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

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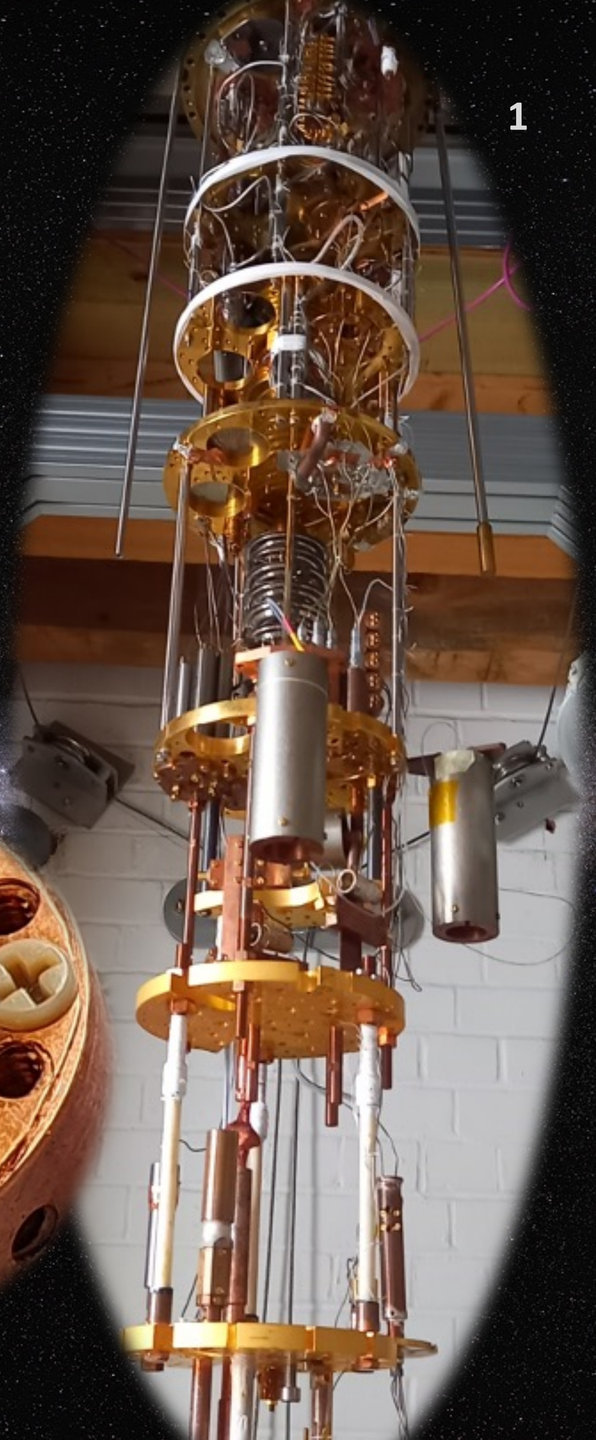

QUEST-DMC

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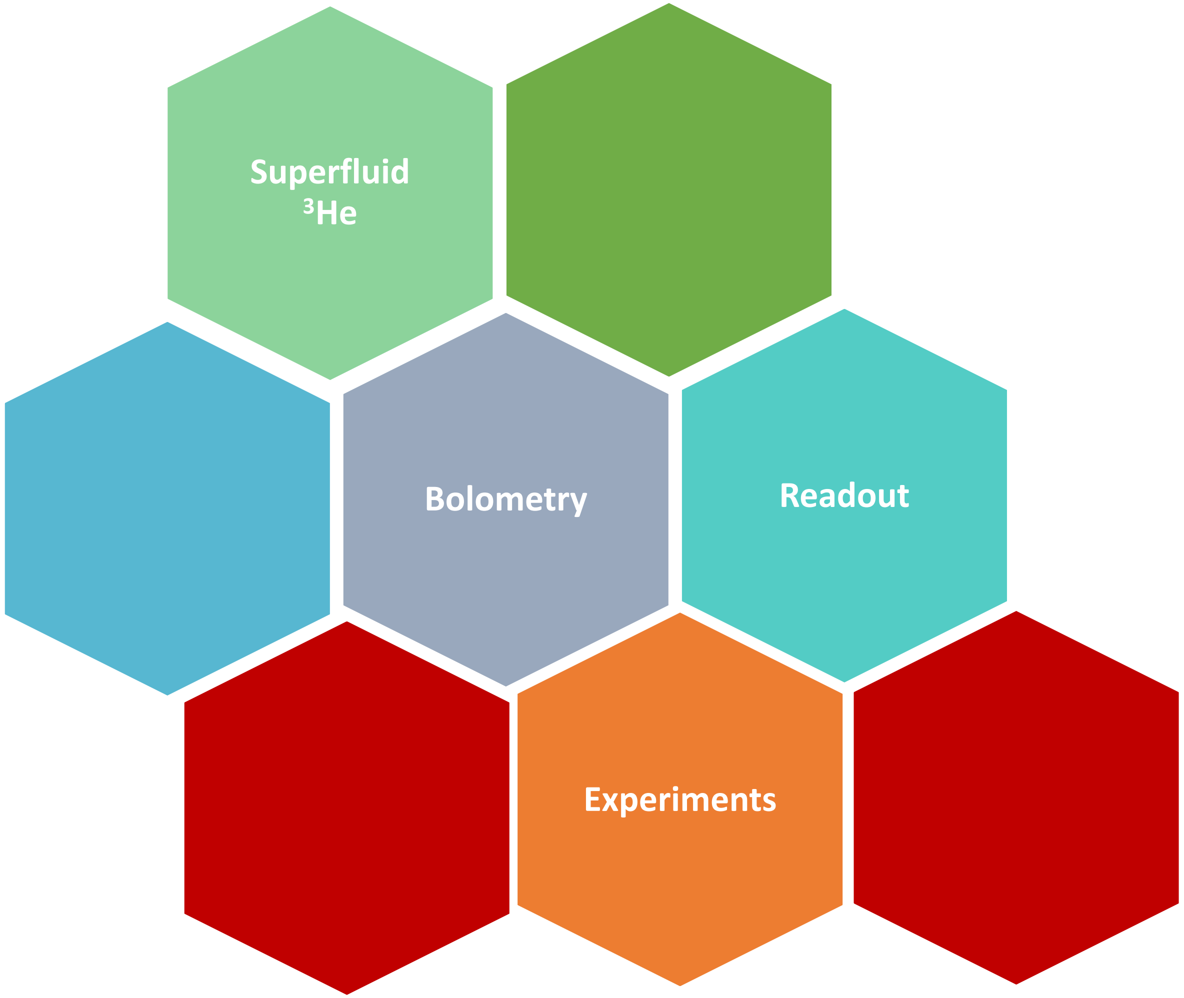
Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

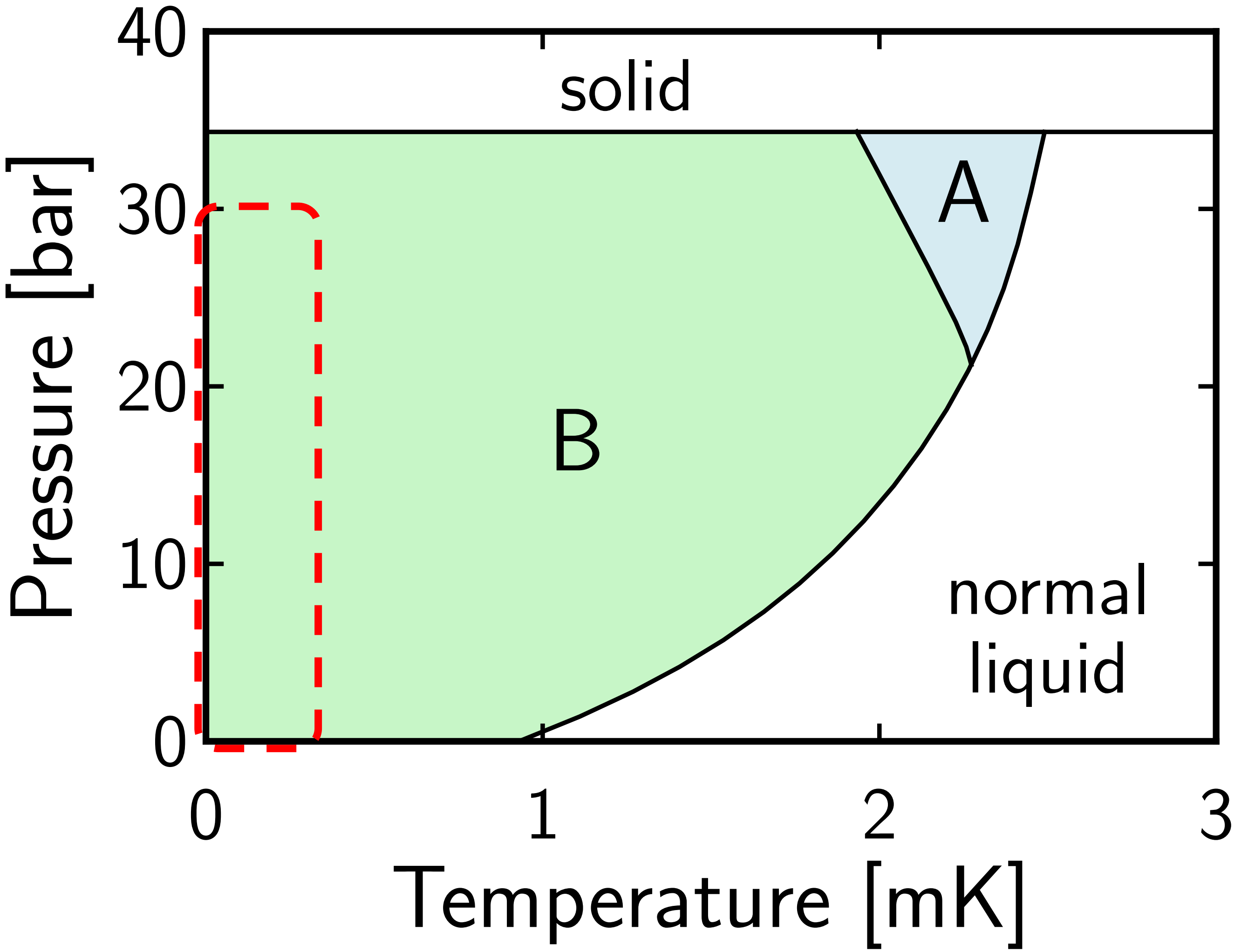
1. Motivation

2. Detector concept

3. Progress and outlook



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)**

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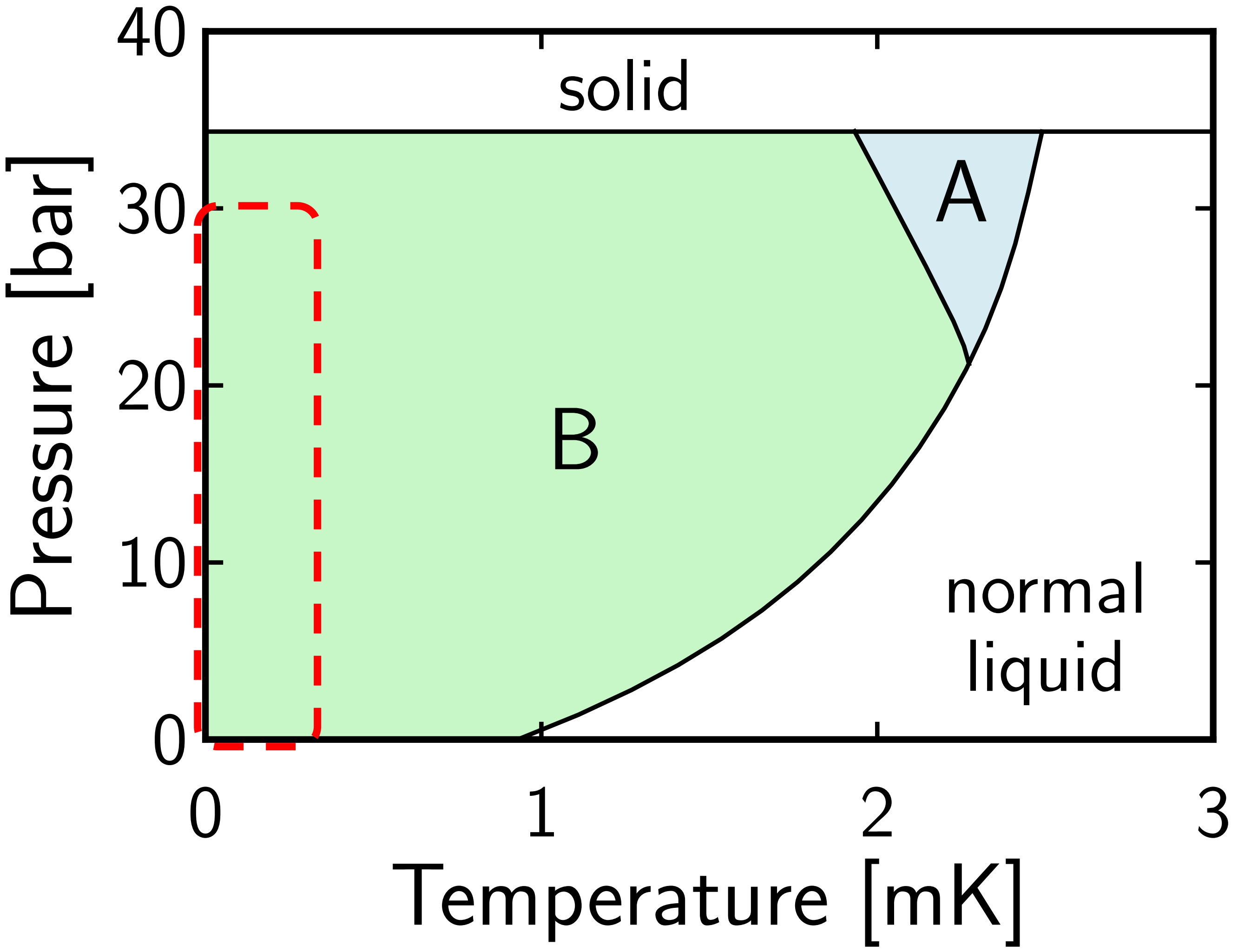

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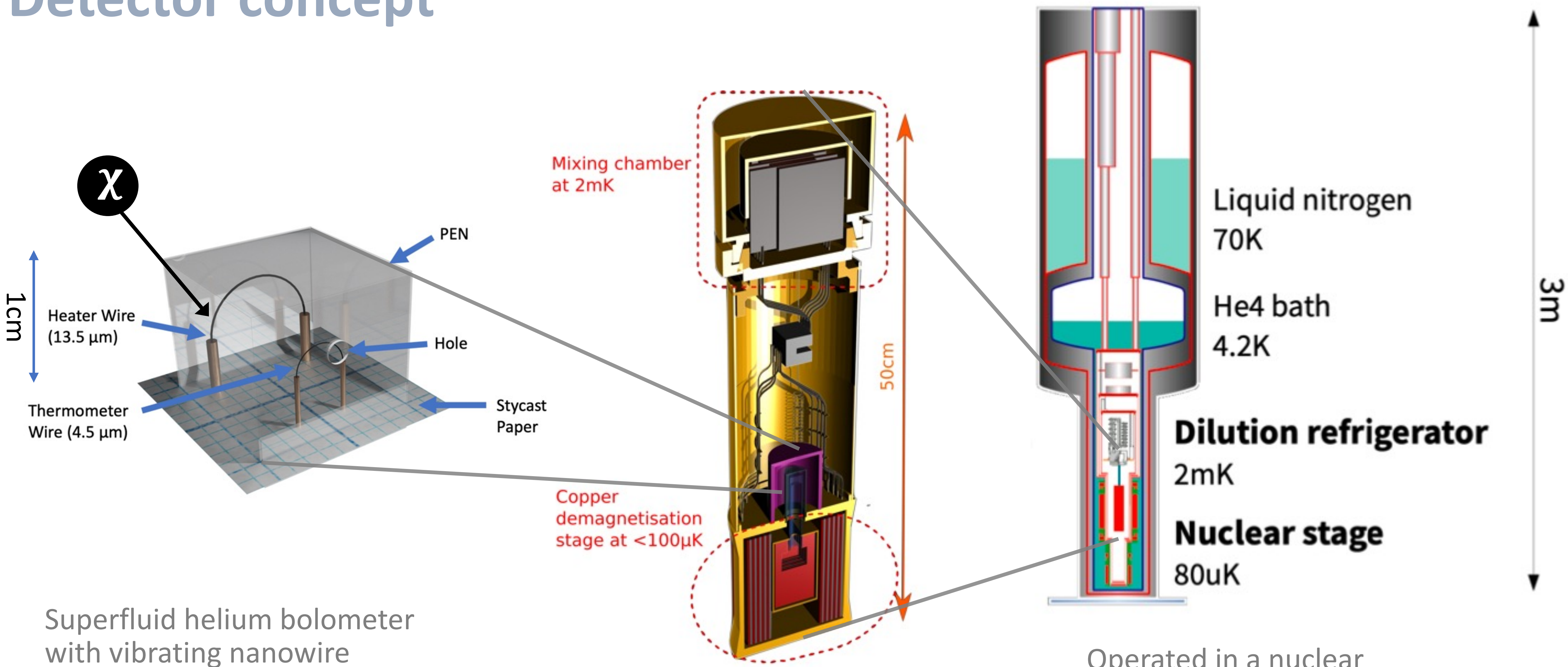
Unpaired nucleon:

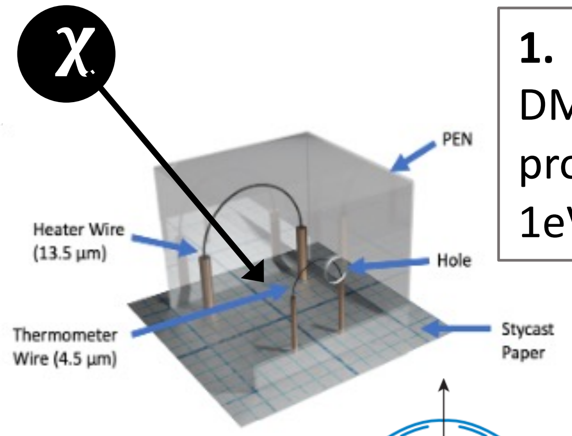
➢Spin dependent dark matter – nucleon interaction

Detector concept



Superfluid helium bolometer with vibrating nanowire resonators (VWRs)

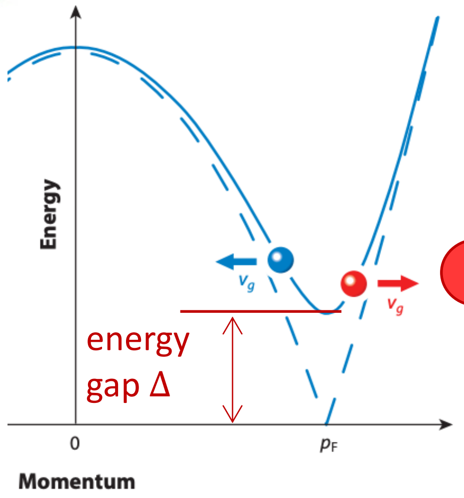
Operated in a nuclear demagnetisation cryostat below 1mK



1. Energy deposit

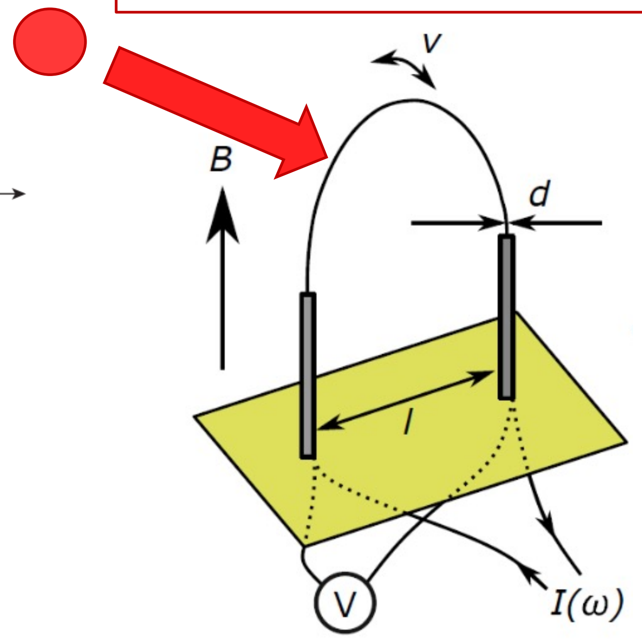
DM – helium scattering produces quasiparticles (QPs)

1eV → 10^7 quanta



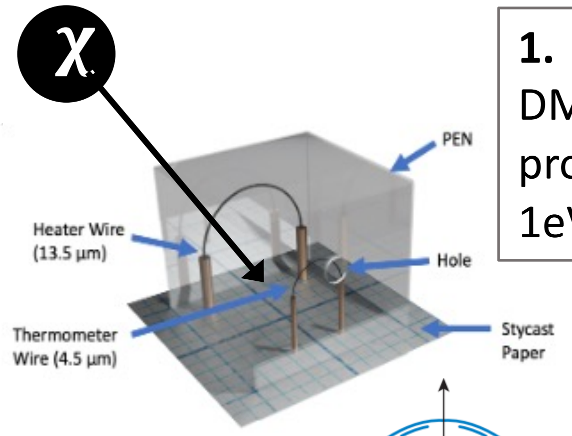
2. Ballistic propagation

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



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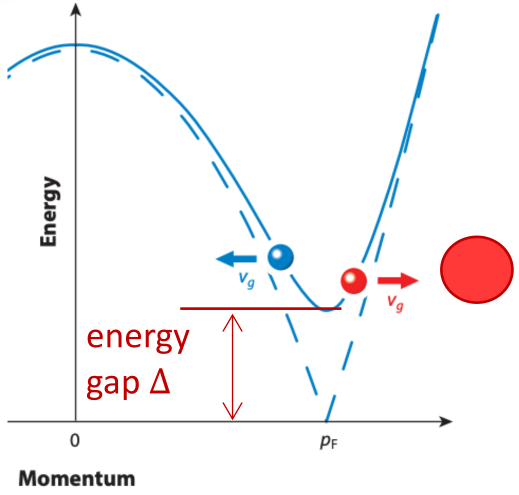
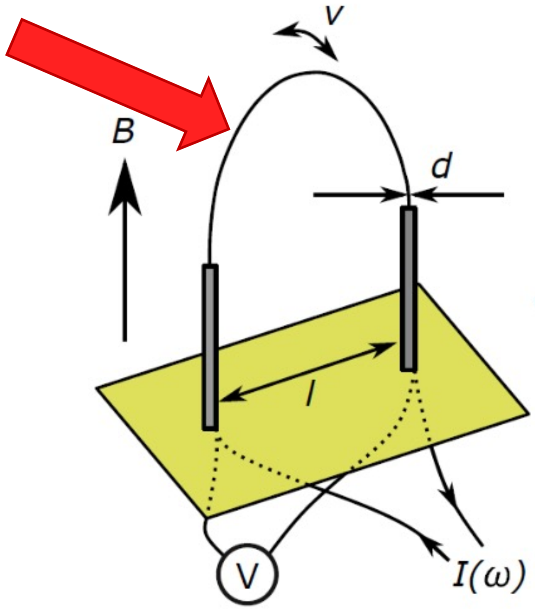


2. Ballistic propagation
QP collisions with nanowire exert damping force

Andreev reflection in superfluid increases damping by ~10^3



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- nanowire driven by AC current in vertical B field
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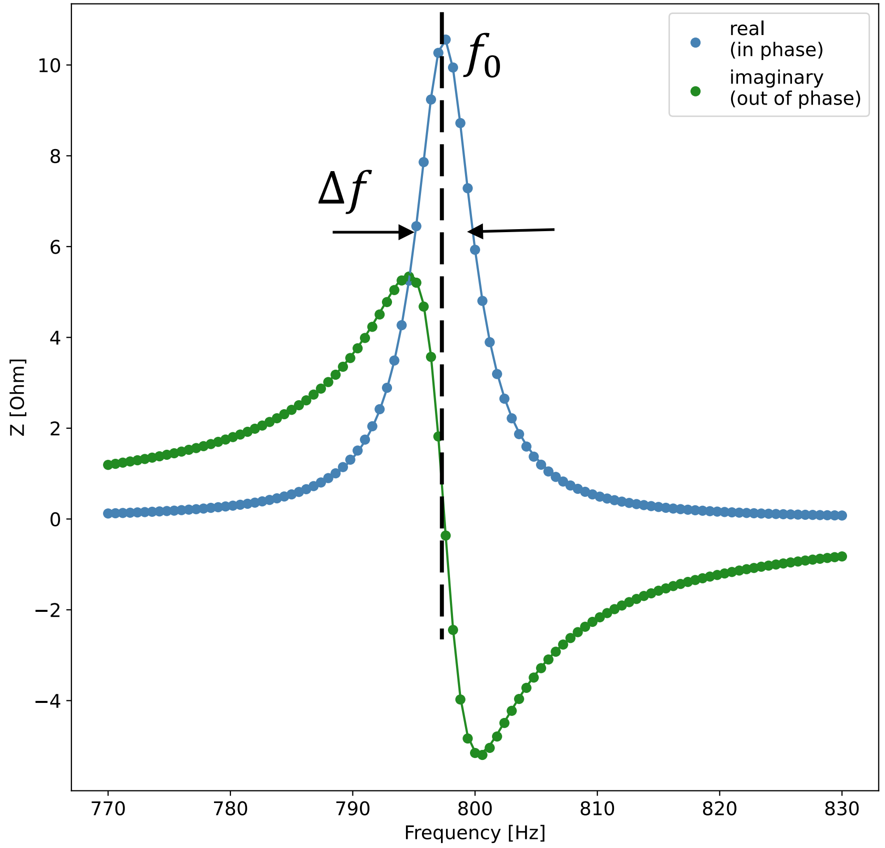
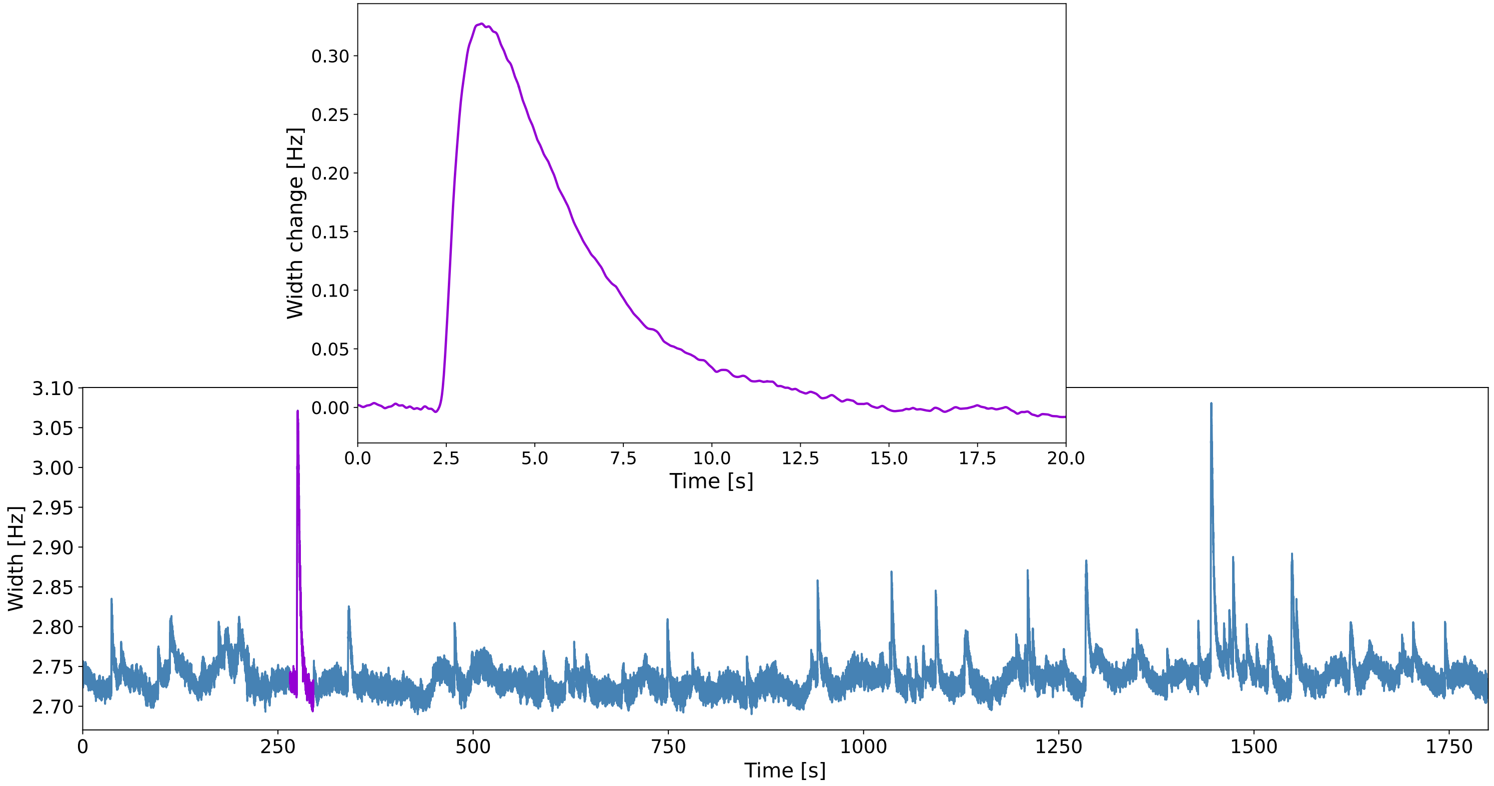
Bolometer measurements

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

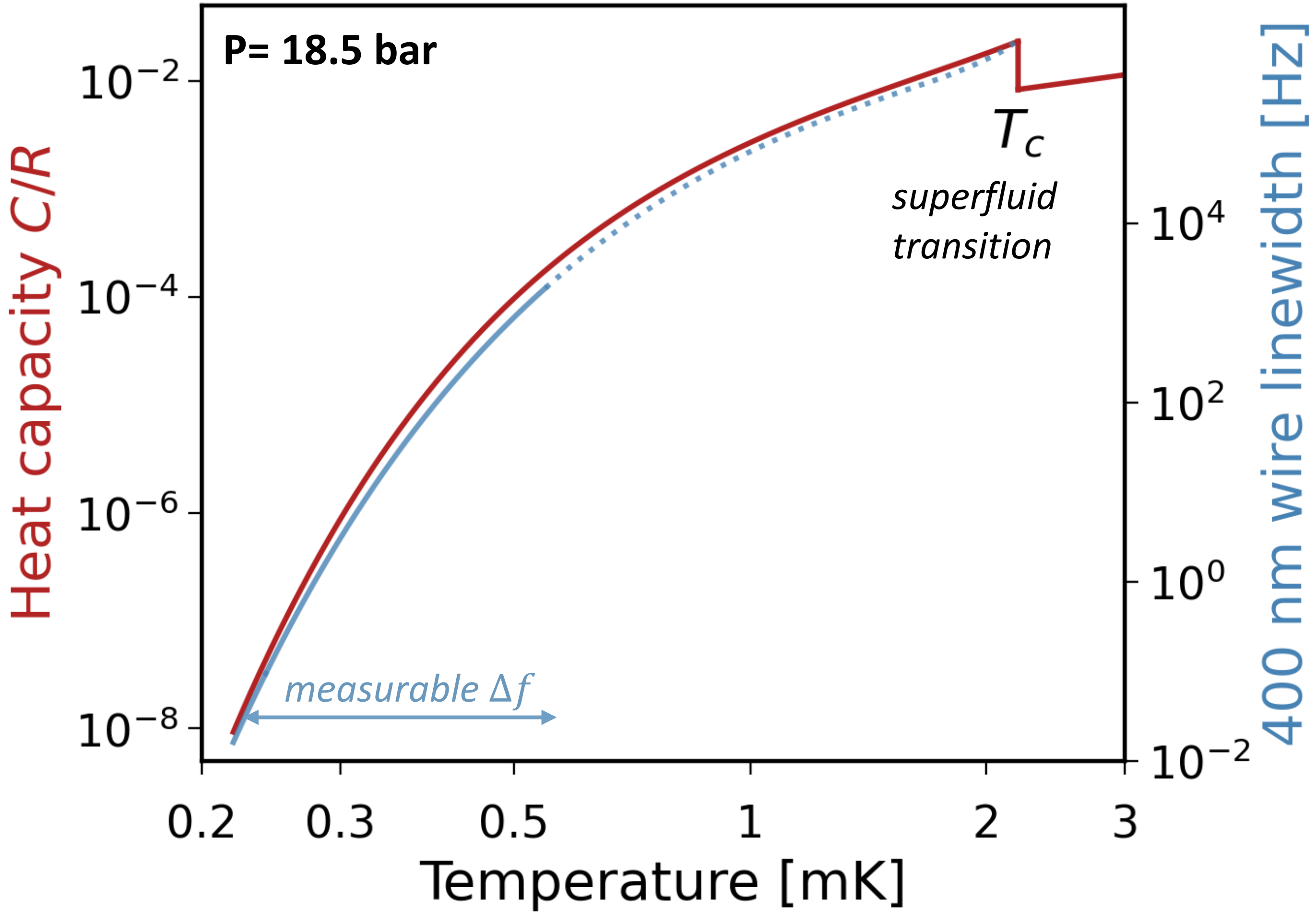




B. Response tracking – drive on resonance

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

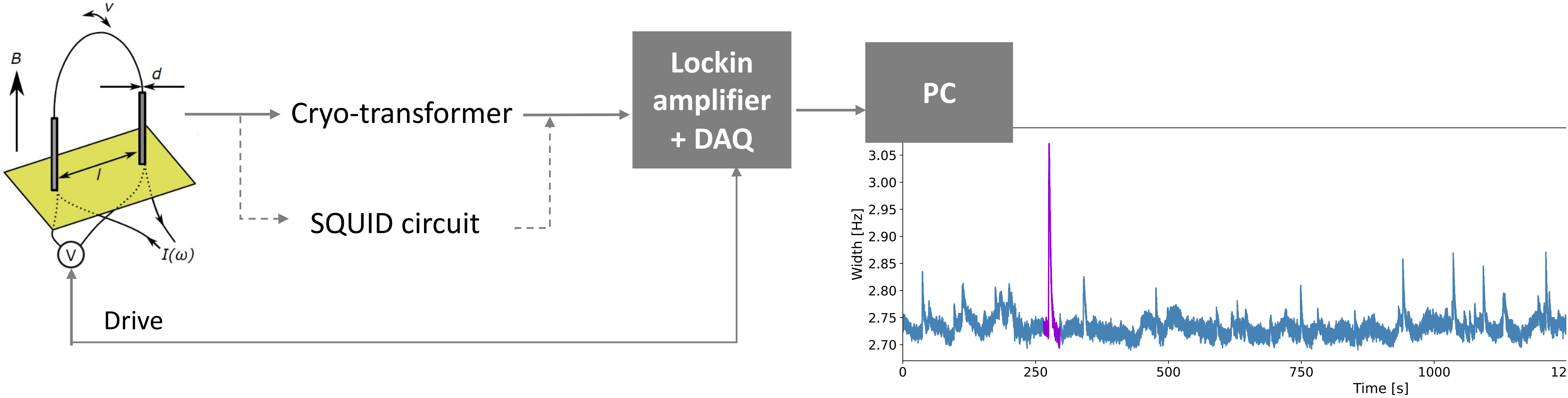
Energy



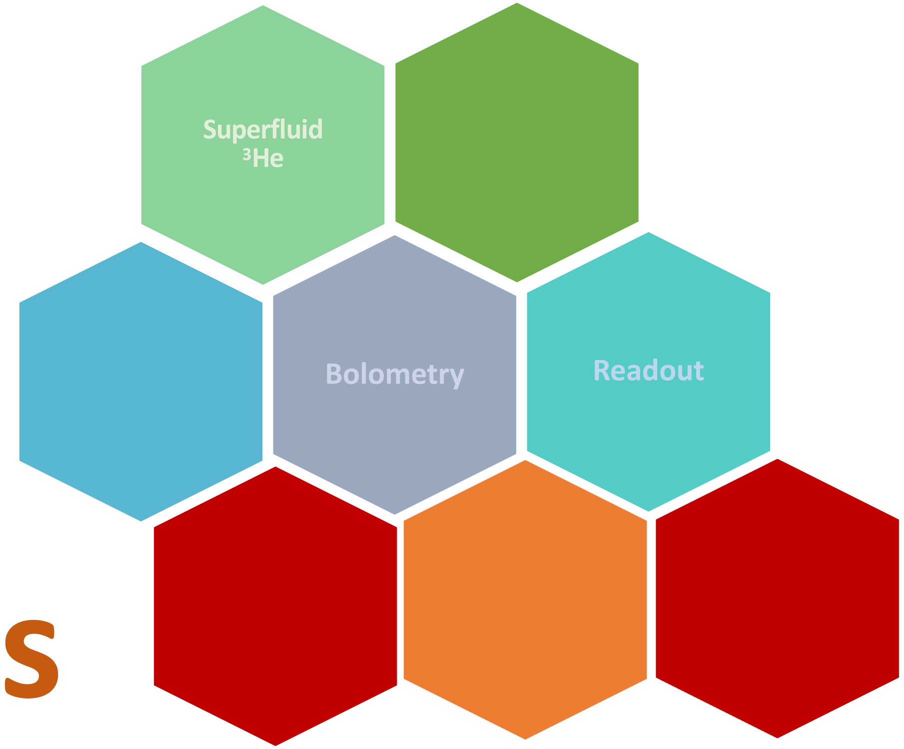
- Very low heat capacity at low temperature – sensitive bolometer
- Linewidth follows heat capacity, simple width change to energy conversion: $E \propto \Delta(\Delta f)$

- **Calibration** using second heater wire
  - drive on resonance above pair breaking velocity to create QPs
  - detect response in thermometer wire
- Also use radiation sources e.g. ^{55}Fe

Low noise readout

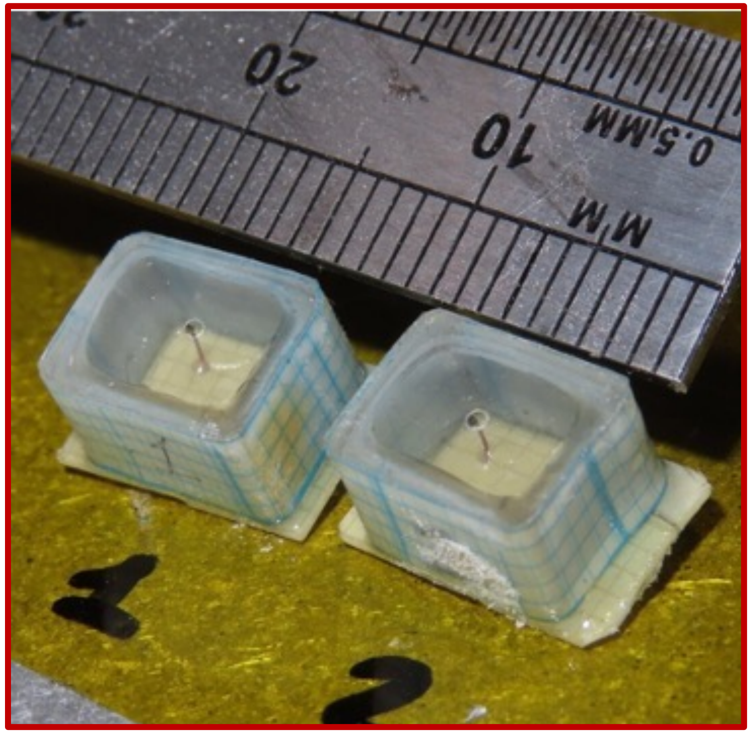


- Noise in V_0 measurement determines energy threshold
- Two readout schemes:
  - **conventional** passive cryo-transformer – room temperature lockin noise dominates
  - **SQUID** preamplifier, higher gain – SQUID noise dominates
- Simulated energy thresholds: 39 eV with conventional readout, 0.71 eV with SQUID readout [QUEST-DMC: *Eur. Phys. J. C* **84**, 248 (2024)]



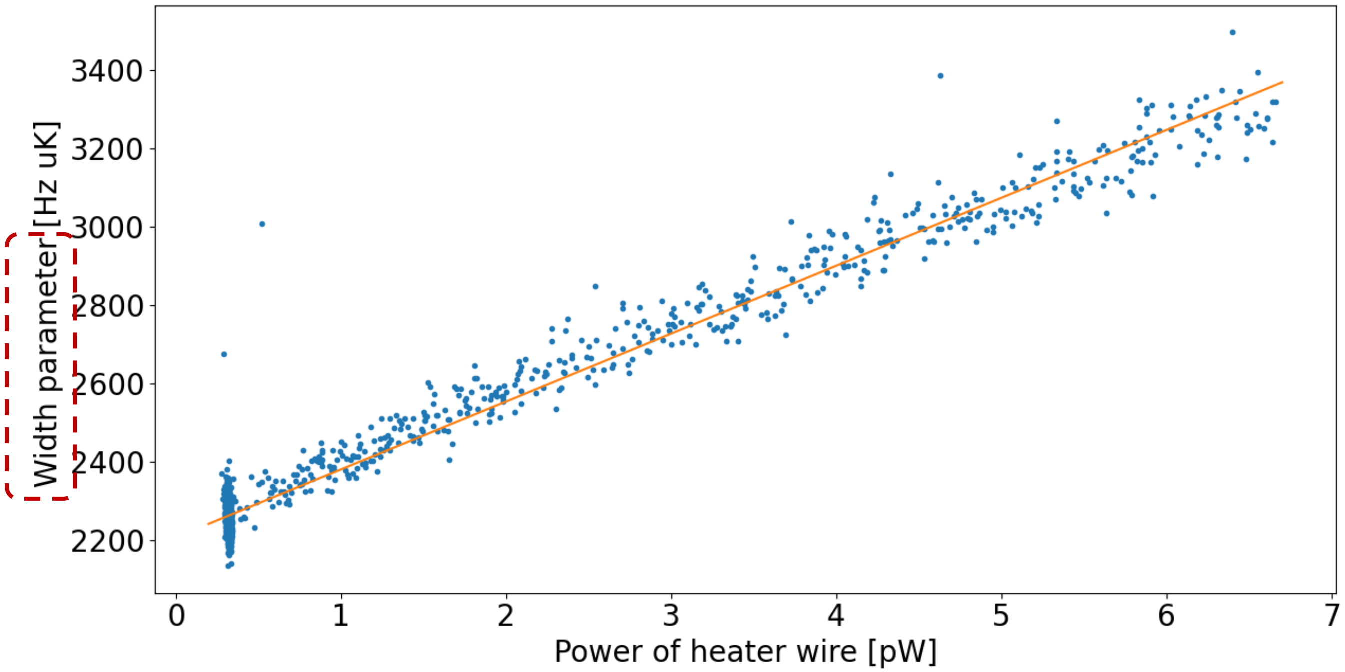
Experiment Progress

Lancaster Run (2023)



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

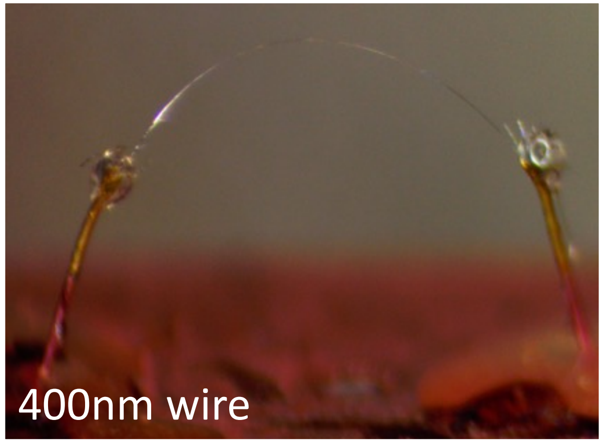
Calibration: change in width of thermometer wire vs (known) injected heater power to find calibration coefficient: $P = K(\Delta\mathrm{f} - \Delta f_0)T$



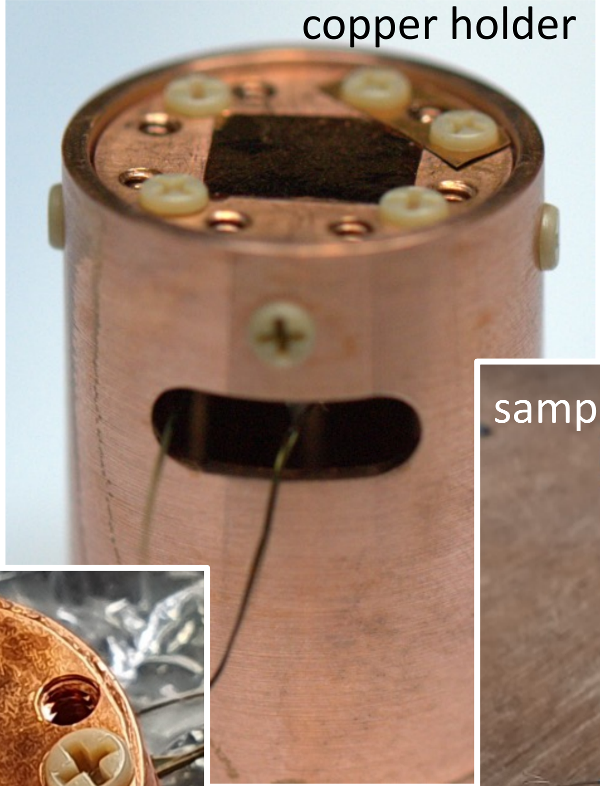
Ran for 8 months achieving temperatures down to 0.15mK

RHUL SQUID readout tests

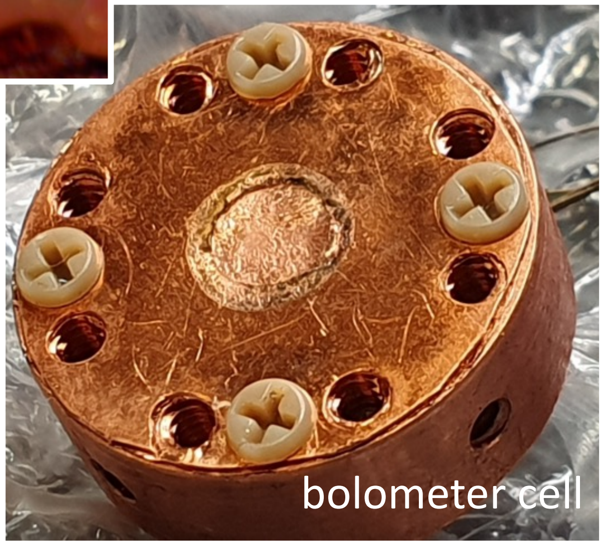
June-Dec. 2024: copper cell containing 400nm and 4500nm VWRs operated ~0.3mK



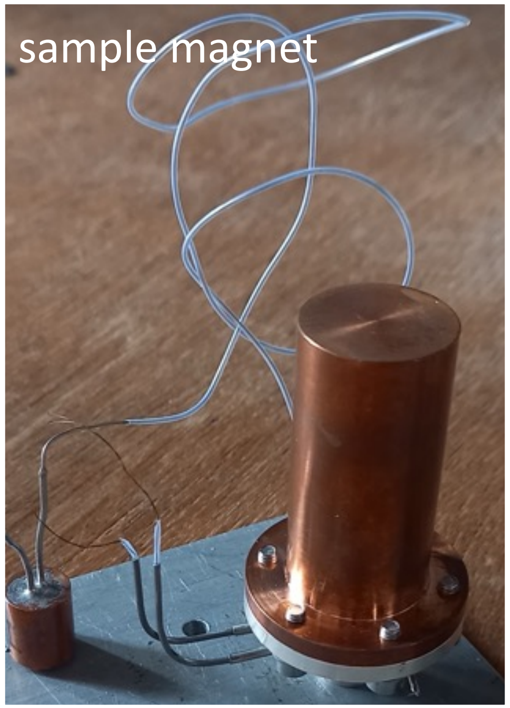
400nm wire



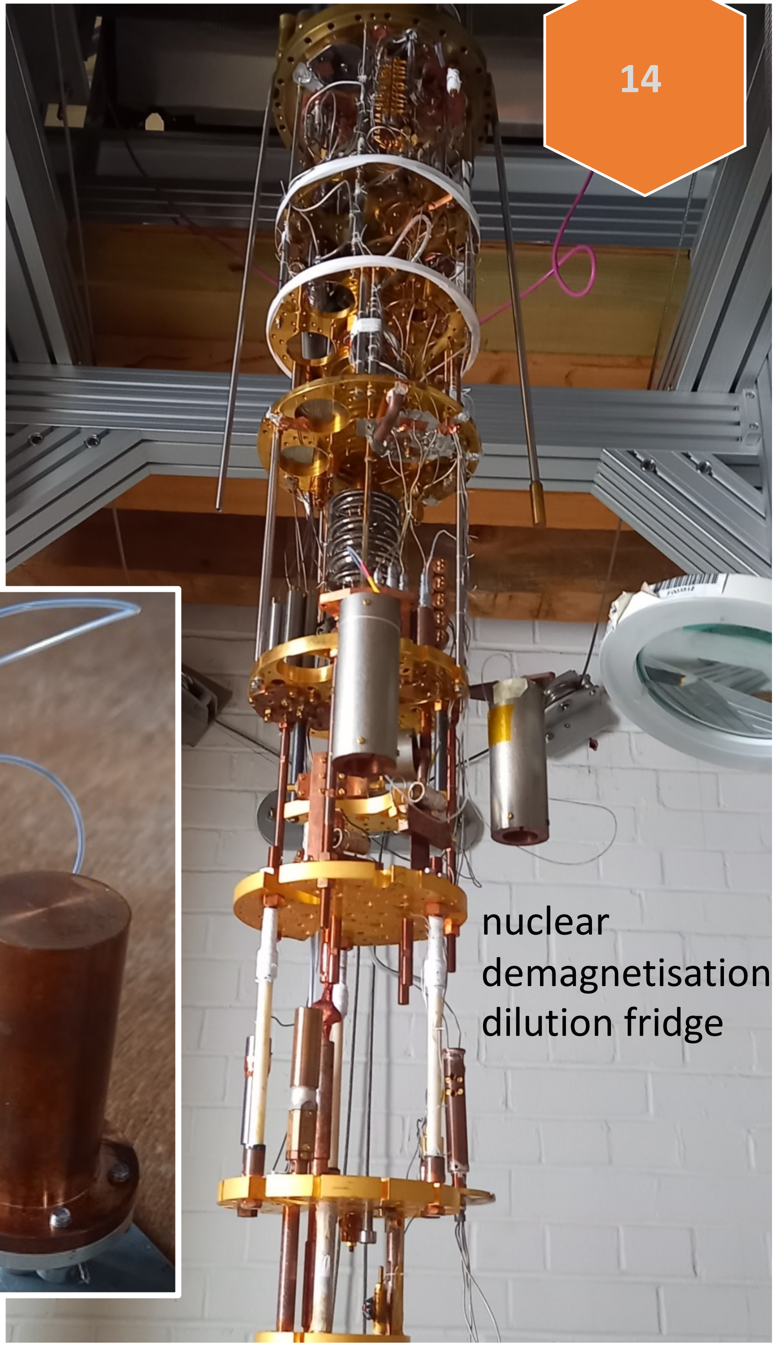
copper holder



bolometer cell



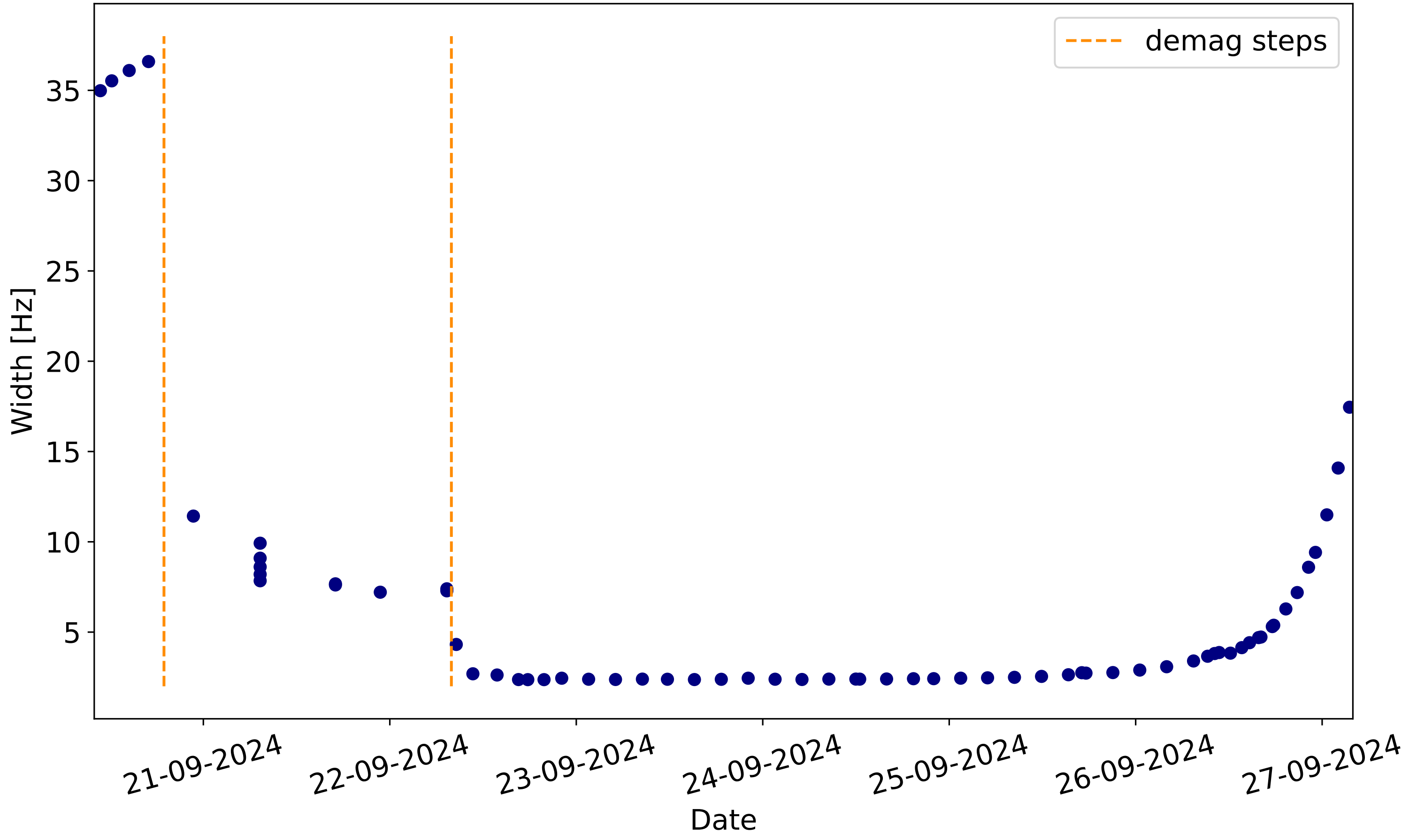
sample magnet



nuclear demagnetisation dilution fridge

RHUL bolometer

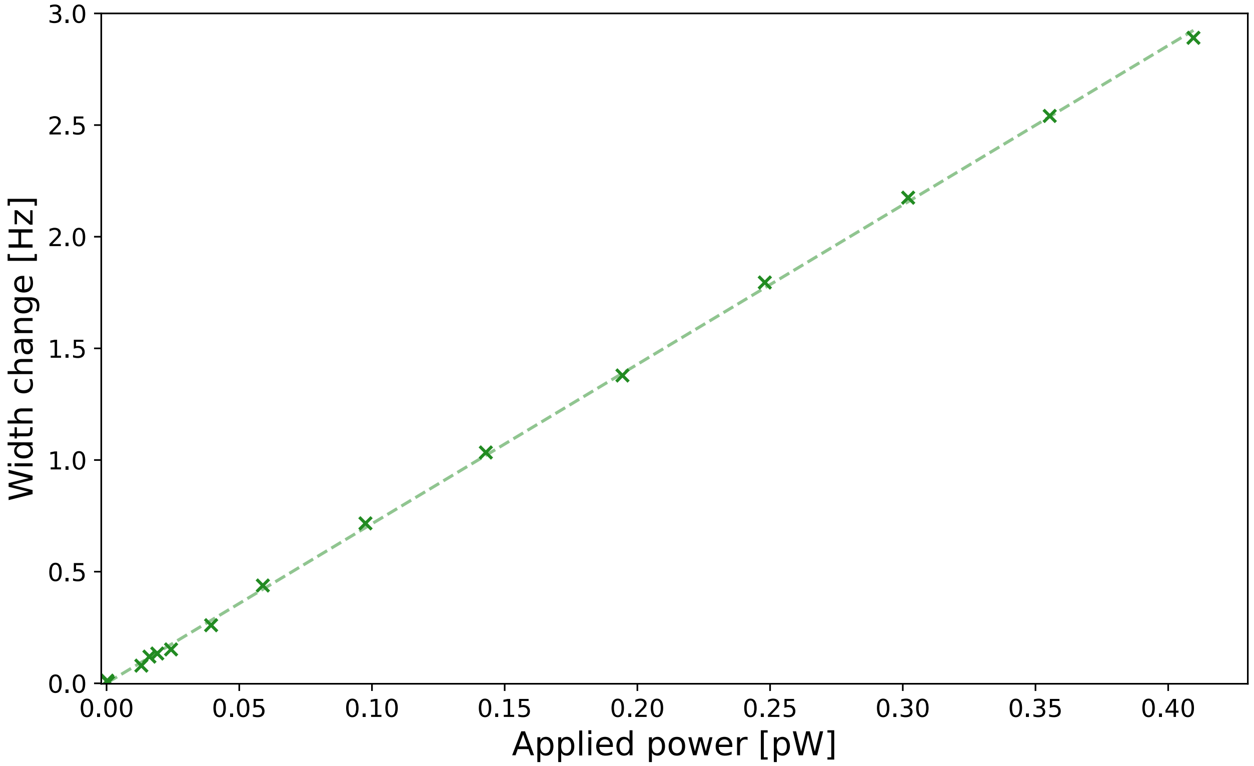
- ✓ operation of 400nm wires in bolometer cell
  - SQUID readout circuit
  - 5 day stable run time (at 0.3mK)
- ✓ noise characterisation and optimisation for SQUID readout
- ✓ heater wire calibrations



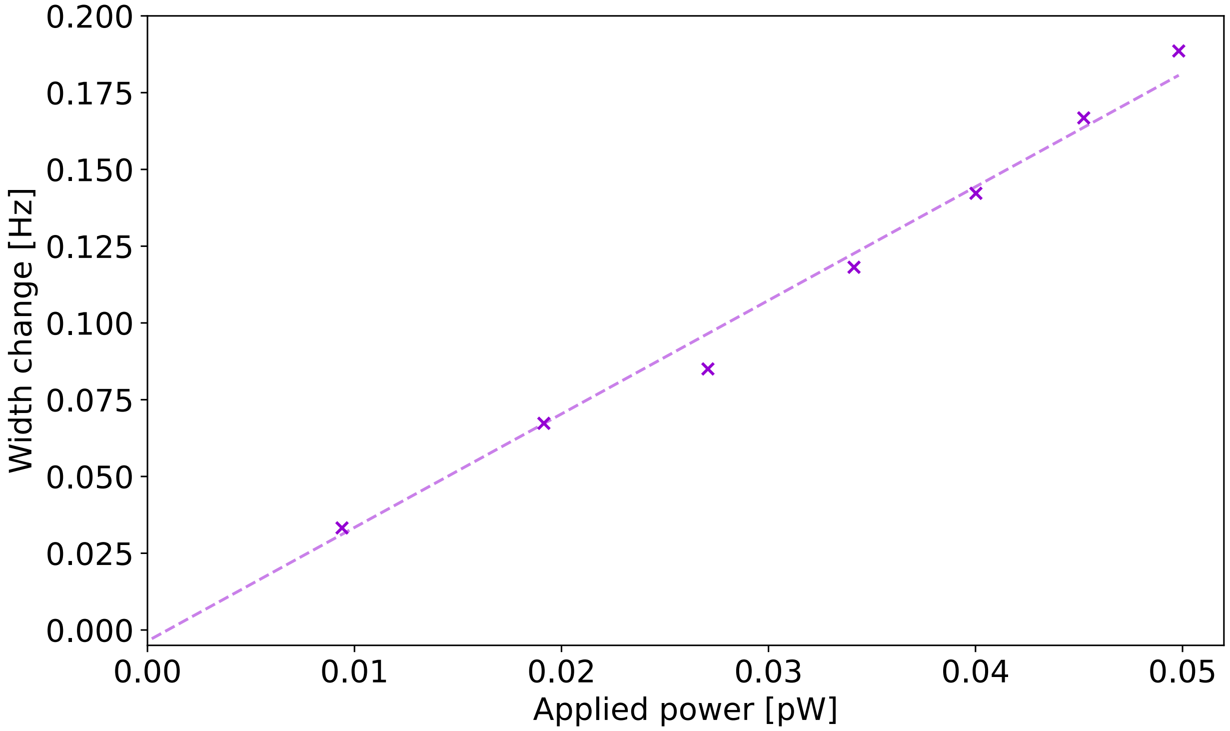
Heater wire calibration

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

A) 400nm detector (4500nm heater)



B) 4500nm detector (400nm heater)



10 fW heat pulses

Outlook

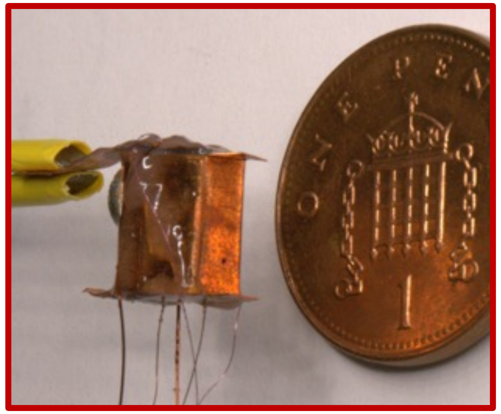
Plans

Lancaster run …

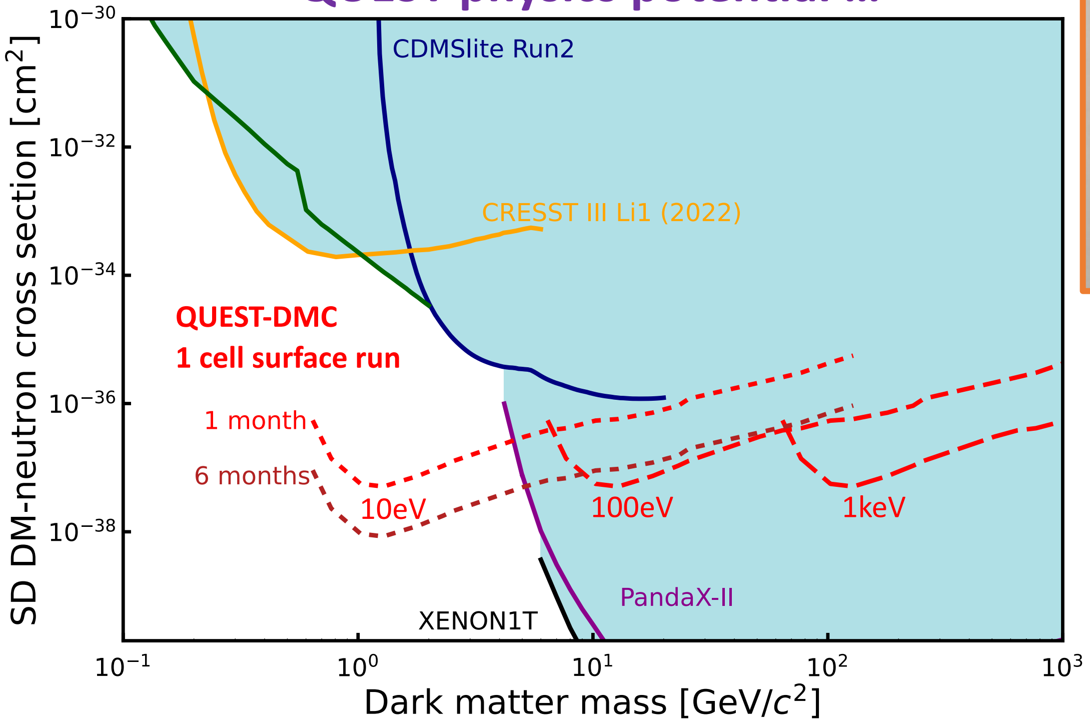
- folder copper cell
- SQUID readout and increased exposure – *main DM search run*

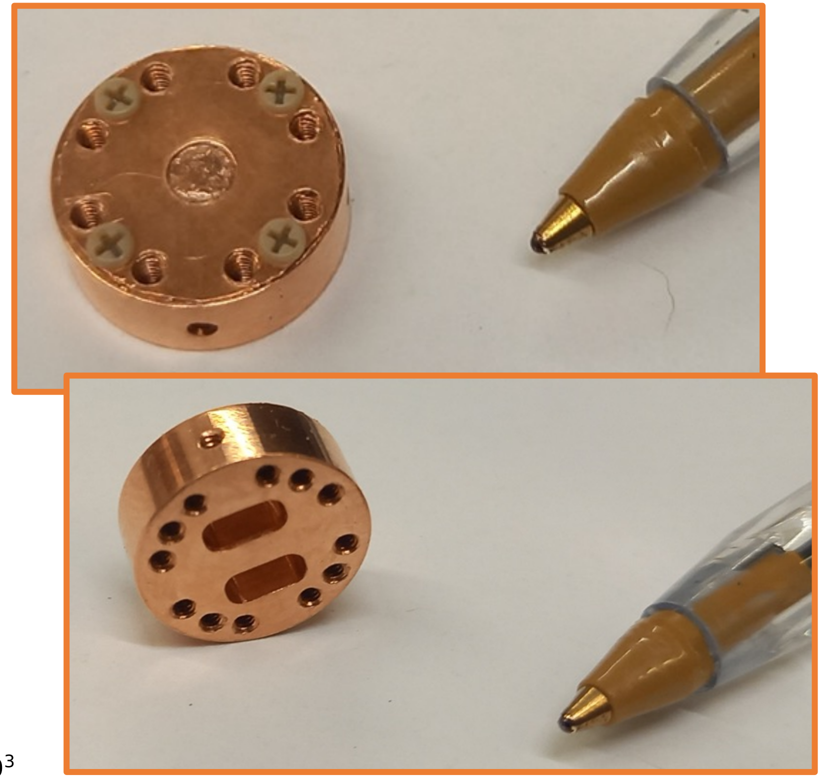
RHUL run …

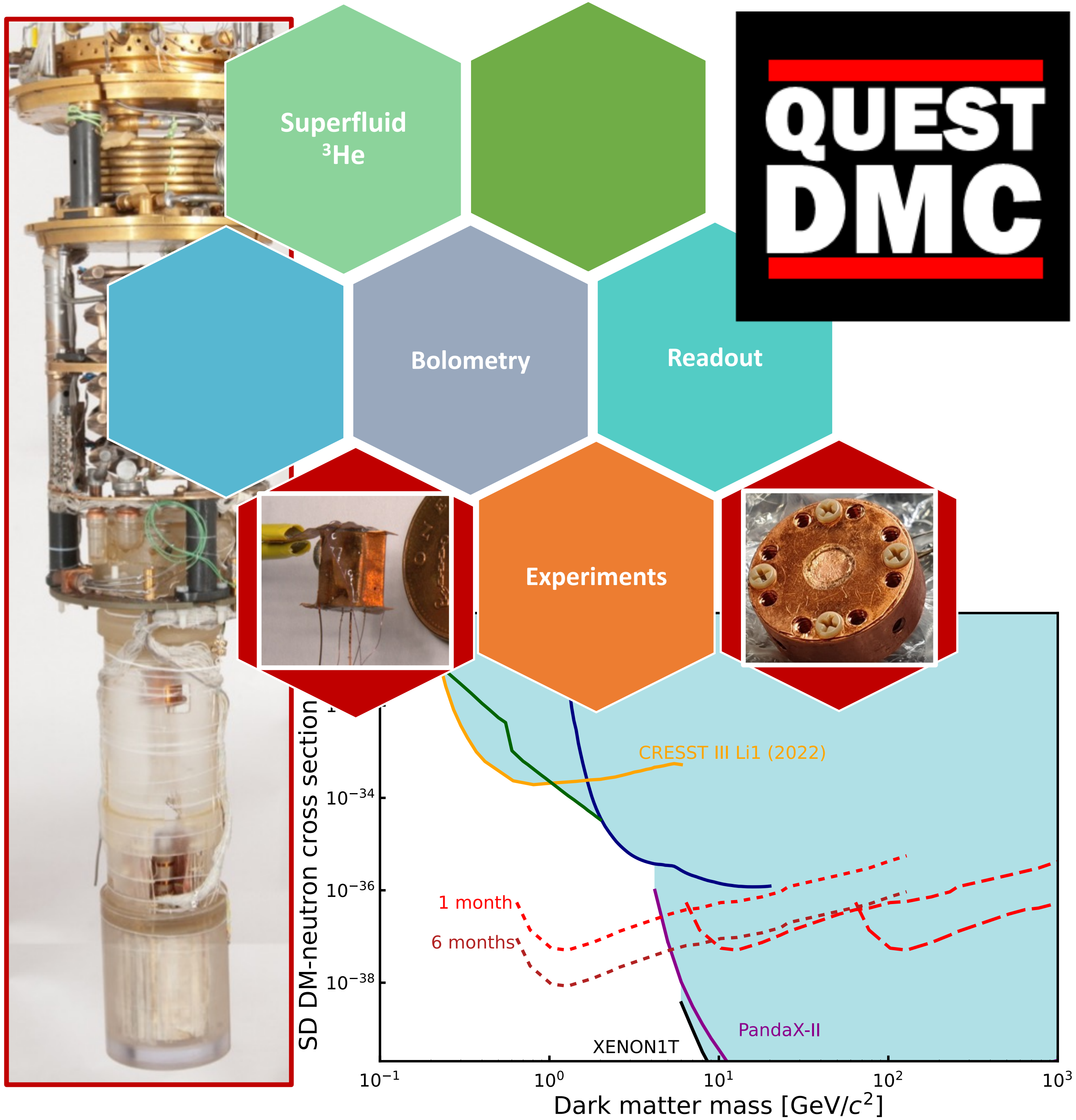
- Machined cell in copper puck
- 400nm and 4.5um nanowires
- SQUID readout noise optimisation
- ^{55}Fe source calibration



QUEST physics potential …







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

2. Proof of principle bolometer operation

- nanowire fabrication
- bolometer DAQ and analysis
- readout optimisation
- calibration strategy

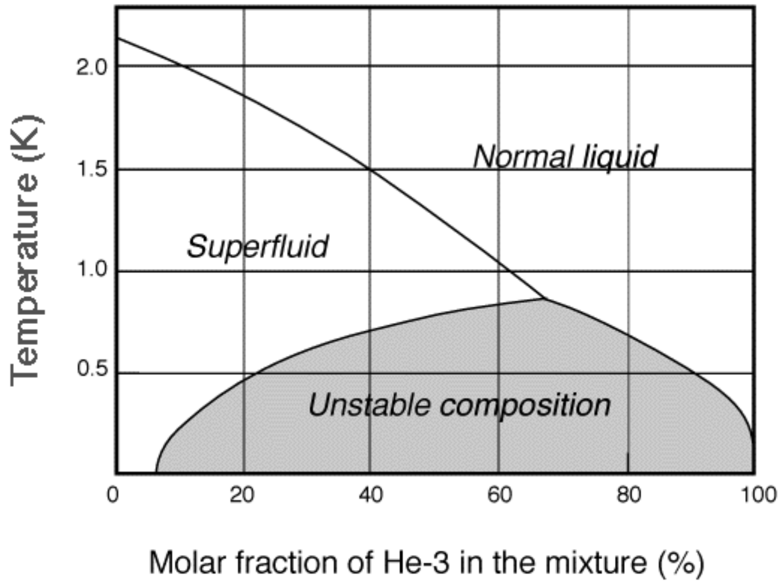
3. Analysis and experimental runs in progress!

Backup

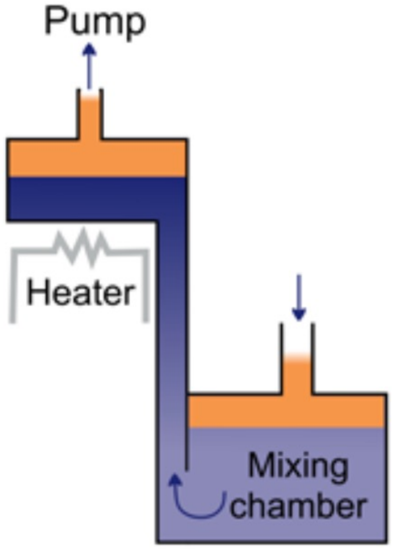
Dilution refrigeration

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:
  $\dot{Q} = 84\dot{n}_3 T^2$ [$\dot{n}_3$ = 3He flow rate across phase boundary]

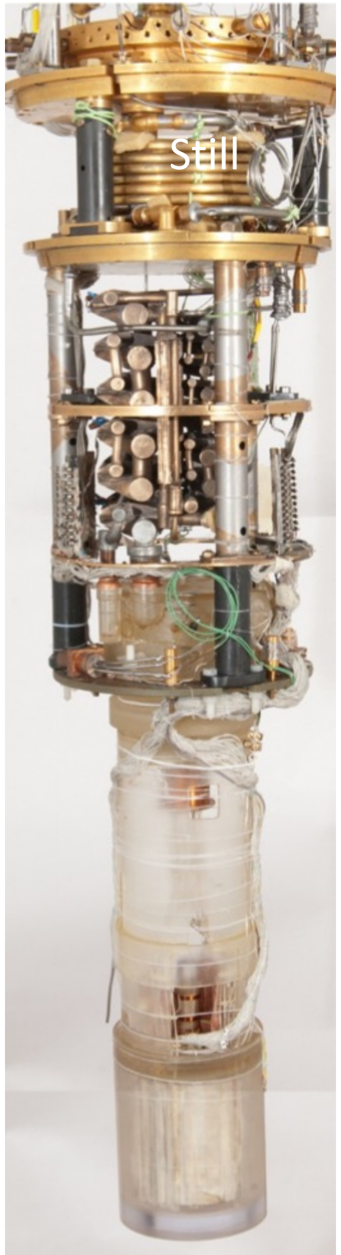


Still



Mixing chamber

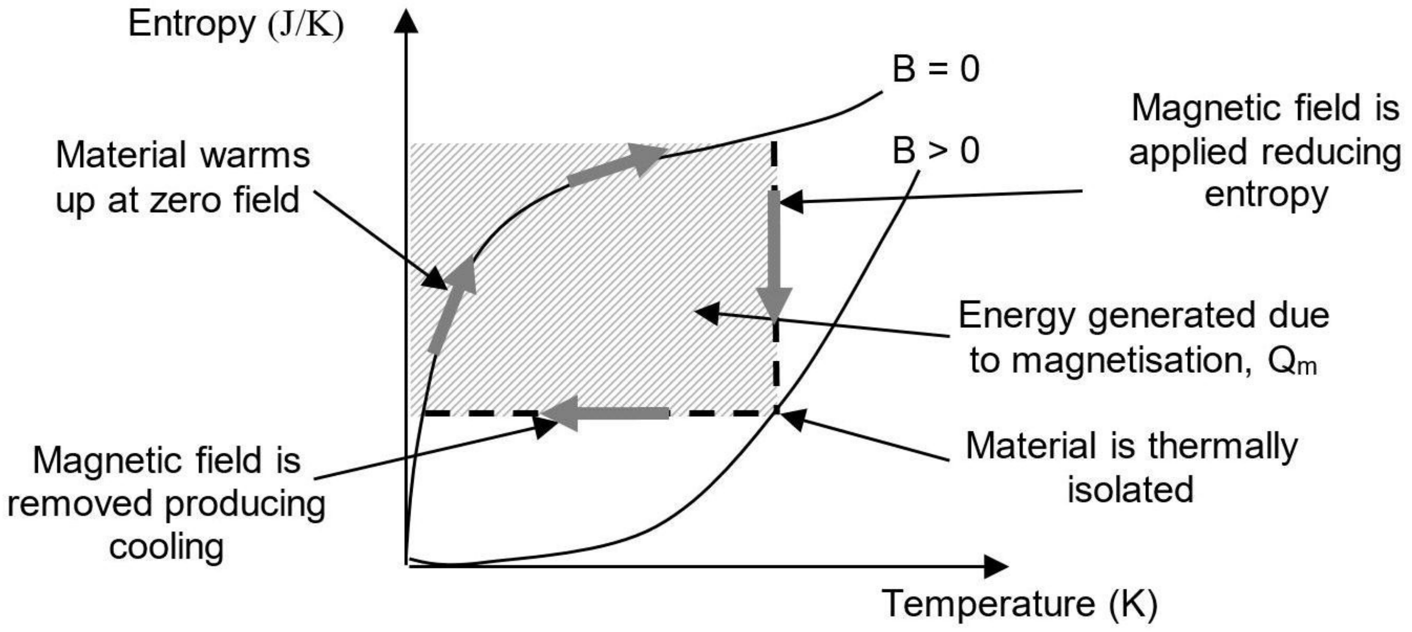
Mixing chamber

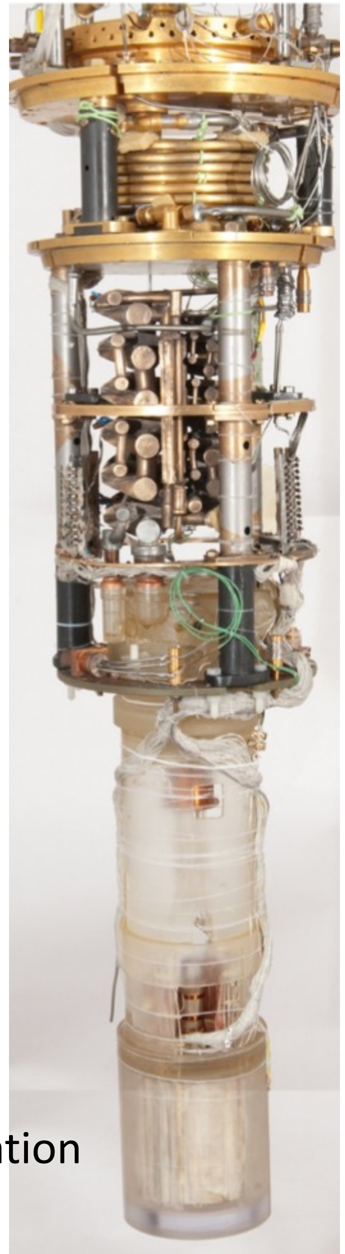


Heat exchangers

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

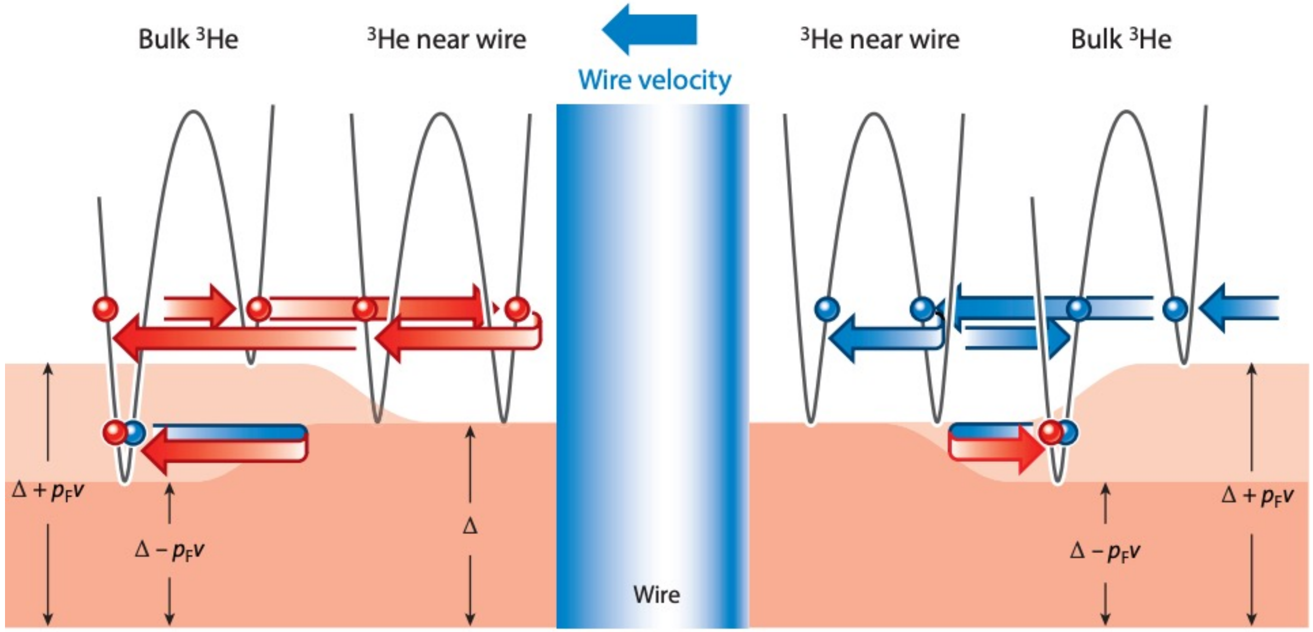




Nuclear demagnetisation stage

Damping force & Andreev scattering

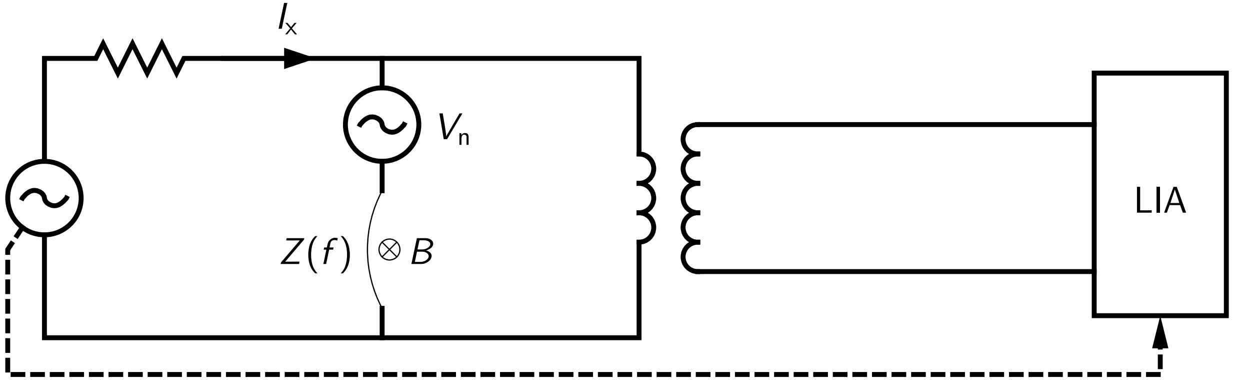
Effect unique to superfluid helium-3 increase QP damping force by 3 orders of magnitude



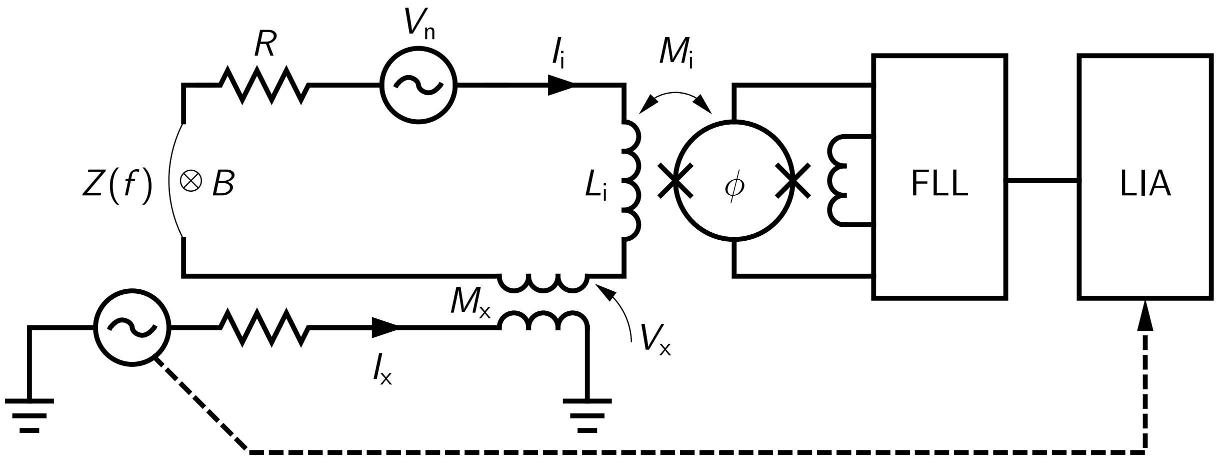
- Fluid flow and relative motion of wire can increase/decrease the gap.
- Only quasiparticles from in front and quasiholes from behind can transfer momentum |2pF|, increasing the damping.

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