Title: The entanglement of quantum computing and dark matter searches

Speakers: Jeter Hall

Series: Particle Physics

Date: May 23, 2023 - 1:00 PM

URL: https://pirsa.org/23050016

Abstract: SNOLAB is a laboratory two kilometers underground in Sudbury, Ontario, Canada. This laboratory boasts the lowest muon flux on Earth. This low muon flux is utilized for a variety of research on Quantum computing and the nature of dark matter, which are some of the highest priority research topics in fundamental and applied physics. New sensors are required for light dark matter searches that extend current capabilities by three orders of magnitude in energy. The required energy scales overlap with the energy scale of environmental disturbances that limit the coherence time of many candidate qubit systems, like superconducting circuits. I will give a short overview of SNOLAB. I will then focus on the requirements and alignment of light dark matter searches and cutting-edge qubit performance. Finally, I will say a few words on how future experiments can leverage these maturing quantum computing technologies for fundamental physics searches.

Zoom Link: https://pitp.zoom.us/j/95345167872?pwd=eDhYREd2Q04yV21DUC84NnVEcHRmUT09

2023/05/23
Perimeter Institute

The entanglement of quantum computing and dark matter searches

Jeter Hall
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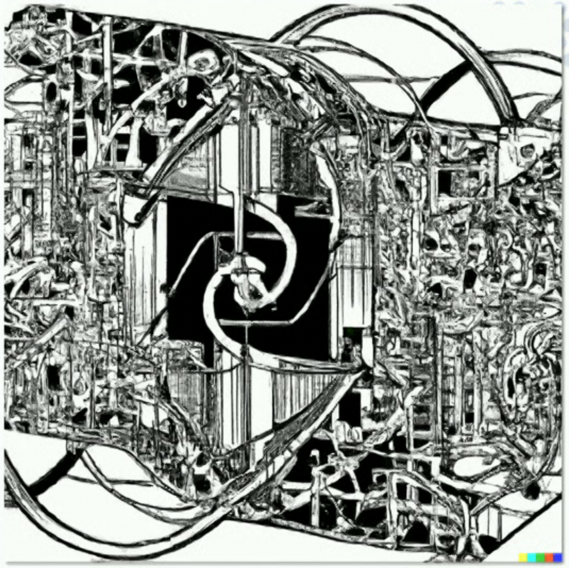

A quantum computer entangled with a dark matter detector in the style of MC Escher. Generated with the assistance of AI.

SNOLAB

Talk Organization

- SNOLAB, a world-class research infrastructure
- Light dark matter searches
- Quantum science and technology
- Future directions
- Final thoughts

We acknowledge that we share the land with those who came here before us

SNOLAB is located on the traditional territory of the Robinson-Huron Treaty of 1850, shared by the Indigenous people of the surrounding Atikameksheng Anishnawbek First Nation as part of the larger Anishinabek Nation.

We acknowledge those who came before us and honour those who are the caretakers of the land and the waters.

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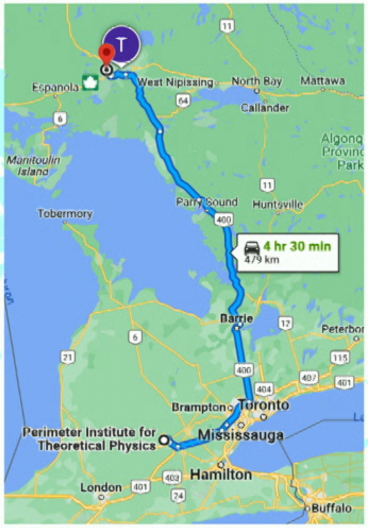
SNOLAB is in Sudbury, Ontario and operated as a joint trust

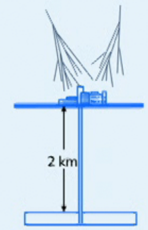
SNOLAB hosts rare event searches and measurements. It's located 2 km underground in the active Vale Creighton nickel mine near Sudbury, Ontario, Canada.

SNOLAB is operated jointly by University of Alberta, Carleton University, Laurentian University, University of Montreal, and Queen's University

SNOLAB operations are funded by the Province of Ontario, and the Canada Foundation for Innovation

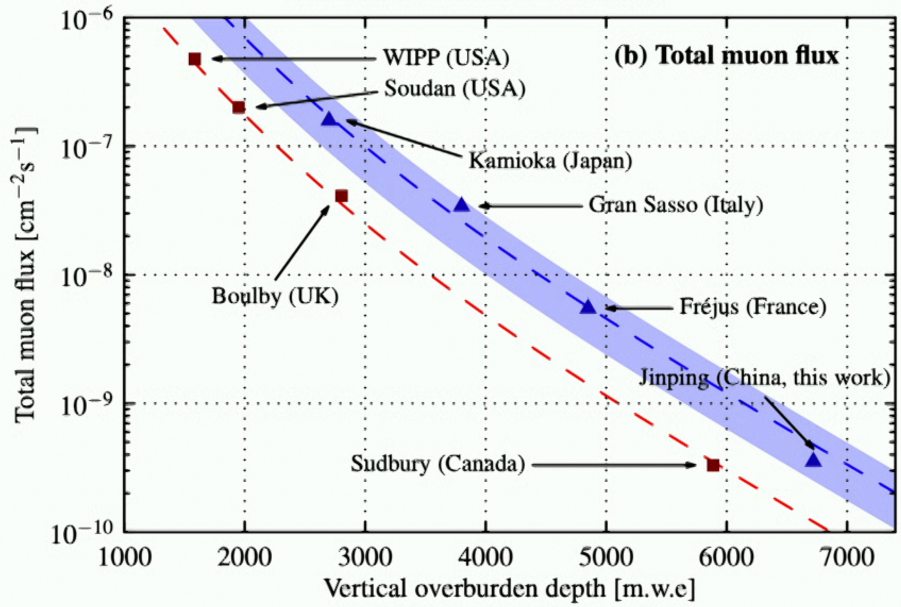


SNOLAB has the lowest muon flux available



- 2 km shield
- SNOLAB has the lowest muon fluxes available
- Clean room throughout the underground facility
  - Dirt is high in radioactivity to us
- Growing community of users

Guo et al., arXiv:2007.15925v2



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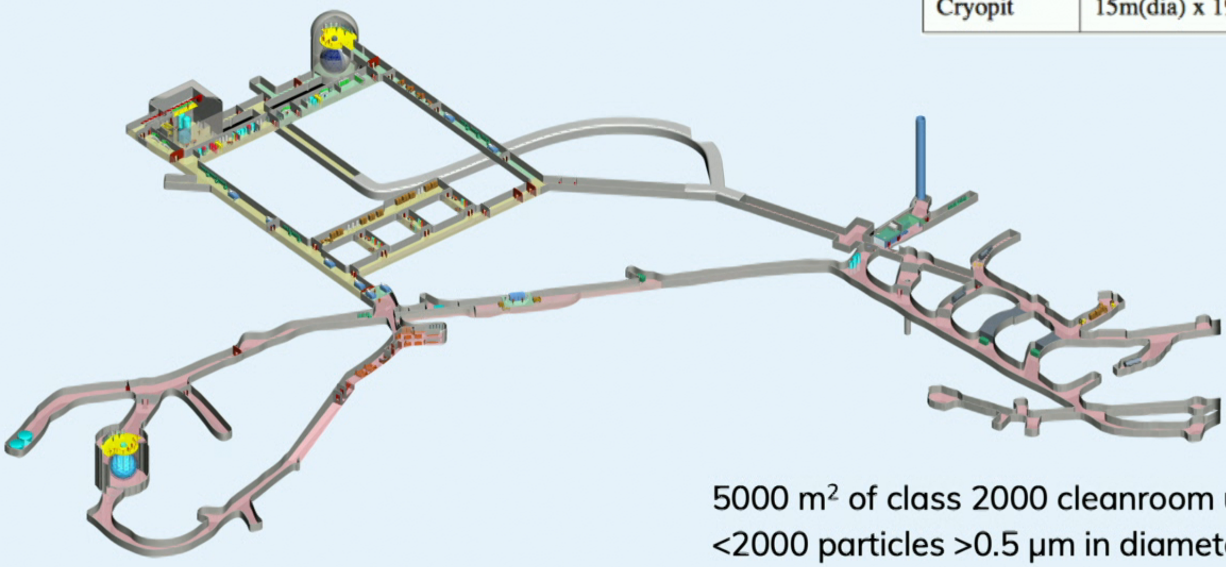
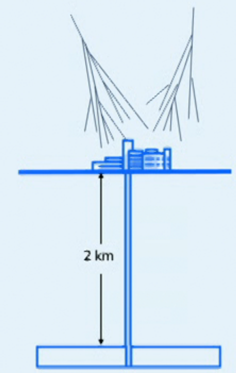
Canada's SNOLAB is a world-class research infrastructure

Area	Dimensions	Area	Volume
SNO Cavern	24m (dia) x 30m(h)	250m^2	9,400 m^3
Ladder Labs	32m(l)x6m(w)x5.5m(h)	190m^2	960 m^3
	23m(l)x7.5m(w)x7.6m(h)	170m^2	1,100 m^3
Cube Hall	18.3m(l)x15m(w) x 19.7m(h)	280m^2	5,600 m^3
Cryopit	15m(dia) x 19.7m(h)	180m^2	3,900 m^3





5000 m^2 of class 2000 cleanroom underground.
<2000 particles >0.5 μm in diameter per ft^3
"A Day at SNOLAB" on YouTube

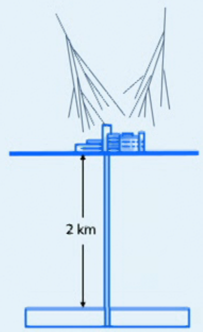
SNOLAB science is focused on the nature of matter

The science at SNOLAB is currently focused on fundamental particle physics. Primarily looking at further **investigating the nature of matter**. Specifically:

- What is the nature of dark matter?
- What are neutrinos? How do neutrinos interact?

SNOLAB is interested in collaborating on any scientific research that requires deep underground facilities. For example:

- Neutrino observatories (solar, supernovae, geo, reactor, etc.)
- Effects of radiation on biological systems
- Environmental monitoring (nuclear non-proliferation, aquifers, etc.)
- Effects of radiation on quantum technologies



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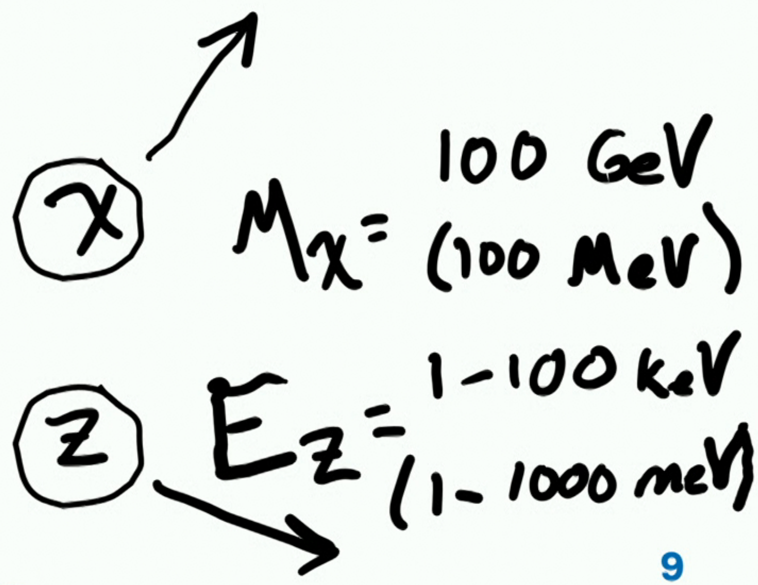
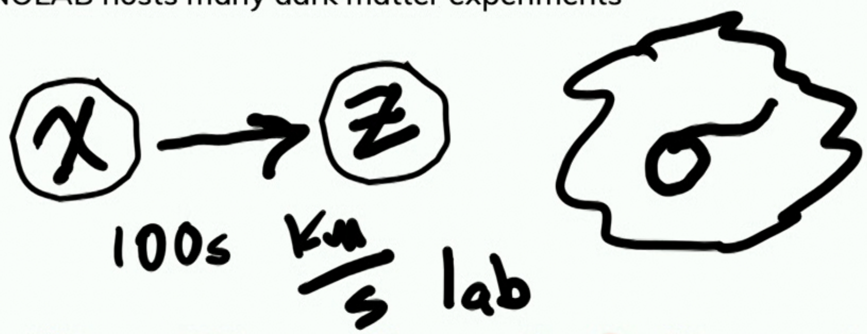
SNOLAB

Dark Matter may interact with baryonic matter in the laboratory

- WIMP dark matter searches have focused on ~100 GeV/c^2 particle interacting at the weak scale "the weak miracle"
- Neutral particles greater than proton mass give keV nuclear recoils
- SNOLAB hosts many dark matter experiments





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Dark matter searches require rare event detection techniques

Brodzinski, Reeves, Avignone, Miley, "The impact of natural radioactivity in solder on low background experiements" NIM A254 (1987)

- Background rate is a primary driver of sensitivity to dark matter parameter space
- Most projects target background rates of <~ 1 / year / experiment
- The projects have been successful in continuously reducing backgrounds for new experiments, based on identifying backgrounds in completed experiments

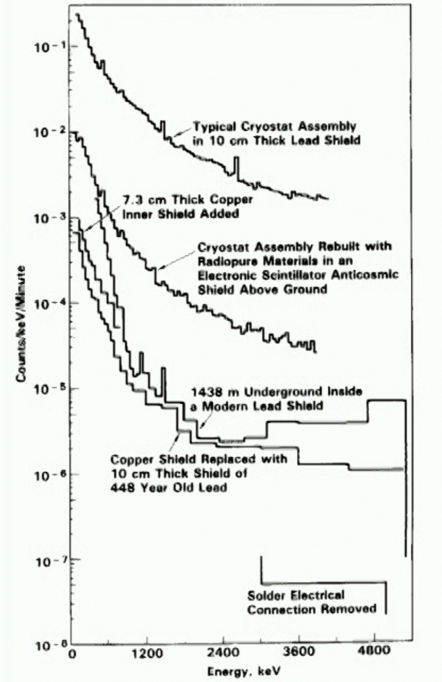
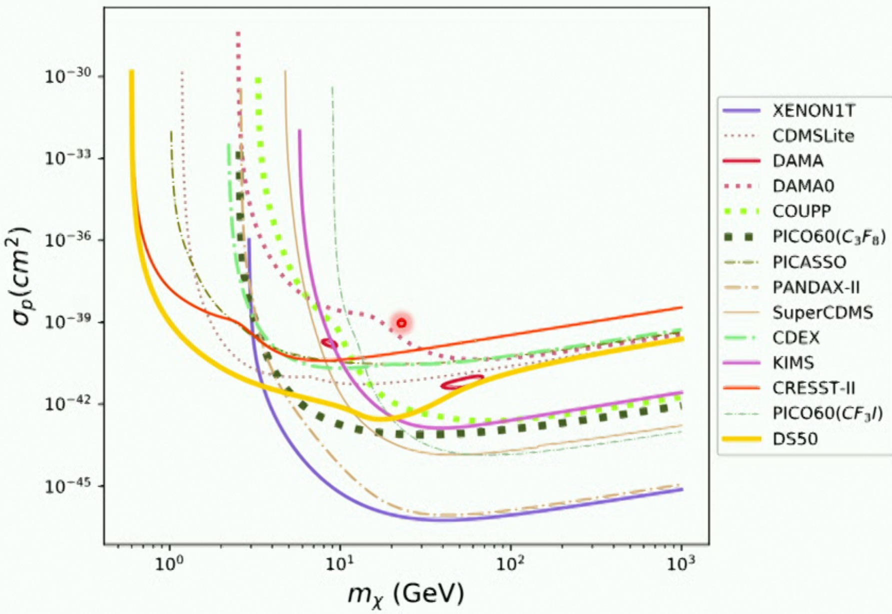


Fig. 1. Background spectra of the PNL/USC, 135 cm³ prototype Ge spectrometer.

Dark matter searches successfully utilized rare event detection techniques over the past two decades

- The projects have been successful in continuously reducing backgrounds for new experiments, based on identifying backgrounds in completed experiments
- This has led to 10 orders of magnitude sensitivity improvement over the past two decades
- Underground infrastructure (atmospheric muon shielding) was required to make this scientific achievement possible



S. Kang, S. Scopel, G. Tomar, J-H Yoon, arXiv:1805.06113

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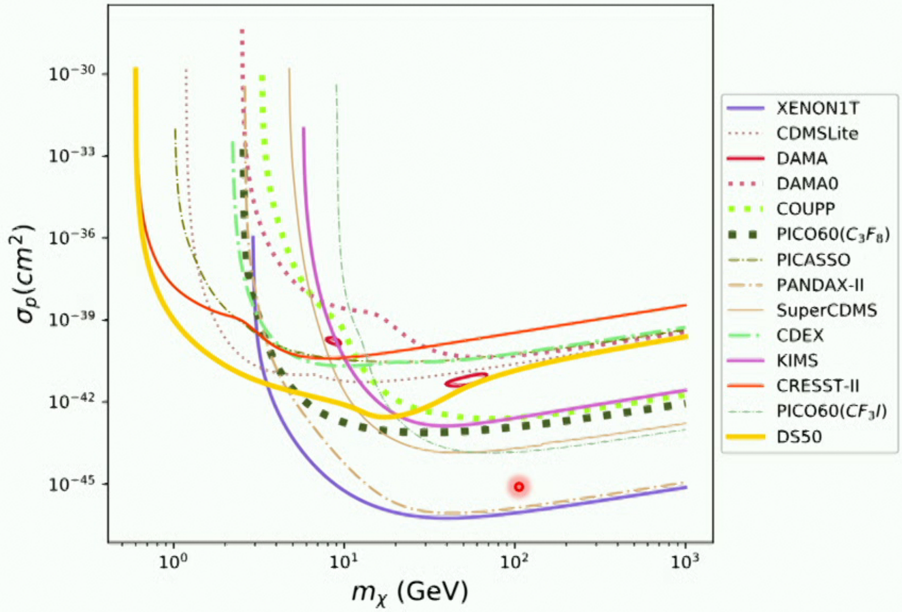


S. Kang, S. Scopel, G. Tomar, J-H Yoon, arXiv:1805.06113

The mass space targeted by the community has grown

- WIMP dark matter searches have not found a hypothesized ~100 GeV/c^2 particle interacting at the weak scale
- Discussions have resulted in broad interest across many orders of magnitude in dark matter mass
- 'Light' dark matter, for this talk, is from ~MeV to ~GeV

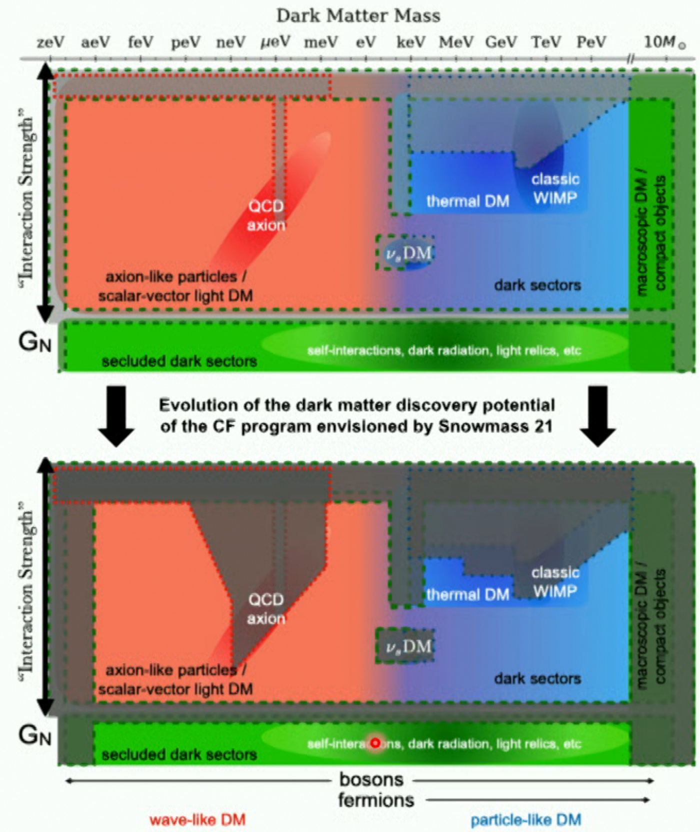
Internal CDMS-II note

A Low Ionization Threshold Experiment with the CDMS Detectors

Jeter Hall
2008/08/08

ABSTRACT

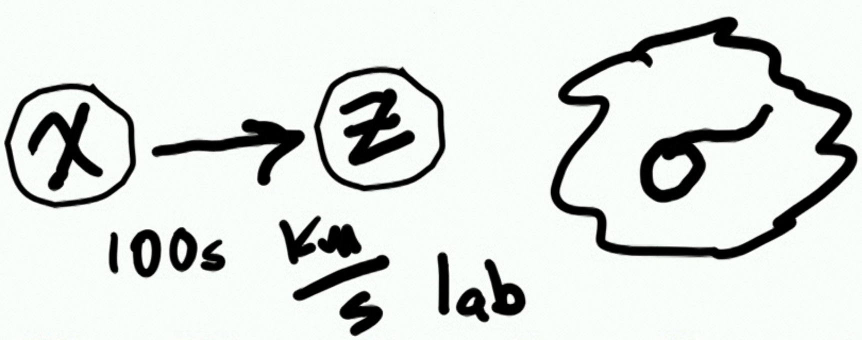
We describe the possibility of using voltage-assisted calorimetric ionization detection with the CDMS detectors. This method could allow an unprecedented low threshold WIMP search with very little disruption to the main CDMS WIMP search. Thresholds as low as, or lower than, a single electron-hole pair could be achieved, which would enable a sensitive search for WIMPs with masses of ~1 GeV.

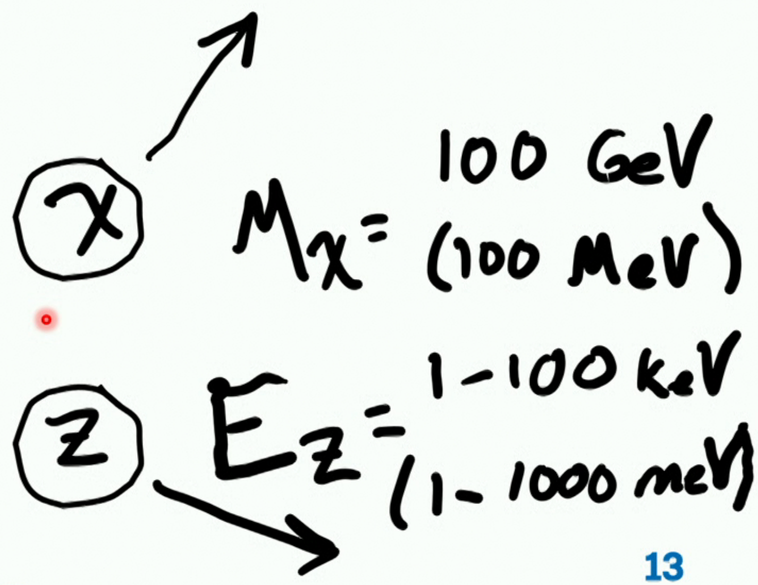


S. Kang, S. Scopel, G. Tomar, J-H Yoon, arXiv:1805.06113

Light dark matter produces much lower energy signals than 100 GeV WIMPs

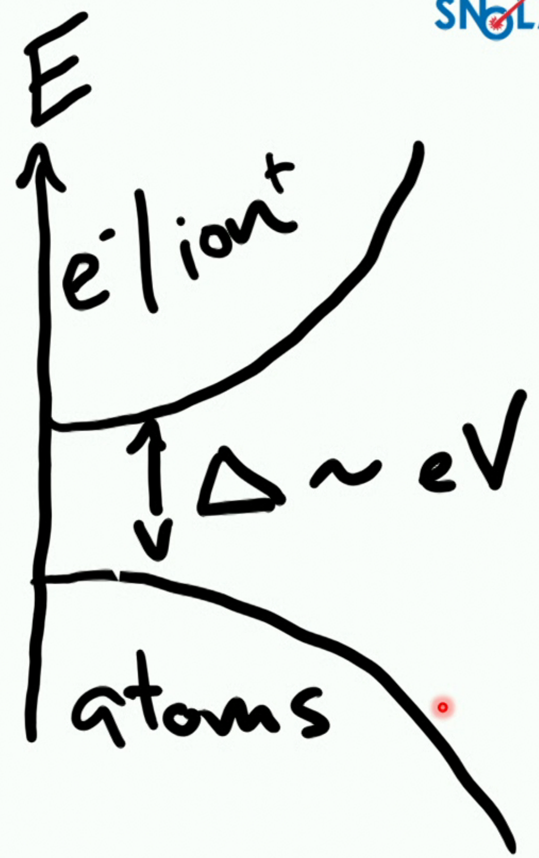
- WIMP dark matter searches have traditionally focused on ~100 GeV/c^2 particle interacting at the weak scale
- Particles greater than proton mass give keV nuclear recoils





Ionizing radiation detectors are fundamentally limited by the energy required to ionize the detector

- For example, many technologies are based on the ionization gap in materials
- Nuclear and particle physics were spawned (largely) from efforts to understand non-thermal ionization processes
- Physicists have split the radiation in nature into “ionizing” and “non-ionizing” radiation at the eV scale
- Fundamental energy threshold limitation for light dark matter searches -- you must have at least one to say you have more than zero...



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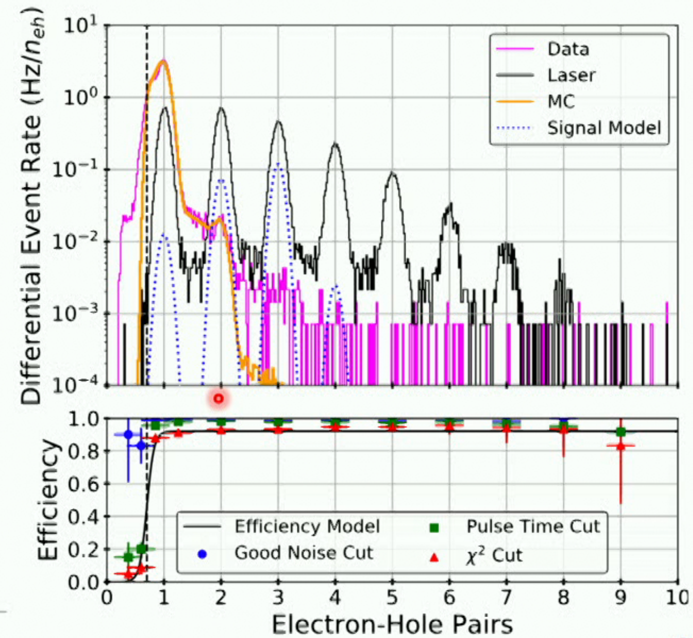
Prototype dark matter detectors have achieved single quanta detection for ionization

- Similar results from other prototype technologies (e.g. skipper CCDs, proportional counters, liquid noble TPCs, scintillators)
- Searches have such sensitivity that unshielded surface detectors have sensitivity to unexplored parameter space
- This is the lower limit on detectable energy in ionization detectors
- Light-er dark matter searches require dramatically lower bandgaps

SuperCDMS Collaboration, PRL 121 (2018) 051301, arXiv:1804.10697



Internal CDMS-II note

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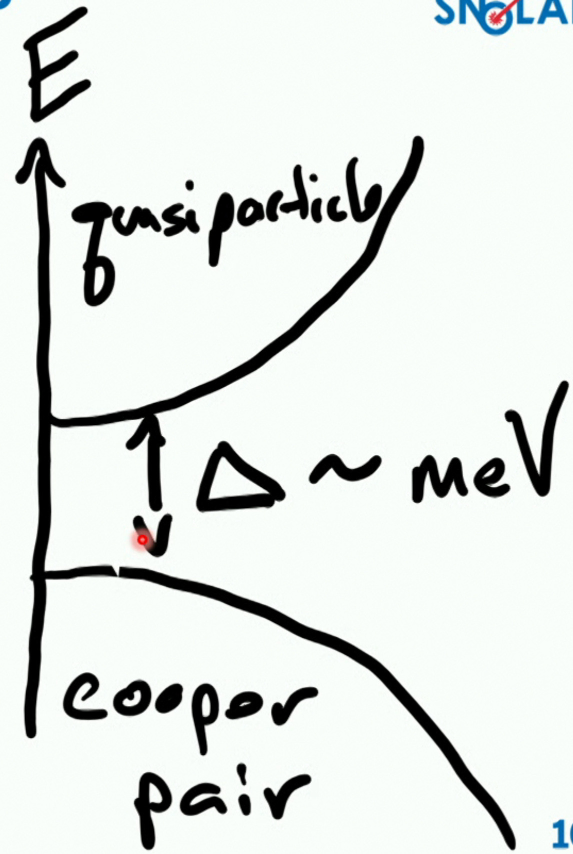
Superconductors are a compelling detector system because of the smaller fundamental quanta

- Counting quasiparticles in superconducting films offers interesting advantages due to the lower energy gap
- Nqp ~ 1000 Ne, so
    - Better energy resolution ~sqrt(N) (~30X better)
    - Lower energy threshold ~N (~1000X lower)
- Allows exploration of a new radiation regime
    - Spectrometers with range [1 meV, 1000s meV]
    - Ideal for light dark matter searches
    - Threshold potentially below the neutrino mass scale!



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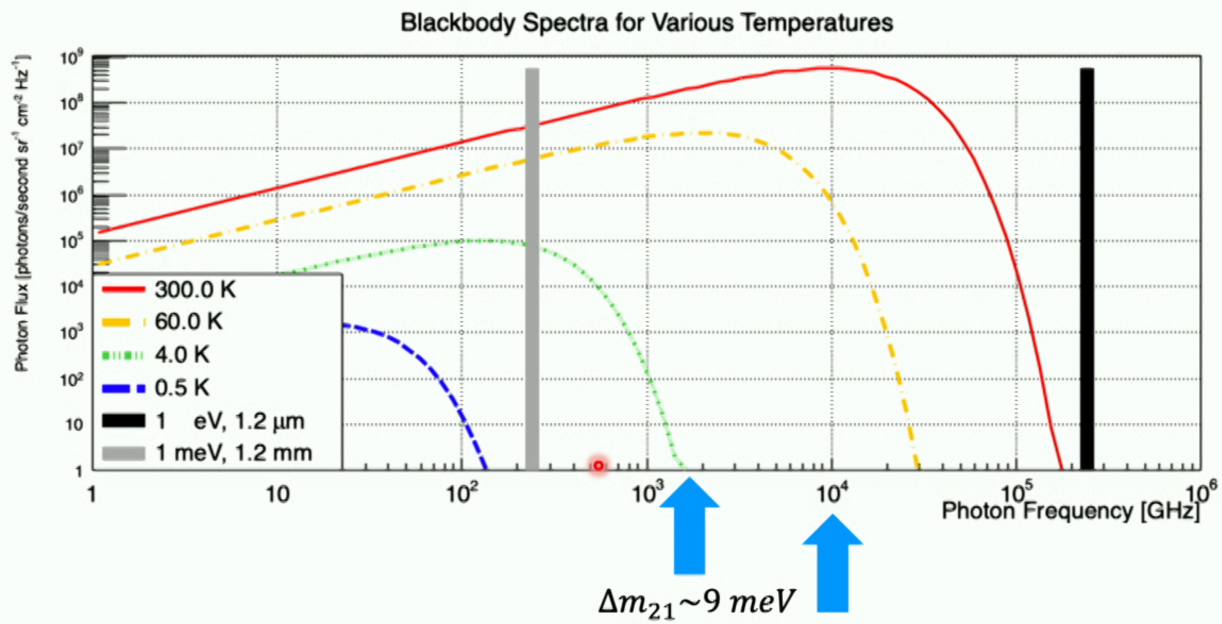
meV backgrounds include known and unknown sources

- Ionizing radiation
- Non-ionizing radiation
- Stray fields
- Vibrations
- Everything...
- Neutrino annihilation? ;)



$\Delta m_{21} \sim 9\ meV$

$\Delta m_{32} \sim 50\ meV$

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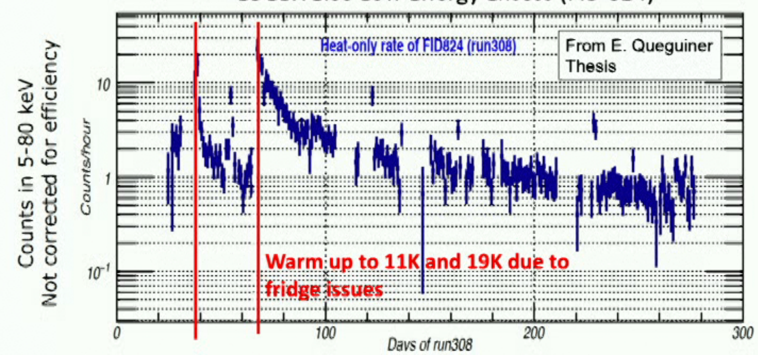
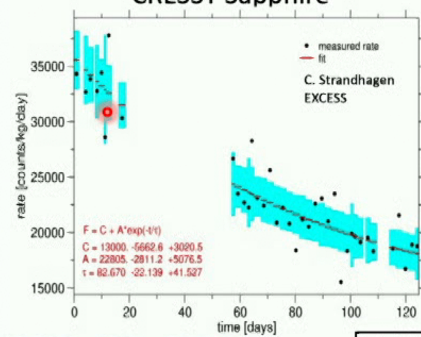
Low threshold dark matter searches all observe low energy excesses

- Most low-temperature results show the low energy backgrounds decay over long timescales.
- Seen at low e/h counts in CCDs, but also some non-ionizing components in CPD/HVeV
- Prediction: The low mass dark matter searches will be grappling with new low energy backgrounds for the next decade

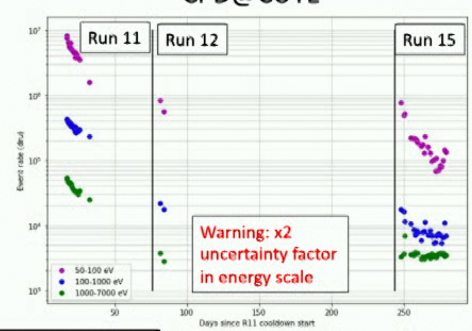
EDELWEISS Low Energy Excess (FID 824)



CRESST Sapphire



CPD@CUTE



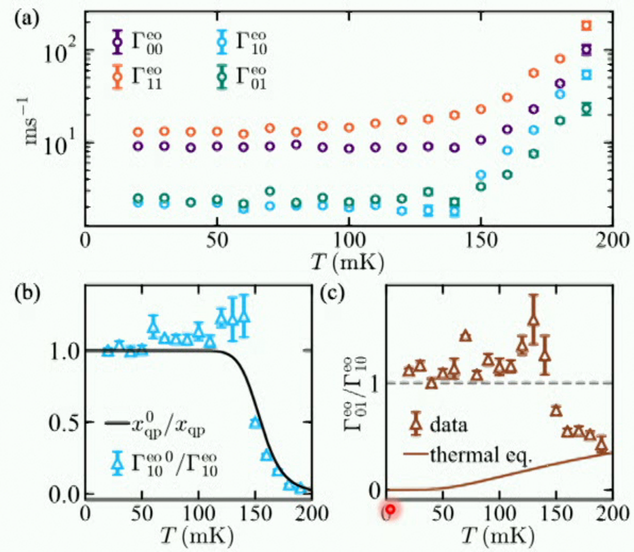
M. Pyle @EXCESS2022

meV backgrounds now entangles with quantum computing

- Quantum computers are based on qubits
- Qubits are made from low energy systems
- Environmental backgrounds are a source of decoherence in qubits
- There are no radiation-hard design rules for quantum technologies

Quantum device developers have spent decades struggling with environmental backgrounds

Serniak et al., PRL 121 (2018) 157701, arXiv:1803.00476



- Non-thermal quasiparticles seem to be a limitation at low temperature
  - "In conclusion, … QP-induced loss can be responsible for a significant fraction of dissipation in state-of-the-art superconducting qubits. Additionally, we confirm that hot QPs with a highly-excited energy distribution are responsible for the residual excited-state population at low temperature in our samples."
- Similar discussions in the literature back to (at least) 2002
- Ionizing radiation is a piece of this puzzle
- Will solving this puzzle yield a new component of nature (e.g. dark matter)?

Experimentalists have shown that ionizing radiation degrades qubit performance

Radioactivity as Source of Decoherence

When we proposed the DEMETRA project (2018, starting grant of INFN), this was just a hypothesis. Today we have many papers stating that:

1. Radioactivity will be (or already is) the ultimate limit for the coherence of qubits

   [Vepsäläinen, Nature 2020]

2. Radioactivity limits quantum error correction in a matrix of qubits

   [Wilen, Nature 2021] and [McEwen, arXiv:2104.05219]

3. Suppressing radioactivity improves the performance of quantum circuits

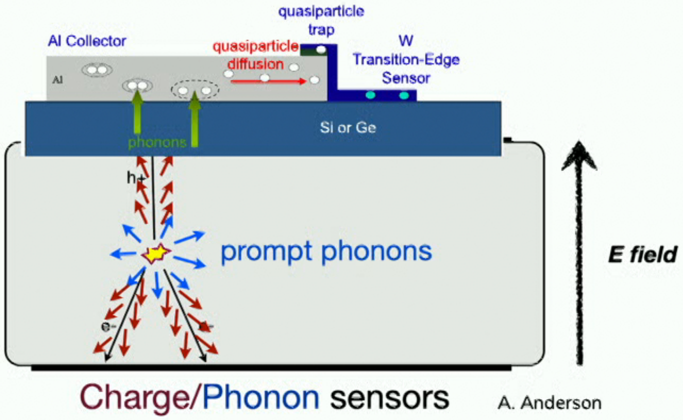
   [Cardani, Nat. Comm. 2021]

Future Project Workshop 2021 7 L. Cardani

SNOLAB Future Projects Workshop, talk by L. Cardani (INFN), May 11, 2021

SuperCDMS detectors are an experimental demonstration of superconducting circuits exhibiting correlated errors from ionizing radiation

- Error correction schemes require uncorrelated errors
- A single ionizing radiation event can simultaneously affect ***every*** superconducting transition edge sensor on the surface of a 100 mm diameter SuperCDMS detector
- A single ionizing radiation event can cause errors in ***every*** qubit on the same substrate (or even in substrates up to 100 m apart)
- Background rate translates into a fundamental limit on quantum computation time



In SuperCDMS, particle interactions generate phonons, which generate quasiparticles in superconducting films, which can be counted

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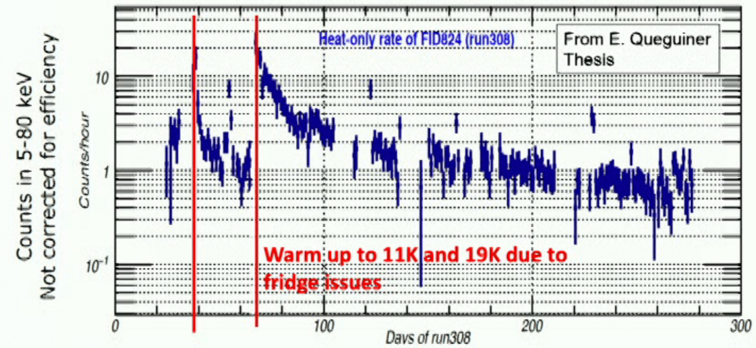

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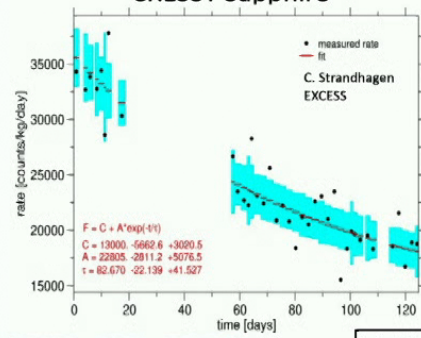

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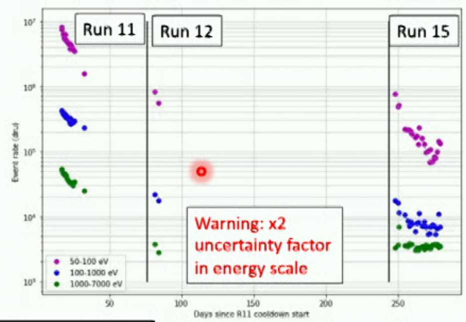
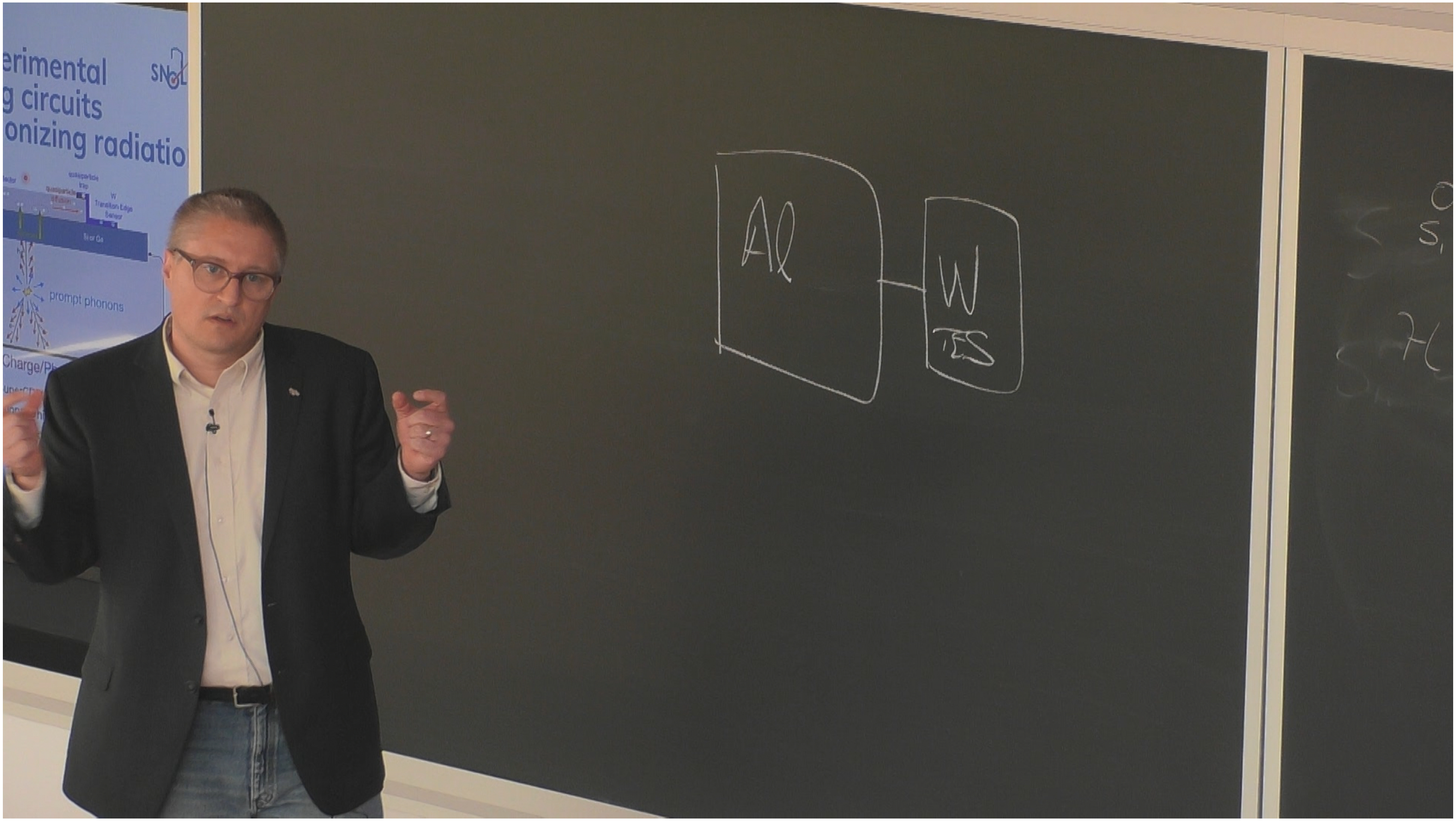


M. Pyle @EXCESS2022



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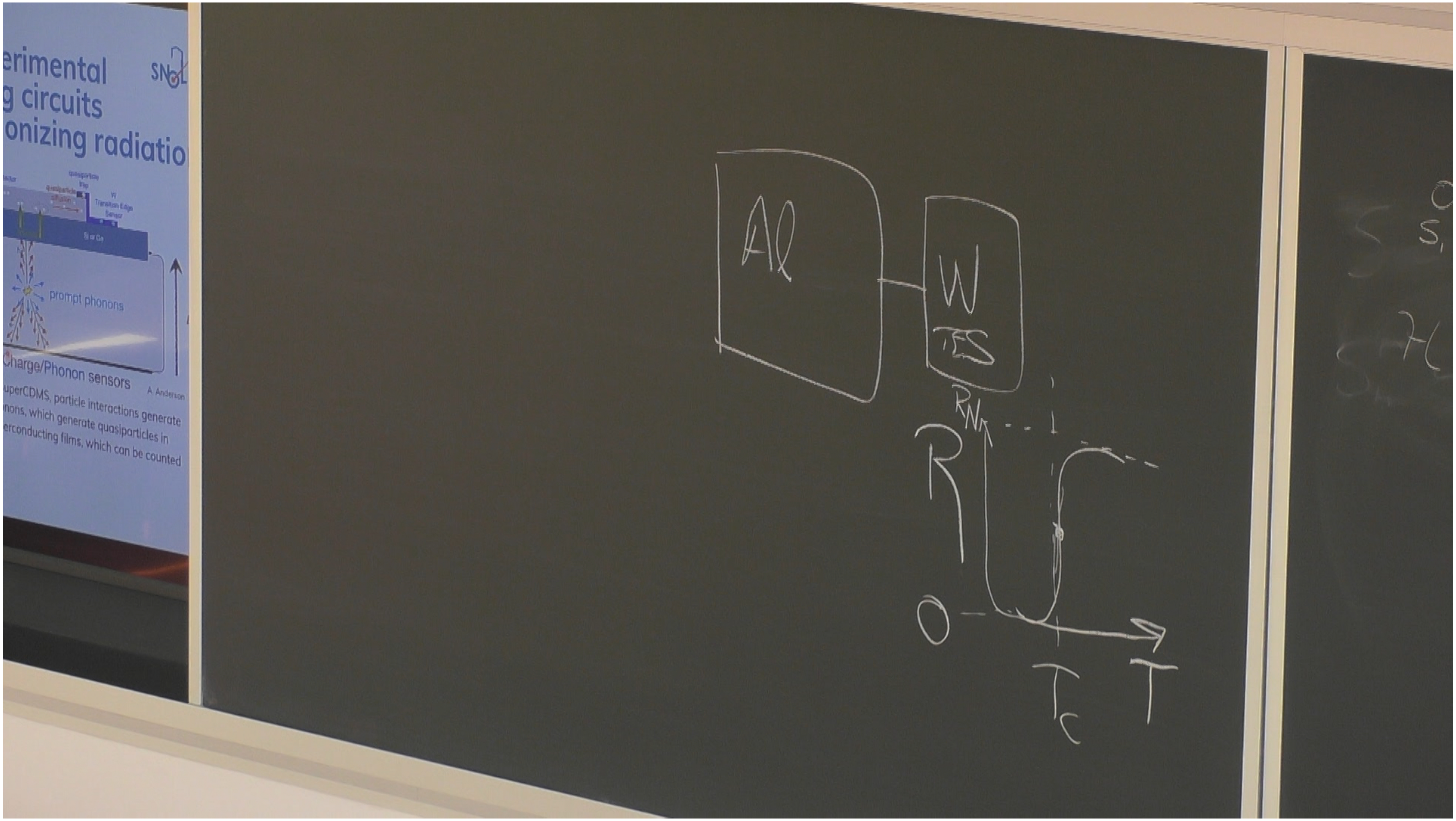
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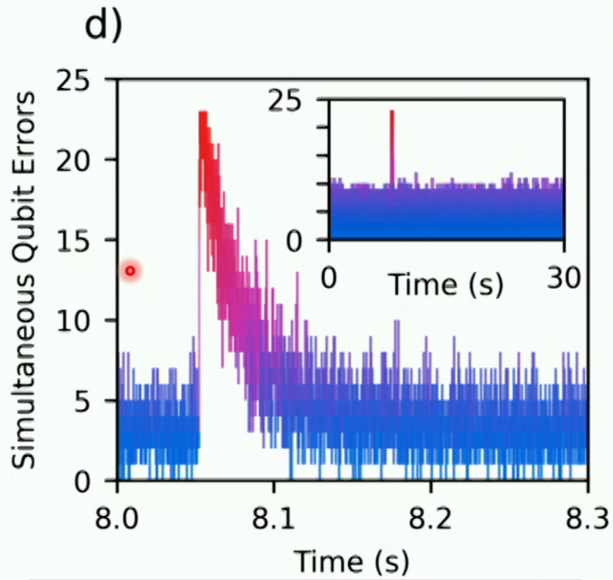
Experiments with cutting edge quantum processors reproduces SuperCDMS with demonstrations of correlated errors

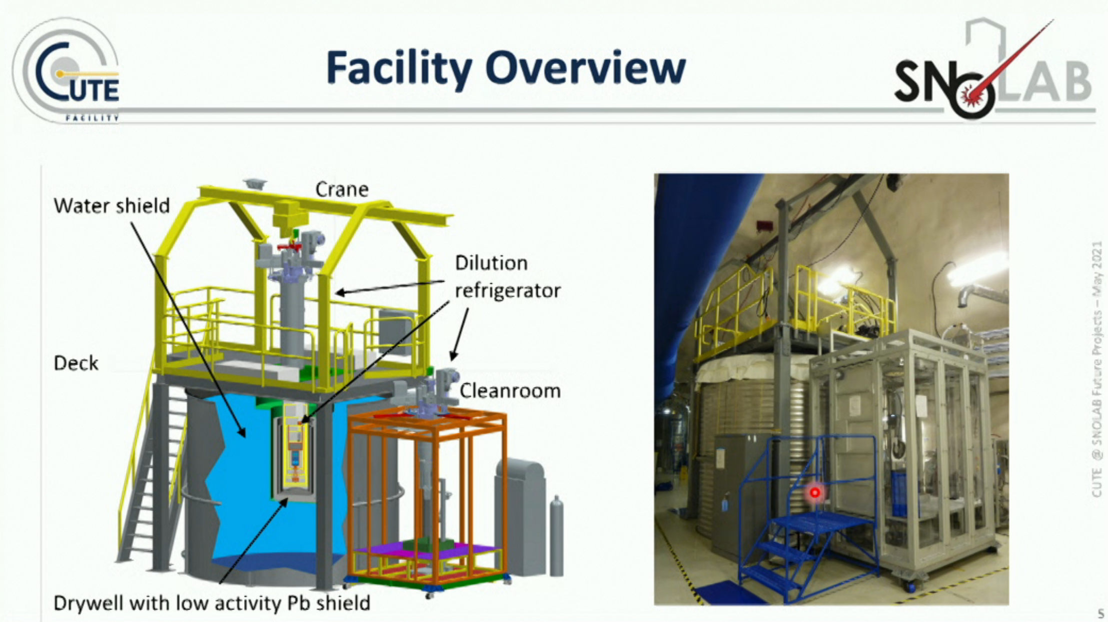
- Search for simultaneous errors with a google quantum processor
- Clear evidence of particle interactions
- Watched evolution of errors start locally, but spread across all qubits
- This represents a fundamental limit on the time for any quantum calculation



M. McEwan, et al., Nat. Phys. **18**, 107 (2022)

SNOLAB hosts the lowest background millikelvin test facility

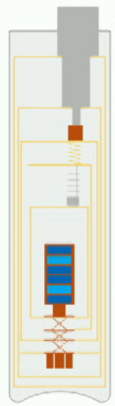
- X10000 reduction from surface background rates
- $X10^8$ reduction in muons
- Allows controlled radiation on/off tests of device performance



SNOLAB Future Projects Workshop, talk by W. Rau (UBC/TRIUMF), May 11, 2021

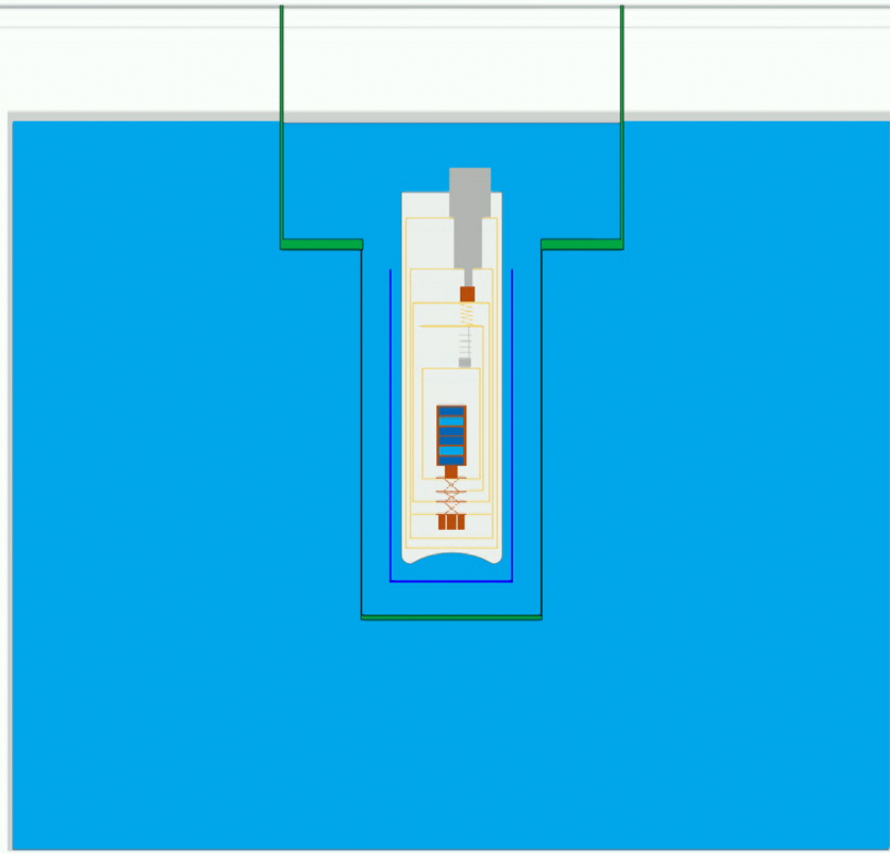
Facility Overview

Main system components:
Payload



W. Rau - CUTE @ SNOLAB – EAC, March 2023

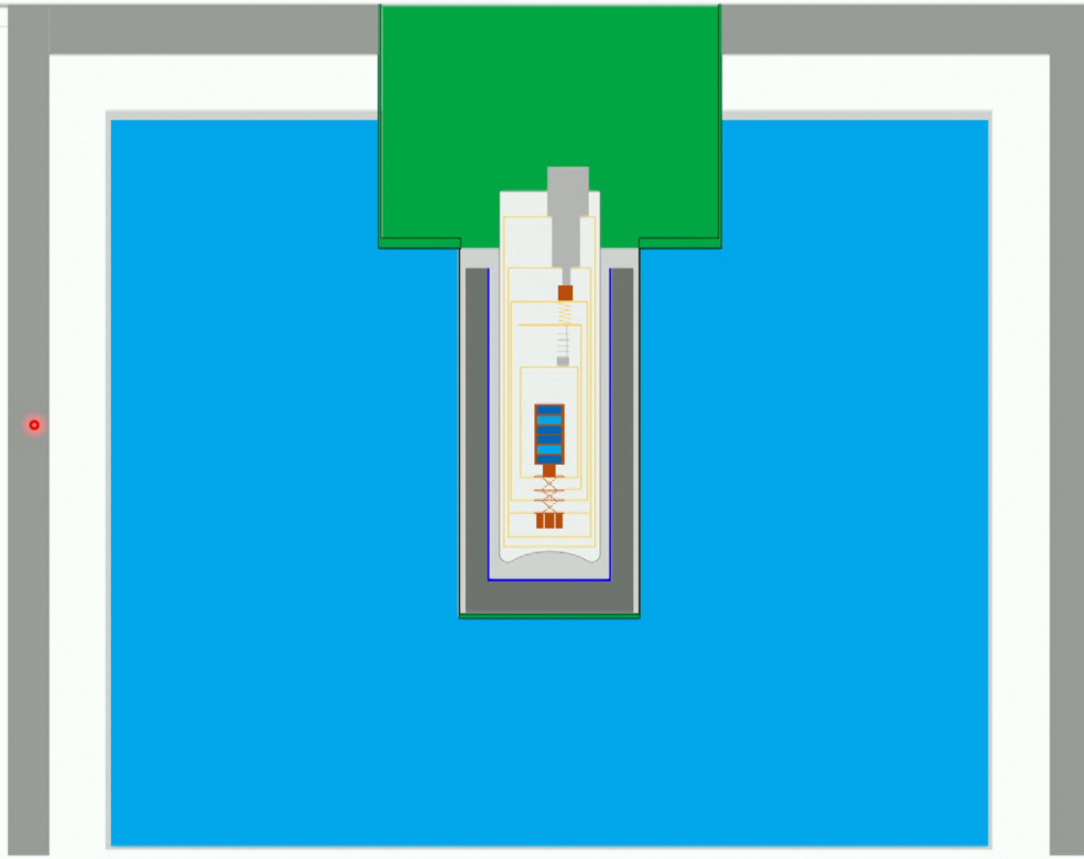
Facility Overview



Main system components:
Payload
Cryostat
Magnetic shielding
Water tank

W. Rau - CUTE @ SNOLAB – EAC, March 2023

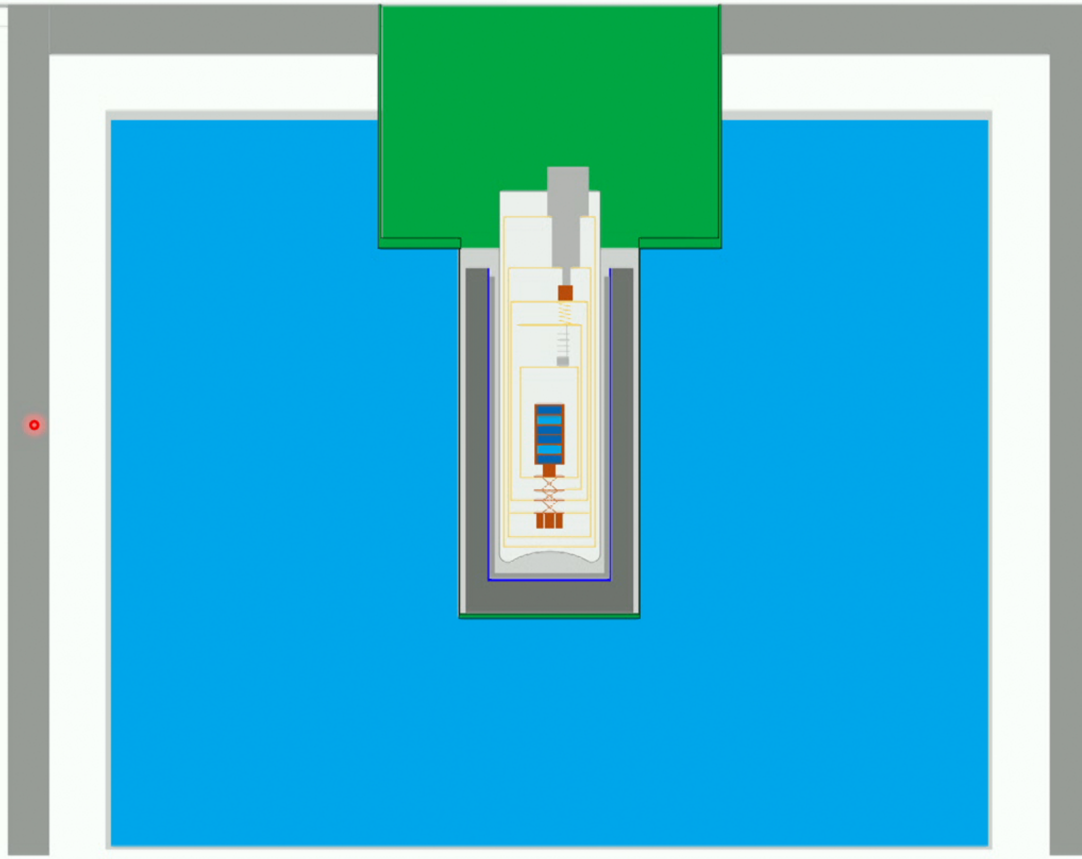
Facility Overview



Main system components:

Payload
Cryostat
Magnetic shielding
Water tank
Drywell
Deck

Facility Overview



Main system components:
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Water tank
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Low activity lead
Very low activity lead

W. Rau - CUTE @ SNOLAB – EAC, March 2023

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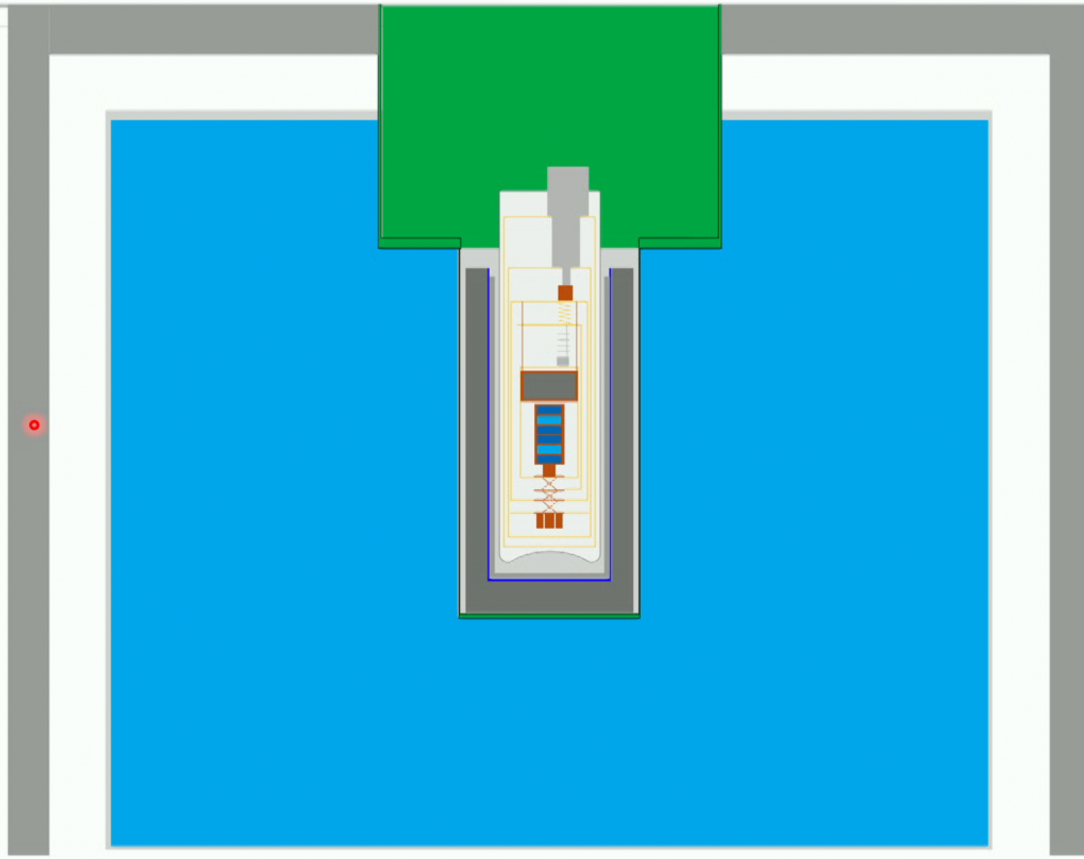

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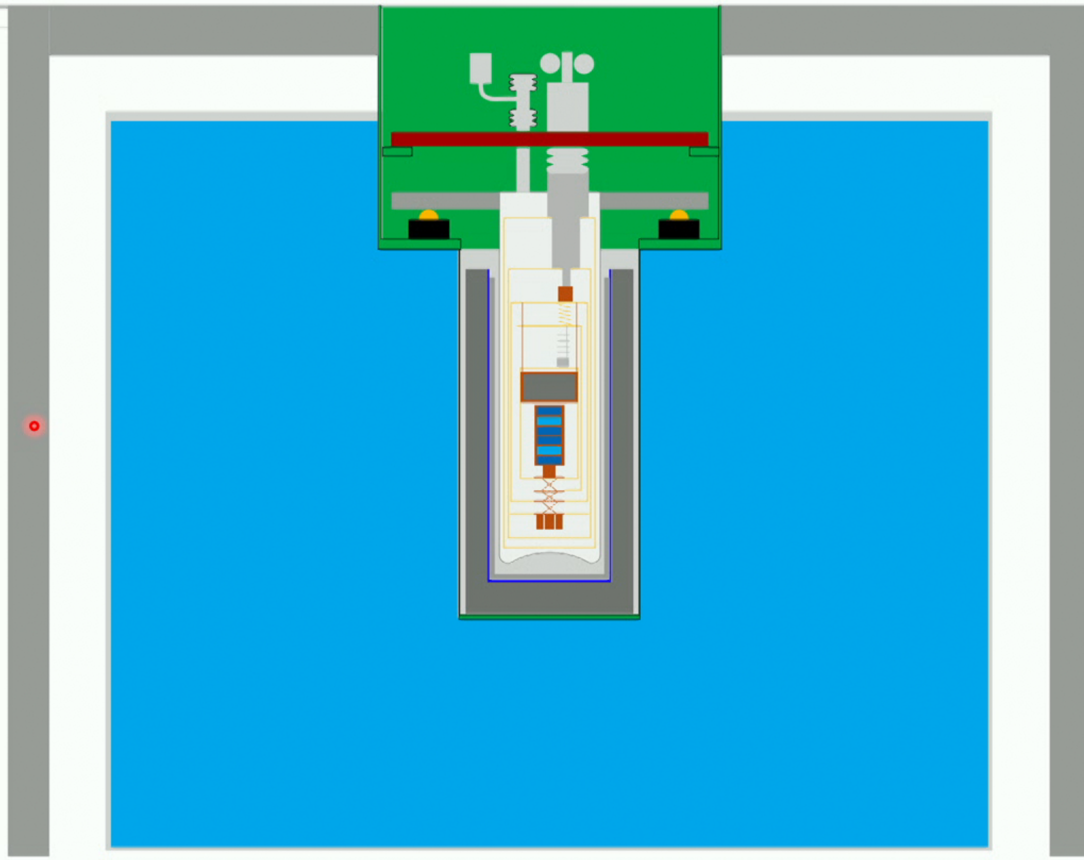
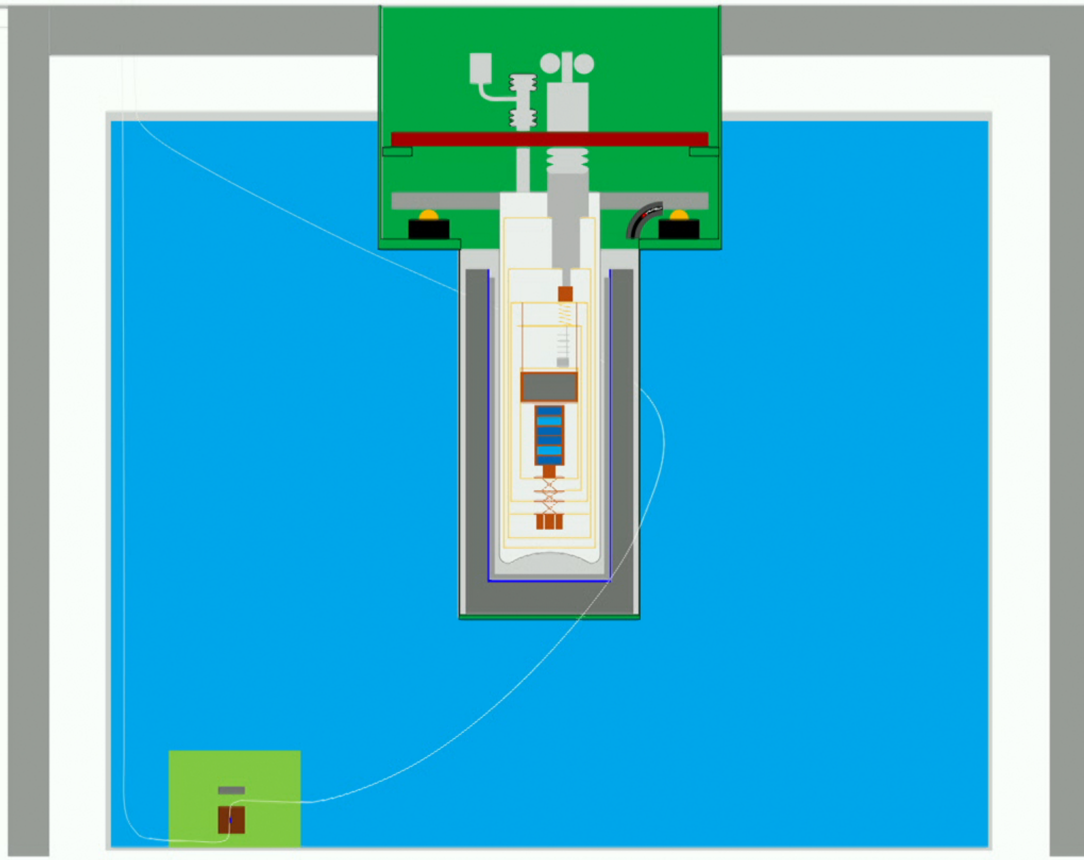


Main system components:

Payload
Cryostat
Magnetic shielding
Water tank
Drywell
Deck
Low activity lead
Very low activity lead
Internal lead
Polyethylene
Suspension system
Extra frame for
Pulse Tube (PT)/turbo

Facility Overview



Main system components:

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Cryostat
Magnetic shielding
Water tank
Drywell
Deck
Low activity lead
Very low activity lead
Internal lead
Polyethylene
Suspension system
Extra frame for
 Pulse Tube (PT)/turbo
Gamma source
Neutron source

W. Rau - CUTE @ SNOLAB – EAC, March 2023

The Institute for Quantum Computing is leading on a project to characterize qubits in the CUTE facility

- ‘Characterization of qubits in a deep underground environment’ chosen for funding by the US Army Research Office
- Prof. Chris Wilson at the IQC is the project leader
- Chalmer’s University will produce cutting-edge superconducting qubit arrays
- Arrays will be tested in Sweden, Waterloo, then SNOLAB
- Project is newly selected, contracting has just started

meV backgrounds now entangles with quantum computing

- Quantum systems are sensitive to radiation from the environment
- Particle physics researchers are gaining an understanding of modern quantum systems by collaborating on background reduction
- New detector concepts are coming based on these collaborations

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New collaborations between fields are resulting in new dark matter detector understanding and ideas

SNOLAB

PHYSICAL REVIEW LETTERS 125, 181102 (2020)

Search for Composite Dark Matter with Optically Levitated Sensors

Fernando Monteiro,[1,*] Gadi Afek,[1] Daniel Carney,[2,3] Gordan Krnjaic,[3,4] Jiaxiang Wang,[1] and David C. Moore[1]
[1]*Department of Physics, Wright Laboratory, Yale University, New Haven, Connecticut 06520, USA*
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Detecting Dark Matter with Superconducting Nanowires

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arXiv:1903.05101

arXiv:2108.03239

Searches for light dark matter using condensed matter systems

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Detection of Light Dark Matter With Optical Phonons in Polar Materials

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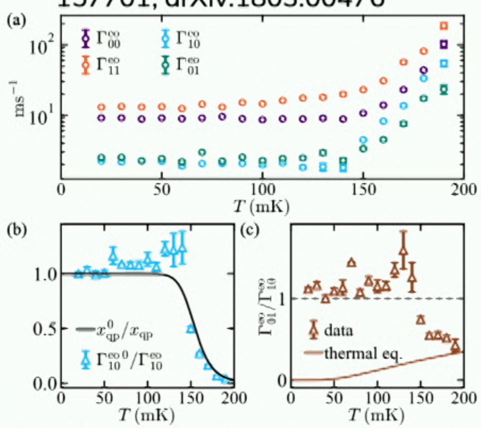
- meV energy detection is a theoretical and experimental challenge that people are tackling
- Quantum 2.0 technologies are enabling new detection concepts
- This is *not* an exhaustive list

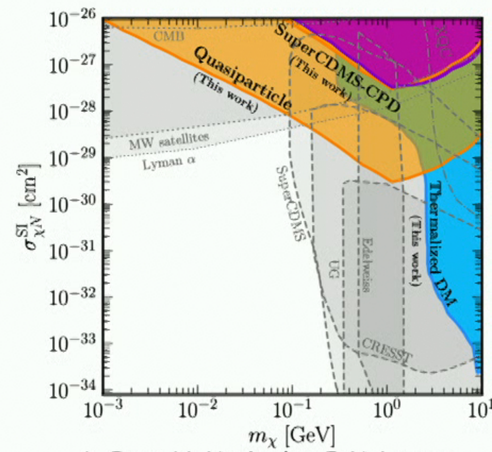
Qubits are meV-threshold dark matter detectors

- If particle interactions cause qubit errors, then qubit errors measure particle interactions
- Old quasiparticle measurements for quantum computing have leading sensitivity to light dark matter

Serniak et al., PRL 121 (2018) 157701, arXiv:1803.00476



This measurement of quasiparticle density for better quantum devices can be reinterpreted as a dark matter limit

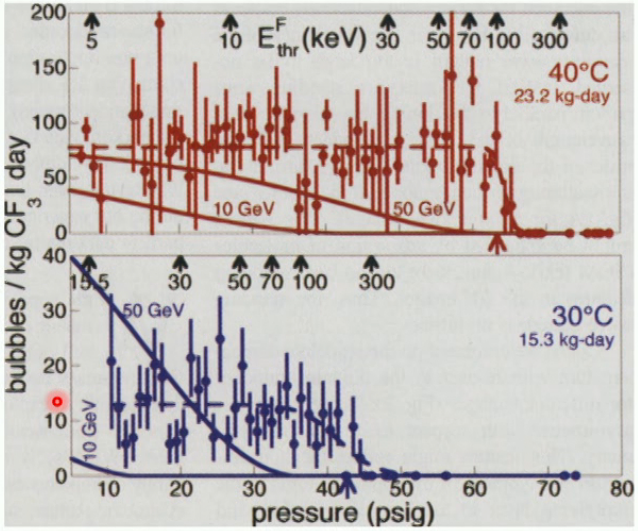


A. Das, N. Kurinsky, R.K. Leane, arXiv:2210.09313

Qubits are meV-threshold dark matter detectors

- Threshold detectors retain no event information about energy
- Statistical energy spectra can be obtained by varying the threshold (e.g. use different superconductors)
- This would lead to orders of magnitude improvement because higher energy backgrounds can be subtracted (and the backgrounds are high)

Superconductor	Transition Temp [K]	Bandgap [meV]
Ir	0.014	0.042
Al	1.2	0.4
Ta	4.5	1.4
Nb	9.3	2.9



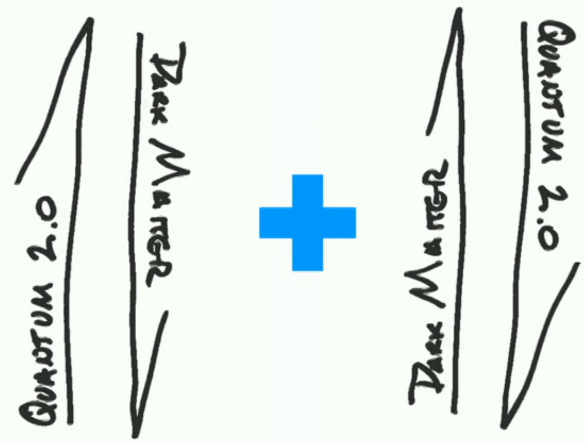
Varying thresholds can yield spectral information. E. Behnke et al. (COUPP Collaboration), Science 319, 2008

In conclusion, light dark matter and quantum computing researchers are in a correlated superposition of research outcomes

SNOLAB

- After we perform the research, we will be in one of two states:
  - Dark matter has been detected, but it is a fundamental limit to quantum device performance, OR
  - We have improved the performance of quantum devices, but we haven't discovered the nature of dark matter

- and SNOLAB is the best place to perform this measurement



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