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

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lancaster University

University of Sussex

UNIVERSITY OF OXFORD

New collaboration funded through QTFP call.

- What are the fundamental questions
- Introduce who we are
- Combining quantum sensors with superfluid ^{3}He at ultralow temperatures.
- WP1: Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter
- WP2: Phase transitions in extreme matter

We will address two fundamental open questions in cosmology

- **In WP1:** What is the nature of Dark Matter?
- **In WP2:** How did the early universe evolve?

Linked through requirement of beyond-standard model physics and the internationally unique experimental approach of combining quantum sensors with ^3He at ultralow temperatures.

Core Team

Experimental	Theory
Dr. Samuli Autti	**Prof. Mark Hindmarsh (Leading WP2)**
Dr. Andrew Casey	Prof. Stephan Huber
Prof. Richard Haley	Prof. John March-Russell
Dr. Petri Heikkinen	Dr. Stephen West
Dr. Sergey Kafanov	
Prof. Jocelyn Monroe (Leading WP1)	
Dr. Jonathan Prance	
Dr. Xavier Rojas	
Prof. John Saunders	
Dr. Michael Thompson	
Dr. Viktor Tsepelin	
Dr. Dmitry Zmeev	
Dr. Vladislav Zavyalov	

QUEST – DMC *Ecosystem*

RHUL
ULT, ^{3}He
Qu Sensors

RHUL
Dark
Matter

ULANC
ULT, ^{3}He
Qu Sensors

QUEST
DMC

RHUL
Beyond the
Standard
Model

SUSSEX
Cosmology
HPC

OXFORD
Beyond the
Standard
Model

cnrs · A! · Cornell University · NPL National Physical Laboratory · Oxford Instruments · HeRald · Boulby Underground Laboratory

UK-CSQS · LANC-QTC · UK National Quantum Technologies Programme · UKRI · NPL National Physical Laboratory

Illinois · Helsinki Institute of Physics · CAPST Northwestern Fermilab · A!

Sauls, Volovik, Nissinen, Leggett, Rummukainen

European Microkelvin Platform
EMP

APPEC
Astroparticle Physics European Consortium

EMP European Microkelvin Platform

Advanced Infrastructure, Horizon 2020:

Research on Quantum Materials, and Quantum Technology at ULT

User Access Facility:

Aalto University

ÚEF SAV

CHALMERS

PTB

VTT

BlueFors CRYOGENICS

CryoConcept

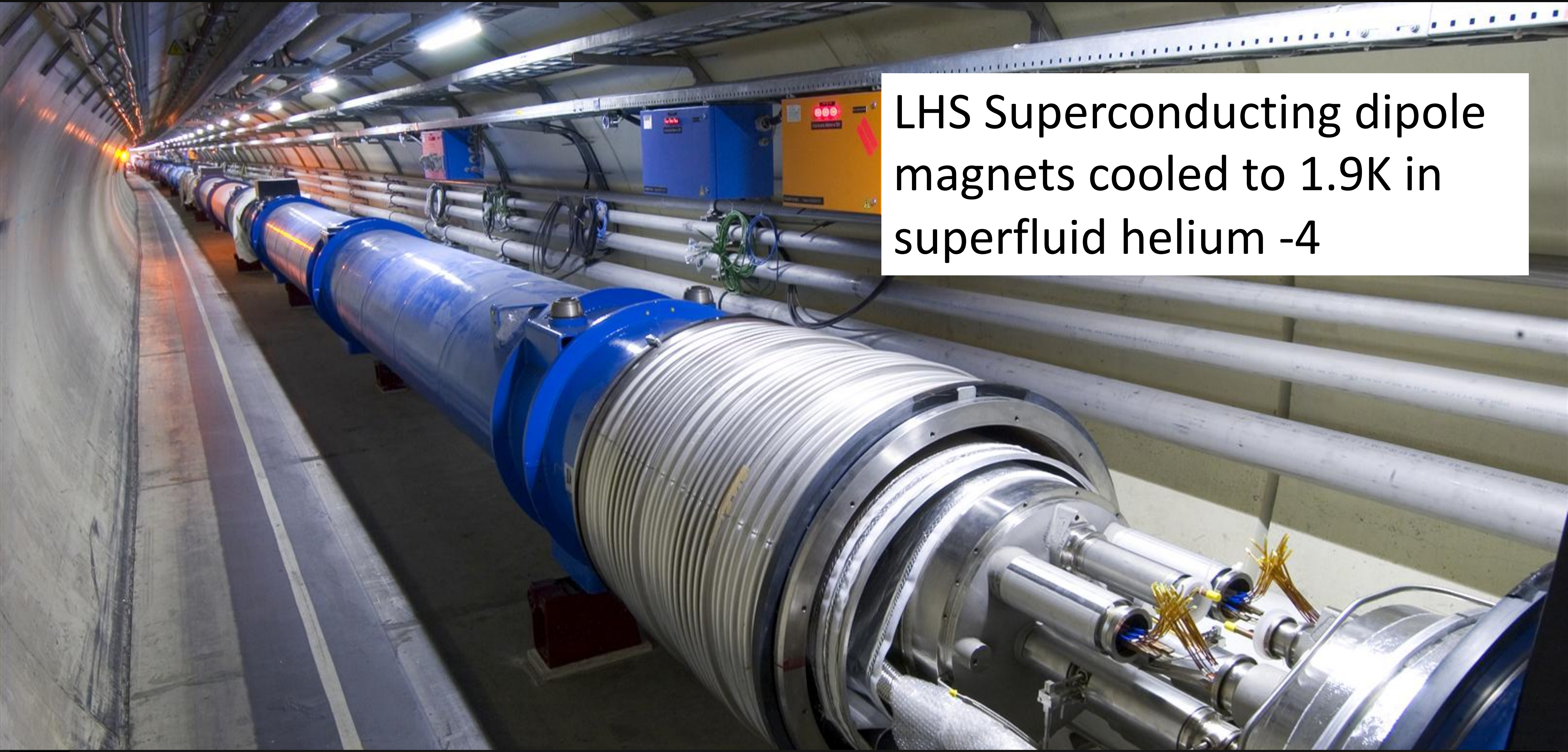
MAGNICON

OXFORD INSTRUMENTS *The Business of Science*

Implementation of current quantum sensors, operated in new regime at ultralow temperatures, and new sensors co-designed for fundamental physics

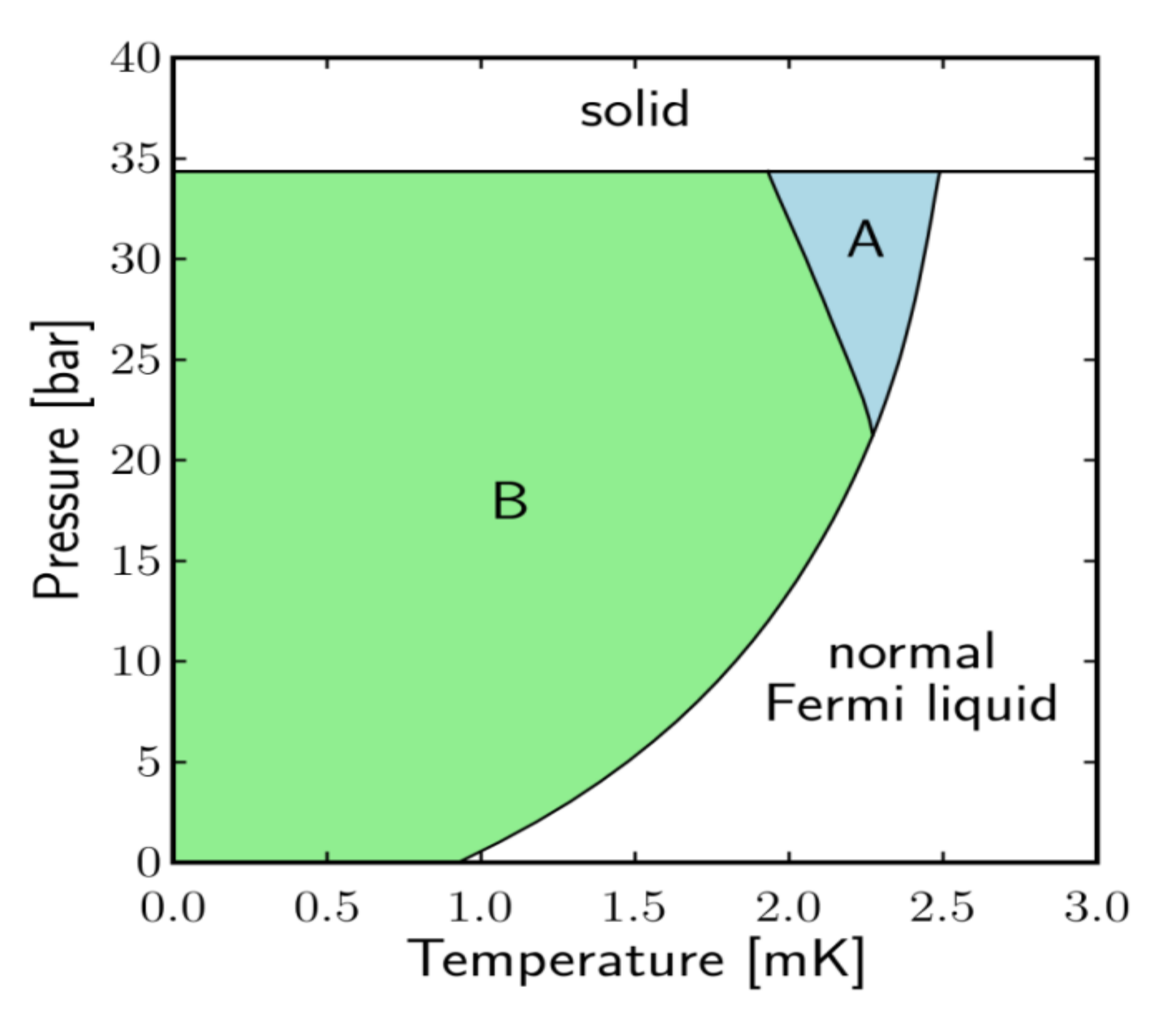
Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology, QUEST –DMC

Superfluid Helium, ^3He



LHS Superconducting dipole magnets cooled to 1.9K in superfluid helium -4

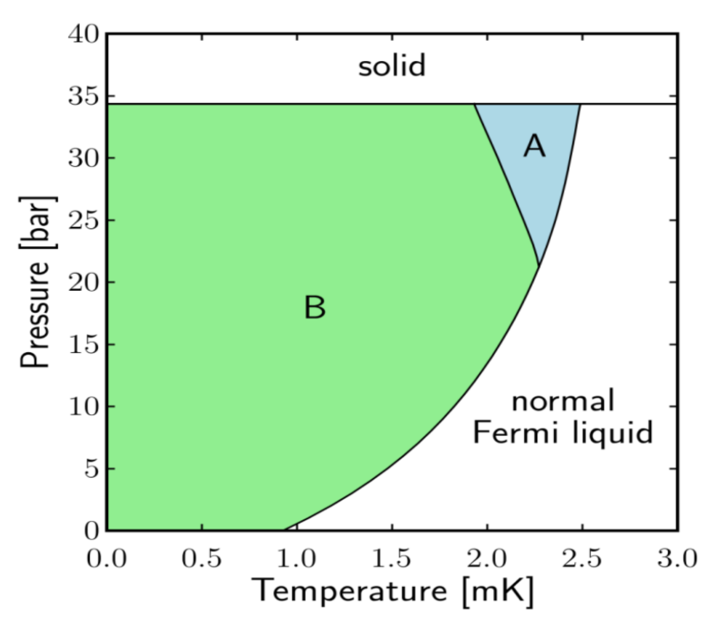
Superfluid Helium, ^3He



- Copper pairs with L=S=1
- 9 component order parameter Ψ:
  - L_z = -1, 0, 1
  - S_z = -1, 0, 1
- Multiple superfluid phases

- In bulk:
  - A-phase: Anderson-Brinkman-Morel
  - B-phase: Balian-Werthamer

Superfluid Helium, ^3He



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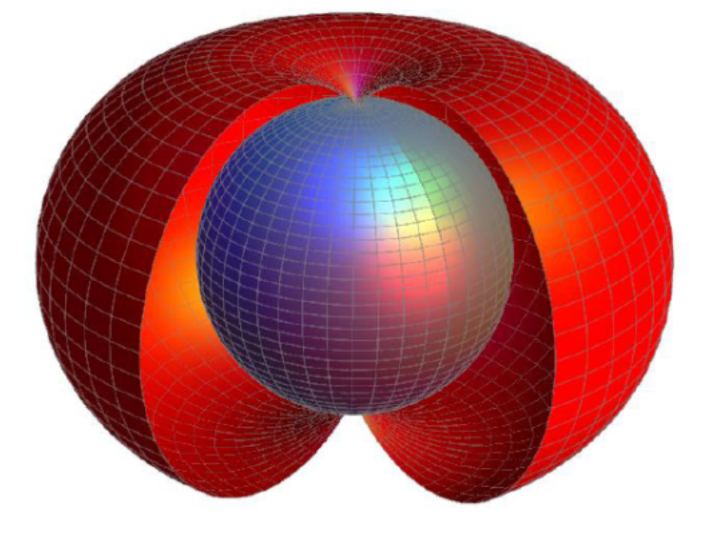
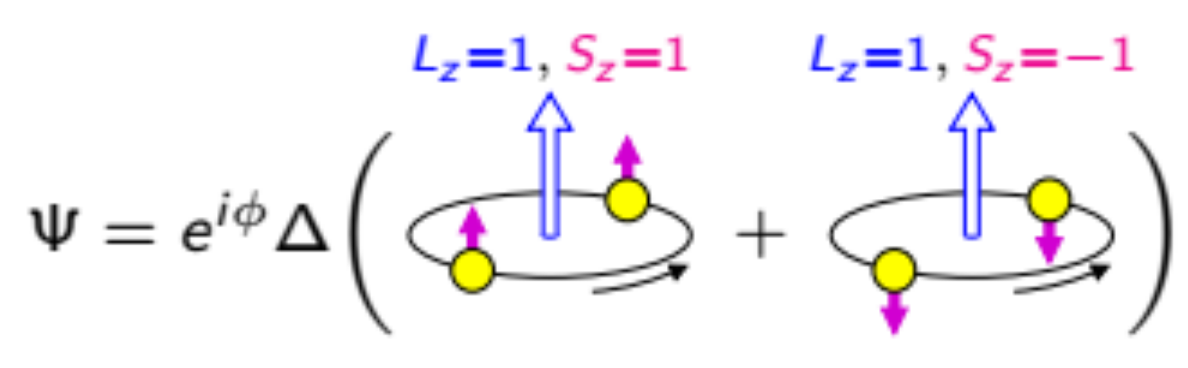
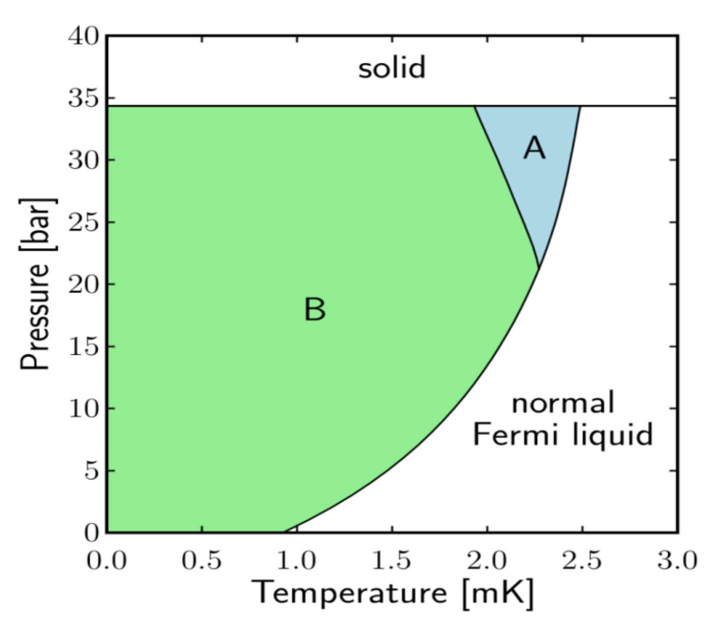


A-phase: Equal Spin Pairing states, Chiral Superfluid, Breaks Time Reversal Symmetry, Anisotropic



Superfluid Helium, ^3He



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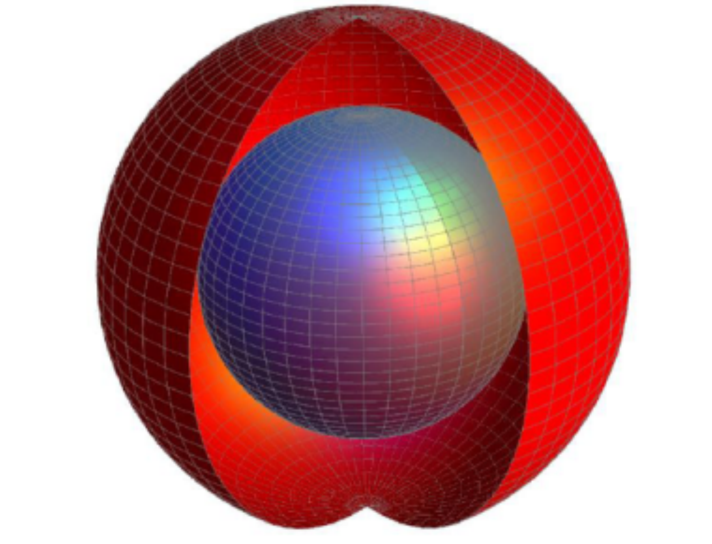
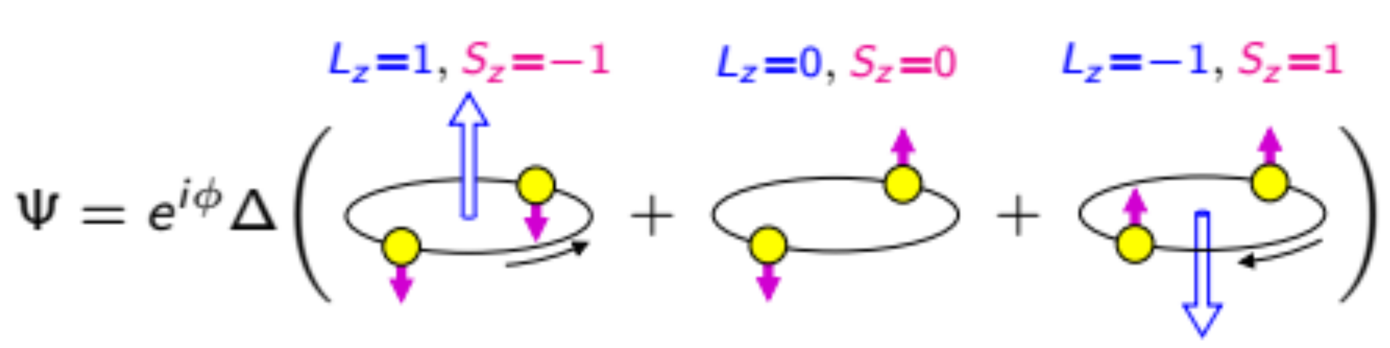
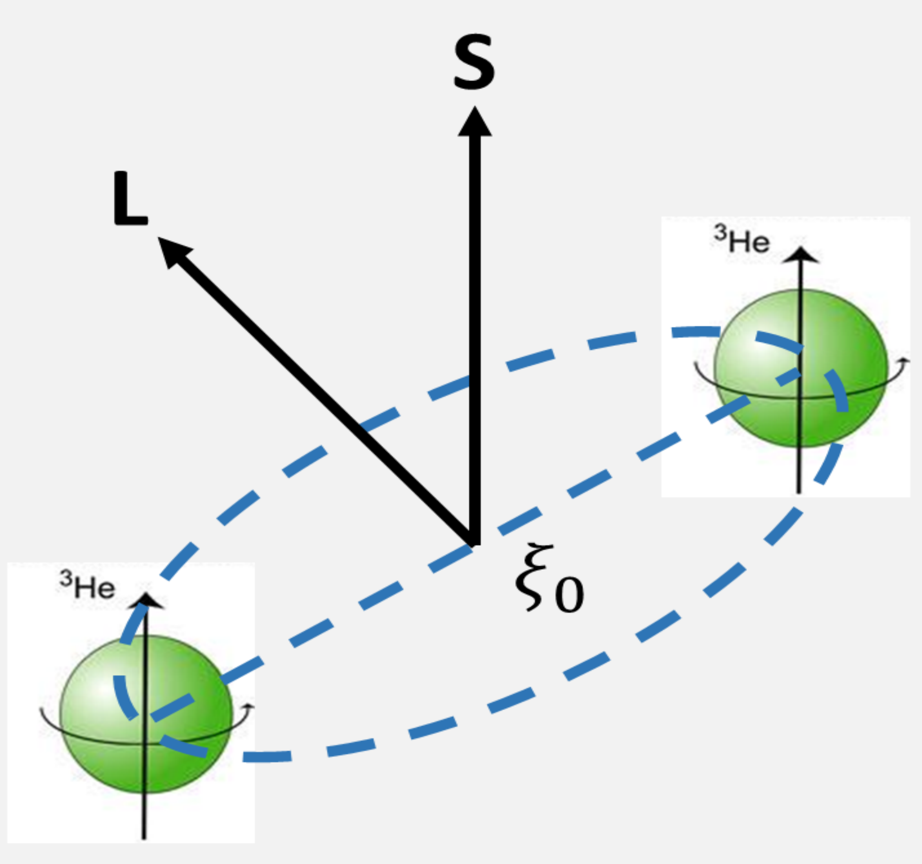
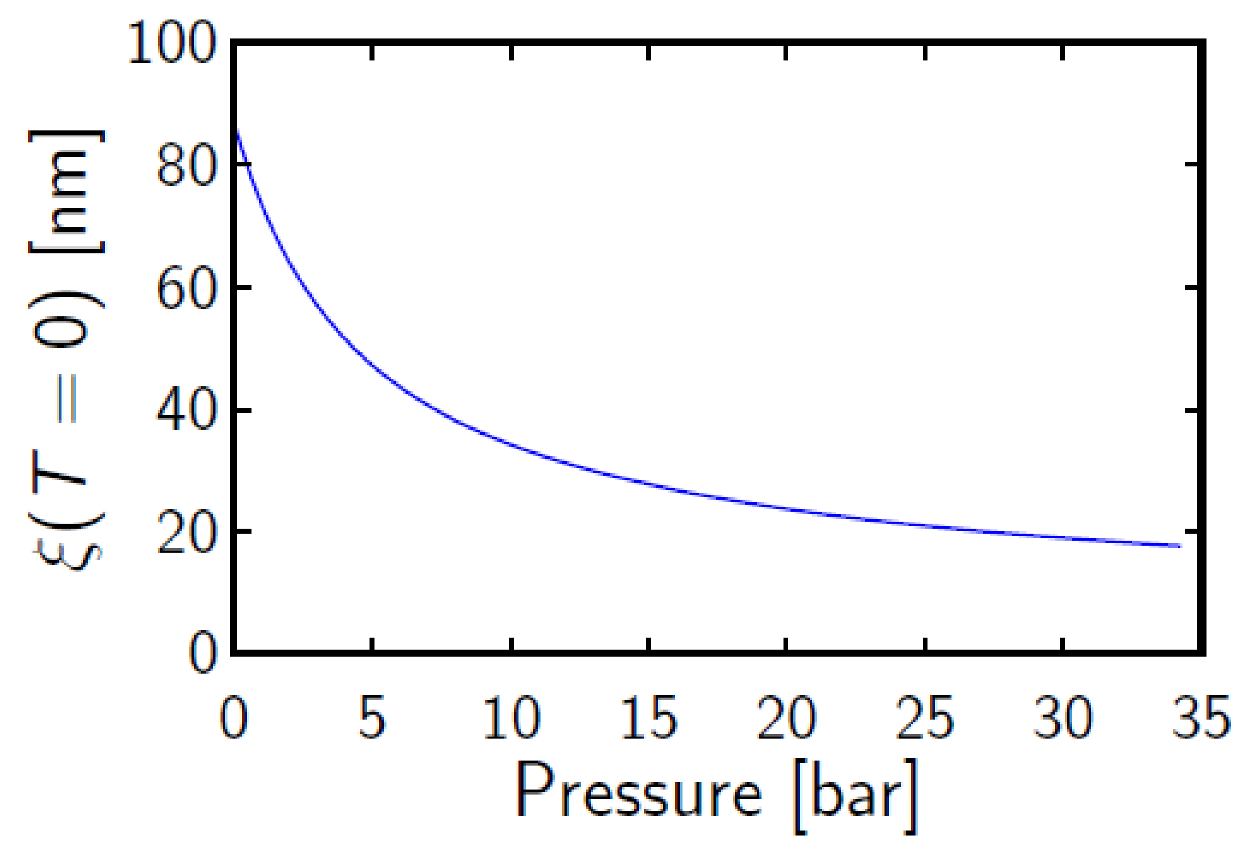


B-phase: Equal admixture of all three states, Time Reversal Invariant, Isotropic energy gap



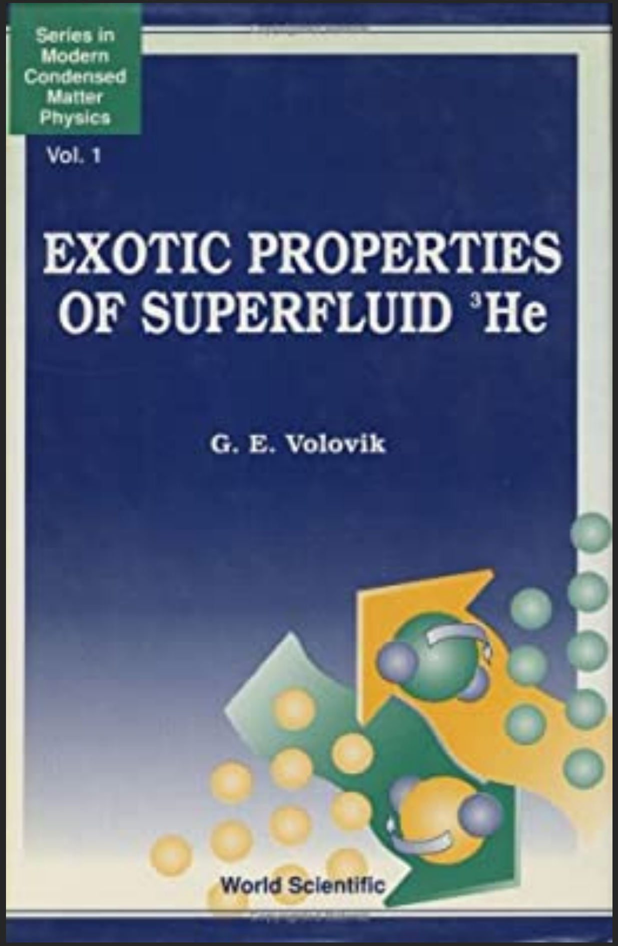
Superfluid Helium, ^3He

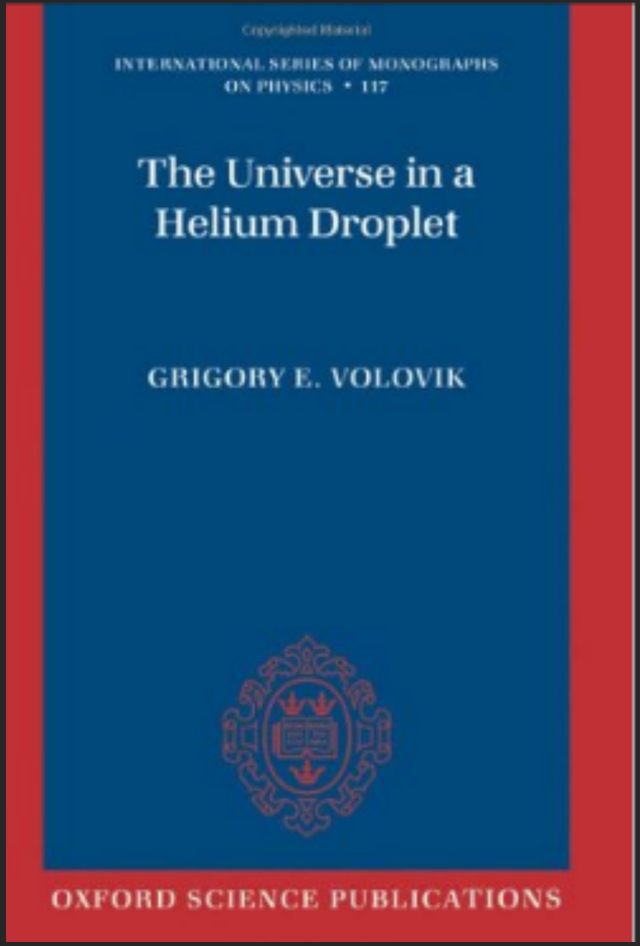




Superfluid Helium, ^{3}He

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



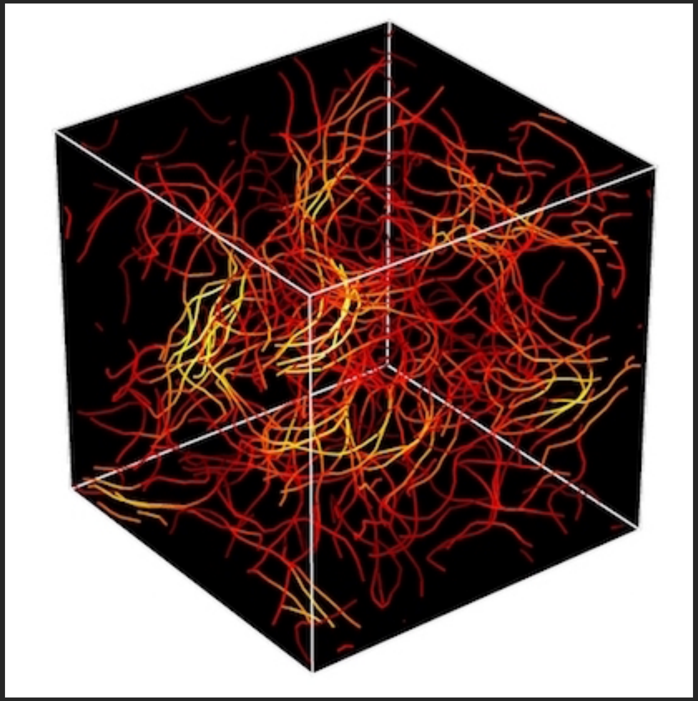


Superfluid Helium, ^3He

Cosmological Analogous Systems

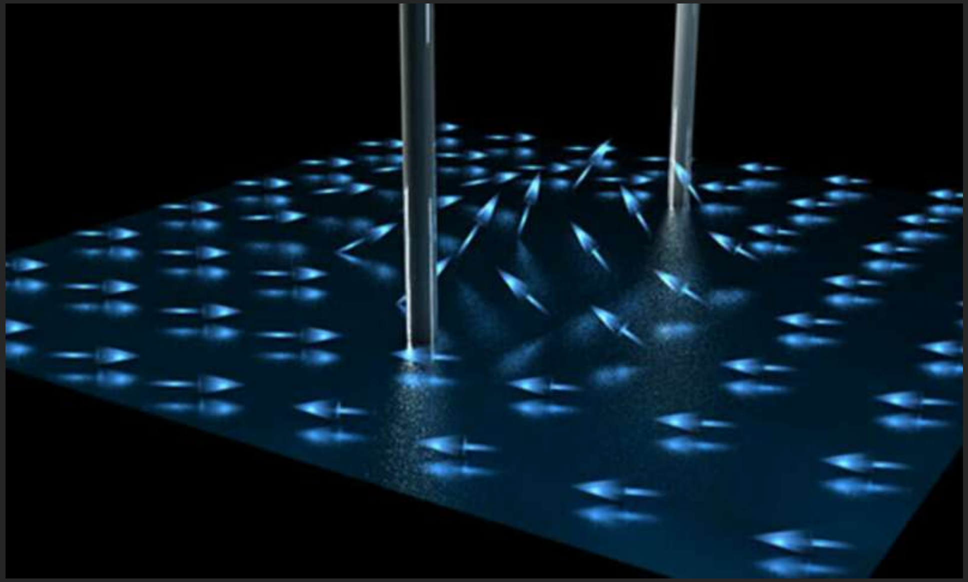
Bradley et al.,
Nature Physics **4**, 46–49(2008)

Quantum Turbulence



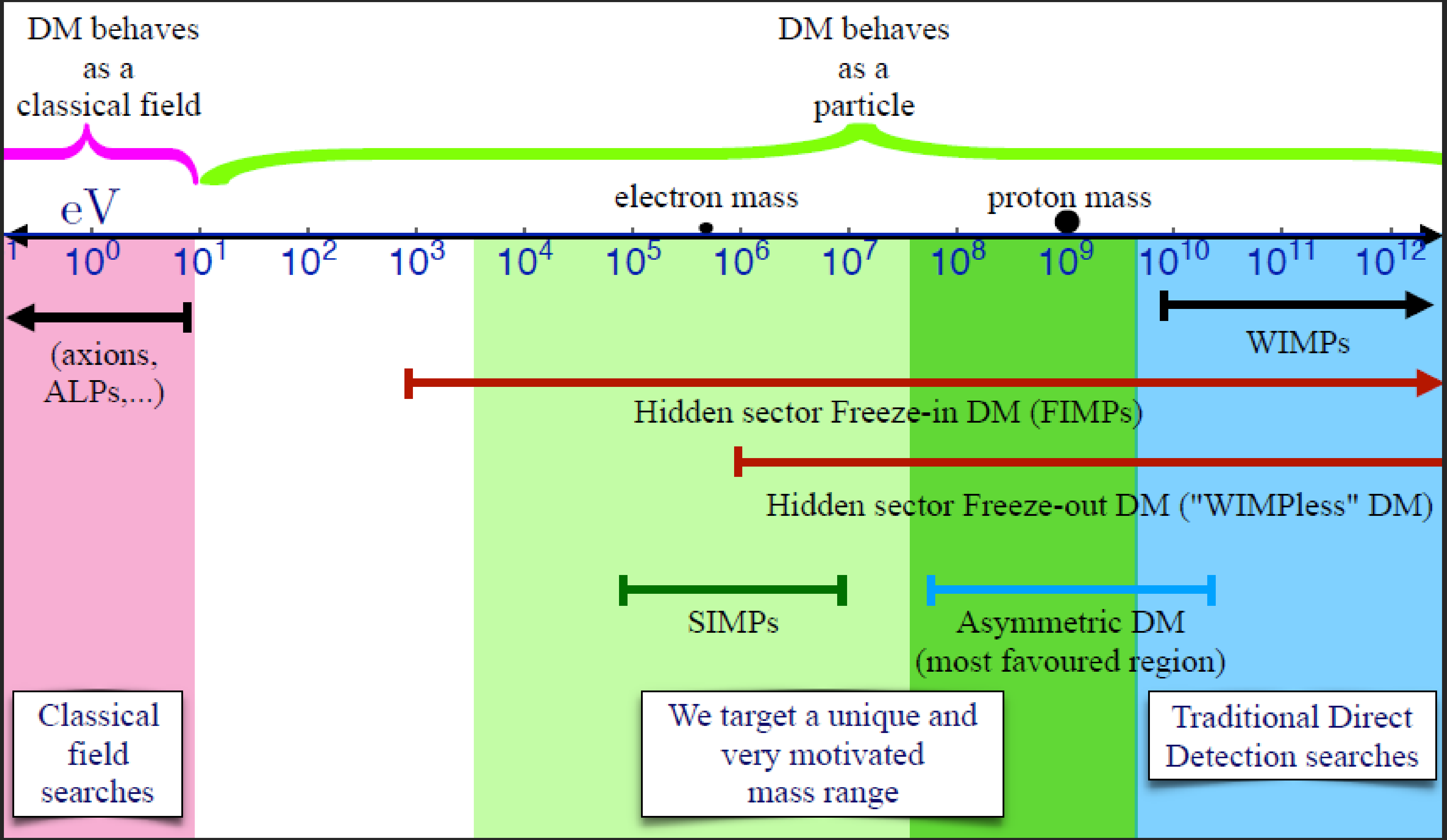
Baggaley et al, *Phys. Rev. Lett.* **109**, 205304 (2012)

Topological Defects



T. Mäkinen et al, *Nature Communications* (2019)

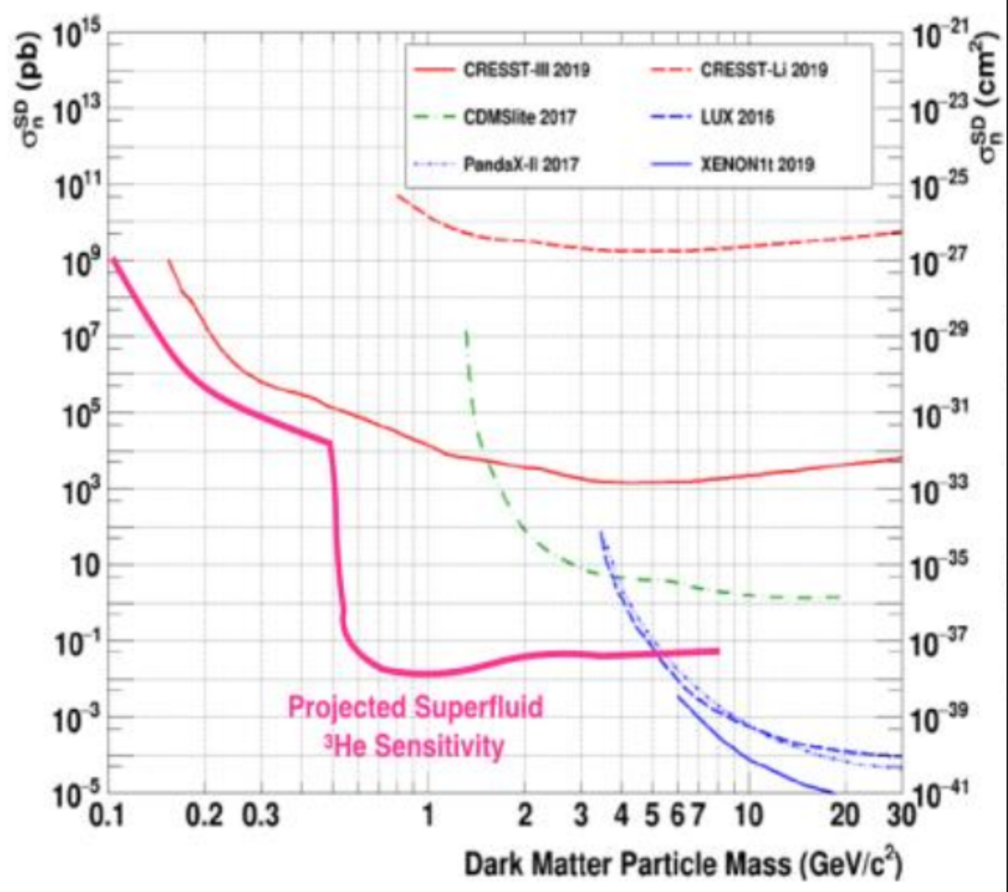
- **In WP1:** What is the nature of Dark Matter?



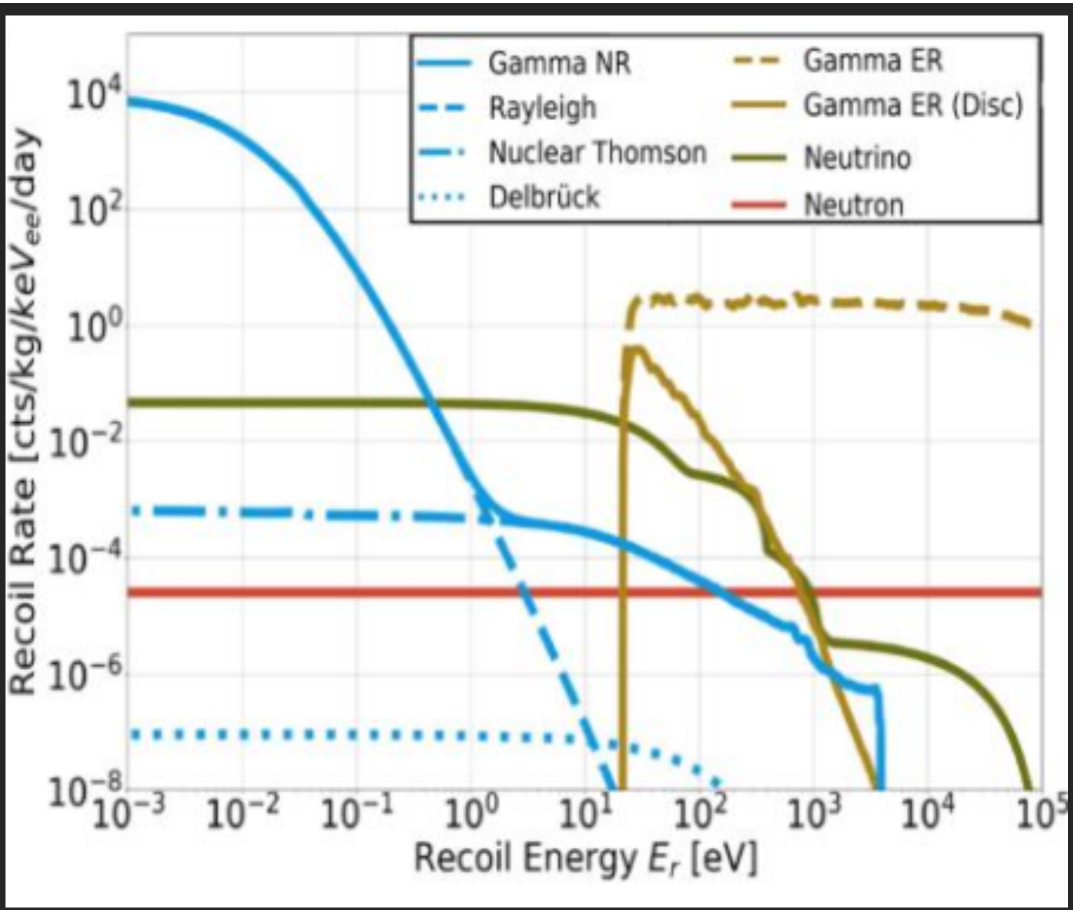
WP1: Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter

Prof Jocelyn Monroe

New mass regime, sensitivity to spin-dependent interactions, predict 10 eV threshold.



A. H. Abdelhameed *et al.* (CRESST Collaboration) Phys. Rev. D **100**, 10200 (2019)

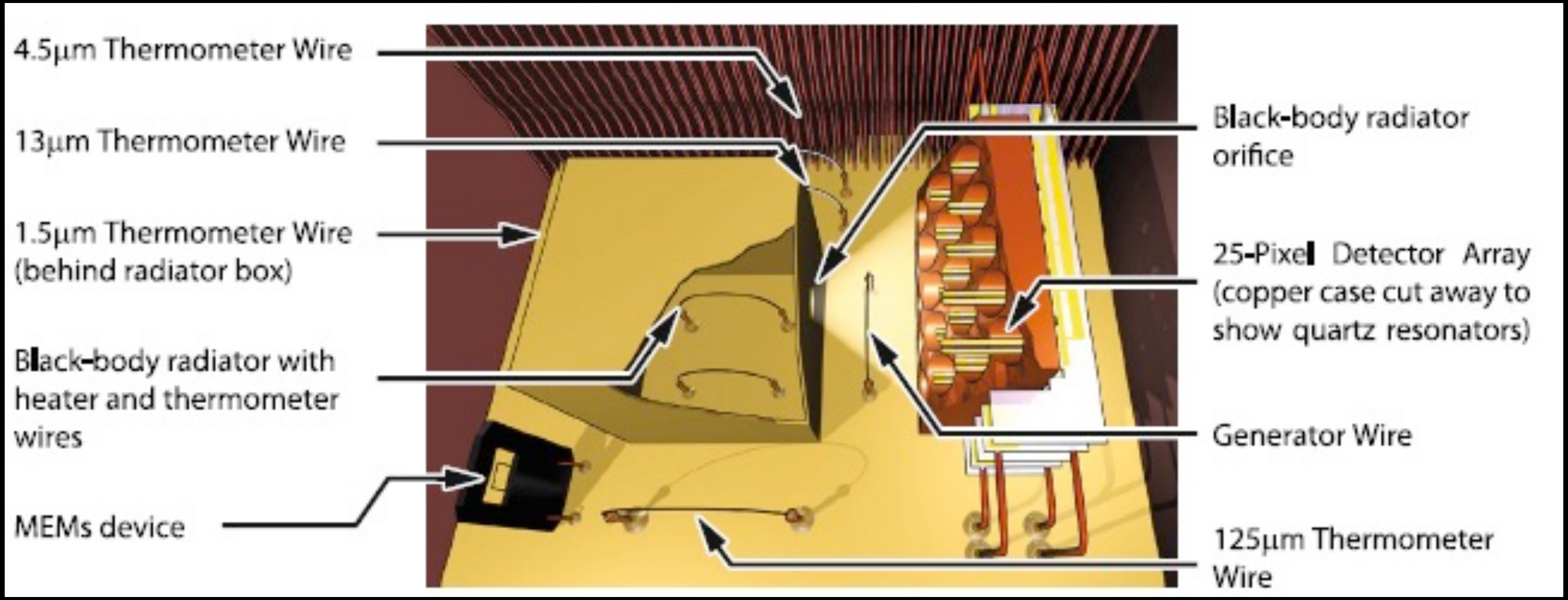


Hertel et al. Phys. Rev. D 100, 092007 (2019)

Vibrating sensors as quasiparticle detectors

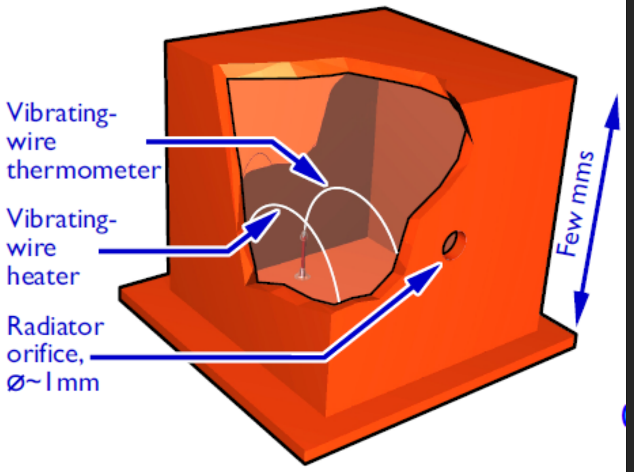
A Quasiparticle Detector for Imaging Quantum Turbulence in Superfluid ^{3}He-B

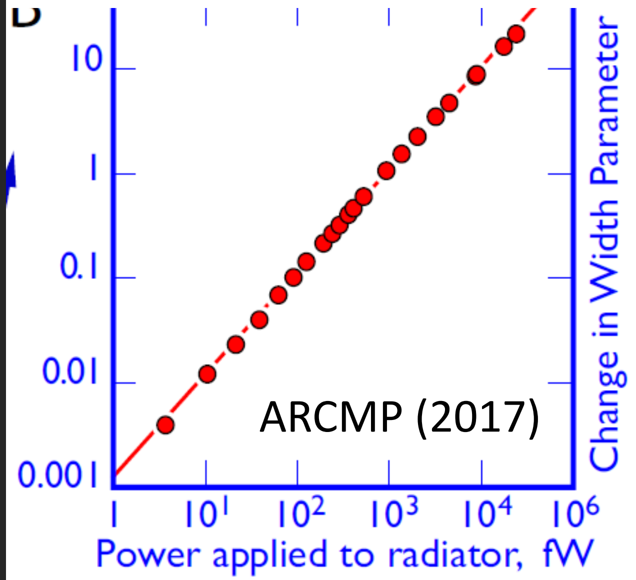
S. L. Ahlstrom · D. I. Bradley · S. N. Fisher · A. M. Guénault · E. A. Guise · R. P. Haley · S. Holt · O. Kolosov · P. V. E. McClintock · G. R. Pickett · M. Poole · R. Schanen · V. Tsepelin · A. J. Woods



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

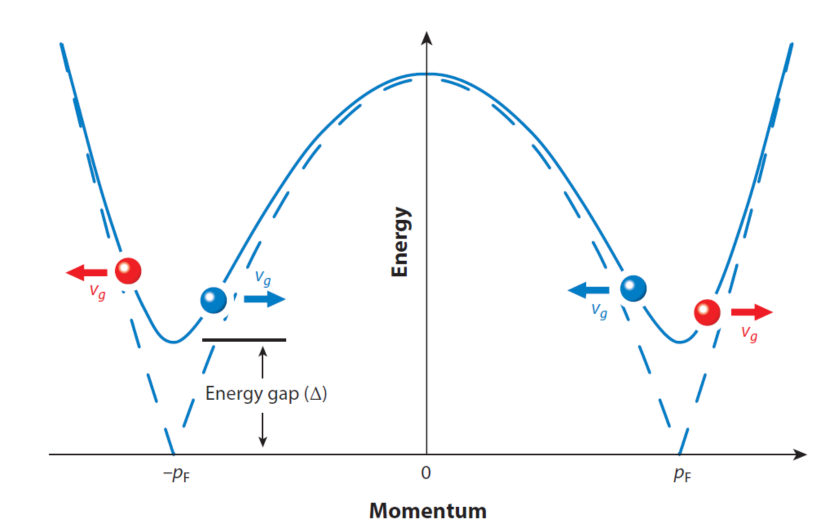
3He-B bolometry offers direct sensing of produced quasiparticles, no Kapitza resistance

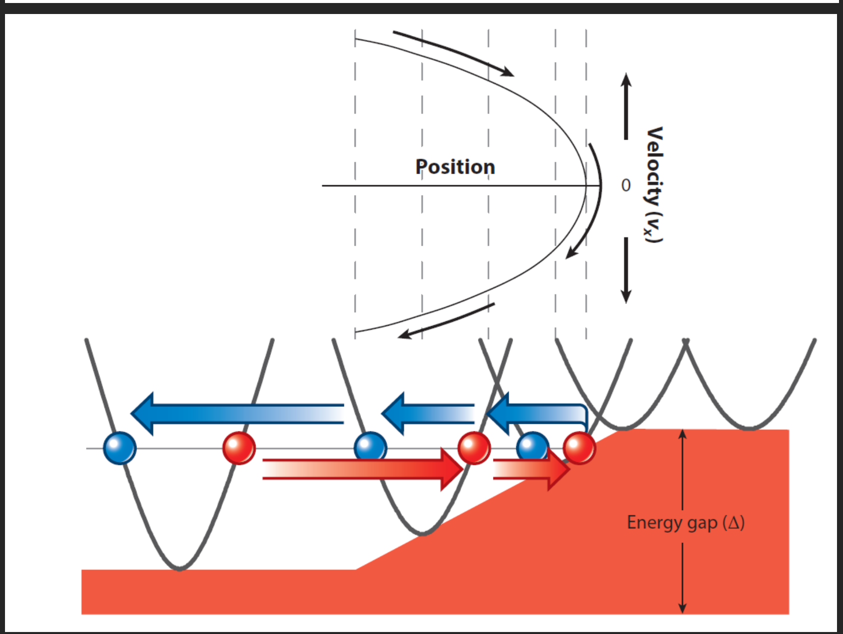


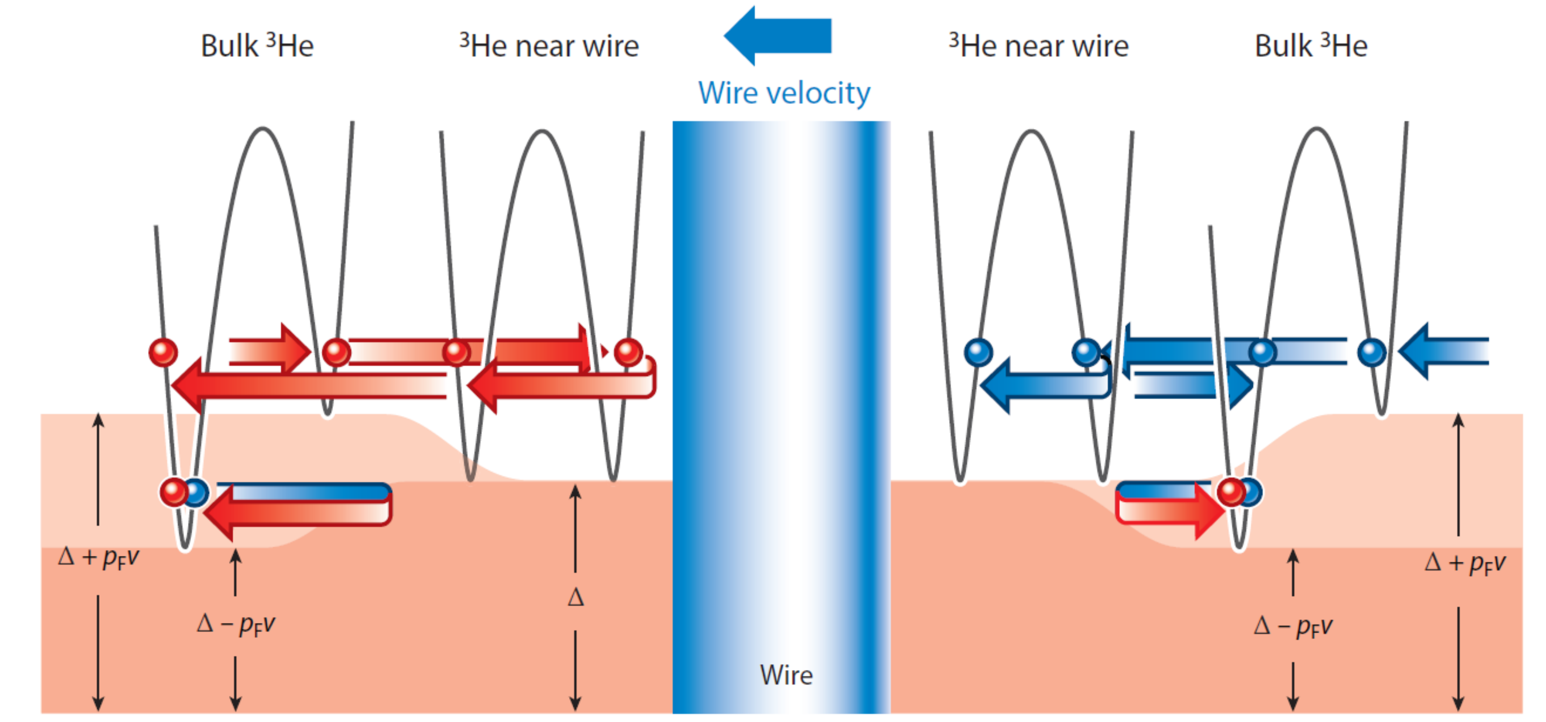


Andreev Scattering

- 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.







NEMs advances: Mass sensitivity 1.7 Yoctogram (10^{-27} kg)

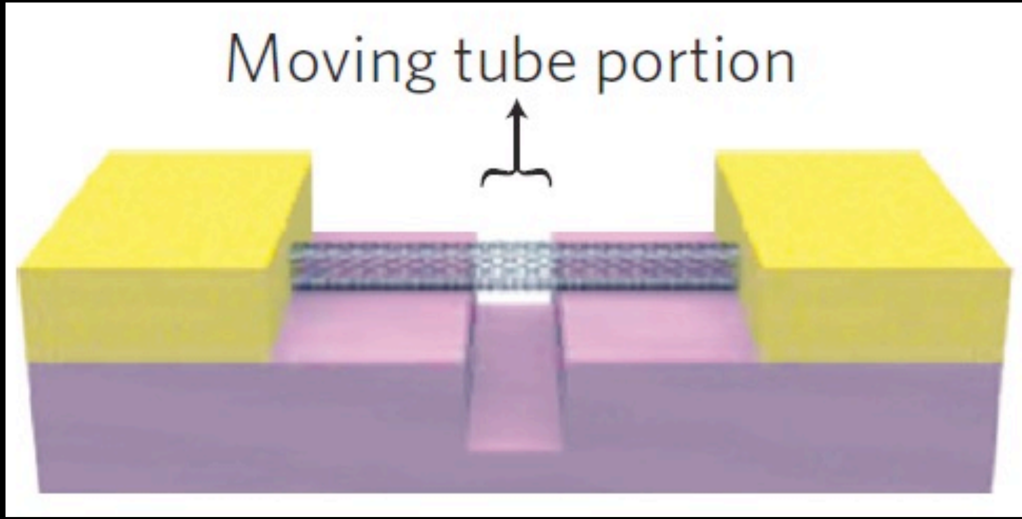
nature nanotechnology

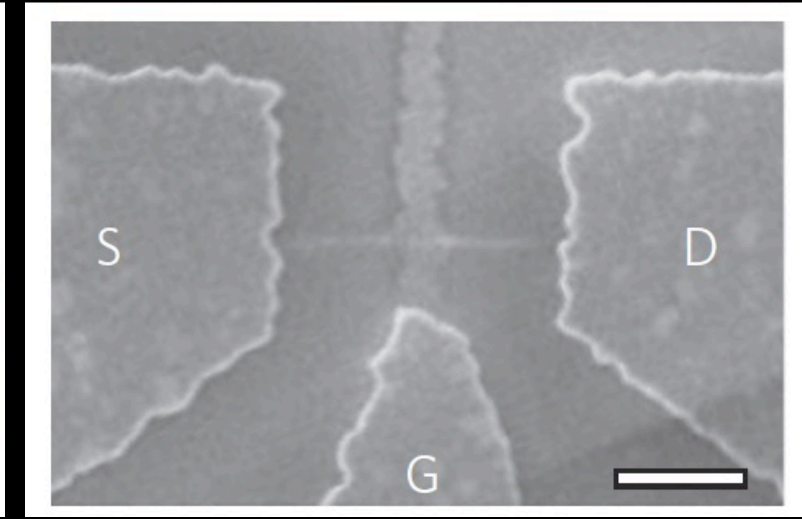
LETTERS

PUBLISHED ONLINE: 1 APRIL 2012 | DOI: 10.1038/NNANO.2012.42

A nanomechanical mass sensor with yoctogram resolution

J. Chaste[1], A. Eichler[1], J. Moser[1], G. Ceballos[1], R. Rurali[2] and A. Bachtold[1]*



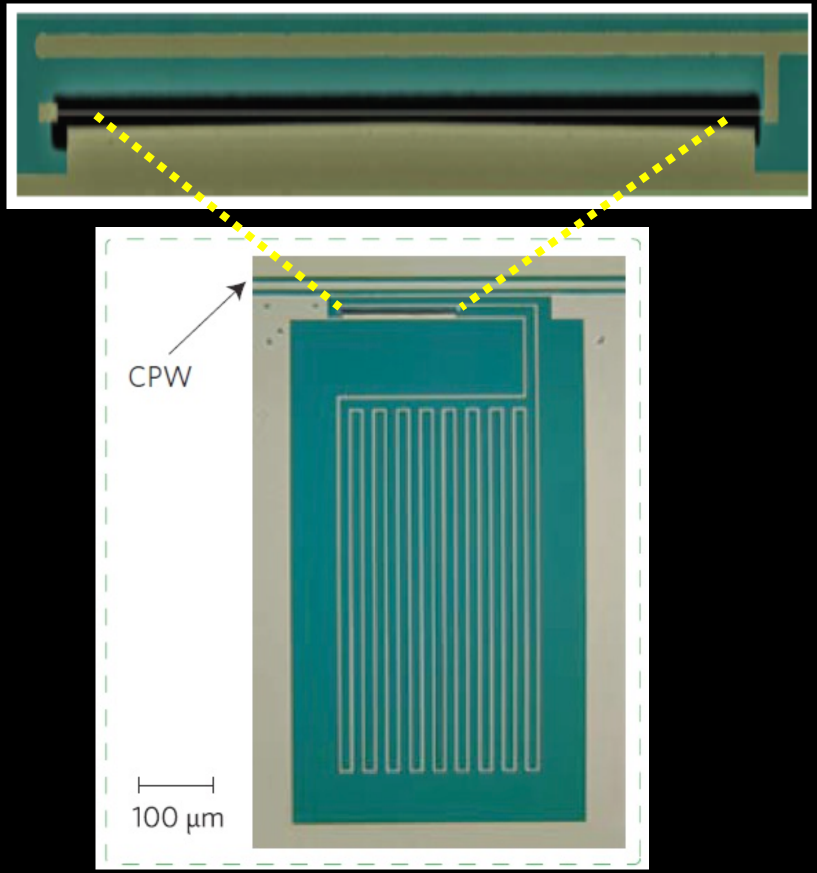


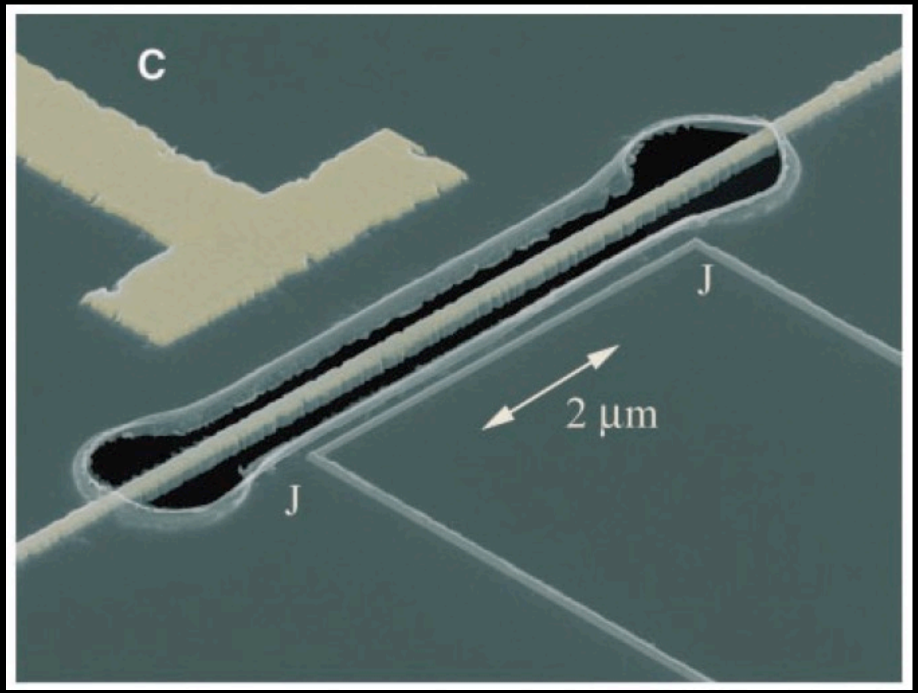
Proton 1.673×10^{-27} kg

Chaste et al. Nat. Nano. 7, 301 (2012)

NEMs advances: Quantum Limited displacement detection

Clerk, Devoret, Girvin, Marquardt, Schoelkopf, Rev. Mod. Phys. **82,** 1155 (2010)



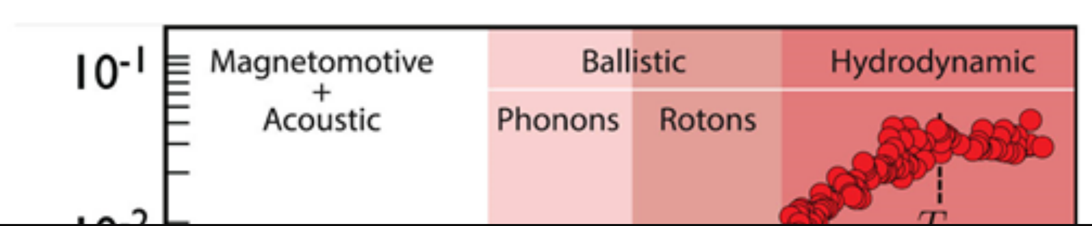


Teufel, *et al.* Nature Nano. (2009)
microwave interferometer

M. D. LaHaye, *et al.*, *Science* **304**, 74 (2004)
Superconducting Single Electron Transistor

WP1:Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter

100x sensitivity and faster times with NEMS



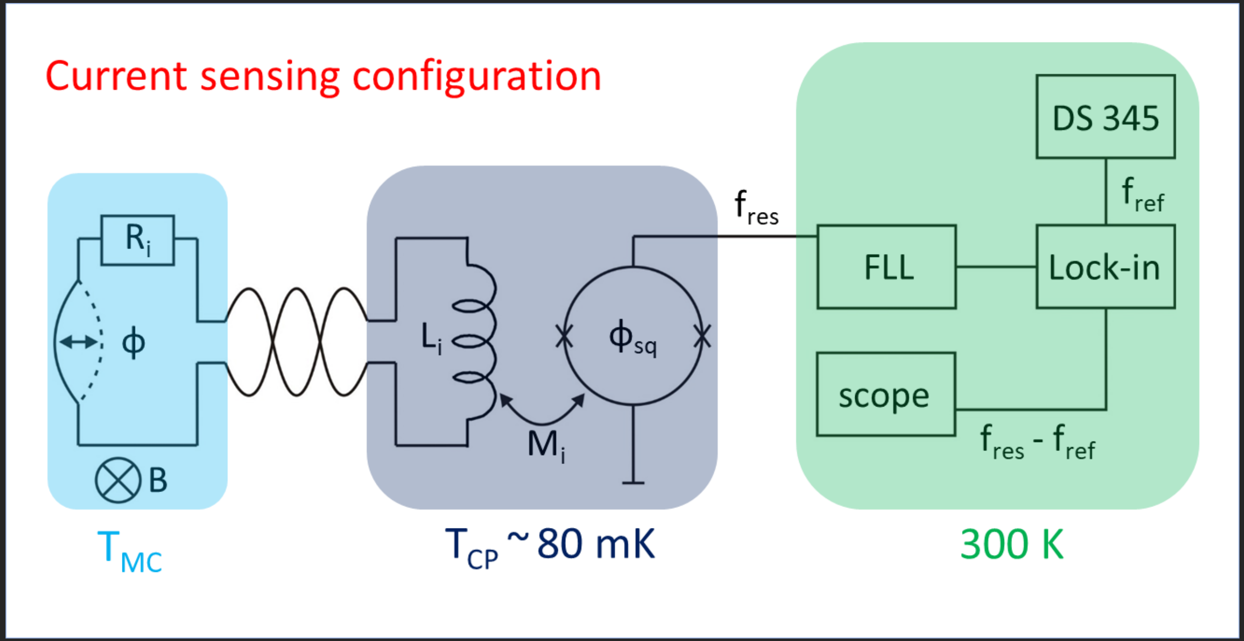
To reach ULT, needed for maximum sensitivity, readout requires:

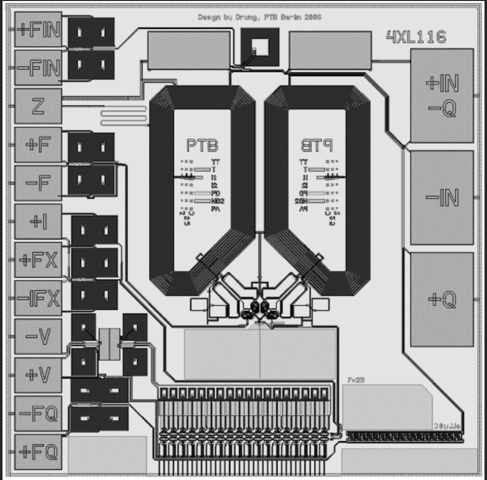
- **low dissipation**
- **low noise**

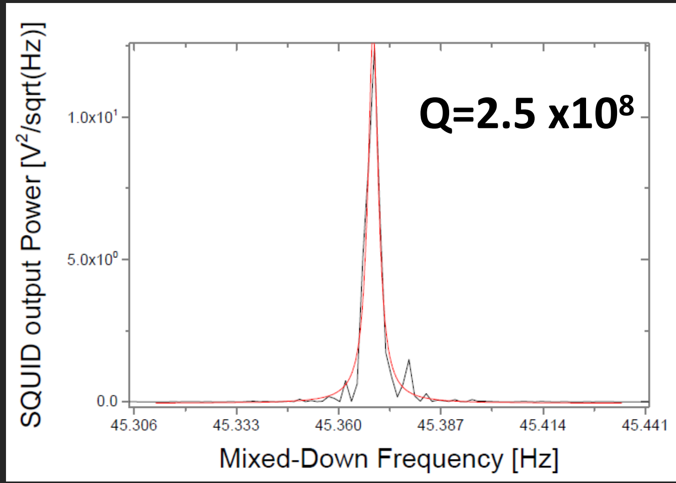
Solution:

Quantum technology for signal amplification

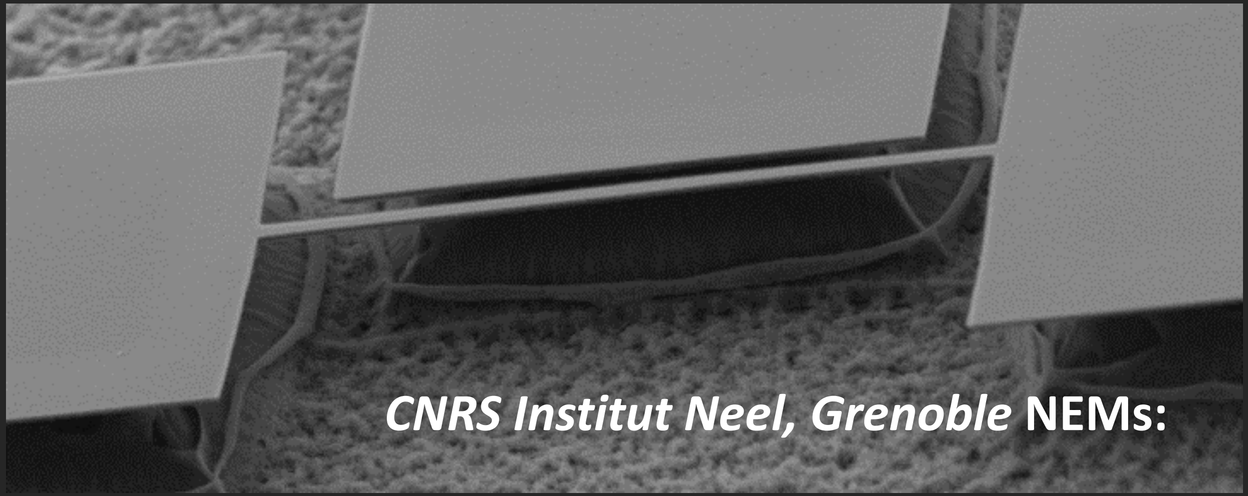
Merging existing state-of-art tech to achieve beyond 10 eV resolution

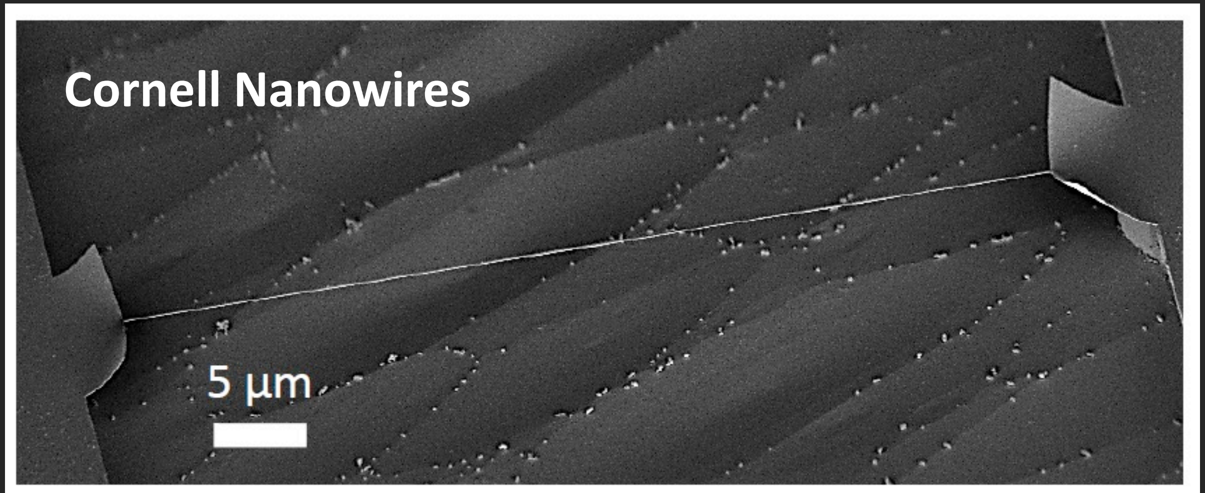






2-stage SQUID amplifier (PTB)
IEEE Trans. Appl. Supercond. 17 (2007)

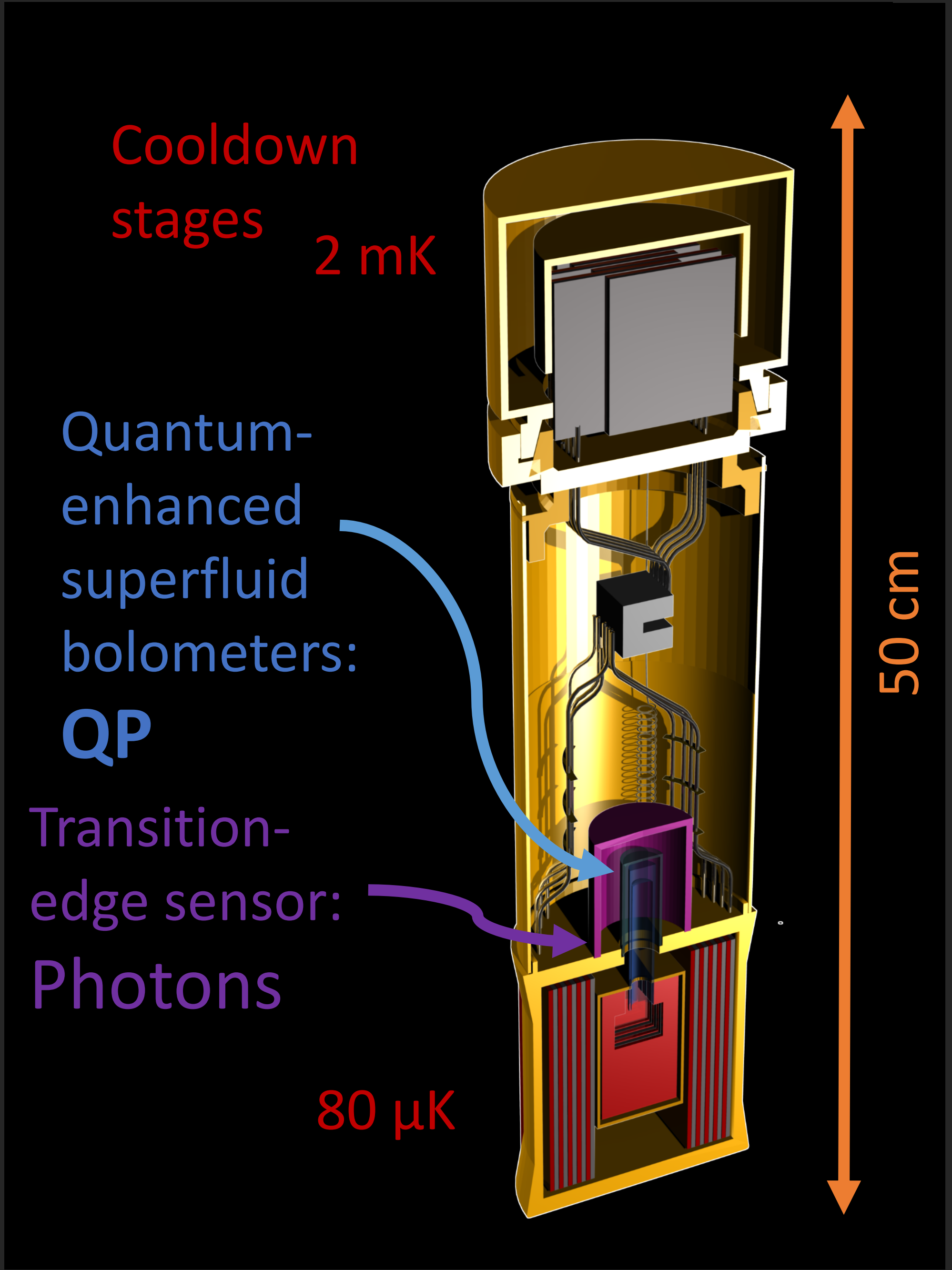




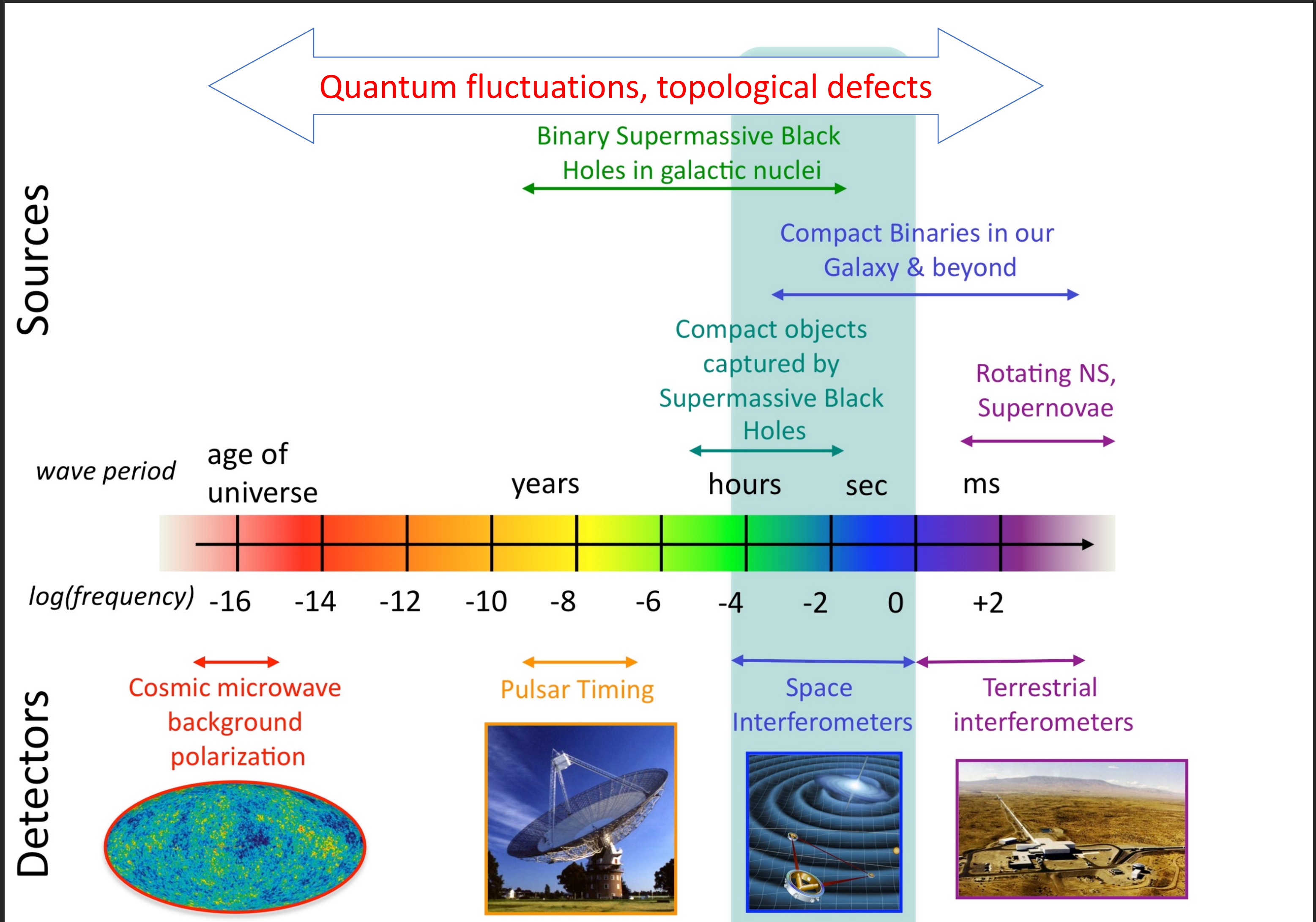
WP1: Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter

Prof Jocelyn Monroe

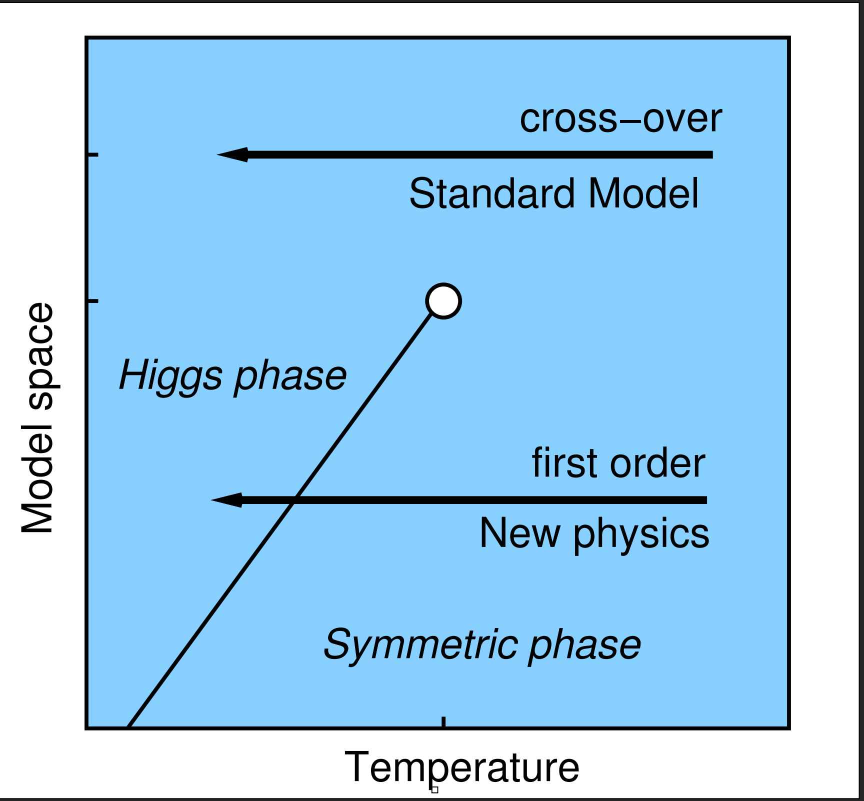
- We will use the existing LANC platform to cool five 1 cm^3 cells, each 0.1 gm of ^{3}He, to 80 μK, instrumented with nanobeams.
- Held in a box made of ultra-low radioactivity materials, inside of a 1000 cm^3 ^{3}He bath.
- The bath will be shielded inside a copper cryostat, cooled by a ^{4}He-filled reservoir, hosted in a 1 m thick concrete shield.
- Quasiparticles generated by a scattering event propagate ballistically until they are detected by a nanobeam.

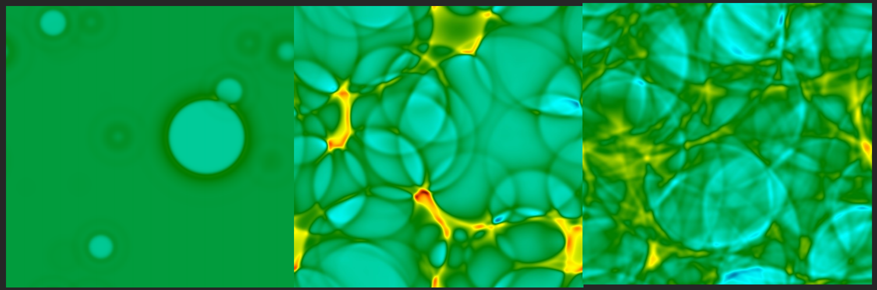


• In WP2: How did the early universe evolve?

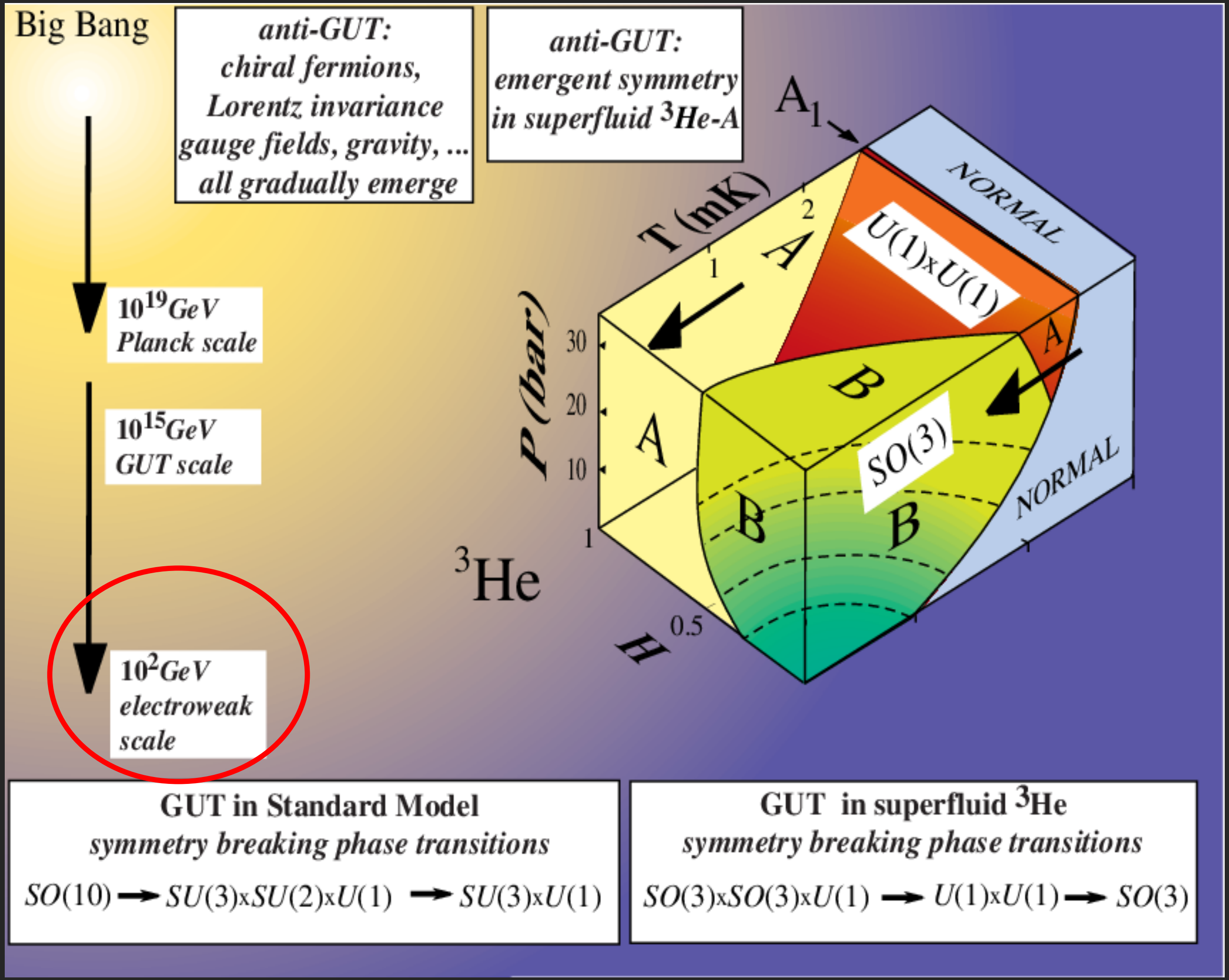


Gravitational waves ESA mission LISA (2034)





Numerical simulation of a phase transition



Precise control of Quantum analogue system, Superfluid ^{3}He & dynamics of phase transitions ***open gravitational wave window to physics beyond the Standard Model in the early universe***

Solve the nucleation puzzle in ^{3}He

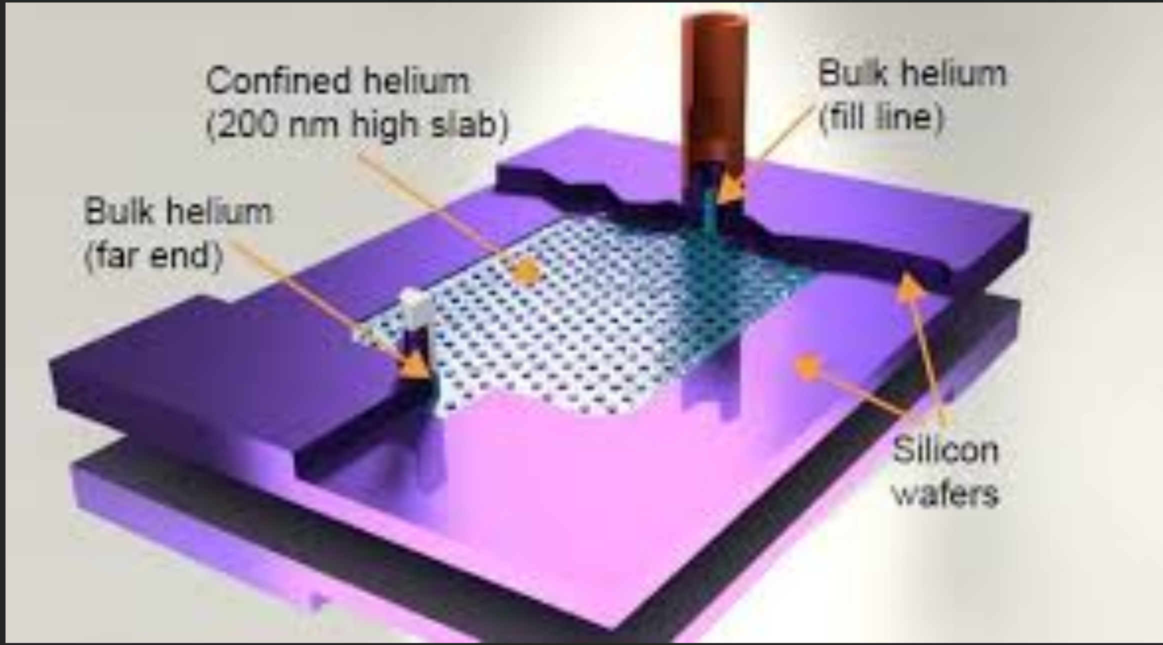
- Cross-disciplinary application of high performance computing using CSC Finland

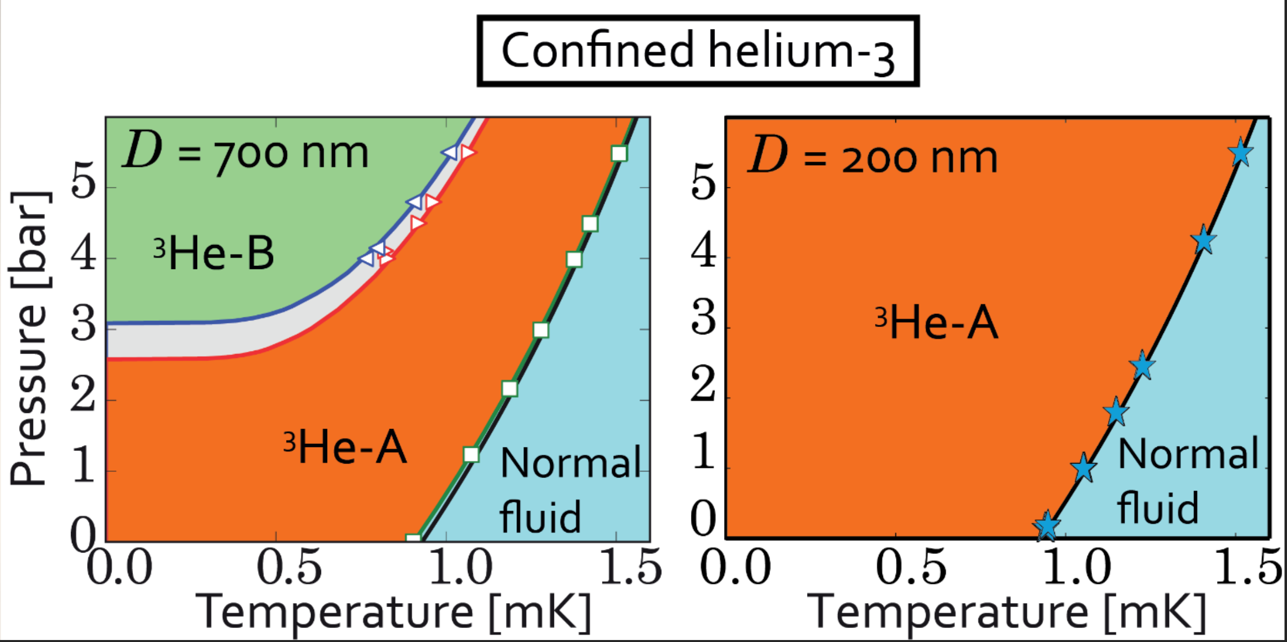
Develop new methods for out-of-equilibrium quantum dynamics

WP2: Phase transitions in extreme matter

Prof Mark Hindmarsh

- Engineer phase transitions between superfluid ^{3}He phases of distinct symmetry (a bulk bubble away from walls, under nanoscale confinement)
- Quantum sensors to probe the nucleation and dynamics of transition, control the free energy landscape with tuning parameters.





Science AAAS

Phase Diagram of the Topological Superfluid ^{3}He Confined in a Nanoscale Slab Geometry

L. V. Levitin,[1] R. G. Bennett,[1*] A. Casey,[1] B. Cowan,[1] J. Saunders,[1†] D. Drung,[2] Th. Schurig,[2] J. M. Parpia[3]

WP2: Phase transitions in extreme matter

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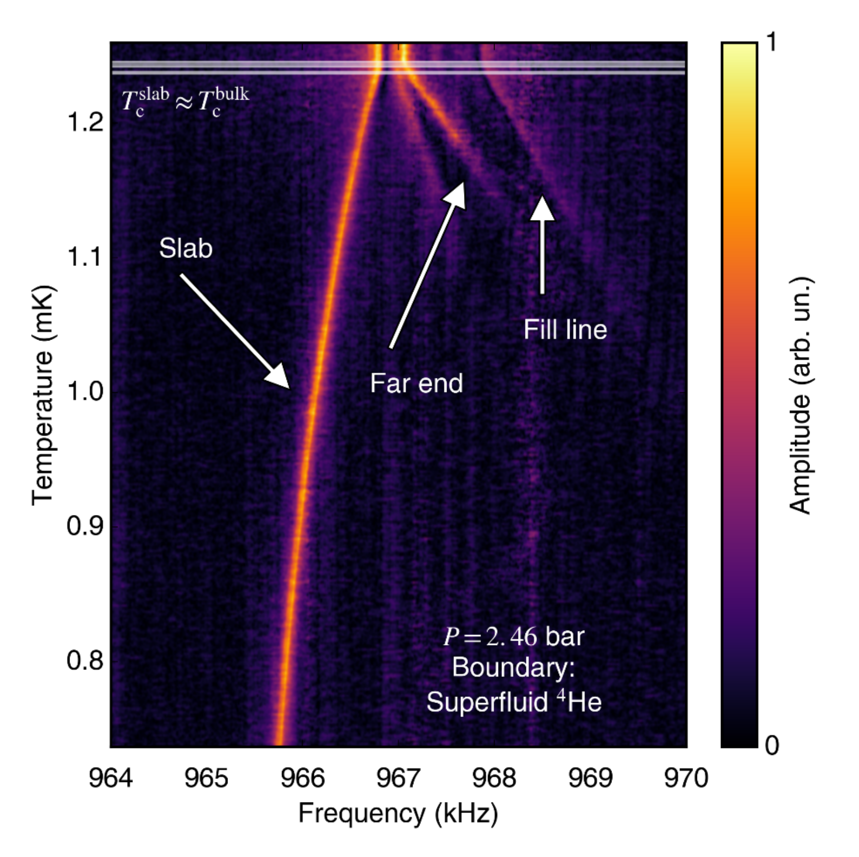

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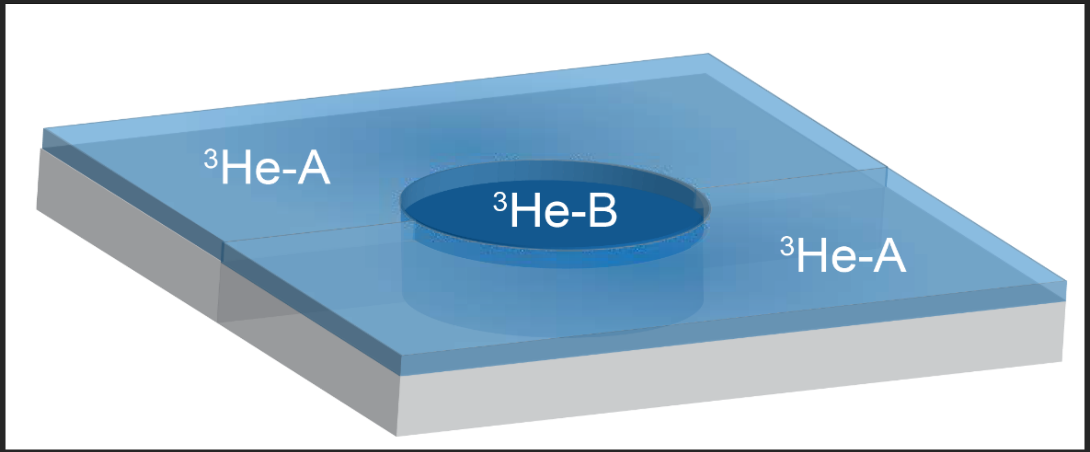

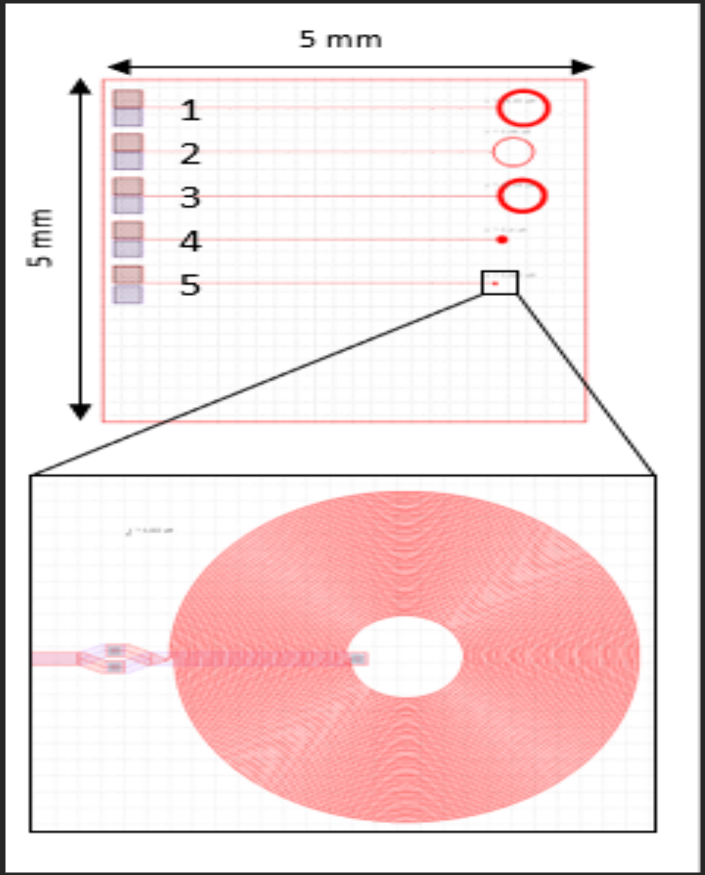

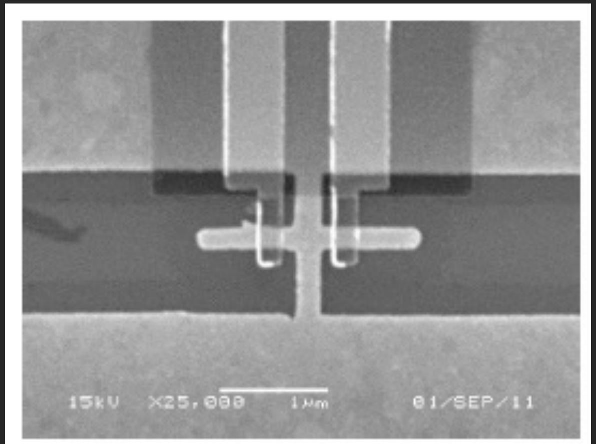

Hybrid Quantum Interference Device (HyQUID)
V T Petrashov, *et al.* Phys Rev Lett 74, 5268 (1995)

WP2: Phase transitions in extreme matter

Prof Mark Hindmarsh

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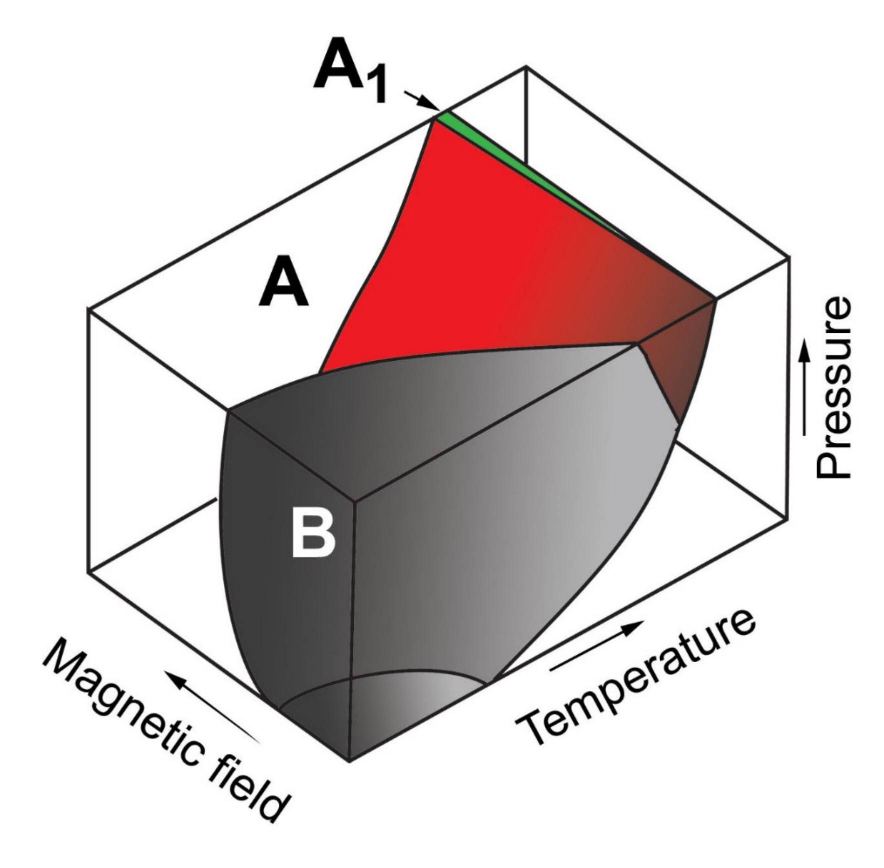
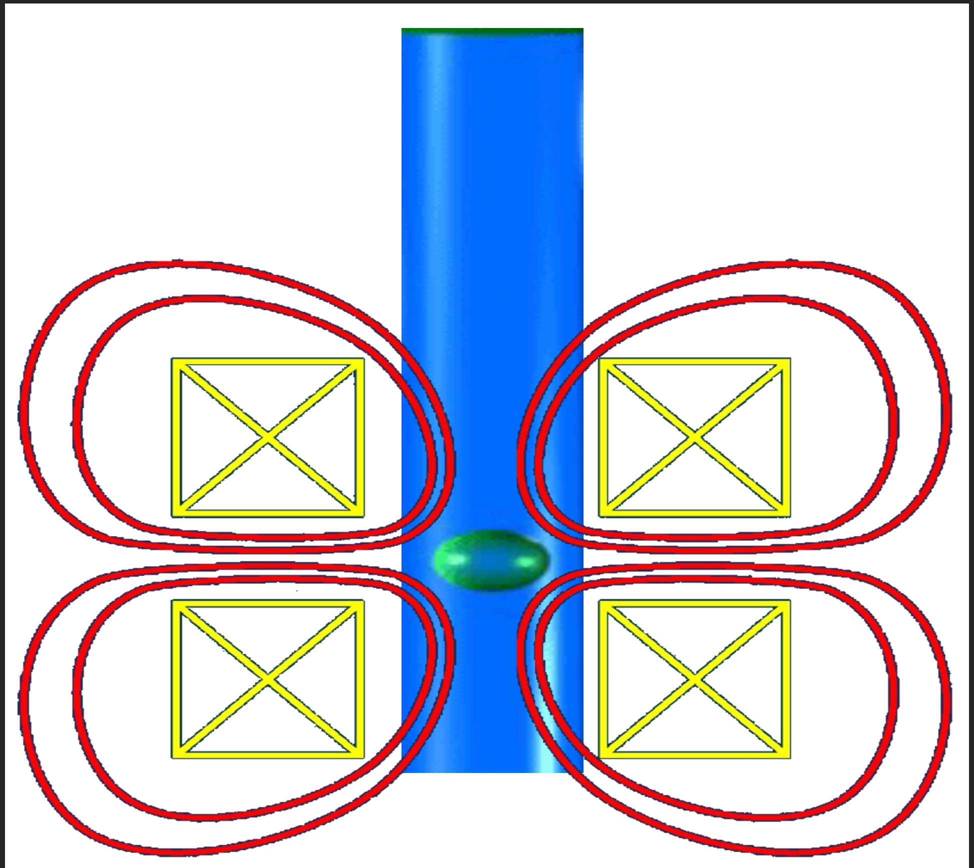
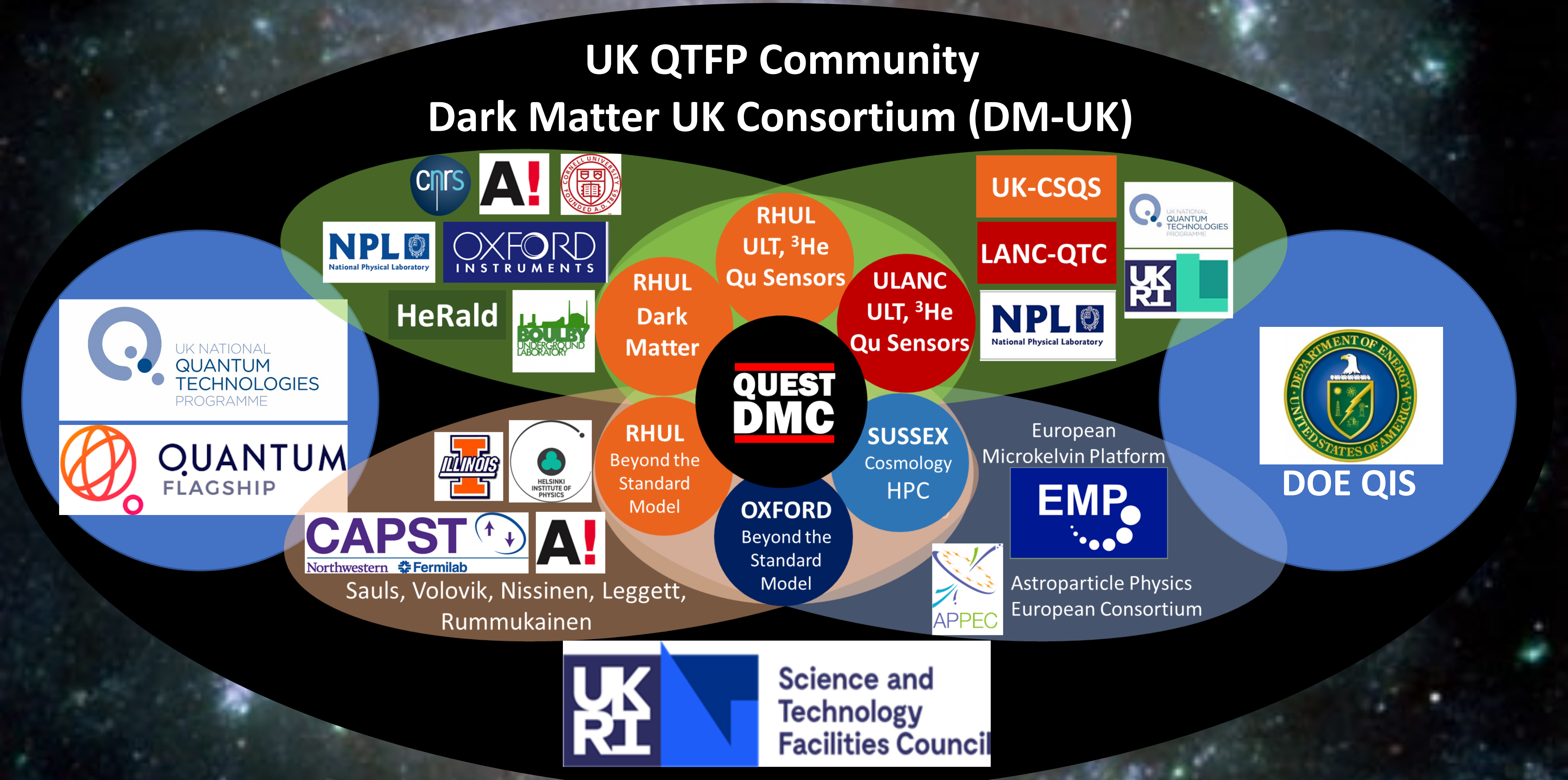




In the lifetime of the project and into the future

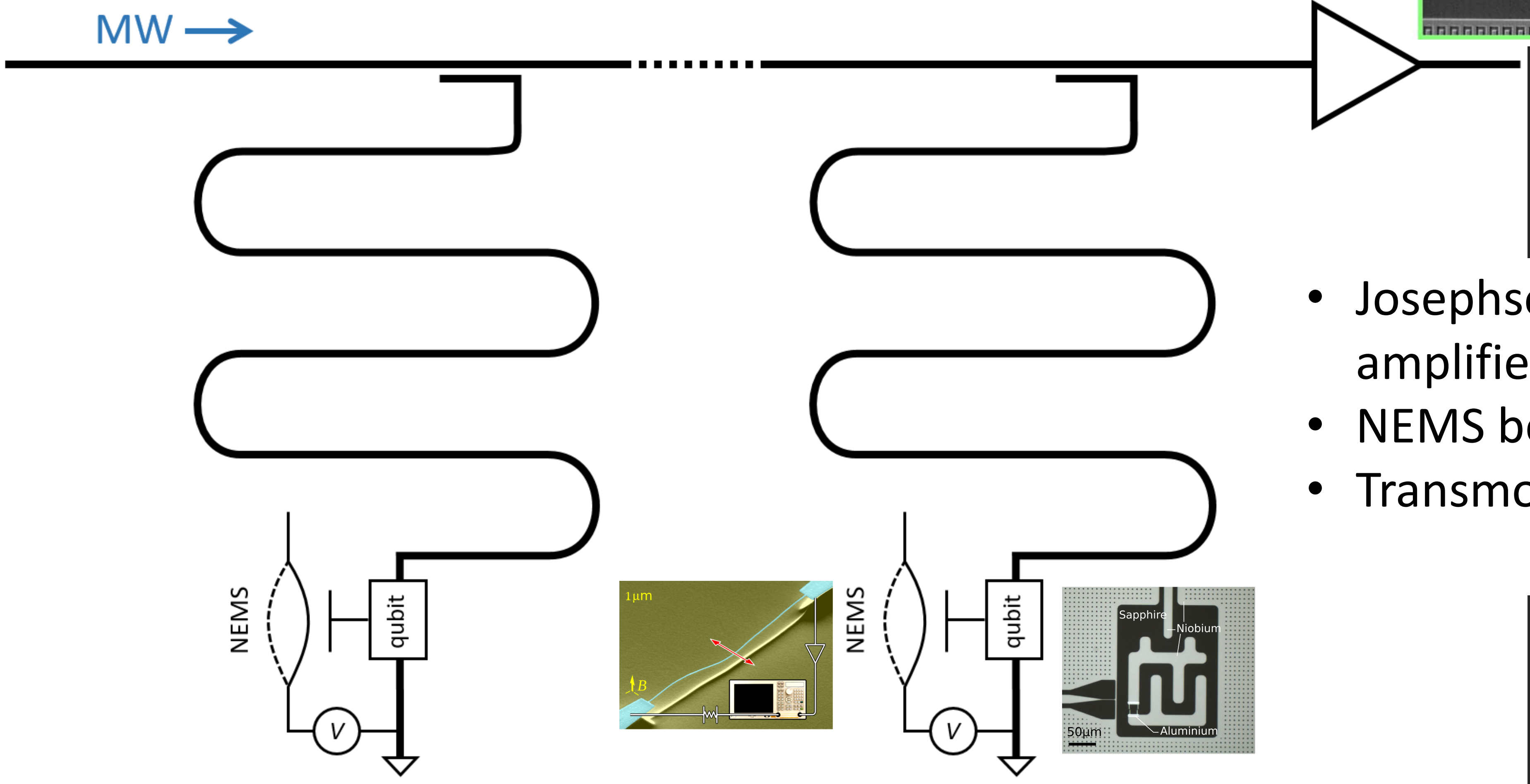
- Developed and operated new hybrid quantum sensors at ULT
  - Impacts on understanding of *Two Level Fluctuators*, leading to improved coherence time for Qubits
- Dark Matter Search, explored a new mass regime with world-leading sensitivity to spin-dependent interactions. Establish a new limit
  - Implement new generation hybrid quantum sensors to lower mass threshold
  - Improvements in background discrimination
  - Theoretical understanding and potential experimental exploitation of exotic properties of superfluid ^{3}He for detection of Dark Matter candidates behaving as classical fields
- Phase transitions in early universe, *solved* the nucleation problem
  - Dynamics of interfaces and Kibble-Zurek mechanisms in superfluid ^{3}He; HPC modelling
  - Reliable predictions of gravitational wave signatures at LISA and of new physics probed by the LHC
  - Expansion of programme to use superfluid ^{3}He as a quantum simulator, providing a driver for further quantum sensors, and more powerful theory (baryogenesis, fermionic Superfluid DM, neutron star matter for LIGO)

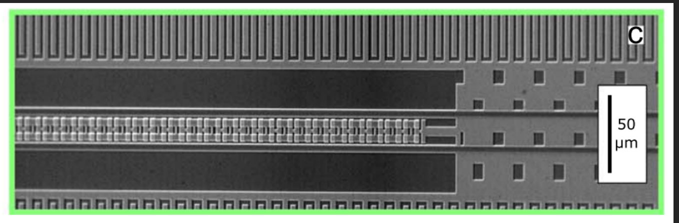

UK QTFP Community
Dark Matter UK Consortium (DM-UK)
HeRald
BOULBY UNDERGROUND LABORATORY
UK-CSQS
LANC-QTC
RHUL ULT, ³He Qu Sensors
RHUL Dark Matter
ULANC ULT, ³He Qu Sensors
QUEST DMC
RHUL Beyond the Standard Model
SUSSEX Cosmology HPC
OXFORD Beyond the Standard Model
UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME
QUANTUM FLAGSHIP
CAPST
Northwestern
Fermilab
HELSINKI INSTITUTE OF PHYSICS
Sauls, Volovik, Nissinen, Leggett, Rummukainen
European Microkelvin Platform
EMP
Astroparticle Physics European Consortium
APPEC
DOE QIS
Science and Technology Facilities Council

Quantum Technologies for Fundamental Physics

- SQUID readout of NEMs
- JPA, Transmon Qubit coupled to NEMs beam to address multiple bolometers
- HyQUIDs
- CQUIDs
- Microcoils coupled to SQUIDs/HyQUIDs

Using Quantum Computing architecture to address multiple bolometers.

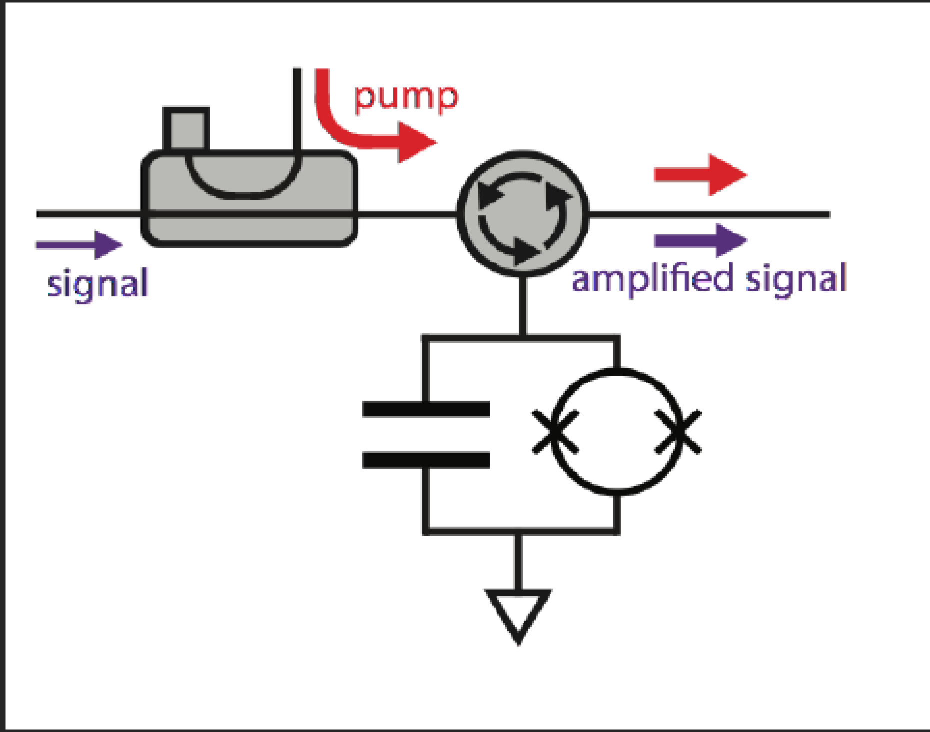


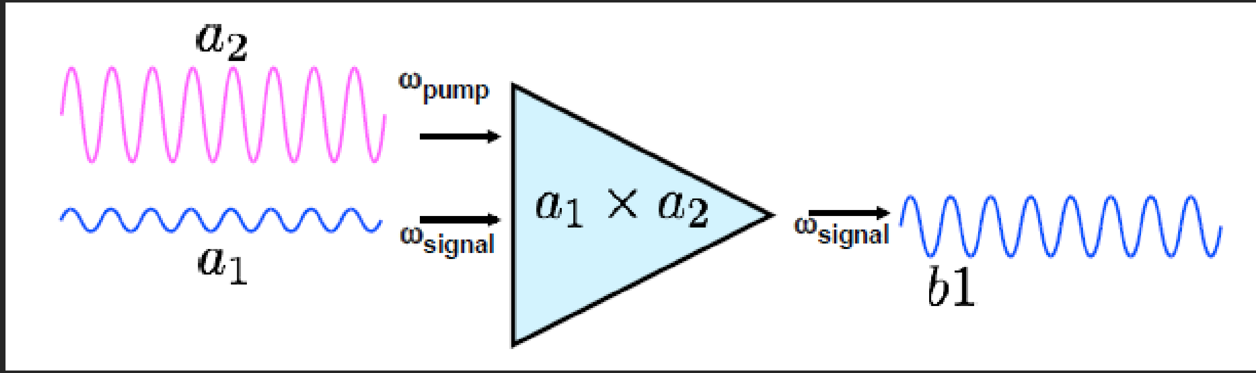


- Josephson Parametric amplifier
- NEMS beam
- Transmon Qubit

Josephson Parametric Amplifiers (JPA)

- Some non-linear element providing coupling between different modes.
- Josephson tunnel junctions non-linear and non-dissipative.

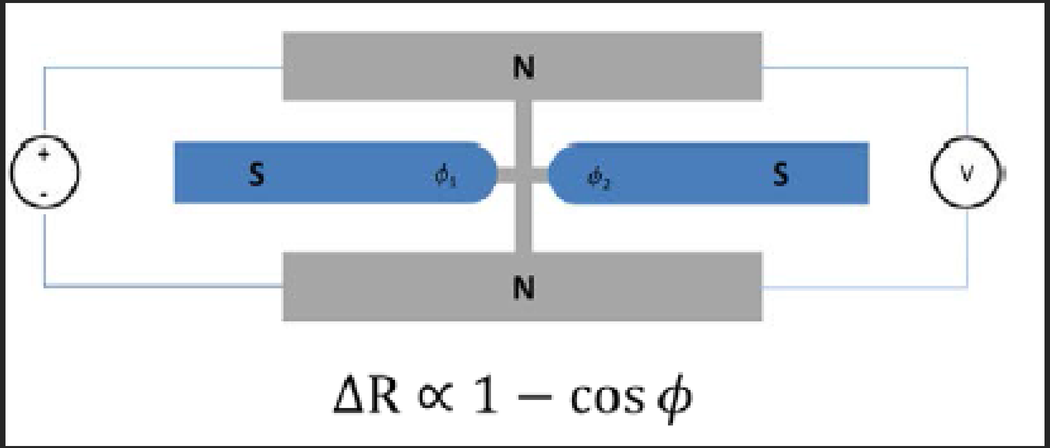


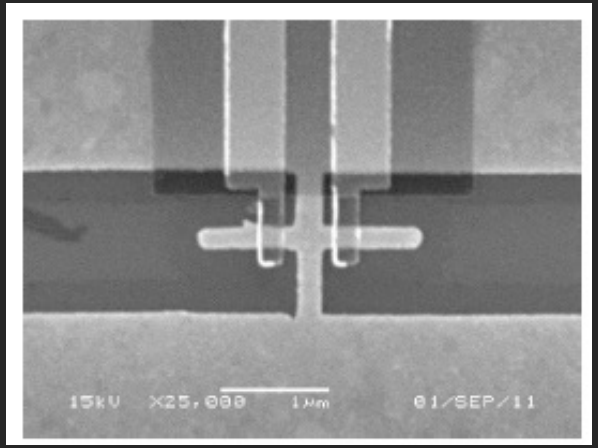


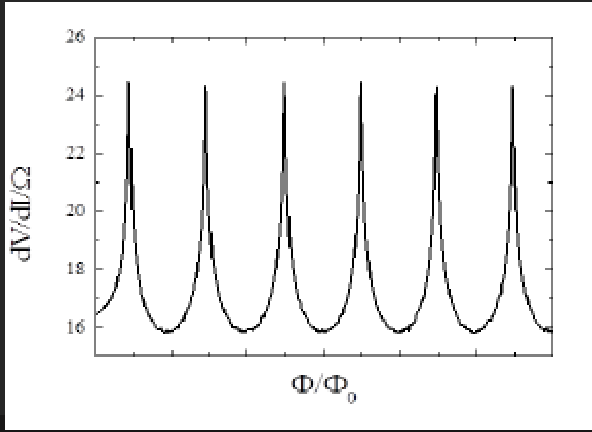
Hybrid Quantum Interference Device (HyQUID)

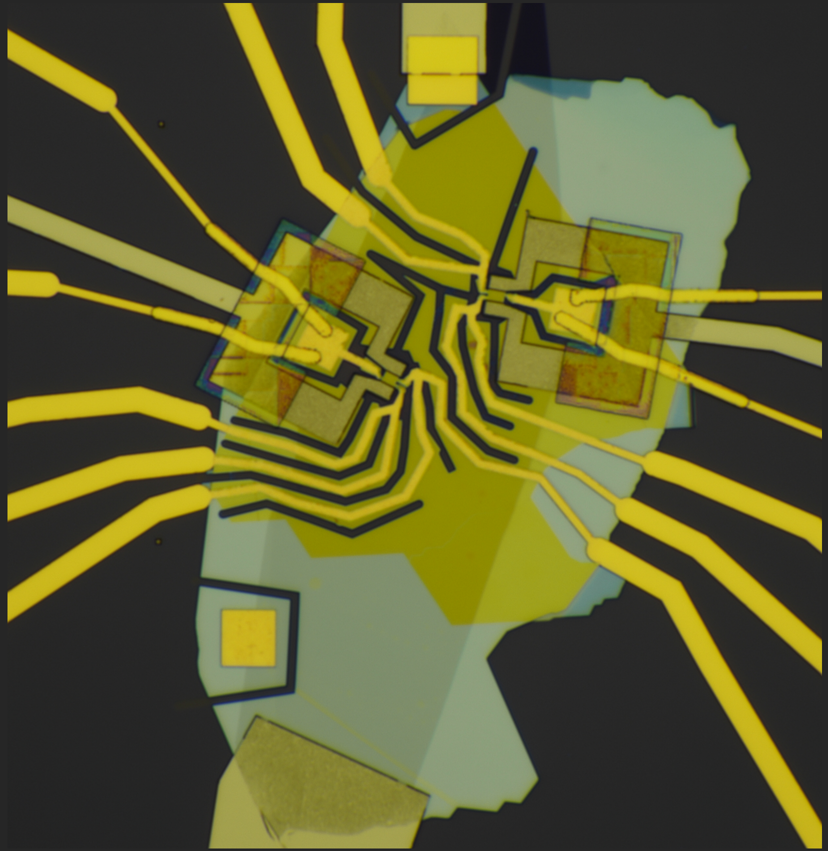
V T Petrashov, *et al.* Phys Rev Lett 74, 5268 (1995)

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



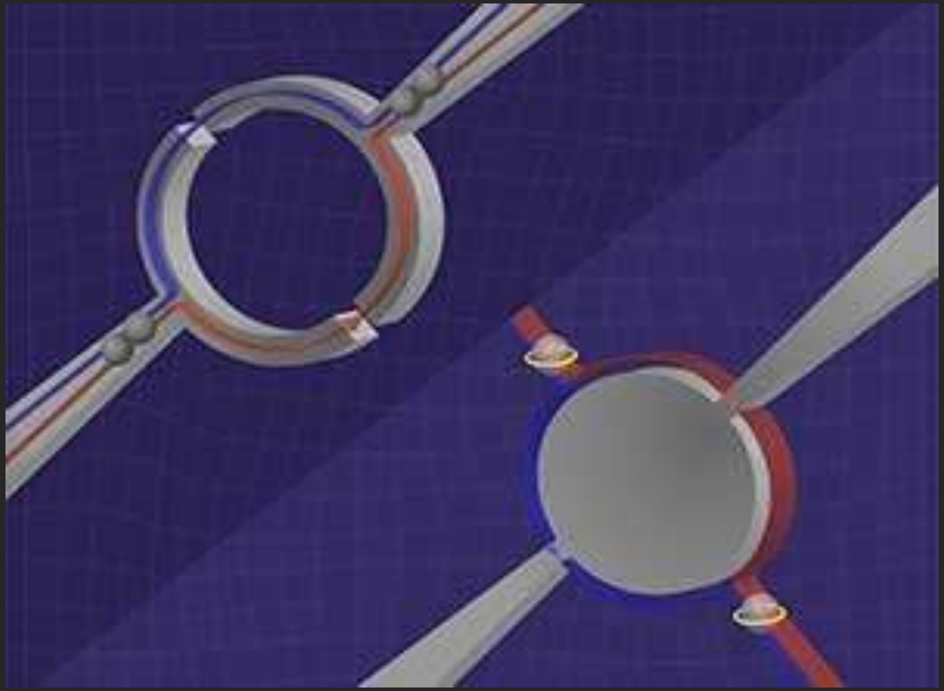






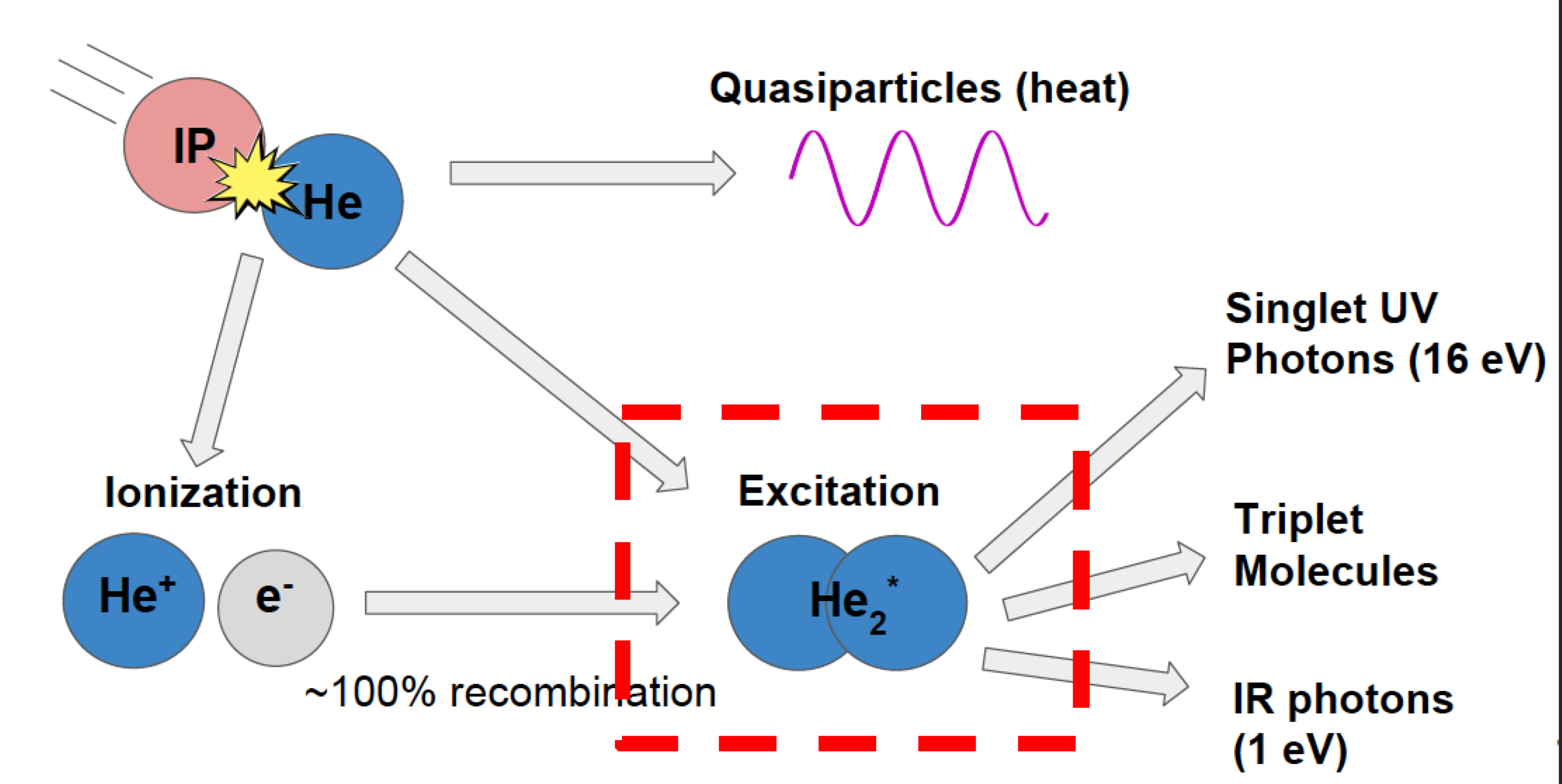
Charge Quantum Interference Device (CQUID)
Nature Physics vol. 14, 590–594 (2018), S.E de Graff et.al

- Instead of sensing a magnetic field via its influence on the current flow (moving charge) like a SQUID, the CQUID works seemingly in the opposite way, sensing charge as a result of quantum interference due to the flow of magnetic flux.
- Coherent quantum phase slips (CQPS) in nanowires of superconductors.

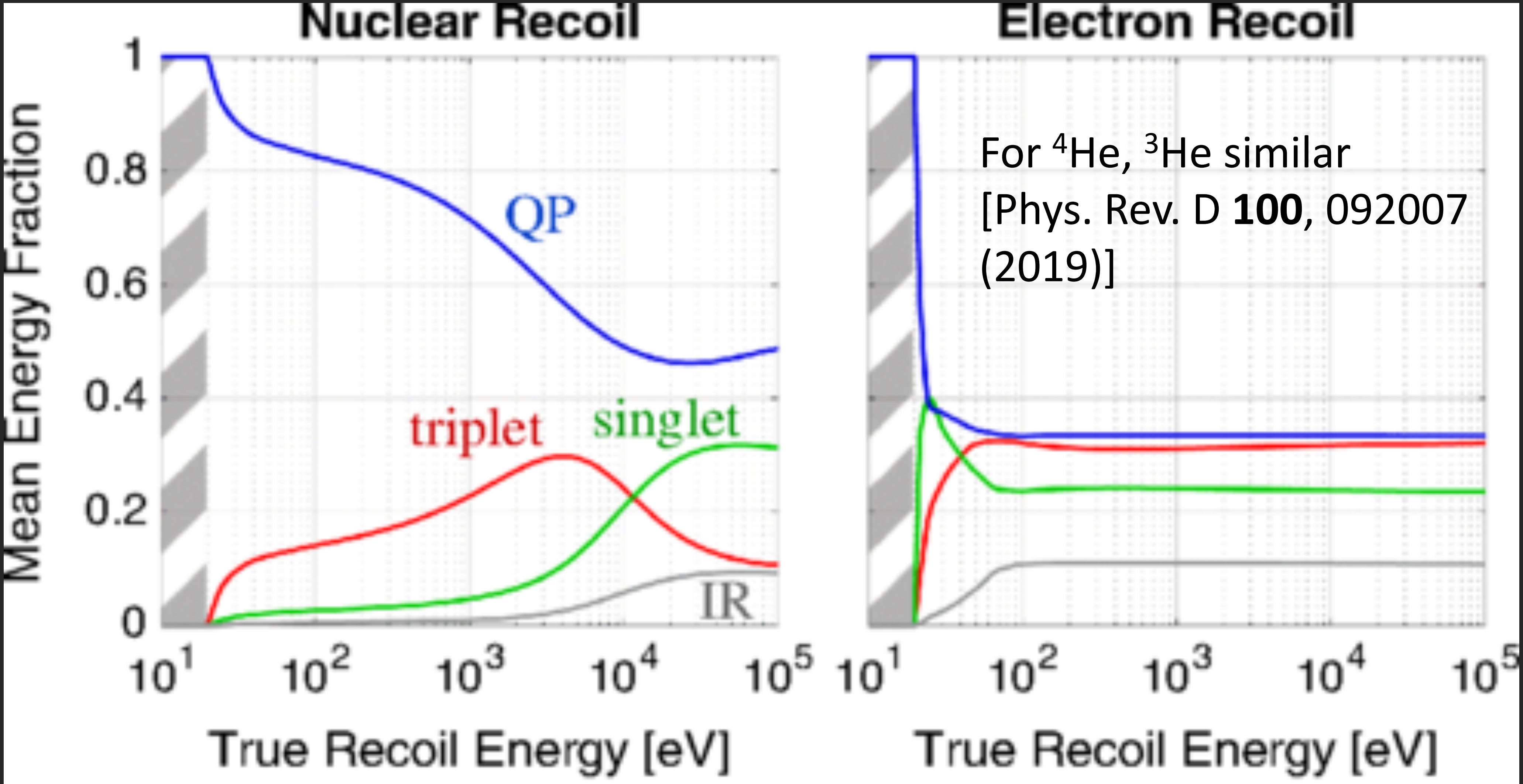


Discrimination of DM event

- **Project supporters/partners from both the US HeRald consortium and the historical ULTIMA project have shared experiences data to develop initial discrimination schemes.**


IP
He
Quasiparticles (heat)
Singlet UV
Photons (16 eV)
Ionization
Excitation
He^+
e^-
He_2^*
Triplet
Molecules
~100% recombination
IR photons
(1 eV)

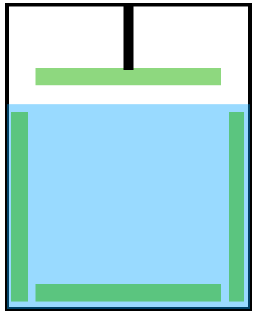
HeRald UV TES

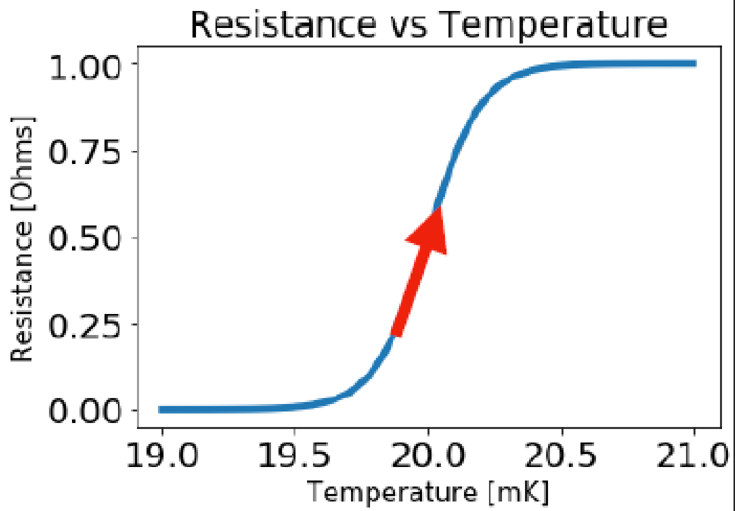


HeRald UV TES

The Calorimeters

- Plans to use Transition Edge Sensor (TES) based calorimetry
- Use sharp superconducting phase transition to convert heat signals to electrical signals
- Small current signals read out by inductively coupled SQUID electronics
- You can increase sensitivity by:
  - Lowering temperature

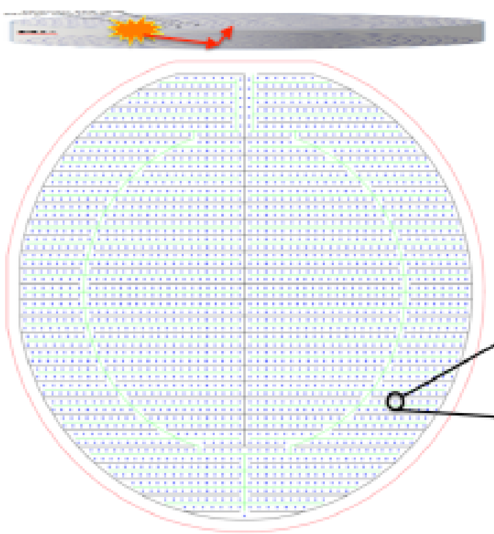




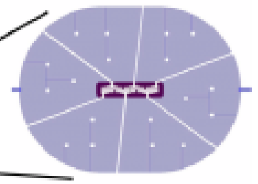
HeRald UV TES

- Calorimetry from M. Pyle at Berkeley (below is from a recent talk)

Large Area Photon Detector: Just Shrink a SuperCDMS detector



- 3" diameter Si wafer (45.6 cm^2)
- 1mm thick
- Distributed athermal phonon sensors minimize phonon collection time (as fast as it can be for its size)
  - Athermal Phonon collection time estimated to be ~20us
  - 2.5% sensor coverage



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