Quantum Systems for Nuclear Physics

Joseph Formaggio

Massachusetts Inst. of Tech.

NSAC Town Hall

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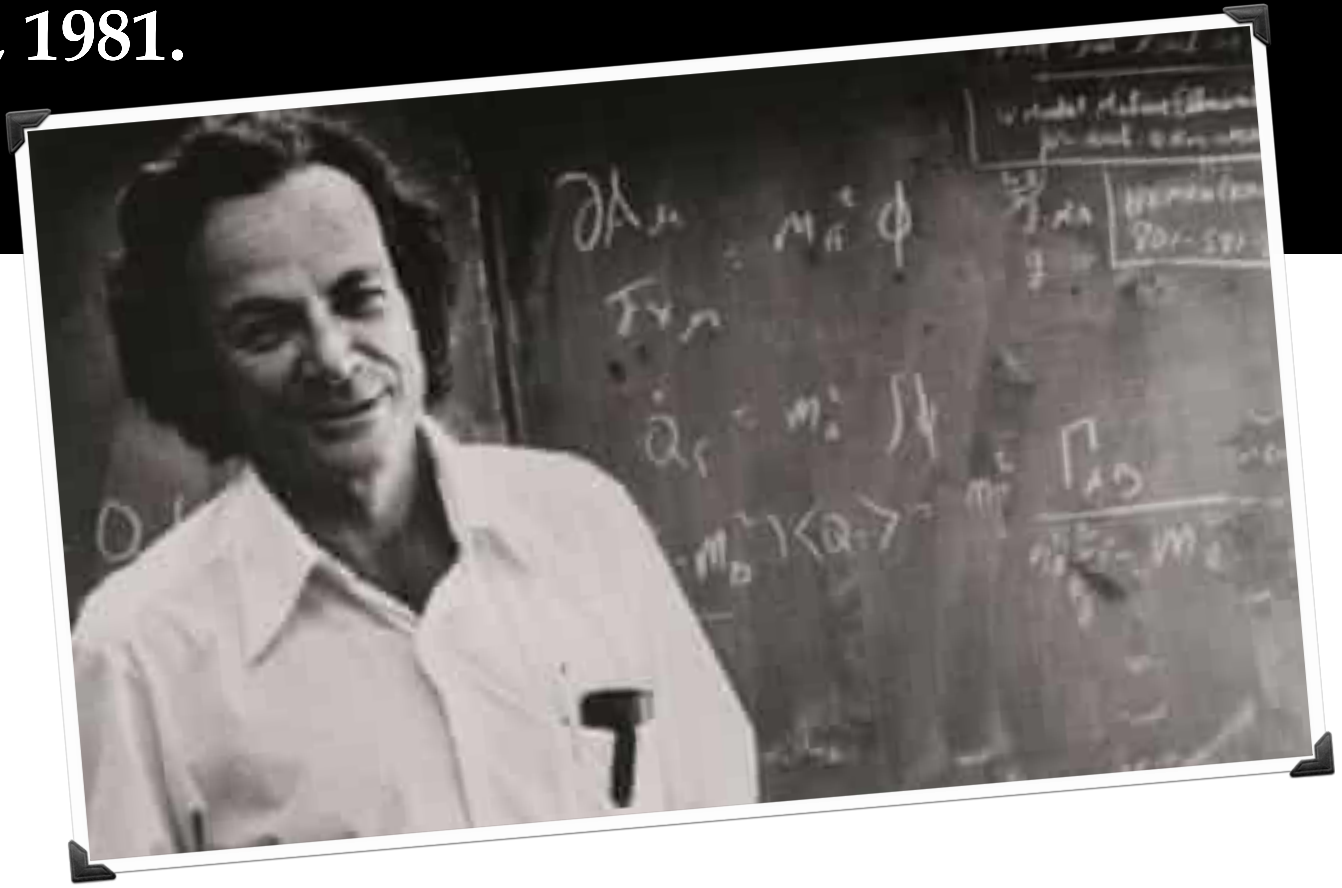
"... trying to find a computer simulation of physics seems to me to be an excellent program to follow out. ... the real use of it would be with quantum mechanics. ... Nature isn't classical ... and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

—Richard Feynman, Keynote address at the MIT Physics of Computation Conference, 1981.



Quantum computing holds great promise for solving some (but not all!) difficult problems; particularly in quantum **chemistry**, **physics**, and **mathematics**.

". . . trying to find a computer simulation of physics seems to me to be an excellent program to follow out. . . . the real use of it would be with quantum mechanics. . . . Nature isn't classical . . . and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

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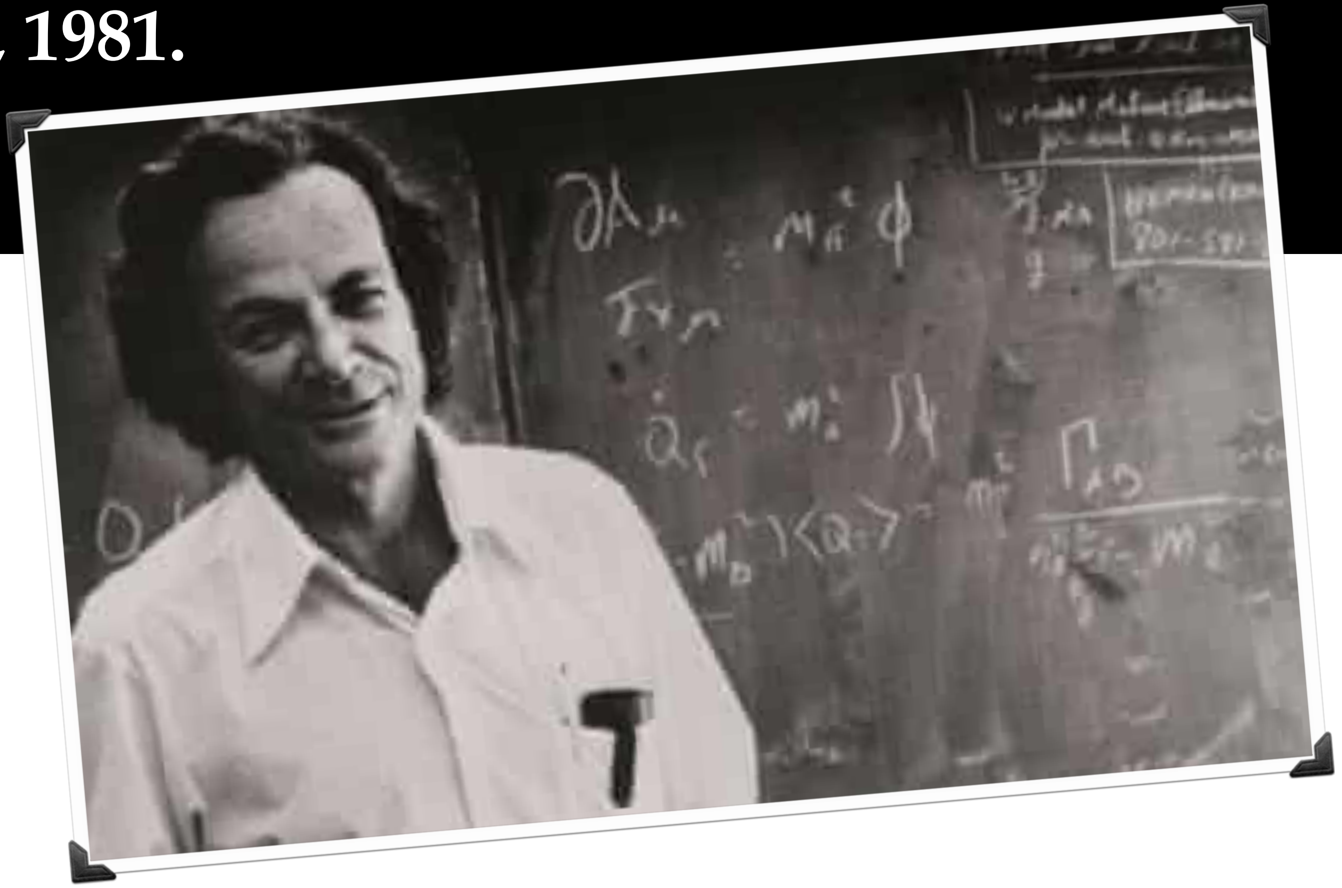

Quantum computers offer the possibility of utilizing **superposition** and **entanglement** to carryout certain otherwise difficult computations.

Quantum Techniques ⇒ Particles & Fields

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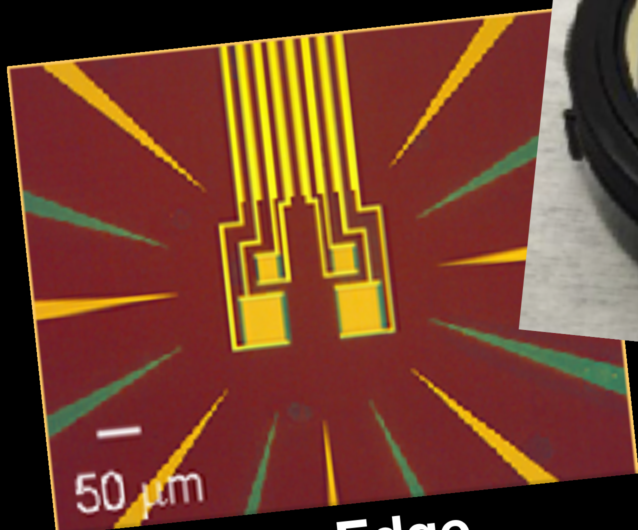
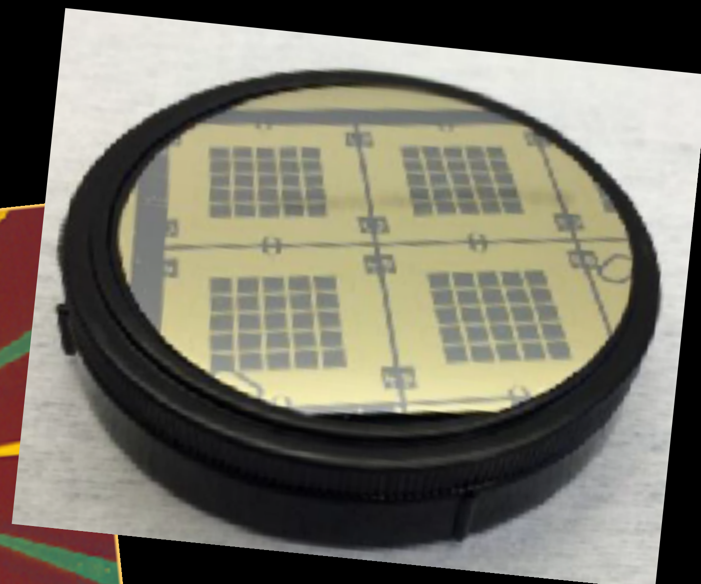
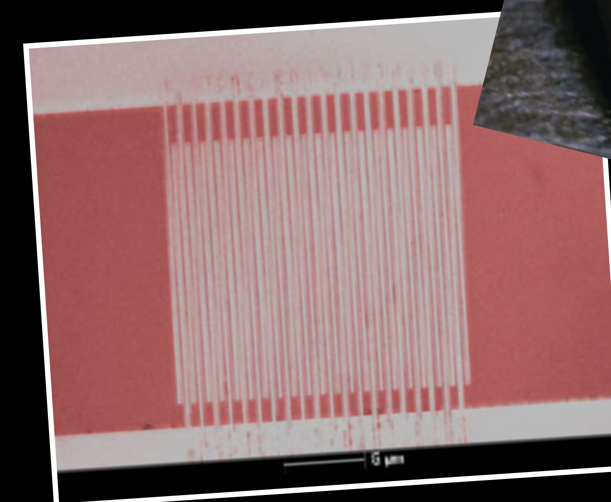
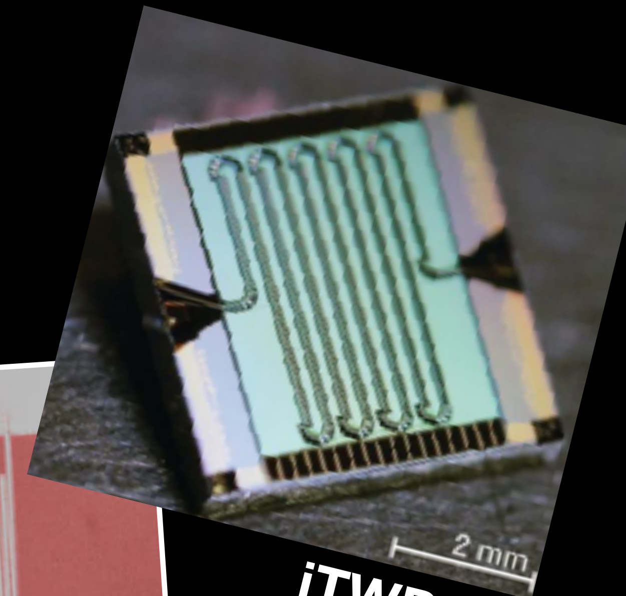
Quantum Sensors



Transition Edge Sensors


mKIDS, TKIDS, BULLKIDS


Nanowire sensors



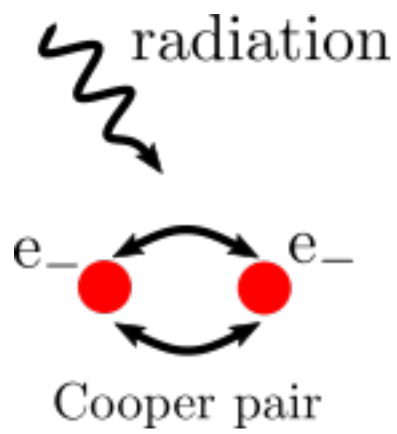
jTWPAs

There is a wealth of new quantum-based sensors that are now in use in nuclear and particle physics.

Taking advantage of new low-gap materials.

I will mention a handful of examples where quantum methods are used in nuclear physics measurements

meV Scale Sensors

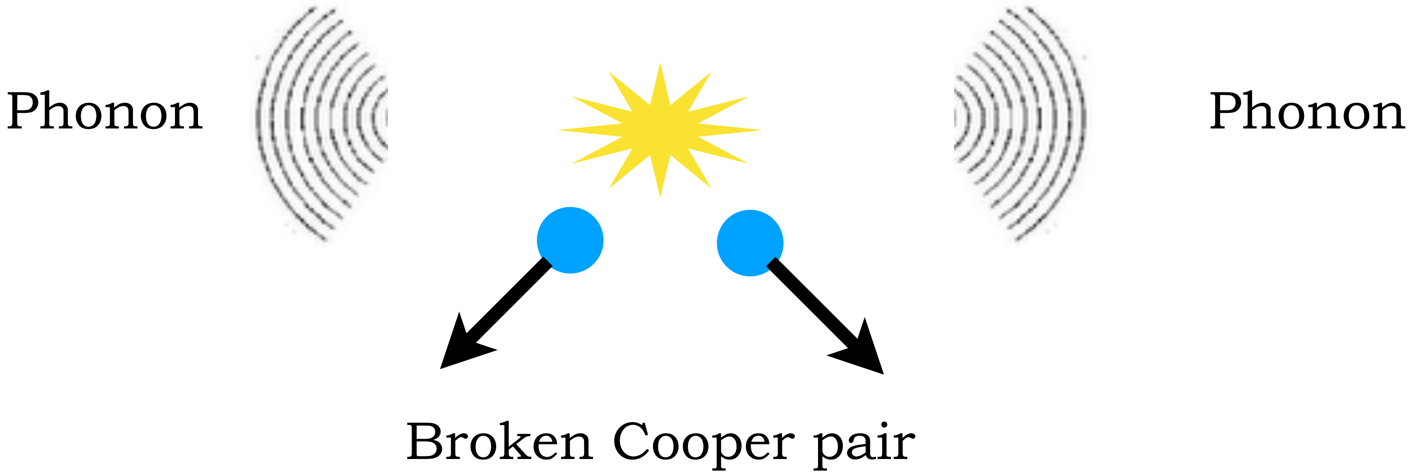


Cooper pairs within superconductors have extremely small (O(*meV*)) gap energies.

Large collection of unit particles that lead to high (meV to eV) energy resolutions.

Type of sensor determined by particle collection.

meV Scale Sensors



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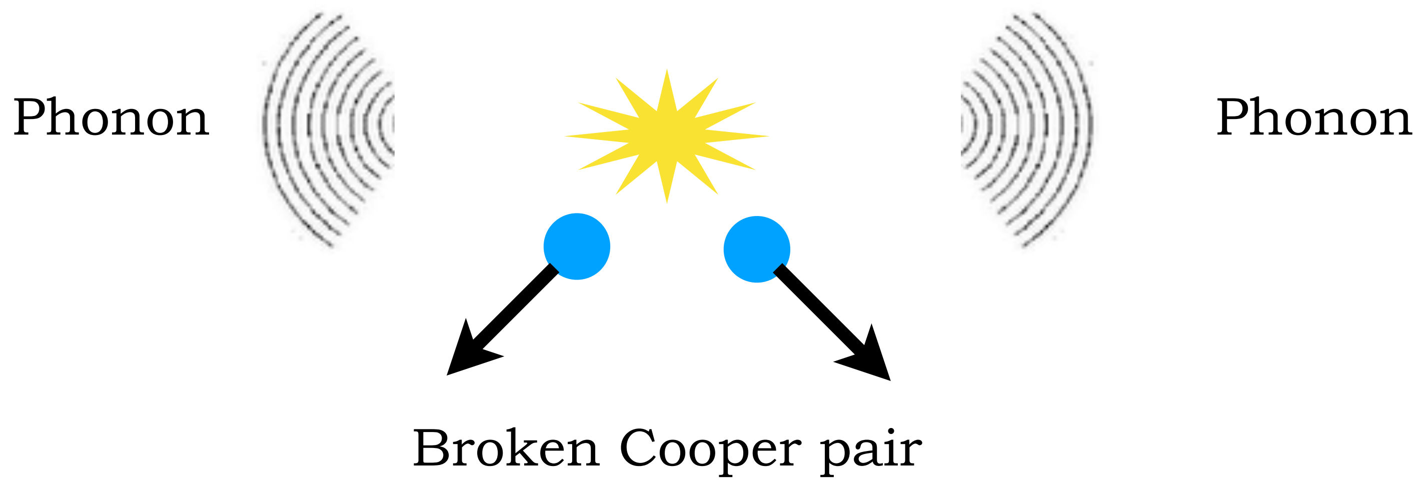
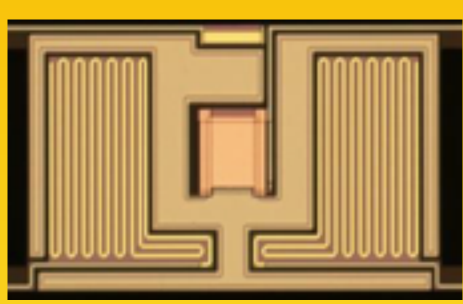
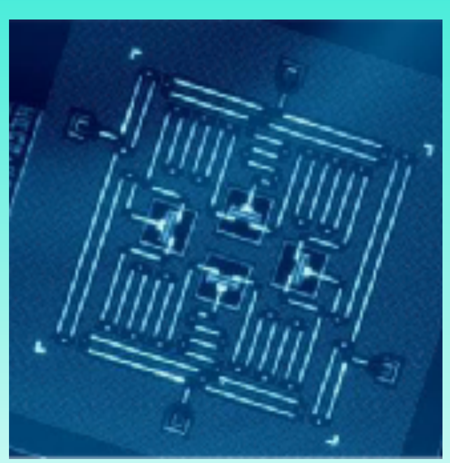


Sensitive to *Quasiparticle* density



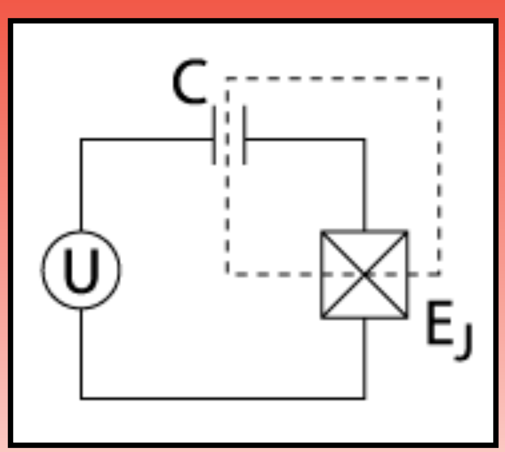
Transition Edge Sensors, Kinetic Induction Devices

Sensitive to *Quasiparticle* tunneling

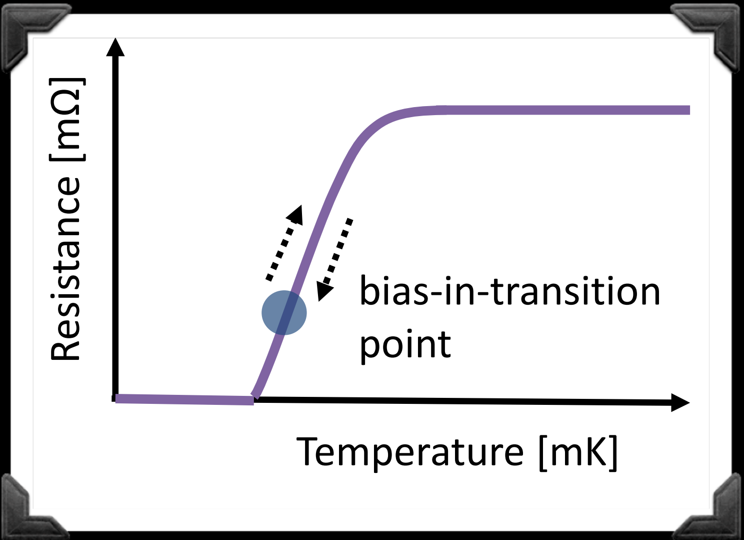


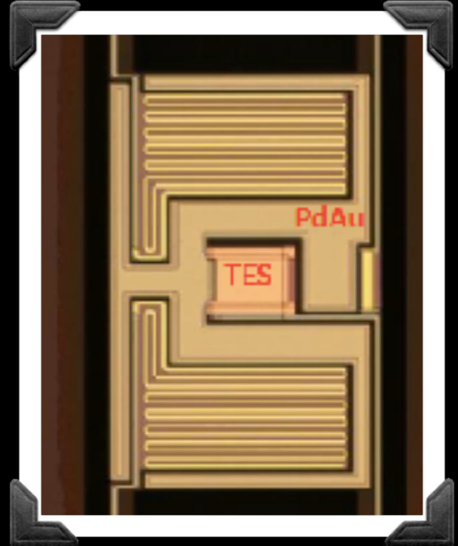
Transmon qubits

Sensitive to *Charge accumulation*



Cooper Pair Boxes, Charge qubits





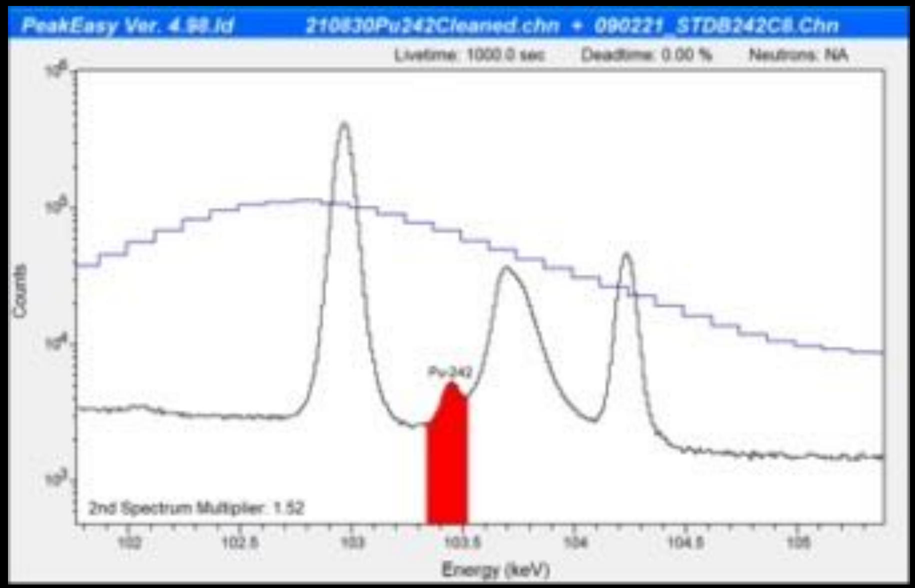
Transition Edge Sensors

Sensitive to thermal changes in absorber.

Transition edge sensors (TESs) and magnetic micro calorimeters (MMCs) now more commonly used in nuclear physics.

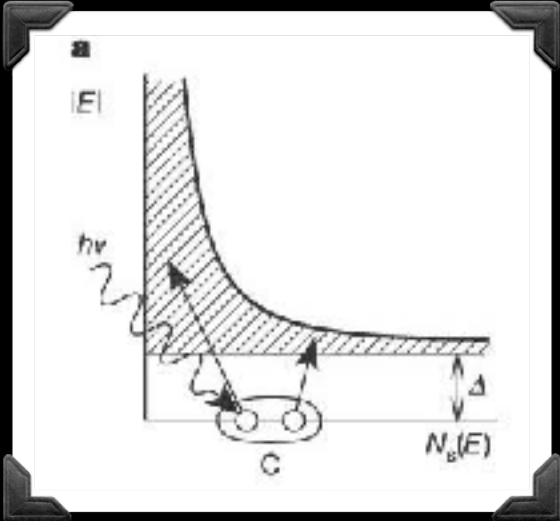
Exquisite energy resolution for gamma/beta radiation.

LANL/NIST/CU TES Ɣ-ray spectrometer

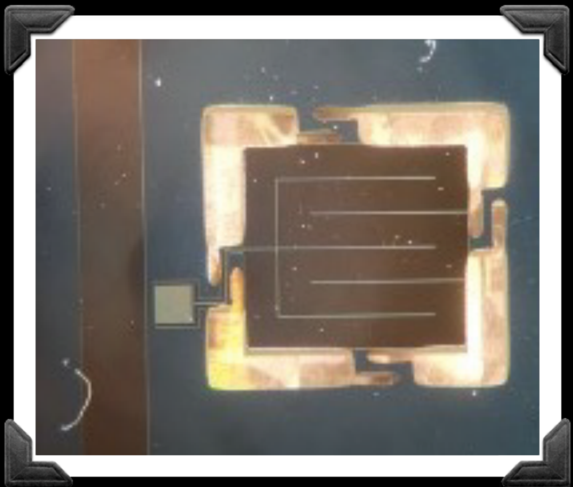


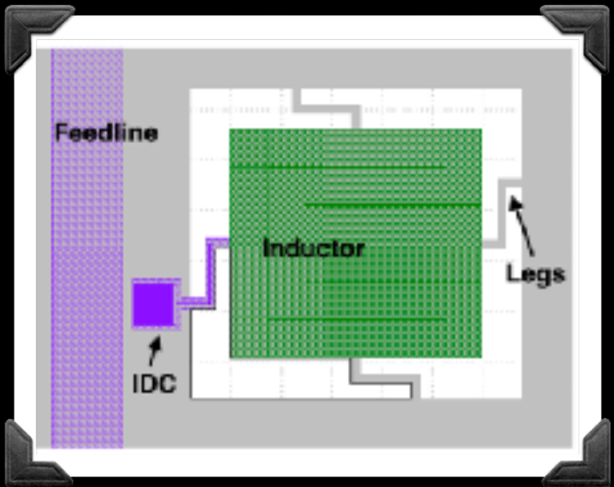
Direct observation of ^{242}Pu Ɣ-rays

Mercer et al
ArXiv 2202.02933



BULLKIDs





TKIDs

Transition Edge Sensors

Sensitive to thermal changes in absorber.

Transition edge sensors (TESs) and magnetic micro calorimeters (MMCs) now more commonly used in nuclear physics.

Exquisite energy resolution for gamma/beta radiation.

Kinetic Inductance Devices

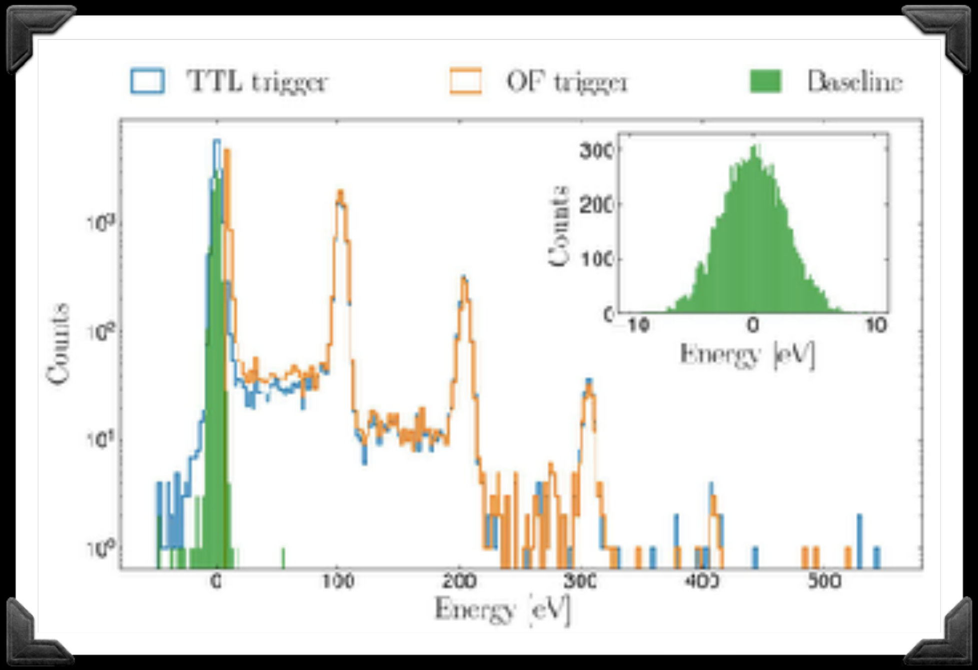
Resonant devices that are highly sensitive to energy deposits from changes in kinetic inductance from changes in QP density.

Recent advances in sensitivity, as well as fabrication on larger absorbers (TKIDs and BULLKIDs).

Potential uses for high energy depositions with high energy resolution.

Recent Performance

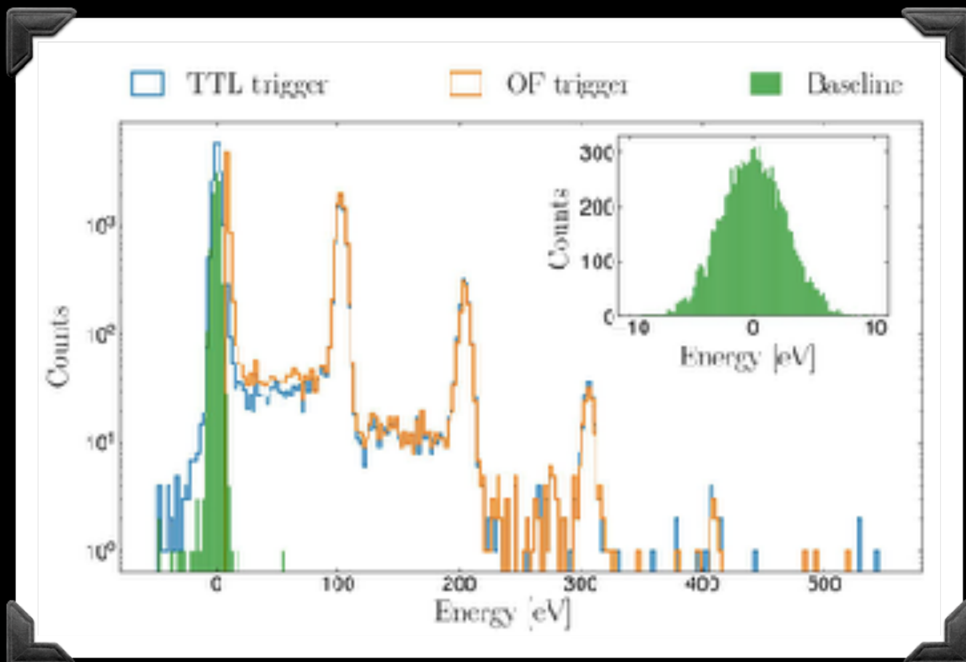
TESs



Substantial progress has been made in phonon and charge sensors so as to reach the eV (and soon sub-eV) energy resolution.

Low Tc TES enables enhanced sensitivity to phonon energy depositions (e.g. HVeV detectors at 2.7 eV resolution).

Recent Performance



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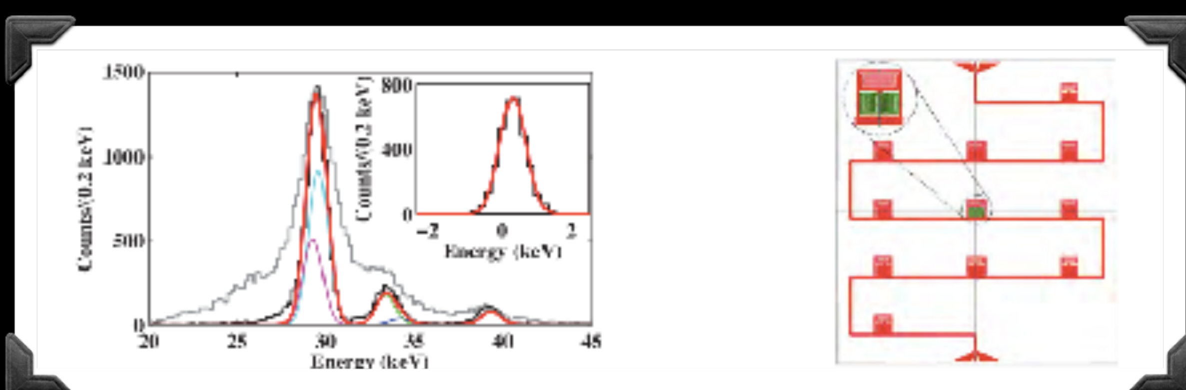
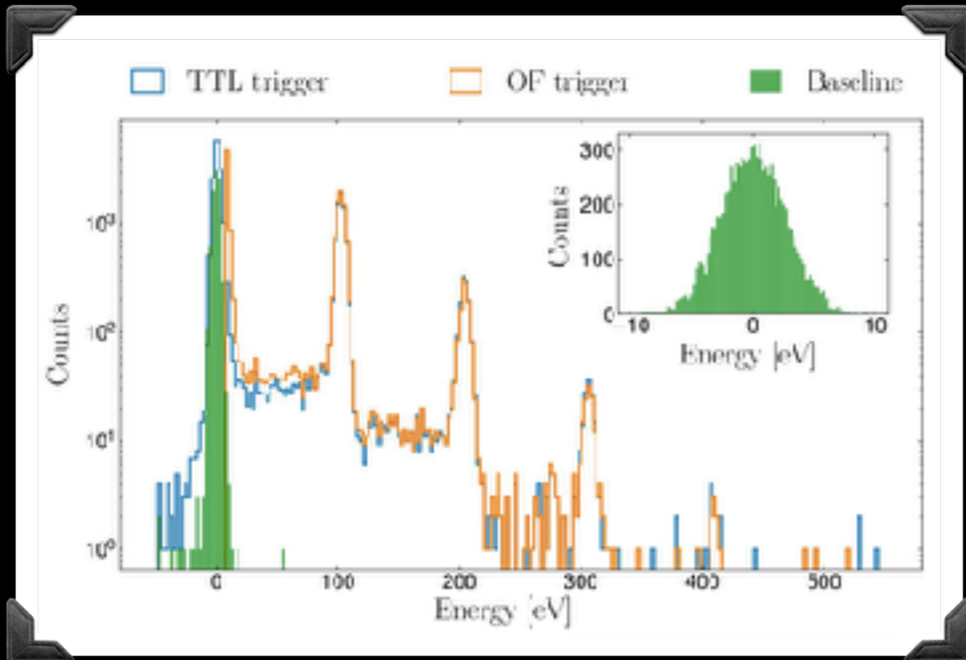


KIDs

KIDs now achieving σ_E = 20 eV or σ_E = 300 eV depending on the size of the architecture.

Steady improvements by using optimized low gap materials should bring this down to eV/ sub-eV scale in near future.

Recent Performance



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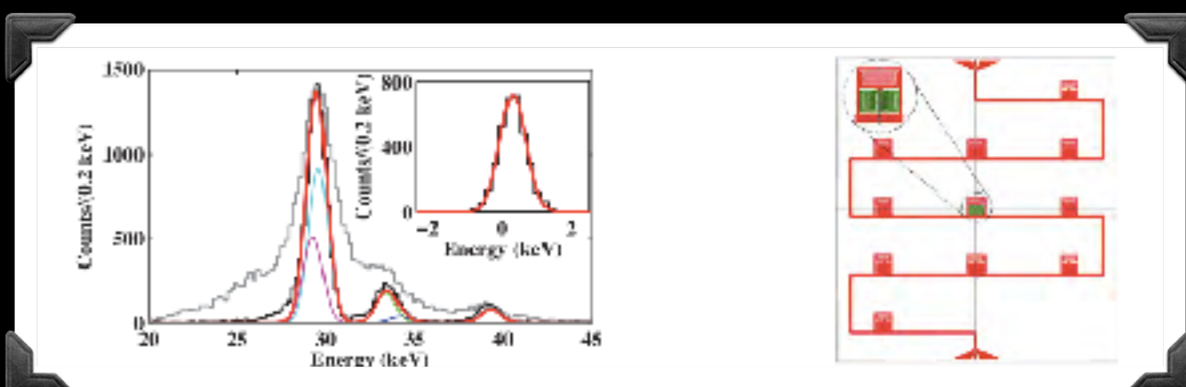

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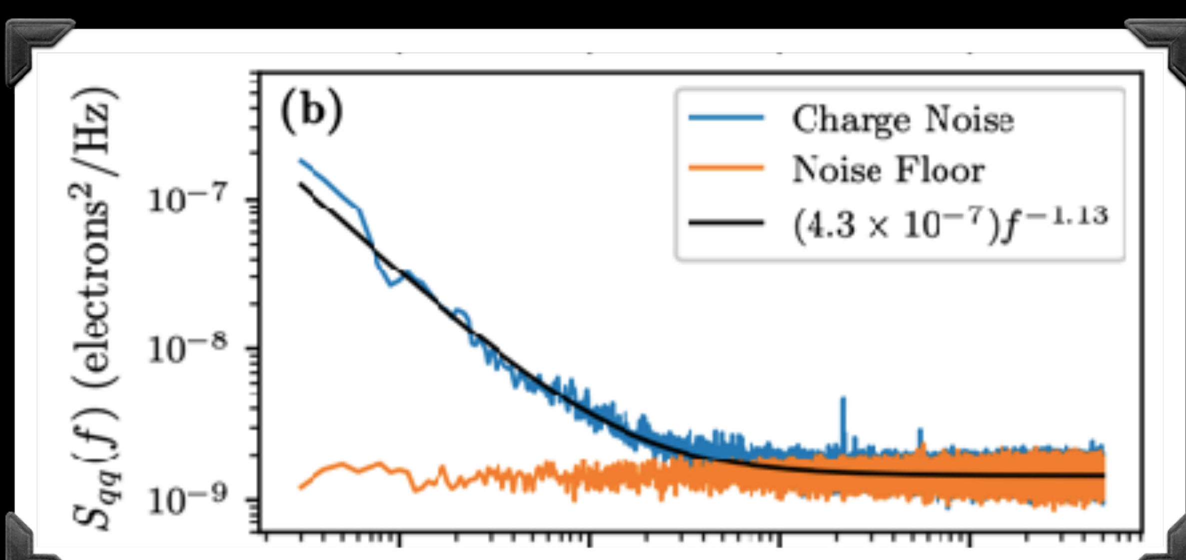
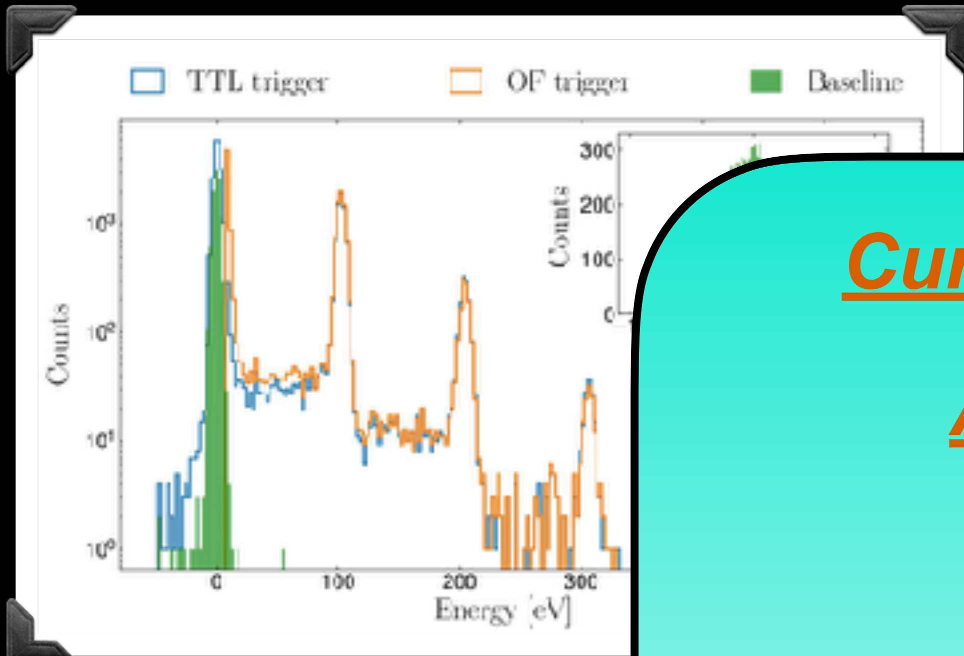
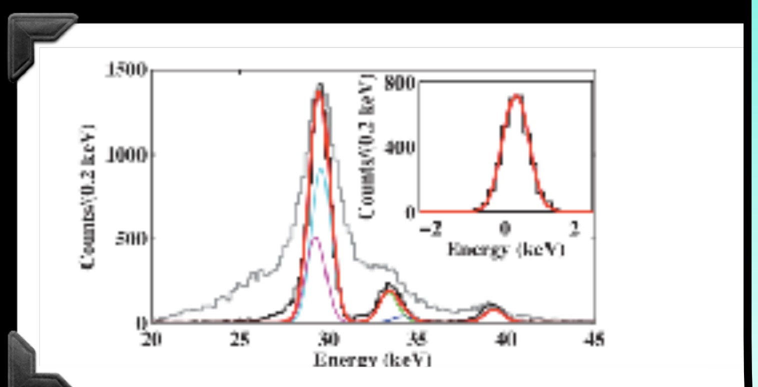
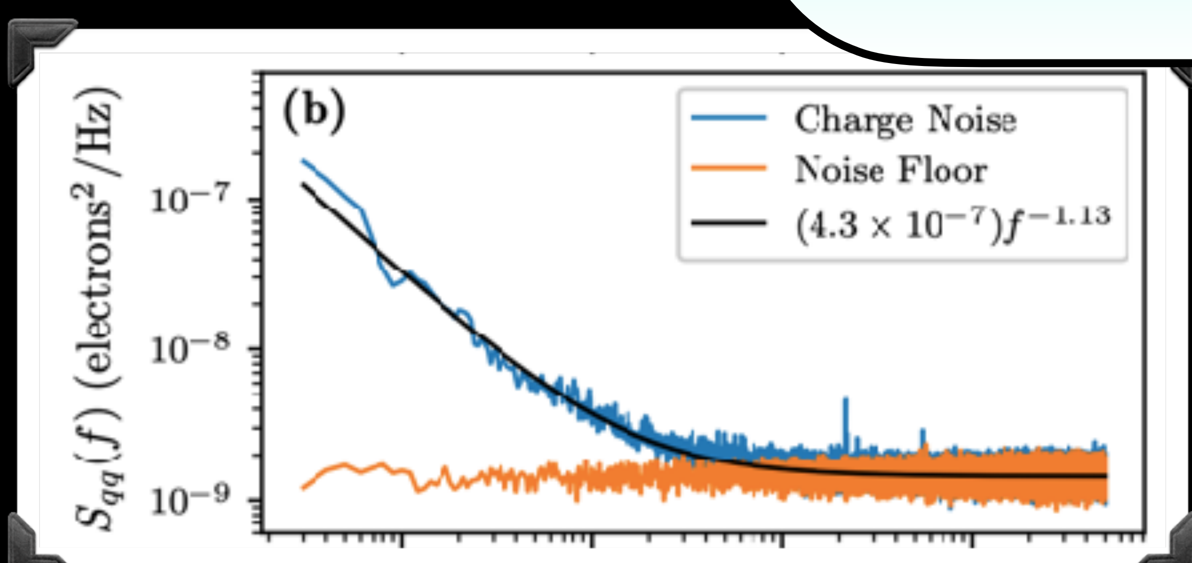


CPBs

Quantum based electrometers now achieving resolutions of σ_n = 0.01 electrons.







Current & Planned Applications

Beta decay

Direct neutrino masses

Gamma spectroscopy

BSM Physics

Recent Performance

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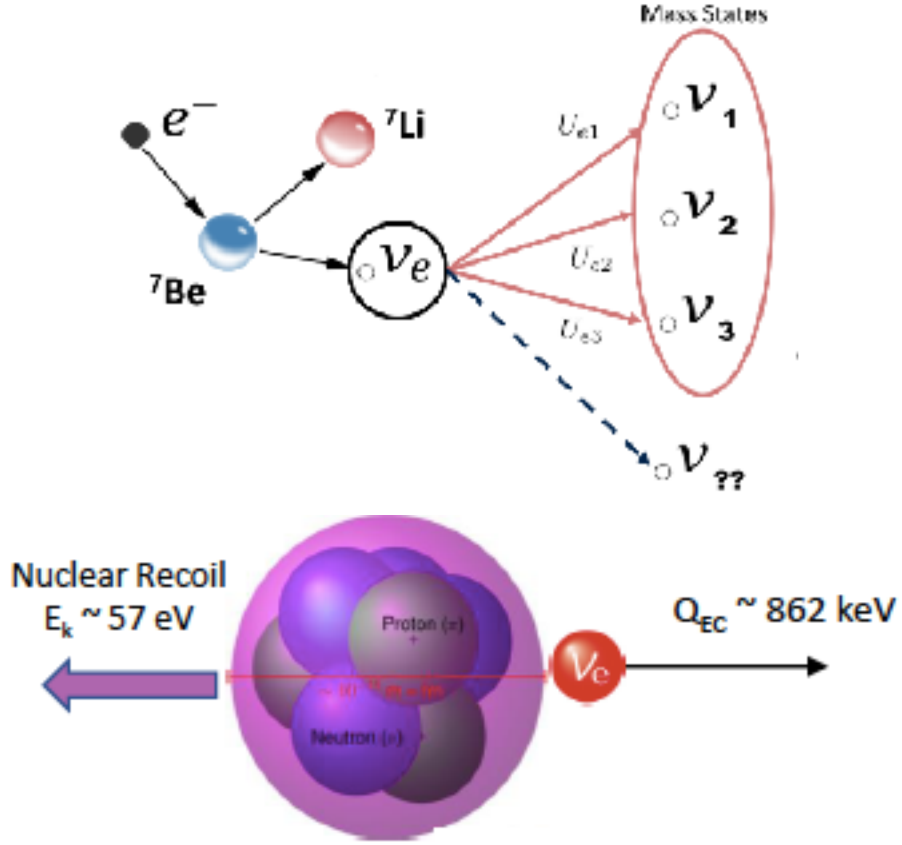
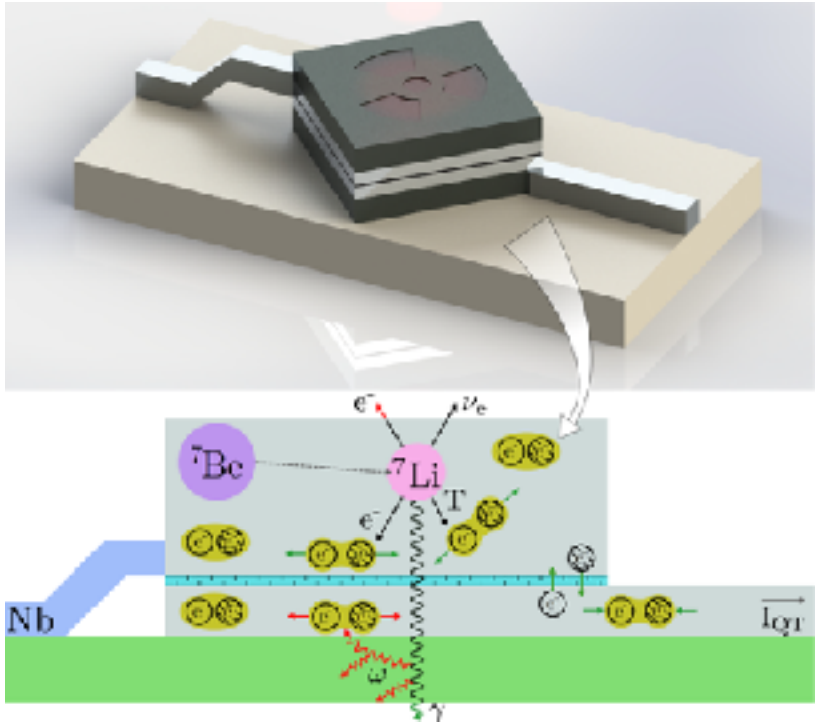
Application:
New Particle Searches

TRIUMF

Rare-isotope implantation at TRIUMF-ISAC

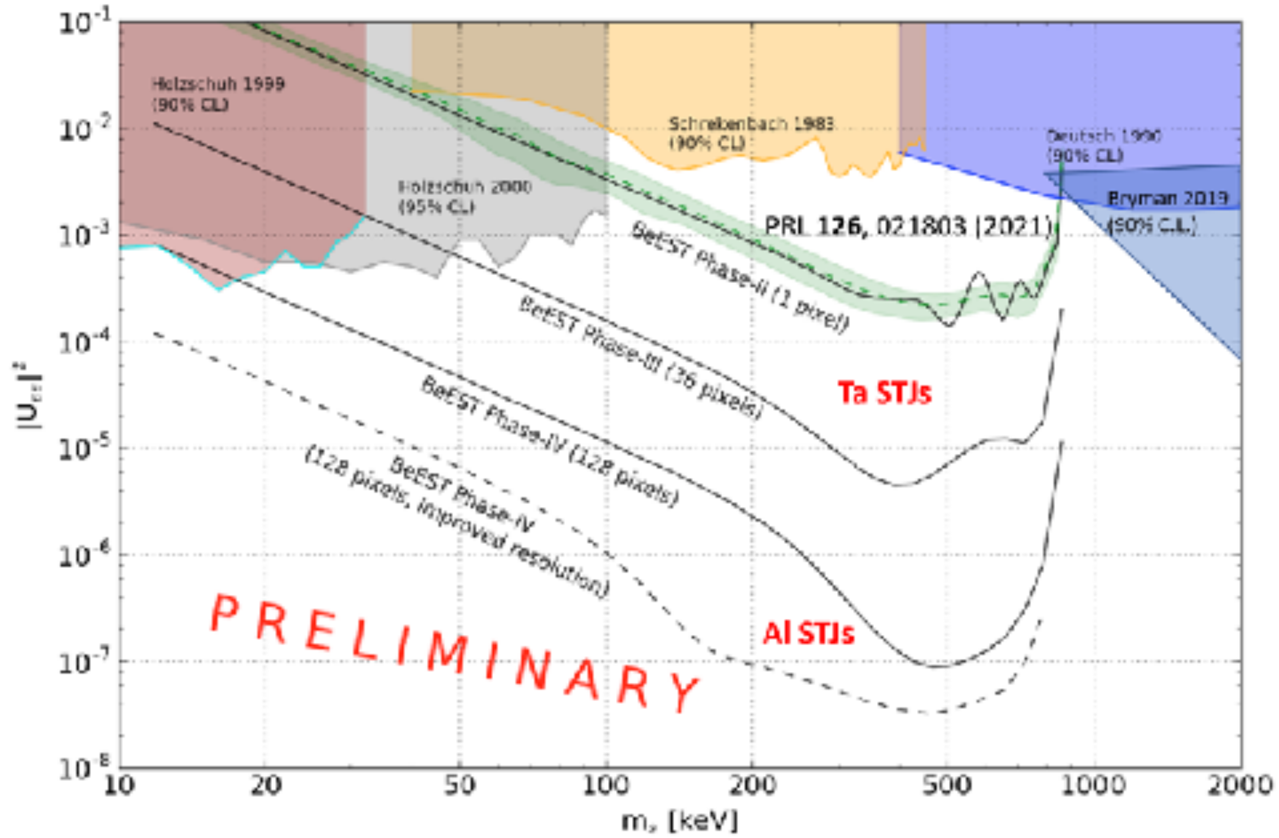




Taking advantage of the low gap energy from superconductors

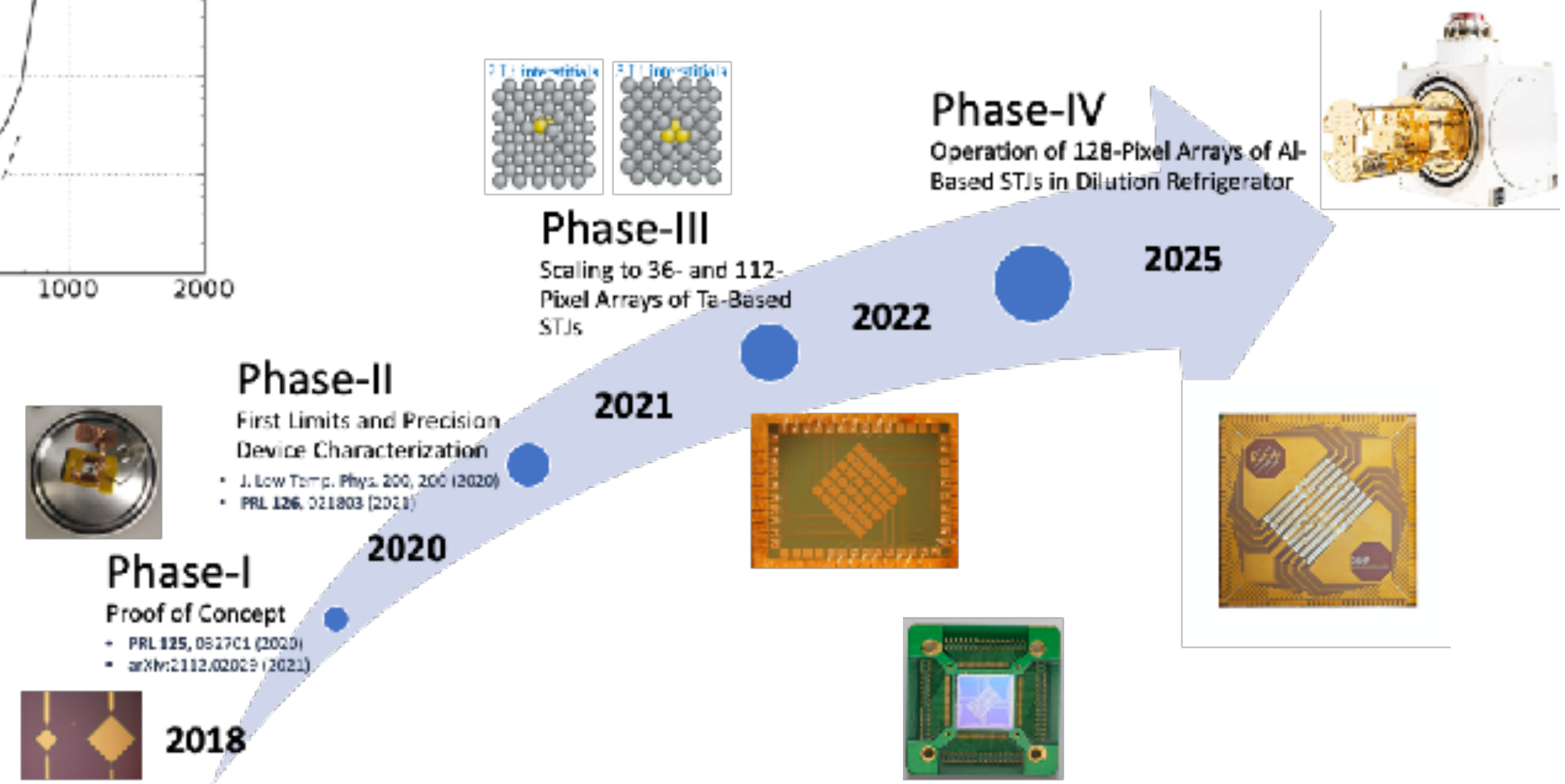
Ideal for nuclear recoil measurements.

Search for keV-scale neutrinos below the MeV scale.



Projected Sensitivity

BeEST's Phased Approach to a 128-pixel detector



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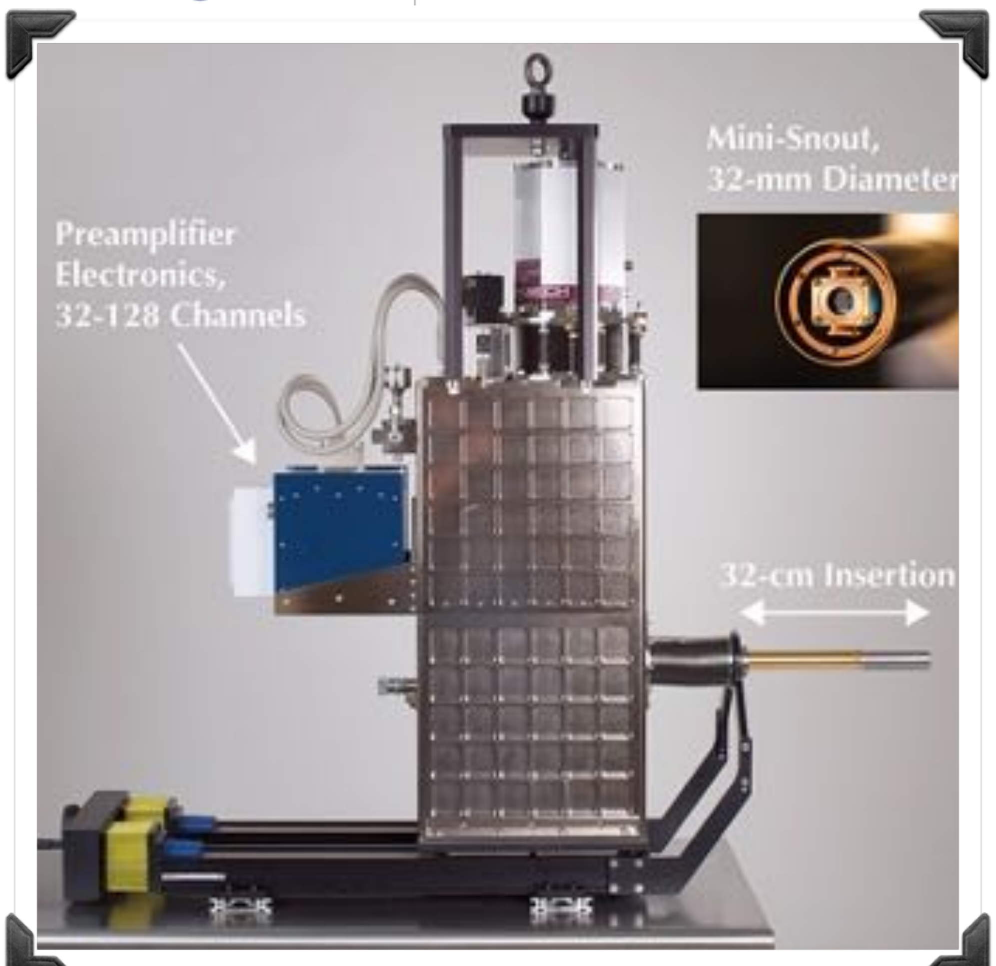
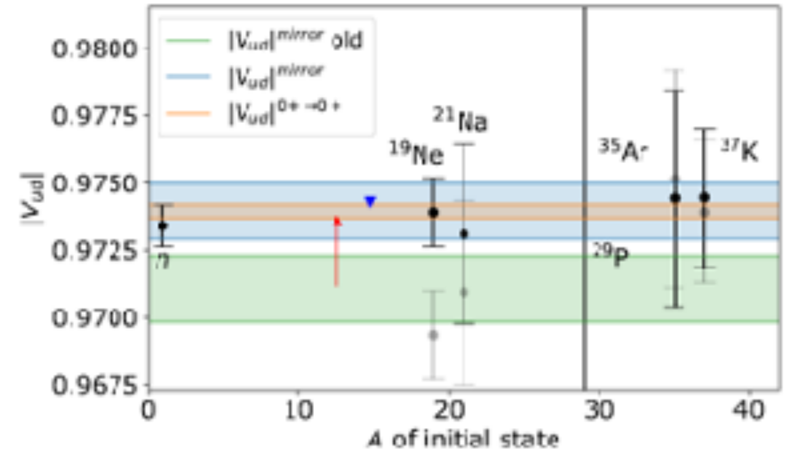
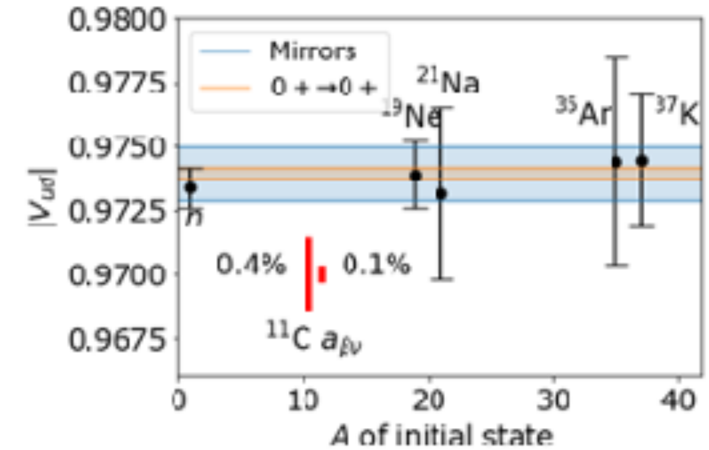
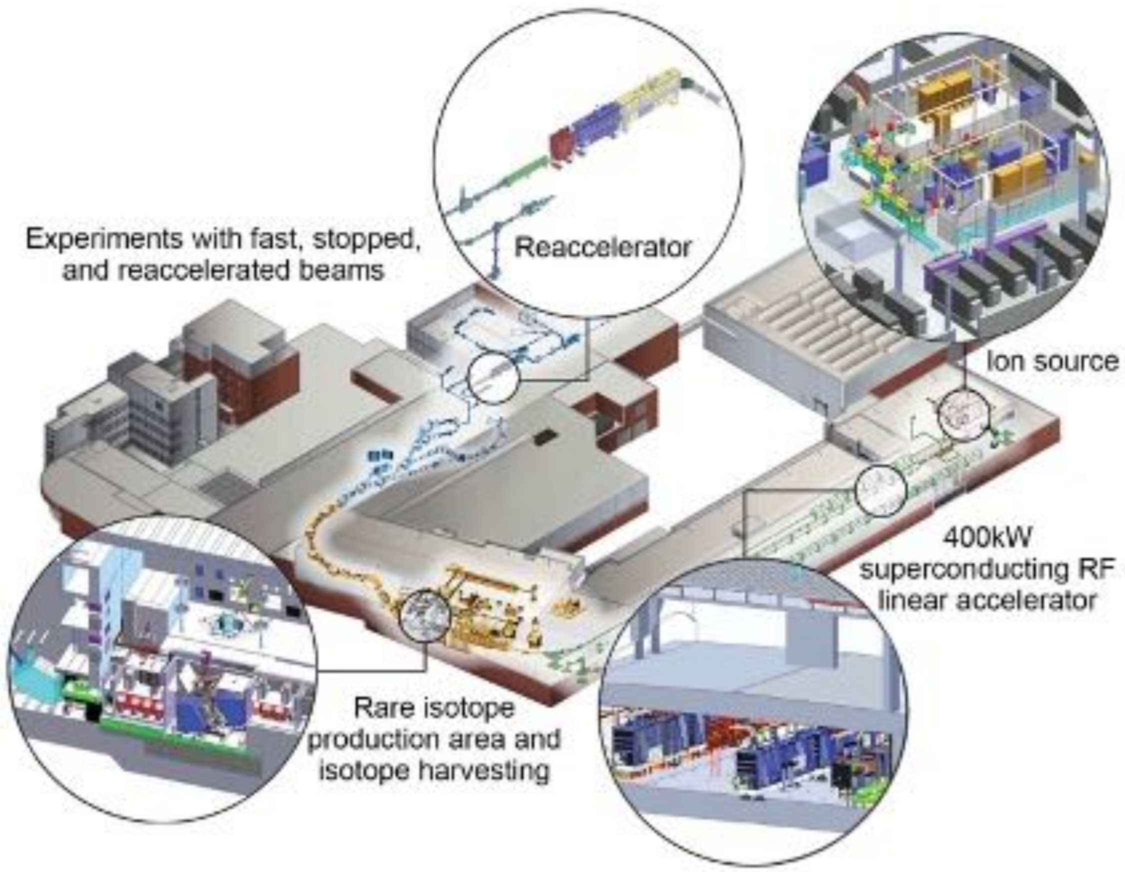
SALER @ FRIB





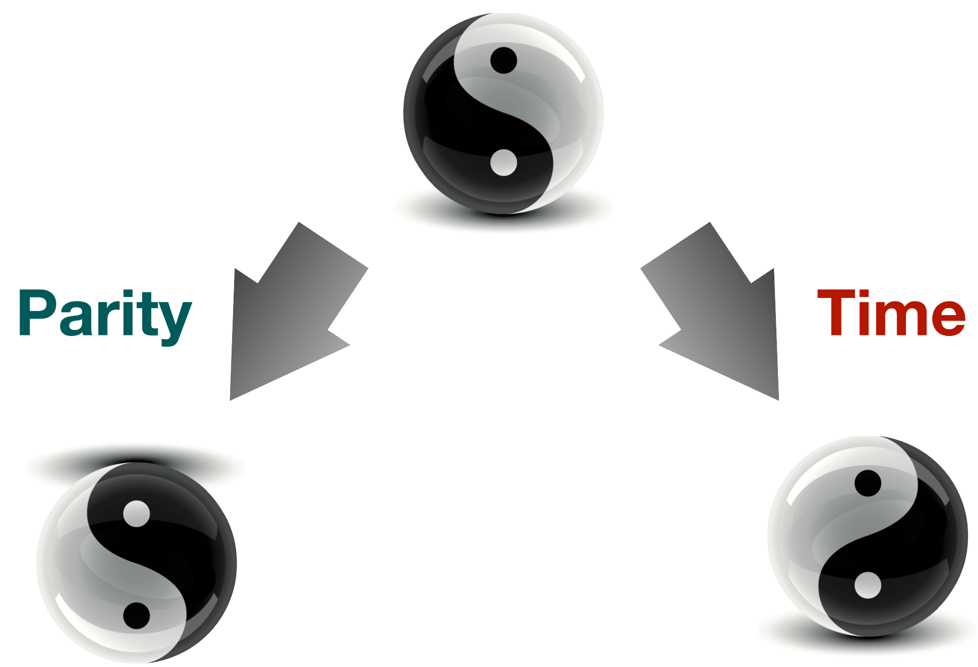




Use embedded STJ detectors to measure precisely the beta decay spectrum.

Plan to use superconducting array to measure nuclear recoil spectroscopy.

Superposition & Symmetry Tests



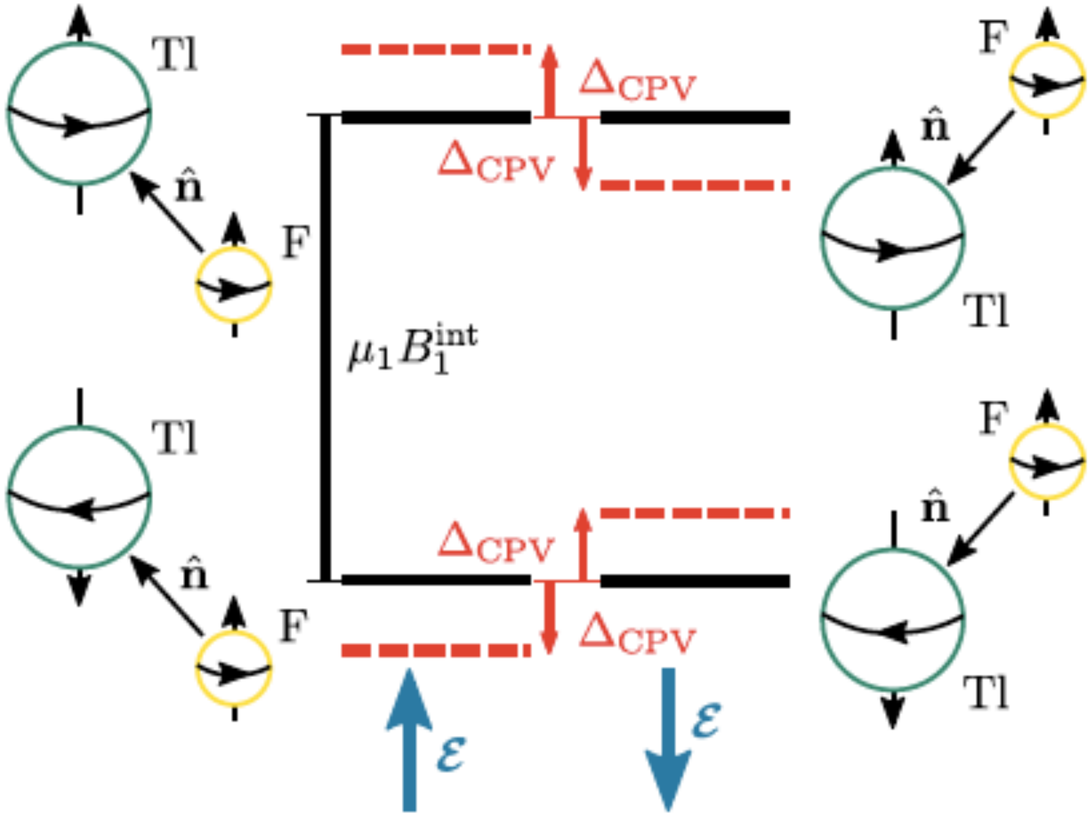
T-violation (or equivalently, Charge-Parity violation) provides insight into the nature of the observed matter anti-matter asymmetry.

Neutrons, protons, and now **molecules** provide a stringent test of CP-violation.

Sensitive to hadronic parity violation, TeV-Z′ bosons, and new physics.

Superposition & Symmetry Tests

$$\mathcal{H}_{\mathrm{CPV}} = W_S S \frac{\mathbf{I}}{I} \cdot \hat{\mathbf{n}}.$$



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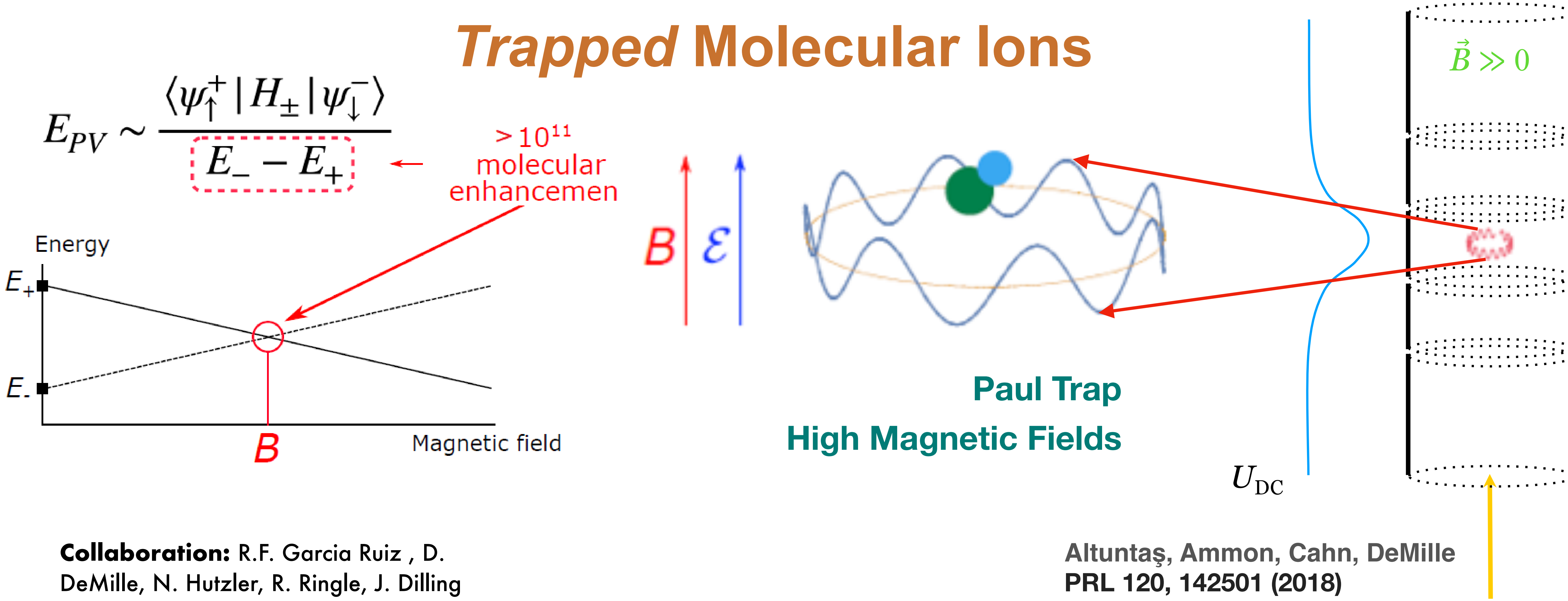
Parity Violation with *Trapped* Molecular Ions



Collaboration: R.F. Garcia Ruiz , D. DeMille, N. Hutzler, R. Ringle, J. Dilling

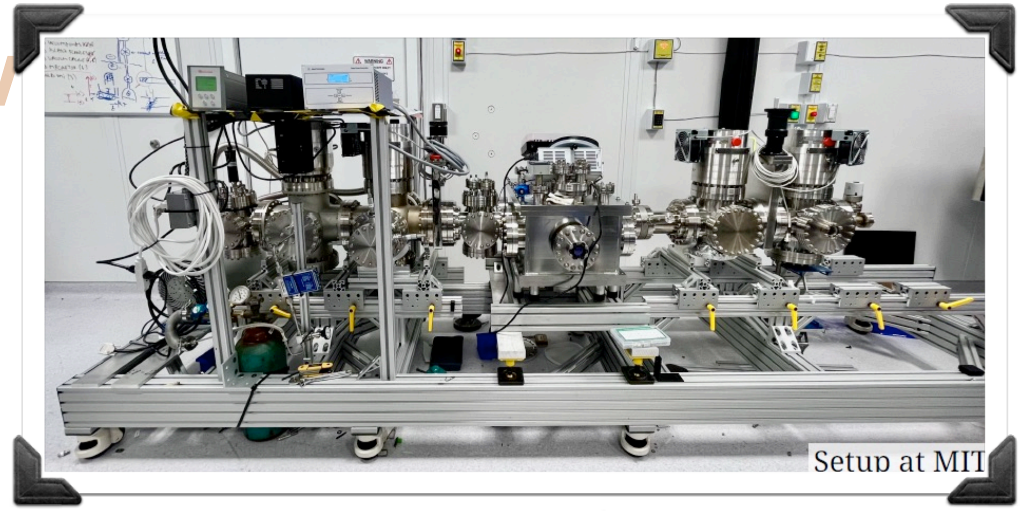
Altuntaş, Ammon, Cahn, DeMille
PRL 120, 142501 (2018)

Trap a single molecular ion in the presence of a high-magnetic field.

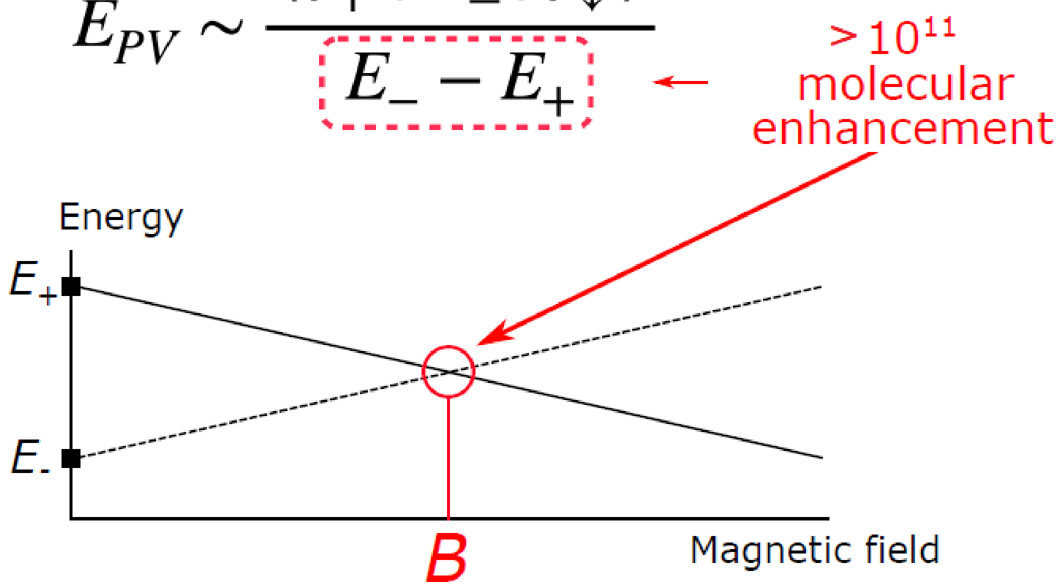
High field produces a **superposition of molecular states** of opposite parity, dramatically enhancing the sensitivity to parity violation.

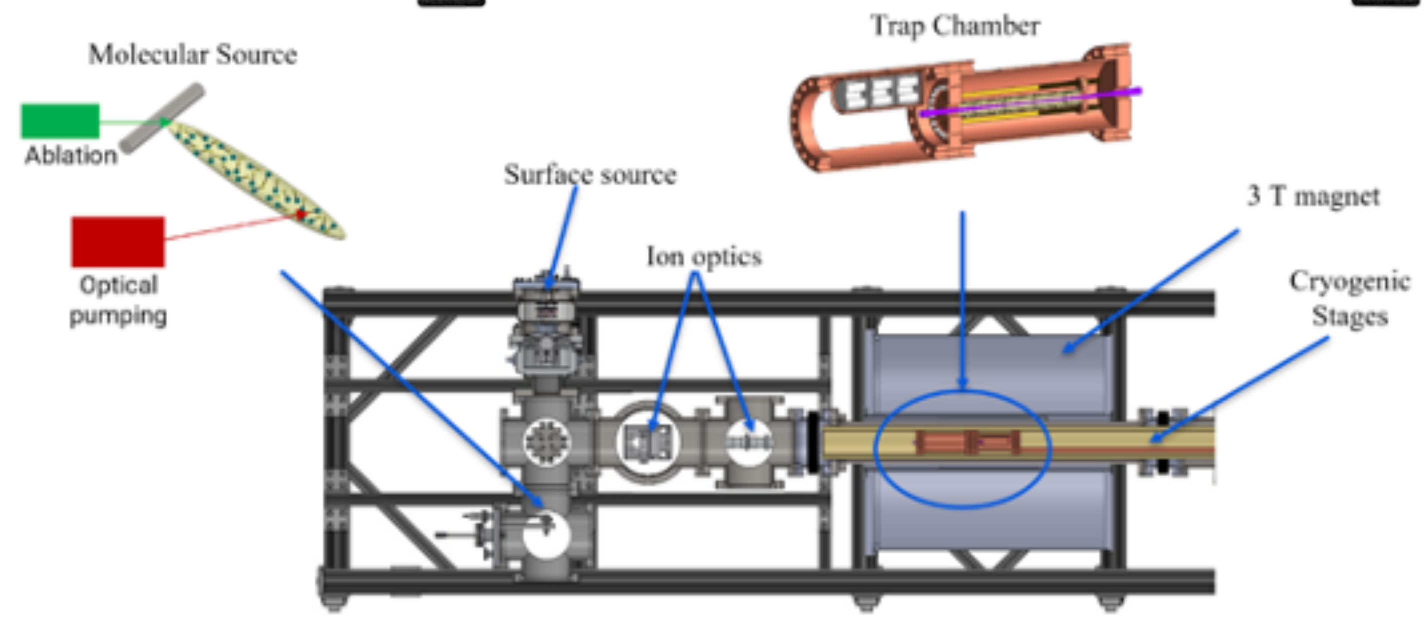
Molecule trapped in Paul trap, creating **long** interaction times for process to occur.

Parity Violation w
Trapped Molecular



$$E_{PV} \sim \frac{\langle \psi_{\uparrow}^{+} | H_{\pm} | \psi_{\downarrow}^{-} \rangle}{E_{-} - E_{+}}$$





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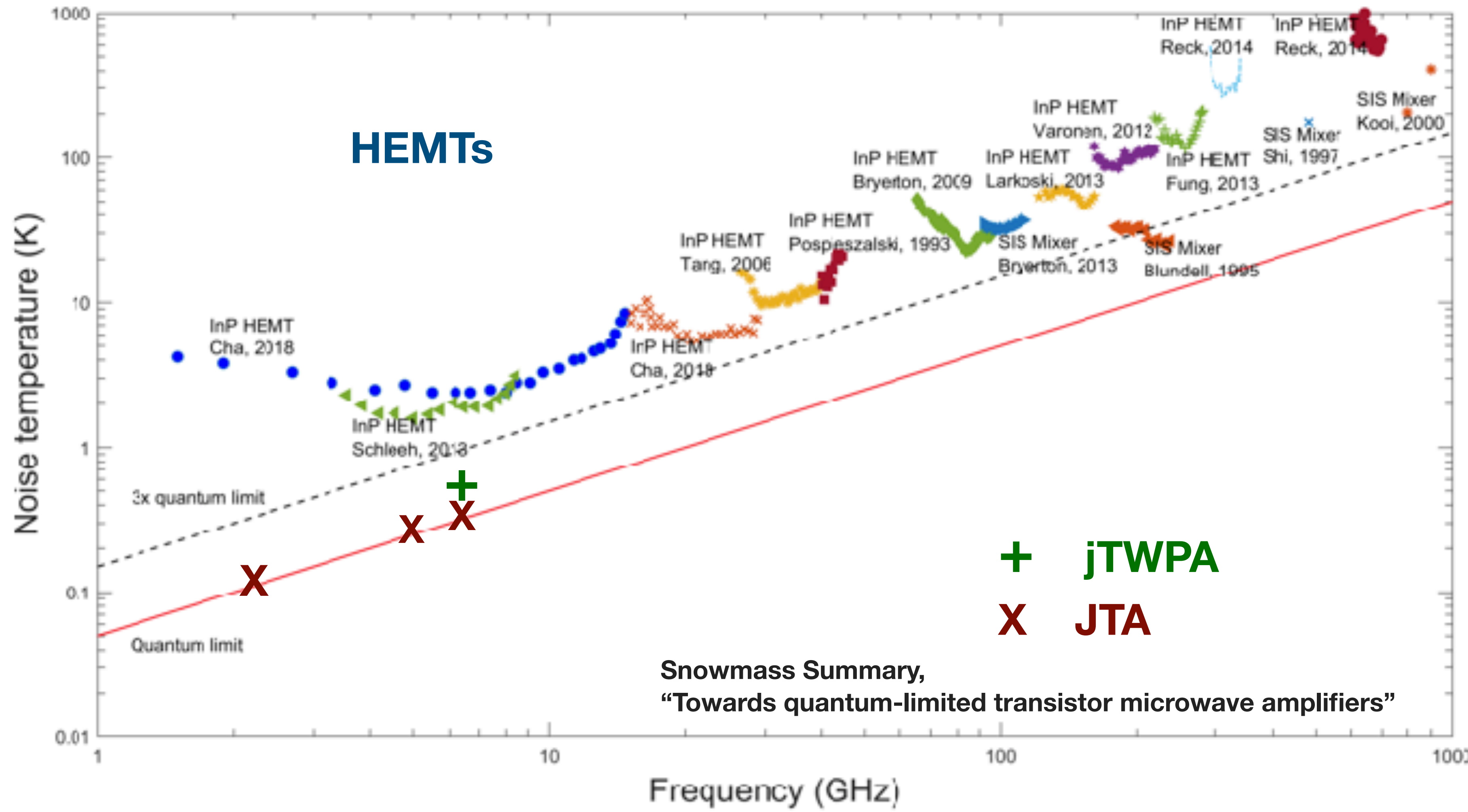
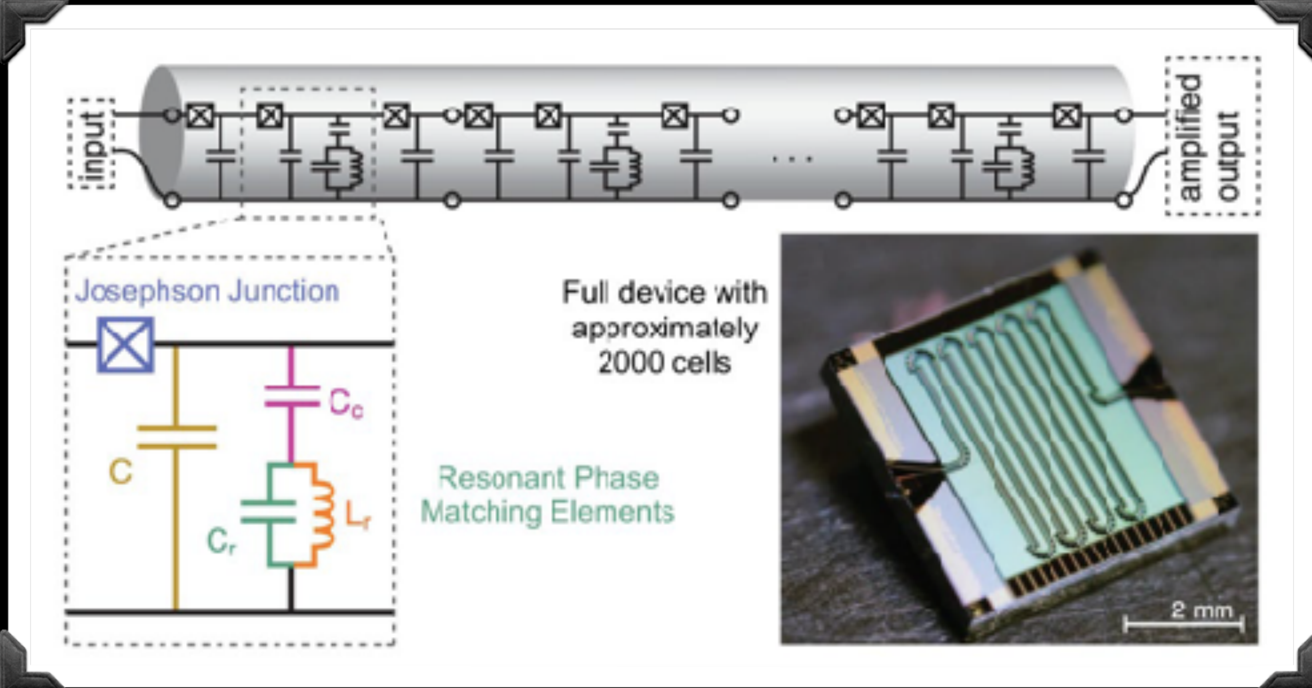
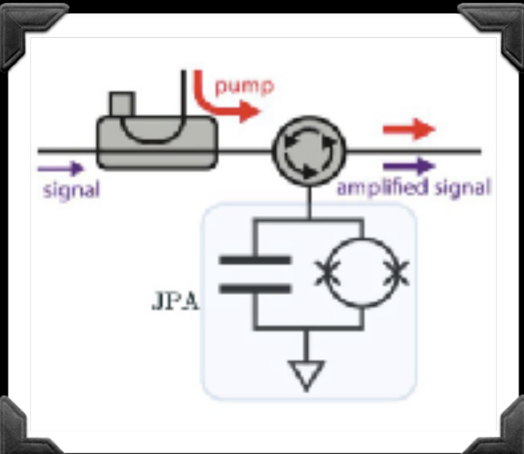
Microwave Detection at the Quantum Limit

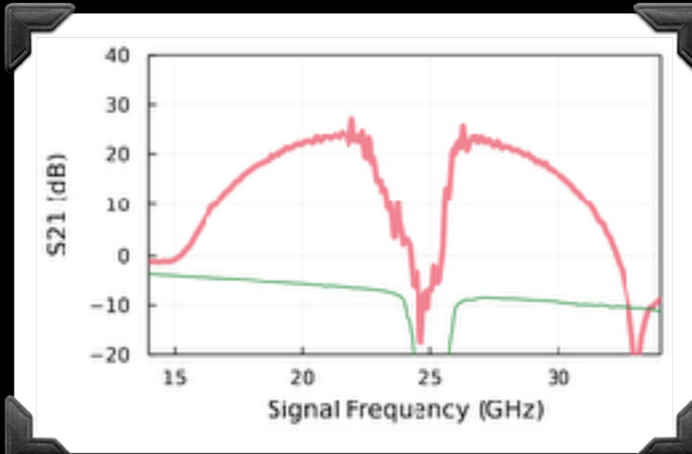


The QIS/QC community has made incredible strides in pushing microwave detection at the quantum limit for detection.

Quantum-limited amplifiers (e.g. TWPAs), Ramsey Interferometers, etc. provide optimized noise suppression with high bandwidth.





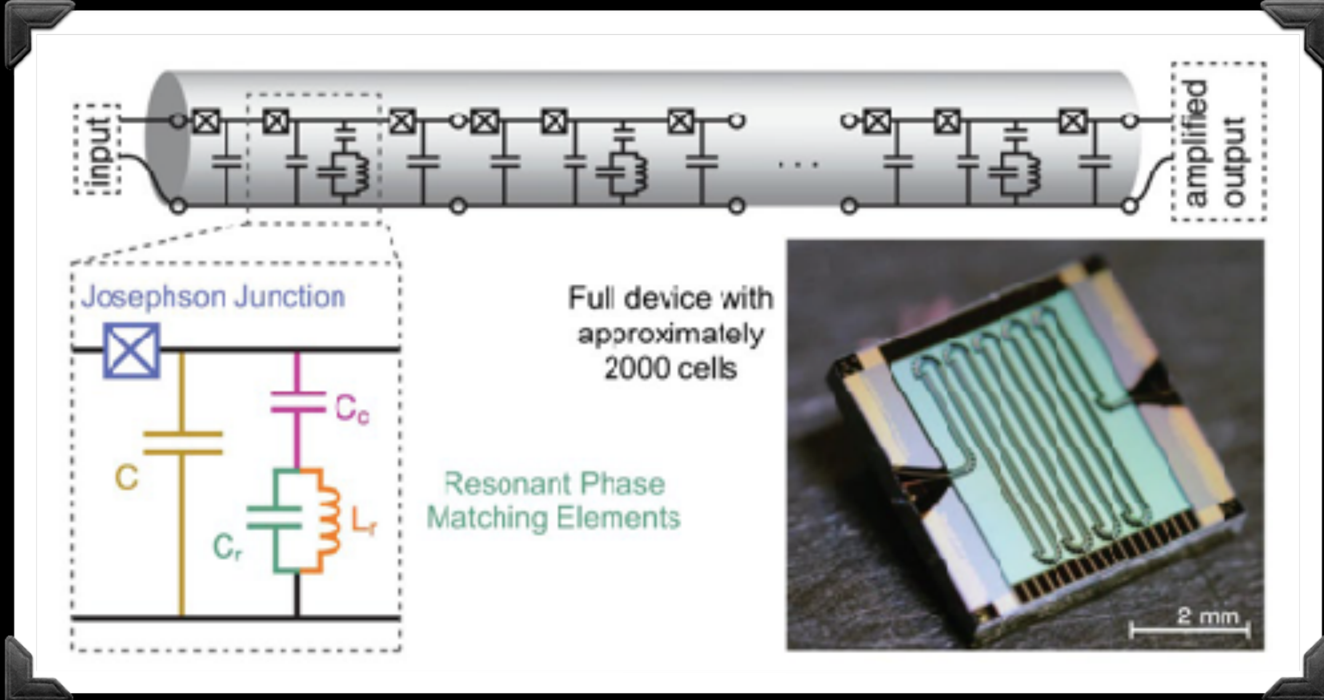


Parametric Amplifiers

JPAs (narrow band) and TWPAs (broadband) now standards in QIS, able to amplify GHz microwaves at or neat the quantum limit.

Are now being developed at both low (sub-GHz) and high (20-30) GHz regimes for different applications.

Axion searches natural application, but also for nuclear physics (e.g. Cyclotron Radiation Emission Spectroscopy).



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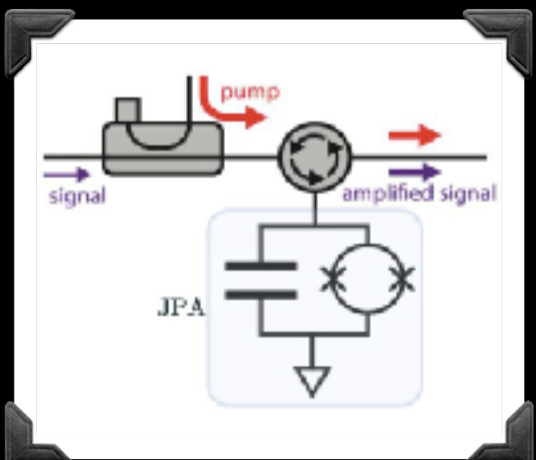
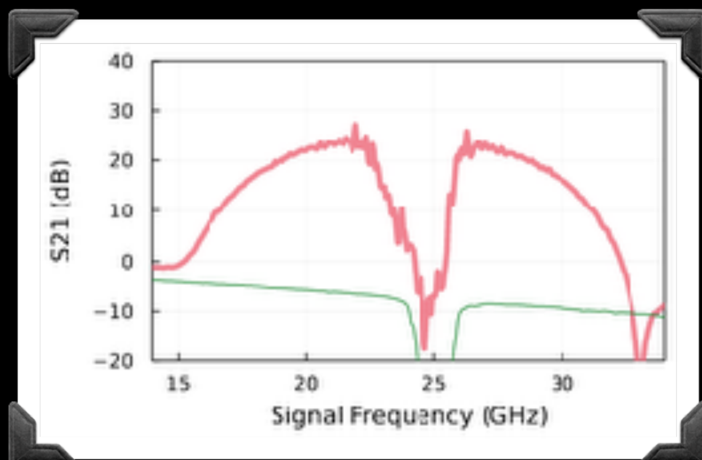
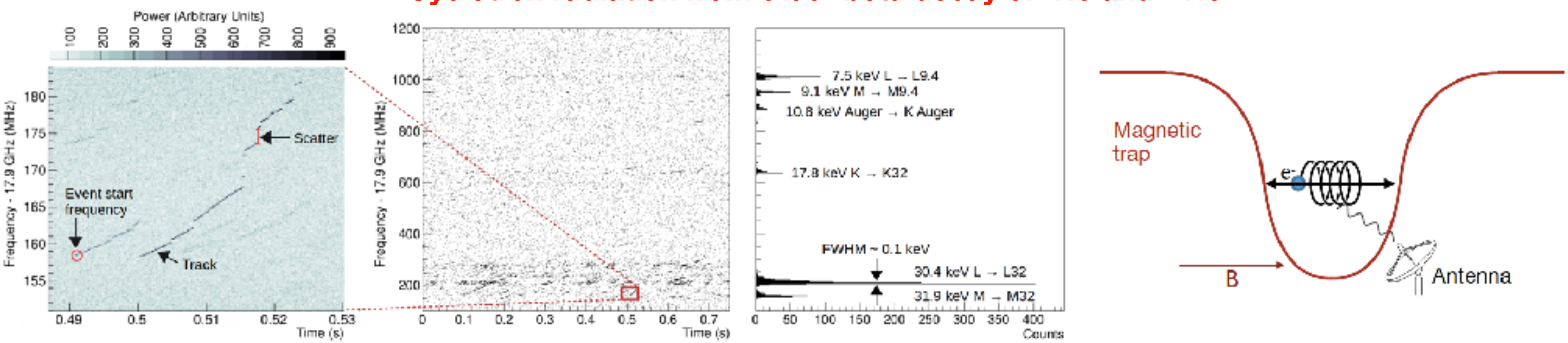
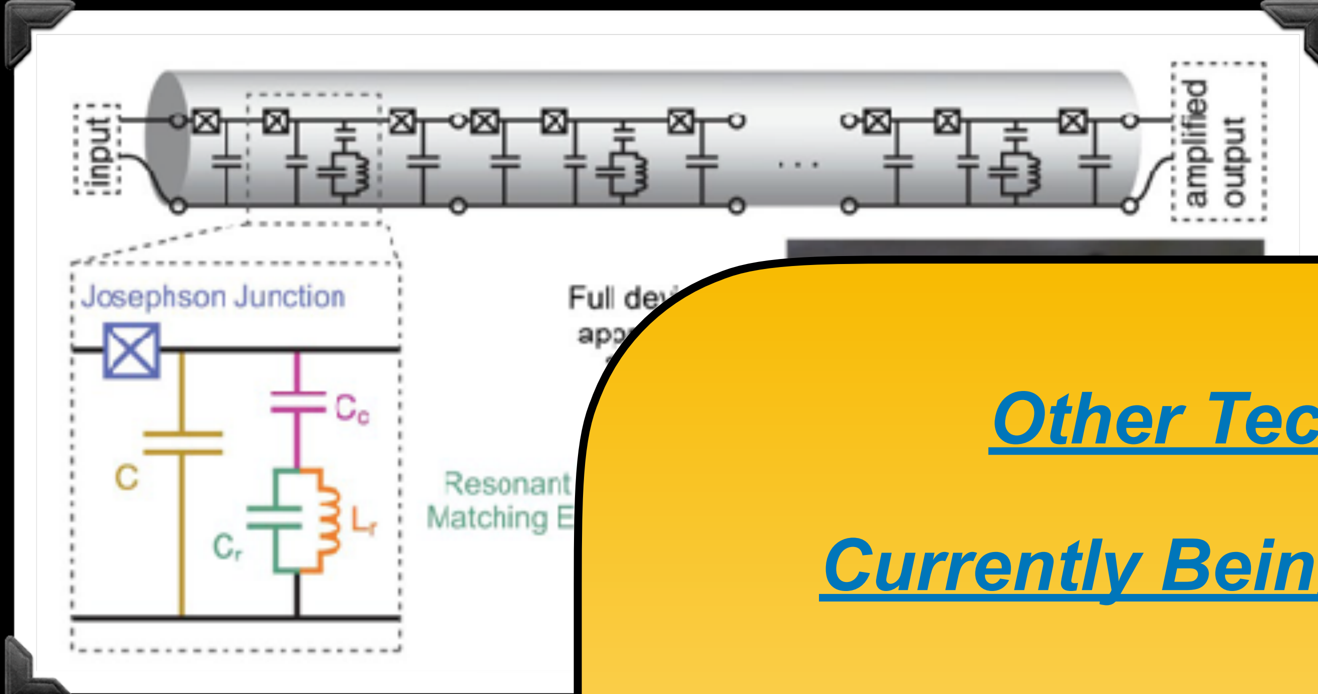




Cyclotron radiation from e+/e- beta decay of ^{6}He and ^{19}Ne



W. Byron et. Al, arXiv:2209.02870v1



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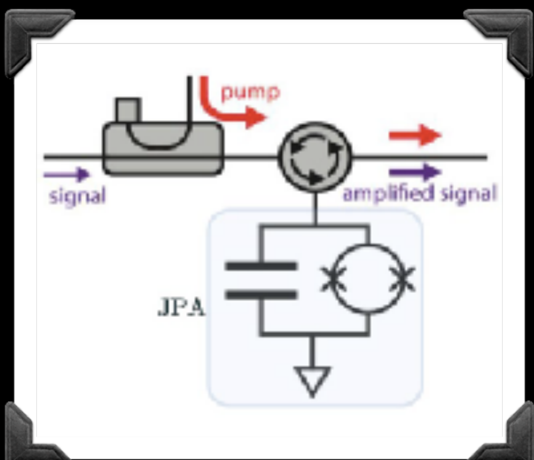


Other Techniques

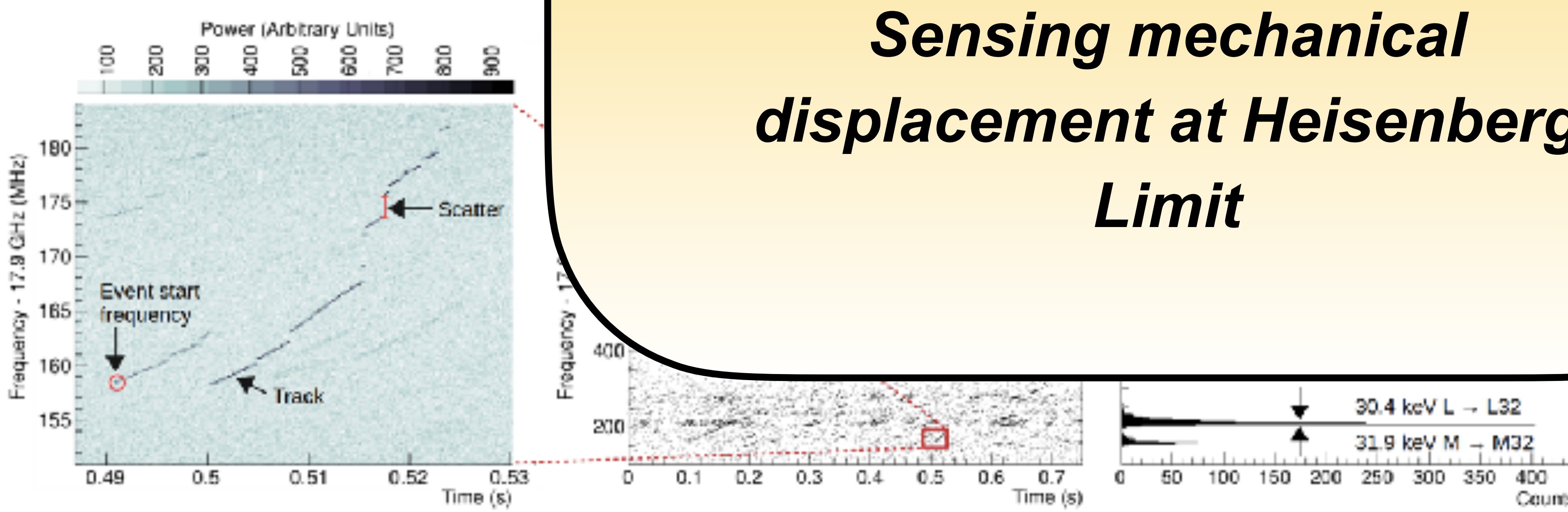
Currently Being Developed:

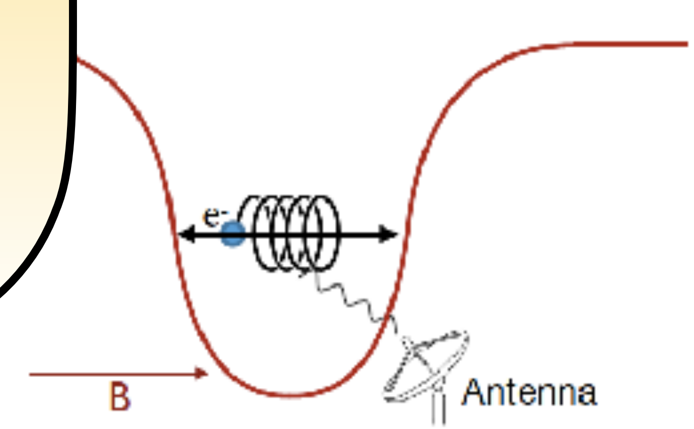
Error correction for noise in quantum sensors

Coupling quantum optics to plasmons

Sensing mechanical displacement at Heisenberg Limit

e





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If quantum systems can be used for searching for new particles and fields…

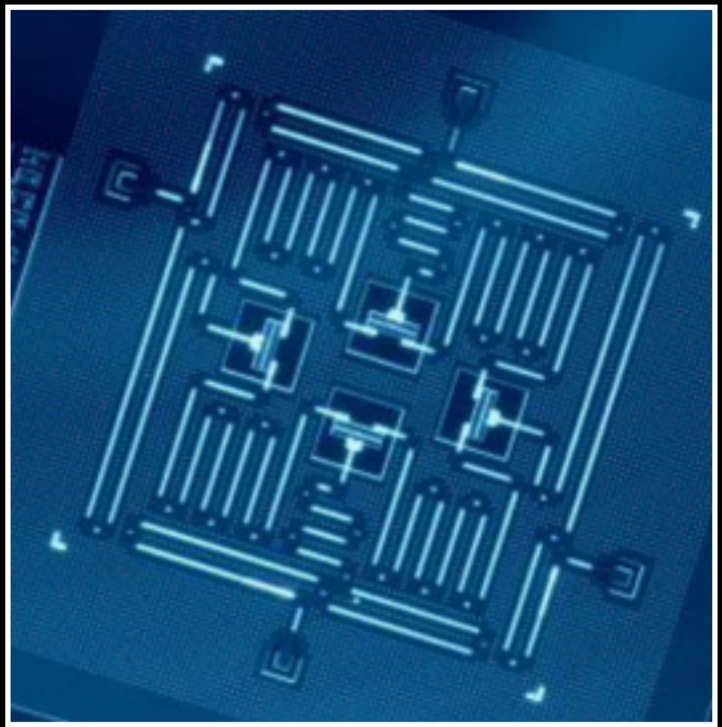
If quantum systems can be used for searching for new particles and fields…

…it should also hold that particles would affect quantum systems

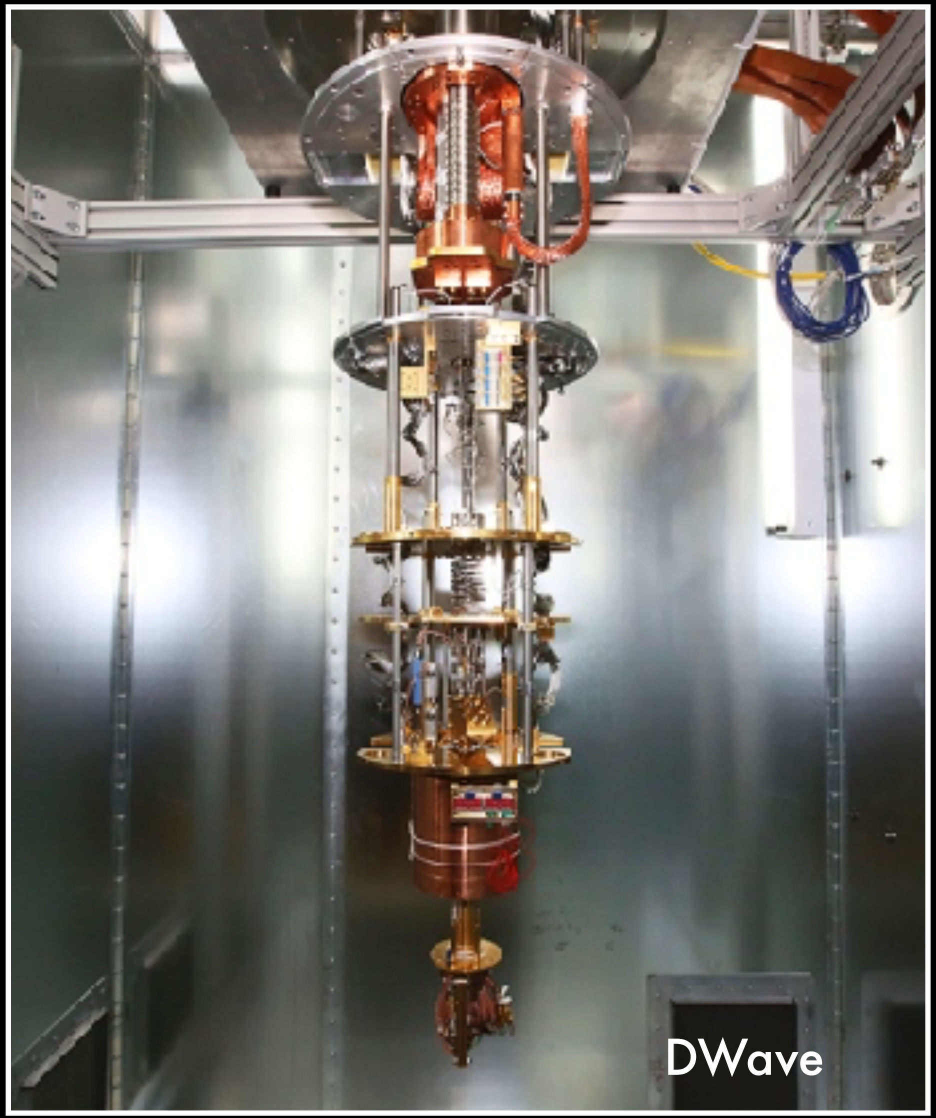
(and sometimes not for the better)

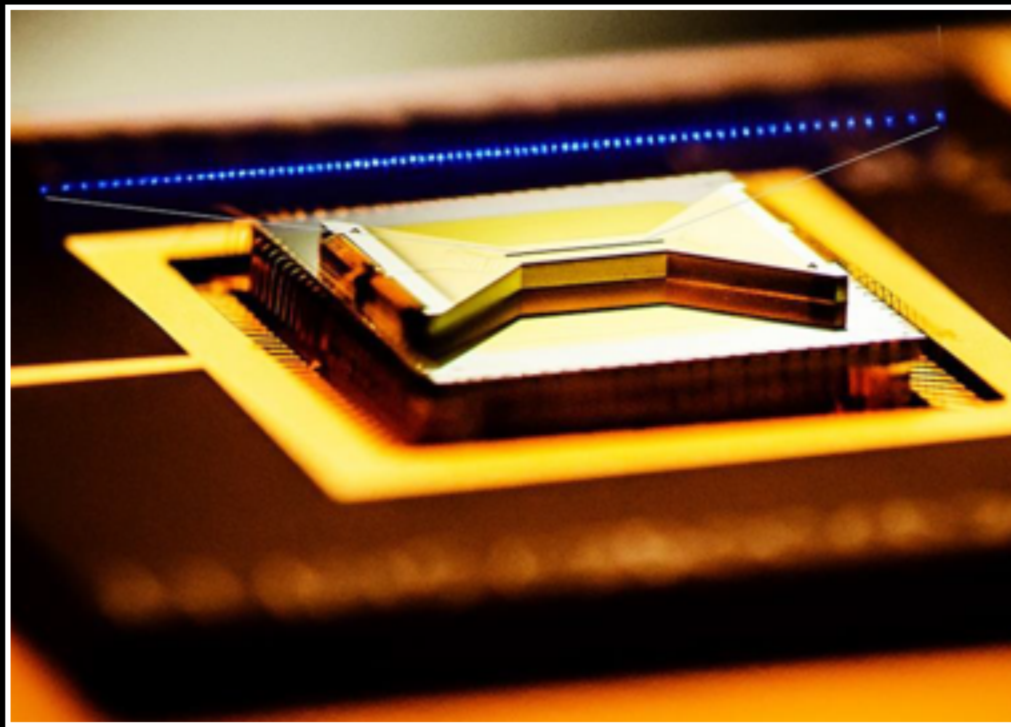
Quantum Techniques ⇐ Particles & Fields

Quantum Techniques ⇐ Particles & Fields



superconducting qubits

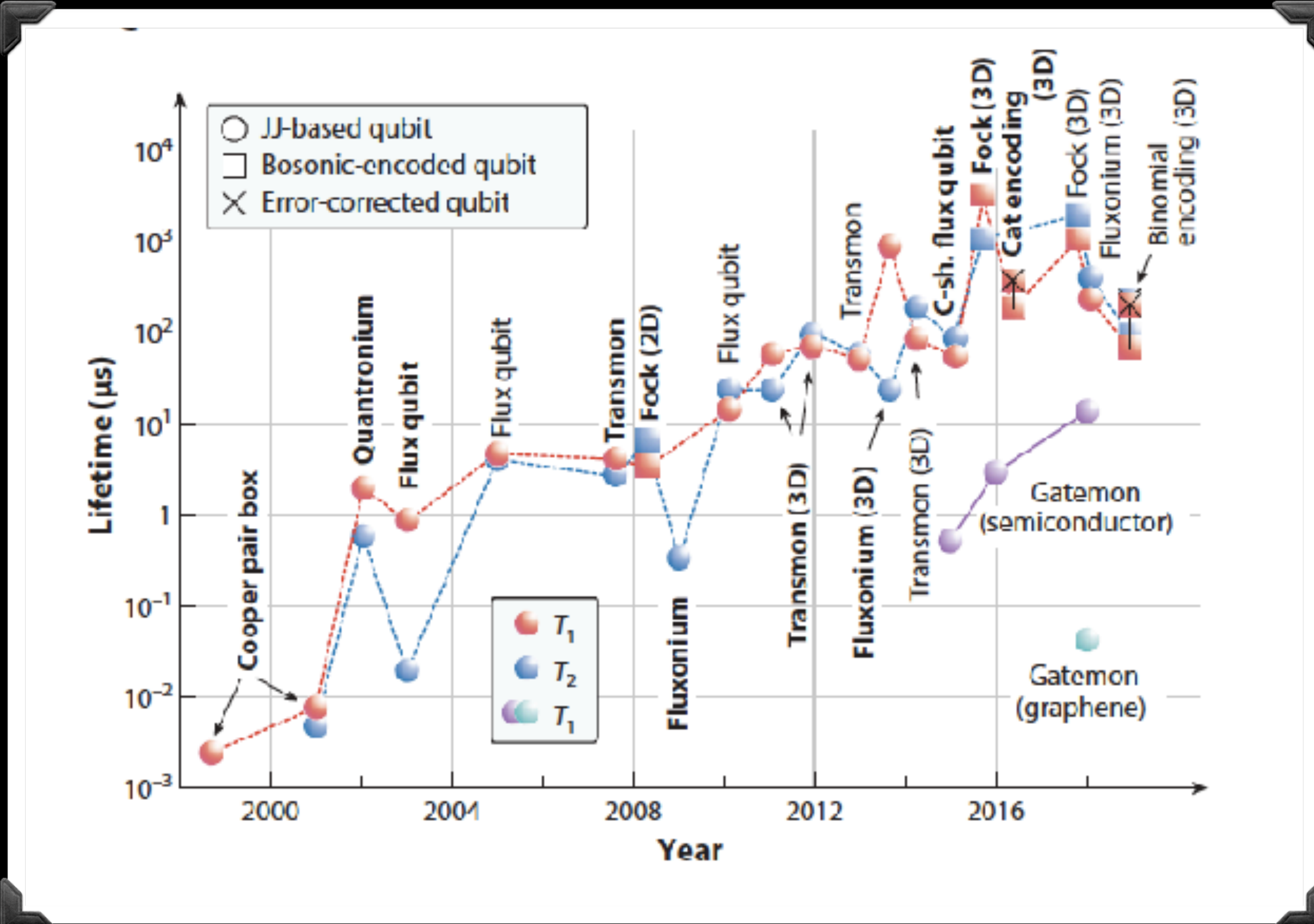




ion traps

Over the past several decades, remarkable strides have been made in developing *<u>scalable</u>* quantum systems.

Two important metrics in quantum computing include **fidelity** and **coherence** times.

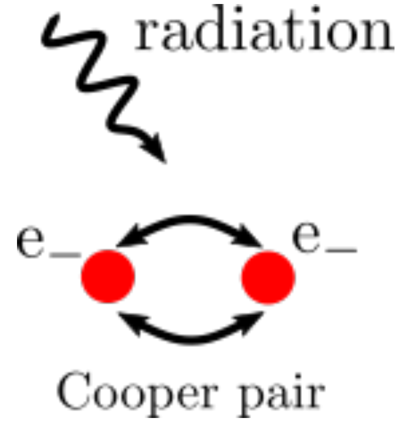


Kjaergaard et al. Annu. Rev. Condens. Matter Phys 11:369 (2020)

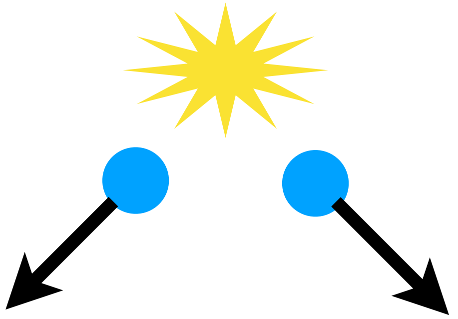
Over the past several decades, remarkable strides have been made in developing *scalable* quantum systems.

Two important metrics in quantum computing include **fidelity** and **coherence** times.

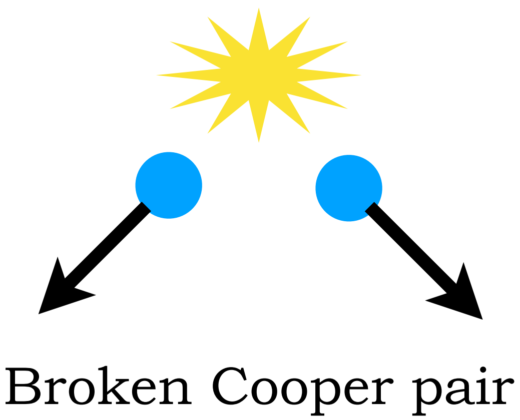
Relaxation Mechanisms



Relaxation Mechanisms


Broken Cooper pair

Relaxation Mechanisms



Quasiparticles (broken Cooper pairs / free electrons) decohere (poison) qubits.

This decoherence time is proportional to the density of quasi-particles.

$$\Gamma_q = \sqrt{2\omega_{01}\Delta/\pi^2\hbar}\, x_{qp} + \Gamma_{\text{other}}$$

ω_{01} = qubit frequency

Δ = s.c. gap

$x_{qp} = n_{qp}/n_{cp}$ =quasi-particle fraction

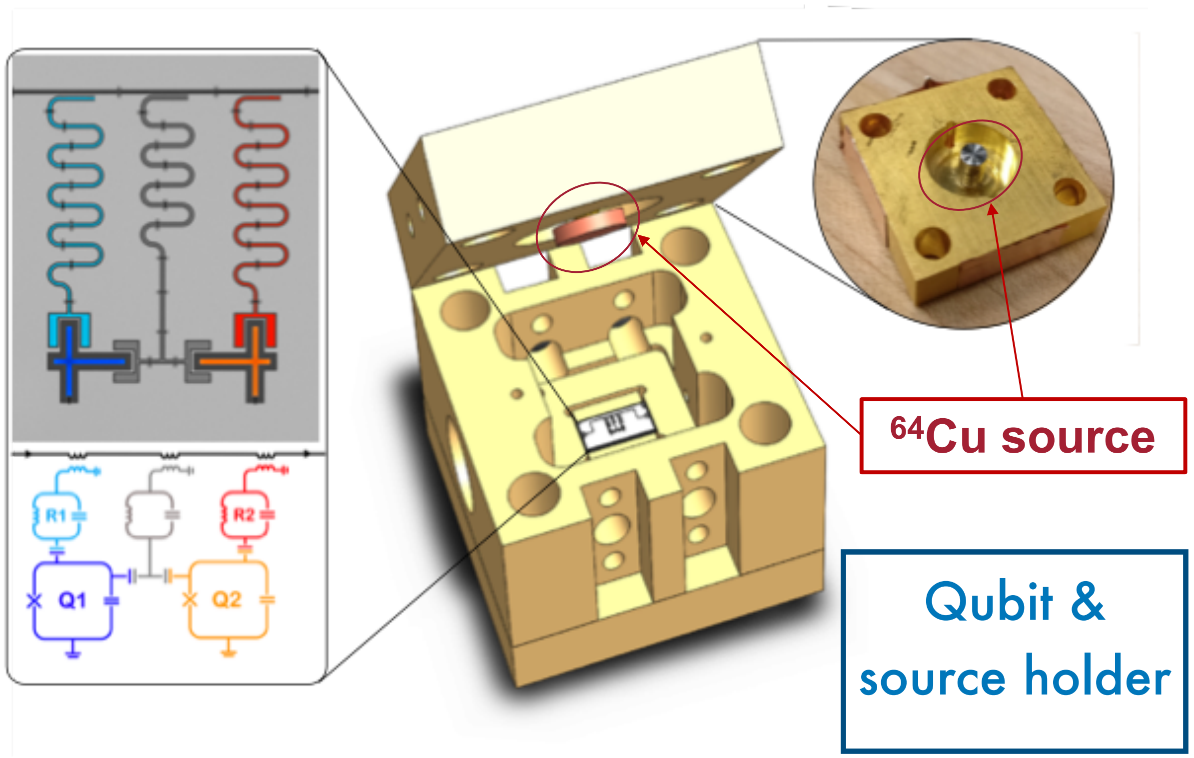
Equilibrium QP density at 40 mK

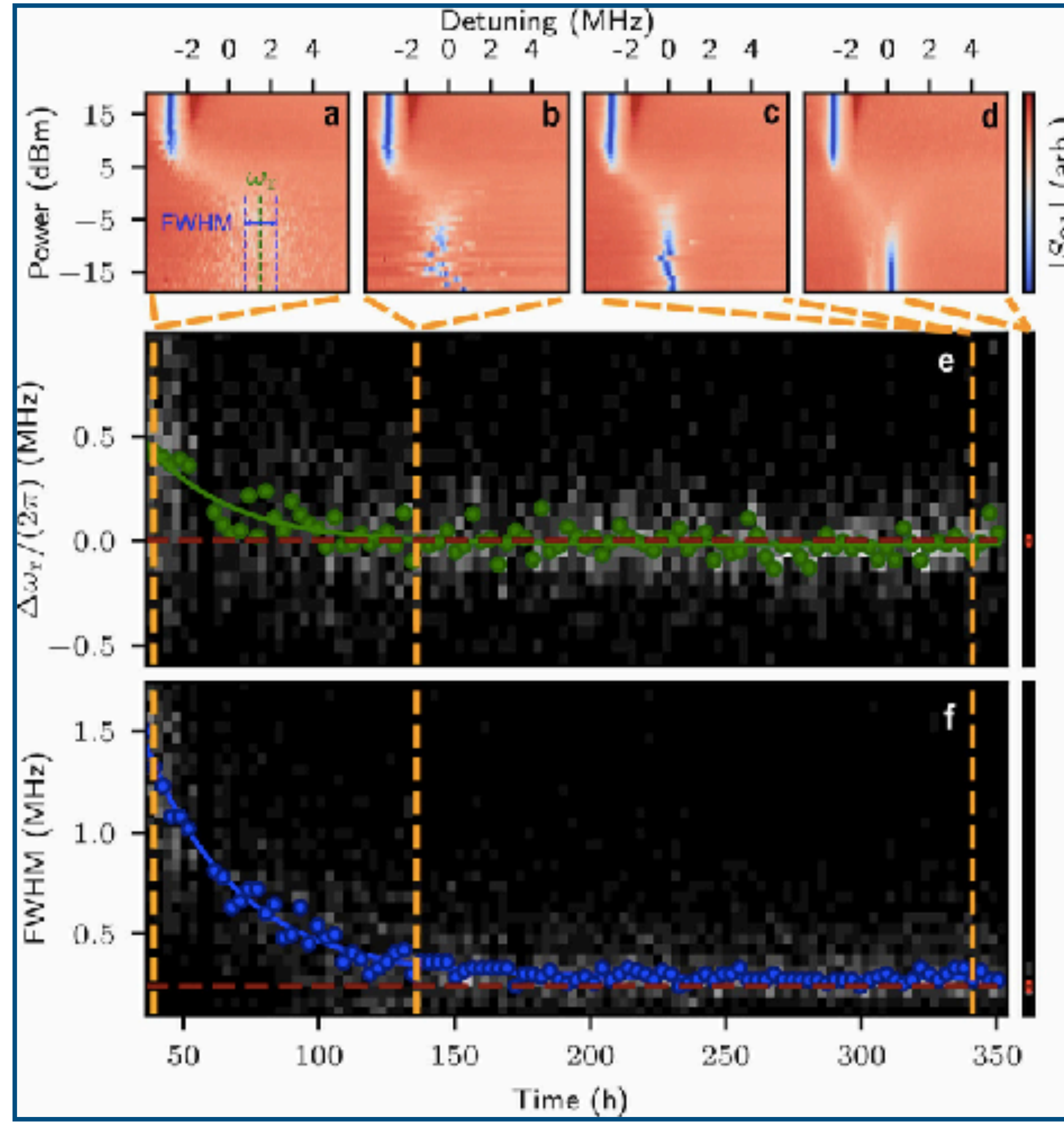
$X_{qp} \approx 10^{-24}$

Observed

$X_{qp} \approx 10^{-6} - 10^{-9}$

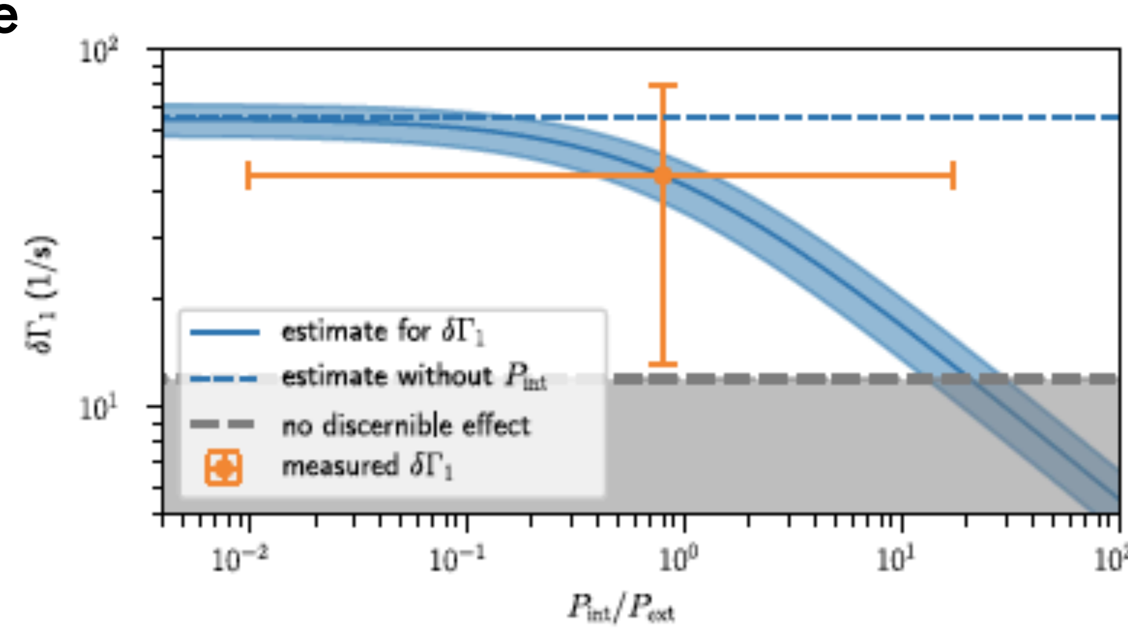
Decoherence from Ionization





Using a short-lived ^{64}Cu β-source, we could link/calibrate qubit coherence with source intensity.

Shielding the qubits showed improvement in coherence times.



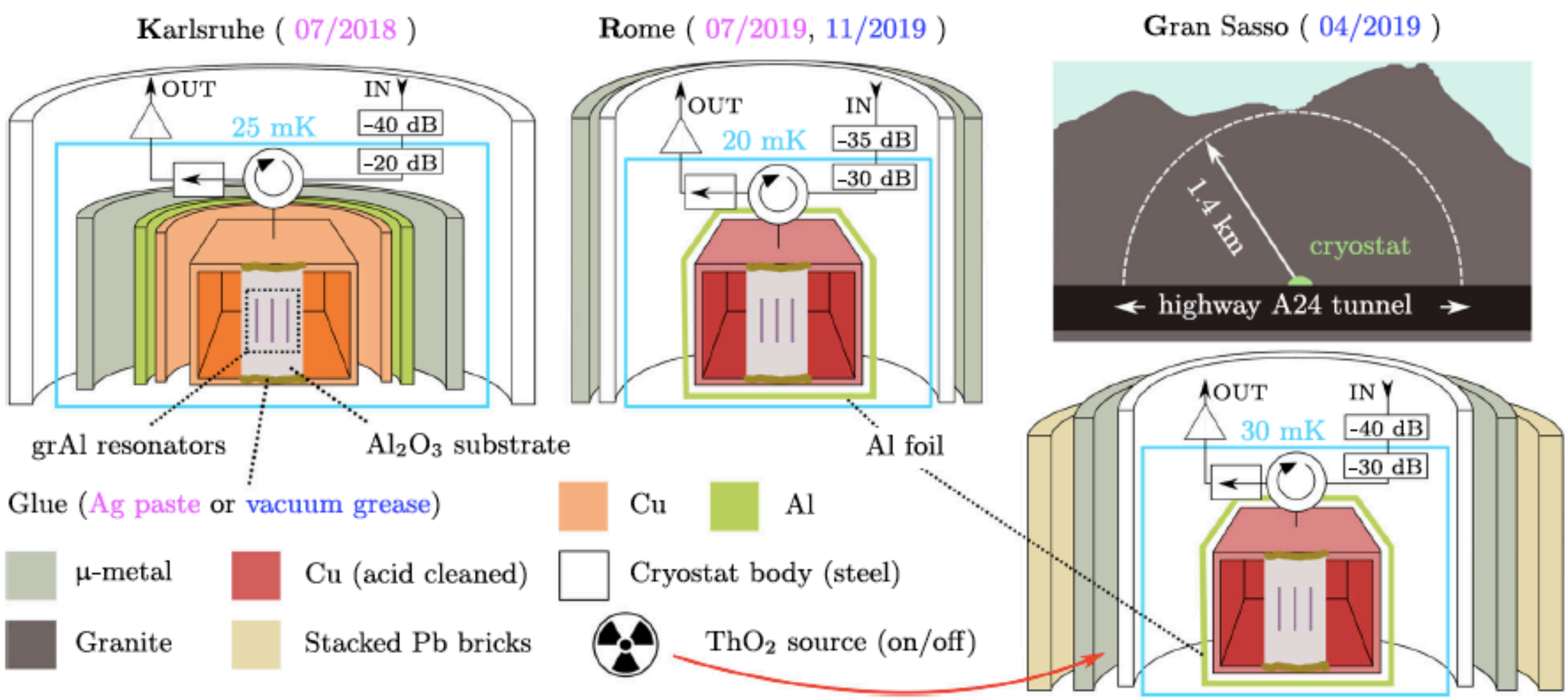
Nature
Antti Vepsäläinen et al volume 584, 551–556 (2020)

Underground Shielding

Nature Communications
Cardani et al.
v 12, Article number: 2733 (2021)

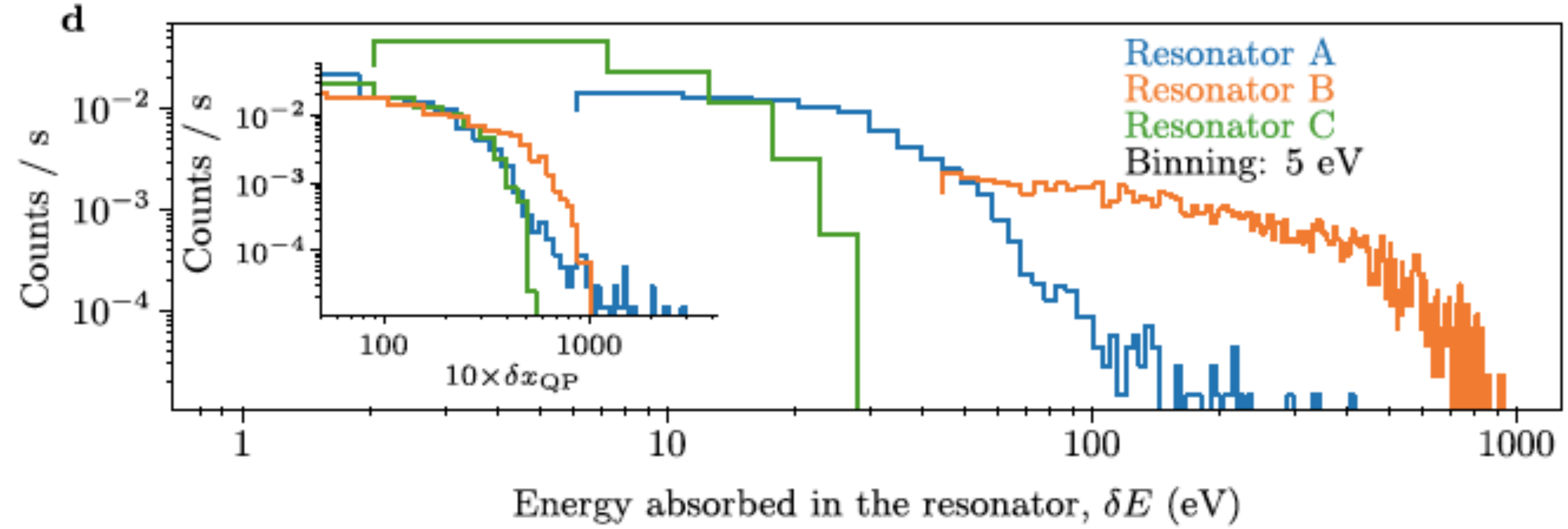
Typical shielding & overburden
(**K**arlsruhe & **R**ome)

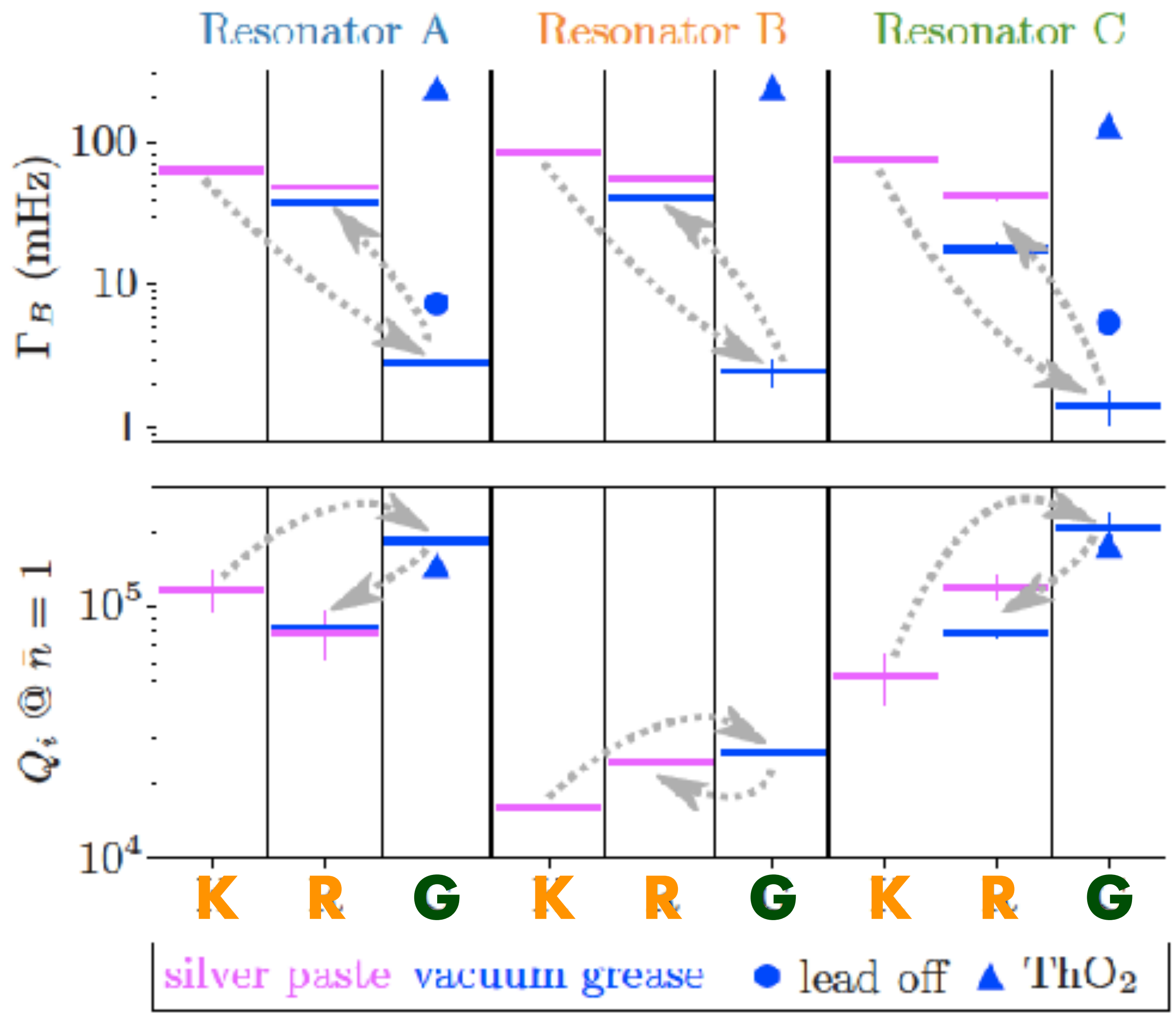
Pb shielding/Underground
(**G**ran Sasso)



Cardani et. al also observe how shielding improves performance of qubit resonators when shielded by cosmic rays and/or lead shielding (Gran Sasso).

Underground Shielding





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Pb shielding/Underground
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Nature Communications
Cardani et al.
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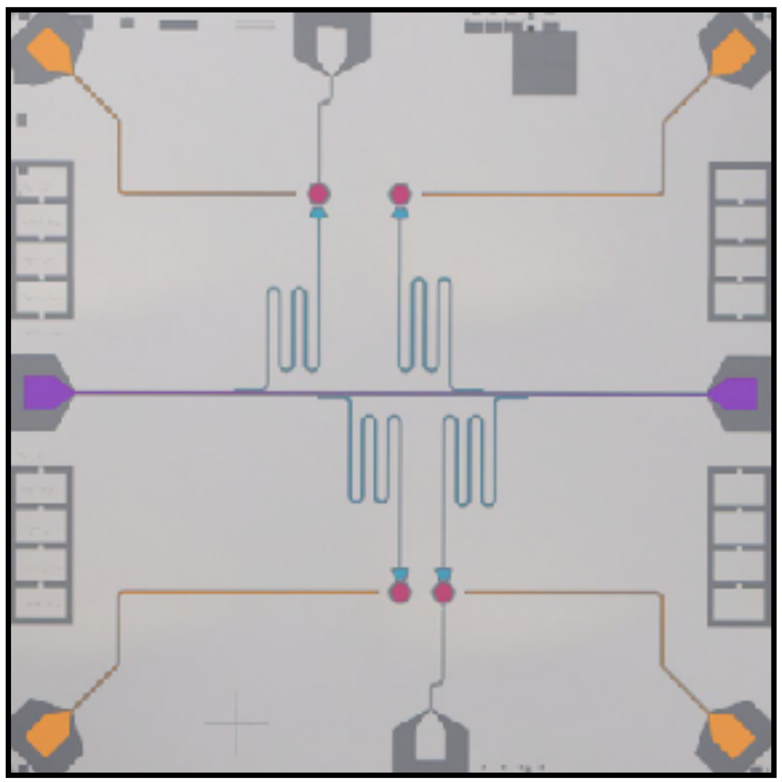
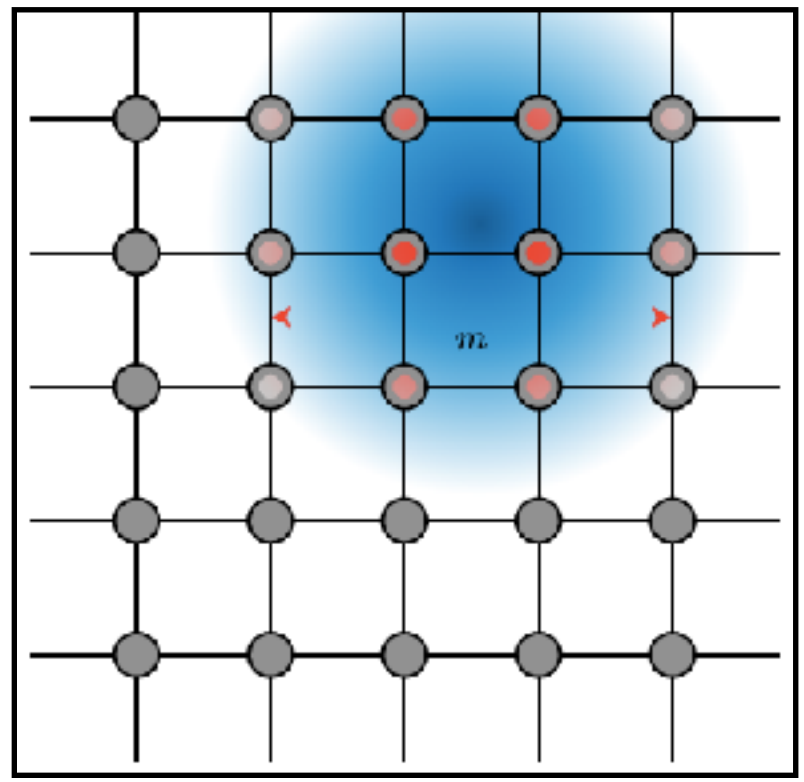
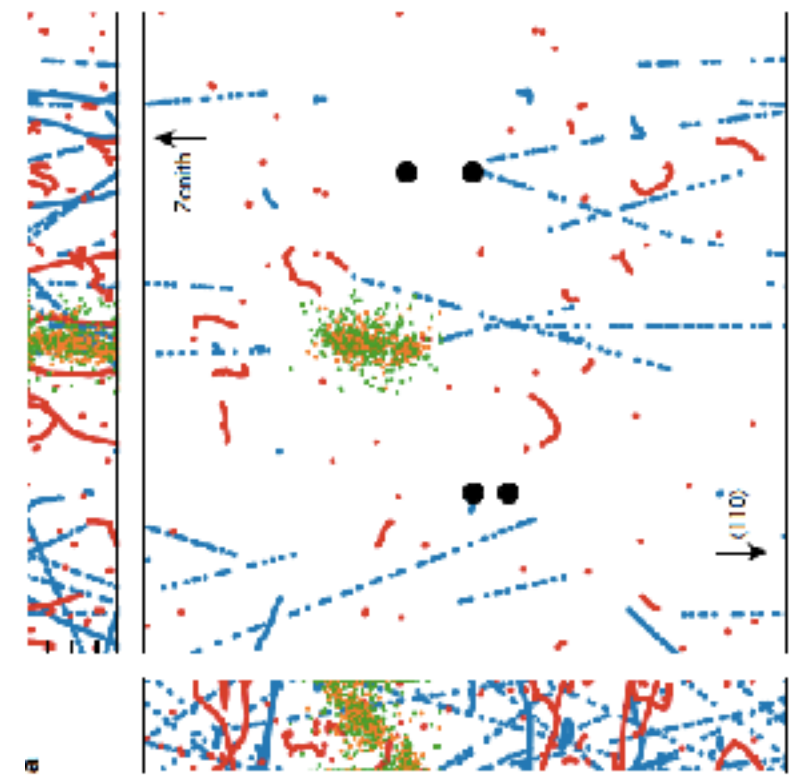
Improved quality factors observed when system under shielding from cosmic rays and environmental radioactivity.

The Danger of *Correlated* Backgrounds

Nature
C. D. Wilen et al.
volume 594, 369–373 (2021)







μ : muons γ : gammas

Robust quantum computation relies on the capability of error correction, particular for large qubit systems. Both computation and error correction tasks rely on **random**, **uncorrelated** qubit flips.

The observation of correlated quantum errors (on par with ionizing radiation) over large length (mm) scale is troubling for large quantum systems.

The Danger of *Correlated* Backgrounds

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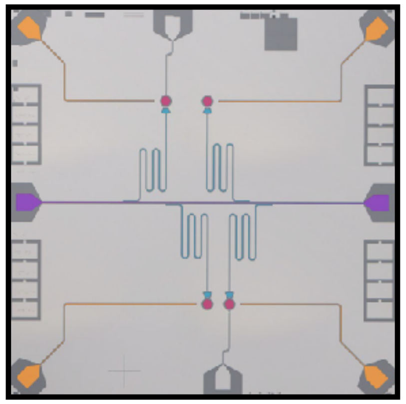

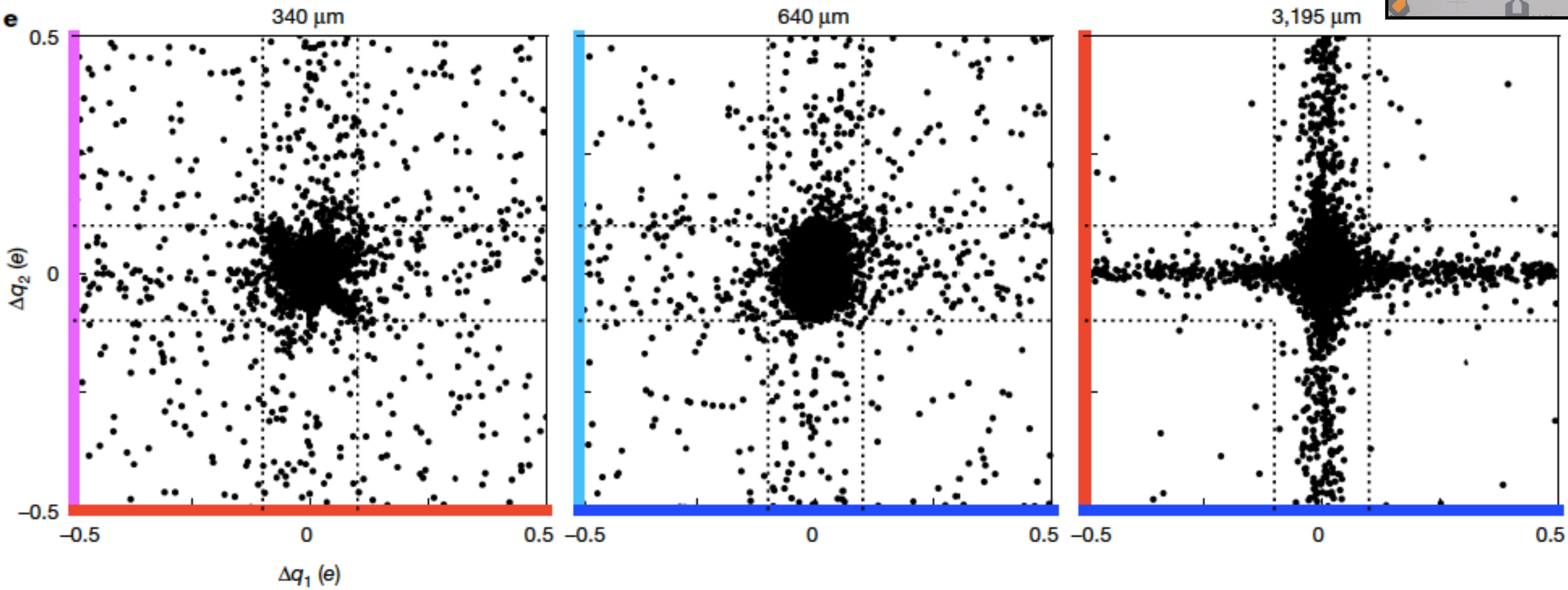

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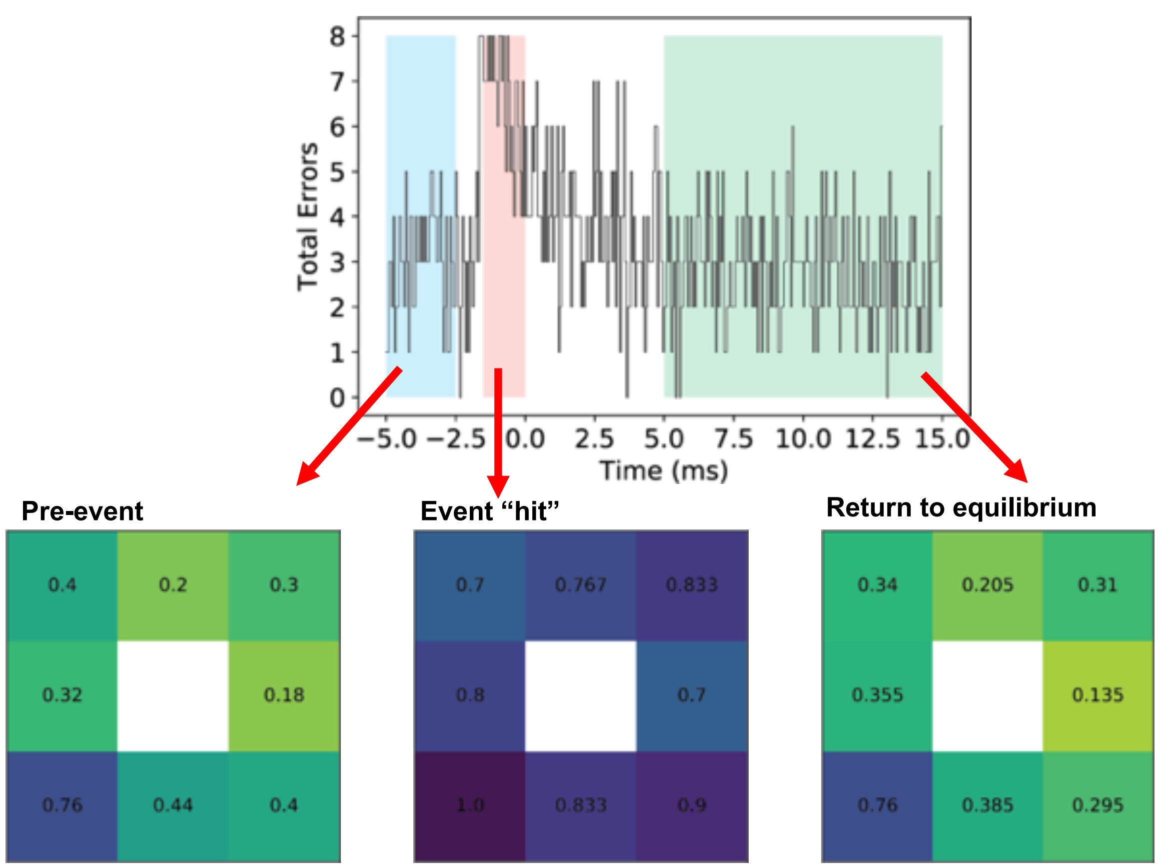
The observation of correlated quantum errors (on par with ionizing radiation) over large length (mm) scale is troubling for large quantum systems.

Catastrophic Errors

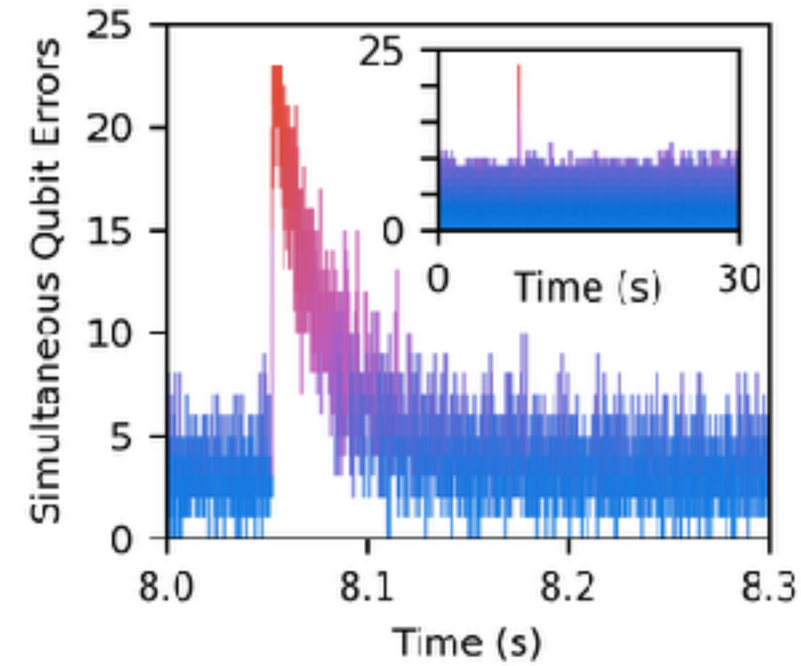
Catastrophic correlated error now observed on several multi (>>1)-qubit systems.

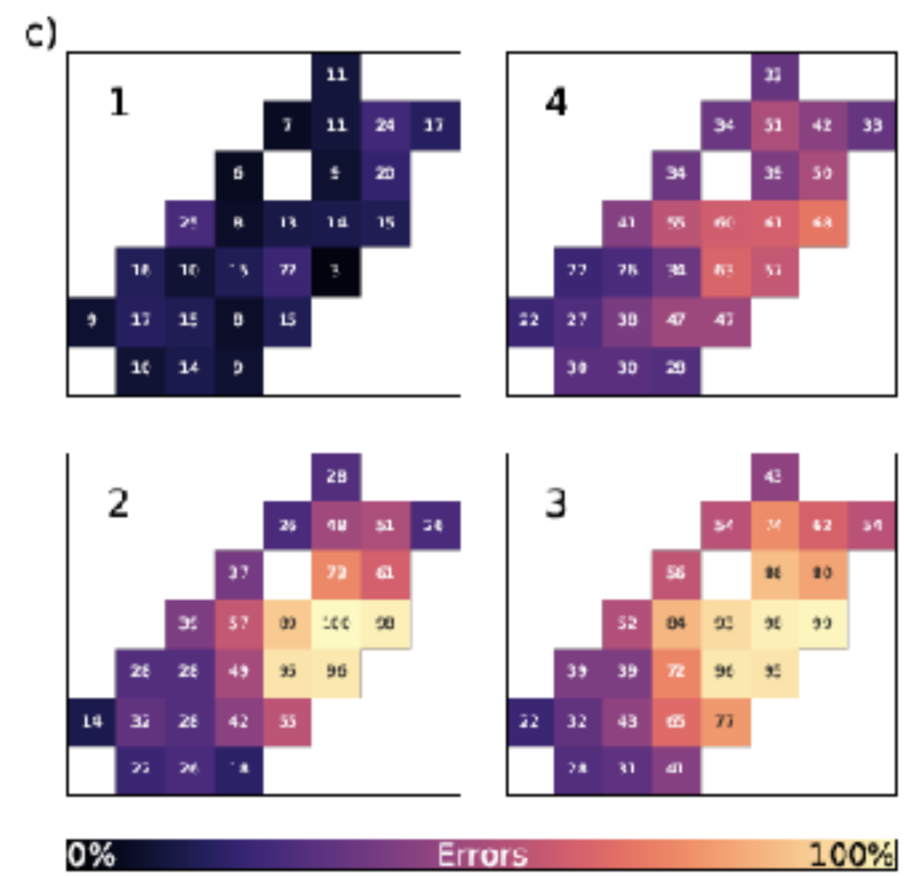
Topology and decay rate consistent with cosmic/radioactive backgrounds creating phonons in underlying substrate.



P. Harrington, W. Oliver (private correspondence)

8-qubit system





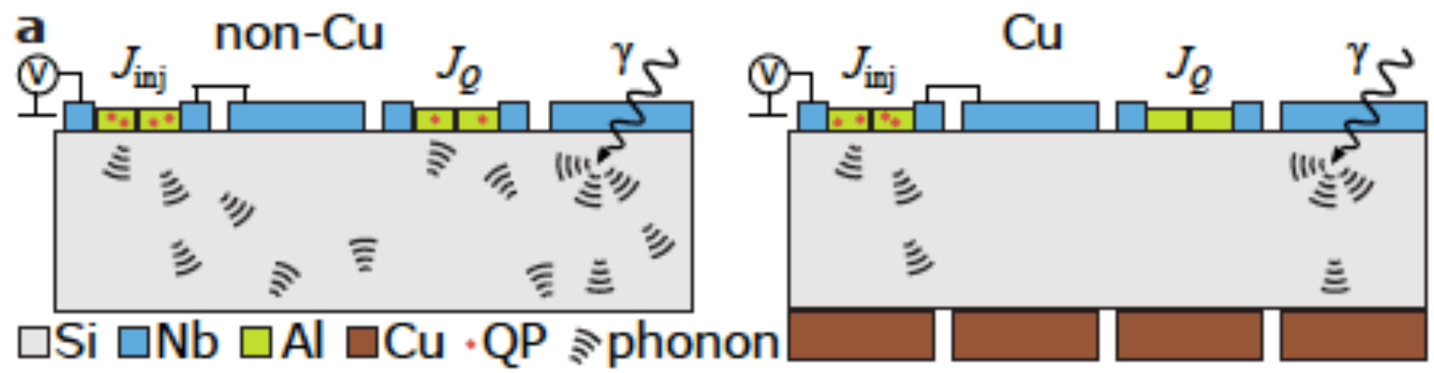
25-qubit system

M. McEwen et al (Google Quantum)
ArXiv 2104.05219 v1

So...

..is quantum computing doomed to live underground?

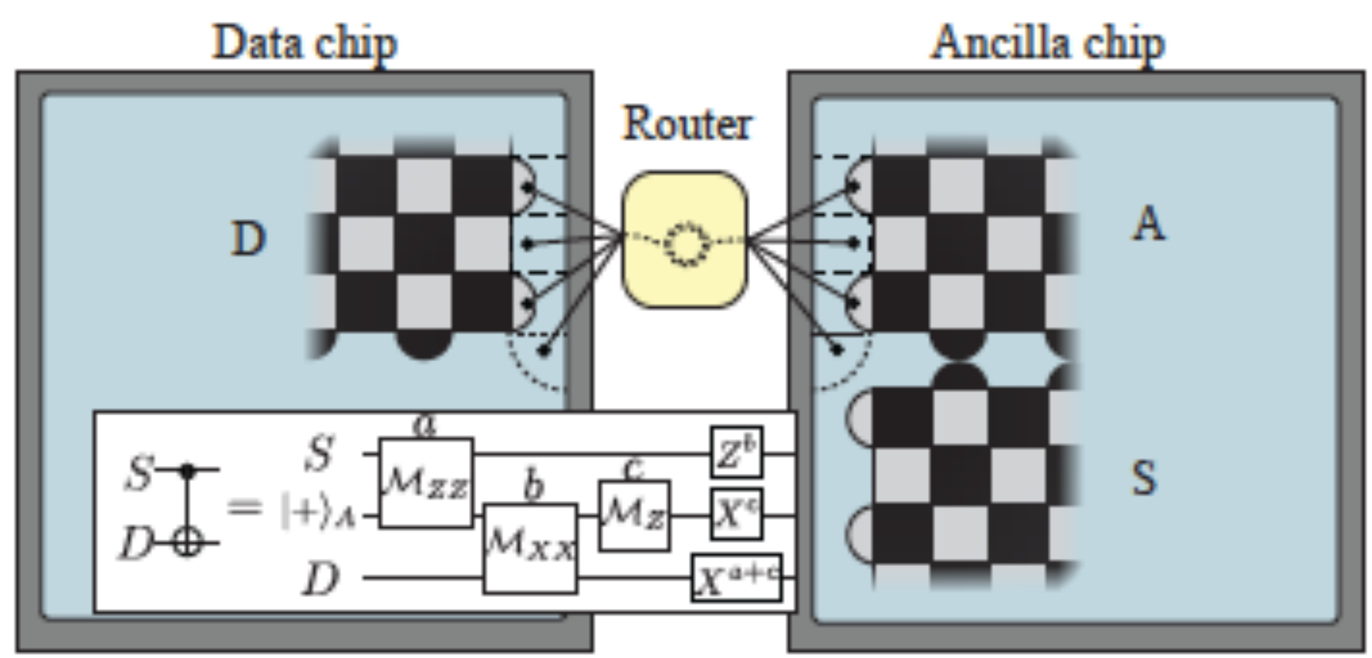
Mitigating "On Chip"



Quasi-particle suppression
V. Iaia et al., arXiv 2203.06586

There are also efforts in place to reduce quasi-particle poisoning on qubit chips themselves, or devise schemes for reducing the impact of decoherence using spatially-separated QEC methods.

Improvements of over x20 in coherence times seen in recent measurements.

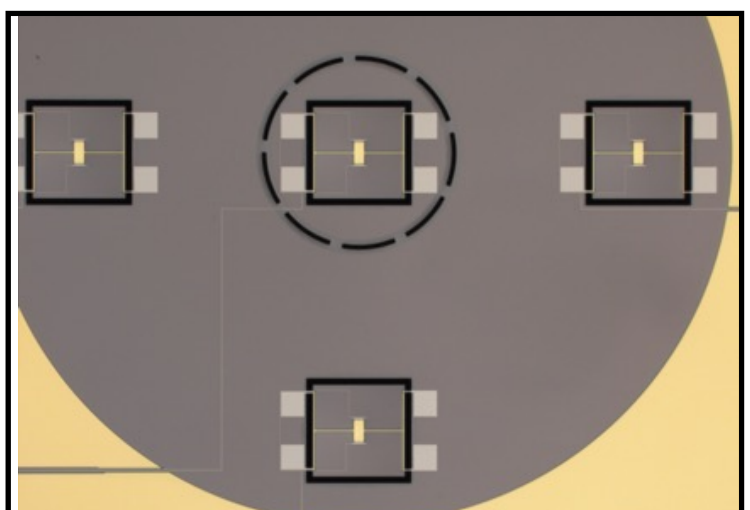


Quasi-particle suppression
Q. Xu et al., arXiv 2203.16488

Nuclear Physicists Wanted

NEXUS facility (courtesy E. Feliciano-Figueroa)

(Courtesy J. Ullom
R. Bunker)



TES array to study energy propagation in Si substrates

Nuclear physics has vast experience in quiet background environments & modeling particle dynamics that can be leveraged.

Low Background; Underground Facilities

New and existing facilities at PNNL, SNOLAB, Fermilab, and Gran Sasso

Understanding Particle Dynamics

Leverage expertise in superconducting sensors and low-background experimentation to measure the impact of naturally occurring radiation.

QIS techniques are now effectively being used by nuclear experiments to search for new physics, and gain higher sensitivity to detecting new and exotic particles.

This is a rapidly growing field.

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This is a rapidly growing field.

Likewise, techniques for detecting (and removing) unwanted particle interactions, pioneered in nuclear physics experiments can prove to be of great use to large quantum systems.

There are areas where NP can have an impact on QIS.

Many thanks to Brent VanDevender, Will Oliver, Kevin O’Brien, Ronald Garcia Ruiz, Dave DeMille, Kyle Leach, Doug Beck, Joel Ullom, Tali Figueroa, Valentine Novosad, Noah Kurinsky, David Moore and Patrick Harrington for their valueable inputs.

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...and to you, for your attention.