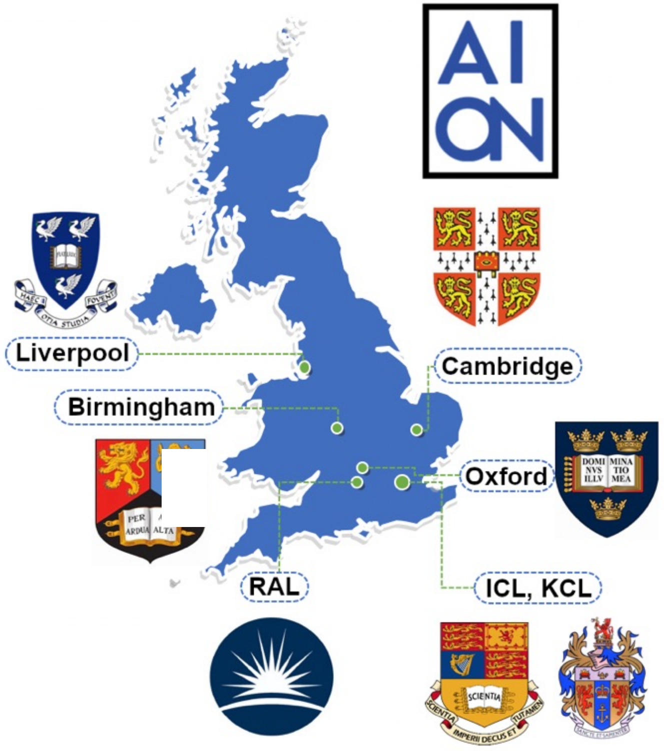
Imperial College London

AION PPTAP detector workshop



The AION Project

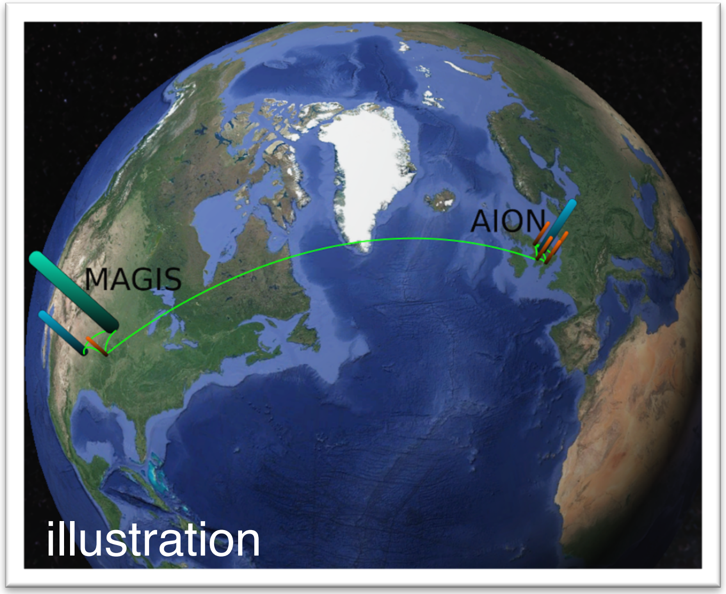
A UK Atom Interferometer Observatory and Network

to explore Ultra-Light Dark Matter and Mid-Frequency Gravitational Waves.

O. Buchmueller, Imperial College London on behalf of the AION Collaboration

L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4], D. Bortoletto[3], T. Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman[5], G. Elertas[5], J. Ellis[1,$,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*], M. Holynski[4], A. Khazov[2], M. Langlois[4], S. Lellouch[4], Y.H. Lien[4], R. Maiolino[7], P. Majewski[2], S. Malik[6], J. March-Russell[3], C. McCabe[1], D. Newbold[2], R. Preece[3], B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. Singh[4], M. Tarbutt[6], M. A. Uchida[7], T. V-Salazar[2], M. van der Grinten[2], J. Vossebeld[4], D. Weatherill[3], I. Wilmut[7], J. Zielinska[6]

[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge

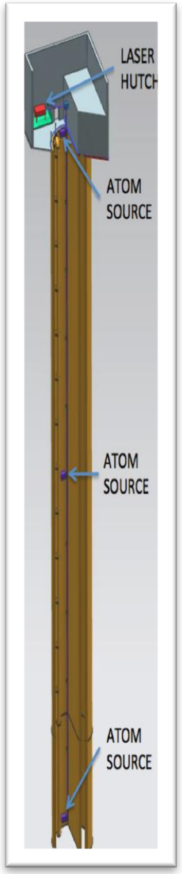


Project executed in national partnership with **UK National Quantum Technology Hub in Sensors and Timing, Birmingham, UK,** and international partnership with **The MAGIS Collaboration and The Fermi National Laboratory, US**

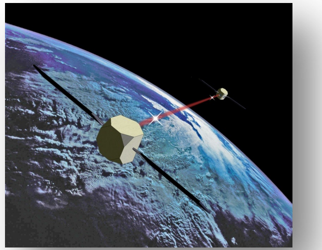
The AION Programme consists of 4 Stages

- **Stage 1:** to build and commission the 10 m detector, develop existing technology and the infrastructure for the 100 m. L ~ 10m
- **Stage 2:** to build, commission and exploit the 100 m detector and carry out a design study for the km-scale detector. L ~ 100m
  - AION was selected in 2018 by STFC as a high-priority medium-scale project.
  - AION will work in equal partnership with MAGIS in the US to form a "LIGO/Virgo-style" network & collaboration, providing a pathway for UK leadership.

Stage 1 is now funded with about £10M by the QTFP Programme and other sources and Stage 2 could be placed at national facility in Boulby or Daresbury (UK), possibly also at CERN (France/Switzerland).



- **Stage 3:** to build a kilometre-scale terrestrial detector. L ~ 1km
- **Stage 4**: long-term objective a pair of satellite detectors (thousands of kilometres scale) [AEDGE proposal to ESA Voyage2050 call]
  - AION has established science leadership in AEDGE, bringing together collaborators from European and Chinese groups (e.g. MIGA, MAGIA, ELGAR, ZAIGA).

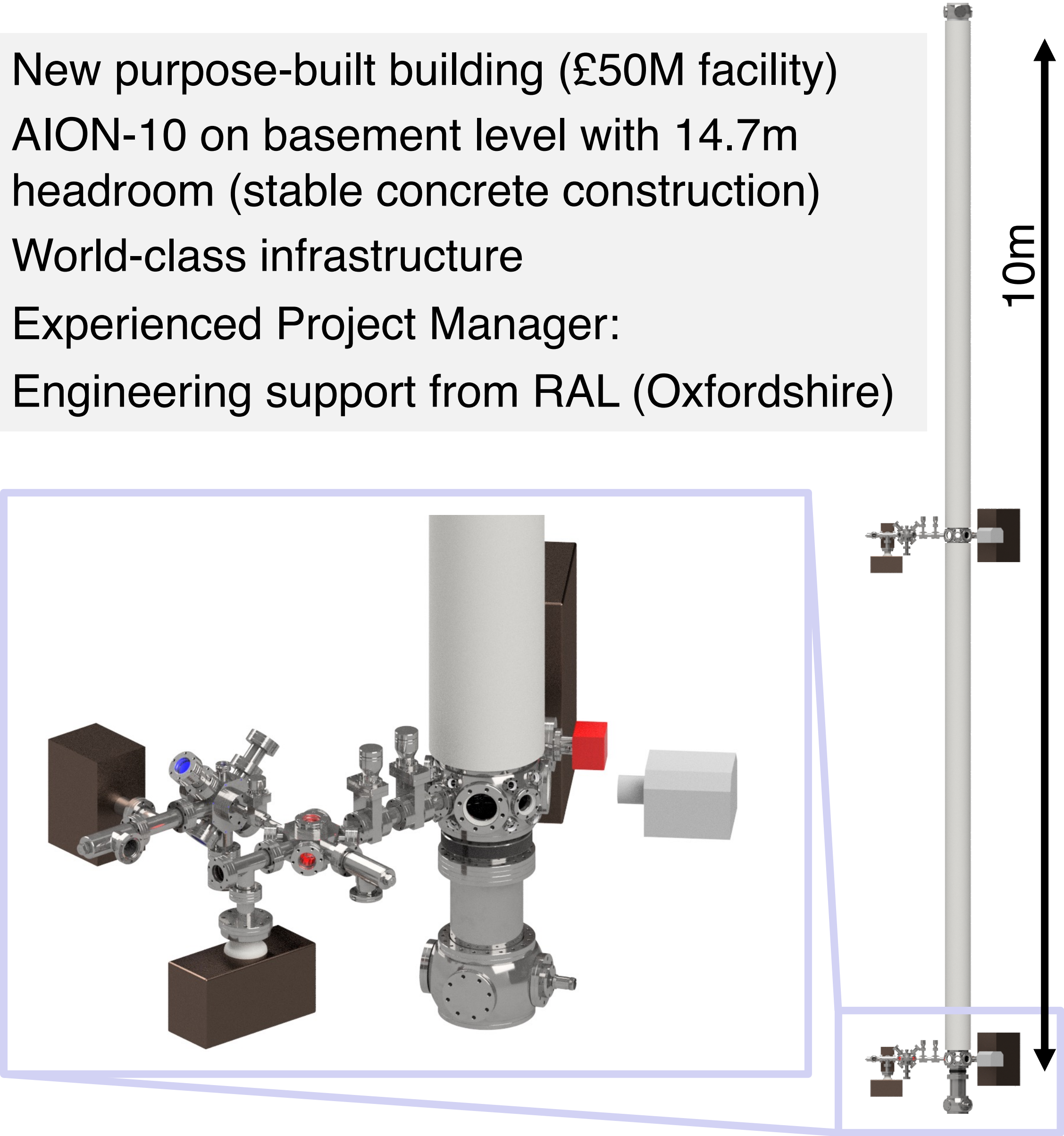


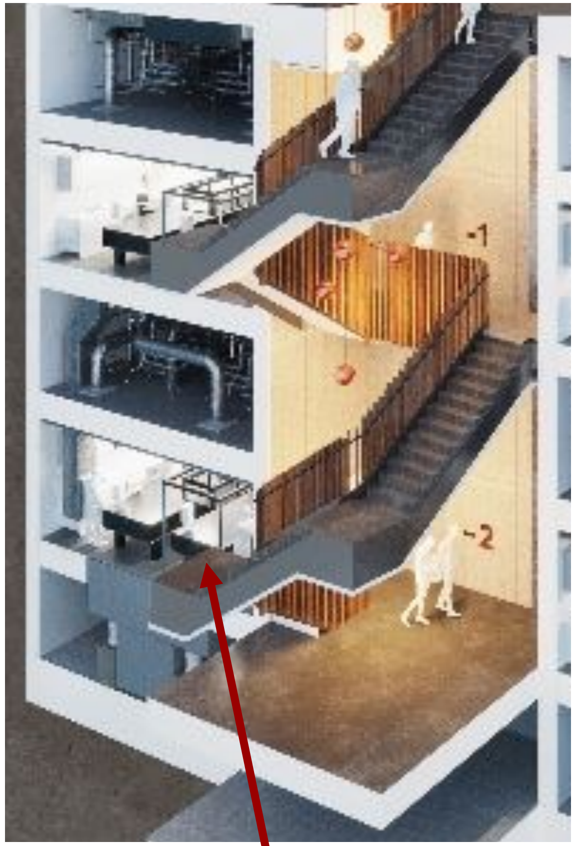
Stage 3 and 4 will likely require funding on international level (ESA, EU, etc) and AION has already started to build the foundation for it.

AION-10 @ Beecroft building, Oxford Physics

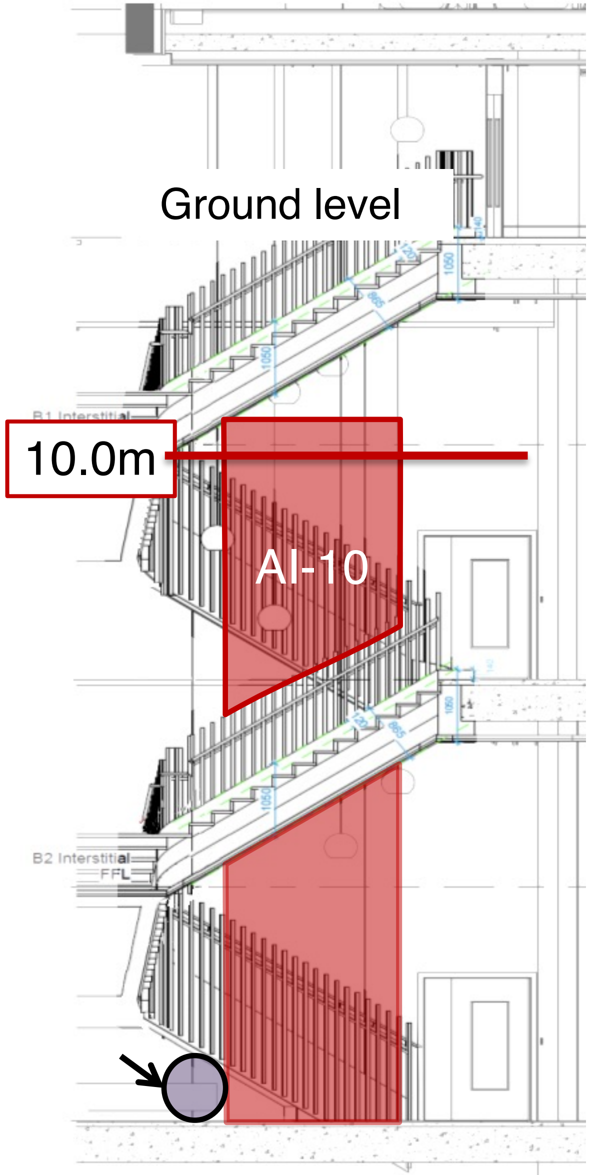
- New purpose-built building (£50M facility)
- AION-10 on basement level with 14.7m headroom (stable concrete construction)
- World-class infrastructure
- Experienced Project Manager:
- Engineering support from RAL (Oxfordshire)

AION PPTAI





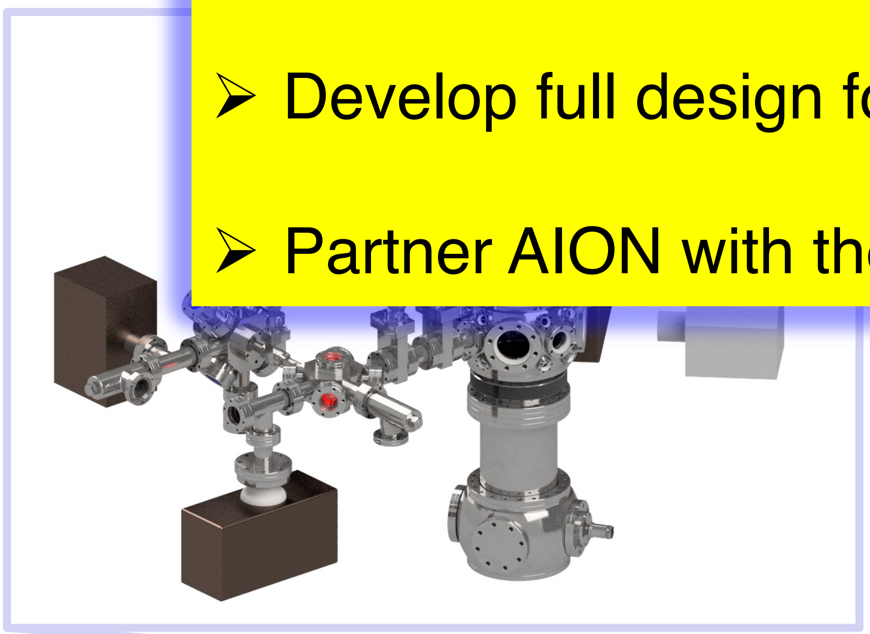
Laser lab for AION
vibration criterion, VC-G = 10nm@10Hz. Temperature (22±0.1)° C



AION-10 @ Beecroft building, Oxford Physics

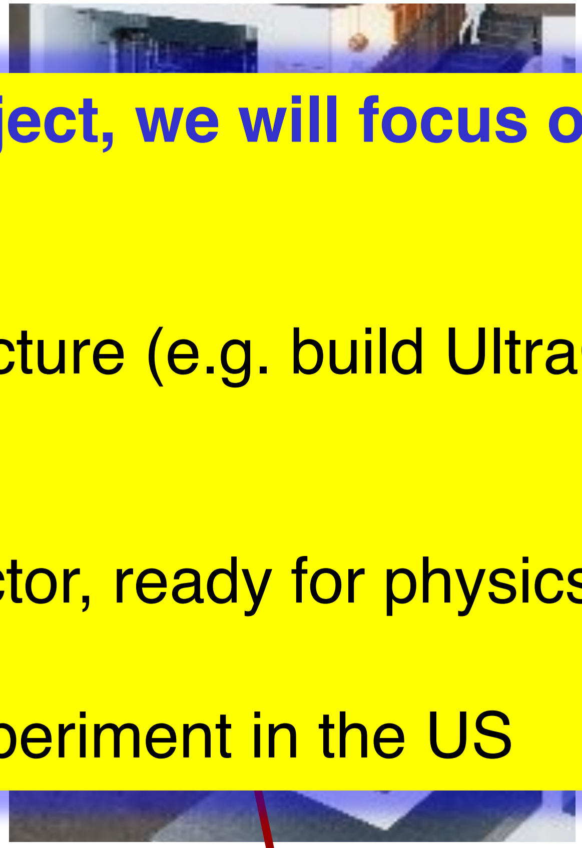
- New purpose-built building (£50M facility)
- AION-10 ... headroo...
- World-cl...
- Experien...
- Enginee...

AION PPTAI



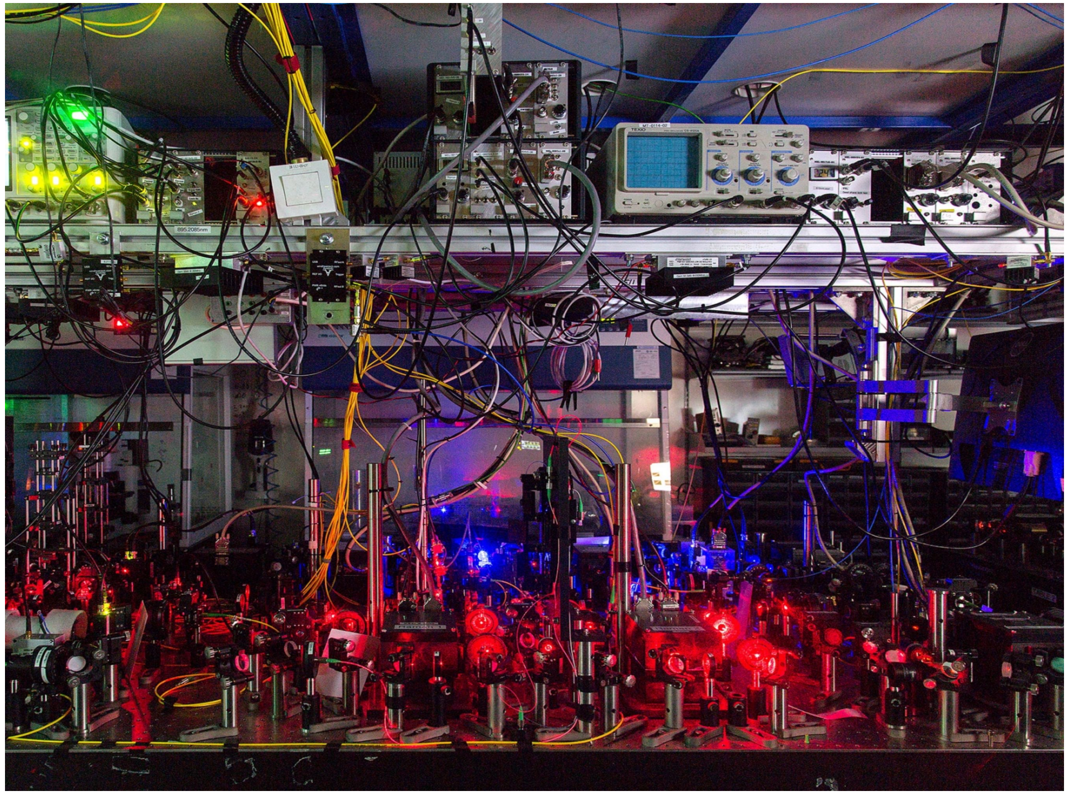
For the first 30 months of the project, we will focus on the perquisites for the 10m detector:

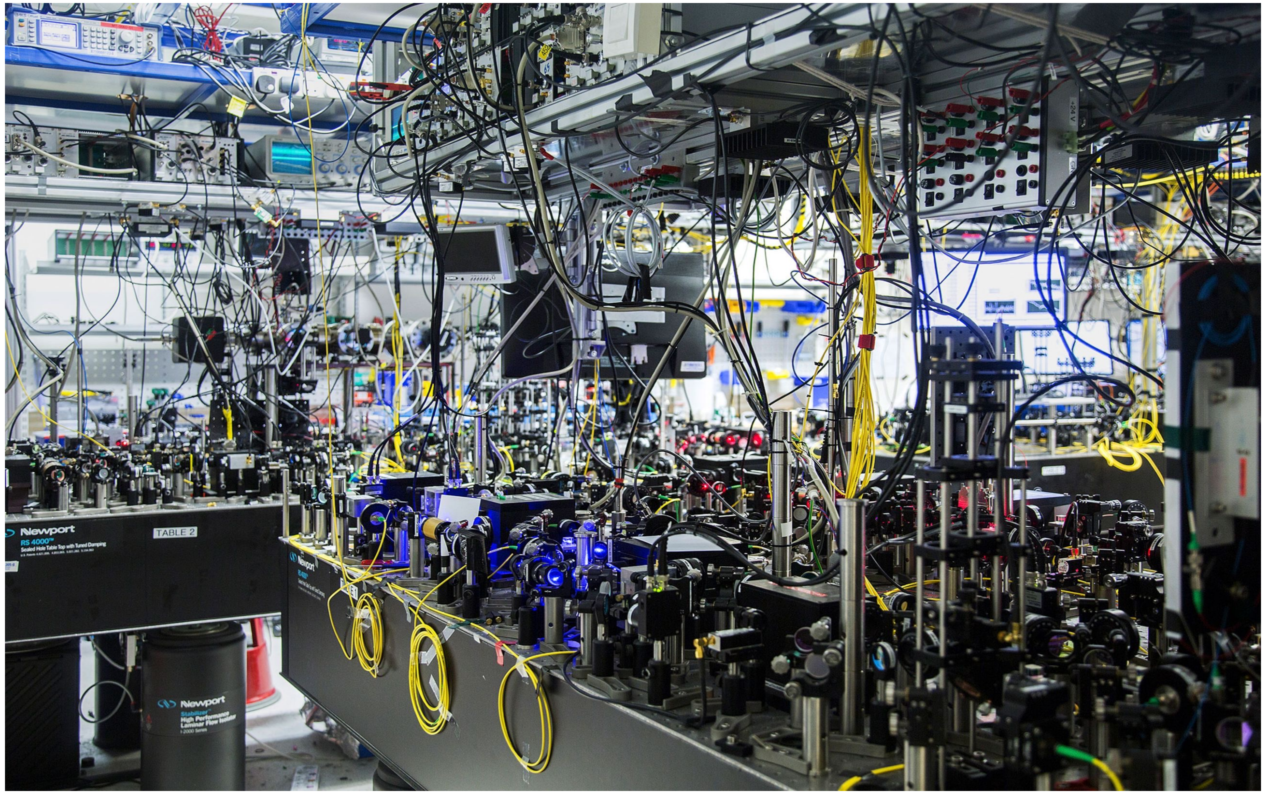
- ➢ Establish the Cold Atom infrastructure (e.g. build UltraCold Sr Laser Labs) and expertise
- ➢ Develop full design for 10m detector, ready for physics exploitation
- ➢ Partner AION with the MAGIS experiment in the US



Laser lab for AION
vibration criterion, VC-G = 10nm@10Hz. Temperature (22±0.1)° C

AION: Ultra-Cold Strontium Laboratories in UK





To push the state-of-the-art single photon Sr Atom Interferometry, the AION project builds dedicated Ultra-Cold Strontium Laboratories in:

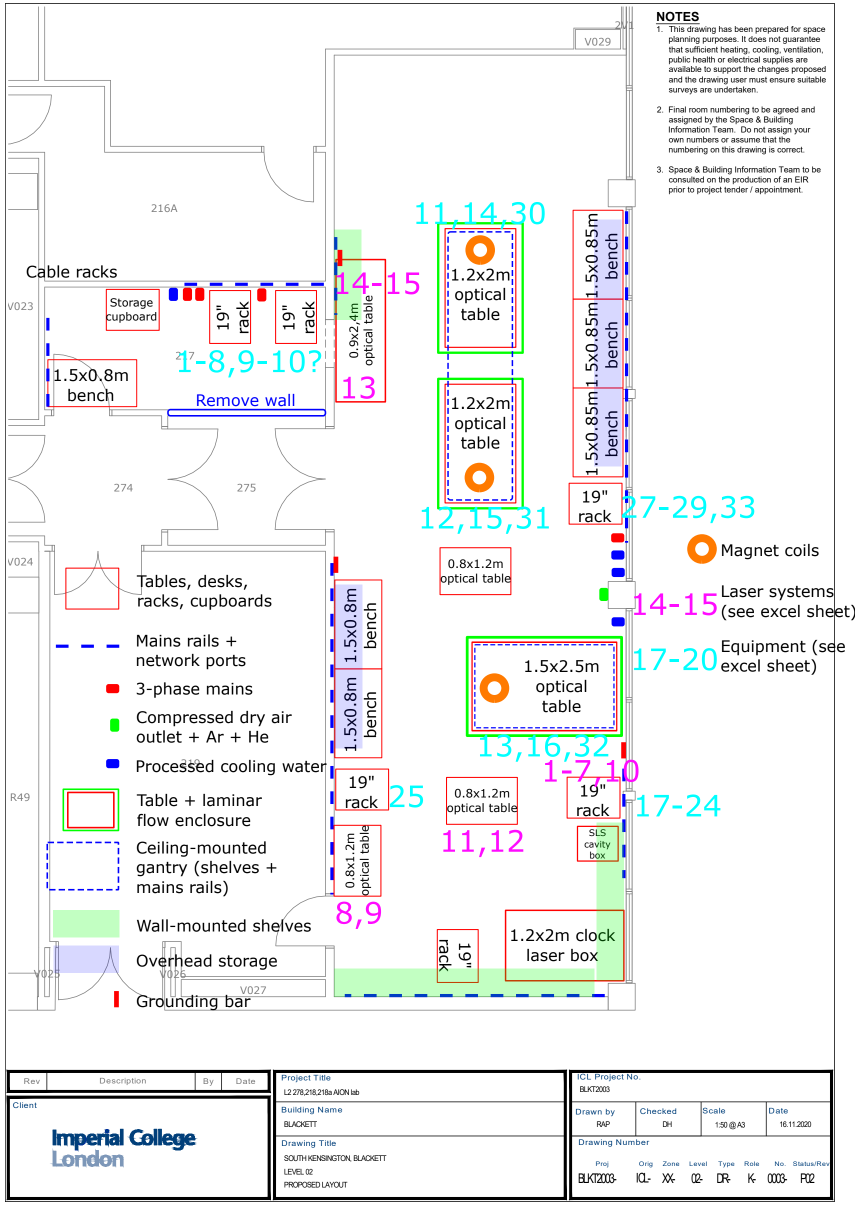
Birmingham, Cambridge, Imperial College, Oxford, and RAL

The laboratories are expected to be fully operational in fall 2021.

Example: New Ultra-Cold Strontium Laboratory at Imperial College

- In the context of the AION project, Imperial College is building a **brand new Ultra-Cold Strontium Laboratory on about 100m² of** high-quality real state in the Blackett Laboratory in central London.
- This Laboratory will extent significant the already very strong Ultra-Cold Atom facilities at Imperial, exploiting strong synergies with existing laboratory space in the same building.
- The new Laboratory will be **operated by world leading experts in Ultra-Cold Strontium Atomic Clocks**, and complements the already established expertise in Rb Atom Interferometry and Magneto-optical trapping and sympathetic cooling of molecules.

➢ **The new Laboratory will be ready for full operation by the end of 2021.**



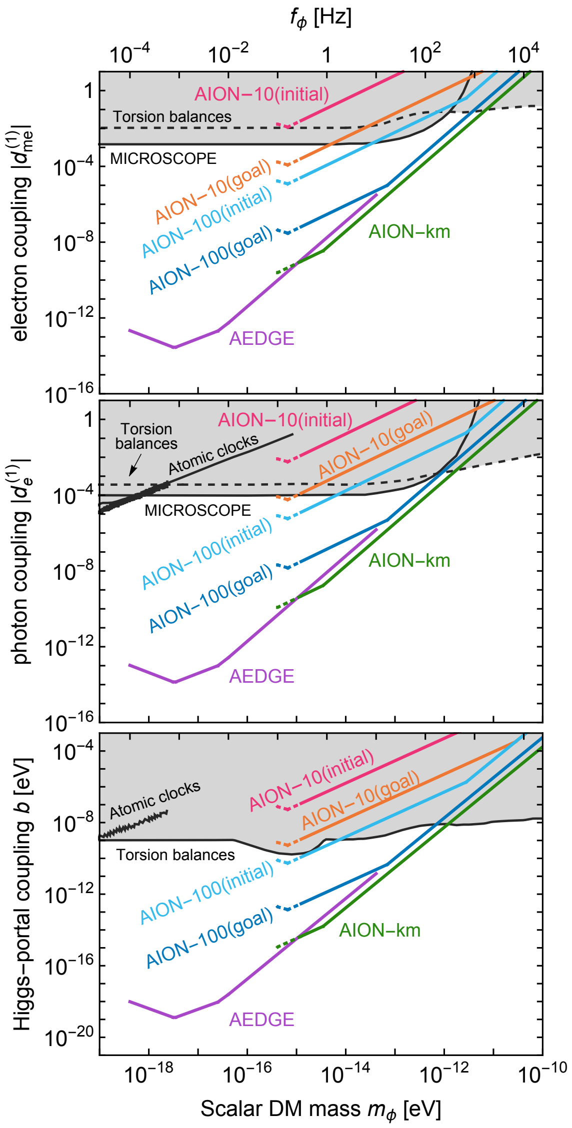
Ultra-Light Scalar Dark Matter

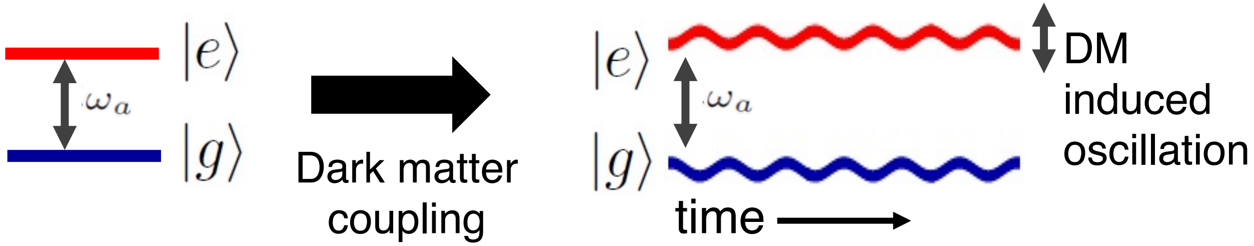
AION PPTAP detector workshop

Coupling to electron

Coupling to photon

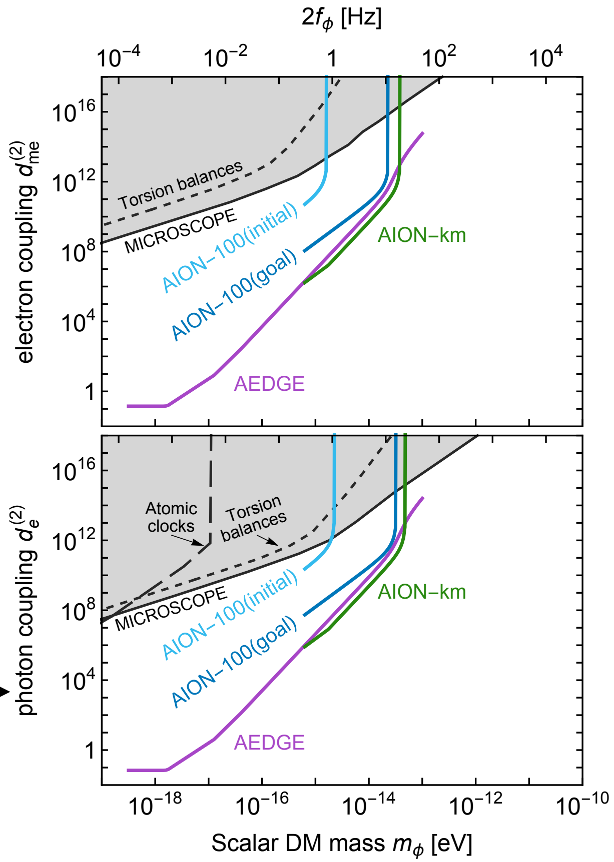
Coupling Higgs-portal





The AION staged programme will have unprecedented sensitivity to DM with scalar couplings to matter, which cause time variation of fundamental constants such as the electron mass.

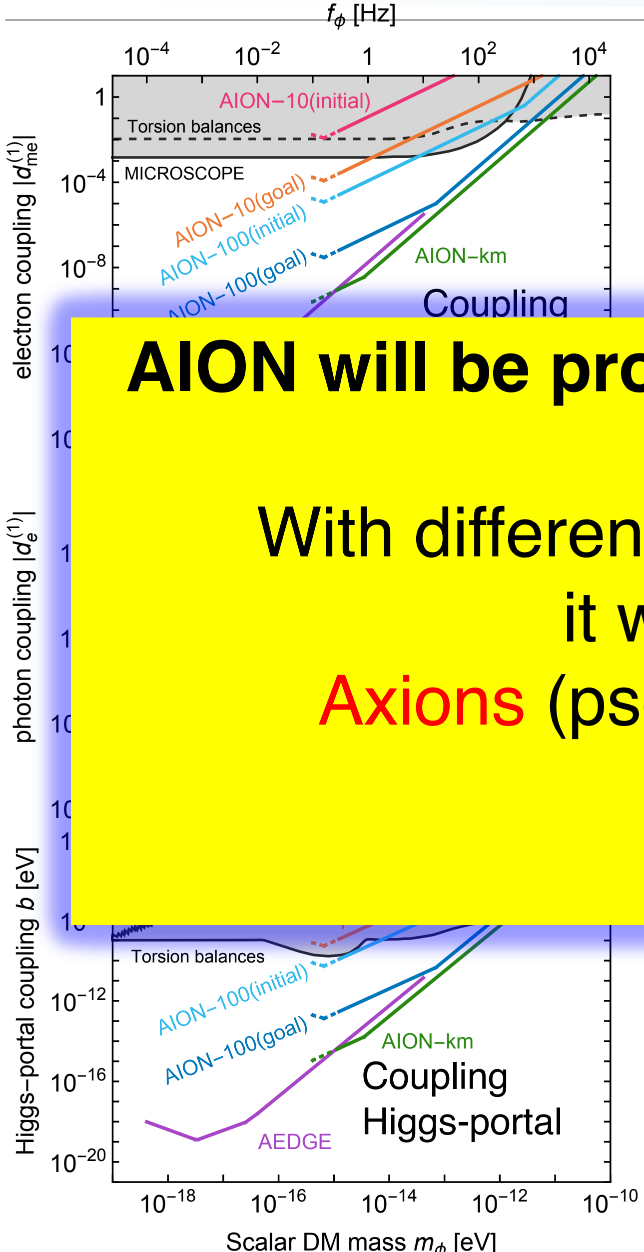
Based on: Arvanitaki et al., PRD **97**, 075020 (2018).

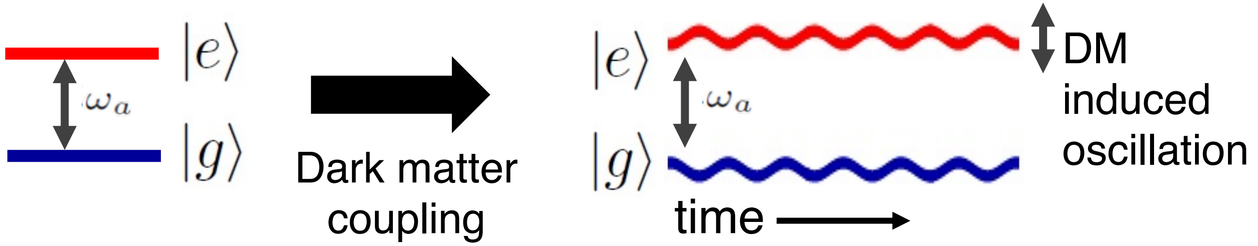


Linear scalar DM interactions

Quadratic scalar DM interactions

Ultra-Light Scalar Dark Matter



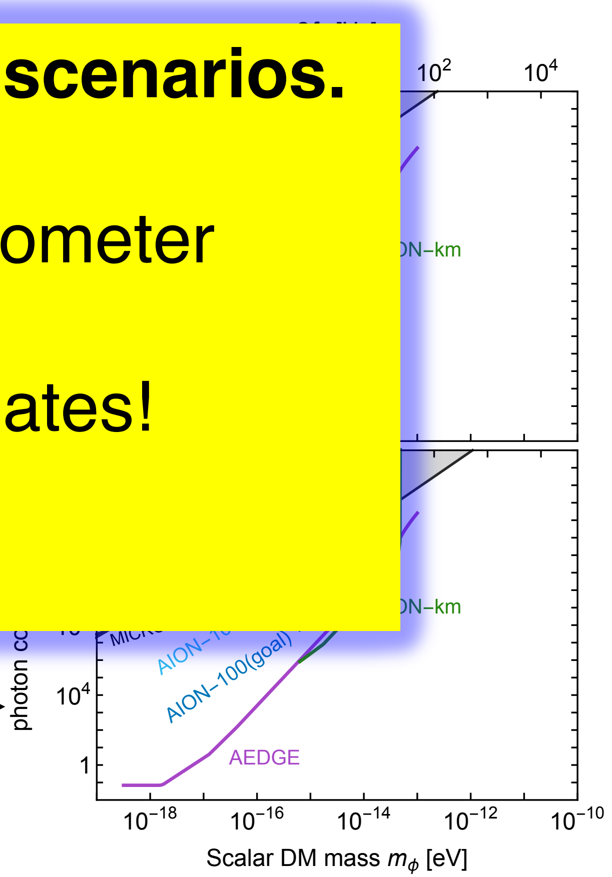


AION will be probing new territory in ULD scalar scenarios.

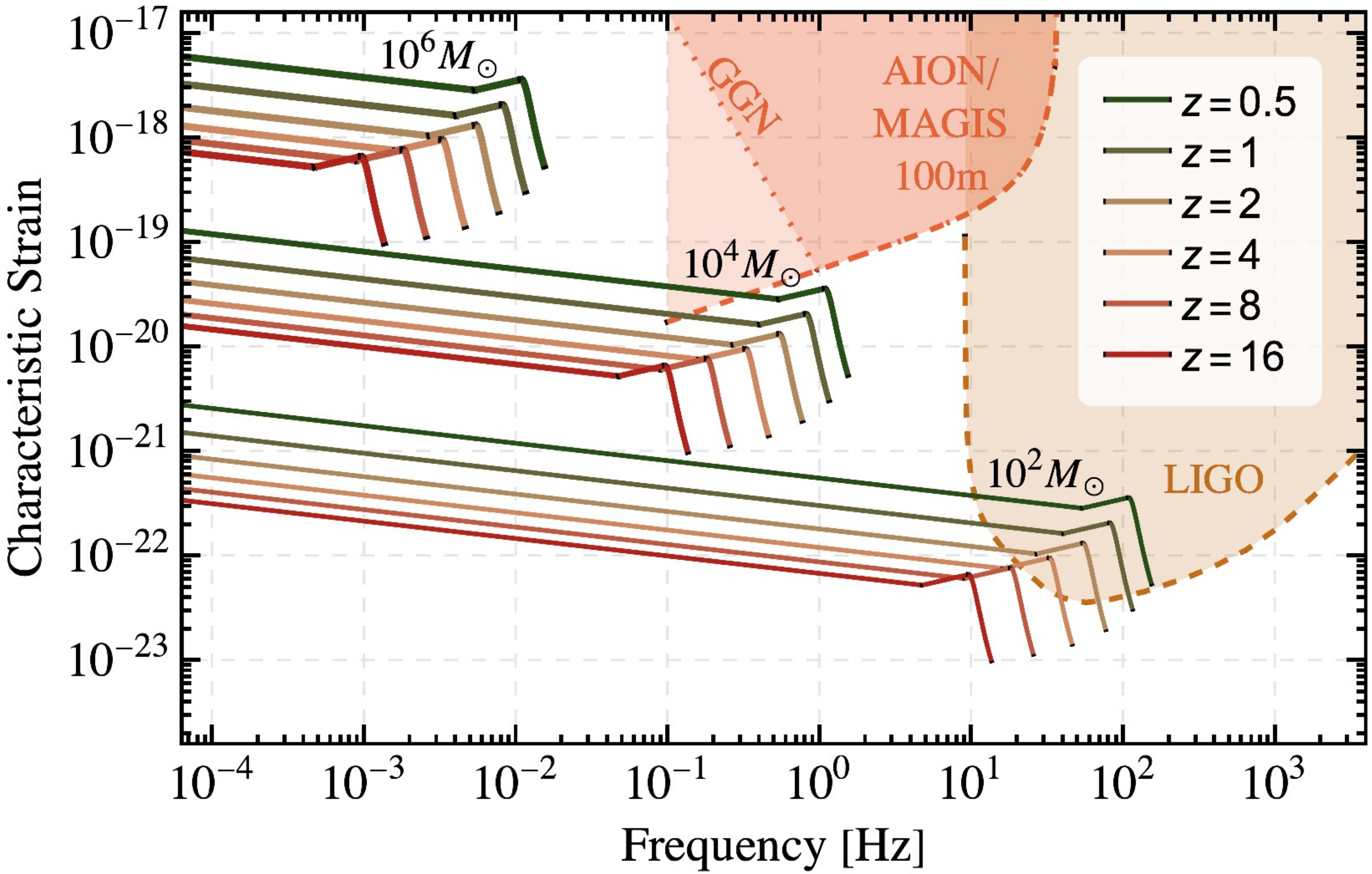
With different configurations of the Atom Interferometer it will be also possible to search for Axions (pseudo-scalar) and Vector DM candidates!
[studies are ongoing]

Linear scalar DM interactions

Quadratic scalar DM interactions

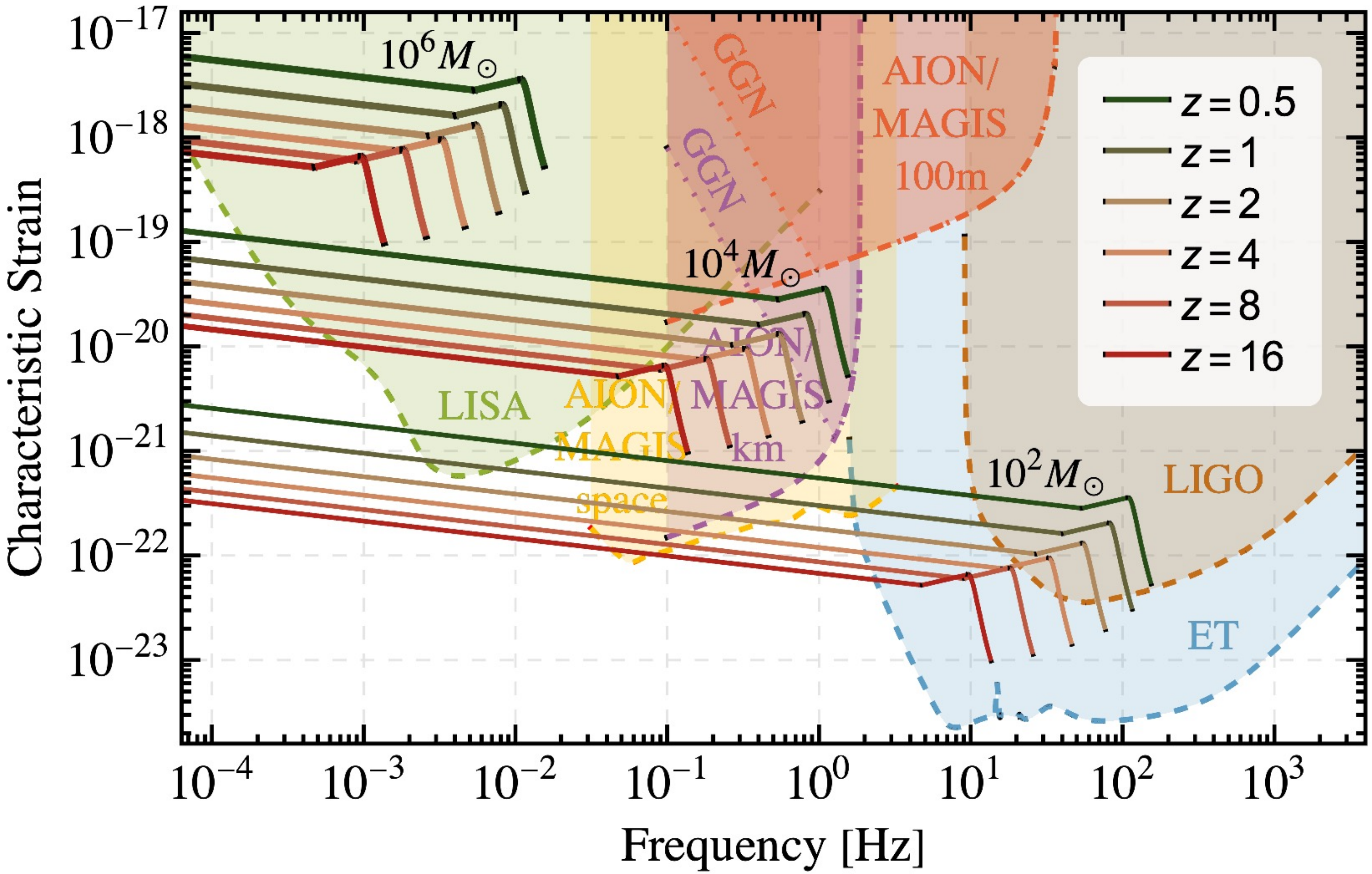


Strain Sensitivity & BH Mergers: 2030ish



The AION frequency range is ideal for observations of mergers involving IMBHs, to which LISA and the LIGO/Virgo/KAGRA/ET experiments are relatively insensitive.

Strain Sensitivity & BH Mergers: Future



The AION frequency range is ideal for observations of mergers involving IMBHs, to which LISA and the LIGO/Virgo/KAGRA/ET experiments are relatively insensitive.

Summary: AION

- AION/MAGIS are uniquely interdisciplinary missions that will harness cold atom technology to explore fundamental physics.

- They open a new window on gravitational physics, astrophysics & cosmology using atom interferometers, leveraging world-wide investment in quantum technologies, providing new opportunities for the international science communities.

- AION-10 was funded by the QTFP programme and will explore parameter space **of ultra-light dark matter (ULDM)** models, partnership with MAGIS in US.

- Preparation for AION-100 (km-scale) with **unique capabilities for detecting gravitational waves** is key deliverable.
  - ➢ Funding required would be similar to that for AION-10, assuming a suitable site.
  - ➢ Possible 100m sites under investigation: Boulby, Daresbury (UK), CERN (France/Switzerland).

QSNET

A network of clocks for measuring the stability of fundamental constants

G. Barontini, V. Boyer, **X. Calmet**, M. Chung, N. Fitch, **R. Godun**, J. Goldwin, V. Guarrera, I. Hill, **M. Keller**, J. Kronjaeger, H. Margolis, C. Mow-Lowry, P. Newman, L. Prokhorov, B. Sauer, M. Schioppo, **M. Tarbutt**, A. Vecchio, S. Worm

Birmingham NPL Sussex Imperial

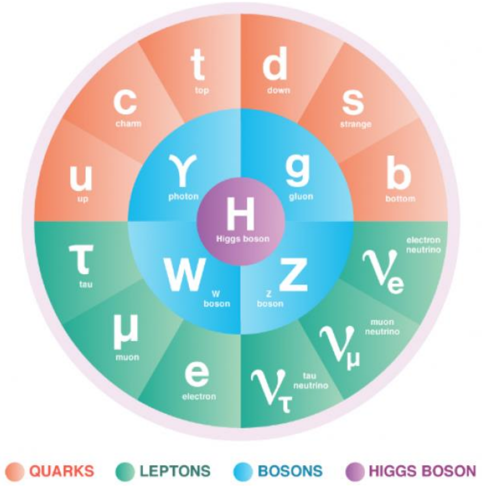
Background

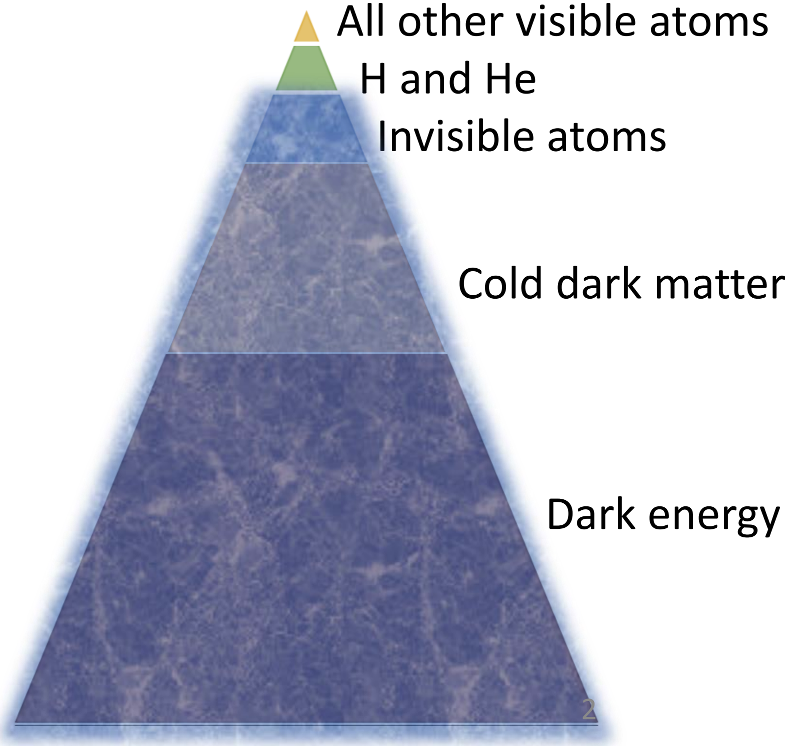
- The Standard Model and General Relativity are very successful theories, but the SM only accounts for 5% of the energy balance of the Universe

- The SM has 19 parameters, supposed to be immutable, referred to as fundamental constants.

- <u>This assumption needs to be tested.</u>

- Any variations of fundamental constants would give us evidence of revolutionary new physics





Background

- WIMP searches have been unsuccessful so far, DM searches are then moving towards well-motivated DM candidates with smaller masses

- Precision measurement techniques based on AMO quantum sensors are well suited to look for DM candidate with masses $<10^{-9}$ eV

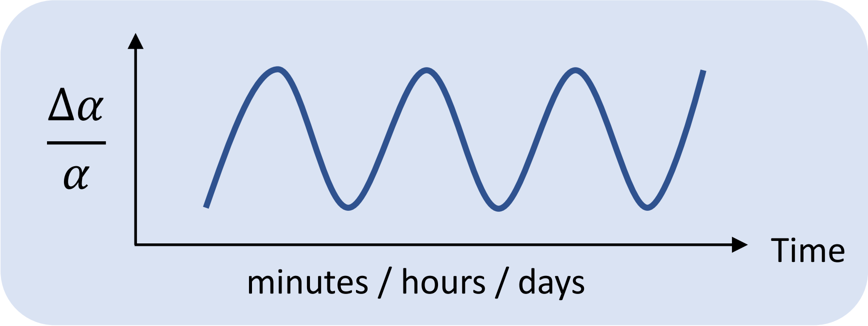
- Light DM candidate have large mode volume occupation number -> can be treated as classical fields

- Scalar fields $\mathcal{L}_{scalar} \supset \frac{\phi^n}{\Lambda_\gamma^n} F_{\mu\upsilon}F^{\mu\upsilon} - \sum_f \frac{\phi^n}{\Lambda_f^n} m_f \bar{f} f$

  - Λ_γ^n alter the fine structure constant α, Λ_f^n the fermionic masses -> manifest as variations of fundamental constants

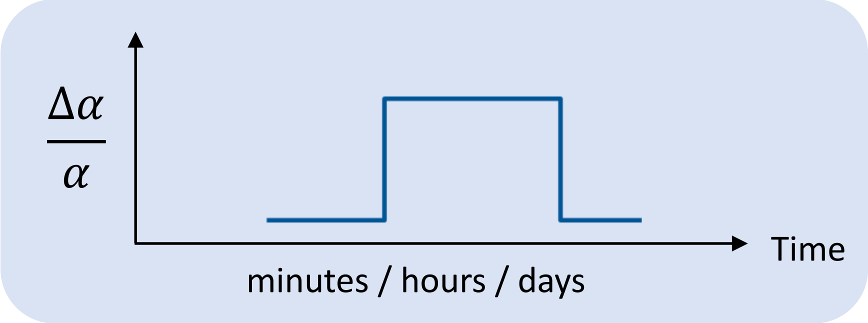
Look for variations on different timescales

- Oscillations



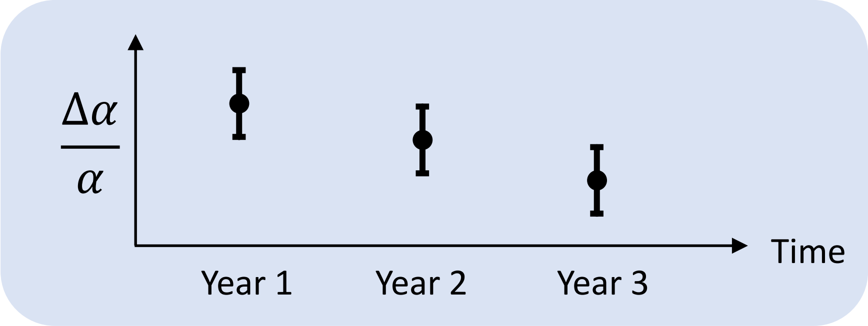
Very light DM

- Fast transients



DM- topological defects

- Slow drifts



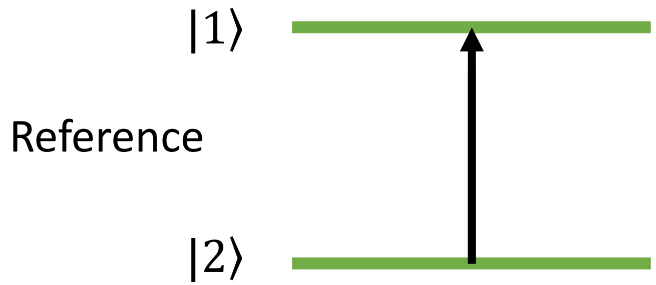
New physics

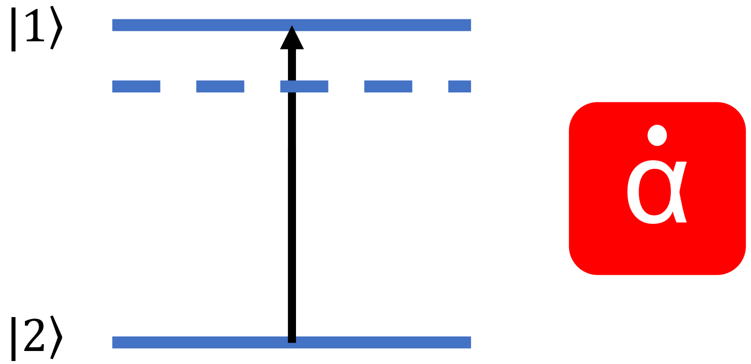
How to measure variations of fundamental constants

- Spectroscopy lends itself to measure variations of:

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \qquad \mu = \frac{m_p}{m_e}$$

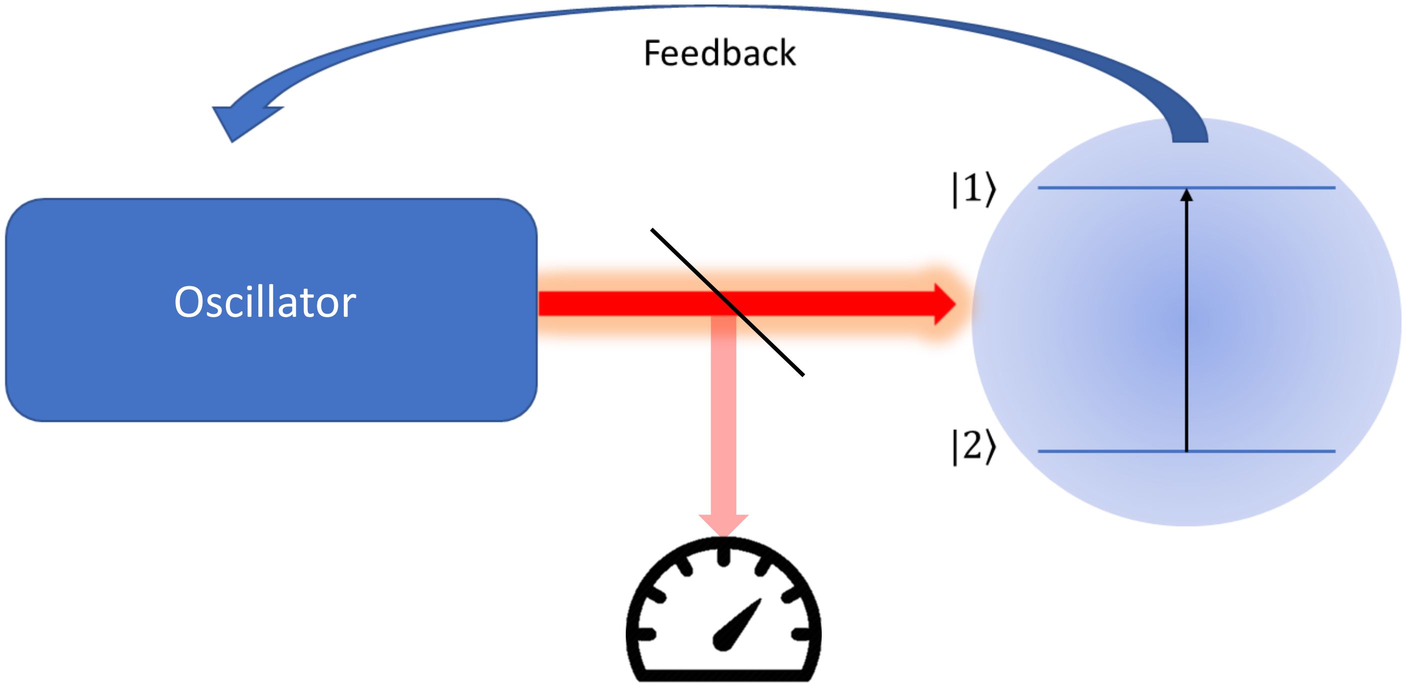
- Choose two (or more) transitions with DIFFERENT sensitivity to the variation of fundamental constants and compare them

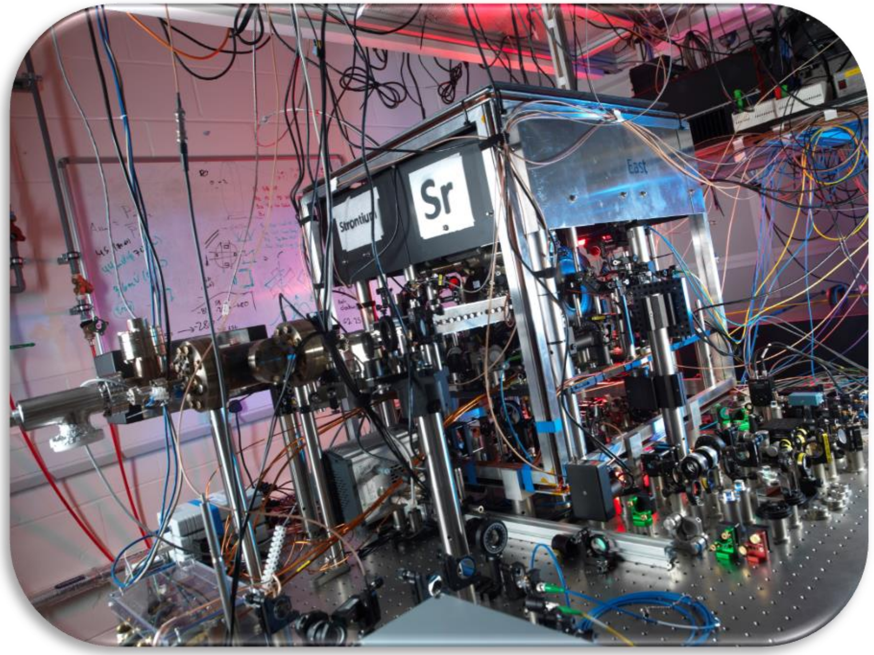




Atomic clocks

- Extremely high-precision spectroscopy



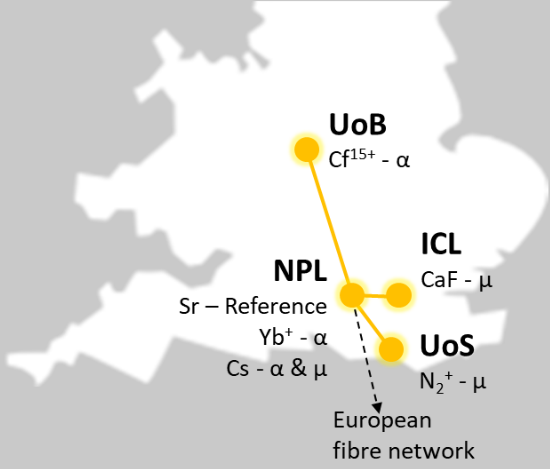


- Stability and accuracy at the 10^{-19} level

The QSNET project

- **Search for variations of fundamental constants of the Standard Model, using a network of quantum clocks**

- A unique network of clocks chosen for their enhanced sensitivities to variations of **α** and **μ**



Clock		Kα	Kμ
Higly-charged ion clock	Cf^{15+} (775 nm)	59	0
Atomic clock	Yb^{+} (467 nm)	-5.95	0
Molecular ion clock	N_2^{+} (2.31 μm)	0	0.5
Molecular clock	CaF (17 μm)	0	0.5
Atomic clock	Sr (698 nm)	0.06	0
	Cs (32.6 mm)	2.83	1

- The quantum clocks will be linked, essential to do clock-clock comparisons

The network approach

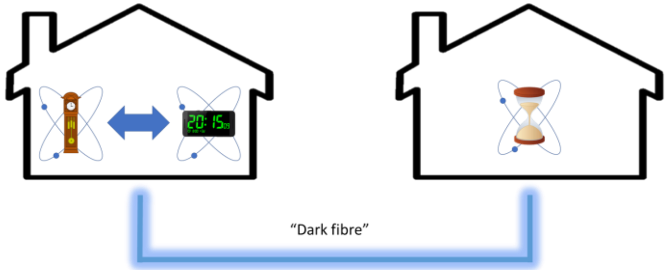
- Needed to perform clock-clock comparison at the ultimate level of accuracy and optimally exploit existing expertise

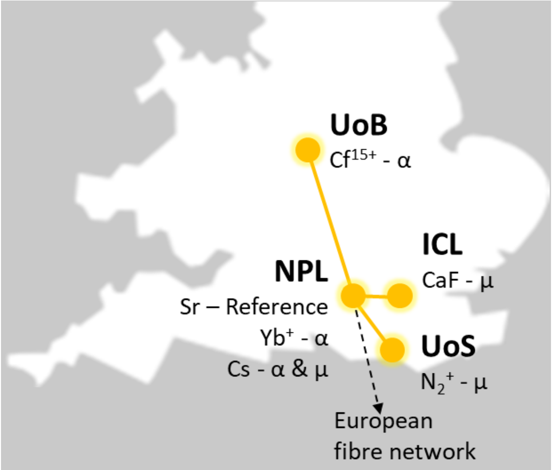
- Sensors with similar sensitivities and different systematics are necessary to confirm any measurements and reject false positives

- Multimessenger detection, discriminate between dark-standard matter couplings.

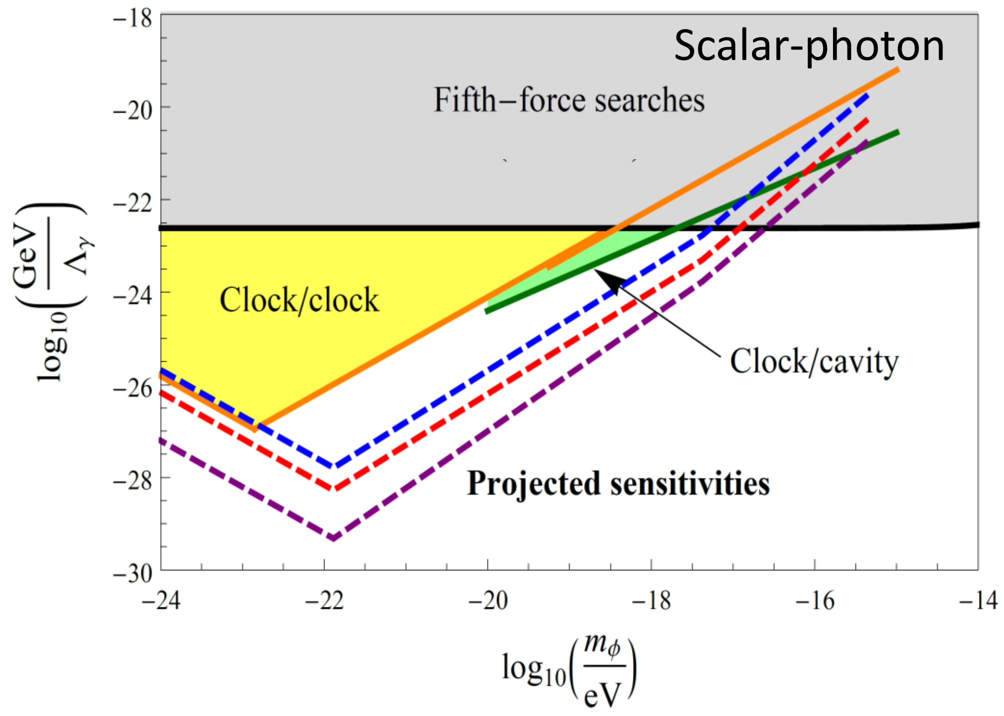
- The possibility of detecting transient events such as topological defects in dark matter fields or oscillations of dark matter

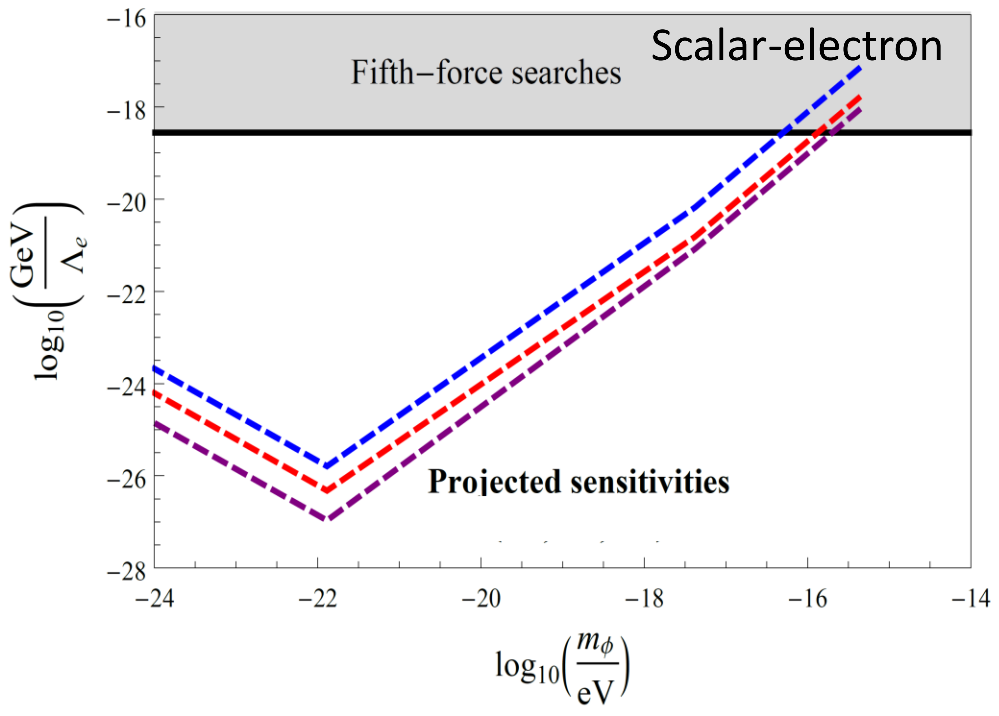
- A new versatile and expandable national infrastructure with possible further applications in and beyond fundamental physics.





QSNET Dark matter exclusion diagrams



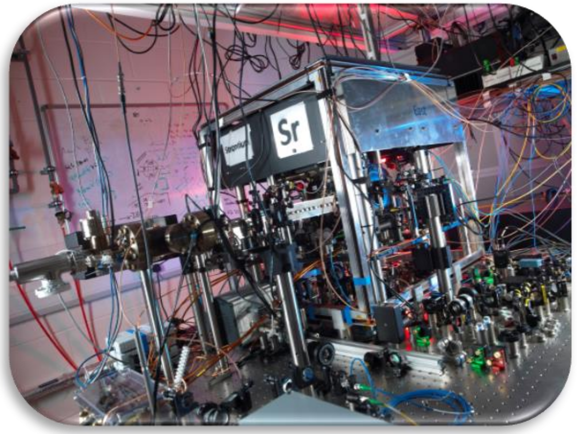


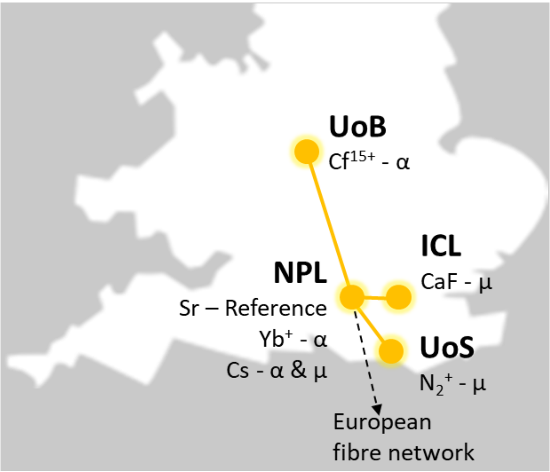
- Large DM mass range
- Multimessenger detection
- Higher order couplings
- Test of quantum gravity

QSNET in a nutshell

α μ

- Extending and exploiting world-class expertise and capabilities developed in NQTP
- Inexpensive table-top experiments with next generation quantum technology
- A unique opportunity for discovery, improving current limits on variations of α and μ by orders of magnitude
- Potential for game-change results on short timescale





Thank you

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P. Newman, L. Prokhorov, B. Sauer, M. Schioppo, **M. Tarbutt**, A. Vecchio, S. Worm

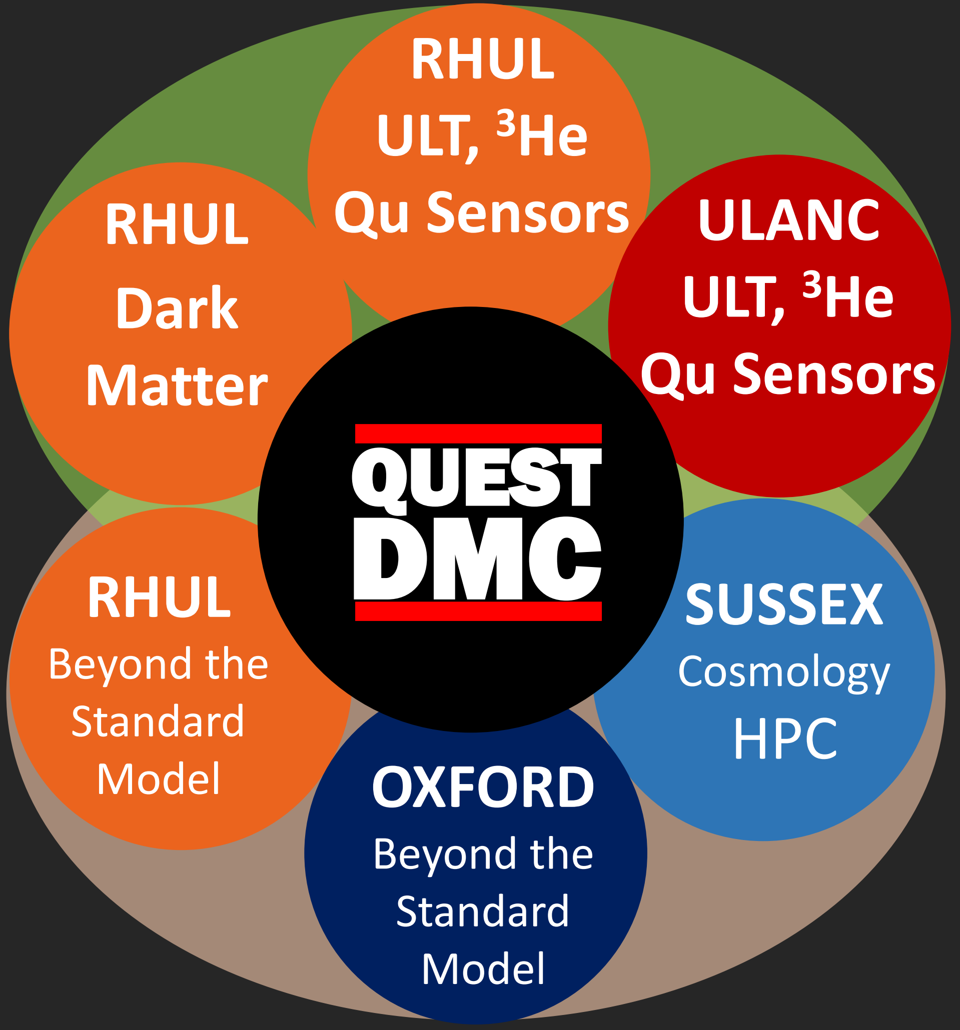
Birmingham NPL Sussex Imperial

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

Experiment:
S. Autti[2], **A. Casey[1]**, R. Haley[2], P. Heikkinen[1], S. Kafanov[2], L.V. Levitin[1], J. Monroe[1], J. Prance[2], X. Rojas[1], J. Saunders[1], A. Singh[1] M. Thompson[2], V. Tsepelin[2], D. Zmeev[2], V. Zavyalov[2]

Theory:
M Hindmarsh[3], S Huber[3], J. March-Russell[4], S. West[1], Q. Zhang[3]

[1]Royal Holloway University of London, [2]Lancaster University, [3]University of Sussex, [4]University of Oxford



QUEST – DMC *Ecosystem*

HeRald

UK-CSQS

LANC-QTC

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

European
Microkelvin Platform

Astroparticle Physics
European Consortium

Sauls, Volovik, Nissinen, Leggett, Rummukainen

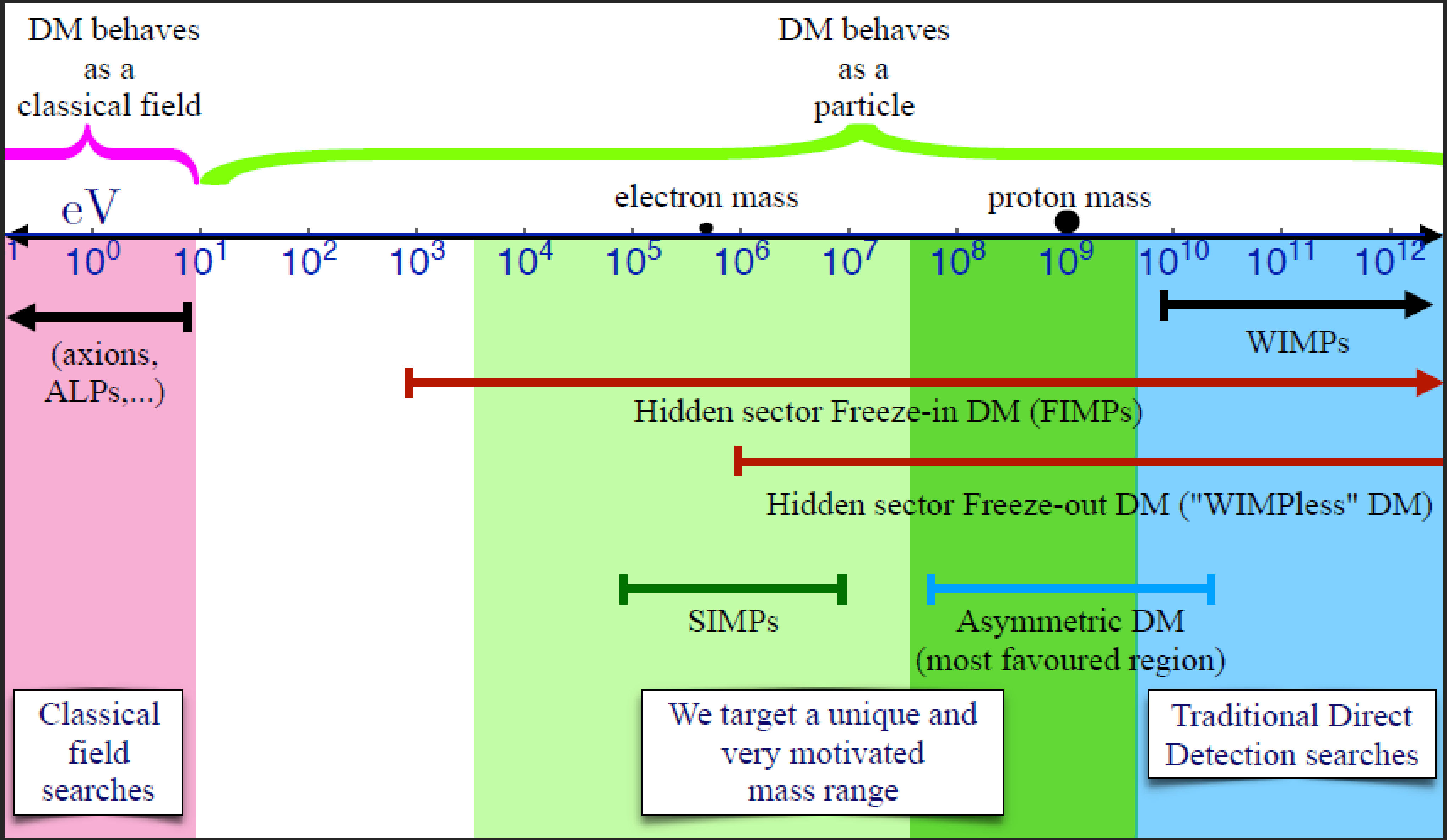
We will address two fundamental open questions in cosmology

- **WP1:** What is the nature of Dark Matter?
  - Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter

- **WP2:** How did the early universe evolve?
  - Phase transitions in extreme matter

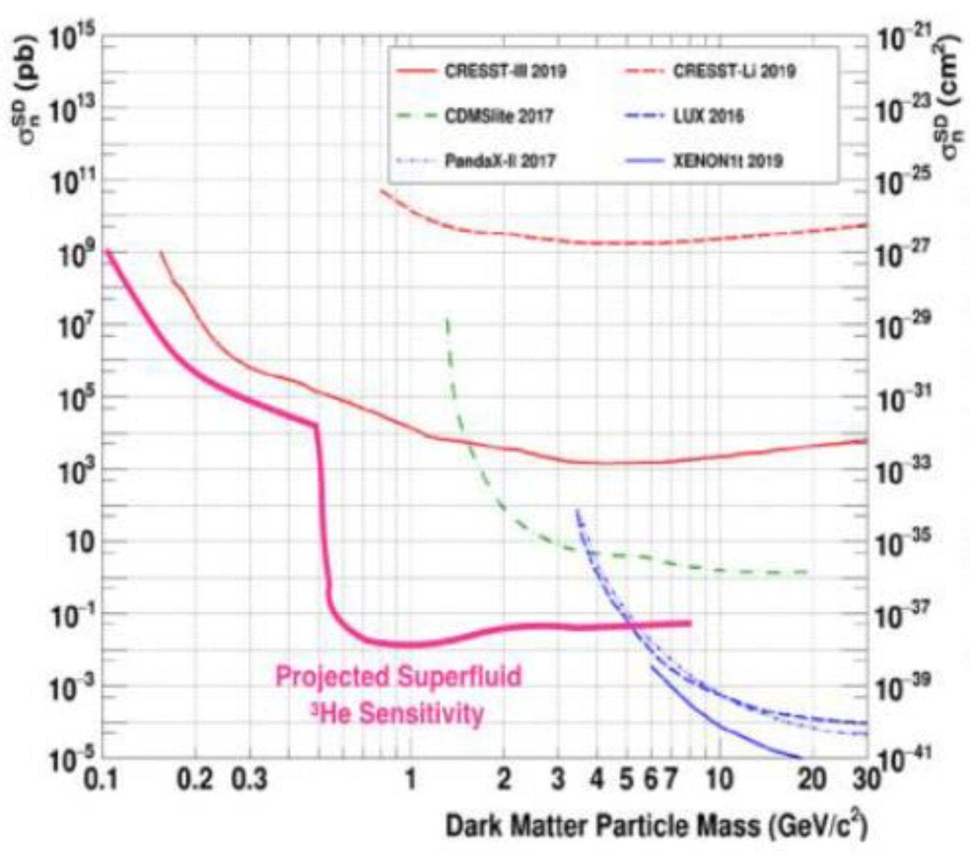
Linked through requirement of beyond-standard model physics and the internationally unique experimental approach of combining quantum sensors with ^{3}He at ultralow temperatures.

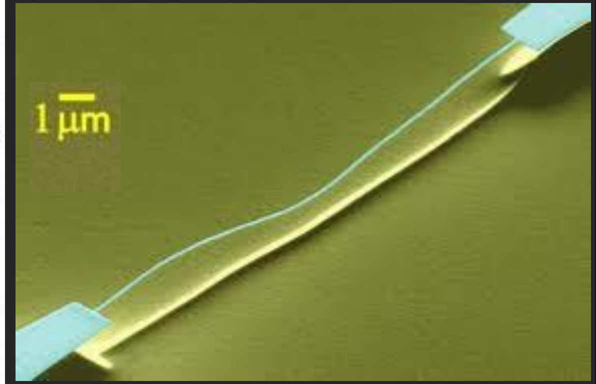
• In WP1: What is the nature of Dark Matter?



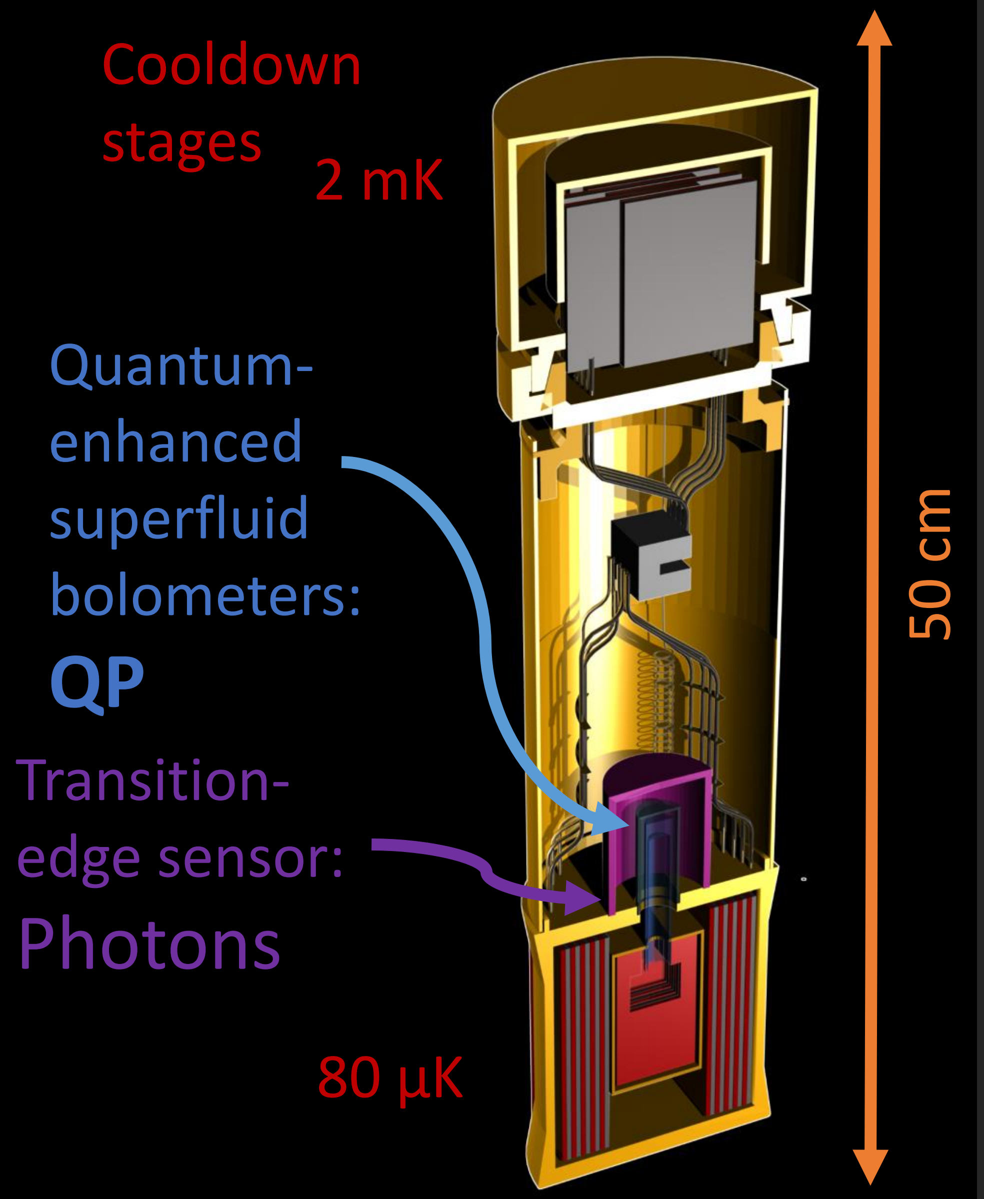
WP1: Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter

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

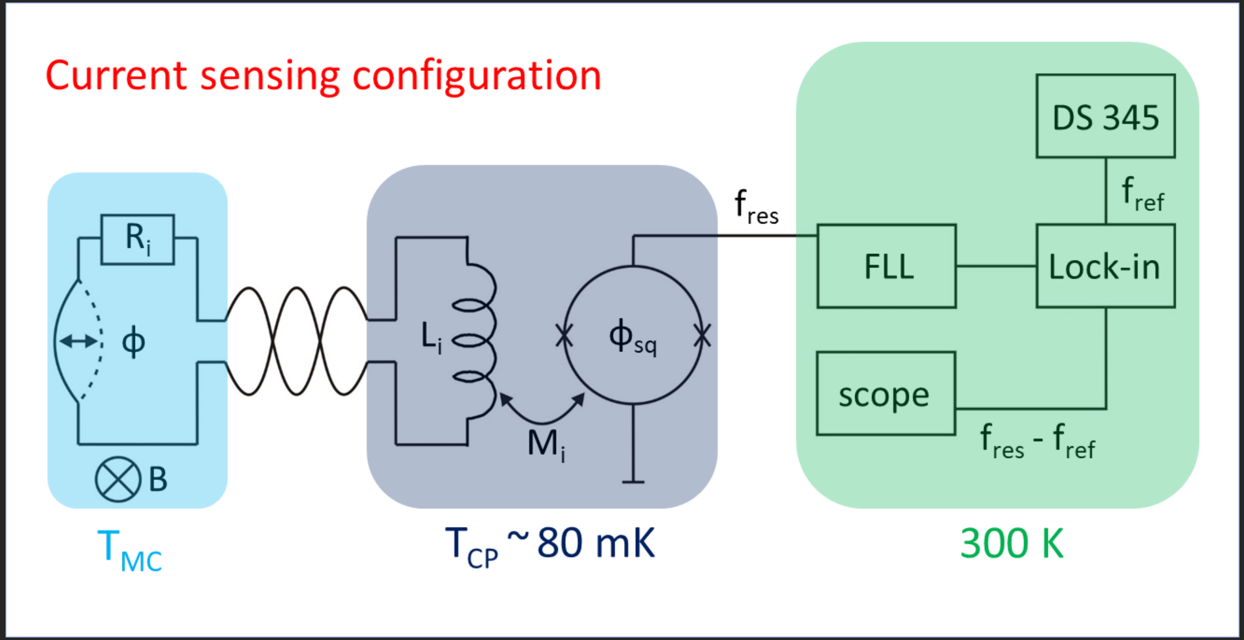


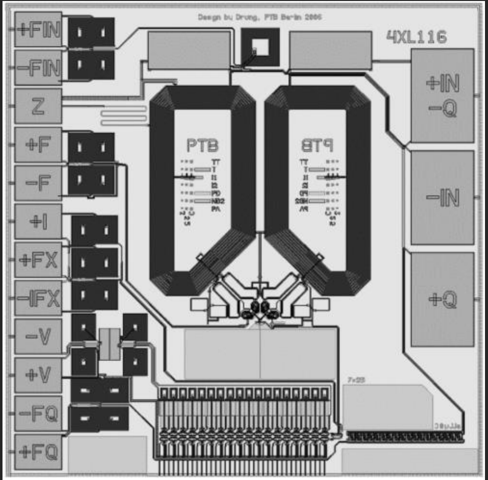


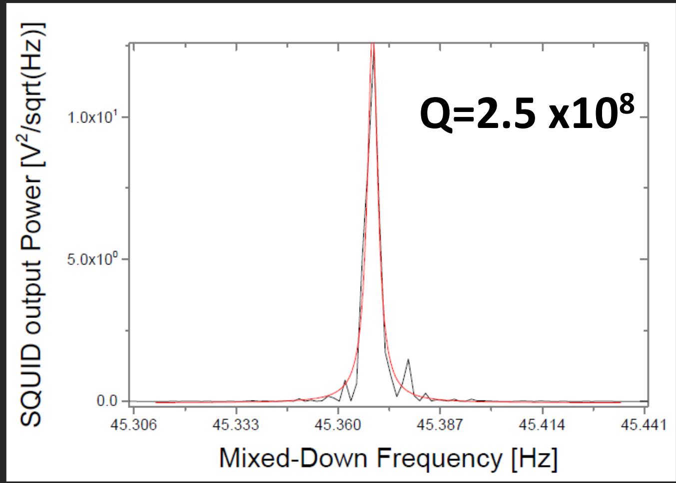
Readout requires low dissipation, low noise, quantum sensor to reach ULT



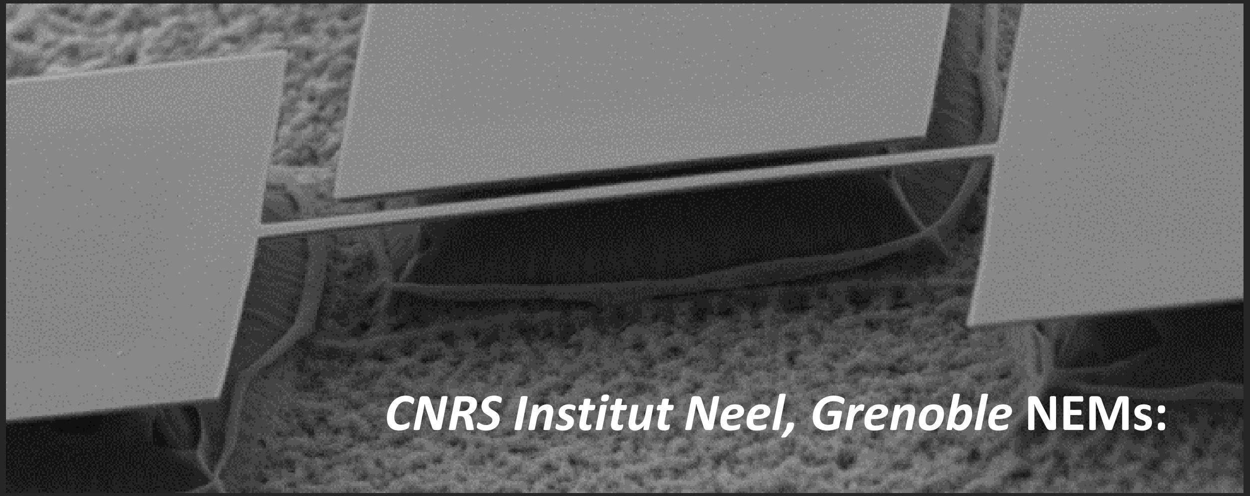
Merging existing state-of-art tech to achieve beyond 10 eV resolution

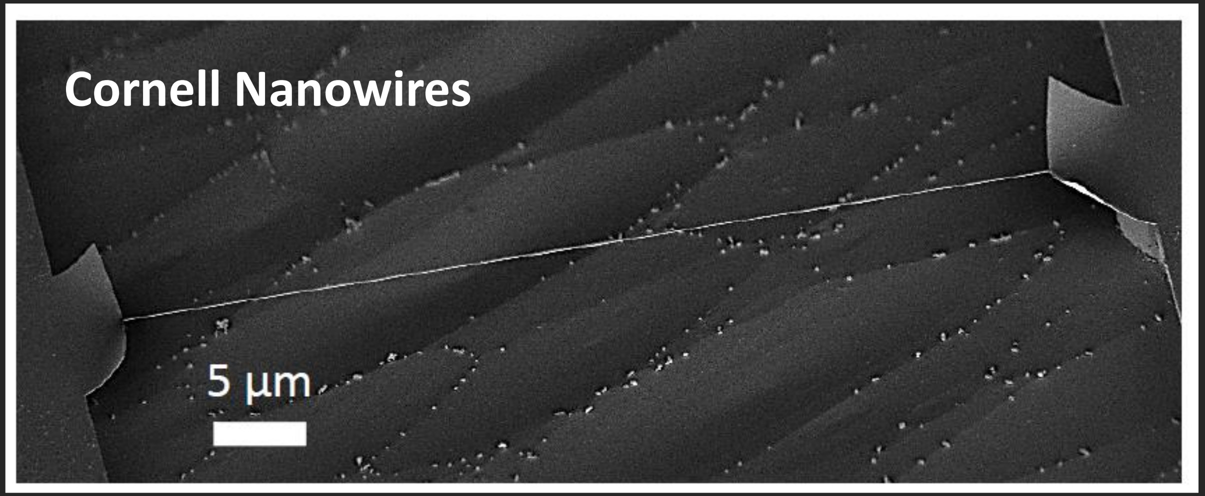




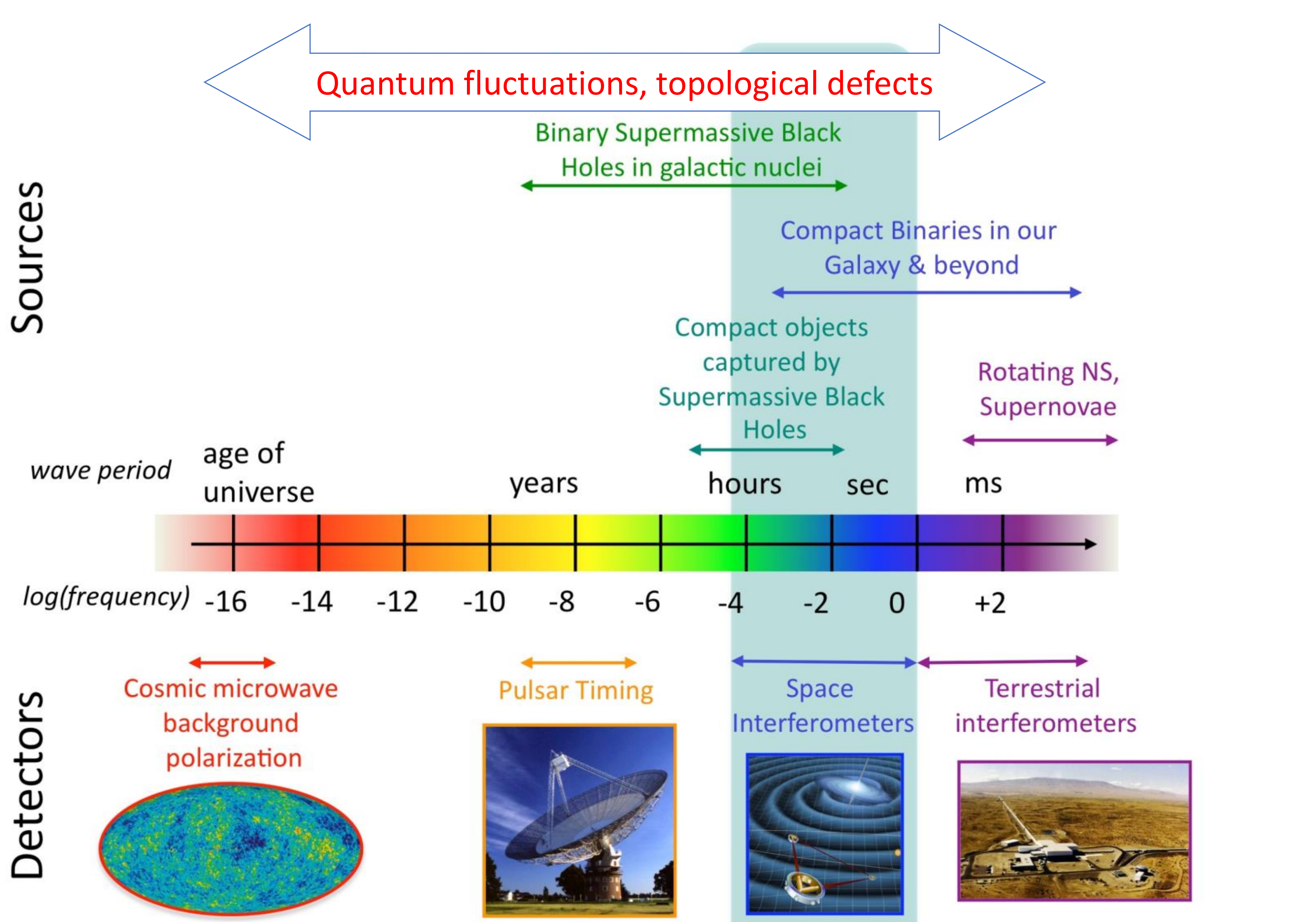


2-stage SQUID amplifier (PTB)
IEEE Trans. Appl. Supercond. 17 (2007)

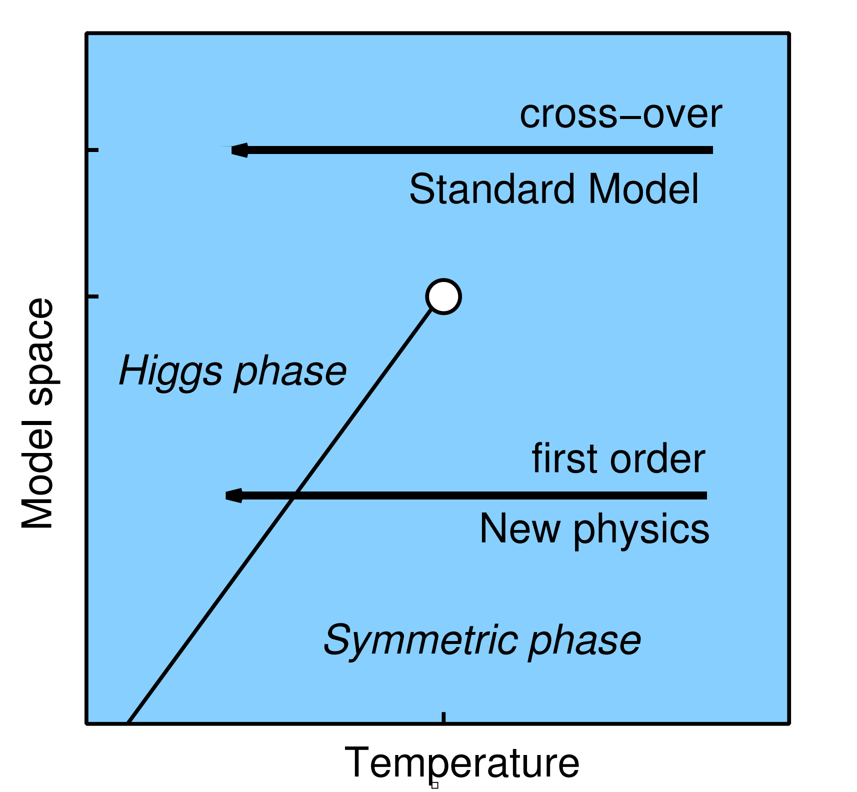


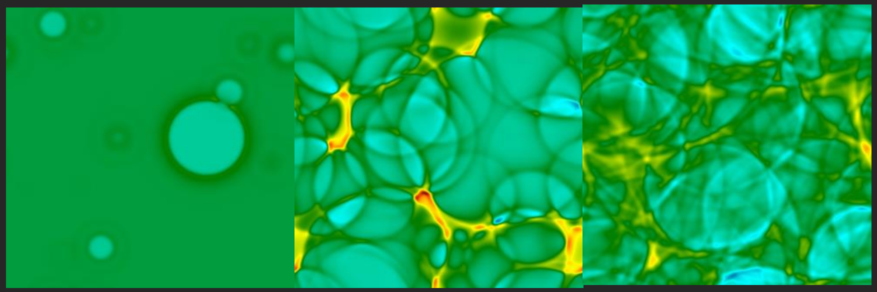


• In WP2: How did the early universe evolve?



Gravitational waves ESA mission LISA (2034)



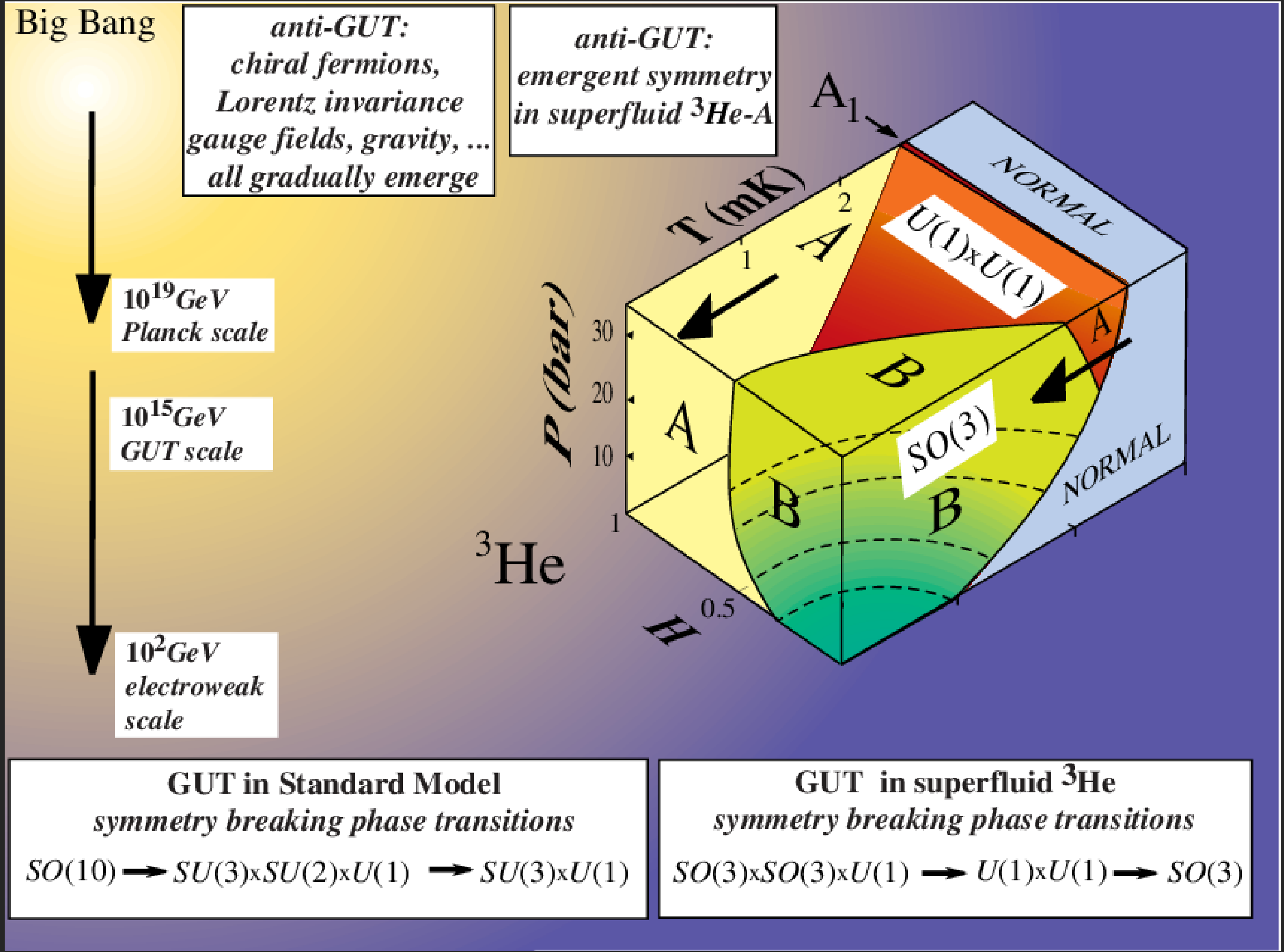


Numerical simulation of a phase transition

WP2: Phase transitions in extreme matter

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



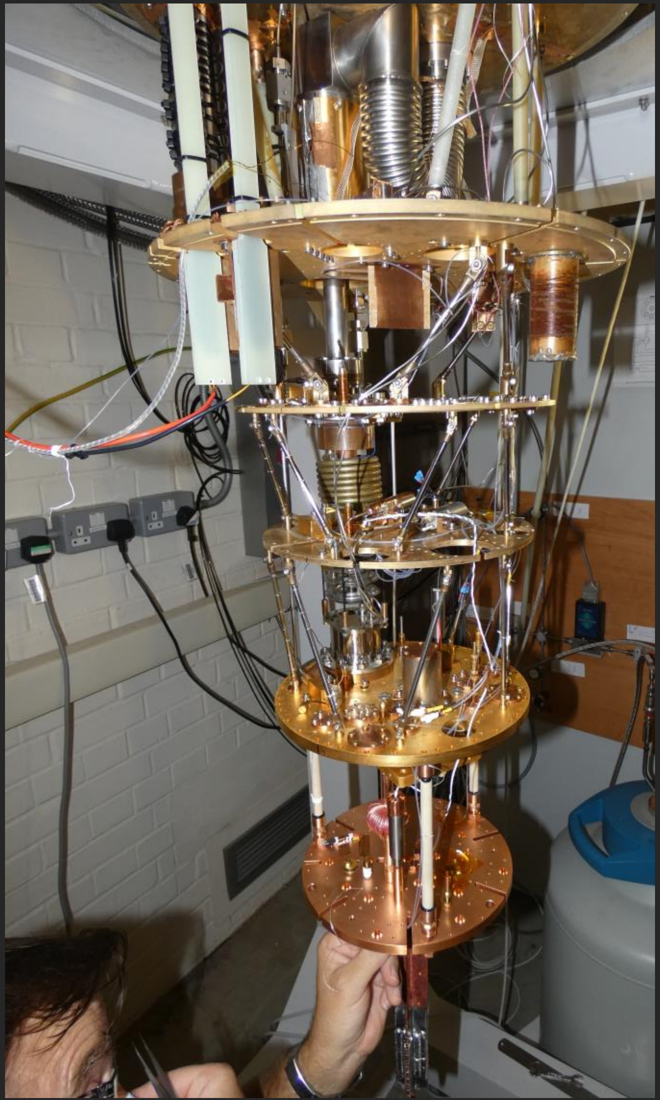
Nucleation puzzle in ^{3}He

- Engineer phase transitions between superfluid ^{3}He 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.



EMP European Microkelvin Platform

A! Aalto University

ÚEF SAV

cnrs

TU WIEN

Advanced Infrastructure, Horizon 2020:
Research on Quantum Materials, and Quantum Technology at ULT

VTT

MAGNICON

OXFORD INSTRUMENTS The Business of Science

BlueFors CRYOGENICS

CHALMERS

CryoConcept

PTB

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)