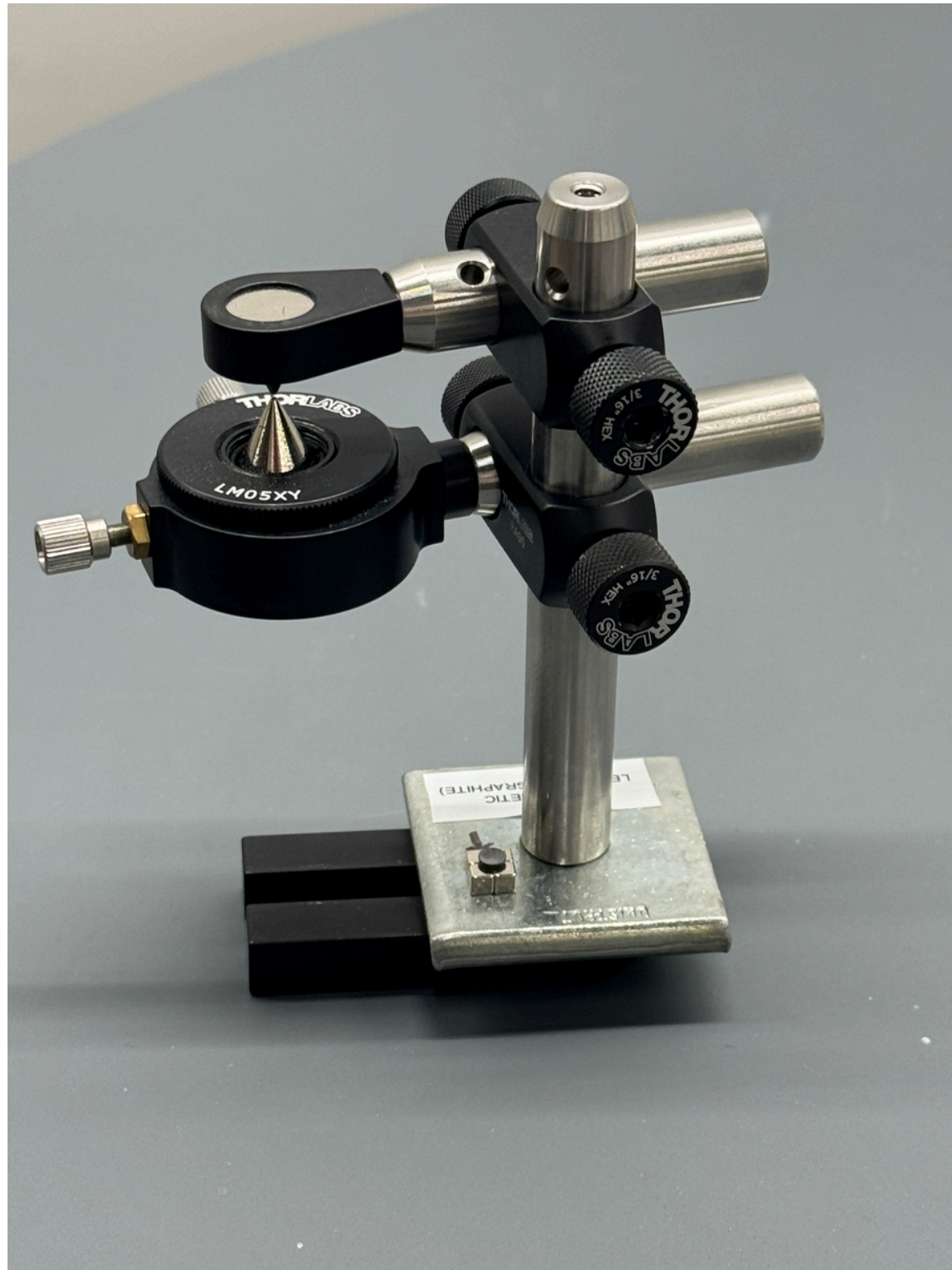
By placing the **qubit in a superposition of spin states, we aim to transfer the superposition to the diamond position itself.** That is, the goal is to create a state for the micron-sized diamond where it is **“in two places at once.”**

If such **macroscopic superpositions** can be created in the laboratory, they may allow us to sense the gravitational field from such a delocalized object, giving information as to whether **gravity itself can entangle massive objects** (i.e., whether spacetime itself can exist in a superposition).



Prof. Dave Moore
campuspress.yale.edu/moorelab

Prototype diamagnetic trap for spin qubits in nanodiamonds



Quantum Optoacoustic Devices

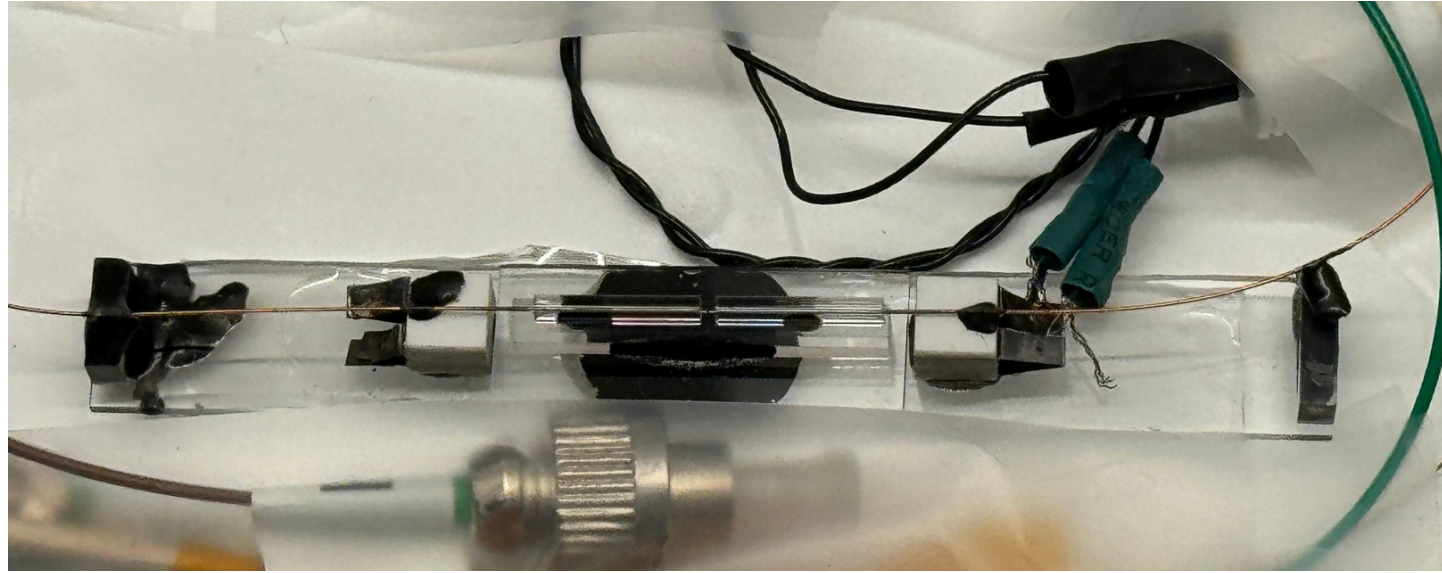


This quantum optoacoustic device is designed to make **light interact strongly with sound**.

It is constructed from optical fibers. At its heart, two mirrors trap laser light between them; they also trap sound in the helium that fills the space between them. By cooling the system to about **one-hundredth of a degree above absolute zero**, and by carefully controlling the light sent into the device, we have been able to observe that **individual particles of light (called photons) create and destroy individual particles of sound (called phonons)**.

In our everyday experience, the sound waves we hear are made of a huge number of phonons, which tends to obscure their quantum nature; as a result, creating and detecting individual phonons gives us access to a fundamentally different form of sound. We are using this access to test **how quantum behavior may emerge in larger, more tangible systems**, and to develop techniques that could be useful for quantum sensing, communication, and information processing.

Quantum Optoacoustic Devices



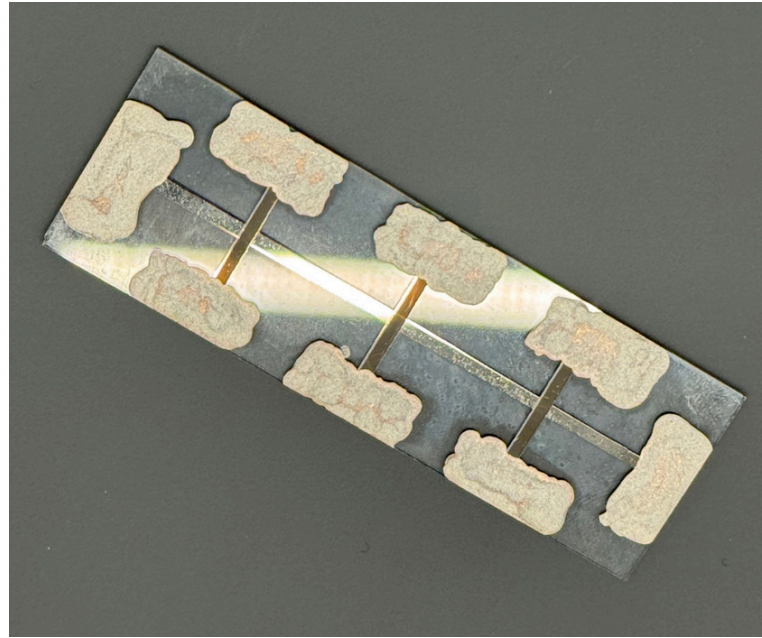
This is a prototype for a **quantum optoacoustic device**. The actual device is presently operating in our lab at a temperature of about one-hundredth of a degree above absolute zero.

These devices are constructed from optical fibers and trap light and sound in a way that **causes the particles of light (called photons) to** create and destroy particles of sound (called phonons).

Compared with earlier versions of these devices, this new design includes a piezoelectric crystal that allows us to precisely adjust the distance between the mirrors. We will use this to adjust two (or more) of the devices so that they trap light (and sound) of the same wavelength, which should cause **the devices to become quantum entangled**.

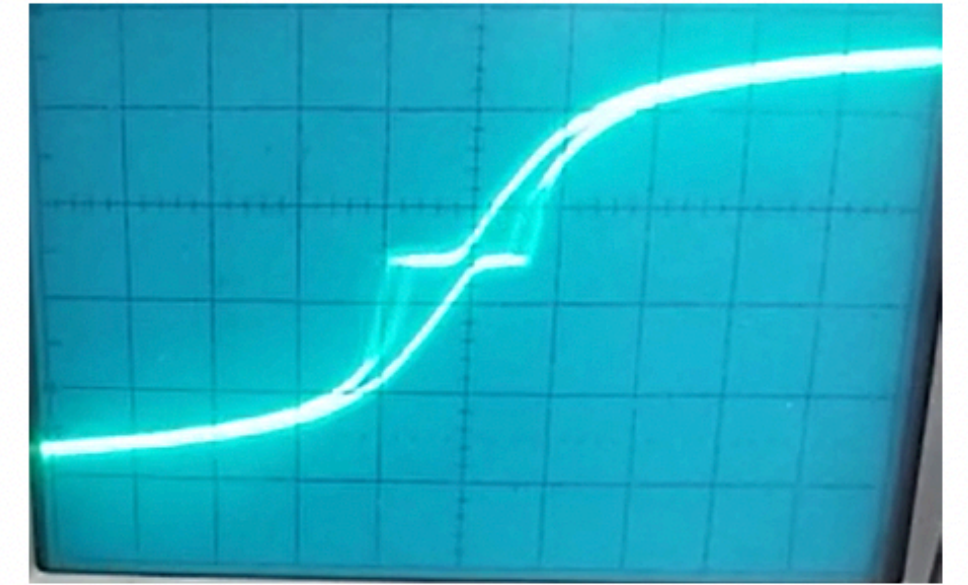
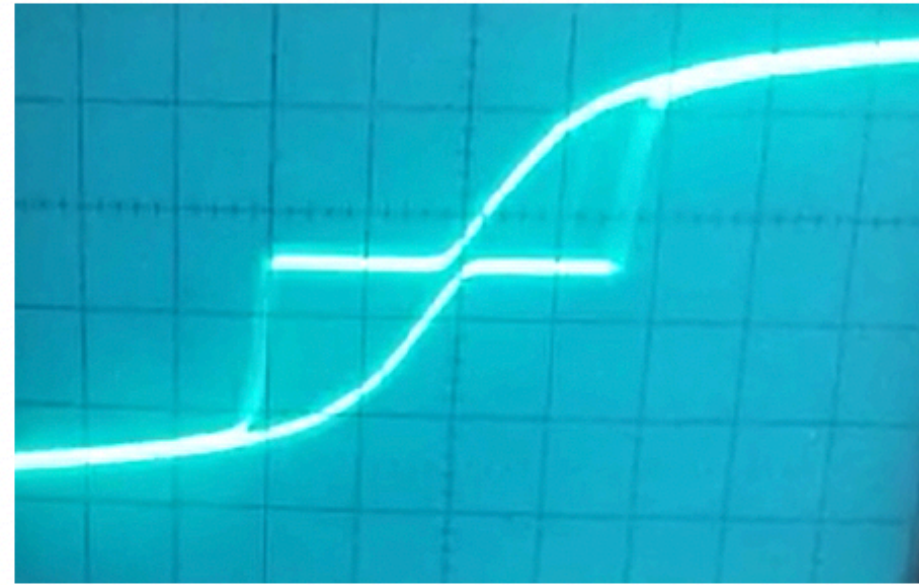
We hope to use this approach to **entangle cavities that are separated by many kilometers of optical fiber**, as this is a key requirement for using existing telecom fiber networks as quantum communication channels.

Observation of the Josephson Supercurrent



The **Josephson junction** is a principal foundational component of modern quantum electronics. It consists of **two superconductors separated by a thin insulating barrier**. This configuration allows a dissipationless current with zero voltage across the junction and switches to a finite-voltage branch when the critical current is exceeded.

In **Yale's advanced physics teaching laboratory**, students fabricated junctions and measured how the current is modulated by a magnetic field—a direct signature of Josephson coupling. The students were able to observe a Josephson supercurrent in the student-fabricated device.



I–V (current-voltage) curves of a **student-fabricated Al/AlOx/Pb junction** for different applied magnetic fields (current on horizontal axis). Increasing field suppresses the zero-voltage supercurrent branch and reduces the switching current. The hysteretic behavior is often controlled by incorporating resistive shunts in parallel with the junction