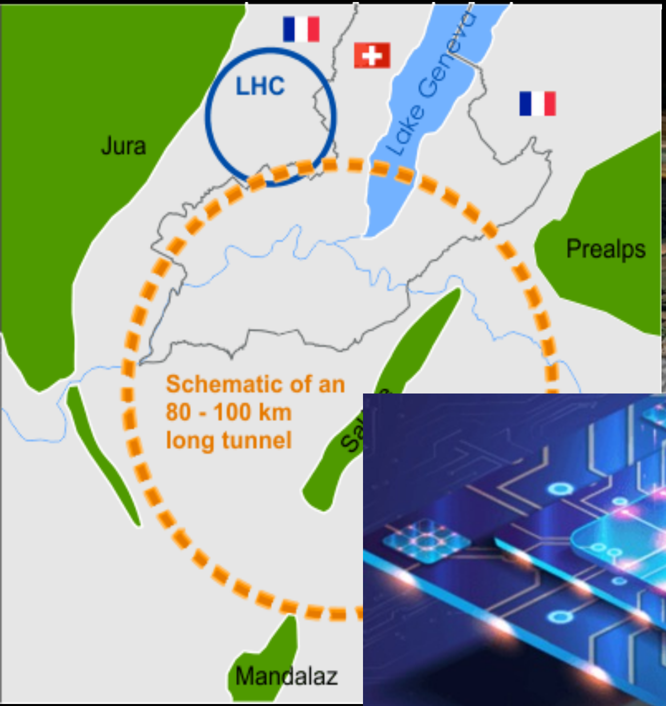
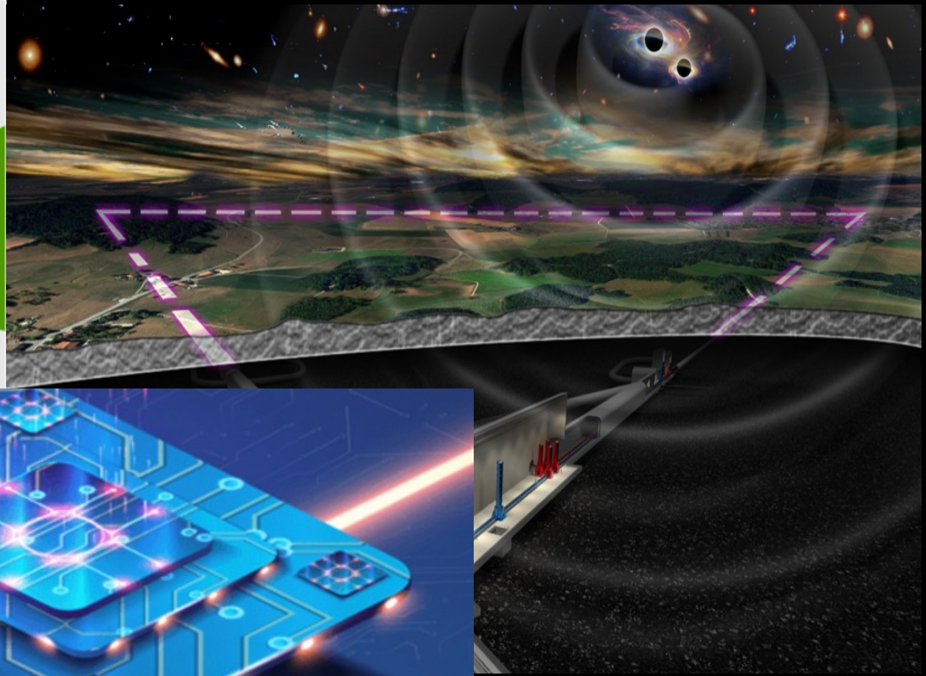
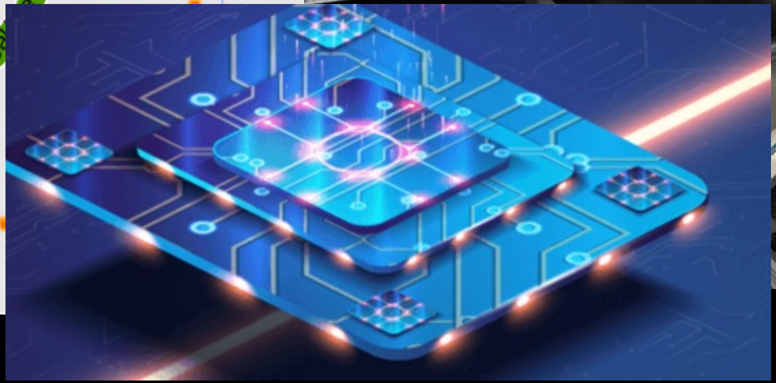
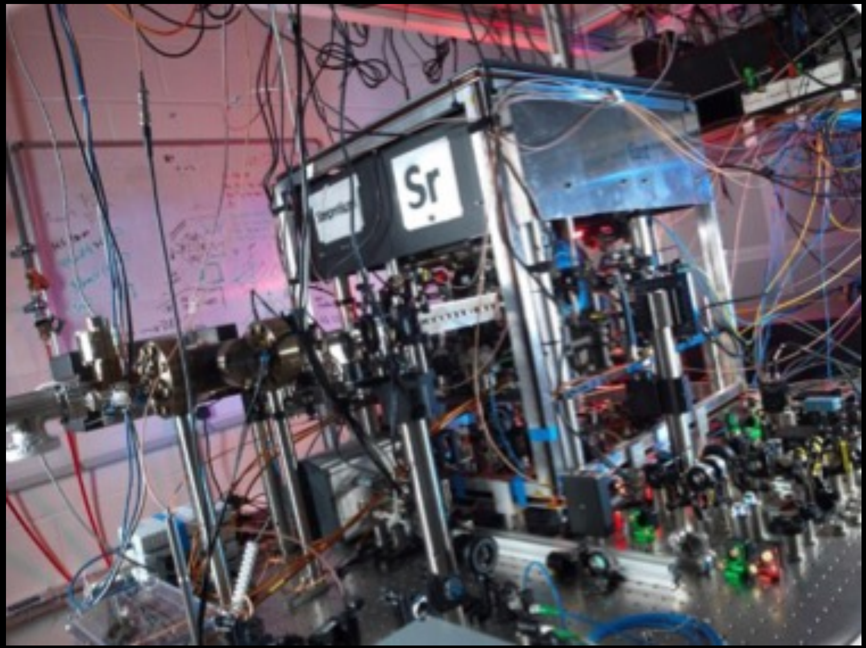
Quantum Technologies for Fundamental Physics

The Science & The Quantum Technologies Landscape









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

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

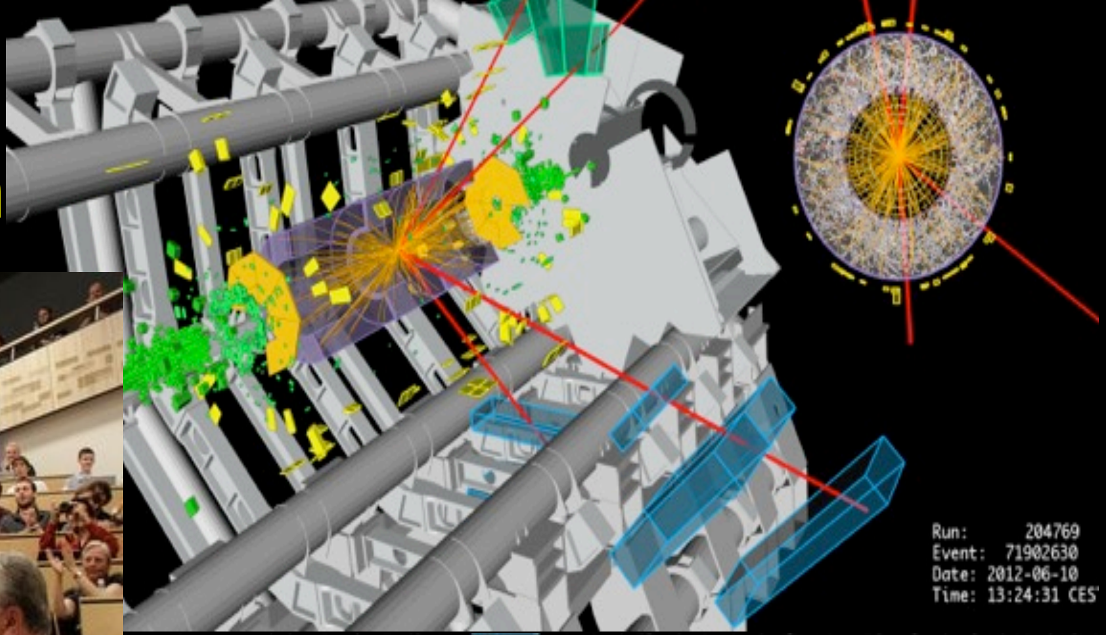
SQMS Quantum for Science

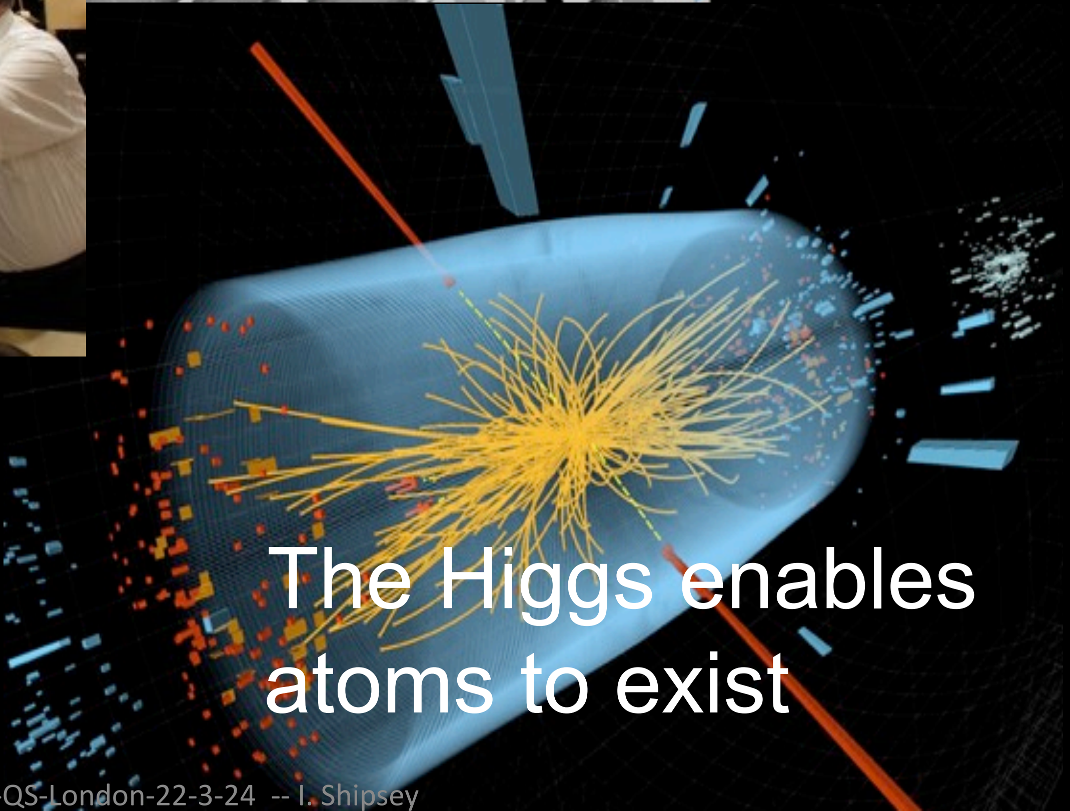
Outline

- The Science
- Quantum Revolution 2.0
- QTFP
- Future

2012.7.4

discovery of Higgs boson



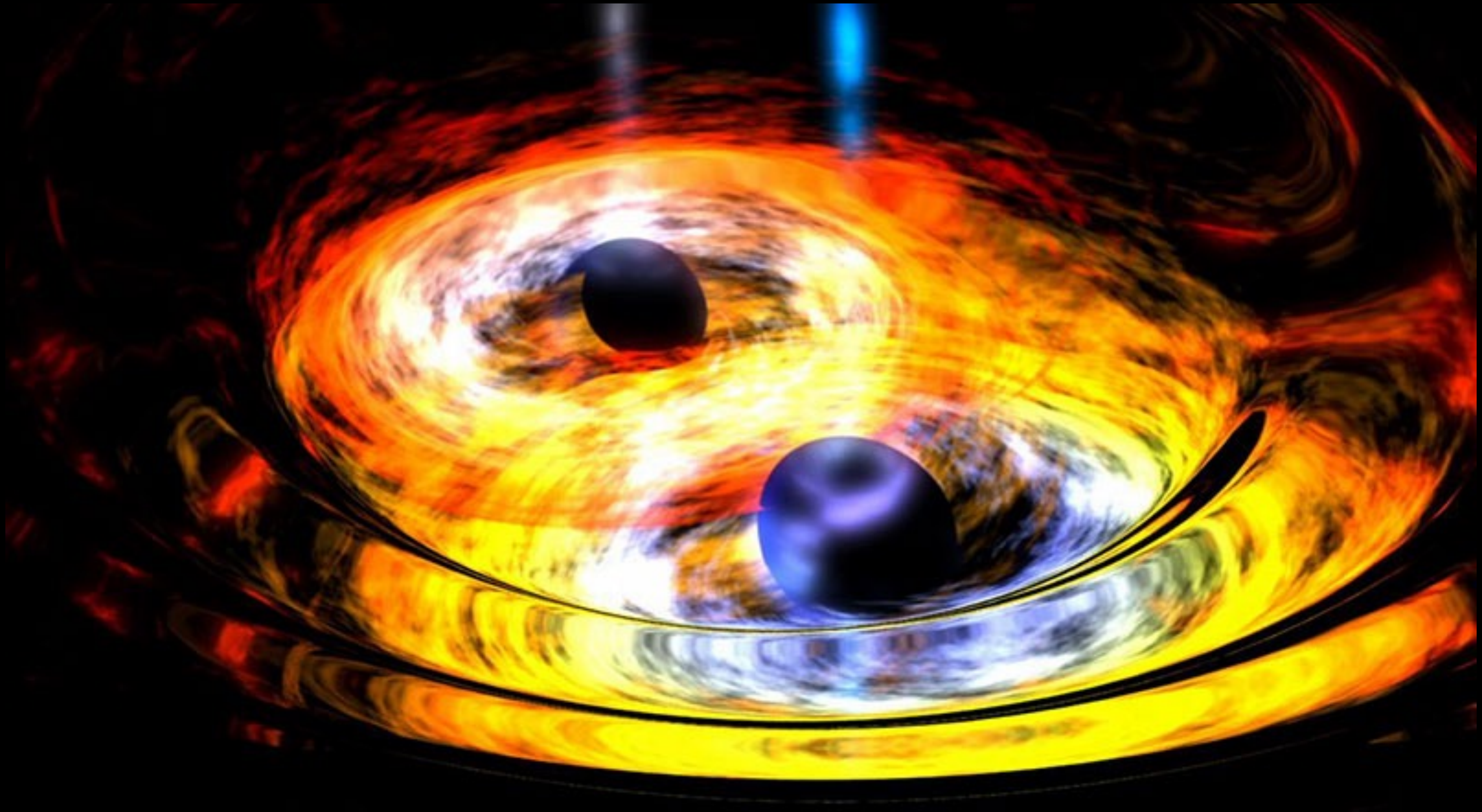


theory : 1964

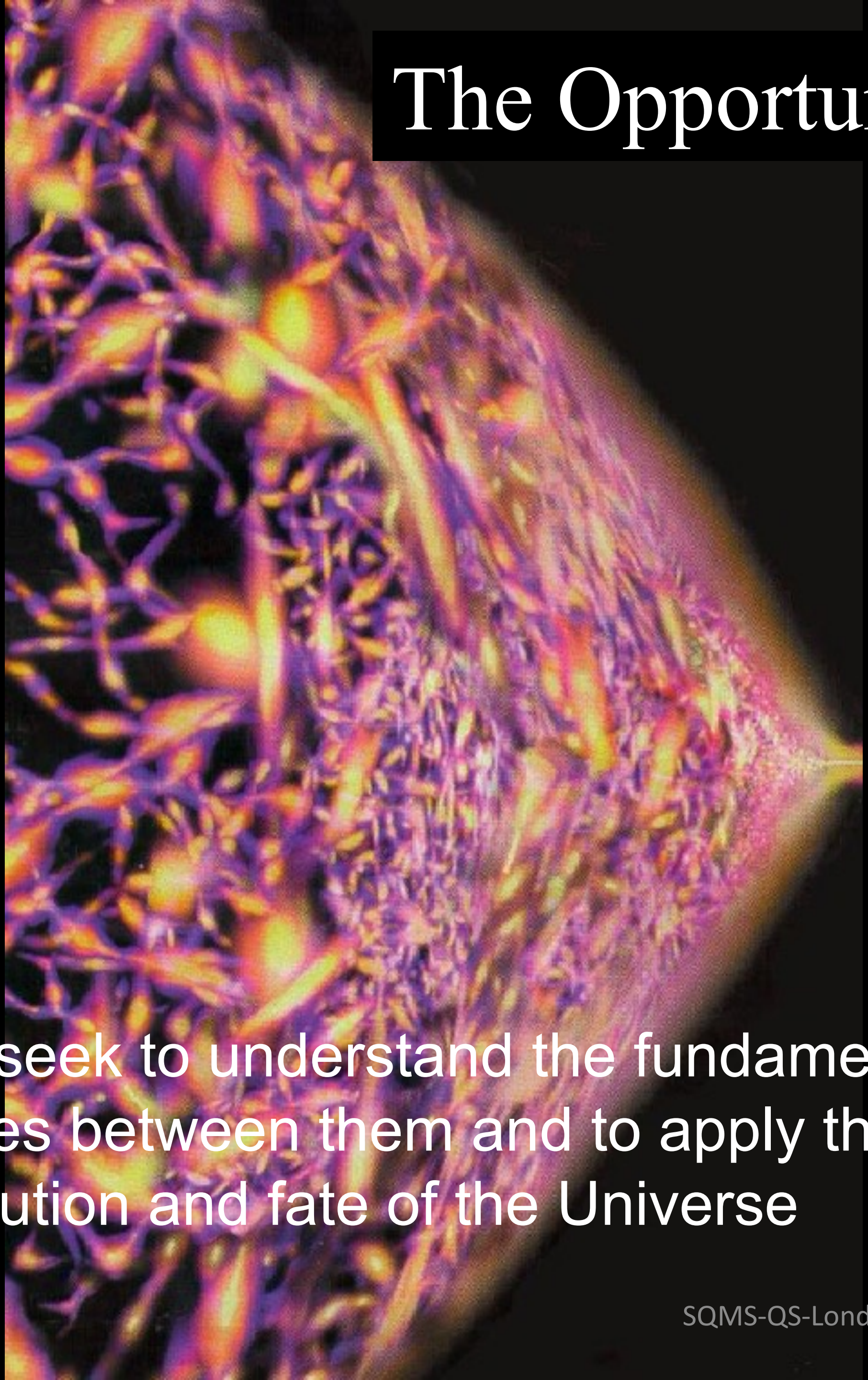
design : 1984

construction : 1998

Detection of gravitational waves
LIGO February, 2016

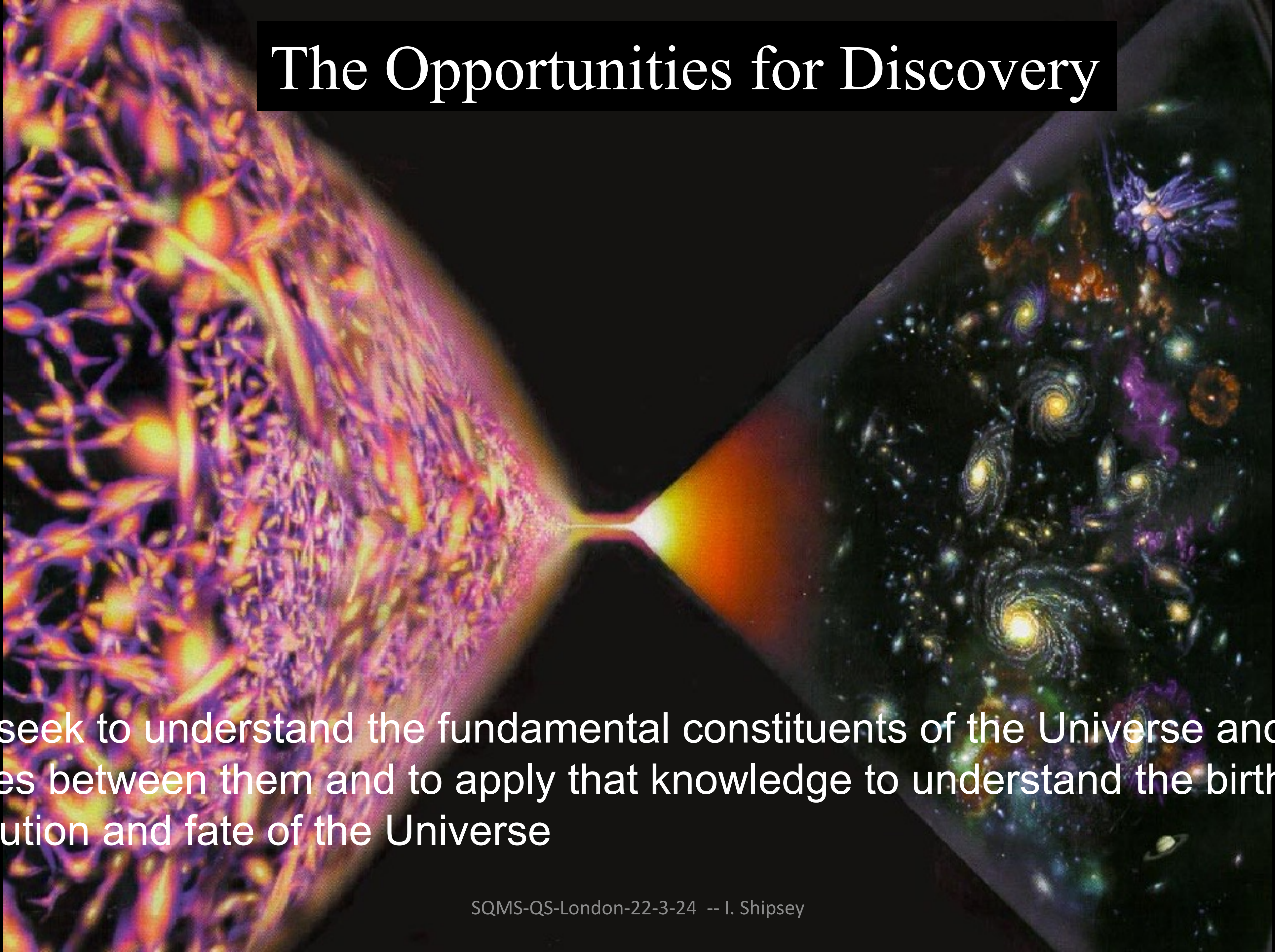


The Opportunities for Discovery



We seek to understand the fundamental constituents of the Universe and the forces between them and to apply that knowledge to understand the birth, evolution and fate of the Universe

The Opportunities for Discovery



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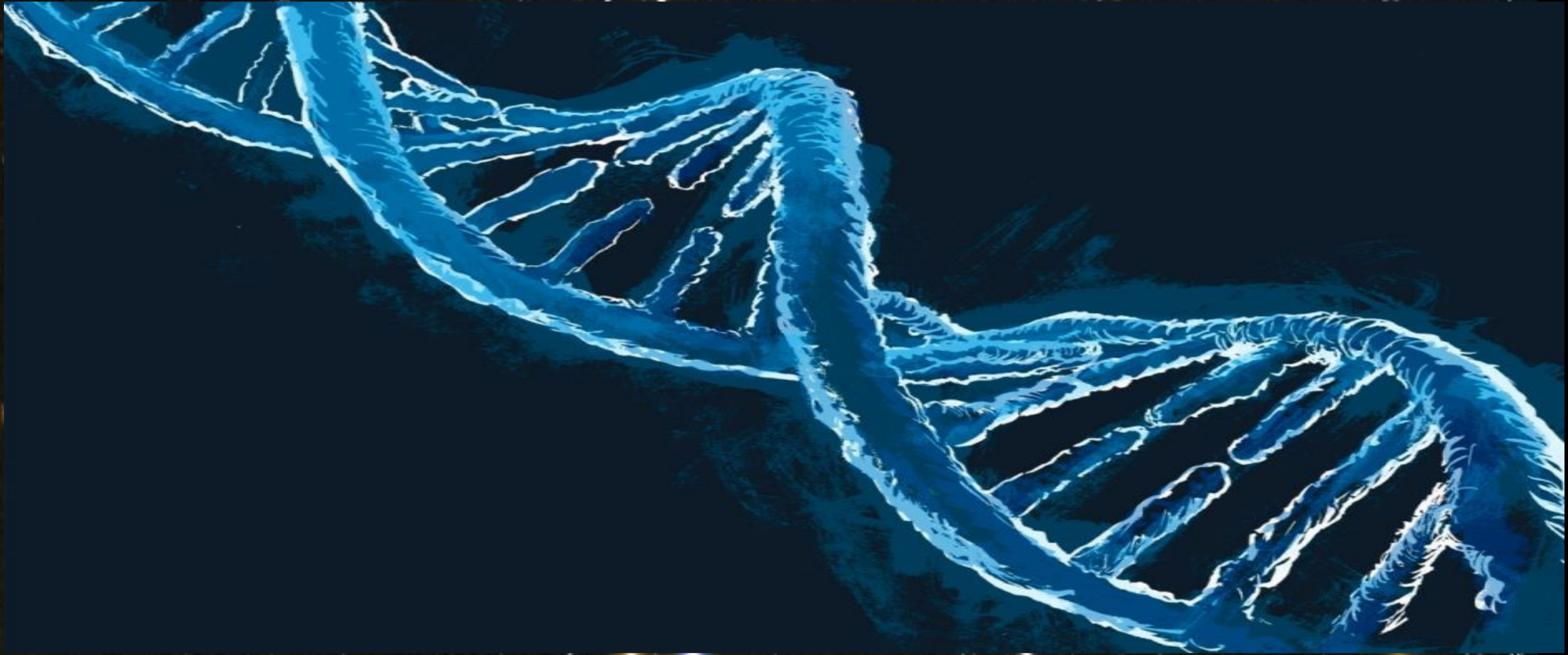
BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Physics has revolutionized human understanding of the Universe – its underlying code, structure and evolution



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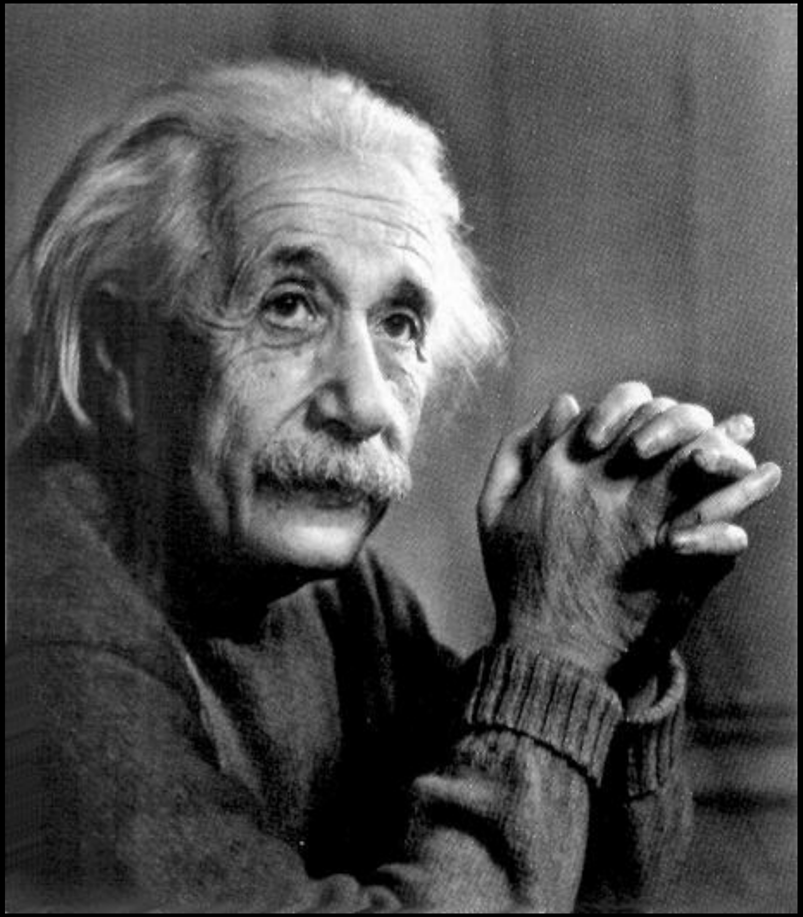
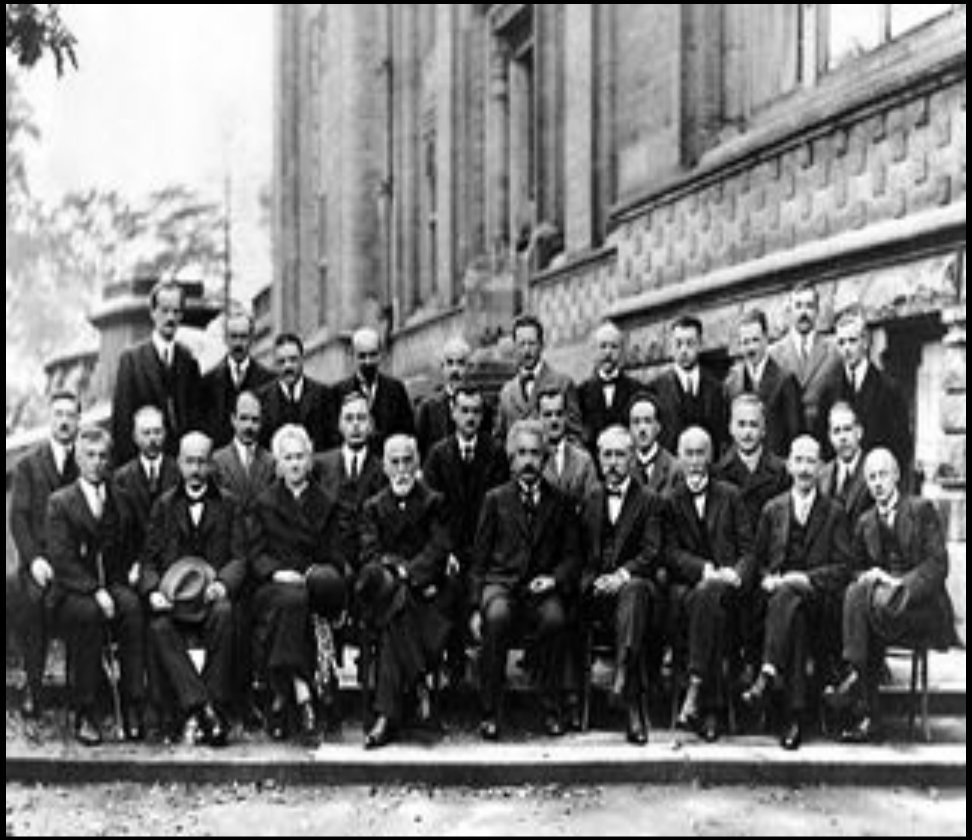


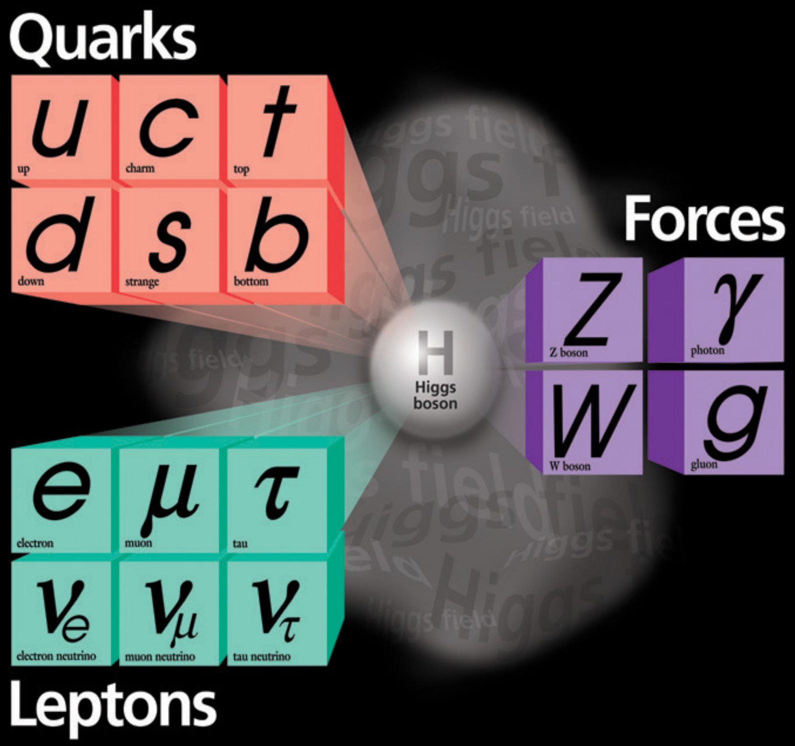
General Relativity



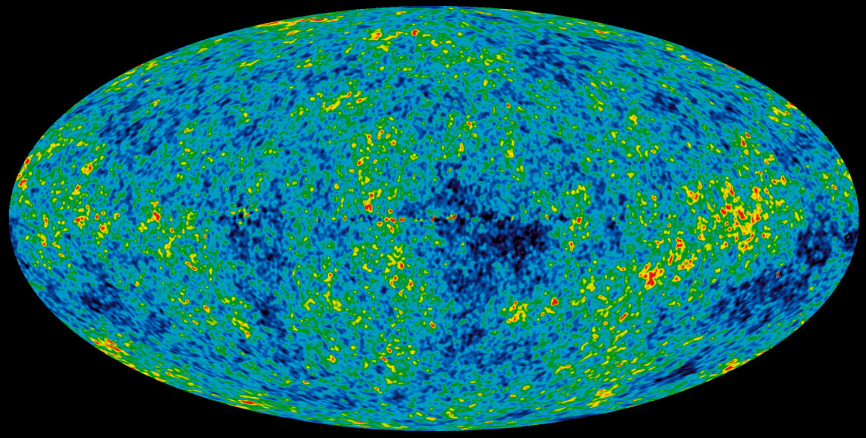
Quantum Mechanics

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Particle Standard Model



Cosmology Standard Model



Λ_{CDM}

……enabled by instrumentation

APPEC
ECFA
NuPECC

Our scope is broad and we deploy many tools; accelerator, non-accelerator, astrophysical & cosmological observations all have a critical role to play

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

- The potential exists now to revolutionize our knowledge again.
- Despite the huge successes, there are deep and fundamental mysteries that are unanswered and for which following traditional methods of exploration and new quantum sensing methods combine to form the optimal approach.

NASA, ESA/JPL-Caltech/B. Mobasher (STScI/ESA)

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

How do quarks and gluons give rise to the properties of nuclei

The mystery of the origin and engine of high energy cosmic particles

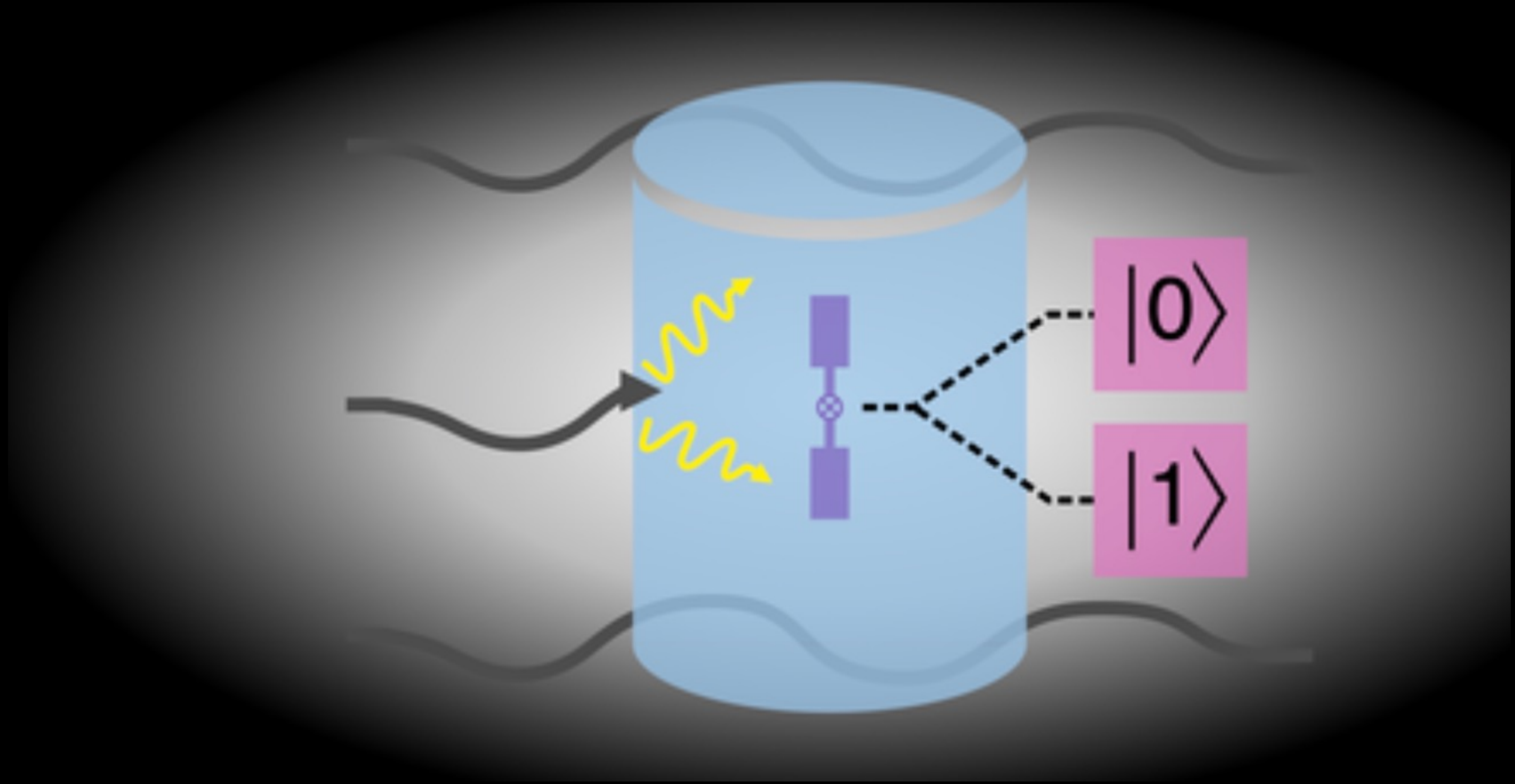
Multiple theoretical solutions – experiment must guide the way

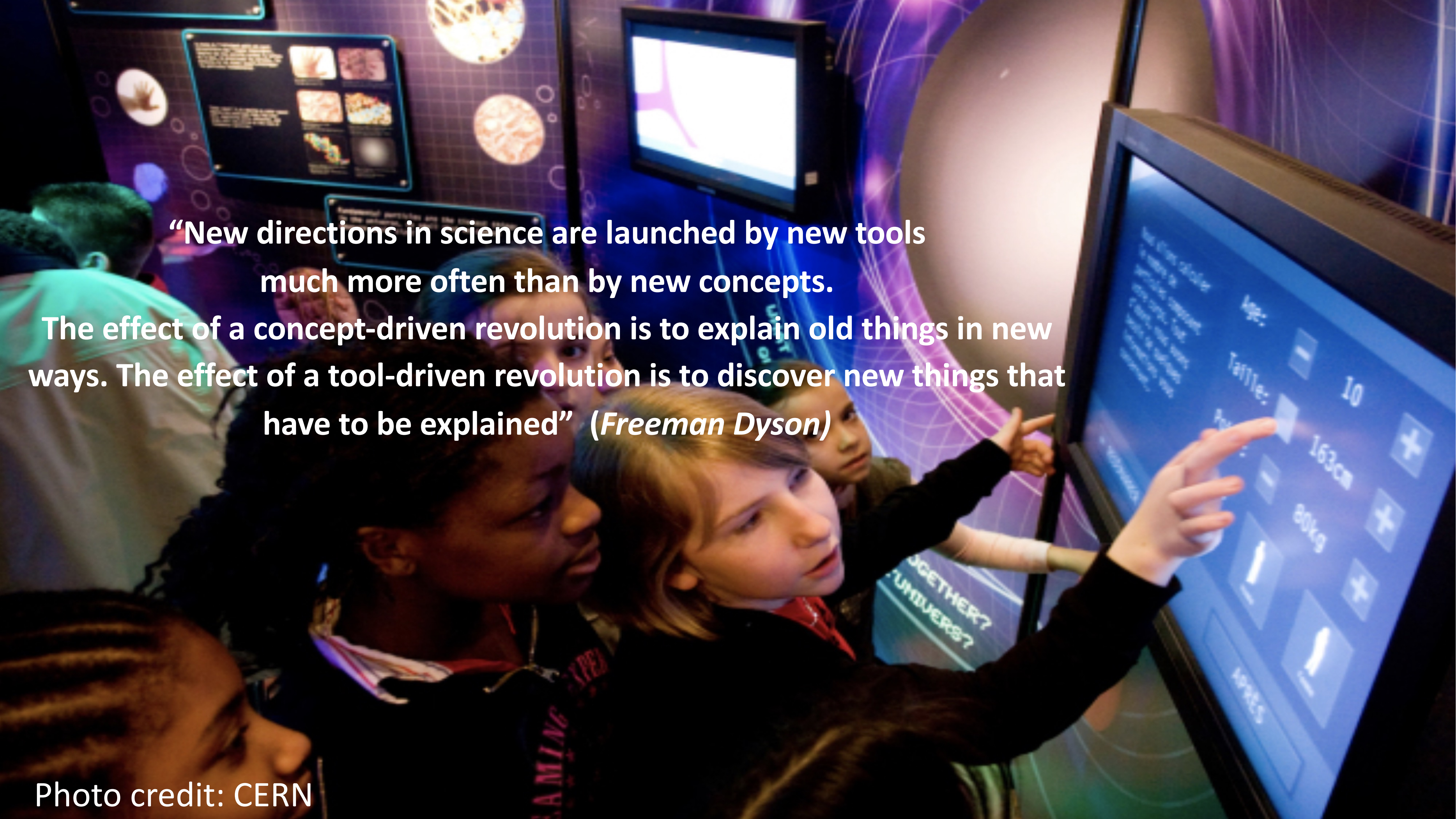
We are very much in a data driven era for which we need new tools!

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

Discoveries in particle physics

Based on an original slide by S.C.C. Ting

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	
AGS BNL (1960)	π N interactions	
FNAL Batavia (1970)	Neutrino Physics	
SLAC Spear (1970)	ep, QED	
ISR CERN (1980)	pp	
PETRA DESY (1980)	top quark	
Super Kamiokande (2000)	Proton Decay	
Telescopes (2000)	SN Cosmology	

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AGS BNL (1960)	π N interactions	Two kinds of neutrinos Time reversal non-symmetry charm quark
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SLAC Spear (1970)	ep, QED	Partons, charm quark tau lepton
ISR CERN (1980)	pp	Increasing pp cross section
PETRA DESY (1980)	top quark	Gluon
Super Kamiokande (2000)	Proton Decay	Neutrino oscillations
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precision instruments are key to discovery when exploring new territory

Outline

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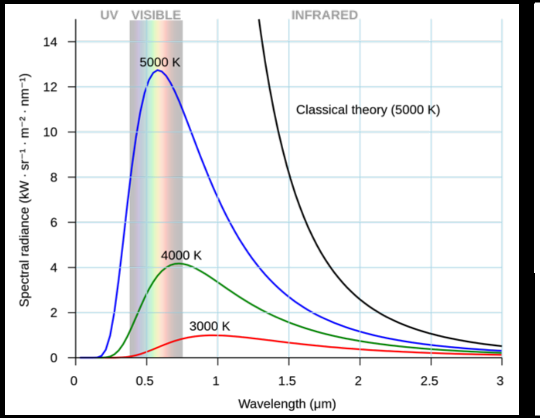
- Future

While quantum sensors are not new they have suddenly become prominent 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

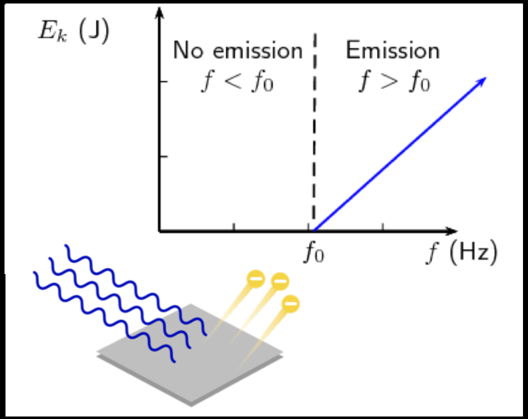
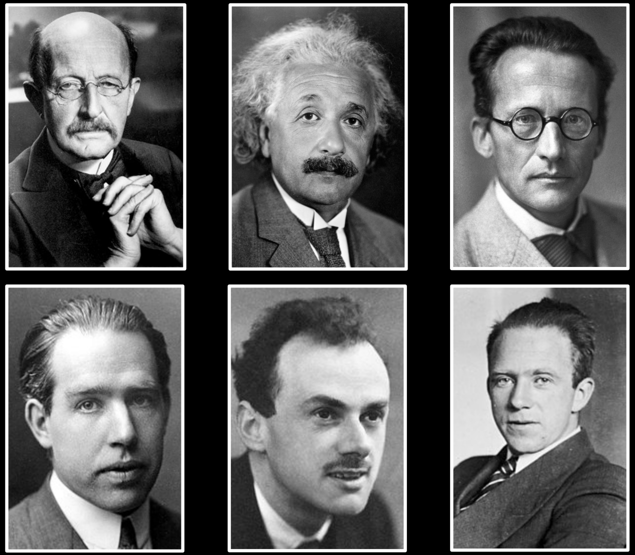
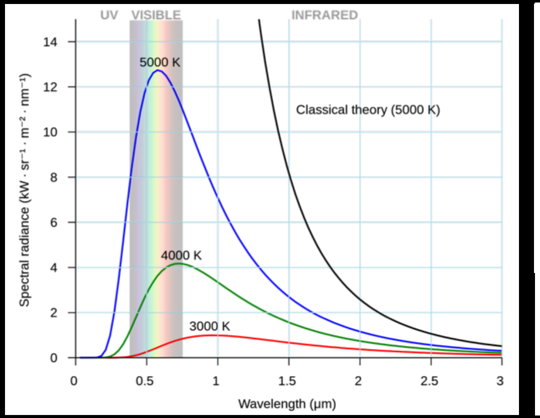


Photo-electric Effect

Quantum Mechanics



Quantum 1.0



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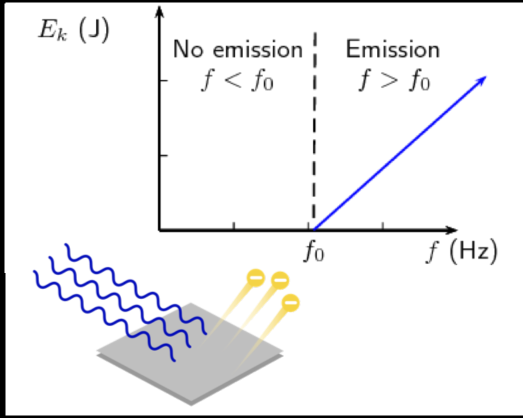
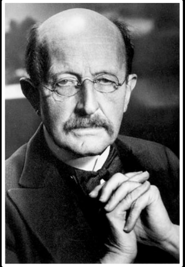
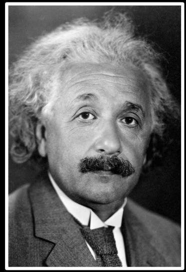


Photo-electric Effect

Quantum Mechanics

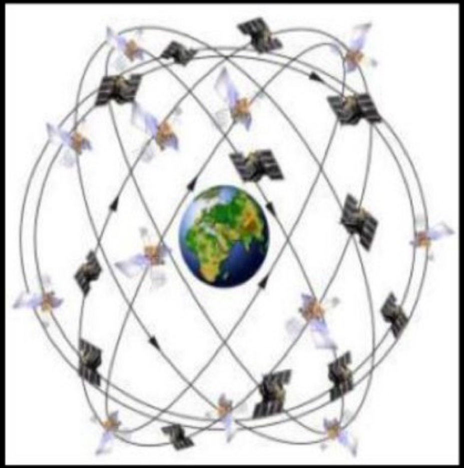





Exascale Computing

Laser Technology

Magnetic Resonance Imaging



Global Positioning System

Quantum 1.0

09:41
100 %
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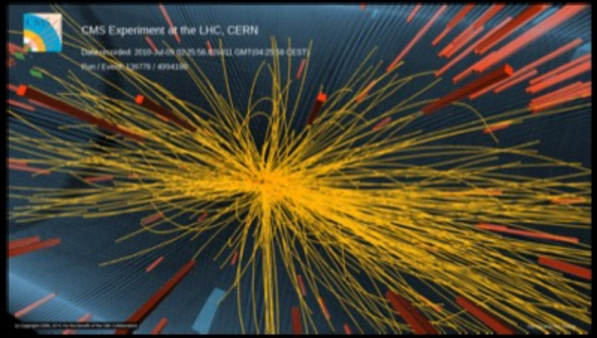
7
Mail
Calendrier
Photos
Appareil photo
Plans
Horloge
Météo
Wallet
Notes
Rappels
Bourse
Vidéos
iBooks
iTunes Store
App Store
Domicile
Santé
Réglages
Téléphone
Safari
Messages
Musique

Quantum 2.0

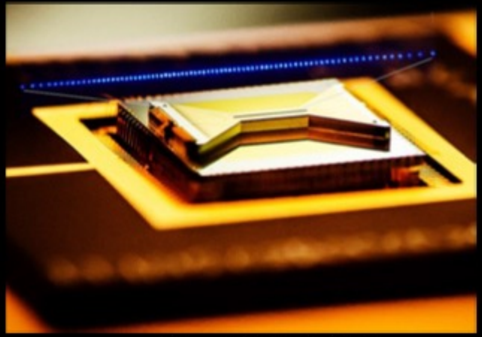
The First Quantum Revolution: exploitation of quantum matter to build devices
Second Quantum Revolution: engineering of large quantum systems with full control of the quantum state of the particles, e.g. entanglement

AI, ML on Quantum annealer



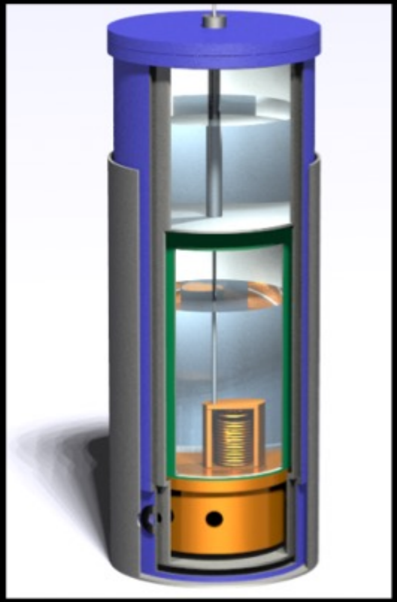
Nature 550 (2017) 375

IonQ >60-qubit



arXiv:1902.10171

Atomic clocks



Nature (564) 87 (2018)

Quantum 2.0

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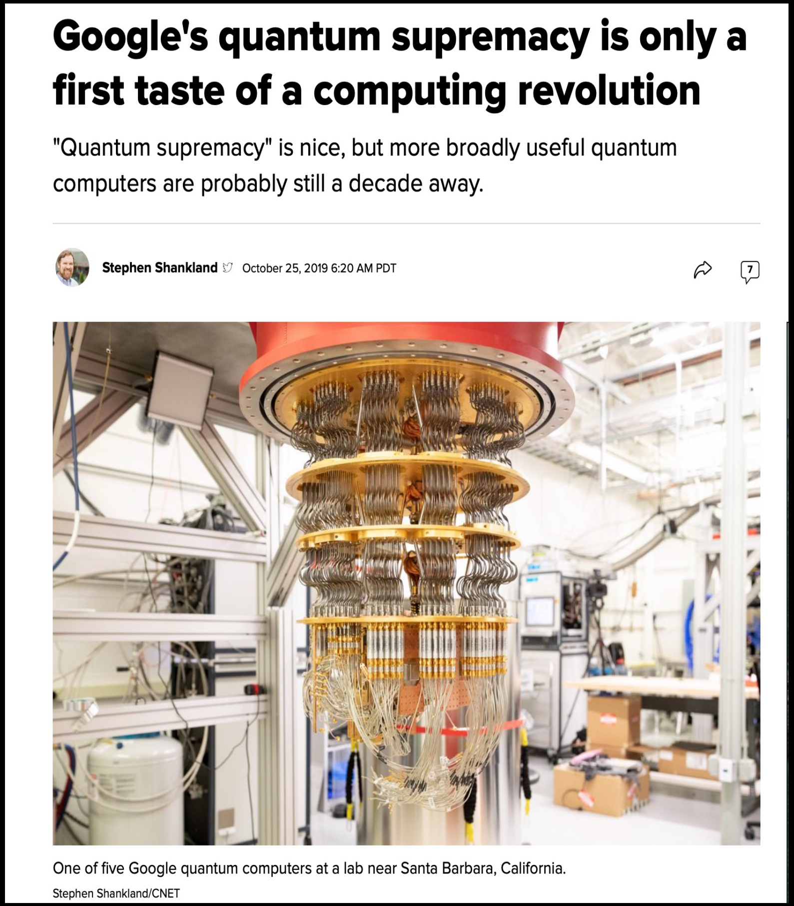


Google's quantum supremacy is only a first taste of a computing revolution

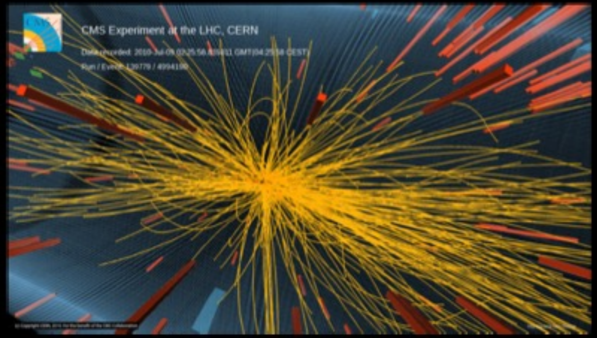
"Quantum supremacy" is nice, but more broadly useful quantum computers are probably still a decade away.

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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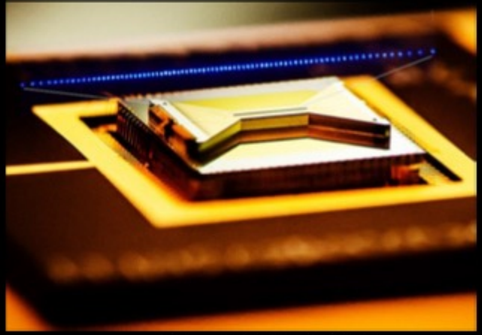

arXiv:1902.10171

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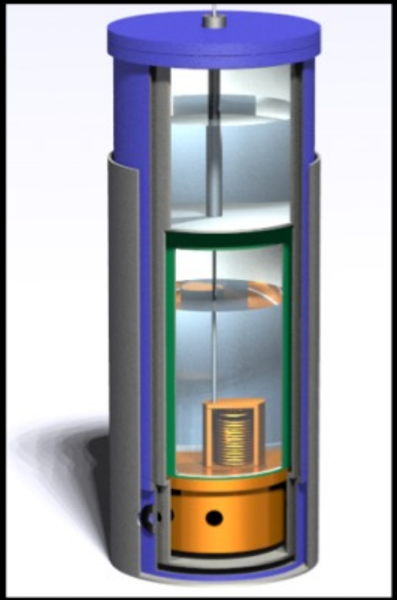

Nature (564) 87 (2018)

Quantum 2.0


09:41
100 %
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7
Mail
Calendrier
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Appareil photo
Plans
Horloge
Météo
Wallet
Notes
Rappels
Bourse
Vidéos
iBooks
iTunes Store
App Store
Domicile
Santé
Réglages
Téléphone
Safari
Messages
Musique

"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,"

What if?

Quantum Internet

Quantum Artificial Neural Network

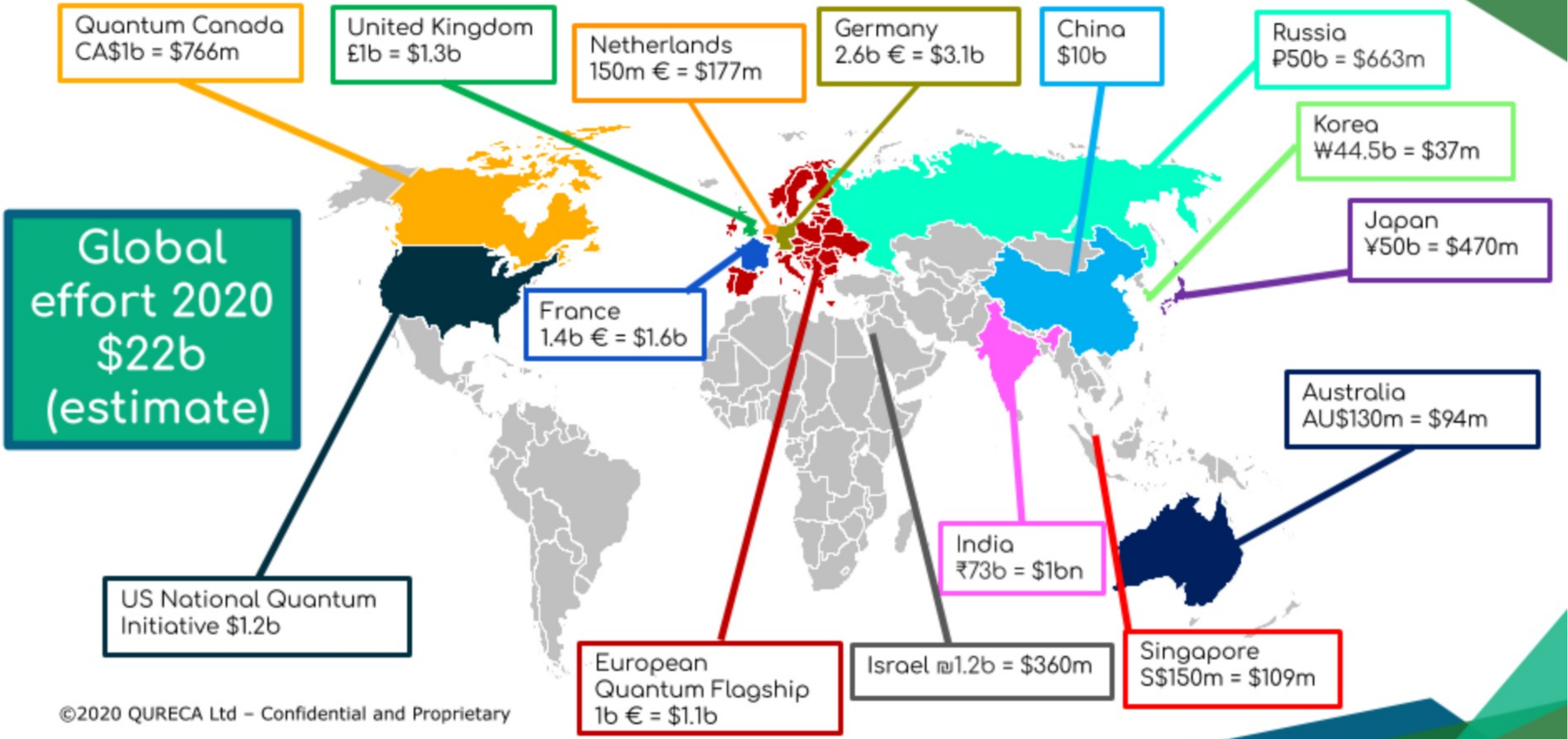
Quantum Liquid Crystals

Quantum Mind Interface

Quantum enabled searches for dark matter

Quantum Gravity

Quantum Technologies Public Funding Worldwide



https://uknqt.ukri.org

Search

UK NATIONAL
QUANTUM
TECHNOLOGIES
PROGRAMME

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

Transforming the world with quantum technology

Building a community: essential for creation of UK program

Quantum Technologies for Fundamental Physics Community Workshop October 2018 Oxford
>140 from EPSRC & STFC in attendance

£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

UKRI Innovate UK

IUK, ISCF, Industry
£450M

Prototypes

Products

Spin-offs

Department for Business, Energy & Industrial Strategy

NPL National Physical Laboratory

Quantum Metrology Institute
£30M

Standards

Validation

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
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£80M

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

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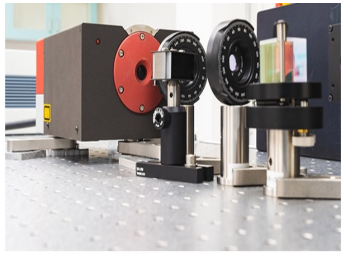
QTFP is a strategic initiative within the National Quantum Technology Programme created with £40M from the UKRI Strategic Priorities Fund in 2019 awarded to EPSRC and STFC with STFC administering the programme.

The primary purpose of QTFP is to enable advanced quantum technologies, innovated and demonstrated during the last 5-10 years to be developed, customised and refined to enable major advances in understanding of some of the greatest scientific mysteries in particle physics, particle astrophysics, cosmology and other areas of fundamental physics

There are seven QTFP projects. Inherently interdisciplinary AMO, CMP, QIS Particle, Astro. A magnet of ECRs and students. Funding commenced in February, 2021 for up to 41 months. QTFP currently comprises 101 faculty and scientists, 66 post docs, 11 Engineers and technicians, 5 administrative staff and 32 PhD students (the students are 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

QTNM QI QSNET QSHS AION QUEST DMC QSimFP

QI

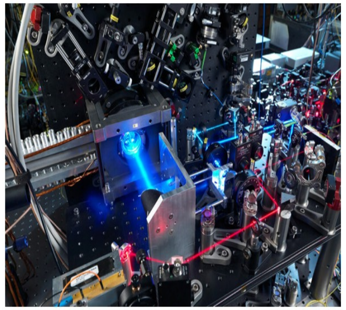


Quantum-enhanced Interferometry for new physics

Principal investigator: Harmut Grote

Using quantum technologies we can now explore new fields of physics, seeking answers to long-standing questions like "what is dark matter?" and "is space-time quantised?"

QSNET



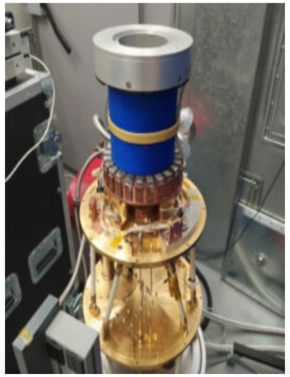
Strontium optical lattice clock experiment

A network of clocks for measuring the stability of fundamental constants

Principal investigator: Giovanni Barontoni

Using quantum technology we can now network ultra-advanced atomic clocks to investigate the origin of dark matter and dark energy, which constitute 95% of the universe, but have so far eluded any detection.

QTNM



Determination of absolute neutrino mass using quantum technologies

Principal investigator: Ruben Saaykan

The QTNM project aims to harness recent breakthroughs in quantum technologies to solve one of the most important outstanding challenges in particle physics – determining the absolute mass of neutrinos.

QSHS

Quantum sensors for the hidden sector

Principal investigator: Ed Daw

Amplifiers operating at the quantum limit are essential for probing the astrophysics of the hidden sector. With this technology, we could solve the dark matter problem.

AION

A UK atom interferometer observatory and network

Principal investigator: Oliver Buchmuller

Using ultracold strontium atom interferometers as quantum sensors to tackle open questions in fundamental physics, such as the nature of dark matter, the existence of new fundamental interactions, and novel sources of gravitational waves.

QUEST DMC

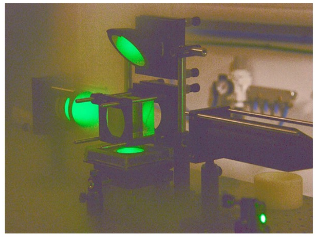
Nuclear demagnetisation experiment

Quantum enhanced superfluid technologies for dark matter and cosmology

Principal investigator: Andrew Casey

Combining Quantum Technology with ultralow temperatures we can now search for dark matter in a mass regime that is strongly motivated by theory, but inaccessible using current techniques.

QSimFP



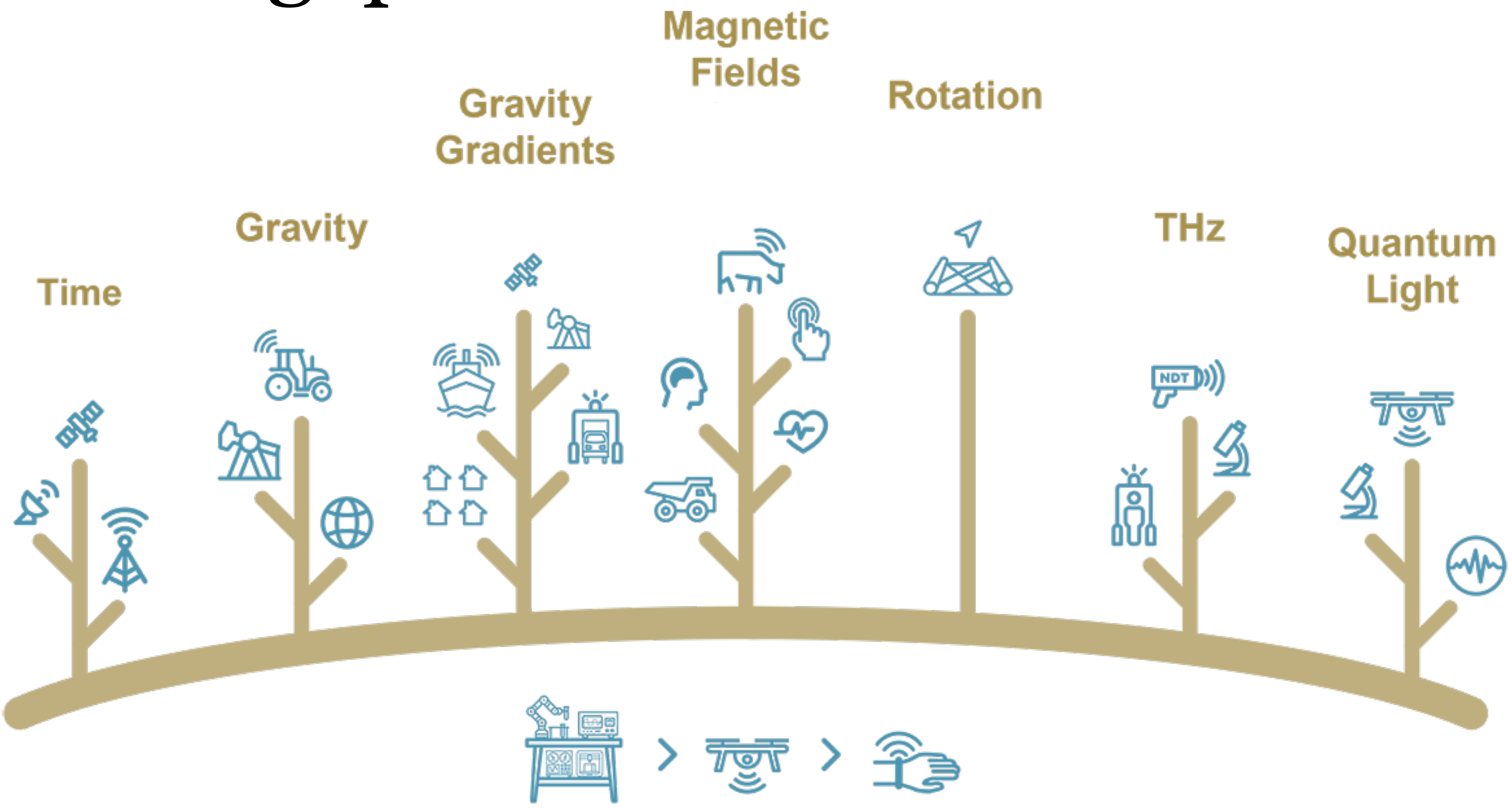
Quantum simulators for fundamental physics

Principal investigator: Silke Weinfurtner

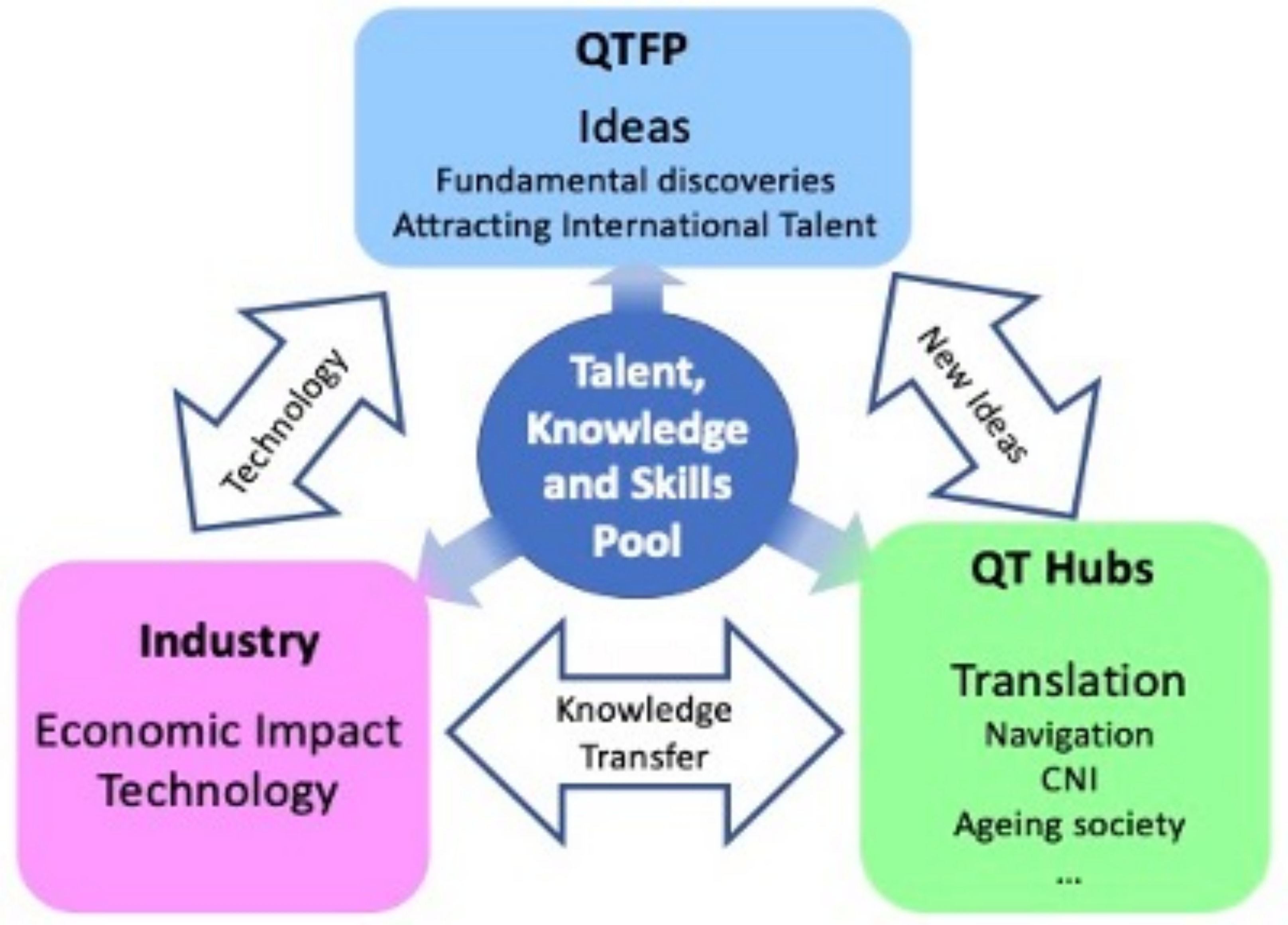
Using a novel high-precision interferometric scheme to observe the surface dynamics of quantum fluids, we will elucidate unifying features of quantum phenomena around rotating black holes and rotating fluid flows.

Translating quantum sensors

UK Quantum Technology Hub Sensors and Timing



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


QTFP
Ideas
Fundamental discoveries
Attracting International Talent
Technology
New Ideas
Talent, Knowledge and Skills Pool
Industry
Economic Impact
Technology
Knowledge Transfer
QT Hubs
Translation
Navigation
CNI
Ageing society
...

•**76 partnerships** between QTFP institutions and international institutions, 4 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).

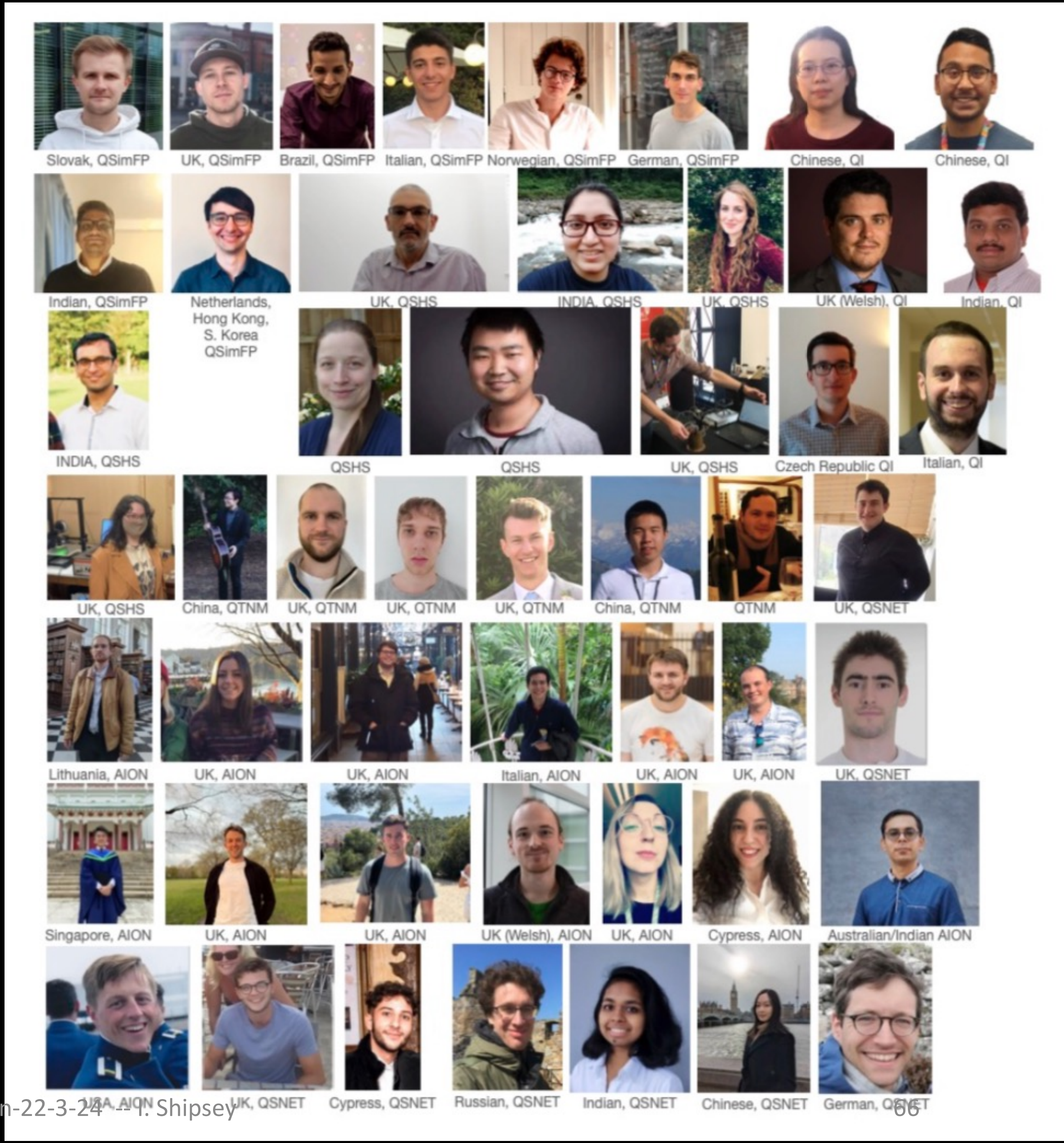
Education and Upskilling: QTFP has generated immense excitement amongst some of the brightest undergraduate and graduate students, postdocs and other early career researchers in the UK and abroad.

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

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.



Quantum Sciences – Opportunities

Emerging QT to revolutionise life: computing, cryptography, imaging, measurement, sensors and simulations

- **UK National Quantum Strategy (2023)**
  - Doubling investment (£1B + £2.5B)
  - 10-year vision plan:
    - Growing knowledge & skills
    - Attract companies & investors
    - Adoption and Use of QT
    - Develop regulatory framework
  - **Investment in QT for Fundamental Physics**
    - Quantum a tool for wider research
    - International partnerships
    - Secure development and employment

Quantum Technology for Fundamental Physics

Vortices in Superfluid Helium 4

Precision tabletop optical interferometry

Ultra-low-noise microwave sensing

Qubit detectors

Photon counting, sub-standard -quantum-limit detection

Multi-Messenger Particle Physics!

QSimFP - PI Silke Weinfurtner - analog **Lab simulation of complex systems** e.g. Black Holes with vortices in liquid helium.
QI - PI Hartmut Grote - Laser interferometry for **UL dark matter, GW, spacetime quantizaion, quantum gravity, semi-classical gravity & macroscopic quantum mechanics** .
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, ULDM (MAGIS)**
QSNET - PI Giovanni Barontini - Network of ultra-precise clocks **probing fundamental constants & UL dark matter**
QUEST-DMC - PI Andrew Casey - **Phase Transitions in the Early Universe & Particle dark matter search with liquid helium 3**

PLUS, 17 other smaller scale funded research projects

Atom interferometry

Neutrino mass direct measurements using cyclotron radiation

Precision atomic clocks, new clock technology

Liquid Helium 3 Universe in a lab

Theory of low-energy states adjacent to the vacuum

Slide from Ed Daw

Quantum Sensors

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

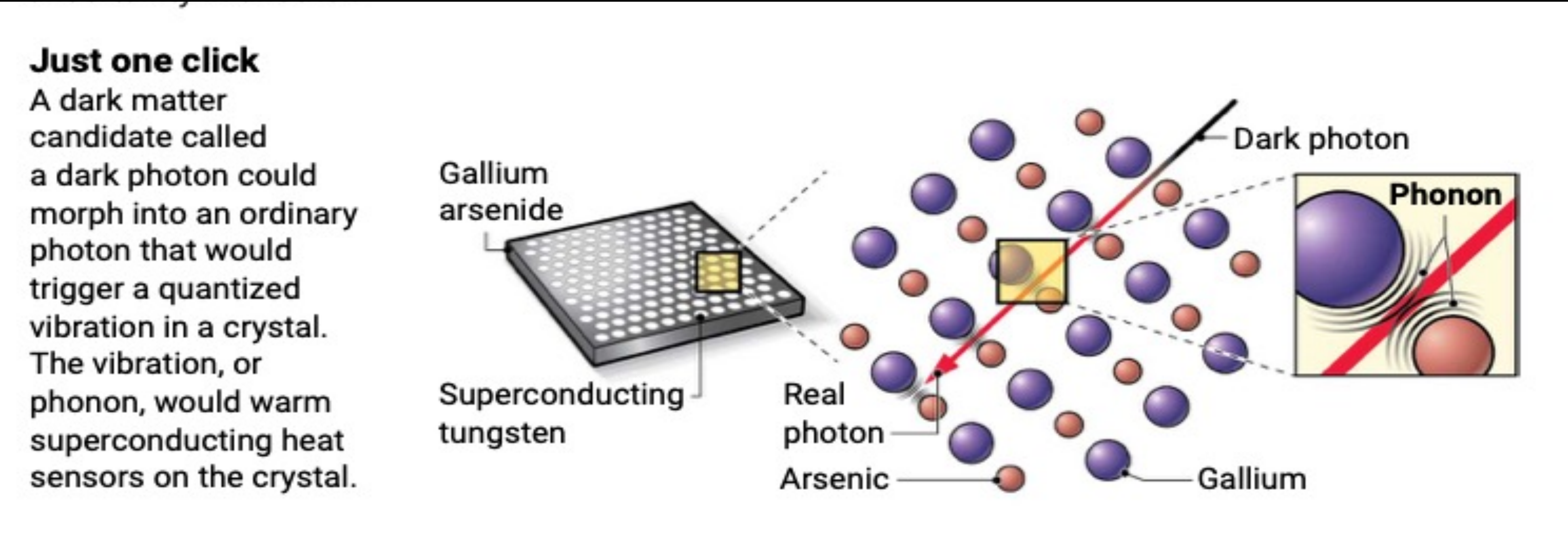
- transition between superconducting and normal-conducting
- transition of an atom from one state to another
- change of resonant frequency of a system (quantized)

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

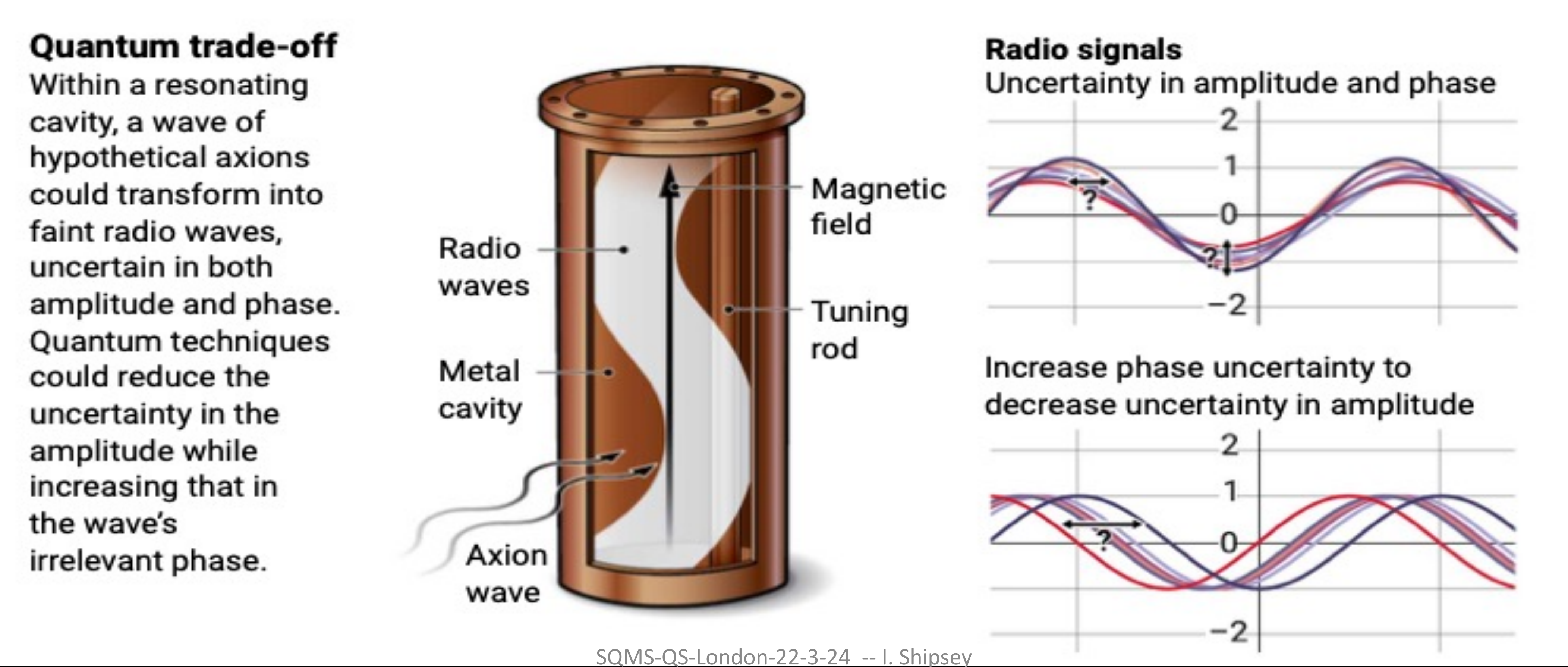


Science

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 and emerging technologies

- **Quantum Technologies are a rapidly emerging area** of technology development to study fundamental physics
- The ability to engineer quantum systems to improve on the measurement sensitivity holds great promise
- **Many different sensor and technologies being investigated**: clocks and clock networks, spin-based, superconducting, optomechanical sensors, atoms/molecules/ions, atom interferometry, …
- Several initiatives started at CERN, DESY, FNAL, US, UK, Japan,…

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

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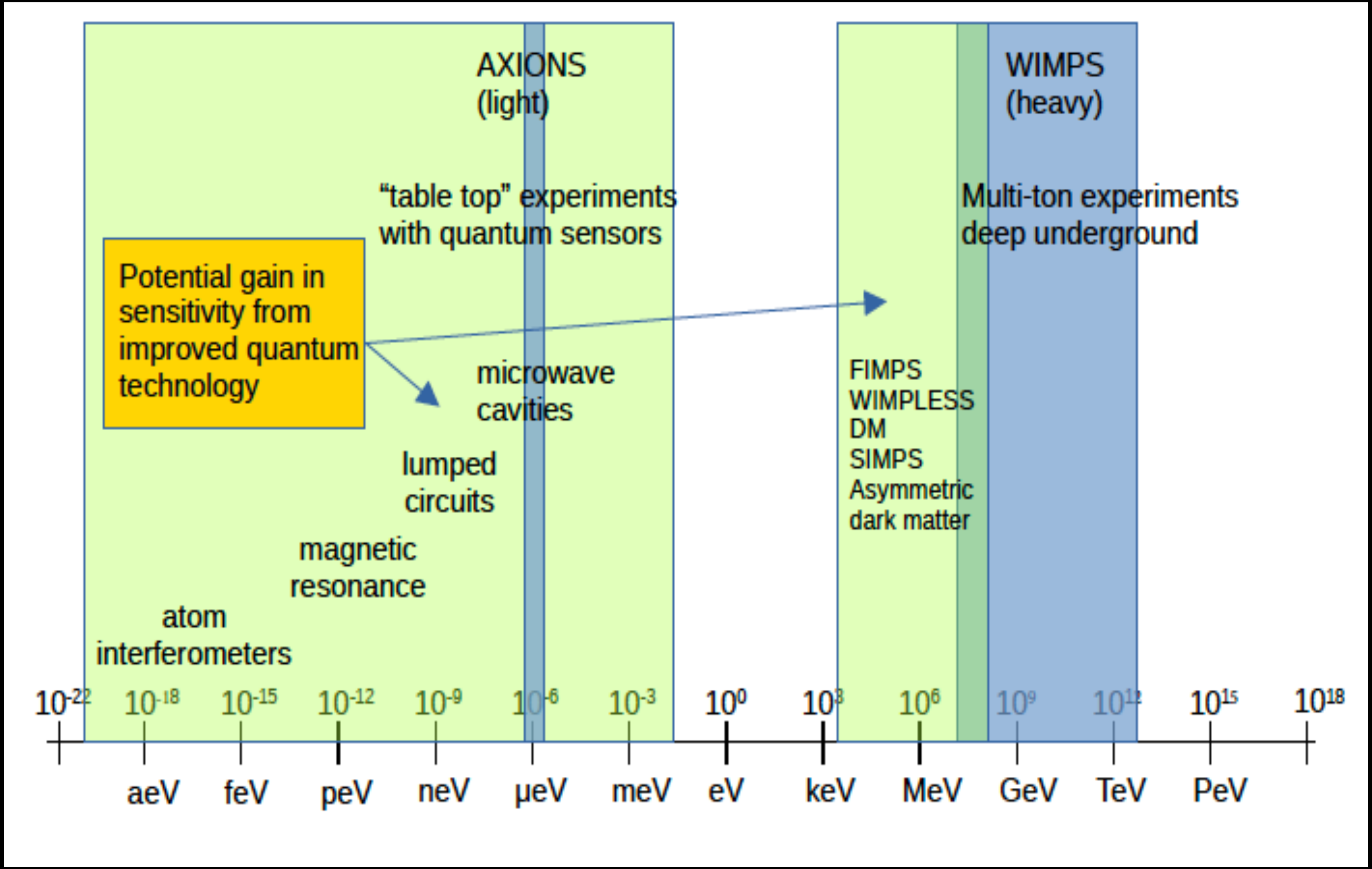
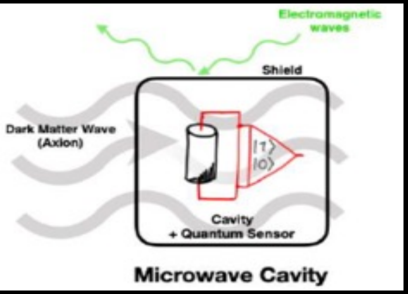
Example: potential mass ranges that quantum sensing approaches open up for DM searches >20 orders of magnitude



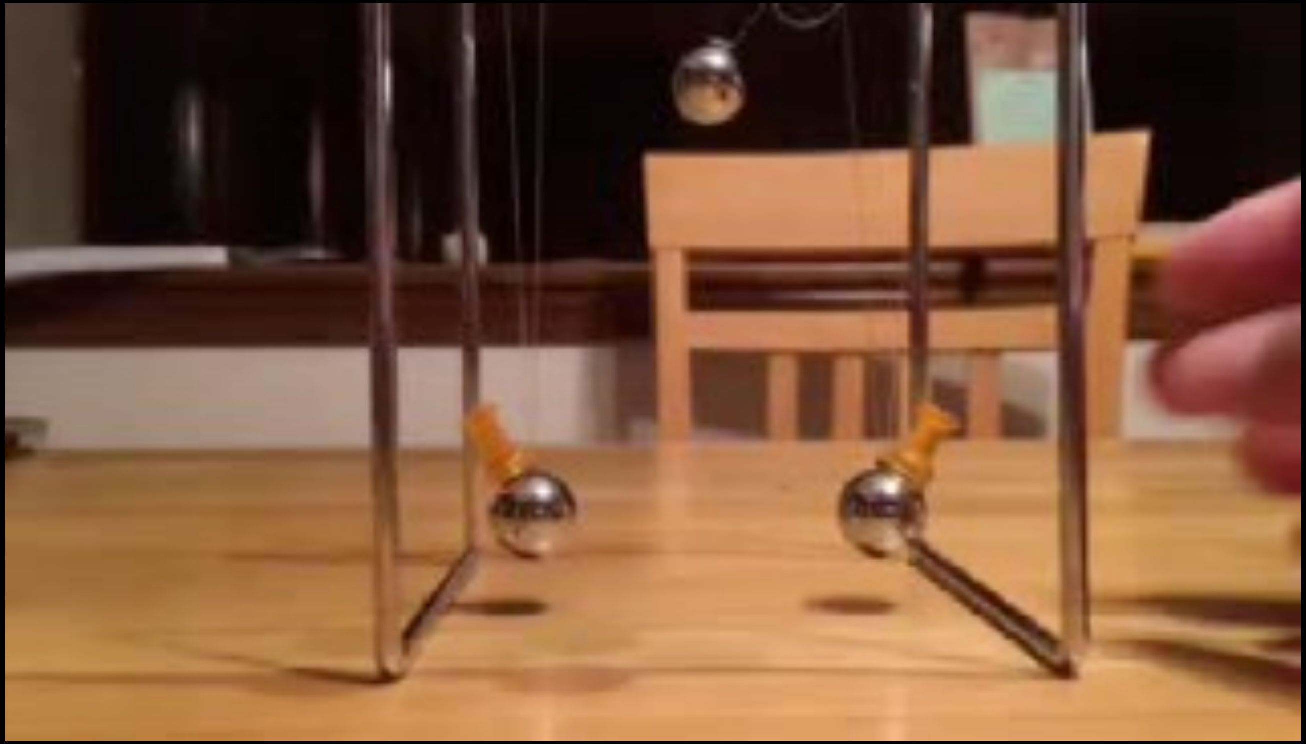
TODAY

\+ Quantum Sensors



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

Detection oscillator



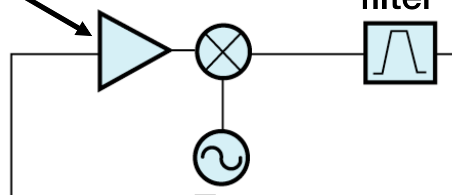
Axion wave

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

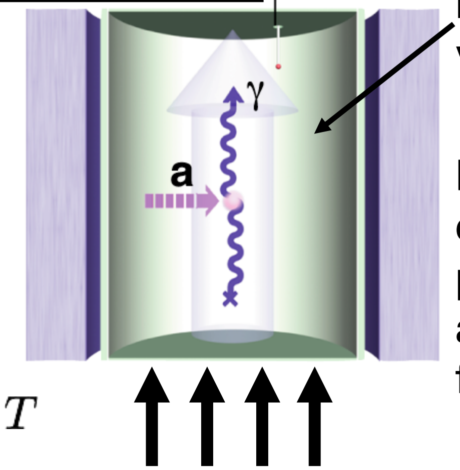
SUPERCONDUCTING QUANTUM ELECTRONICS:
- SQUIDs
- Josephson Parametric Amplifiers
- Travelling Wave Parametric Amplifiers
- Bolometers
- Qubits / QuBit arrays

Bandpass filter



Data Acquisition

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



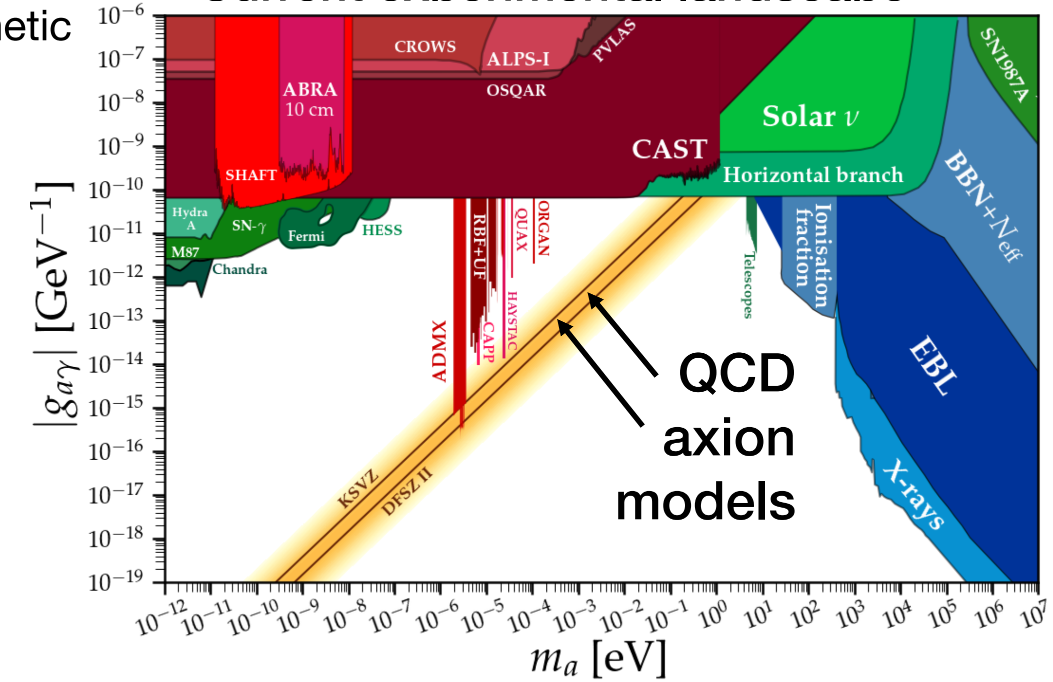
Electromagnetic resonantor volume V

Halo axions convert to photons in a magnetic field

System noise temperature: T

Static Magnetic Field B

Current experimental landscape

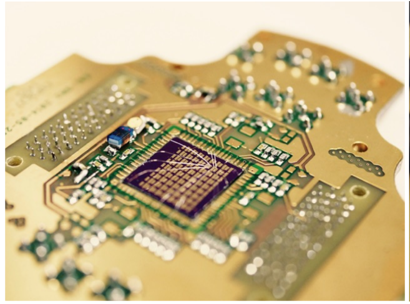
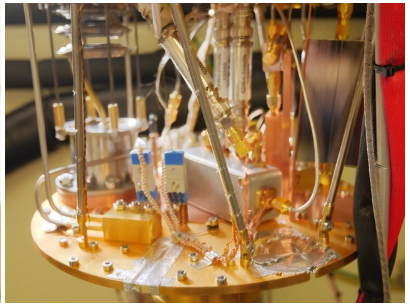


- Non resonant experiments have broad mass coverage, but insensitive to QCD axions
- Resonant experiments much more sensitive. ADMX is the only experiment to have probed a broad range of existing axion models. However, mass coverage too slow. Can speed up: 1. By using a new generation of quantum electronics;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

Quantum Electronics for QSHS

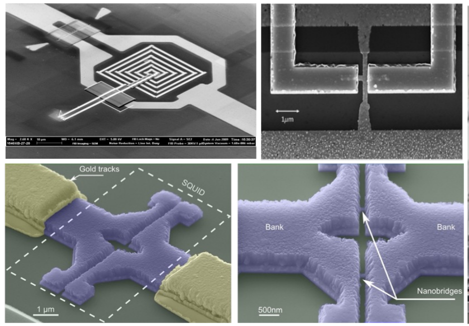
Josephson parametric amplifiers (JPAa) / Travelling wave parametric amplifiers (TWPAs)

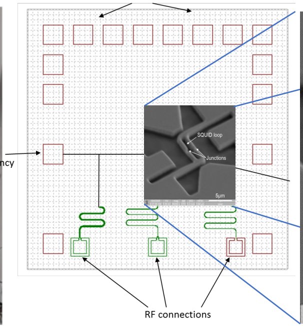
Lancaster University · Royal Holloway University of London · University of Oxford

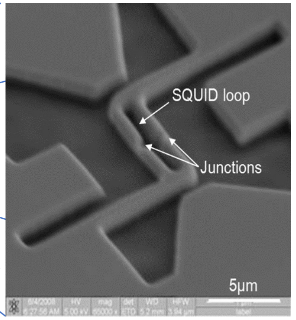




SLUG loaded SQUID amplifiers

UCL · NPL National Physical Laboratory

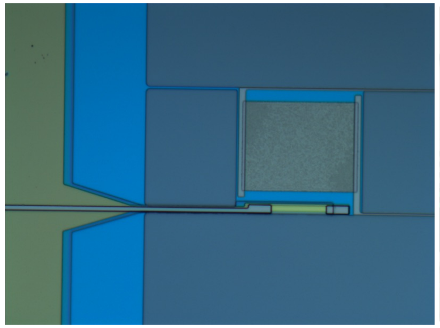
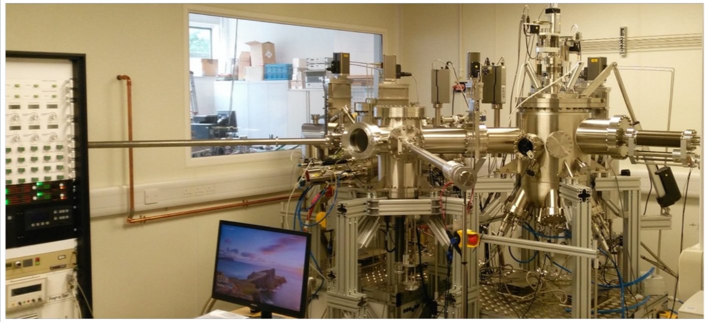




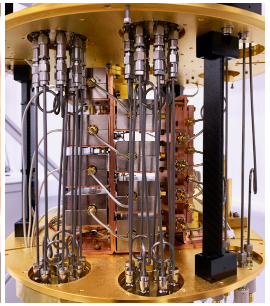
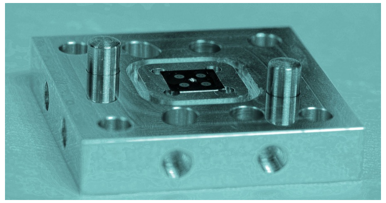
Cryogenic bolometer arrays

University of Cambridge

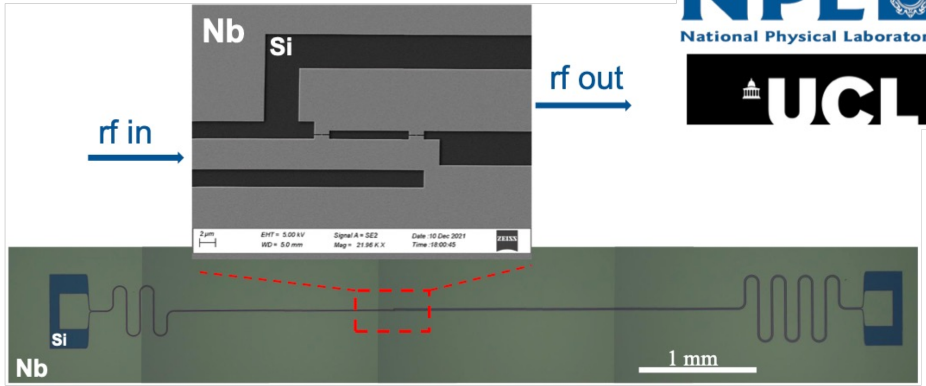
Qubit arrays

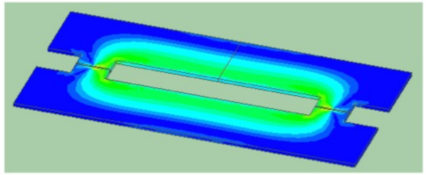
University of Oxford · Royal Holloway University of London

Progress

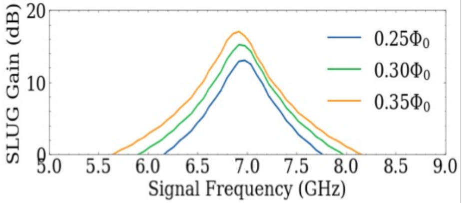
First SLUG loaded SQUID devices fabricated by the NPL/UCL group, Nov/Dec 2021. Currently under test.



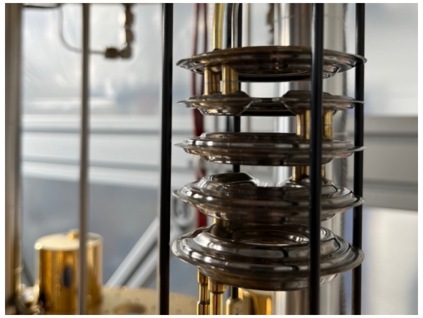


Ansys Maxwell – simulated inductance / capacitance of SLUG loop

Python – simulated frequency-dependent gain of SLUG amplifier



Claude Mostyn and Paul Smith (QSHS Ph.D. student, postdoc) with the dismantled fridge two days ago. Now re-assembled.

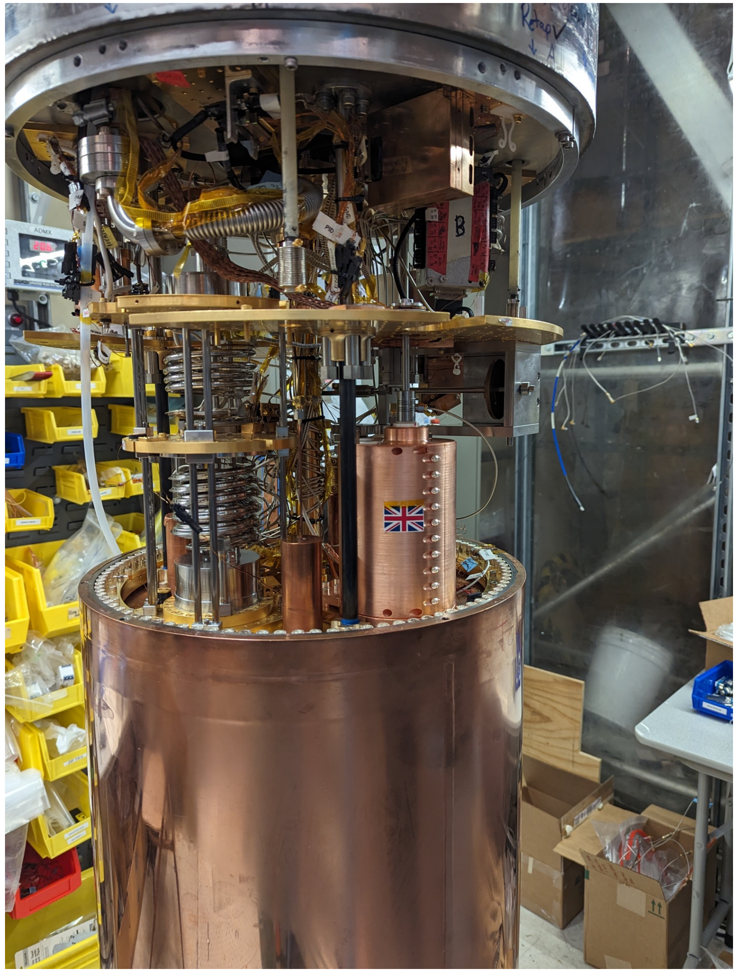


Lower heat exchanger

4m high lab space for the 20cm prototype at Sheffield

QSHS-ADMX collaboration

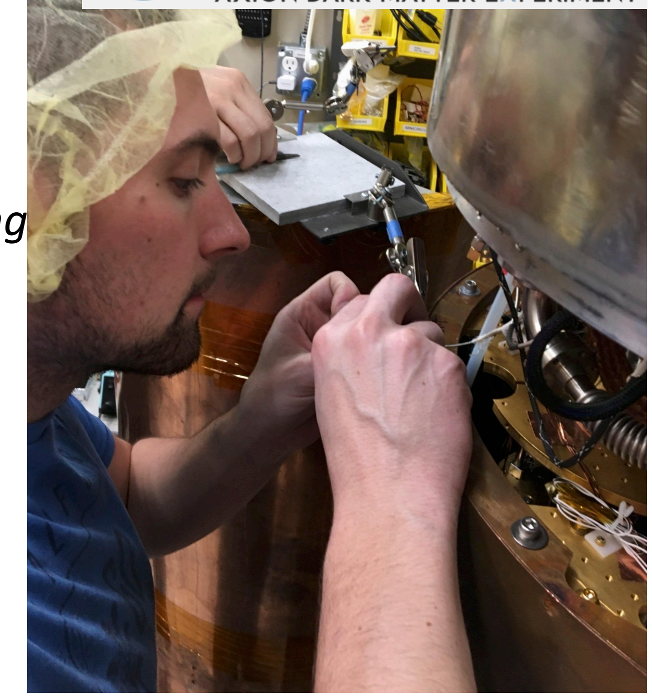
Sheffield (Ed Daw PI), Oxford, UCL, NPL, RHUL, Lancaster, Cambridge



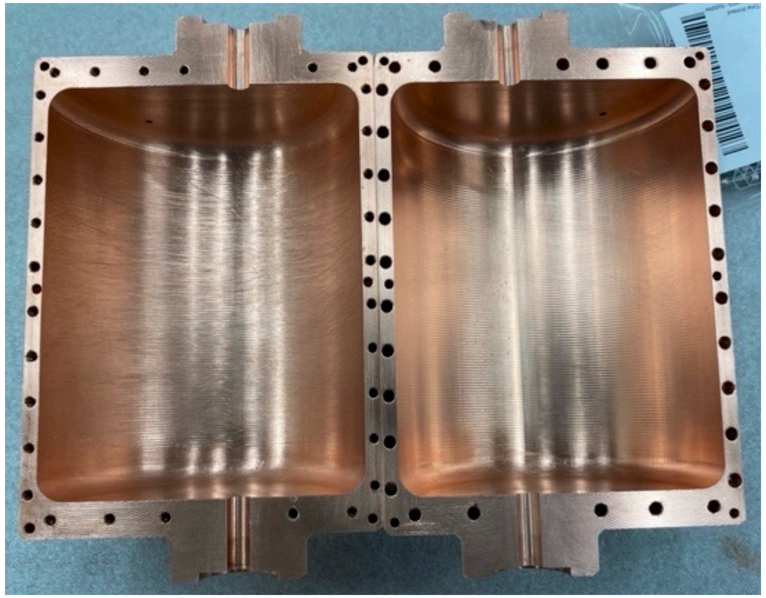
ADMX detector with UK sidecar cavity installed, ready for cooling. December 2023.

- 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. See QSHS talk later today.**

Mitch Perry working on the ADMX insert.



QSHS cavity for ADMX



Future Plans

See QSHS talk by Ed Daw

QSHS Phase 1 (current STFC Support Until 3/25)

- First tests of developed quantum electronics this summer
- Run 1 with a single cavity, first untuned, then with tuned.
- Evaluation of superconducting elements in field for ADMX
- Establish sensitivity to axion dark matter, extrapoloate to projected sensitivity at lower noise, larger volume.
- Test resonant feedback at room temperature

maybe during phase 1

- Integrate Quantum Electronics with axion receiver
- Noise temperature determination, science data taking
- Cold tests of resonant feedback system in QSHS

QSHS phase 2 requires support.

- Further tests of quantum electronic readout schemes.
- Tests of non-cavity electromagnetic structures.
- Further cavity development in collaboration with ADMX.
- Continuing science runs, search for hidden sector new physics

Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

QUEST DMC

ROYAL HOLLOWAY UNIVERSITY OF LONDON

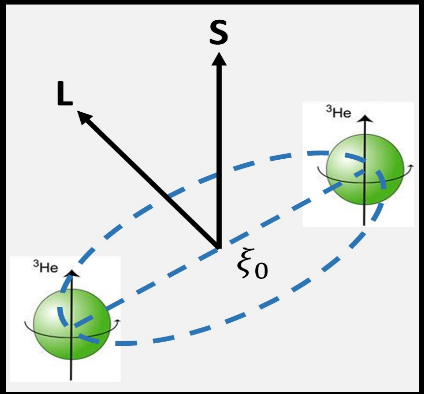
Lancaster University

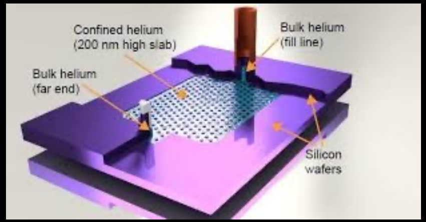
University of Sussex

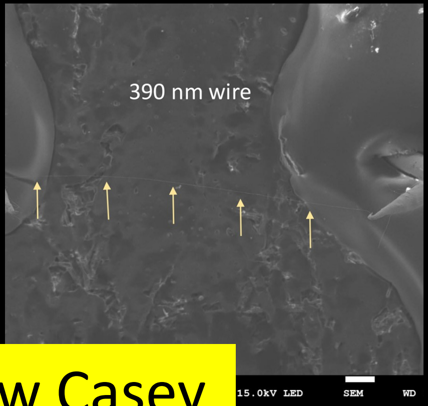
UNIVERSITY OF OXFORD

UNIVERSITY OF LIVERPOOL

ULT + Superfluid ^3He + Quantum Technologies

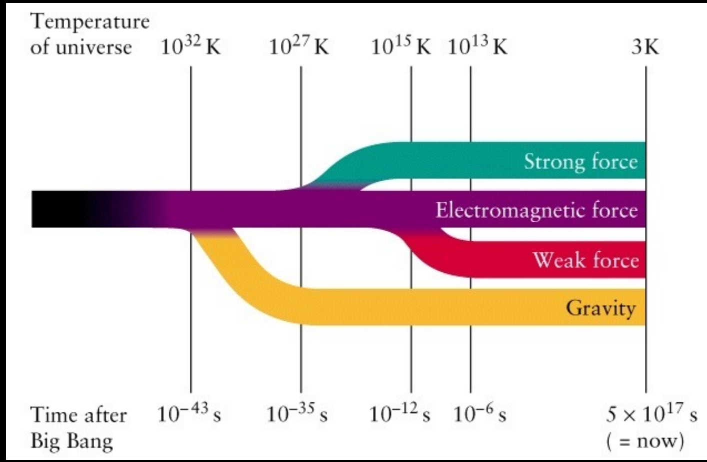


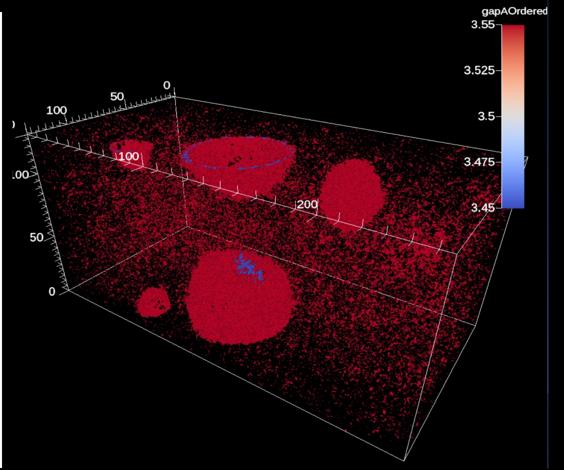




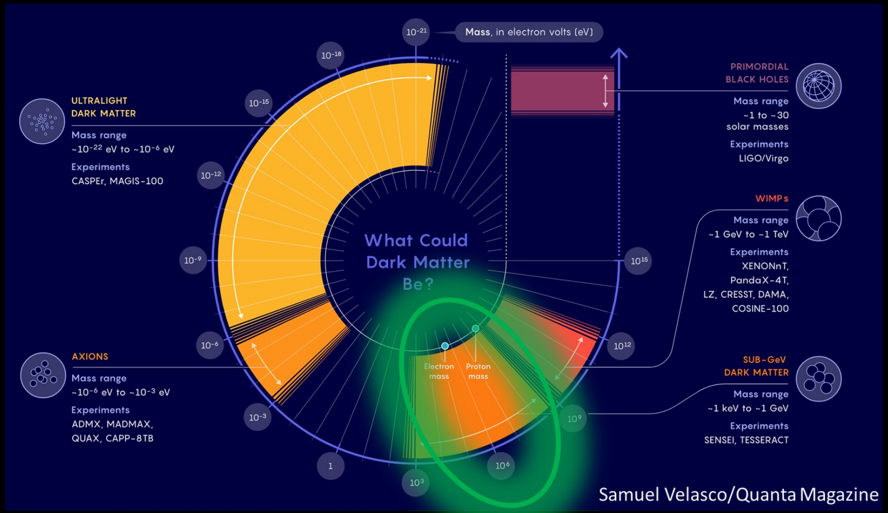
See QUEST-DMC talk by Andrew Casey

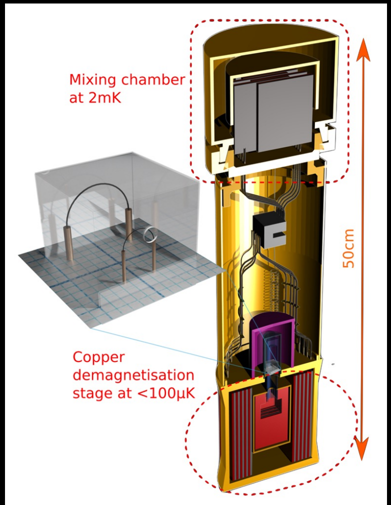
Phase Transitions in the Early Universe



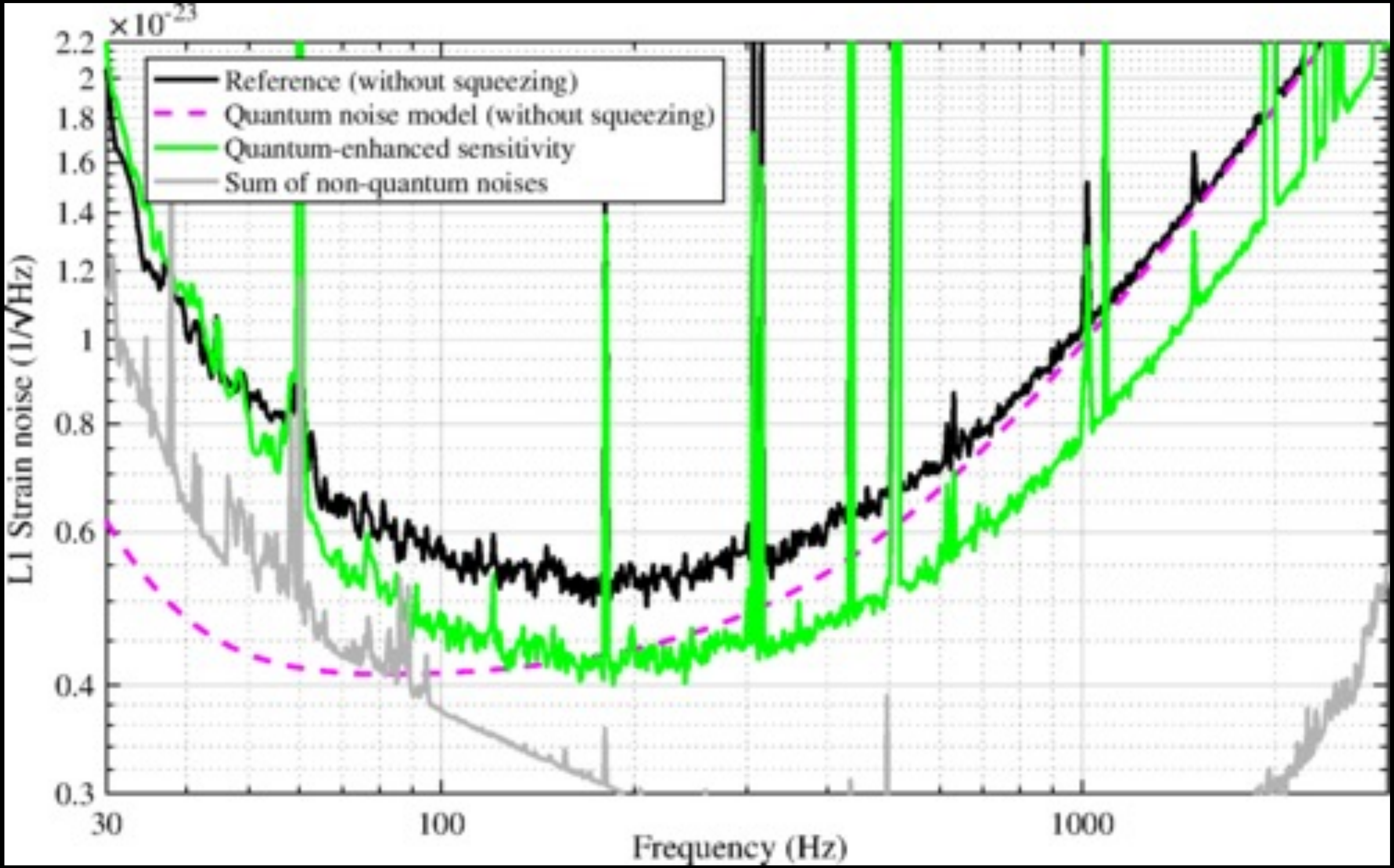


Detection of sub-GeV dark matter





LIGO: Quantum enhanced sensing-Squeezed light for improved sensitivity

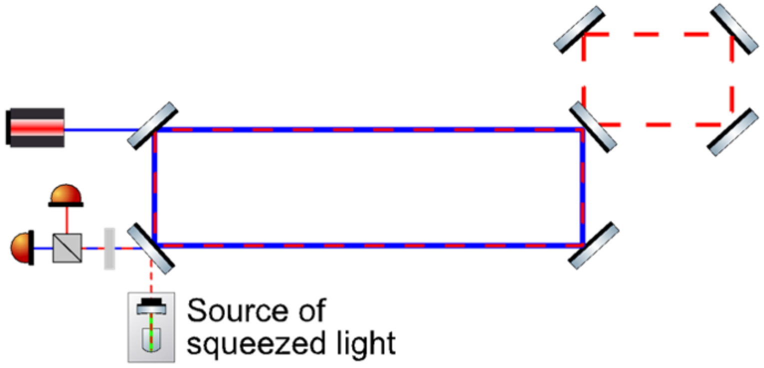


https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.231107
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.231108

Work Packages

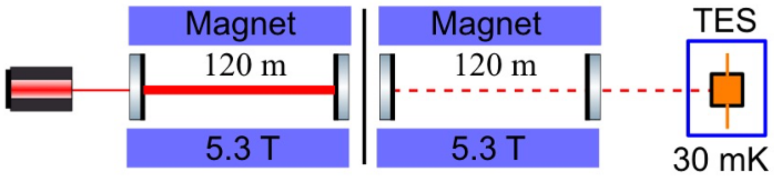
WP 1: Axions in the galactic halo

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



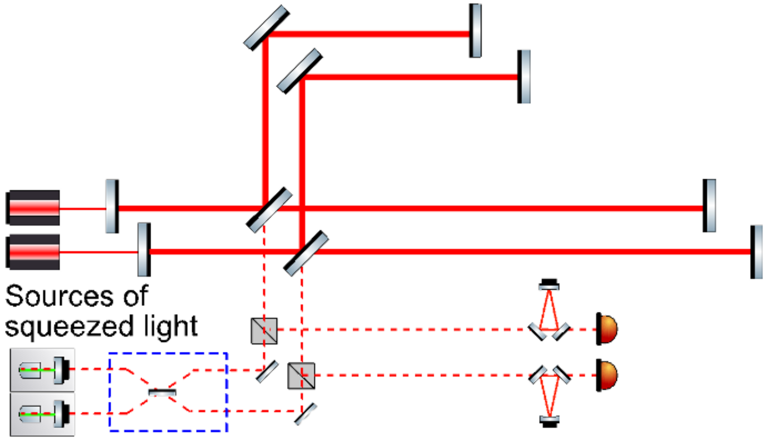
WP 2: Light-shining-through-wall (collab.)

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



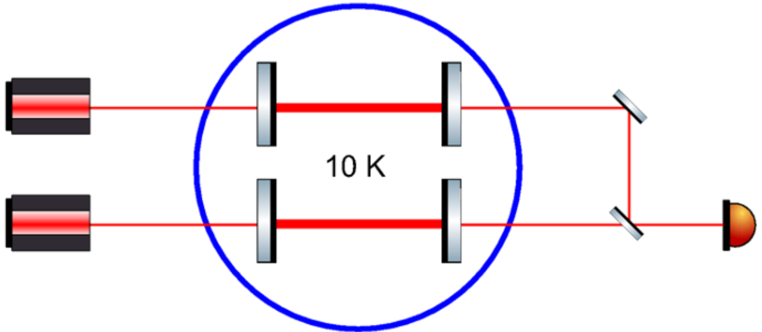
WP 3: Quantisation of space-time

- Testing ideas on quantization of space-time
- Sensitivity of $2\text{x}10^{-19}$ 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



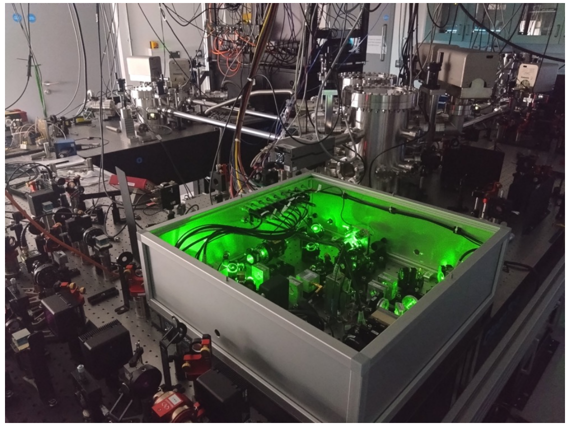
QI Quantum-Enhanced Interferometry for New Physics

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

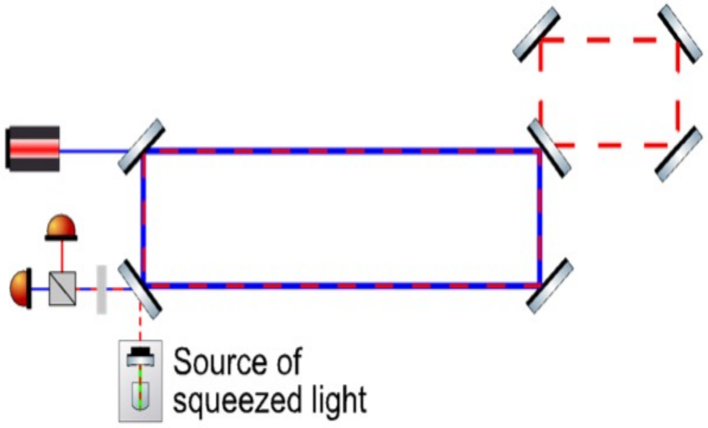


QUEST

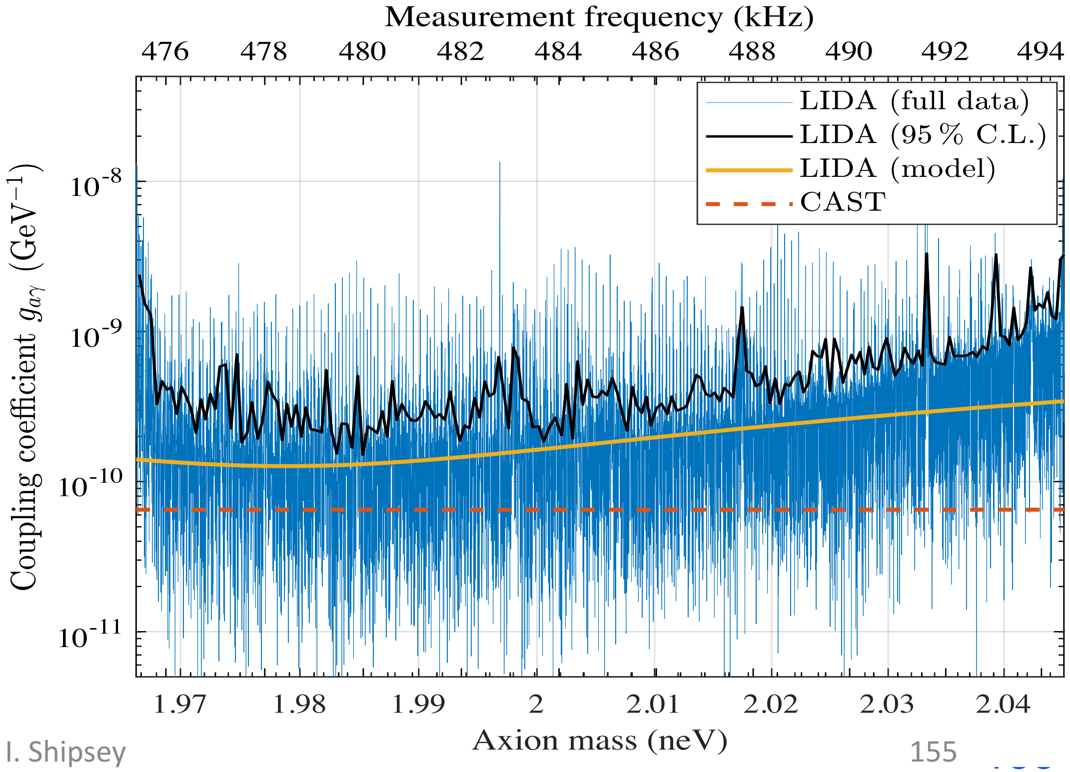
WP 1: Laser interferometeric detector for axions (LIDA)

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

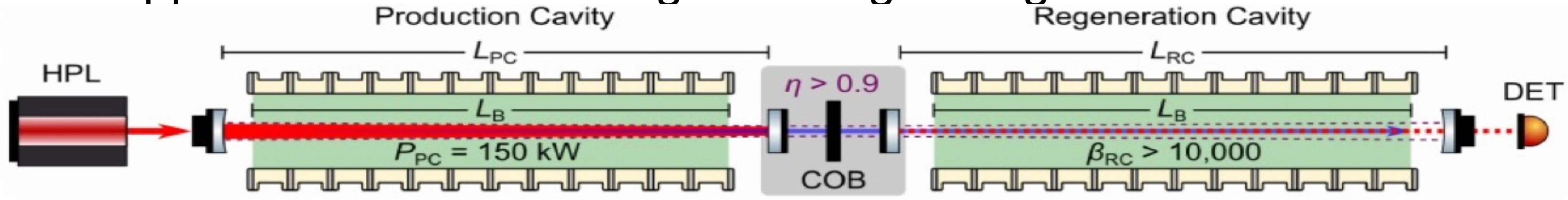


- Completed the first science run to search for axions with mass of 2 neV
- Leading observatory in its class (compared to the MIT’s and U Tokyo’s setups)
- Achieved the world record intensity in laser interferometers (4.5 MW / cm^2)
- Proposed axion searches with photon counting

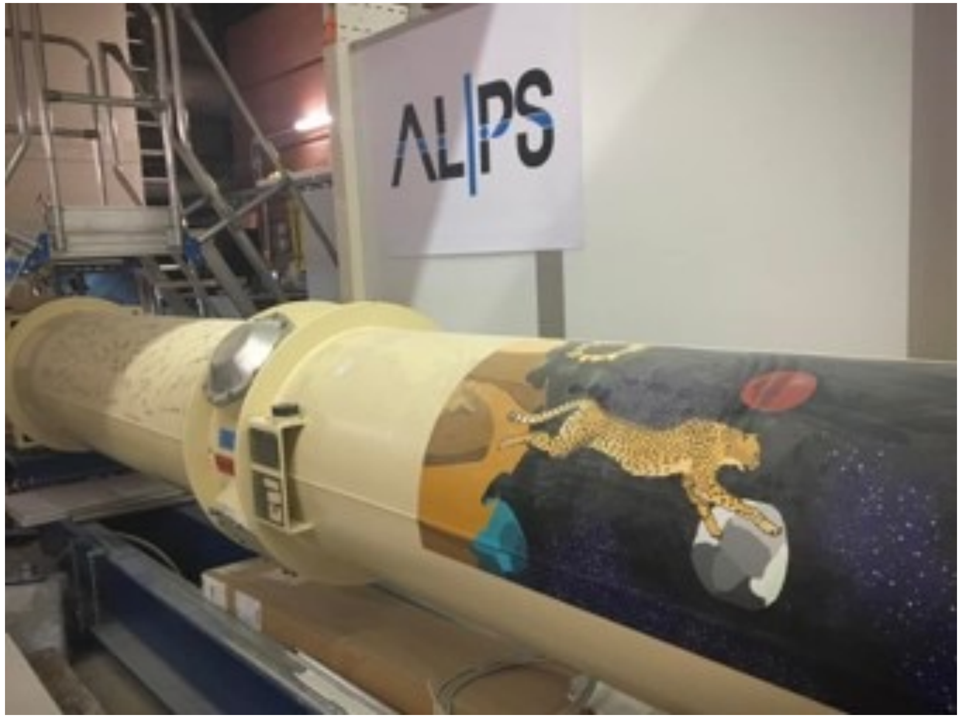


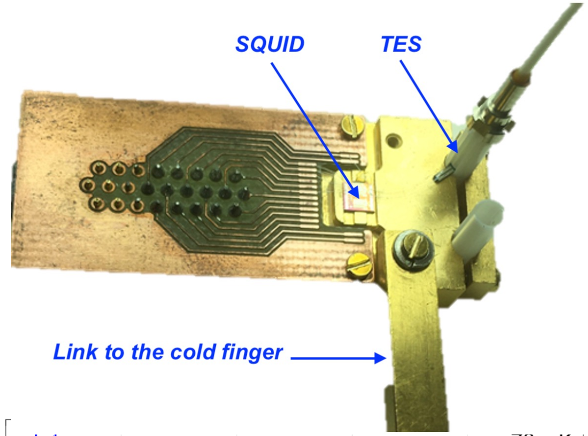
arXiv:2307.01365 arXiv:2401.11907 arXiv:2309.03394

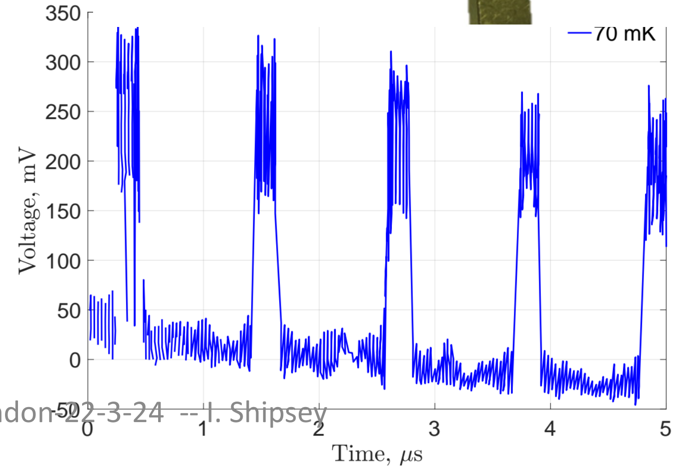
WP 2: Support for the ALPS II Light shining through walls Axion search experiment



- ALPS II is a new particle search experiment at DESY in Hamburg
- QI support to commissioning: Milestone of current first science run reached world record for light storage time in 2-mirror cavity (67 ms)
- New TES detector under commissioning

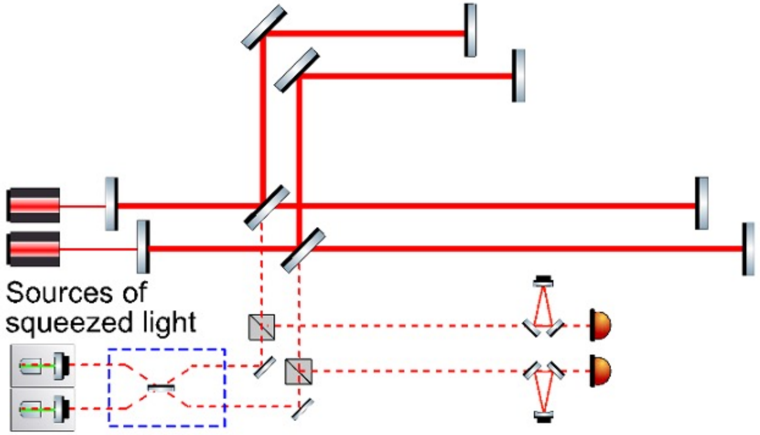


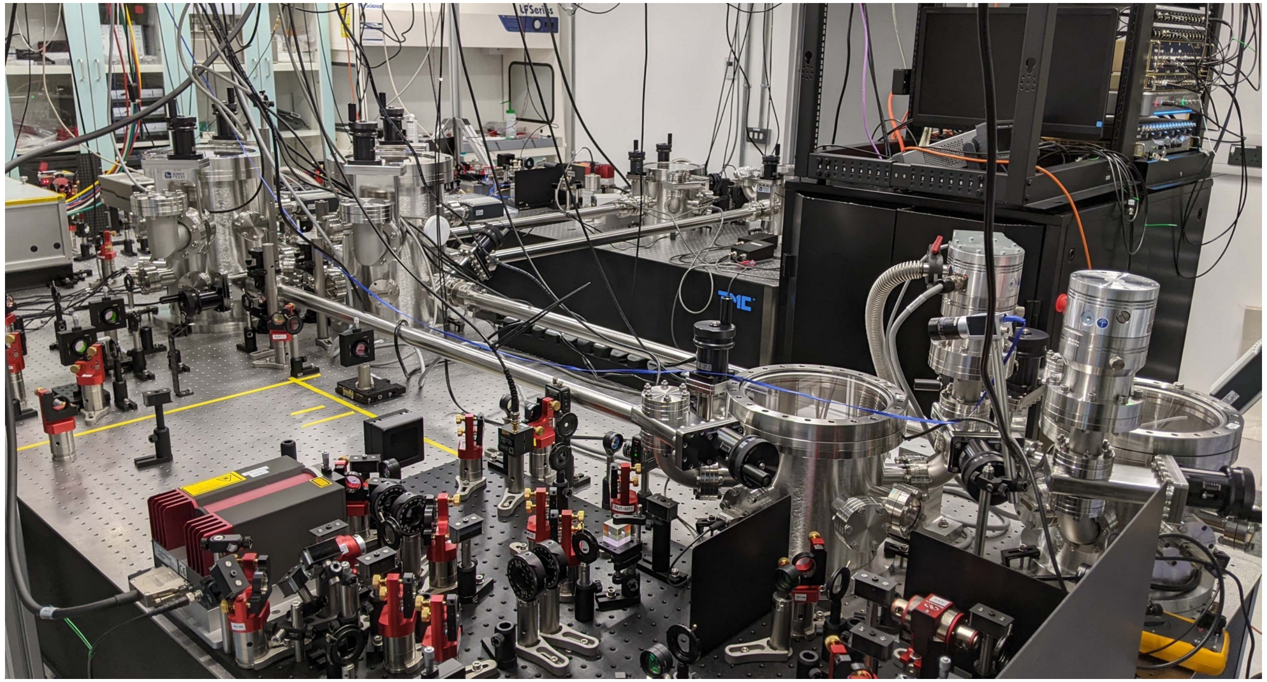


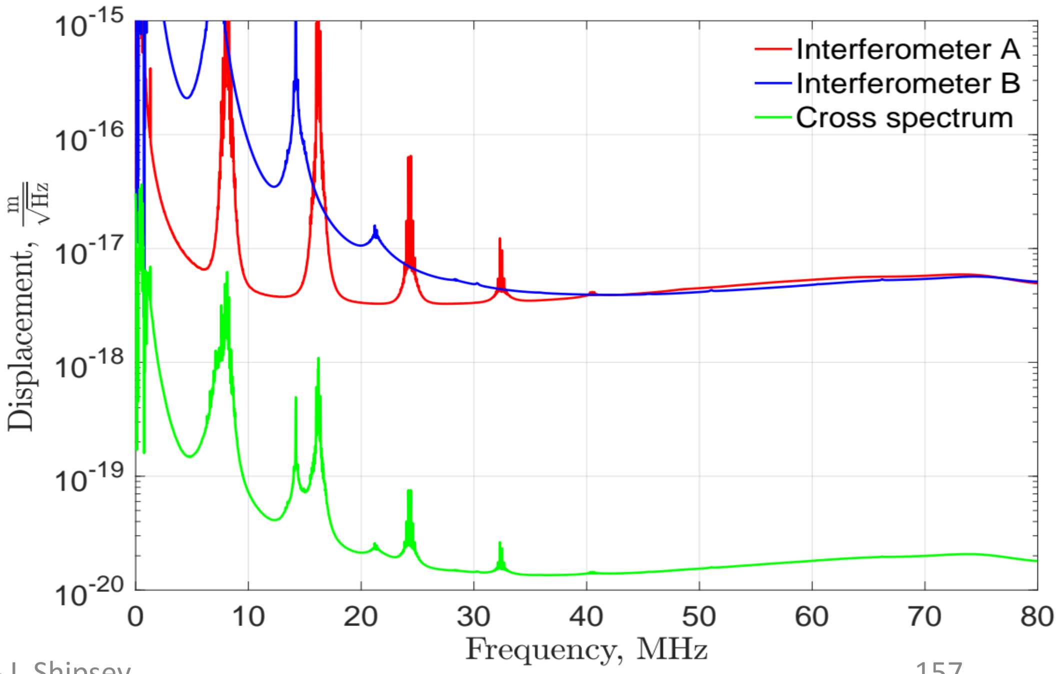


WP 3: QUantum-Enhanced Space-Time experiment (QUEST)

- 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

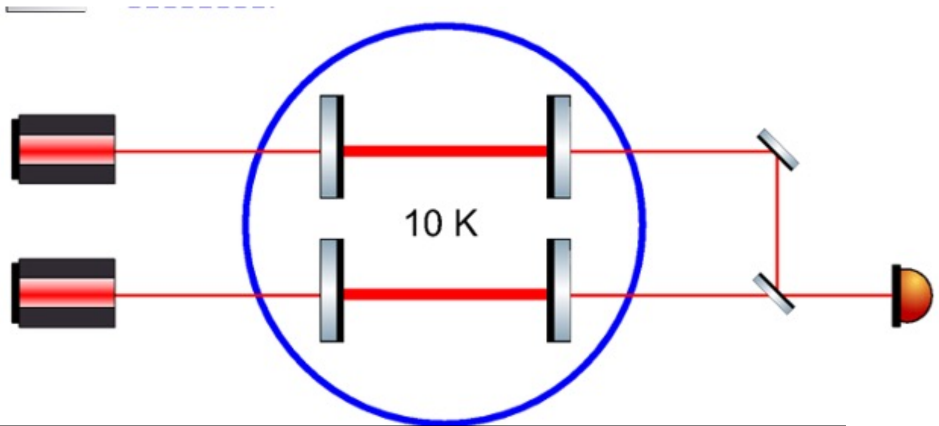




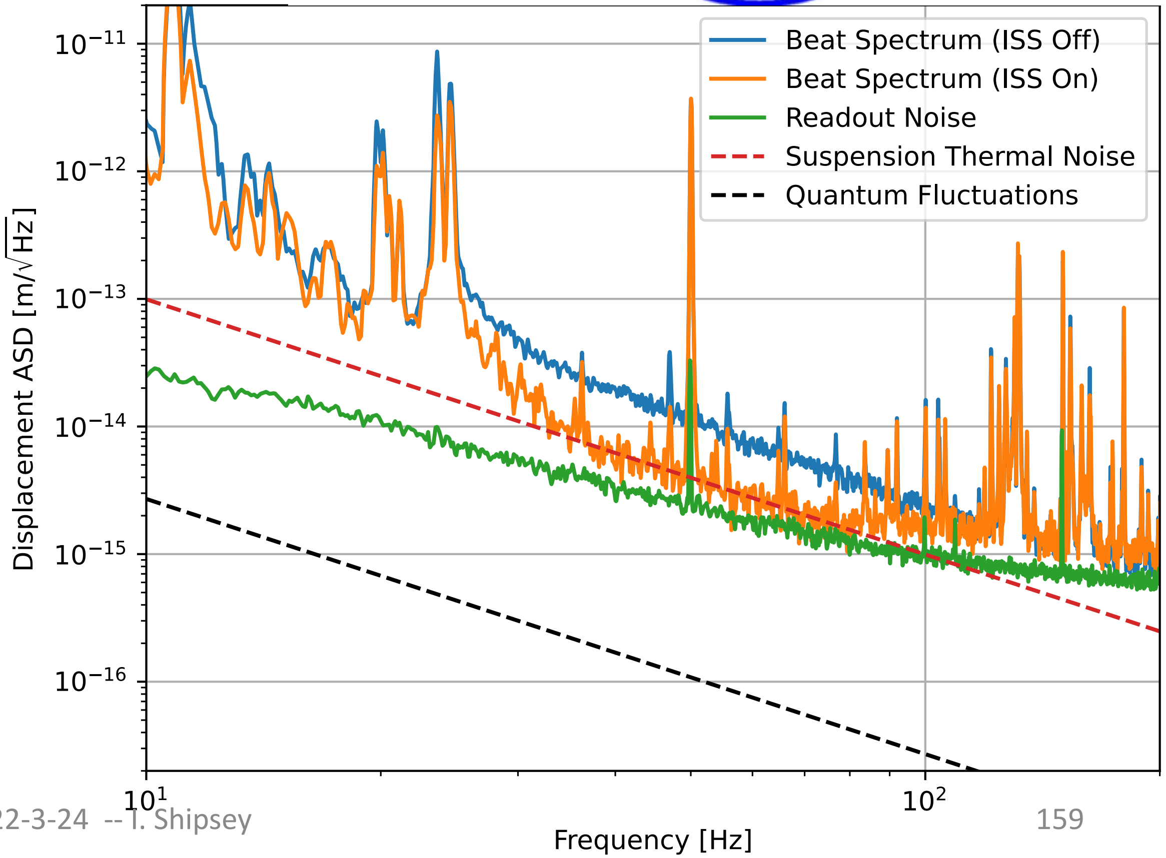


ArXiv 2008.04957

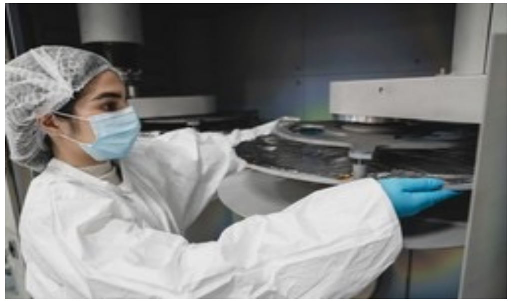
WP 4: searches for semiclassical gravity

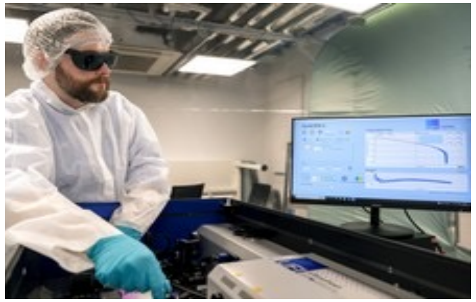


- State-of-the-art passive and active inertial isolation of optical cavities
- Reached the suspension thermal noise level (significant milestone)
- Tested the “pre-selection” model of semiclassical gravity (data analysis ongoing)



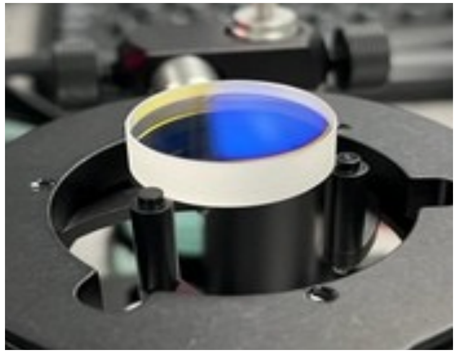
- **arXiv:2402.00821**

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

- UK's first production site for ion beam deposited (IBD) optical coatings (www.epoc.scot).
- Largest IBD system in world in terms of coating uniformity area (2 × 620 dia / 200kg substrates).
- Optical absorption @1064 nm < 1 ppm achieved.
- Reflectivity @1064 nm > 99.97% achieved for QI testbeds.
- Laser damage threshold 58.3 J/cm^2 (1064nm, 11.6ns pulse, 100Hz rep rate).
- QI project the first to demonstrate precision optics (mirrors and antireflection coatings) in 2022/23 – requests from other academic and commercial projects increasing *e.g.* mirrors at 689 nm manufactured by QI consortium for quantum/atomic clocks for BT and MSquared for high-speed telecoms testbeds in December 2023 (already in optical cavities / under test)

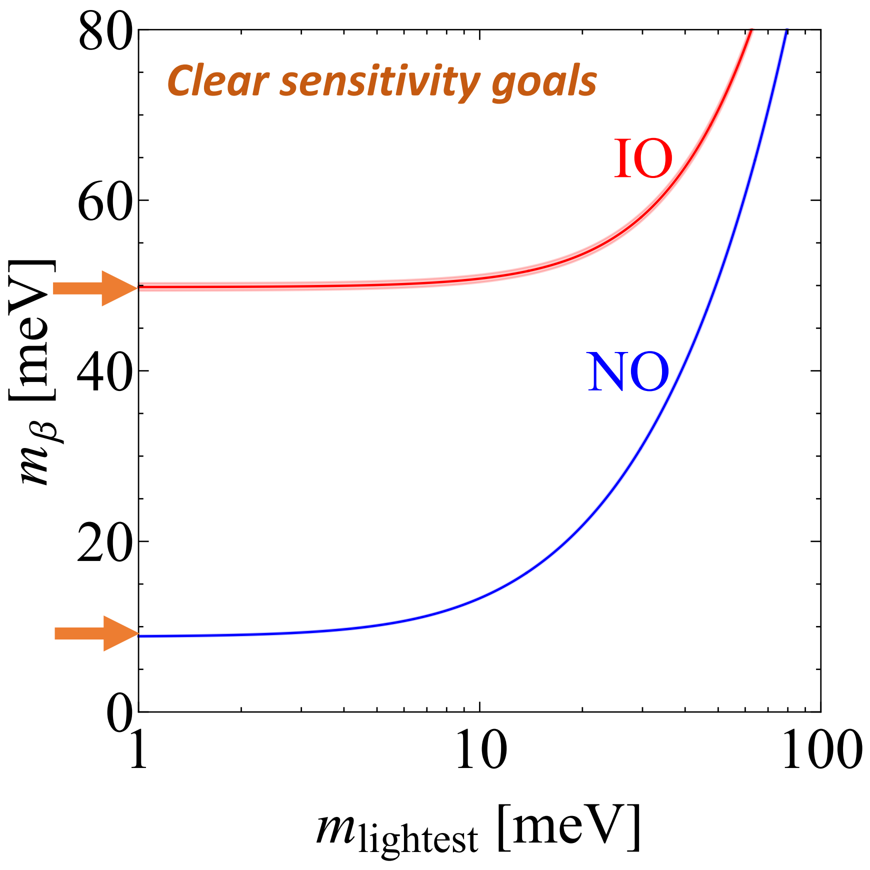


Mirror for QI project with *R*=99.9738%

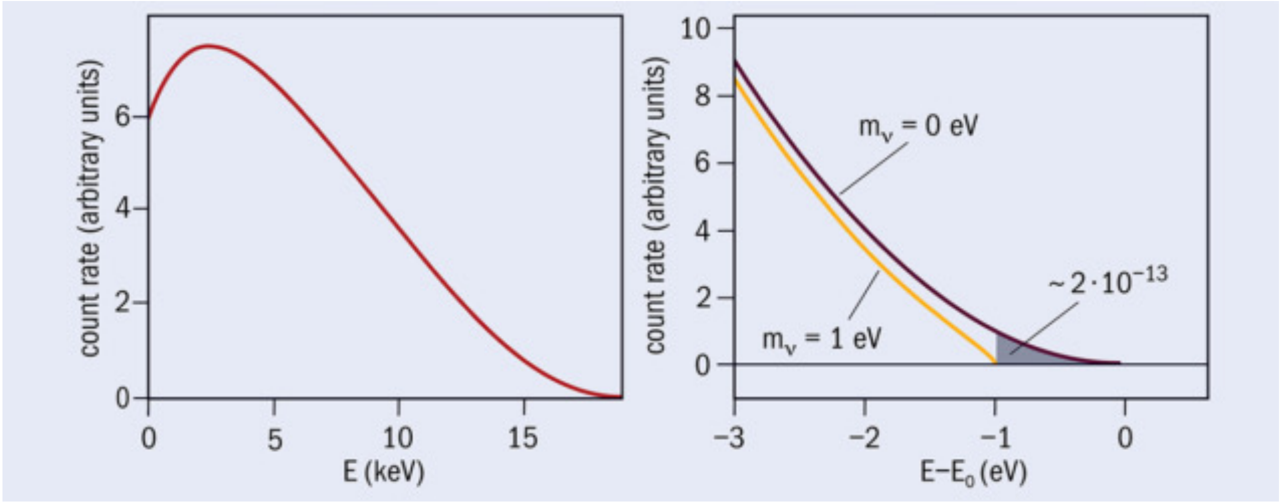
Neutrinos

Absolute neutrino mass

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

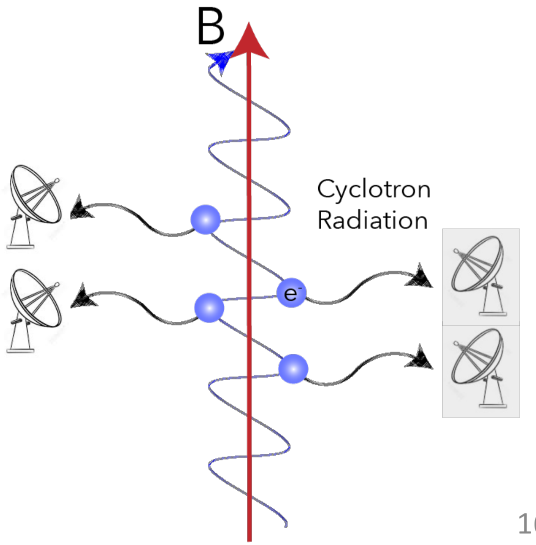


*Atomic ^3H β-decay – **model independent***



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

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



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

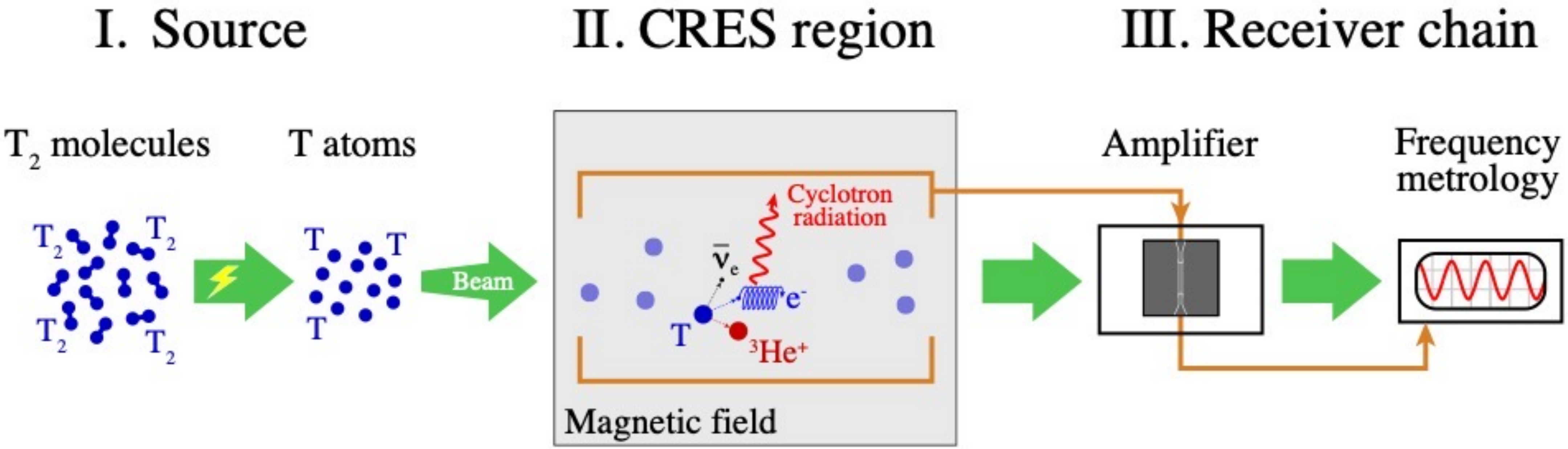
Neutrino mass measurement from atomic ^{3}H β-decay via Cyclotron Radiation Emission Spectroscopy using latest advances in quantum technologies.

Current project (QTFP Wave 1, 2021-2025)

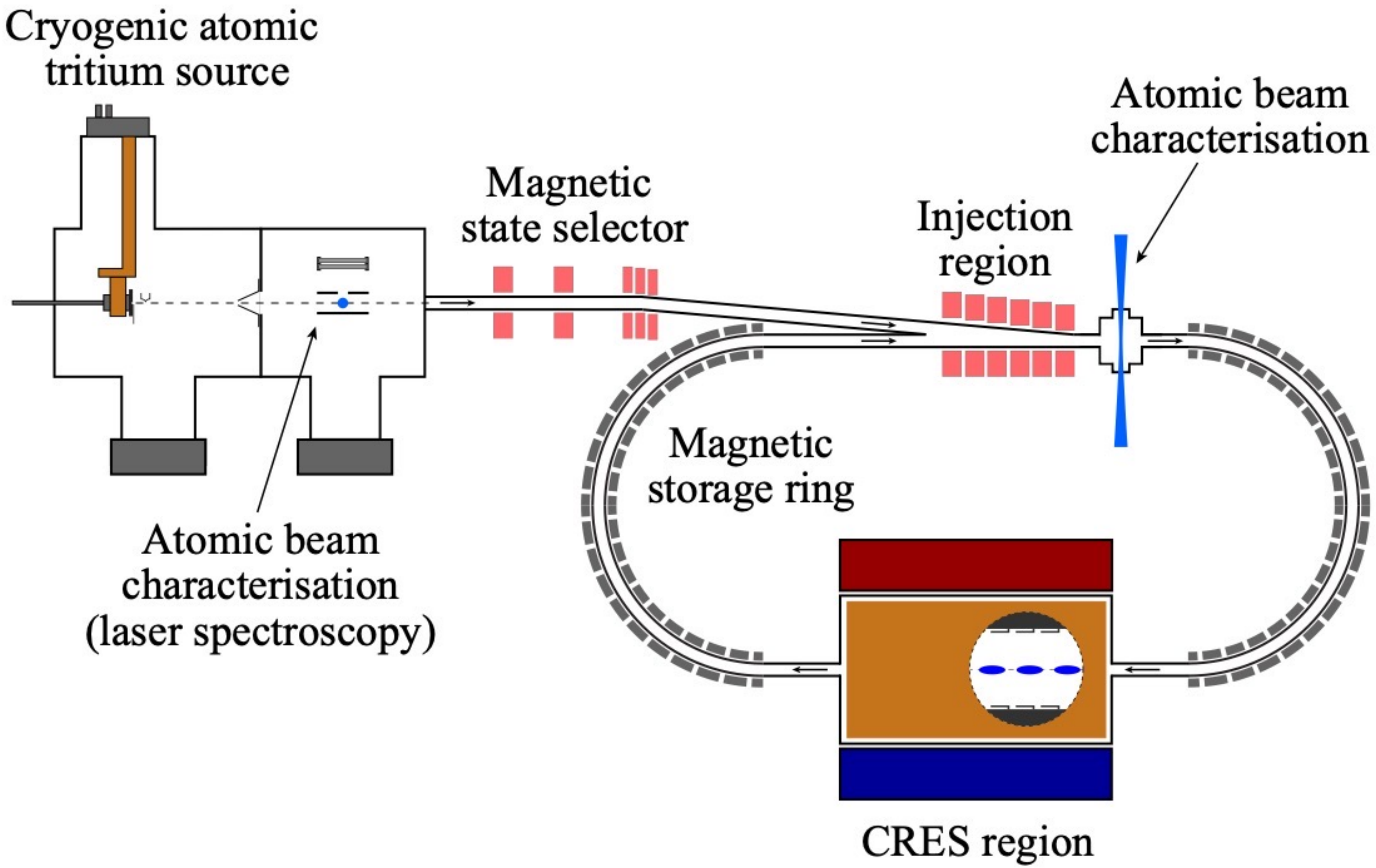
Technology Demonstration: CRESDA = CRES Demonstration Apparatus

- **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

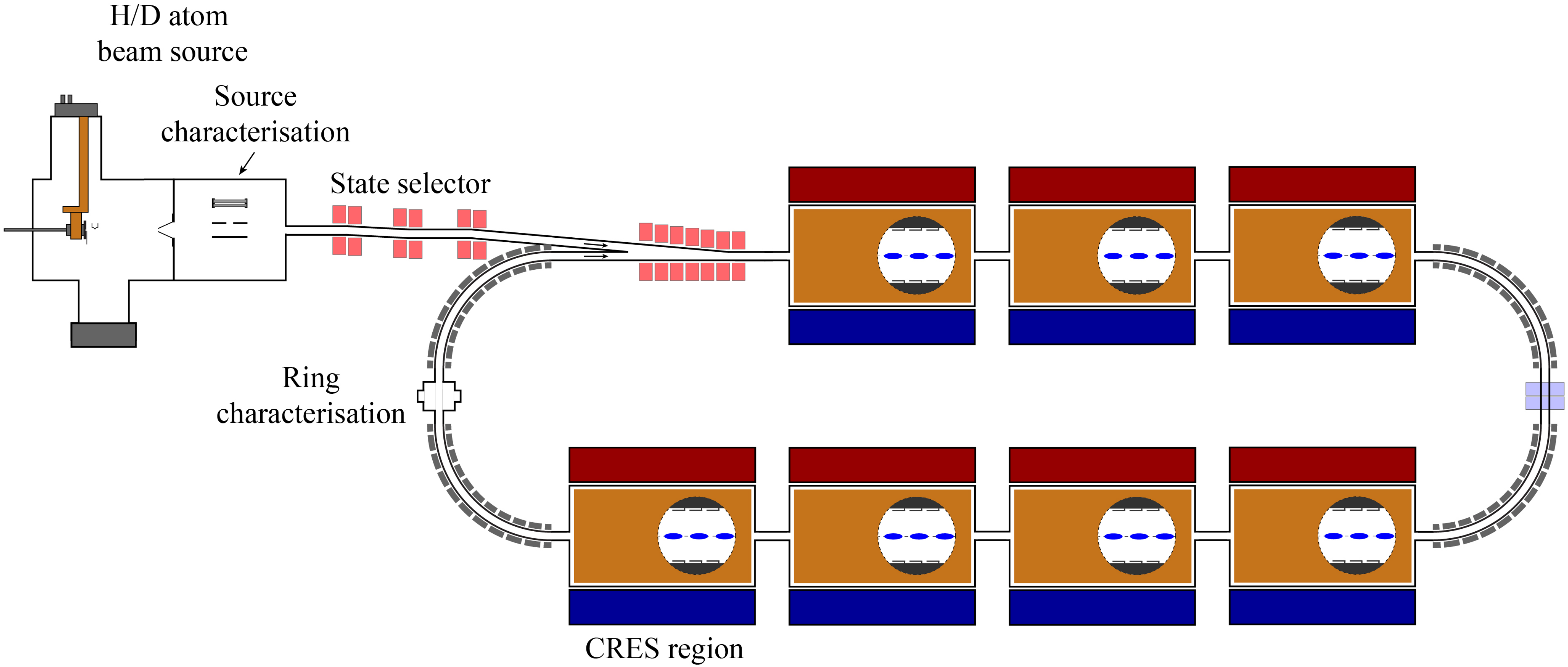
CRESDA Scheme



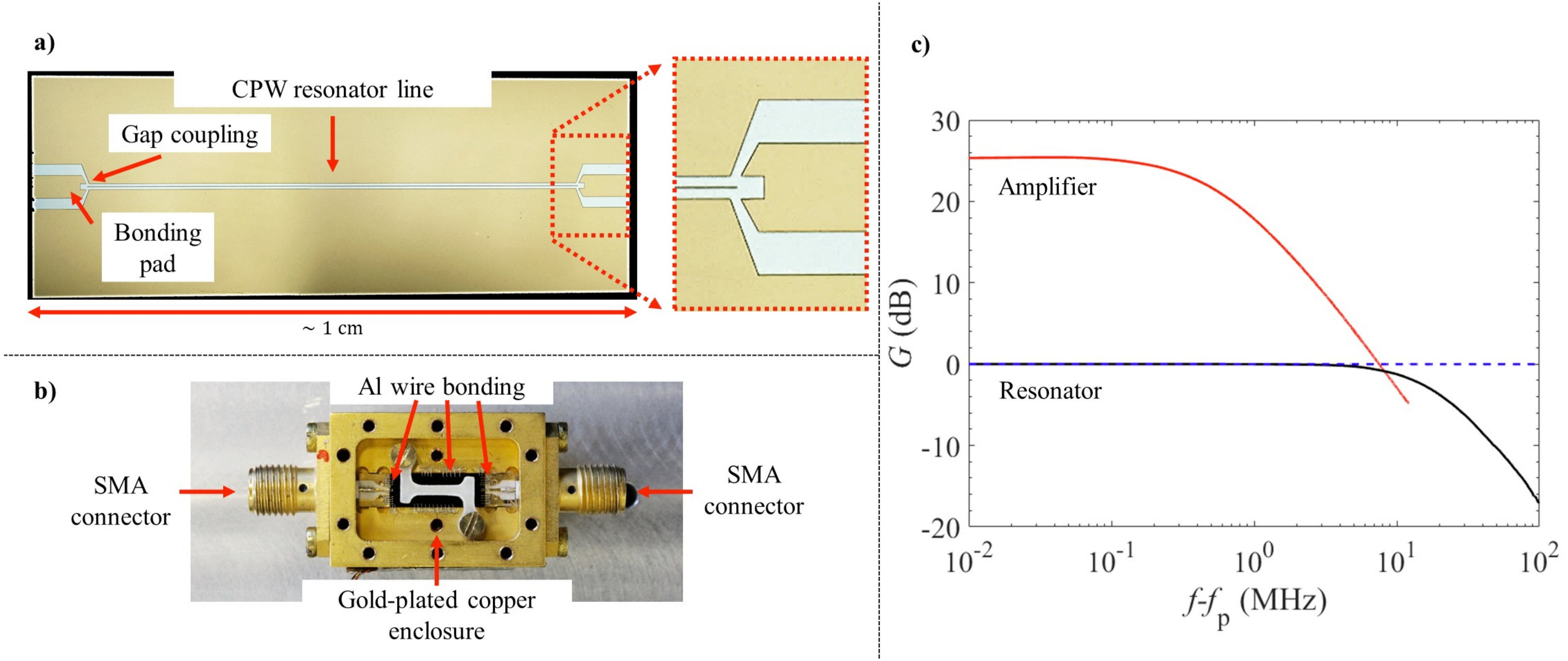
CRESDA Outline



Scalability of Storage Ring Concept



Superconducting kinetic inductance parametric amplifiers

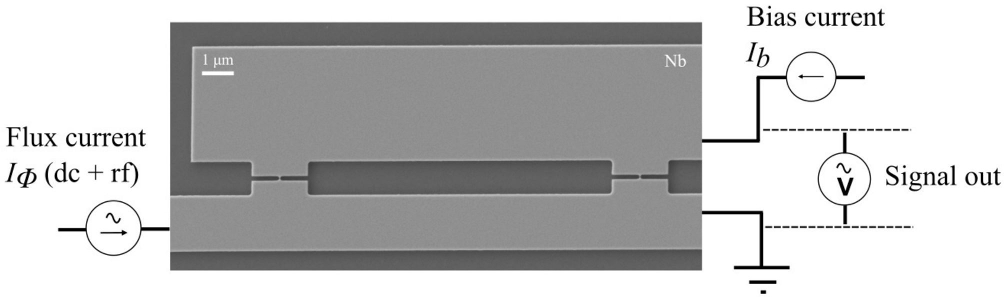


Zhao et al., Supercond. Sci. Technol. 36 105010 (2023)

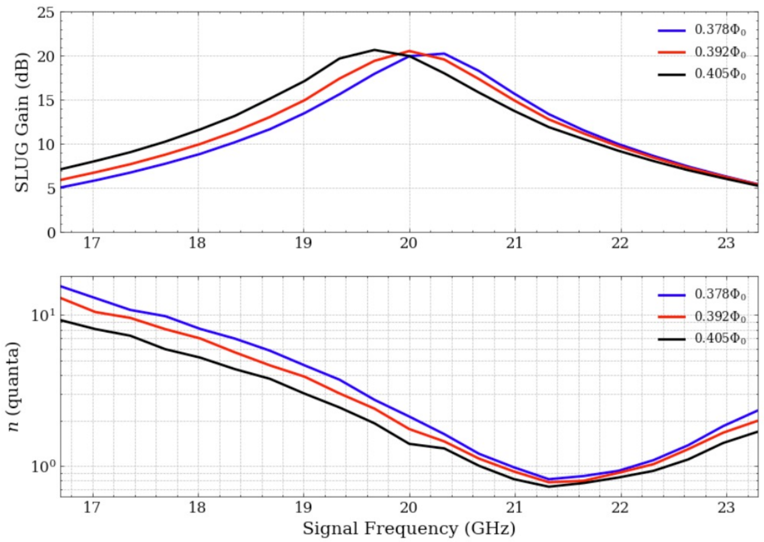
- NbN, Nb, Al, Ti paramps *fabricated* and *tested* at 18 GHz
- Robust and repeatable fabrication, *quantum-noise limited* performance
- Can be operated at 4K – potential for *two-stage* amplification
- Expect to reach *TRL7/8* by end of current phase (Mar-2025)

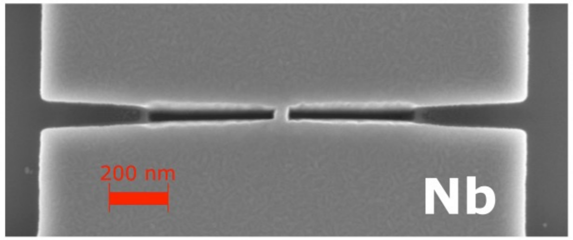
SLUG Amplifiers

a)



b)





- **S**uperconducting **L**ow-inductance **U**ndulatory **G**alvanometer
- Amplifiers based on nanobridge SLUGs comprehensively modelled, demonstrating *high gain* and *large bandwidths*
- SLUG elements with Nb nanobridges fabricated by several methods and characterised in detail

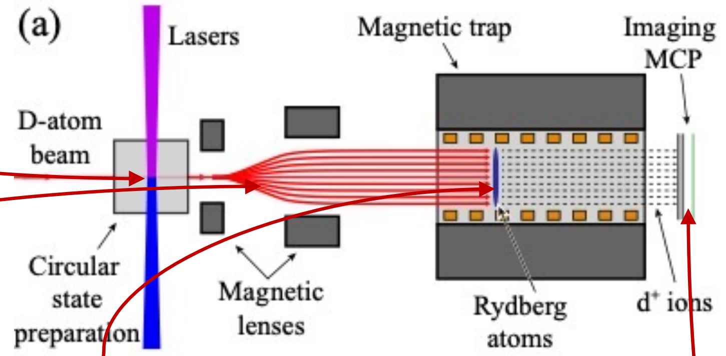
G. Chapman et al., IEEE Transactions on Applied Superconductivity 34 (2024).

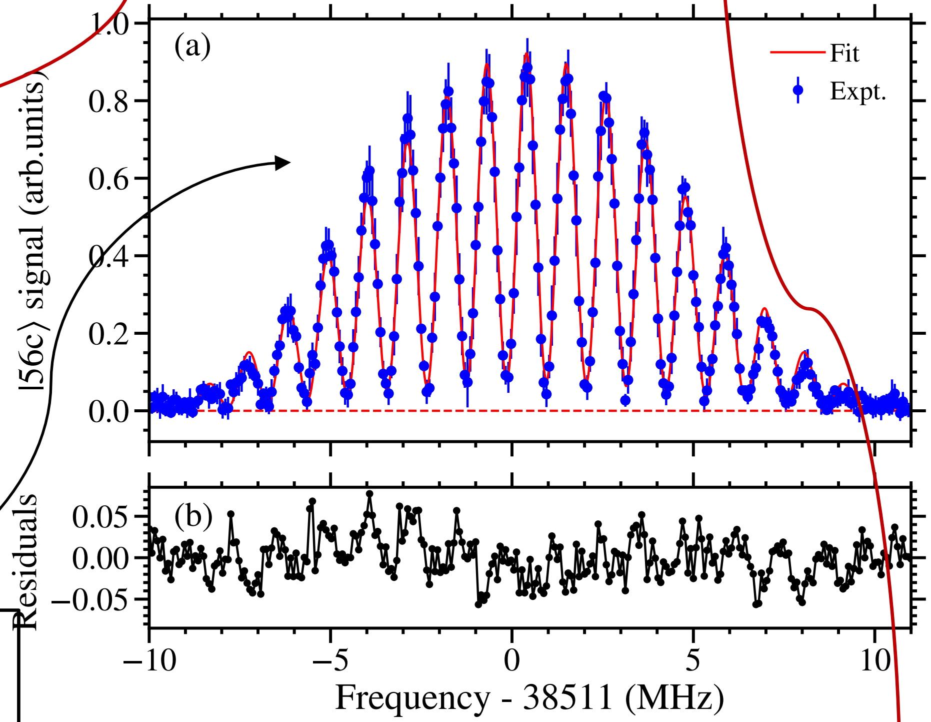
Precise B-field mapping using H-atoms as ***quantum sensors*** – Rydberg Magnetometry

H/D/T atoms are prepared in circular Rydberg states

Beam is expanded to fill the CRES region

At selected time pulses of MW-radiation applied within CRES volume drive Rydberg-Rydberg transition.
These transitions are sensitive to B-field variations at <***1*** μ**T level with a ~1mm spatial resolution**





Current results (!) Phys. Rev. A **107**, 062820

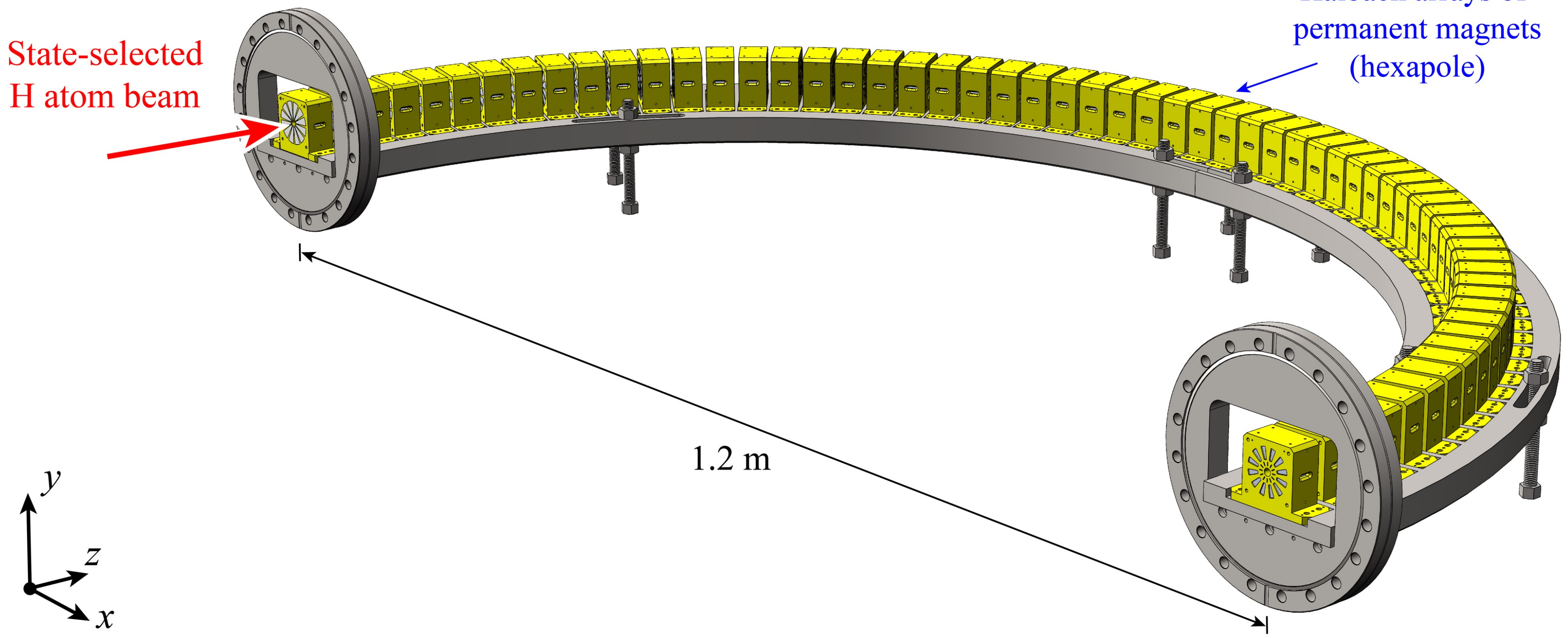
- **Absolute precision ±2 μT, relative ±900nT**
- **Spatial resolution ±0.87mm**
- **Electrometry abs precision ~ 85 μV/cm**
- **Limited by control of stray electric fields. Will improve**

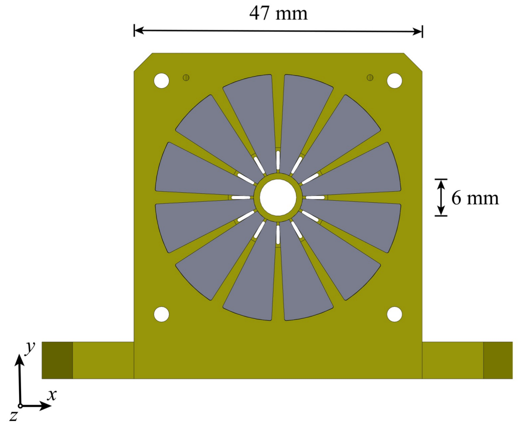
Transitions are detected by state-selective ionisation

Ramsey spectrum of MW-transition between circular Rydberg states (Helium example)

H/D/T-atoms confinement with storage ring

- Confine and guide spin-polarised beams of H/D/T
- Separate confinement fields from CRES field
- Components manufactured and delivered
- Assembly underway

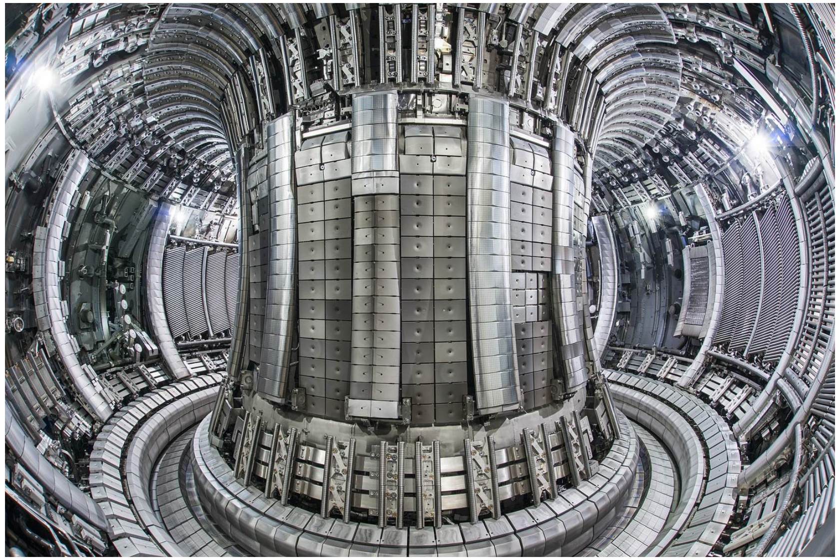


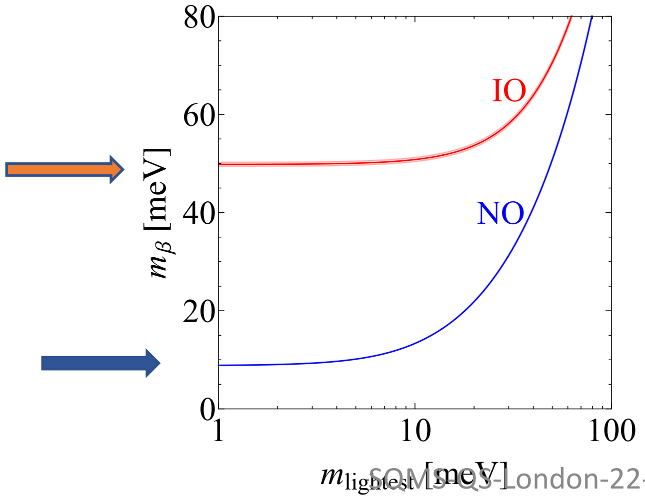


Outlook

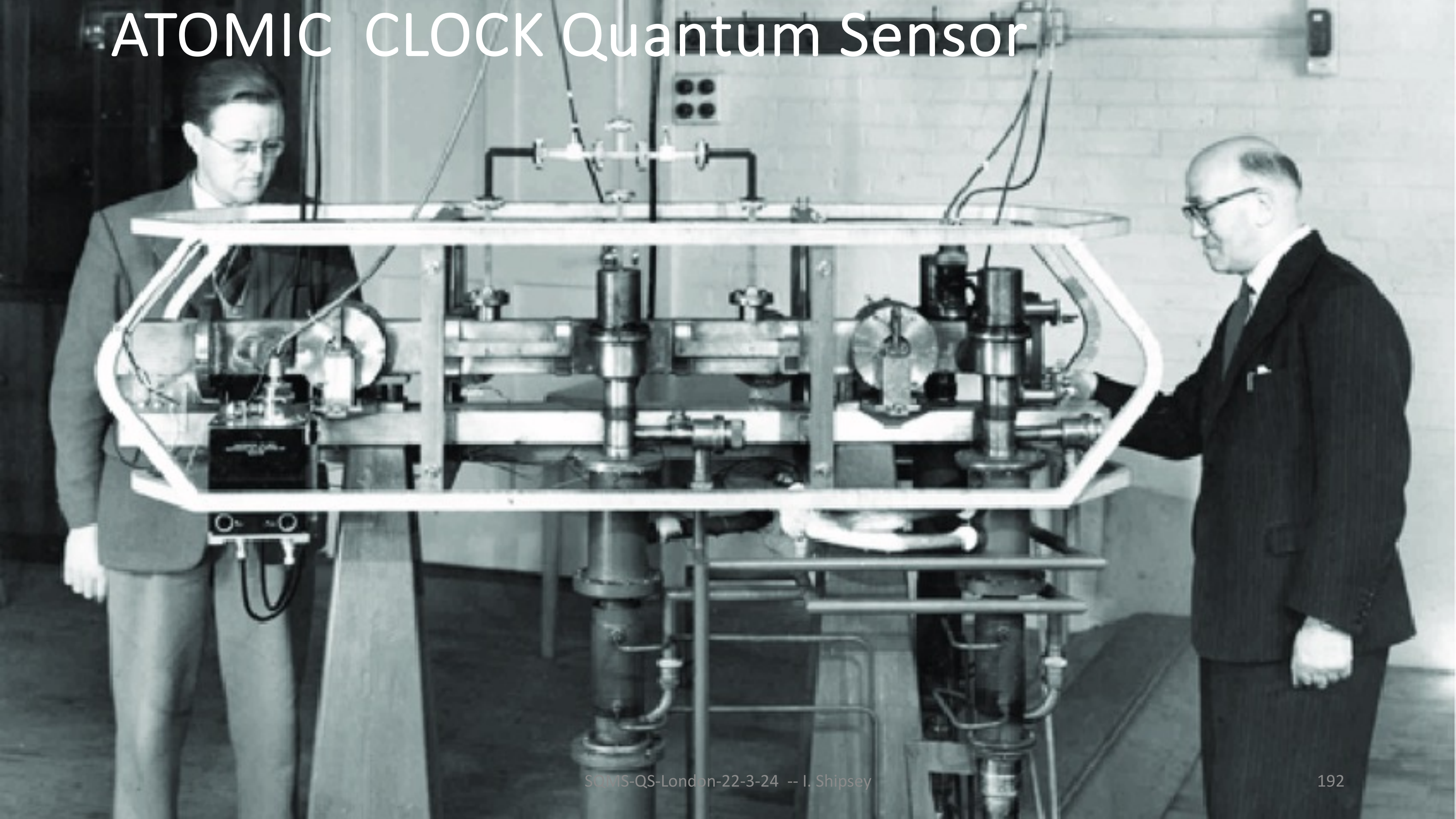
CCFE
CULHAM CENTRE FOR FUSION ENERGY

- 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)

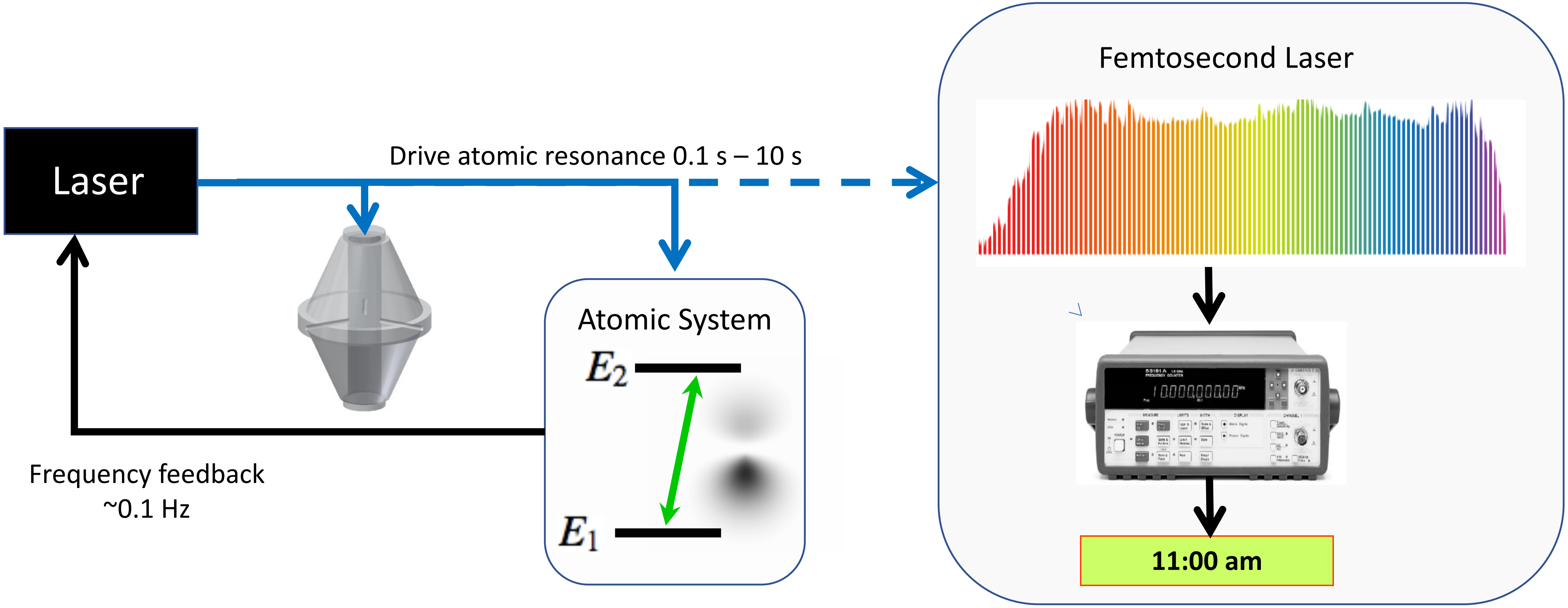




ATOMIC CLOCK Quantum Sensor



Principle of Optical Clocks



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

Slide credit: David Hume

QSNET

A network of clocks for measuring the stability of fundamental constants

Giovanni Barontini

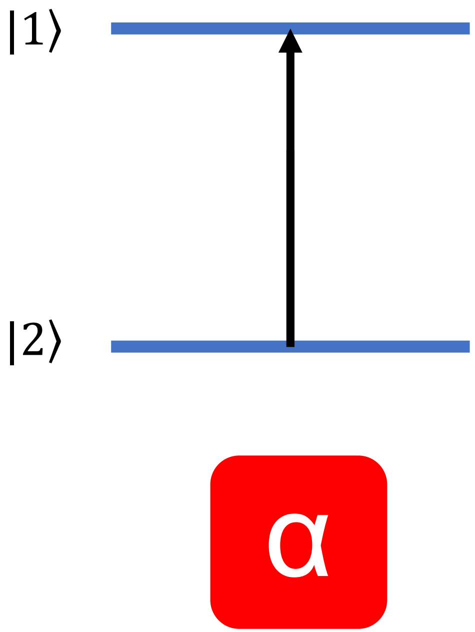
Birmingham NPL Sussex Imperial

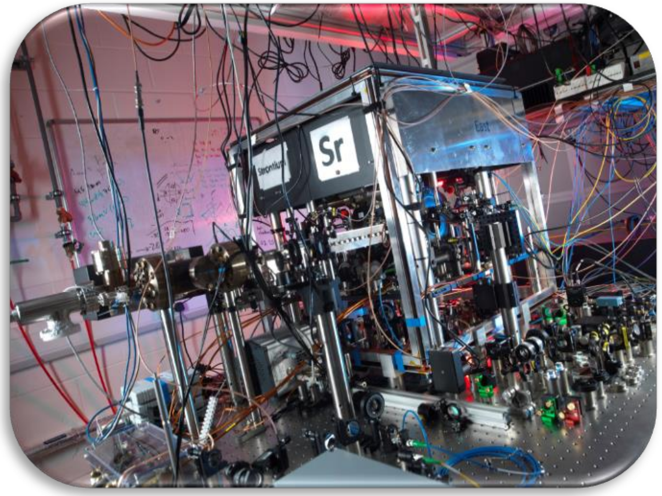
Sensitive probes

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

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

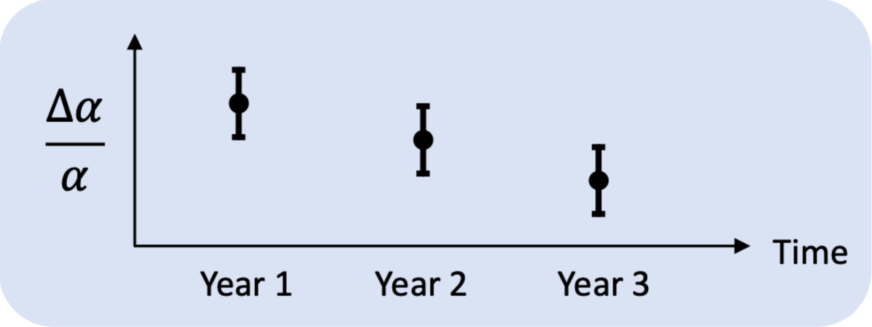
- Atomic an molecular spectra can be measured with extreme precision using atomic clocks
- Stability and accuracy at the 10^{-18} level





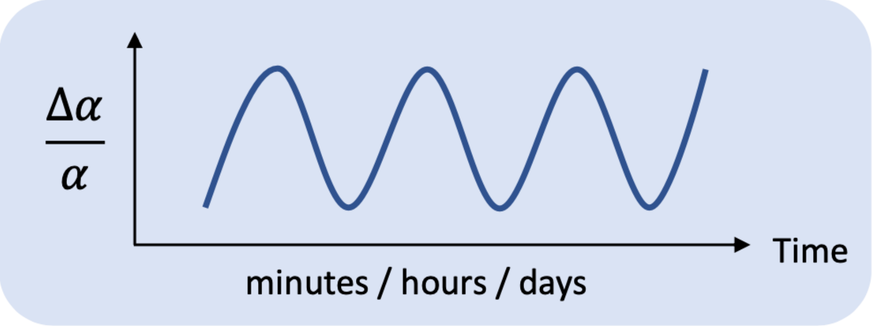
Look for variation on different timescales

- Slow drifts



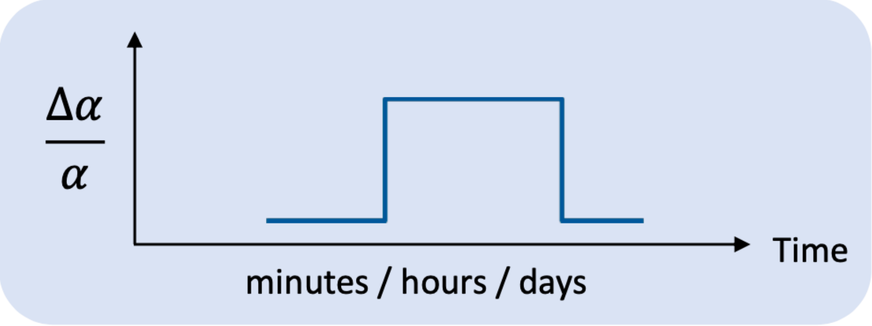
New physics

- Oscillations



Very light dark matter

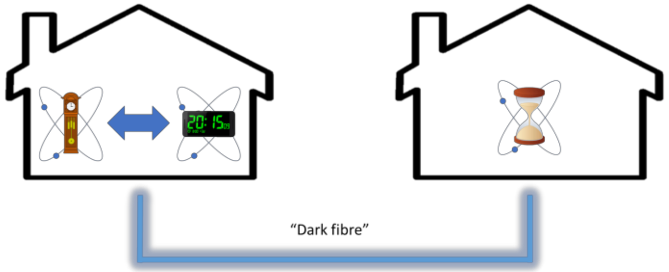
- Fast transients



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

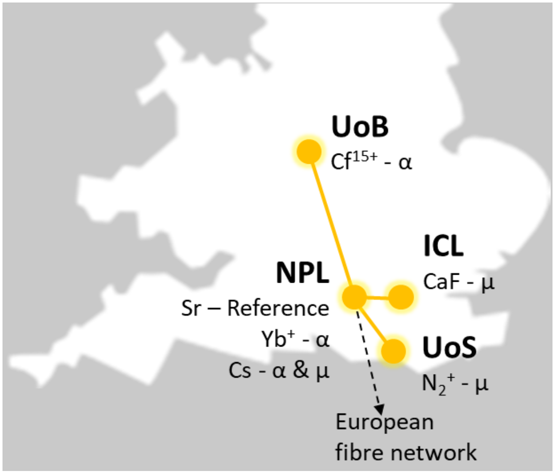


- Sensors with similar sensitivities and different systematics are necessary to confirm any measurements and reject false positives

- Networks enable probing of space-time correlations

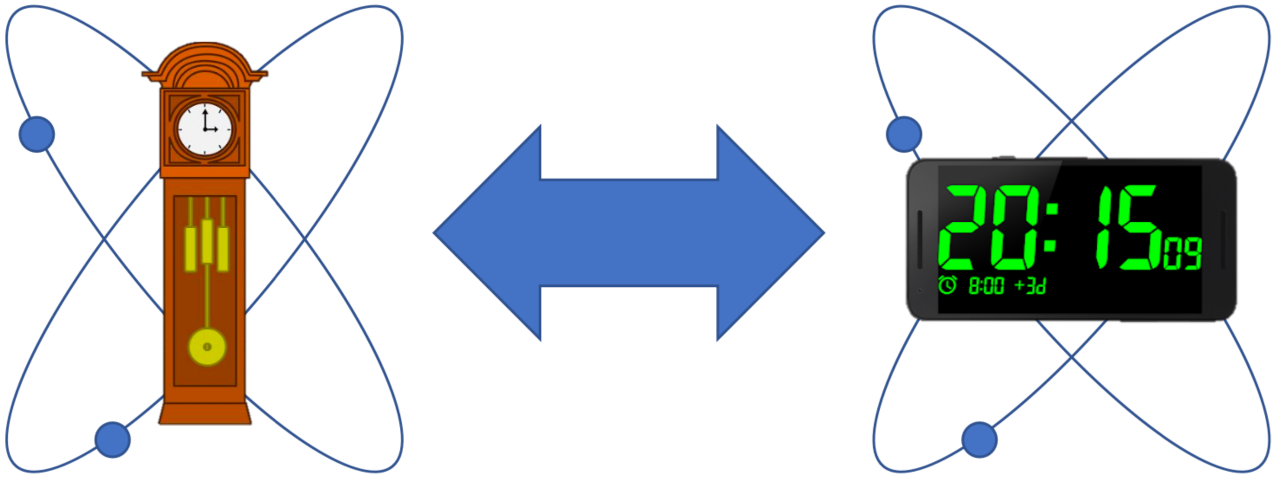
- The possibility of detecting transient events such as topological defects in dark matter fields or oscillations of dark matter

- 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

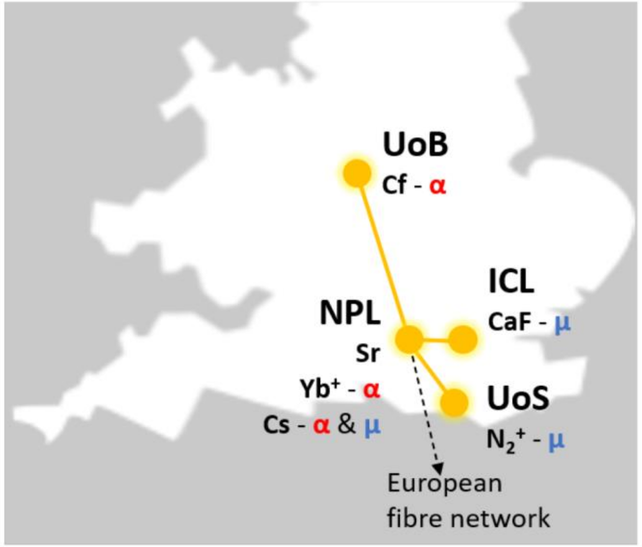
$$\frac{\Delta f1}{\Delta f2} = |K_{1x} - K_{2x}| \frac{\Delta x}{x} \qquad x = \alpha, \mu$$

10

The QSNET project

- **Search for variations of fundamental constants of the Standard Model, using a <u>network of clocks</u>**

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

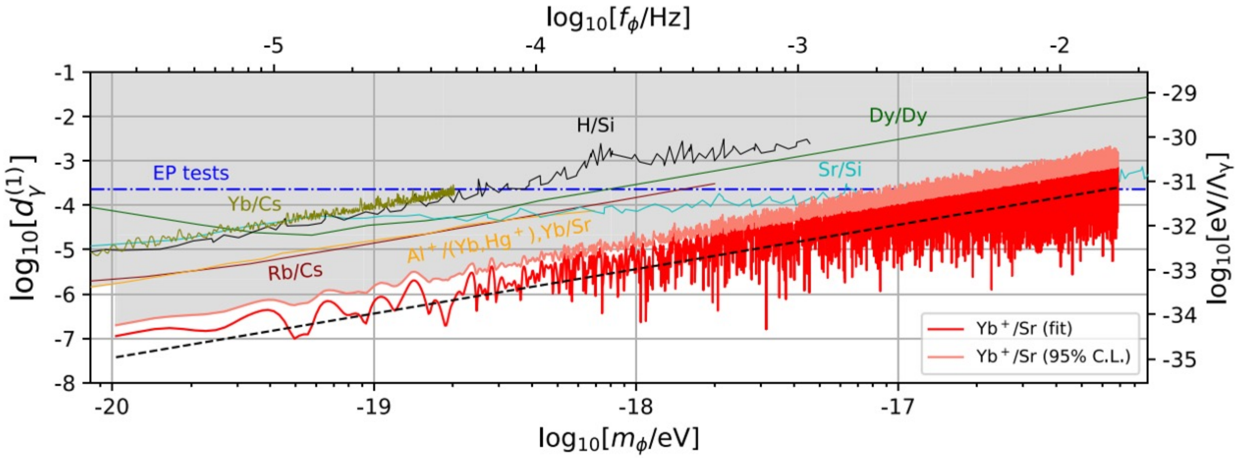


Clock	Kα	Kμ
Yb^{+} (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N_2^{+} (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

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

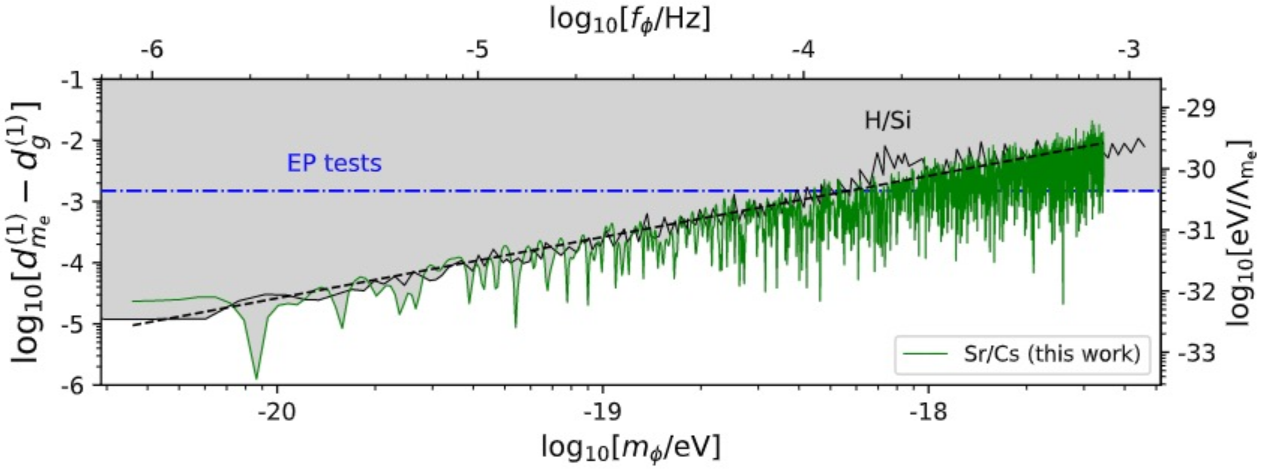
QSNET results (2023)

[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.

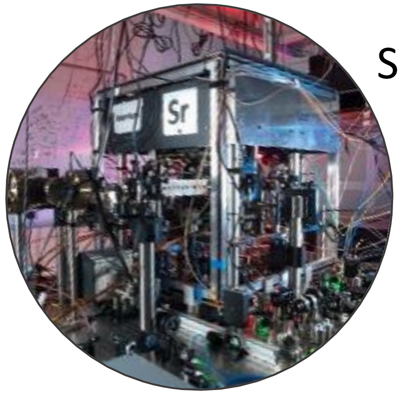
- Frequency ratios between Yb^+, Sr and Cs have placed constraints on oscillations in α and μ beyond the previous state-of-the-art.



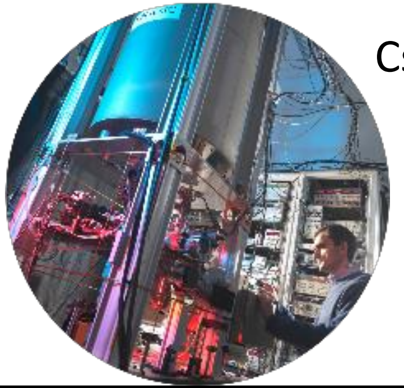
Progress, NPL

- Improved robustness and automation of optical clock operation, to record longer time series of frequency data
- Expect constraints on α and μ to exceed the current state-of-the-art before the end of Phase 1
- μ-sensitive ratio (Sr / H-maser) has revealed better stability and wider frequency range than previously published results

Yb^+



Sr

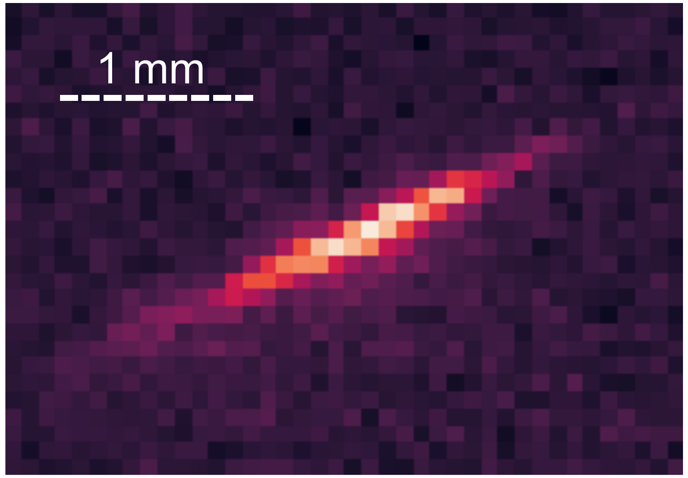


Cs

Progress, Imperial

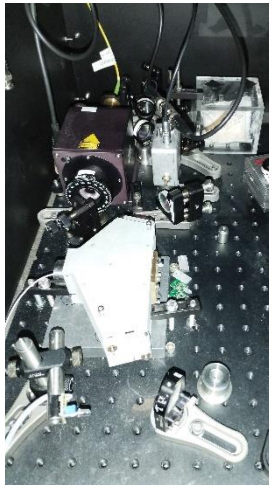
- Idea: clock based on vibrational transition in a molecule, sensitive to m_e / m_p
- Recent breakthrough: have trapped CaF molecules in a 1D optical lattice
- Laser systems for the clock are currently being developed

Ultracold CaF in a 1D lattice



Progress, Sussex

- Spectroscopy lasers setup finished
- Successful loading of nitrogen in to ion trap by REMPI
- Development of novel ionisation laser in progress
- Development of novel quantum logic spectroscopy in progress

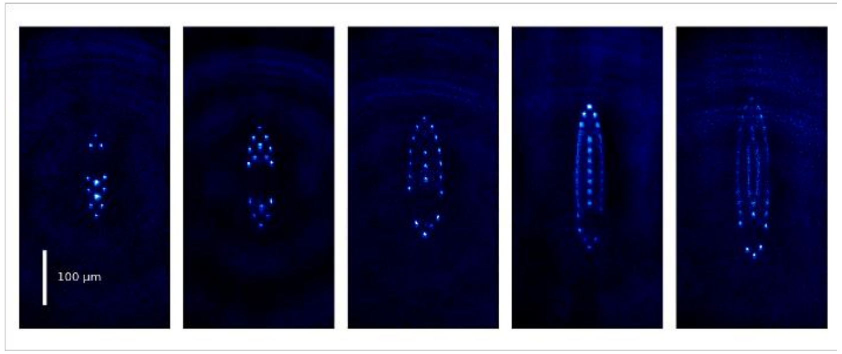


Progress, Birmingham

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

- Realisation of a compact Electron Beam Ion Trap (cEBIT) for highly charged ions of Cf

- Characterisation of a superconducting Paul trap for singly charged and highly charged ions



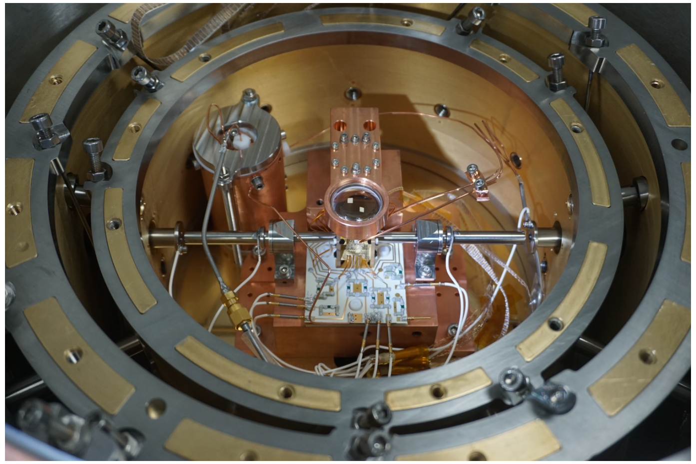
- Realisation of a ultra-low vibration cryogenic vacuum system for trapping ofhighly charged ions

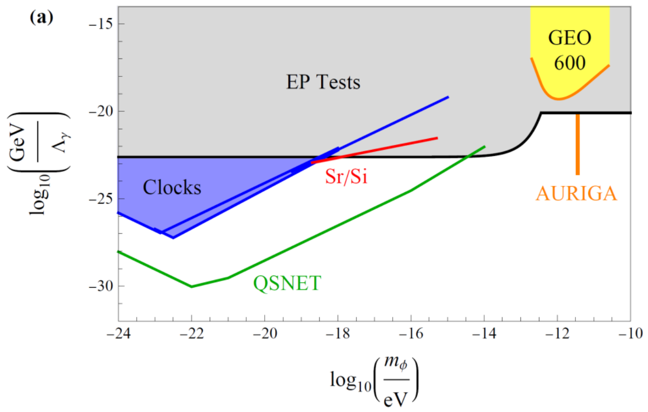
Goals for Phase 1

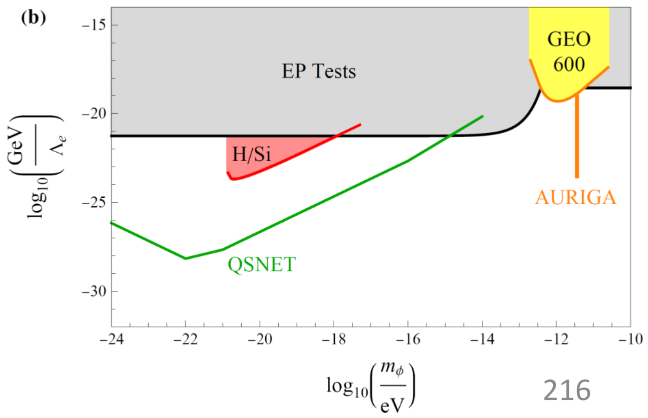
1. New constraints on $\Delta\mu/\mu$ on timescales from 10-1000 s, targeting 4×10^{-15} at 1000 s
2. Measure $\Delta\alpha/\alpha$ on fast timescales targeting 1×10^{-17} at 1000 s, exceeding current state of-the-art sensitivity
3. Realization of a Cf^{15+} and Cf^{17+} cEBIT
4. Measure the N_2^+ clock 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.

Beyond phase 1

- Complete the low TRL clocks that will enable orders of magnitude improvements in sensitivity
- Connect the clocks with fibre links to run clock/clock comparisons campaigns
- Run increasingly longer measurement campaigns
- Development of quantum correlations between the nodes
- Constantly improve the performance to probe variations of fundamental constants. If no variation is detected, evaluate the impact on theories beyond the standard model



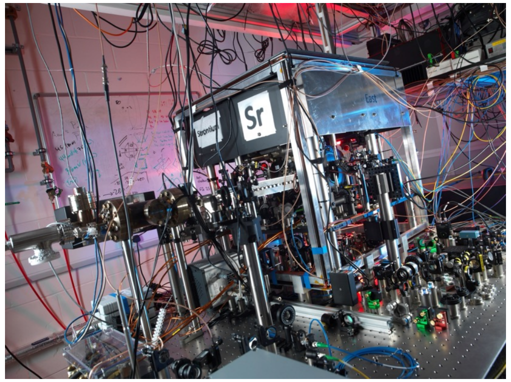




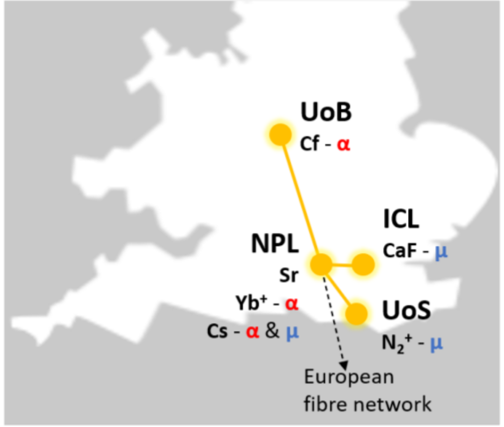
Economic Impact of QSNET

- 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



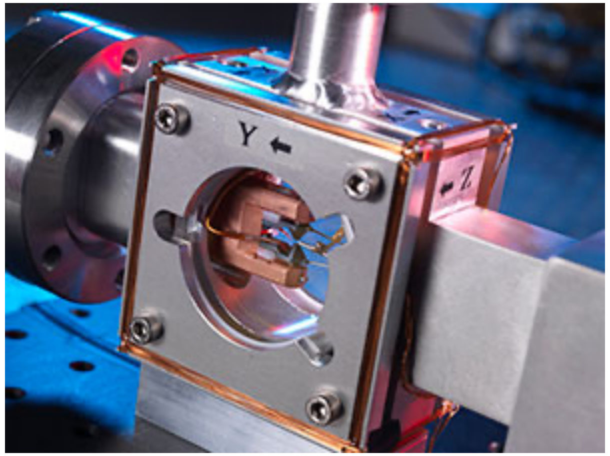
2. QSNET is developing an **optical fibre network** linking the different clocks
    - A high-resolution frequency comparison between QSNET nodes will mark a crucial **technological milestone** for the UK
    - This **infrastructure** will enable interaction between different quantum technologies including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



Applications of clocks and clock networks

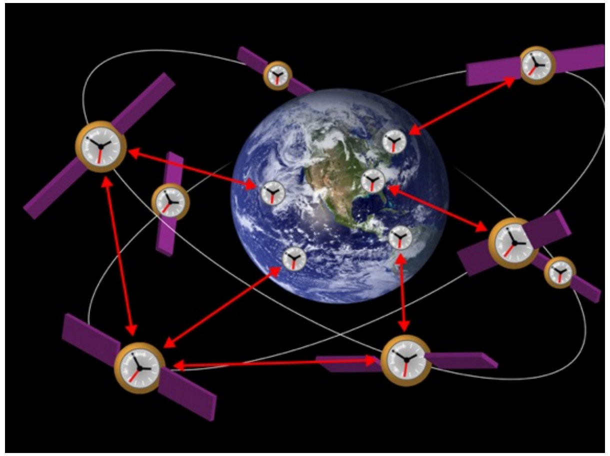
Applications of **ultra-precise clocks** include:

- 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

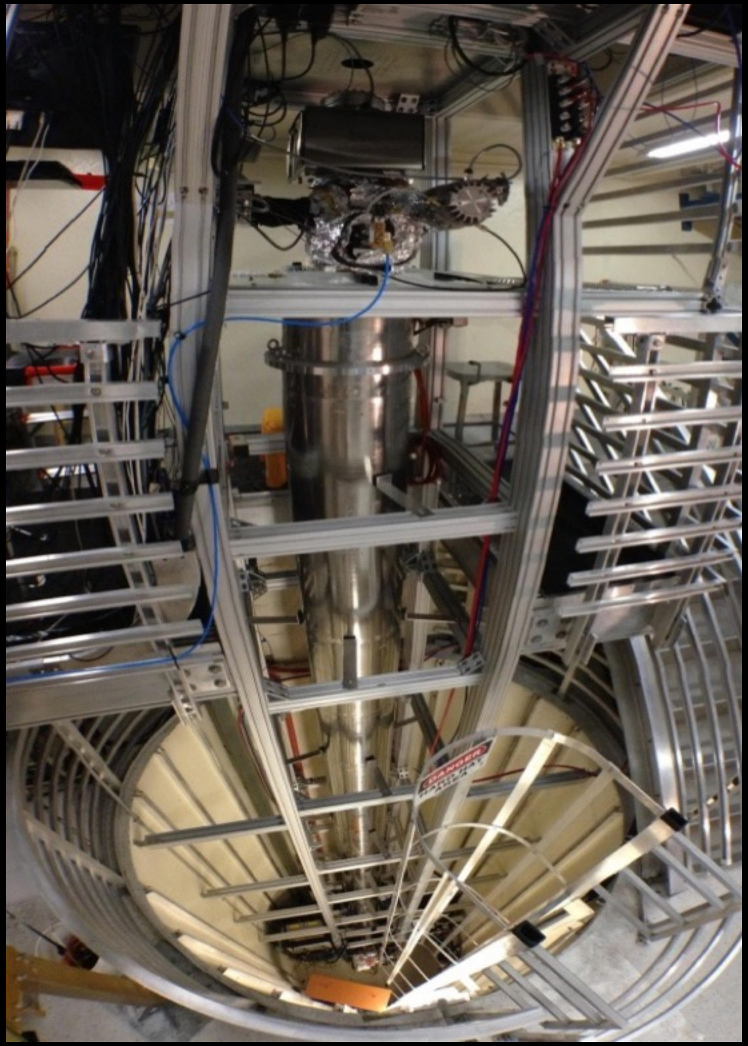


Applications of **networks of clocks** include:

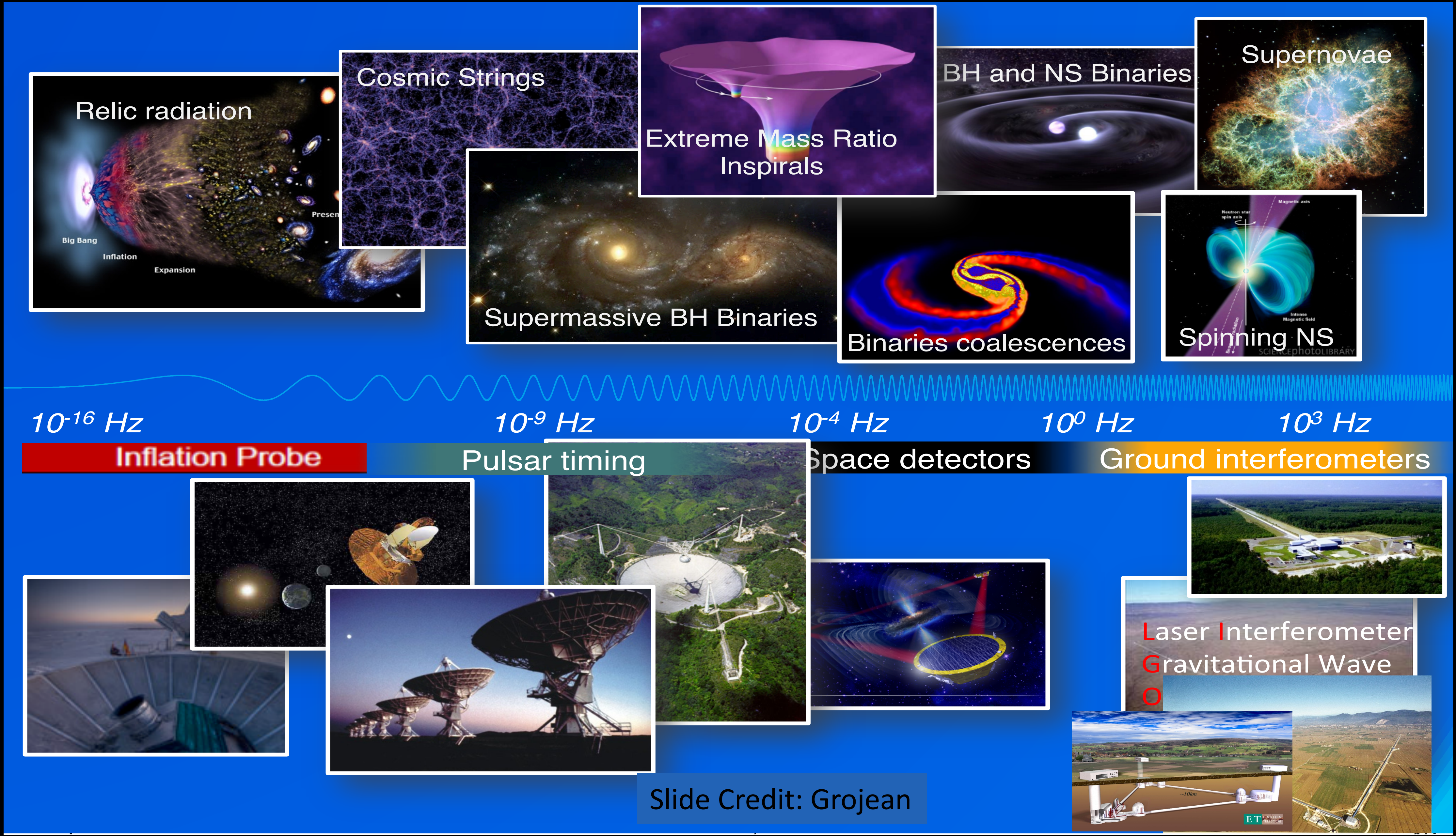
- geodetic measurements (e.g. time-varying gravity potentials)
- seismic effects
- environment monitoring
- synchronisation and timing signals for radio astronomy
- radar technology



Atom Interferometry

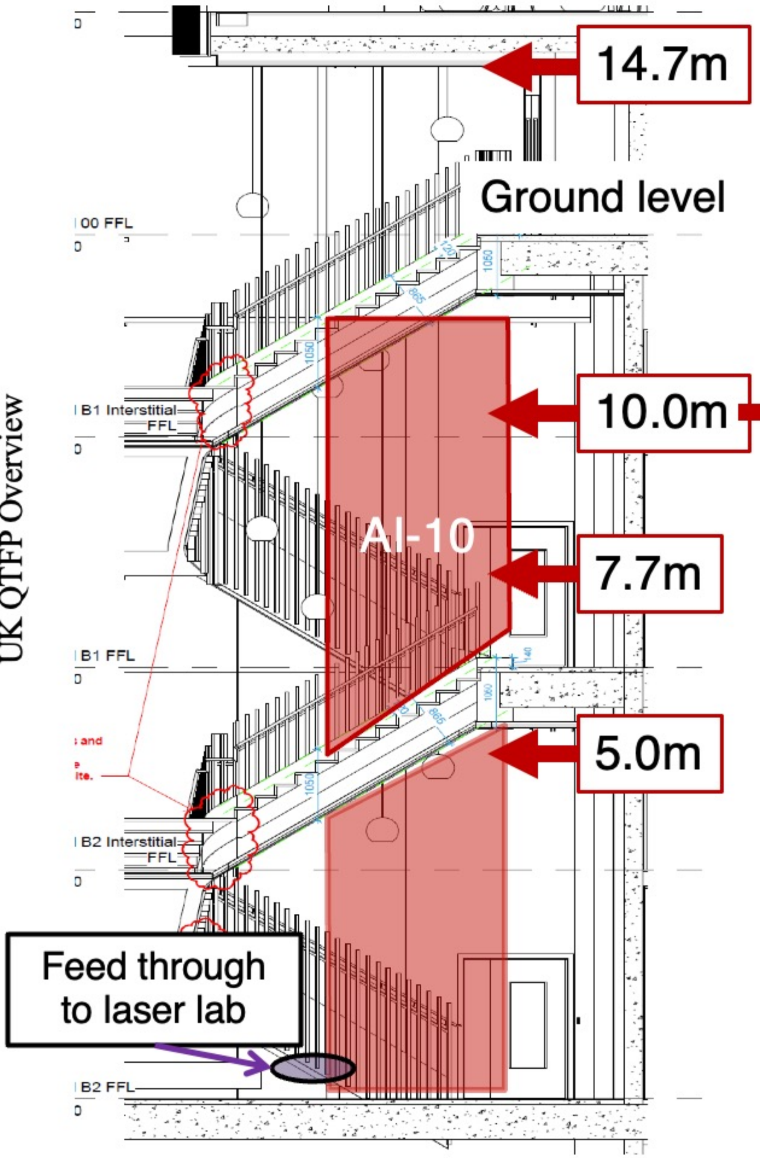


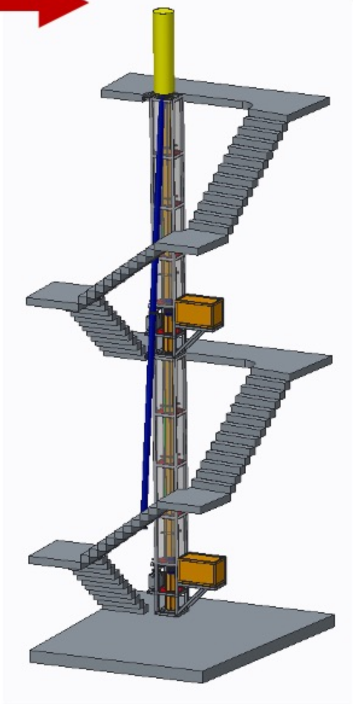
Gravitational Waves: Cosmology and Astrophysics



Slide Credit: Grojean

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
The laboratories are expected to be fully operational in summer 2023.

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
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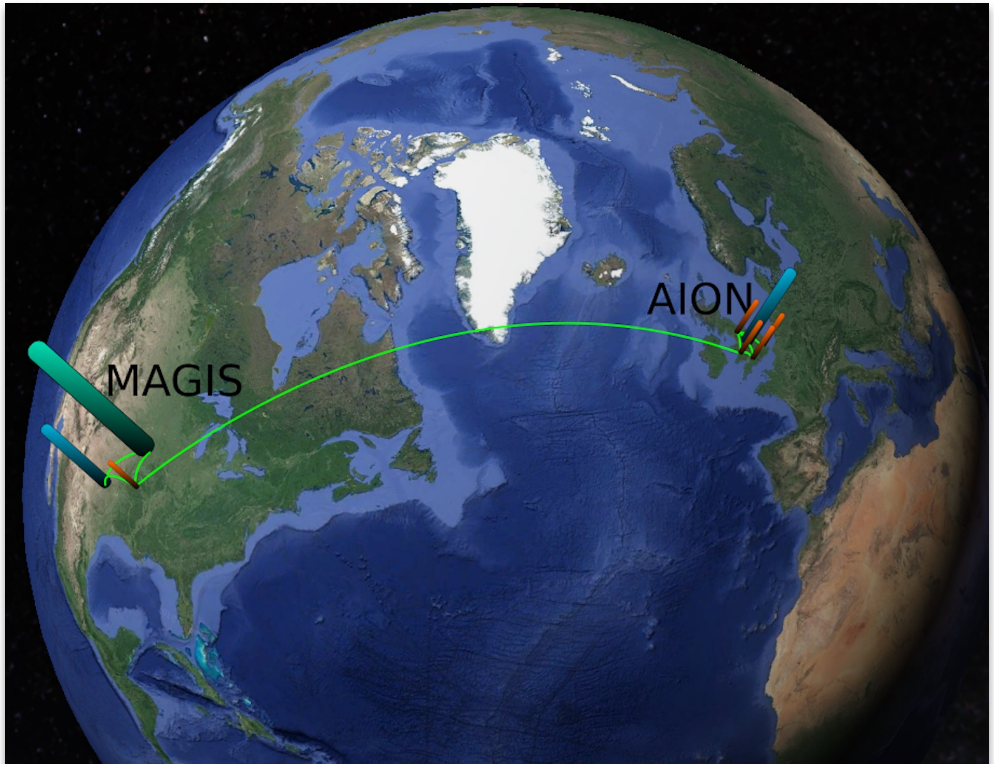
Northwestern University
Fermilab
SLAC
THE UNIVERSITY OF CHICAGO
UNIVERSITY OF CAMBRIDGE
Northern Illinois University
UNIVERSITY OF OXFORD
UNIVERSITY OF LIVERPOOL



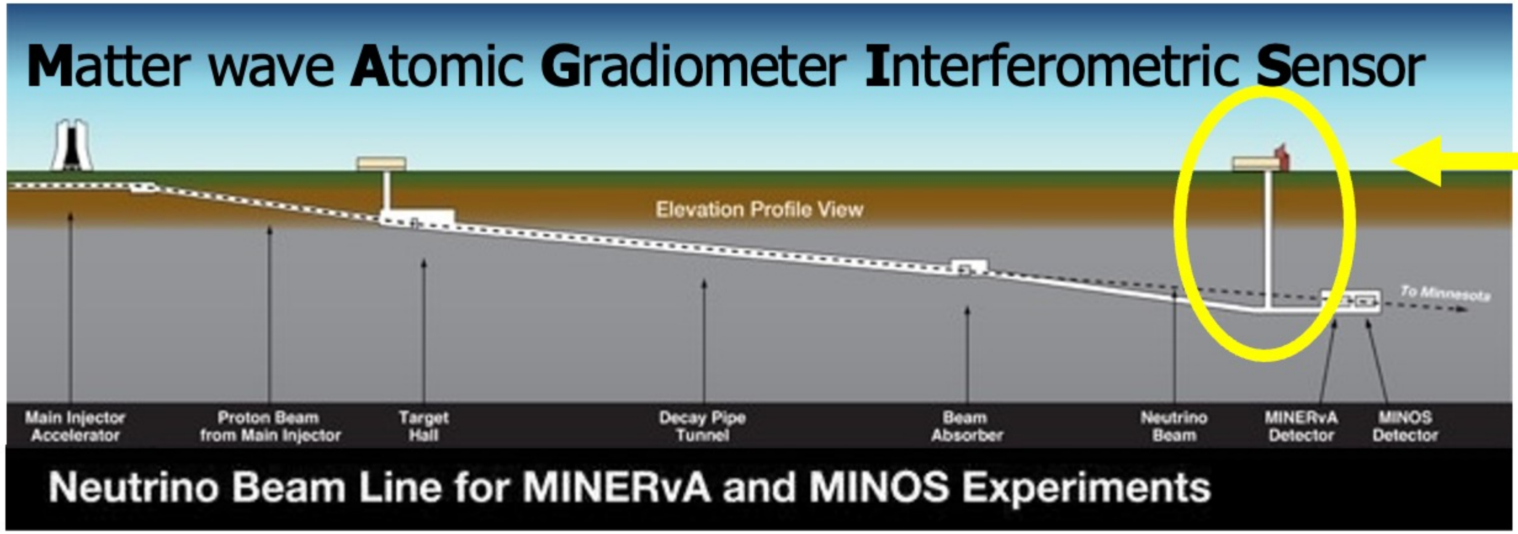
AION (UK) and MAGIS (US) work in equal partnership to form a "LIGO/Virgo-style" network & collaboration, providing a pathway for international leadership in this exciting new field.

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.

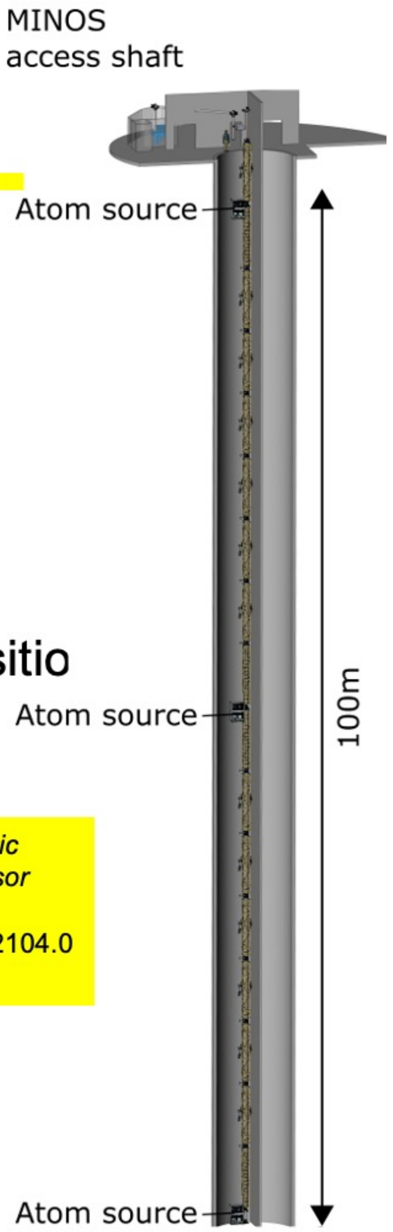
This stands as a successful instance of UK-US cooperation in the fields of science and quantum technology development, with the potential to unlock additional synergies and opportunities.

MAGIS-100 at Fermilab



- 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].



AION UK Contribution to MAGIS-100

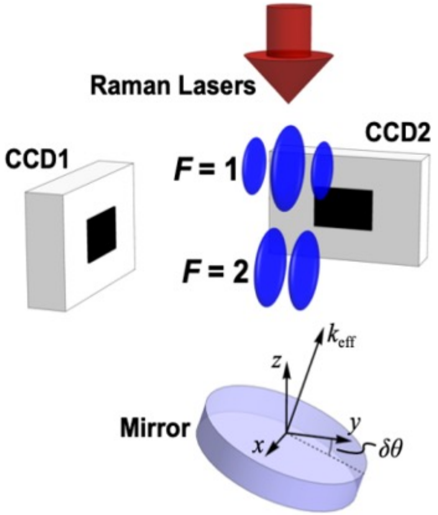
Detection system is UK contribution

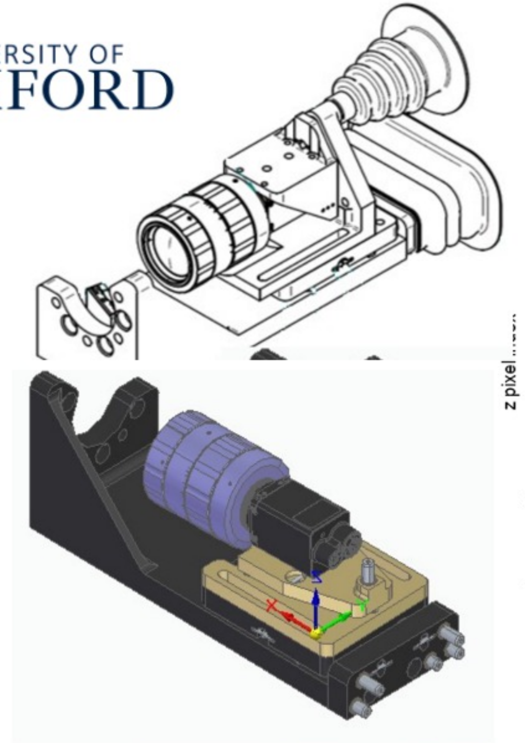
- **Enable single-shot phase extraction**
- In-vacuum optics and mechanical support systems for piezo-driven phase-shear readout and optical lattice-launch
  - Includes control and monitoring
- Low-noise calibrated imaging systems from LSST expertise
- Experimental FPGA control and precision timing systems
- Computing infrastructure, simulations, and networking for AION-MAGIS-100 correlation

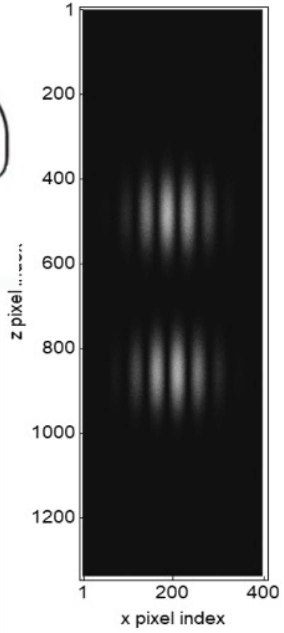
UNIVERSITY OF LIVERPOOL

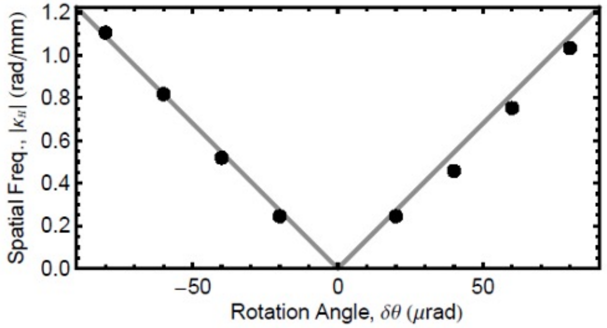
UNIVERSITY OF OXFORD

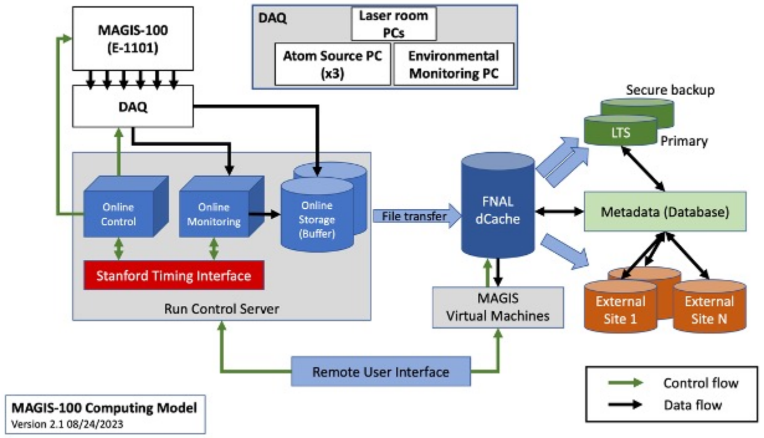
UNIVERSITY OF CAMBRIDGE

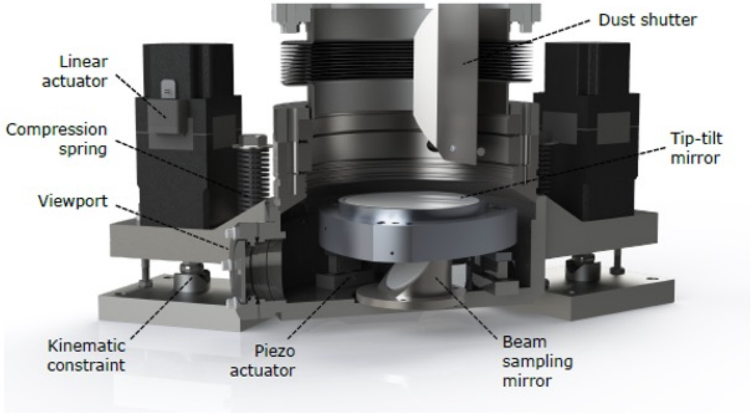












http://dx.doi.org/10.1103/PhysRevLett.111.113

AION

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).

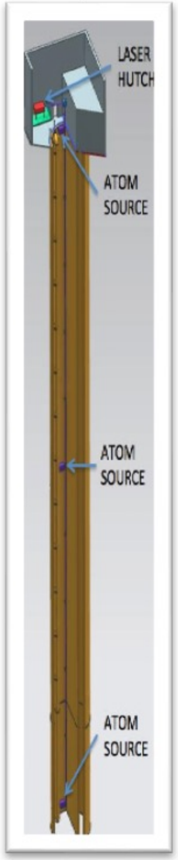
- ❑ **Stage 3:** to build a kilometre-scale terrestrial detector.
- ❑ **Stage 4**: long-term objective a pair of satellite detectors (thousands of kilometres scale) [AEDGE proposal to ESA Voyage2050 call]
  - ➢ AION has established science leadership in AEDGE, bringing together collaborators from European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

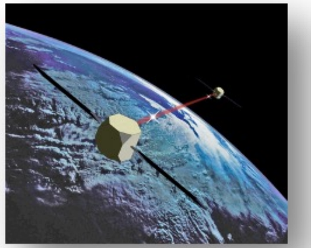
Stage 3 and 4 will likely require funding on international level (ESA, EU, etc) and AION has already started to build the foundation for it.

L ~ 10m

L ~ 100m

L ~ 1km



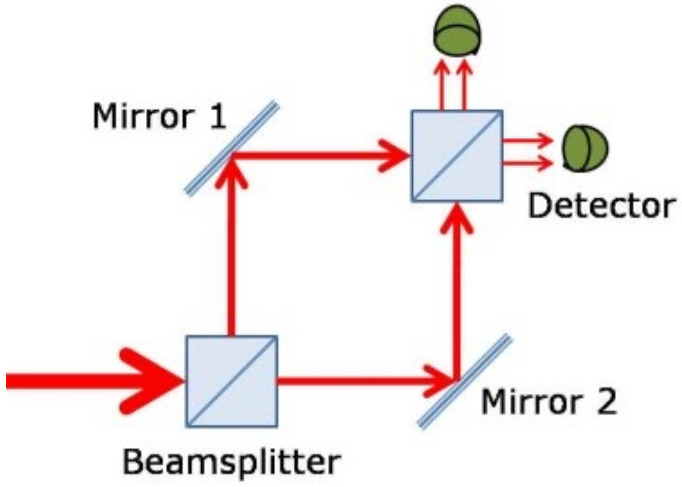


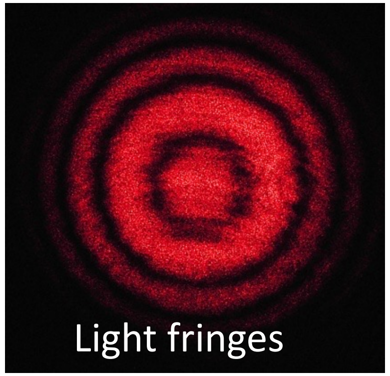
AION Collaboration Days in Oxford: Fall 2021

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

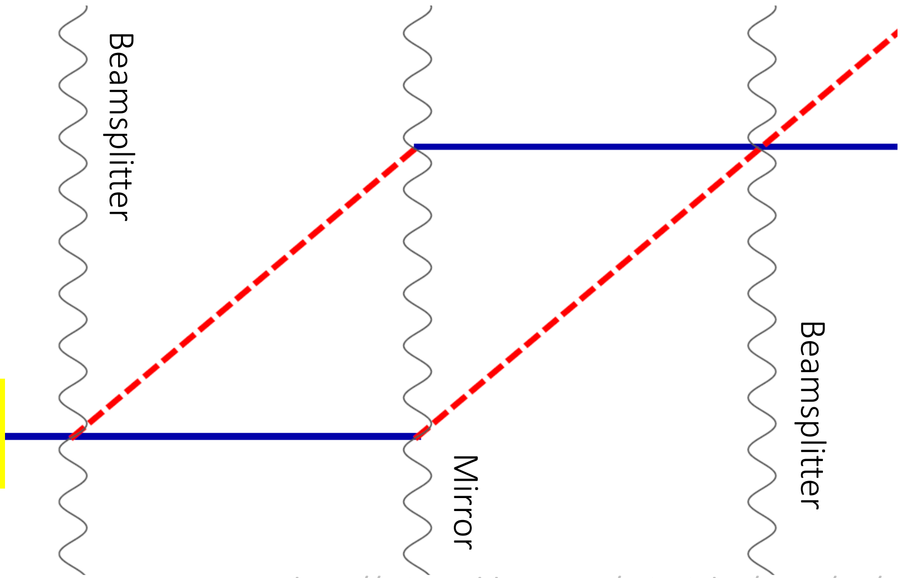
Light vs. Cold Atoms: Atom Interferometry

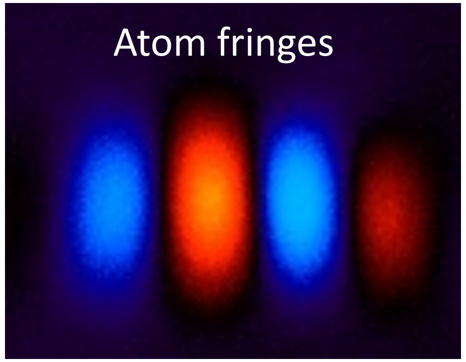
Light interferometer





Atom interferometer



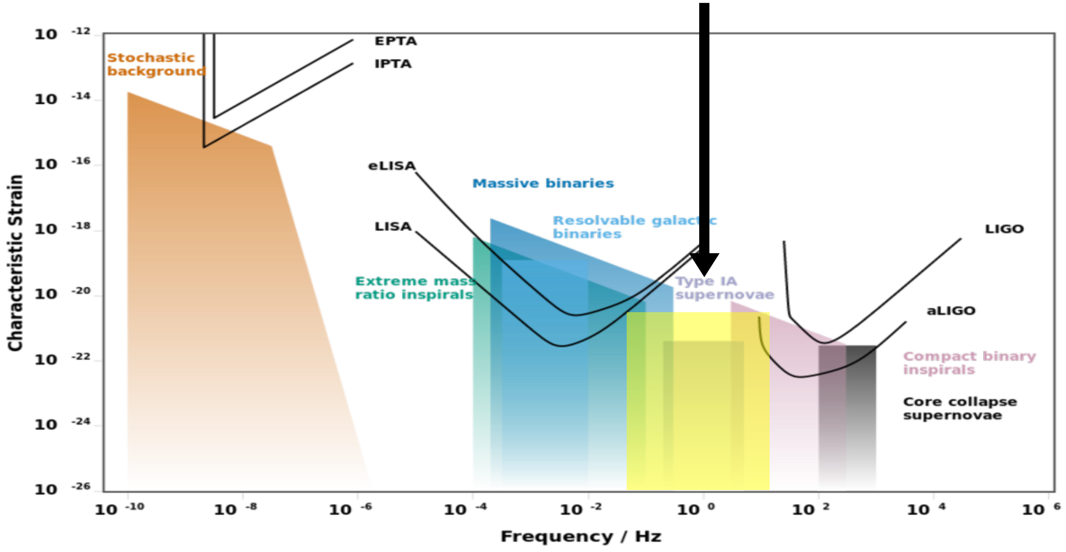


See talk of Tim Kovachy

http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

Long baseline atom interferometry science

Mid-band: 0.03 Hz to 3 Hz



Mid-band gravitational wave detection

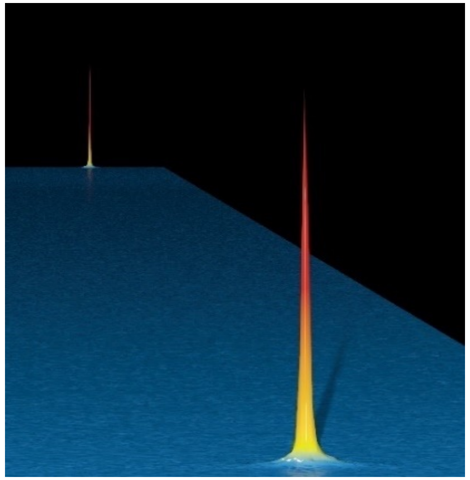
- LIGO sources before they reach LIGO ban
- Multi-messenger astronomy: optimal band for sky localization
- Cosmological sources

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

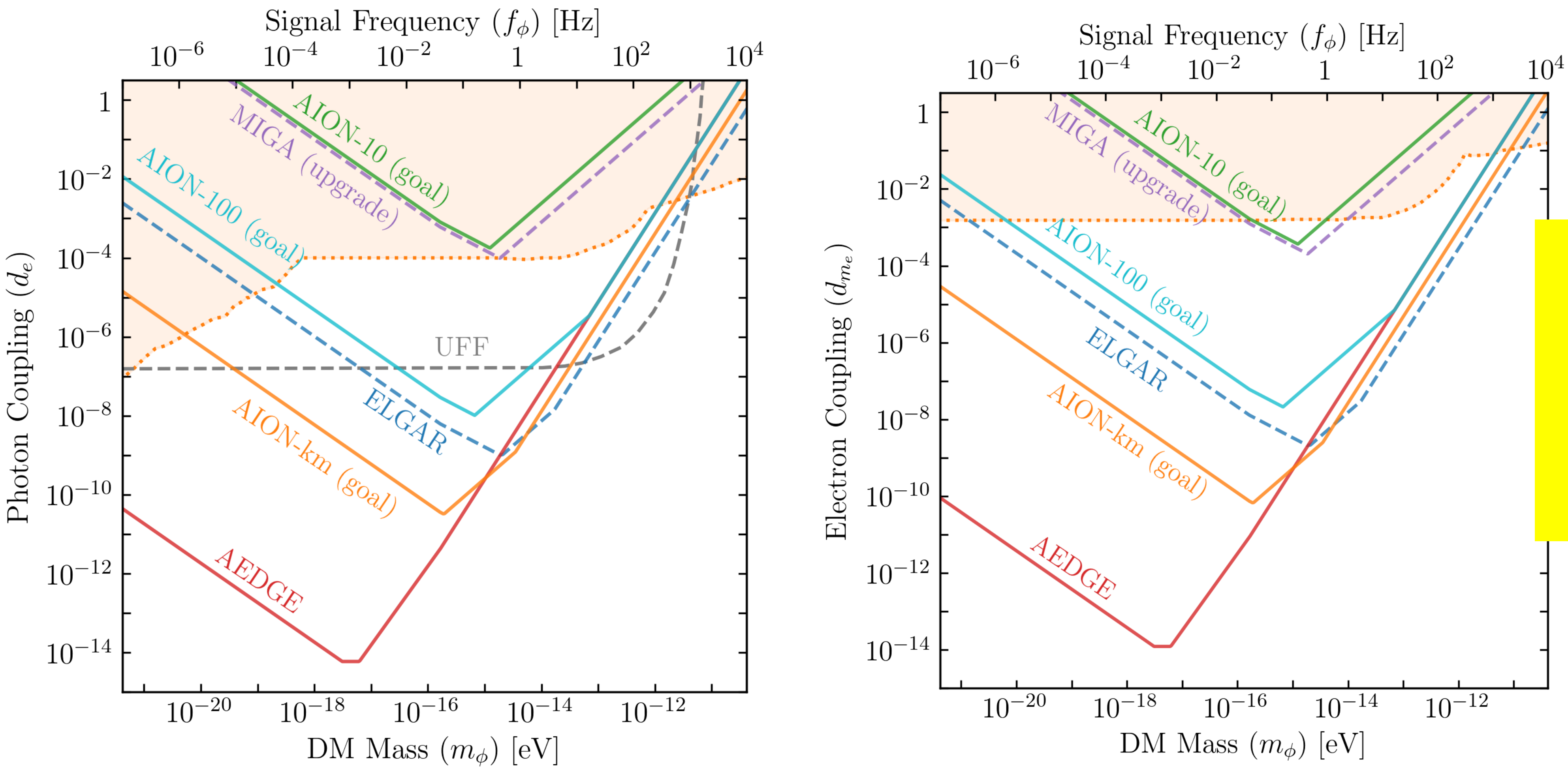
- Meter-scale wavepacket separation, duration of seconds
- Decoherence, spontaneous localization, non-linear QM, …



Rb wavepackets separated by 54 cm

Slide credit: Jason Hogan

Search for Ultra-Light Dark Matter

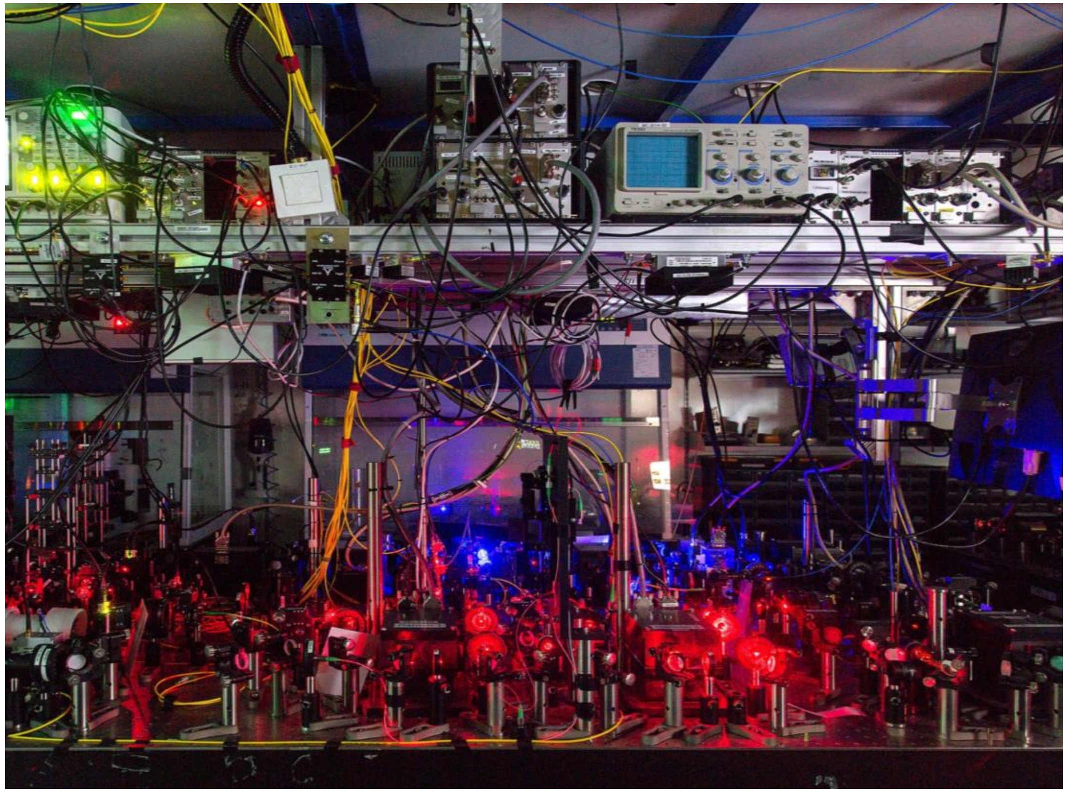


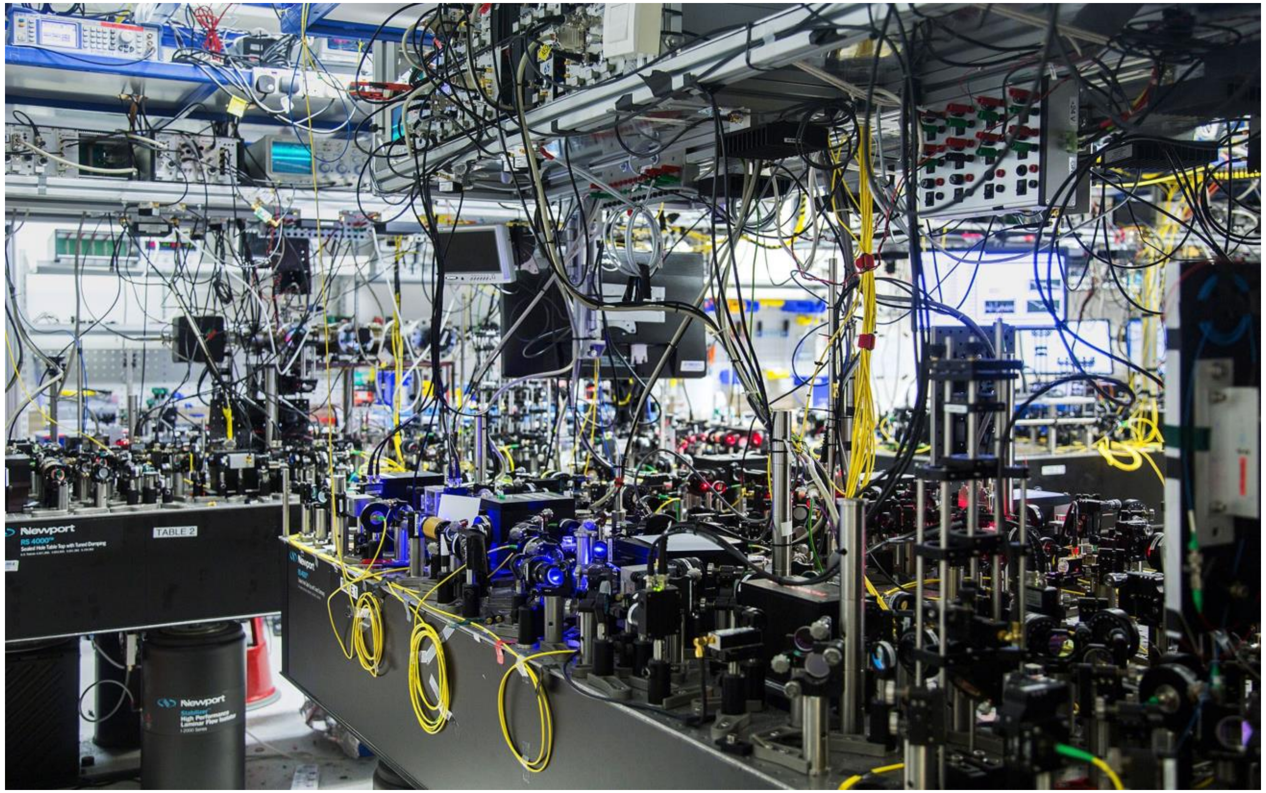
Orders of magnitude improvement over current sensitivity

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

AION: Ultra-Cold Strontium Laboratories in UK

AION Update QTFP Meeting in Oxford





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

Birmingham, Cambridge, Imperial College, Oxford, and RAL

The laboratories are expected to be fully operational in fall 2022.

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:

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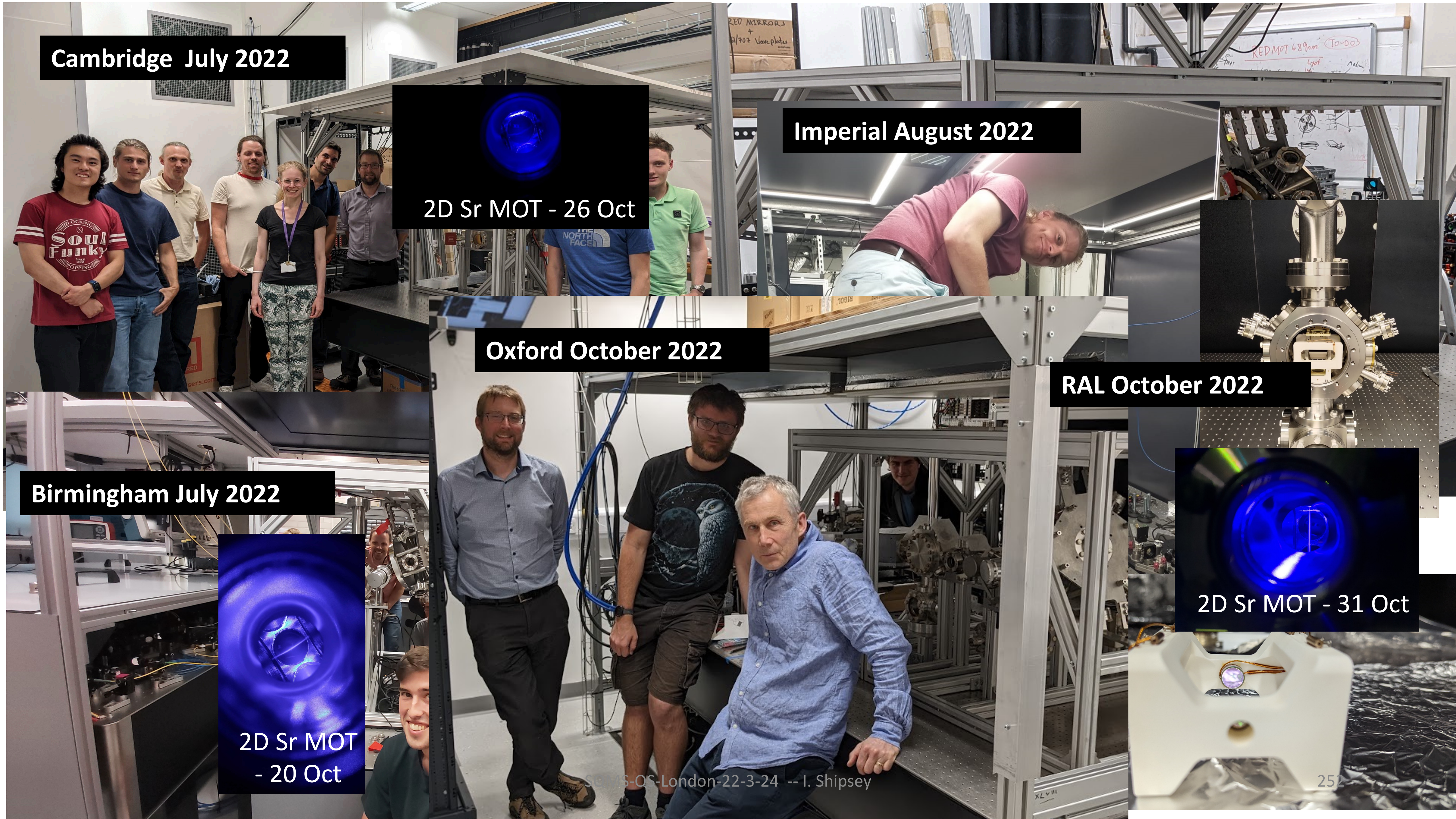
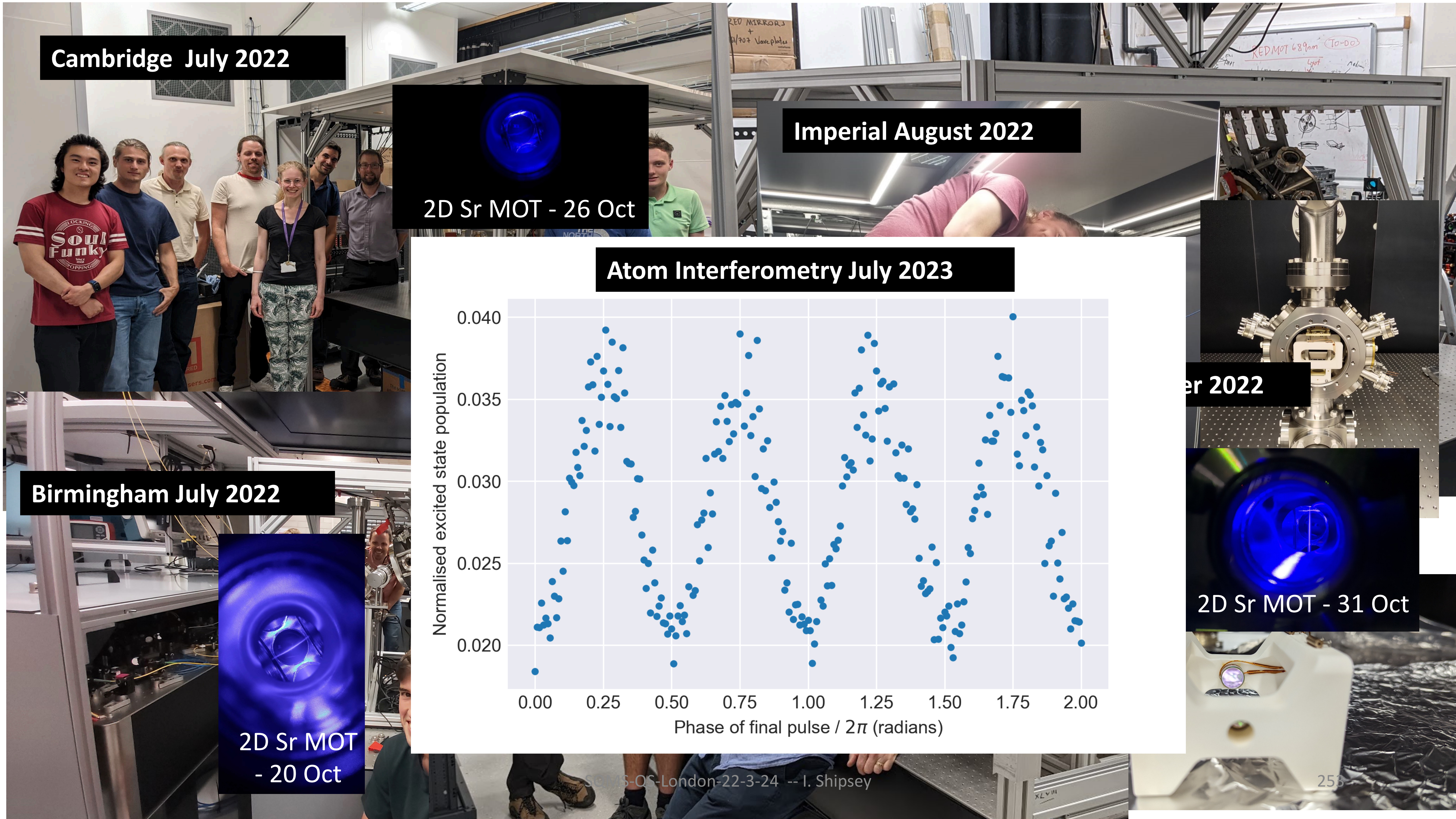
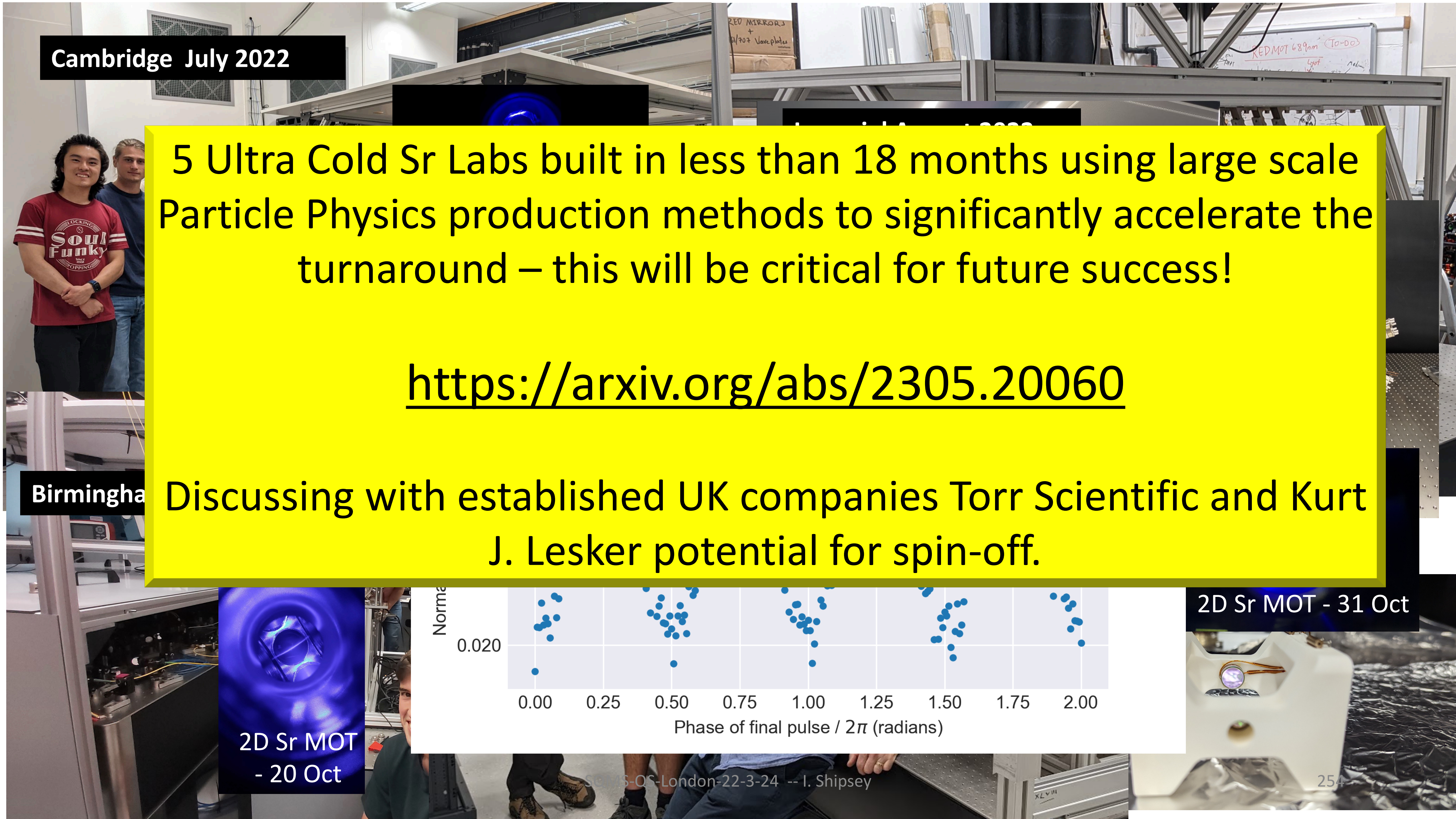

Cambridge July 2022
2D Sr MOT - 26 Oct
Imperial August 2022
Oxford October 2022
RAL October 2022
Birmingham July 2022
2D Sr MOT - 20 Oct
2D Sr MOT - 31 Oct

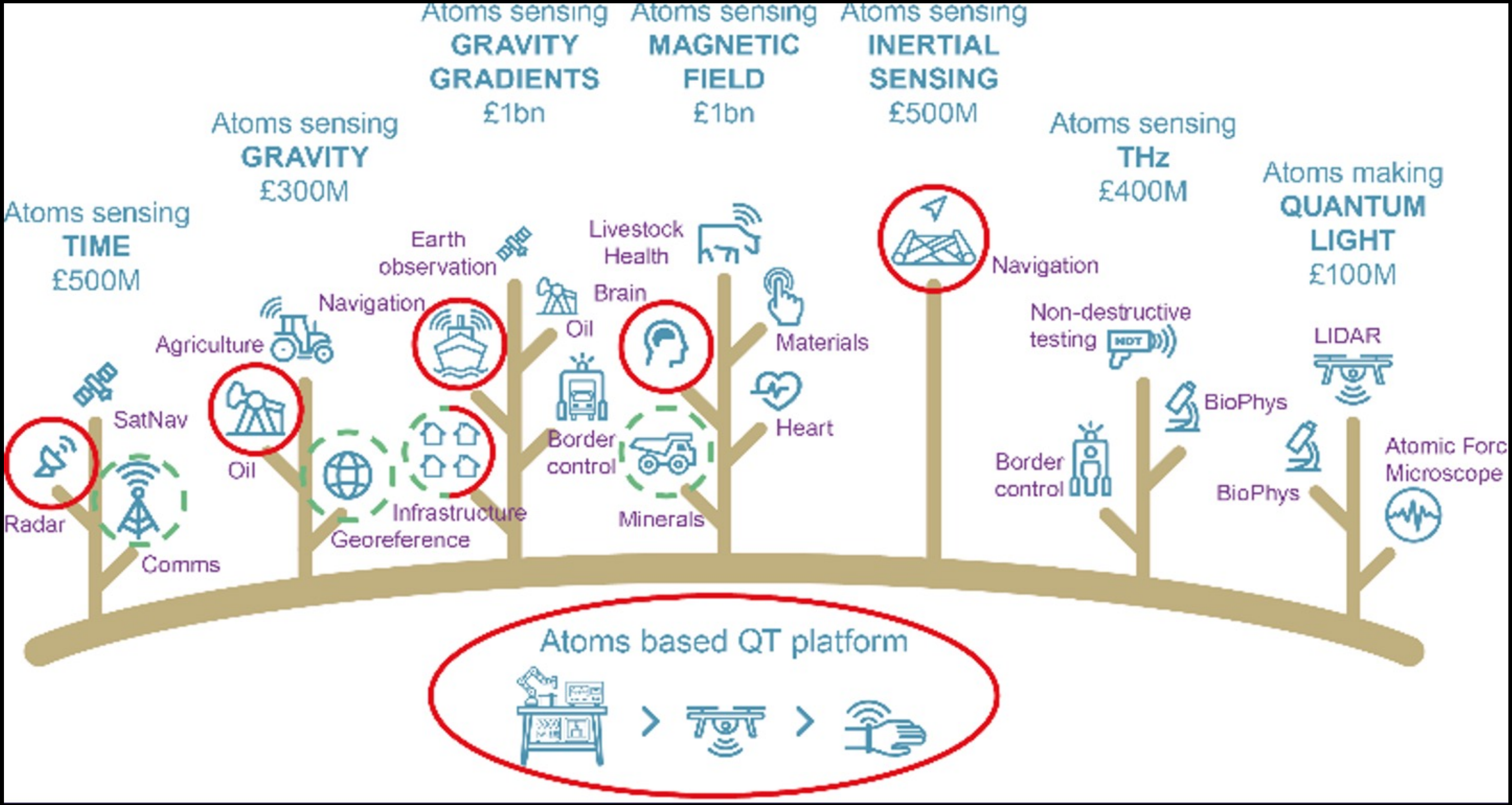

Cambridge July 2022
2D Sr MOT - 26 Oct
Imperial August 2022
Atom Interferometry July 2023
Normalised excited state population
0.040
0.035
0.030
0.025
0.020
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Phase of final pulse / 2π (radians)
er 2022
2D Sr MOT - 31 Oct
Birmingham July 2022
2D Sr MOT
- 20 Oct



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
Brain
Oil
Materials
Navigation
Agriculture
Non-destructive testing
NDT
LIDAR
SatNav
Heart
BioPhys
Border control
Oil
Radar
Comms
Georeference
Infrastructure
Minerals
Border control
BioPhys
Atomic Forc
Microscope
Atoms based QT platform

AION Related Publications (so far)

- AtomECS: Simulate laser cooling and magneto-optical traps (X. Chen, M. Zeuner, U. Schneider, C.J. Foot, T. L. Harte, E. Bentine) [arXiv:2105.06447]
- High-fidelity atom optics with polychromatic light pulses (S. Lellouch, O. Ennis, R. Haditalab, M. Langlois, M. Holynski) [Patent pending]
- Refined Ultra-Light Scalar Dark Matter Searches with Compact Atom Gradiometers (L. Badurina, D. Blas, C. McCabe) [arXiv:2109.10965]
- Prospective Sensitivities of Atom Interferometers to Gravitational Waves and Ultralight Dark Matter (L. Badurina, O. Buchmueller, J. Ellis, M. Lewicki, C. McCabe, M. Lewicki) [arXiv:2108.02468]
- Cold Atoms in Space: Community Workshop Summary and Proposed Road-Map (I. Alonso, L. Badurina, O. Buchmueller, J. Coleman, G. Elertas, J. Ellis, C. McCabe, ...)[arXiv:2201.07789]
- Snowmass 2021: Quantum Sensors for HEP Science - Interferometers, Mechanics, Traps, and Clocks (D. Carney, ..., J. Ellis et al) [arXiv:2203.07250]

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

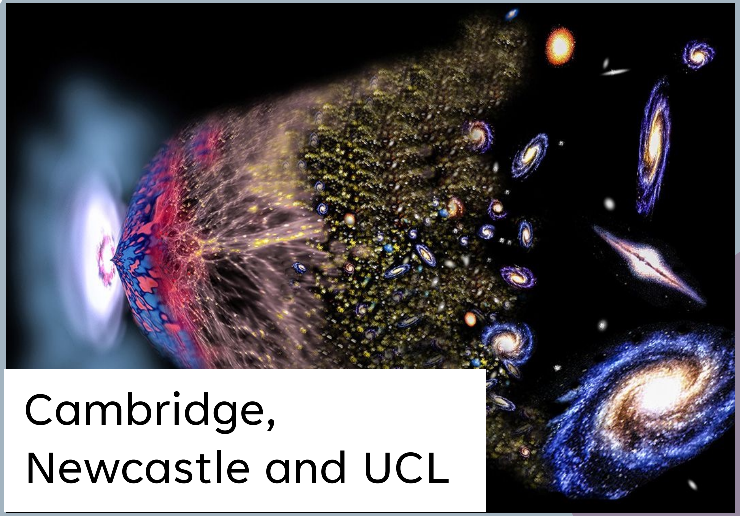
Silke Weinfurtner (PI, Nottingham)

Zoran Hadzibabic (Cambridge)

Ruth Gregory (KCL)

Vision

See lalk of Silke Weinfurtner



Cambridge, Newcastle and UCL

KCL and Newcastle

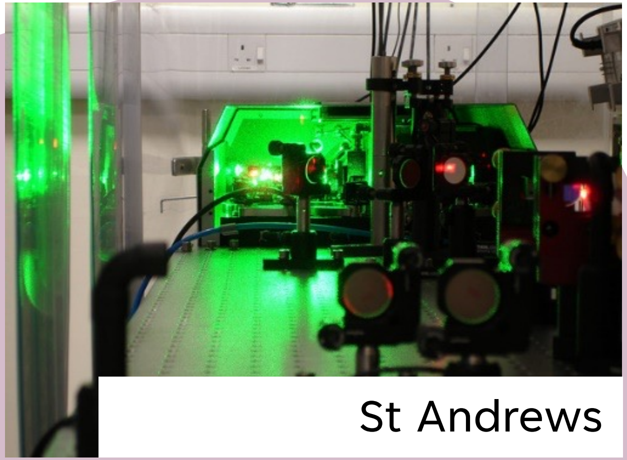
QSimFP

Quantum Vacuum:

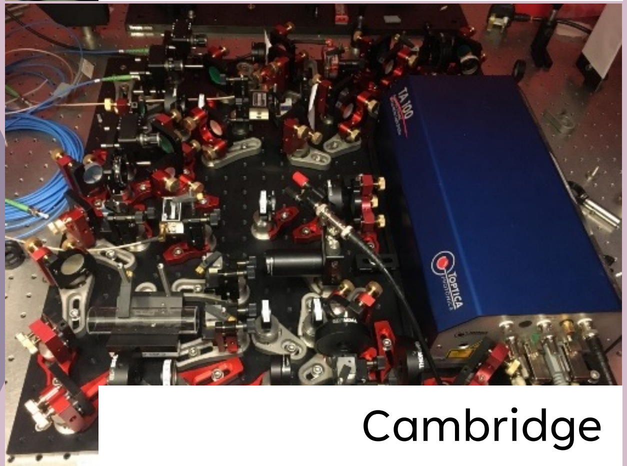
- False Vacuum Decay

Quantum Black Hole:

- Black hole ring-down



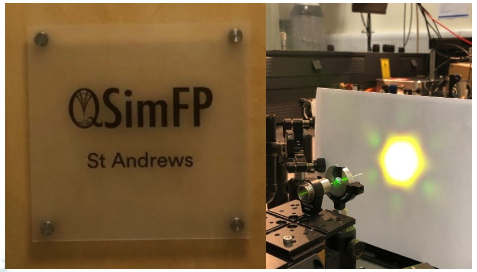
St Andrews



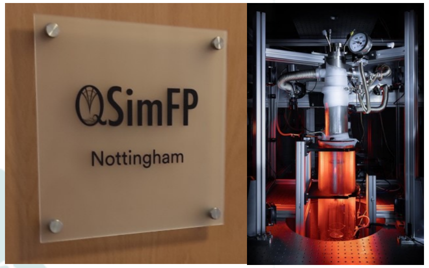
Cambridge

Nottingham and RHUL

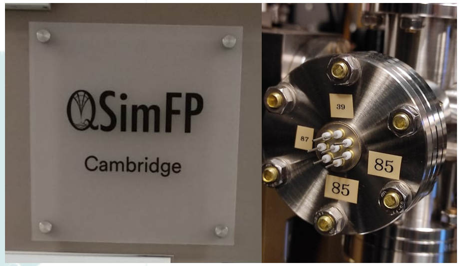
Facilities



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

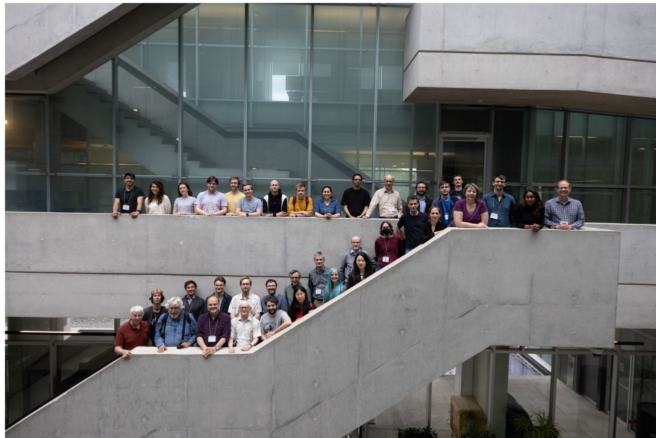
2+1-Dimensional Black Hole Simulator
- State-of-the-art nanotechnology facilities
- Superconducting microwave micro-structures
- Quantum Fields Dynamics & Quantised Rotation

Community

IOP, London, UK, QSimFP 2022

Location	STFC Funding	External Funding
University of St. Andrews	2	4
Newcastle University	4	5
Nottingham University	7	22
Cambridge University	2	8
Royal Halloway University London	3	4
University College London	4	4
King's College London	2	5
Sheffield University	3	3
UK (Southampton, Glasgow, York)	0	5
Canada/USA	0	7
Europe (Austria, Germany, Italy)	0	10
Total	**27**	**77**

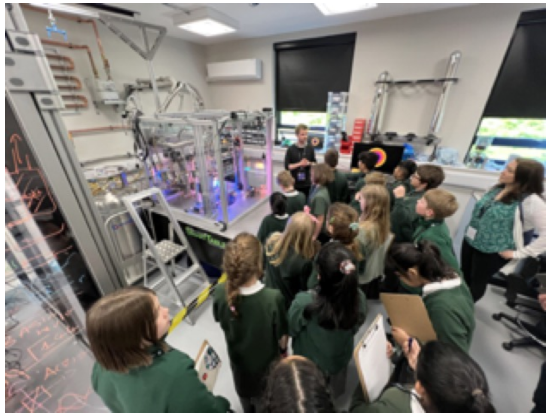
Perimeter Institute, Waterloo, Canada, QSimFP 2022



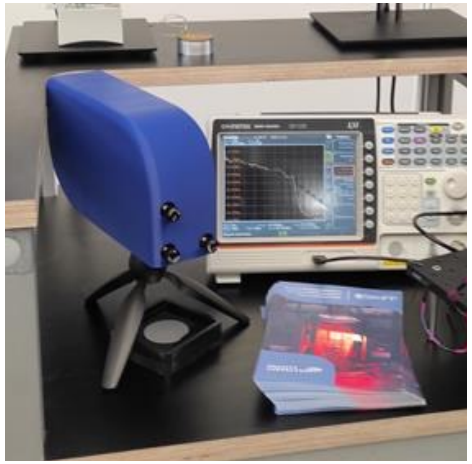
Impact

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

Synthetic Quantum Systems

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

Enhanced Quantum Capabilities: Leveraging techniques and facilities honed through the NQTP program to precisely control and discern quantum systems, pertinent to fundamental physics applications.

Opportunity:

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

Immediate and long-term Fundamental Physics

- Black Hole Ringdown:
  - Spectral Stability
  - Black Hole Bound States (Axion Fields)
  - Non-linearities in Black Hole Bombs
- Holographic Superfluid:
  - Exploration of Strongly Dissipative FTs
- Mutual Information / Area Law:
  - Expansion beyond 1+1 Dim Systems
- 1st and 2nd Relativistic Phase Transitions:
  - False Vacuum Decay (1st Order)
  - Tachyonic Field Decay (2nd Order)
- Non-equilibrium (Open) Field Theory Simulator:
  - Investigation into Multi-mode Scattering Processes
  - Extraction of Scattering Amplitudes

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

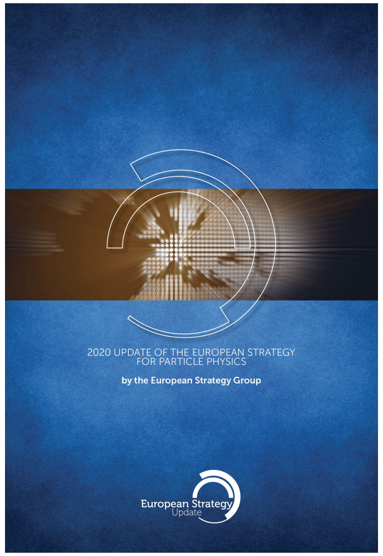
… the connection …

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 … | … the connection … | … the small

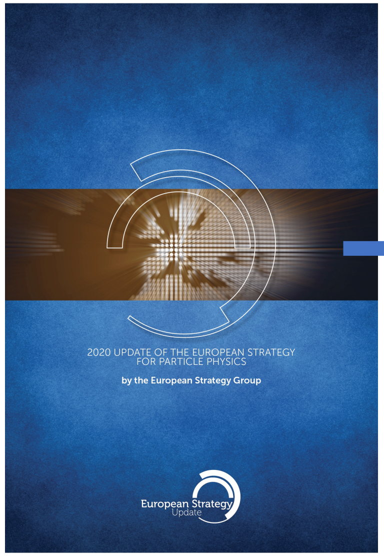
weblink

2017-2026 European Astroparticle Physics Strategy

weblink

Long Range Plan 2017 Perspectives in Nuclear Physics

weblink

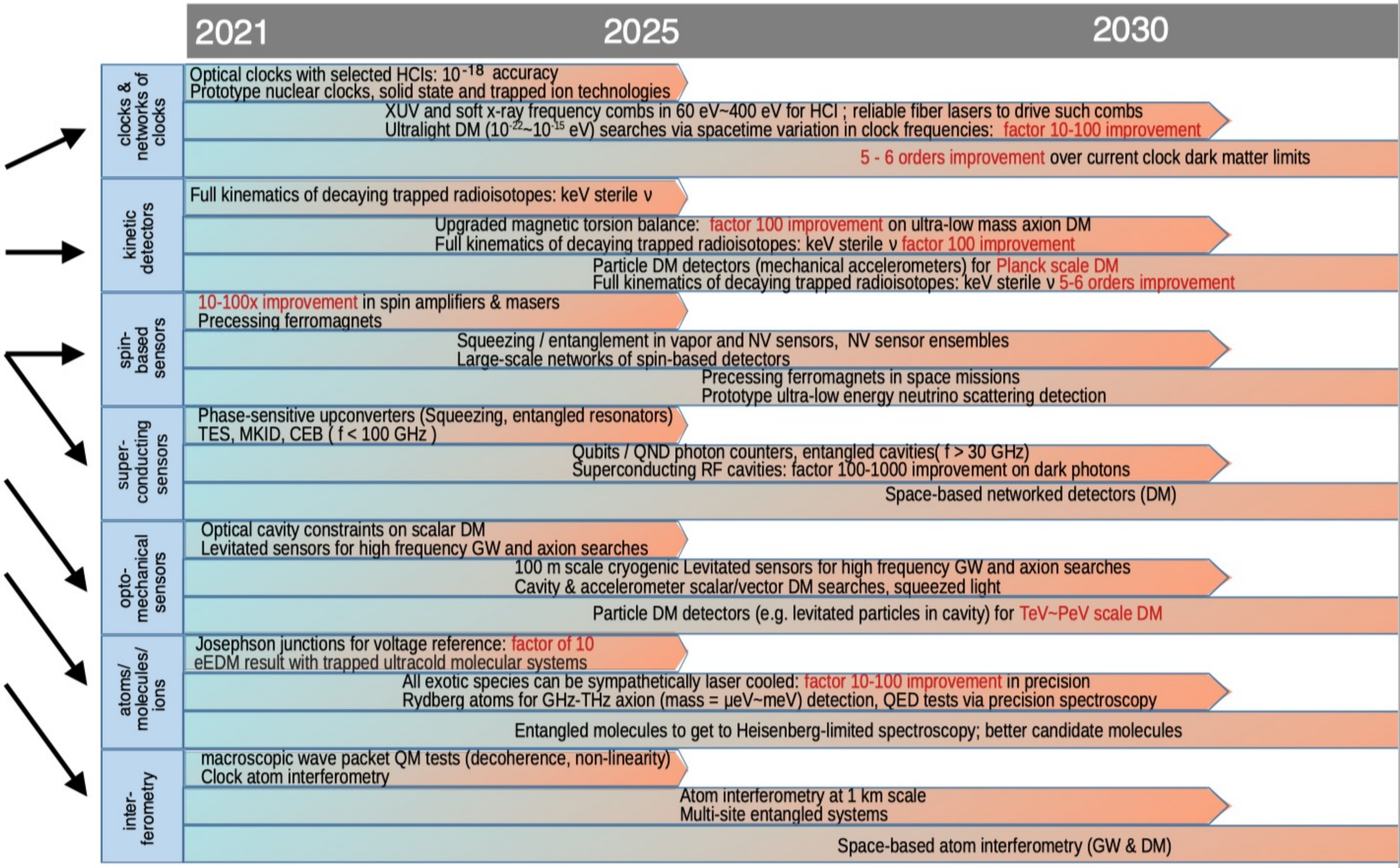


2020 Update of the European Particle Physics Strategy

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!

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)**

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 and proposals written

CERN HAS A DEVELOPING QUANTUM PROGRAMME

FERMILAB IS A DOE QUANTUM SCIENCE CENTER

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
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

THE NEW UK QUANTUM STRATEGY (15 MARCH 2023) PROVIDES AN ENVIRONMENT FOR QTFP TO CONTINUE TO THRIVE

1+1 =3 A US + UK PARTNERSHIP CAN ACHIEVE MORE THAN EITHER NATION WORKING ALONE
THERE IS EXCITING SCIENCE AHEAD!

"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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