Detection of Sub-GeV Dark Matter using Superfluid Helium-3 with the QUEST-DMC Detector

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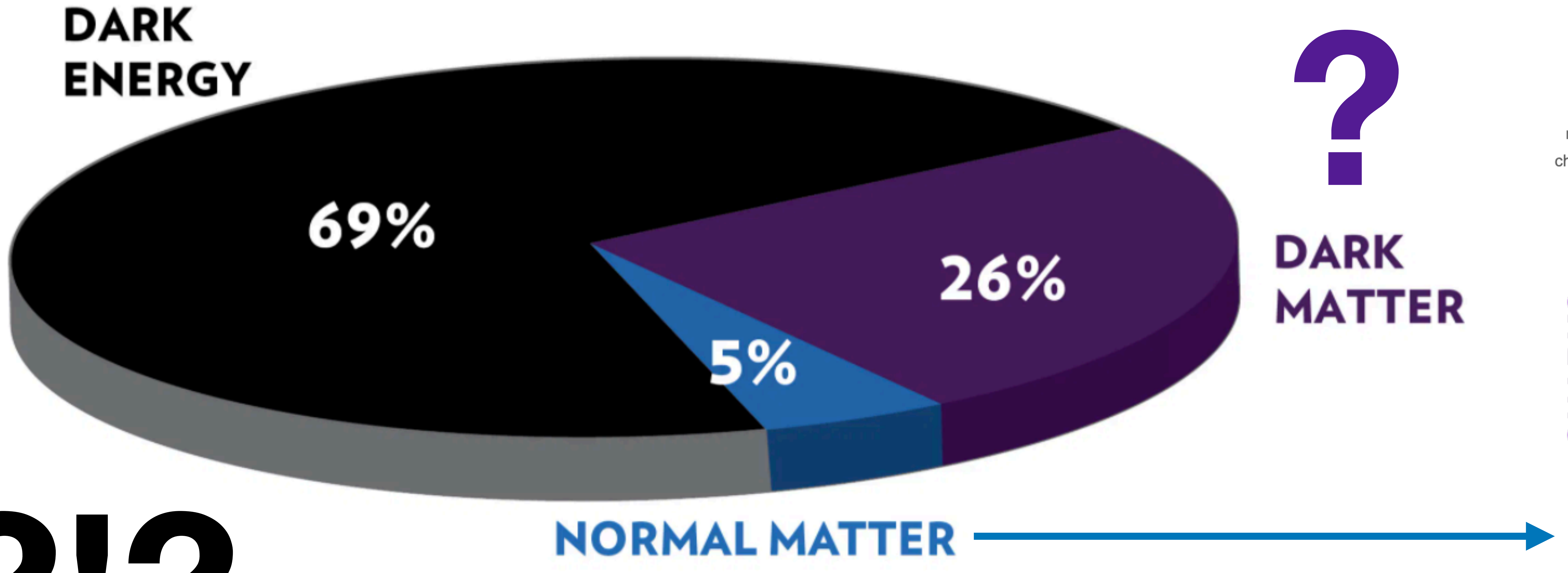
We all know about Dark Matter…

The existence of a mysterious, non-luminous type of matter known as dark matter (DM), is well established.

Astrophysical and cosmological observations show that DM makes up 27% of the total energy density of the Universe, and is approximately five times more abundant than the ordinary matter component comprised of Standard Model particles.



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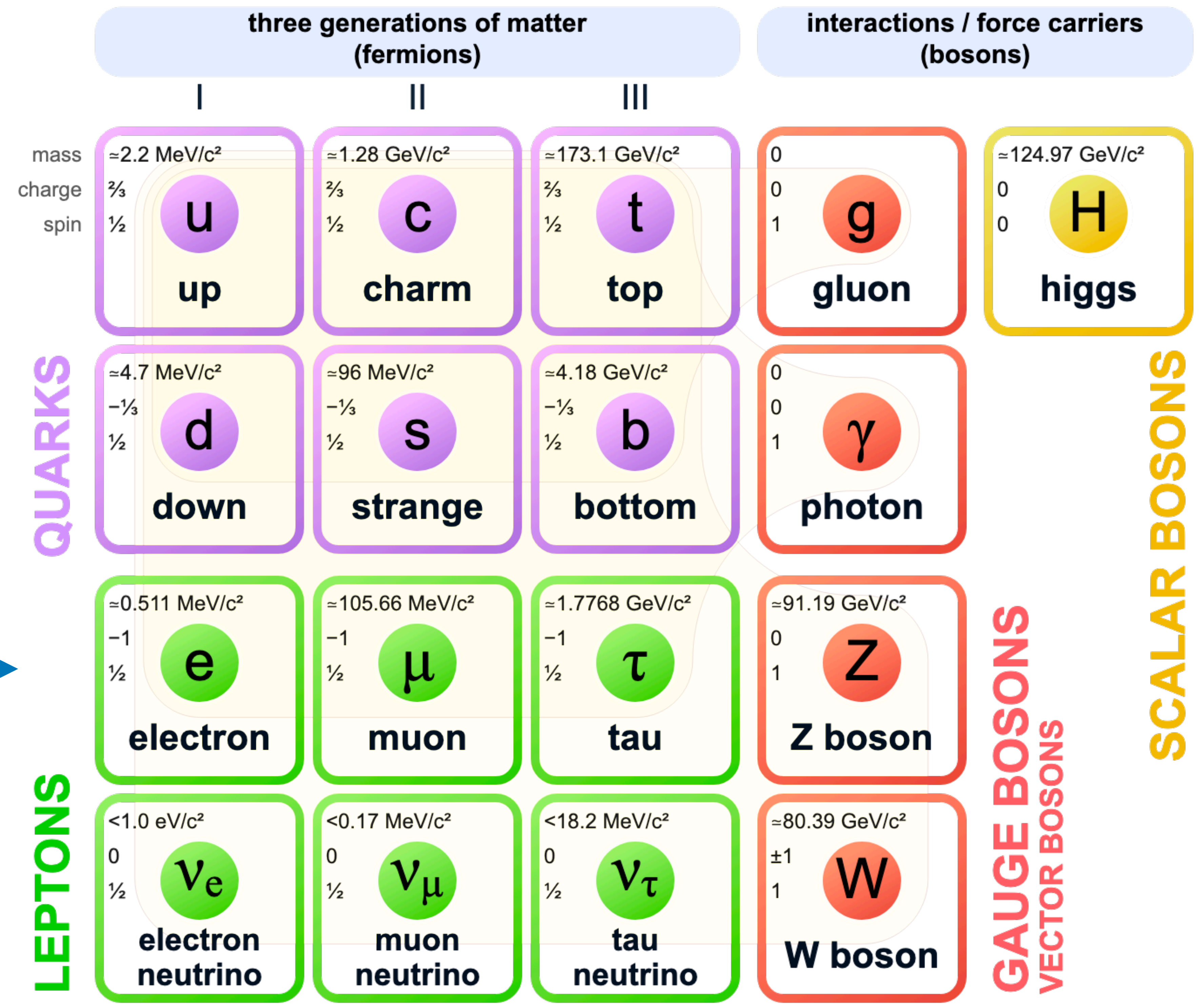


QUEST – DMC *Ecosystem*

QUEST-DMC Programme

The QUEST-DMC programme will attempt to experimentally answer Beyond the Standard Model Physics (BSM) questions which remain a mystery…

Work Package WP 1

What is the nature of Dark Matter?

- Search for spin-dependent dark matter interactions, with world-leading sensitivity to a range of theoretically-motivated dark matter candidates in the sub-GeV mass range.

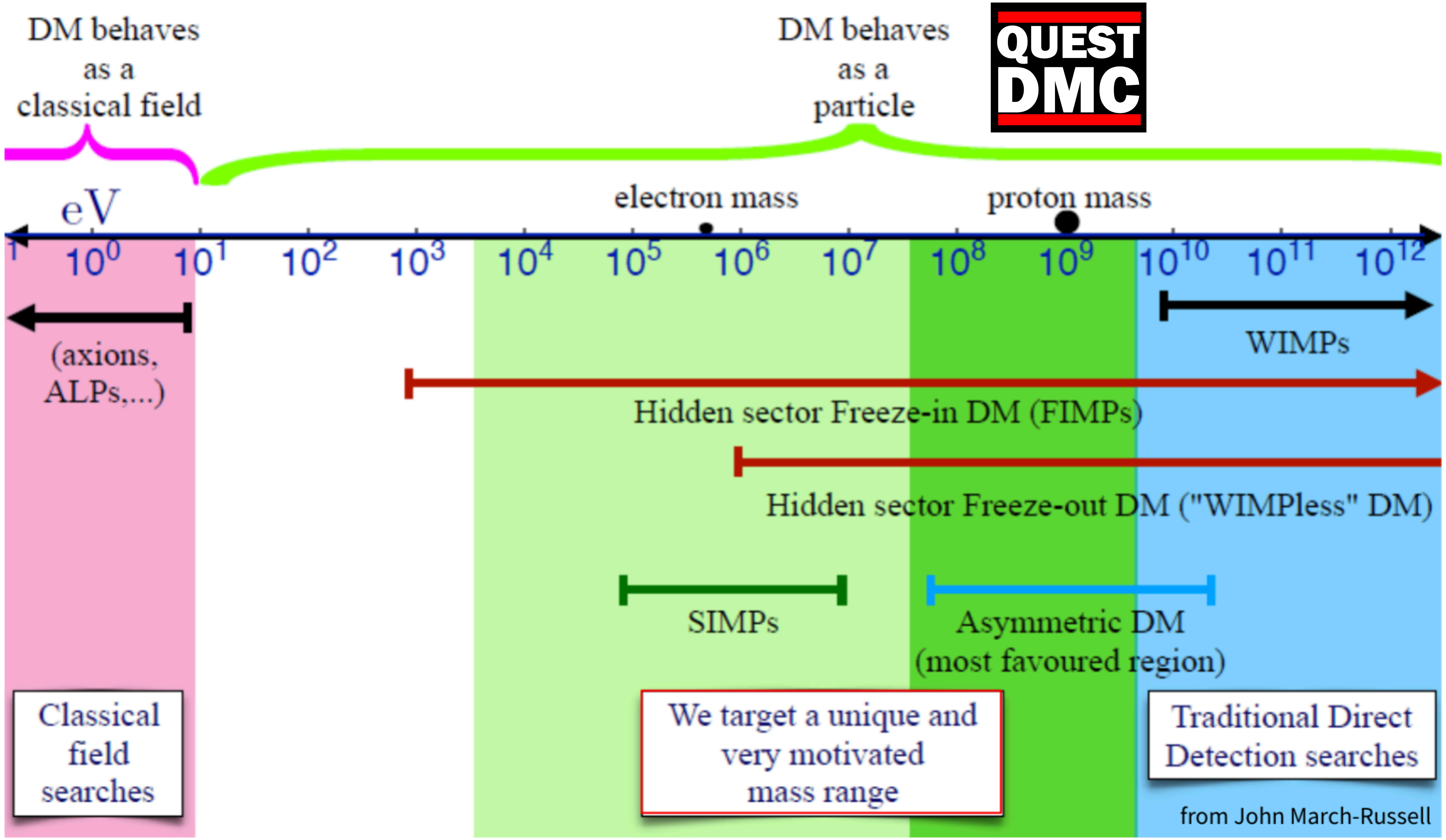
Work Package WP 2

How did the early universe evolve?

- Test nucleation theory of phase transitions in the quantum vacuum of the early universe, which critically informs predictions of gravitational wave production.

QUEST-DMC will probe relatively unexplored parameter space…

QUEST-DMC can probe unique and motivated WIMP mass range on the order of the mass of the proton— highly motivated by theories that can explain matter-antimatter asymmetry of Universe!



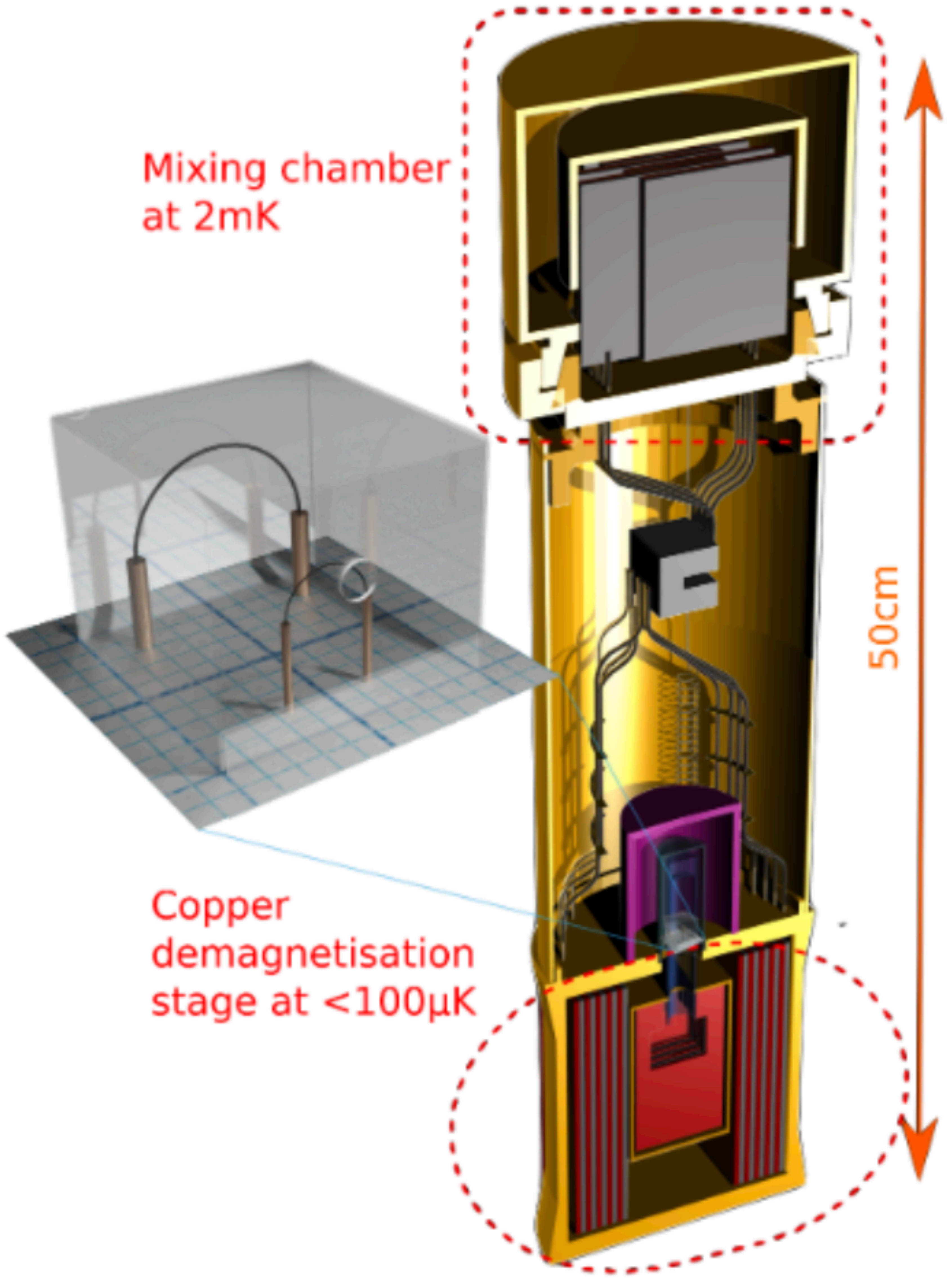
The General Concept of QUEST-DMC

In a χ-^{3}He scattering event, energy transferred to struck ^{3}He atom is deposited in the detector volume as heat and ionisation energy loss, forming **quasiparticles** and **scintillation photons** (from de-excitation) respectively.

Superfluid ^{3}He target enclosed in a small $\mathcal{O}(1\ \text{cm}^3)$ bolometer cell, instrumented with vibrating nanowires sensitive to quasiparticles. Readout of nanowire performed with lock-in amplifier or SQUID.

Photon detectors to be located above the ^{3}He target.

Schematic shown to the right: QUEST-DMC will be located in ^{3}He/^{4}He dilution refrigerator, operating at sub-100 μK temperatures.



Helium-3 Target

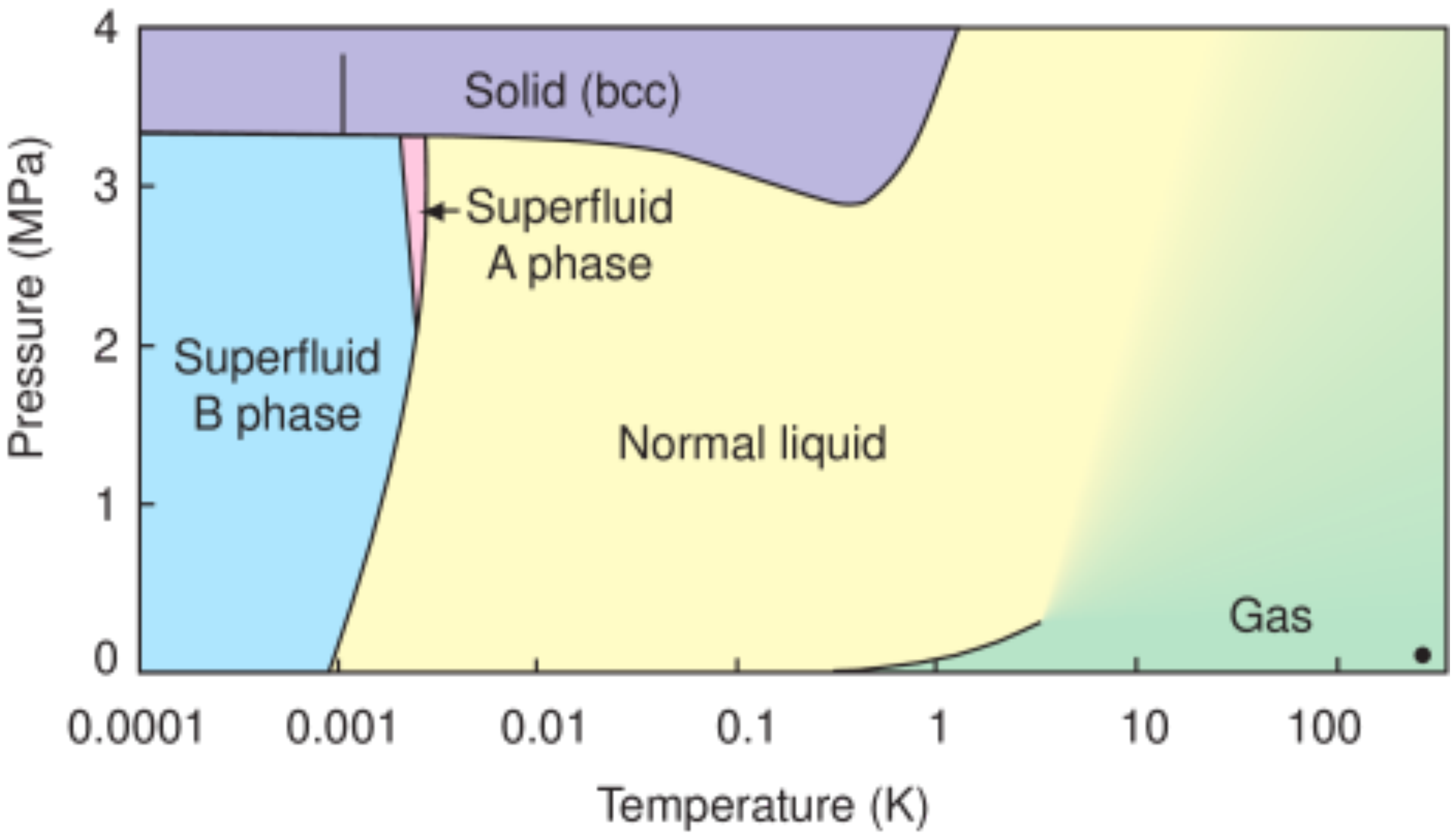
Helium is second most abundant element in our Universe.

Popular in cryogenics as the most important refrigerant for reaching extremely low temperatures ever since first liquified in 1908.

Two isotopes: ^{4}He (2p,2n) and ^{3}He (2p,1n).
- ^{4}He (99.9999%) far more abundant than ^{3}He (0.0001%)
- Different physical properties related to difference in net spin…

With the use of ^{3}He, QUEST-DMC can probe both spin-independent AND spin-dependent interactions!

Phase diagram of ^{3}He



^{3}He nucleus has 2 protons and just 1 neutron.
- Spin 1/2 ^{3}He fermion; superfluidity from Cooper pairs of ^{3}He atoms.
- B-phase at ~ 100 μK.
- Small superfluid gap ~Δ 10^{-7} eV between Cooper pairs and quasiparticles (QPs), i.e., thermal excitations.

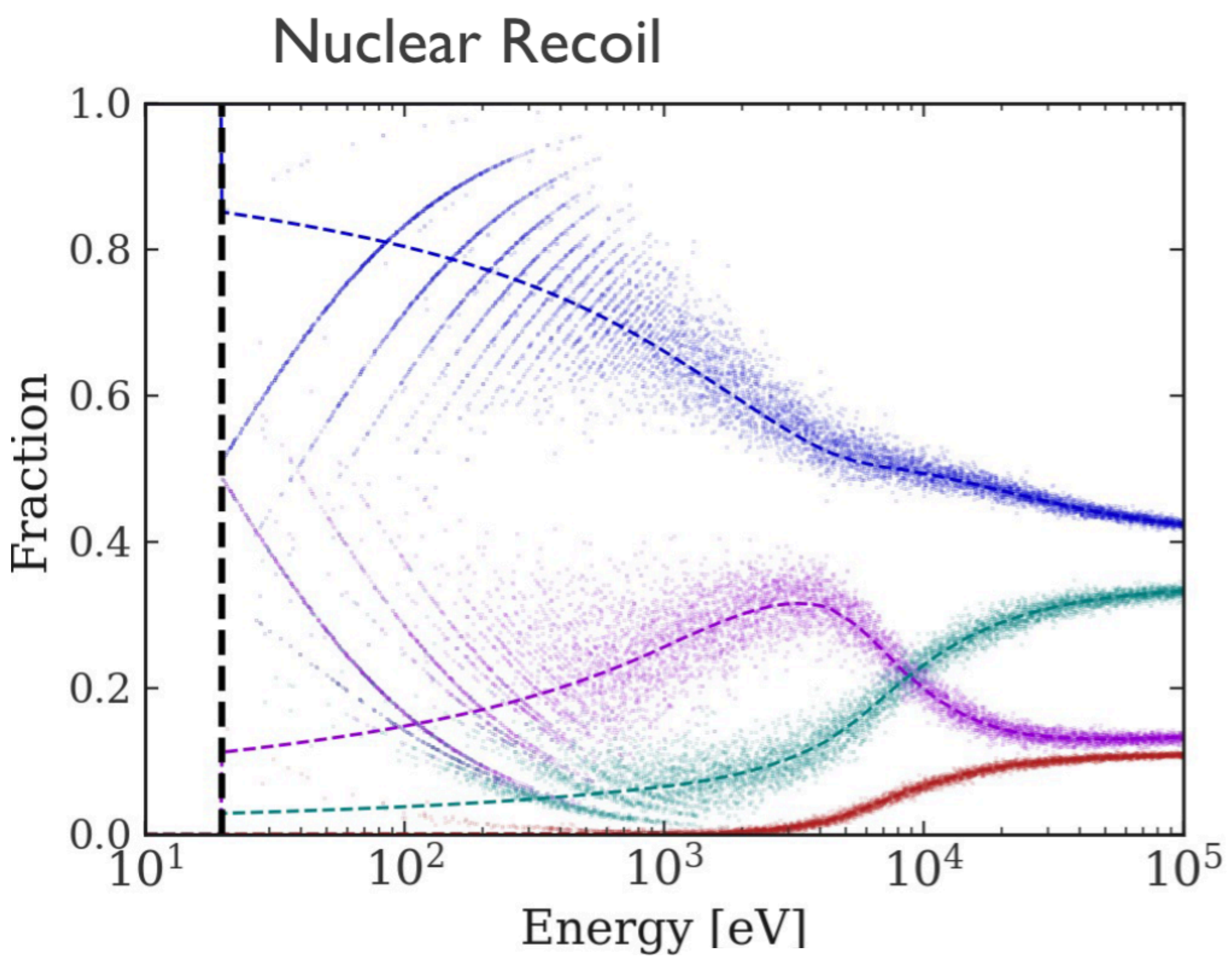
Energy Deposition in Superfluid ^{3}He

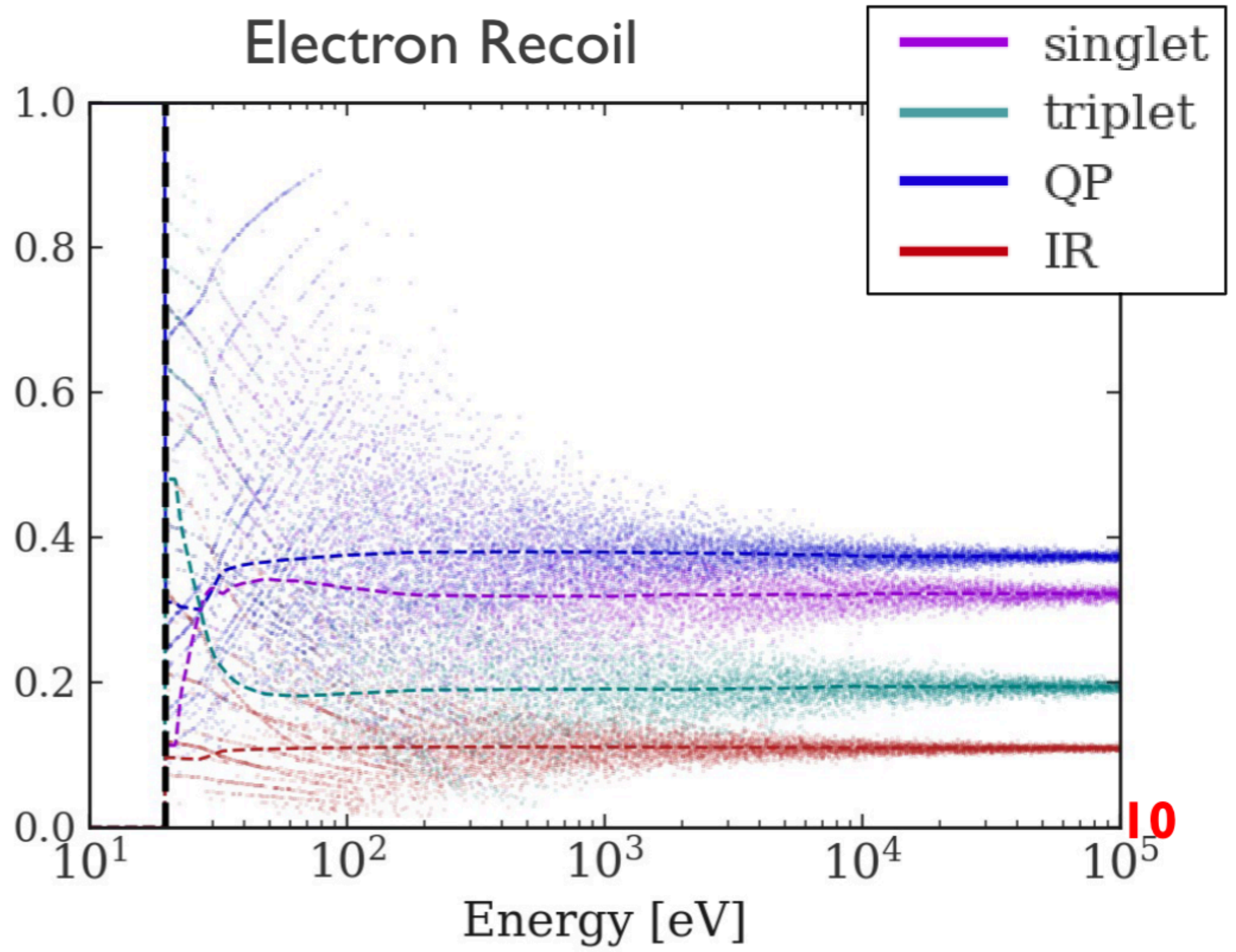
Scattering event between WIMP and ^{3}He nucleus [nuclear recoil] / atomic electron [electron recoil results in **heat from QP excitations**, and **scintillation light** from de-excitation.

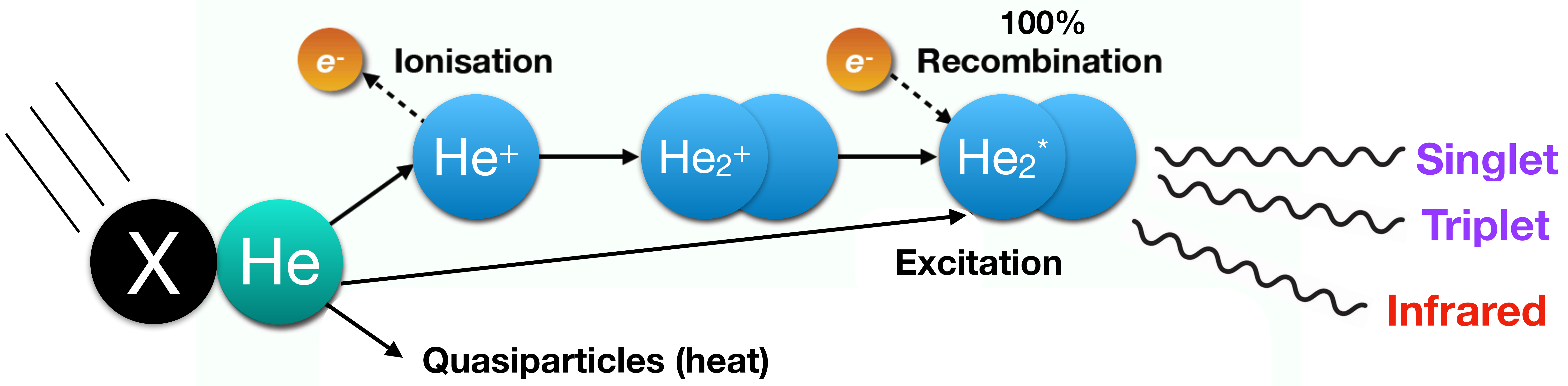
19.7 eV threshold for ERs [== ionisation energy in He].

10^7 QP produced per eV deposition in ^{3}He.

Fraction of energy deposited in heat vs light is different for NRs and ERs, and is a function of energy.







Bolometry in ^{3}He with Vibrating Nanowire Detectors

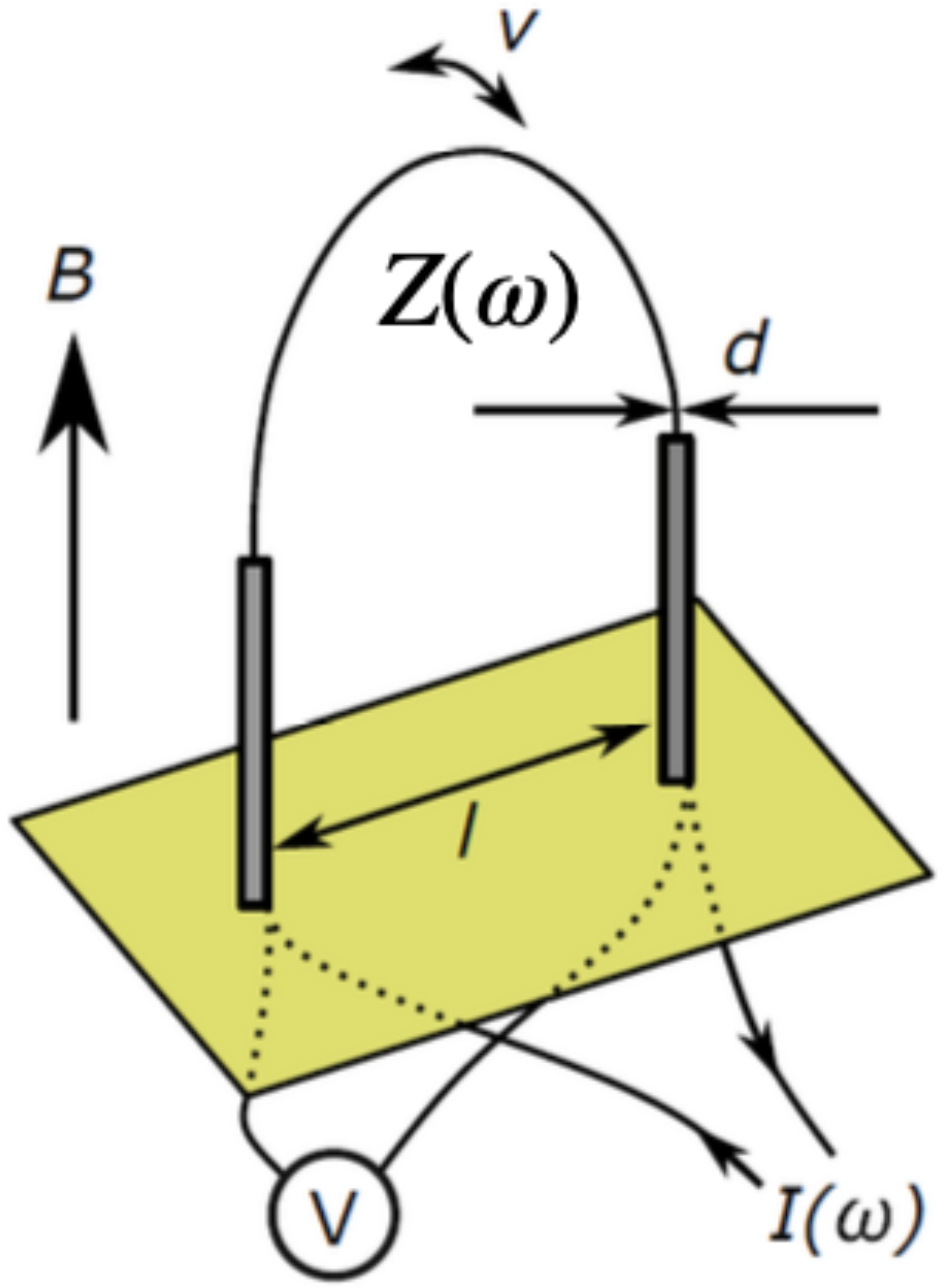
Nanowire in ^{3}He box subjected to B field and driven by AC current oscillates at frequency, ω.

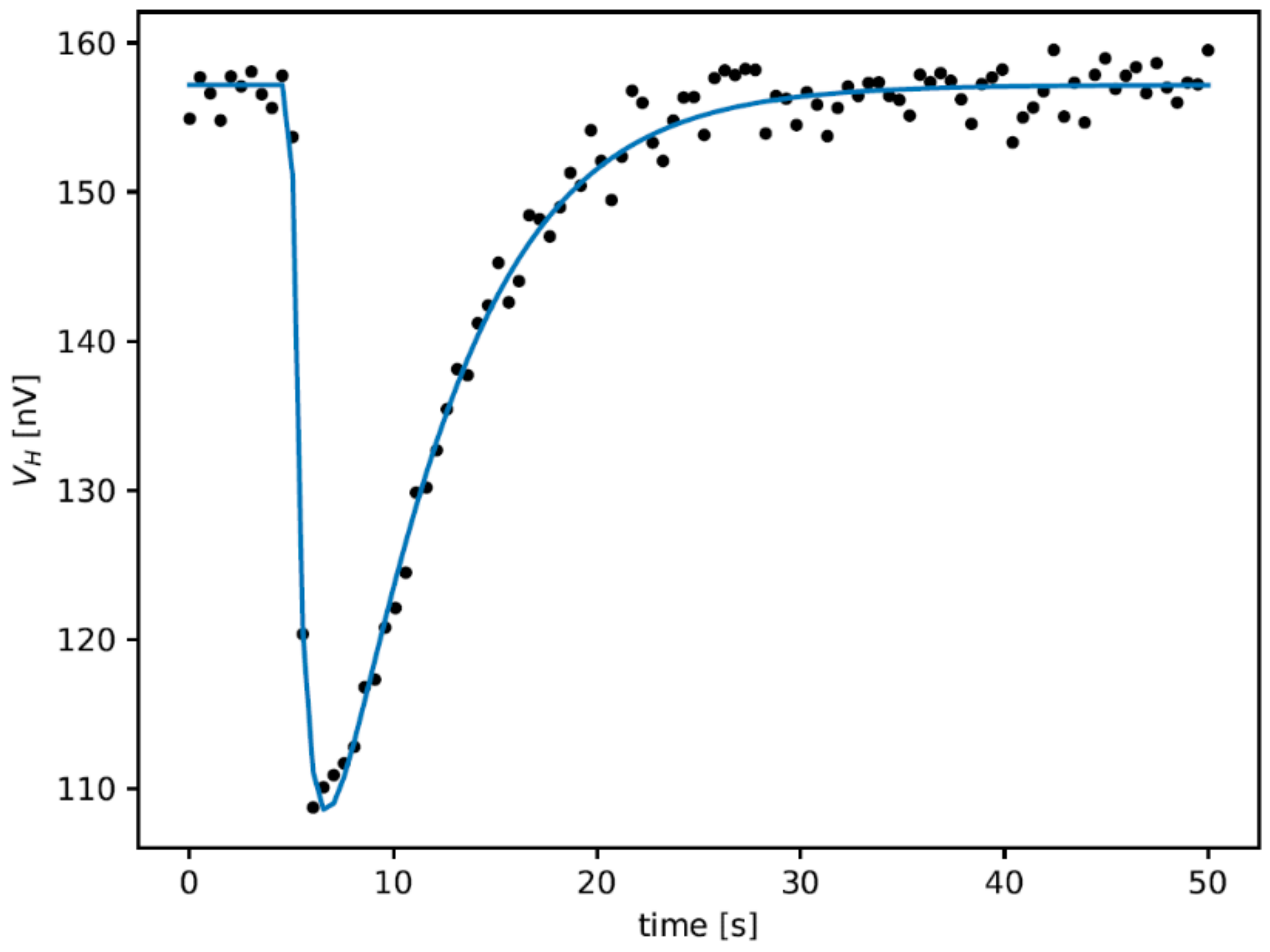
Nanowire experiences damping force due to interactions between wire and QPs.
- Enhanced by Andreev reflections.

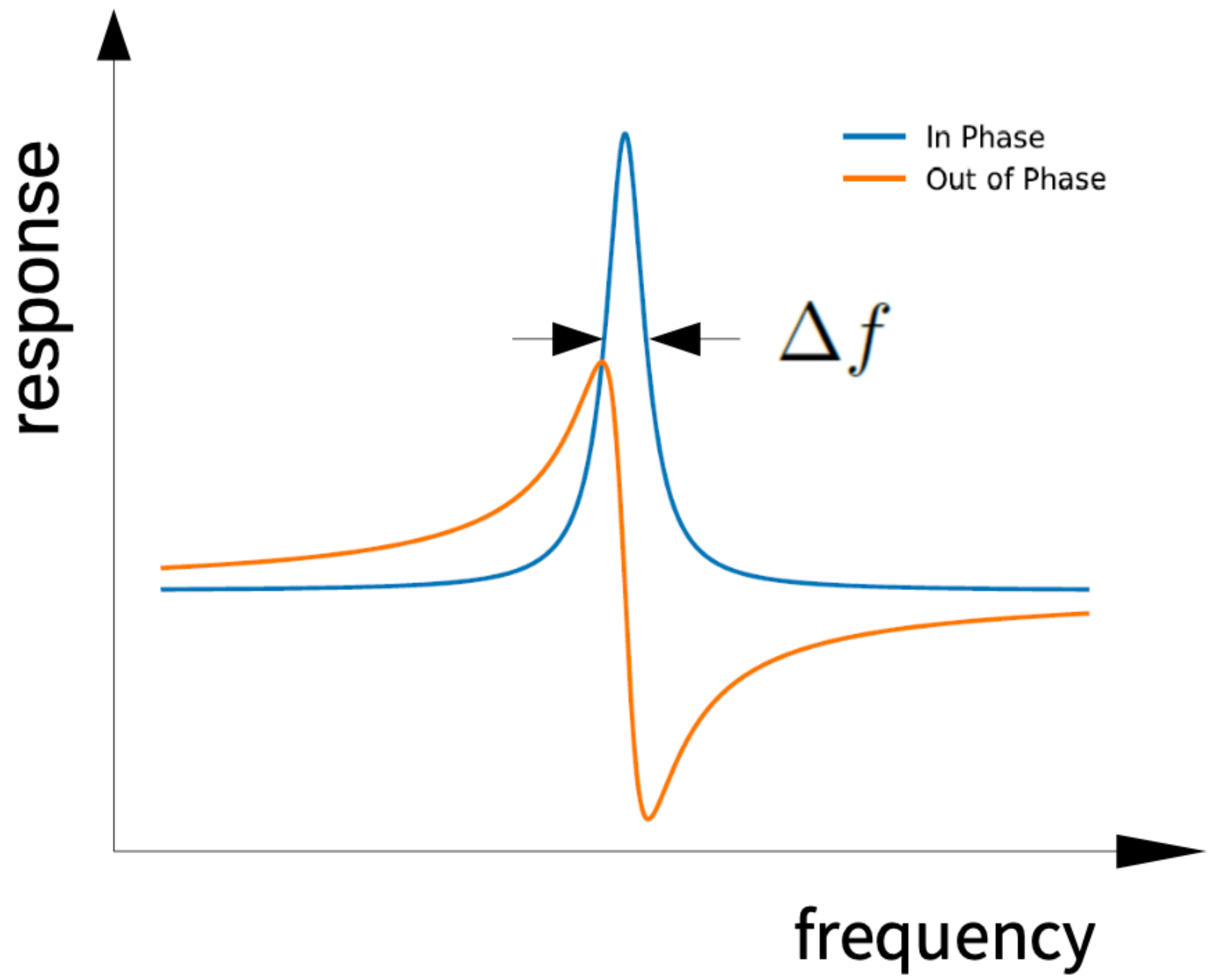
Measure induced voltage: $I(\omega) \rightarrow V(t)$.

Energy from variation of resonance width: $\Delta Q = \alpha(T_0, P)\Delta(\Delta f)$.
- Highly-dependent on pressure and temperature.

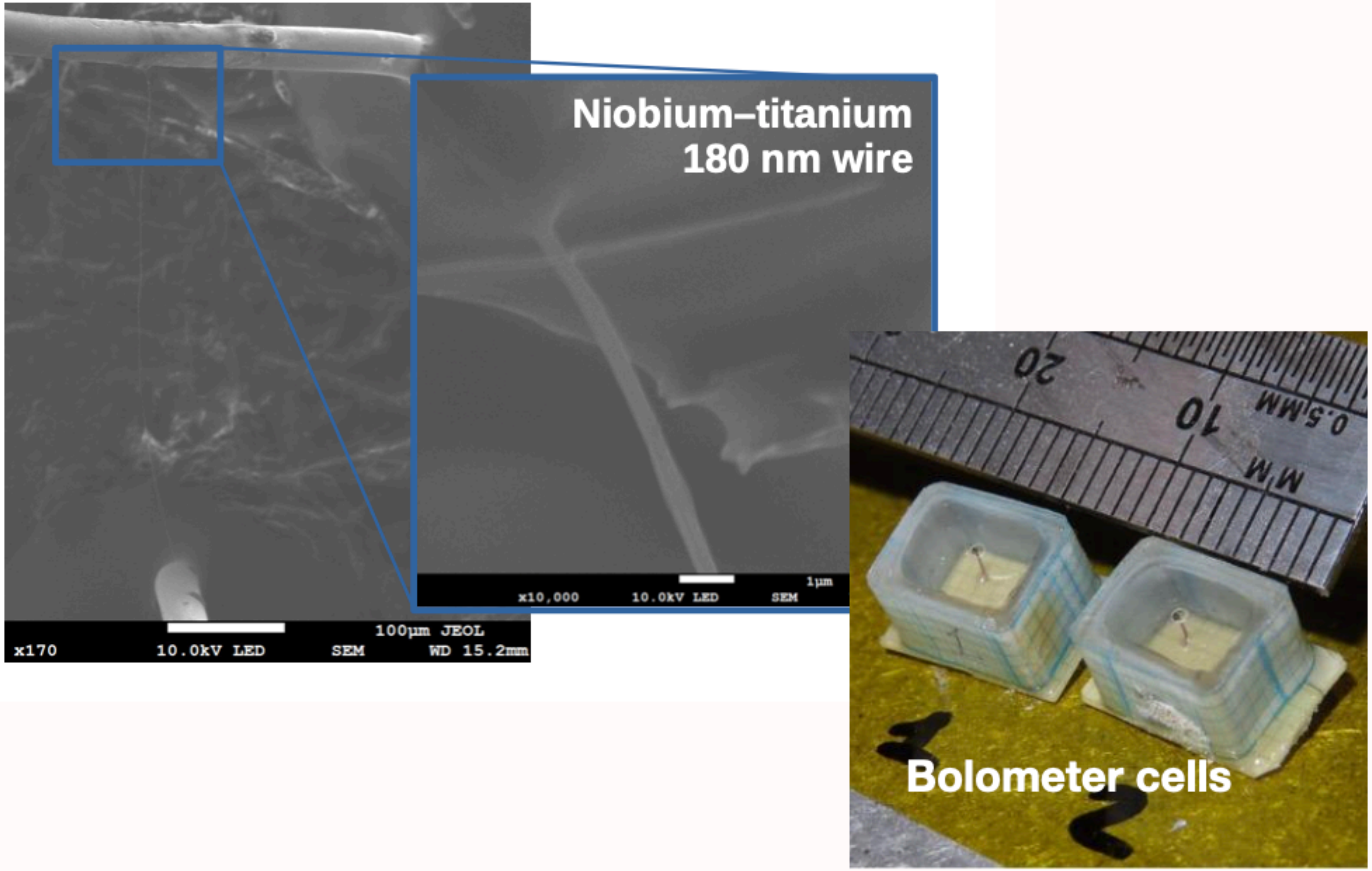
Readout using lock-in amplifier or SQUID (more details in back-up).







Bolometry in ^{3}He with Vibrating Nanowire Detectors



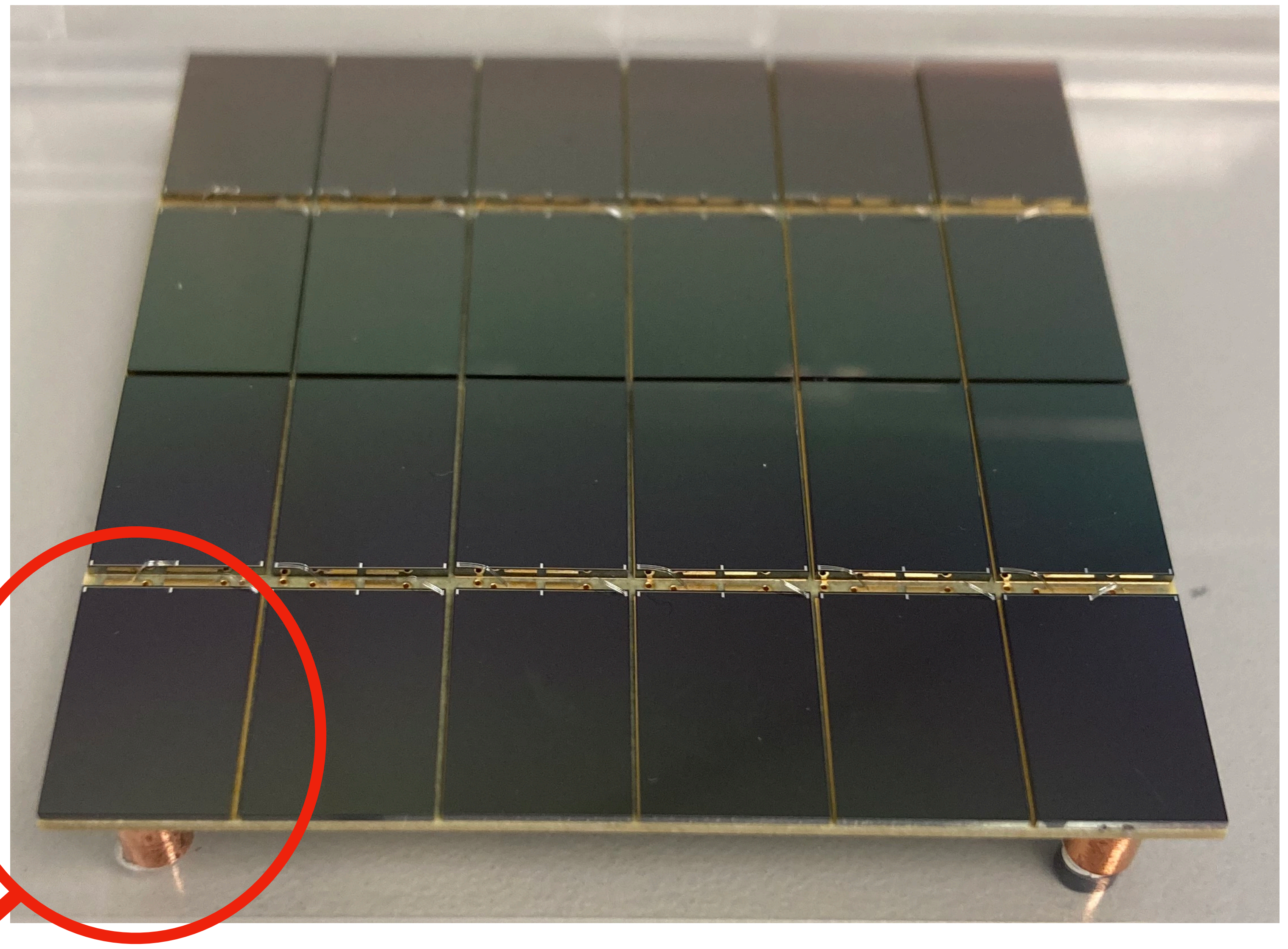
Courtesy of Dima Zmeev, Rob Smith

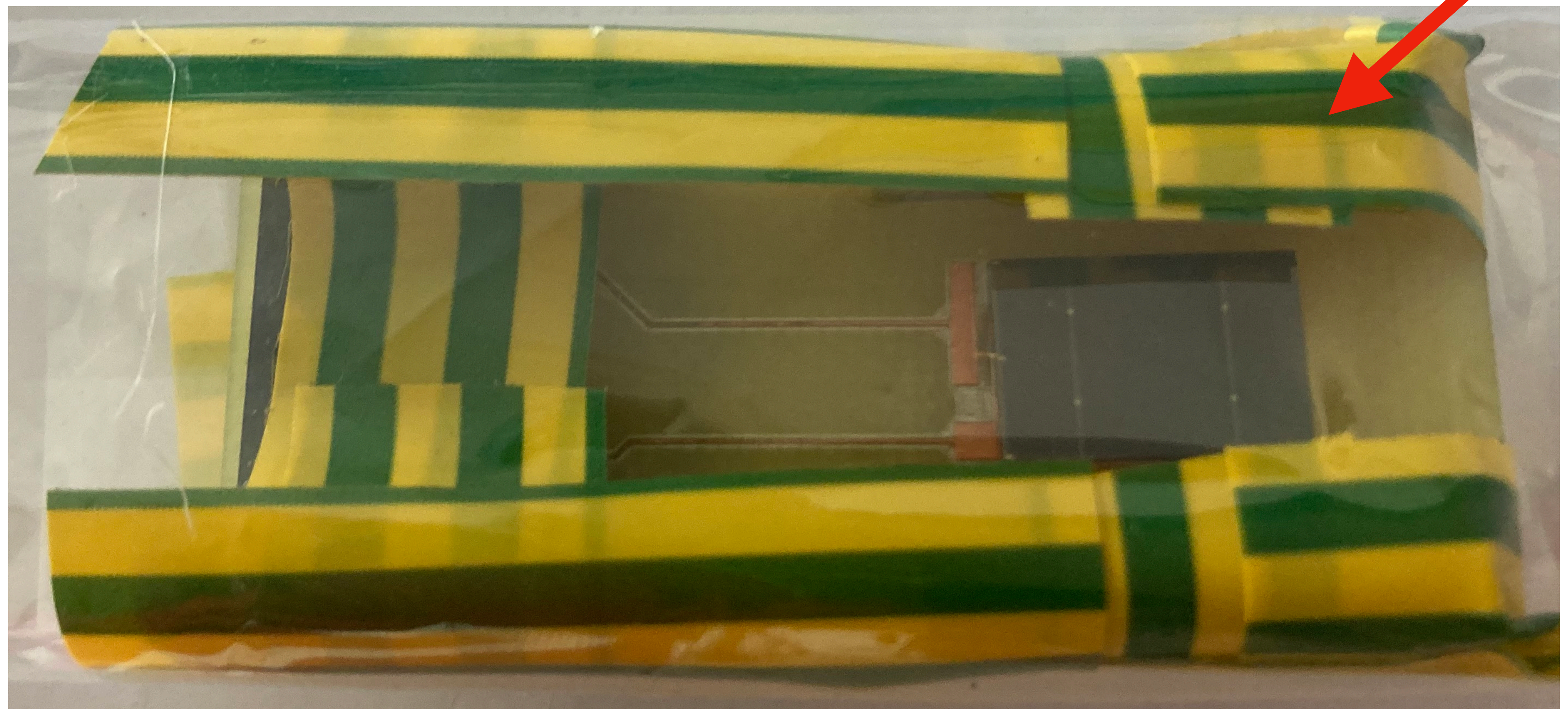
Photon Sensing in QUEST-DMC

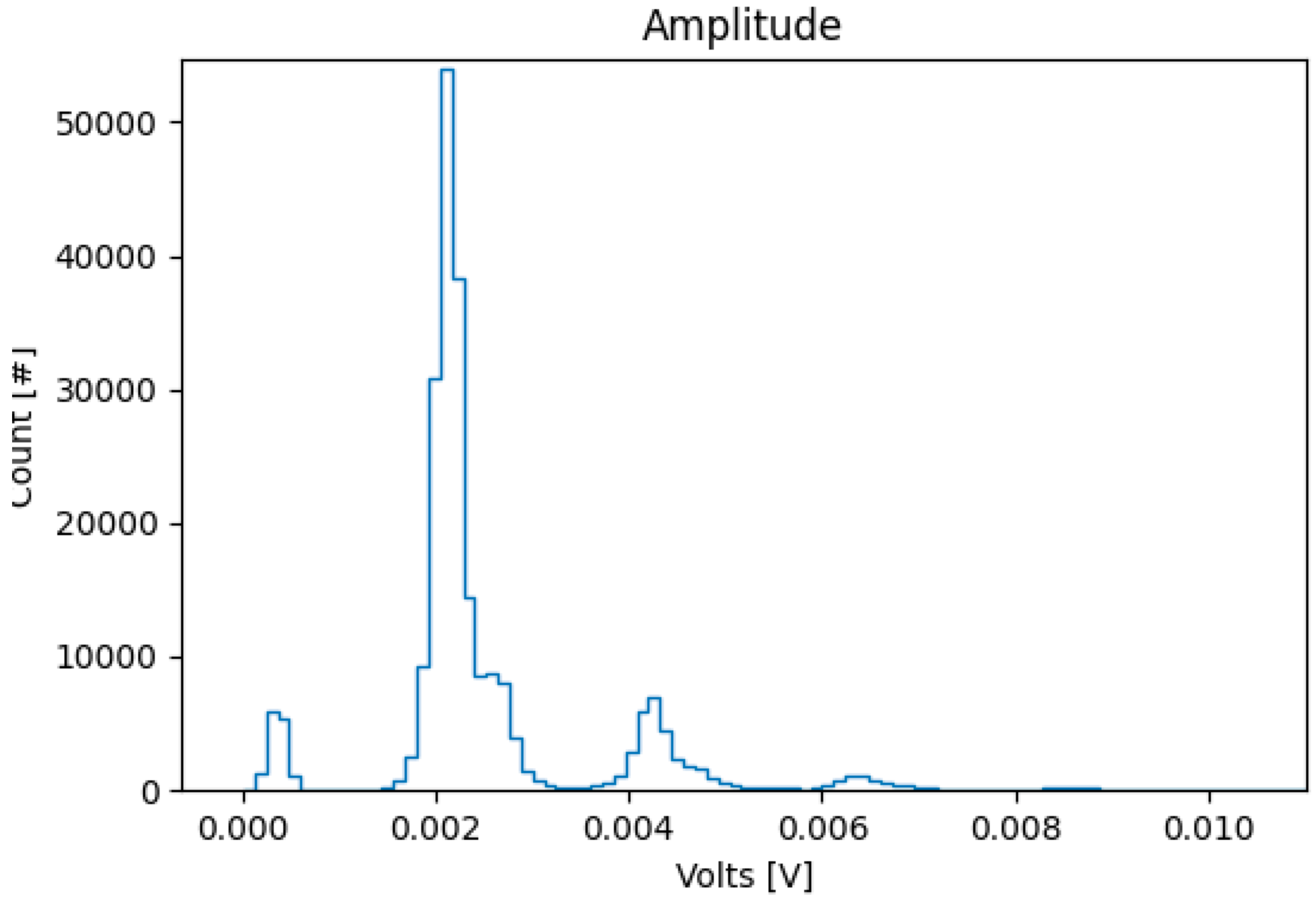
Currently exploring Silicon Photomultiplier (SiPM) technology as an option for photon sensing in QUEST-DMC.

SiPMs boast high quantum efficiency and excellent single-photon resolution.

Successful test of SiPM feasibility at 4 K!
- FBK NUV LF SiPMs: Ferri, A, et al. "Performance of FBK low-afterpulse NUV silicon photomultipliers for PET application." *Journal of Instrumentation* 11.03 (2016): P03023.





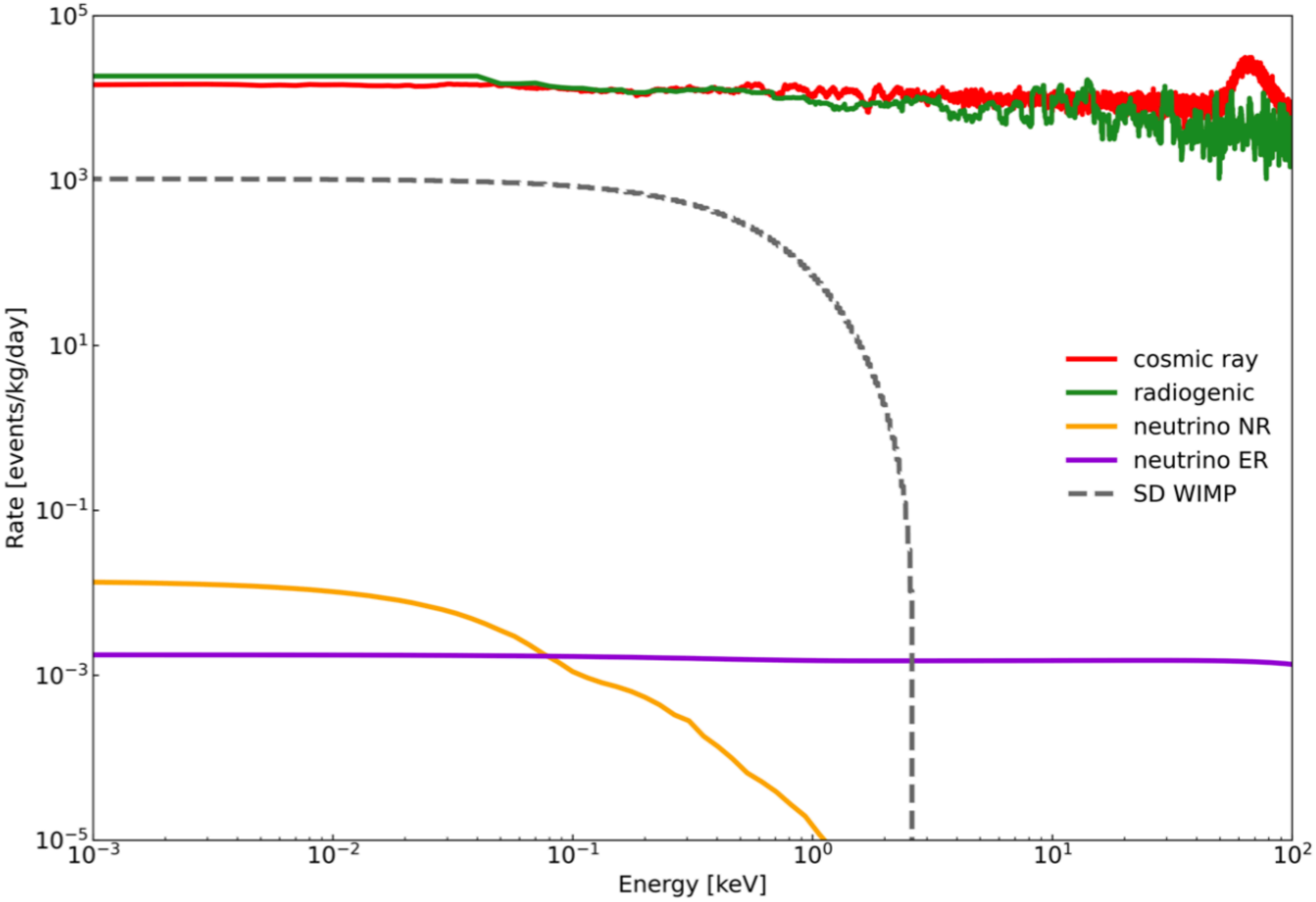


Background Model

Background	Events/cell/day [0 - 10 keV]
Cosmic Rays	3.31
Radiogenic	2.61
PP neutrino	4.76×10^{-7}
CN neutrino	2.01×10^{-9}

Cosmic rays estimated using CRY and Geant4, assuming 90% veto efficiency and no shielding.

Radiogenics estimated using material screening results and Geant4.



Detector Response Model

Any uncertainty on the energy measurement has a direct impact on the energy threshold achievable by the detector.

1. QP production fluctuations.
2. Readout: lock-in (conventional) vs SQUID.
3. Shot noise from fluctuations on QPs incident on nanowires.

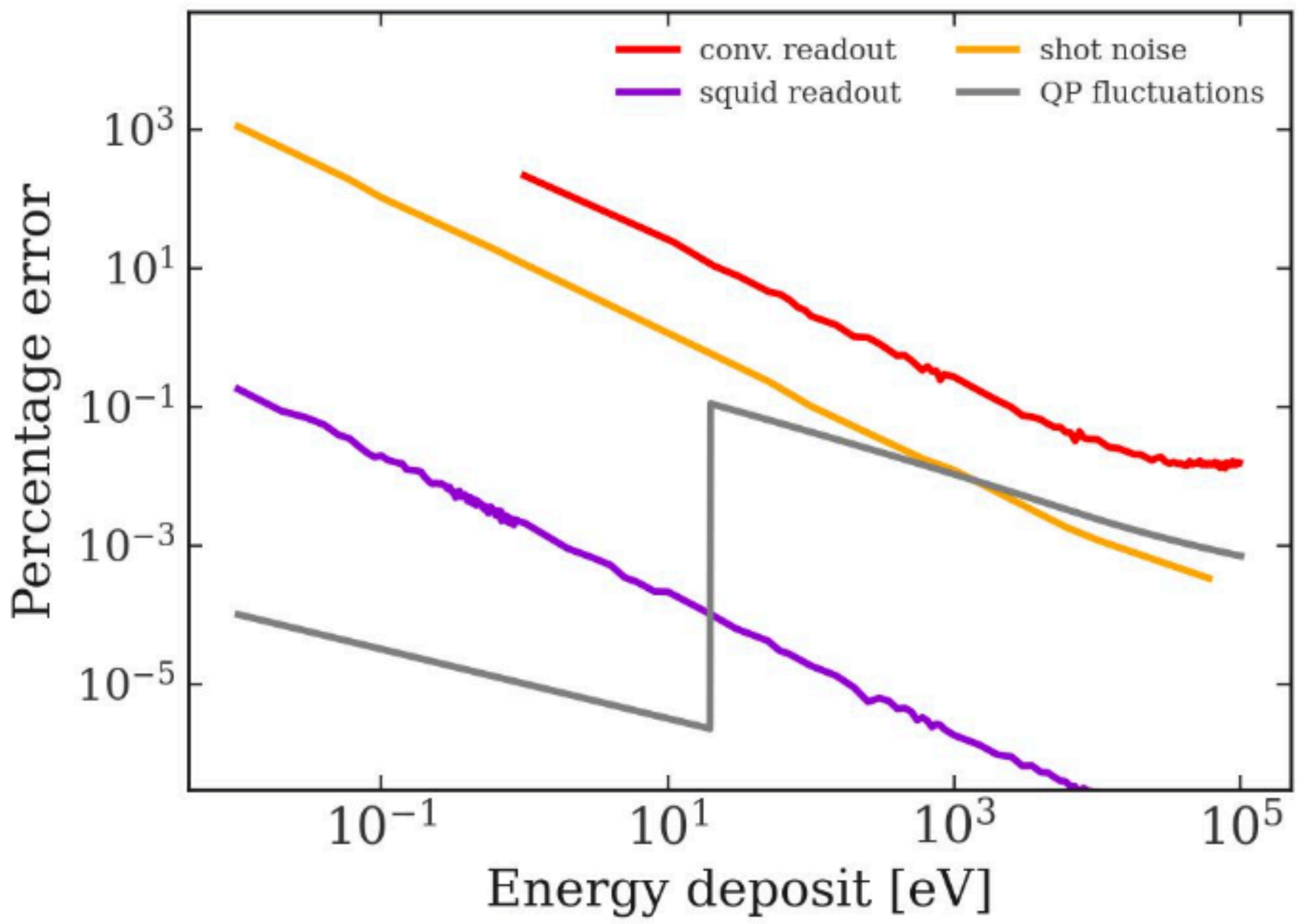
Energy threshold limited by readout noise and shot noise.

SQUID could reduce readout noise, reducing the energy threshold thus enhancing the dark matter sensitivity.

Nuclear Recoil Energy Thresholds for a 400nm diameter wire at 0.12 T/Tc.

Conventional readout $E_{th,conv} = 39$ eV

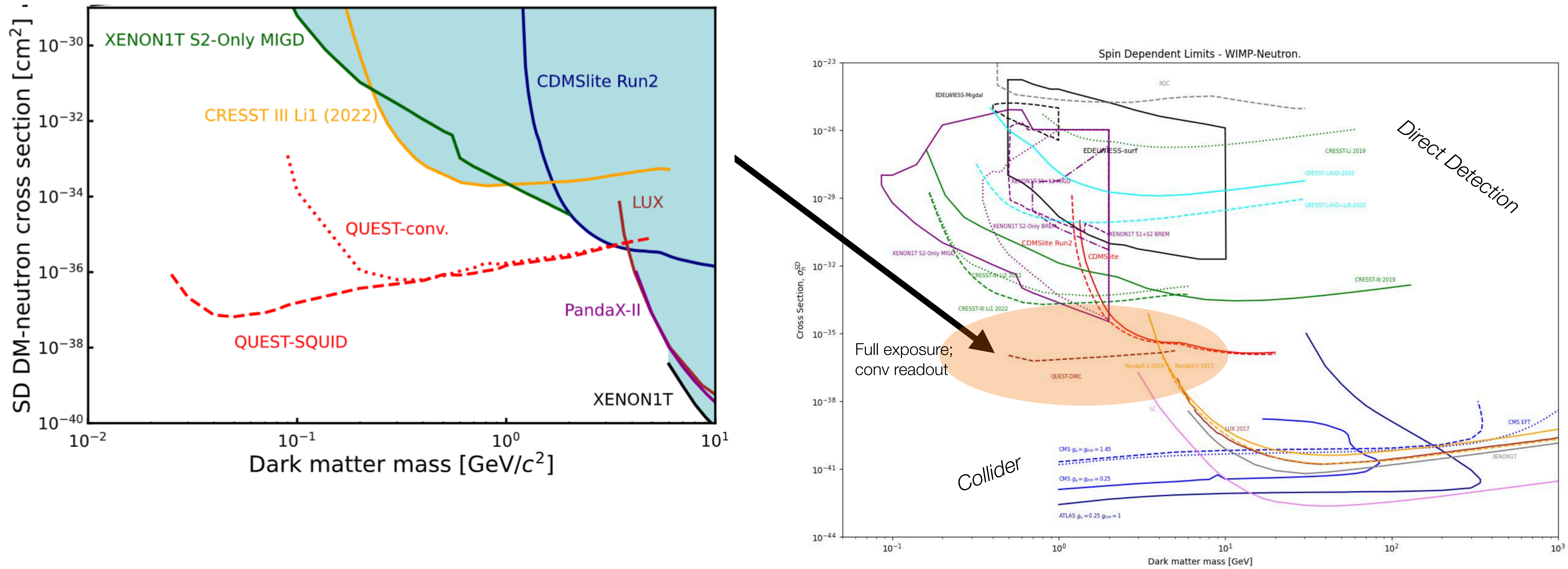
SQUID readout $E_{th,SQUID} = 0.71$ eV



Energy threshold defined as energy that can be statistically determined to be non-zero at 95% C.L.

Dark Matter Sensitivity Projection

Spin-dependent sensitivity projection for: 6 month run; 50% duty cycle; 5 x 0.3 cm^3 ^3He cells (0.1 g/cm^3).



Summary and Outlook

QUEST-DMC is a superfluid ^{3}He bolometer instrumented with **vibrating nanowire detectors** that aims to set **world-leading sensitivity** to GeV and sub-GeV mass dark matter with **~eV scale energy threshold.**

High resolution quantum readout (SQUID) is being developed in order to **improve energy threshold by at least an order of magnitude** compared to conventional readout (lock-in amplifier) - has currently been tested at 4 K.

Simulation and analysis tools in place (Geant4, Profile Likelihood Ratio statistical analysis code, etc).

Current sensitivity **~10^{-36} cm^2 at 1 GeV/c^2** with a **0.71 eV threshold (SQUID readout).**

Work In Progress:
- Develop energy calibration of the bolometer.
- Demonstrate SQUID readout at ~μK temperatures.
- Develop and implement a photon detector to a) detect scintillation light from events above ionisation energy, or b) to act as a cosmic veto for events below ionisation energy.

Paper on arXiv in coming weeks- watch this space!

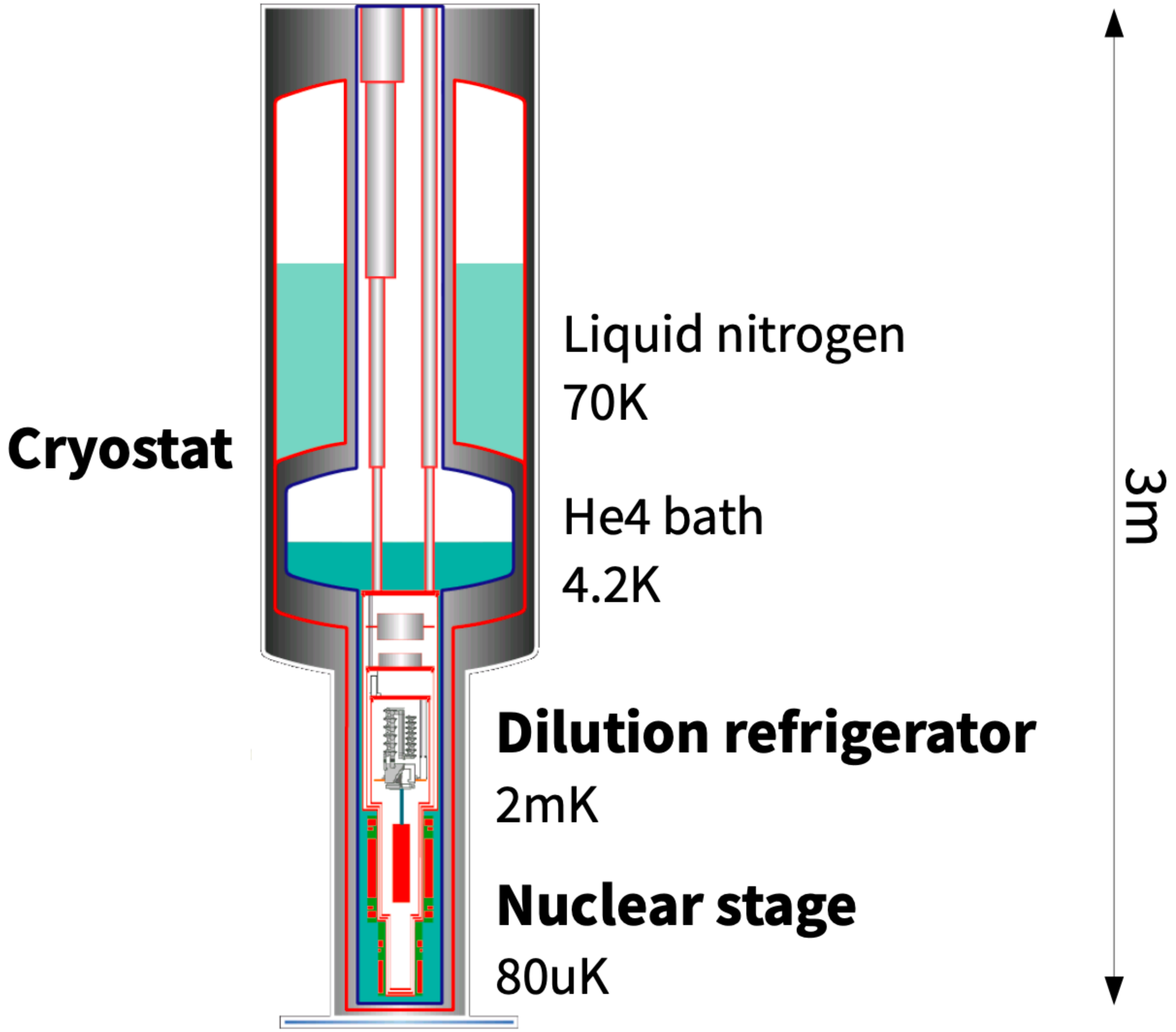
Back-Up

Refrigerator at Lancaster

To reach the superfluid phase, ^{3}He has to be cooled to sub-mK temperatures, and QUEST-DMC intends to operate at sub-100 μK temperatures.

This will be achieved with the use of an advanced refrigerator based at Lancaster University.

Cool-down system consists of three stages:
- Liquid nitrogen and ^{4}He bath.
- ^{3}He/^{4}He dilution refrigerator.
- Nuclear demagnetisation refrigerator.



Courtesy of Paolo Franchini

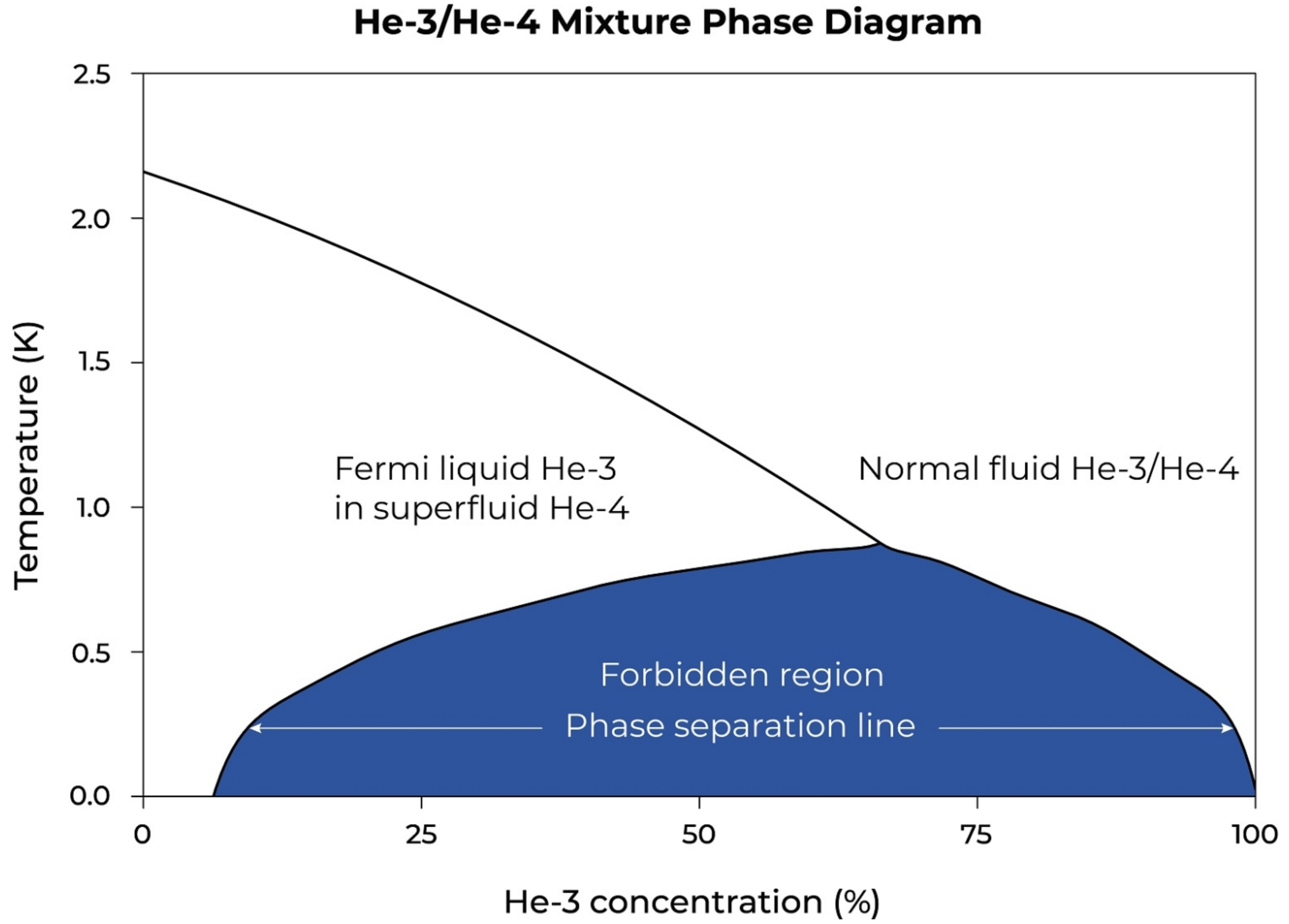
Cryostat & Wet Dilution Refrigerator

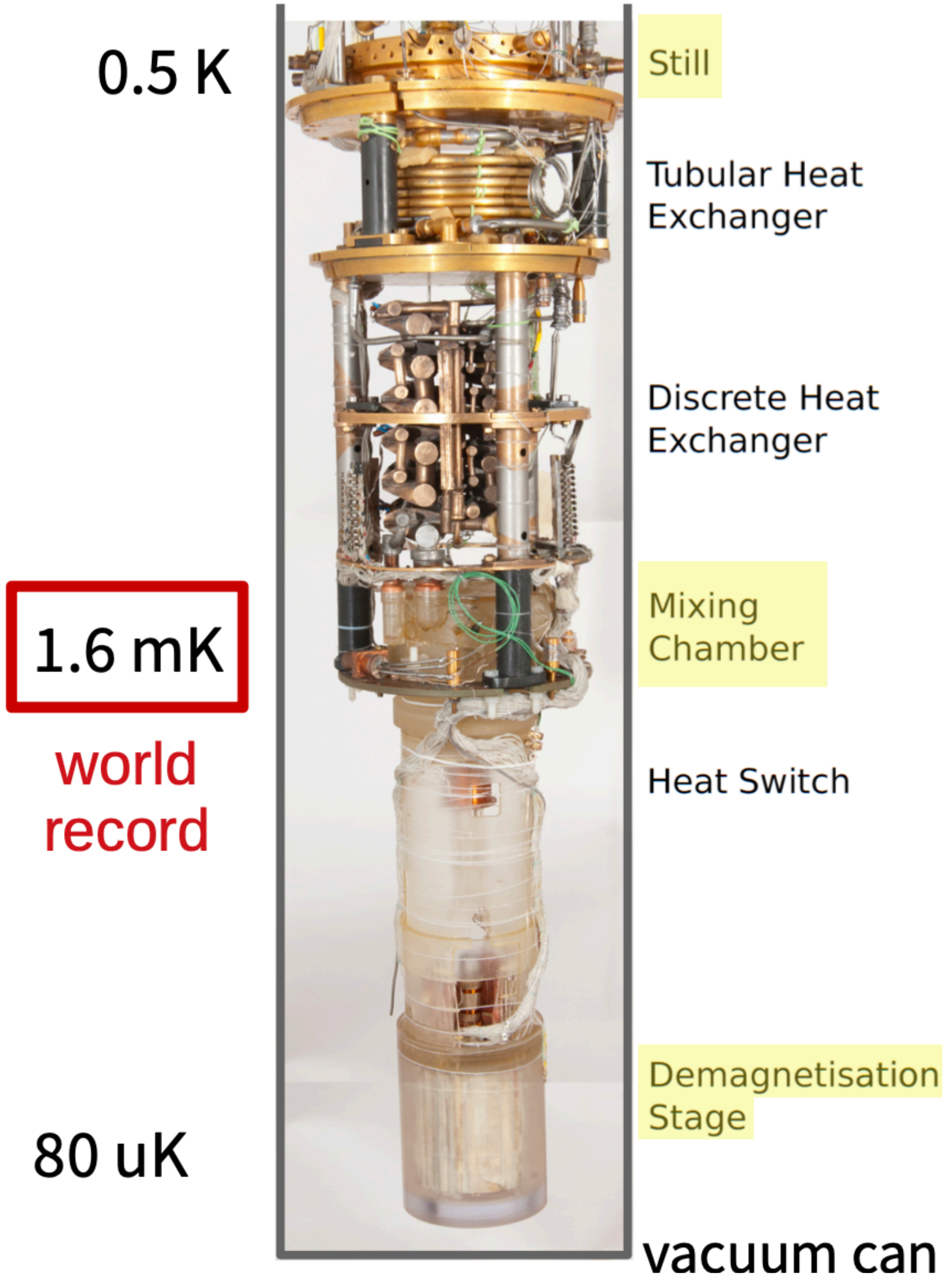
^{3}He gas cooled in first stage through liquid nitrogen (77 K), liquid ^{4}He bath (4.2 K), and pressurised liquid ^{4}He bath known as the 1K “pot”.

- Liquid ^{3}He achieved at 1.6 K

Next part of cool-down stage is wet dilution refrigerator:

- ^{4}He still
- Heat exchangers
- ^{4}He/^{3}He mixing chamber: cooling is based on ^{3}He requiring heat when pumped into the dilute phase from concentrated phase, which provides cooling in the environment this happens in.





Courtesy of Paolo Franchini

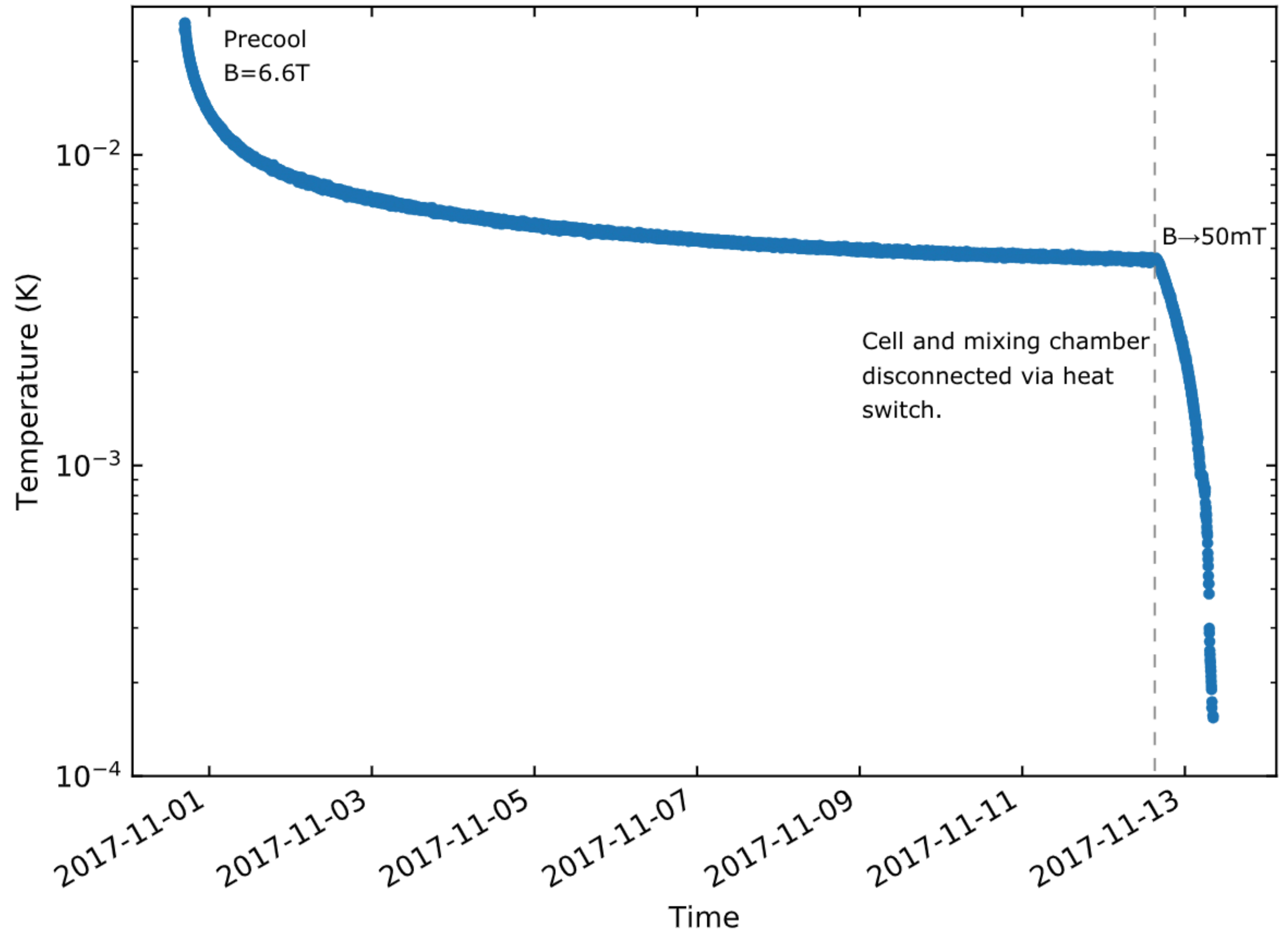
Nuclear Demagnetisation Cooling

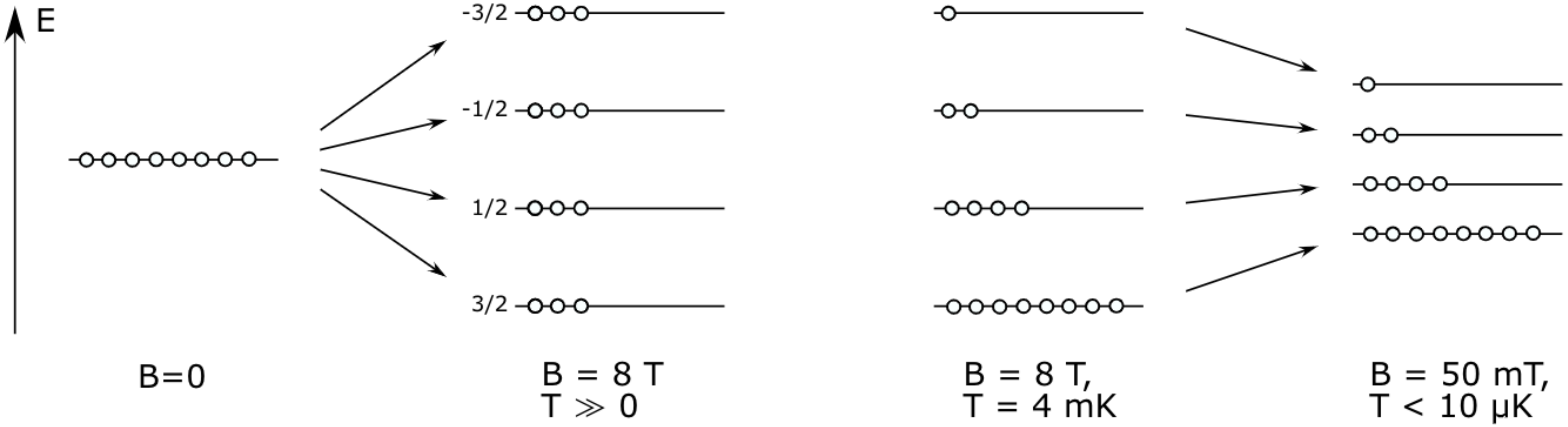
Adiabatic demagnetisation of a magnetic material can cause cooling in the material and systems in thermal contact with it.

Coolant material is Copper, Cu (Nuclear spin of 3/2).

In presence of B field, nuclear energy levels split into four via the Zeeman effect.

- At high temperatures energy levels equally populated.
- As temperature decreases, lowest energy level becomes energetically favourable, holding a high population of atoms.
- B field reduced, raises energy of Cu nuclei whilst maintaining constant entropy - results in cooling of nuclear temperature.
- Conduction electrons in the Cu lattice provide the necessary thermal link to ^{3}He via lattice phonons and the atomic nuclei.





Noble, Mark Theodore. New methods of measurements in superfluid helium. Lancaster University (United Kingdom), 2019.

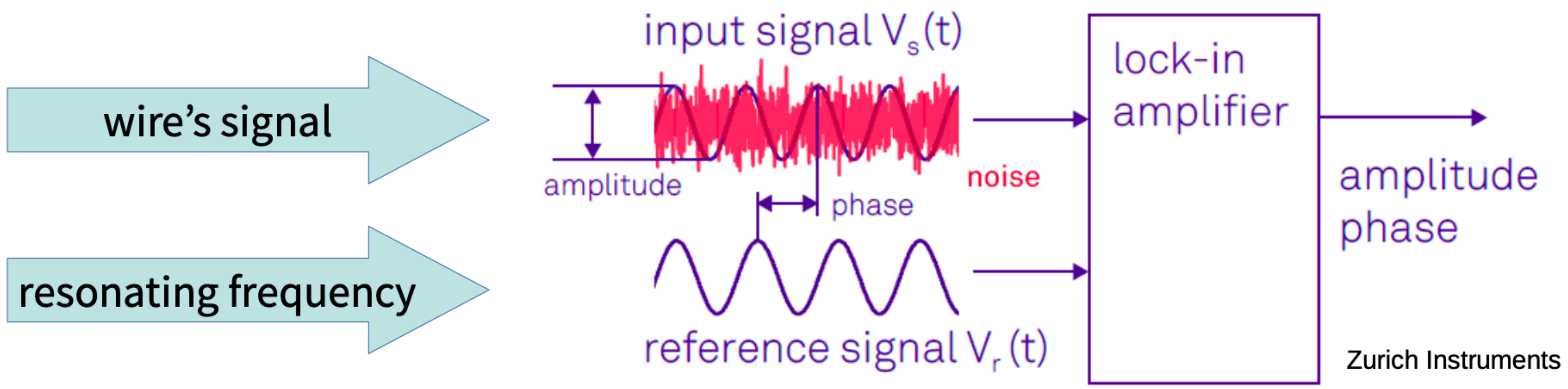
Nanowire Readout Methods

Vibrating nanowire can be read out via…

Lock-in Amplifier

Lock-in amplifier compares input signal $V_s(t)$ (amplitude, phase) to a reference signal $V_r(t)$ to extract signal from noisy background.

1:100 Transformer used to amplify signal.



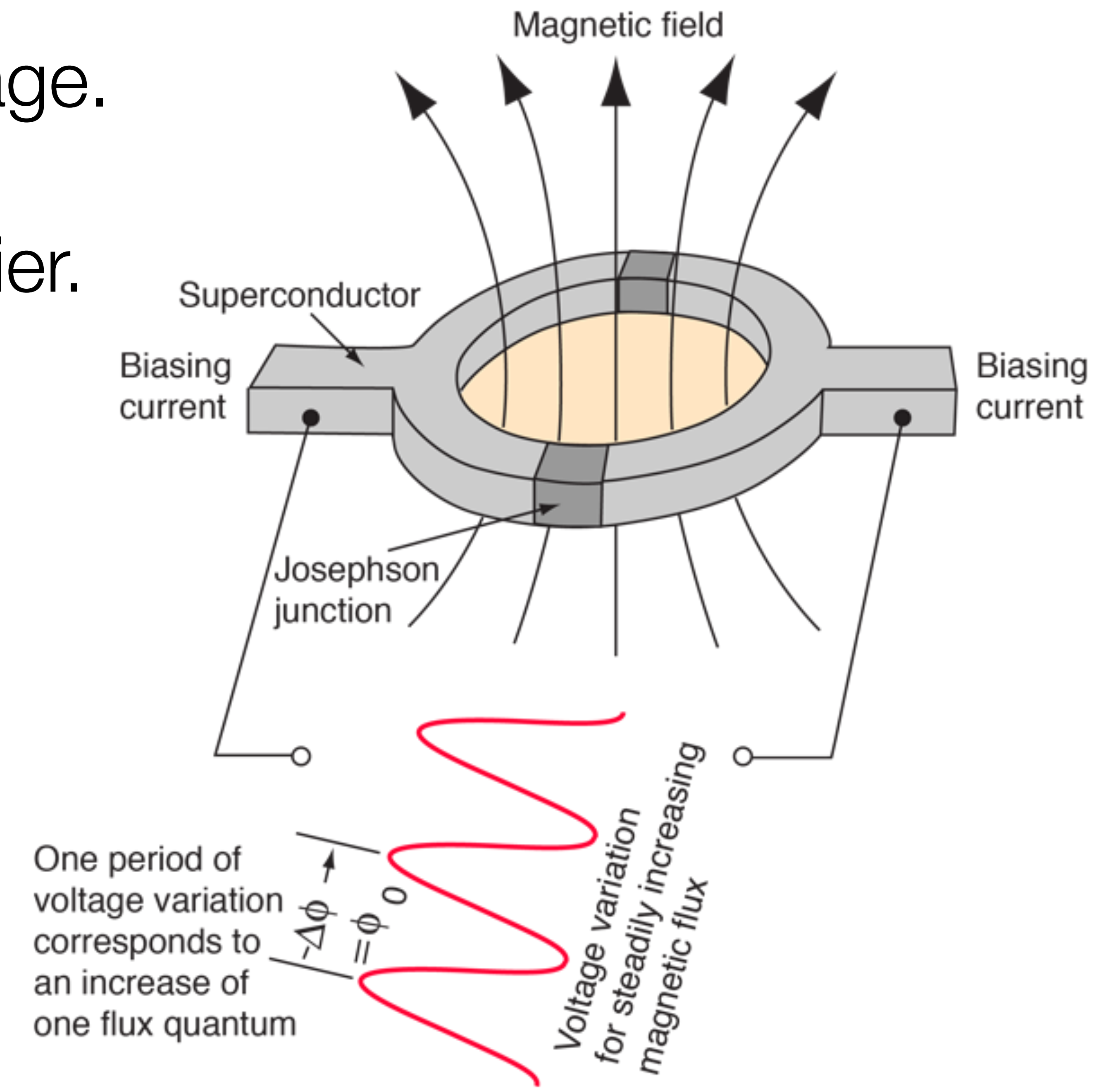
Courtesy of Paolo Franchini

Superconducing QUantum Interference Device

SQUID is a magnetometer sensitive to ~10^{-14} T, order of magnitude less than the brain.

Converts magnetic flux into voltage.

SQUID readout by lock-in amplifier.

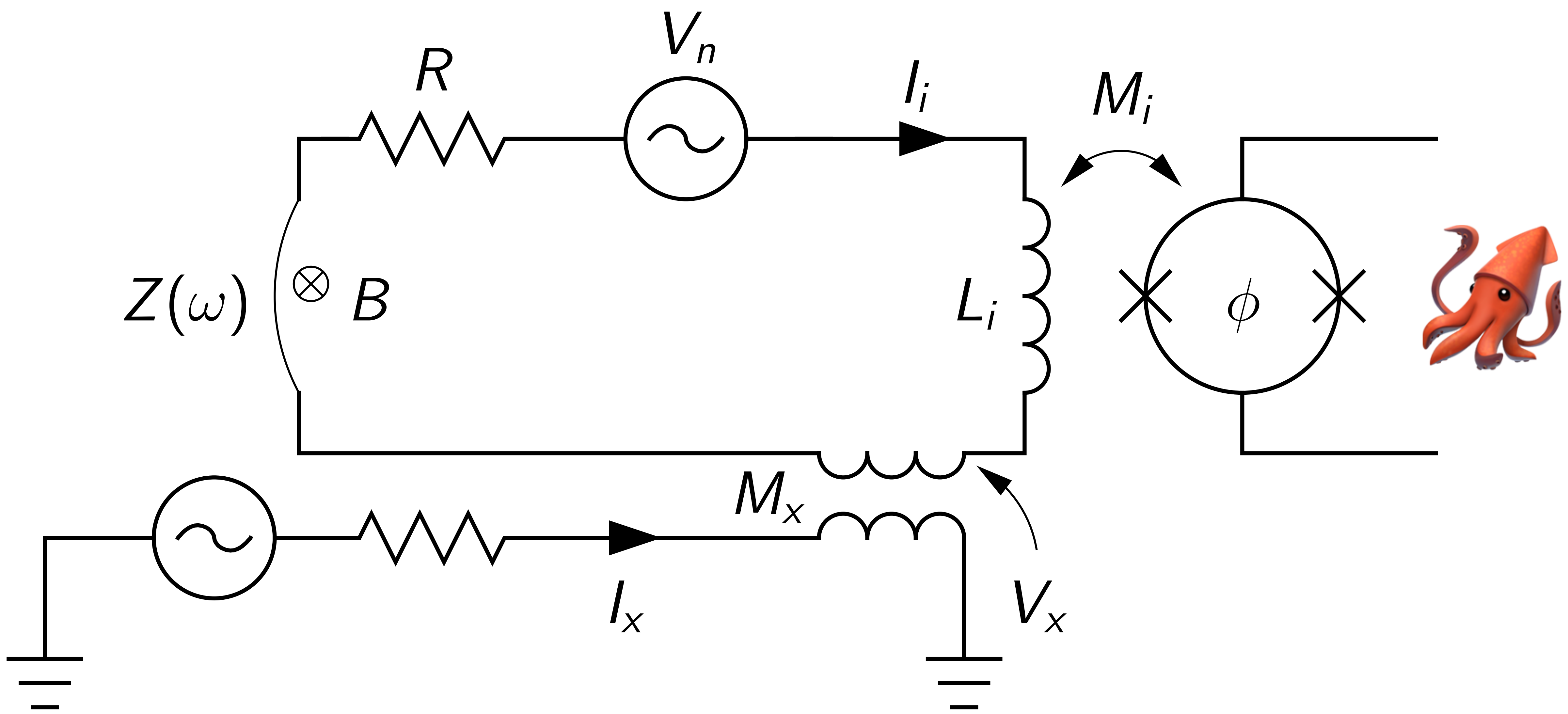


http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/Squid.html

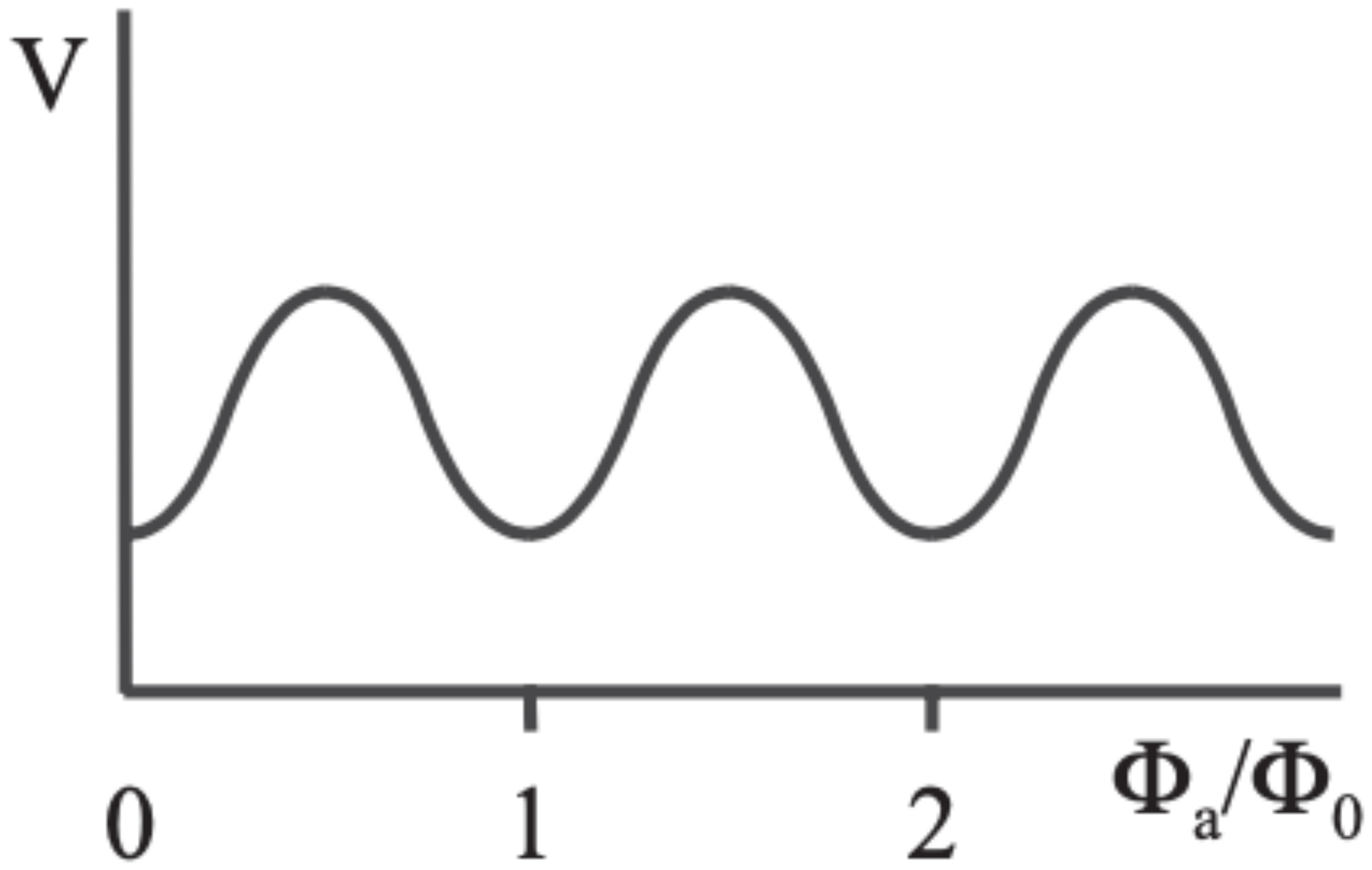
Nanowire Readout using a SQUID

DC SQUID: Superconducting loop with two Josephson junctions, constantly biased.

- Without external B field, input current splits into two branches equally.
- If small external magnetic field is applied, screening current circulates the loop.
- Flux enclosed in superconducting loop must be an integer number of flux quanta; current changes direction periodically every time flux increases by additional half-integer multiple of magnetic flux quantum Φ_0.
- Count periodic-Φ_0 oscillations of the voltage to measure flux change.



The resonator is driven inductively by drive current I_x via coupling inductance M_x, applying voltage excitation V_x. SQUID current sensor detects current I_i flowing through the wire with impedance $Z(\omega)$, contact resistance R and SQUID-readout input coil L_i. Noise sources are represented by their equivalent voltage V_n.



$$V_{RMS} = \sqrt{\left|Z(\omega_0) + R + i\omega_0 L_i\right|^2 S_\phi \Delta f / M_i^2 + 4k_B T R \Delta f + k_B T l B^2/m}$$