QUEST-DMC: superfluid helium-3 bolometry for low mass dark matter searches

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IoP Joint APP HEP
Annual Conference
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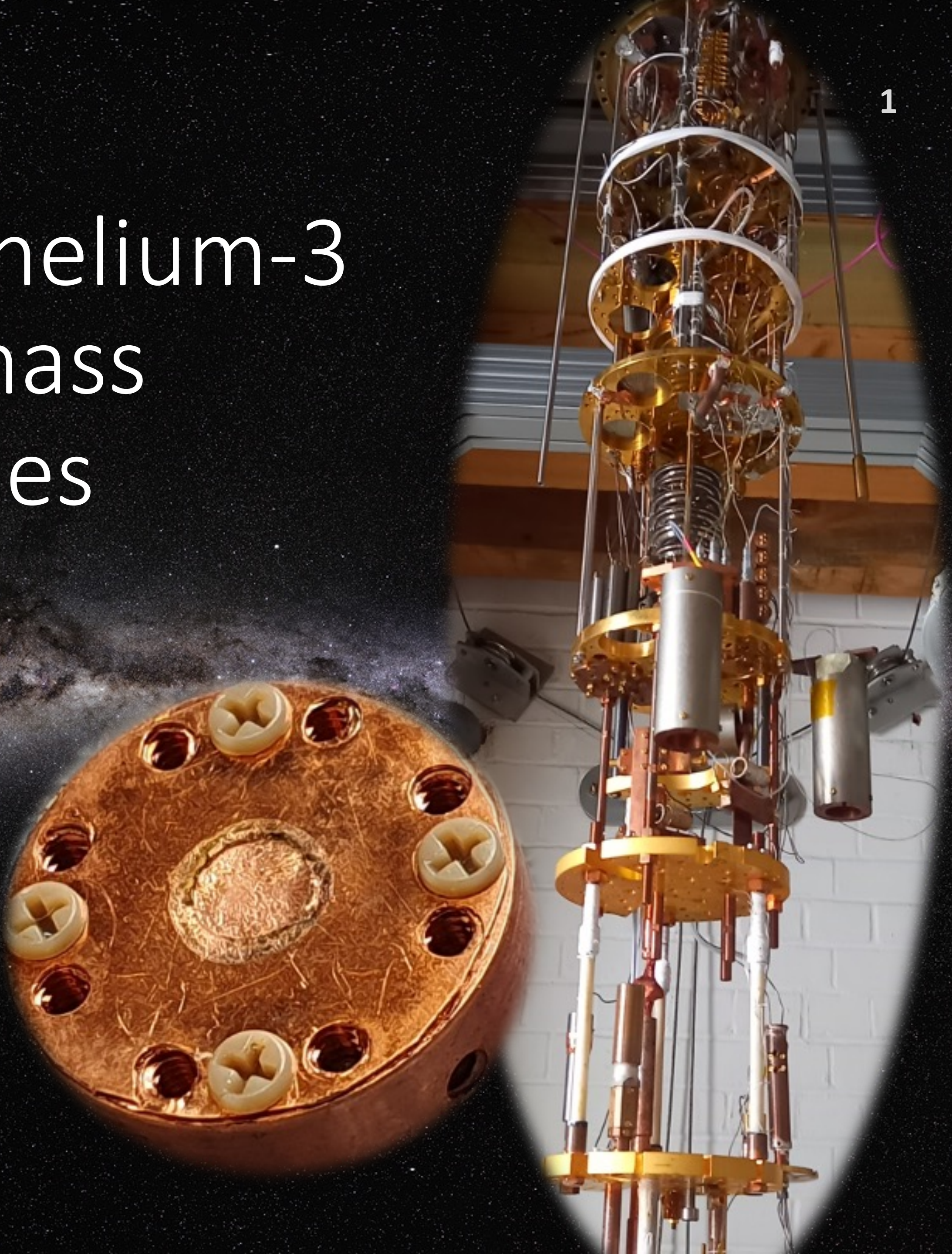
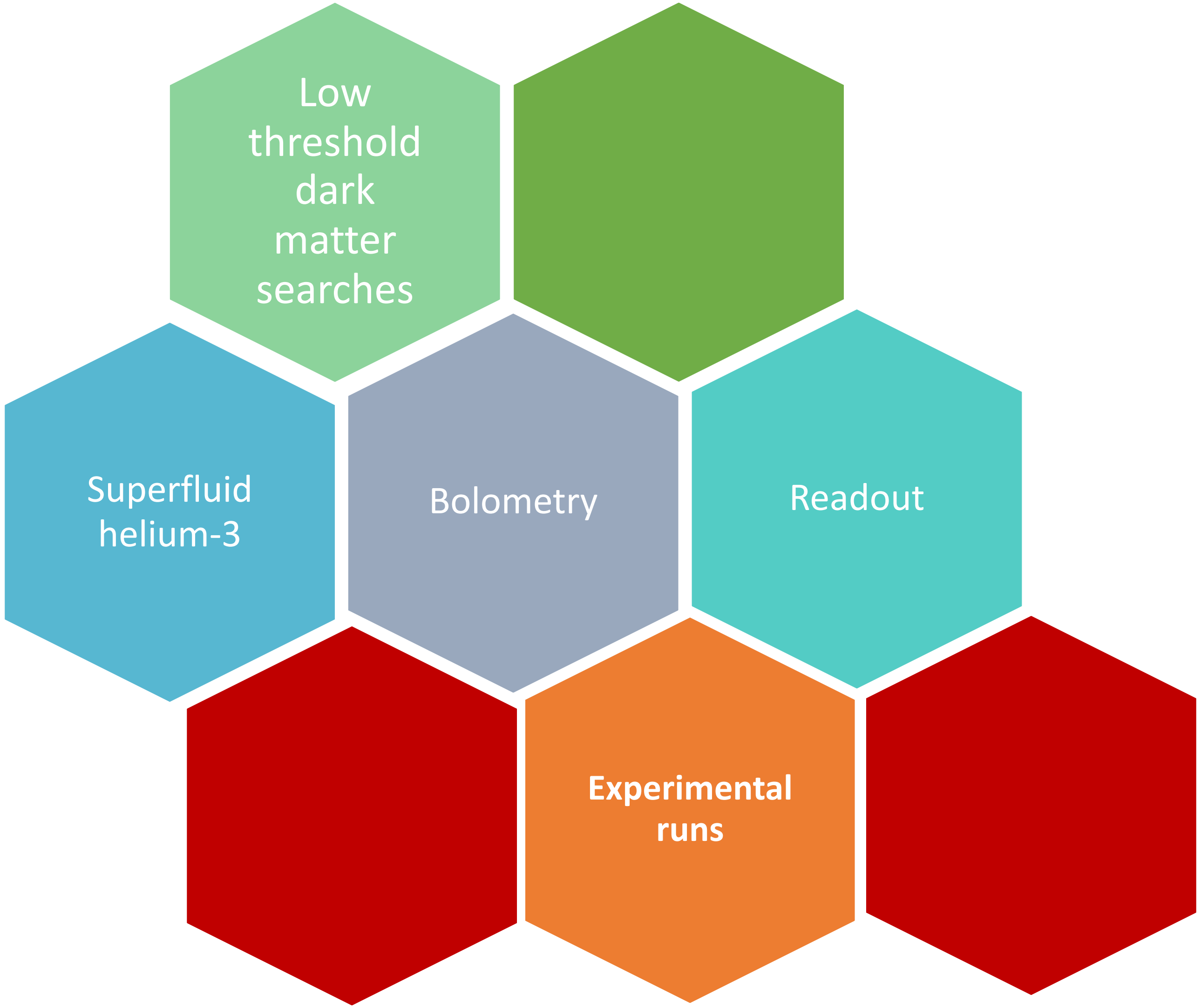


1. Motivation

2. Detector concept

3. Progress and outlook



Low threshold dark matter searches

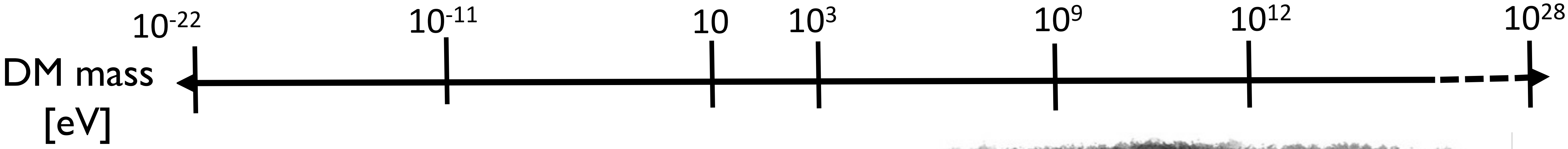
Superfluid helium-3

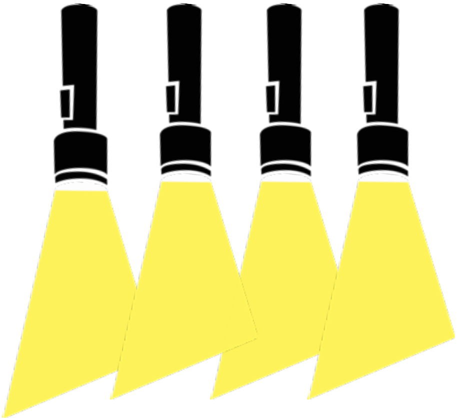
Bolometry

Readout

Experimental runs

Motivation





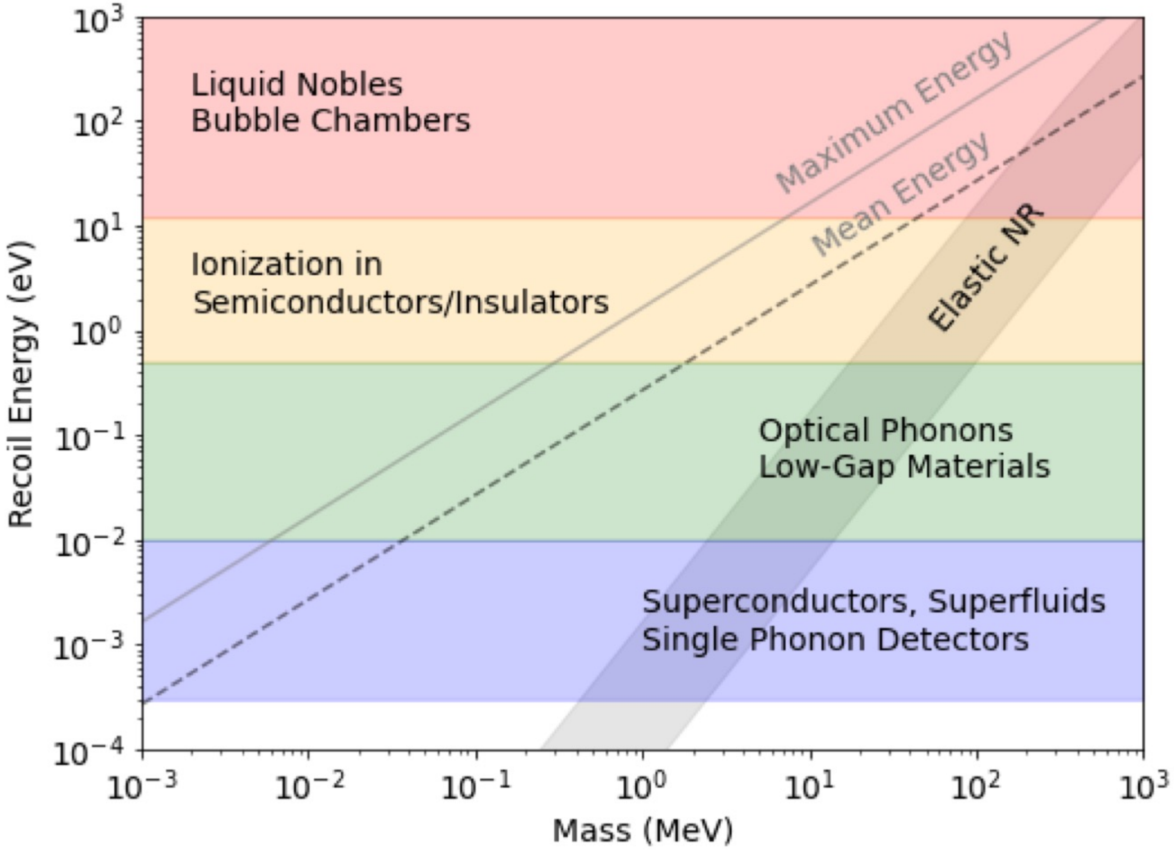
QUEST DMC

Low mass particle DM direct detection - very low energy threshold

Low energy threshold

For low mass dark matter direct detection mean recoil energy: $E_R[\text{eV}] \sim 30\left(m_\chi[\text{MeV}]\right)^2$

Fundamental threshold limit from quanta production

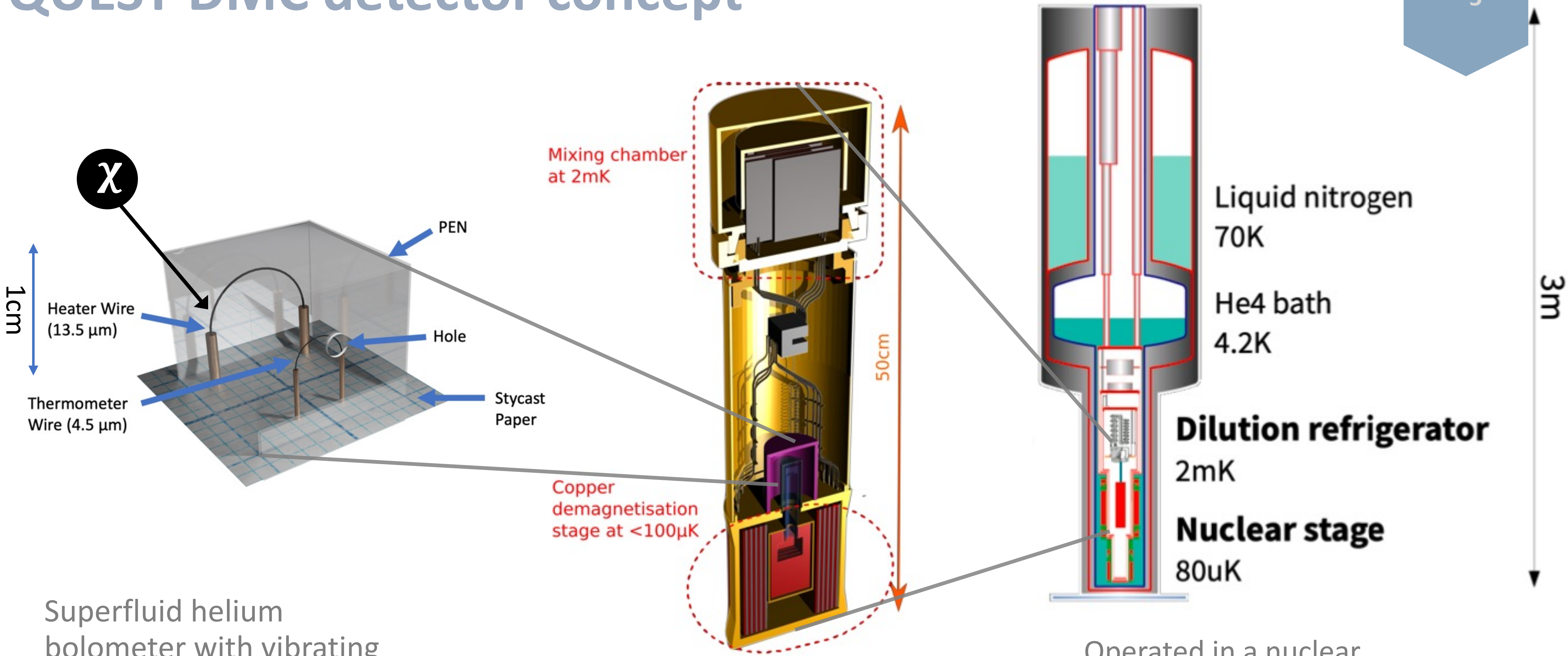


Snowmass report 2022

Superfluid helium-3 target

- Cooper pairing of He atoms - superfluid <2mK
- Energy **$\Delta \sim 10^{-7}$eV** required to break Cooper pairs and give single **quasiparticles (QPs)**
- Unpaired nucleon: Spin dependent dark matter – nucleon interaction

QUEST-DMC detector concept



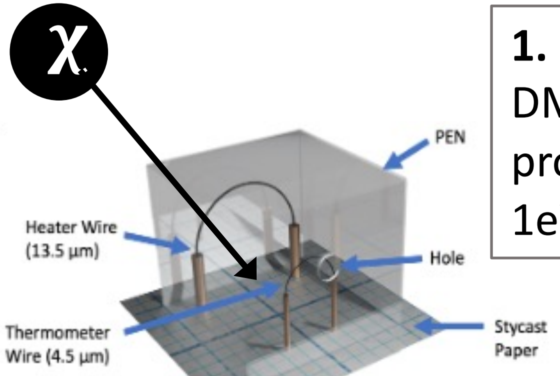
Superfluid helium bolometer with vibrating nanowire resonators

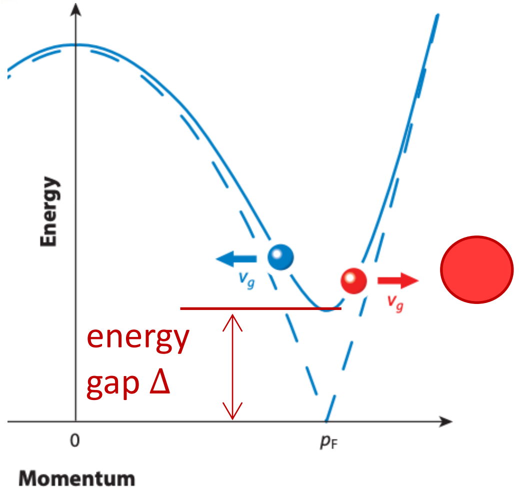
Operated in a nuclear demagnetisation cryostat below 1mK

1. Energy deposit

DM – helium scattering produces quasiparticles (QPs)

1eV → 10^7 quanta

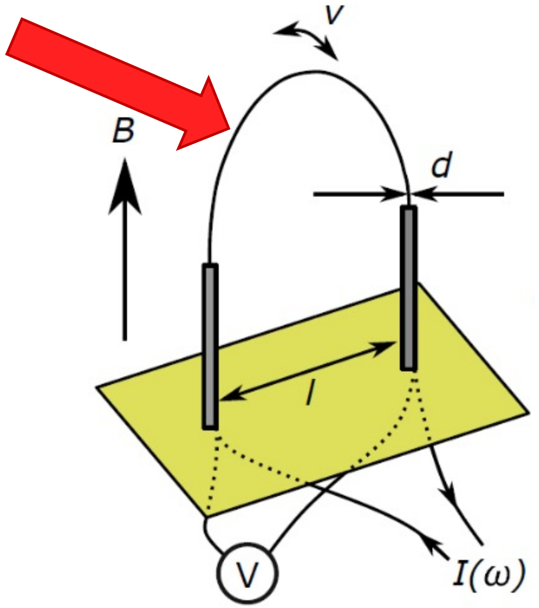




2. Ballistic propagation

QP collisions with nanowire exert damping force

Andreev reflection in superfluid increases damping by ~10^3



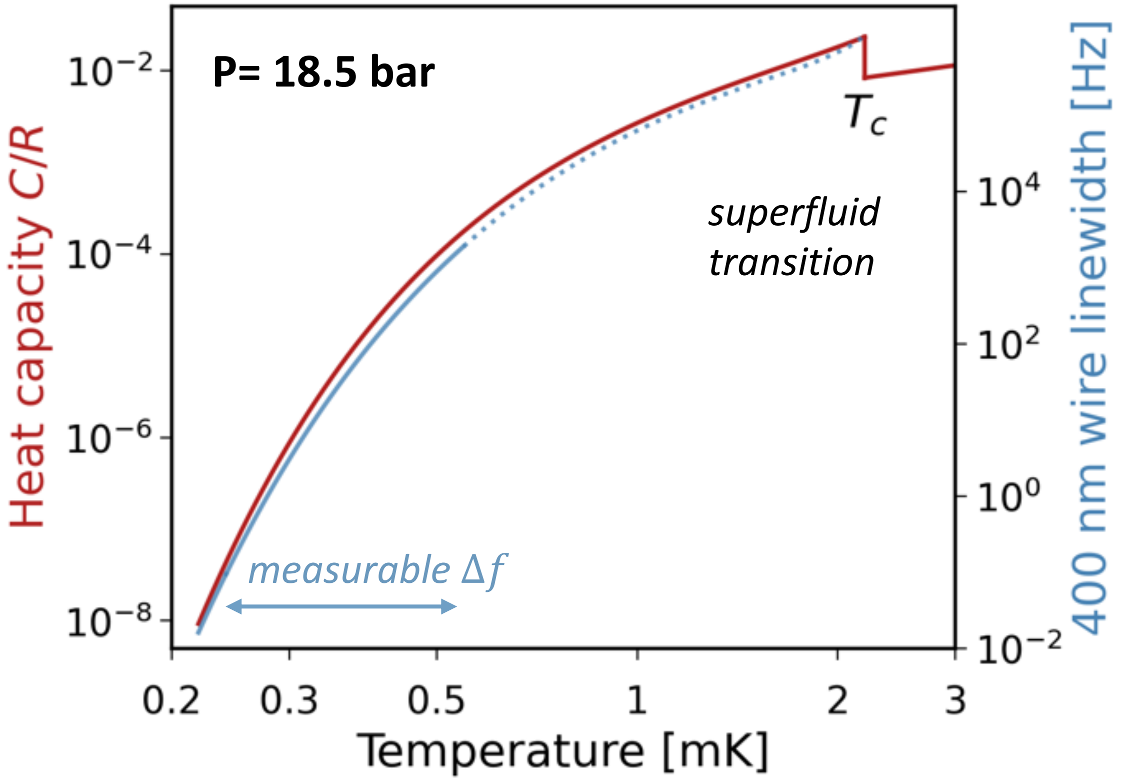
3. Bolometry

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

Achieving low threshold

Ultra-low temperature operation:

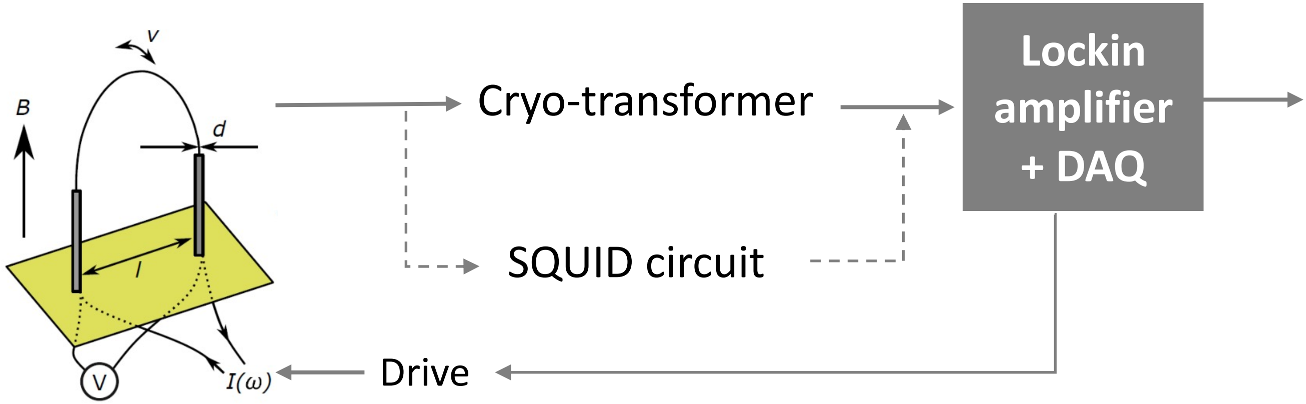
- Small energy → small width change
- Linewidth follows heat capacity
- Temperature determines energy threshold



Low noise readout:

- Noise in voltage measurement determines energy threshold
- **Conventional readout:** passive cryo-transformer
- **SQUID** preamplifier, higher gain and lower noise

- Simulated energy thresholds: 39 eV with conventional readout, 0.71 eV with SQUID readout
  QUEST-DMC:*Eur. Phys. J. C* **84**, 248 (2024)



Cryo-transformer

SQUID circuit

Lockin amplifier + DAQ

Drive

Experiment Runs

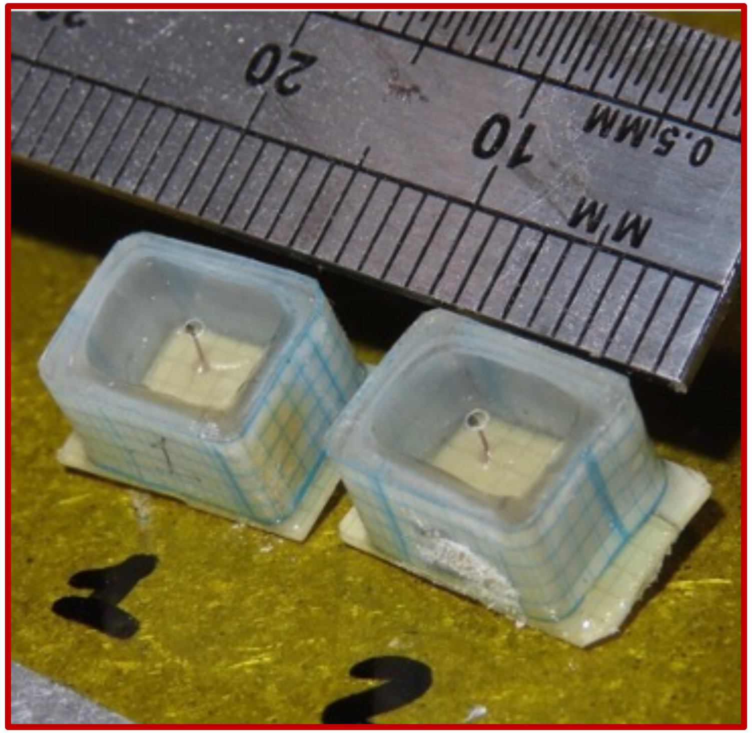
Low threshold dark matter searches

Superfluid helium-3

Bolometry

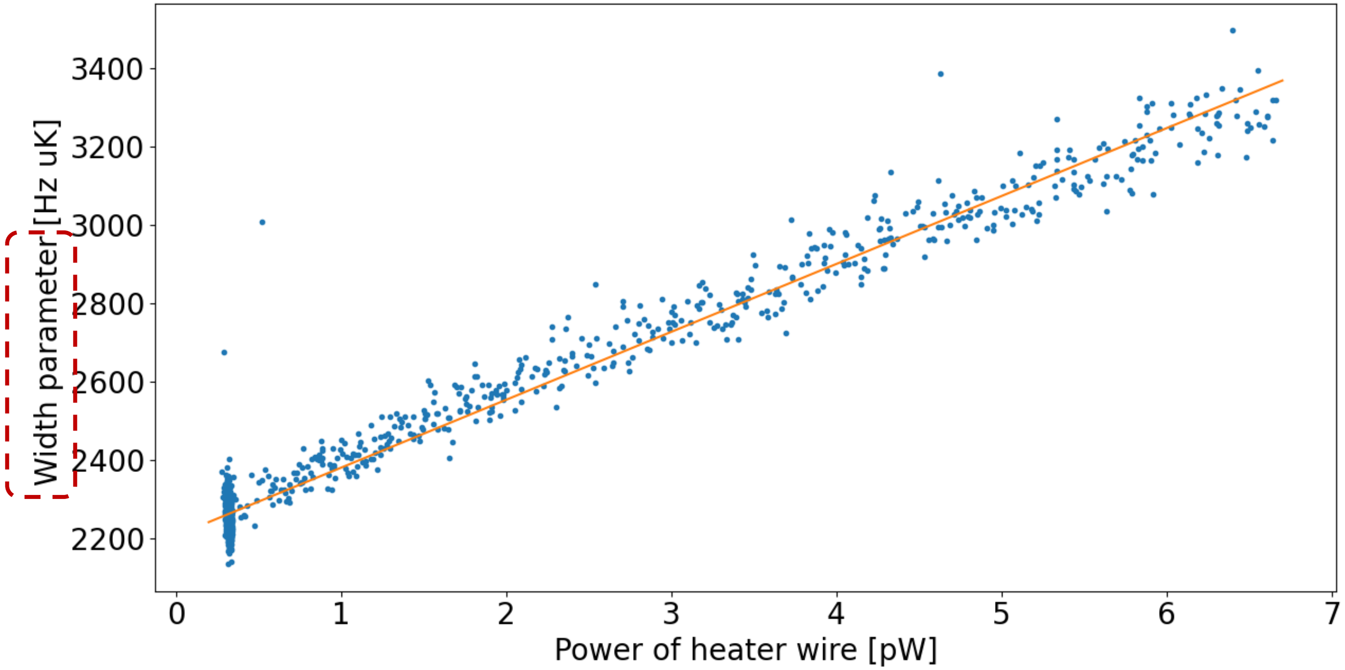
Readout

Lancaster Run (2023)



Stycast bolometers with (4.5μm) thermometer wire and (13.5μm) heater wire, **conventional readout**

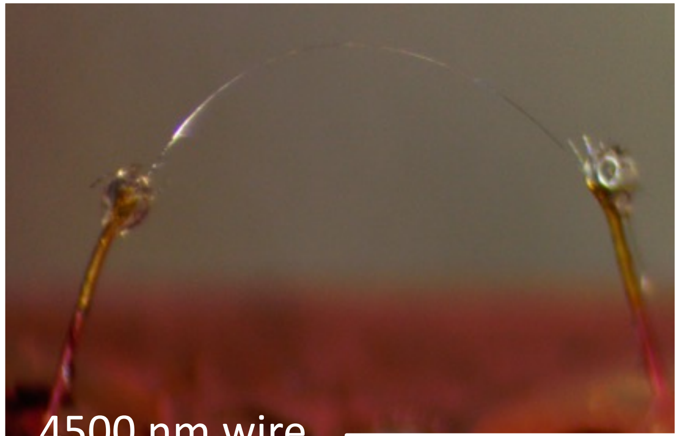
Calibration: change in width of thermometer wire vs (known) injected heater power to find calibration coefficient: $P = K(\Delta f - \Delta f_0)T$

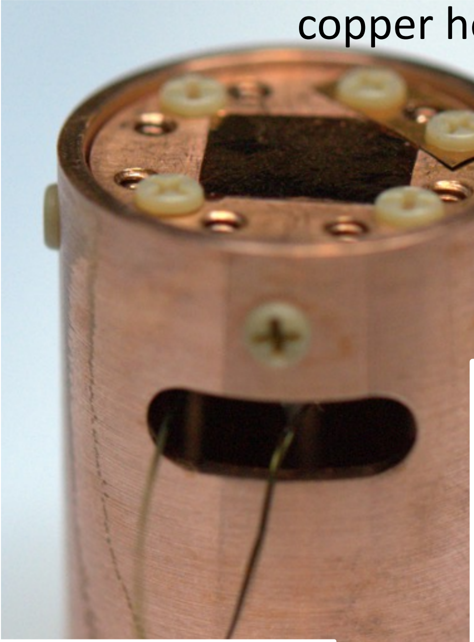


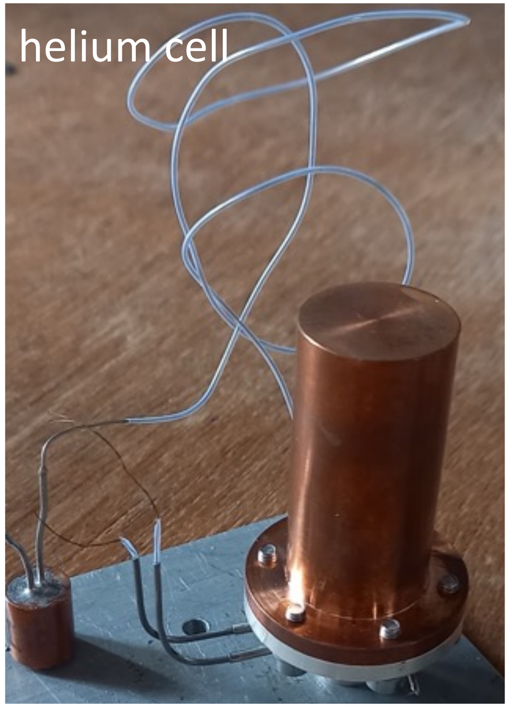
Ran for 8 months achieving temperatures down to 0.15mK

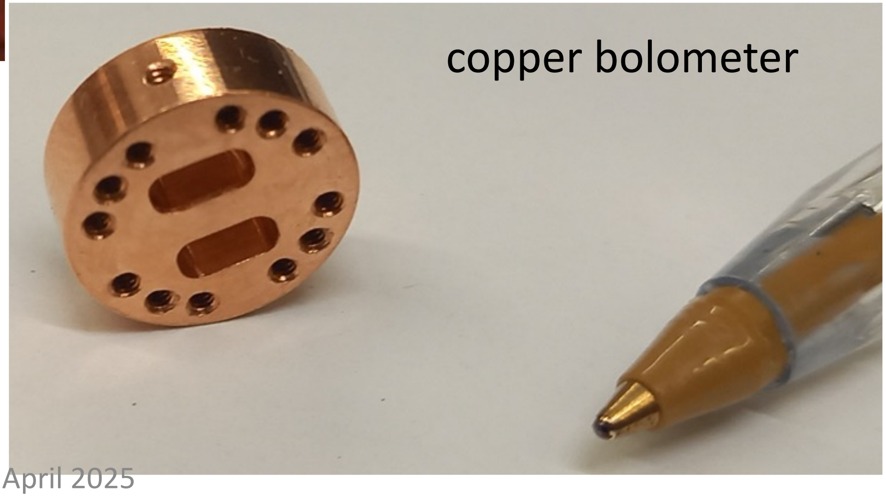
RHUL SQUID readout tests

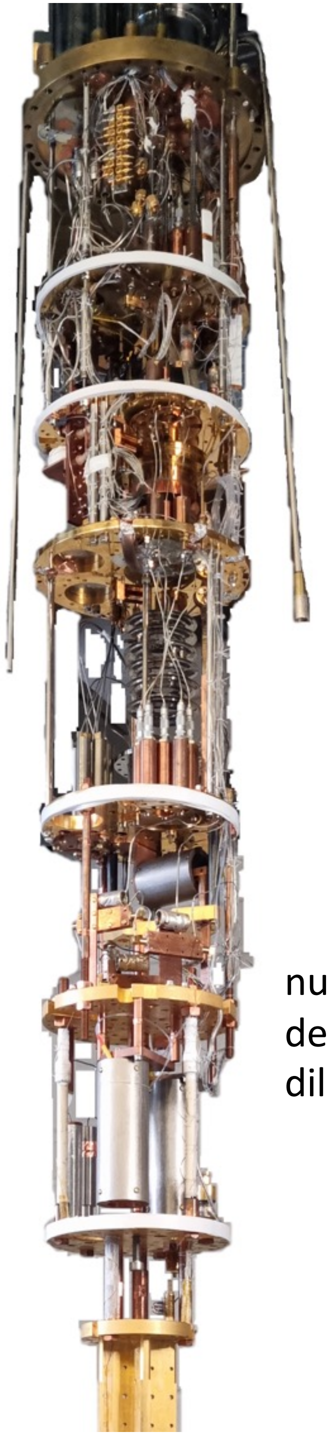
June-Dec. 2024: copper cell containing 400 nm and 4500 nm operated ~0.3mK


4500 nm wire


copper holder

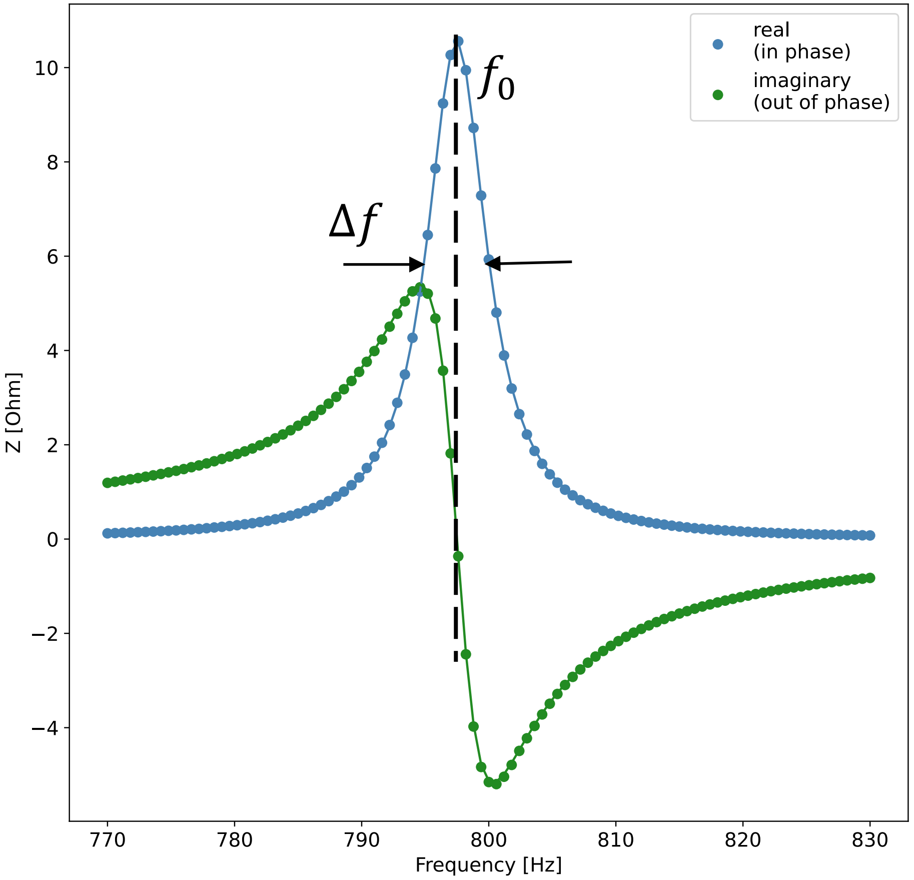

helium cell


copper bolometer


nuclear demagnetisation dilution fridge

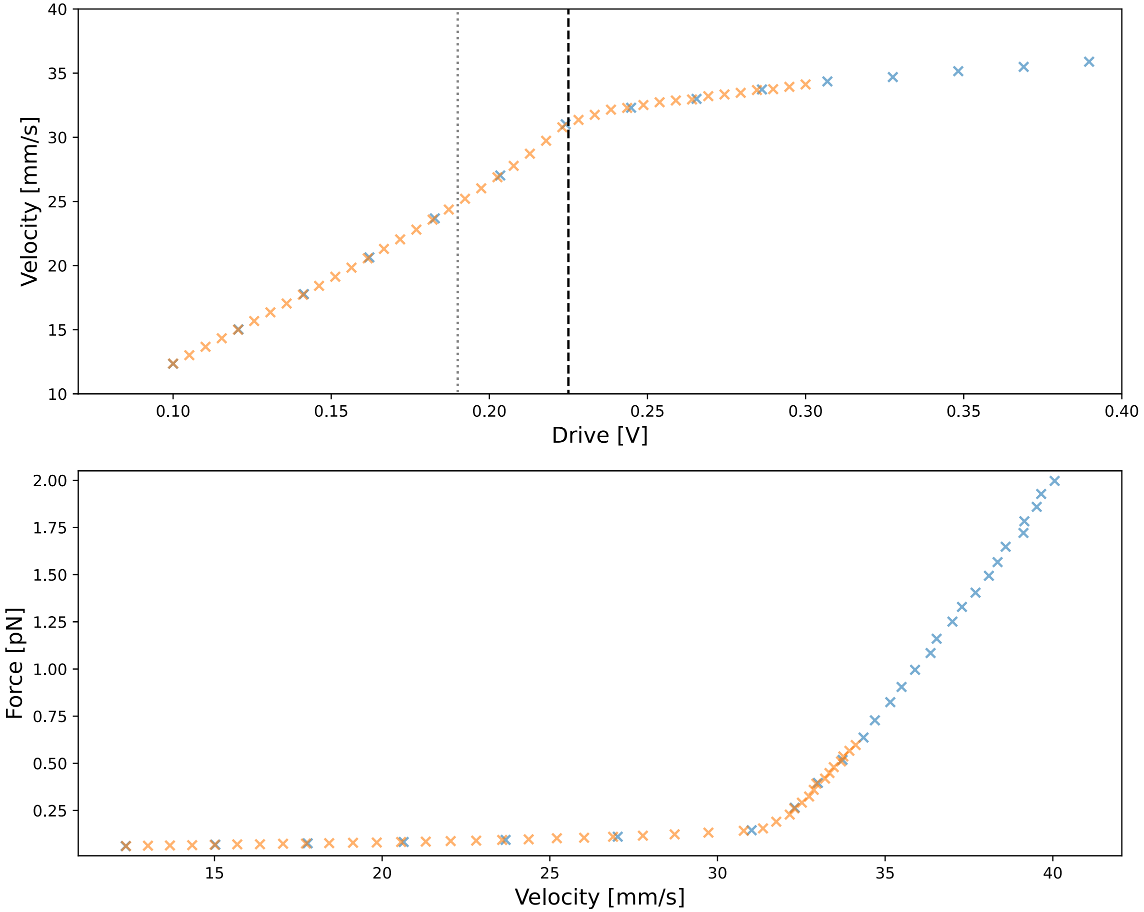
Resonator characterisation

Frequency sweep: resonant frequency and width from Lorentzian fit.

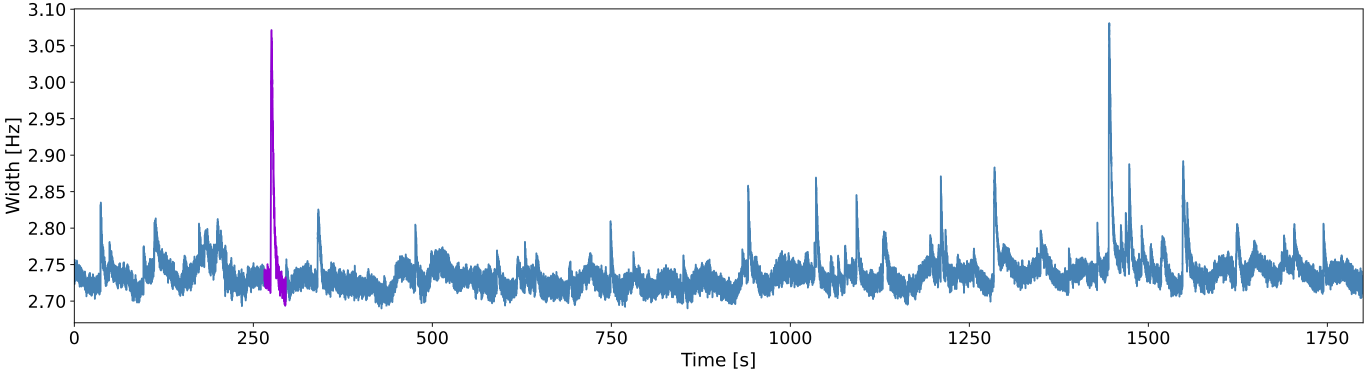


Drive amplitude sweep, operating regimes:

- Linear – damping force ∝ velocity (<5 mm/s)
- Pair breaking – quasiparticle generation (> 33 mm/s)
- Optimise SNR – operate at 19 mm/s

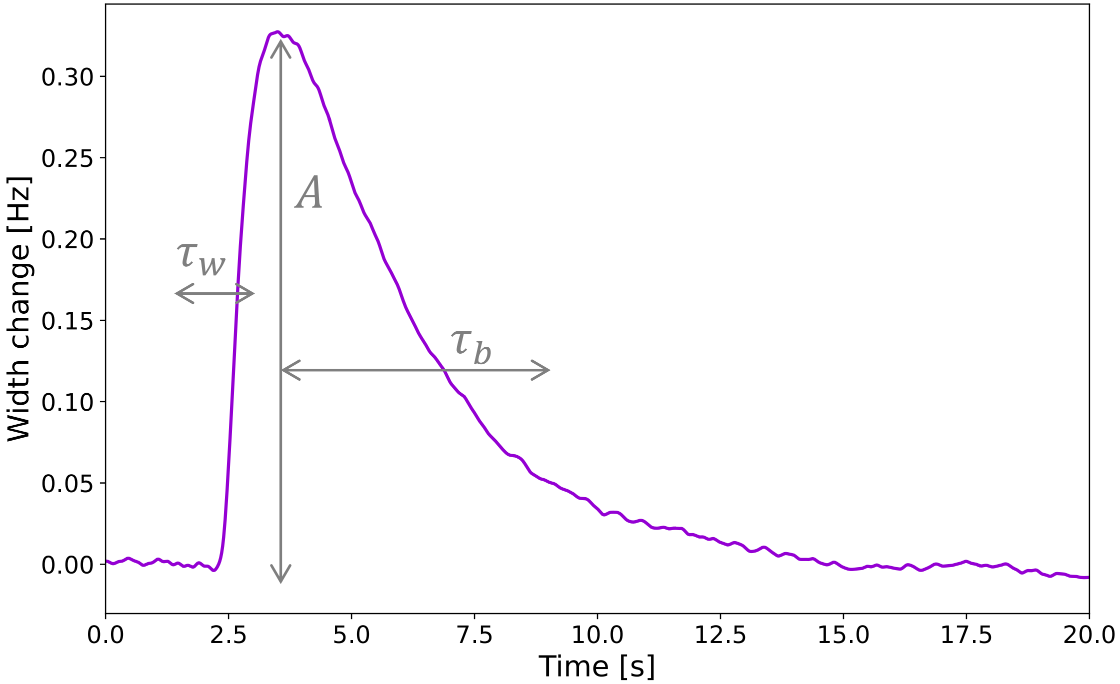


Bolometer tracking data



Response tracking – drive on resonance

- Measure induced voltage across wire, V_0
- For fixed drive current $\Delta f \times V_0$ = const.
- Convert V_0 to width change
- Apply pulse finding and shape discrimination
- Convert width change to energy

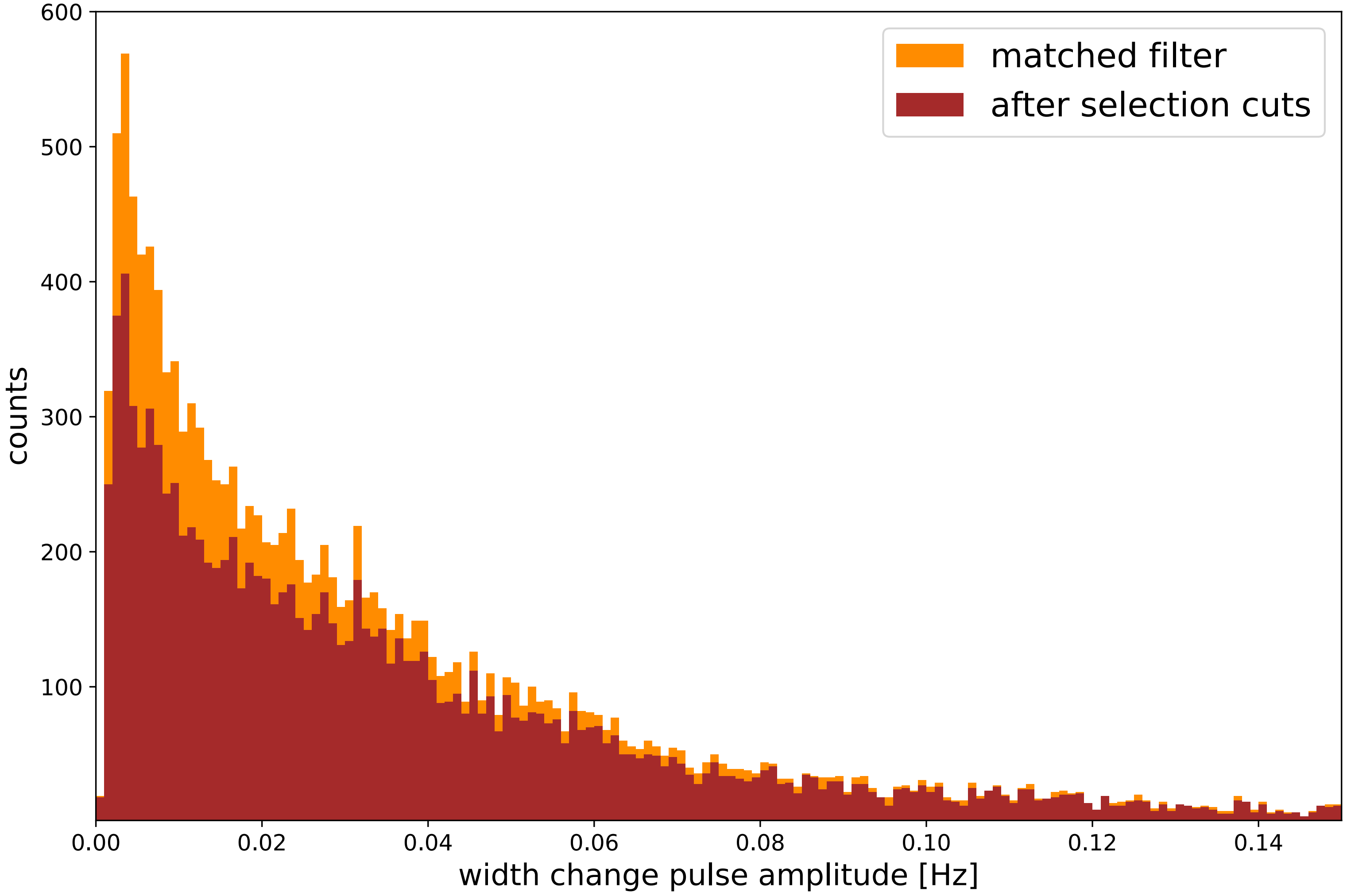


Characteristic pulse shape, three parameters:

- Rise time, τ_w - nanowire
- Decay time, τ_b - bolometer
- Amplitude, A – heating event (energy)

Pulse analysis

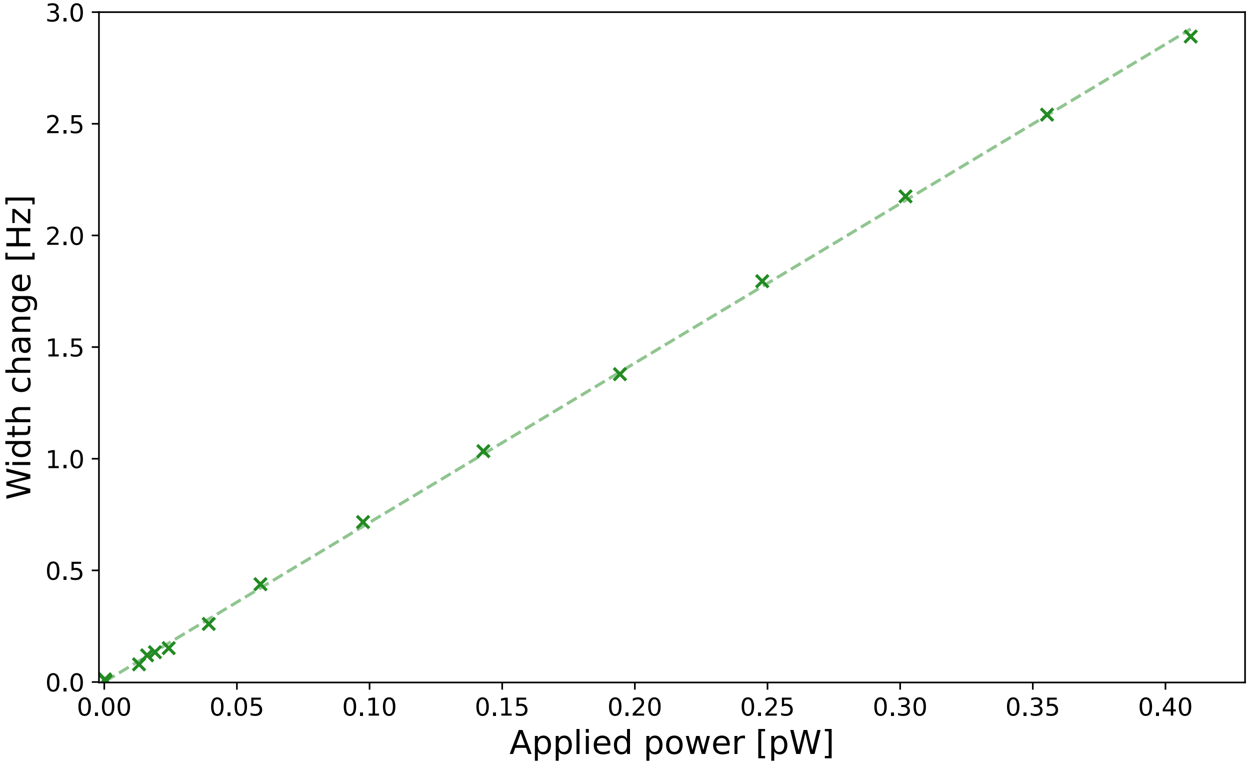
- Pulse finding and selection using matched filter.
- Pulse rejection - shape information.
- Measured amplitude histogram for subset of tracking data.



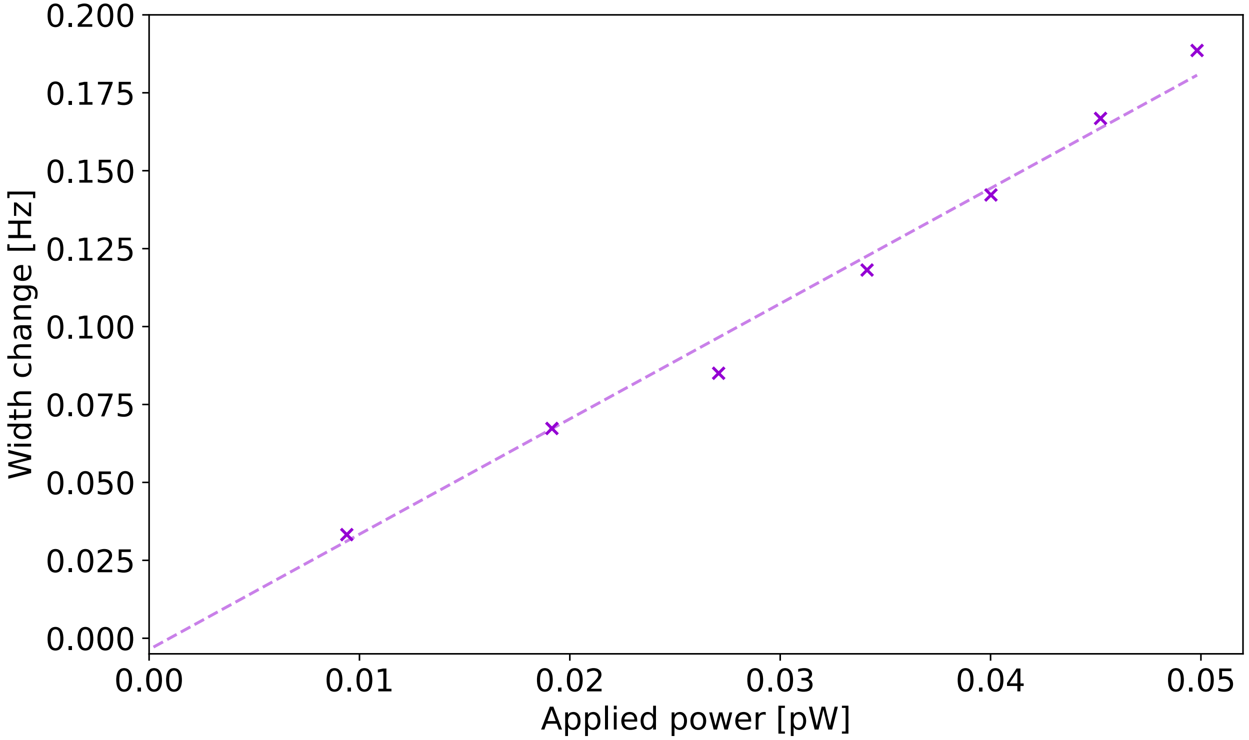
Heater wire calibration

With SQUID readout scheme can drive both wires hard enough to generate quasiparticles and detect proportional response with other wire

A) 400 nm detector (4500 nm heater)



B) 4500 nm detector (400 nm heater)

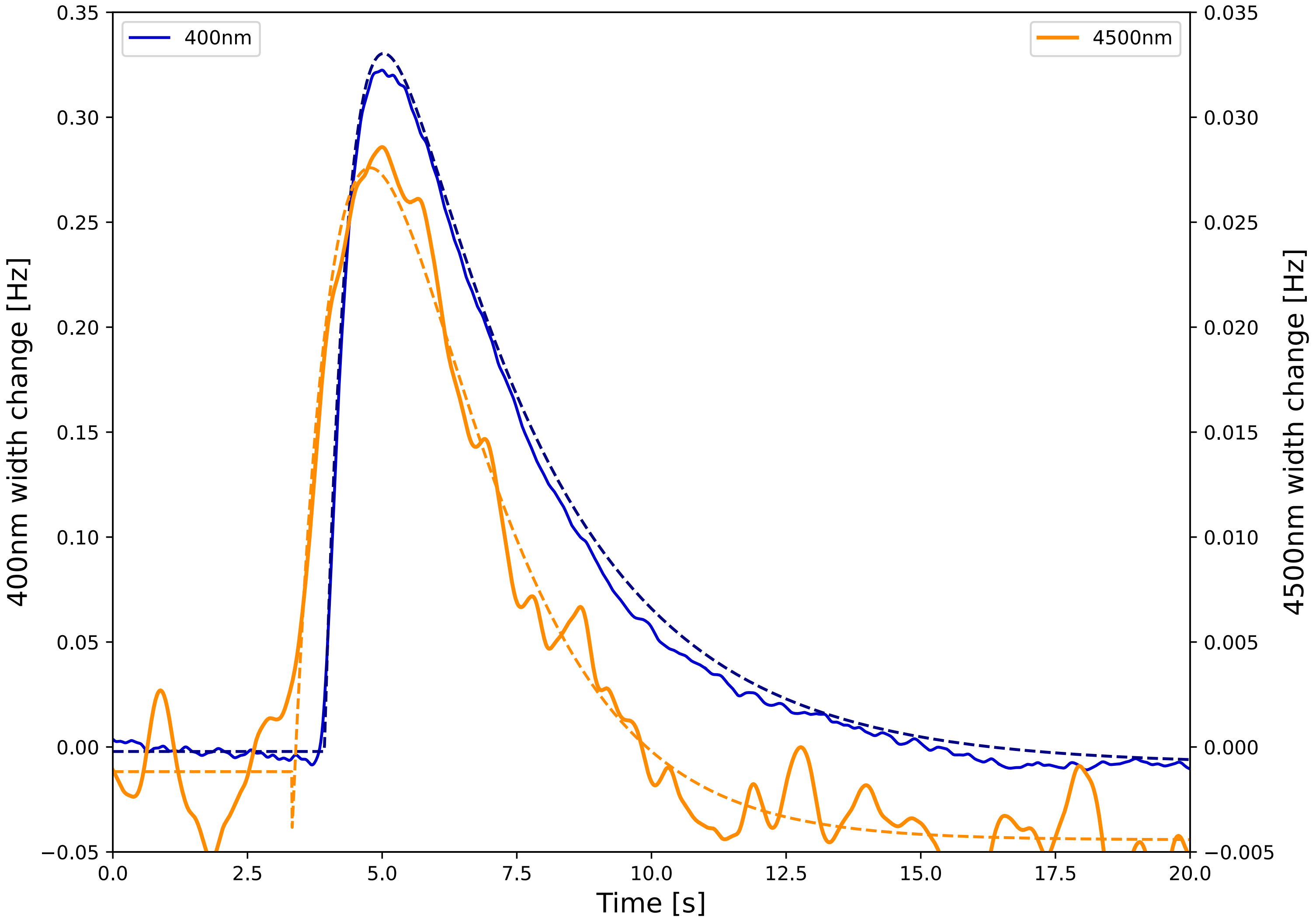


10 fW heat pulses!

Coincident pulses

Tracking on both wires – coincident bolometer pulses.

Factor ~10 difference in width change and slower rise time – expected for different wire diameters.

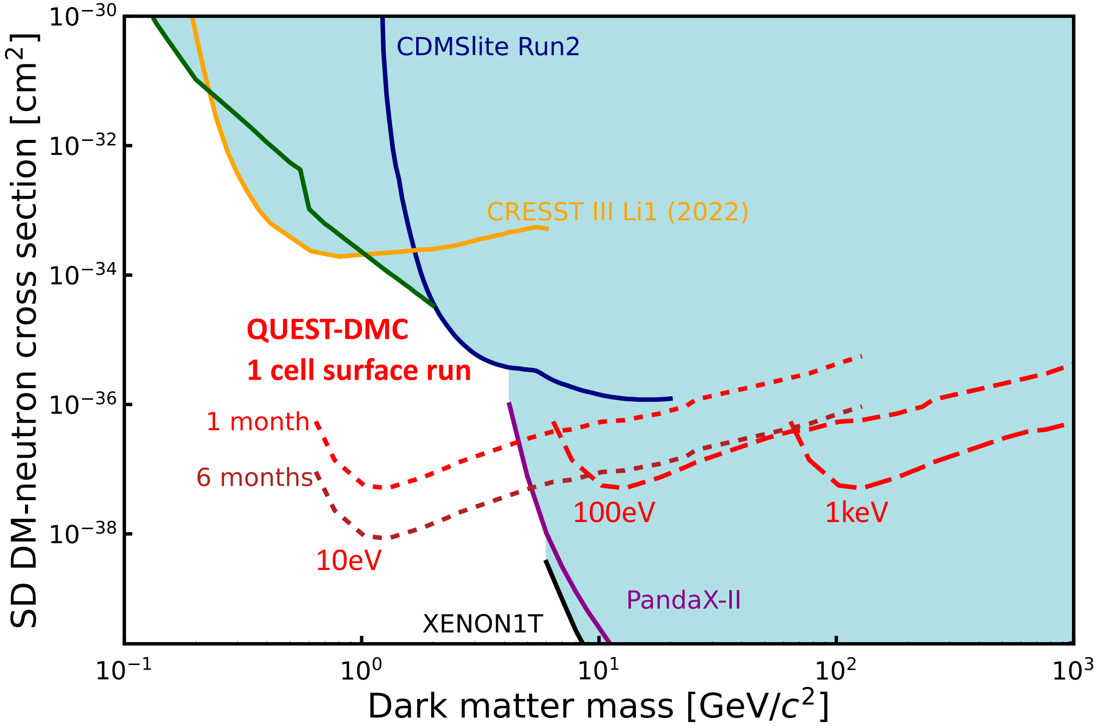


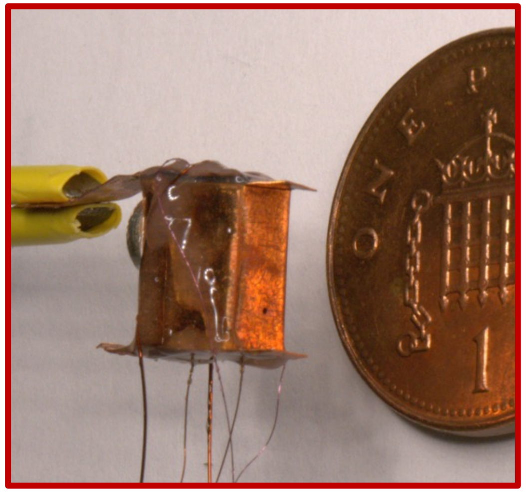
Summary

1. Superfluid helium-3 ultra low threshold potential, **10^{-7} eV gap**

2. Proof of principle bolometer operation and data analysis

3. Experimental runs in progress:
   - Lancaster: folder copper cell, SQUID readout – *main DM search run*
   - RHUL: SQUID readout noise optimisation ^{55}Fe source calibration





QUEST DMC

See posters:

Backgrounds in the QUEST-DMC Experiment (R. Smith)

Sensitivity Ceilings for the QUEST-DMC Detector (N. Darvishi)

Recent paper:

Dark Matter Attenuation Effects: Sensitivity Ceilings for Spin-Dependent and Spin-Independent Interactions [arxiv:2502.10251]

Backup

QUEST-DMC

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lancaster University

University of Sussex

UNIVERSITY OF OXFORD

UNIVERSITY OF LIVERPOOL

Science & Technology Facilities Council

EXPERIMENTAL

- Dr Samuli Autti
- Prof. Andrew Casey
- Dr. Paolo Franchini
- Prof. Richard Haley
- Dr. Petri Heikkinen
- Dr Sergey Kafanov
- Dr Ashlea Kemp
- Dr. Elizabeth Leason
- Dr. Lev Levitin
- Prof. Jocelyn Monroe
- Dr Theo Noble
- Dr Jonathan Prance
- Dr Xavier Rojas
- Prof. John Saunders
- Robert Smith, Lizzie Blooomfield
- Dr Michael Thompson
- Dr Viktor Tsepelin
- Dr Dmitry Zmeev
- Dr Vladislav Zavyalov
- Tineke Salmon, Luke Whitehead

THEORY

- Dr Neda Darvishi
- Prof. Mark Hindmarsh
- Prof. Stephan Huber
- Dr Asier Lopez-Eiguren
- Prof. John March-Russell
- Dr Juri Smirnov
- Prof. Stephen West
- Dr. Quang Zhang

QUEST DMC

UKRI Engineering and Physical Sciences Research Council

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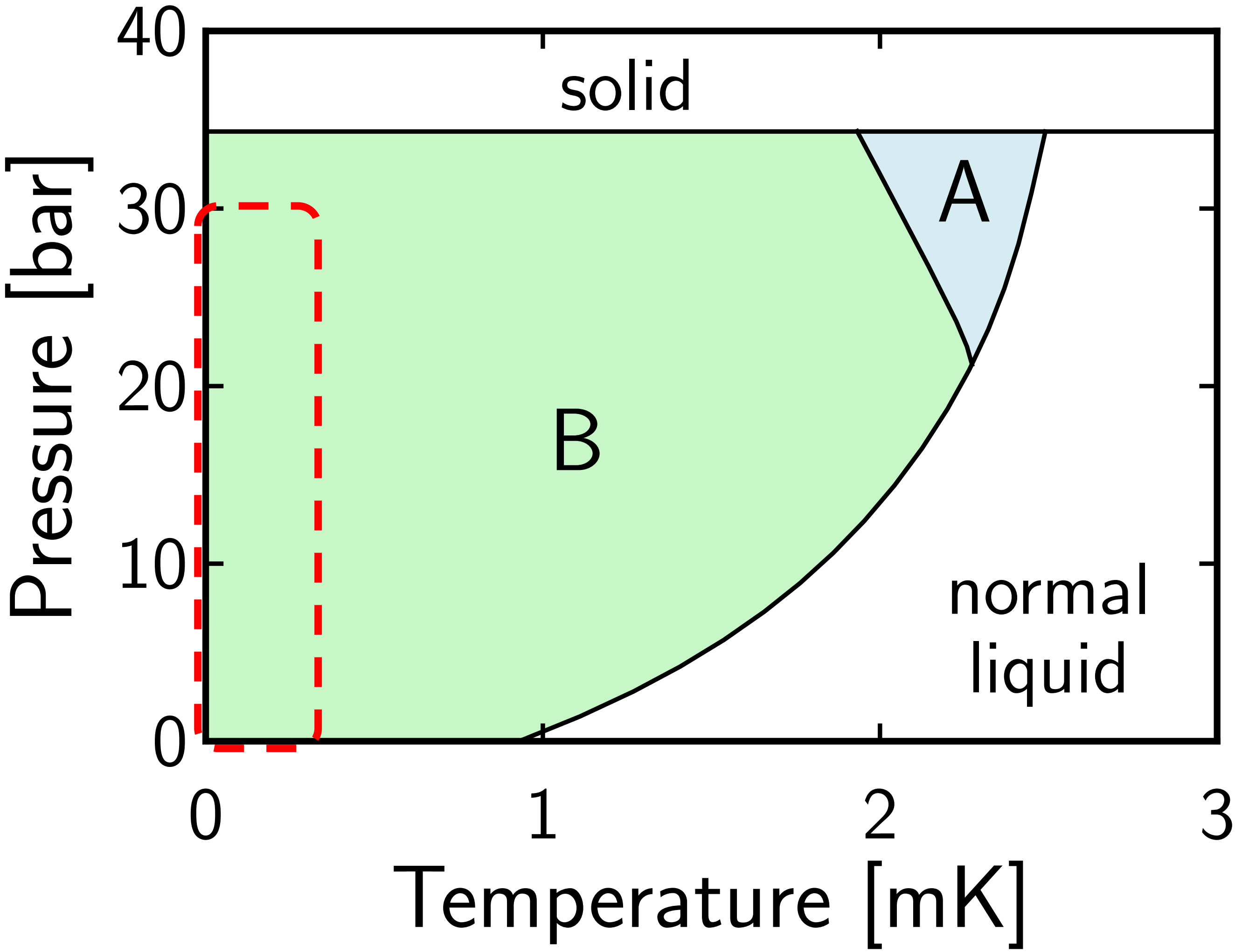
EMP

NPL National Physical Laboratory

OXFORD INSTRUMENTS

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Superfluid helium-3 target



- Cooper pairing of He atoms - superfluid <2mK
- Energy $\boldsymbol{\Delta \sim 10^{-7}}$ **eV** required to break Cooper pairs and give single **quasiparticles (QPs)**

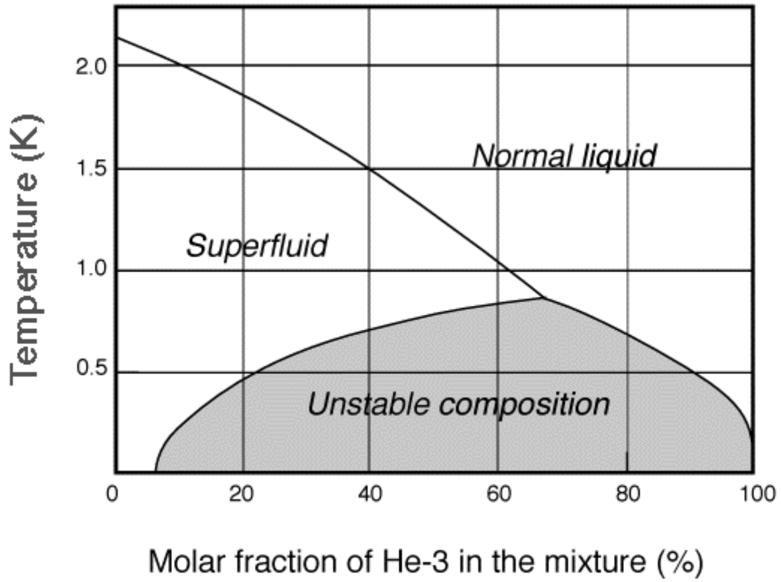
Unpaired nucleon:

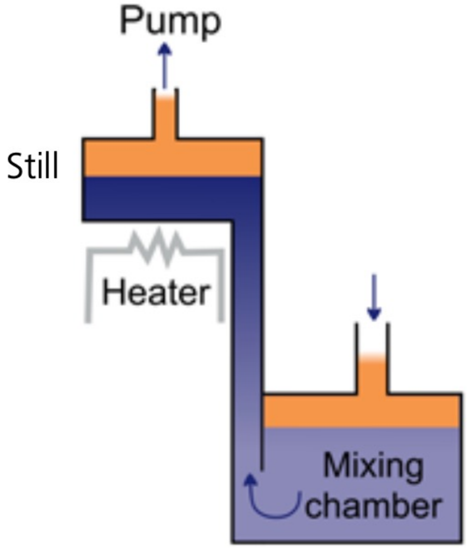
➢Spin dependent dark matter – nucleon interaction

Dilution refrigeration

4He – 3He dilution gives 2.3mK base temperature

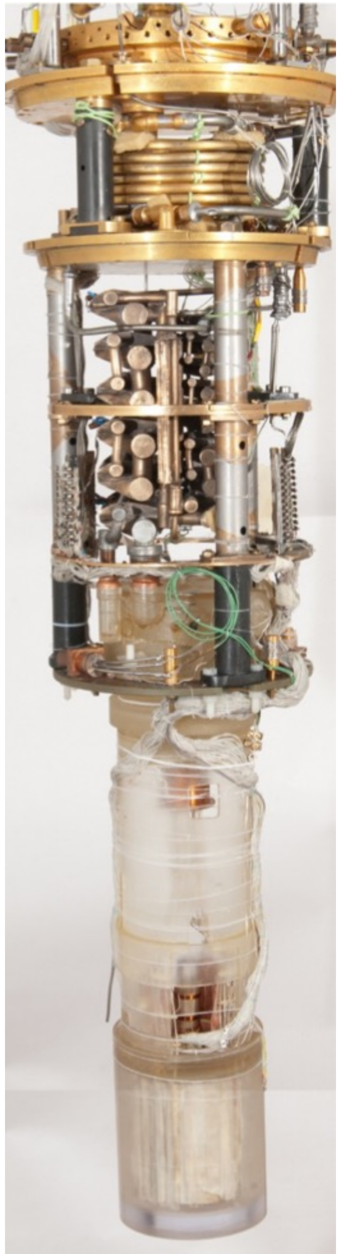
- Phase separation in 3He – 4He mix at low temperatures, higher entropy in dilute phase
- 3He atoms removed from dilute phase replaced from concentrated phase – increase in entropy removes heat from surroundings:
  $\dot{Q} = 84\dot{n}_3T^2$ [$\dot{n}_3$ = 3He flow rate across phase boundary]





Mixing chamber

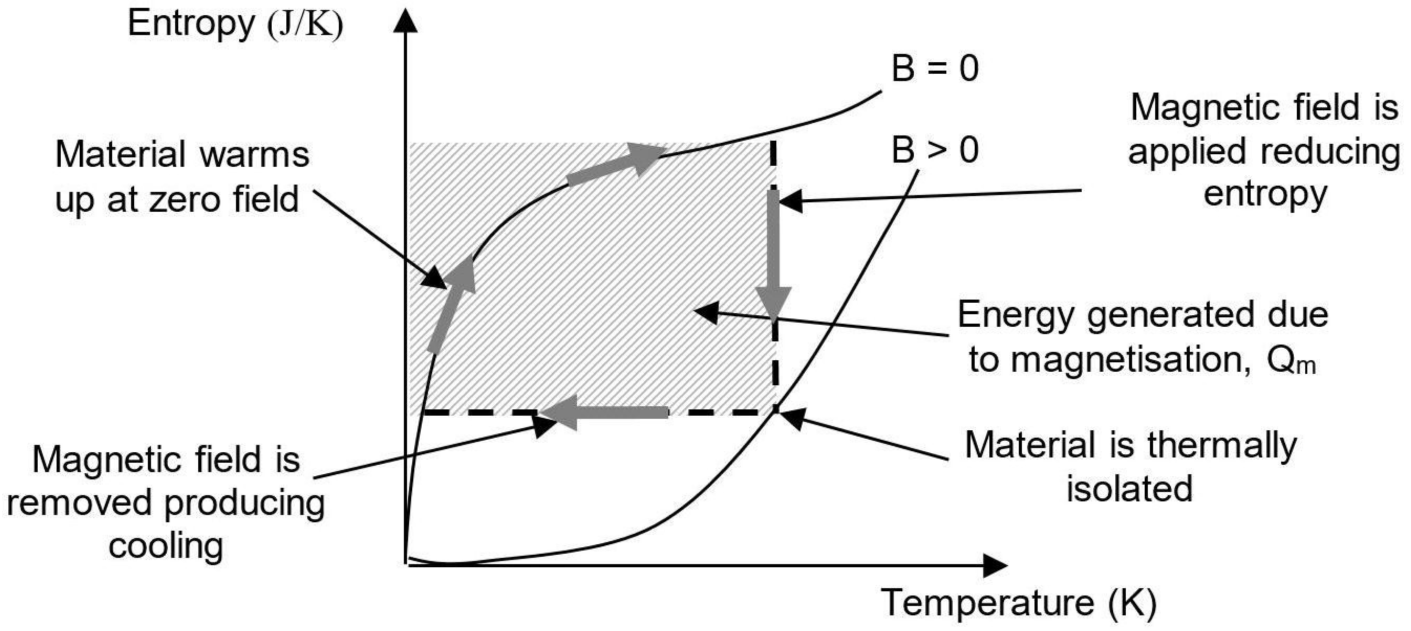
Mixing chamber



Heat exchangers

Adiabatic demagnetisation

- Following pre-cool to ~mK
- Adiabatic demagnetisation for single shot cooling to ~100uK
- Copper – spins more ordered at high B field, entropy increases when field decreases



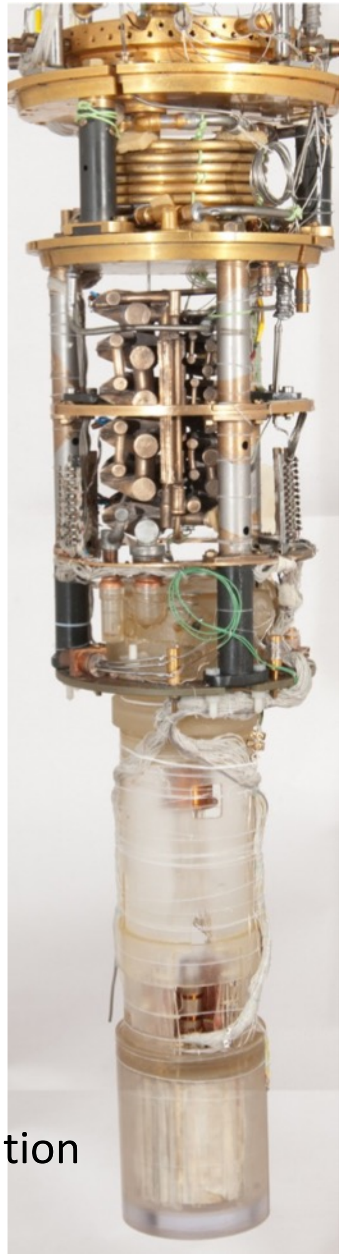
Material warms up at zero field

Magnetic field is applied reducing entropy

Energy generated due to magnetisation, Q_m

Material is thermally isolated

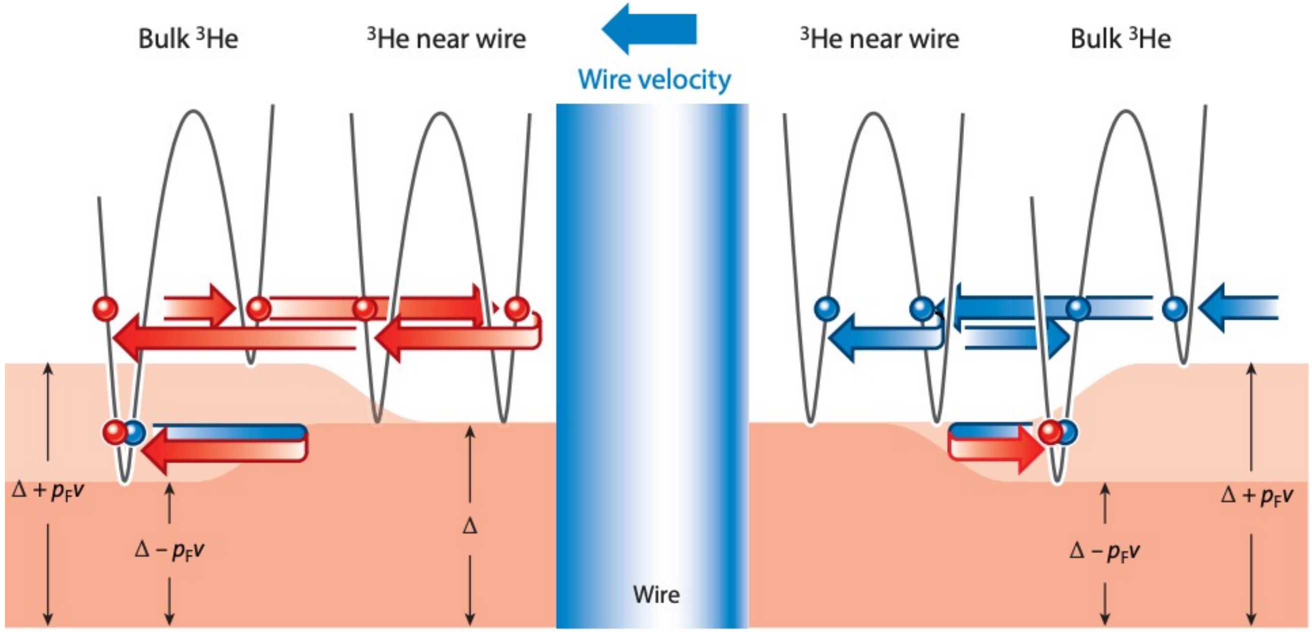
Magnetic field is removed producing cooling



Nuclear demagnetisation stage

Damping force & Andreev scattering

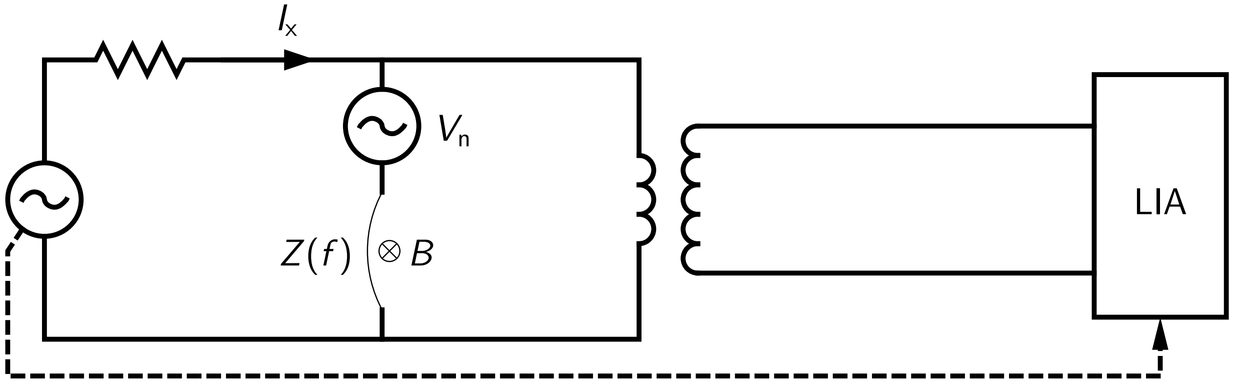
Effect unique to superfluid helium-3 increase QP damping force by 3 orders of magnitude

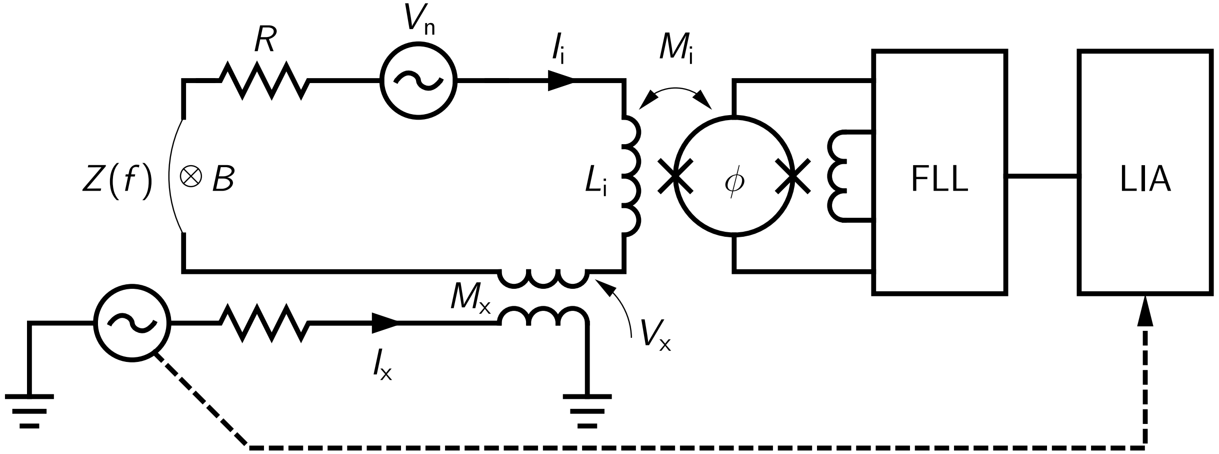


- Fluid flow and relative motion of wire can increase/decrease the gap.
- Only quasiparticles from in front and quasiholes from behind can transfer momentum |2pF|, increasing the damping.

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

Readout schemes



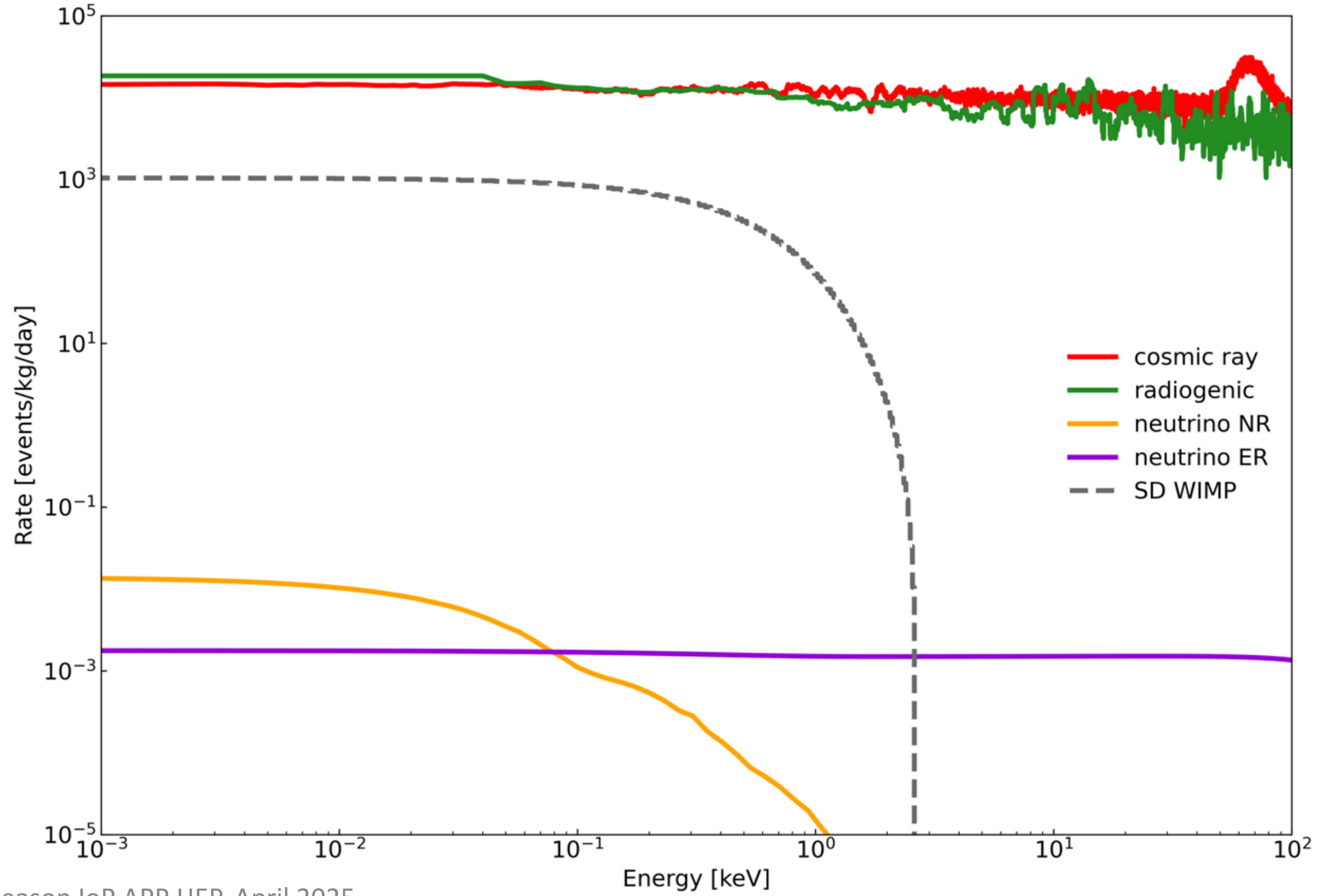


- Conventional – cold transformed plus lockin amplifier
- SQUID readout scheme:
  - Voltage applied inductively through Mx
  - SQUID current sensor detects current Ii in wire (with impedance Z(f), contact resistance R, and SQUID input coil inductance Li)
  - SQUID connected to lockin via room temp. flux-locked-loop electronics

Expected backgrounds

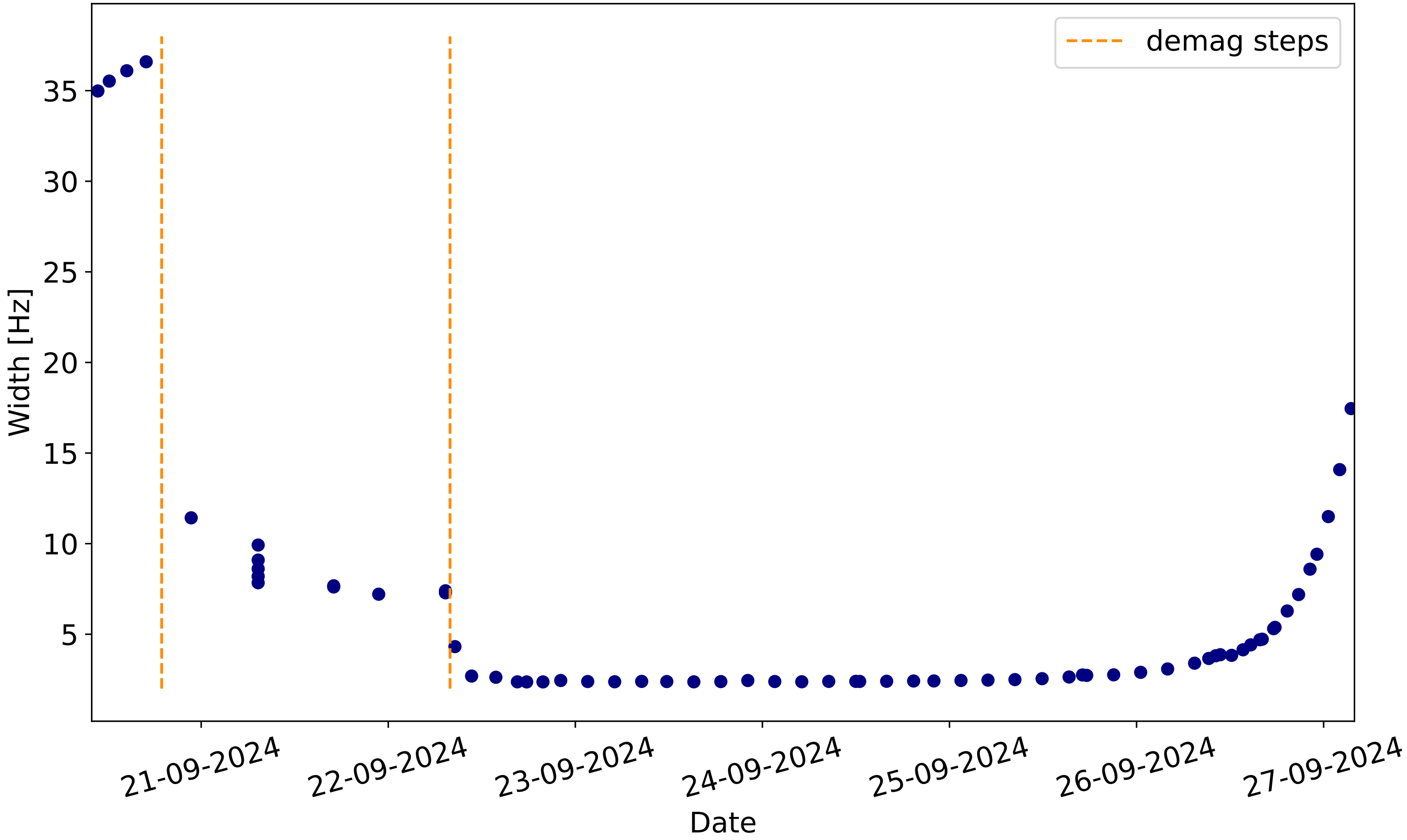
Background	Events/cell/day [0-10keV]
Cosmic rays	3.31
Radiogenic	2.61
PP neutrino	4.76e-7
CN neutrino	2.01e-9

- Cosmic rays – CRY + Geant4, no shielding and 90% veto efficiency
- Radiogenic - material screening and Geant4

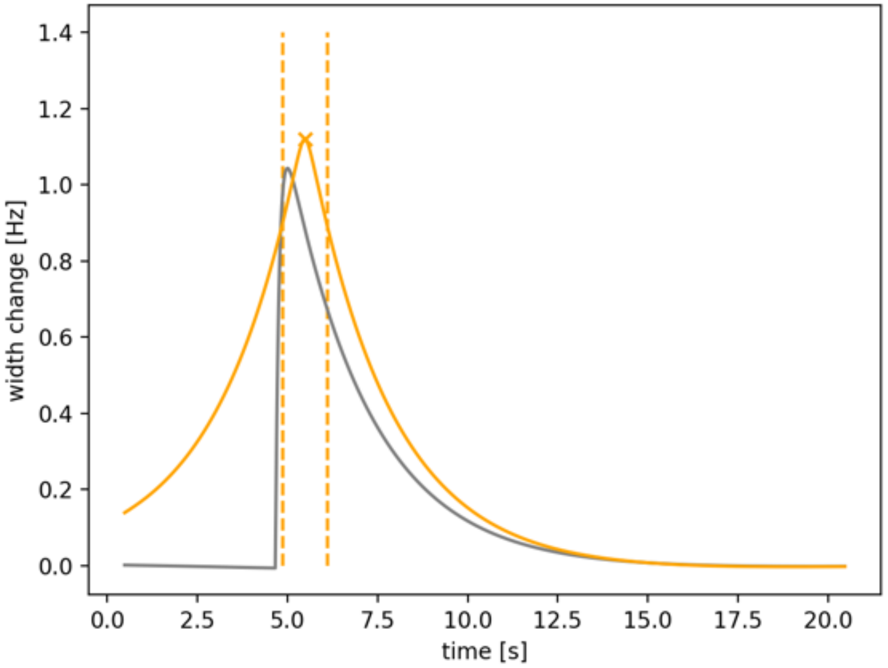


RHUL bolometer

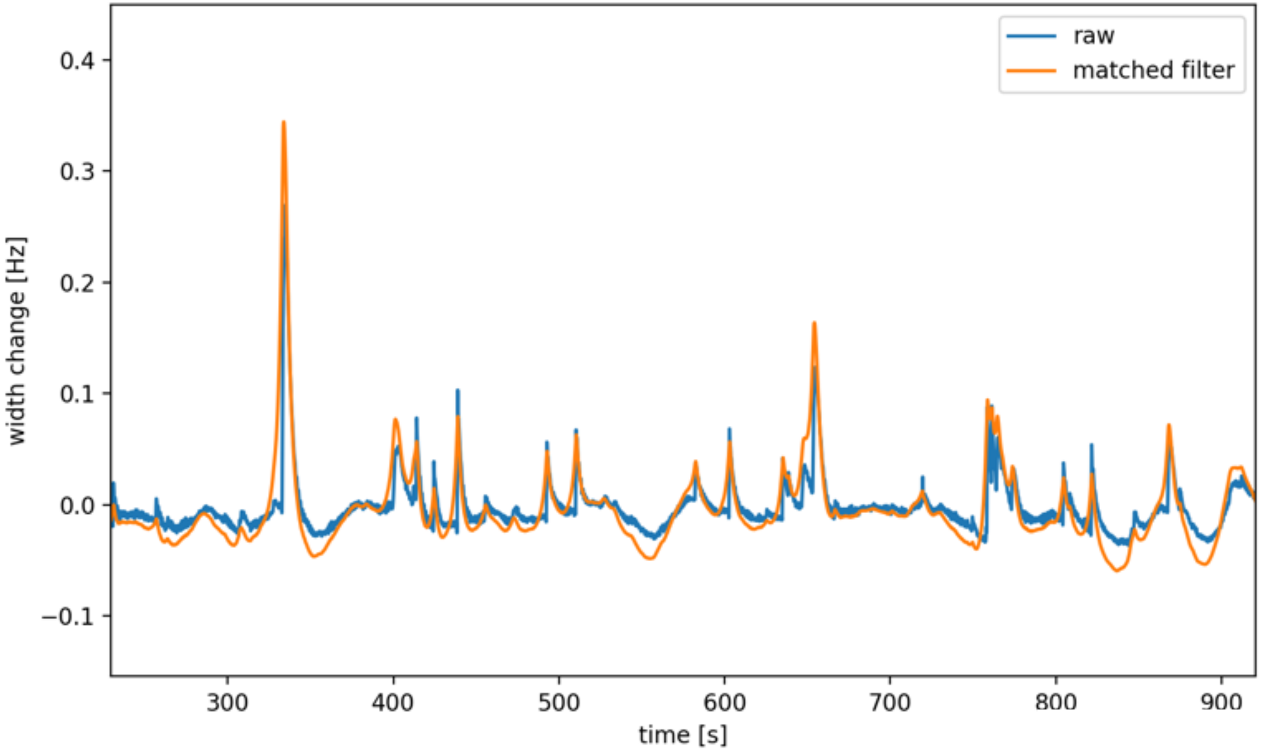
- ✓operation of 400nm wires in bolometer cell
  - SQUID readout circuit
  - 5 day stable run time (at 0.3mK)
- ✓noise characterisation and optimisation for SQUID readout
- ✓heater wire calibrations



Pulse finding

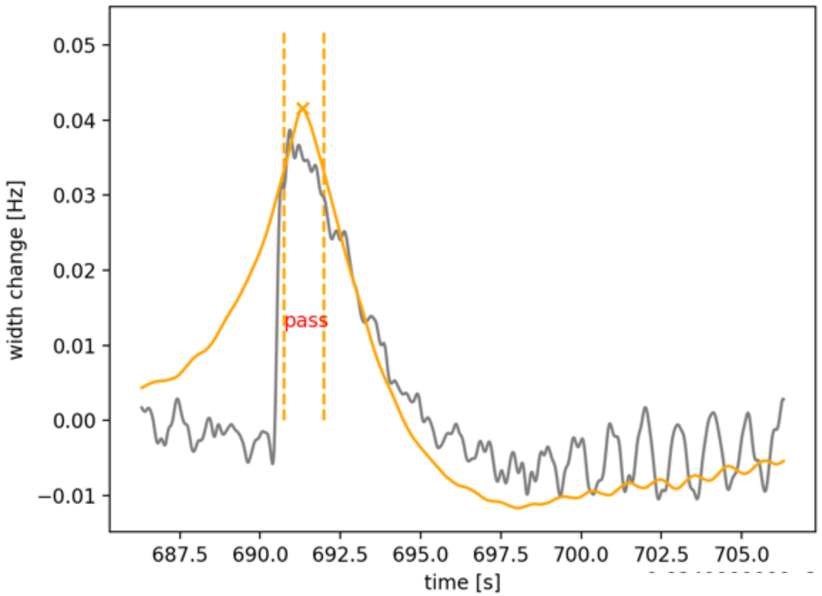


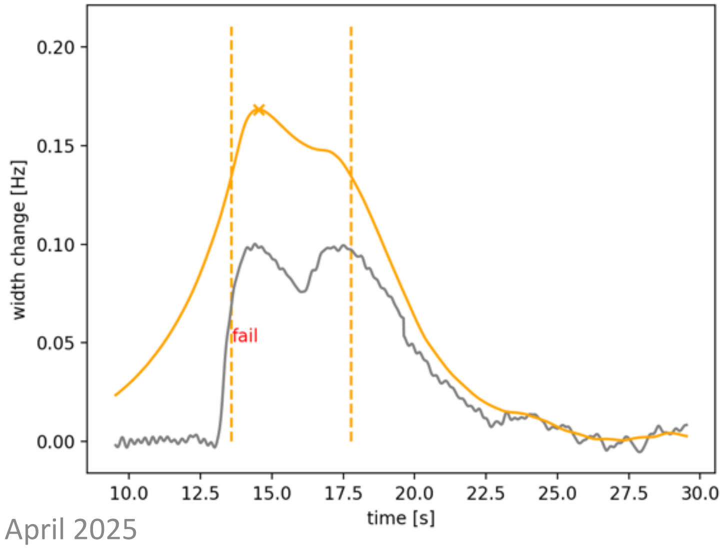
- Large pulse finding threshold – make signal template to define a **matched filter.**
- Apply matched filter to template – ideal response.



- Apply matched filter to all data.
- Low threshold pulse finding.

Pulse selection





- Apply pulse selection on matched filter output – width and symmetry criteria.
- Amplitude histogram for subset of tracking data.