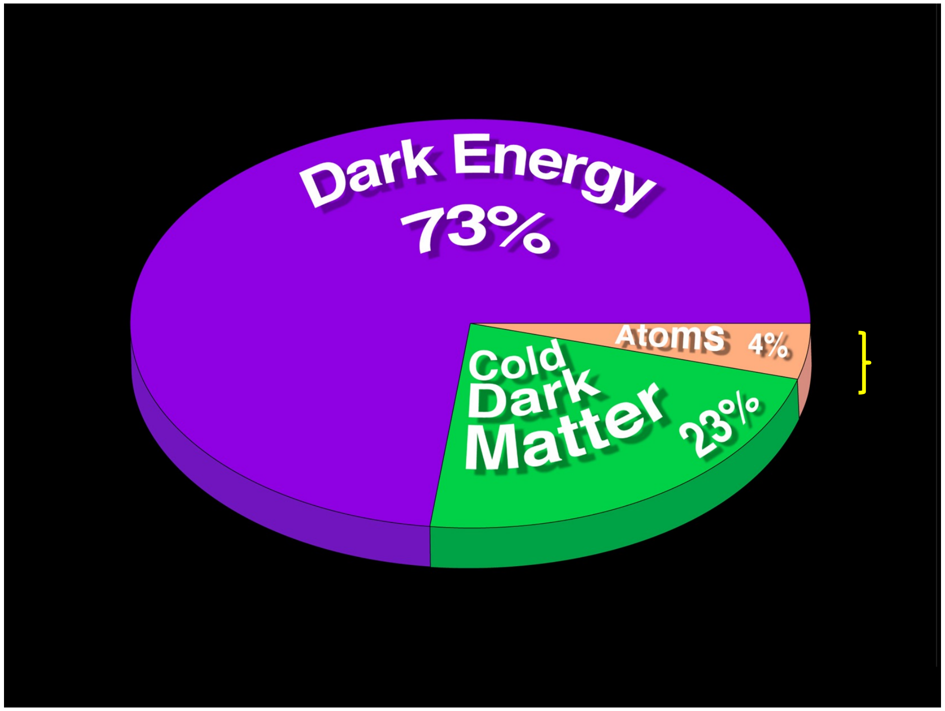
Quantum Computers as Dark Matter Detectors

Aaron S. Chou (Fermilab)

QICK Workshop
January 12, 2023

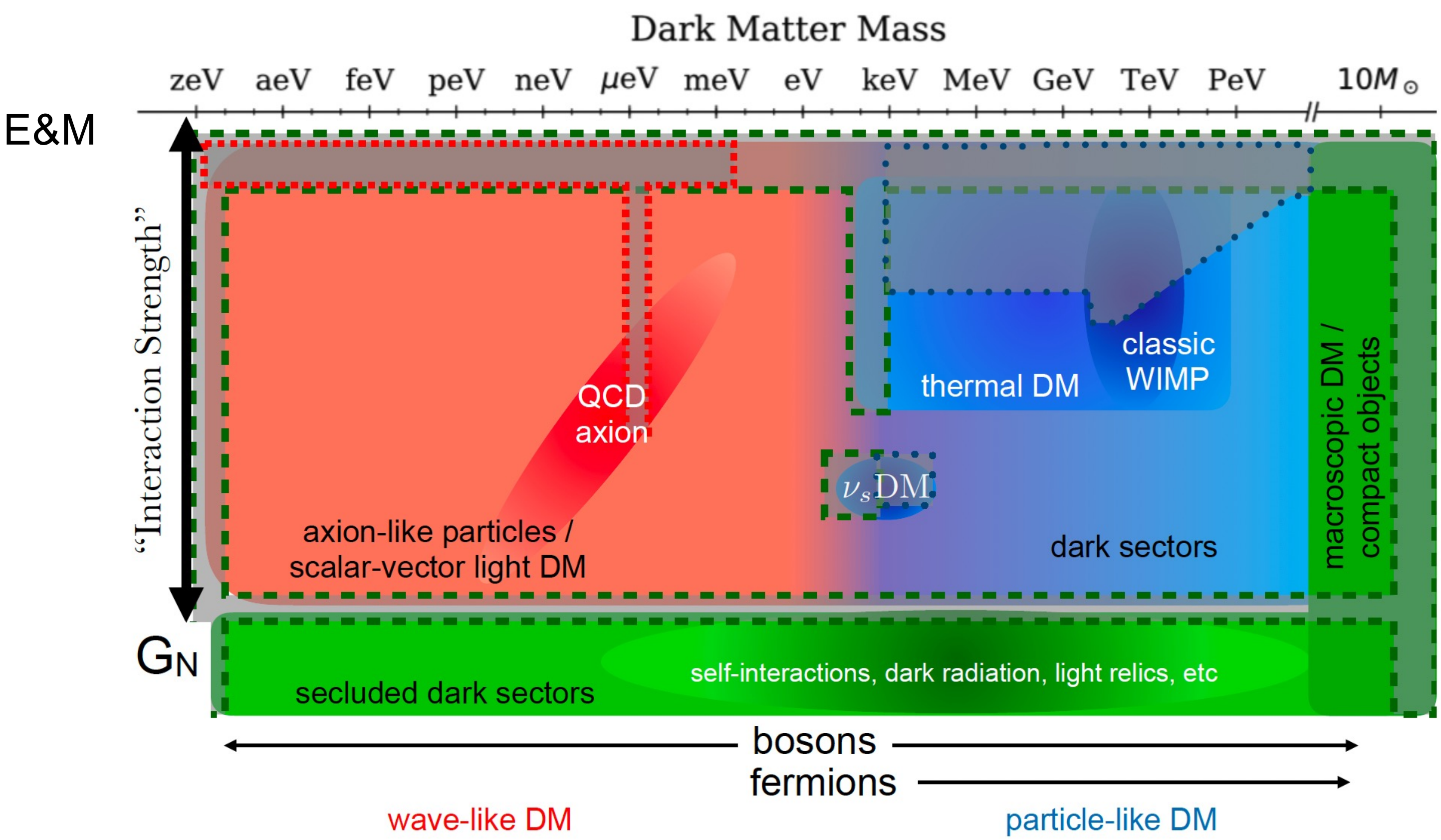
Energy budget of the universe
(from various experimental probes)



Things we design our shielding for

We have *no* idea what is all of this other dark stuff all around us.
It has so far been undetectable other than via its gravitational effects.
Prime experimental target for QUANTUM SENSING!

Our current understanding of the dark matter landscape (APS-DPF Snowmass Study, July 2022)



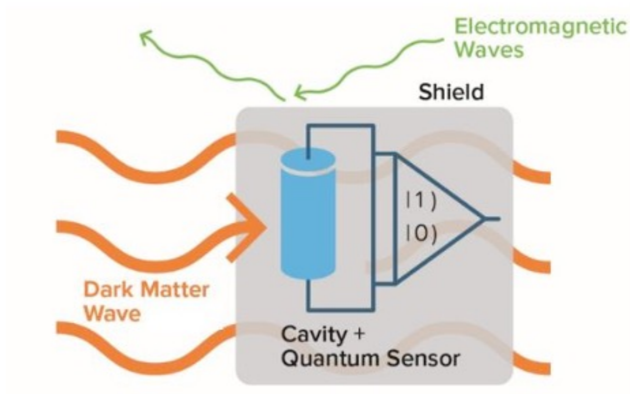
A diverse variety of experimental techniques are proposed to cover every decade of possible dark matter mass.

Dark matter of some sort is probably flying through your lab.

Does it have interactions stronger than gravity???

Hmmm… quantum computing platforms look just like dark matter searches:

DOE-OHEP
Basic Research Needs
white paper, 2018

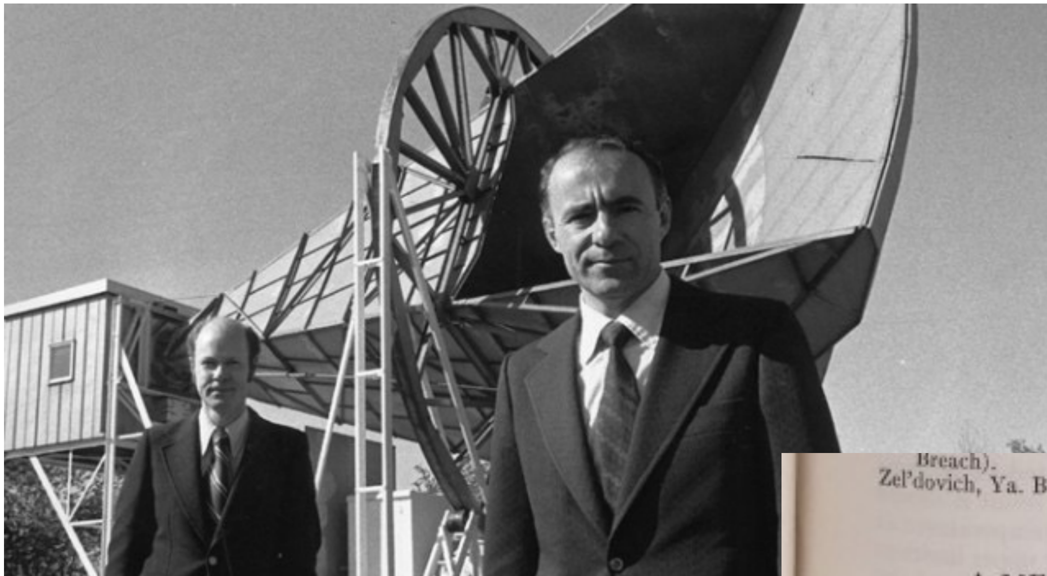


Sensitive single-quantum devices are operated in a cryostat and/or vacuum system and well-shielded from external disturbances (heat, light, sound) in order to maximize their coherence time.

Impossible to shield from the dark matter – the DM interacts so weakly that it flies right through the walls.

If your quantum computer crashes, it could be due to dark matter!
… but as consolation, you'll get a Nobel prize anyway for the discovery.

Mystery noise in your experimental apparatus is not necessarily mundane



Penzias and Wilson, 1965:
After chasing away nesting birds with a shotgun, discovered the cosmic microwave background

– They had no idea that this was first evidence for the big bang theory
– Nobel Prize, 1978

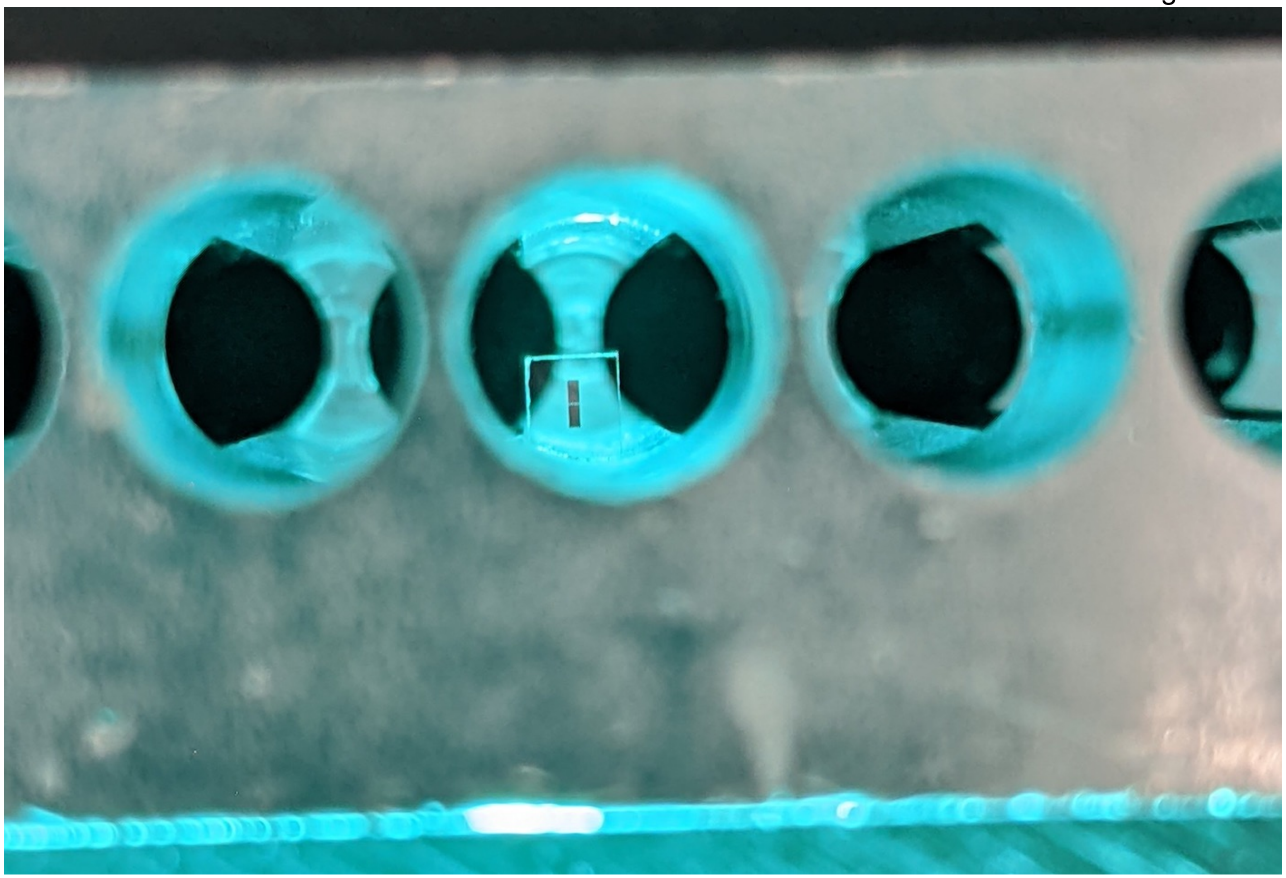
Breach).
Zel'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, 14, 1143.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

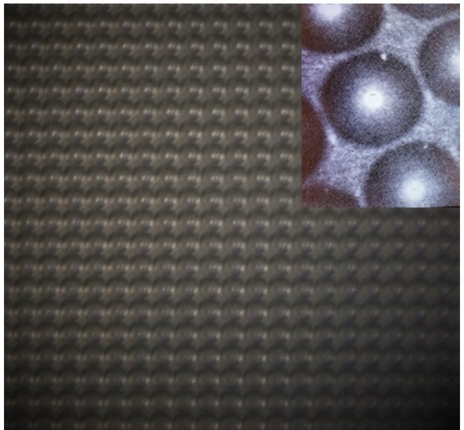
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

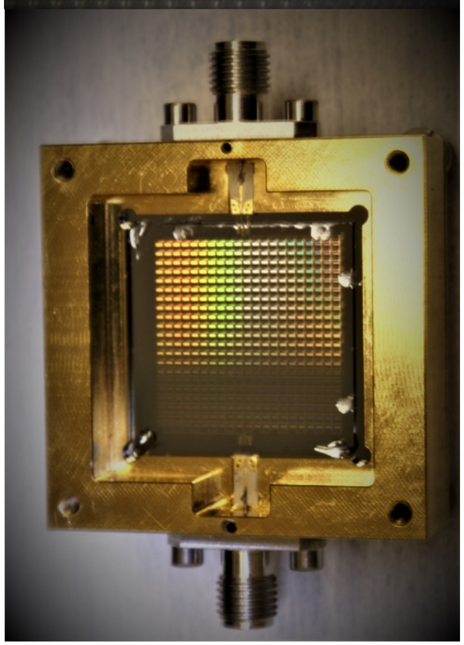
Transmon qubit in 6 GHz aluminum cavity

Image credit: Akash Dixit



Dark matter waves scatter on walls of cavity, depositing occasional single photon.
Measure quantized AC Stark shift of qubit frequency to ascertain presence of the signal photon.





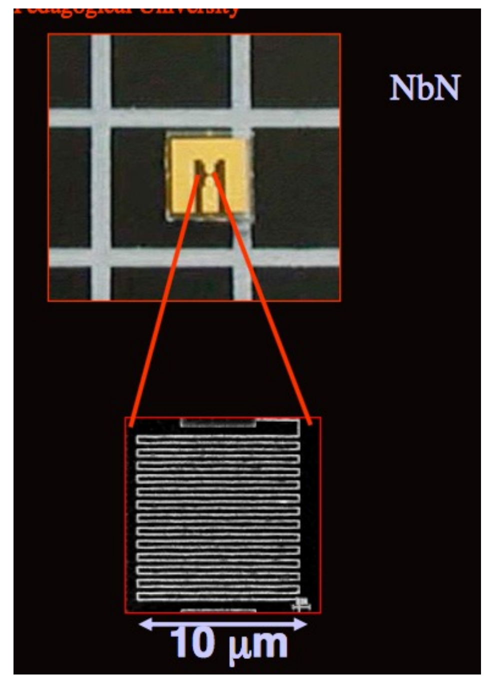
P. Echternach (JPL)

Metrology gain vs Standard Quantum Limit for various single photon detectors

Transmon qubits (artificial atomic clock)
Effective occupation number $n=10^{-3}$ ← (SQL corresponds to n=1)
Effective noise squeezing factor = 1/sqrt(n) = 16 dB

Quantum capacitance detector (charge qubits)
Dark Rate R = 1 Hz
Bandwidth B = 1 THz
Effective occupation number $n = R / B = 10^{-12}$
Effective noise squeezing factor = 1/sqrt(n) = 60 dB

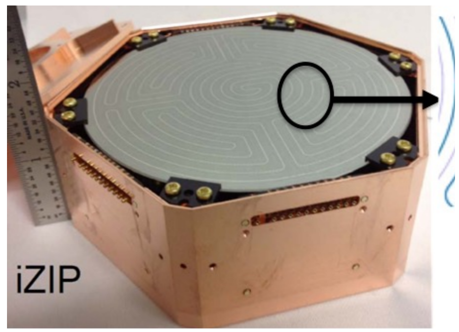
Superconducting nanowire single photon detectors
Dark Rate $R = 10^{-5}$ Hz
Bandwidth $B = 10^{15}$ Hz (or smaller if narrow band filtered)
Number of modes N_{modes}= Area/(wavelength)^2 = 10^2
Effective occupation number $n = (R / B) / N_{modes} = 10^{-22}$
Effective noise squeezing factor = 1/sqrt(n) = 110 dB

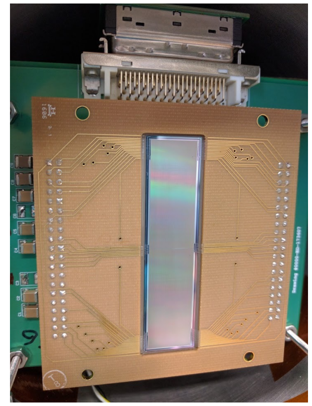


K. Berggren, S. Nam, et al.

Cooper pair-breaking detectors for micro-calorimetry

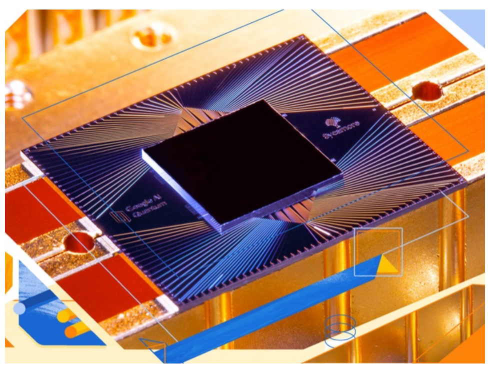
HEP silicon detector (SuperCDMS, SENSEI)





Single electronics:
1 eV threshold to create electron/hole pair in silicon or germanium

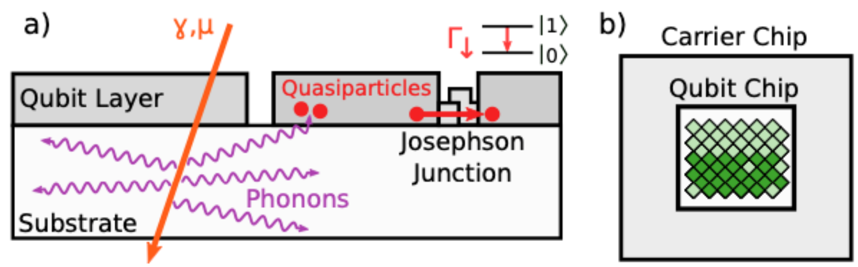
Google Sycamore chip



Single Cooper pair-onics: 10^{-4} eV threshold to break Cooper pair

All qubits on chip wiped out by single cosmic ray, 100 keV energy deposit

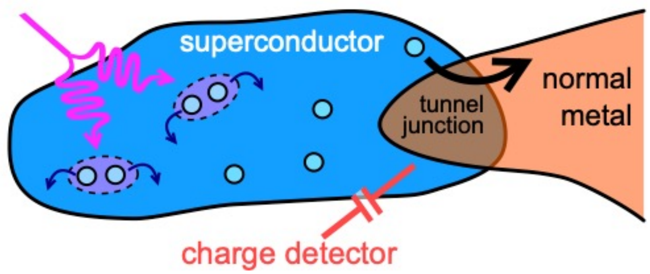
M. McEwen, et al., Nature Physics 18 (2022)

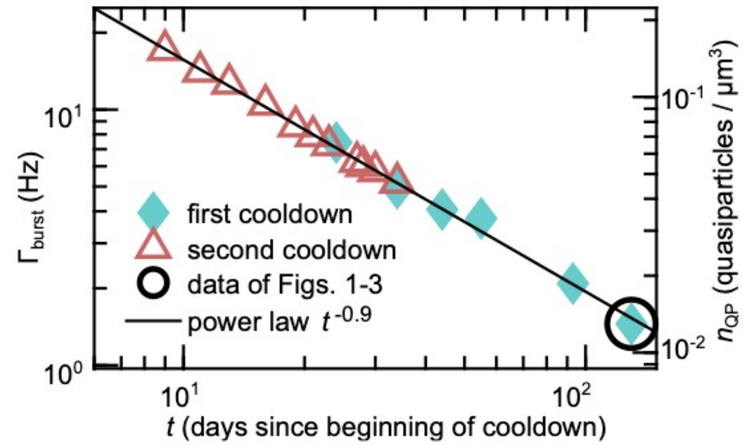


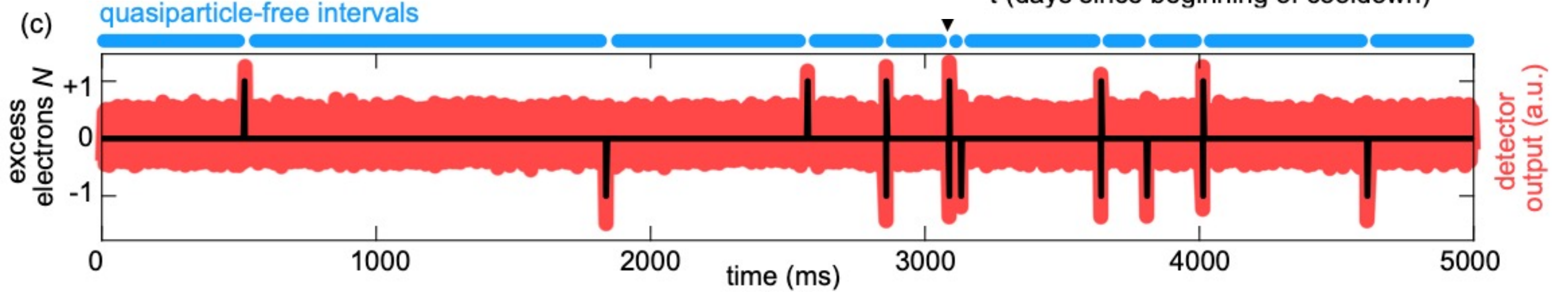
Superconducting devices all suffer from mysterious non-equilibrium quasiparticle population >> Boltzmann suppressed n = $e^{-1.2K/0.01K} = 10^{-52}$

These now appear to be created in discrete, time-resolved events with much higher rate than cosmic rays.

E.T. Mannila, et al., Nature Physics 18 (2022)

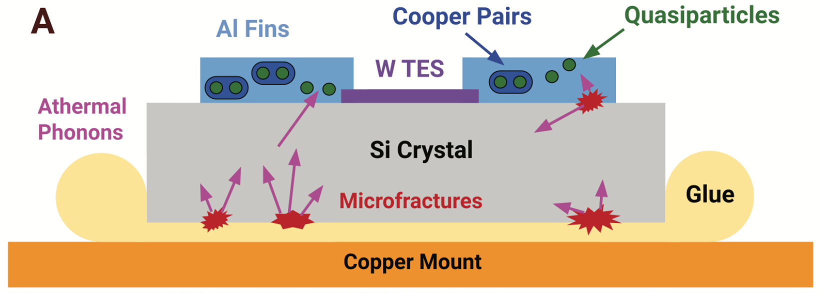






Origins of events still a 20-year-old mystery …
have we discovered millicharged dark matter?

Low gap materials experience noise due to coupling to background phonons from substrate microfracture events

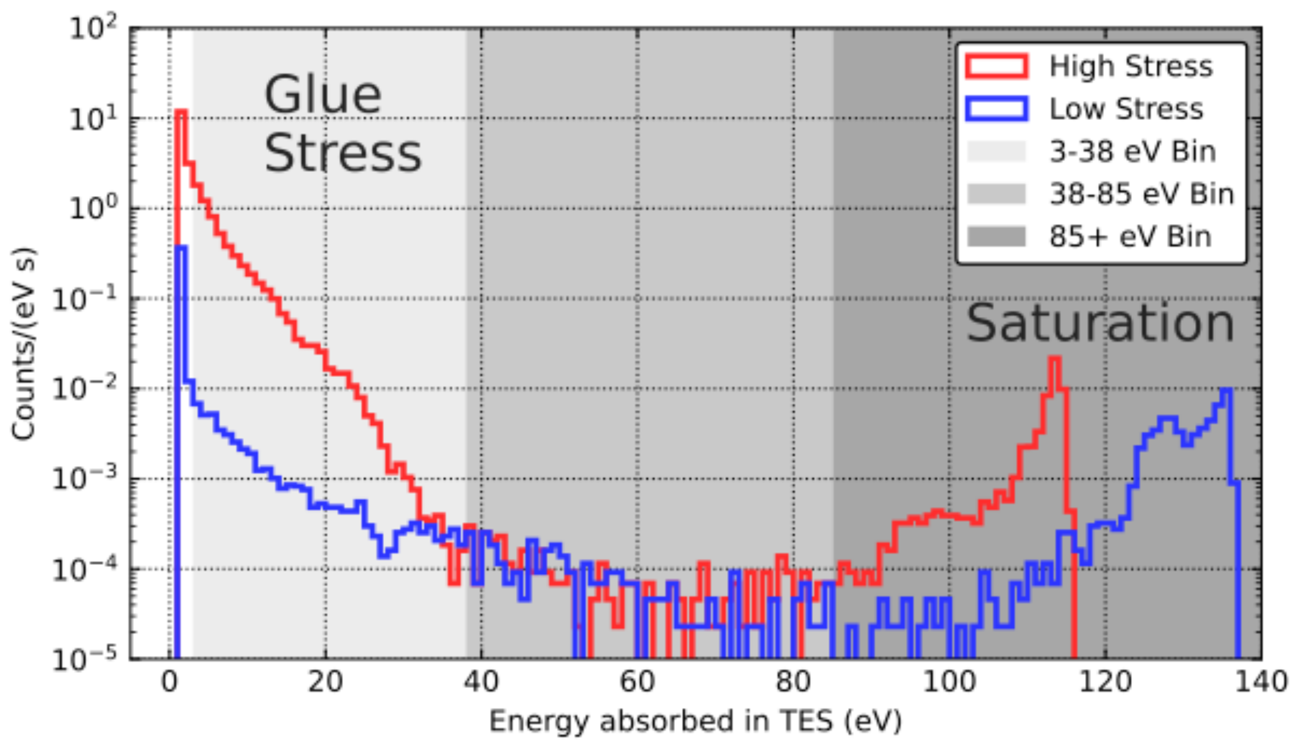


R. Anthony-Petersen, … **M.Pyle**, et al., arxiv:2208.02790

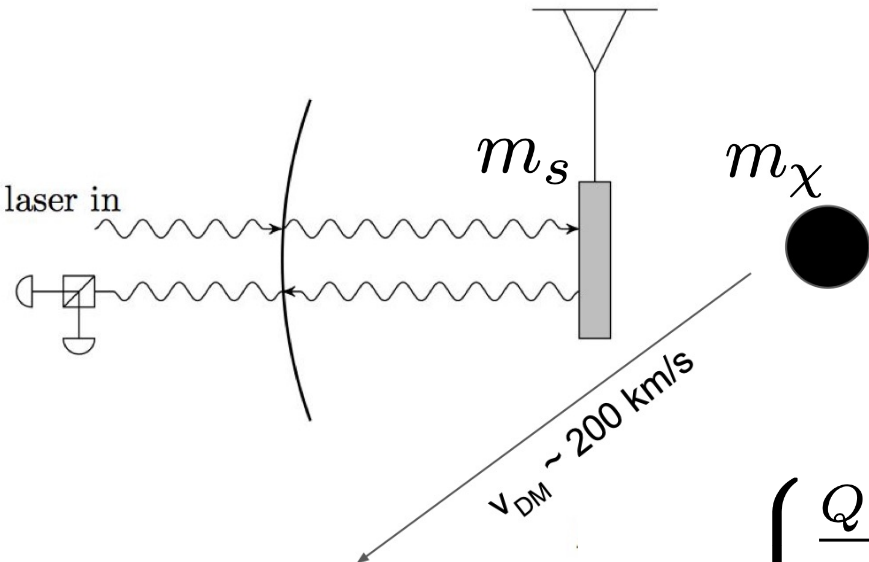
Measure spectrum using tiny, cold, low heat capacity TES sensors developed for dark matter searches.

Non-equilibrium particles are **probably** not due to dark matter but rather due to mechanical disturbances.

Next generation qubit-based microcalorimeters will reduce thresholds to milli-eV, provide first look at sub-eV spectrum.
Need large numbers of qubit control channels to instrument this microcalorimeter.



Accelerometers to sense force from passing dark matter



Impulse: $\Delta p = F \cdot \frac{r}{v}$

Energy transfer: $\Delta E = \frac{(\Delta p)^2}{2m_s}$

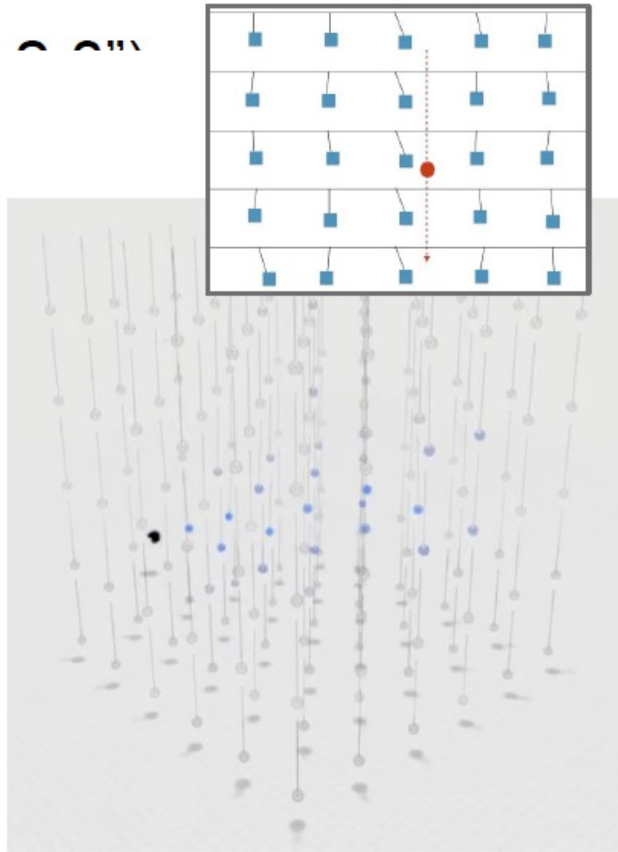
$$F = \begin{cases} \frac{Q_s Q_\chi}{r^2} & \text{(Spin-1)} \\ \frac{G m_s m_\chi}{r^2} & \text{(Spin-0, 2)} \end{cases} \Rightarrow \Delta E = \begin{cases} \frac{1}{2m_s}\left(\frac{Q_s Q_\chi}{rv}\right)^2 \\ \frac{m_s}{2}\left(\frac{G m_\chi}{rv}\right)^2 \end{cases}$$

Low mass ions are better for spin-1 mediated long range forces

Windchime concept:

Larger mass accelerometers needed for detecting gravitational (spin-2) force from DM

Phys.Rev.D 102 (2020) 7, 072003



Cubic meter array of **10^9 accelerometers** with millimeter spacing to detect force from passing dark matter. Probably gravitational force is too weak but can still focus on scalar or vector-mediated forces.

How to affordably read out sensor array and reconstruct track of 1000 excitations in real-time???

- Probably impossible with classical computers.
  - cf. LHC = 400M channels
  - Heat load = 5 dedicated nuclear power plants
- **If Dark matter detector = Quantum Computer**
  → Should provide in-situ processing of tracks
- E.g. co-located trapped ion computer seems well-suited to detect long correlation length excitations.

Need to control large numbers of sensor/qubit channels for such multi-sensor arrays