

Quantum **E**nhanced **S**uperfluid **T**echnologies for **D**ark **M**atter & **C**osmology

Dr Rob Smith, Rutherford Appleton Laboratory, UK, 12th August 2026

Outline

- The theoretical and experimental landscape of direct dark matter detection
- Where QUEST-DMC fits in
- An overview of the QUEST-DMC experiment
- Operation of the QUEST-DMC experiment
- Physics potential

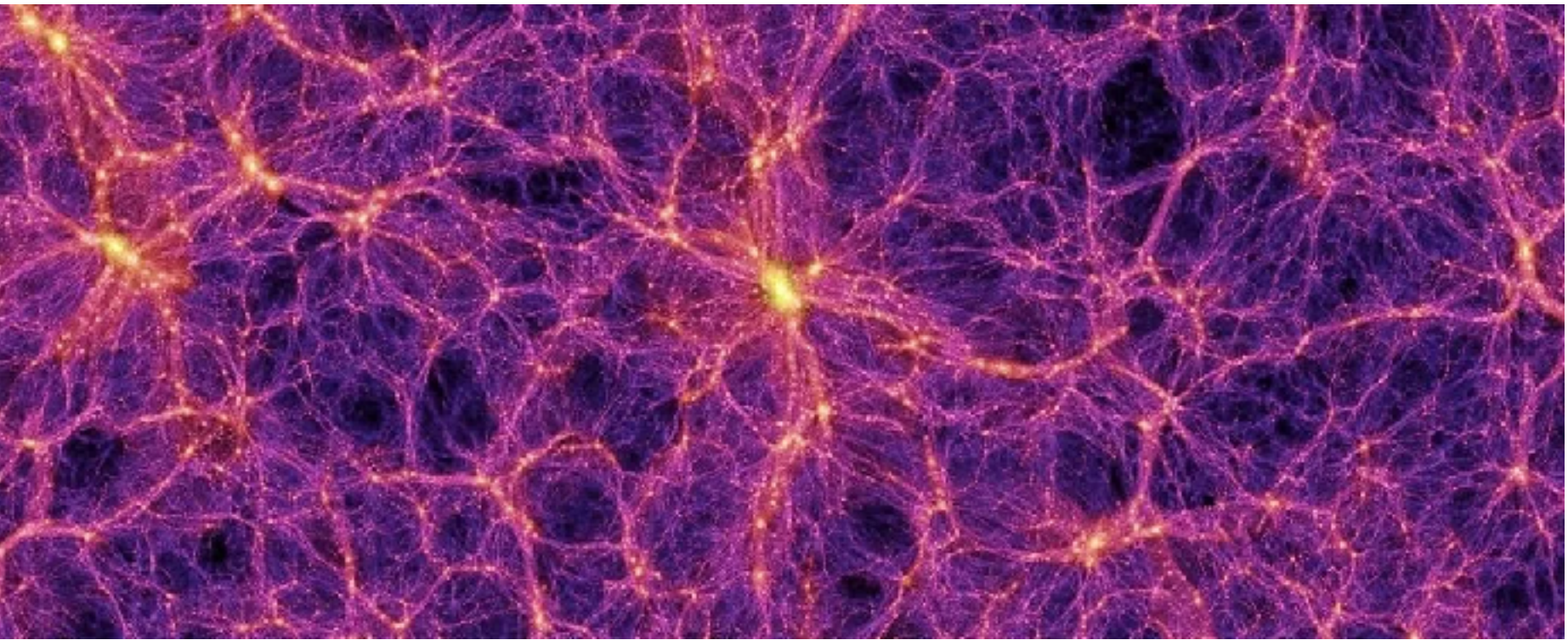
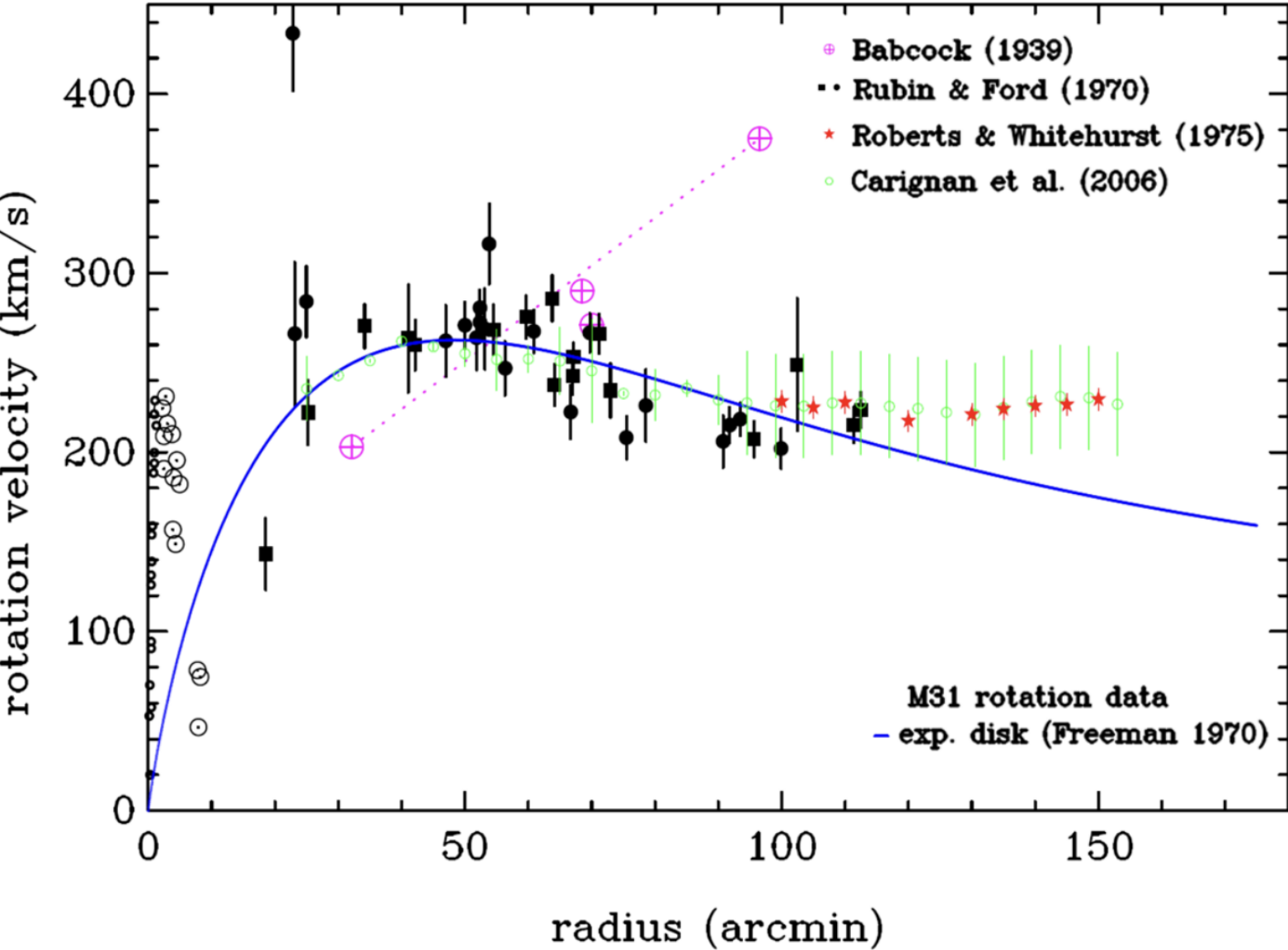
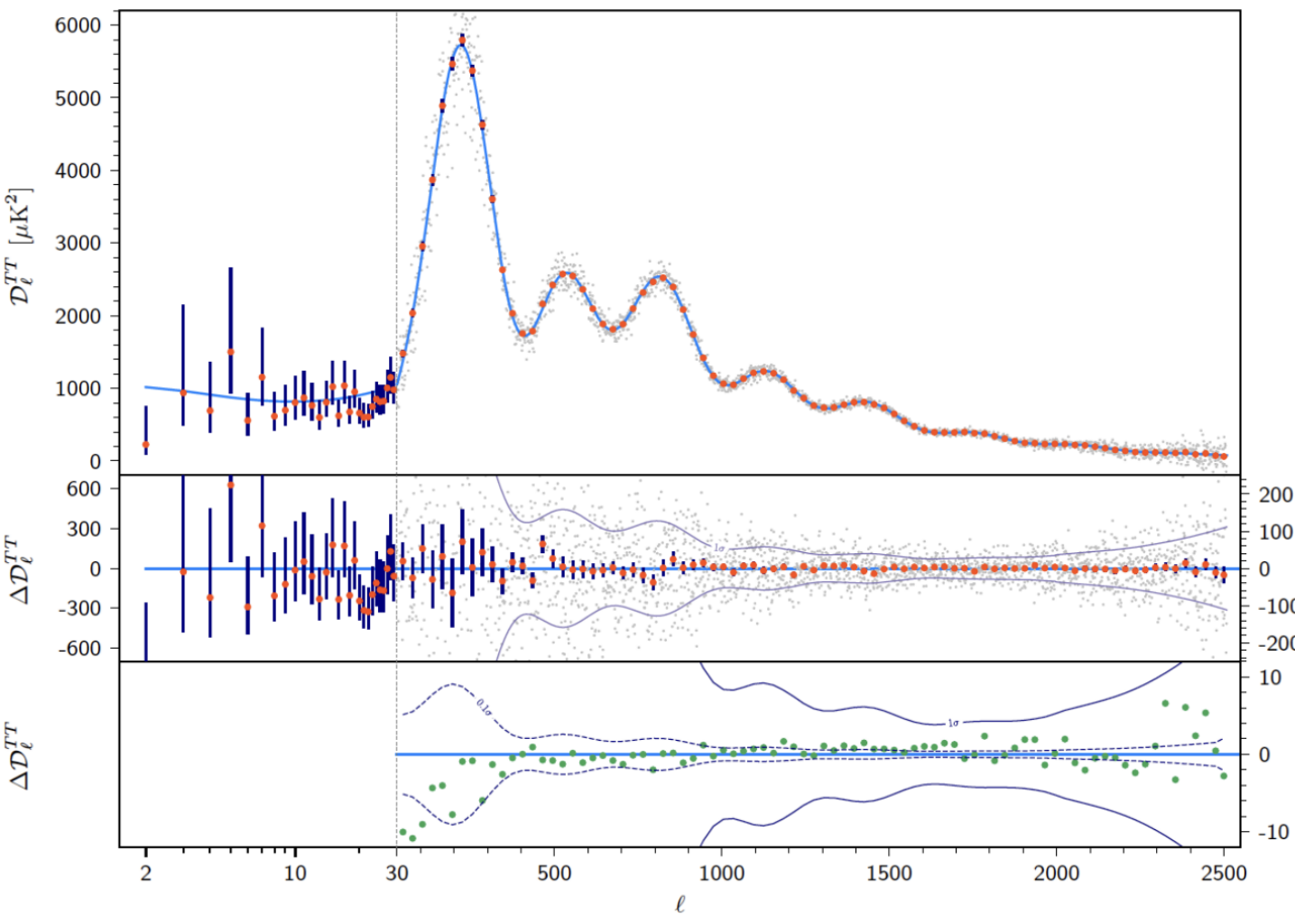
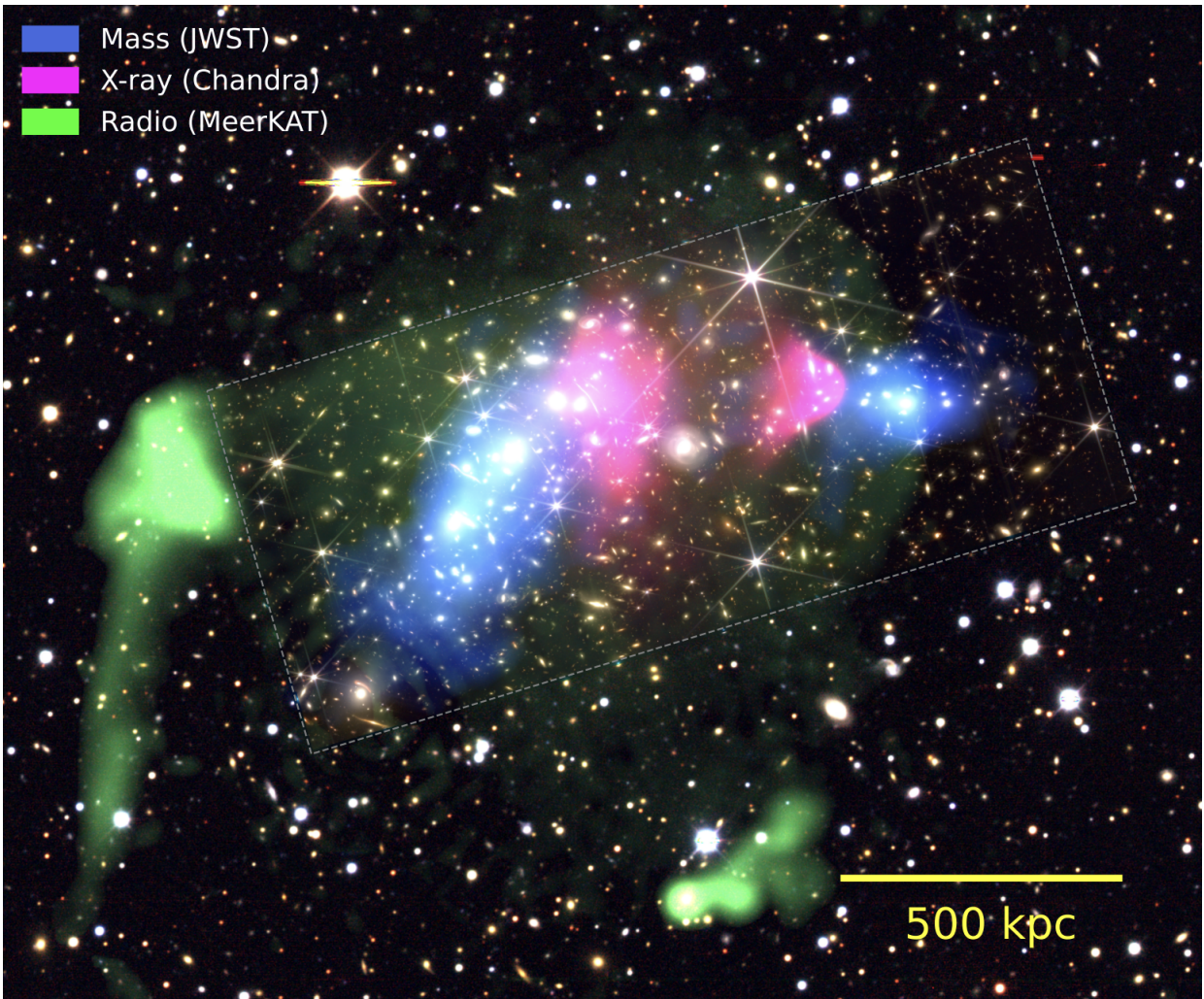
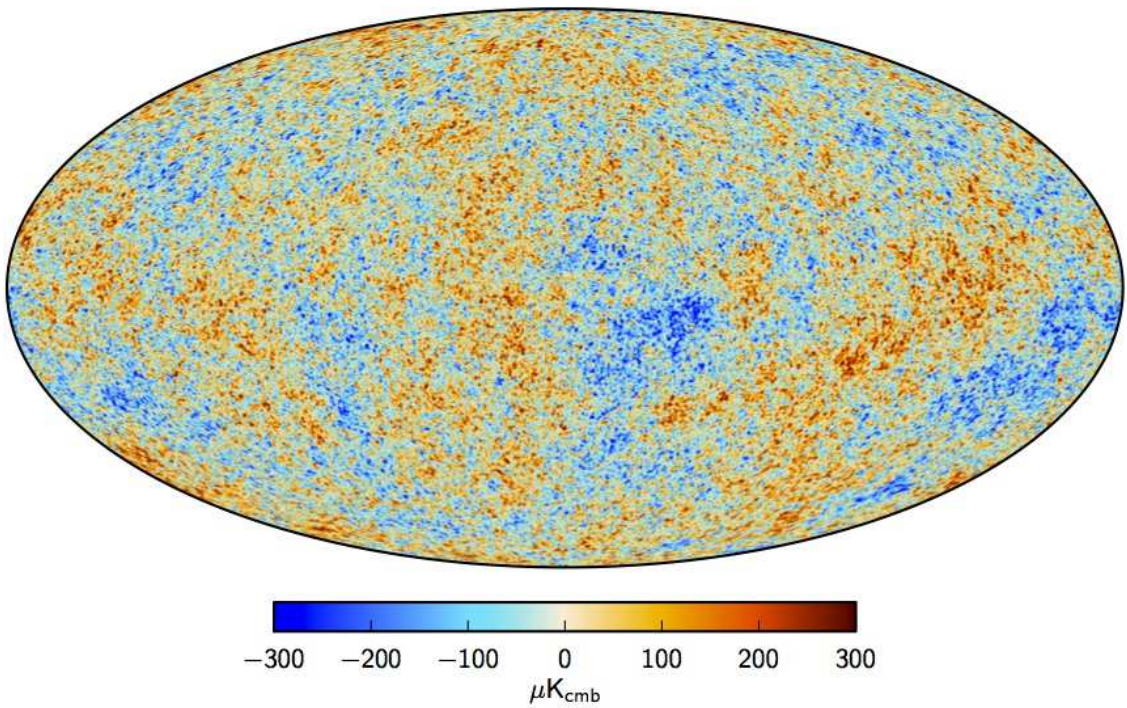
Theoretical and Experimental Landscape

Big Picture

Some of the biggest questions in the physics of our universe today:

- Quantum gravity
- Matter/antimatter asymmetry
- Dark energy
- **Dark matter**

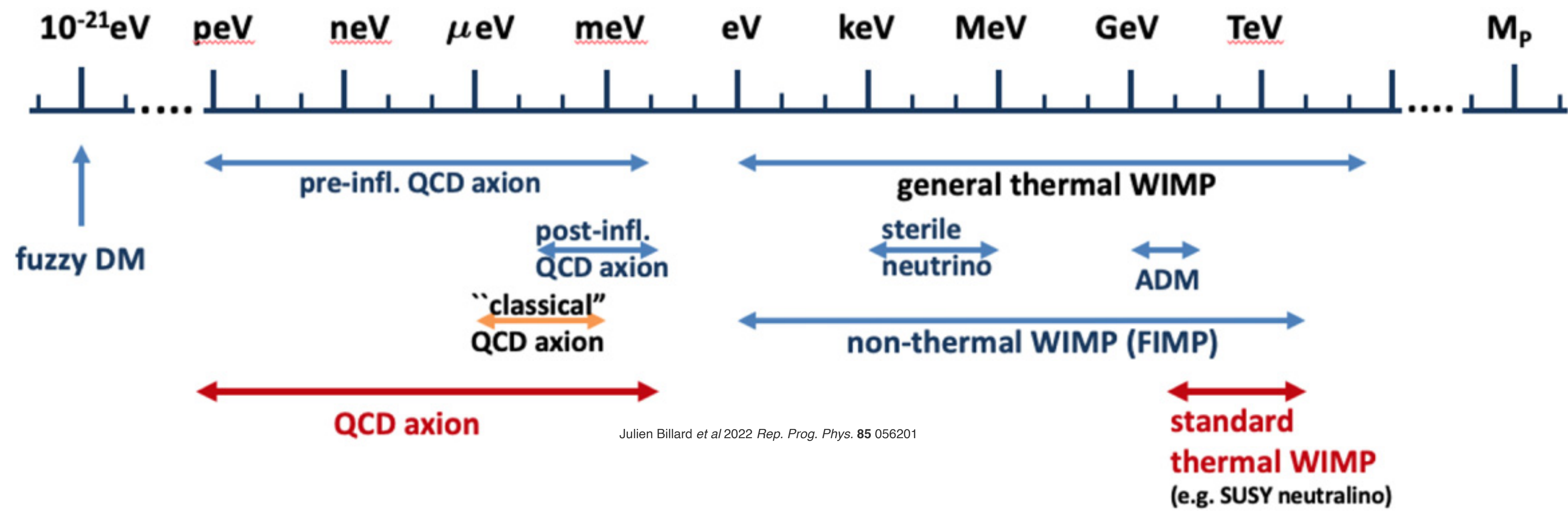
Evidence for Dark Matter



What Makes a Good Candidate?

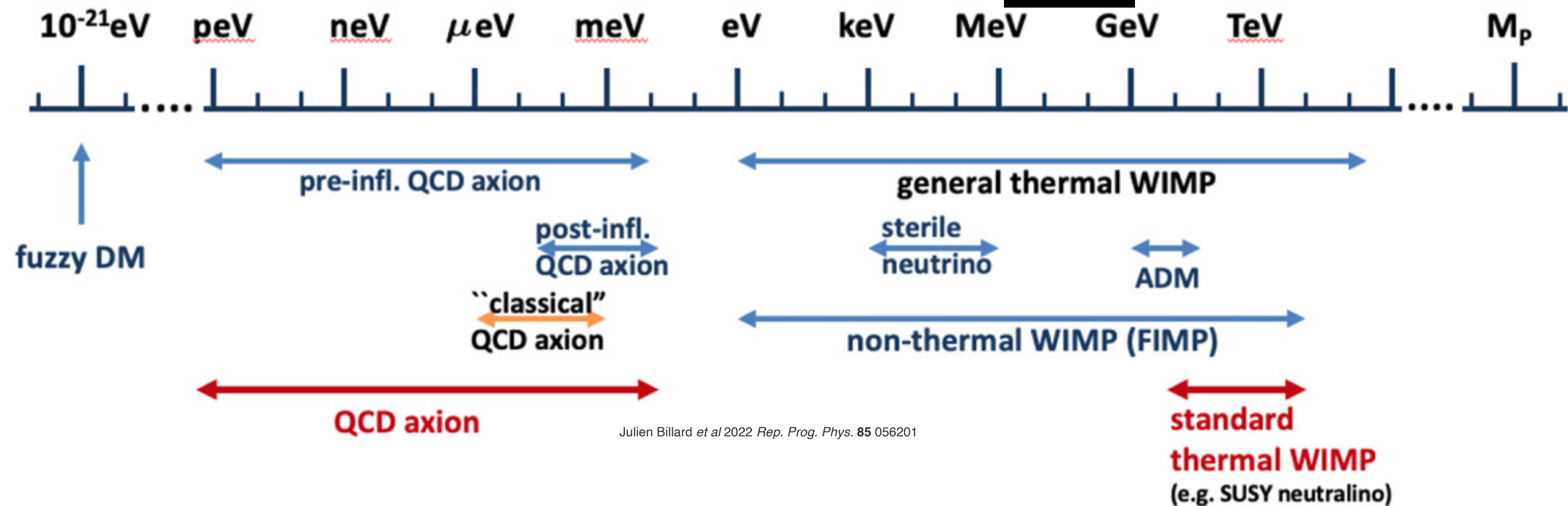
- Stable (or at least on scales similar to the lifetime of the universe)
- Electrically neutral (or incredibly weakly charged)
- Has mass
- Non-baryonic
- Cold (non-relativistic)

BSM Candidates



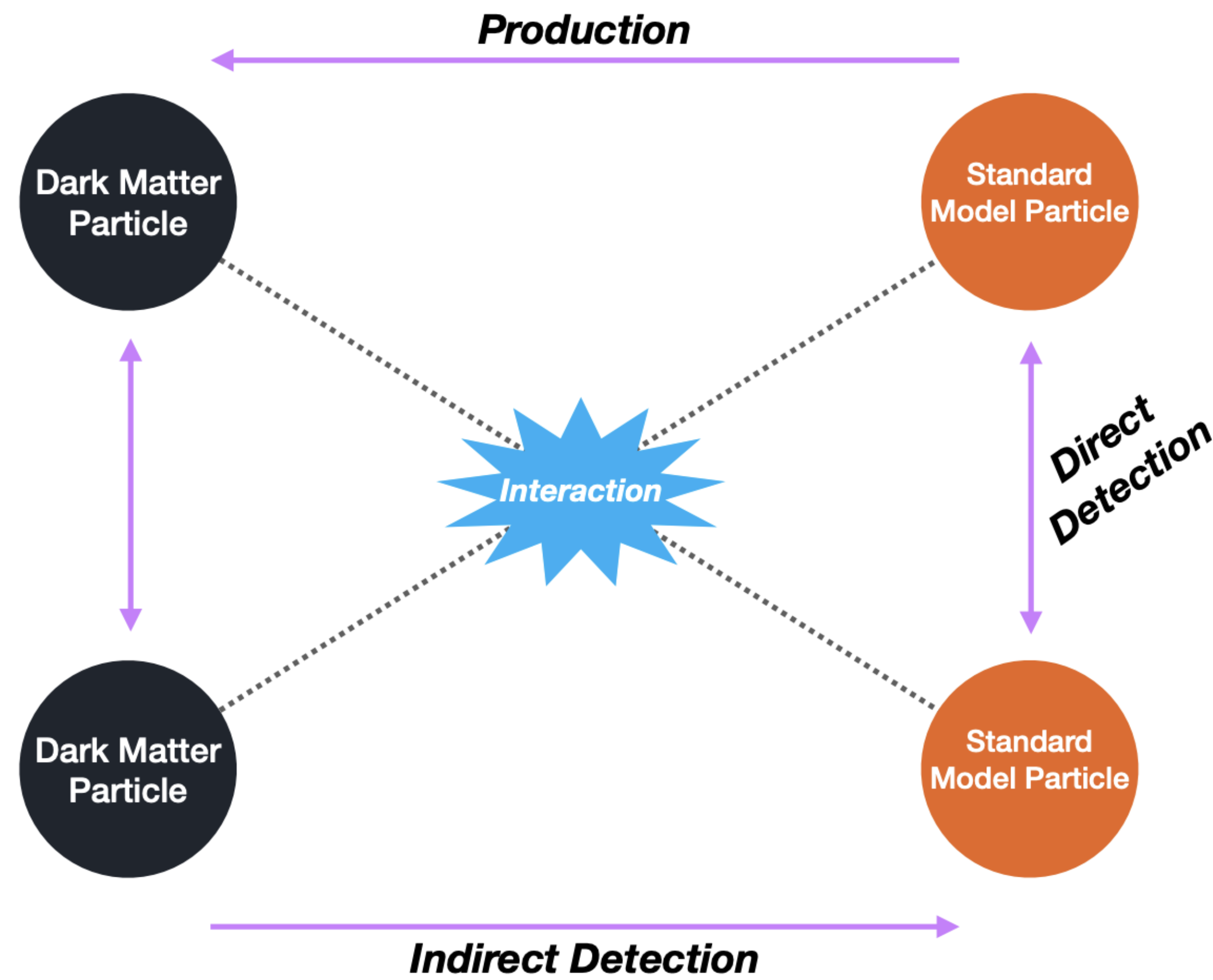
Julien Billard et al 2022 Rep. Prog. Phys. 85 056201

BSM Candidates



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

Interactions With The Standard Model



Interactions With The Standard Model

Interactions between DM and nucleons are parameterised in terms of non-relativistic effective field theory (NREFT) operators

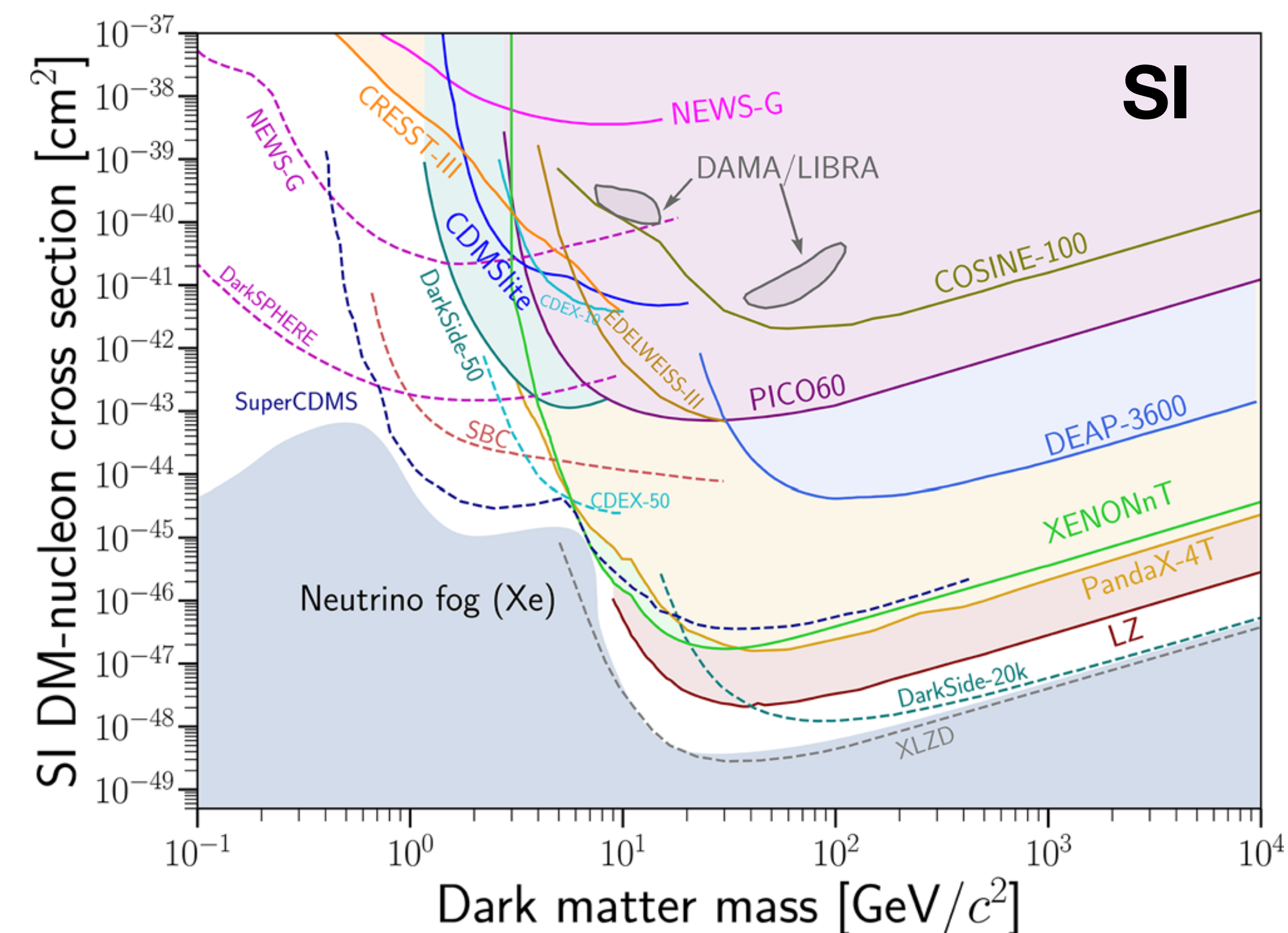
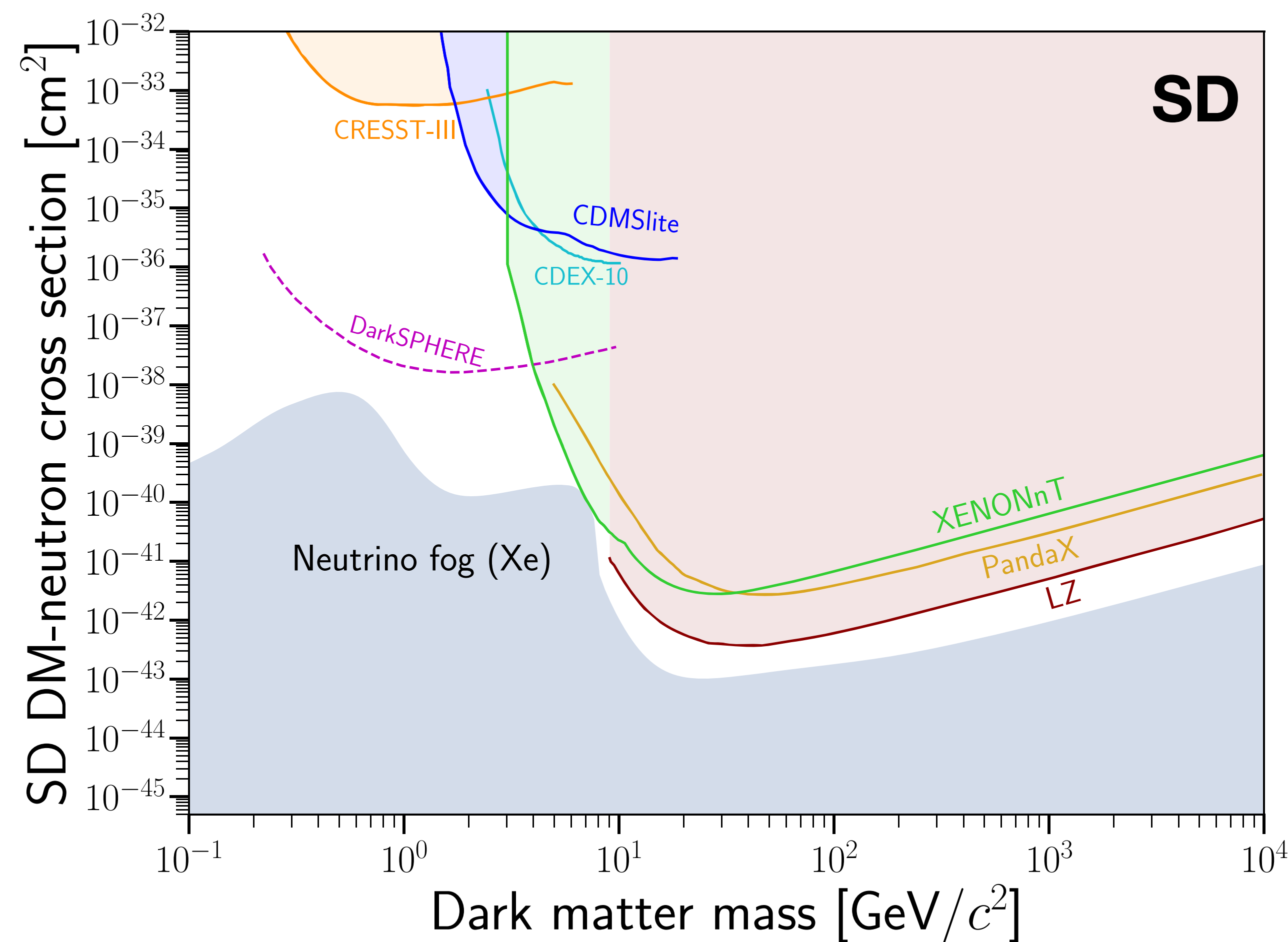
The most widely benchmarked operators are:

$$\mathcal{L}_{int} = \sum_{N=n,p} \sum_i c_i^{(N)} \mathcal{O}_i \chi^+ \chi^- N^+ N^-$$

Spin Independent $\mathcal{O}_1 = 1$ Coherent scattering with all nucleons, vector or scalar coupling, cross section scales with atomic mass number

Spin dependent $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$ Axial vector coupling to nuclear spin, requires unpaired nucleon, cross-section does not scale with atomic mass number

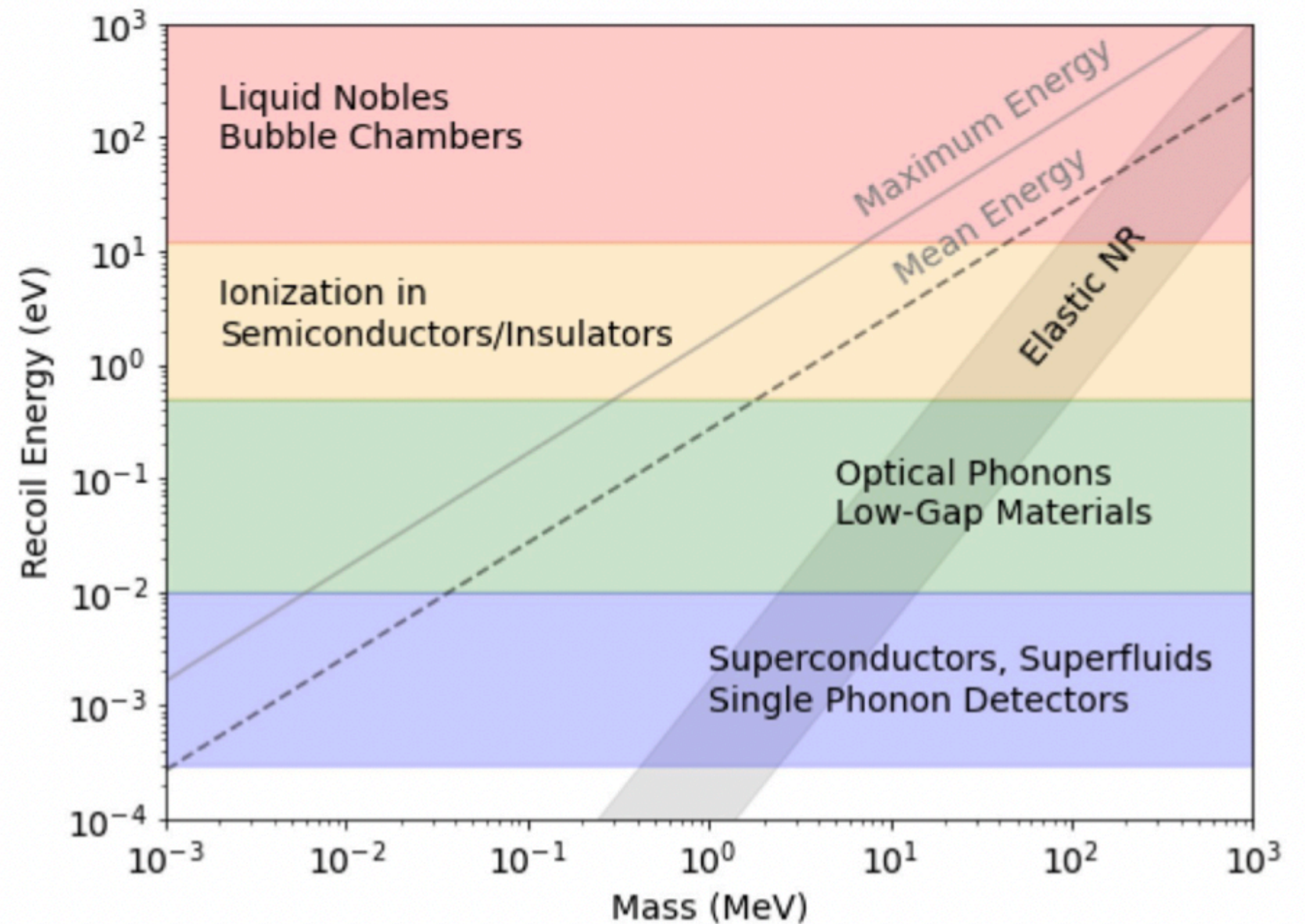
Direct Detection Landscape



Where QUEST-DMC Fits in

Fundamental threshold limit from physical process for quanta production:

- $\sim 10\text{eV}$ Xe, Ar ionisation
- $\sim 1\text{eV}$ semiconductor gap Ge, Si
- $\mu\text{eV} - \text{meV}$ collective excitations doped semiconductors, superconductors, Dirac materials
- $< \mu\text{eV}$ - superfluids



Snowmass report 2022

QUEST-DMC Collaboration



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

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



QUEST-DMC Collaboration



Dark matter with a
new ^3He calorimeter

Dark matter, relevant to
dark matter production

The QUEST-DMC Experiment

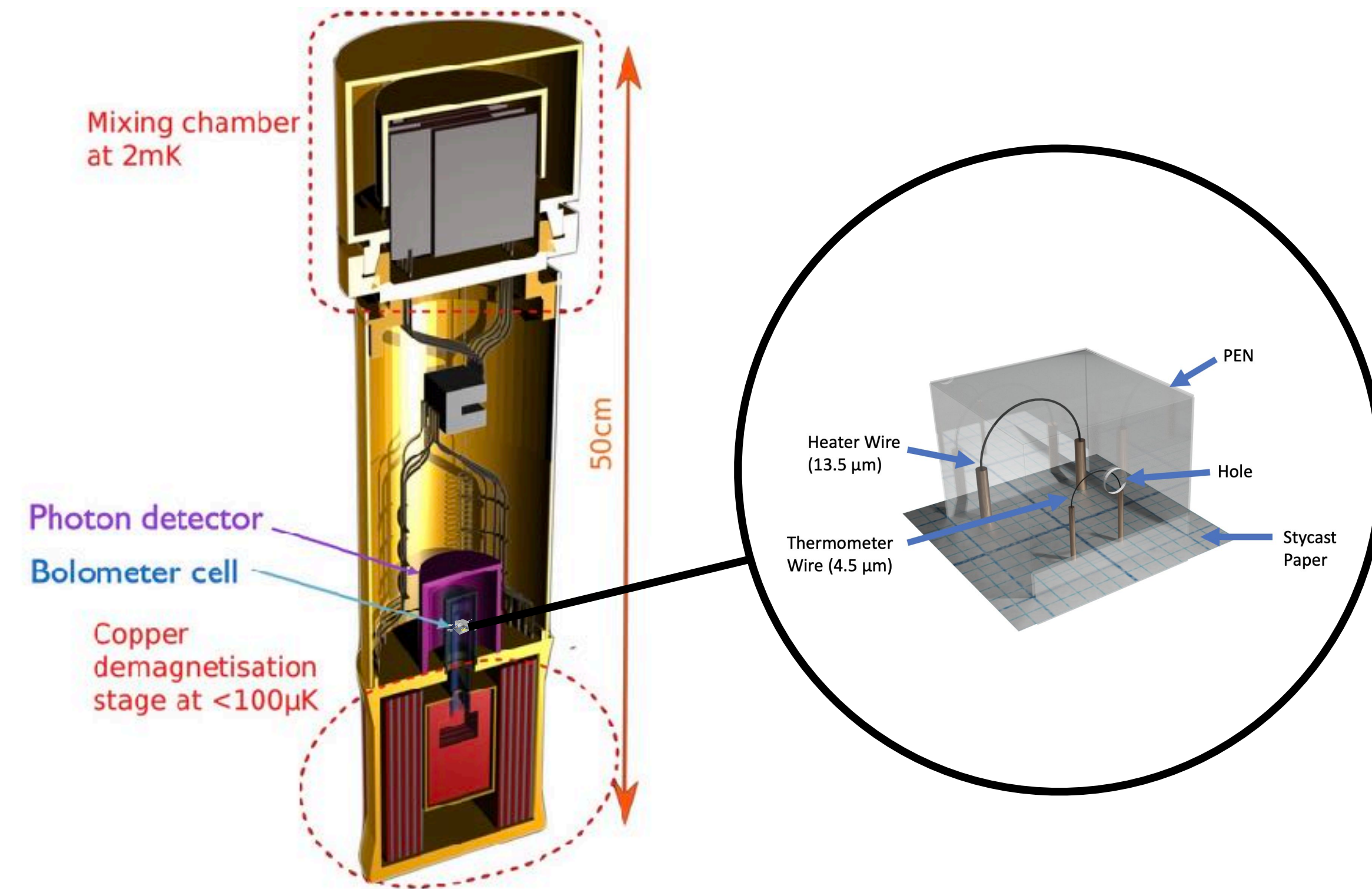
QUEST-DMC

Goal of the experiment:

- Low-threshold dark matter search

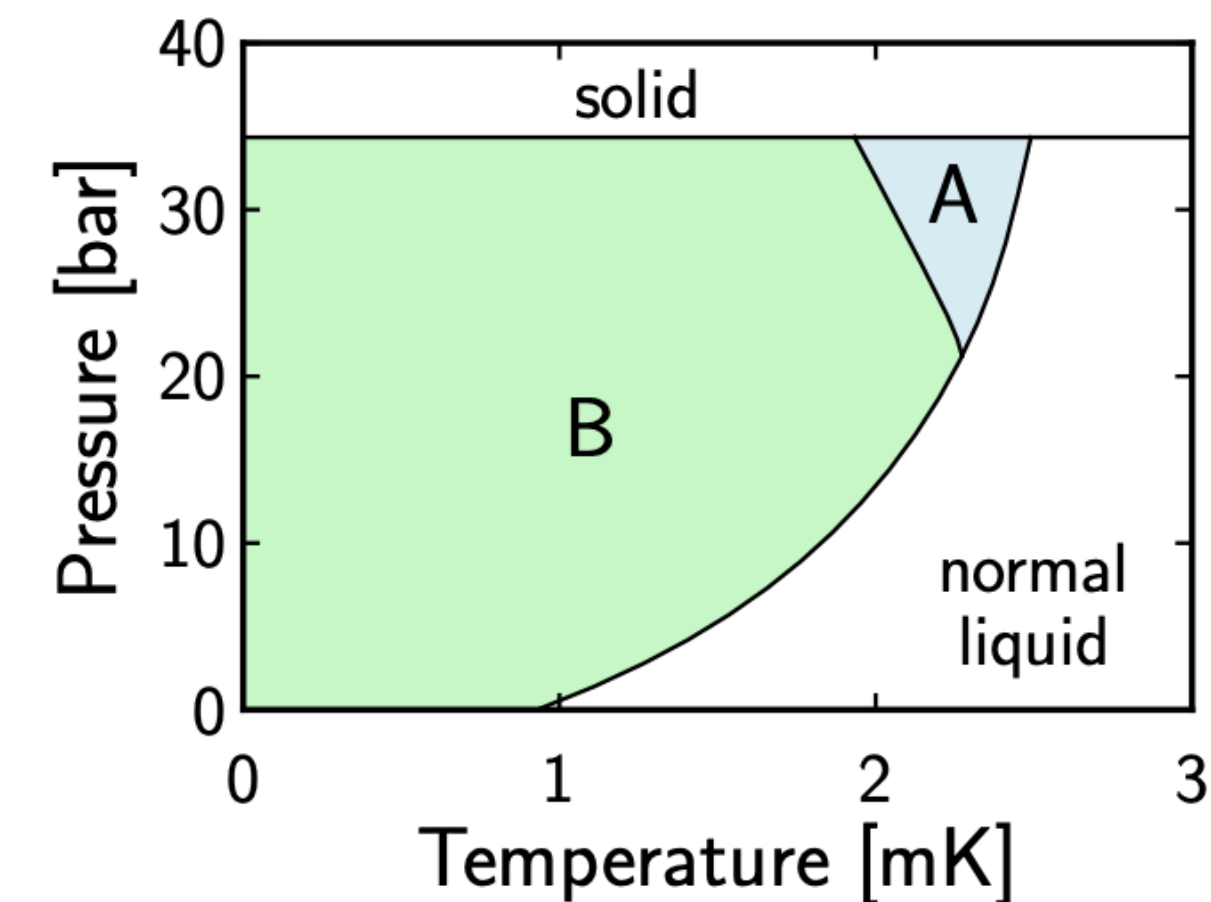
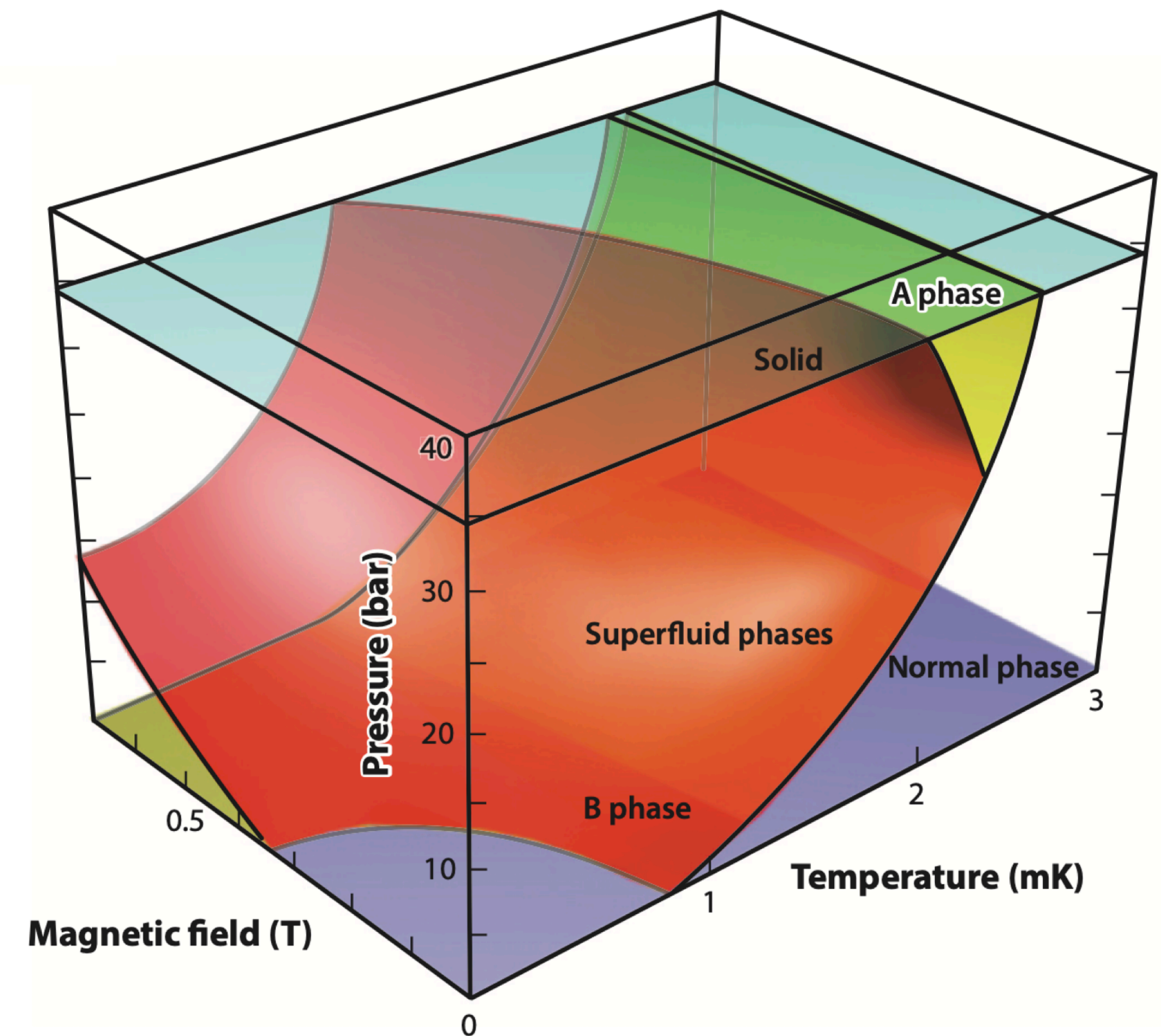
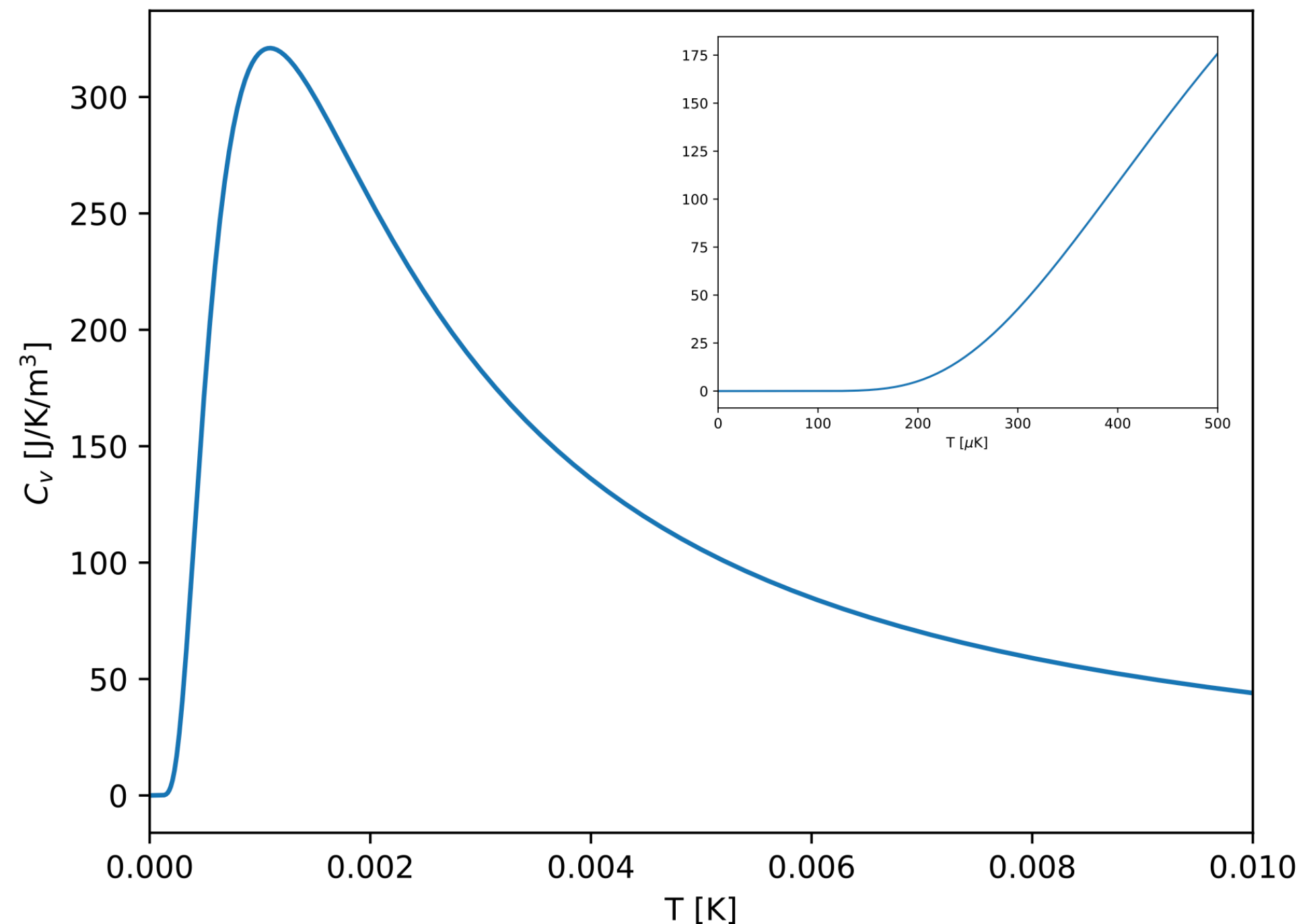
How do we achieve this?

- Ultra-low temperatures ($\sim 100 \mu\text{K}$)
- Extremely small quanta ($\sim 10^{-7} \text{ eV}$)
- Quanta detection (nanoelectromechanical resonators)
- Low noise quantum readout (SQUIDs)

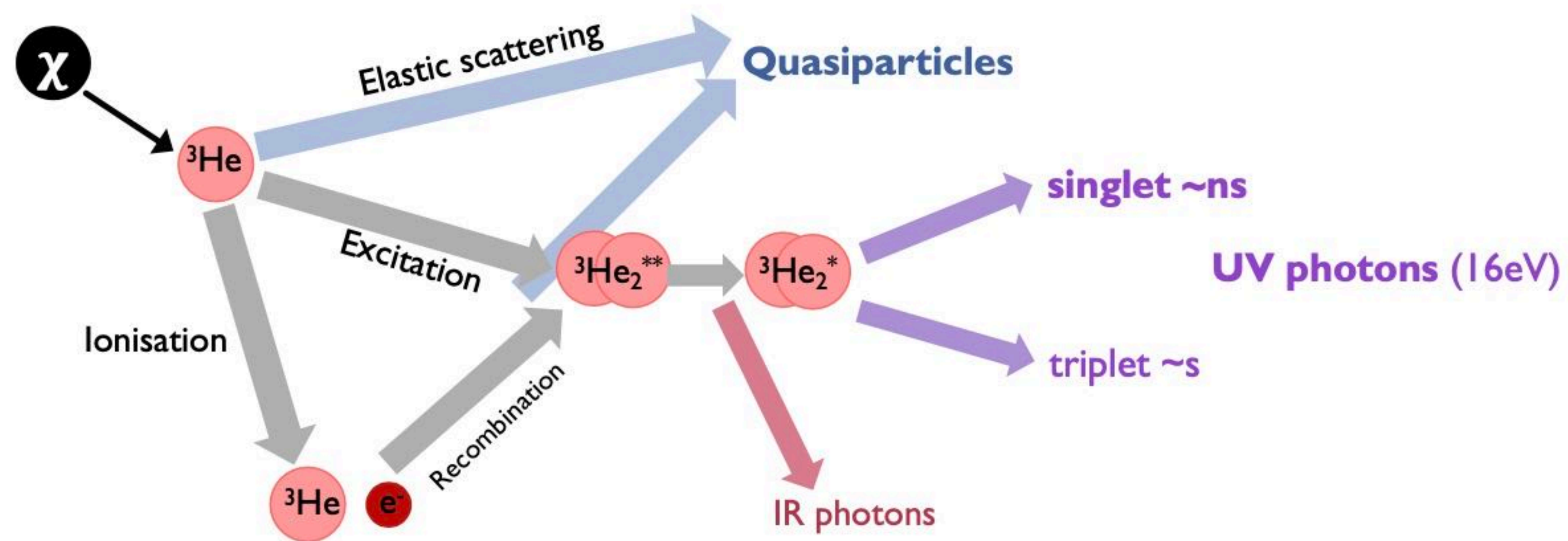


Superfluid Helium-3

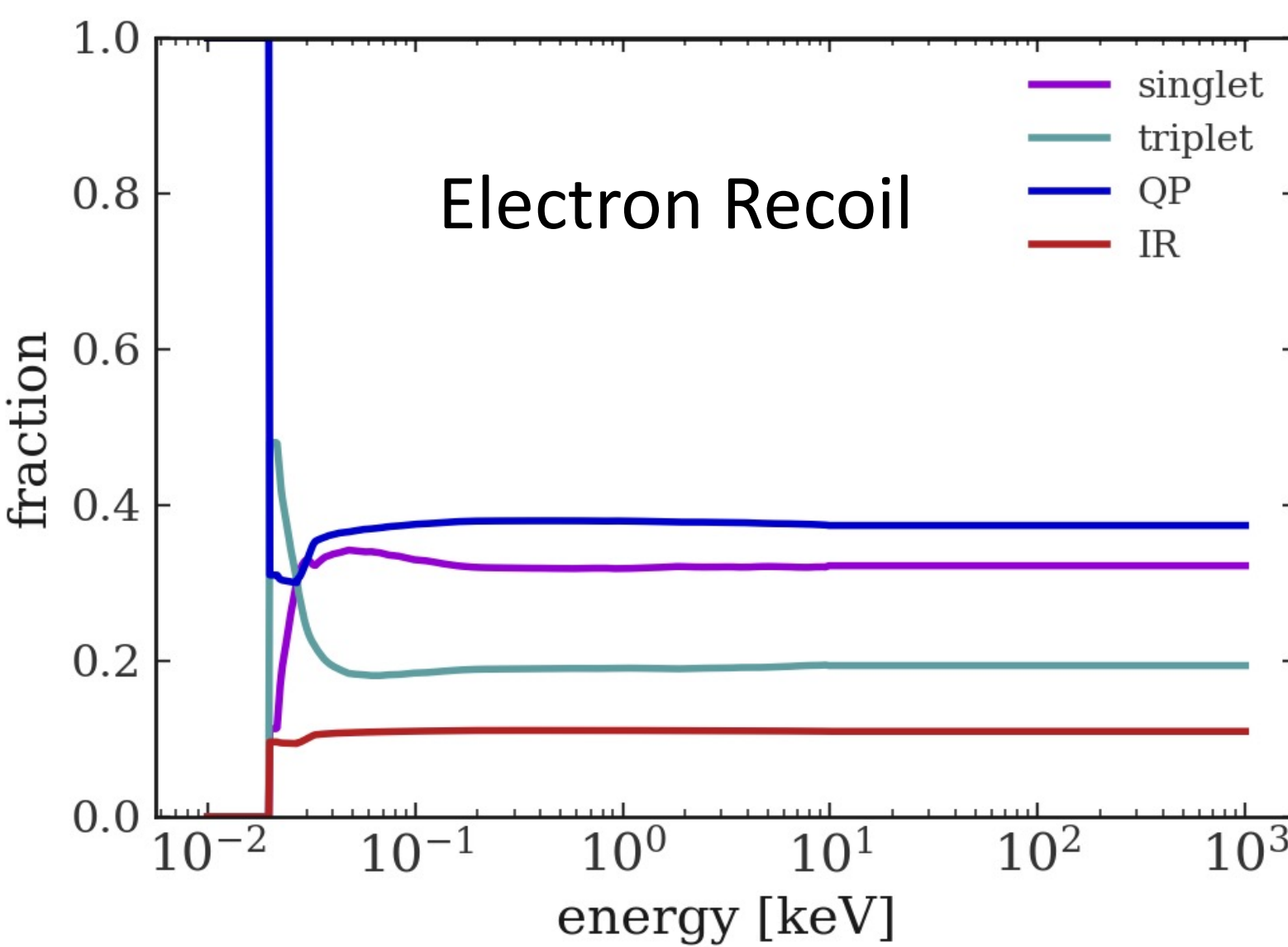
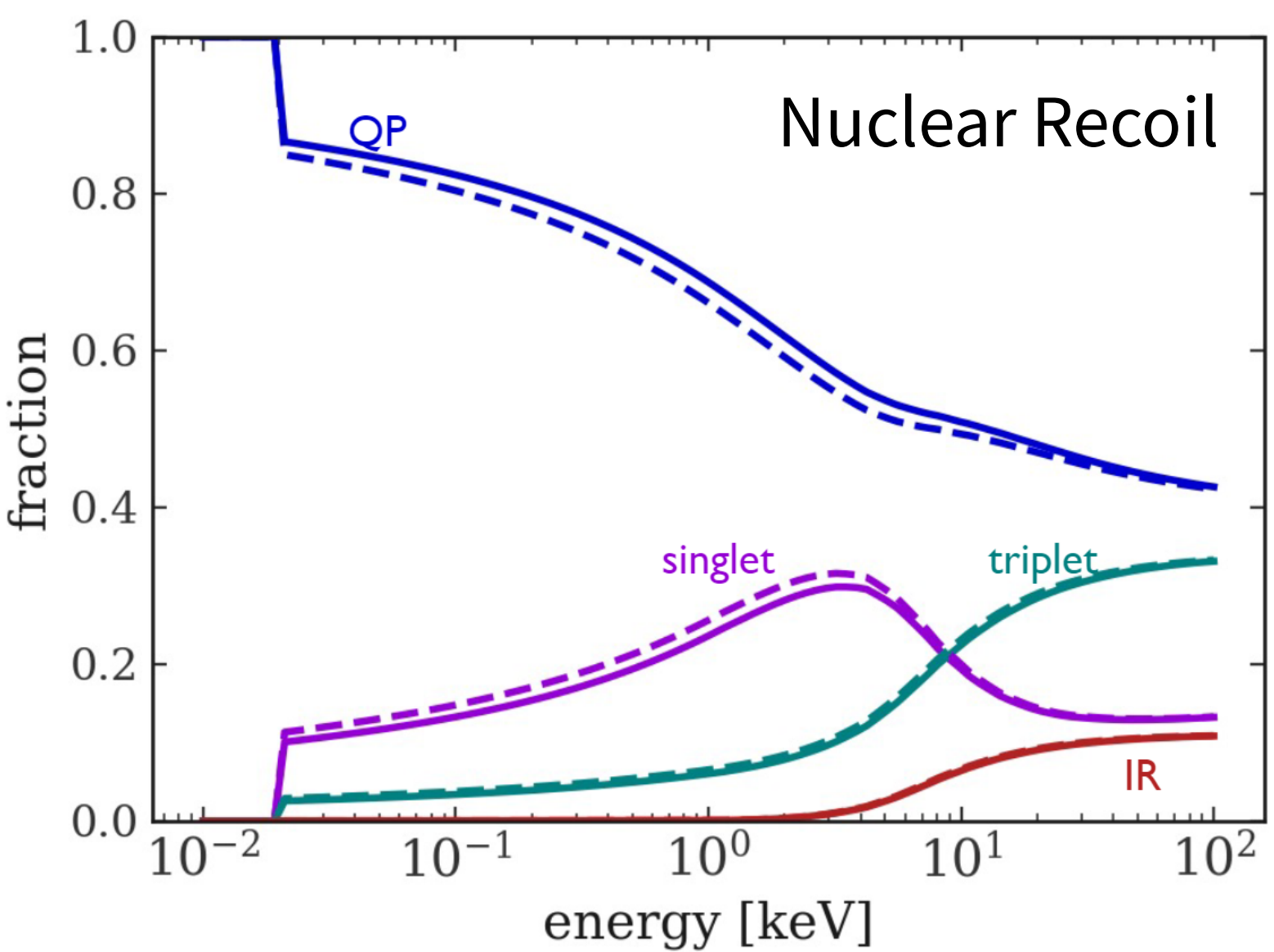
- Cooper pairing of He atoms below ~ 2 mK
- Two superfluid phases, A-phase (spin-ordered) and B-phase (isotropic)
- Superfluid gap of 10^{-7} eV, with quasiparticle excitations above this energy



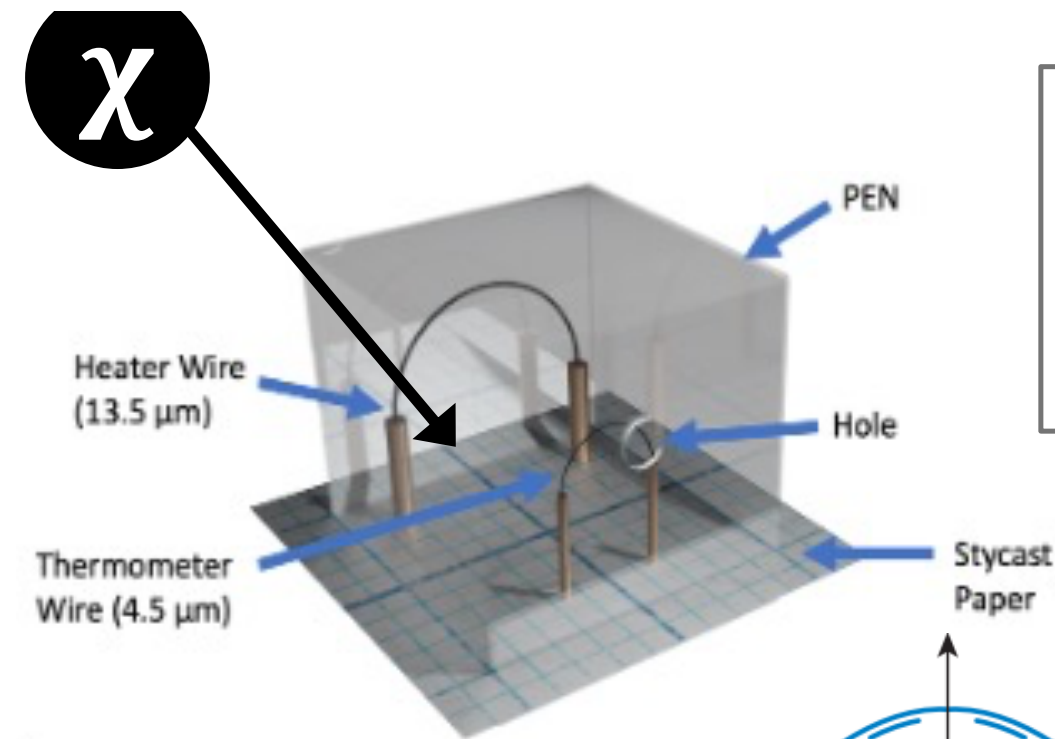
Energy Partitioning



Based on work by Ito & Seidel “Scintillation of liquid helium for low-energy nuclear recoils”,
Physical Review C 88.2 (Aug. 2013)

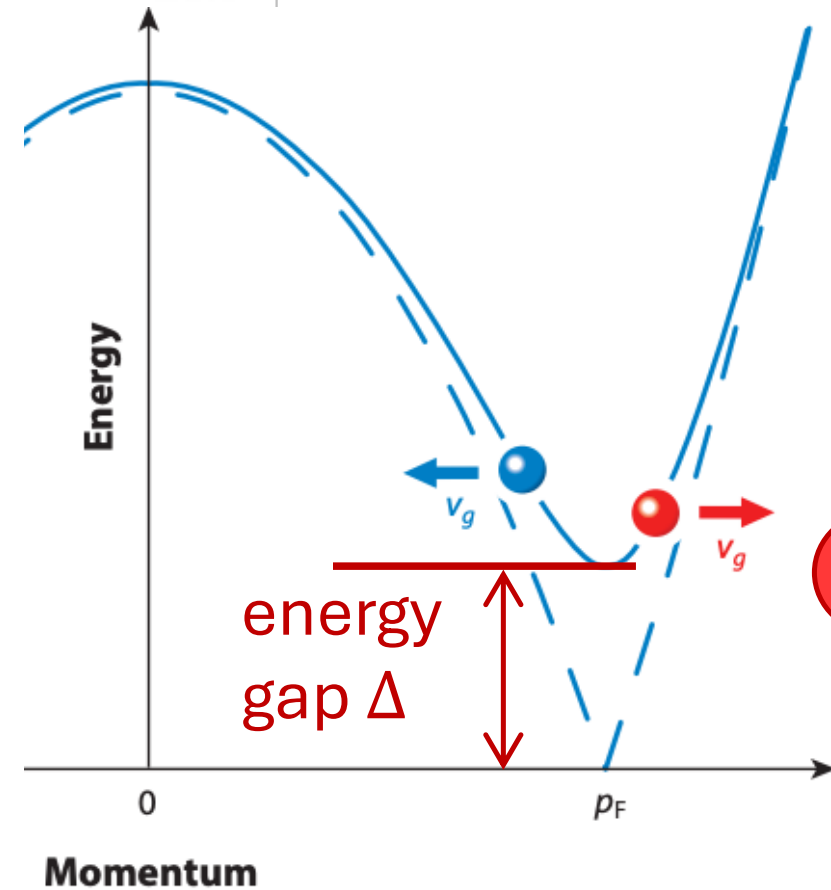


Detection Principle



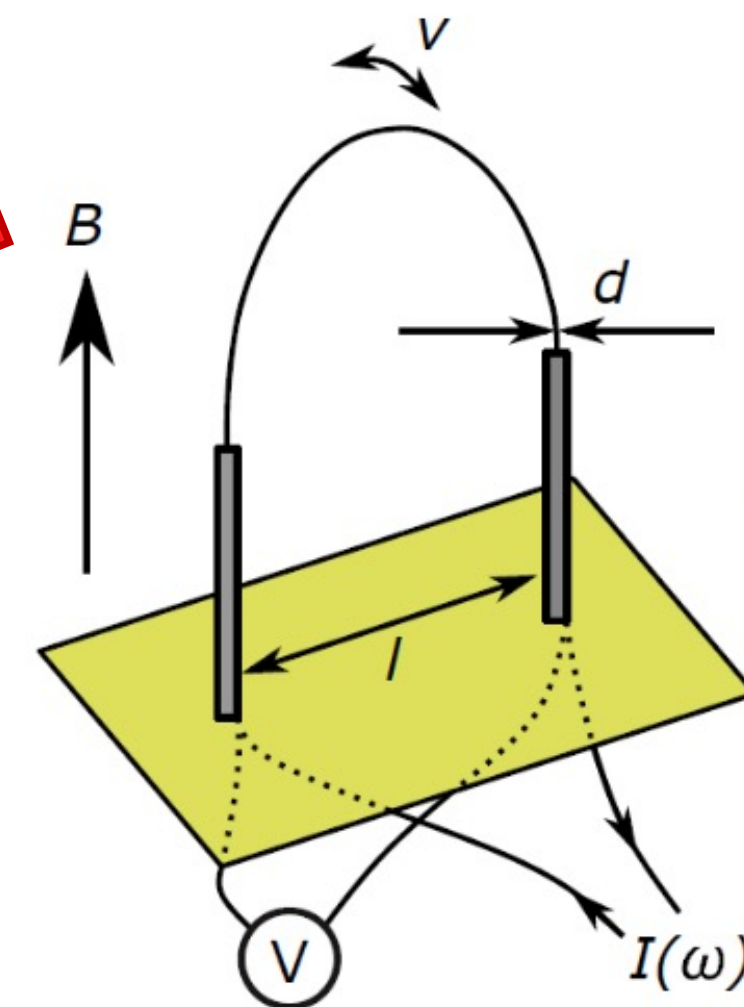
1. Energy deposit

DM – helium scattering produces
quasiparticles (QPs) $1\text{eV} \rightarrow 10^7$ quanta



2. Ballistic propagation

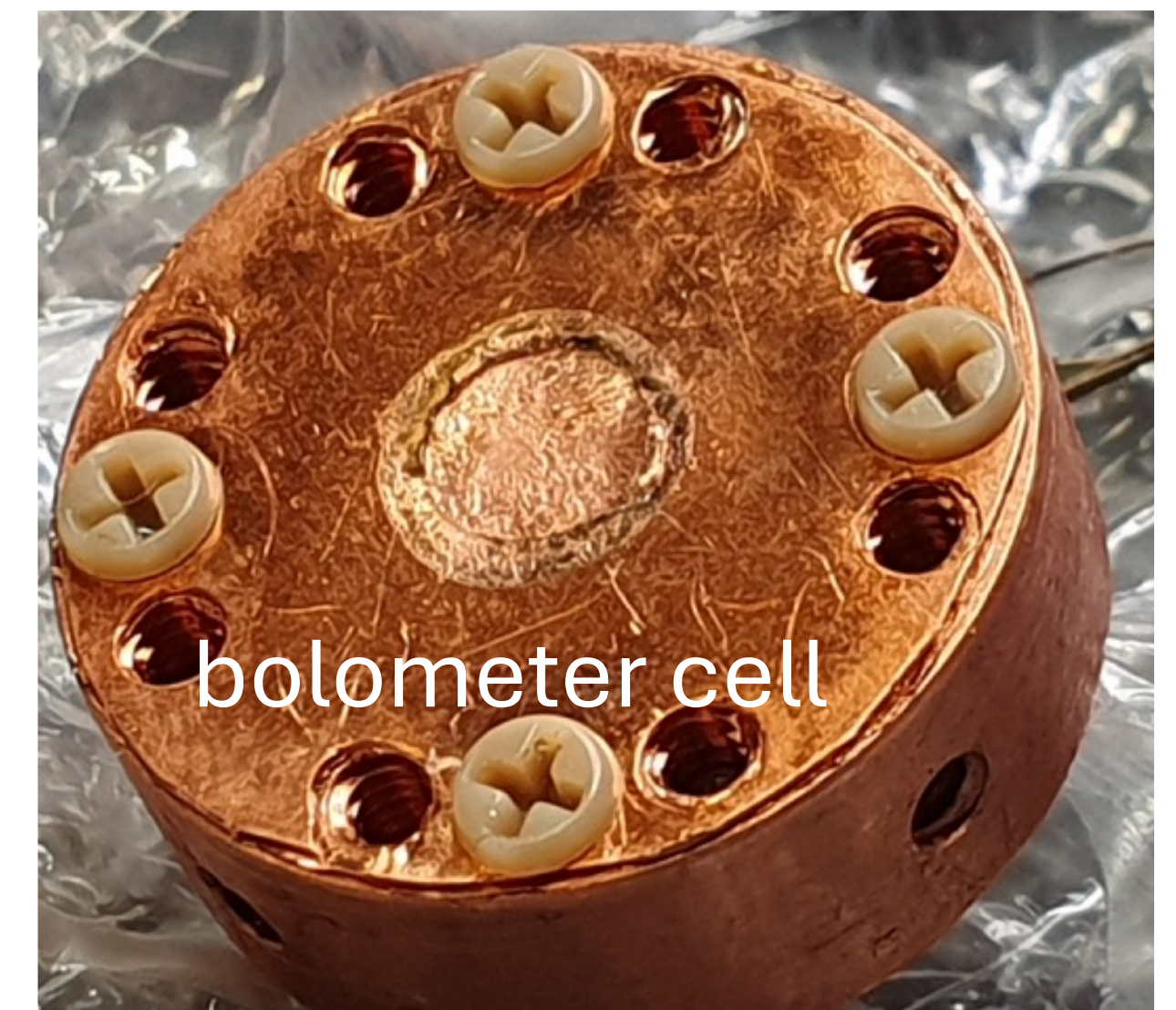
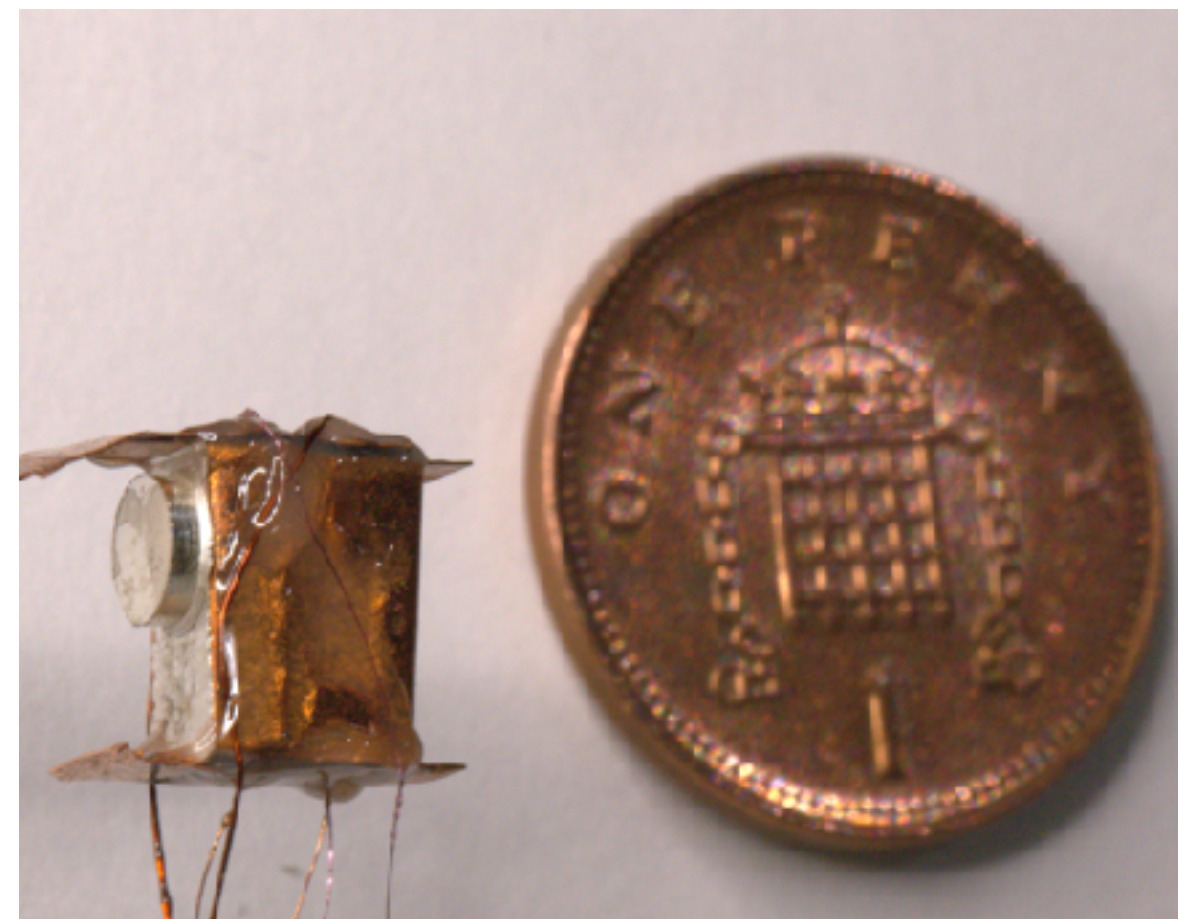
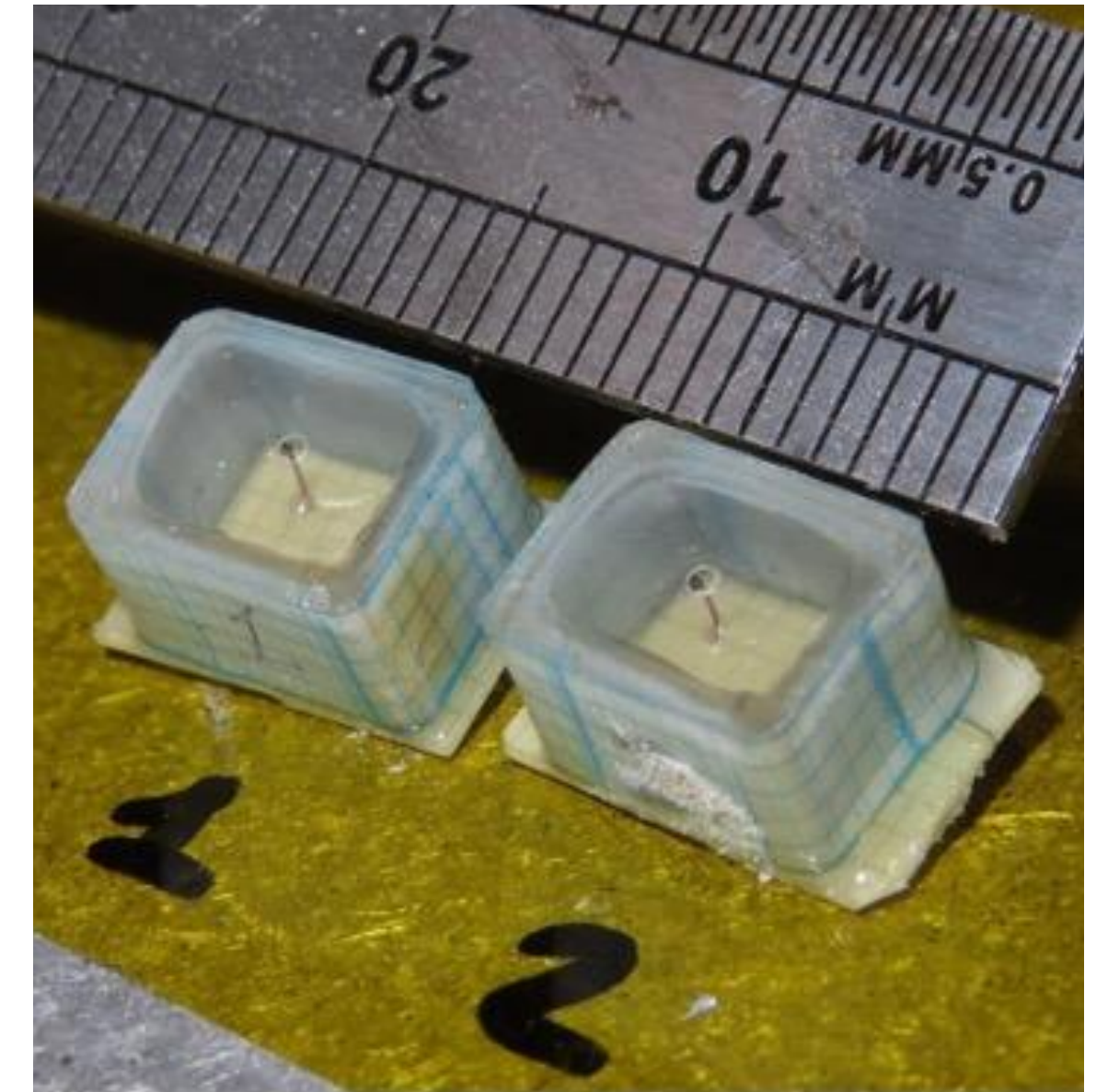
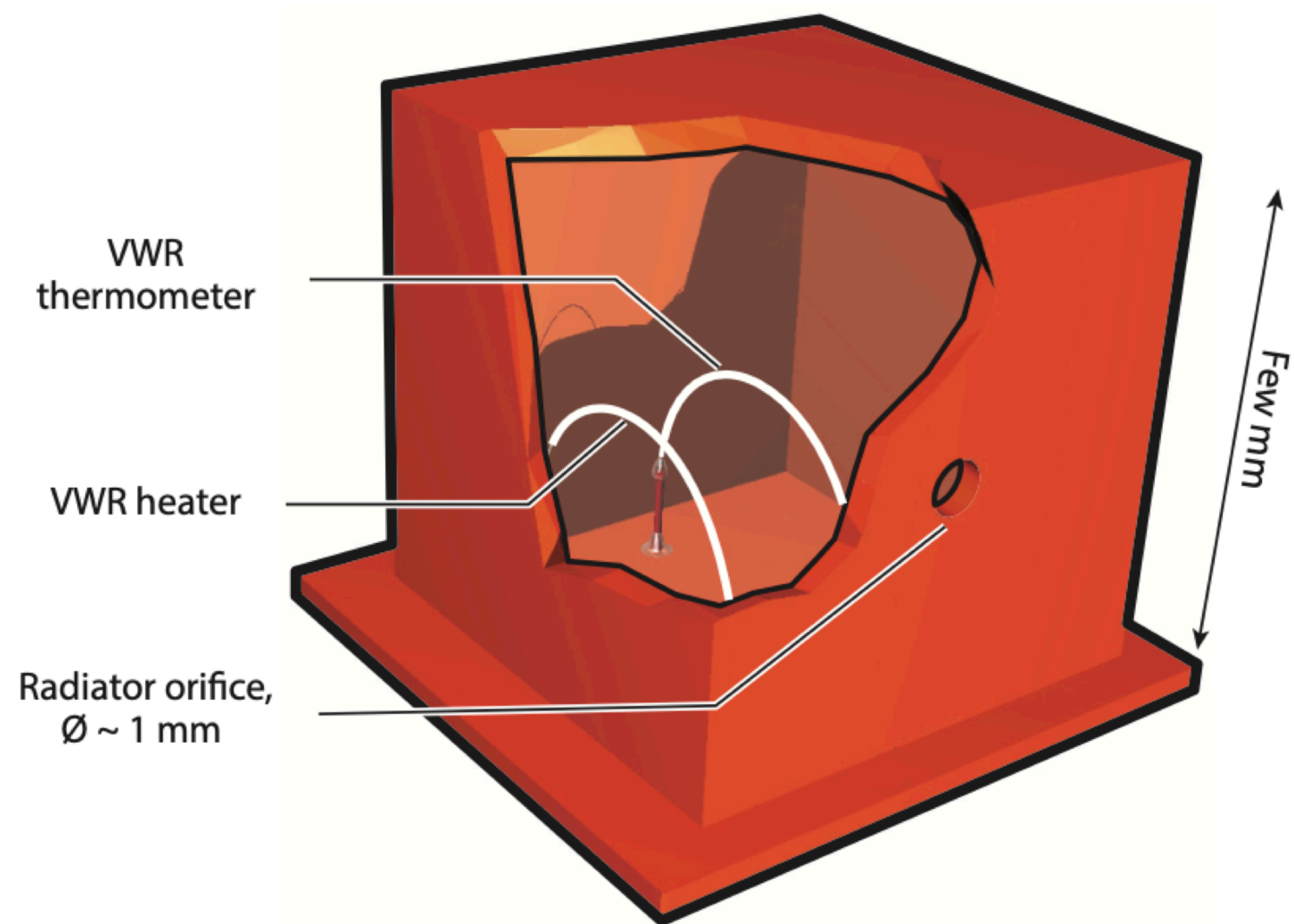
QP collisions with nanowire
exert damping force



3. Bolometry

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

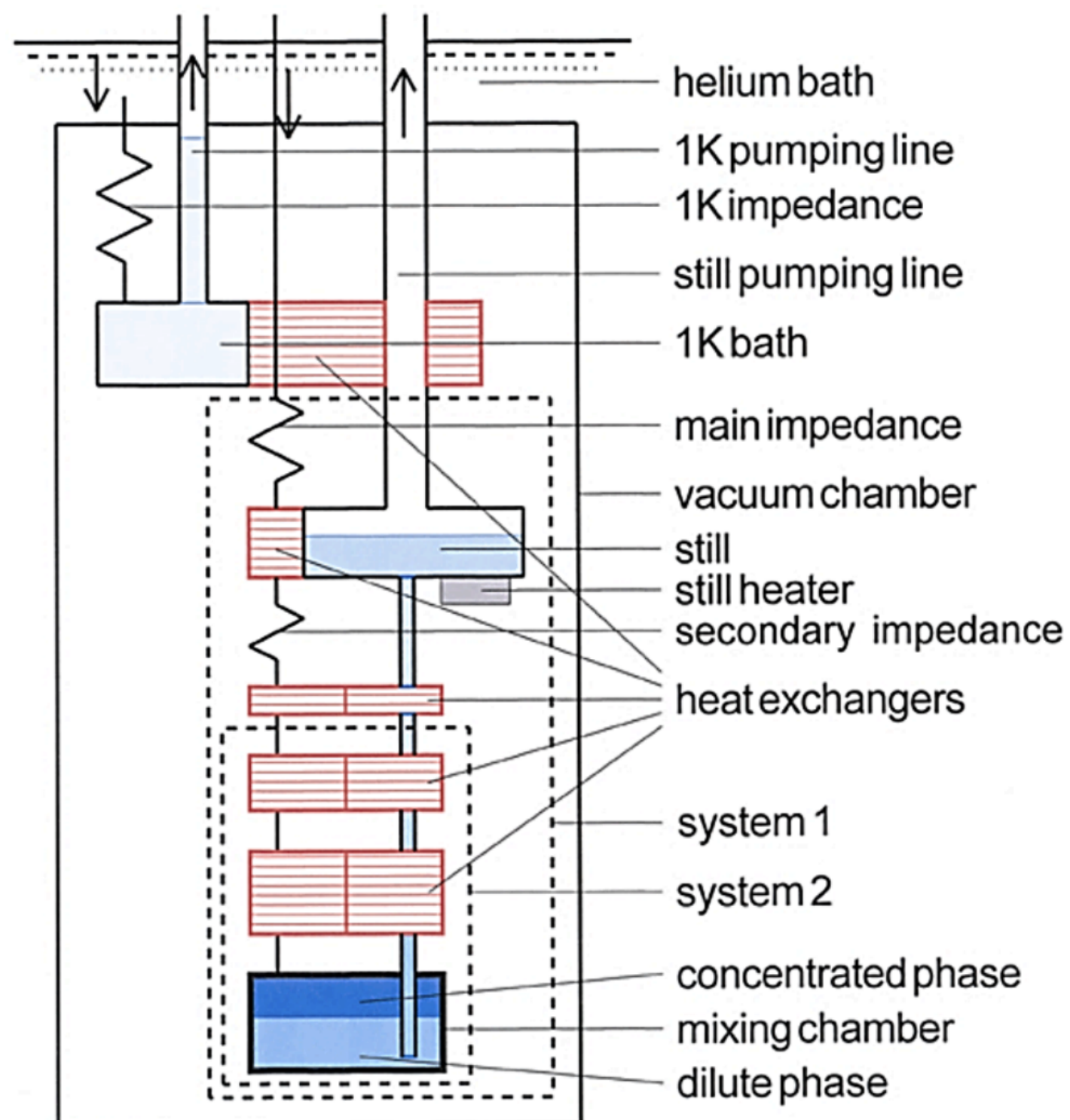
Superfluid ^3He Bolometers



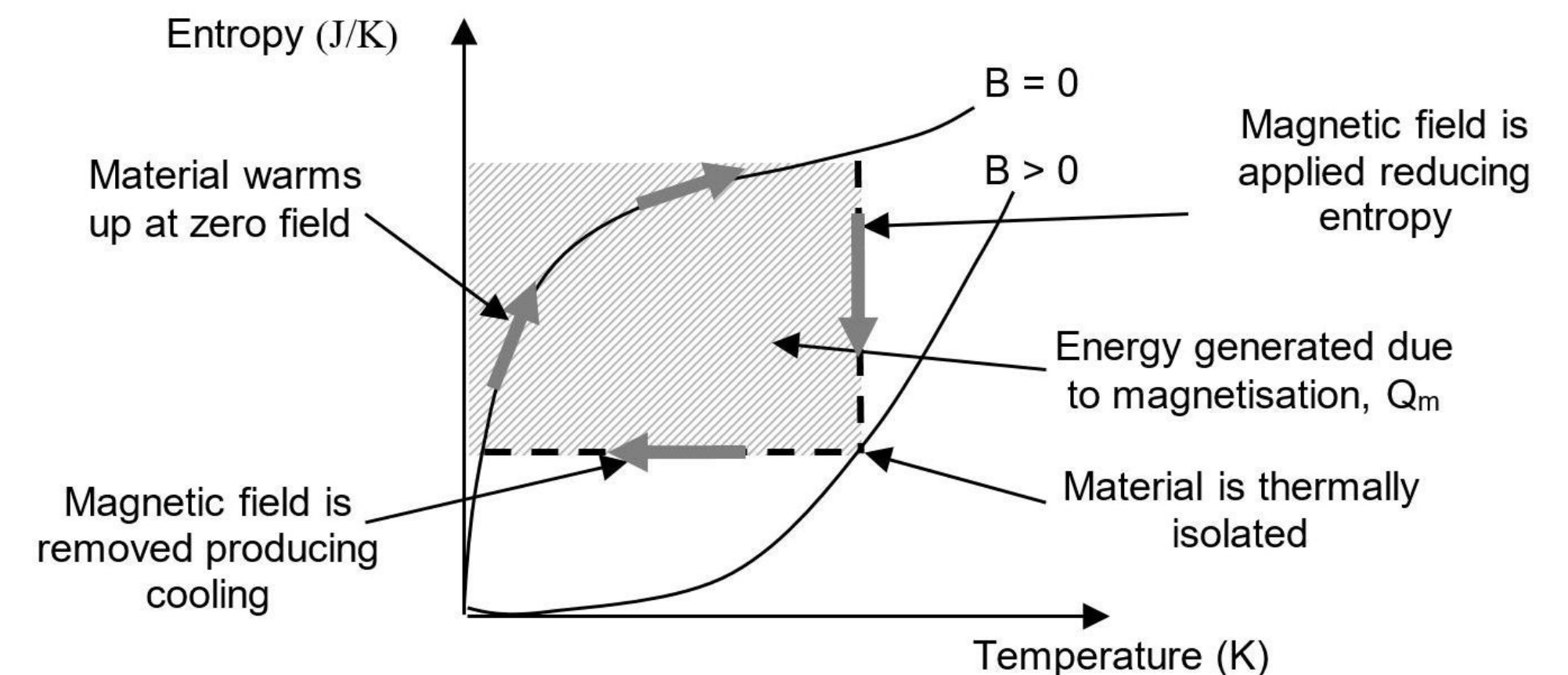
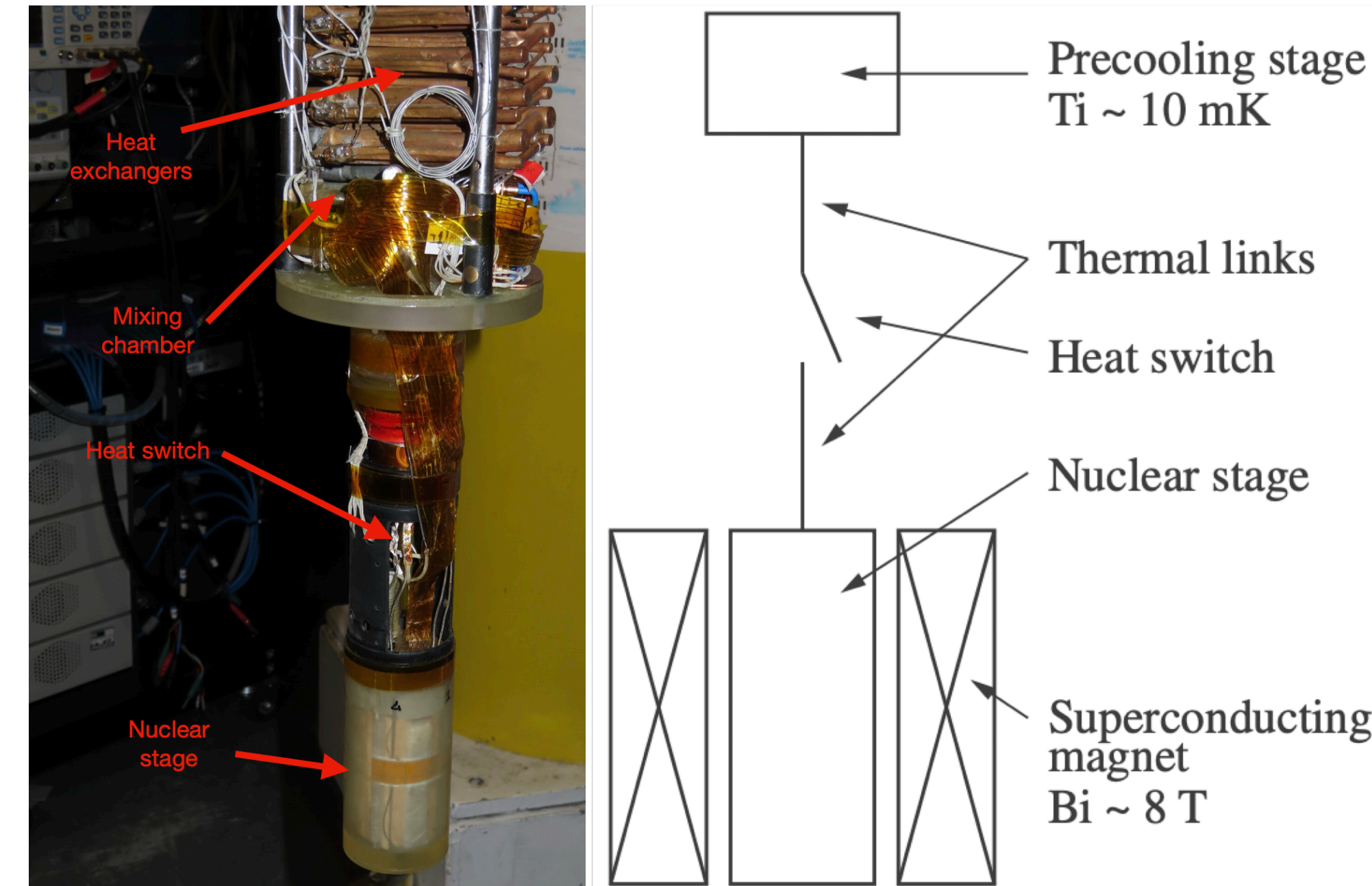
Cryogenics

Dilution Refrigeration (to ~ 10 mK)

Adiabatic nuclear demagnetisation (to ~ 100 μ K)



- $^3\text{He}/^4\text{He}$ mixture pre-cooled to 4K, then at mixing chamber separate into dilute (6.6% ^3He) and concentrated phases
- ^3He pumped from mixing chamber into still, evaporation of ^3He from concentrated phase to dilute phase costs enthalpy - cools the mixing chamber



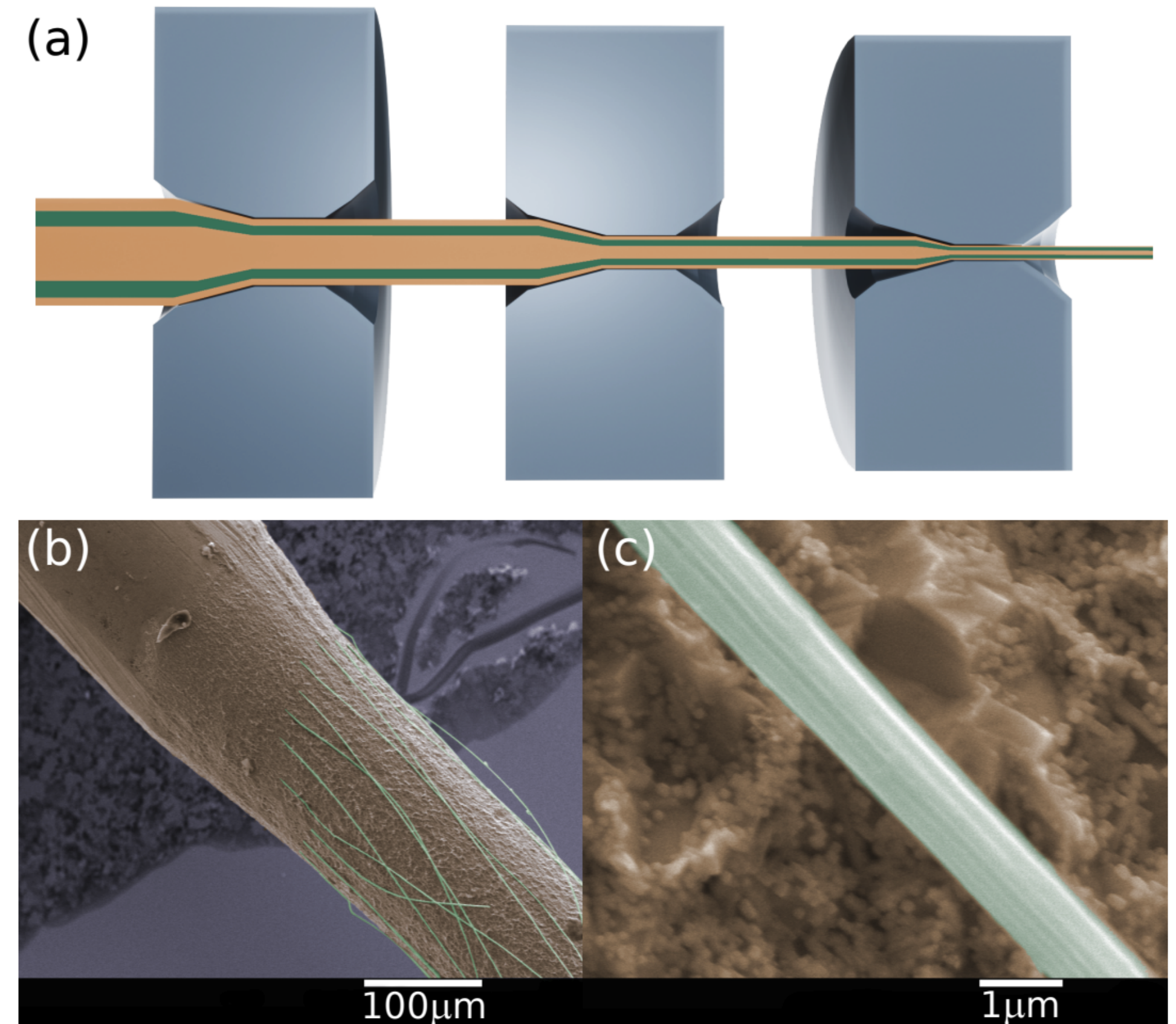
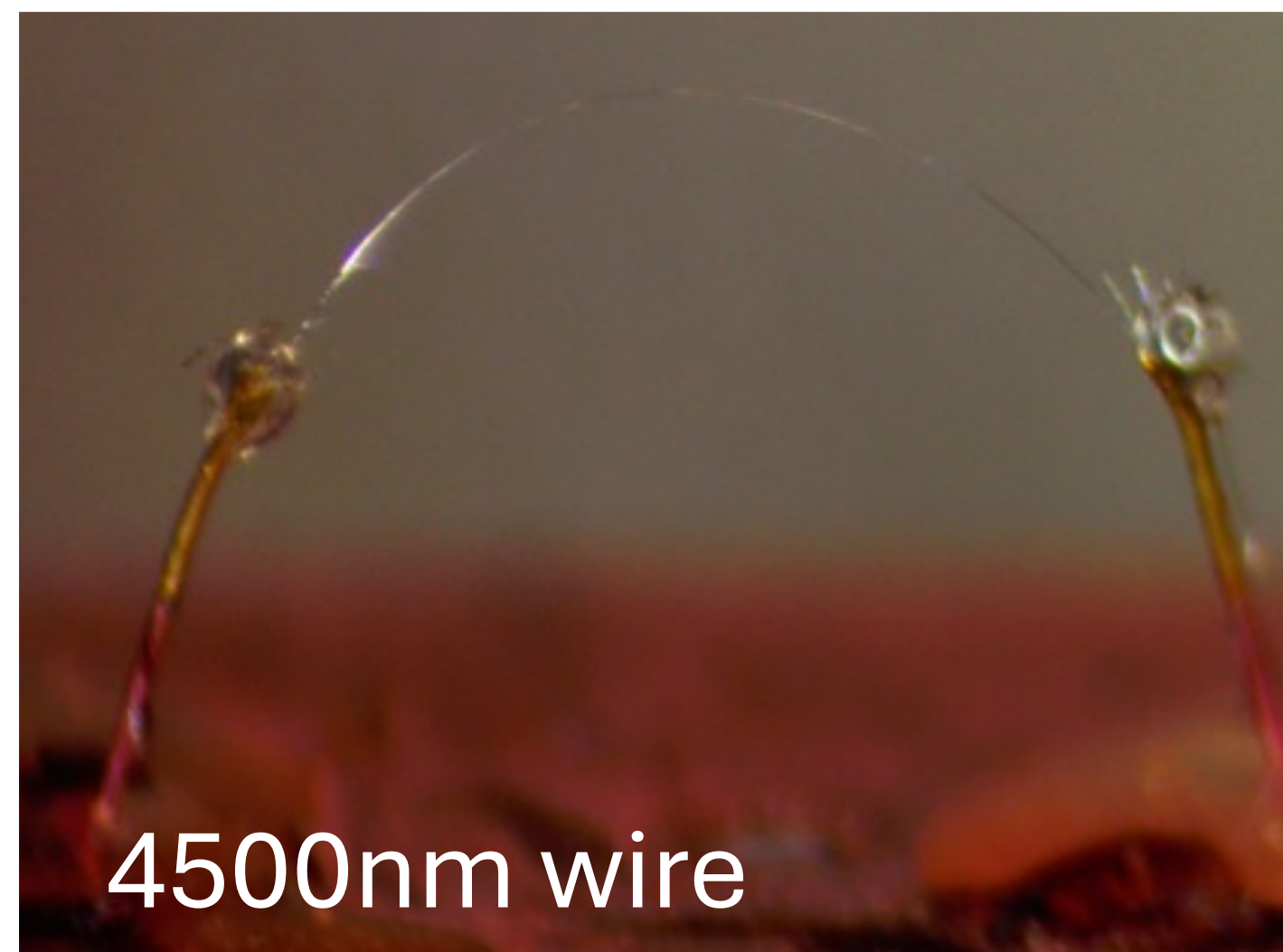
NEMS



400nm nanowire

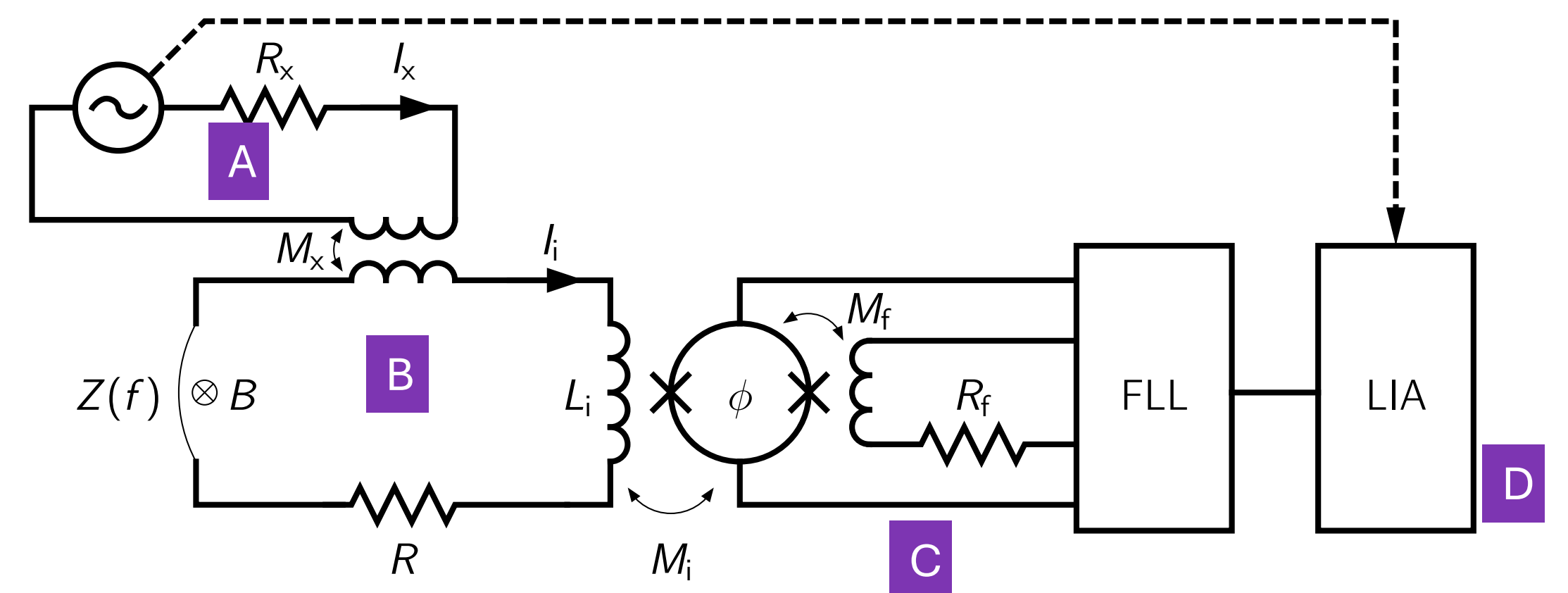
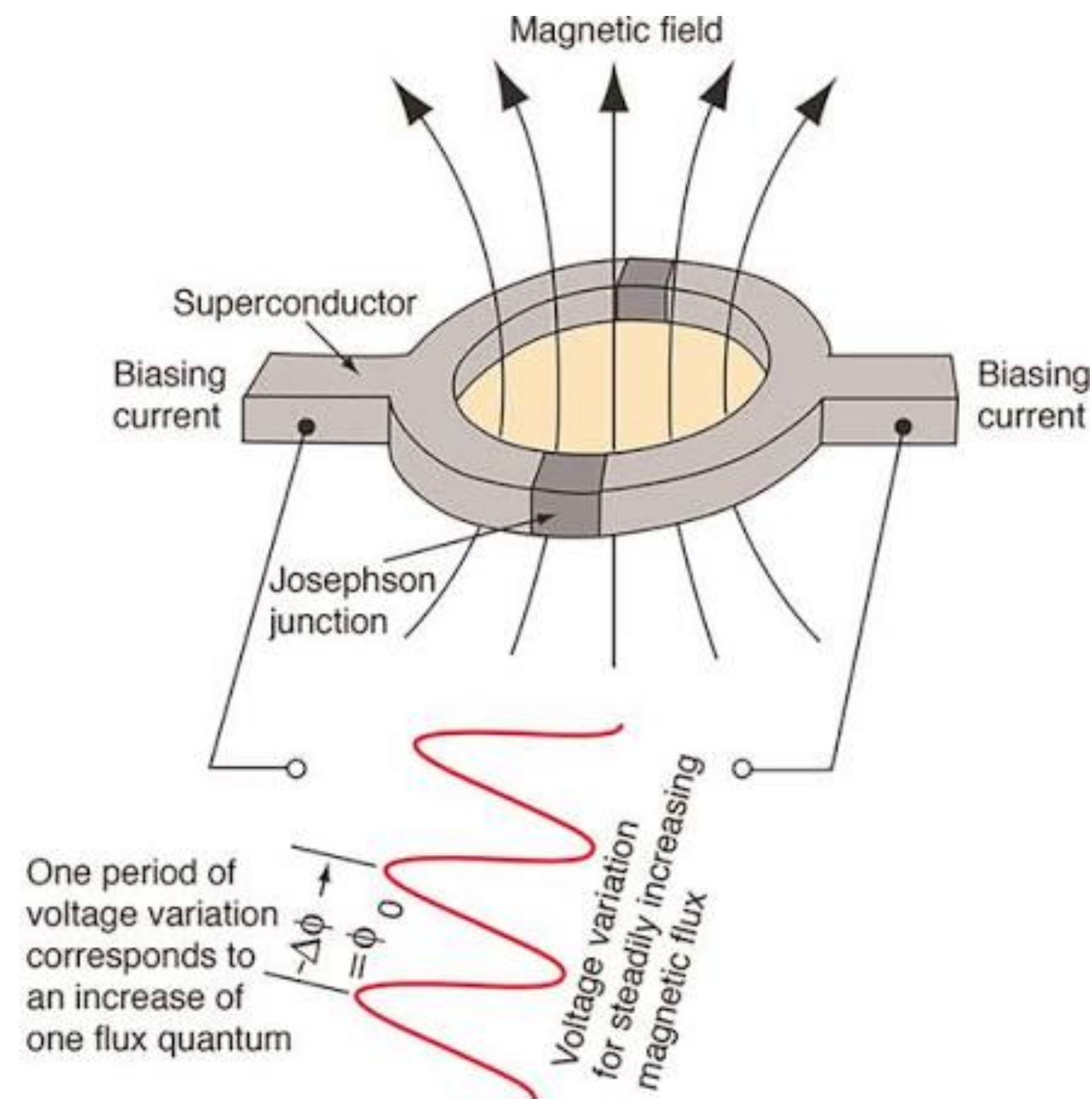
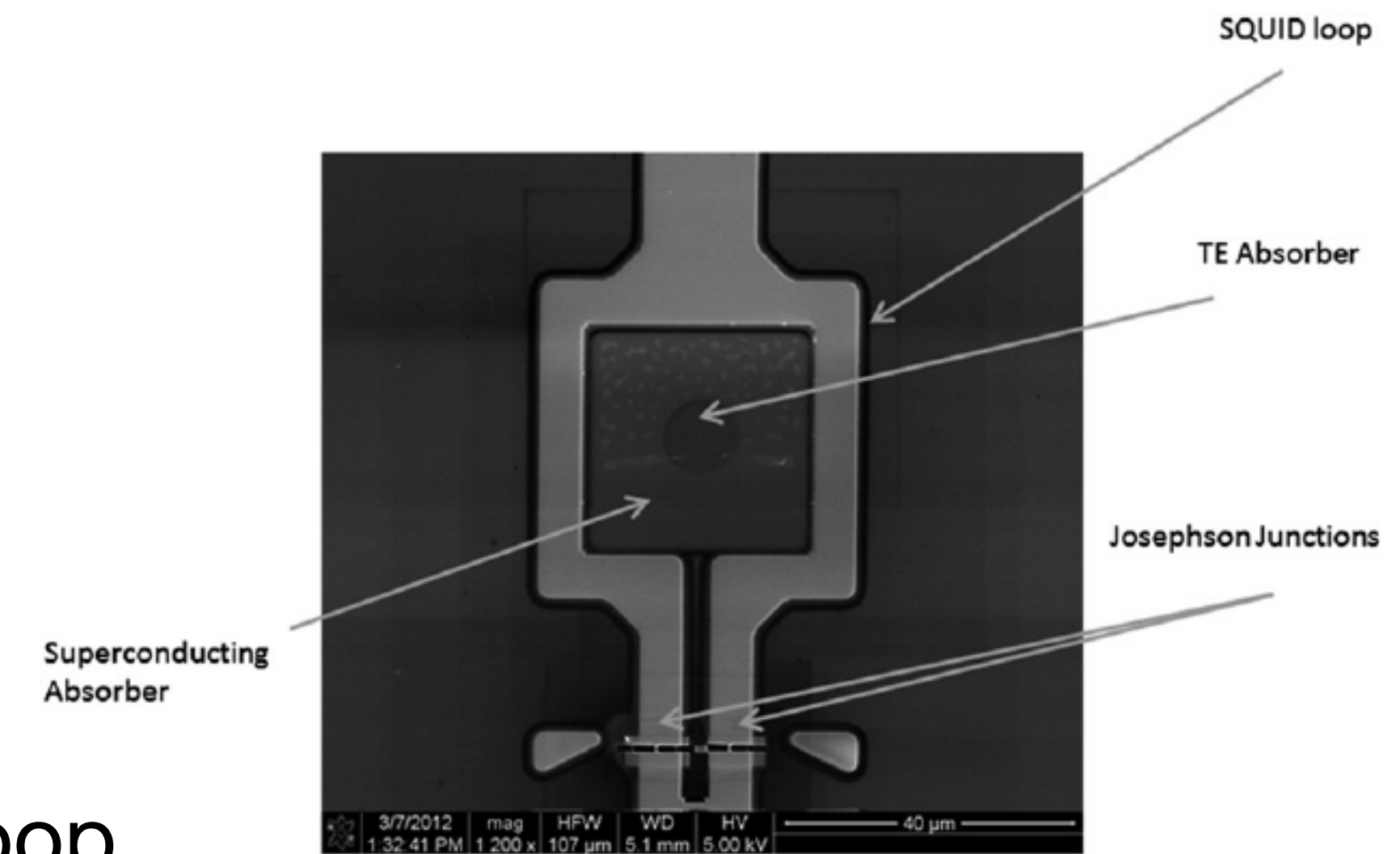
NbTi vibrating
wire resonators
made in
Lancaster

[arXiv:2311.02452](https://arxiv.org/abs/2311.02452)



SQUIDs

- Very sensitive magnetometers
- Arrays of SQUIDs can be used as signal amplifiers
- Two Josephson junctions either side of a superconducting loop



A. Voltage drive coupled inductively via transformer : $V_x = 2\pi f M_x I_x$

B. SQUID input loop: wire $Z(f)$, contact resistance R , input coil L_i

C. SQUID in flux locked loop mode detects current: $I_i = \frac{V_x}{Z + R + 2i\pi f L_i}$

D. Measured by room temperature lockin amplifier

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

QUEST-DMC Operation

SQUID Readout Tests

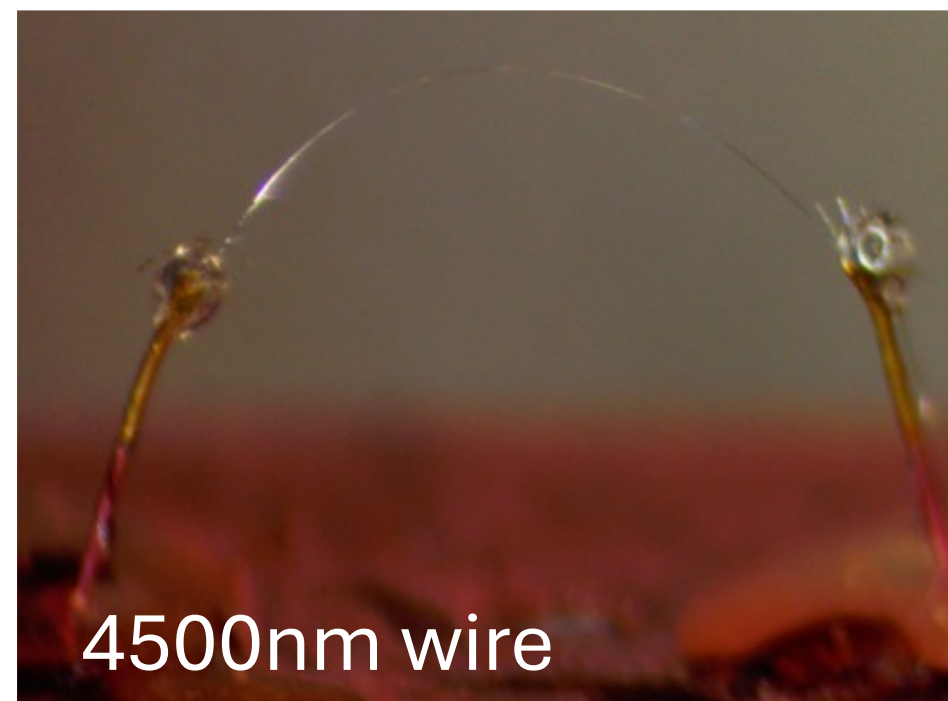
Recent paper “Development of Superfluid Helium-3 Bolometry Using Nanowire Resonators with SQUID Readout for the QUEST-DMC Experiment. Leason, E., Levitin, L.V., Autti, S. *et al.* *J Low Temp Phys* **222**, 39 (2026)”



400nm nanowire

NbTi vibrating
wire resonators
made in
Lancaster

[arXiv:2311.02452](https://arxiv.org/abs/2311.02452)



4500nm wire

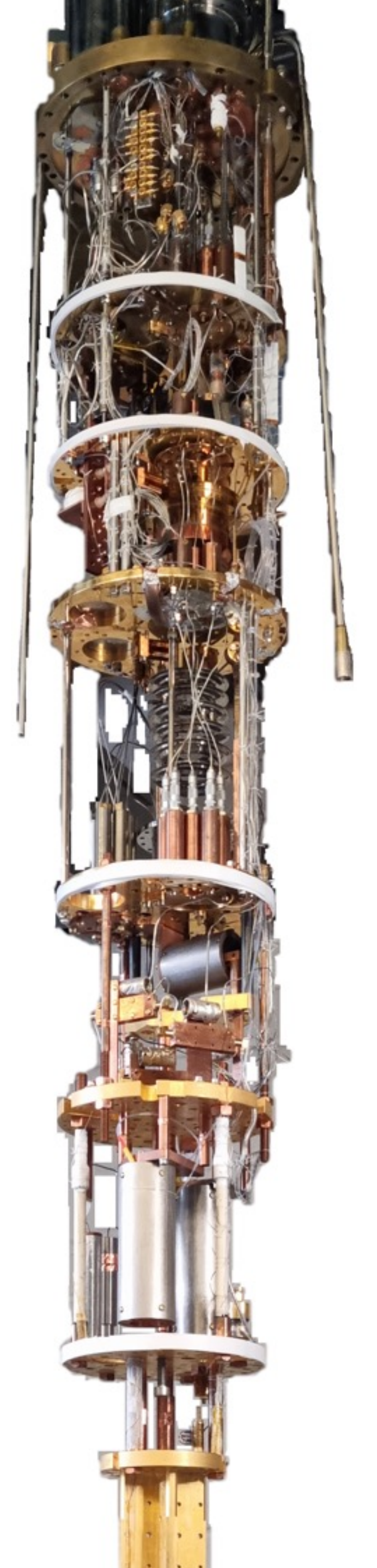
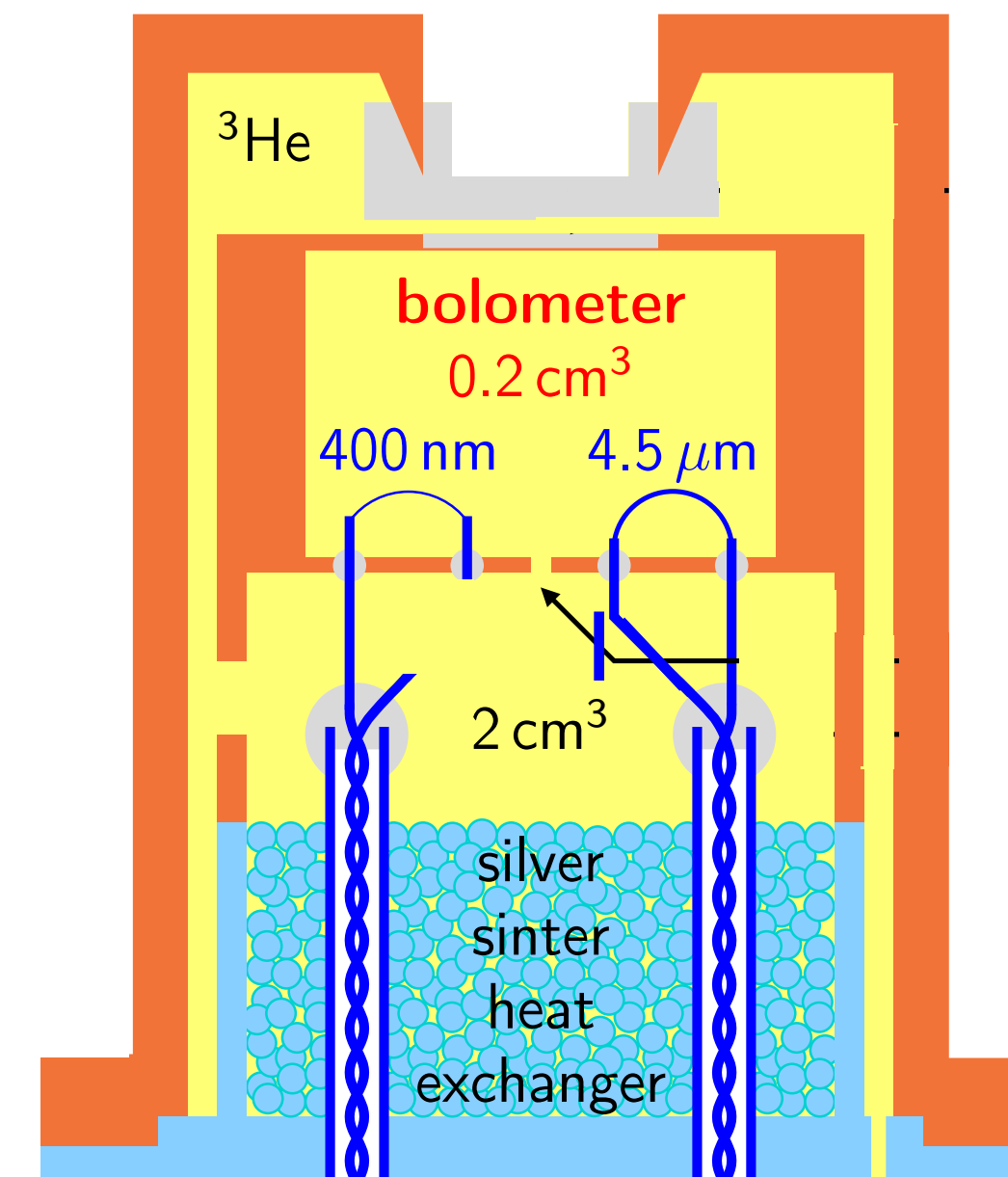


bolometer cell

cell holder and
heat exchanger



cuboid copper bolometer
inside 3He cell

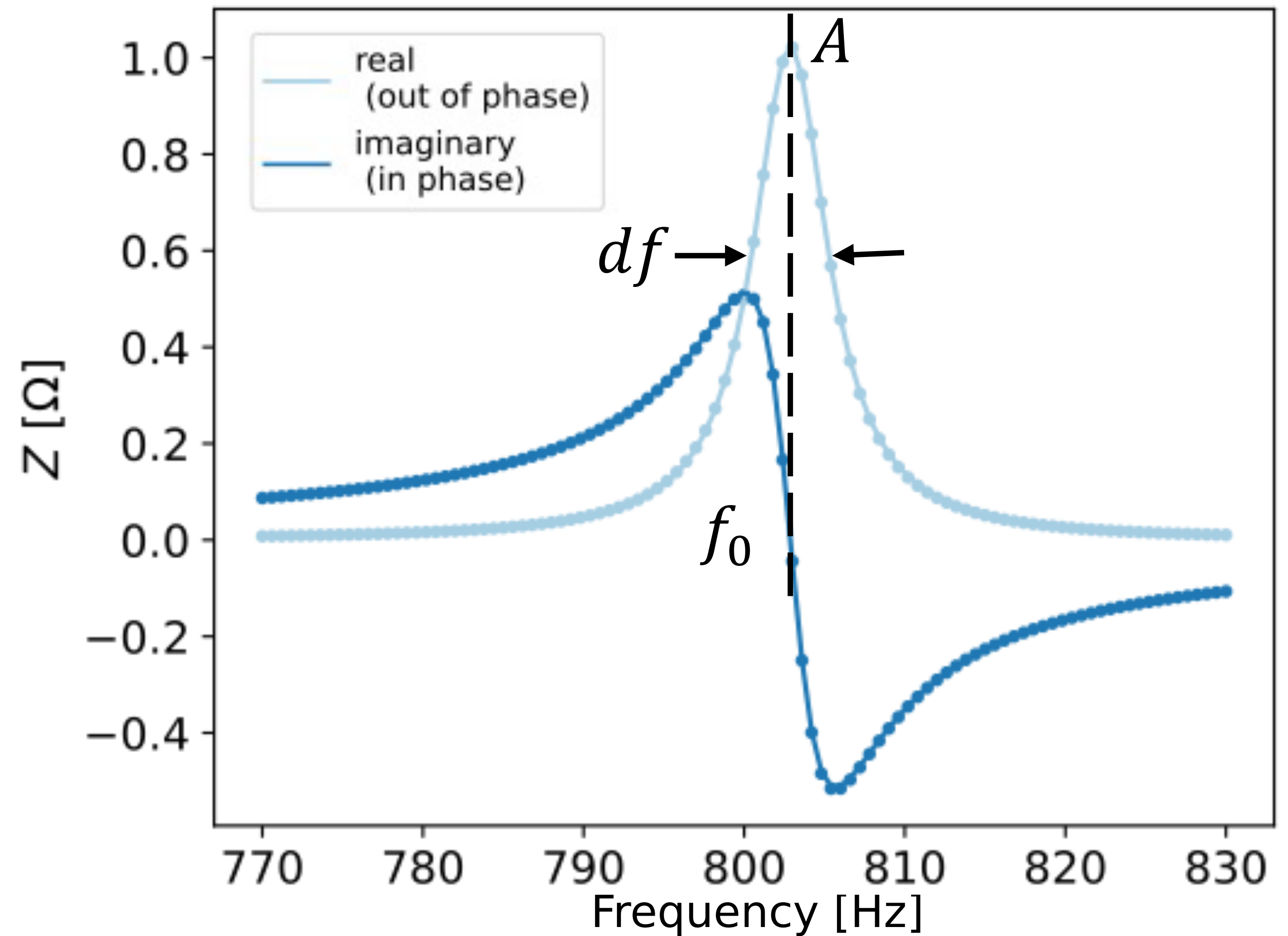


Resonance Sweeps

- To characterise a NEMS device first a large sweep over frequencies is done to find its resonance
- A shorter sweep across the resonance is then done, where the frequency dependence of the impedance can be fit to a complex Lorentzian

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

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

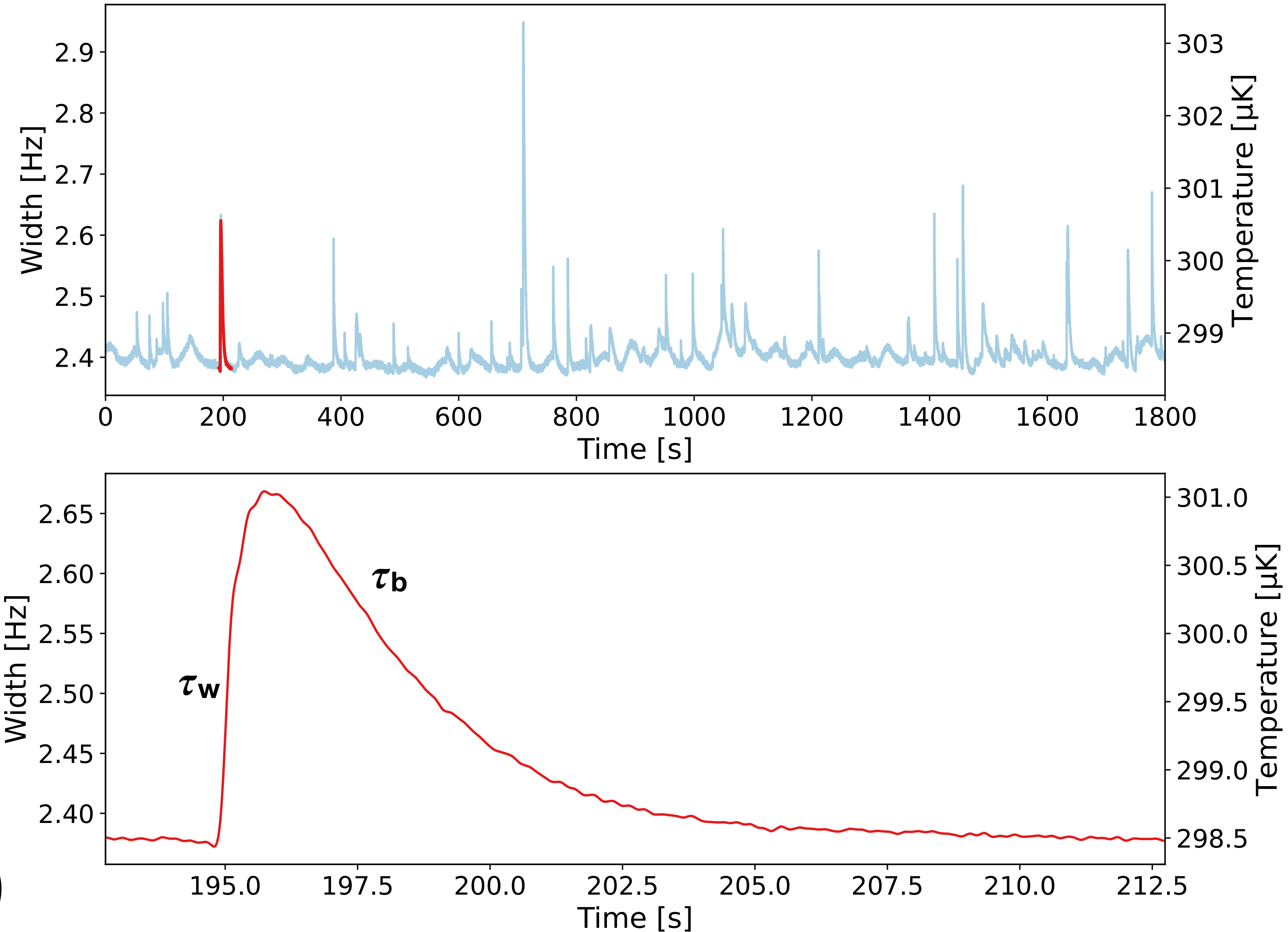


Resonance Tracking

1. Drive wire on resonance
2. Measure impedance of wire, Z
3. Use frequency sweep measurement to convert to width (δf)
4. Perform filtering + pulse finding
5. Convert pulse amplitude to energy

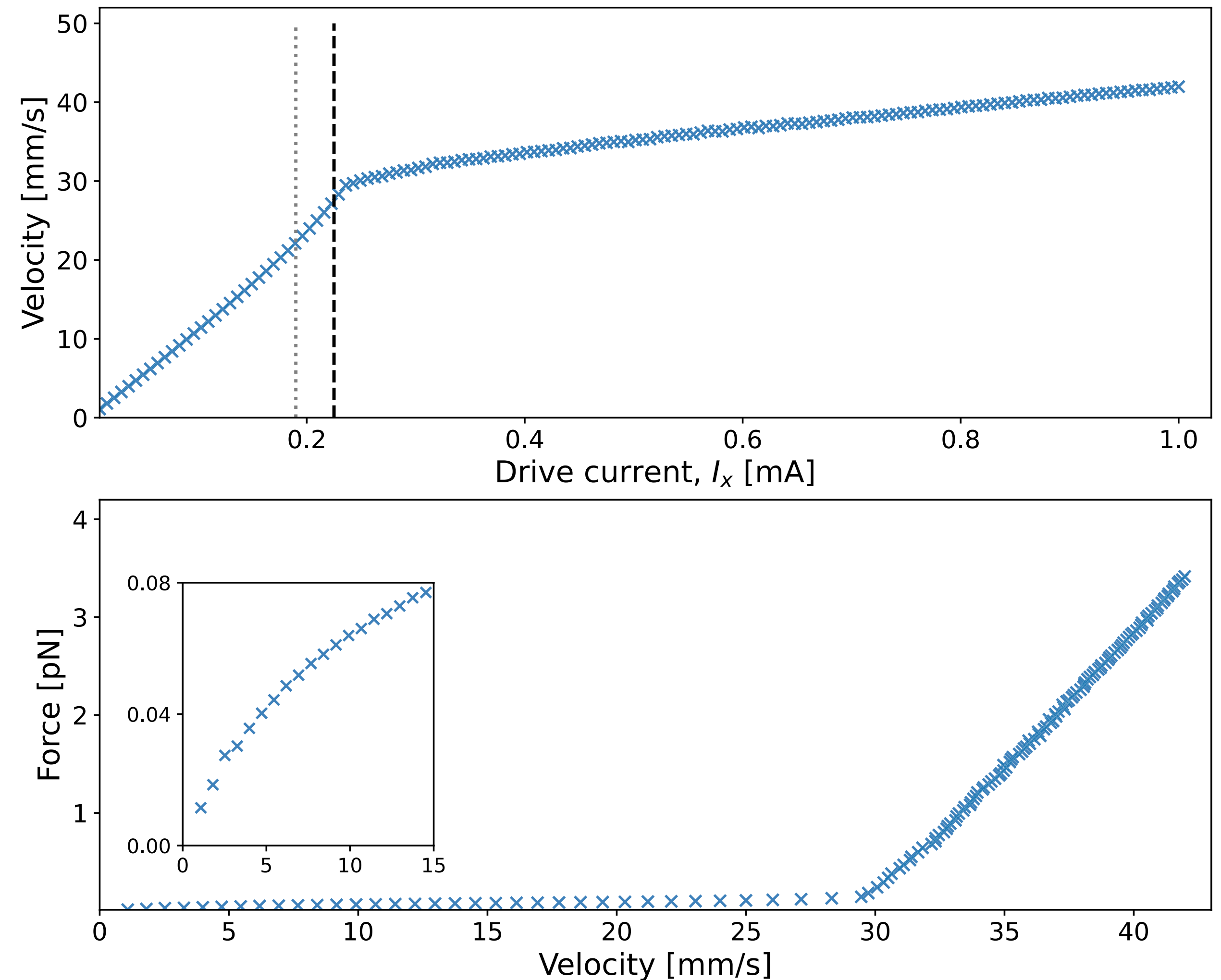
Pulses have characteristic double exponential based on wire time constant, τ_w , and bolometer time constant, τ_b

$$\delta f(t) = \delta f_{\text{base}} + \Delta(\delta f) \left(\frac{\tau_b}{\tau_w} \right)^{\tau_w / (\tau_b - \tau_w)} \times \frac{\tau_b}{\tau_b - \tau_w} \left(e^{-t/\tau_b} - e^{-t/\tau_w} \right)$$



Drive Amplitude Sweeps

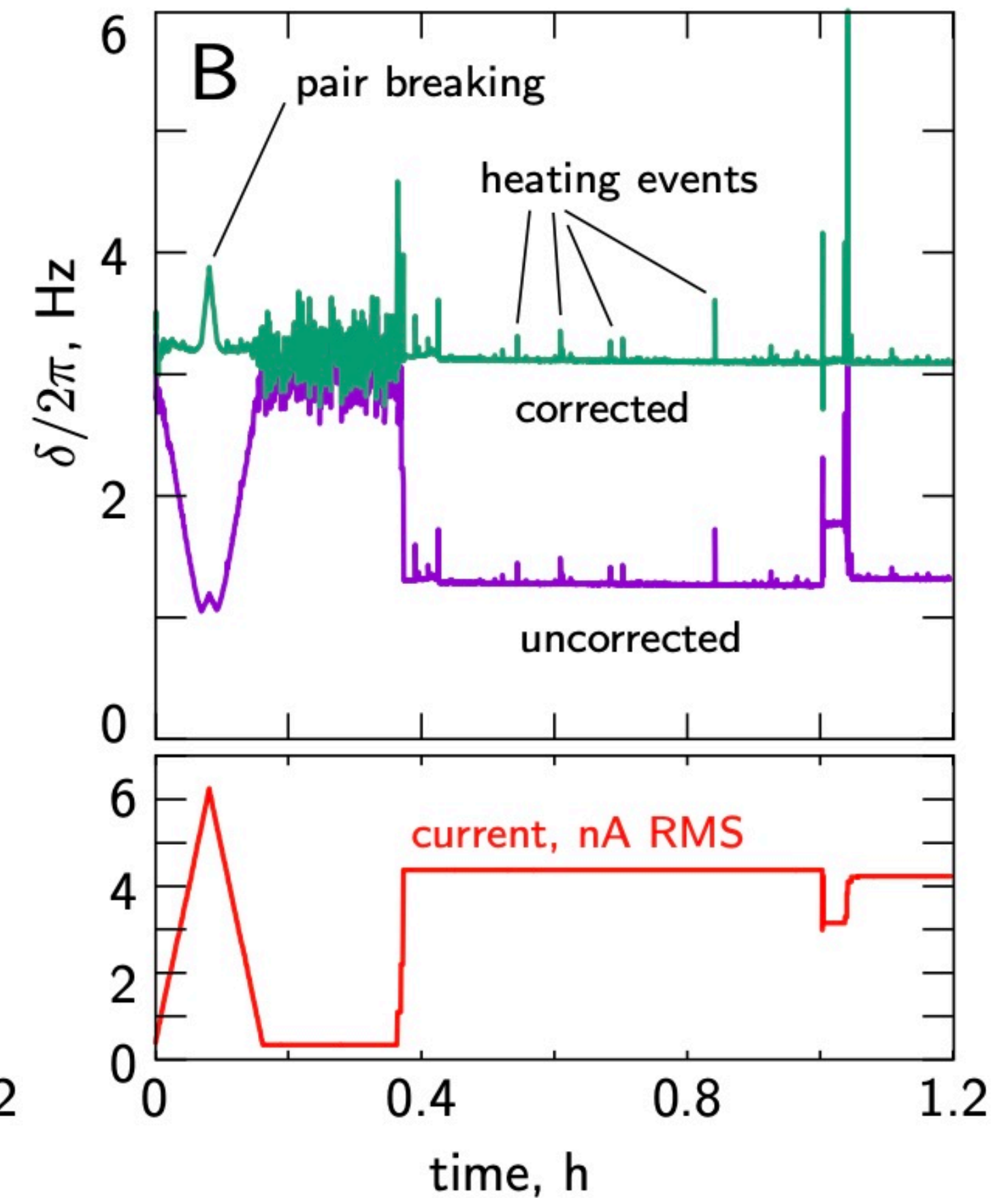
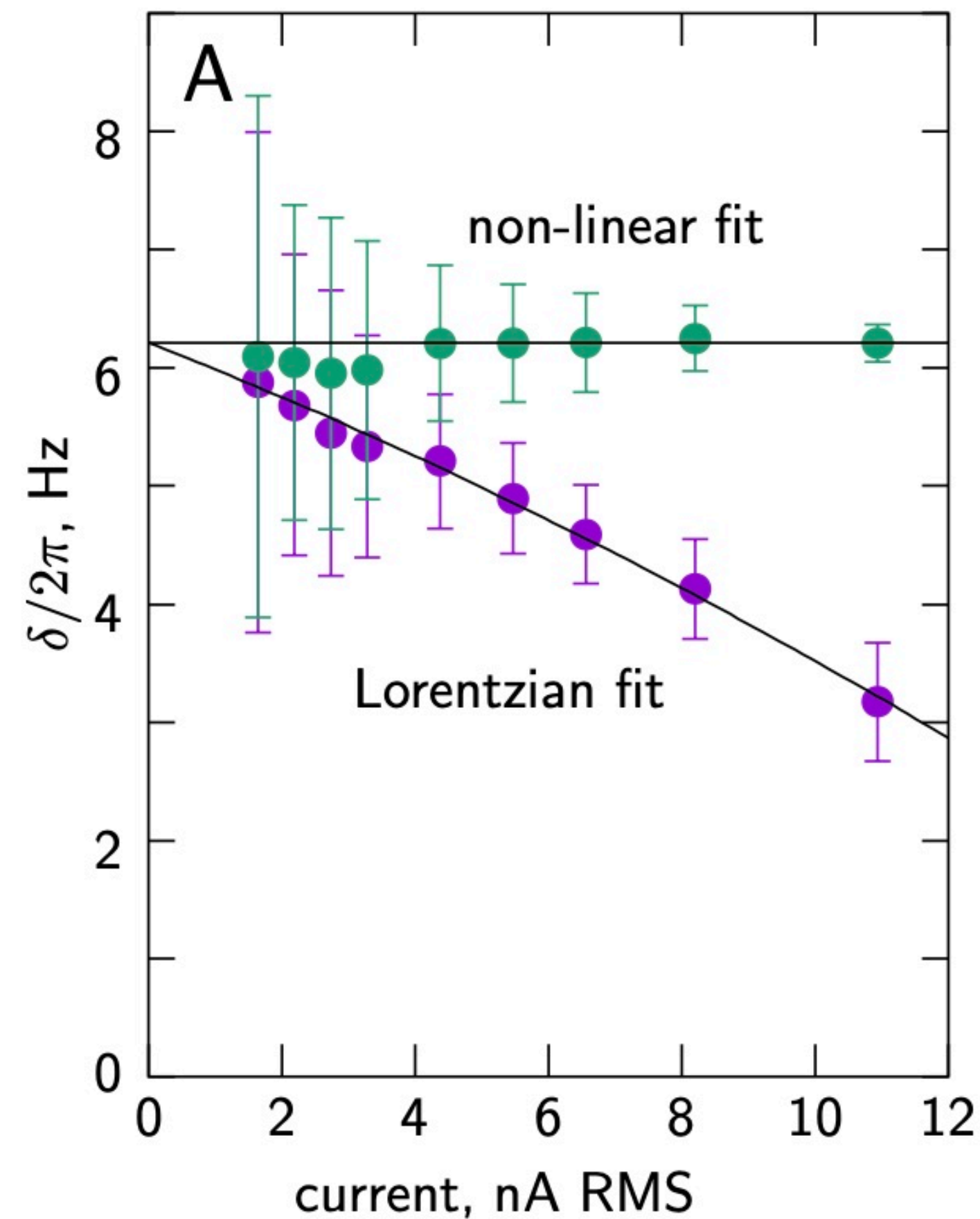
- Measure wire response to increasing drive amplitude
- Operate below pair-breaking velocity
- Wire response to damping force becomes non-linear at higher velocities (below pair-breaking)



Non-linear Drive Regime

- Larger drives increase signal to noise
- Add complexity from non-linear response of wire velocity to damping force
- Non-linear velocity dependent correction S , is used to reconstruct the width

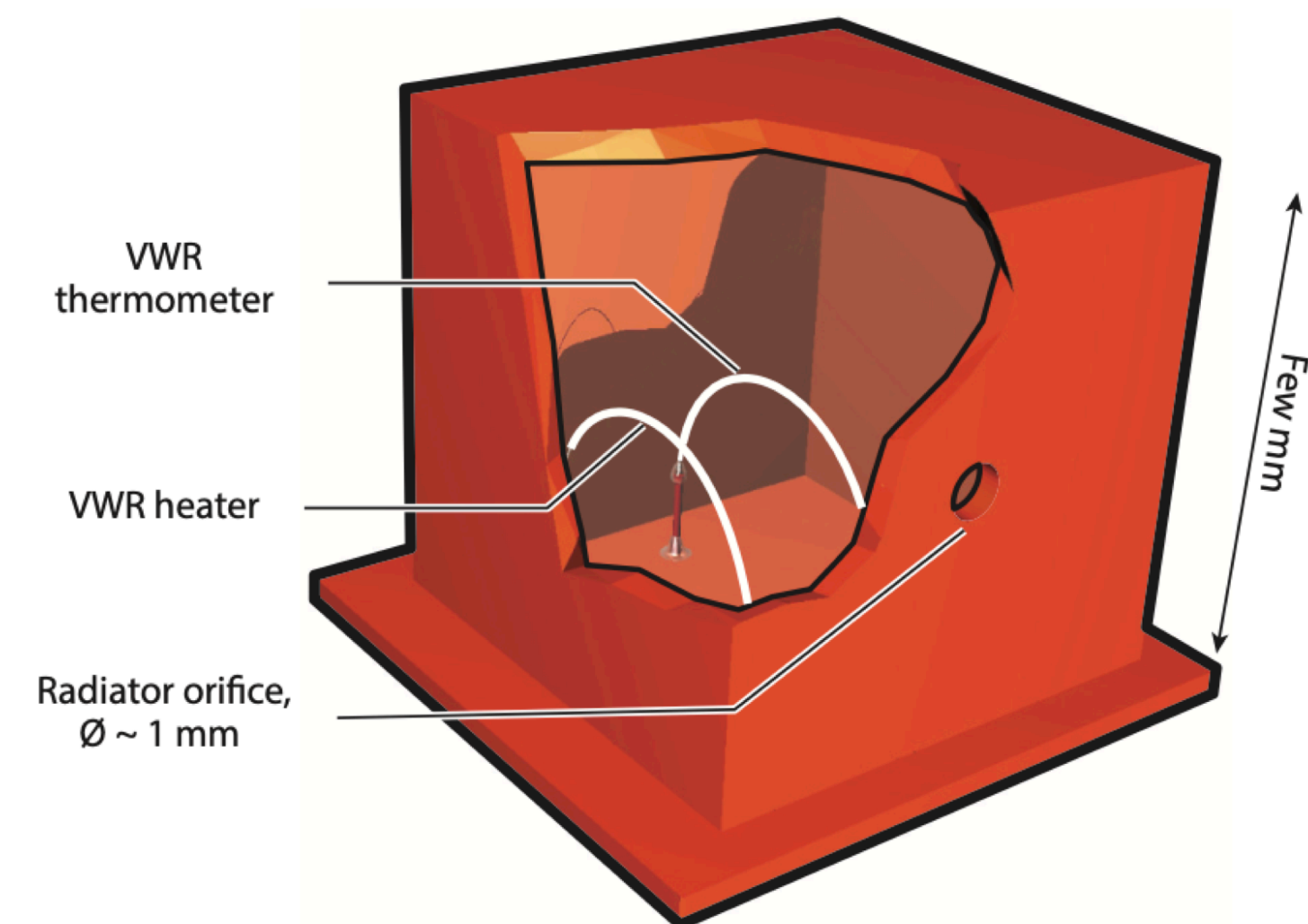
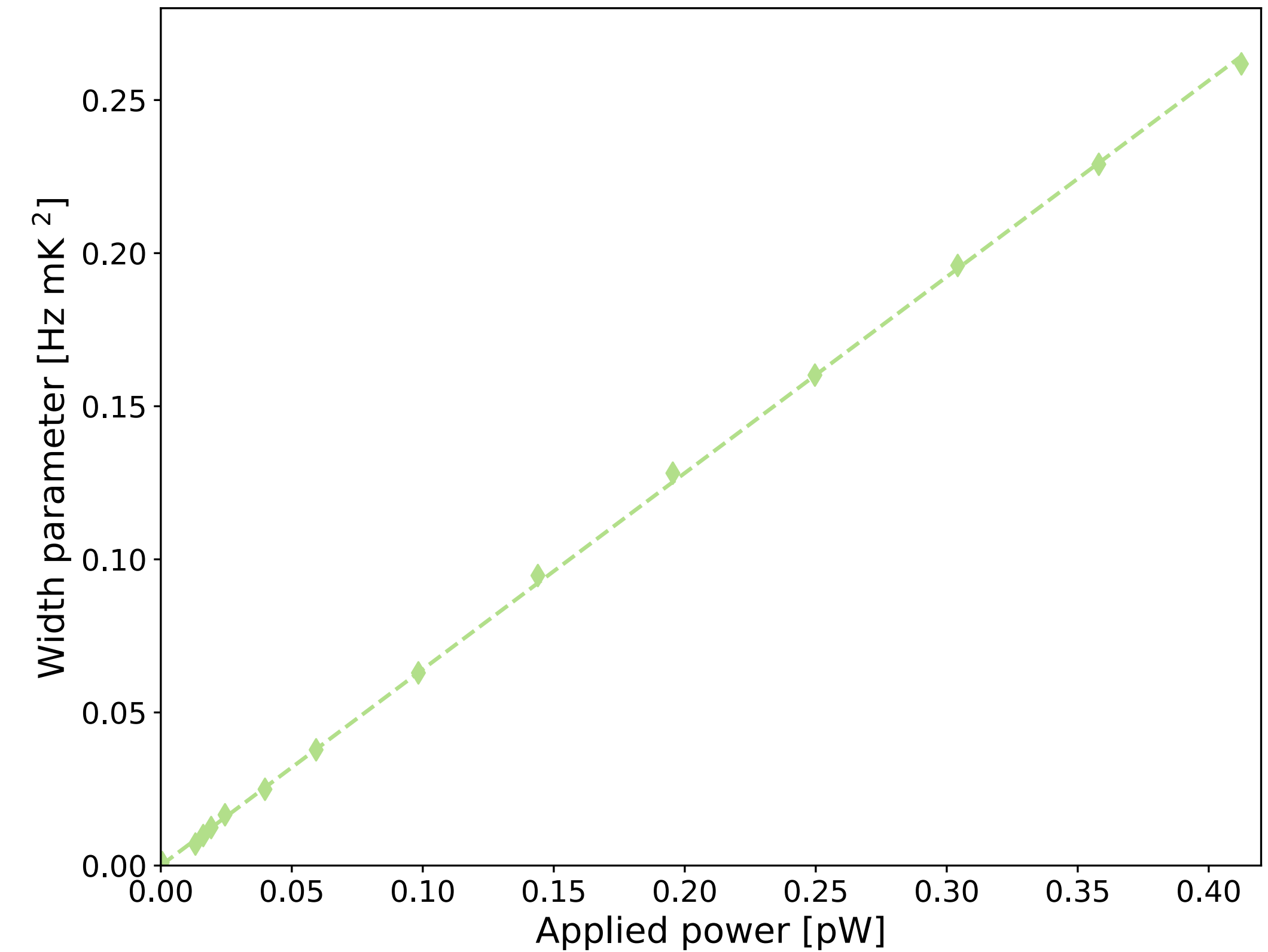
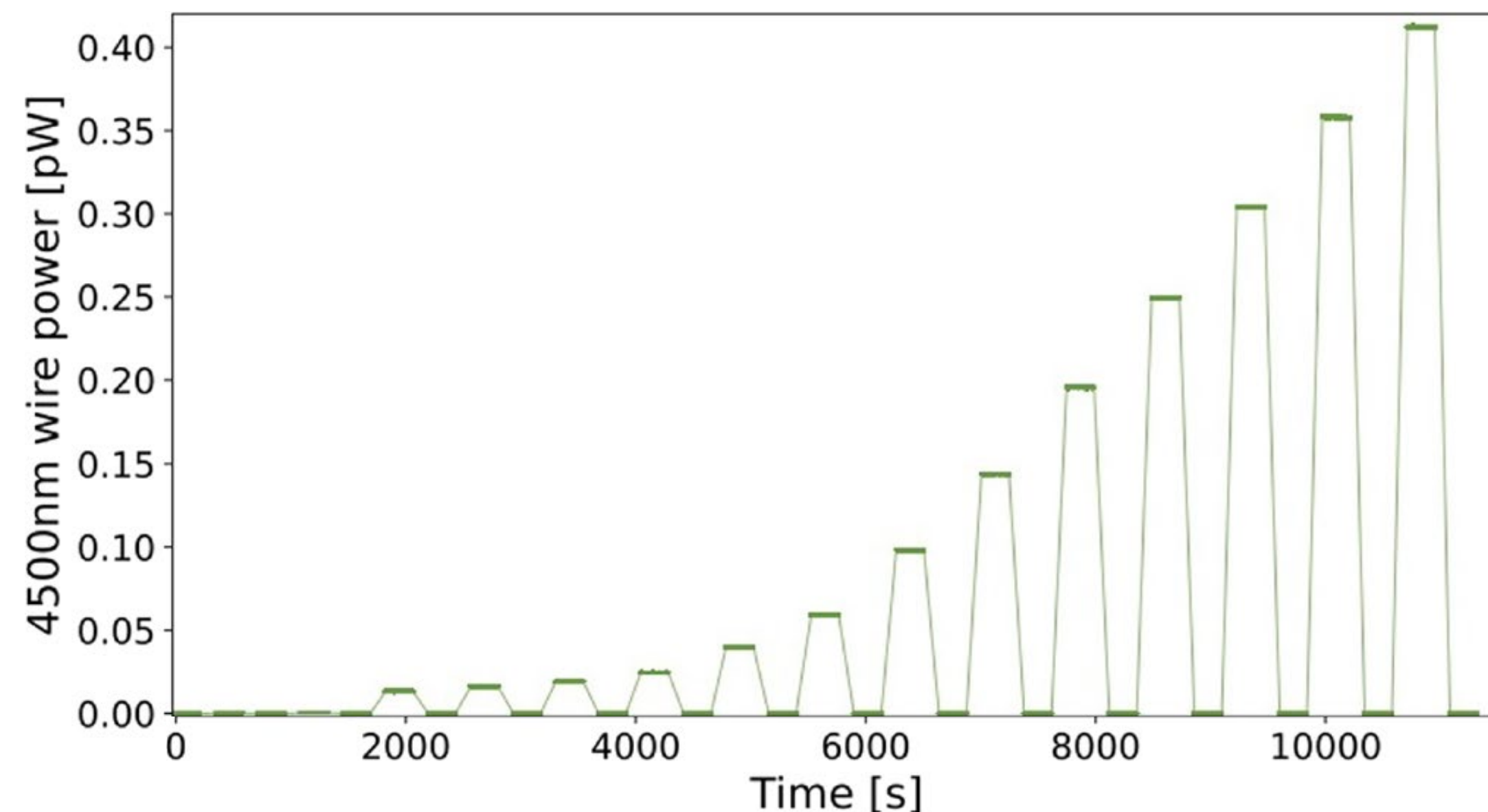
$$\Delta f(v) = \Delta f_i + \Delta f_0 S(\gamma v/v_0)$$



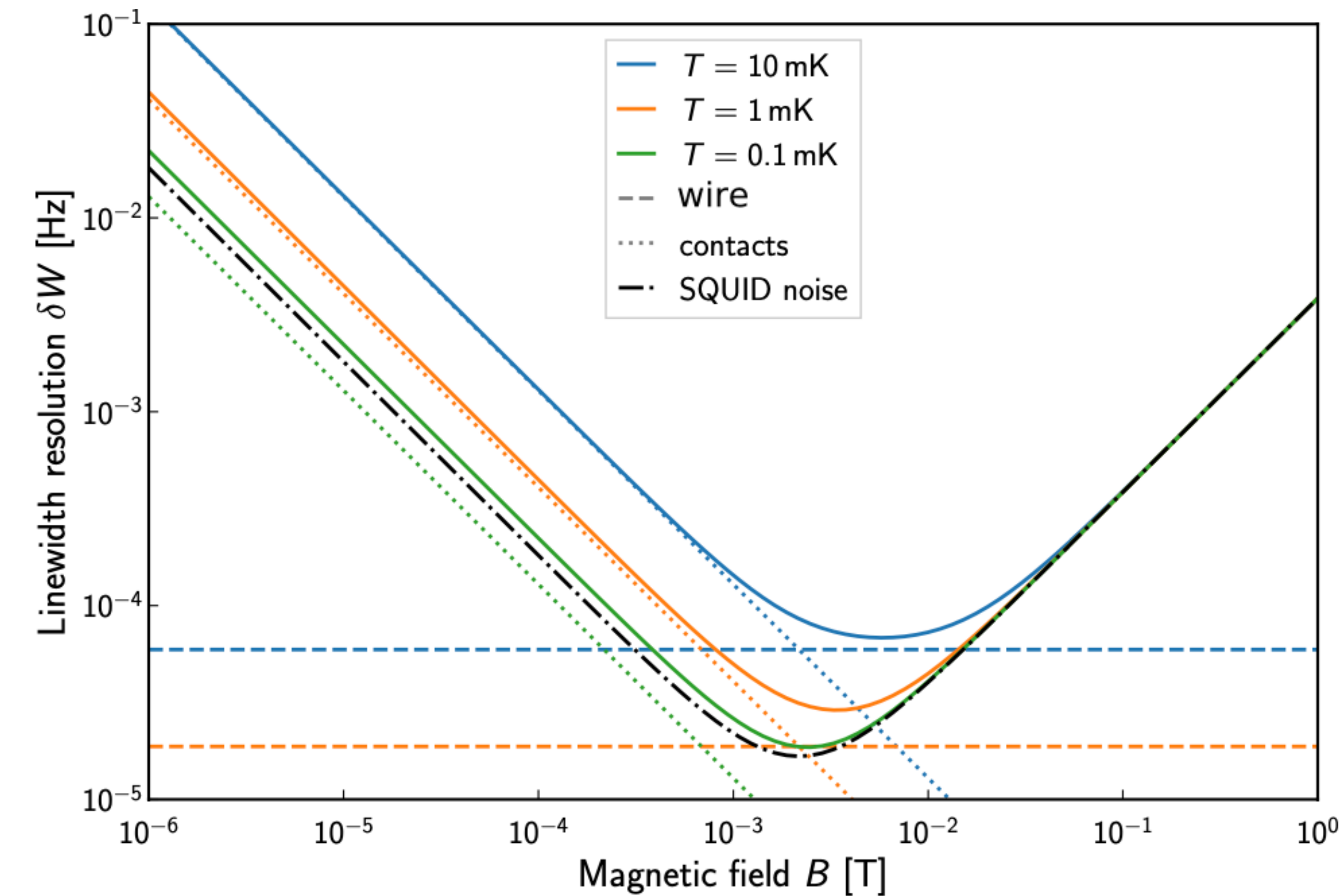
Heater Power Calibration

1. Drive heater wire past pair-breaking velocity
2. Inject known power and measure response in thermometer wire
3. Produce calibration constant for quasiparticle partition

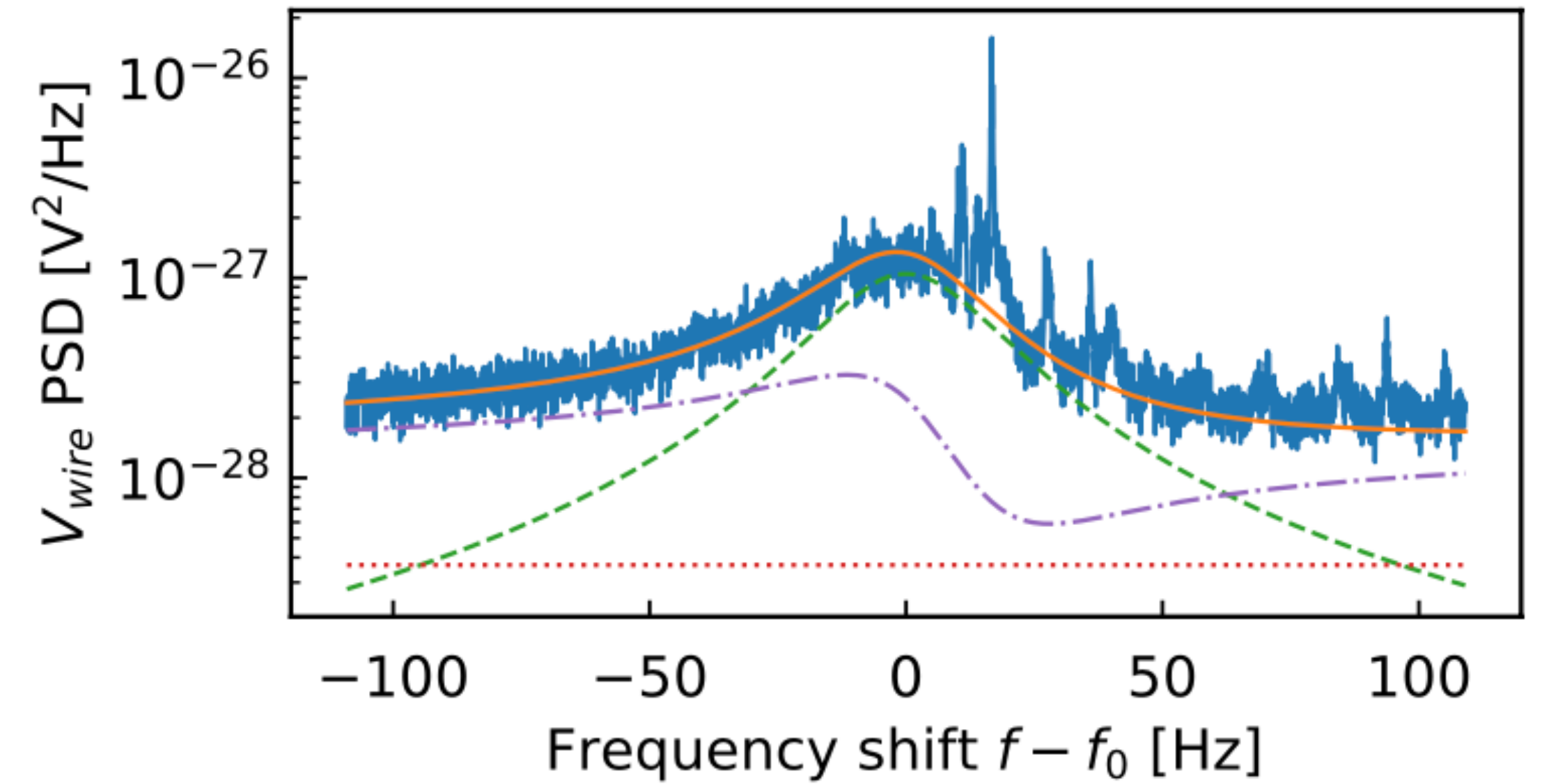
Currently commissioning ^{55}Fe calibration source



Sources of Noise



data
model:
total
wire
contacts
SQUID



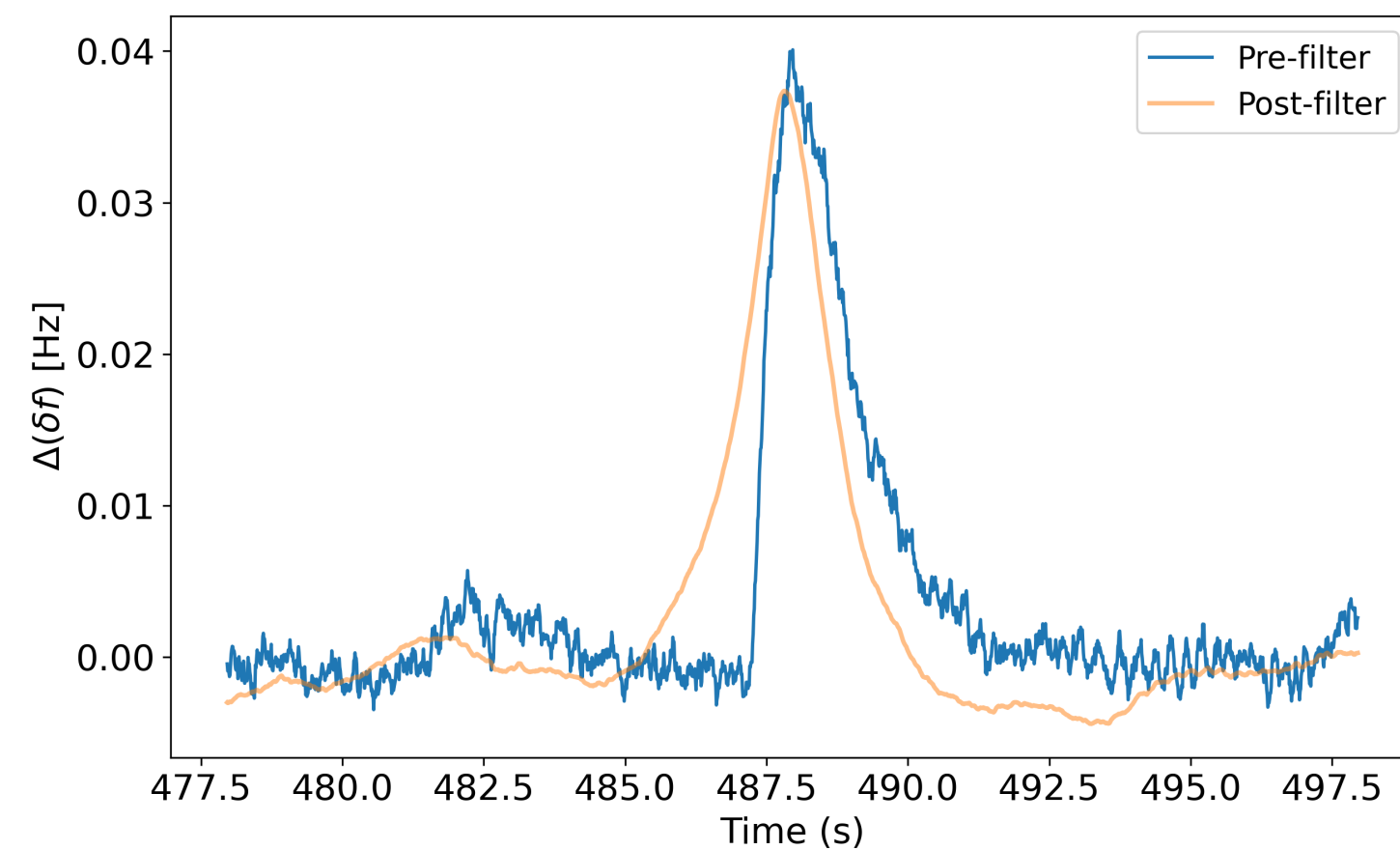
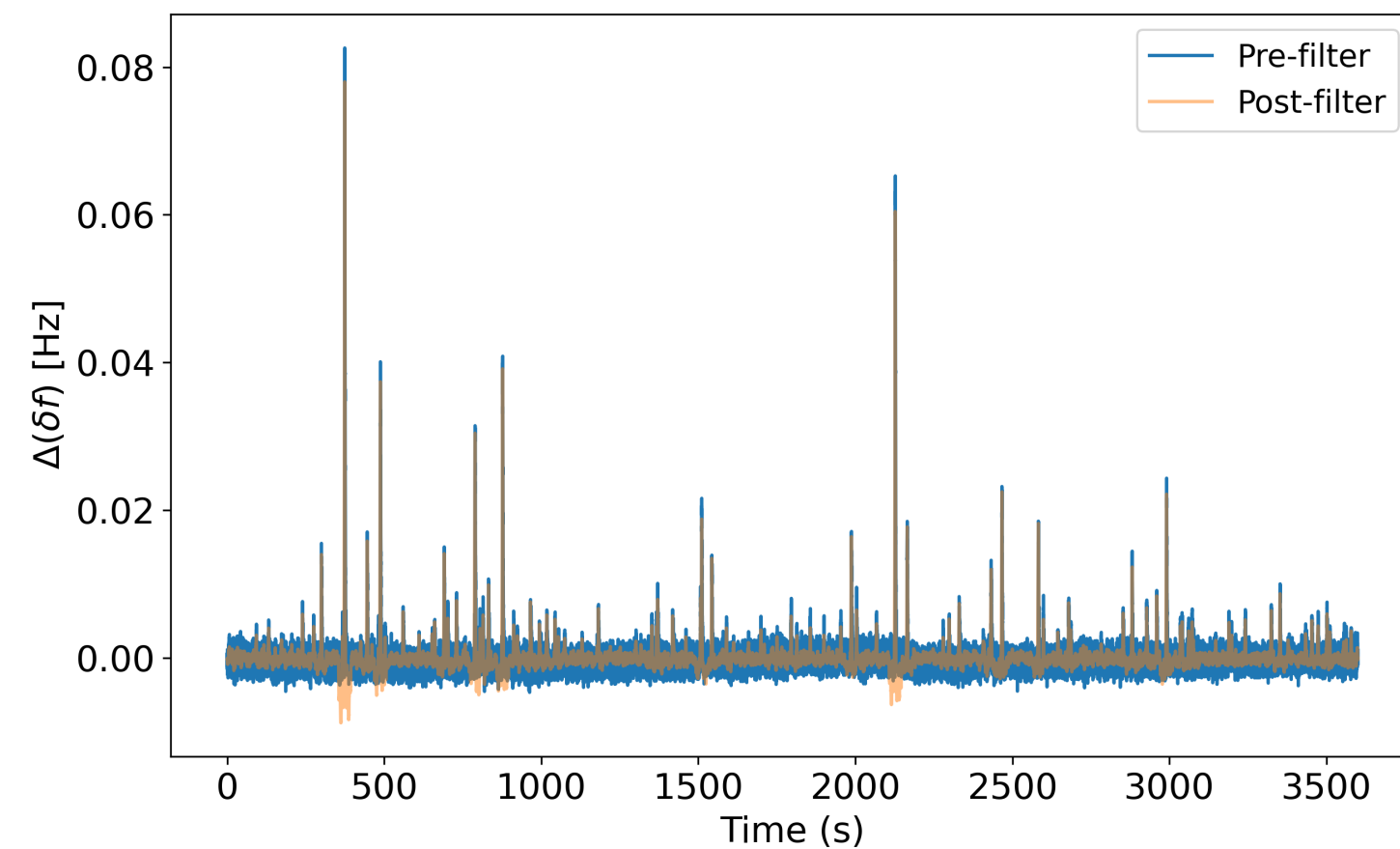
- Vibrations coupling to the wire
- Operation of the SQUID (vibrational, magnetic field, temperature)

Lower noise $\rightarrow$ lower pulse finding threshold $\rightarrow$ sensitivity to lower DM masses

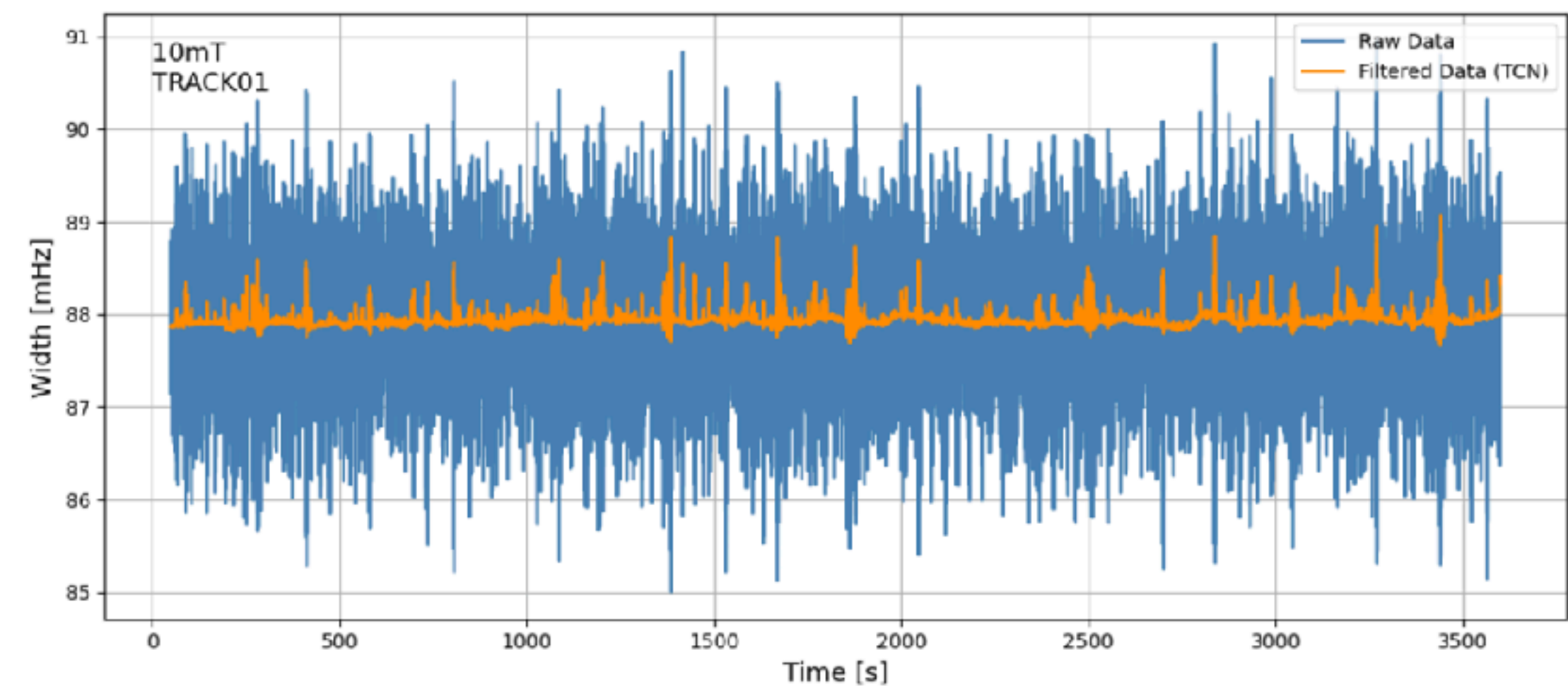
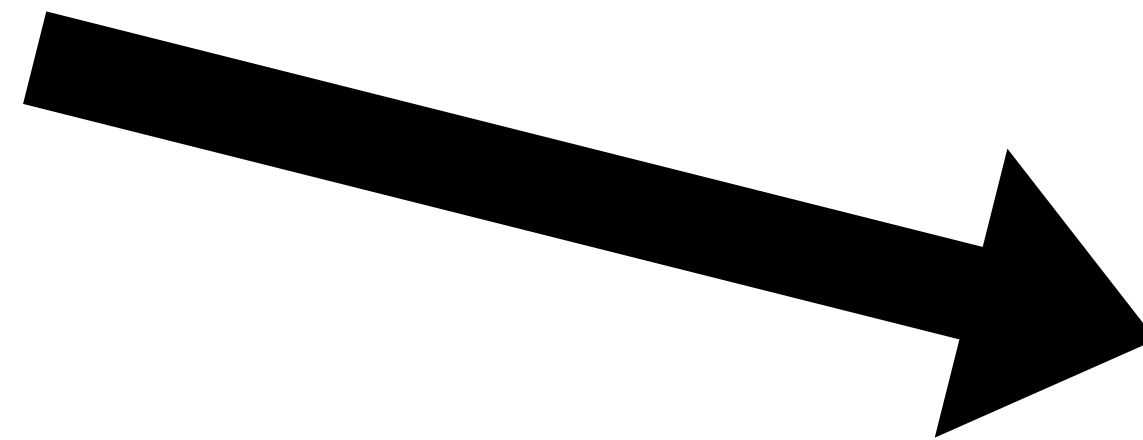
Filtering

Gatti-Manfredi optimal filter

$$\chi^2(f; a) = \sum_f \frac{|S(f) - aT(f)|^2}{N(f)}$$



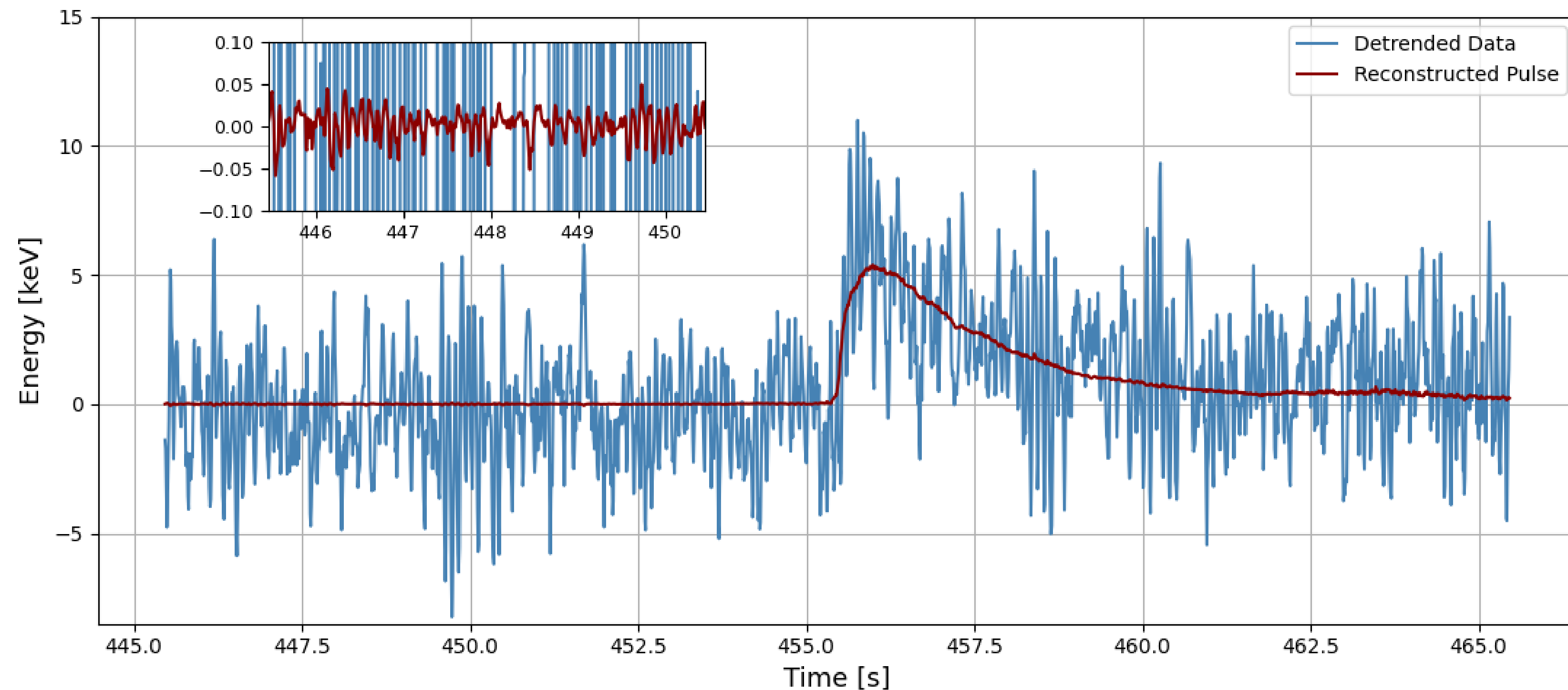
Possible future improvement



Temporal convolutional network (TCN),
machine learning based noise reduction

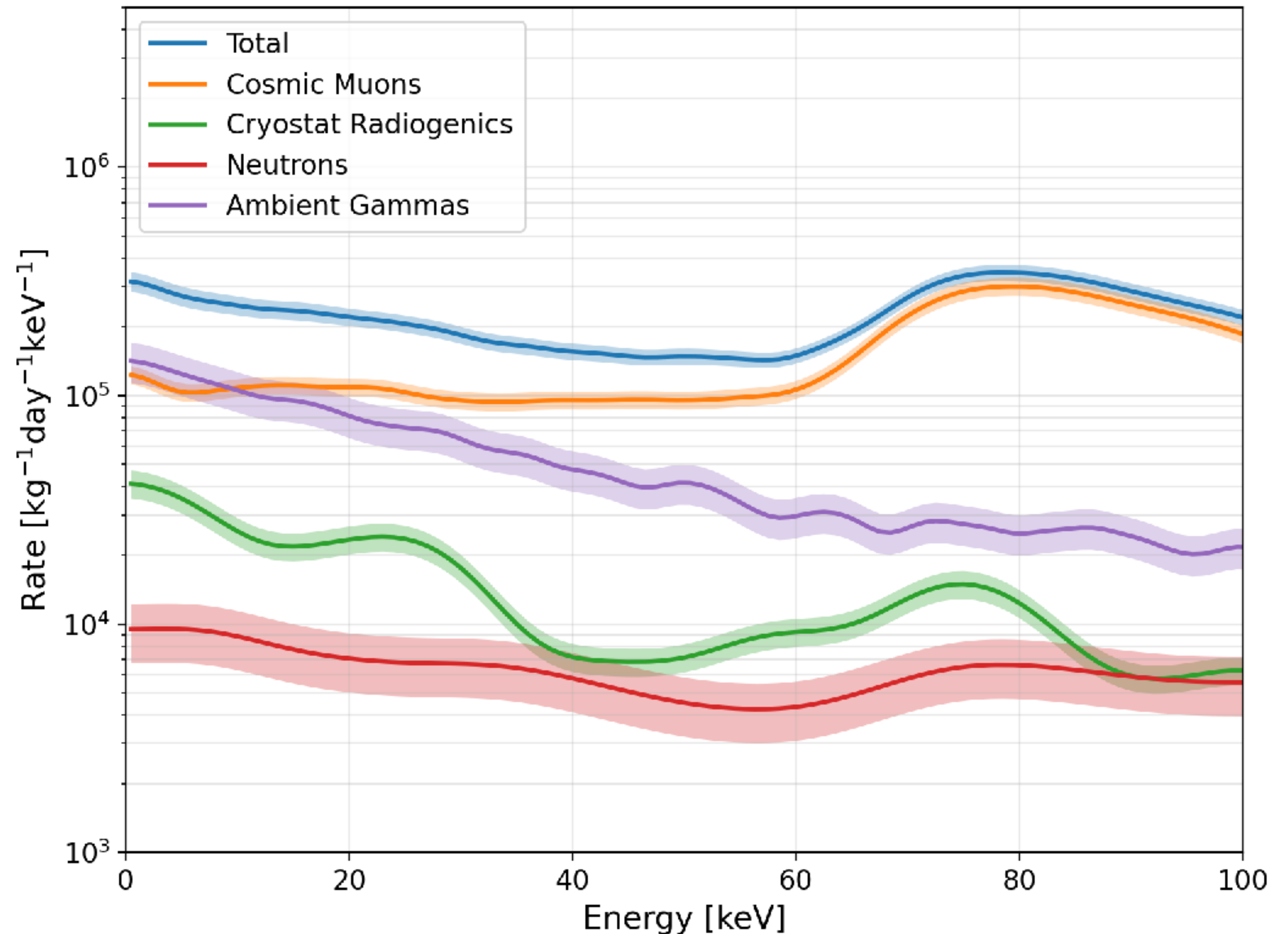
Current Operation

- Currently operating a new bolometer and fridge in Lancaster
- Coldest bolometers yet ($\sim 120\ \mu\text{K}$!)
- SQUID readout



Sources of Background

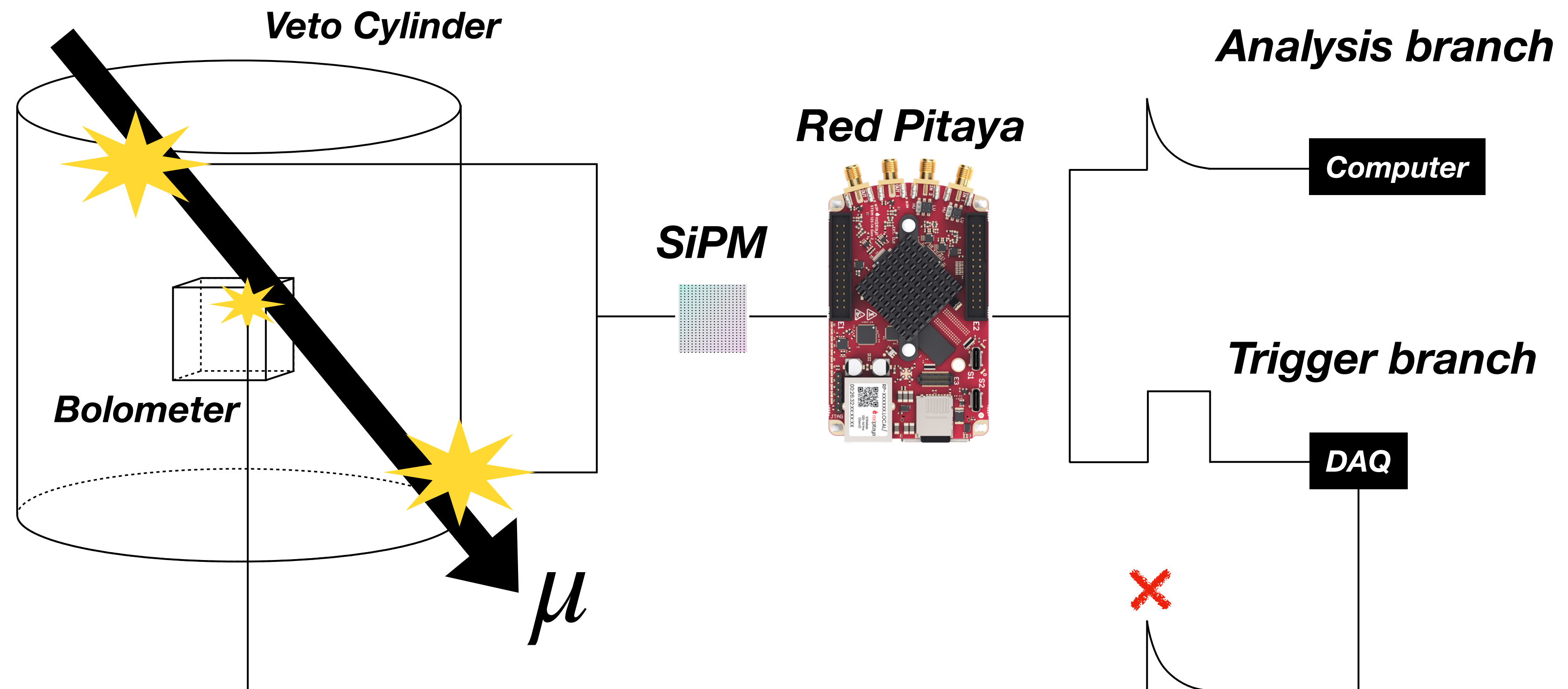
- Expected background rates in a Lancaster bolometer produced from Geant4 simulation
- Largest expected contribution from cosmic rays
- Improved veto power → improved sensitivity to DM interactions



Cosmic Muon Veto System

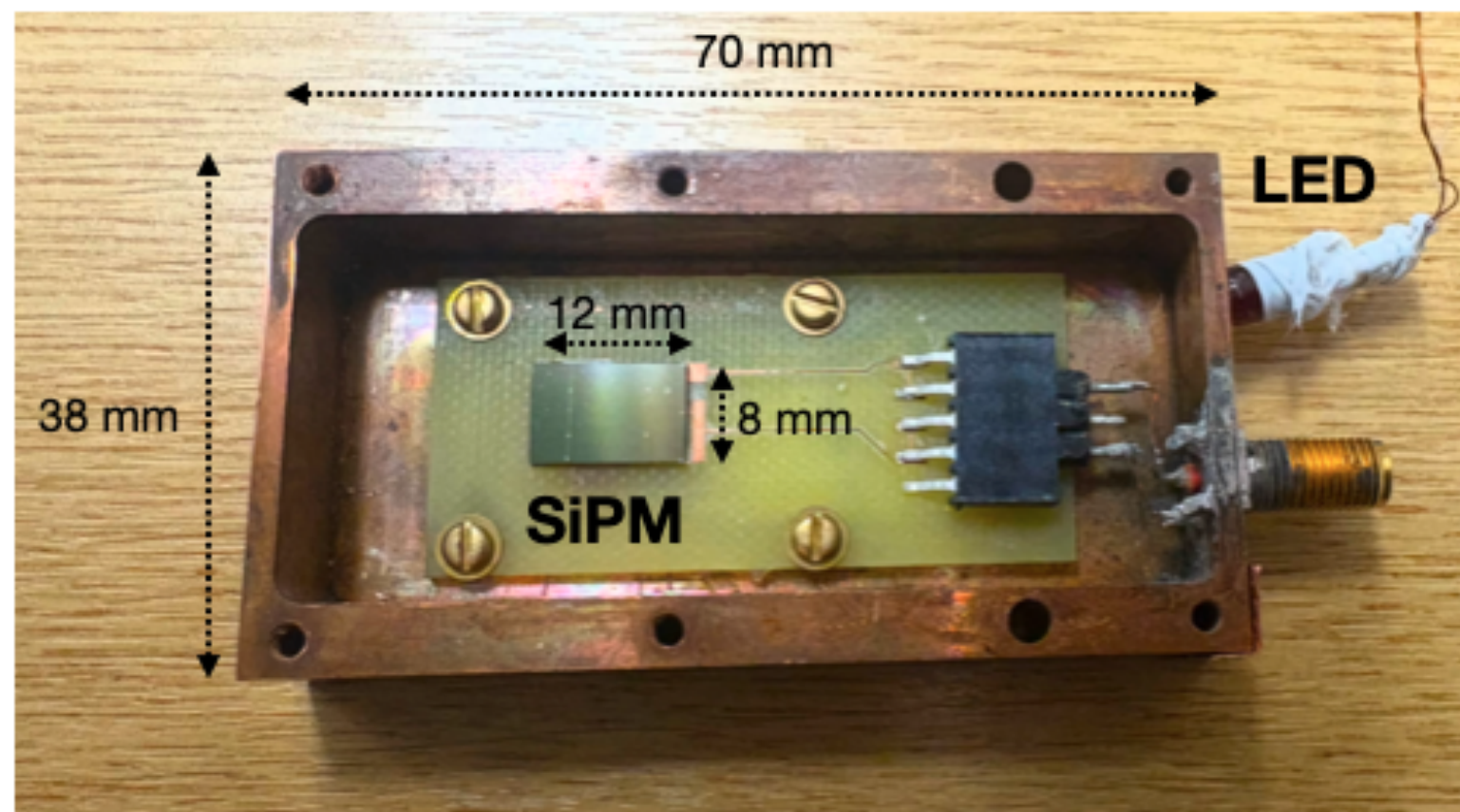
Development of veto system happening here at RAL

- Scintillator block moulded to fit around bolometer inside fridge
- Coupled to photon readout (SiPM for example)
- Use of a Red Pitaya FPGA development board to create trigger logic for muon signals
- Ability to reject coincident signals between veto detector and bolometer

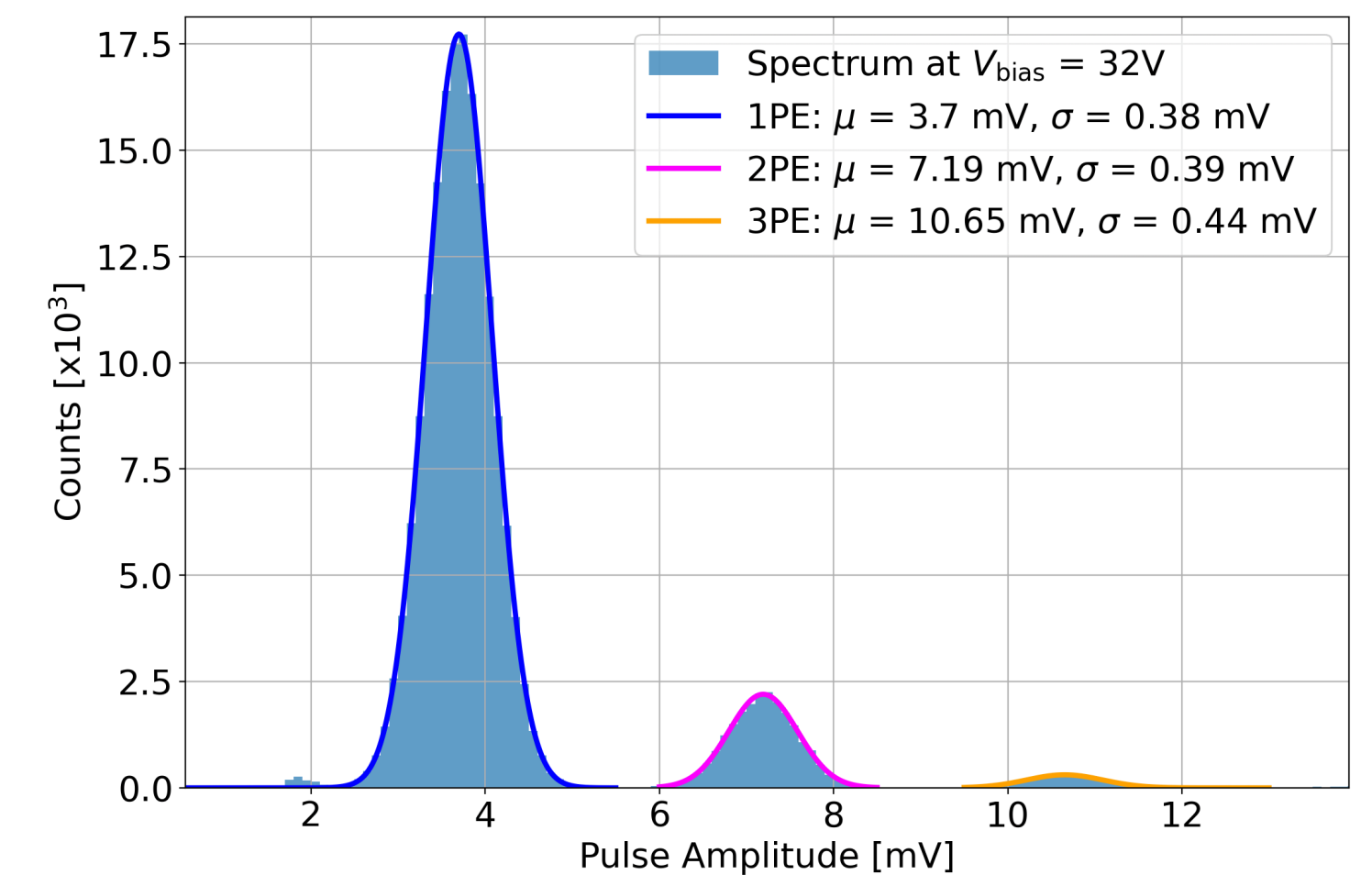
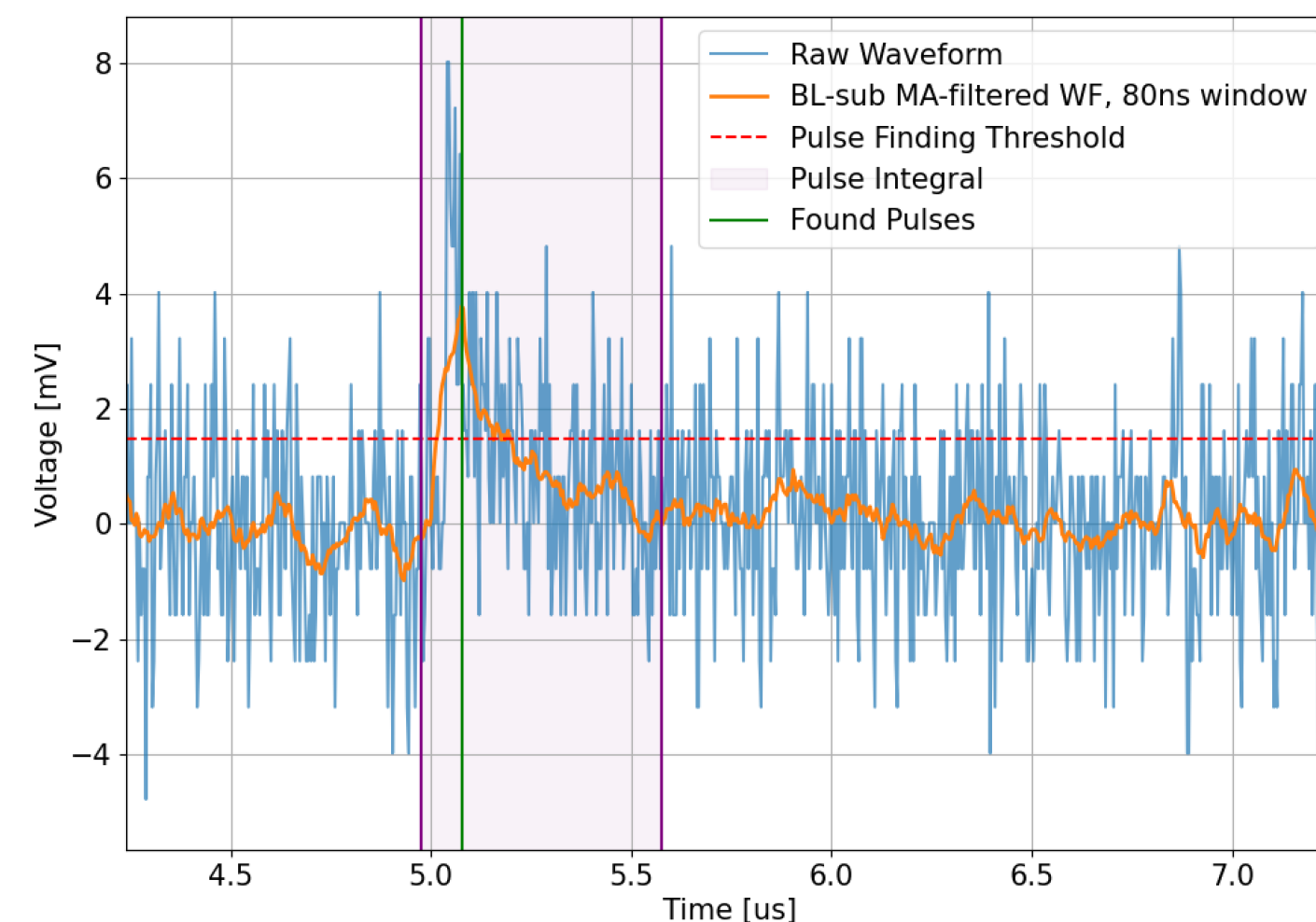
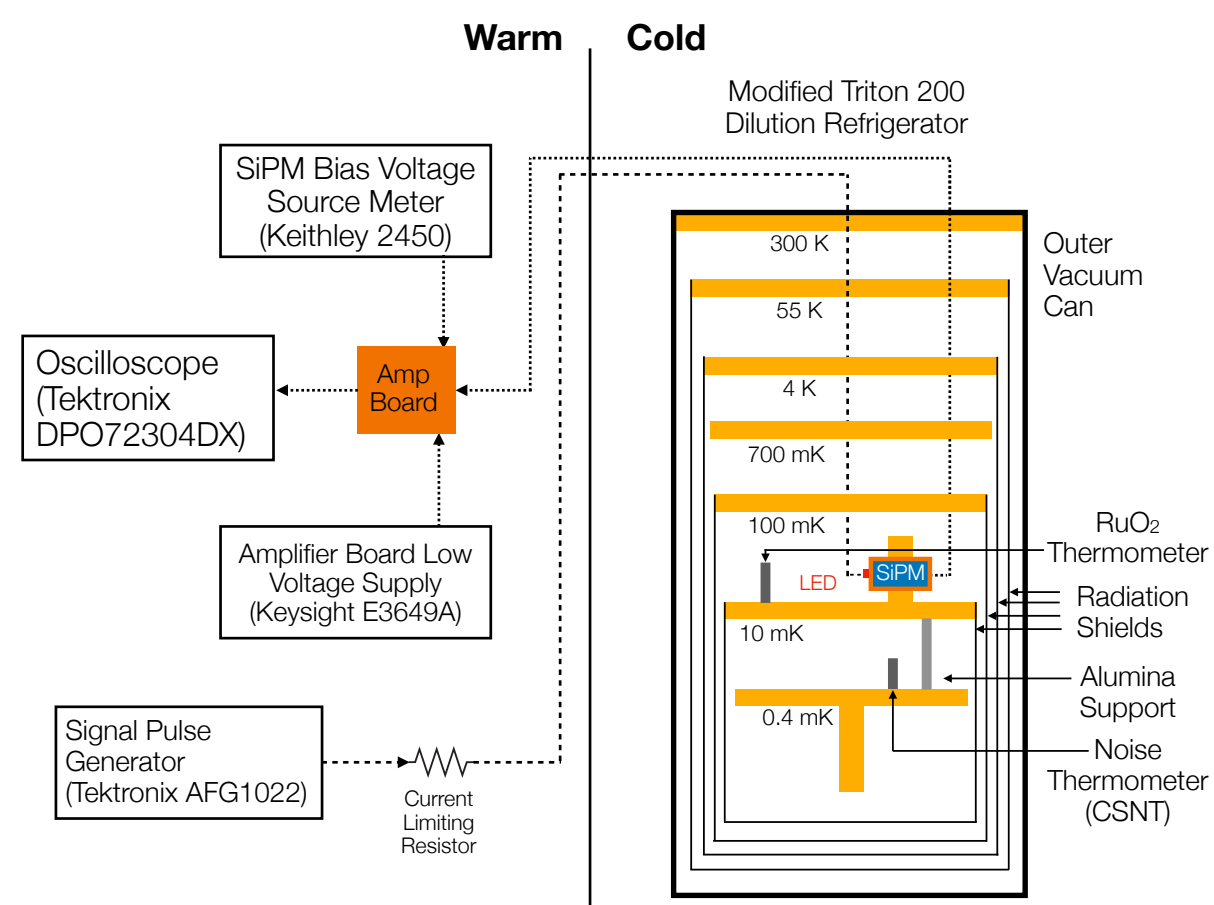


Photon Channel Readout

- Photon detection at mK temperatures - 'Characterisation of silicon photomultipliers in a dilution refrigerator down to 9.4 mK towards a cryogenic cosmic-ray muon veto system', A. Kemp *et al* 2026 *JINST* **21** P05008)

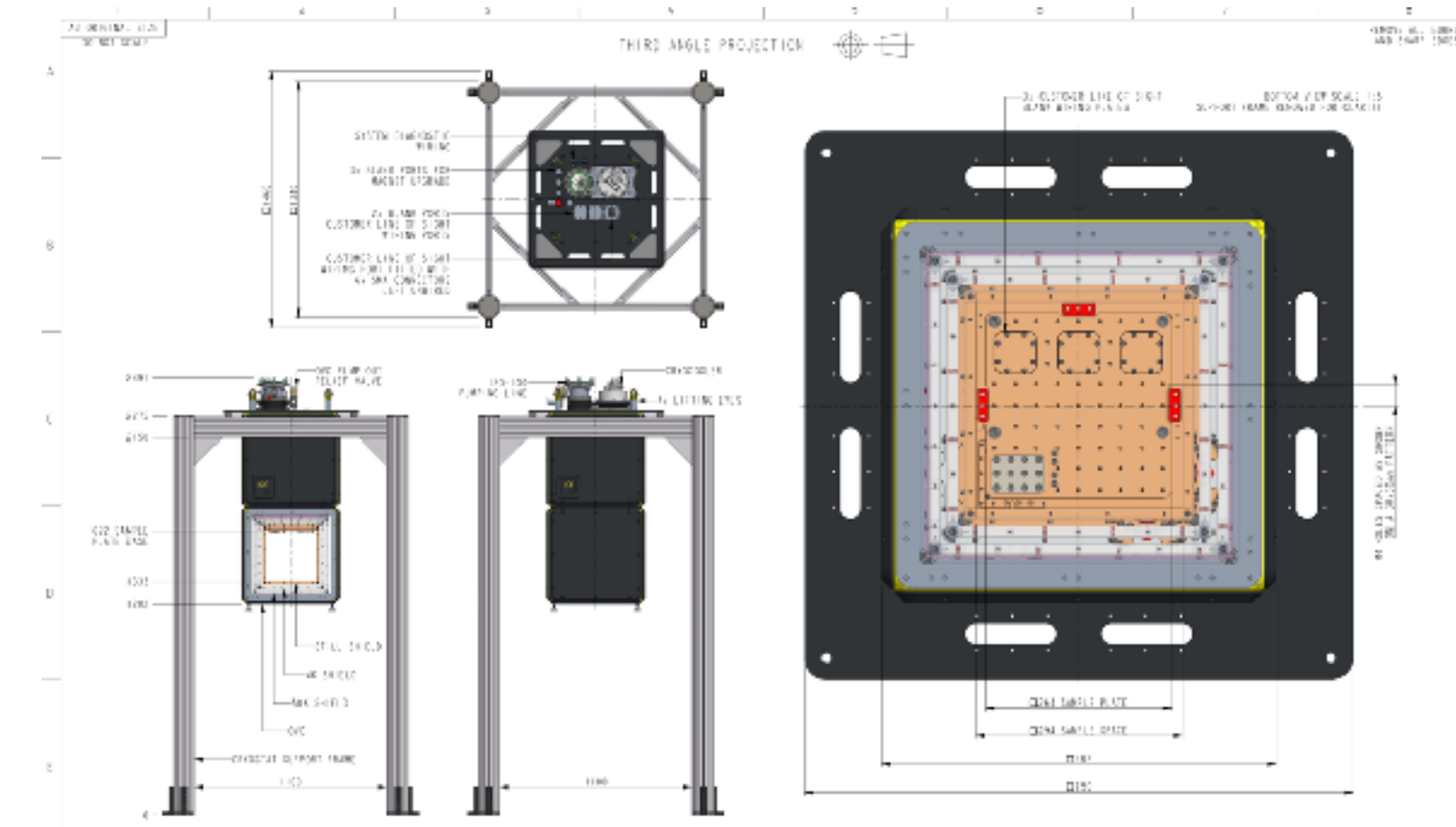
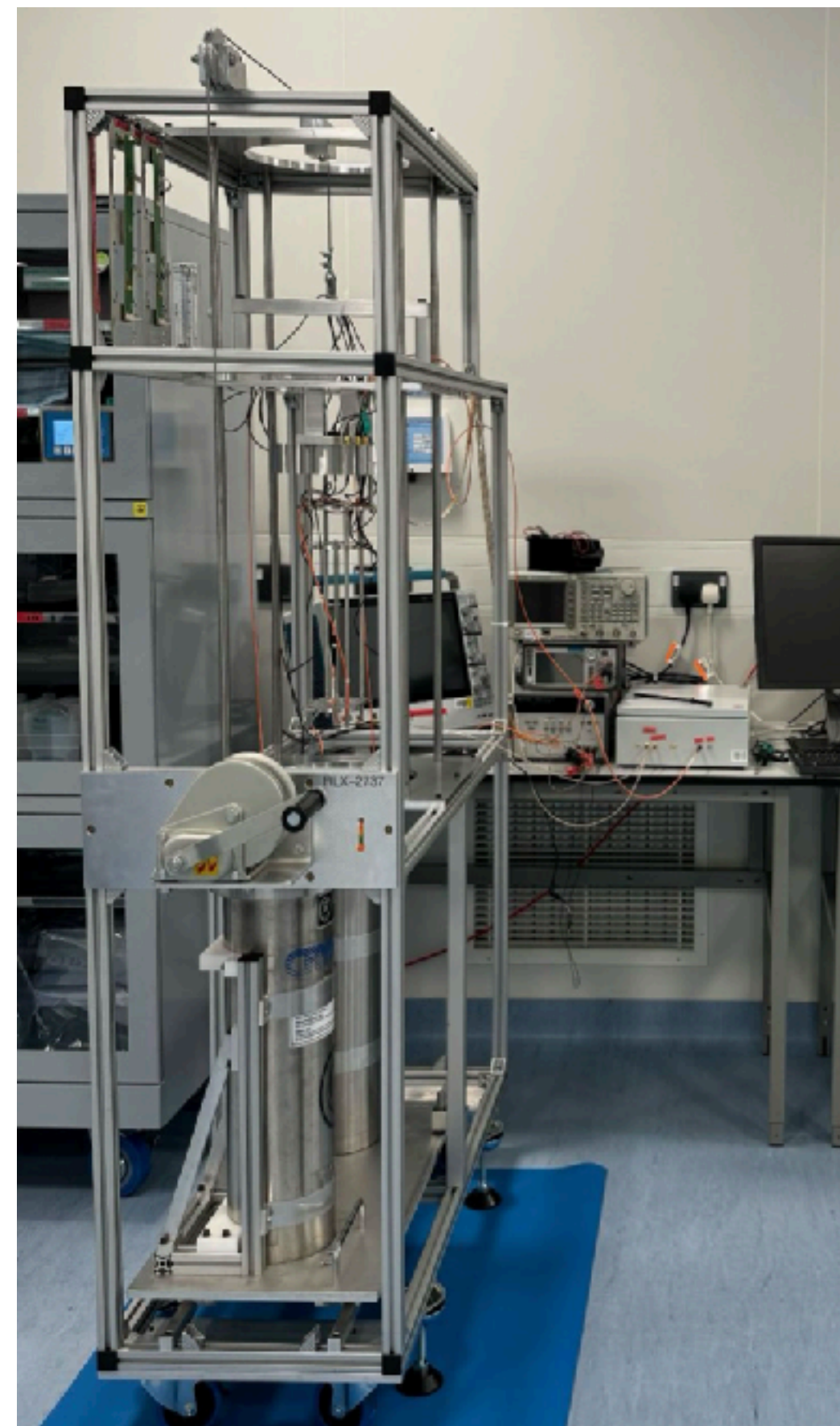


- Demonstration of operation and good single photon resolution at 10 mK



QUEST-DMC at RAL PPD

- Data processing and infrastructure for current operation in Lancaster
- Development of machine learning based filtering/pulse finding to reduce experimental threshold
- R&D for cosmic muon veto system, links to quantum error correction
- Commissioning of cryolab in lab 9, 20 mK fridge to arrive in the very near future!
- Heavy involvement in producing a low-threshold Dark Matter search



Physics Potential

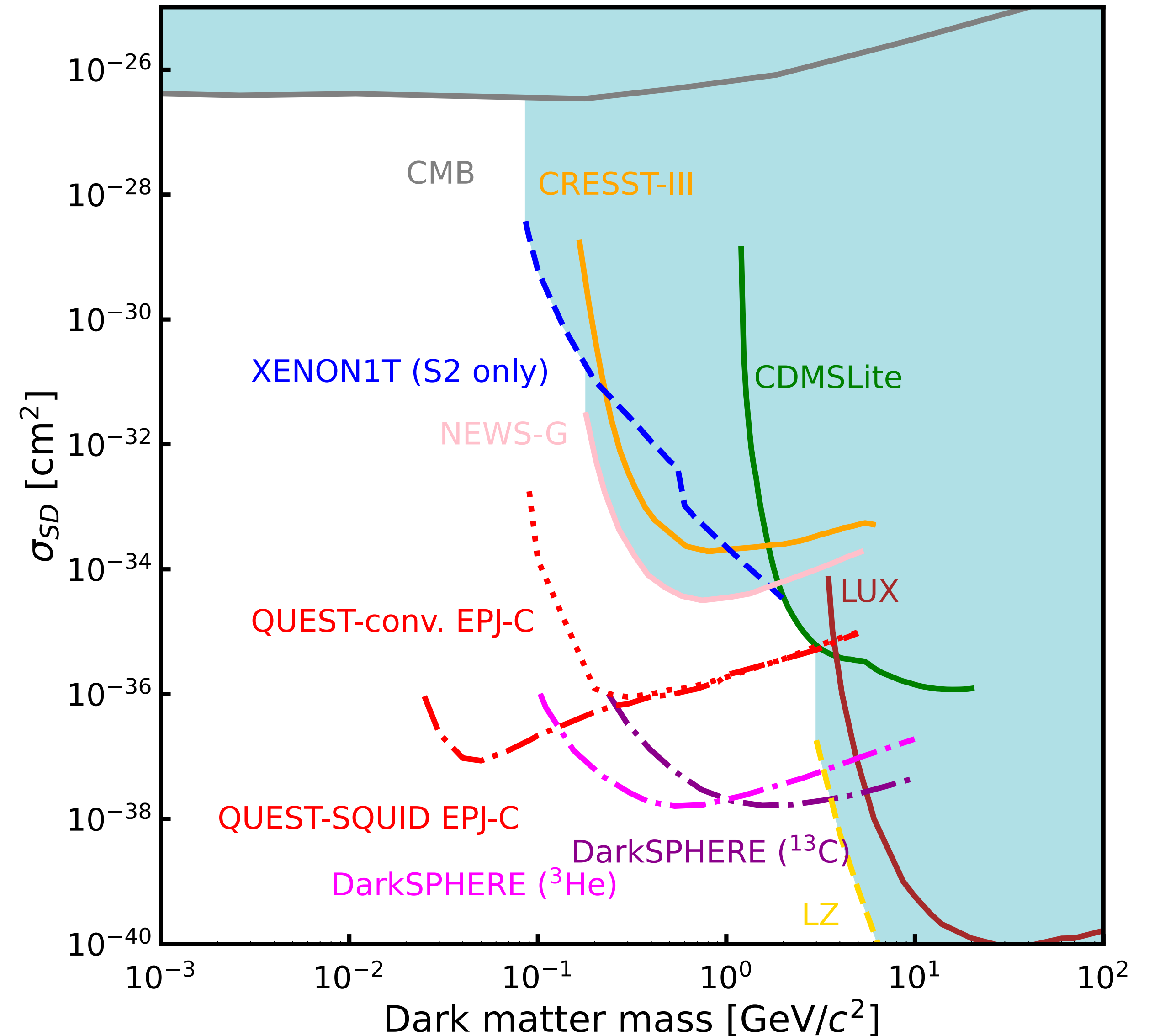
Potential Sensitivity

Spin dependent sensitivity projection for:

- 5 x 0.3 cm³ cells
- 6 month run with 50% duty cycle
- 0.51 eV threshold with SQUID readout

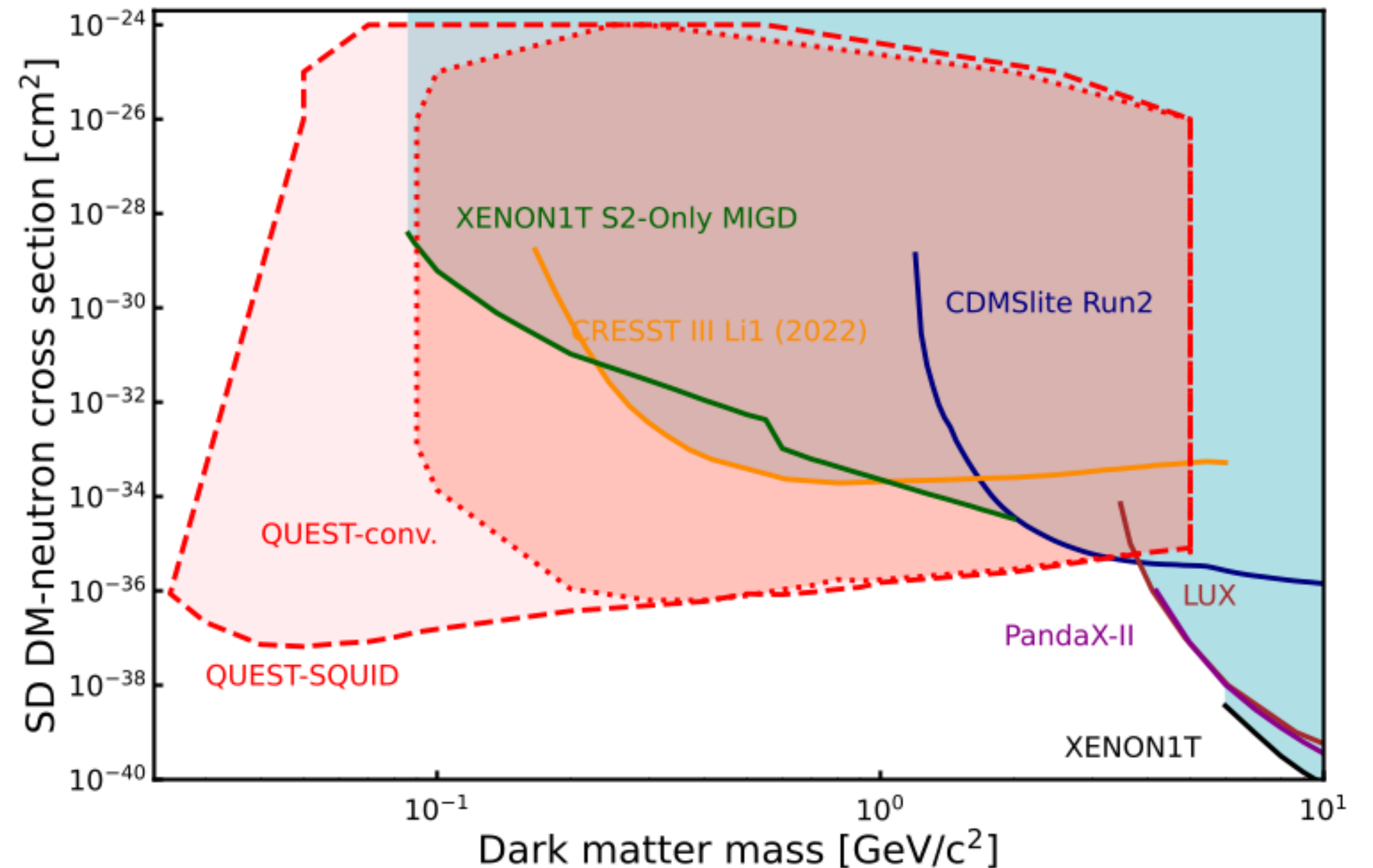
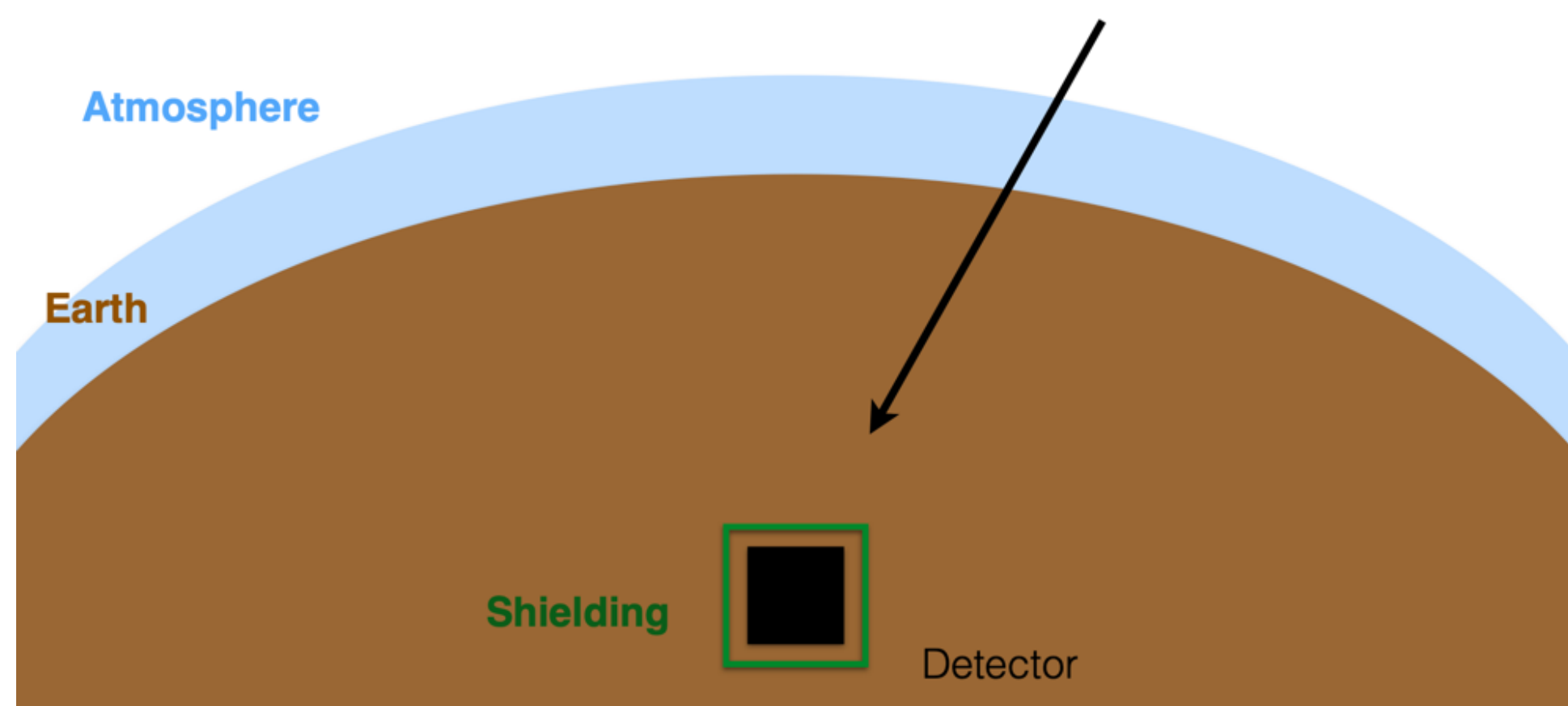
Systematics: background rate, energy scale and galactic escape velocity.

Reported in: [*Eur. Phys. J. C \(2024\)*](#)



Earth Shadowing

- DM scattering in atmosphere/Earth/shielding can alter path and reduce energy of incoming DM
- Flux and energy reduced until no events exceed threshold
- No sensitivity at highest cross sections!



Reported in: [JCAP04\(2025\)017](#)

Conclusions & Outlook

- QUEST-DMC collaboration is searching for sub-GeV dark matter using superfluid Helium-3 and low noise quantum readout
- Demonstrated SQUID readout of vibrating nanowires and pulse detection
- Currently operating our coldest bolometer so far, which includes SQUID readout
- Heavy involvement from PPD group (development of veto system and cryolab)
- Working towards world-leading sensitivity to spin-dependent dark matter interactions
- The future looks bright!

Backup

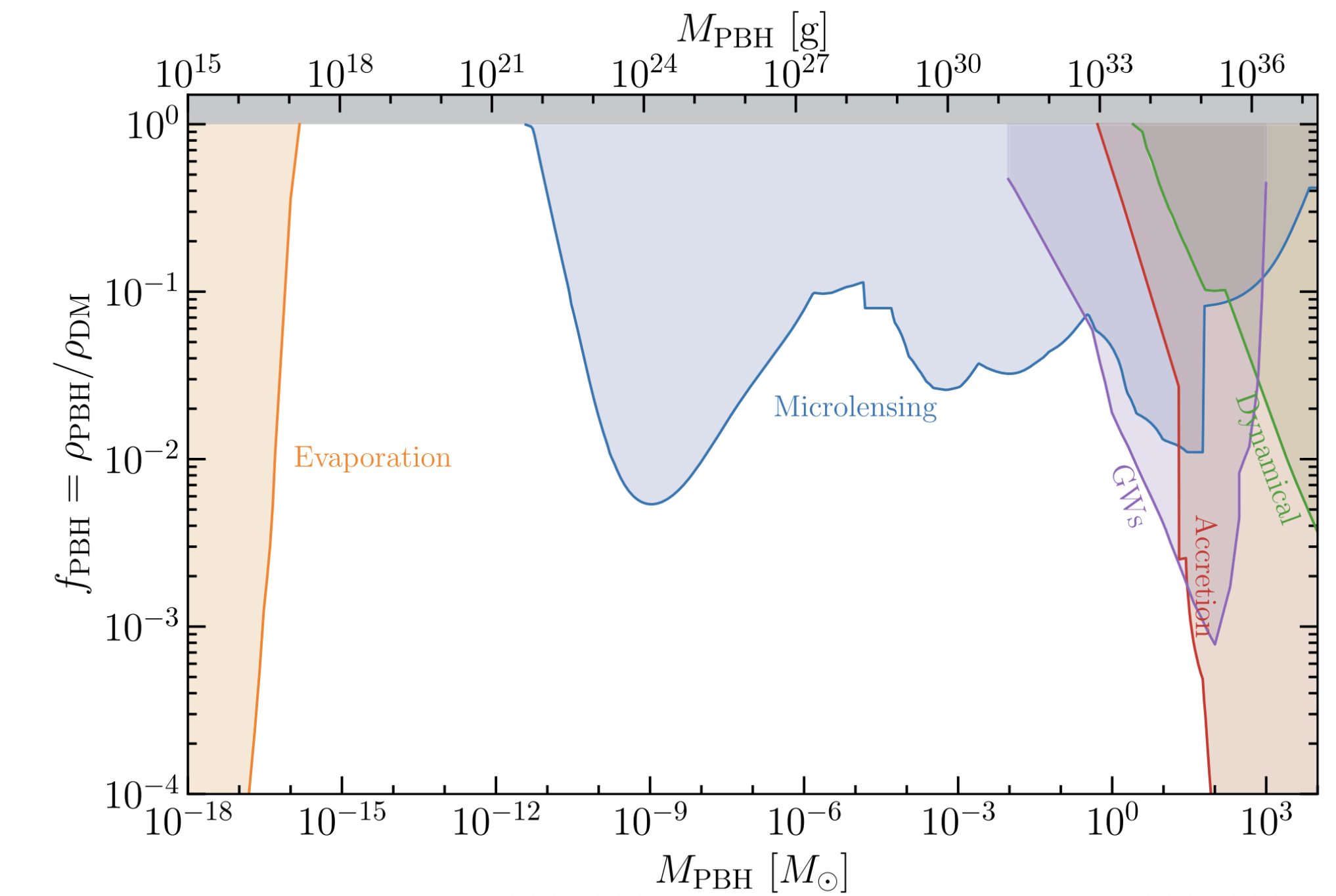
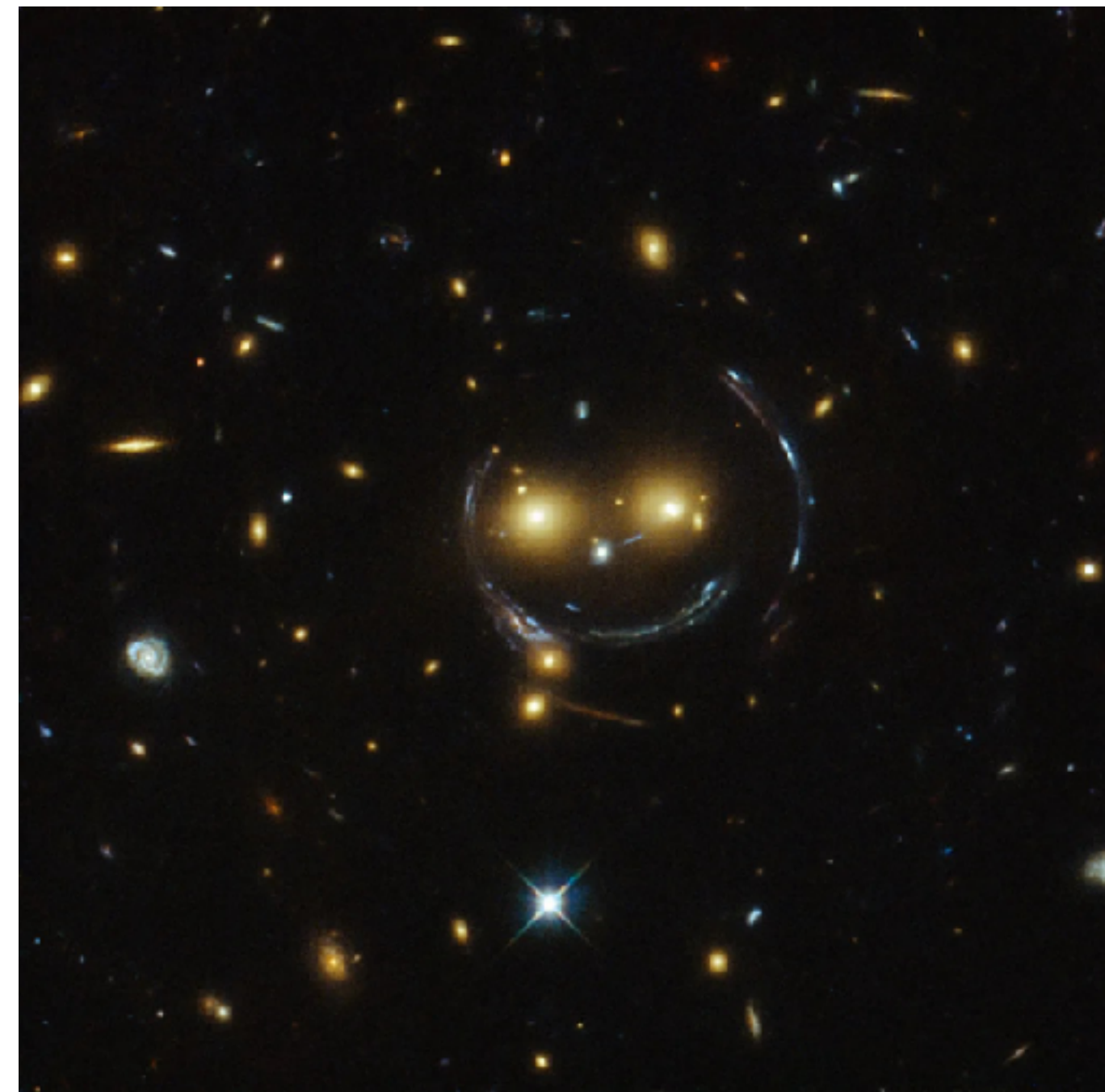
Standard Model Candidates

Baryonic:

- PBHs
- MACHOs

Fermionic:

- Neutrinos



Superfluids

1908: Heike Kamerlingh Onnes liquifies Helium for the first time in Leiden

1937: Kapitsa (then independently Allen and Misener) discover a 'superfluid' phase of Helium, with almost 0 resistance to flow below $\sim 2\text{K}$ (*Nobel prize 1978*)

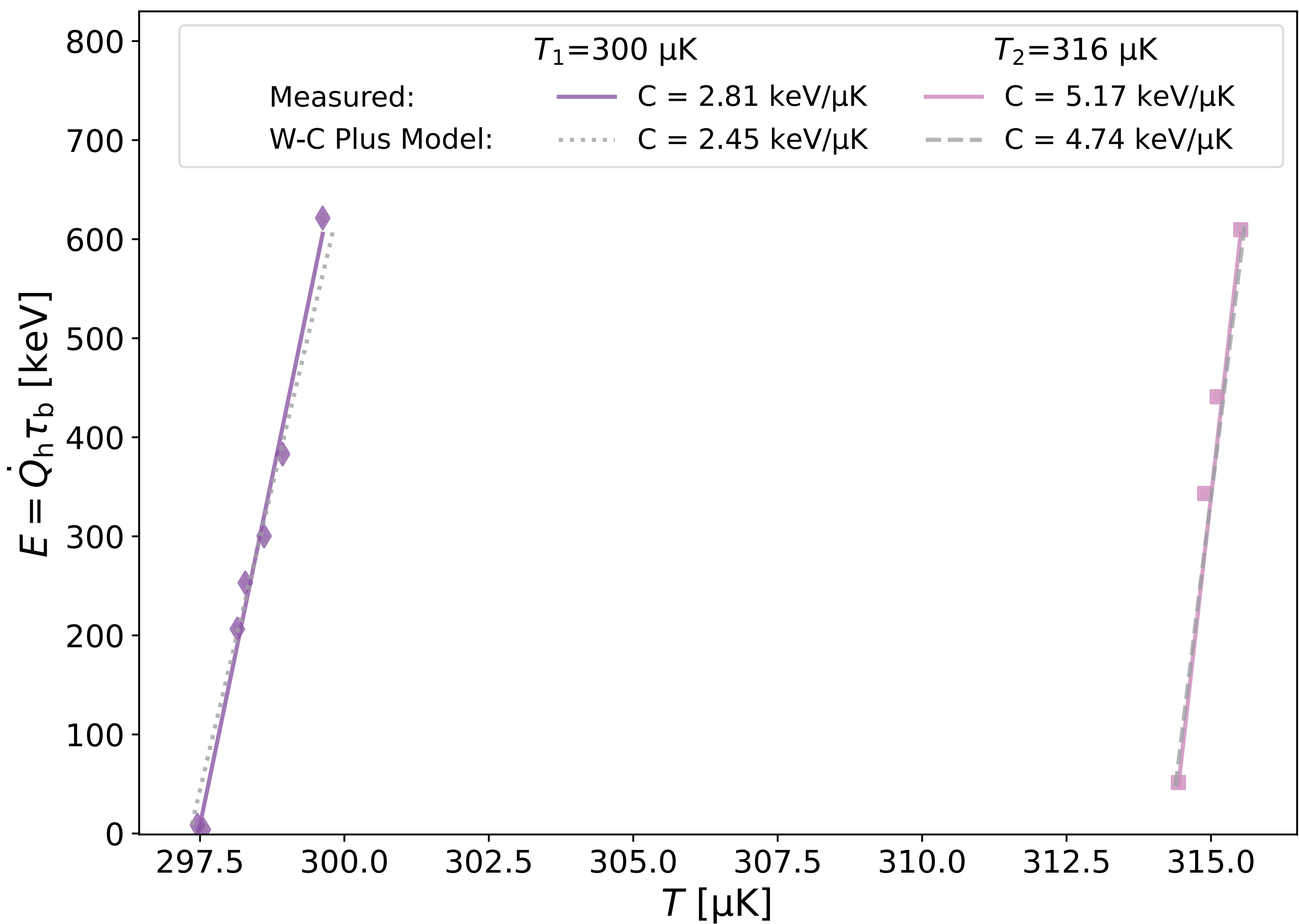
1941: Landau produces his theory of superfluidity in Helium-4 (*Nobel prize 1962*)

1957: Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity introduced (*Nobel prize 1972*)

1972: Lee, Richardson and Osheroff observe two phase transitions in Helium-3 (*Nobel prize 1996*)

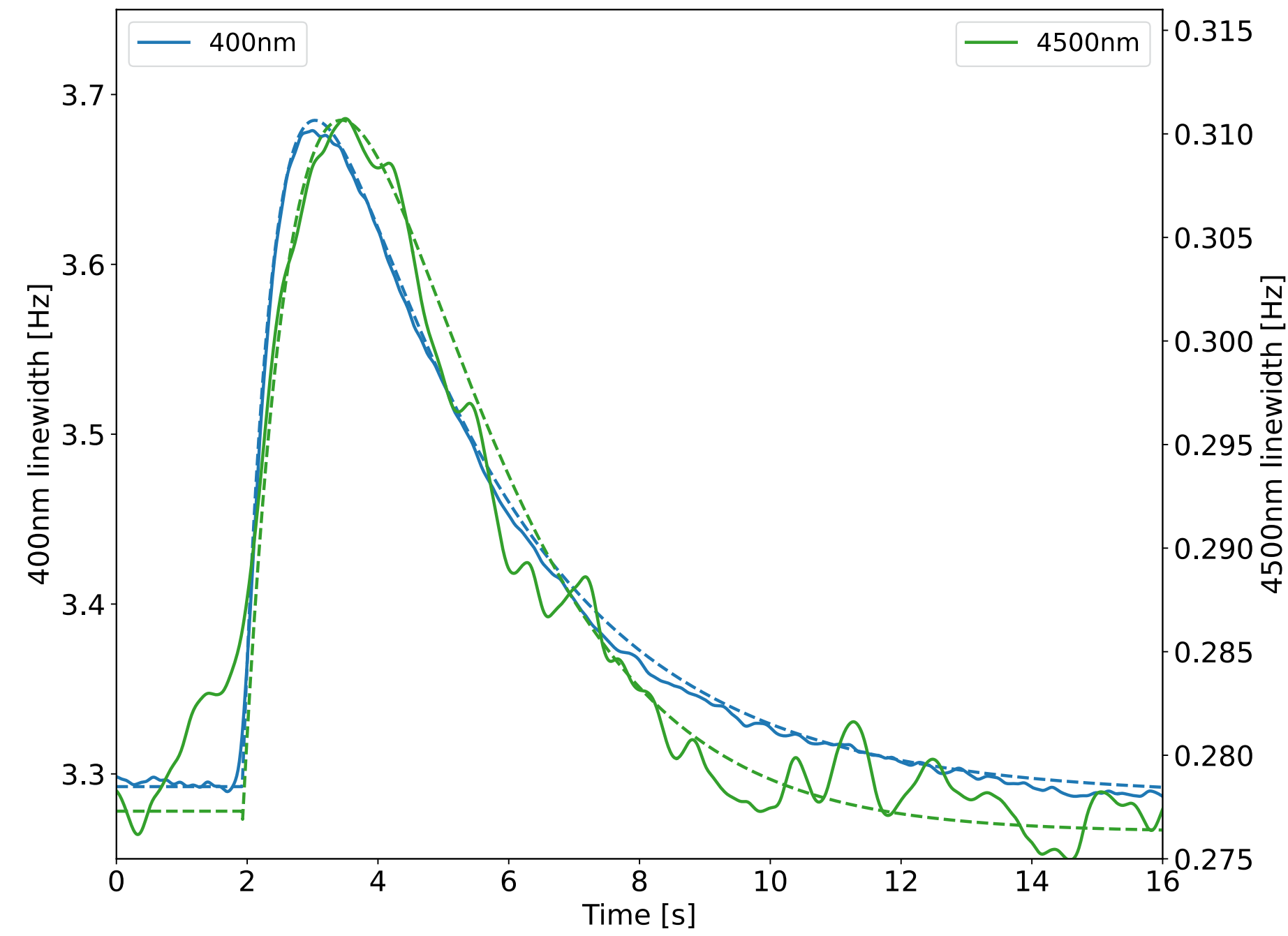
1972: Leggett develops the BCS theory of Helium-3 superfluidity (*Nobel prize 2003*)

Heater Power Calibration

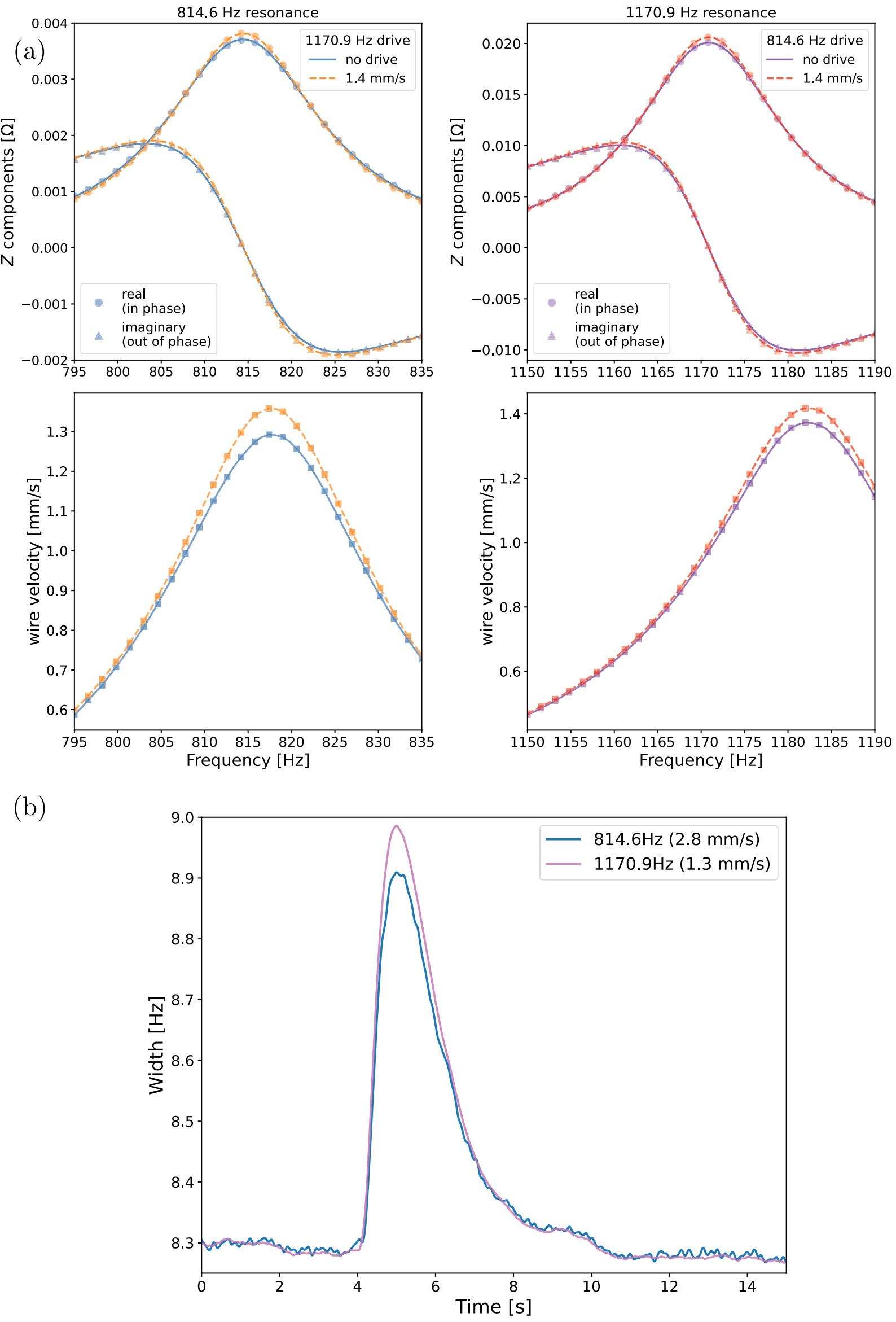


Simultaneous Measurements

Simultaneous pulse
between two wires



Multiplexing:
tracking
multiple
resonances on
the same wire

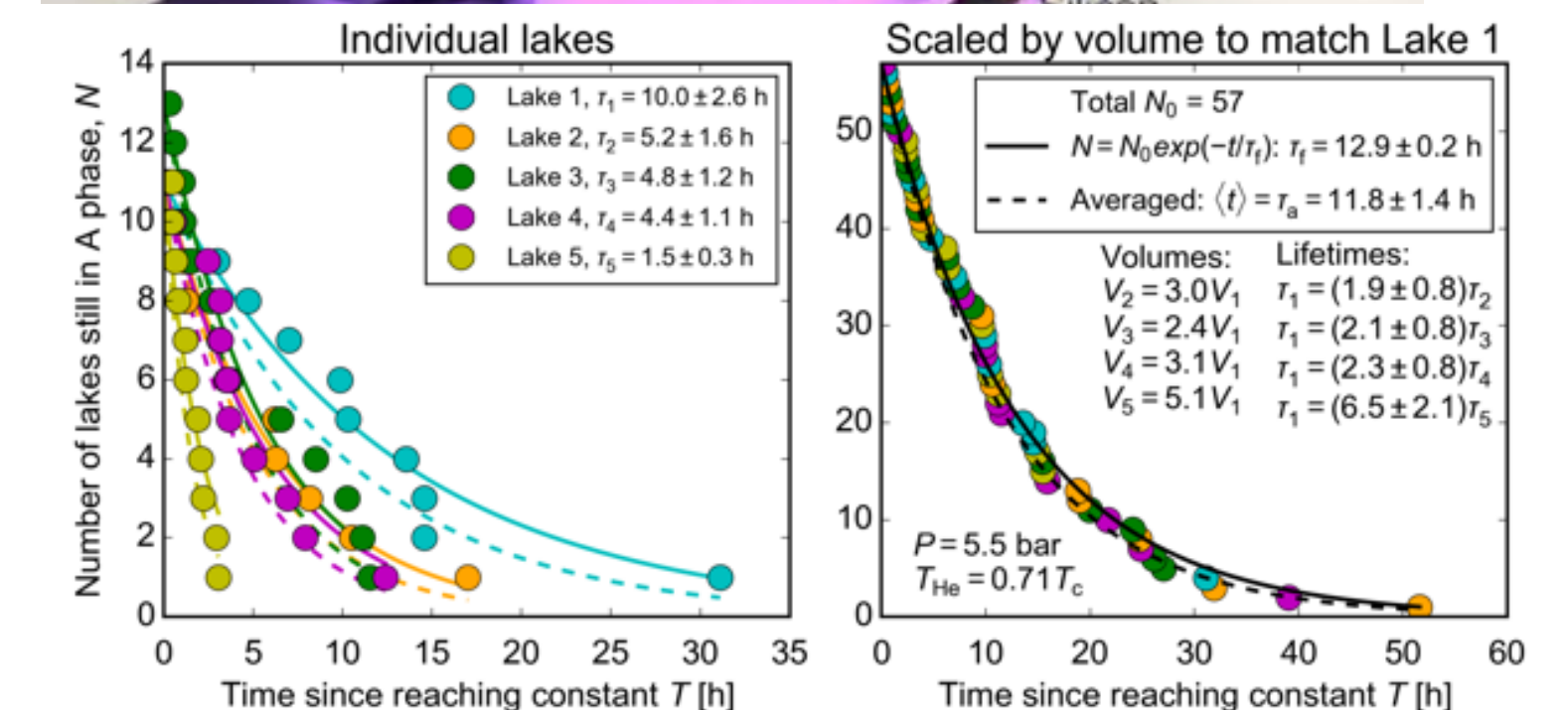
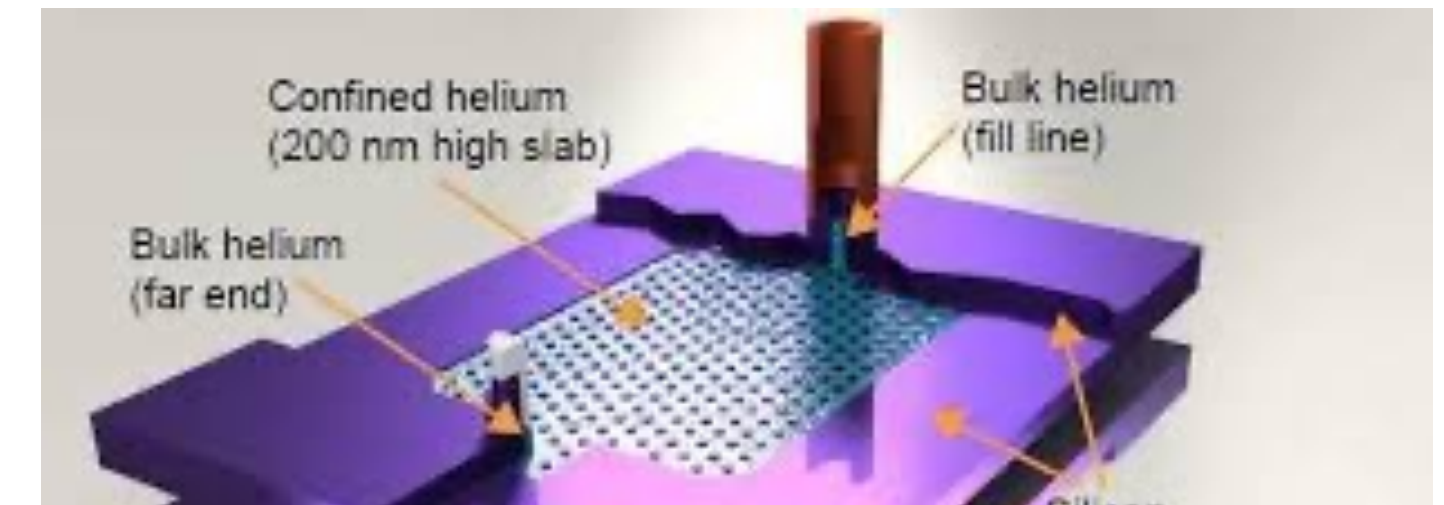
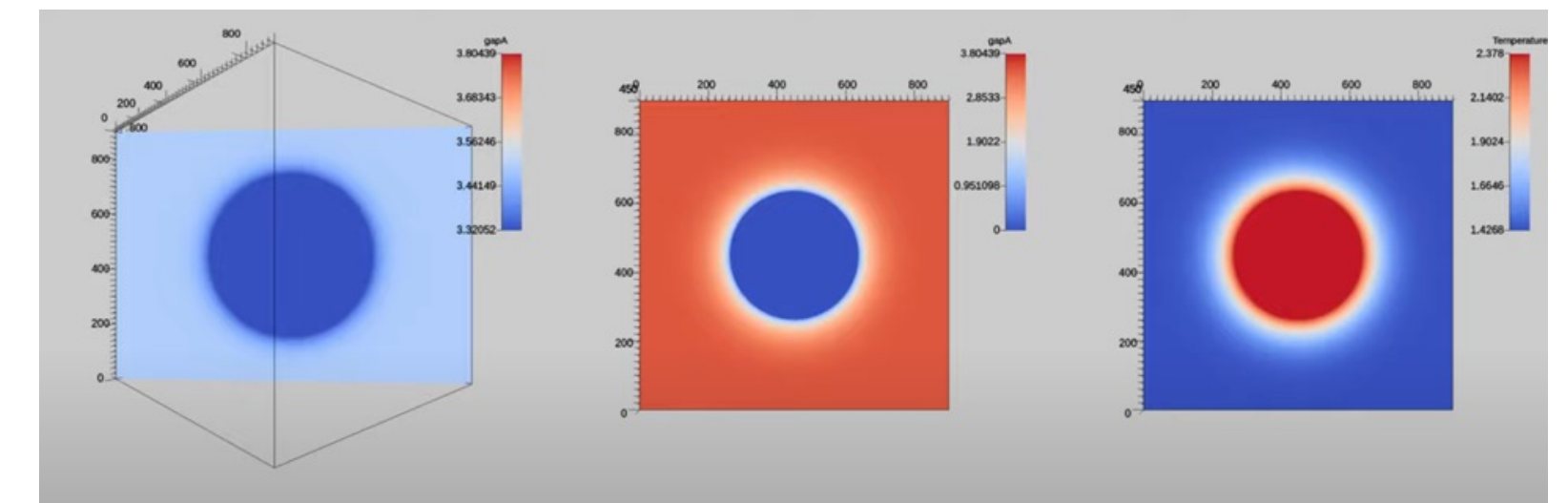


WP2 Experiments

- Early universe phase transitions in first few minutes of universe not fully understood, SM and BSM predictions
- E.g. BSM first order electroweak phase transition (~ 100 GeV, 10 ps after the Big Bang) - dark matter and baryon asymmetry.

Understanding these

- Cosmology
 - GW background signature from first order phase transitions – probe using LISA space interferometer, [M. Hindmarsh et al., SciPost Phys. Lect. Notes 24 \(2021\)](#), NANOgrav terrestrial radio
 - Simulations – predict phenomena/observables e.g. GW, axions [M. Hindmarsh et. al, arxiv:2512.13653](#)
- Helium-3
 - AB phase transition mechanism open question - first order phase transition in a pure system
 - Phase-transition rate (lifetime of the metastable phase) and the phase-boundary speed are key parameters in defining the GW spectrum



- Simulations of phase transitions in helium-3 computational methods from cosmology
- Nanofluidic confinement: ~ 100 s nm scale cells with atomically smoother walls to isolate transition, [L. V. Levitin et. al, Science 340 \(2013\)](#).
- A $\rightarrow$ B phase transition observed, try to understand mechanism. Radiation sources? Geant4 models?

Dark Matter Scattering Rates

$$\frac{dR}{dE_{\text{NR}}} = \frac{\rho_{\chi}}{m_{\chi}m_N} \int_{v_{\text{min}}}^{\infty} \frac{d\sigma}{dE_{\text{NR}}} v f(\vec{v}) d^3v$$