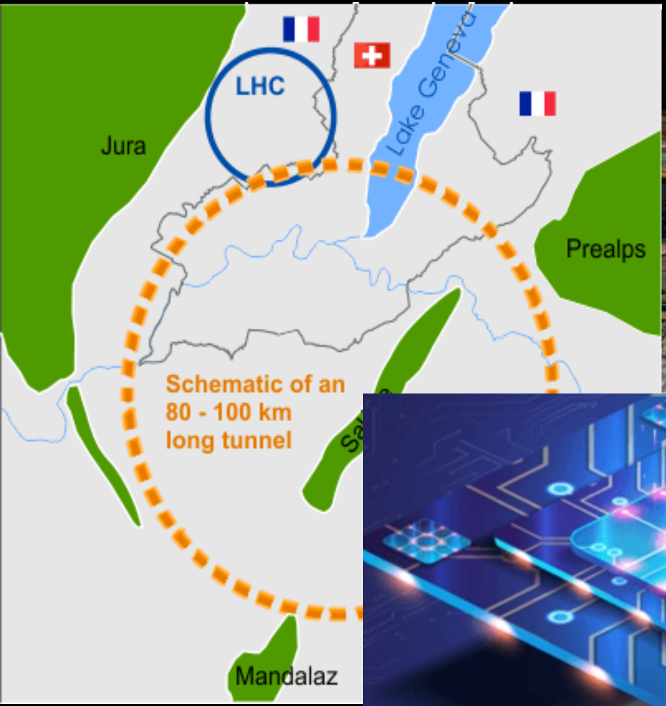
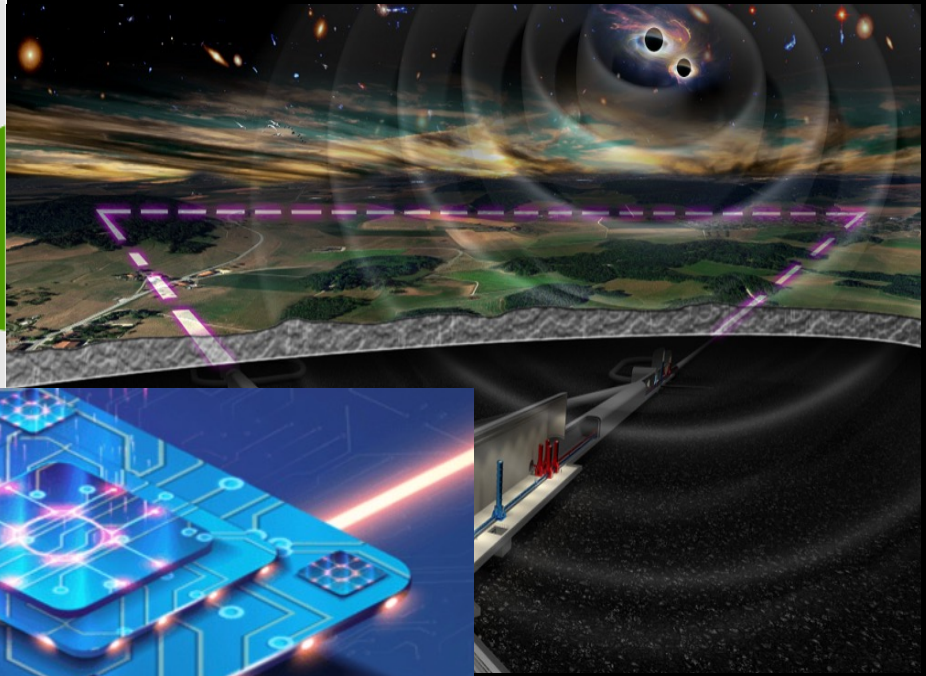
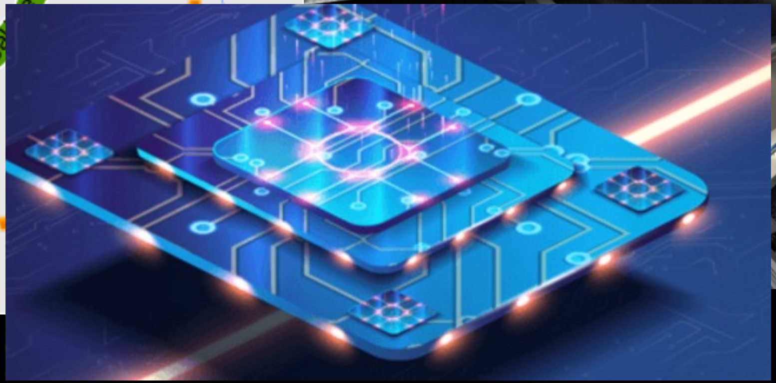
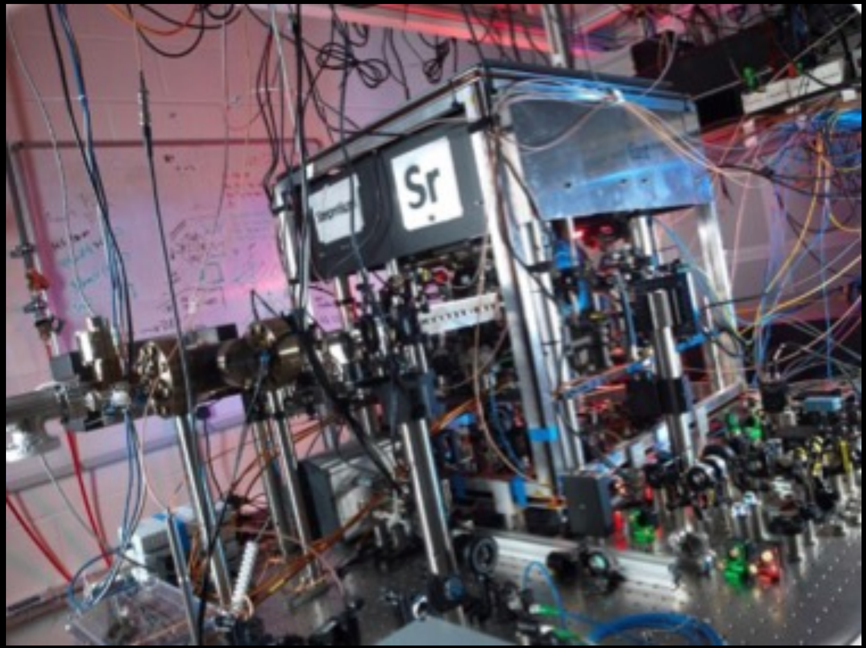
Quantum Technologies for Fundamental Physics

The Science & The Quantum Technologies Landscape









Ian Shipsey,
Oxford University
(on behalf of the QTFP projects)

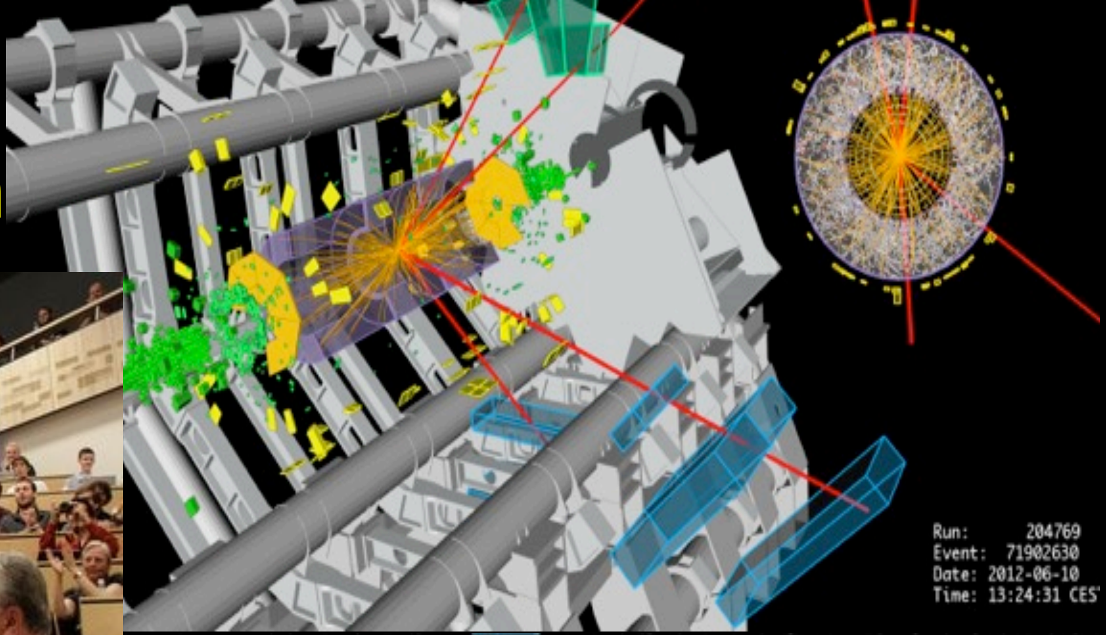
UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Outline

- The Science
- Quantum Revolution 2.0
- QTFP
- QTFP & ECFA-UK & the PPAP/PAAP/PPAN (Science Board) process

2012.7.4

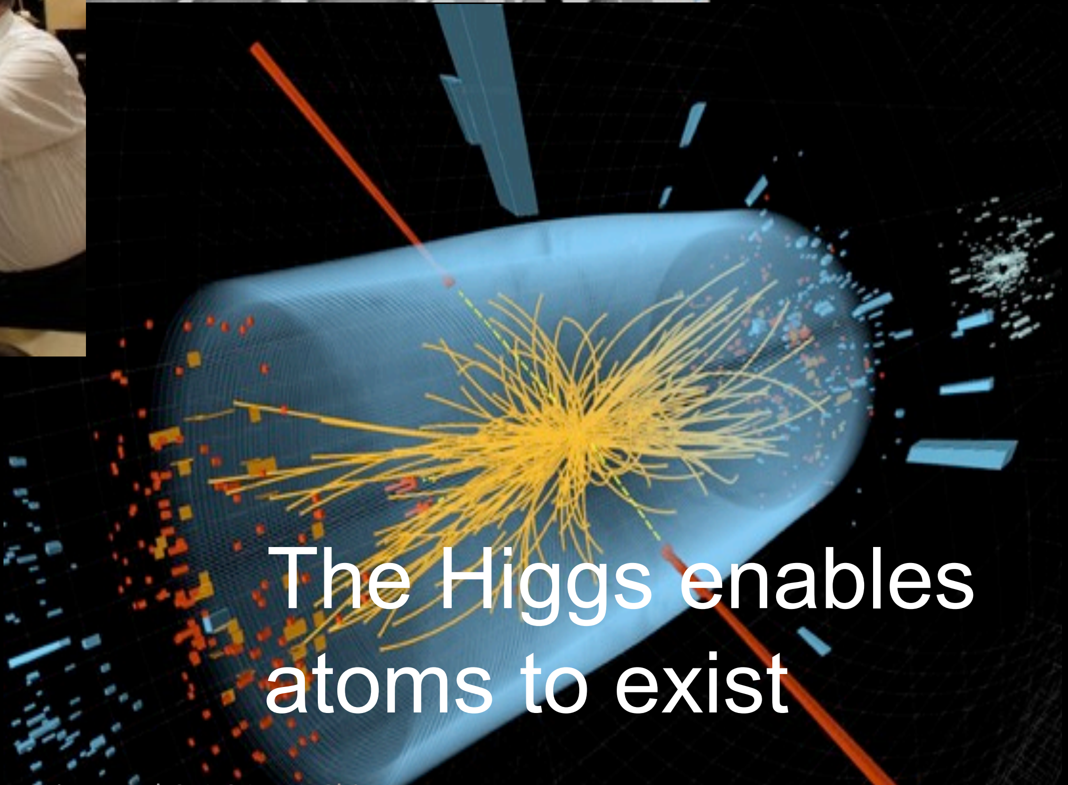
discovery of Higgs boson



theory : 1964

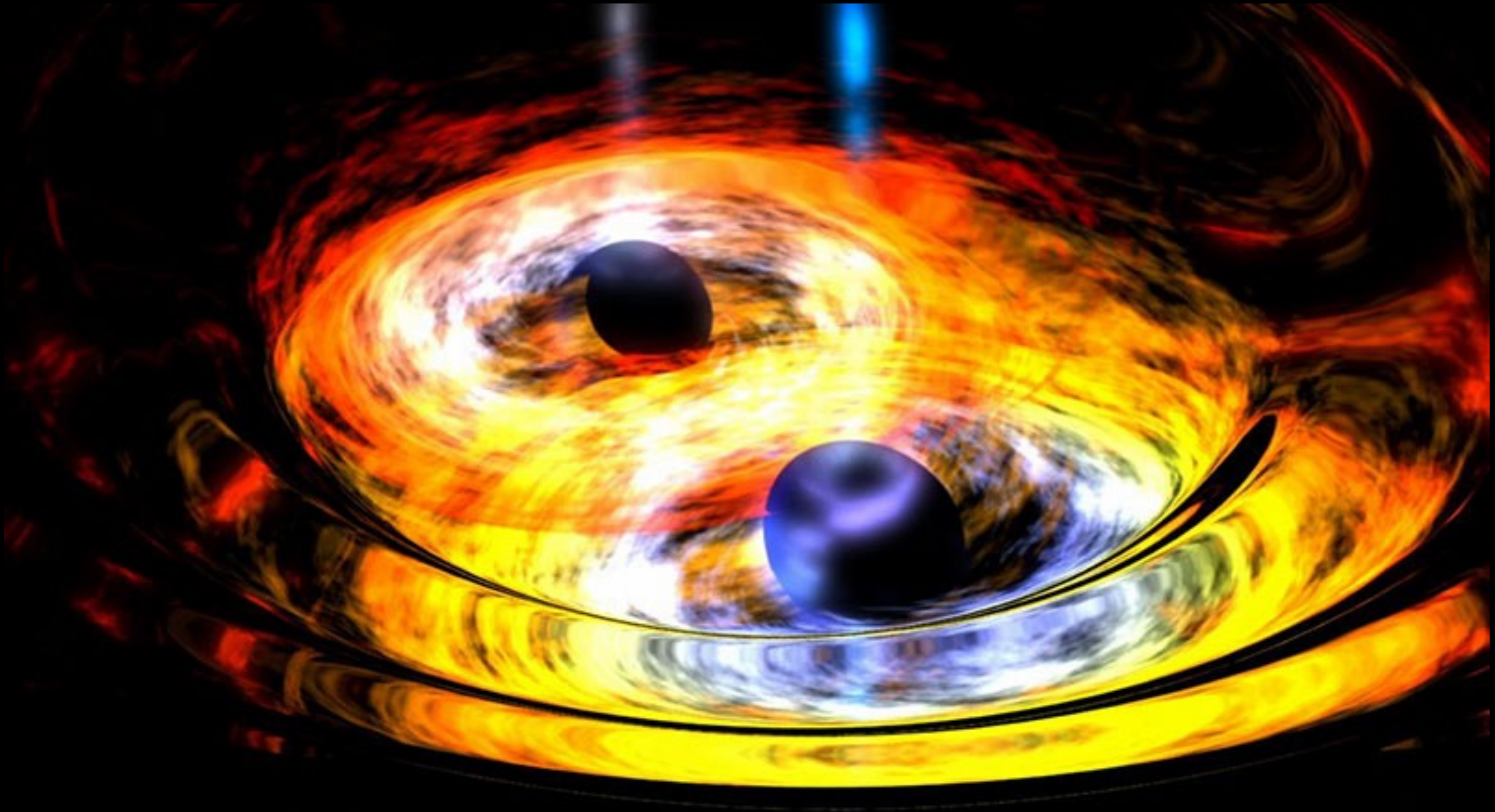
design : 1984

construction : 1998



The Higgs enables atoms to exist

Detection of gravitational waves
LIGO February, 2016



Opportunities for Discovery

Many mysteries to date go unanswered including:

- The mystery of the Higgs boson
- The mystery of Neutrinos
- The mystery of Dark Matter
- They mystery of Dark Energy
- The mystery of quarks and charged leptons
- The mystery of Matter – anti-Matter asymmetry
- The mystery of the Hierarchy Problem
- The mystery of the Families of Particles
- The mystery of Inflation
- The mystery of Gravity

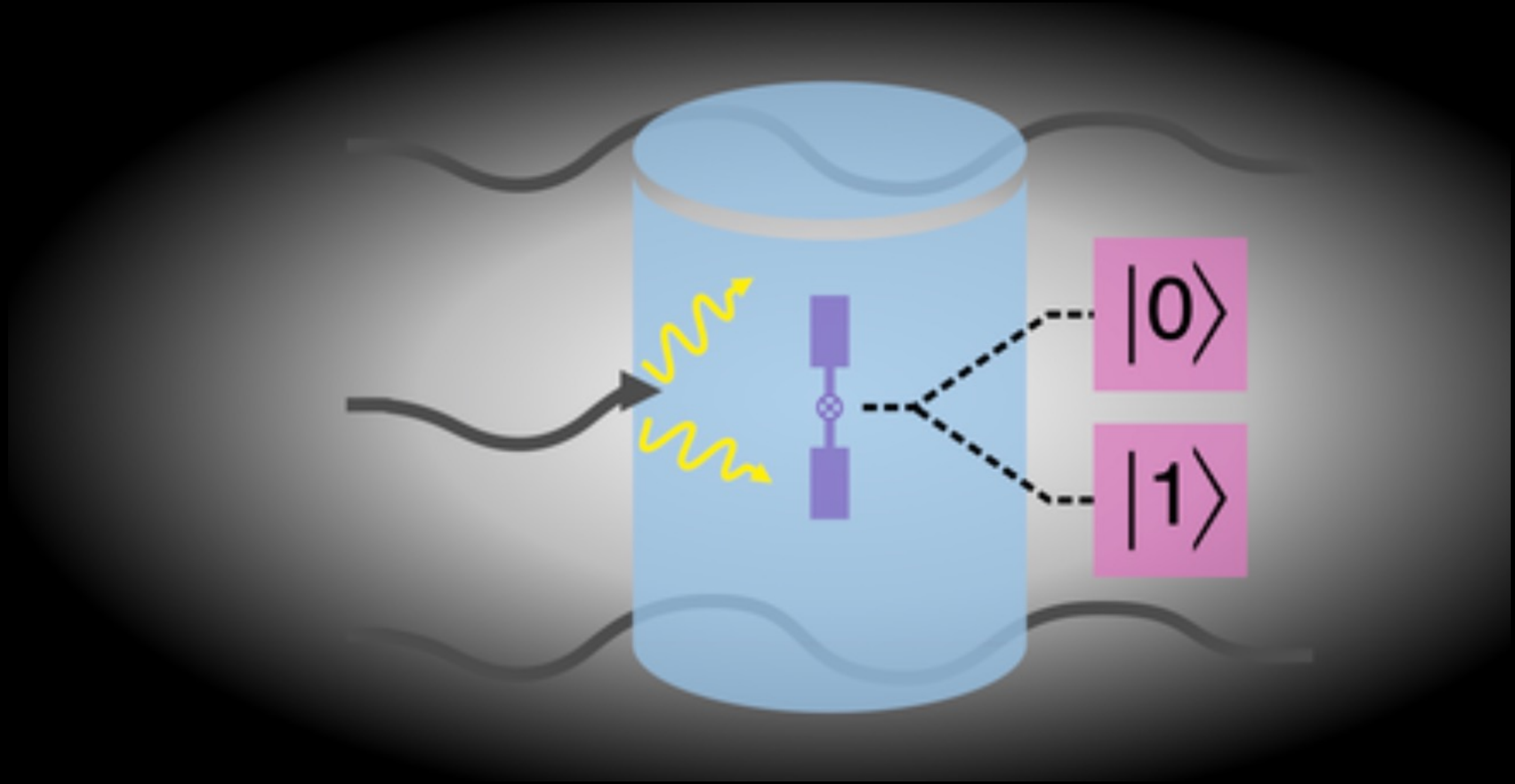
Multiple theoretical solutions – experiment must guide the way

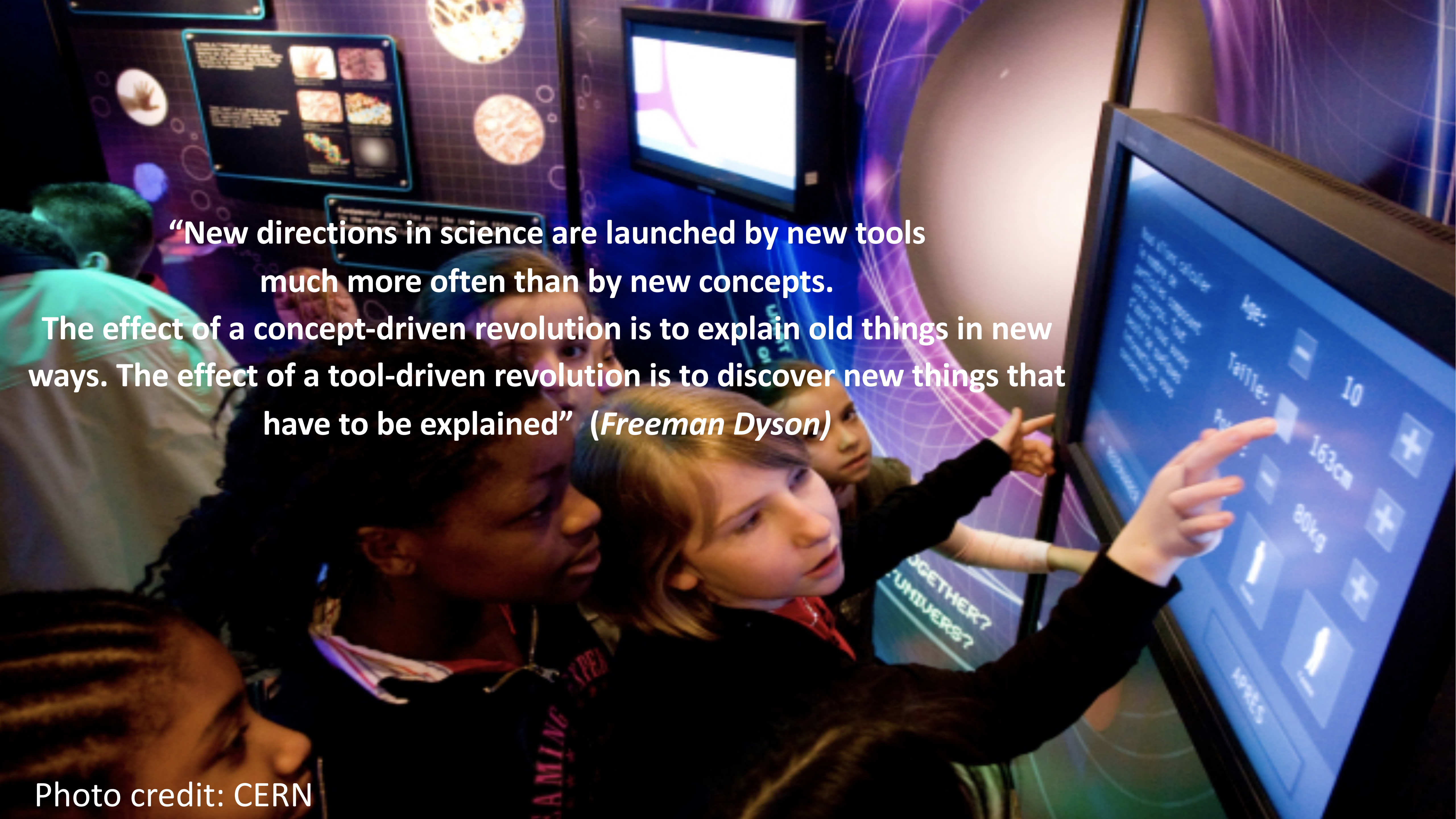
We are very much in a data driven era for which we need new tools!

New tools:
e.g. the HL-LHC upgrades &
later FCC-ee/hh etc.

Only ~4% of the complete LHC/ HL-LHC data set has been delivered to date
There is every reason to be optimistic that an important discovery could come at any time

New tools e.g. Qubits as cameras





"New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained" (*Freeman Dyson)*

Photo credit: CERN

"Measure what is measurable, and make measurable what is not so" (*Galileo Galilei*)

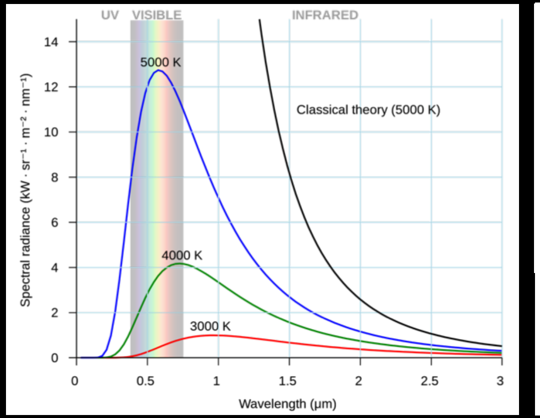
Photo credit: CERN

Outline

- The Science
- Quantum Revolution 2.0
- QTFP
- Future

While quantum sensors are not new they have suddenly become promenent and this is due both to technological advances & to greater appreciation in the world for quantum mechanics leading to national quantum technology programs which have provided the necessary preconditions for the application of quantum technologies to fundamental physics

Quantum 1.0



Blackbody Radiation

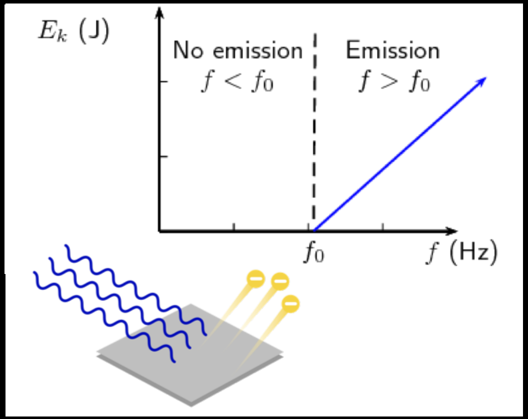
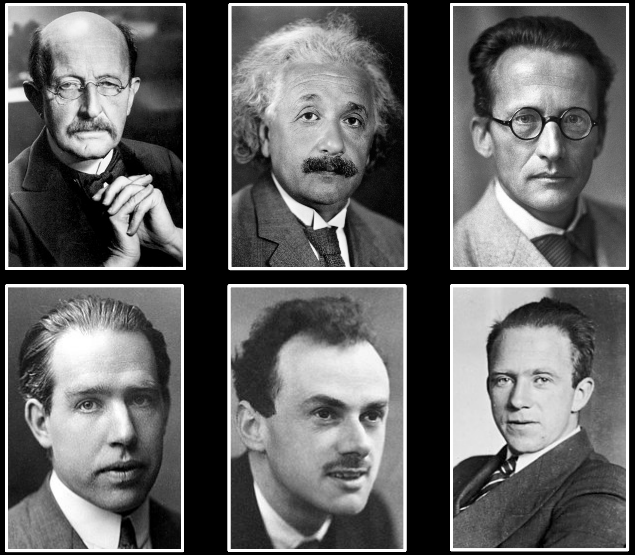
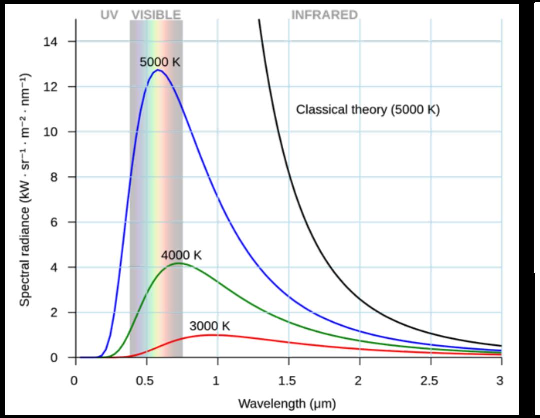


Photo-electric Effect

Quantum Mechanics



Quantum 1.0



Blackbody Radiation

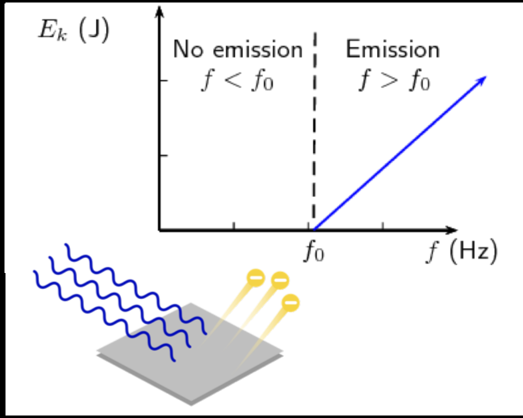
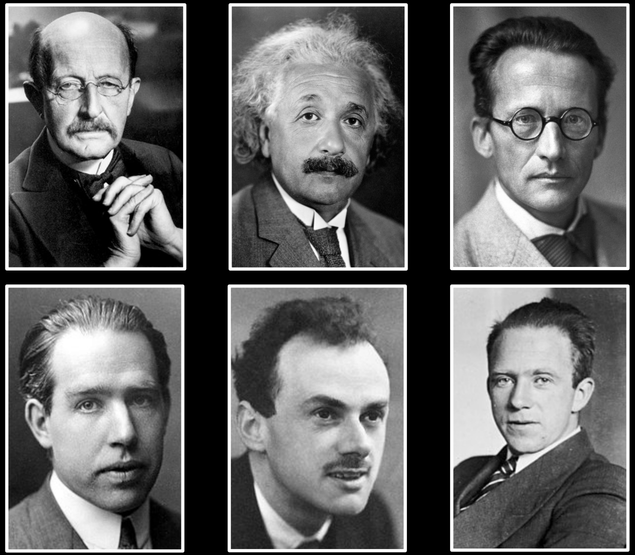


Photo-electric Effect

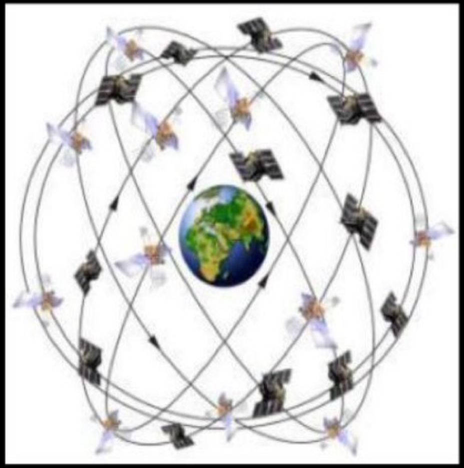
Quantum Mechanics



Exascale Computing

Laser Technology

Magnetic Resonance Imaging

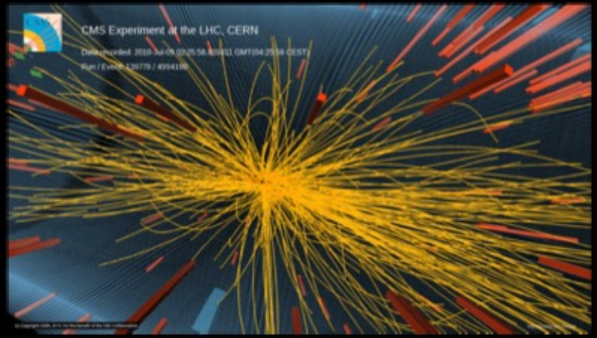


Global Positioning System

Quantum 2.0

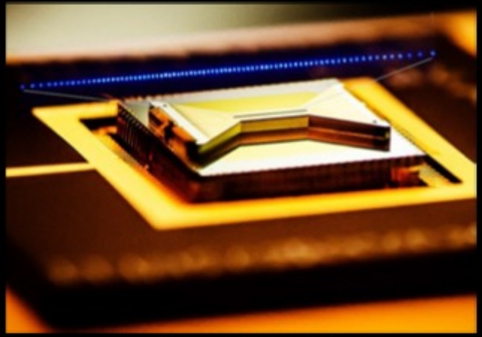
The First Quantum Revolution: exploitation of quantum matter to build devices
Second Quantum Revolution: engineering of large quantum systems with full control of the quantum state of the particles, e.g. entanglement

AI, ML on Quantum annealer



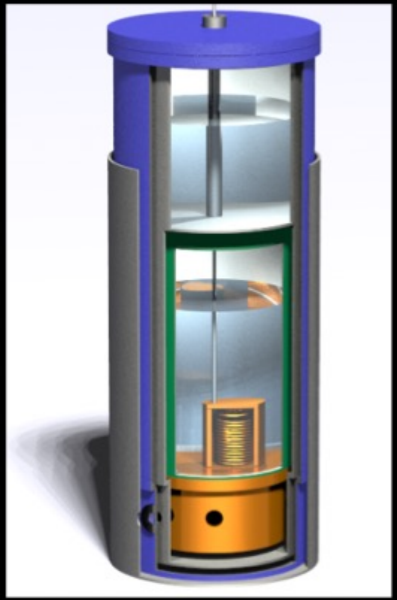
Nature 550 (2017) 375

IonQ >60-qubit



arXiv:1902.10171

Atomic clocks



Nature (564) 87 (2018)

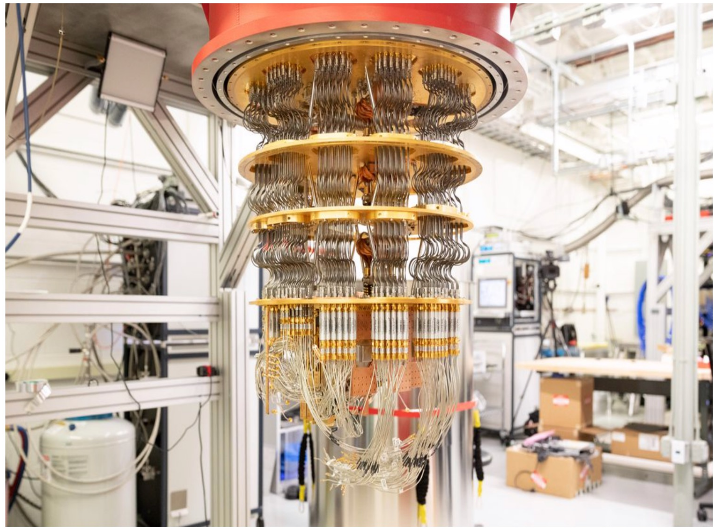
Quantum 2.0

The First Quantum Revolution: exploitation of quantum matter to build devices
Second Quantum Revolution: engineering of large quantum systems with full control of the quantum state of the particles, e.g. entanglement

Google's quantum supremacy is only a first taste of a computing revolution

"Quantum supremacy" is nice, but more broadly useful quantum computers are probably still a decade away.

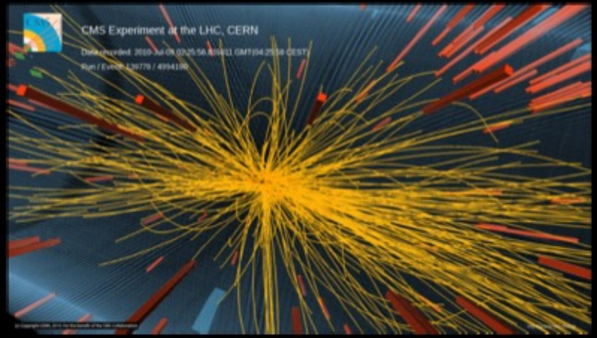
Stephen Shankland October 25, 2019 6:20 AM PDT



One of five Google quantum computers at a lab near Santa Barbara, California.

Stephen Shankland/CNET

AI, ML on Quantum annealer



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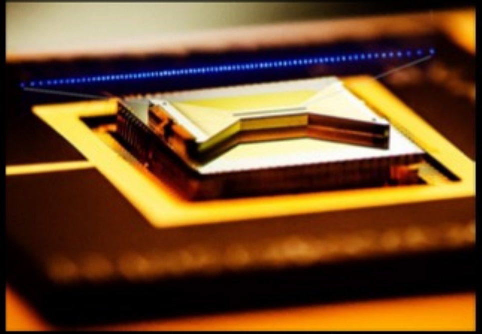
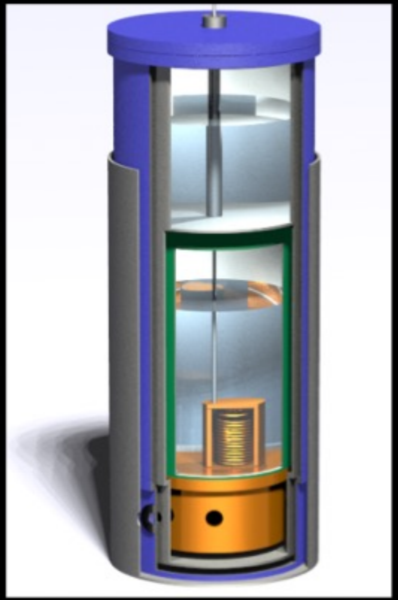


arXiv:1902.10171

Atomic clocks



Nature (564) 87 (2018)

"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical," Feynmann (1981).

You can approximate nature with a simulation on a classical computer, but Feynman wanted a quantum computer that offers the real thing, a computer that "will do exactly the same as nature,"

Drug Design, protein folding, Black Holes…..

What if?

Quantum Internet

Quantum Artificial Neural Network

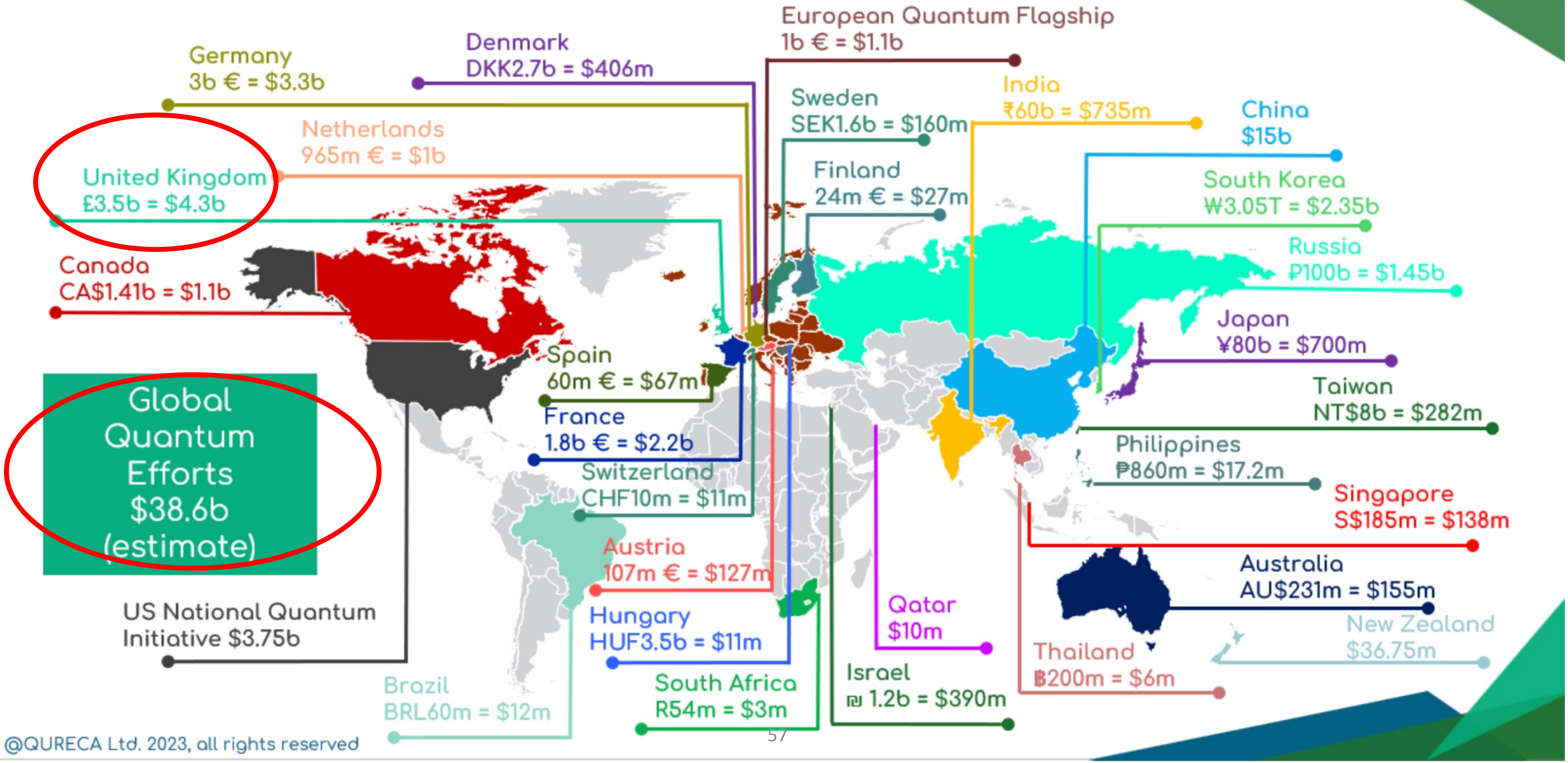
Quantum Liquid Crystals

Quantum Mind Interface

Quantum enabled searches for dark matter

Quantum Gravity

Quantum Technologies Public Funding Worldwide (2023)



https://uknqt.ukri.org

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

About us | Our programme | Opportunities | News and events | Resources

£1bn UK National Quantum Technology Programme Pillars

2019

UKRI Engineering and Physical Sciences Research Council

QT Hubs, Training and Skills, CDTs
£360M

Translating research into applications

Industry-pick up points

Department for Business, Energy & Industrial Strategy

NPL National Physical Laboratory

Quantum Metrology Institute
£30M

Standards

Validation

UKRI Innovate UK

IUK, ISCF, Industry
£450M

Prototypes

Products

Spin-offs

GCHQ [dstl] Ministry of Defence

Other
£80M

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

£1bn UK National Quantum Technology Programme Pillars

2020

UKRI Science and Technology Facilities Council · UKRI Engineering and Physical Sciences Research Council

Quantum Technologies for Fundamental Physics (QTFP)
£40M

New Ideas

Attracting worldwide talent

Internationally leading science across 7 projects

National Quantum Computing Centre
£93M

UKRI Engineering and Physical Sciences Research Council

QT Hubs, Training and Skills, CDTs
£360M

Translating research into applications
Industry-pick up points

Department for Business, Energy & Industrial Strategy · NPL National Physical Laboratory

Quantum Metrology Institute
£30M

Standards

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GCHQ · [dstl] · Ministry of Defence

Other
£80M

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

History of QTFP

July 2018 Idea presented to STFC

October 2018 Opportunities grant: Quantum Sensors for Fundamental Physics (QSFP) and Society awarded

Oct 2018/Jan 2019 QSFP Community workshops

March 2019 Business case approved UKRI SPF

May 2019 STFC Led Community workshop

September 2019 First Call announced

January 2020 QSFP 1st School

January 2021 Successful proposals announced

November 2021 QTFP presence at NQTP Showcas

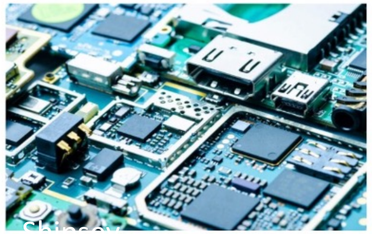
September 2022 Successful second call proposals announced

QSFP UK Institutions

The first Quantum Sensors for Fundamental Physics Community Workshop

Quantum projects launched to solve the universe's mysteries

£6 million to spur the UK's quantum leap



UKRI Engineering and Physical Sciences Research Council

UKRI Science and Technology Facilities Council

QTFP Objectives

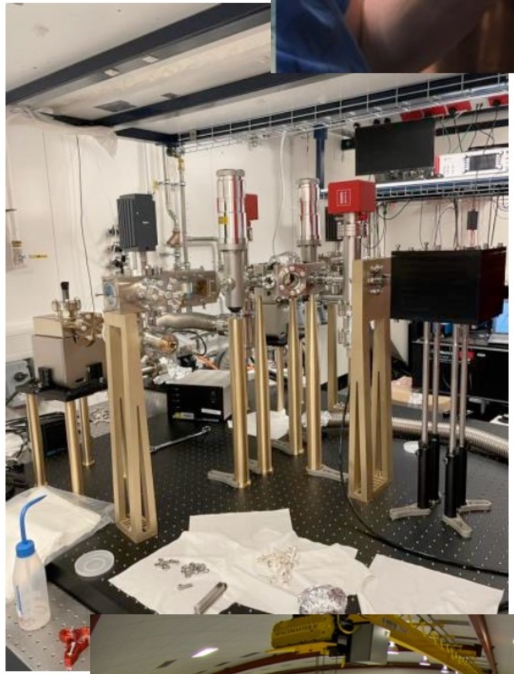
- Establish a new community to exploit quantum technology for fundamental physics. Generating research outputs deemed excellent by international peer review

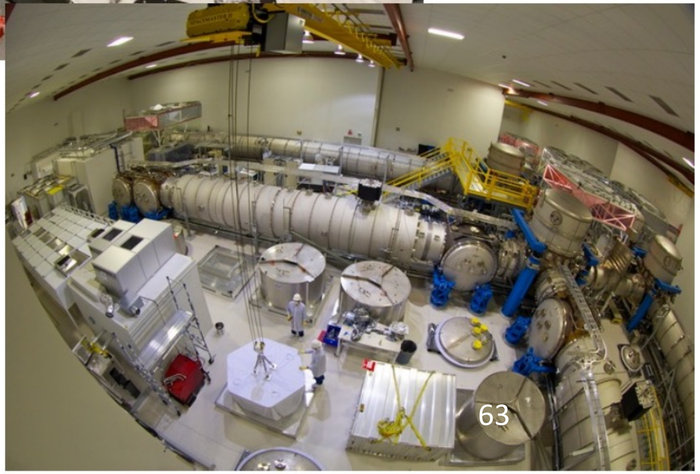
- Position the UK as a first rank nation in the scientific exploitation of quantum technology for physics applications

- Become an active player in the National Quantum Technology Programme (NQTP)

- Create the opportunity in the UK for new patents, new products and start-up companies as a result of developing new or improved equipment that will be needed to support the scientific work programme

A QTFP virtuous circle

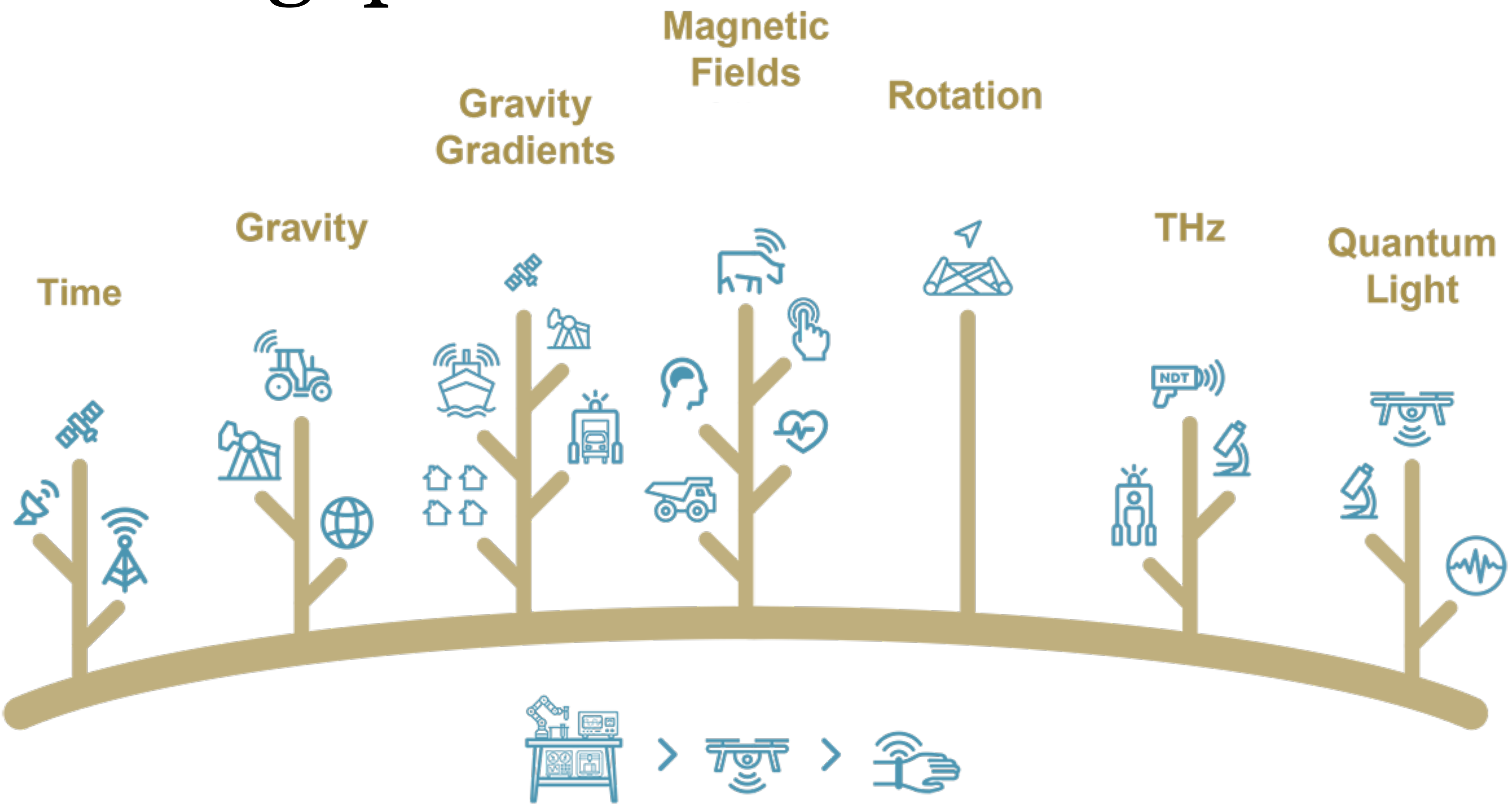




Engineering and Physical Sciences Research Council

Science and Technology Facilities Council

Translating quantum sensors



The World Economic Forum recognised Quantum Sensing as one of the top 10 emerging technologies for 2020

QTFP is building a new community of EPSRC and STFC Scientists

There are 7 QTFP projects.
Inherently interdisciplinary AMO, CMP, QIS Particle, Astro.
A magnet of ECRs and students.

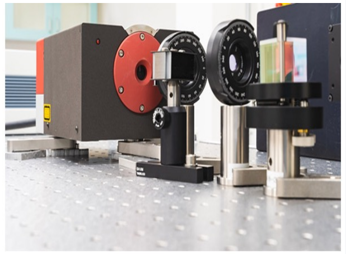
Funding: February, 2021 – March, 2025
Scale: 101 faculty/scientists, 66 PDRA, 11 Engineers and technicians, 5 administrative staff and 32 PhD students (funded from other sources)
– 220 people, 15 UK universities & national labs.

Each project has built its own collaboration, including formal working agreements with some of the best overseas scientific teams

QI

Quantum-enhanced Interferometry for new physics

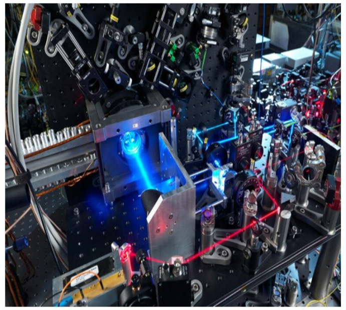
Principal investigator: Harmut Grote



QSNET

A network of clocks for measuring the stability of fundamental constants

Principal investigator: Giovanni Barontoni

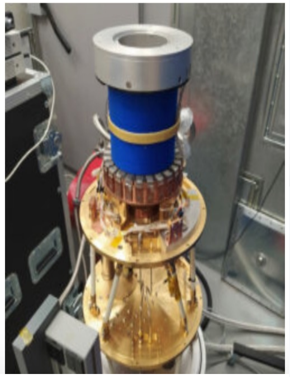


Strontium optical lattice clock experiment

QTNM
Quantum Technologies for Neutrino Mass

Determination of absolute neutrino mass using quantum technologies

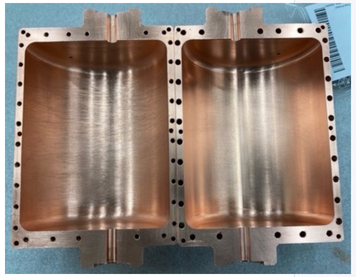
Principal investigator: Ruben Saaykan



QSHS

Quantum sensors for the hidden sector

Principal investigator: Ed Daw



AION

A UK atom interferometer observatory and network

Principal investigator: Oliver Buchmuller

AION

QUEST DMC

Quantum enhanced superfluid technologies for dark matter and cosmology

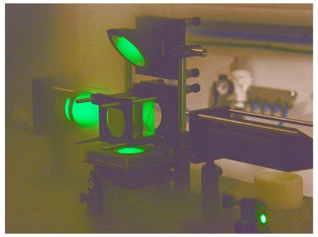
Principal investigator: Andrew Casey

Nuclear demagnetisation experiment

QSimFP

Quantum simulators for fundamental physics

Principal investigator: Silke Weinfurtner

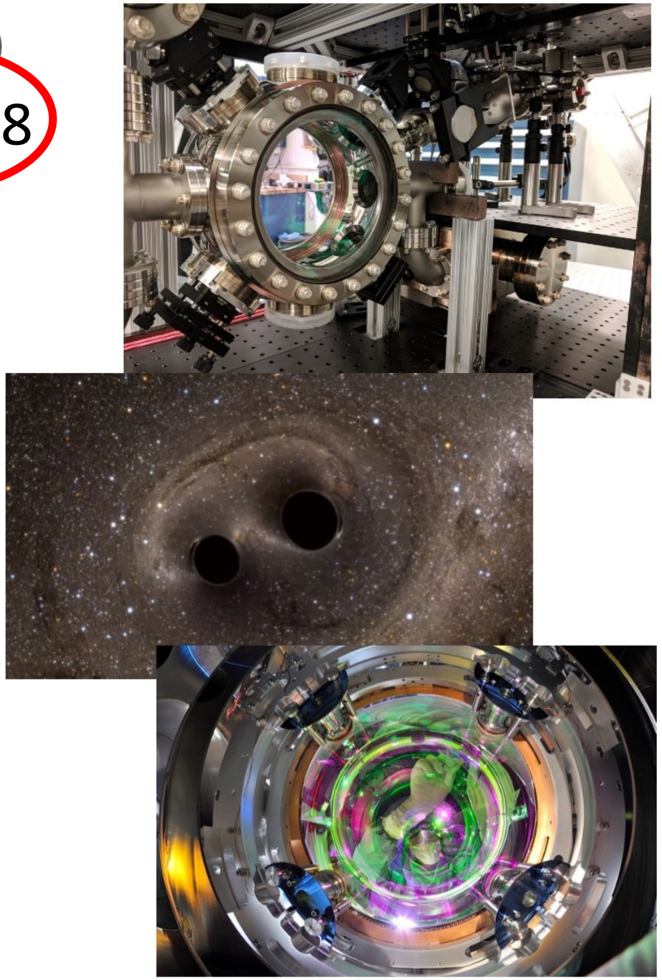


7 main projects (2020)
17 smaller projects (2022)

International Partnerships

QTFP provides an opportunity for increasing international cooperation

- Atom Interferometry Observatory and Network – MAGIS (Fermilab)
- Determination of Absolute Neutrino Mass Using Quantum - Project 8
- Quantum Sensors for the Hidden Sector – ADMX
- Quantum Enhanced Interferometry for New Physics – Deutsches Elektronen-Synchrotron (DESY), Germany as well as collaborators across the US
- QSNET – Max-Planck Institute for Nuclear Physics, Germany
- Quantum Simulators for Fundamental Physics - project partners in Canada, Germany and Austria
- QUEST DMC – projects partners in US



Engineering and Physical Sciences Research Council

Science and Technology Facilities Council

Images: Simulating eXtreme Spacetimes (SXS) Project; Stanford University; Project websites

•**76 partnerships** between QTFP institutions and international institutions, 3 UK-US QTFP consortia level agreements and many institution-to-institution collaborations.

Fig. 2 – International groups collaborating with QTFP: UK Organizations (yellow), and International Partners of QSimFP (orange), QI (red), QSNET (purple), QSHS (green), QTNM (turquoise), AION (brown) and QUEST-DMC (gray).

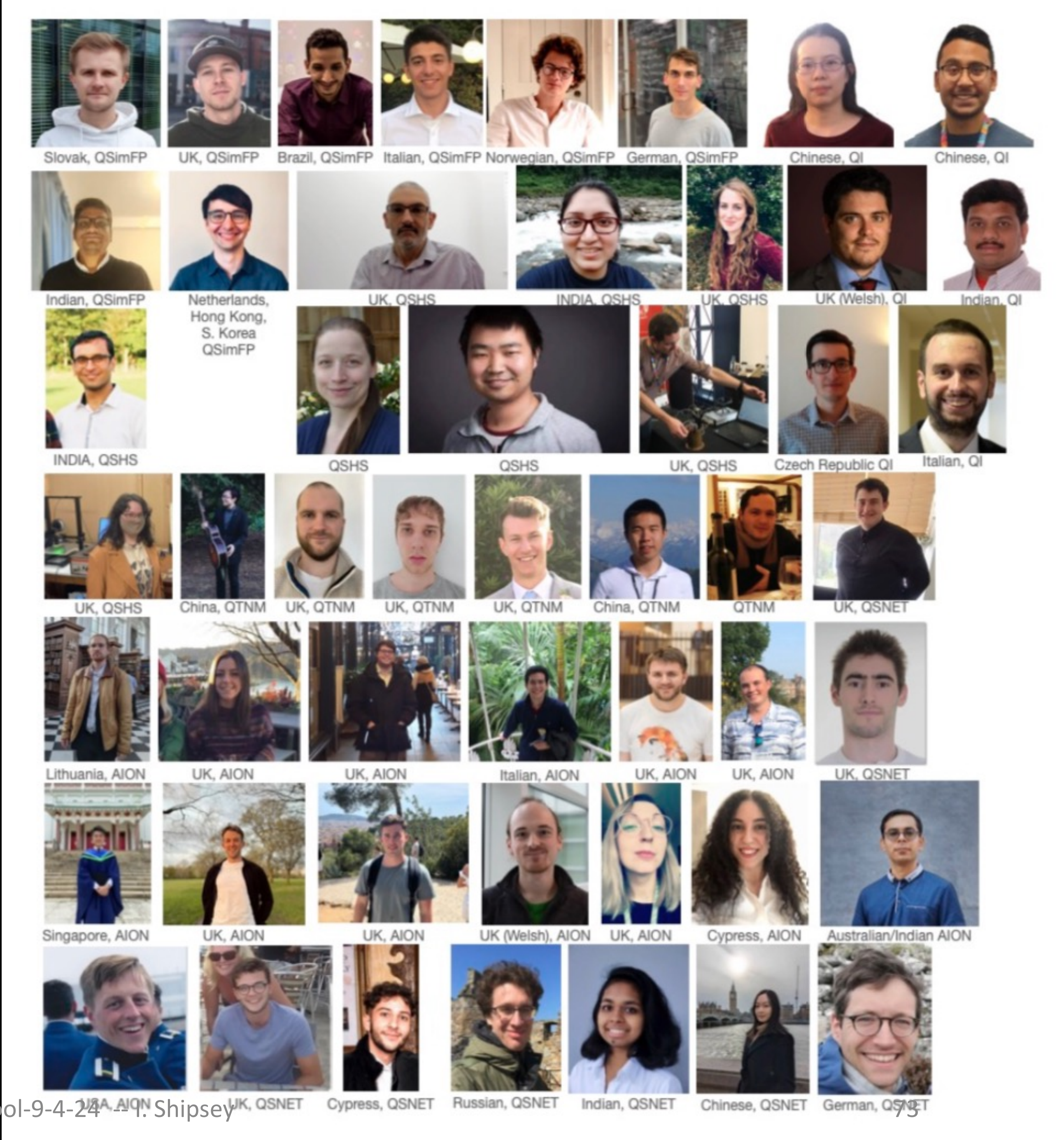
Education and Upskilling: QTFP has generated immense excitement amongst some of the brightest undergraduate and graduate students, postdocs and other early career researchers in the UK and abroad.

The young talent attracted is diverse. 50/ 98 early career researchers and PhD students, including 27 from overseas, are pictured

Attracting school leavers into science and engineering, both at undergraduate and technician level, is often motivated by the thrill of being involved in big science projects and delivering seemingly impossible technology.

The importance of having as much thrilling science and thrilling engineering out in the public domain as possible Is crucial.

QTFP will continue to develop and train talent for the UK helping to address the skills shortage and thereby help to build the quantum economy and sustain it.



UK NATIONAL QUANTUM PROGRAMME

A Brief Timeline

- **UK National Quantum Strategy (2023)**
  - Doubling investment (£1B + £2.5B)

Launch The UK National Quantum Technologies Programme (NQTP)

2013 → 2014 → 2019 → 2023 → 2024 - 2034

PHASE 0:

Workshop at Chicheley Hall

PHASE 1:

Focus on converting research and excellence into technology prototypes and plugging the skills deficit

£380m investment over 5 years.

PHASE 2:

Focus on driving commercialisation and economic impact (investment, supply chain growth, international collaboration)

Additional £350m over 5 years plus £153m for industry-led activities.

National Quantum Computing Centre (NQCC) launched Sept 2020

PHASE 3

Publication of UK Quantum Strategy affirms UK continued commitment to quantum technologies for the next 10 years. Strategy provides an additional investment of £2.5 billion, starting in 2024

So far, NQTP has provided awards to over 123 businesses and 38 universities and RTOs collaborating in over 95 projects

Slide Credit: Peter Knight & DSIT

Department for Science, Innovation & Technology

progress since March 2023 to deliver the strategy

R&D & Skills

- £100m for R&D incl. Research Hubs
- Centres for Doctoral Training competition
- £30m National Quantum Computing Centre testbeds

Business support

- £70m for near-term computing and PNT missions
- £20m Networking accelerator competitions
- Royal Academy Engineering Infrastructure Review underway

Adoption

- £15m Quantum Catalyst Fund

Regulation

- Commissioned review on future regulatory challenges
- Quantum standards pilot launched

International Partnerships

- Signed agreements with Canada, Netherlands and Australia

Long-term Missions announced

Slide Credit: Peter Knight & DSIT

UK Quantum Missions: vision for 2024-2035

By 2035, there will be accessible, **UK-based quantum computers capable of running 1 trillion operations** and supporting applications that provide benefits well in excess of classical supercomputers across key sectors of the economy.

By 2035, the UK will have deployed the **world's most advanced quantum network at scale**, pioneering the future quantum internet.

By 2030, every **NHS Trust will benefit from quantum sensing-enabled solutions**, helping those with chronic illness live healthier, longer lives through early diagnosis and treatment.

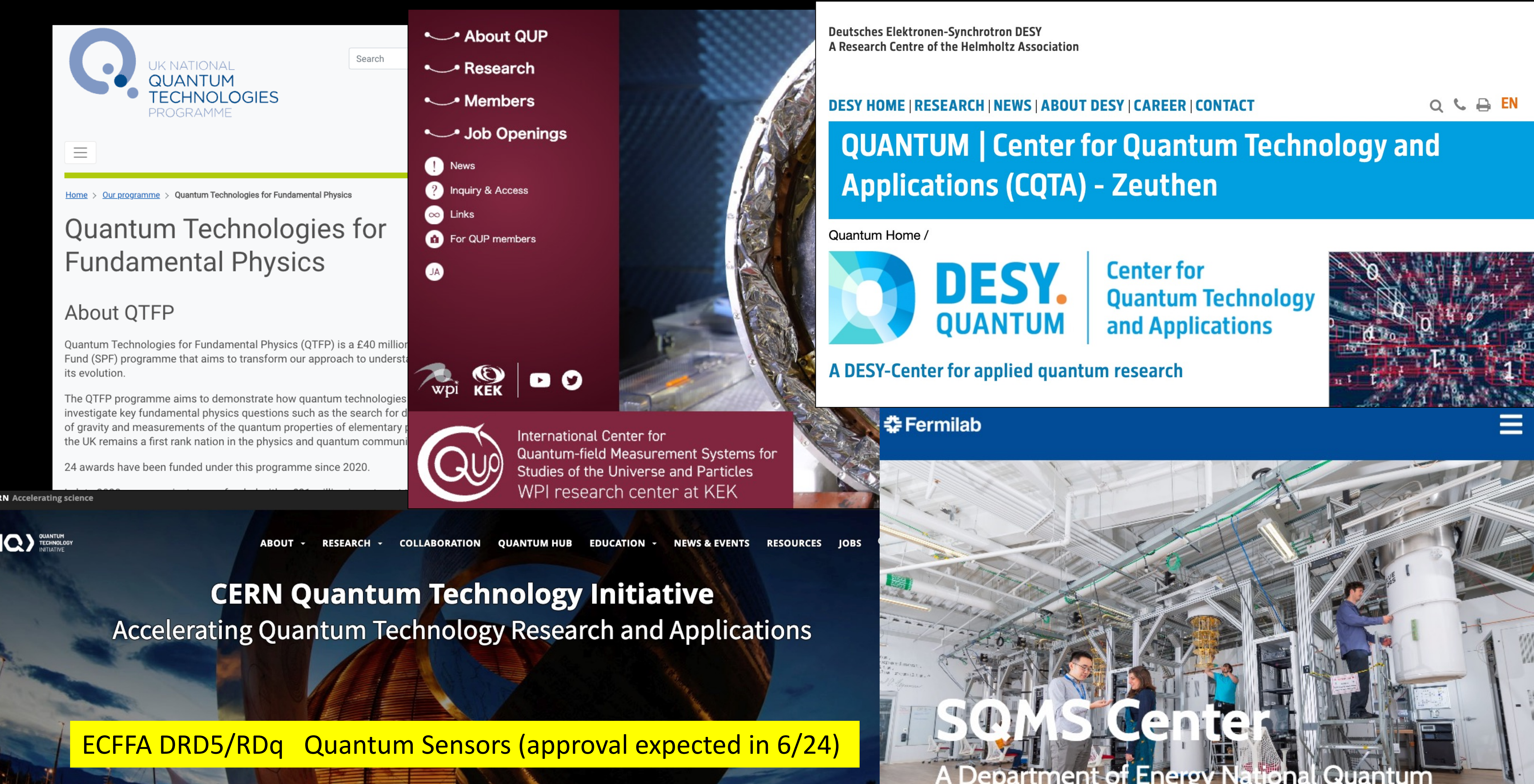
By 2030, **quantum navigation systems, including clocks, will be deployed on aircraft**, providing next-generation accuracy for resilience that is independent of satellite signals.

By 2030, **mobile, networked quantum sensors will have unlocked new situational awareness** capabilities, exploited across critical infrastructure in the transport, telecoms, energy, and defence sectors.

Slide Credit: Peter Knight & DSIT

Department for Science, Innovation & Technology

Quantum Sensing for Fundamental Physics Rapidly Expanding Globally



ECFFA DRD5/RDq   Quantum Sensors (approval expected in 6/24)

Quantum Sensors

quantum sensors register a change of quantum state caused by the interaction with an external system:

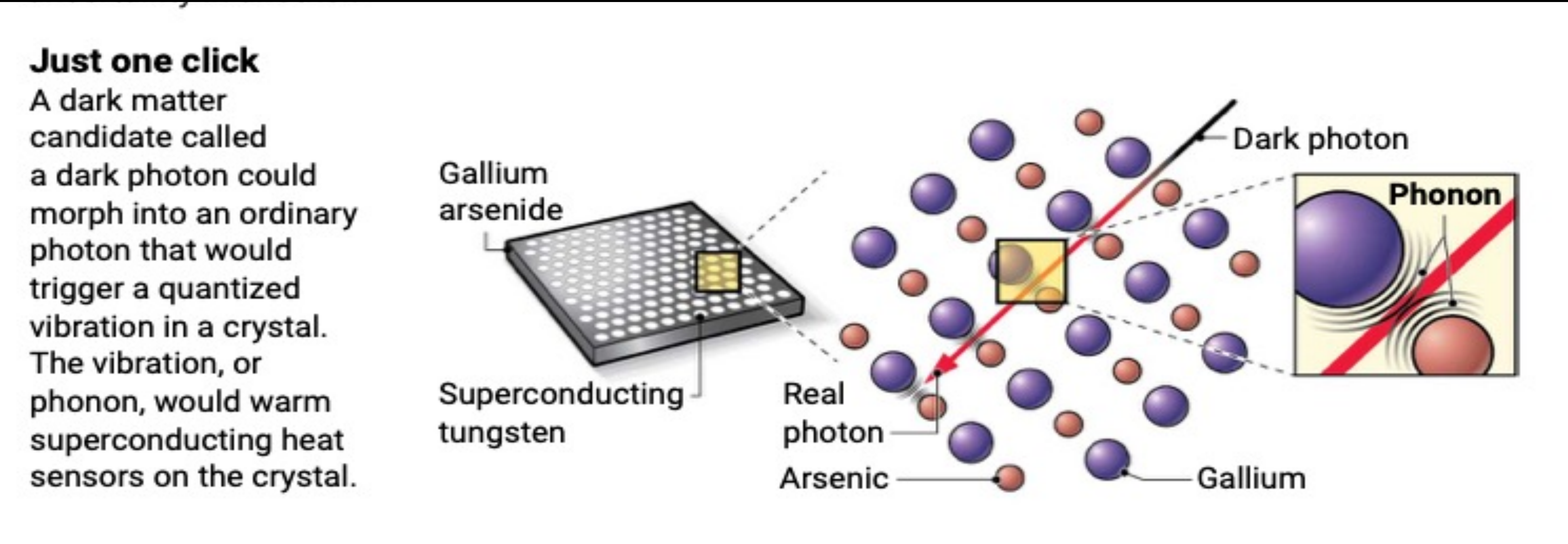
- transition between superconducting and normal-conducting
- transition of an atom from one state to another
- change of resonant frequency of a system (quantized)

Then, ***a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and read out its quantum states***.

and because the commensurate energies are very low, unsurprisingly, quantum sensors are ideally matched to low energy (particle) physics;

Particles & waves

Quantum detectors include devices that can detect a single quantum e.g. a photon

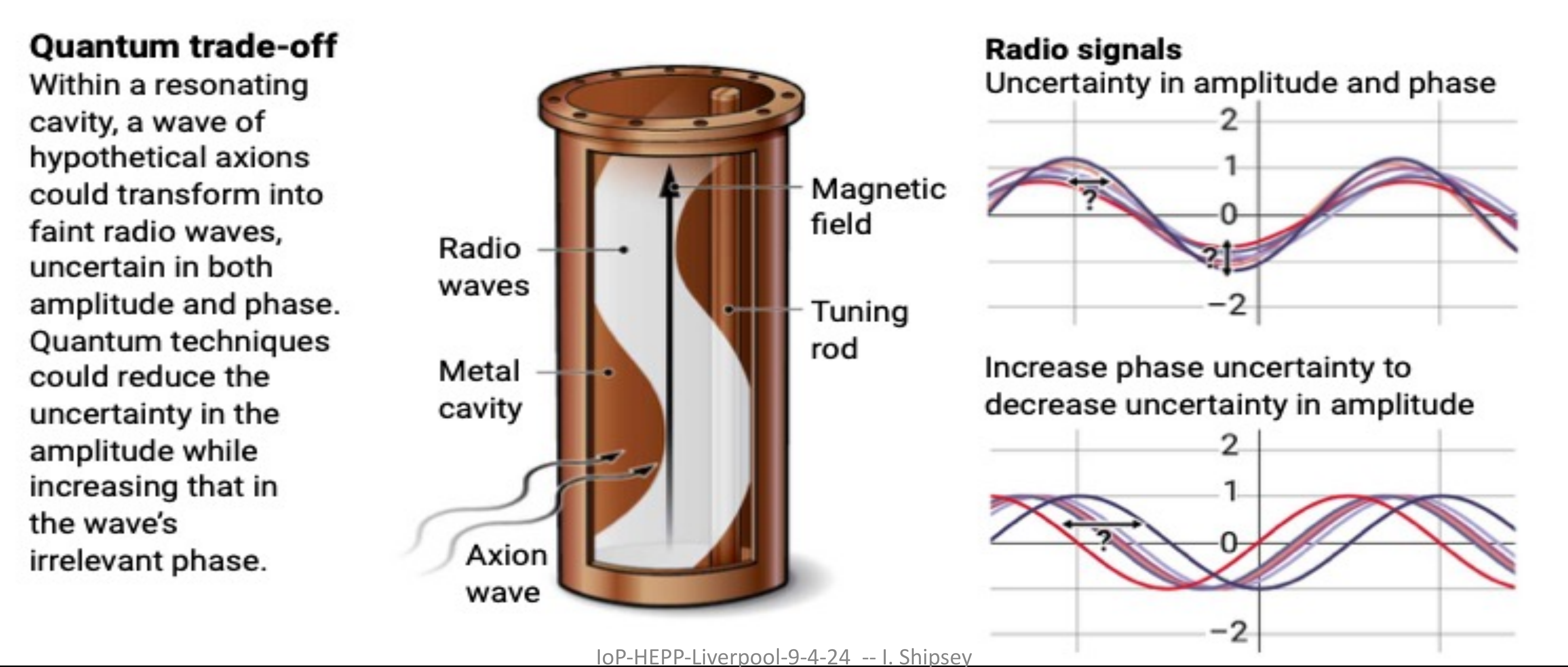


Science

Particles & waves

& devices that exploit a quantum trade-off to measure one variable more precisely at the cost of greater uncertainty in another

Science



Quantum Technologies and Fundamental Physics

- The nature of dark matter
- The earliest epochs of the universe at temperatures >> 1TeV
- The existence of new forces
- The violation of fundamental symmetries
- The possible existence of dark radiation and the cosmic neutrino background
- The possible dynamics of dark energy
- The measurement of neutrino mass
- Tests of the equivalence principle
- Tests of quantum mechanics
- A new gravitational wave window to the Universe:
  - LIGO sources before they reach LIGO band
  - Multi-messenger astronomy: optimal band for sky localization
  - Cosmological sources

QTFP & the European Strategy for Particle Physics

The QTFP projects will collectively write and submit a whitepaper to STFC's PPAP and PAAP panels and UK-ECFA as a contribution to the European Particle Physics Strategy Update and the PPAP and PAAP Roadmaps feeding into the PPAN (Science Board) Roadmap over the course of the summer

As part of this :

a. QTFP projects encourage theorists, phenomenologists and experimentalists to come up with new ideas for physics, and physics studies, that one or more of the 7 QTFP projects could be sensitive to, and reach out to the relevant QTFP project(s) with their ideas and their results/publications.

b. QTFP projects encourage instrumentation/device physics/quantum technologies colleagues with relevant experience and interest to contact any QTFP project where their ideas might enhance the physics reach of the project for discussions.

c. QTFP projects welcome new members

Quantum Technologies and Fundamental Physics

- The nature of dark matter
- The earliest epochs of the universe at temperatures >> 1TeV
- The existence of new forces
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- The possible existence of dark radiation and the cosmic neutrino background
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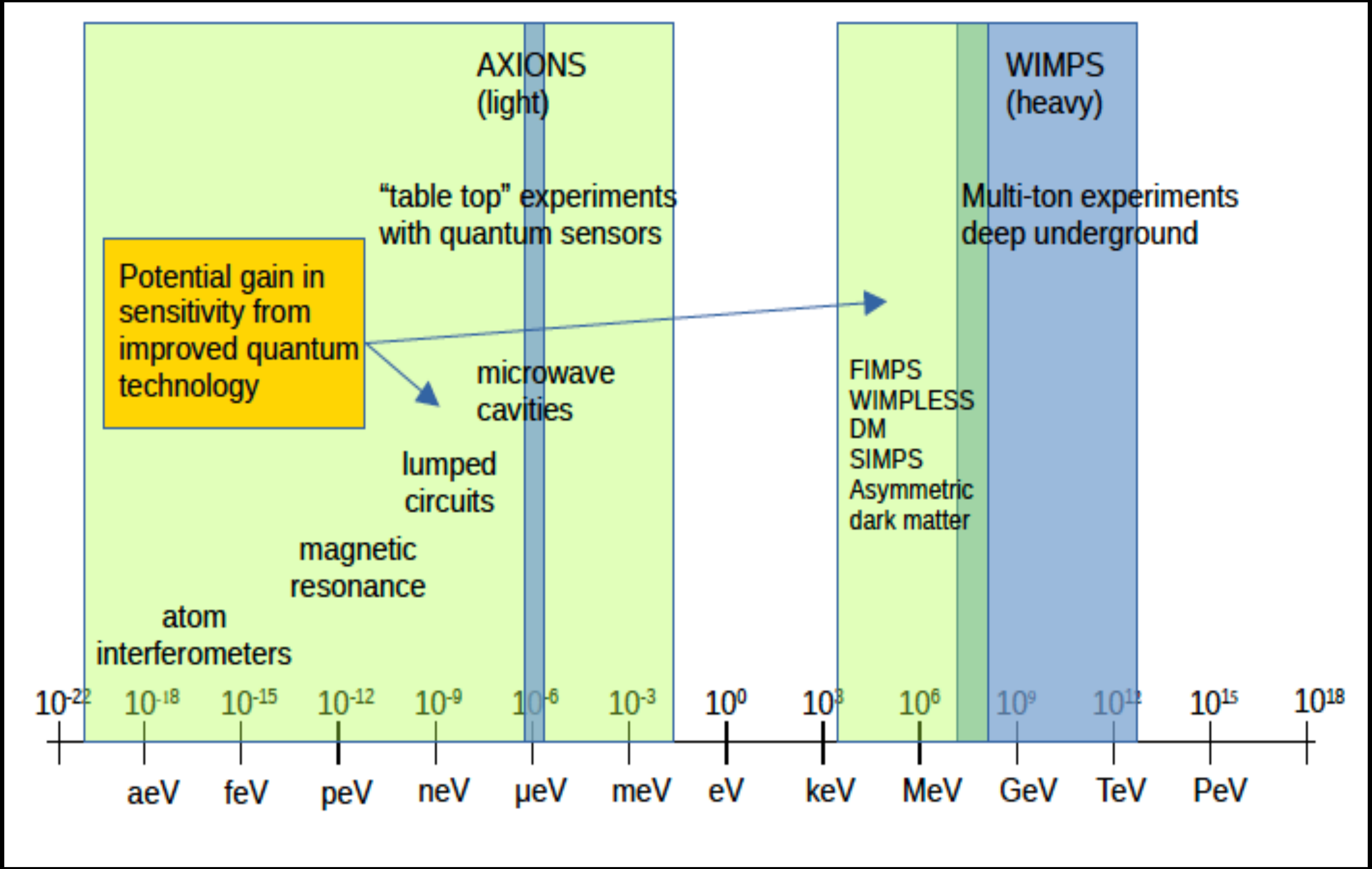
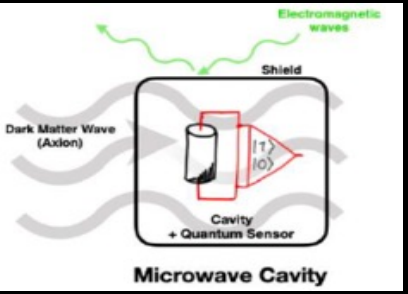
Example: potential mass ranges that quantum sensing approaches open up for DM searches >20 orders of magnitude



TODAY

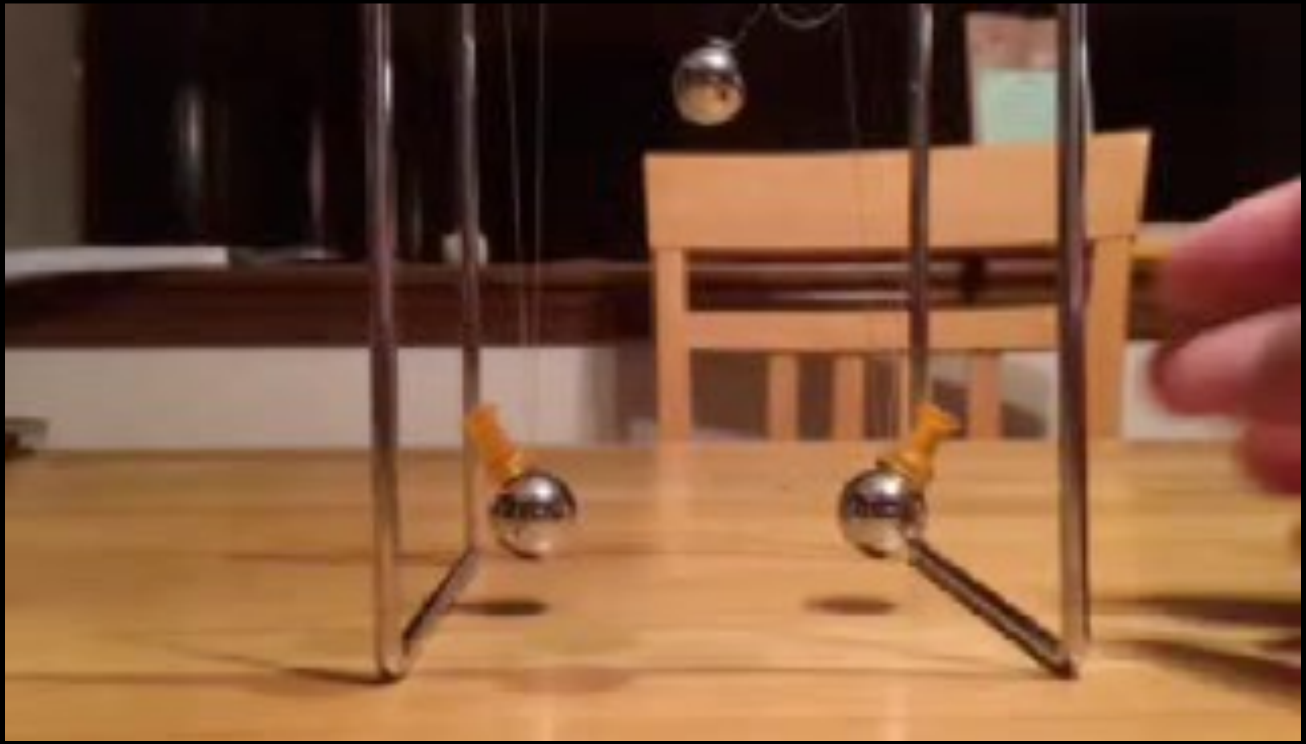
\+ Quantum Sensors

See talk by Sally Shaw for non-QTFP Dark Matter



An oscillator (resonance) detector can accumulate the weak interactions of light dark matter over many “swings”

Detection oscillator



Axion wave

Weak coupling -- takes many swings to fully transfer the wave amplitude.
In real life, Q = number of useful swings is limited by coherence time.

Axion Detectors and the Current Landscape

SUPERCONDUCTING QUANTUM ELECTRONICS:
- SQUIDs
- Josephson Parametric Amplifiers
- Travelling Wave Parametric Amplifiers
- Bolometers
- Qubits / QuBit arrays

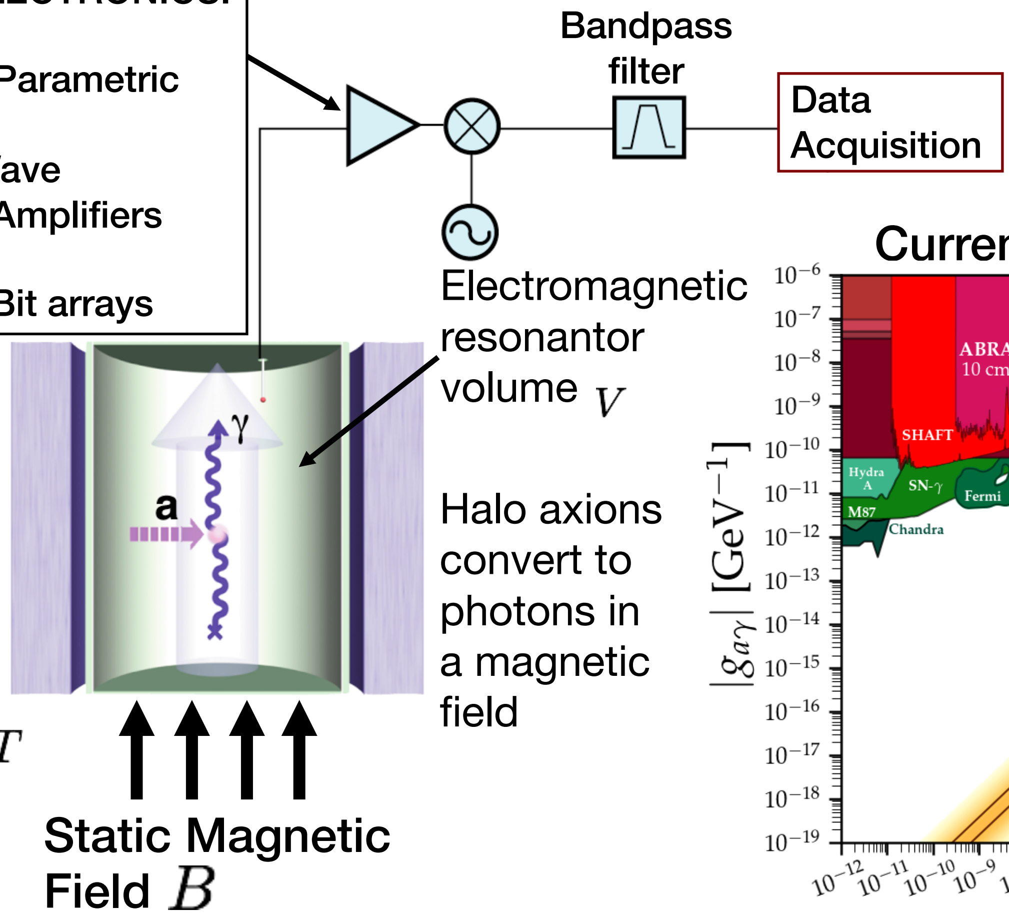
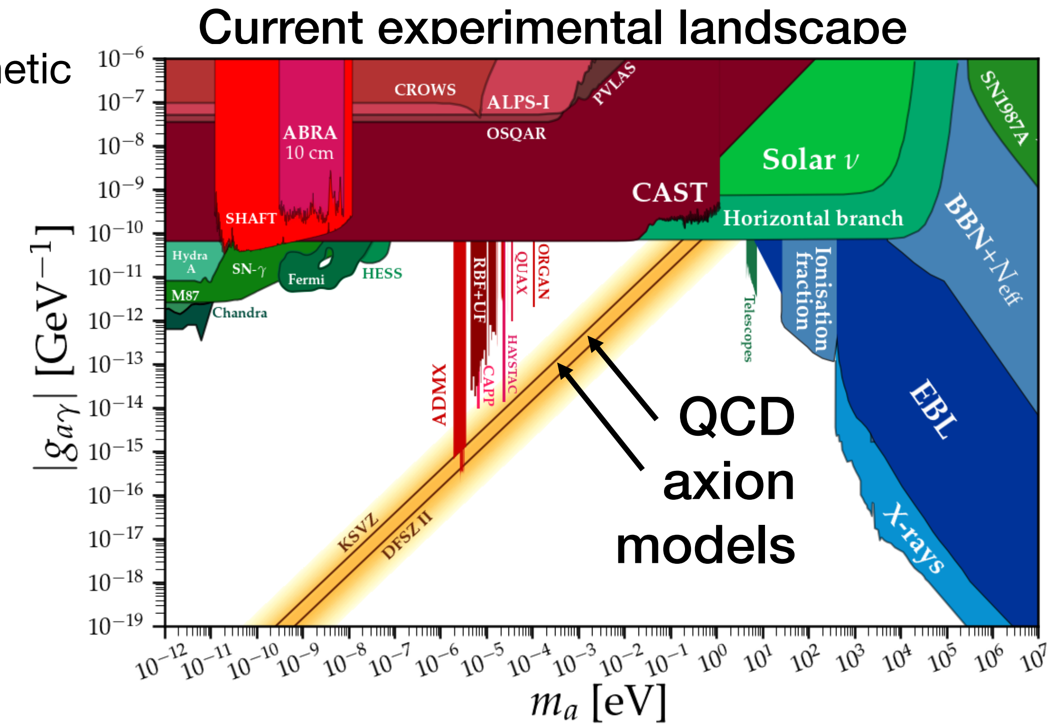


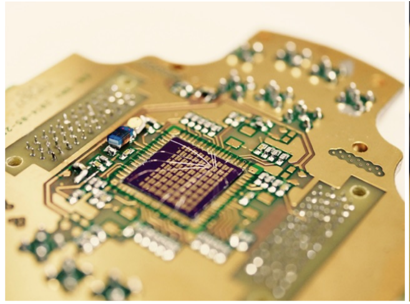
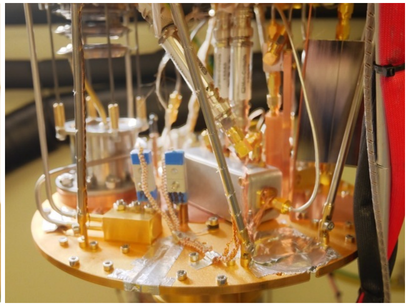
Figure of merit for detector sensitivity: $\frac{B^2 V}{T}$



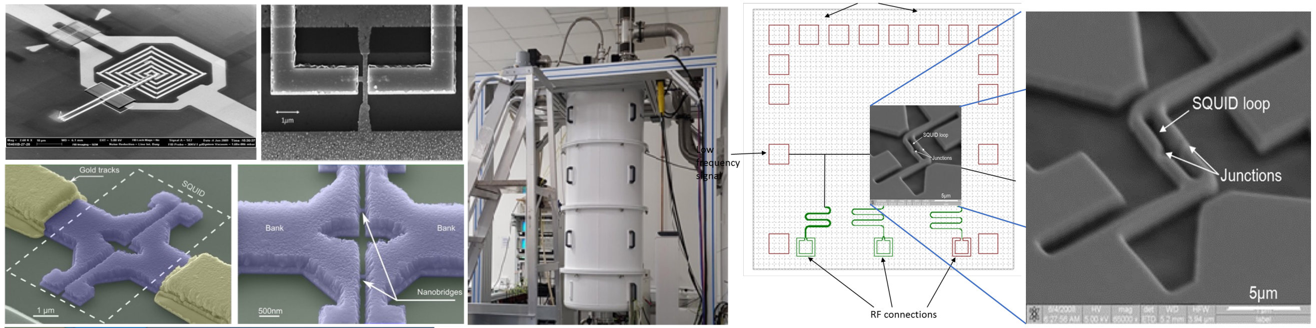
- Non resonant experiments have broad mass coverage, but insensitive to QCD axions
- Resonant experiments much more sensitive. ADMX is the only experiment to have probed a broad range of existing axion models. However, mass coverage too slow. Can speed up: 1. By using a new generation of quantum electronics; 2. By using a larger, higher field magnet; 3.A lower system temperature; 4. Using multiple resonators in parallel.

Quantum Electronics for QSHS

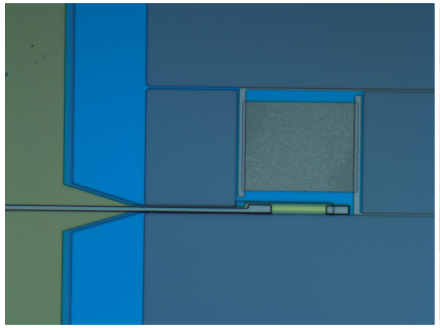
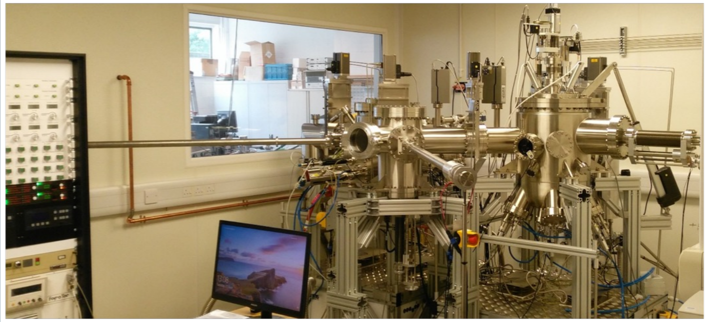
Josephson parametric amplifiers (JPAa) / Travelling wave parametric amplifiers (TWPAs)

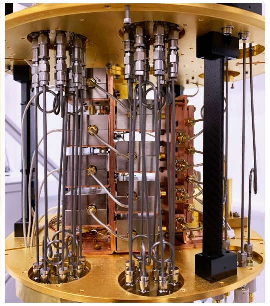
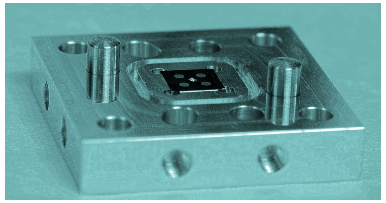

SLUG loaded SQUID amplifiers



Cryogenic bolometer arrays

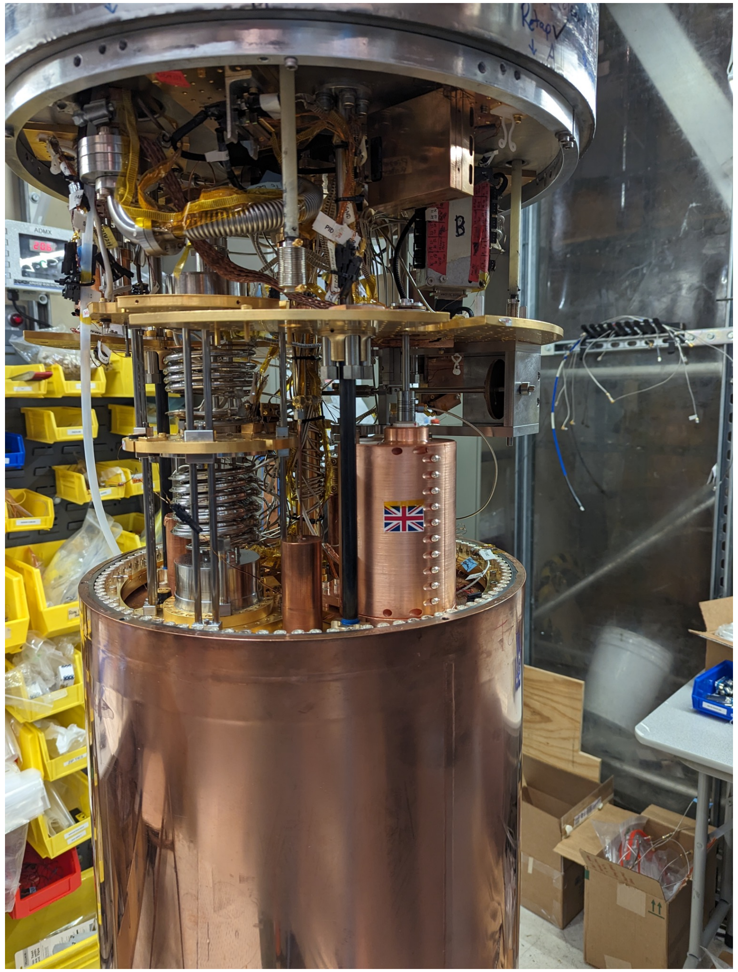



Qubit arrays

QSHS-ADMX collaboration

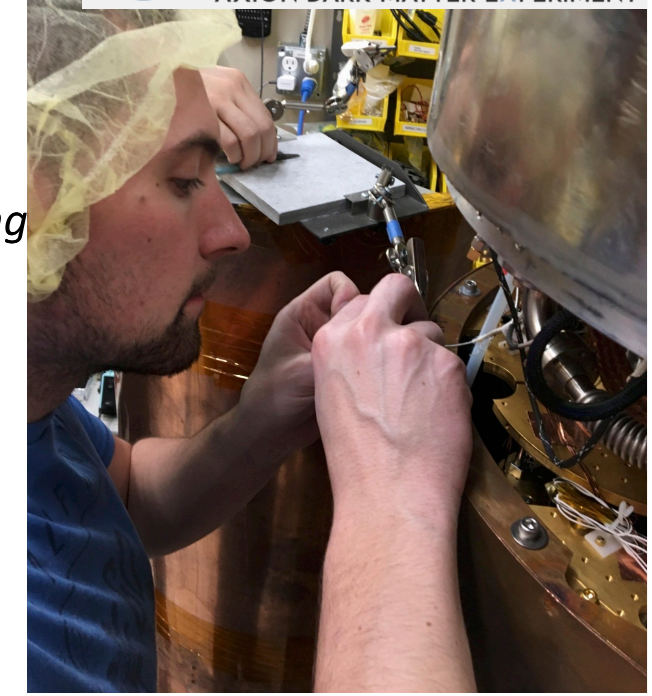
Sheffield (Ed Daw PI), Oxford, UCL, NPL, RHUL, Lancaster, Cambridge



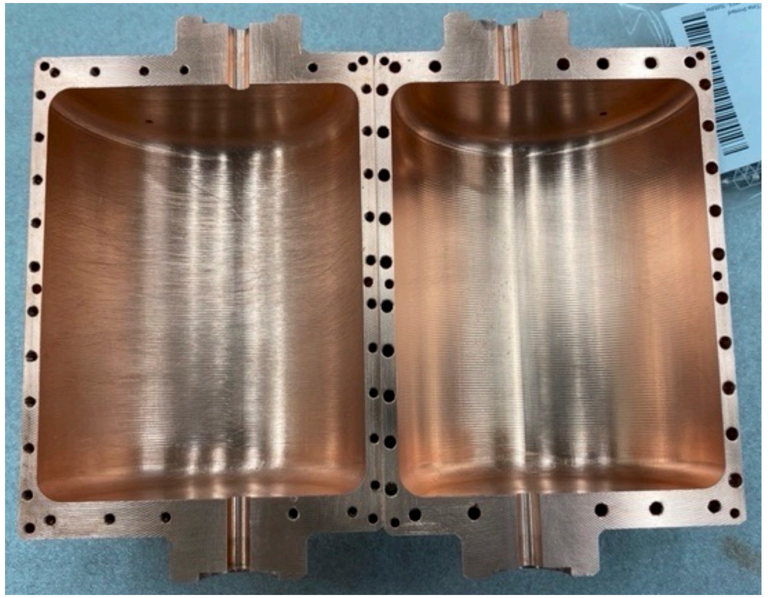
ADMX detector with UK sidecar cavity installed, ready for cooling. December 2023.

- ADMX and QSHS are both ***direct searches for dark matter axions***.
- Daw member of ADMX since 1993 (first Ph.D. student on ADMX)
- QSHS/ADMX MoU signed in 2022.
- ***Cavity research and development***
- ***Resonant feedback research***
- ***Data analysis*** – UK access to ADMX analysis codes, playground data. Reciprocal arrangement on QSHS.
- UK Ph.D. student (Claude Mostyn) spent 3 months at ADMX on long term attachment in 2023.
- Daw, Perry (Ph.D. student) on the ADMX author list. More to follow and possible US authors on QSHS list as collaboration deepens.
- Future collaboration deepening into superconducting electronics.
- **Sheffield dilution fridge and magnet installed.**

Mitch Perry working on the ADMX insert.



QSHS cavity for ADMX



Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

QUEST DMC

ROYAL HOLLOWAY UNIVERSITY OF LONDON

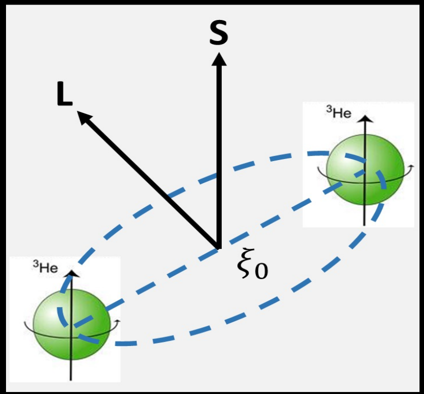
Lancaster University

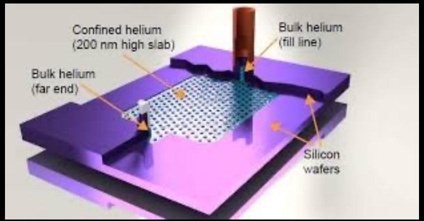
US University of Sussex

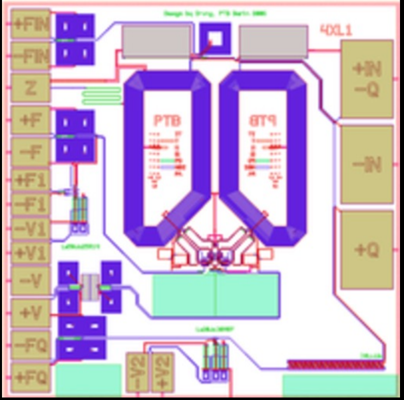
UNIVERSITY OF OXFORD

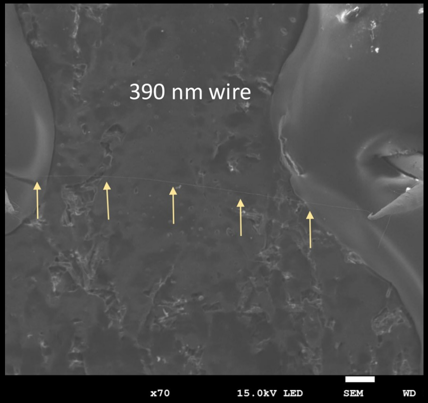
UNIVERSITY OF LIVERPOOL

ULT + Superfluid ^{3}He + Quantum Technologies

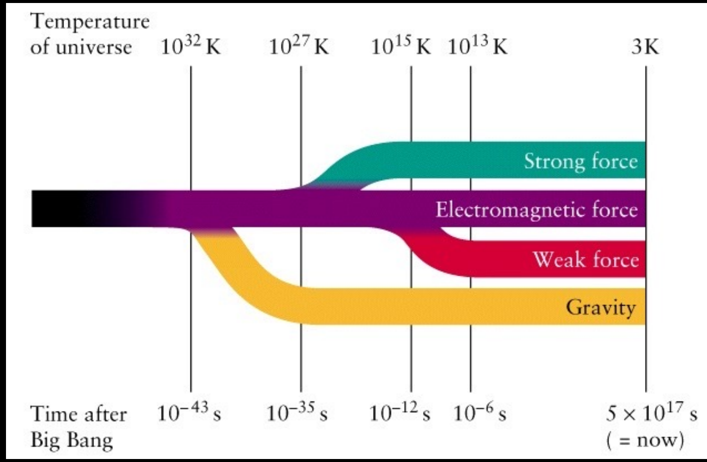


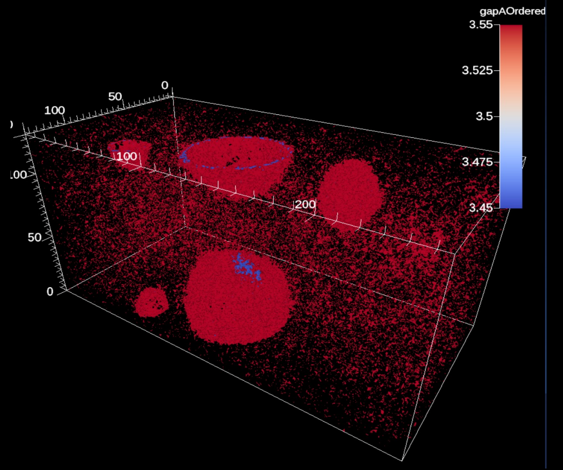




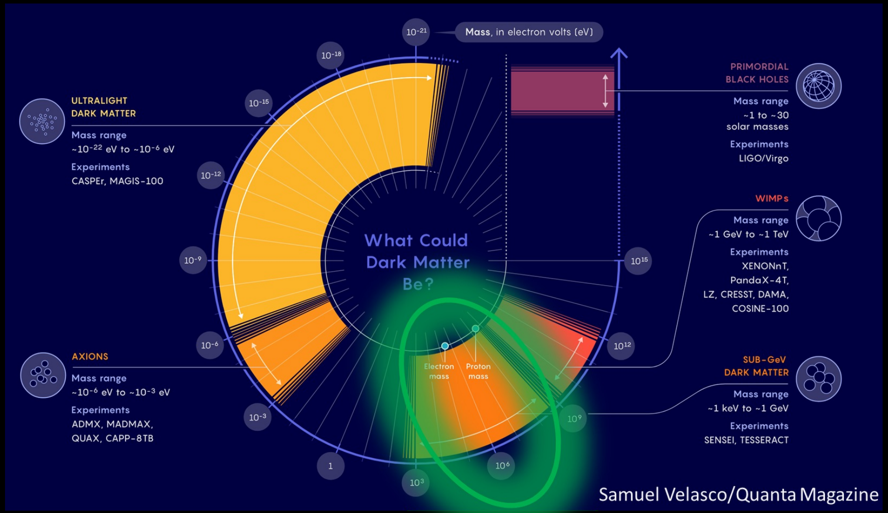


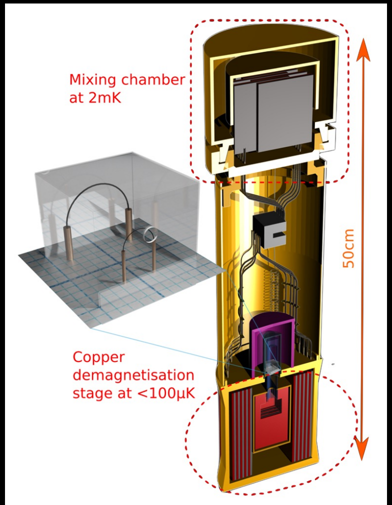
Phase Transitions in the Early Universe



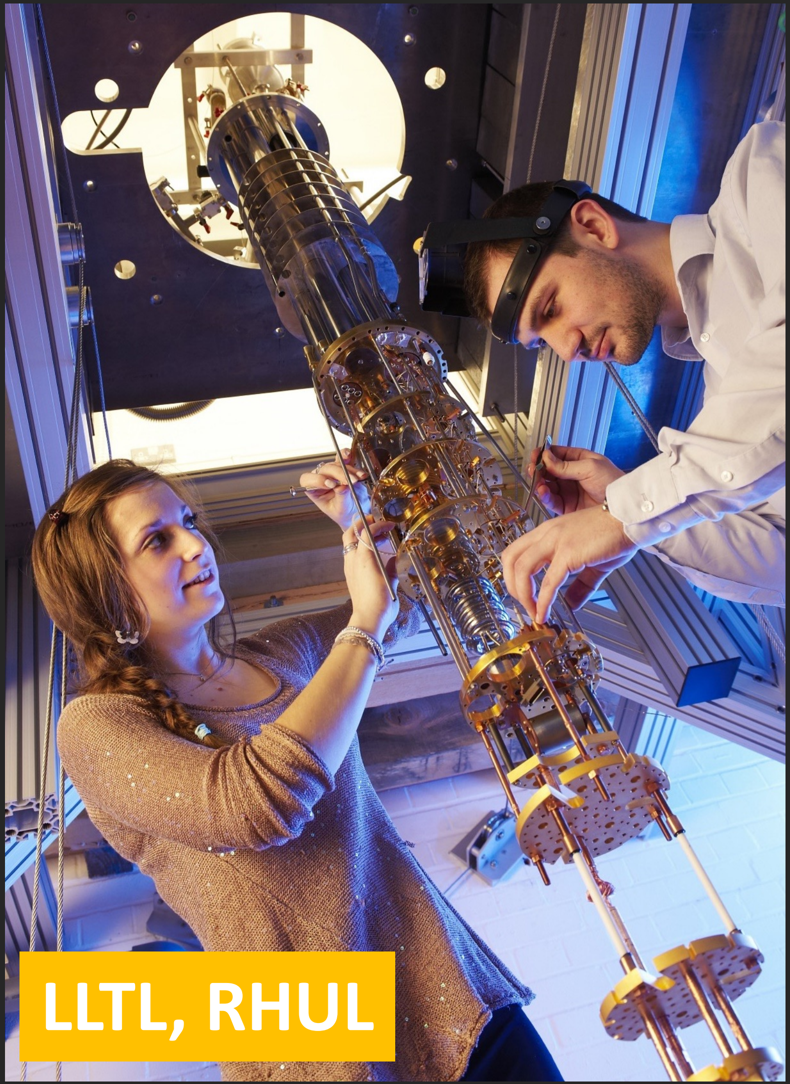


Detection of sub-GeV dark matter



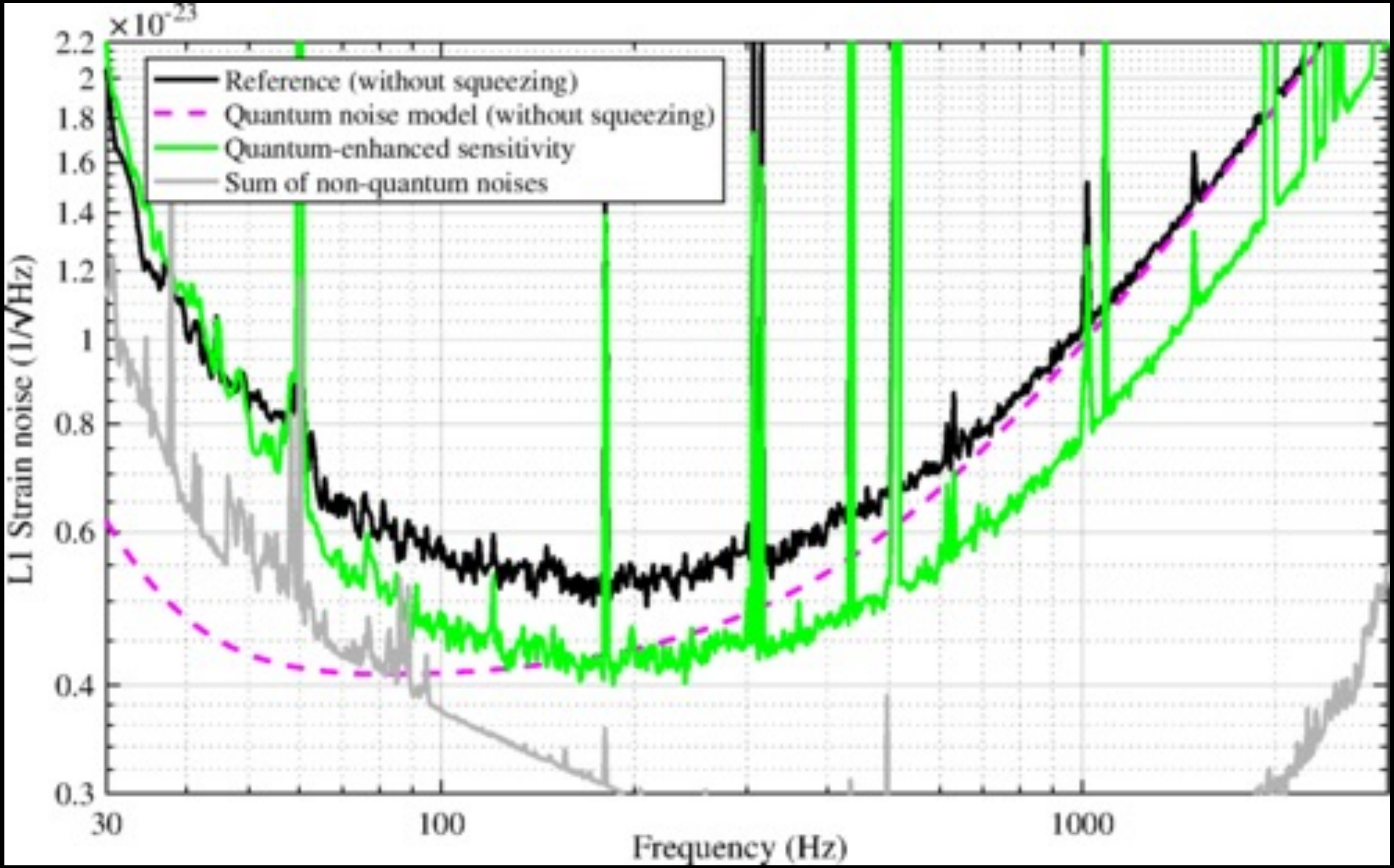


Implementation of current quantum sensors, operated in new regime at ultralow temperatures, and new sensors co-designed for fundamental physics



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

LIGO: Quantum enhanced sensing-Squeezed light for improved sensitivity

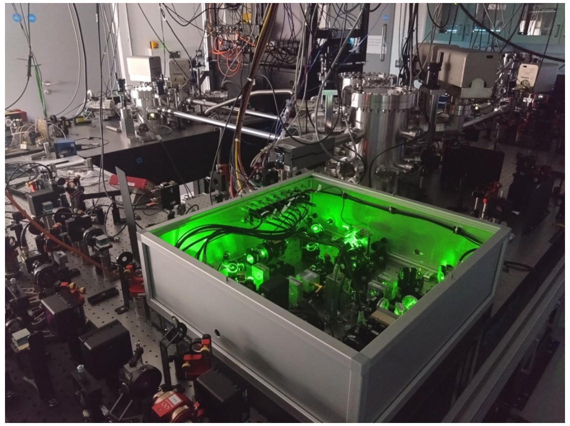


https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.231107
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.231108

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)



QUEST

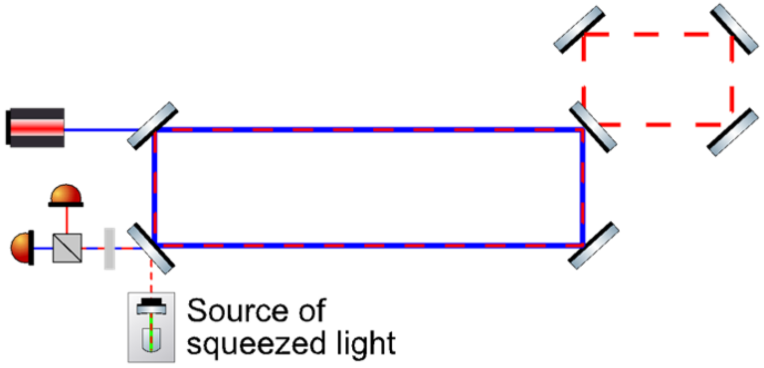
Status:

- 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)
- QUEST Quantized space-time search: 1 engineering run completed. Theory work: 2306.17706

Work Packages

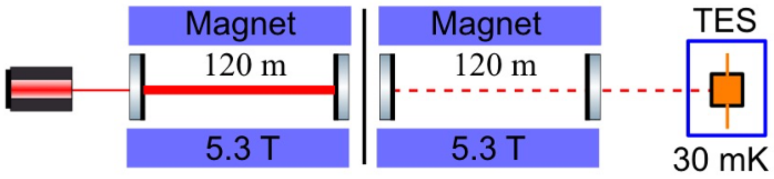
WP 1: Axions in the galactic halo

- An 'interferometry haloscope' (PRD 101, 095034)
- Axions with masses from 10^{-16} eV up to 10^{-8} eV



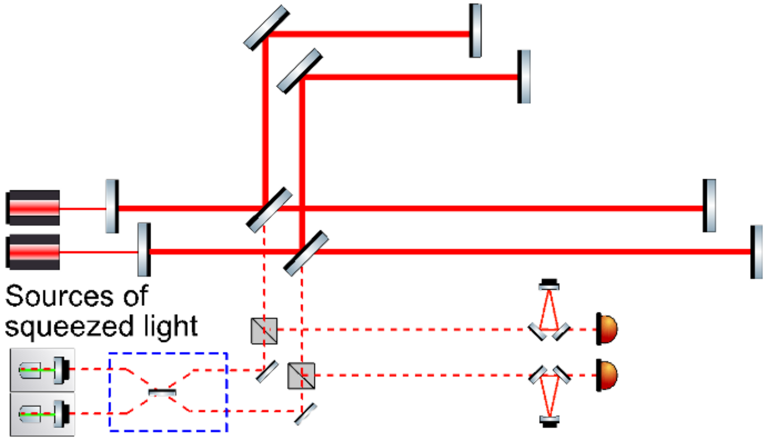
WP 2: Light-shining-through-wall (collab.)

- Making and detecting axion-like particles
- Transition edge sensor with background $<10^{-6}$/s



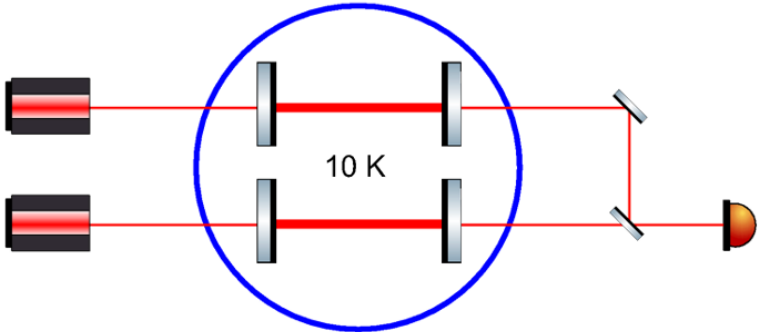
WP 3: Quantisation of space-time

- Testing ideas on quantization of space-time
- Sensitivity of 2×10^{-19} m/rt(Hz) above 1 MHz



WP 4: Semiclassical gravity

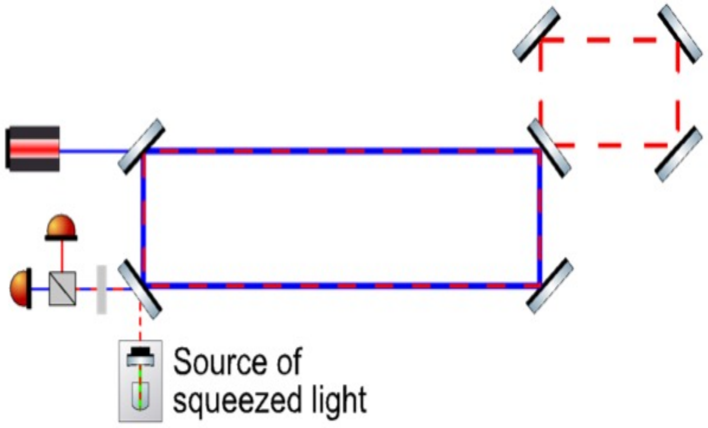
- Testing semiclassical gravity predictions
- Test-bed for other forms of possible quantum/gravity interaction experiments



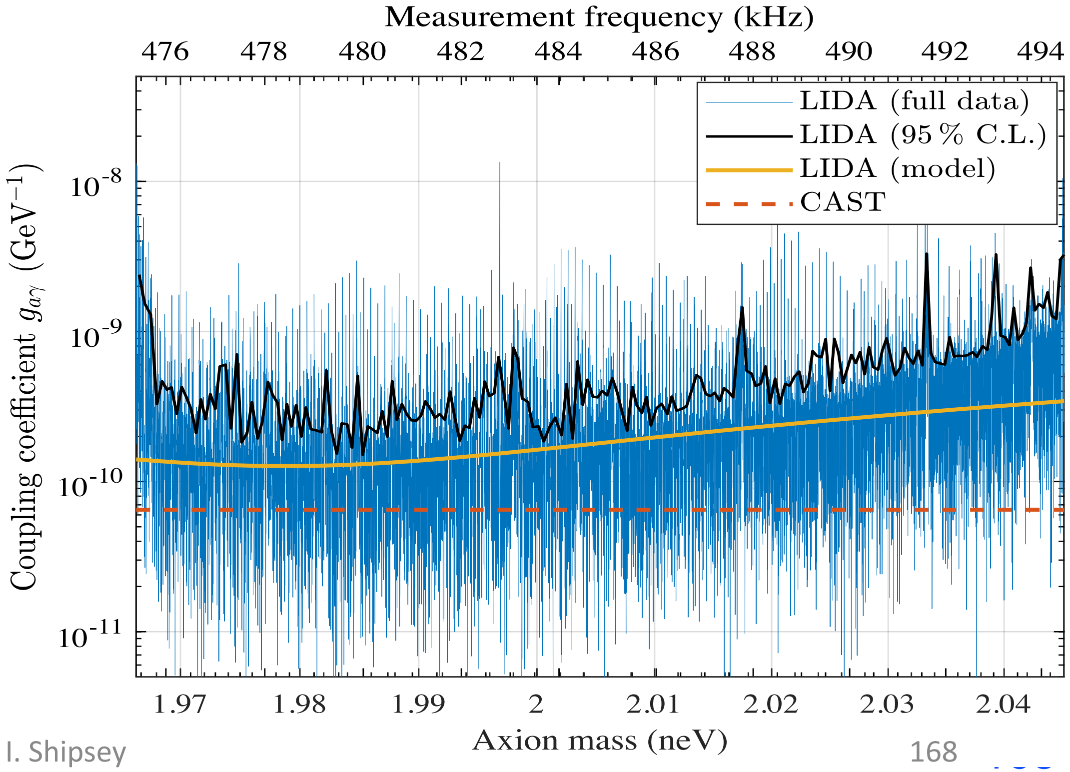
WP 1: Laser Interferometeric Detector for Axions (LIDA)

WP 1: Axions in the galactic halo

- An ‘interferometry haloscope’ (PRD 101, 095034)
- Axions with masses from 10^{-16} eV up to 10^{-8} eV

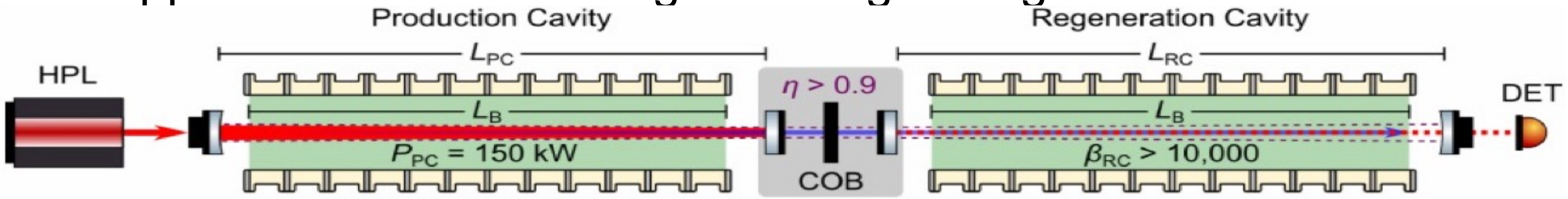


- Completed the first science run to search for axions with mass of 2 neV
- Leading observatory in its class (compared to the MIT’s and U Tokyo’s setups)
- Achieved the world record intensity in laser interferometers (4.5 MW / cm^2)
- Proposed axion searches with photon counting



arXiv:2307.01365 arXiv:2401.11907 arXiv:2309.03394

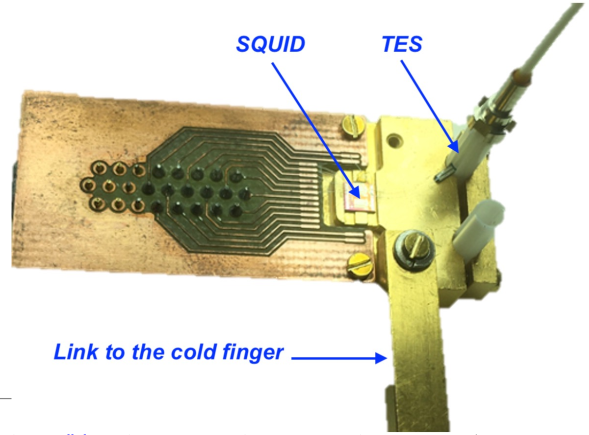
WP 2: Support for the ALPS II Light shining through walls Axion search experiment

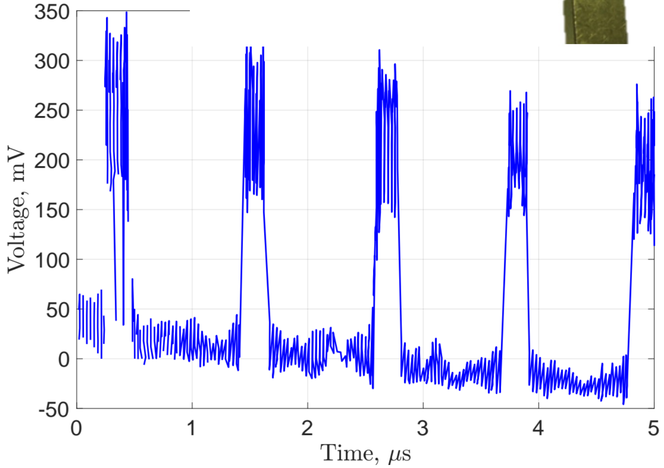


- ALPS II is a new particle search experiment at DESY in Hamburg (human-made axions not cosmological)
- QI support to commissioning: Milestone - current first science run reached

world record for light storage time in 2-mirror cavity (67 ms)

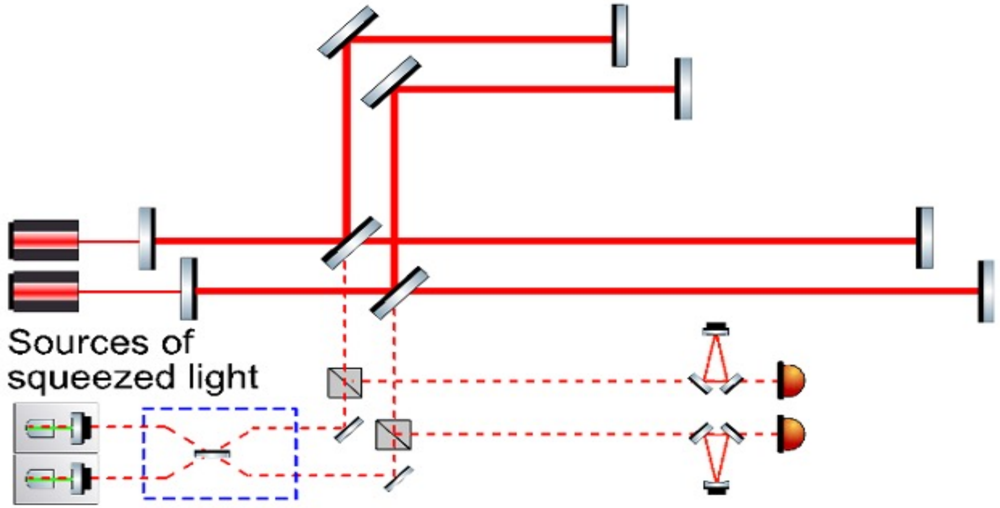
- New TES detector under commissioning

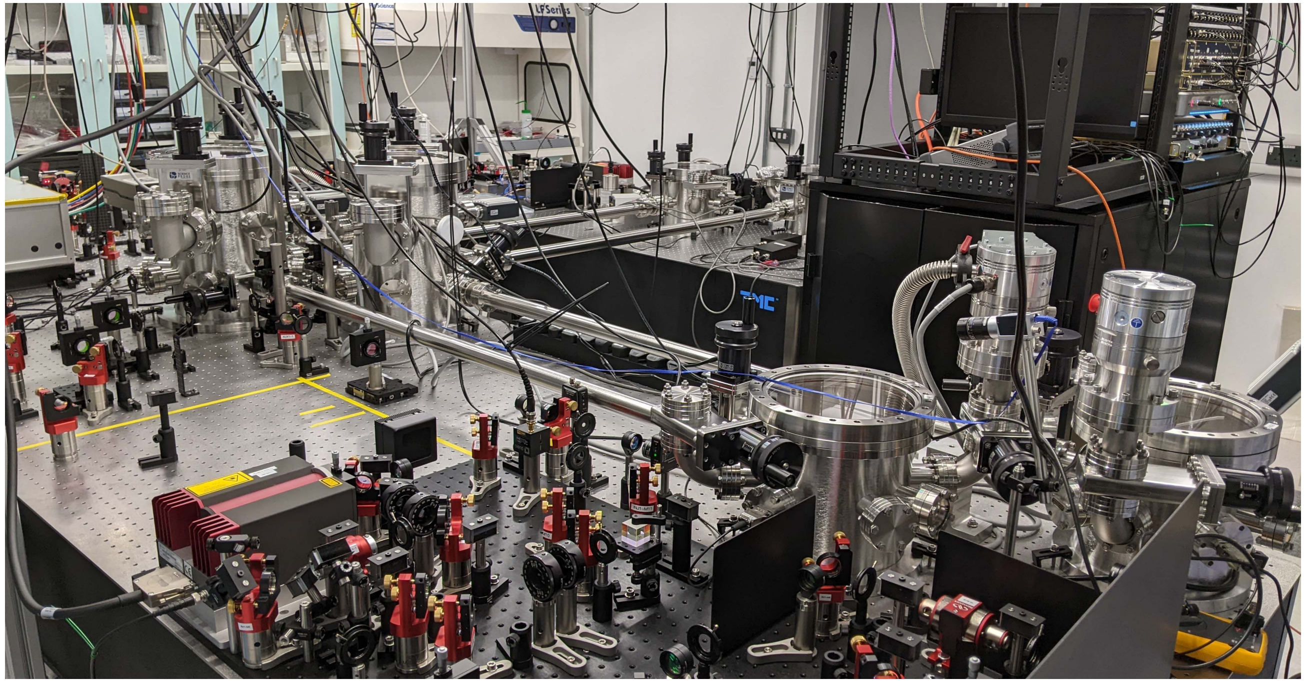


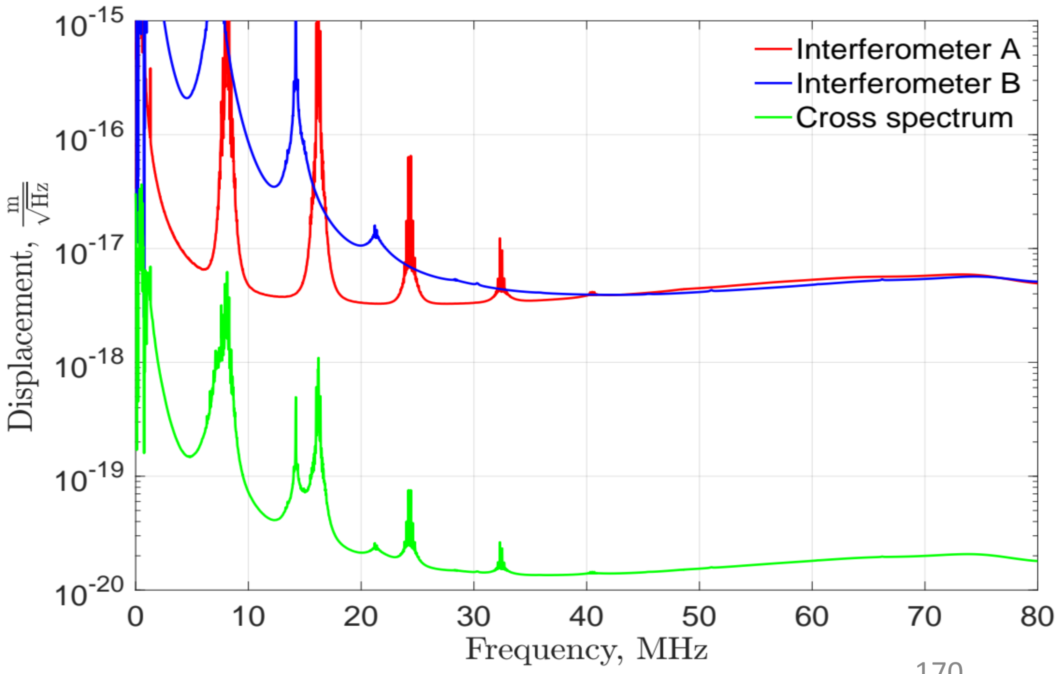


WP 3: QUantum-Enhanced Space-Time experiment (QUEST)

- World's most sensitive table-top interferometer
- First engineering run achieved with cross-correlated sensitivity near 10^{-20} m/rt(Hz)
- Quantum / Squeezed light sources to enhance sensitivity
- Searching for signatures of quantum gravity / quantized space-time



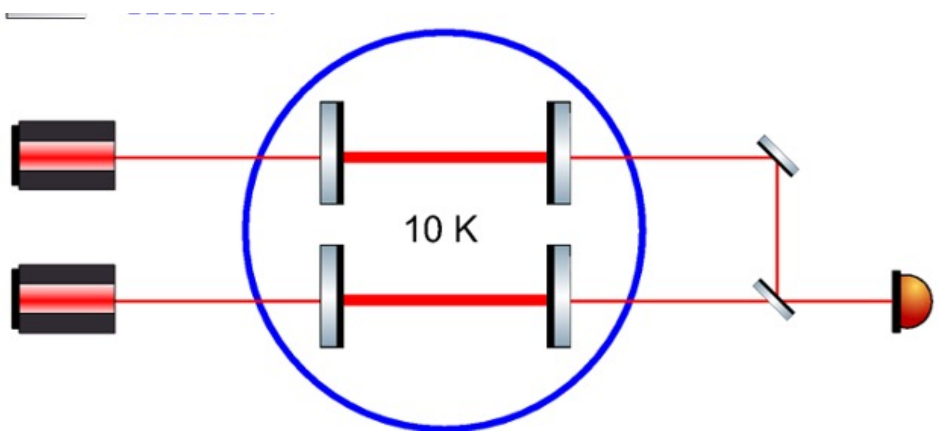




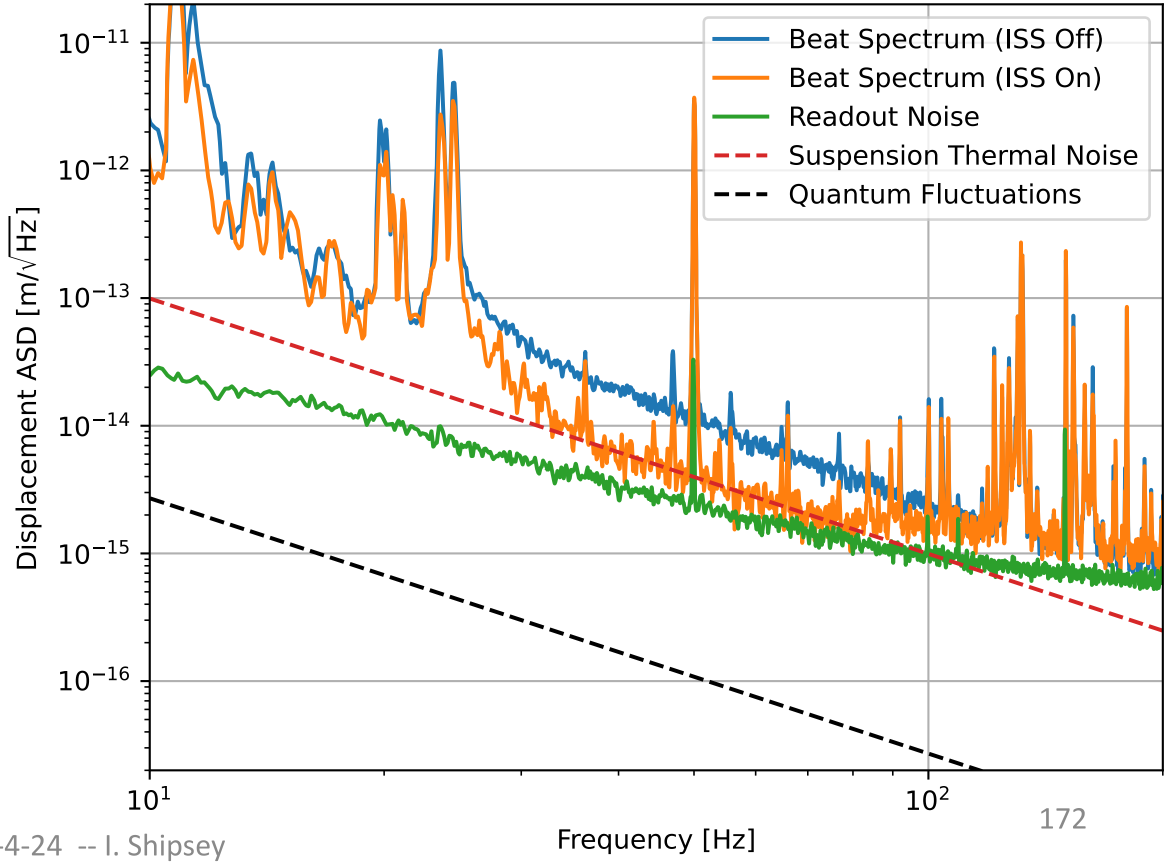
ArXiv 2008.04957

WP 4: searches for semiclassical gravity

- State-of-the-art passive and active inertial isolation of optical cavities
- Reached the suspension thermal noise level (significant milestone)
- Tested the “pre-selection” model of semiclassical gravity (data analysis ongoing)



arXiv:2402.00821



Optical coatings manufacture at the National Manufacturing Institute Scotland (NMIS)

Quantum Interferometry Future Plans

WP1: axion searches

- Produced competitive limits for masses of 2 neV
- Aim to tune the observatory for lower masses (feV – peV)
- Aim to increase the observatory length
- Aim to utilise single photon detectors to surpass shot noise

WP2: light shining through wall

- First observing run of ALPS II is ongoing
- Aim to utilise superconducting nanowires for keV dark matter searches
- Aim to measure vacuum magnetic birefringence with ALPS II

WP3: searches for quantised space-time

- Produced first correlation spectra for table-top interferometers
- Aim to increase observatory length
- Aim to test different interferometer topologies
- Aim to utilise single photon detectors

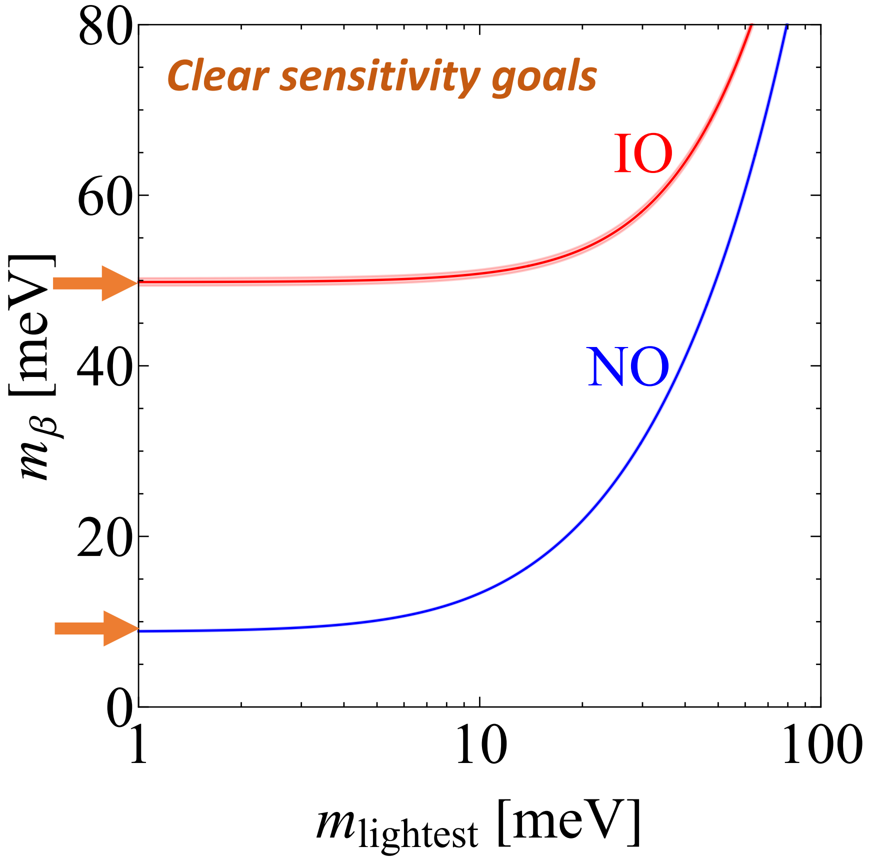
WP4: searches for semiclassical gravity

- Experimentally tested pre-selection models
- Aim to test new models of semiclassical gravity
- Aim to test entanglement of masses in semiclassical gravity models

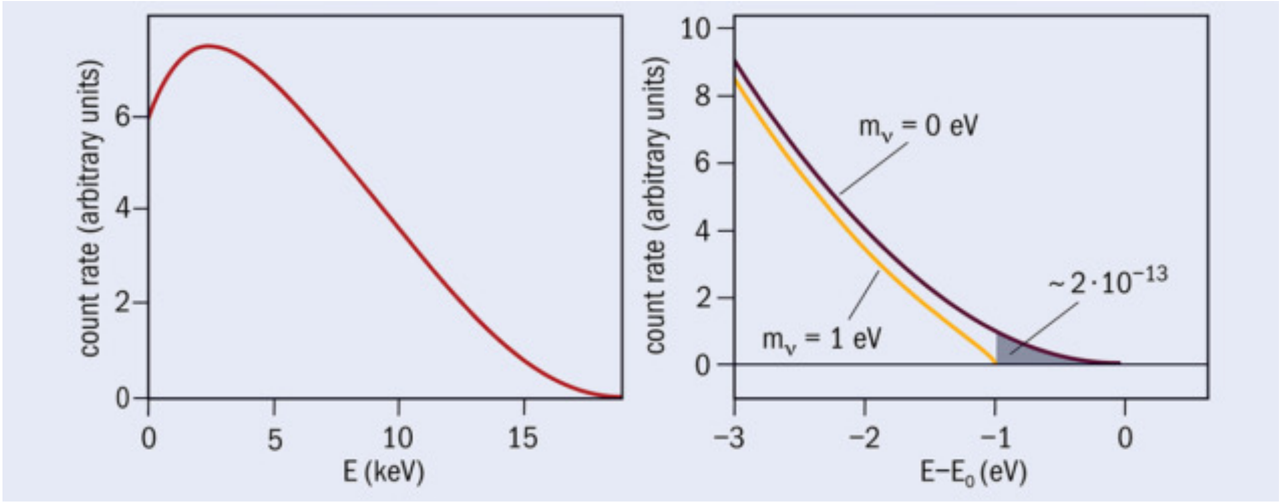
Neutrinos

Absolute neutrino mass

- *Most window to BSM physics*
- *Lab measurement → important input to cosmology*

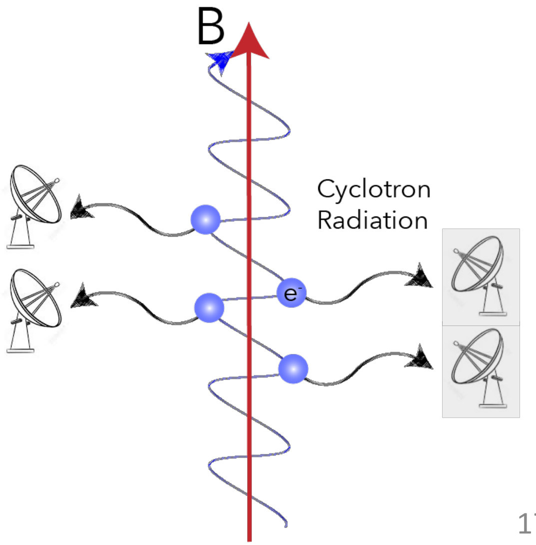


*Atomic ^3H β-decay – **model independent***



Cyclotron **R**adiation **E**mission **S**pectroscopy **CRES** + **Quantum Technologies**
to overcome limitations of current state-of-art (KATRIN) (0.8 ev to 0.2eV)

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



See talk by Kirsty Duffy
for neutrinos including QTNM

QTNM Quantum Technologies for Neutrino Mass

UCL | University of Oxford | University of Cambridge | NPL National Physical Laboratory | Warwick The University of Warwick | Prifysgol Abertawe Swansea University

Goal

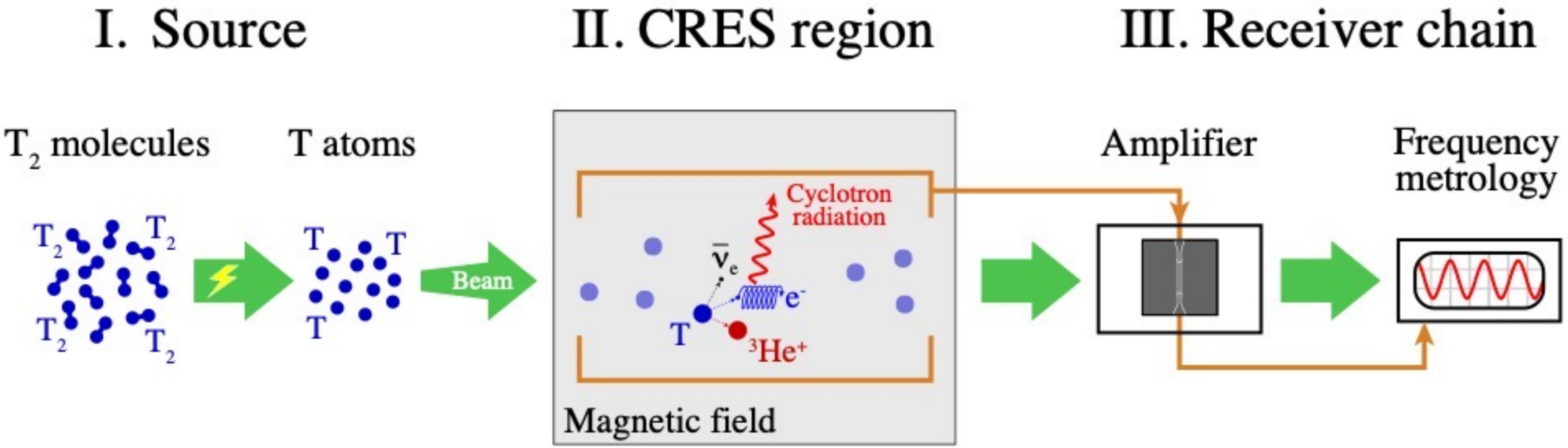
Neutrino mass measurement from atomic ^{3}H β-decay via Cyclotron Radiation Emission Spectroscopy using latest advances in quantum technologies.

Current project (QTFP Wave 1, 2021-2025)

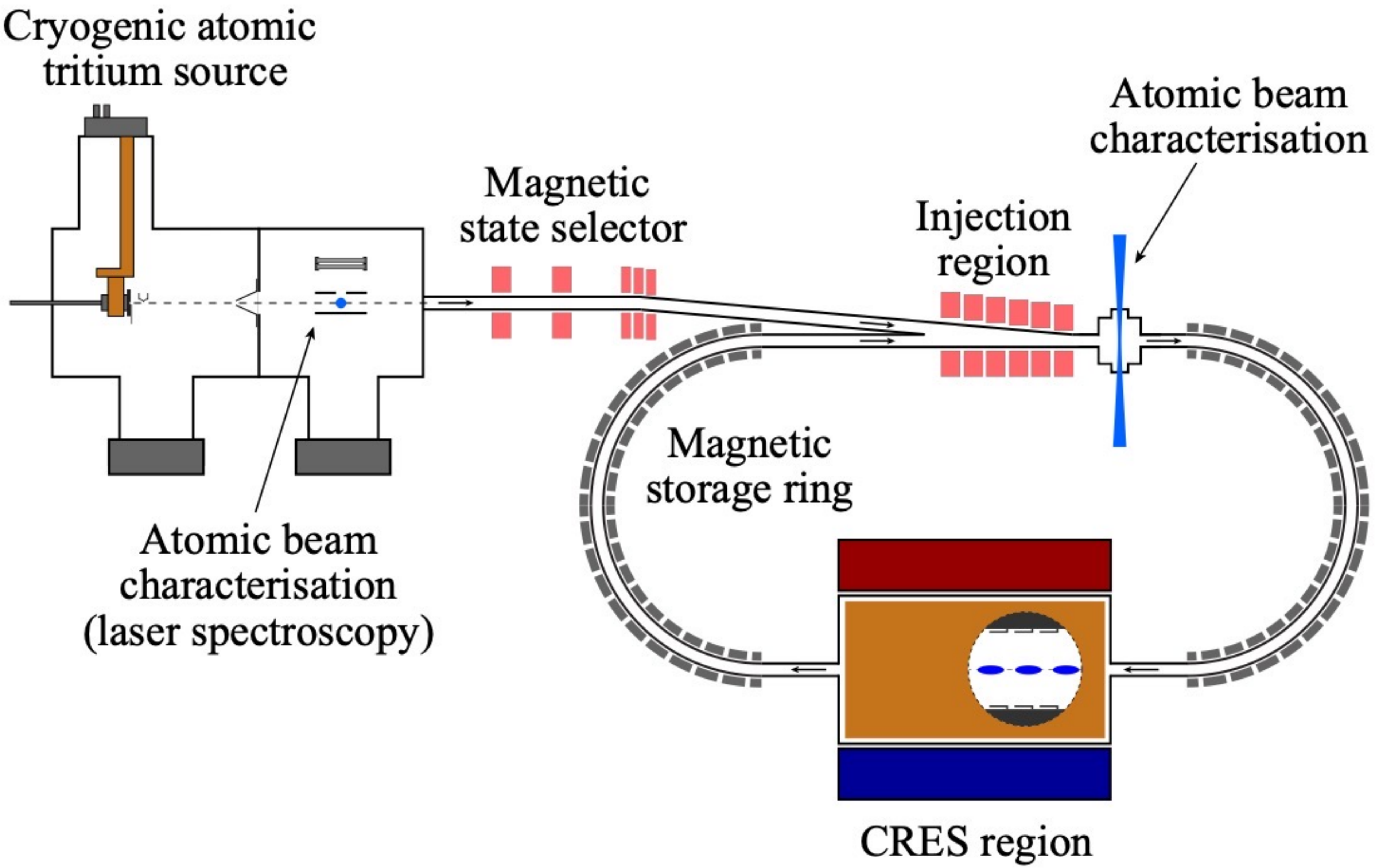
Technology Demonstration: CRESDA = CRES Demonstration Apparatus

- **Quantum** noise limited microwave **sensors** at TRL7/8 for CRES at ~18GHz (corresponding to 0.7T field)
- 3D B-field mapping with $\lesssim 1\ \mu$T 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

CRESDA Scheme



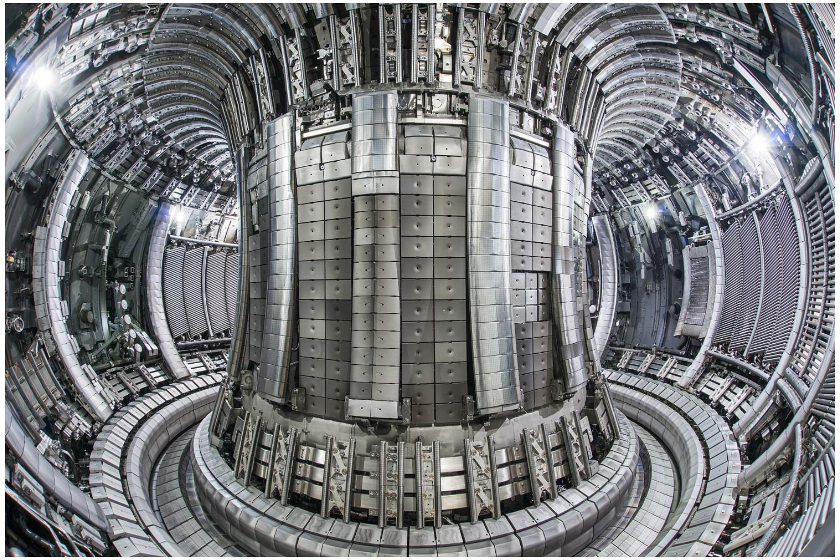
CRESDA Outline

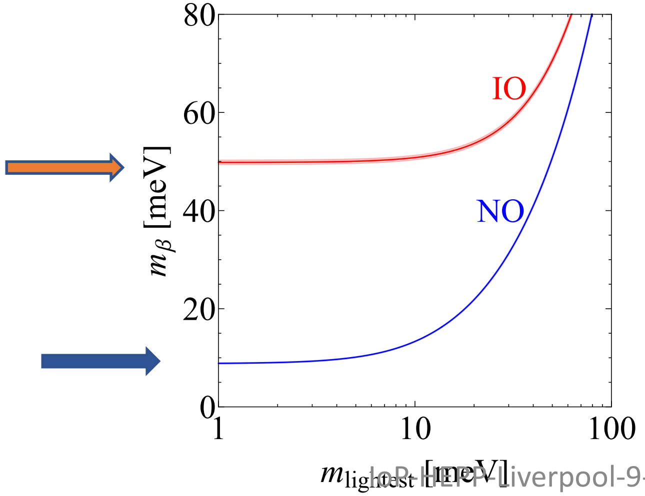


Outlook

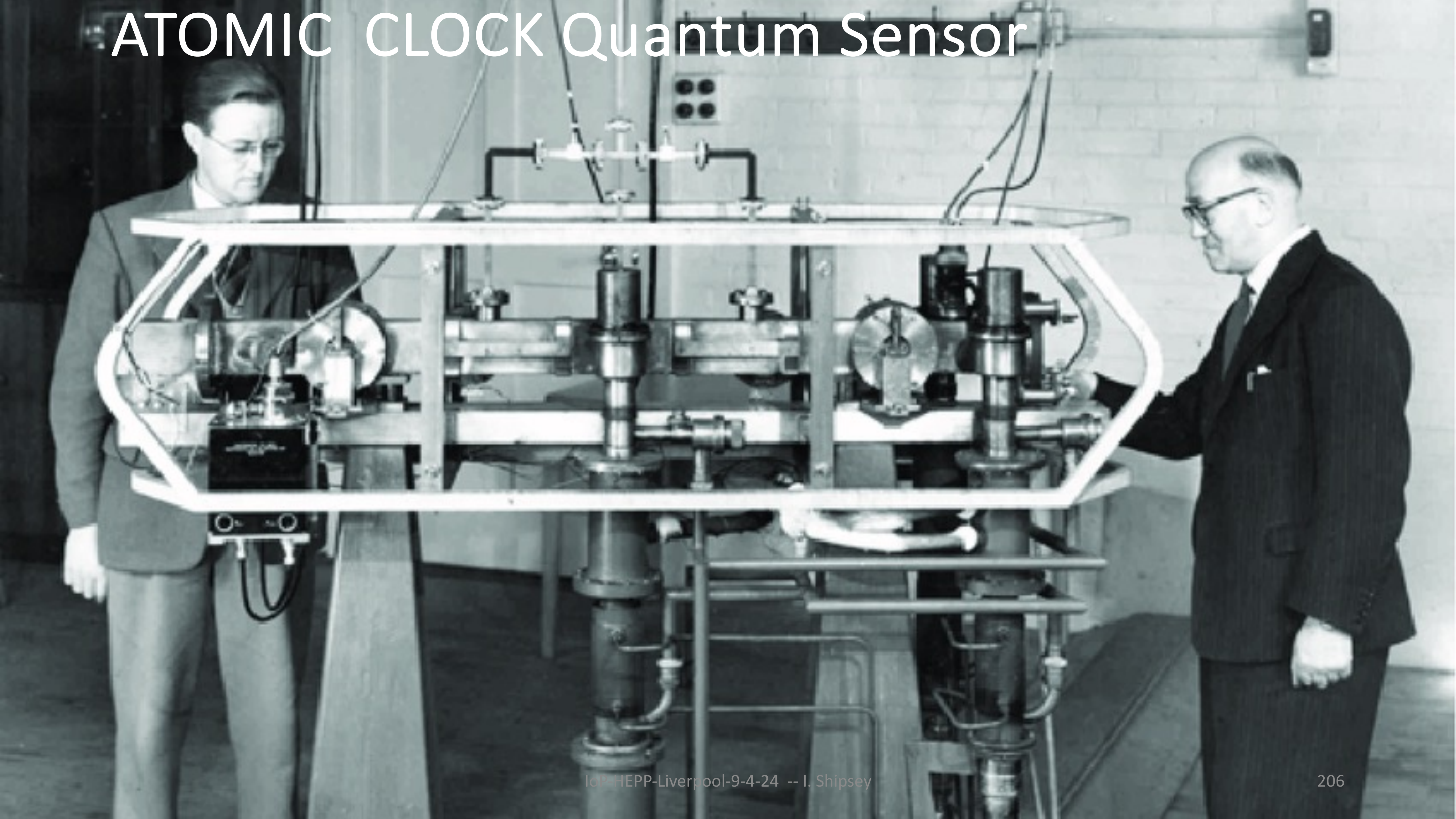
- Technology demonstration (2021-2025)
- Atomic tritium source development at Culham Centre for Fusion Energy – TRITON proposal for UKRI IF (2025-2028)
- Tritium run with O(0.1eV) sensitivity (2028-2031)
- Final neutrino mass experiment with 10-50 meV sensitivity at CCFE or similar facility (2030-2040)

CCFE
CULHAM CENTRE FOR FUSION ENERGY

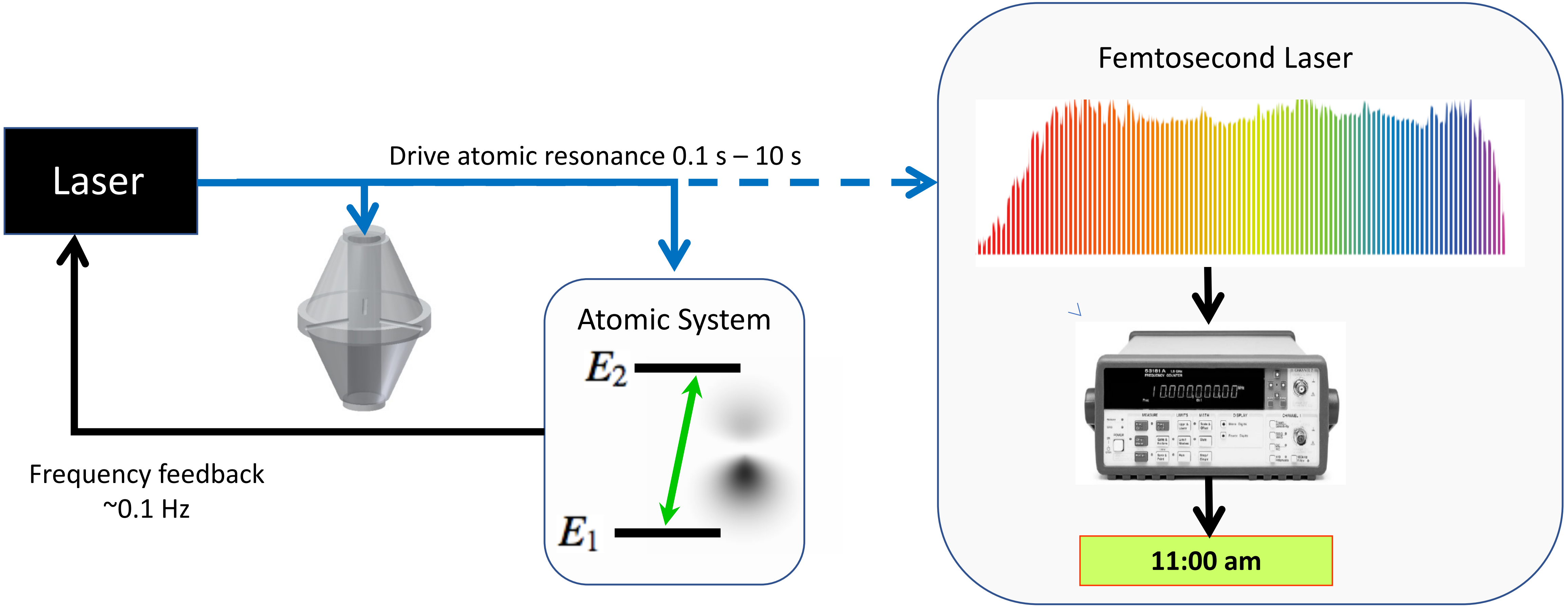




ATOMIC CLOCK Quantum Sensor



Principle of Optical Clocks



Clock frequency: $f_0 = \dfrac{E_2 - E_1}{h}$ ≈10^{15} Hz

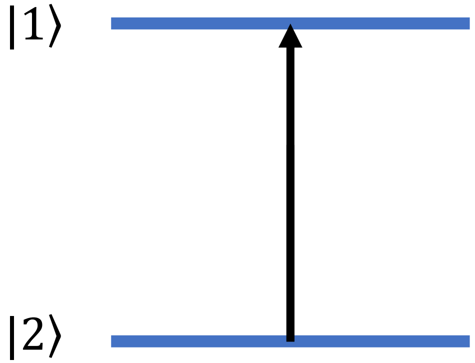
QSNET

A network of clocks for measuring the stability of fundamental constants

Giovanni Barontini

Birmingham NPL Sussex Imperial

Sensitive probes

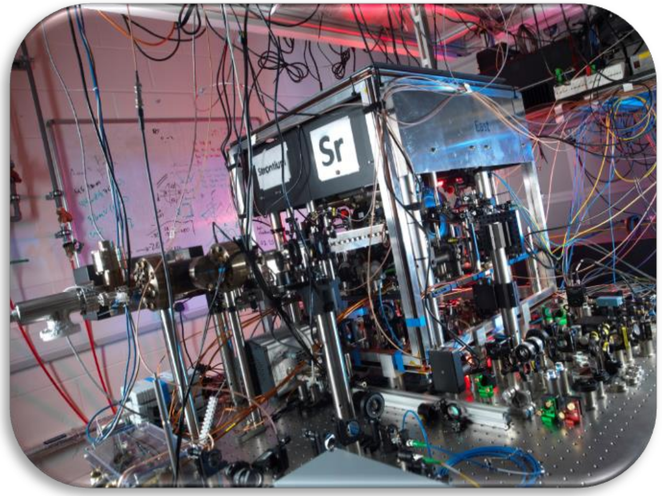


- All atomic and molecular energy spectra depend on the fundamental constants of the Standard Model
- Spectroscopy lends itself to measure variations of:

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

α

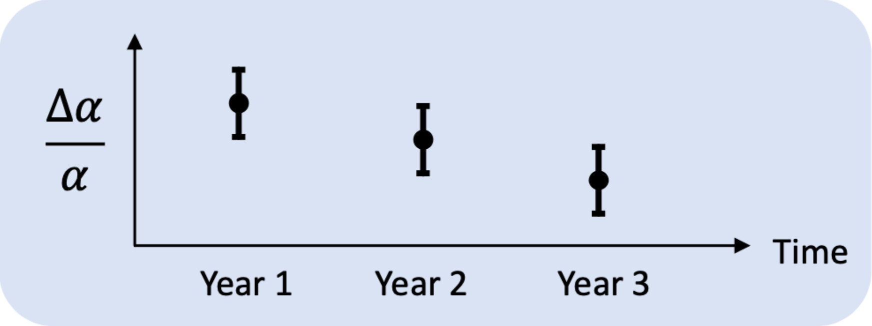
- Atomic an molecular spectra can be measured with extreme precision using atomic clocks



- Stability and accuracy at the 10^{-18} level

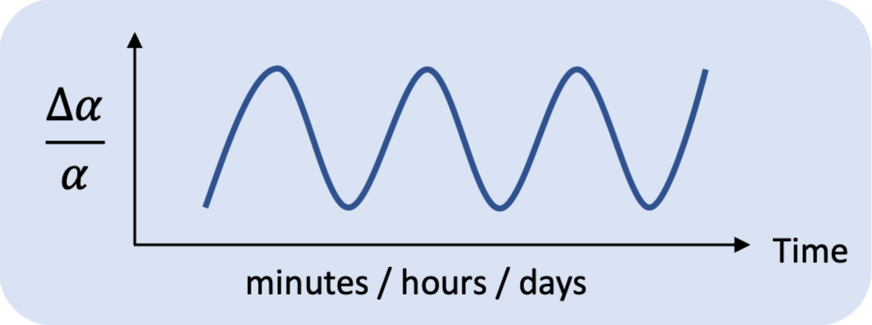
Look for variation on different timescales

- Slow drifts



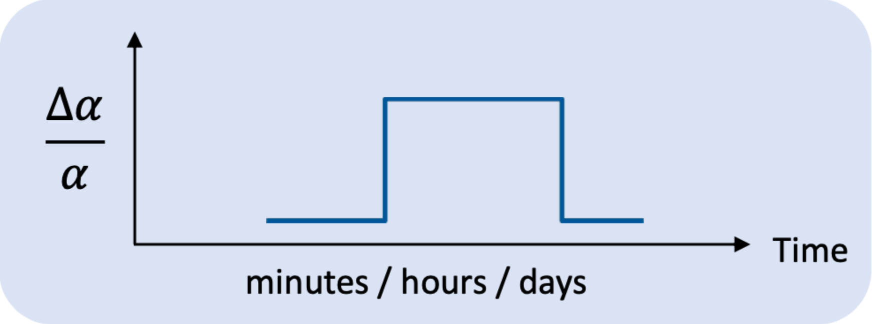
→ New physics

- Oscillations



→ Very light dark matter

- Fast transients



→ Dark matter - topological defects

The network approach

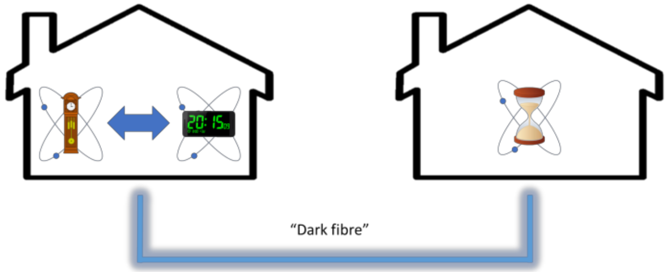
- Optimally exploit existing expertise. No single institution has the range of expertise required to run a sufficiently large and diverse set of clocks

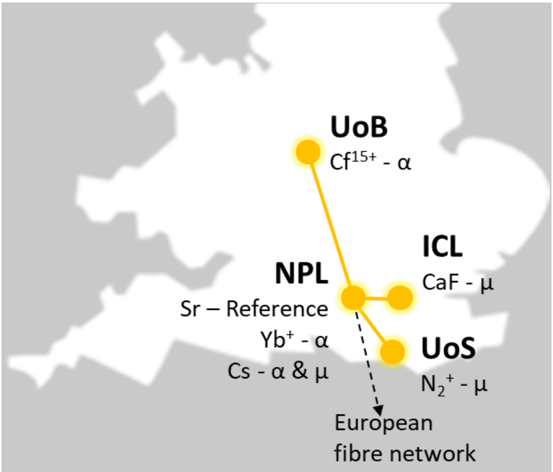
- Sensors with similar sensitivities and different systematics are necessary to confirm any measurements and reject false positives

- Networks enable probing of space-time correlations

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

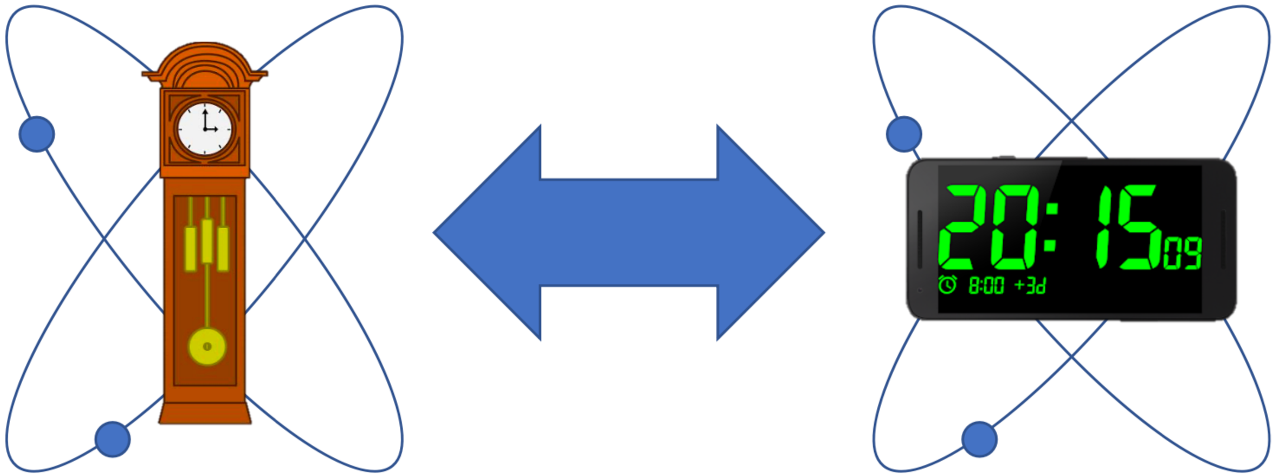
- A new versatile and expandable national infrastructure with possible further applications in and beyond fundamental physics.





How to measure variations of fundamental constants

- Different clock transitions have different sensitivities to fundamental constants



- Measure ratio f_1 / f_2
- Look for changes over time

$$\frac{\Delta f1}{\Delta f2} = |K_{1x} - K_{2x}| \frac{\Delta x}{x} \qquad x = \alpha, \mu$$

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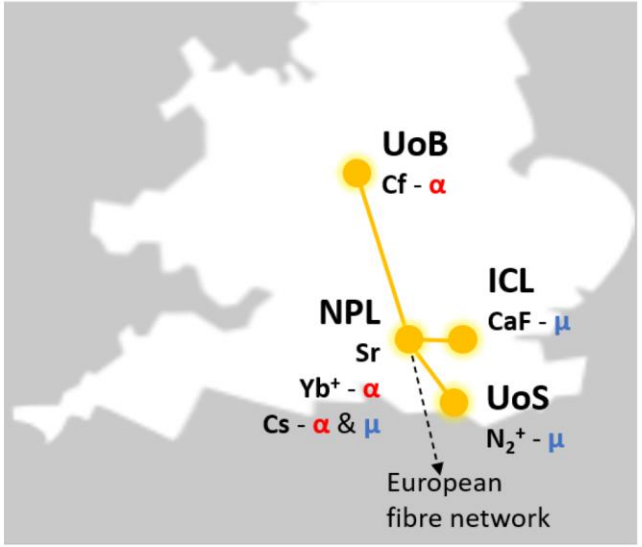
The QSNET project

- **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**

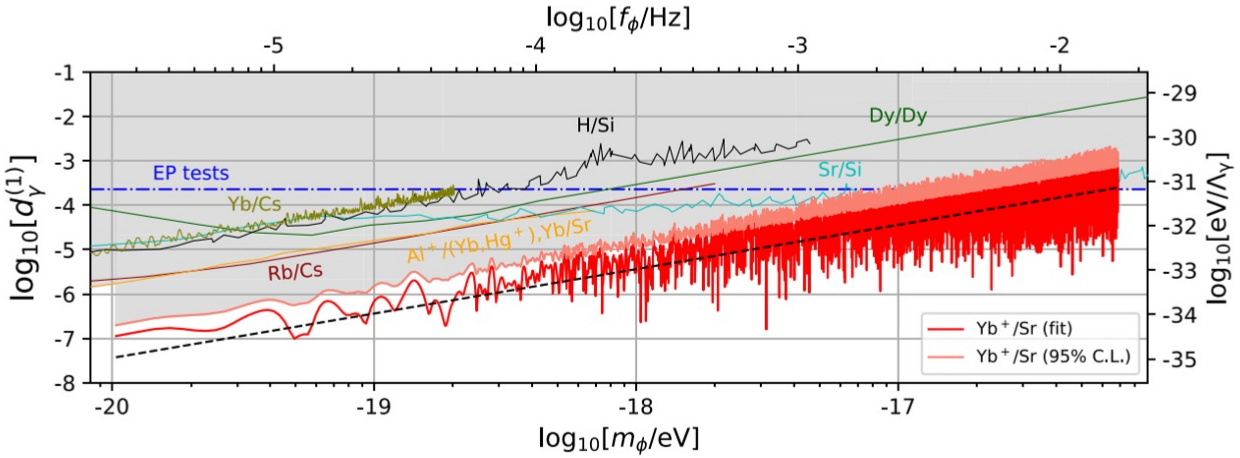


Clock	Kα	Kμ
Yb^{+} (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N_2^{+} (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

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

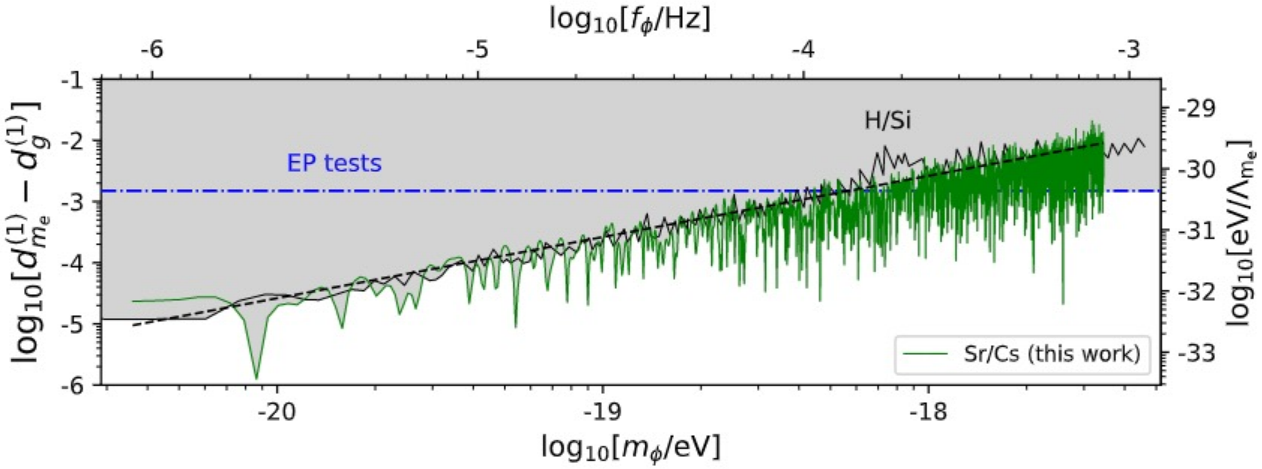
QSNET results (2023)

[World-leading results [New J. Phys. 25 (2023) 9, 093012] [arXiv:2302.04565]]

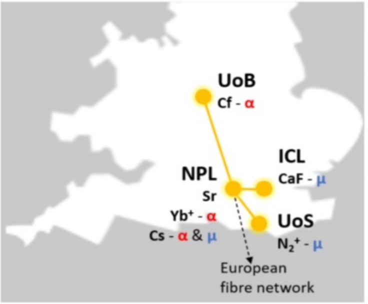


- Yb^+/Sr ratios have revealed that slow-drift variation in α is consistent with zero, with a fractional uncertainty of 1.9×10^{-18} per year.

- Frequency ratios between Yb^+, Sr and Cs have placed constraints on oscillations in α and μ beyond the previous state-of-the-art.



A network of clocks for measuring the stability of fundamental constants



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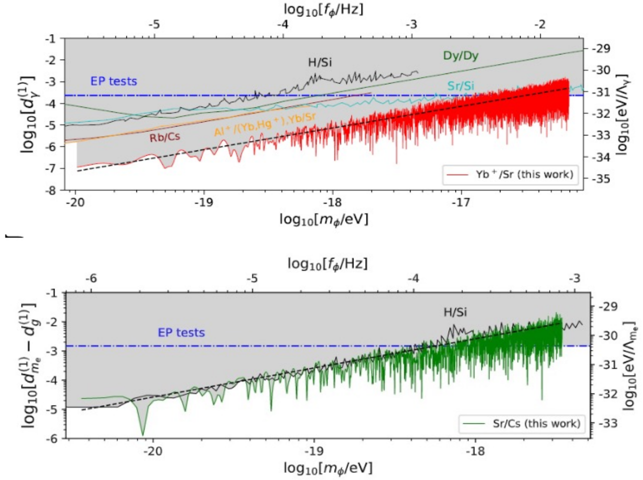
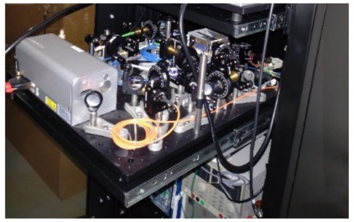
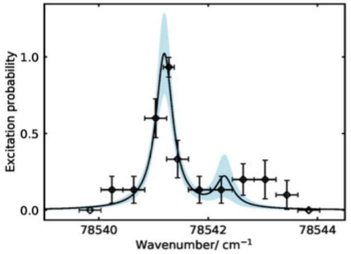
TRL

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

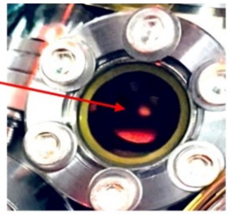
A unique network of clocks chosen for their different sensitivities to variations of **α** and **μ**

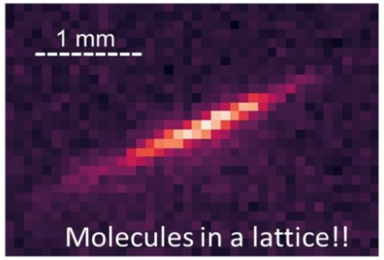


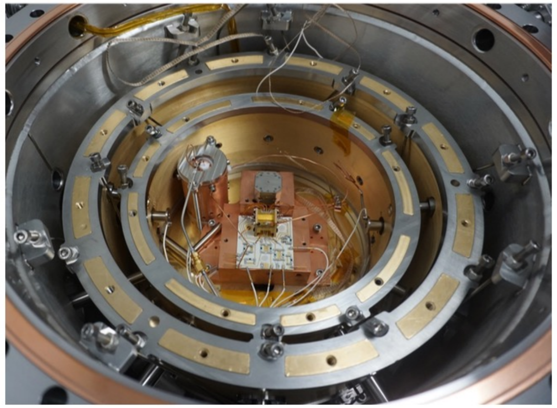




Ultracold CaF molecules







NPL clocks & Sussex theory
- World-leading results: new constraints on ultra-light dark matter
- Model independent analysis
- 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 a compact electron beam ion trap to produce highly charged ions
- Realised ultra-low vibration cryogenic vacuum systems

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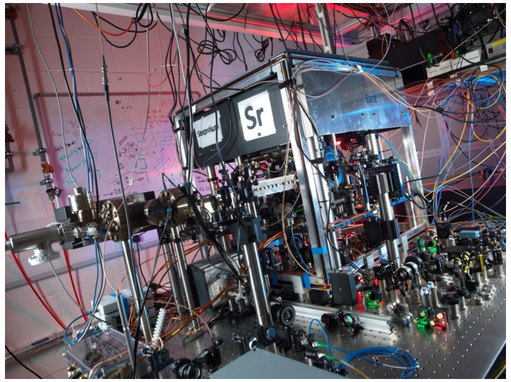
QSNET
Goals for Phase 1

1. New constraints on $\Delta\mu/\mu$ on timescales from 10-1000 s, targeting 4×10^{-15} at 1000 s
2. Measure $\Delta\alpha/\alpha$ on fast timescales targeting 1×10^{-17} at 1000 s, exceeding current state of-the-art sensitivity
3. Realization of a Cf^{15+} and Cf^{17+} cEBIT
4. Measure the N_2^+ clock transition
5. Quantify the impact of the new limits on unified models and dark matter models
6. Load CaF molecules in optical lattices and identify the clock transition
7. Using available data, provide first tests of model-independent parametrization for variations of fundamental constants and theoretical bounds on dark matter masses.

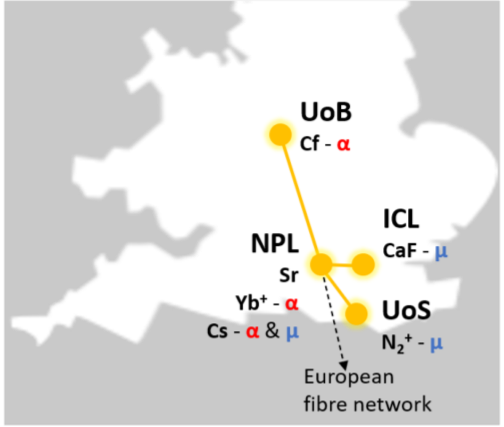
Economic Impact of QSNET

- QSNET is accelerating the economic impact of atomic clocks in two key ways:

1. QSNET is developing a range of clocks with different TRLs
   - We are pushing the performance of **atomic clocks** beyond the state-of-the-art
   - We are pioneering the development of **highly charged ion clocks**, that will allow us to realise clocks in the UV and XUV frequency range
   - We are leading the development of **molecular clocks**, that will provide us with ultra-precise references in the THz range



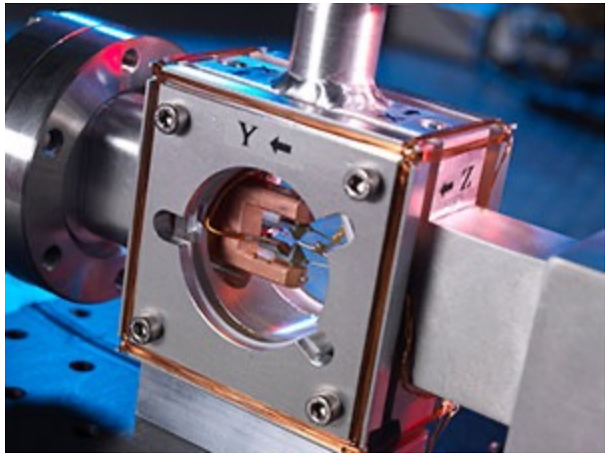
2. QSNET is developing an **optical fibre network** linking the different clocks
   - A high-resolution frequency comparison between QSNET nodes will mark a crucial **technological milestone** for the UK
   - This **infrastructure** will enable interaction between different quantum technologies including quantum communications and remote quantum computing



Applications of clocks and clock networks

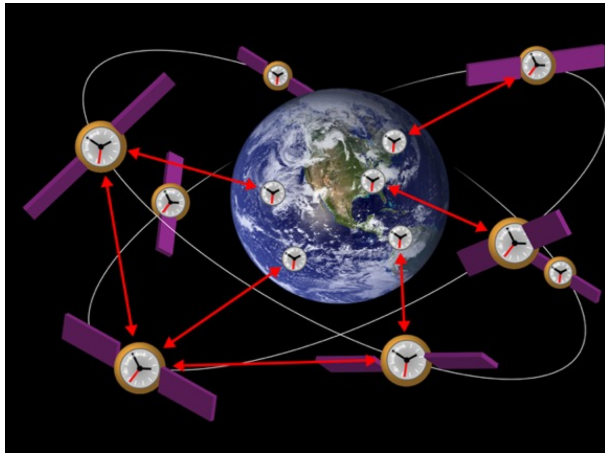
Applications of **ultra-precise clocks** include:

- Global navigation satellite systems (GNSS)
- Telecommunications (including mobile phones, internet)
- Energy networks and financial trading
- Security and defence transactions.
- Geodesy, inertial navigation
- Define the SI unit of time, the second

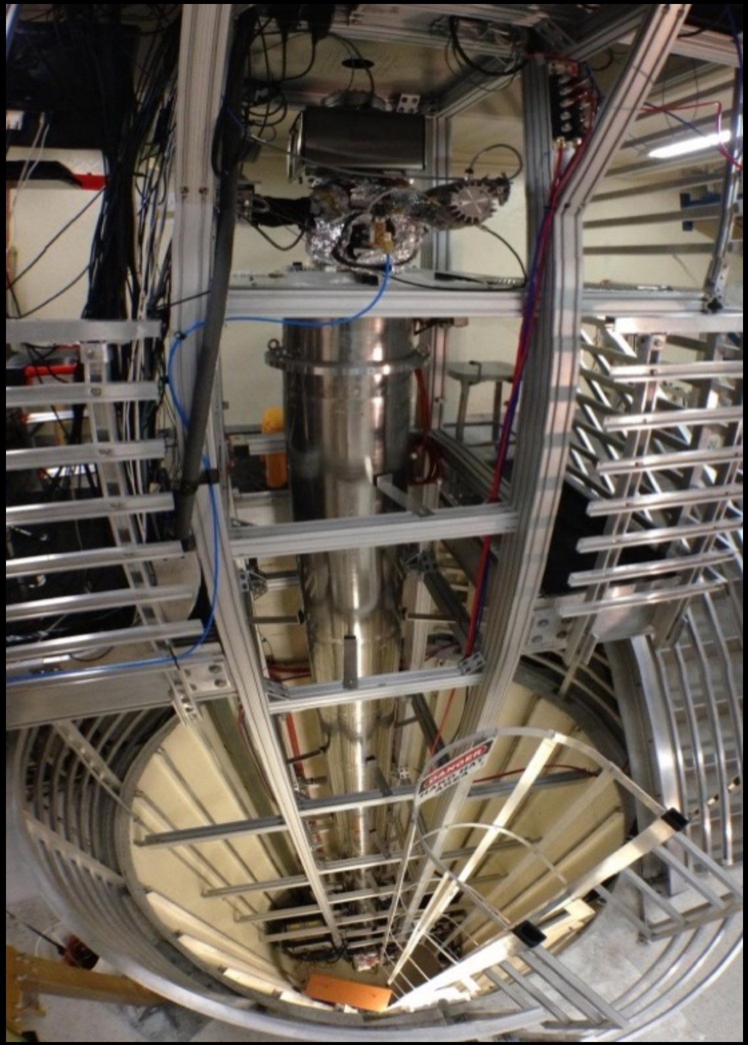


Applications of **networks of clocks** include:

- geodetic measurements (e.g. time-varying gravity potentials)
- seismic effects
- environment monitoring
- synchronisation and timing signals for radio astronomy
- radar technology



Atom Interferometry

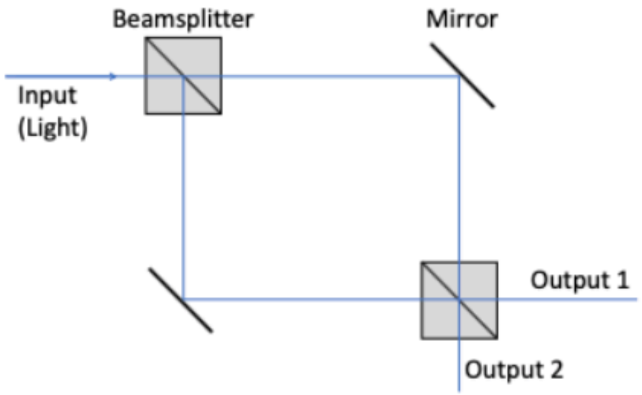


Gravitational Waves: Cosmology and Astrophysics

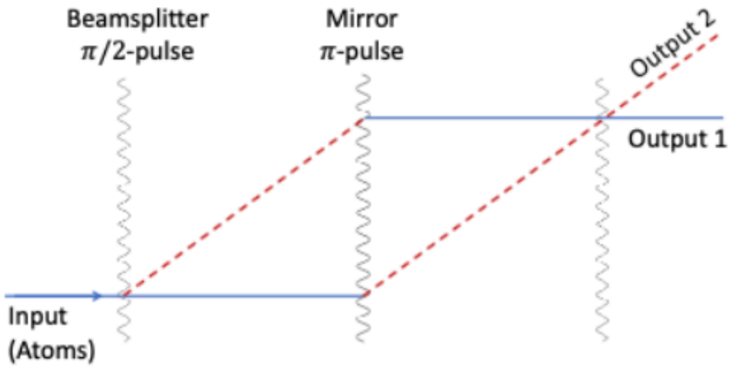
Slide Credit: Grojean

Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

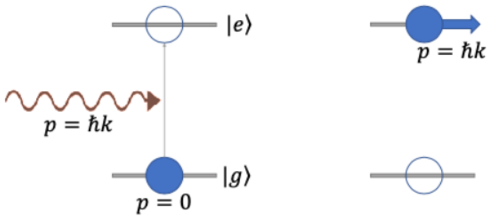


Atom Interferometer

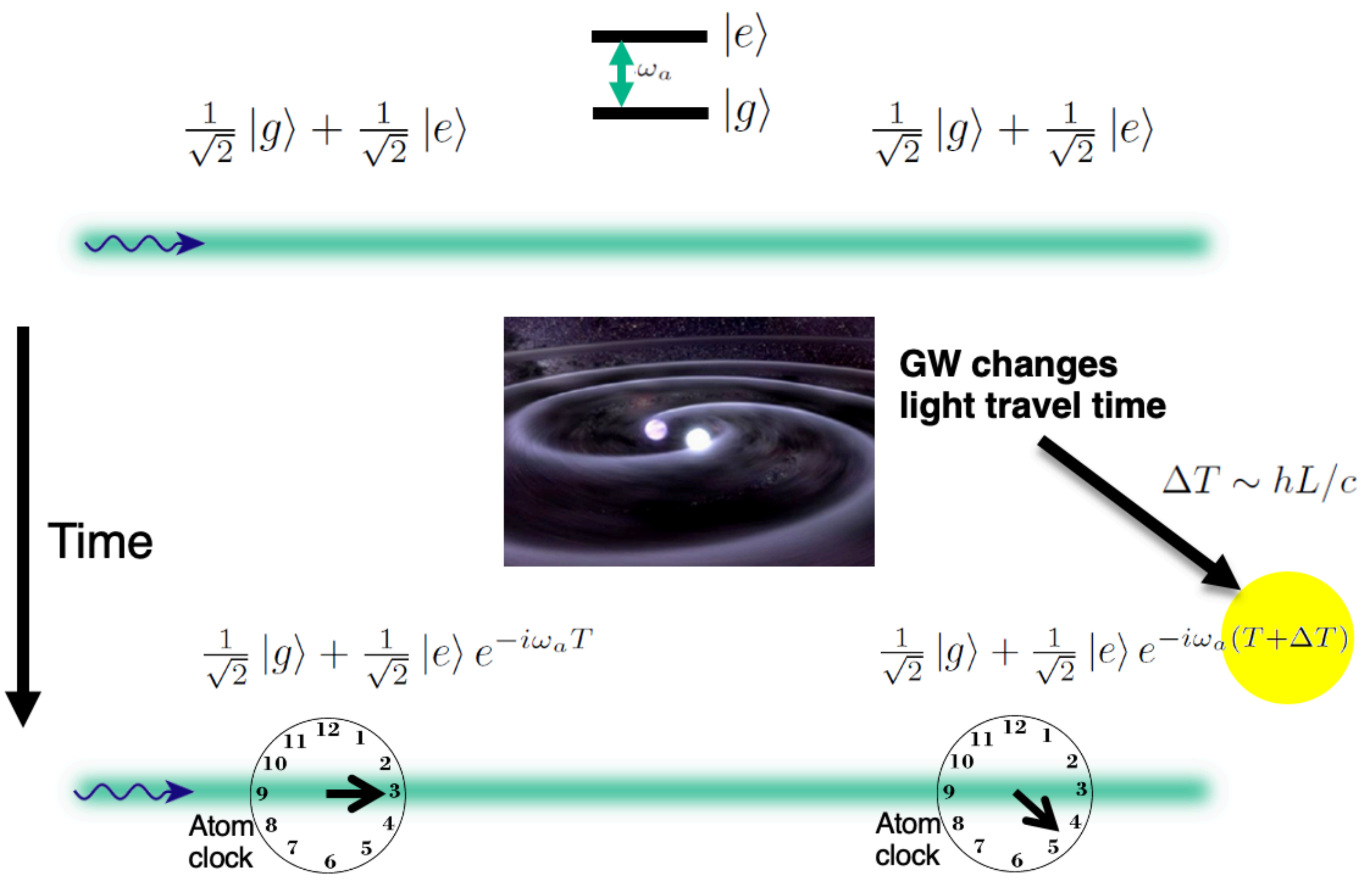


Laser excitation gives momentum kick to excited atom, which follows separated space-time path

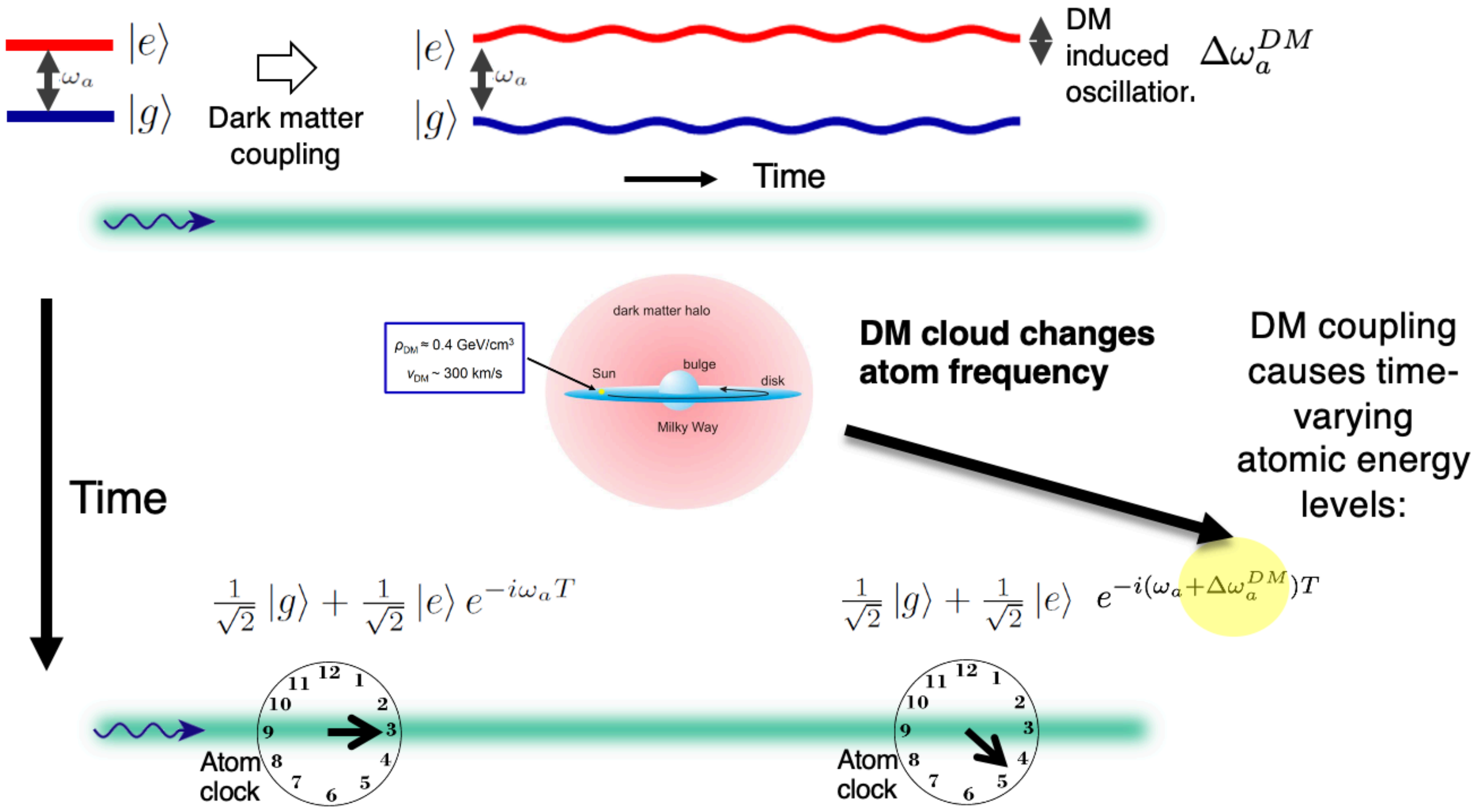
Interference between atoms following different paths



Effect of Gravitational Wave on Atom Interferometer



Effect of Dark Matter on Atom Interferometer

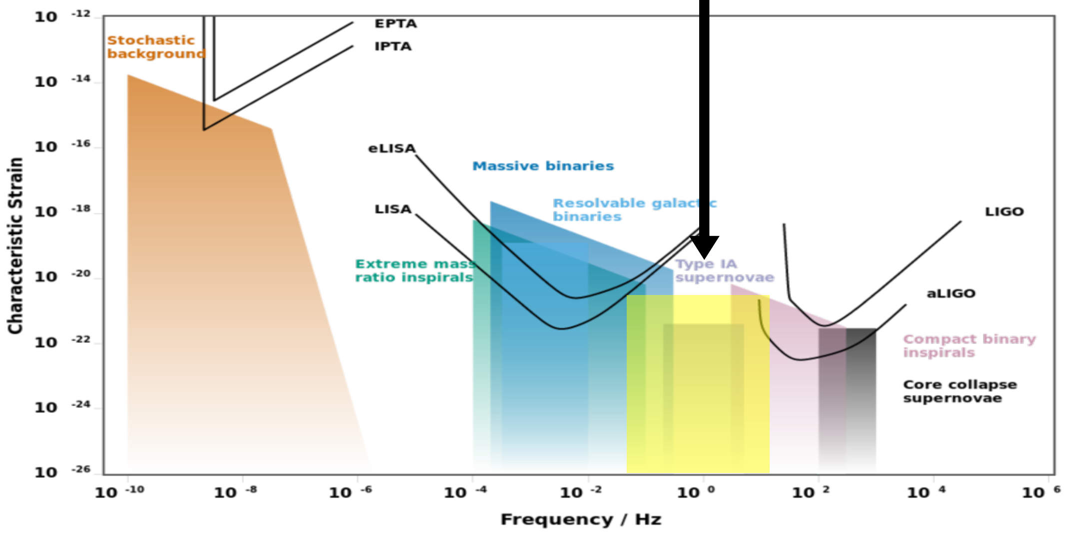


Long baseline atom interferometry science

Mid-band: 0.03 Hz to 3 Hz

Mid-band gravitational wave detection

- LIGO sources before they reach LIGO band
- Multi-messenger astronomy: optimal band for sky localization
- Cosmological sources

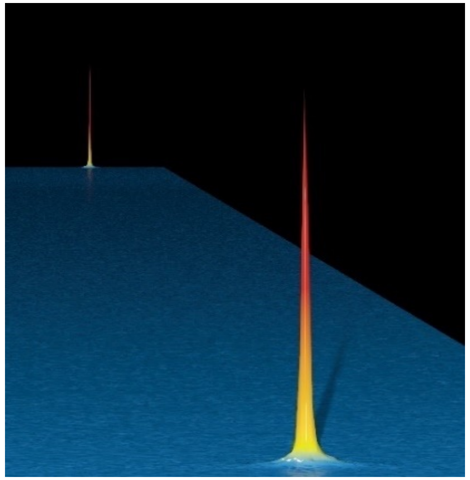


Ultralight wave-like dark matter probe

- Mass $<10^{-14}$ eV (Compton frequency in ~Hz range)
- Scalar- and vector-coupled DM candidates
- Time-varying energy shifts, EP-violating new forces, spin-coupled effects

Tests of quantum mechanics at macroscopic scales

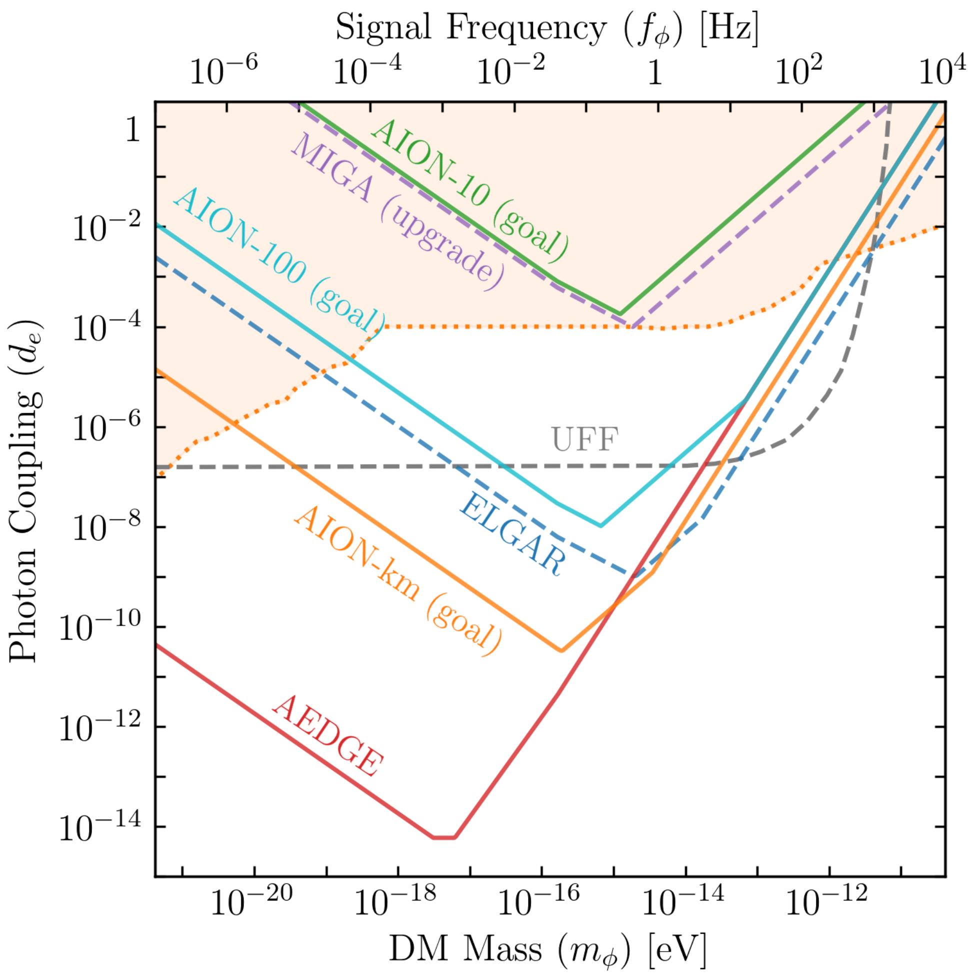
- Meter-scale wavepacket separation, duration of seconds
- Decoherence, spontaneous localization, non-linear QM, …

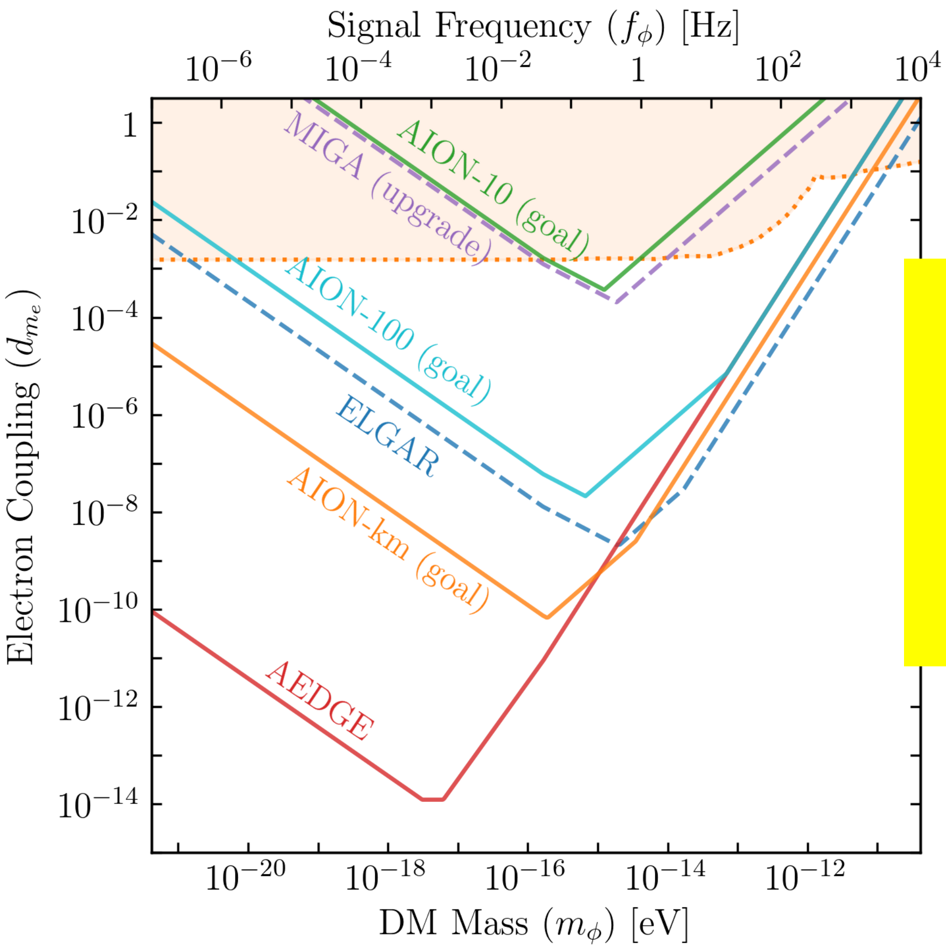


Rb wavepackets separated by 54 cm

Slide credit: Jason Hogan

Search for Ultra-Light Dark Matter





Orders of magnitude improvement over current sensitivity

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755; Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

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.
- ❑ **Stage 2:** to build, commission and exploit the 100 m detector and carry out a design study for the km-scale detector.
  - ➢ 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).

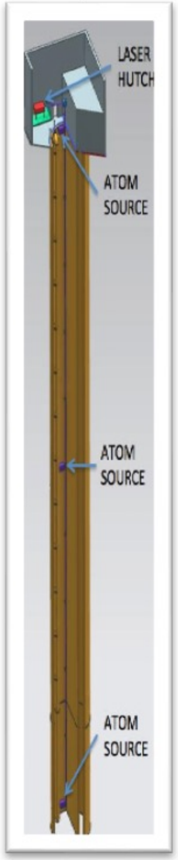
- ❑ **Stage 3:** to build a kilometre-scale terrestrial detector.
- ❑ **Stage 4**: long-term objective a pair of satellite detectors (thousands of kilometres scale) [AEDGE proposal to ESA Voyage2050 call]
  - ➢ AION has established science leadership in AEDGE, bringing together collaborators from European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

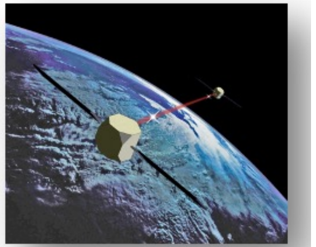
Stage 3 and 4 will likely require funding on international level (ESA, EU, etc) and AION has already started to build the foundation for it.

L ~ 10m

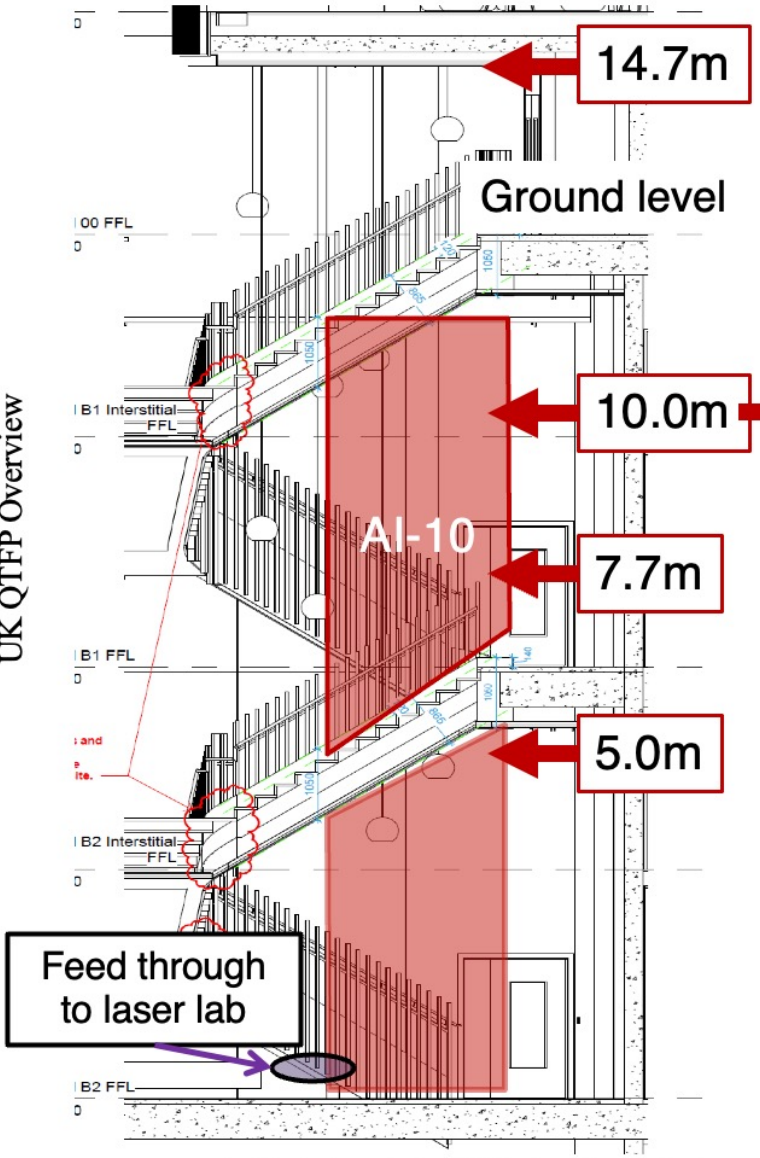
L ~ 100m

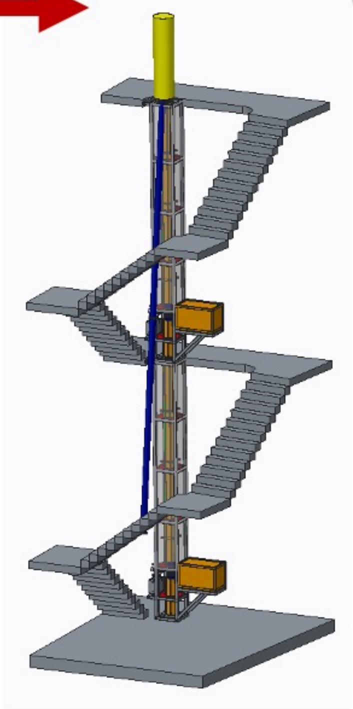
L ~ 1km





AION Project in the UK





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**

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

L. Badurina et al., *AION: An Atom Interferometer Observatory and Network*, *JCAP* **05** (2020) 011, [arXiv:1911.11755]

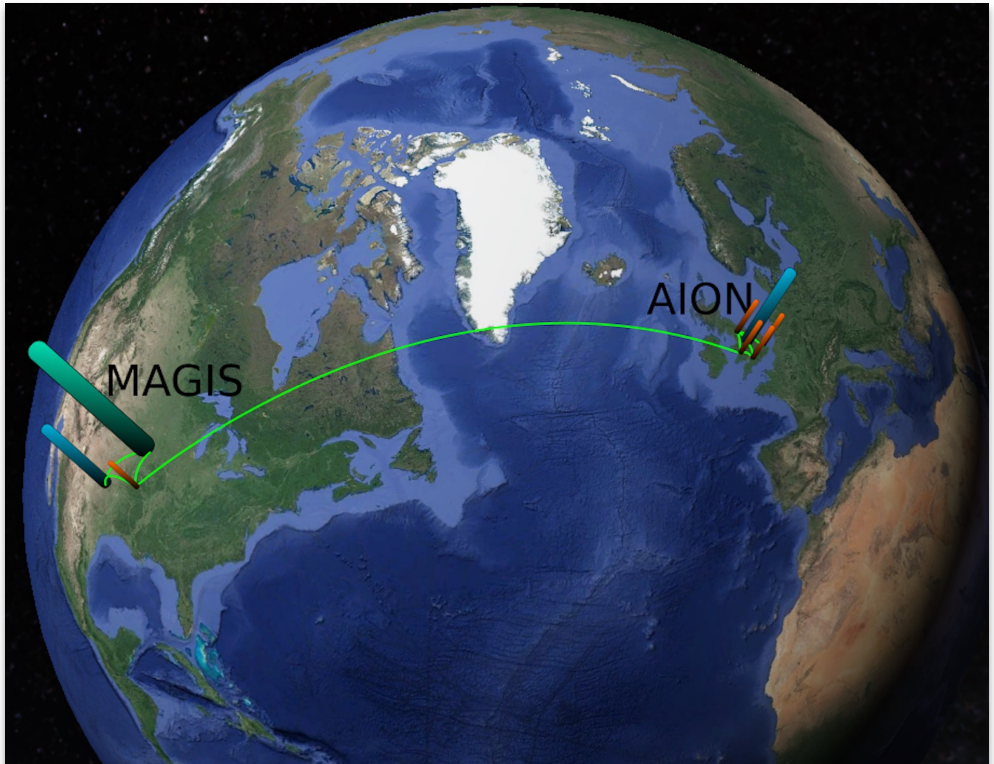
Ongoing Atom Interferometry Projects in US & UK

AION Collaboration arXiv:1911.11755

MAGIS-100

MAGIS Collaboration : arXiv:2104.02835

STANFORD · JOHNS HOPKINS UNIVERSITY · Northwestern University · Fermilab · SLAC · THE UNIVERSITY OF CHICAGO · UNIVERSITY OF CAMBRIDGE · Northern Illinois University · UNIVERSITY OF OXFORD · UNIVERSITY OF LIVERPOOL



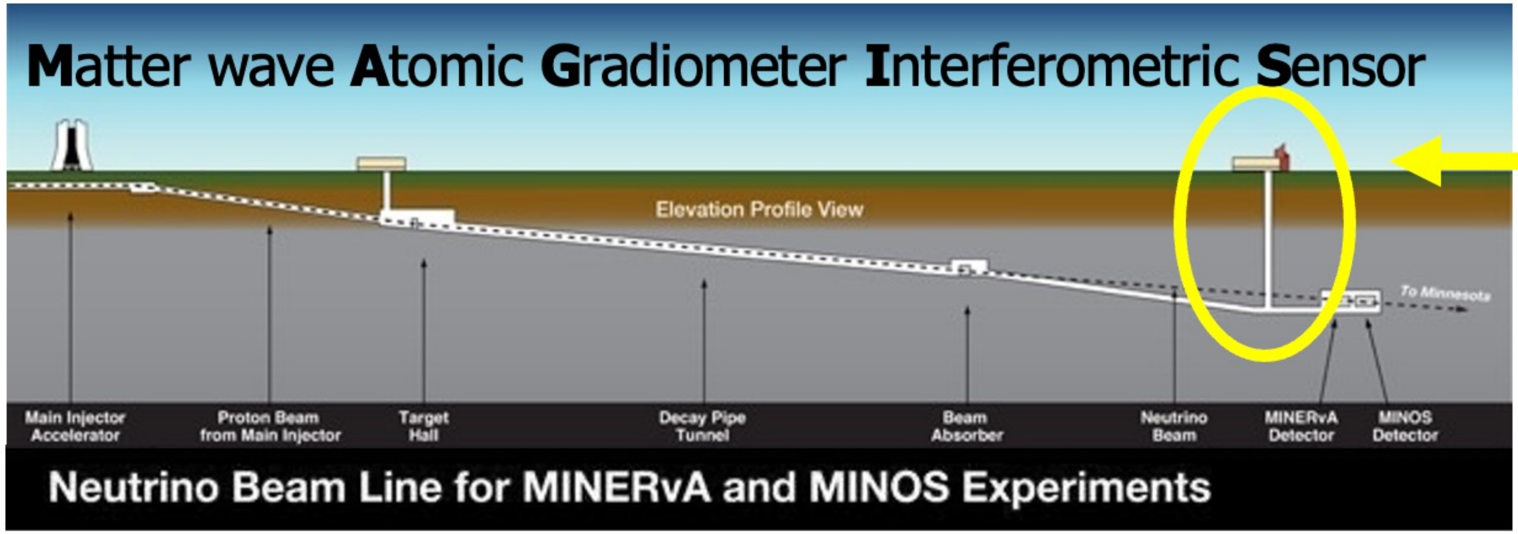
AION (UK) and MAGIS (US) work in equal partnership to form a “LIGO/Virgo-style” network & collaboration, providing a pathway for international leadership in this exciting new field.

MAGIS-100 ICRADA Ceremony at Fermilab on Nov 16, 2023

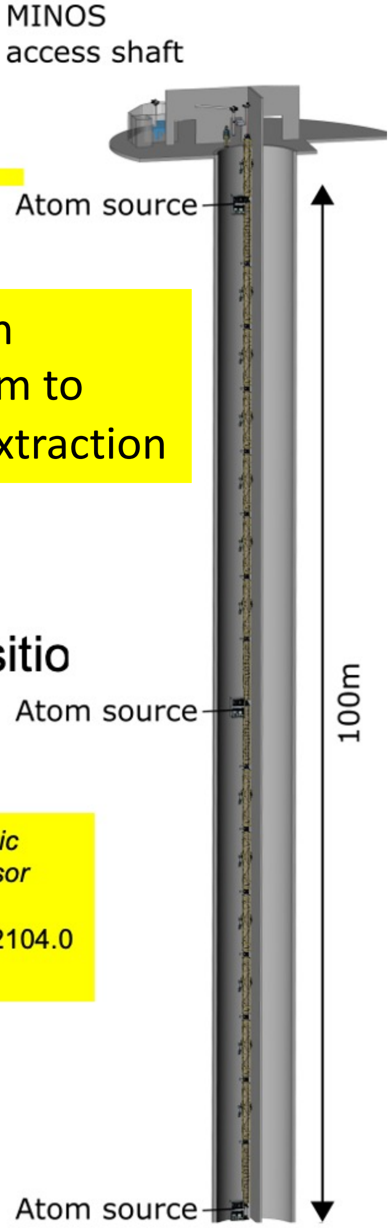
Formalising the long-standing UK-US partnership between MAGIS and AION, in conjunction with the participating UK institutions.

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 opportunities.

MAGIS-100 at Fermilab



UK Contribution detection system to enable phase extraction



- 100-meter baseline atom interferometry in MINOS shaft at Fermilab
- Gravitational wave detector pathfinder, ultralight dark matter search, extreme quantum superpositio states (> metre wavepacket separation)
- Design and construction underway; commissioning early 2025
- ~ $15M scope (Gordon and Betty Moore Foundation + DOE funding)
- 2024: commitment of ~ $20M from DOE to finalise construction of 100m
- Collaboration of 9 institutions, > 50 people

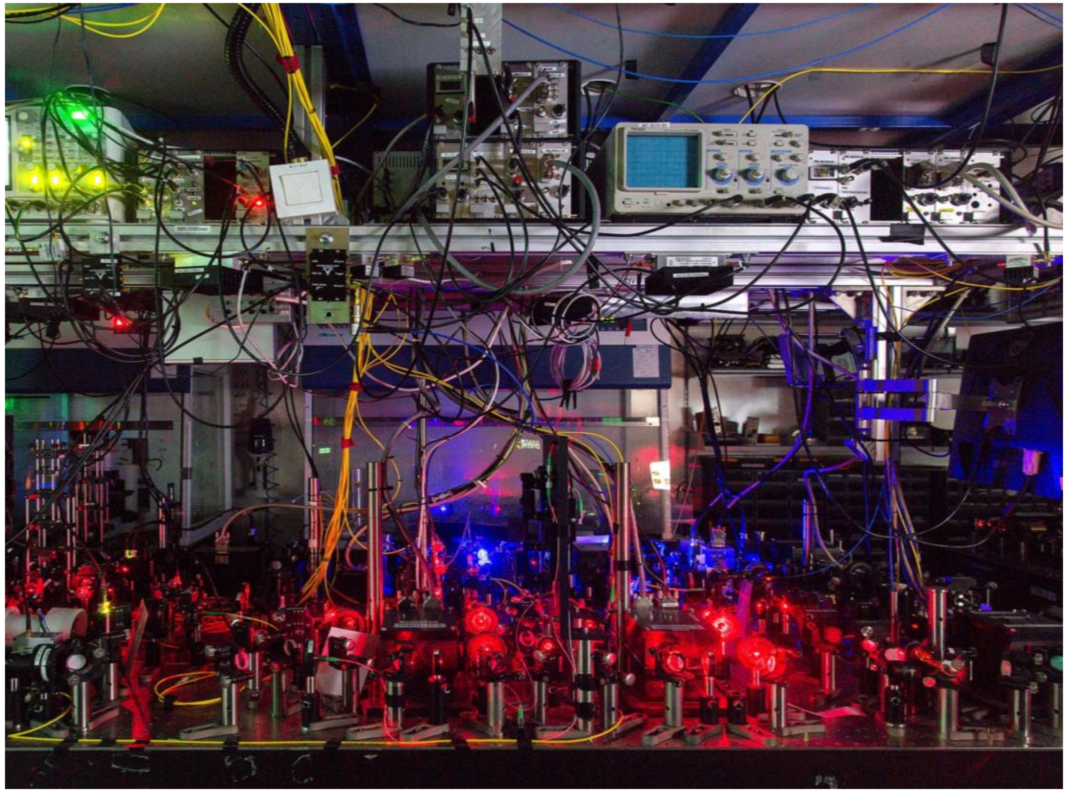
M. Abe et al., *Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)*, *Quantum Sci. Technol.* 6 (2021) 4, 044003, [arXiv:2104.0 2835].

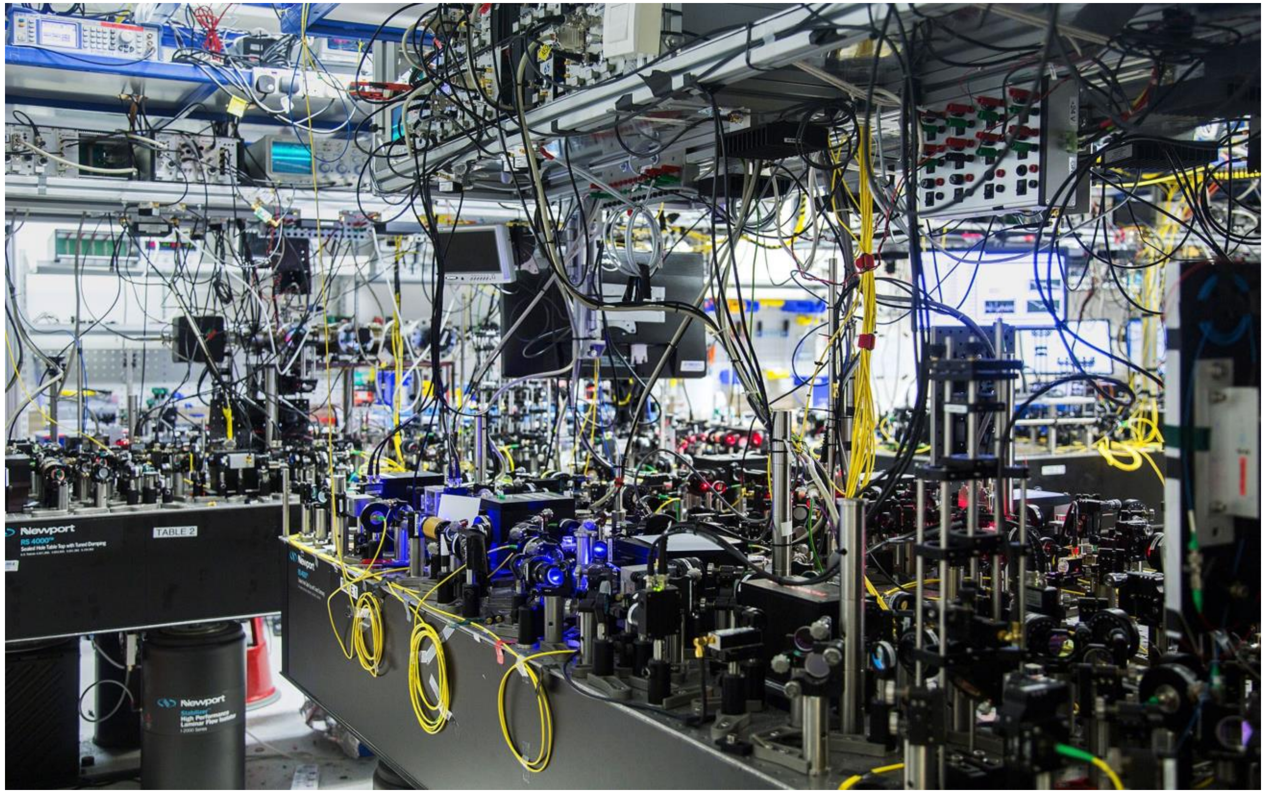
Stanford, Johns Hopkins University, Northwestern University, Fermilab, SLAC, MAGIS-100, University of Cambridge, Old Dominion University, University of Oxford, University of Liverpool

AION Collaboration Days in Oxford: Fall 2021

Ratio of Cold Atom : Particle/Fundamental Physics people is 1:1

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

AION: Ultra-Cold Strontium Laboratories in UK

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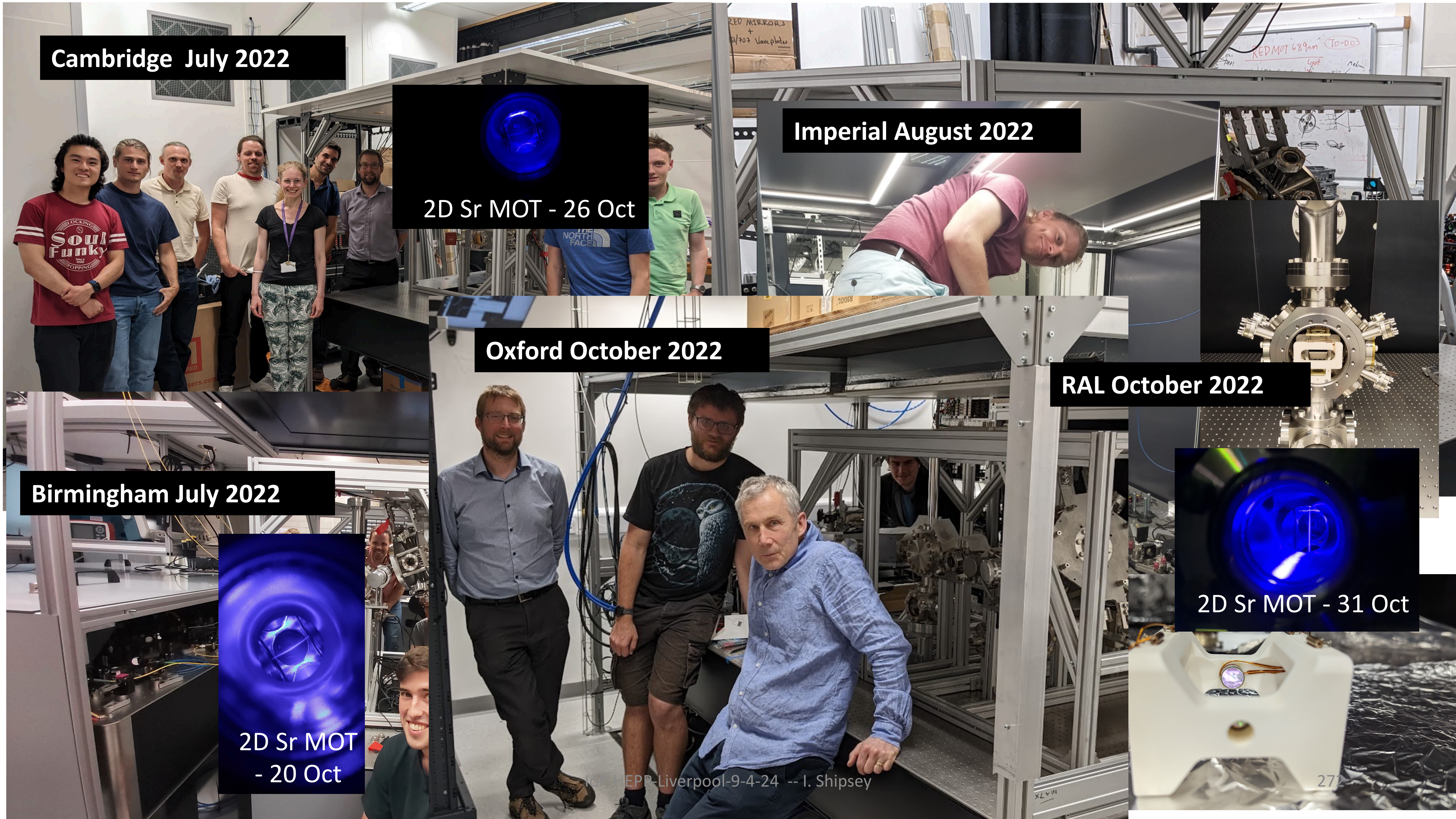
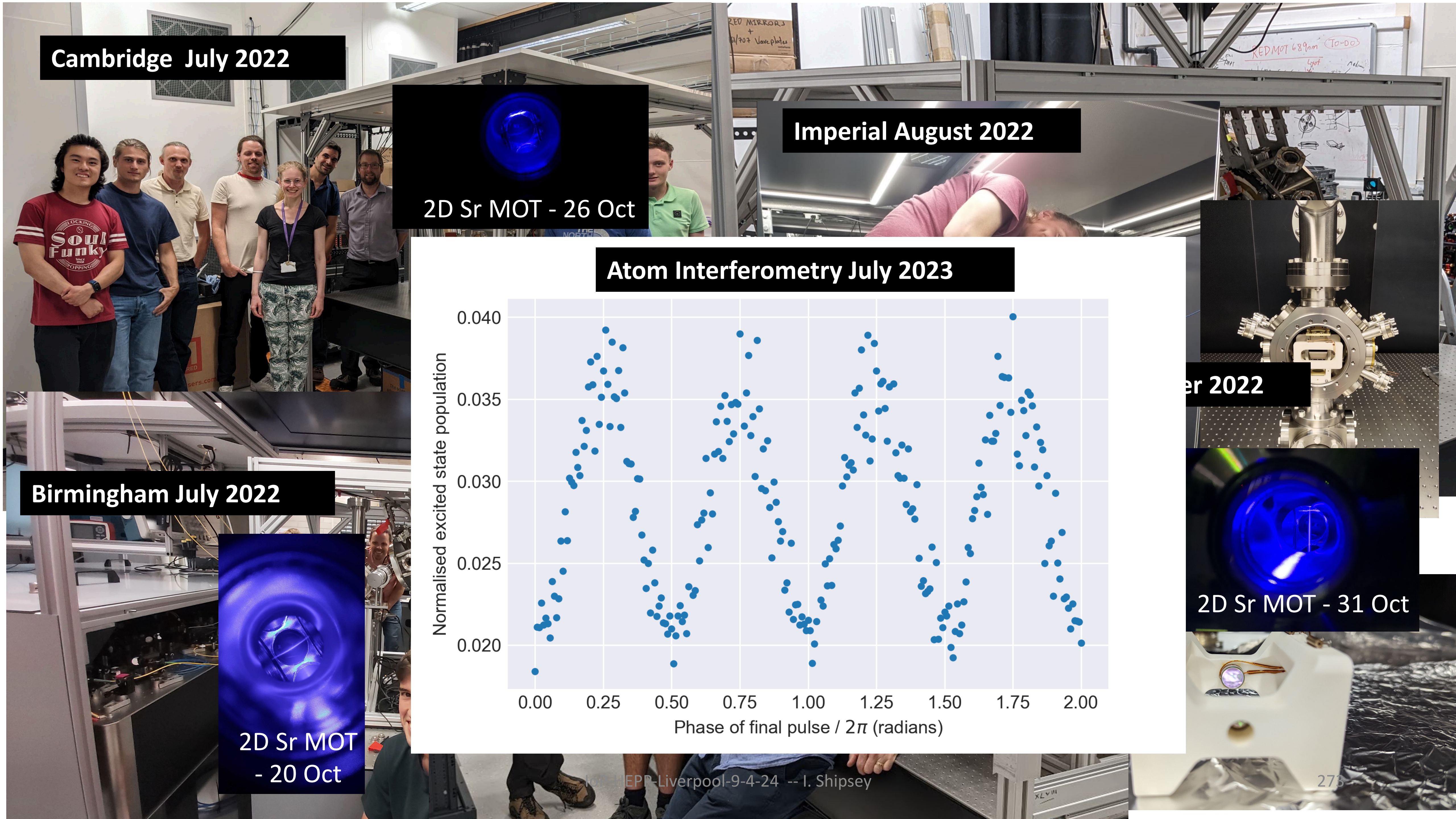
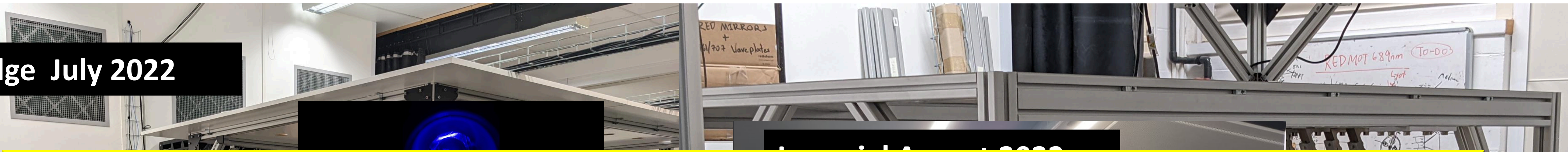

Cambridge July 2022
2D Sr MOT - 26 Oct
Imperial August 2022
Oxford October 2022
RAL October 2022
Birmingham July 2022
2D Sr MOT - 20 Oct
2D Sr MOT - 31 Oct

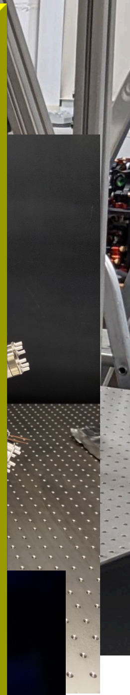

Cambridge July 2022
2D Sr MOT - 26 Oct
Imperial August 2022
Atom Interferometry July 2023
0.040
0.035
0.030
0.025
0.020
Normalised excited state population
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Phase of final pulse / 2π (radians)
er 2022
2D Sr MOT - 31 Oct
Birmingham July 2022
2D Sr MOT
- 20 Oct

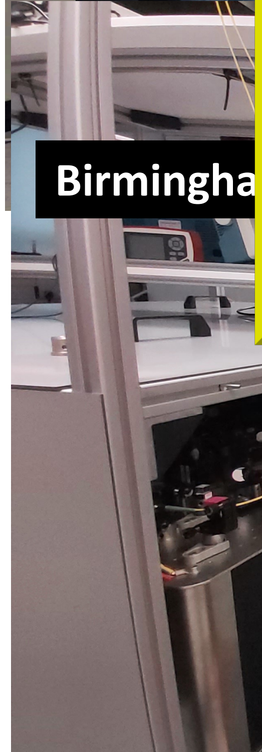


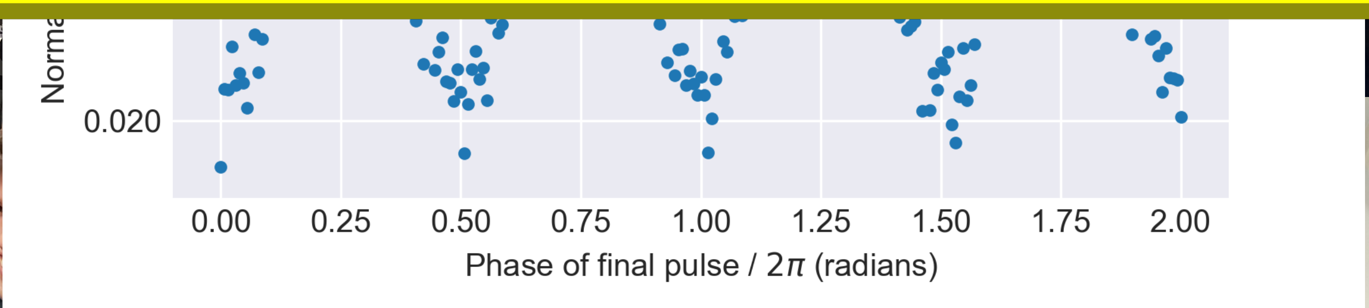
5 Ultra Cold Sr Labs built in less than 18 months using large scale Particle Physics production methods to significantly accelerate the turnaround – this will be critical for future success!

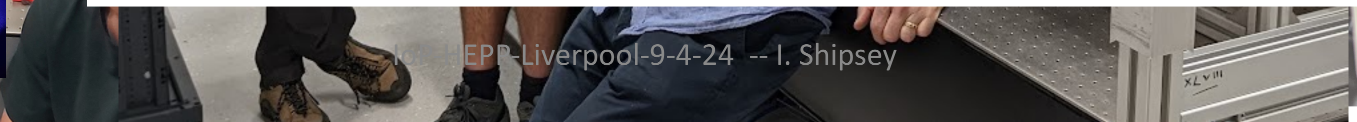
https://arxiv.org/abs/2305.20060

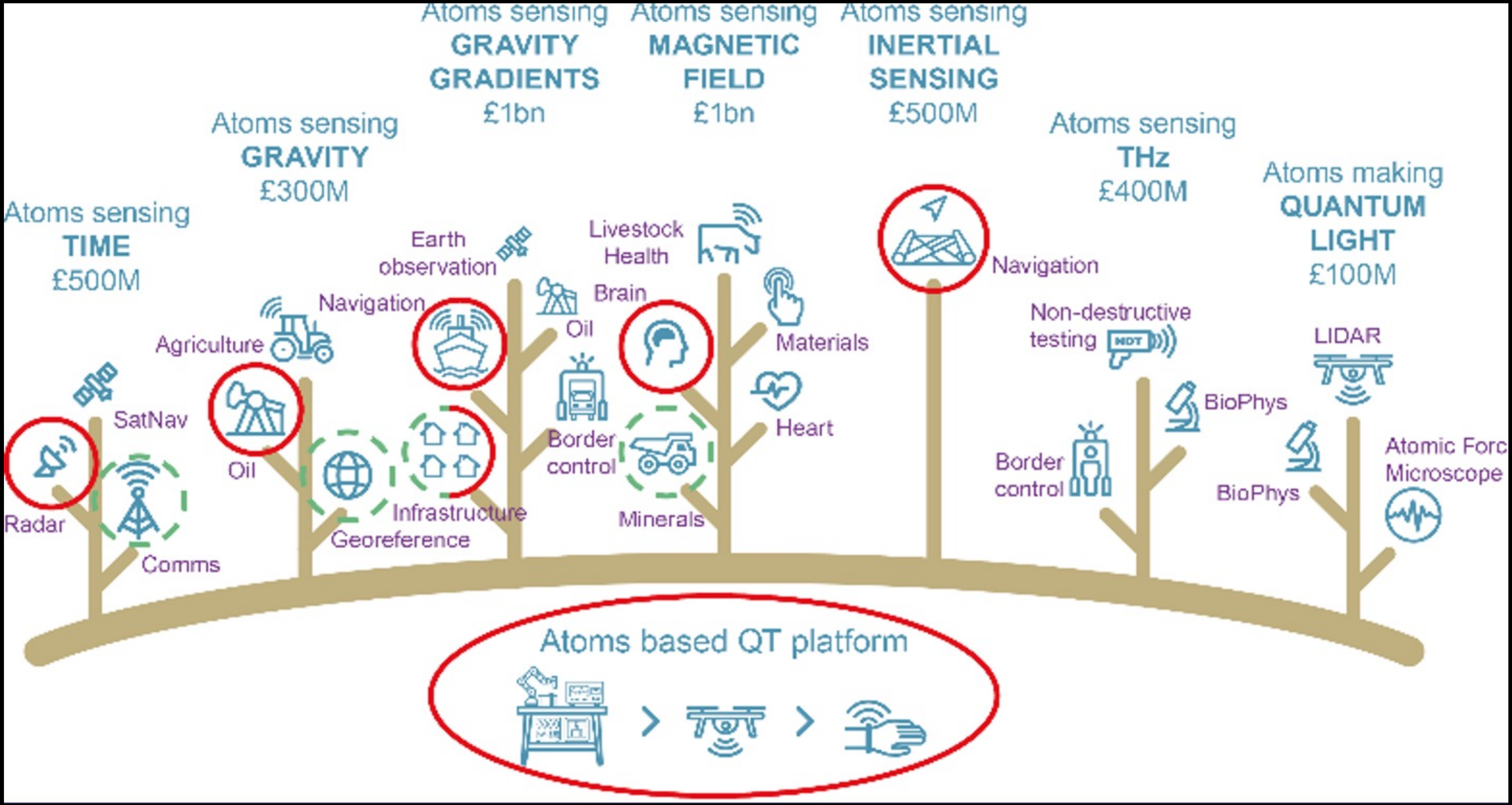
Discussing with established UK companies Torr Scientific and Kurt J. Lesker potential for spin-off.











Atoms sensing
GRAVITY GRADIENTS
£1bn
Atoms sensing
MAGNETIC FIELD
£1bn
Atoms sensing
INERTIAL SENSING
£500M
Atoms sensing
GRAVITY
£300M
Atoms sensing
THz
£400M
Atoms making
QUANTUM LIGHT
£100M
Atoms sensing
TIME
£500M
Earth observation
Livestock Health
Navigation
Brain
Navigation
Oil
Agriculture
Materials
Non-destructive testing
LIDAR
SatNav
Heart
BioPhys
Oil
Border control
Border control
Atomic Forc
Microscope
Radar
Infrastructure
Minerals
BioPhys
Georeference
Comms
Atoms based QT platform

QSimFP | Quantum Simulators for Fundamental Physics

Scientific Goals

Quantum Simulations of Black Hole and Early Universe Processes

Community

50-50 QT-FP researchers

27 QTFP funded (48 Partners)

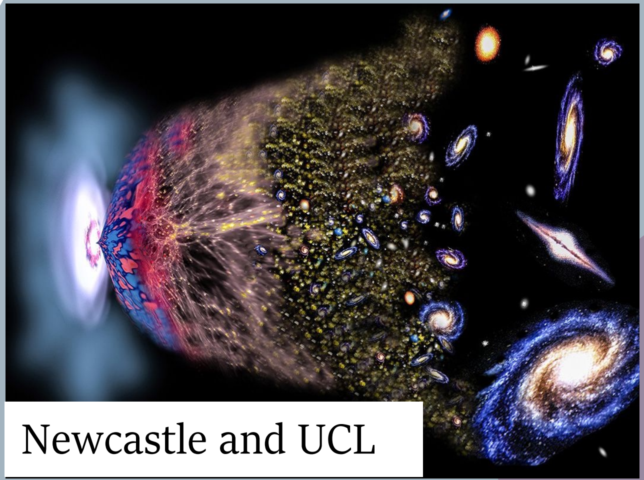
Governance

Silke Weinfurtner (PI, Nottingham)

Zoran Hadzibabic (Cambridge)

Ruth Gregory (KCL)

Vision

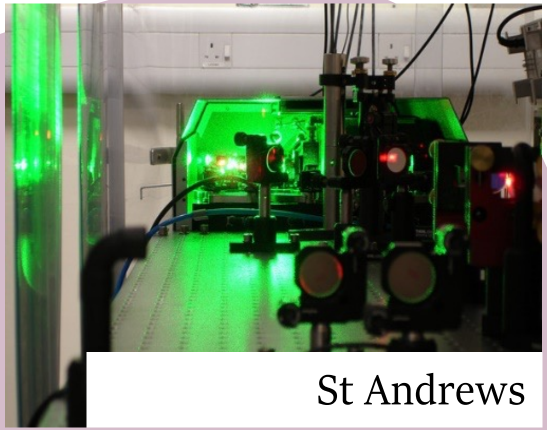

Newcastle and UCL

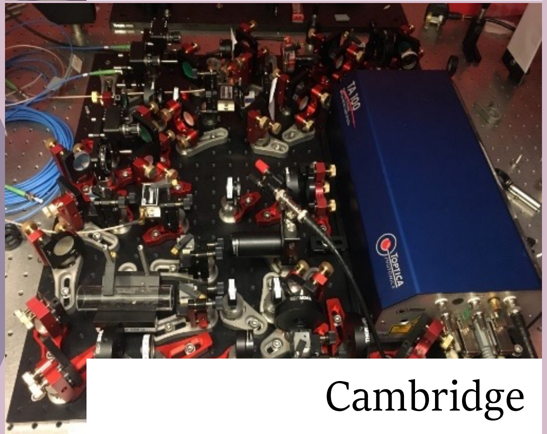

KCL

QSimFP

Quantum Vacuum:
- False Vacuum Decay

Quantum Black Hole:
- Black hole ring-down

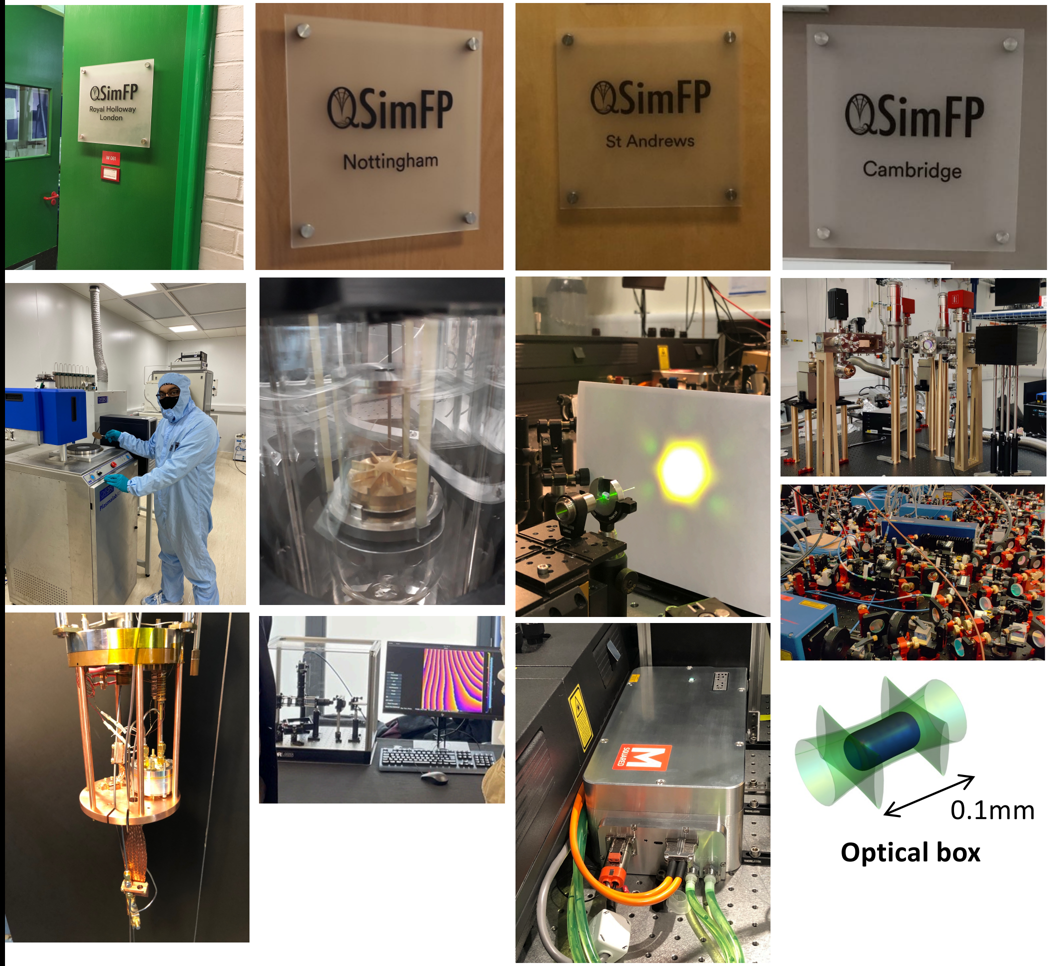

St Andrews


Cambridge


Nottingham and RHUL

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

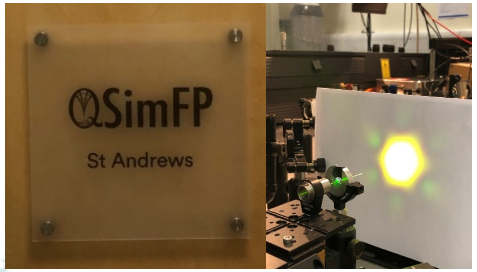
QSimFP



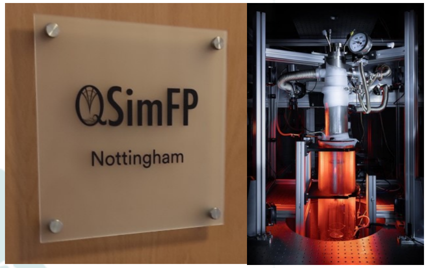
Experimental setups constructed and now benchmarked:

- Ultra-cold atoms system (Cambridge)
- Quantum optics (St. Andrews)
- Superfluid opto-mechanics (Nottingham)
- Superfluid nanofabrication (Royal Holloway London)
- Patent application Oct 2022:
  - Off-axis holography technique to detect fluid interfaces at room and ultra-low temperatures

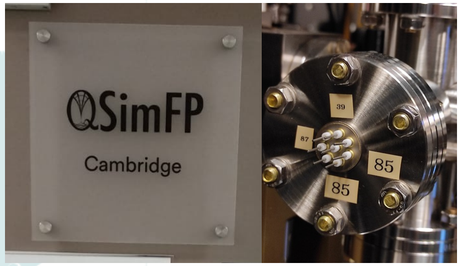
Facilities



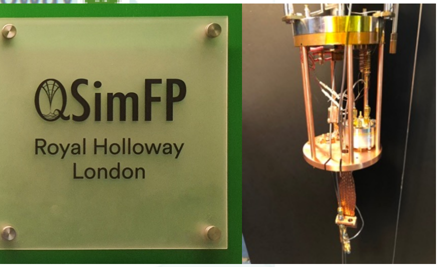
1+1-Dimensional Black Hole Simulator
- Fibre-optical solitons
- Quantum Light Detectors
- **Black Hole Spectral Stability**



2+1-Dimensional Black Hole Simulator
- Biggest Quantum Vortex Flows
- Off-axis Holography Detectors
- **Black Hole Bound states and Instabilities**



2+1-Dim. False Vacuum Decay Simulator
- Ultracold-atoms in optical box traps
- Biggest Potassium Condensate
- First-order Relativistic Phase-Transitions

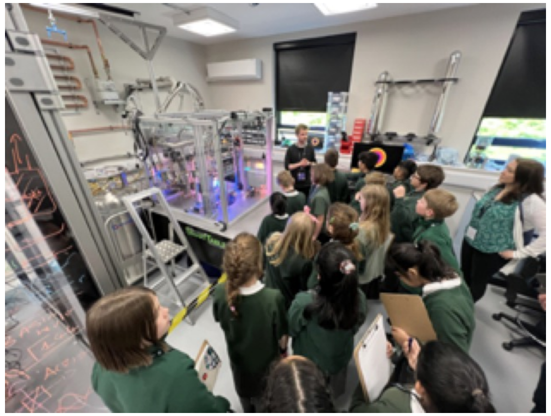


2+1-Dimensional Black Hole Simulator
- State-of-the-art nanotechnology facilities
- Superconducting microwave micro-structures
- Quantum Fields Dynamics & Quantised Rotation

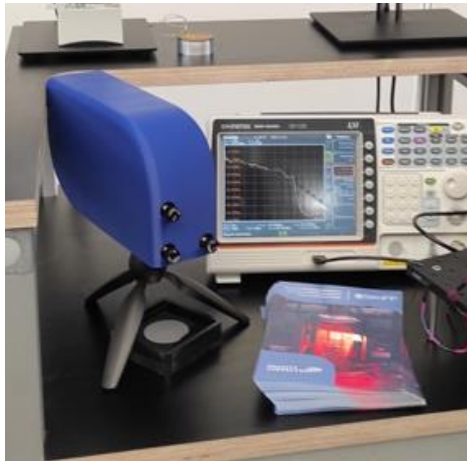
Impact

nature
International weekly journal of science

Scientific Impact:
- 1 publication / month
- Phys Rev Editor's Suggestions
- Physical Review Letters
- 2 Nature Publications



Widening Communities:
- School Kids Event
- Artist Residency
- APEX Grant: Philosophy-QSimFP
- Artlab Nottingham



Patent Application 2214343.2 &
Applied Optics, Vol. 62, pp. 7175-7184
- Optical Path Length Characterisation
- Compact and modular
- Applicable for fluids and gases
- EPSRC IAA Impact Exploration Grant

Engagement Highlights
- Arte '42' TV Show: 1M+ views
- The Guardian Feature
- Quanta Magazine Feature
- New Scientist Cover Story (x2)
- The Skye at Night BBC
- Cheltenham Science Festival

Quantum Technologies and Particle Physics

- The nature of dark matter
- The earliest epochs of the universe at temperatures >> 1TeV
- The existence of new forces
- The violation of fundamental symmetries
- The possible existence of dark radiation and the cosmic neutrino background
- The possible dynamics of dark energy
- The measurement of neutrino mass
- Tests of the equivalence principle
- Tests of quantum mechanics
- A new gravitational wave window to the Universe:
  - LIGO sources before they reach LIGO band
  - Multi-messenger astronomy: optimal band for sky localization
  - Cosmological sources

Most recent European Strategies

the large …

weblink

2017-2026 European Astroparticle Physics Strategy

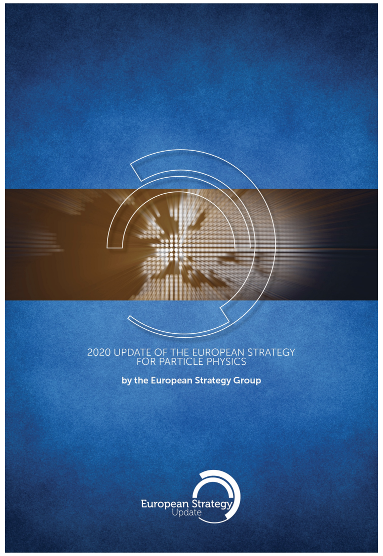
… the connection …

weblink

Long Range Plan 2017 Perspectives in Nuclear Physics

… the small

weblink



2020 Update of the European Particle Physics Strategy

Are community driven strategies outlining our ambition to address compelling open questions

Guidance for funding authorities to develop resource-loaded research programmes

Most recent European Strategies

the large …

weblink

2017-2026 European Astroparticle Physics Strategy

… the connection …

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Long Range Plan 2017 Perspectives in Nuclear Physics

… the small

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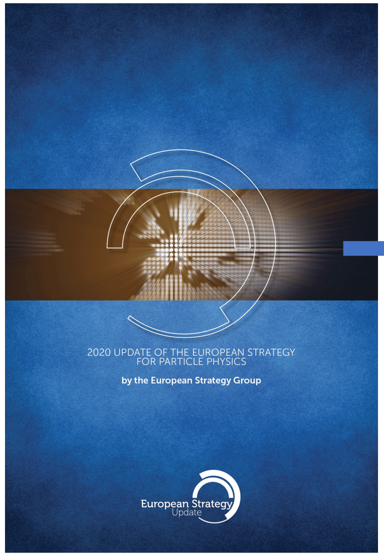


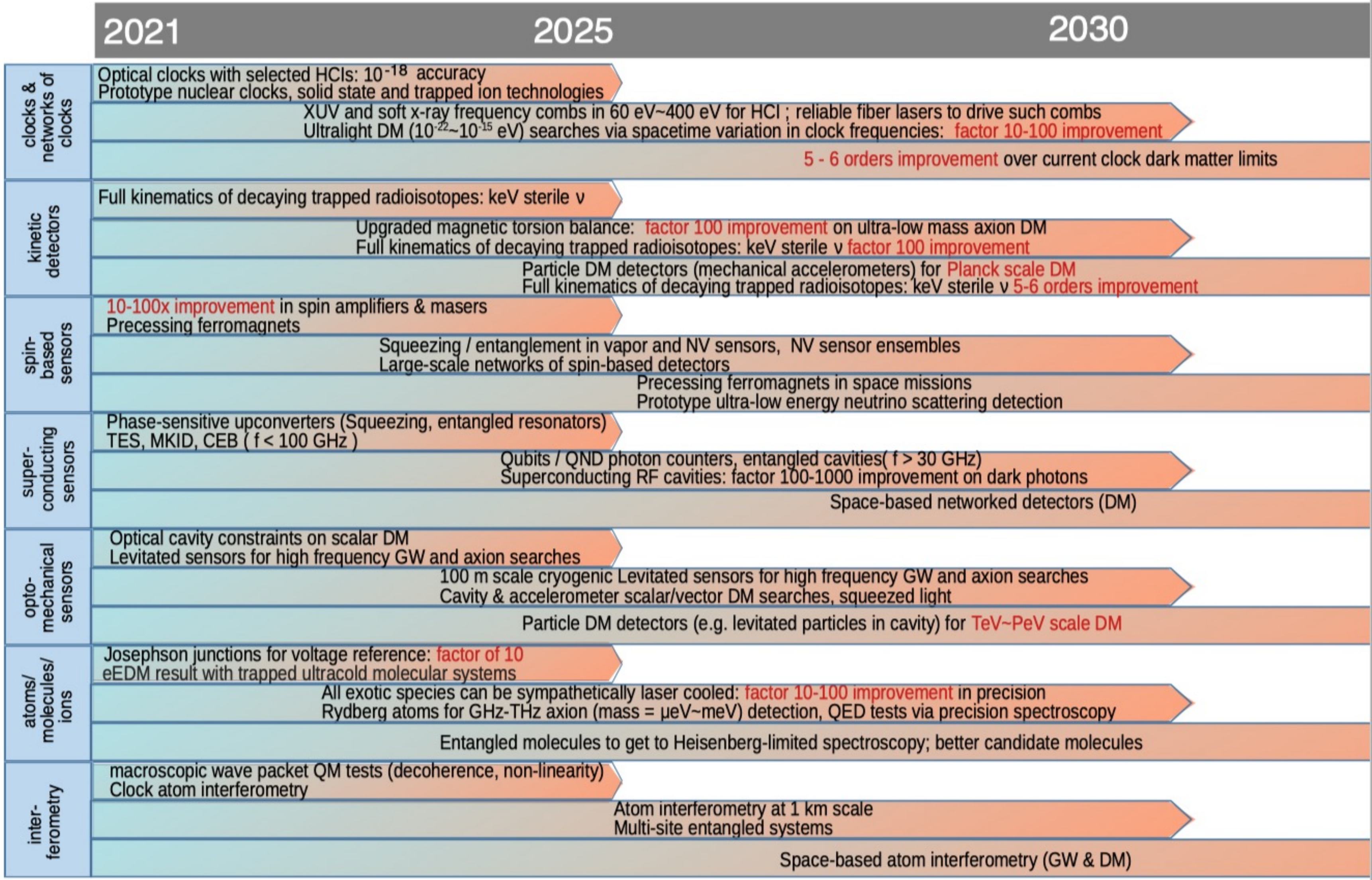
2020 Update of the European Particle Physics Strategy

ECFA Detector R&D Roadmap

In line with the RECFA R&D roadmap, it makes sense to consider a quantum-sensing R&D program that brings together the following strands:

- Clocks and clock networks 5.3.1
- Kinetic detectors 5.3.2
- Spin-based sensors 5.3.3
  Superconducting sensors 5.3.3
- Optomechanical sensors 5.3.4
- Atoms/molecules/ions 5.3.5
  Atom interferometry 5.3.5
- Metamaterials, 0/1/2D-materials
  Quantum materials 5.3.6

also for HEP!



https://doser.web.cern.ch

Quantum Sensors for high energy particle physics

Reference work

frontiers | Frontiers in Physics

ORIGINAL RESEARCH
published: 24 June 2022
doi: 10.3389/fphy.2022.887738

Quantum Systems for Enhanced High Energy Particle Physics Detectors

M. Doser[1], E. Auffray[1], F.M. Brunbauer[1], I. Frank[1,2], H. Hillemanns[1], G. Orlandini[1,3] and G. Kornakov[4]*

[1]CERN, Geneva, Switzerland, [2]Faculty of Physics, Ludwig Maximilian University of Munich, Munich, Germany, [3]Dept. of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany, [4]Faculty of Physics, Warsaw University of Technology, Warsaw, Poland

+ talk by IS at **International Conference on Quantum Technologies for High-Energy Physics (QT4HEP22)**

https://doser.web.cern.ch

drd5 / rdq - implementation | homepage | drd5/rdq collaboration | jobs

https://doser.web.cern.ch

Roadmap topics ⟶ Proposal themes ⟶ Proposal WP's

M. Doser talk presenting DRD5 proposal to DRDC

Roadmap topics

Proposal WP's

Sensor family → / Work Package ↓	clocks & clock networks	superconducting & spin-based sensors	kinetic detectors	atoms / ions / molecules & atom interferometry	opto-mechanical sensors	nano-engineered / low-dimensional / materials
WP1 *Atomic, Nuclear and Molecular Systems in traps & beams*	X			X	(X)	
WP2 *Quantum Materials (0-, 1-, 2-D)*		(X)	(X)		X	X
WP3 *Quantum superconducting devices*		X				(X)
WP4 *Scaled-up massive ensembles* (spin-sensitive devices, hybrid devices, mechanical sensors)		X	(X)	X	(X)	X
WP5 *Quantum Techniques for Sensing*	X	X	X	X	X	
WP6 *Capacity expansion*	X	X	X	X	X	X

Ensure that all sensor families that were identified in the roadmap as relevant to future advances in particle physics are included

WP ⟶ sub-WP ⟶ sub-sub-WP

QTFP in a nutshell

- **Quantum Technologies for Fundamental Physics (QTFP):** Part of the UK's National Quantum Technology Programme, involving over 200 university and research staff, focusing on quantum technology development.
- **Research and Education:** Central to creating a sustainable ecosystem for quantum technology in the UK, seeking funding beyond March 2025.
- **Innovation and Impact:** Engages in groundbreaking research on the universe's origins, dark matter, and more, aiming to educate and upskill the future quantum workforce.
- **Commercialisation and Applications:** Highlights the UK's heritage in technology innovation and the transformative potential of quantum technologies across computing, healthcare, and science.
- **Funding and International Collaboration**: Initiated with £40M from the Strategic Priorities Fund, emphasizing the importance of continued investment and international partnerships.
- **Education and Upskilling:** Focuses on attracting talent and providing high-level training to sustain the UK's quantum economy.
- **Vision for the Future:** Advocates for sustained investment to maintain global leadership in quantum technologies for fundamental physics, emphasizing long-term scientific and socio-economic benefits.

THE EUROPEAN STRATEGY UPDATE CALLED FOR A DETECTOR R&D ROADMAP – QUANTUM SENSORS
IS A KEY AREA and an ECFA and a UK DRD collaboration have been formed ECFA DRD/RDq proposal to be approved June/2024

CERN HAS A DEVELOPING QUANTUM PROGRAMME, FERMILAB IS A DOE QUANTUM SCIENCE CENTER, KEK, DESY…

THE FIRST DOE REVIEW OF THE FUTURE OF THE US NATIONAL INSTRUMENTATION PARTICLE PHYISCS RESEARCH
(September, 2020) IDENTIFED AN AMBITIOUS PROGRAMME OF QUANTUM SENSOR RESEARCH,
THIS HAS BEEN FOLLOWED BY SNOWMASS (2022), P5 (12/23) & DOE INTERNATIONAL BENCHMARK PANEL 11/23
DOE & CPAD HAVE CREATED RD COLLABORATIONS MIRRORING ECFA WITH CLOSE COLLABORATION/COORDINATION
QUANTUM TECHNOLOGIES FOR PARTICLE PHYSICS WILL BE A PROMINENT PLAYER FOR THE NEXT SEVERAL DECADES

THE ESSENTIAL INGREDIENTS THAT HAVE MADE QTFP POSSIBLE ARE:

- COMPELLING SCIENCE
- QUANTUM REVOLUTION 2.0
- THE NATIONAL QUANTUM TECHNOLOGY PROGRAM
- A STRONG COMMUNITY
- STRONG FUNDING SUPPORT FROM STFC & EPSRC via the UKRI SPF

THE NEW UK QUANTUM STRATEGY (15 MARCH 2023) PROVIDES AN ENVIRONMENT FOR QTFP TO CONTINUE TO THRIVE
1+1 =3 UK QTFP PARTNERSHIPS WITH OTHER NATIONS CAN ACHIEVE MORE THAN NATIONS WORKING ALONE
THERE IS EXCITING SCIENCE AHEAD!

QTFP & the European Strategy for Particle Physics

The QTFP projects will collectively write and submit a whitepaper to STFC's PPAP and PAAP panels and UK-ECFA as a contribution to the European Particle Physics Strategy Update and the PPAP and PAAP Roadmaps feeding into the PPAN (Science Board) Roadmap over the course of the summer

As part of this :

a. QTFP projects encourage theorists, phenomenologists and experimentalists to come up with new ideas for physics, and physics studies, that one or more of the 7 QTFP projects could be sensitive to, and reach out to the relevant QTFP project(s) with their ideas and their results/publications.

b. QTFP projects encourage instrumentation/device physics/quantum technologies colleagues with relevant experience and interest to contact any QTFP project where their ideas might enhance the physics reach of the project for discussions.

c. QTFP projects welcome new members

QTNM QI QSNET QSHS AION QUEST DMC QSimFP

"The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark" *(Michelangelo)*

Aim high or we will not realize the potential of our field, discovery will be stalled and we betray ourselves and the next generation.

Photo credit: Michael Hoch/CERN

Acknowledgements

Many thanks to all 7 QTFP projects & their Pis: Giovanni Barontini, Oliver Buchmueller, Andrew Casey, Ed Daw, Hartmut Grote, Ruben Saakyan, Silke Weinfurtner

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Mina Arvanitaki, Themis Bowcock, Chip Brock, Oliver Buchmueller, Nathaniel Craig, Marcel Demarteau, Savas Dimopoulos, Michael Doser, Gerry Gabrielse, Andrew Geraci, Peter Graham, Joanne Hewett, Rafael Lang, David Hume, Jason Hogan, John March-Russell, Hitoshi Murayama, Marianna Safronova, Alex Sushkov, Chris Tully, Stafford Withington & the UK Quantum Technologies for Fundamental Physics Program