Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

Richard Haley

January 2024

INTRO

Collaboration funded through the joint UKRI STFC/EPSRC Quantum Technologies for Fundamental Physics programme.

- People and places
- Combining quantum sensors with superfluid ^{3}He at ultralow temperatures
- WP1: Superfluid helium-3 dark matter detector
- WP2: Phase transitions in extreme matter

Implementing current quantum sensors in new 100μK ultralow temperature regime and co-designing new sensors for fundamental physics.

CORE TEAM

Royal Holloway University of London
Lancaster University
University of Sussex
University of Oxford

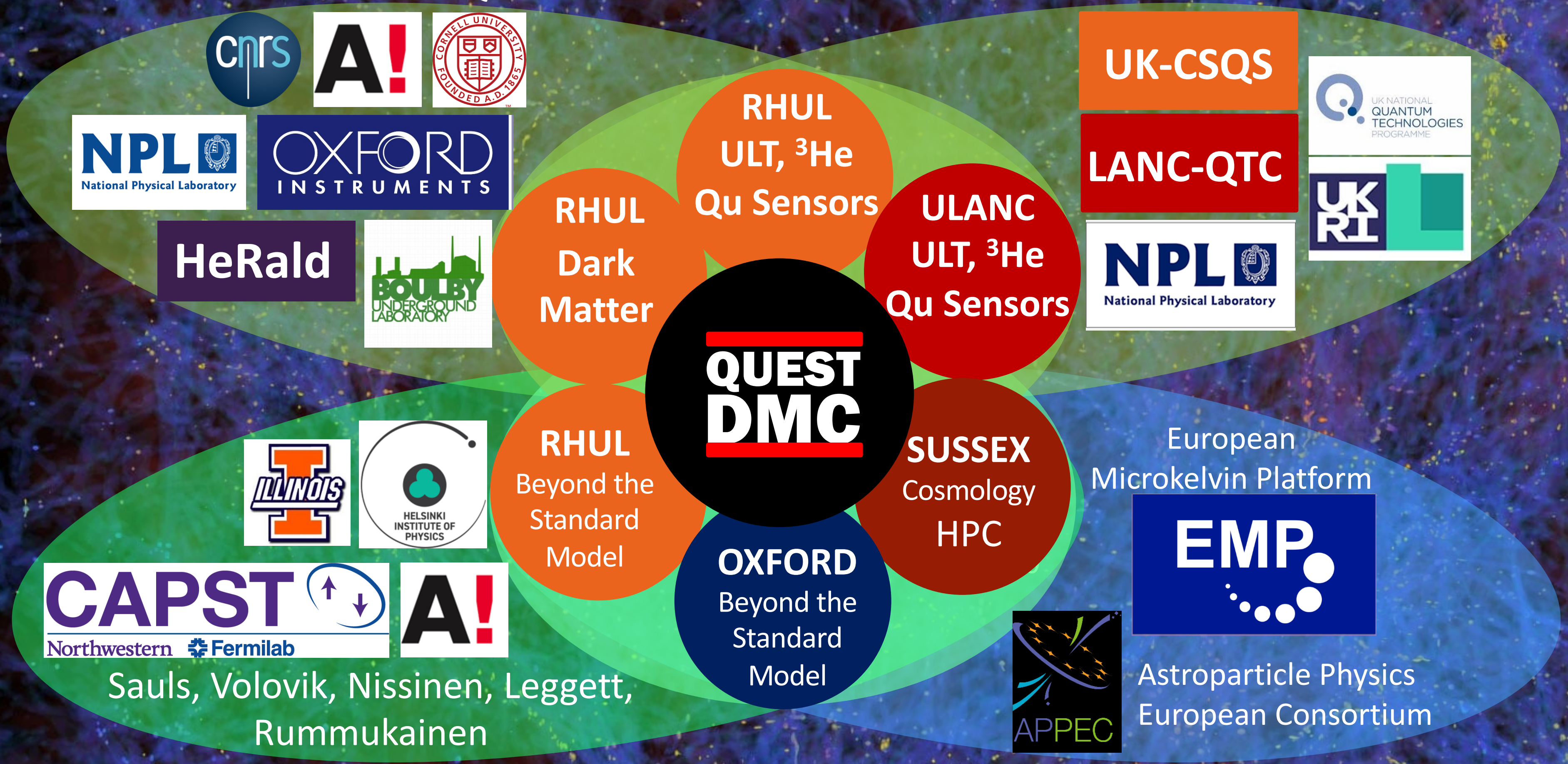
EXPERIMENTAL

- Dr. Samuli Autti
- Prof. Andrew Casey (PI)
- Nathan Eng
- Dr. Paolo Franchini
- Prof. Richard Haley (PO & INNO)
- Dr. Petri Heikkinen
- Dr. Sergey Kafanov
- Dr. Elizabeth Leason
- Dr. Lev Levitin
- Prof. Jocelyn Monroe (WP1 lead)
- Ashlea Kemp
- Dr. Adam Mayer
- Dr. Theo Noble
- Dr. Jonathan Prance
- Dr. Xavier Rojas
- Tineke Salmon
- Prof. John Saunders
- Robert Smith
- Dr. Michael Thompson
- Dr. Viktor Tsepelin
- Luke Whitehead
- Dr. Vladislav Zavyalov
- Dr. Dmitry Zmeev

THEORY

- Dr. Neda Darvishi
- Prof. Mark Hindmarsh (WP2 lead)
- Prof. Stephan Huber
- Prof. John March-Russell
- Dr. Stephen West
- Dr. Quang Zhang

QUEST–DMC *ECOSYSTEM*

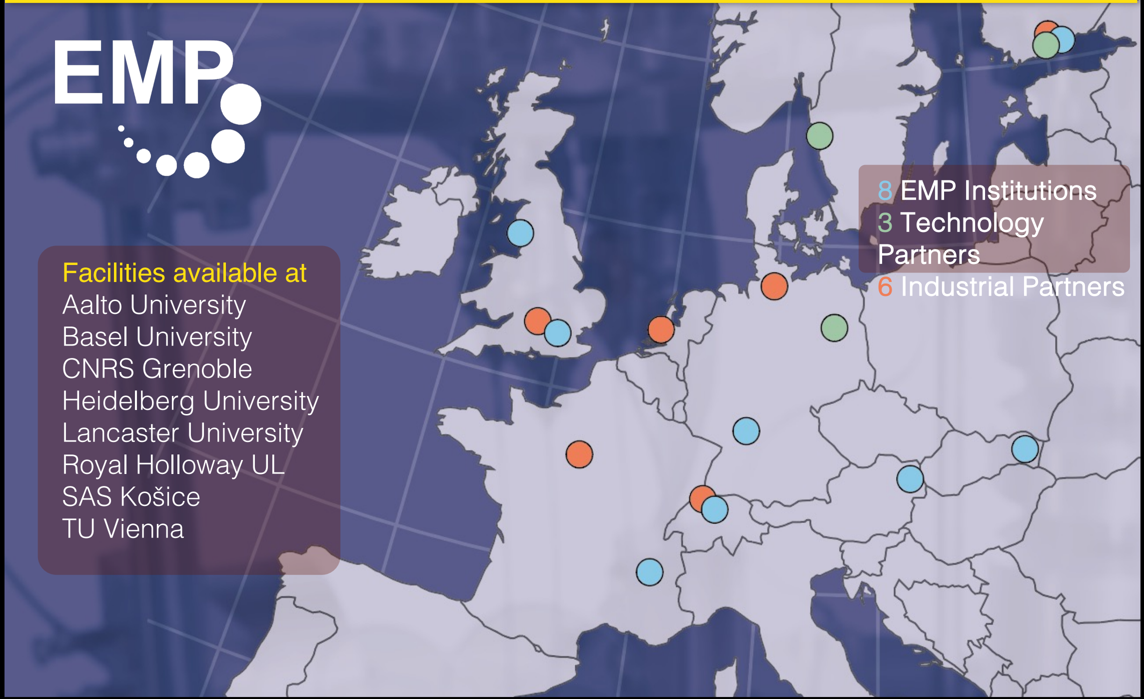


European Microkelvin Platform

A Joint European Ultralow Temperature Laboratory

EU

EMP



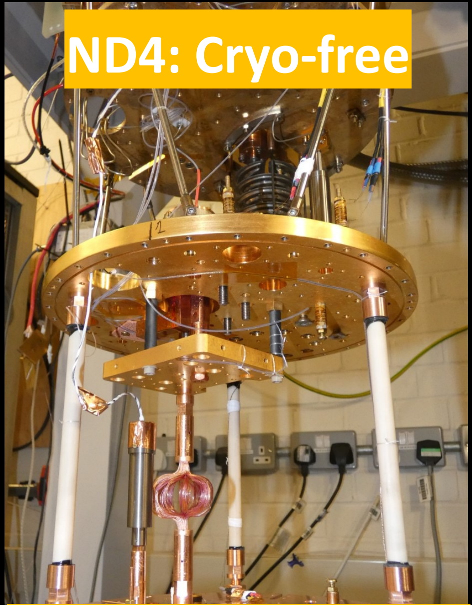
Facilities available at

Aalto University
Basel University
CNRS Grenoble
Heidelberg University
Lancaster University
Royal Holloway UL
SAS Košice
TU Vienna

FACILITIES & CAPABILITIES

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Cooling and measuring samples and sensors in the sub-mK regime by exploiting adiabatic nuclear demagnetisation.

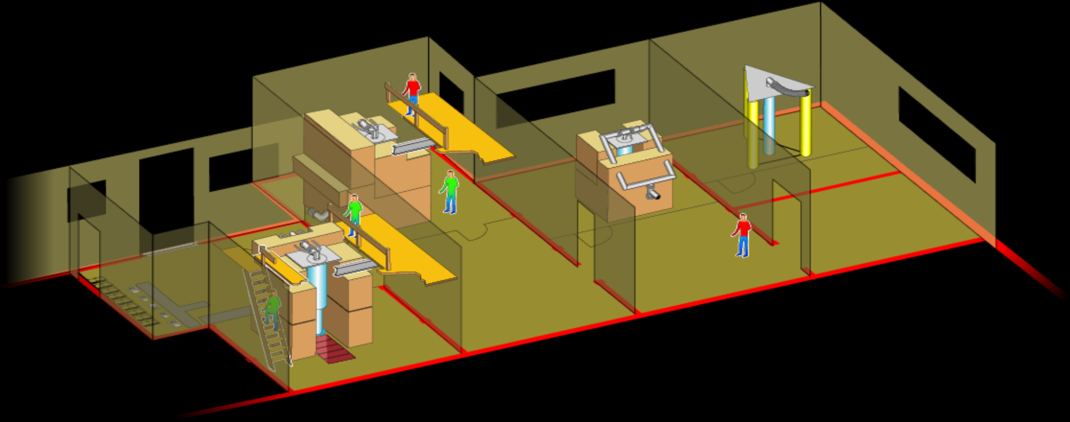


High performance cryogen-free microkelvin platform
Phys. Rev. Applied 18, L041002 (2022)

FACILITIES & CAPABILITIES

Lancaster University

- 4 custom Lancaster-style wet dilution refrigerators with 100μK helium-3 copper demag stages
- 5 commercial dry fridges
- Cryogenics and low temperature skills training suite
- Ultra-pure helium-4 supplier
- Consultancy and collaborative R&D



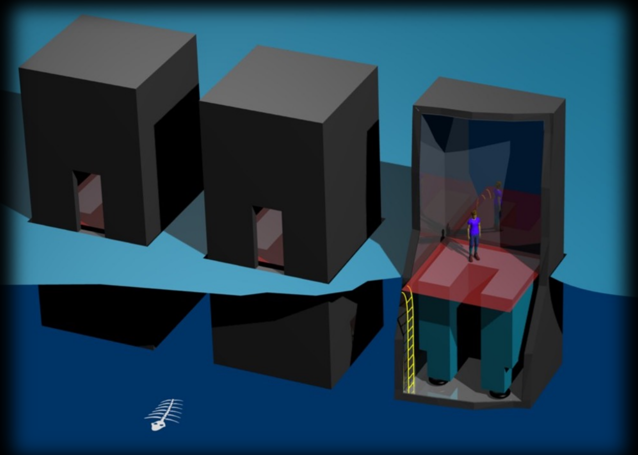
FACILITIES & CAPABILITIES

In-house nanofabrication

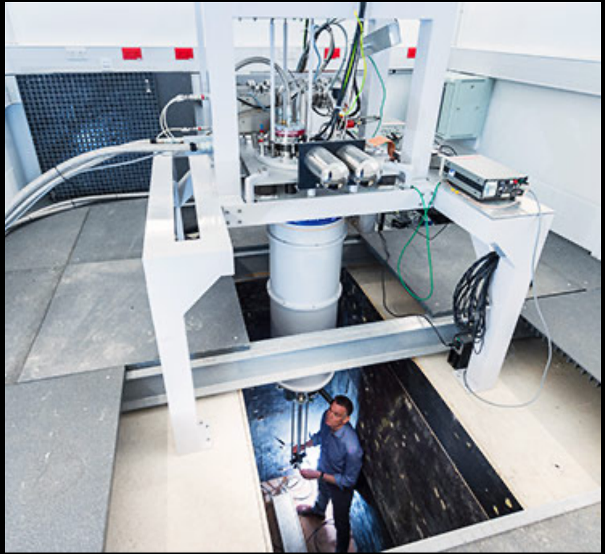
Quantum Technology Centre

Superfab
UK Centre for Superconducting and Hybrid Quantum Systems

IsoLab



Ultra-isolated low noise environment for characterisation of quantum-enhanced devices.



QUEST-DMC PROJECTS

Work Package 1

Superfluid helium-3 dark matter detector

Develop and demonstrate a quantum-amplified superfluid ^3He calorimeter to search for sub-GeV dark matter.

Lead: Jocelyn Monroe.

- Sub-mK superfluid helium-3 bolometers
- NEMS
- State-of-the-art SQUID amplifiers
- Detector know-how

arXiv:2310.11304: *QUEST-DMC superfluid ^3He detector for sub-GeV dark matter*

Work Package 2

Phase transitions in extreme matter

Investigate early universe phase transitions and analogue first-order nucleation in superfluid ^3He.

Lead: Mark Hindmarsh.

- Sub-mK helium-3 as a quantum simulator
- HPC study of statics and dynamics
- Experimental studies of nucleation problem
- Cosmological phase transition know-how

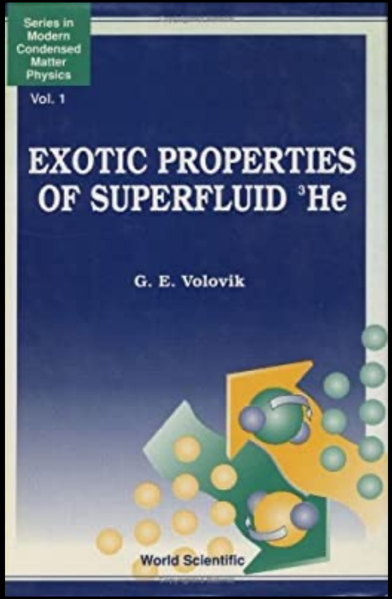
arXiv:2401.07878: *A-B transition in superfluid ^3He and cosmological phase transitions*

arXiv:2401.06079: *Nanofluidic platform for studying the first-order phase transitions in superfluid helium-3*

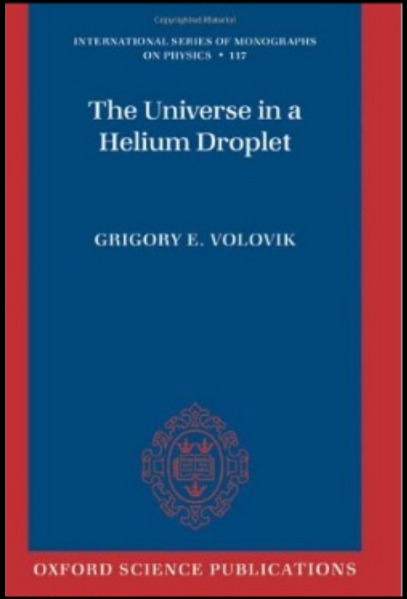
Linked through combining quantum sensors with superfluid ^3He at ultralow temperatures

SUPERFLUID HELIUM-3

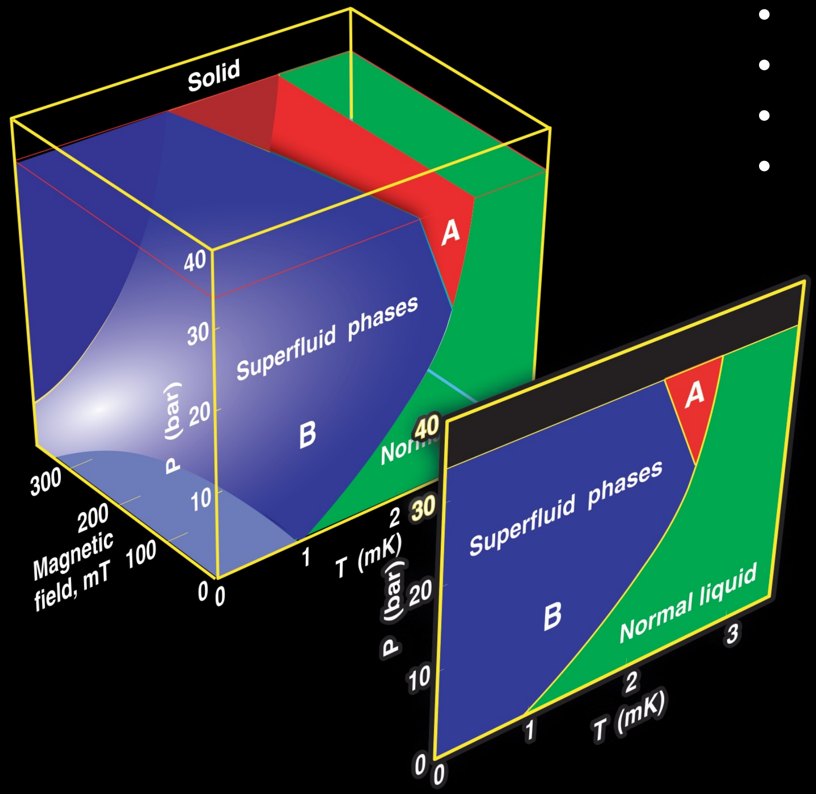
"The most complex system for which we already have the Theory of Everything"



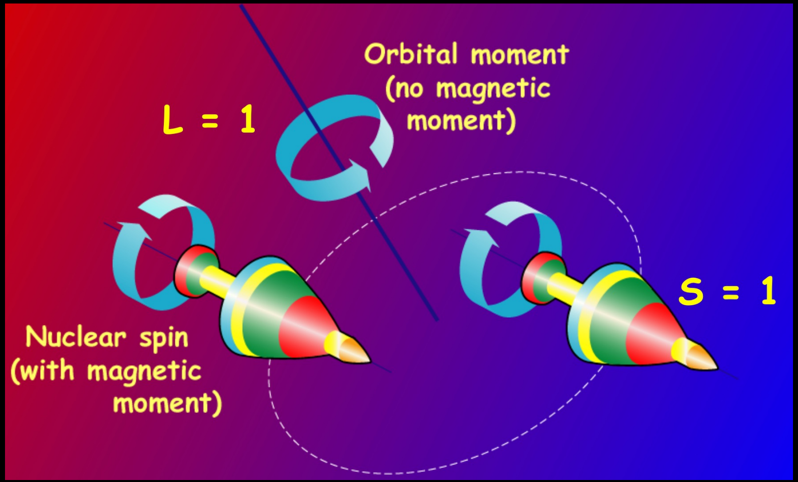
G.E. Volovik



SUPERFLUID HELIUM-3

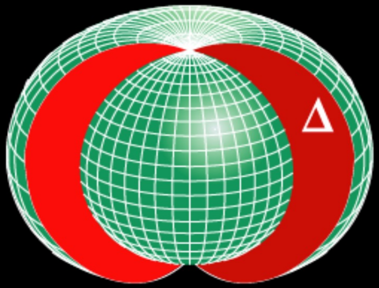


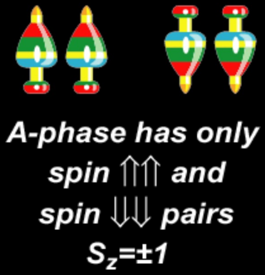
- BCS condensate – p wave superfluid
- Cooper pairs with L=S=1
- 18 component order order parameter (L_z, S_z = -1, 0, 1)
- Coherence length ~50nm



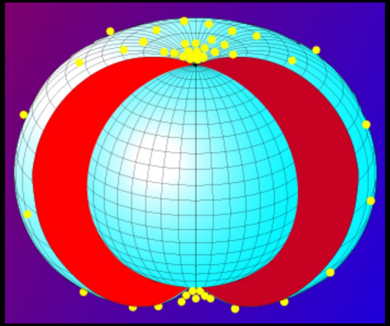
SUPERFLUID HELIUM-3

A:





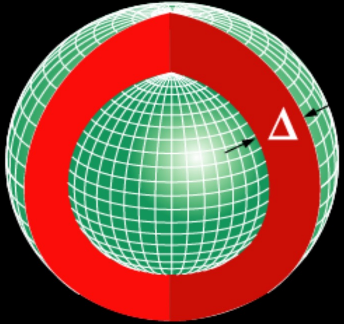
Equal spin-paired
Axial state
Anisotropic
Textures



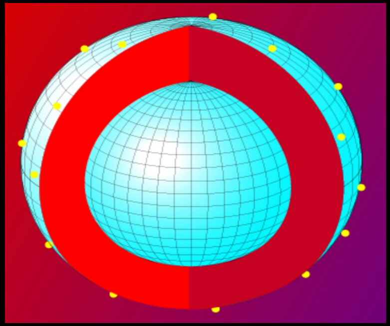
Energy gap/
Order parameter

Quasiparticles
Broken Cooper pairs

B:

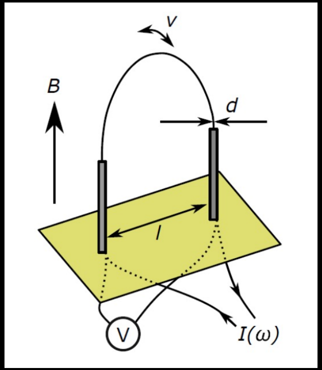


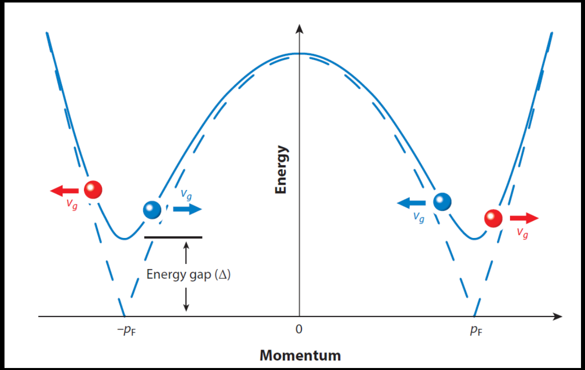
“pseudo-isotropic”

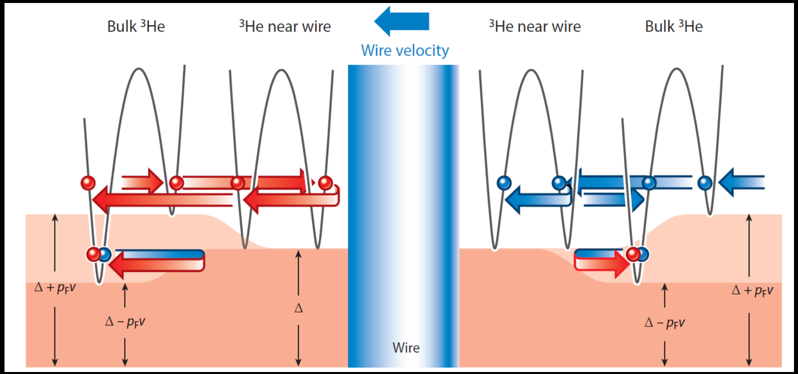


Energy Δ ~ 10^{-7} eV
Mean free path >> container size

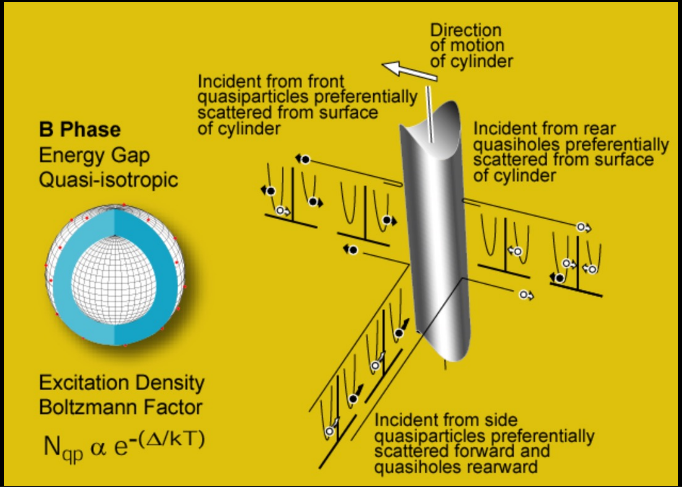
SUPERFLUID HELIUM-3



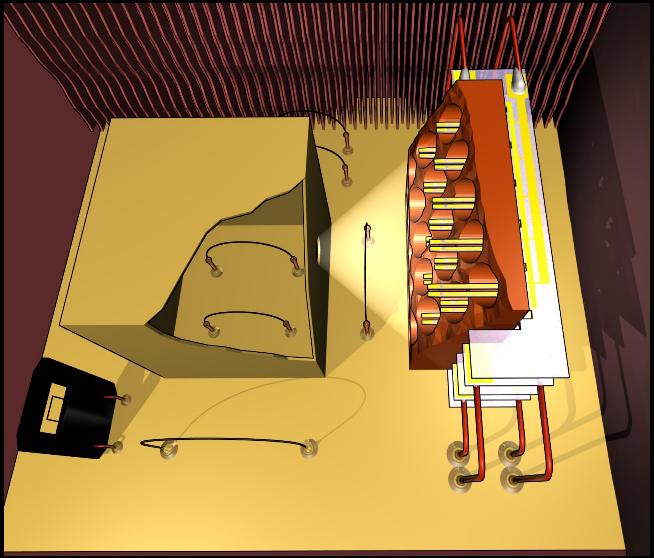


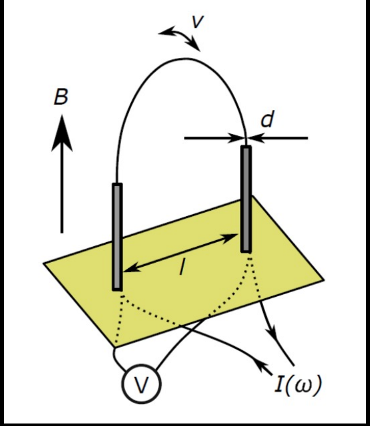


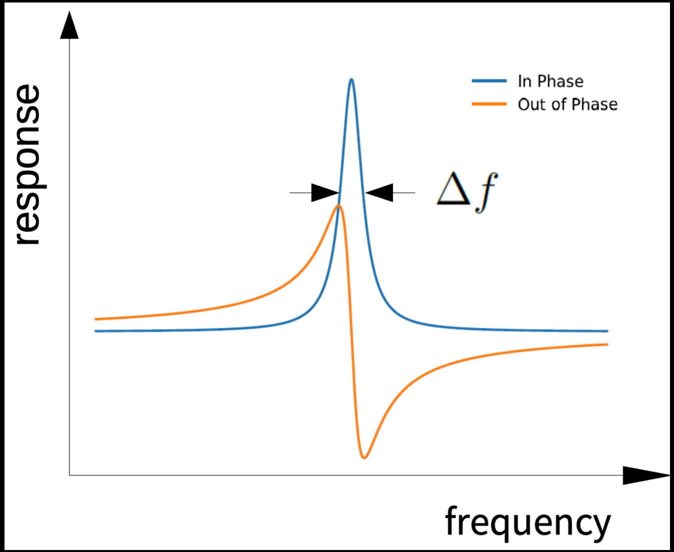
- Probe damping of moving mechanical objects
- Fermionic dispersion curves canted by motion
- Quasiparticles (and holes) interact with objects and flow field
- Andreev scattering enhances quasiparticle damping
- Retroreflection reverses velocity but not momentum p_F



QUASIPARTICLE SENSING







- Many types of probe
- Damping from resonance width or peak height
- Relate damping to Boltzmann quasiparticle density

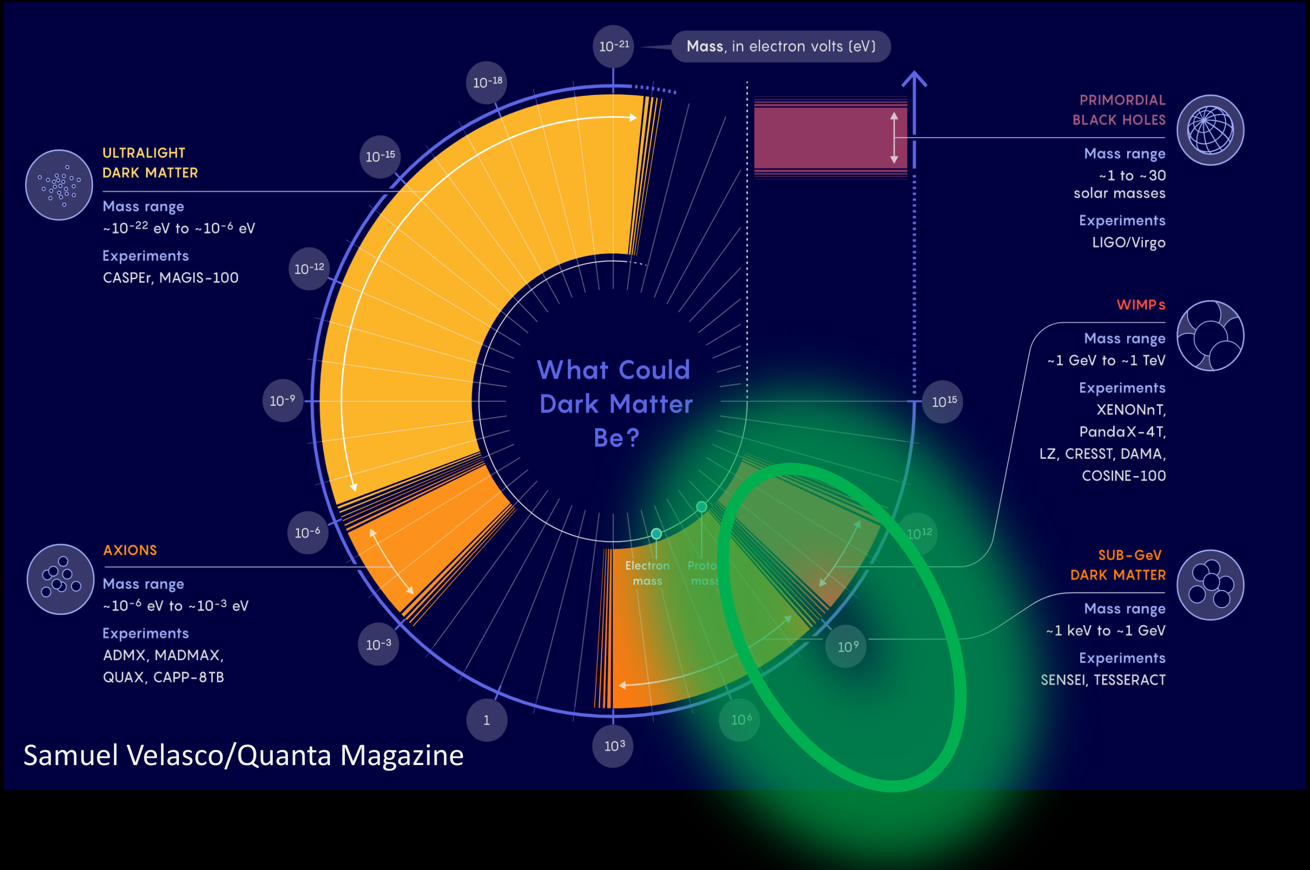
WP1 DETECTOR CONCEPT

Sub-GeV/c^2 mass range:

- Widens the search
- Masses in nucleon range

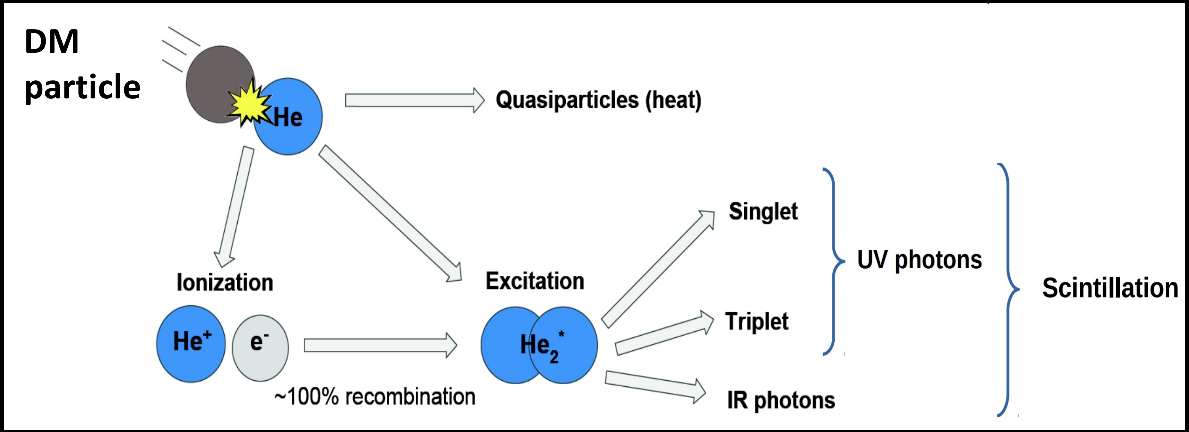
Helium-3

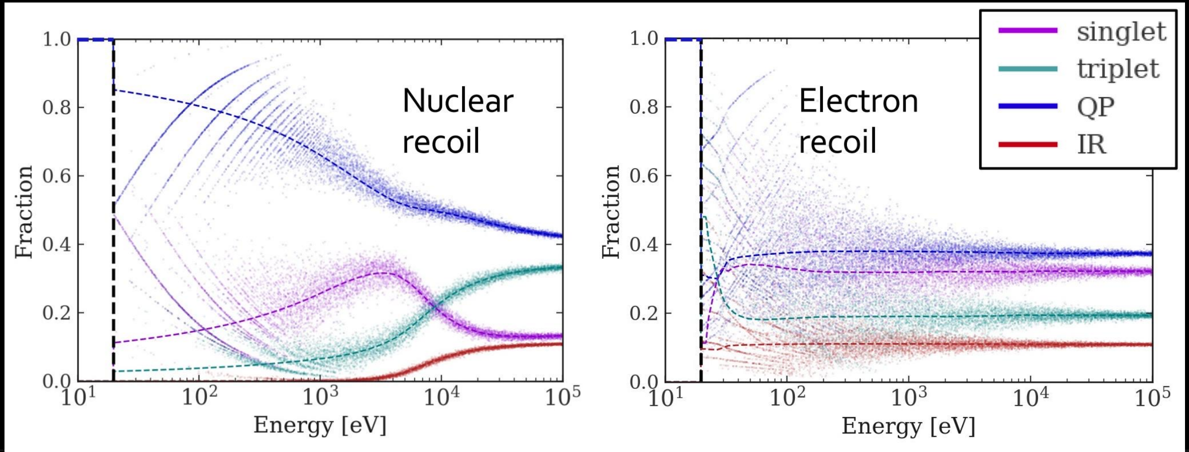
- Light mass
- Spin



Samuel Velasco/Quanta Magazine

WP1 DETECTOR CONCEPT





Energy partition:

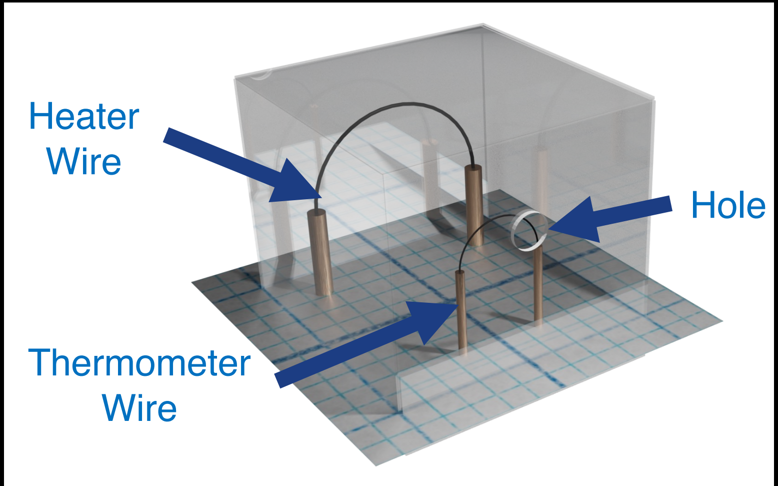
- Nuclear recoil
- Electron recoil

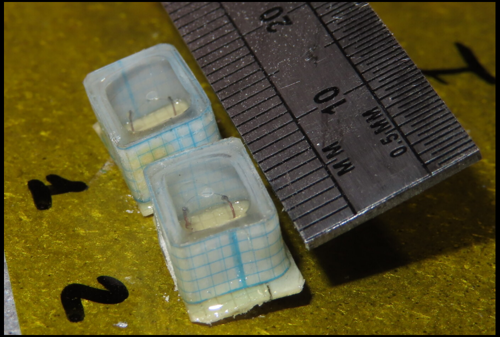
Detect:

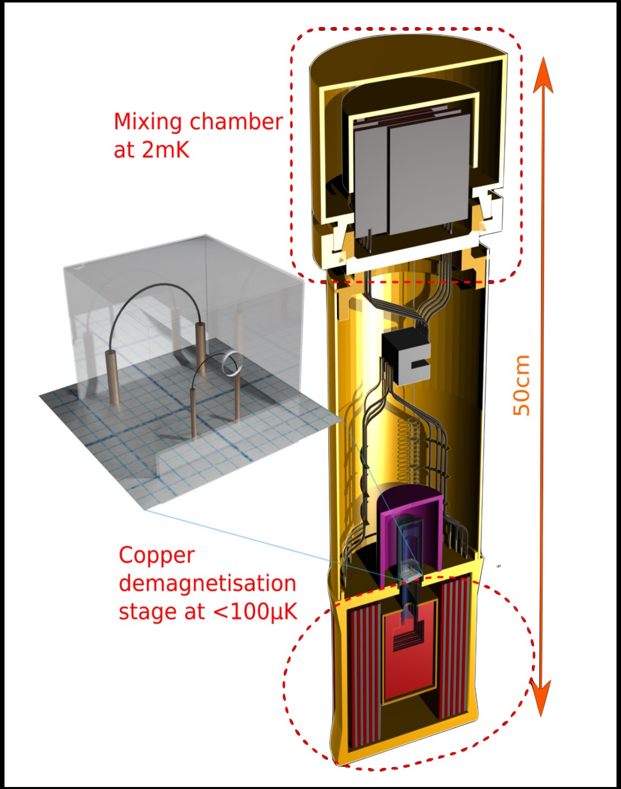
- Heat - quasiparticles
- Scintillation photons (ionization threshold ~20 eV)

Target energy threshold <10eV

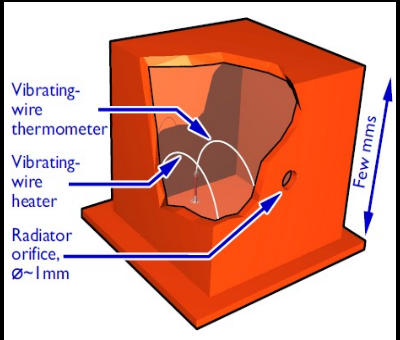
BOLOMETER & OPERATION



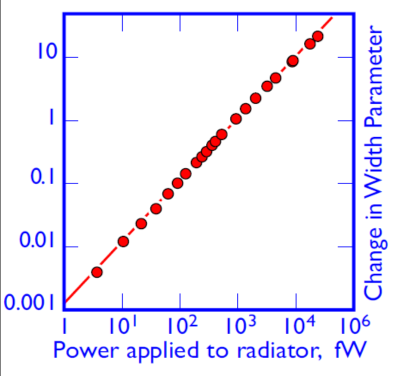




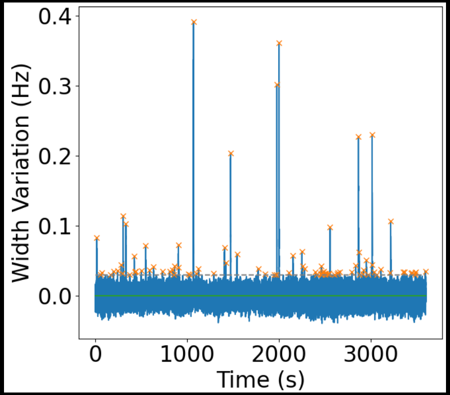
BOLOMETER & OPERATION



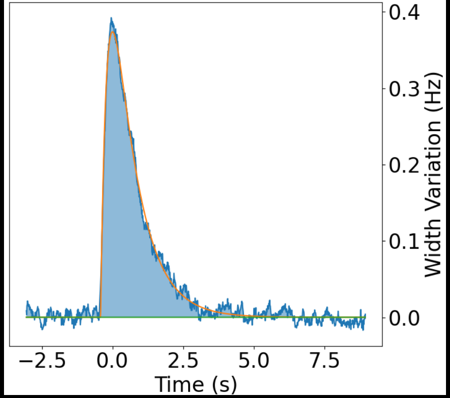
Bolometer cut-away.
Damping width calibration.



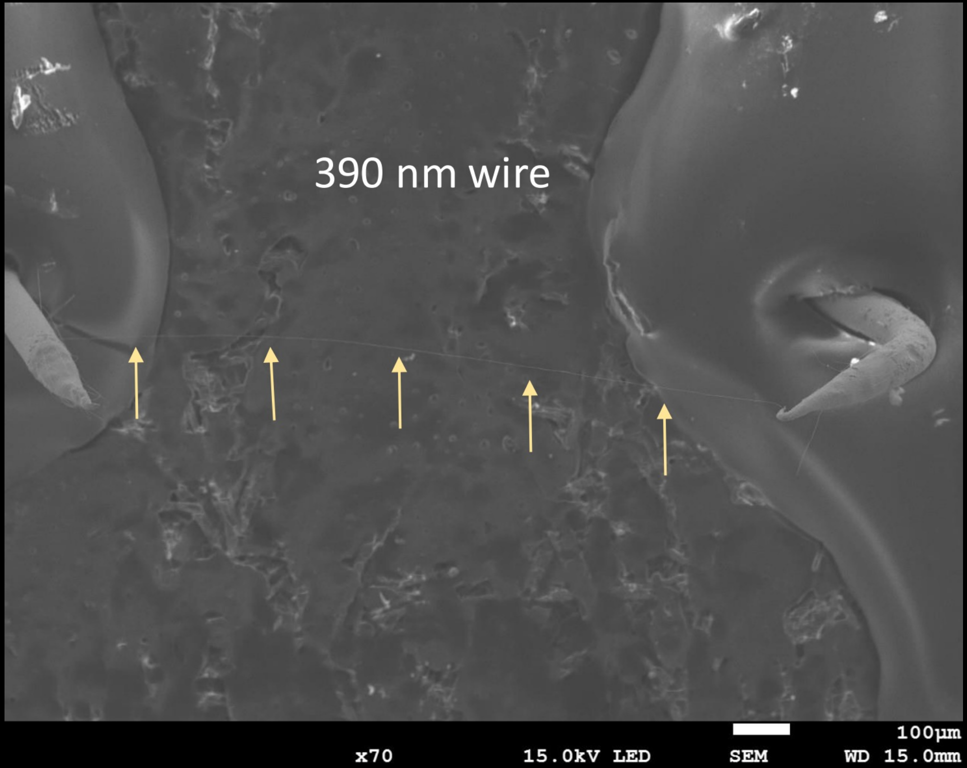
- Direct sensing of quasiparticles (no Kapitza)
- Heater and thermometer wires for calibration
- Radiator hole and wire ring-down determine time constants
- Optimise wire size and readout to lower energy threshold

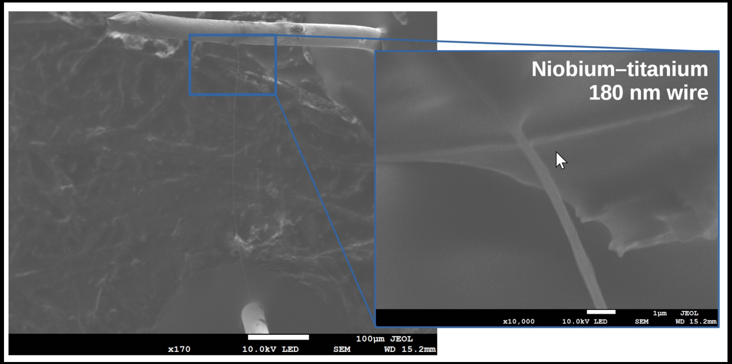


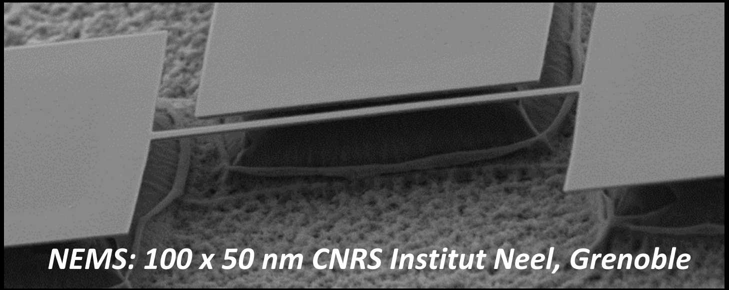
Typical signal trace,
peak detection and fitting.



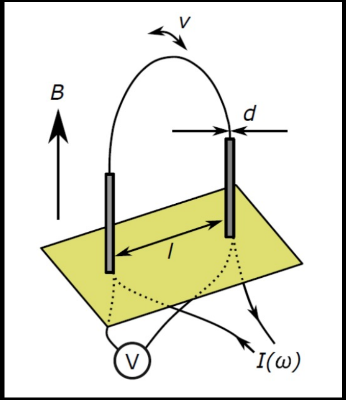
Wire/beam size and geometry



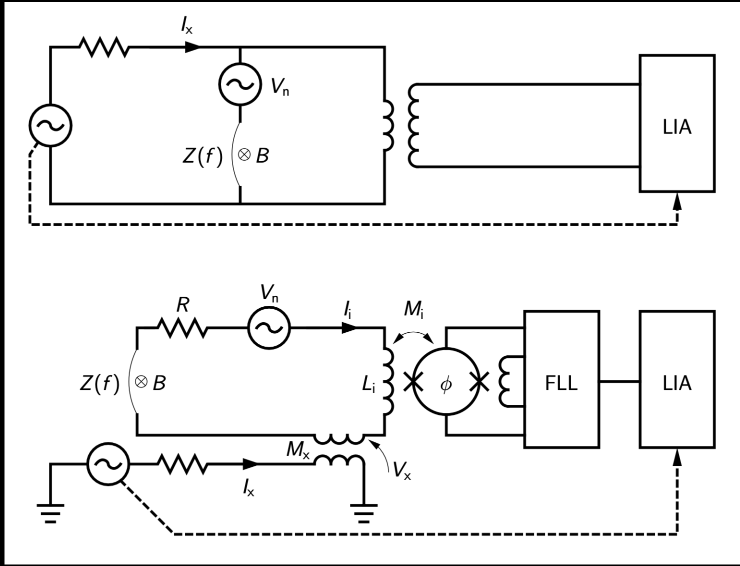



NEMS: 100 x 50 nm CNRS Institut Neel, Grenoble

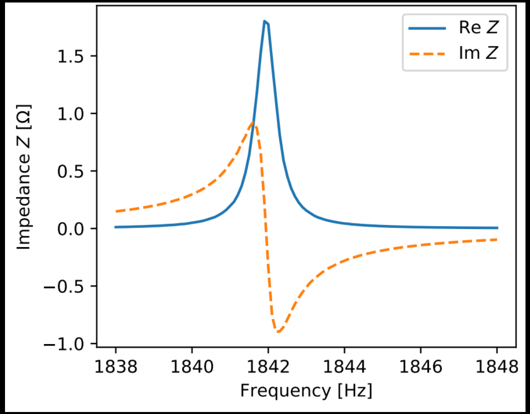
SQUID readout

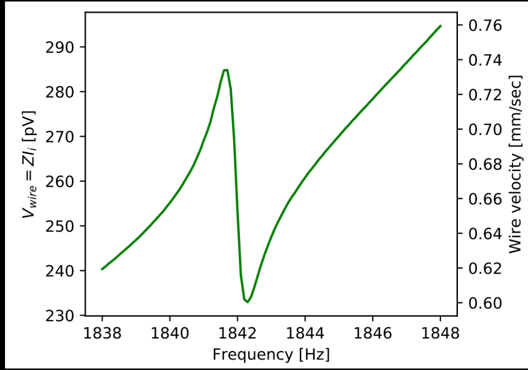


Replace conventional readout
with SQUID (or other alternative)



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



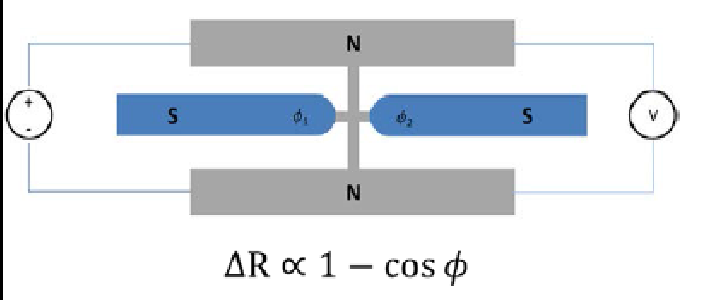


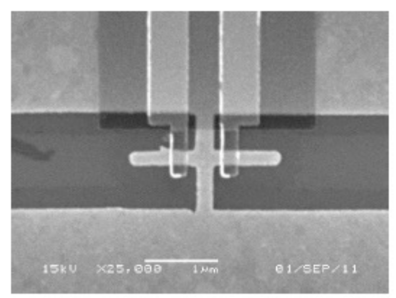
SQUID alternatives

HyQUID: Hybrid Quantum Interference Device

Based on Andreev interferometer with two SN contacts

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

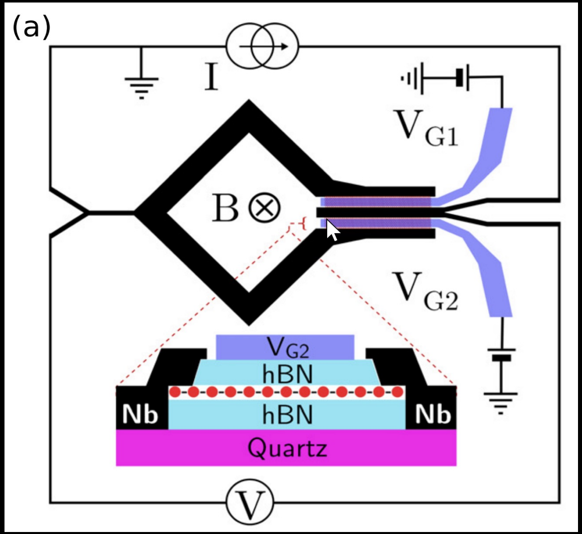




G-SQUID: Graphene-based tunable SQUIDs

Based on controlling ballistic Josephson junctions

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



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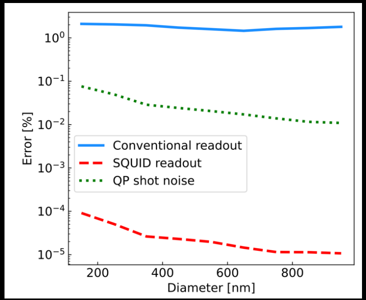
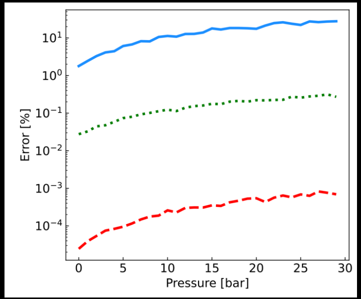
Lancaster University

OPTIMISING SENSITIVITY – simulated responses

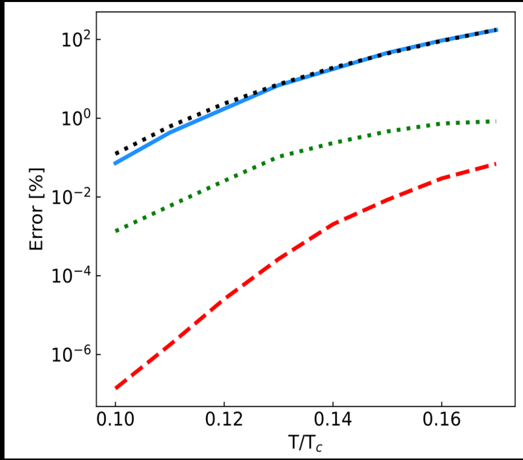
Tune wire diameter at 0.12 T_c for 10 eV



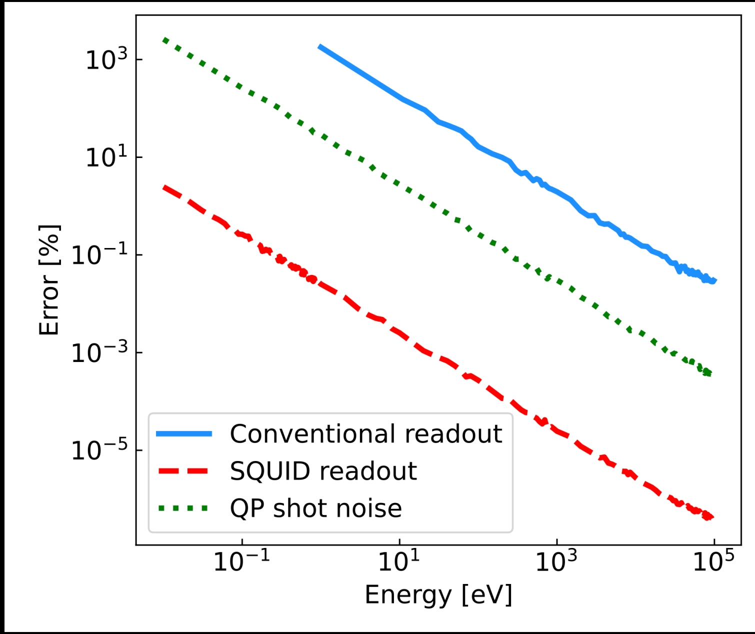
Tune pressure at 0.12 T_c for 10 eV



Tune temperature for 10eV



Importance of cold operation



Operation at 0.12 T_c

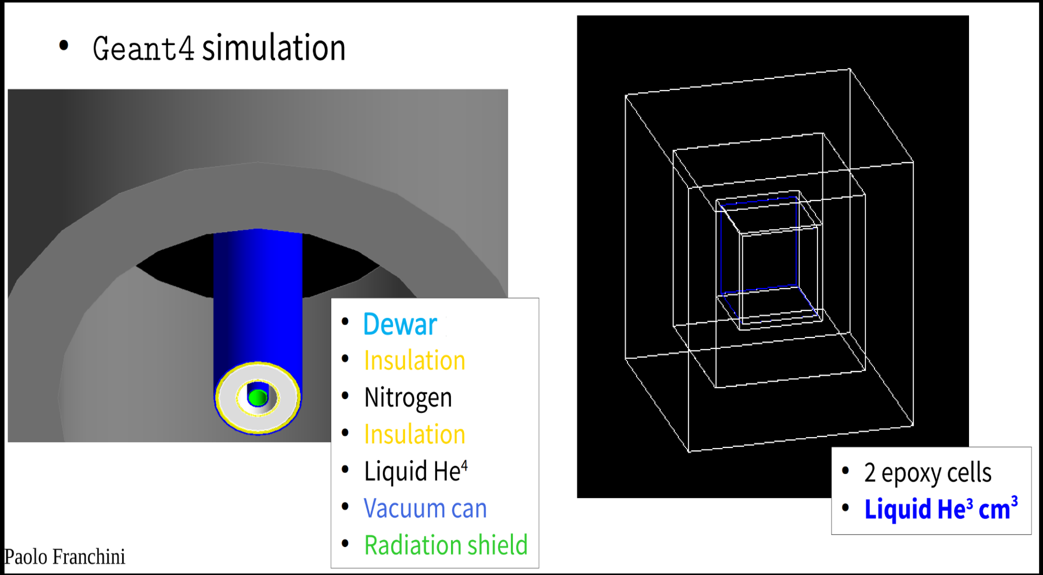
- SQUID readout required
- Shot noise problem?

BACKGROUNDS

Leason *et al,* QUEST-DMC: *Background Modelling and Resulting Heat Deposit for a Superfluid Helium-3 Bolometer* (to be published 2024)

Material
Concrete
Aluminium
Insulation
Stainless Steel
Steel
Araldite
Stycast

Boulby assay
SNOLAB database



- Materials choices?
- Shielding?
- Underground?

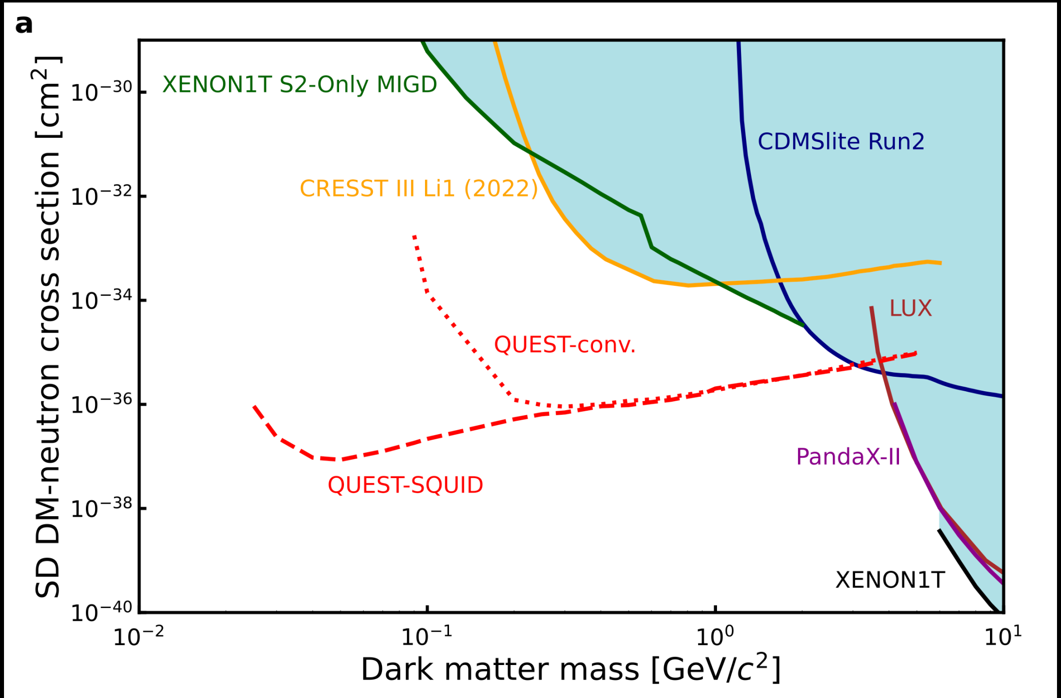
IONISATION CHANNEL

- SiPMs (developed for Darkside) normally operated at LN2
- Matrix of single photon avalanche diodes with high gain and single photo-electron resolution
- First use as Veto rather than measure energy partition fraction
- Tested at 4K

SENSITIVITY

Spin-dependent sensitivity projection for:

- 5 x 0.3 cm^3 bolometers
- 6 month run at 50% duty cycle



See: ArXiv:2310.11304, *QUEST-DMC superfluid ^{3}He detector for sub-GeV dark matter*

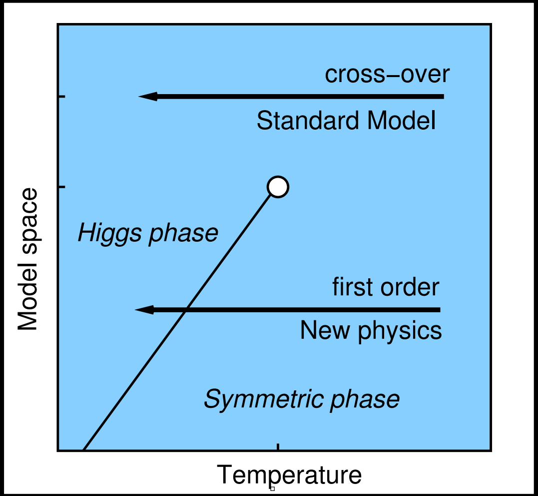
WP2 PHASE TRANSITIONS CONCEPT

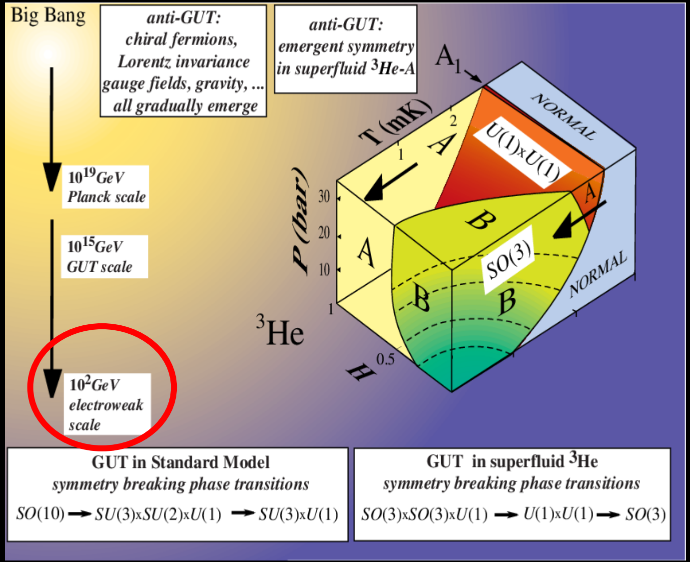
Motivations

- Early-Universe first-order phase transitions and associated gravitational wave generation
- The AB nucleation puzzle

Methods

- Apply cosmology computation methods to simulate ^{3}He phase transitions
- Use ^{3}He as a quantum analogue to test nucleation theory and out-of-equilibrium dynamics

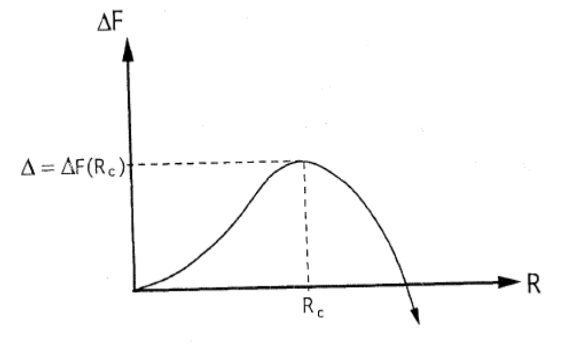


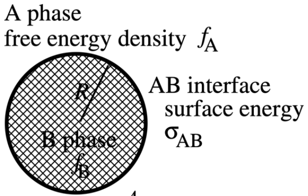


WP2 PHASE TRANSITIONS CONCEPT

The nucleation problem in ^3He

- Homogeneous nucleation theory predicts VERY slow transition rates (lifetime of Universe).
- But the transition does happen.
  (eg: Kleinberg et al 1974; Hakonen et al 1985; Fukuyama et al 1987; Swift, Buchanan 1987; Schiffer et al 1992; O'Keefe, Barker, Osheroff 1996 Bartkowiak et al 2000; Zhelev et al 2017; Tian et al 2023)
- Many models but none consistent with all experimental observations
  (eg: Leggett 1984, Bunkov &Timofeevskaya 1998; Leggett & Yip 1990; Balibar, Mizusaki, Sasaki 2000; Hong 1988; Tye & Wohns 2011)
- Extrinsic vs intrinsic mechanisms?



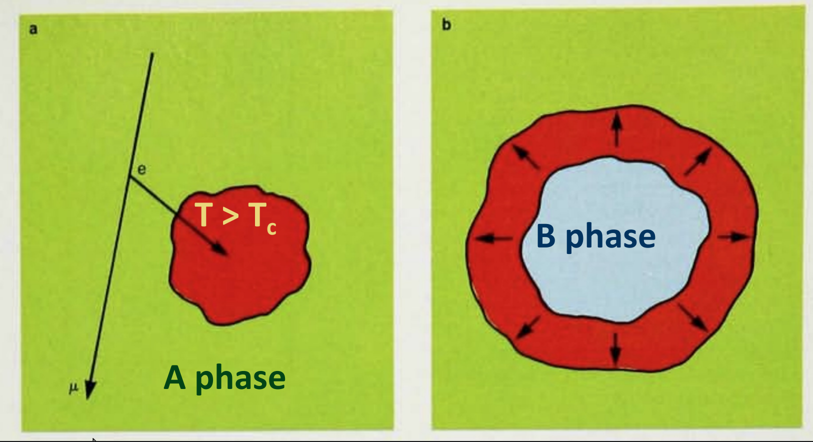


$$E(R) = 4\pi R^2 \sigma_{AB} - \frac{4\pi}{3} R^3 (f_A - f_B)$$

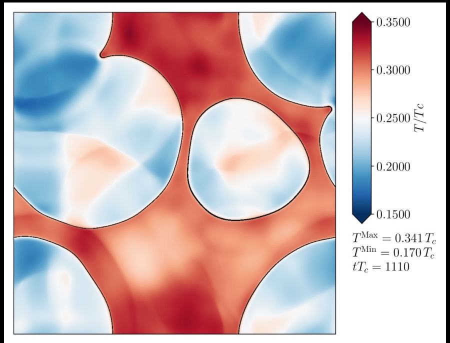
Critical bubble:

$$\left.\frac{dE}{dR}\right|_{R_c} = 0, \quad E_c = \frac{16\pi}{3} \frac{\sigma_{AB}^3}{|f_A - f_B|^2}$$

Incident radiation and "Baked Alaska"?



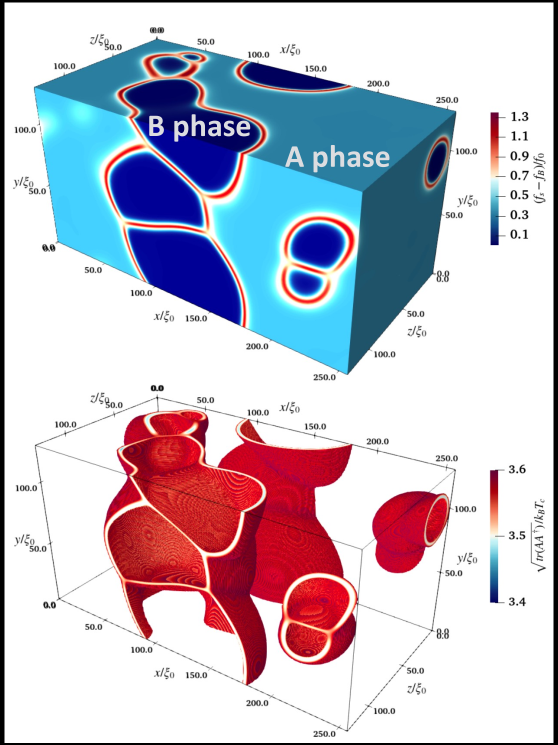
SIMULATION APPROACH



Numerical simulation of cosmological phase transition
(Cutting, Hindmarsh, Weir 2019)

Perform simulations using time-dependent Ginzburg-Landau on large grids

- 3x3 complex superfluid ^{3}He order parameter
- Implement boundary conditions (or none)
- Compute phase transition dynamics

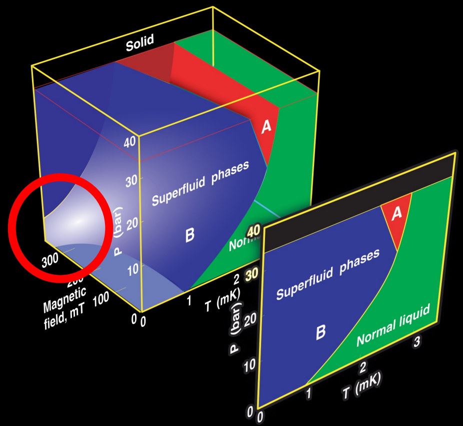


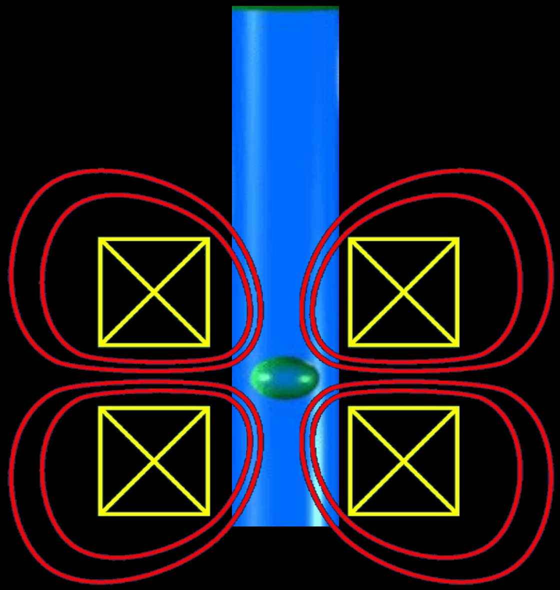
Hindmarsh *et al*, arXiv:2401.07878: *A-B transition in superfluid ^{3}He and cosmological phase transitions*

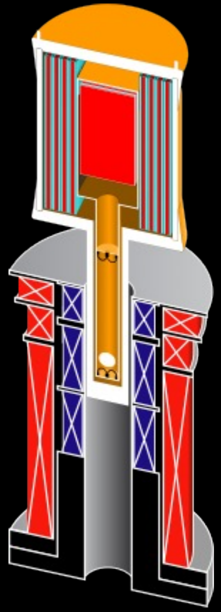
EXPERIMENTAL APPROACH 1

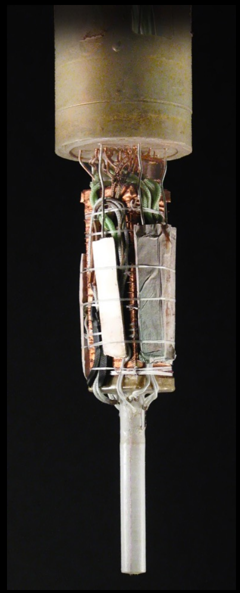
Eliminate boundary effects

- Exploit magnetic field dependence of phase boundary
- Control transition with shaped magnetic fields
- Remove influence of physical walls







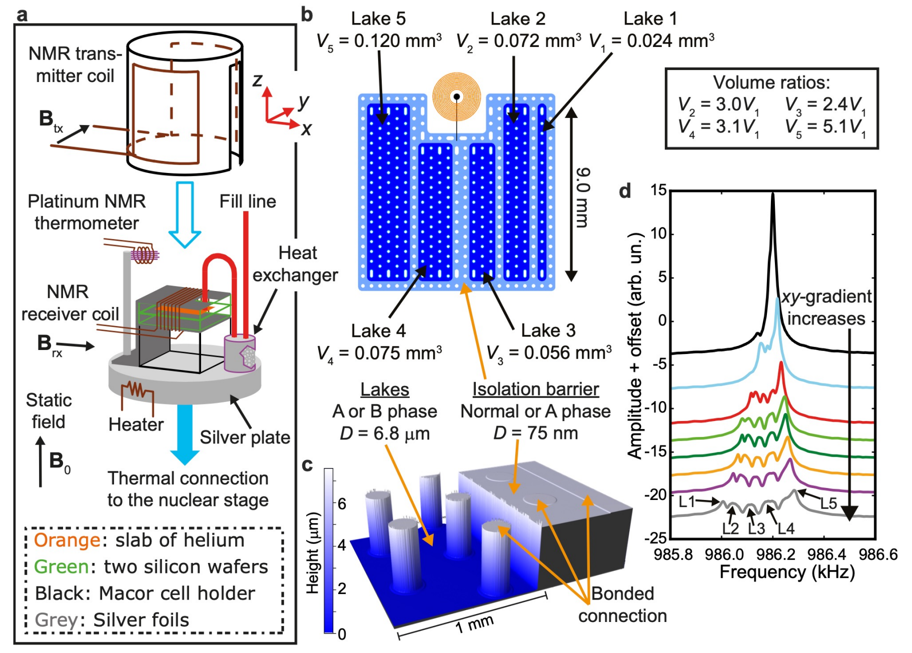


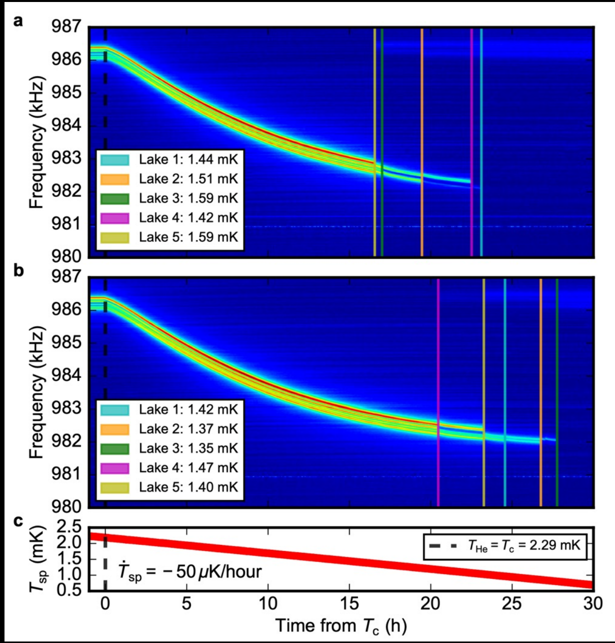
Haley *et* al: AIP Conf. Proc (2006)
A levitated droplet of superfluid He-3-B entirely surrounded by He-3-A.

EXPERIMENTAL APPROACH 2

Control and investigate boundary effects

- Transition under confinement with atomically smooth walls
- Probe dynamics with microcoils & SQUID-NMR





Heikkinen *et al*: arXiv:2401.06079

Nanofluidic platform for studying the first-order phase transitions in superfluid helium-3

SUMMARY

Work Package 1

Superfluid helium-3 dark matter detector

Develop and demonstrate a quantum-amplified superfluid ^{3}He calorimeter to search for sub-GeV dark matter.

- Quantum-amplified sub-mK superfluid helium-3 calorimeter developed
- Sensitive to spin-dependent detection with predicted 10eV threshold
- First measurement run Spring 2024

Future

- Exploit more sensitive amplifier technology
- Multiplexing?
- Low radiogenic background cryostats?
- Underground?

arXiv:2310.11304: *QUEST-DMC superfluid ^{3}He detector for sub-GeV dark matter*

Work Package 2

Phase transitions in extreme matter

Investigate early universe phase transitions and analogue first-order nucleation in superfluid ^{3}He.

- Simulations producing new insight into dynamics of the AB transition
- Smooth-walled nanofluidic cell collecting data on supercooling (and superheating)
- Magnetic control system under construction

Future

- Run of 3D bubble cell
- Simulate existing nucleation scenarios
- Understand influence of cosmic rays and radiogenics

arXiv:2401.07878: *A-B transition in superfluid ^{3}He and cosmological phase transitions*
arXiv:2401.06079: *Nanofluidic platform for studying the first-order phase transitions in superfluid helium-3*

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QUEST DMC

Thank you!

SNOLAB

Lancaster University

Ultra Low Temperature

Lancaster Quantum Technology Centre

UKRI Science and Technology Facilities Council

UKRI Engineering and Physical Sciences Research Council