QUEST DMC

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# QUantum Enhanced Superfluid Technologies for Dark Matter & Cosmology

Astroparticle Symposium, Institut Pascal, Université Paris-Saclay, 02/11/25

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# Outline

- Goals & motivation
- Why superfluid $^3$He?
- Detector concept
- Superfluid bolometry and energy calibration
- Physics Potential

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# Introduction

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# QUEST-DMC Collaboration

UNIVERSITY OF LIVERPOOL

UNIVERSITY OF SUSSEX

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lancaster University

UNIVERSITY OF OXFORD

**Work Packages**

**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

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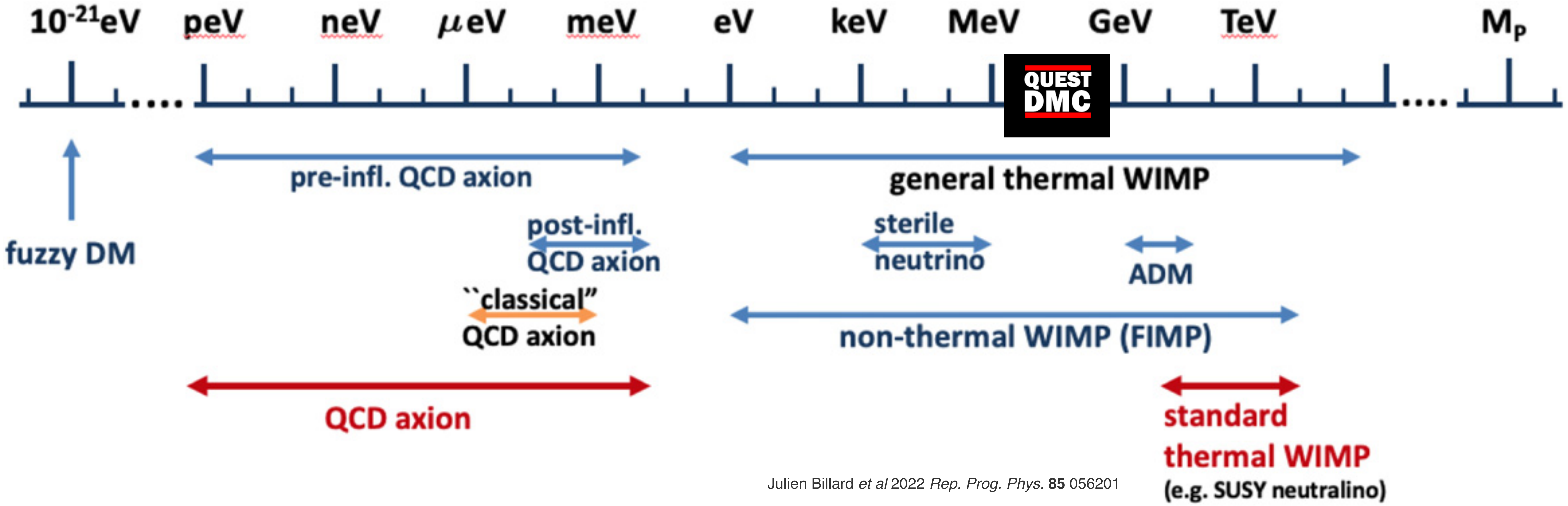
# Motivation & Goals

- Aiming for world-leading sensitivity to spin-dependent dark matter-nucleon interactions with sub-GeV mass candidates
- Use superfluid $^3He$ and low-noise quantum sensor readout to reach sub-eV scale recoil energy thresholds




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

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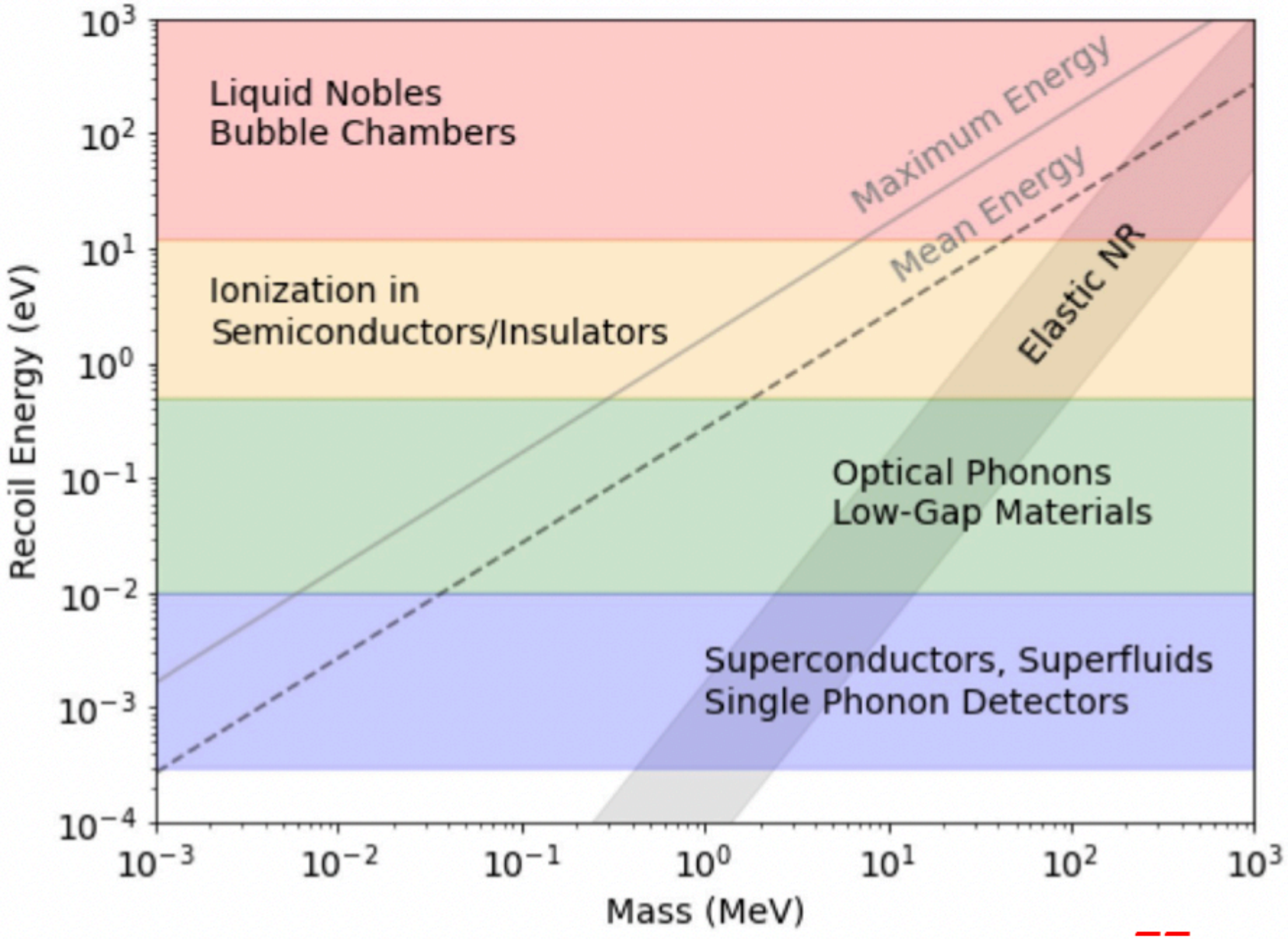
# Reaching Lower Thresholds




Snowmass report 2022

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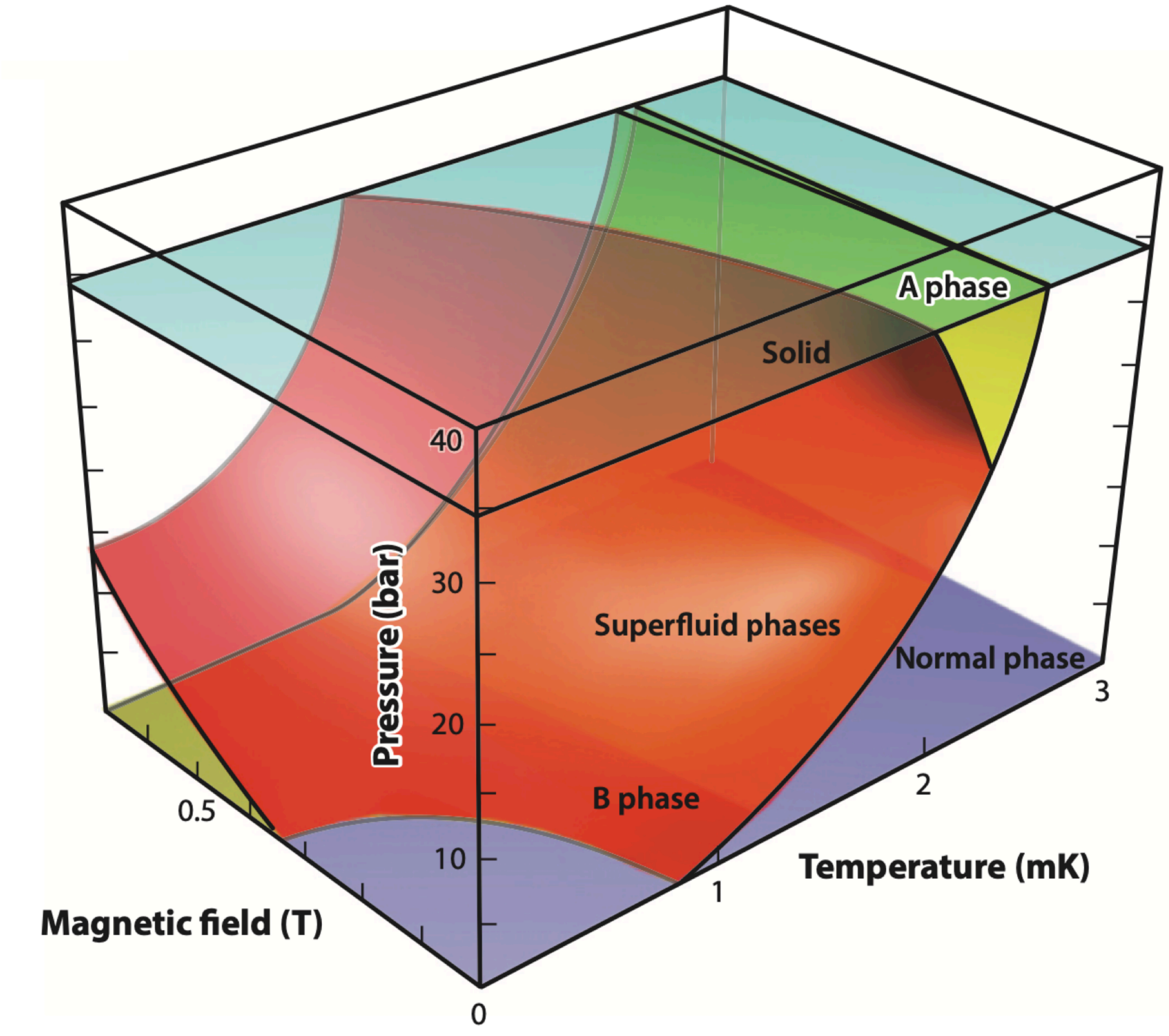
# Superfluid $^3$He

- Forms a superfluid state when cooled below ~1 mK at 0 bar pressure
- Superfluidity described by the Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity
- Helium atoms form Cooper pairs, with an energy gap of ~ $10^{-7}$ eV for single particle excitations
- Different phases depending on allowed spin states
- A-phase ($\langle\downarrow\downarrow\rangle$ and $\langle\uparrow\uparrow\rangle$)
- B-phase ($\langle\downarrow\downarrow\rangle$ and $\langle\downarrow\uparrow+\uparrow\downarrow\rangle$ and $\langle\uparrow\uparrow\rangle$)

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# QUEST-DMC Detector

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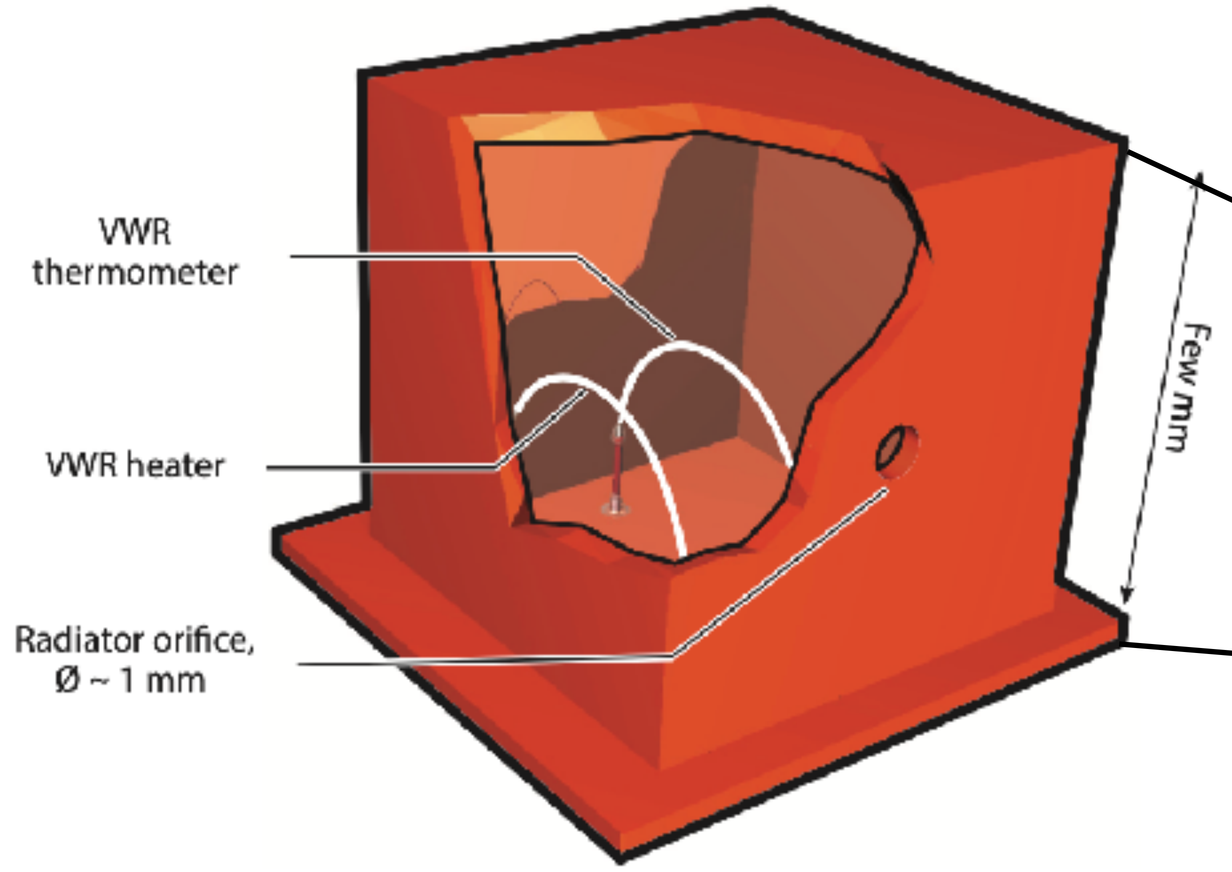
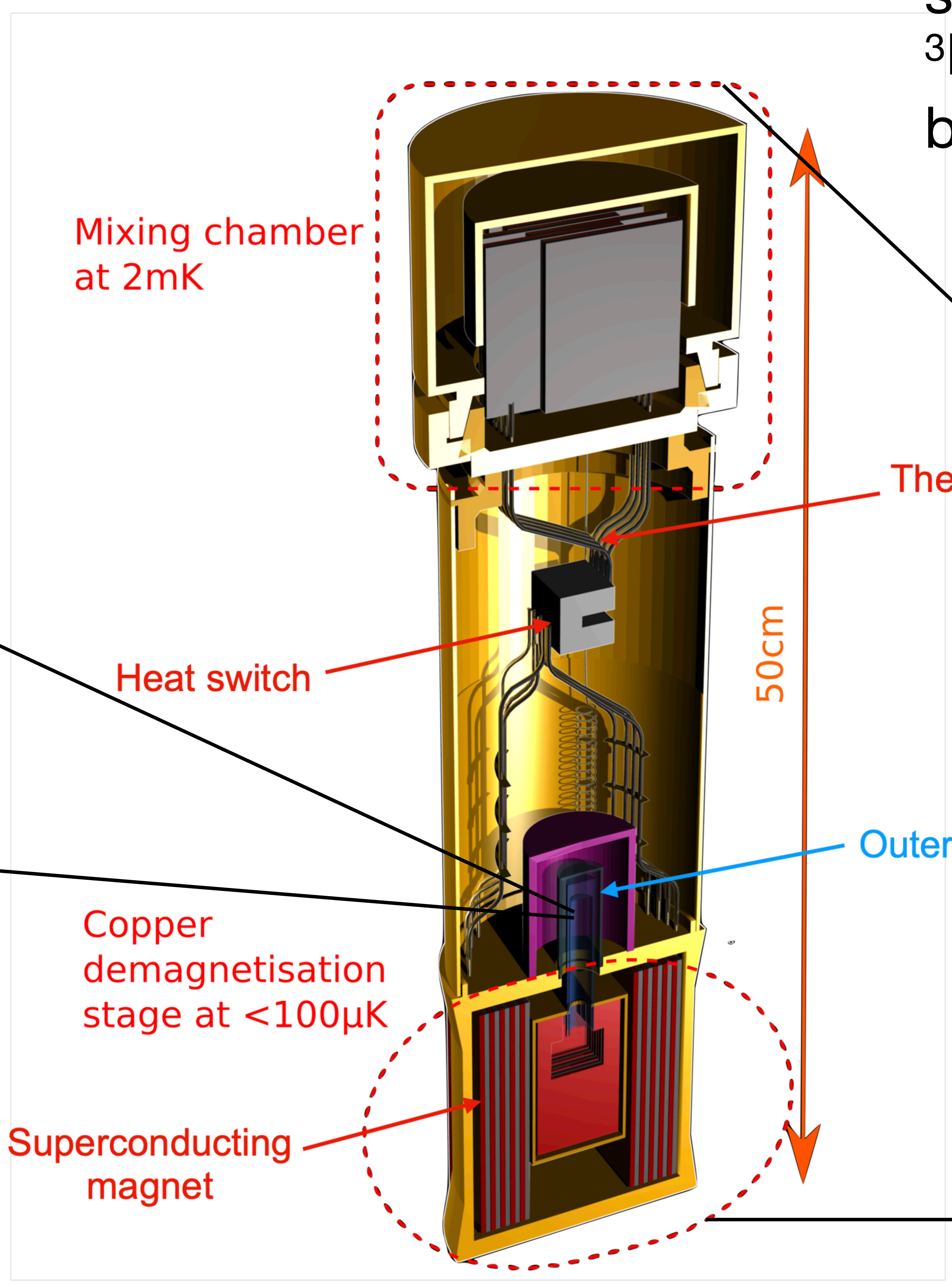
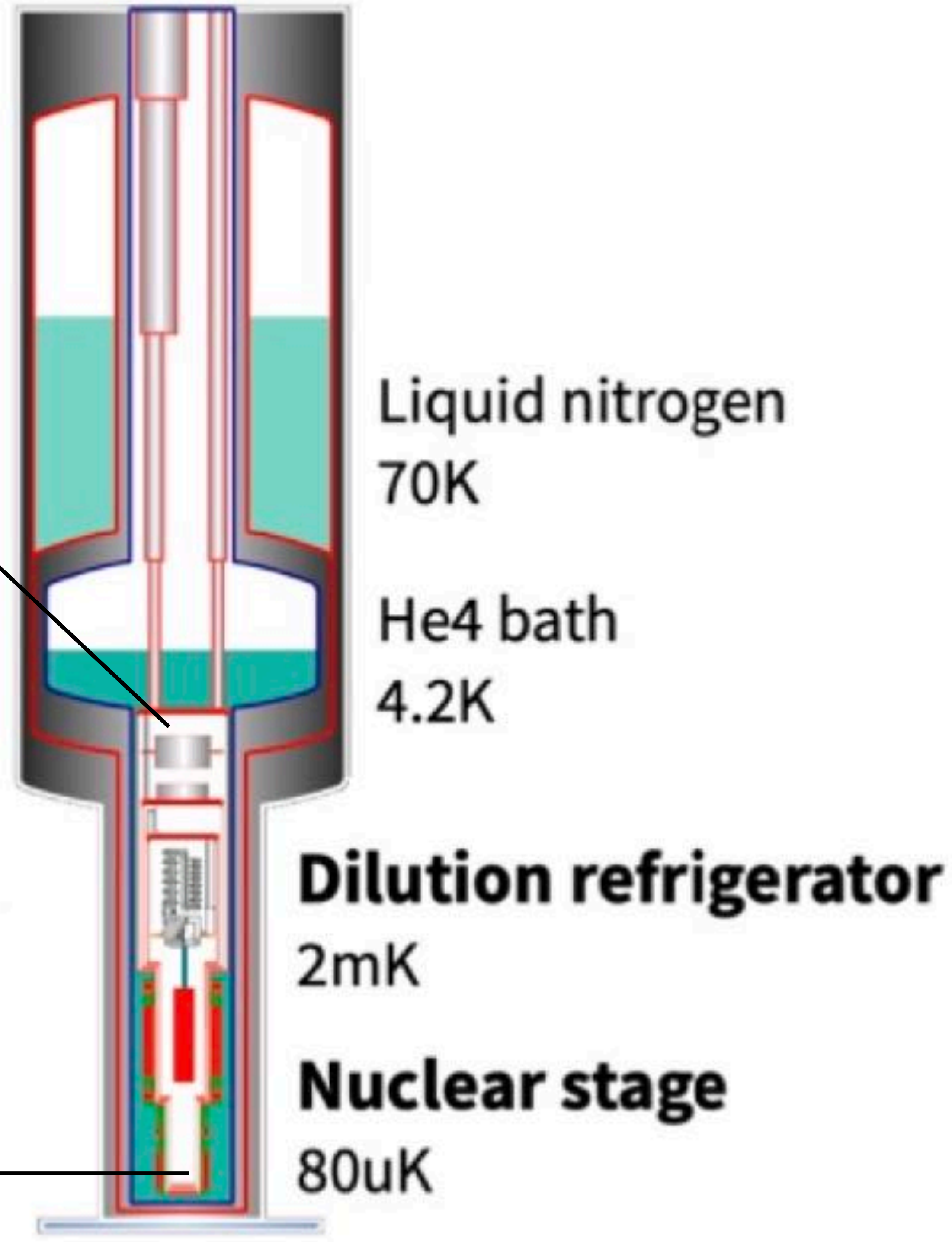
# Detector Concept

Experimental region coupled to nuclear stage of fridge to reach $^3$He temperatures below 200 $\mu$K

Superfluid $^3$He bolometer fitted with nanoelectromechanical resonators

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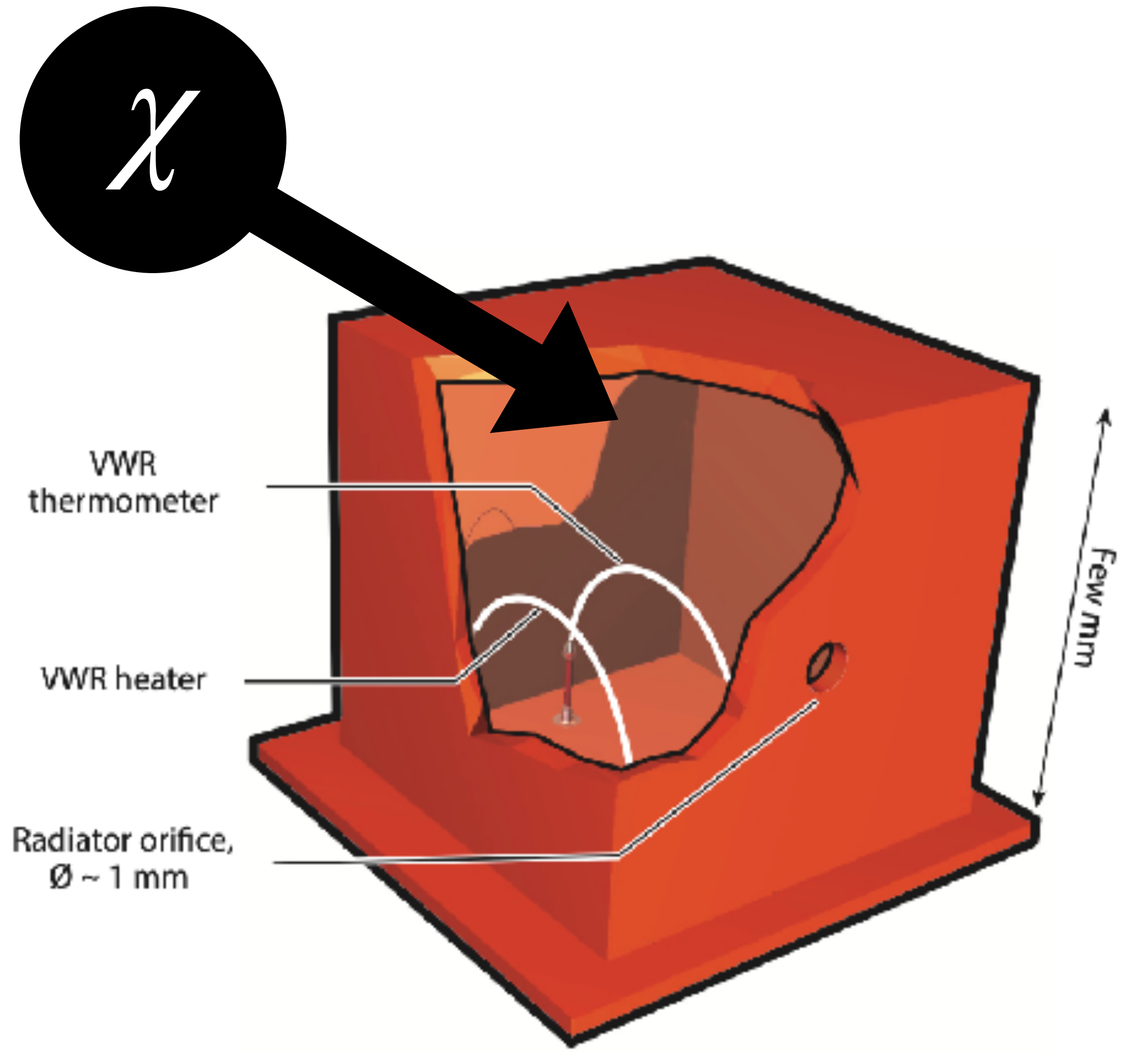
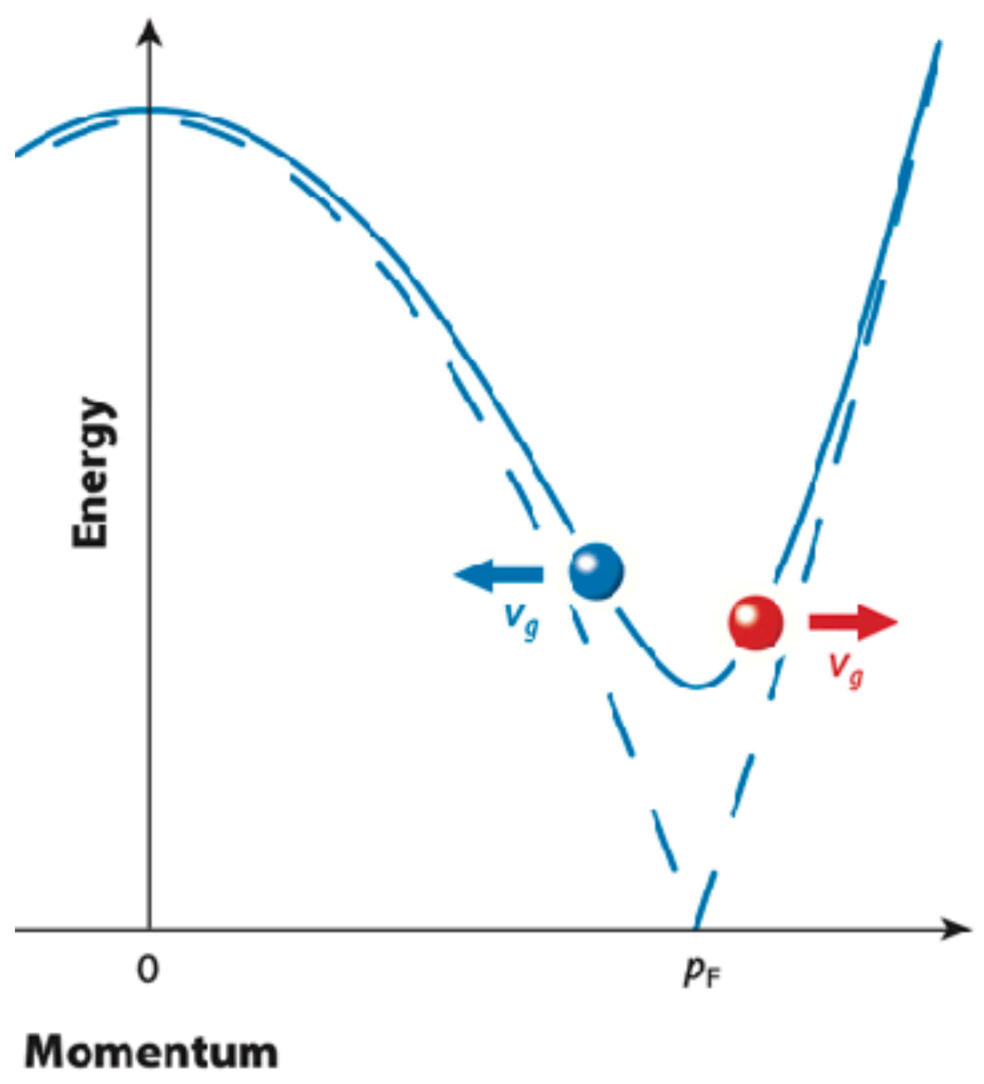
# Detector Concept

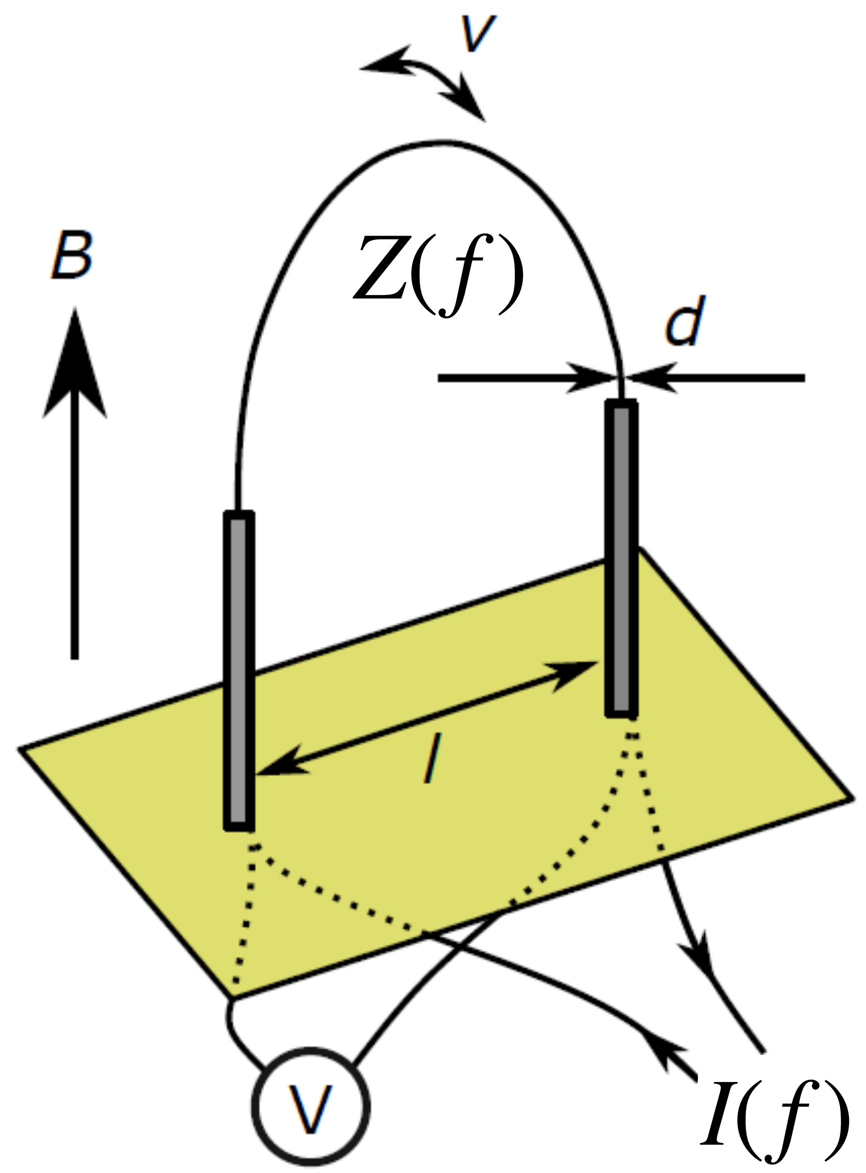



**1. Energy deposit**
DM – helium scattering produces quasiparticles (QPs) 1eV → $10^7$ quanta



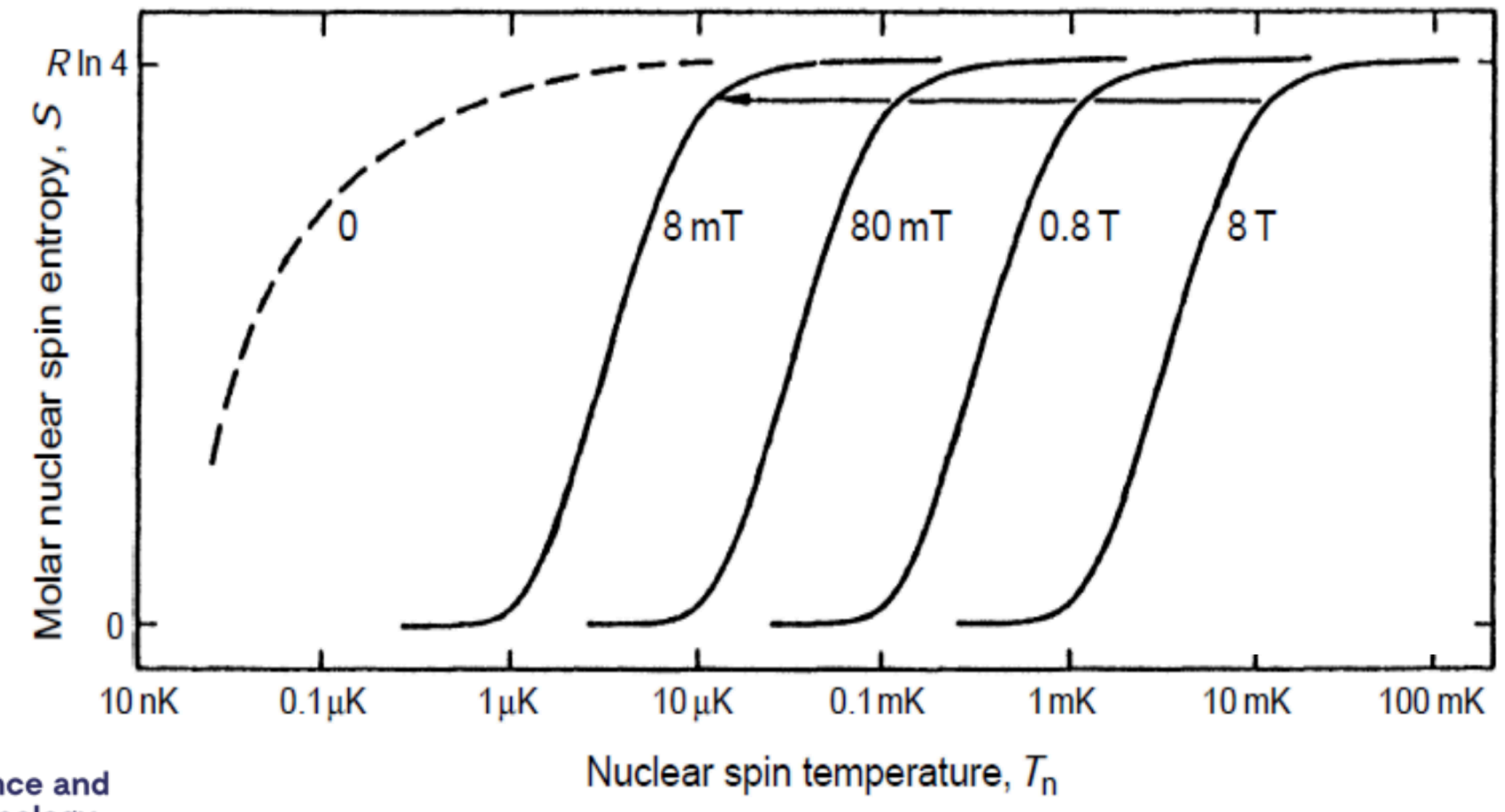

**2. Ballistic propagation**
QP collisions with nanowire exert damping force

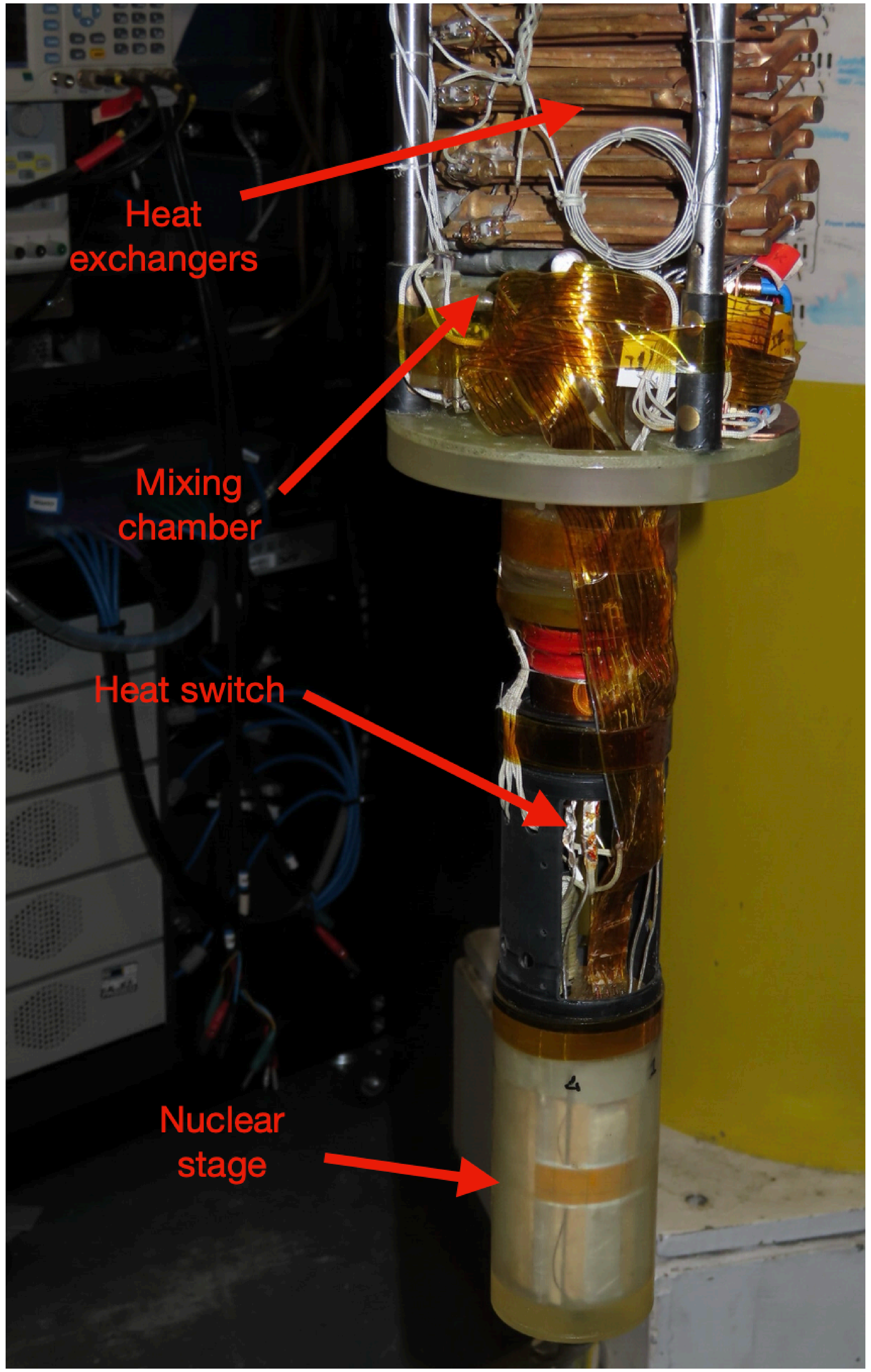
**3. Bolometry**
- nanowire driven by AC current in vertical B field
- measure increase in resonance width from damping



# Nuclear Demagnetisation

- Dilution fridge used to pre-cool nuclear stage
- This stage is then thermally isolated using a heat switch
- Reduction of magnetic field applied to copper nuclear stage leads to further cooling, down to <100 $\mu$K

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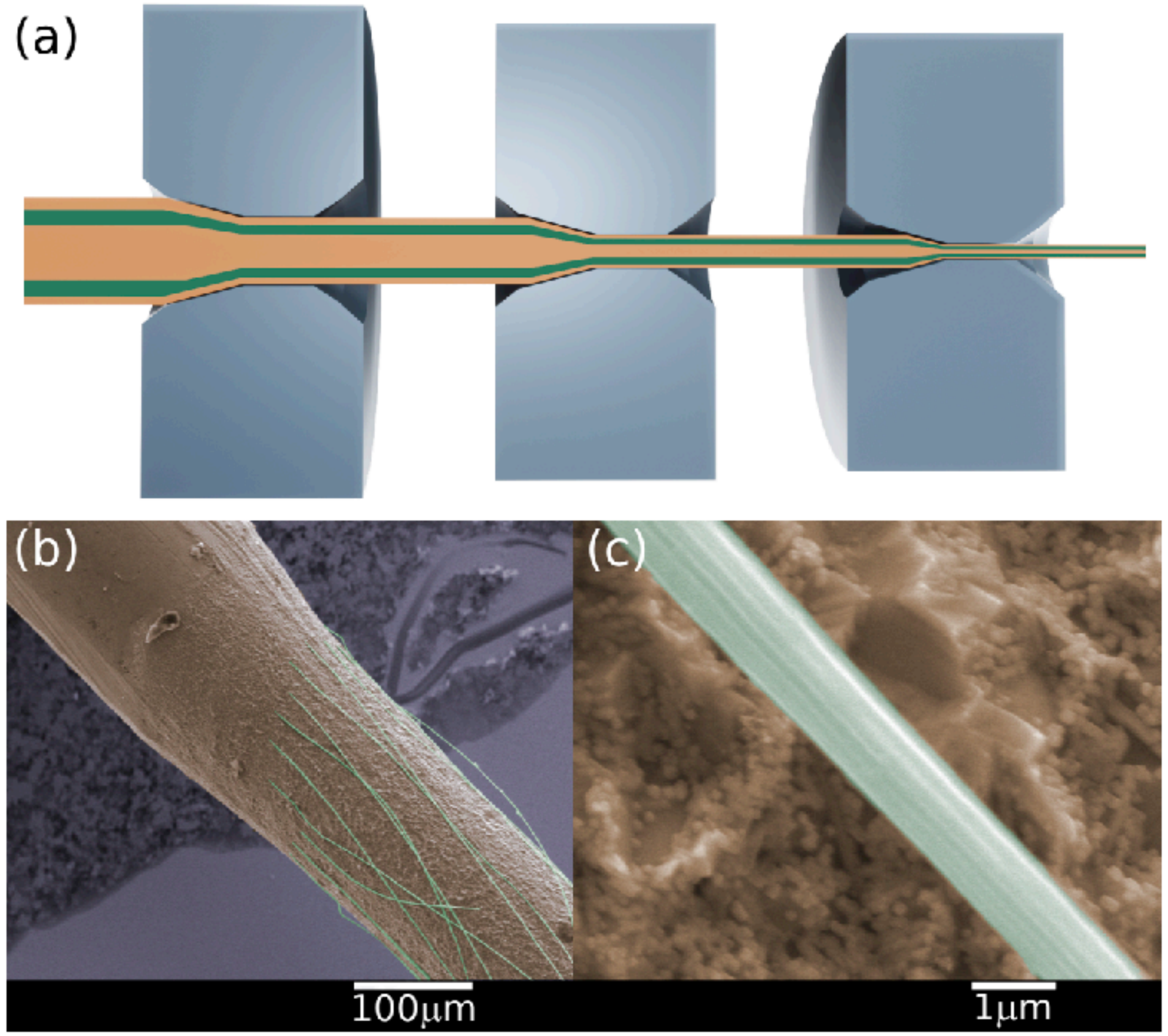
# NEMS

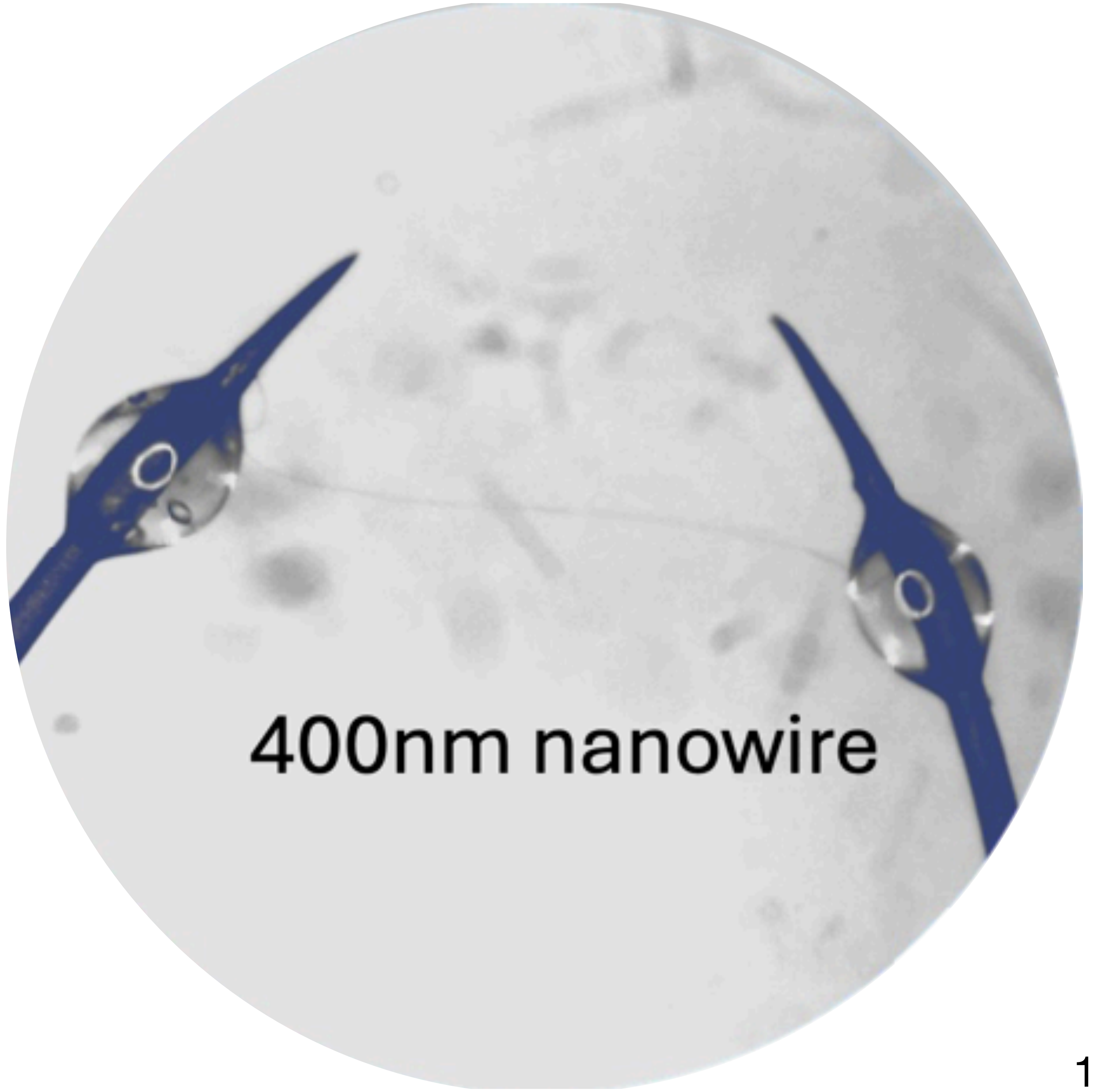
Superfluid $^3$He thermometry done using nanoelectromechanical resonators (NEMS)

Superconducting NbTi wires

Cu/NbTi wire stretched through set of diamond dies and filaments removed one by one

Paper on fabrication https://arxiv.org/abs/2311.02452

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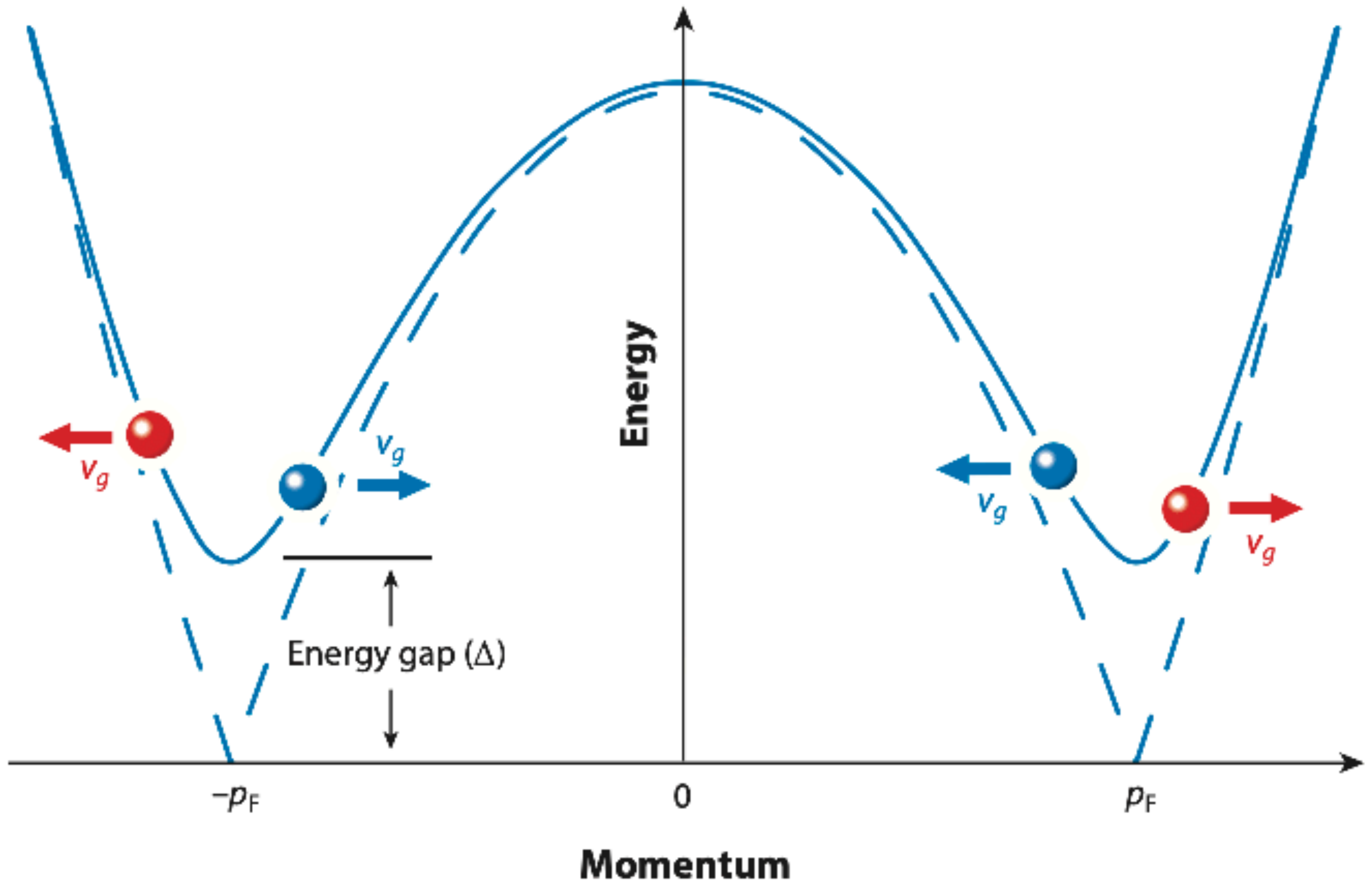
# Andreev Scattering

Regular dispersion curve

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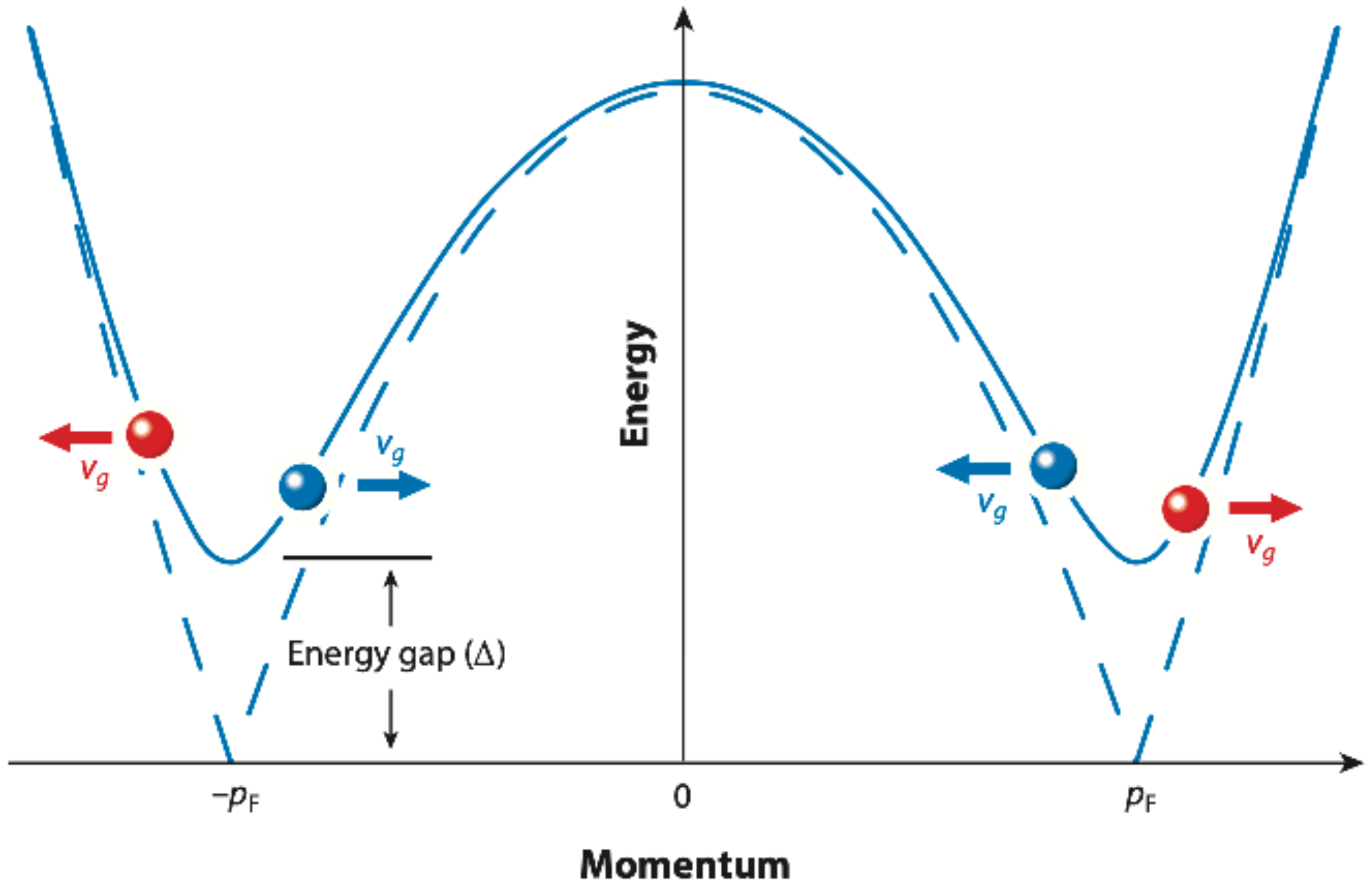
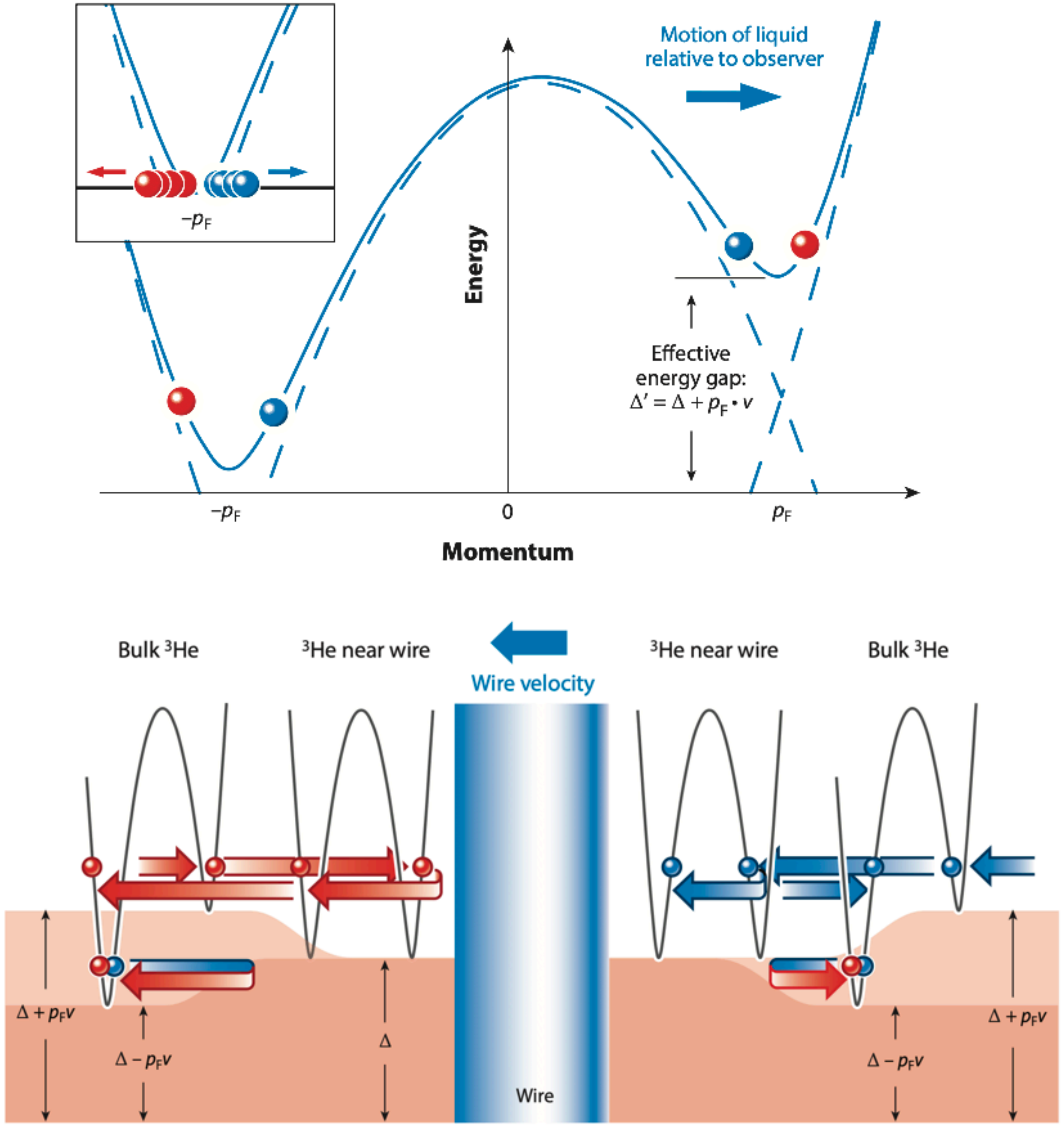
# Andreev Scattering

Regular dispersion curve




Modified dispersion curve

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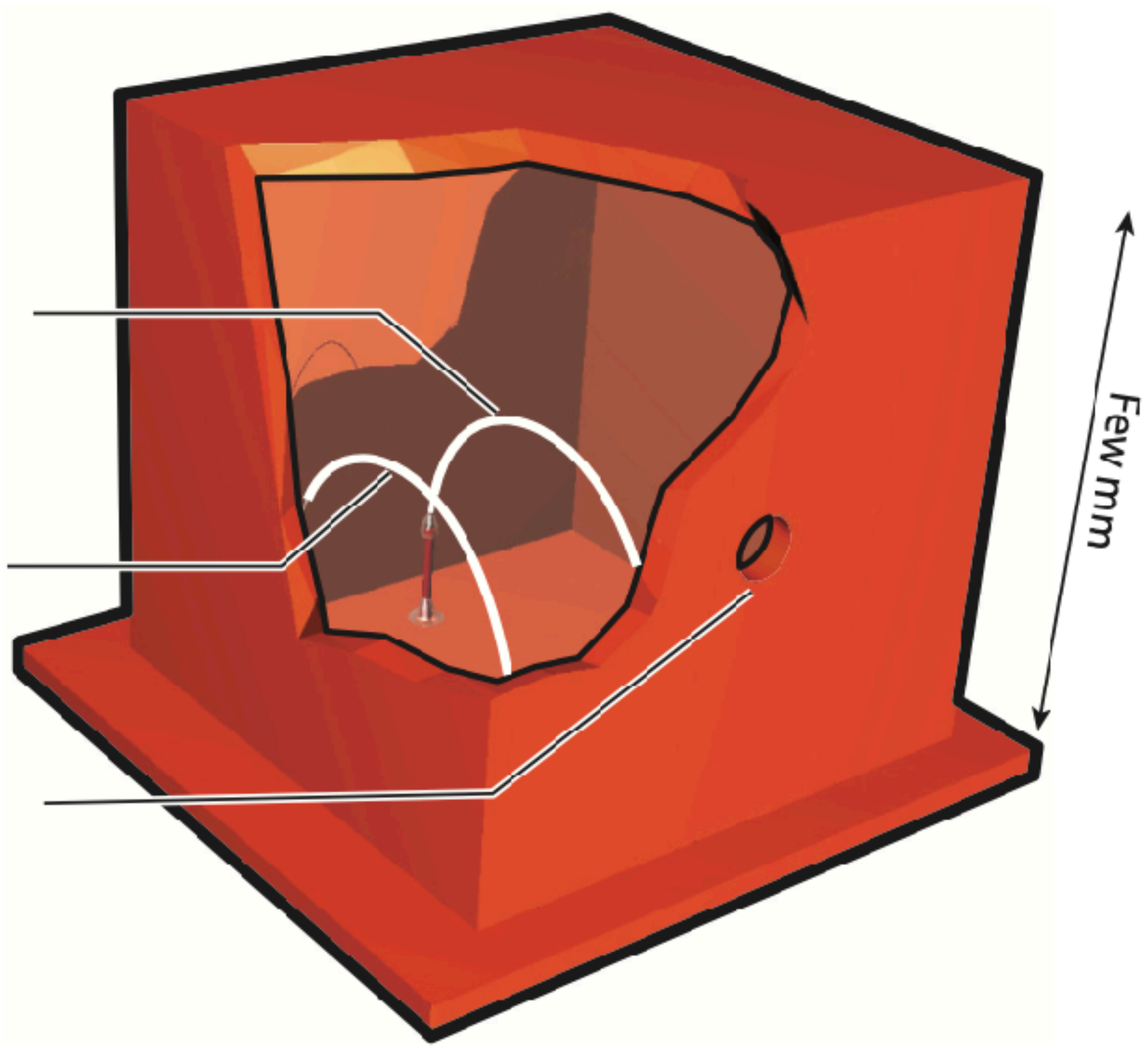
# Bolometer Design

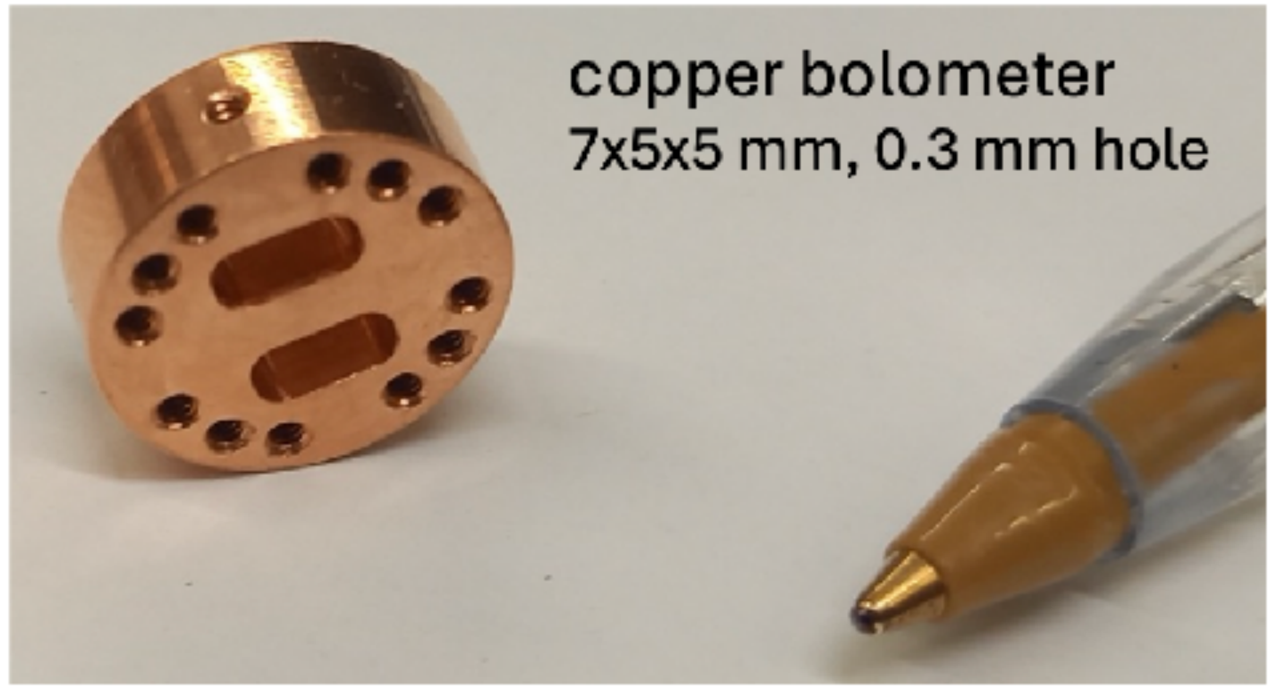
Quasiparticle blackbody radiator

Orifice allows quasiparticles to escape and thermalise back to base temperature after a heating event

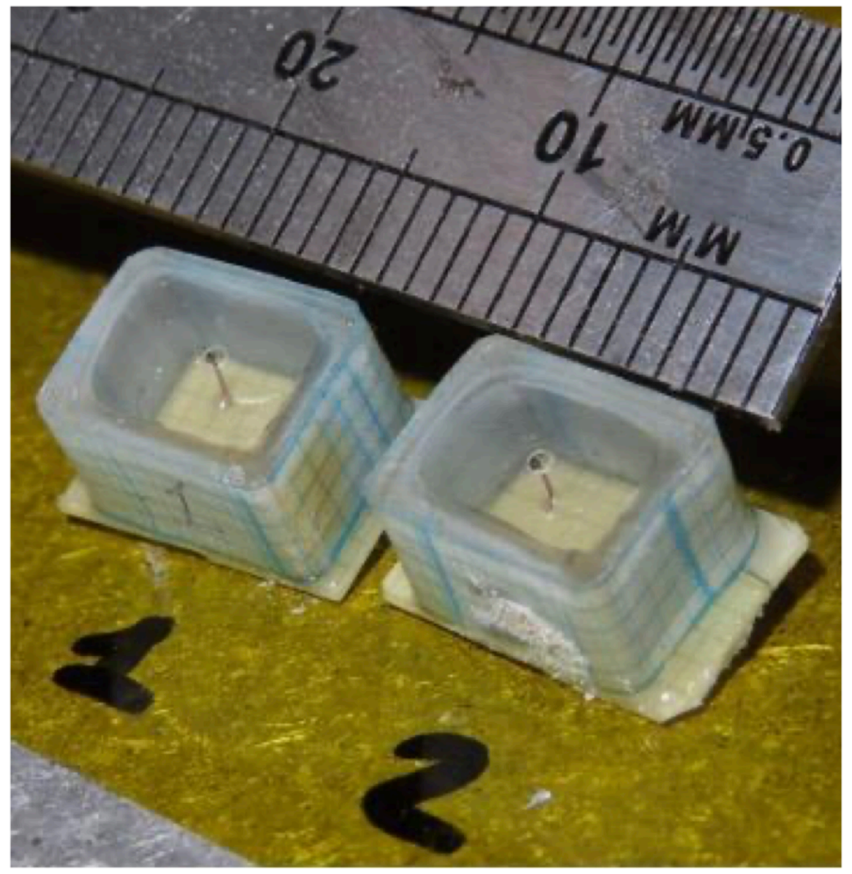
Size of orifice determines thermalisation time constant

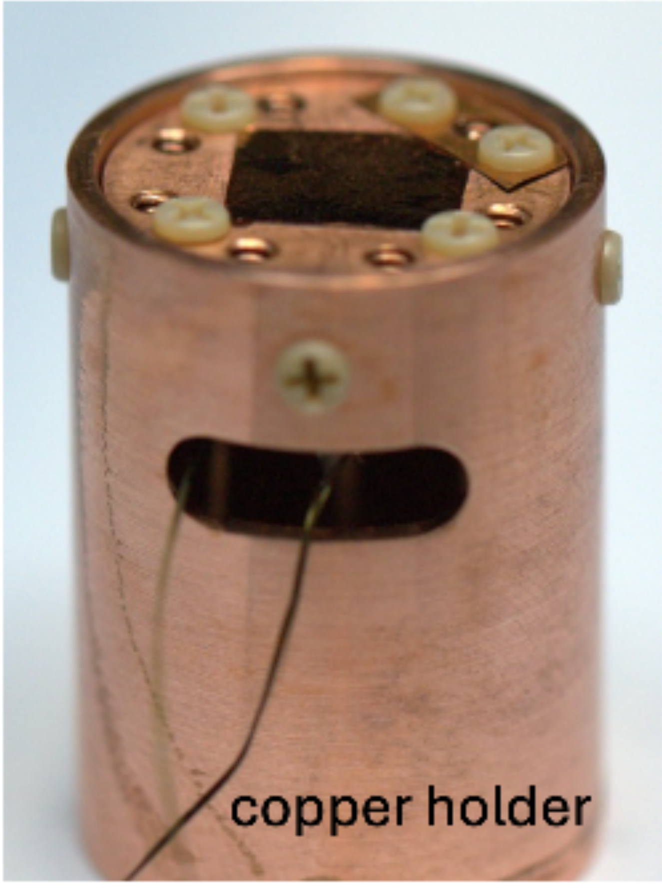


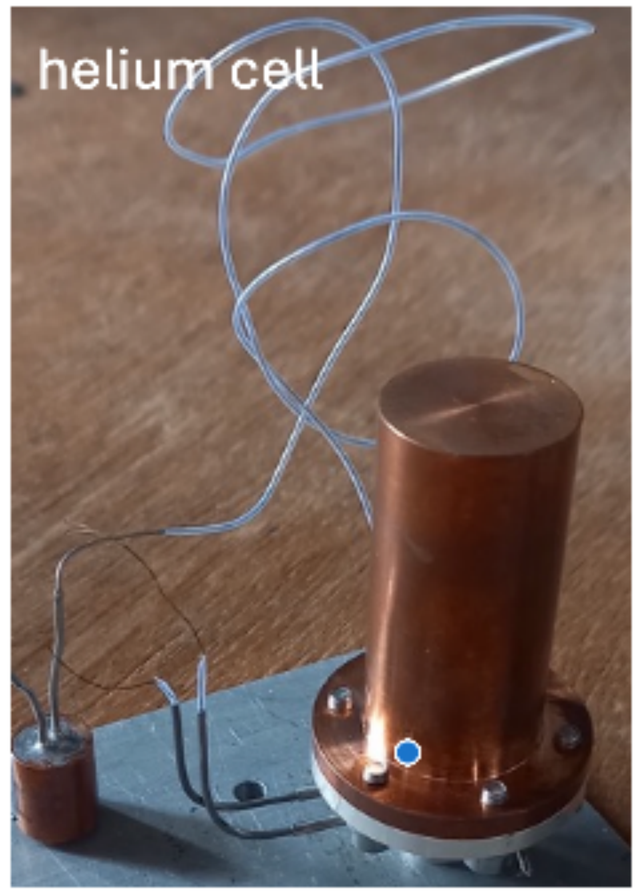

Gen. 2




Gen. 1

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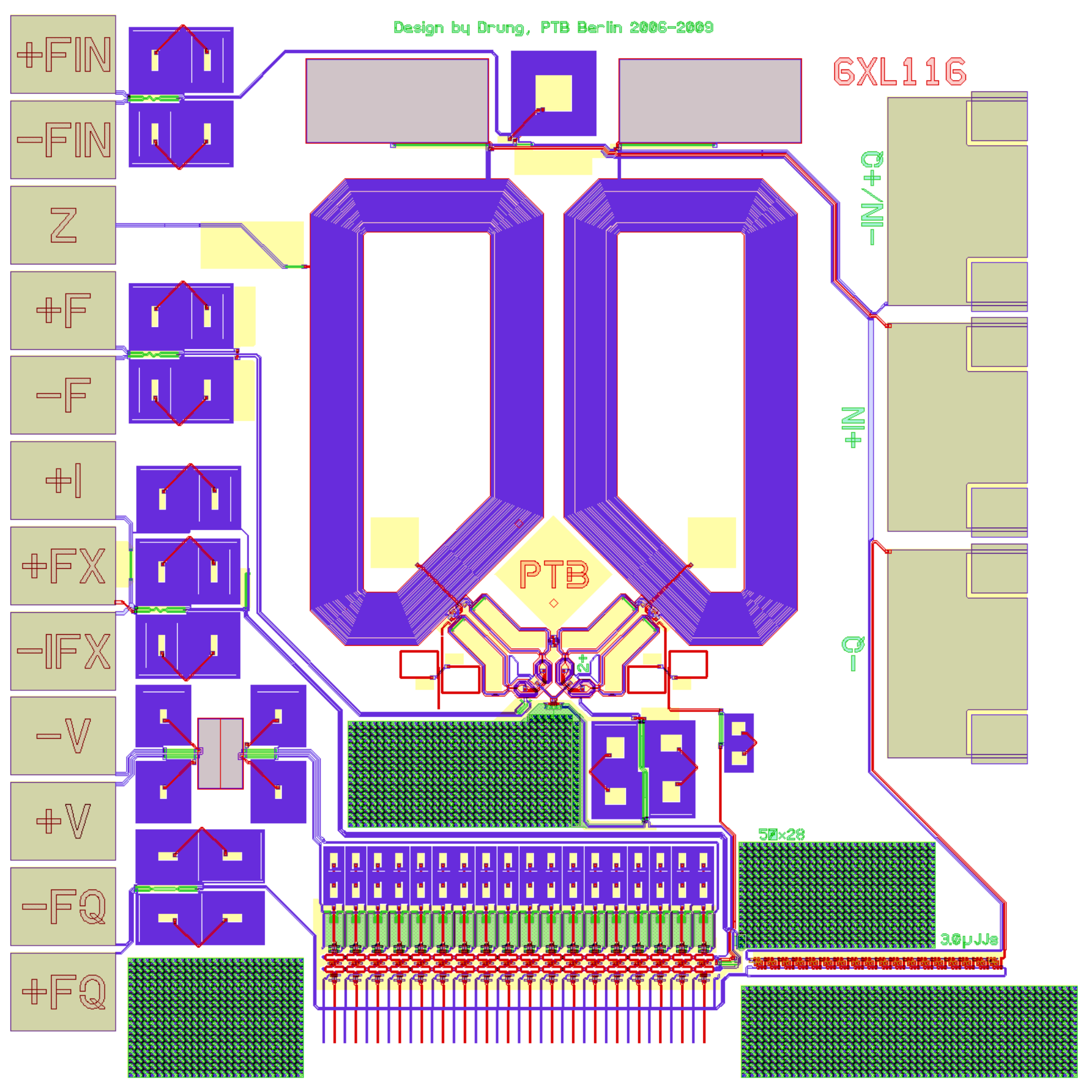
# Readout Schemes

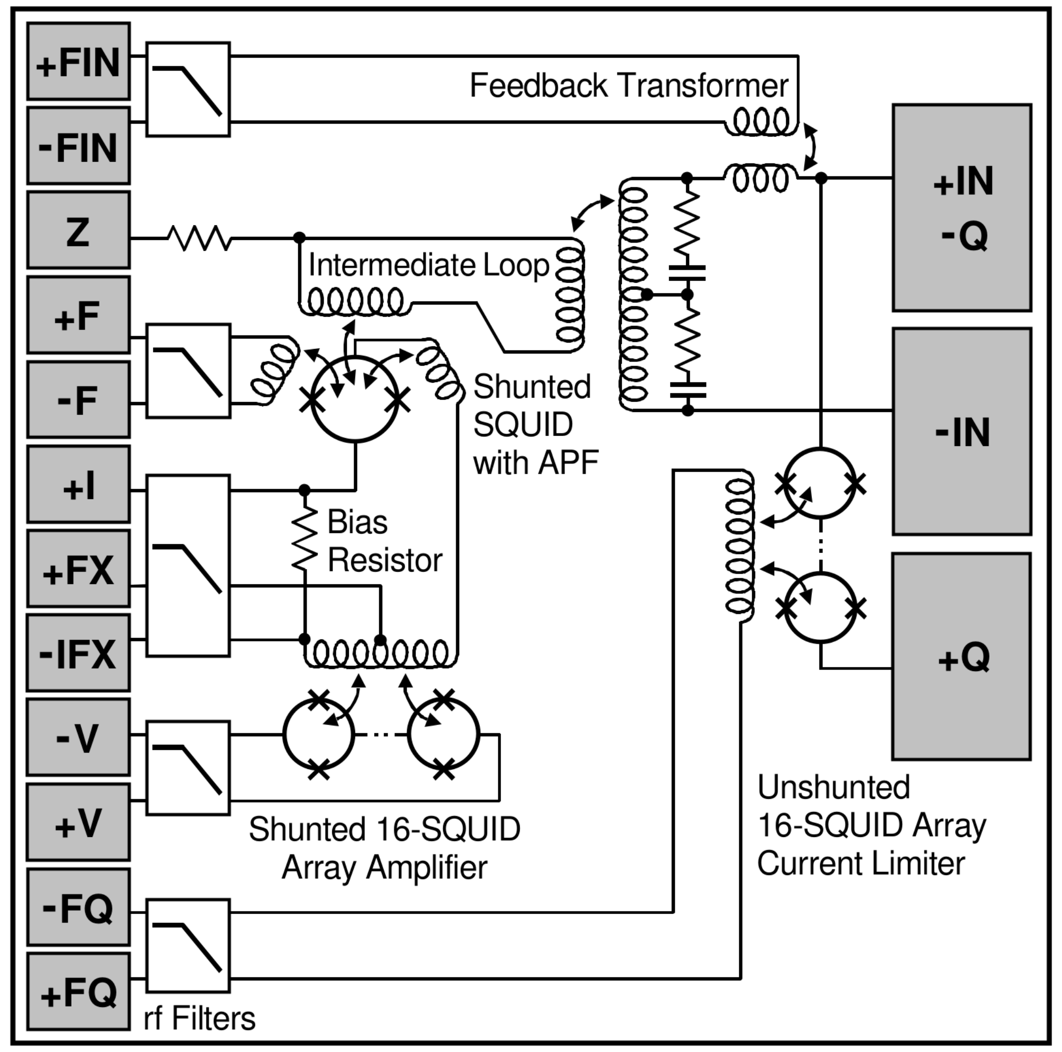
Conventional readout - using cold transformer amplifier

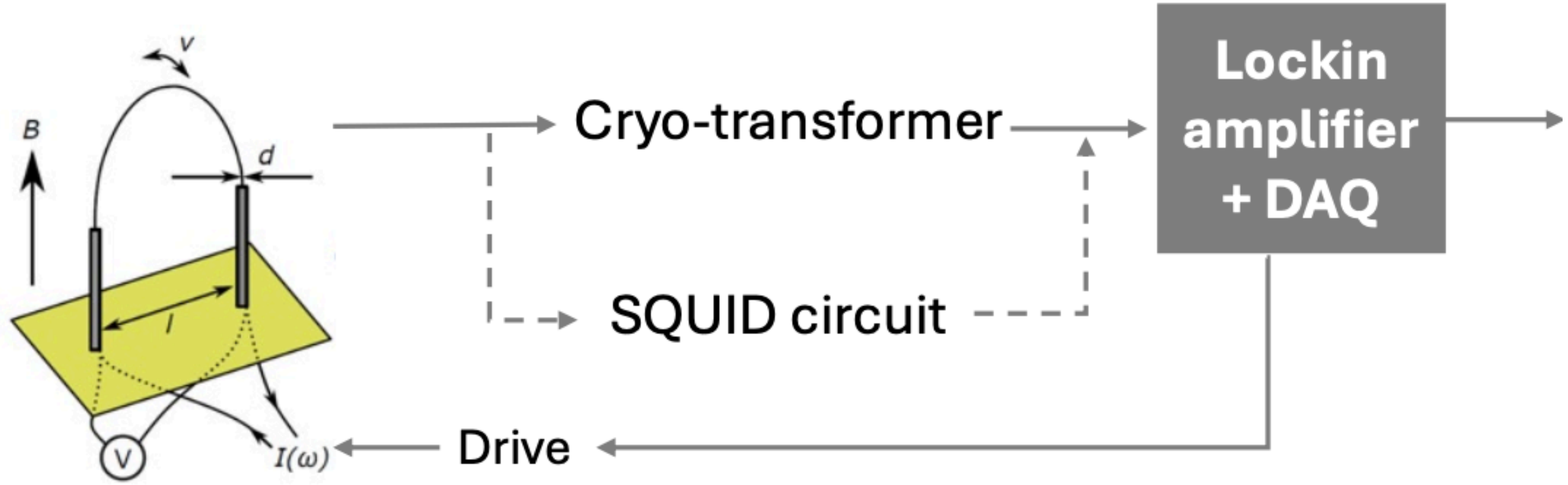
Newer QUEST detectors fitted with two-stage SQUID current amplifiers

New paper on reading out NEMS with these SQUIDs

https://arxiv.org/abs/2508.10602




https://ieeexplore.ieee.org/document/4277368

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# NEMS Measurements

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# Narrow Frequency Sweeps

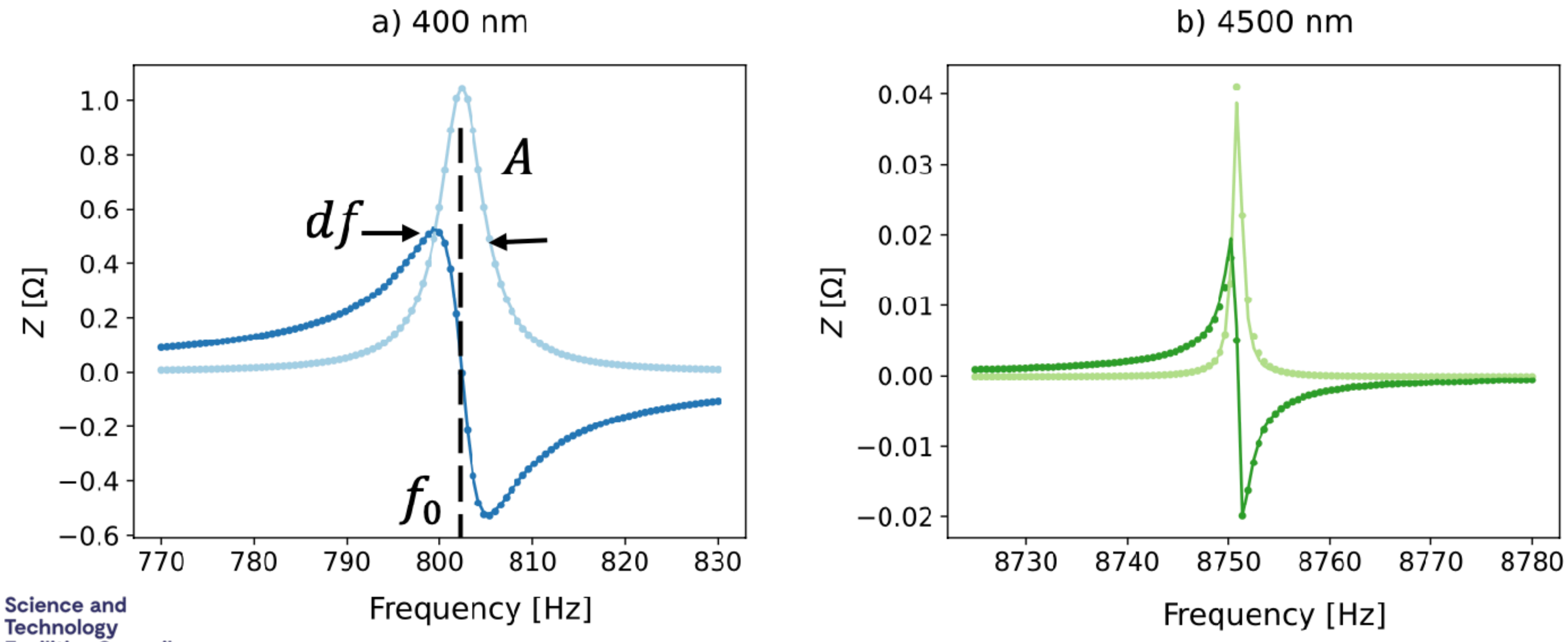
Characterise resonance of each wire by sweeping over frequencies

Lorentzian fit:

$$Z(f) = \frac{ifA}{f_0^2 - f^2 + ifdf}$$

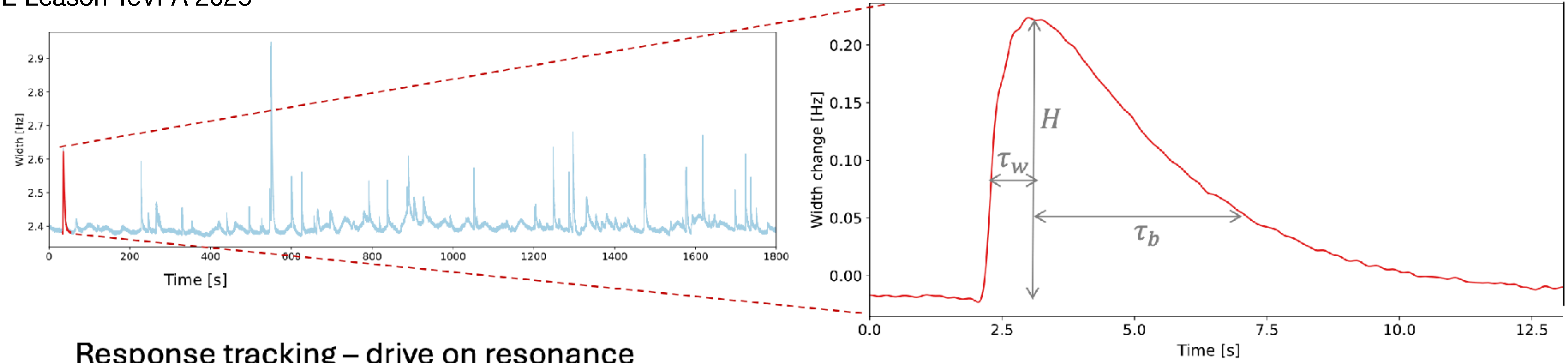
Amplitude:

$$A = \frac{\ell B^2}{2\pi m}$$



# On-resonance Measurements

E Leason TeVPA 2025




Response tracking – drive on resonance

- Measure impedance of wire, Z
- Convert to width, using measured amplitude A from frequency sweep:

$$df = Re\left(\frac{A}{Z}\right)$$

- Track over time and apply pulse finding

Characteristic pulse shape, three parameters:

- Rise time, $\tau_w$ - nanowire
- Decay time, $\tau_b$ - bolometer
- Height, $H$ – heating event (energy)

[C.Winkelmann, NIMA(2007)]

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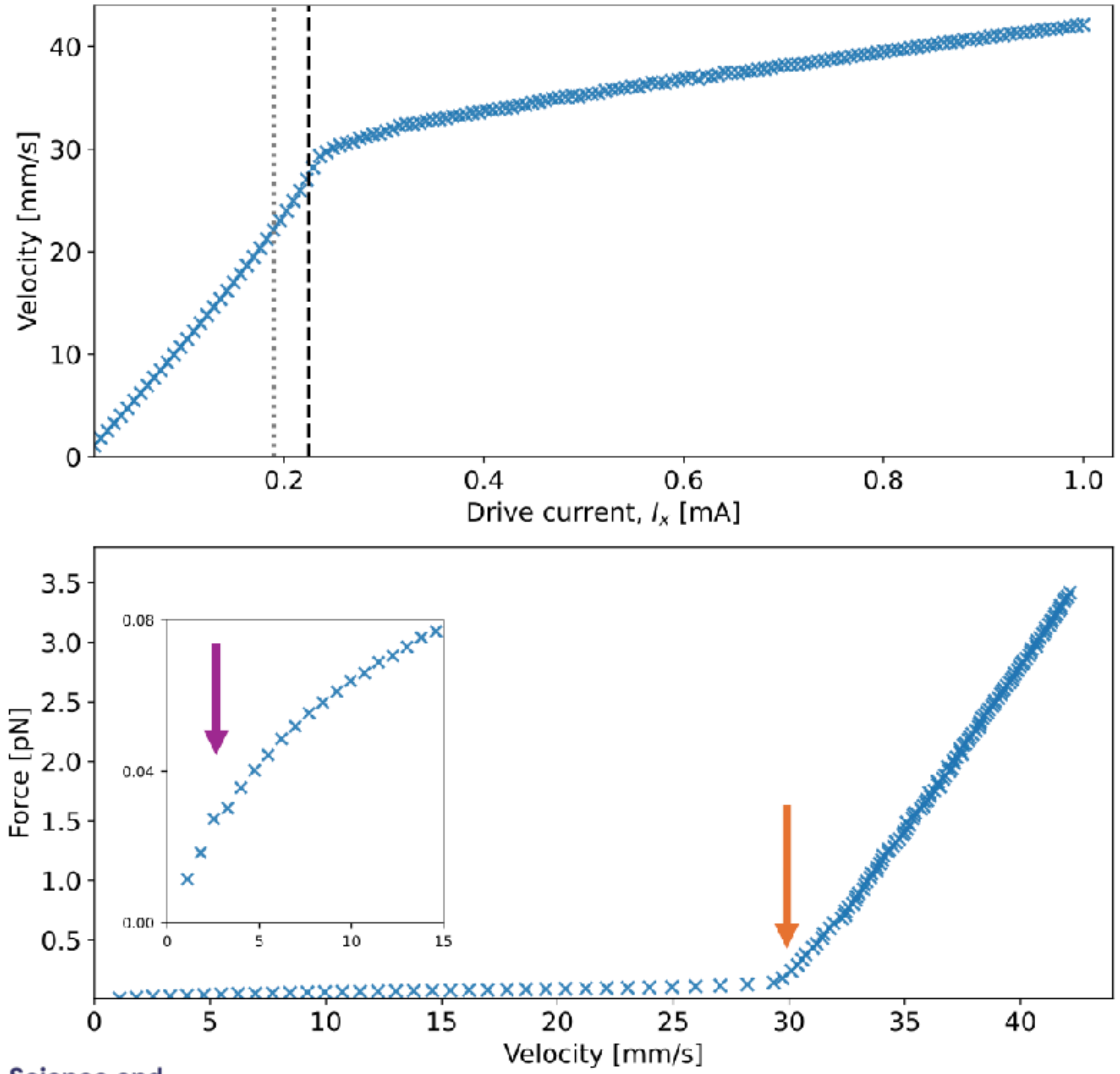
# Drive Amplitude Sweeps

https://arxiv.org/abs/2508.10602




Drive amplitude sweep:

- non-linearity >4 mm/s
- quasiparticle emission >30 mm/s

Operate in non-linear regime (below critical velocity) and use width correction [V.Zavjalov arXiv:2303.01189]

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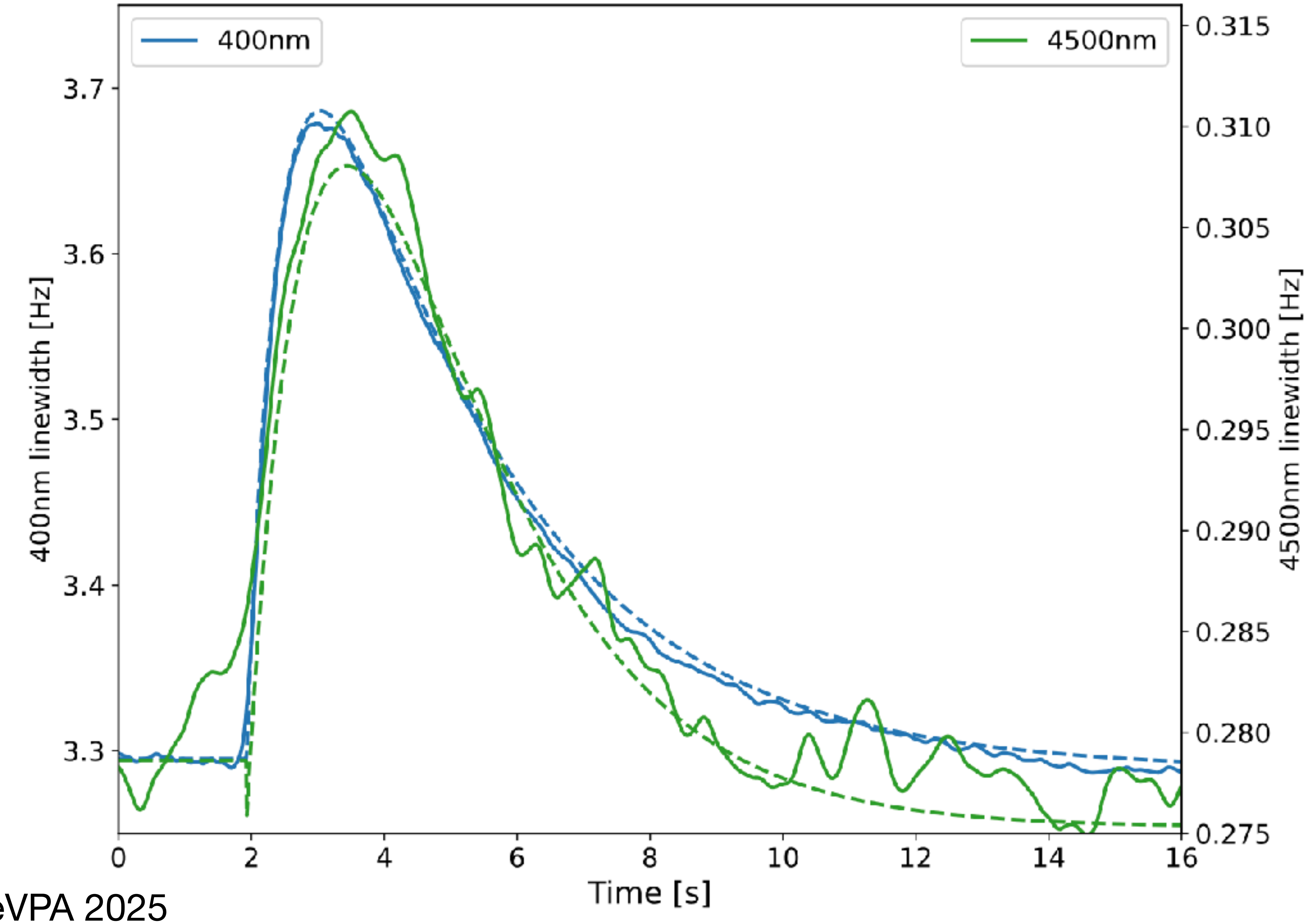
# Simultaneous Tracking

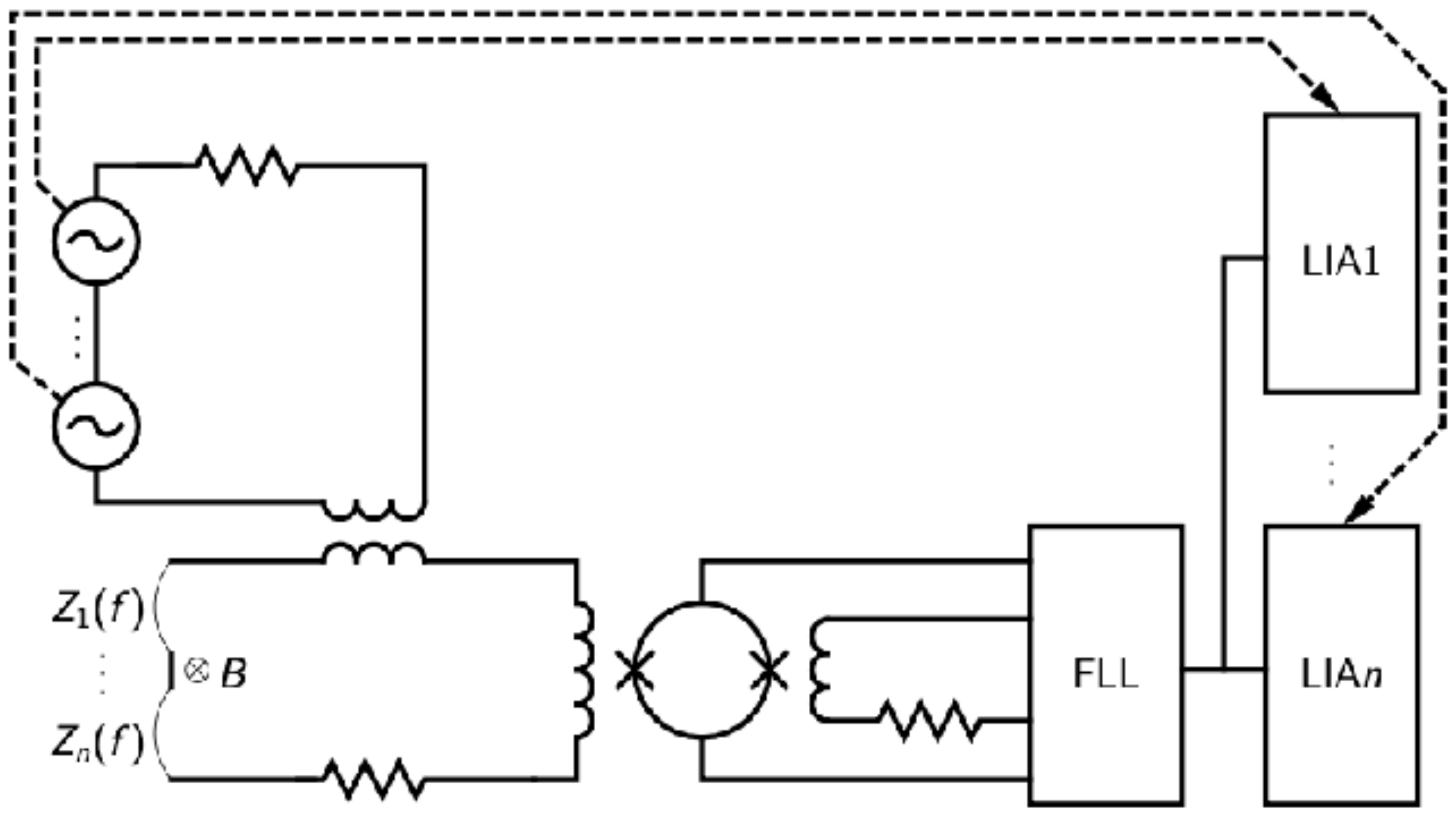
Tracking on both wires, driven on resonance at 70% critical velocity.

Observe coincident bolometer pulses.

Factor ~10 difference in width change and different rise times, expected for different wire diameters.



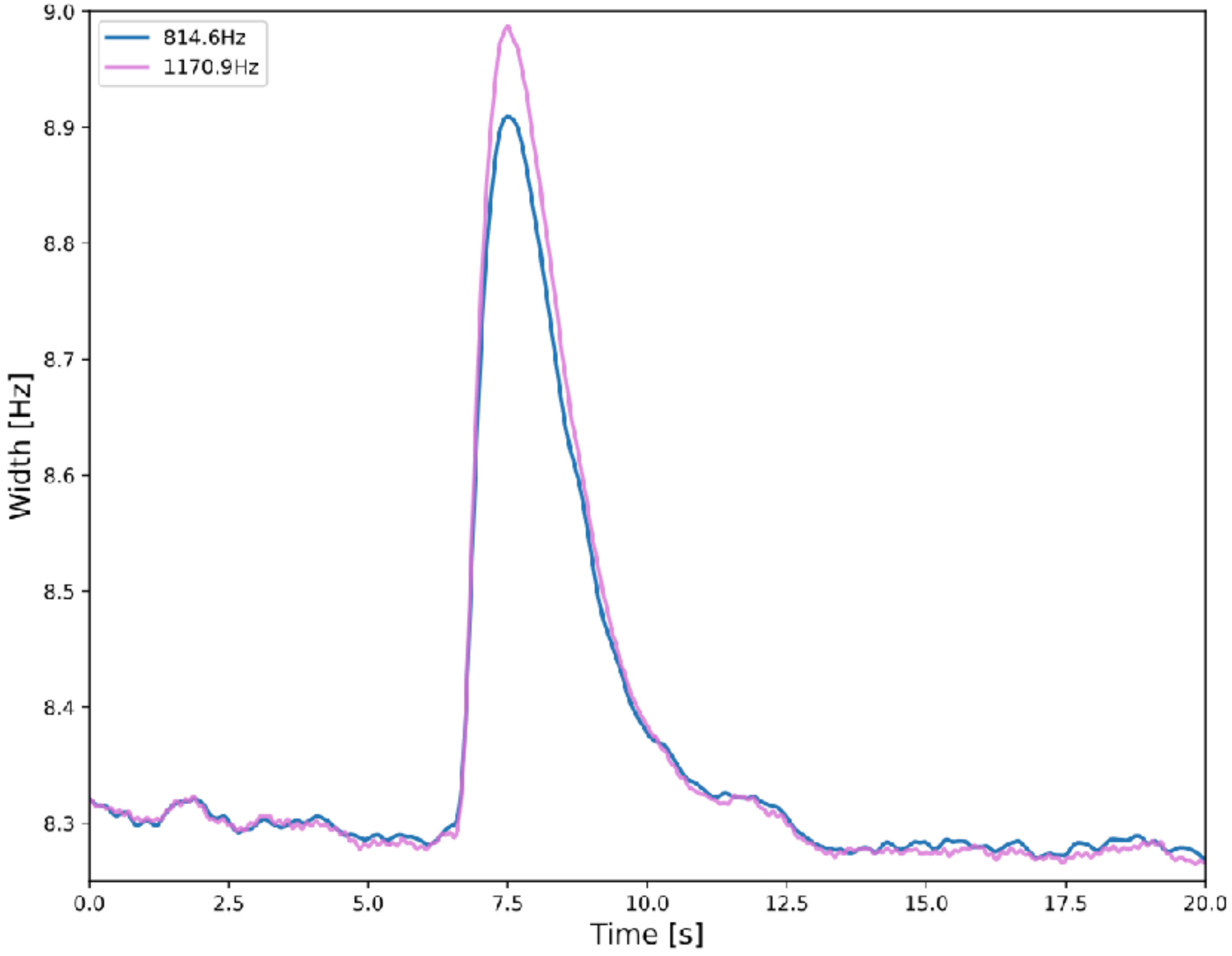
# Multiplex Readout




**Future:** readout multiple VWRs with single SQUID sensor

**Proof of concept:** simultaneously readout two vibrational modes on a 400 nm wire

- low drive on mode does not interfere with other
- both resonances driven and detected with a single multichannel lockin amplifier




Coincident events on both modes

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E Leason TeVPA 2025

# Energy Partitioning

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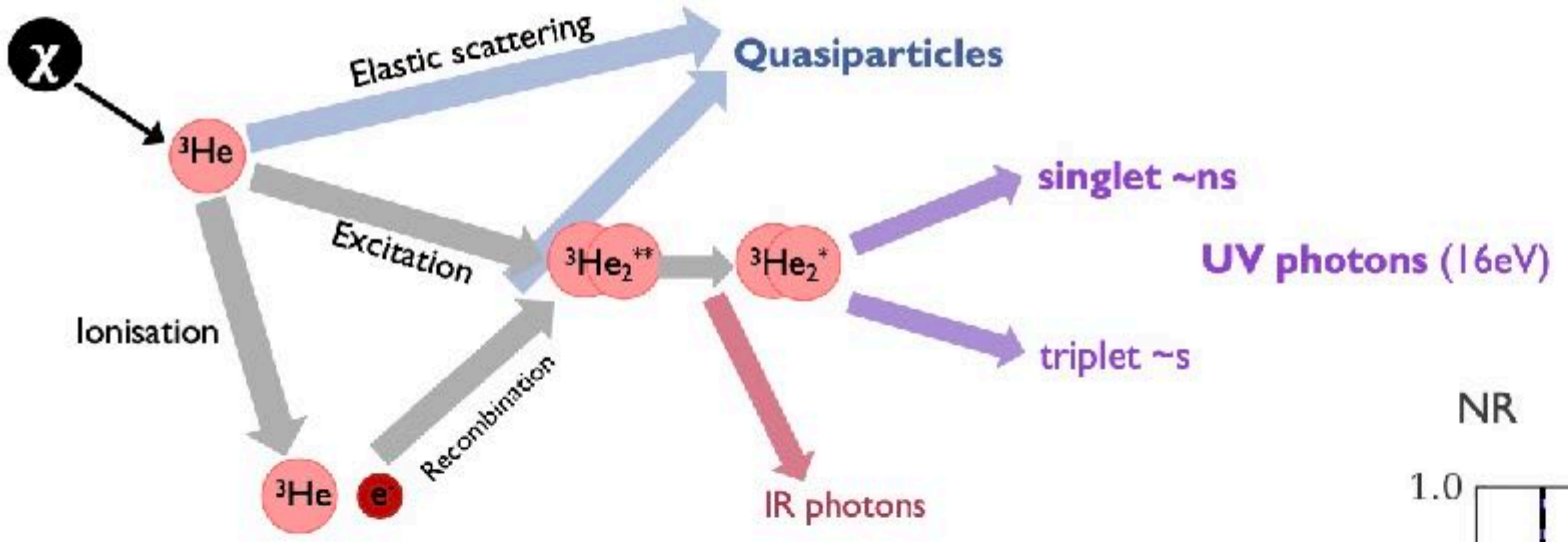
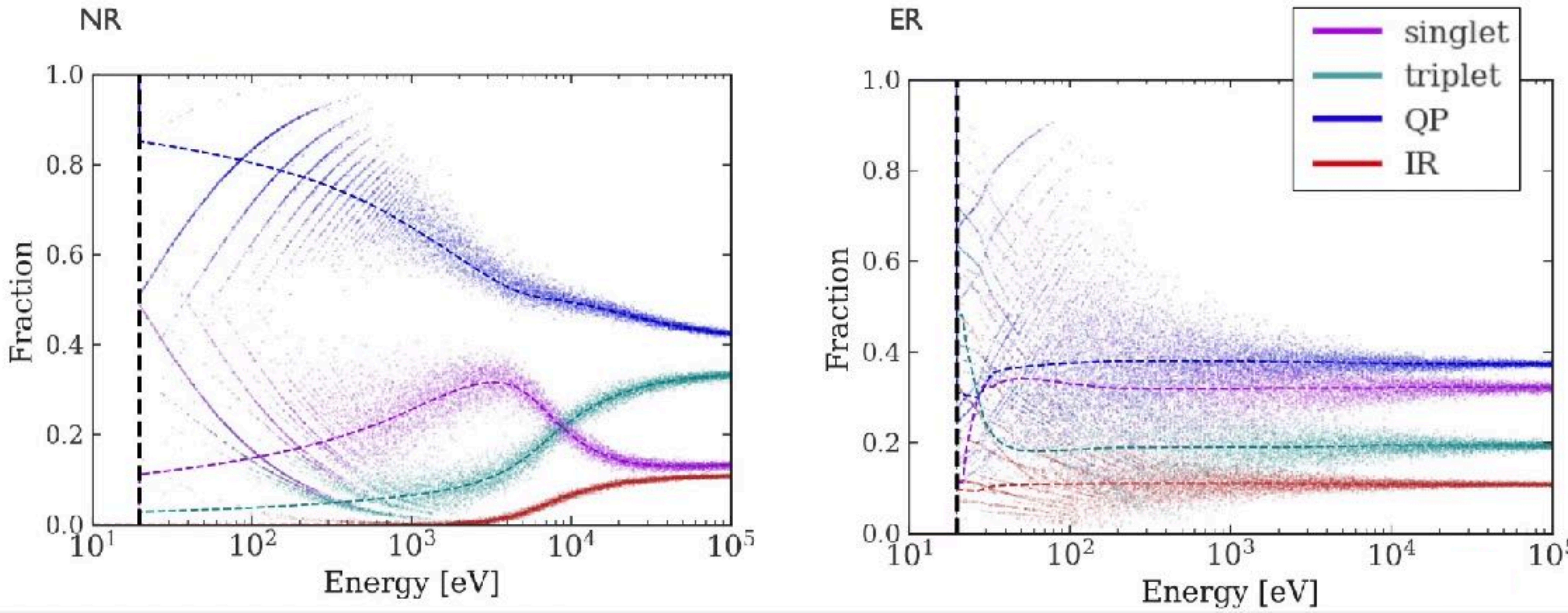
# ER vs. NR

Based on semi-empirical model by Ito & Seidel https://journals.aps.org/prc/abstract/10.1103/PhysRevC.88.025805

Possibility for NR/ER discrimination using scintillation channel



# Energy Calibration

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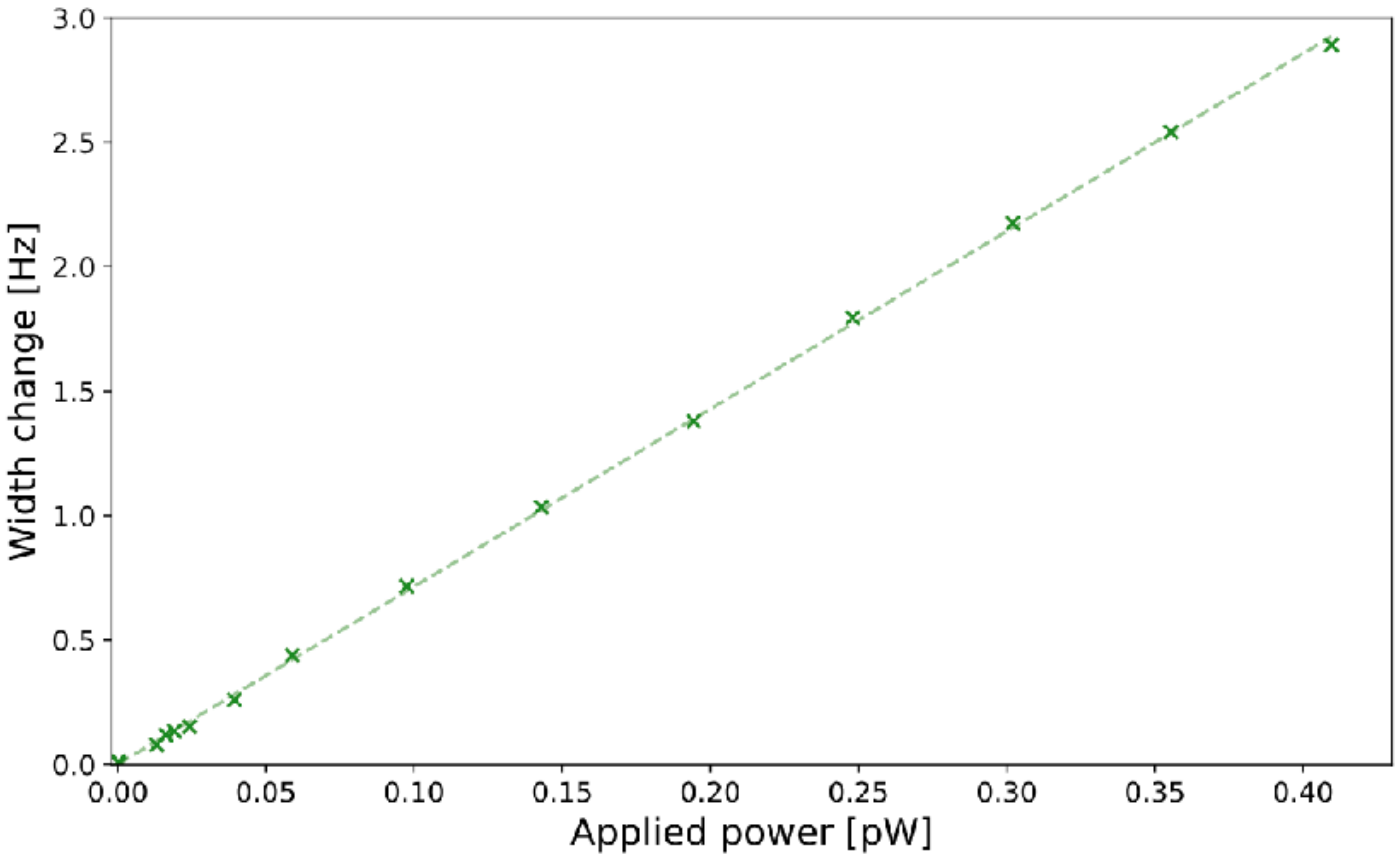
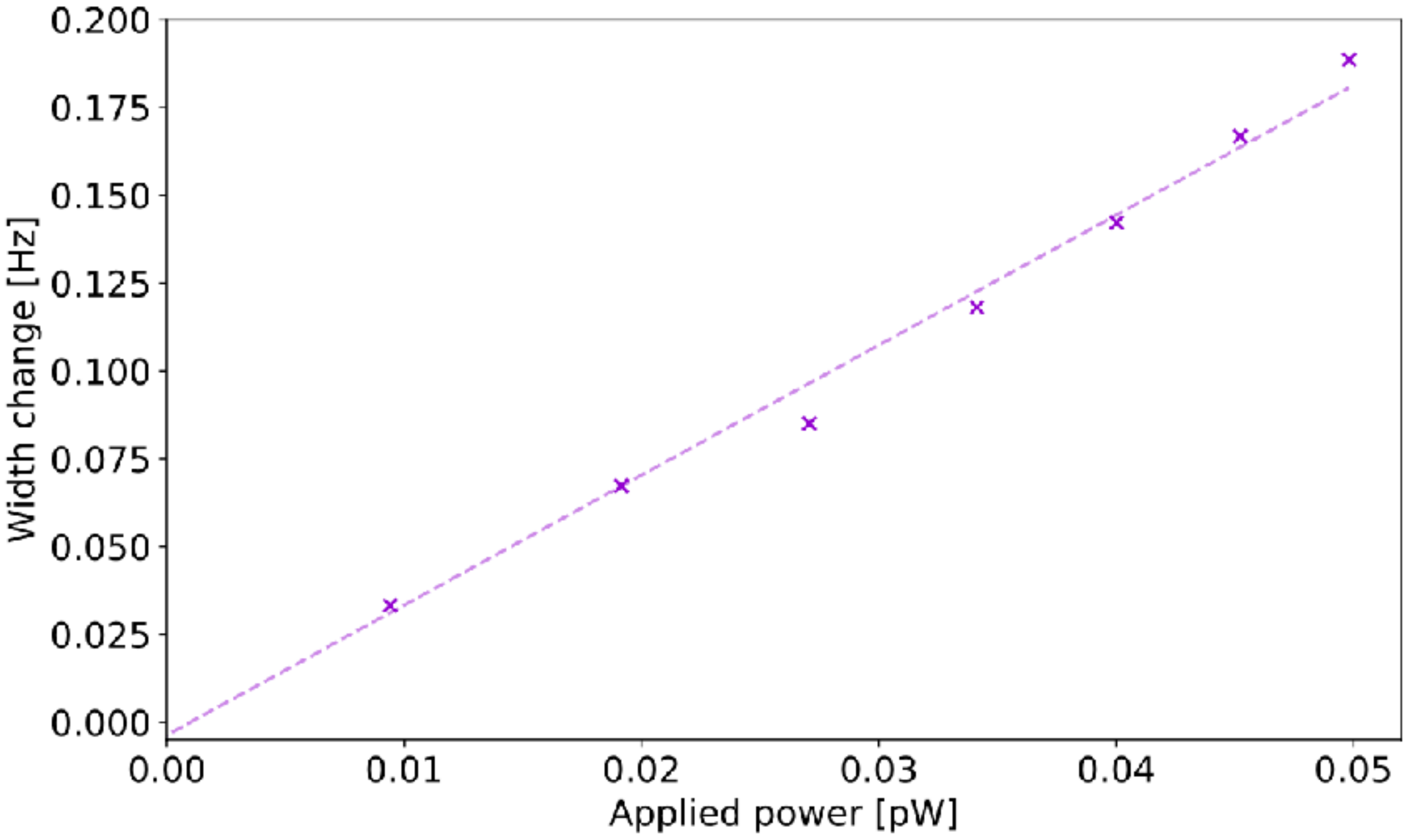
# Heater Wire Calibration

Stepped power injections above critical velocity generate quasiparticles by mechanical dissipation. Detect proportional response with other wire.

A) 400 nm detector (4500 nm heater)




B) 4500 nm detector (400 nm heater)

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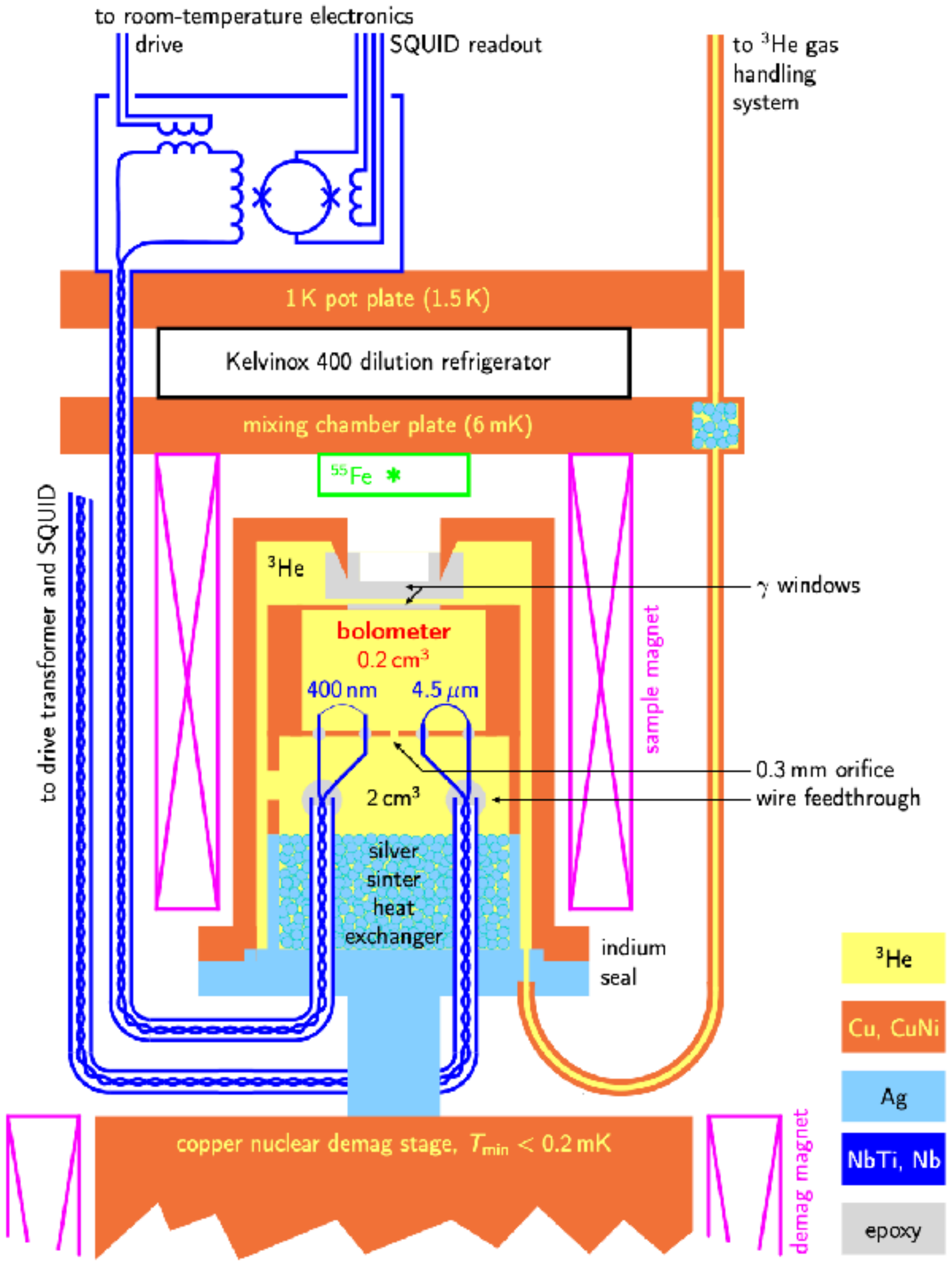
# $^{55}$Fe Source Deployment




Calibration planned using 5 keV lines from $^{55}$Fe source

Comparison to energy partitioning model

Bolometer fitted with window at the top to allow for less attenuation of source X-rays

Data currently being taken at Royal Holloway, University of London

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# Physics Potential

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# Nuclear Recoil Sensitivity

Expected sensitivity to spin-dependent nucleon interactions assuming 6 months, 50% livetime and 0.5 g $^{3}He$

https://arxiv.org/pdf/2310.11304

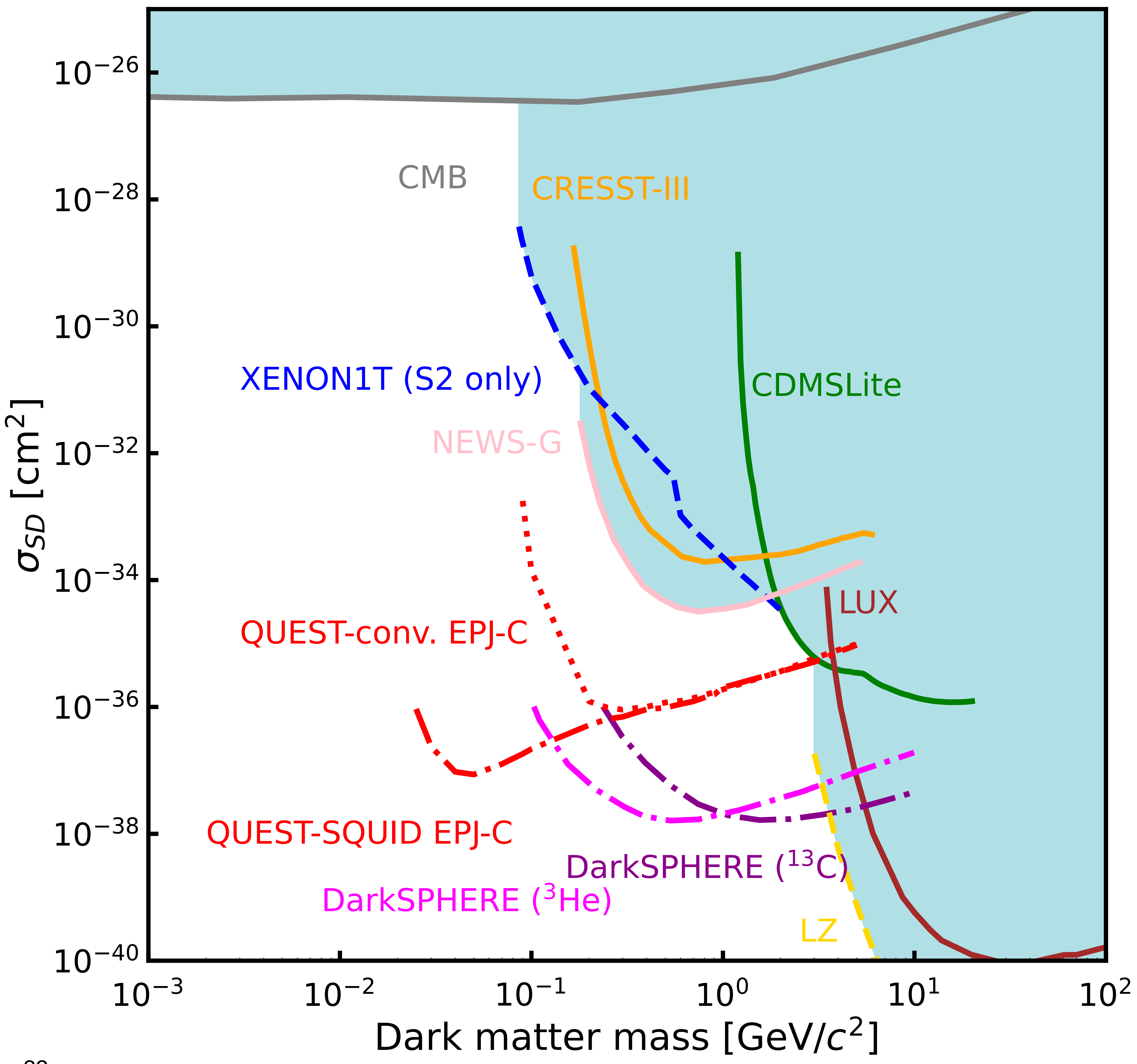
Simulated thresholds of 31 eV for conventional readout 0.71 eV for SQUID

Dark matter attenuation paper:

https://arxiv.org/abs/2502.10251

EFT landscape with QUEST-DMC:

https://arxiv.org/abs/2505.17995

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# Conclusion & Outlook

- QUEST-DMC has the potential for world-leading sensitivity to spin-dependent nucleon interactions with sub-GeV dark matter candidates

- Uses superfluid $^3$He with low-noise quantum sensor readout to reach low threshold energy measurement

- We have characterised and operated NEMS devices coupled to SQUID readout

- Calibrated using heat injection, current bolometer running with $^{55}$Fe source

- Lancaster cryostat cooling down as we speak - expecting to reach colder temperatures than any other QUEST bolometer so far!

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# Backups

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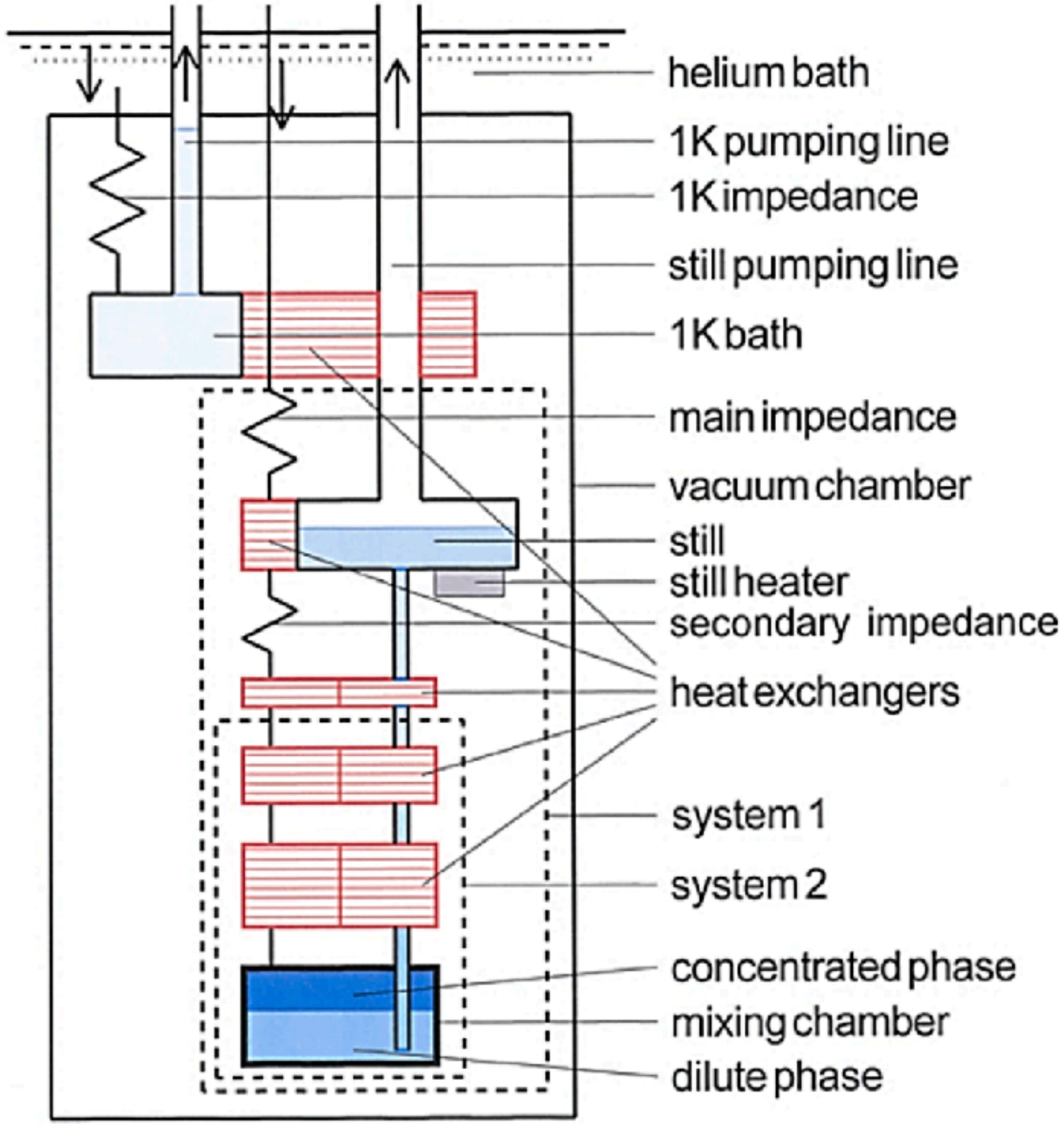
# Dilution Refrigeration

- $^3$He pre-cooled to 1K with $^4$He
- Pumped through various impedances and heat exchangers before $^4$He /$^3$He mixed
- Separates into concentrated phase (all $^3$He) and saturated dilute phase (6.6% $^3$He)
- Cooling caused by change in entropy as $^3$He moves from dilute phase to concentrated phase
- Can reach ~2 mK using this technique

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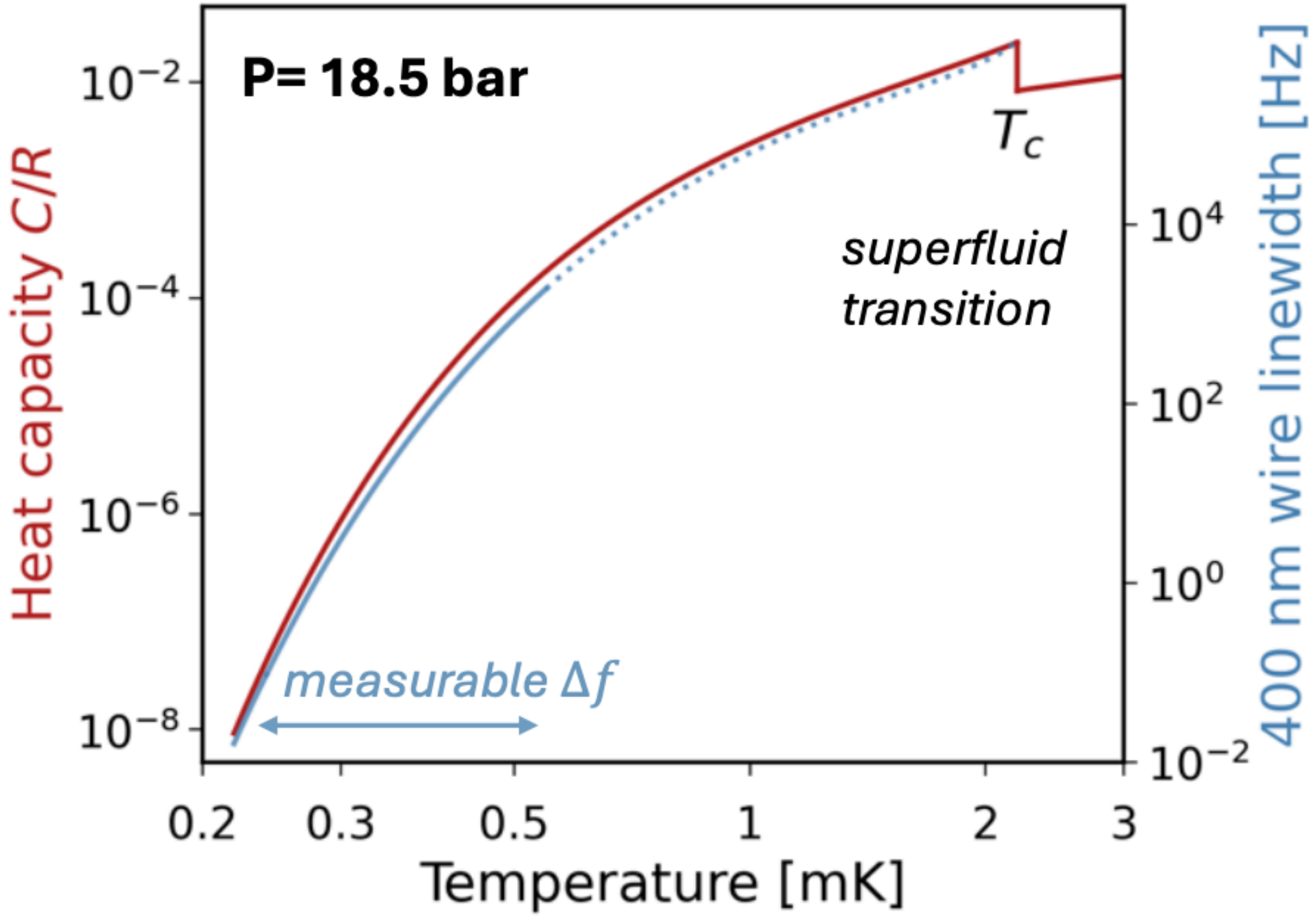
# Heat Capacity

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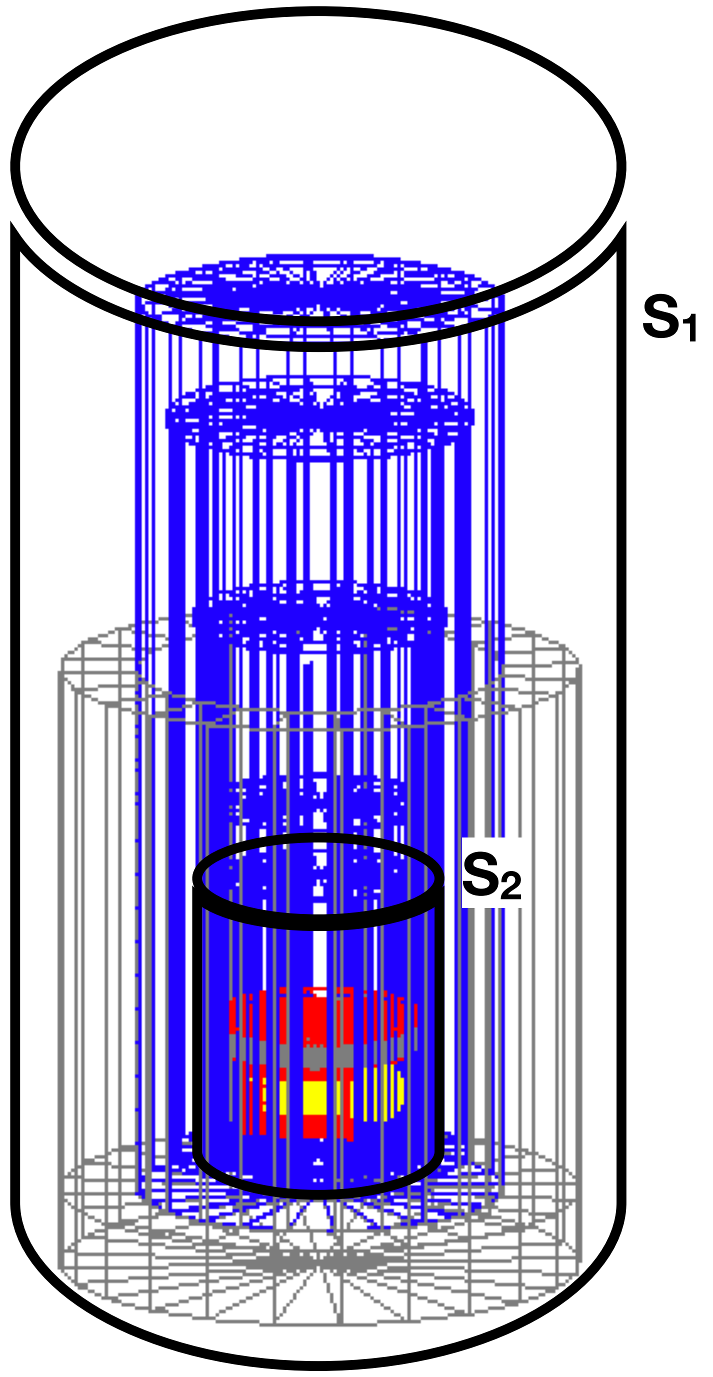
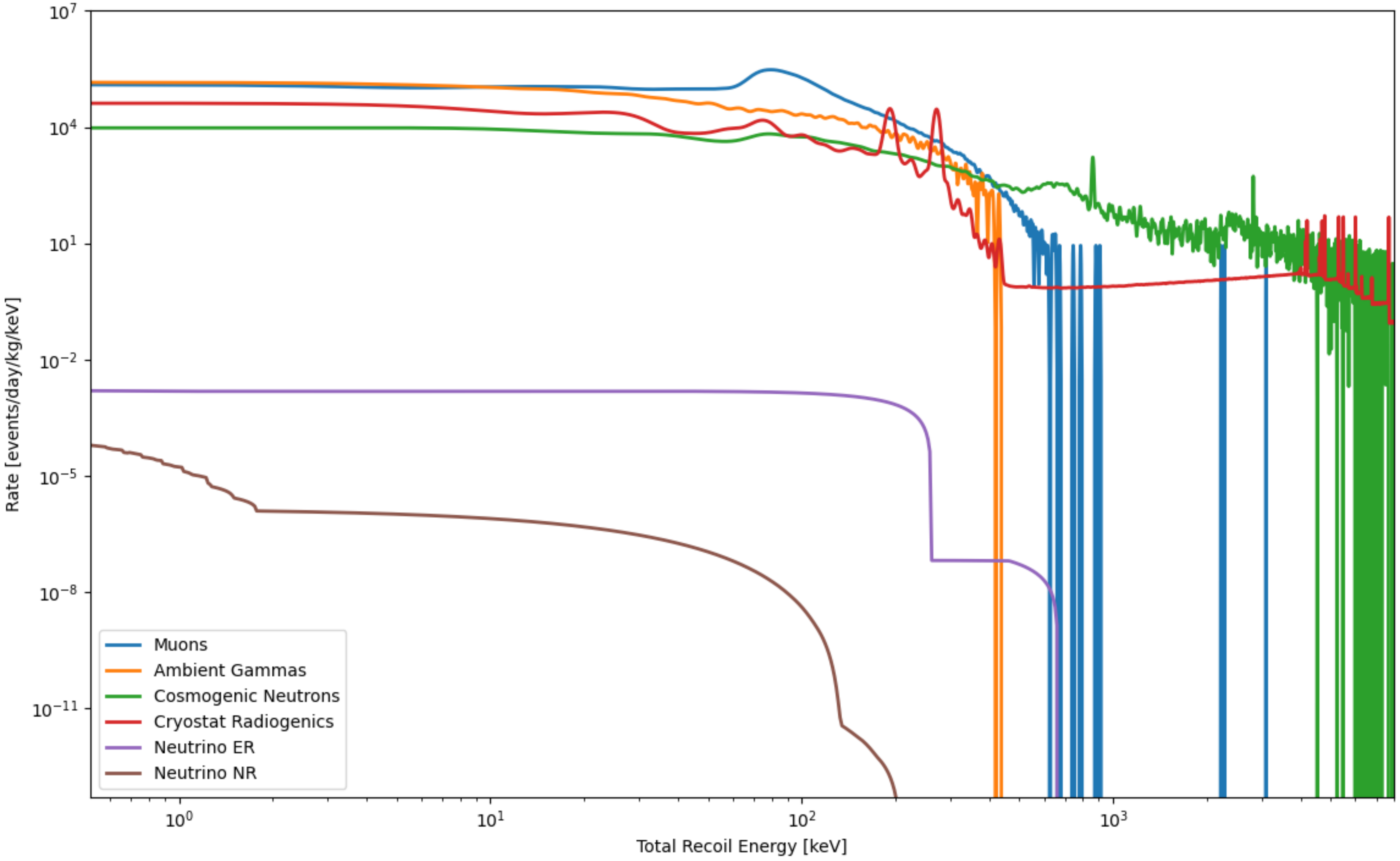
# Background Modelling

- Full Geant4 modelling of each cryostat using rethrow generator technique to improve statistics in small detector volume

https://doi.org/10.1140/epjc/s10052-023-11199-2

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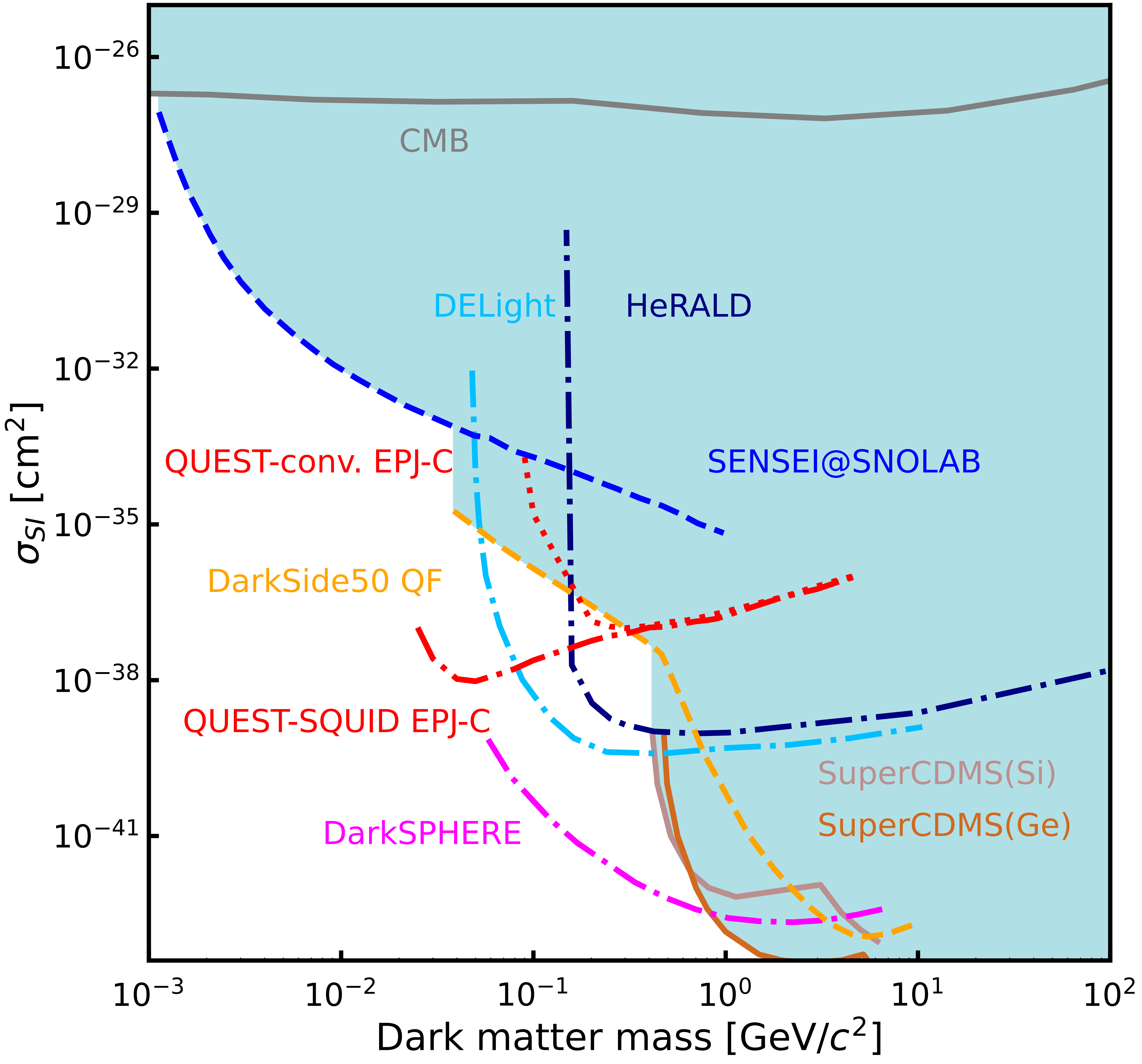
# Spin-Independent

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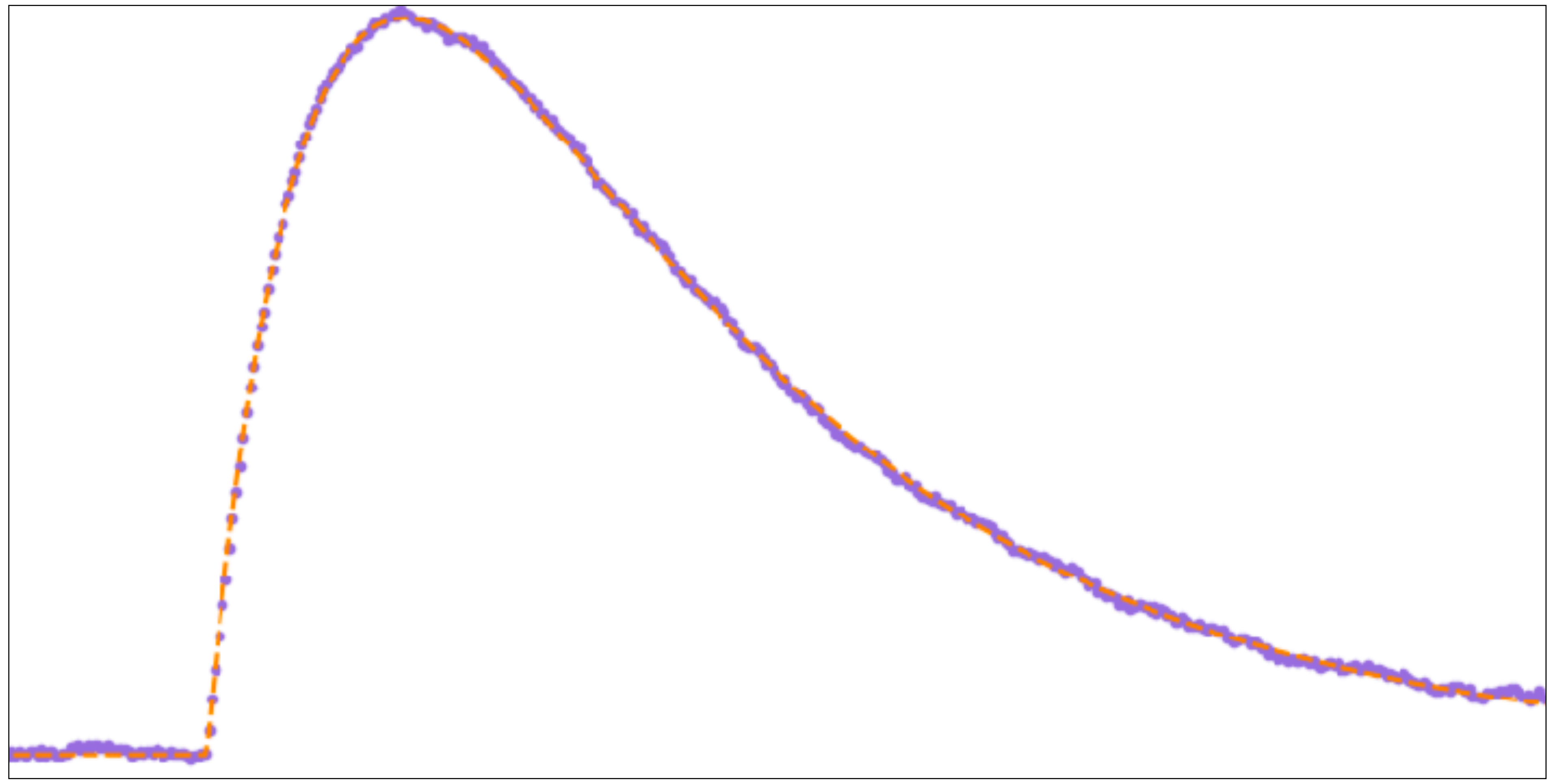
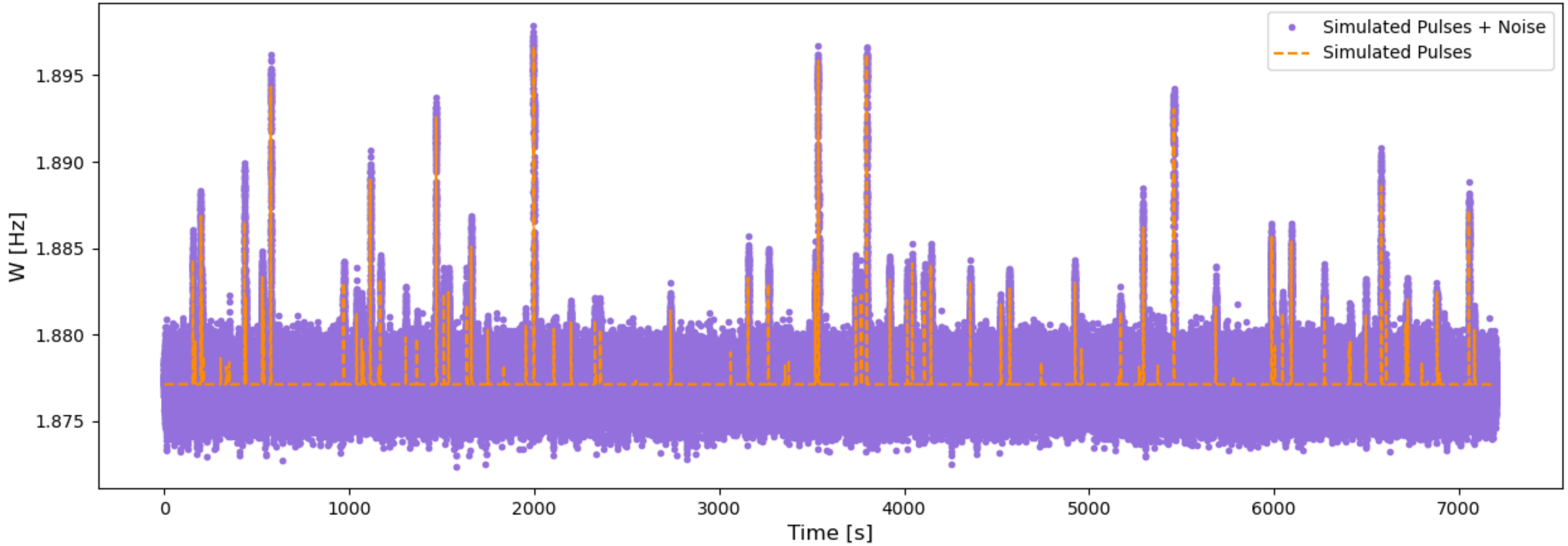
# Detector Response

$$\delta W = A\frac{\tau_b}{\tau_b - \tau_w}\left[e^{-(t-t_0)/\tau_b} - e^{-(t-t_0)/\tau_w}\right]\Theta(t - t_0)$$

https://doi.org/10.1016/j.nima.2007.01.180



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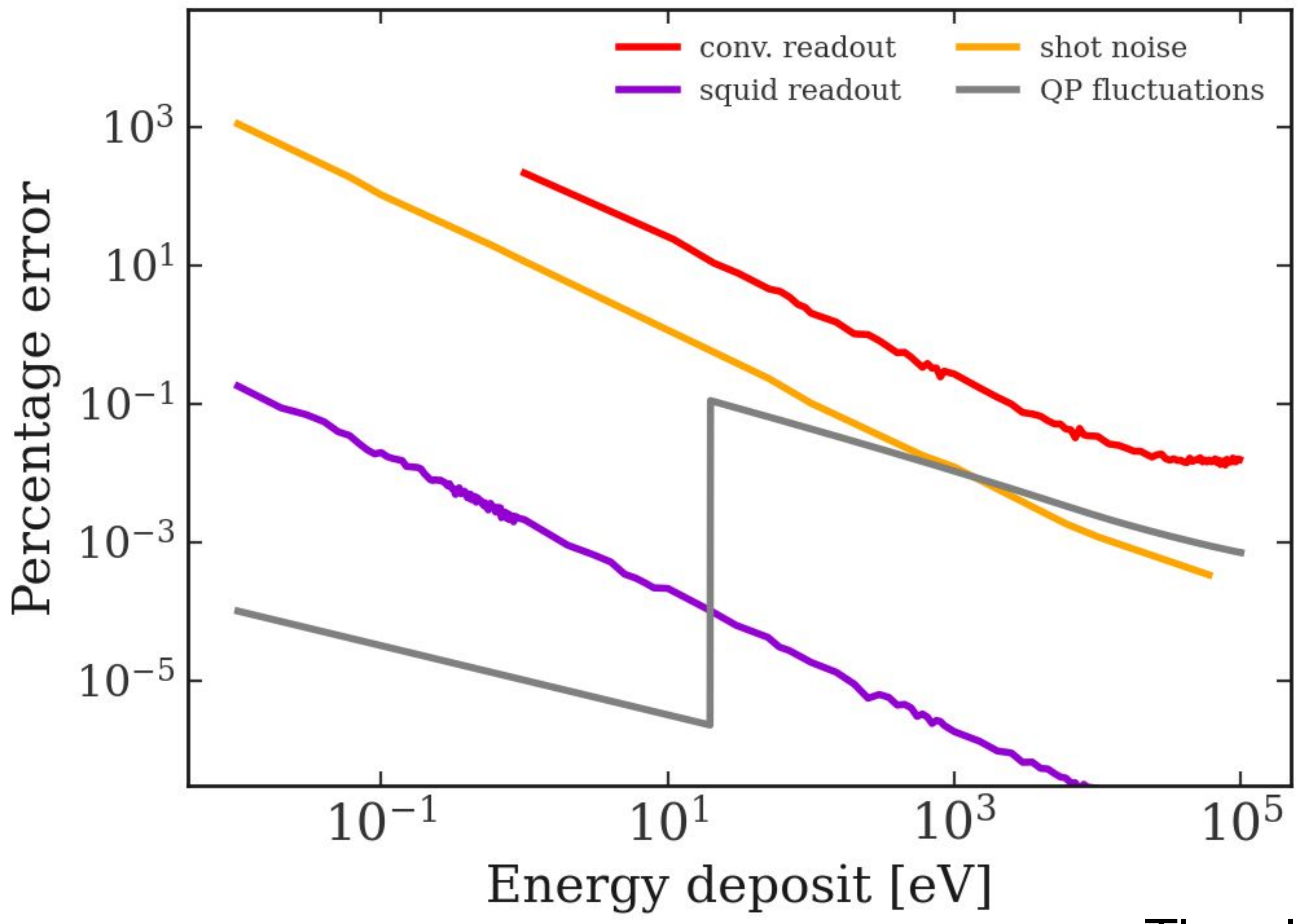
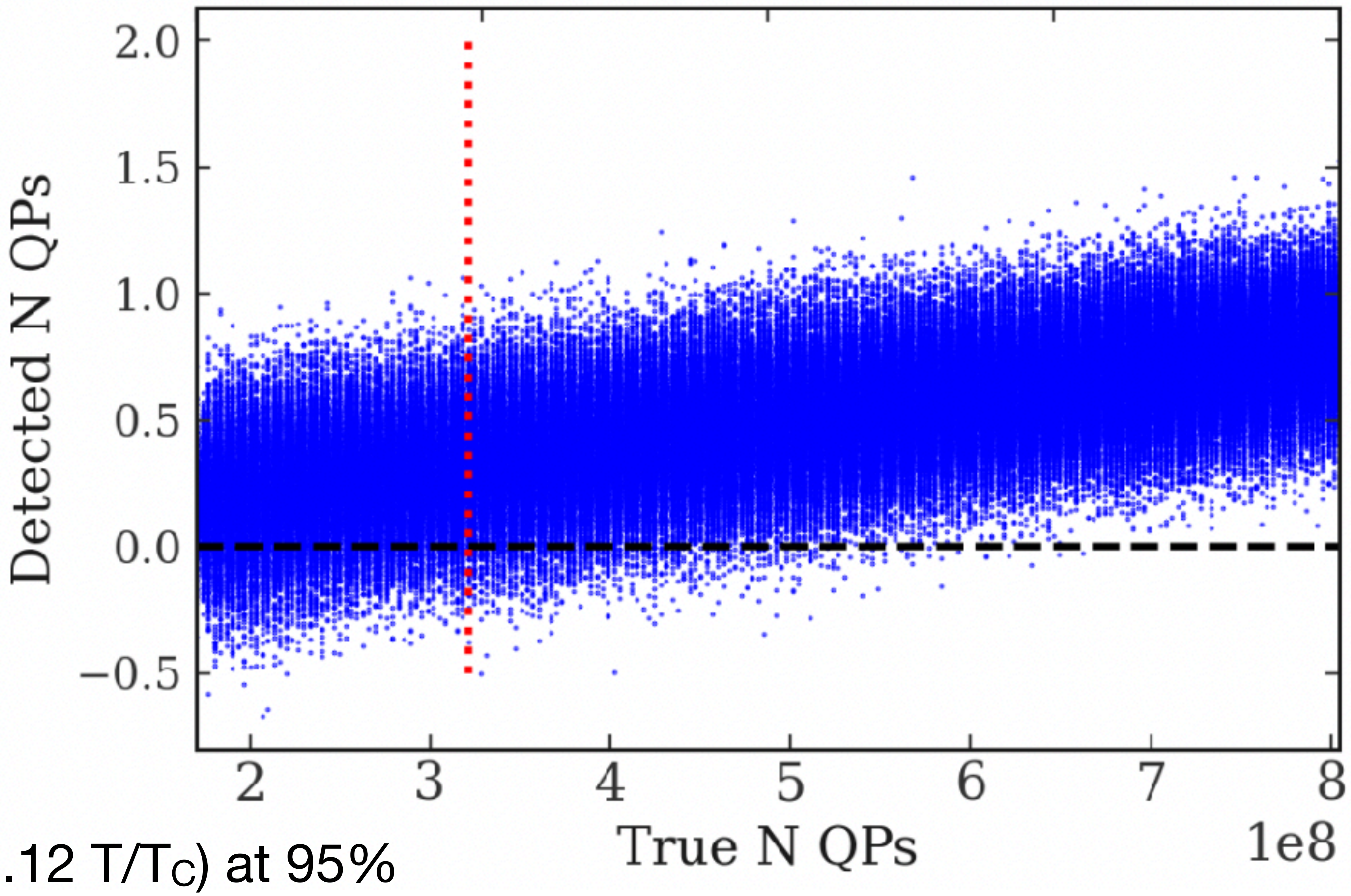
# Simulated Sensitivity Threshold

0.12 T/Tc




Smear 'true' energy




Threshold (0.12 $T/T_C$) at 95% confidence measured energy > 0

Conventional Readout: 39 eV

SQUID Readout: 0.71 eV