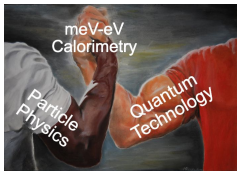
The Cross Point Between QiS Techniques and Particle Physics

P. Giampa, Quantum Workshop, SNOLAB



Overview

2022 @ TRIUMF
2023 @ Université de Montreal
2024 @ Toronto

GUINEAPIG: GeV and Under Invisibles with New Experimental Assays for Particles In the Ground

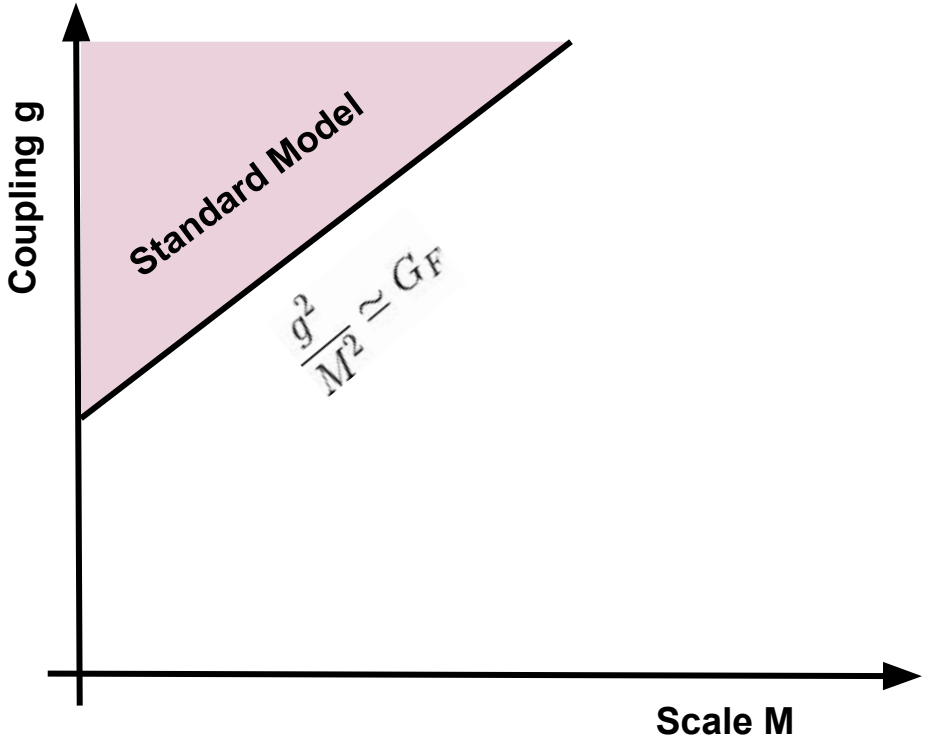
Overview

- Why Bother with Quantum Techniques in Particle Physics?
- How Does Particle Radiation Impact Quantum Sensors?
- What Possible Applications Would Quantum Sensors Have in PP?
- Conclusions

Why Bother with Quantum Techniques in Particle Physics?

Life Beyond The Standard Model of PP

We can generally parametrize new effects in terms of coupling (g) and energy distance^{-1} scale.



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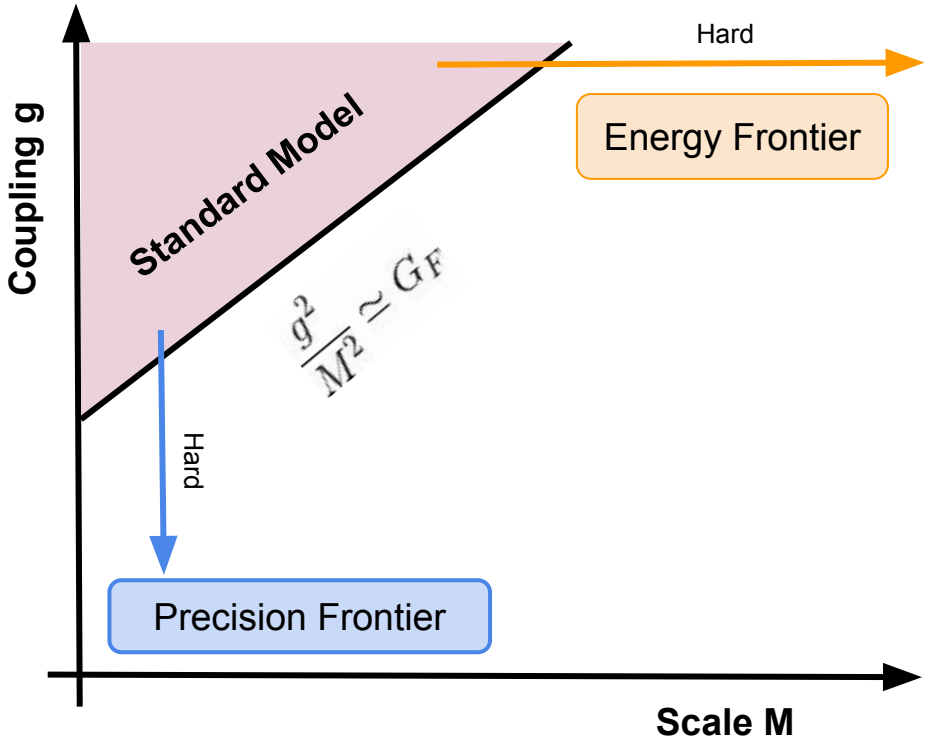

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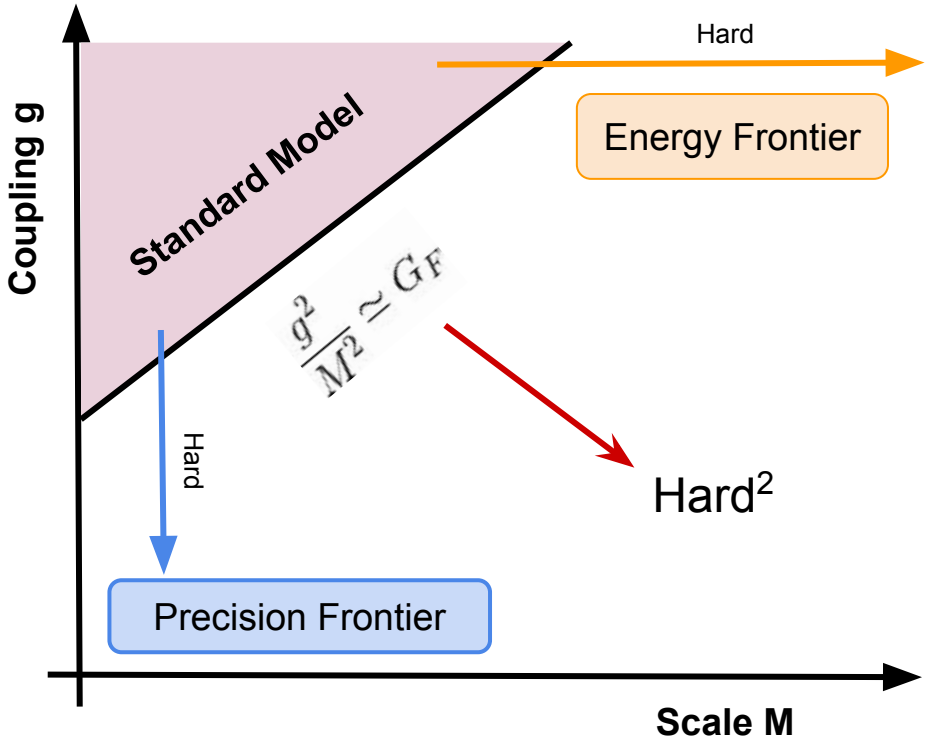
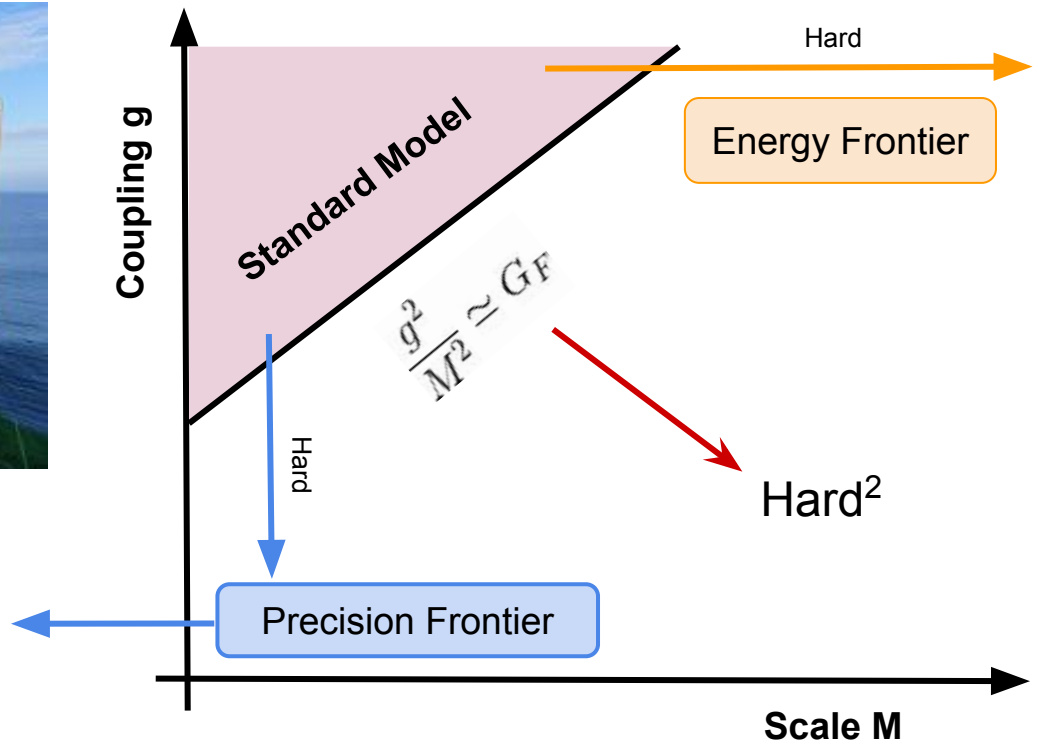


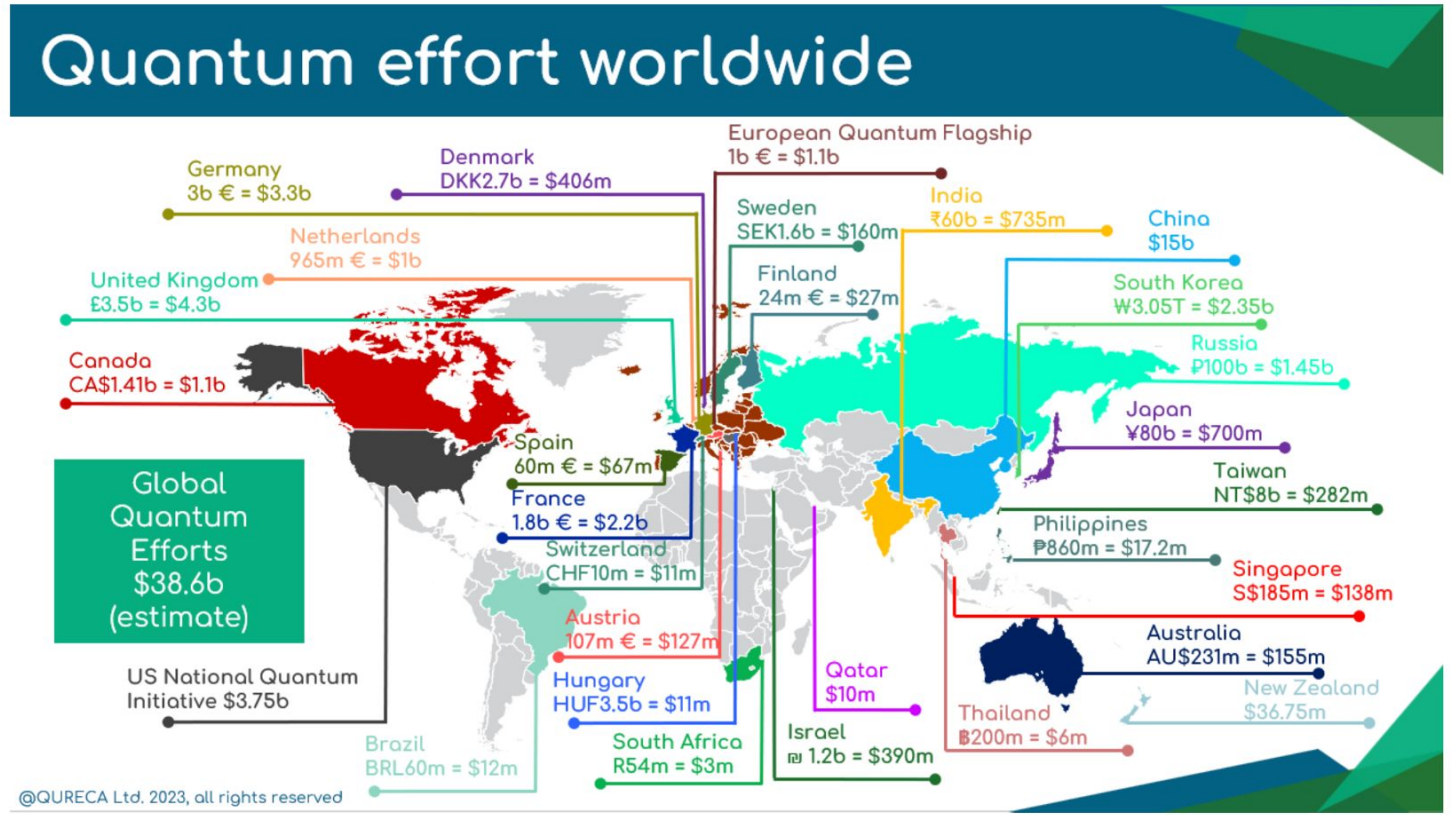
Life Beyond The Standard Model of PP

This requires new ideas and innovative technologies.

[meV-eV Calorimetry Needed??]



Quantum Technology - $$$ Follows Great Ideas



Quantum Technology - Definition

I. Use of a quantum object to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized energy levels. Specific examples include electronic, magnetic or vibrational states of superconducting or spin qubits, neutral atoms, or trapped ions.

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

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

Degen, Reinhard, Cappellaro, Rev. Mod. Phys. 89, 035002 (2017)

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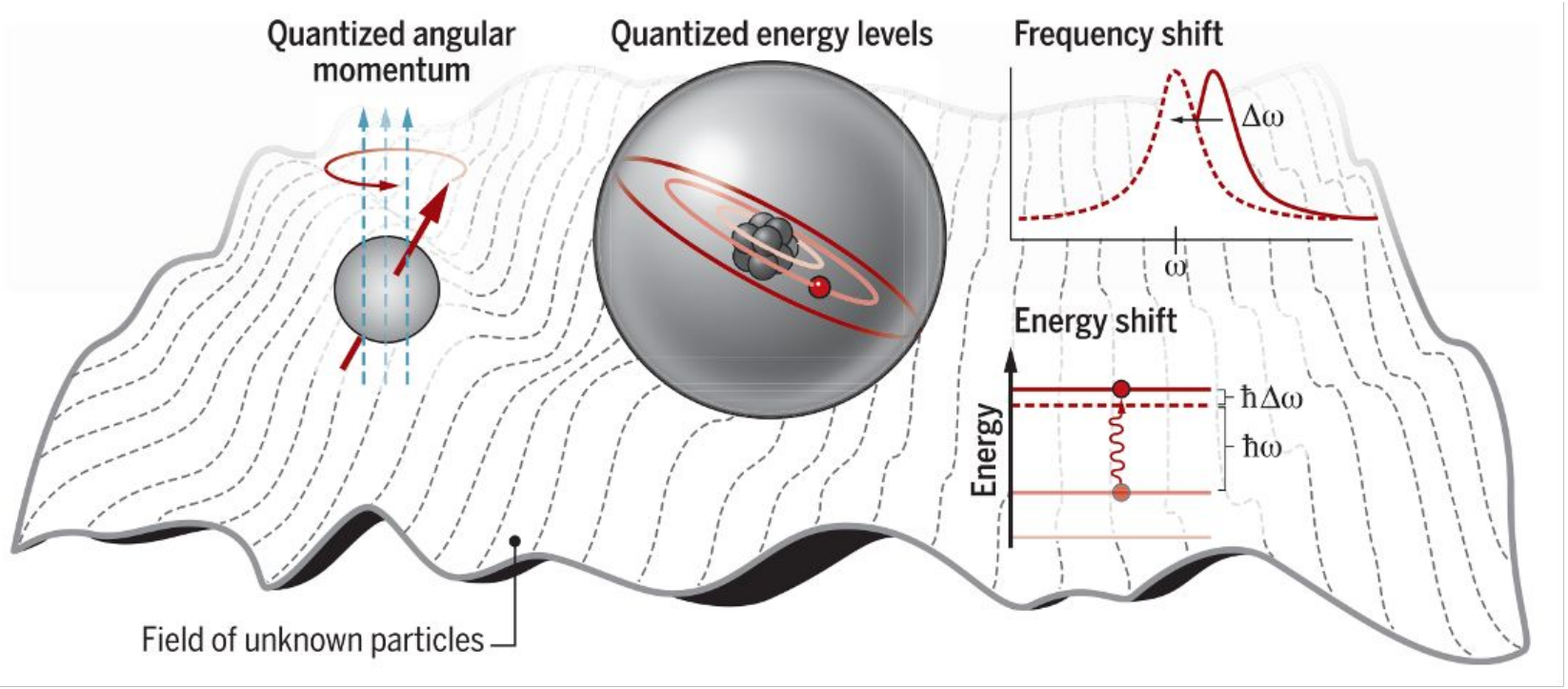
You need the Hamiltonian in order to “operate” the device.

Quantum Technology - Definition

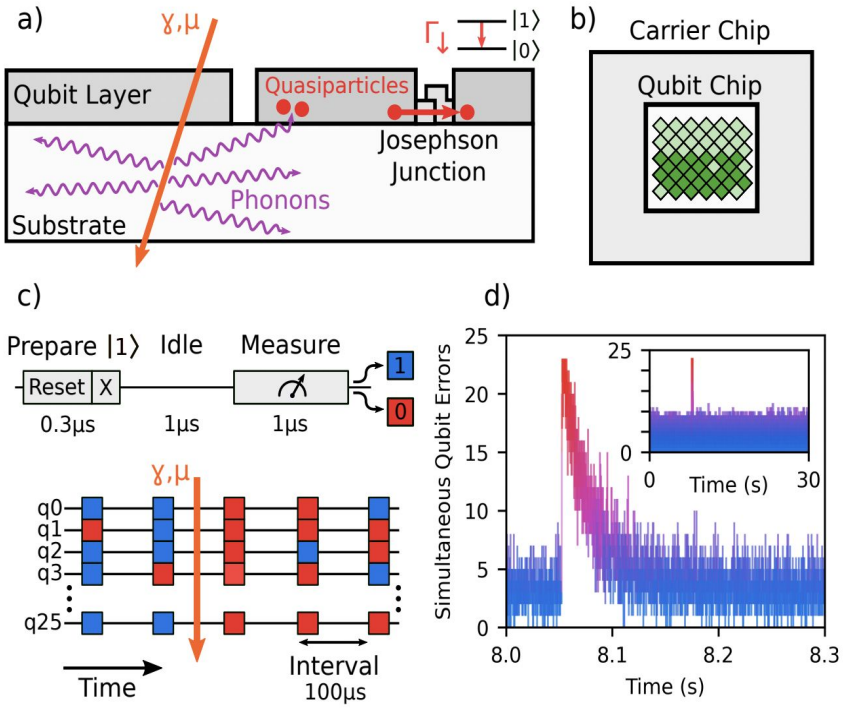


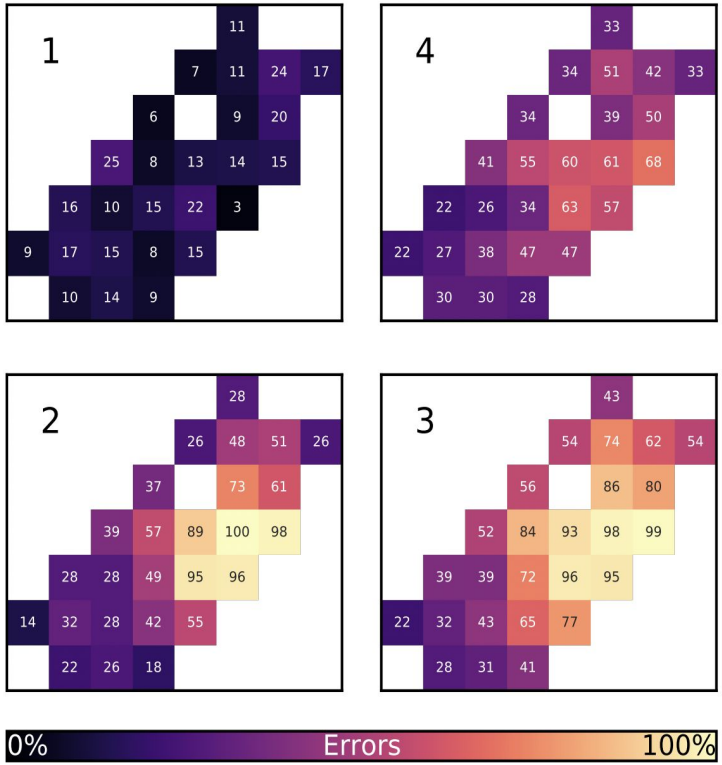
DeMille et al., Science 357, 990 (2017)

How Does Particle Radiation Impact Quantum Sensors?

The Story So Far …

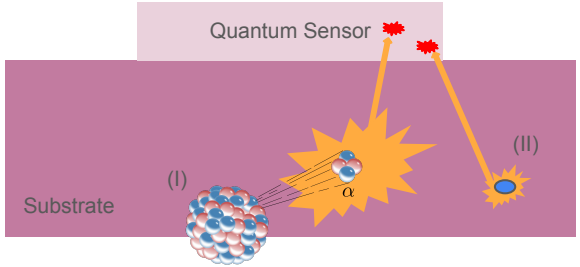
Nature Physics 18, 107-111





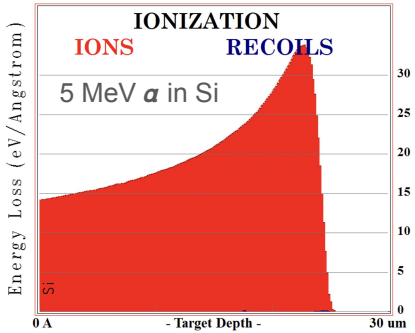
What About The Rest of the Particle Zoo?

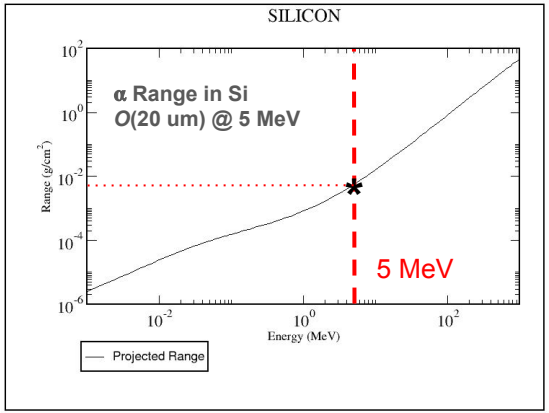
Heavy Charged Particles

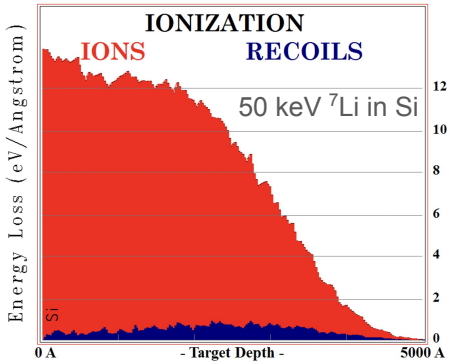


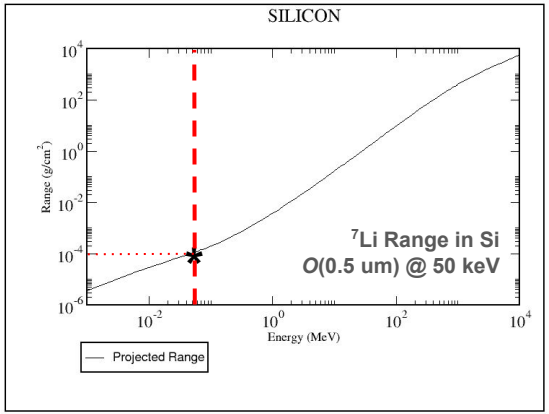
(I) Alphas - Mostly from either radioactivity within the device materials, or plated onto the surface of the device during fabrication/installation. Dust is the enemy generally, but there can also be alpha activity residue from hatching and other surface treatments.

(II) Low-Energy Ion Recoil. Compared to alpha it generates a very faint signal, but it's still accessible with meV-eV sensitivity.



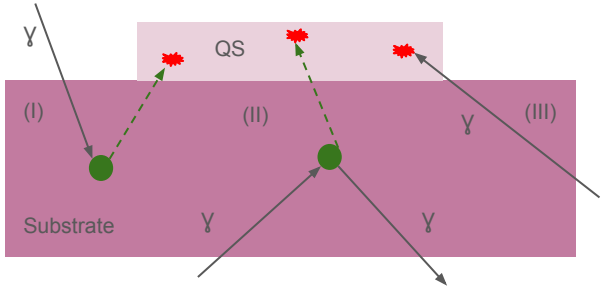




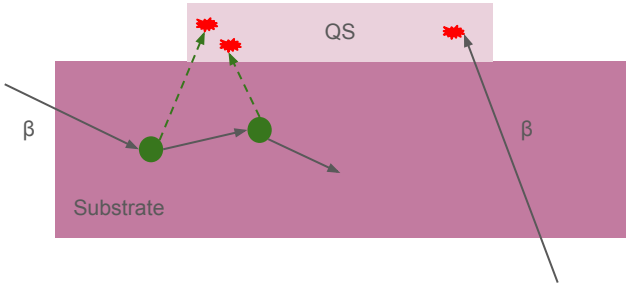


What About The Rest of the Particle Zoo?

Photons



Electrons

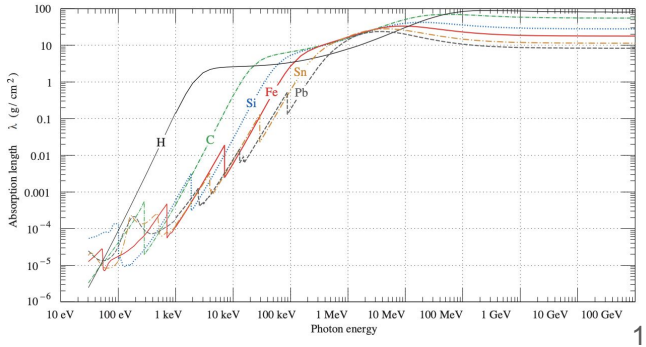


Weather it is IR emission from detector materials, or simple gamma emission from radioactivity in the experiment/surroundings. keV-MeV. Depending on the energy / interaction this could lead to either a faint or shock-wave to the Quantum Sensor.

(I) Absorption / Photoelectric Effect
σ(E) ~ Z^5 / E^3.5

(II) Compton Scattering
σ(E) ~ Z/E * Log(E)

(III) Cooper Pair Breaking



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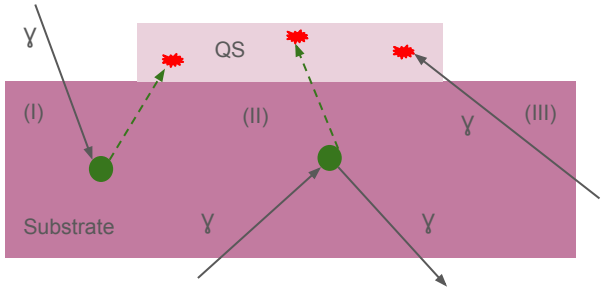

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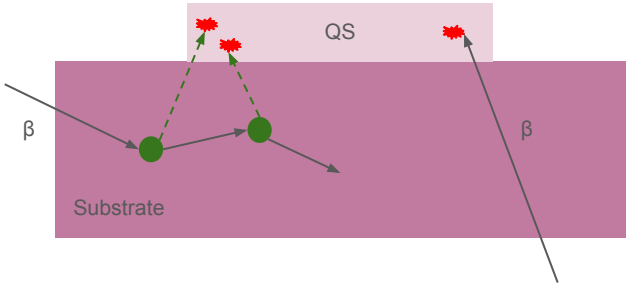
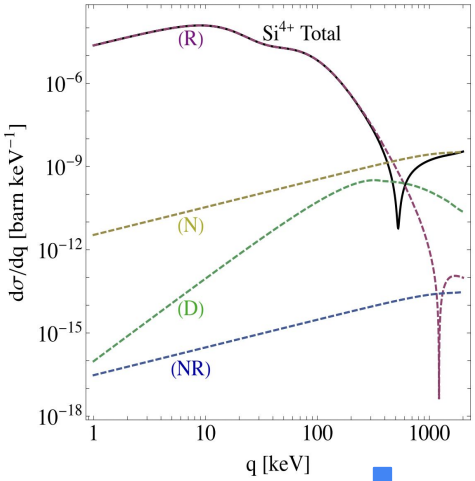
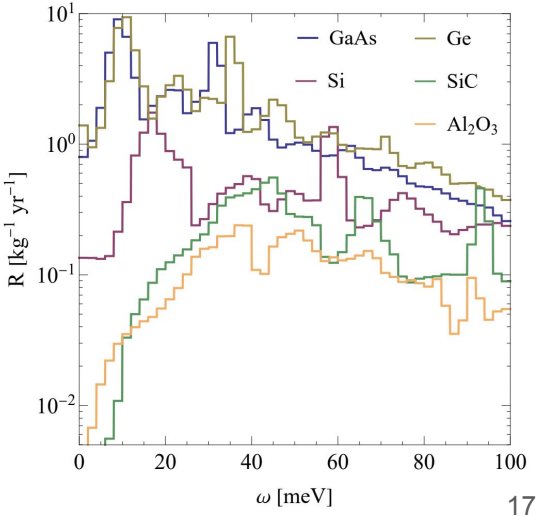


Photon-ion scattering cross section in Si



Phys. Rev. D **106**, 023026

Expected phonon spectrum from high-energy background photon scattering



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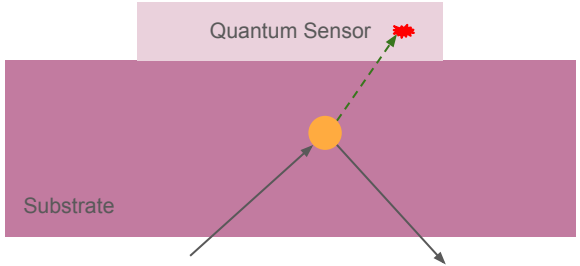
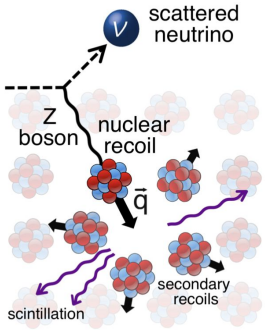
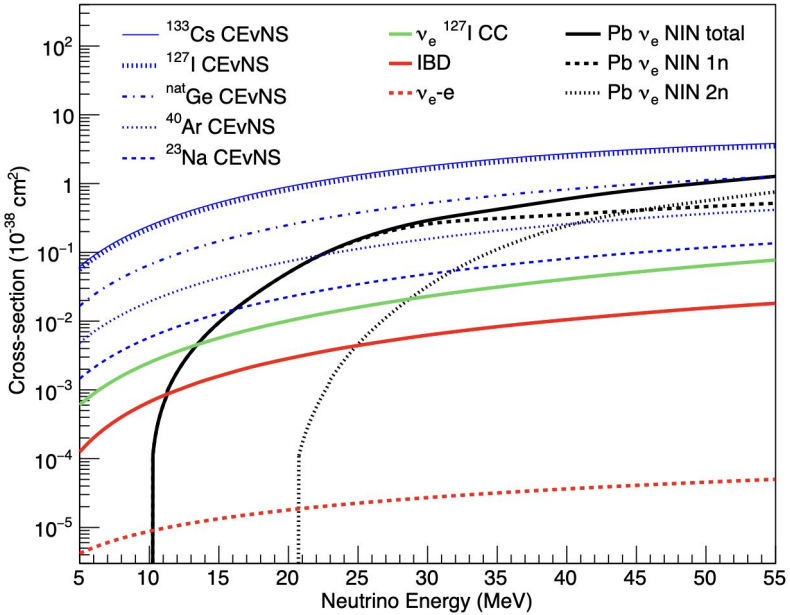
Neutrinos



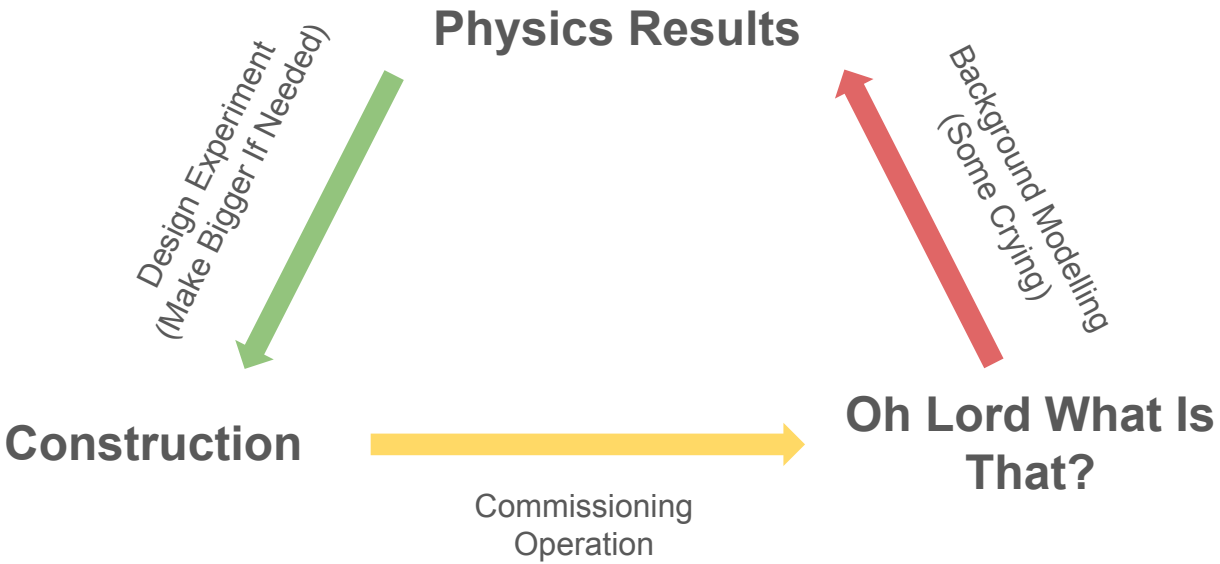


ν + A = **ν** + A
Neutrinos can interact coherently with the nucleus as a whole.

Not a concerned at the current scales as noise.



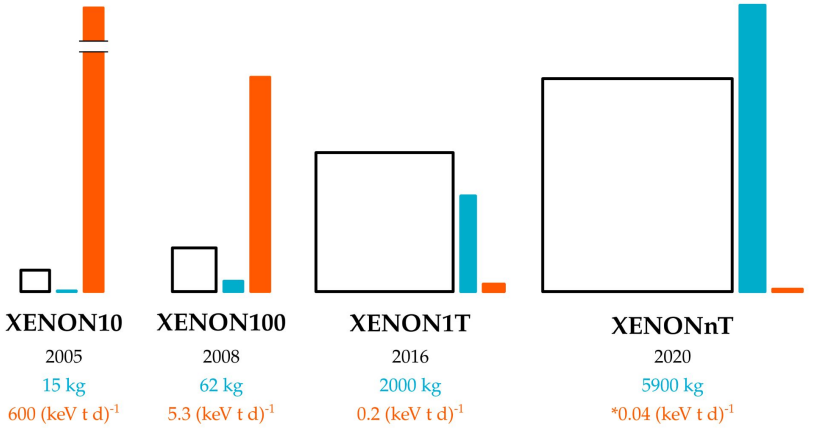
Background Modeling = New Physics



Background Modeling = New Physics

Example: LXe Time-Projection-Chambers:

- Early 2000s identified as a great technique to measure nuclear recoils with thresholds of the order of few 10s of keV.
- Today, “Low-Background” LXe TPC are multi-tonne in size and operate with energy thresholds of of a few keV.



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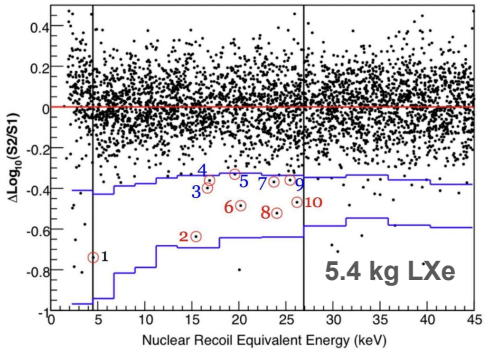
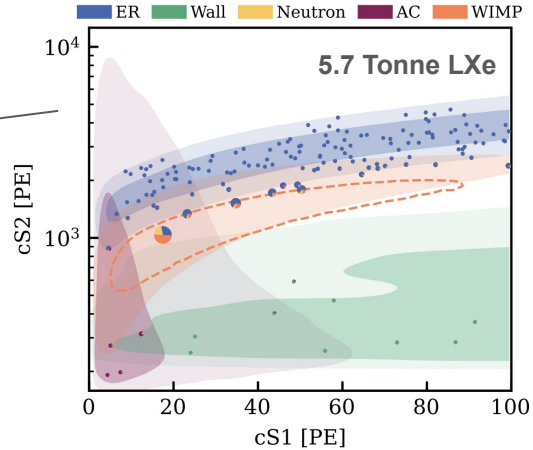


Achieved By Backgrounds Modeling
Surface alphas, general surface effects, PMT flasher, Radon pollution, Tritium pollution, unexpected fluorescences, unexplained nuclear mechanisms, quenching ….



Background Modeling = New Physics

SNOLAB **Low Background Counting Facility**

https://www.snolab.ca/users/services/gamma-assay/index.html

Pacific Northwest NATIONAL LABORATORY

radiopurity.org

SNOLAB

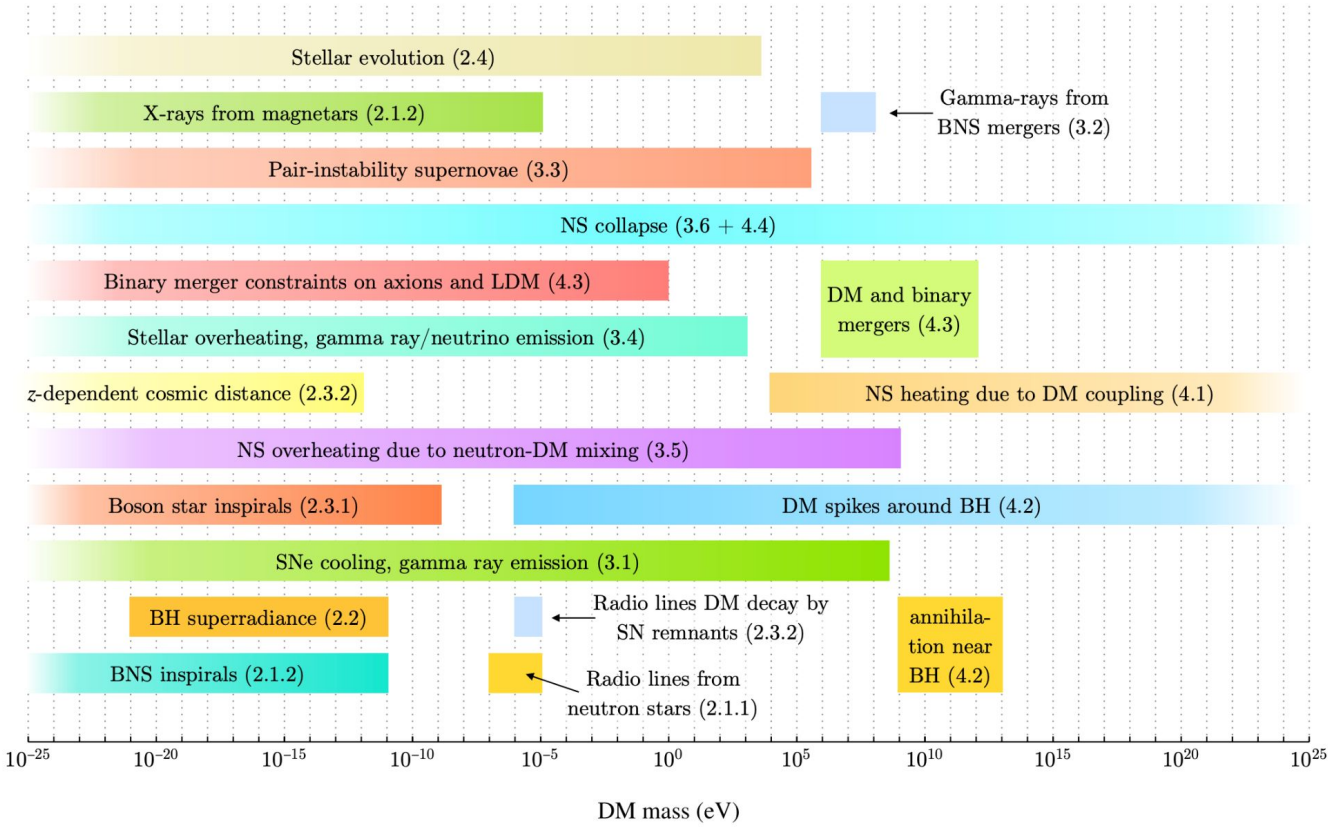
name: Canadian Coatings EP100 Epoxy	**grouping:** LRT 2010	**published**	**Ra-226**: 324.48 mBq/kg **Pa-234m**: 305.45 mBq/kg **Th-232**: 231.78 mBq/kg **K-40**: 77440.76 mBq/kg **Co-60**: 5.33 mBq/kg **Cs-137**: 4.66 mBq/kg
name: epoxy Hysol RE2039	**grouping:** TREX-DM (2019)	**published**	**U-238**: 273.0 mBq/kg **Ra-226**: 16.0 mBq/kg **Th-232**: 20.0 mBq/kg **Th-228**: 16.0 mBq/kg **K-40**: 83.0 mBq/kg **Co-60**: 4.2 mBq/kg **Cs-137**: 4.5 mBq/kg
name: Two component epoxy, Epoxies Etc.	**grouping:** EXO (2008)	**published**	**K**: 20 ppb **Th**: 23 ppt **U**: 44 ppt
name: Silver epoxy, Emerson-Cumings	**grouping:** Majorana (2016)	**published**	**K**: 2000 ppb **Th-232**: 3000 ppt **U-238**: 1000 ppt
name: Resin epoxy, RE4210 Hysol	**grouping:** ILIAS ROSEBUD	**published**	**Th-234**: 50 mBq/kg **Pb-214**: 5 mBq/kg **Bi-214**: 6 mBq/kg **Ac-228**: 10 mBq/kg **Pb-212**: 4 mBq/kg **Tl-208**: 6 mBq/kg **U-235**: 5 mBq/kg **Cs-137**: 1 mBq/kg **K-40**: 40 mBq/kg **Co-60**: 0.6 mBq/kg
name: Resin epoxy, RE2039 Hysol	**grouping:** ILIAS ROSEBUD	**published**	**Th-234**: 50 mBq/kg **Pb-214**: 8 mBq/kg **Bi-214**: 6 mBq/kg **Ac-228**: 4 mBq/kg **Pb-212**: 3 mBq/kg **Tl-208**: 6 mBq/kg **U-235**: 5 mBq/kg **Cs-137**: 2 mBq/kg **K-40**: 100 mBq/kg **Co-60**: 1 mBq/kg

Example: quick search for epoxy

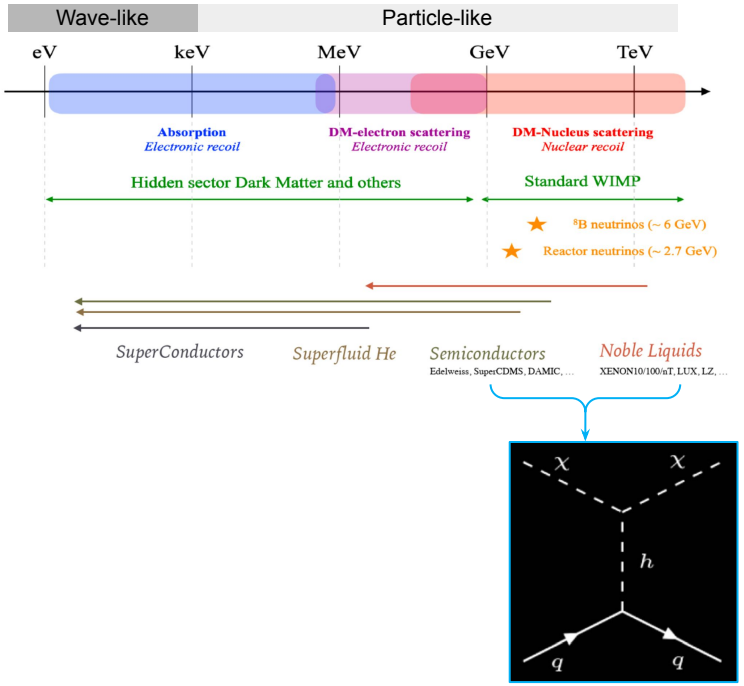
What Possible Applications Would Quantum Sensors Have in PP?

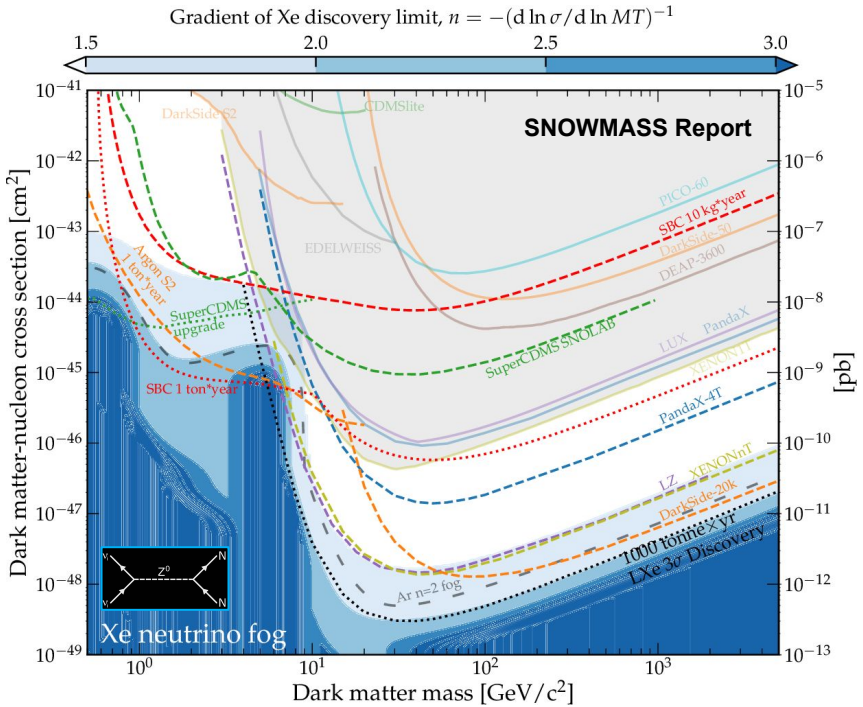
Quest For Dark Matter

https://arxiv.org/abs/2203.07984

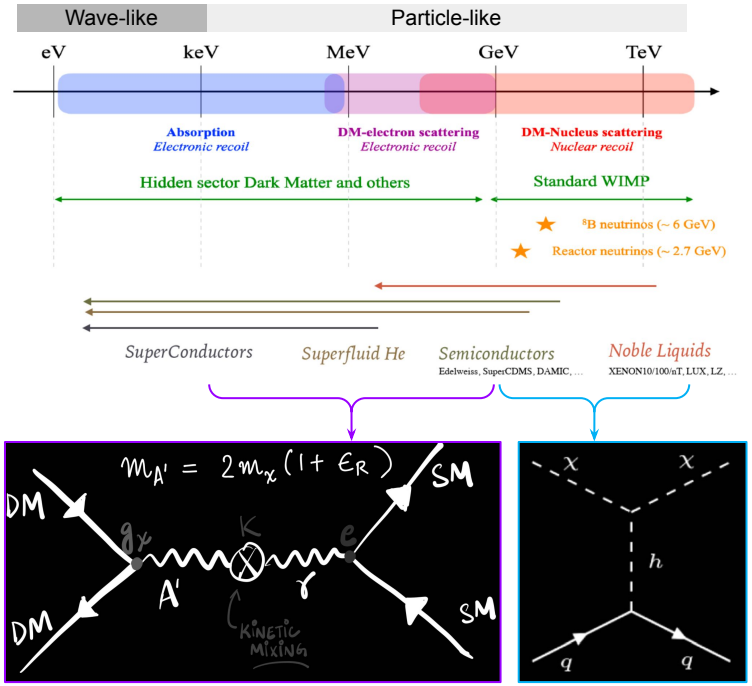


Quest For Dark Matter

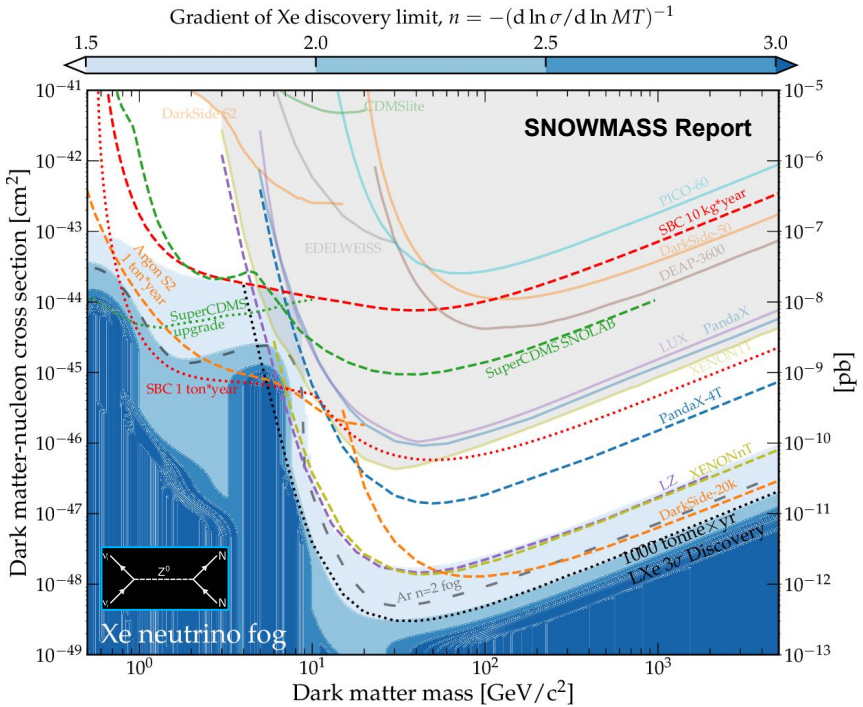




Quest For Dark Matter



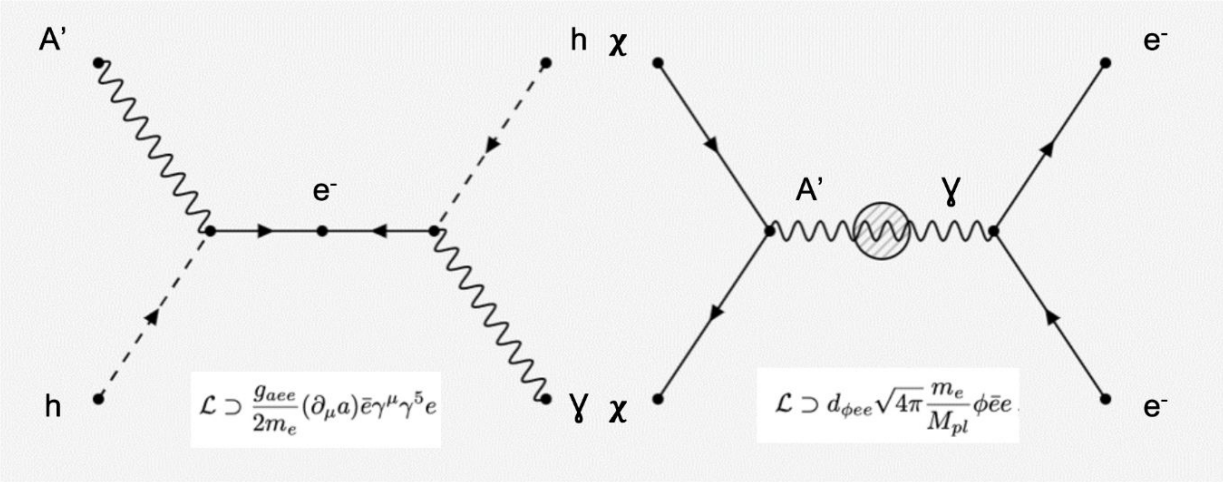
S. Heeba (LINK)



Quest For Dark Matter

Absorption / Cooper-pair breaking
$A' + N \rightarrow N' \rightarrow N + \gamma$

Electron scattering
$\chi^i + e^- \rightarrow \chi^j + e^-$



Kinetic mixing
Pseudoscalar

Fermionic interaction +
kinetic mixing
Scalar

Mechanism:
Absorption, or e^--scattering
$A' + N \rightarrow N'$ or $\chi^i + e^- \rightarrow \chi^j + e^-$

Energy Depositions:
O(10s meV)

Backgrounds:
Can it break cooper pairs?

Challenges:
Mitigate IR light
Modeling qp formation

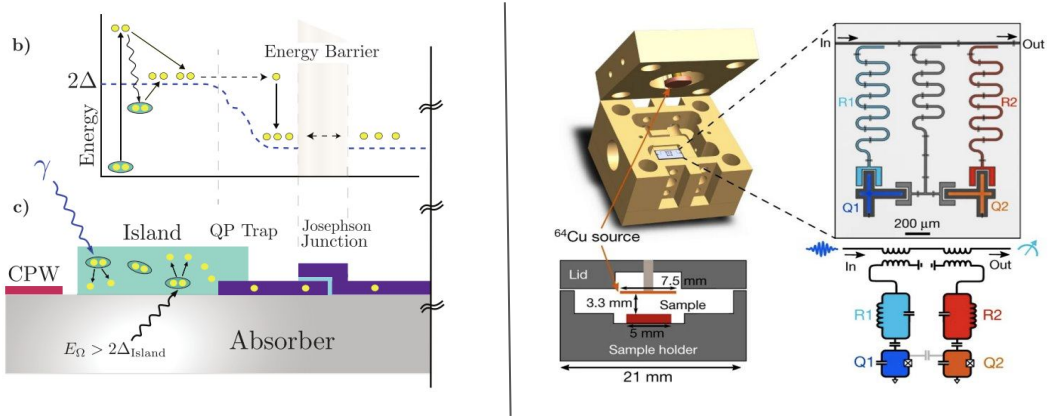
Operation T:
mK

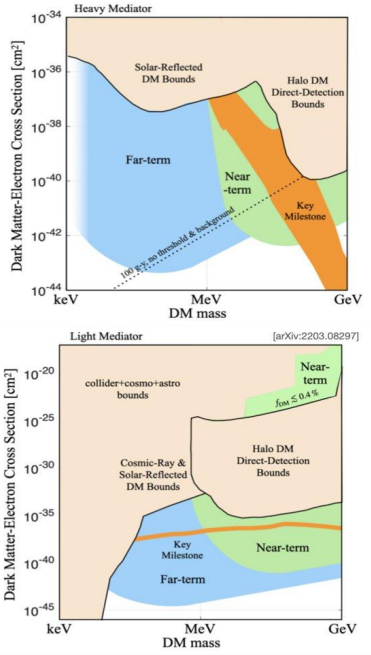
Examples Of Possible Dark Matter Detector

https://arxiv.org/pdf/1604.06800.pdf
https://arxiv.org/pdf/1712.06598.pdf
https://arxiv.org/pdf/1902.08623.pdf

Absorber + Type I QS -> Dark Matter Scattering (eV) | qubit relaxation

Type I QS Only -> Dark Matter Absorption (meV-eV) | SCNW



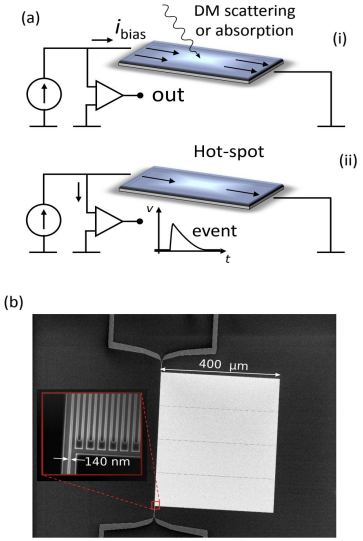


Crystal/SC kg*y target, sensitive to O(0.5 eV) e/phonon interactions

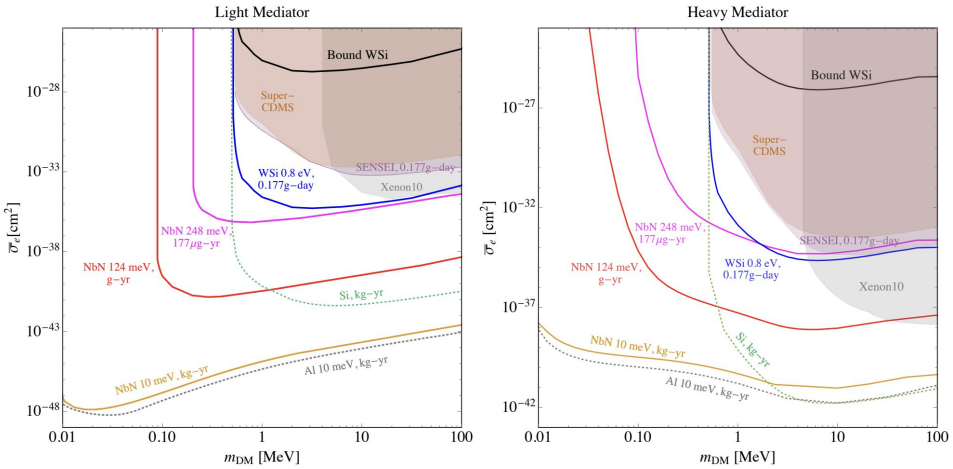
Examples Of Possible Dark Matter Detector

Absorber + Type I QS -> Dark Matter Scattering (eV) | qubit relaxation

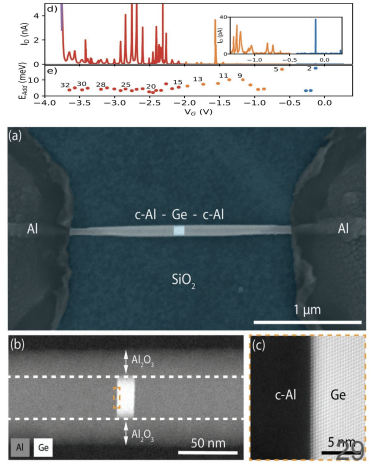
Type I QS Only -> Dark Matter Absorption (meV-eV) | SCNW



Nature Physics 18, 107-111

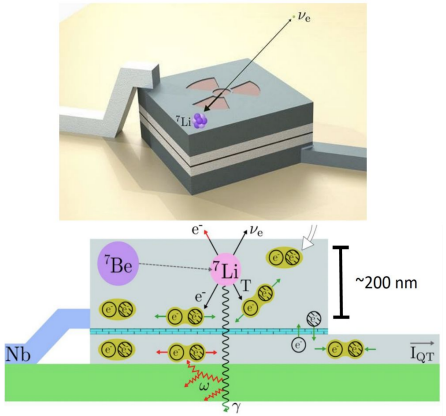


https://doi.org/10.1002/adma.202101989



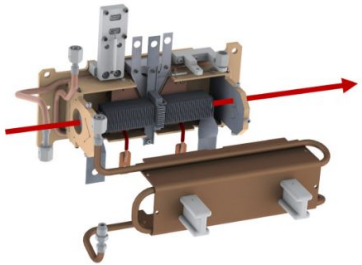
BeEST - Beryllium Electron-capture with Superconducting Tunnel junctions

The BeEST experiment searches for sterile neutrinos in the keV mass range using the nuclear electron capture decay of ^{7}Be implanted into superconducting tunnel junction (STJ) radiation detectors.



480 MeV p+ beam produced in cyclotron

UC_x production target

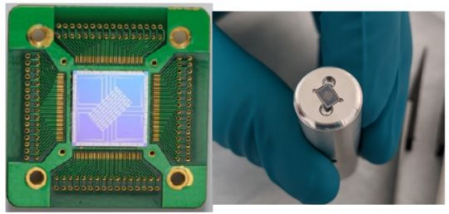


Laser ionization

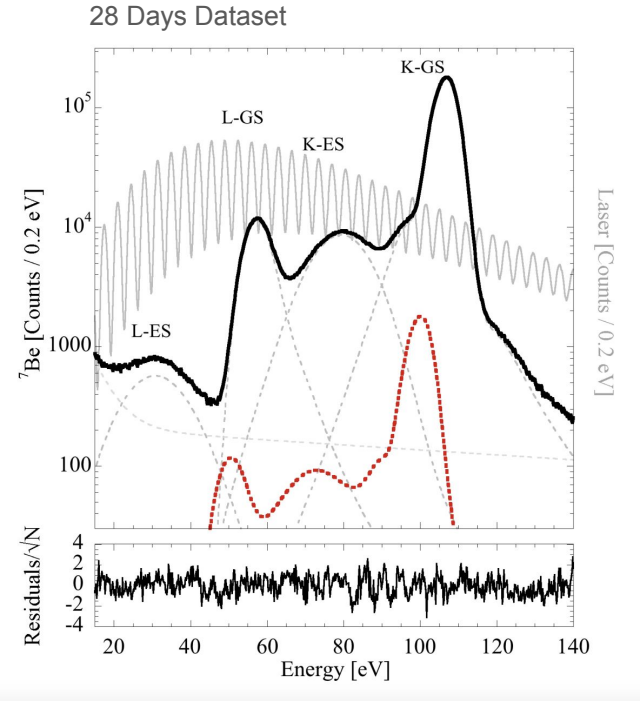
^{7}Be ($T_{1/2}$ = 53 d)

20 - 30 kV acceleration

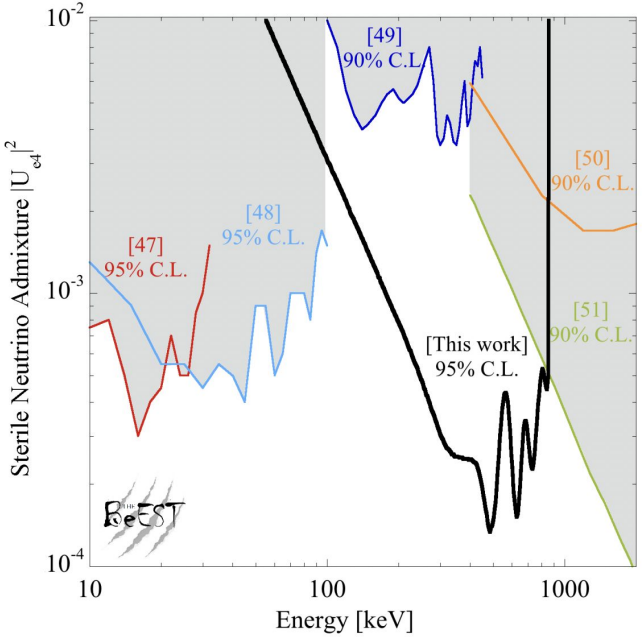
Implant into Superconducting Tunnel Junction (STJ) Sensors at TRIUMF-ISAC



BeEST - Beryllium Electron-capture with Superconducting Tunnel junctions



Phys. Rev. Lett. 126, 021803 (2021)



Other Sources of Backgrounds

- Cosmogenic Activities
- Intrinsic Radioactivity
- IR Emission
- ……..

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- Cosmogenic Activities
- Intrinsic Radioactivity
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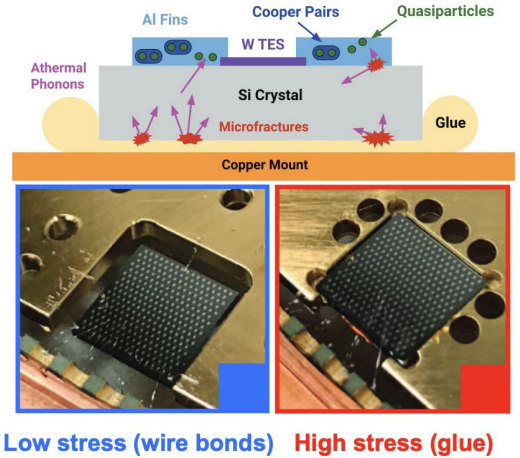
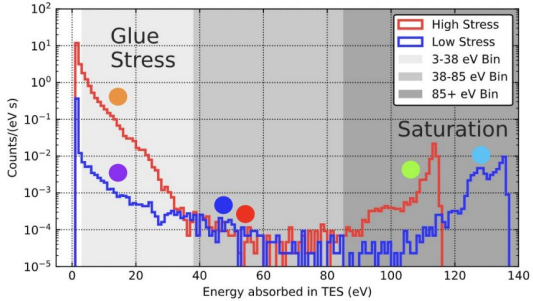
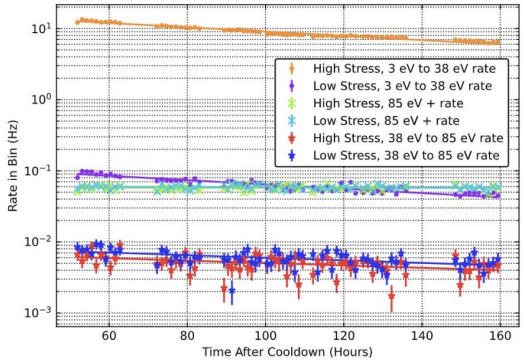
- ……..
- Induced Stress
- Production defects

- A Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning
  - R. Anthony-Petersen et al., arXiv:2208.02790 (2022)

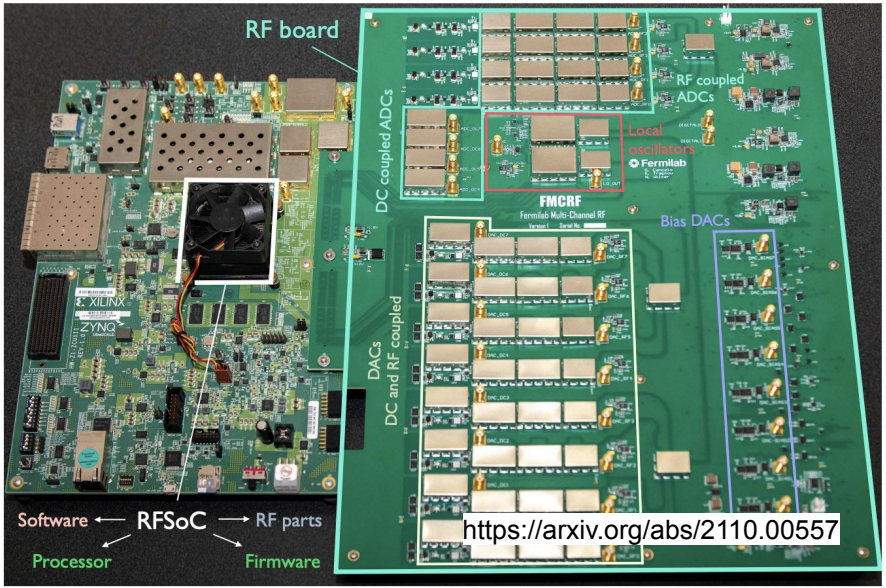






Orrell, GUINEAPIG 2022

What About Readout & DAQ?



QICK = “Quantum Instrumentation Control Kit”

- Fully integrated readout & control system for QIS. No extra room temperature hardware needed.
- A factor of ~20 cheaper compared to off-the-shelf equipment.

MIDAS Website

DAQ: Lots of expertise in the MIDAS data acquisition system.

Currently being used from R&D to large scale detectors (DEAP-3600, UCN, P-ONE, Alpha-g, more …).

Conclusions

Conclusions

- The ongoing effort to study and characterize the impact of particle radiation in quantum sensors has already benefited the QiS community and it's showing signs of very promising prospects for a meV-eV calorimetry.

- Understand "backgrounds" down to meV is key, but we have the combined expertise to fully characterize this in the coming years (Solid State + Condensed Matter + Particle Physics + Low Background Techniques) Not much different than the DM problem that requires PP,NP,Chem,Astro

- We are just starting to see some real particle physics applications for Quantum Technologies … Most interesting time.

Thank You
Merci