IOP APP, HEPP and NP Conference
10/04/2024
Liverpool

QUEST DMC

QUantum Enhanced Superfluid Technologies for Dark Matter & Cosmology

Searching for Sub-GeV Dark Matter Using a Helium-3 Calorimeter and Quantum Sensor Readout

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QUEST-DMC Collaboration

University of Liverpool

University of Sussex

Royal Holloway University of London

Lancaster University

University of Oxford

1. Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter

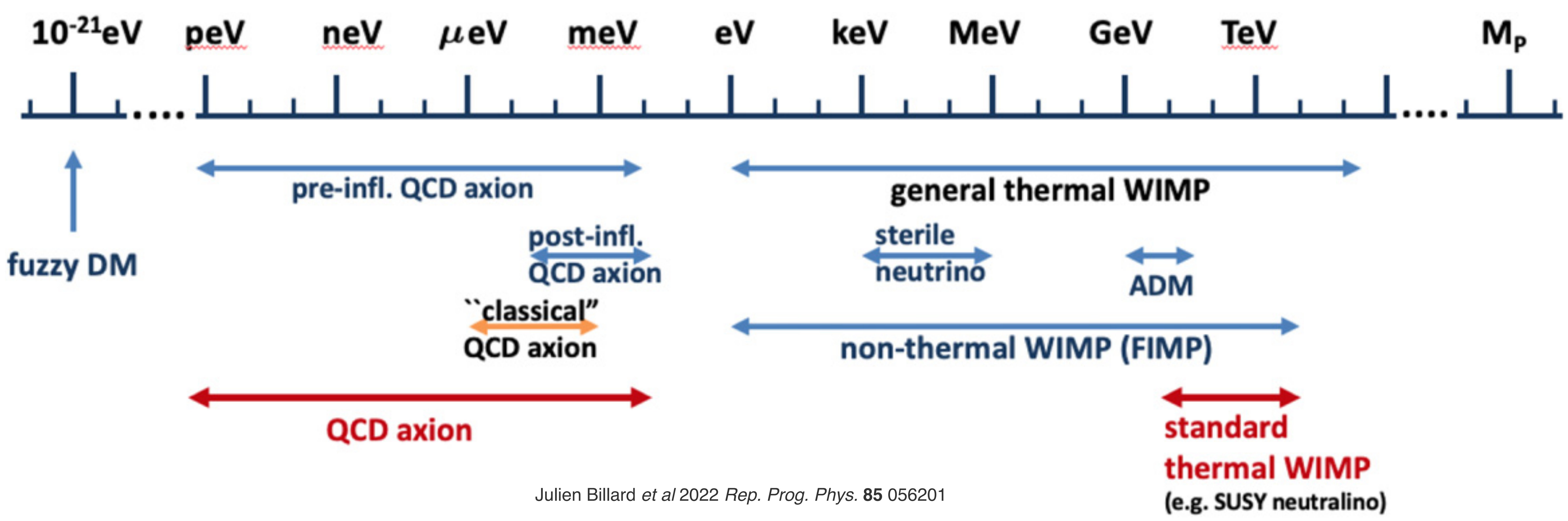
2. Phase transitions in extreme matter, relevant to cosmology and gravitational wave production

UKRI Engineering and Physical Sciences Research Council

UKRI Science and Technology Facilities Council

Motivations & Goals

- 85% of matter in the universe is “dark”
- Theoretical motivation for sub-GeV dark matter (ADM, Hidden Sector, Freeze-in…)
- Lower threshold = lower mass DM interaction reach
- Superfluid ^{3}He target enables eV scale recoil threshold and increased spin-dependent interaction sensitivity



Julien Billard *et al* 2022 *Rep. Prog. Phys.* **85** 056201

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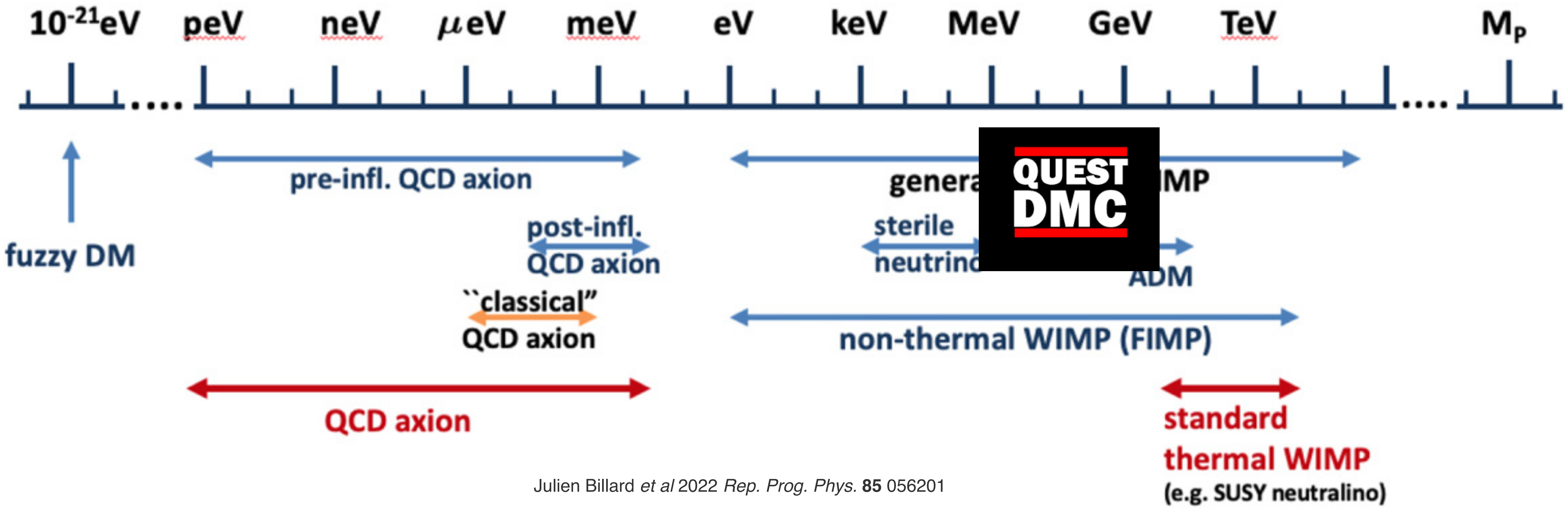

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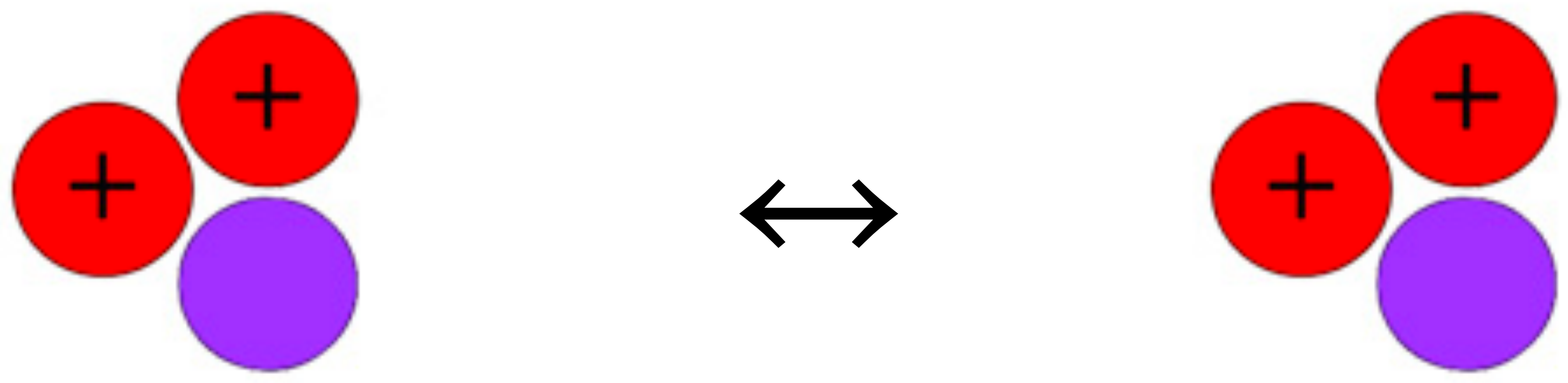
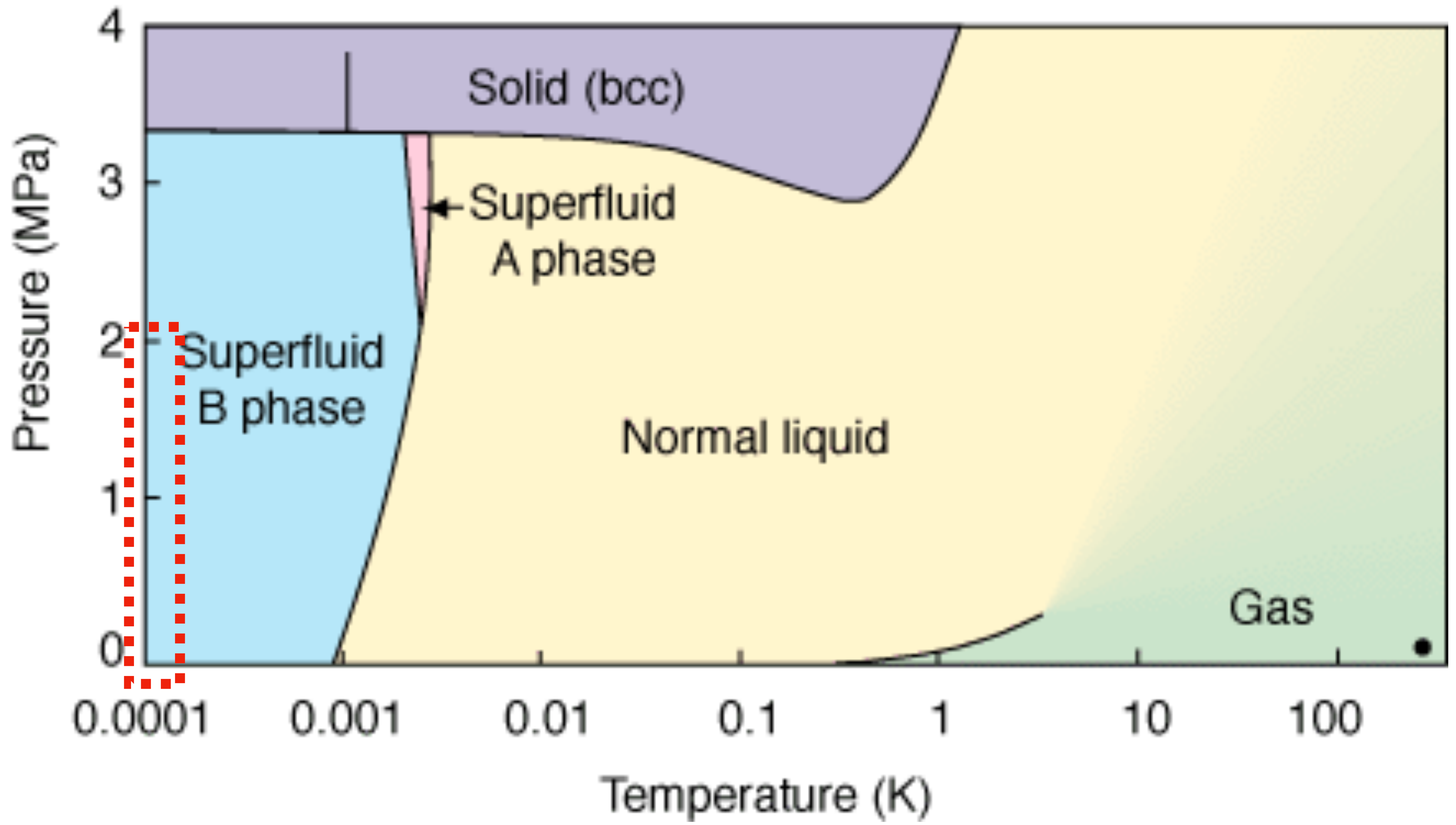
Why Helium-3?

- Spin 1/2 nucleus - sensitivity to spin-dependent interactions
- Superfluid below T_C of ~1 mK (0 bar)
- Form bound states analogous to Cooper pairs in superconductors
- Quanta of **10^{-7} eV**



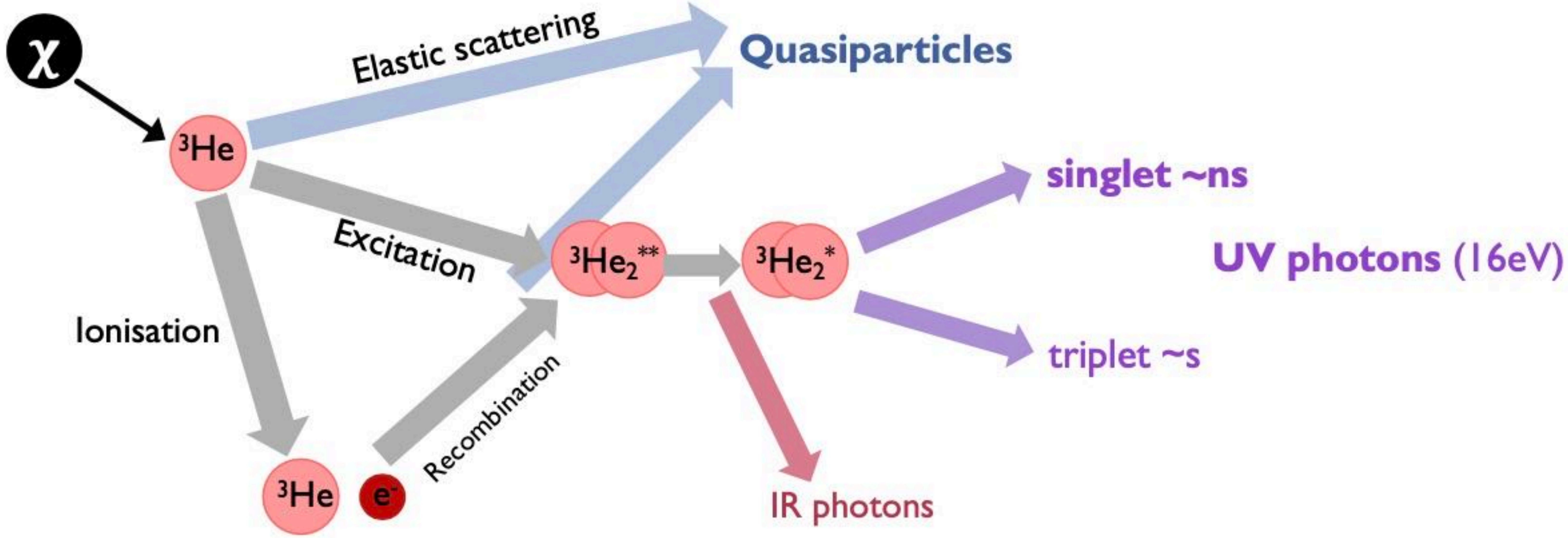
Δ_{gap} = 10^{-7} eV

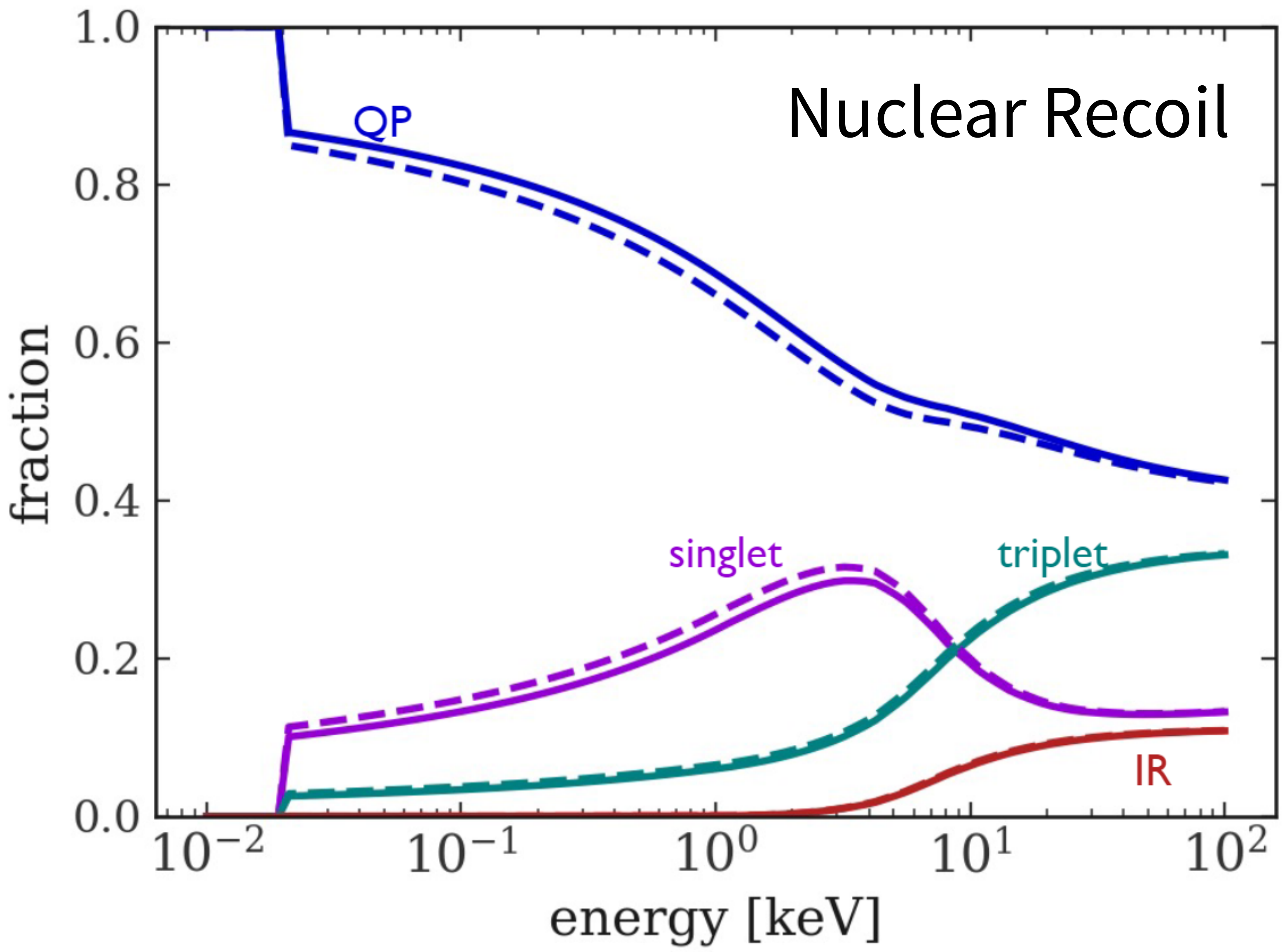


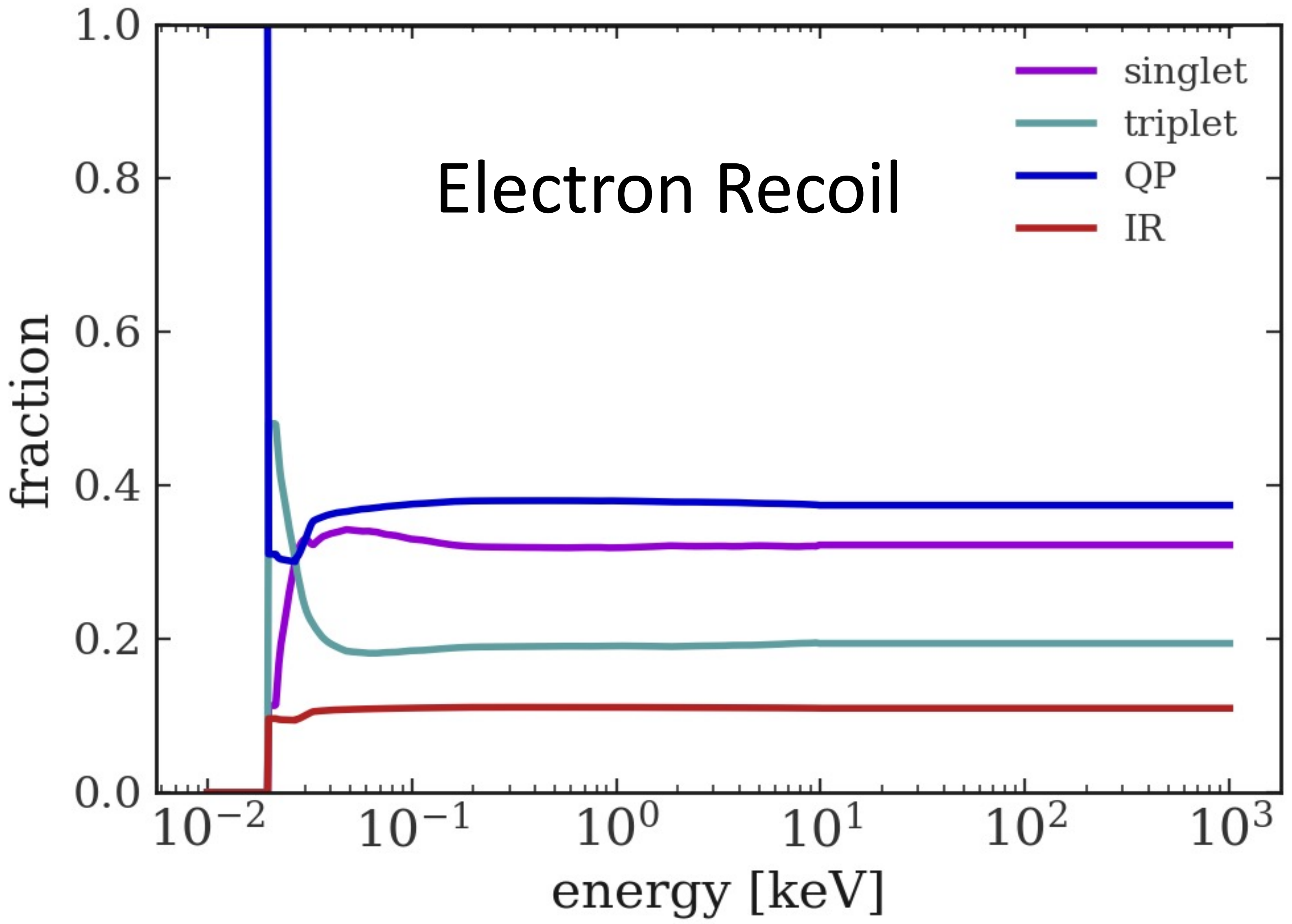
Phase diagram for ^{3}He

Interaction Response

- Sensitive to DM interactions producing nuclear & electronic recoils (20 eV threshold for ER)
- Quasiparticles (QP) released from breaking of Cooper pairs (10^7 QP per eV deposit)
- Secondary signal from scintillation

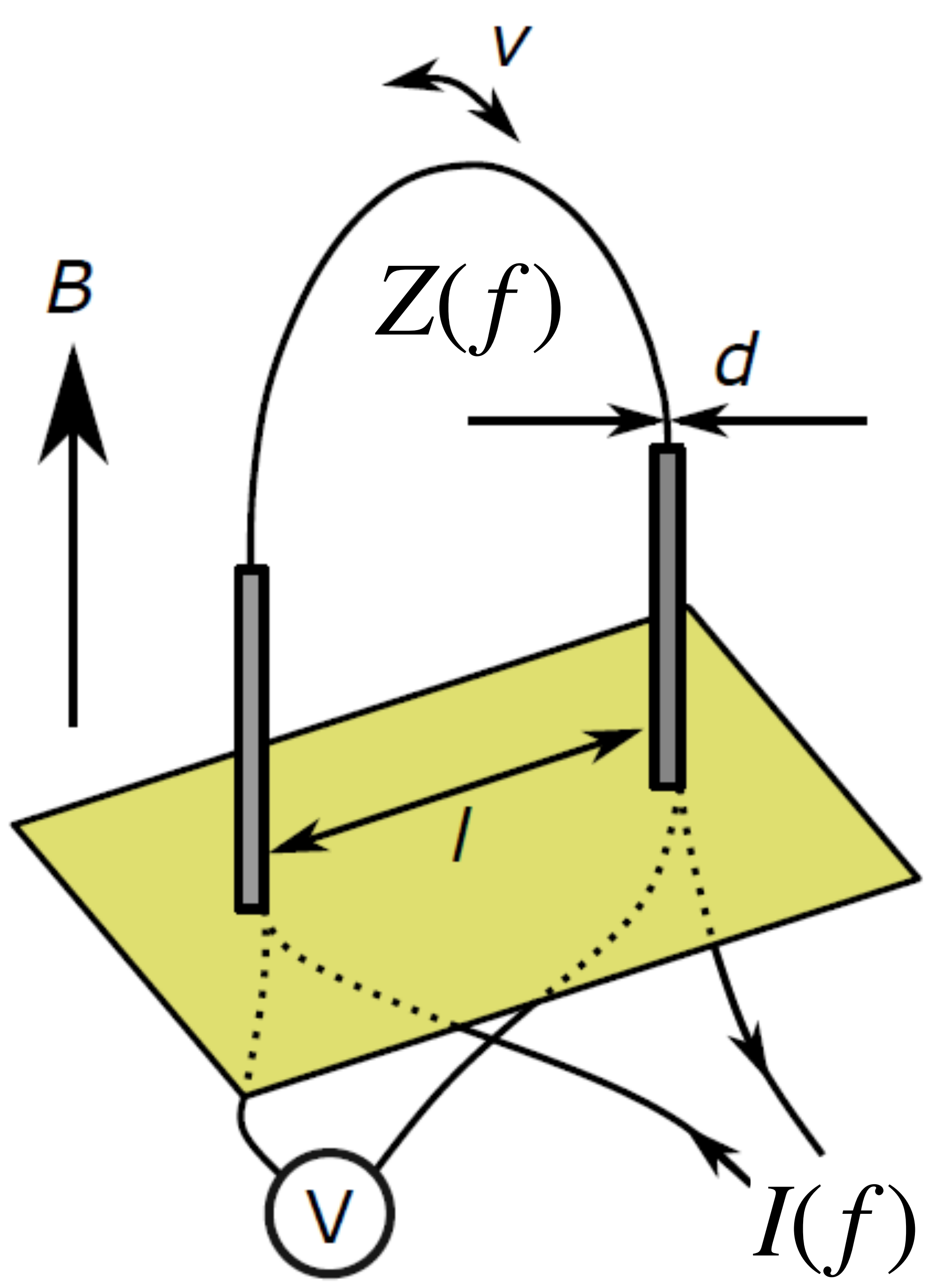






QUEST-DMC Detector

Oscillating superconducting wire in a magnetic field **B** driven at frequency **f**



$Z(f)$

QUEST-DMC Detector

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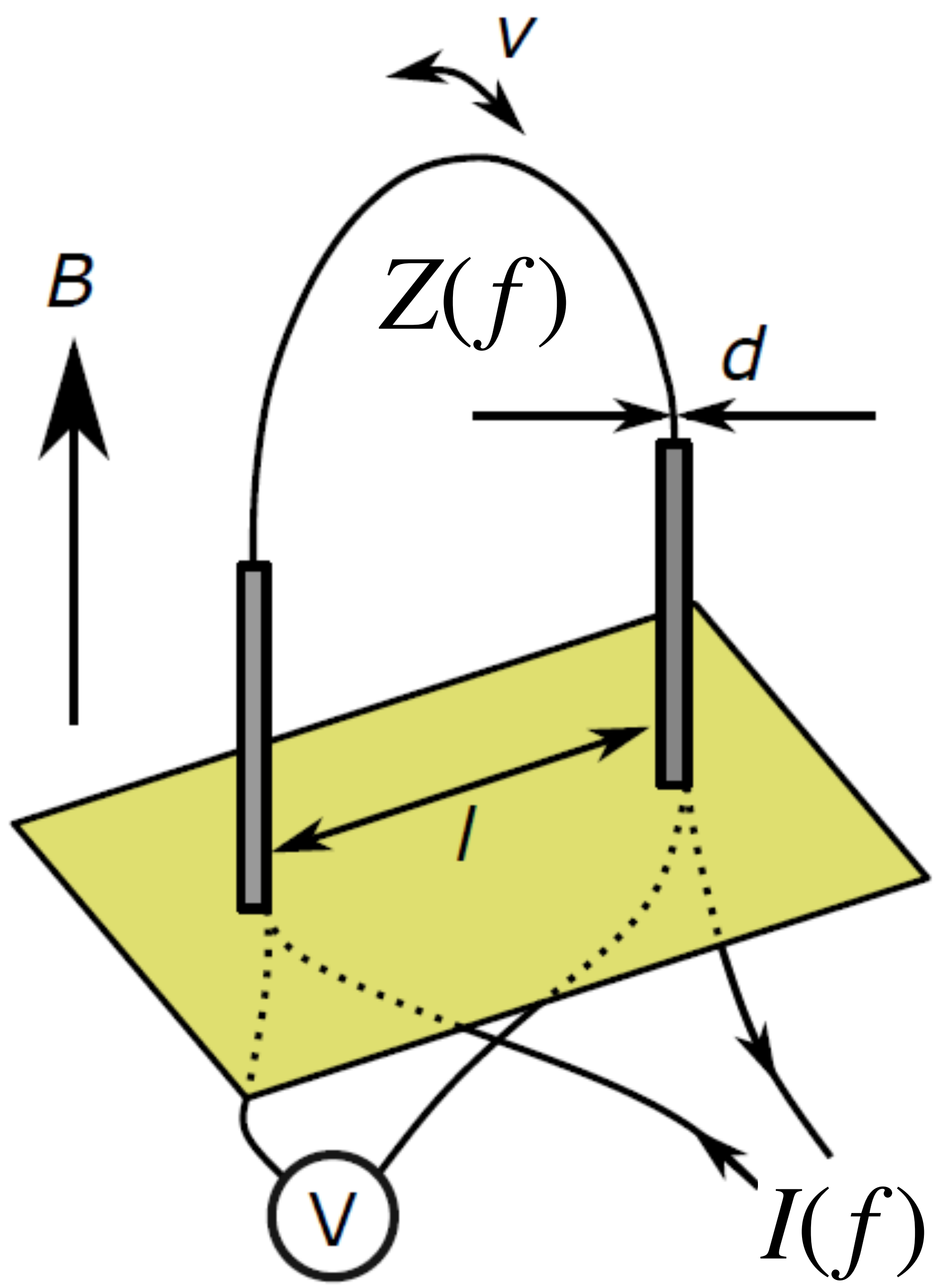
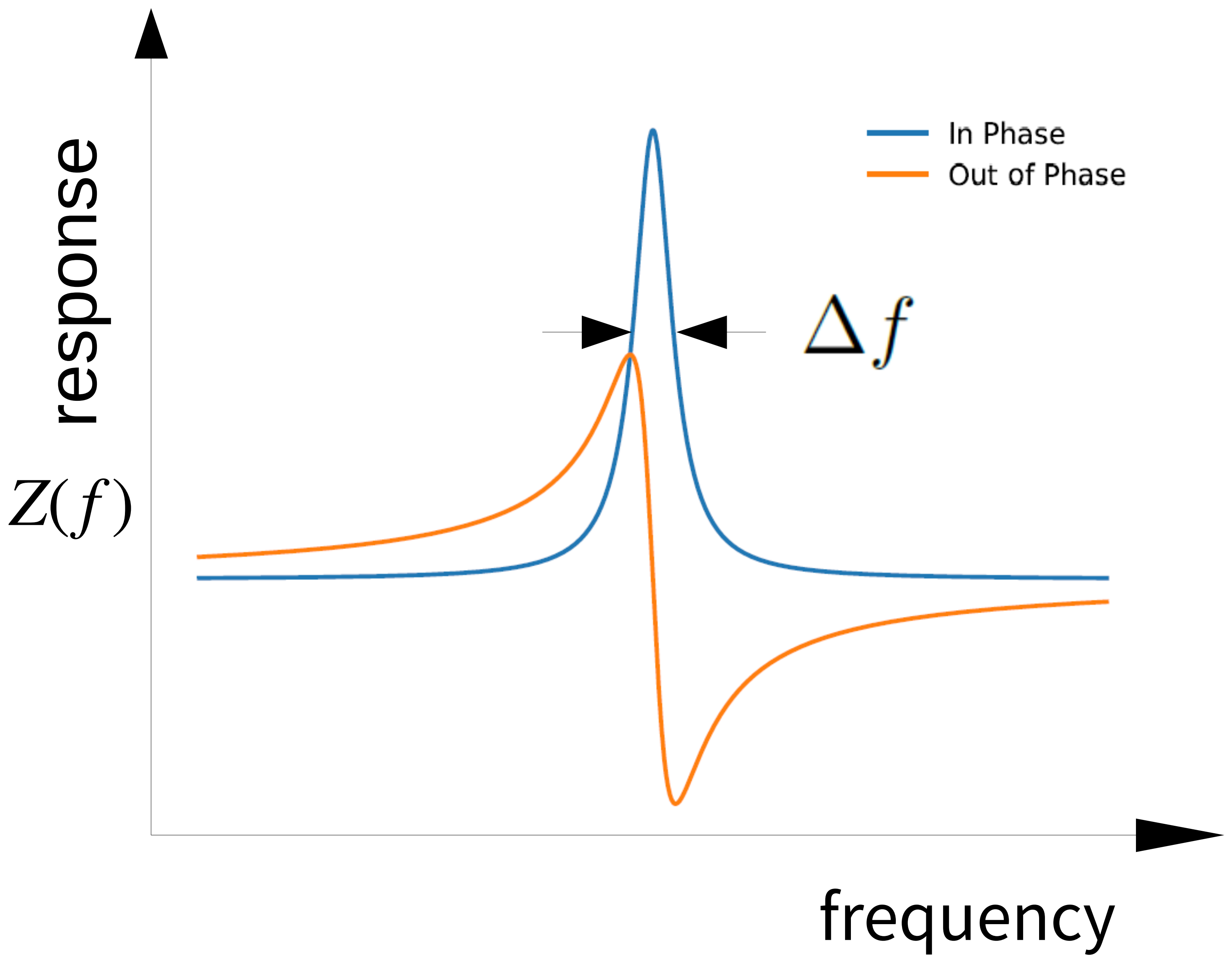


Impedance **Z(f)** of circuit Lorentzian in shape with some FWHM Δf



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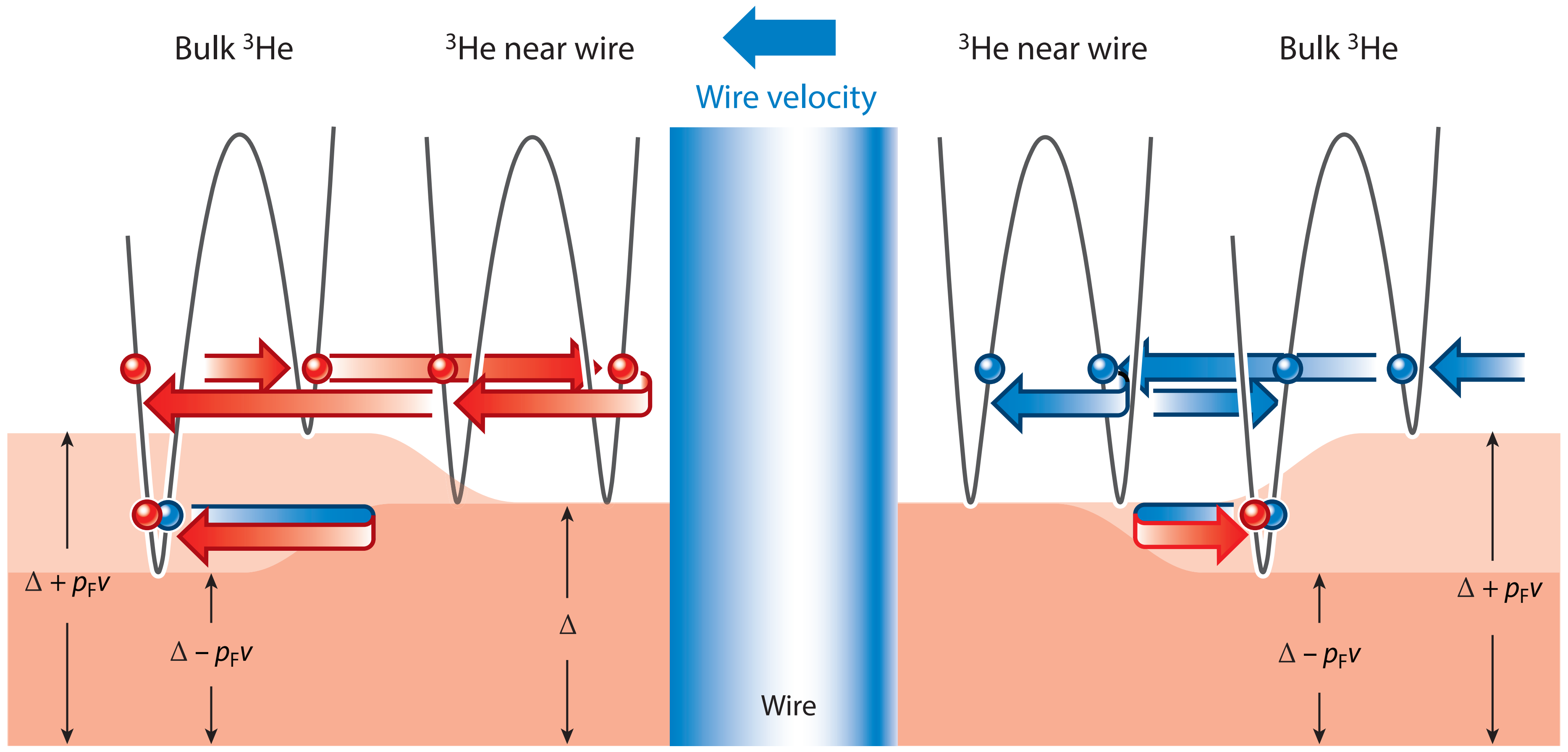

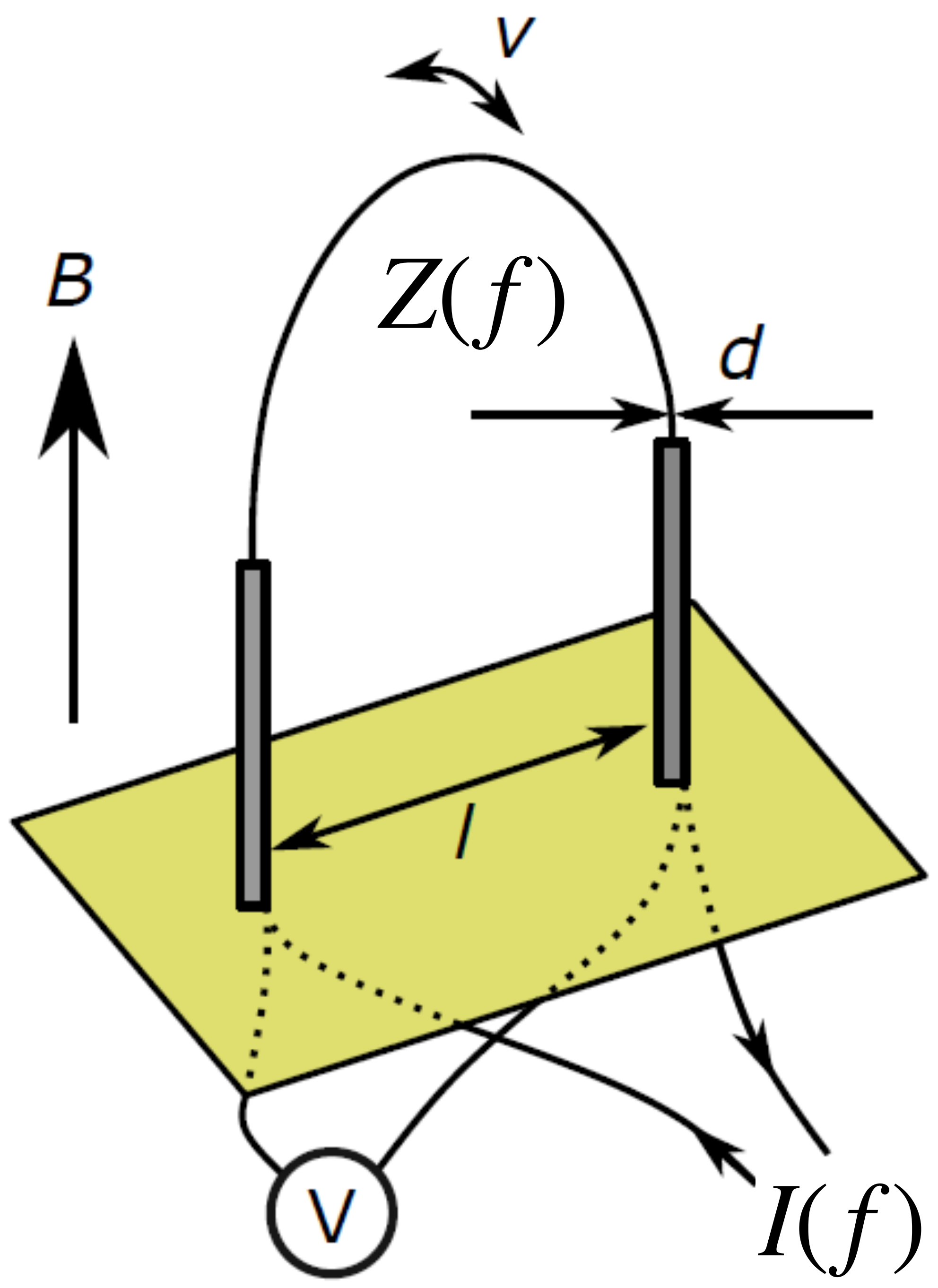

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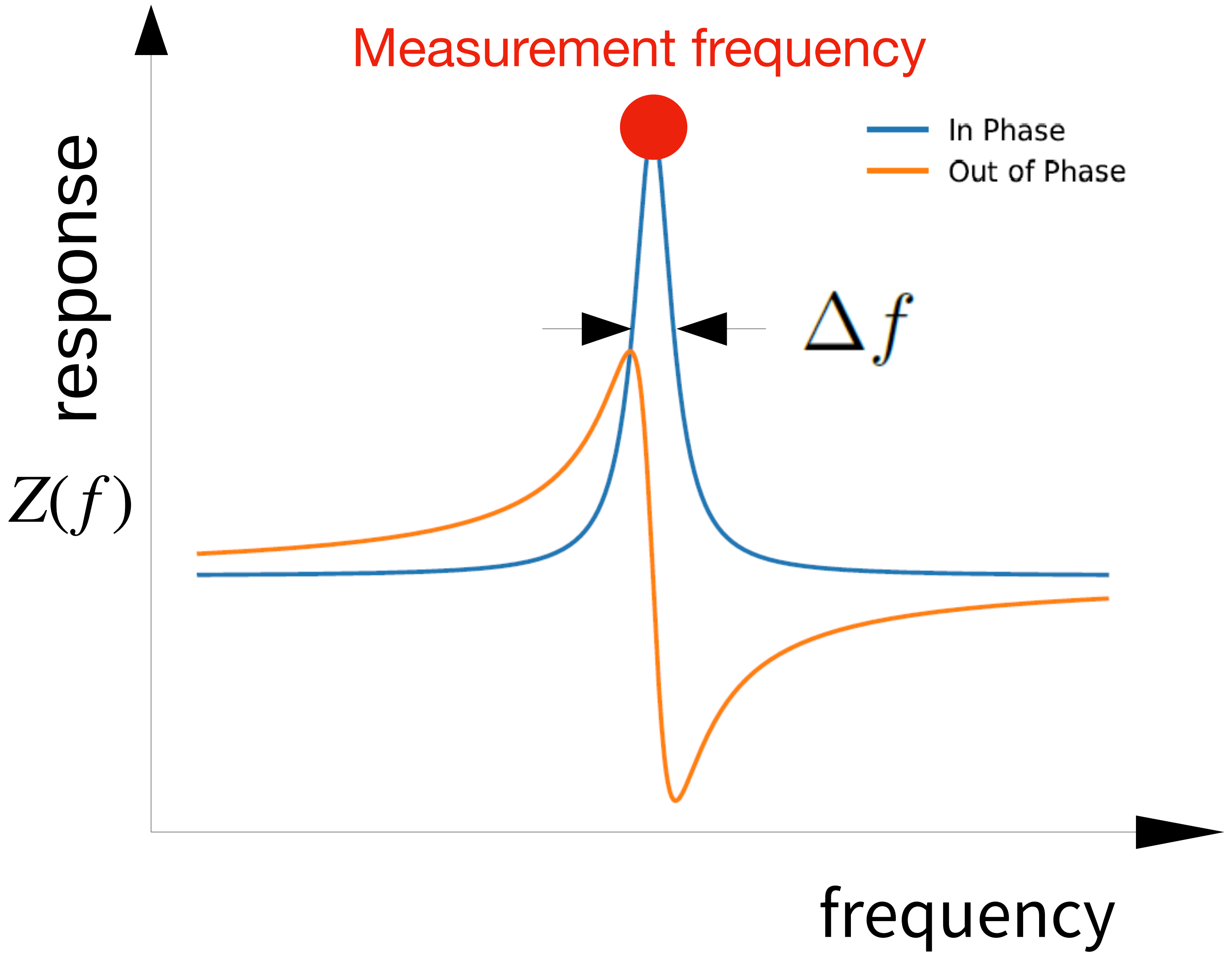

Damping force F on wire due to QP interactions - Δf directly proportional to F

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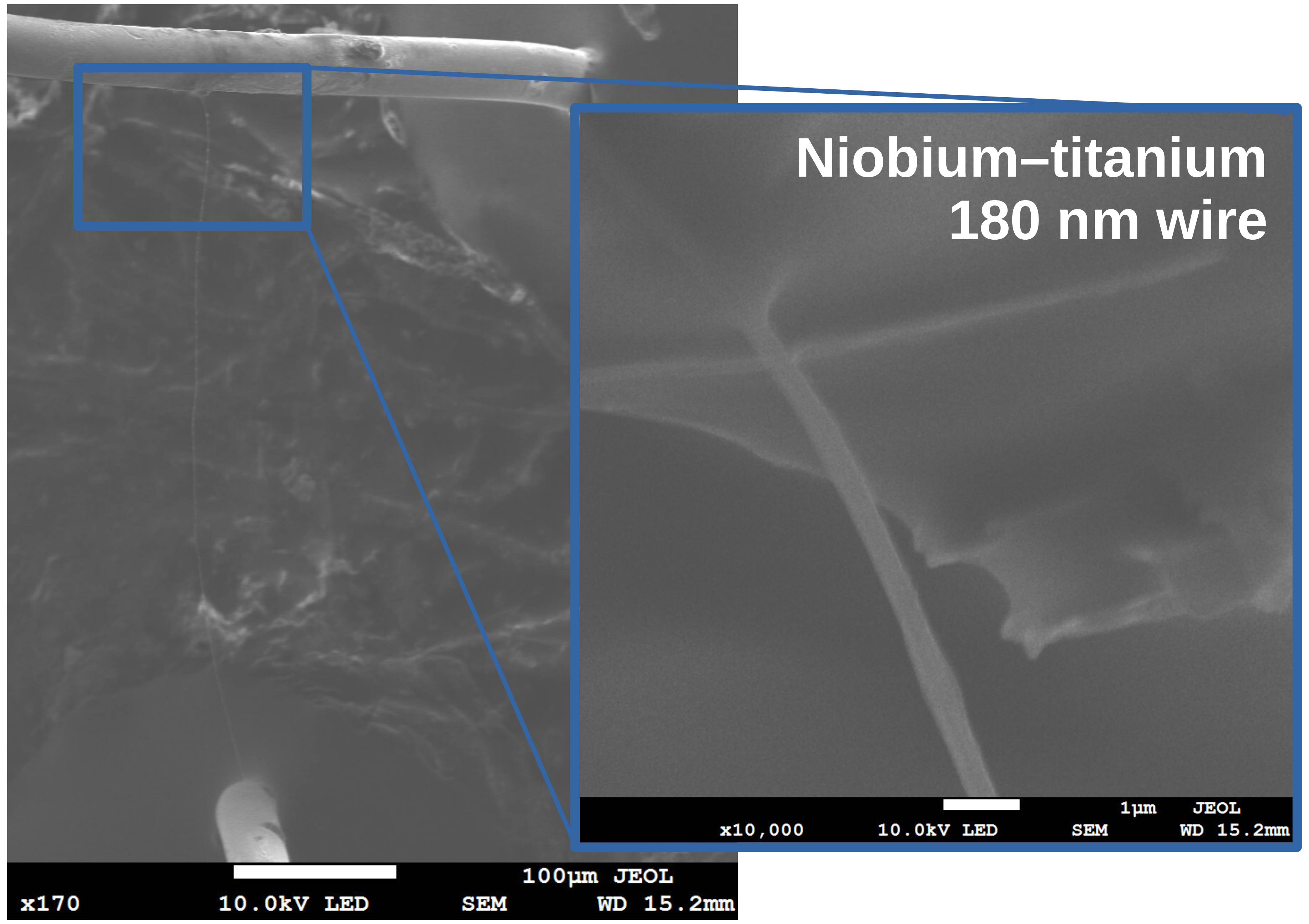

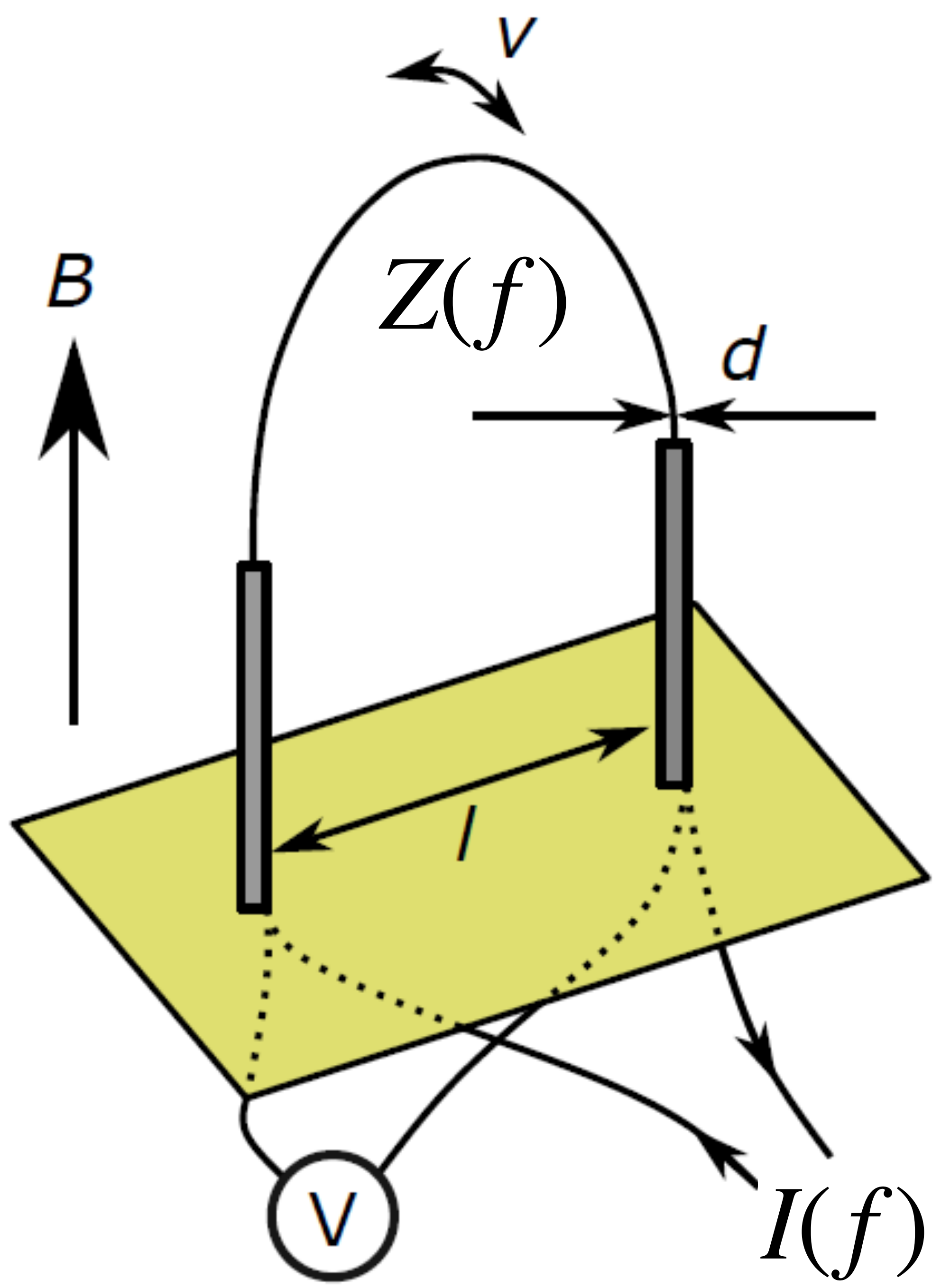

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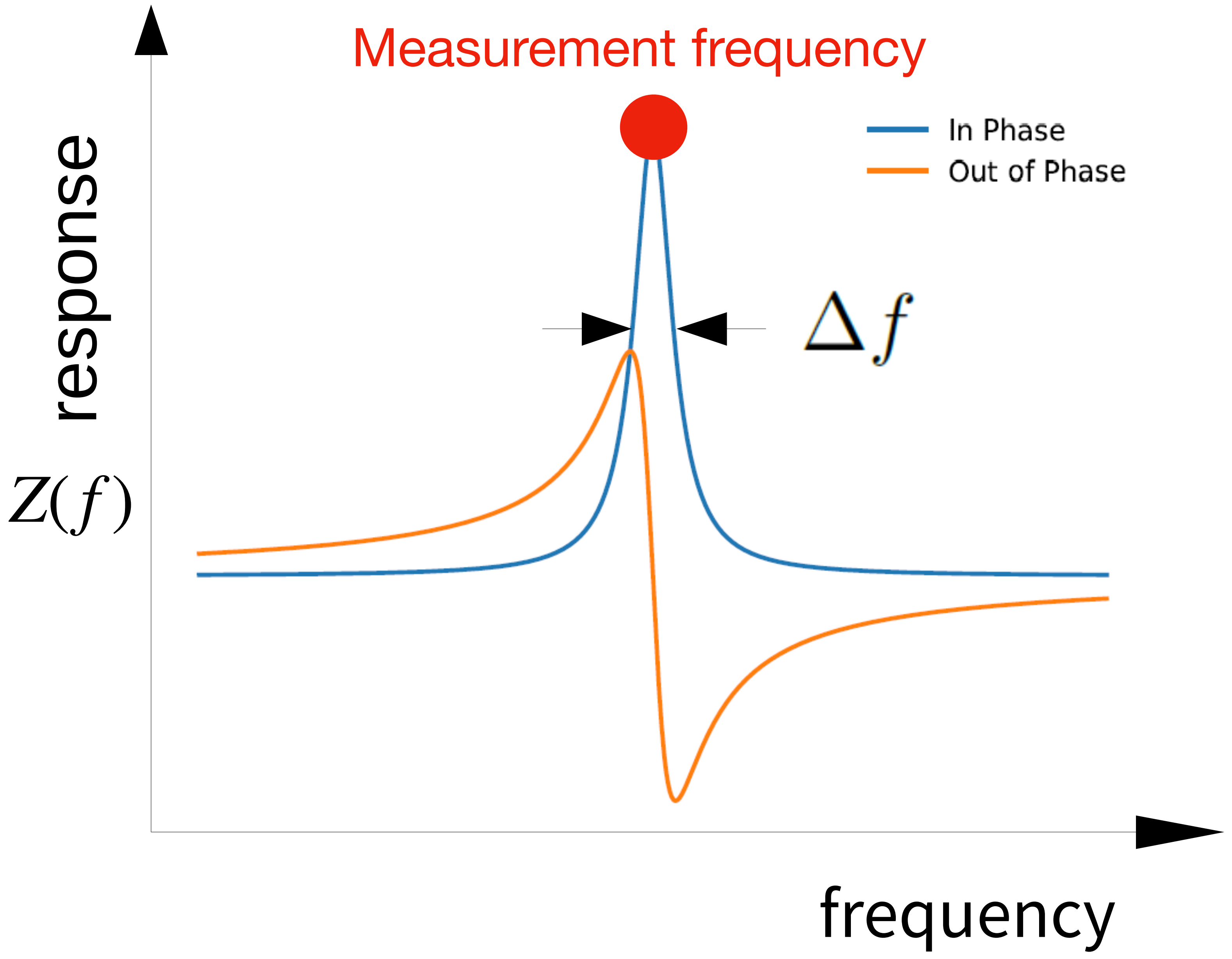
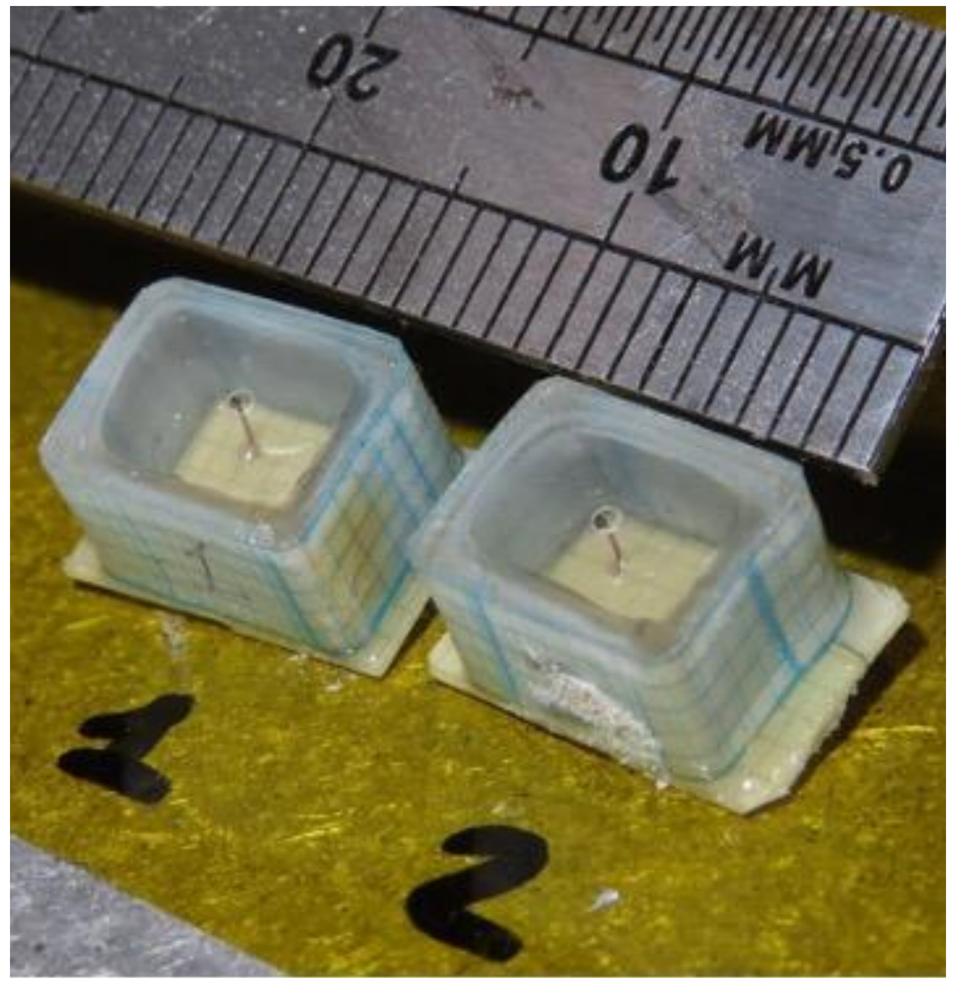
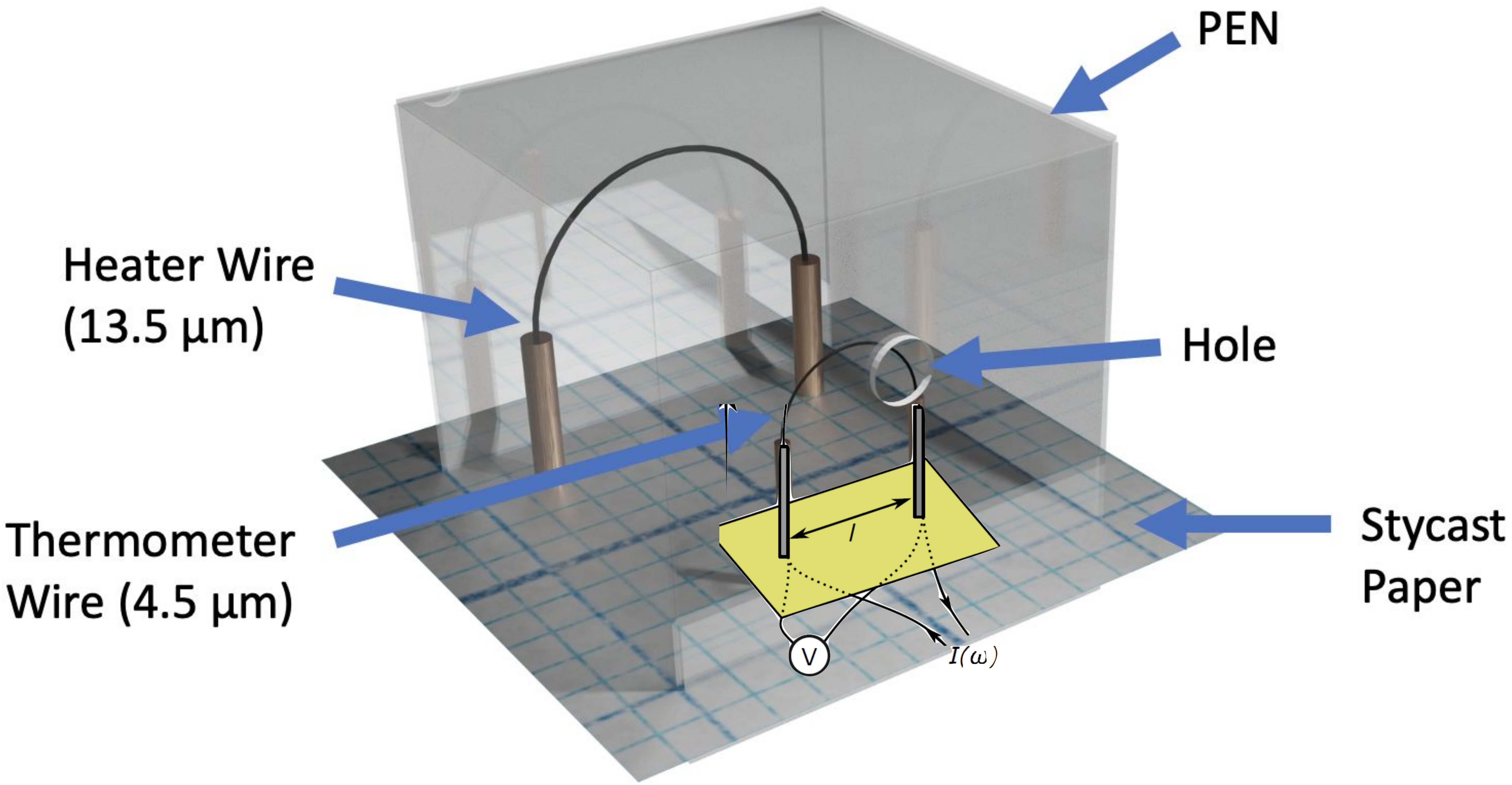


Paper on nanowire production: https://arxiv.org/abs/2311.02452

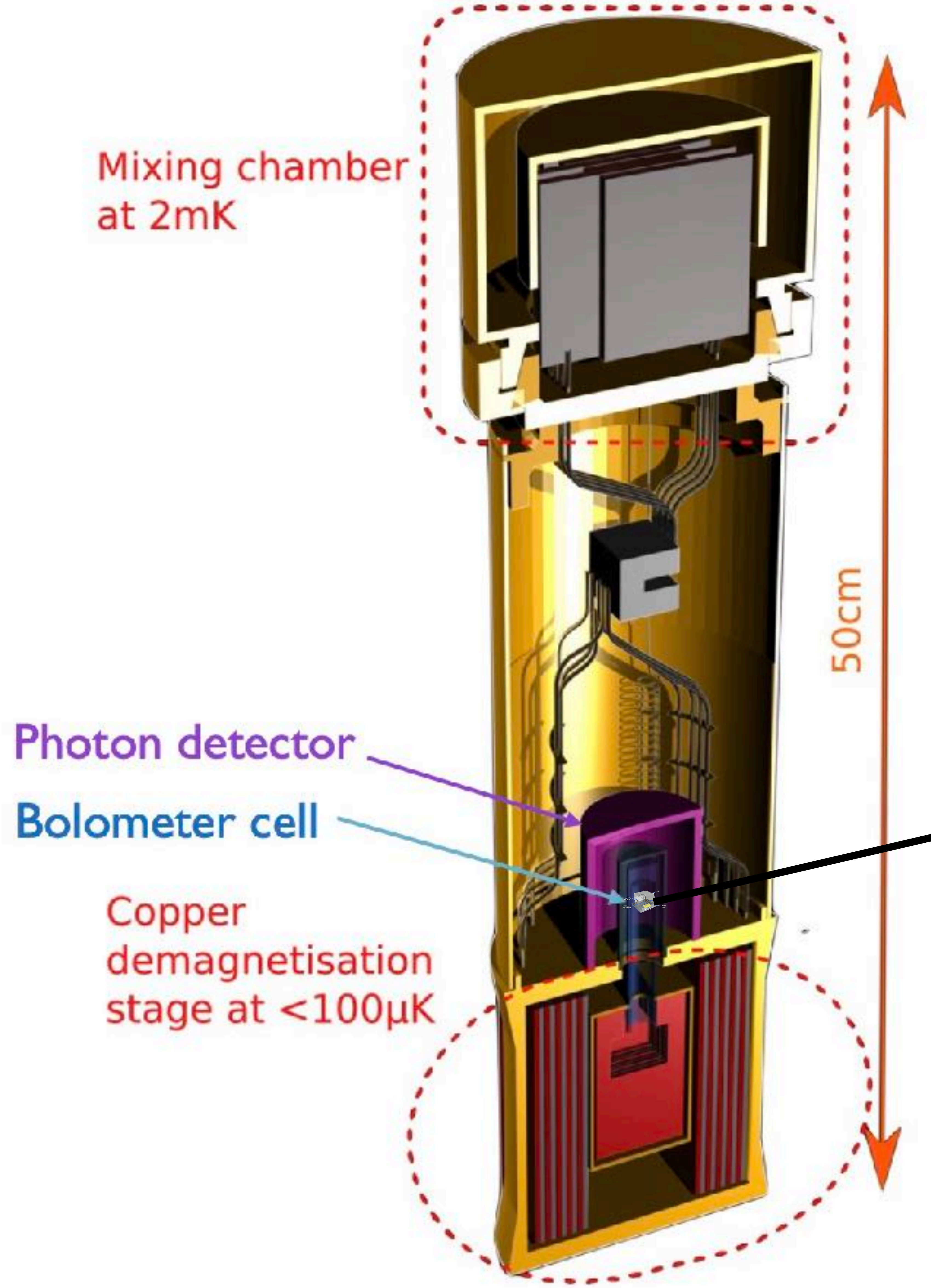
QUEST-DMC Detector

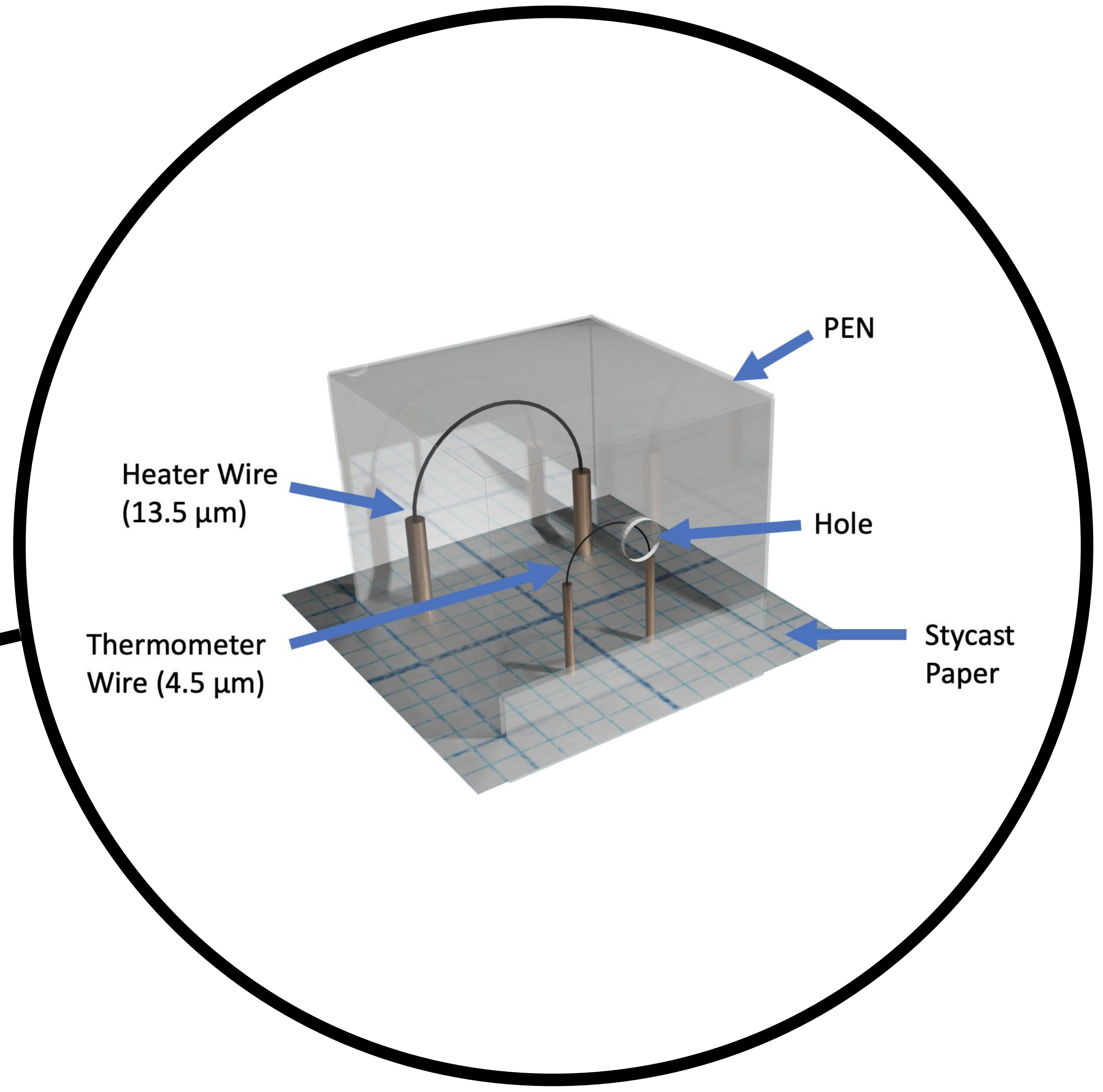




1st generation prototype cell ~ 0.33 cm^3

QUEST-DMC Detector





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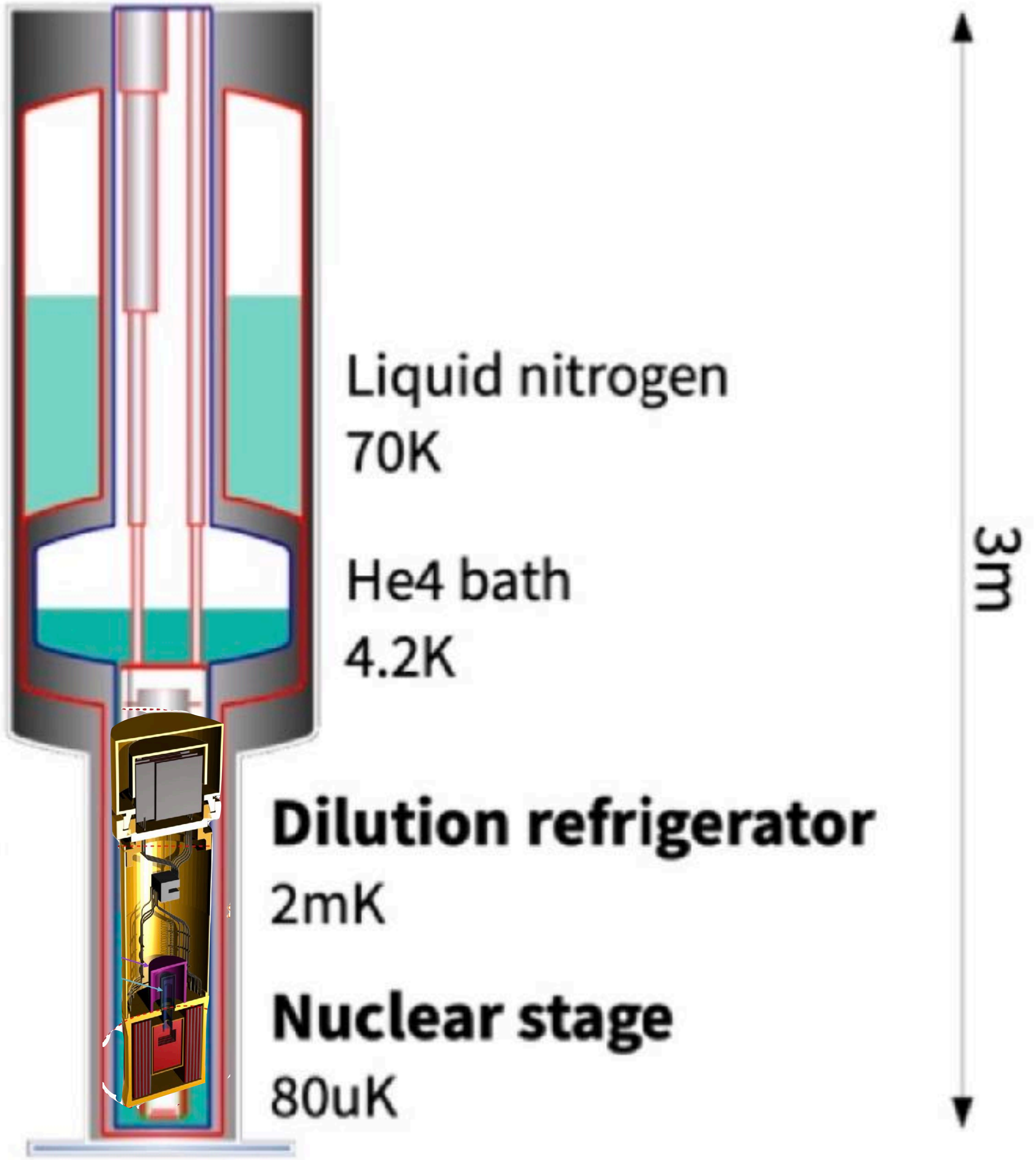
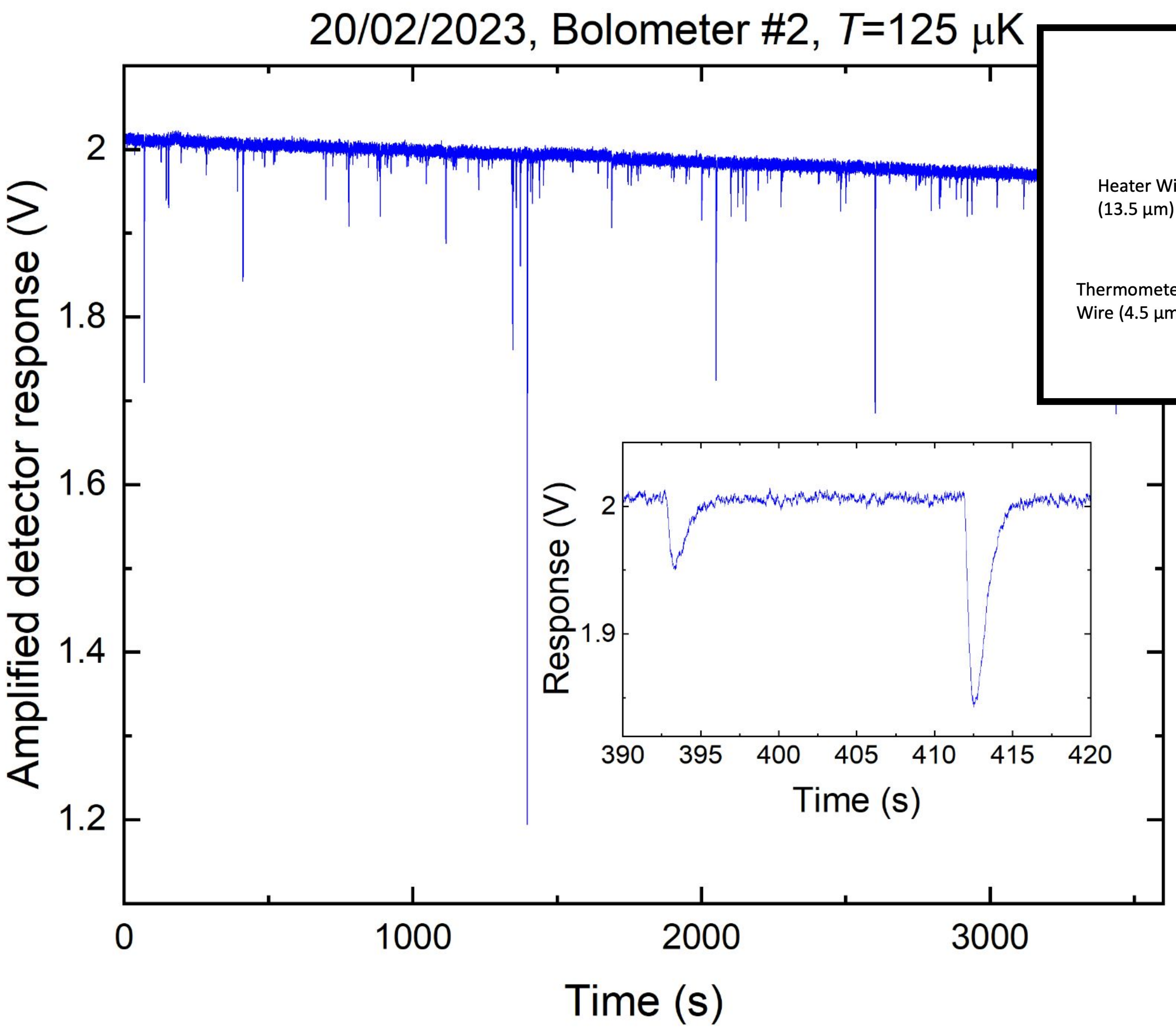
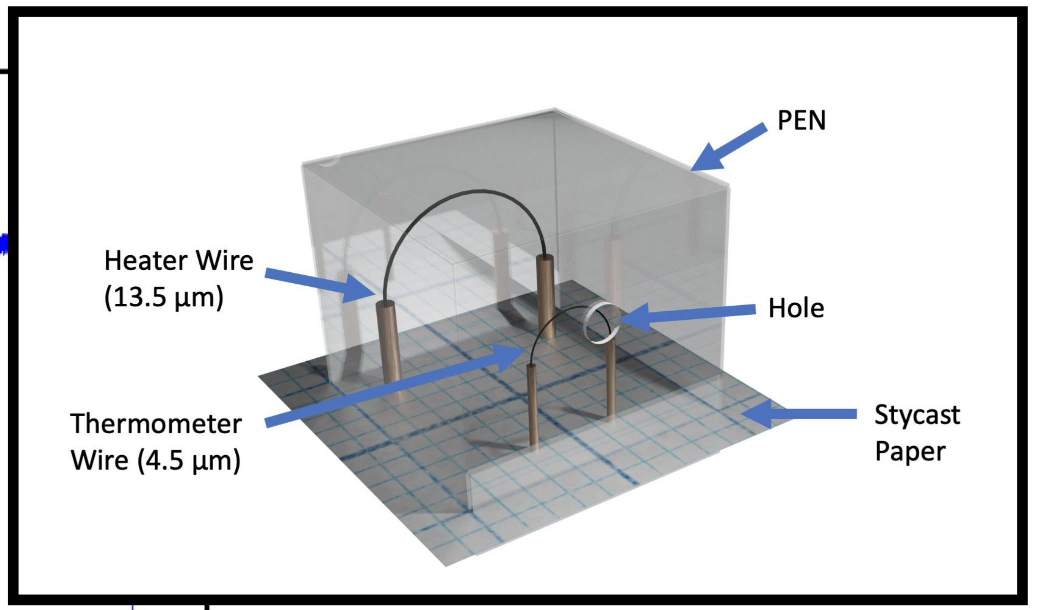


Quasiparticle Calorimetry

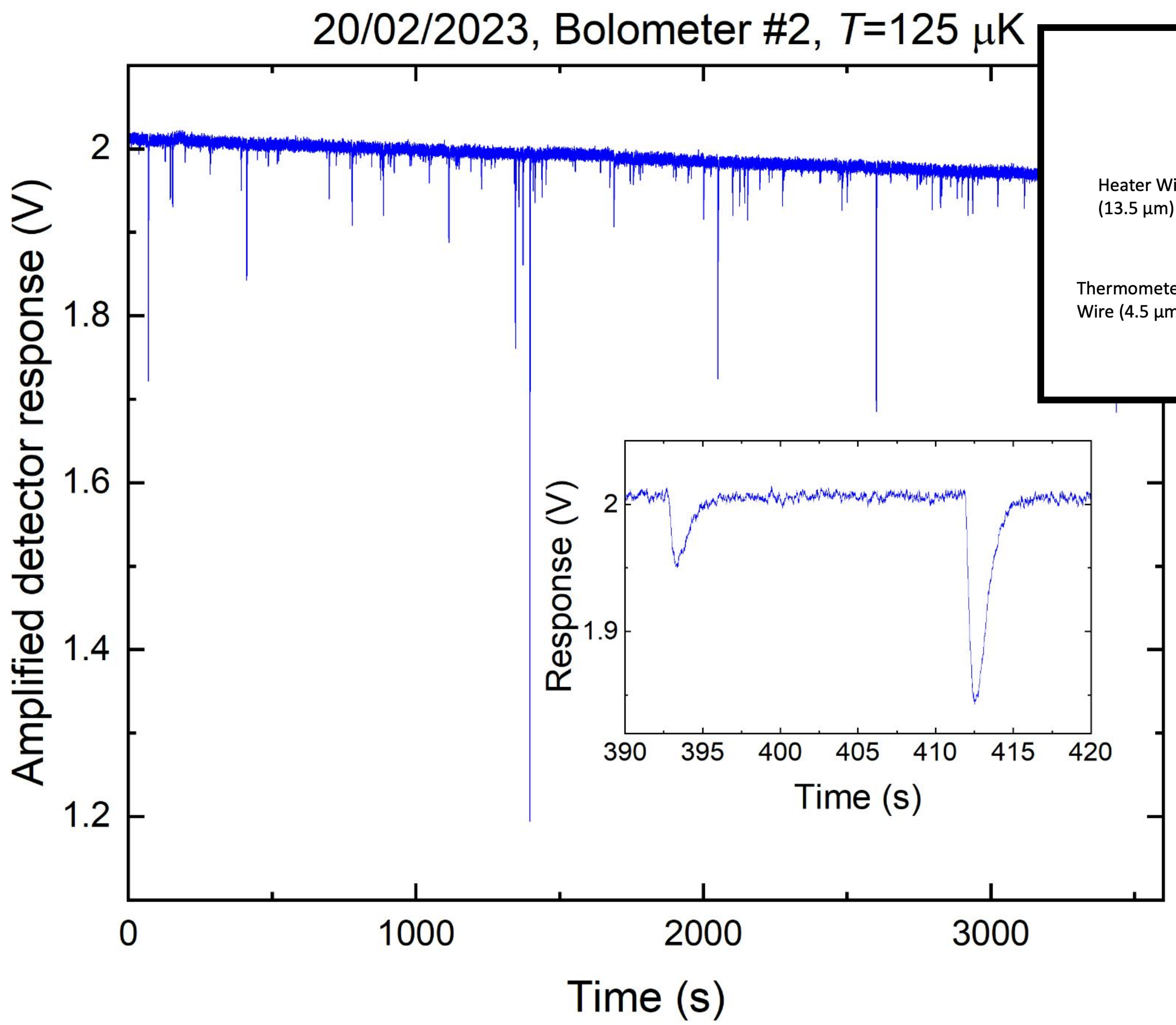


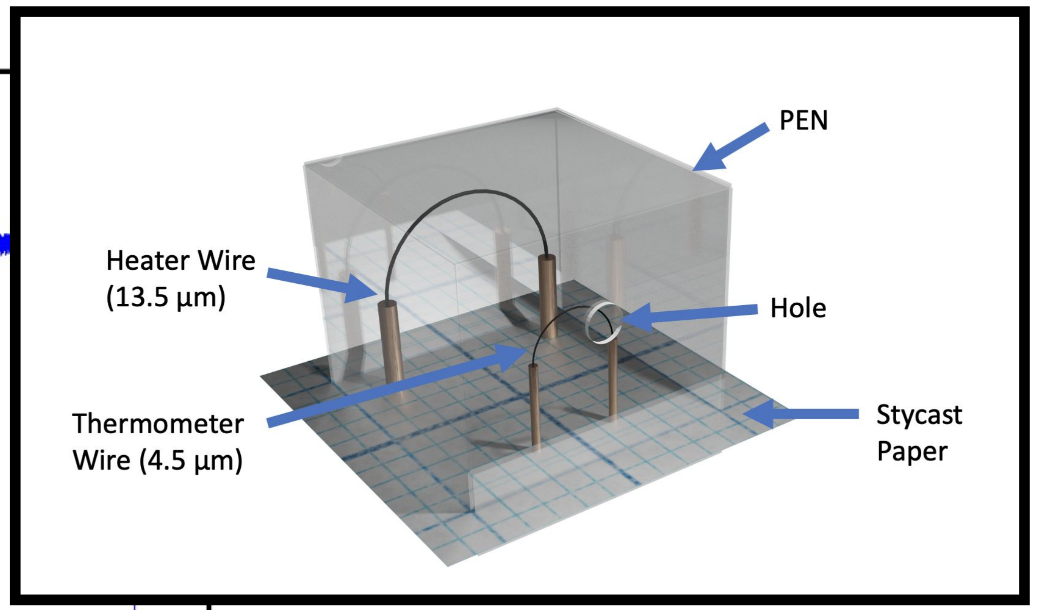


Raw data from bolometer - pulses due to heating events

Quasiparticle Calorimetry

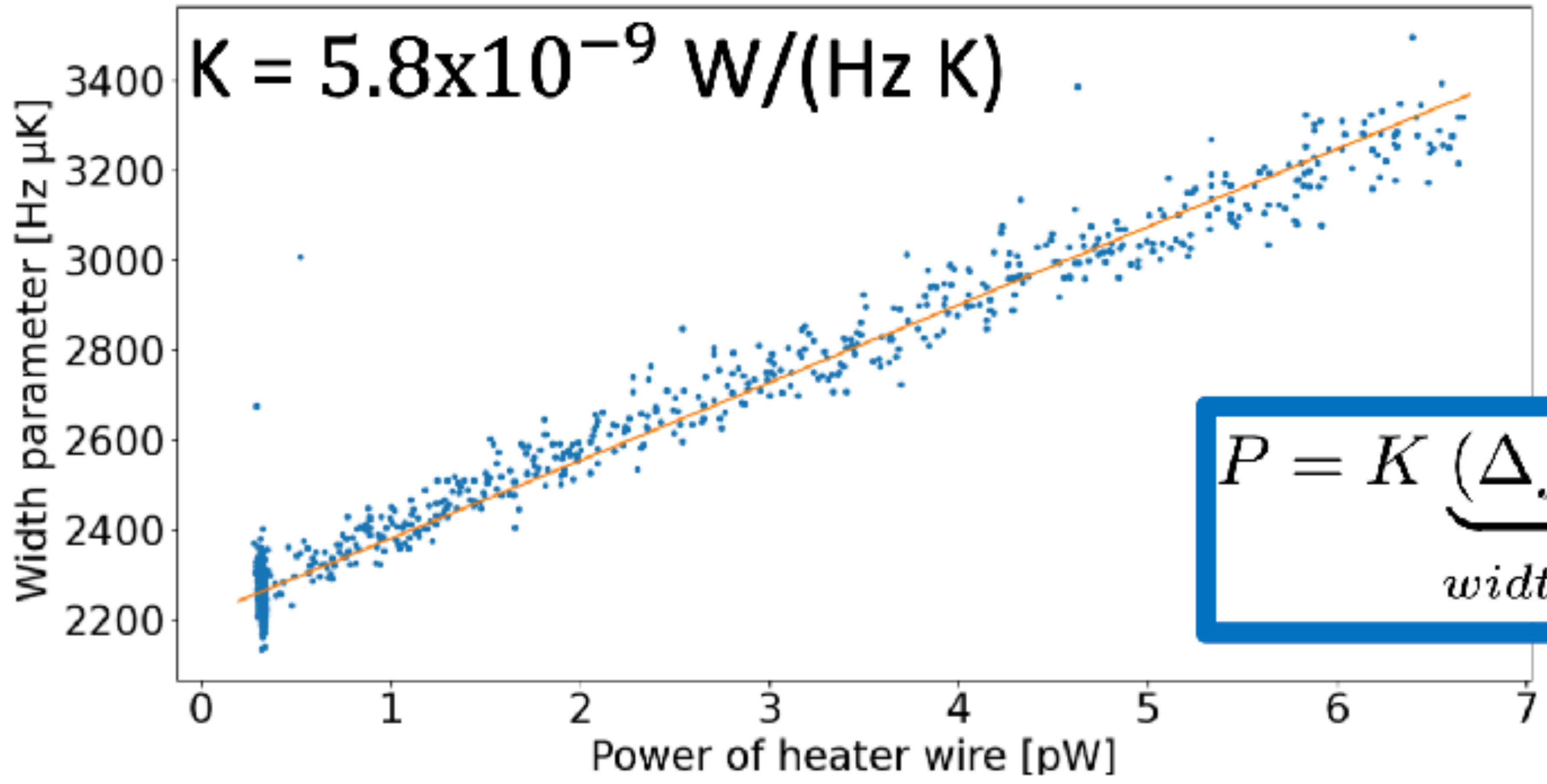
Drive heater wire past Cooper pair breaking velocity and measure thermometer wire response



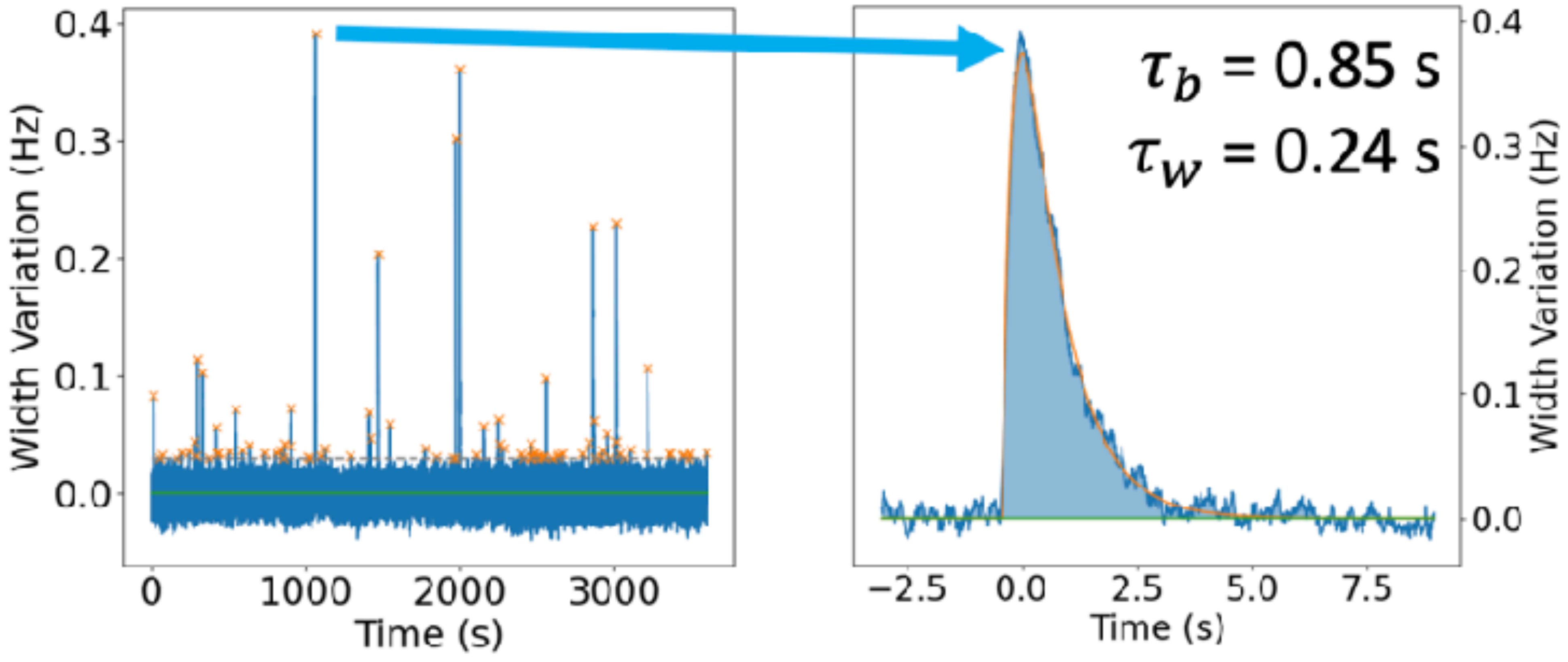


Raw data from bolometer - pulses due to heating events

Calibration & Pulse fitting



$$P = K \underbrace{(\Delta f - \Delta f_0)}_{width\ parameter} T$$

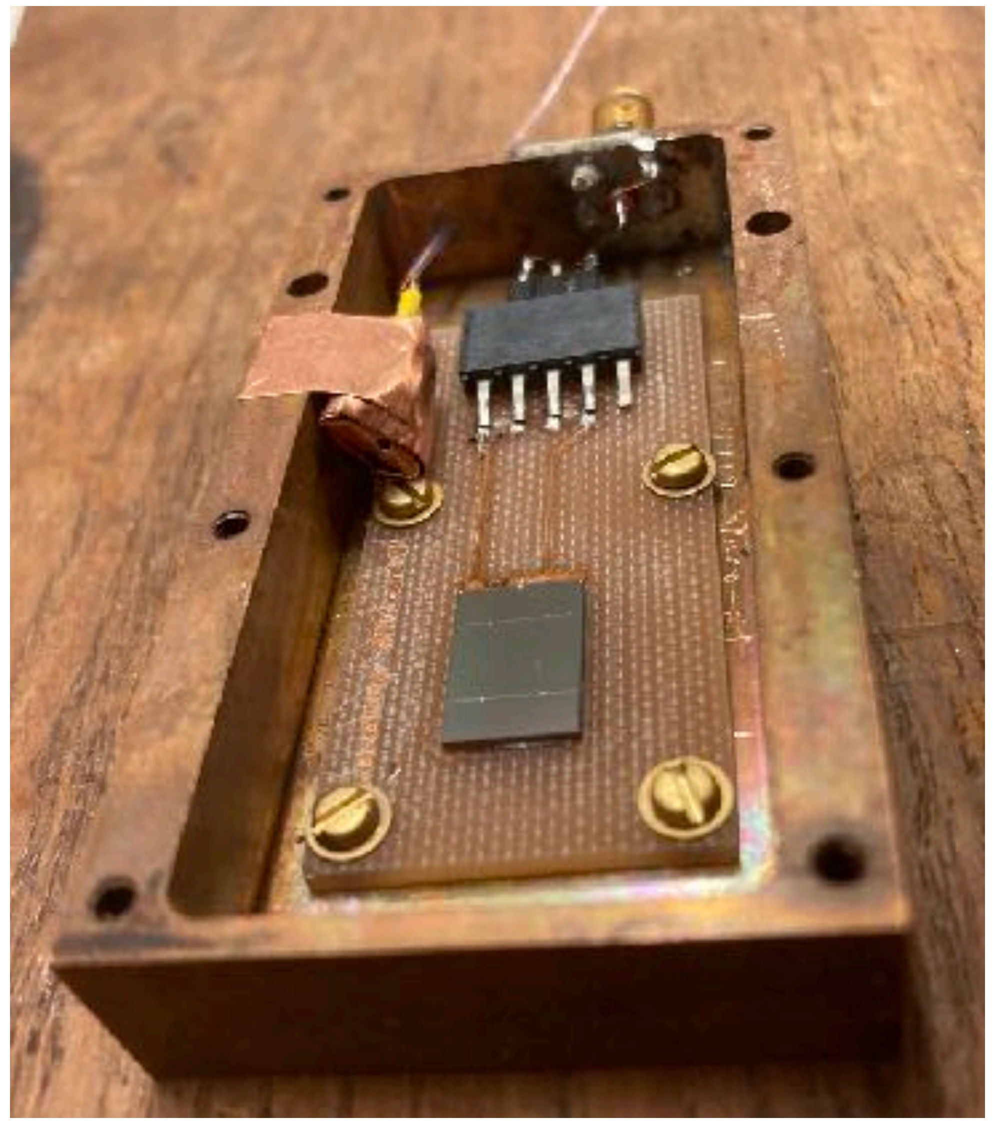


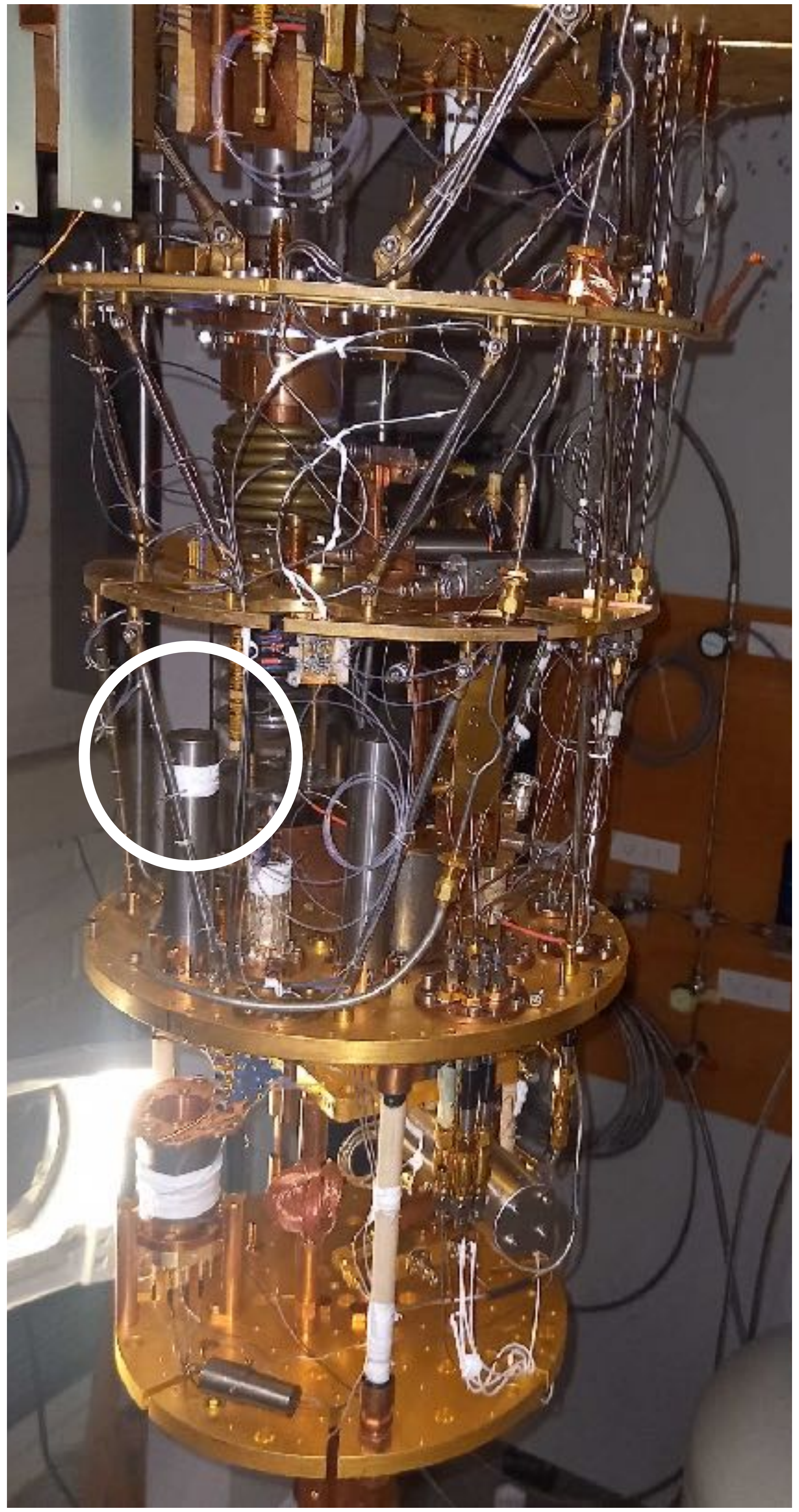
$$E_{heat} = K * Temp * Area_{pulse}$$

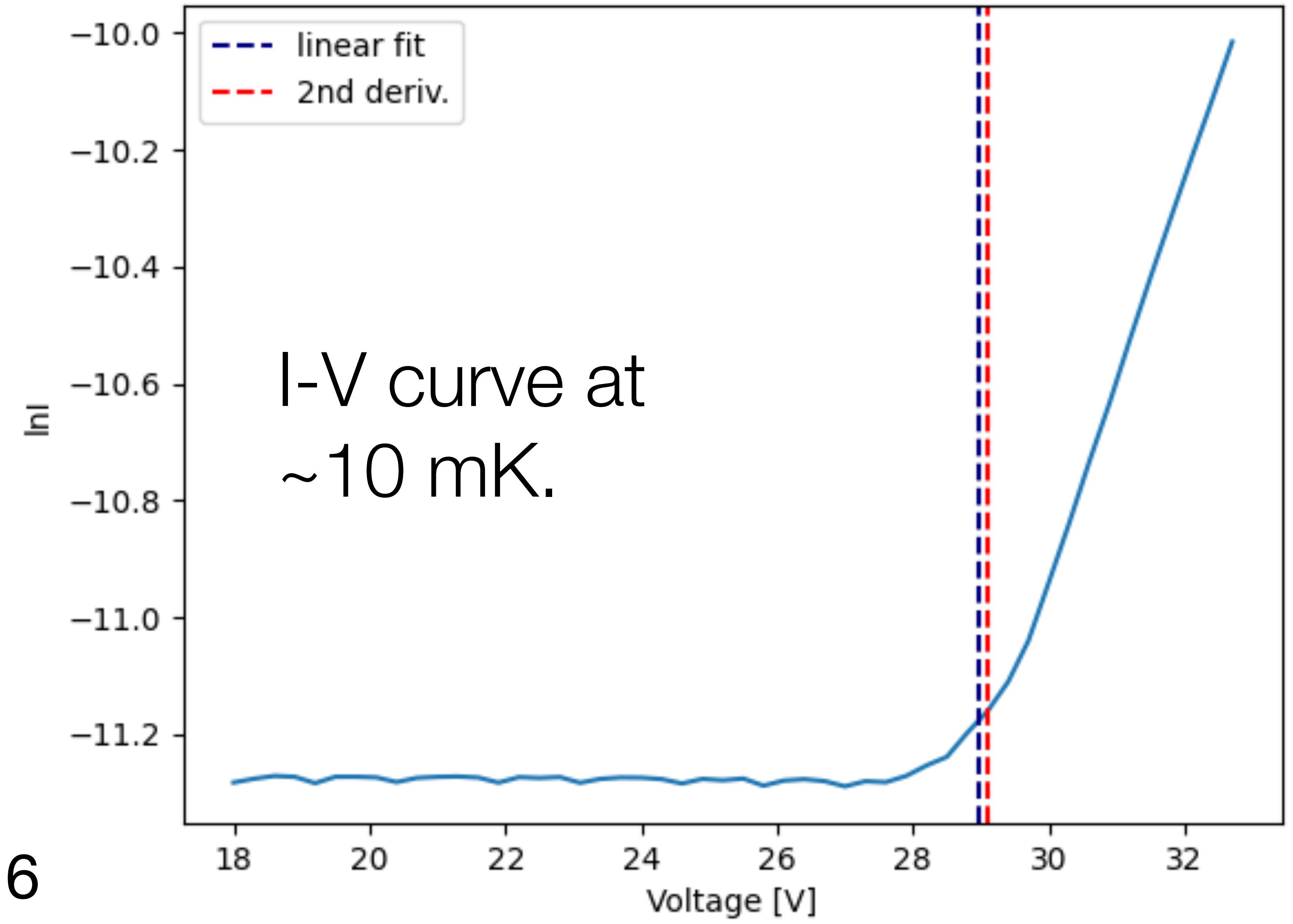
Photon Detection

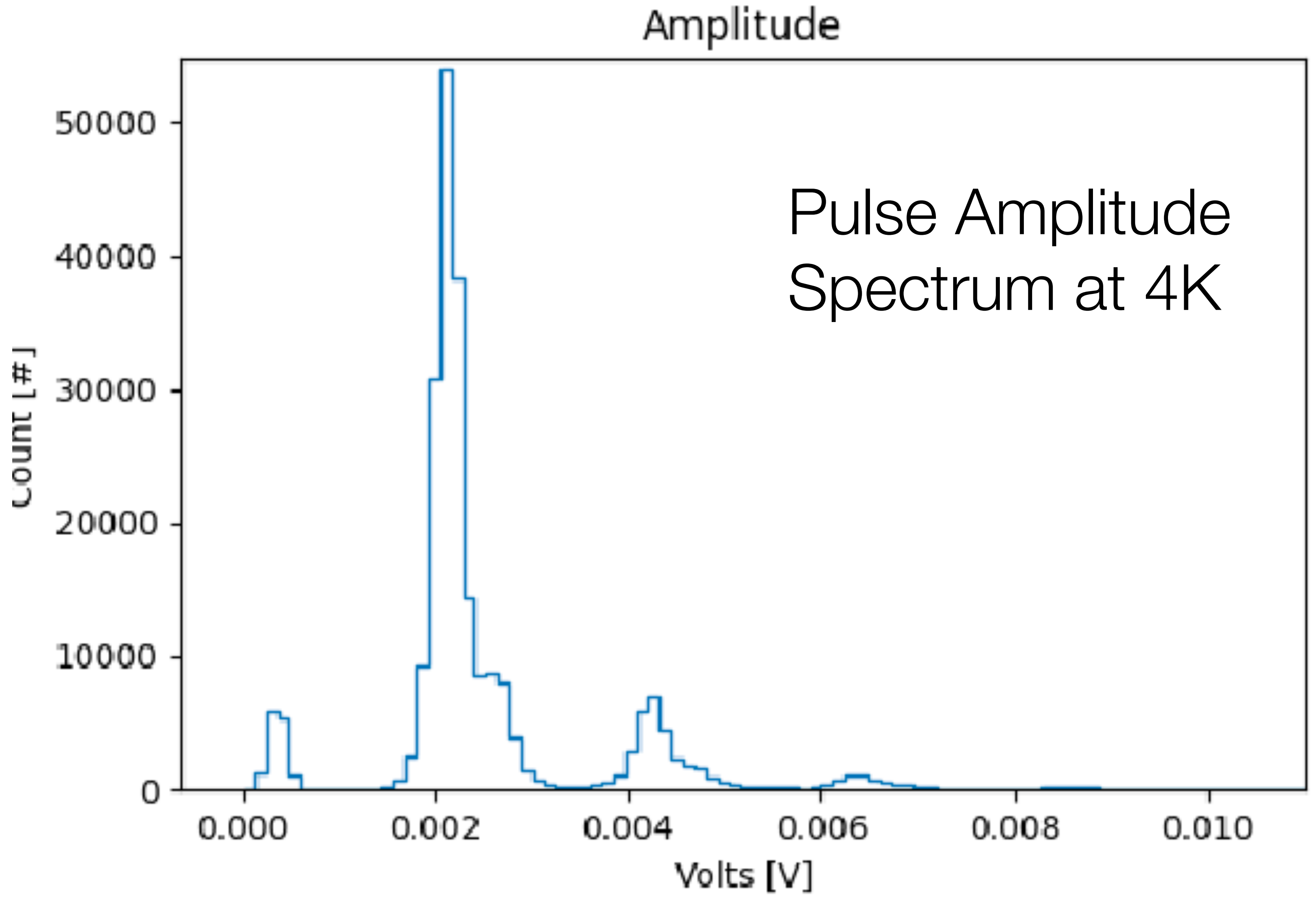
Current tests: Operating the SiPM in a dilution refrigerator at ~10 mK.

Early tests indicate the SiPM does operate at 10 mK - Work is ongoing to characterise the device at 10 mK and optimise the readout noise.

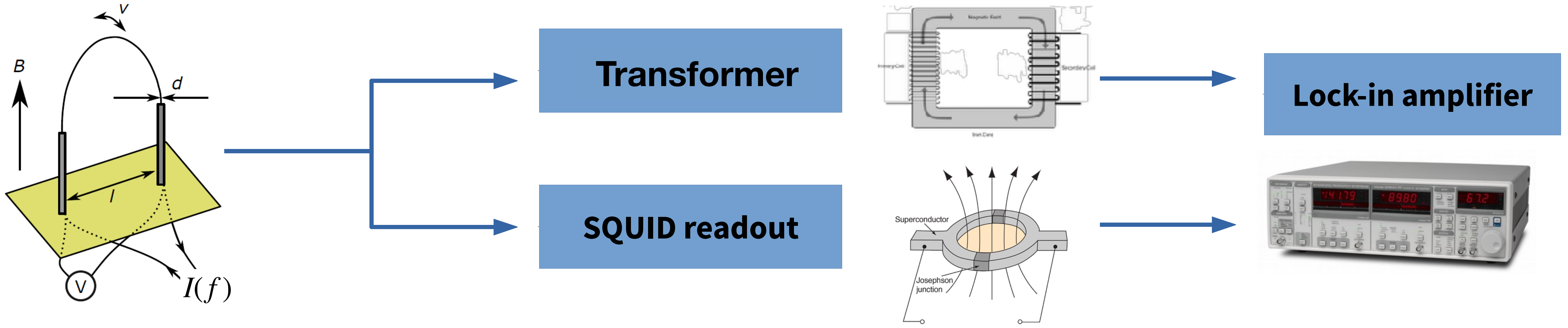








SQUID Readout

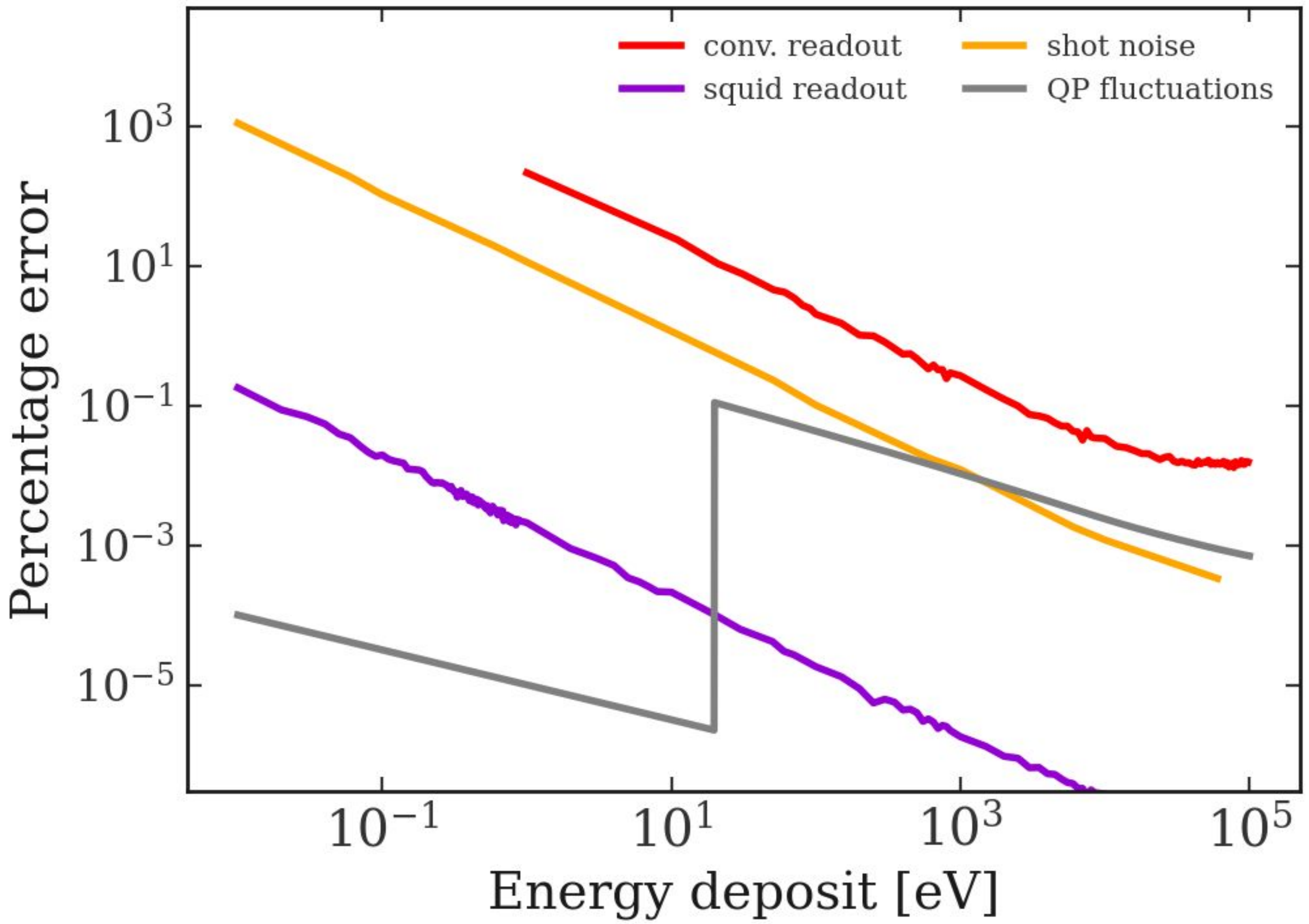


Conventional readout noise dominates over intrinsic limitation of QP noise

SQUID (Superconducting QUantum Interference Device) can reduce noise of readout by orders of magnitude (< pV scale)

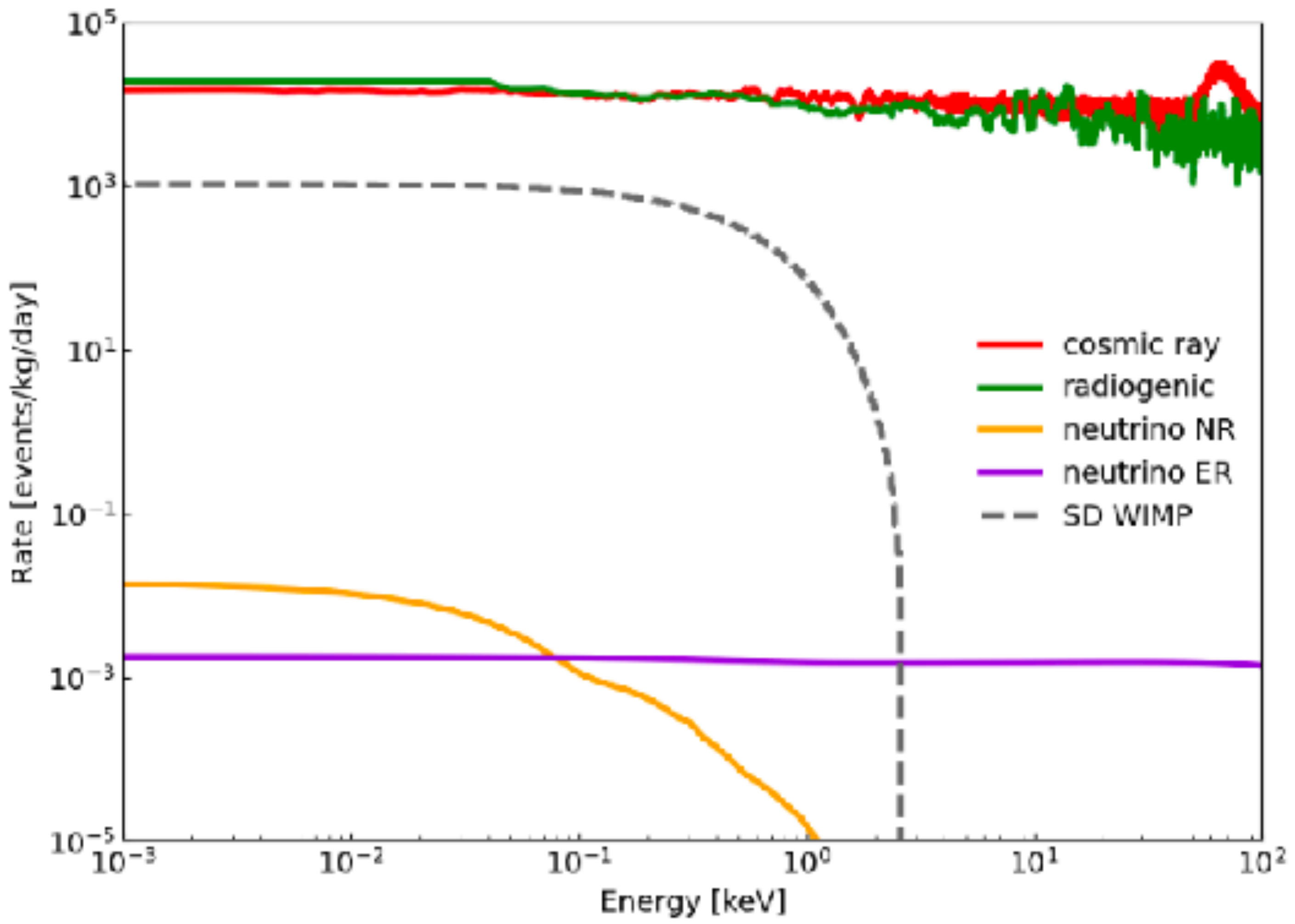
SQUID readout of nanowire operated at < mK scale

Ongoing work to measure QP shot noise at RHUL



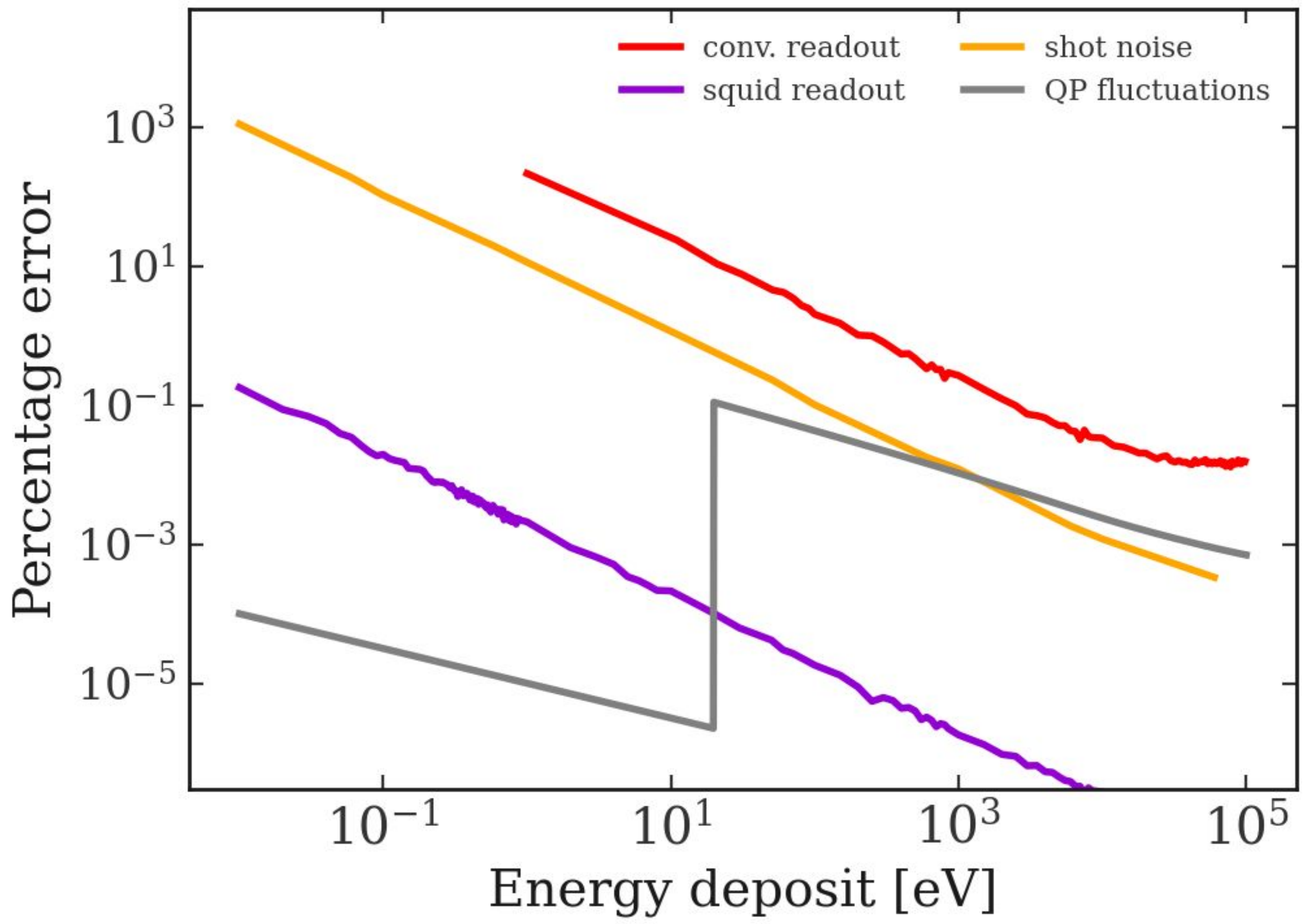
Estimated Sensitivity

Geant4 background simulation + radioassay measurements



$E^{Conventional}_{Threshold}$
39 eV

$E^{SQUID}_{Threshold}$
0.71 eV



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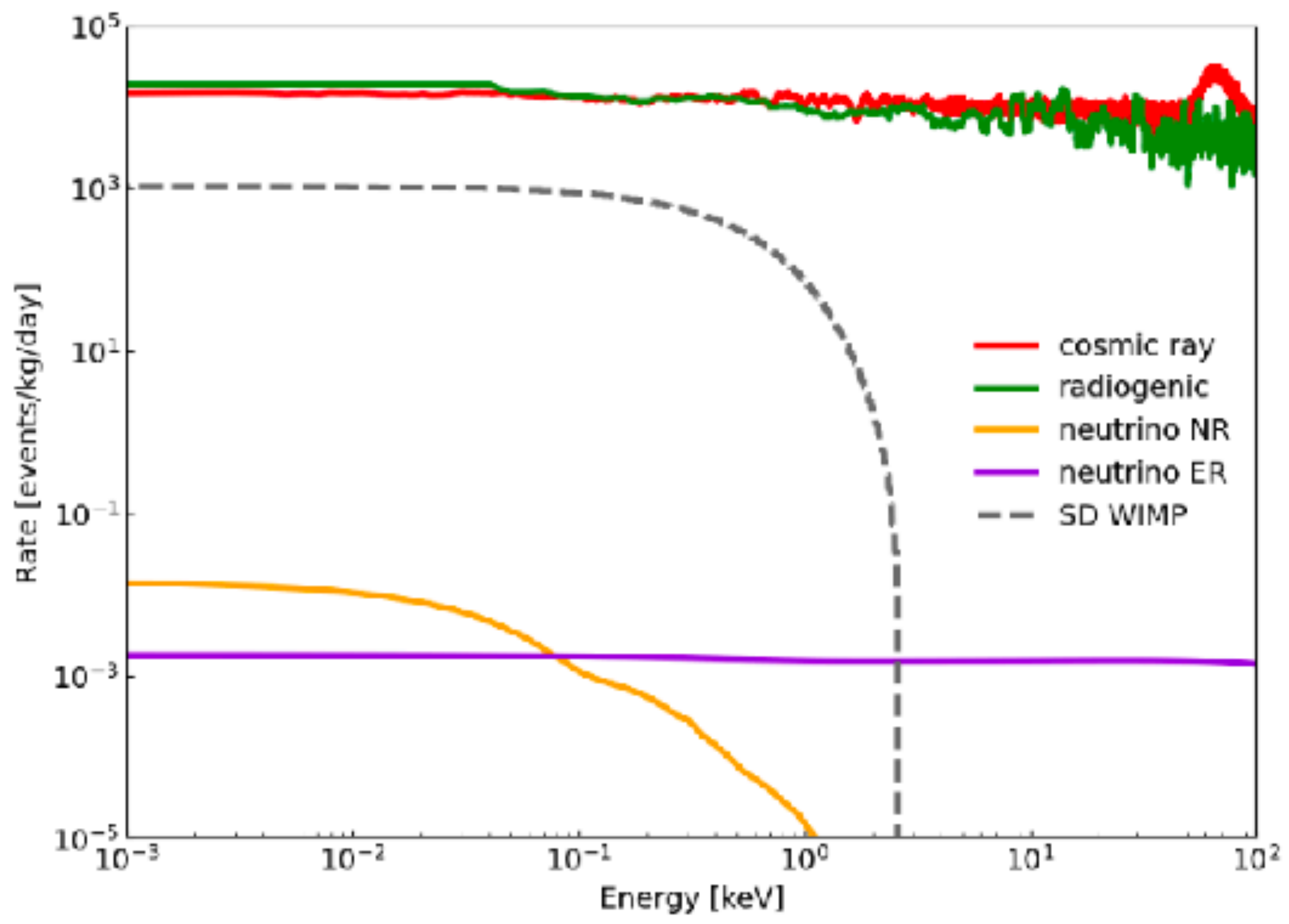

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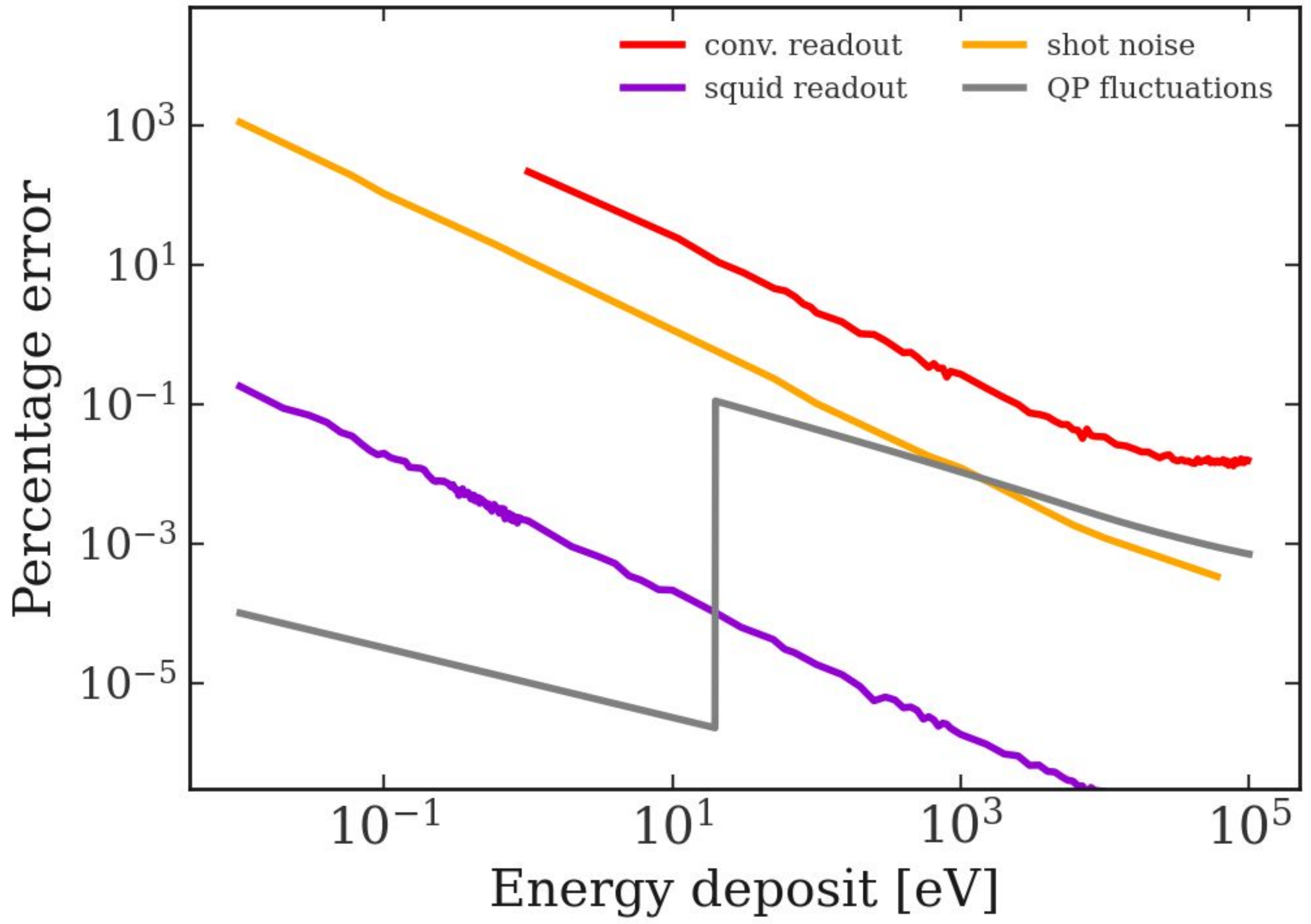
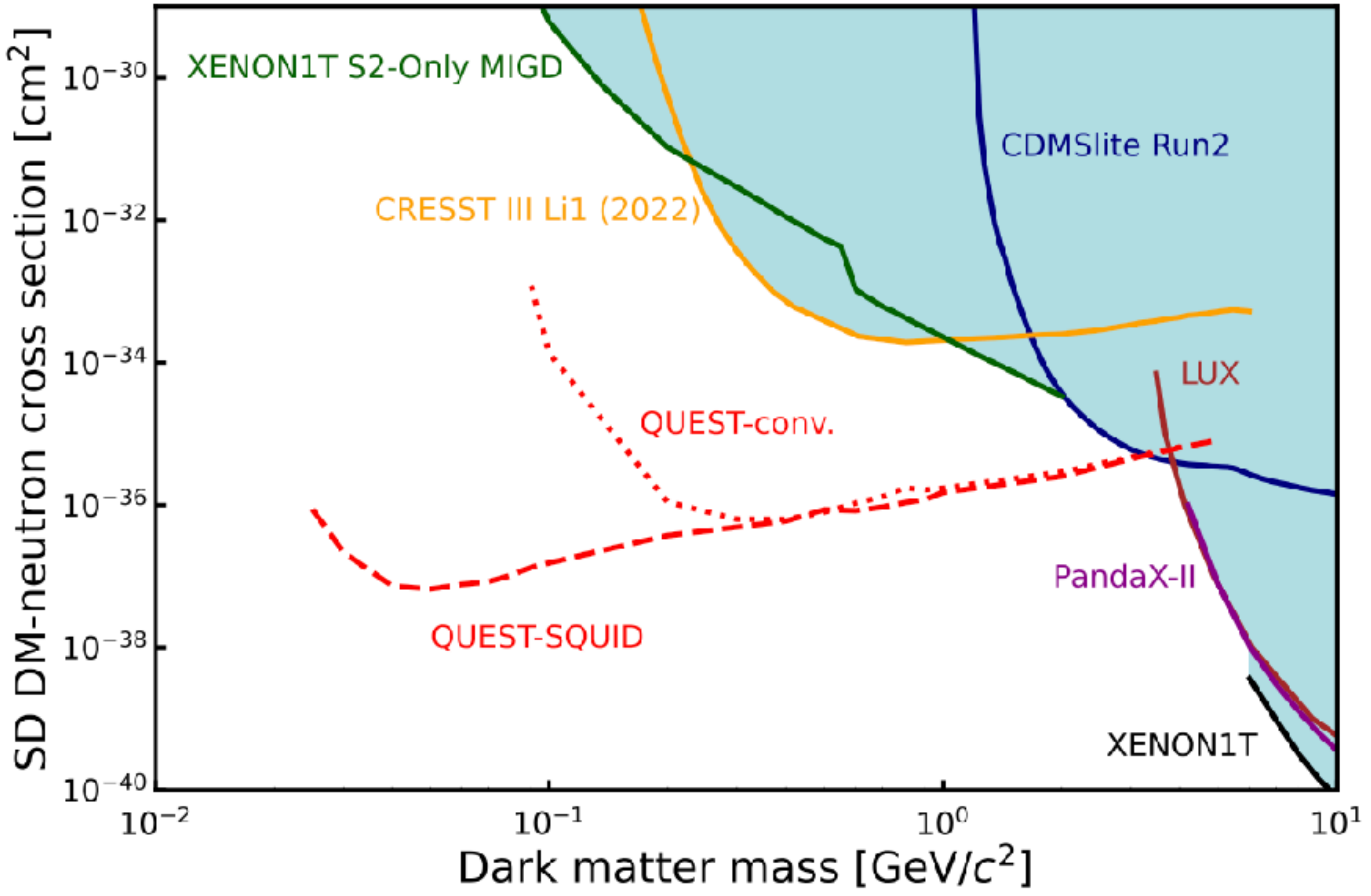


6 month run, 50% livetime, 200nm wire, 5 x 1cm³ cells (0.1 g / cm³)

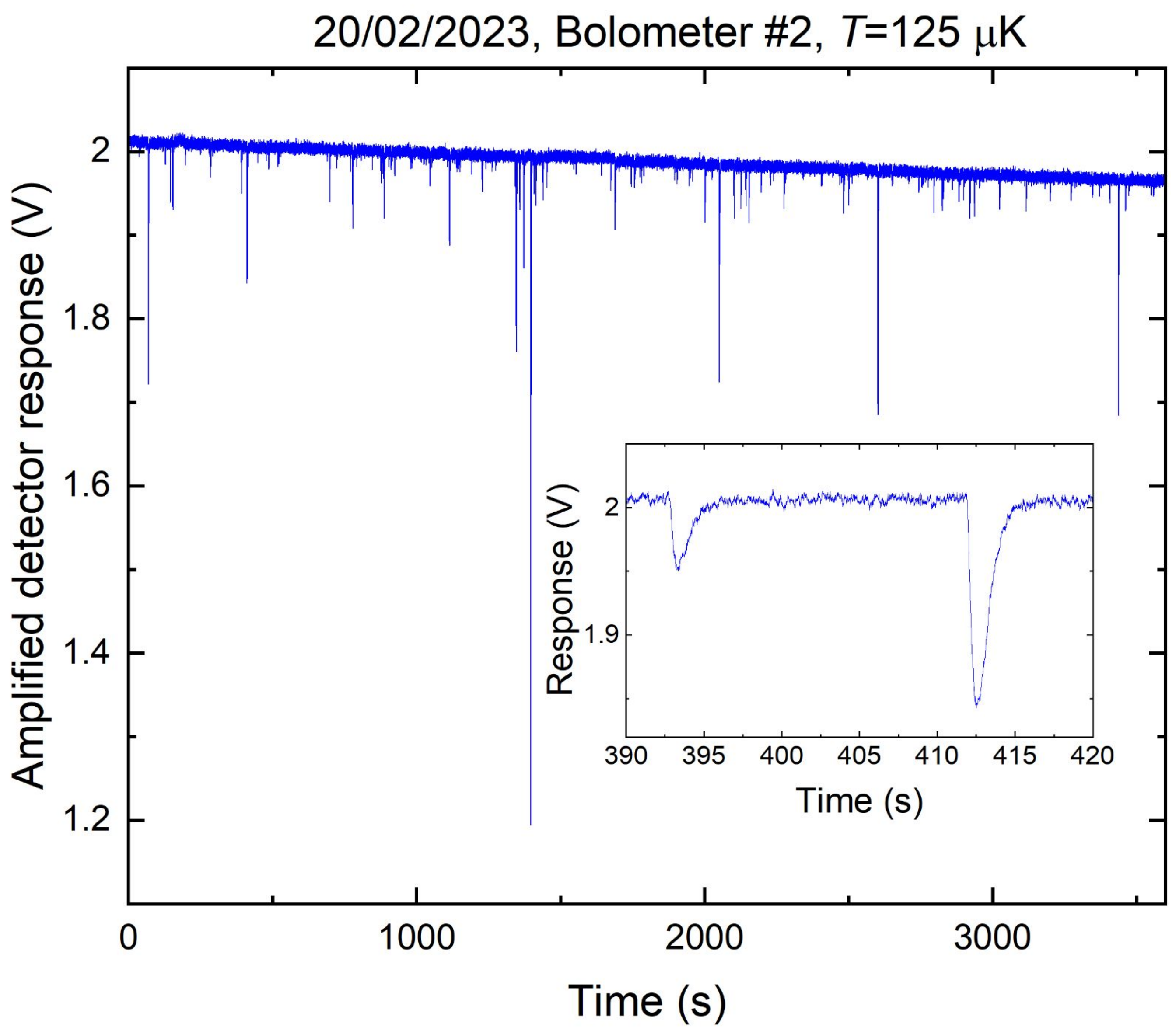


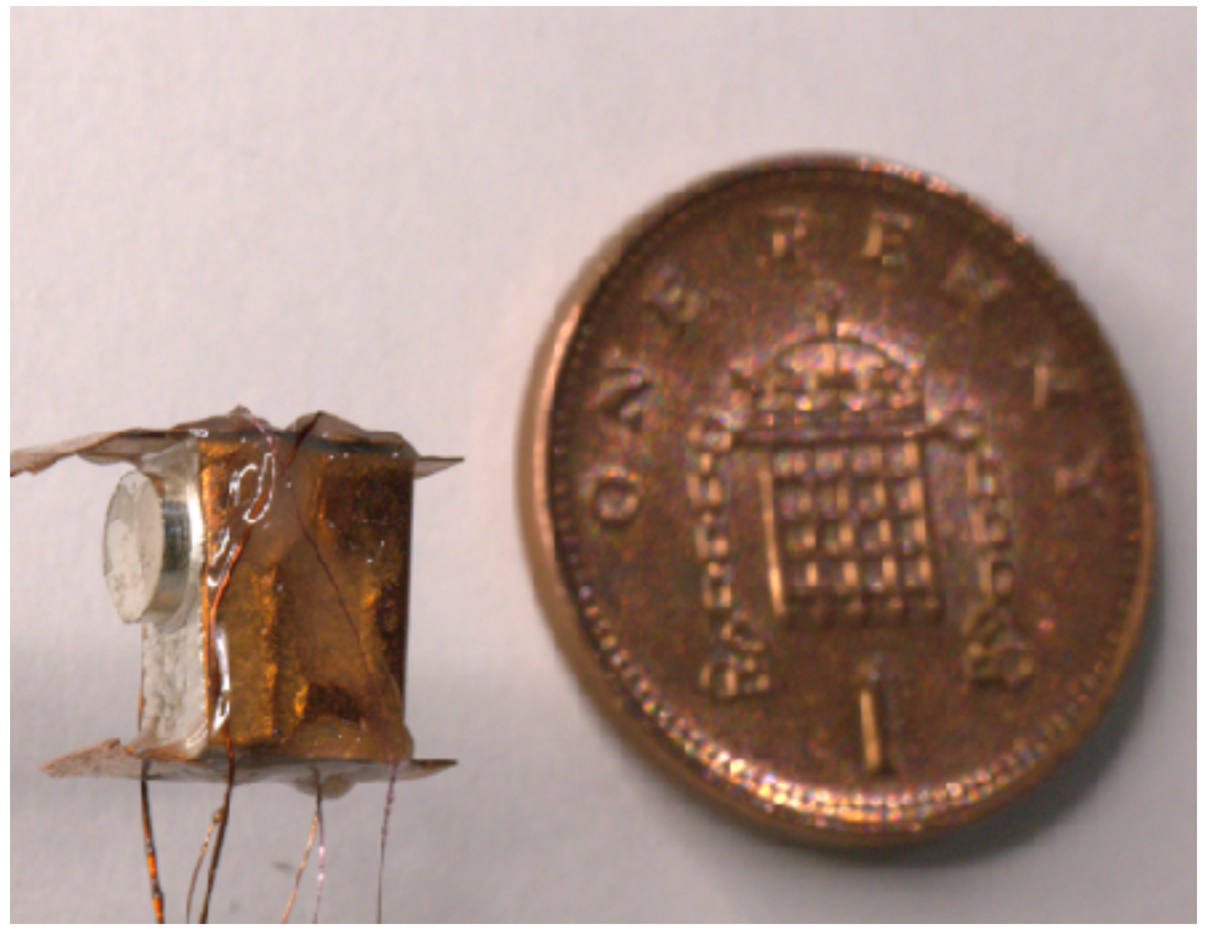
https://doi.org/10.1140/epjc/s10052-024-12410-8

Conclusions

Proof of concept for eV scale threshold DM detector

Operated bolometers with nano-electromechanical resonator (NEMs) detector





Ongoing work:

Next generation bolometer (see above) to be installed at Lancaster with full SQUID readout

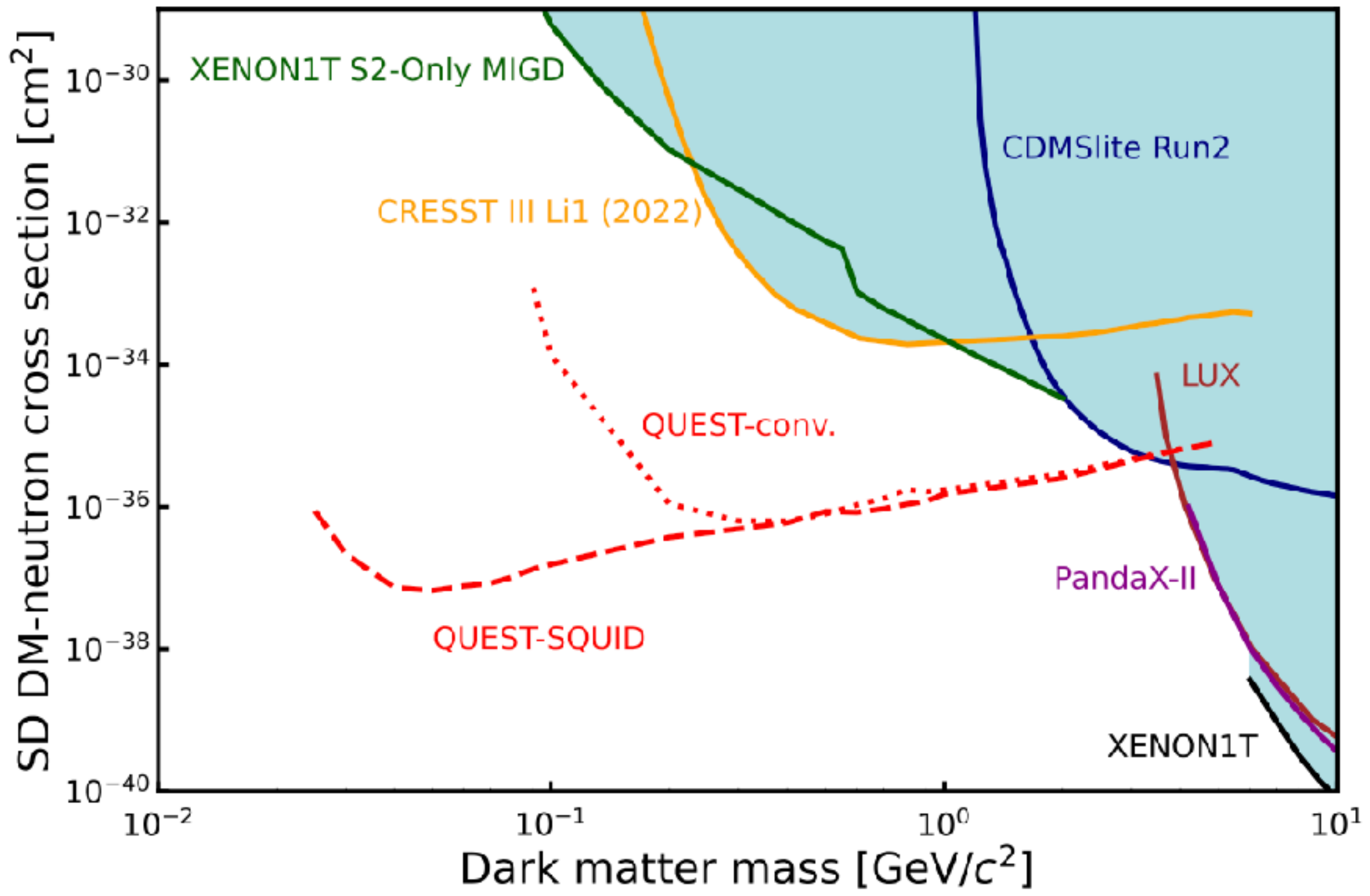
mK scale photon detection, shot noise measurement, monoenergetic source calibration

Aim: 6 month dark matter search data taking run

Sensitivity paper in EPJ-C:

https://doi.org/10.1140/epjc/s10052-024-12410-8

For more ideas of physics potential: see talk by **N Darvishi**



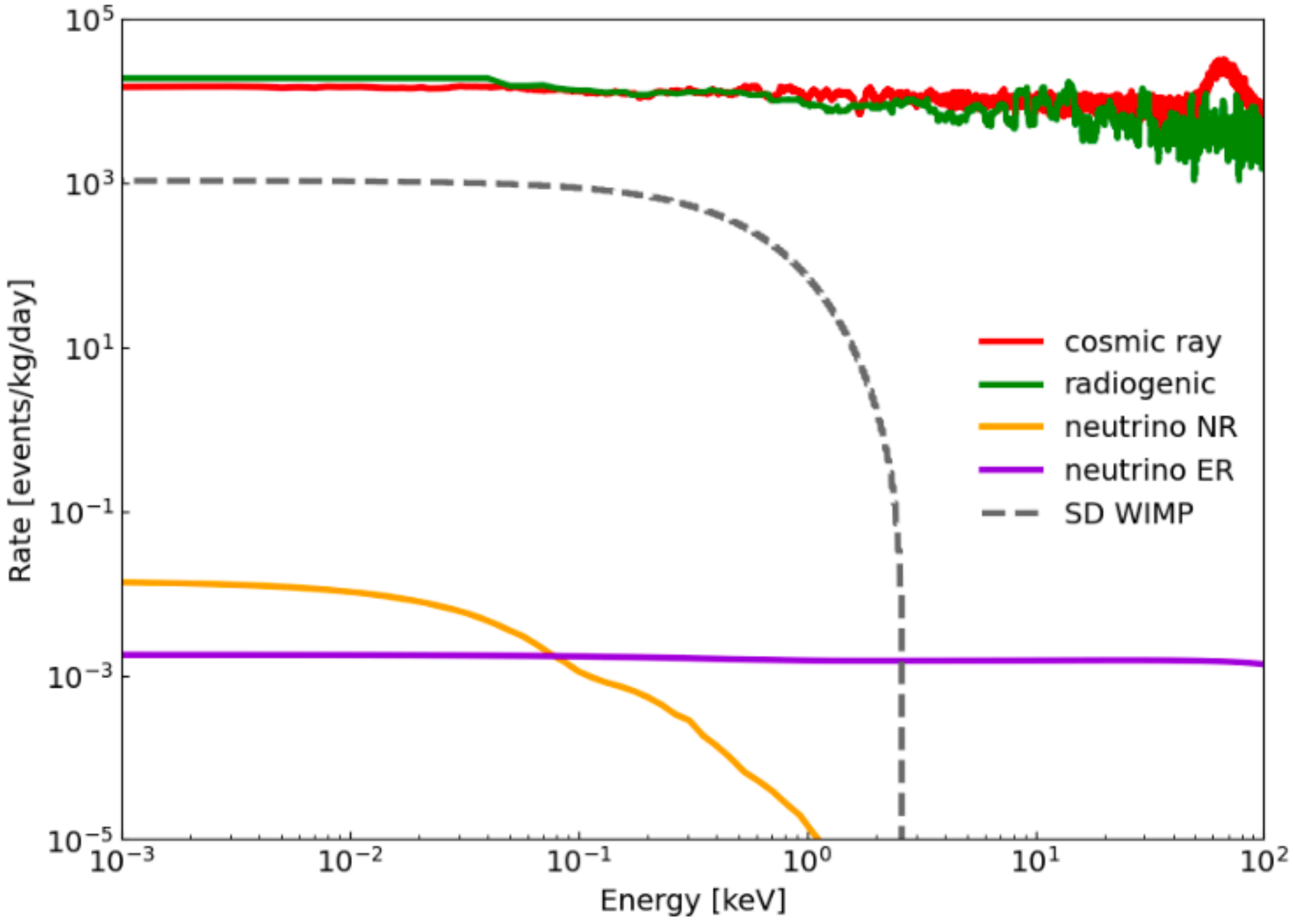
Backup Slides

Background

- G4 simulation done for cosmic ray and radiogenic event rates
- BUGS (Boulby Underground Germanium Suite) used for extensive radioassay of detector and cryostat materials

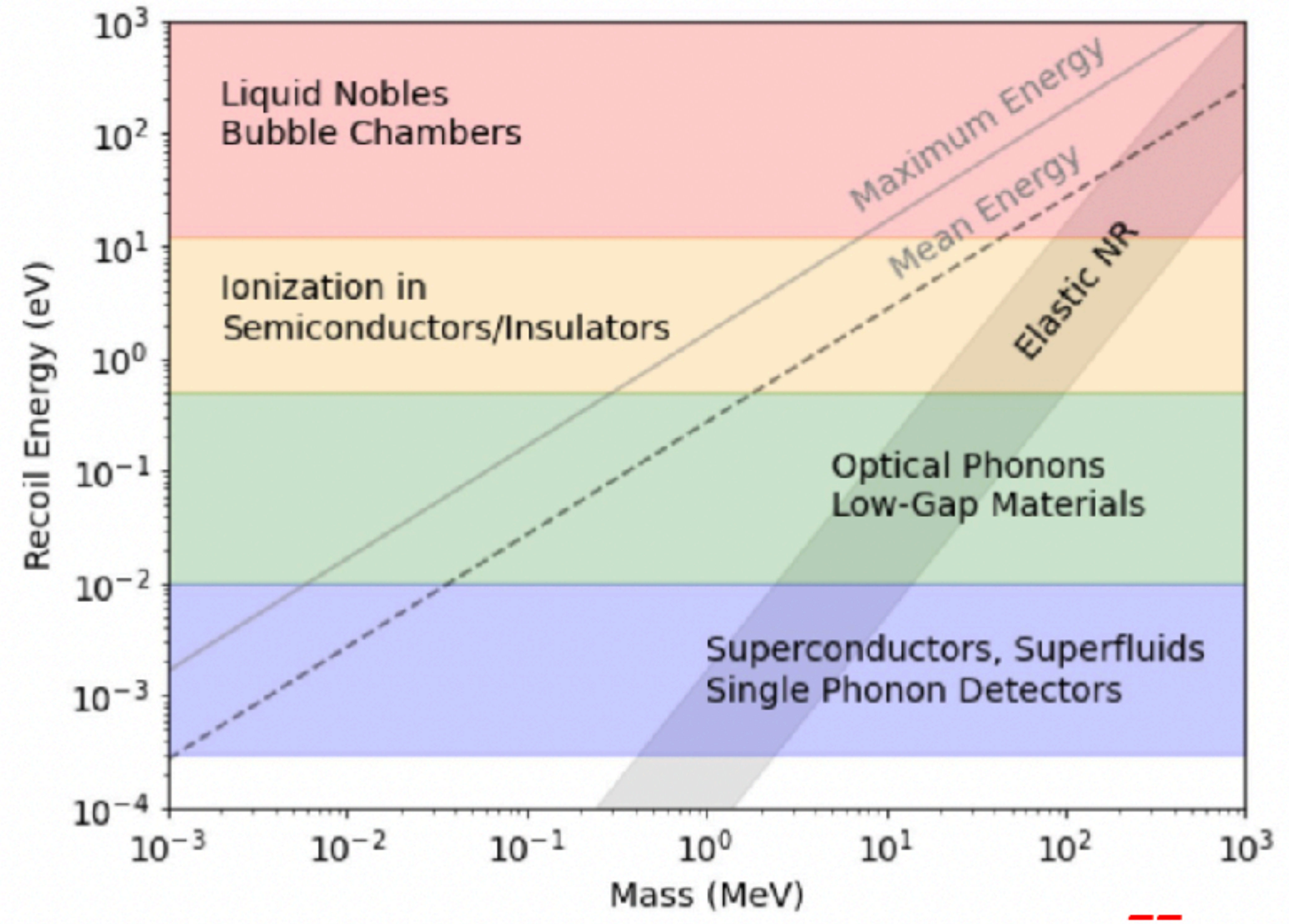
Component	Expected counts [0-10 keV] /kg/day	/cell/day	Uncertainty
Cosmic ray	1.05×10^5	3.31	11 %
Radiogenic ER	8.31×10^4	2.61	14 %
Solar ν ER	1.51×10^{-2}	4.76×10^{-7}	2 %
Solar ν NR	6.37×10^{-4}	2.01×10^{-9}	2 %
TOTAL	1.88×10^5	5.92	

Expected background rates in ROI (0-10 keV) per kg and per cell (0.033 g) assuming 90% CR veto

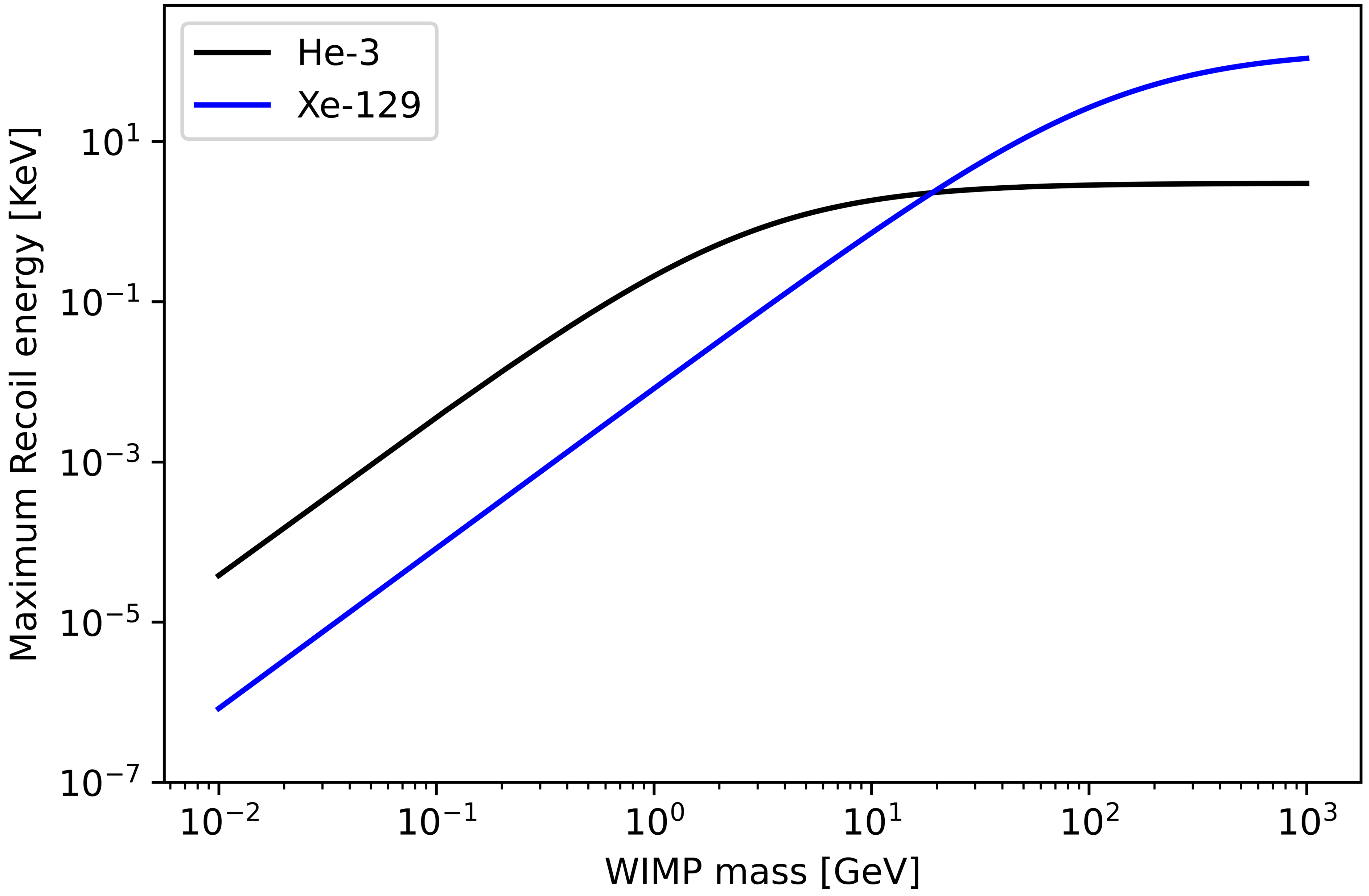


Recoil Energies

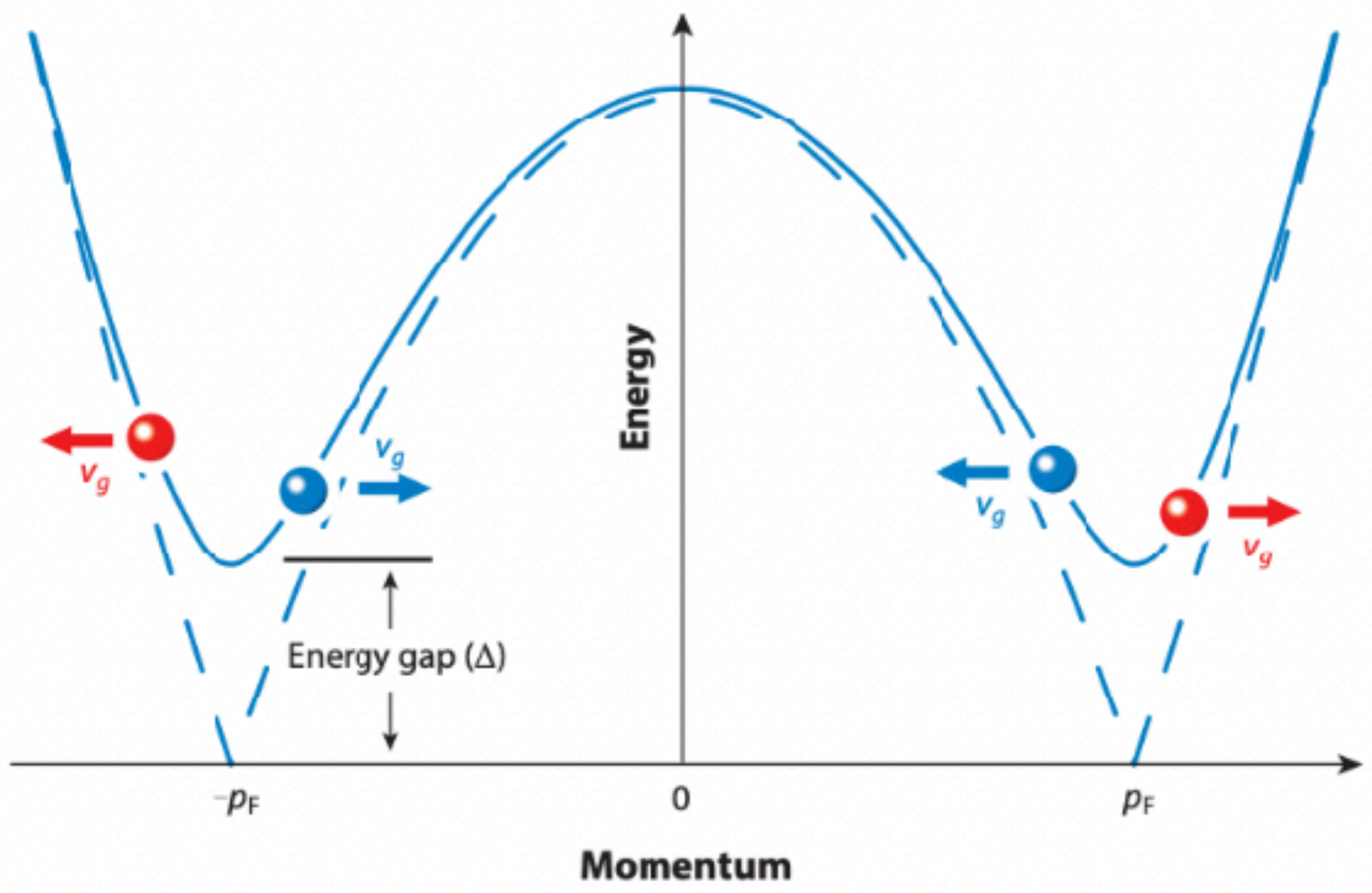
- Lower mass nucleus = lower maximum recoil energies with lighter DM
- Superfluids able to reach low recoil energy/low mass parameter space



Snowmass report 2022

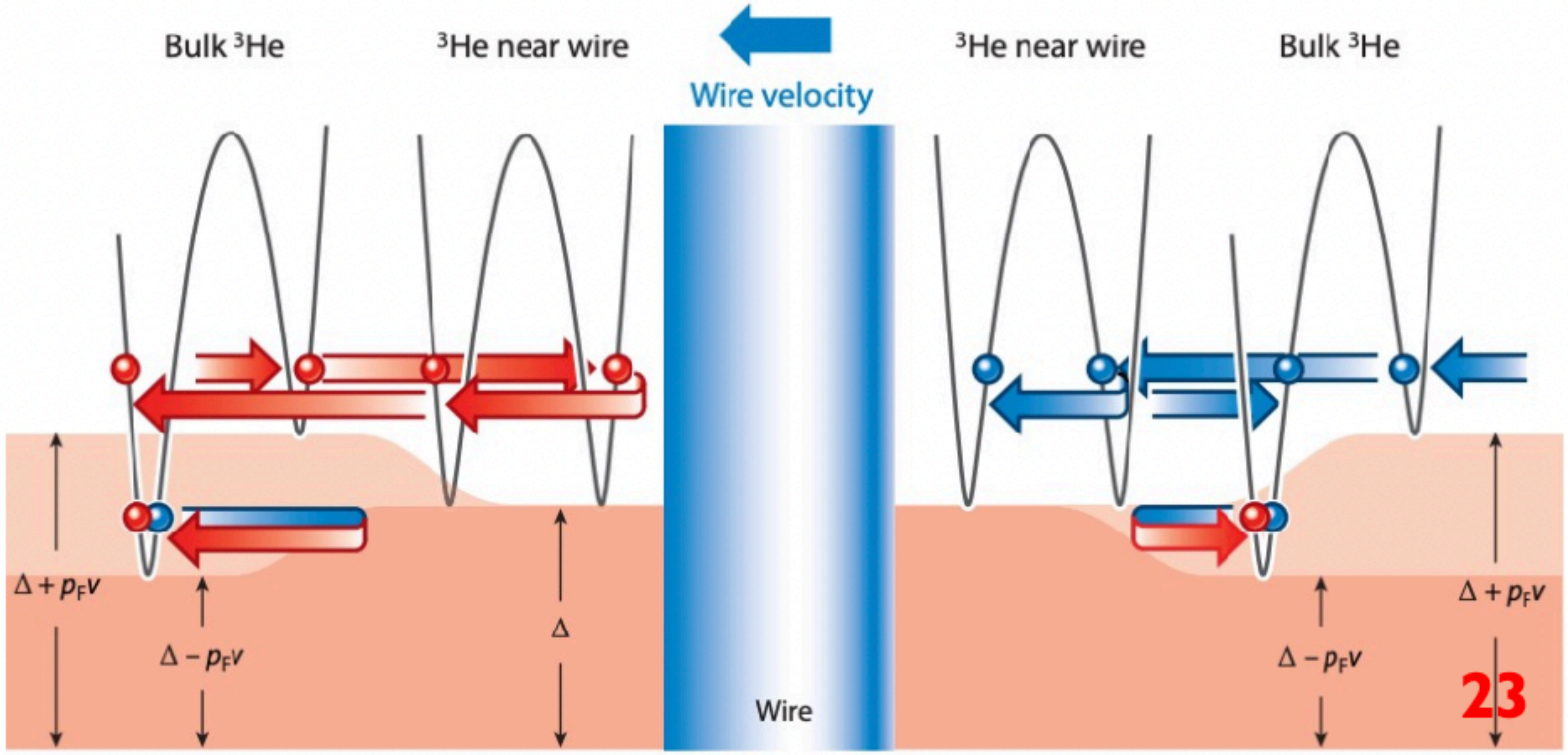


Andreev Scattering



- Quasiparticle dispersion curve , with energy minima at the Fermi momentum.
- Group velocity (slope) parallel to momentum for particles and antiparallel for holes. Becomes zero at pF, so in some scattering process particle drops to min then moves up other side of curve as a hole, with velocity reversed but momentum same.

- Fluid flow and relative motion of an object can increase/decrease the gap.
- Only quasiparticles from in front and quasiholes from behind can transfer momentum |2pF|, increasing the damping.

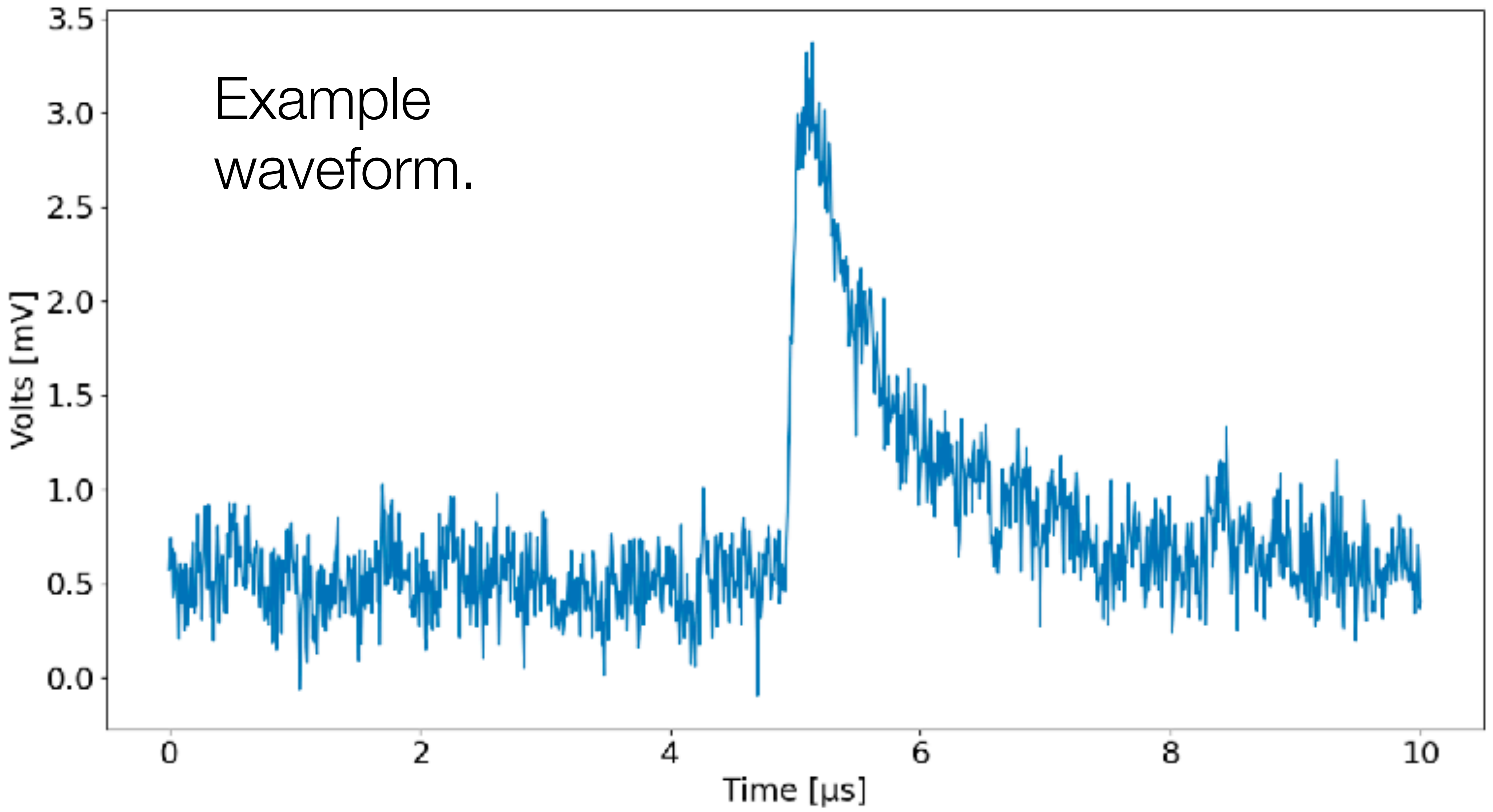


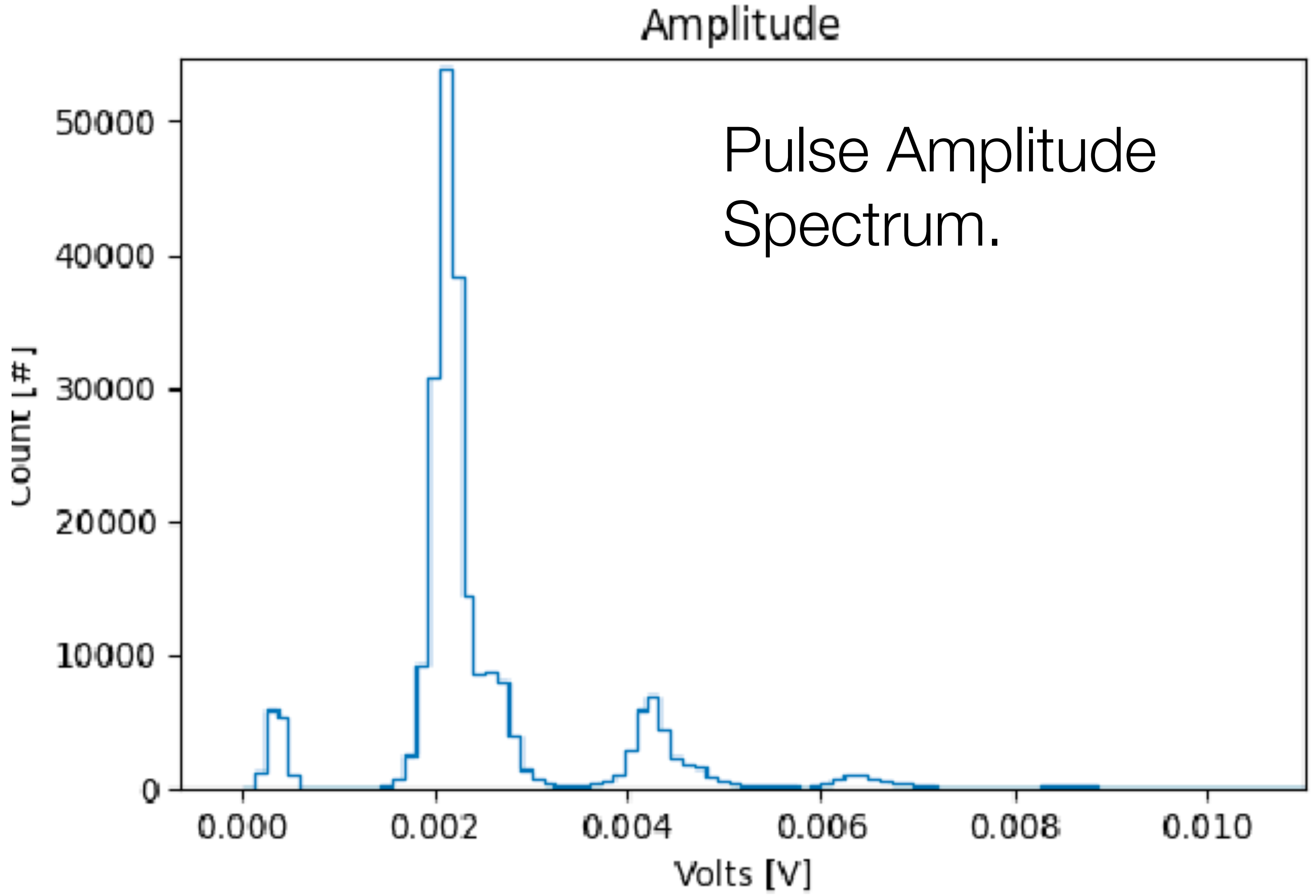
Ref https://www.annualreviews.org/doi/pdf/10.1146/annurev-conmatphys-031016-025411

Detector - Scintillation

First test: Operated a SiPM in LHe, at 4 K

Clearly saw signals at 4 K! First demonstration of the feasibility of operating SiPMs in ULT required for QUEST



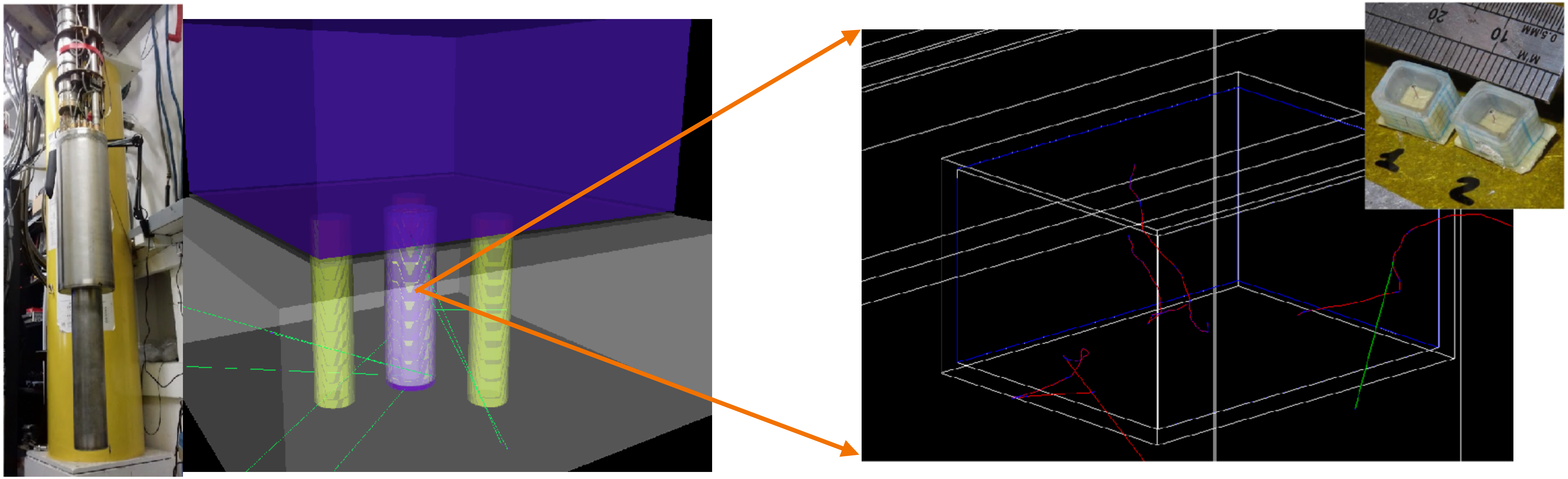


Simulation

G4 geometry of cryostat and surrounding materials

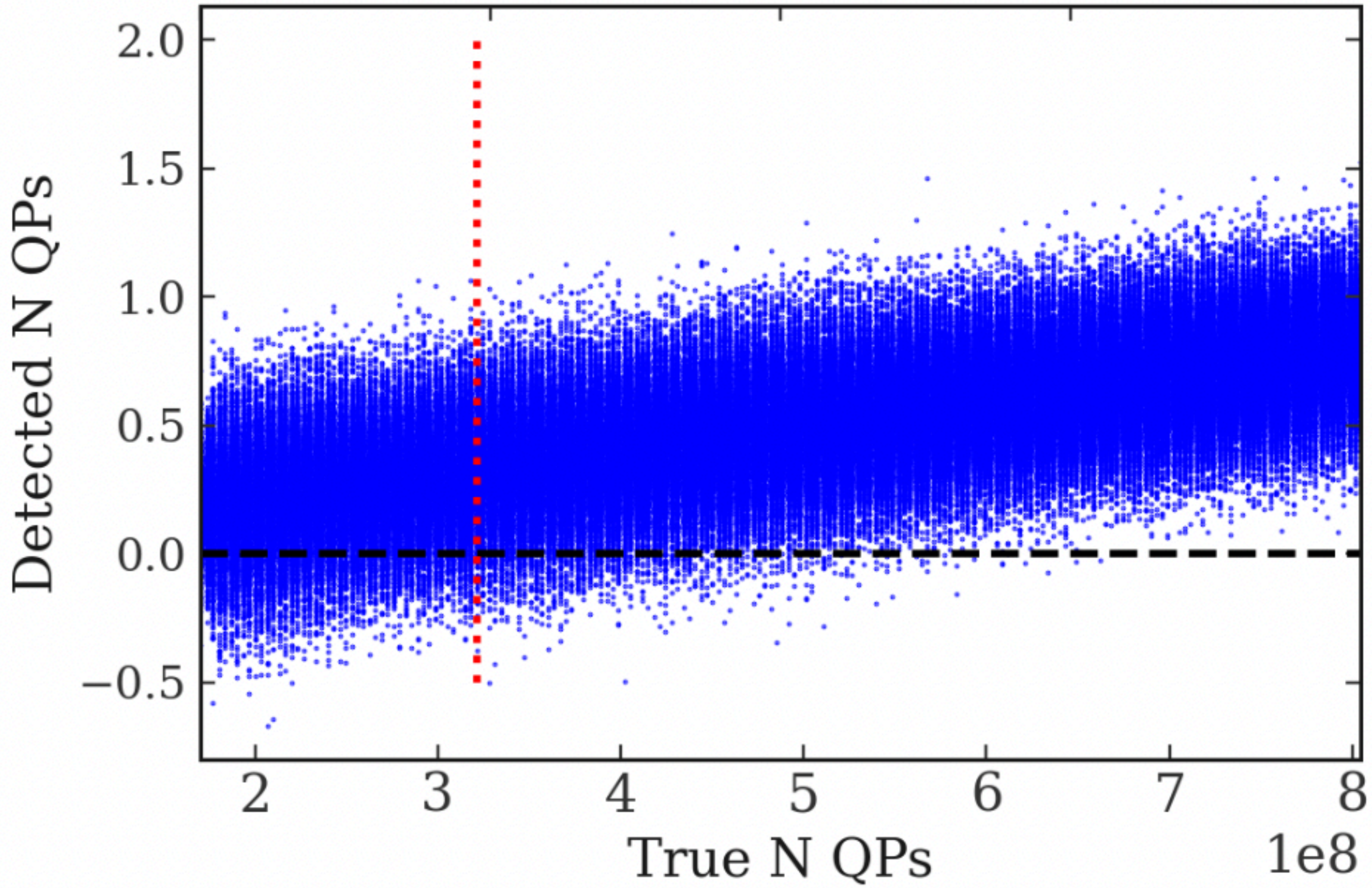
MC event rates produced within cell of ^3He

Normalise with reference values to produce expected bg event rates



Credit: P Franchini

Energy Threshold



Resolution at threshold – 95% confidence energy > zero.

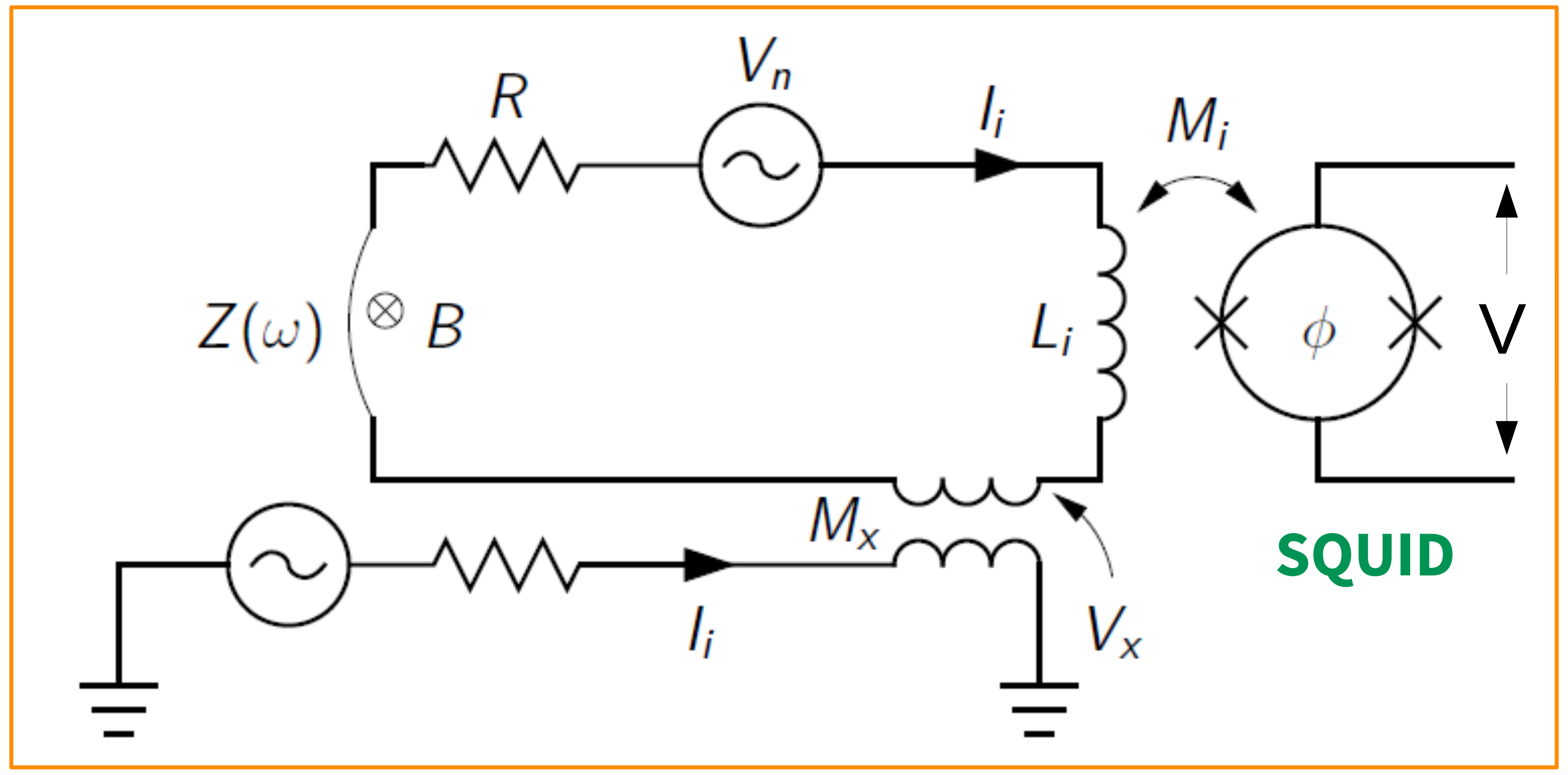
- Conventional readout: 39 eV
- Squid readout reduces noise, so resolution is dominated by shot noise.
- Squid readout: 0.71 eV

Credit: E Leason

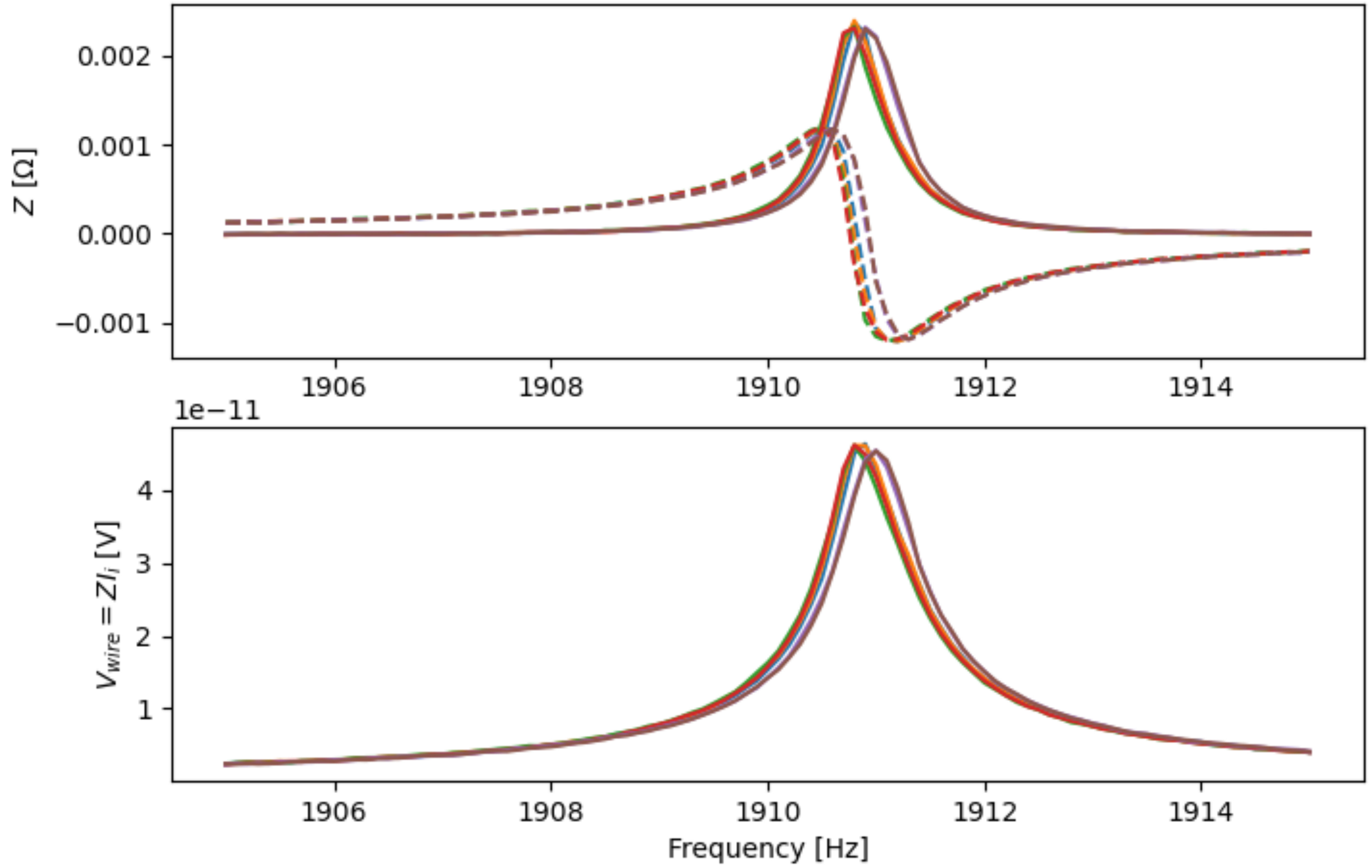
DC SQUID

- Quantum interference between the junctions leads to extreme sensitivity to changes in magnetic flux
- Detected as change in IV characteristics sensitive to 1/2 integer values of applied flux
- Phase sensitive measurement of Ii/Ix is used to extract impedance of the wire

$$Z(\omega) = \frac{i\omega M_x I_x}{I_i} - R - i\omega L$$



Credit: L Levitin



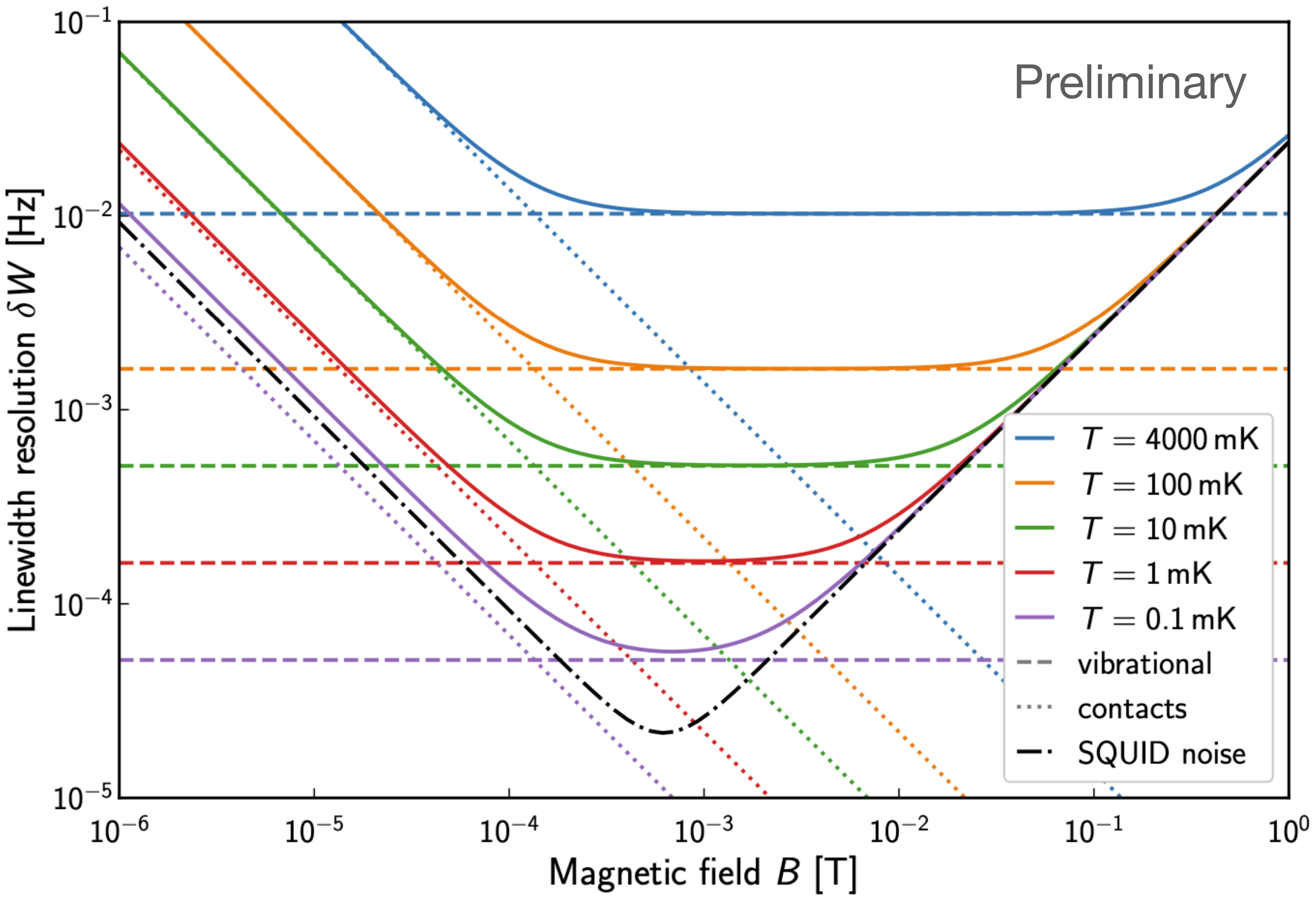
Frequency sweeps of 315nm wire taken at 4.2K

SQUID Resolution Model

Expected SQUID noise in width measurement in ^{3}He bolometer at 130μK and 5 bar of pressure

Ratio between sum of noise contributions and maximum voltage across the wire

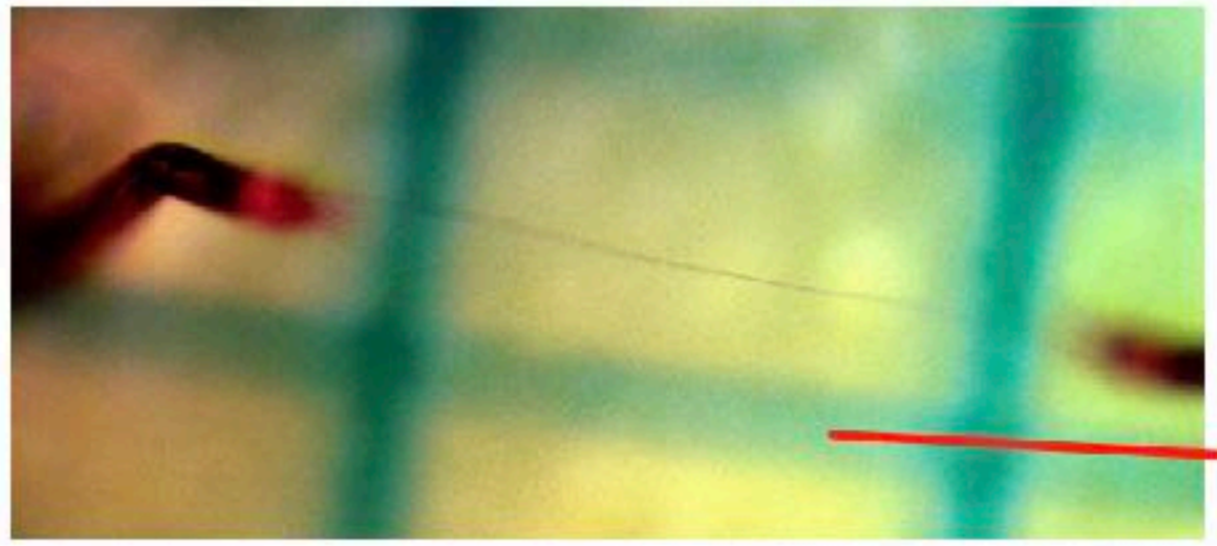
$$\frac{\delta W}{W} = \frac{\sqrt{\left|Z(\omega_0) + R + i\omega(1-\alpha^2\eta)L_i\right|^2 S_\phi \Delta f / M_i^2 + 4k_B T R \Delta f + k_B T l B^2/m}}{V_v^{\max}}$$

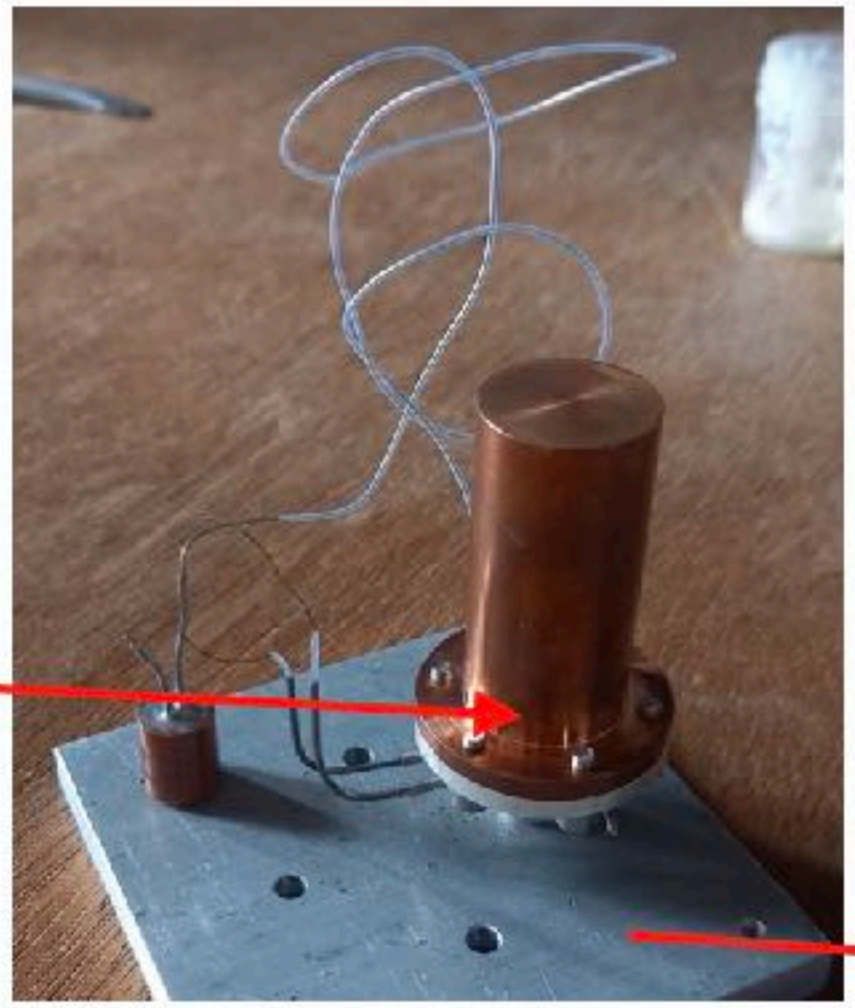


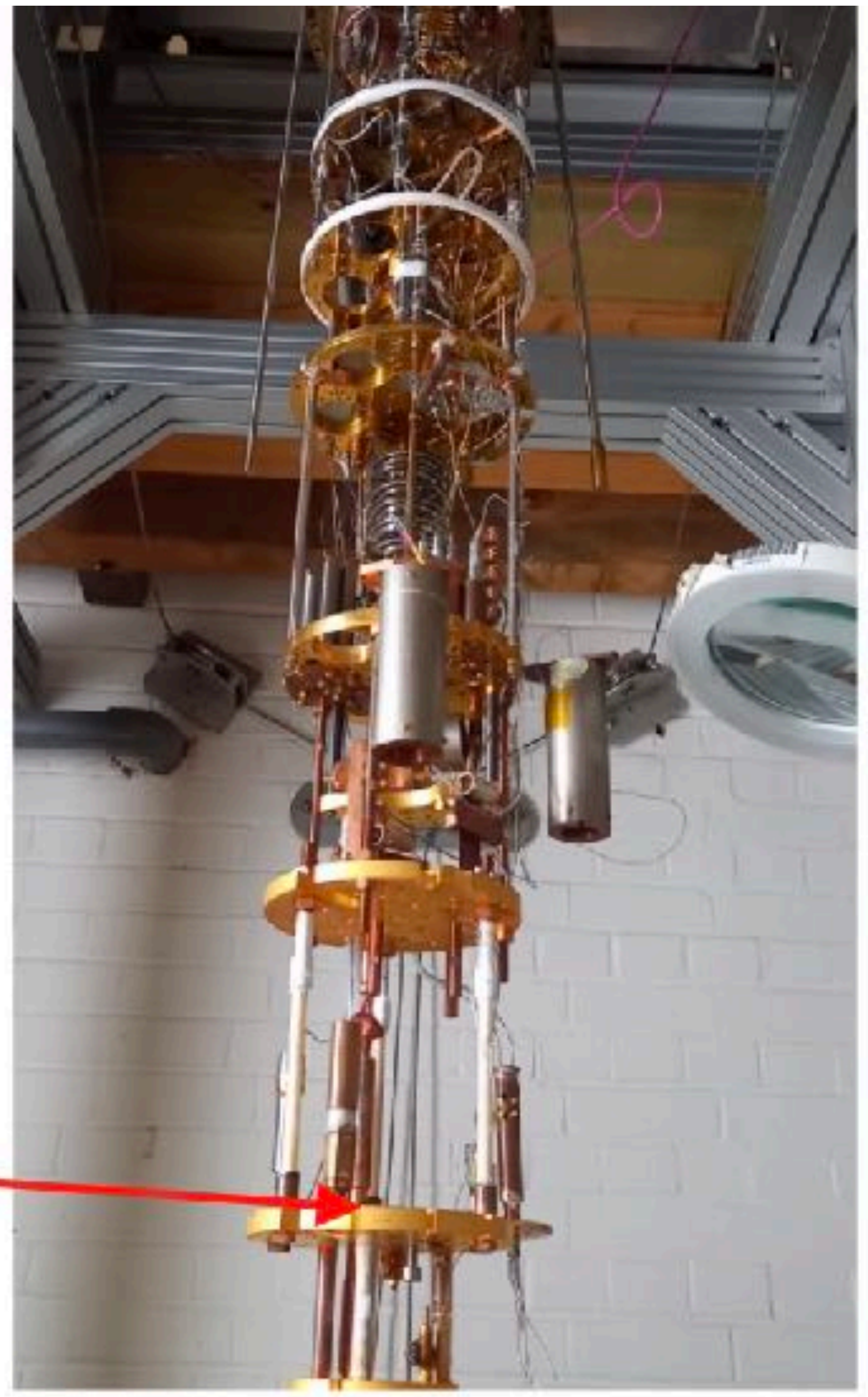
Credit: L Levitin

SQUID Readout

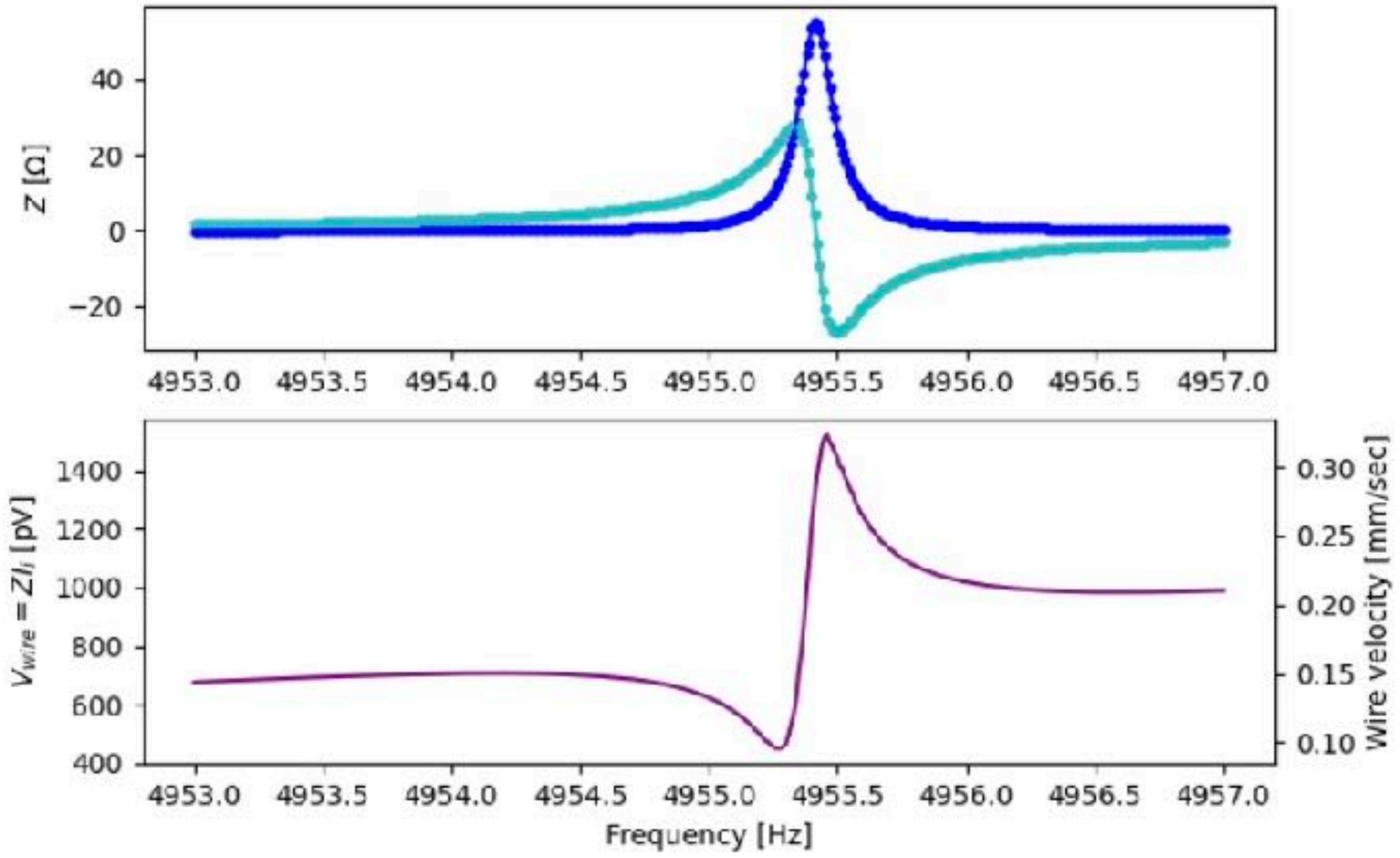
400nm wires down to 0.2mK







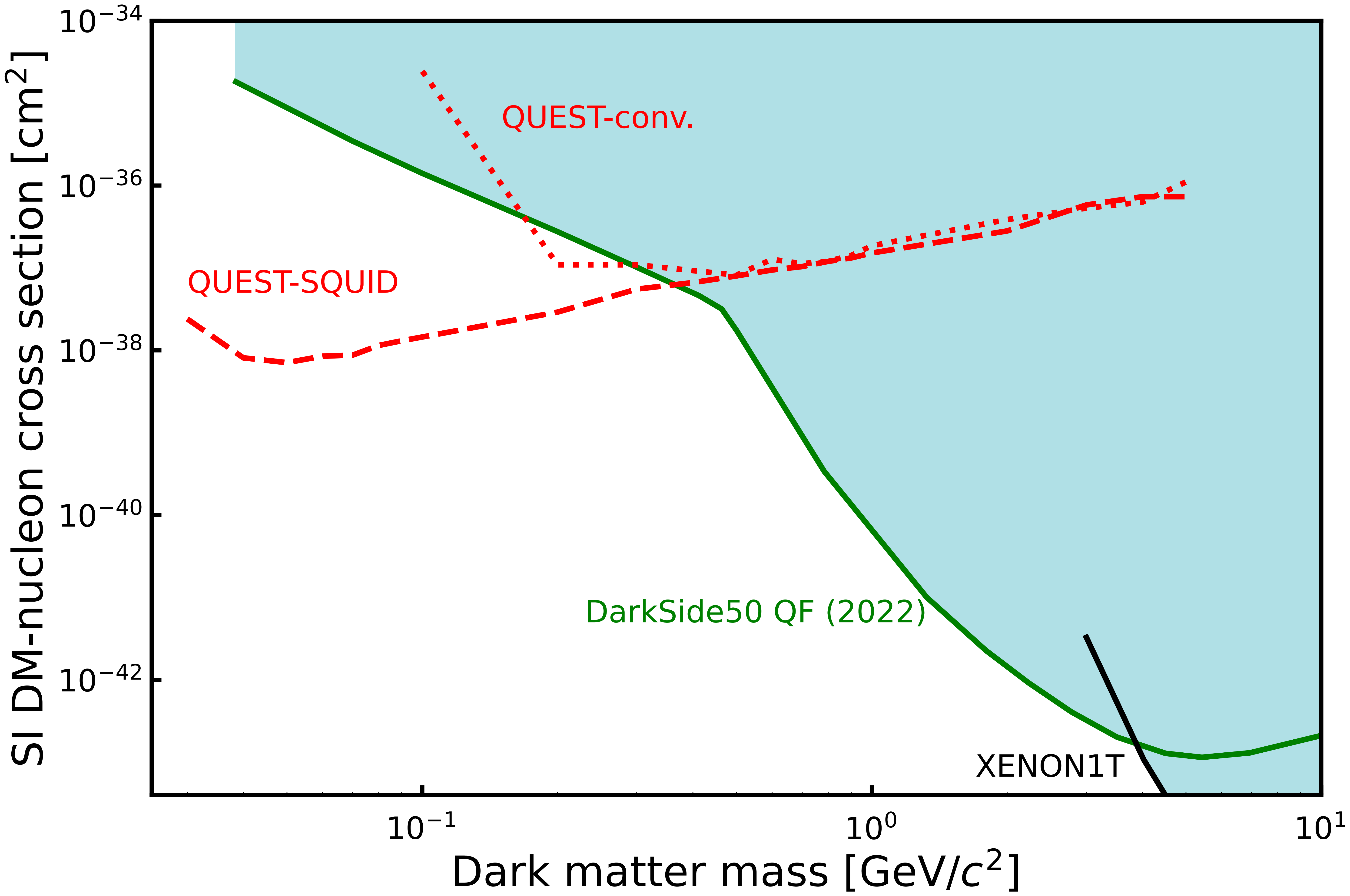
SQUID readout of VWR operated at sub-mK scale



Ongoing work at RHUL to measure QP shot noise and monoenergetic calibration source

Next generation bolometer to be installed at Lancaster

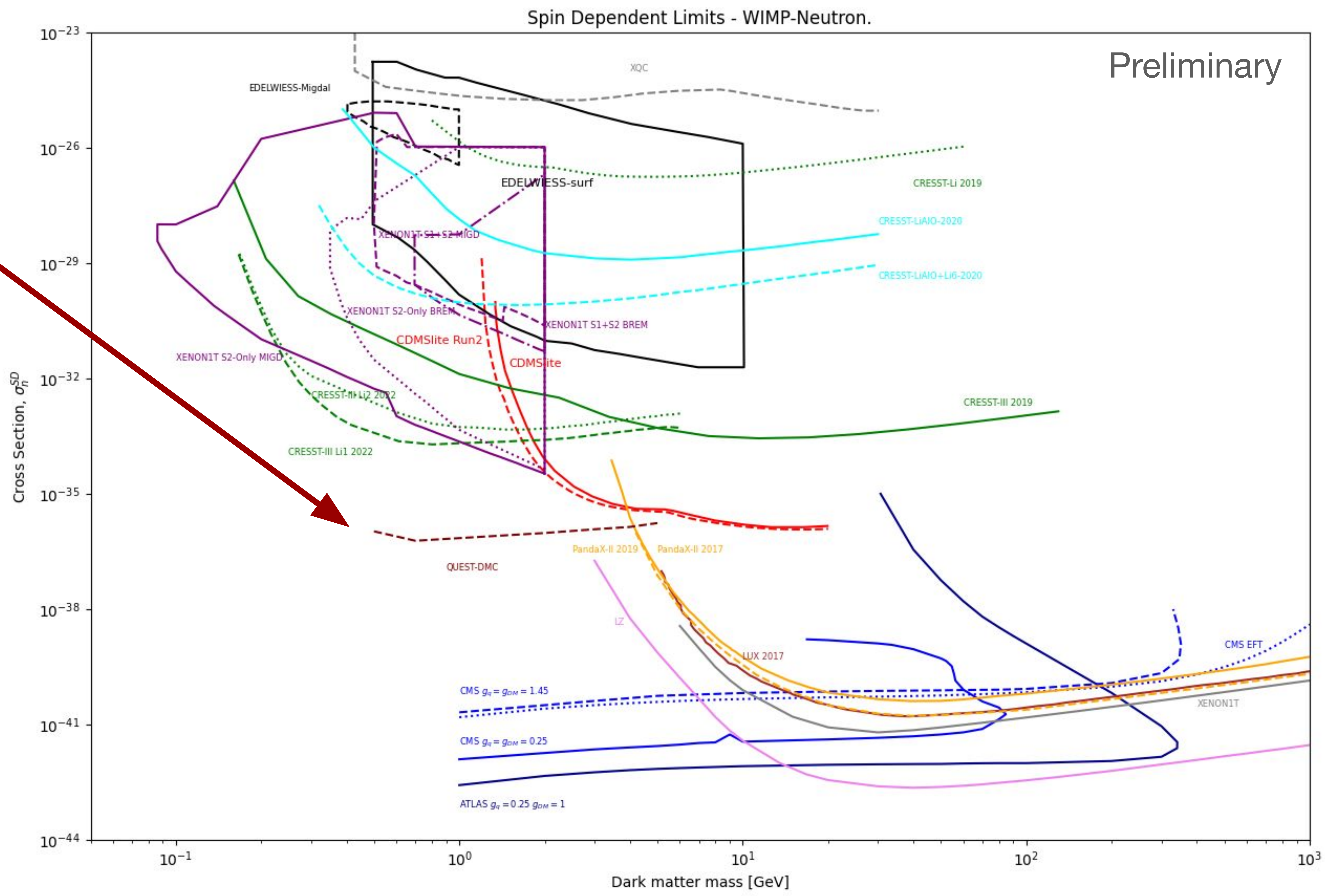
Spin-Independent Sensitivity



Credit: E Leason, N Darvishi S West

Sensitivity Wider Context

QUEST full exposure, conv. readout



Direct detection

Collider

Credit: E Leason, N Darvishi S West