Quantum Sensing Approaches to Fundamental Physics Searches

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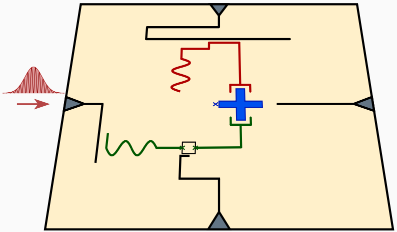
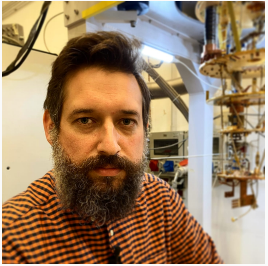
INFN Istituto Nazionale di Fisica Nucleare

CSN5 Technological research



A Few Words About Myself



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Project Leader and Coordinator

- Longstanding experience in experiments for neutrino and rare event physics (HOLMES, CUORE, CUPID, PTOLEMY, etc.);
- Former visiting faculty at the University of Colorado Boulder and the National Institute of Standards and Technology (NIST);
- PI and co-PI of projects in quantum sensing and quantum computing (DARTWARS, DARTWARS-MSCA, Qub-IT, QUART&T MiSS);

#nikhef50 Happy Birthday

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🎂 Buon compleanno, **Nikhef (National Institute for Subatomic Physics)**!
Dalle onde gravitazionali alla fisica delle particelle: la collaborazione tra l'INFN e NIKHEF è sempre più solida. Insieme, lavoriamo a Virgo, il rivelatore dell'Osservatorio Gravitazionale Europeo, che ci permette di osservare minuscole vibrazioni dello spaziotempo, le **#ondegravitazionali**, ai principali esperimenti del **CERN**, che hanno portato alla scoperta del **#BosoneDiHiggs**, e all'esperimento **KM3NeT Neutrino**, che ci ha permesso di osservare la particella elementare più energetica di sempre. E siamo sicuri che il nostro futuro insieme sarà ricco di nuove avventure e scoperte. I nostri più sentiti auguri alle colleghe e ai colleghi di NIKHEF! **#nikhef50**

🎂 Happy birthday, NIKHEF!
From gravitational waves to particle physics: the collaboration between INFN and NIKHEF is growing ever stronger. Together, we work on Virgo, the detector of the European Gravitational Observatory, which allows us to observe tiny ripples in spacetime, the **#gravitationalwaves**; on the main experiments at CERN, which led to the discovery of the **#HiggsBoson**, and on the KM3NeT experiment, which detected the most energetic elementary particle ever observed.
We are confident that our future together will be full of new adventures and discoveries. Our warmest wishes to all our colleagues at NIKHEF!

🎂 Gelukkige verjaardag, NIKHEF!
Van zwaartekrachtsgolven tot deeltjesfysica: de samenwerking tussen INFN en NIKHEF wordt steeds hechter. Samen werken we aan Virgo, de detector van het European Gravitational Observatory, die ons in staat stelt piepkleine rimpelingen in de ruimtetijd waar te nemen — de **#zwaartekrachtsgolven** — aan de belangrijkste experimenten van CERN, die hebben geleid tot de ontdekking van het **#HiggsBoson**, en aan het KM3NeT experiment, dat ons heeft geholpen het meest energetische elementaire deeltje ooit waar te nemen.
We zijn ervan overtuigd dat onze gezamenlijke toekomst rijk zal zijn aan nieuwe avonturen en ontdekkingen. Onze hartelijke felicitaties aan alle collega's van NIKHEF!

Nikhef 50 Years Young

Nikhef
50

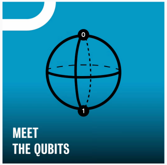
Happy Birthday Nikhef 🎂

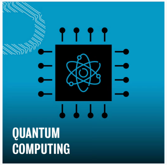
Quantum Information Science and Technology

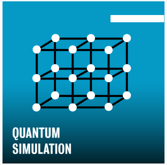
Quantum Information Science and Technology (QIST) is an interdisciplinary field that studies how information is represented, processed, transmitted, and measured using the principles of quantum mechanics.

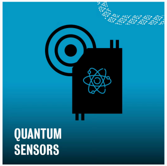
It brings together ideas from physics, computer science, mathematics, and engineering to develop new paradigms for:

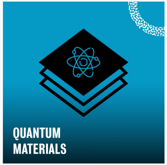
- **Computation:** exploiting quantum bits (qubits) and superposition to solve certain problems exponentially faster;
- **Communication:** ensuring secure information transfer via quantum entanglement and quantum key distribution;
- **Simulation:** modeling complex quantum systems beyond classical capabilities.
- **Sensing and Metrology:** achieving high-precision measurements using quantum coherence and entanglement;

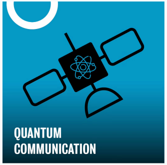










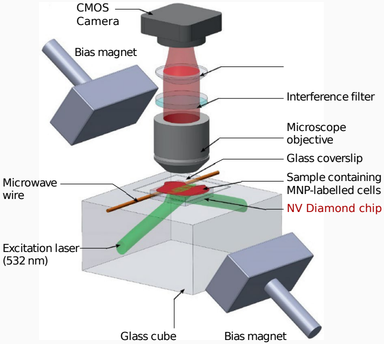


Quantum sensors exploit uniquely quantum properties such as superposition, entanglement, and quantum coherence to perform measurements with ultra-high precision and sensitivity.

They are essential in applications ranging from fundamental physics to navigation, medicine, and materials science.

Examples of quantum sensors:

- **NV centers in diamond:** sensitive magnetometers and electric field sensors;
- **Atomic vapor magnetometers:** ultra-sensitive magnetic field detectors;
- **SQUIDs:** measure extremely small magnetic flux with high precision;
- **Atom interferometers:** used for gravimetry and inertial navigation;
- **Optomechanical sensors:** detect tiny forces and displacements;
- **Superconducting qubits:** used as sensors in dark matter and photon detection.

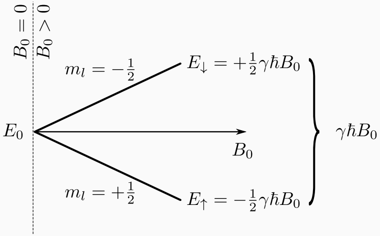


Nat. Rev. Phys. 5, 157–169 (2023)

Quantum sensing is typically used to describe one of the following:

- Use of a quantum object to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized energy levels;

$$H = \frac{\hbar\omega_0}{2}\sigma_z + \hbar\gamma B_0 \sigma_z,$$

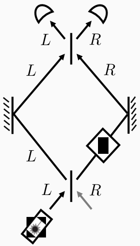


- Use of quantum coherence (i.e., wave-like spatial or temporal superposition states) to measure a physical quantity;

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + e^{i\phi(t)}|1\rangle\right)$$

- Use of quantum entanglement to improve the sensitivity or precision of a measurement, beyond what is possible classically

$$|\mathrm{GHZ}\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle^{\otimes N} + |1\rangle^{\otimes N}\right)$$



defitinions from Rev. Mod. Phys. 89, 035002 (2017)

Quantum sensing is becoming increasingly relevant in High-Energy Physics, where detecting faint and rare signals requires unprecedented sensitivity and quantum-limited measurements.

Quantum-enhanced approaches in HEP include (incomplete list):

- **Pair-breaking detectors:** detect energy deposition via the breaking of Cooper pairs in superconductors;
  $\Rightarrow$ quantum statistics of quasiparticles and macroscopic quantum coherence.
- **Quantum-limited amplifiers (e.g., TWPAs, JPAs):** boost weak signals in cryogenic microwave detectors;
  $\Rightarrow$ quantum squeezing, parametric amplification, and vacuum noise engineering.
- **Entangled probes:** proposed for precision measurements in clock comparisons and searches for time-variation of constants (e.g. Gravitational wave detection);
  $\Rightarrow$ quantum entanglement to surpass the Standard Quantum Limit and approach the Heisenberg Limit
- **Atomic interferometry:** used in gravimetry and inertial sensing;
  $\Rightarrow$ matter-wave interference and superposition of motional quantum states.
- **Superconducting qubits and resonators:** used as single-photon detectors in axion and dark photon searches;
  $\Rightarrow$ quantum coherence and discrete energy levels.

Table from
Quantum Sensors for High Energy Physics
arxiv.org/abs/2311.01930

Technology	Dark waves	Dark particles	Cosmology, dark energy, phase transitions	Testing quantum mechanics	Quantum gravity	Telescope	Collider, fixed target, high event rate	Symmetry violations
SC qubits, SC cavities, SC continuous variables (JPAs, RQUs, KI-TWPAs, etc), squeezing, transduction	■	■		■				■
SC pairbreaking sensors (QCD, TES, MKID, SNSPD)	■	■	■		■	■	■	
Microcalorimetry, single phonon		■						
AMO, clocks, atom and photon interferometry	■	■	■	■	■	■		■
NMR	■	■	■					■
Optomechanics (squeezing, back-action evasion, etc)	■	■		■	■			
Quantum networks	■		■			■		
Sensor arrays, high channel count	■	■	■			■	■	
Quantum materials, metamaterials	■	■				■		

Proposal on R&D on quantum sensors: the DRD5/RDq proto-collaboration

(signatory list in section 13.2)

ABSTRACT

The detector R&D roadmap initiated by ECFA in 2020 highlighted the large number of particle physics opportunities that targeted and collaborative R&D in the field of quantum sensors and related technologies can enable. The involved communities and the roadmap's Task Force 5 (TF5) have established a list of the most promising areas for investment and defined the R&D that would be needed to bring these to the level at which experiments building on them can be envisaged. This proposal lays out the resulting high level work packages with deliverables and milestones and proposes the structure of a collaboration (the DRD5 / RDq collaboration) that would enable such R&D to be pursued at a global scale.

cds.cern.ch/record/2901426/files

- Investigate how quantum sensors (e.g., single-photon detectors, squeezed light, atom interferometry, superconducting devices) can be applied to HEP experiments.
- Support synergies between the HEP community and the rapidly growing quantum technology field.
- Enable cross-disciplinary R&D, including collaboration with national quantum initiatives, universities, and technology providers.
- Explore quantum-enhanced detection techniques for applications such as dark matter searches, neutrino physics, and precision measurements.

The **INFN** and **University of Milano-Bicocca (Unmib)** are actively involved in the development of advanced quantum sensing technologies for fundamental physics.

Key research activities include:

- **Pair-breaking detectors:** ultra-sensitive calorimetric sensors for rare event detection (e.g., neutrino mass, dark matter);
- **Quantum-limited amplifiers:** development of traveling-wave parametric amplifiers for low-noise microwave readout in fundamental physics experiments;
- **Superconducting qubits:** devices operated as sensors and platforms for quantum-enhanced measurements of light dark matter.

These technologies are at the core of current and future experiments aiming to probe physics beyond the Standard Model.

This seminar will focus on these quantum-enhanced technologies, with emphasis on ongoing developments at INFN and Unimib.

MARIE CURIE ACTIONS
GA: 101027746

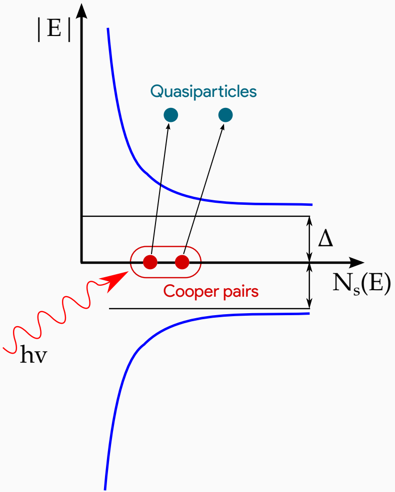
Quantum sensing includes technologies where the quantization of light and matter plays a fundamental role.

Single-Photon Detection
Operate by detecting energy deposited by photons or particles, breaking Cooper pairs in a superconductor.

$$|n\rangle \xrightarrow{h\nu > 2\Delta} |n+1\rangle \quad \Rightarrow \quad \text{quasiparticles}$$

Examples of pair-breaking detectors:

- **TESs** (Transition-Edge Sensors): measure resistance change at the superconducting transition.
- **MKIDs** (Microwave Kinetic Inductance Detectors): measure changes in kinetic inductance due to quasiparticles.
- **SNSPDs** (Superconducting Nanowire Single-Photon Detectors): detect localized Cooper pair disruption by photon absorption, creating resistive hotspots.

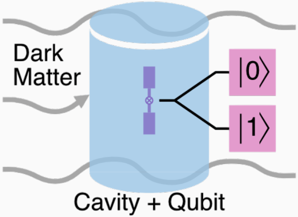


Applications: single-photon counting, cosmic microwave background studies, X-ray and gamma-ray astronomy, dark matter and neutrino detection.

Qubits act as highly sensitive two-level quantum systems whose states can be perturbed by extremely weak classical or quantum fields.

Examples of target signals:

- Electromagnetic signals induced by axions or dark photons
- Phase shifts generated by gravitational waves
- Couplings from hidden-sector interactions



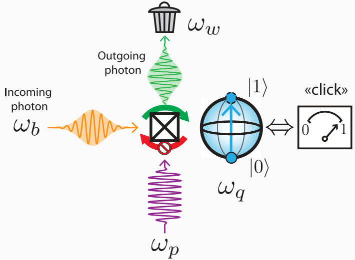
Example: Dispersive qubit readout coupled to a resonator tuned to the axion conversion frequency.

Measurement based on the effective Hamiltonian:

$$H = \frac{1}{2}\hbar\omega_q\sigma_z + \hbar g\, a^\dagger a\, \sigma_z \quad \xrightarrow{\text{photon}} \quad \delta\omega_q = g\langle a^\dagger a\rangle$$

where the signal alters the average photon number $\langle a^\dagger a\rangle$, shifting the qubit frequency.

Requires quantum-limited amplifiers (e.g., JPAs, TWPAs) for high-fidelity readout of extremely low-energy excitations.



Quantum-Limited Amplification
These are not quantum sensors, but they rely on quantum mechanics to amplify weak signals with minimal noise and preserve quantum coherence during measurement.

Key devices:

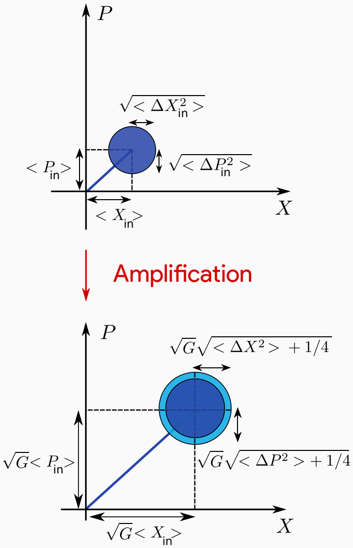
- **Josephson Parametric Amplifiers (JPAs):** resonant devices, quantum limited, high gain over narrow bandwidths.
- **Traveling Wave Parametric Amplifiers (TWPAs):** nonlinear transmission lines, near quantum limited, broadband, wide frequency coverage.

Fundamental noise limit:

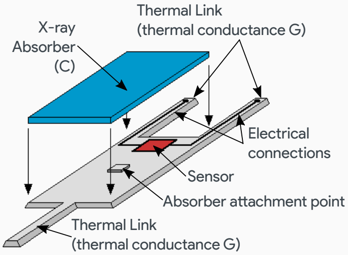
$$n_{\text{added}} \geq \frac{1}{2} \quad \text{(for phase-insensitive amplifiers)},$$

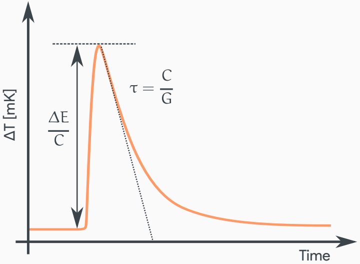
Applications:

- Qubit state readout in superconducting quantum processors.
- Detection of extremely weak signals in fundamental physics experiments (e.g., axion haloscopes, dark matter searches).

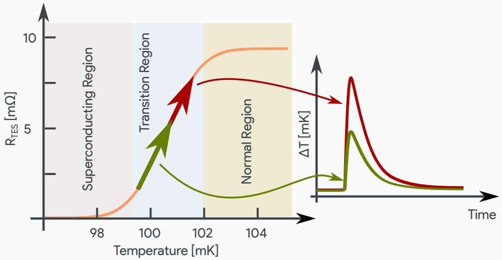


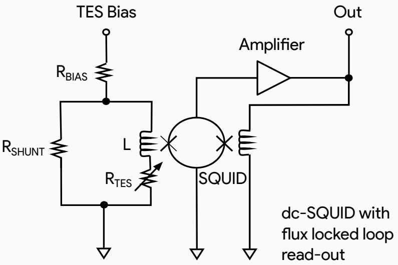
Transtion Edge Sensor for Quanta Measurement



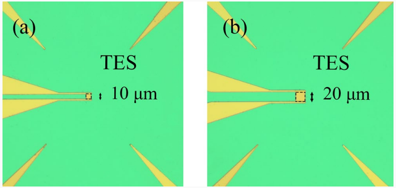


- A low-temperature calorimeter senses the heat generated by a photon (particle) absorbed and thermalized in an element with very low heat capacity.
- Complete energy thermalization: ionization, excitation $\Rightarrow$ heat (mostly via phonons) $\Rightarrow$ calorimetry
- $\Delta T = \Delta E / C$, where ΔE is the deposited energy and C the total heat capacity:
  - Absorber with very low heat capacity: $C \downarrow \quad \Rightarrow \quad \Delta T \uparrow$
  - Debye law for superconductors below T_C and dielectrics: $C \propto (T/\Theta_D)^3$
  - Very low temperatures are required: $T \downarrow \Rightarrow C \downarrow \Rightarrow \Delta T \uparrow \Rightarrow \quad T = 10\text{–}100$ mK
- Fundamental limit to energy resolution: statistical fluctuation of internal energy $\Rightarrow \quad \Delta E_{rms} = \sqrt{k_B T^2 C}$

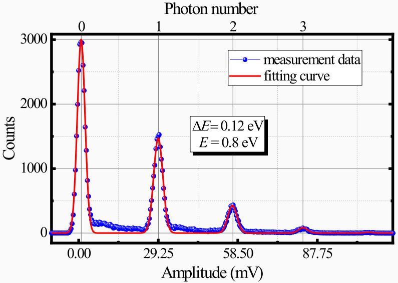




- Superconductor biased in its transition region $\Rightarrow$ strongly temperature-dependent resistance;
- “Self-biased” operation $\Rightarrow$ the power dissipated in the device remains constant under bias;
  - Electrothermal feedback: if $R_{TES} \uparrow \Rightarrow I_{TES} \downarrow \Rightarrow P_J \downarrow \Rightarrow$ device cools back to equilibrium;
- Very low resistance $\Rightarrow$ read out with SQUIDs (Superconducting Quantum Interference Devices);
  - TES is in series with an input coil L, inductively coupled to the SQUID;
  - Changes in TES current $\Rightarrow$ changes in magnetic flux through the SQUID;
- SQUID-based multiplexing $\Rightarrow$ readout of many detectors with fewer amplifier channels;
- Pair-breaking detectors: energy from Cooper-pair breaking thermalizes in the absorber $\Rightarrow$ temperature rise.



Courtesy of INRiM



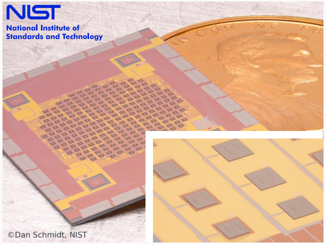
IEEE Trans. Appl. Supercond., 34(3), 3350569 (2024)

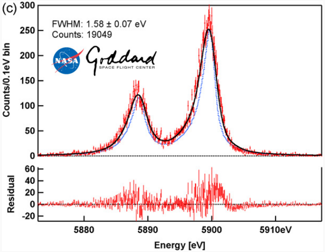
Transition Edge Sensors (TES) provide excellent photon-number resolution making them ideal for quantum optics and quantum communication.

- High detection efficiency (>95%) in the optical and near-infrared range;
- Ultra-low dark count rate $\Rightarrow$ high fidelity in photon counting;
- Energy-resolving capability allows discrimination of multi-photon states;

$$\Delta E_{\mathrm{FWHM}} = 0.12\text{ eV @ }0.8\text{ eV} \quad (1550\text{ nm})$$

- Time resolution of a few μs, sufficient for many quantum optics applications;
- Used in Quantum optics, Quantum Communication and Quantum key distribution (QKD), Photonic quantum computing, Quantum metrology, ...





J. Appl. Phys. 128, 224501 (2020)

Transition Edge Sensors (TES) are used in quantum calorimeters to detect the tiny energy deposited by single quantum events (e.g., photon or particle absorption).

- Widely supported by the X-ray astrophysics community, as well as in dark matter and rare-event searches;
- Small size $\Rightarrow$ low heat capacity C $\Rightarrow$ excellent energy resolution:

$$\Delta E_{\text{FWHM}} = \begin{cases} 1.26\text{ eV @ }1.5\text{ keV} \\ 1.58\text{ eV @ }6\text{ keV} \\ 1.94\text{ eV @ }8\text{ keV} \end{cases}$$

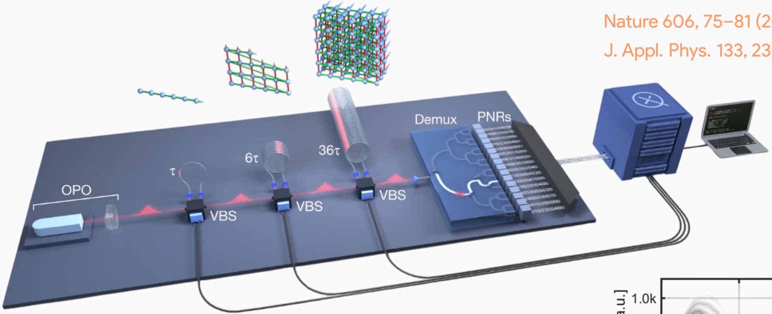
- Negative electrothermal feedback ensures fast time response and prevents thermal runaways;
- Large arrays ($> 10^3$–10^5 pixels) deployed in astrophysical applications.

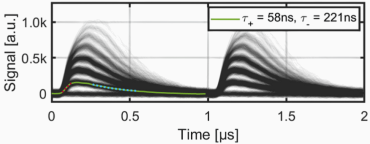
XANADU

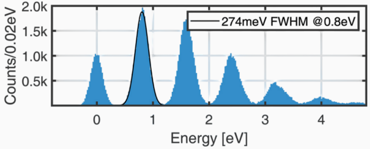
National Institute of Standards and Technology

Nature 606, 75–81 (2022).

J. Appl. Phys. 133, 234502 (2023)







- A single laser light source (i.e quantum dot) generates pairs of photonic qubits;
- Qubits then pass through a single gate that consists of a maze of interferometers
- Programmable interferometers implements quantum gate sequence on the qubit;
- A photon-number resolving TES detectors array measures the finale qubit states;
- Quantum Advantage by demonstrated in 2022 for a specific task;

TES detectors can be read out using **resonator-based microwave multiplexing**:

- The current variations in the TES circuit are translated into shifts in the resonance frequency of a microwave resonator;
- Efficiently reduces wiring complexity at cryogenic temperatures;
- Enables scalable readout of large TES arrays.

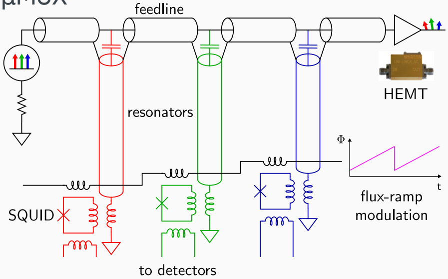
μMUX (Microwave SQUID Multiplexing):

- Each TES is coupled to an rf-SQUID and a high-Q microwave resonator;
- Resonators are tuned to different frequencies $\Rightarrow$ multiplexed in frequency domain;
- A single feedline reads out hundreds of channels simultaneously.

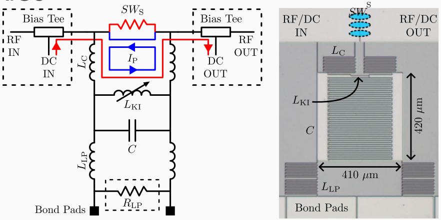
KICS (Kinetic Inductance Coupled Systems) 🚀:

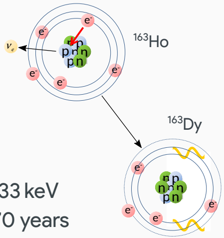
- TES current modulates a superconducting resonator via kinetic inductance;
- Similar multiplexing principle to MKIDs, adapted to TES readout;
- Passive and compact architecture with low cross-talk.

µMUX

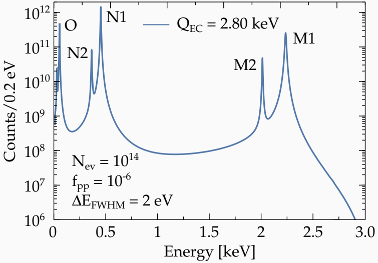


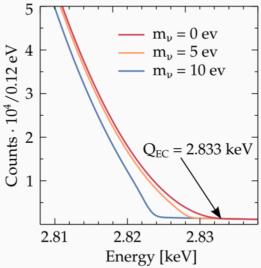
KICS





$Q_{EC} = 2.833$ keV
$\tau_{1/2} \simeq 4570$ years





- Electron capture from shell $\geq$ M1 $\Rightarrow$ $^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e(E_c)$;
- End-point shaped by $\sqrt{(Q - E_e)^2 - m_\nu^2}$ (the same of the β-decay);
- Searching for a tiny deformation caused by a non-zero neutrino mass to the spectrum near its end point;
- Calorimetric measurement of Dy atomic de-excitations (mostly non-radiative)

  $\Rightarrow$ measurement of the entire energy released except the ν energy;

proposed for the first time
by A. De Rujula e M. Lusignoli in 1982
Phys. Lett. 118B (1982) 429
Nucl. Phys. B219 (1983) 277-301

more details on A. Nucciotti
Adv. High En. Phys. 2016 (2016) 9153024
and M. Galeazzi *et al.*
arXiv:1202.4763 [physics.ins-det]

NIST

Boulder, CO, USA

- Detectors design
- Detectors fabrication
- Readout development

PAUL SCHERRER INSTITUT — PSI

Villigen, Switzerland

- Chemical purification
- Chemical separation

ILL — NEUTRONS FOR SOCIETY

Grenoble, France

- Isopote production

INFN — Istituto Nazionale di Fisica Nucleare / Università degli Studi di Milano Bicocca

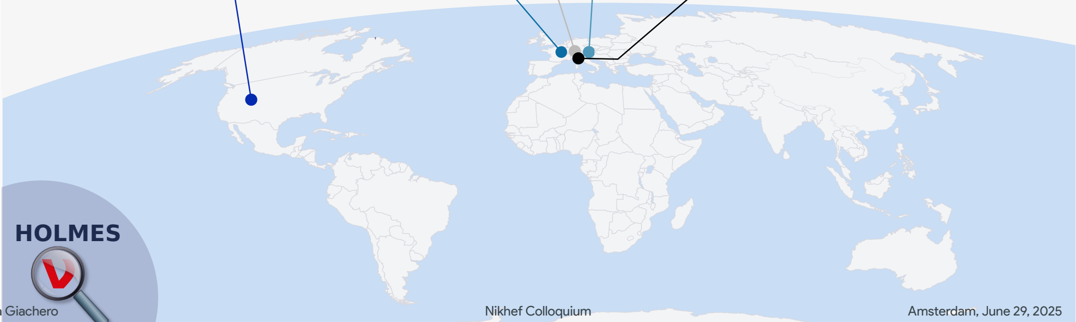
Milan, Italy

- Deposition chamber
- Detector characterization
- Readout development
- Data taking
- Data Analysis
- Management

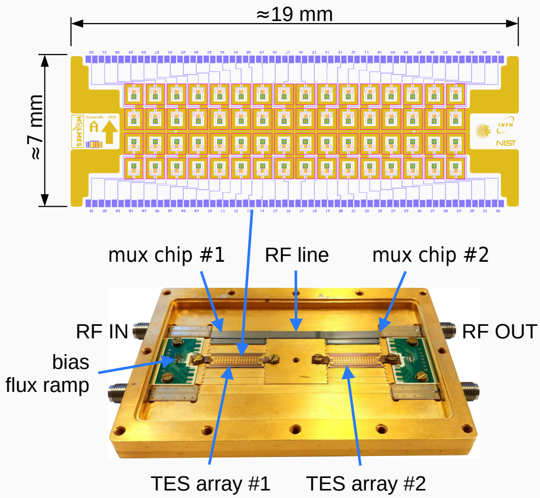
INFN — Istituto Nazionale di Fisica Nucleare / Università di Genova

Genoa, Italy

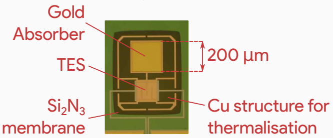
- Isotope Implantation
- Ion Source development
- Sputtered Target
- Data Analysis
- Management



HOLMES

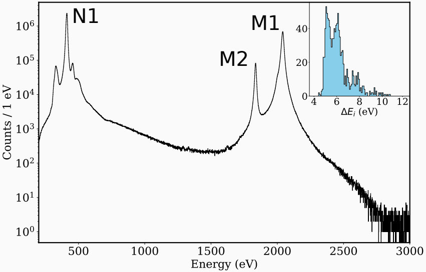


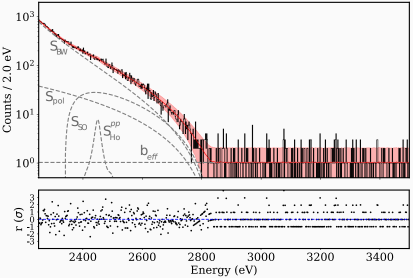
Single Pixel
(real photo)



- 64 TES pixels with ^{163}Ho implanted into the detector absorber;
- 52 active pixels, with an average activity of $\langle A \rangle = 0.325$ Bq;
- Energy resolution of $\Delta E_{\text{FWHM}} = (4.2 \pm 0.1)$ eV at the Mn Kα X-ray peak;
- Readout performed using two 32-channel μMUX chips;

arxiv.org/abs/2506.13665 submitted to EPJC





- First phase concluded in 2024 with a demonstrator array of 64 pixels;
- A total of $7 \cdot 10^7$ decay events recorded over two months;
- Upper limit on the neutrino mass:

$$m_\beta < 27\,\mathrm{eV}/c^2 \quad \text{(90\% credibility)}$$

- Strongest bound ever achieved on the neutrino mass from the EC decay of ^{163}Ho;
- Still far from the $0.45\,\mathrm{eV}/c^2$ limit reached by classical mass spectrometry,
  but based on a more scalable technique;
- The next phase will employ 256 implanted TES detectors;
- Final goal: a next-generation experiment with a larger number of pixels, aiming for sub-0.1 eV sensitivity.

arxiv.org/abs/2503.19920, accepted in PRL

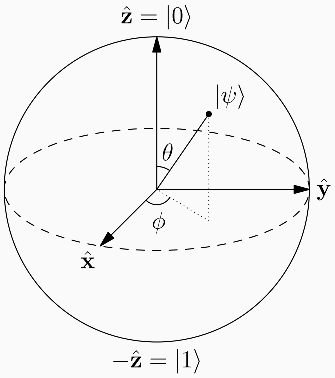
Qubits as Microwave Photon Detector

- A classical bit is the most basic unit of information and can be in one of two discrete states: 0 or 1.
- A quantum bit (qubit) can exist in an arbitrary superposition of the basis states $|0\rangle$ and $|1\rangle$:

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$$

  where $|\alpha|^2$ and $|\beta|^2$ are the probabilities of measuring the states $|0\rangle$ and $|1\rangle$, respectively, and $|\alpha|^2 + |\beta|^2 = 1$.

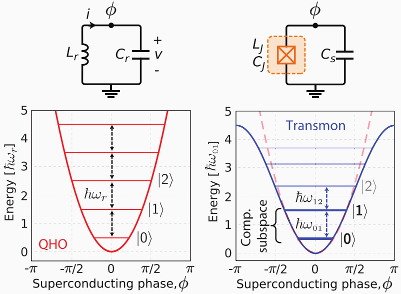
- *n* classical bits can only be in one of the 2^n possible configurations.
- *n* qubits can exist in a superposition of all 2^n basis states.
- A quantum processor can encode and process exponentially more information than a classical one (in principle).

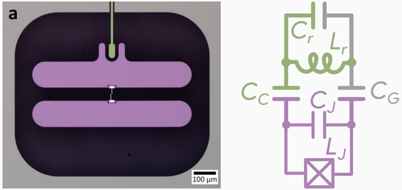


$$|\psi\rangle = \underbrace{\cos\frac{\theta}{2}}_{\alpha}\,|0\rangle + \underbrace{e^{i\varphi}\sin\frac{\theta}{2}}_{\beta}\,|1\rangle$$

Superconducting Qubit

- A **superconducting qubit** is an artificial atom built from superconducting circuits operating at millikelvin temperatures.
- The qubit states $|0\rangle$ and $|1\rangle$ correspond to two energy levels of a nonlinear oscillator formed by:
  - a **Josephson junction**, which provides nonlinearity without dissipation;
  - a large capacitor in parallel with the Josephson junction, forming a quantum LC circuit.
- Several types exist: **transmon**, **flux qubit**, **phase qubit**, etc.
- Example: the **transmon qubit** suppresses charge noise by operating in the $E_J \gg E_C$ regime.
- Transmon qubits are a popular choice for building quantum computers because they offer a good balance of coherence, ease of fabrication, and controllability





Transmon Control and Readout

- **Control:** Microwave pulses at the qubit transition frequency ω_q drive coherent Rabi oscillations between $|0\rangle$ and $|1\rangle$.

$$\omega_q = (E_1 - E_0)/\hbar$$

where E_0 and E_1 are the energies of the ground and first excited states.

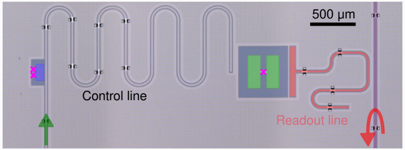
- **Readout:** The transmon is dispersively coupled to a resonator. The resonator frequency depends on the qubit state.

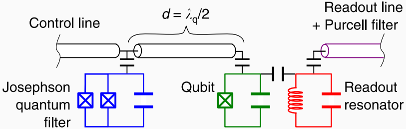
- The effective Hamiltonian in the dispersive regime:

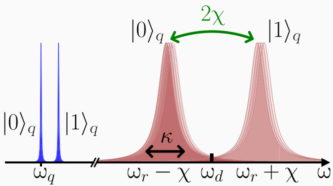
$$H = \underbrace{\frac{\hbar\omega_q}{2}\sigma_z}_{\text{free}} + \underbrace{\hbar\omega_r a^\dagger a}_{\text{readout}} + \underbrace{\hbar\chi\, a^\dagger a\, \sigma_z}_{\text{dispersive}}$$

where ω_r is the resonator frequency and $\chi \approx \frac{g^2}{\Delta}$ is the dispersive shift with $\Delta = \omega_q - \omega_r$.

- A probe tone at ω_r experiences a qubit-state-dependent phase shift, enabling **Quantum Non-Demolition (QND)** readout.







- Superconducting qubits can be strongly coupled to both:
  - **3D cavities:** High-Q resonators machined from bulk aluminum.
  - **Planar (2D) resonators:** Coplanar waveguide or lumped-element resonators on-chip.

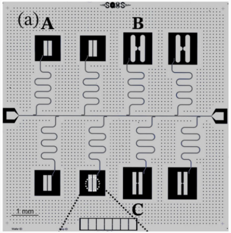
- Both platforms enable qubit control and readout via microwave photons.

- **3D cavities:**
  - Longer coherence times (less surface loss).
  - Lower integration density.

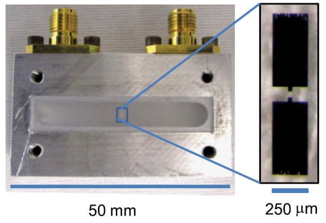
- **Planar cavities (resonators):**
  - Easier on-chip integration and scalability.
  - Typically lower Q but more compact.
  - Used in large scale quantum computers (IBM, Google);

- Choice depends on application: coherence vs scalability trade-off.

Qubit with planar resonators



Qubit in 3D cavity

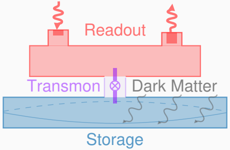


- A qubit is a quantum two-level system with discrete energy levels $|0\rangle$ and $|1\rangle$.
- When a photon with energy $\hbar\omega \approx E_1 - E_0$ arrives, it can induce a transition:

$$|0\rangle \rightarrow |1\rangle$$

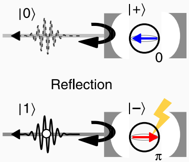
- **Strong coupling** between the qubit and an electromagnetic mode allows efficient photon–qubit interaction.
- The qubit state can be read out with high fidelity using QND techniques.
- **Two detection modalities:**
  - **Absorptive (destructive):** Qubit absorbs the photon and flips from $|0\rangle$ to $|1\rangle$.
  - **Dispersive (QND):** Photon causes a qubit-state-dependent shift, enabling indirect detection.
- **Applications:** Single-photon counting, time-resolved detection, microwave quantum optics.

Direct Detection of cavity photons



Phys. Rev. Lett. 126, 141302 (2021)

Detection of itinerant photons



Nature Phys 14, 546–549 (2018)

Axion-like Particles

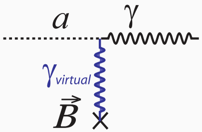
- Inverse Primakoff effect: axions convert into photons in the presence of a magnetic field.
- Conversion occurs in resonant cavities tuned to:

$$f = \frac{m_a c^2}{h}$$

- Large B fields enhance the conversion rate: $P \propto B^2$

$$\mathcal{L} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

$$P_{a\to\gamma} = g^2_{a\gamma\gamma} \rho_a B^2 V C \frac{Q}{m_a}$$



Dark Photons

- Hypothetical hidden-sector gauge bosons.
- Couple via kinetic mixing with standard photons:

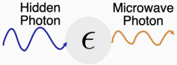
$$\mathcal{L} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

- Conversion in resonant cavities tuned to:

$$f = \frac{m_{A'} c^2}{h}$$

- No magnetic field required.

$$P_{A'\to\gamma} = \epsilon^2 \rho_{A'} V \frac{Q}{m_{A'}} \cdot \frac{1}{1 + 4\left[Q \frac{(f - f_0)}{f_0}\right]^2}$$



Transmon-based single-photon counters operate in the 5–10 GHz range, corresponding to 20–40 μeV masses.

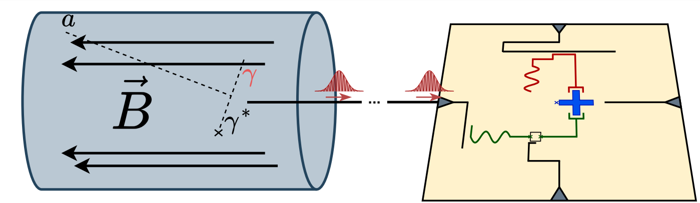
Motivation from Fundamental Physics:

- Axions: originally proposed to solve the strong CP problem in QCD.
- Axion-like particles and dark photons are compelling **dark matter candidates**.
- These particles arise naturally in many extensions of the Standard Model (e.g., string theory).

Why Qubits?

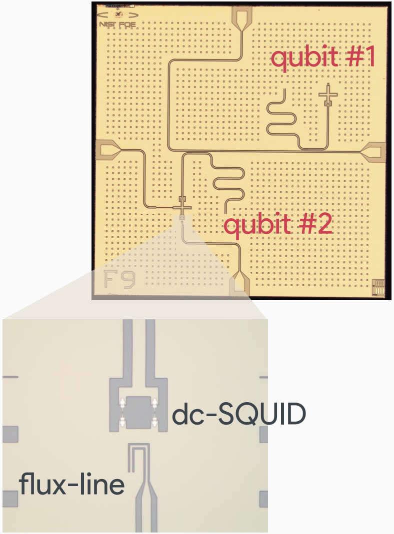
- Axions and dark photons in the **μeV mass range** emit **GHz photons** on conversion.
- Qubits offer:
  - **Single-photon sensitivity** in the microwave domain.
  - Operation at cryogenic temperatures, matching the DM energy scale.
  - Quantum-limited or sub-quantum-limited detection noise.
  - Faster scans, lower noise, and smarter, non-destructive photon counting with respect normal haloscope;
- Enable new strategies: **QND detection**, photon counting, and **quantum-enhanced sensitivity**.

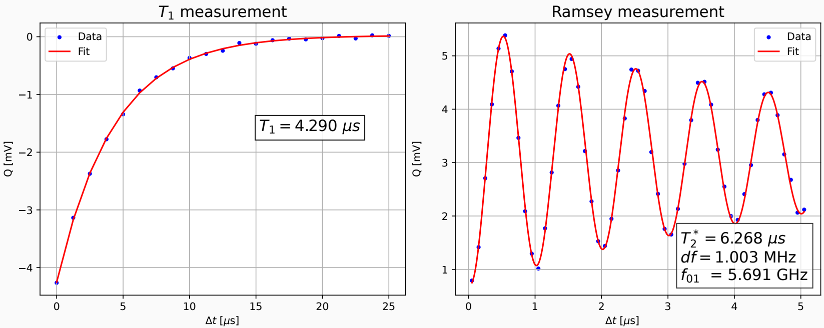
Impact:
Exploring new physics in the μeV range with quantum sensors expands our reach into the **light dark matter frontier**.



- The axion field *a*, interact with the magnetic field $\vec{B}$ inside the haloscope,
- The interaction Produces a real photon γ and a virtual photon γ^*.
- The real photon is absorbed by a tunable storage cavity (shown in green).
- The photon presence induces a phase precession in the qubit (shown in blue).
- Repeated photon detection is achieved via parity measurements through the readout resonator.
- Activity funded as exploratory R&D within INFN.

- Demonstrative two-qubit chip fabricated in collaboration with the Superconductive Electronics Group at NIST:
  - Qubit in grounded xmon transmon layout;
  - One fixed-frequency resonator driven transmon (qubit #1);
  - One tunable-frequency transmon with dedicated drive-line (qubit #2);
  - Transmission/readout line (feedline) through a $\lambda/4$ resonator;
- Fabrication
  - Substrate: 380 nm high-resistive silicon;
  - Metal: 100 nm Niobium;
  - Junctions: Al-AlOx-Al;
  - Niobium etched also in the JJ area;
- Main goals
  - Validate and calibrate the design and simulation steps;
  - Benchmark for future possibile fabrications in Italy (CNR-IFN, FBK, and INRiM)

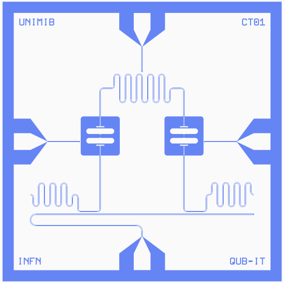




- The longer T_1, the higher the fidelity of qubit detection — less likely to miss a photon.
- Long cavity photon lifetimes enable multiple interrogation cycles, improving the signal-to-noise ratio.
- Measured decoherence times are one order of magnitude lower than those estimated by simulations.
- This is a first design and fabrication step — leaving room for new solutions with improved performance.

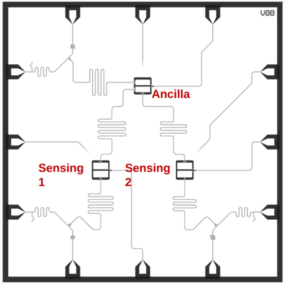
Future Developments

Planar qubits coupled by a resonator-mediated coupling



- The photon in the storage resonator is sensed by two different qubits;
- The qubits acquire a corresponding phase shift;
- Further reduction in dark counts;
- Operates both as a quantum gate and a photon counter;

Planar qubits coupled by an ancilla qubit



- Two qubits are used for sensing, and one qubit is used as an ancilla (helper);
- Ancilla qubits are temporary, intermediate qubits used to facilitate computation;
- The three qubits form a small quantum processor capable of enhancing the signal-to-noise ratio;

We are not the only ones

PHYSICAL REVIEW X **15,** 021031 (2025)

Quantum-Enhanced Sensing of Axion Dark Matter with a Transmon-Based Single Microwave Photon Counter

PHYSICAL REVIEW LETTERS **131,** 211001 (2023)

Detecting Hidden Photon Dark Matter Using the Direct Excitation of Transmon Qubits

PHYSICAL REVIEW D **110,** 115021 (2024)

Search for QCD axion dark matter with transmon qubits and quantum circuit

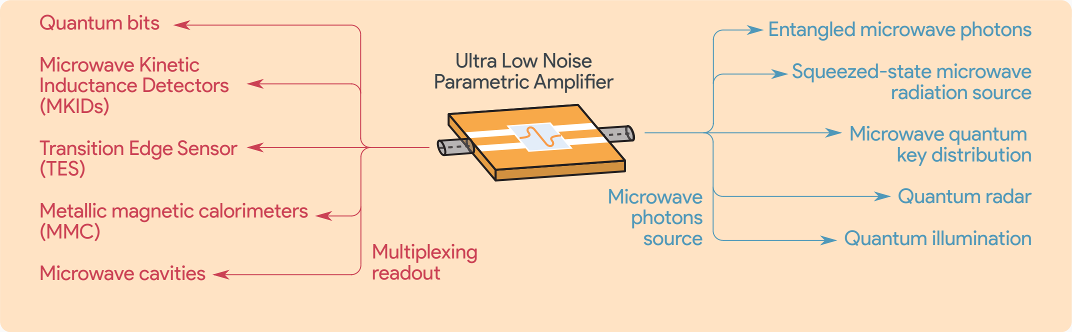
PHYSICAL REVIEW LETTERS **126,** 141302 (2021)

Featured in Physics **Searching for Dark Matter with a Superconducting Qubit**

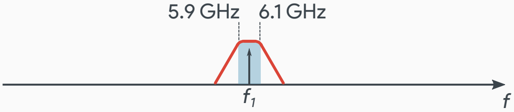
Quantum Limited Amplifiers

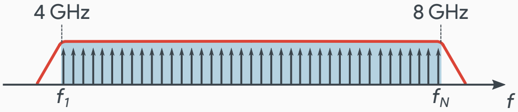
Low-Noise Microwave Amplifiers Play a Central Role in Many Applications

Ultralow-noise broadband amplifiers in the microwave range are essential readout devices for cryogenic detectors and superconducting qubits, with a broad range of applications in quantum sensing and quantum communication.

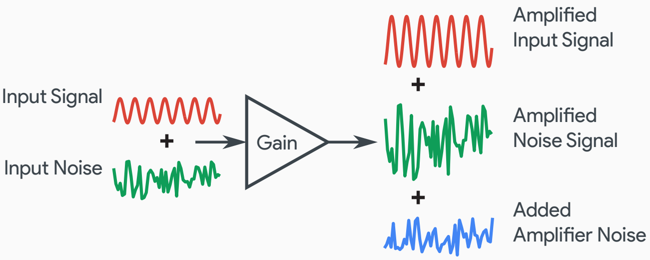


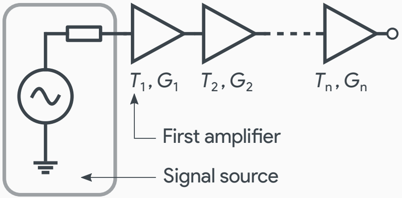
These applications require broadband operation, minimal added noise, and faithful information preservation.





- Multiplexed readout enables the simultaneous measurement of multiple signals or parameters using a single system $\Rightarrow$ multitone readout;
- Multitone readout $\Rightarrow$ requires amplifiers that can efficiently amplify multiple signals across a broad frequency range;
- Essential in communication systems (e.g., radar) $\Rightarrow$ simultaneous readout of signals with different frequencies;
- Microwave frequency-division multiplexing allows for the simultaneous readout of multiple detectors or qubits through a common feedline;

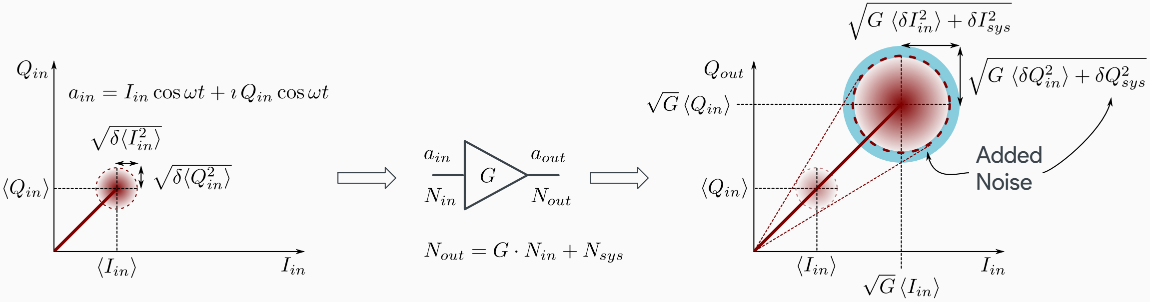




- The amplifier input is sensitive to both the signal and the noise present at its input;
- Added noise can originate from various sources (e.g., thermal fluctuations, electron-hole recombination, etc.);
- The first amplifier in a chain has the most significant impact on the total noise figure, according to Friis' formula:

$$T_{\text{tot}} = T_1 + \frac{T_2 - 1}{G_1} + \frac{T_3 - 1}{G_1 G_2} + \cdots + \frac{T_n - 1}{G_1 G_2 \cdots G_{n-1}} \xrightarrow{G_1 \gg 1} T_{\text{tot}} \simeq T_1$$

- The Heisenberg uncertainty principle sets a fundamental lower bound on the added noise of any phase-insensitive amplifier;



Luca Planat, Ph.D. thesis, 2020

- The Heisenberg uncertainty principle sets a fundamental lower bound on the added noise
- A quantum-limited amplifier is an amplifier whose added noise reaches the Standard Quantum Limit:

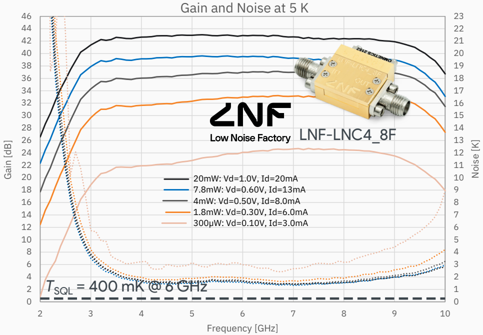
$$T_{\mathrm{SQL}} = \frac{\hbar\omega}{2k_B} = \frac{hf}{2k_B} \quad\Rightarrow\quad N_{\mathrm{SQL}} = \frac{1}{2}\ \text{(quanta)} \quad\Rightarrow\quad T_N \geq \frac{\hbar f}{2k_B} = T_{\mathrm{SQL}} \sim \frac{25\ \mathrm{mK}}{\mathrm{GHz}}$$

A quantum-limited amplifier (QLA):

- Is indispensable for reading out qubits with high fidelity, ensuring reliable computation in the presence of noise and errors;
- Enables improved sensitivity for detectors using frequency-multiplexed readout.

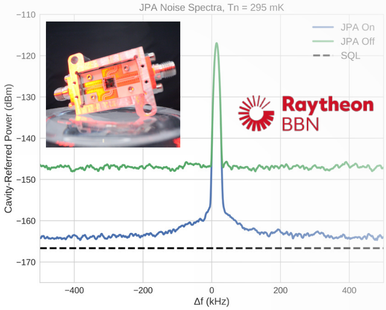
Are amplifiers broadband and quantum limited?

High-electron-mobility transistor (HEMT)



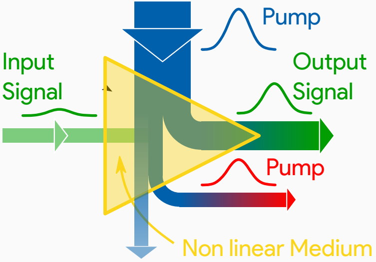
- Low Noise Amplifier in semiconductor technology;
- Gain: $G = 44$ dB;
- Bandwidth: 4 GHz;
- Noise temperature: $T_N = 1.5$ K @ 6 GHz;
- Broadband Amplifier but not Quantum Limited;

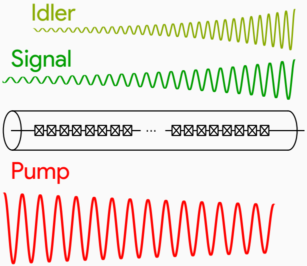
Josephson Parametric Amplifier (JPA)

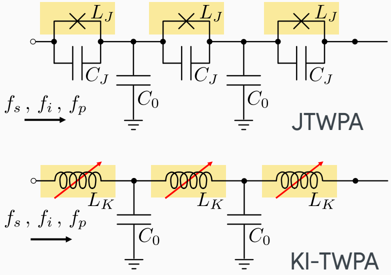


- Low Noise Amplifier in superconducting technology;
- Gain: $G = 20$ dB;
- Bandwidth: 300 MHz;
- Noise temperature: $T_N = 300$ mK @ 6.8 GHz;
- Quantum Limited Amplifier but not broadband;

Traveling Wave Parametric Amplifiers (TWPAs)



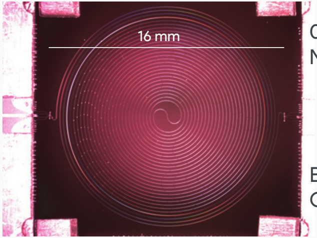




Appl. Phys. Lett. 119, 120501 (2021)

- Microwaves travelling along a transmission line with embedded non-linear medium;
- The non-linear medium can be implemented by Josephson Junction (JJ) or Kinetic Inductance (KI) of superconductors;
- A large pump tone modulates this element, coupling the pump (f_p) to a signal (f_s) and idler (f_i) tones via frequency mixing;
- The non-linear medium to convert the energy of the pump into an amplified signal;
- The total system noise target is the standard quantum limit (SQL) over a large bandwidth.

Kinetic inductance traveling wave amplifier (KI-TWPA)

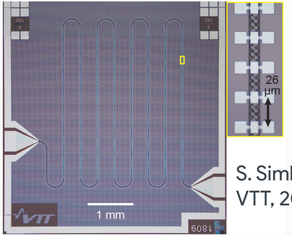


0.8 m length of NbTiN CPW line

Byeong Ho Eom *et al.* Caltech, 2012.

Nature Phys 8, 623–627 (2012)

Josephson traveling wave parametric amplifiers (JTWPA)



1632 SNAILs
4.2 cm length

S. Simbierowicz *et al.* VTT, 2021

Rev. Sci. Instrum. 92, 034708 (2021)

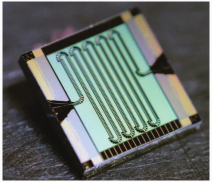
- Parametric amplification $\Rightarrow$ periodic variation of a parameter generates amplification
- Tunable element $\Rightarrow$ inductance $\Rightarrow$

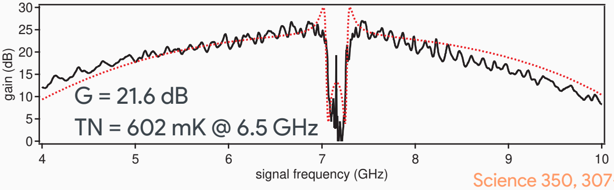
$$\begin{cases} \text{Josephson junction (JJ):} & L_J(I) = L_{J_0} \dfrac{\arcsin(I/I_c)}{I/I_c} \\ \text{Kinetic inductance (KI):} & L_K(I) = L_{K_0}\left(1 + \dfrac{I^2}{I_*^2}\right) \end{cases}$$

TWPA: two different approaches (cont.)

Josephson traveling-wave parametric amplifier (JTWPAs):

- have become important for superconducting-circuit experiments such as multiplexed qubit readouts and sensing;
- are commercially available from QuantWare (www.quantware.com) and Silent-Wave (silent-waves.com) ;





Science 350, 307-310 (2015)

... however, the development of Kinetic Inductance TWPA (KI-TWPA or KIT) is particularly significant because they

- are simple to fabricate and require only few lithography and etching steps, without overlapping structures;
- provide a high dynamic range, high gain, and operate near the SQL;
- can operated also at higher temperatures, from millikelvin to 4 K (space application, spin-qubit, ...);
- are resilient to high magnetic fields (spin-qubit, axion search, ...);

Kinetic Inductance

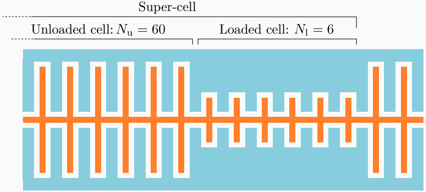
- Superconducting materials, such as NbTiN and NbN, exhibit a nonlinearity that is uniquely dissipationless in their kinetic inductance;
- Kinetic inductance per unit length L_k of a superconducting transmission line can be expanded as

$$L_k(I) = L_d\left(1 + \varepsilon I + \xi I^2\right) \quad \text{with} \quad L_d = L_0\left(1 + \frac{I_{dc}^2}{I_*^2}\right)$$

$$\text{and} \quad \varepsilon = \frac{2\, I_{dc}}{I_*^2 + I_{dc}^2} \quad , \quad \xi = \frac{1}{I_*^2 + I_{dc}^2}$$

- ξI^2 permits the 4-wave-mixing: $2\, f_p = f_s + f_i$
- εI permits the 3-wave-mixing: $f_p = f_s + f_i$
- The scaling current I_* sets the scale of the nonlinearity

Dispersive lumped element line



- Lumped element line with stubs for tuning the characteristic impedance to $Z_0 = 50\,\Omega$;
- Periodic loading with $Z_0 > 50\,\Omega$ along the line:
- Dispersive line $\Rightarrow$ modified phase velocities;
- Extra delay at the pump frequency to create phase-matching:
- Exponential gain: $G_s = \left|\frac{I_s(x)}{I_s(0)}\right|^2 = \cosh^2\left(\frac{\delta_L\, k_p\, x}{8}\right)$

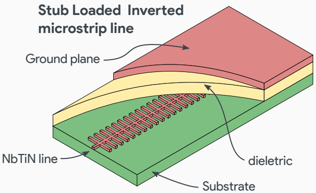
The Milano-Bicocca Unimib/INFN group is involved in two different projects in this field with similar aims

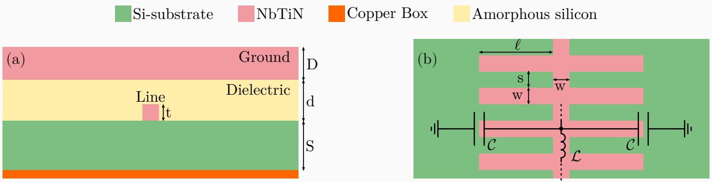
DARTWARS Project

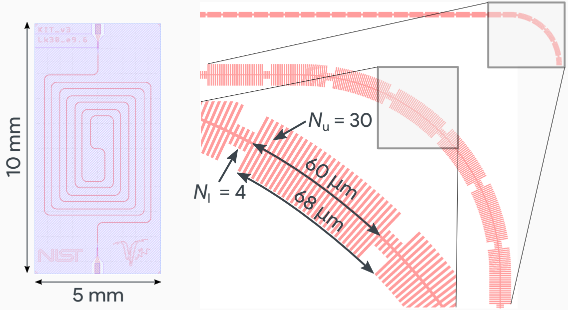
- Goal: develop state-of-art JTWPA and KI-TWPA for detector and qubit array;
- Funded by the Italian Institute of Nuclear Physics (INFN) through a competitive call;
- Involved institutions: INFN (Bicocca, LNF, Lecce, Salerno, TIFPA), Italian National Institute of Metrology (INRiM), and Bruno Kessler Foundation (FBK);

MSCA Project

- Goal: develop innovative KI-TWPA for detector and qubit array;
- Funded by the European Union through a competitive H2020-MSCA-IF-2020 call;
- Involved institutions: University of Milano-Bicocca, University of Colorado Boulder (CO, USA), National Institute of Standards and Technology (NIST, CO, USA);

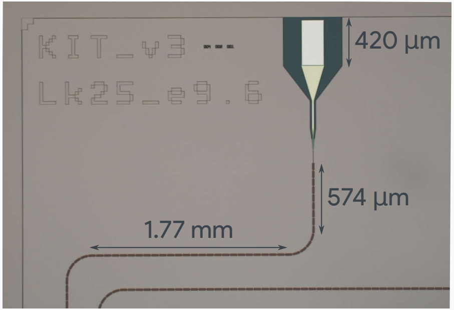


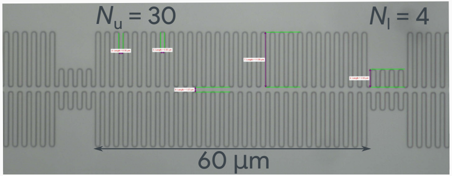


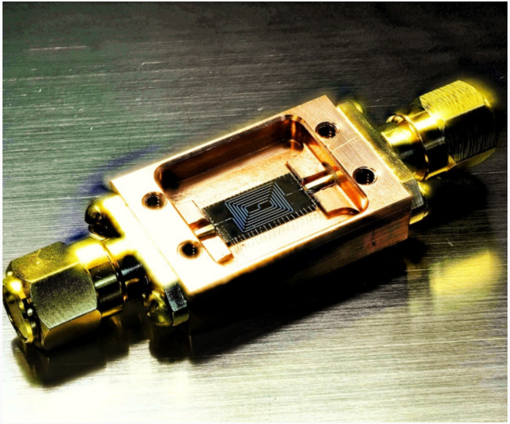


- NbTiN line with high kinetic inductance $L_k = 30$ pH/sq
- Two-arm spiral layout to optimize the chip size;
- Total number of supercells: $N_{sc} = 1290$;
- Total number of cells: $N_c = 43860$
- Total line length: $L_{tot} \sim 8.8$ cm
- Chip sizes: 1×0.5 cm^2

Devices production at NIST microfabrication facilities







- First version (v1) published in J. Low. Temp. Phys. (2024)
- Improved version (v2) presented APS March Meeting 2024
- Version v3 presented at the ASC2024 conference

For all the tested prototypes :

- Measured gain $G > 20\,\mathrm{dB}$ ✔ ☺;
- Fabrication yield: >90%

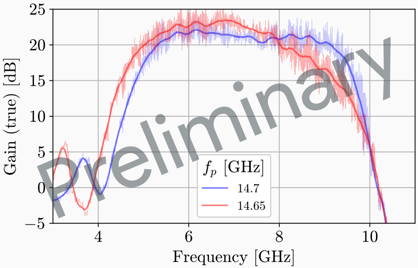
For the best devices:

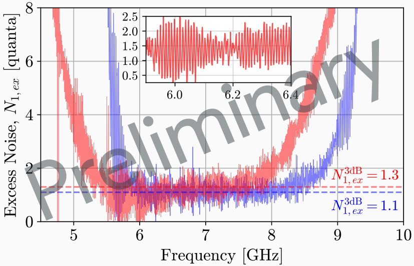
Critical current:	$I_c \sim 0.8\,\mathrm{mA}$
Scaling current around:	$I_* \sim 2.8\,\mathrm{mA}$
Bias current around:	$I_{dc} \sim 0.22\,\mathrm{mA}$
Pump power:	$P_p \sim -40\,\mathrm{dBm}$
1 dB compression point:	$P_{1\mathrm{dB}} \sim -70\,\mathrm{dBm}$
3 dB bandwidth:	$B = 3.2\,\mathrm{GHz}$

KI-TWPA performance creeping up on the SQL ✔ ☺:

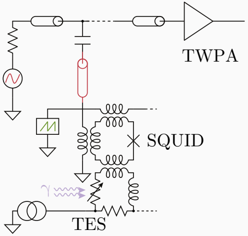
$$N_{\mathrm{add}} \simeq 1\,\mathrm{quanta} \Rightarrow T_N = 400\,\mathrm{mK} \ @\ 8\,\mathrm{GHz}$$

Results submitted to PRX Quantum





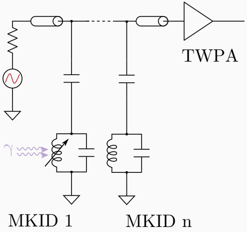
TES and MMC detectors



rf-SQUID multiplexing of TES/MMC microcalorimeter arrays for x-ray and gamma-ray spectroscopy.

Appl. Phys. Lett. 122, 214001 (2023)

MKIDs detectors

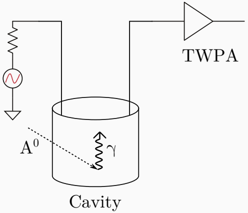


Optical or Phonon-Mediated MKIDs are naturally frequency domain multiplexed detectors

Appl. Phys. Lett. 115, 042601 (2019)

arXiv:2402.05419 [physics.ins-det]

Resonant microwave cavity

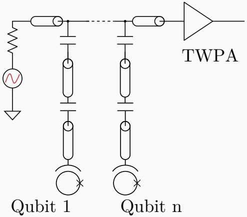


Resonant cavity haloscope readout to perform broadband axion searches

Rev. Sci. Instrum. 94, 044703 (2023)

Phys. Rev. D 108, 062005

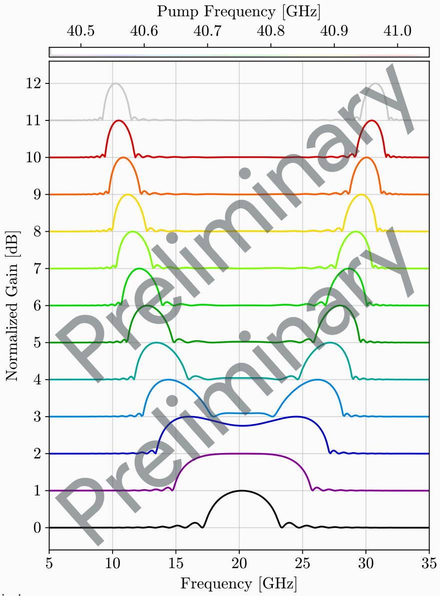
Quantum bit



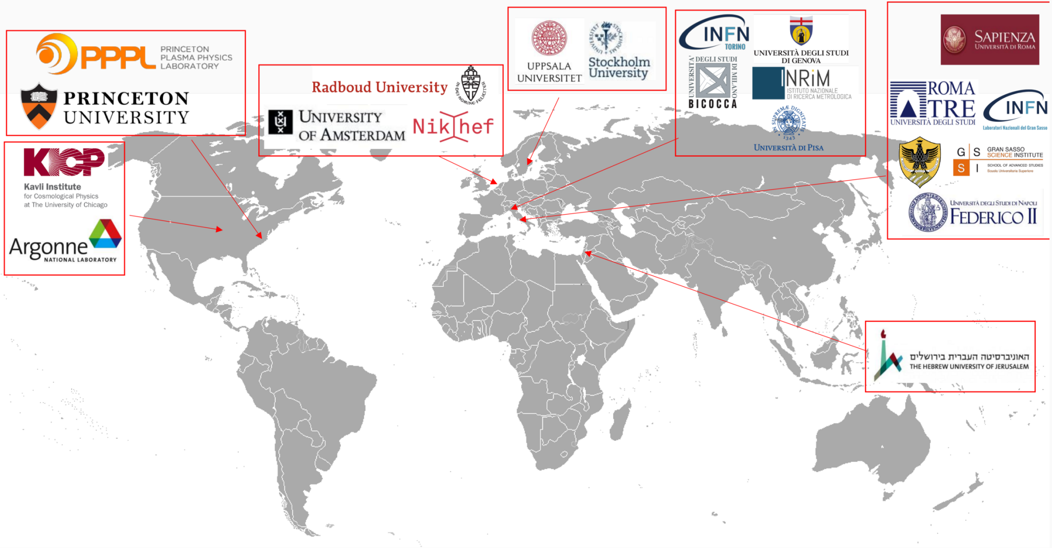
Fast and high-fidelity readout of simultaneous superconducting qubits

Appl. Phys. Lett. 113, 242602 (2018)

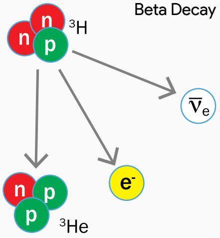
Phys. Rev. Applied 10, 034040 (2018)



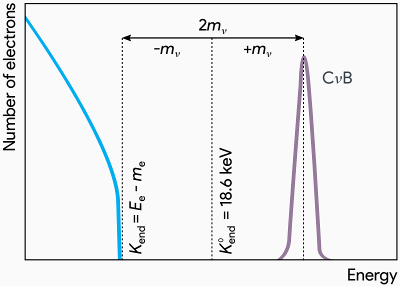
- TWPAs are typically designed to operate in the 4–10 GHz range:
- This range is typical for:
  - Superconducting qubits;
  - Microwave Kinetic Inductance Detectors (MKIDs);
  - Microwave-multiplexed Transition Edge Sensors (TESs);
  - Haloscope resonant cavities.
- Kinetic-inductance-based TWPAs can also be designed for higher frequencies.
- Possible applications:
  - Hot qubits: qubits operating at higher temperatures and frequencies (e.g., 20 GHz);
  - Haloscope cavities targeting different axion mass ranges;
  - Detection of Cyclotron Radiation Emission Spectroscopy (CRES) signals.

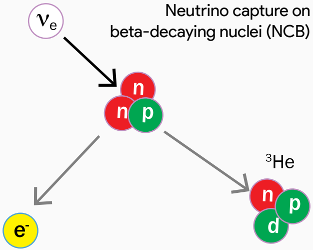

PPPL
PRINCETON PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY
Radboud University
UNIVERSITY OF AMSTERDAM
Nikhef
UPPSALA UNIVERSITET
Stockholm University
INFN TORINO
UNIVERSITÀ DEGLI STUDI DI GENOVA
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA
UNIVERSITÀ DI PISA
SAPIENZA UNIVERSITÀ DI ROMA
ROMA TRE UNIVERSITÀ DEGLI STUDI
INFN Laboratori Nazionali del Gran Sasso
GSSI GRAN SASSO SCIENCE INSTITUTE
UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II
KICP
Kavli Institute for Cosmological Physics at The University of Chicago
Argonne NATIONAL LABORATORY
האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

Neutrino capture in a β-decaying nucleus



$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \overline{\nu_e}$$

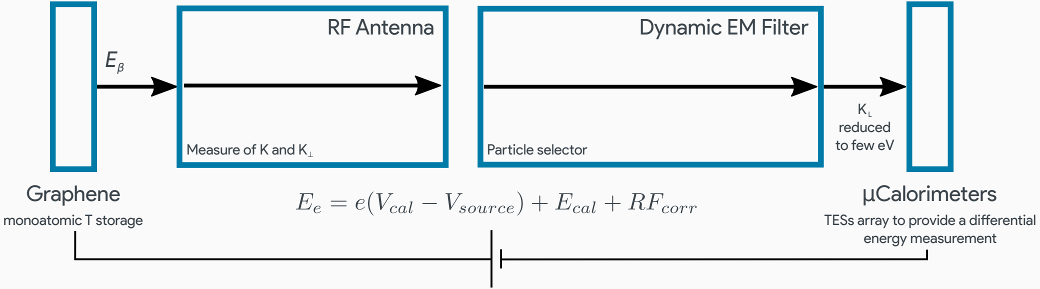




$$\nu_e + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$$

- Tritium can decay via β decay and undergo neutrino capture on beta-decaying nuclei (NCB);
- The NCB process produces a peak in the electron spectrum at an energy of $2m_\nu$ above the beta decay endpoint;
- Studying this spectrum with high energy resolution allows the investigation of the neutrino mass and the possible detection of relic neutrinos;
- Tritium (^{3}H) is the best candidate due to its high neutrino capture cross section, low Q-value, and long half-life;
- Detecting the NCB peak requires an energy resolution better than $m_\nu = \mathcal{O}(0.1\,\mathrm{eV})$;

The PTOLEMY Detector

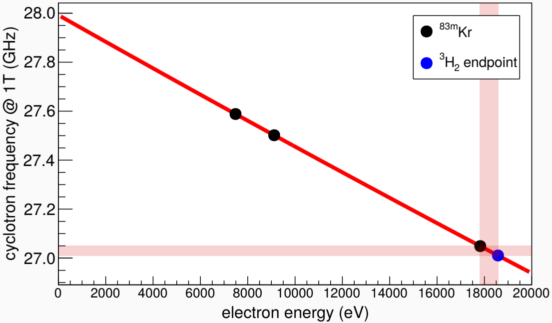


$$E_e = e(V_{cal} - V_{source}) + E_{cal} + RF_{corr}$$

- Electrons from weakly-bound tritium are emitted from a cold target surface.
- Electrons drift through an RF antenna region, where their momentum components are measured with a resolution of a few eV.
- Filter electrodes are set approximately 1 ms before the electrons enter the filter region.
- The kinetic energy of the electrons is reduced as they climb a potential via gradient-*B* drift.
- Electrons with energies of a few eV in a low-*B*-field region are transported into a microcalorimeter array.

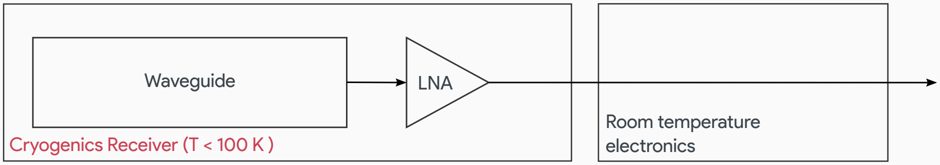
A charged particle (like an electron) moving perpendicular to a magnetic field undergoes circular motion at a frequency called the cyclotron frequency:

$$f_c = \frac{e\,B}{\gamma\, m_e} = \frac{1}{2\pi} \cdot \frac{e\,B}{K_{in}/c^2 + m_e}$$

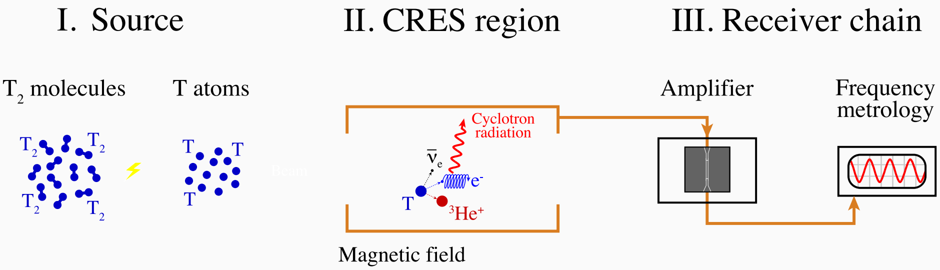


- The electron emits weak microwave radiation ($\sim$ 27 GHz range @ 1 T), which is picked up by a nearby antenna or waveguide system.
- The kinetic energy of electrons in a known magnetic field can be determined by measuring their cyclotron radiation.
- By measuring the electron energy, it is possible to tune the dynamic RF filter in real time.
- An antenna coupled to a cryogenic low-noise amplifier detects the photons emitted by the electron.

Improving CRES Measurements with GHz-Bandwidth TWPA



- **Broadband Detection:** TWPAs amplify weak microwave signals (GHz range) emitted by single electrons across a wide range of frequencies.
- **Low-Noise Amplification:** Near quantum-limited noise performance enhances signal-to-noise ratio, crucial for detecting weak cyclotron radiation.
- **Real-Time Tuning:** Accurate energy readout enables adaptive RF filtering and dynamic tracking of single-electron events.
- **Scalability:** Supports simultaneous detection of multiple electrons, enabling high-rate data acquisition and large-scale implementation.
- **High Energy Resolution:** Essential for resolving the small spectral signature of neutrino capture above the tritium beta decay endpoint.



- UK based experiment: University College London (UCL) leads the demonstrator;
- Utilizes CRES to determine electron energy from tritium (or deuterium) β-decay;
- Designs a microwave/phased-array antenna system to capture single-electron cyclotron signals in the 20–30 GHz range;
- Deploys quantum-noise-limited superconducting amplifiers—such as kinetic inductance parametric amplifiers and SLUGs—to reach noise close to the standard quantum limit;
- Aims to achieve sub-eV neutrino mass sensitivity through high-precision spectroscopy of the β-decay spectrum endpoint.

Conclusion

- Quantum sensing is reshaping what can be measured in fundamental physics.
- From TES calorimeters to superconducting qubits and quantum limited amplifier, new tools push the sensitivity frontier.
- These technologies are now entering the domain of dark matter, neutrino physics, and precision measurements.
- The convergence of quantum information and high-energy physics opens unprecedented discovery potential.

Thank you!

Questions?