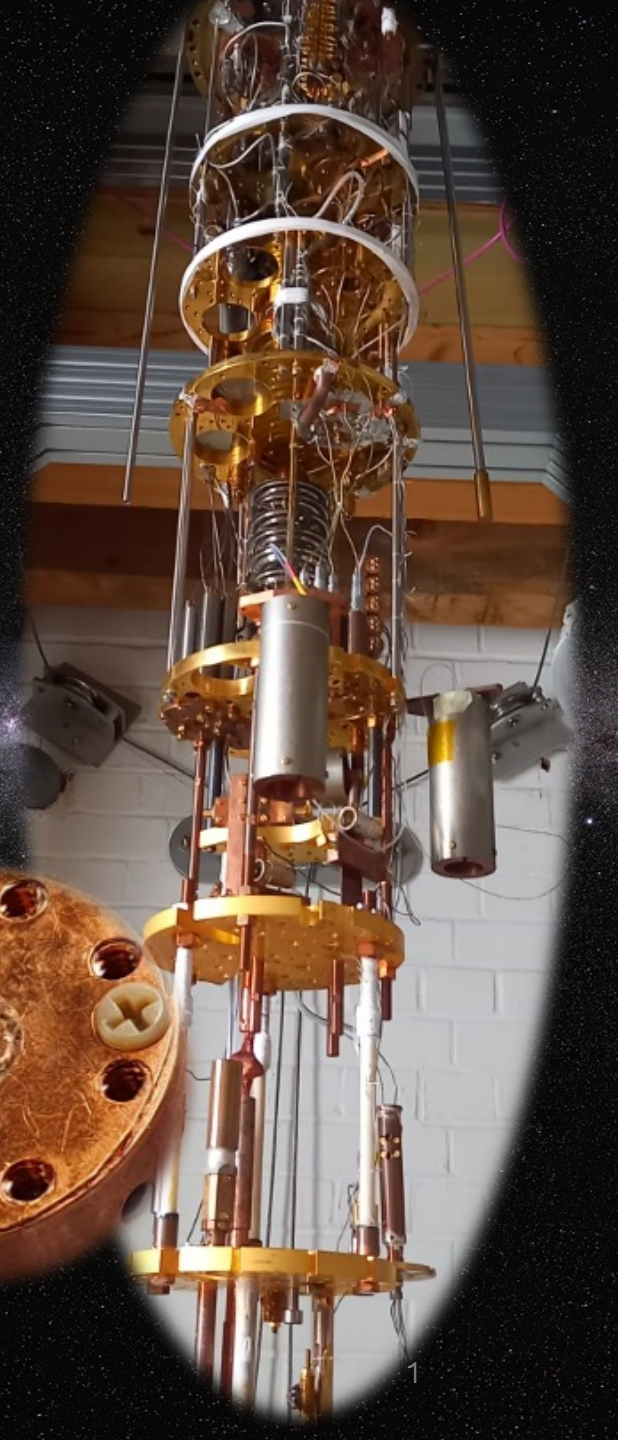
Superfluid He-3 bolometry for the QUEST-DMC project using nanowires with SQUID readout

QUEST DMC

Elizabeth Leason,
on behalf of QUEST-DMC

TeVPA 04/11/2025, Valencia



UNIVERSITY OF OXFORD

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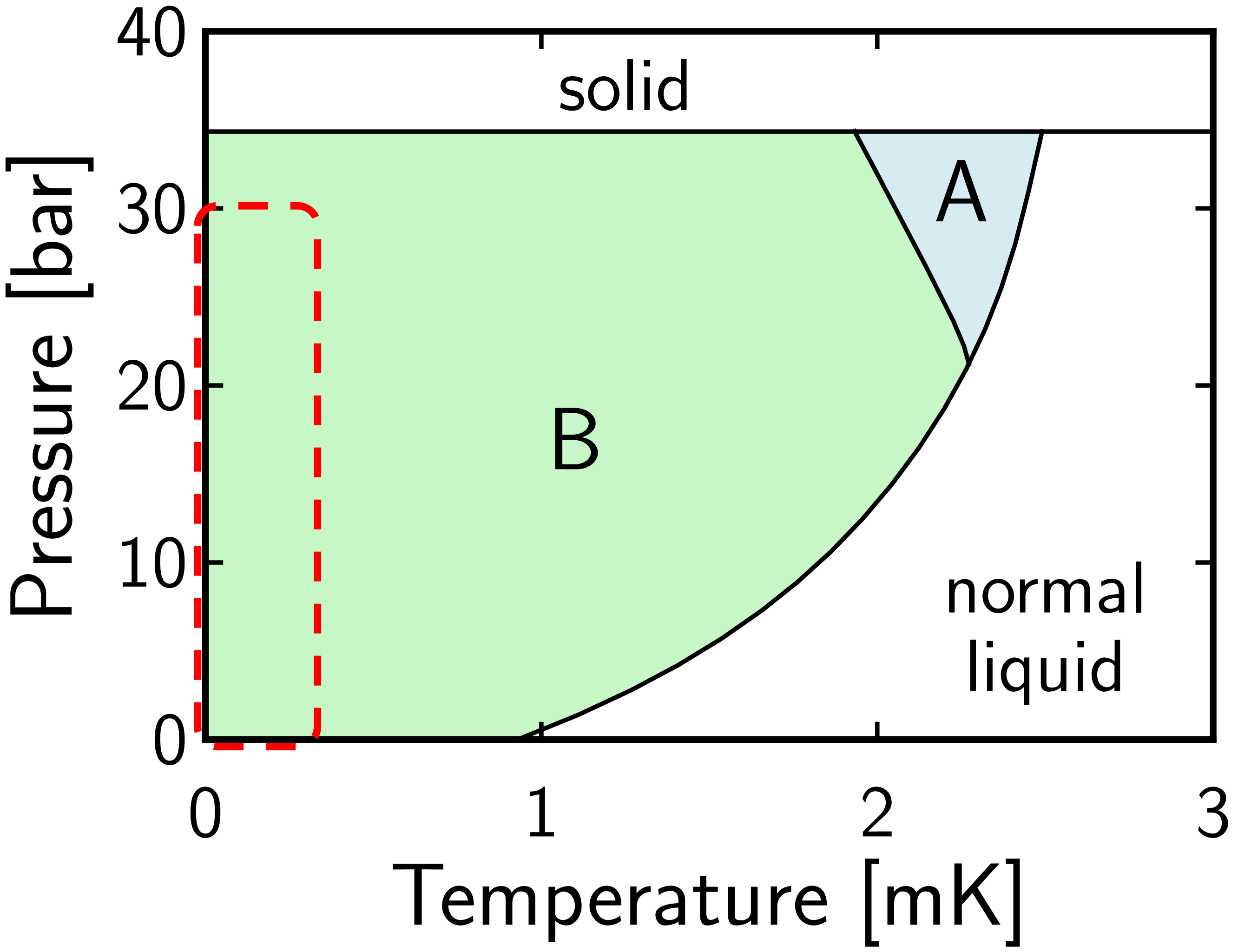
Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology, QUEST–DMC

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

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

Why superfluid helium 3?

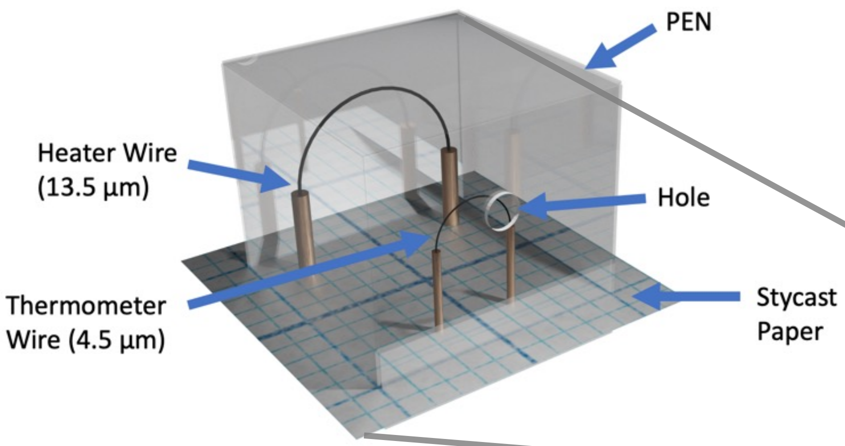


- Cooper pairing of He atoms - superfluid <2mK
- Energy $\Delta \sim 10^{-7}$**eV** required to break Cooper pairs and give single **quasiparticles (QPs)**

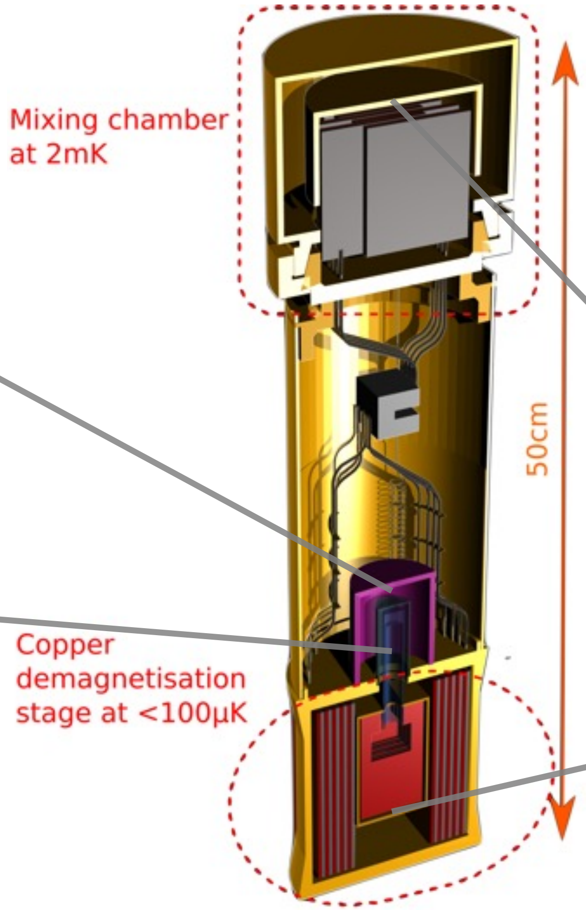
Unpaired nucleon:

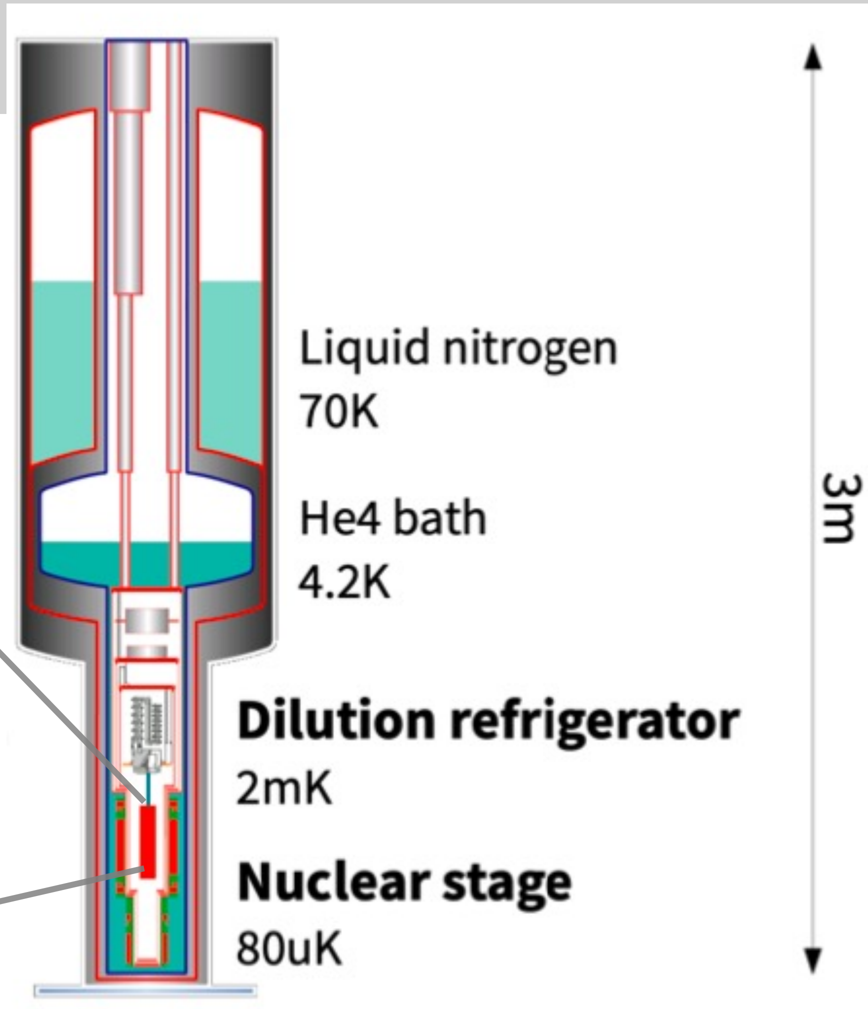
➢Spin dependent dark matter – nucleon interaction

Detector concept



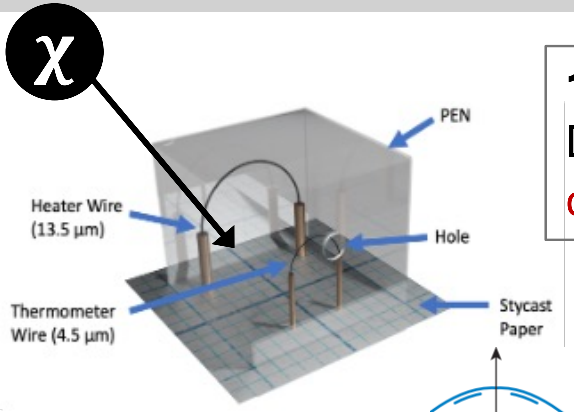
Superfluid helium bolometer with vibrating nanowire resonators (VWRs)



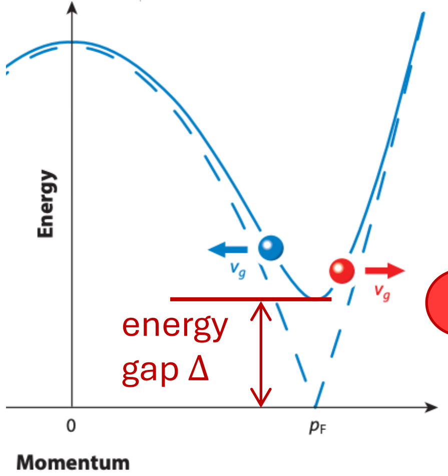


Operated in a nuclear demagnetisation cryostat below 1mK

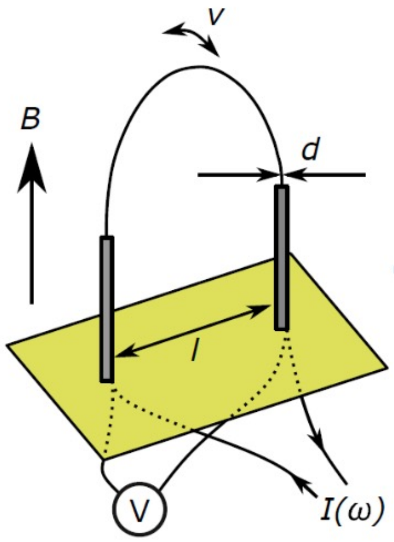
Bolometer principle



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



2. Ballistic propagation
QP collisions with nanowire exert damping force



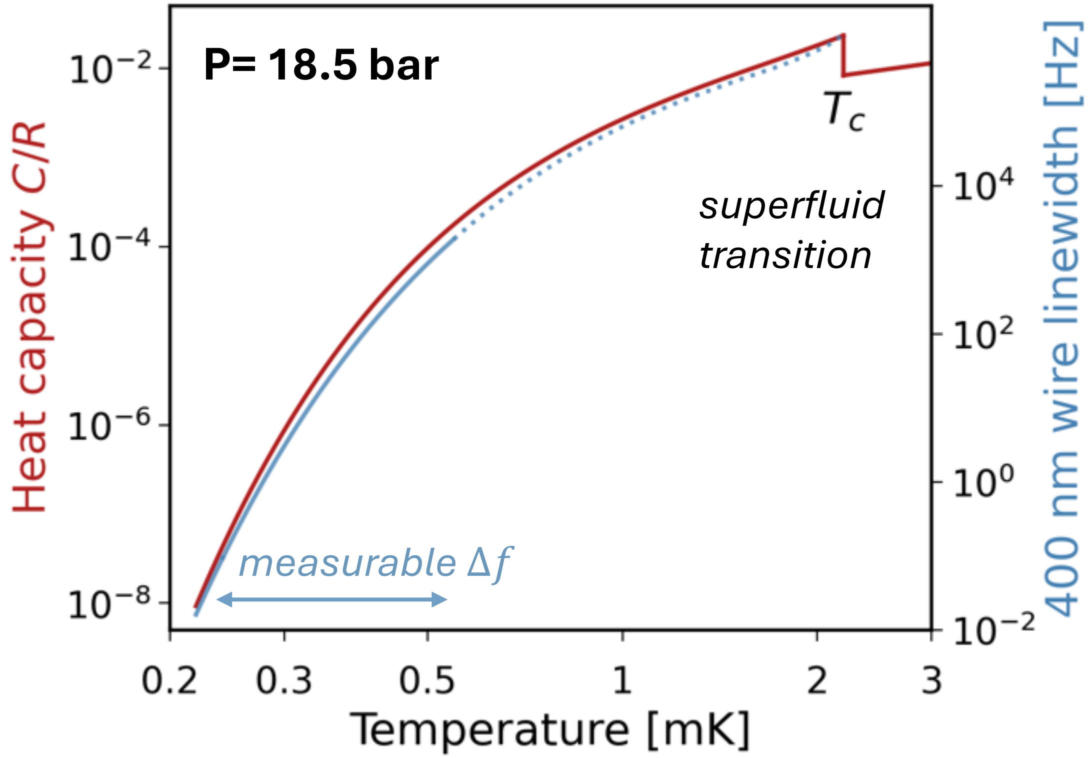
3. Bolometry

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

Achieving low threshold

Ultra-low temperature operation:

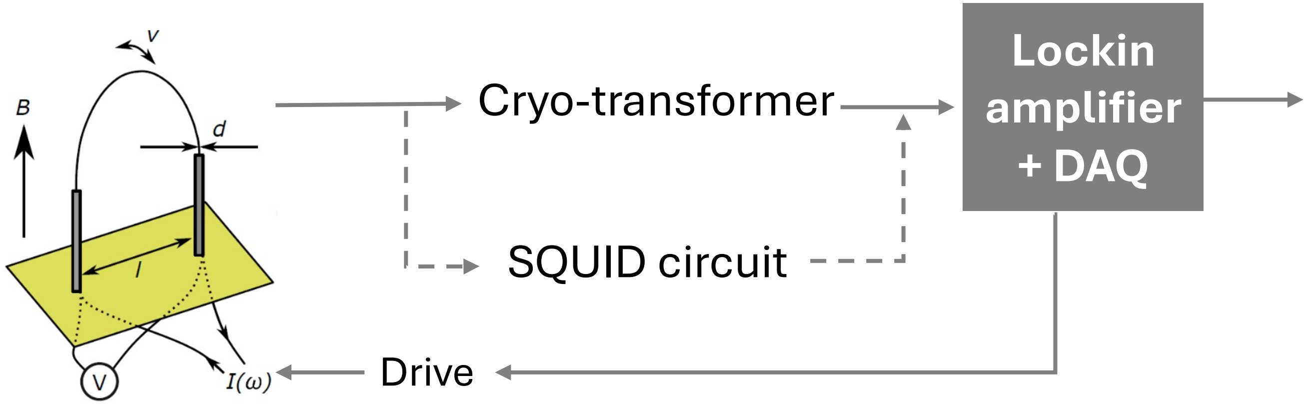
- Small energy → small width change
- Linewidth follows heat capacity



Low noise readout:

- Conventional readout: passive cryo-transformer
- SQUID preamplifier, higher gain and lower noise

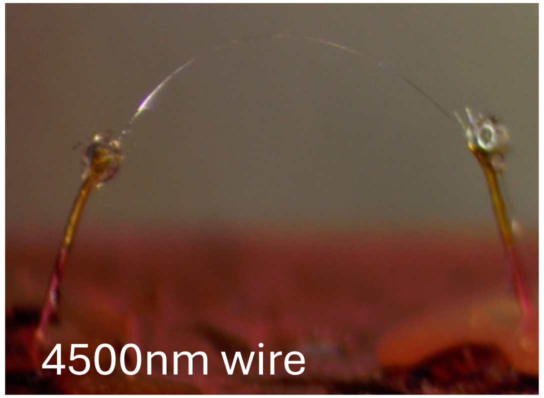
- Simulated energy thresholds: 39 eV with conventional readout, 0.71 eV with SQUID readout [QUEST-DMC:*Eur. Phys. J. C* **84**, 248 (2024)]



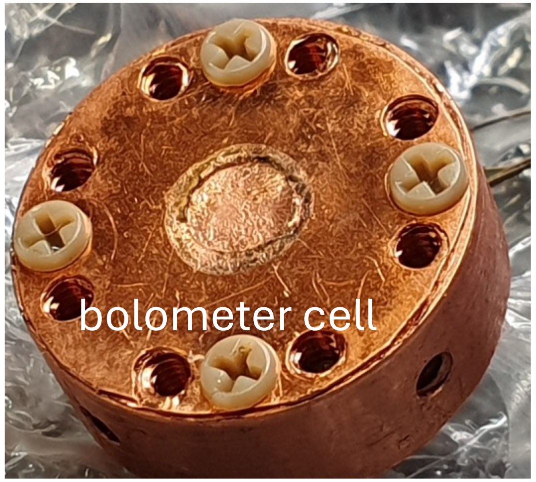
SQUID readout tests

NEW paper: arxiv:2508.10602

400nm nanowire

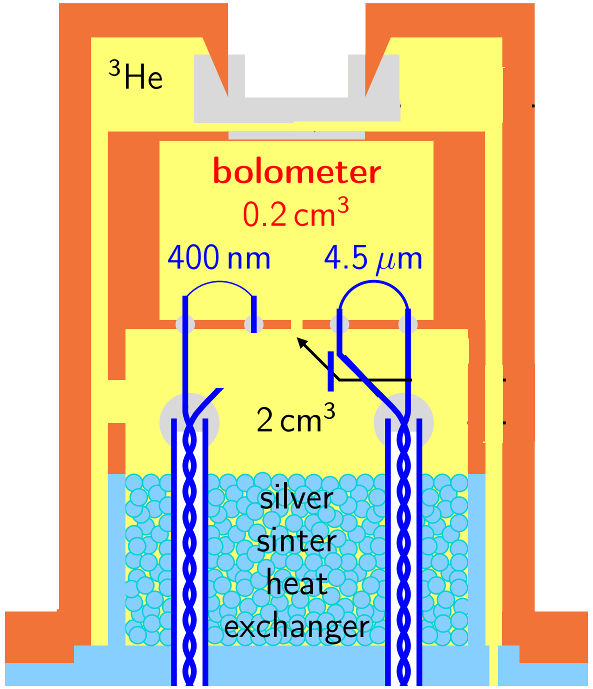


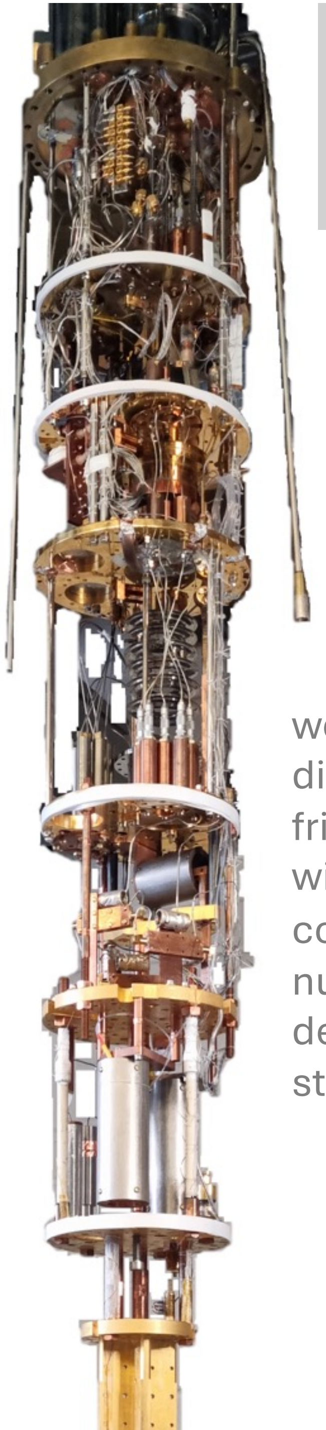
NbTi vibrating wire resonators made in Lancaster
arXiv:2311.02452



cell holder and heat exchanger

cuboid copper bolometer inside 3He cell

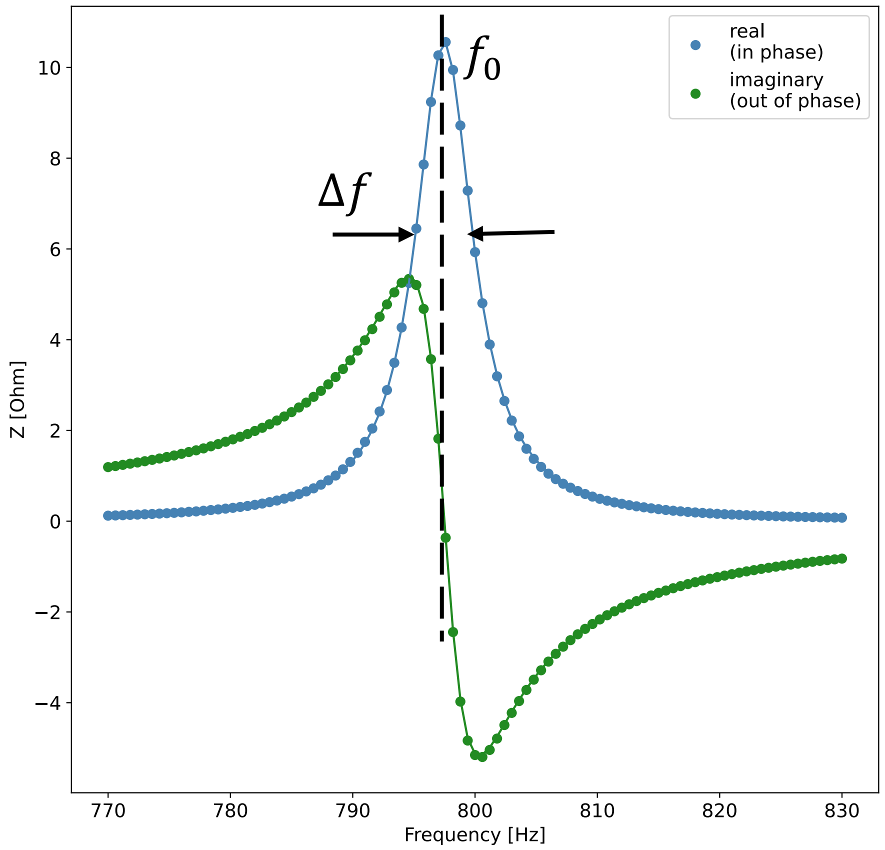


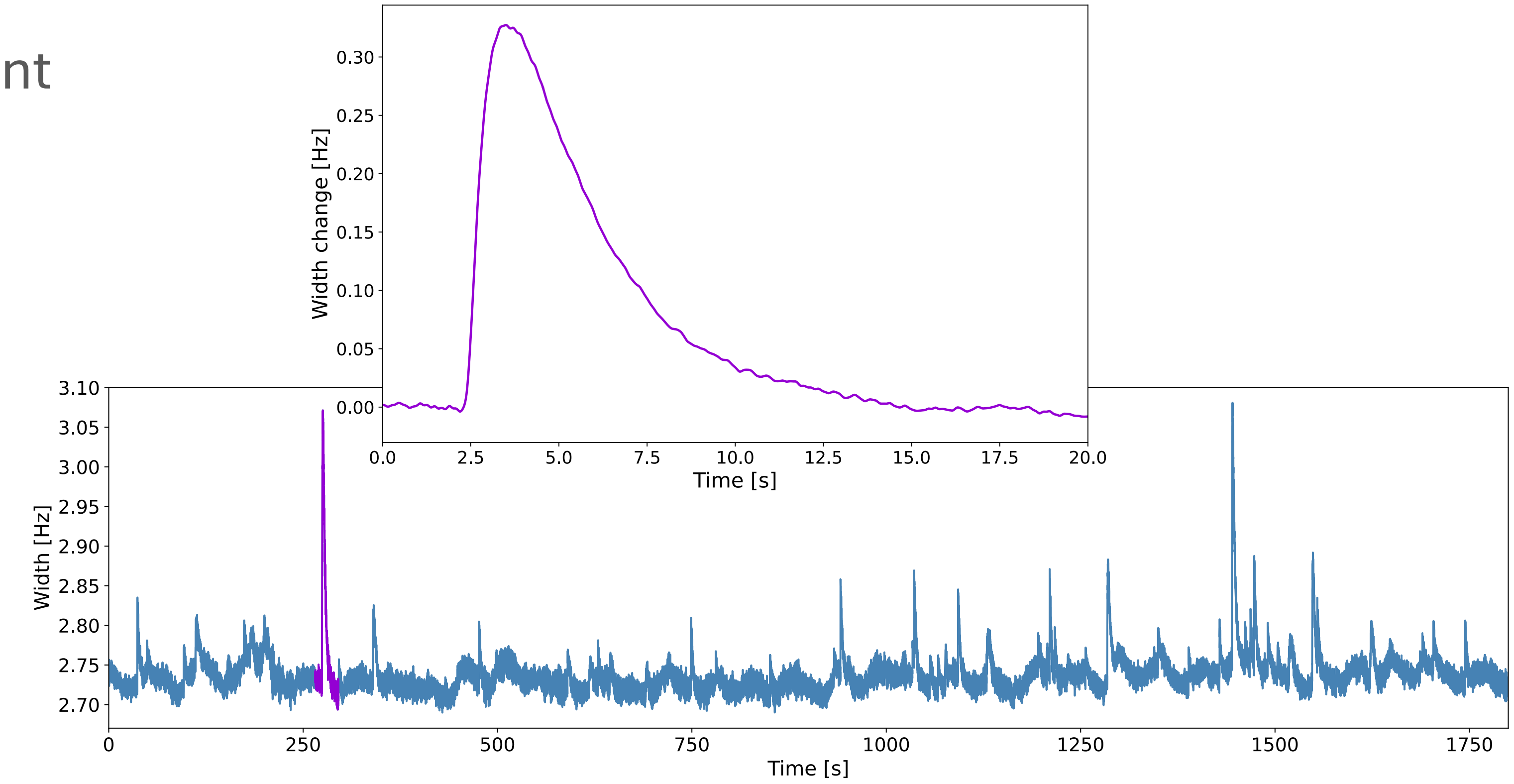


wet dilution fridge with copper nuclear demag. stage

Bolometer measurements

A. Frequency sweep – find resonant frequency, base width and amplitude from Lorentzian fit





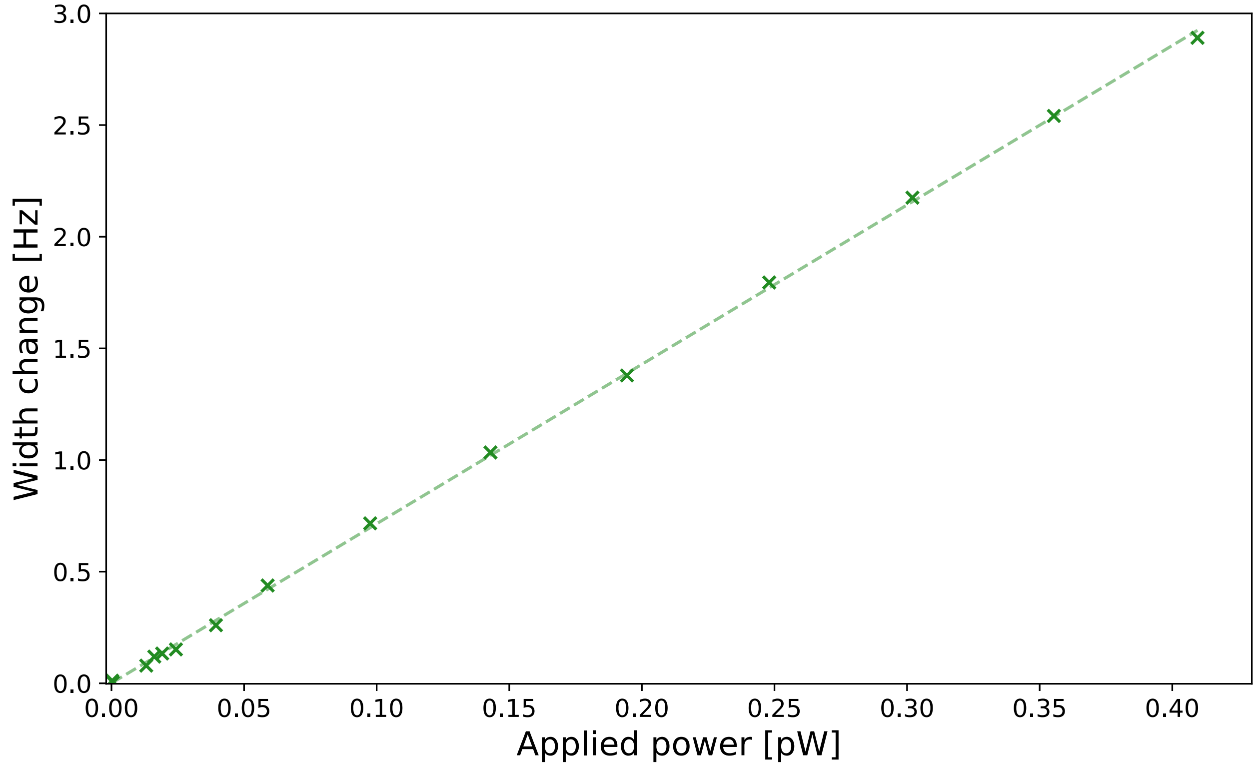
B. Response tracking – drive on resonance

- Measure induced voltage across wire
- Convert to resonance width change
- Apply pulse finding and fitting

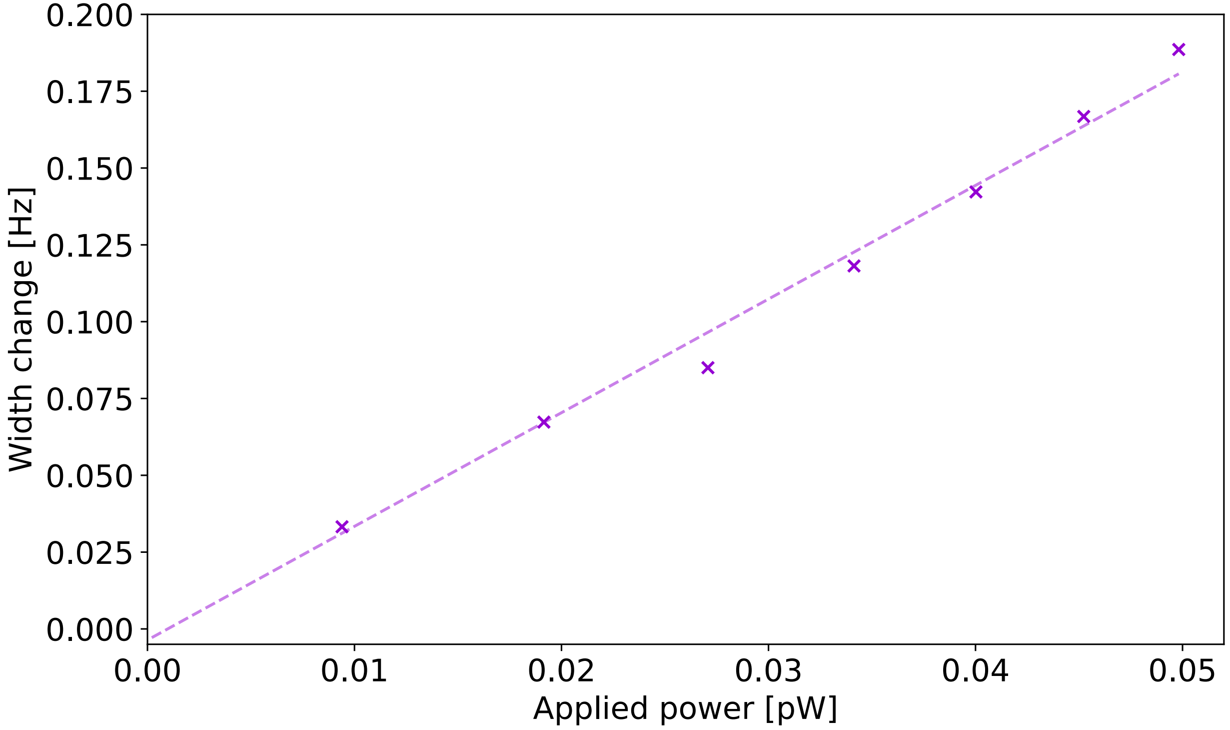
Heater wire calibration

Direct injection of QPs into superfluid by driving wire above critical velocity, observe proportional response on other wire.

A) 400nm detector (4500nm heater)



B) 4500nm detector (400nm heater)

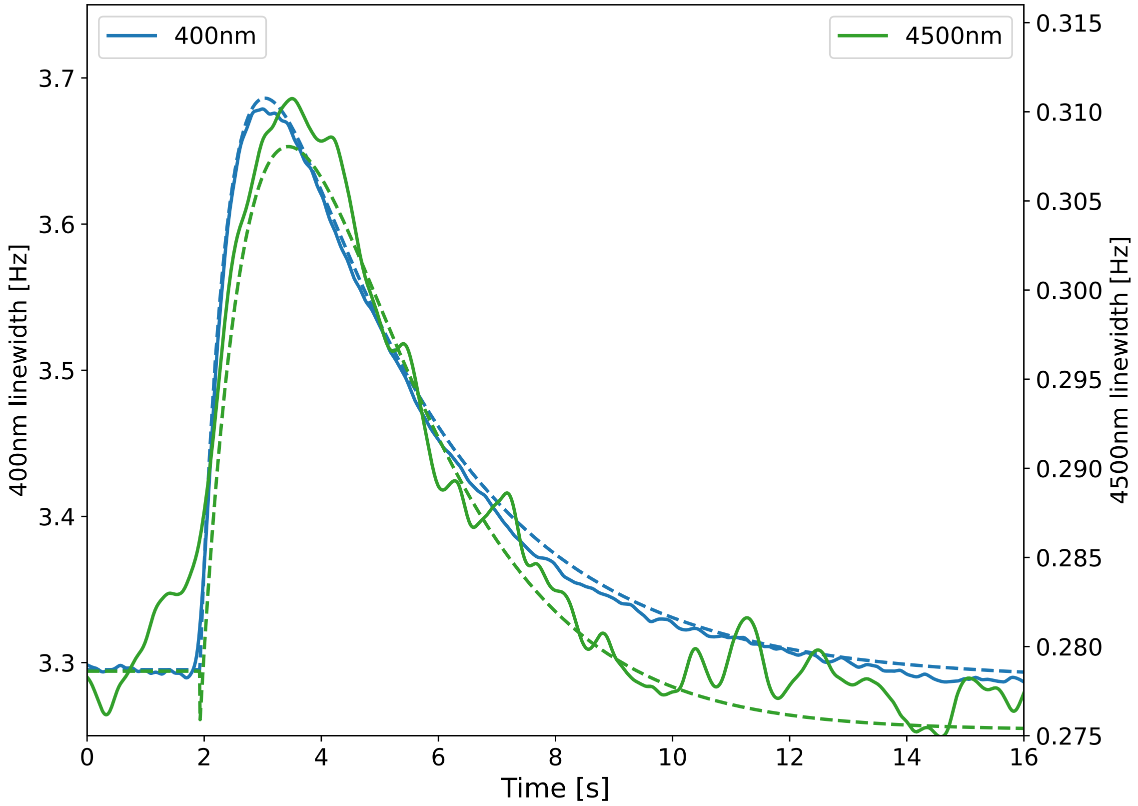


~10keV heat injection!

Other measurements

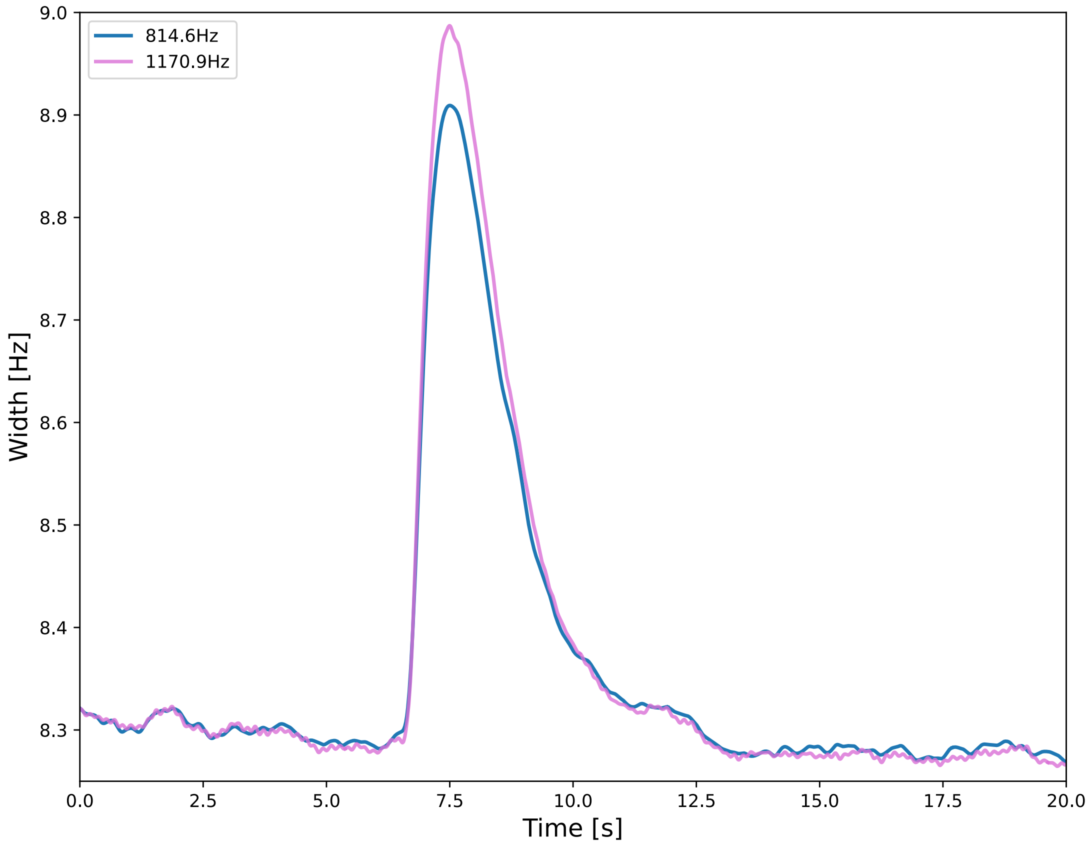
Simultaneous tracking: on both wires

- ➢ observe coincident bolometer pulses



Frequency multiplexed readout: with single SQUID

- ➢ coincident events seen on both modes
- ➢ separate wires in future (scale up experiment)

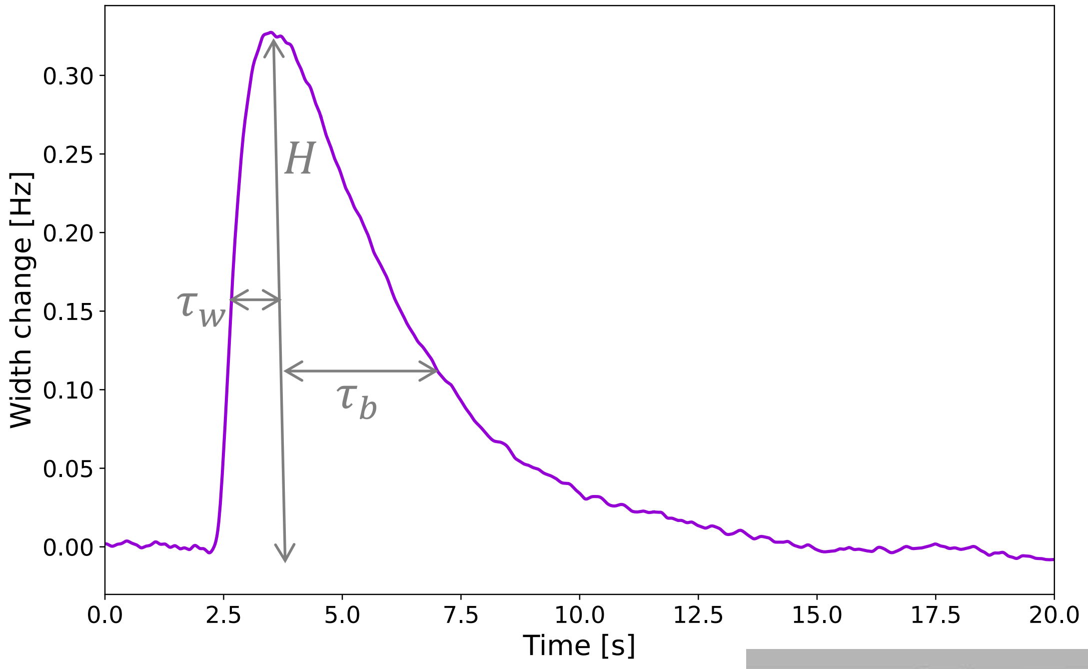


Pulse analysis and Geant4 comparison

Characteristic heat pulse shape, three parameters:

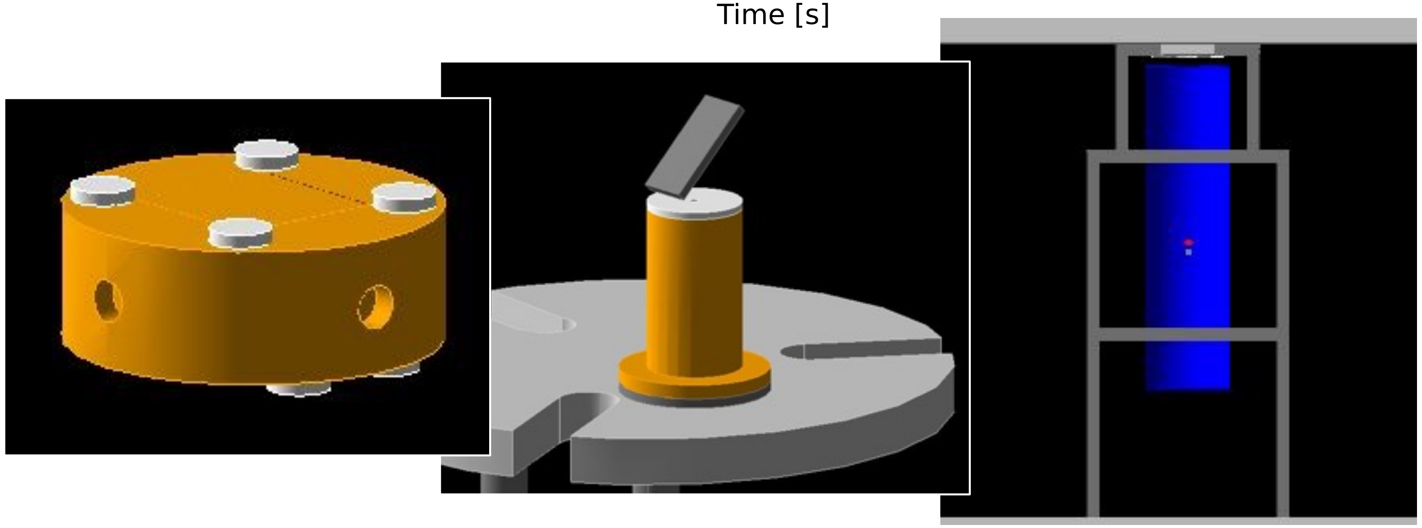
- Rise time, τ_w - nanowire
- Decay time, τ_b - bolometer
- Height, H – heating event (energy)

[C.Winkelmann, NIMA(2007)]

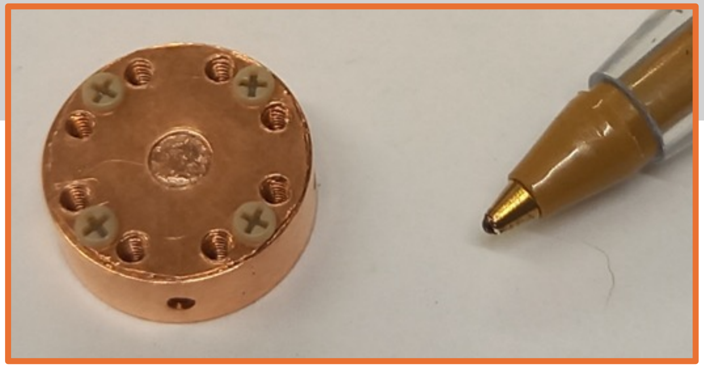


Background model (cosmic ray, gamma, detector radiogenics)

- Full Geant 4 model
- Boulby material screening JLTP(QFS2023)



Summary



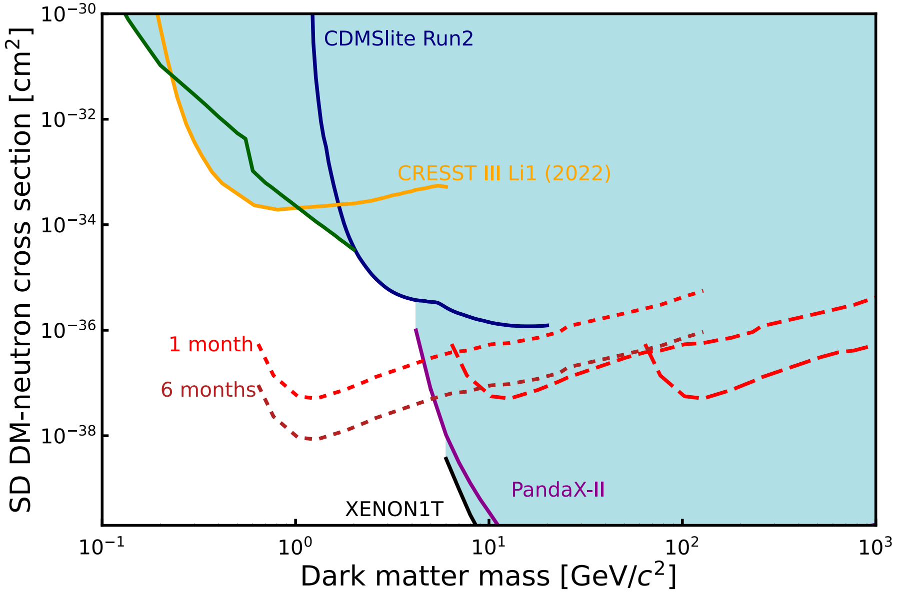
Demonstrated superfluid helium-3 bolometer with SQUID readout of nanomechanical resonators (arxiv:2508.10602):

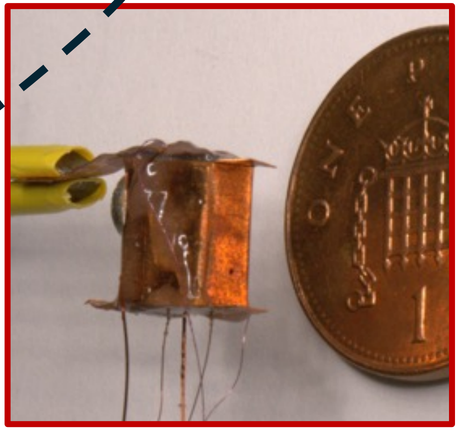
- ✓heat injection calibration
- ✓simultaneous tracking
- ✓frequency multiplexing

__Next:__ particle calibration, noise optimisation and resonator design

Goal: <100 eV energy threshold for < GeV/c^2 dark matter

- *Earth shadowing effects: JCAP04(2025)017*
- *Non-relativistic EFT operators: JCAP10(2025)044*



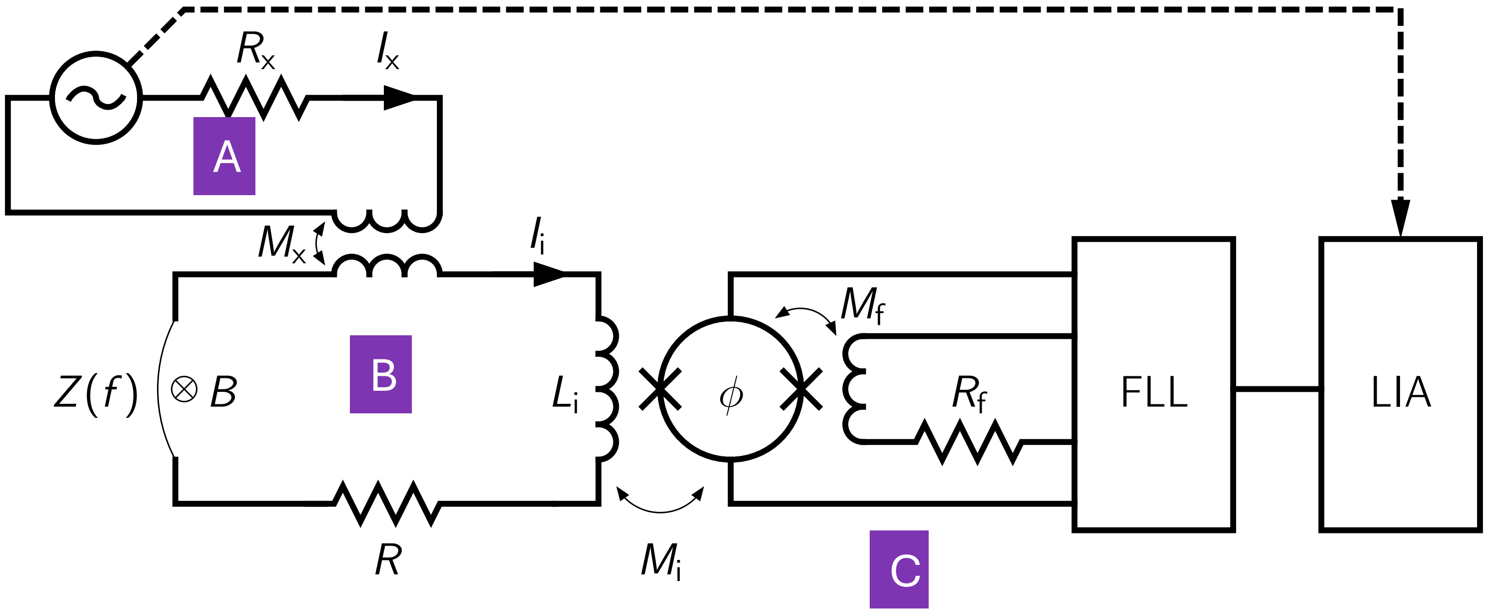


Dark matter search run

Backup

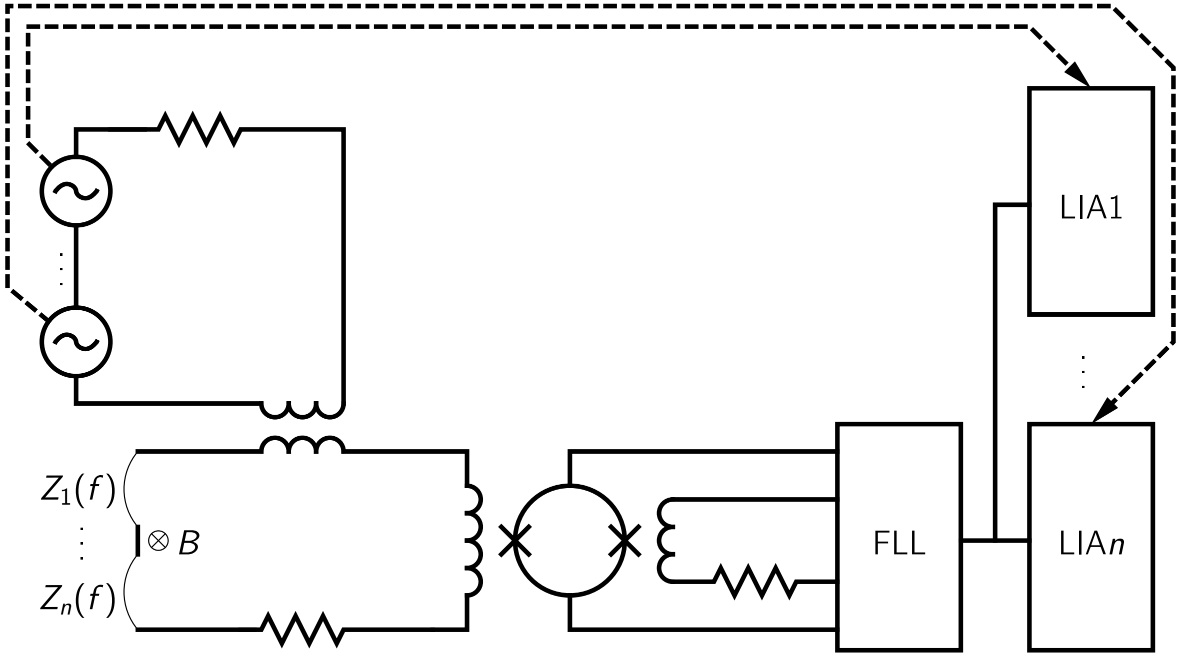
SQUID readout scheme

A. Voltage drive coupled inductively (via transformer with mutual inductance M_x)
B. SQUID input loop: wire $Z(f)$, contact resistance R, input coil L_i
C. SQUID in flux locked loop mode detects current I_i



Two-stage SQUID current sensor:
[D.Drung et.al., IEEEAppl.Supercond.**17**(2007)]

Multiplexed readout circuit



Multiple wires connected in series to a single SQUID (keeping the squid and input loops the same)

Resonator characterisation

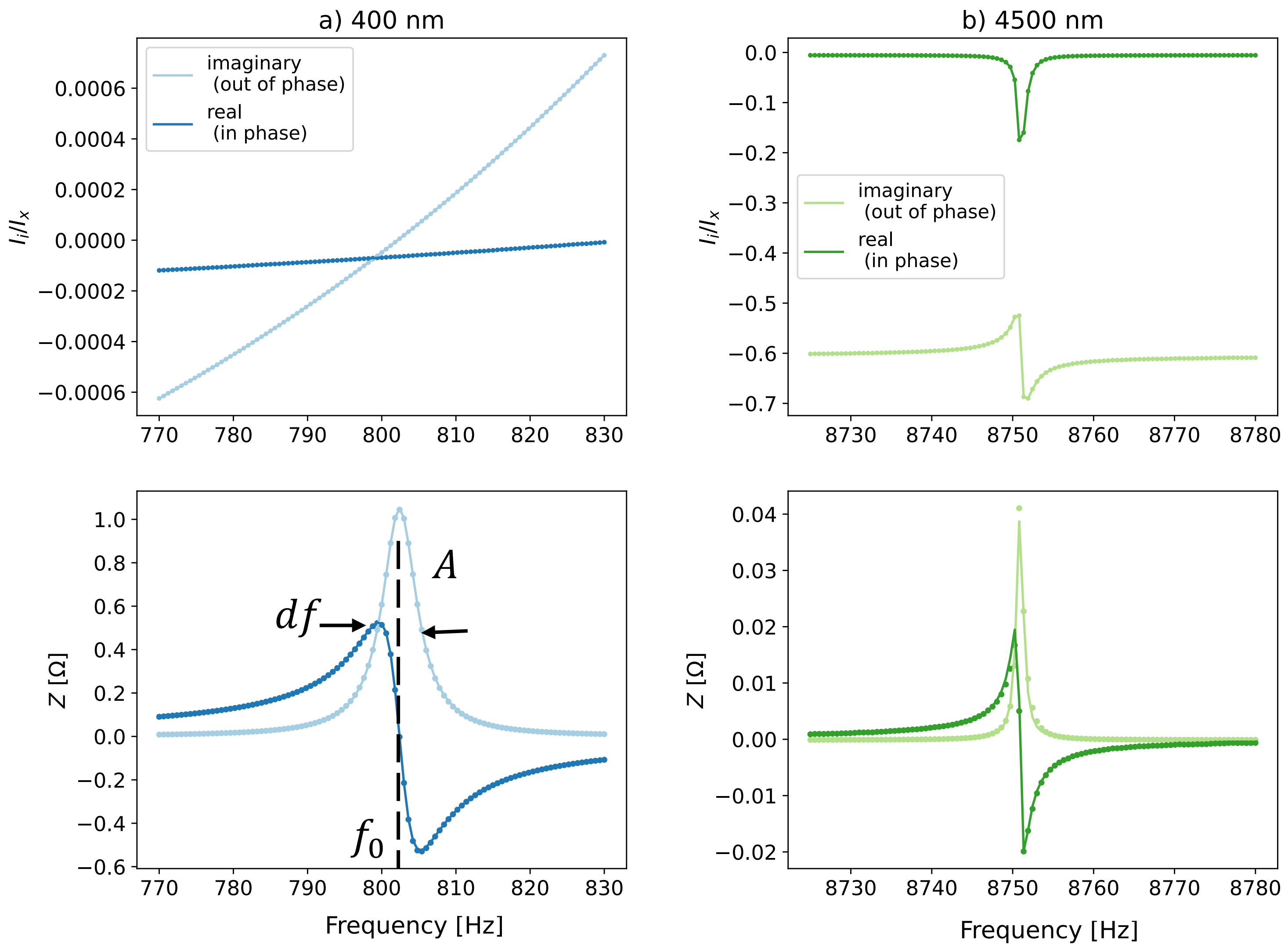
Frequency sweeps for both wires.

Lorentzian fit:

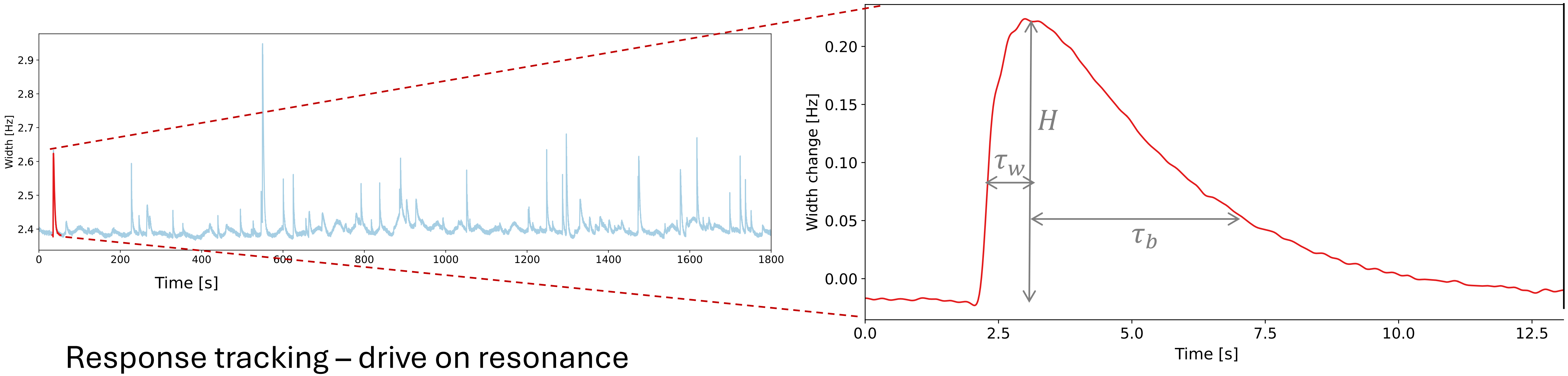
$$Z(f) = \frac{ifA}{f_0^2 - f^2 + ifdf}$$

Amplitude:

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



Bolometer tracking data



Response tracking – drive on resonance

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

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

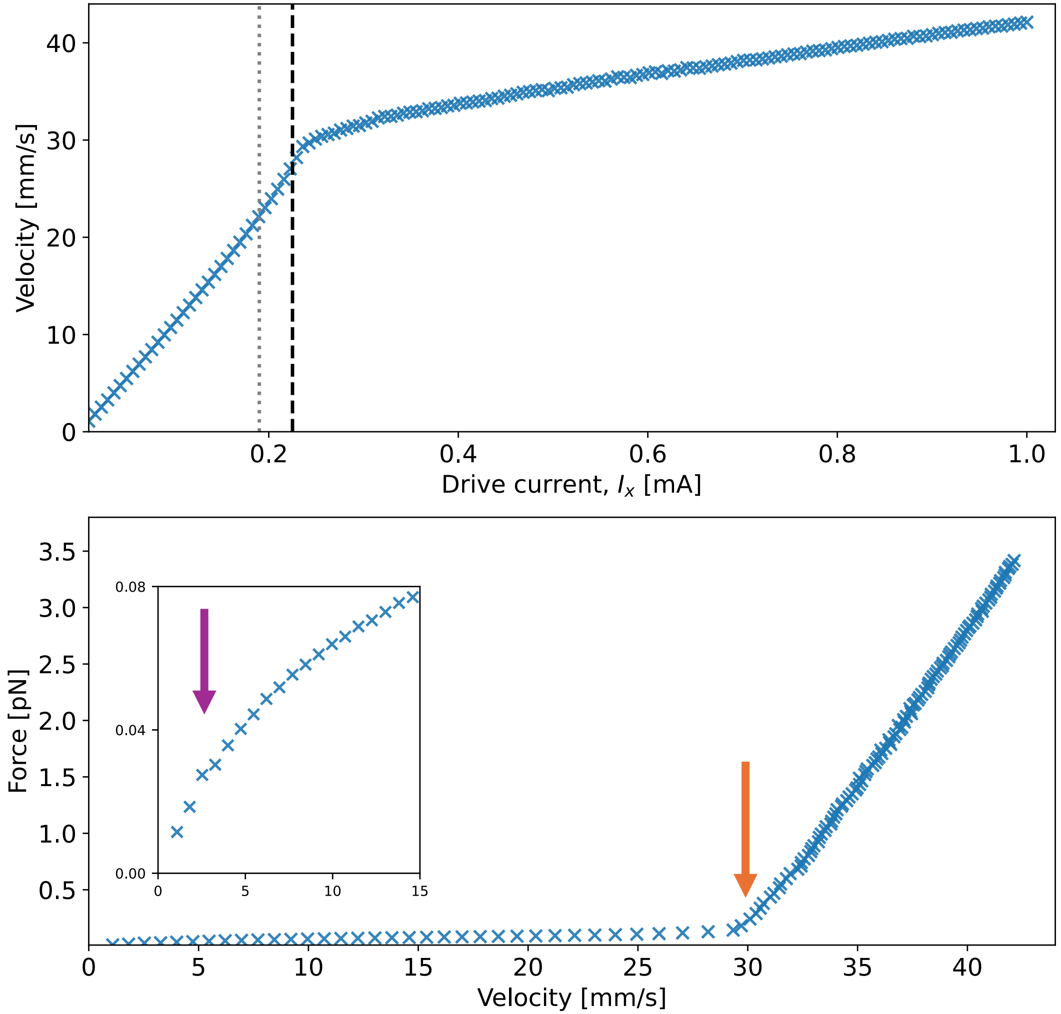
- Track over time and apply pulse finding

Characteristic pulse shape, three parameters:

- Rise time, τ_w - nanowire
- Decay time, τ_b - bolometer
- Height, H – heating event (energy)

[C.Winkelmann, NIMA(2007)]

Drive amplitude selection



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]