2022/06/15

Backgrounds in Qubits

Jeter Hall
SNOLAB/Laurentian University

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.

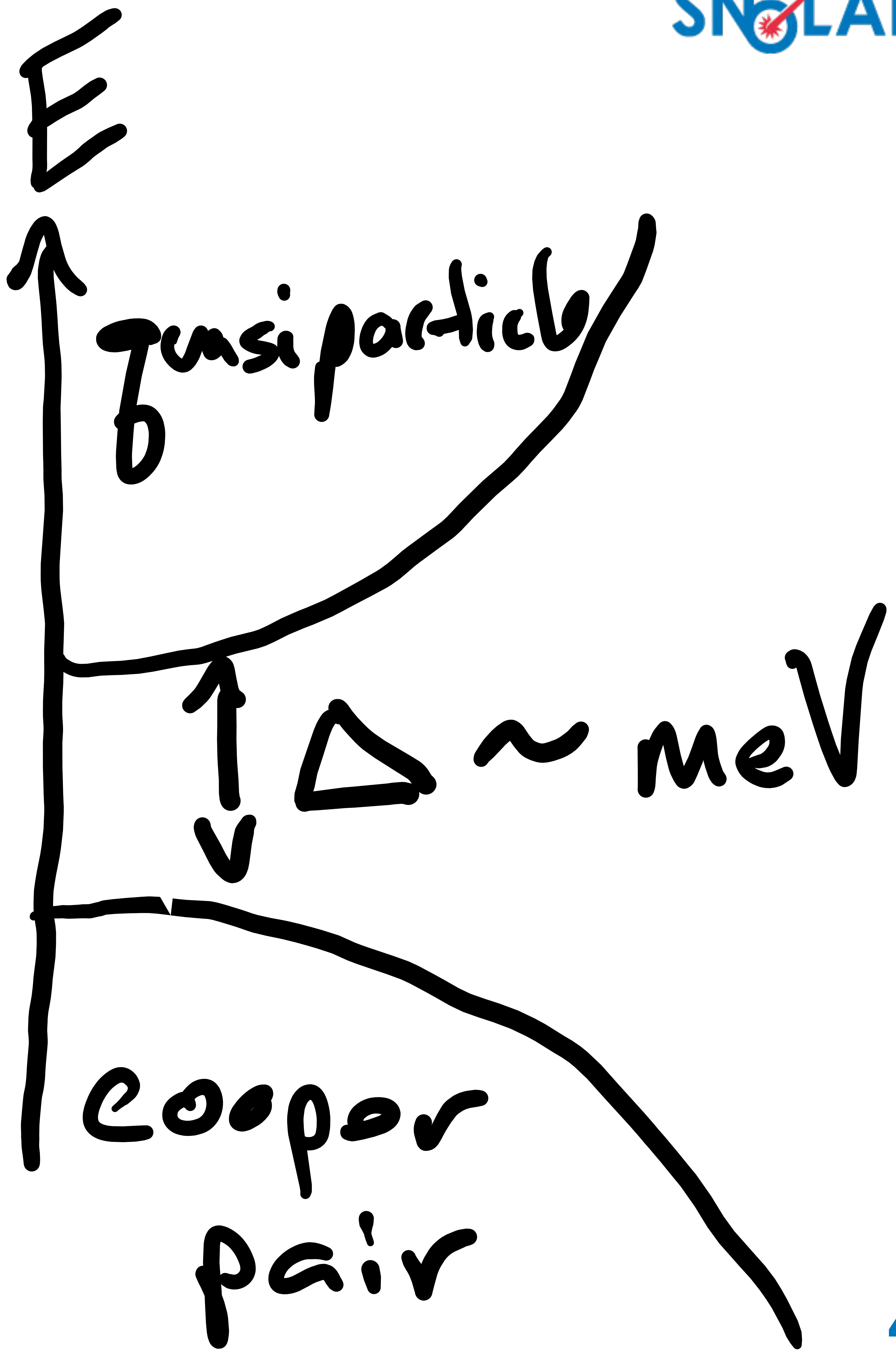
We acknowledge those who came before us and honour those who are the caretakers of the land and the waters.

Qubit Backgrounds

Dark Matter Backgrounds
Qubit Backgrounds = Dark Matter Backgrounds

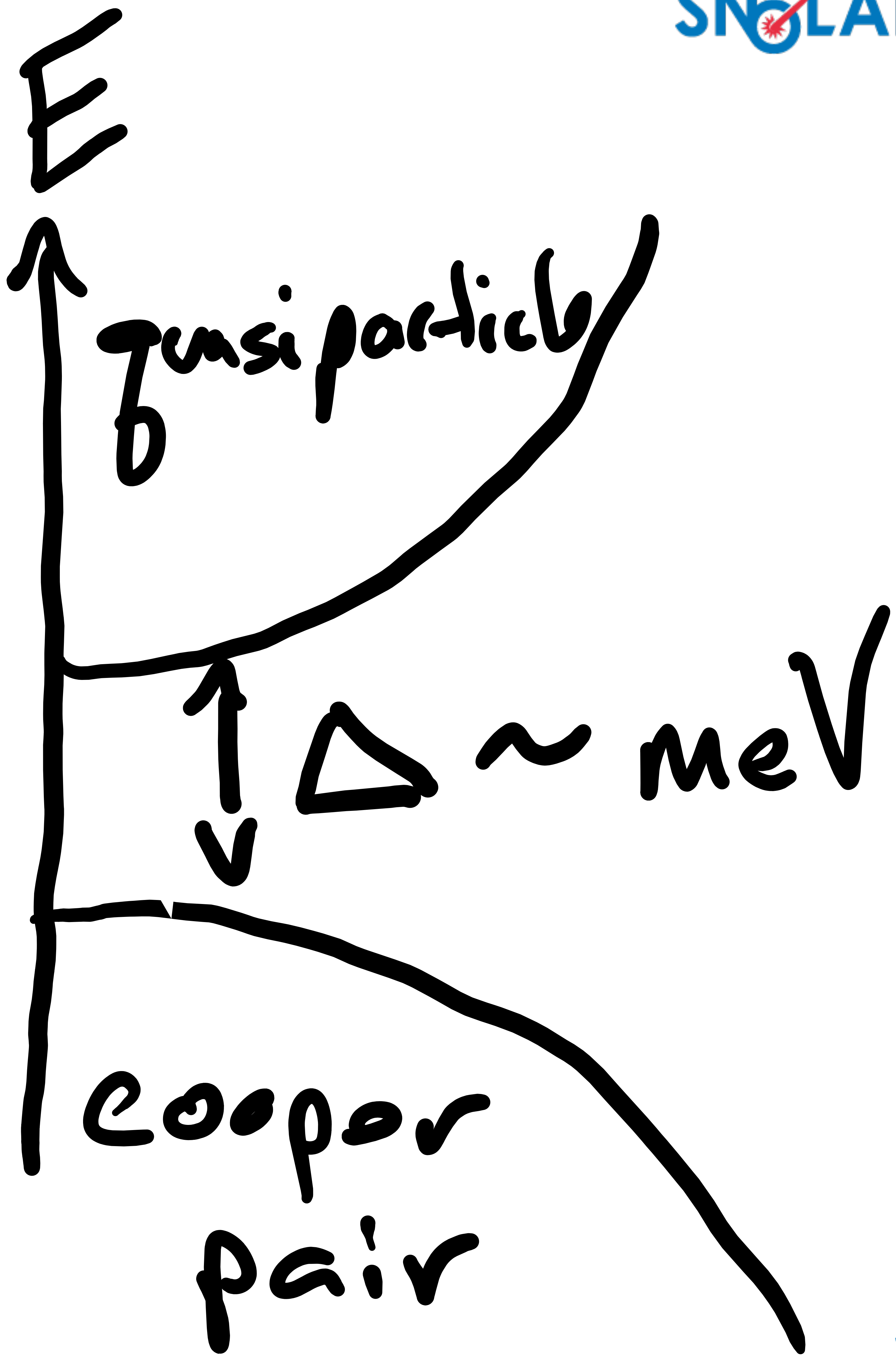
Superconducting bandgaps are small, so superconductors are sensitive to small energy depositions.

- Typical low-temperature bandgaps are a fraction of a milli-electron volt.
- Incident energy can break cooper pairs, which forms quasiparticles in the superconductor.
- Using superconductors as a proxy for several low energy systems.



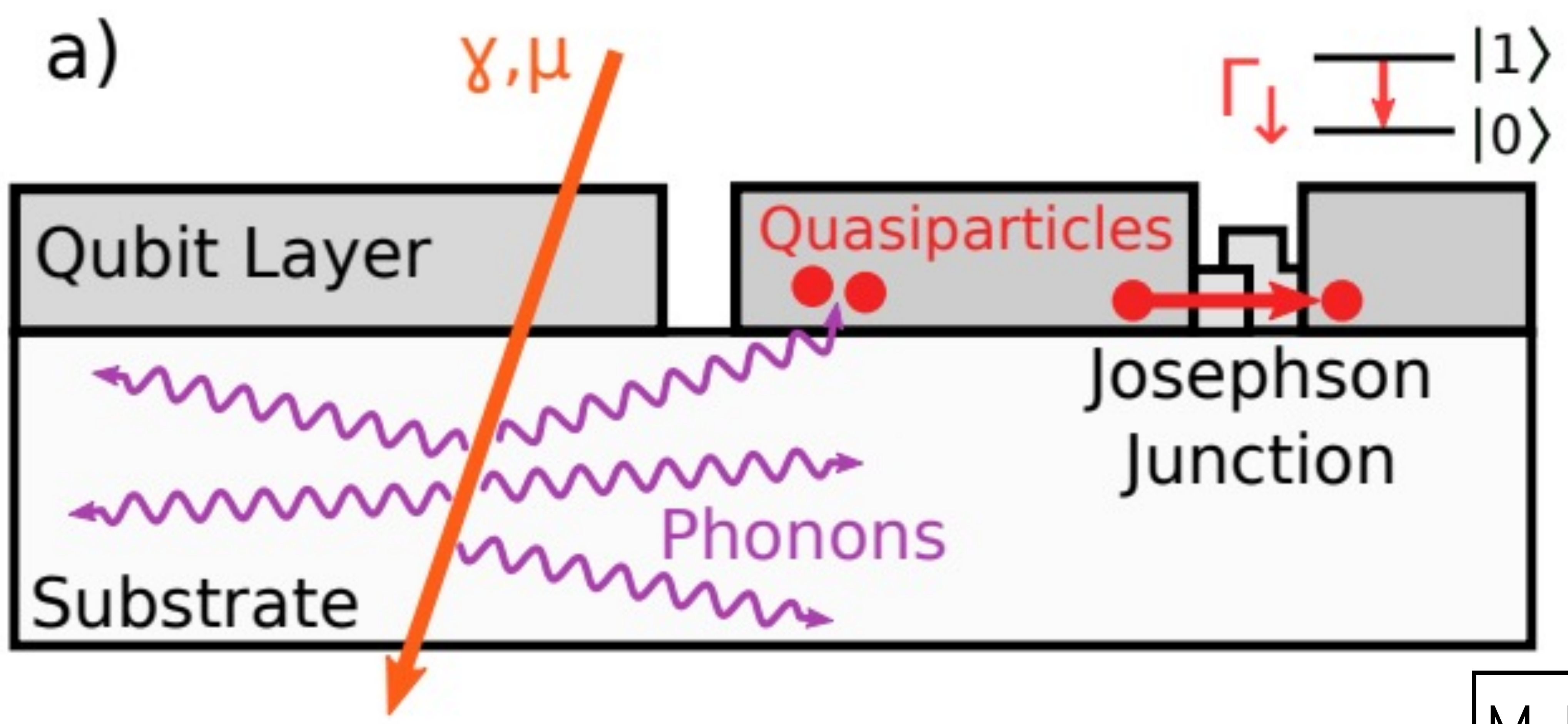
Quasiparticles can poison superconducting electronics.

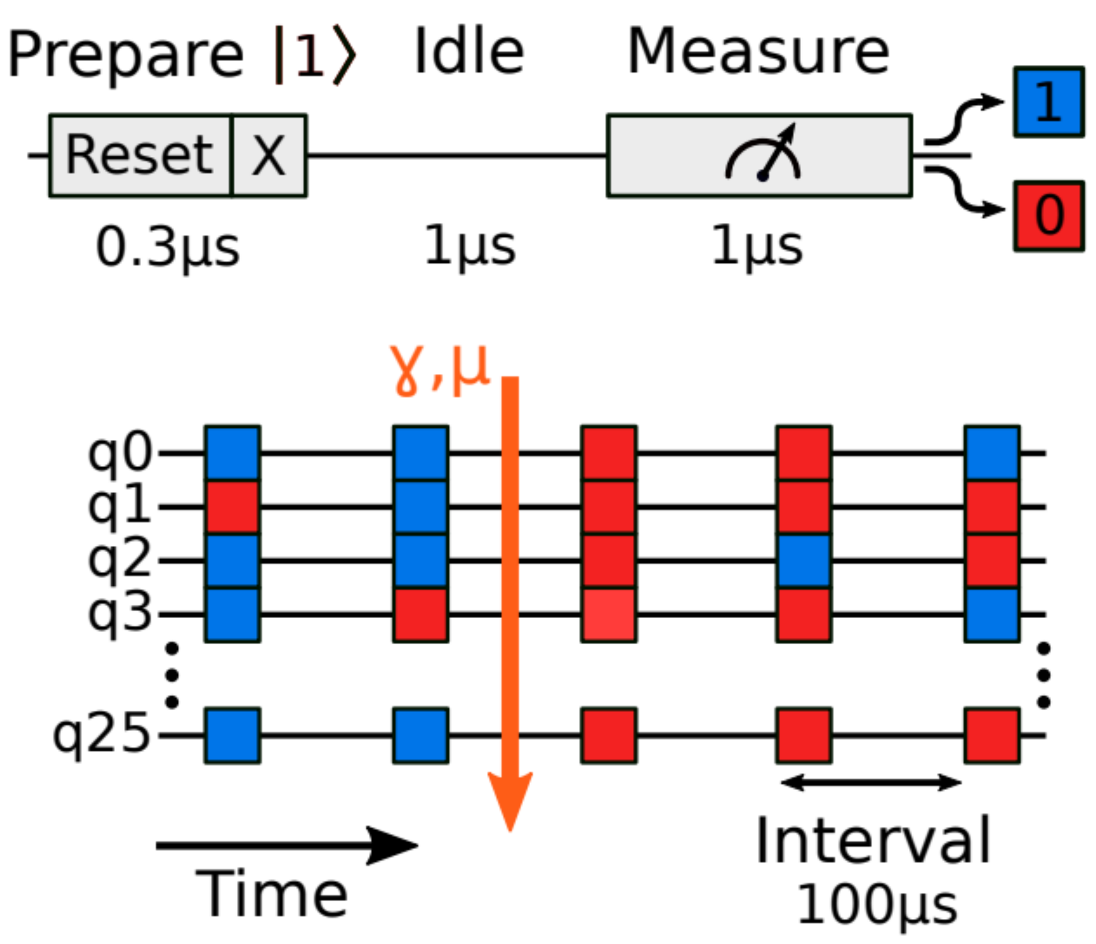
- Quantum circuits involve preparing systems in energy states.
- Superconducting qubits have energy state differences <1 meV.
- Quasiparticles can absorb energy from quantum circuits and change the energy state (from, say, |1> to |0>).



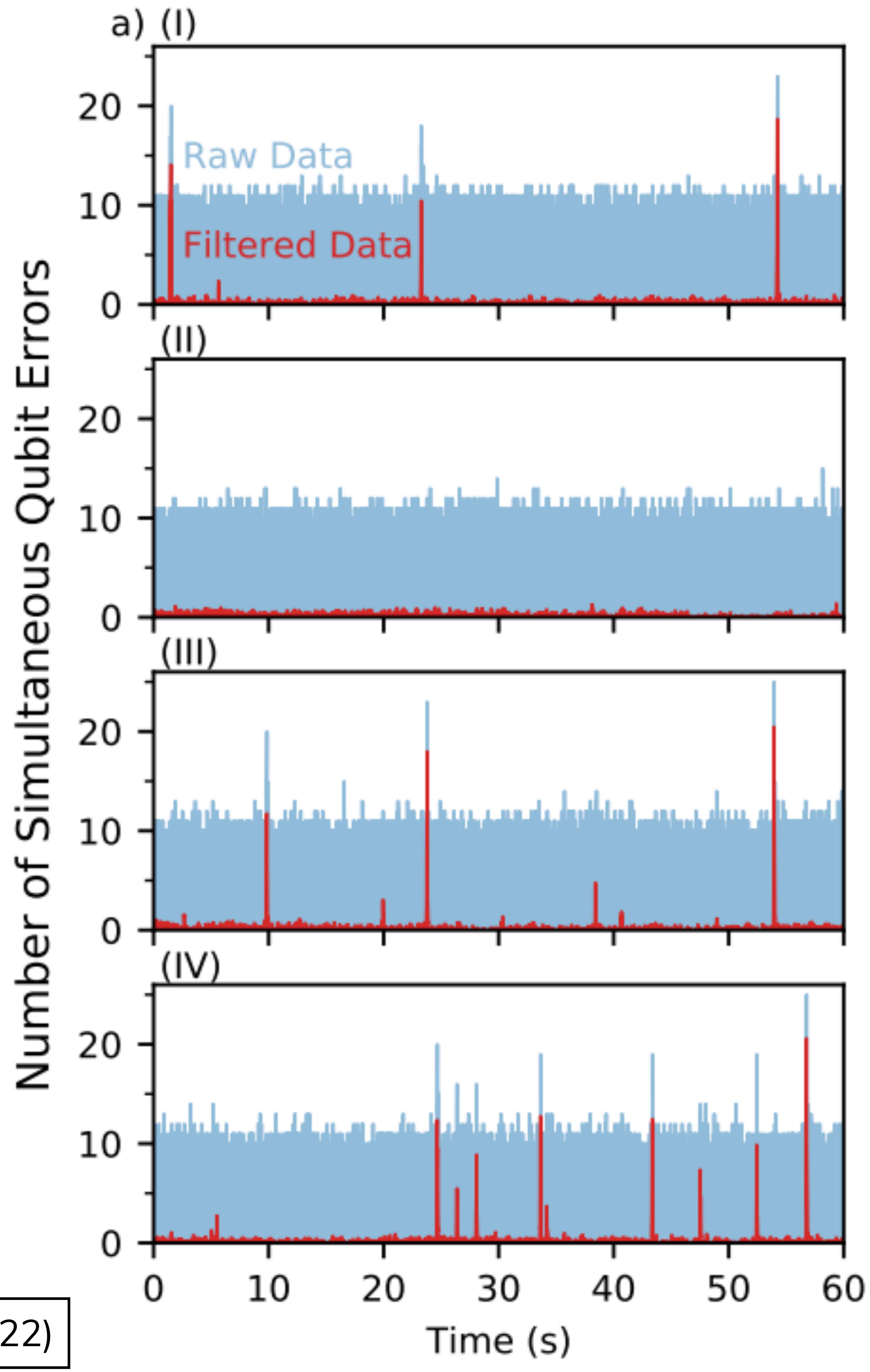
Ionizing radiation can cause correlated errors.

- Error correction is critical for quantum computing scaling.
- Correlated errors will complicate error correction.
- Rate in a Google Sycamore processor measured at ~0.1 Hz.



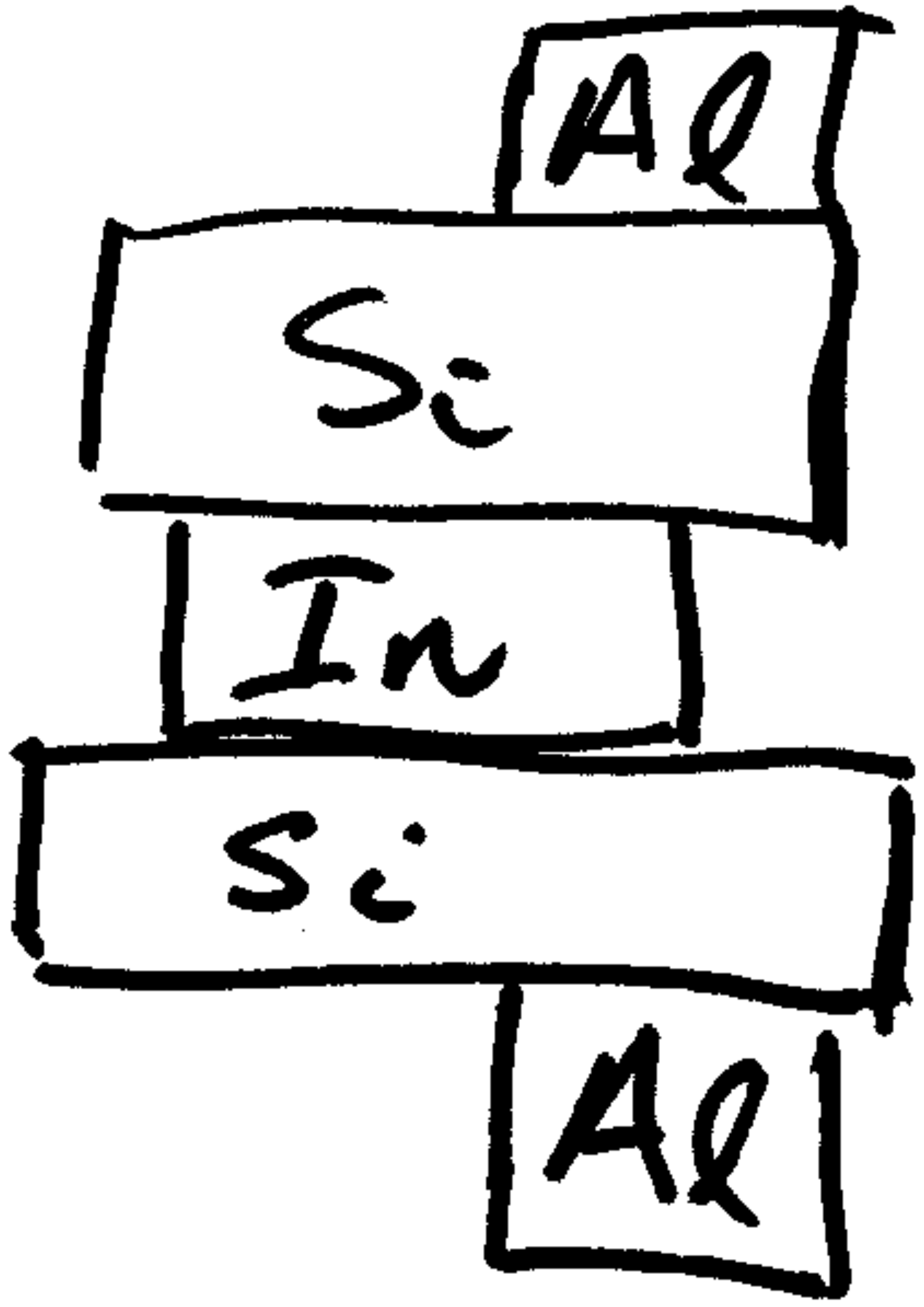


M. McEwan, et al., Nat. Phys. **18**, 107 (2022)



Ionizing radiation backgrounds will need consideration in large integrated quantum circuits.

- Rate in a Google Sycamore processor measured at ~0.1 Hz.
- Device is silicon substrate with superconducting films.
- Superconductors can couple the energy between silicon crystals.
- Features “significant volumes of indium”… indium “bump bonds are 5 micron tall and cover ~15% of the surface.”

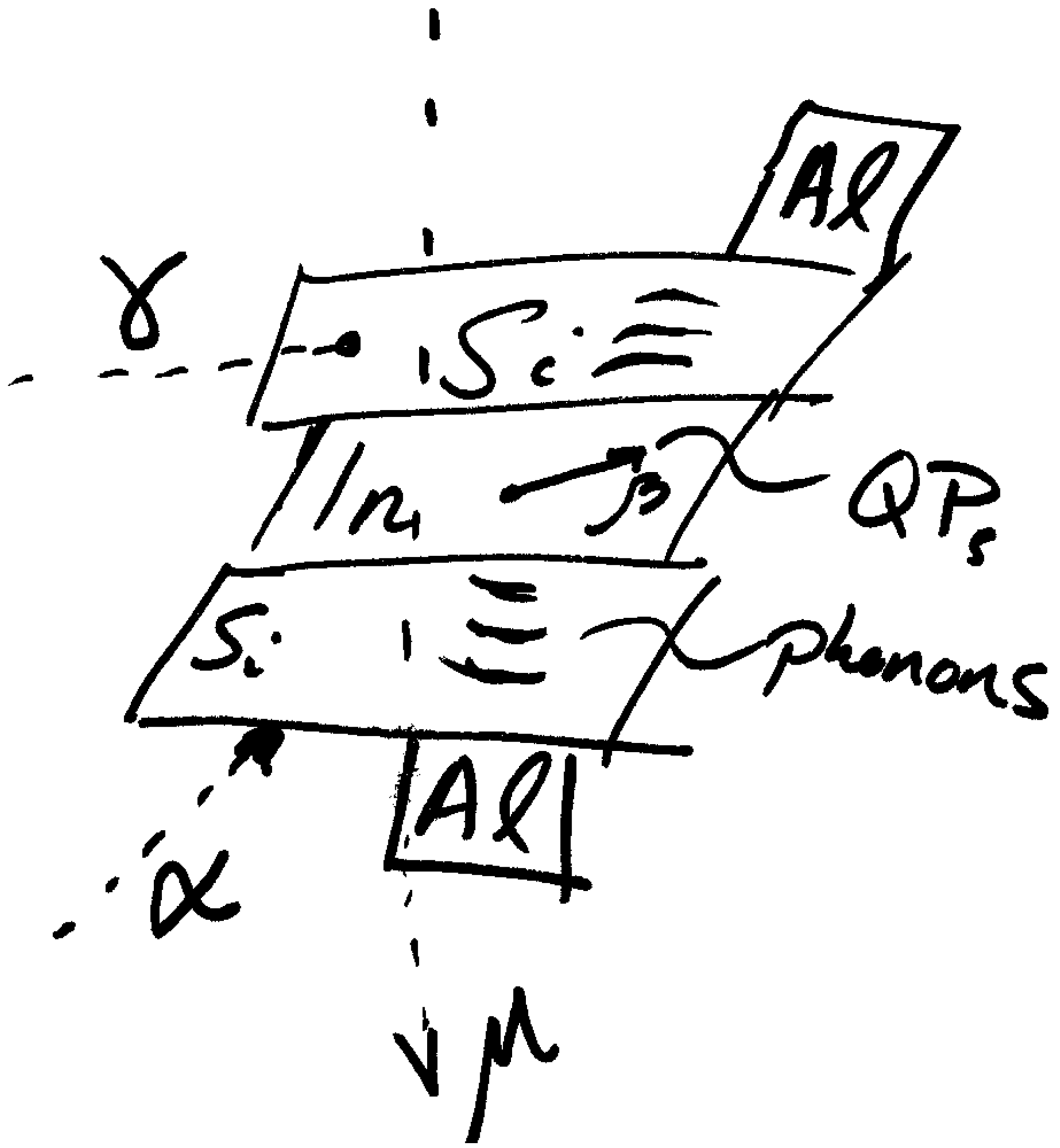


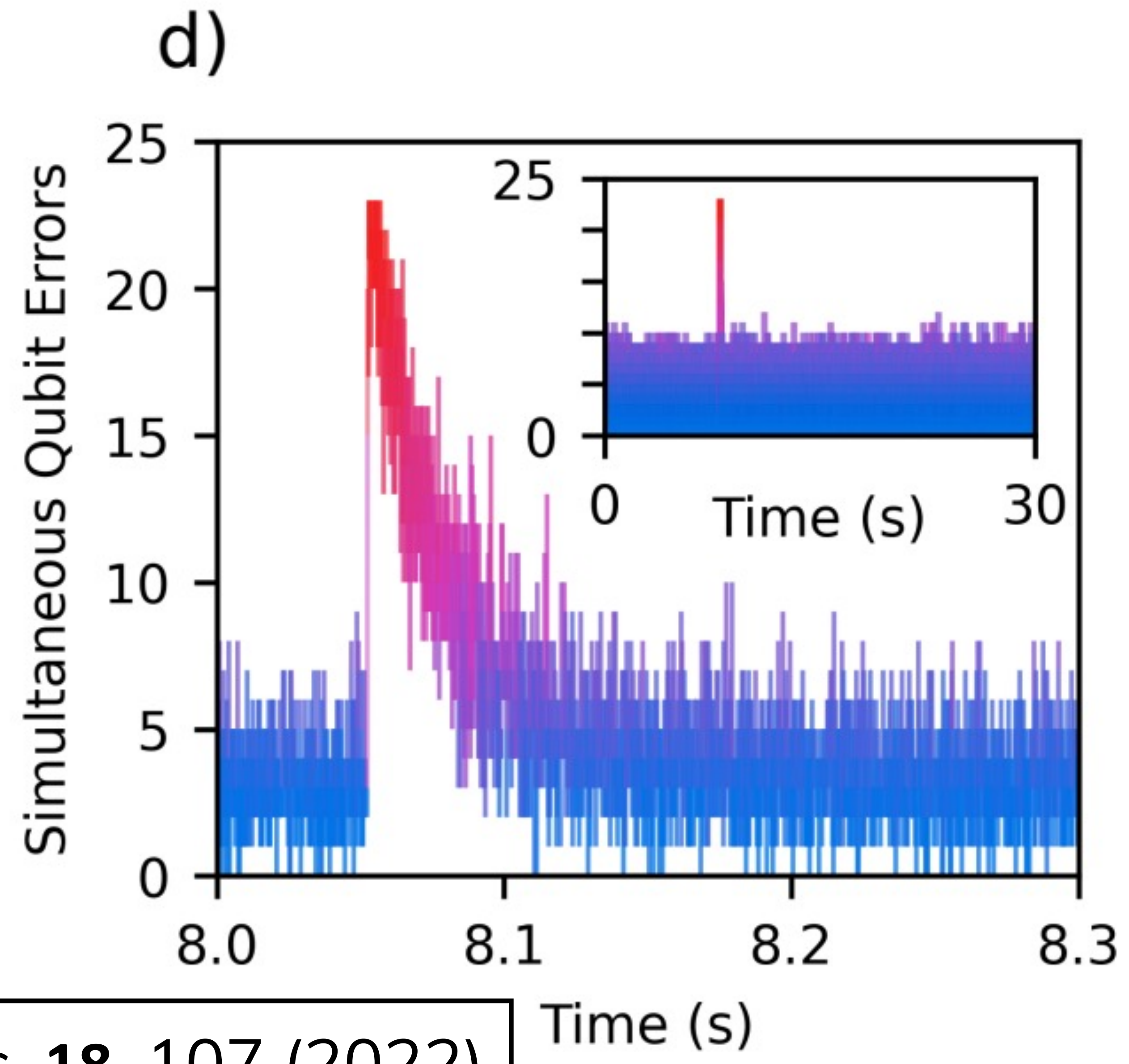
*not to scale…

Ionizing radiation backgrounds are a design constraint in large integrated quantum circuits.

- Rate in a Google Sycamore processor measured at ~0.1 Hz.
- This is comparable to
  - the cosmic-ray rate, See talk by G. D'Imperio in this session!
  - the beta-decay rate in indium,
  - and (likely) the gamma-ray rate from the materials like cables and connectors.
- Measured rate in Google Sycamore manageable with some error identification scheme and design considerations

See talk by X. Li in this session!





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

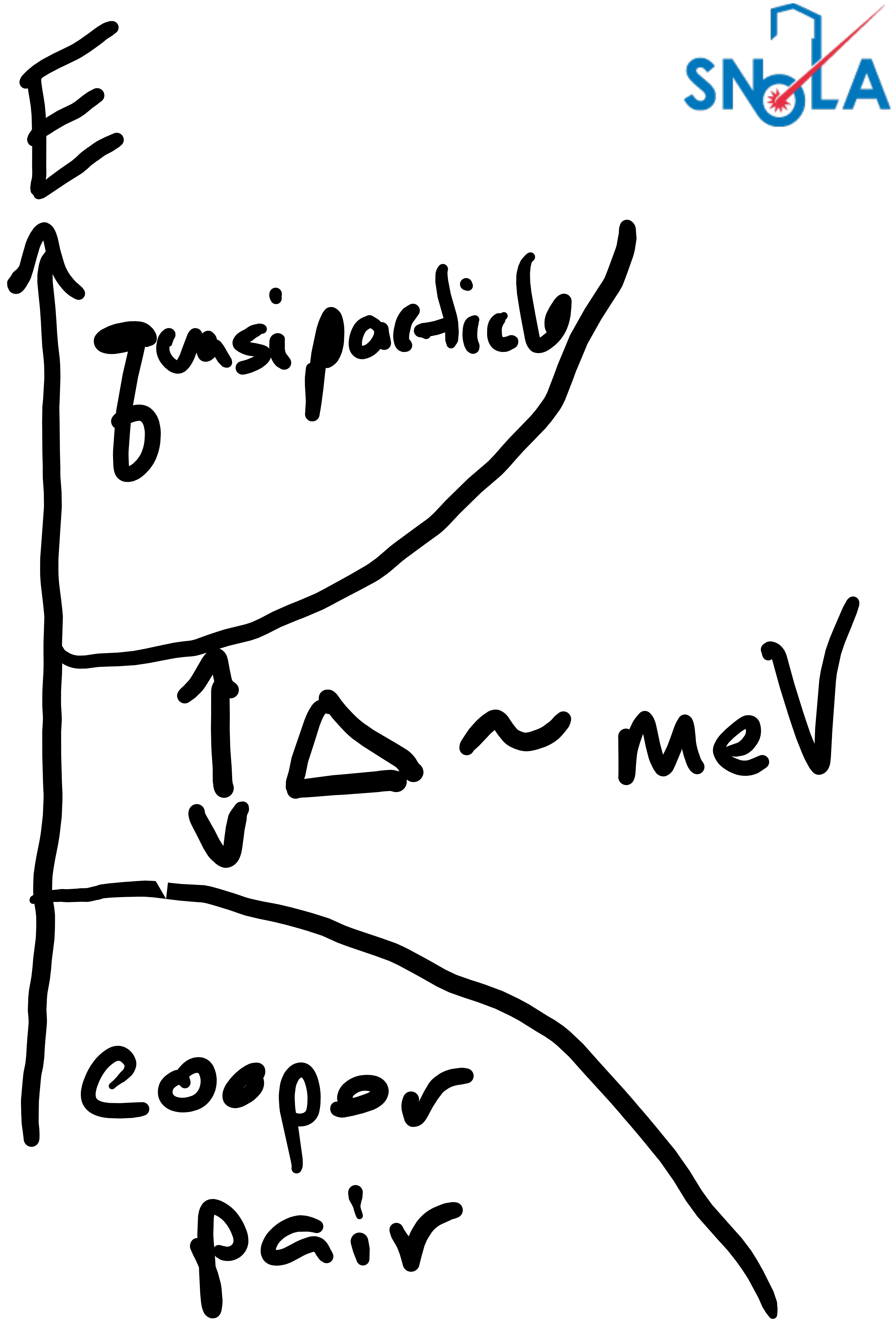
Qubit Backgrounds

Dark Matter Backgrounds

Qubit Backgrounds = Dark Matter Backgrounds

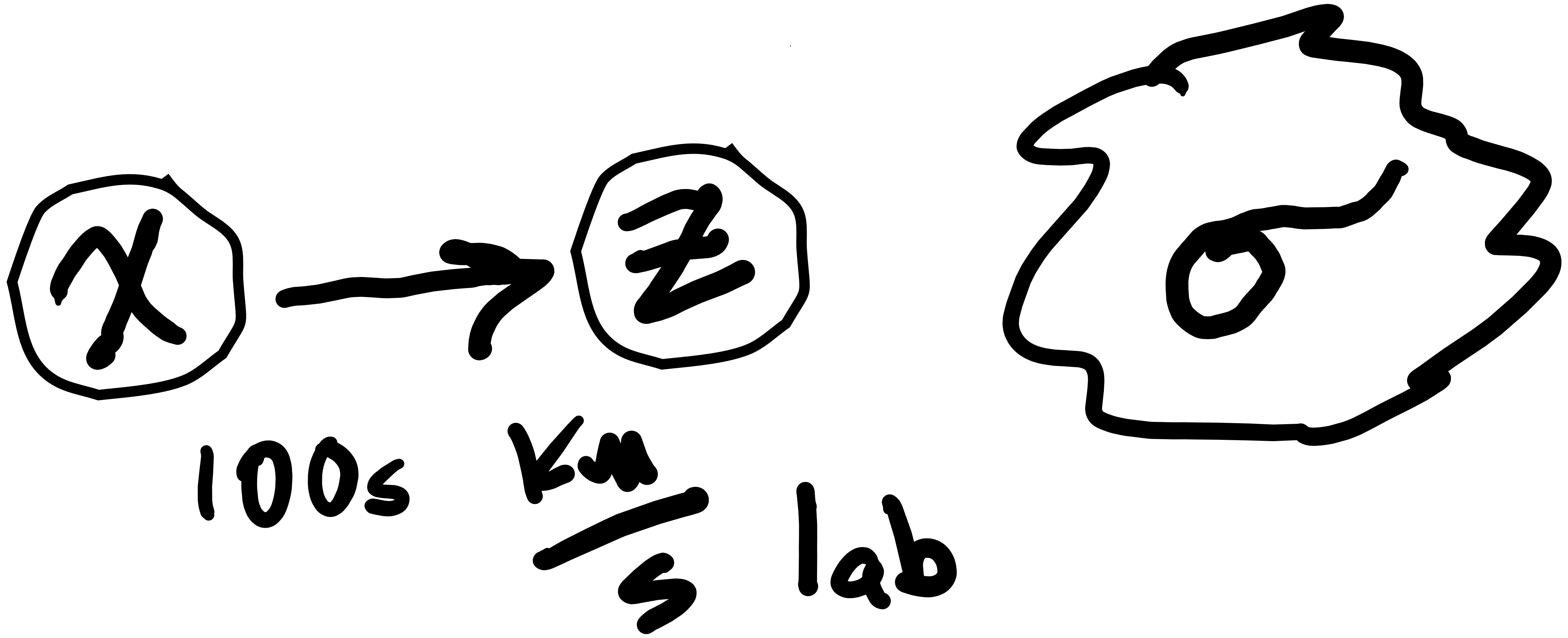
Superconductors are attractive particle detectors in the modern context.

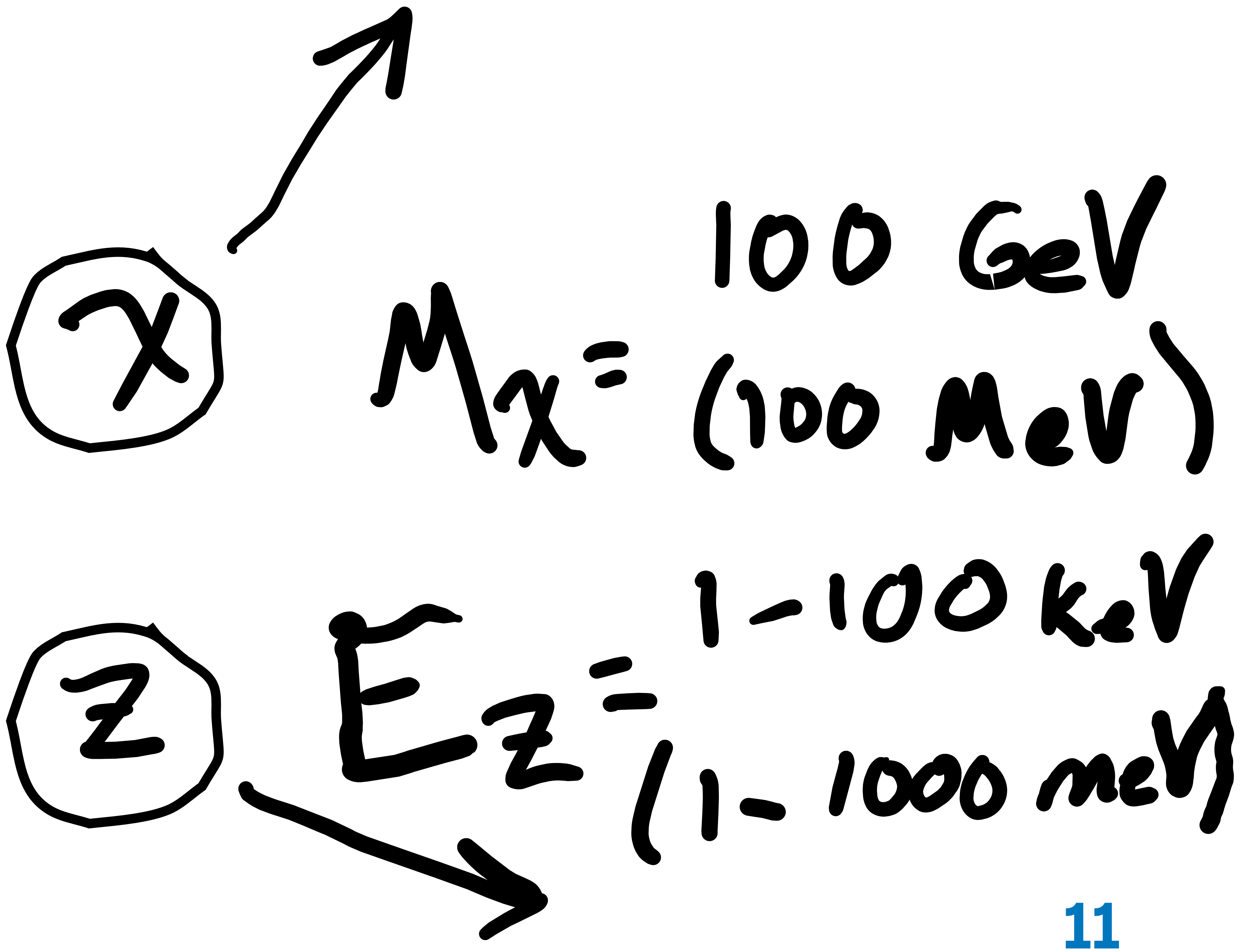
- Counting quasiparticles in superconducting films offers interesting advantages due to the lower energy gap
- Nqp ~ 1000 Ne, so
  - Better energy resolution ~sqrt(N) (~30X better)
  - **Lower energy threshold ~N (~1000X lower)**
- Allows exploration of a new radiation regime
  - Spectrometers with range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



Low thresholds are required for low mass dark matter searches.

- After no discoveries from beyond the standard model searches (DM, LHC, etc) in the 2000s, searches have broadened.
- Theory has targeted smaller masses 0-10 GeV/c^2





Low thresholds are required for low mass dark matter searches.

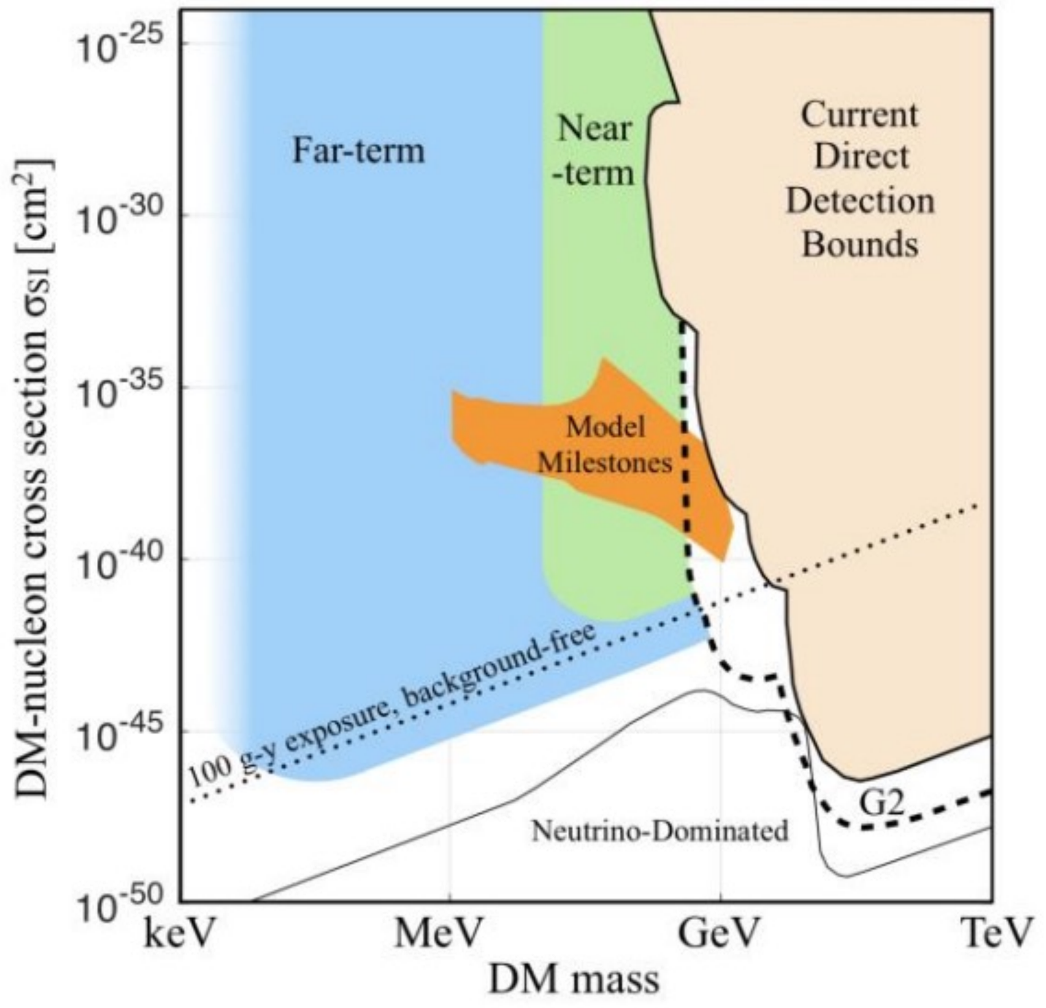
Department of Energy, Office of Science, Office of High Energy Physics

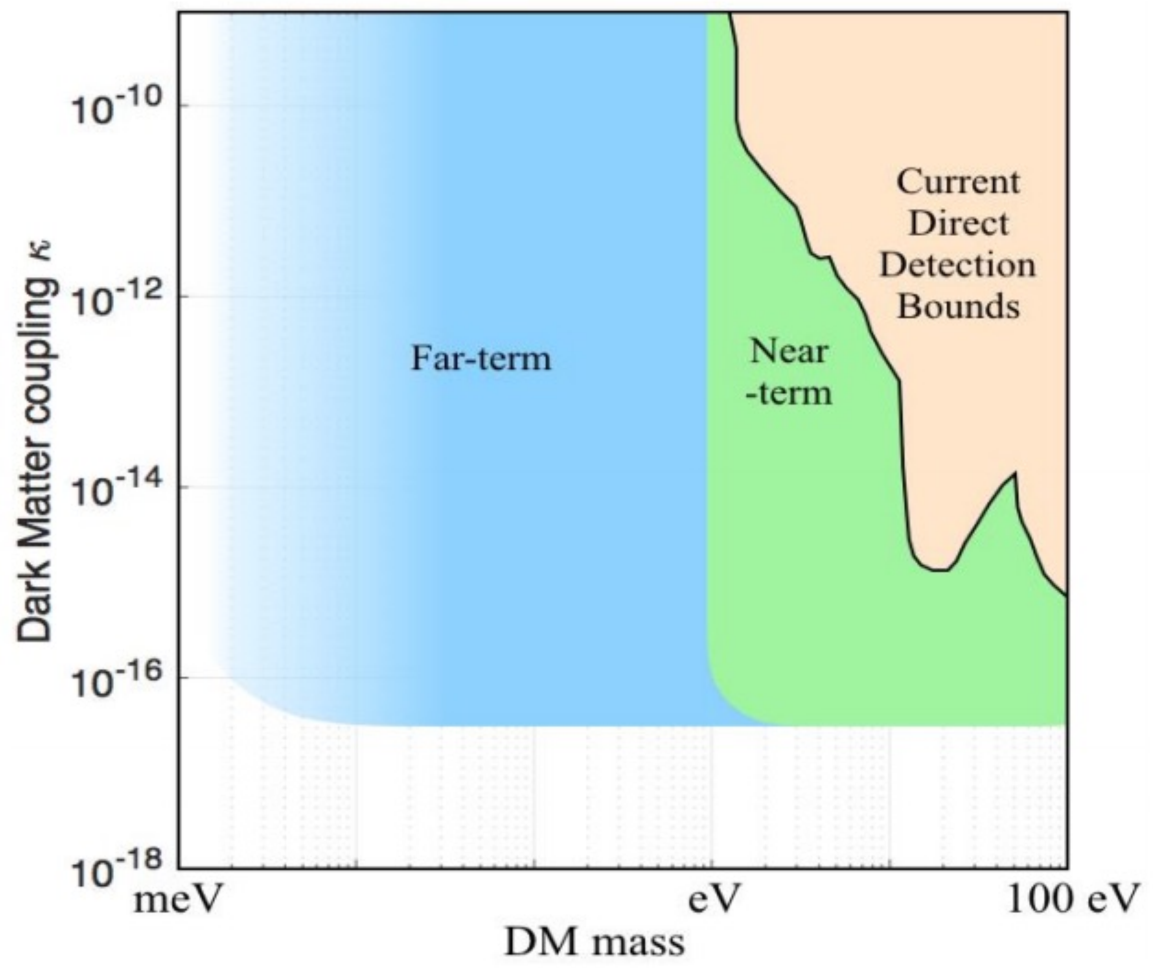
Basic Research Needs for
Dark Matter Small Projects New Initiatives

- Low mass dark matter is a community priority.
- Addition BRN on detector development targets 1 meV threshold detectors to address this scientific goal.

Science	Measurement	Technical Requirement (TR)	PRD
Test for meV–GeV mass dark matter particles	Search for scattering or absorption of meV–GeV dark matter via coupling to nucleons	**Near Term:** TR 3.13 Threshold ∼1 eV; TR 3.14 Target Mass ∼1 kg with negligible background **Long Term:** TR 3.15 Threshold ∼1 meV; TR 3.16 Target Mass ∼100 kg with negligible background	5, 6, 11, 14, 24, 25, 26 5, 6, 14, 25, 26
Test for meV–GeV mass dark matter particles	Search for scattering of meV–GeV dark matter with normal matter via coupling to electrons	**Near Term:** TR 3.17 Threshold ∼1 eV; TR 3.18 Target Mass ∼1 kg with negligible background **Long Term:** TR 3.19 Threshold ∼1 meV; TR 3.20 Target Mass ∼100 kg with negligible background	5, 6, 11, 14, 24, 25, 26 6, 14, 25, 26

https://www.osti.gov/servlets/purl/1659761



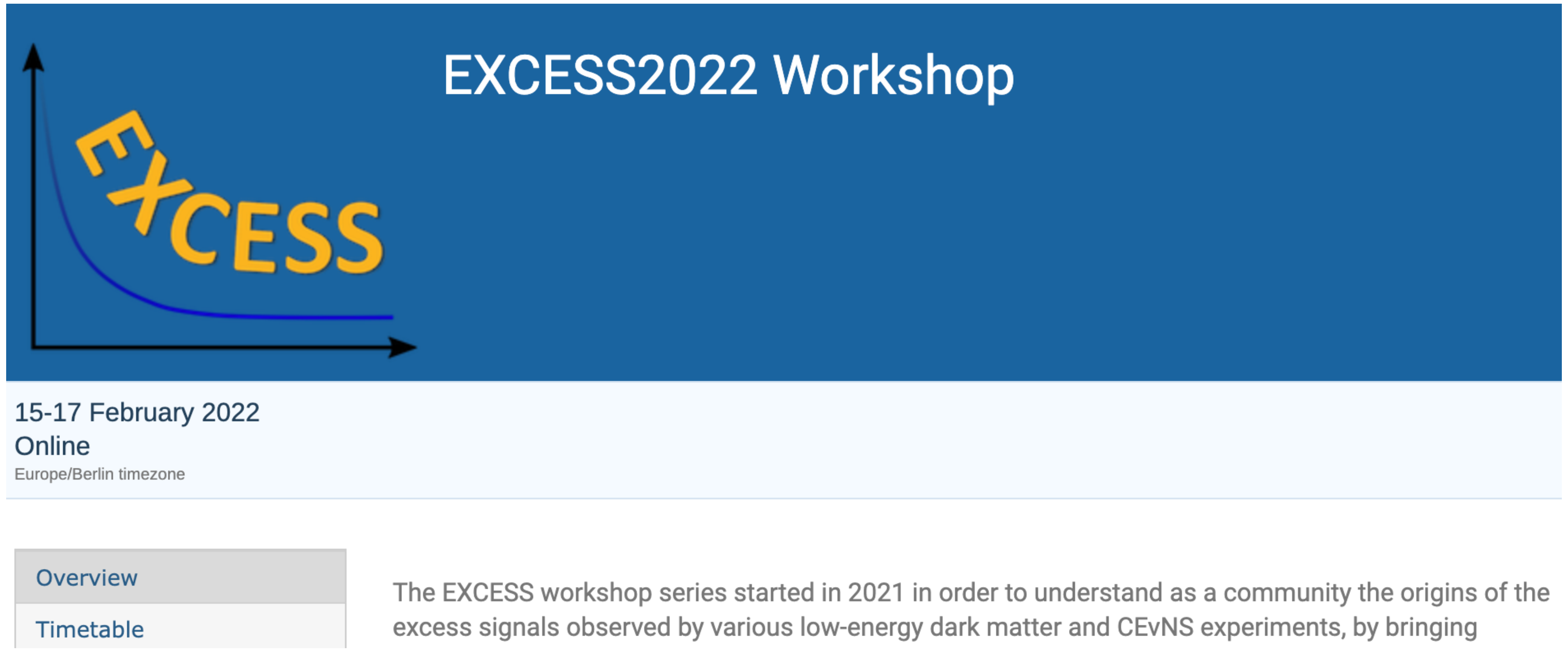


https://www.osti.gov/servlets/purl/1659757

See talk by N. Kurinsky coming up next!

Low threshold dark matter searches all observe low energy excesses.

- Already unexplained couplings to the environment with ~eV thresholds.
- Everything is a background at these energies.

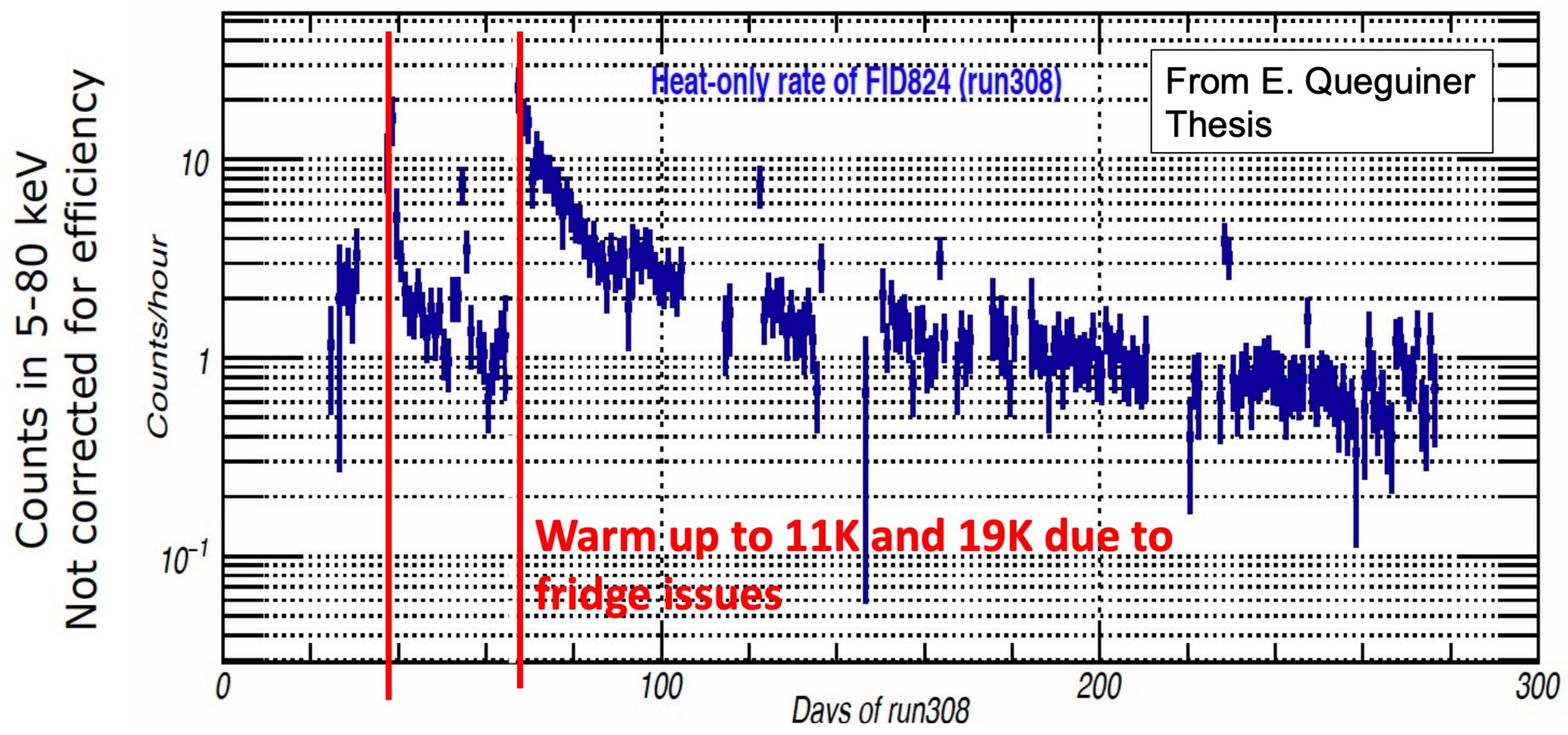


https://indico.scc.kit.edu/event/2575/overview

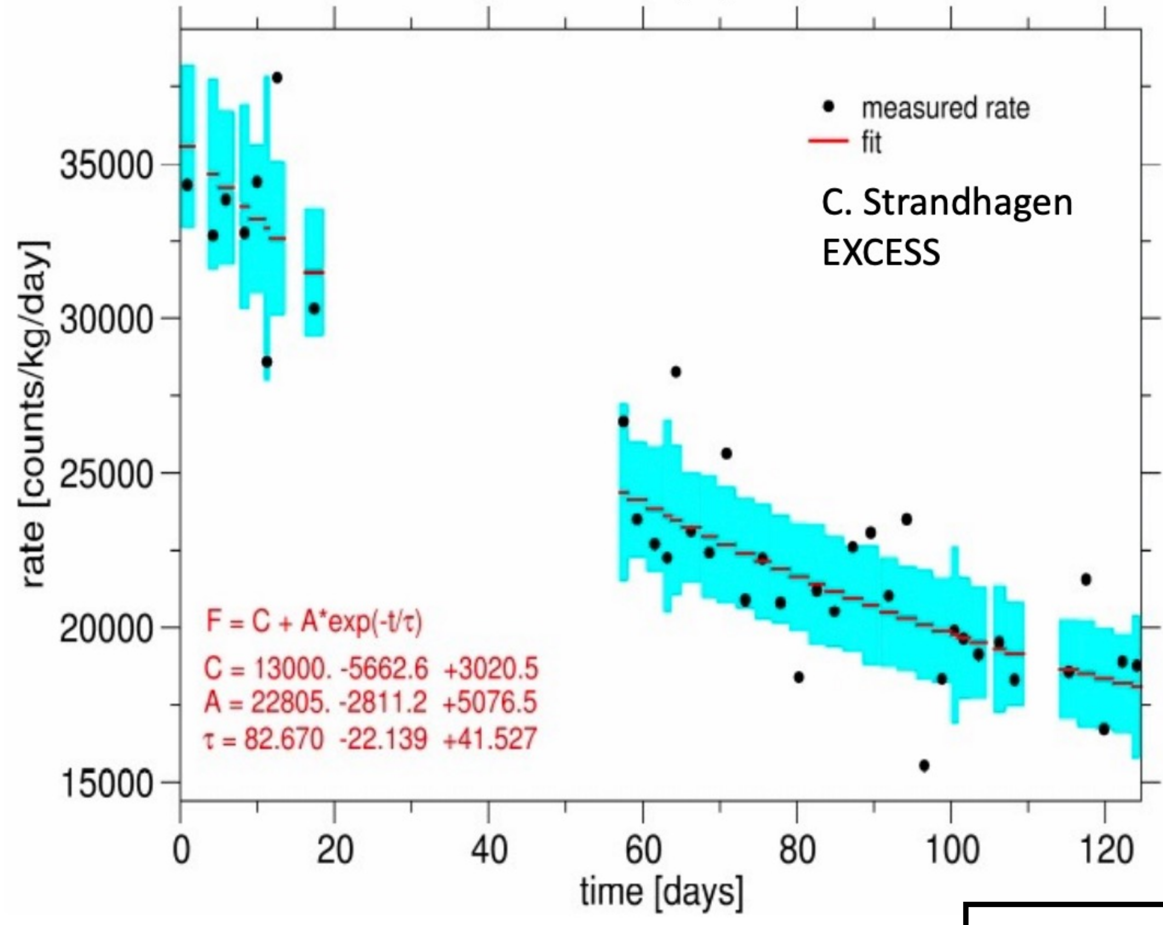
Low threshold dark matter searches all observe low energy excesses.

- 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
- Conclusion: The low mass dark matter searches will be grappling with new low energy backgrounds for the next decade

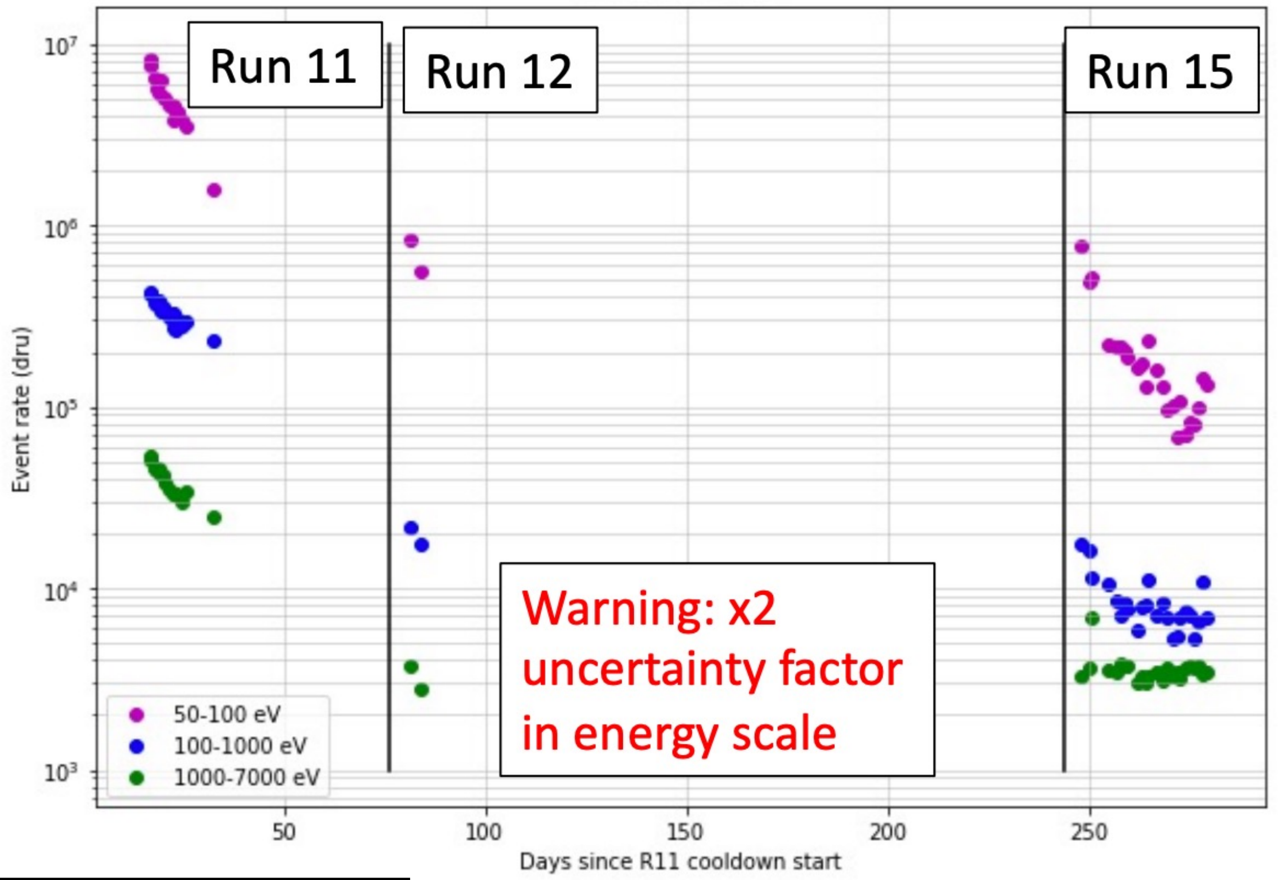
EDELWEISS Low Energy Excess (FID 824)



CRESST Sapphire



CPD@CUTE



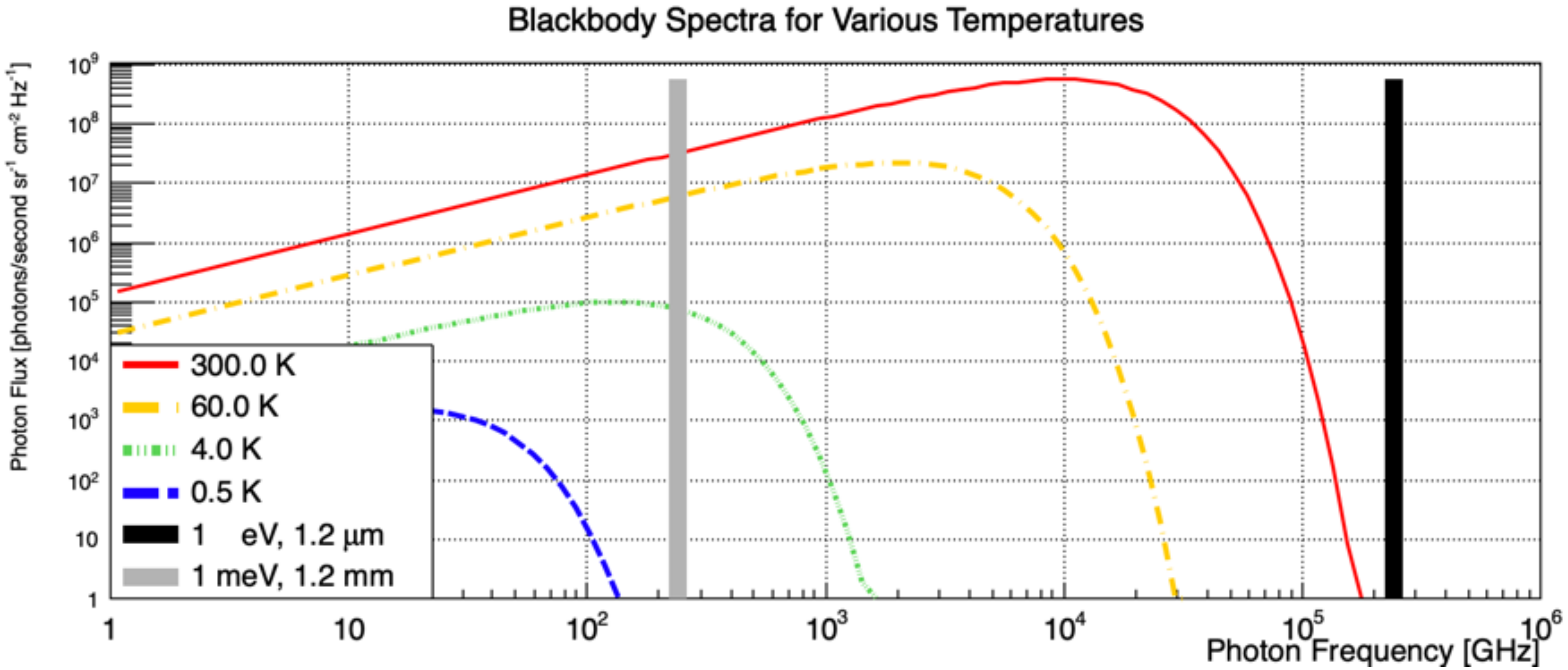
M. Pyle @EXCESS2022

Qubit Backgrounds
Dark Matter Backgrounds

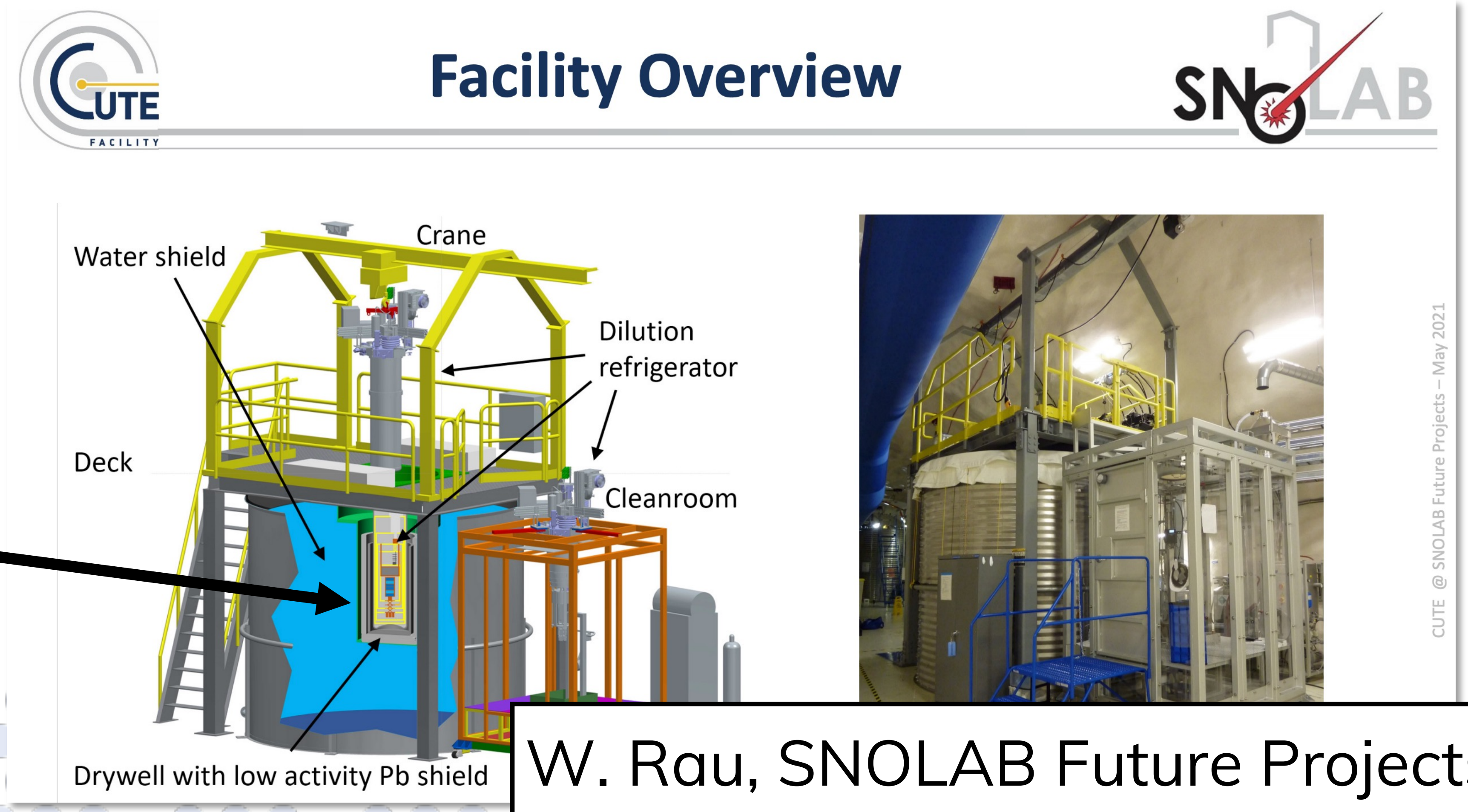
Qubit Backgrounds = Dark Matter Backgrounds

Known environmental backgrounds are a common challenge.

- Small project to model the thermal background in CUTE,
- and explore instrumentation to measure the low energy photon background.
- Photons, vibrations, RF, stray fields.
- Standard backgrounds measurement techniques to compare results.
- Additionally, we may find some unexpected backgrounds.



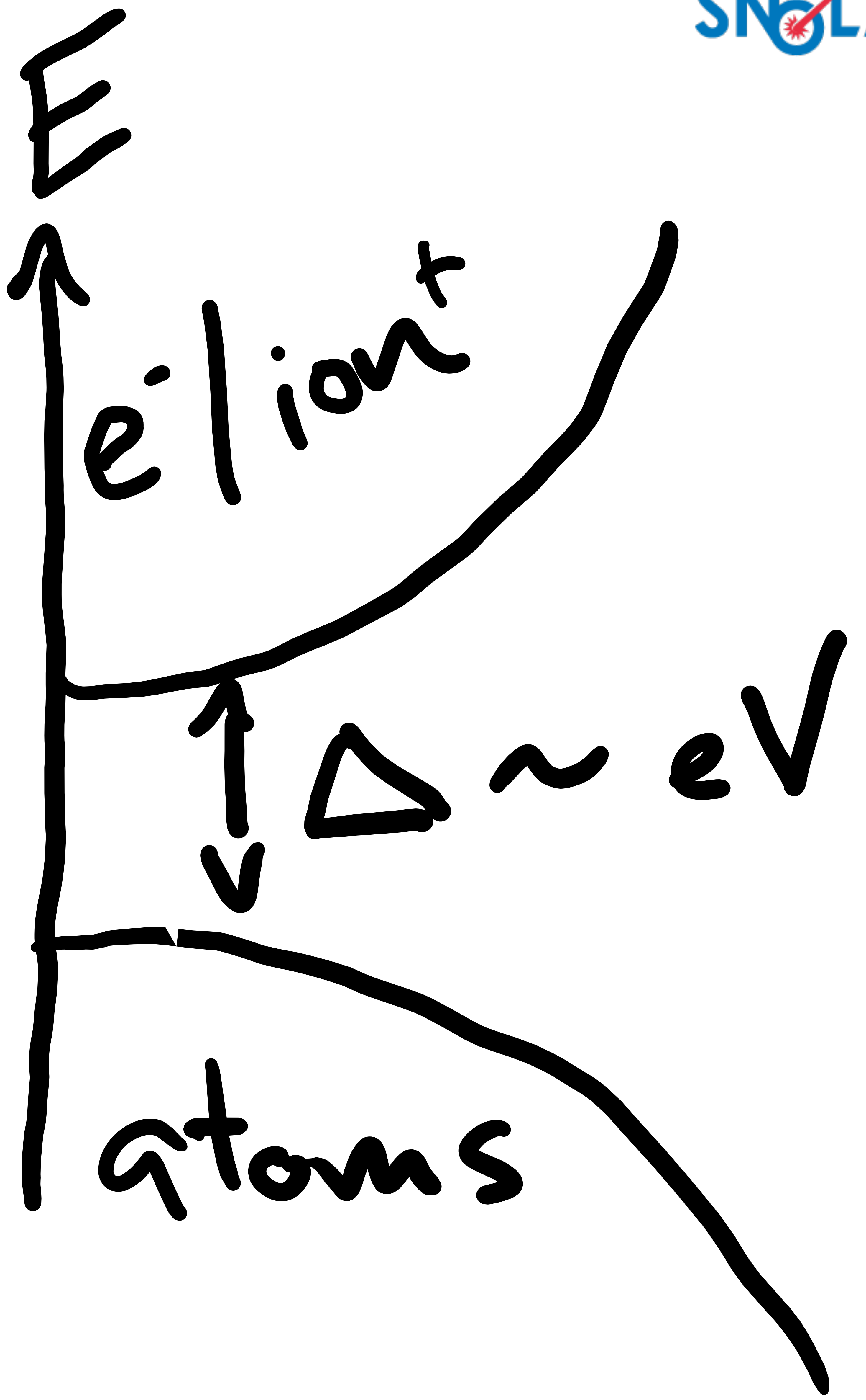
~5 dru!



W. Rau, SNOLAB Future Projects Workshop 2021

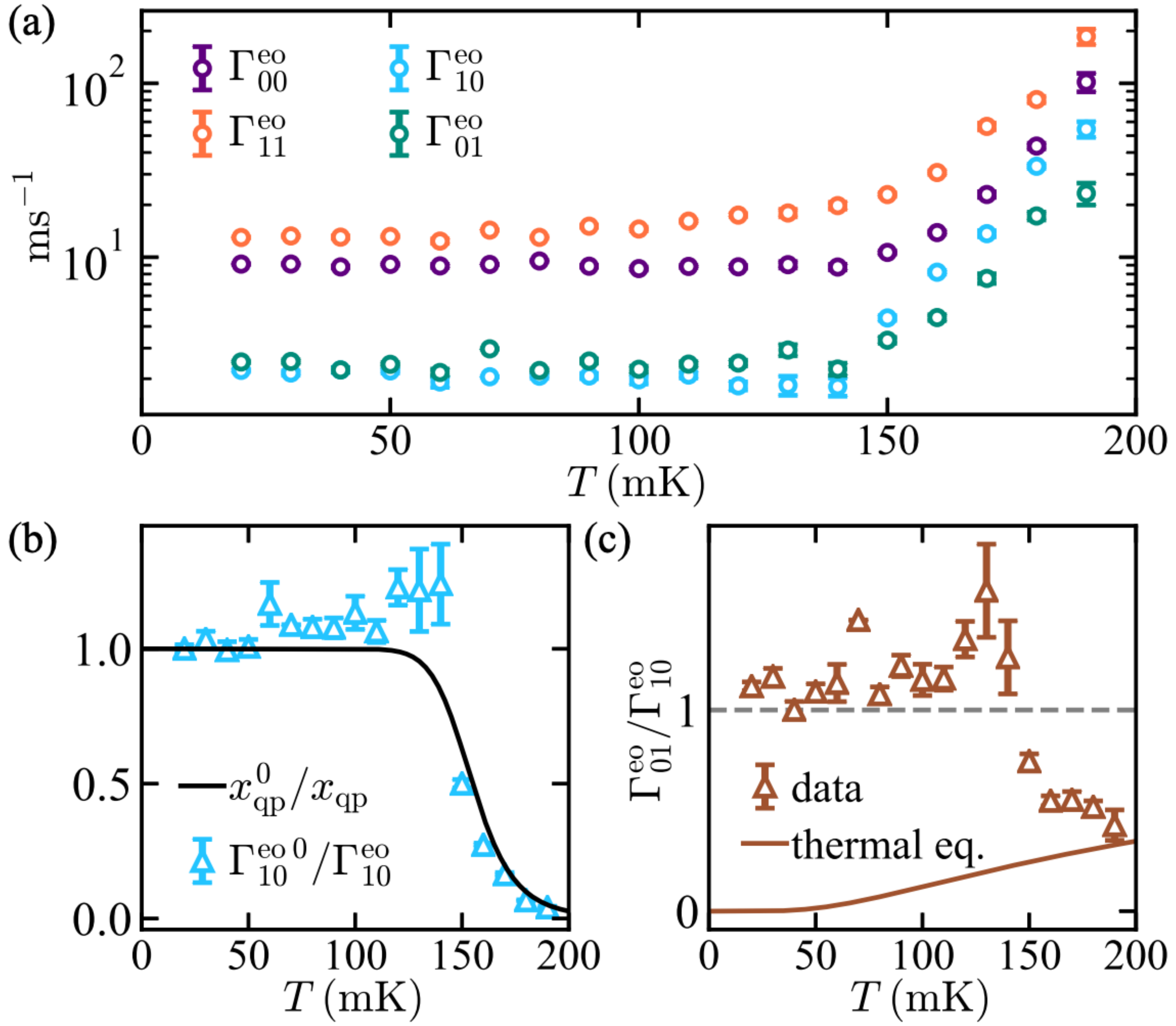
Ionizing radiation detection is a foundational element of nuclear and particle physics.

- Most detection technologies are based on the ionization gap in materials
- Nuclear and particle physics (partially) originated in 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



Quasiparticle poisoning of superconducting circuits is a major, poorly-understood design constraint.

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



- 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
- Non-thermal QP densities are observed in all <100 mK superconducting films

In conclusion, there is a convergence of research between quantum device engineering and dark matter searches.

- Observation of low mass dark matter would transform particle physics,
  - and be a fundamental limitation to quantum devices.
- Ruling out low mass dark matter would have us still trying to understand the nature of dark matter,
  - but would result in techniques to improve cutting-edge quantum devices
- Understanding the backgrounds is a path for both fields, and we are learning from each other.
- Infrastructure will be key to supporting rapid progress.
  - Underground work ongoing at PNNL, FNAL, SNOLAB, and LNGS
  - Surface work done at labs including MIT and LBL/Berkeley

J. Formaggio @ LRT2022

Questions?

Discussion