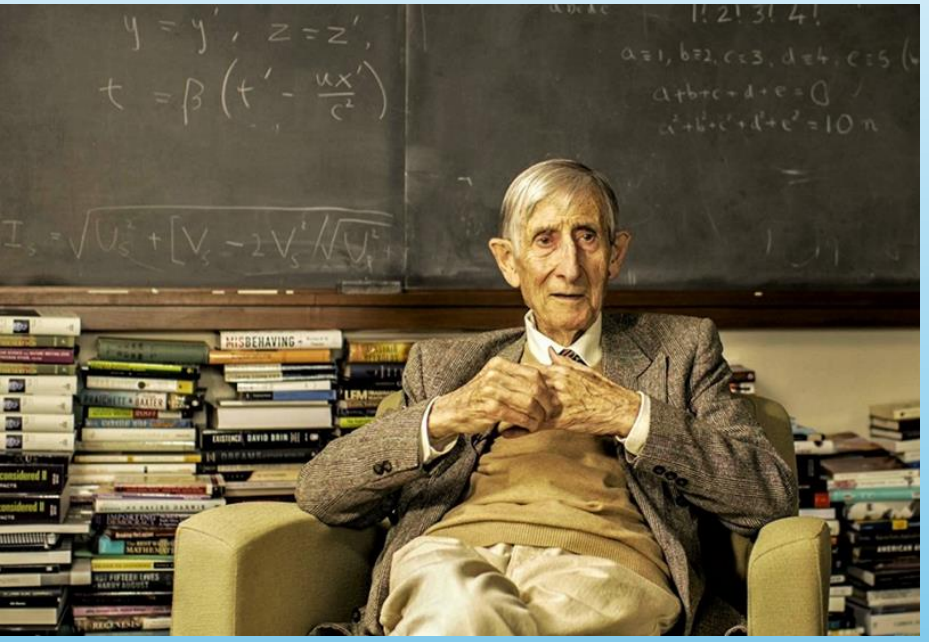
# Quantum Technologies for Particle and Astro-Particle Physics



*"New directions in science are launched by new tools much more often than by new concepts"*

*-- Freeman Dyson*

**Ruben Saakyan (UCL)**

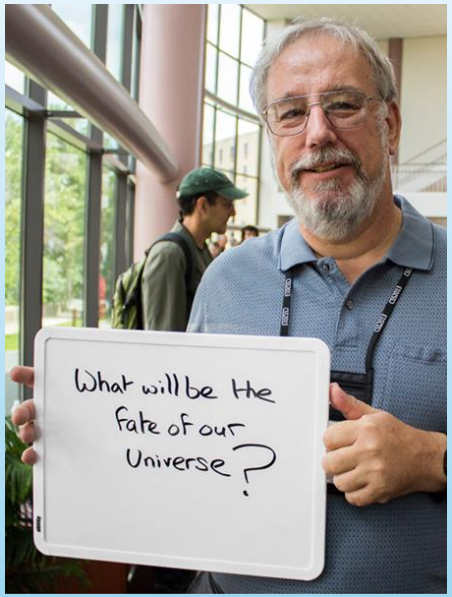
**13-June-2025**

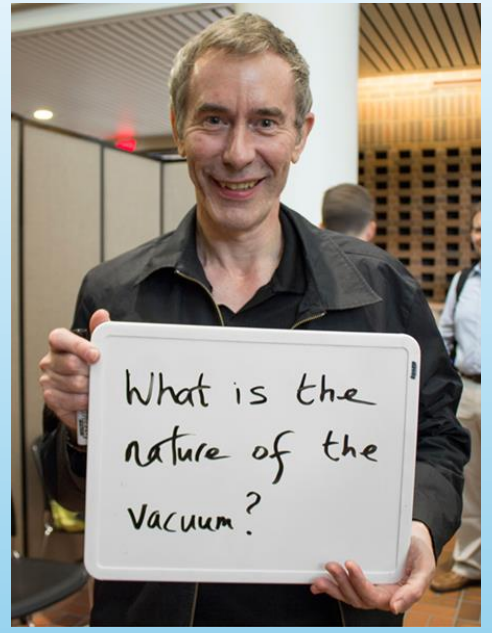
**WIN-2025**

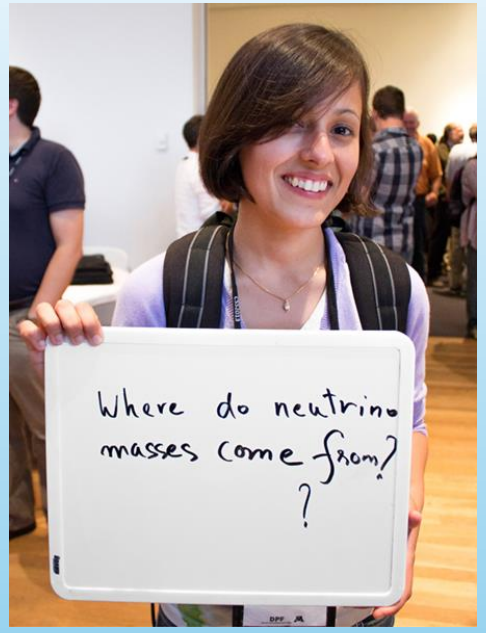
**Brighton**

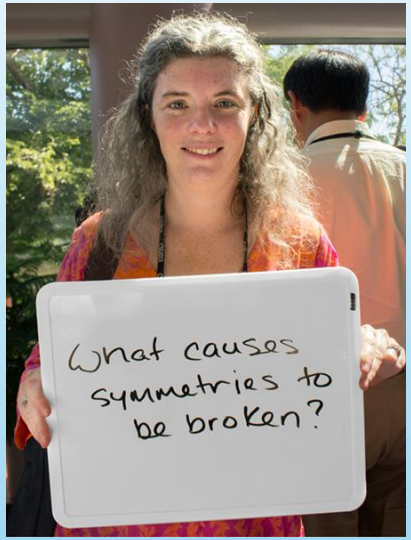
# *Open questions in fundamental physics*

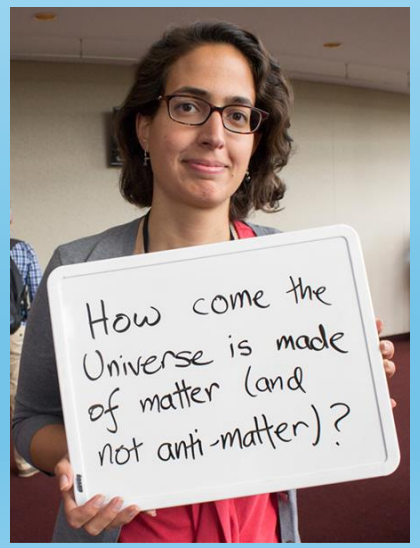
From Symmetry Magazine

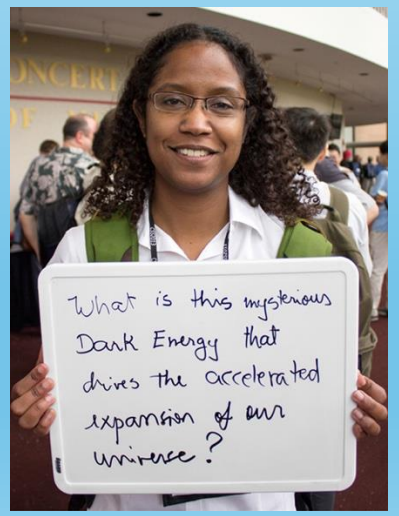


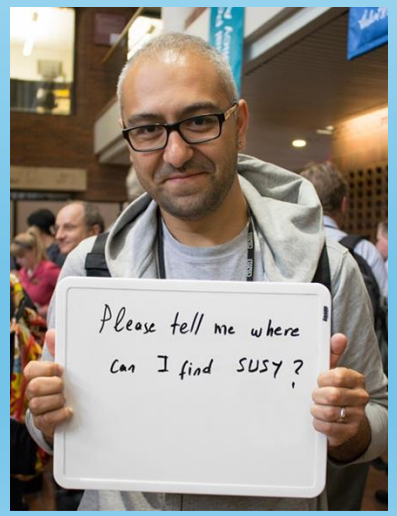



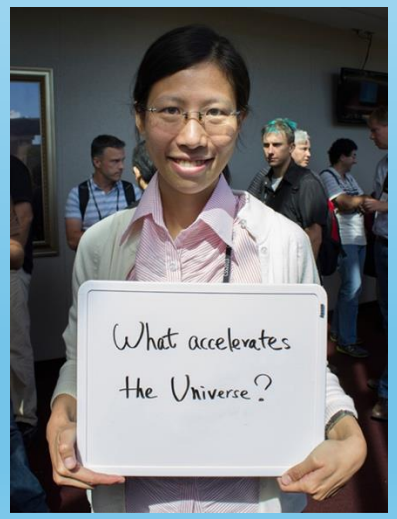



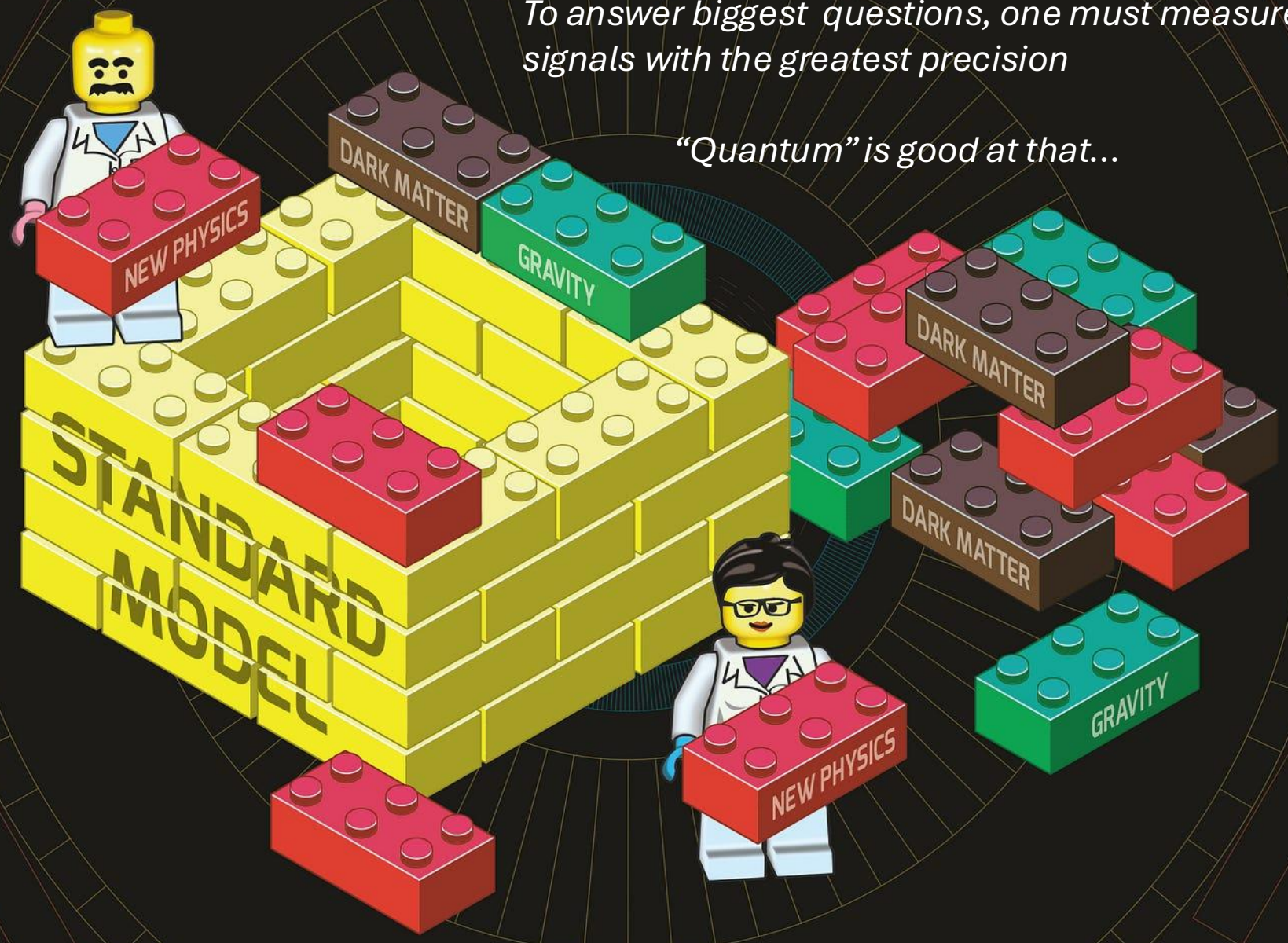



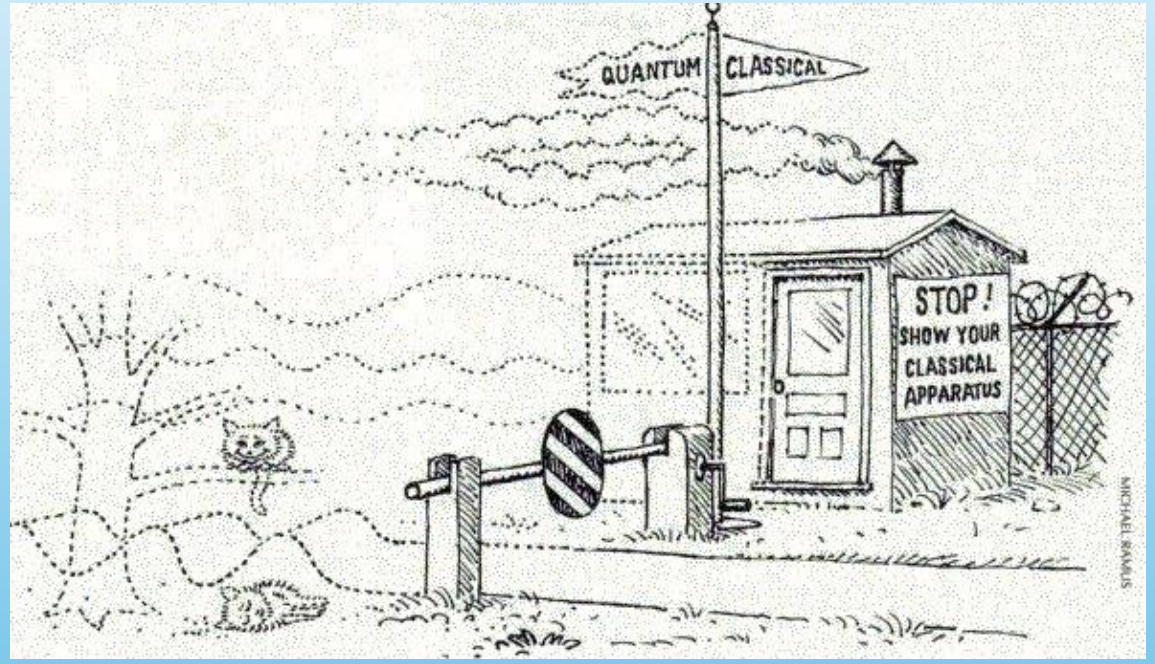
*To answer biggest questions, one must measure the smallest signals with the greatest precision*

*"Quantum" is good at that…*



# When technologies become “quantum” (personal view)

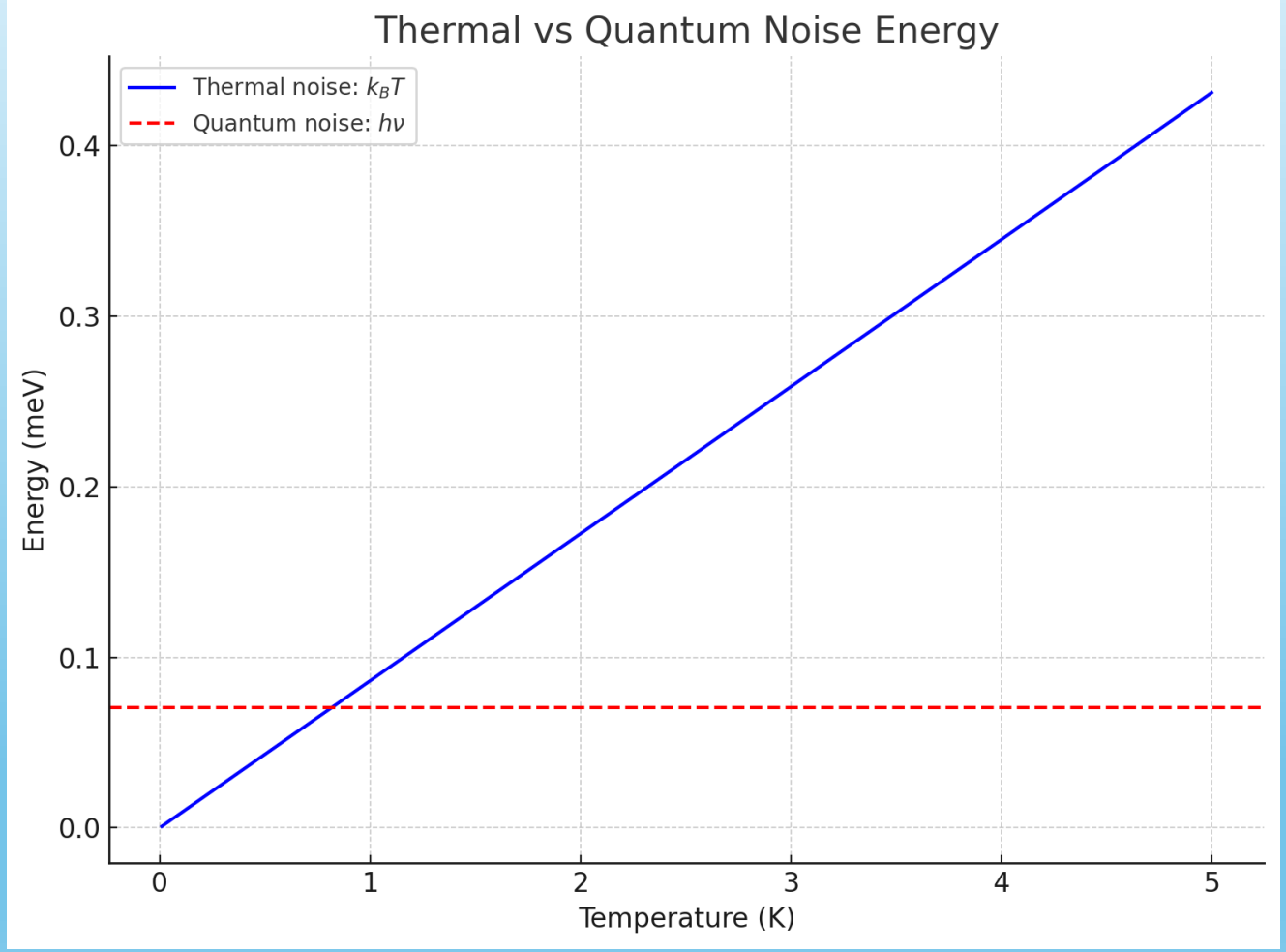
- When intrinsically quantum phenomenon is part of technology:
  - Qubits in Quantum Computing
  - Quantum sensors exploiting,
    - Quantum states superposition
    - Entanglement
    - Quantum “squeezing”
    - Sensors requiring quantum modelling for their design and fabrication (e.g. quantum amplifiers)
    - …




*Or more succinctly, when your measurement requires*

$$h\nu \geq k_B T$$

Example QTNM (Quantum Technologies for Neutrino Mass): measure cyclotron radiation of 18.6 keV electrons in 0.7T magnetic field .




$$\nu = 17GHz, h\nu \approx 0.07\ meV$$

$$k_B T \approx 0.086\ meV\ at\ T = 1K$$

- Community-driven process from 2018 to explore application of quantum tech for fundamental physics.
- Experts from particle and cold atom physics, AMOPP, quantum electronics, etc

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# Quantum Technologies for Fundamental Physics QTFP

On 30 September STFC and EPSRC will open a research call for the Quantum Technologies for Fundamental Physics (QTFP) programme. This is a new programme which, building on the investments of the National Quantum Technology Programme, aims to demonstrate how the application of quantum technologies will advance the understanding of fundamental physics questions.

The call has total funding of c.£36m and will look to fund up to seven projects of £2m and above each (80% fEC). Requests for over £5m should contact the office before applying. The call will be for research consortia, i.e. joint proposals with a common research programme from groups of researchers in more than one organisation. Successful applications will require interdisciplinary research teams comprising researchers from both the fundamental physics and quantum technology communities.

The call's fundamental physics remit covers quantum science, astronomy, particle physics, particle astrophysics and nuclear physics. Applications to the call will be expected to show how quantum technologies will enhance or enable their research area of interest.

The call will be open to all individuals and organisations eligible for UKRI funding. PSREs are asked to contact the office to check if they are eligible. Grants will commence on 1 May 2020 and end no later than 30 September 2023. Successful projects will be expected to show tangible outcomes and results within the lifespan of the funding. The standard STFC/EPSRC expectation for Research Organisations to contribute to the cost of equipment at around the 50% level will apply.

Applicants will be required to complete an online Intention to Submit form on the STFC website by 31 October 2019 prior to submitting a full application. The closing date for full proposals will be 3 December 2019. Full details on the call, including the application process and assessment criteria, will be published on the STFC website.

- ***£40M investment in 2019 from new UKRI money***
- ***Funding started in 2021 following competitive process***
- ***7 large projects funded in Wave 1***
- ***Further 17 smaller projects funded in 2022***

https://uknqt.ukri.org/our-programme/qtfp/

# QTFP 7 Large Consortia

Over 200 academics, senior researchers, early-career scientists, engineers, technicians and doctoral students

- AION, atom interferometer observatory and network. Gravitational waves, dark matter
- Quantum Interferometry (QI), space-time quantisation, dark matter
- Quantum Technologies for Neutrino Mass (QTNM), measure absolute neutrino mass
- Quantum Sensors for the Hidden Sector (QSHS), wave-like dark matter, axions
- Quantum Simulations for Fundamental Physics (QSimFP), early universe and dark matter
- Quantum Sensors Network (QSNET), variations of fundamental constants
- QUEST-DMC, superfluid technologies for dark matter and cosmology.

# Diverse programme with 17 smaller projects funded by QTFP in 2022

- **Quantum sensing for antimatter gravity**
  Institution: UCL
  Principal investigator: D. Cassidy
- **MeVQE: A world-leading centre for MeV scale entanglement physics**
  Institution: University of York
  Principal investigator: D. Watts
- **Development of levitated quantum optomechanical sensors for dark matter detection**
  Institution: UCL
  Principal investigator: P. Barker
- **Simulating high energy physics with quantum photonics**
  Institution: University of Bristol
  Principal investigator: A. Laing
- **ParaPara: A quantum parametric amplifier using quantum paraelectricity**
  Institutions: Lancaster University, UCL
  Principal investigator: E. Laird, E. Romans
- **Quantum computing for nuclear physics**
  Institution: University of Surrey
  Principal investigator: P. Stevenson
- **Supercooled cosmological simulator**
  Institution: Newcastle University
  Principal investigator: T. Billam
- **Testing theories of dark energy using atom interferometry**
  Institutions: Imperial College London, The University of Nottingham
  Principal investigator: E. Hinds, E. Copeland
- **Differential atom interferometry and velocity selection using the clock transition of strontium atoms for AION**
  Institutions: Imperial College London, University of Oxford, STFC laboratories, University of Birmingham, University of Cambridge
  Principal investigator: O. Buchmueller, C. Foot, P. Majewski, M. Holynski, U. Schneider
- **Penrose processes in an analogue black hole formed in hybrid light-matter (polariton) superfluid**
  Institution: The University of Sheffield
  Principal investigator: D. Krizhanovskii
- **Synthesising quantum states of sound and listening to what they tell us about the universe**
  Institution: Imperial College London
  Principal investigator: M. Vanner
- **Quantum simulation algorithms for quantum chromodynamics**
  Institution: University of Cambridge
  Principal investigator: S. Strelchuk
- **Accelerating the development of novel clocks for measuring varying fundamental constants**
  Institutions: University of Birmingham, Imperial College London
  Principal investigator: G. Barontini, M. Tarbutt
- **A quantum jump sensor for dark matter detection**
  Institution: Imperial College London
  Principal investigator: J. Devlin
- **Increasing the science reach for quantum enhanced interferometry**
  Institutions: Cardiff University, University of Strathclyde, University of Birmingham, University of Warwick, University of Glasgow
  Principal investigator: H. Grote, S. Reid, D. Martynov, A. Datta, R. Hadfield
- **Trapped electron for neutrino mass measurement**
  Institution: University of Sussex
  Principal investigator: J. V. Galiana
- **Levitated Quantum Diamonds**
  Institutions: University of Warwick, UCL
  Principal investigator: G. Morley, S. Bose

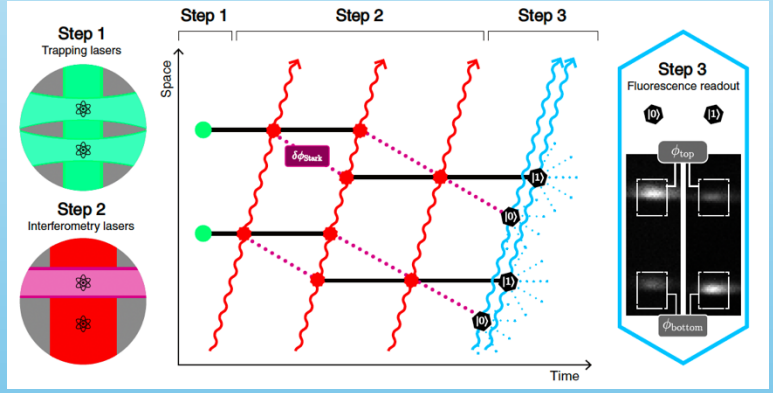
*Credit: O. Buchmuller*

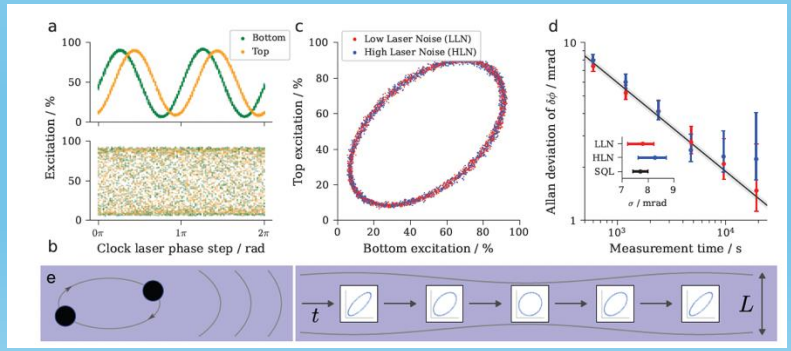
# Atom Interferometer Observatory and Network

**Primary objectives:**

- Develop atom interferometry network to probe fundamental physics with staged baseline scaling over decades
- Build supporting R&D infrastructure and highly-trained scientists and engineers

Partnership with MAGIS (USA)



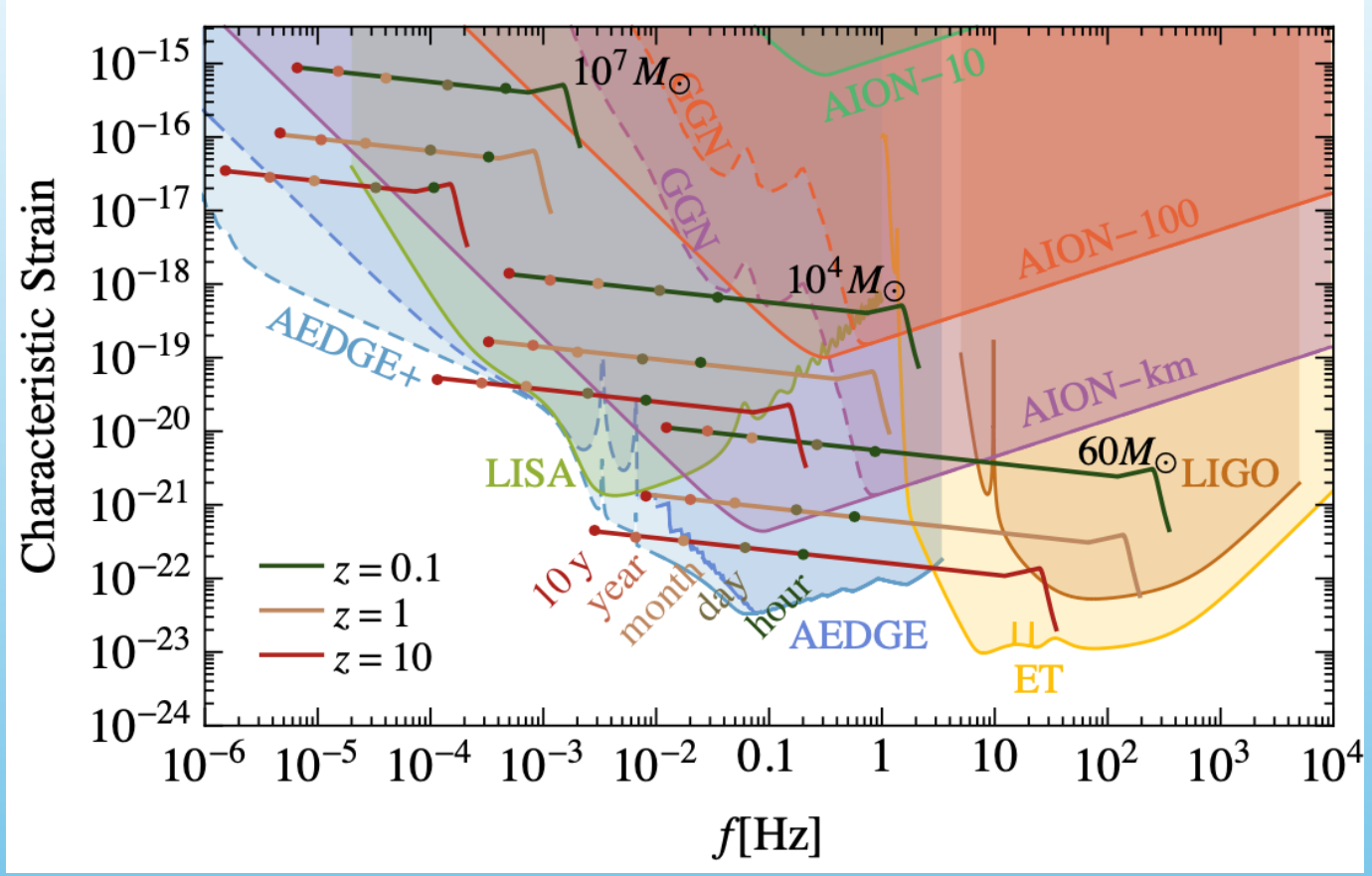

## Research highlight

- First demonstration of gradiometer measurement on the $^{87}$Sr clock transition (key to scaling baseline!)
- Tabletop demonstrator: differential measurement between two spatially-separated atom clouds
- Demonstrated cancellation of laser phase noise
- Crucial proof-of-principle of mechanism for detection of gravitational waves and other physics goals

*Manuscript accepted for peer-review by Nature [arXiv:2504.09158 (2025)]*

AION

*Credit: O. Buchmuller*




**Science case:**

- Decihertz gravitational waves [1]
- Fine-structure constant measurements [2]
- Probing dark energy models [3]
- Ultralight (wavelike) dark matter [4]
- Equivalence principle tests [5,6]
- Earth science and seismology [7]

**Technology development:**

High-precision quantum control

- Atom flux and interferometer repetition rate
- Atom kinematics, temperature, collimation
- Laser frequency, phase, and pointing stability
- Quantum enhancements to measurement: squeezed states
- Interferometer readout
- Temperature, vacuum, stray magnetic fields, and vibrations
- Gravitational static gradients and moving masses
- Subsampling instrument, aliasing L. Badurina *et al.*, Phys. Rev. D **108**, 083016 (2023)

Mitigation of environmental noise sources

- Seismic and atmospheric gravity gradient noise L. Badurina *et al.* Phys. Rev. D **107**, 055002 (2023); J. Mitchell *et al.*, *J. Inst.*, **17**, 01 (2022)
- Random anthropogenic and synanthropic noise J. Carlton and C. McCabe, Phys. Rev. D **108**, 123004 (2023)

Scaling baseline

- High power laser sources; optics stability and ruggedisation
- Shaft and environment engineering


[1] P.W. Graham *et al.* Phys. Rev. Lett. **110**, 171102 (2013).
[2] J. Schelfhout *et al.* Phys. Rev. A **110**, 053309 (2024).
[3] B. Elder et al., Phys. Rev. D **94**, 044051 (2016).
[4] L. Badurina, et al. Phys. Rev. D **107**, 055002 (2023).
[5] G. Rosi *et al.* Nat. Commun. **8**, 15529 (2017).
[6] P. Asenbaum et al. PRL **125**, 191101 (2020).
[7] J. Mitchell *et al.*, *J. Inst.*, **17**, 01 (2022).

# QI: Quantum Enhanced Interferometry for New Physics

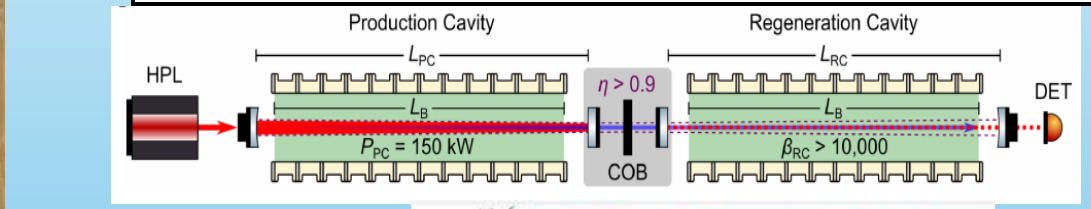
*Credit: H. Grote*

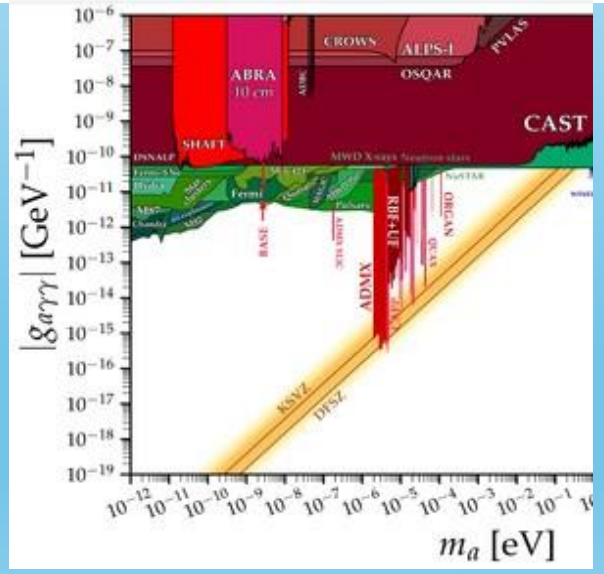
International partners:
Max Planck, DESY, NIST, U Chicago, MIT

**4 Projects, covering dark matter and quantum gravity:**

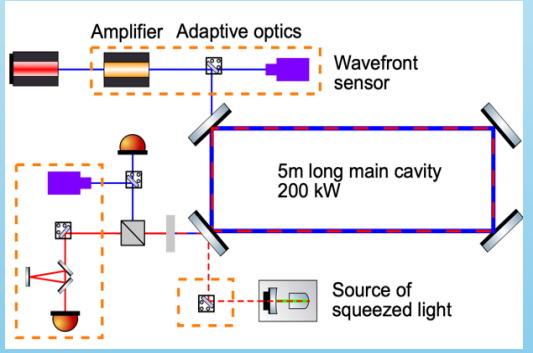
- **Search for Axion particles with ALPS II (at DESY)**
- **Search for Axion dark matter with interferometry**
- Search for Quantum Gravity with interferometry
- Search for semi-classical gravity with interferometry
- + Theory and Advanced Coatings facility EPOC

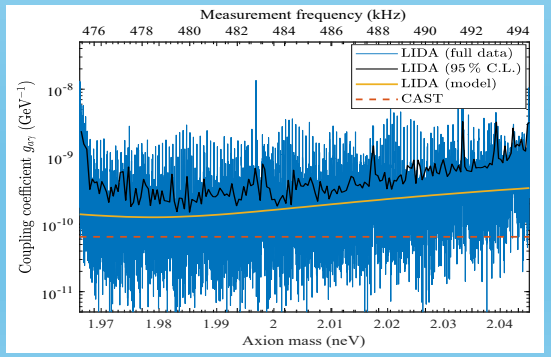
ALPS II at DESY:
A novel TES single photon detector






LIDA: an axion haloscope interferometer using squeezed states of light



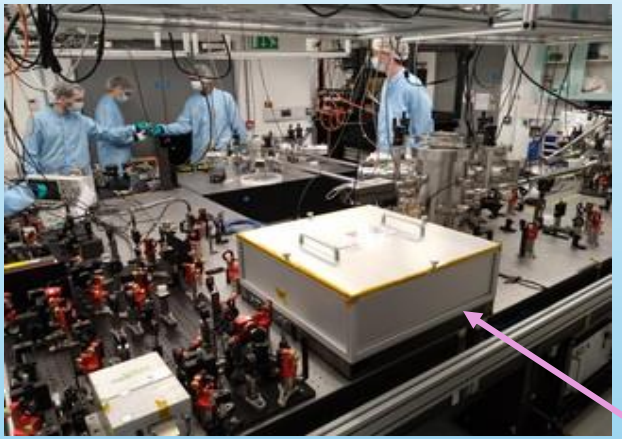



**4 Projects, covering dark matter and quantum gravity:**

- Search for Axion particles with ALPS II (at DESY)
- Search for Axion dark matter with interferometry
- **Search for Quantum Gravity with interferometry**
- **Search for semi-classical gravity with interferometry**
- **+ Theory and Advanced Coatings facility EPOC**

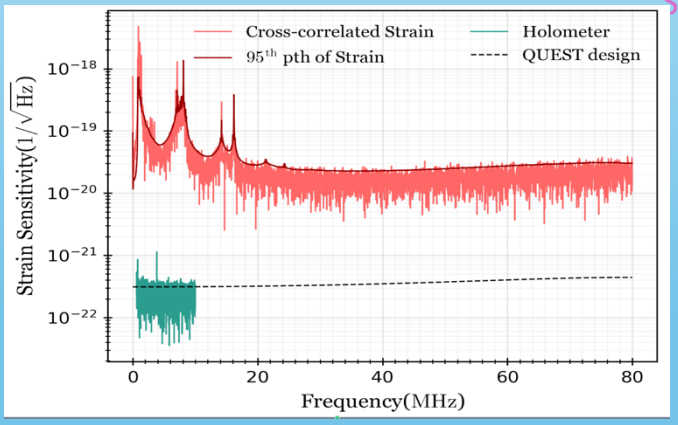
*Credit: H. Grote*

QUEST: QUantum-Enhanced Space-Time experiment



- World's only table-top co-located interferometer
- Main science target is quantum gravity, but also sensitive to dark matter and VHF gravitational waves

Squeezed light source

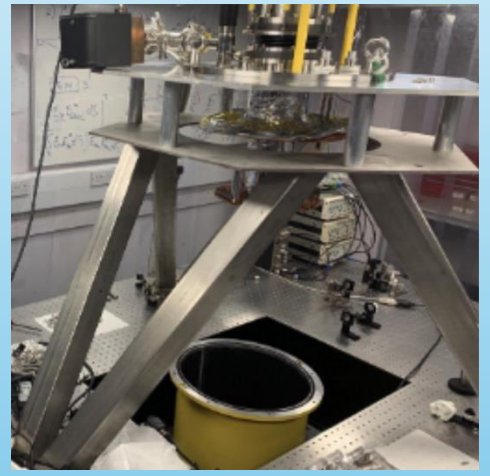


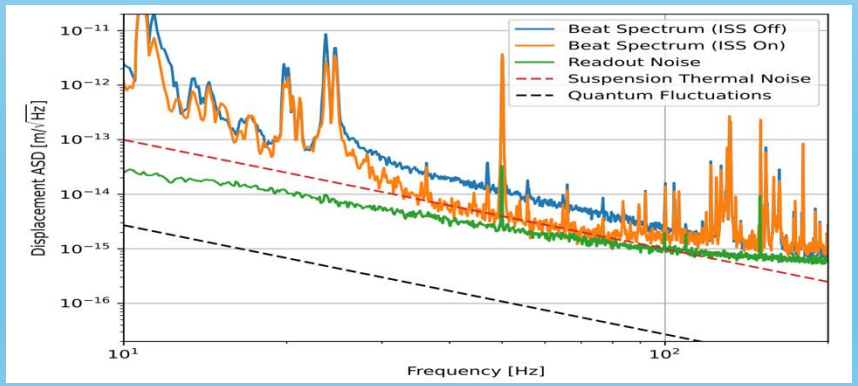

- Most stringent limits on VHF gravitational waves from 13 to 80 MHz
- Sub-shot-noise sensitivity from cross-correlation of two interferometers

ArXiv: 2410.09175 (2024);

Nature 600, 424-428 (2021)

Searches for Semi-Classical gravity



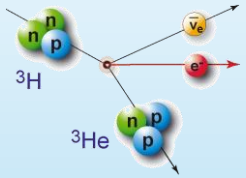



- Motion of oscillators at their quantum limit may show deviations from the standard quantum mechanics
- Study space-time evolution in classical spacetime with suspended cavities and a torsion balance

*Sensors 24*(7), 2375 (2024); ArXiv: 2411.17817 (2024)

# Quantum Technologies for Neutrino Mass

QTNM Quantum Technologies for Neutrino Mass

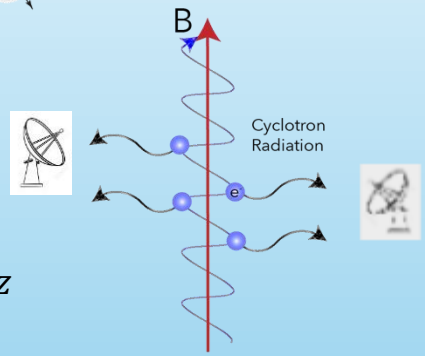


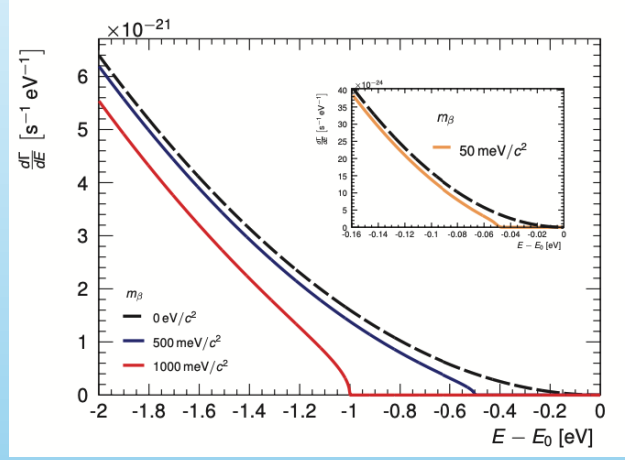

$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}X' + e^- + \bar{\nu}_e$$

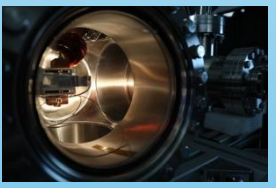
$$Q - E_e^{\max} \approx m_\nu c^2$$

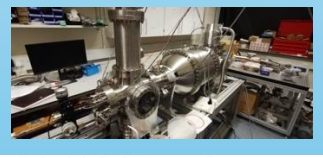
$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\mathrm{kin}}/c^2}$$

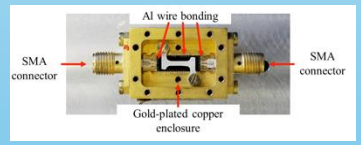
$$B = 0.7T \rightarrow f \approx 17\ GHz$$

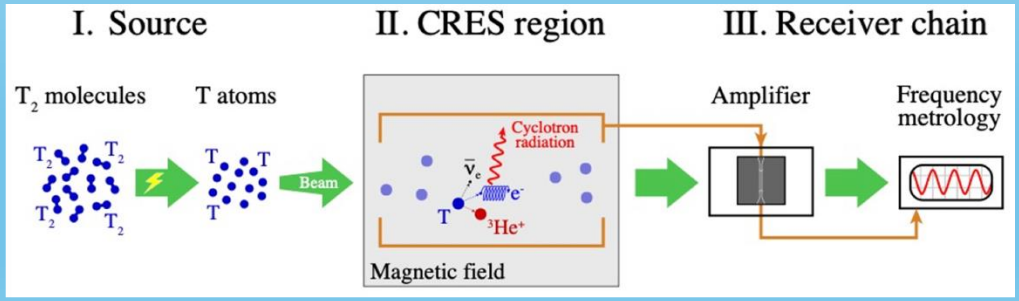






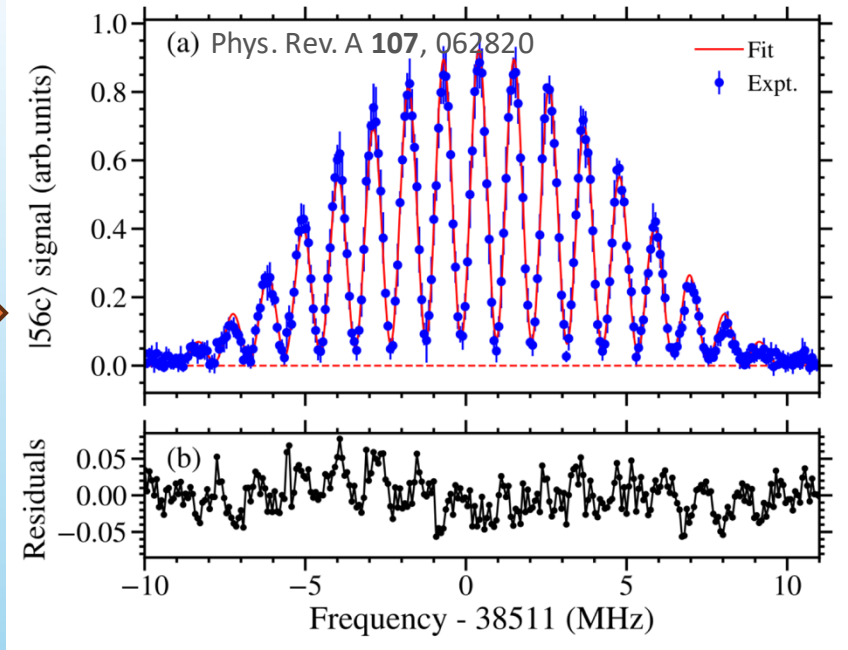

**CRESDA**-0 (CRES Demonstrator Apparatus):
from $^1$H/$^2$H to $^3$H. Demonstrating key technologies

- Quantum noise limited microwave sensors at high TRL for CRES at ~17 GHz
- 3D B-field mapping with 1 uT precision, using H-atoms as quantum sensors (Rydberg Magnetometry)
- Production and confinement of H-atoms $10^{12}$ cm-3
- Modelling tools for CRES and neutrino mass

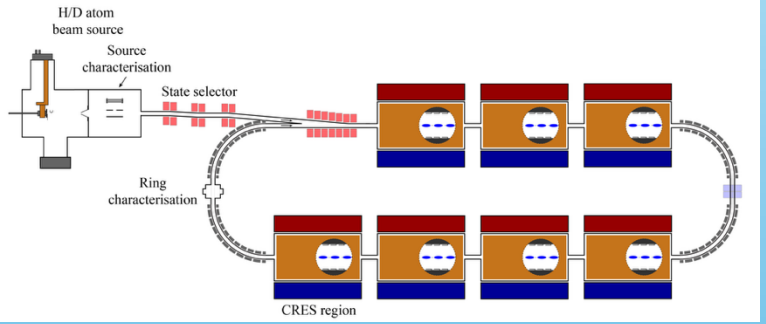
QTNM Quantum Technologies for Neutrino Mass

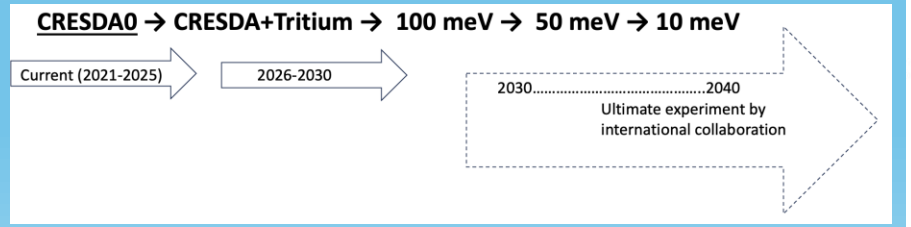
## Technology and Impact

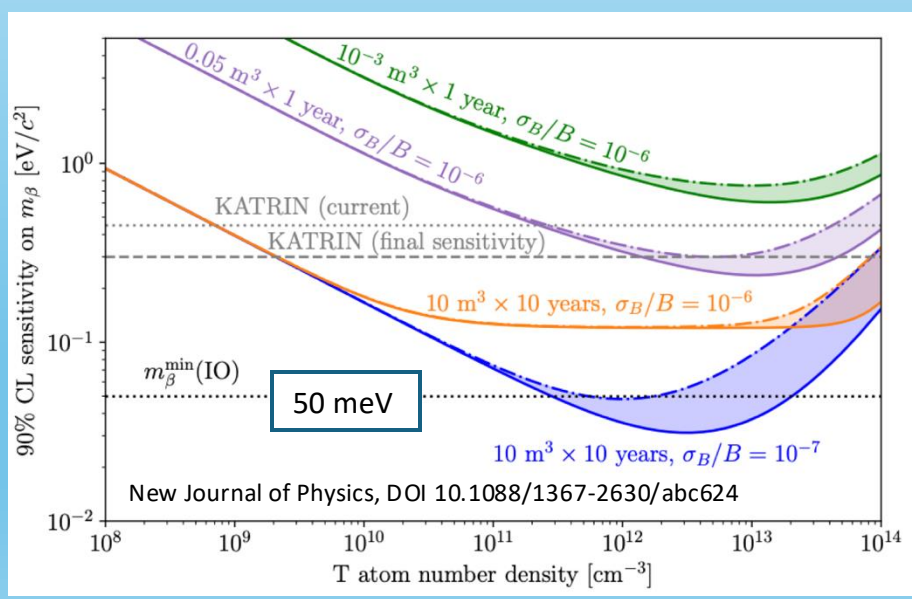
- Potential future particle physics experiment at Culham
- Non-linearity in superconducting amplifiers — applicable to qubits + more
- Sub-ppm cryogenic magnetic and electric field sensing, enabling applications from brain activity monitoring to nanoscale device diagnostics
- Highest phase-space density atomic hydrogen source — opens new frontiers in precision fundamental physics




## Future Outlook




## Project Partners

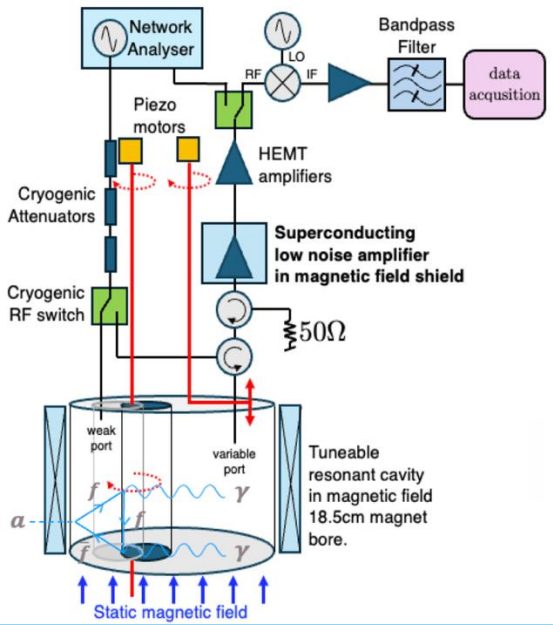
CCFE Culham Centre for Fusion Energy

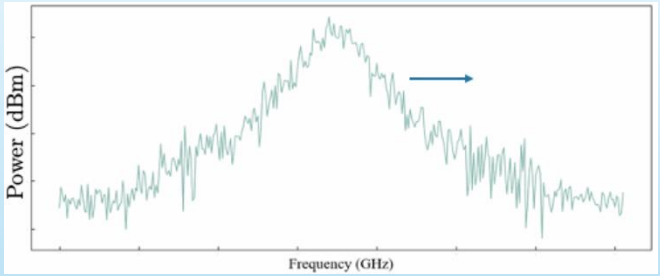
PROJECT 8

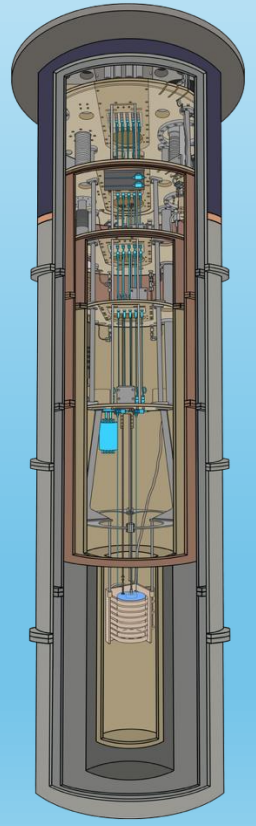
*Credit: E. Daw*

# Quantum Sensors for Hidden Sector

International Partner ADMX AXION DARK MATTER EXPERIMENT



## Science Goals

- Axion searches, hidden sector theory, quantum devices
- Develop and test quantum and high-sensitivity electronics for axion dark matter and other hidden sector particle searches
- Drive operating temperature of cavity searches down to ~10 mK: enable single photon detection operation.
- **Perform first search for galactic halo axion dark matter at ~μeV mass scale**

## Technology and impact

- New quantum transducers for use in physics experiments
- Tuneable digital resonant filters developed for resonant feedback
- Field-tolerant superconducting RF cavities
- Public engagement: Royal Society Summer Science Exhibition 2024:

https://www.lancaster.ac.uk/physics/outreach/royal-society-summer-science-exhibition/

*Credit: E. Daw*

## Updates and Outlook

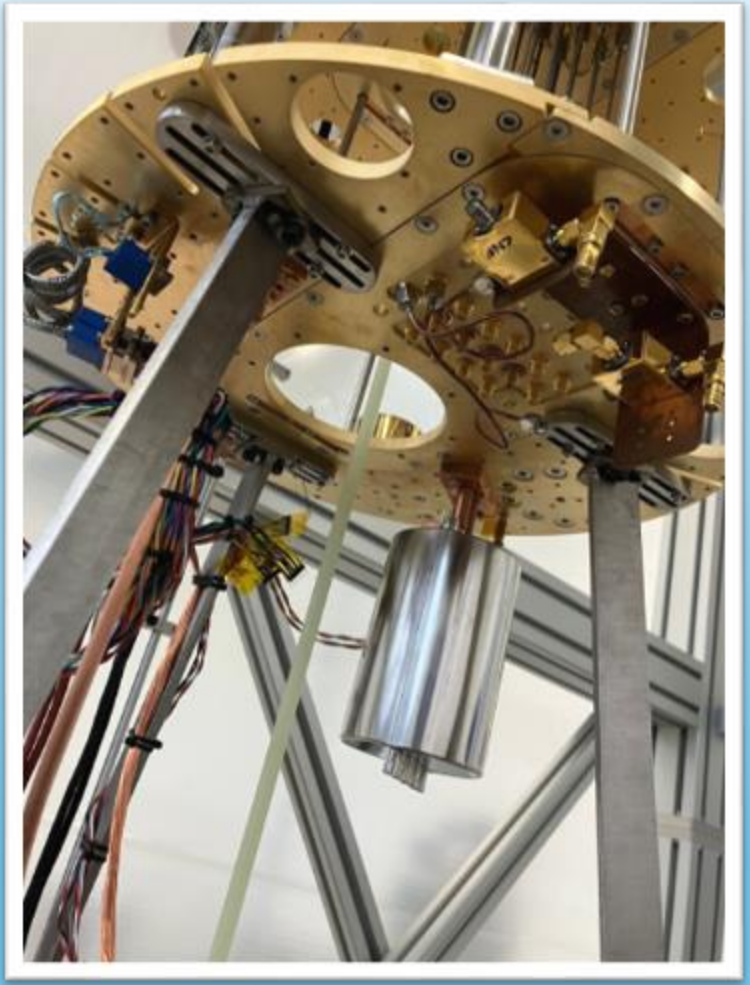
QSHS instrument paper submitted to New Journal of Physics. https://arxiv.org/html/2504.12257v1

Study of unloaded Aluminum 'sidecar' cavity also submitted to New Journal of Physics. https://arxiv.org/abs/2503.22637

Magnet achieved full field of 8T in the Sheffield lab in April 2025

Cryogenic tests, including superconducting TWPA underway

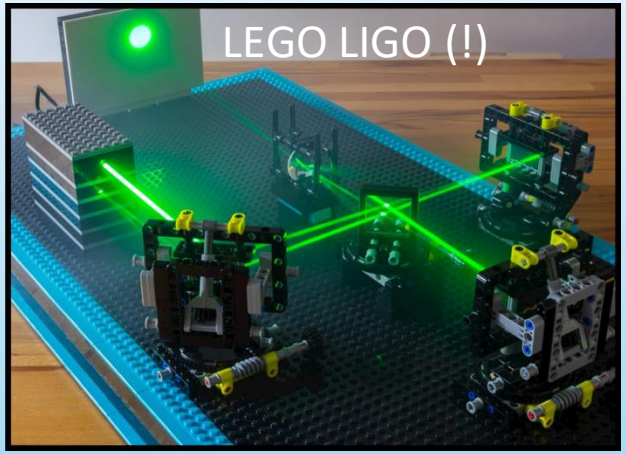
First science data from QSHS this summer.



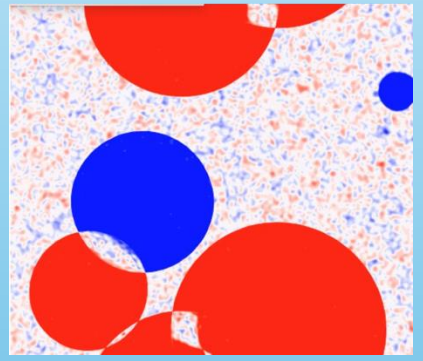
# QSimFP

# Quantum Simulators for Fundamental Physics

*Credit: S. Weinfurtner*

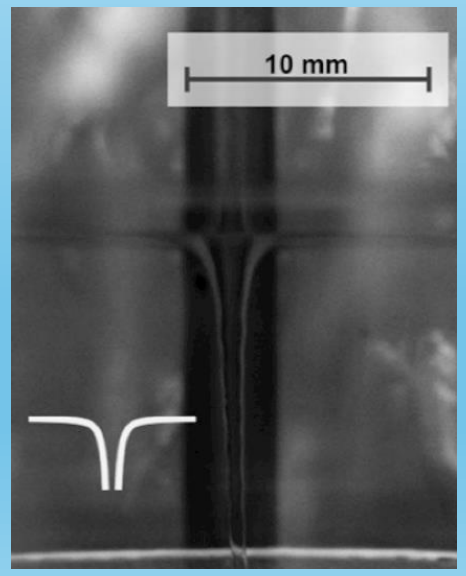



Primary objective:
Establish quantum field theory simulators using quantum gases, liquids, and optical systems

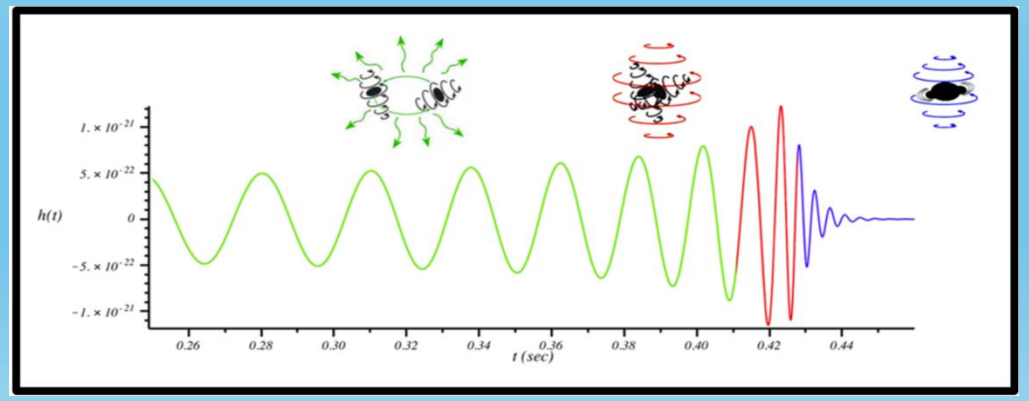


Particle physics-inspired cosmological theories exhibit false vacuum decay via bubble nucleation: first-order phase transitions

Giant quantum vortex flows in superfluid $^4$He




Spectral properties of black holes

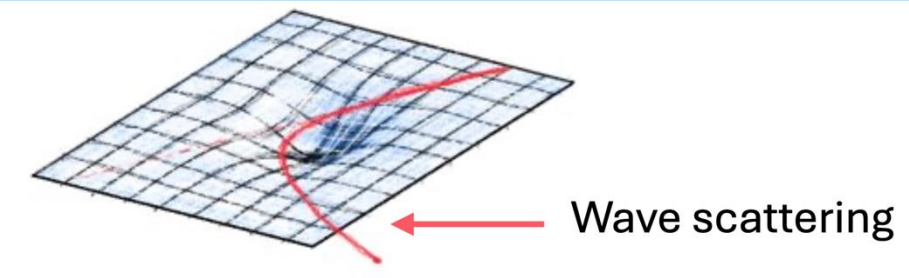


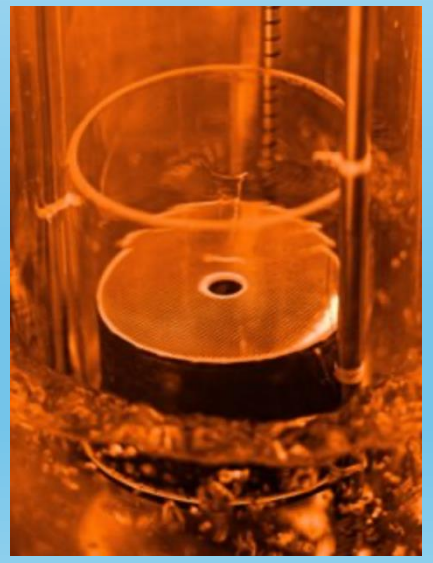

- Validate advanced mathematical frameworks. for fundamental physics
- Explore genuine relativistic quantum process
- Translate abstract concepts into reality
- Simulate the uncalculatable

# Research highlight: Quantum Black-Hole Simulator

*Credit: S. Weinfurtner*

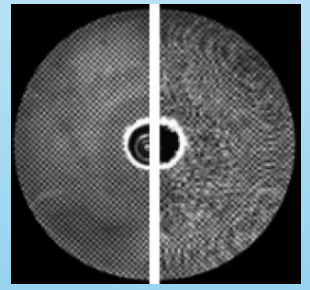
Principle: Waves propagating on a moving fluid perceive an effective, curved spacetime metric akin to rotating black holes



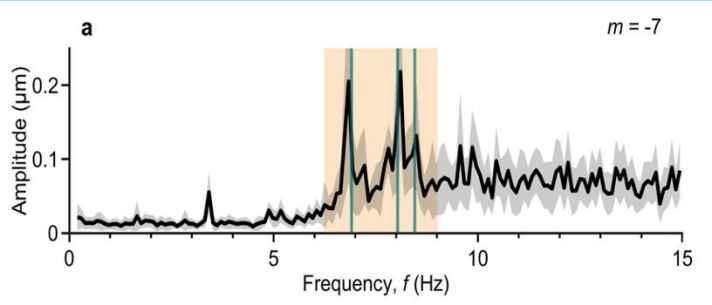
**Superfluid helium**: Strongly-interacting quantum liquid with well-defined interface

Theory: Modelling techniques of wave propagation to improve understanding of experimental data and uncover new phenomena in field theory on curved spacetimes



**Experiment**: Fully transparent helium cryostat: facilitates space/time-resolved detection of ripples on superfluid interface
Establishes experimental platform for black-hole simulation

Superfluid Helium as a laboratory analogue for black-hole ringdown



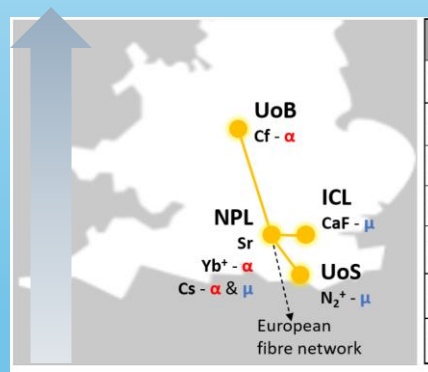

1) arXiv preprint arXiv:2406.11013 (2024)
Under review in Phys. Rev. Lett
2) arXiv preprint arXiv:2502.11209 (2025).

# Quantum Sensors Network

*Credit: G. Barontini*

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

$$\frac{\delta f}{f} = K_\alpha \frac{\delta\alpha}{\alpha} + K_\mu \frac{\delta\mu}{\mu} + \cdots$$




| Clock | Kα | Kμ |
|---|---|---|
| $Yb^+$ (467 nm) | -5.95 | 0 |
| Sr (698 nm) | 0.06 | 0 |
| Cs (32.6 mm) | 2.83 | 1 |
| CaF (17 μm) | 0 | 0.5 |
| $N_2^+$ (2.31 μm) | 0 | 0.5 |
| $Cf^{15+}$ (618 nm) | 47 | 0 |
| $Cf^{17+}$ (485 nm) | -43.5 | 0 |

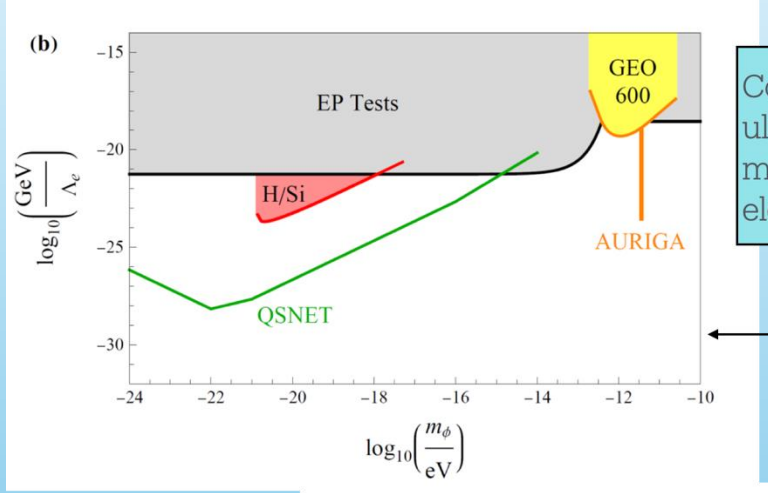
**TRL**

## Physics

- Tests of quantum gravity and grand unification theories
- Detection of transient events
- Search for variations in fine structure constant α and electron-to-proton mass μ
- Comparison between two clocks to search for time variation of α and set constraints on ultralight dark matter

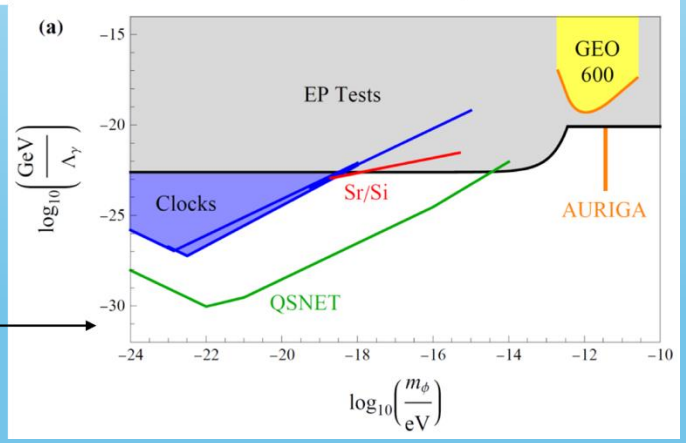
## Technology

- Optical clock development (neutral atoms, ions, highly charged ions, molecules)
- Measure ratio of frequencies from different pairs of optical clocks ($10^{-18}$ level)




Coupling of ultralight dark matter to electrons

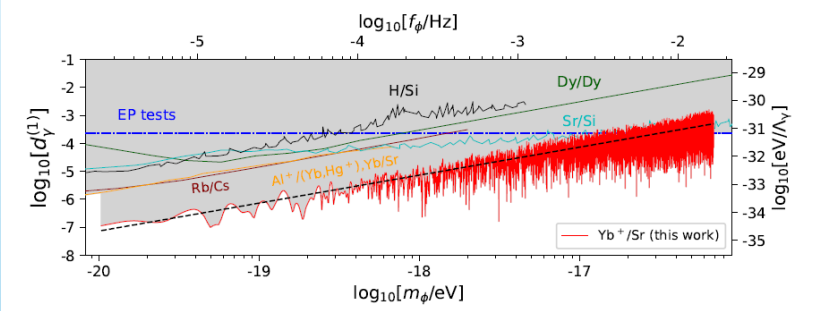
Coupling of ultralight dark matter to photons

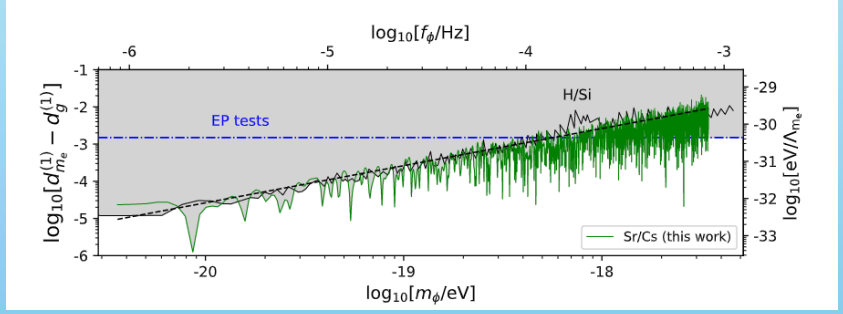



[EPJ QT 9, 12 (2022) ]

*Credit: G. Barontini*

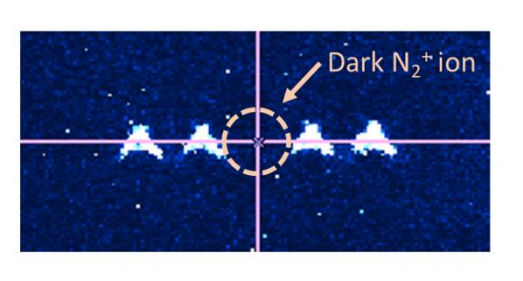
# Results

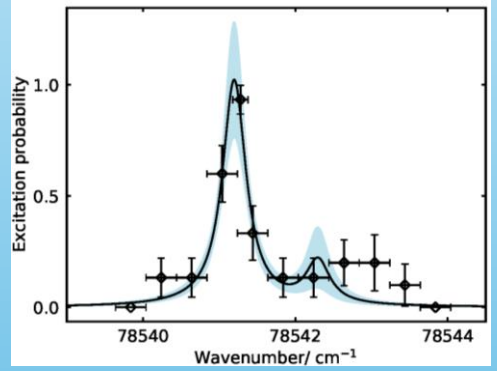



## NPL clocks & Sussex theory

- World-leading results: new constraints on ultra-light dark matter [New J. Phys. 25 9, 093012 (2023)]
- Most accurate clock in Europe
- More than 30 theory papers

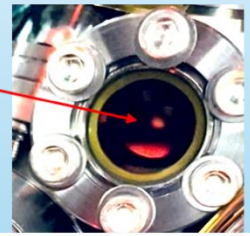


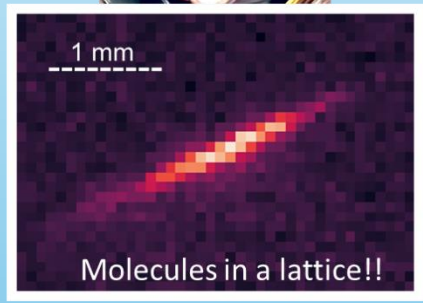




## Sussex experiment

- Coulomb crystal with cold N2+ molecule
- Quantum logic spectroscopy

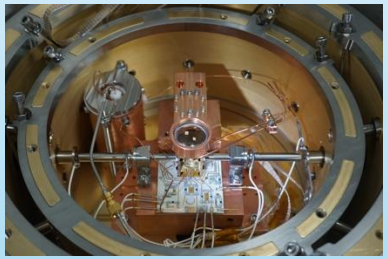
Ultracold CaF molecules

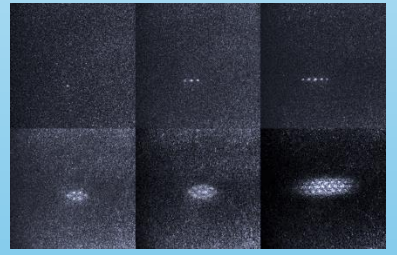





## Imperial

- Achieved cooling and trapping of molecules in an optical lattice
- Vibrational transition spectroscopy
- Advanced laser systems





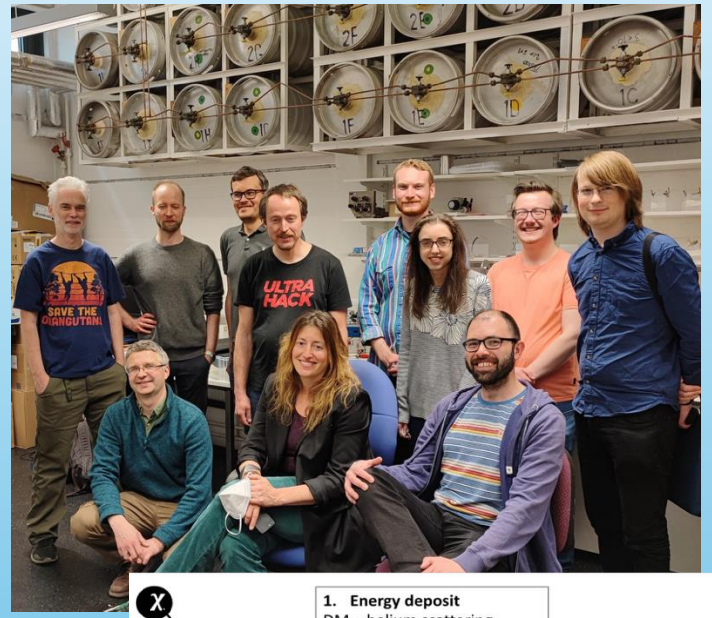
## Birmingham

- First compact electron beam ion trap in UK
- Coulomb crystal of Ca+ in cryogenic trap
- Production and slow down of highly charged ions

# QUantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

*Credit: A. Casey, A. Kemp*

*Two major physics goals linked experimentally through combining quantum sensors with superfluid $^3$He at ultra-low temperatures:*

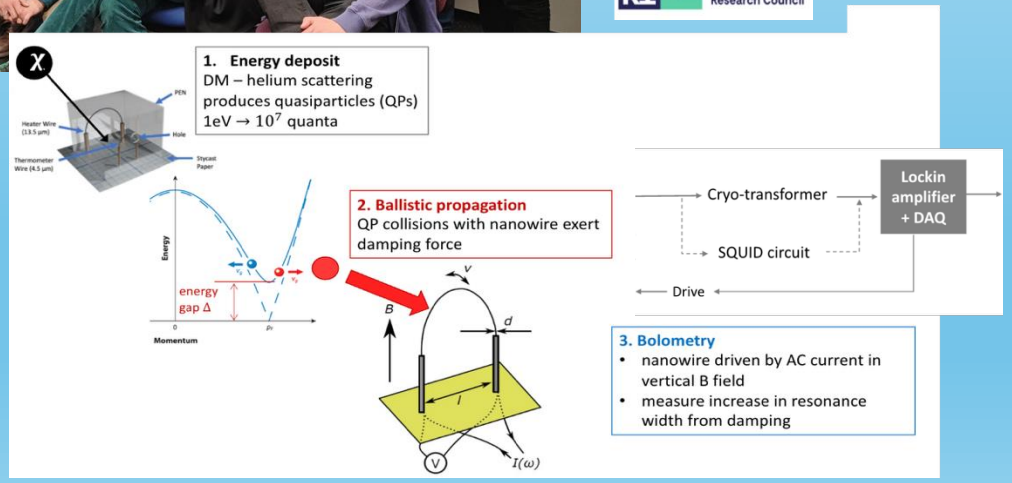


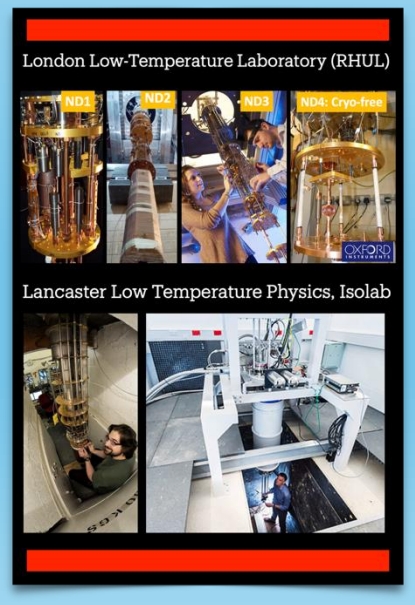
Superfluid $^3$He provides quantum analogue of cosmological first-order phase transition predicted ~10 ps after Big Bang in BSM models

**How did the early universe evolve?**

Search for sub-GeV dark matter with spin-dependent interactions with quantum tech :
Superfluid $^3$He
Nanomechanical resonators (NEMS)
Superconducting Quantum Interference Device (SQUID) readout

**What is the nature of Dark Matter?**

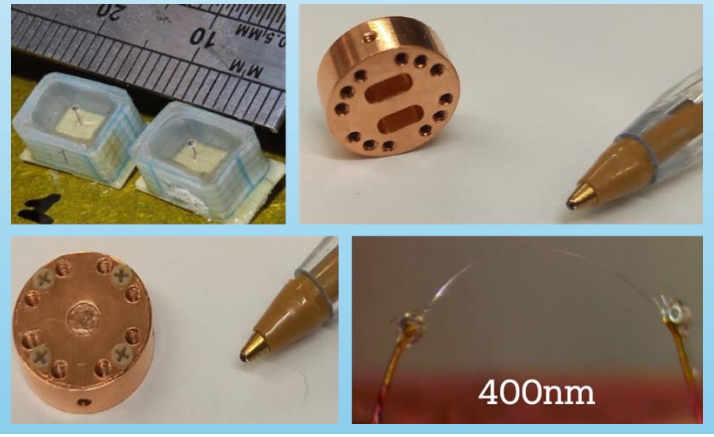


# Proof-of-Principle Bolometer Operation at T~μK

*Credit: A. Casey, A. Kemp*

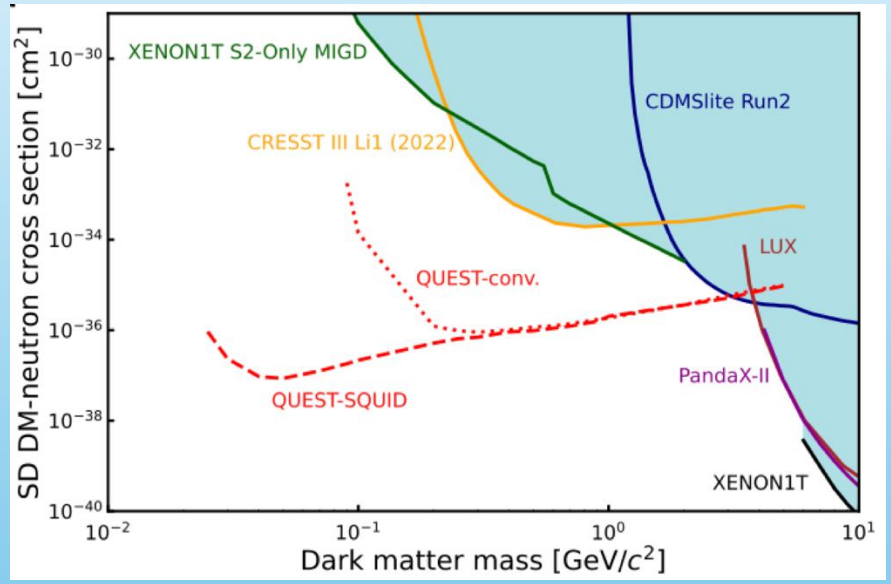
Operated up to 4 bolometers at <300 μK with smallest nanowires ever made

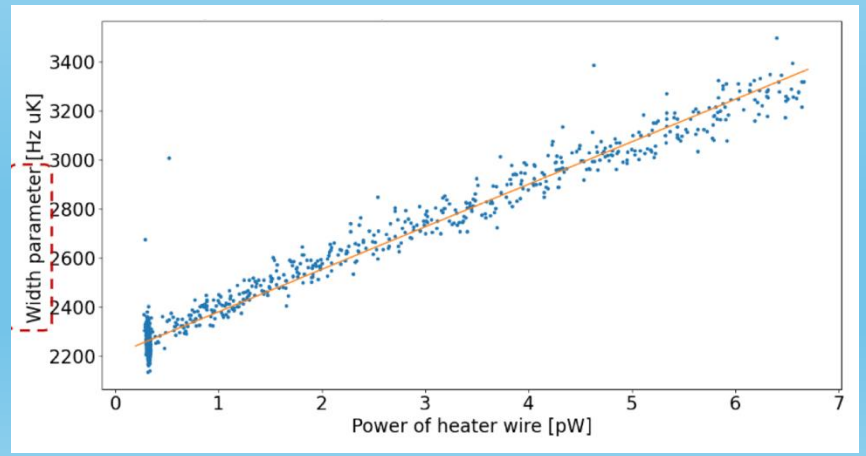


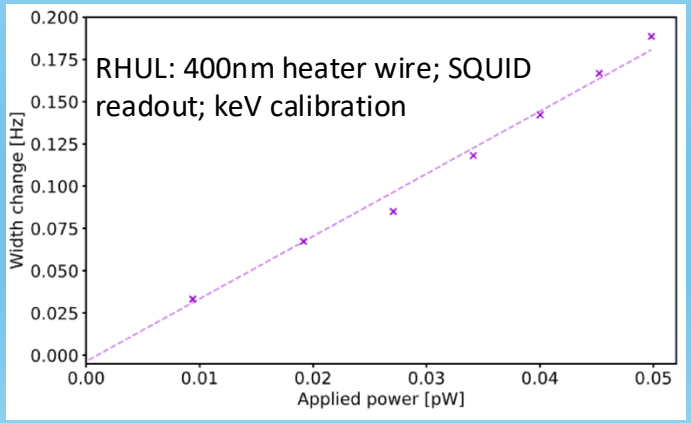

Underpinning of multiple technologies critical for achieving goal of world-leading sensitivity to sub-GeV dark matter candidates.

Demonstrated calibration down to femtowatt scales (~few keV)!

Eur. Phys. J. C (2024) 84:248



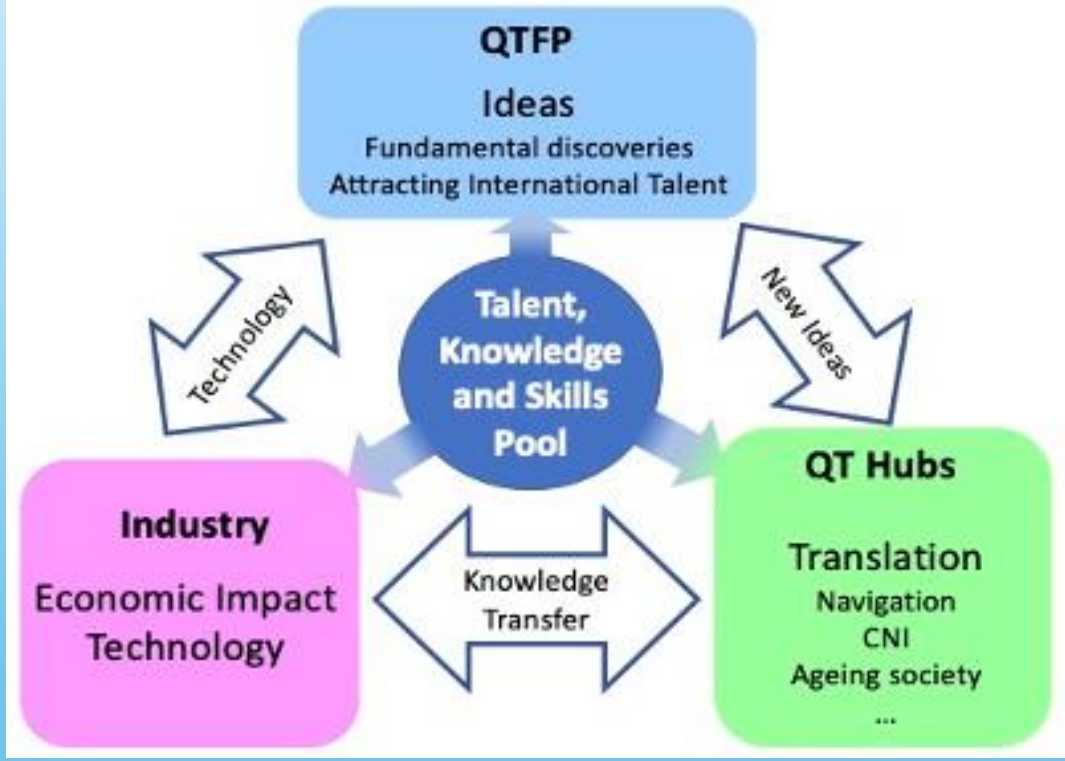

31 eV (0.51 eV) threshold for conventional (SQUID) readout, operating 5 x 0.03g cells for 6 months

# Quantum Technologies for Fundamental Physics

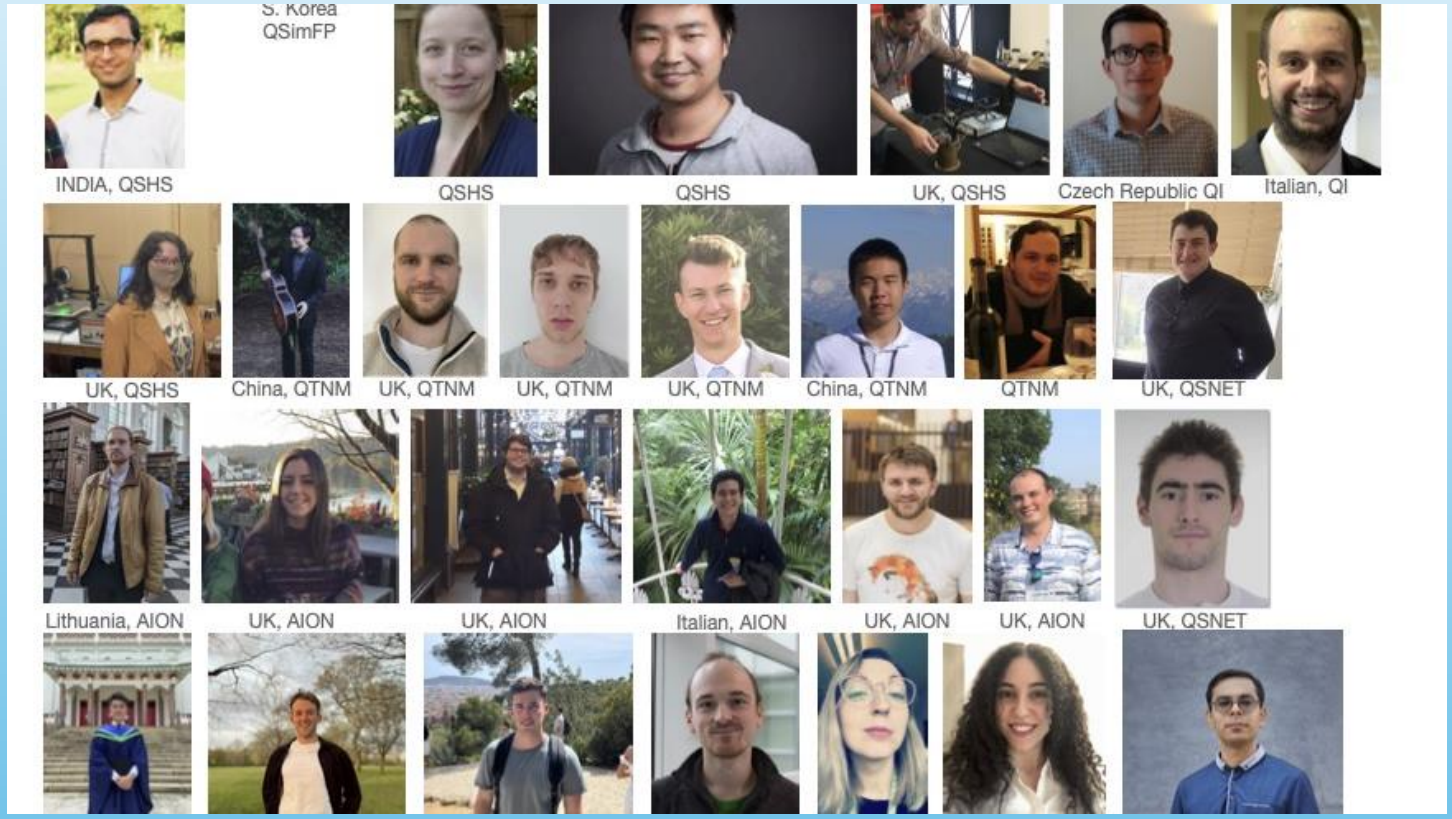
## QTFP Phase I (2021-2025) Science Review 2024,

## Headline Findings

- High standard and **transformational**
- Industry connection → **quantum economy**
- Clear evidence for **world-leading results**
- **Cross-disciplinary Community** building has been exemplary
- Did particularly well in attracting and training **ECR**
- UK set the standard with QTFP but it will require a **concerted effort** to maintain that lead



# QTFP Community



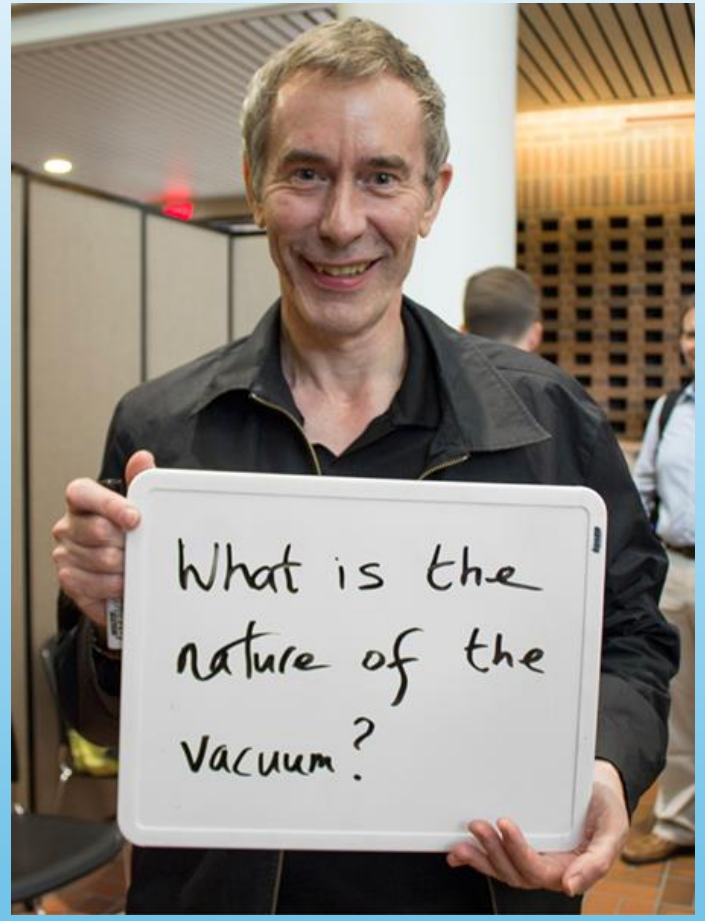

QTFP ***Community*** Workshop, Glasgow, 21-22 Jan 2025,
https://indico.stfc.ac.uk/event/1182/

Early Career Researchers Community

# Concluding Remarks

- The Standard Model works (almost) for ~5% of the universe — **quantum tools** may reveal what lies beyond.
  - Neutrino mass, dark matter, gravitational waves: all demand radical sensitivity.
- A **unique opportunity** to unite disciplines, train a new generation, and lead globally.
- QTFP programme gave UK a head start as global leader.
  - Community driven **roadmap** and **whitepaper**
  - Integral part of DRD-Collaboration: DRD5 "Quantum Sensors".
- **Ongoing uncertainties** risk not only delaying progress, but derailing the programme entirely

# Prof. Ian Shipsey (1959 – 2024)




**Thank you, Ian, for making QTFP possible!**