54TH SLAC SUMMER INSTITUTE (SSI 2026)

SUPERCONDUCTING SENSORS FOR PARTICLE-LIKE DARK MATTER SEARCHES AND BEYOND

CLARENCE CHANG
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Thanks to:
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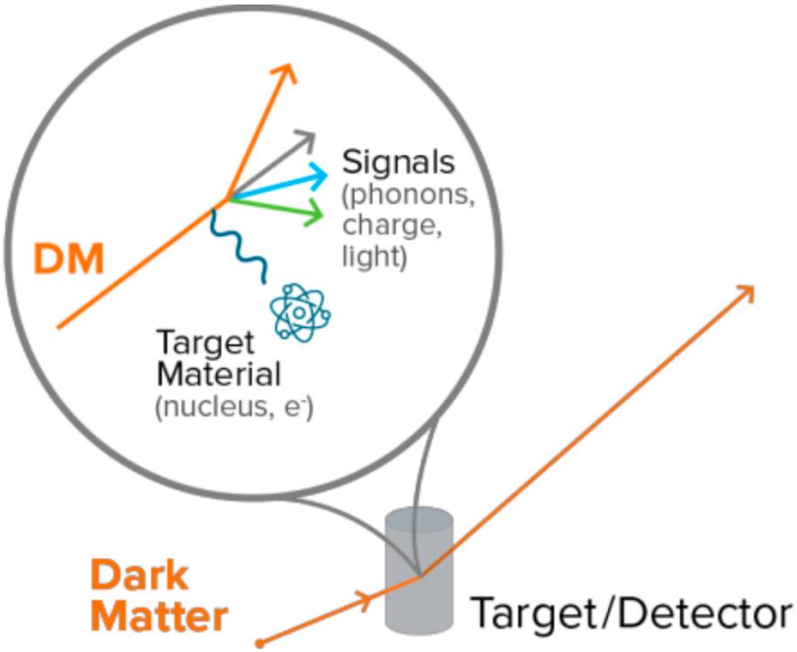
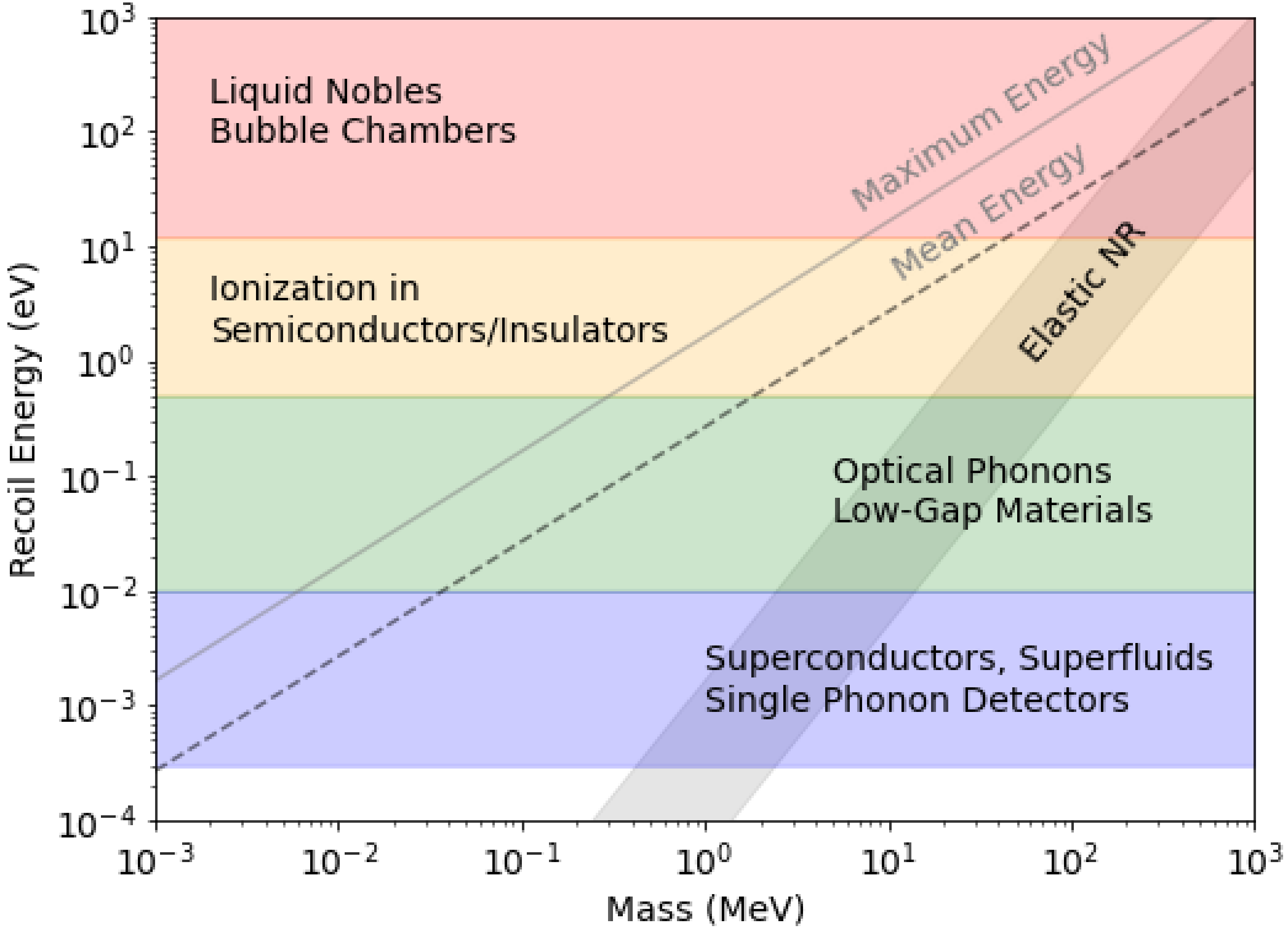
PARTICLE INTERACTIONS IN MASSIVE TARGETS



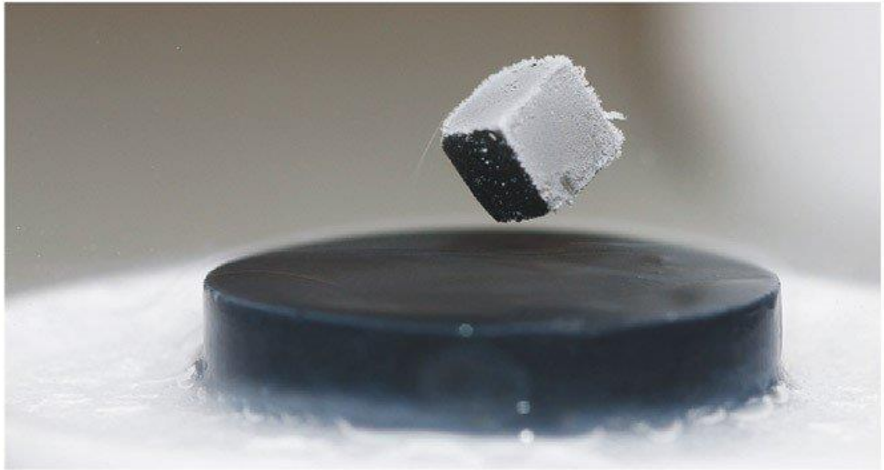
Energy from dark matter interacting w/ target
- **ns**: Initial recoil
- ***μs***: athermal excitations
  - Collective excitations: Phonons, rotons, magnons
  - Ionization, scintillation
  - Photon emission
- **ms**: thermalization



arXiv:2203.08297

SUPERCONDUCTIVITY

Common perceptions



SUPERCONDUCTING SENSORS

- There are applications that require/benefit from low temperatures
  - Sensing applications where signal thresholds are <1eV (gap of Si)
  - Amplification of low freq EM signals
  - Calorimetric/bolometric applications where noise from thermal fluctuations need to be minimized
- Superconductivity corresponds to phase transition that takes place at these temperatures and energy scales
  - Rich set of phenomena
  - Can develop/build many kinds of devices
  - Integrate to realize complex detectors

SUPERCONDUCTING DEVICES FOR QUANTUM PARTICLE DARK MATTER

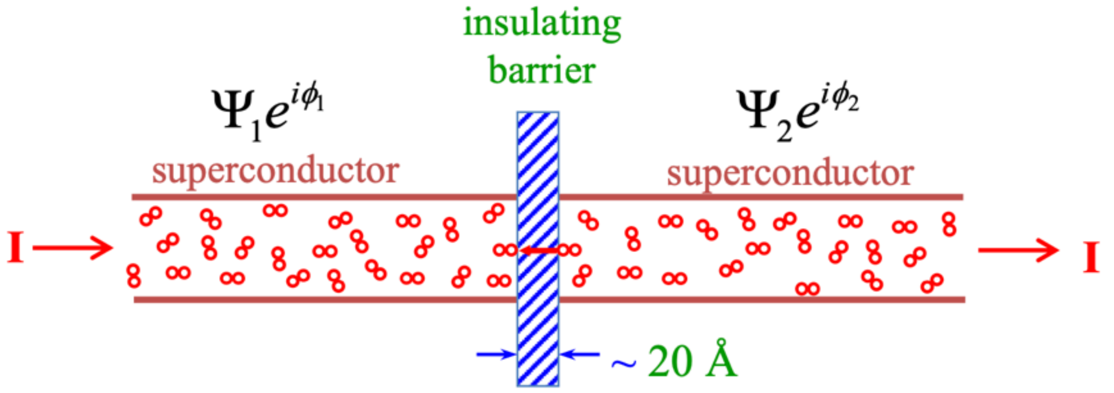
Quantum state

Transition to zero resistance

Pairing/bandgap

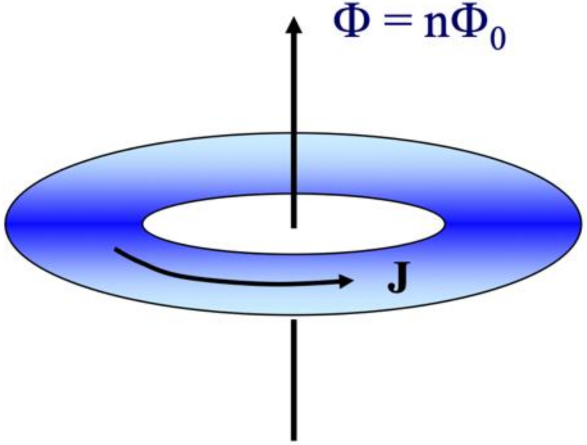
COHERENT QUANTUM STATE

“Macroscopic,” can access phenomena with “reasonable” size devices



$$\delta = \phi_1 - \phi_2$$

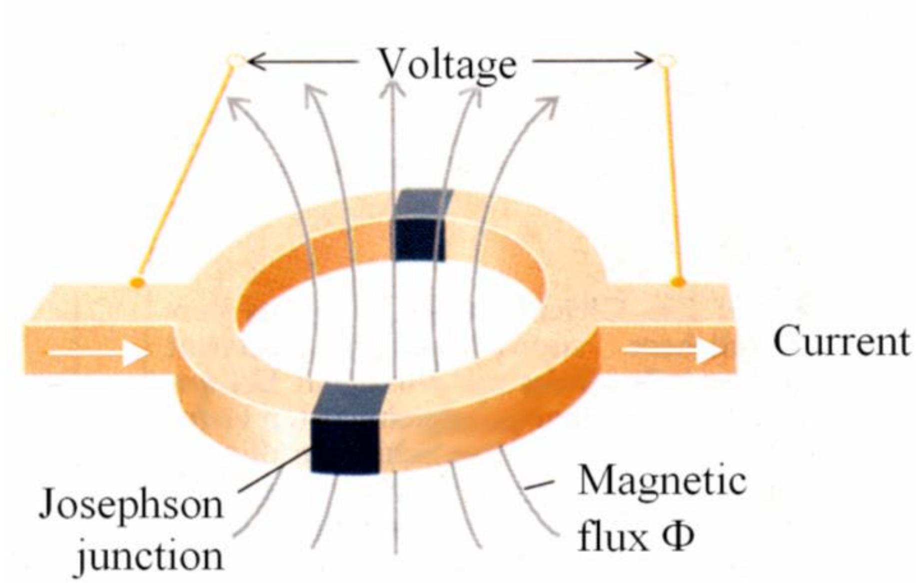
Tunneling



$$\Phi = n\Phi_0 \ (n = 0, \pm1, \pm2, \ldots)$$
$$\Phi_0 = h/2e \approx 2.07\ 10^{-15}\ \mathrm{Wb}$$

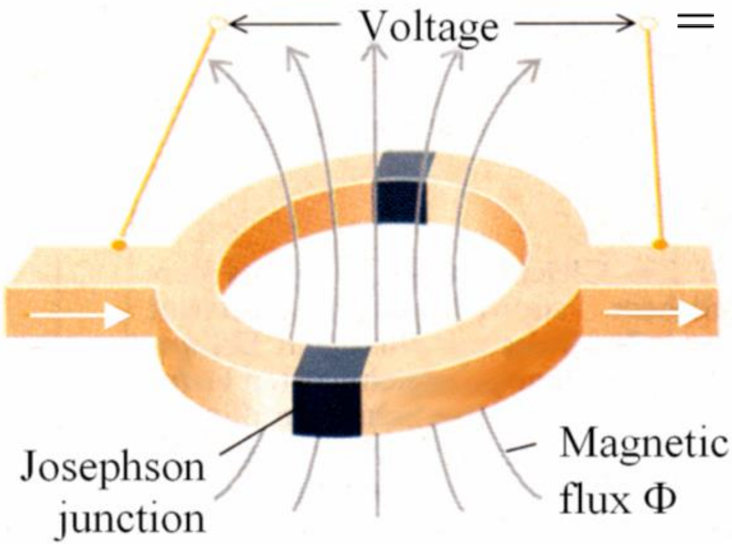
Flux quantization

SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE



SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE

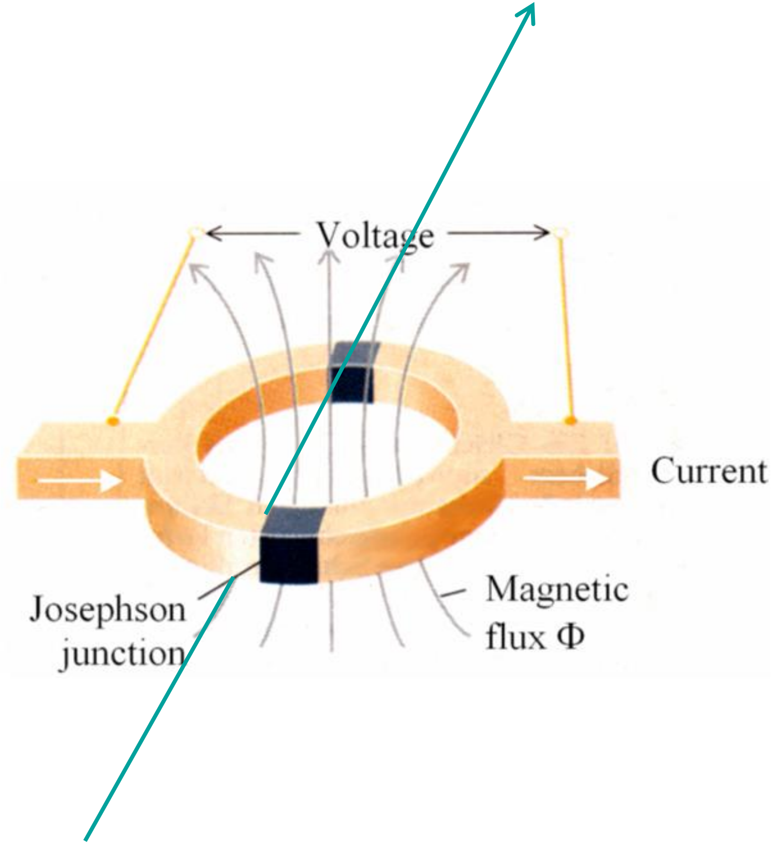
For Current > I_c,
there will be a voltage

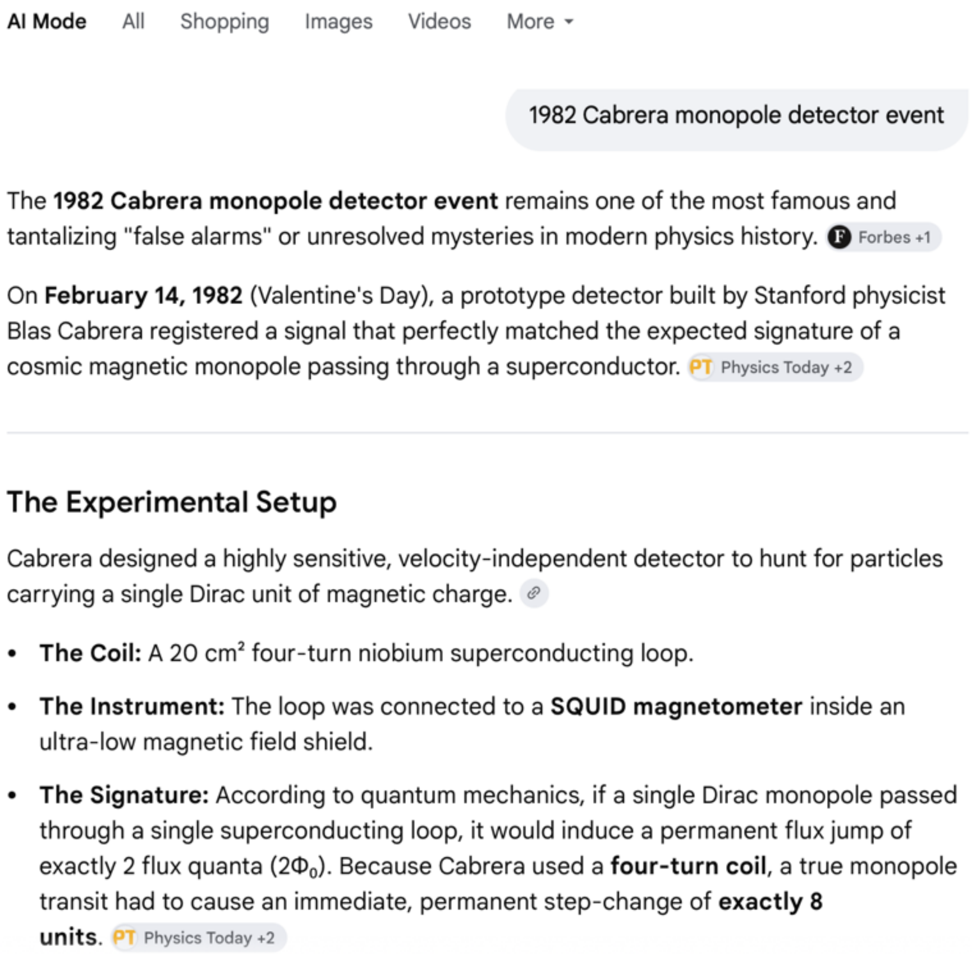


$$= \frac{\Phi_0}{2\pi}\frac{d\phi}{dt}$$

$$\text{Current} = I_c \sin\phi + \frac{\Phi_0}{2\pi R}\frac{d\phi}{dt} + C\left(\frac{\Phi_0}{2\pi}\right)^2 \frac{d^2\phi}{dt^2}$$

$$= \int A \cdot dl = \int \nabla\phi \cdot dl = 2\pi n = n\Phi_0$$





1982 Cabrera monopole detector event

The **1982 Cabrera monopole detector event** remains one of the most famous and tantalizing "false alarms" or unresolved mysteries in modern physics history. Forbes +1

On **February 14, 1982** (Valentine's Day), a prototype detector built by Stanford physicist Blas Cabrera registered a signal that perfectly matched the expected signature of a cosmic magnetic monopole passing through a superconductor. Physics Today +2

The Experimental Setup

Cabrera designed a highly sensitive, velocity-independent detector to hunt for particles carrying a single Dirac unit of magnetic charge.

- **The Coil:** A 20 cm² four-turn niobium superconducting loop.
- **The Instrument:** The loop was connected to a **SQUID magnetometer** inside an ultra-low magnetic field shield.
- **The Signature:** According to quantum mechanics, if a single Dirac monopole passed through a single superconducting loop, it would induce a permanent flux jump of exactly 2 flux quanta ($2\Phi_0$). Because Cabrera used a **four-turn coil**, a true monopole transit had to cause an immediate, permanent step-change of **exactly 8 units**. Physics Today +2

Phys. Rev. Lett. 48, 1378

First Results from a Superconductive Detector for Moving Magnetic Monopoles

Blas Cabrera

Physics Department, Stanford University, Stanford, California 94305

(Received 5 April 1982)

A velocity- and mass-independent search for moving magnetic monopoles is being performed by continuously monitoring the current in a 20-cm^2-area superconducting loop. A single candidate event, consistent with one Dirac unit of magnetic charge, has been detected during five runs totaling 151 days. These data set an upper limit of 6.1×10^{-10} cm^{-2} sec^{-1} sr^{-1} for magnetically charged particles moving through the earth's surface.

PACS numbers: 14.80.Hv

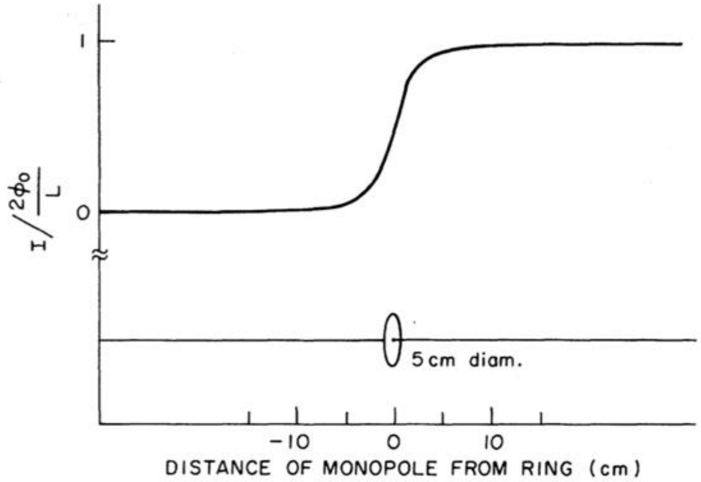


FIG. 1. Induced current in a superconducting ring for an axial monopole trajectory.

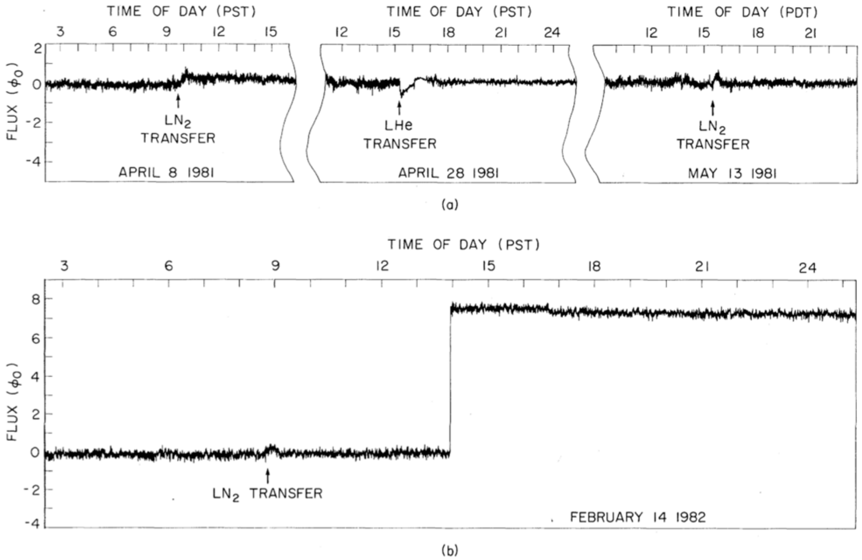
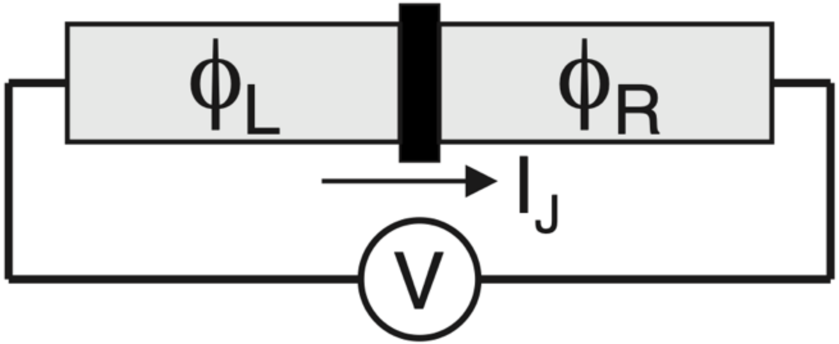


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

RF SQUID



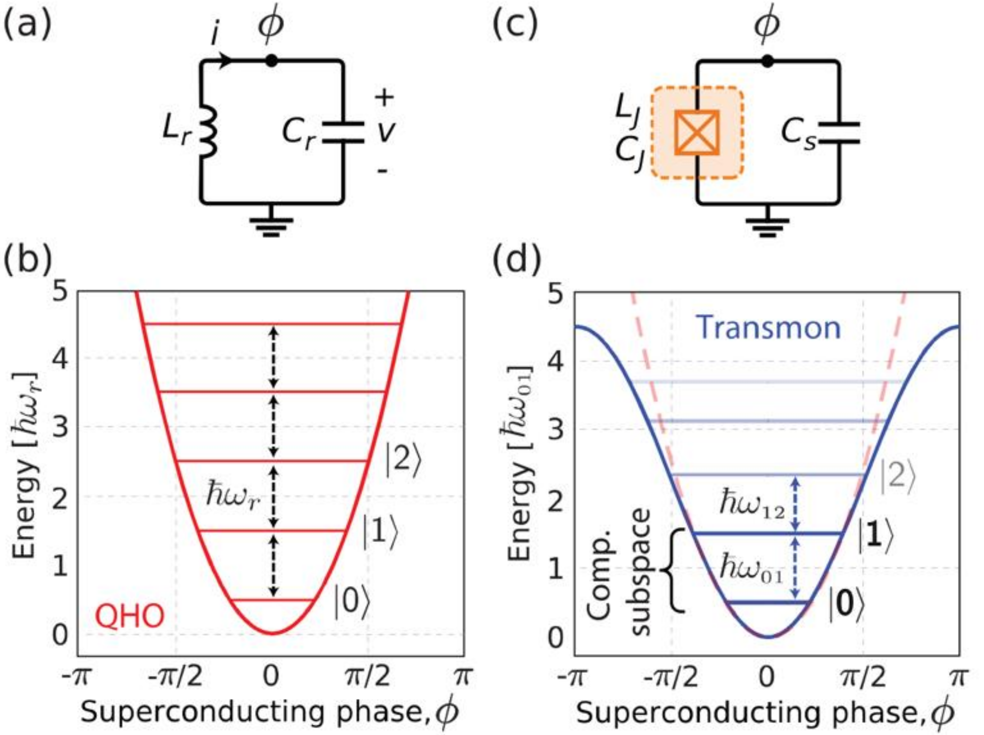
$$I_J = I_0 \sin\delta$$

$$V = \frac{\Phi_0}{2\pi}\frac{d\delta}{dt},$$

$$\frac{dI_J}{dt} = I_0 \cos\delta \, \frac{2\pi}{\Phi_0} V.$$

$$\boxed{L_J = \frac{\Phi_0}{2\pi I_0 \cos\delta}.}$$

QUBITS

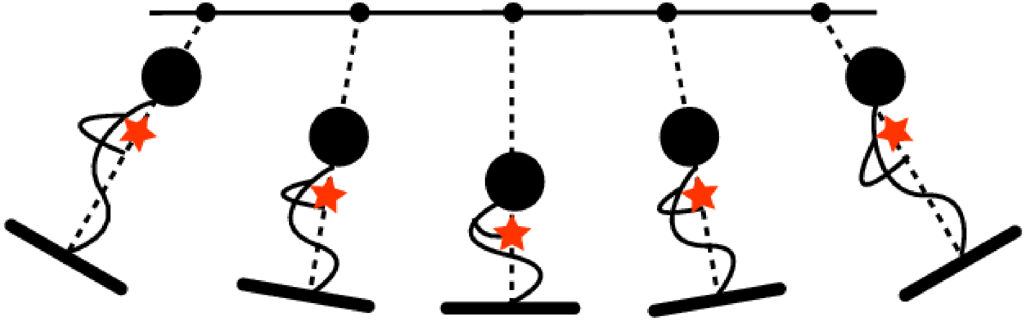

(a)
i
ϕ
L_r
C_r
+
V
-
(c)
ϕ
L_J
C_J
C_S
(b)
Energy [$\hbar\omega_r$]
5
4
3
2
1
0
$\hbar\omega_r$
$|2\rangle$
$|1\rangle$
$|0\rangle$
QHO
-π
-π/2
0
π/2
π
Superconducting phase, ϕ
(d)
Energy [$\hbar\omega_{01}$]
5
4
3
2
1
0
Transmon
$|2\rangle$
$\hbar\omega_{12}$
$|1\rangle$
$\hbar\omega_{01}$
$|0\rangle$
Comp. subspace
-π
-π/2
0
π/2
π
Superconducting phase, ϕ

PARAMETRIC AMPLIFICATION

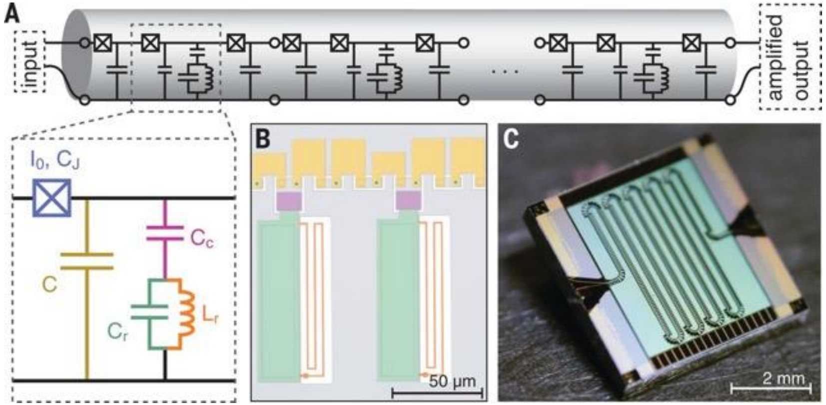
- Harmonic oscillator whose physical properties (**parameters**) vary with time

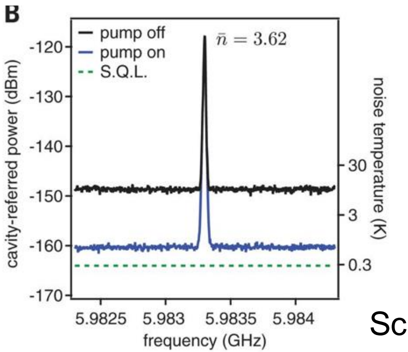
$$\frac{d^2x}{dt^2} + \beta(t)\frac{dx}{dt} + \omega^2(t)x = 0$$

  - Nonlinear inductance provides this parametric property for an electric circuit
- Can pump the oscillator by varying β, ω such that the oscillator phase locks to the pump and absorbs energy

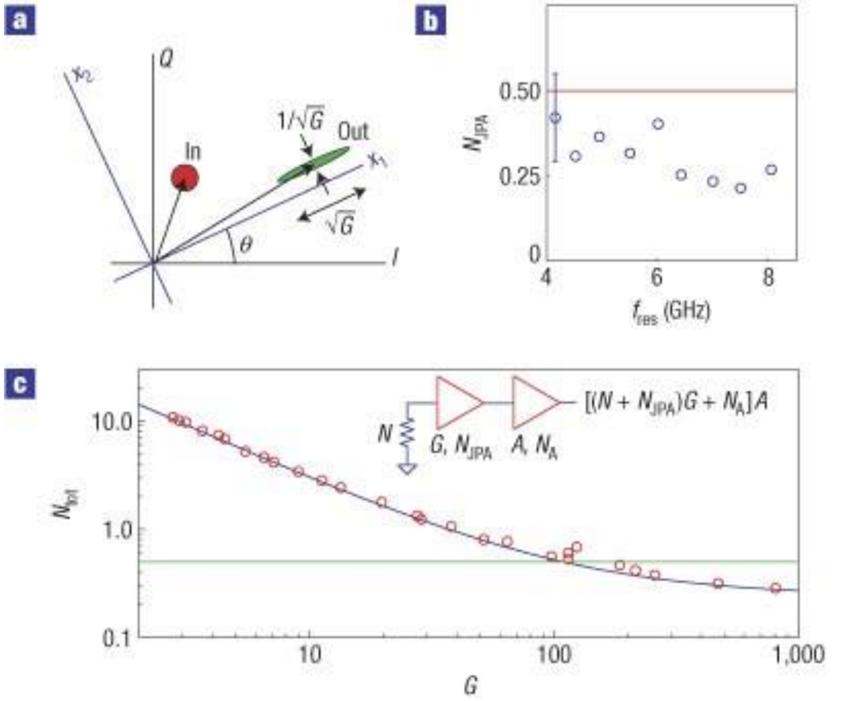


JOSEPHSON PARAMETRIC AMPLIFIERS





Science 350,307-310 (2015)



Nature Physics volume 4, pages929–931 (2008)

CRITICAL TOOLS FOR SUPERCONDUCTING QUANTUM COMPUTING

IBM RELEASES FIRST-EVER 1,000-QUBIT QUANTUM CHIP

The company will now focus on developing smaller, more reliable processors.

By Davide Castelvecchi

IBM has unveiled the first quantum computer with more than 1,000 qubits – the equivalent of the digital bits in an ordinary computer. But the company says that it will now shift gears and focus on making its machines more error-resistant

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IBM's
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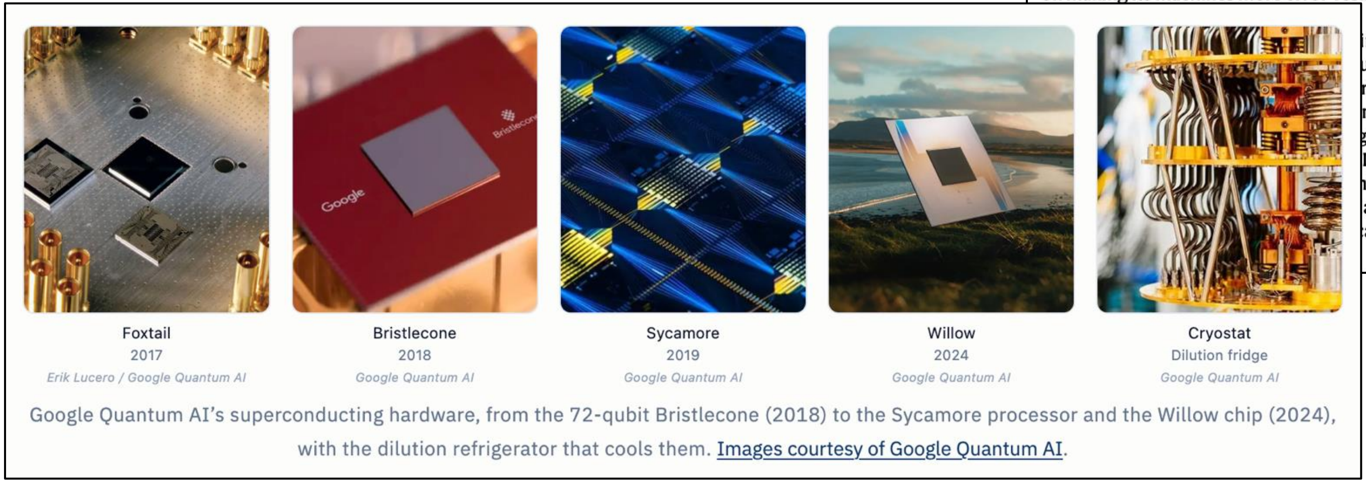
IBM's Heron quantum processor.

RYAN LAVINE FOR IBM



Foxtail
2017
Erik Lucero / Google Quantum AI

Bristlecone
2018
Google Quantum AI

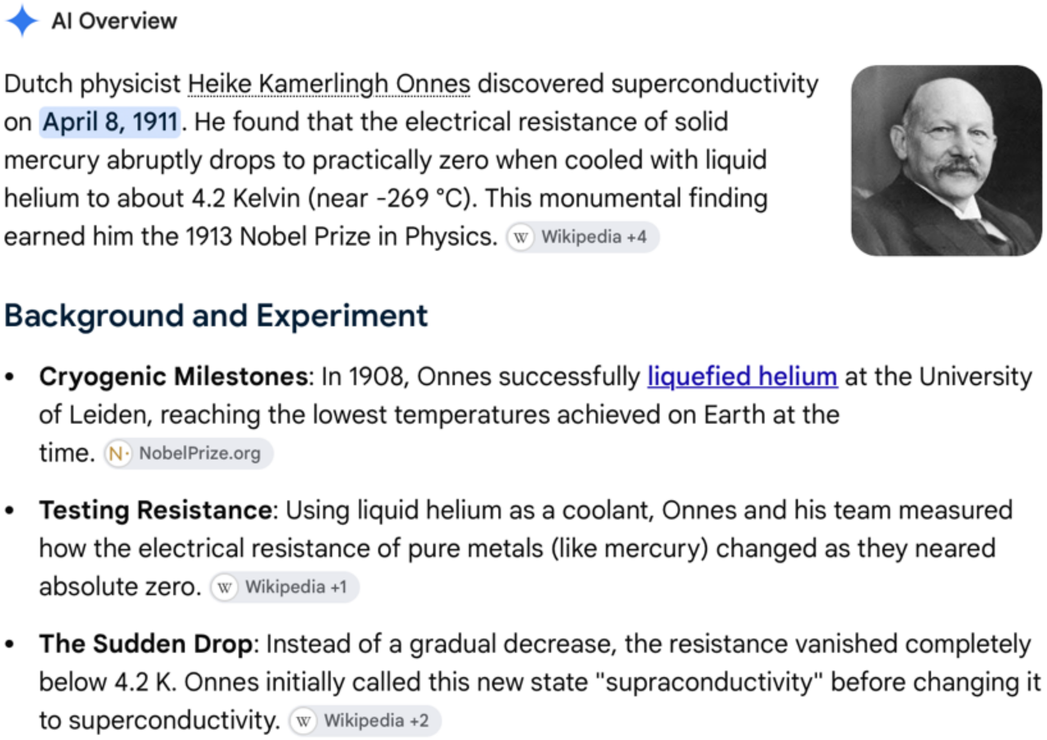
Sycamore
2019
Google Quantum AI

Willow
2024
Google Quantum AI

Cryostat
Dilution fridge
Google Quantum AI

Google Quantum AI's superconducting hardware, from the 72-qubit Bristlecone (2018) to the Sycamore processor and the Willow chip (2024), with the dilution refrigerator that cools them. Images courtesy of Google Quantum AI.

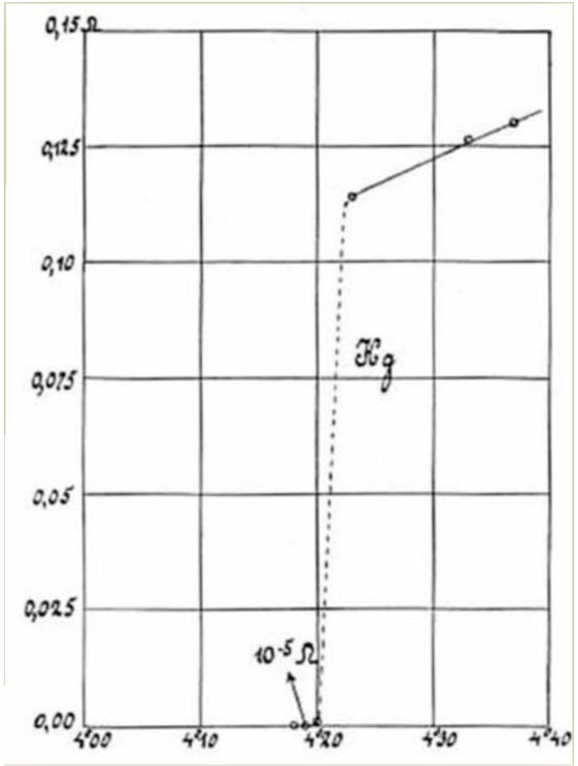
ZERO ELECTRICAL RESISTANCE



Dutch physicist Heike Kamerlingh Onnes discovered superconductivity on April 8, 1911. He found that the electrical resistance of solid mercury abruptly drops to practically zero when cooled with liquid helium to about 4.2 Kelvin (near -269 °C). This monumental finding earned him the 1913 Nobel Prize in Physics. Wikipedia +4

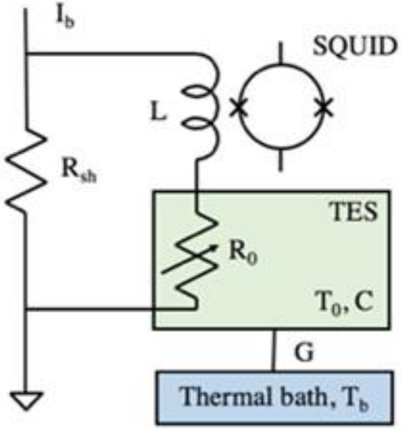
Background and Experiment

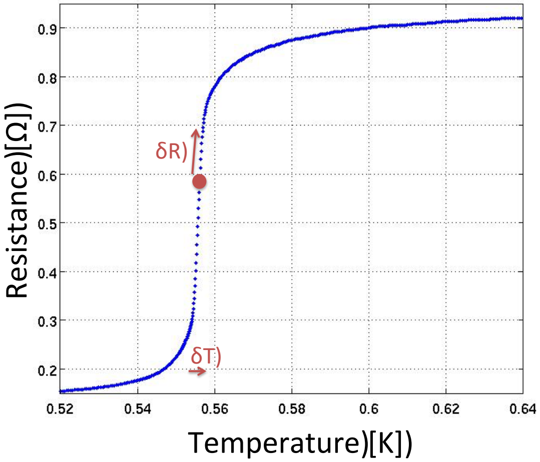
- **Cryogenic Milestones**: In 1908, Onnes successfully liquefied helium at the University of Leiden, reaching the lowest temperatures achieved on Earth at the time. NobelPrize.org
- **Testing Resistance**: Using liquid helium as a coolant, Onnes and his team measured how the electrical resistance of pure metals (like mercury) changed as they neared absolute zero. Wikipedia +1
- **The Sudden Drop**: Instead of a gradual decrease, the resistance vanished completely below 4.2 K. Onnes initially called this new state "supraconductivity" before changing it to superconductivity. Wikipedia +2



H. Kamerlingh Onnes, Commun. Phys. Lab. Univ. Leiden. Suppl. 29 (Nov. 1911)

THERMAL SENSOR

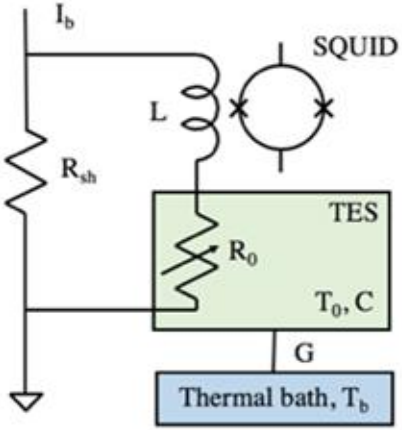


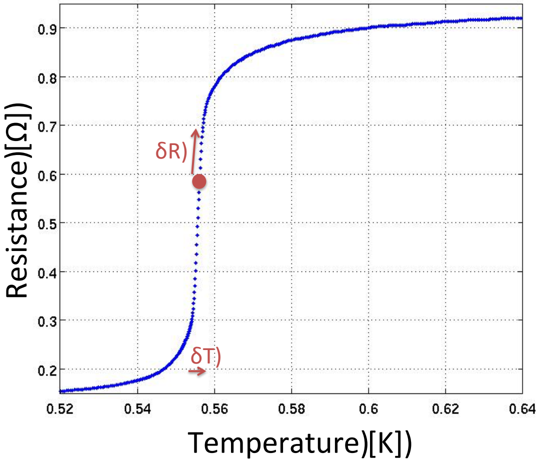


$$P_{Joule} = \frac{V_0^2}{R(T)}$$

Appl. Phys. Lett. 66, 1998–2000 (1995)

THERMAL SENSOR



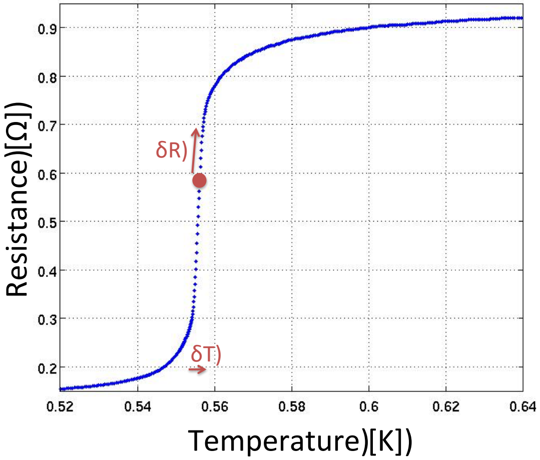


$$P_{Joule} = \frac{V_0^2}{R(T)}$$

$$\delta P_{Joule} = \frac{d}{dT}\left(\frac{V_0^2}{R(T)}\right) = -\left(\frac{V_0}{R}\right)^2 \frac{dR}{dT}\delta T$$

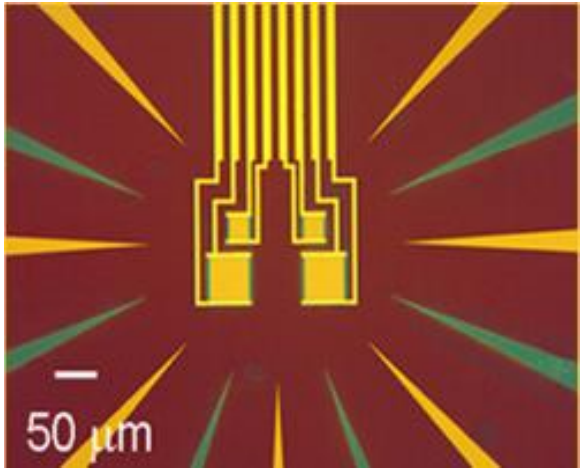
OPERATING PRINCIPLES

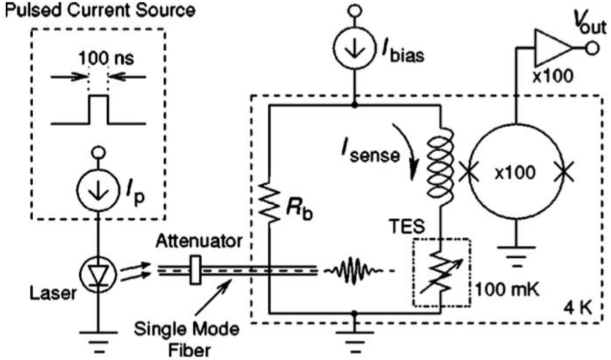
- Device stabilizes at T_c. Temperature is nearly constant.
- Linearity:
  - — $\Delta P_{\text{absorbed}} \approx \Delta P_{\text{bias}} = V_{\text{bias}} \times \Delta I_{\text{TES}}$
- Increased bandwidth
- Voltage bias using shunt resistor
  - — Measure current using high sensitivity SQUID
- Fundamental noise comes from thermal fluctuations (~kT), which can be made small by choosing suitable T_c.

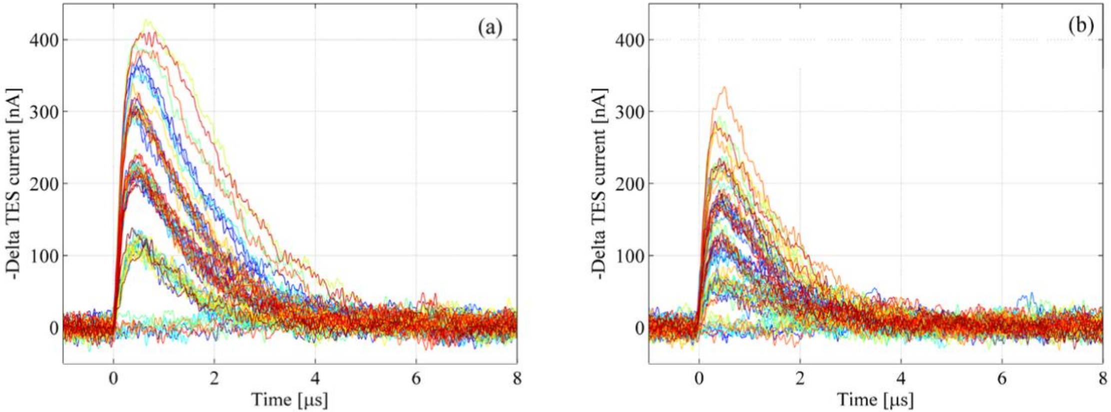


DETECTING EVENTS

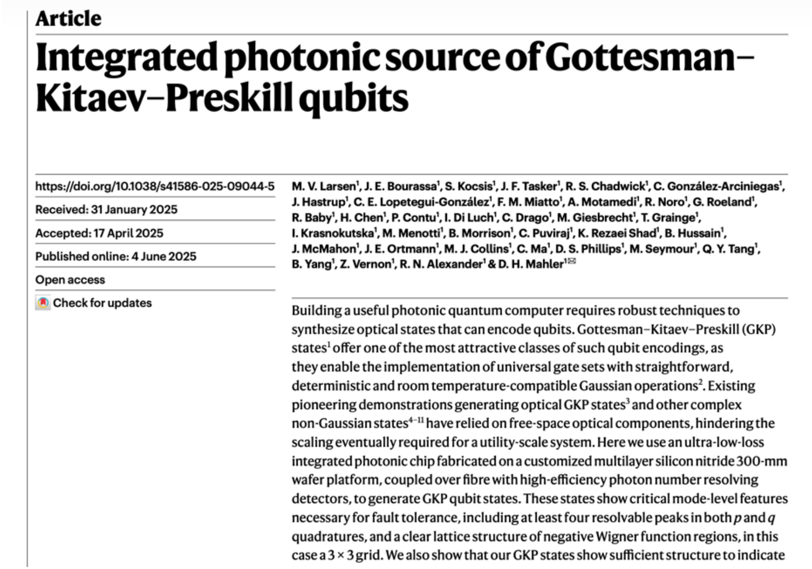
- Energy deposition heats up TES
- Negative-feedback (from change in resistance) counters the change by reducing bias power
  - TES temperature nearly constant, change in supplied power/current (voltage biased)







Appl. Phys. Lett. 83, 791–793 (2003)



Article

Integrated photonic source of Gottesman–Kitaev–Preskill qubits

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Accepted: 17 April 2025

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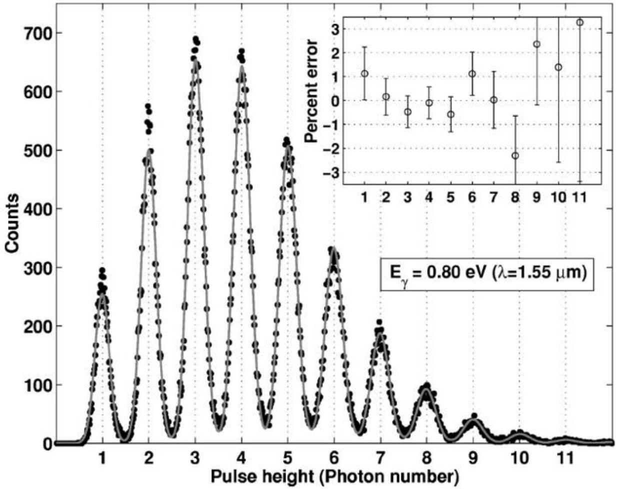
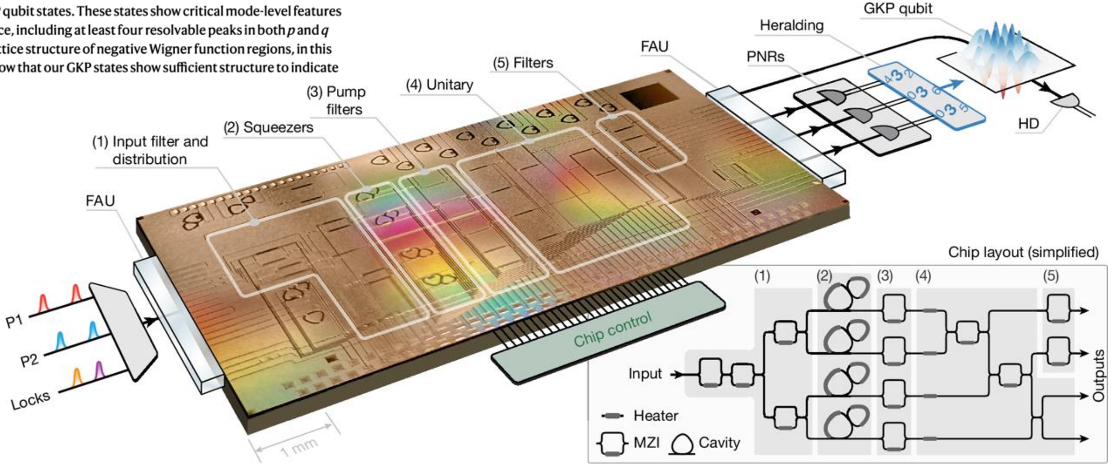
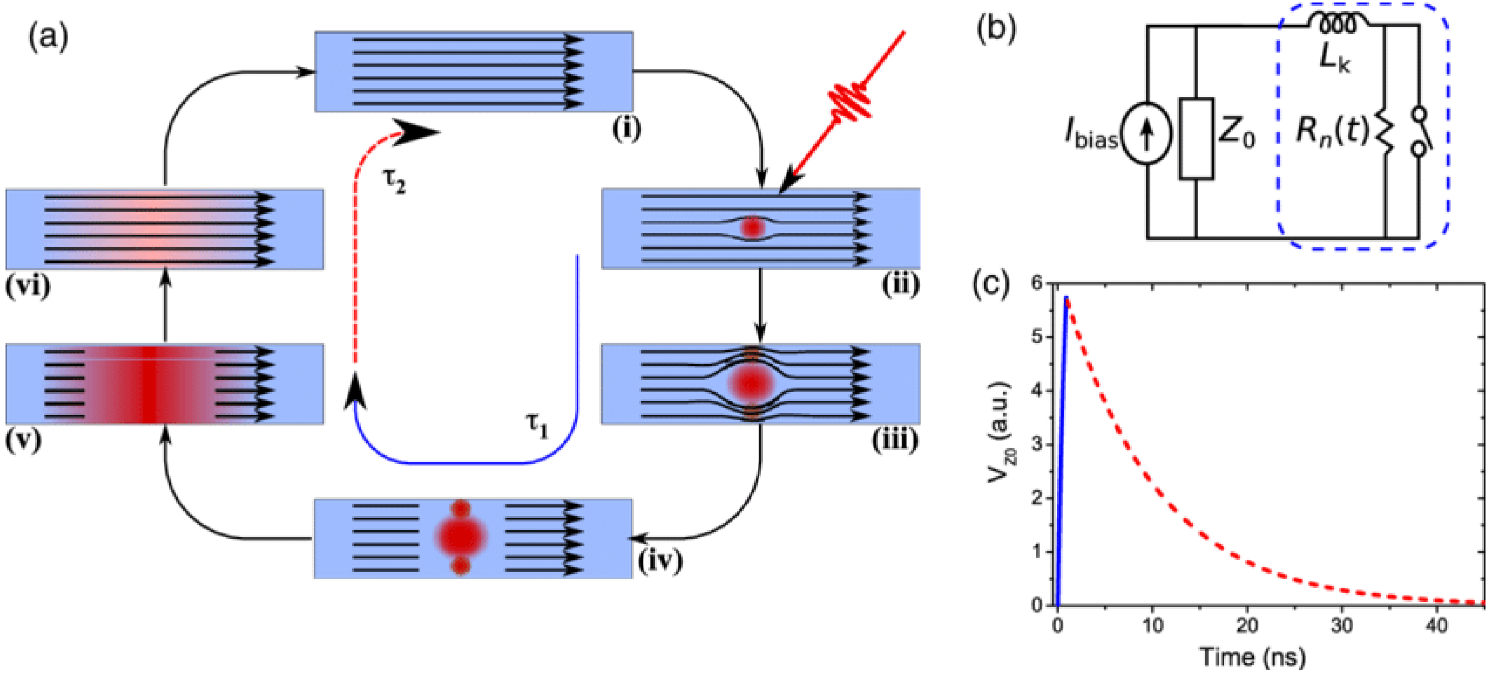
Building a useful photonic quantum computer requires robust techniques to synthesize optical states that can encode qubits. Gottesman–Kitaev–Preskill (GKP) states[1] offer one of the most attractive classes of such qubit encodings, as they enable the implementation of universal gate sets with straightforward, deterministic and room temperature-compatible Gaussian operations[2]. Existing pioneering demonstrations generating optical GKP states[3] and other complex non-Gaussian states[4–11] have relied on free-space optical components, hindering the scaling eventually required for a utility-scale system. Here we use an ultra-low-loss integrated photonic chip fabricated on a customized multilayer silicon nitride 300-mm wafer platform, coupled over fibre with high-efficiency photon number resolving detectors, to generate GKP qubit states. These states show critical mode-level features necessary for fault tolerance, including at least four resolvable peaks in both *p* and *q* quadratures, and a clear lattice structure of negative Wigner function regions, in this case a 3 × 3 grid. We also show that our GKP states show sufficient structure to indicate





Nature 642, 587–591 (2025)

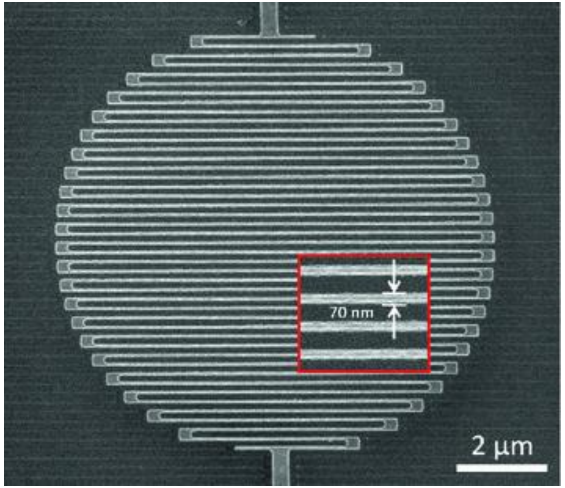
SUPERCONDUCTING “NANO”-WIRE SINGLE PHOTON DETECTOR

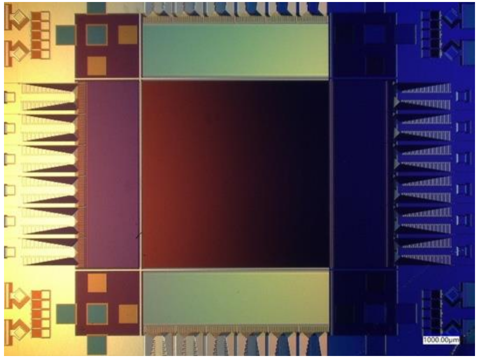


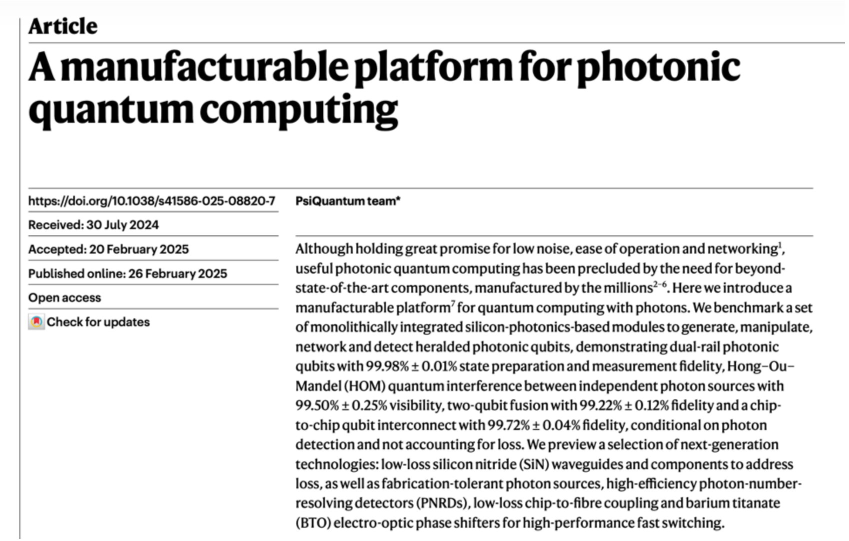
Appl. Phys. Lett. 79, 705–707 (2001)

SUPERCONDUCTING "NANO"-WIRE SINGLE PHOTON DETECTOR

- Materials and processing
  - Good uniformity
  - Good precision in patterning
- High kinetic inductance materials
  - Current doesn't restore before superconductivity fully re-established
- Strengths
  - Fast
  - High detection efficiency
  - Low dark counts
  - Non-dilution cryogenics







Article

A manufacturable platform for photonic quantum computing

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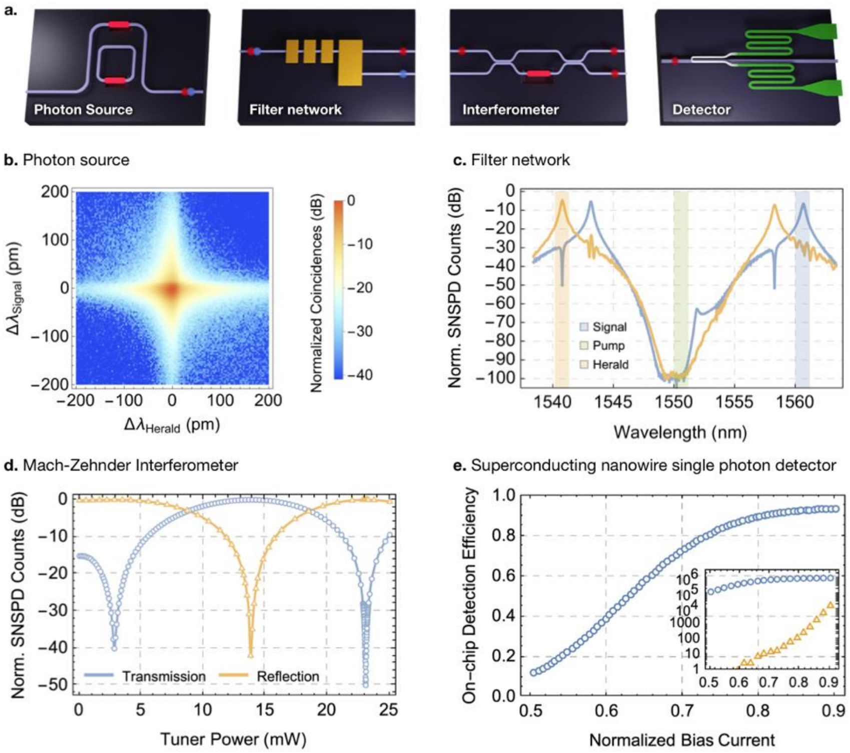
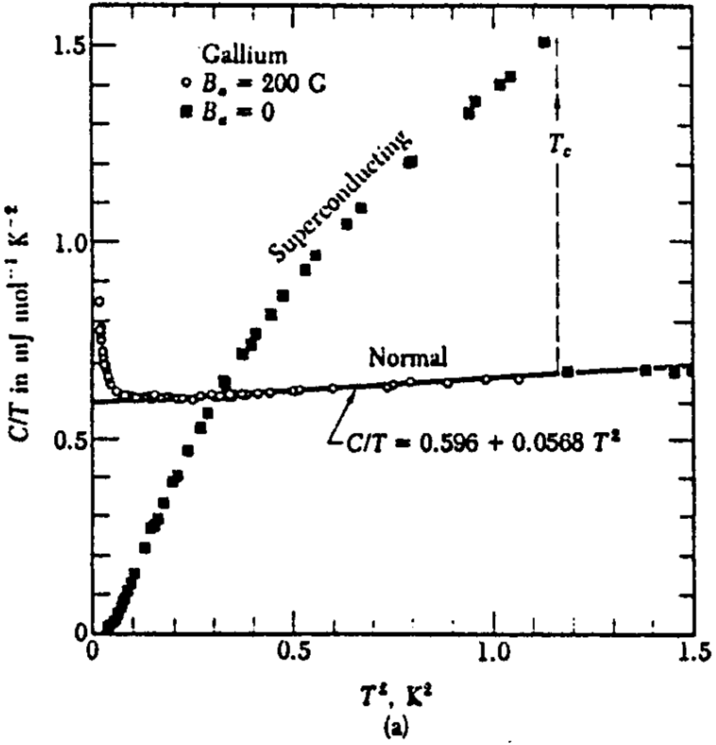
PsiQuantum team*

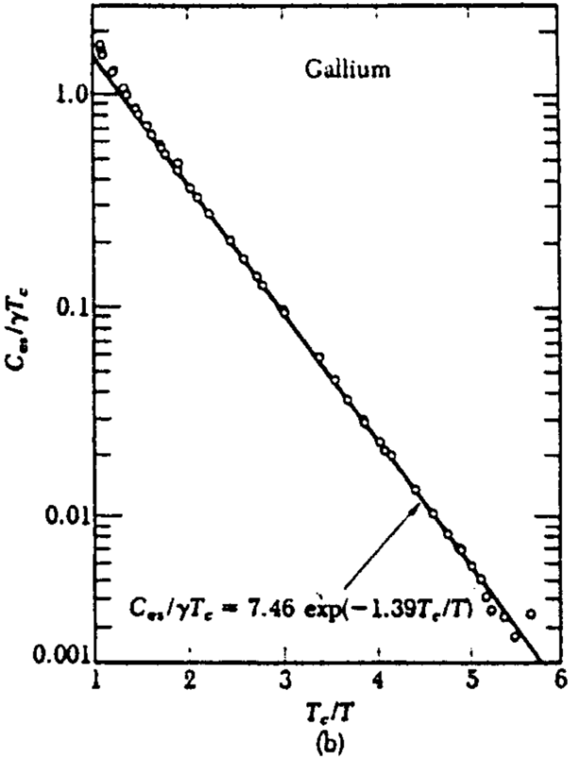
Although holding great promise for low noise, ease of operation and networking[1], useful photonic quantum computing has been precluded by the need for beyond-state-of-the-art components, manufactured by the millions[2–6]. Here we introduce a manufacturable platform[7] for quantum computing with photons. We benchmark a set of monolithically integrated silicon-photonics-based modules to generate, manipulate, network and detect heralded photonic qubits, demonstrating dual-rail photonic qubits with 99.98% ± 0.01% state preparation and measurement fidelity, Hong–Ou–Mandel (HOM) quantum interference between independent photon sources with 99.50% ± 0.25% visibility, two-qubit fusion with 99.22% ± 0.12% fidelity and a chip-to-chip qubit interconnect with 99.72% ± 0.04% fidelity, conditional on photon detection and not accounting for loss. We preview a selection of next-generation technologies: low-loss silicon nitride (SiN) waveguides and components to address loss, as well as fabrication-tolerant photon sources, high-efficiency photon-number-resolving detectors (PNRDs), low-loss chip-to-fibre coupling and barium titanate (BTO) electro-optic phase shifters for high-performance fast switching.



PAIRING & THE SUPERCONDUCTING GAP



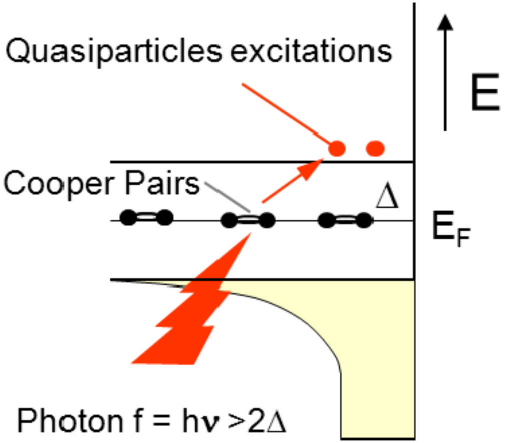
(a)

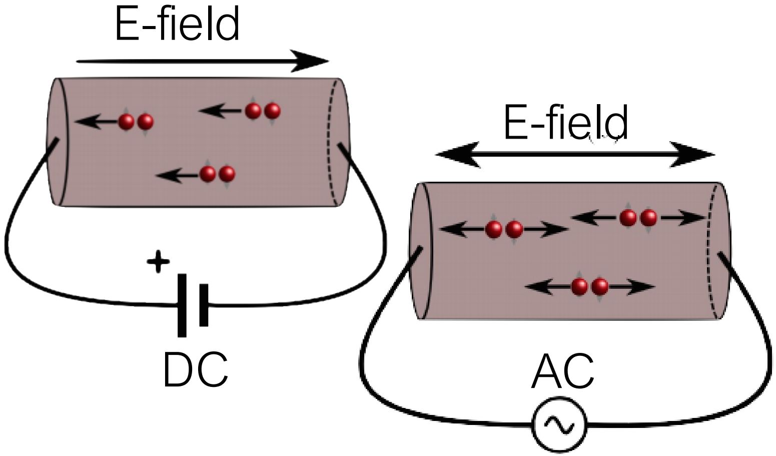


(b)

KINETIC INDUCTANCE

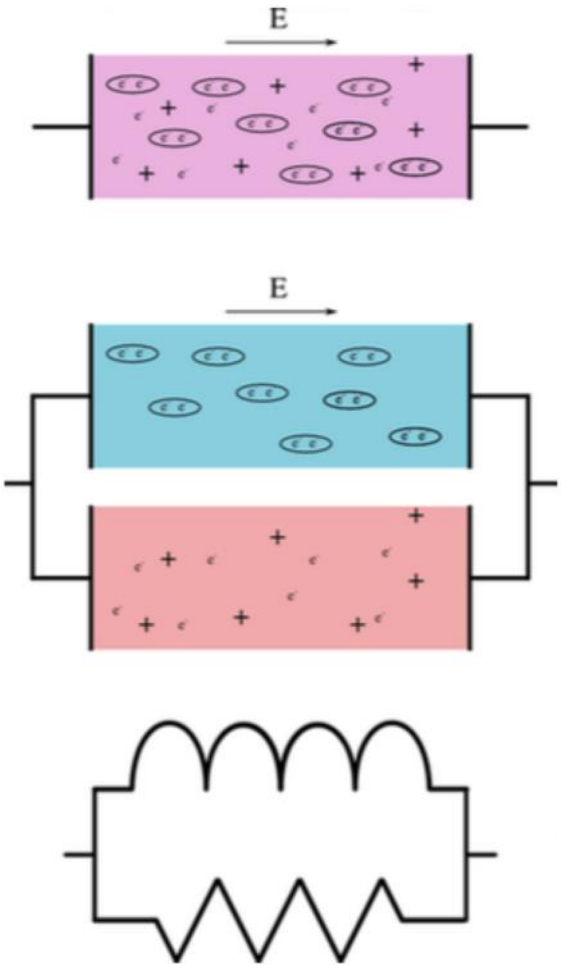
- Pairing of electrons into Cooper pairs
  - Energy gap between ground state and next excited state
- Quasiparticles are Cooper pair “excitations”
  - Fermions vs bosons
  - “Broken” Cooper pairs
- Cooper pairs have mass and momentum
  - Do not scatter. Charge flow (current) has no dissipation (real(Z) = 0)
  - Inertial response to changes in E-field. Charge flow lags field (imag(Z) ≠ 0)





SURFACE IMPEDANCE

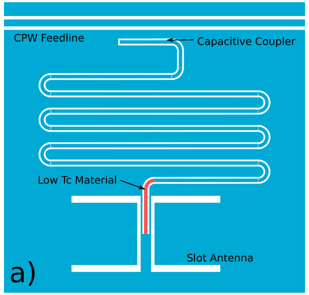
- Imagine superconductor as a fluid with two particles (Cooper pairs and quasiparticles)
- Complex conductivity depends on contributions from both
  - Cooper pairs:
    - No dissipation. Kinetic inductance.
  - Quasiparticles:
    - Dissipate
    - Small kinetic inductance
- Total complex conductivity depends on the population of pairs vs qps
  - Breaking pairs lead to a change in the complex impedance



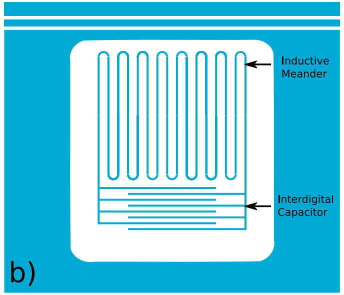
KINETIC INDUCTANCE DETECTORS

Measure Lk, Rs shift using LC resonator

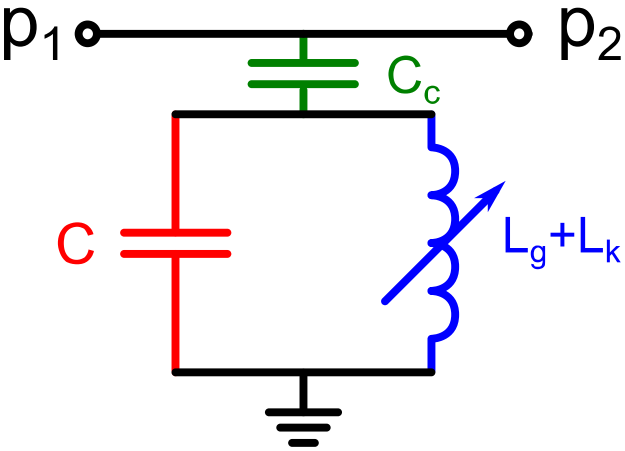
- Two methods: distributed, lumped element
- Resonator complex transfer function → phase + amplitude, frequency + Q

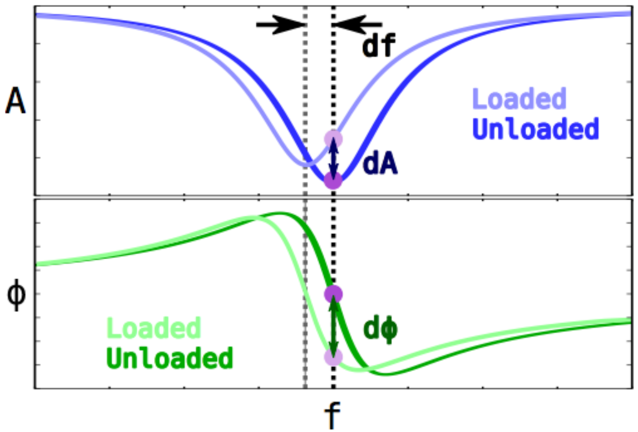


Distributed



Lumped element





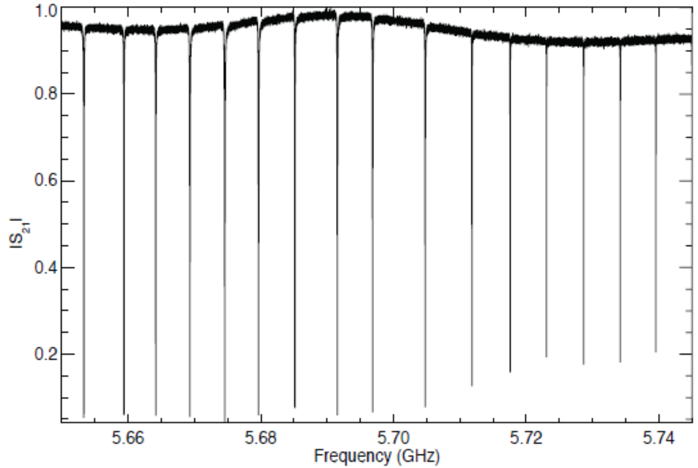
$$\omega_0 = \frac{1}{\sqrt{LC}}$$

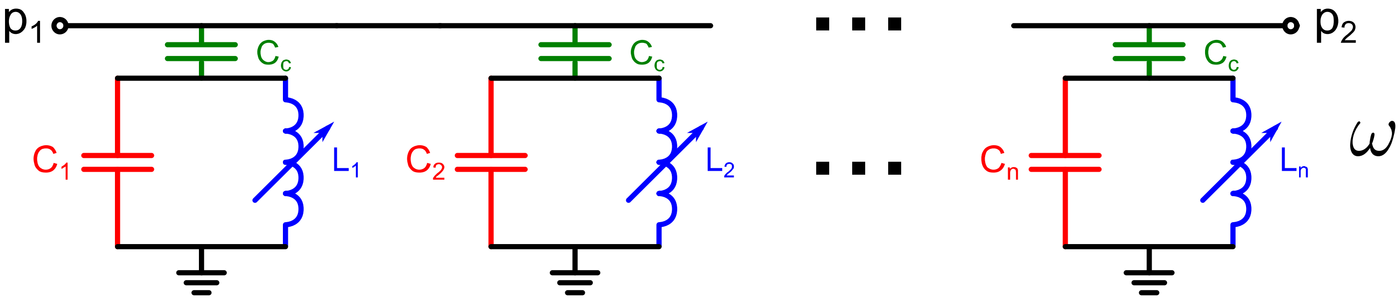
$$Q_i = \frac{\omega_0 L}{R}$$

Nature. 425 (6960): 817–821

NATURALLY MULTIPLEXED

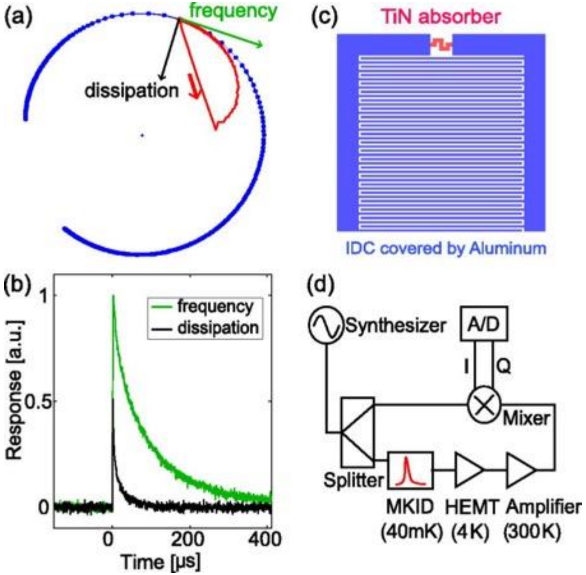
- LC resonator has specific F0
- Multiple resonators on a single line (just design w/ different f0s)
  - Readout w/ RF electronics
- Should be able to achieve few 10^3 / octave

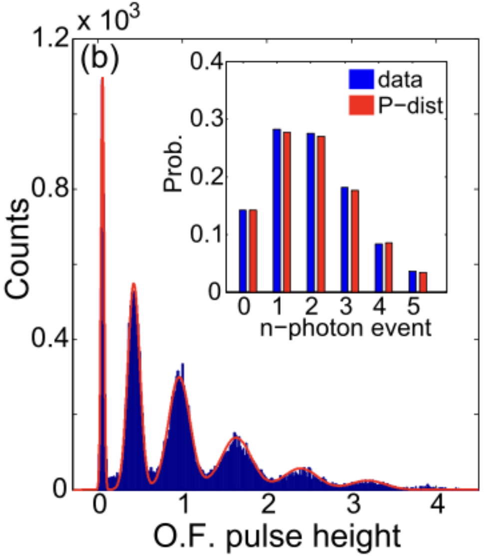




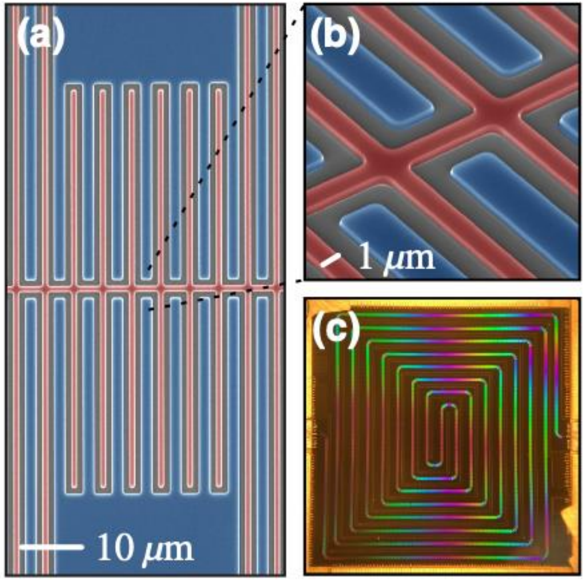
$$\omega_n = \frac{1}{\sqrt{L_n C_n}}$$

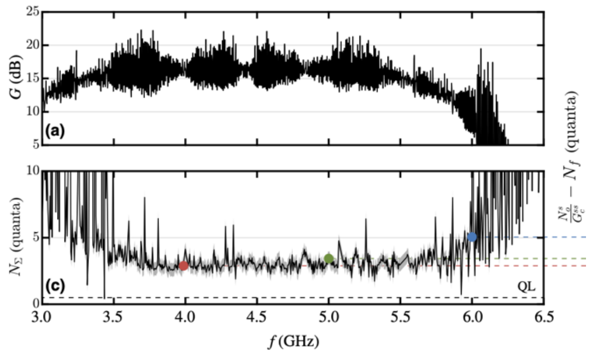
MKIDS: PNRD AND KI-PA





Appl. Phys. Lett. 110, 212601 (2017)





PRX Quantum 2, 010302

SUPERCONDUCTING DEVICES FOR QUANTUM PARTICLE DARK MATTER

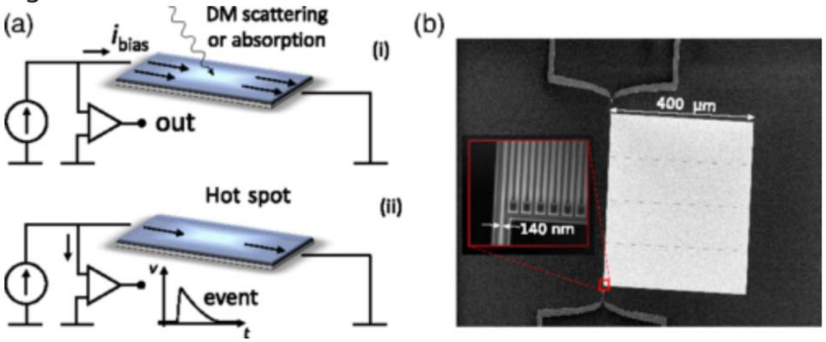
Quantum state	Transition to zero resistance	Pairing/bandgap
SQUIDs, JPA, JTWPA	TES for PNRD	MKIDs for PNRD
Qubits	SNSPDs	KI-TWPA

SNSPDS FOR DARK MATTER

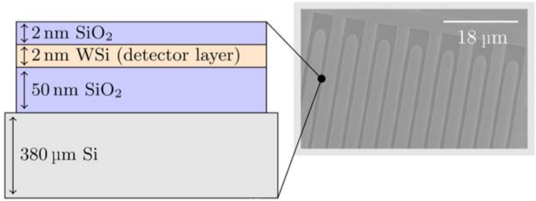
QROCODILE

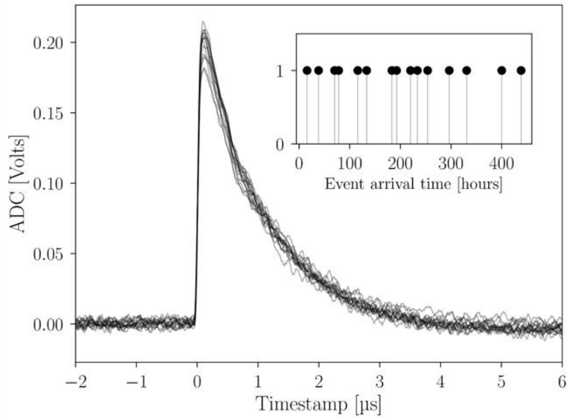
- 10x10 mm^2 chip size
- 600x600 µm^2 active area with 1 µm wire width
- 25% filling factor
- WSi 45:55 superconducting layer 2 nm thick
- Transition temperature at 1.73 K
- Si/SiO$_2$ substrate

Figure 1



Phys. Rev. Lett. 123, 151802

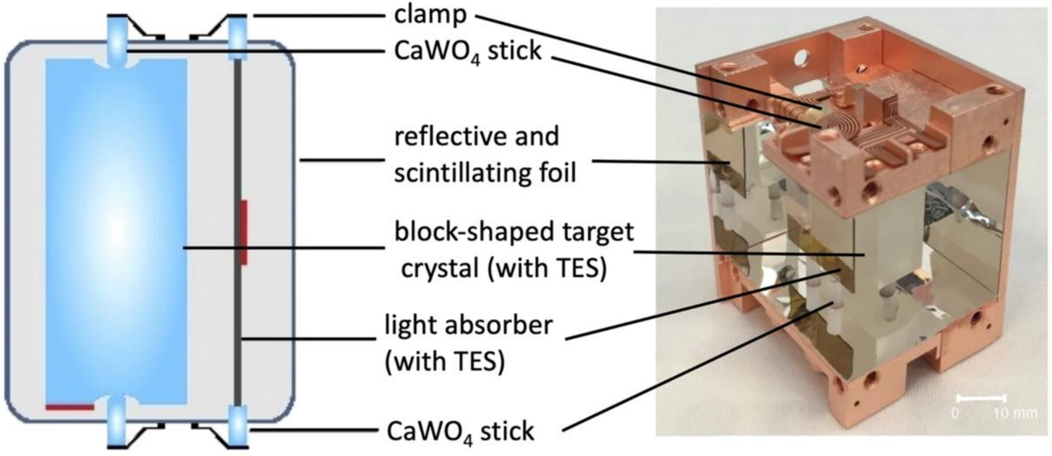


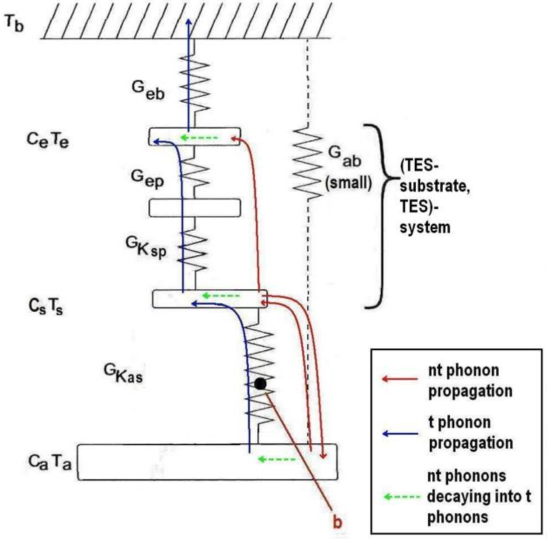


Phys. Rev. Lett. 135, 081002

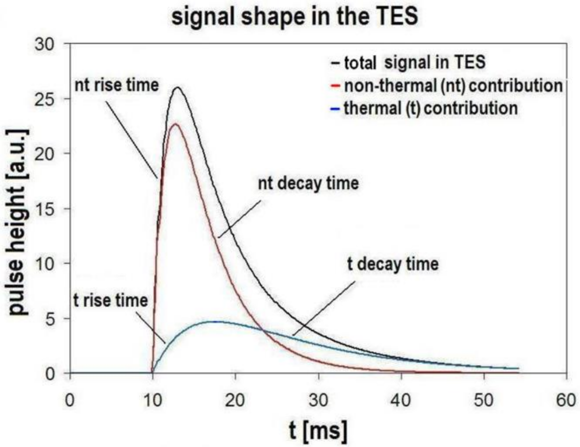
DARK MATTER

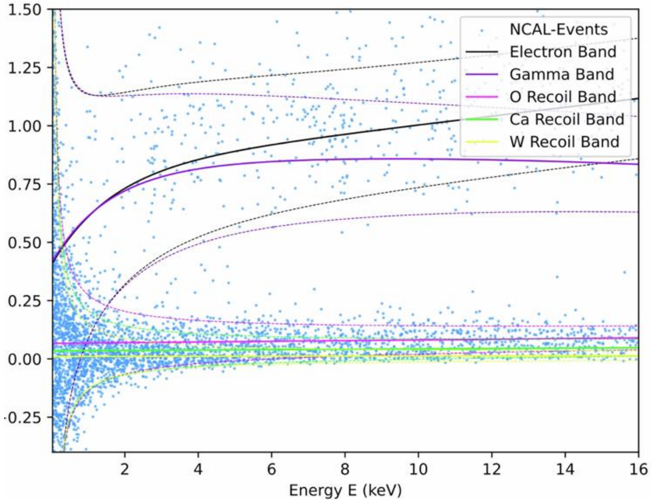
CRESST





2008 J. Phys.: Conf. Ser. 136 042085



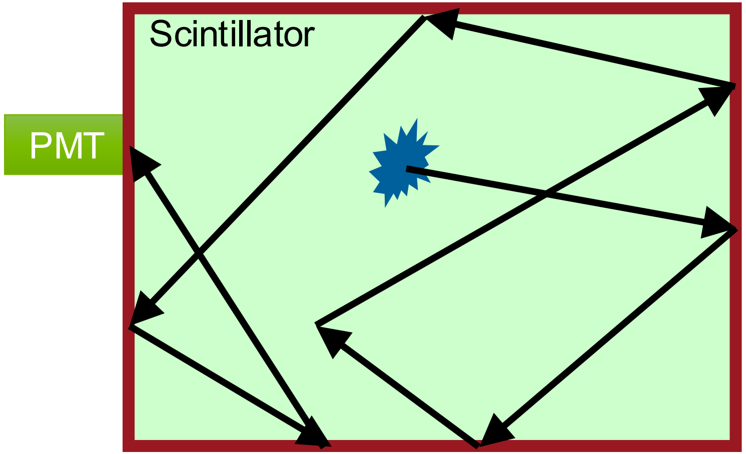


Commun Phys 9, 163 (2026)

ATHERMAL SIGNALS

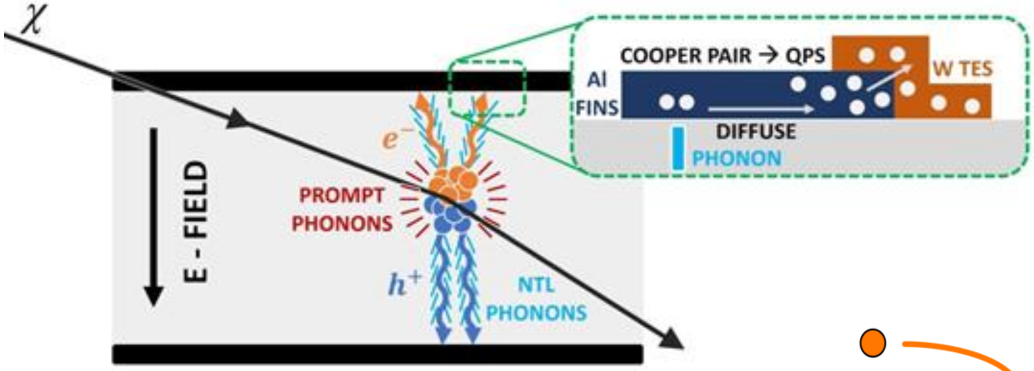
Analogy with PMTs…

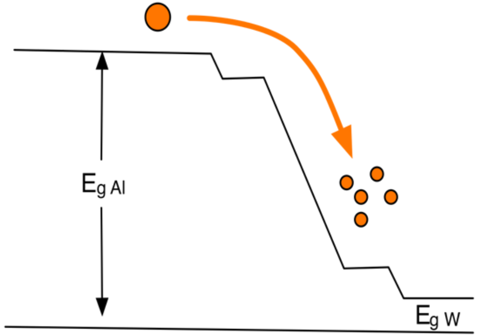
- Will these detectors have the same energy sensitivity?
- Yes, if:
  - — Lifetime of the athermal excitation (photon) is really long
  - — Excitation absorption dominated by sensor

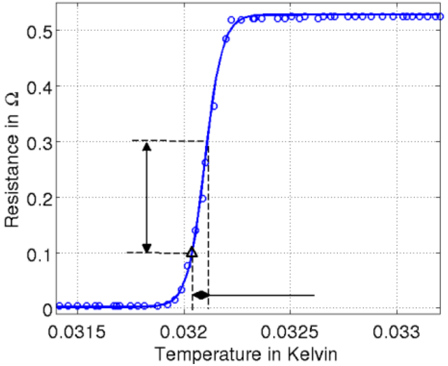


TES FOR DARK MATTER

SuperCDMS

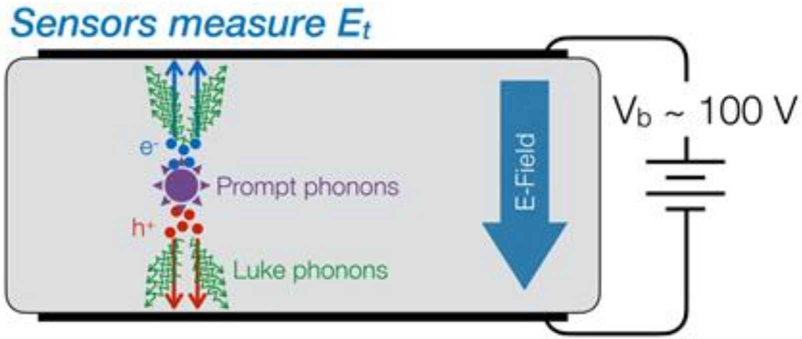


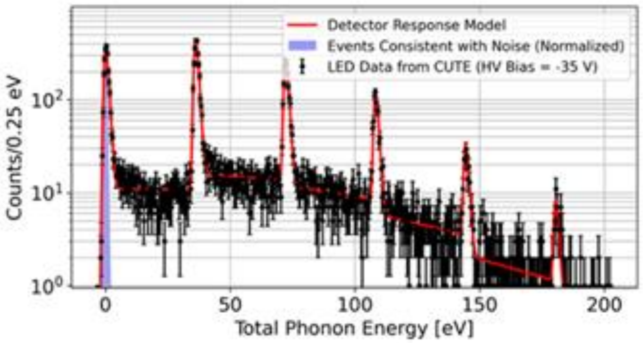




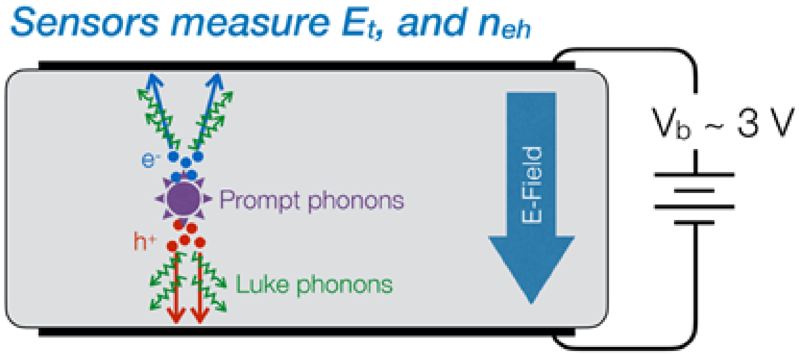
TES FOR DARK MATTER

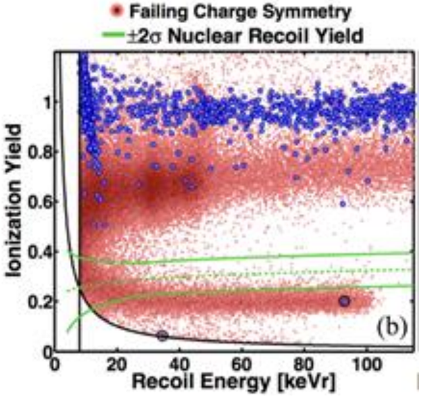
SuperCDMS





NIMA 1091 (2026) 171753

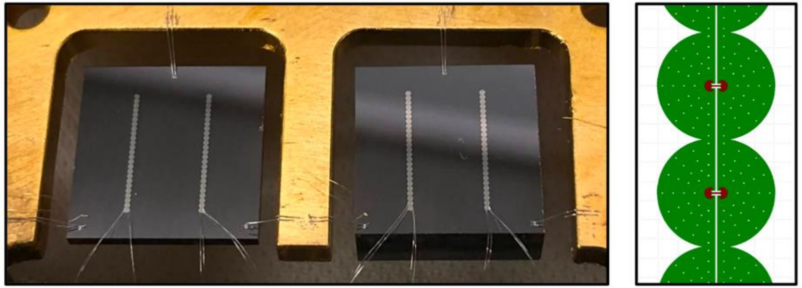




Phys. Rev. D 95, 082002 (2017)

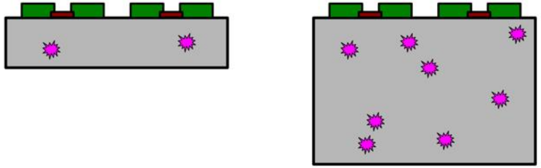
TES FOR DARK MATTER

TESSERACT



1 mm thick detector

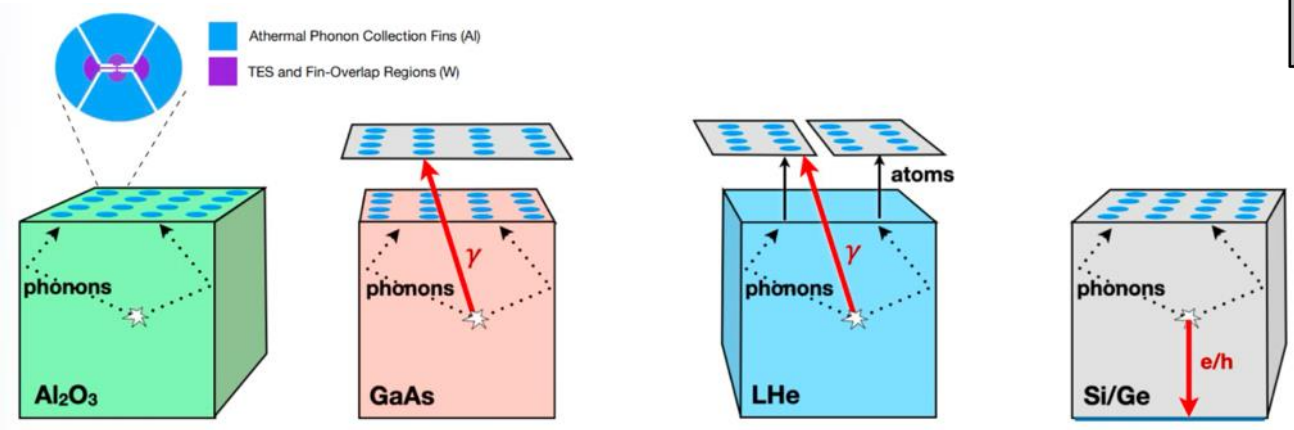
4 mm thick detector



Aluminum Phonon Collection Fins

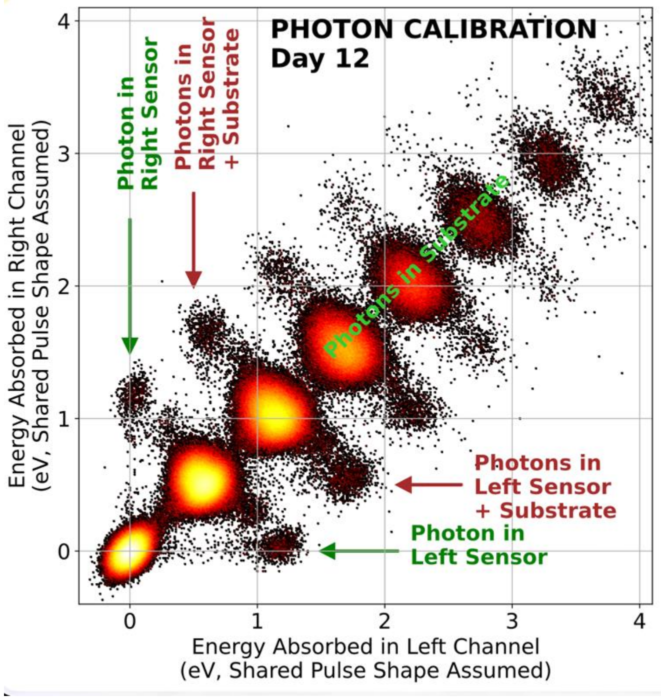
Tungsten TESs

Silicon Detector Substrate

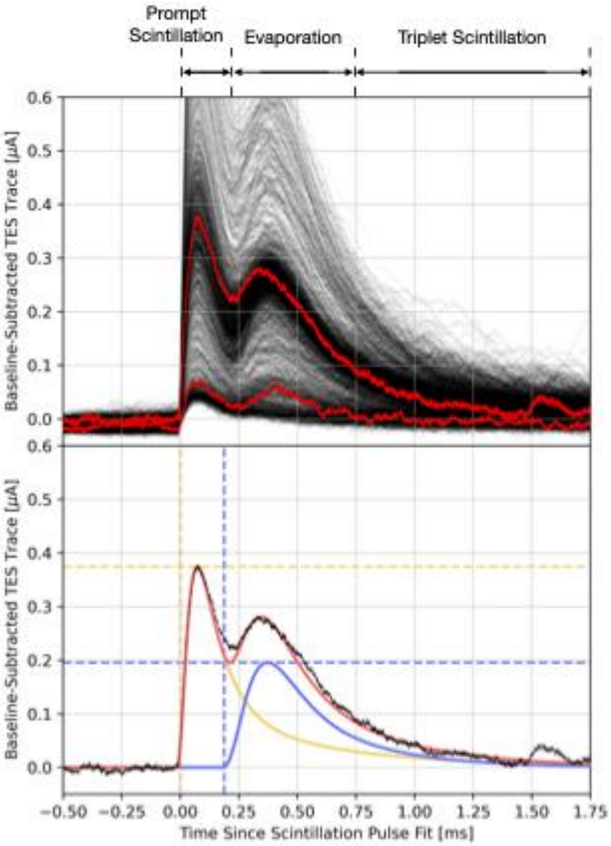


TES FOR DARK MATTER

TESSERACT



Appl. Phys. Lett. 127, 263502 (2025)



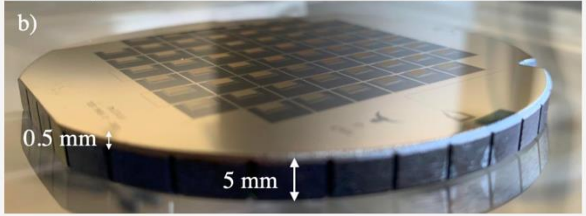
Phys. Rev. D 110, 072006

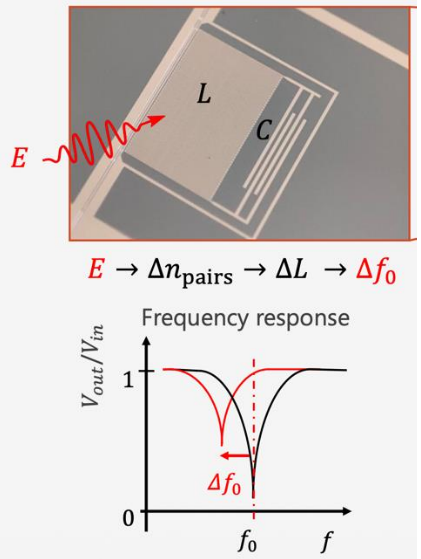
MKIDS FOR DARK MATTER

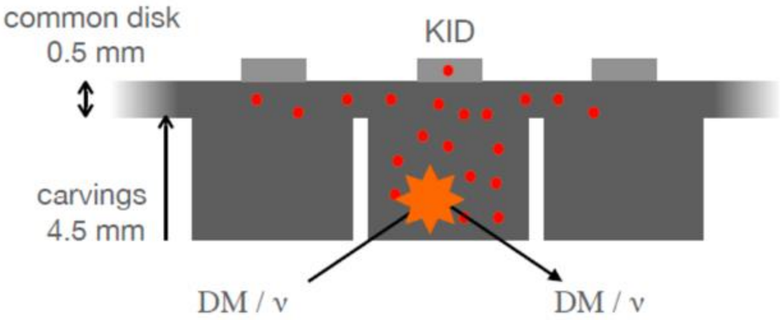
BULLKID

Diced silicon absorber

KID array on the other side of the wafer hosting 60 resonators (60 nm Al)





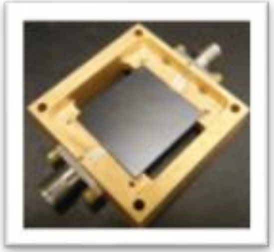


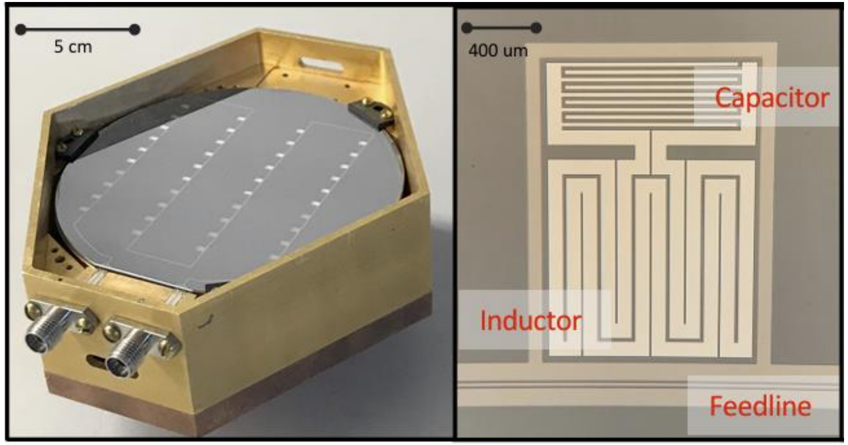
Appl. Phys. Lett. 121, 213504 (2022)

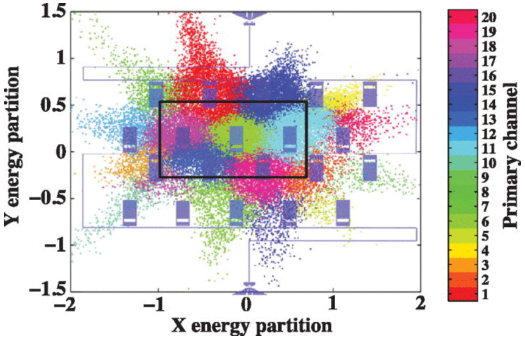
IEEE Transactions on Applied Superconductivity, vol. 36, no. 6, pp. 1-8, Sept. 2026, Art no. 1500408

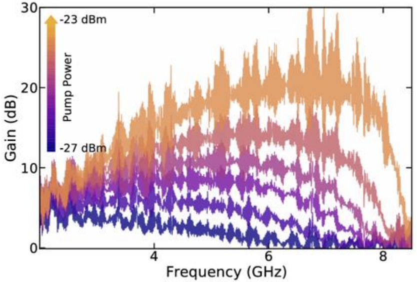
MKIDS FOR DARK MATTER

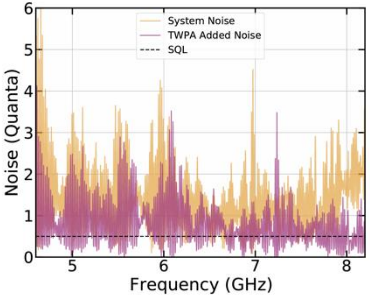
KIPM





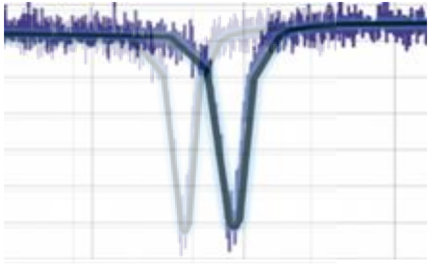




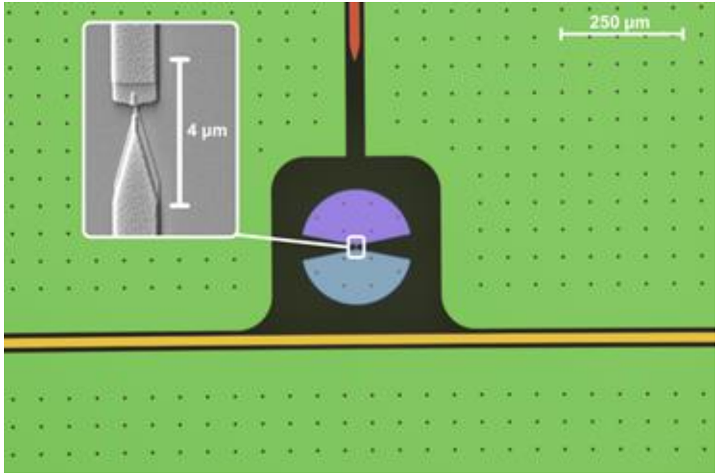


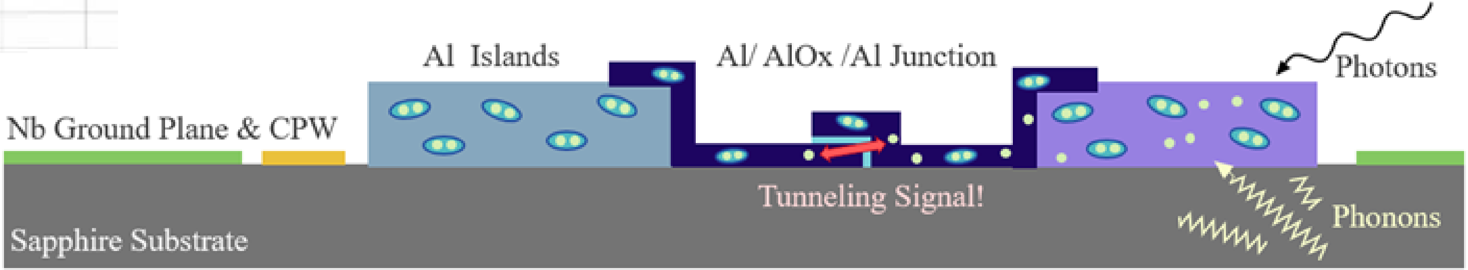
QUBITS FOR DARK MATTER

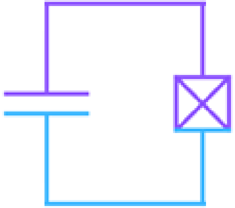
SQUAT

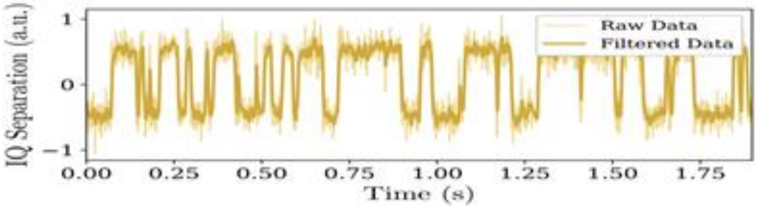


Frequency





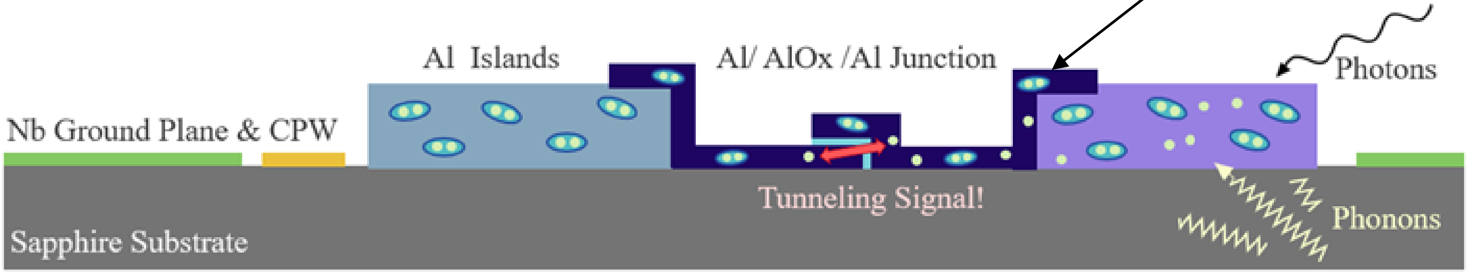




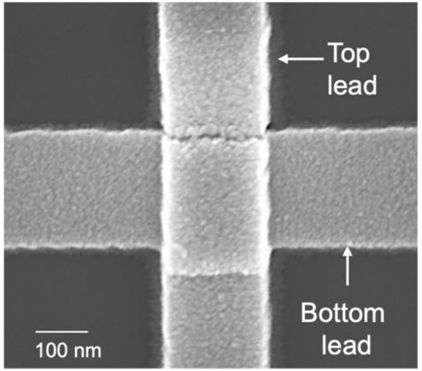
arXiv:2601.16261

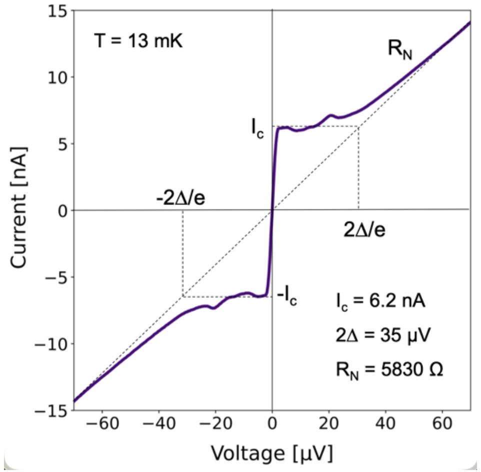
QUBITS FOR DARK MATTER

SQUATs



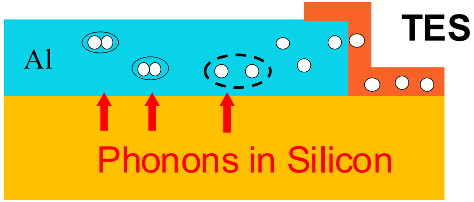
Lower gap (Tc)

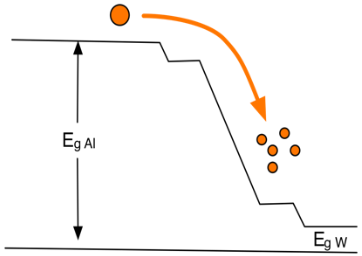


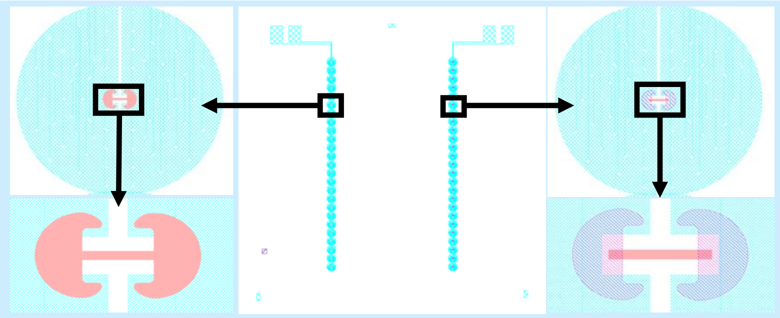


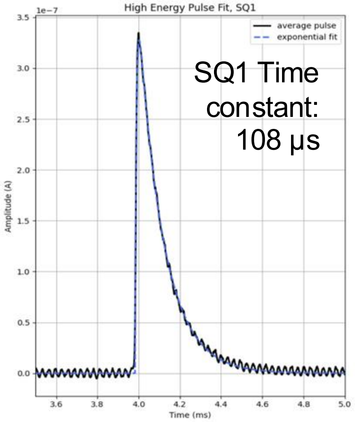
arXiv:2510.25203

QP DOWNCONVERSION IN LOWER TC TRAPS

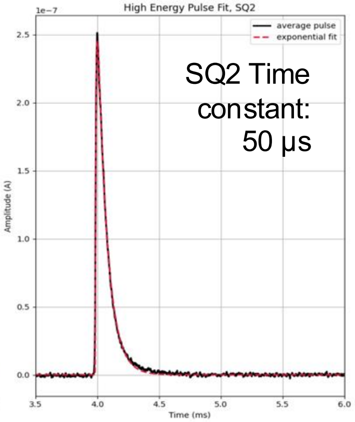




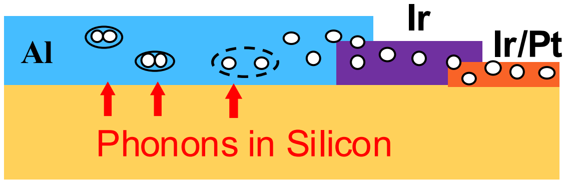


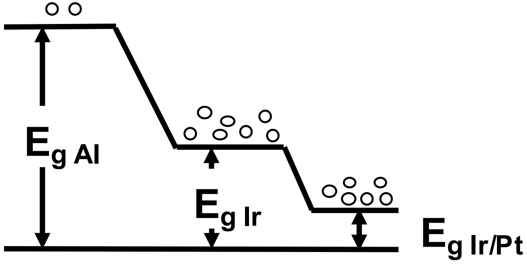


SQ1 Time constant: 108 μs



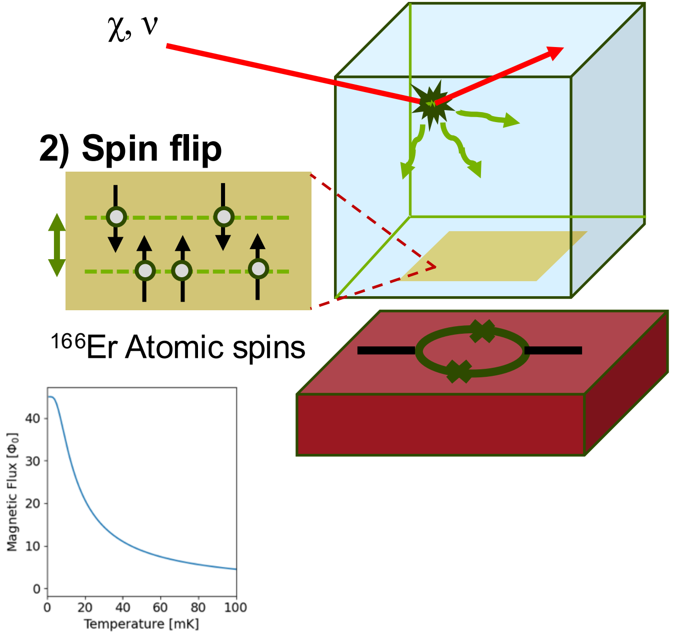
SQ2 Time constant: 50 μs





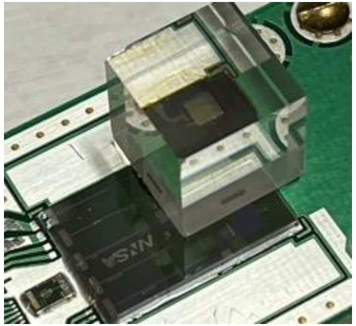
SQUIDS FOR DARK MATTER

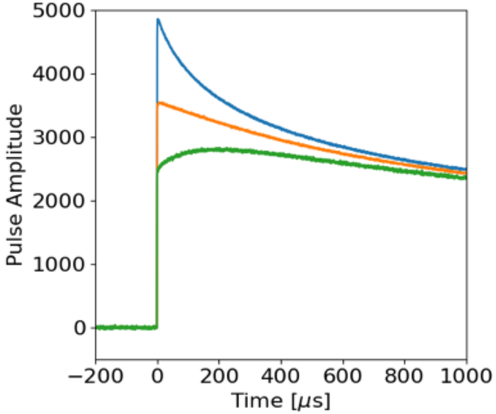
MMC



2) Spin flip

^{166}Er Atomic spins



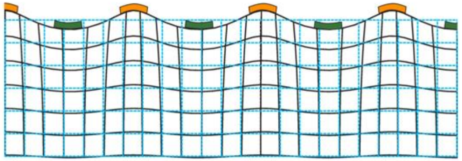


Physical Review D 111.7 (2025): 072009.

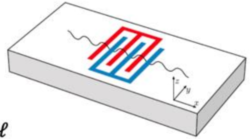
QUBITS FOR DARK MATTER

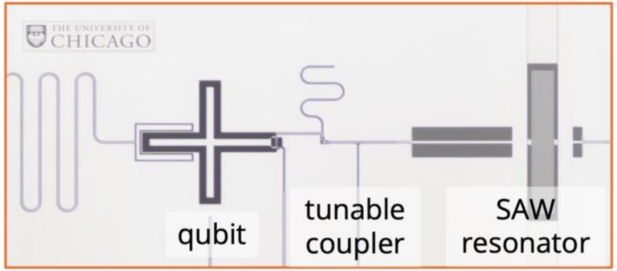
Quantum Acoustics

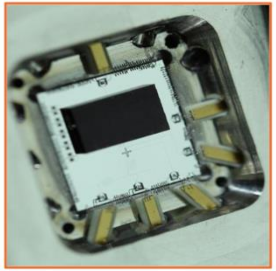
Nature volume 563, pages661–665 (2018)

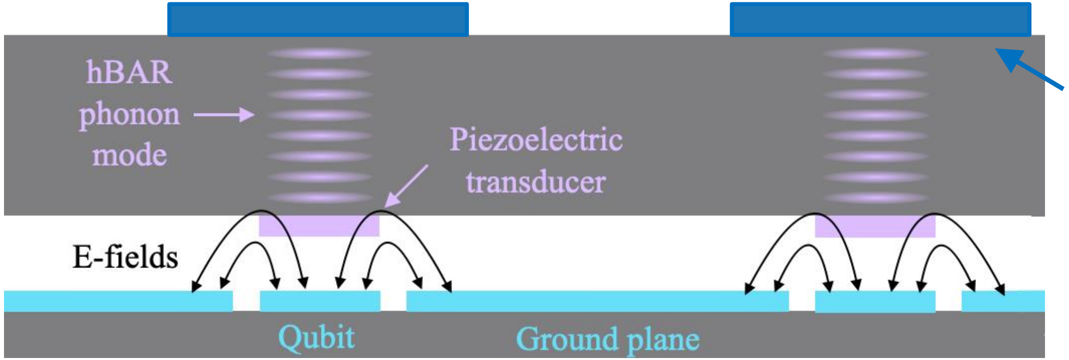


$v_{saw} < v_t, v_\ell$







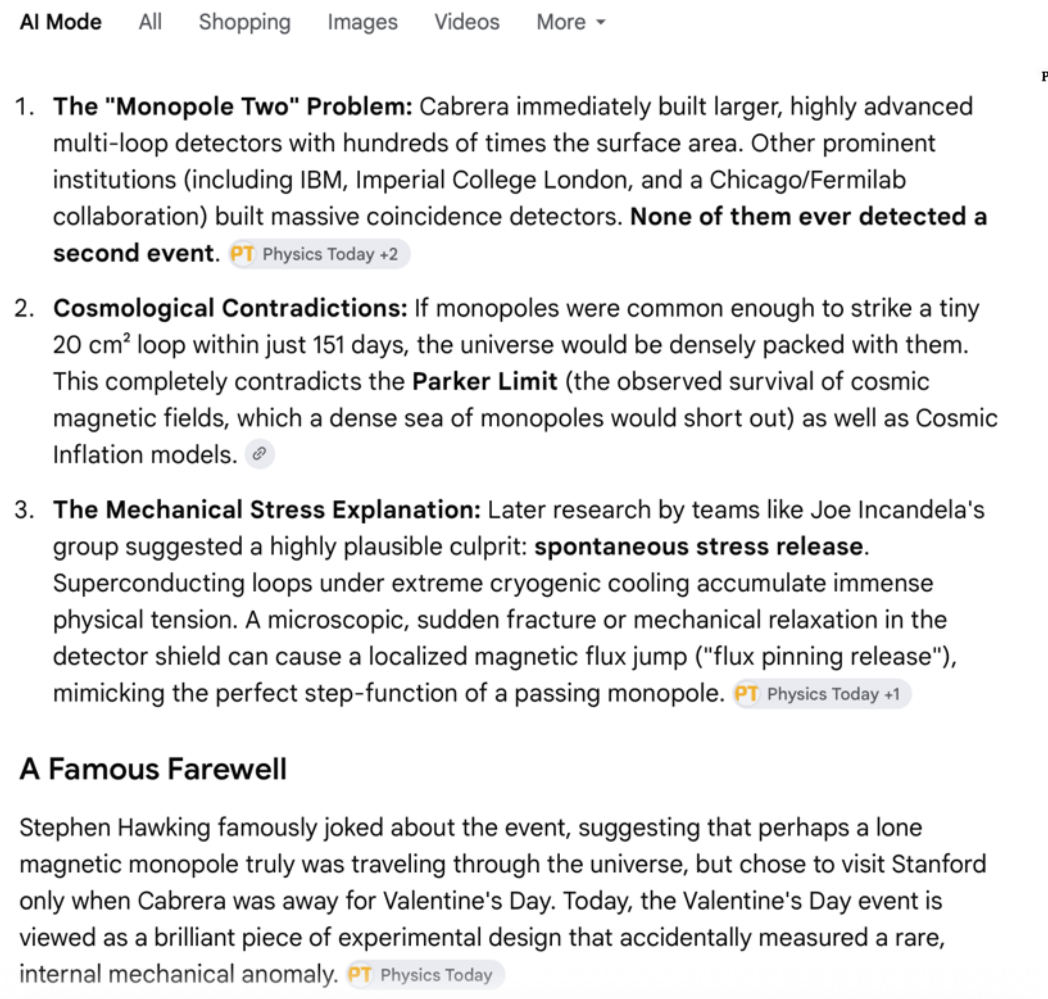


Small gap SC films

Phys. Rev. D 112, 115005

SUPERCONDUCTING DEVICES FOR QUANTUM PARTICLE DARK MATTER

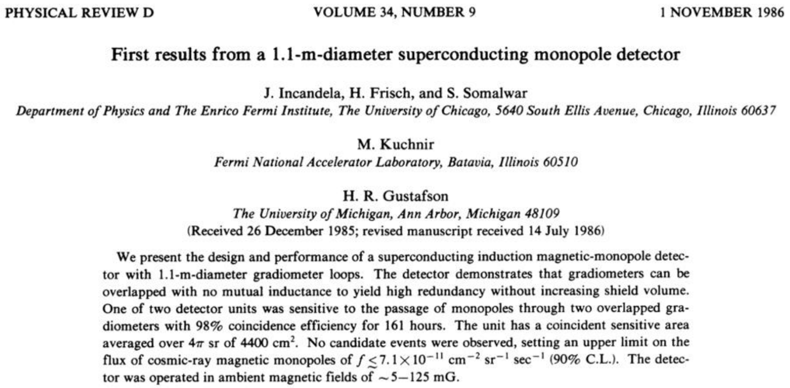
Quantum state	Transition to zero resistance	Pairing/bandgap
SQUIDs, JPA, JTWPA	TES for PNRD	MKIDs for PNRD
Qubits	SNSPDs	KI-TWPA
MMC SQUAT SAW/HBAR	Qrocodile CRESST SuperCDMS (HVeV) TESSERACT	BULLKID KIPM+KITWPA



1. **The "Monopole Two" Problem:** Cabrera immediately built larger, highly advanced multi-loop detectors with hundreds of times the surface area. Other prominent institutions (including IBM, Imperial College London, and a Chicago/Fermilab collaboration) built massive coincidence detectors. **None of them ever detected a second event.** PT Physics Today +2
2. **Cosmological Contradictions:** If monopoles were common enough to strike a tiny 20 cm^2 loop within just 151 days, the universe would be densely packed with them. This completely contradicts the **Parker Limit** (the observed survival of cosmic magnetic fields, which a dense sea of monopoles would short out) as well as Cosmic Inflation models.
3. **The Mechanical Stress Explanation:** Later research by teams like Joe Incandela's group suggested a highly plausible culprit: **spontaneous stress release**. Superconducting loops under extreme cryogenic cooling accumulate immense physical tension. A microscopic, sudden fracture or mechanical relaxation in the detector shield can cause a localized magnetic flux jump ("flux pinning release"), mimicking the perfect step-function of a passing monopole. PT Physics Today +1

A Famous Farewell

Stephen Hawking famously joked about the event, suggesting that perhaps a lone magnetic monopole truly was traveling through the universe, but chose to visit Stanford only when Cabrera was away for Valentine's Day. Today, the Valentine's Day event is viewed as a brilliant piece of experimental design that accidentally measured a rare, internal mechanical anomaly. PT Physics Today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First results from a 1.1-m-diameter superconducting monopole detector

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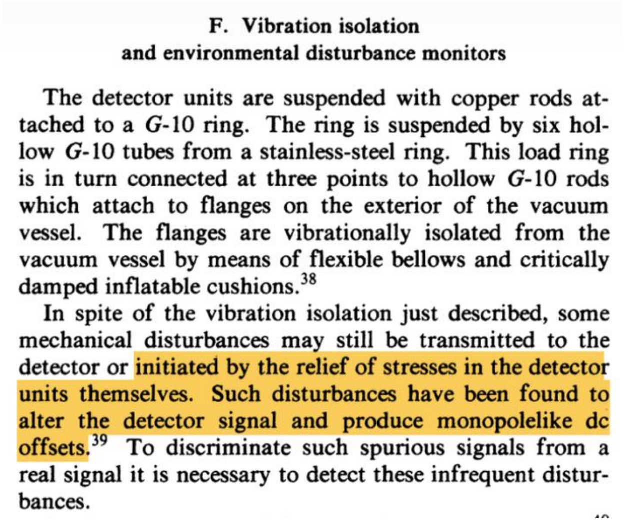
We present the design and performance of a superconducting induction magnetic-monopole detector with 1.1-m-diameter gradiometer loops. The detector demonstrates that gradiometers can be overlapped with no mutual inductance to yield high redundancy without increasing shield volume. One of two detector units was sensitive to the passage of monopoles through two overlapped gradiometers with 98% coincidence efficiency for 161 hours. The unit has a coincident sensitive area averaged over 4π sr of 4400 cm^2. No candidate events were observed, setting an upper limit on the flux of cosmic-ray magnetic monopoles of $f \lesssim 7.1\times10^{-11}$ cm^{-2} sr^{-1} sec^{-1} (90% C.L.). The detector was operated in ambient magnetic fields of ~5–125 mG.


F. Vibration isolation and environmental disturbance monitors

The detector units are suspended with copper rods attached to a *G*-10 ring. The ring is suspended by six hollow *G*-10 tubes from a stainless-steel ring. This load ring is in turn connected at three points to hollow *G*-10 rods which attach to flanges on the exterior of the vacuum vessel. The flanges are vibrationally isolated from the vacuum vessel by means of flexible bellows and critically damped inflatable cushions.[38]

In spite of the vibration isolation just described, some mechanical disturbances may still be transmitted to the detector or initiated by the relief of stresses in the detector units themselves. Such disturbances have been found to alter the detector signal and produce monopolelike dc offsets.[39] To discriminate such spurious signals from a real signal it is necessary to detect these infrequent disturbances.

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