Invisibles Workshop
31/08/23
Alte Mensa, Göttingen University, Germany

QUantum Enhanced Superfluid Technologies for Dark Matter & Cosmology

Concept for the detection of sub-GeV Dark Matter using a Helium-3 calorimeter

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QUEST-DMC Collaboration

QUEST DMC

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

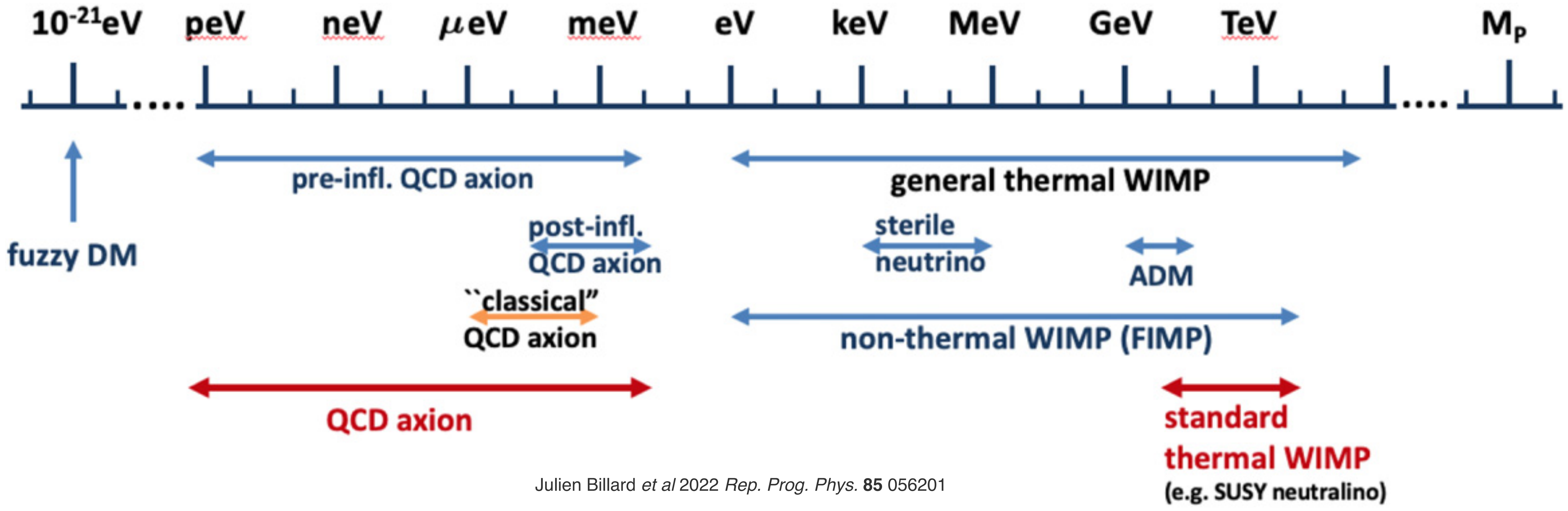
2. Phase transitions in extreme matter, relevant to cosmology and gravitational wave production

UKRI Engineering and Physical Sciences Research Council

UKRI Science and Technology Facilities Council

Motivations

- 85% of matter in the universe is "dark"
- Theoretical motivation for sub-GeV dark matter (ADM, Hidden Sector, Freeze-in…)
- Aim for eV scale recoil energy threshold
- Superfluid ^{3}He target (~100 μK) with low noise readout



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

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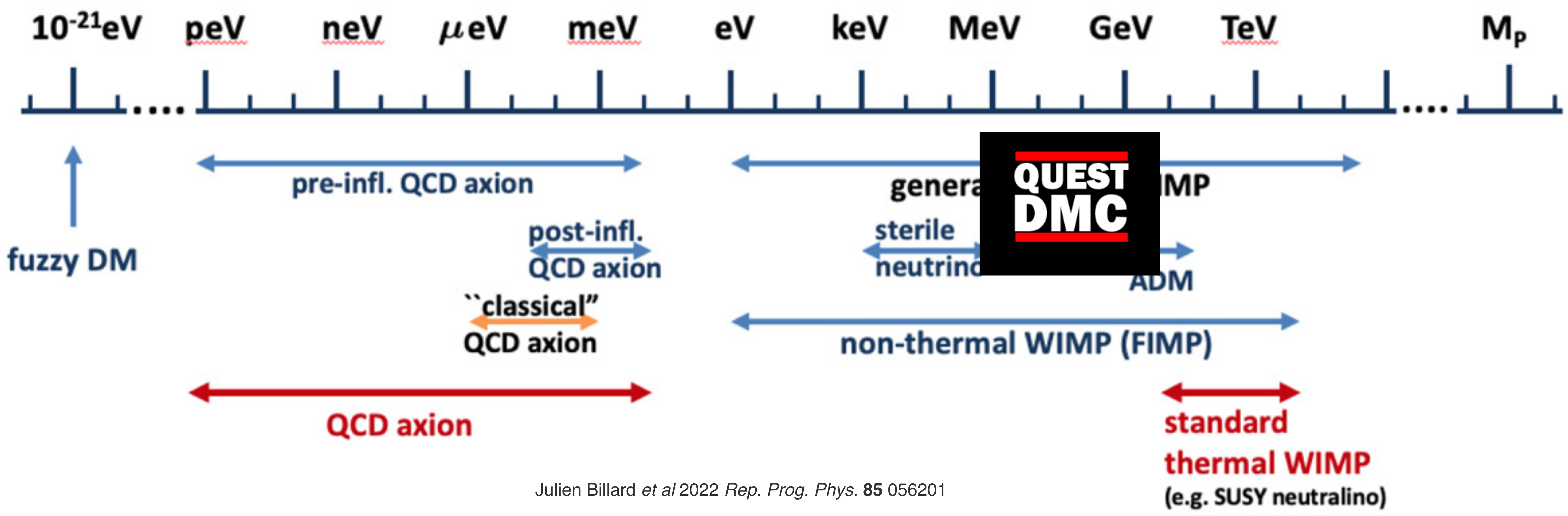

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Outline

Target → Detector → Readout → Sensitivity

Target: Superfluid ^3He

Detector: Vibrating wire resonators + Photomultipliers

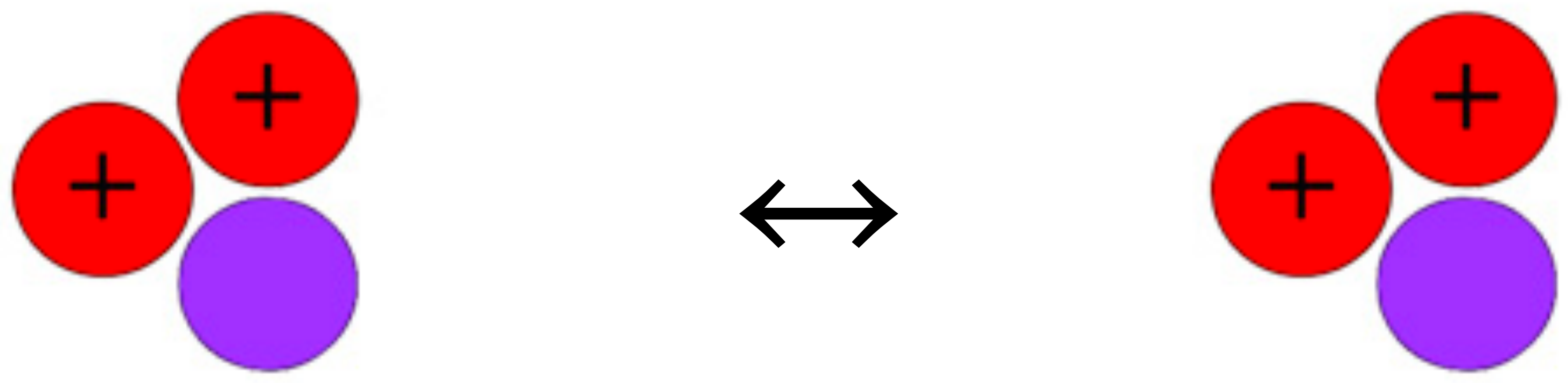
Readout: Quantum sensor (SQUIDs)

Sensitivity: Statistical methods

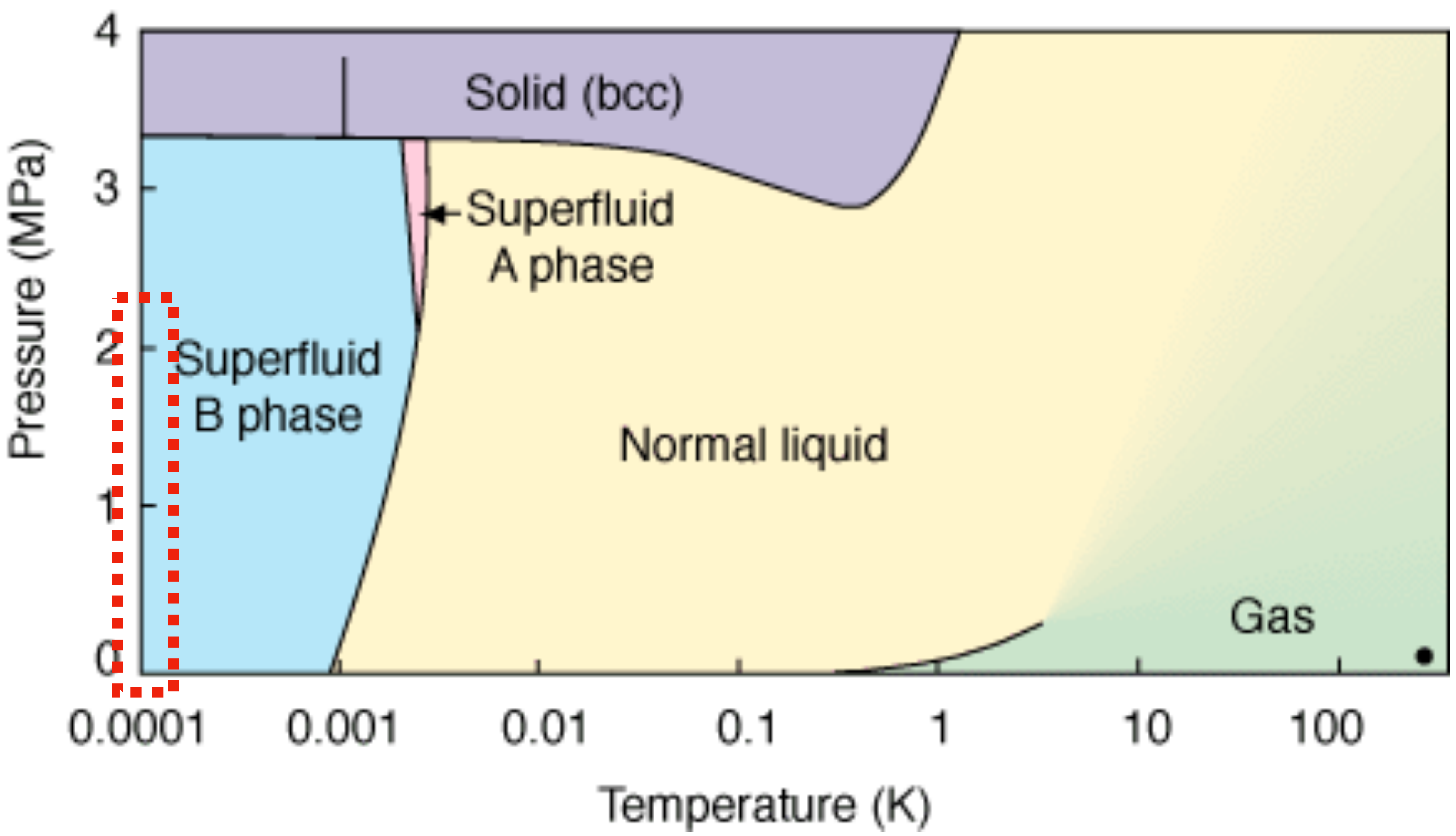
Target: ^3He

Superfluidity

- 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



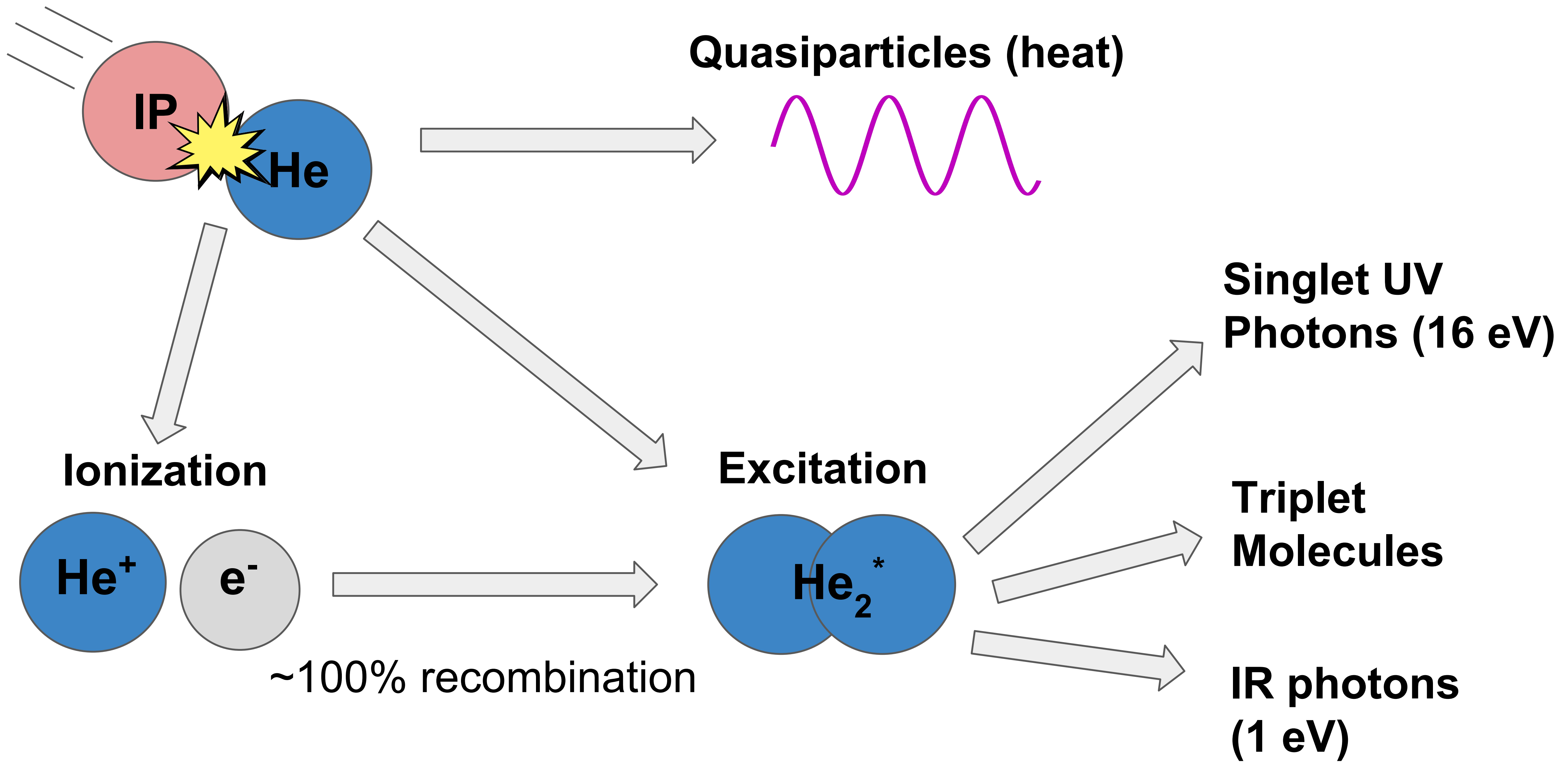
$$\Delta_{gap} = 10^{-7}\ \text{eV}$$

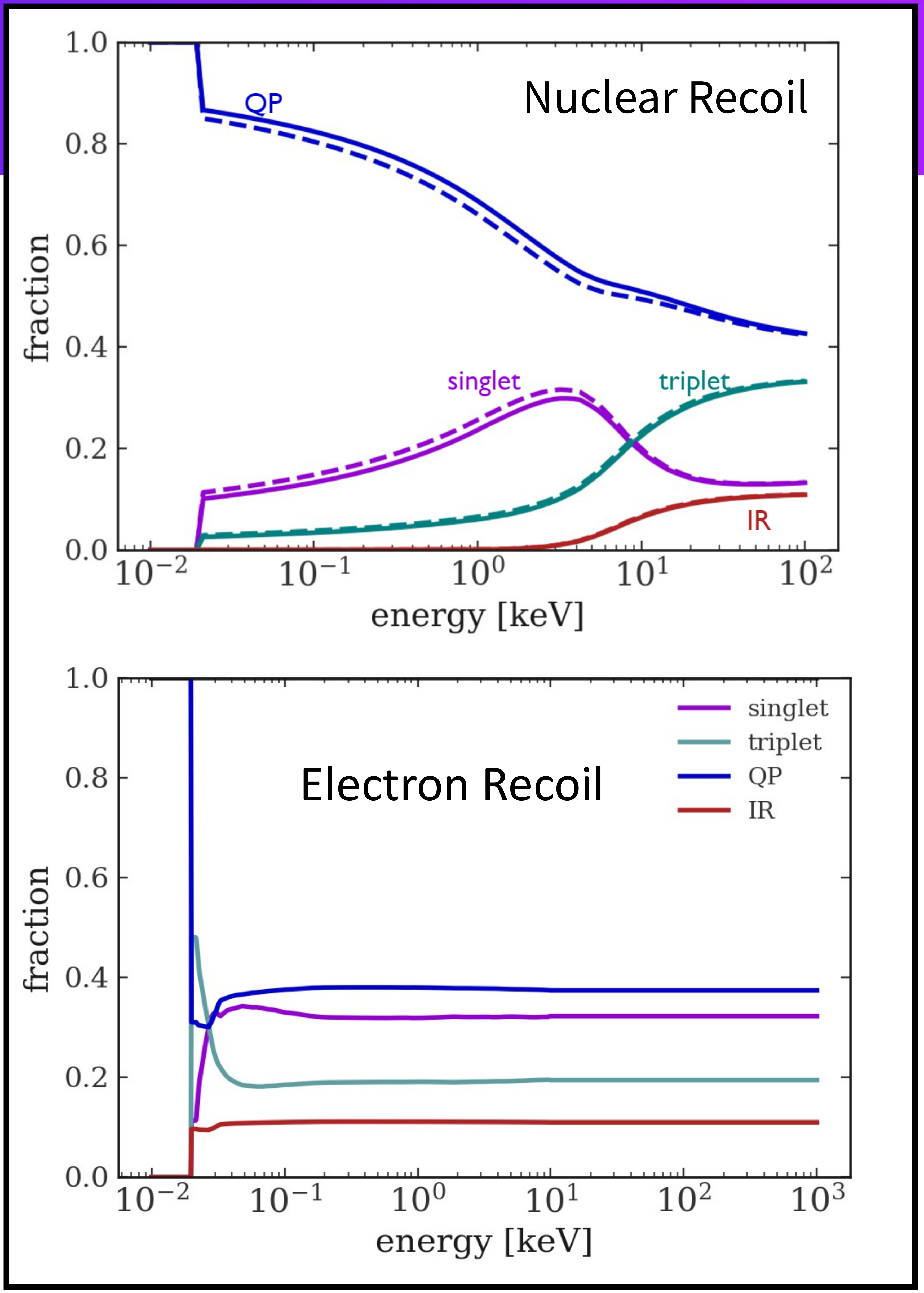


Phase diagram for ^3He

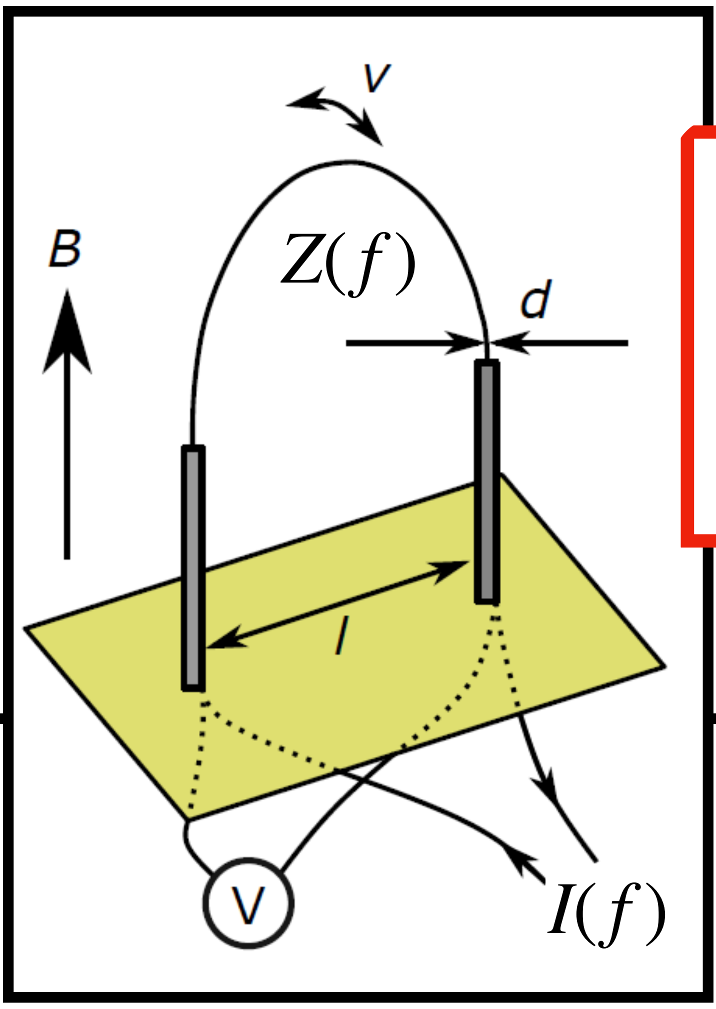
Target: ^3He
Interaction Response

- Quasiparticles (QP) released from breaking of Cooper pairs (10^7 QP per eV deposit)
- Both nuclear & electron recoils (20 eV threshold for ER)
- Secondary signal from scintillation

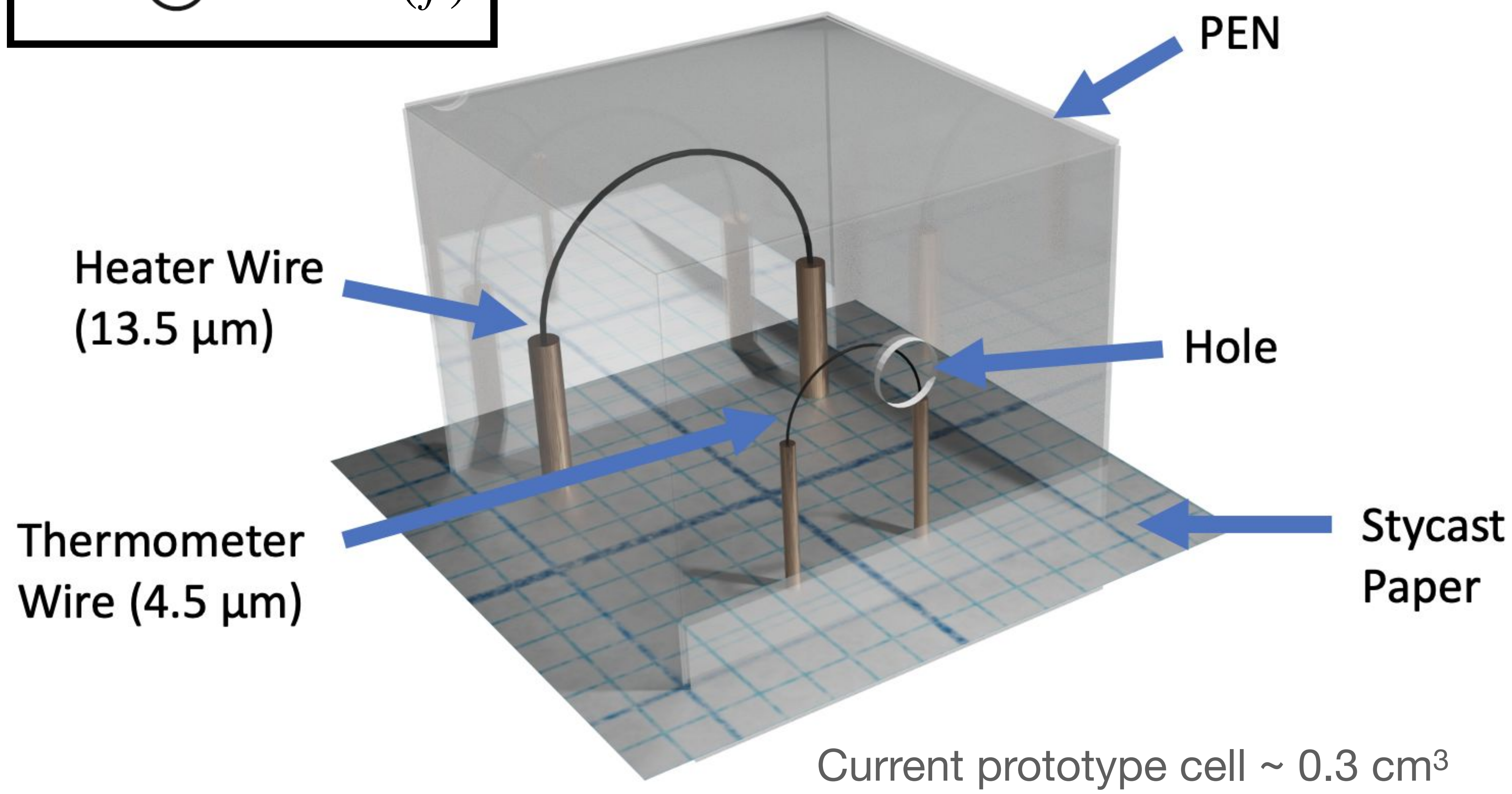




Detector: Vibrating Wires

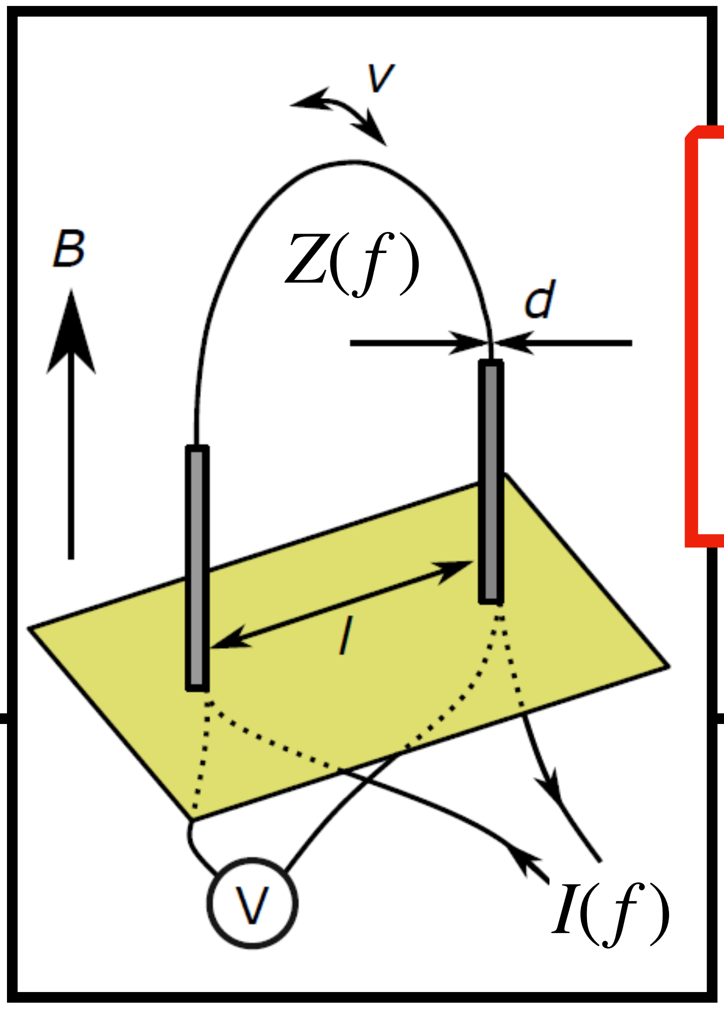


1. Oscillating wire in a magnetic field driven at frequency f



Current prototype cell ~ 0.3 cm^3

Detector: Vibrating Wires



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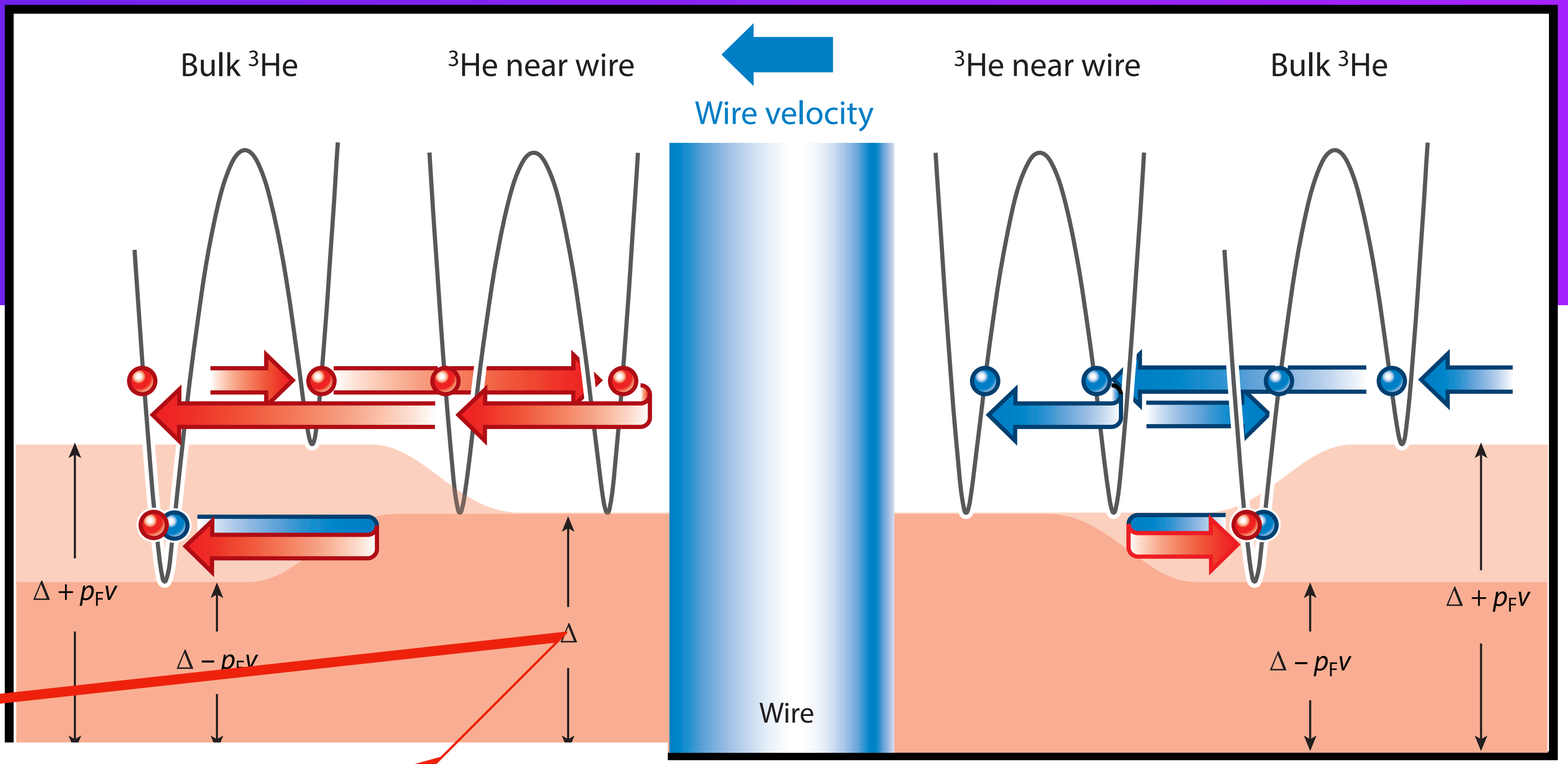
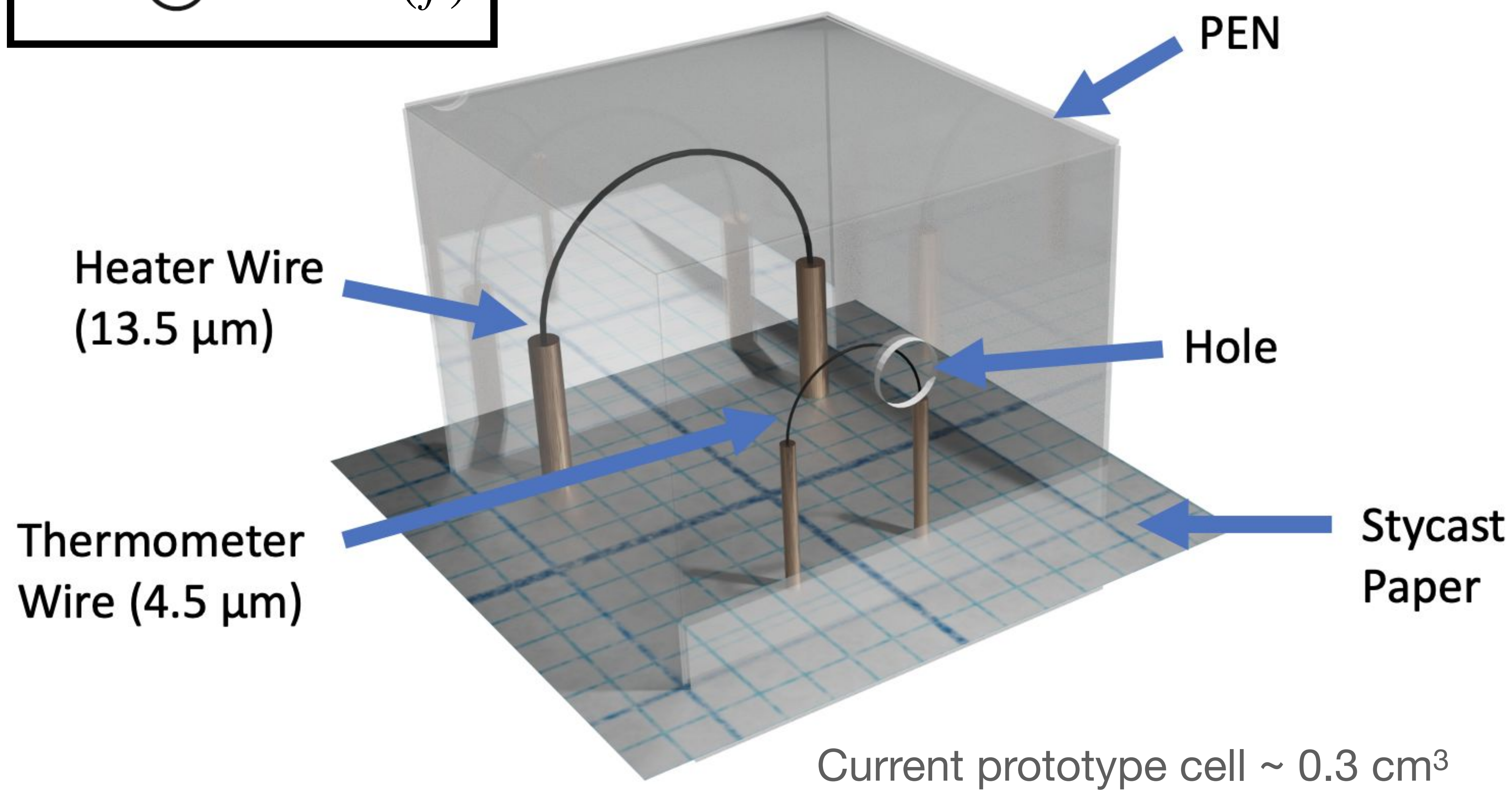
Good Vibrations



2. Damping force on wire due to QP interactions

https://doi.org/10.1146/annurev-conmatphys-031016-025411



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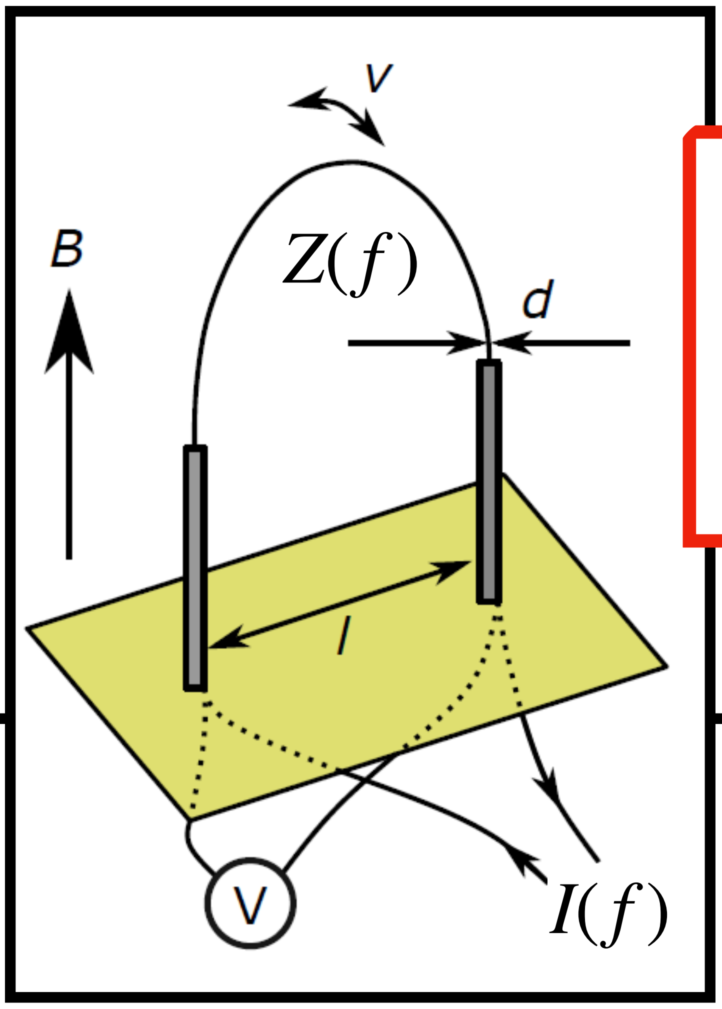

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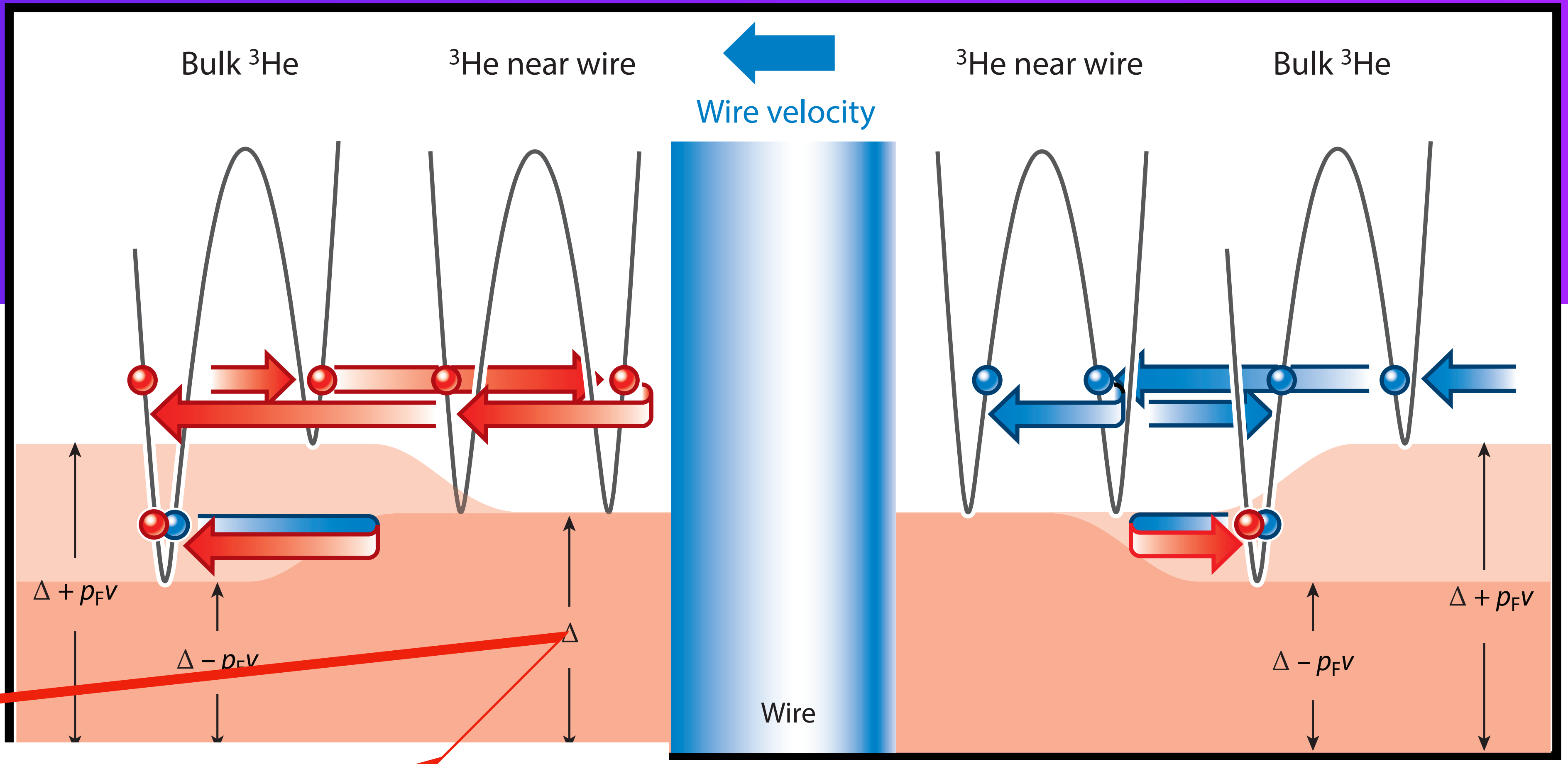

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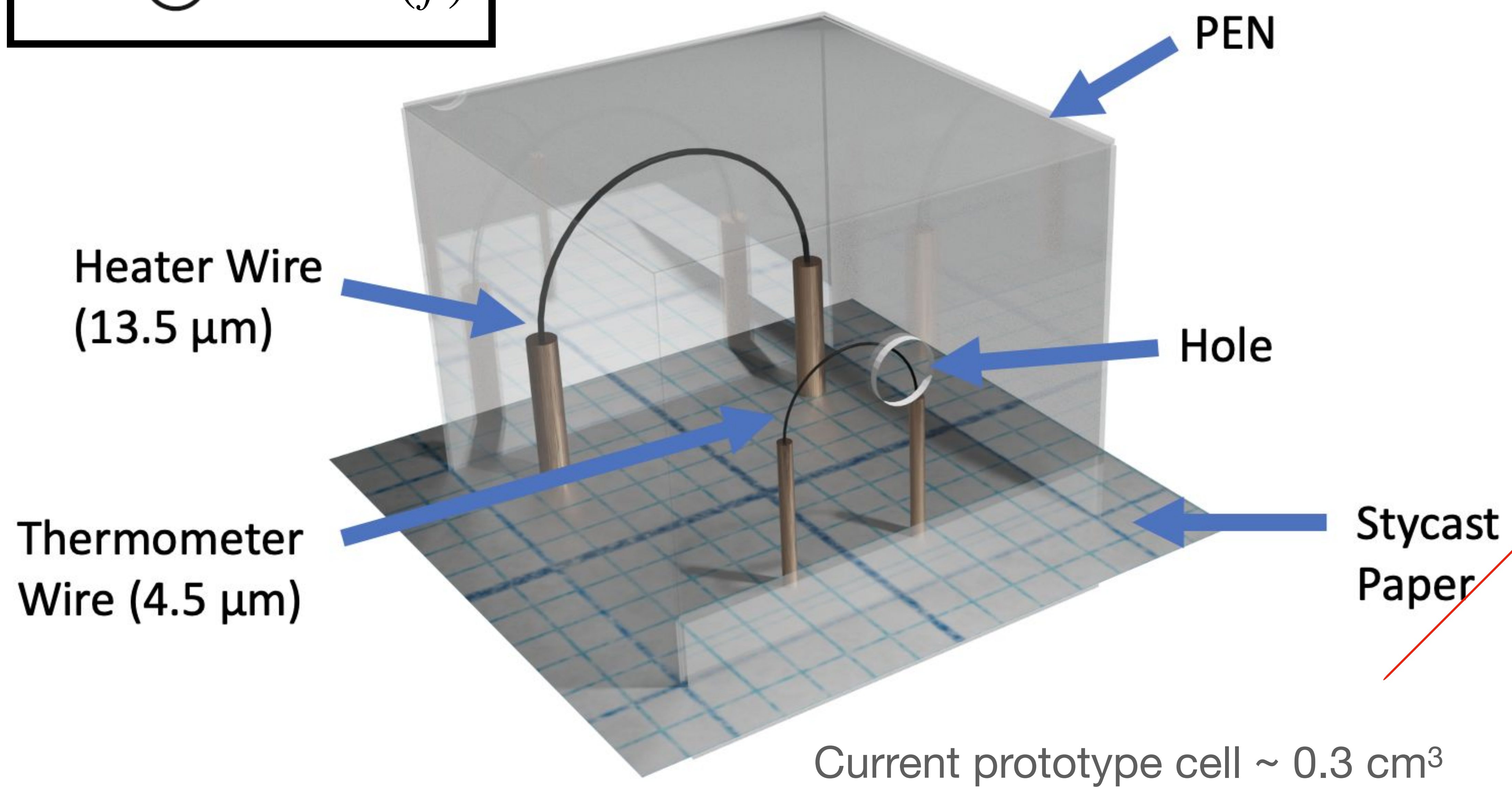
Excitations



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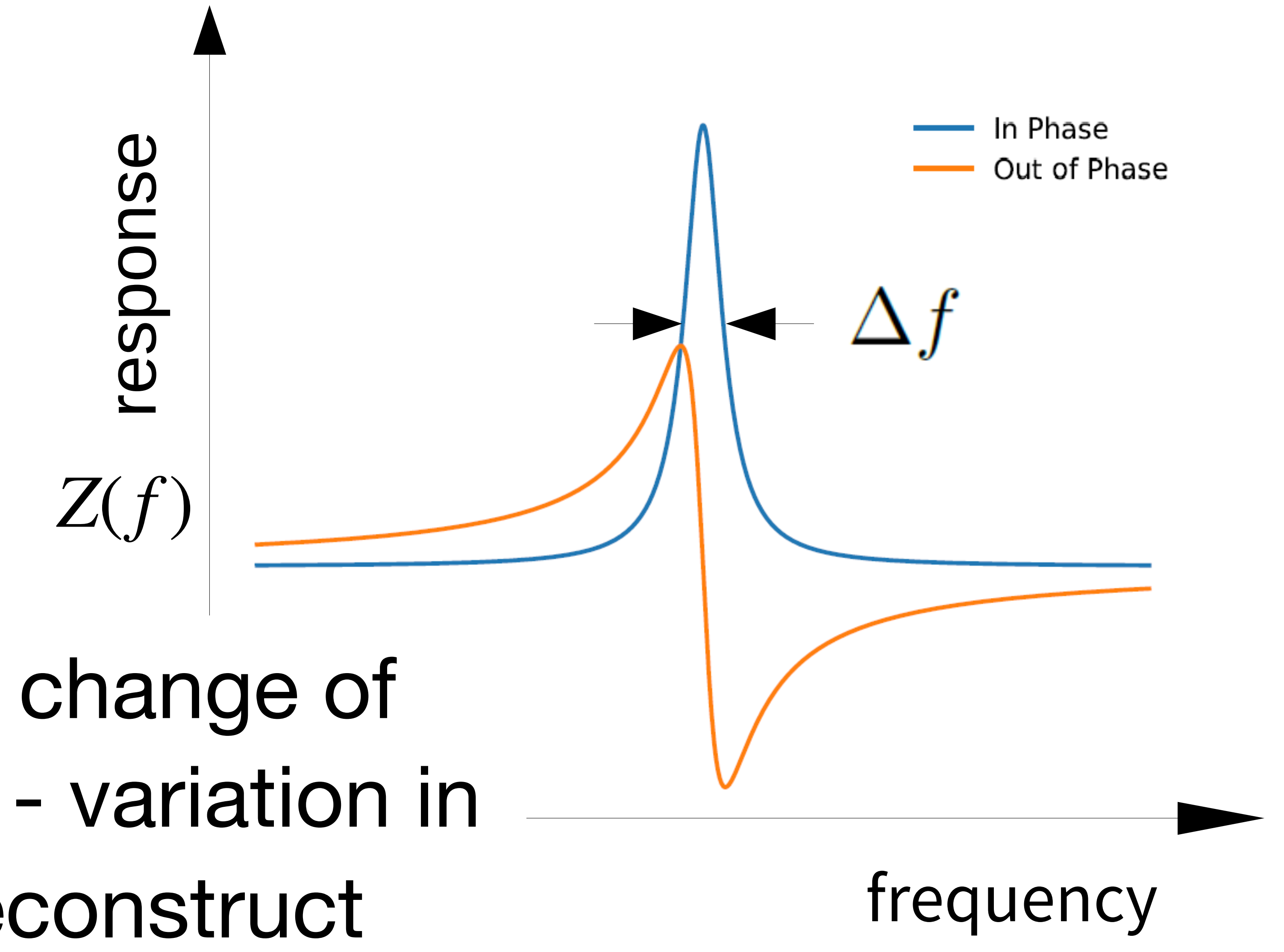
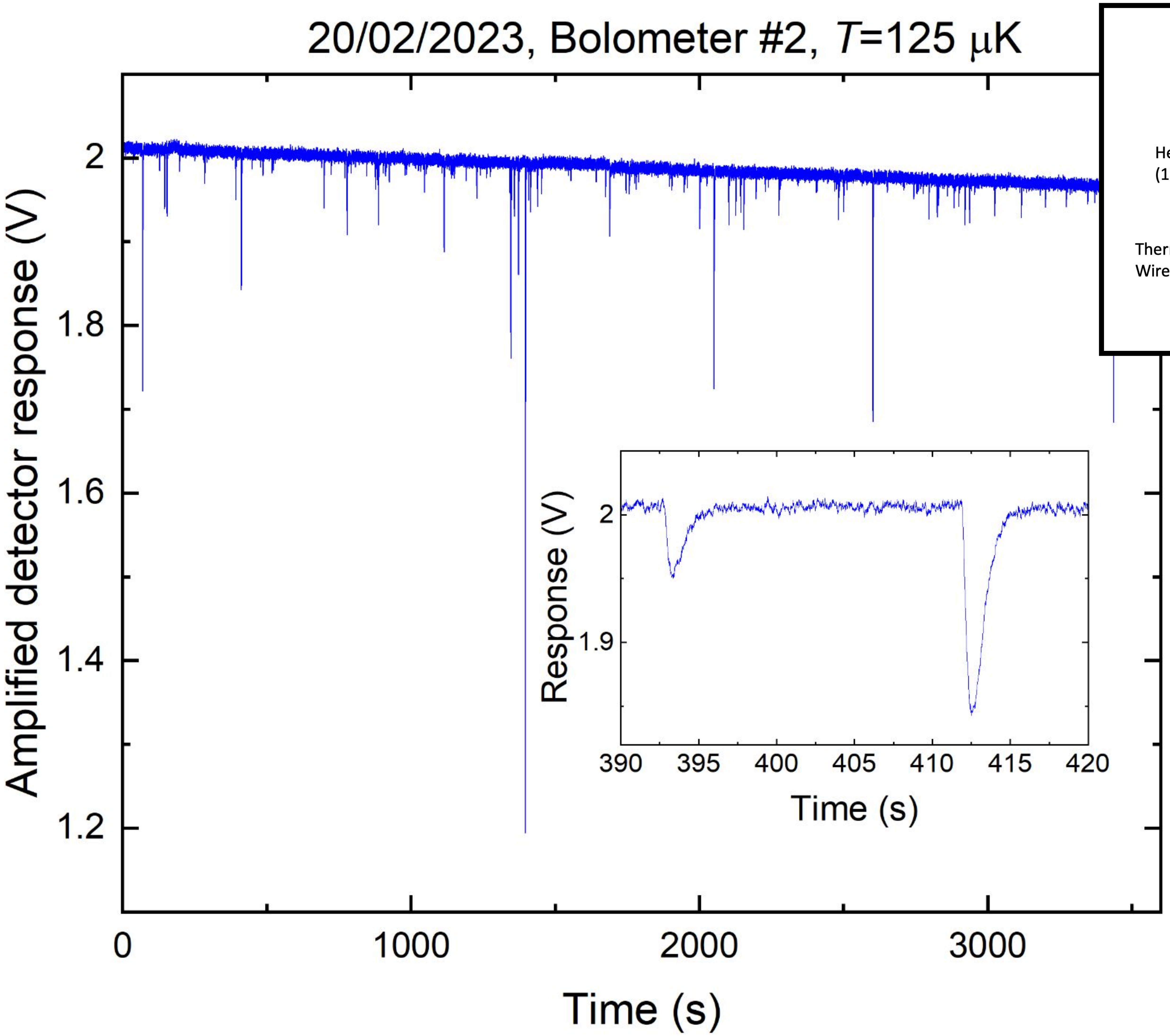
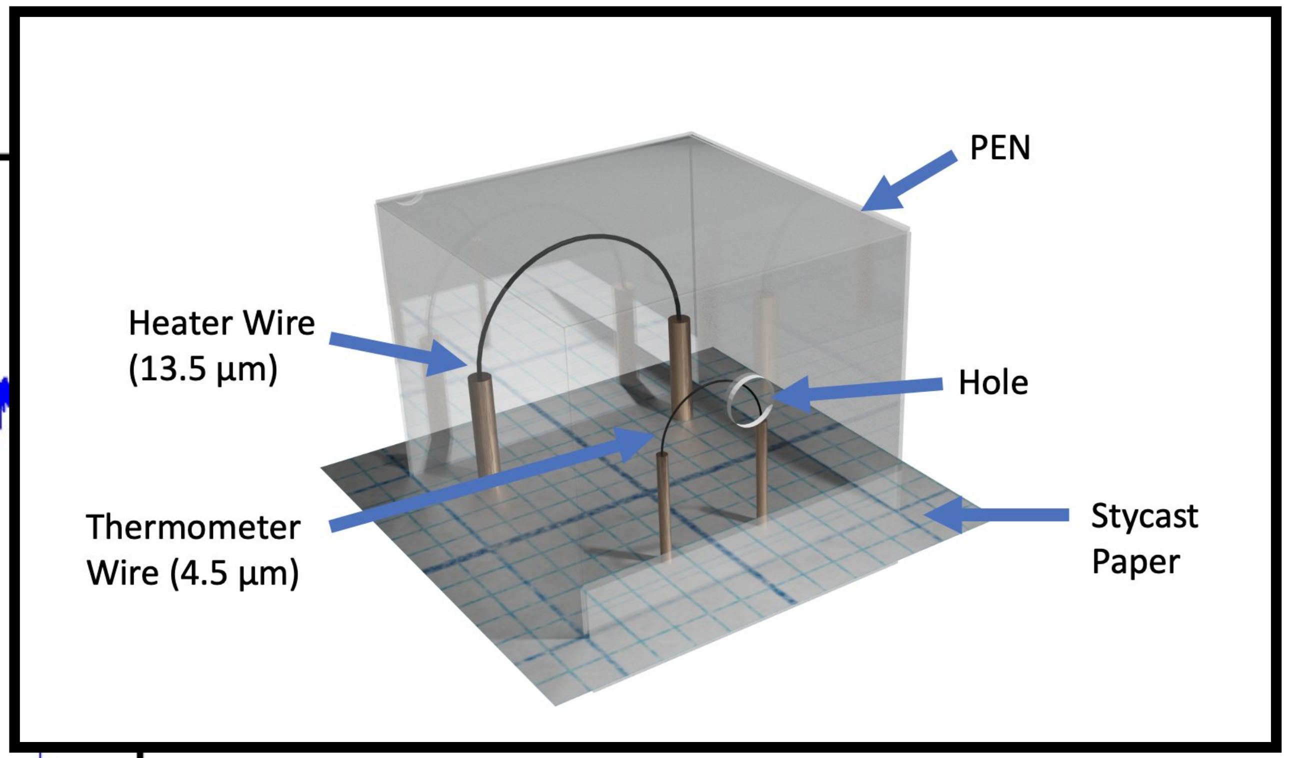


3. Detected as change of impedance $Z(f)$ - variation in Δf used to reconstruct energy:

Winkelmann et al: https://doi.org/10.1016/j.nima.2007.01.180

Detector: Calorimetry

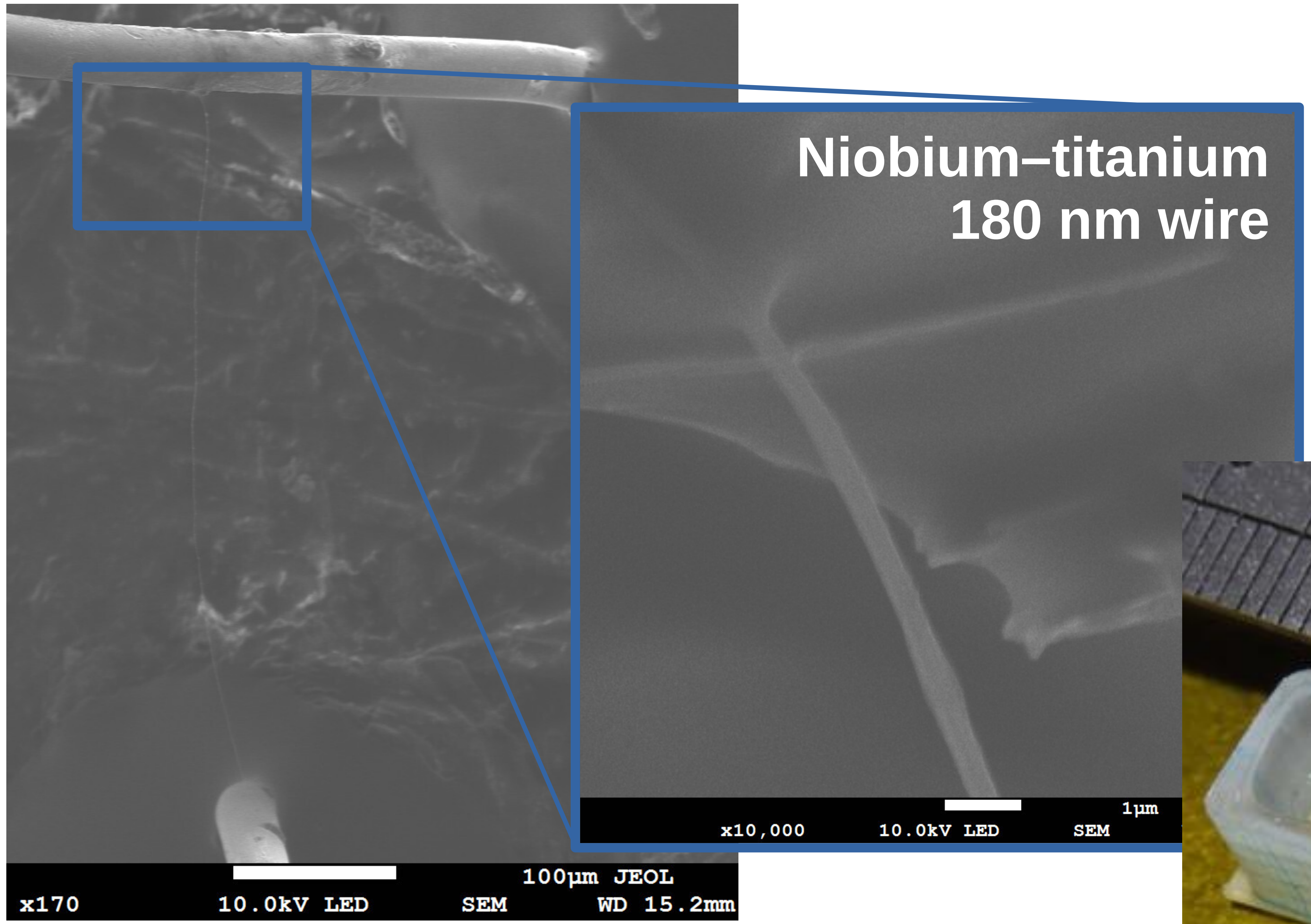




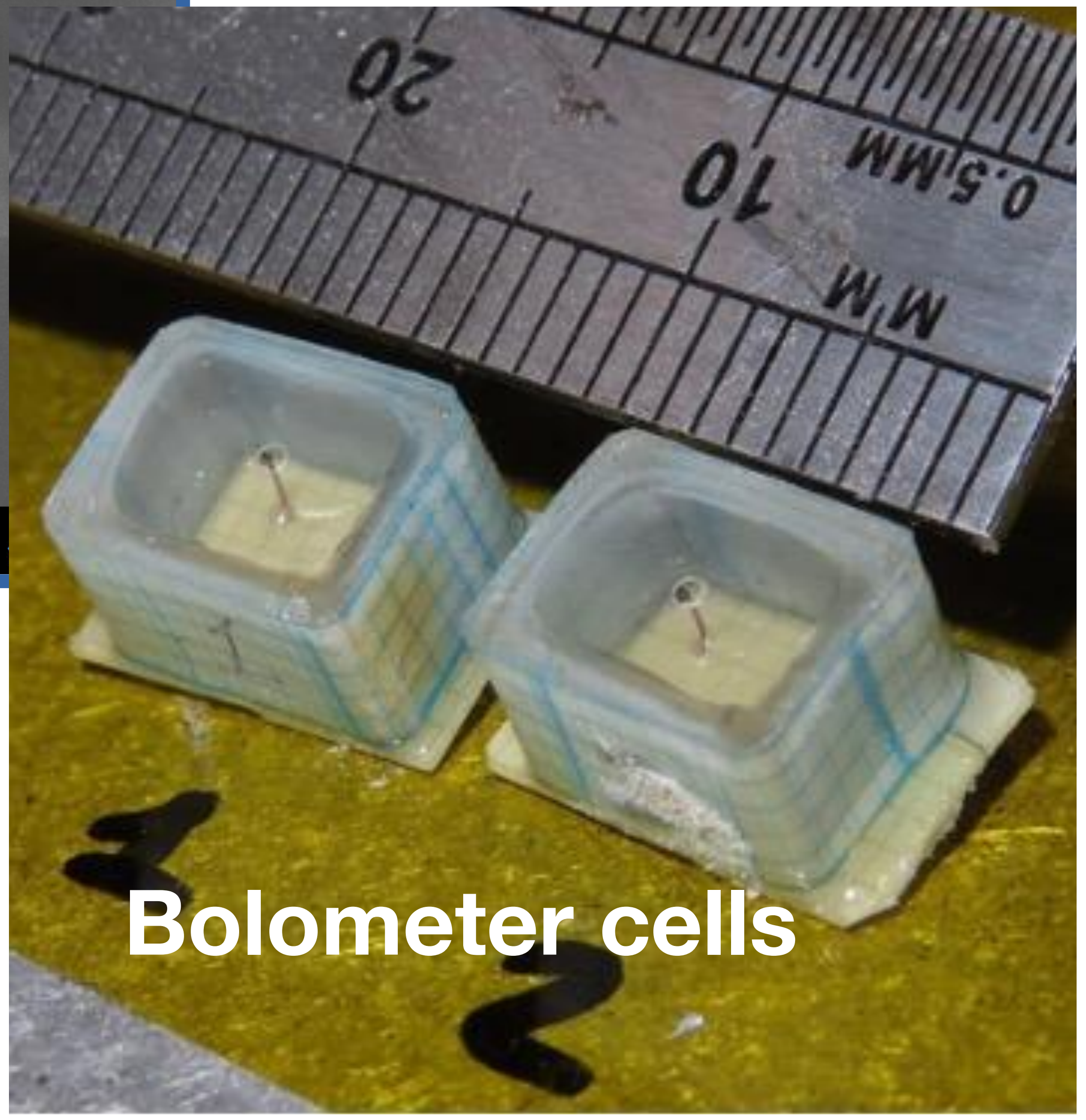
Data!

Pulses caused by heating events - use to reconstruct energy

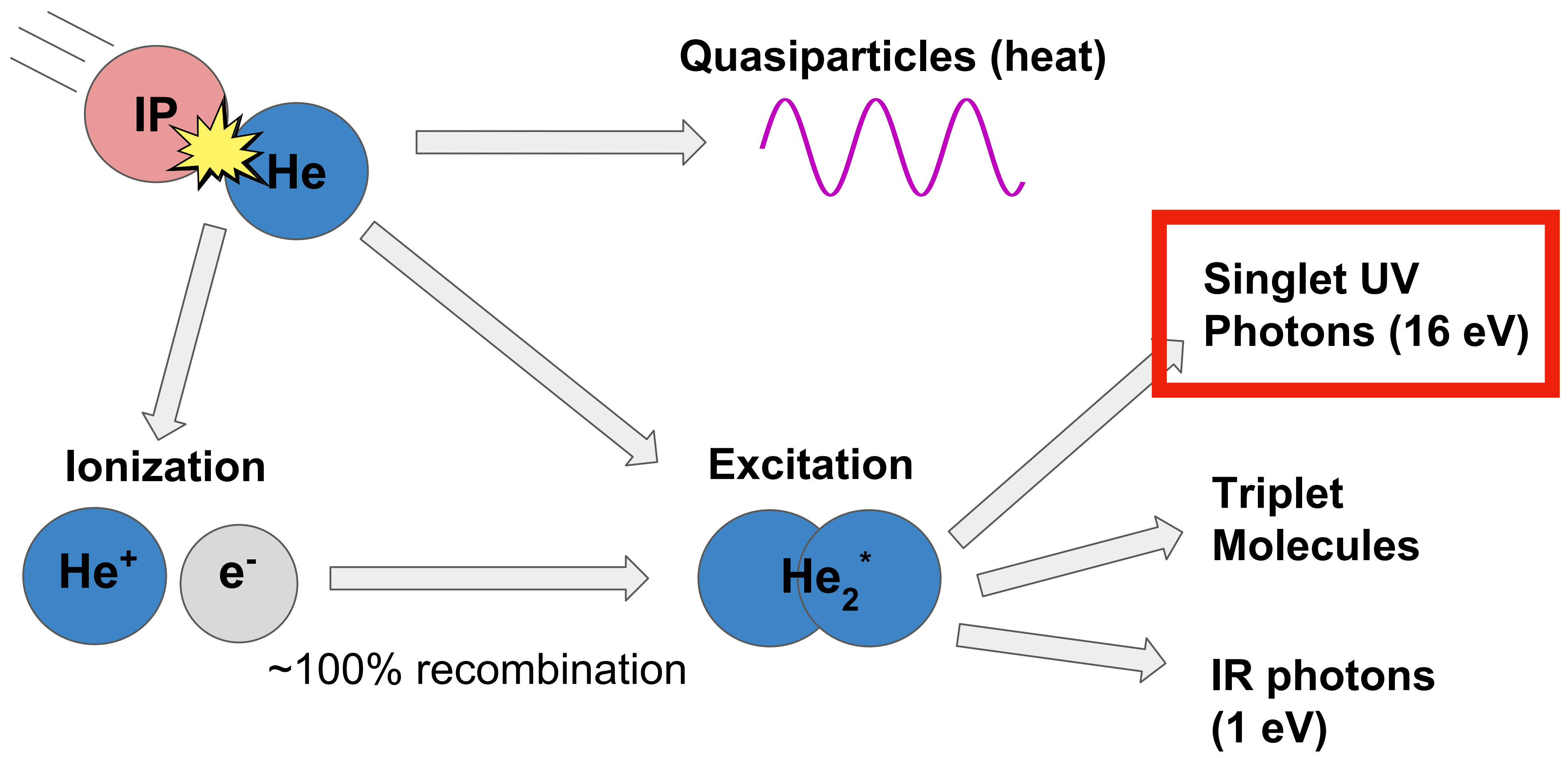
Detector: Nanowires & Cryostat

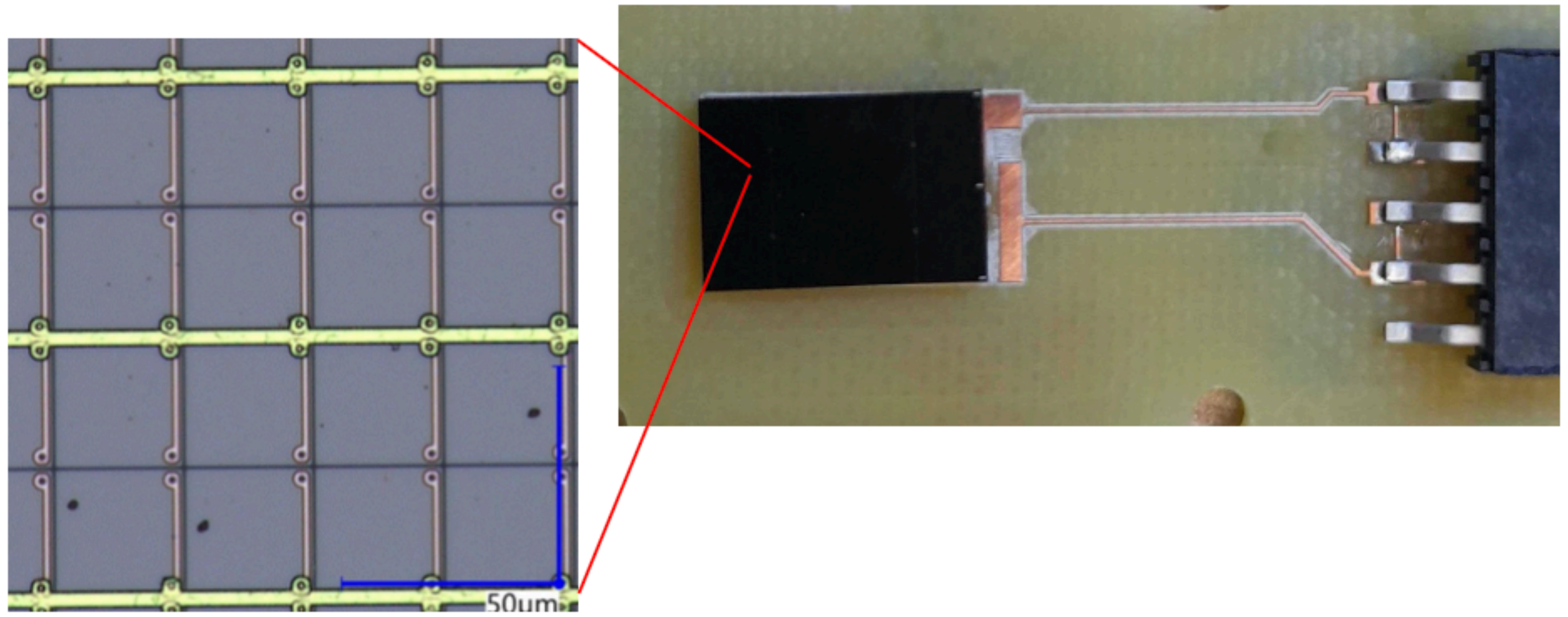


Credit: D Zmeev

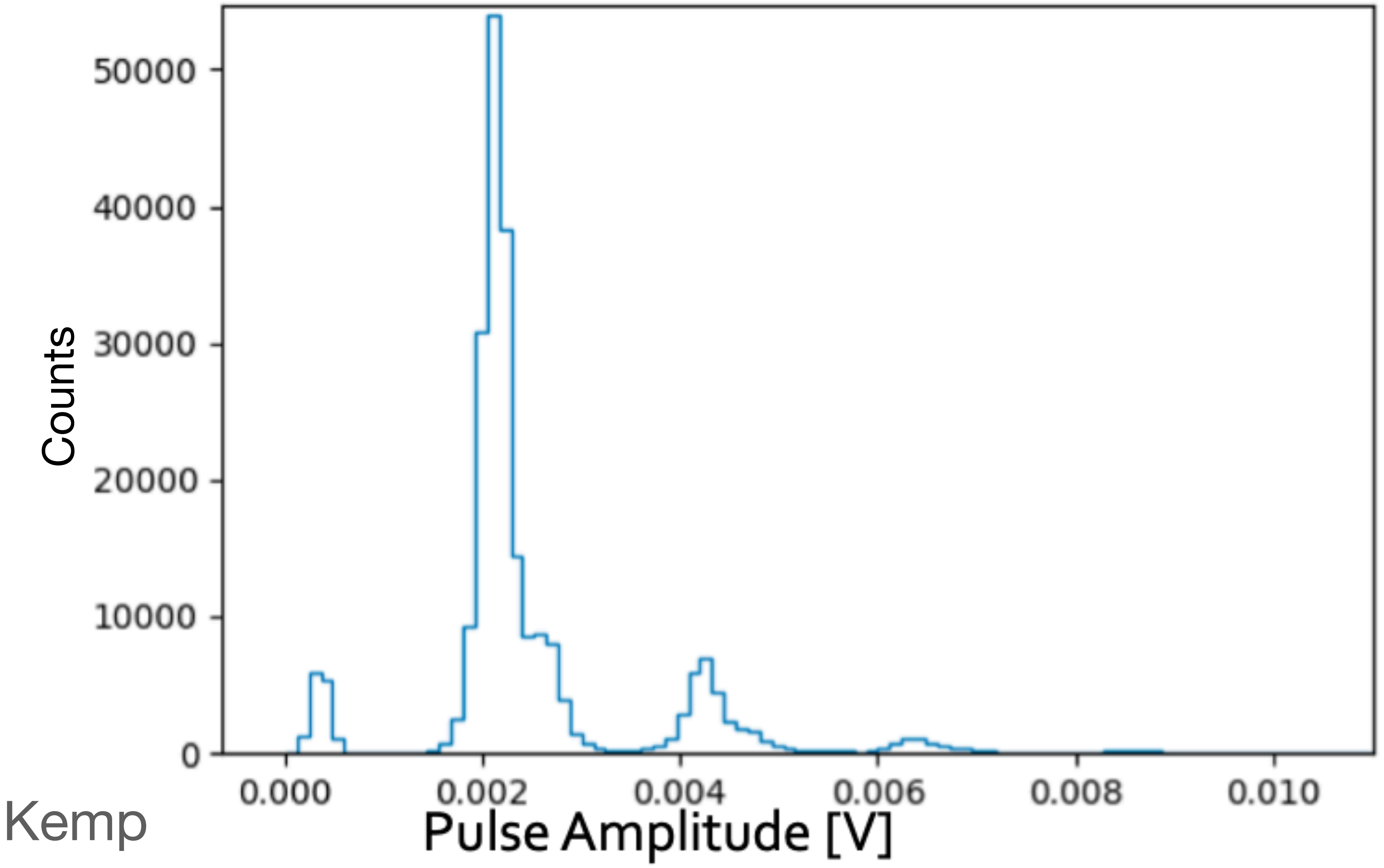


Detector: Measuring Ionisation





- Important for cosmic ray or electronic recoil veto
- Silicon photomultipliers - arrays of single photon avalanche diodes
- Single photo-electron (p.e.) resolution
- Successful test done at 4K



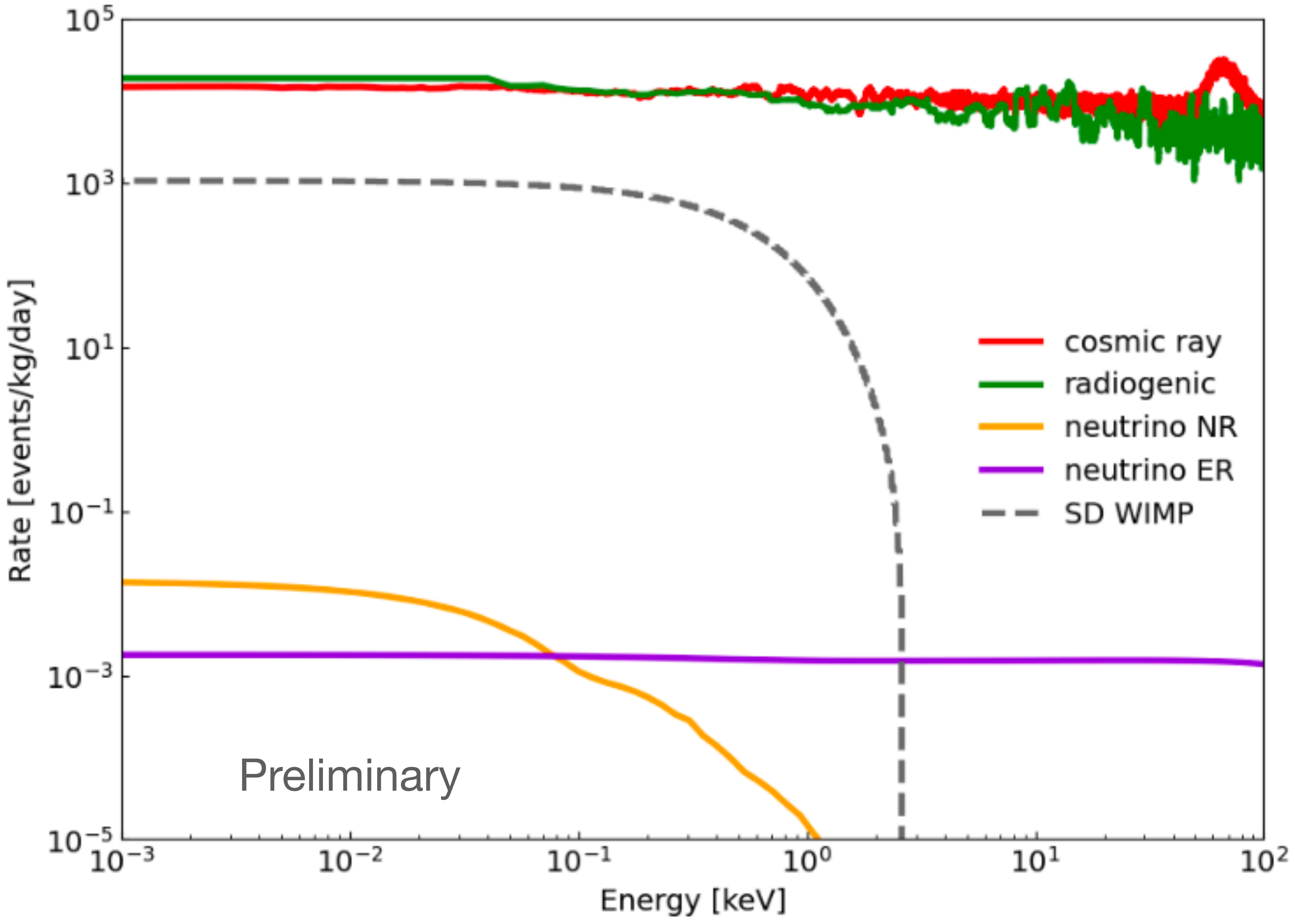
Credit: E Leason, A Kemp

Detector: Background

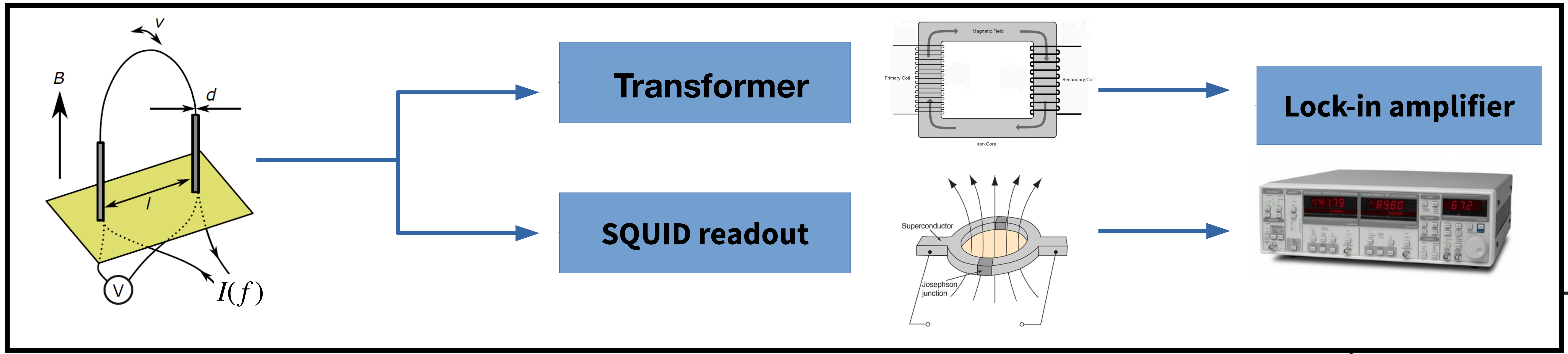
- G4 simulation done for cosmic ray and radiogenic event rates
- BUGS (Boulby Underground Germanium Suite) used for extensive radioassay of detector and cryostat materials

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	

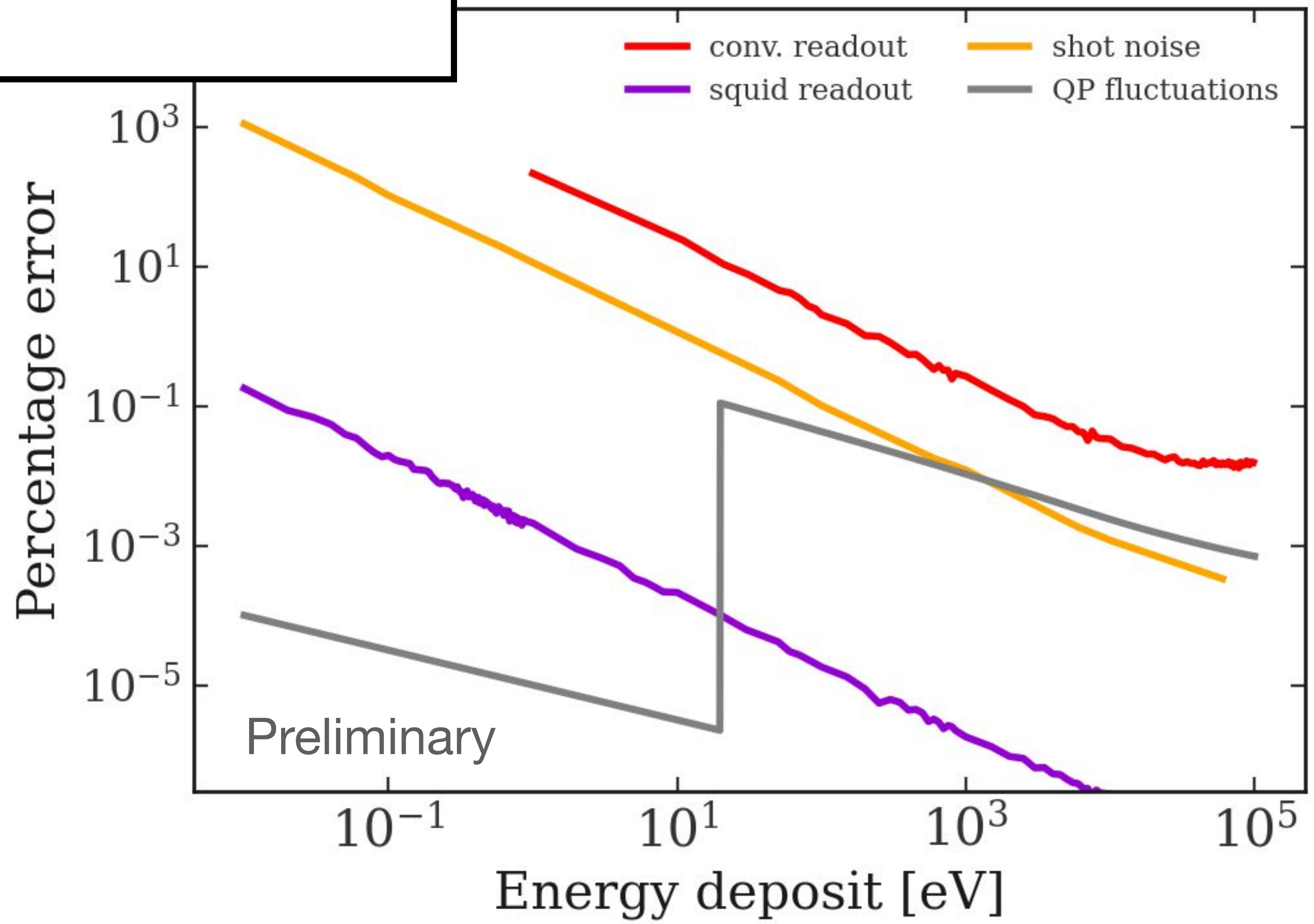
Expected background rates in ROI (0-10 keV) per kg and per cell (0.033 g) assuming 90% CR veto



Readout: SQUID vs Conventional

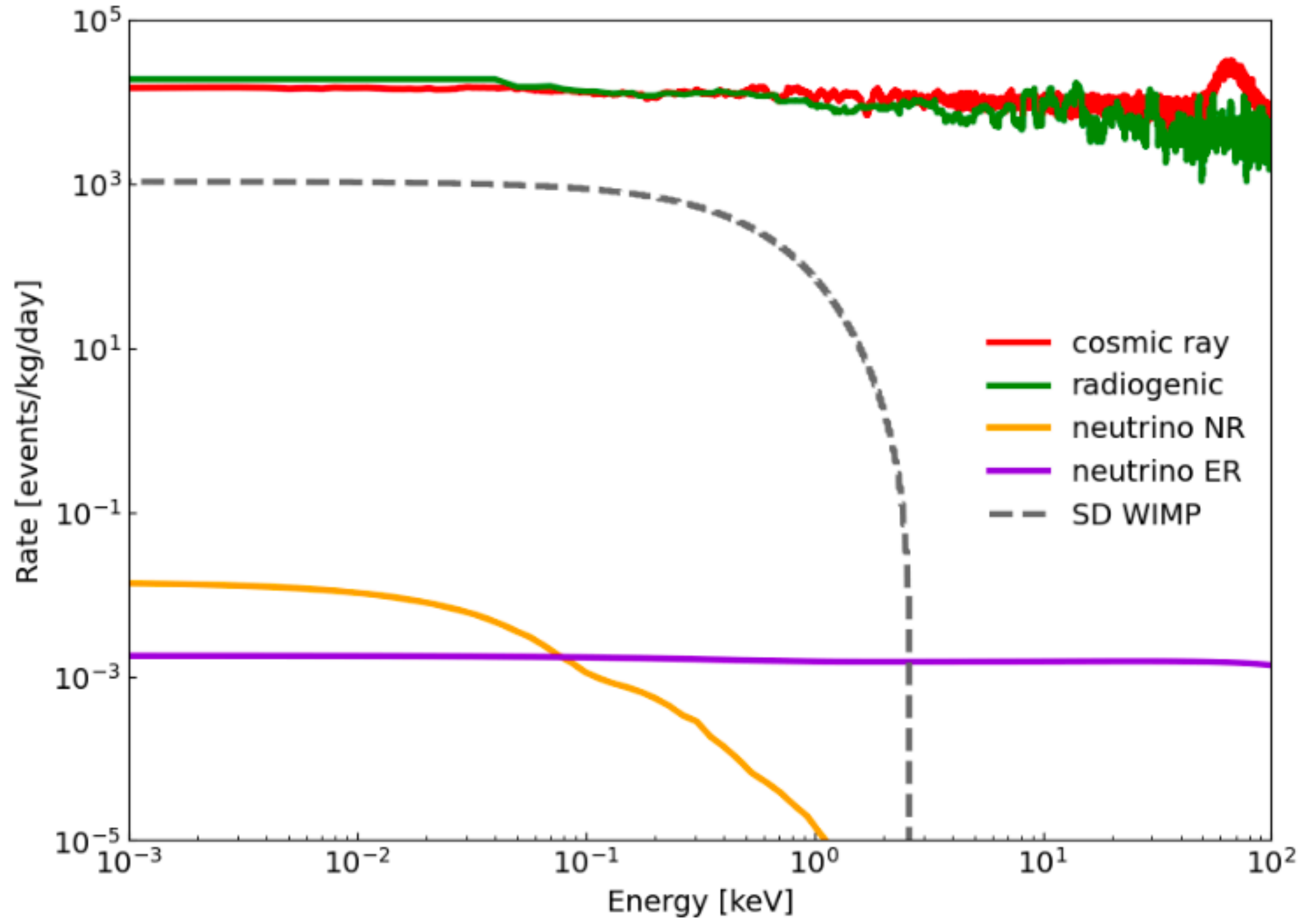


- Error on energy measurement ↔ DM energy threshold
- Conventional readout noise dominates over intrinsic limitation of QP noise
- SQUID (Superconducting QUantum Interference Device) can reduce noise of readout (< pV scale)
- Tested SQUID readout of nanowire (315nm) at 4.2K



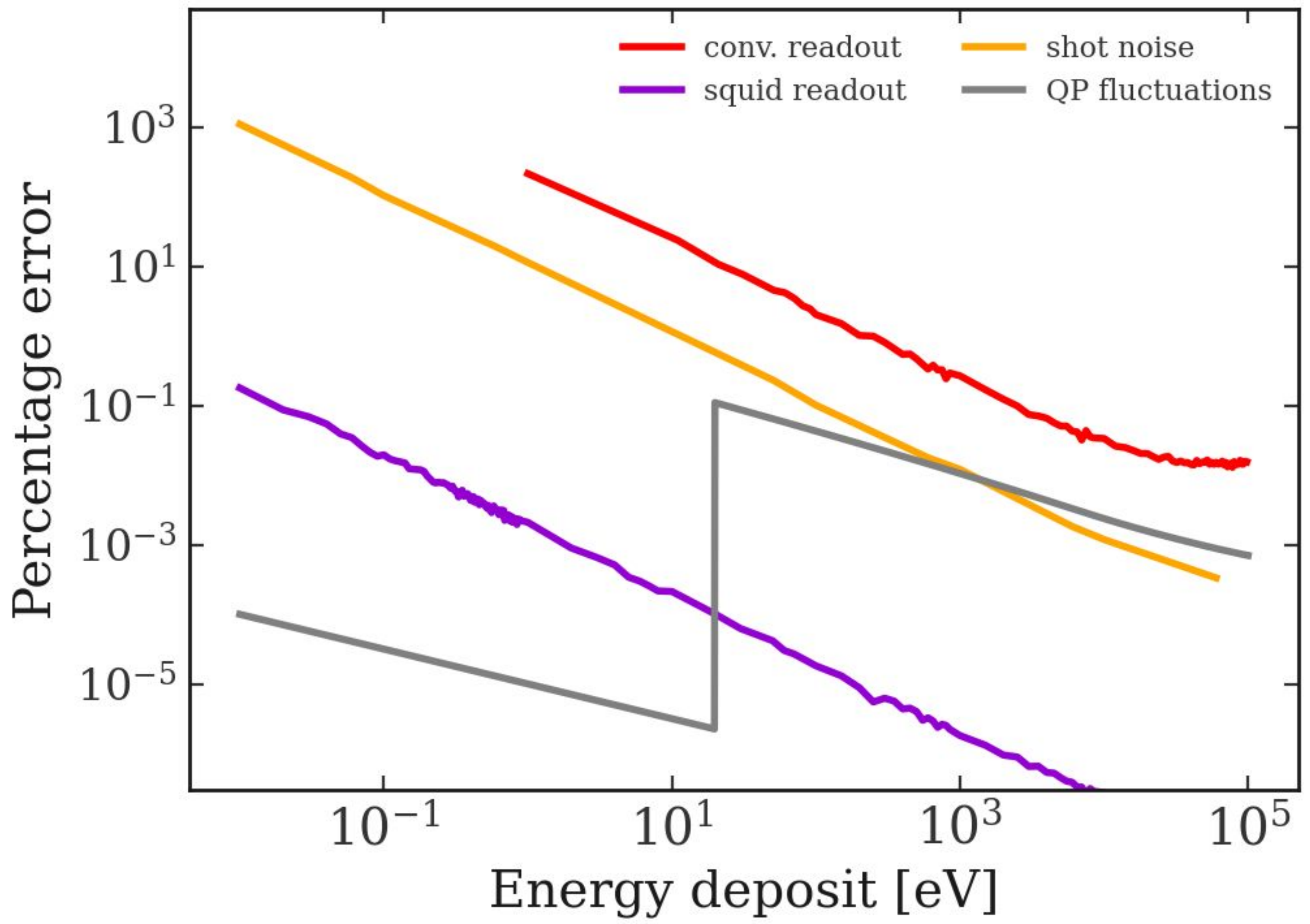
Estimated Sensitivity

Background simulation



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

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



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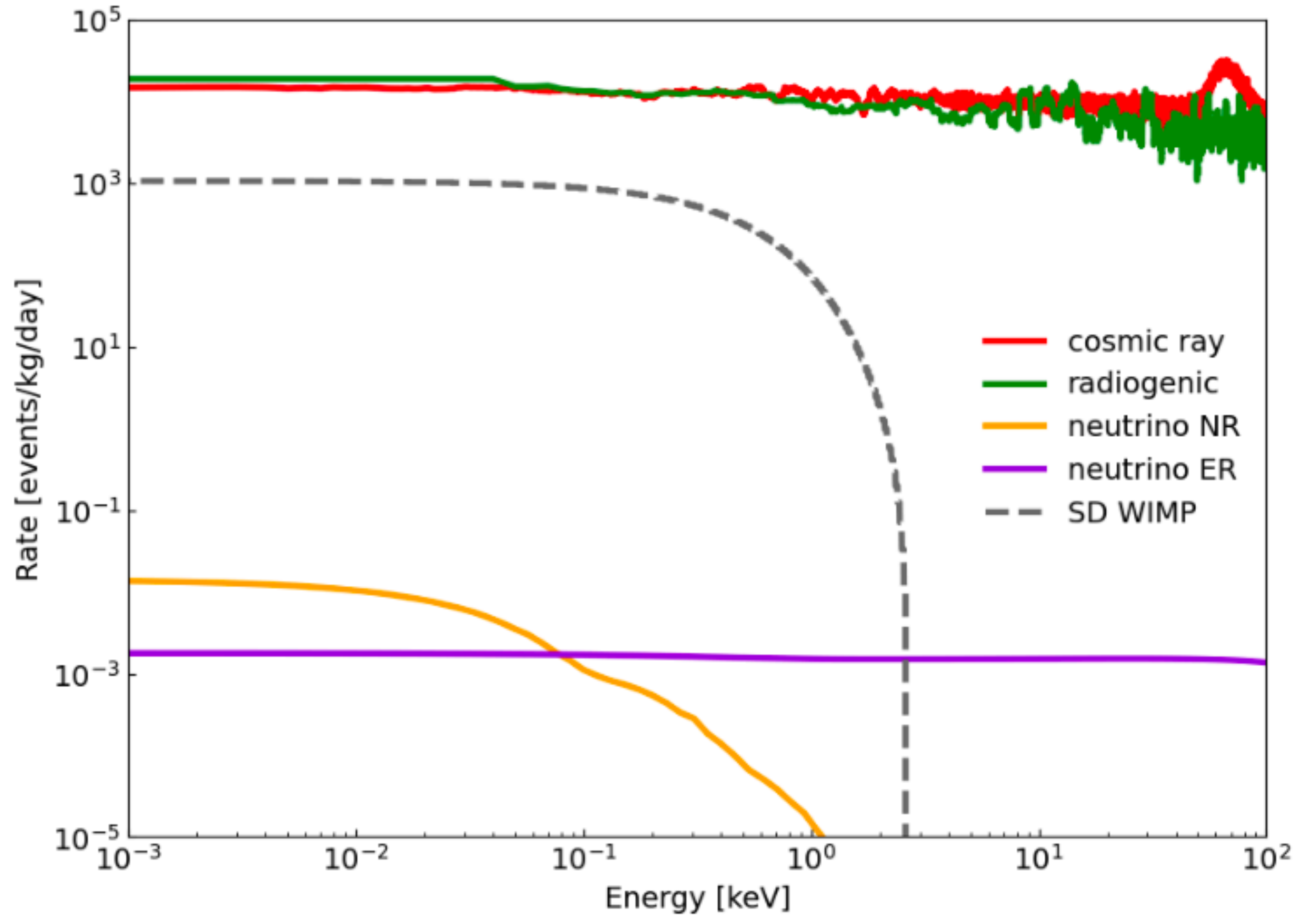

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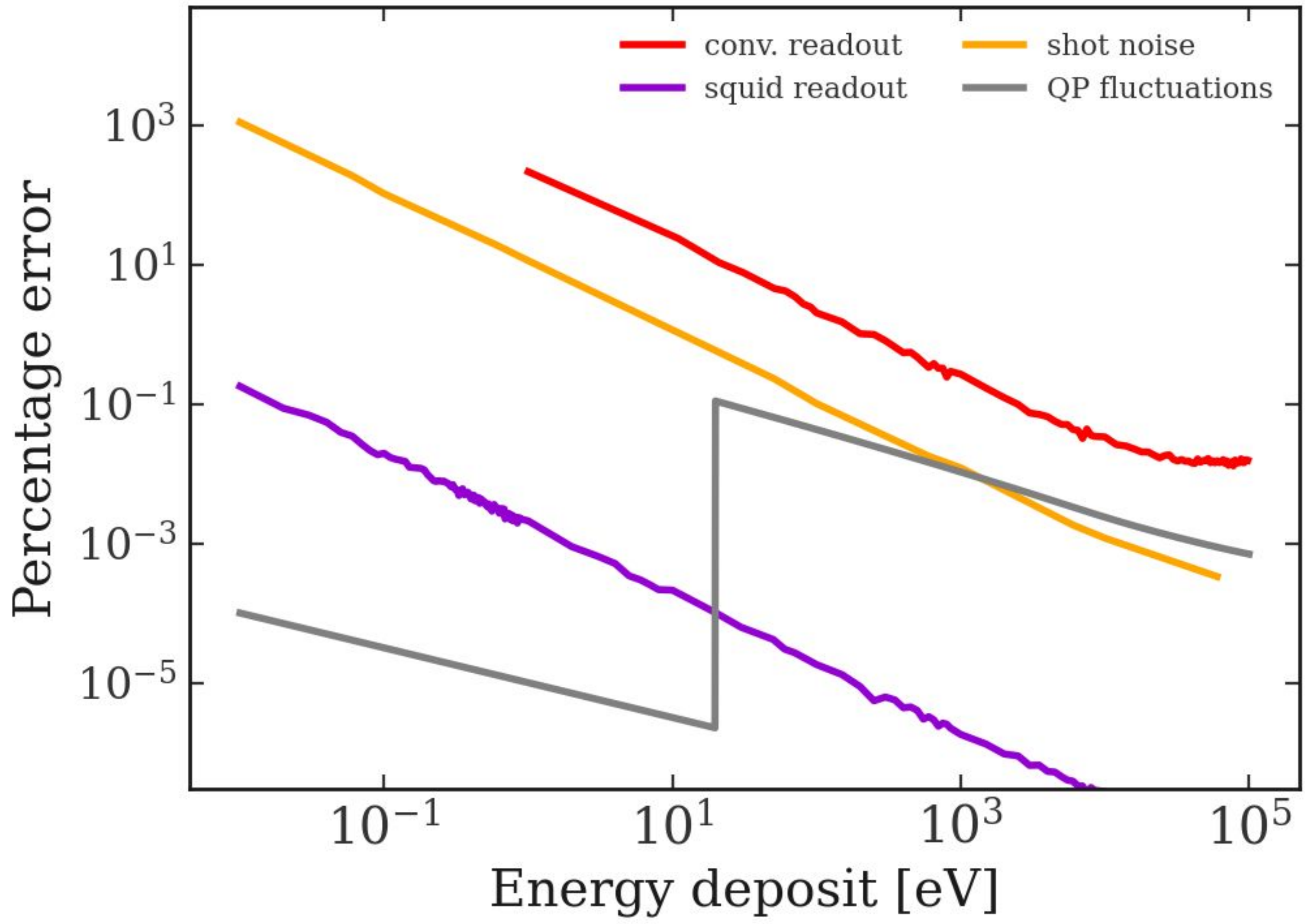
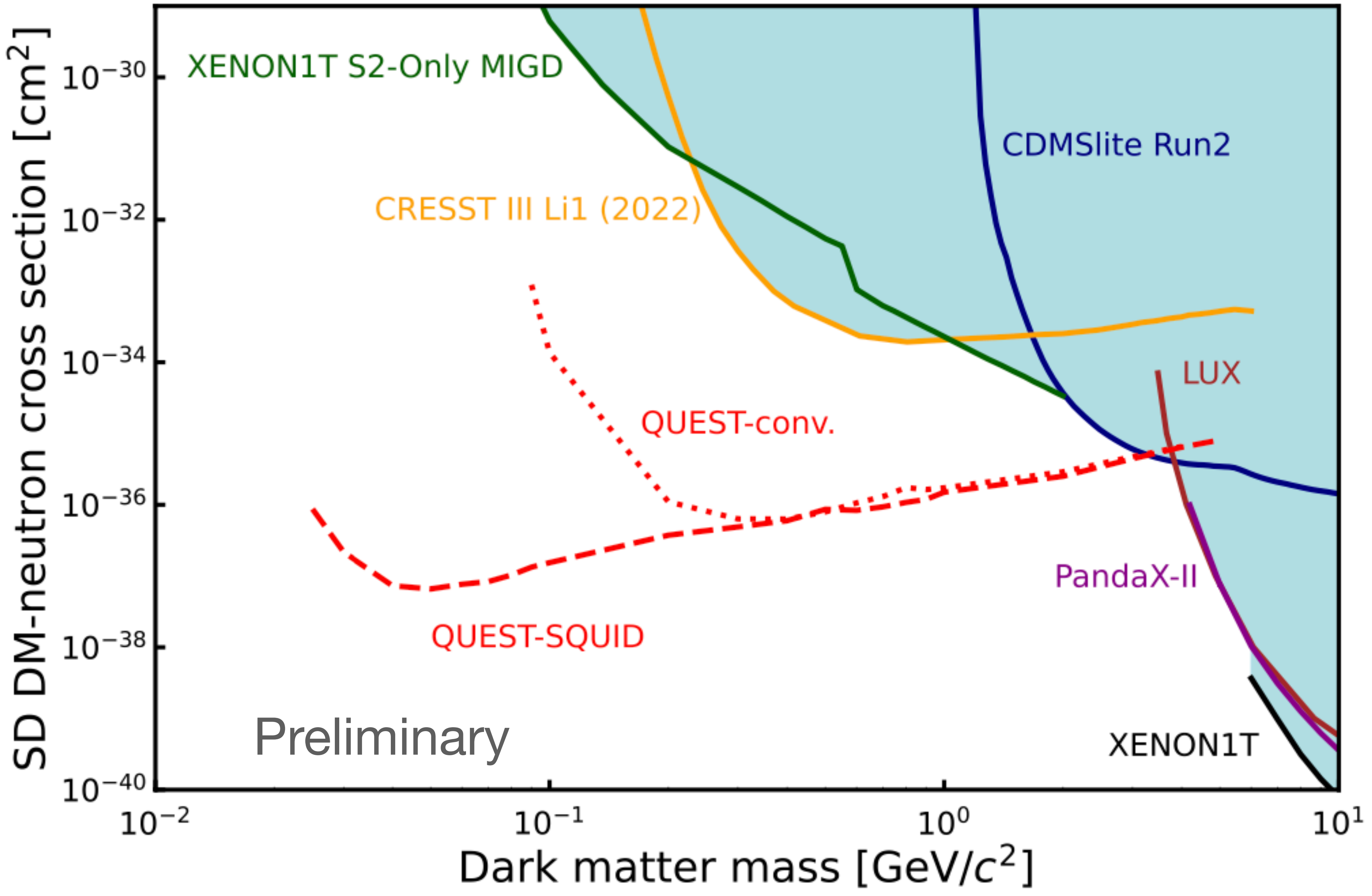


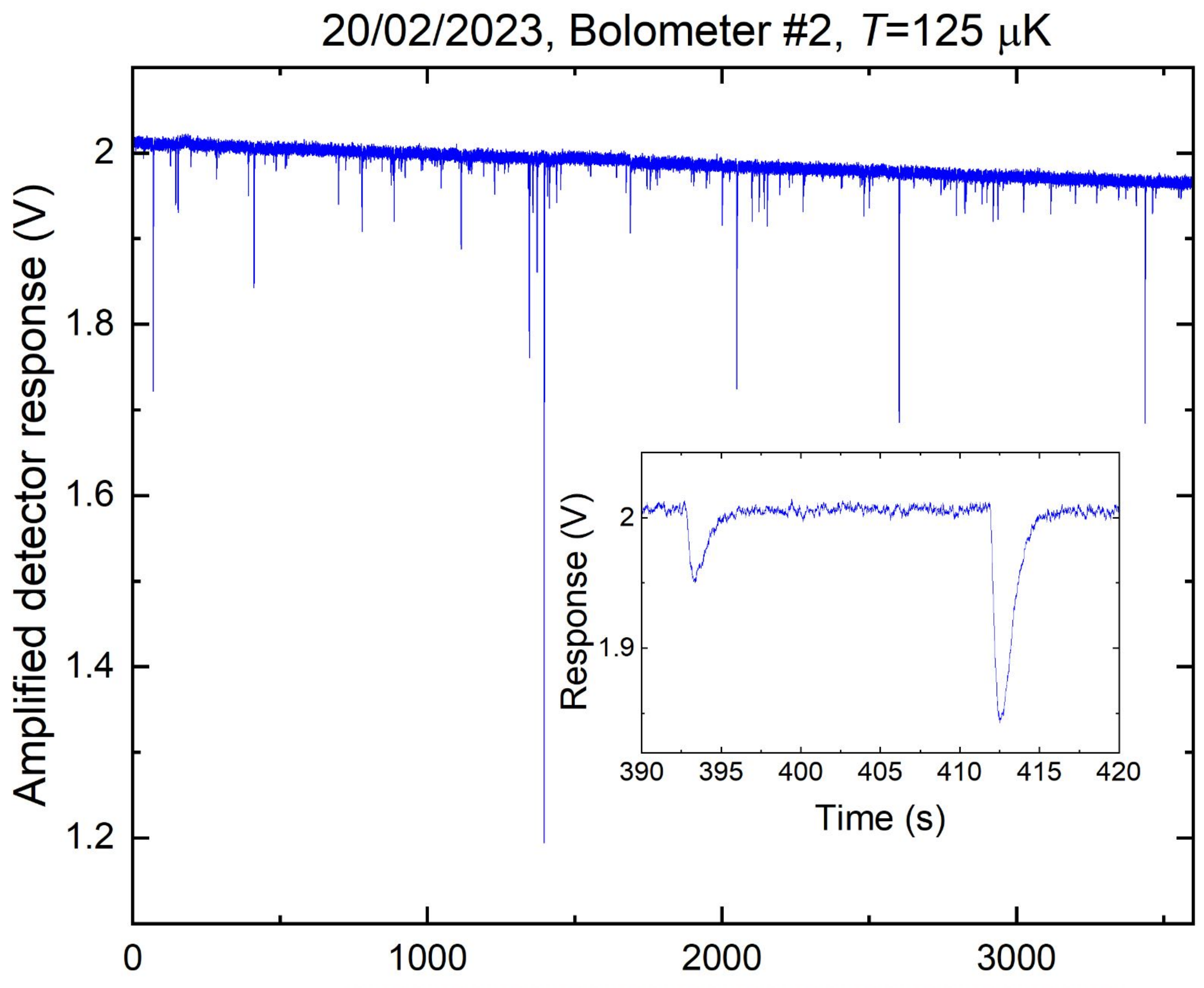
6 month run, 50% livetime, 200nm wire,
5 x 1cm³ cells (0.1 g / cm³)

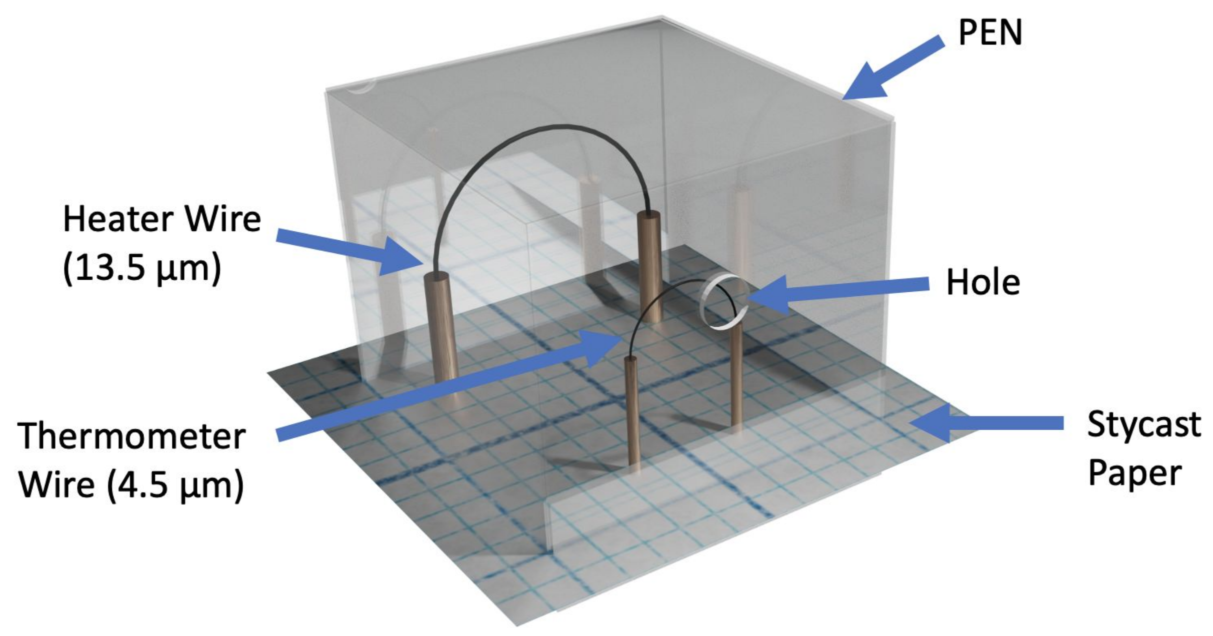


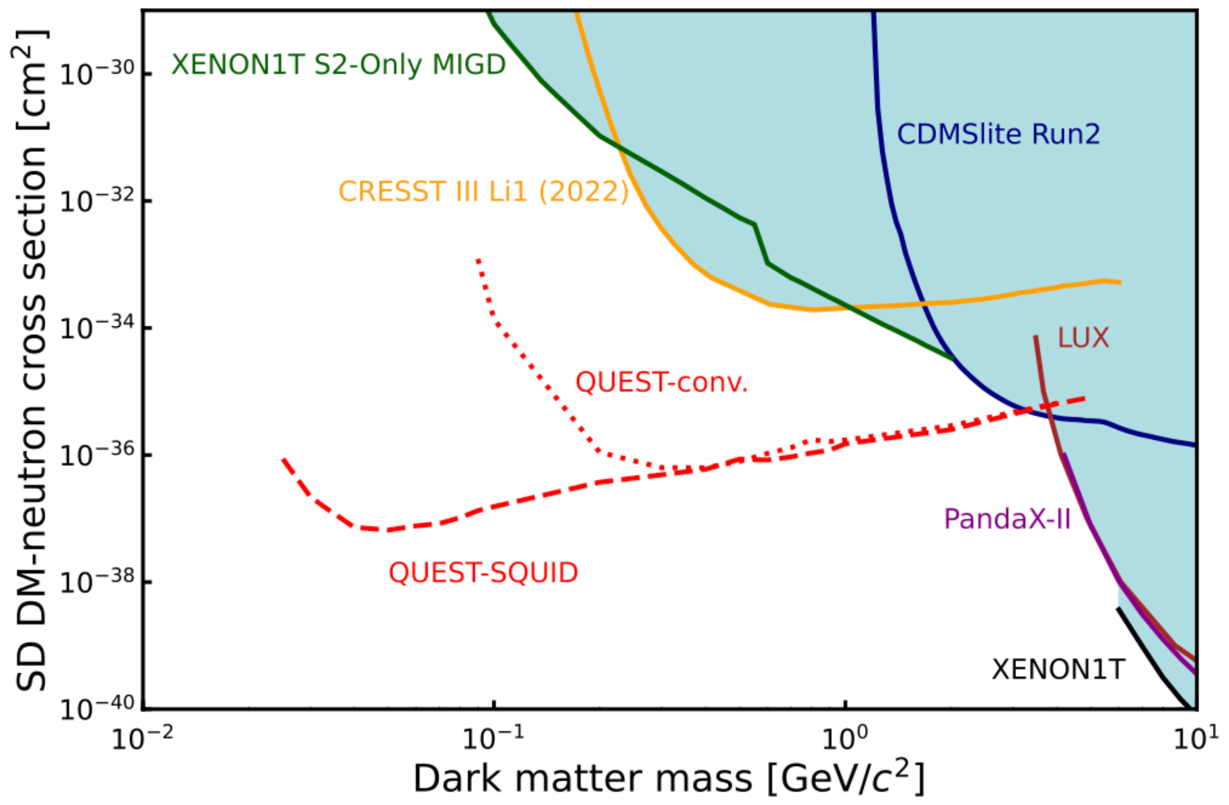
Credit: E Leason, N Darvishi, S West

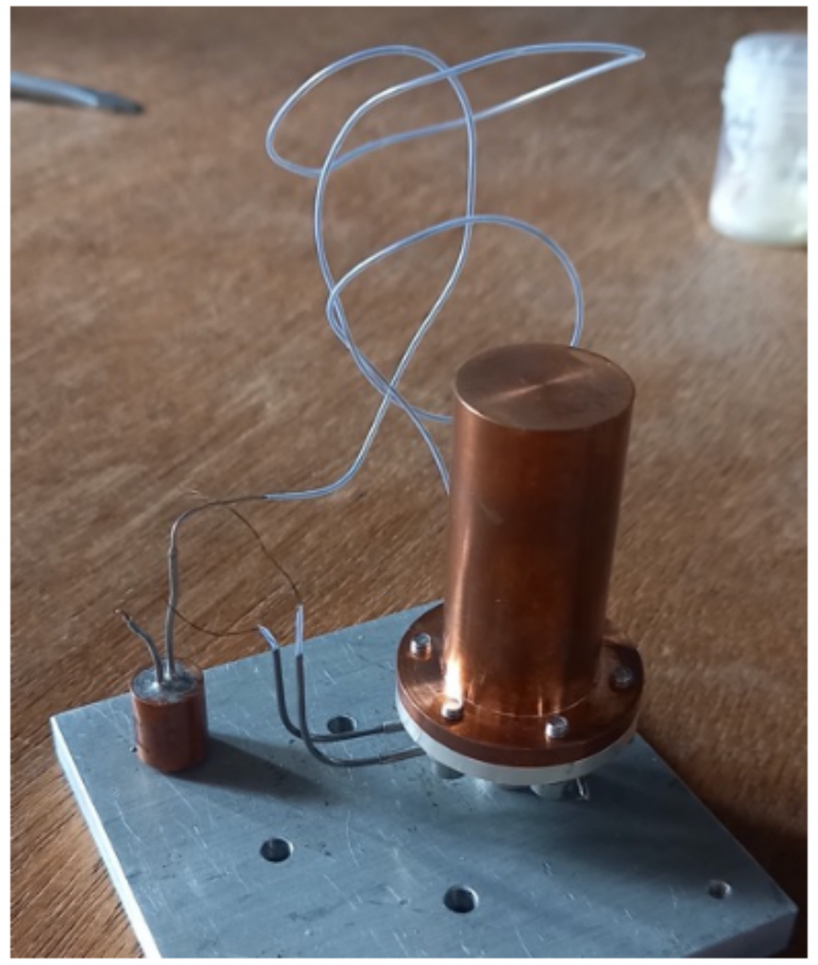
Conclusion & Future Work

- Proof of concept for eV scale threshold DM detector
- Data being taken from 4.5 μm diameter wire
- SQUID readout tested at 4K - soon to be tested at lower temp
- Energy calibration and photon detection work ongoing
- First paper submitted and under review - watch this space!







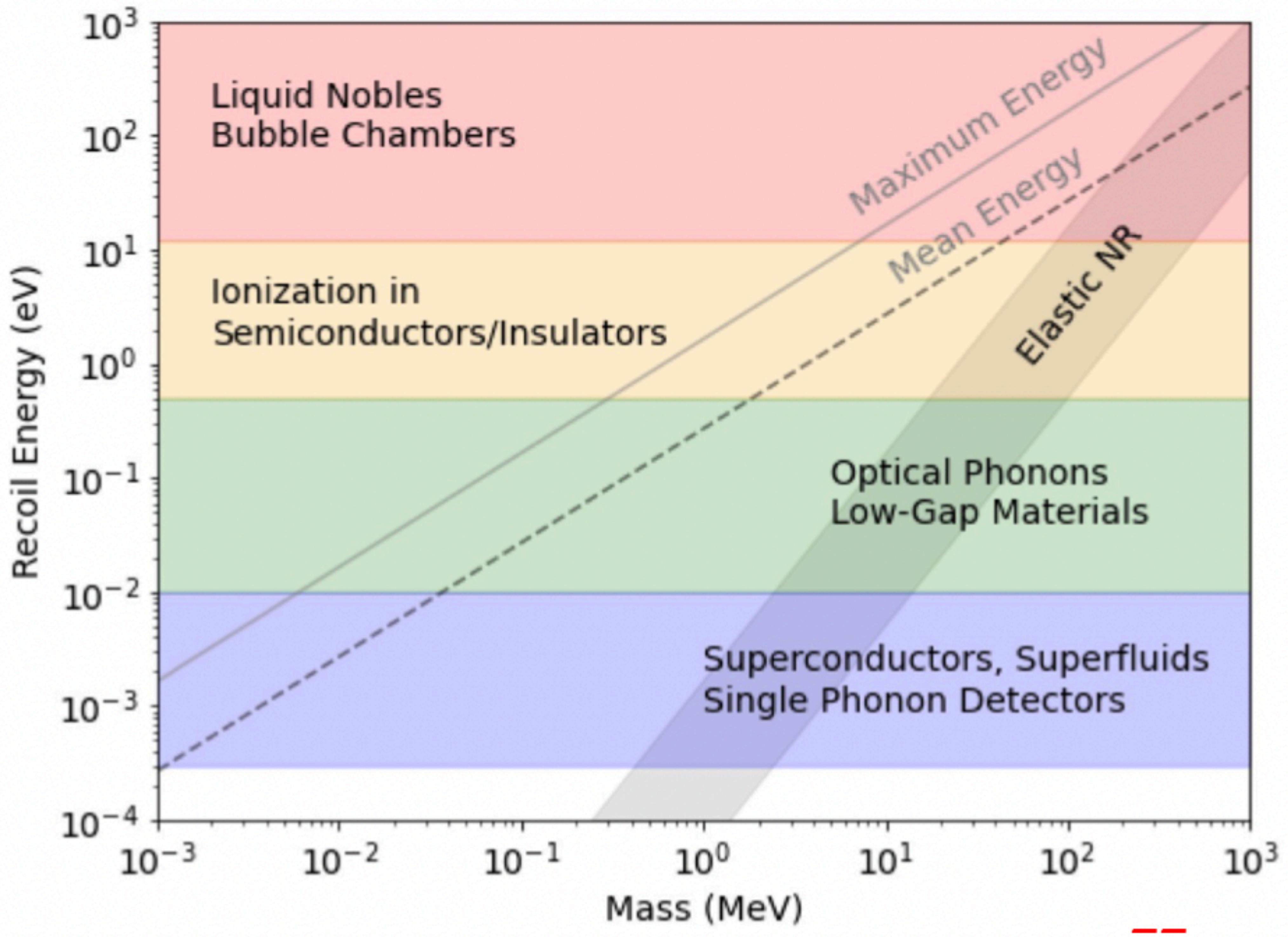


Copper cell for mK SQUID readout bolometry - data in coming weeks

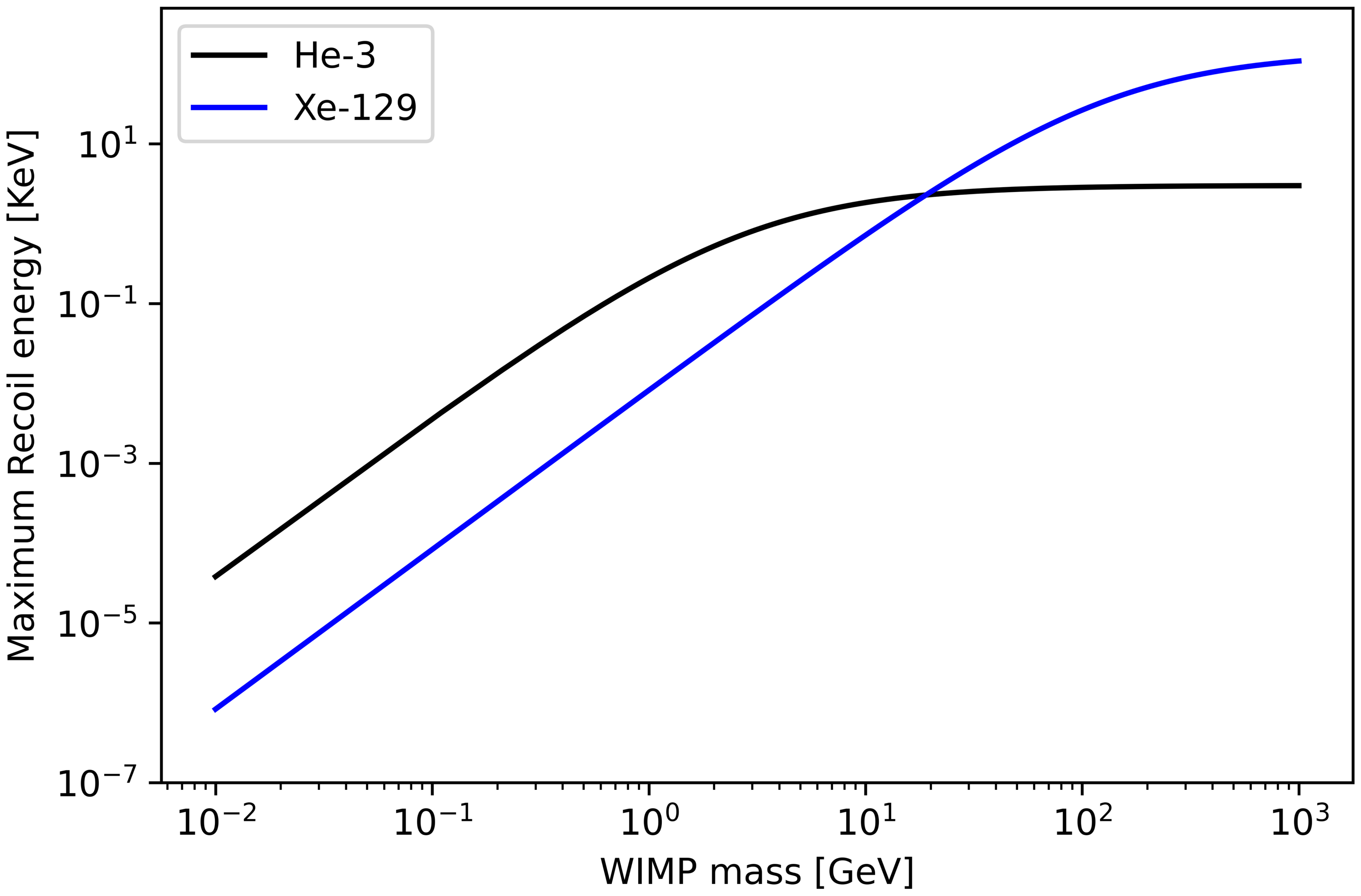
Backup Slides

Recoil Energies

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

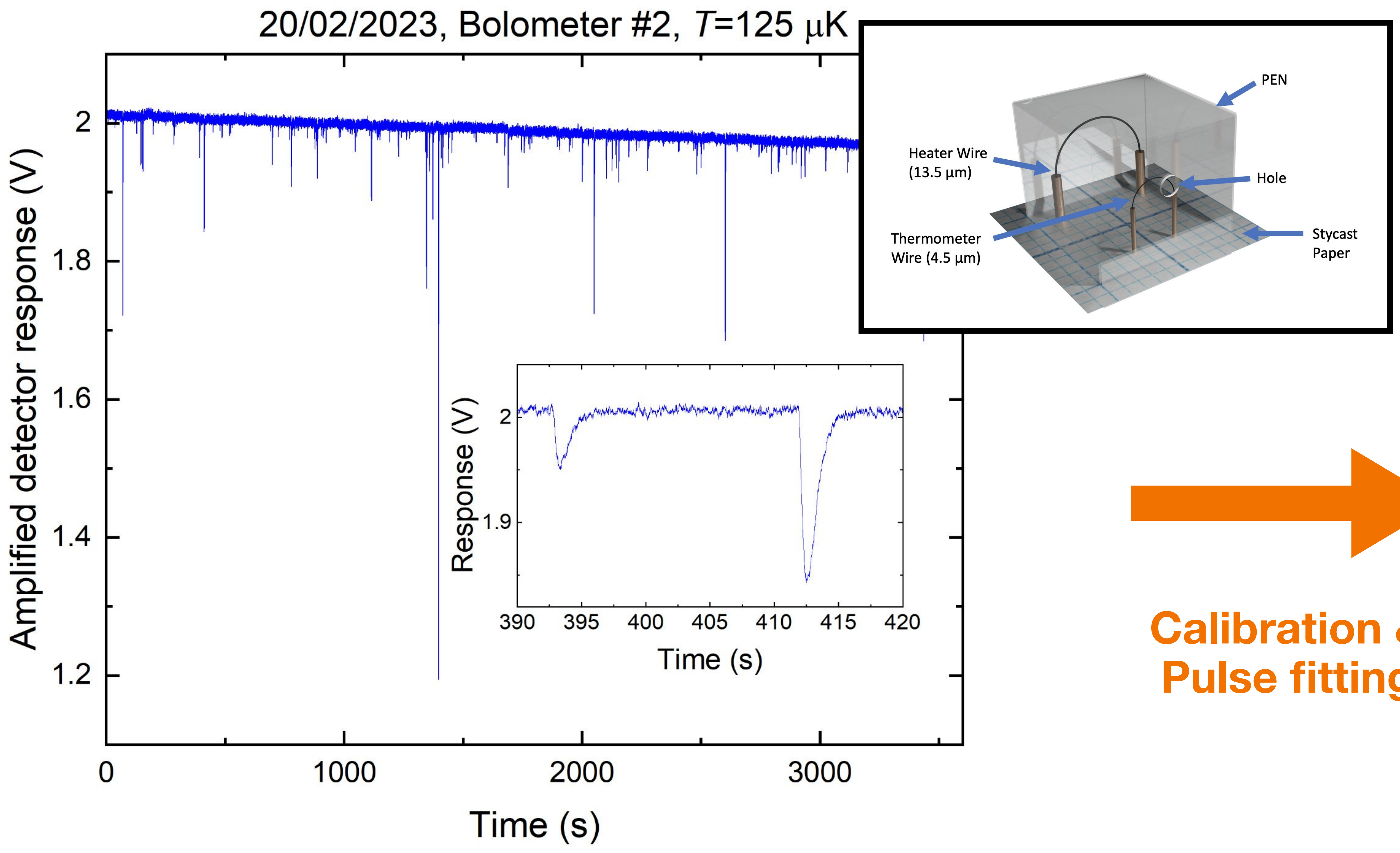


Snowmass report 2022



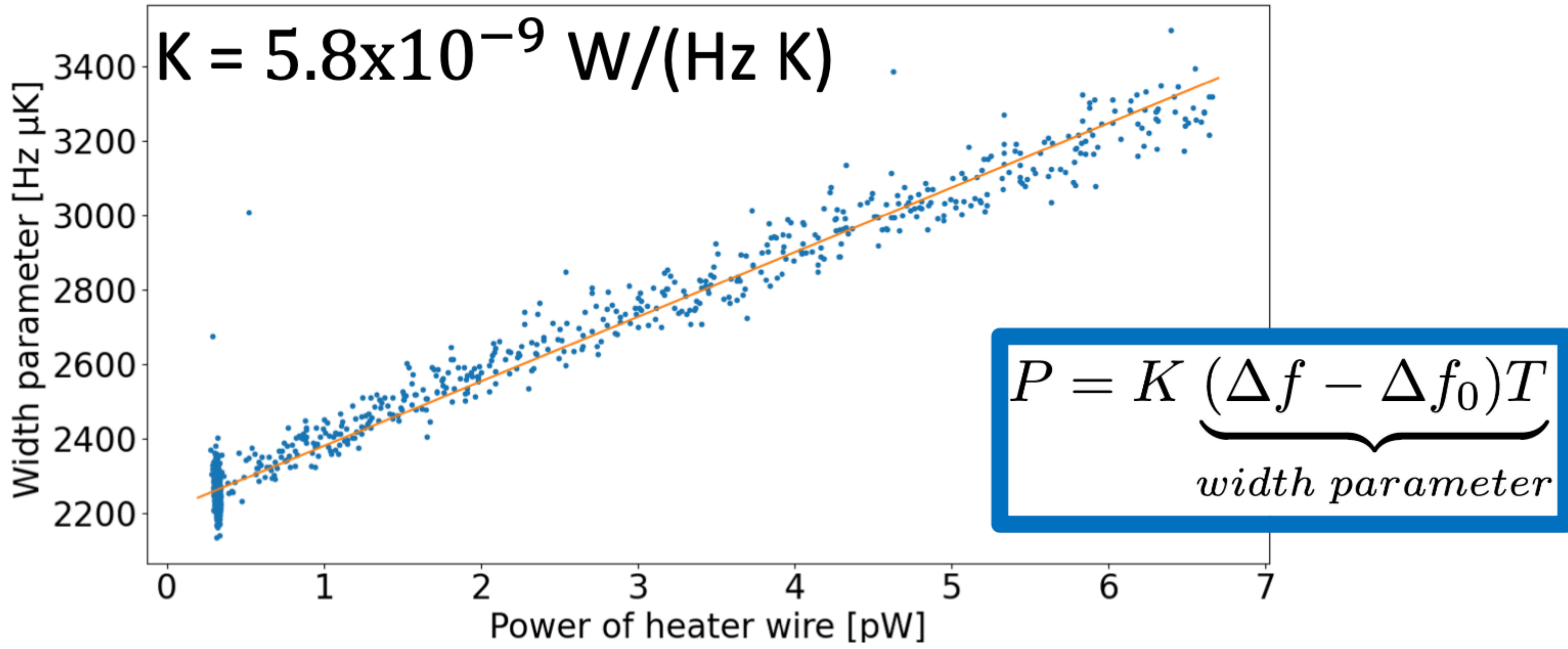
Detector: Calorimetry

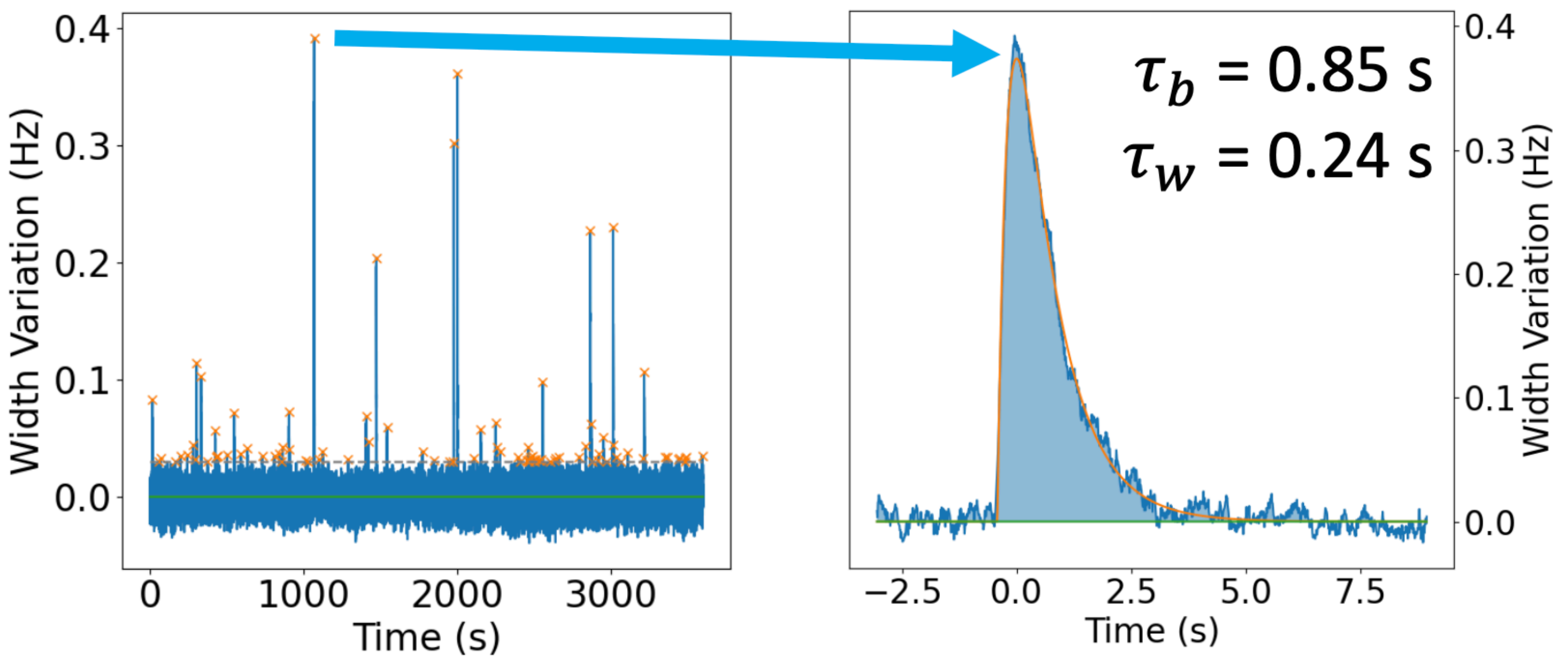
Credit: T Salmon



Data!

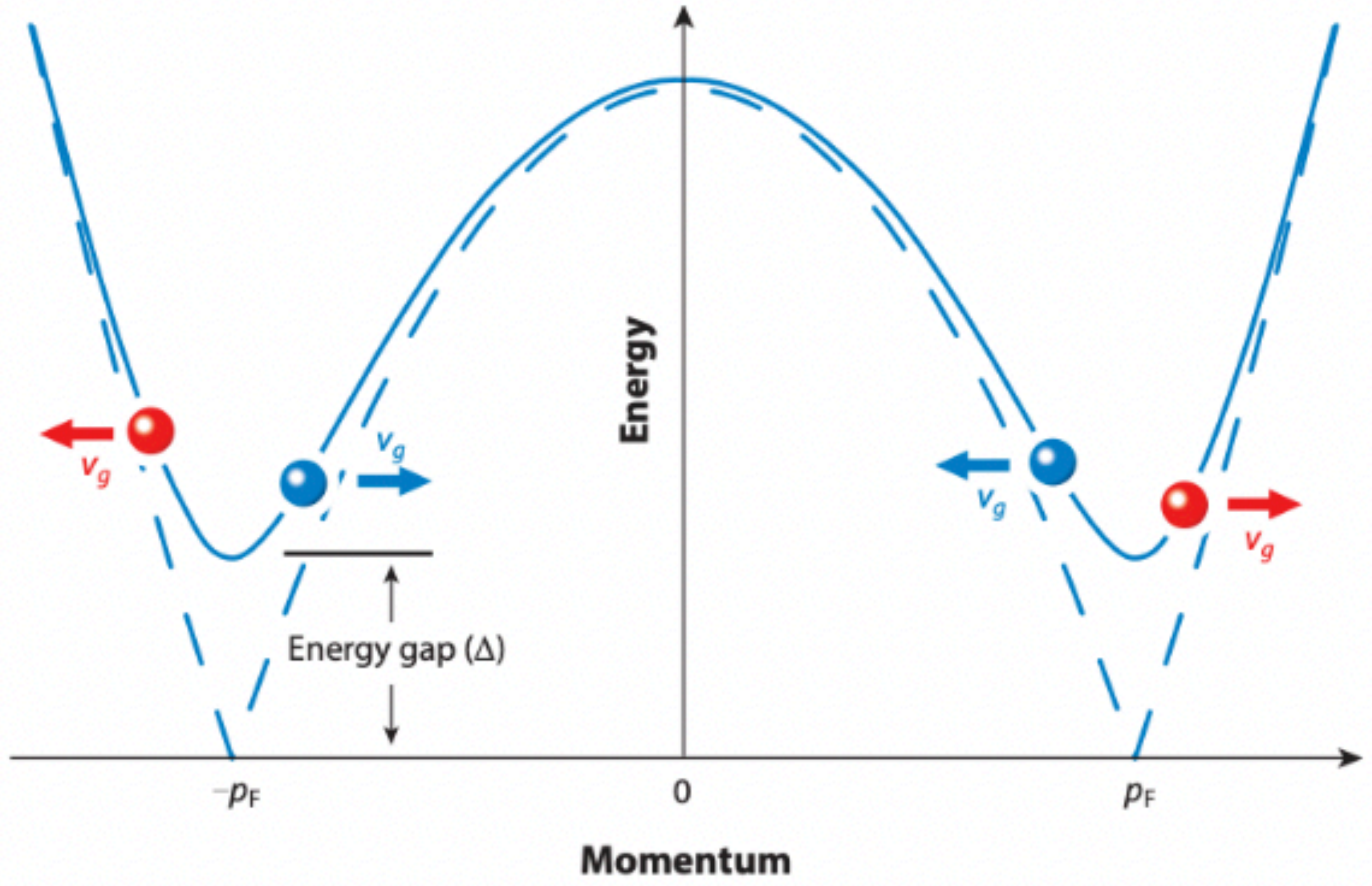
Calibration & Pulse fitting





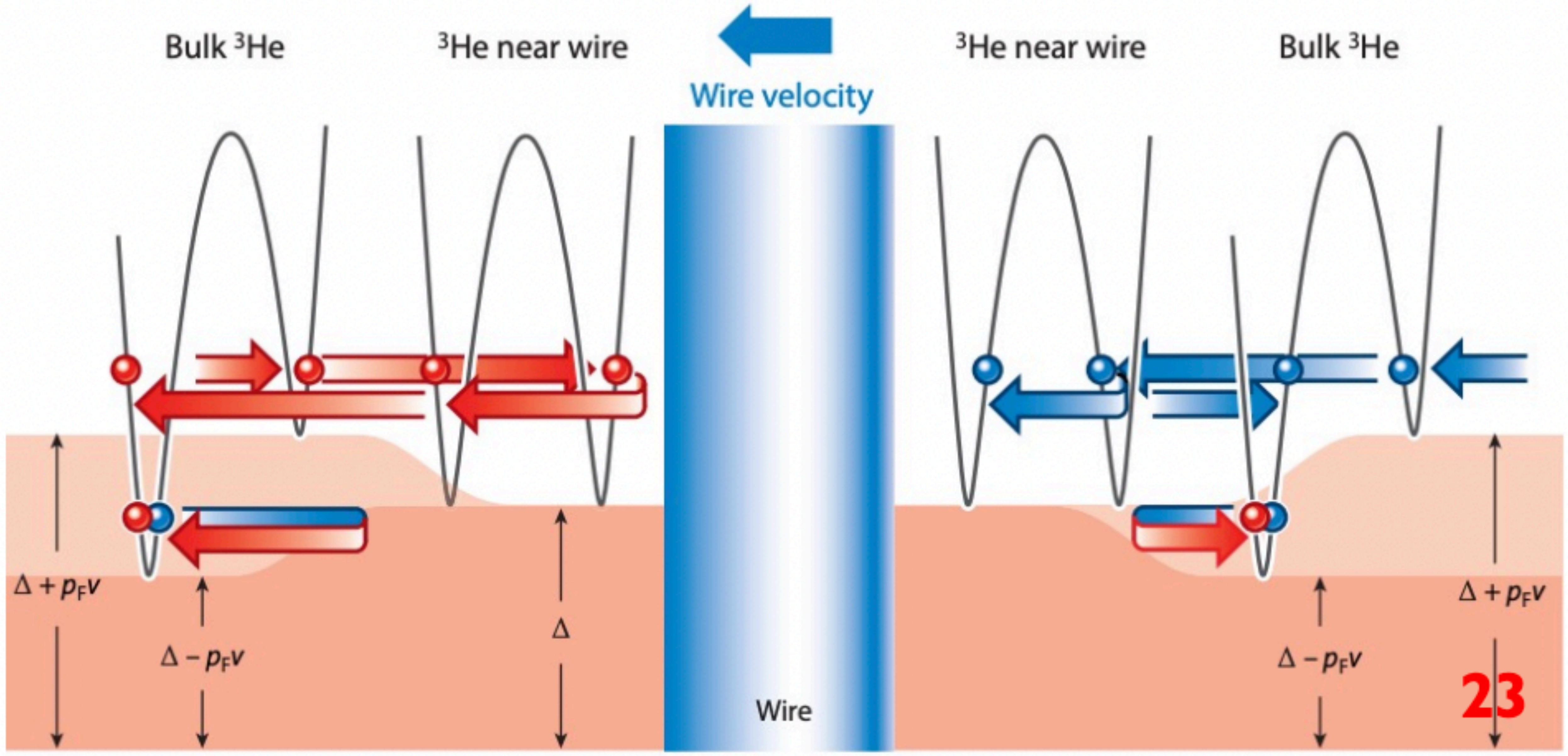
$$E_{heat} = KTA_{pulse}$$

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.



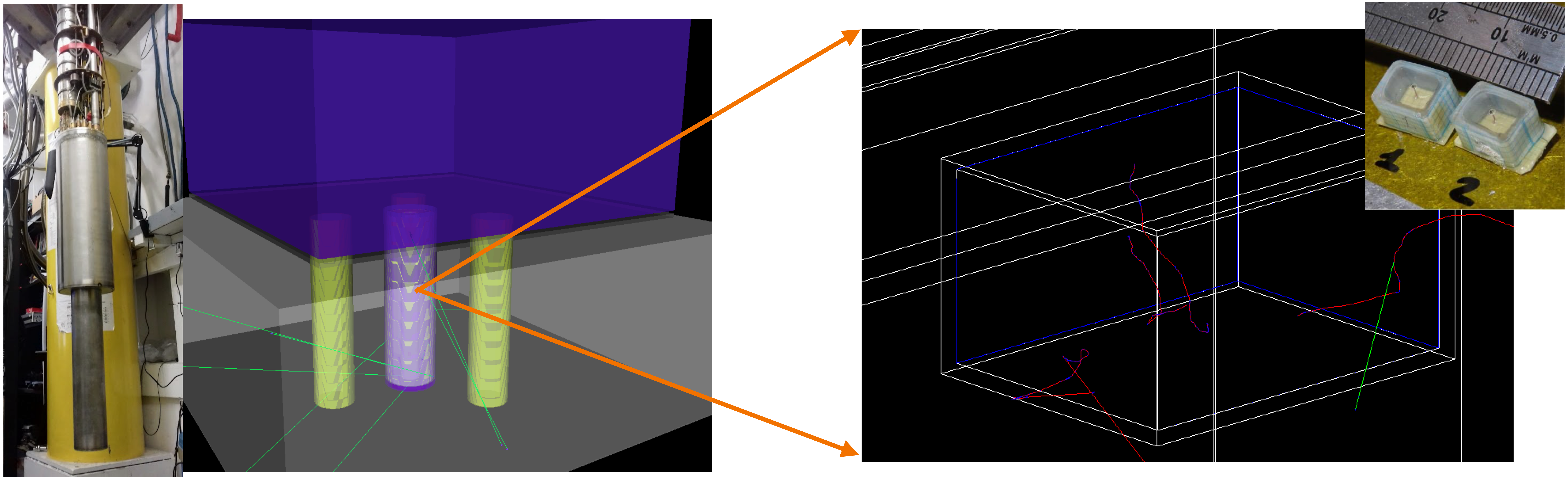
Ref https://www.annualreviews.org/doi/pdf/10.1146/annurev-conmatphys-031016-025411

Detector: Simulation

G4 geometry of cryostat and surrounding materials

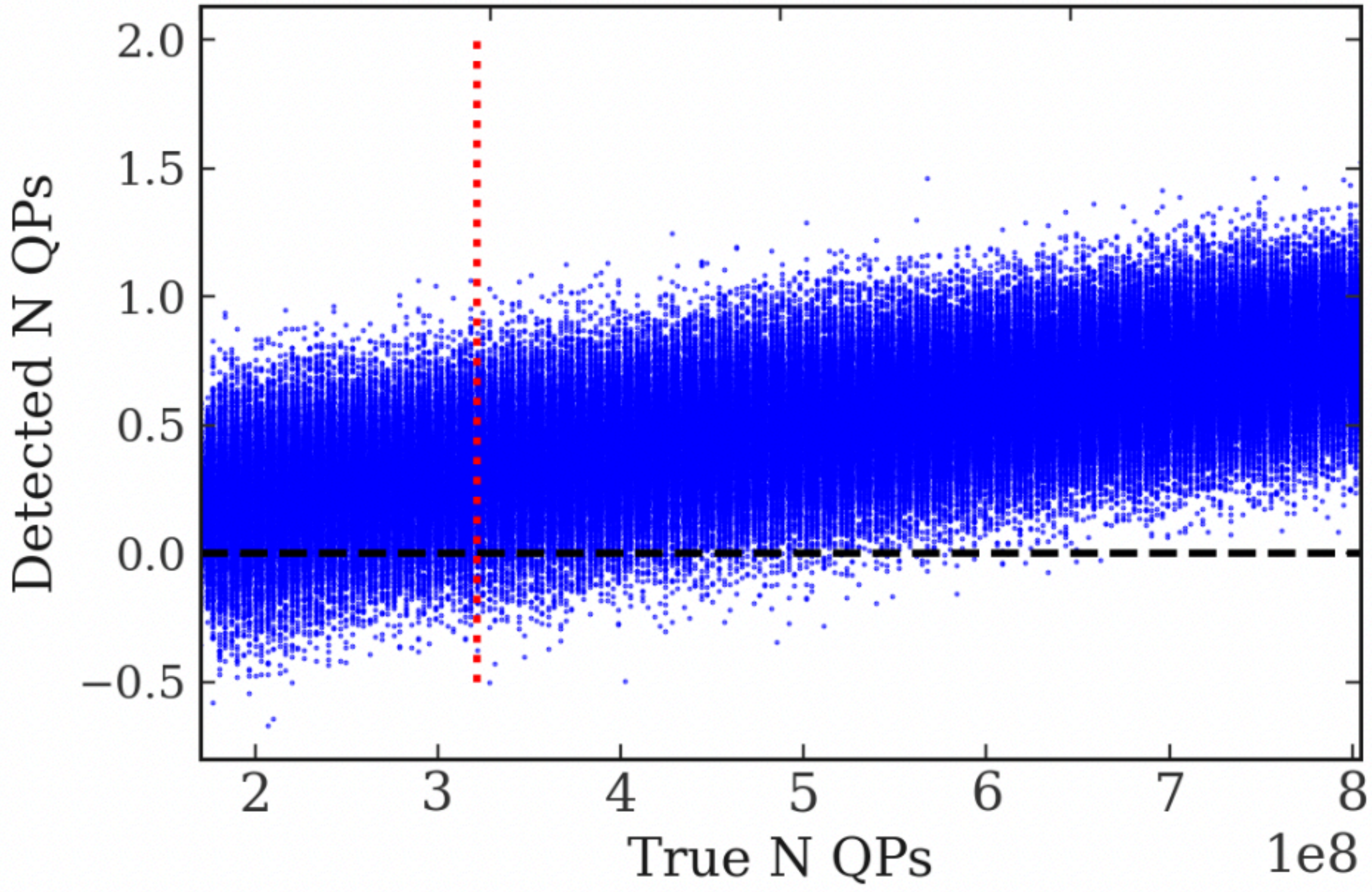
MC event rates produced within cell of ^{3}He

Normalise with reference values to produce expected bg event rates



Credit: P Franchini

Energy Threshold



Resolution at threshold – 95% confidence energy > zero.

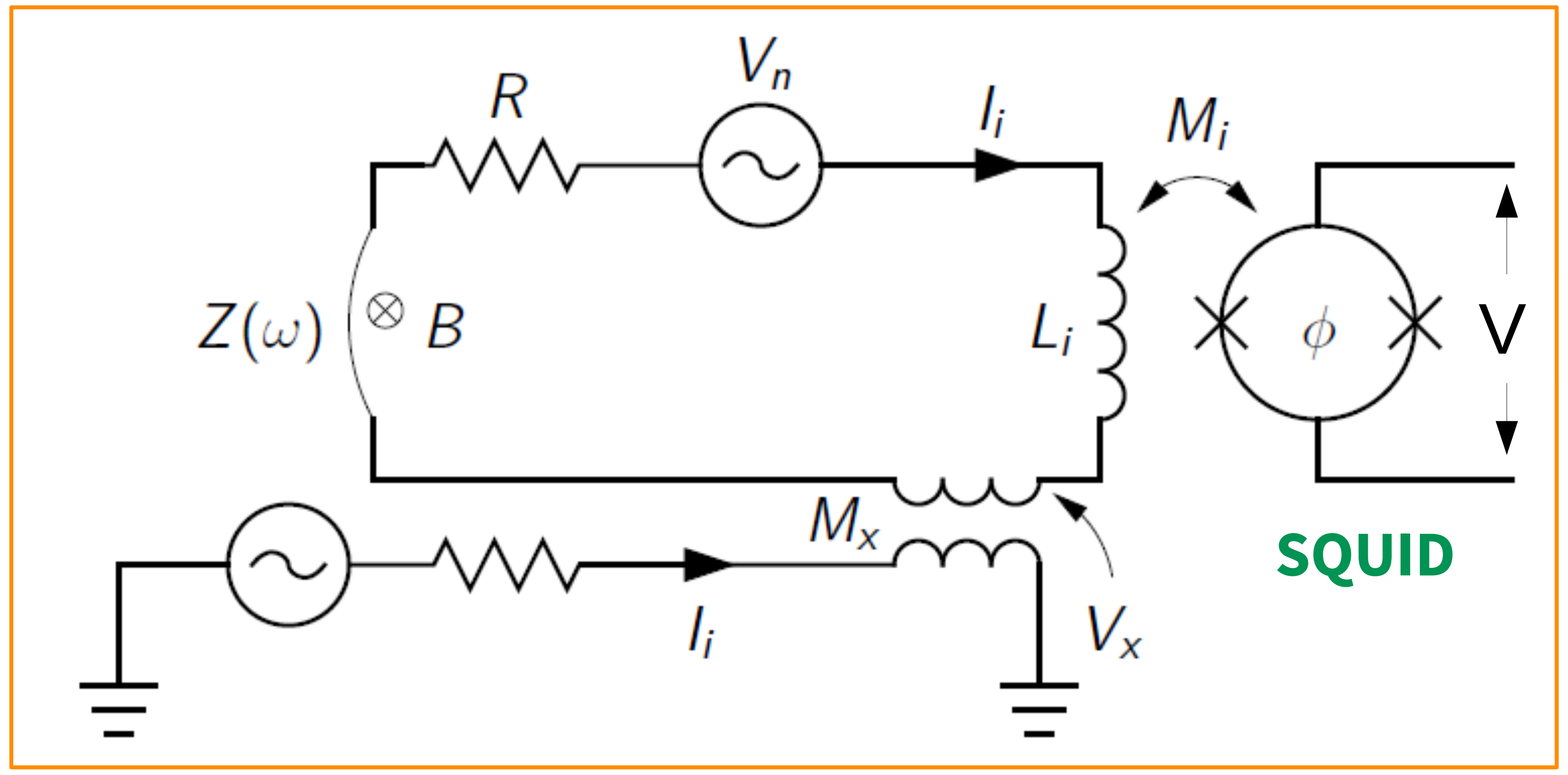
- Conventional readout: 39 eV
- Squid readout reduces noise, so resolution is dominated by shot noise.
- Squid readout: 0.71 eV

Credit: E Leason

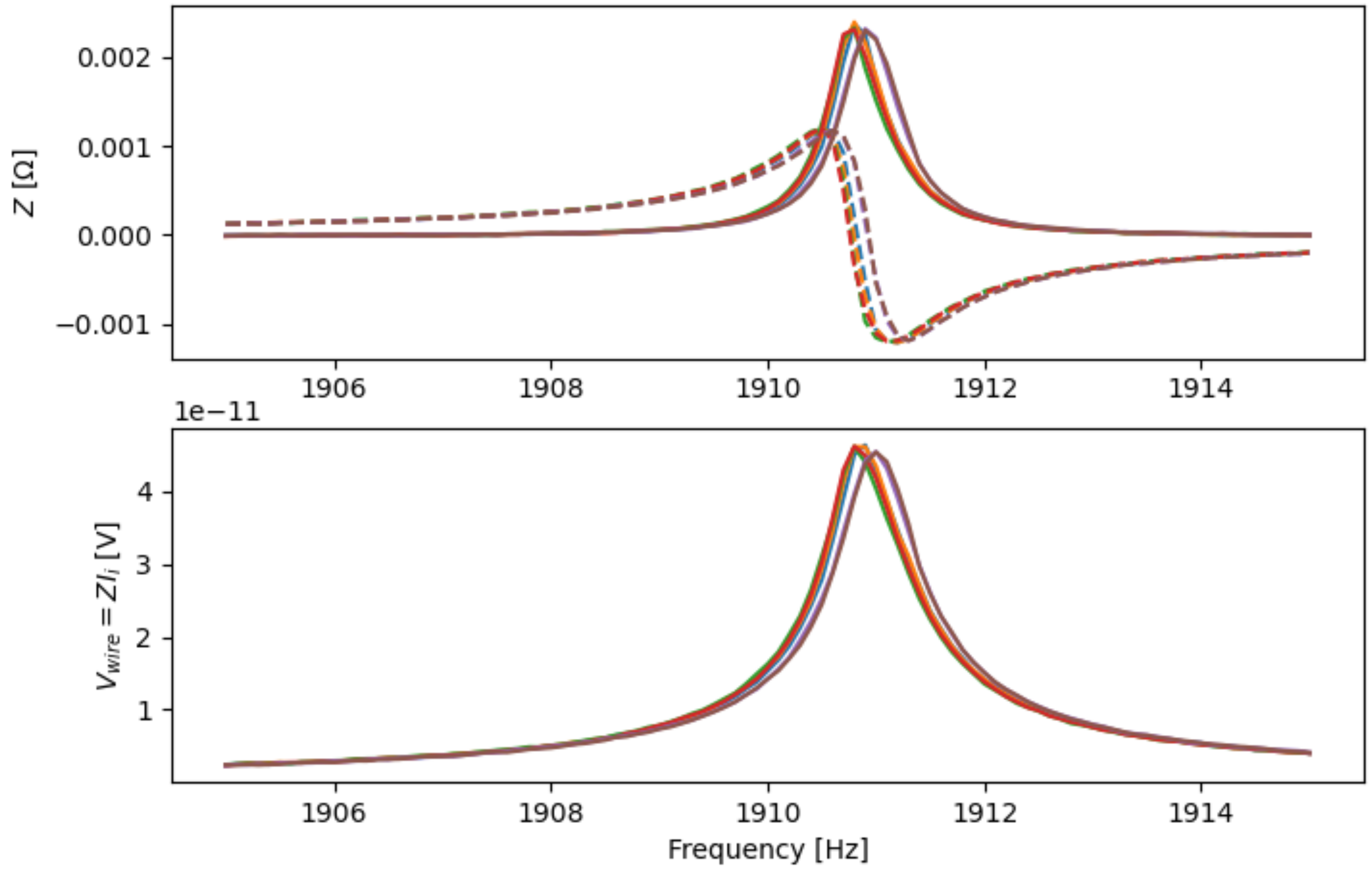
Readout: DC SQUID

- 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



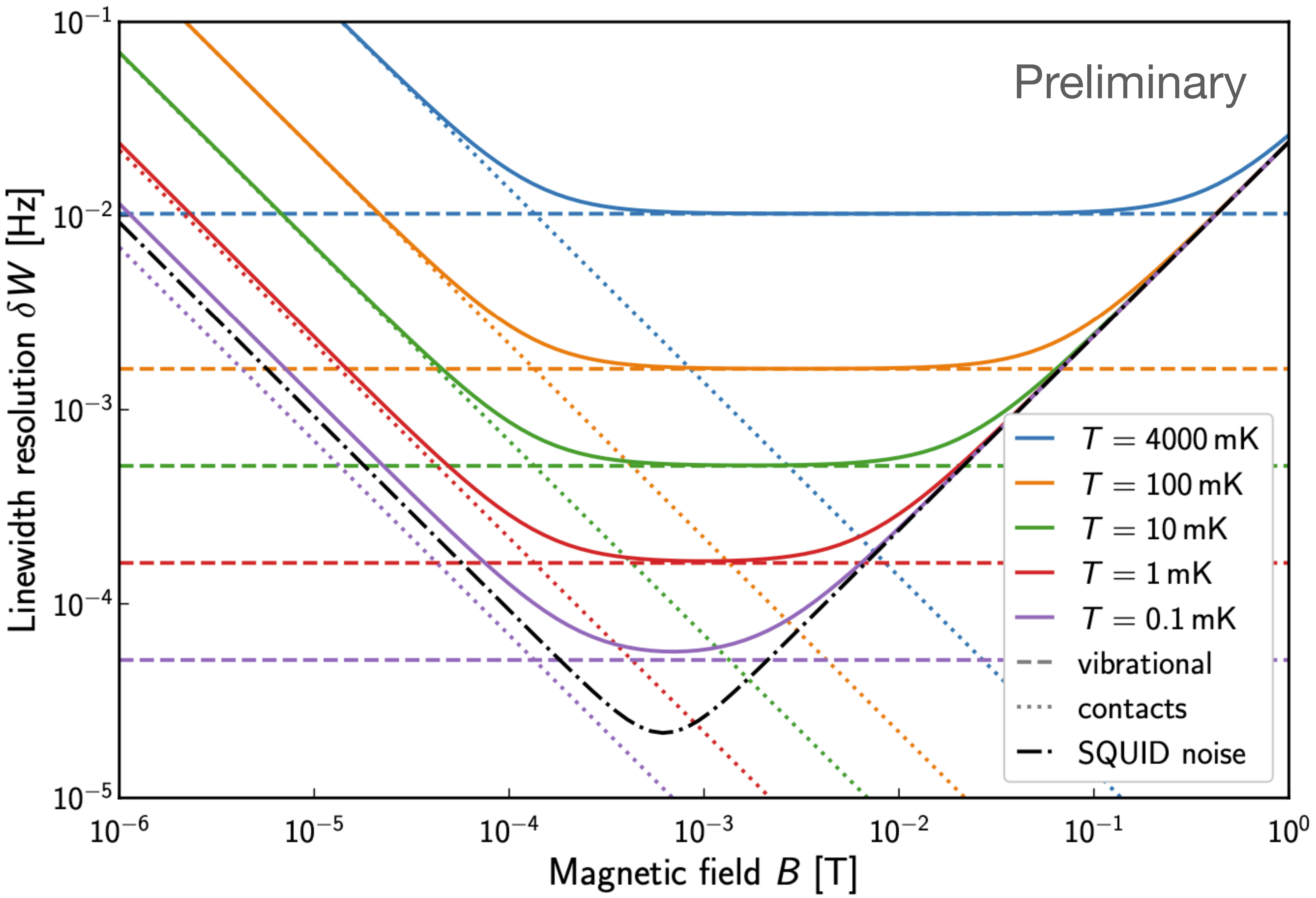
Frequency sweeps of 315nm wire taken at 4.2K

SQUID Readout Resolution

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

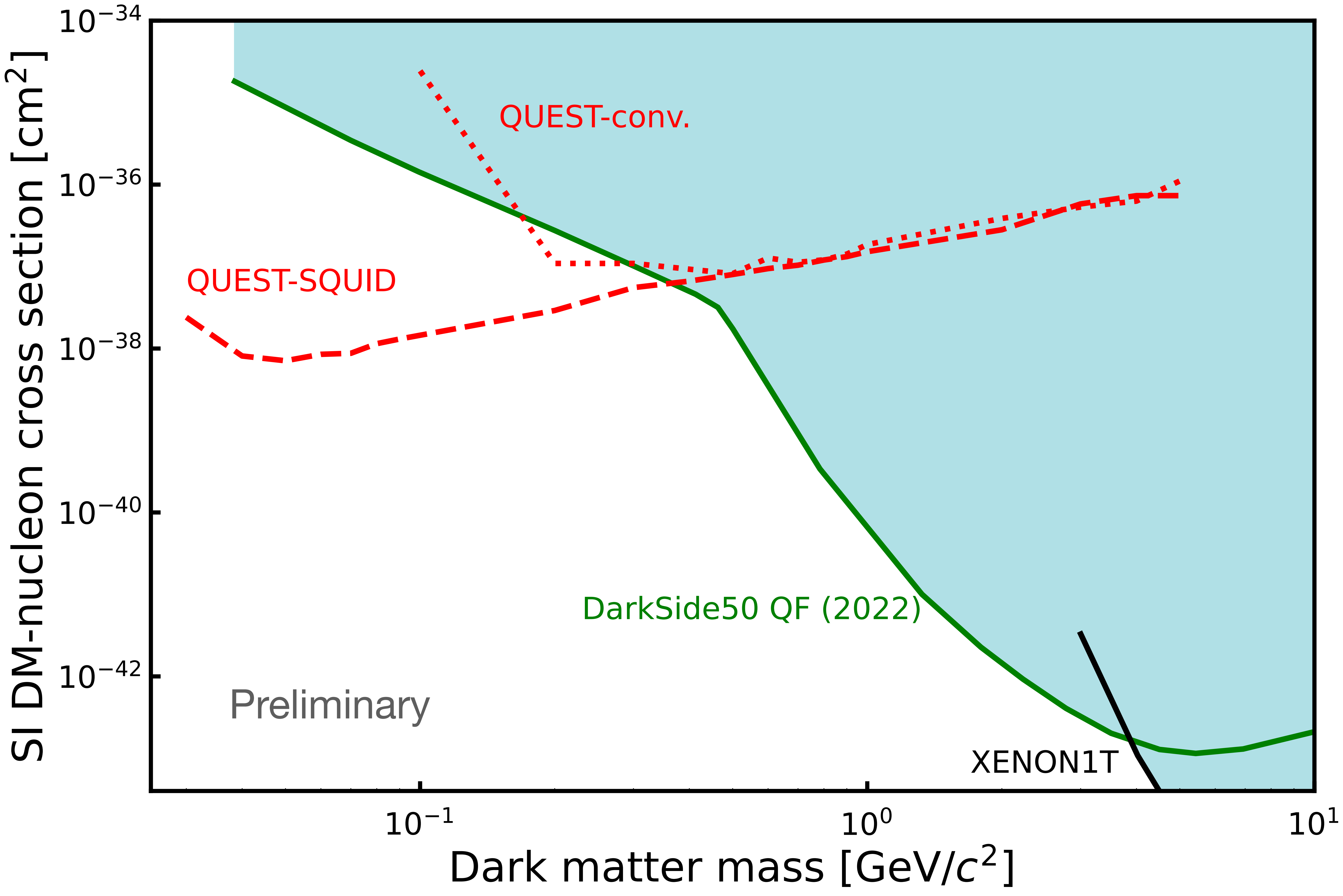
Ratio between sum of noise contributions and maximum voltage across the wire

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



Credit: L Levitin

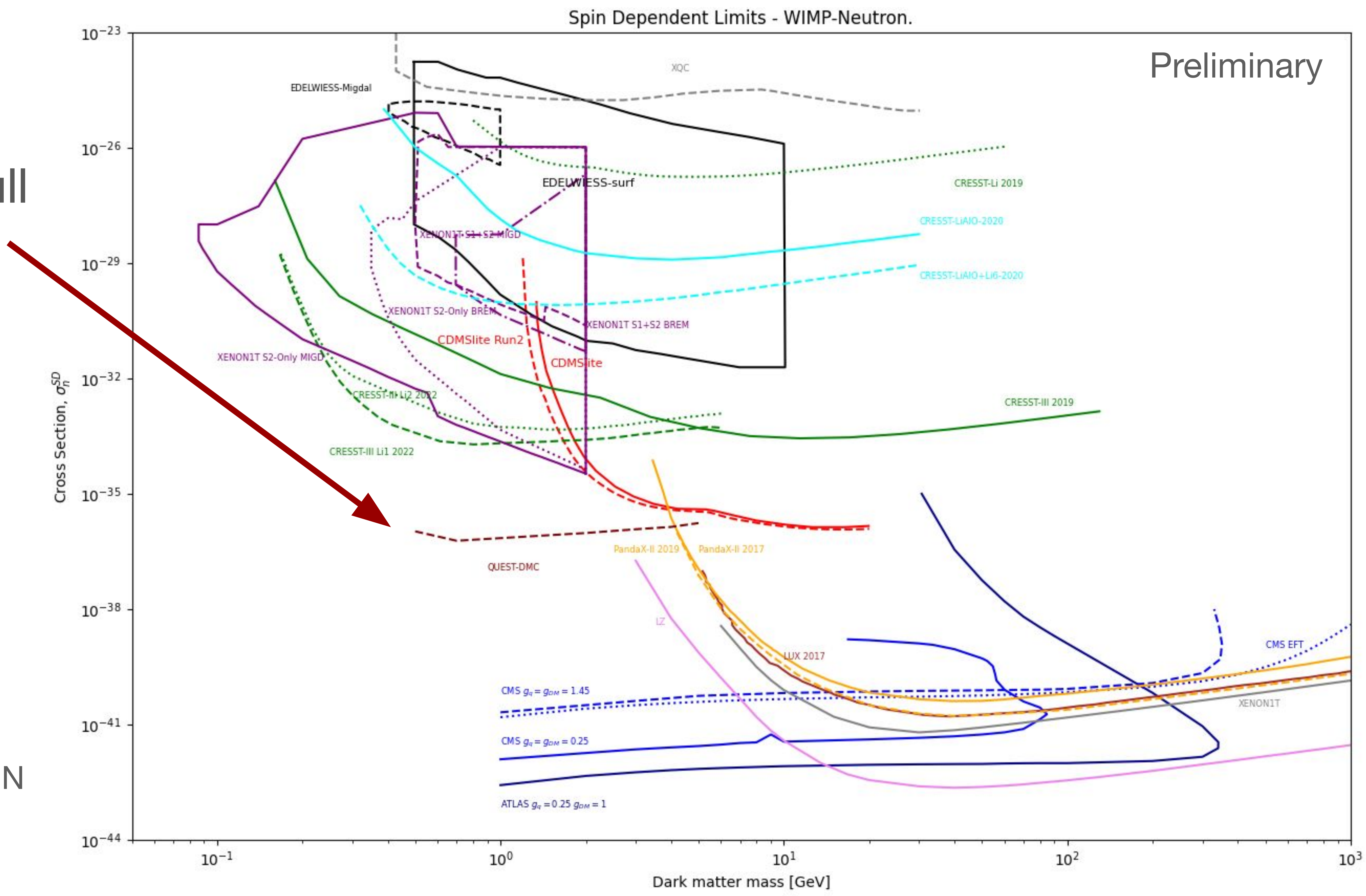
Spin Independent Sensitivity



Credit: E Leason, N Darvishi S West

Wider Context for Estimated Sensitivity

QUEST full exposure, conv. readout



Direct detection

Collider

Credit: E Leason, N Darvishi S West