

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



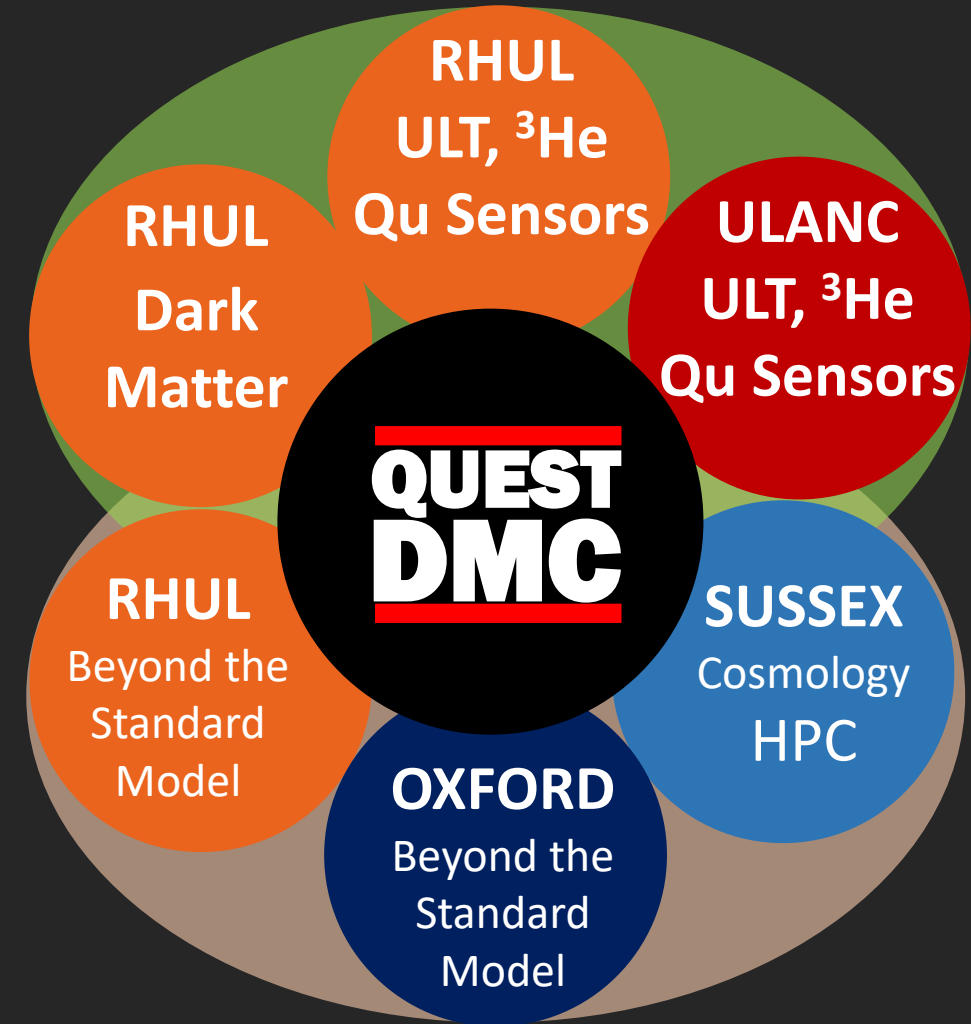
Experiment:

S. Autti², A. Casey¹, R. Haley², P. Heikkinen¹, S. Kafanov², L.V. Levitin¹, J. Monroe¹, J. Prance², X. Rojas¹, J. Saunders¹, A. Singh¹, M. Thompson², V. Tsepelin², D. Zmeev², V. Zavyalov²

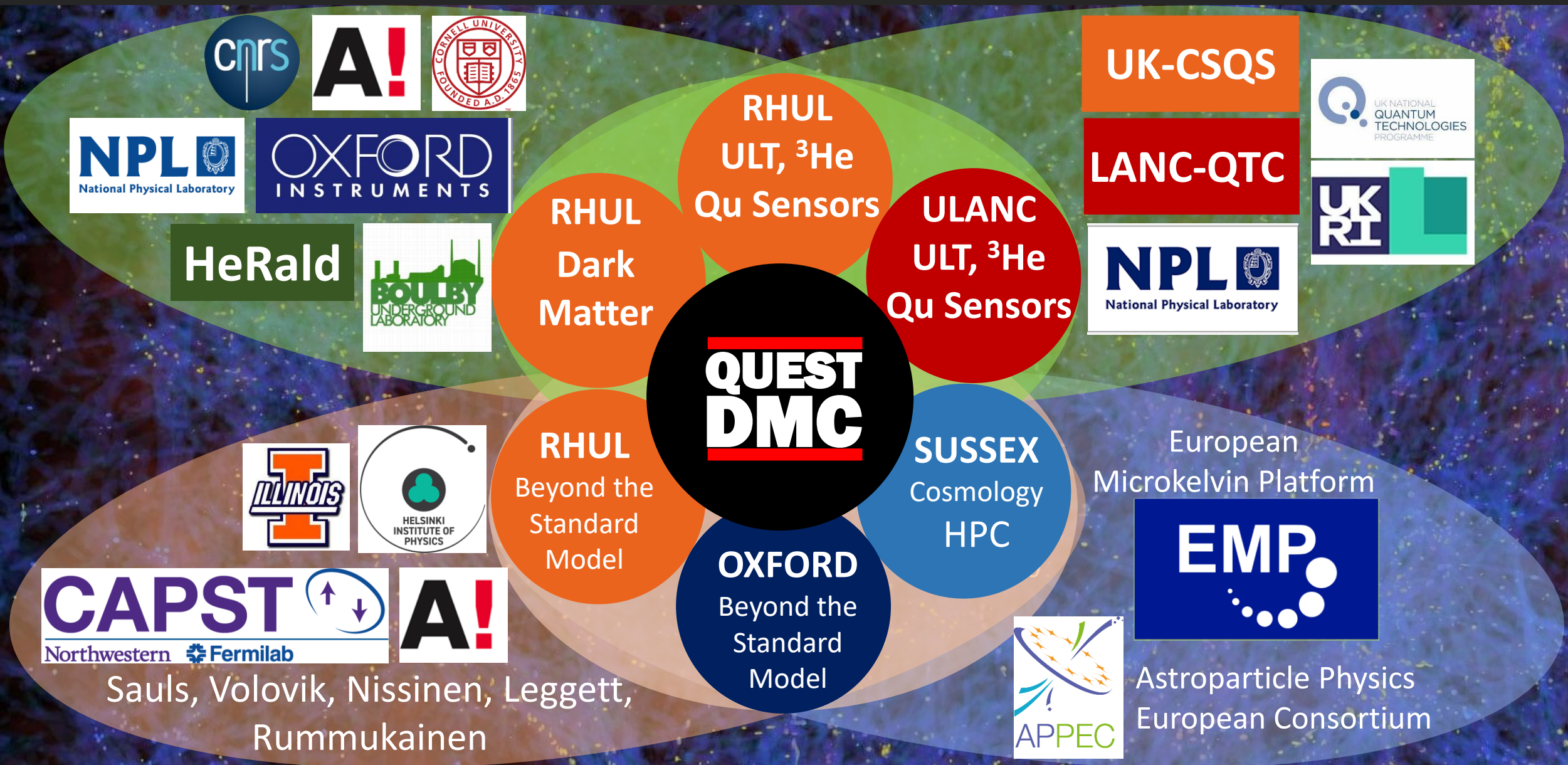
Theory:

M Hindmarsh³, S Huber³, J. March-Russell⁴, S. West¹, Q. Zhang³

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QUEST – DMC Ecosystem



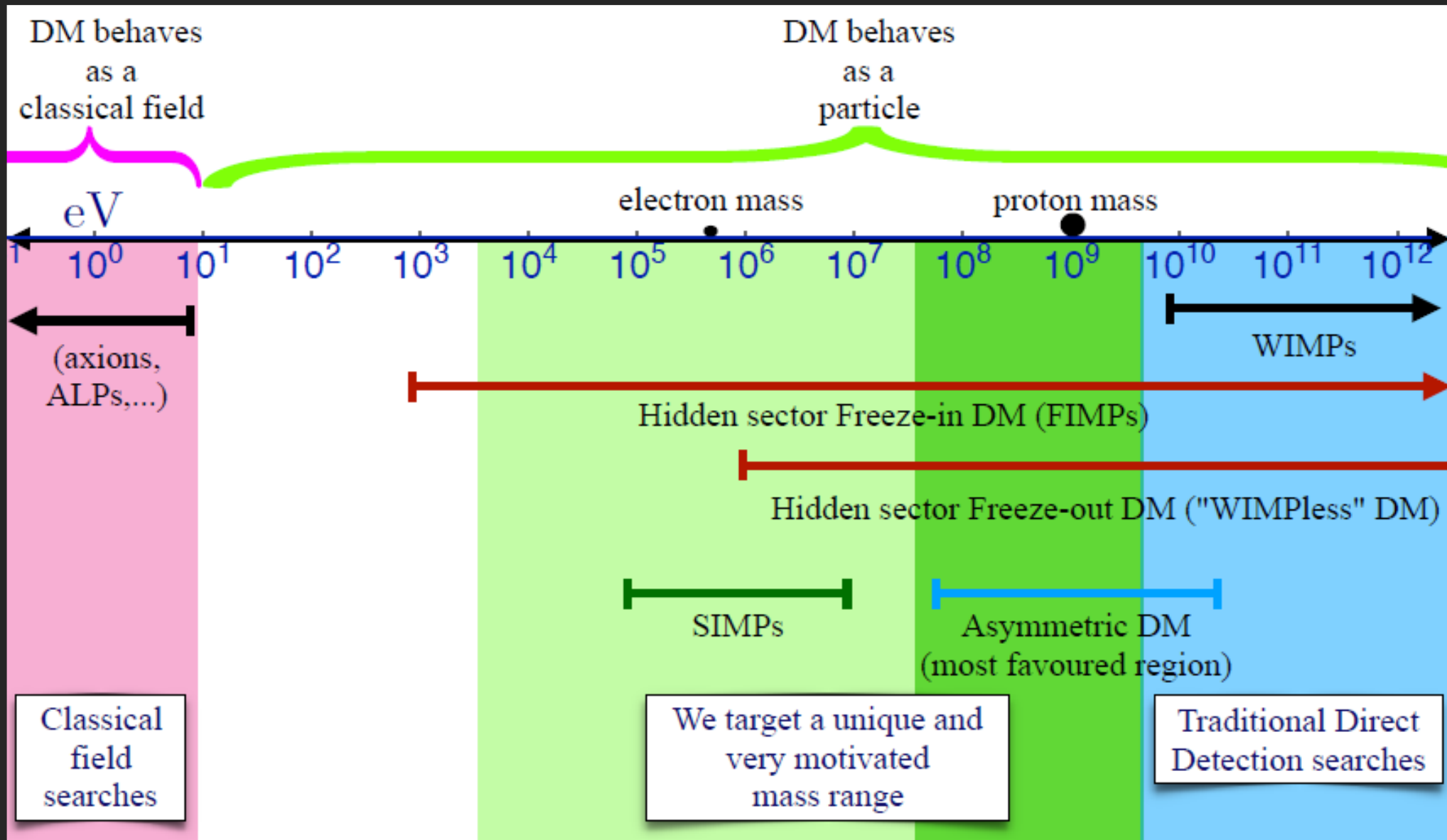
Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

We will address two fundamental open questions in cosmology

- **WP1:** What is the nature of Dark Matter?
 - Detection of sub-GeV dark matter with a quantum-amplified superfluid ^3He calorimeter
- **WP2:** How did the early universe evolve?
 - Phase transitions in extreme matter

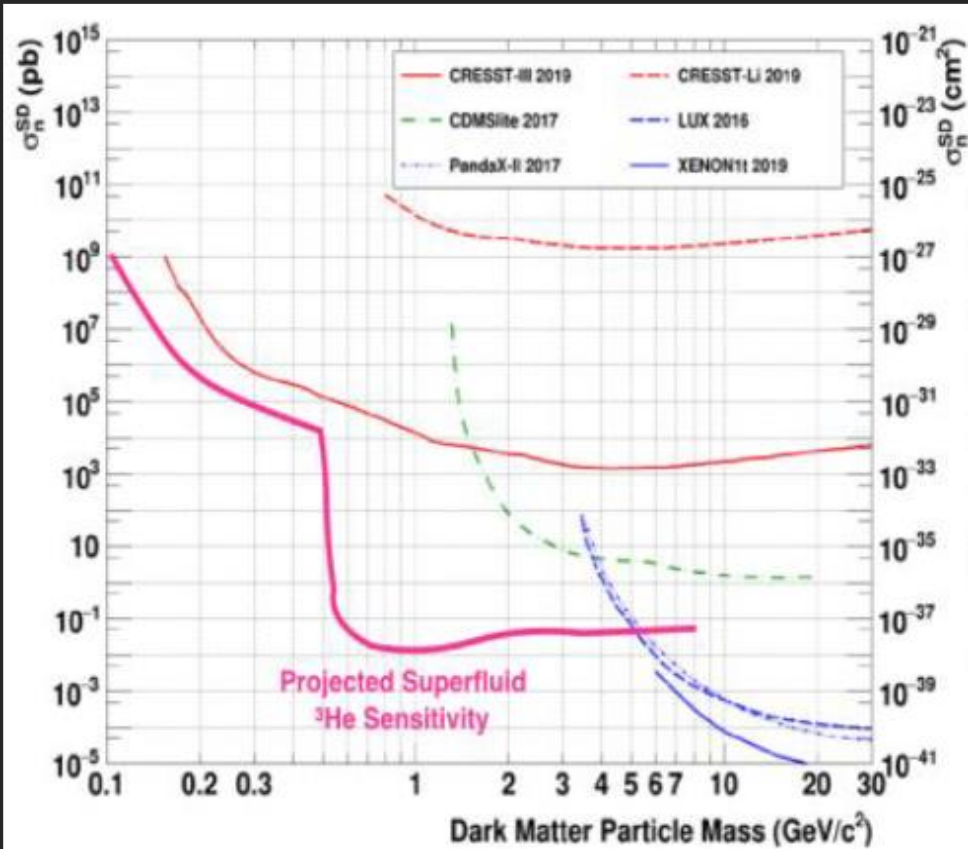
Linked through requirement of beyond-standard model physics and the internationally unique experimental approach of combining quantum sensors with ^3He at ultralow temperatures.

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



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

New mass regime with world-leading sensitivity to spin-dependent interactions, 10 eV threshold



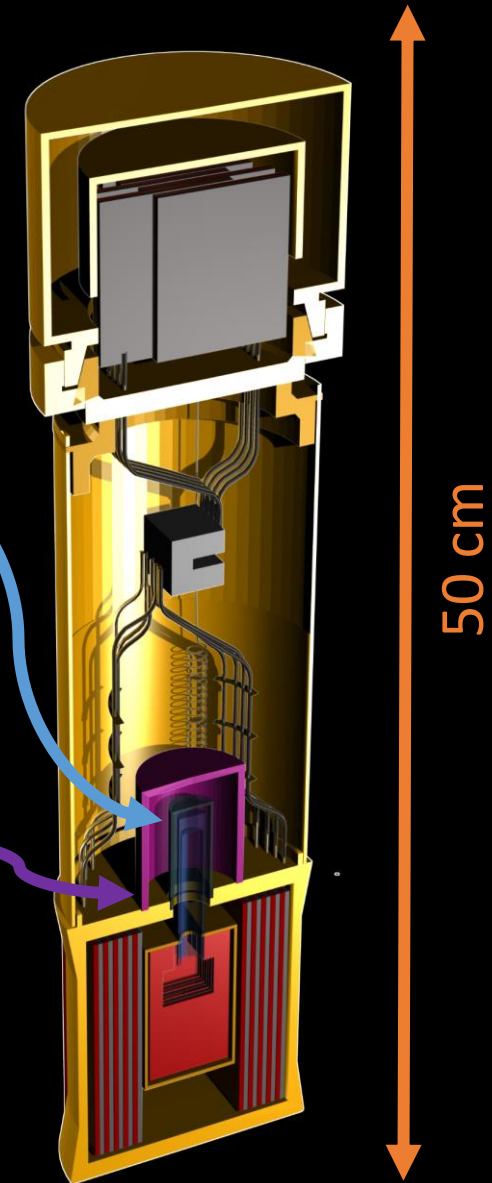
Readout requires low dissipation, low noise, quantum sensor to reach ULT

Cooldown stages 2 mK

Quantum-enhanced superfluid bolometers: QP

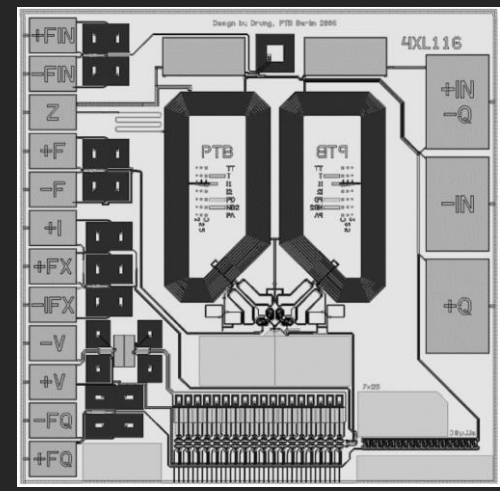
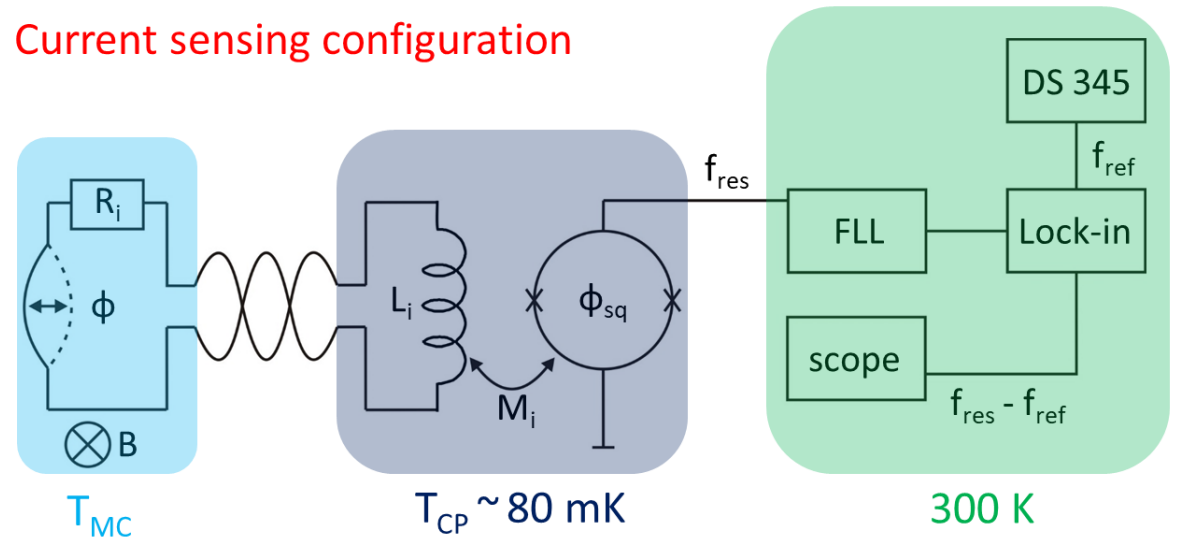
Transition-edge sensor: Photons

80 μK

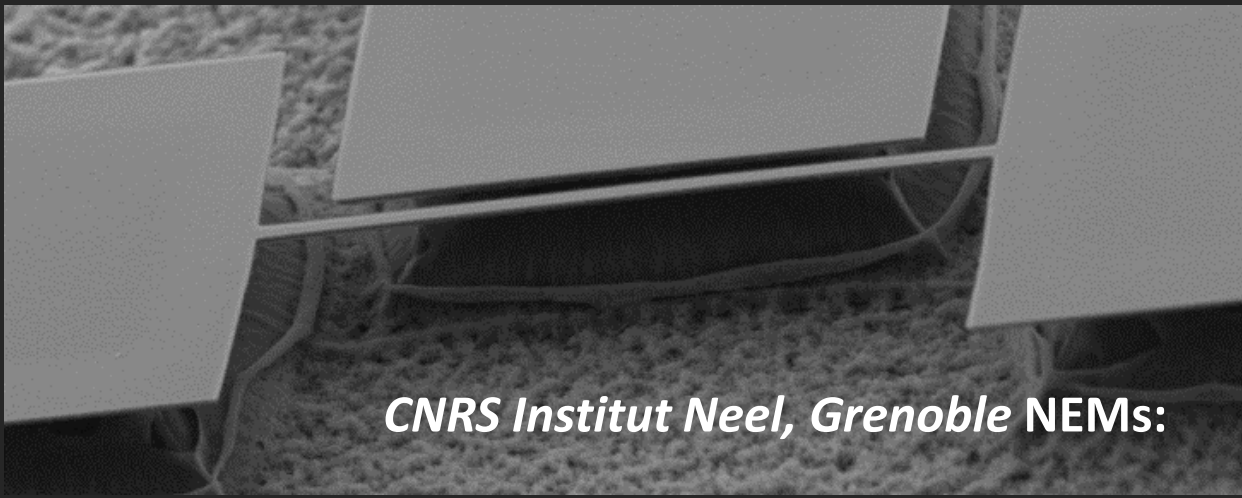
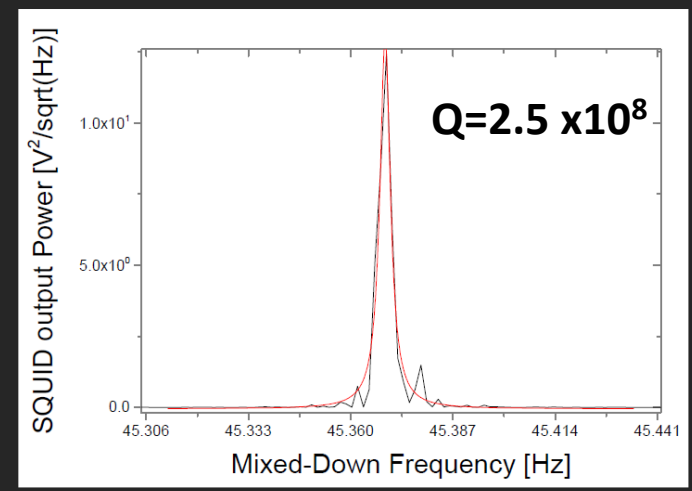


Merging existing state-of-art tech to achieve beyond 10 eV resolution

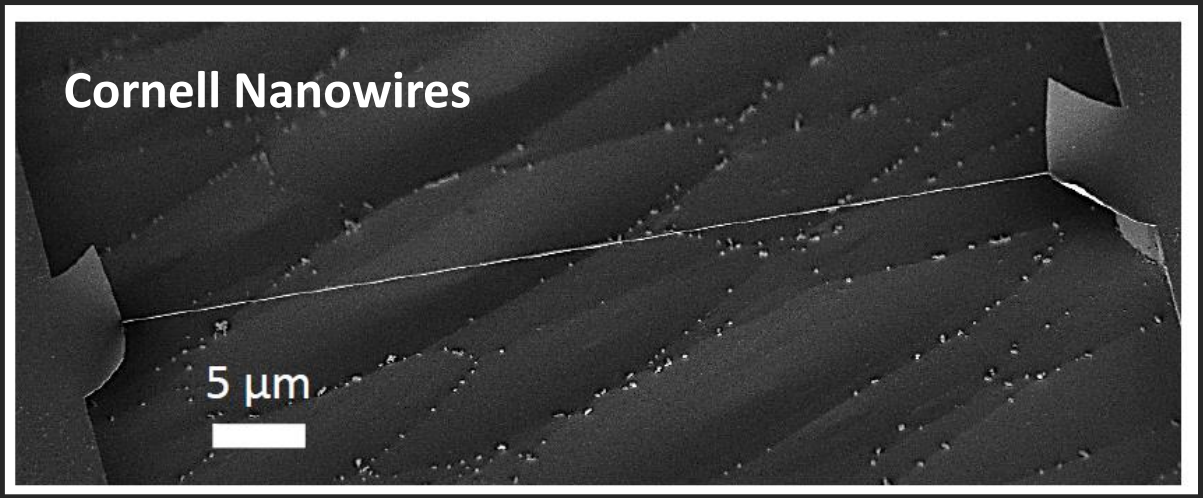
Current sensing configuration



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

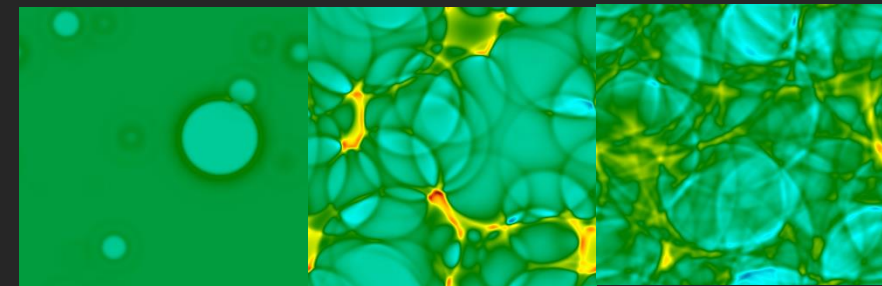
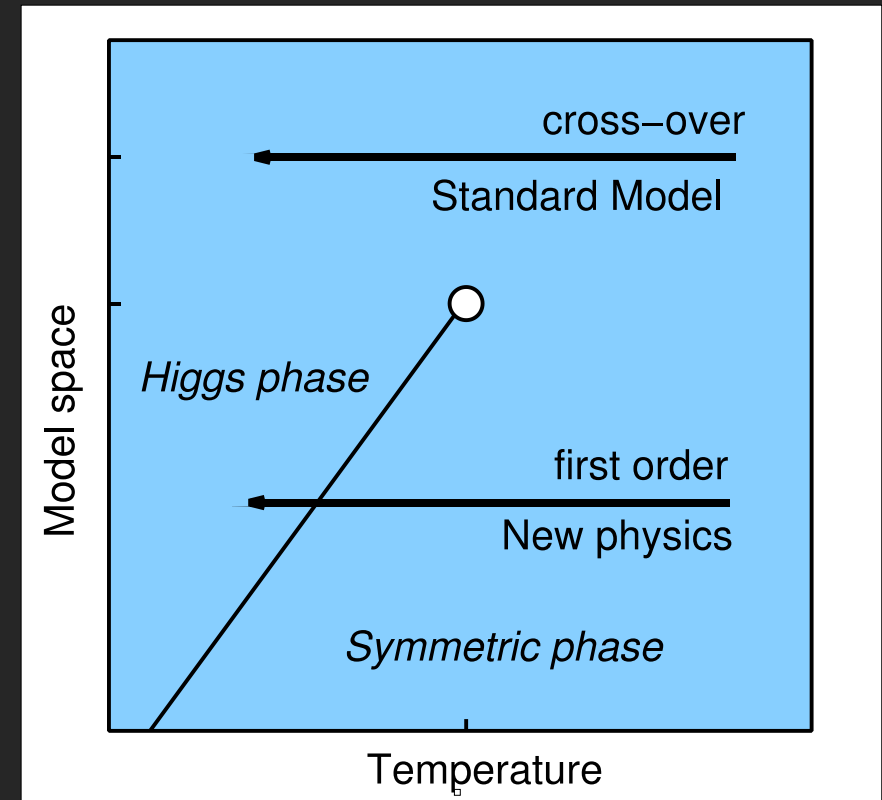
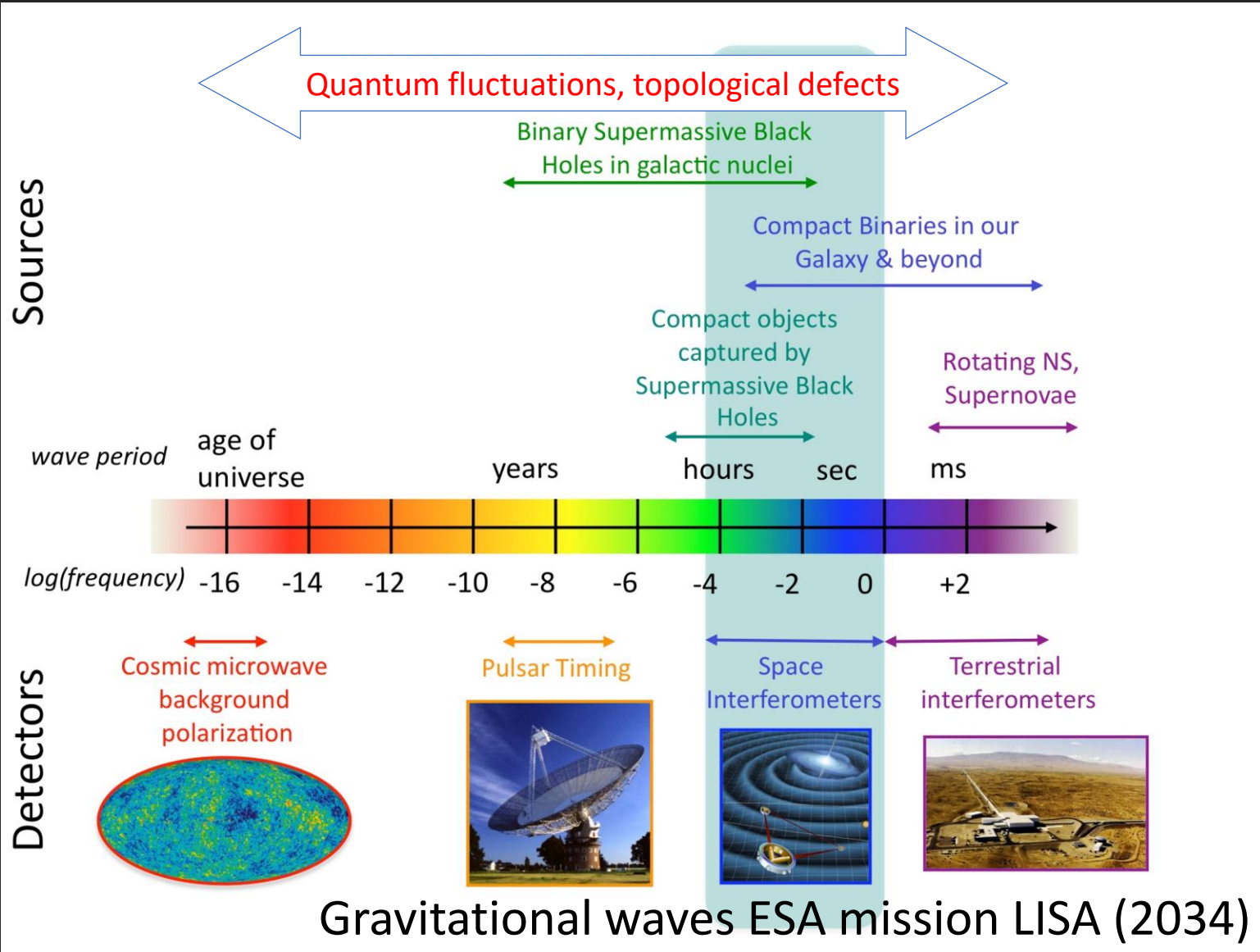


CNRS Institut Neel, Grenoble NEMs:



Cornell Nanowires

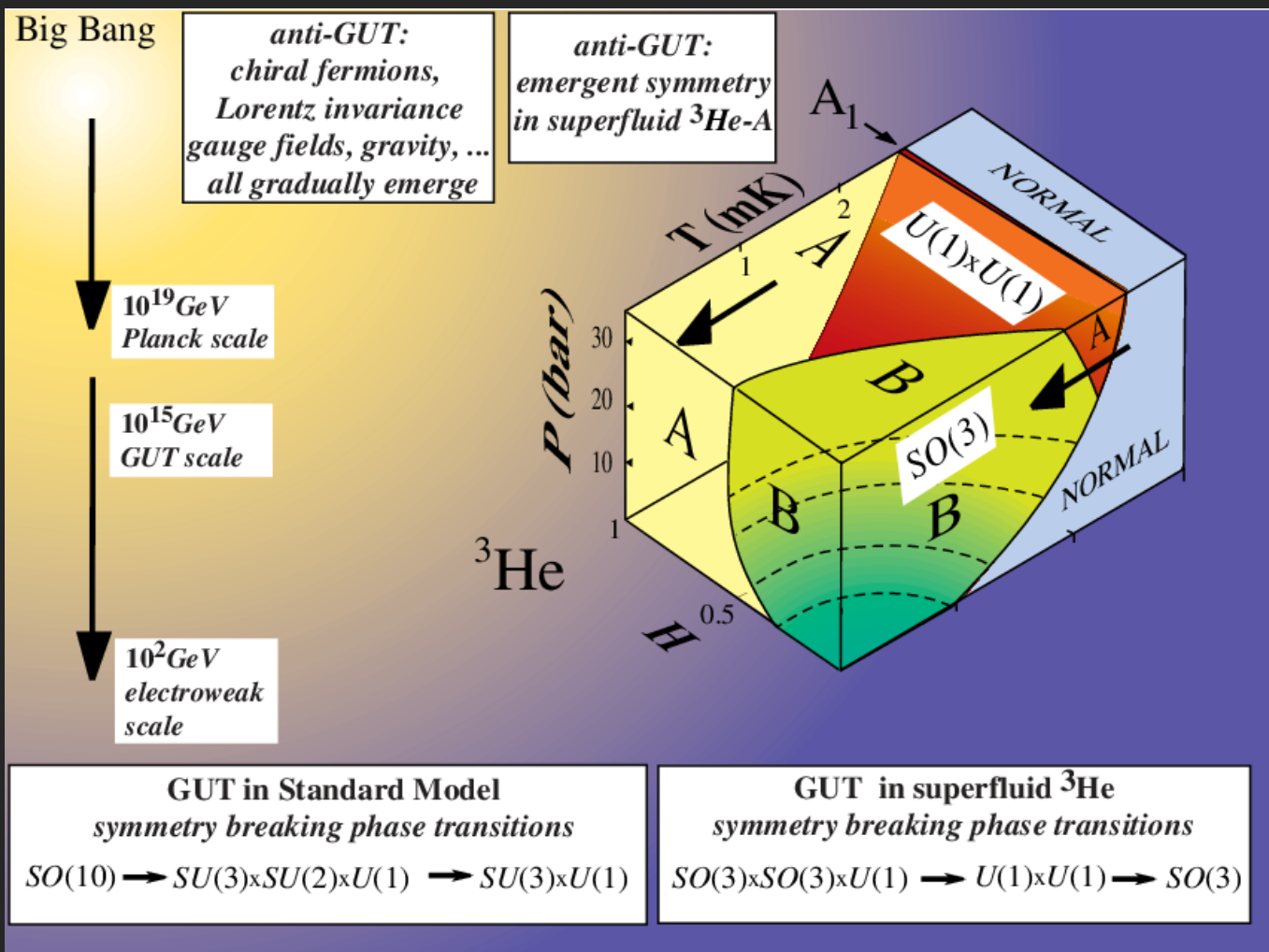
- In WP2: How did the early universe evolve?



Numerical simulation of a phase transition

WP2: Phase transitions in extreme matter

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



Nucleation puzzle in ^3He

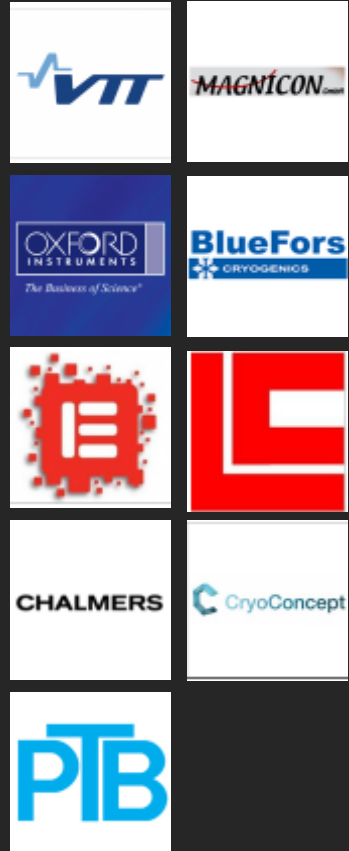
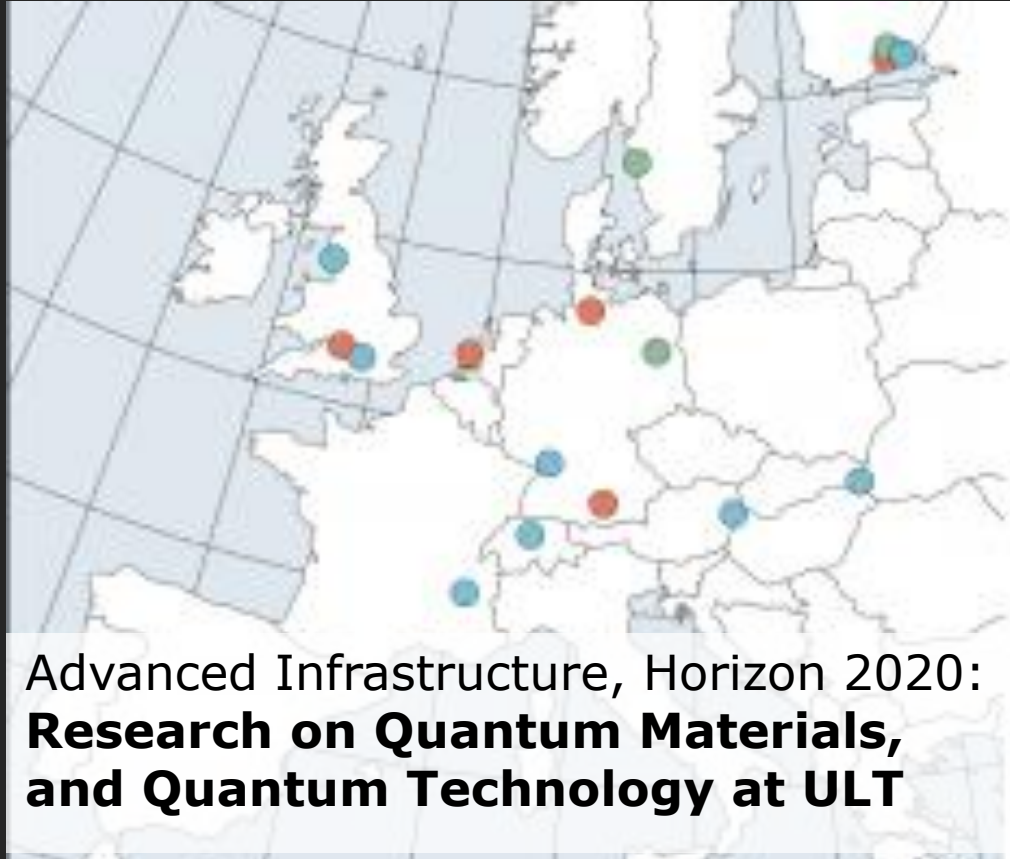
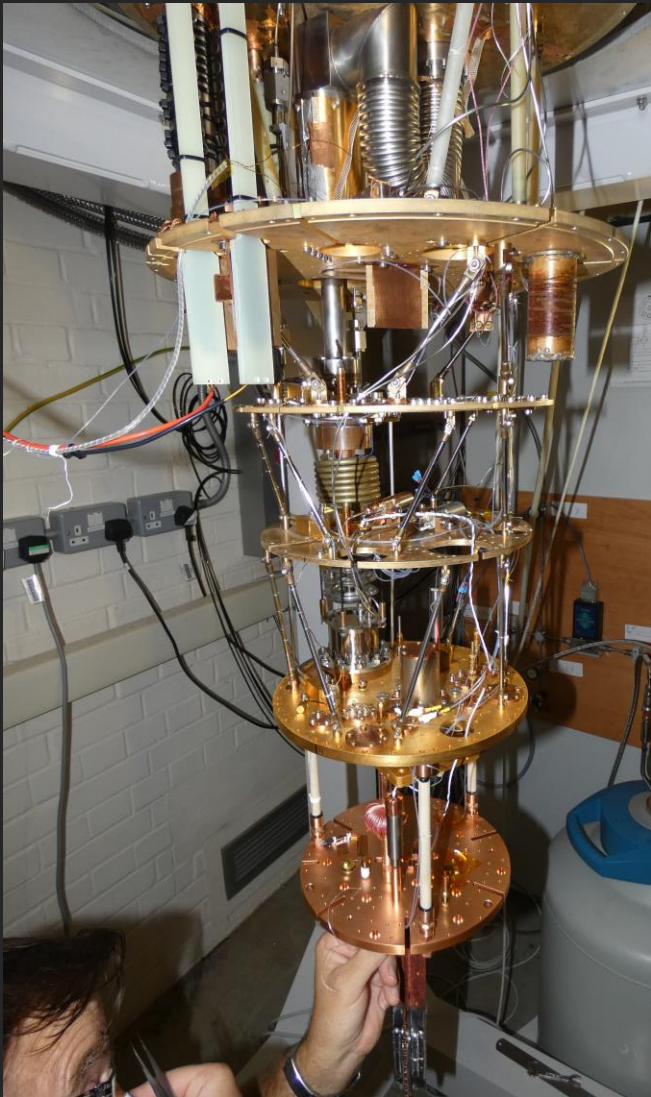
- Engineer phase transitions between superfluid ^3He phases of distinct symmetry.
- Quantum sensors to probe the nucleation and dynamics of transition, control the free energy landscape with tuning parameters.
- Application of high performance computing using CSC Finland

Develop new methods for out-of-equilibrium quantum dynamics

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



A fast turnaround cryogen-free sub-500 μK platform providing large ultraquiet experimental volume.



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 ^3He 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 ^3He ; HPC modelling
 - Reliable predictions of gravitational wave signatures at LISA and of new physics probed by the LHC
 - Expansion of programme to use superfluid ^3He as a quantum simulator, providing a driver for further quantum sensors, and more powerful theory (baryogenesis, fermionic Superfluid DM, neutron star matter for LIGO)