Transition-Edge Sensors vs. Superconducting Qubits for Particle Detection

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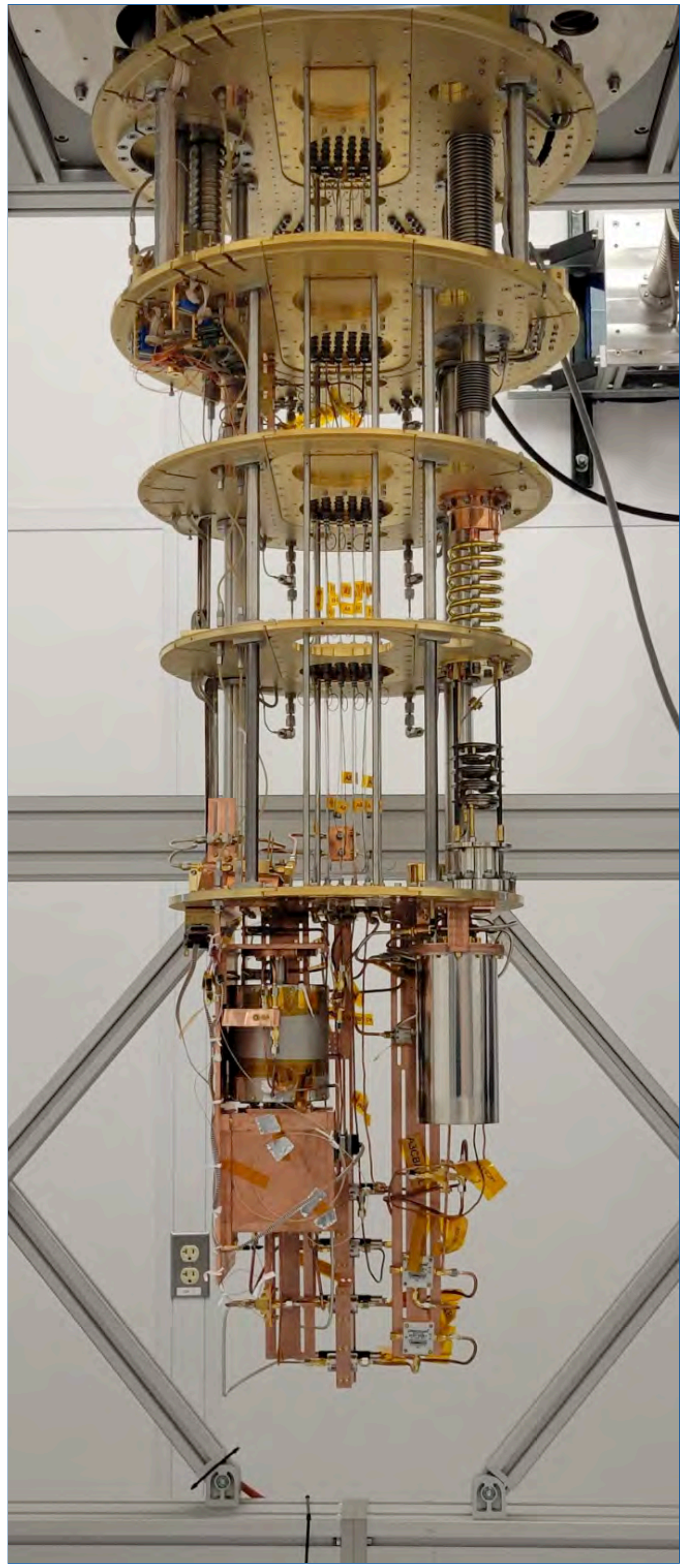
Northwestern

QUANTUM SCIENCE CENTER

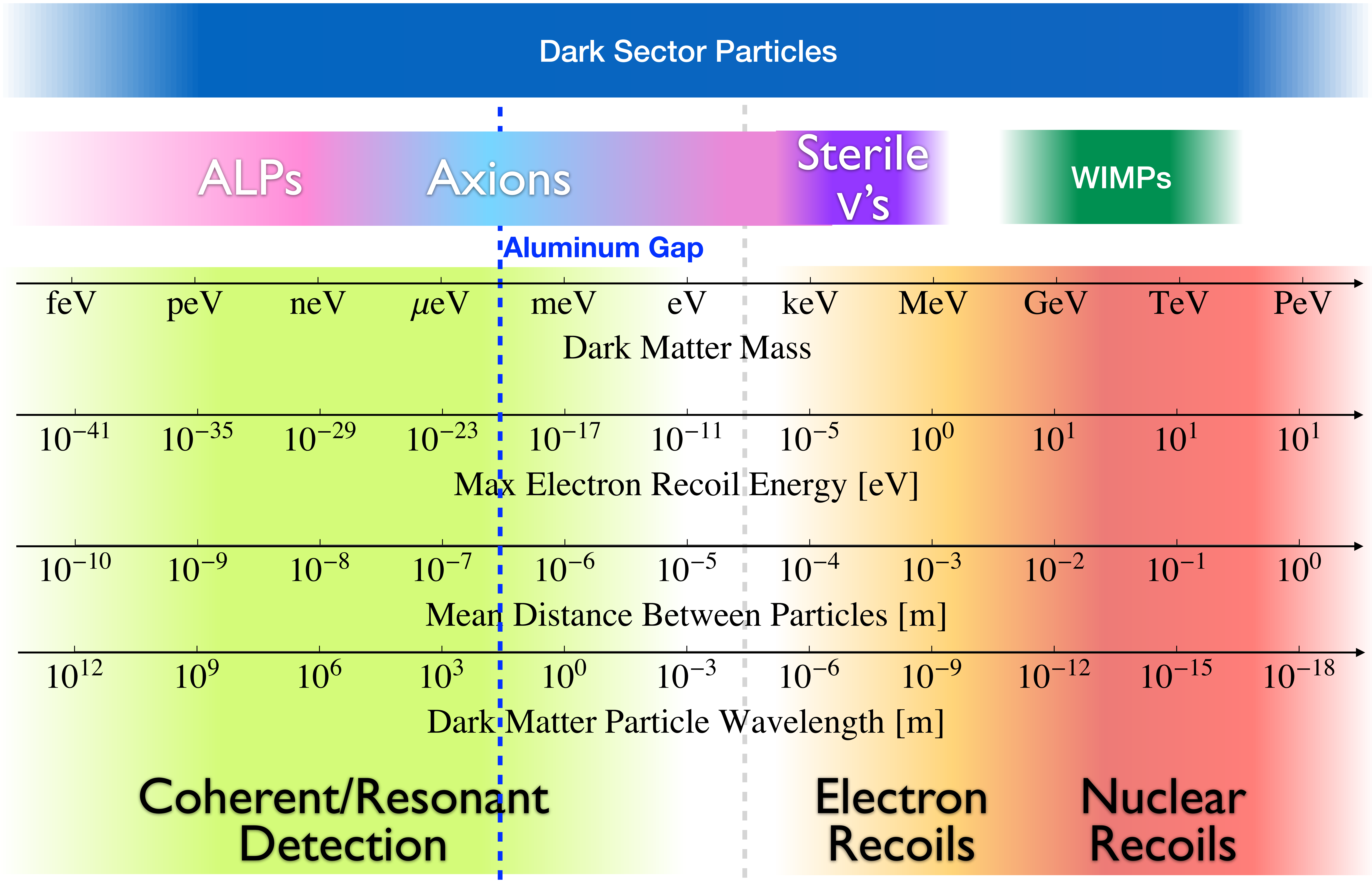
Fermilab

Outline

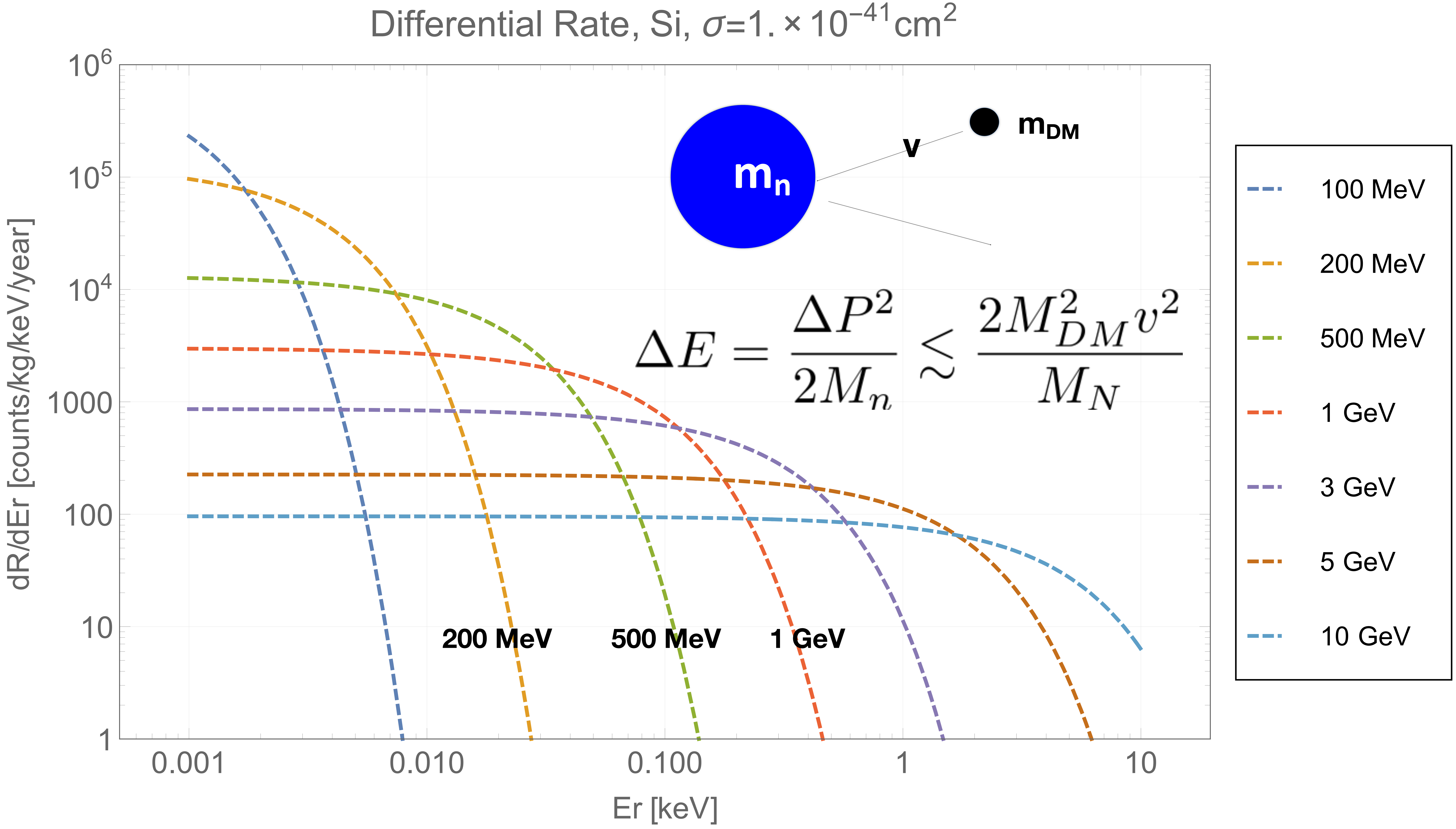
- Introduction to **<u>direct detection</u>** of **<u>particle</u>** **<u>dark matter</u>**
- Dark matter search with SuperCDMS detectors
- Superconducting qubits for particle detection
- Upcoming plans for Cosmic Quantum (**CosmiQ**) group at FNAL



Dark Matter Detection Channels

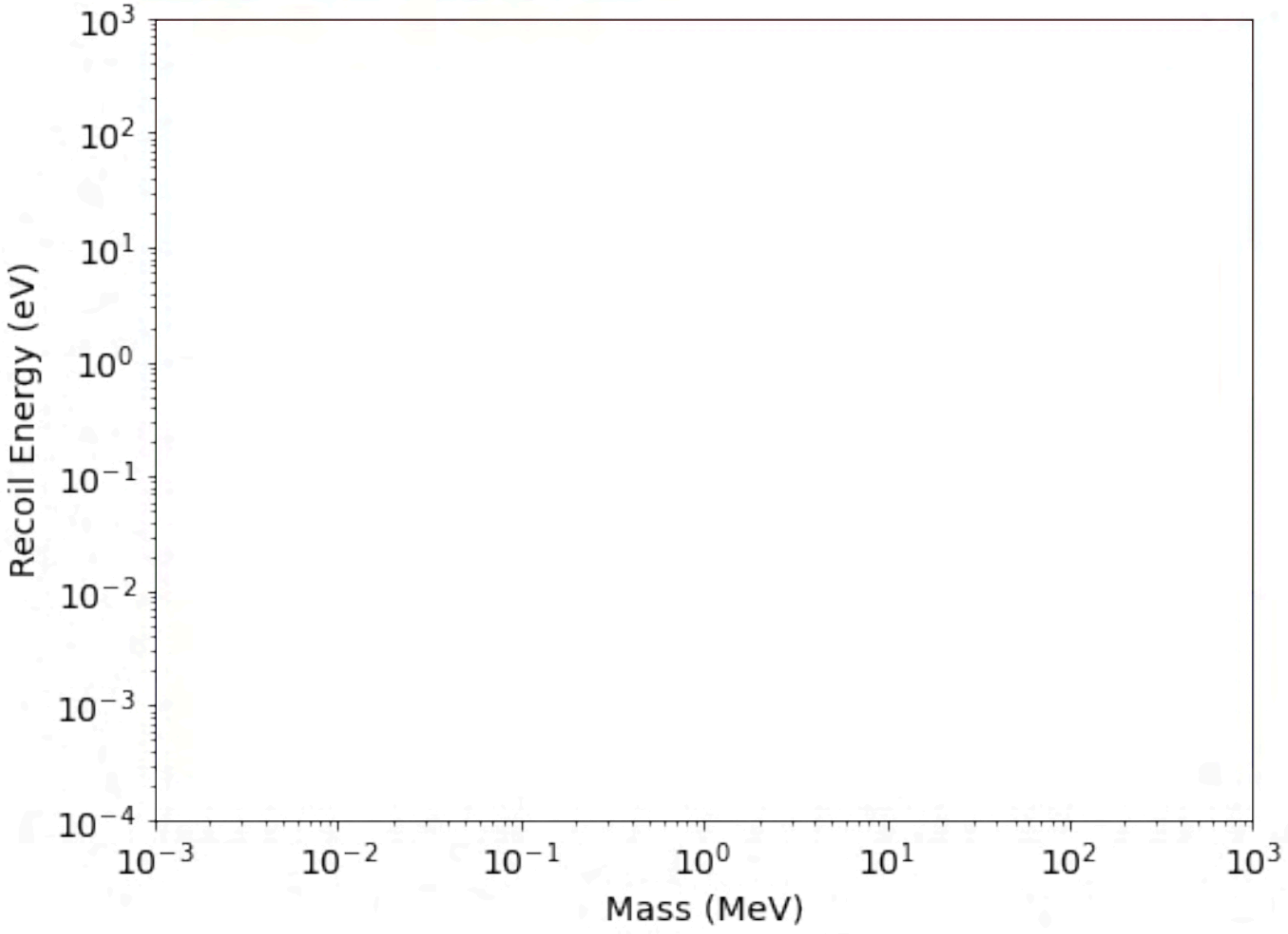


The low-mass DM Direct Detection Challenge



The low-mass DM Direct Detection Challenge

Fig. adapted from 2203.08297



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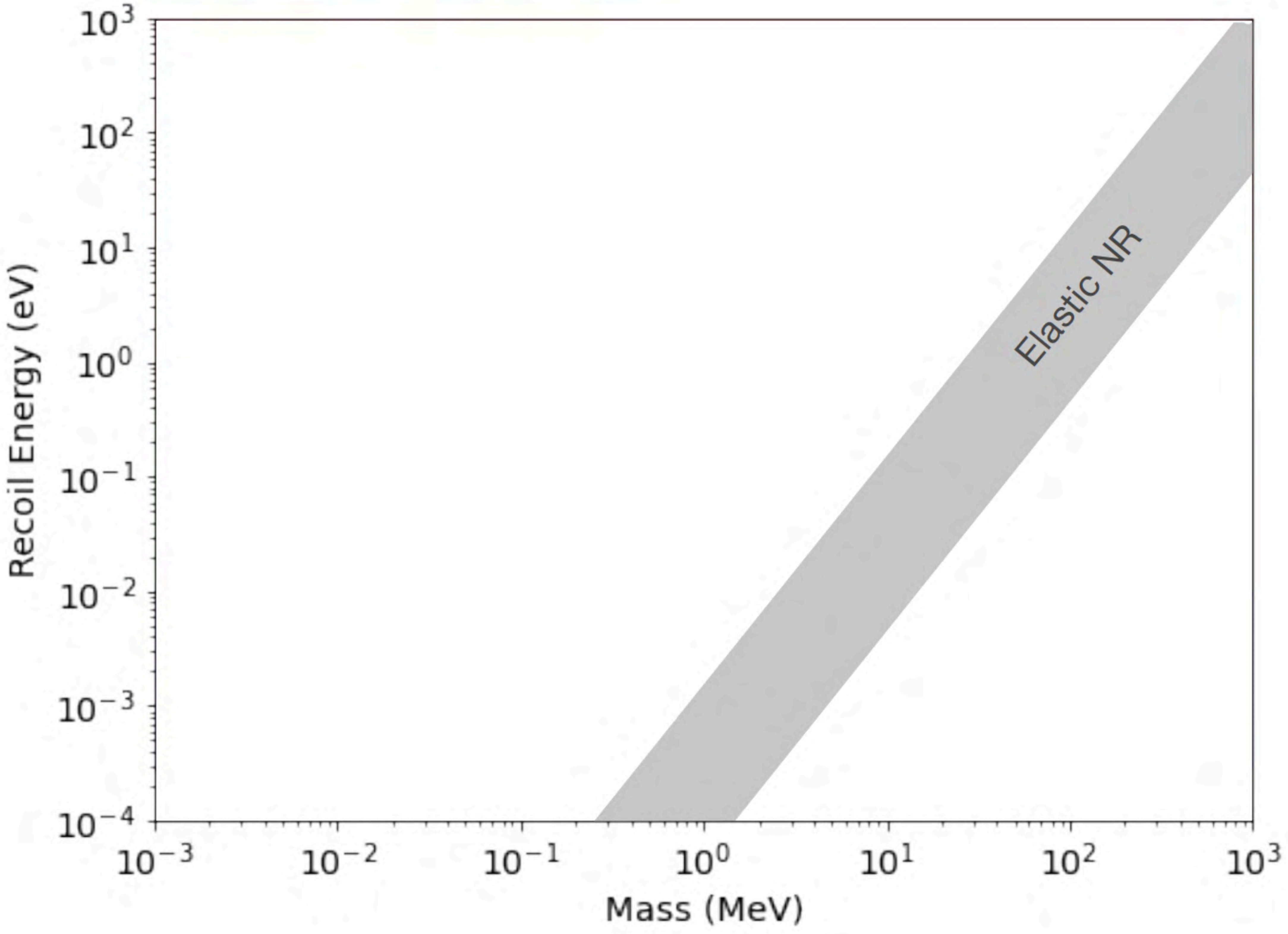

elastic DM-nucleus scattering:

$$E_{\mathrm{NR}} = \frac{q^2}{2m_N} \sim 1\ \mathrm{eV} \left(\frac{m_{\mathrm{DM}}}{100\ \mathrm{MeV}}\right)^2 \left(\frac{28\ \mathrm{GeV}}{m_N}\right)$$

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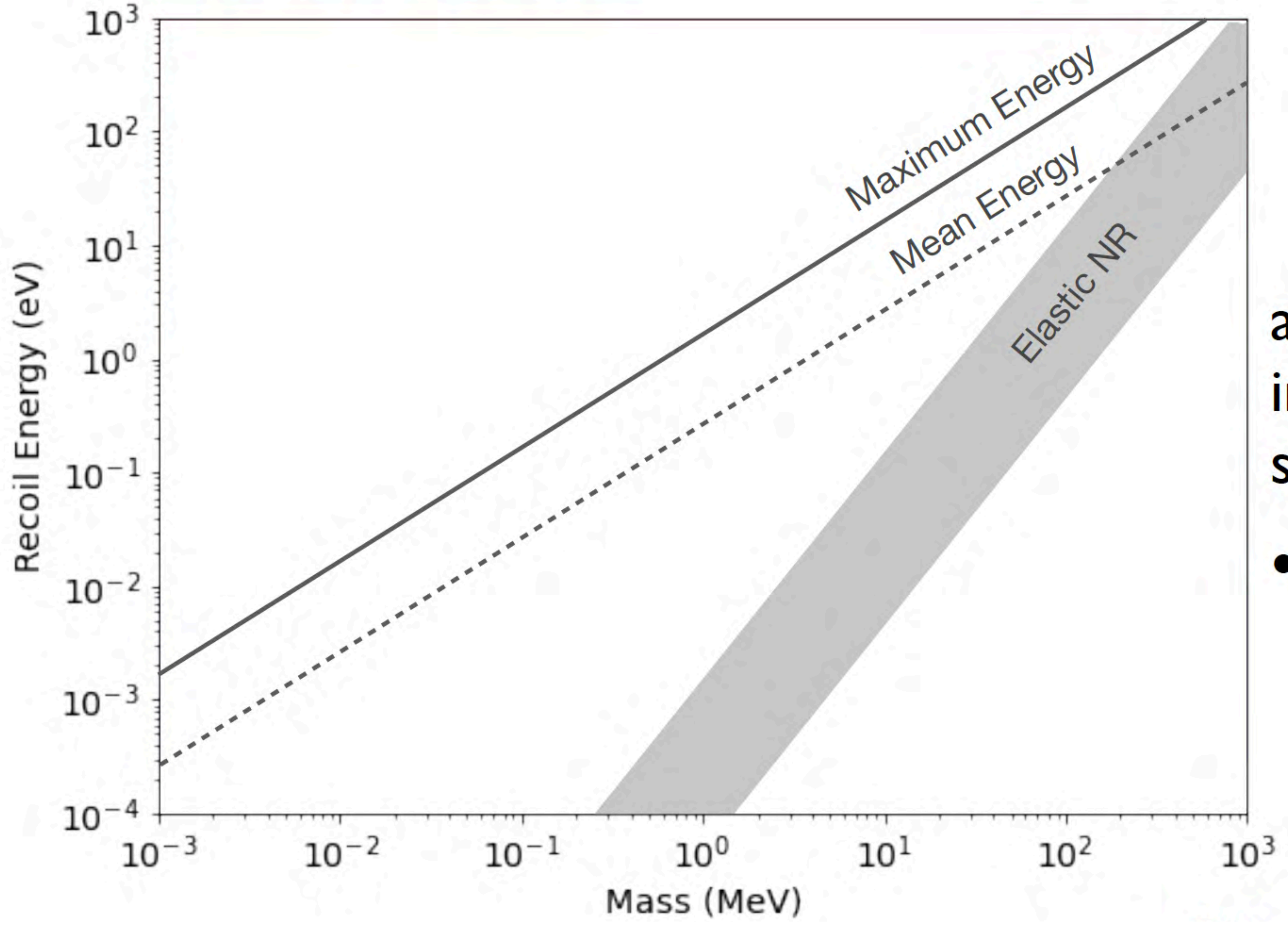
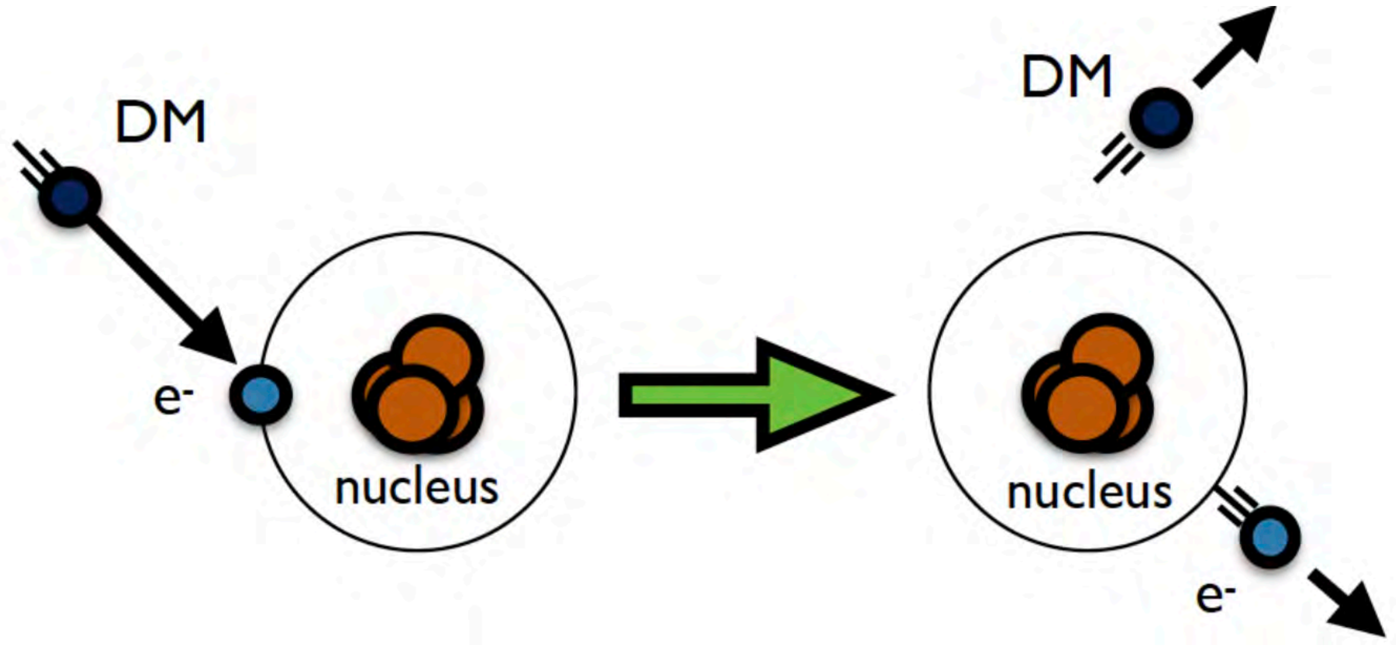


accessible through <u>inelastic</u> interactions (sometimes w/ suppressed rate), e.g.:

- DM-e scattering



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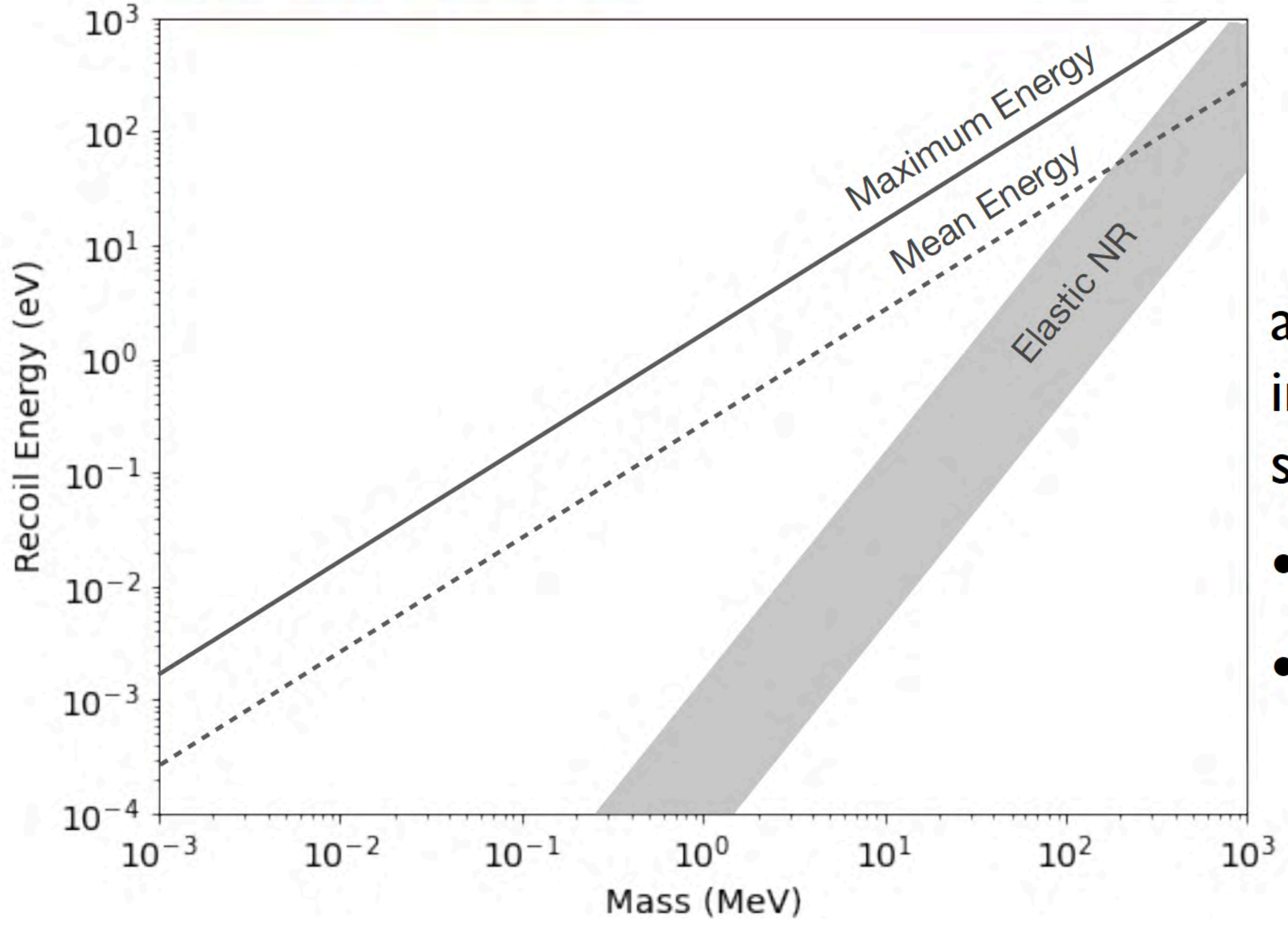
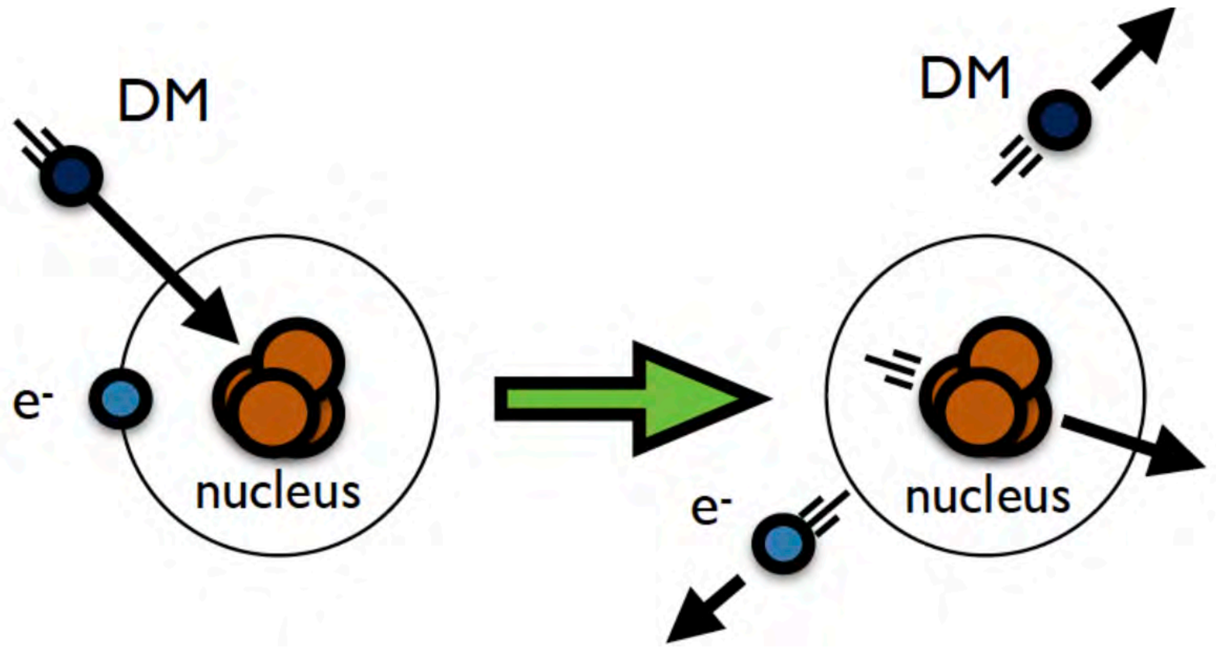


accessible through <u>inelastic</u> interactions (sometimes w/ suppressed rate), e.g.:

- DM-e scattering
- DM-N scattering w/ Migdal



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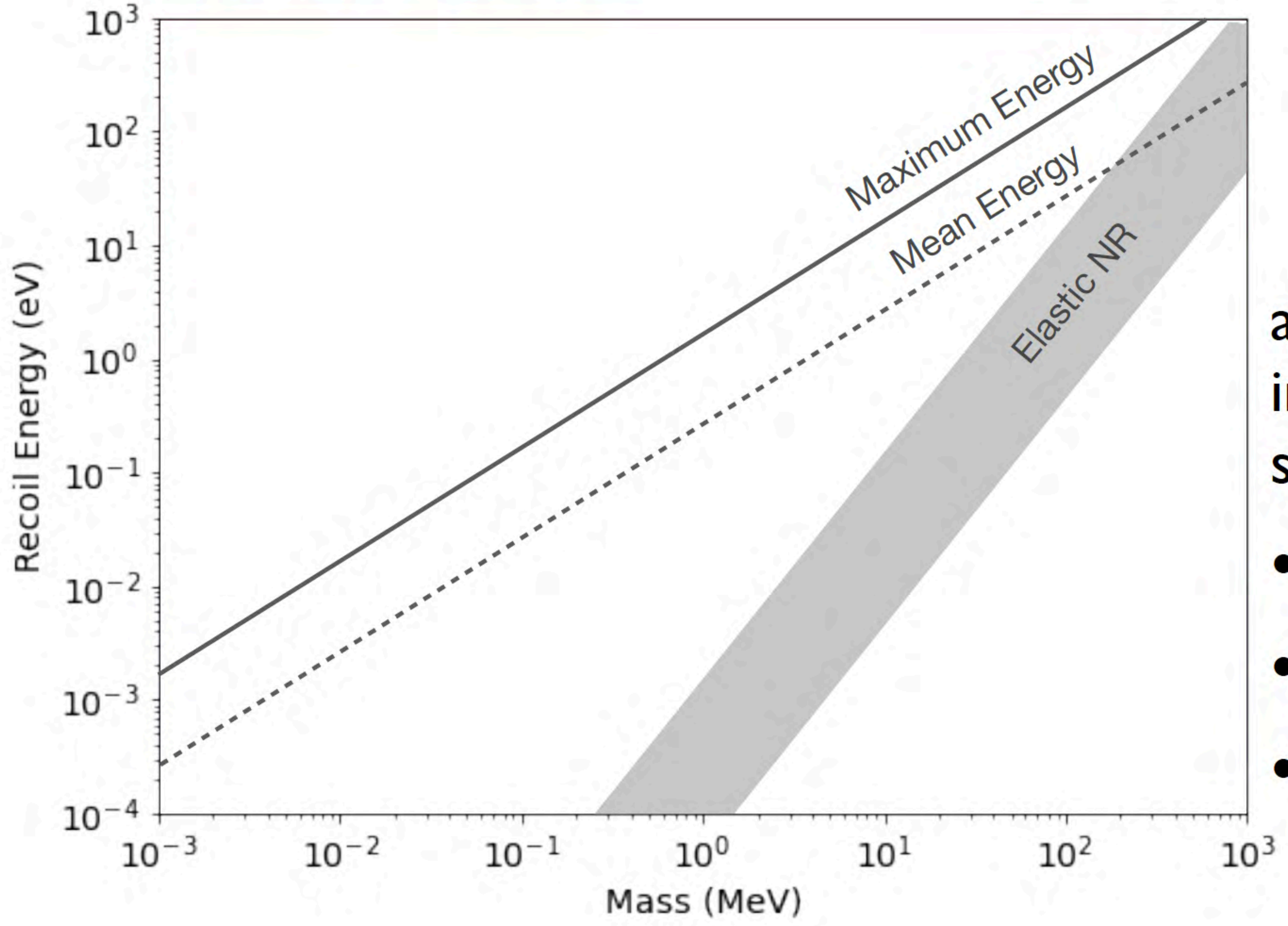
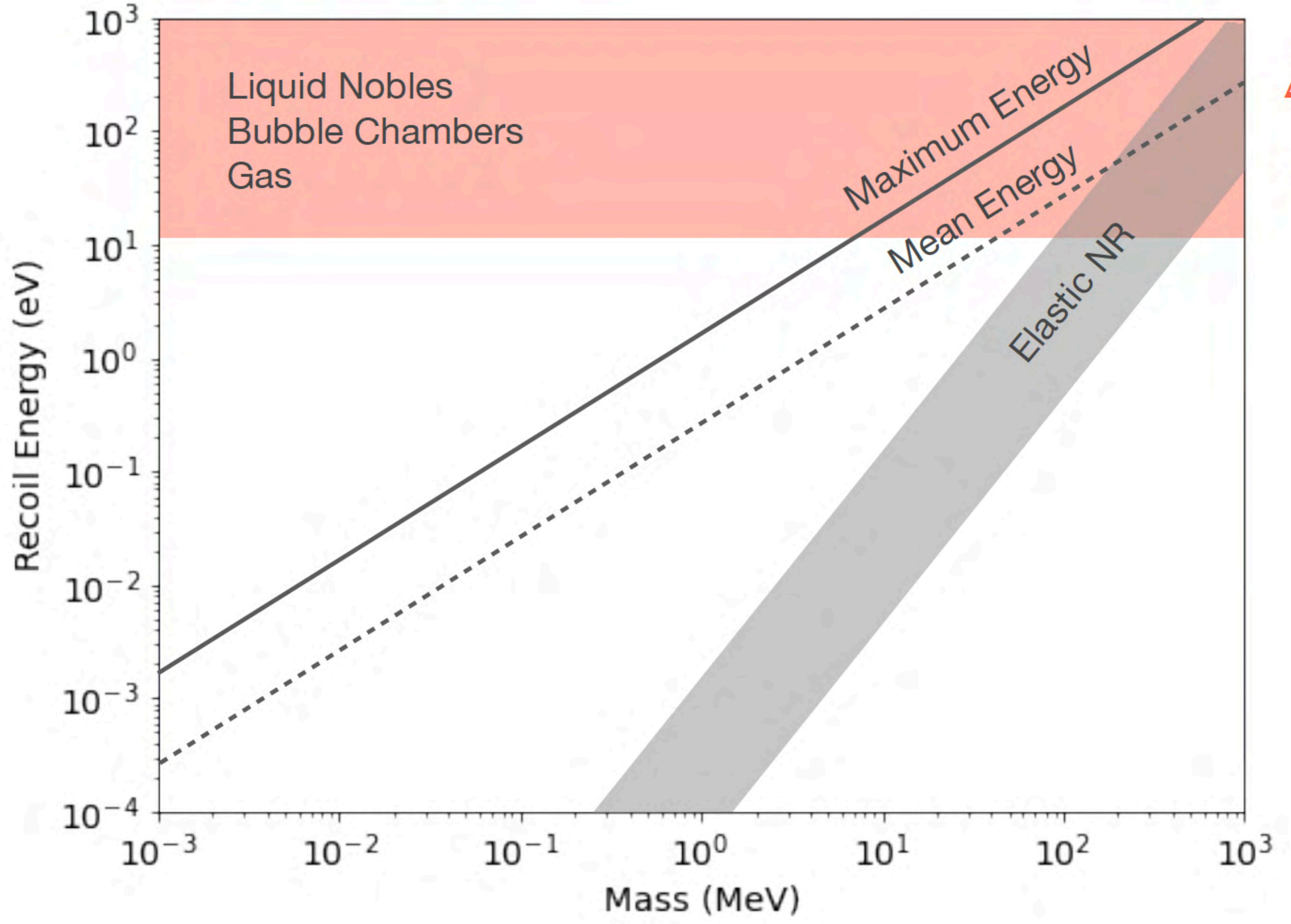


accessible through <u>inelastic</u> interactions (sometimes w/ suppressed rate), e.g.:

- DM-e scattering
- DM-N scattering w/ Migdal
- DM scattering w/ collective modes (e.g. phonons, magnons)

The low-mass DM Direct Detection Challenge

Fig. adapted from 2203.08297

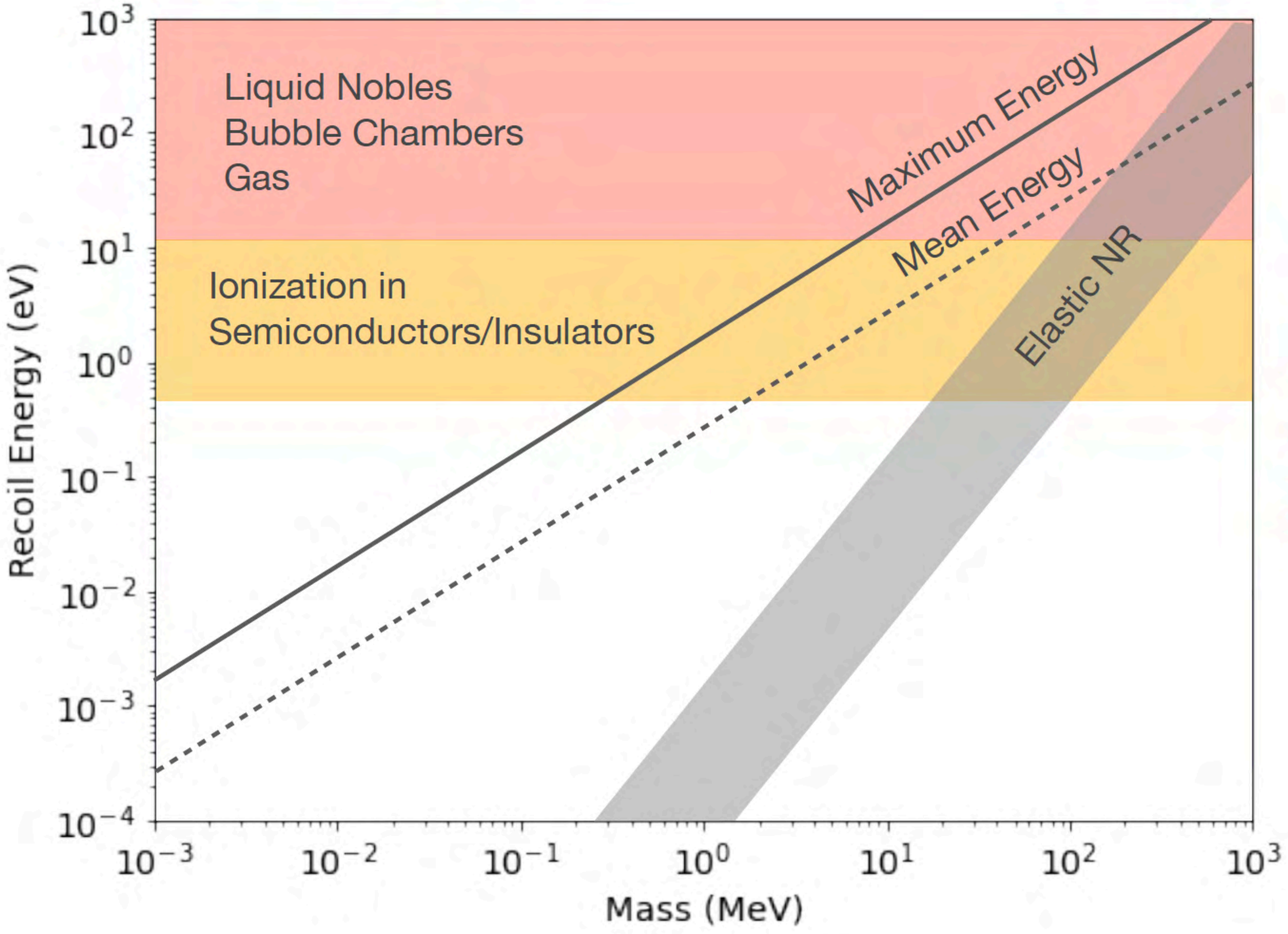


$\Delta E \sim 10$ eV

e.g. Xe, Ar, He

The low-mass DM Direct Detection Challenge

Fig. adapted from 2203.08297

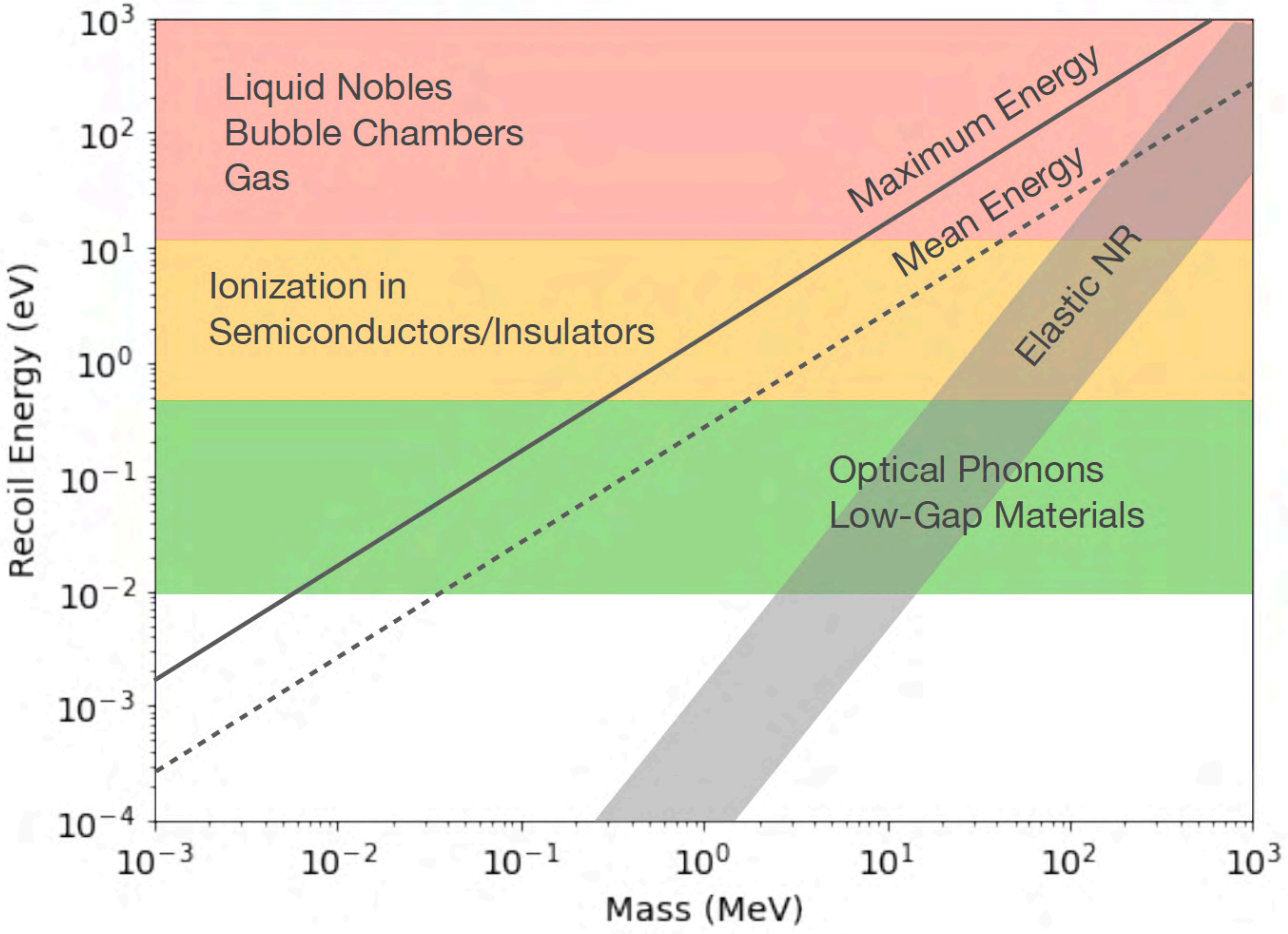


$\Delta E \sim 1$ eV

e.g. Si, Ge, GaAs, diamond, Quantum Dots, organic scintillators…

The low-mass DM Direct Detection Challenge

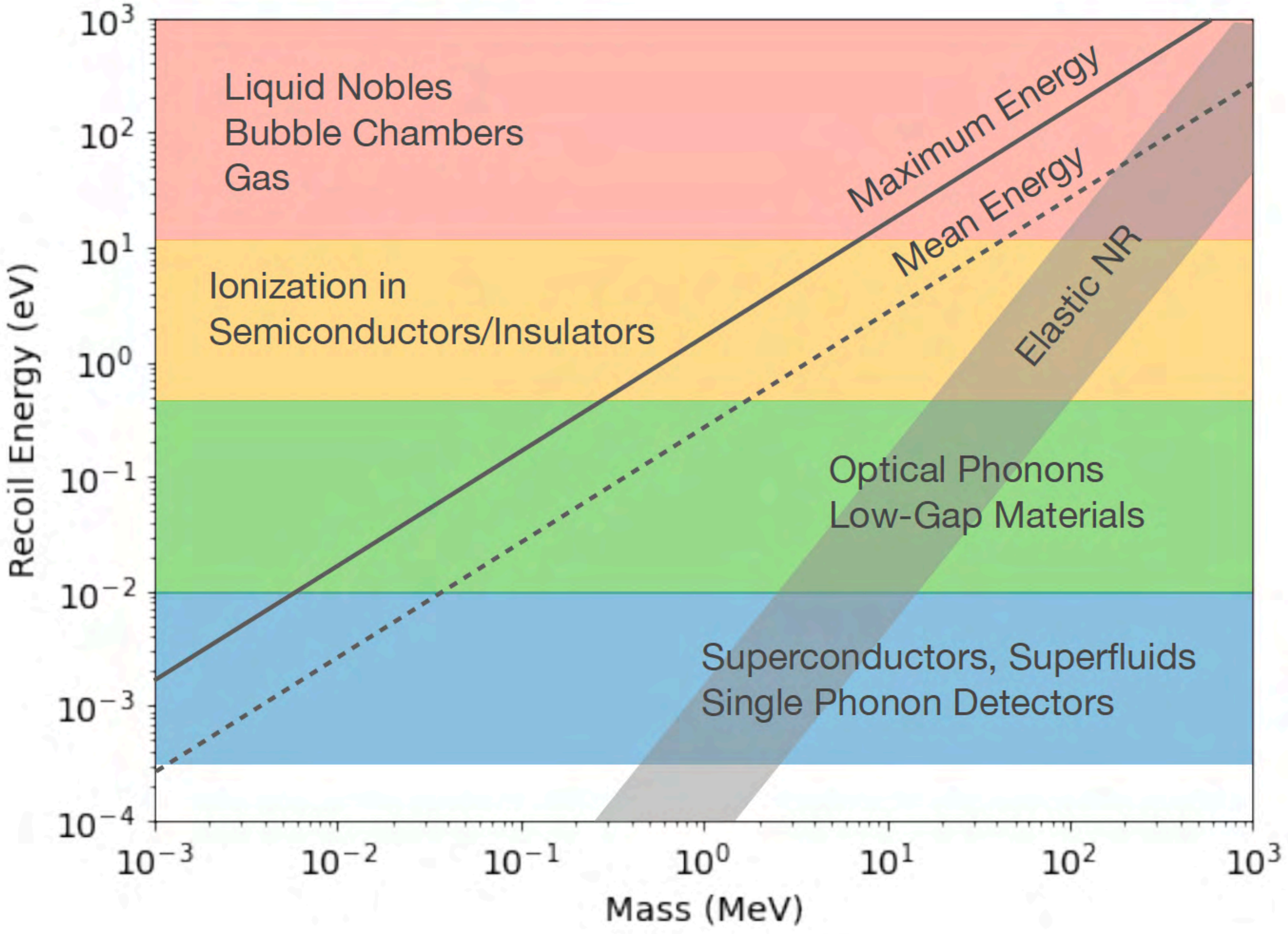
Fig. adapted from 2203.08297



$\Delta E \sim 10 - 100$ meV
e.g. GaAs, sapphire, Dirac materials, doped s/c, …

The low-mass DM Direct Detection Challenge

Fig. adapted from 2203.08297



$\Delta E \sim 1 \text{ meV}$

e.g. superfluids, superconductors

The low-mass DM Direct Detection Challenge

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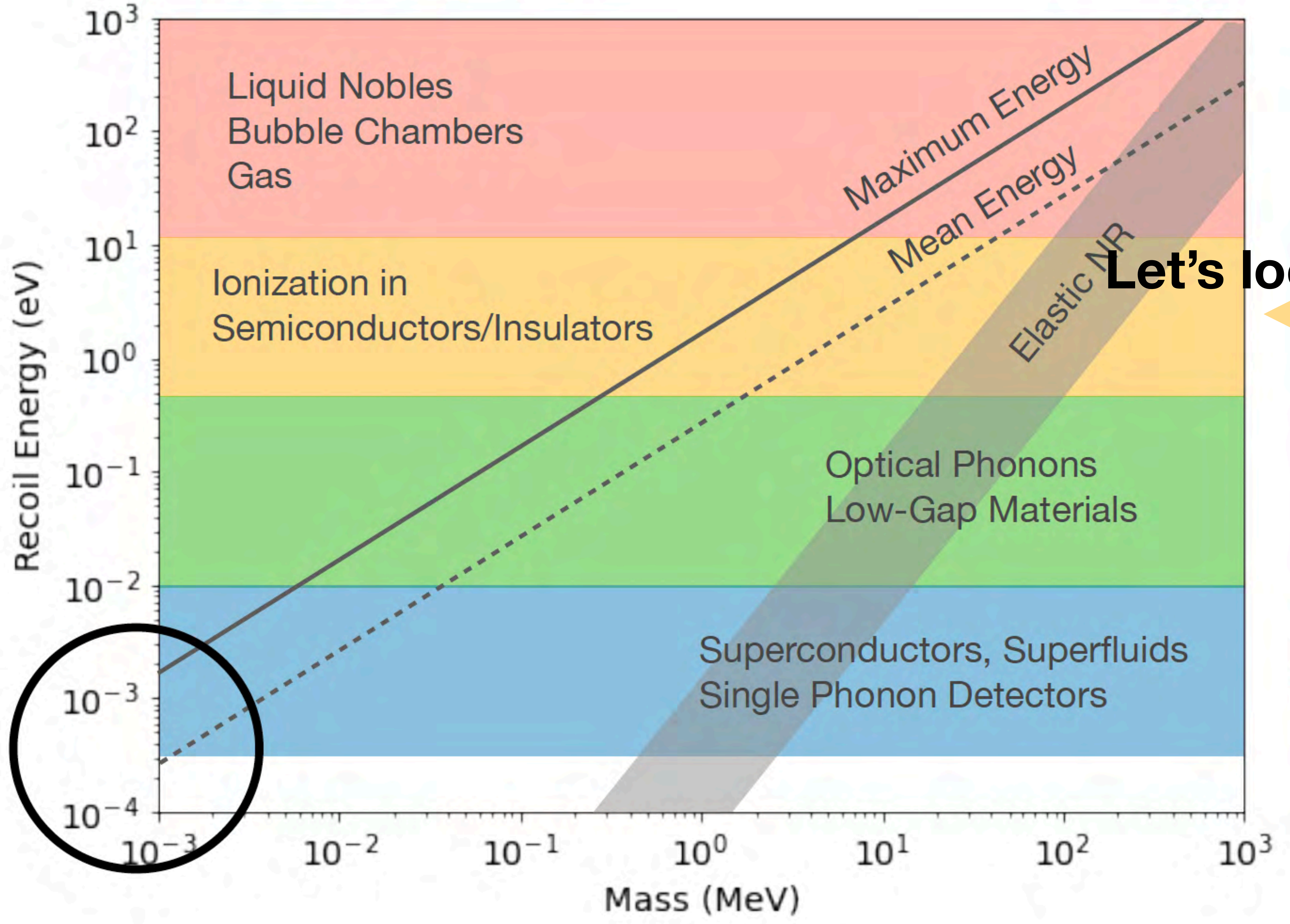


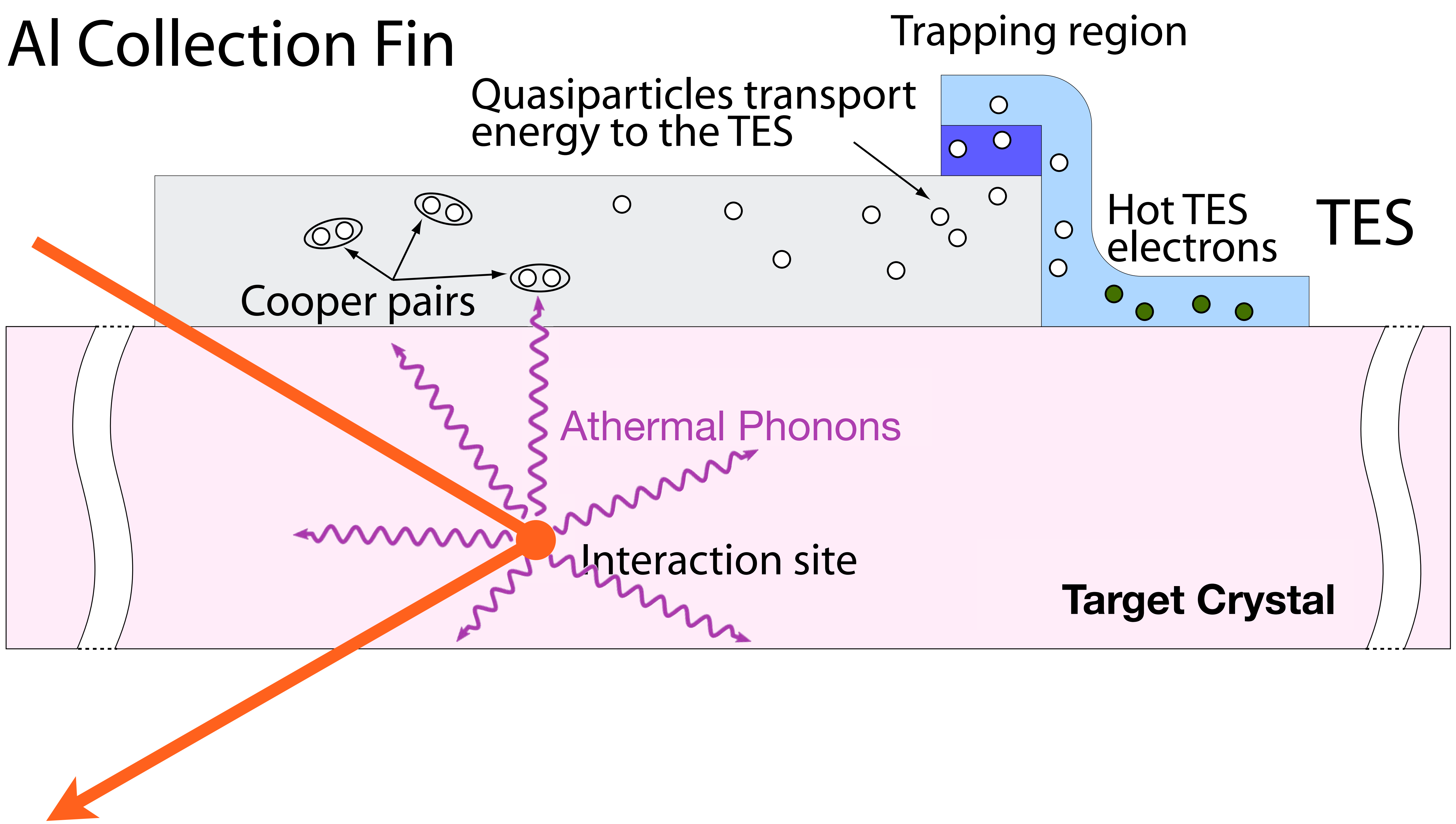
Let's look at an example of these.

$\Delta E \sim 1$ meV

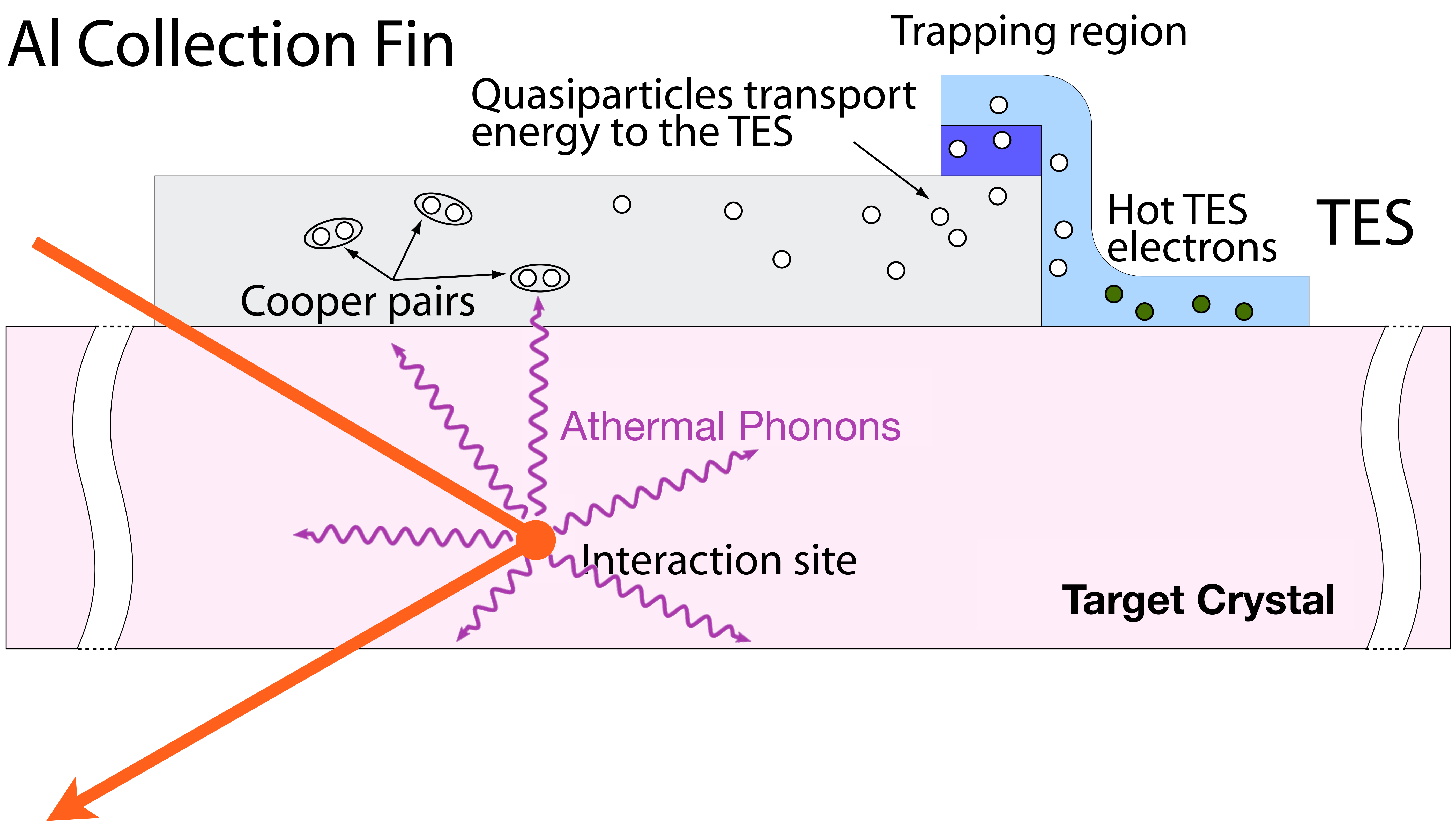
e.g. superfluids, superconductors

ultimate reach: keV masses w/ single phonon excitations or electron recoils from low-gap materials

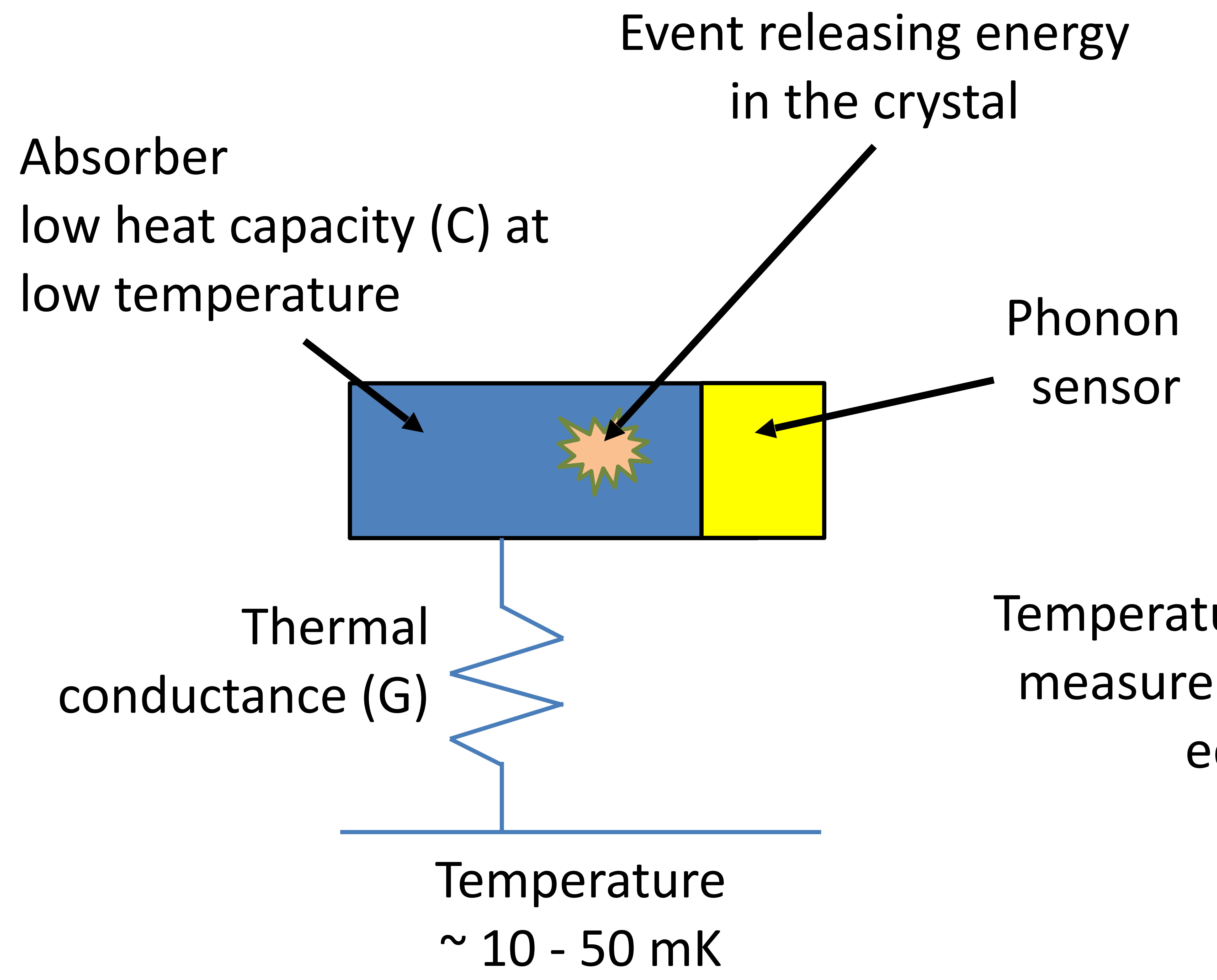
Dark Matter Particle Detection at keV and below

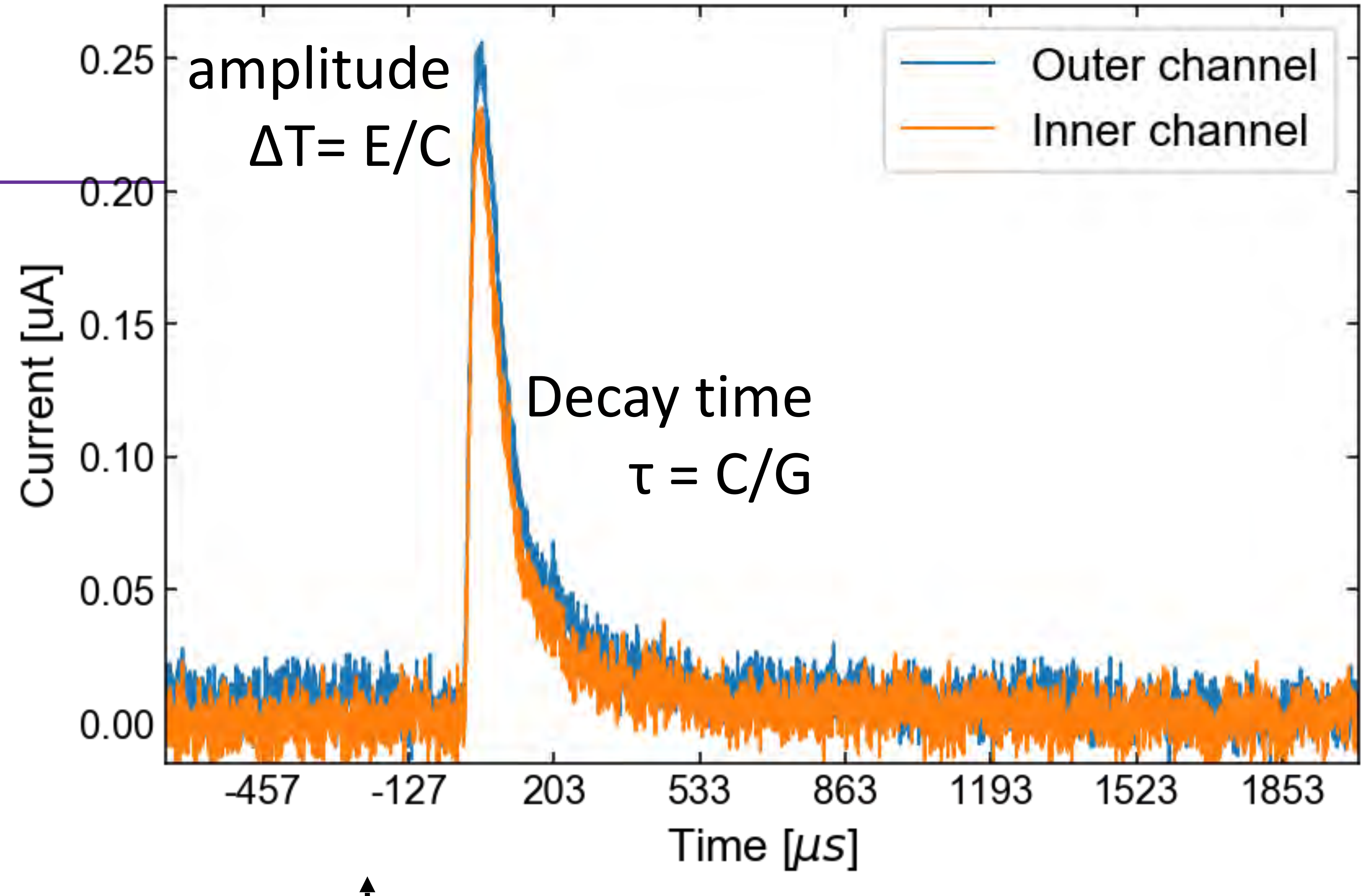


SuperCDMS Technology: Athermal Phonons

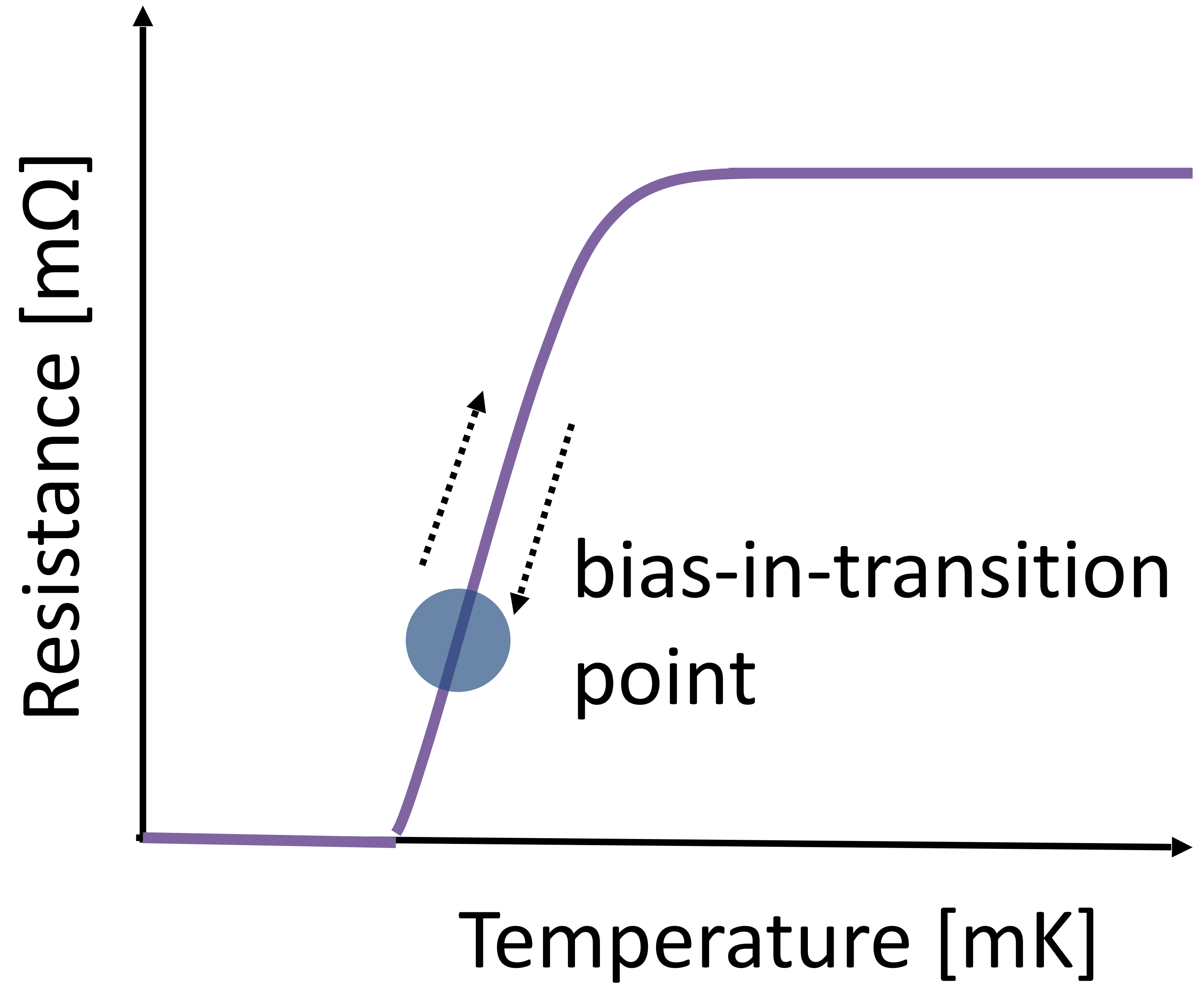


Calorimetric technique



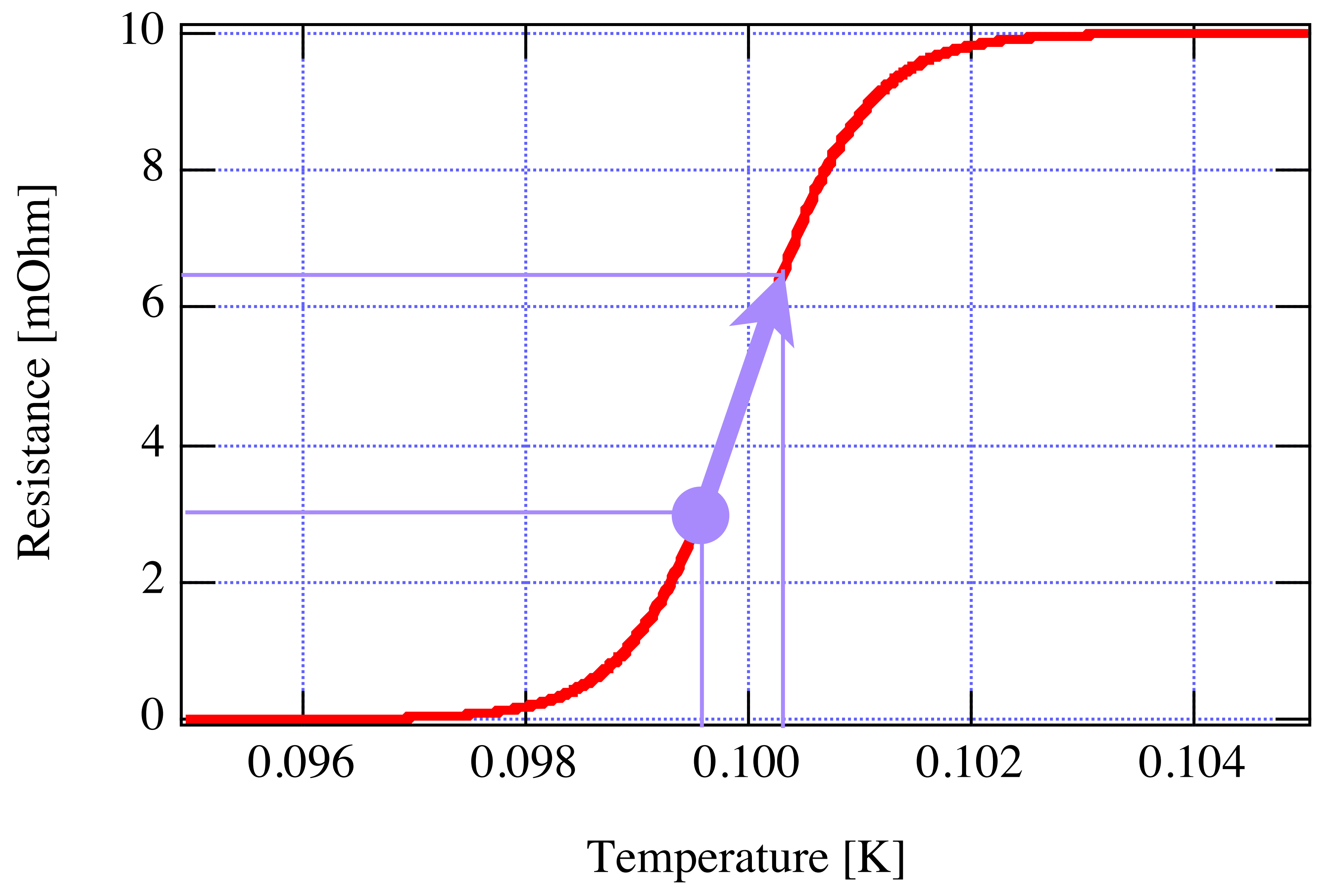


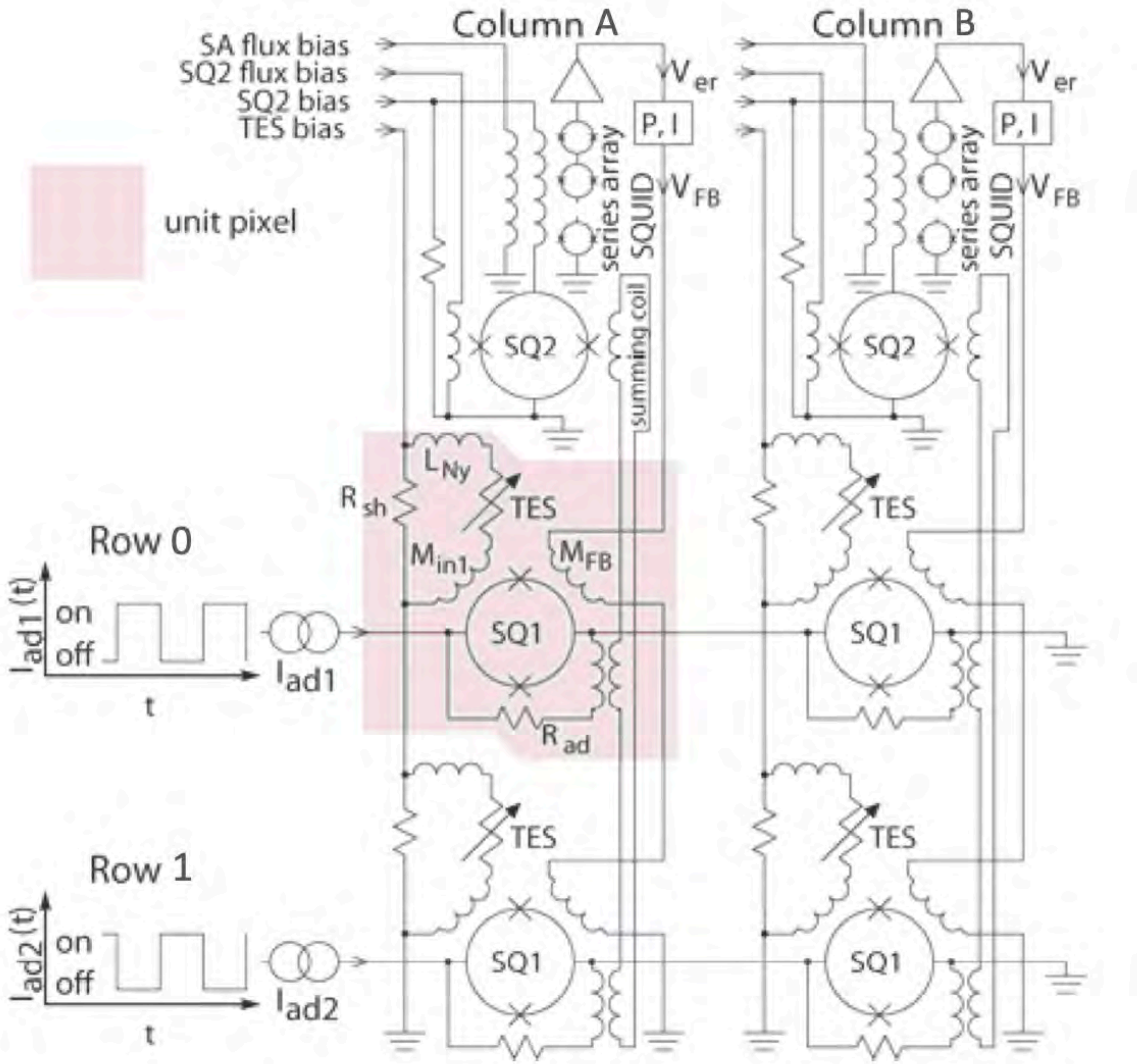
Temperature variations are measured with transition-edge sensors (TES)



Transition-Edge Sensors and SQUIDS

- Refrigerator temperature has to be close to absolute zero
- A TES is a thin film made out of either Mo/Au (for X-ray detectors), W (for dark matter detectors) or Al/Mn (for neutrino detectors)
- Readout is done with Superconducting Quantum Interference Devices (SQUIDs)





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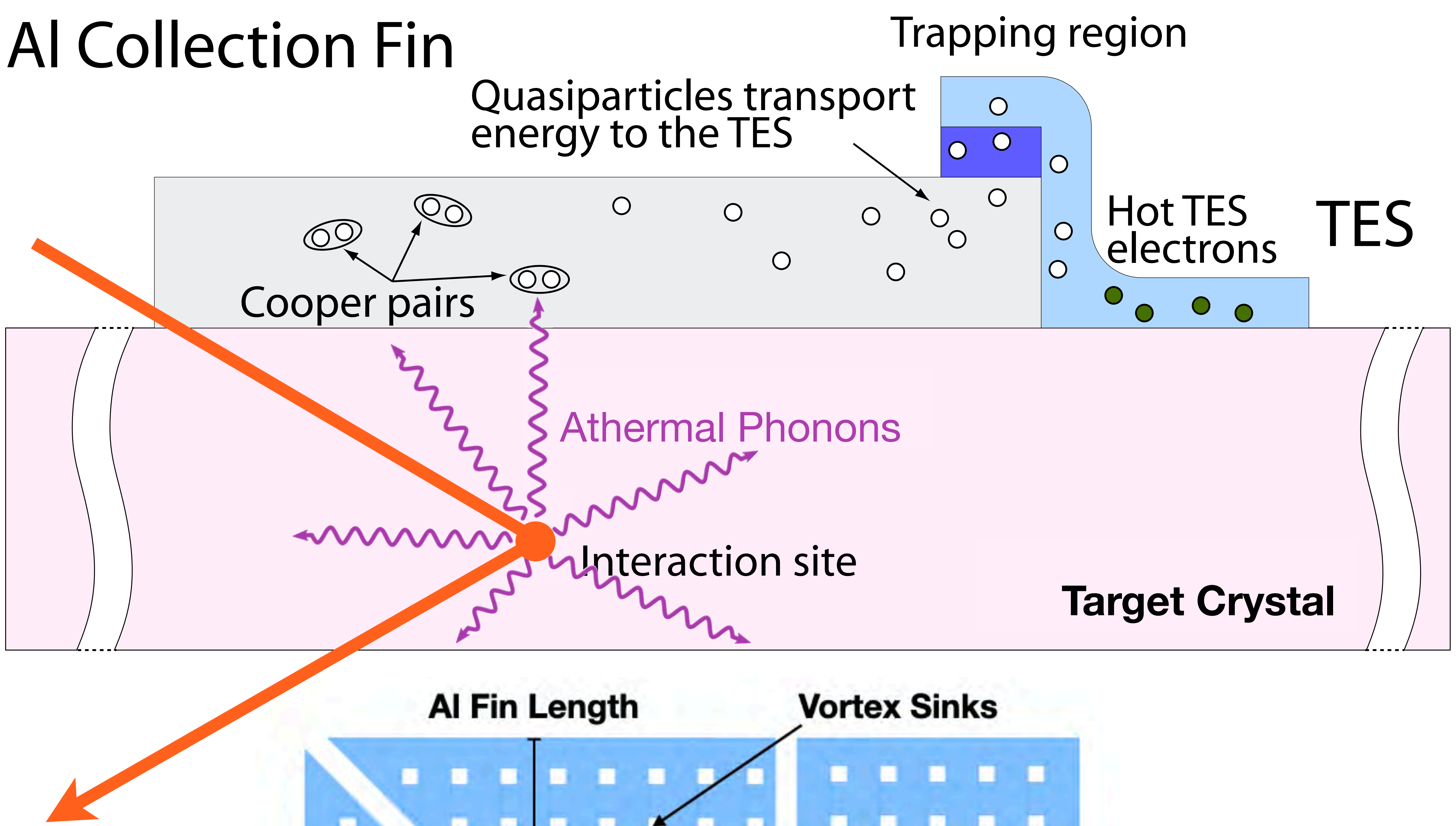
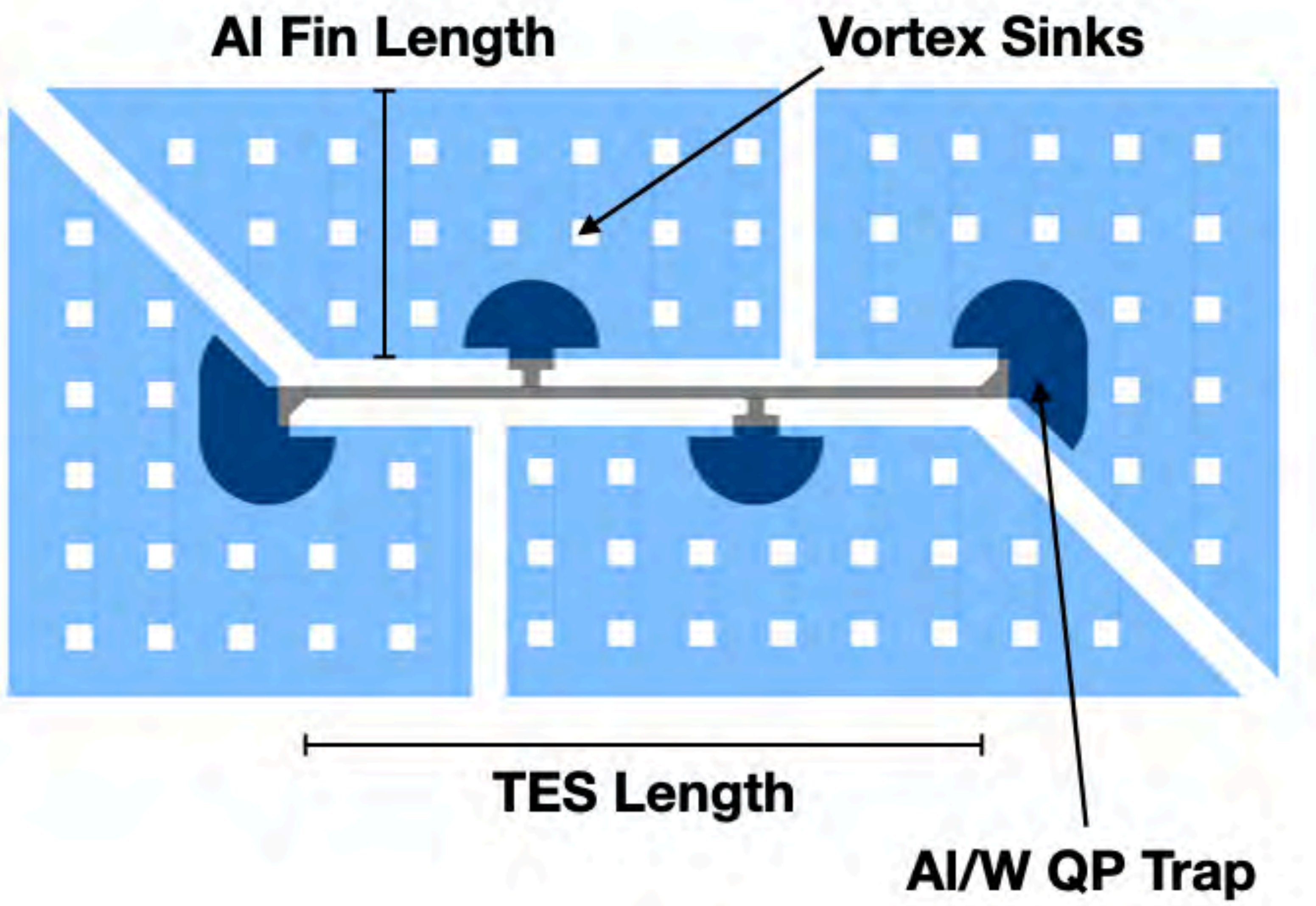
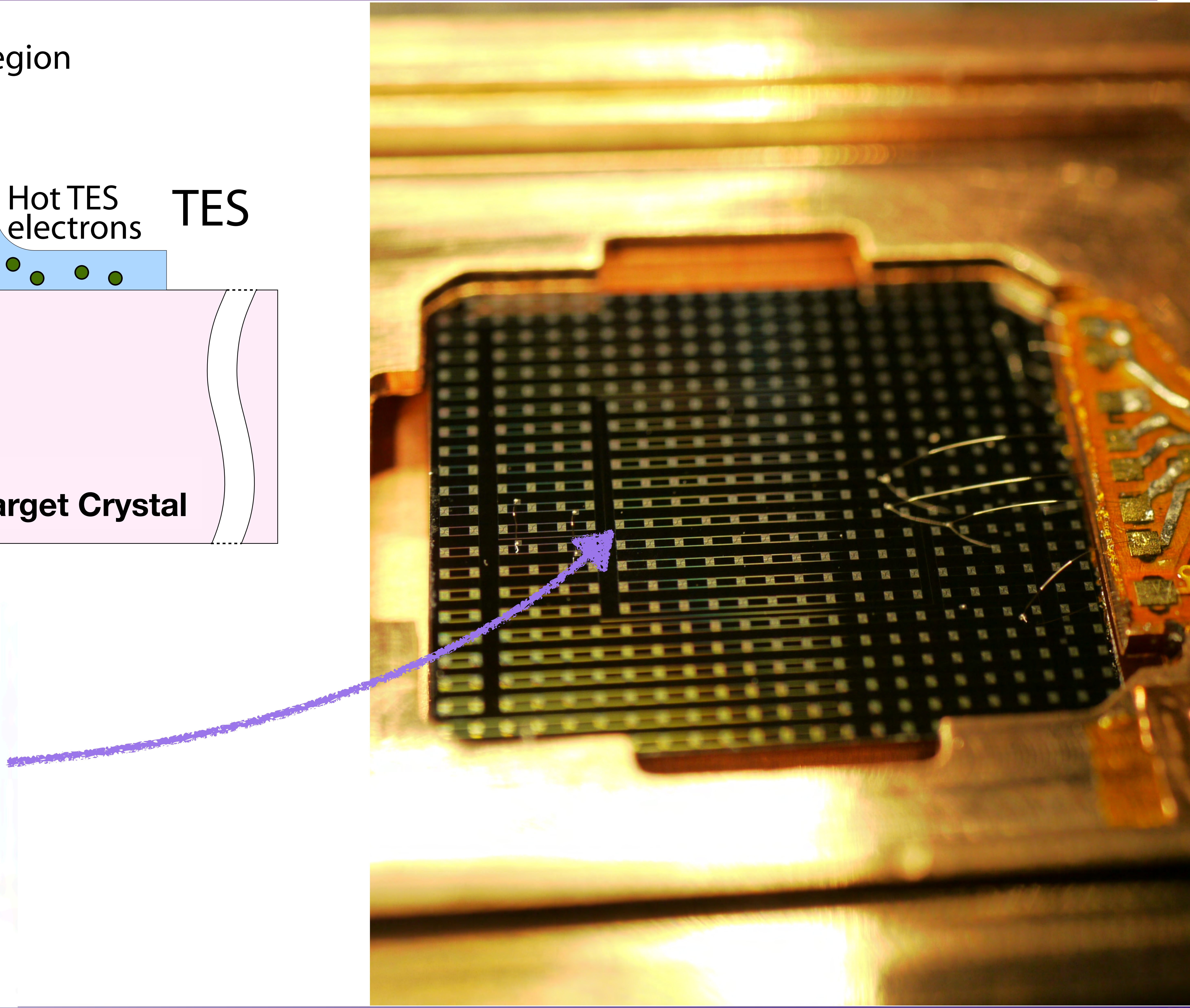






Anatomy of an Event

Turn off – nuclear recoil
Turn on – charge detector

Sensors measure E_{ph}

Charge signals are amplified with an electric field across the crystal

$$E_{ph} = E_{recoil} + E_{NTL} = E_{recoil}\left(1 + \frac{e \bullet V_{NTL}}{\varepsilon}\right)$$

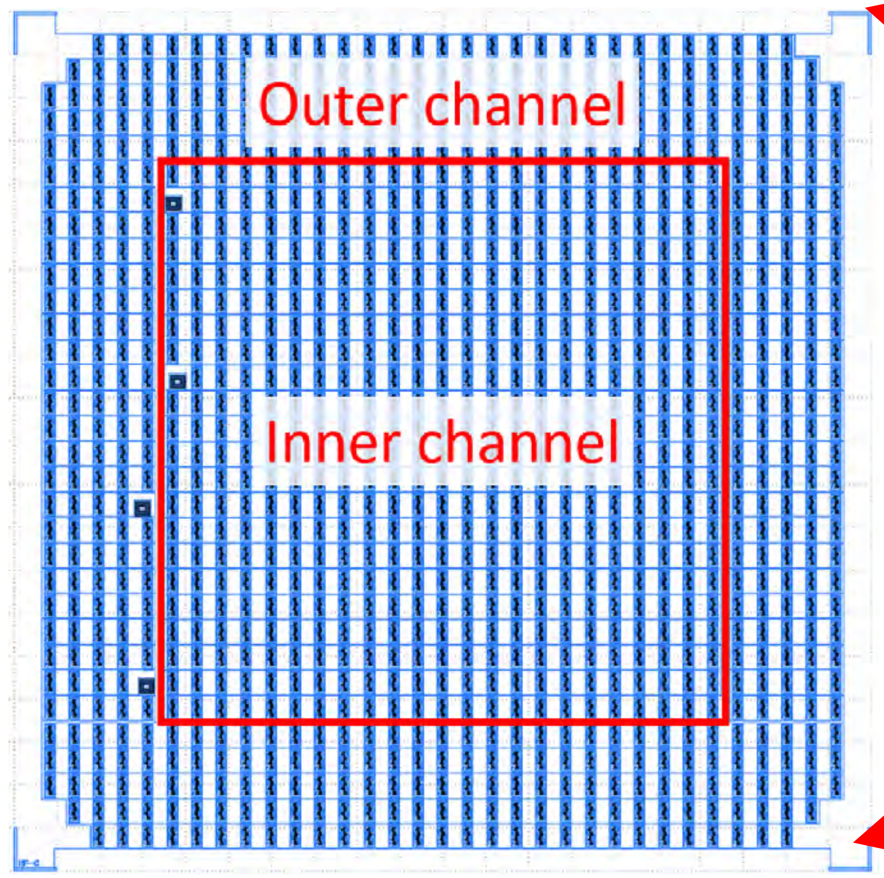
Total phonon energy

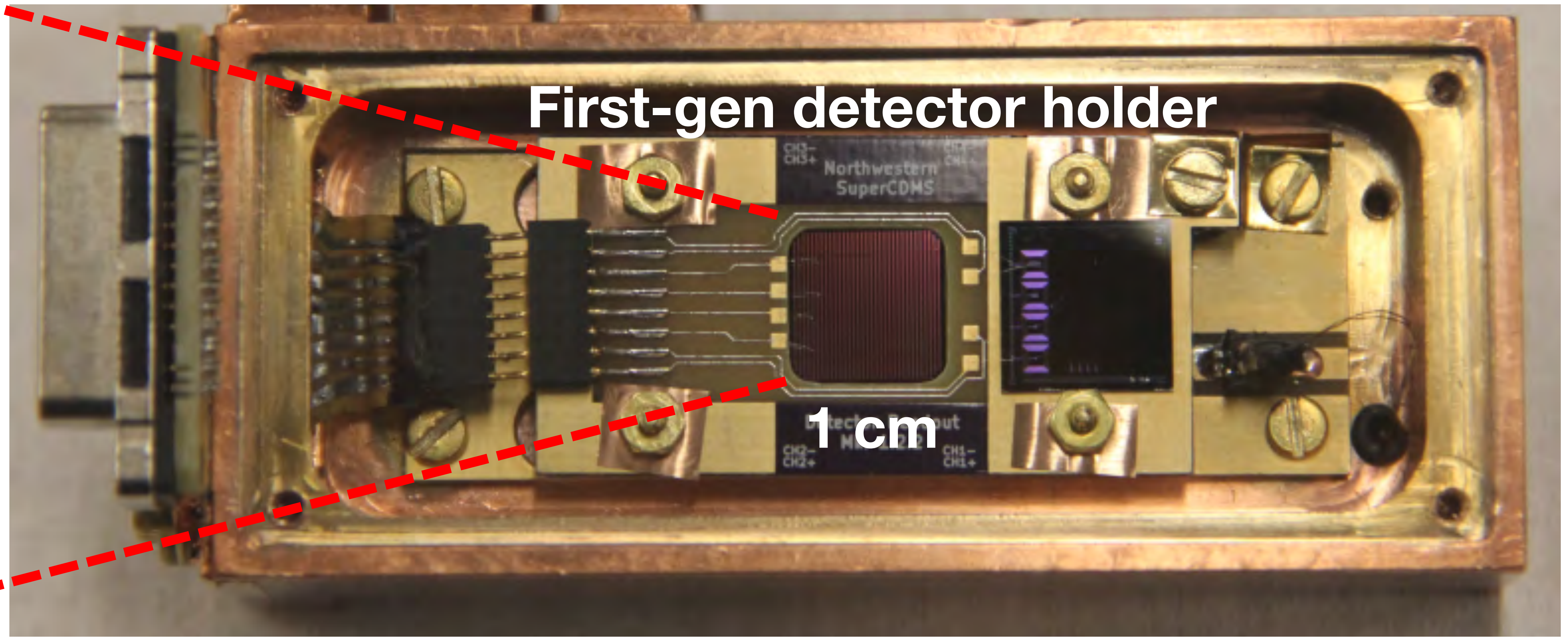
B. S. Neganov and V. N. Trofimov, Otkryt. Izobret., 146, 215 (1985)
P. N. Luke, J. Applied Phys. 64,6858 (1988)

HVeV = High-Voltage, eV Scale

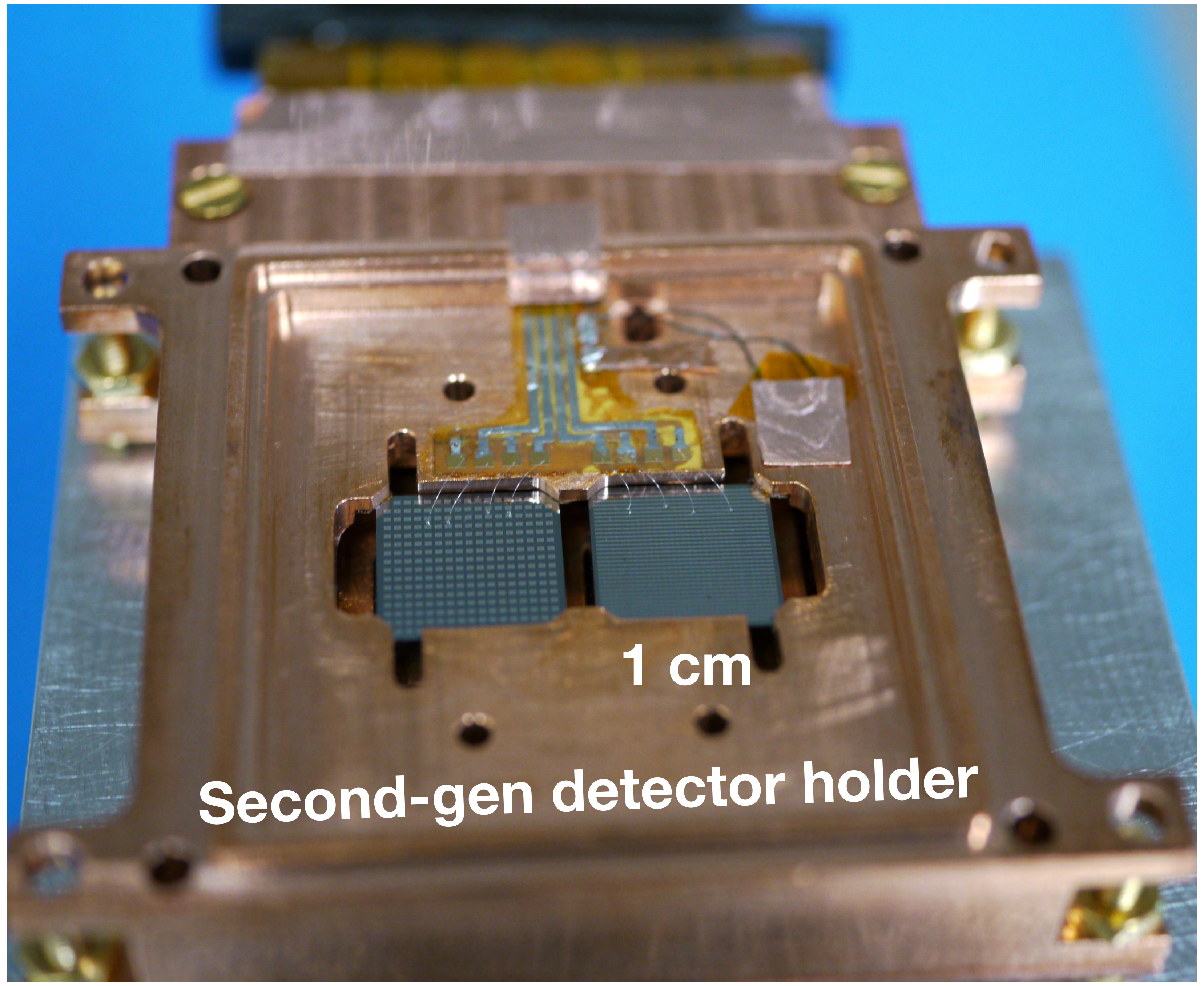
- 1x1x0.4 cm³ 0.93 g silicon crystal
  2 equal-area TES sensors

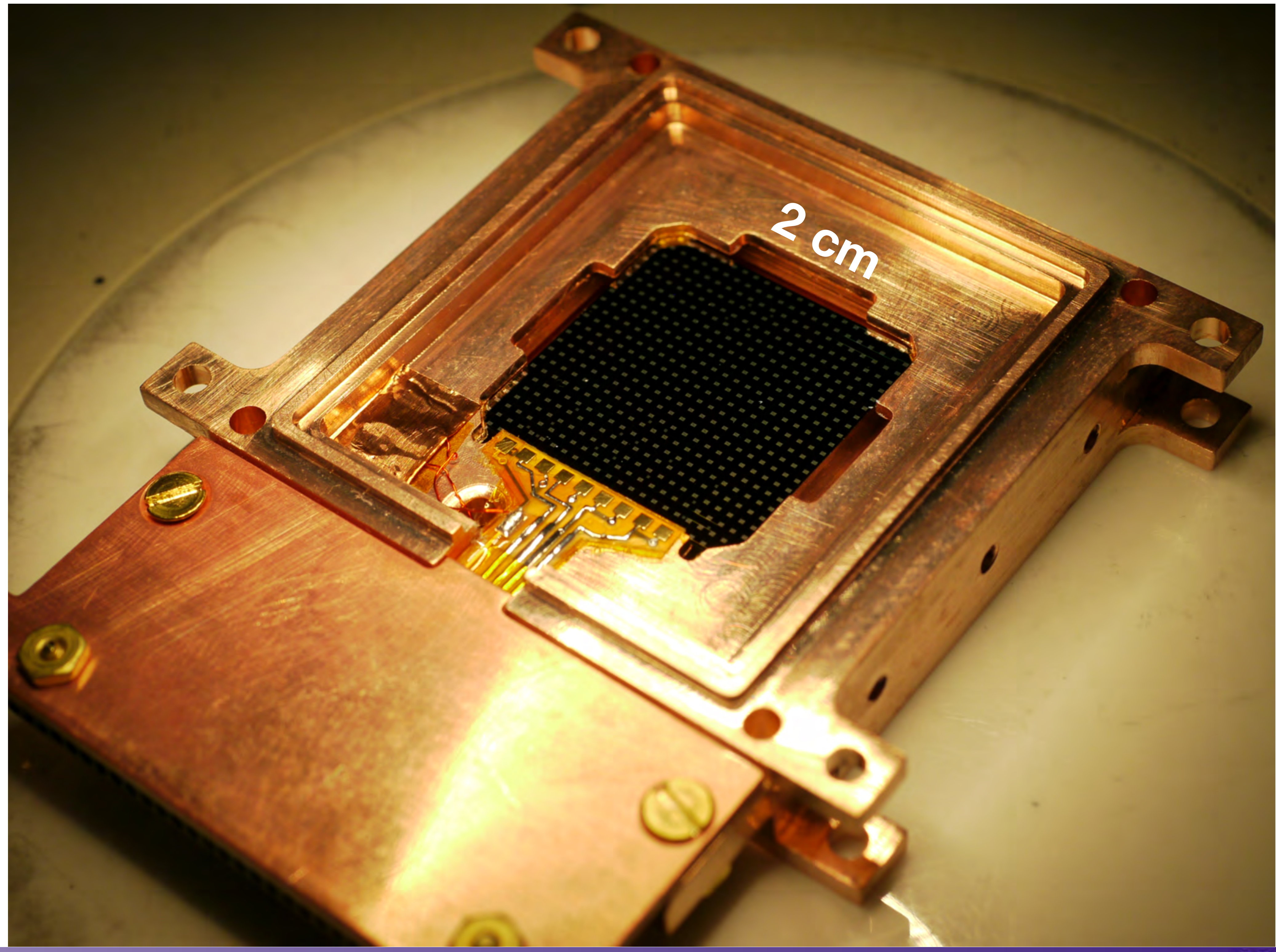
- 2x2x0.4 cm³ 3.72 g silicon crystal
  4 equal-area TES sensors



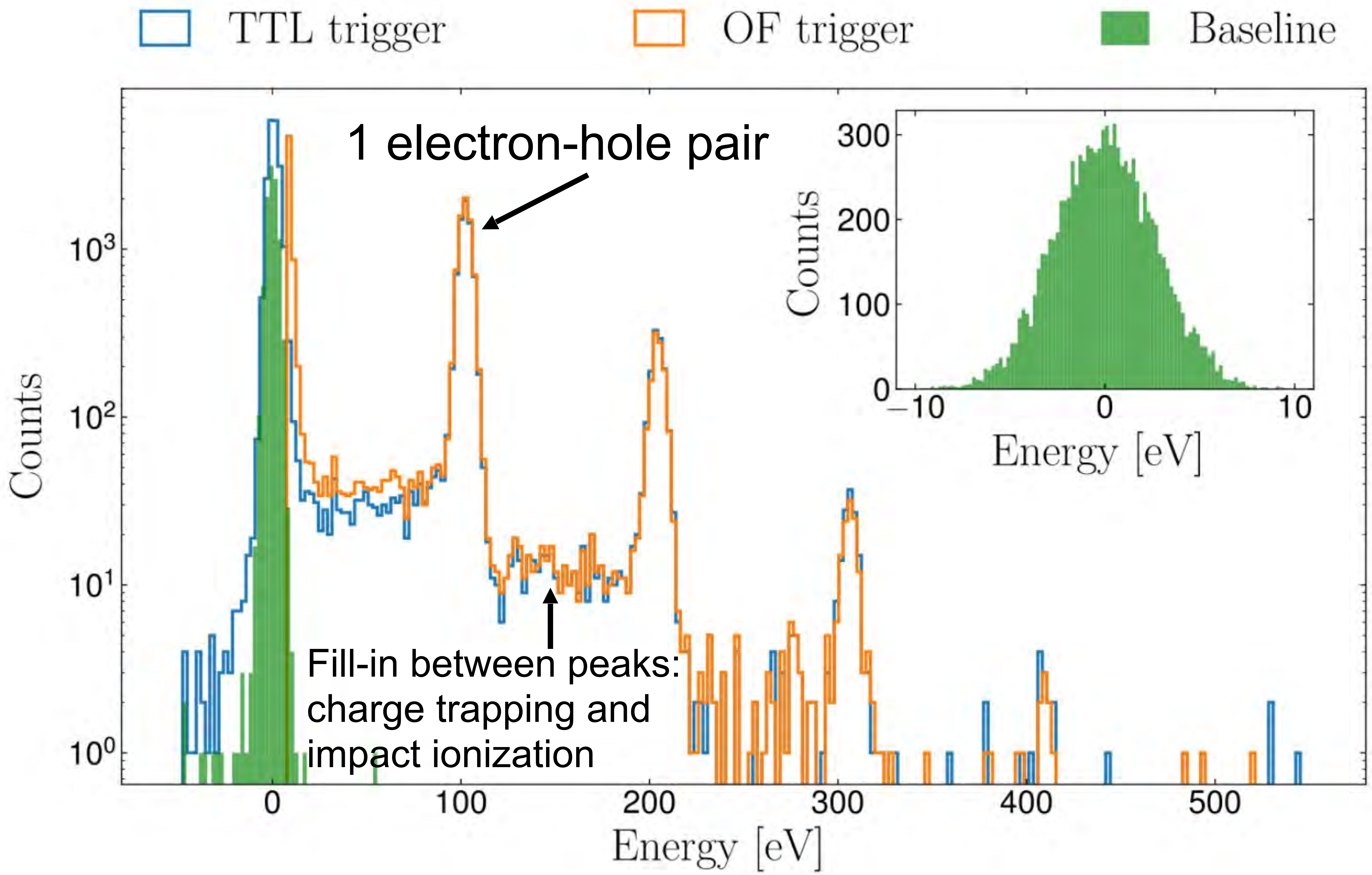


- Detector technology advancement from a collaboration between Northwestern University and Fermilab

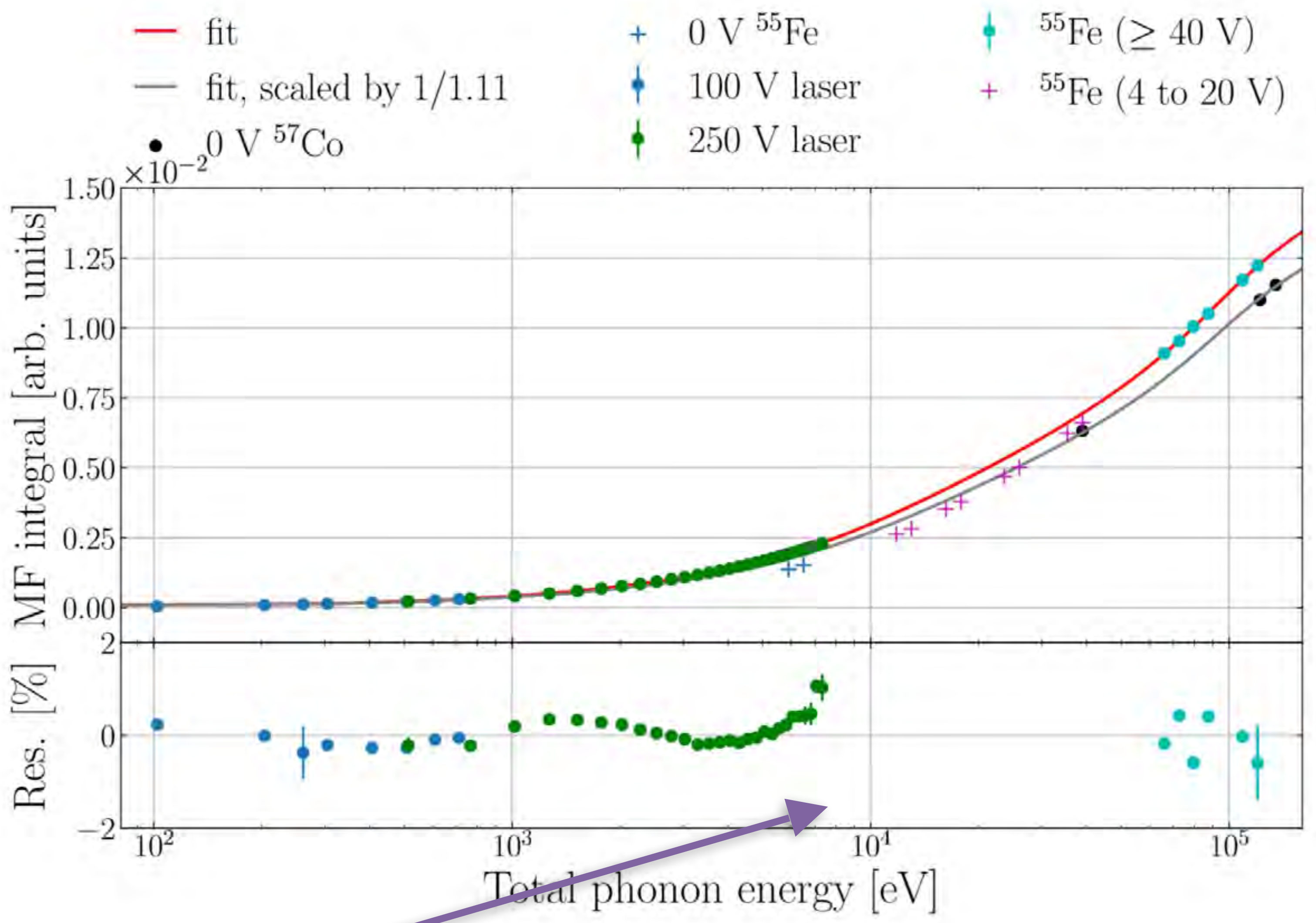


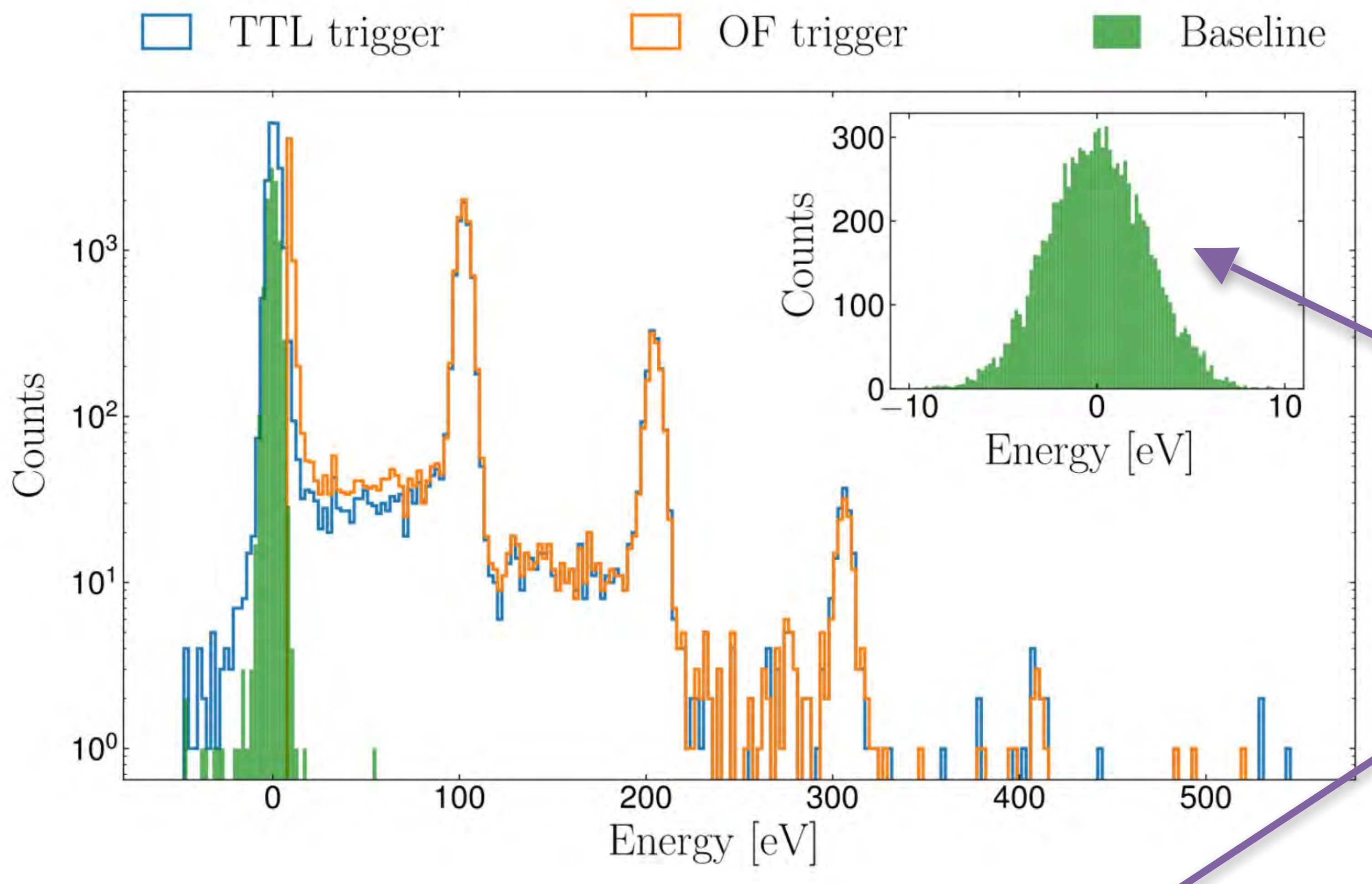


Single electron-hole pair sensitivity

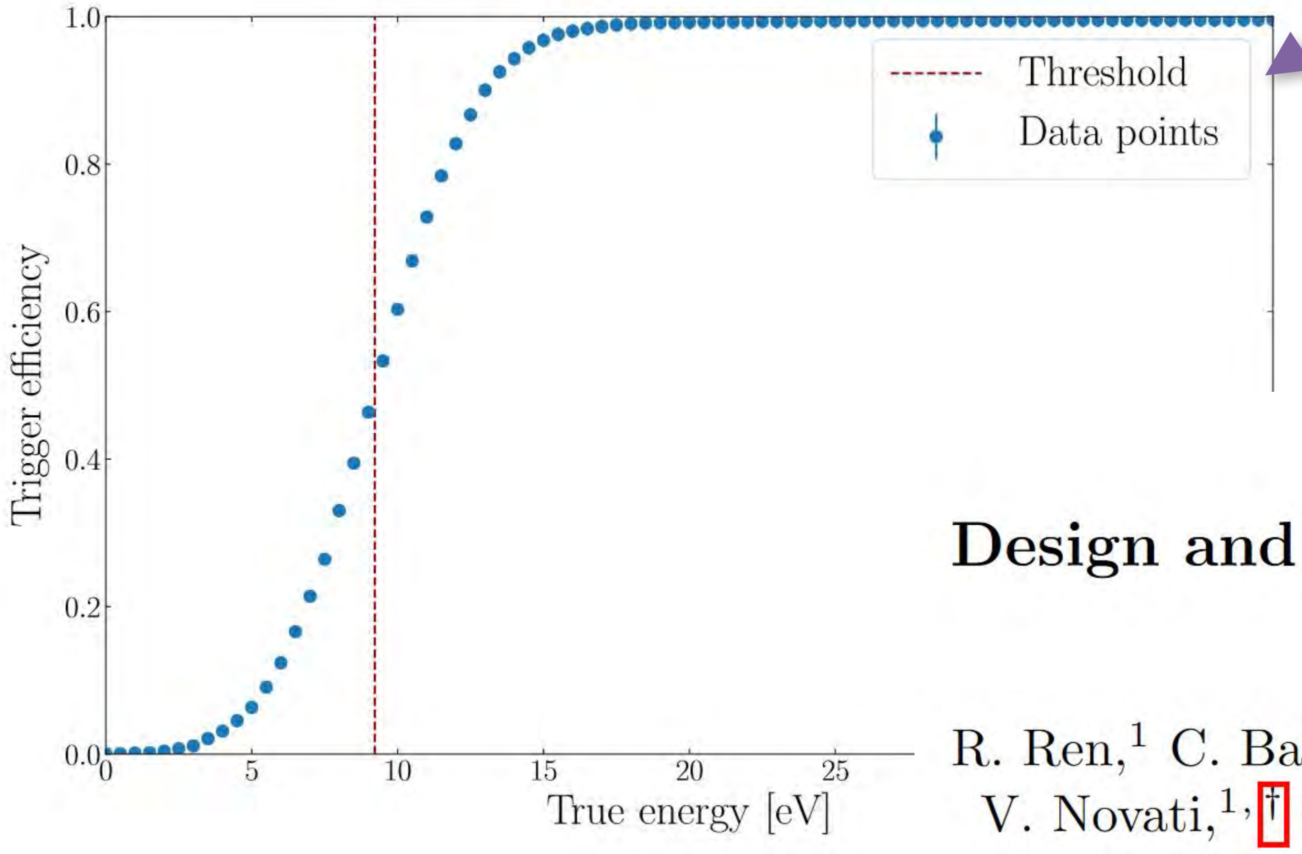


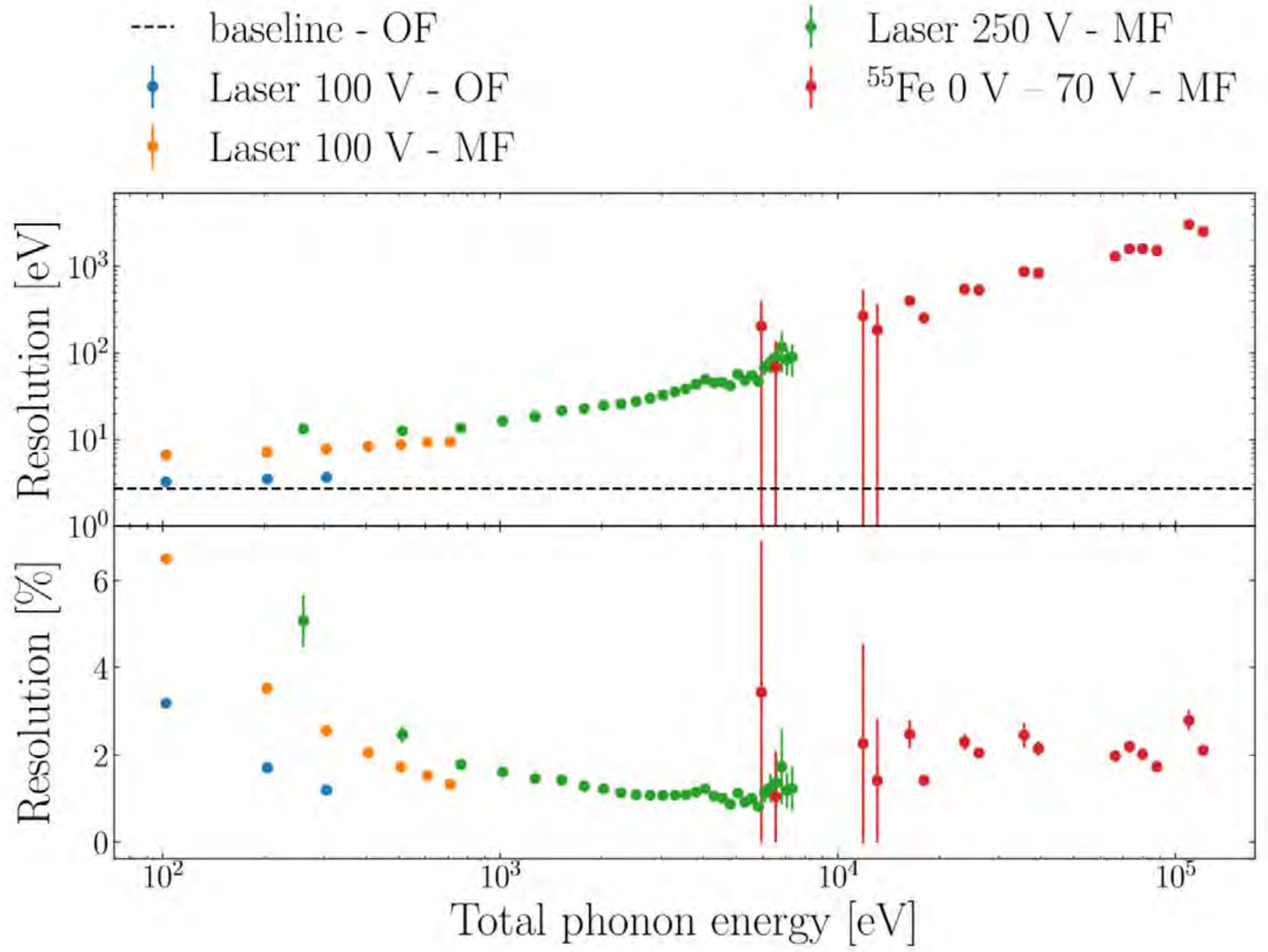
An exceptional detector …





- 2.7 eV baseline resolution
- 9.2 eV threshold
- First eV-scale detector with a bandpass of hundreds of keV (4 orders of magnitude)
- Energy resolution < 5 % over the full energy range





Design and Characterization of a Phonon-Mediated Cryogenic Particle Detector with an eV-Scale Threshold and 100 keV-Scale Dynamic Range

R. Ren,[1] C. Bathurst,[2] Y.Y. Chang,[3] R. Chen,[1] C.W. Fink,[4] Z. Hong,[1] N.A. Kurinsky,[5,6,*] N. Mast,[7] N. Mishra,[5] V. Novati,[1,†] G. Spahn,[5] H. Meyer zu Theenhausen,[8] S.L. Watkins,[4] Z. Williams,[7] M.J. Wilson,[8,9] A. Zaytsev,[8] D. Bauer,[5] R. Bunker,[10] E. Figueroa-Feliciano,[1] M. Hollister,[5] L. Hsu,[5] P. Lukens,[5] R. Mahapatra,[11] N. Mirabolfathi,[11] B. Nebolsky,[1] M. Platt,[11] F. Ponce,[12] M. Pyle,[4] T. Reynolds,[2] and T. Saab[2]

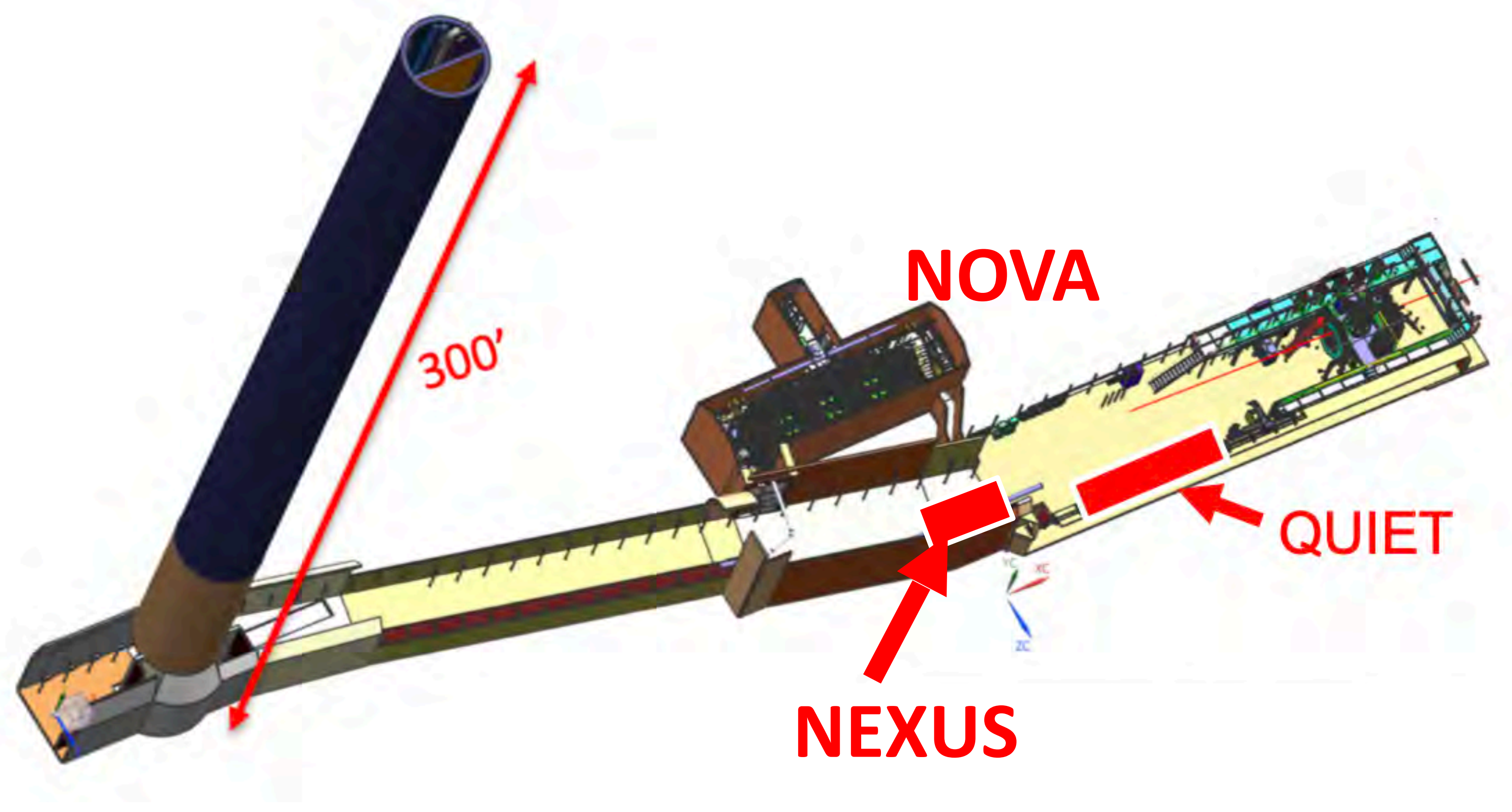
[1] *Department of Physics & Astronomy, Northwestern University, Evanston, IL 60208-3112, USA*

R. Ren et al., ArXiv:2012.12430 (2020)

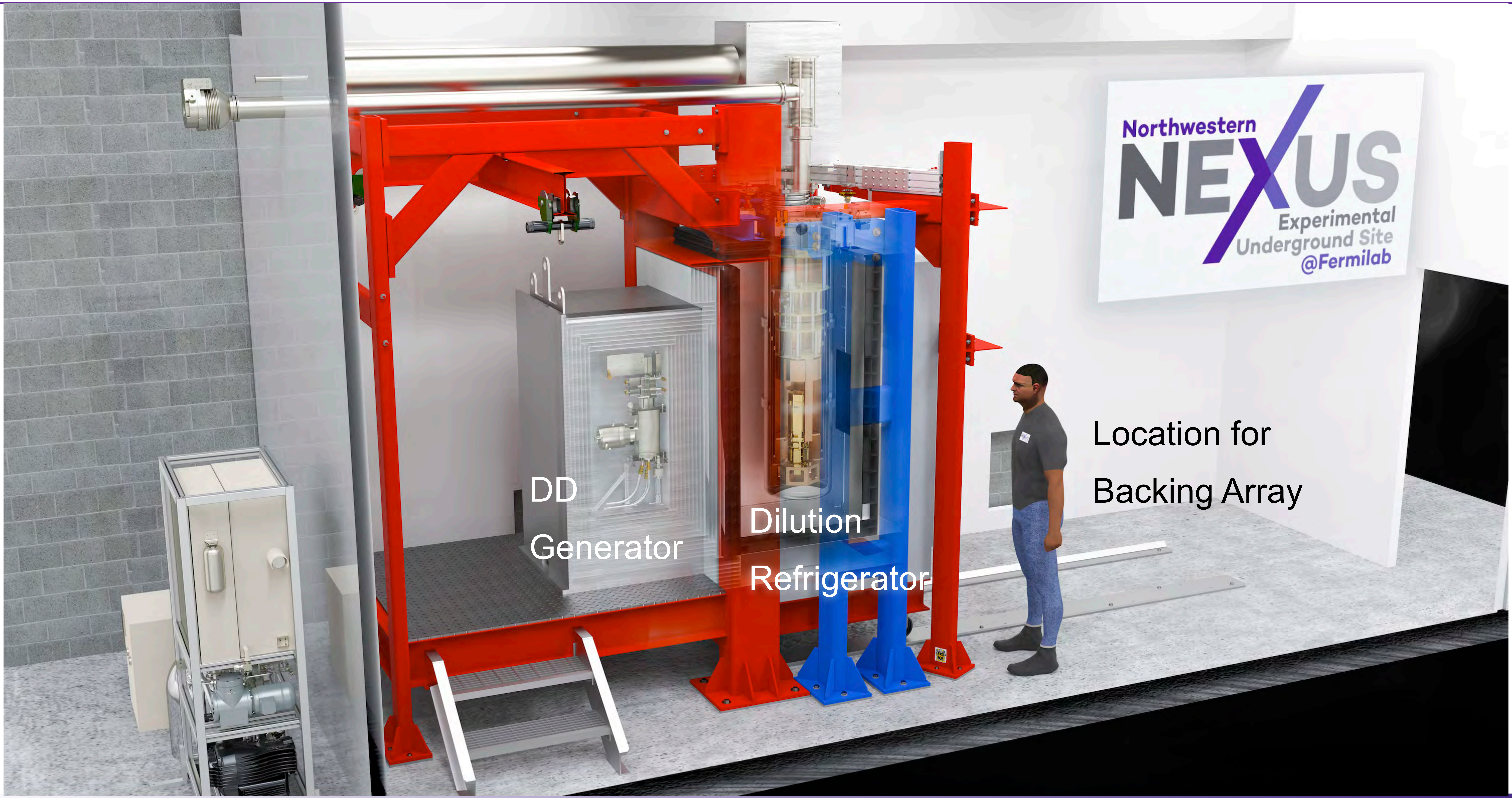

Northwestern
NEXUS
Experimental
Underground Site
@Fermilab

Northwestern Experimental Underground Site @ Fermilab

- Located in the MINOS hall at Fermilab
  - 100 m (225 mwe) underground for cosmic radiation shielding
  - Easy access
  - Internal lead shield + movable external lead castle

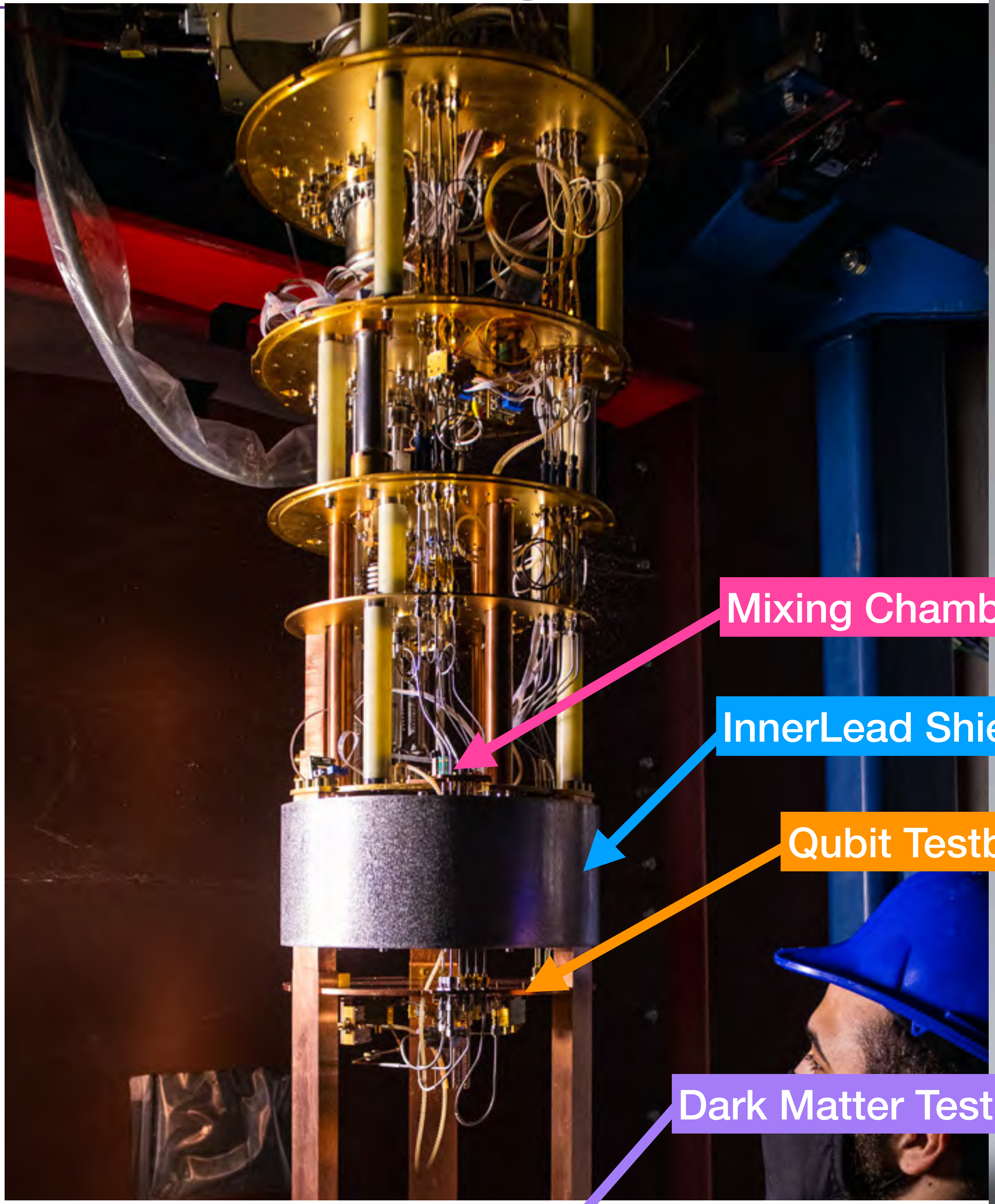
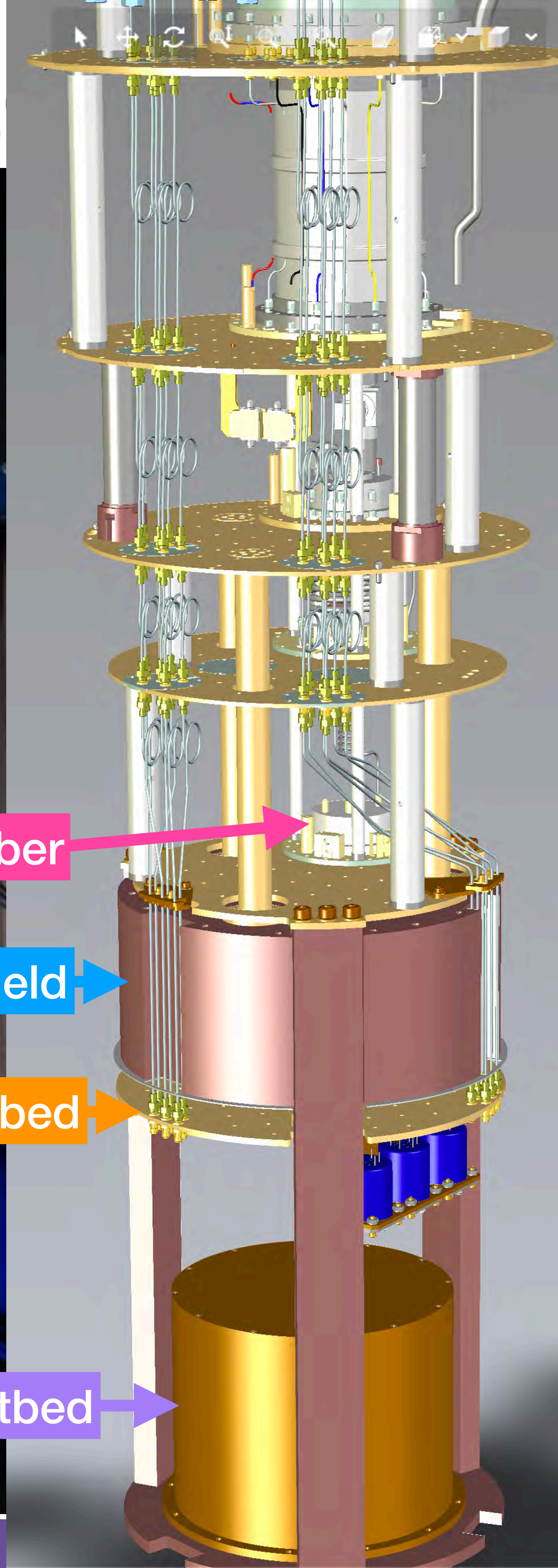


Northwestern Experimental Underground Site @ Fermilab



NEXUS is a multi-user underground fa

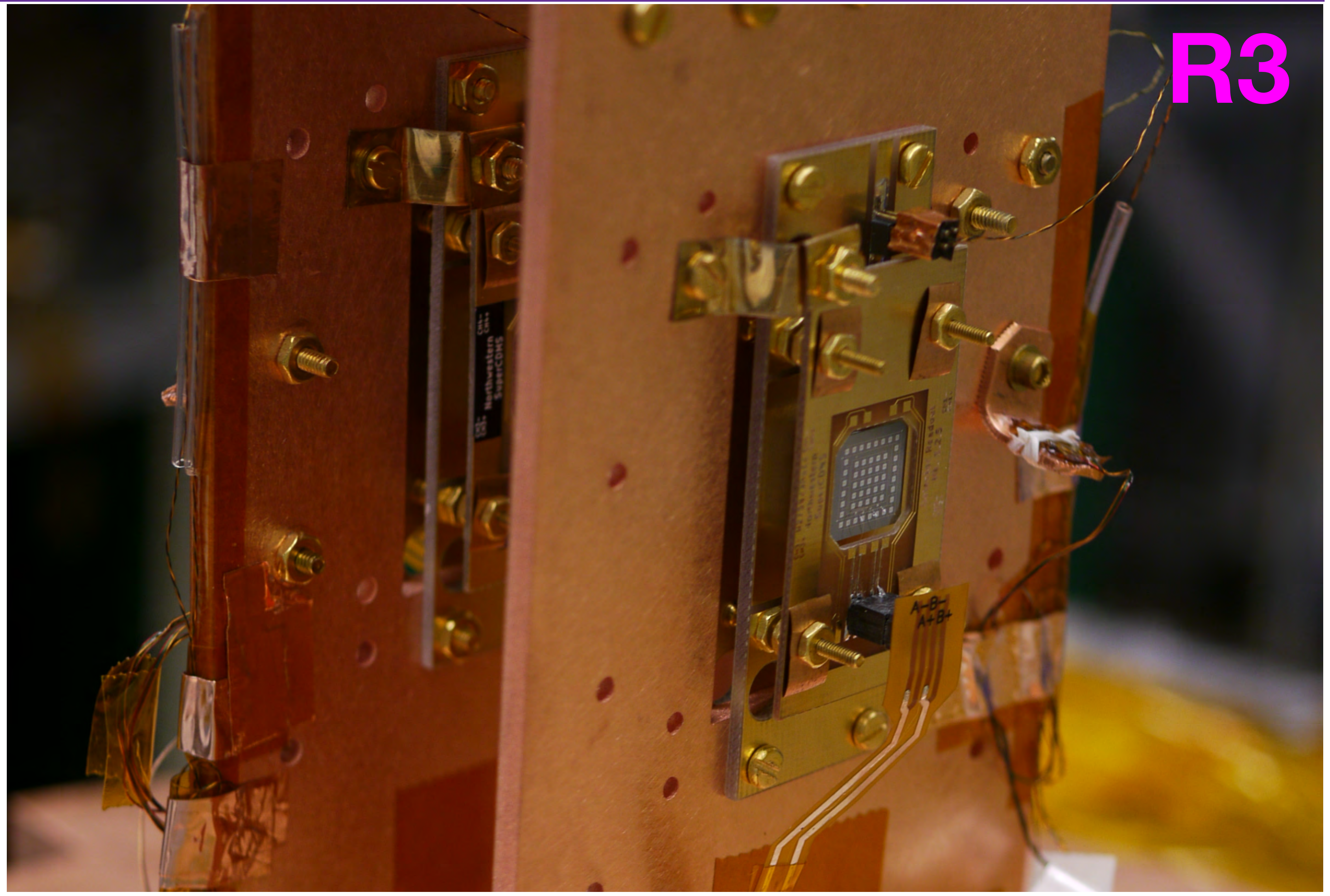
- 100 m of rock (300 meter water-equivalent) lowers muon rates to 7 evt/cm^2/day and hadronic showers to negligible levels.
- Lead inner and outer shields give a low gamma background environment of 100 evts/kg/day at 100 keV.
- 10 RF lines currently used for qubit and kinetic inductance detector work
- 8 DC SQUID channels used for neutrino and dark matter detector experiments.

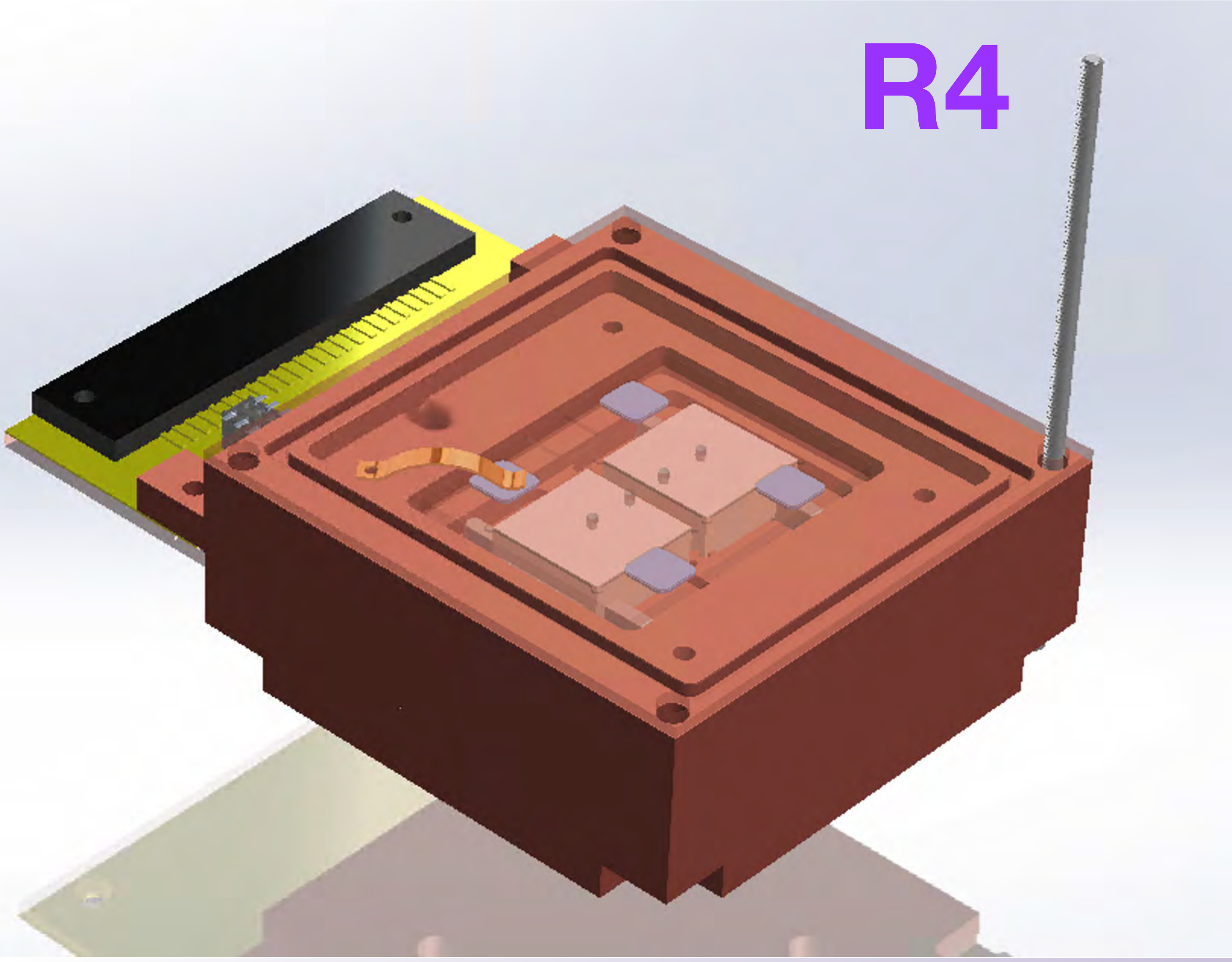



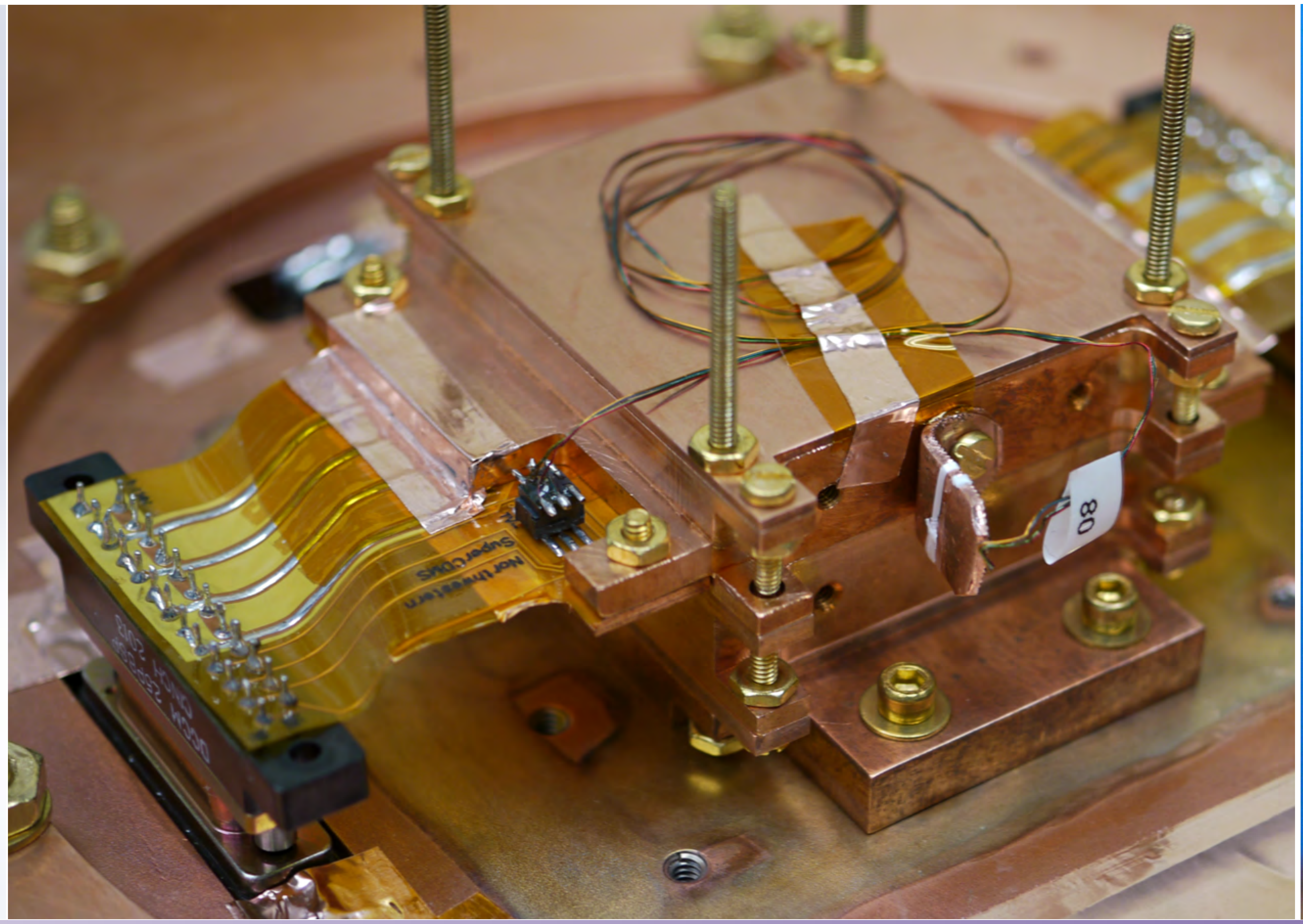
HVeV runs (R3 and R4) at NEXUS

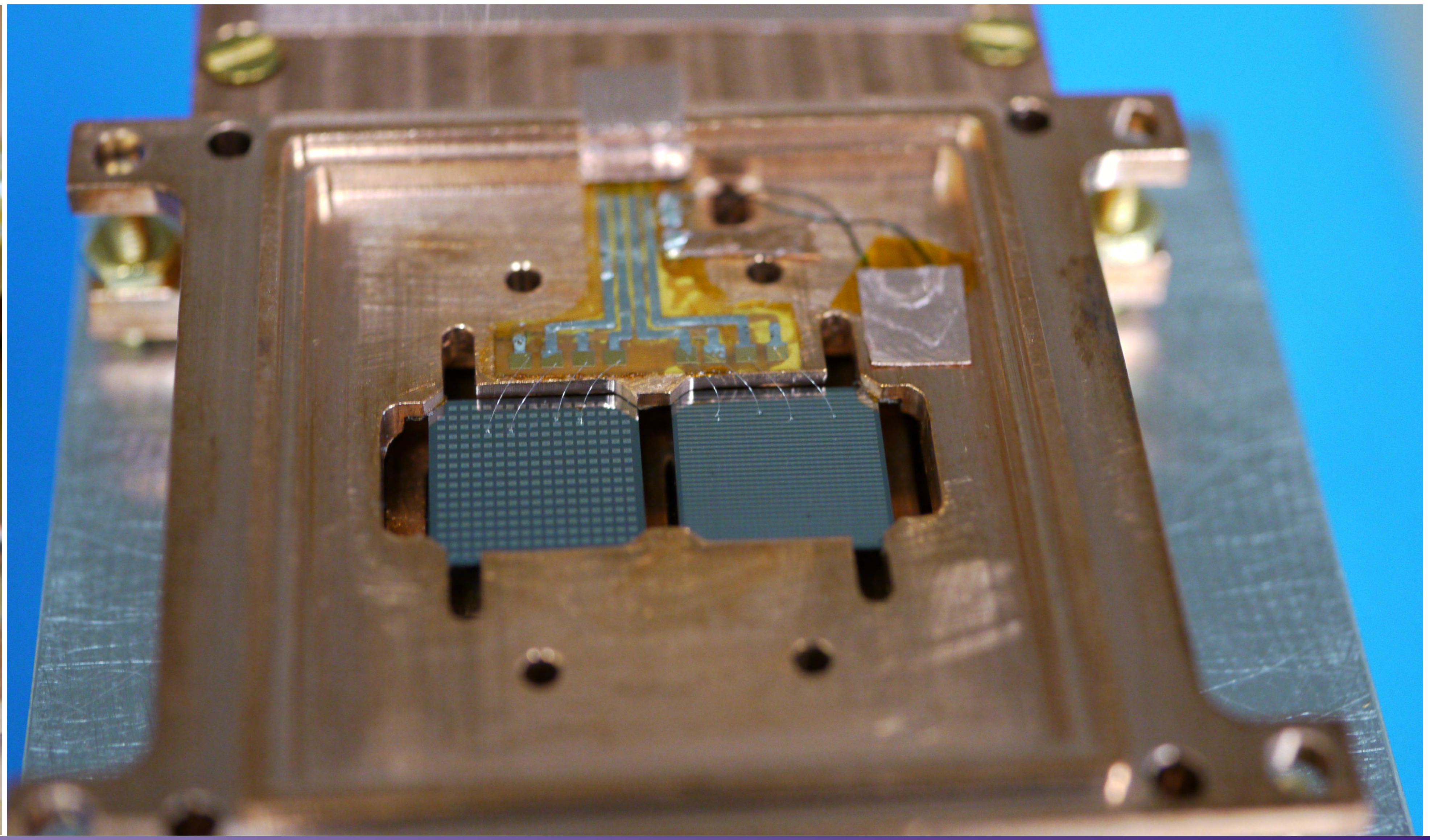
- HVeV Run 3 at NEXUS (2020): 4 detectors back-to-back for coincident measurement to test and reject FR-4 luminescence

- HVeV Run 4 at NEXUS (2022): Month-long data set with four detectors in new copper housing with no FR4, minimizing amount of insulator material, and improved IR shielding

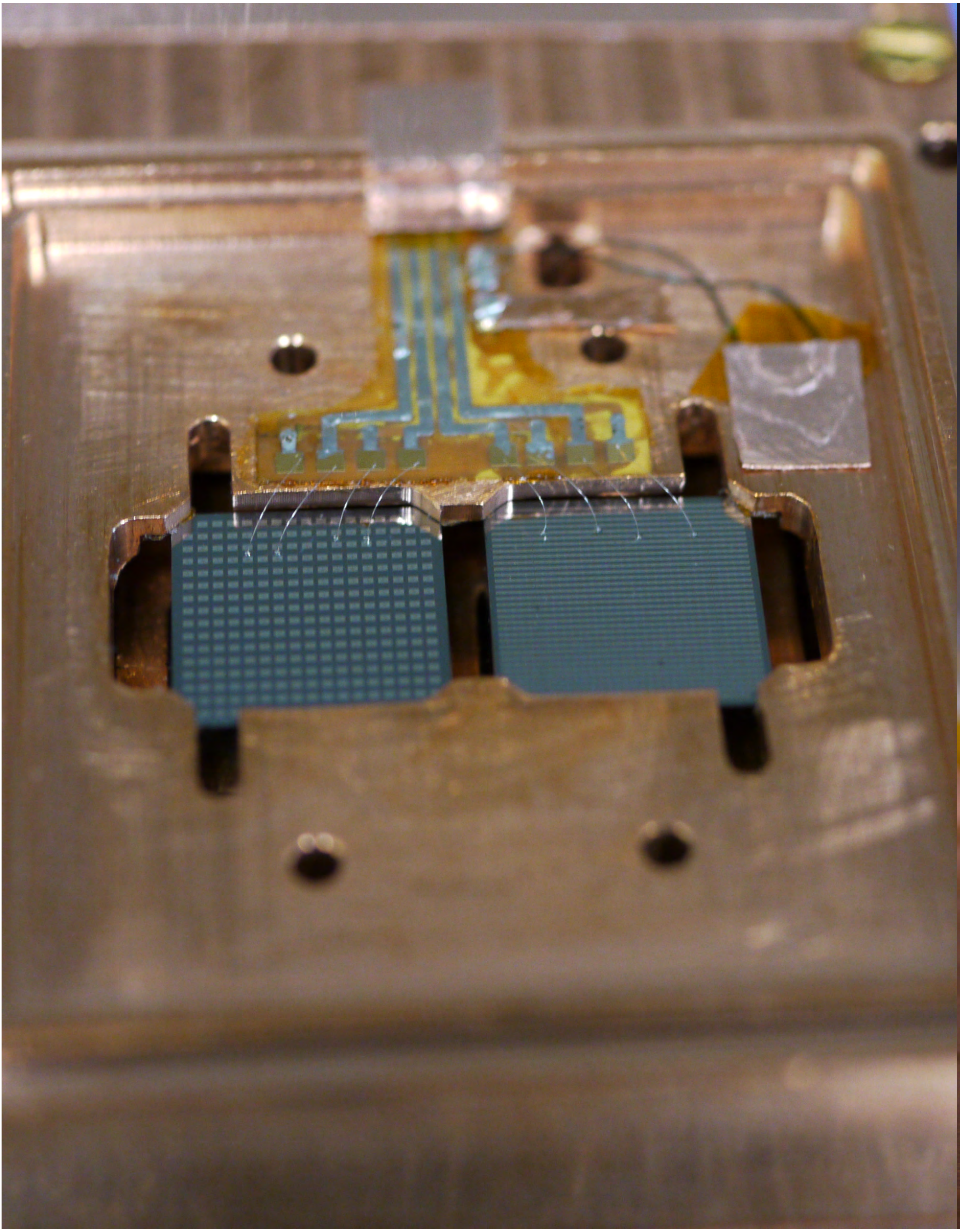


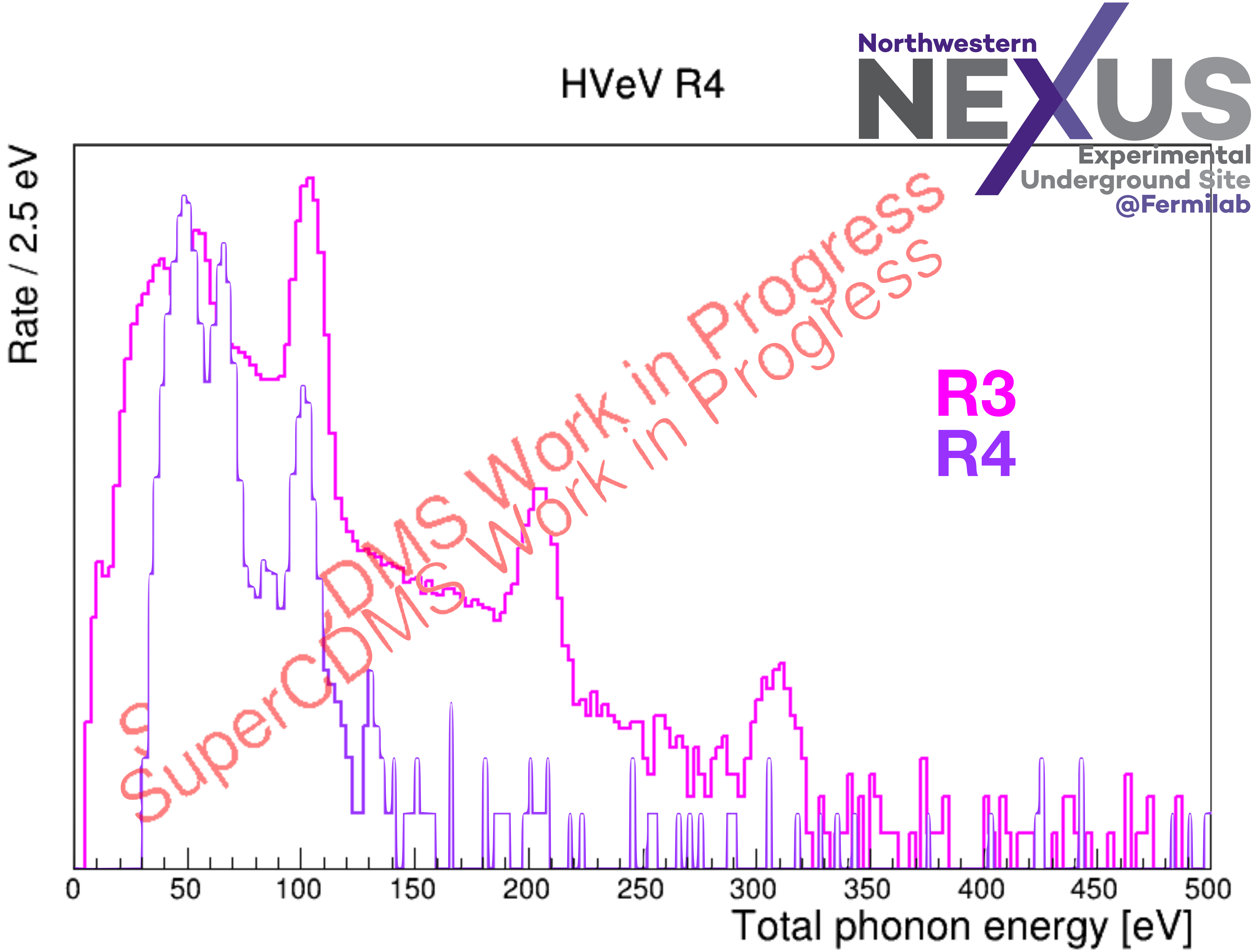






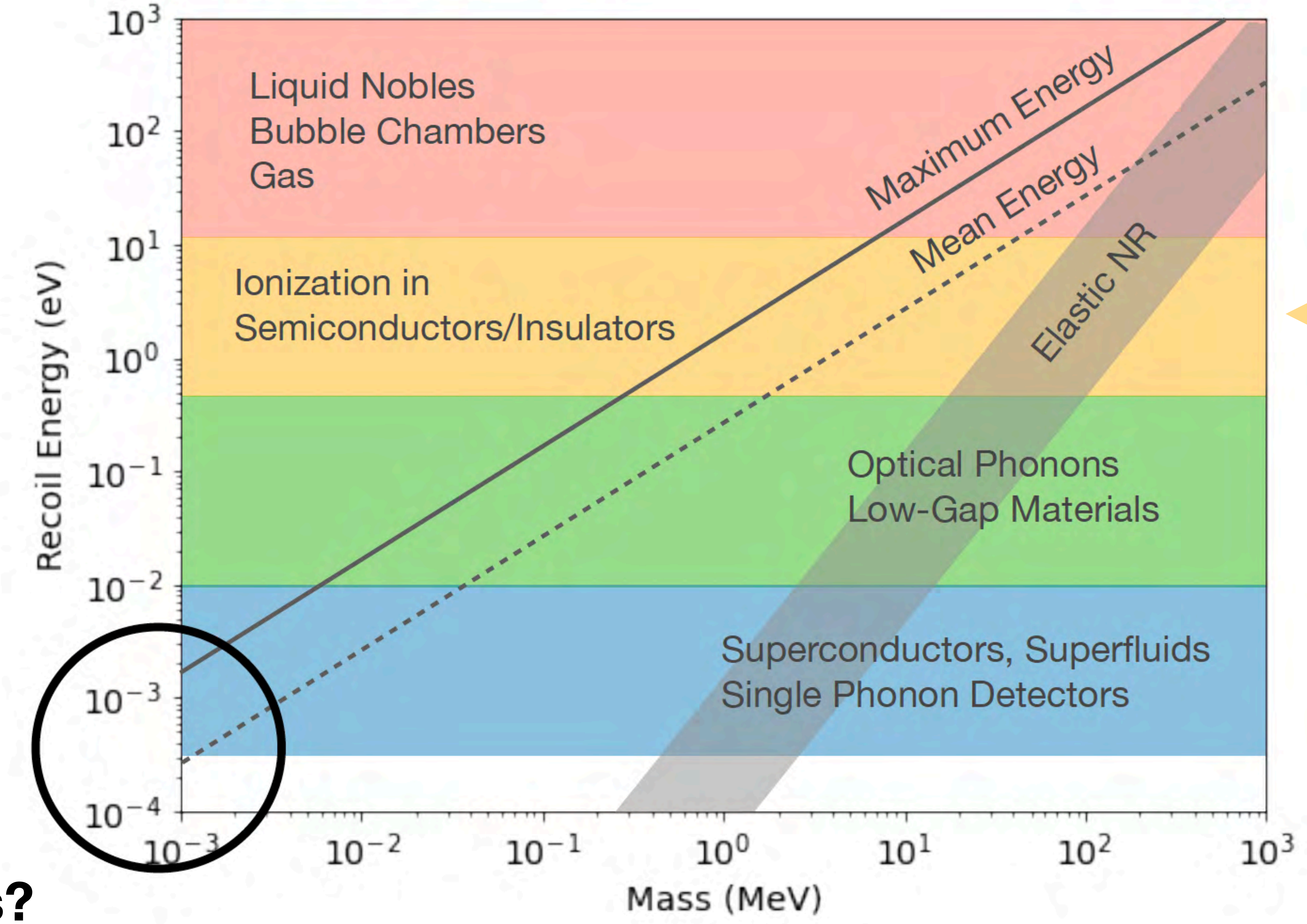
World-leading sensitivity to dark matter!





But we want to go to lower thresholds!

Fig. adapted from 2203.08297



SuperCDMS HVeV

$\Delta E \sim 1$ meV

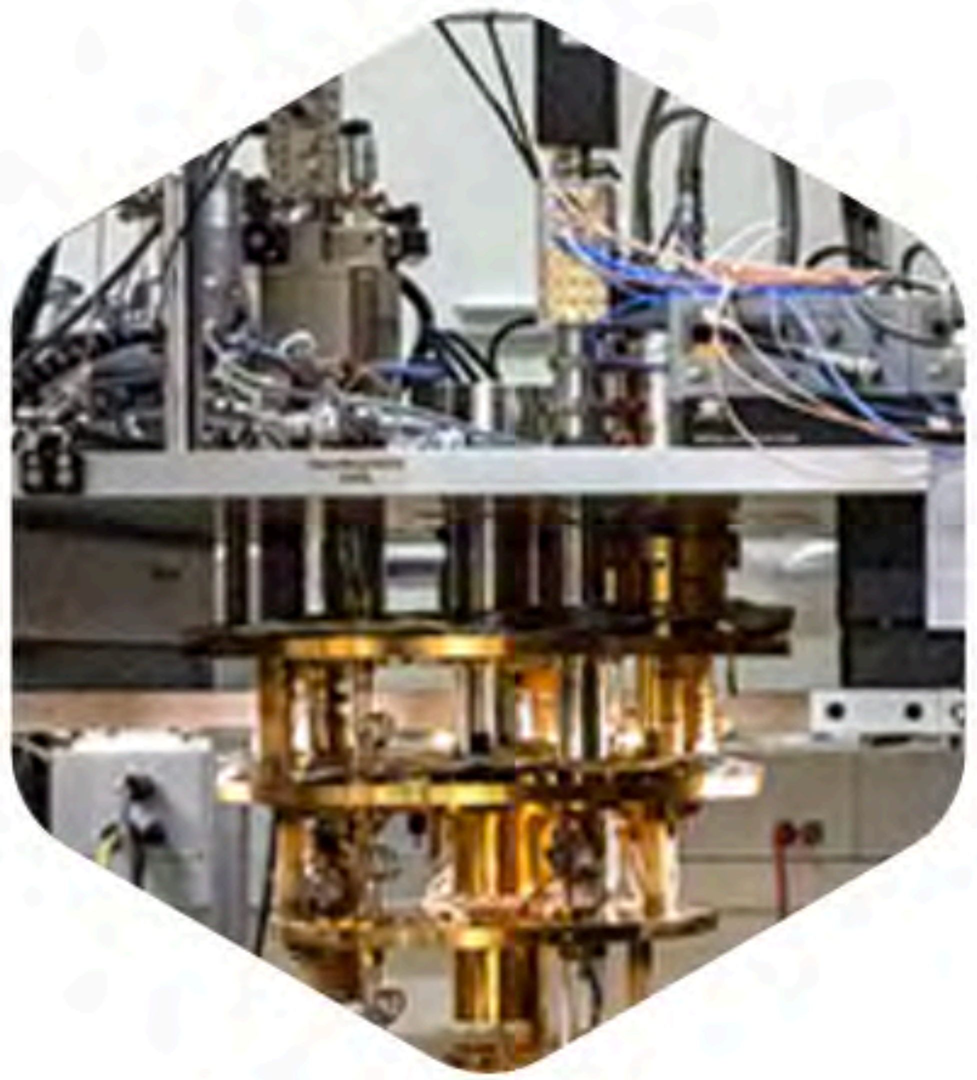
TES?
Qubits?

ultimate reach: keV masses w/ single phonon excitations
or electron recoils from low-gap materials

Quantum Science Center

- US Department of Energy funded five National Quantum Information (NQI) Science Research Centers to advance QIS technologies in the US

- ORNL hosts the **Quantum Science Center** (QSC) which includes as one of its three thrusts the goal of ensuring some of this investment goes back into discovery science (led by FNAL)



Thrust 3: Quantum Devices and Sensors for Discovery Science

Thrust 3 develops an understanding of fundamental sensing mechanisms in high-performance quantum devices and sensors. This understanding allows QSC researchers, working across the Center, to co-design new quantum devices and sensors with improved energy resolution, lower energy detection thresholds, better spatial and temporal resolution, lower noise, and lower error rates. Going beyond proof-of-principle demonstrations, the focus is on implementation of this hardware in specific, real-world applications.

Led by Fermilab's Aaron Chou

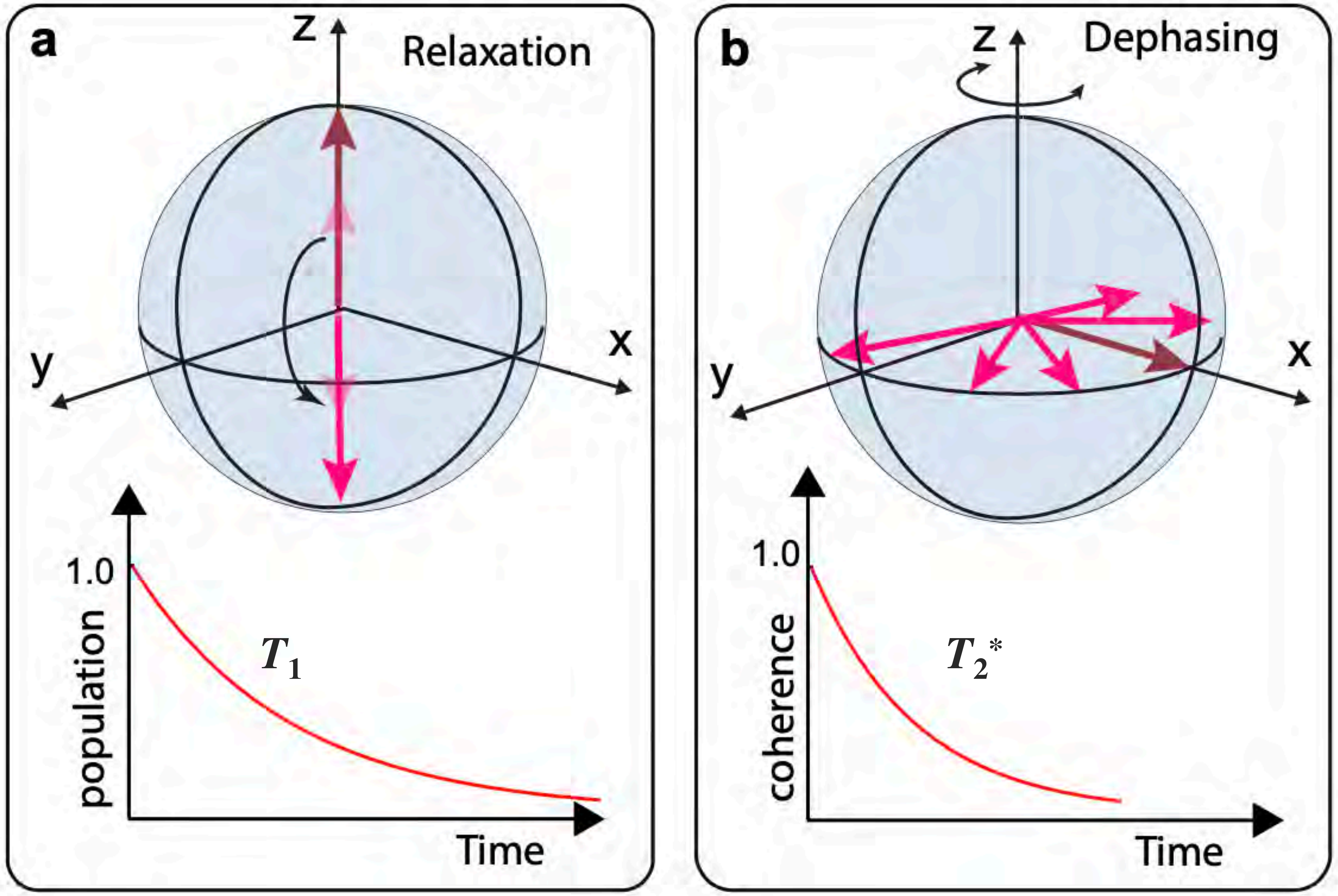
Superconducting Qubits

Could they be useful for particle dark matter detection?

- Decoherence – loss of the qubit state due to relaxation or dephasing
  - Bad for QIS
  - Good for DM detection?

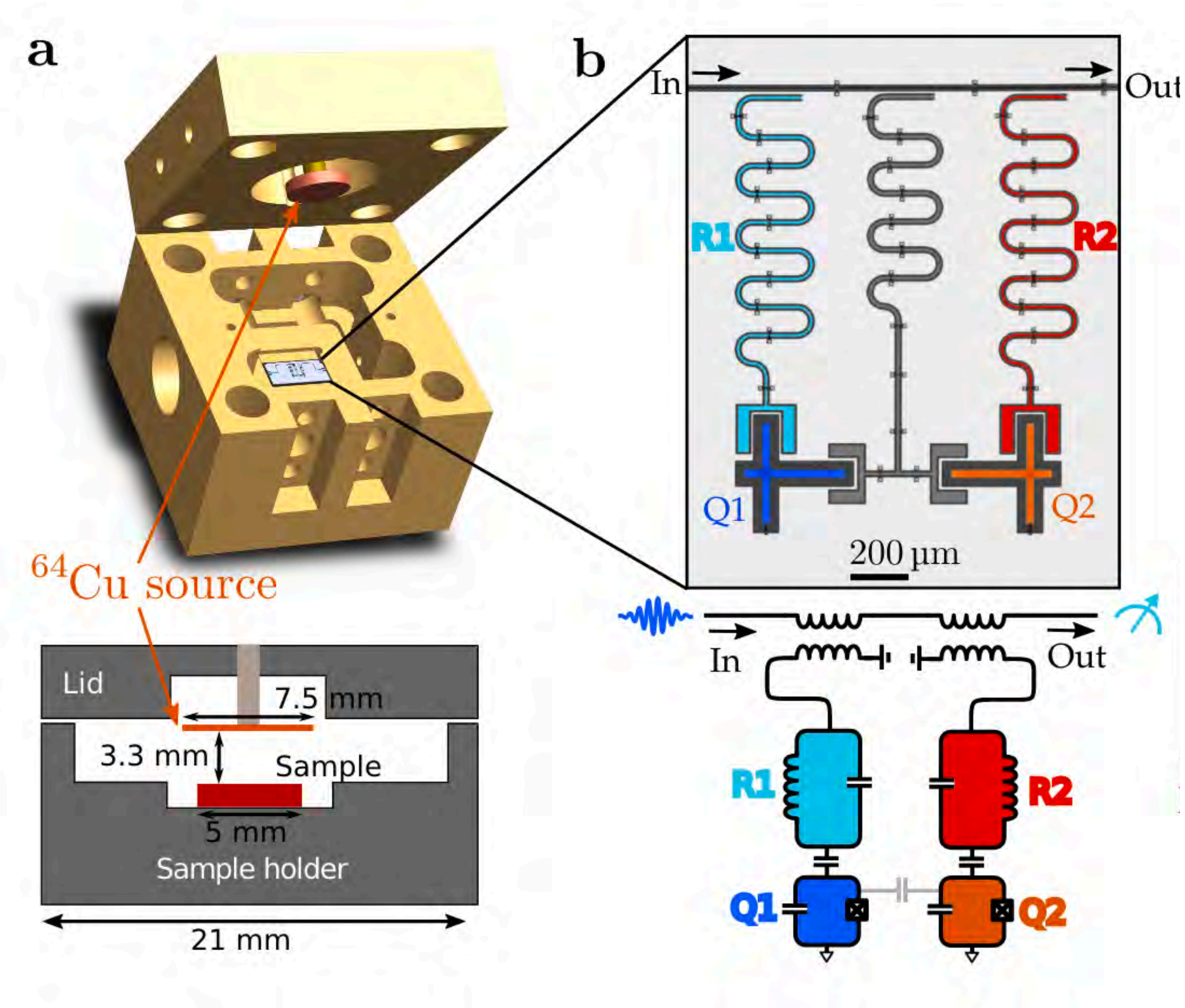
- T_1 = Relaxation Time – timescale for loss of the energy of the qubit state (ie, 1 → 0)

- T_2^* = Dephasing Time – timescale for loss of the coherence of the qubit state



Mahdi Naghiloo, (2019) [arXiv:1904.09291]

Background Radiation on Superconducting Qubits



- Measurements of decoherence relaxation rates ($1/T_1$) in the presence of a ^{64}Cu source
- Clear correlation between T_1 and decay of ^{64}Cu source in two separate qubit sensors!
- Strong evidence that quasiparticle poisoning due to radiation breaking Cooper pairs can be a limiting factor in superconducting qubits for QIS

Vepsäläinen et al, Nature 584, 551 (2020) [arXiv:2001.09190]

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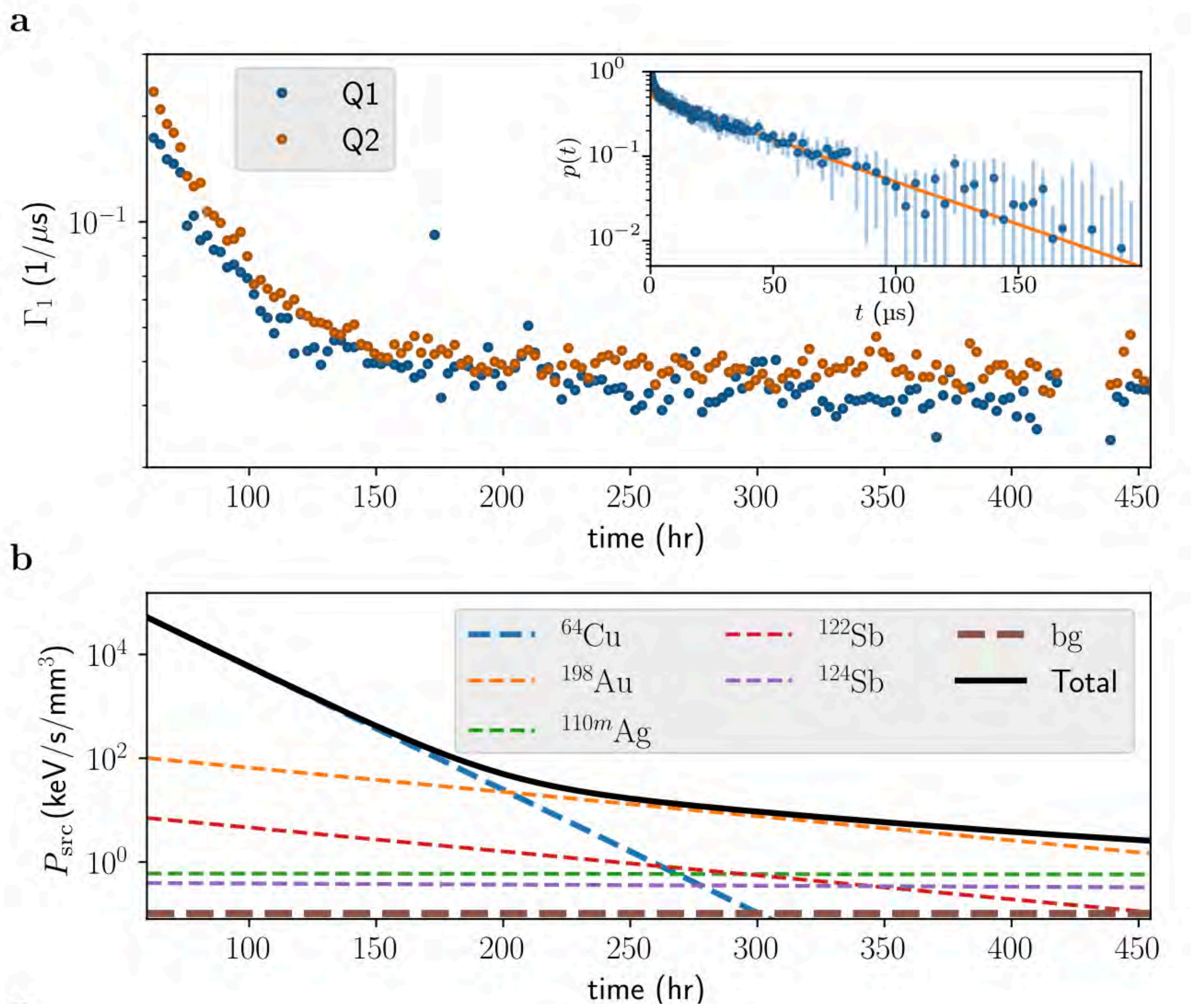

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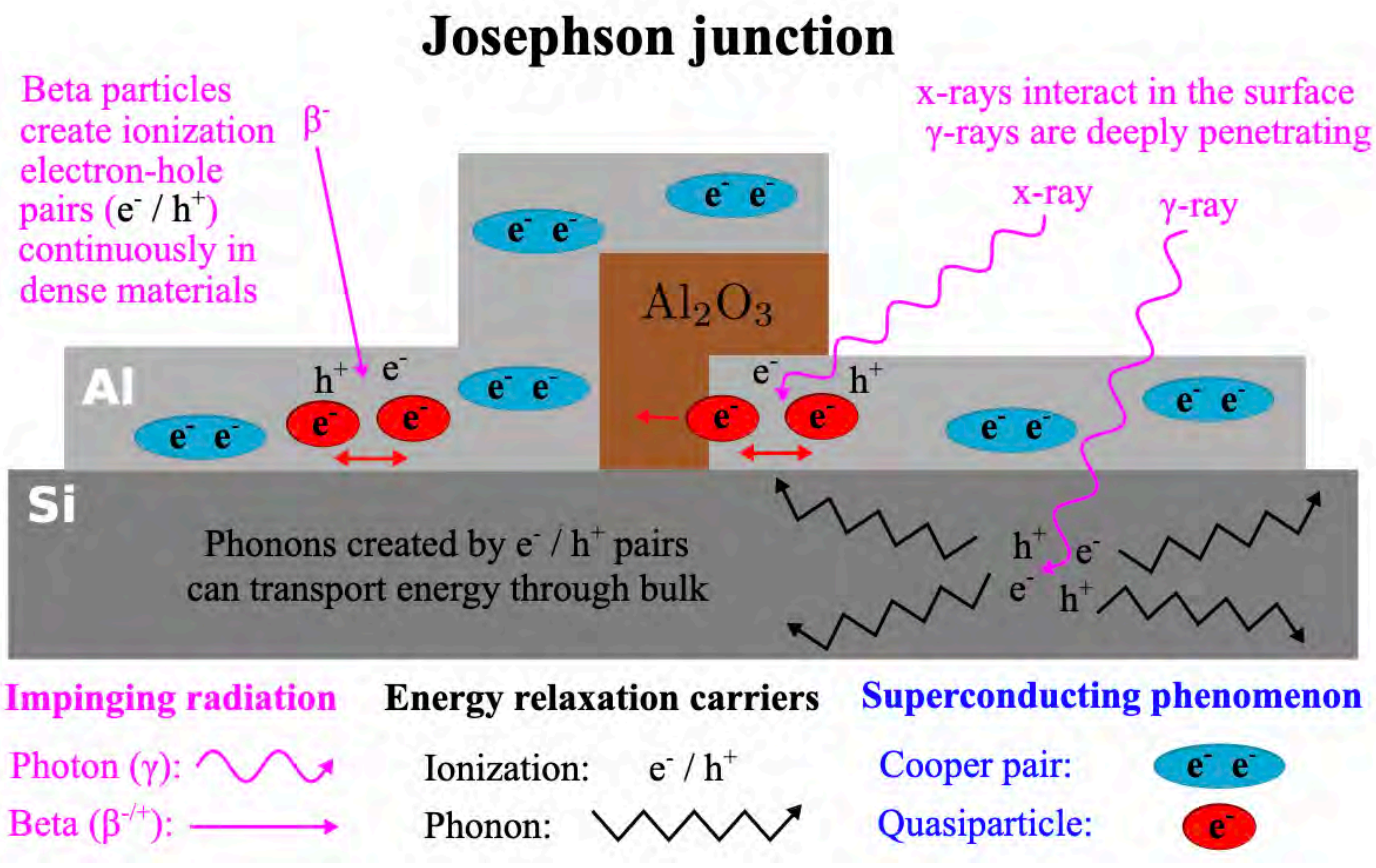

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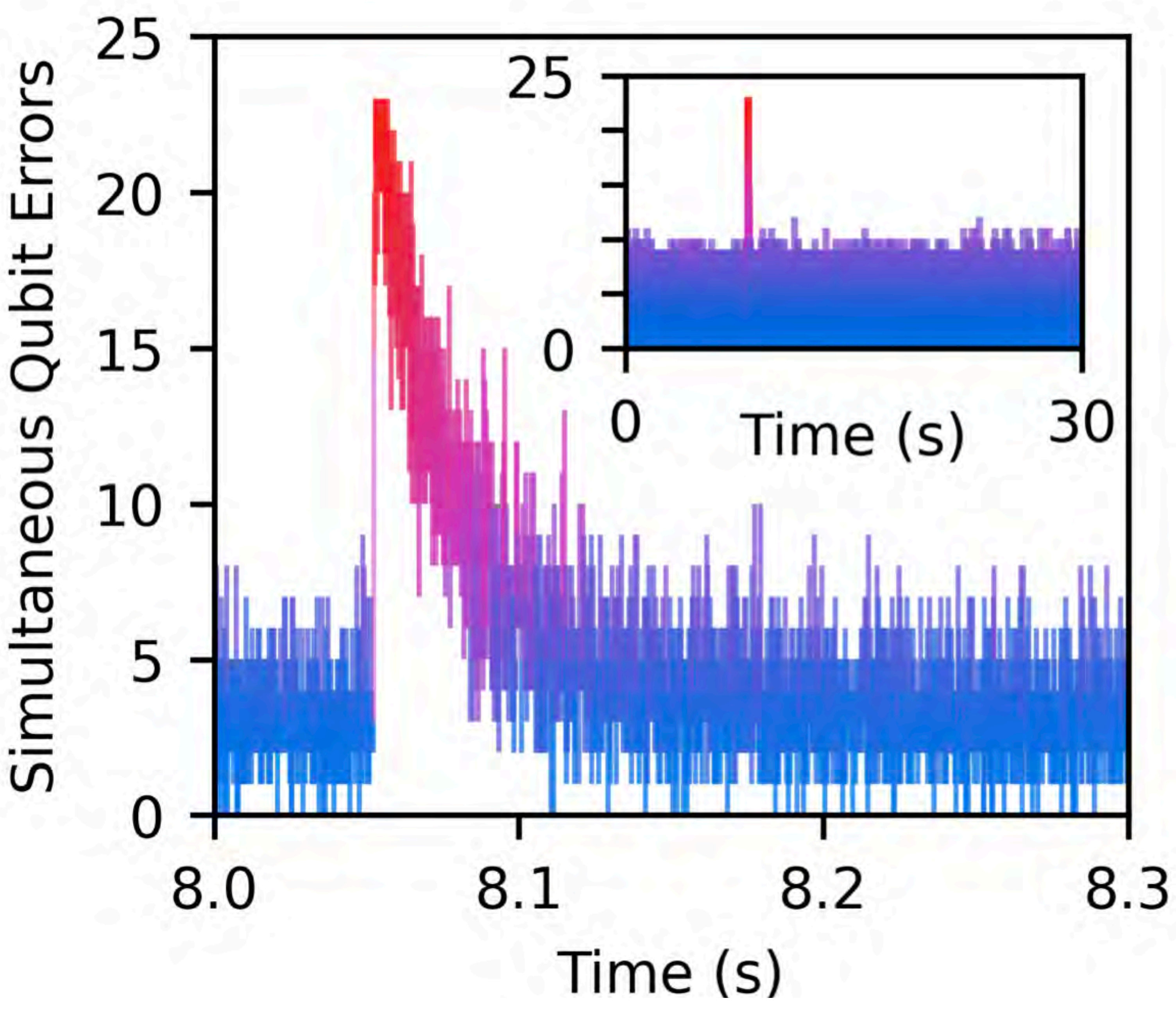
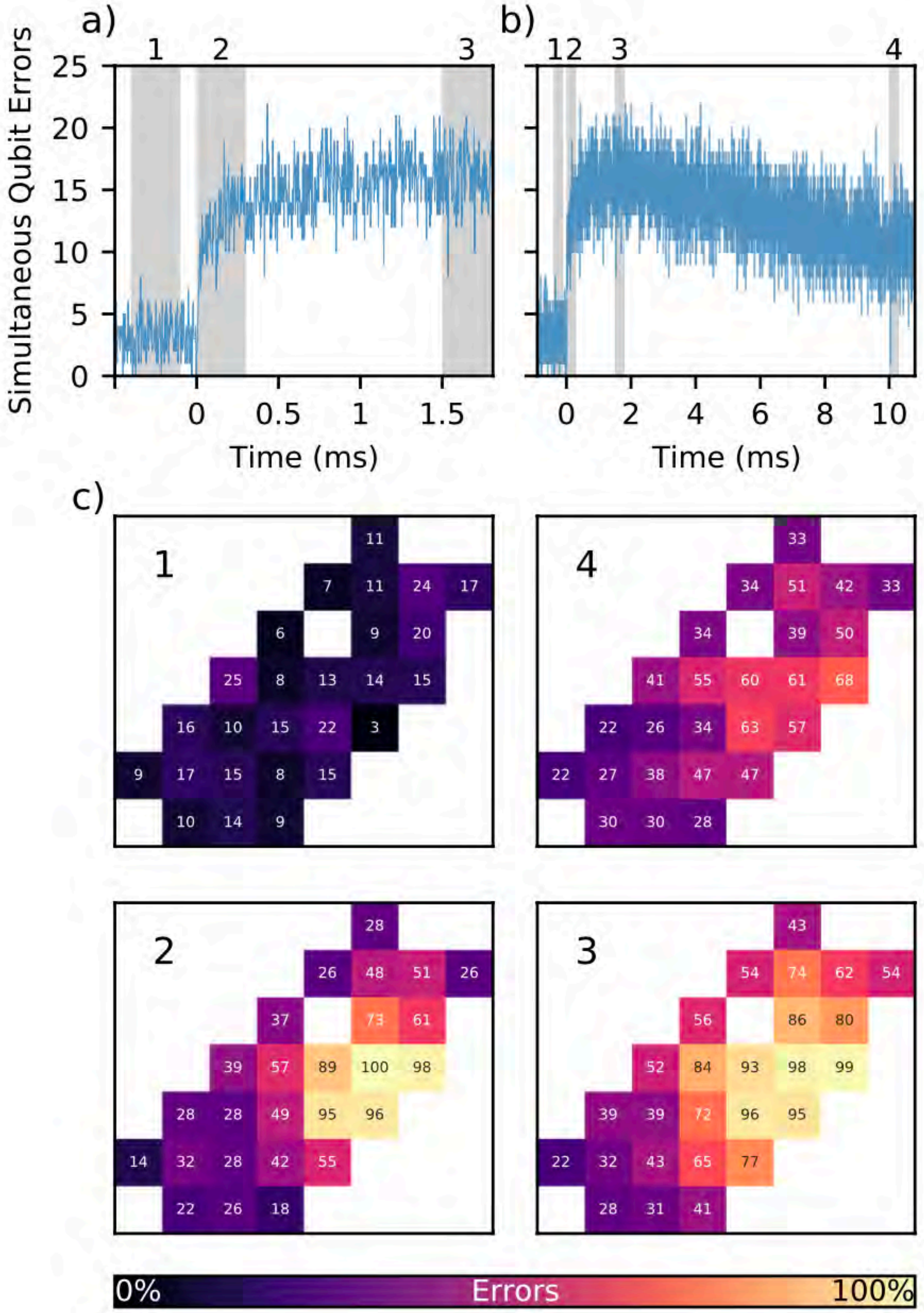
Catastrophic Error Bursts from Cosmic Rays

- This study found correlated errors in qubits across the device due to energy depositions in common substrate (information destroyed every 10s!)
- This alone isn't enough to say that qubits can be useful as meV-scale detectors, since we aren't only interested in minimum ionizing events (which have keV-MeV energy depositions)

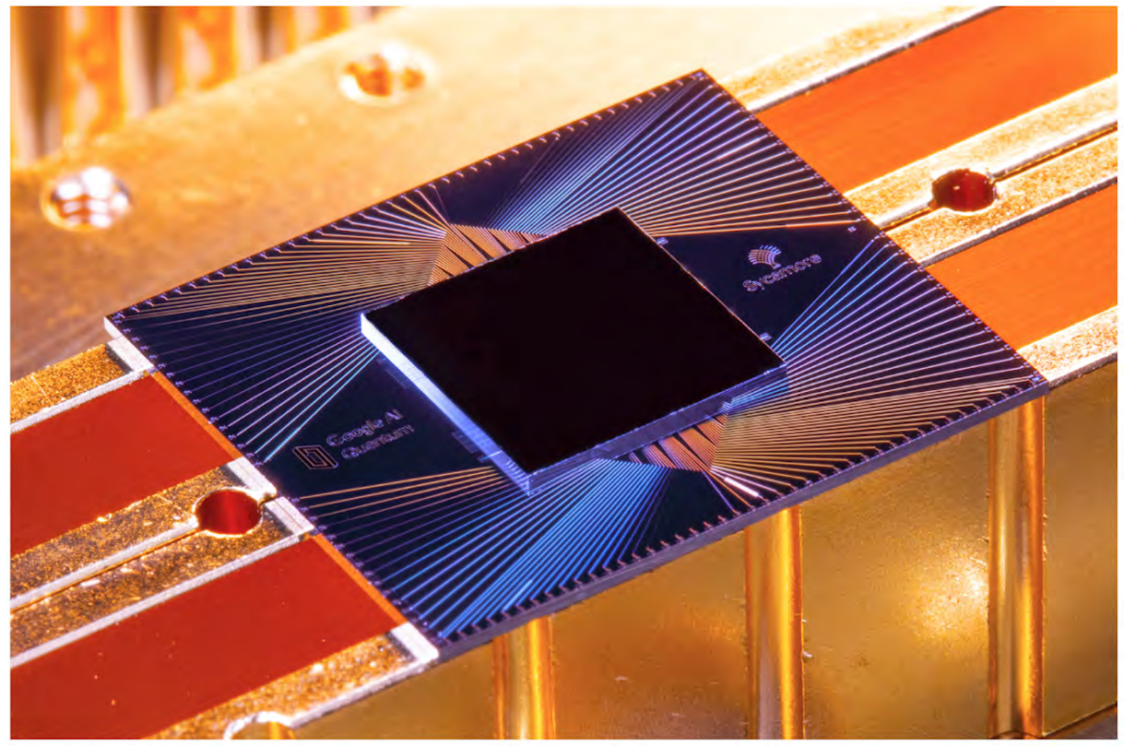


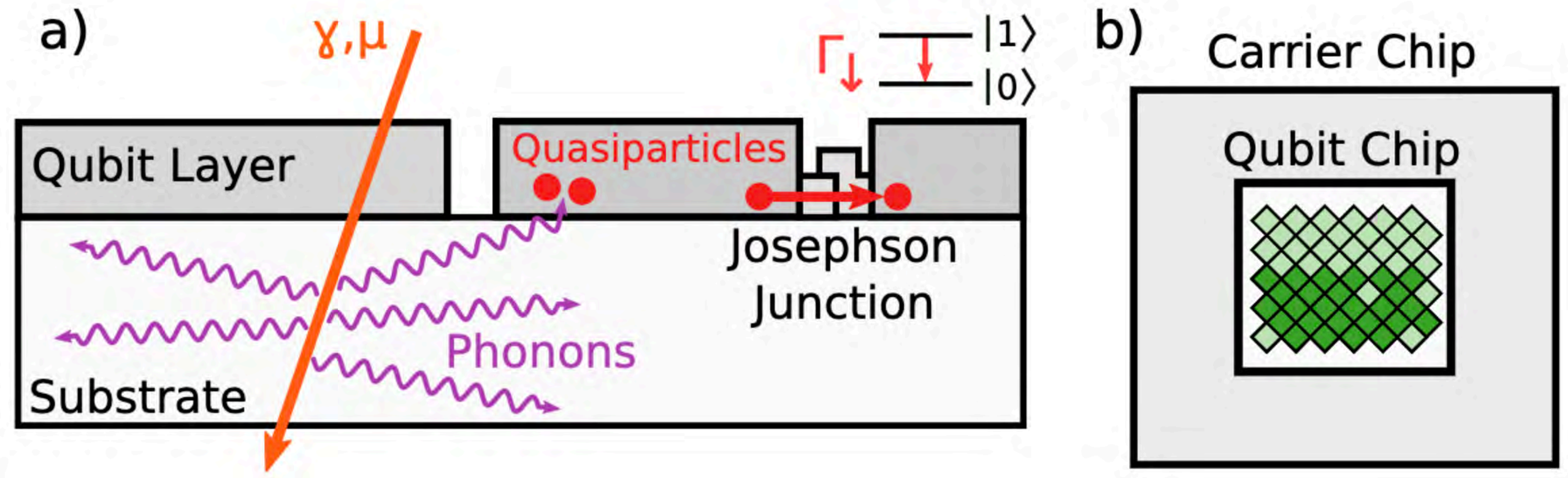


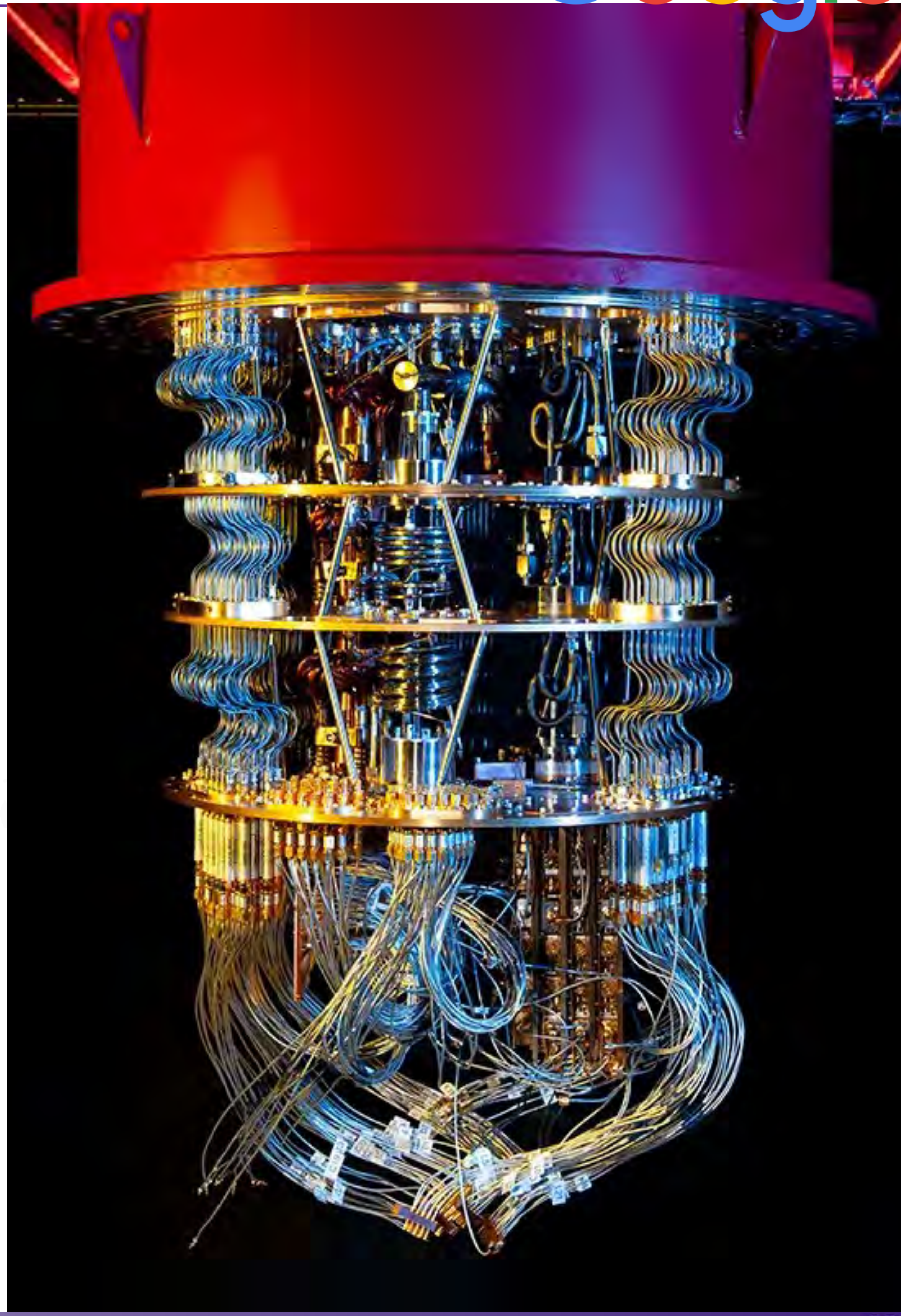
McEwen et al, Nature 18, 107 (2022) [arXiv:2104.05219]

Catastrophic Error Bursts from Cosmic Rays

- <u>Hypothesis</u>: energy depositions in a substrate cause *correlated* decoherence across qubits due to quasiparticle poisoning that can be exploited as a means of particle (and specifically dark matter) detection.

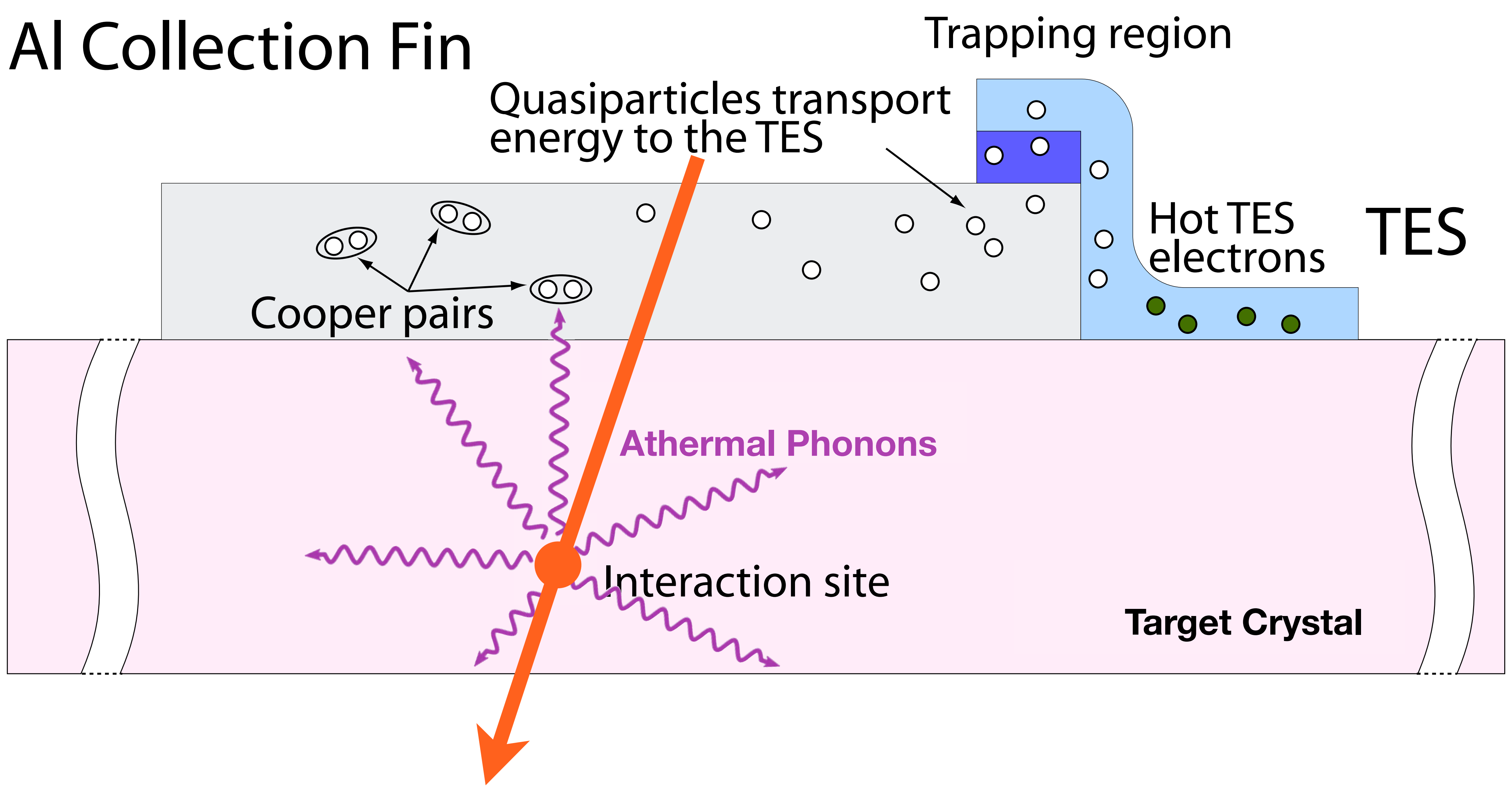




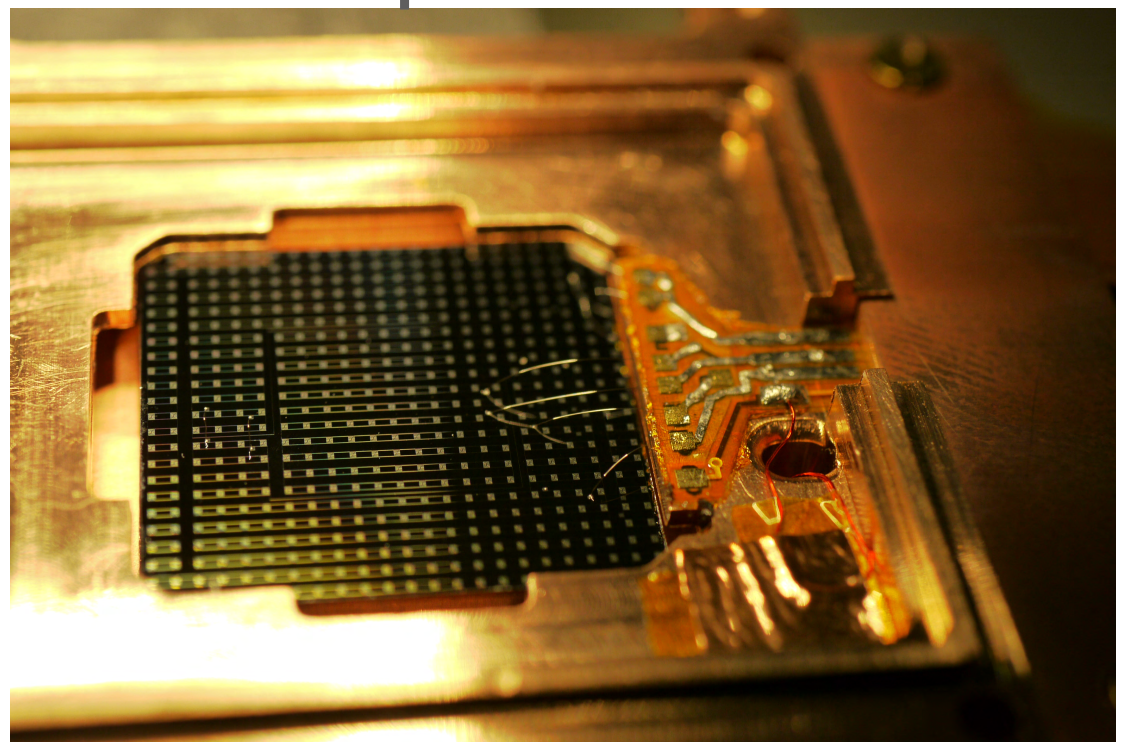


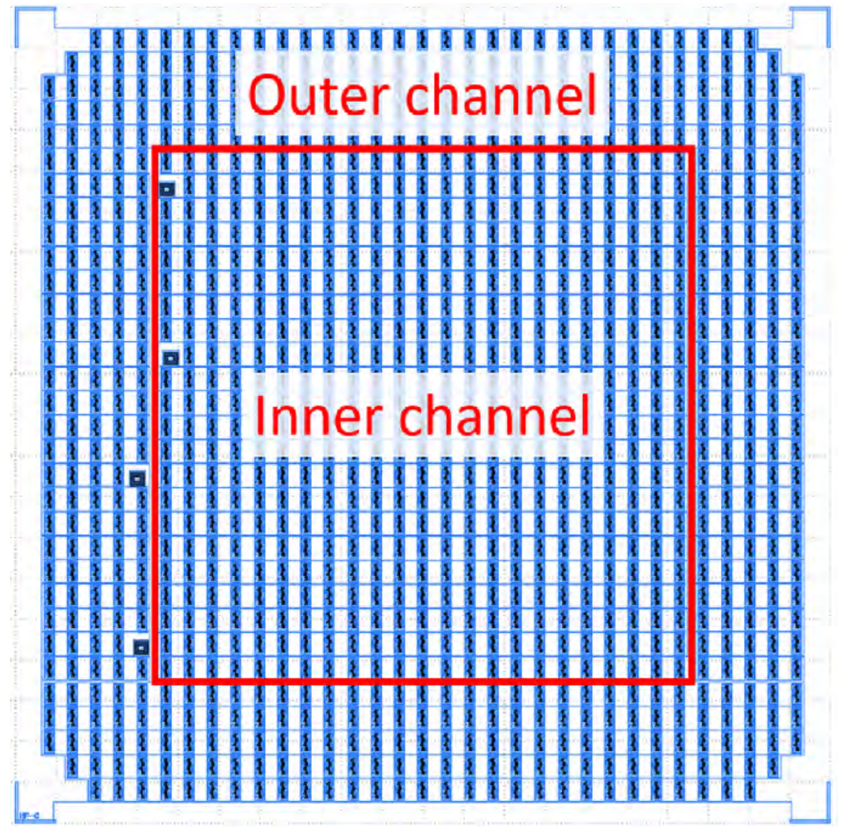
Catastrophic Error Bursts from Cosmic Rays

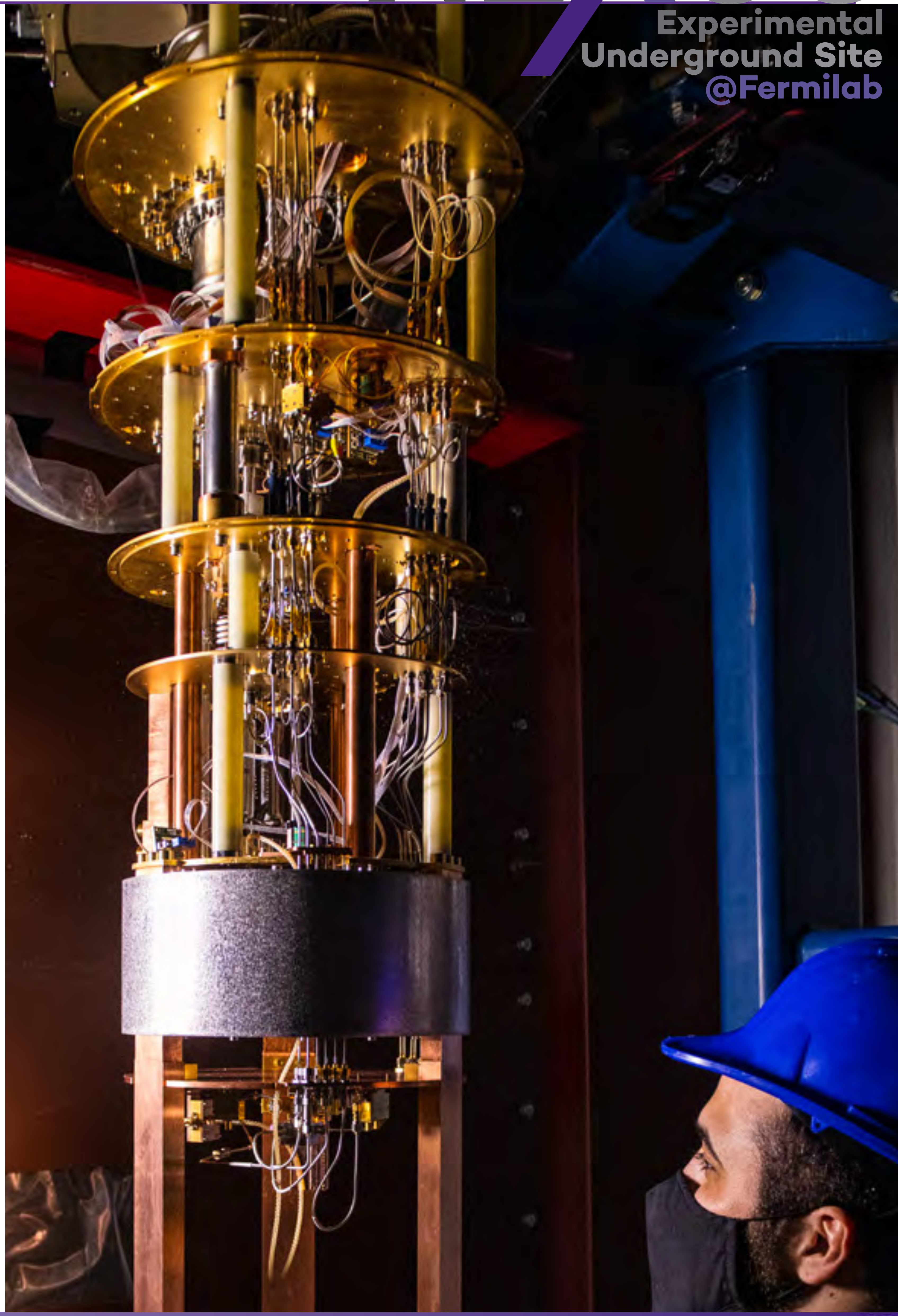
- We have all the tools to work on this problem!
- Our dark matter detectors work by measuring phonons in silicon through TES detectors and Al superconducting collectors films
- We are bringing our knowledge of cryogenics, background reduction, particle detection, phonon and quasiparticle physics, and superconducting readout to Quantum Computing Problems



SuperCDMS Detector



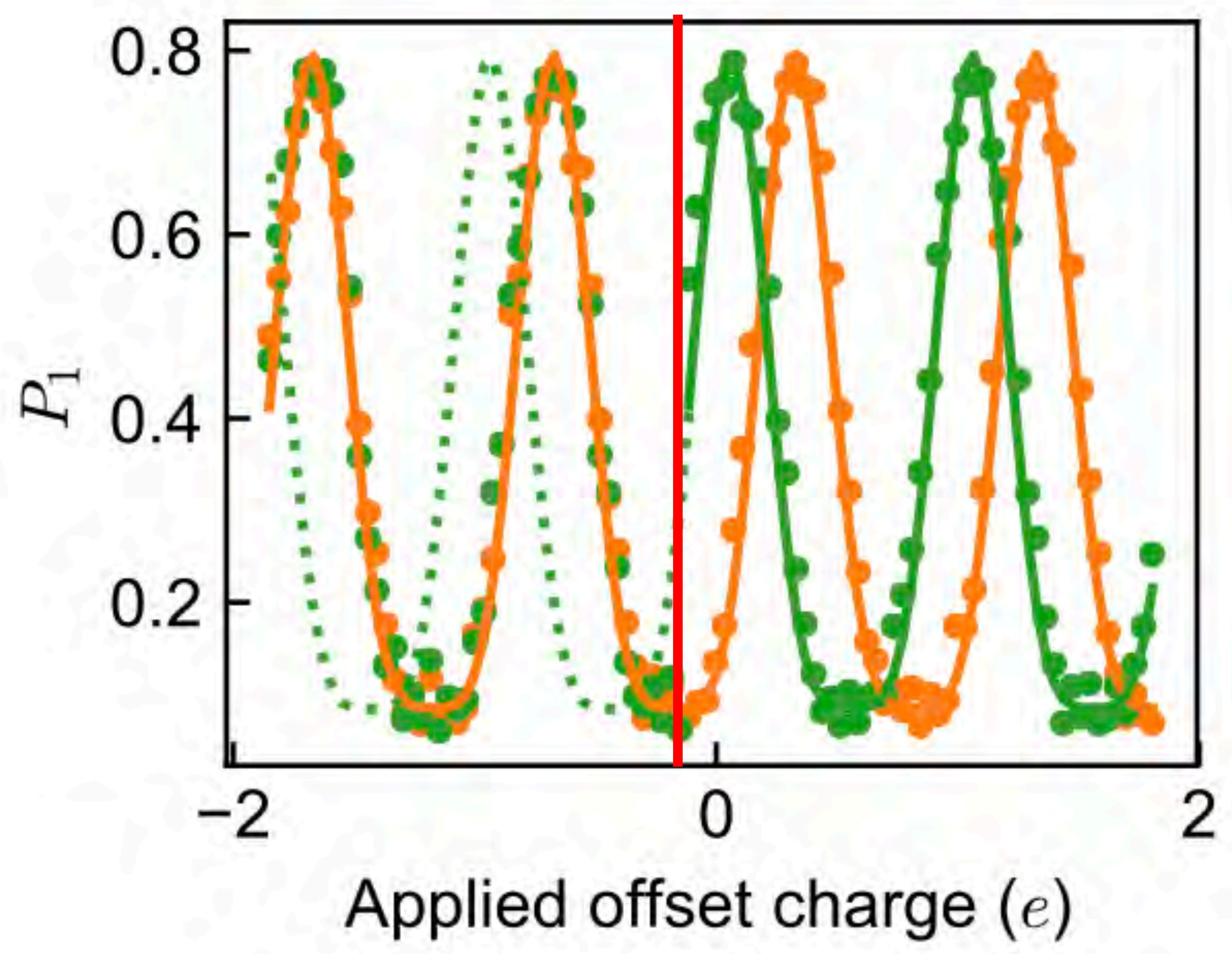


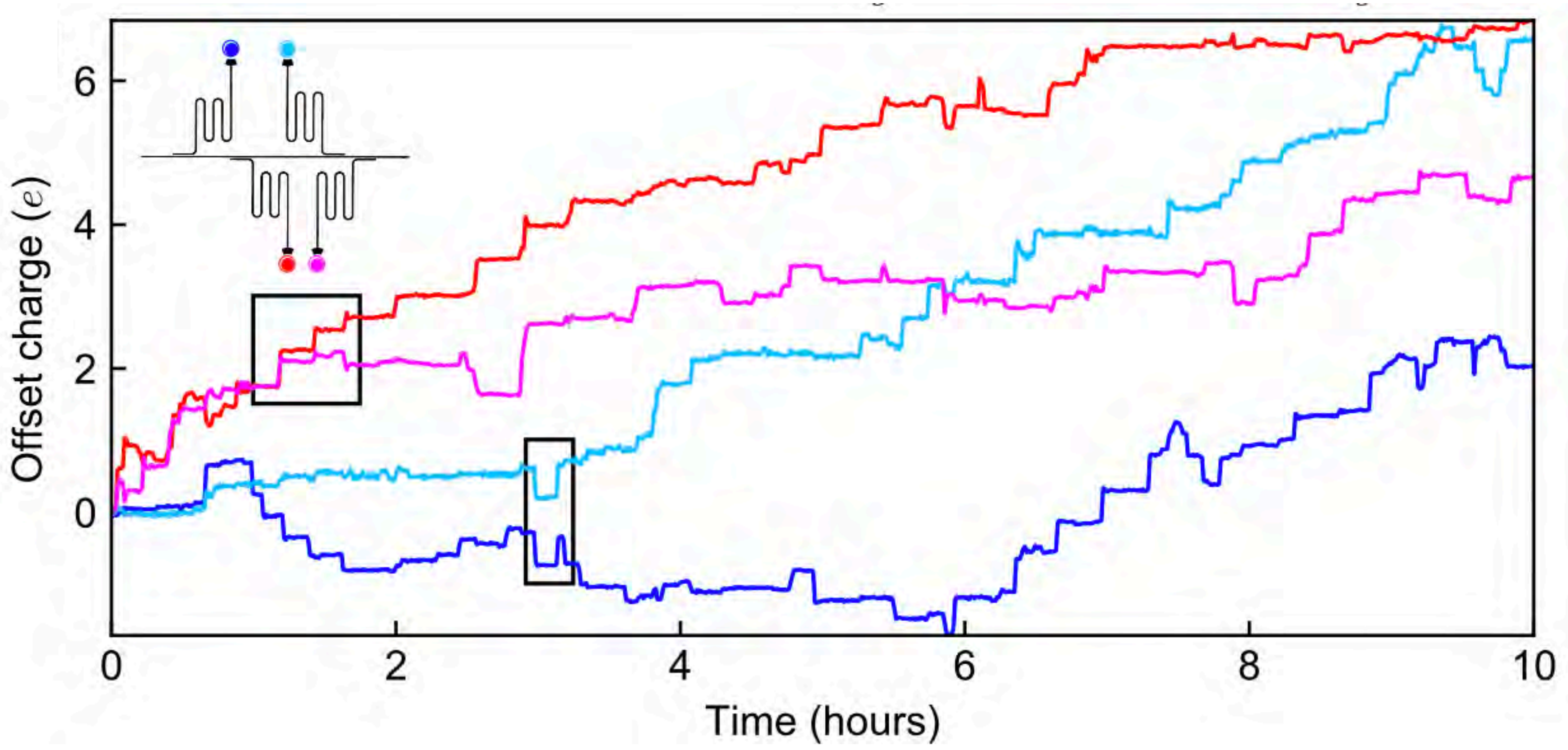


Correlated charge offset jumps

Wilen et al, Nature 594, 369 (2021) [arXiv:2012.06029]

Ramsay amplitude vs. offset charge

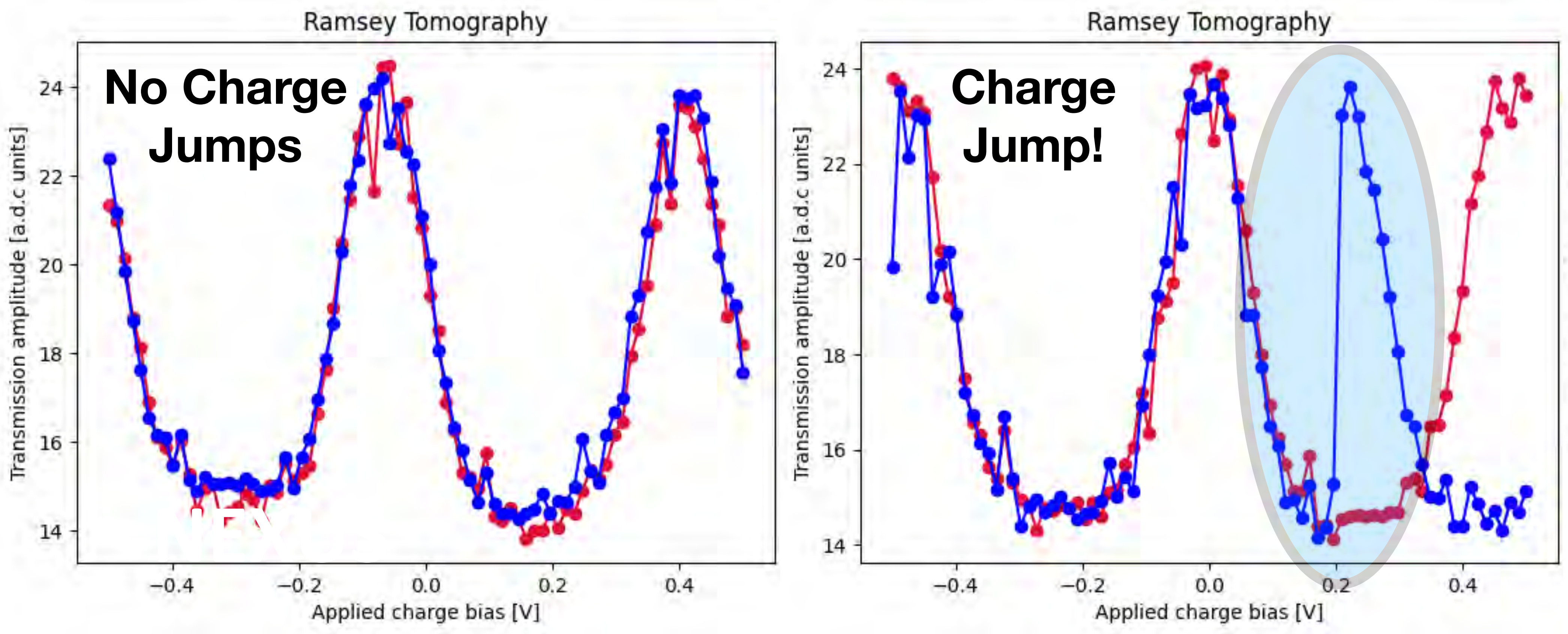


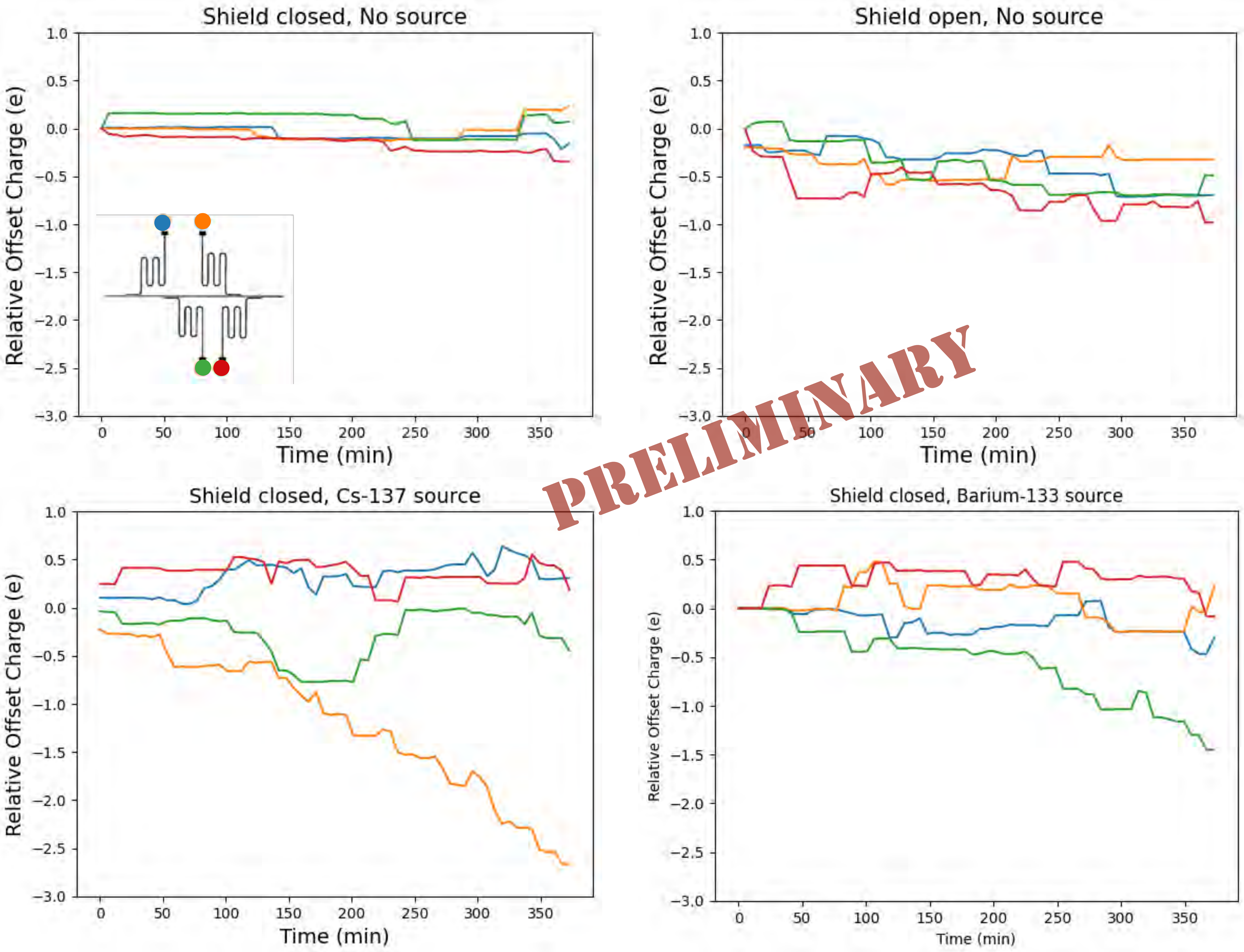


Chip w/ four weakly charge-sensitive transmon qubits demonstrates clear **<u>correlated</u>** offset charge jumps over long times

Correlated charge offset jumps @ NEXUS

- See a clear correlation in charge jump rate with radiation environment.
- Currently analyzing this data to quantify the effect of different types of radiation in the qubit chip.
- First results paper expected by the end of the year!





Work by Kester Anyang, Dan Baxter, Daniel Bowring, Grace Bratrud, EFF, Sami Lewis, Hannah Magoon, and Jialin Yu

Correlated charge offset jumps @ NEXUS

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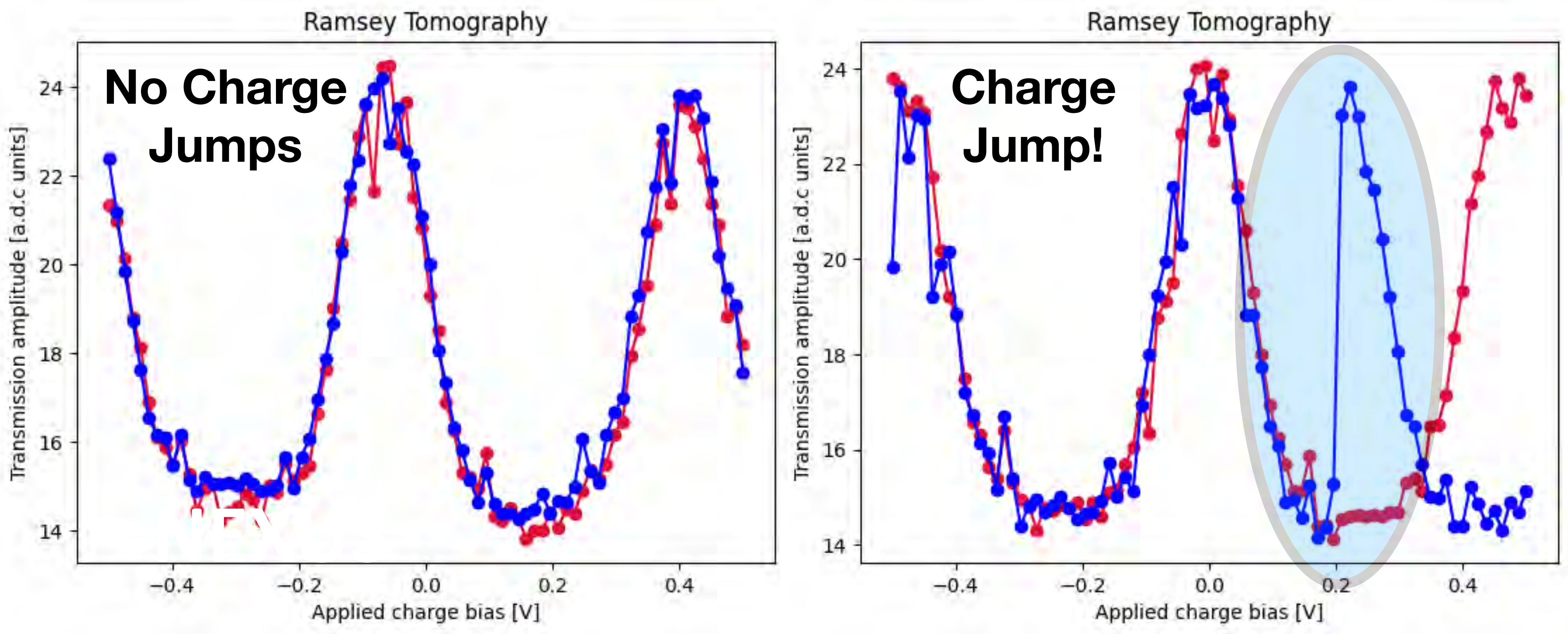
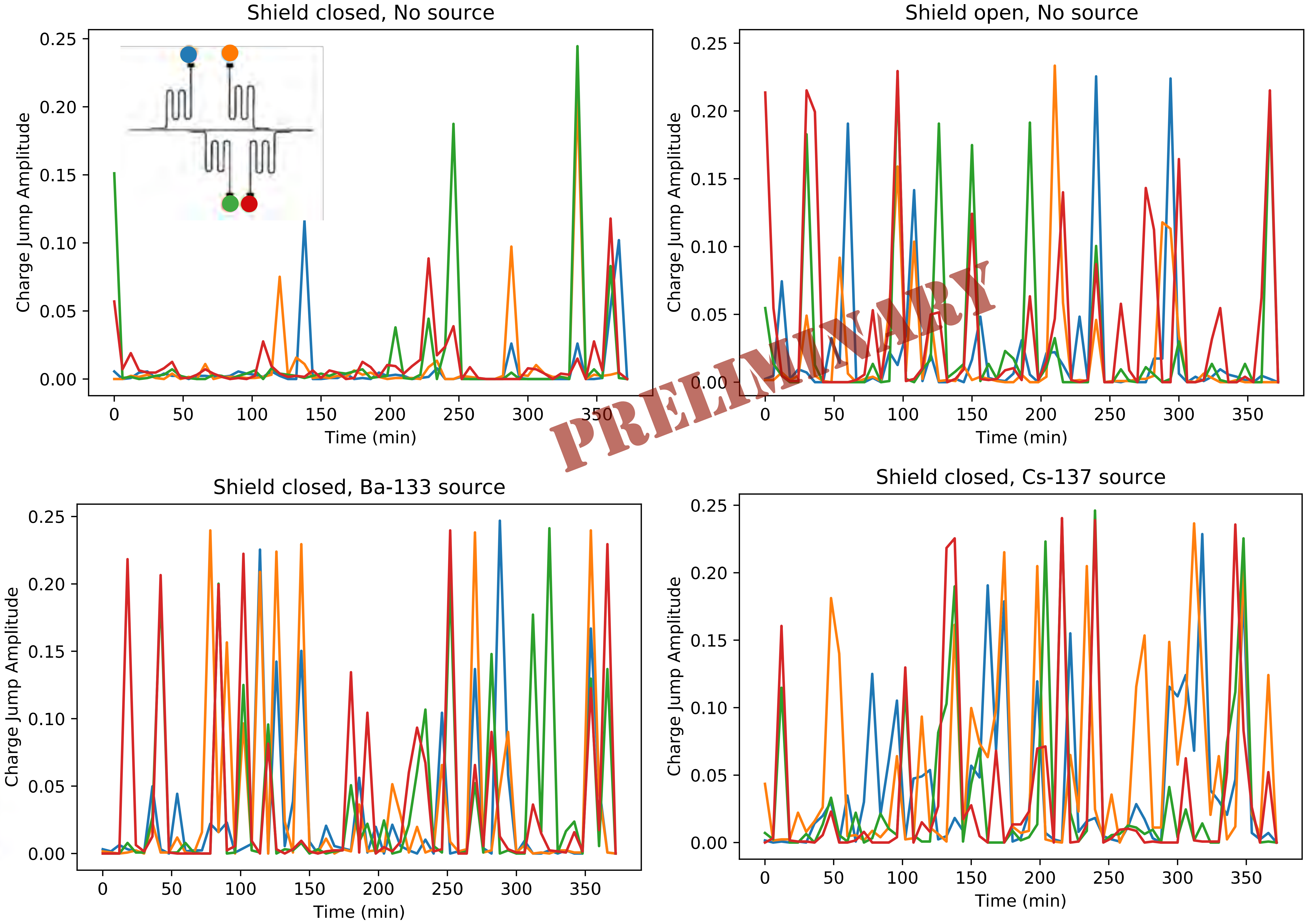




Work by Kester Anyang, Dan Baxter, Daniel Bowring, Grace Bratrud, EFF, Sami Lewis, Hannah Magoon, and Jialin Yu

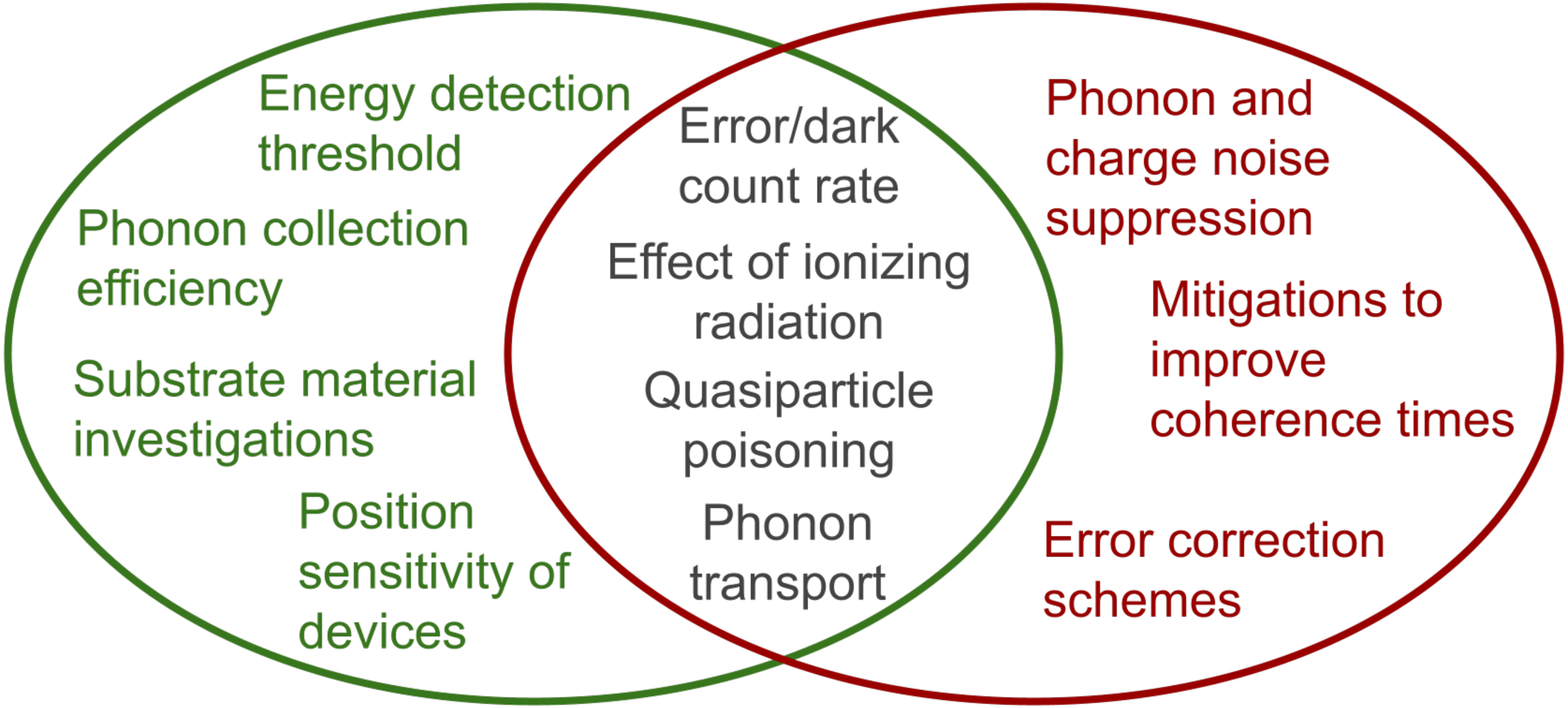
Study Comparison

	Year	# of Qubits	Shielding?	Source?	Result/Goal
P1, Vepsäläinen et al	2020	2	Above-ground, no rad shield [for shown results]	^{64}Cu	Radiation → More relaxation errors
P2, McEwen et al	2022	26	Above-ground, no rad shield	None	Radiation → Errors correlated in *space and time*
P3, Wilen et al	2021	4	Above-ground, no rad shield	None	Radiation → Correlated charge jumps in charge sensitive qubit
Our Work		4	Underground, rad shield [multiple configurations]	^{133}Ba, ^{137}Cs, Neutrons…	**Controlled** radiation → **Controlled** correlated charge jump rate

<u>**Objective**</u>: obtain controlled responses to quasiparticle density in qubits, to engineer both energy-sensitive (detection) and energy-insensitive (computing) qubits.

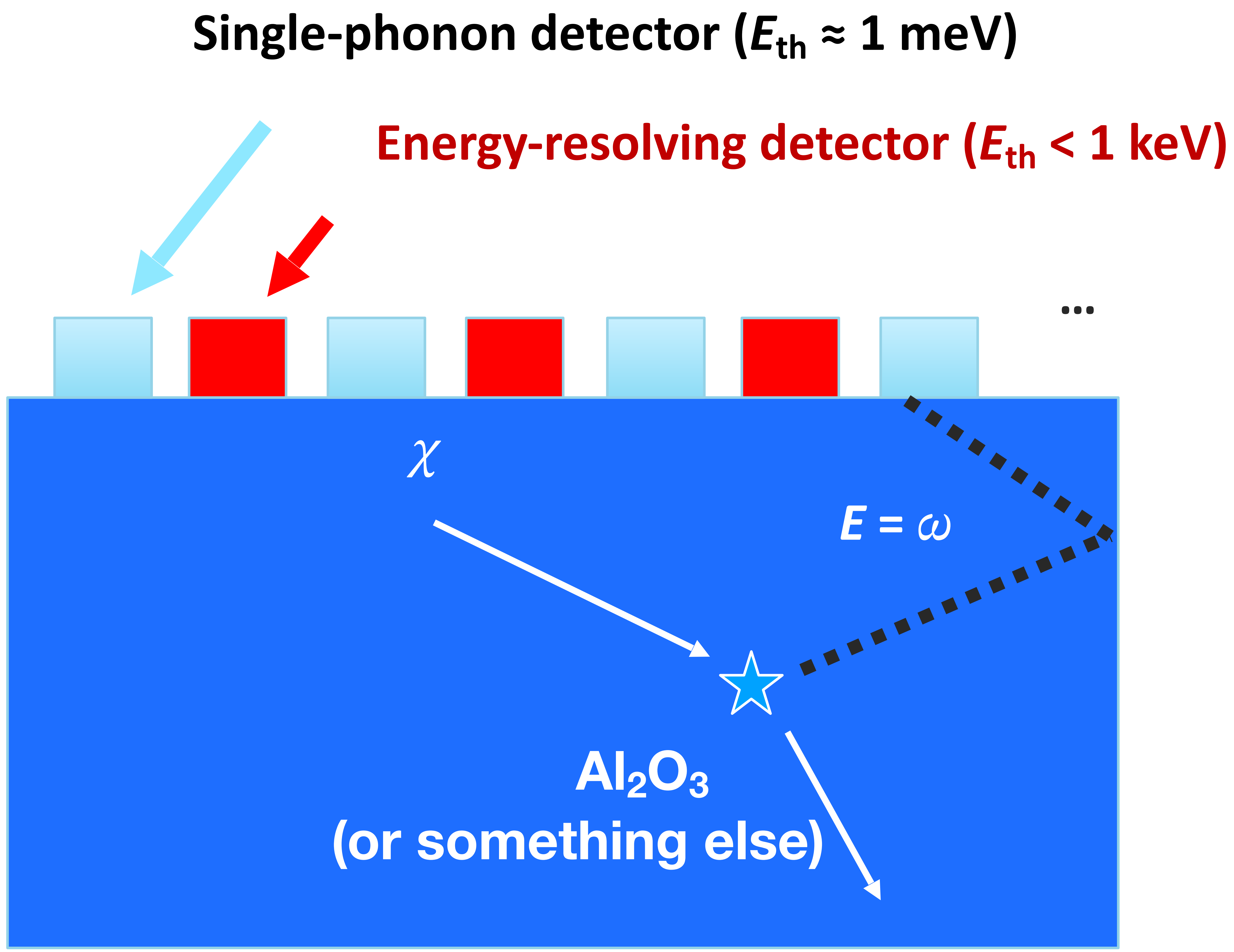
How does this impact QIS technology development?

SC Qubits for Dark Matter **SC Qubits for Quantum Computing**



Designing an Experiment – Big Picture

Proposing a novel, multiplexed quantum device for particle physics detection



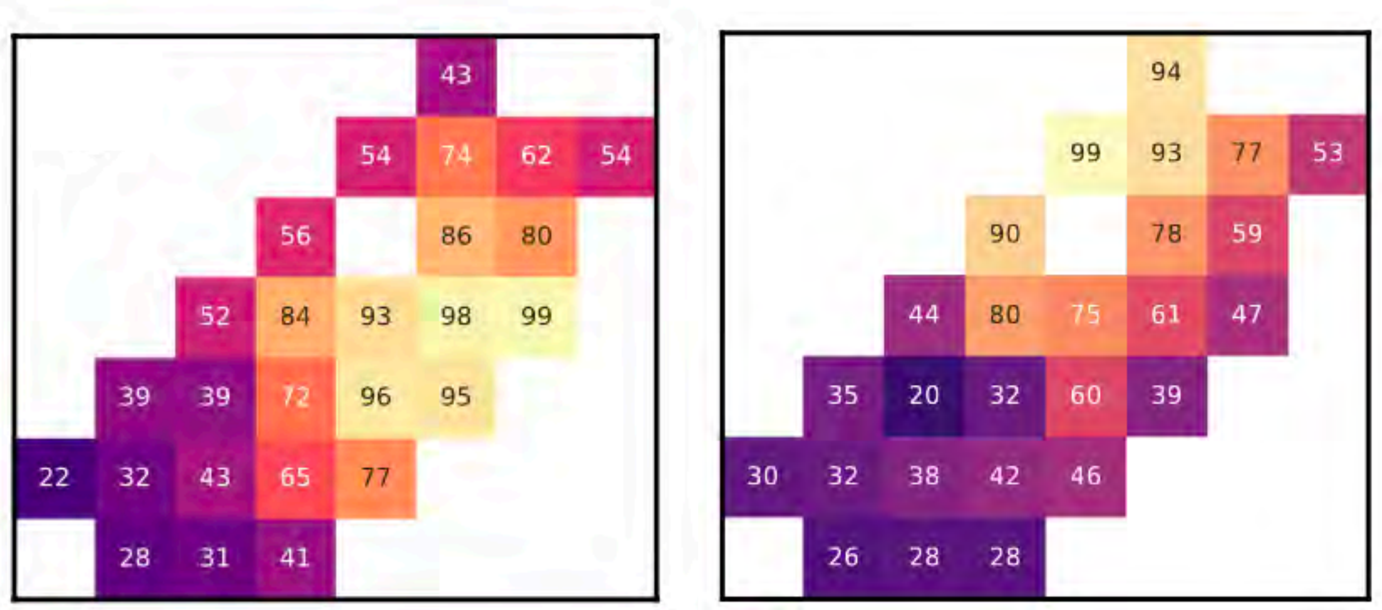
- A low-mass DM recoil will deposit order meV-keV of energy ω in the substrate at location $\boldsymbol{r}$, producing phonons
- These will break Cooper-pairs in aluminum which are measured in quasiparticle detectors (qubits)
- The energy-resolving detectors (veto), which have much higher thresholds, should see no simultaneous hits, since the energy deposition is below detector threshold

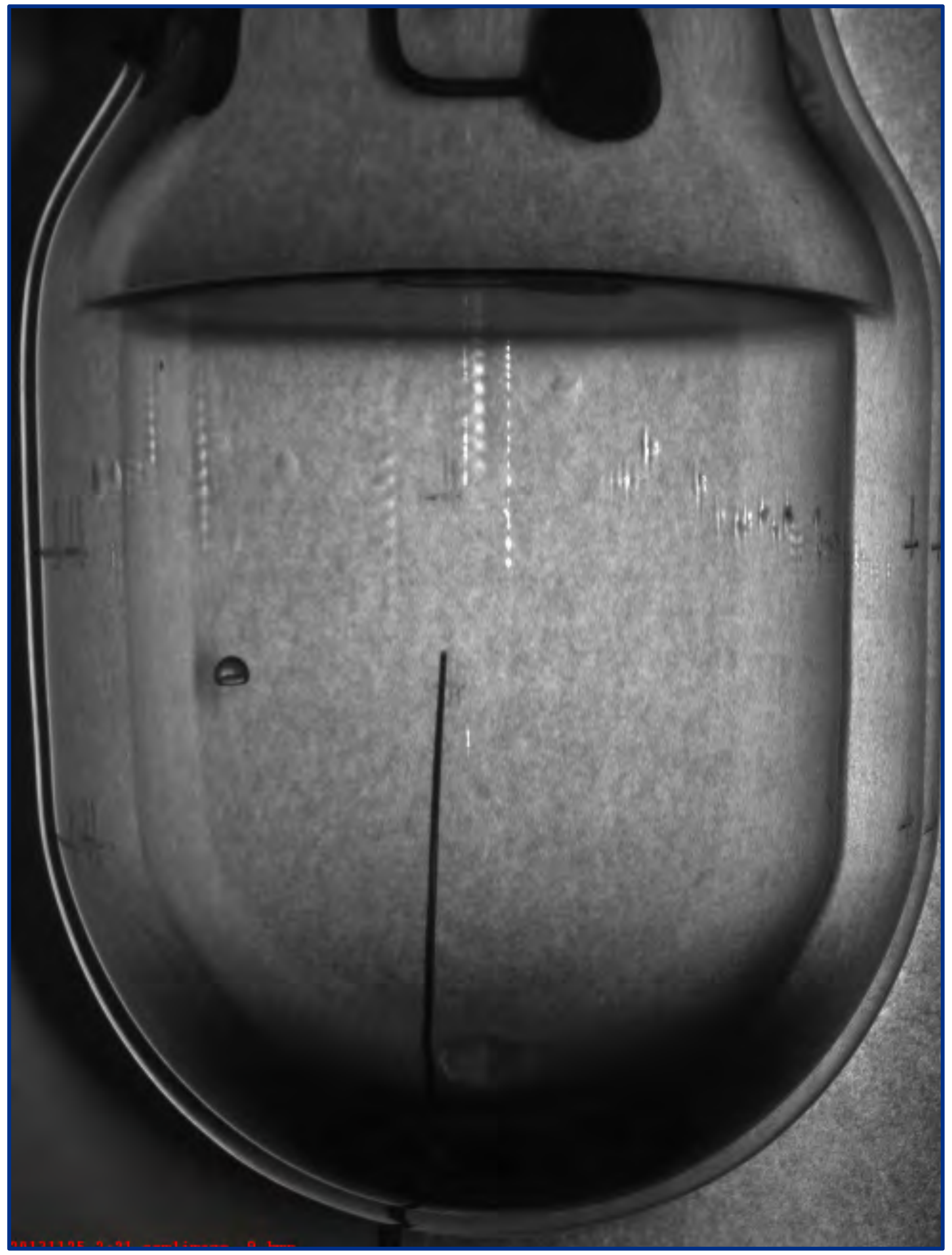
Designing an Experiment – Big Picture

From the perspective of experimental design, this is very similar to a (tiny) bubble chamber!

- A “run” consists of a series of exposures, at the end of each the system is assessed for whether there was a state change (bubble OR $|1\rangle \rightarrow |0\rangle$)

- The majority of background events will be higher energy (> eV) at scales we are very good at detecting
  - → this means we can veto them!
- Similar to a bubble chamber, no primary energy information
  - → but yes to position information!





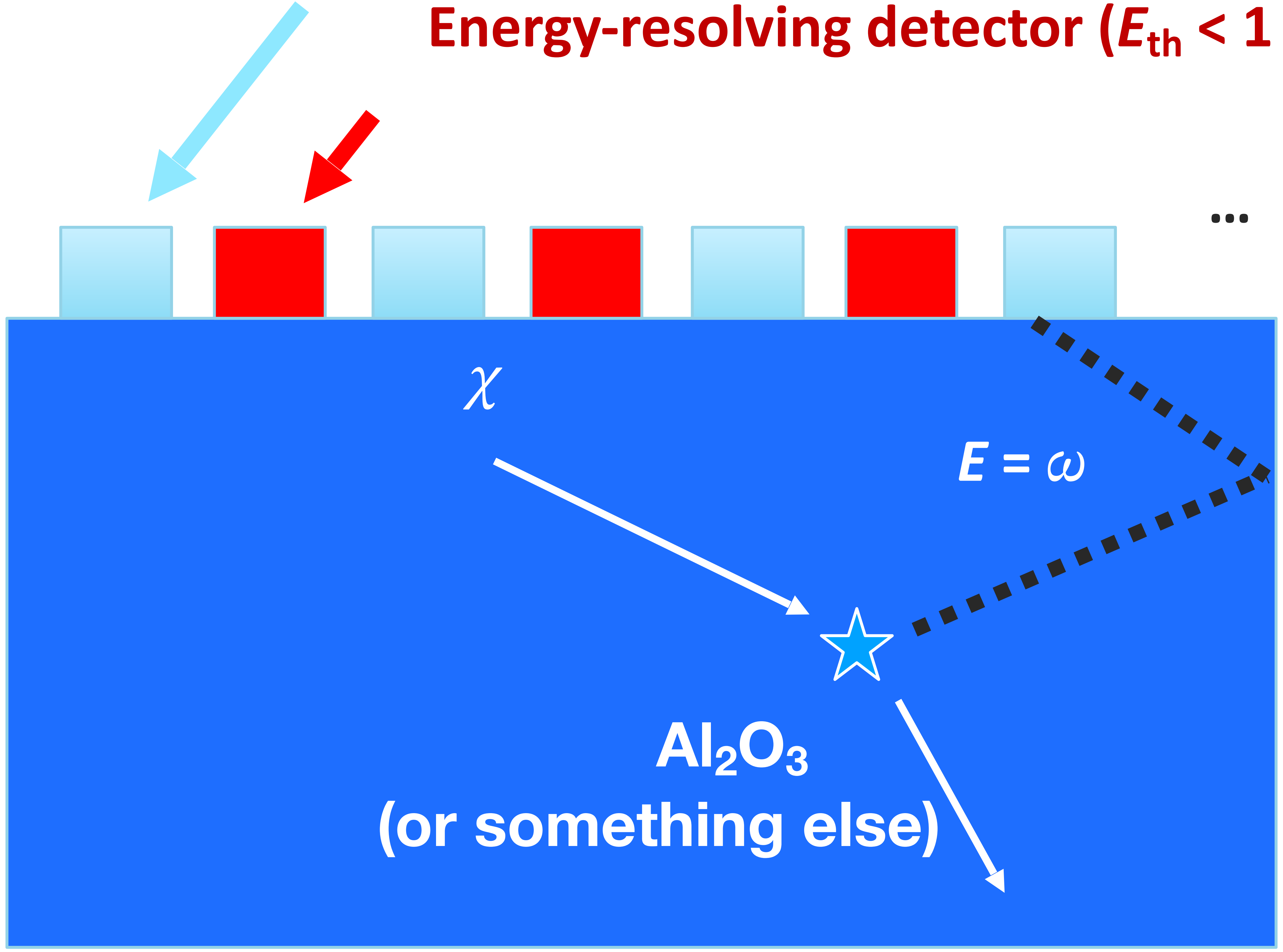
McEwen et al, Nature 18, 107 (2022) [arXiv:2104.05219]

Designing an Experiment – Big Picture

Proposing a novel, multiplexed quantum device for particle physics detection

Single-phonon detector ($E_{th} \approx 1$ meV)

Energy-resolving detector ($E_{th} < 1$ keV)



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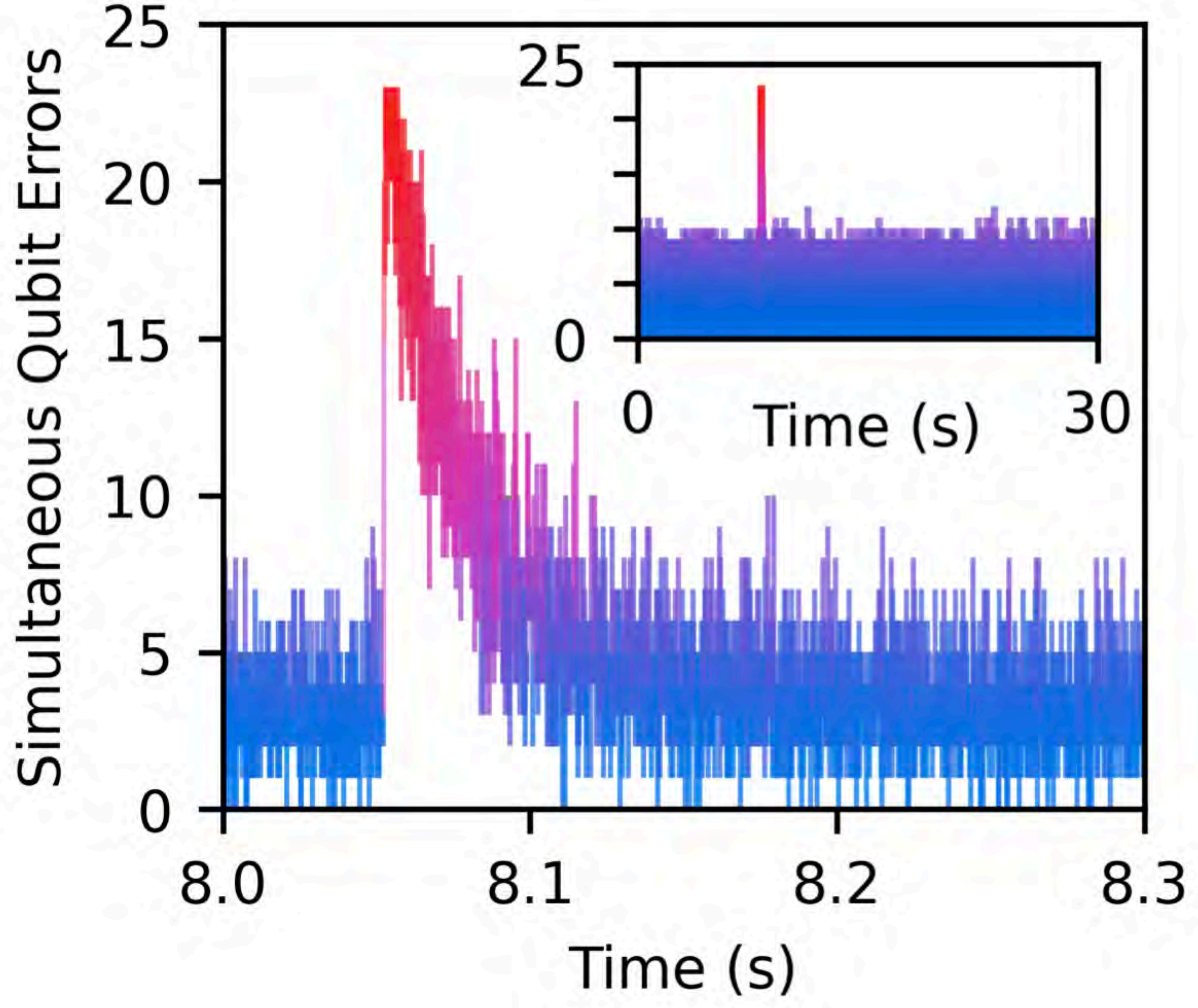

Designing an Experiment – Big Picture

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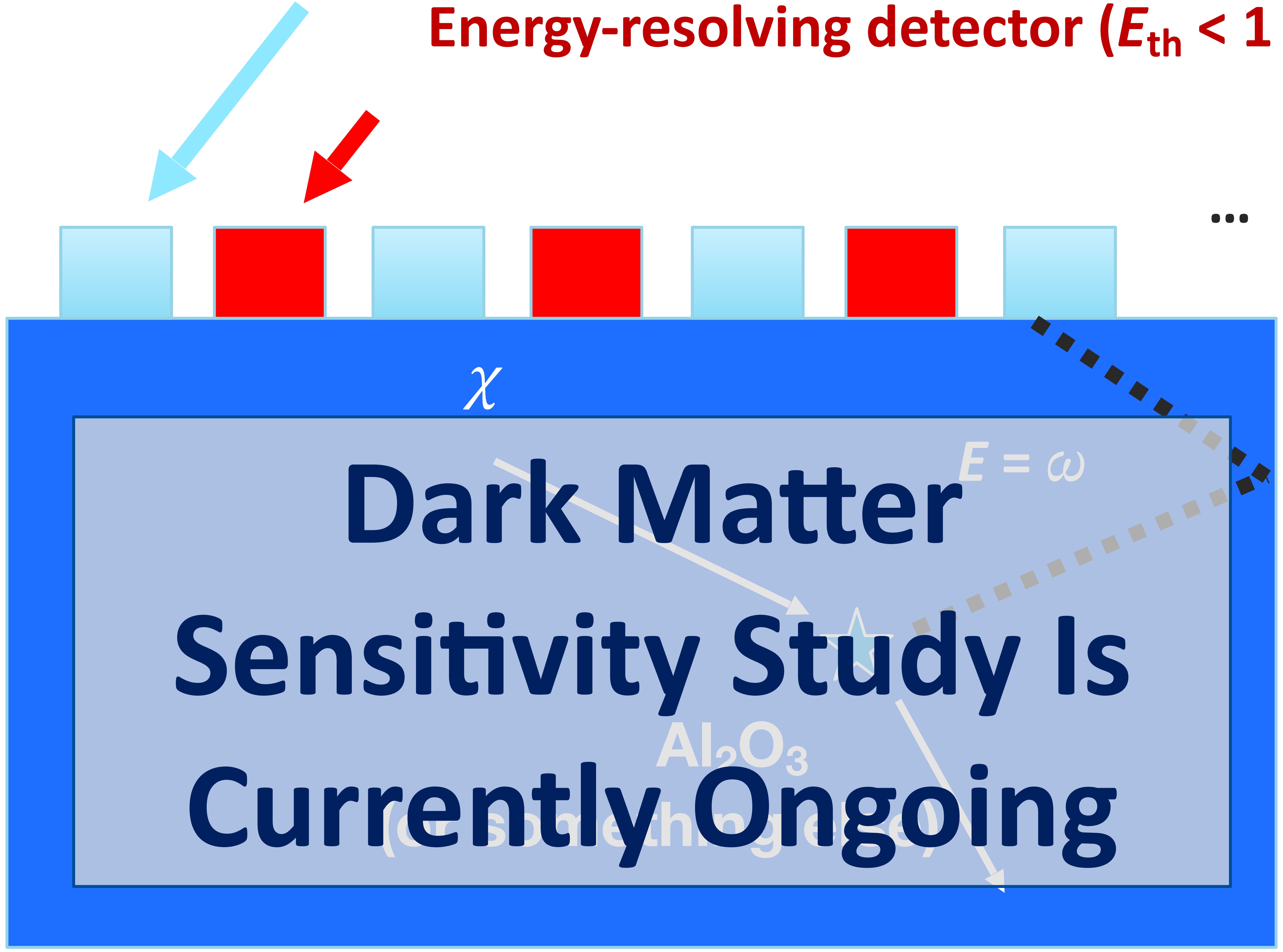
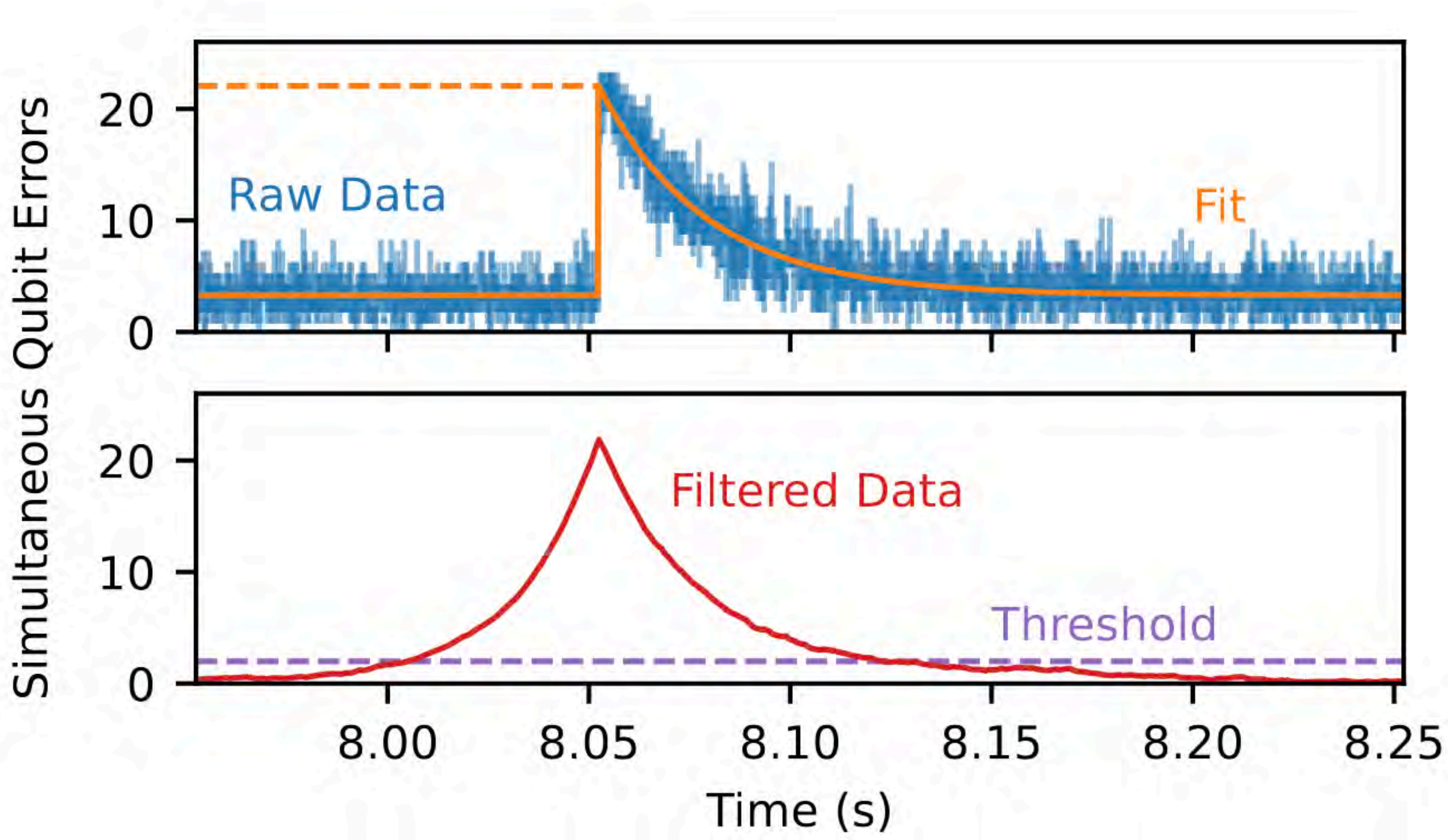


Dark Matter Sensitivity Study Is Currently Ongoing

McEwen et al, Nature 18, 107 (2022) [arXiv:2104.05219]



What's the reach of energy-dependent decoherence?

Energy decoherence detection relies on long <u>T1 decoherence times</u>.

- "Base" energy decoherence timescale due to all environmental dissipation
- Often limited by qubit architecture (not QPs)
- Need base T_1 large enough that QPs can induce observable changes in it

Decoherence rate $1/T_{1,qp}$

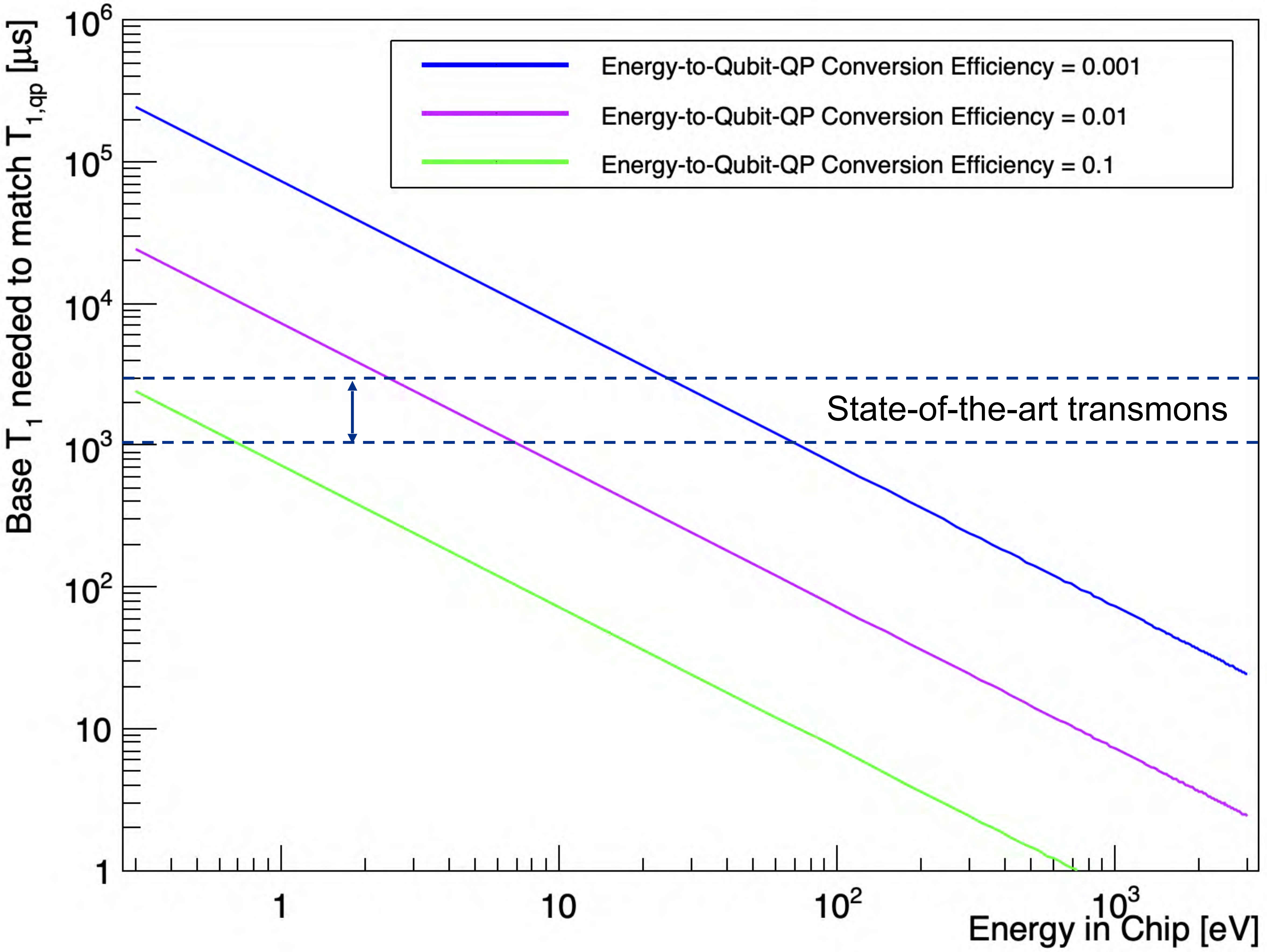
Qubit frequency

Superconducting gap

$$\Gamma_{qp} = \sqrt{\frac{2\omega_q \Delta}{\pi^2 \hbar}}\, x_{qp}$$

Reduced QP density

For "un-optimized" energy collection, state-of-the-art Al transmons could hit **O(10eV) threshold**.



Rate equation from Wang, C., Gao, Y., Pop, I. et al. "Measurement and control of quasiparticle dynamics in a superconducting qubit." *Nat Commun* 5, 5836 (2014) (link)

Source on "state of the art": Kjaergaard et al., "Superconducting Qubits: Current State of Play," https://doi.org/10.48550/arXiv.1905.13641

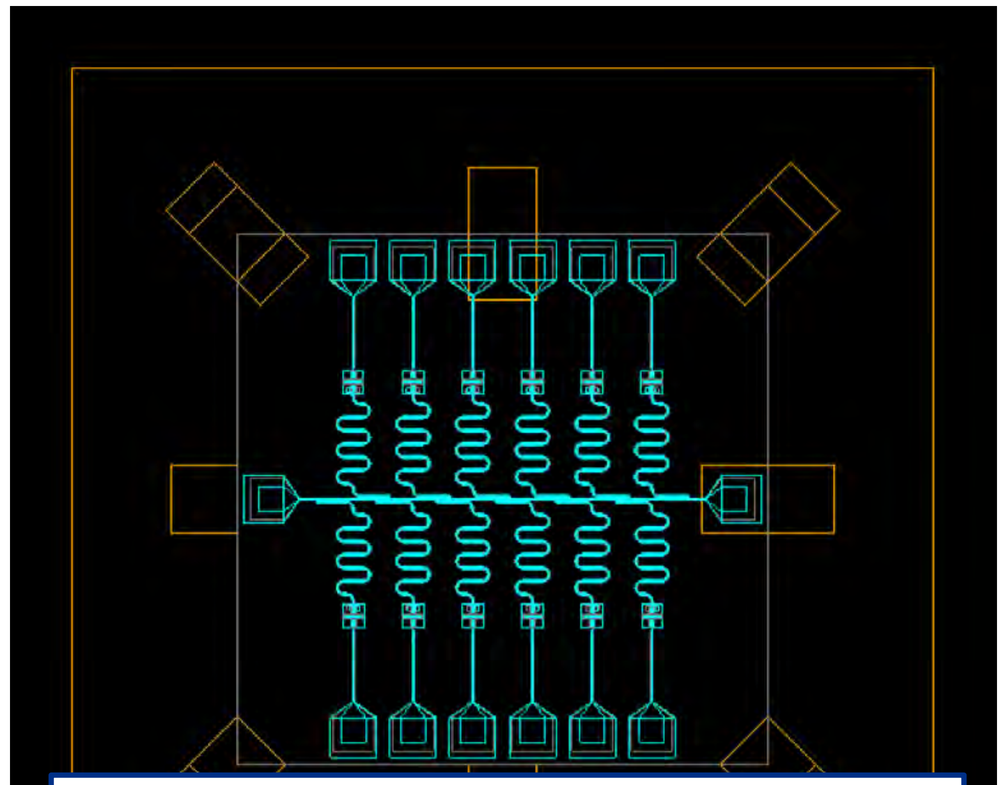
QSC@FNAL: Developing Simulations Chain

To get a mature estimate of reach, we need to simulate how energy deposits propagate through a detector to impact T1 decoherence times.

DM scattering, energy deposition → Energy propagation through chip → QP production in qubits → QP time evolution in qubits → $T_{1,qp}$ evolution in qubits

G4CMP simulation

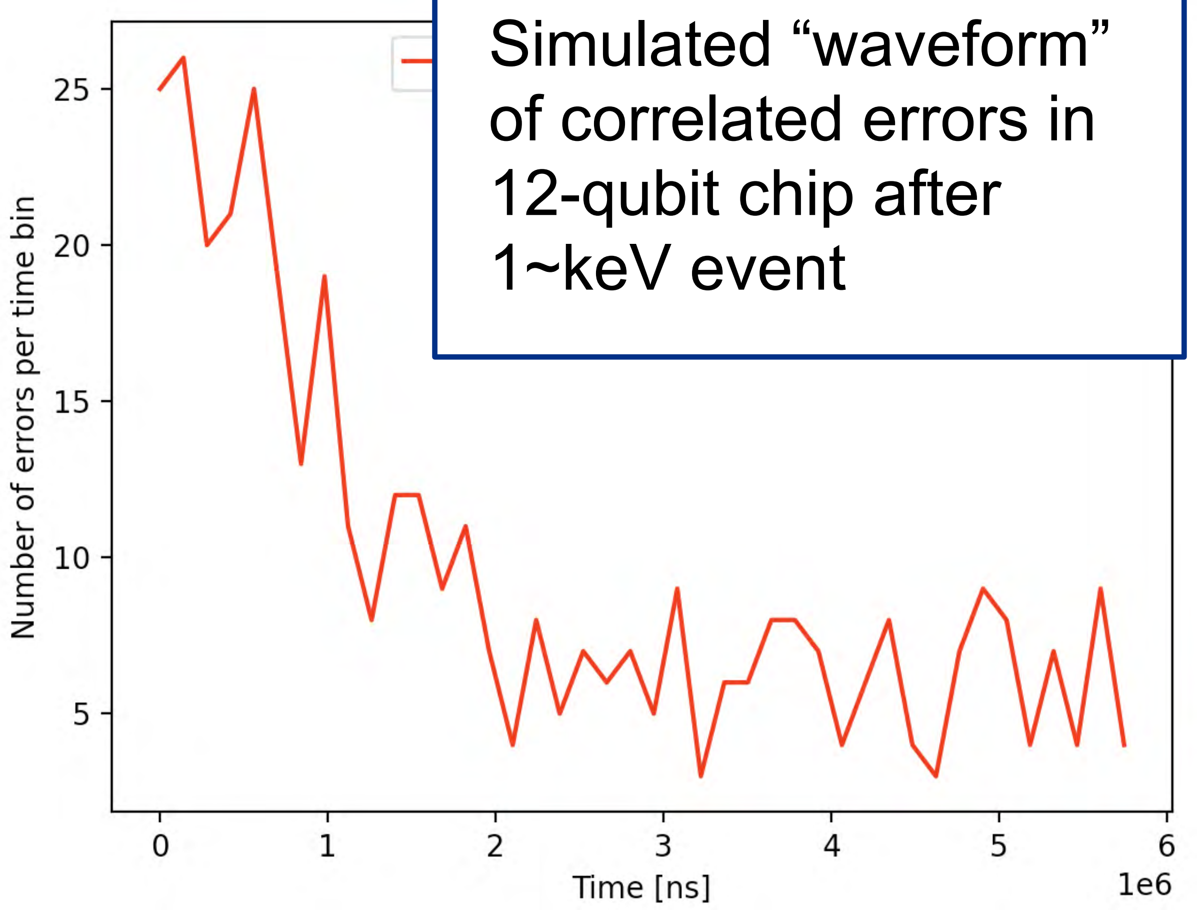
- Geant4-based
- Phonon and e/h pair tracking
- Simple QP modeling
- Extensions being developed by community



G4CMP Chip Geometry

Quantum Device Response (QDR)

- Folds in detection scheme, critical readout parameters
- Flexible: models multiple sensor types (MKIDs, Transmons), even on same chip!

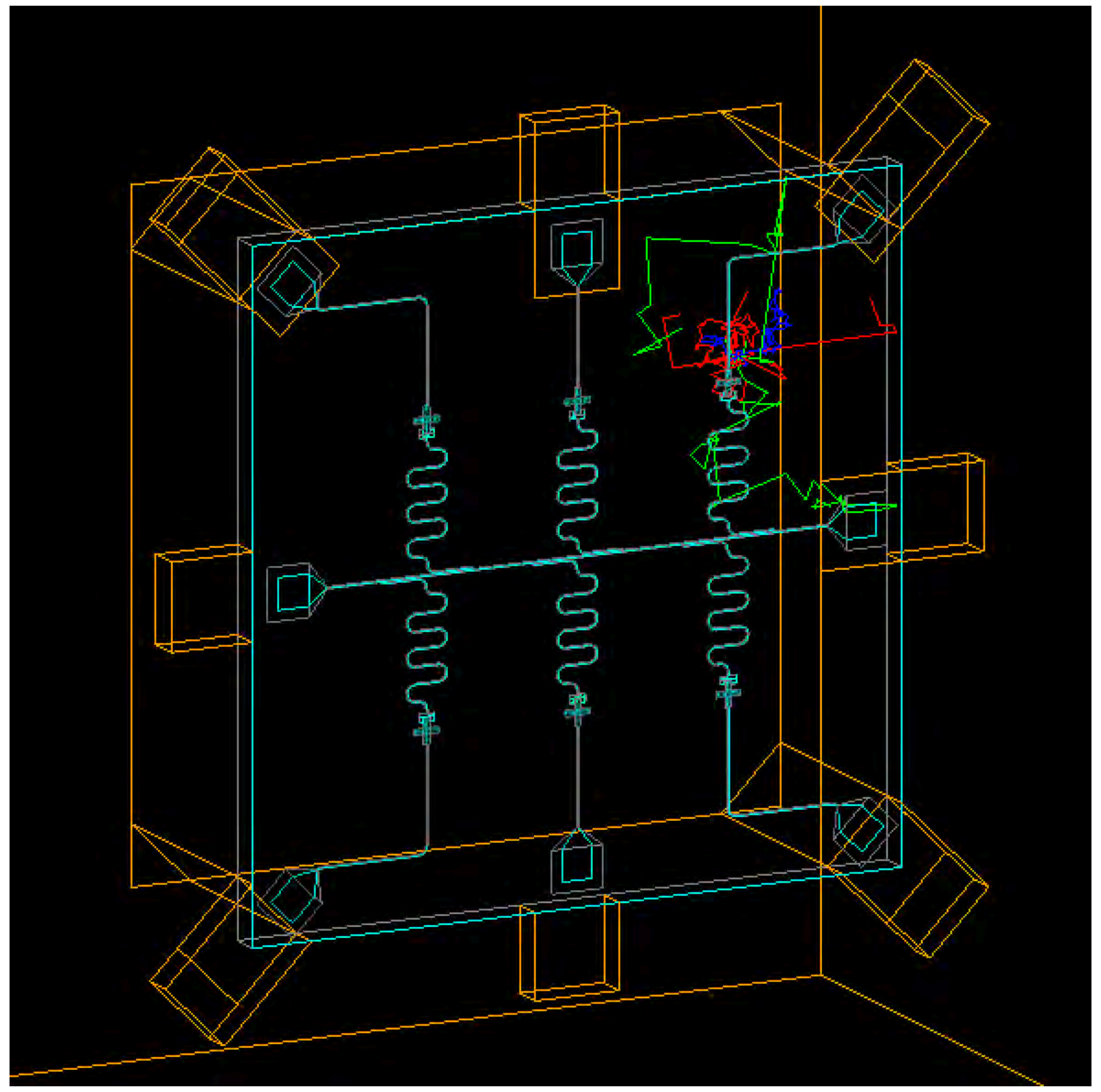


Simulated "waveform" of correlated errors in 12-qubit chip after 1~keV event

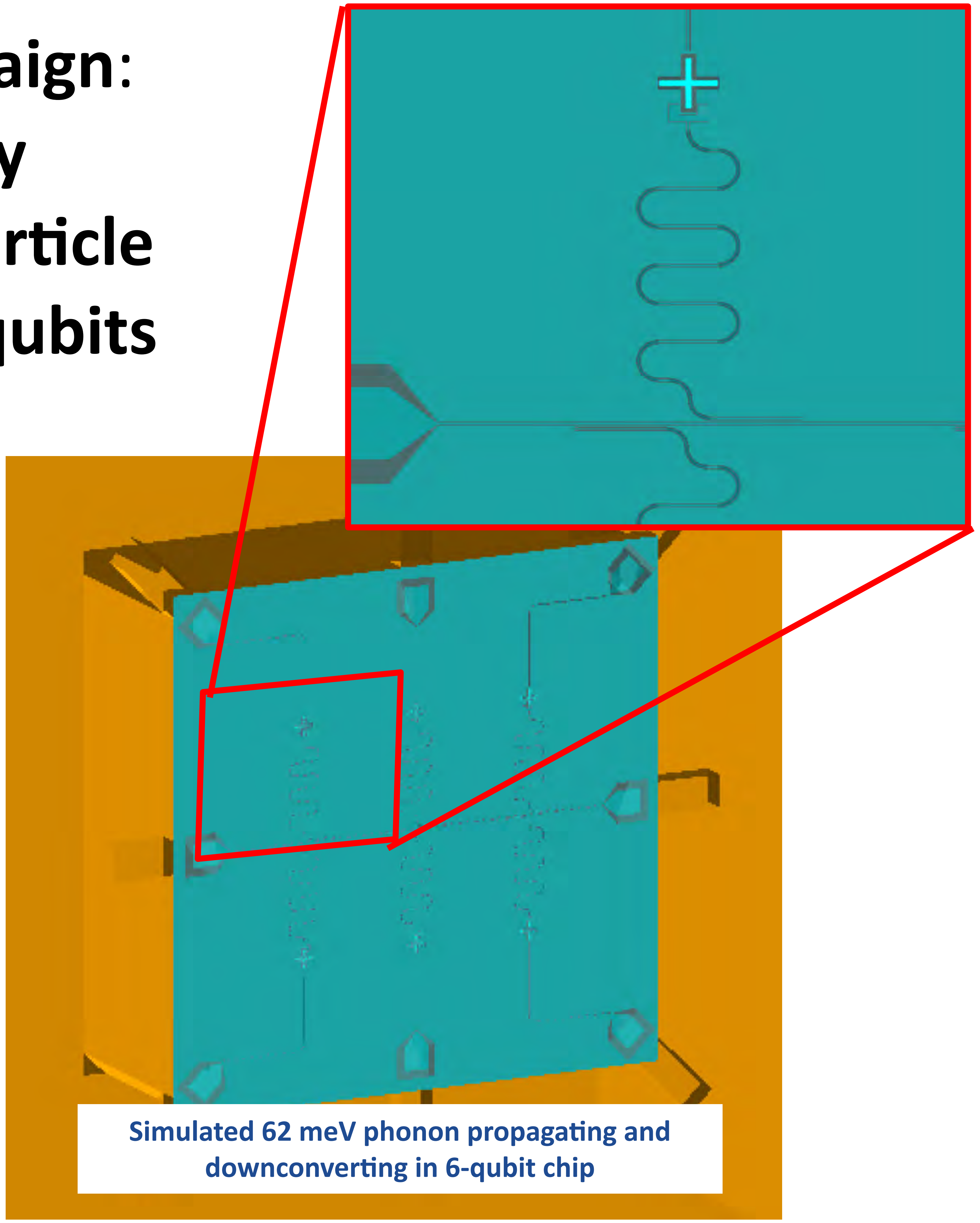
Credit: Ryan Linehan

Designing an Experiment – Zooming In

Current G4CMP campaign: map in-chip energy depositions to quasiparticle populations affecting qubits



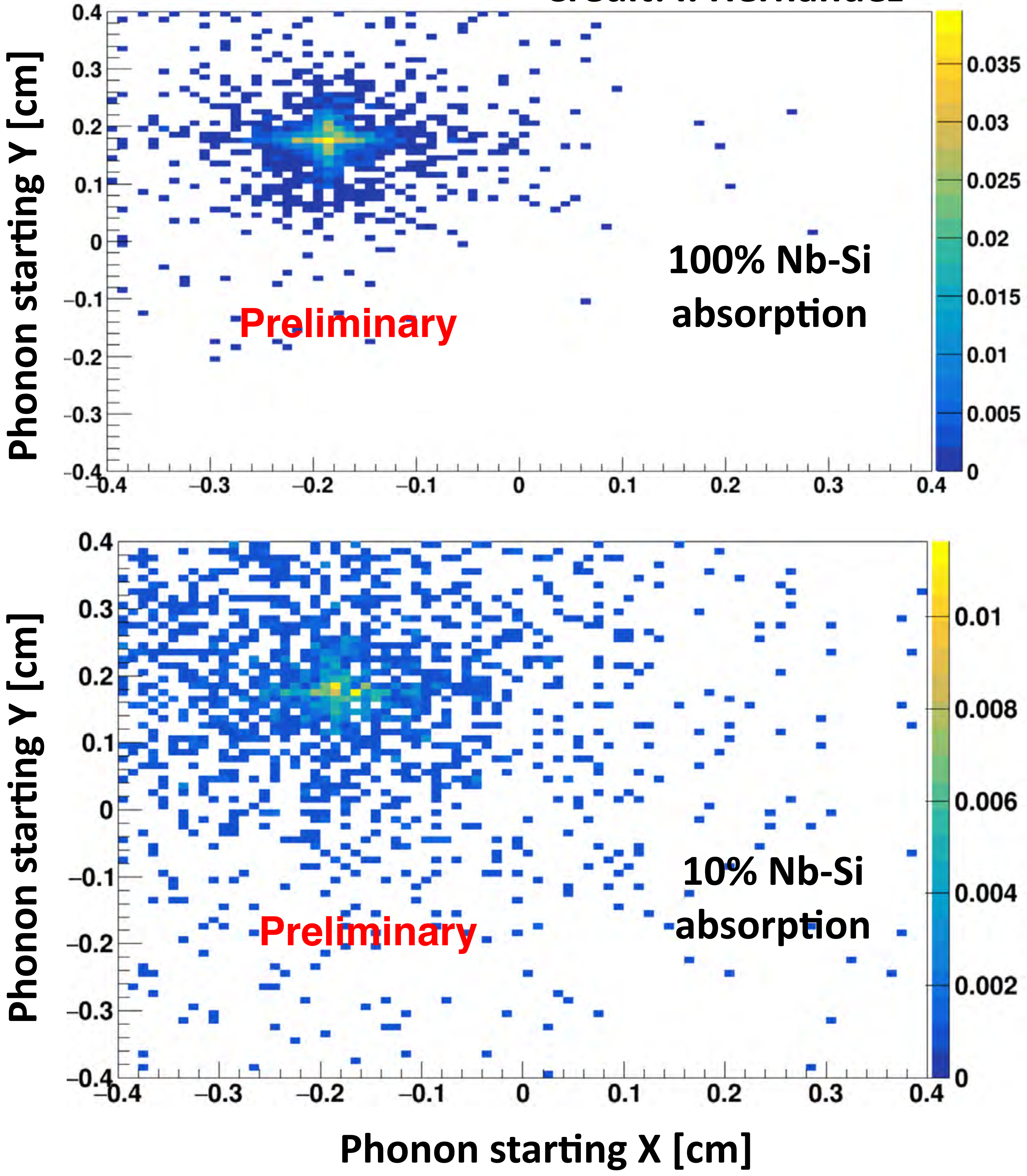
Work by Israel Hernandez & Ryan Linehan



Simulated 62 meV phonon propagating and downconverting in 6-qubit chip

Phonon collection efficiencies in transmon shunt capacitor (G4CMP)

Credit: I. Hernandez



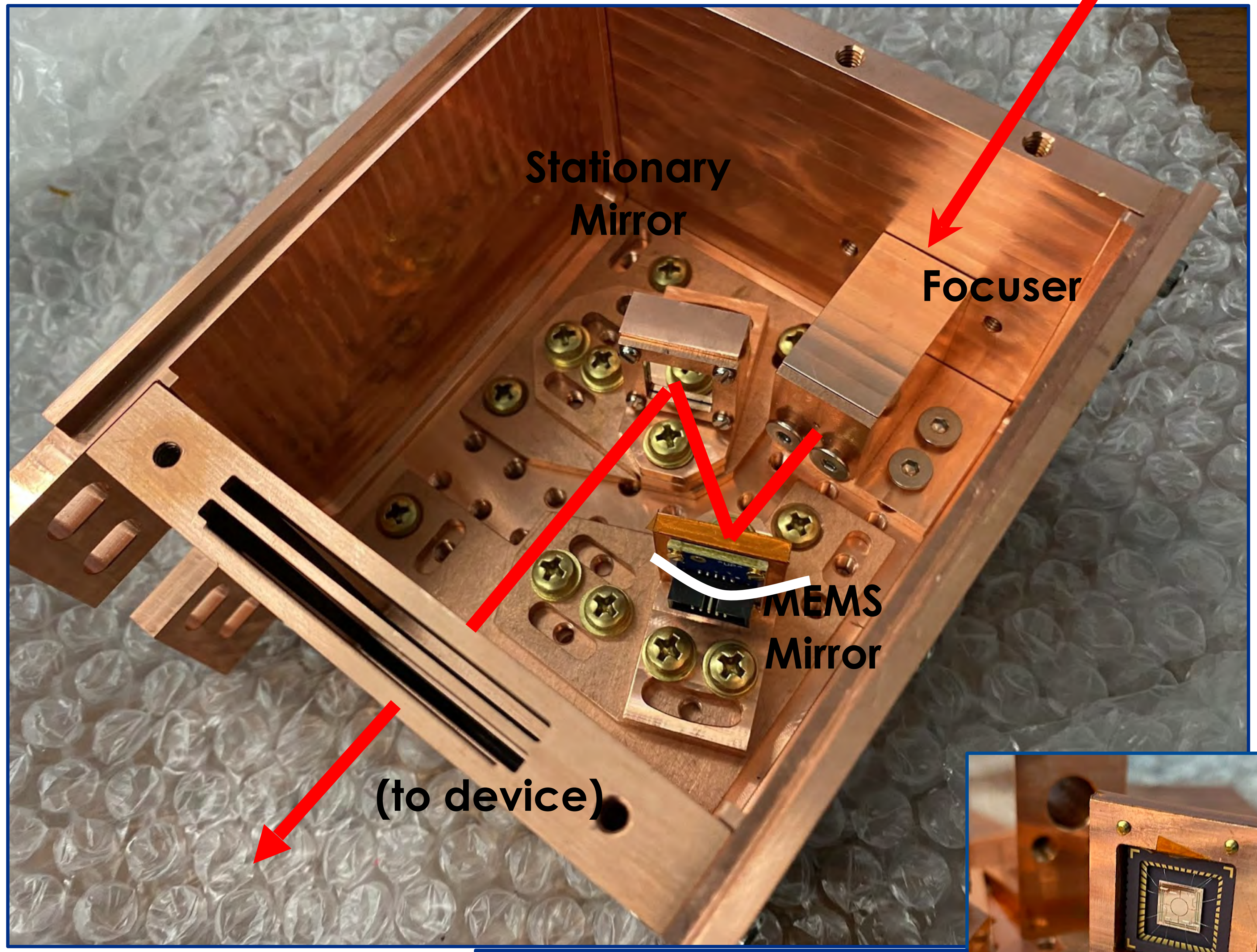
Designing an Experiment – Calibration Development

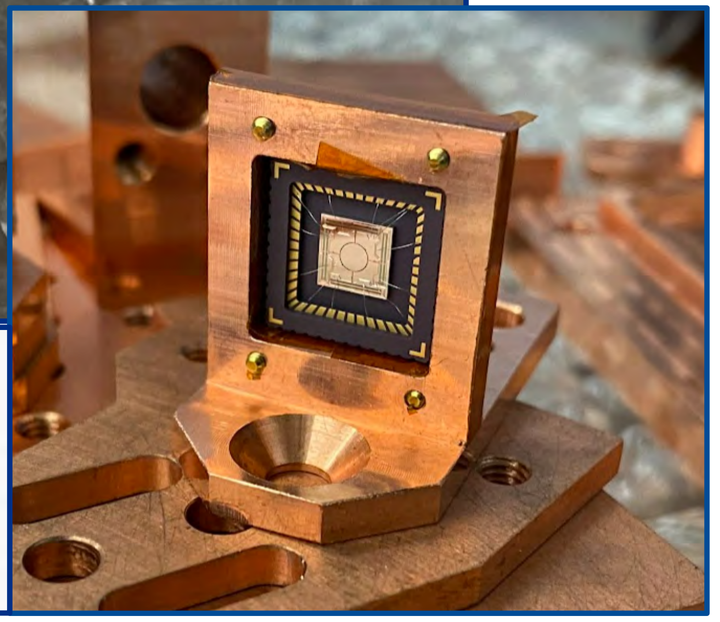
MEMS mirror used to steer laser beam

- **No power dissipation while stationary**
- **Modified control lines to function at cryogenic temperatures (>10mK)**
- **Large deflection angles (< ±5°)**
- **High deflection resolution (>0.001°)**
- **High broadband reflectance**

Work by Kelly Stifter & Hannah Magoon

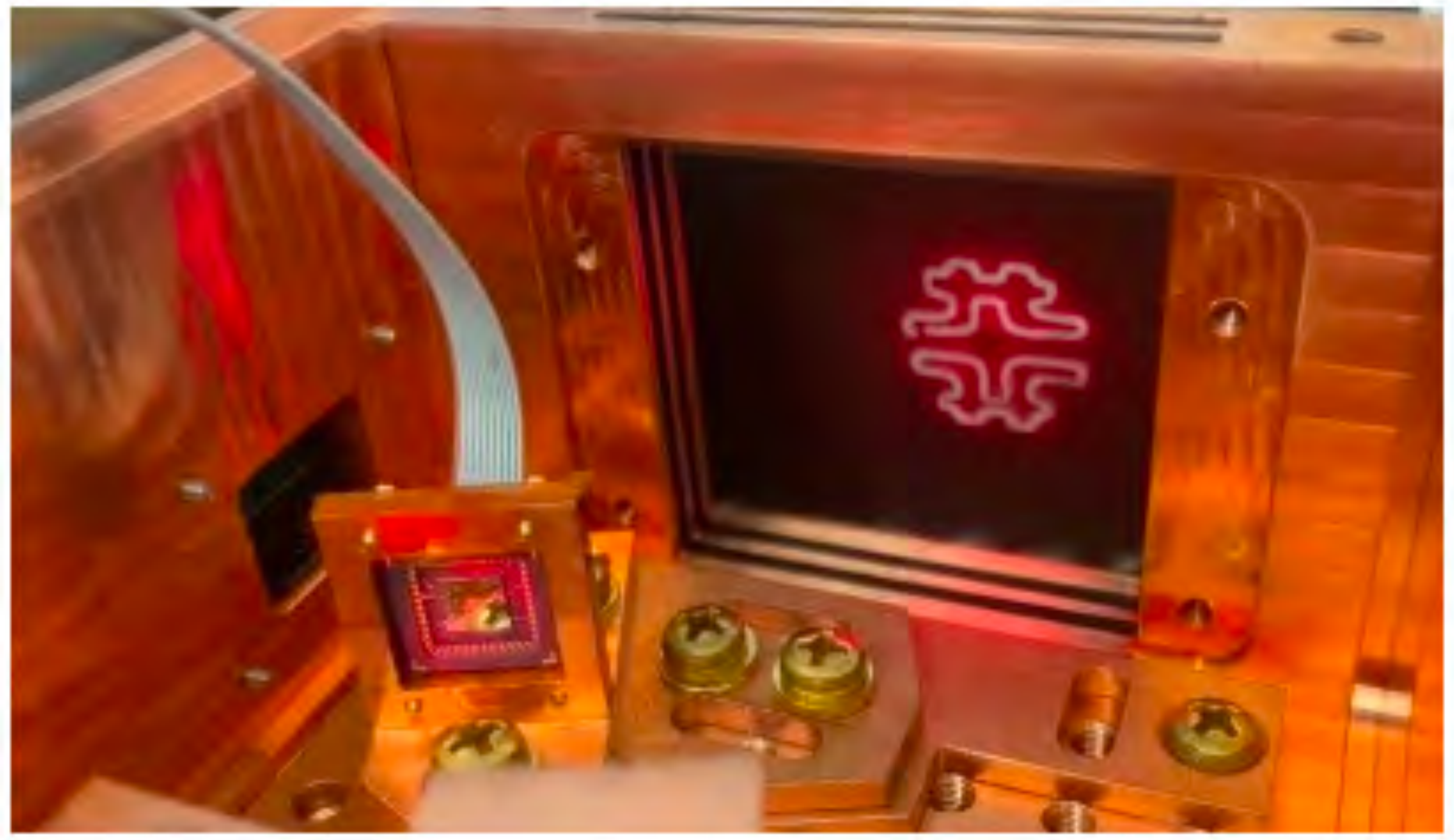
Optical Cable
(from laser into dilution fridge)

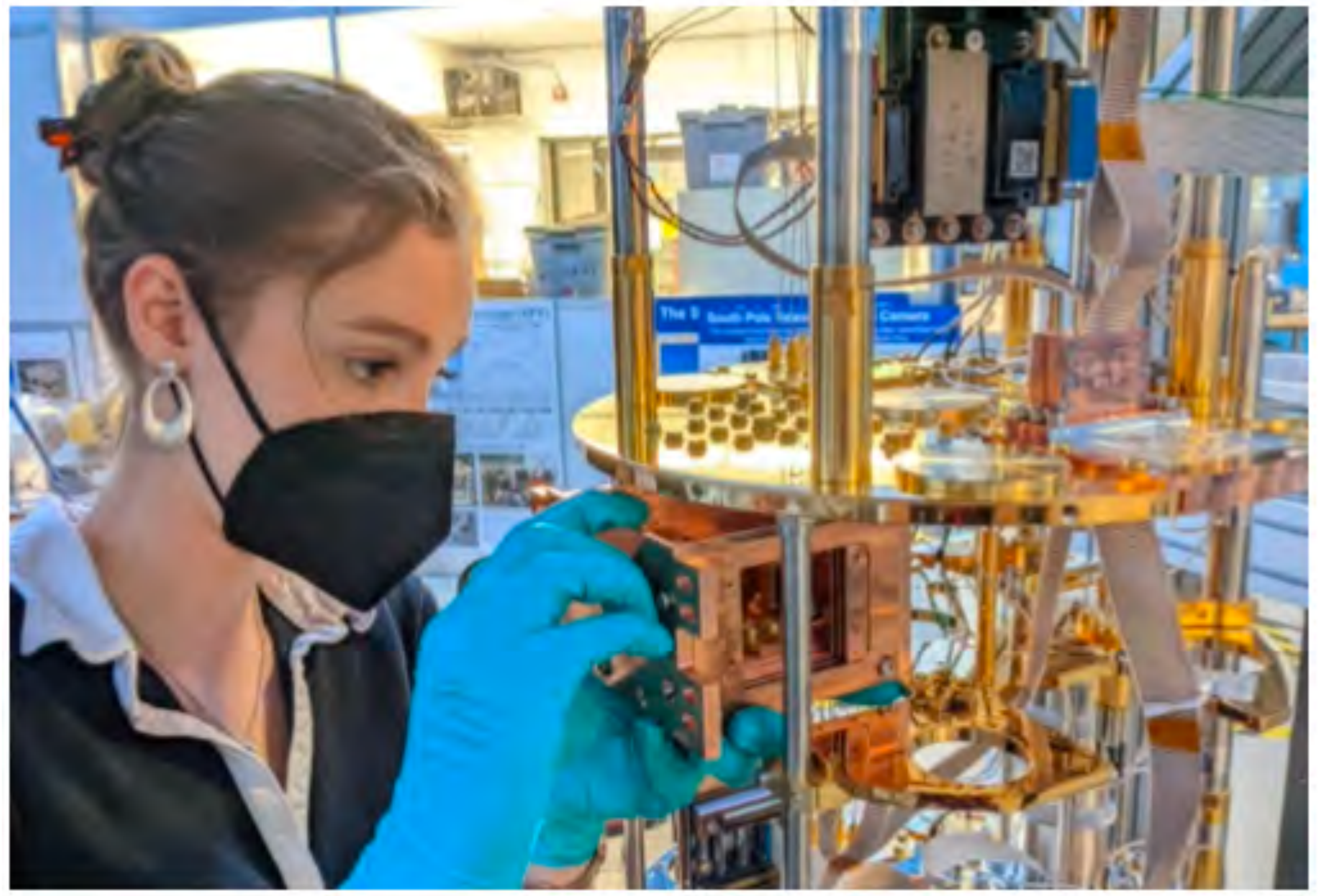




mirrorcle TECHNOLOGIES, INC.

Designing an Experiment – Calibration Development

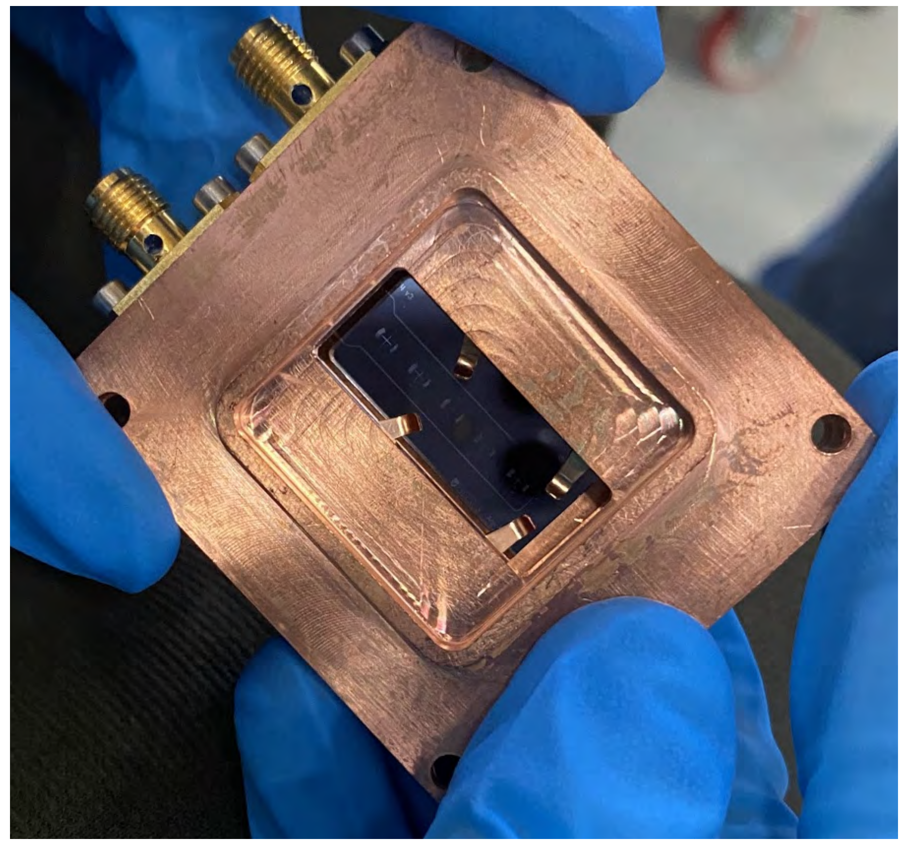


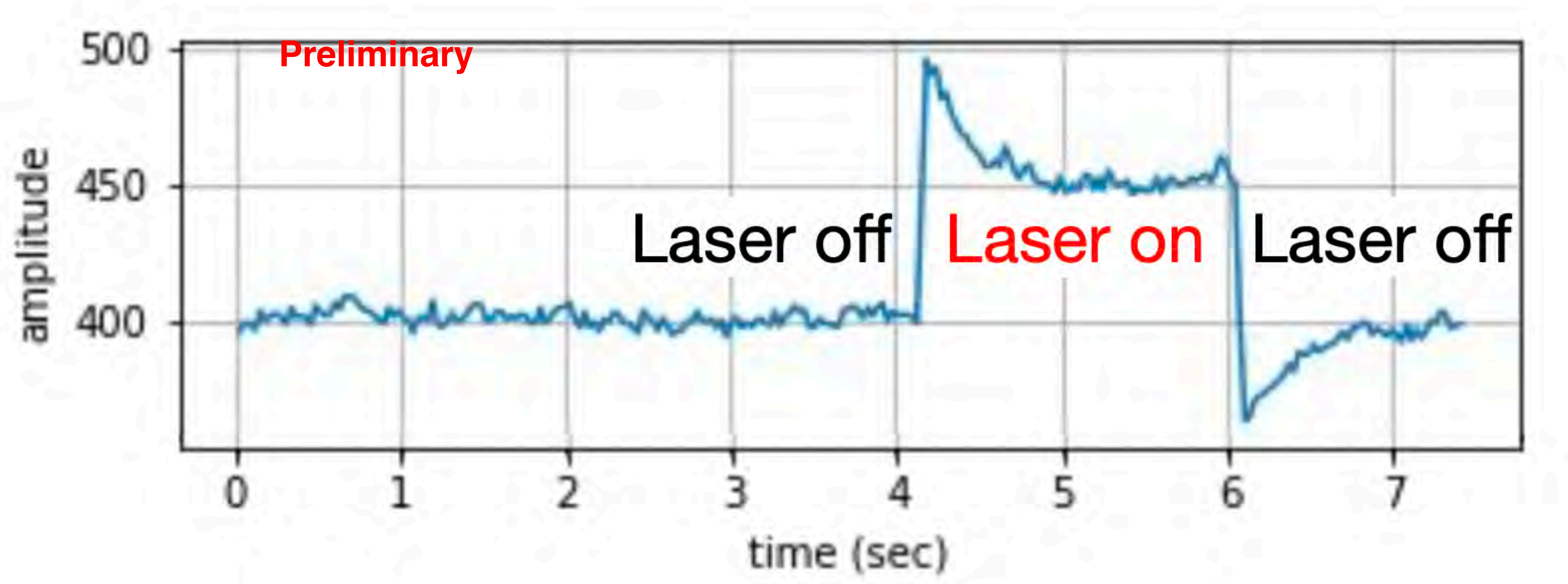


Work by Kelly Stifter & Hannah Magoon

Anticipated Functionality

<100μm spot size
~10μm position resolution
O(100)Hz scanning speed
O(μs) pulse width
O(10mK) operating temperature
Single wavelength within 0.6-6.9eV
Up to 1”x1” scanning range



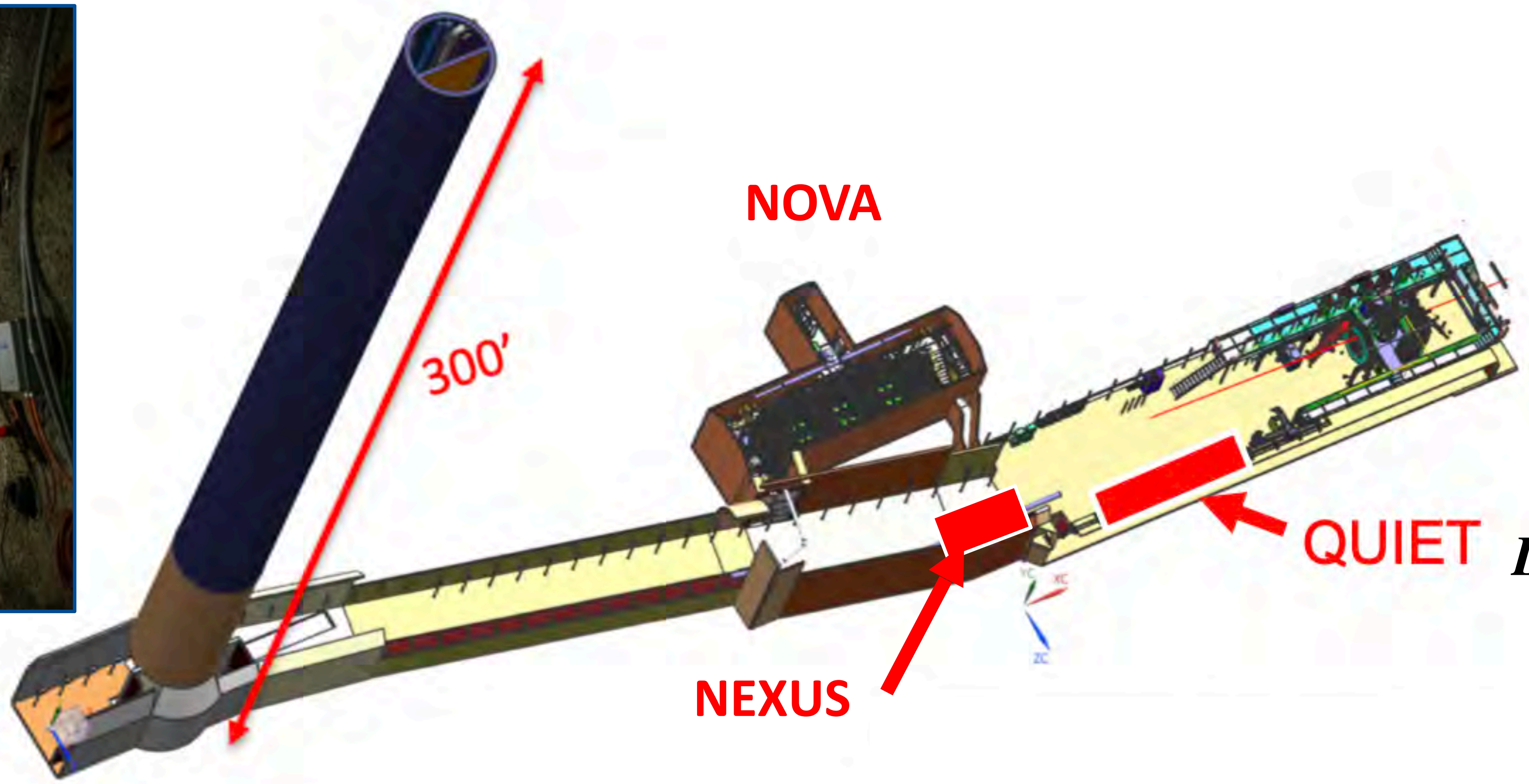


Designing an Experiment – Test Facilities

FNAL group has progress on many fronts towards this goal!

In addition to NEXUS, we have two identical new facilities at FNAL!

- LOUD – high-throughput surface facility to advance qubit-based technology necessary to develop DM & radiation detectors
- QUIET – underground clean facility (next to NEXUS; 225 mwe) to operate characterized devices in low-background (target 100 dru) environment (x10^3 reduction)



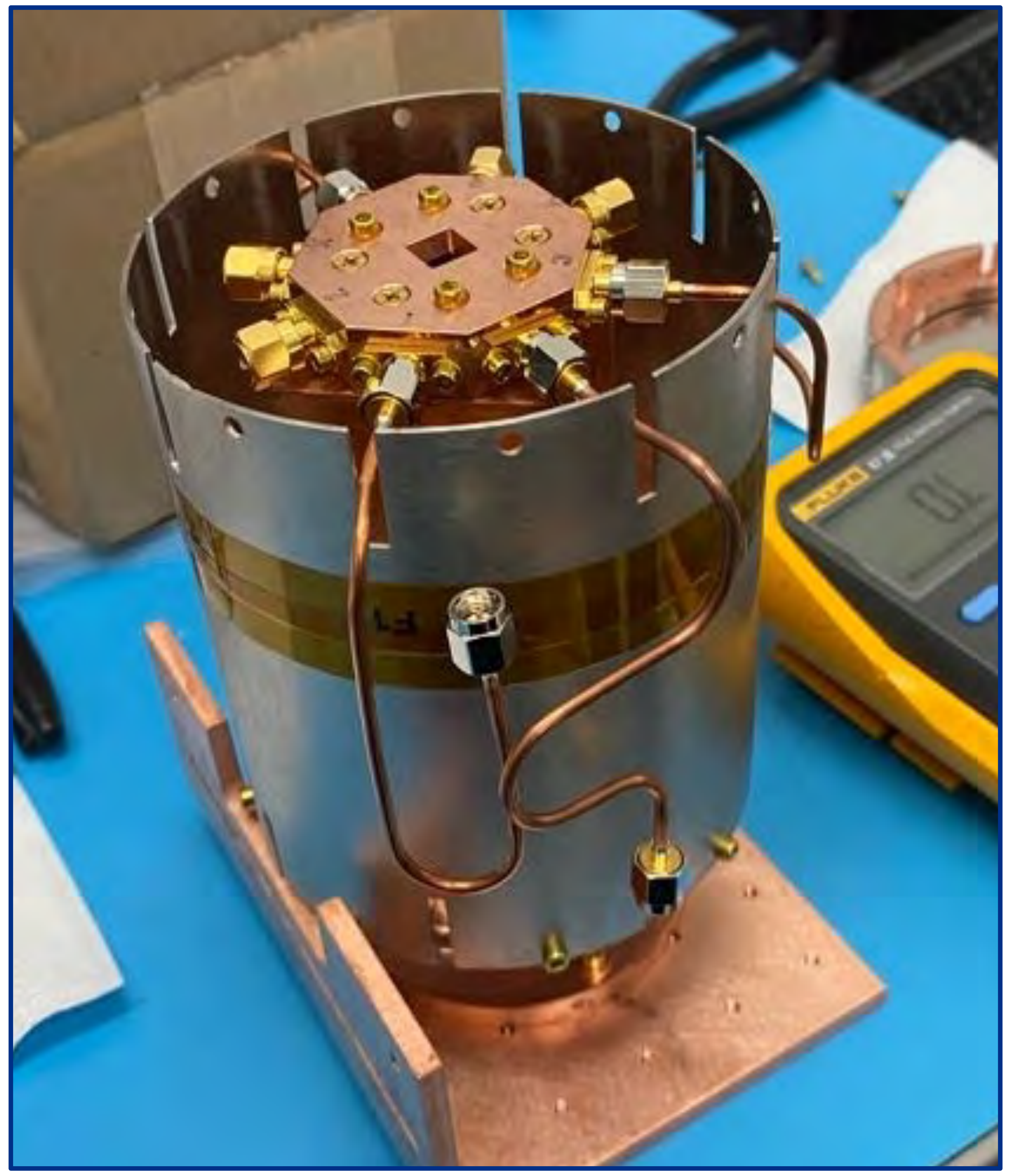
LOUD Run Coordinator: Ryan Linehan

Test Facilities – LOUD

New DR installed at FNAL

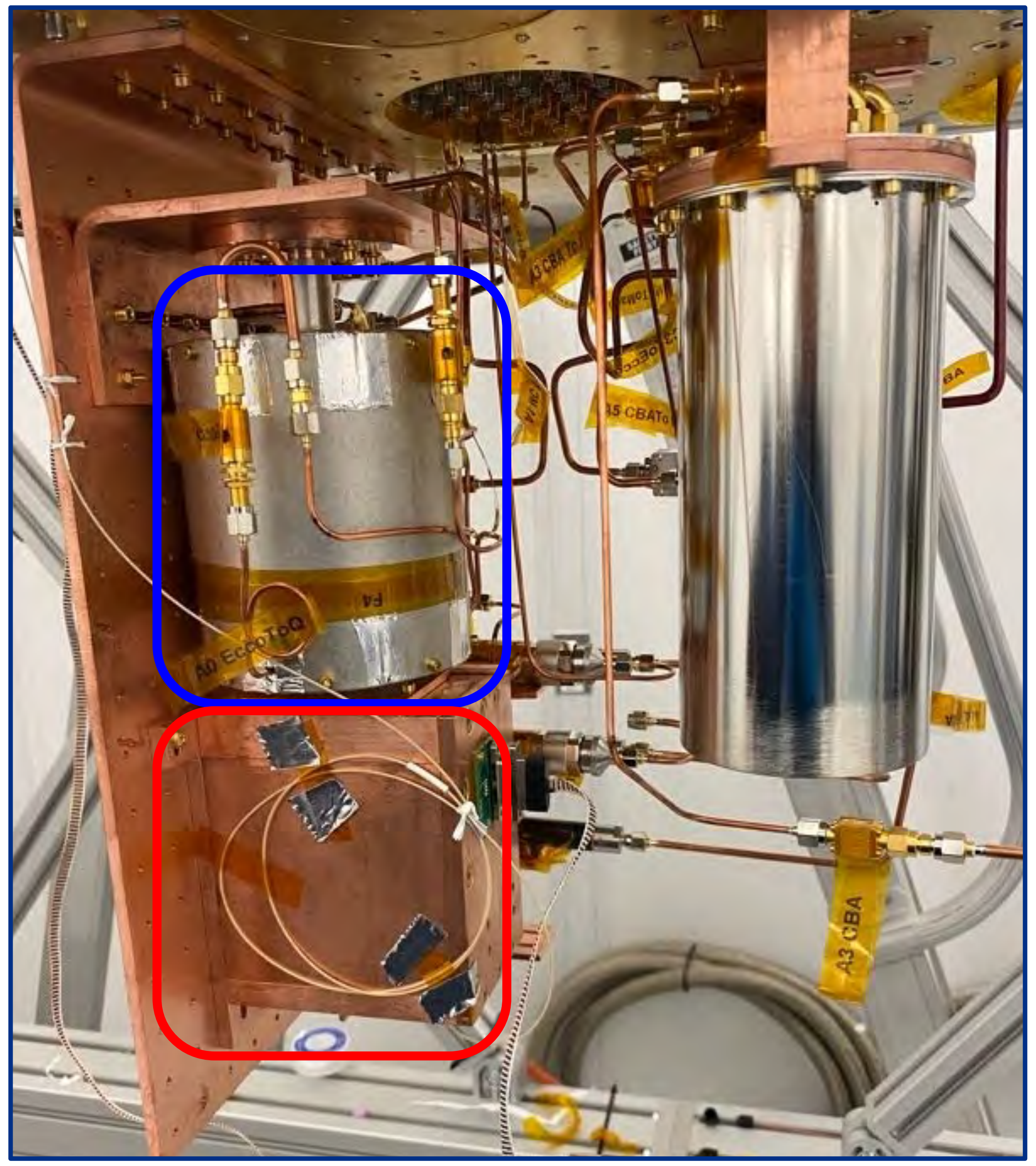
(August 2022)

6-qubit array borrowed from McDermott group



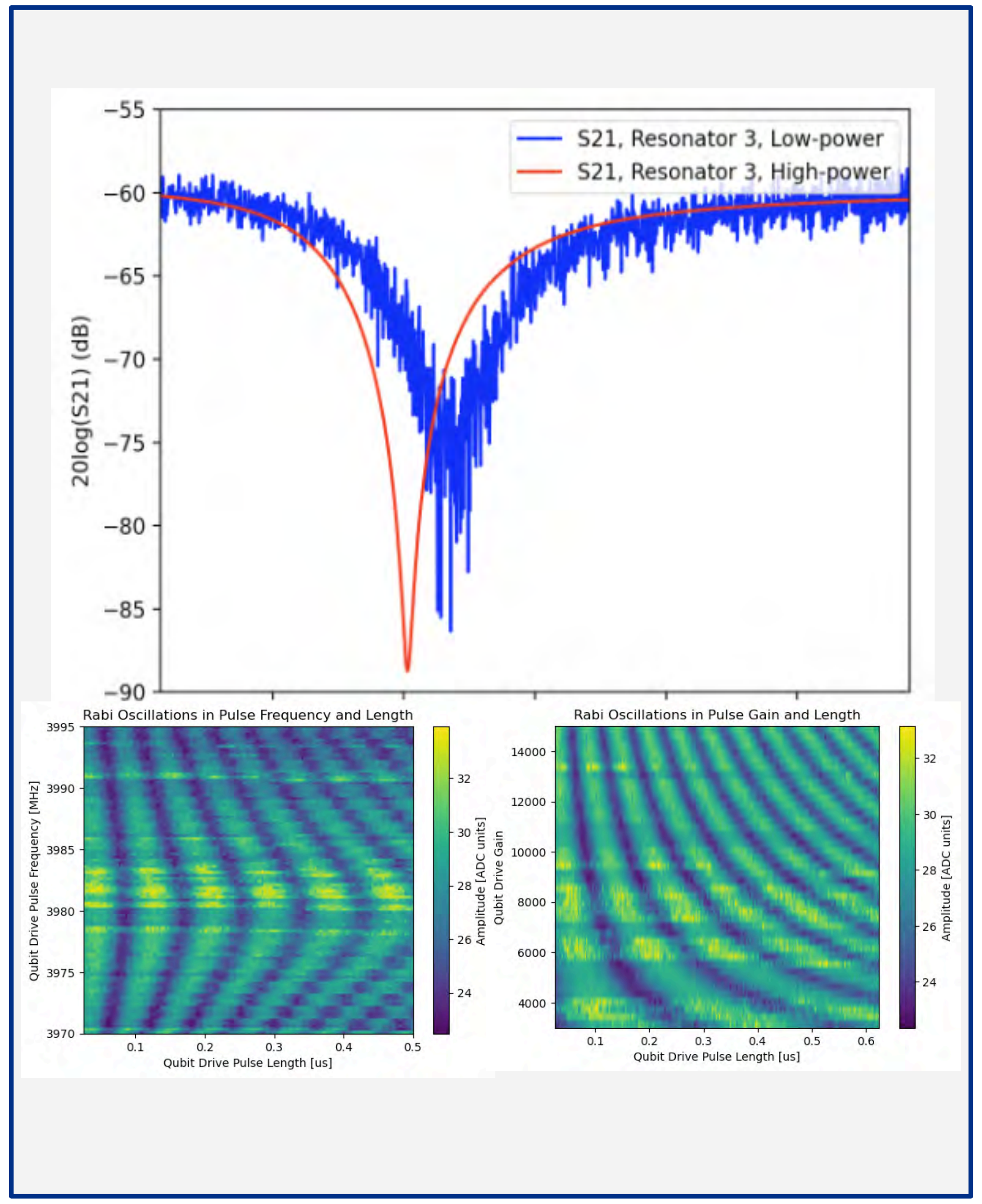
(October 2022)

Magnetic shielding coupled to scanning unit and installed in DR



(November 2022)

<u>Run 1</u>: First demonstration of live qubits



(February 2023)

Test Facilities – QUIET

Quantum Underground Instrumentation Experimental Testbed

This QSC facility, once complete, will house one of the only dedicated, low-background cryostats for superconducting qubit operations

- Class 10,000 clean room
- 50 ft² antechamber for gowning and material cleaning
- 250 ft2 main room will contain a shielded Oxford dil. fridge w/ up to 16(48) NbTi(SS) RF lines
- Design of the QUIET radiation shield and muon veto is underway in parallel
- Utility installation is now proceeding, including power, chilled water, fiber internet, and fire suppression systems

Conclusions

- Work at NEXUS is bridging TES and qubit technologies
- We've taken world-leading DM data with our SuperCDMS HVeV Detectors
- We are performing the first comprehensive low-background/high background radiation study on qubits
- The CosmiQ group @ FNAL is focusing on applying quantum detectors for dark matter:
  - Determine, quantitatively, the effects of radiation on detector performance (qubit decoherence) in collaboration with QIS community
  - Understand how to maximize/minimize radiation sensitivity in qubits for DM/QIS
  - Develop calibration sources to mimic the scattering of sub-MeV DM
  - Understand background contributions down to and below a few eV
- We're just starting the process of turning quantum sensors into DM detectors, making this an interesting time on the cusp of a lot of new, exciting science

Acknowledgments

QSC Local Group Members:

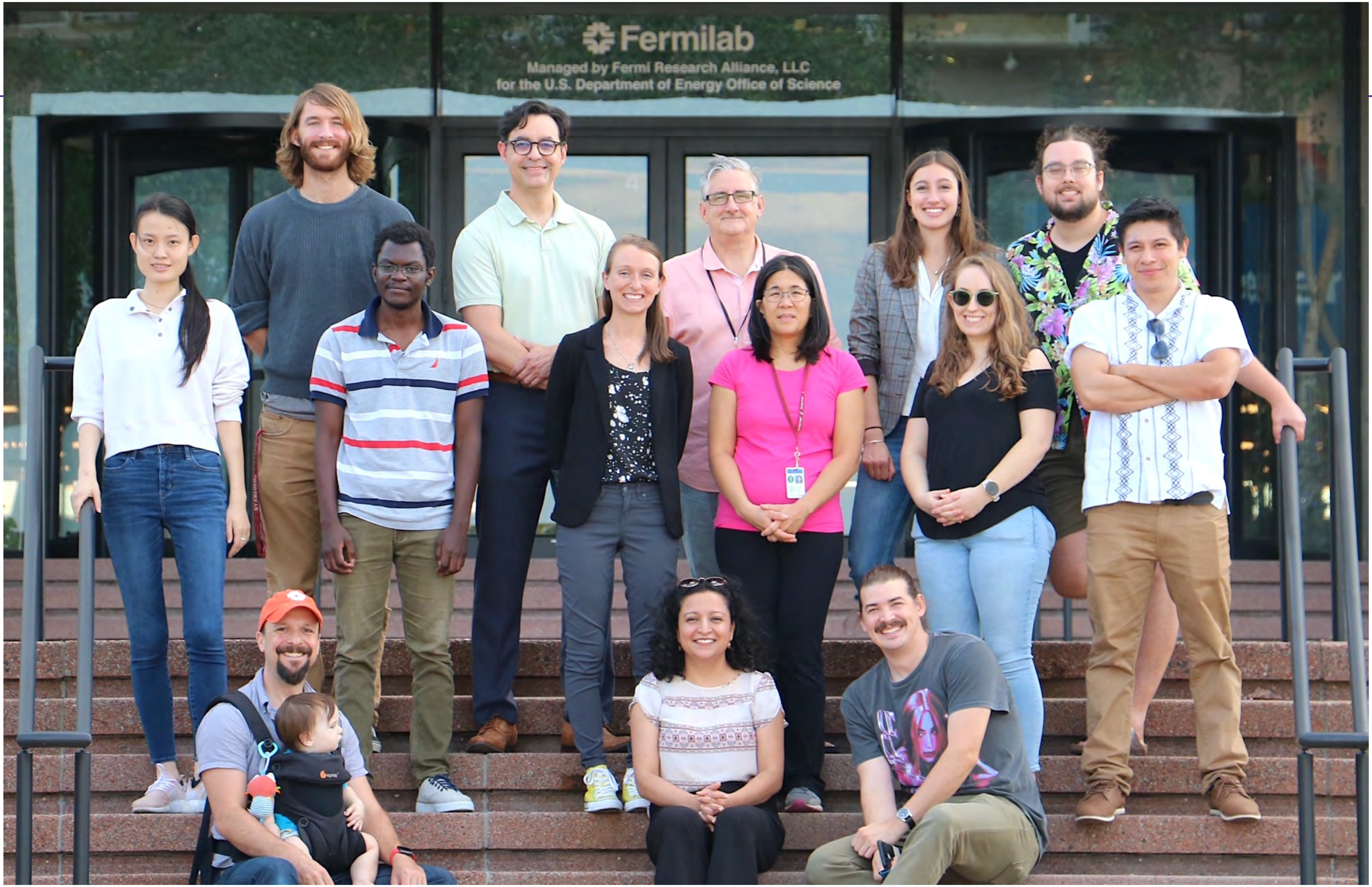
- **FNAL**: Aaron Chou, Daniel Bowring, Gustavo Cancelo, Lauren Hsu, Adam Anderson, Daniel Baxter, Sami Lewis, Ryan Linehan, Kelly Stifter, Dylan Temples
- **IIT**: Rakshya Khatiwada (joint w/ FNAL), Kester Anyang, Israel Hernandez, Jialin Yu
- **Northwestern University**: Enectali Figueroa-Feliciano (joint w/ FNAL), Valentina Novati, Grace Bratrud, Alejandro Rodriguez

QSC External Collaborators:

- **UW Madison**: Robert McDermott, Sohair Abdullah, Gabe Spahn
- **SLAC**: Noah Kurinsky, Taj Dyson
- **Tufts**: Hannah Magoon (co-op w/ FNAL)

Postdocs/Students

Work supported by Daniel Bowring's ECA



Not pictured:
Aaron Chou (FNAL)
Gustavo Cancelo (FNAL)
Adam Anderson (FNAL)
Valentina Novati (NU)
Grace Bratrud (NU)
Alejandro Rodriguez (NU)

Postdocs Available!

Figueroa Lab

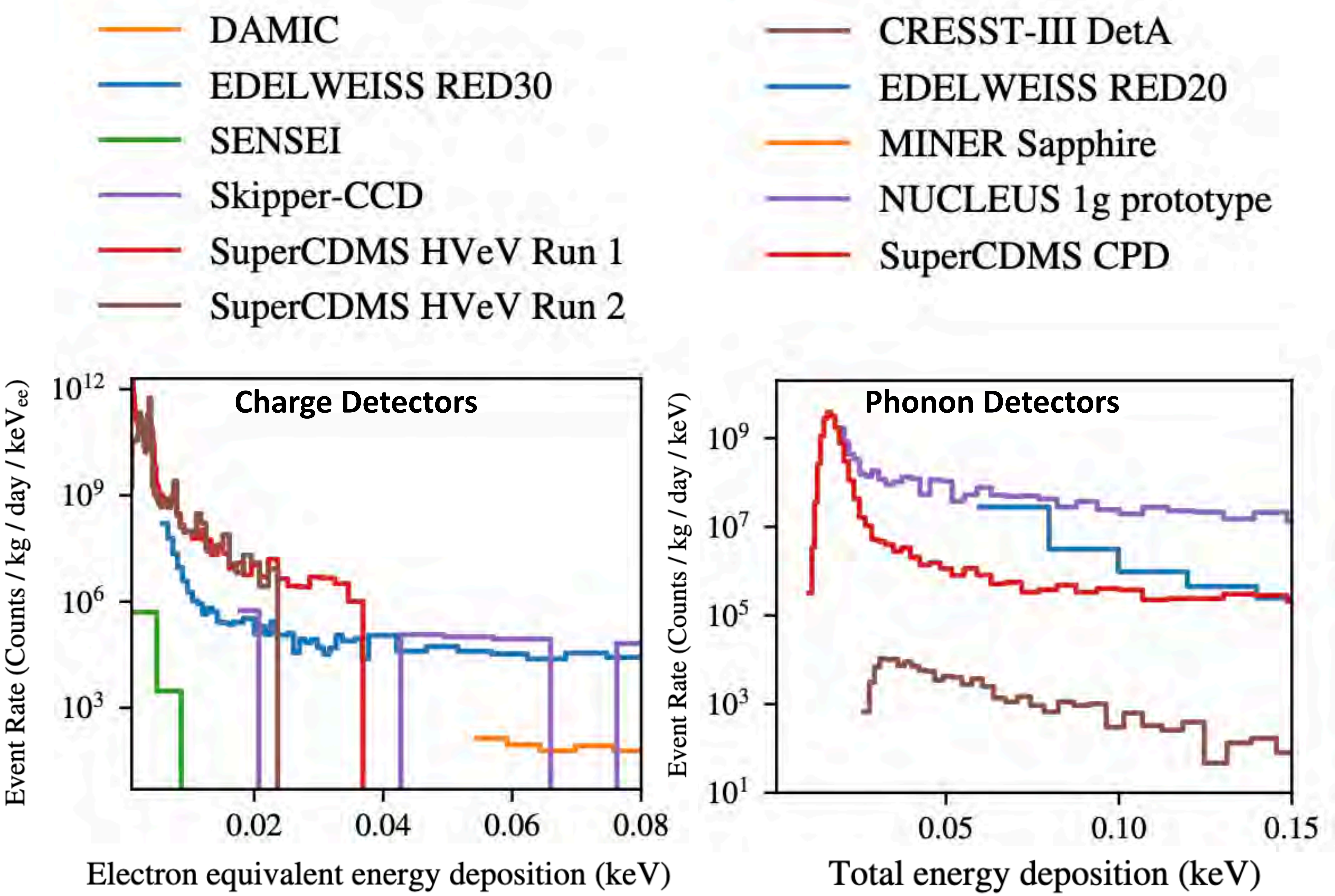
Backup Slides

Detector Backgrounds

What do backgrounds even look like below eV energies..?

Detector Backgrounds – The Phonon low-energy Excess

- **Problem! All low-threshold phonon detectors have large, unmodeled, uncalibrated backgrounds**



Summary of what we know:

1. **Non-ionizing**: produces a phonon signal, not charge
2. **Power Law**: spectral shape follows a power law out to high energies
3. **Time-since-cooldown**: background seems to decay with a long time constant since reaching mK temperatures

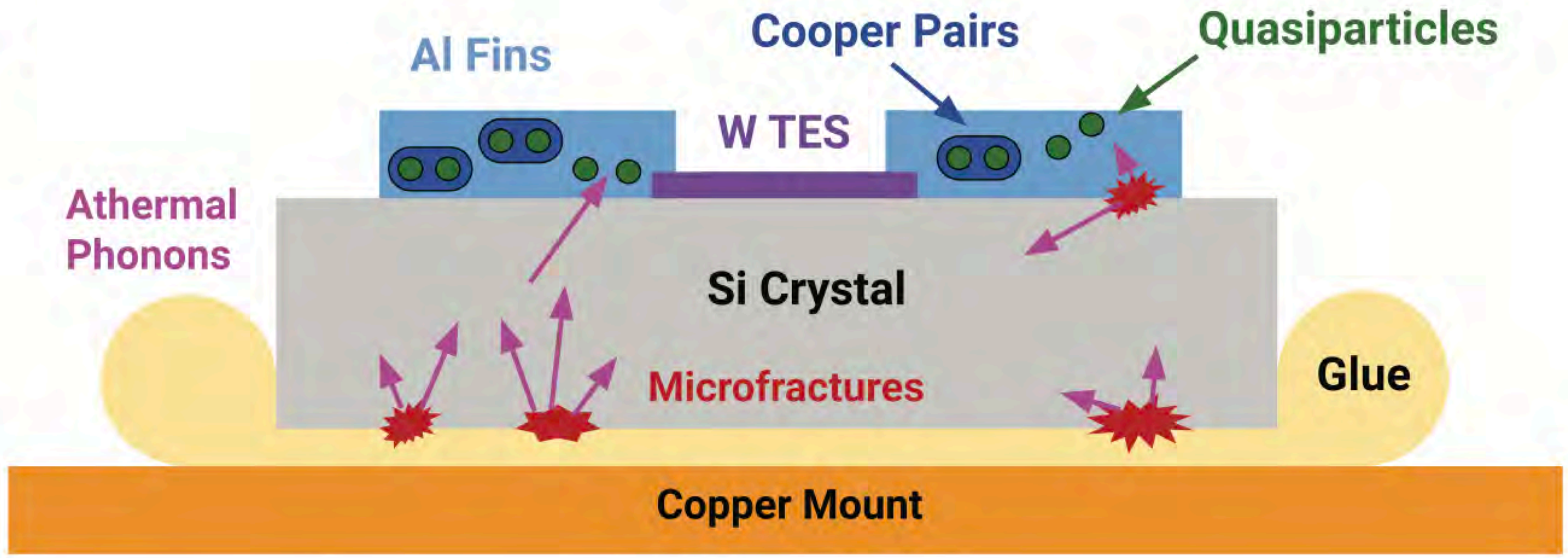
Adari et al, SciPost Phys. Proc. 9, 001 (2022) [arXiv:2202.05097]

Detector Backgrounds – The Phonon Excess

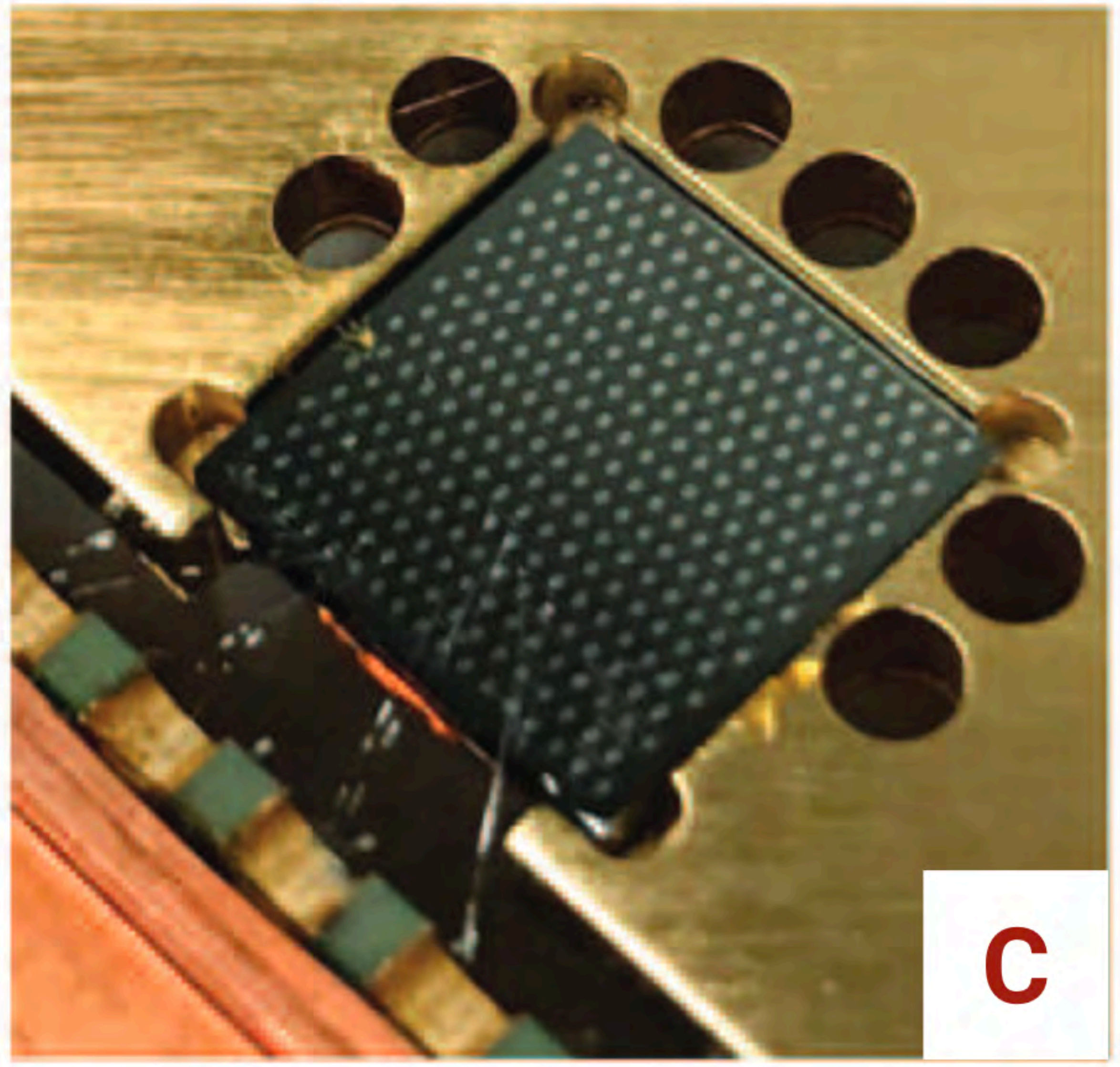
A Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning

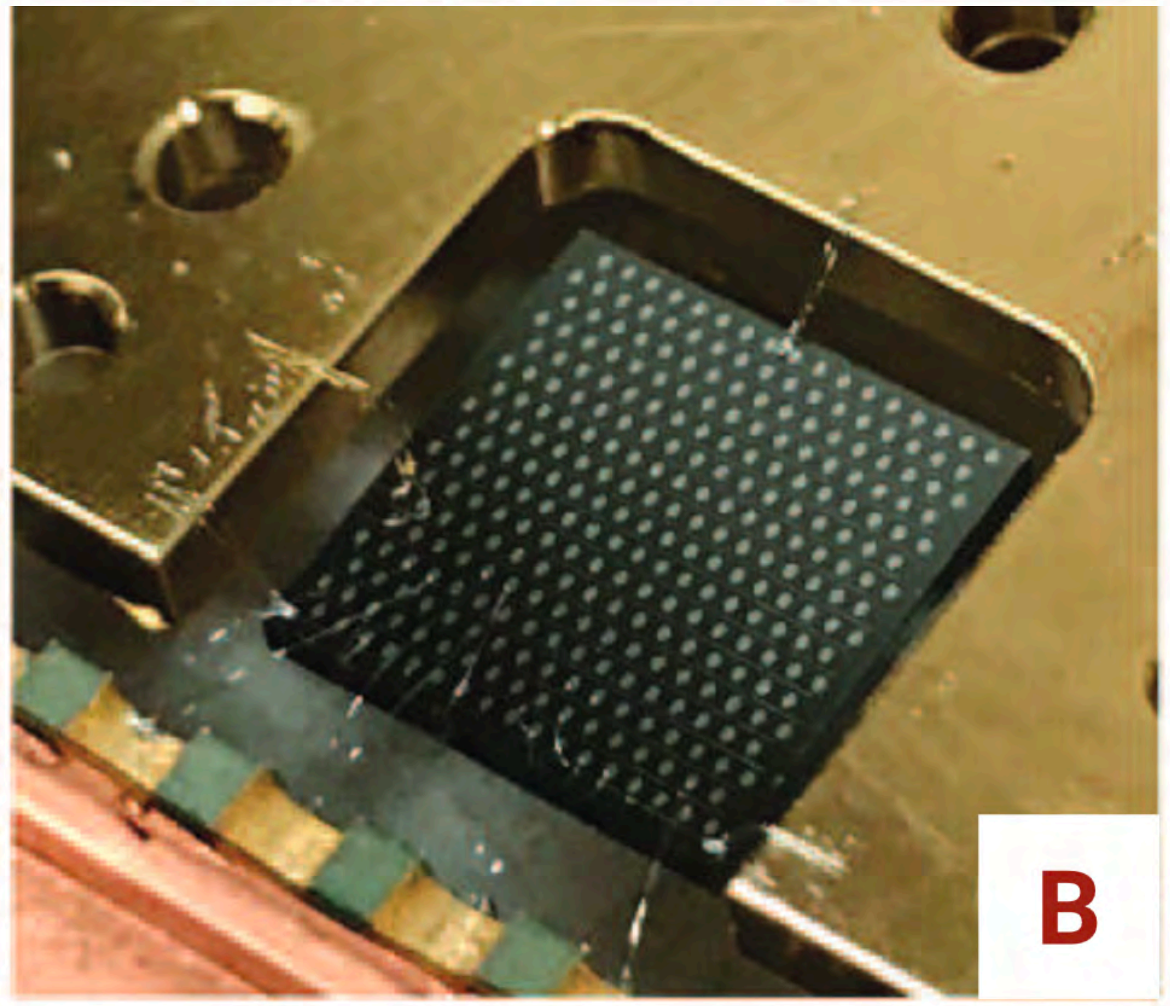
R. Anthony-Petersen,[1] A. Biekert,[1,2] R. Bunker,[3] C.L. Chang,[4,5,6] Y.-Y. Chang,[1] L. Chaplinsky,[7] E. Fascione,[8,9] C.W. Fink,[1] M. Garcia-Sciveres,[2] R. Germond,[8,9] W. Guo,[10,11] S.A. Hertel,[7] Z. Hong,[12] N.A. Kurinsky,[13] X. Li,[2] J. Lin,[1,2] M. Lisovenko,[4] R. Mahapatra,[14] A.J. Mayer,[9] D.N. McKinsey,[1,2] S. Mehrotra,[1] N. Mirabolfathi,[14] B. Neblosky,[15] W.A. Page,[1,*] P.K. Patel,[7] B. Penning,[16] H.D. Pinckney,[7] M. Platt,[14] M. Pyle,[1] M. Reed,[1] R.K. Romani,[1,*] H. Santana Queiroz,[1] B. Sadoulet,[1] B. Serfass,[1] R. Smith,[1,2] P. Sorensen,[2] B. Suerfu,[1,2] A. Suzuki,[2] R. Underwood,[8] V. Velan,[1,2] G. Wang,[4] Y. Wang,[1,2] S.L. Watkins,[1] M.R. Williams,[16] V. Yefremenko,[4] and J. Zhang[4]

arXiv:2208.02790

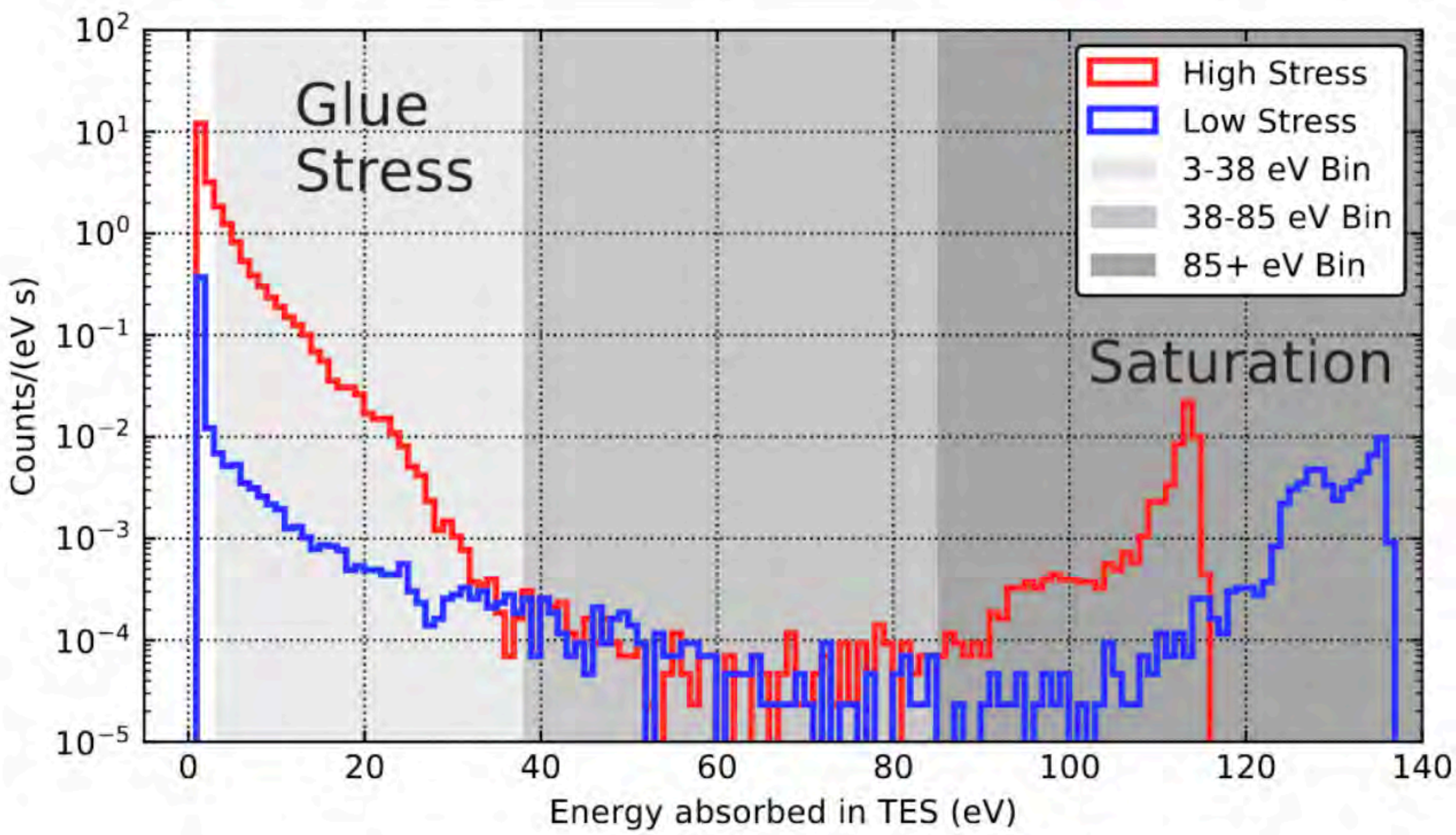


Detector Backgrounds – The Phonon Excess





Anthony-Petersen et al, (2022) [arXiv:2208.02790]



Detector Backgrounds – The Phonon Excess

- For two studies of superconducting qubit decoherence, this could be a dominant source of quasiparticle poisoning over high-energy contributions!!!

Impact of ionizing radiation on superconducting qubit coherence

Antti P. Vepsäläinen, Amir H. Karamlou, John L. Orrell, Akshunna S. Dogra, Ben Loer, Francisca Vasconcelos, David K. Kim, Alexander J. Melville, Bethany M. Niedzielski, Jonilyn L. Yoder, Simon Gustavsson, Joseph A. Formaggio, Brent A. VanDevender & William D. Oliver

Nature **584**, 551–556 (2020) | Cite this article

A superconductor free of quasiparticles for seconds

E. T. Mannila, P. Samuelsson, S. Simbierowicz, J. T. Peltonen, V. Vesterinen, L. Grönberg, J. Hassel, V. F. Maisi & J. P. Pekola

Nature Physics **18**, 145–148 (2022) | Cite this article

Anthony-Petersen et al, (2022) [arXiv:2208.02790]

In the case of the qubit, we find that our stress-induced background would produce a reduced quasiparticle density of $x_{qp} \approx 5.0 \times 10^{-8}$, while high-energy backgrounds should induce $x_{qp} \approx 1.5 \times 10^{-8}$. The latter is in general agreement with the lower bound of $x_{qp} \geq 7 \times 10^{-9}$ estimated in Ref. [11] for high-energy backgrounds. For the system in Ref. [15], we find that our stress events induce $x_{qp} \approx 2.8 \times 10^{-11}$, while high-energy backgrounds induce $x_{qp} \approx 3.3 \times 10^{-10}$.

7/8/2023 Enectali Figueroa-Feliciano \ Northwestern University \ RIKEN Colloquium

Summary of NEXUS Work

Dark Matter Searches with SuperCDMS

- Dark Matter Limits from runs at Northwestern and NEXUS
- Ionization measurements at Duke through the IMPACT program

Neutrino Physics with Ricochet and CUPID

- Developed new modular architecture for neutrino physics detectors
- Deploying at Ricochet next year
- R&D for future CUPID upgrades

Low-background Quantum Computing

- Qubit testing underway underground at NEXUS
- Developing R&D program for low-background quantum architectures

SUPER CDMS
Cryogenic Dark Matter Search

RICOCHET

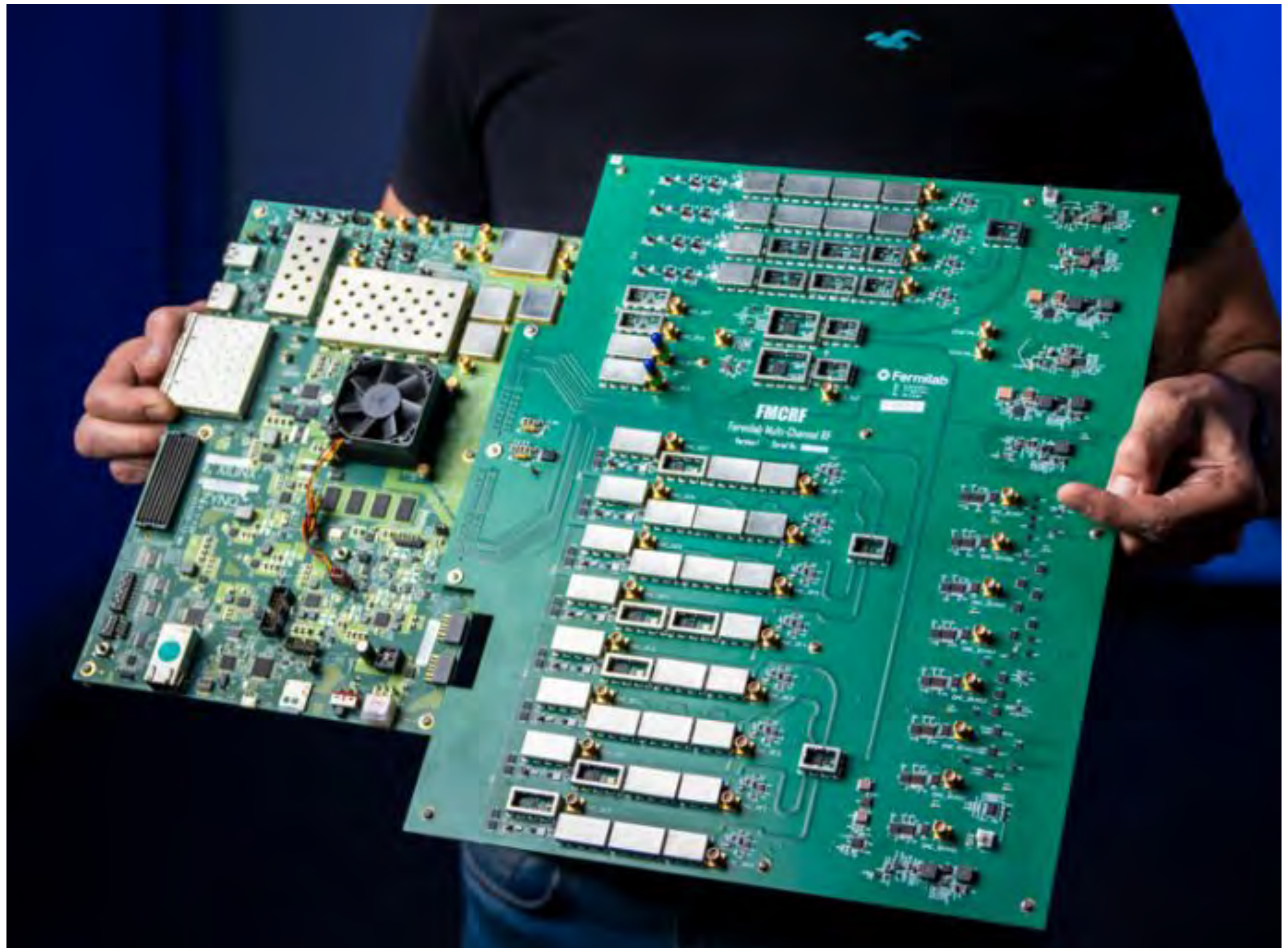
CUPID

Northwestern NEXUS
Experimental Underground Site @Fermilab

Designing an Experiment

FNAL group has progress on many fronts towards this goal!

[QICK = “Quantum Instrumentation Control Kit”]



- **Fully integrated readout & control system for QIS, quantum networks, and superconducting detectors**
  - No extra room temperature hardware needed.
  - QICK paper made the cover of AIP RSI
  - 11 talks at APS March Meeting (not including the 2 from FNAL)
- A factor of ~20 cheaper compared to off-the-shelf equipment
- Plans for frequency-multiplexed readout and control of multiple qubits this Fall

Stefanazzi et al, Rev. Sci. Instrum. 93, 044709 (2022) [arXiv:2110.00557]