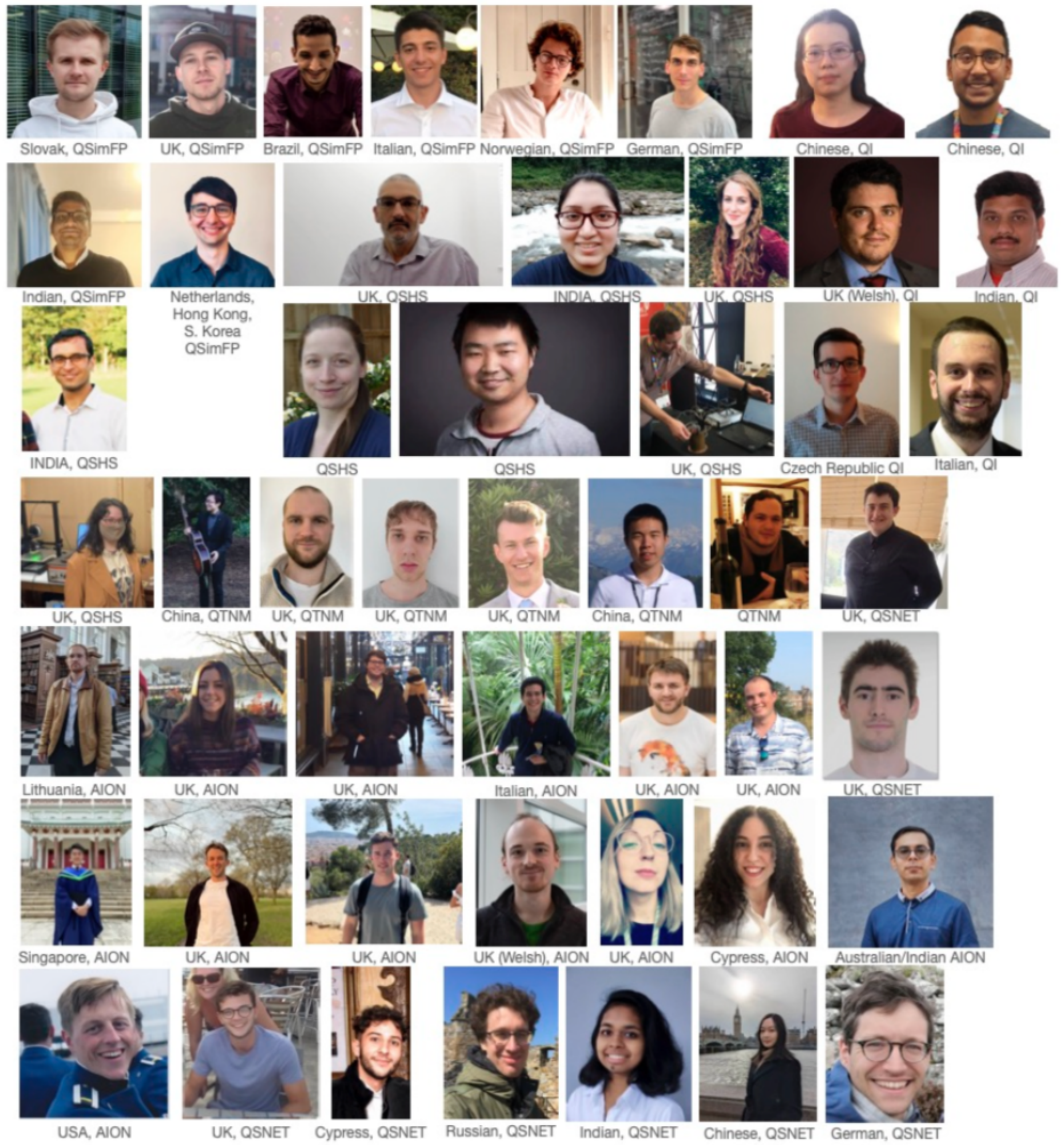
Quantum Technologies for Fundamental Physics

Ed Daw, The University of Sheffield

Principal Investigator-Quantum Sensors for the Hidden Sector

UK Particle Physics Community Meeting, Birmingham University, 26th June 2024



Quantum Technologies for Fundamental Physics

Multi-Messenger Particle Physics!

Vortices in Superfluid Helium 4

Precision tabletop optical interferometry

Ultra-low-noise microwave sensing of microwaves

Qubit detectors

Photon counting, sub-standard-quantum-limit detection

QSimFP - PI Silke Weinfurtner - analog **Lab simulation of complex systems** with vortices in liquid helium.
QI - PI Hartmut Grote - Laser interferometry for **ALP dark matter, GW, spacetime quantisation** research.
QSHS - PI Ed Daw - Axion, **Hidden sector dark matter** search with quantum electronics. **(ADMX)**
QTNM - PI Ruben Saakyan - **Neutrino mass** measurement with cyclotron radiation **(Project 8)**
AION - PI Oliver Buchmueller - Ultra-sensitive interferometry with atomic beams for **GW, ALPS (MAGIS)**
QSNET - PI Giovanni Barontini - Network of ultra-precise clocks **probing fundamental constants.**
QUEST-DMC - PI Richard Haley - **Particle dark matter search with liquid helium 3**

PLUS, 17 other smaller scale funded research projects

Atom interferometry

Neutrino mass direct measurements using Cerenkov radiation

Neutrino mass direct measurements using Cerenkov radiation

Precision atomic clocks, new clock technology

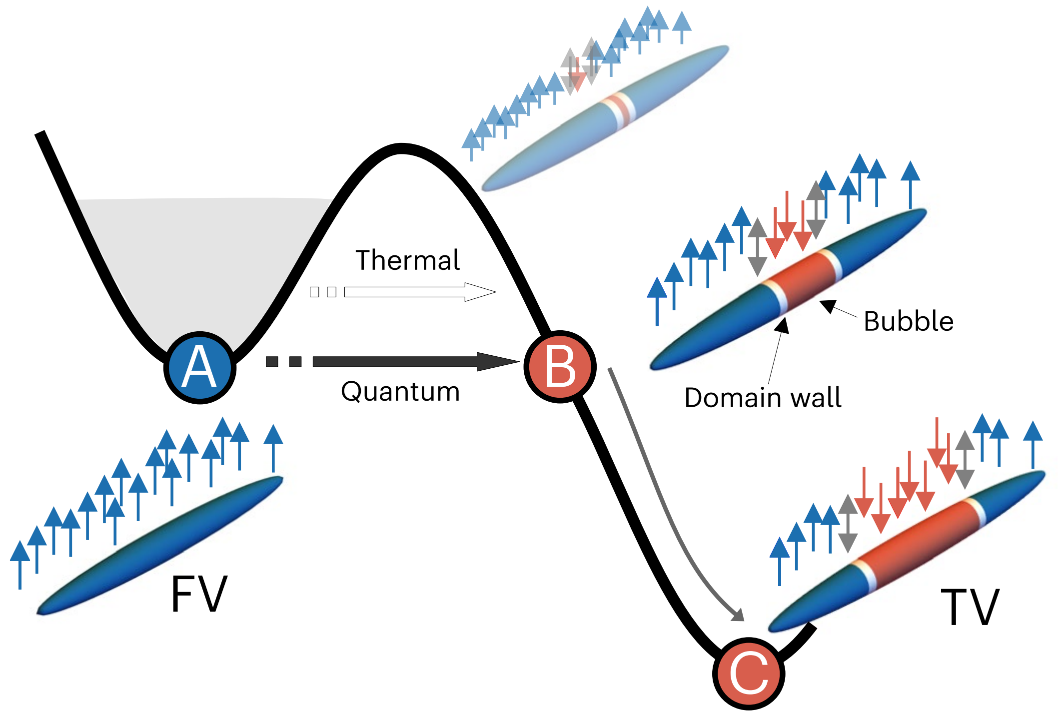
Liquid Helium 3 'Universe in a lab'

Theory of low-energy states adjacent to the vacuum

QSimFP

Nature Physics | Volume 20 | April 2024 | 558–563

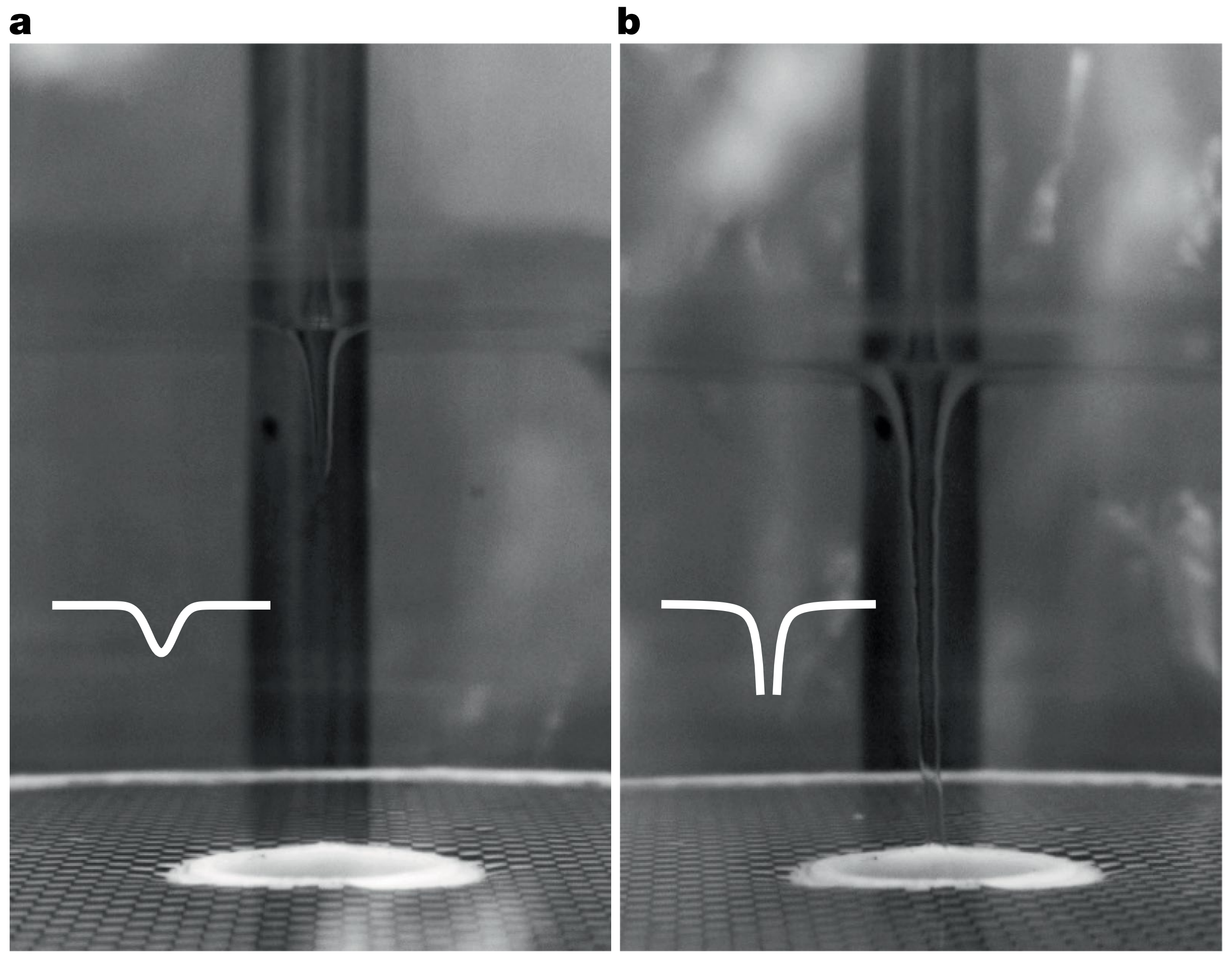
False vacuum decay via bubble formation in ferromagnetic superfluids



- Establishes consistency of observed bubble nucleation of a low energy ground vacuum state from a higher energy false vacuum in a ferromagnetic gas of Sodium-23.
- Connects the observed bubble nucleation rate with predictions from the theory of instantons.

66 | Nature | Vol 628 | 4 April 2024

Rotating curved spacetime signatures from a giant quantum vortex



- Quantum analogue between fluid dynamics and gravity achieved in superfluid Helium-4.

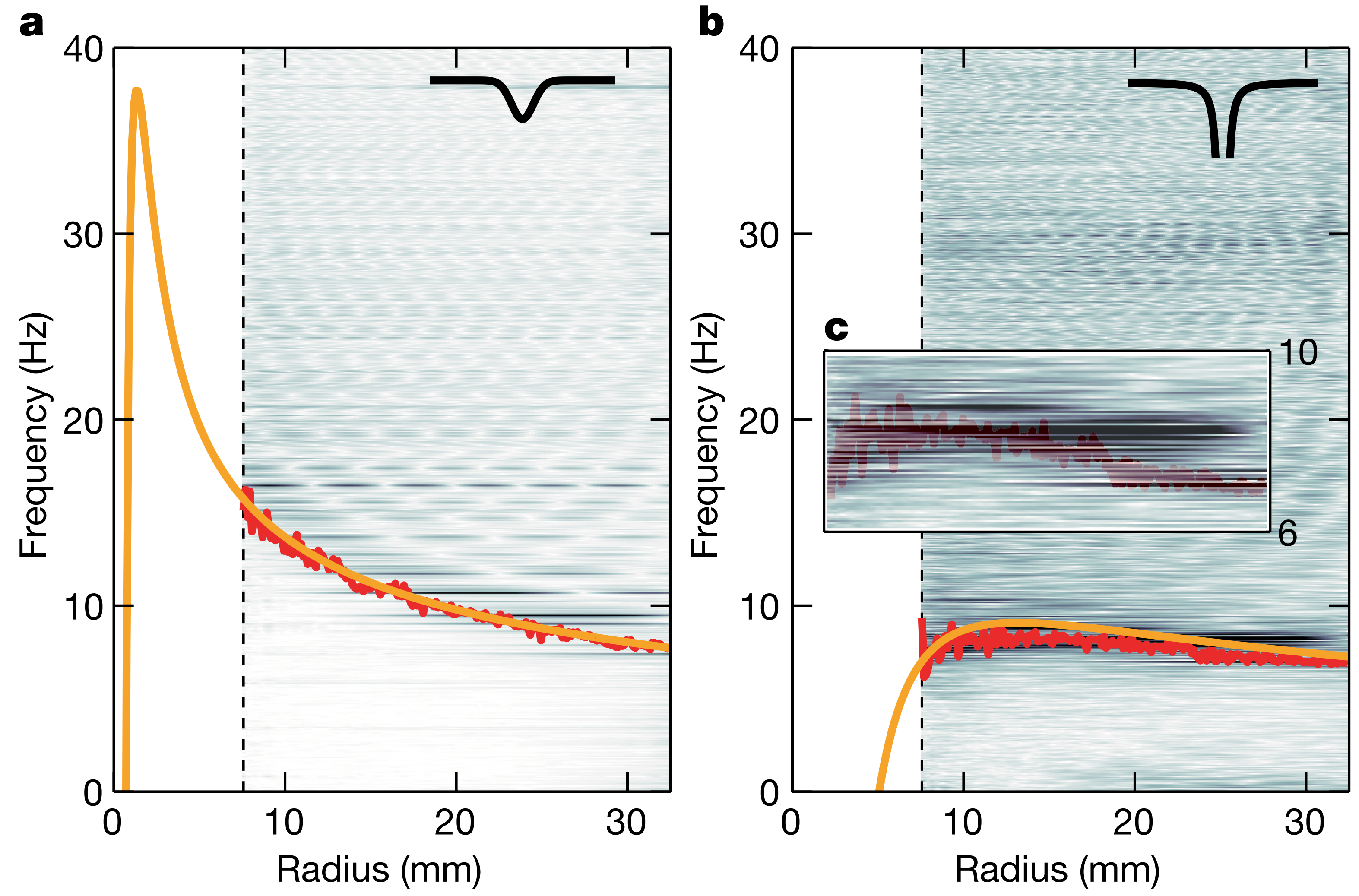
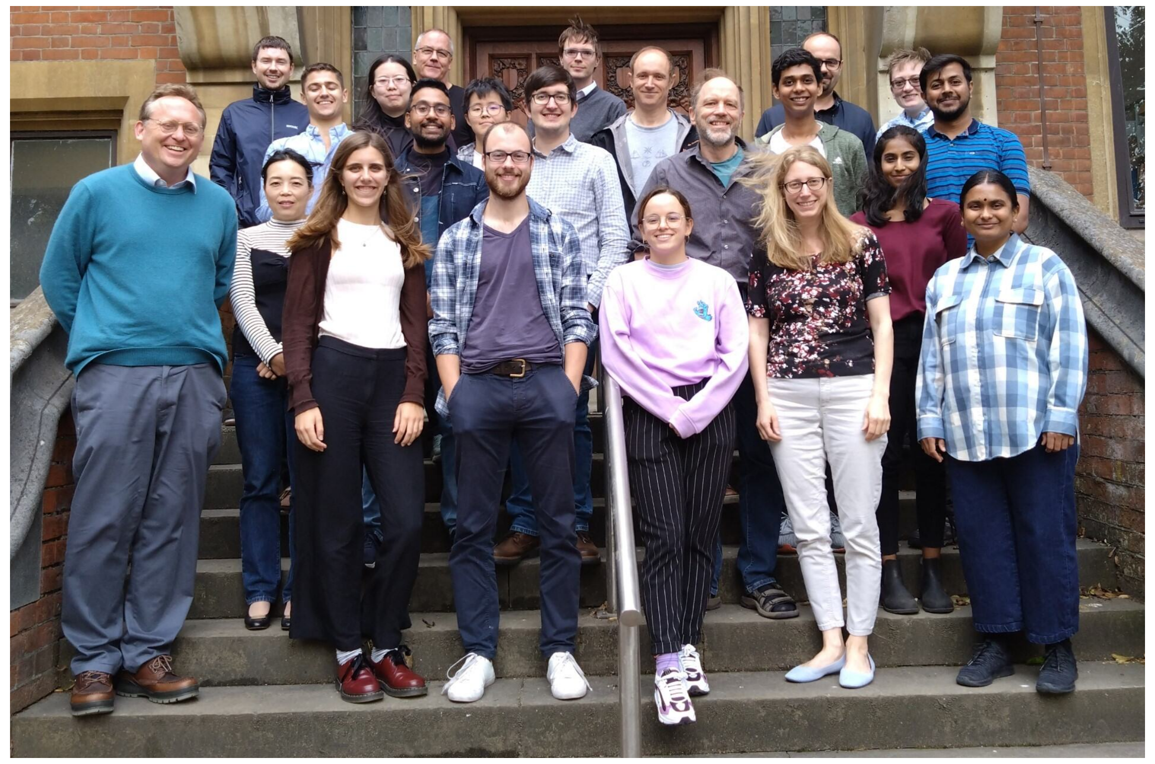


Fig. 5 | Bound states and ringdown modes in counter-rotating waves. Fourier amplitudes of interface waves (same colour scale as in Fig. 4) corresponding to $m = -8$ mode interact with the effective potential barrier

Quantum-Enhanced Interferometry for New Physics

- Novel searches for dark matter and axion-like particles: LIDA, ALPS II
- Novel searches for signatures of quantum gravity: QUEST, CRYO-BEAT
- Quantum technologies: Squeezed light and TES single photon detection

- UK members: Birmingham, Cardiff, Glasgow, Strathclyde, Warwick; International Partners: Fermilab / U Chicago, NIST, MIT, Caltech (US), DESY, PTB, Max Planck (Germany), Vienna (Au), U Western Australia (A)



Status:

- Novel axion interferometer method established: 2307.01365; 2309.03394; 2401.11907
- TES detector is under commissioning and ALPS II design: 2009.14294
- Scalar field dark matter searches: Nature 600, 424 (2021); PRL 128, 121101 (2022); 2402.18076 (2024)

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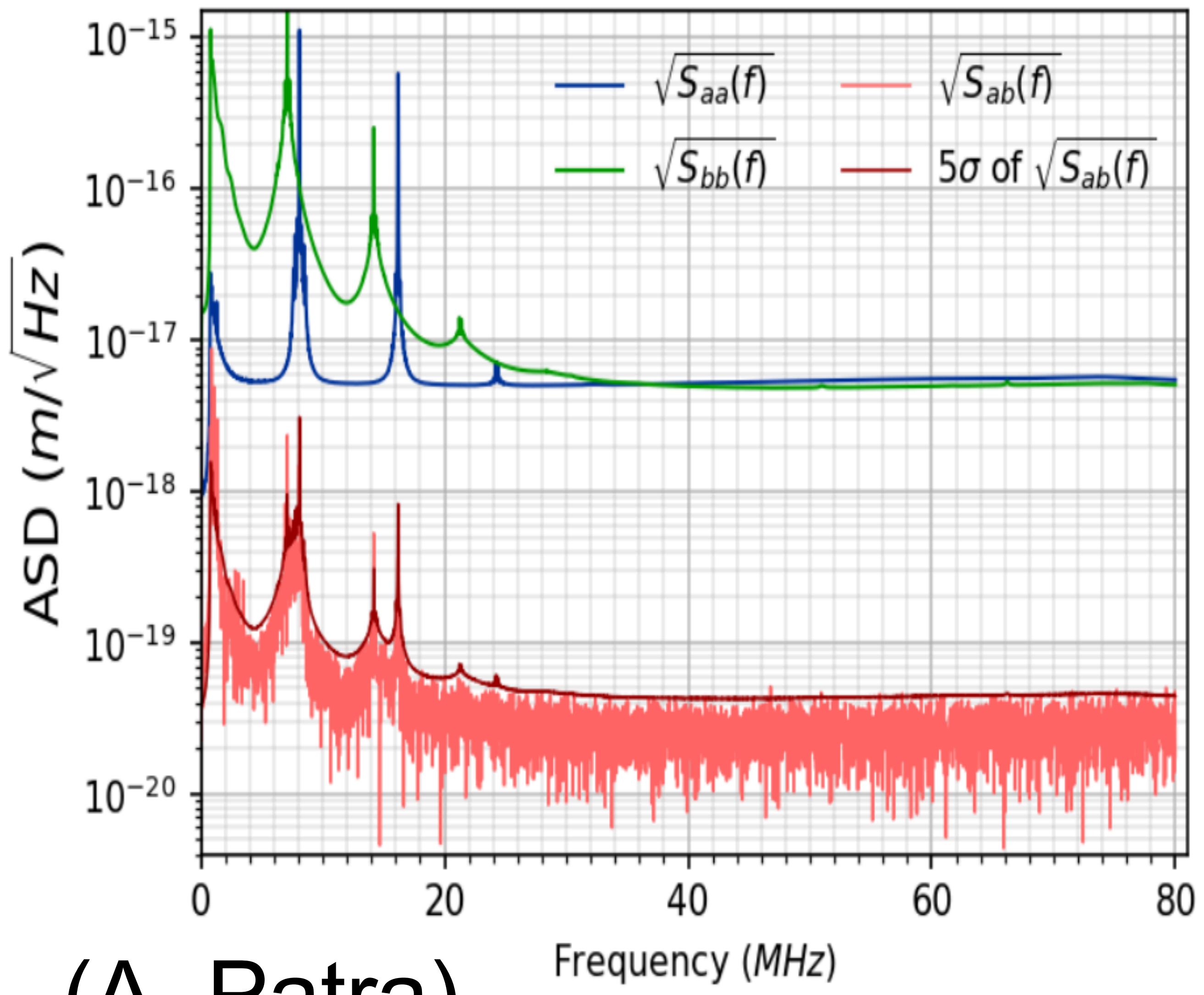
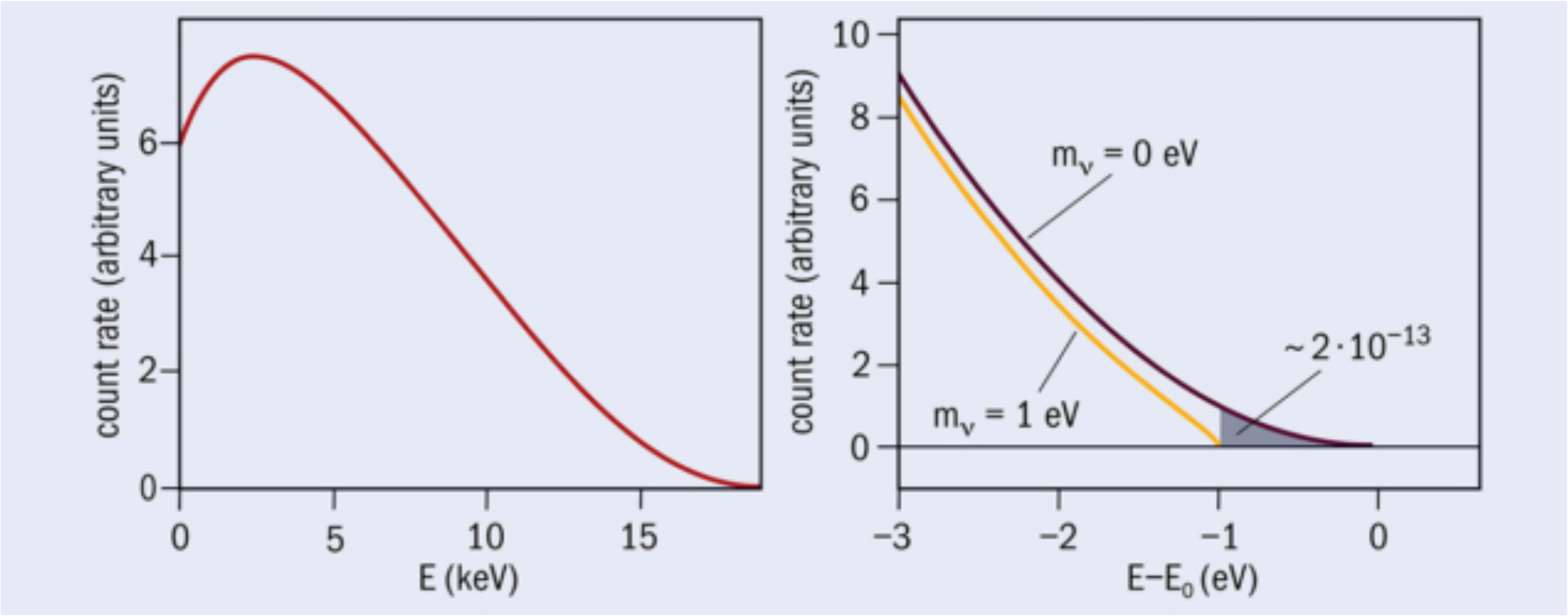
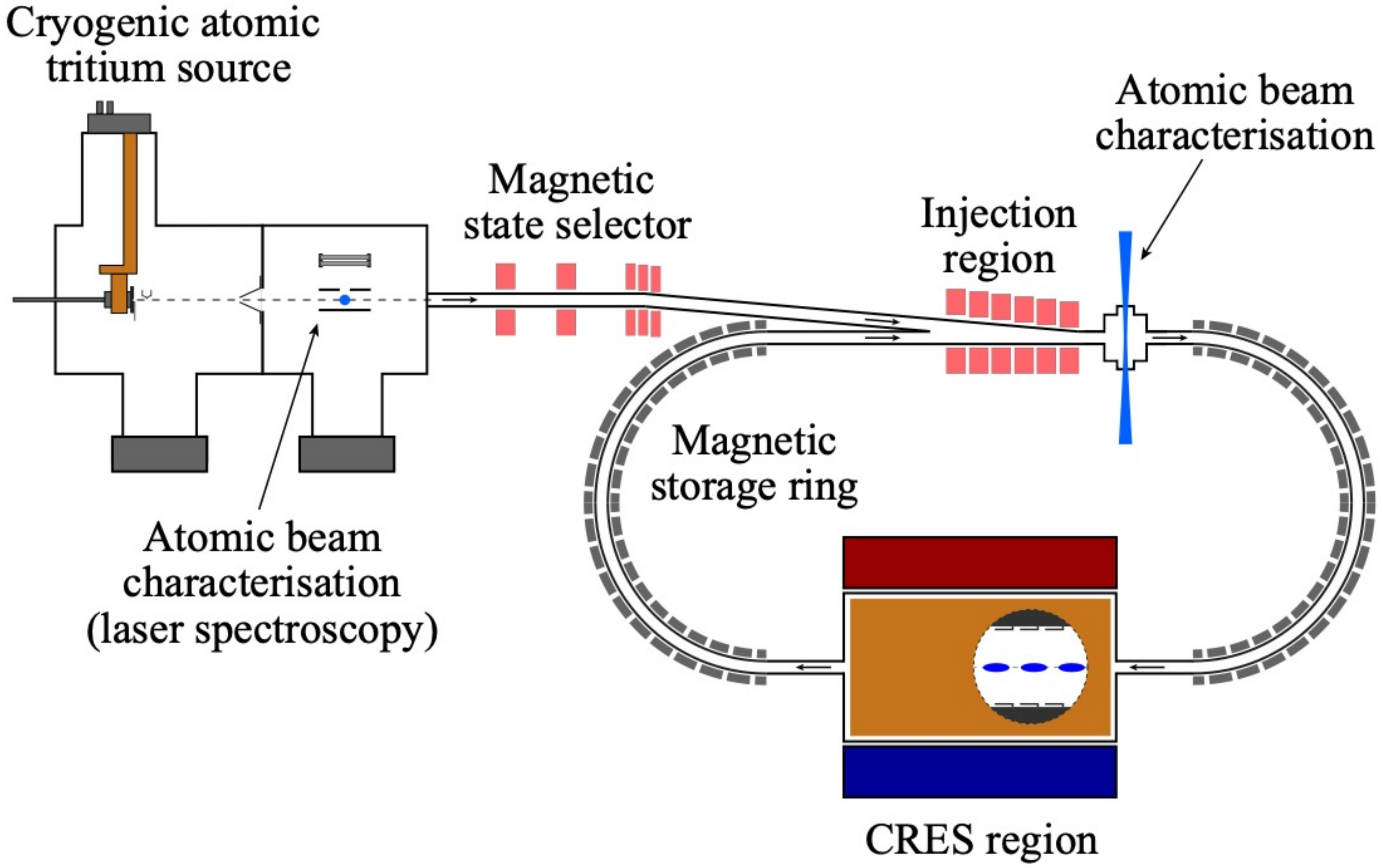


(A. Patra)

QTNM

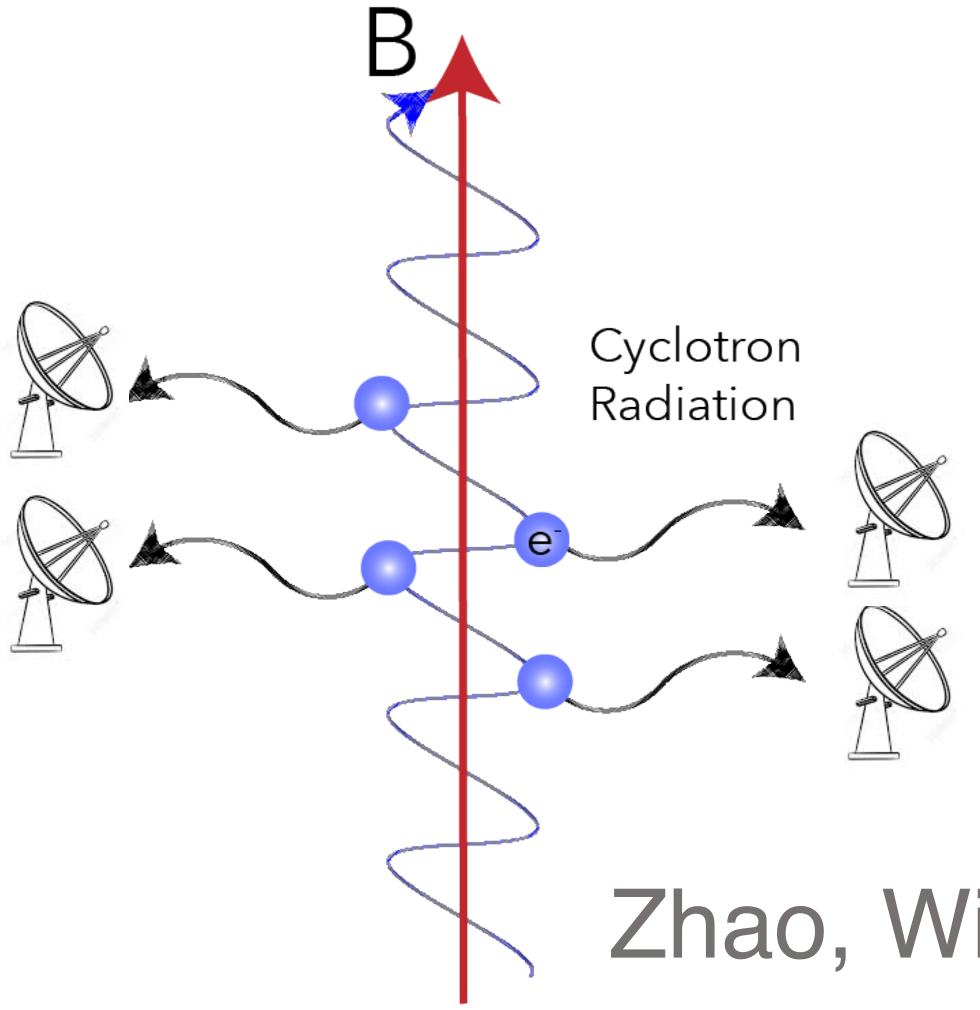
Atomic ^{3}H β-decay – model independent

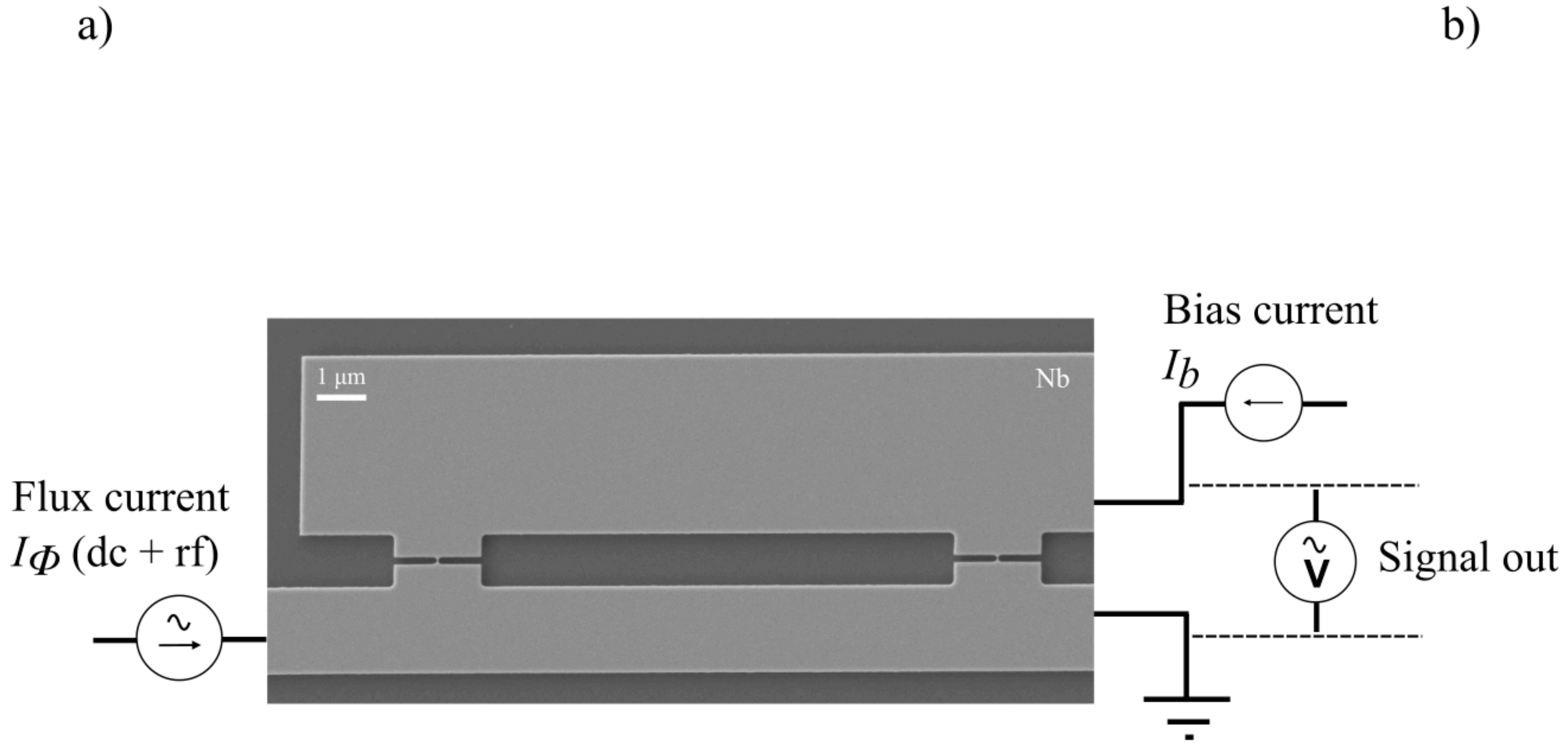


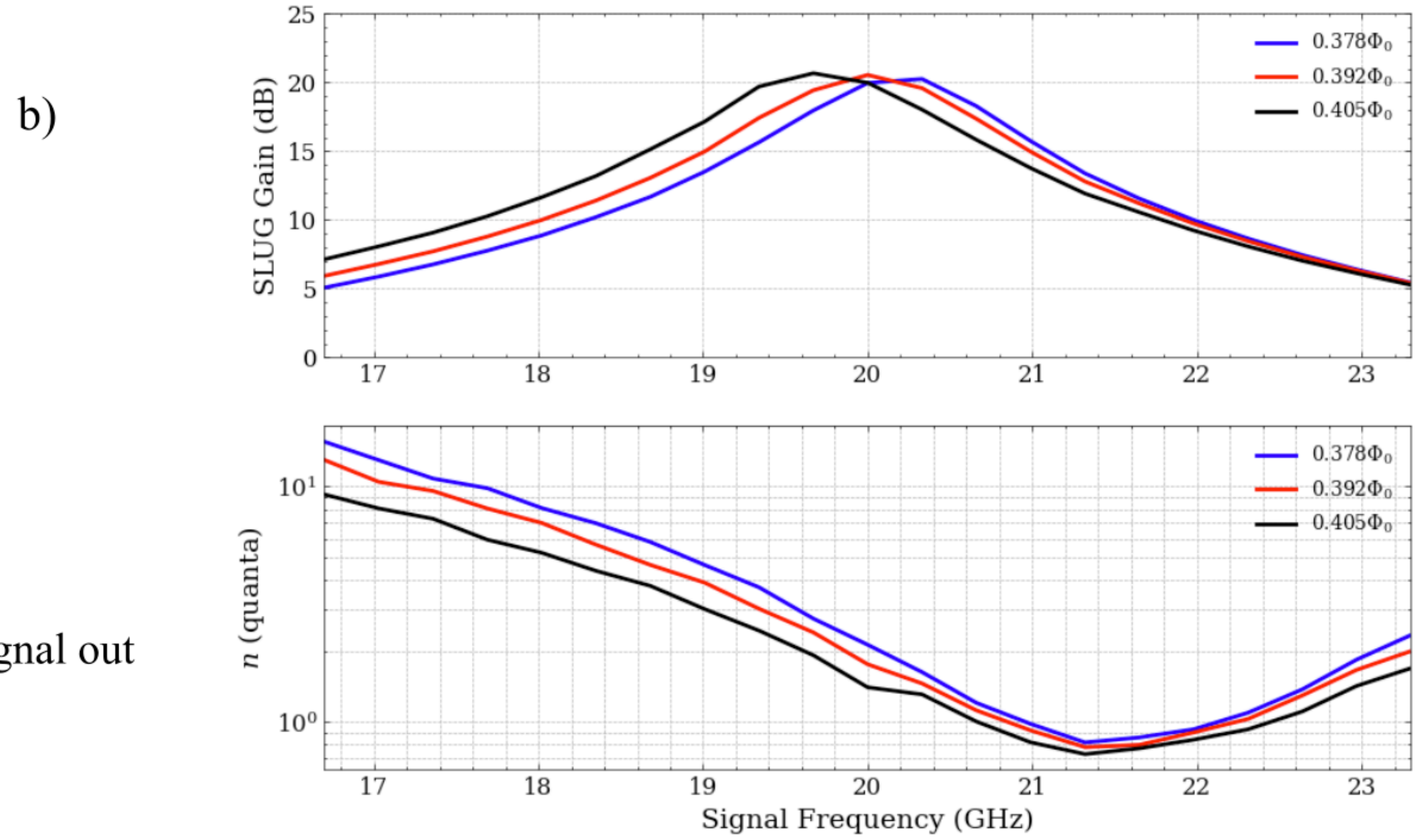


Cyclotron **R**adiation **E**mission **S**pectroscopy + **Quantum Technologies** to overcome limitations of current state-of-art (KATRIN)

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

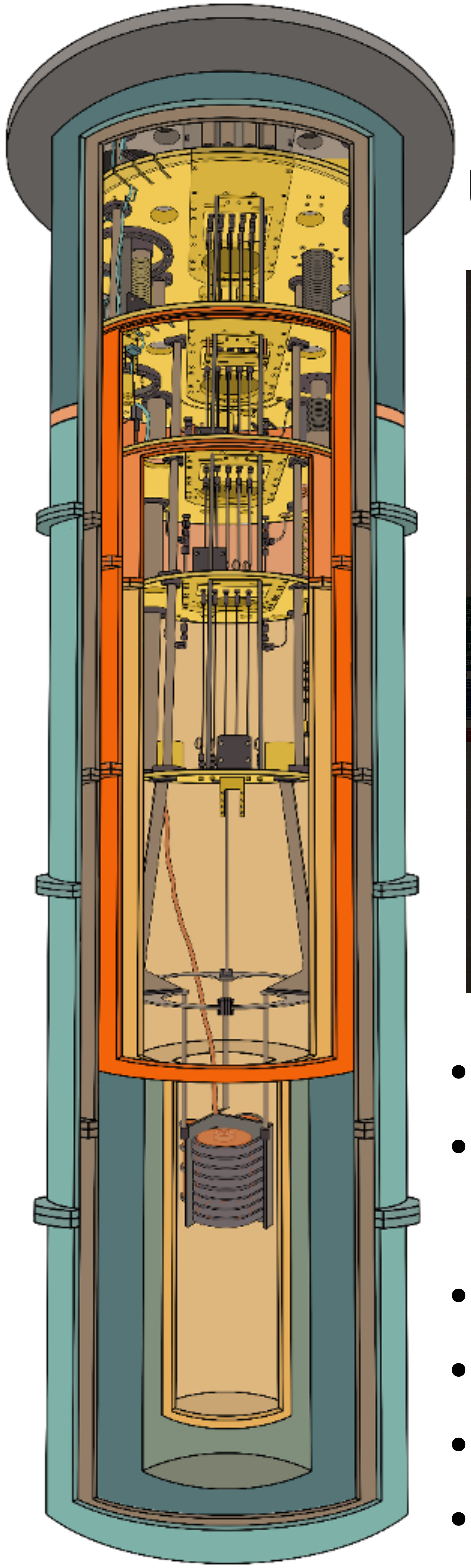






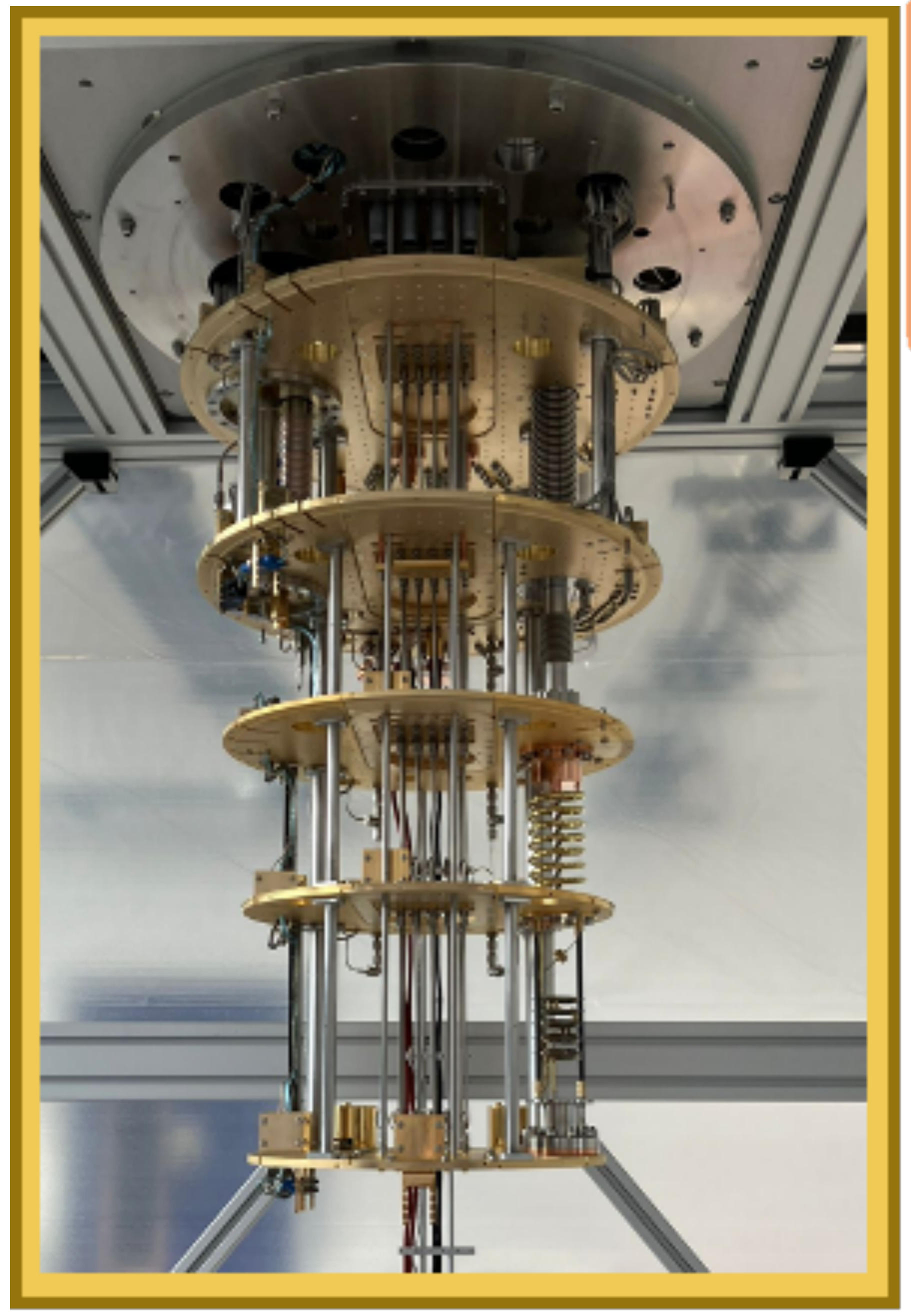
Zhao, Withington and Thomas, arXiv:2406.02455v2 (2024)

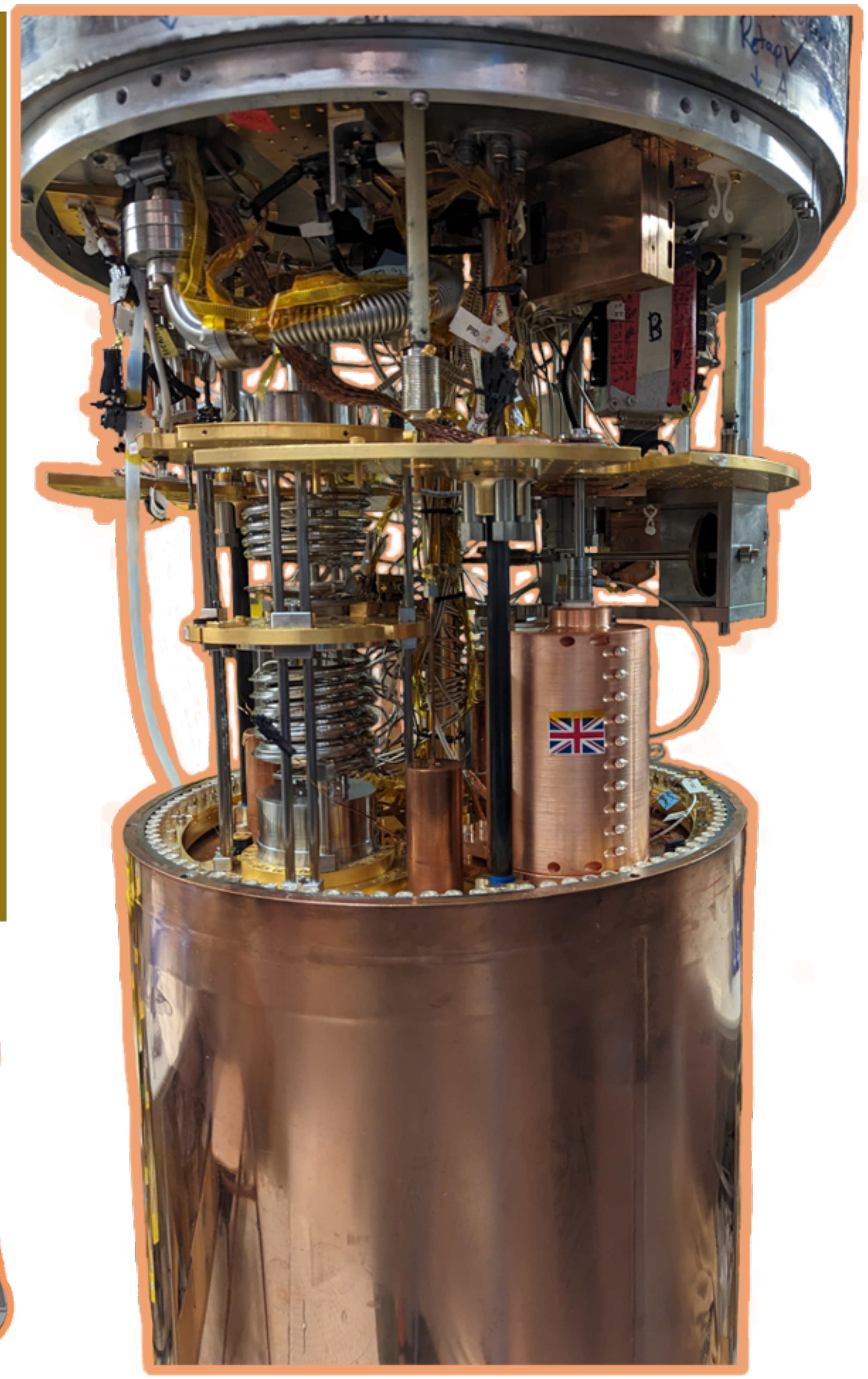
G. Chapman et al., IEEE Transactions on Applied Superconductivity 34 (2024).



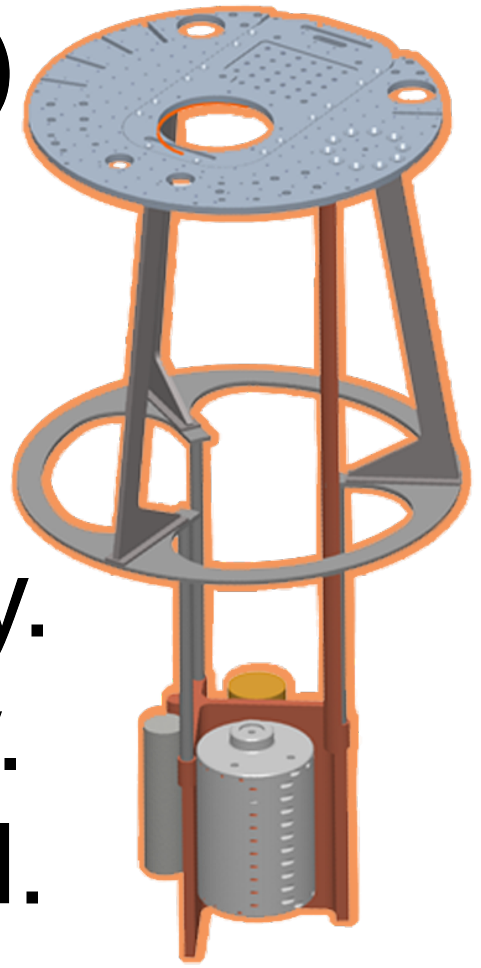
QSHS

Ultra low physical temperature (8.5mK) resonant axion search at 25 to 40 micro-eV.





- Dilution fridge installed, cooled to 8.5mK (already)
- Cavities and tuning rods manufactured and installed in ADMX.
- Currently preparing to cool cavity in QSHS.
- Magnetic field shield almost finished, ready in July.
- Magnet already reached 6T, 8T version underway.
- Cryogenic amplifier design R&D rather like QTNM.



Imperial College London

AION

Developments in strontium beam atom interferometry for fundamental physics.

AION

Build 5 AION Labs

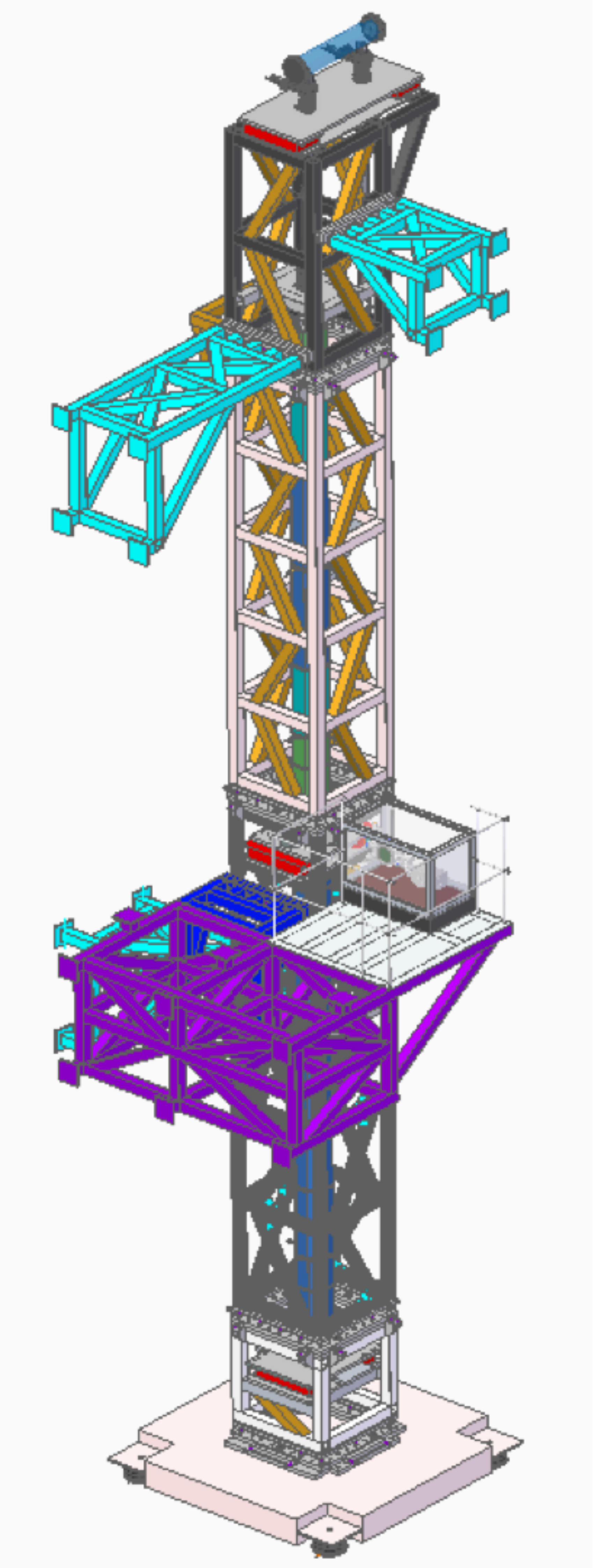
5 Ultra Cold Sr Labs build in less than 24 months using large scale Particle Physics production methods to significantly accelerate the turnaround – this will be critical for future success!

More than doubled the Ultra-Cold Sr R&D capacity in the UK and increased it by about 25% worldwide.

https://doi.org/10.1116/5.0172731
[published *AVS Quantum Sci.* 6, 014409 (2024)]

Discussing with established UK companies Torr Scientific and Kurt J. Lesker potential for spin-off.

Design of 10m Oxford Tower

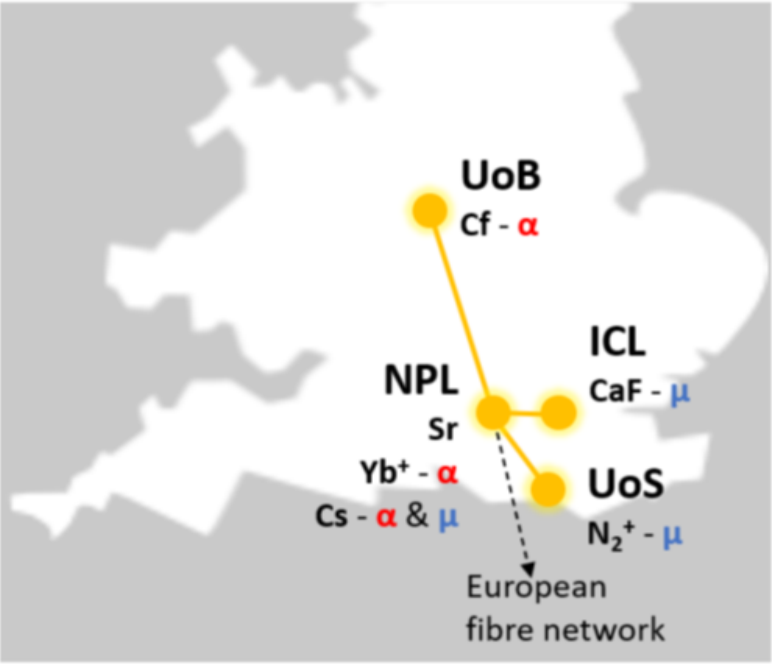


Formlise UK-US Partnership

Formalising the long-standing UK-US partnership between MAGIS and AION, in conjunction with the participating UK institutions.

This stands as a successful instance of UK-US cooperation in the fields of science and quantum technology development, with the potential to unlock additional synergies and

A network of clocks for measuring the stability of fundamental constants

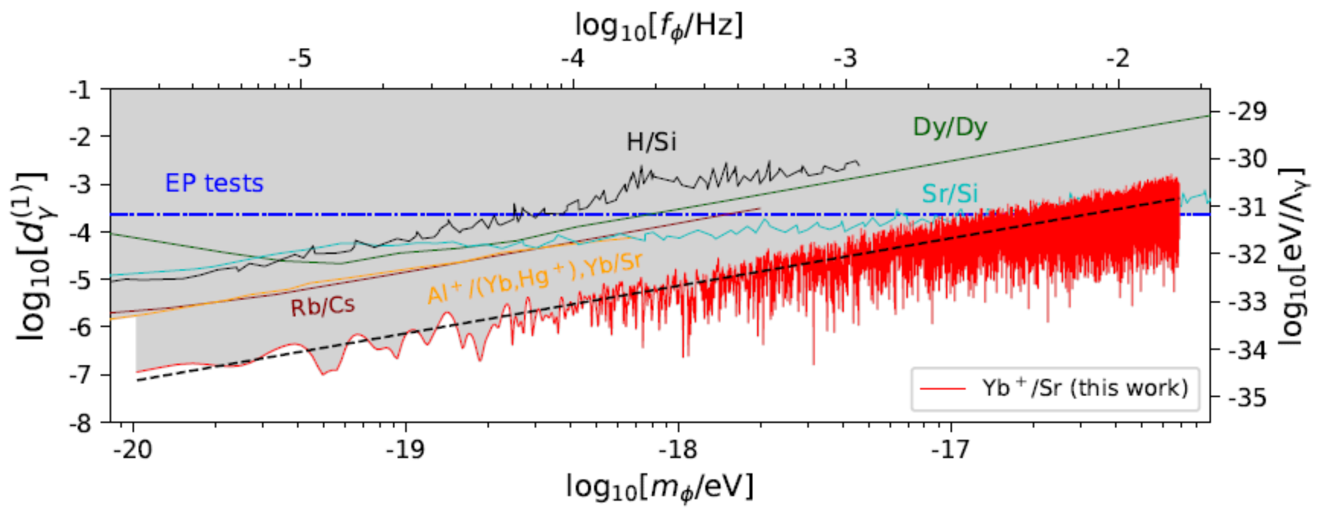


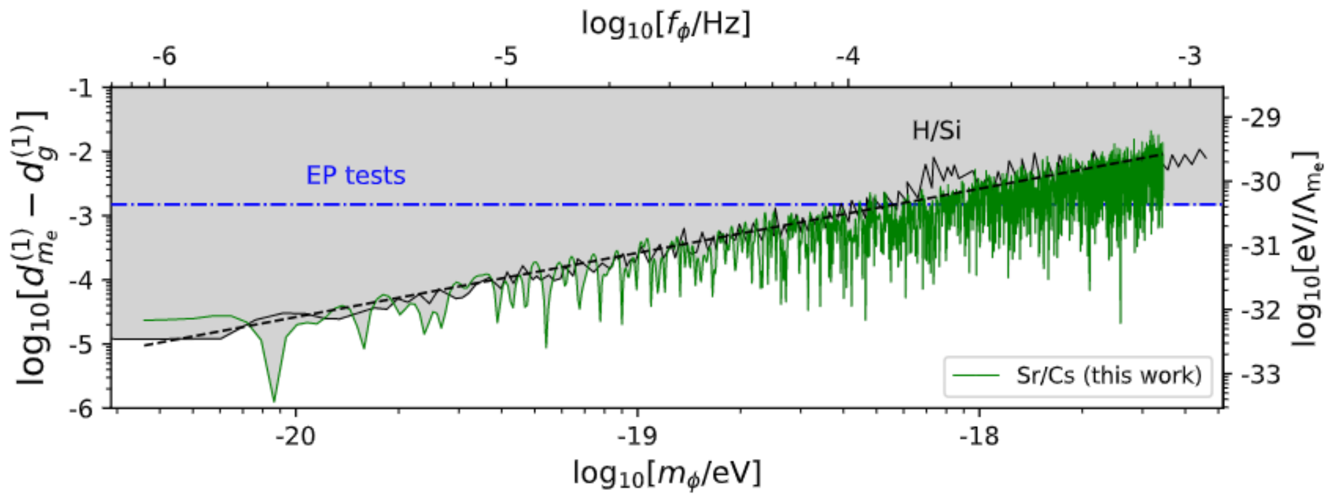
Clock	Kα	Kμ
Yb^{+} (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N_2^{+} (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

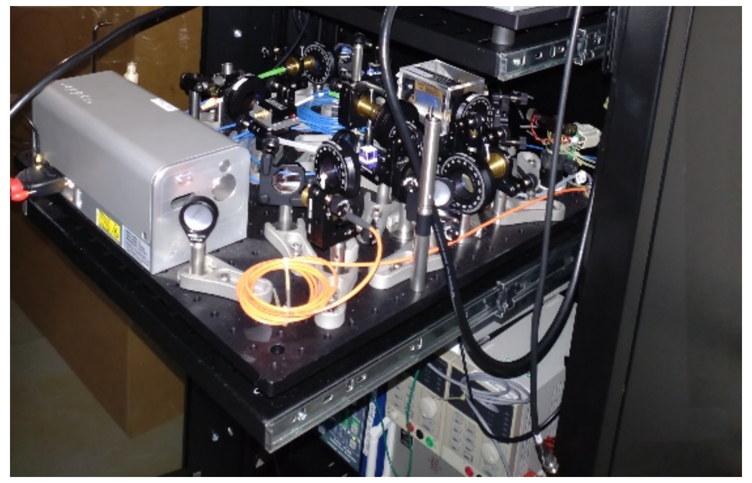
TRL

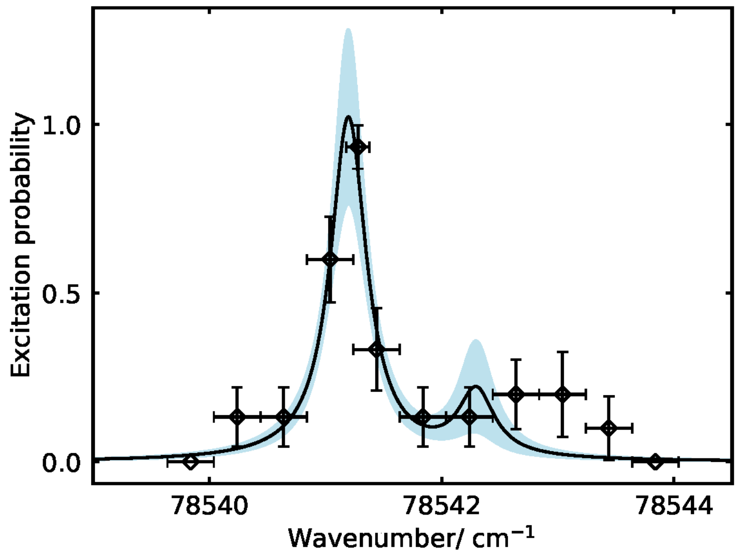
Search for variations of fundamental constants of the Standard Model, using a network of clocks

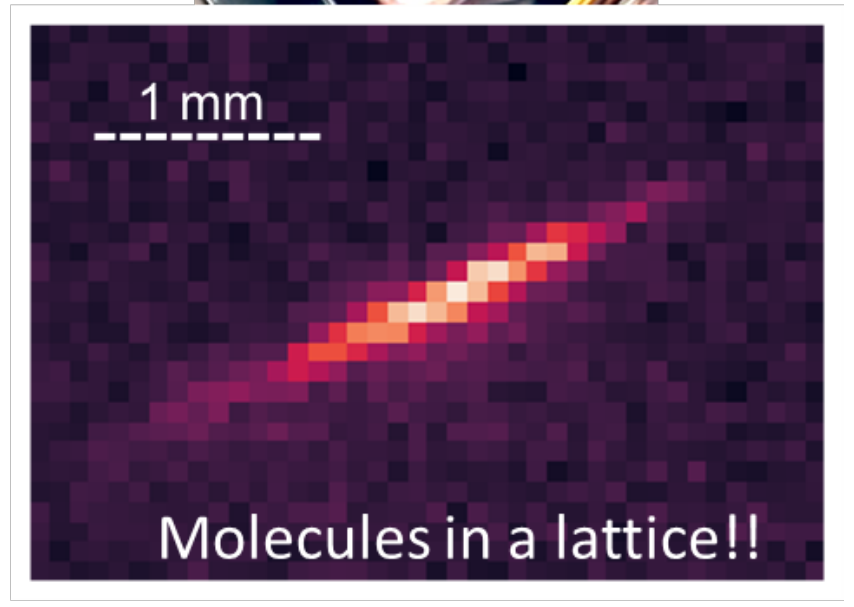
A unique network of clocks chosen for their different sensitivities to variations of **α** and **μ** [EPJ QT 9, 12 (2022)]

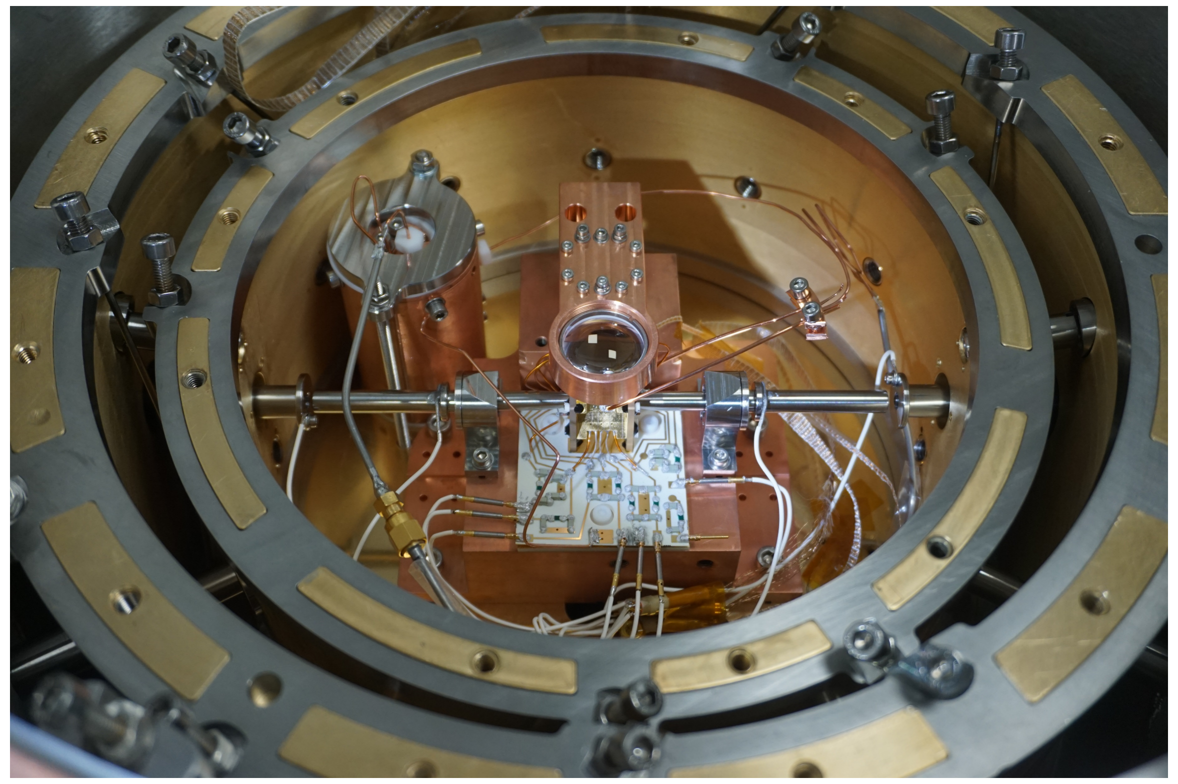












NPL clocks & Sussex theory

- World-leading results: new constraints on ultra-light dark matter [New J. Phys. 25 9, 093012 (2023)]
- Improved the best UK atomic clocks

Sussex experiment

- Developed sideband cooling for molecular ions and quantum logic spectroscopy
- Developed new lasers

Imperial

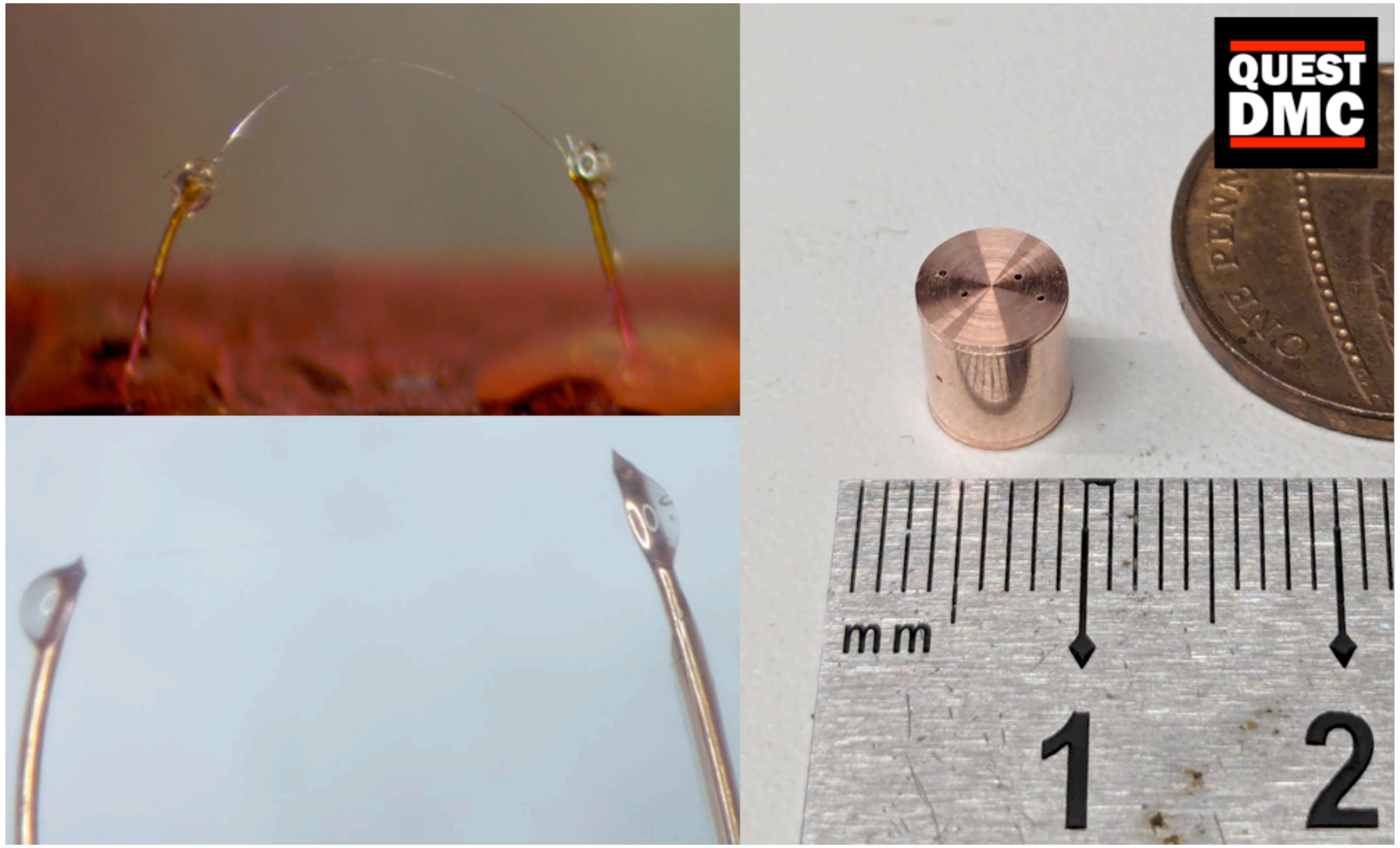
- Achieved cooling and trapping of molecules in an optical lattice
- Realised vibrational transition spectroscopy
- Developed laser systems

Birmingham

- Realised first compact electron beam ion trap in UK
- Realised first cryogenic vacuum systems to trap and cool highly charged ions in UK

QUEST-DMC

Light WIMP search exploiting coherent quantum states of superfluid helium 3



4.5um (top) and 450nm (bottom) nanowire detectors for broken Cooper pairs in superfluid Helium-3.
Cylindrical container for the helium and nanowire sensors.

Autti, S., Casey, A., Eng, N. *et al.* QUEST-DMC: Background Modelling and Resulting Heat Deposit for a Superfluid Helium-3 Bolometer. *J Low Temp Phys* (2024).

Further supported projects (under 'Developing quantum technologies for fundamental physics')

(Total funding for DevQTFP is £4M.)

1. Quantum sensing for antimatter gravity
2. MeVQE: A world-leading centre for MeV scale entanglement physics
3. Development of levitated quantum optomechanical sensors for dark matter detection
4. Simulating high energy physics with quantum photonics
5. ParaPara: A quantum parametric amplifier using quantum paraelectricity
6. Quantum computing for nuclear physics
7. Supercooled cosmological simulator
8. Testing theories of dark energy using atom interferometry
9. Differential atom interferometry and velocity selection using the clock transition of strontium atoms for AION
10. Penrose processes in an analogue black hole formed in hybrid light-matter (polariton) superfluid
11. Synthesising quantum states of sound and listening to what they tell us about the universe
12. Quantum simulation algorithms for quantum chromodynamics
13. Accelerating the development of novel clocks for measuring varying fundamental constants
14. A quantum jump sensor for dark matter detection
15. Increasing the science reach for quantum enhanced interferometry
16. Trapped electron for neutrino mass measurement
17. Levitated Quantum Diamonds

Discussion points

- We are in an era of uncertainty in particle physics. Nobody knows where the next new physics will manifest itself.
- In this context, it makes sense to try many new things.
- Particle physics will benefit from closer association with other research areas.
- Quantum sensing is a neighbouring field with many commonalities with high energy physics and particle physics.
- Government has just committed £2.5B over 10 years to quantum.
- There is currently no guaranteed funding for QTFP projects beyond March 2025.
- Young scientists thinking about entering the field can be hesitant because there are no assurances of future viability of the field. This is a problem.
- In the background, the whole of the PAAP portfolio (within STFC core) currently receives 3-4% of the STFC budget - funds at least 5 whole research fields.
- Finding a more assured funding route for QTFP, and improved support for particle astrophysics in general, will nurture a growing and exciting field, and greatly increased discovery potential for new physics.