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

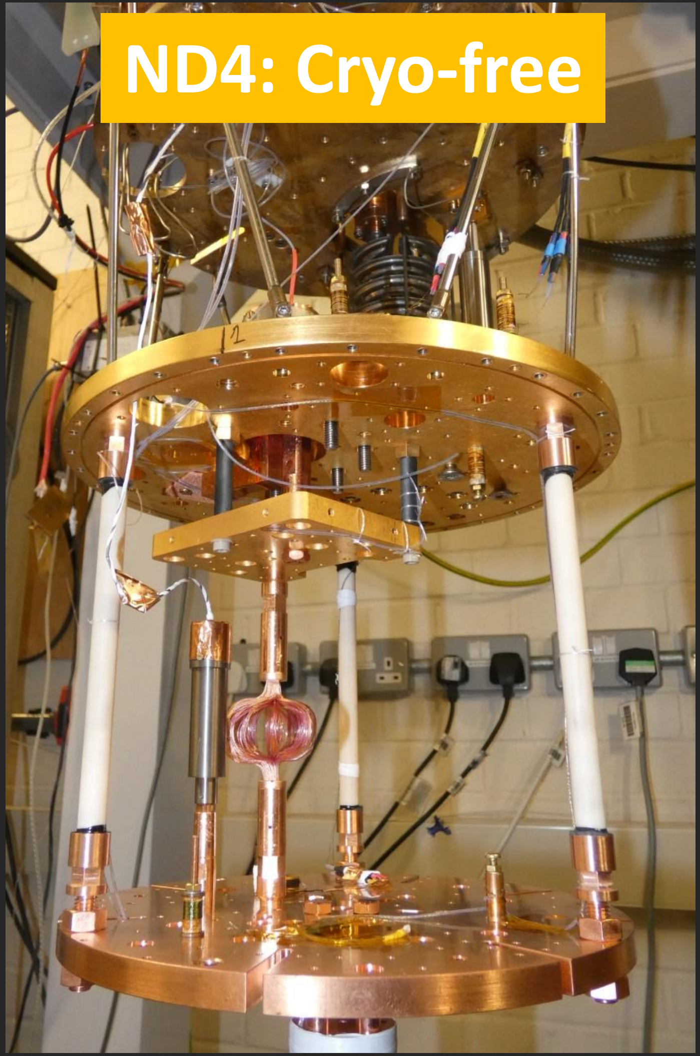
- Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter

- Phase transitions in extreme matter

Linked through beyond-standard model physics, and experimental approach of combining quantum sensors with ^{3}He at ultralow temperatures

ROYAL HOLLOWAY UNIVERSITY OF LONDON
Lancaster University
University of Sussex
UNIVERSITY OF OXFORD
UNIVERSITY OF LIVERPOOL
UKRI Engineering and Physical Sciences Research Council
UKRI Science and Technology Facilities Council

Quantum sensors operated in ultralow temperatures regime, 100 μK

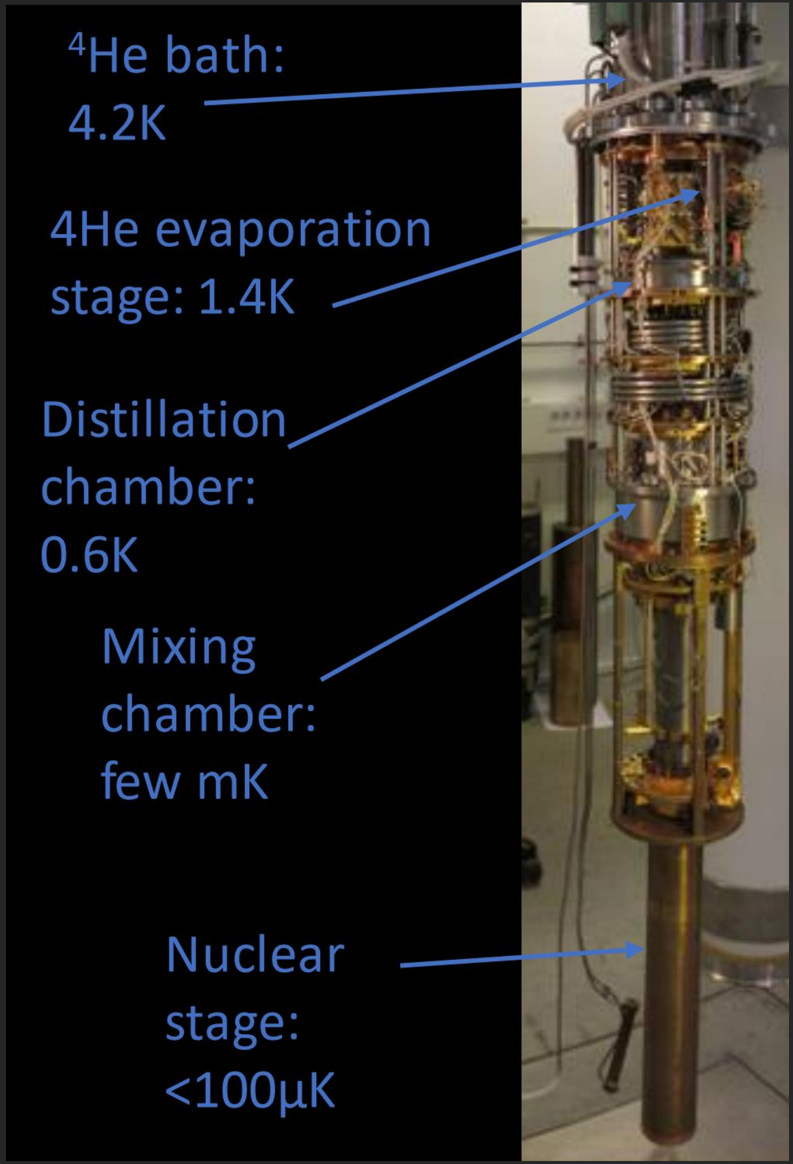


ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lucas, M., Danilov, A.V., Levitin, L.V. *et al.* Quantum bath suppression in a superconducting circuit by immersion cooling. *Nat Commun* **14**, 3522 (2023)

Quantum sensors operated in ultralow temperatures regime, 100 μK

Lancaster University



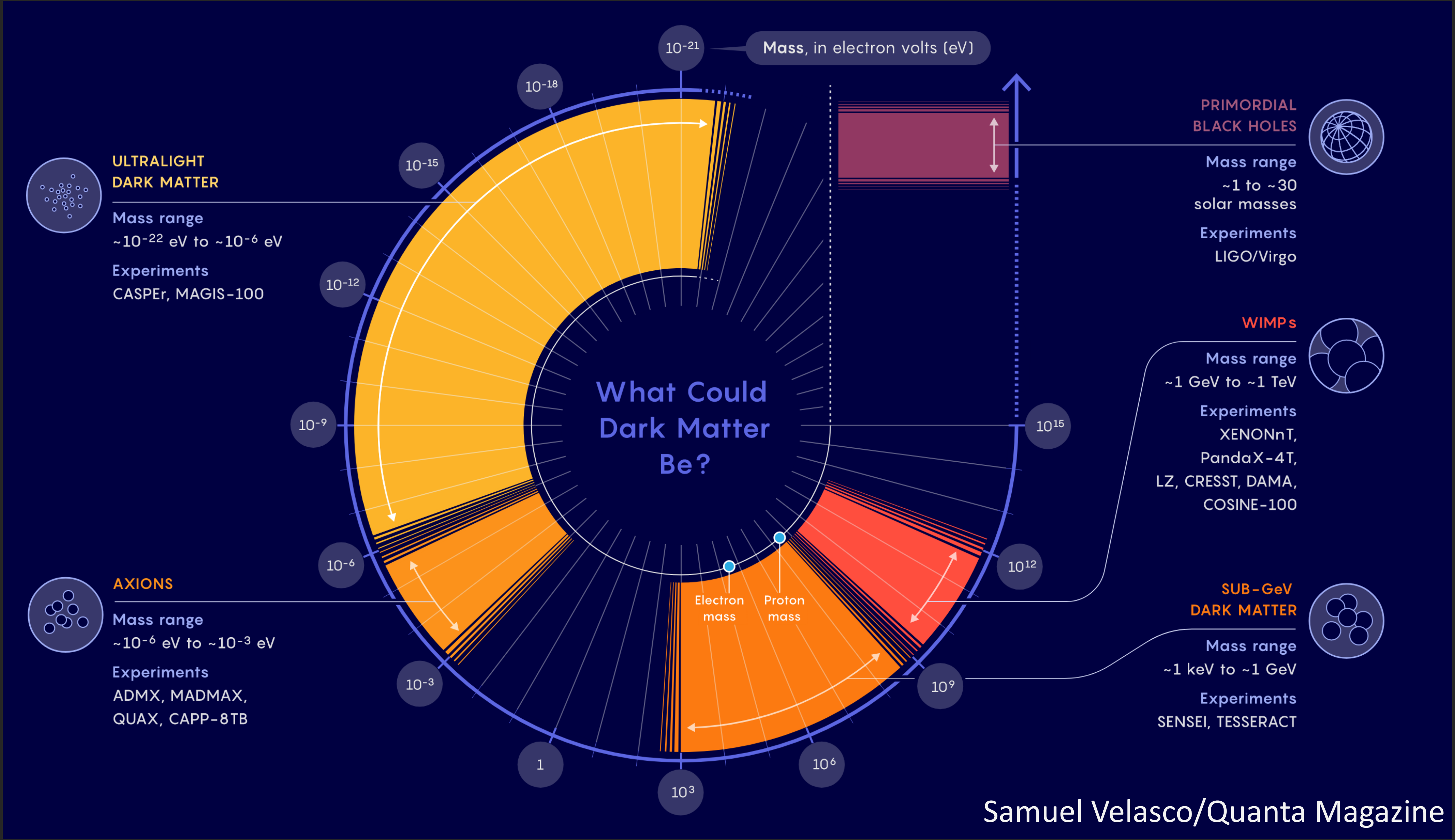
Nanofabrication facilities

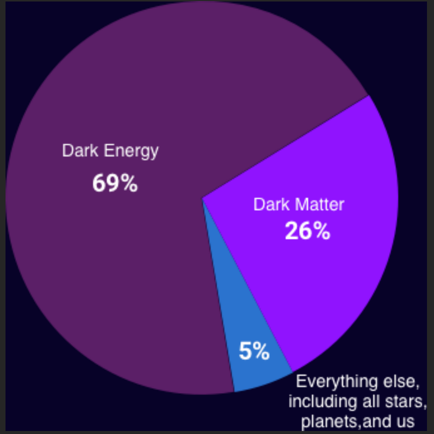
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Quantum Technology Centre, ULANC

UK CSQS-Centre for Superconducting and Hybrid Quantum Systems, RHUL

What mass range are we trying to find?





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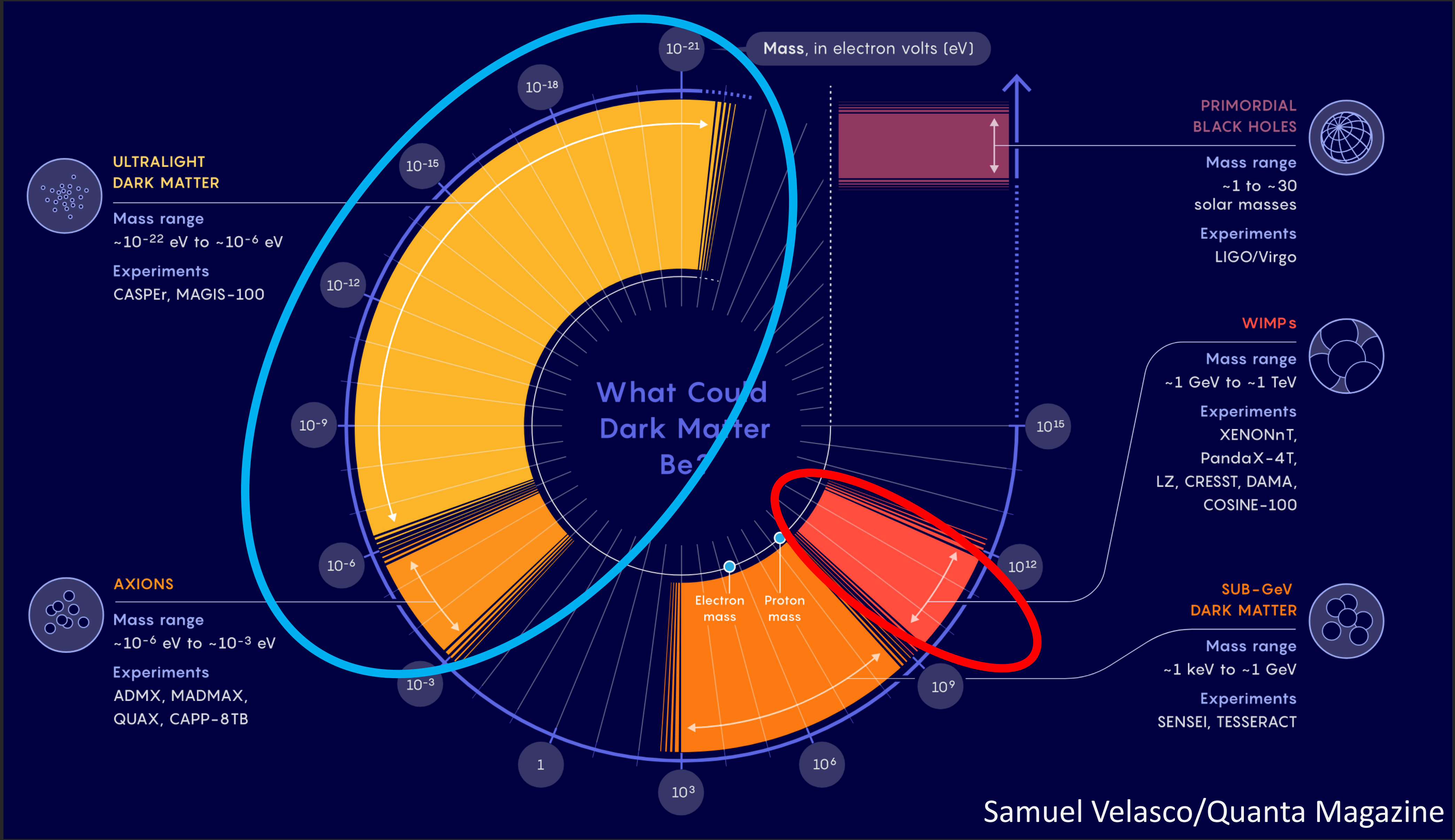

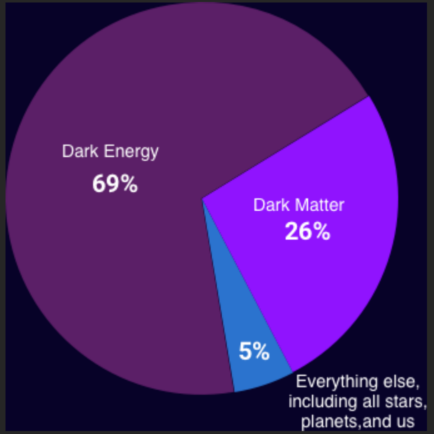

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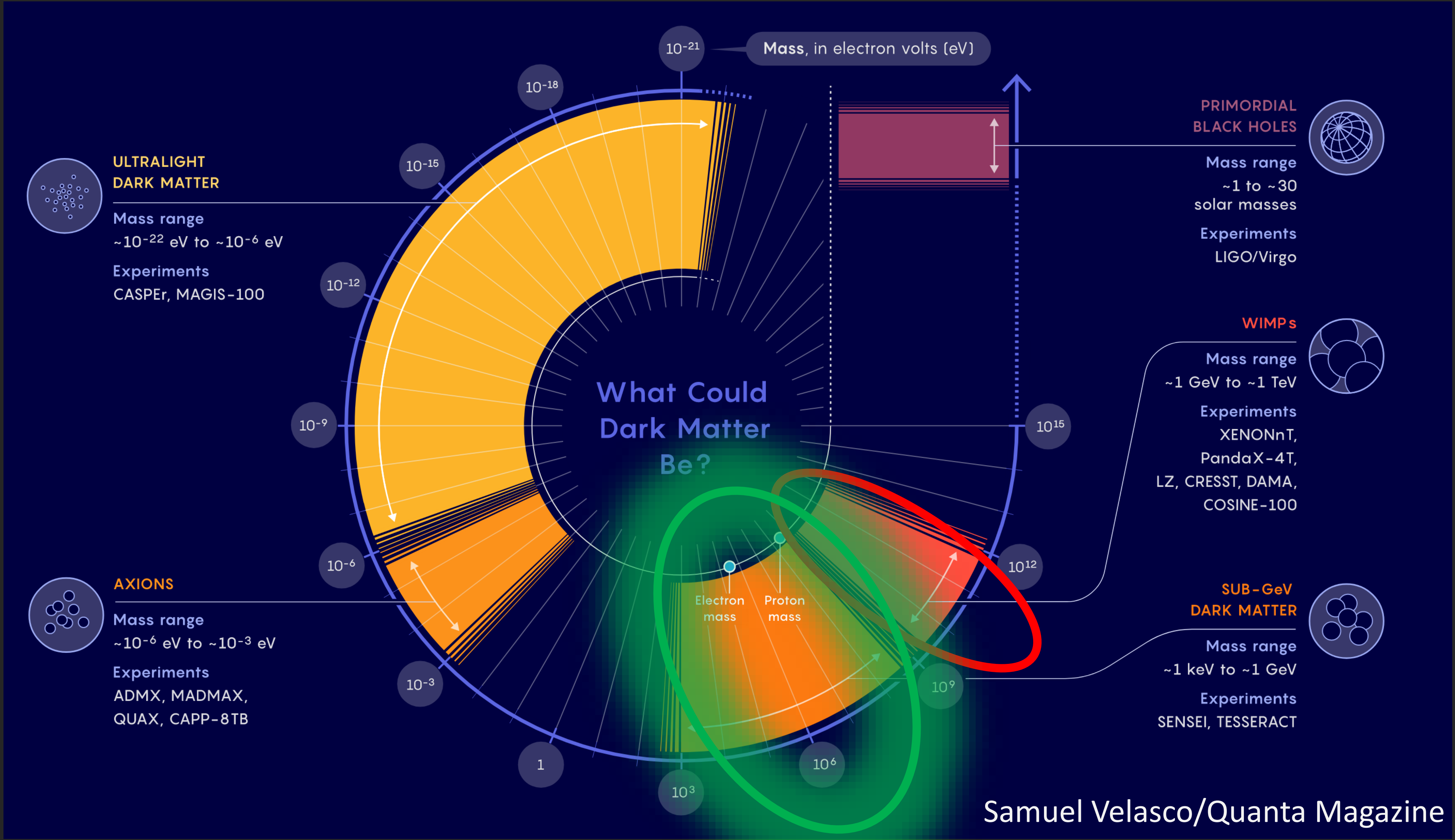
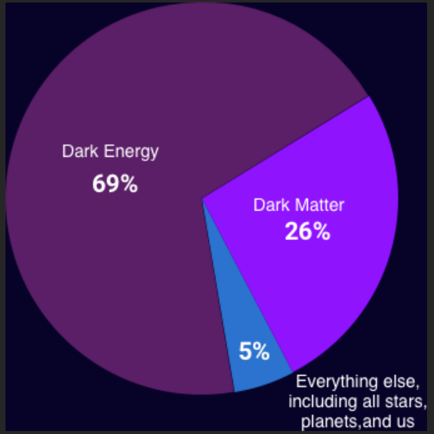
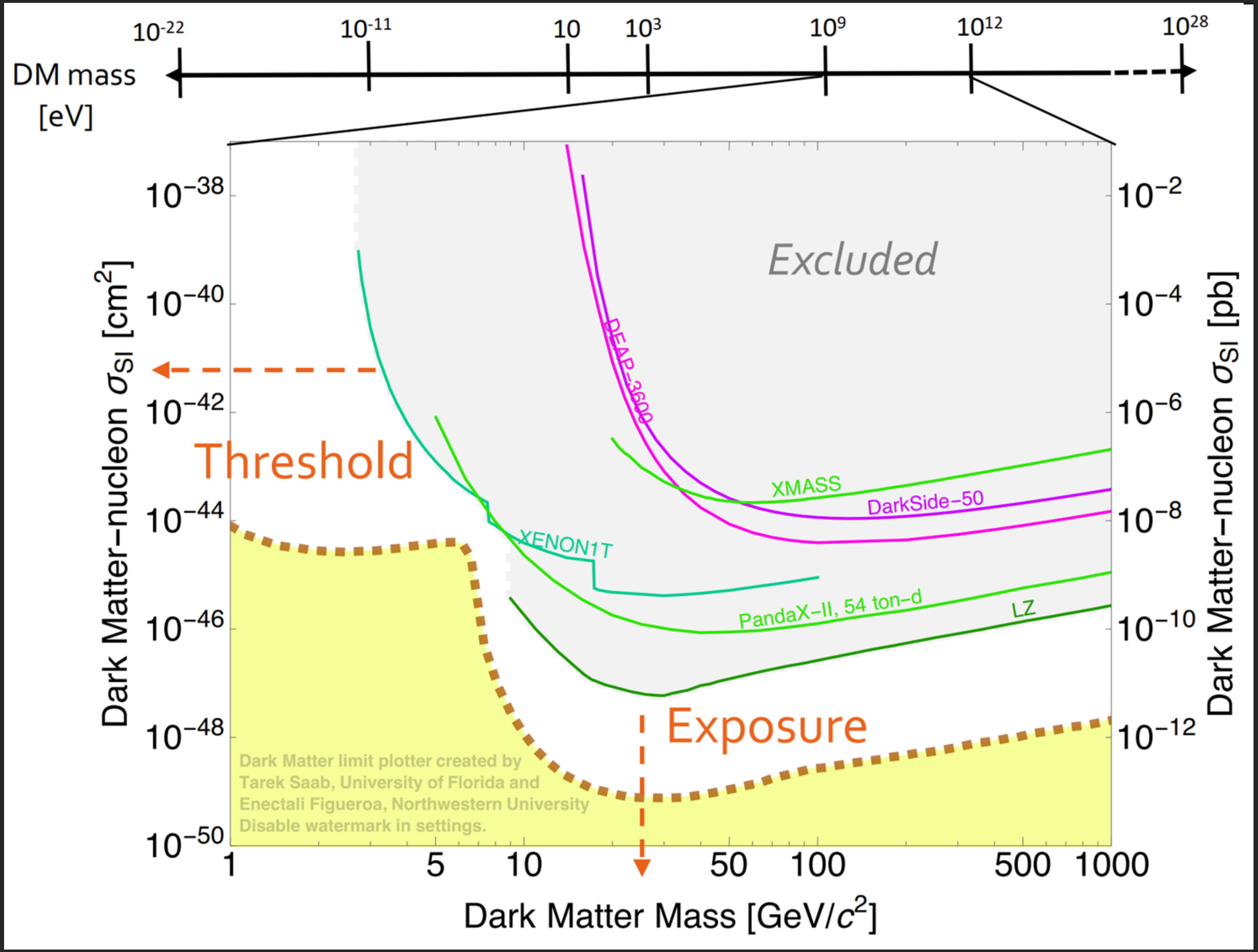


Samuel Velasco/Quanta Magazine



Mass range of the order GeV theoretically motivated by *Asymmetric dark matter models*

Optimising Search



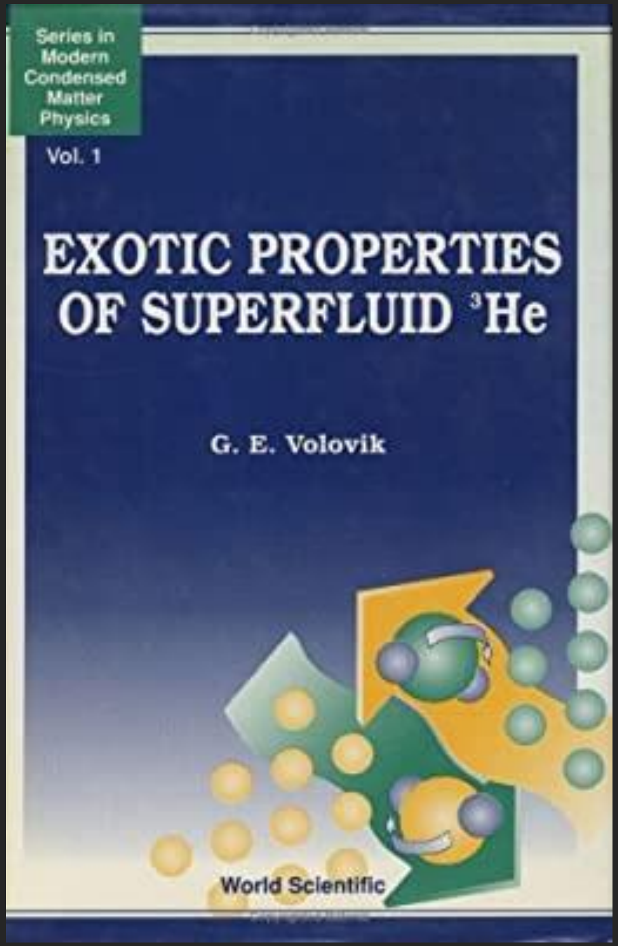
Lower cross-sections:

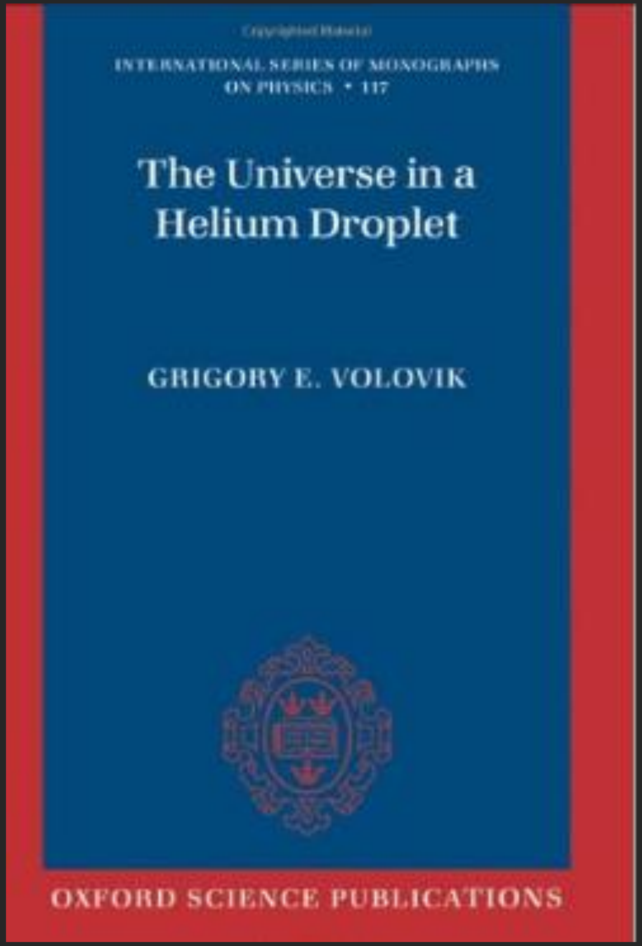
- More exposure, maximise interaction rate
- Lower backgrounds

Lower the mass range

- Reduce the energy thresholds

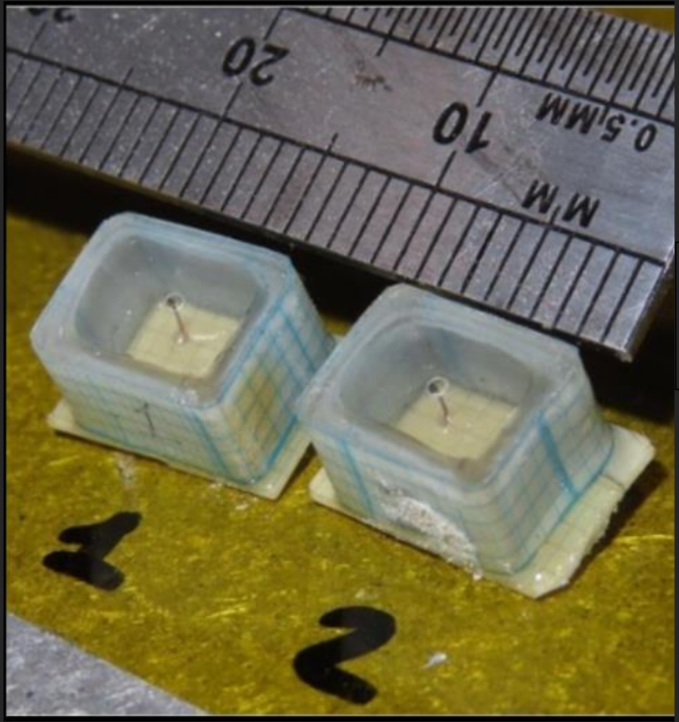
Superfluid ^{3}He is most complex system for which we already have the “Theory of Everything"



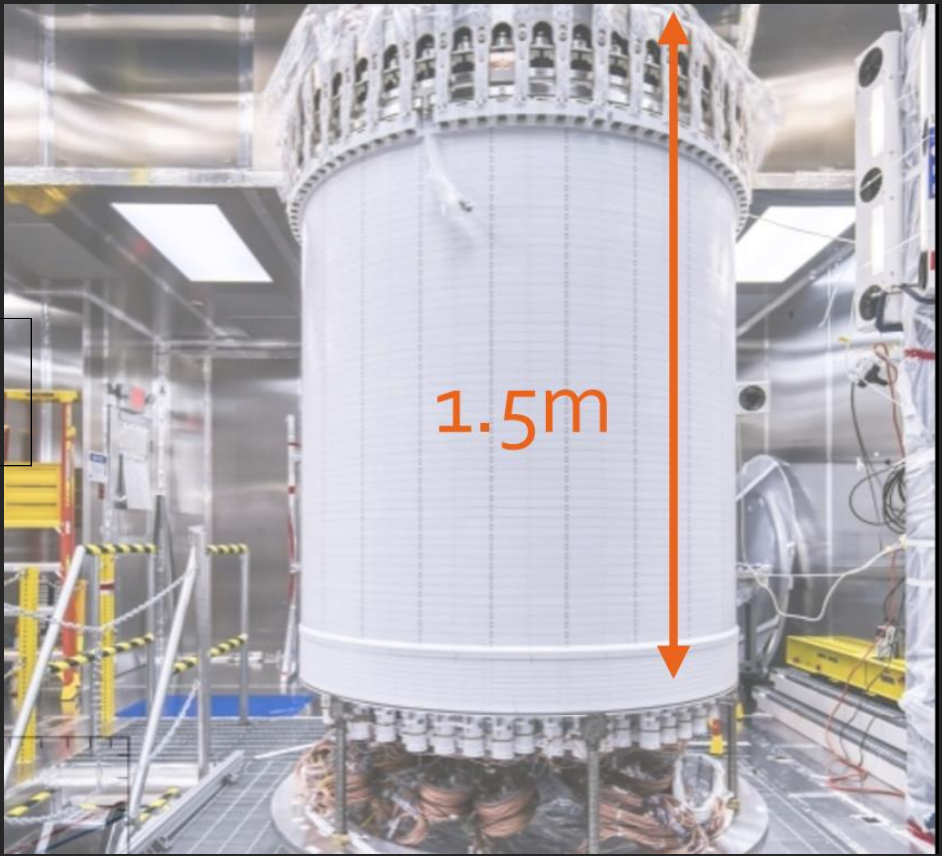


Superfluid Helium, ^{3}He

Collision WIMP - ^{3}He atom (mass 3 versus argon - 39.948, xenon -131.293)



0.3 g ^{3}He vs 7 tonne Xe
e.g.LZ,PRL,131,041002(2023)

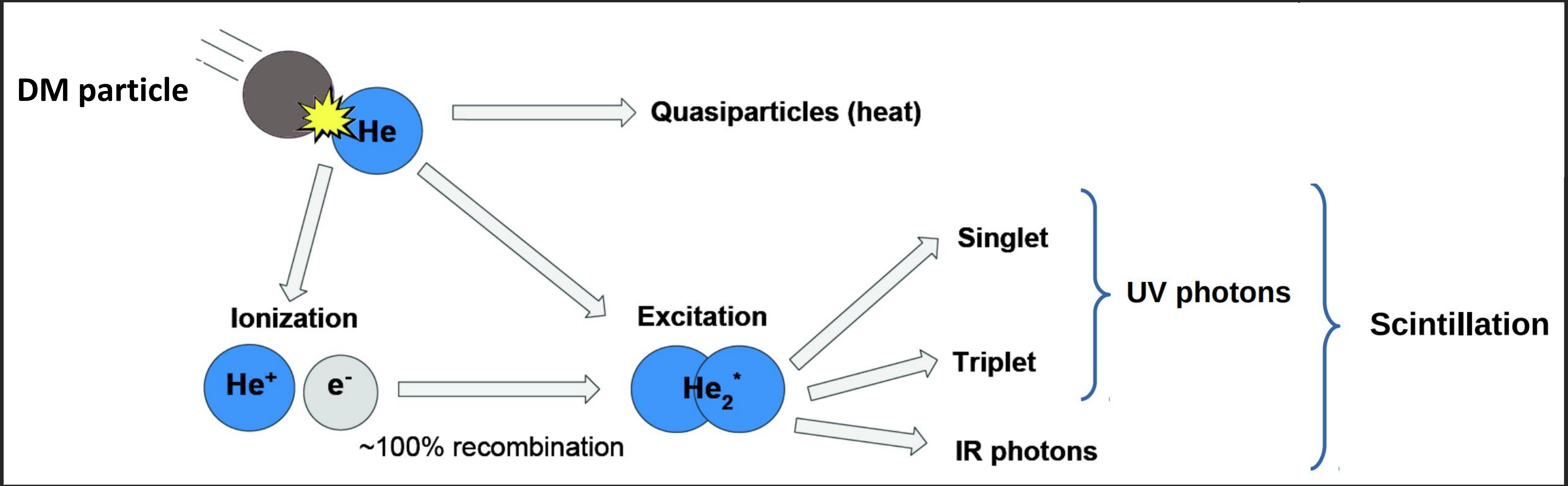


ULTIMA: D.I. Bradley, et al., Nucl. Instrum. Methods A 370, 141 (1996); C.B. Winkelmann, et al., Nucl. Instrum. Methods A 559, 384 (2006); C.B. Winkelmann, et al., Nucl. Instrum. Methods A 574, 264 (2007).

^{4}He target HeRald: S. A. Hertel, A. Biekert, J. Lin, V. Velan, and D. N. McKinsey Phys. Rev. D **100**, 092007 (2019)

Superfluid Helium, ^3He

Collision WIMP - ^3He atom (mass 3 versus argon - 39.948, xenon -131.293)
– Heat as quasiparticle excitations
– Light from de-excitation, threshold for ionization is ~ 20 eV



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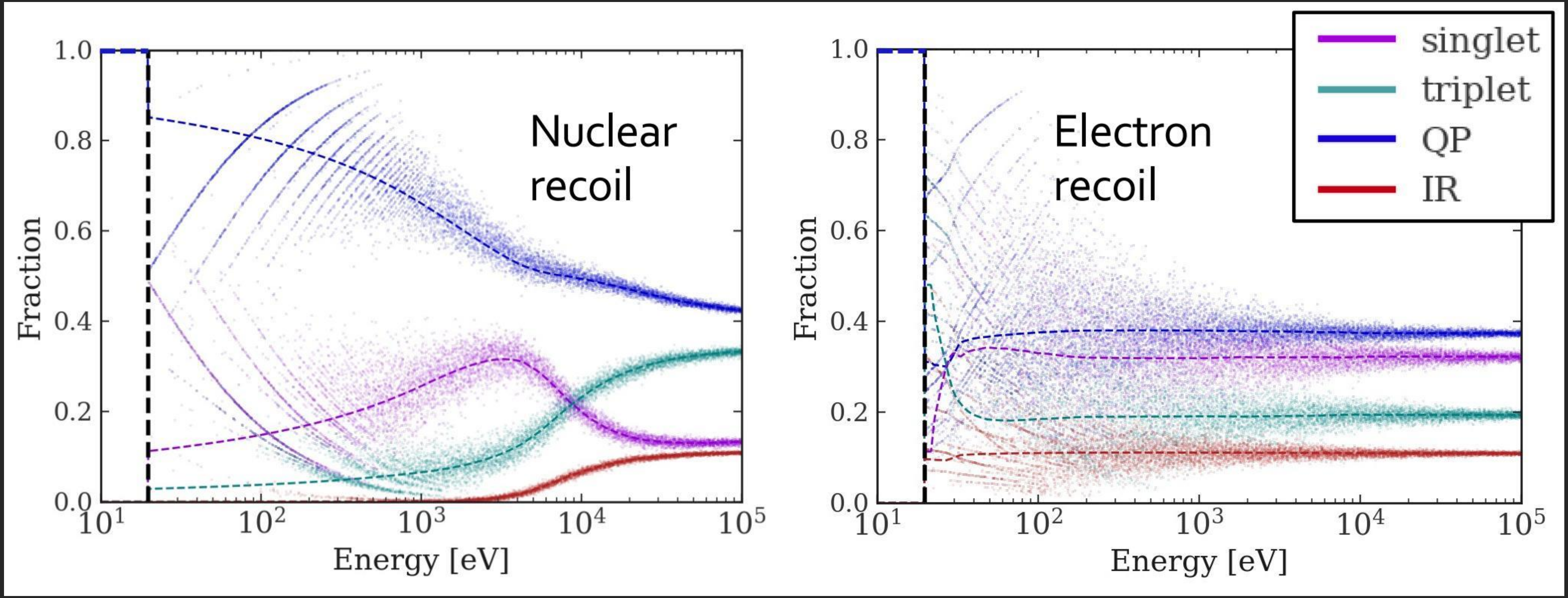
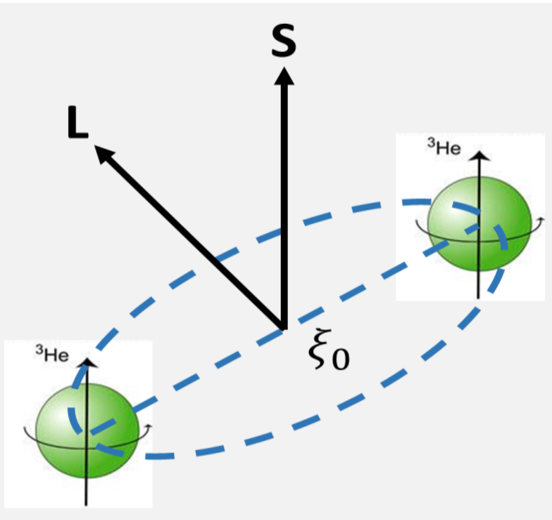
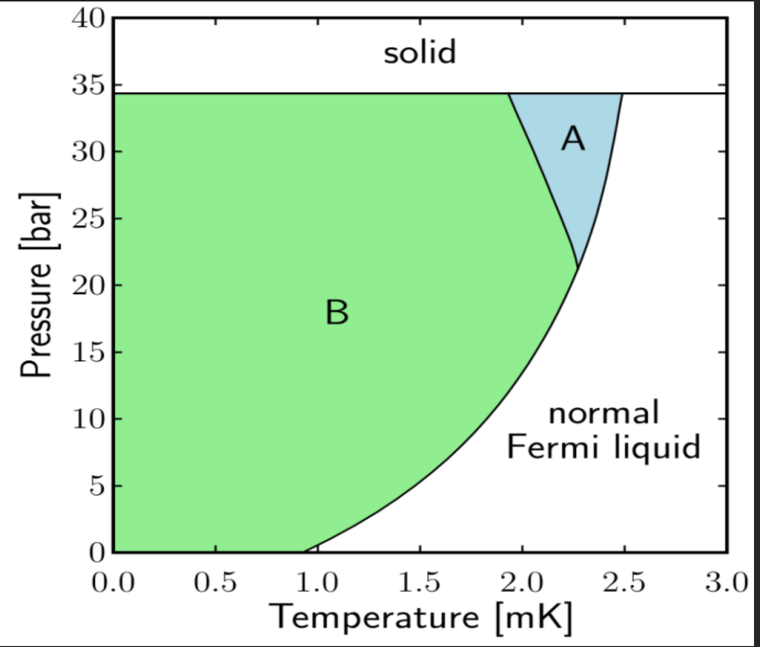
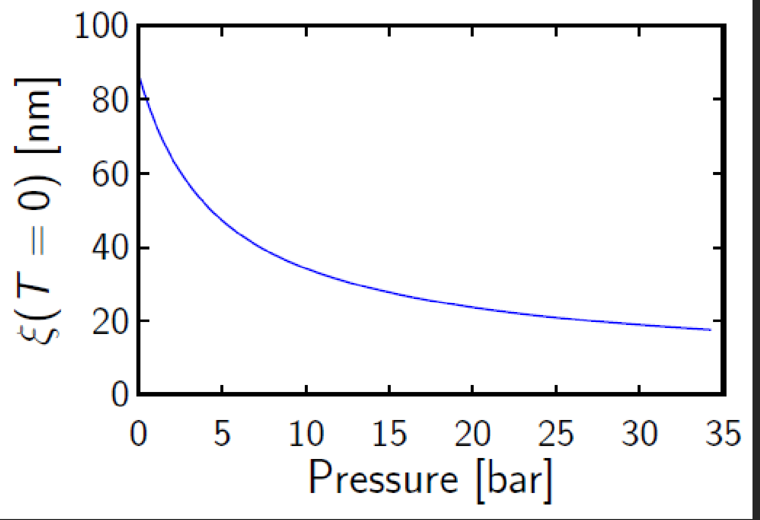


Superfluid Helium, ^3He

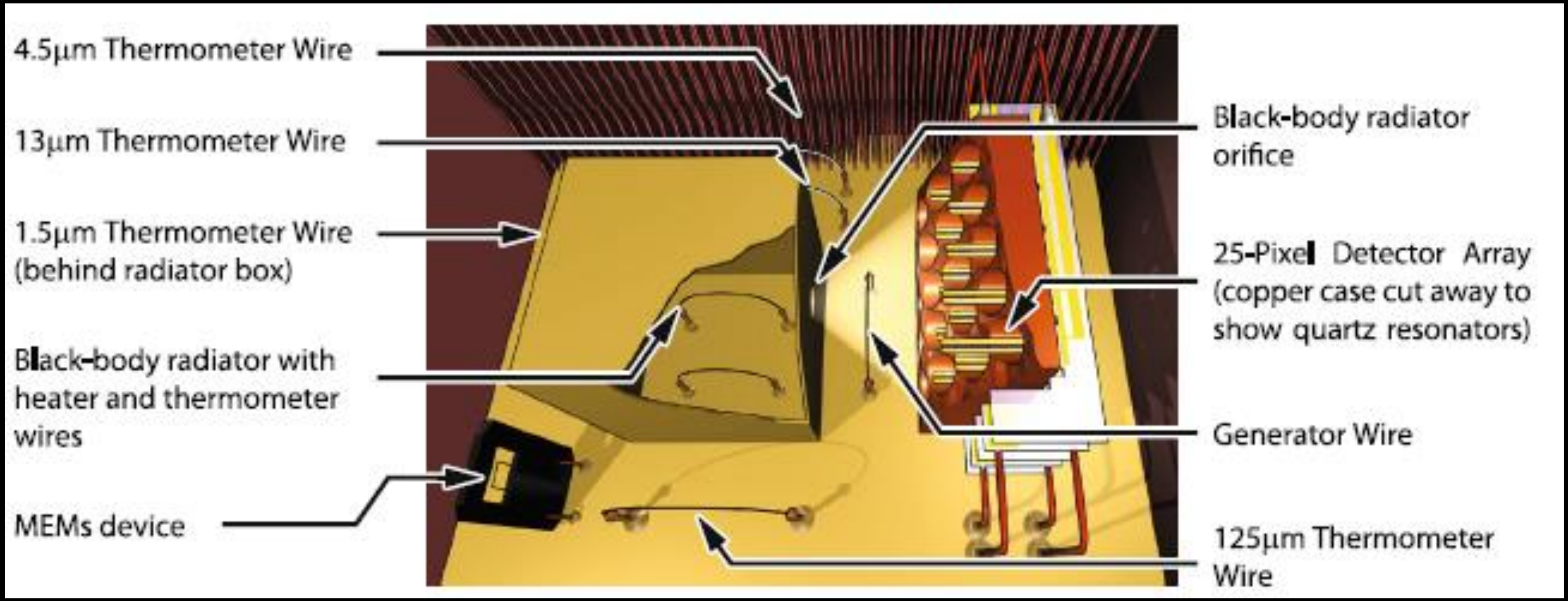
- Cooper pairs with L = S = 1
- 18-component order parameter
  - L_z = -1, 0, 1
  - S_z = -1, 0, 1
- Multiple superfluid phases
  - A-phase: Anderson-Brinkman-Morel
  - B-phase: Balian-Werthamer
- Broken Cooper pairs = thermal excitations with energy $\Delta \sim 10^{-7}$ eV







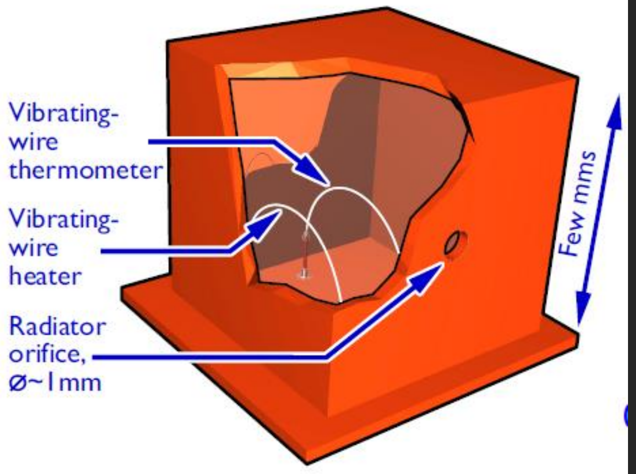
Vibrating sensors as quasiparticle detectors

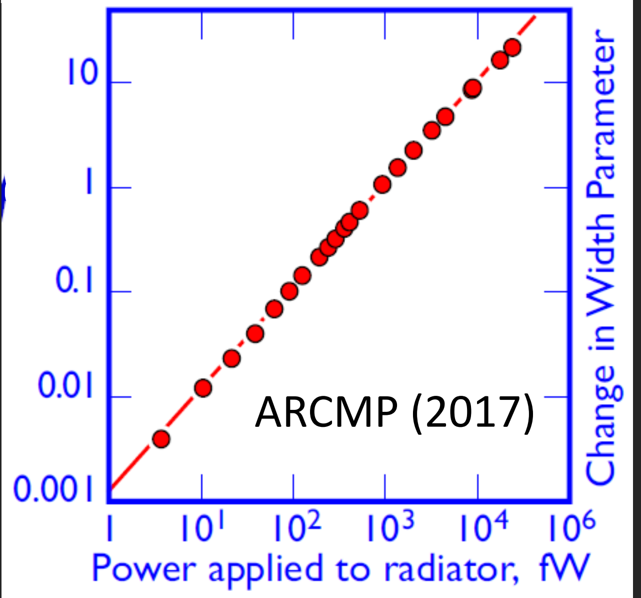


J Low Temp Phys **175**, 725-738 (2014)

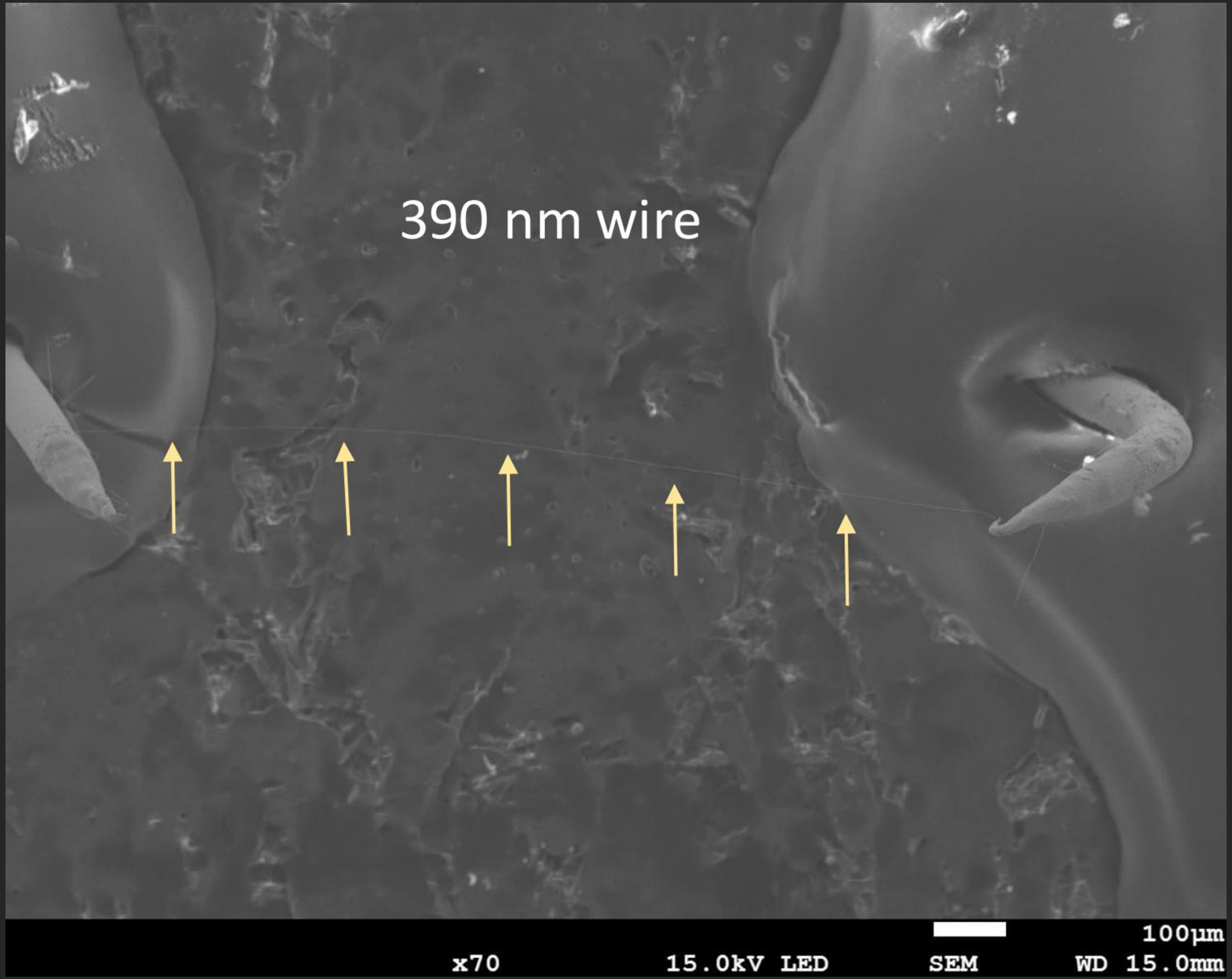
- **ULANC demonstrated bolometer performance using vibrating objects.**
- **Hole in the box determines time constant**
- **Optimise wire size and readout to lower energy threshold**

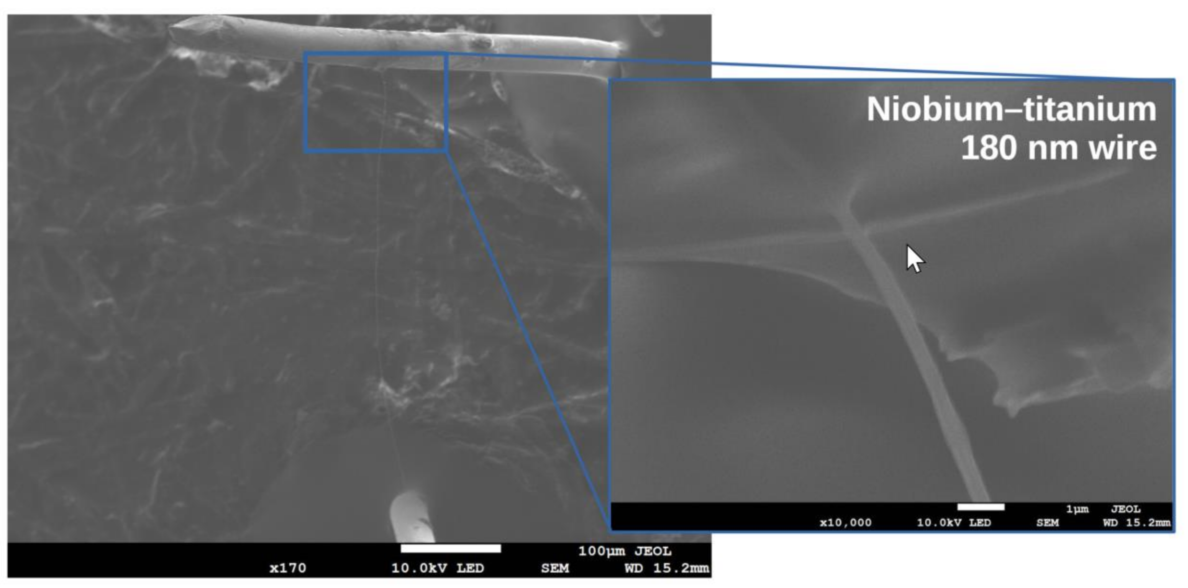
3He-B bolometry offers direct sensing of produced quasiparticles, no Kapitza resistance

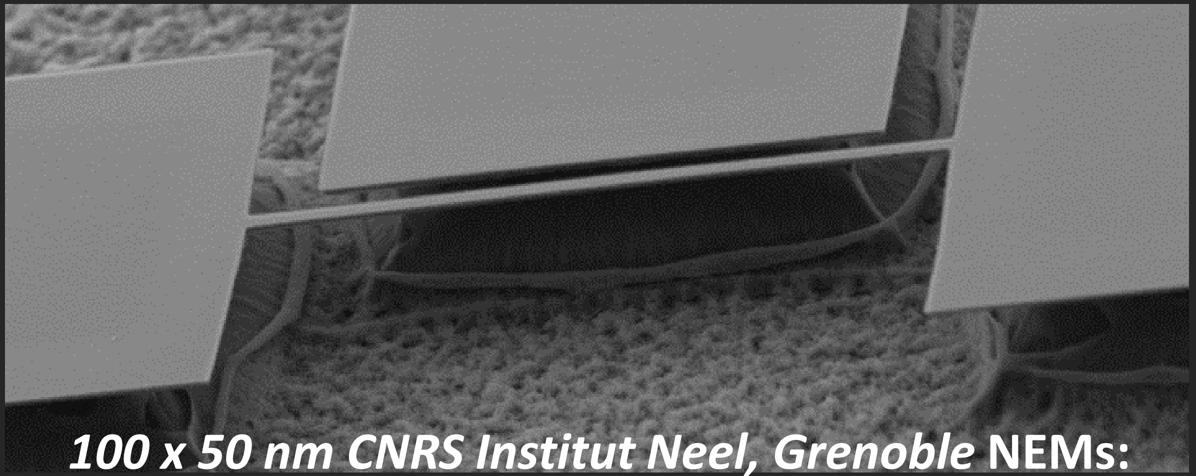




Optimising beam/wire geometry for and both He and SQUID response







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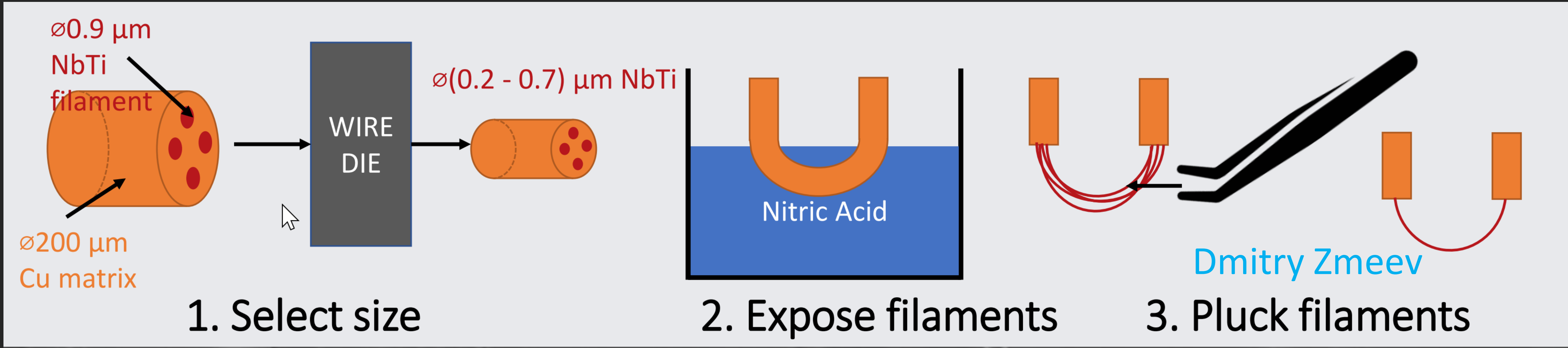
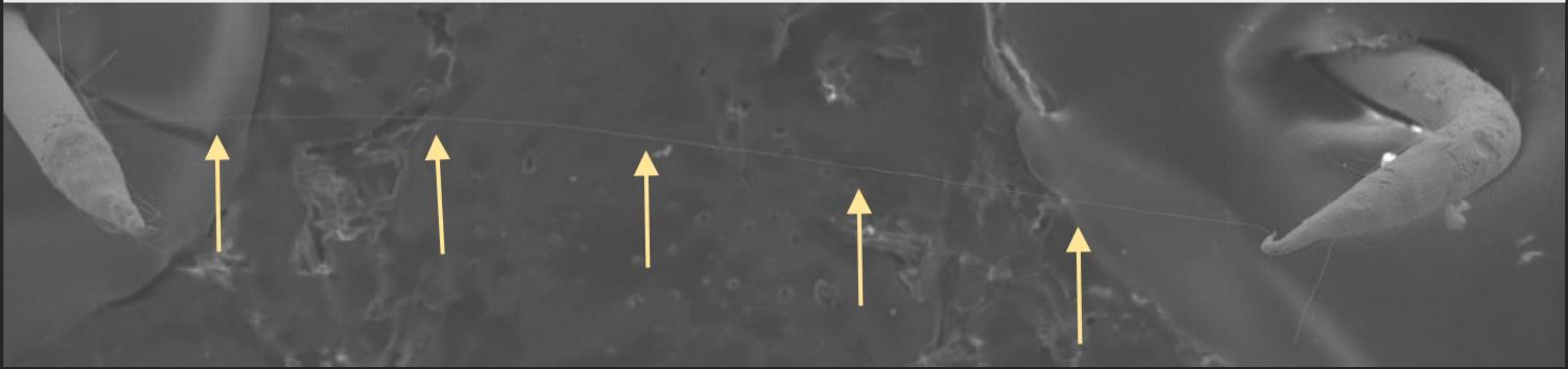
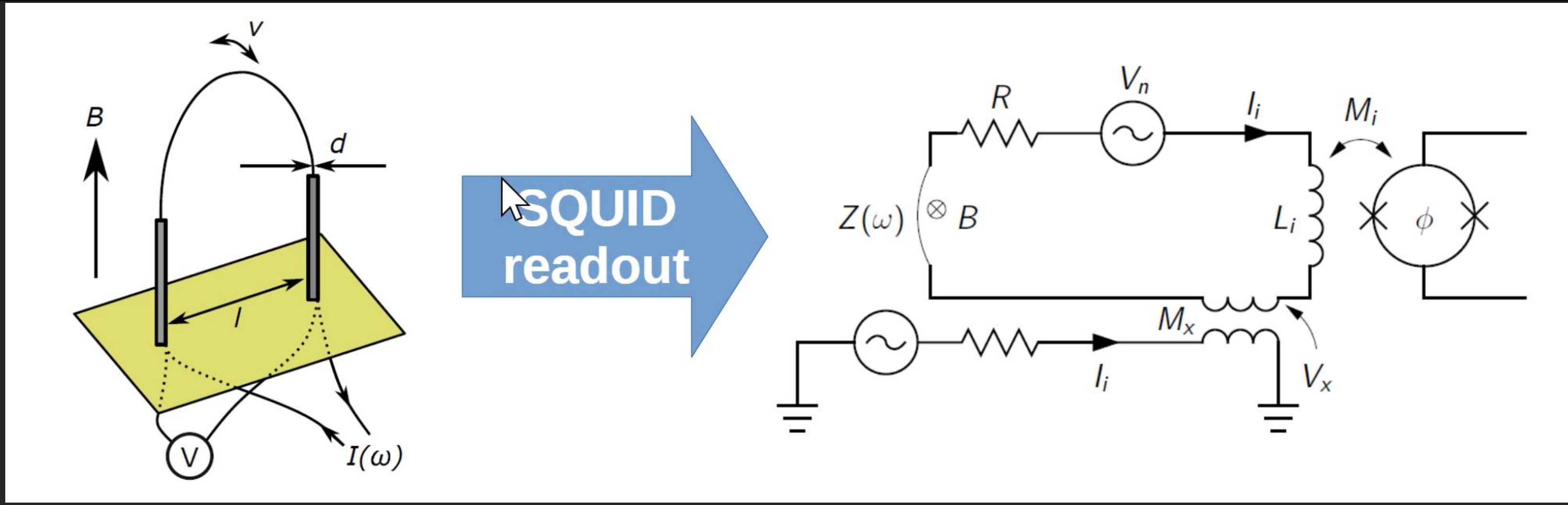




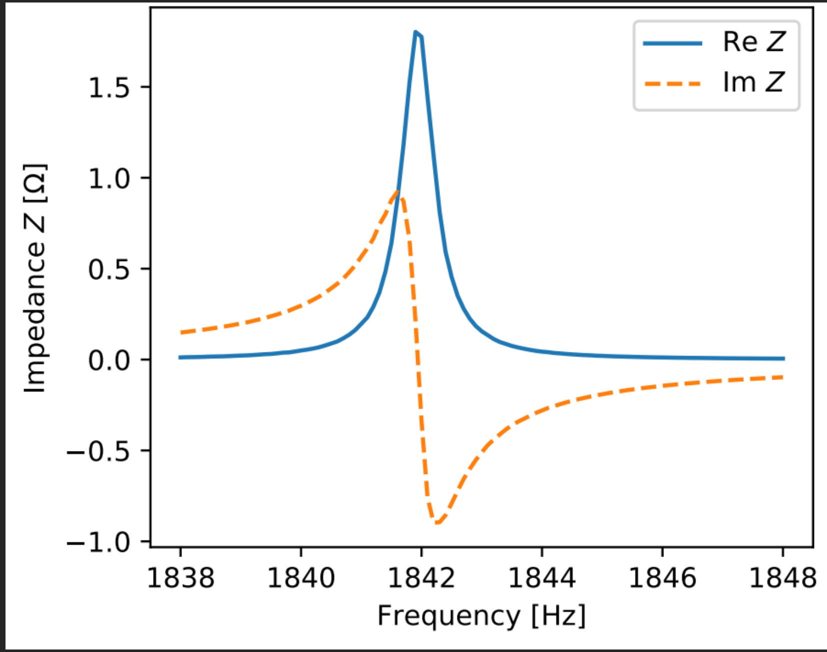
SQUID readout of nanowire

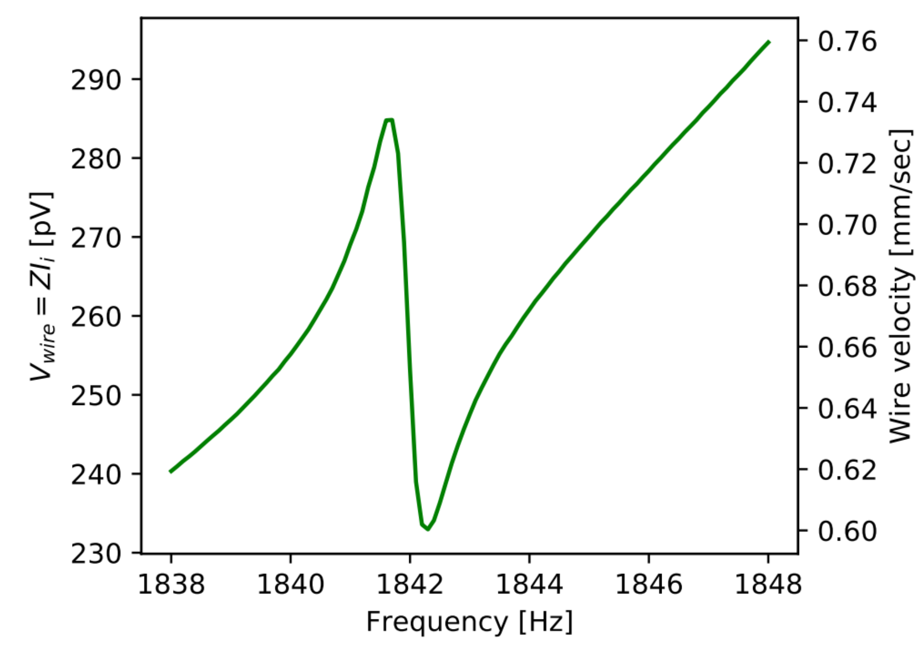


2-stage SQUID amplifier (PTB)
IEEE Trans. Appl. Supercond. 17 (2007)

Vacuum characterisation of SQUID nanowire readout. 315 nm wire, 8.5 mT, 4.2 K

$$\Delta Q = \alpha(T_0, P)\Delta(\Delta f)$$





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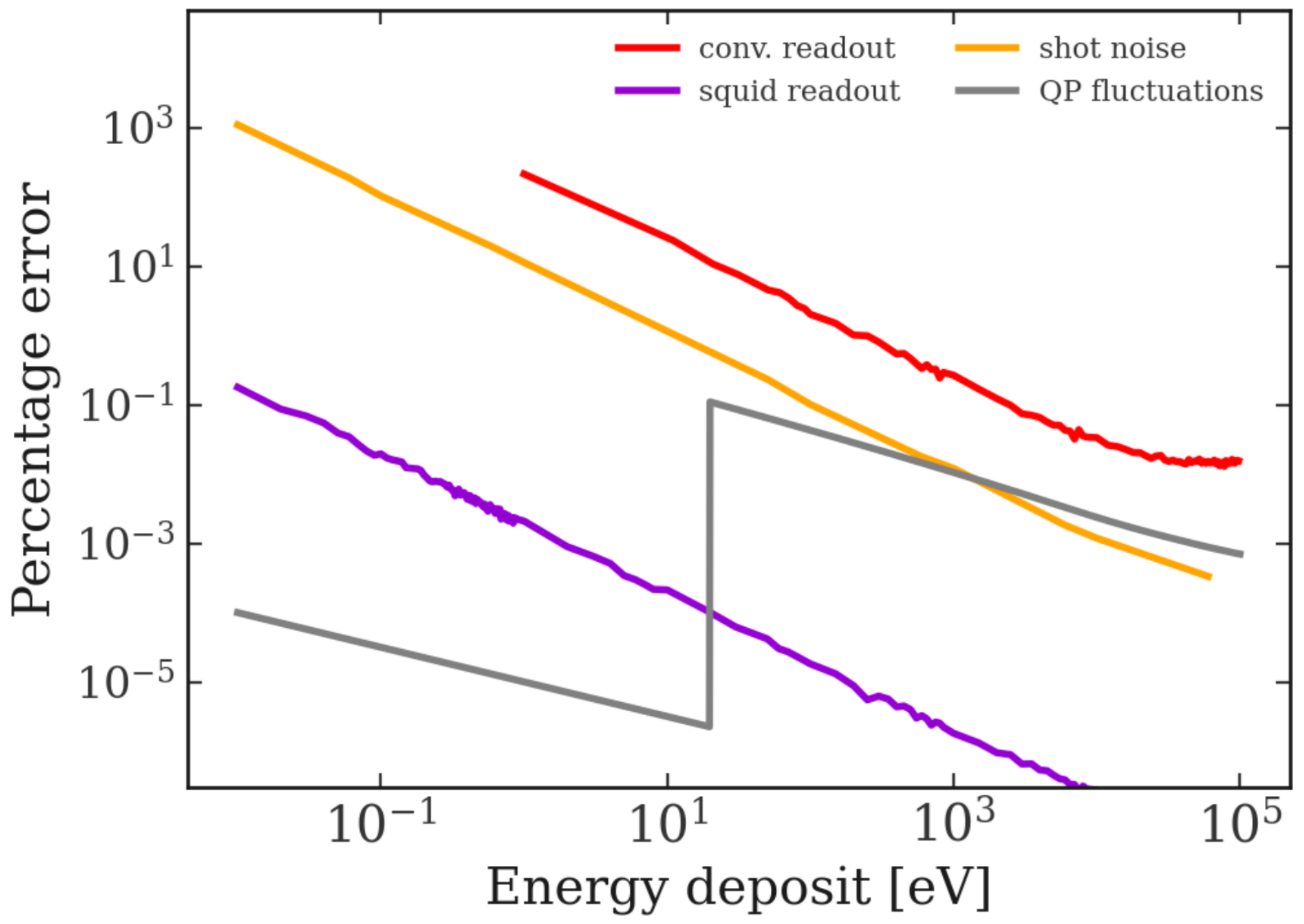


Simulation model of full system:

- Quasiparticle (QP) production fluctuations
- Readout noise – conventional vs SQUID
- Shot noise – fluctuations on incident QPs

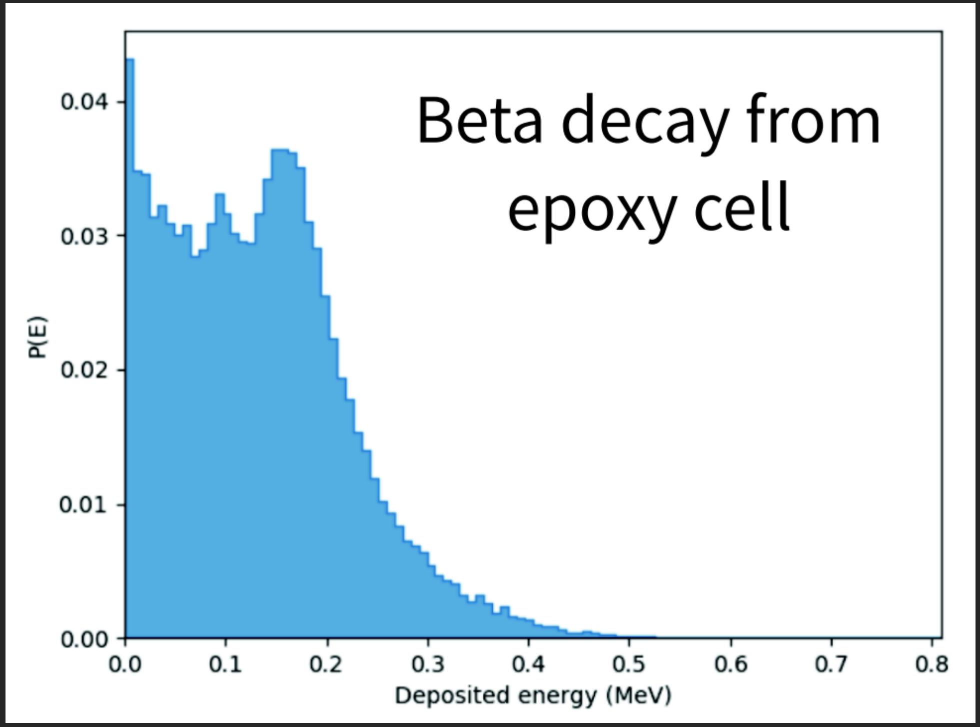
Resulting **energy thresholds**:

- Conventional readout: 39 eV
- SQUID readout: 0.71 eV

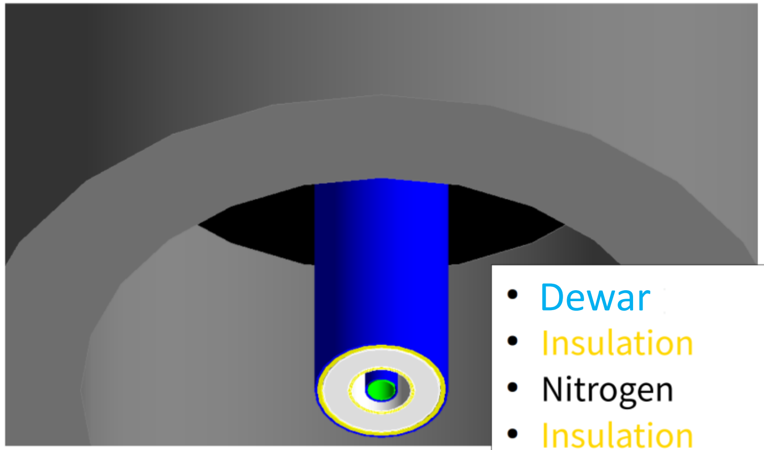
[400nm diameter wire at 0.12 T/Tc]

Simulation of decays, radiopurity screening (Boulby, database)

Material	Up ^{238}U	Lower ^{238}U	^{210}Pb	Upper ^{232}Th	Lower ^{232}Th	^{235}U	^{137}Cs	^{40}K	^{60}Co	^{54}Mn
Concrete	1.6E+05	1.5E+04	1.0E+07	7.6E+03	7.6E+03	7.2E+03	8.0E+02	4.2E+04	7.0E+02	0.0E+00
Aluminium	8.3E+03	1.5E+01	7.1E+01	3.6E+02	3.3E+02	6.0E+01	9.4E-01	3.1E+00	1.1E+00	0.0E+00
Superinsulation	6.8E+02	2.0E+02	3.9E+03	2.0E+02	2.0E+02	4.9E+00	0.0E+00	3.5E+03	4.0E+02	0.0E+00
Stainless Steel	1.6E+01	2.5E+00	8.2E+01	3.1E+00	3.9E+00	1.2E-01	2.0E+00	6.2E+00	5.2E+00	1.7E+00
Steel	1.2E+01	1.2E+01	1.2E+04	4.9E+00	4.9E+00	3.0E+00	2.0E+00	3.4E+01	3.0E+01	1.0E+00
Araldite	3.60E+00	4.80E+00	1.45E+01	3.40E+00	2.20E+00	2.60E-02	2.00E+00	2.55E+01	8.00E+00	0.00E+00
Stycast	1.05E+01	9.50E+00	1.49E+01	1.28E+01	6.20E+00	7.62E-02	2.00E+00	1.22E+02	1.00E+01	0.00E+00

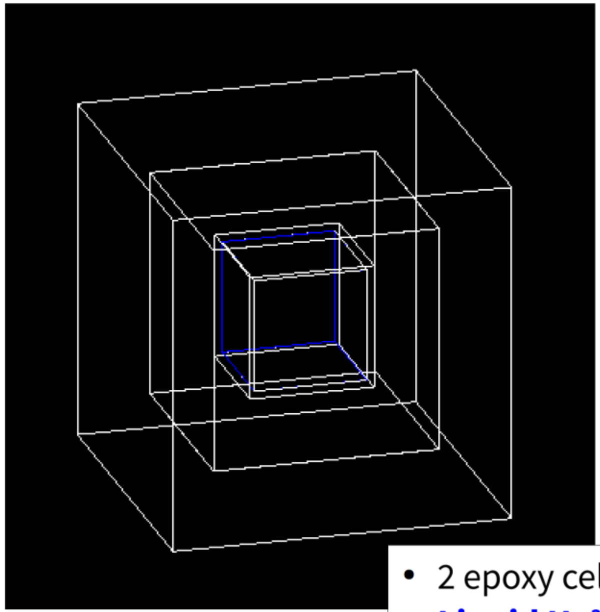


- Geant4 simulation



- Dewar
- Insulation
- Nitrogen
- Insulation
- Liquid He^4
- Vacuum can
- Radiation shield

Paolo Franchini



- 2 epoxy cells
- **Liquid He^3 cm^3**

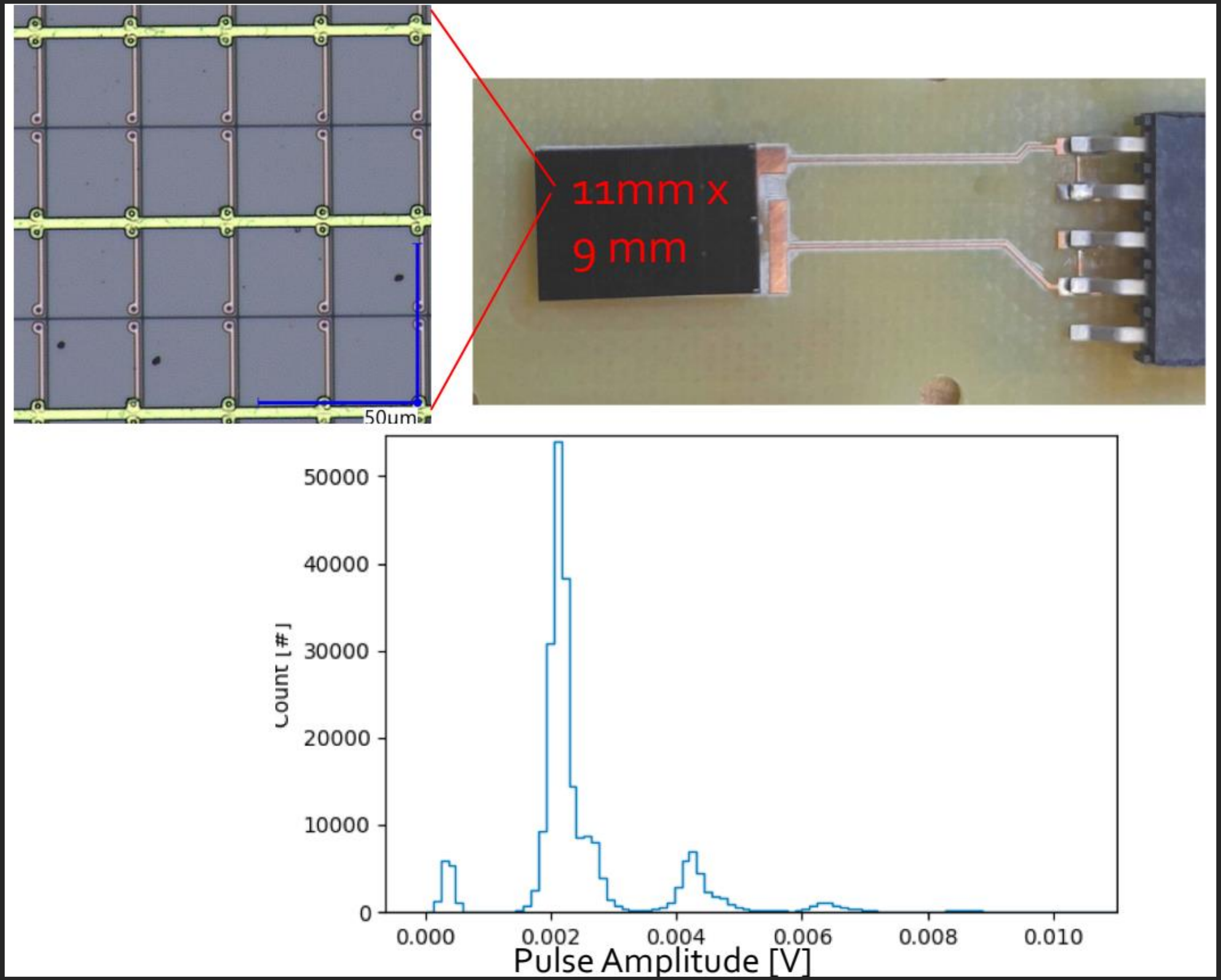
Ionisation energy channel

Test of SiPMs at 4K

- Superconducting devices:
- TES, Nanowires, mKIDs

- SiPMs (developed for Darkside) normally operated at LN2 consists of matrix of single photon avalanche diodes. High gain and single photo-electron resolution.

- In the first instance use as Veto rather than measure energy partition fraction.

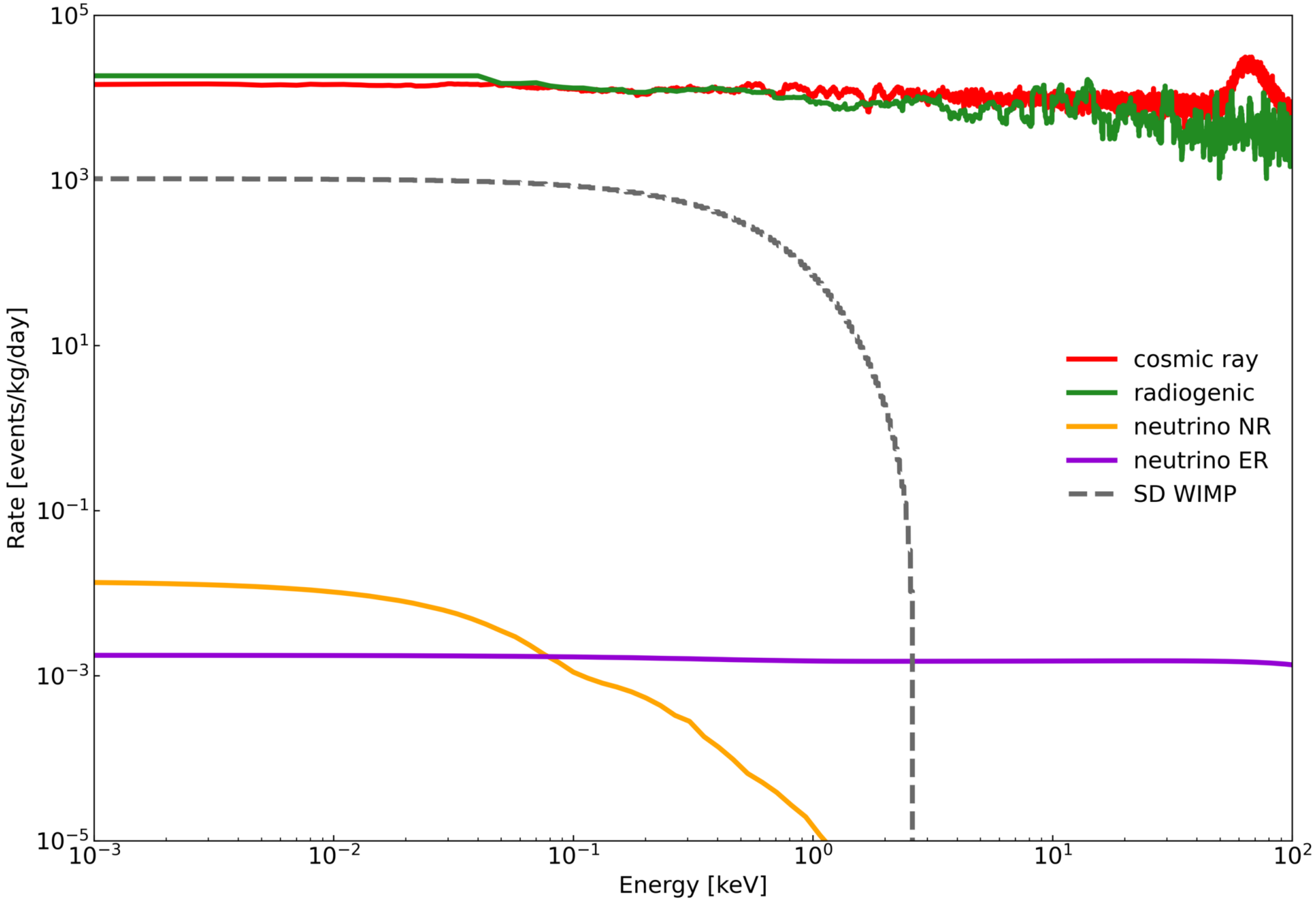


Simulation of decays, radiopurity screening (Boulby, database)

Background	Events/cell/day [all energies]
Cosmic rays	162.4
Radiogenic	32.8
PP neutrino	0.01
CN neutrino	0.0003

Cosmic ray detector around the target (90% veto efficiency).

Even better – go underground!
UKRI preliminary infrastructure bid

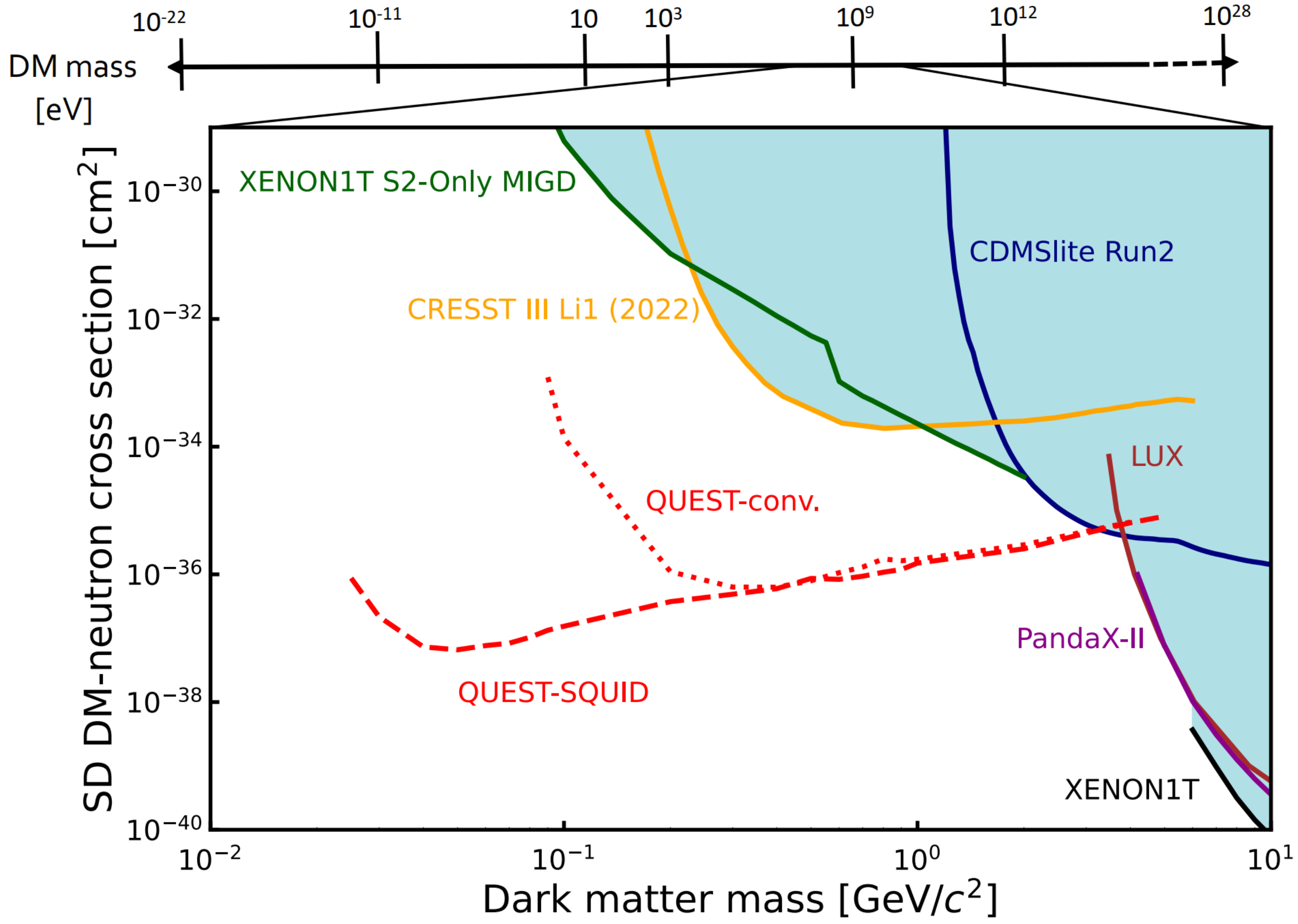


Optimising beam/wire geometry for and both He and SQUID response

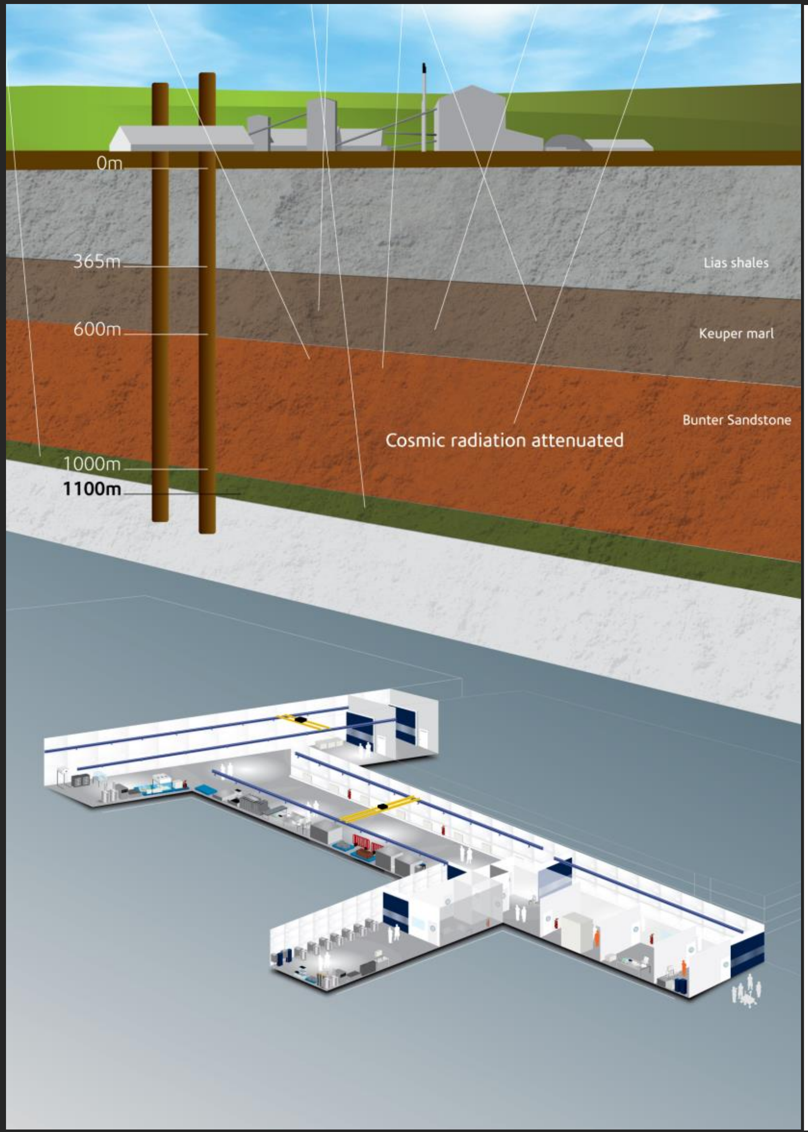
Spin dependent sensitivity projection for:

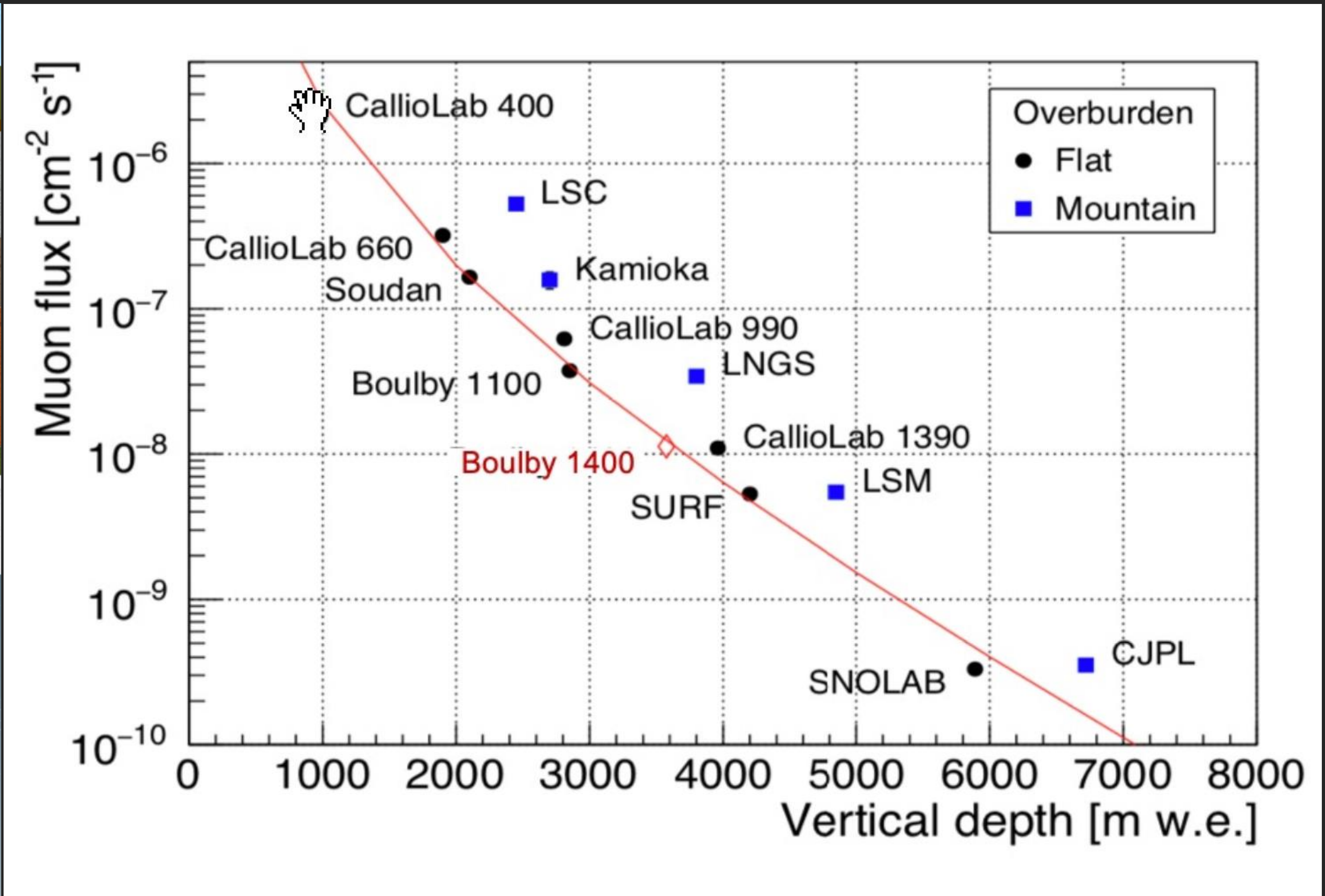
- 5 x 0.3 cm³ cells
- 6 month run with 50% duty cycle

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



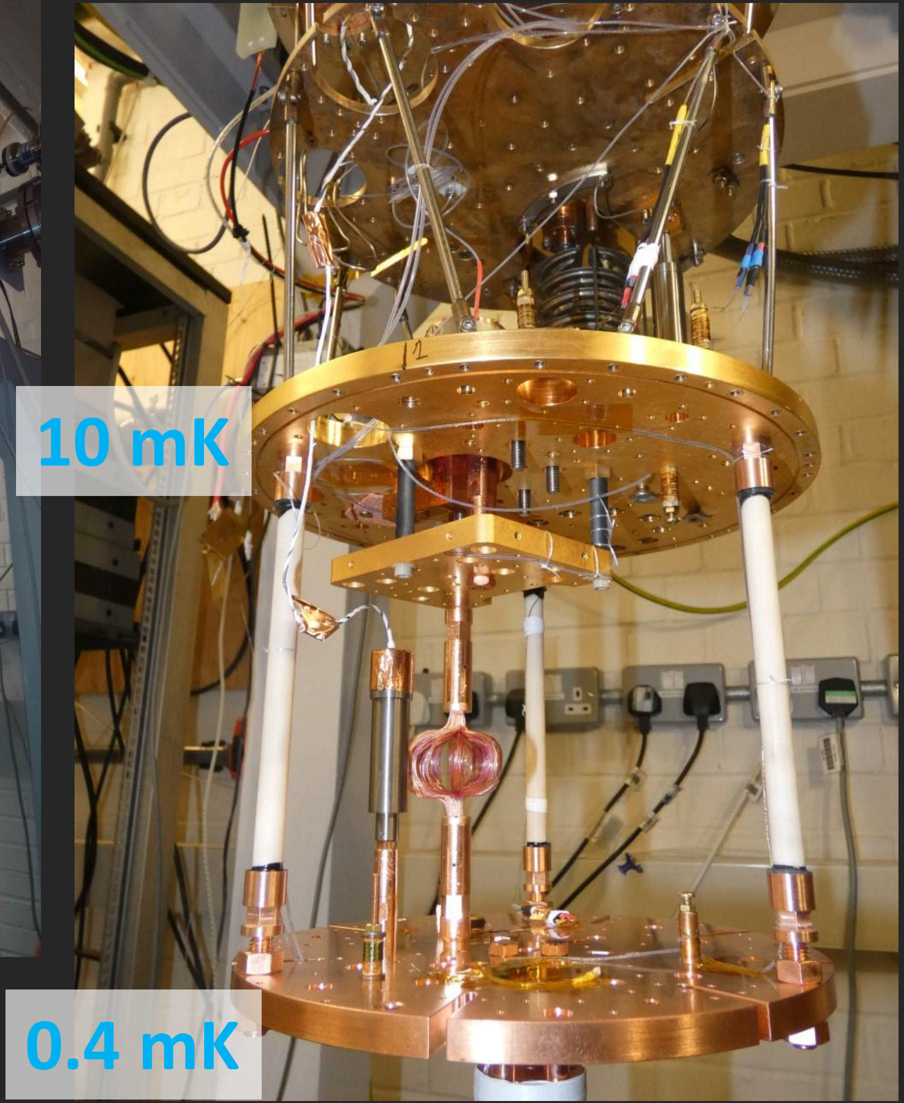
Future Prospects: ULT Underground



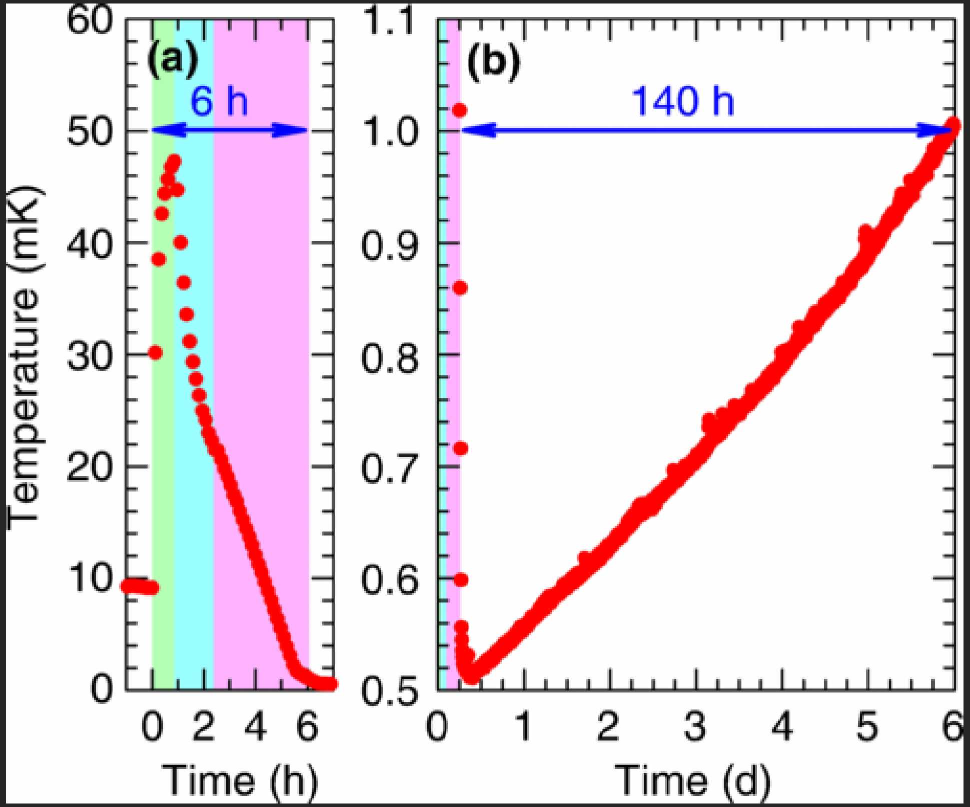


Future Prospects: ULT Underground

- Cryogen-free microkelvin platforms, rapid access to ULT

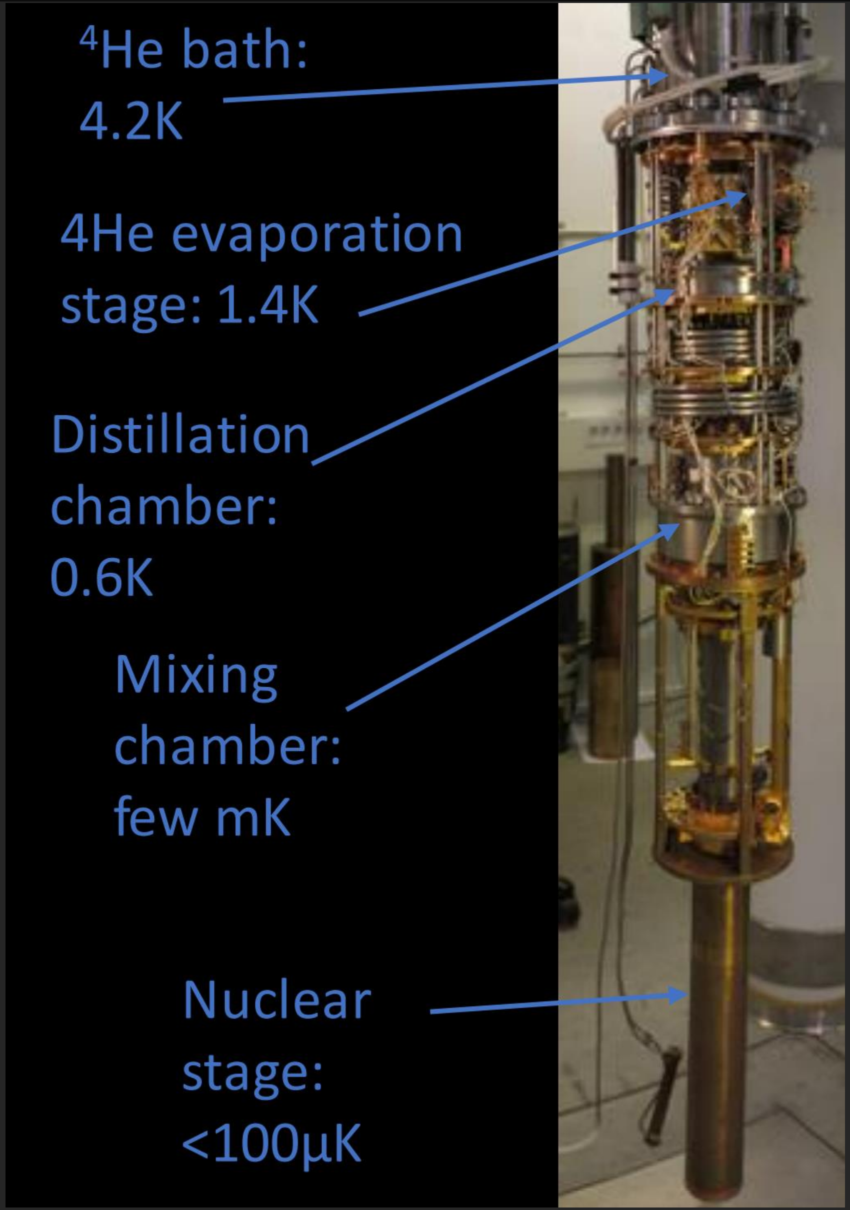


High performance cryogen-free microkelvin platform
J. Nyéki, M. Lucas, P. Knappová, L.V. Levitin, A. Casey, J. Saunders, H. van der Vliet, and A.J. Matthews, Phys. Rev. Applied **18**, L041002 **(2022)**



Summary

- QUEST-DMC designed, and are constructing an experiment for the direct detection of sub-GeV dark matter with a quantum-amplified superfluid ^3He calorimeter
- New mass regime, sensitivity to spin-dependent interactions, predict 10 eV threshold.
- 1st Experimental measurement run due to start end of 2023
- Future plans, to exploit more sensitive quantum sensors (for both QP and Ionisation channels), low radiogenic background cryostats, underground lab?

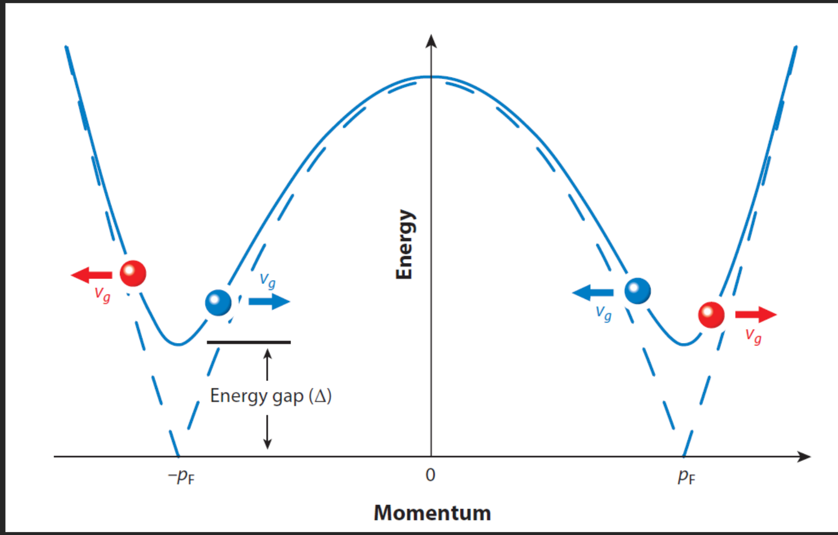


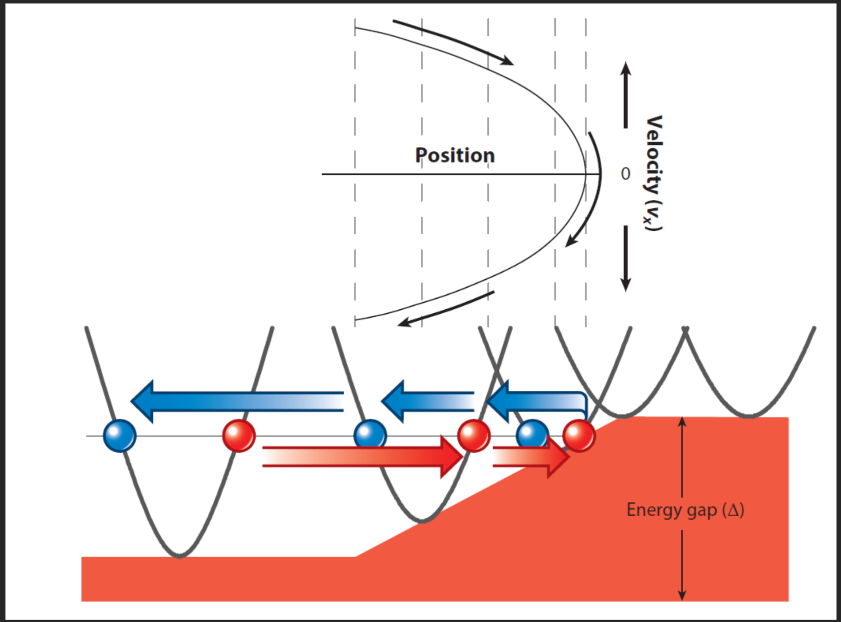
Core Team

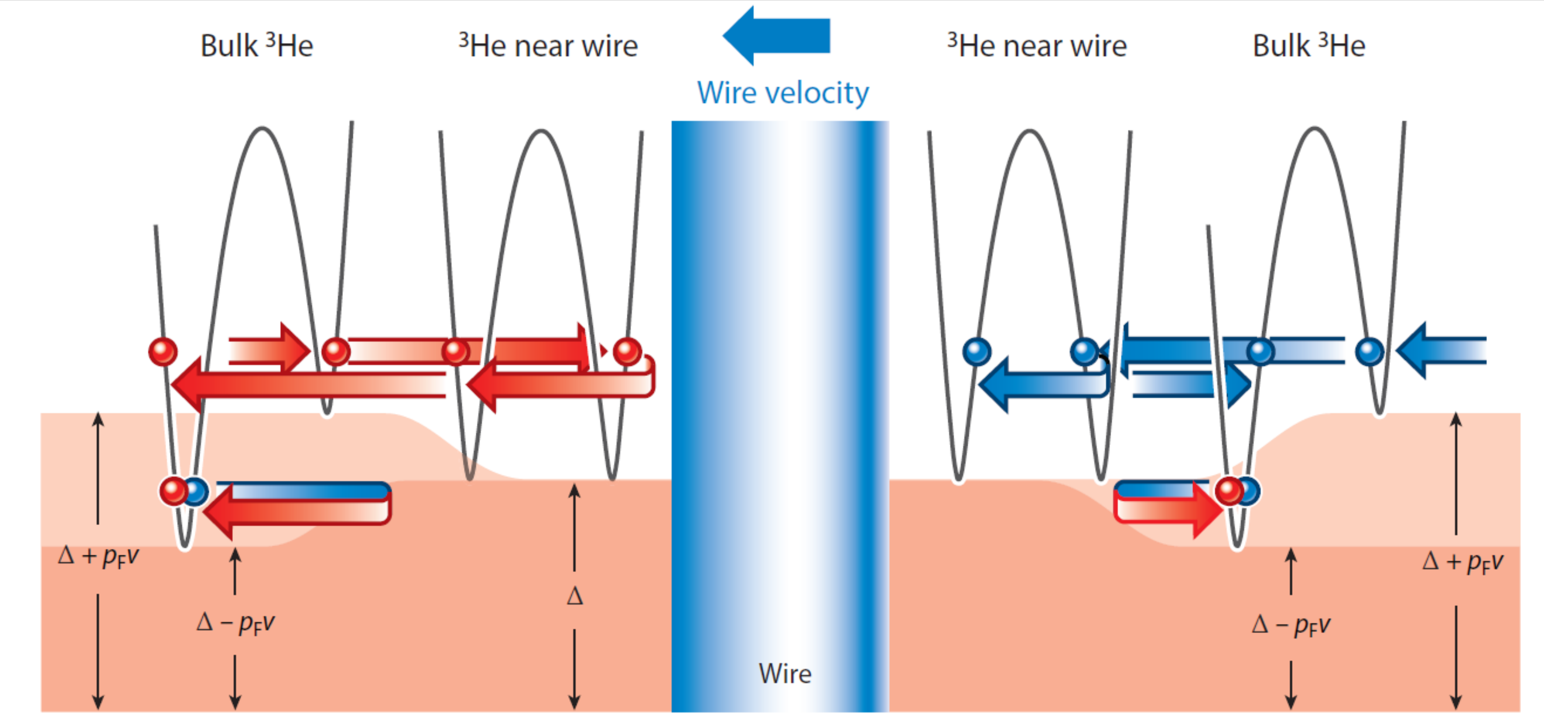
EXPERIMENTAL	
Dr. Samuli Autti	Tineke Salmon
Dr. Andrew Casey	Prof. John Saunders
Nathan Eng	Robert Smith
Dr. Paolo Franchini	Dr. Michael Thompson
Prof. Richard Haley	Dr. Viktor Tsepelin
Dr. Petri Heikkinen	Dr. Vladislav Zavyalov
Dr. Sergey Kafanov	Dr. Dmitry Zmeev
Dr. Elizabeth Leason	**THEORY**
Dr. Lev Levitin	Dr. Neda Darvishi
Prof. Jocelyn Monroe (Leading WP1)	Prof. Mark Hindmarsh (Leading WP2)
Dr. Theo Noble	Prof. Stephan Huber
Dr. Jonathan Prance	Prof. John March-Russell
Dr. Xavier Rojas	Dr. Stephen West
	Dr. Quang Zhang

Andreev Scattering

- P wave superfluid, Retroreflection, reverses velocity but not momentum (Fermi Momentum)
- When the superfluid is in motion (around beam), canting of the dispersion curve results in a strong damping term.



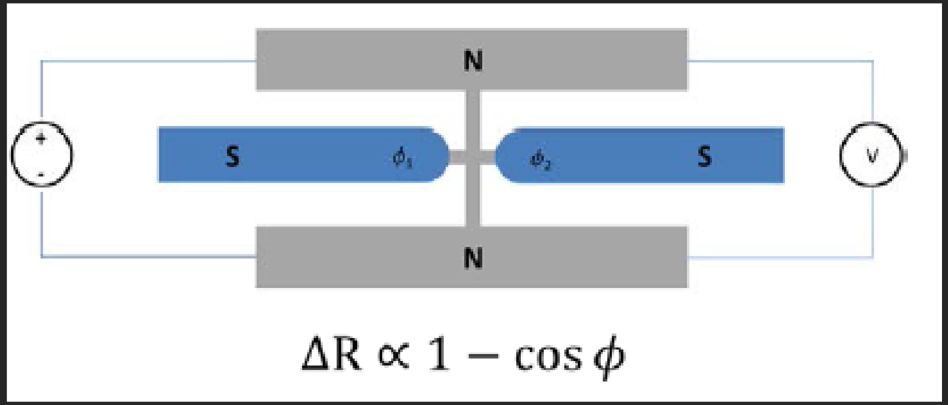


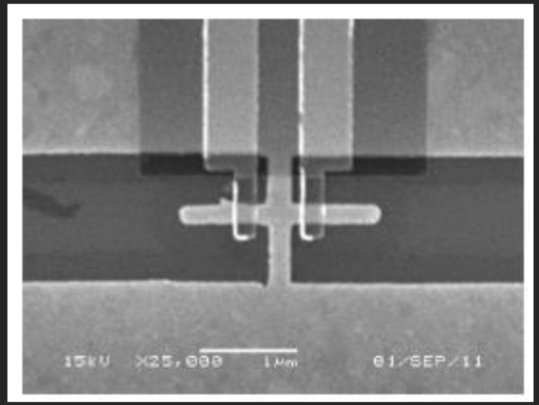


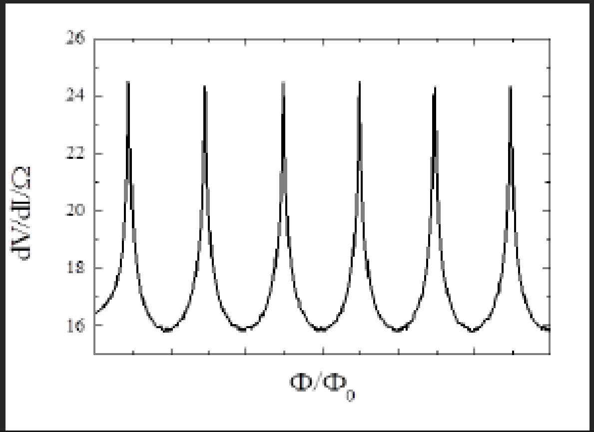
Hybrid Quantum Interference Device (HyQUID)

V T Petrashov, *et al.* Phys Rev Lett 74, 5268 (1995)

- HyQUID sensor based on Andreev interferometer with two SN contacts
- Current biased, dV/dI output is periodic with flux Φ

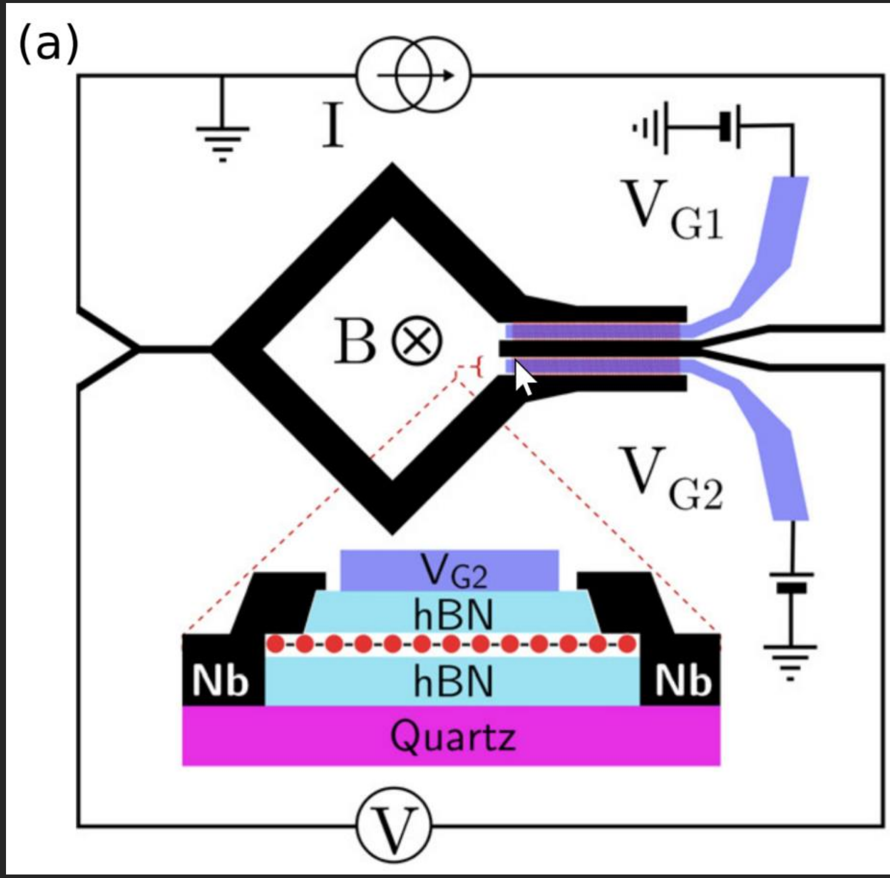






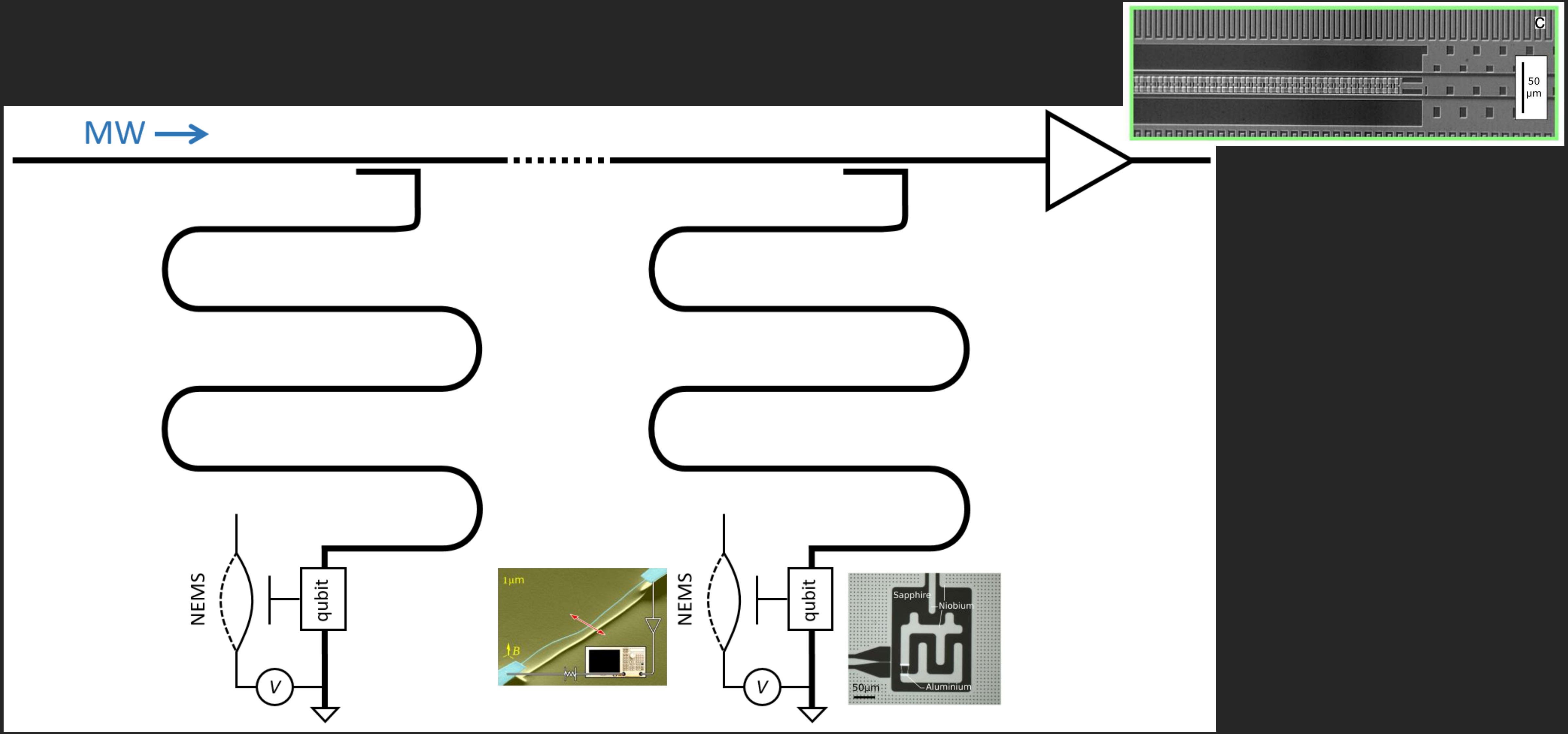
Graphene-based tunable SQUIDs

M. D. Thompson, et al. Appl. Phys. Lett. **110**, 162602 (2017)



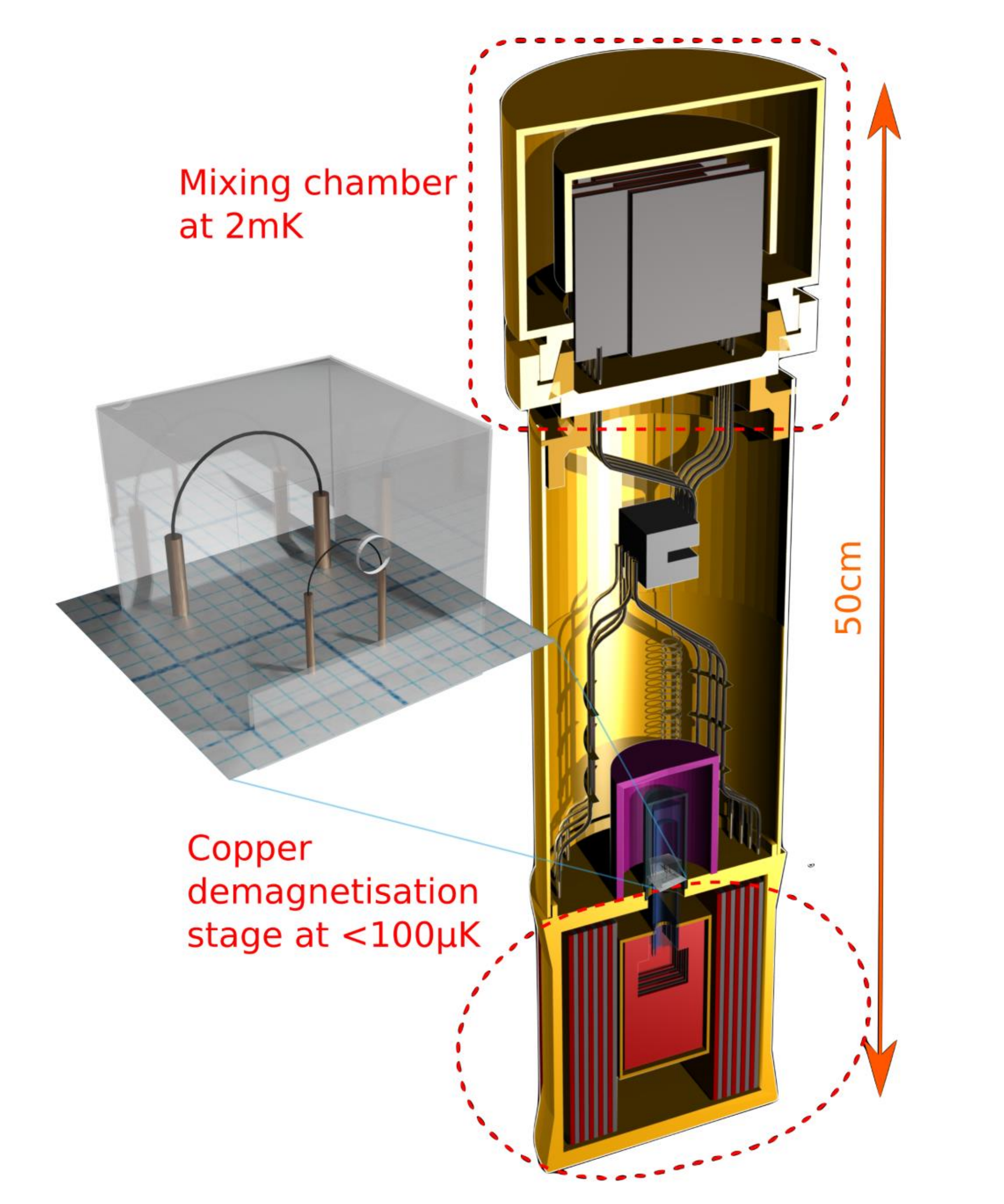
Encapsulated graphene (in red)

Using Quantum Computing architecture to address multiple bolometers.

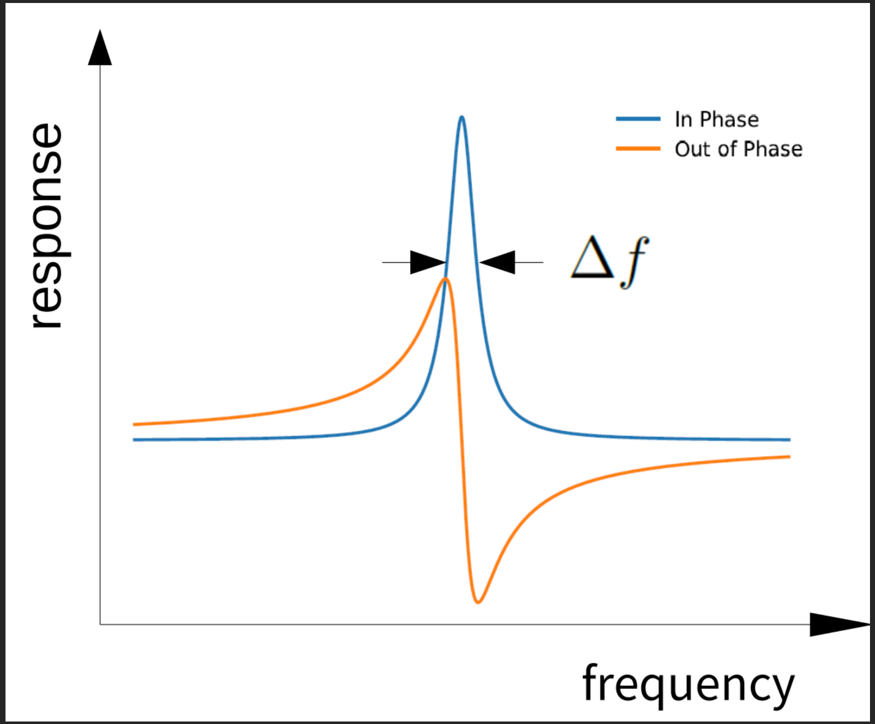


The superfluid ^{3}He calorimeter at ULT

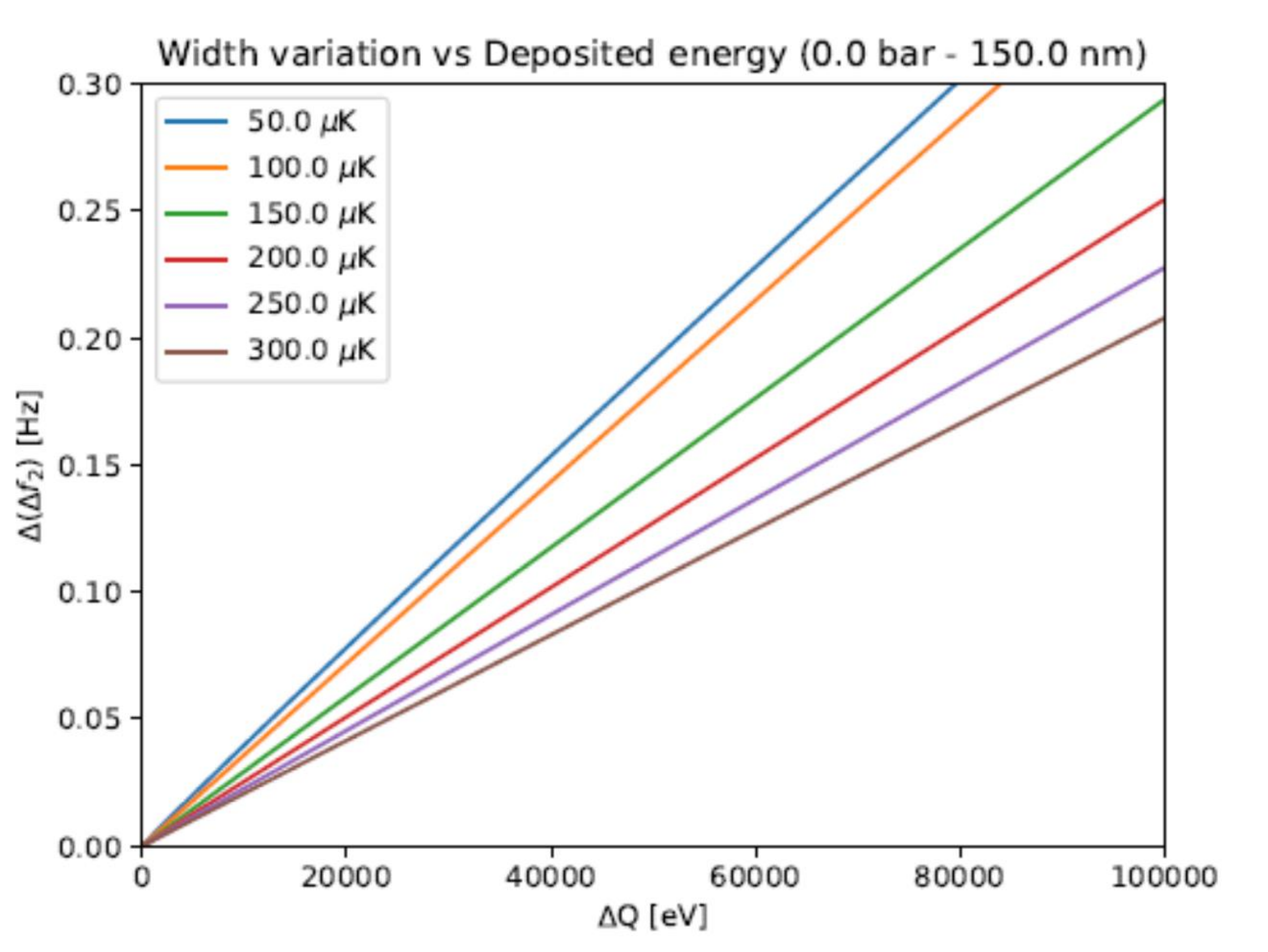
- The existing LANC ND to cool five 1 cm^3 cells, each 0.1 gm of ^{3}He, to 80 μK, instrumented with nanowires.
- Held in a box made of ultra-low radioactivity materials.
- The bath will be shielded inside a copper cryostat, cooled by a ^{4}He-filled reservoir.
- Quasiparticles generated by a scattering event propagate ballistically until they are detected by a nanowire.
- Photon detection for veto



Energy deposition as variation of the resonance width



$$\Delta Q = \alpha(T_0, P)\Delta(\Delta f)$$



- After characterisation, drive on resonance, measure amplitude change