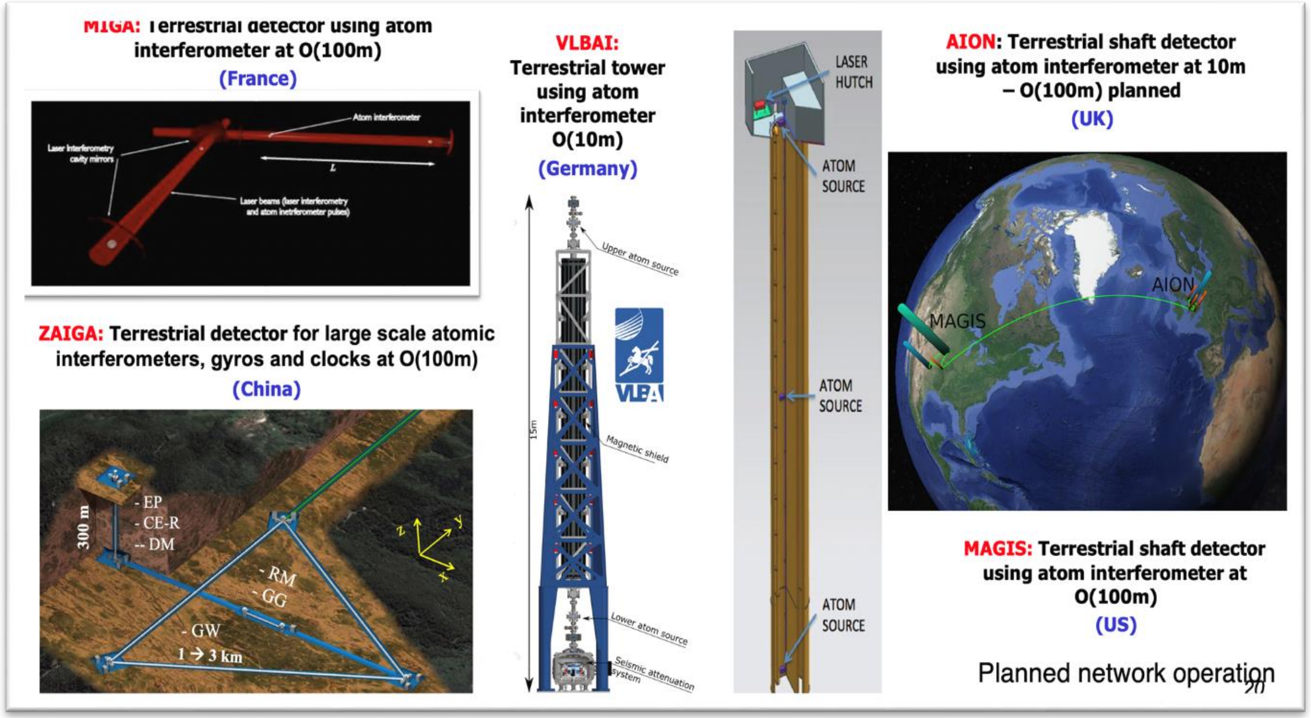
Imperial College London

UK Quantum Technology for Fundamental Physics (QTFP)

QSNET AION QUEST DMC QI QSHS QSimFP QTNM



Oliver Buchmueller

Imperial College London, Oxford University, Royal Society Leverhulme Trust Senior Research Fellow

DOE-STFC-FNAL US-UK Partners Event

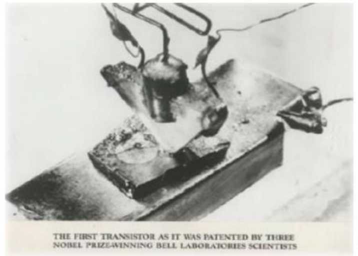
UK QTFP Overview

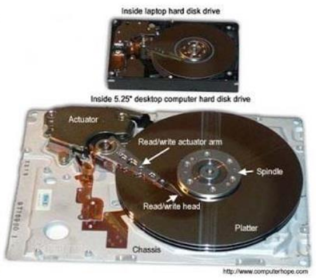
Example of Open Questions in Fundamental Physics

- What is dark matter made of?
- What is dark energy made of?
- Why is there more matter than antimatter in the universe?
- How heavy are the neutrinos? What was their role in the formation of the universe?
- Is there a quantum theory of gravity that can describe the universe we live in?
- What is the number of dimensions in a fundamental theory of nature?
- … and many more

Example of Open Questions in Fundamental Physics

… and how the Quantum Revolutions could help addressing them





Planck's quantum theory — beginning of 20th century

transistor — 1947

hard disk — 1954

laser — 1960

Albert Einstein (1879-1955)

Werner Heisenberg (1901-1976)

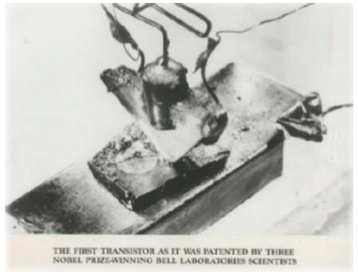
Erwin Schrödinger (1887-1961)

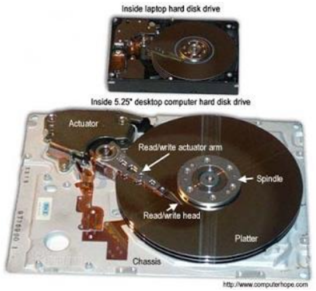
The first quantum revolution

Observation and macroscopic manifestation of quantum principles

Example of Open Questions in Fundamental Physics

… and how the Quantum Revolutions could help addressing them





Planck's quantum theory — transistor — hard disk — laser

beginning of 20th century — 1947 — 1954 — 1960 — end 20th / beginning 21st

Control of single quantum particles
First quantum algorithms

Richard Feynman
(1918–1988)

Serge Haroche

And also Alain Aspect, Charles Bennett, Gilles Brassard, Artur Ekert, Peter Shor…

The second quantum revolution

Active manipulation of single quantum particles and interaction between multiple particles for applications 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

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

Validation

UKRI Innovate UK

IUK, ISCF, Industry
£450M

Prototypes

Products

Spin-offs

GCHQ [dstl] Ministry of Defence

Other
£80M

UK National Quantum Technologies Programme

Slide from Ian Shipsey

£1bn UK National Quantum Technology Programme Pillars

2020

There will be more about QTFP in Dave Newbold's talk

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

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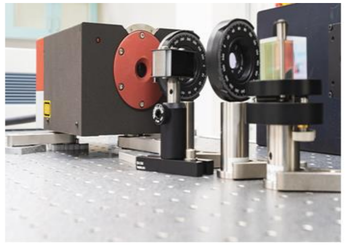
UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Slide from Ian Shipsey

QI

Quantum-enhanced Interferometry for new physics

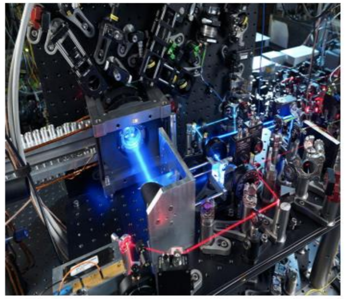


Principal investigator: Harmut Grote

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

A network of clocks for measuring the stability of fundamental constants



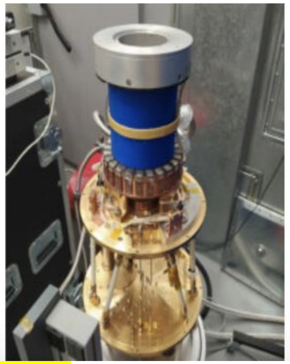
Strontium optical lattice clock experiment

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.

7 main projects plus 17 other
smaller scale funded research projects.
See backup for information

Slide from Ian Shipsey

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

Quantum enhanced superfluid technologies for dark matter and cosmology

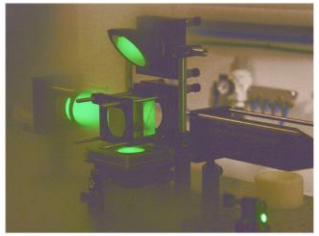
Nuclear demagnetisation experiment

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

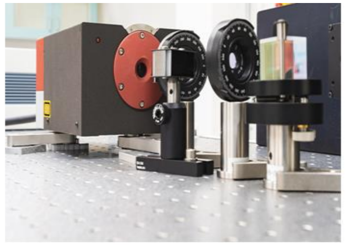
Quantum simulators for fundamental physics



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.

QI



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QSNE

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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.

QTNM

Determir

Principal in

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.

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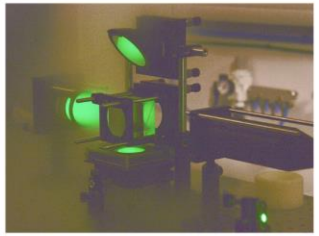
QSimFP



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Slide from Ian Shipsey

- **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).

Slide from Ian Shipsey

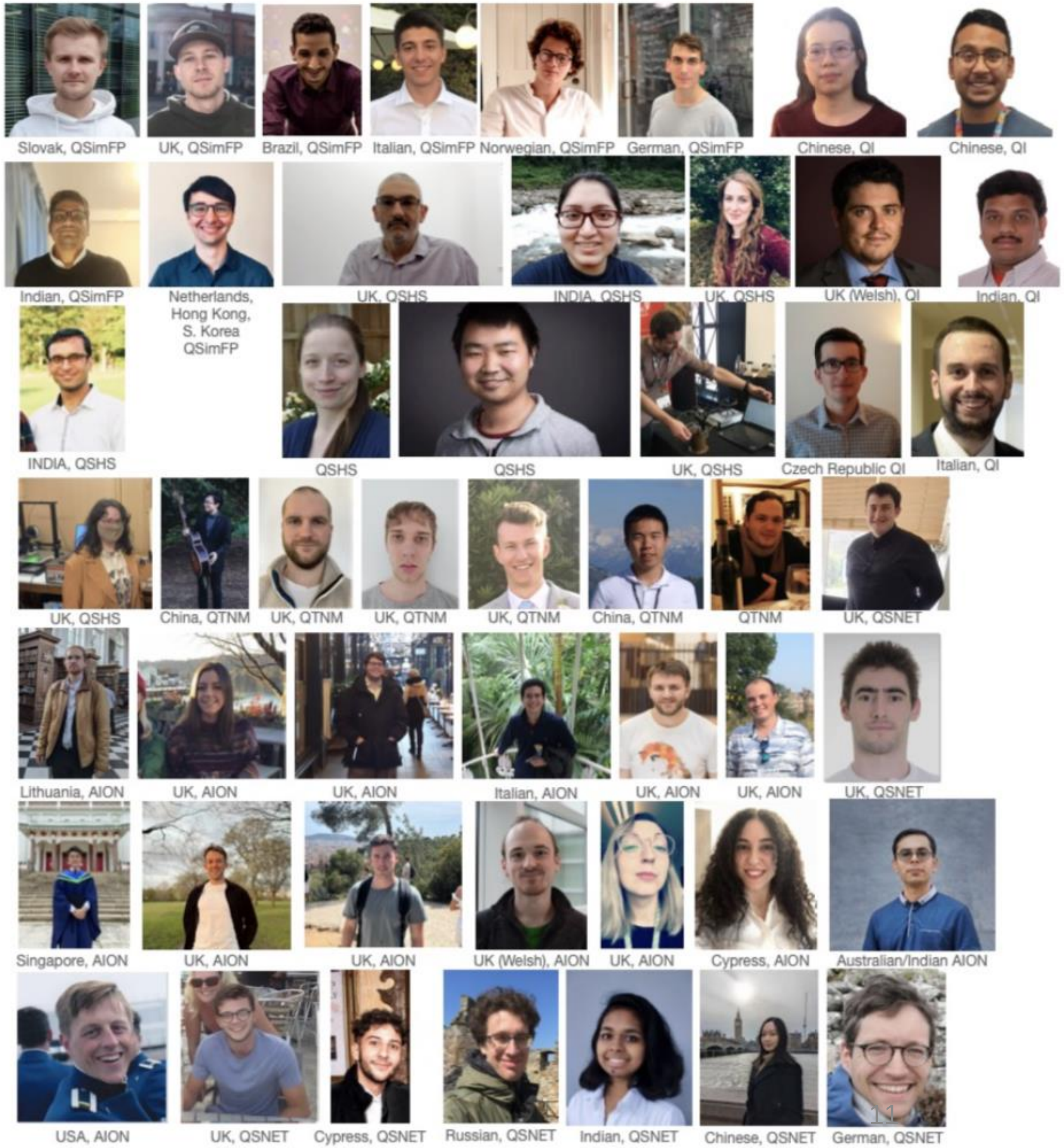
Education and Upskilling: QTFP has generated immense excitement amongst some of the brightest undergraduate and graduate students, postdocs and other early career researchers in the UK and abroad.

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.



Slide from Ian Shipsey

Quantum Technology for Fundamental Physics

Vortices in Superfluid Helium 4

Precision tabletop optical interferometry

Ultra-low-noise microwave sensing of microwaves

Qubit detectors

Photon counting, sub-standard -quantum-limit detection

Multi-Messenger Particle Physics!

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

PLUS, 17 other smaller scale funded research projects

Atom interferometry

Neutrino mass direct measurements using Cerenkov radiation

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 Dawn

Quantum Technology for Fundamental Physics

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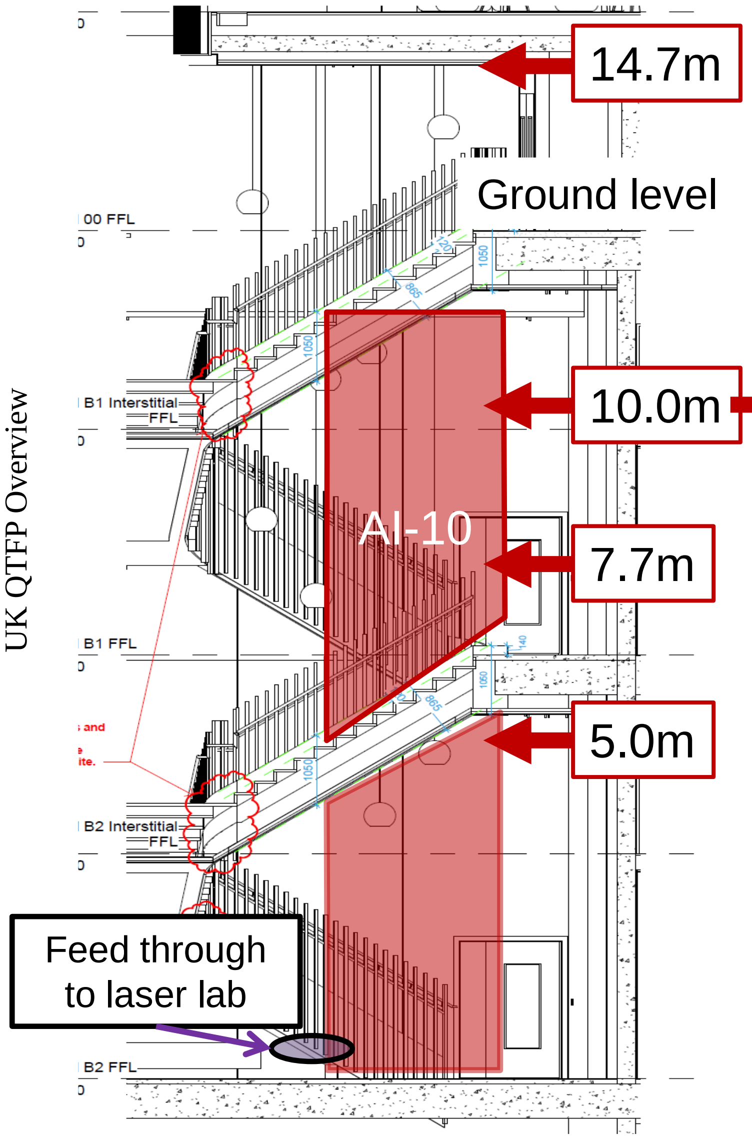
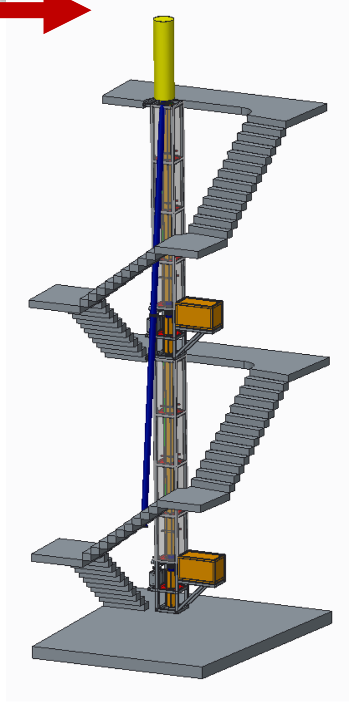
Imperial College London

AION

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]

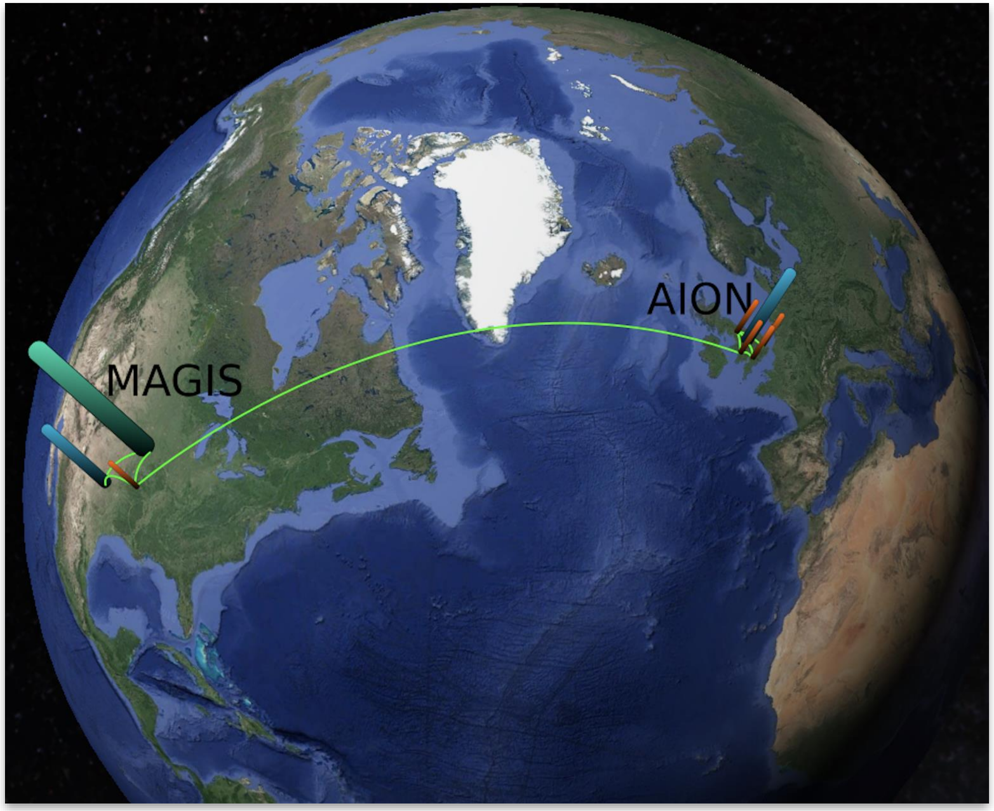
Ongoing Atom Interferometry Projects in UK and US

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.

Imperial College London

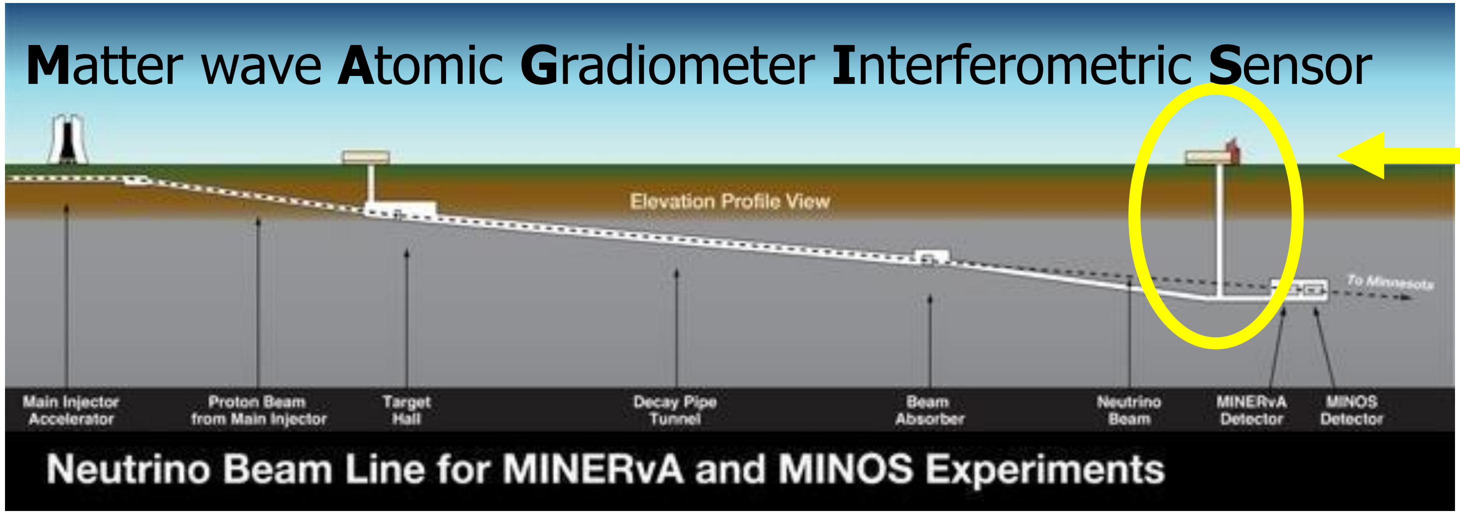
AION

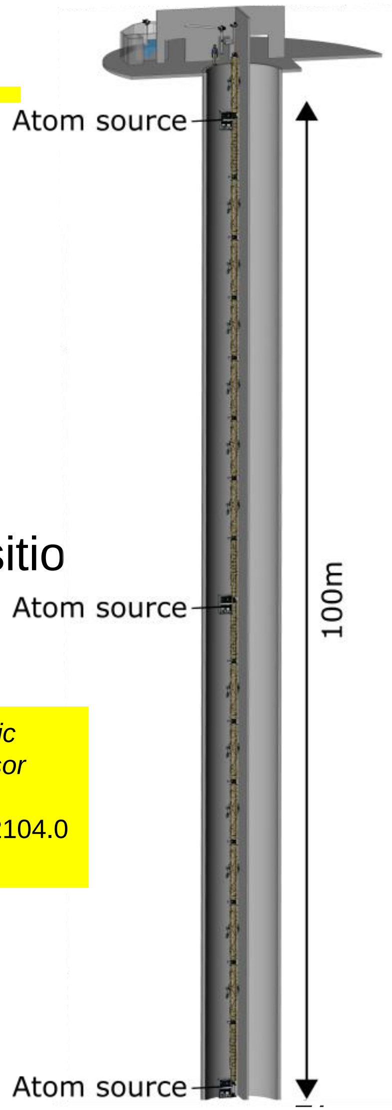
MAGIS-100 ICRADA Ceremony at Fermilab on Nov 16, 2023

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:2104.02835].

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

Imperial College London

AION

AION UK Contribution to MAGIS-100

UK QTFP Overview

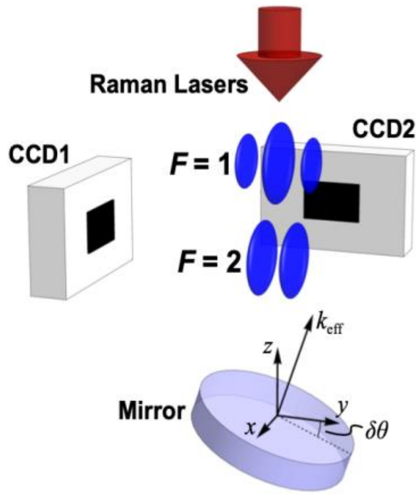
Detection system is UK contribution

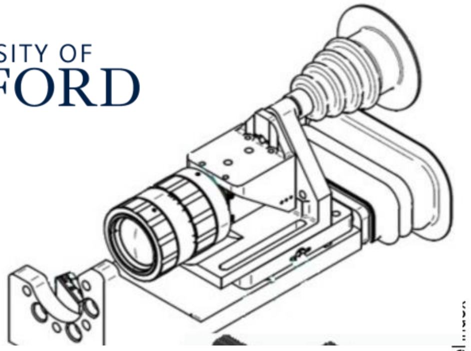
- **Enable single-shot phase extraction**
- In-vacuum optics and mechanical support systems for piezo-driven phase-shear readout and optical lattice-launch
  - Includes control and monitoring
- Low-noise calibrated imaging systems from LSST expertise
- Experimental FPGA control and precision timing systems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

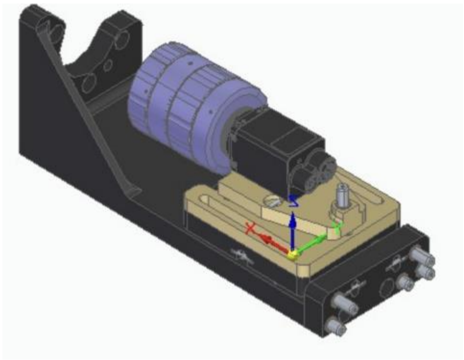
UNIVERSITY OF LIVERPOOL

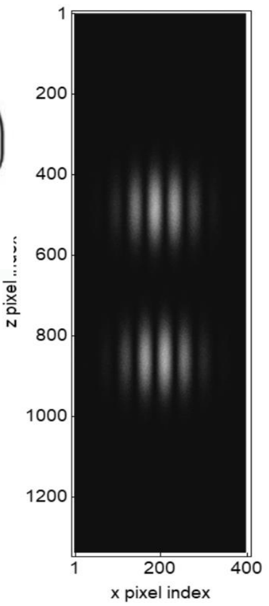
UNIVERSITY OF OXFORD

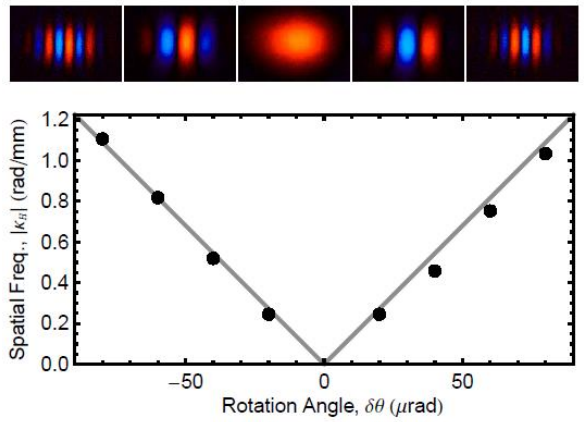
UNIVERSITY OF CAMBRIDGE

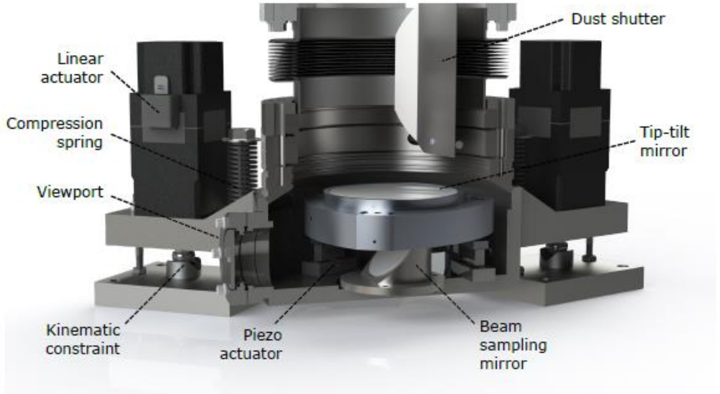


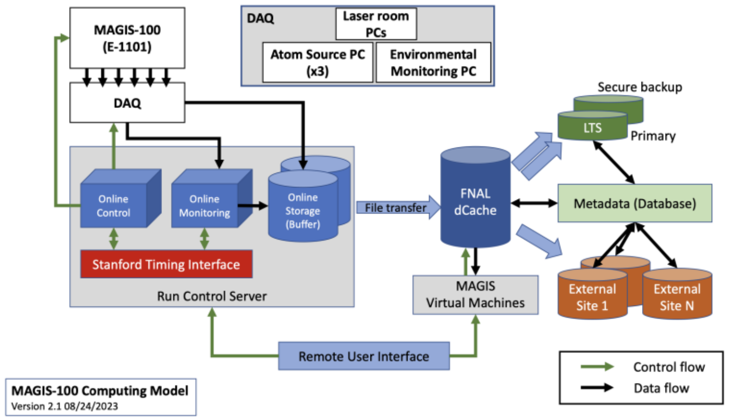












http://dx.doi.org/10.1103/PhysRevLett.111.1130 2

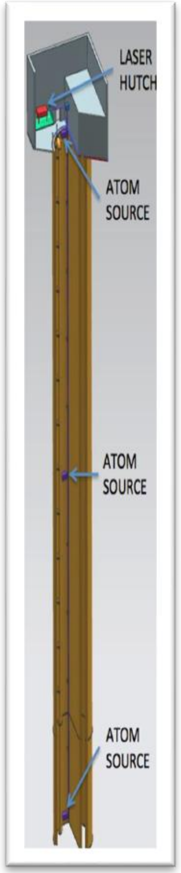
Imperial College London

AION

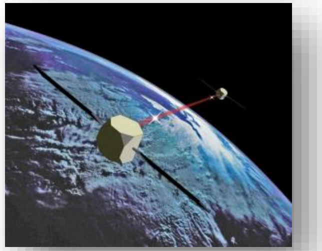
The AION Programme consists of 4 Stages

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

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



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



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

AION

AION Collaboration Days in Oxford: Fall 2021

UK QTFP Overview

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

AION Collaboration Days in Oxford: Fall 2021

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FIRST LESSONS LEARNED AFTER 24 MONTHS

PF4QT

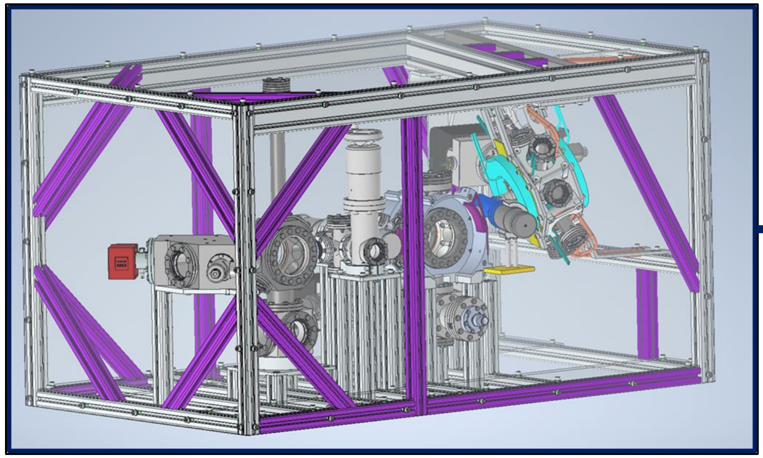
Centralise the design and production of major components:

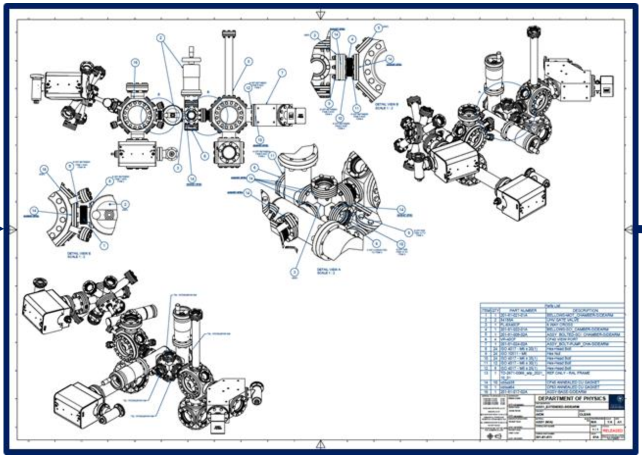
- **Ultra High Vacuum System**
- **Laser Stabilization System**
- **…**

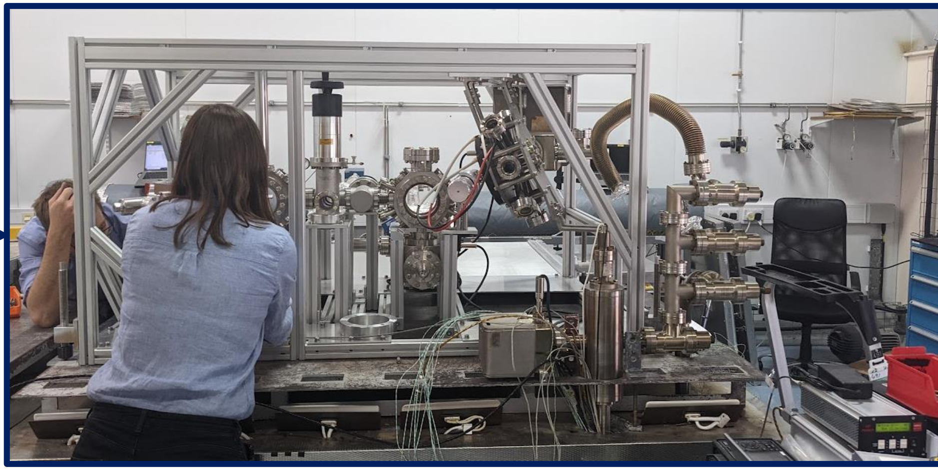
and make use of expertise at National Laboratories like Rutherford Appleton and Daresbury Laboratory!

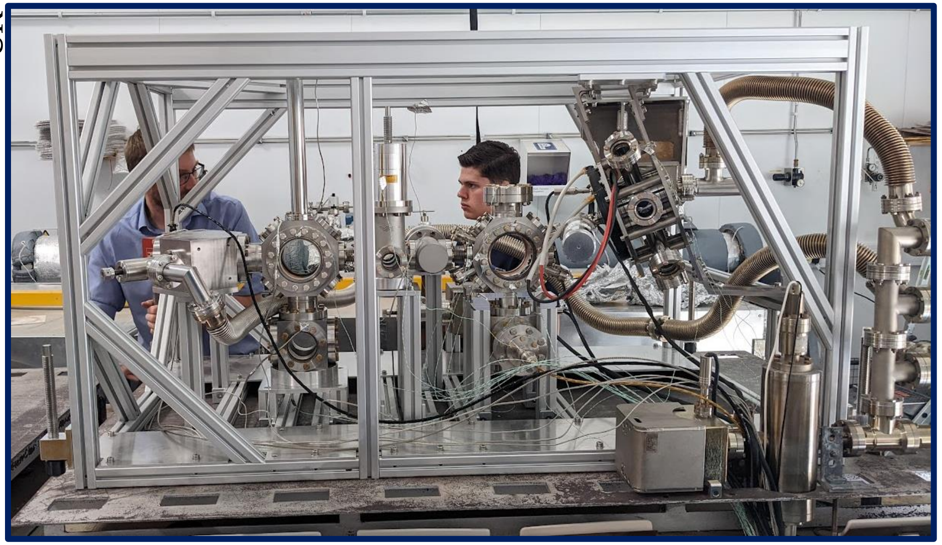
Ultra-High Vacuum System: Centralized Construction

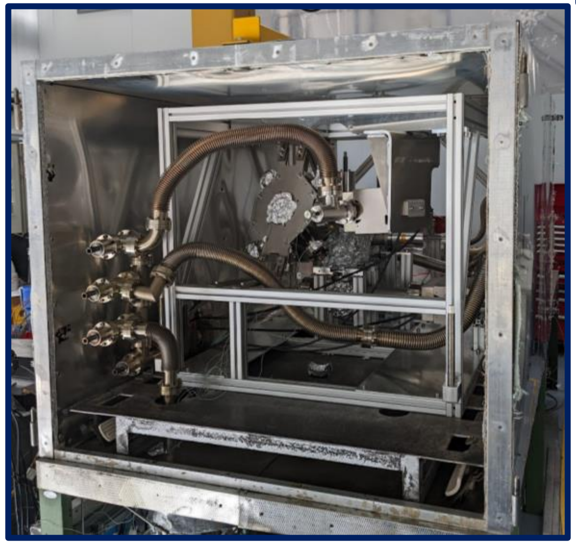
Manufacturing, Assembly and Installation

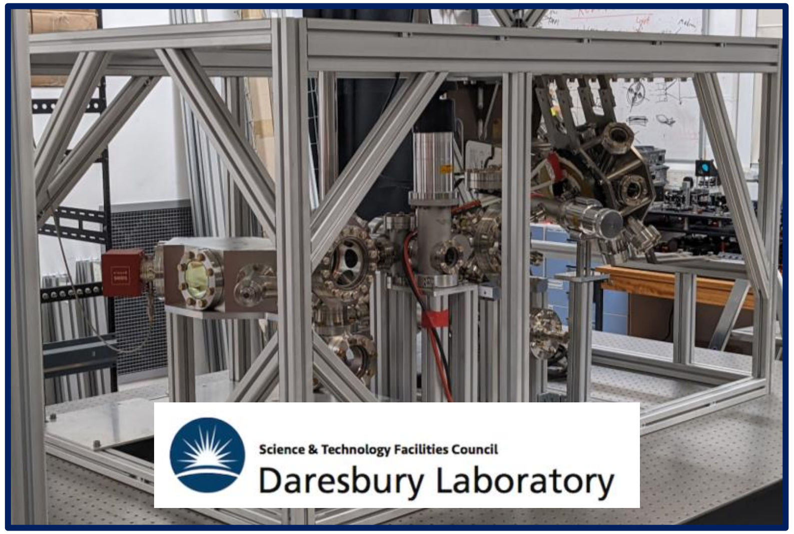


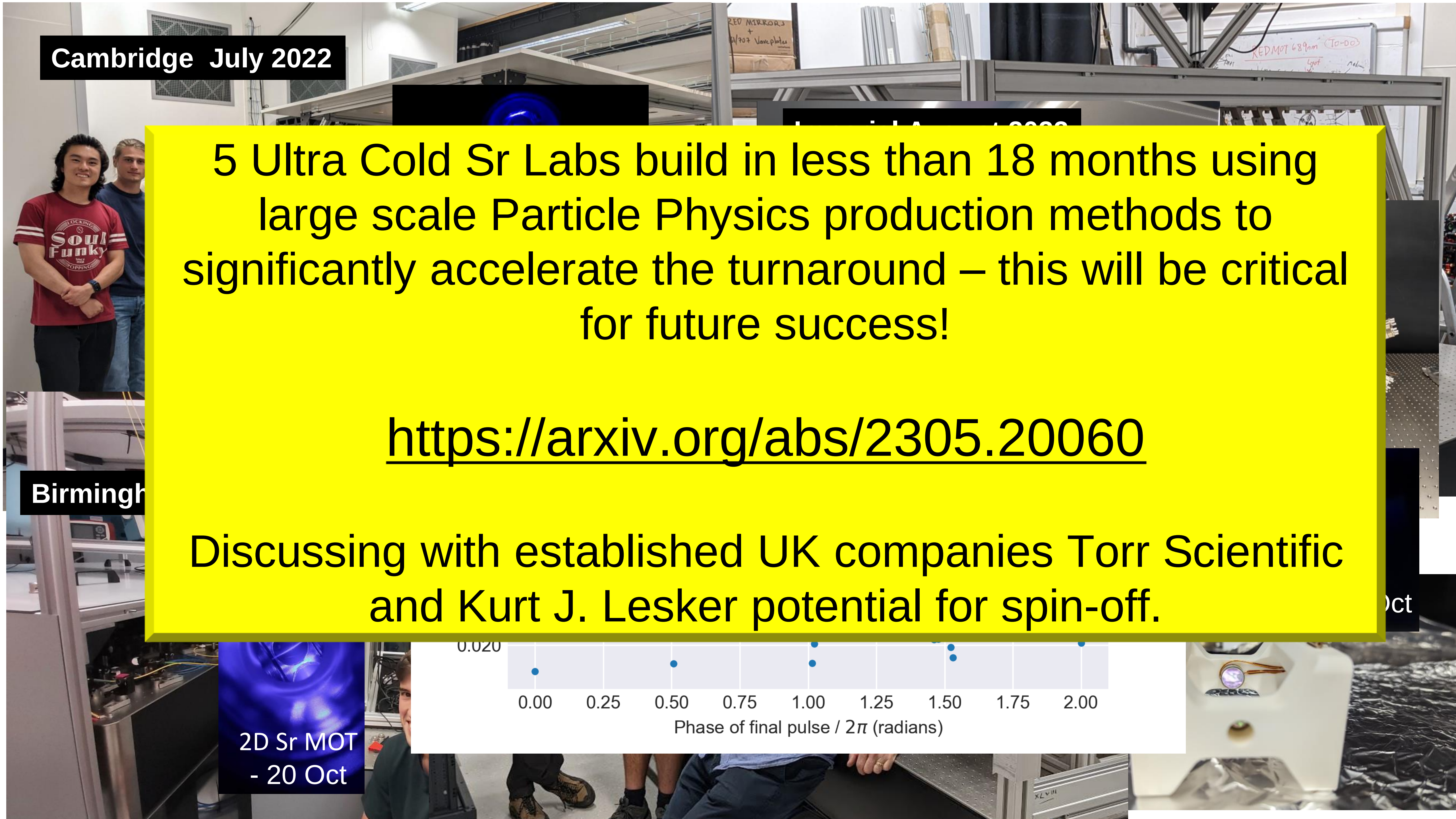












Cambridge July 2022
Birmingh
2D Sr MOT
- 20 Oct
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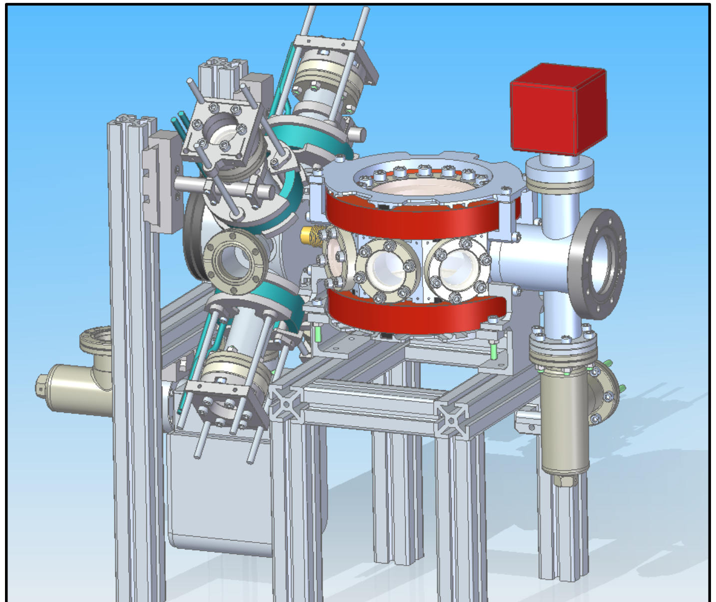
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00
Phase of final pulse / 2π (radians)
)ct
5 Ultra Cold Sr Labs build in less than 18 months using large scale Particle Physics production methods to significantly accelerate the turnaround – this will be critical for future success!
https://arxiv.org/abs/2305.20060
Discussing with established UK companies Torr Scientific and Kurt J. Lesker potential for spin-off.

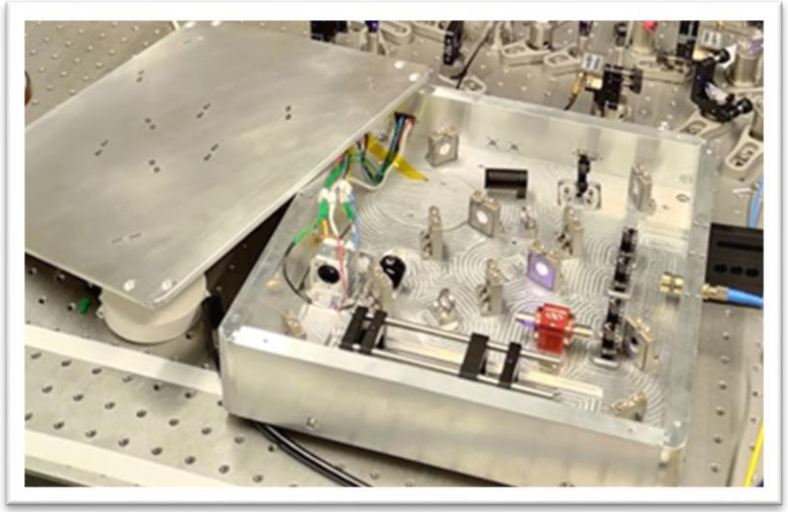
High Flux Atom Interferometry Source (HiFAIS)

The International Science Partnerships Fund (ISPF) supports collaborations between UK researchers and innovators and their peers from around the world.

The work will bolster the ongoing **AION/MAGIS projects** while also holding significant implications for **atomic clocks** and **innovative quantum computing platforms**.



Based on AION design



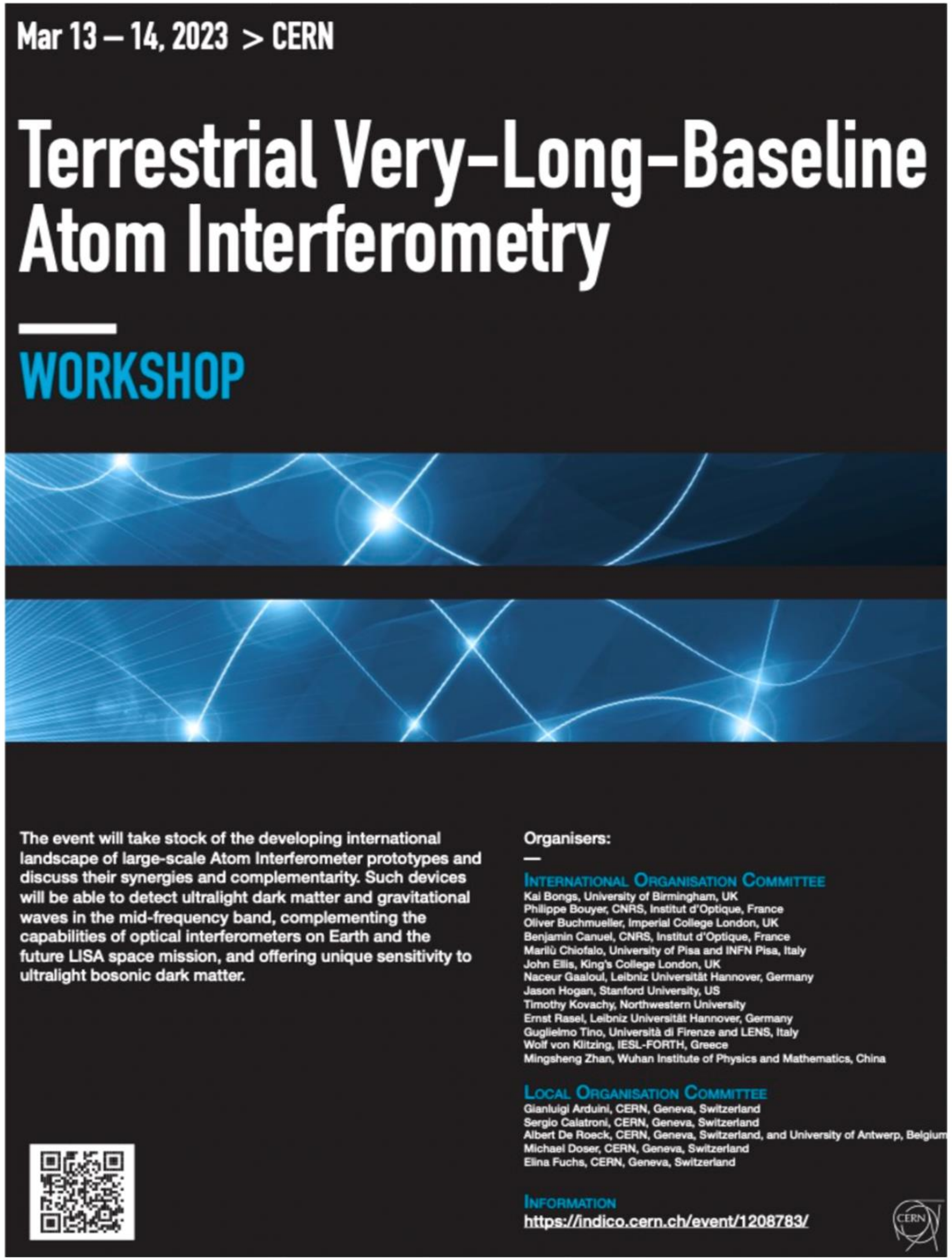
HiFAIS project goals:

- **Increase atomic flux**
- **Reduce size, weight and power**

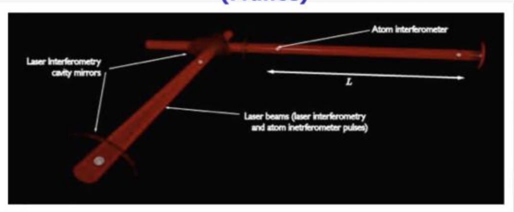
Techniques:

- Improved oven design and first stage cooling
- Development of a continuous sub-μK atom source
- Improved integrated optics setup for 461nm light

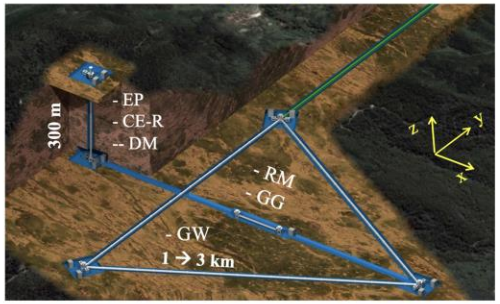
UKRI Science and Technology Facilities Council RAL Space | UKRI Science and Technology Facilities Council Particle Physics | Imperial College London | University of Oxford | Stanford University



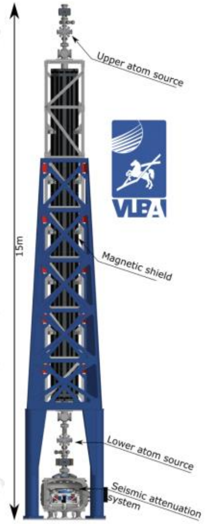
MIGA: Terrestrial detector using atom interferometer at O(100m) **(France)**

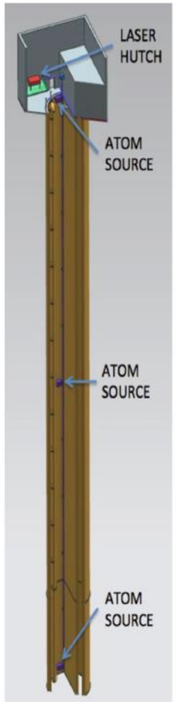


ZIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m) **(China)**



VLBAI: Terrestrial tower using atom interferometer O(10m) **(Germany)**





AION: Terrestrial shaft detector using atom interferometer at 10m – O(100m) planned **(UK)**

MAGIS: Terrestrial shaft detector using atom interferometer at O(100m) **(US)**

Planned network operation

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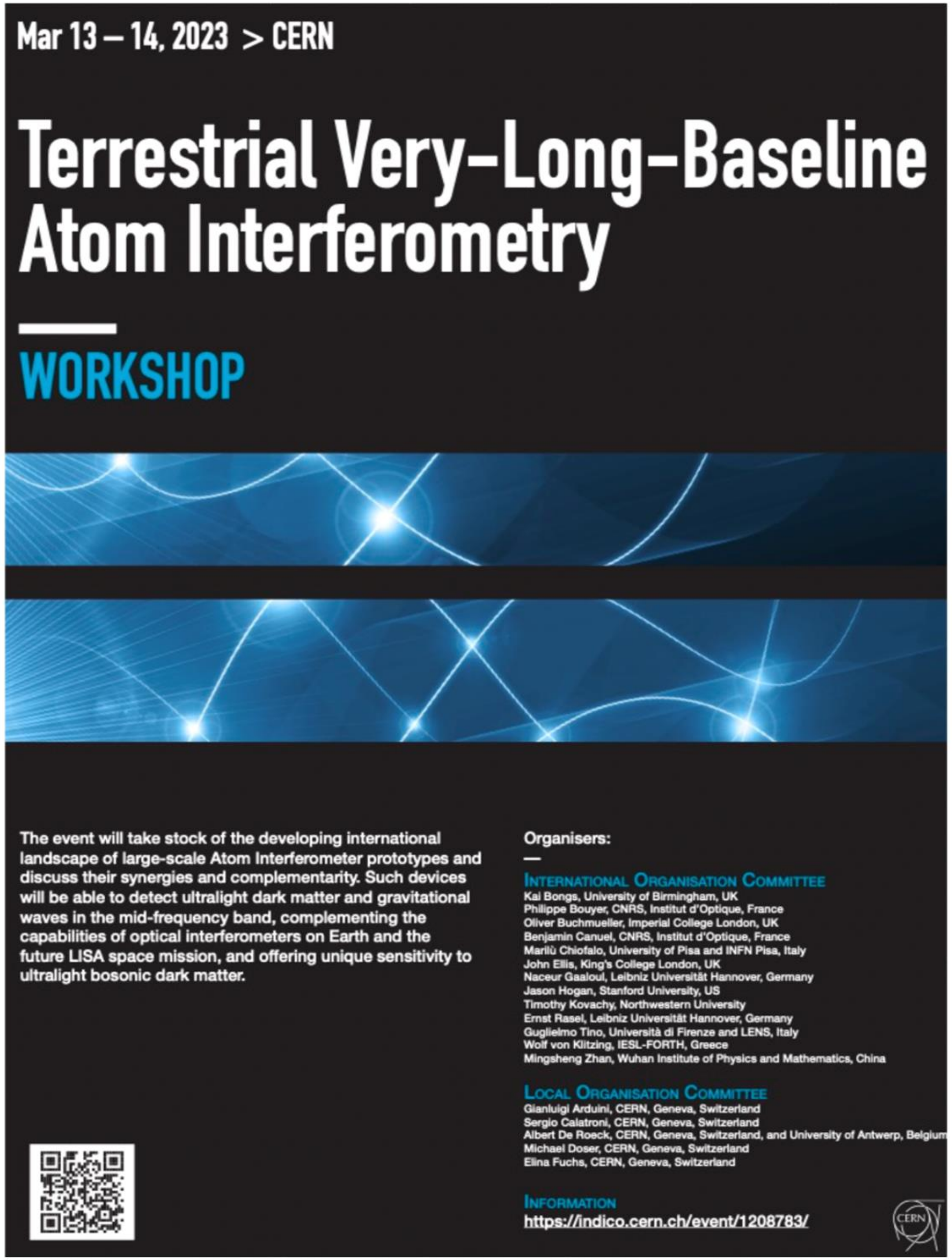
Michael Doser, CERN, Geneva, Switzerland
Elina Fuchs, CERN, Geneva, Switzerland

Physics Beyond Colliders

AIP Publishing

IQ QUANTUM TECHNOLOGY INITIATIVE



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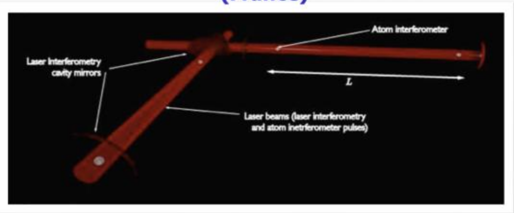

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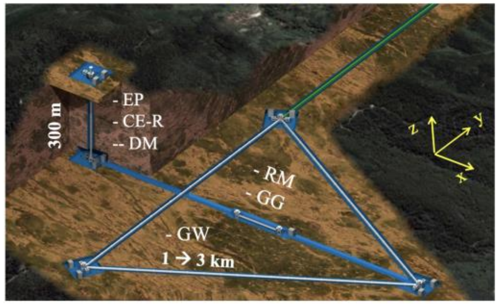

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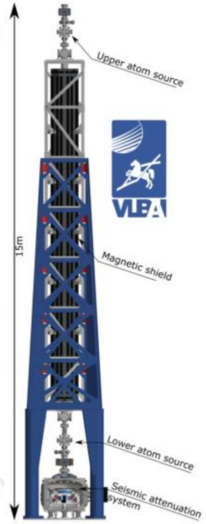

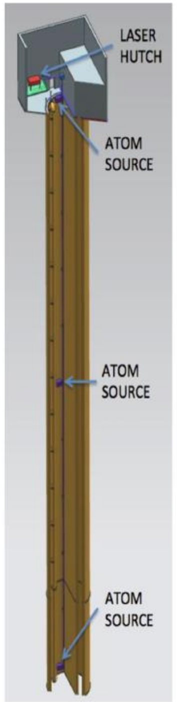

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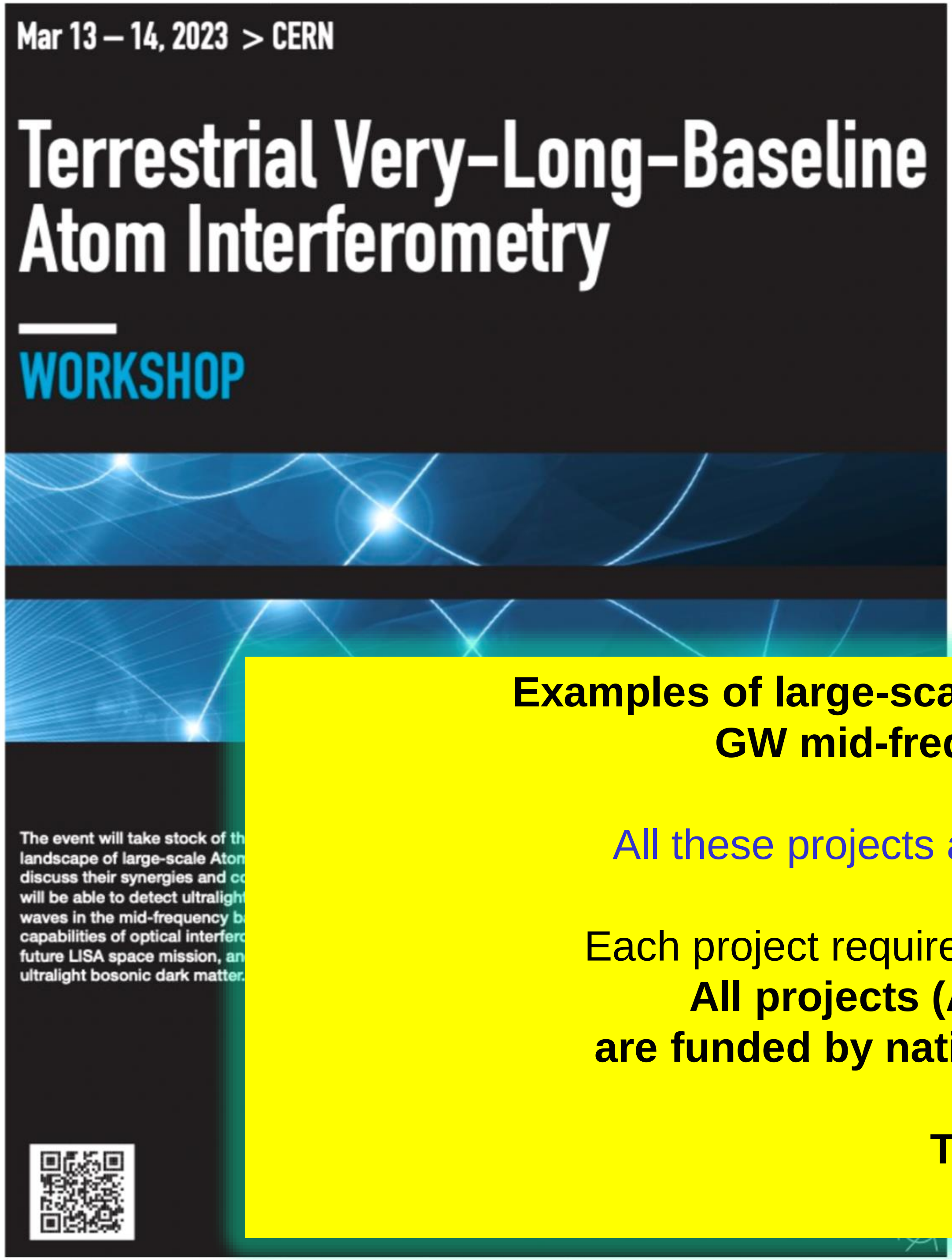

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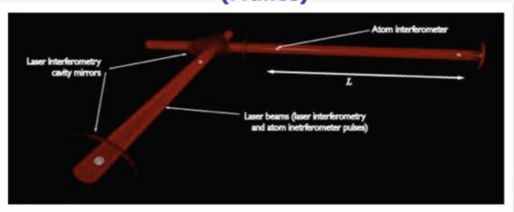

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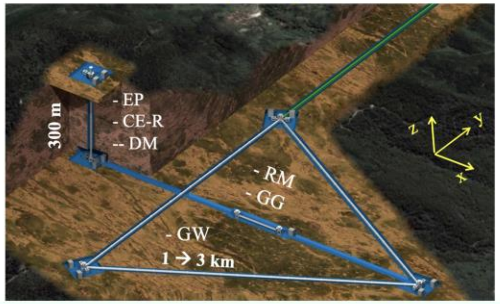

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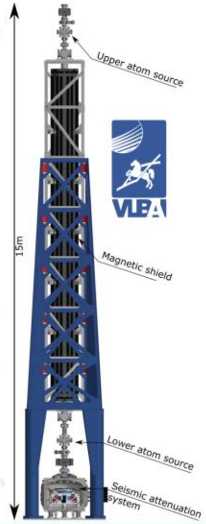
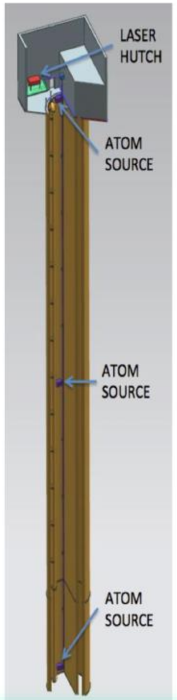




AION: Terrestrial shaft detector using atom interferometer at 10m – O(100m) planned (UK)

MAGIS: Terrestrial shaft detector using atom interferometer at O(100m) (US)

Planned network operation

International Organisation Committee

Examples of large-scale CA projects that act as demonstrators for GW mid-frequency band and ULDM detectors.

All these projects are represented in the TVLBAICommunity.

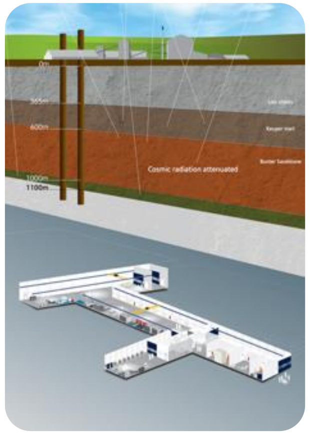
Each project requires an investment of O(10M+) currency units.
All projects (AION, MAGIS, MIGA, VLBAI, ZAIGA) are funded by national funding agencies and foundations.

Timeline 2020 to 2030ish

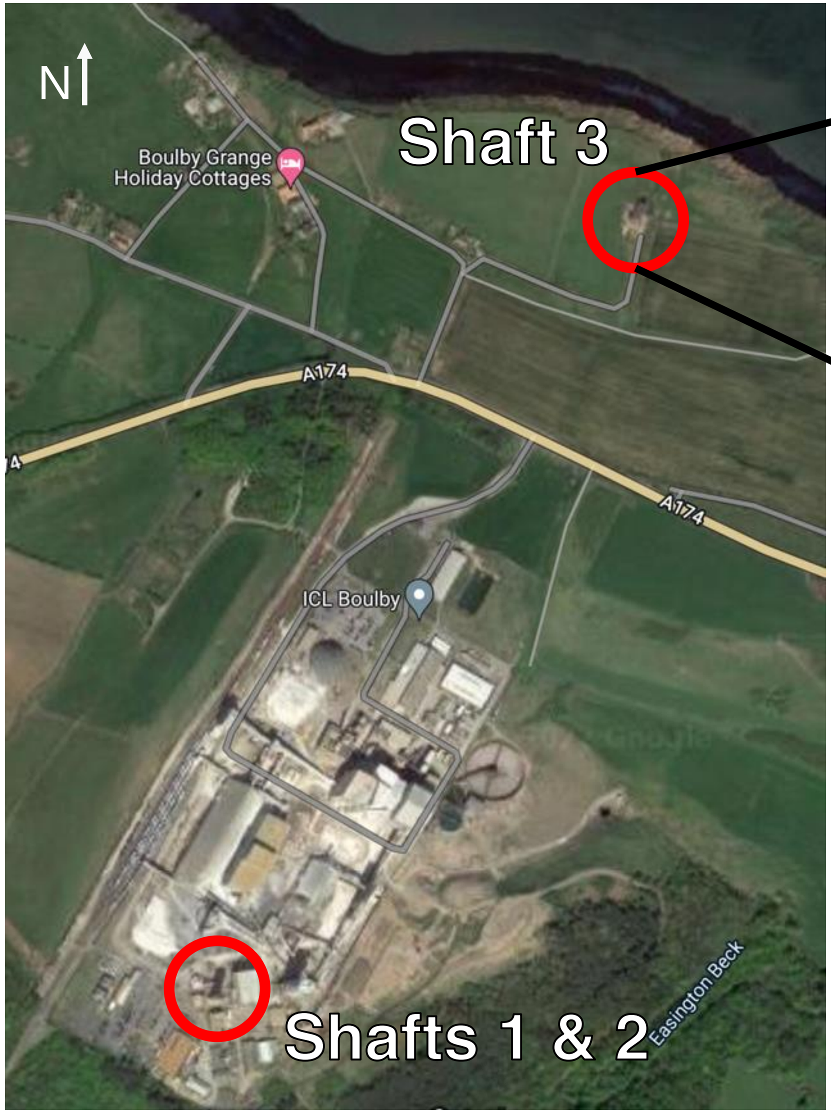
Elina Fuchs, CERN, Geneva, Switzerland

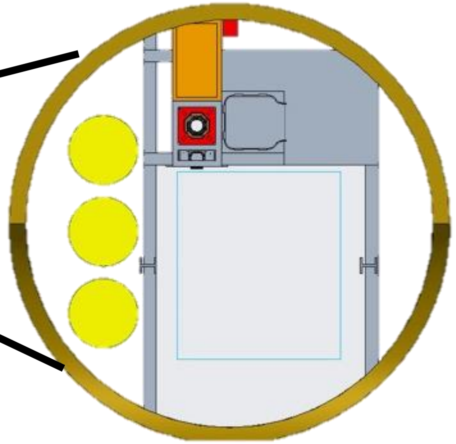
AION at Boulby Underground Laboratory: Potential 100m and 1km site

- Site of the STFC Boulby Underground Laboratory, at a working mine located on the North-East Coast England
- Good existing science support infrastructure and demonstrated technical capability.
- Strong local and national science community
- Characterization of seismic and magnetic environment planned



Shaft 1 & 2 (depth-1.1 km): Deep access shafts
Shaft 3 (depth-180 m): Tailings Shaft





Shaft 3

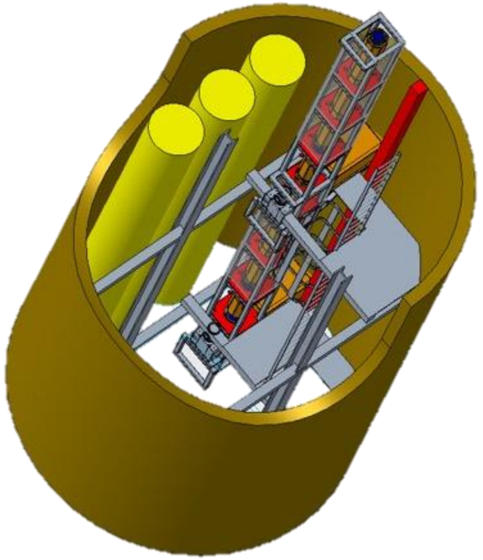
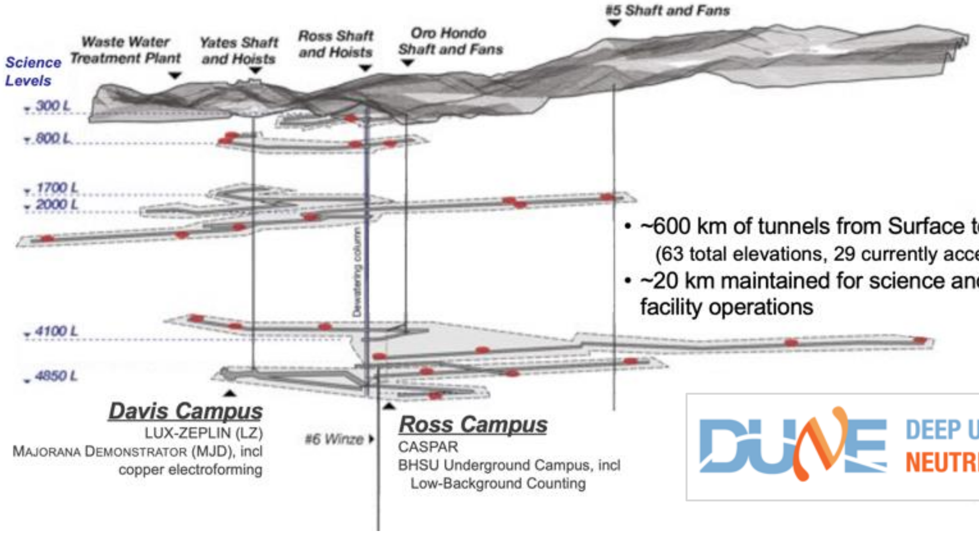


Image: google maps

Science and Technology Facilities Council

SURF (USA) and Calliolab (Finland) Underground Laboratories :

Sanford Underground Research Facility



- ~600 km of tunnels from Surface to 2.4 km deep (63 total elevations, 29 currently accessible)
- ~20 km maintained for science and facility operations

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

CALLIO LAB
Underground Center for Science and R & D

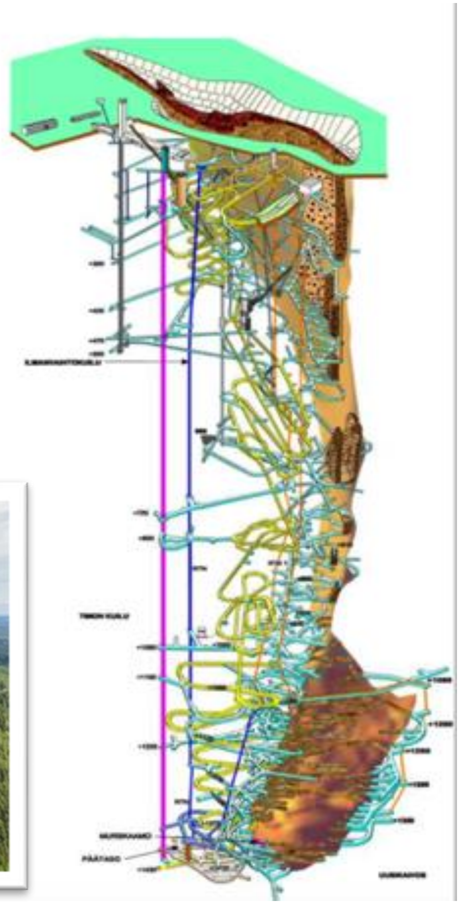
Jari Joutsenvaara
Julia Puputti

UNIVERSITY OF OULU

LOCATED AT THE 1.4 KM (4100 MWE) DEEP PYHÄSALMI MINE, PYHÄJÄRVI, FINLAND

UNIQUE UNDERGROUND RESEARCH NETWORK AND INFRASTRUCTURE - ACCESS, DEPTH, FACILITIES

CURRENTLY SIX UNDERGROUND HALLS OR TUNNEL NETWORKS HAVE BEEN TURNED INTO MINE RE-USE FACILITIES: LABS.



Mar 13 – 14, 2023 > CERN

Terrestrial Very-Long-Baseline Atom Interferometry

WORKSHOP

The event will take stock of the developing international landscape of large-scale Atom Interferometer prototypes and discuss their synergies and complementarity. Such devices will be able to detect ultralight dark matter and gravitational waves in the mid-frequency band, complementing the capabilities of optical interferometers on Earth and the future LISA space mission, and offering unique sensitivity to ultralight bosonic dark matter.

Organisers:

International Organisation Committee
Kai Bongs, University of Birmingham, UK
Philippe Bouyer, CNRS, Institut d'Optique, France
Oliver Buchmueller, Imperial College London, UK
Benjamin Canuel, CNRS, Institut d'Optique, France
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Albert De Roeck, CERN, Geneva, Switzerland, and University of Antwerp, Belgium
Michael Doser, CERN, Geneva, Switzerland
Elina Fuchs, CERN, Geneva, Switzerland

Information
https://indico.cern.ch/event/1208783/

April 3-5, 2024 > Imperial College - London

Terrestrial Very-Long-Baseline Atom Interferometry

2nd WORKSHOP

Next TVLBAI Workshop will be in LONDON in APRIL with the goal of forming a proto-collaboration at this event.

The primary objectives of the workshop are to discuss the technology and physics drivers for large-scale Atom Interferometry as well as to establish the foundation for an international TVLBAI proto-collaboration. This proto-collaborative effort aims to bring together researchers from diverse institutions, fostering strategic discussions and securing funding for terrestrial large-scale Atom Interferometer projects. The goal is to develop a comprehensive roadmap outlining design choices, technological considerations, and science drivers for one or more kilometer-scale detectors, expected to become operational in the mid-2030s.

International Organisation Committee
Gianluigi Arduini, CERN, Geneva, Switzerland
Kai Bongs, DLR Institute for Quantum Technologies, Germany
Philippe Bouyer, University of Amsterdam, Netherlands
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Local Organisation Committee
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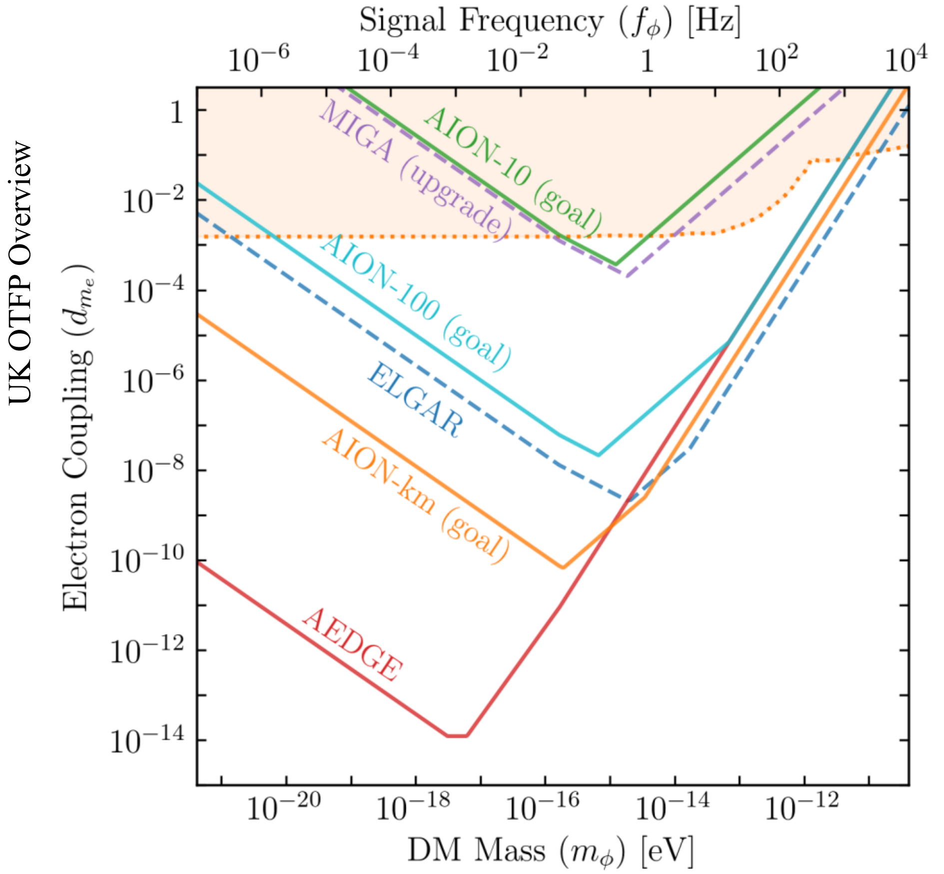
John Ellis, King's College London, UK
Richard Hobson, Imperial College London, UK
Adam Lowe, Oxford University, UK
Christopher McCabe, King's College London
Sean Paling, Boulby Underground Laboratory, UK
Ulrich Schneider, Cambridge University, UK
Dennis Schlippert, Leibniz University Hannover, Germany
Maurits van der Grinten, Rutherford Appleton Laboratory, UK

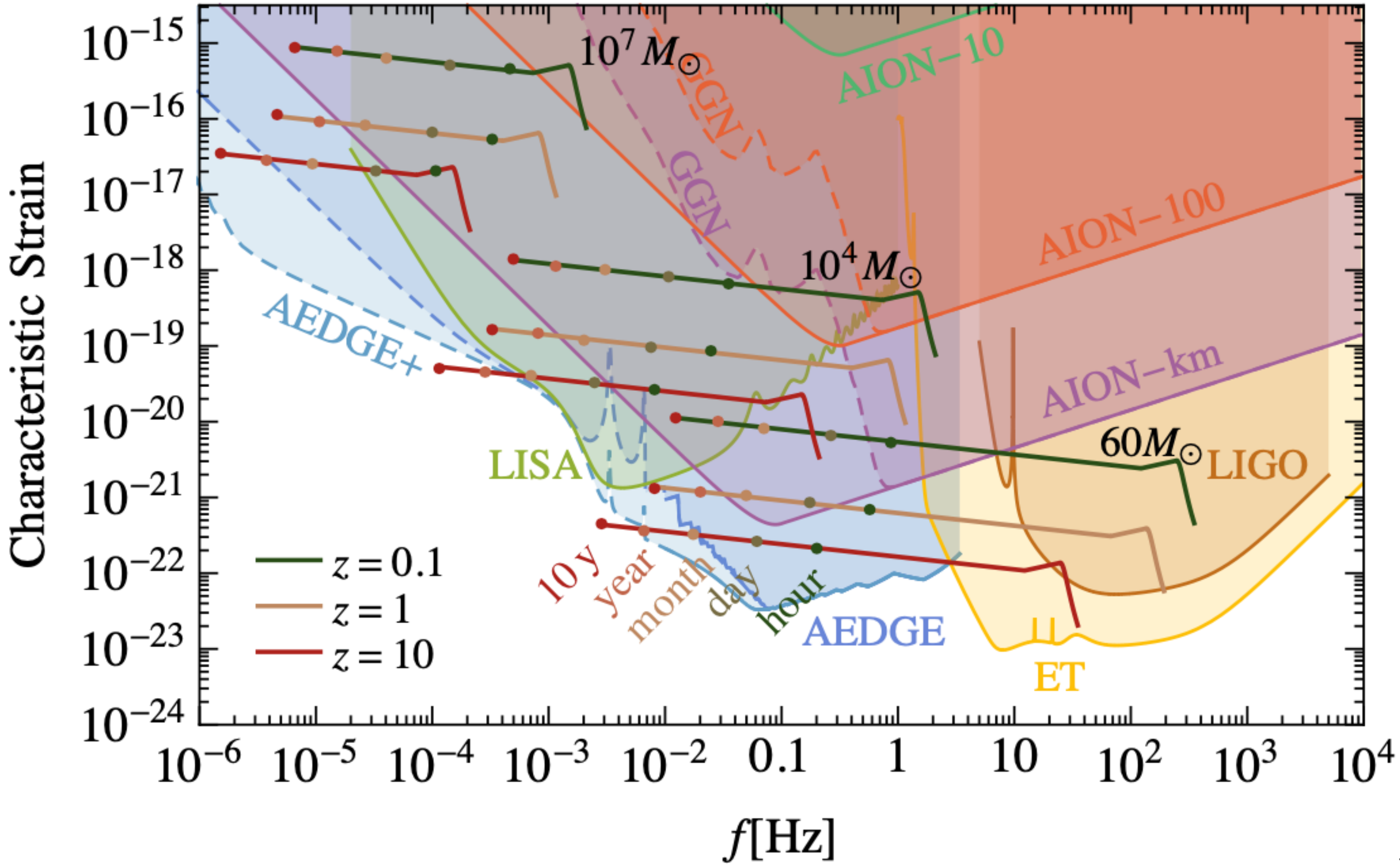
Imperial College London

Information
https://indico.cern.ch/event/1369392/

Physics Potential

Unlocking the potential for observation of Ultra-Light Dark Matter and Gravitational Waves from cosmological and astrophysical sources in the unexplored mid-frequency band



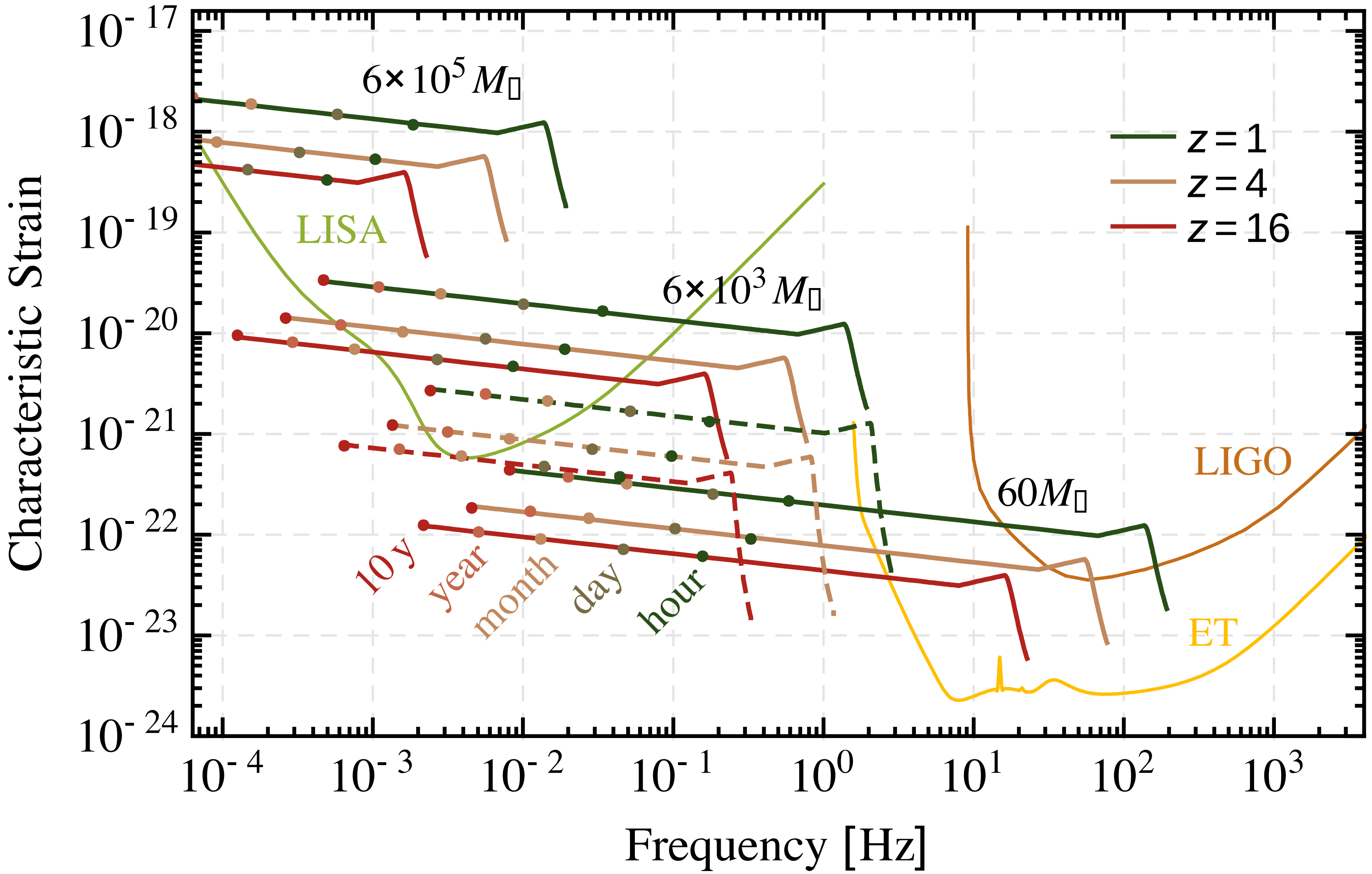


THE SCIENCE CASE

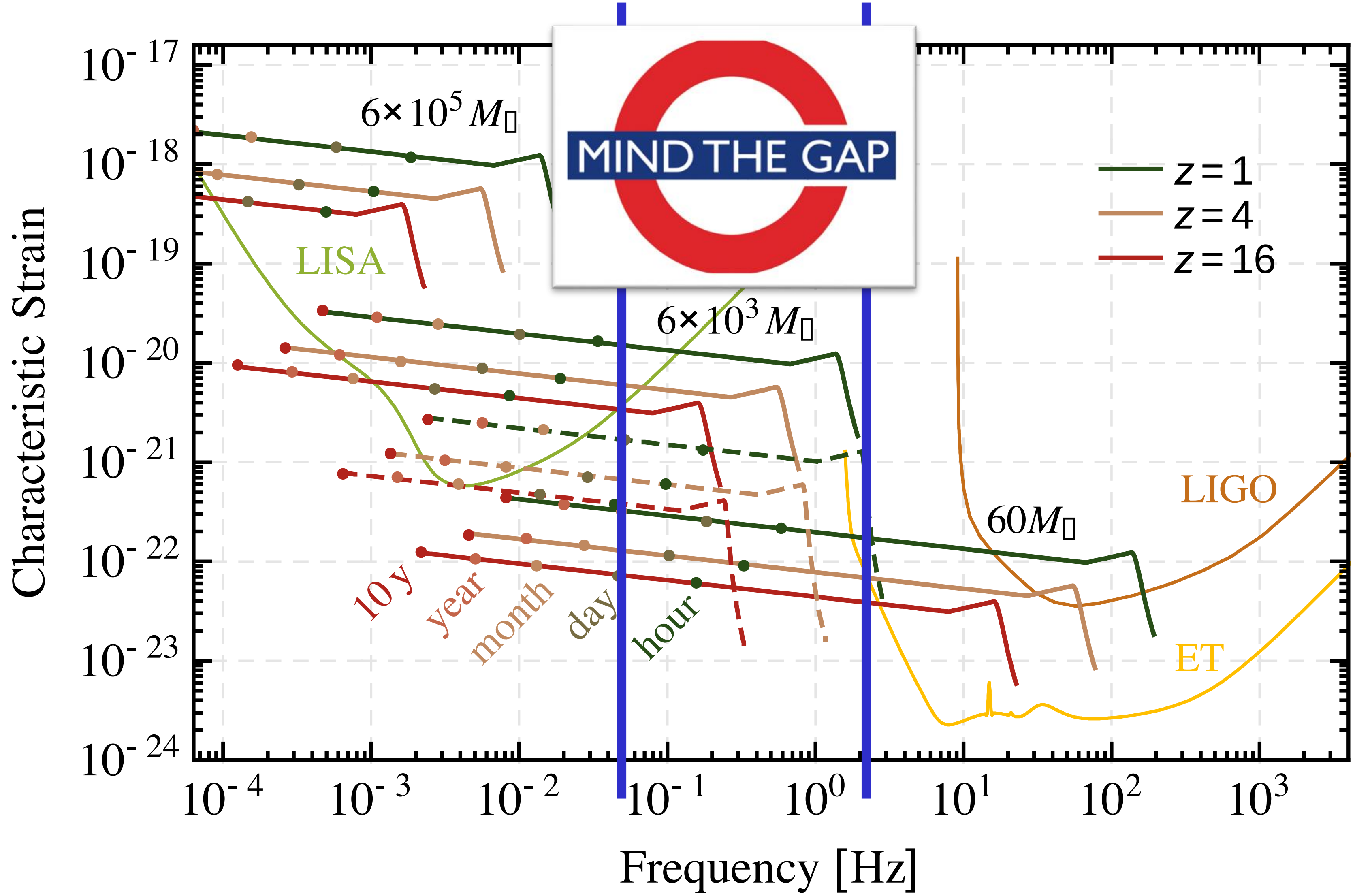
UNEXPLORED MID-FREQUENCY GRAVITATIONAL WAVES

AION

Pathway to the GW Mid-(Frequency)



Pathway to the GW Mid-(Frequency)

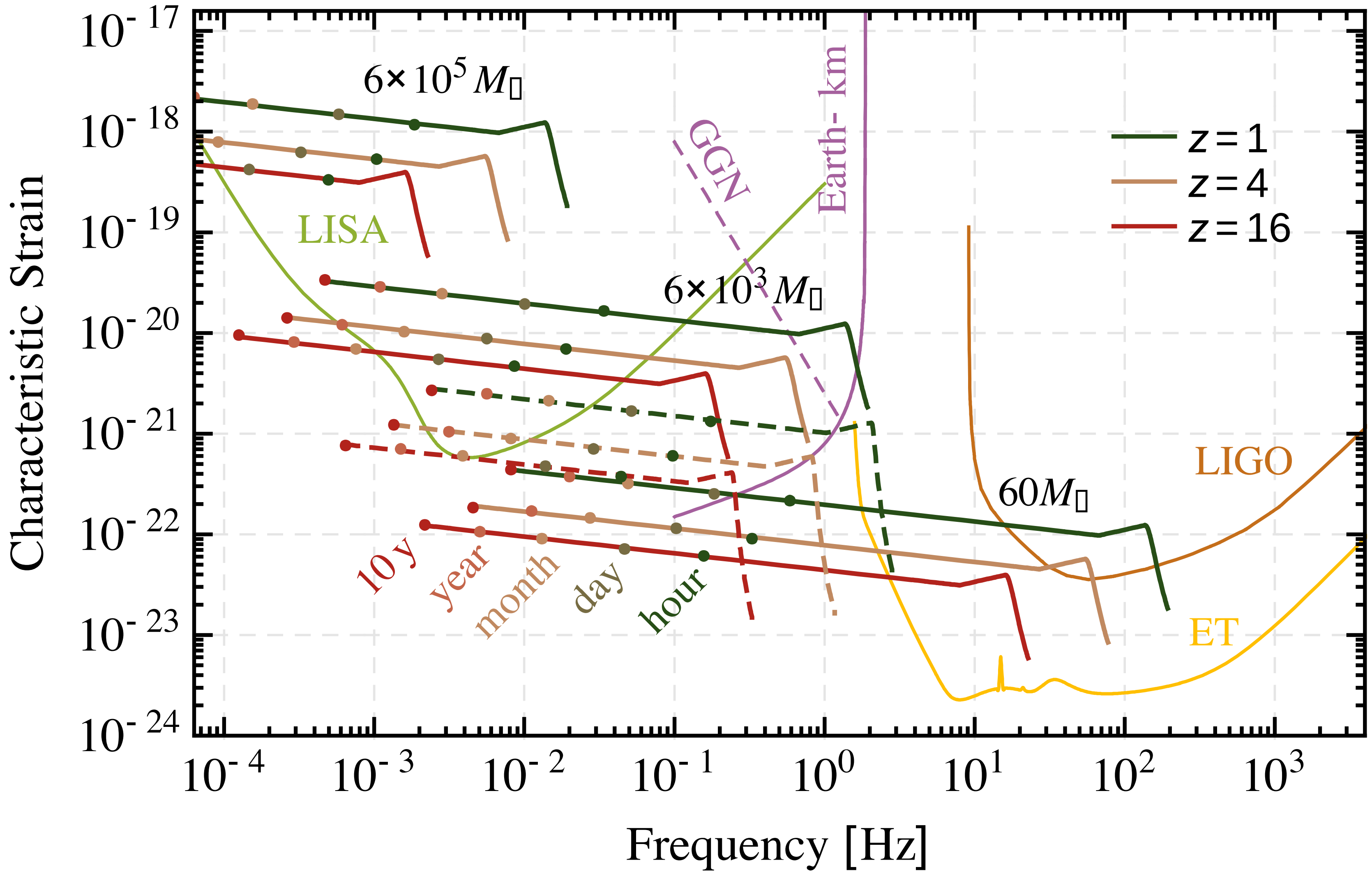


Mid-band science

- Detect sources BEFORE they reach the high frequency band [LIGO, ET]
- Optimal for sky localization: predict when and where events will occur (for multi-messenger astronomy)
- Search for Ultra-light dark matter in a similar frequency [i.e. mass] range

Mid-Band currently NOT covered

AION: Pathway to the GW Mid-(Frequency)



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AION: Terrestrial detectors can start filling this gap

Sky position determination

Sky localization precision:

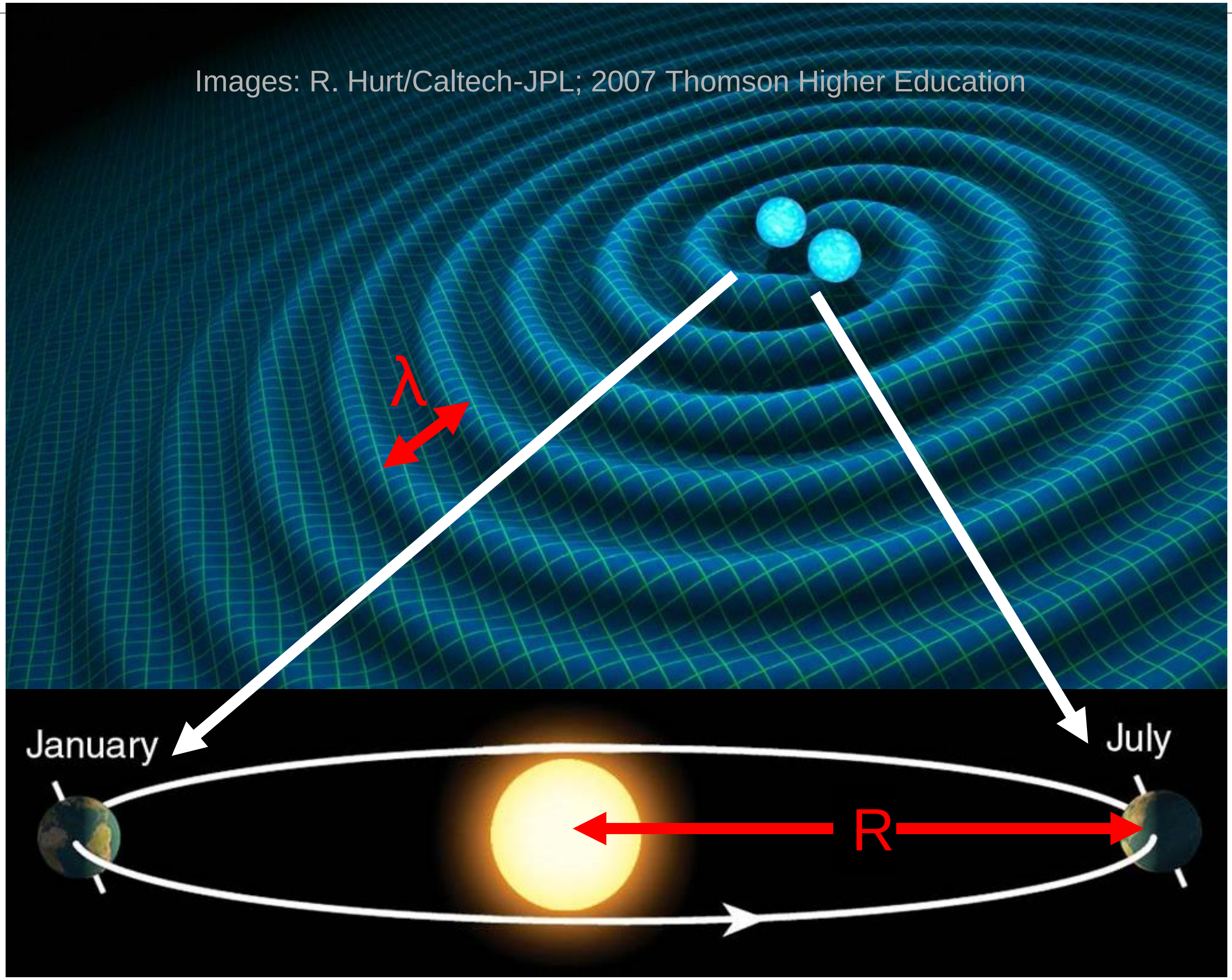
$$\sqrt{\Omega_s} \sim \left(\mathrm{SNR} \cdot \frac{R}{\lambda}\right)^{-1}$$

Mid-band advantages

- Small wavelength λ
- Long source lifetime (~months) maximizes effective R

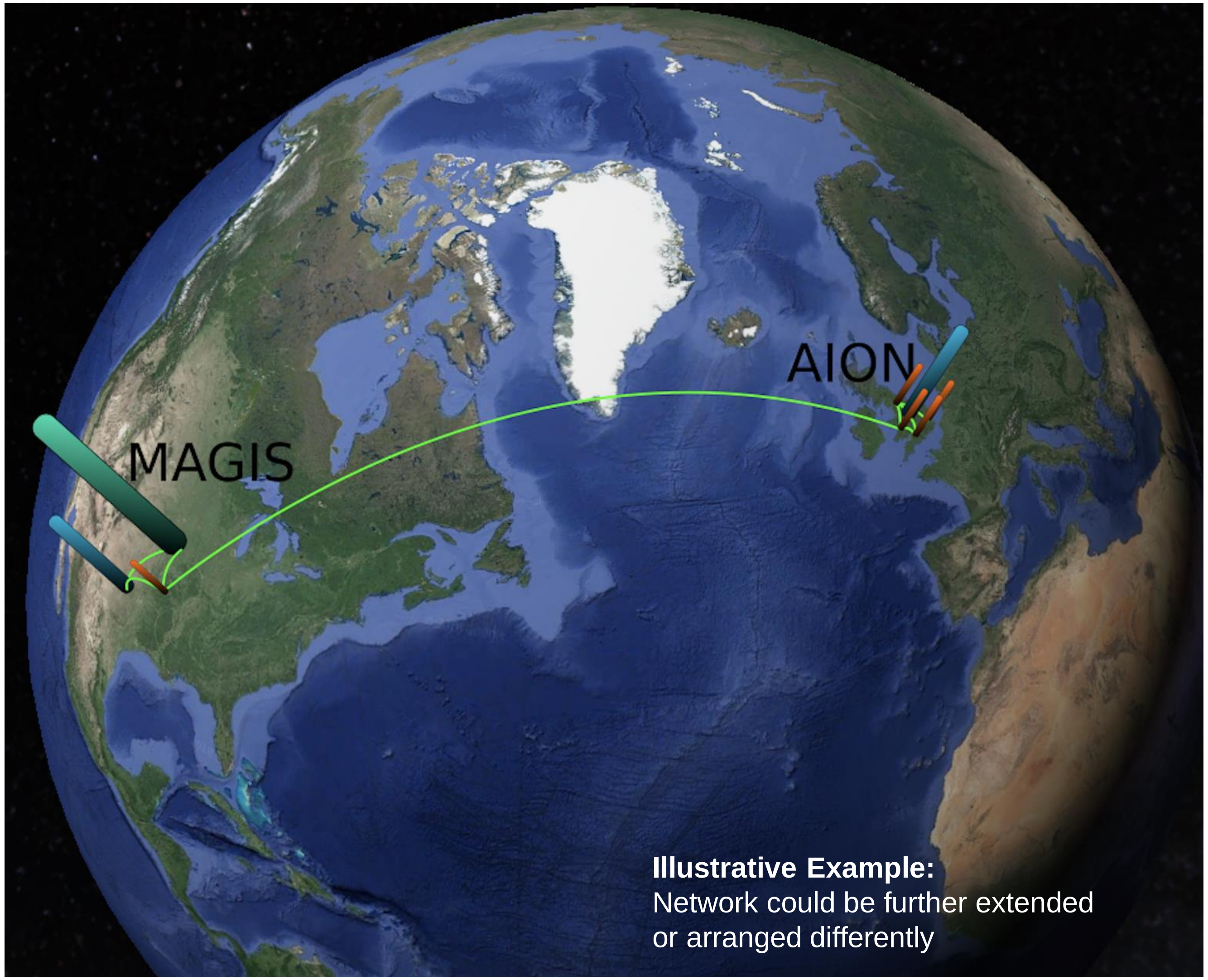
Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19

Courtesy of Jason Hogan!



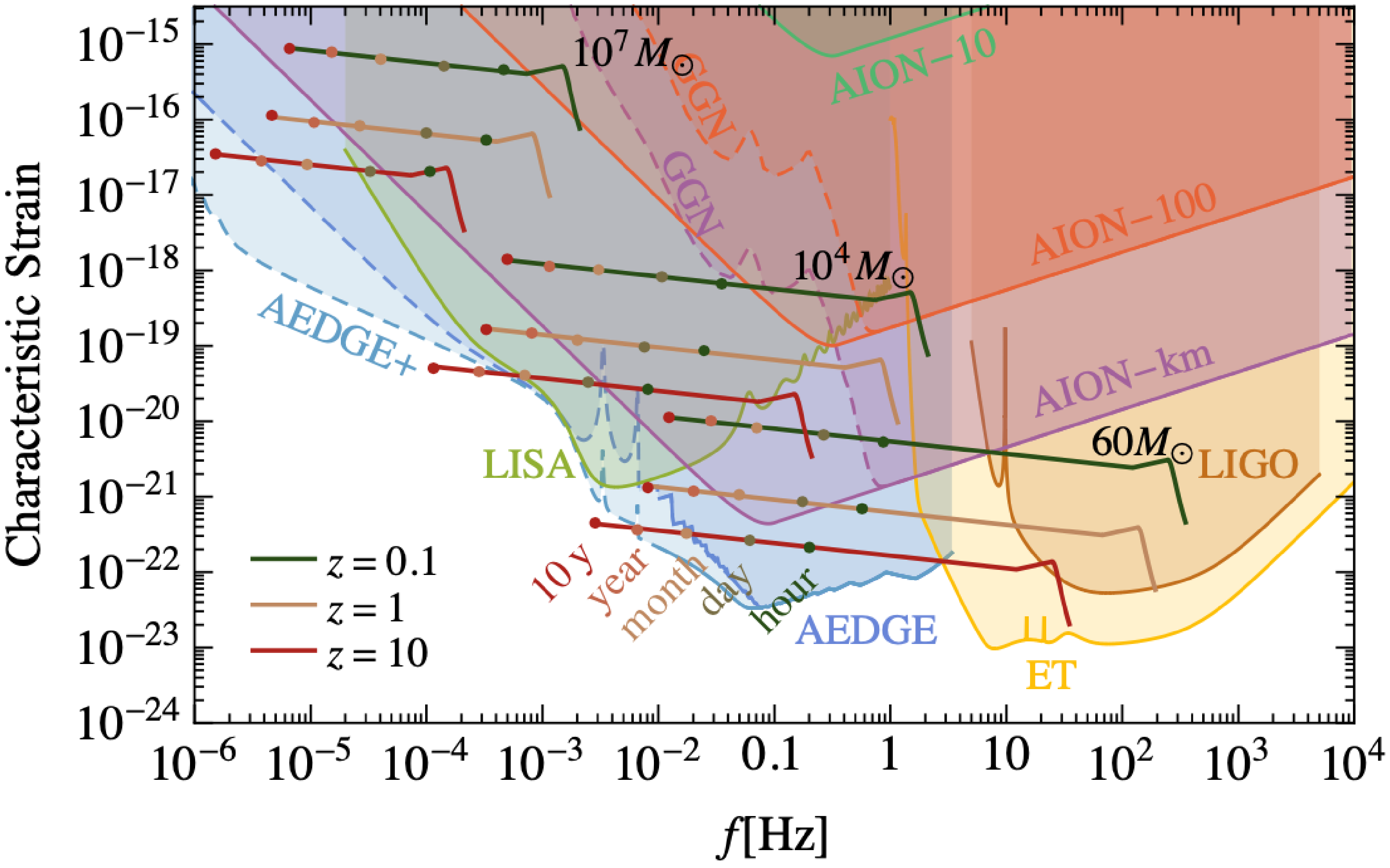
Ultimate sensitivity for terrestrial based detectors is achieved by operating 2 (or more) Detectors in synchronisation mode

Ultimate Goal: Establish International Network



Vision for 2045+

Probe formation of SMBHs: Synergies with other GW experiments (LIGO, LISA), test GR



AION Collaboration (Badurina, OB,…, John Ellis et al): arXiv:1911.11755

Badurina, OB, John Ellis, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

Other Fundamental Physics

Ultra-high-precision atom interferometry may also be sensitive to other aspects of fundamental physics beyond dark matter and GWs, though studies of such possibilities are still at exploratory stages.

Examples may include:

- The possibility of detecting the astrophysical neutrinos
- Probes of long-range fifth forces.
- Constraining possible variations in fundamental constants.
- Probing dark energy.
- Probes of basic physical principles such as foundations of quantum mechanics and Lorentz invariance.

A very exciting new research avenue is ahead of us ….

Summary: 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.

BACKUP

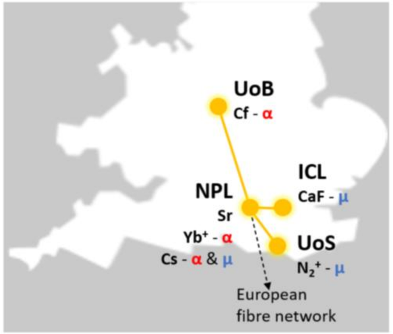
QTFP PROJECTS

Imperial College London

QSNET

AION

A network of clocks for measuring the stability of fundamental constants

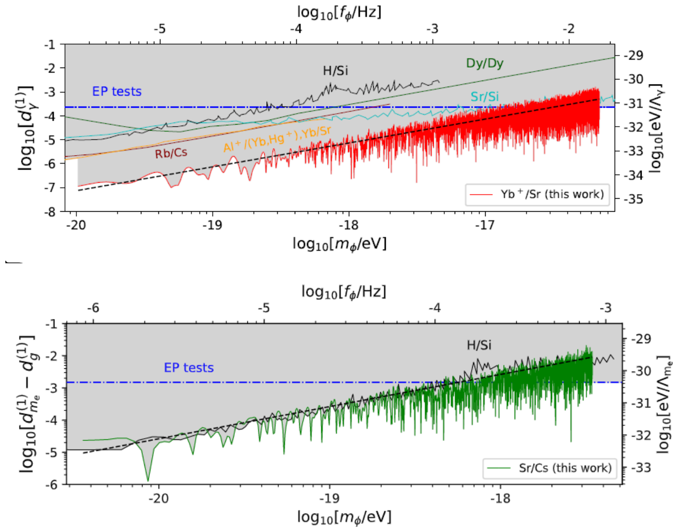


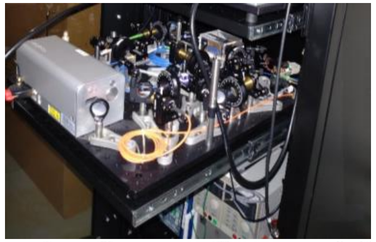
Clock	Kα	Kμ
Yb^{+} (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N_2^{+} (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

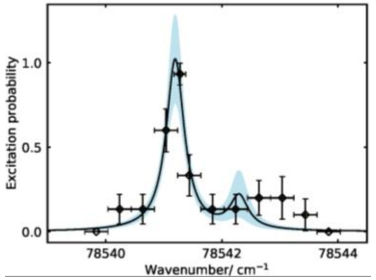
TRL

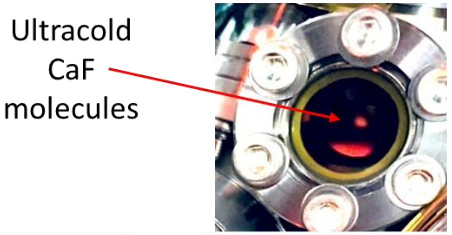
Search for variations of fundamental constants of the Standard Model, using a network of clocks

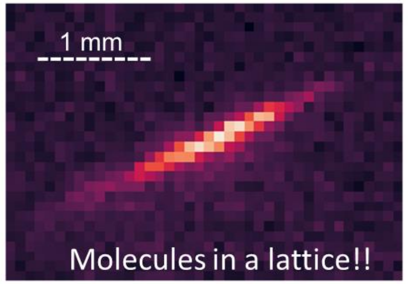
A unique network of clocks chosen for their different sensitivities to variations of **α** and **μ**

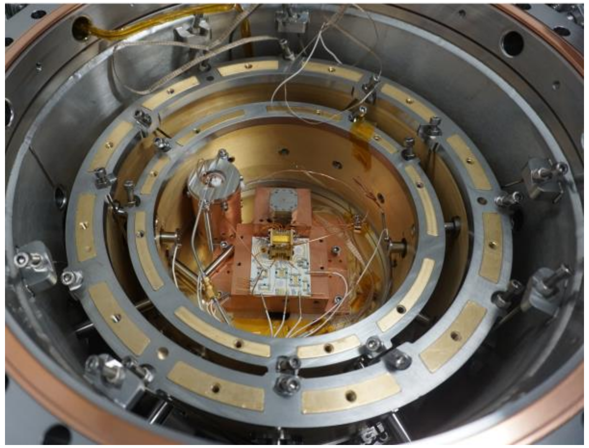












NPL clocks & Sussex theory

- 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

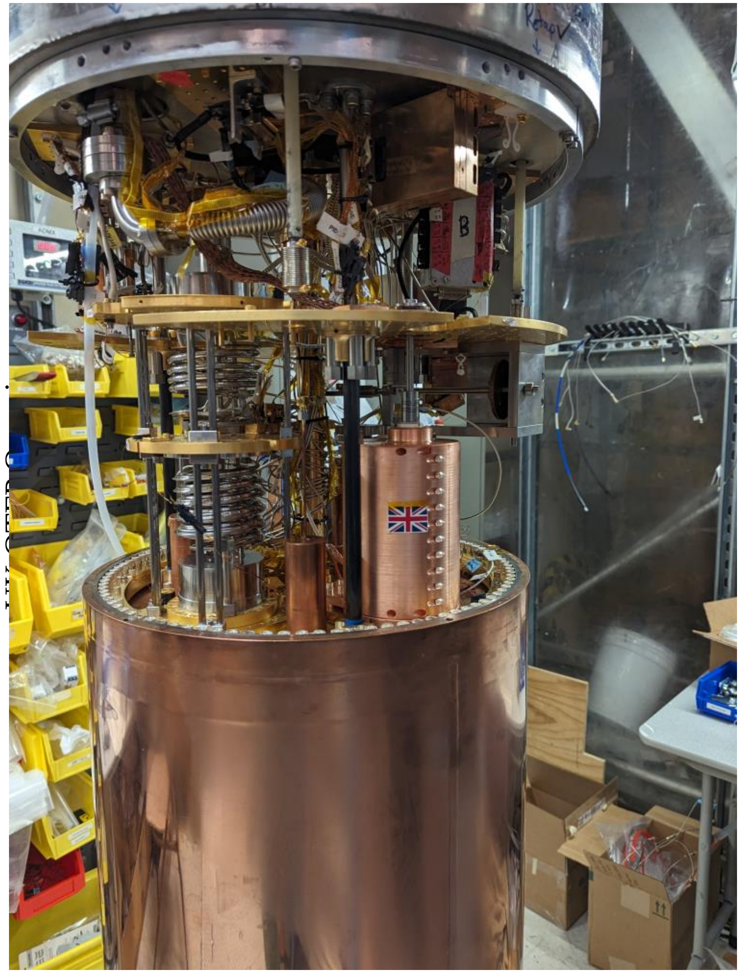
Birmingham

- Realised a compact electron beam ion trap to produce highly charged ions
- Realised ultra-low vibration cryogenic vacuum systems

QSHS-ADMX collaboration

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

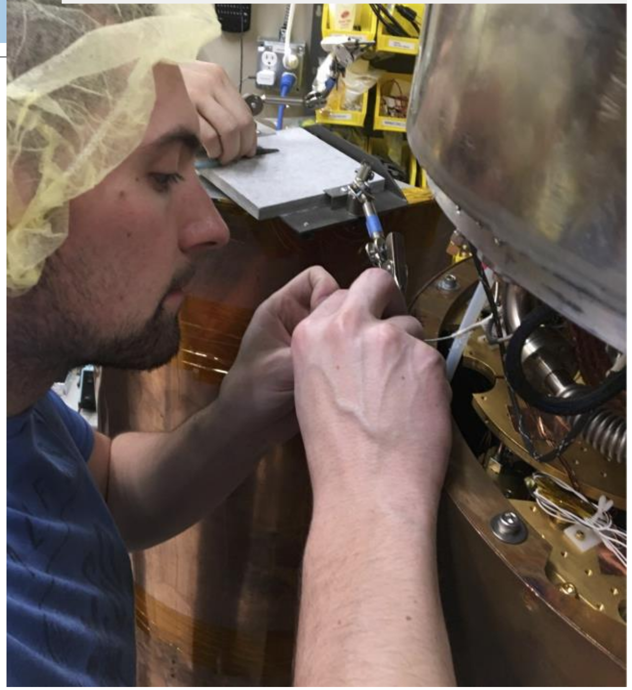
AXION DARK MATTER EXPERIMENT



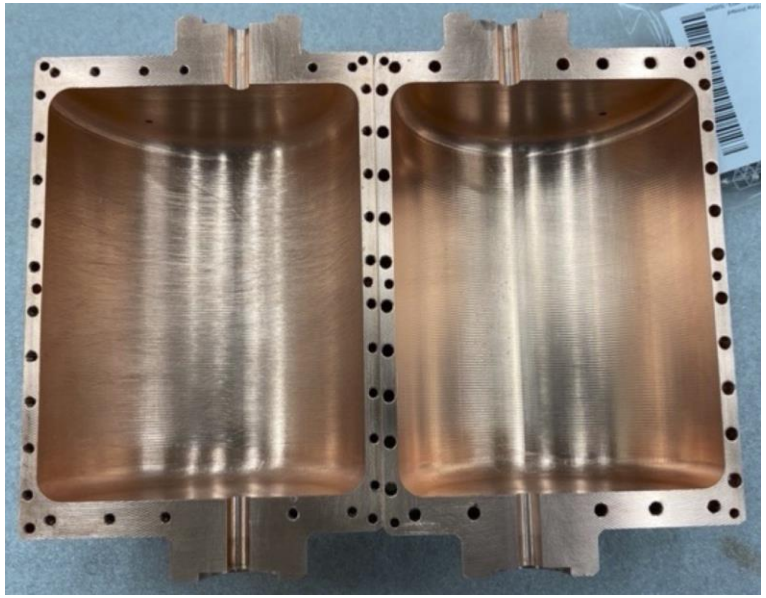
ADMX detector with UK sidecar cavity installed, ready for cooling. December 2023.

- 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 to be installed 26th February.**

Mitch Perry working on the ADMX insert.



QSHS cavity for ADMX



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

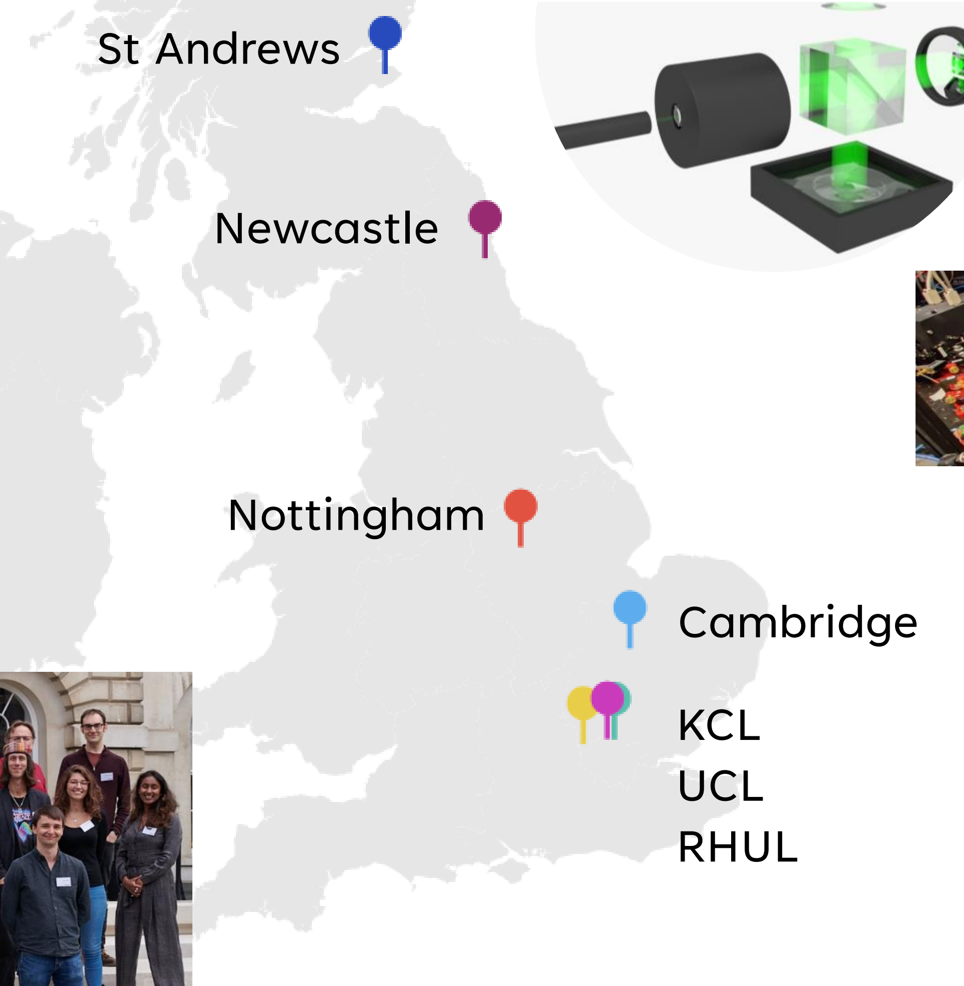
Silke Weinfurtner (PI, Nottingham)

Zoran Hadzibabic (Cambridge)

Ruth Gregory (KCL)

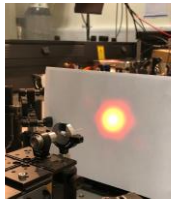
Outputs (start 2021)

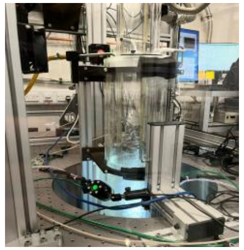
- 1 Patent Application
- 25 Publications (+ 7 Pre-prints), including publications in Nature
- 4 Feature News Articles (e.g. Quanta Magazine and New Scientist)
- BBC 'Sky At Night', German/French TV
- 4 QSimFP facilities



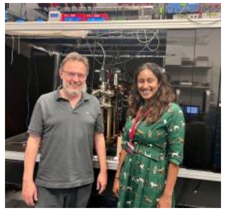
AION

Experimental Facilities





Modelling Support



Quantum Technology for Fundamental Physics

About QTFP

- £40 million programme to **transform our approach** to understanding the universe and its evolution.
- **QTFP to demonstrate** how quantum technologies could solve some of the greatest mysteries in fundamental physics, e.g.
  - search for dark matter
  - nature of gravity
  - …

Quantum-enhanced Interferometry for new physics
Principal investigator: Hartmut Grote

A network of clocks for measuring the stability of fundamental constants
Principal investigator: Giovanni Barontoni

Determination of absolute neutrino mass using quantum technologies
Principal investigator: Ruben Saaykan

Quantum sensors for the hidden sector
Principal investigator: Ed Daw

A UK atom interferometer observatory and network
Principal investigator: Oliver Buchmuller

Quantum enhanced superfluid technologies for dark matter and cosmology
Principal investigator: Andrew Casey

Quantum simulators for fundamental physics
Principal investigator: Silke Weinfurtner

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 Enhanced Superfluid Technologies for Dark Matter and

QUEST DMC

Royal Holloway University of London

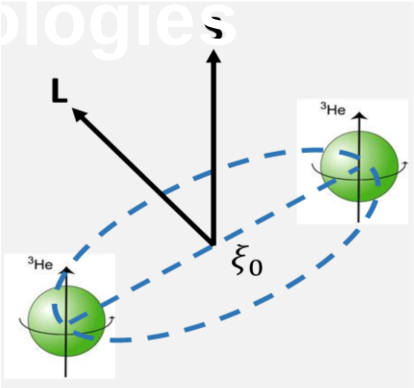
Lancaster University

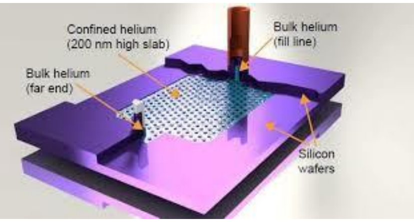
University of Sussex

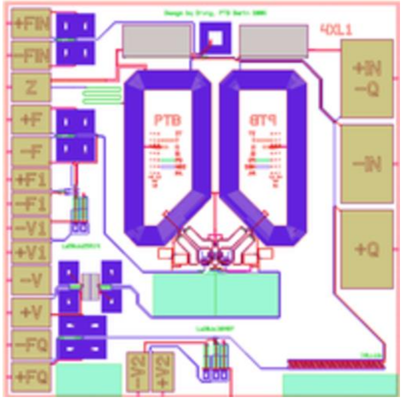
University of Oxford

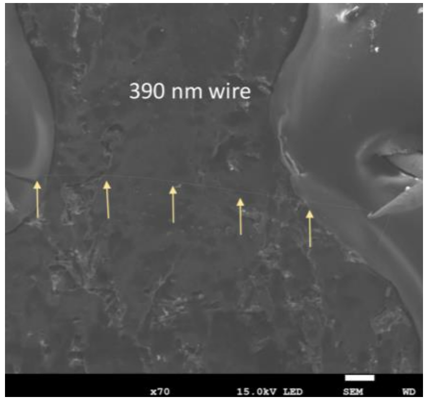
University of Liverpool

ULT + Superfluid ^{3}He + Quantum Technologies

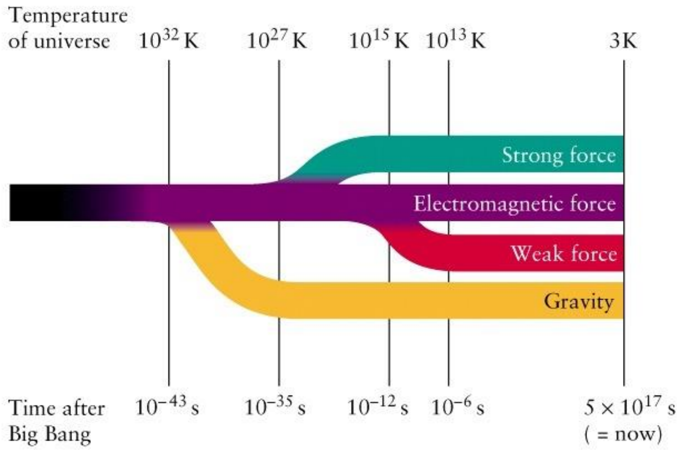


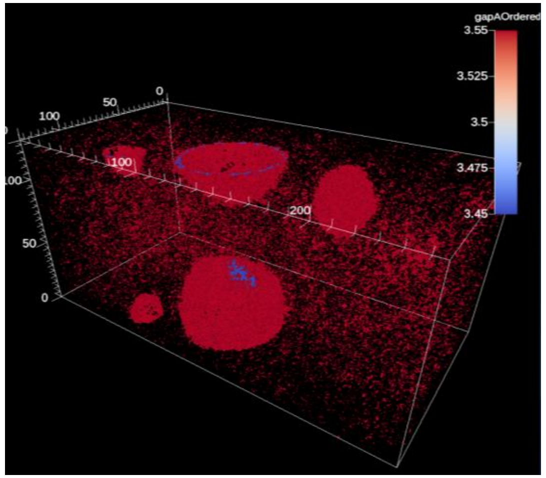




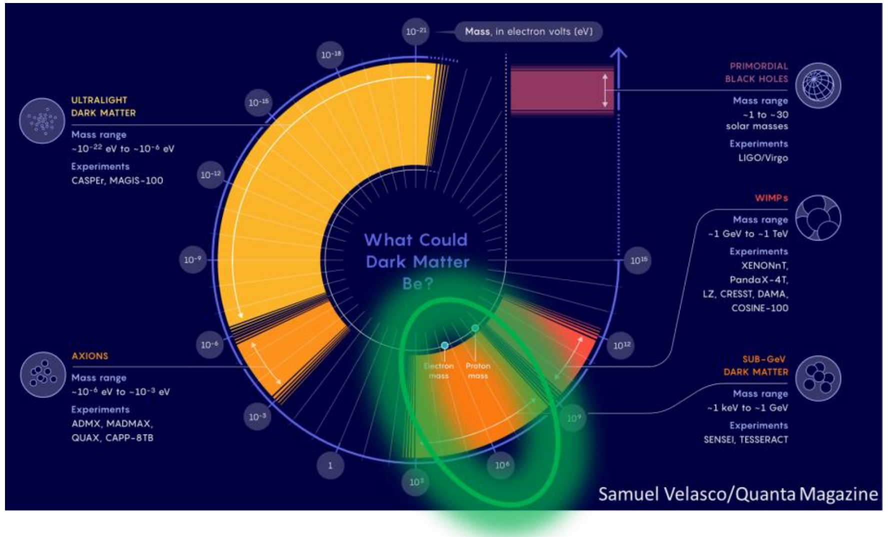


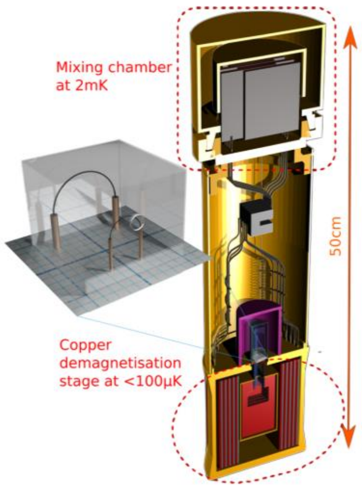
Phase Transitions in the Early Universe





Detection of sub-GeV dark matter

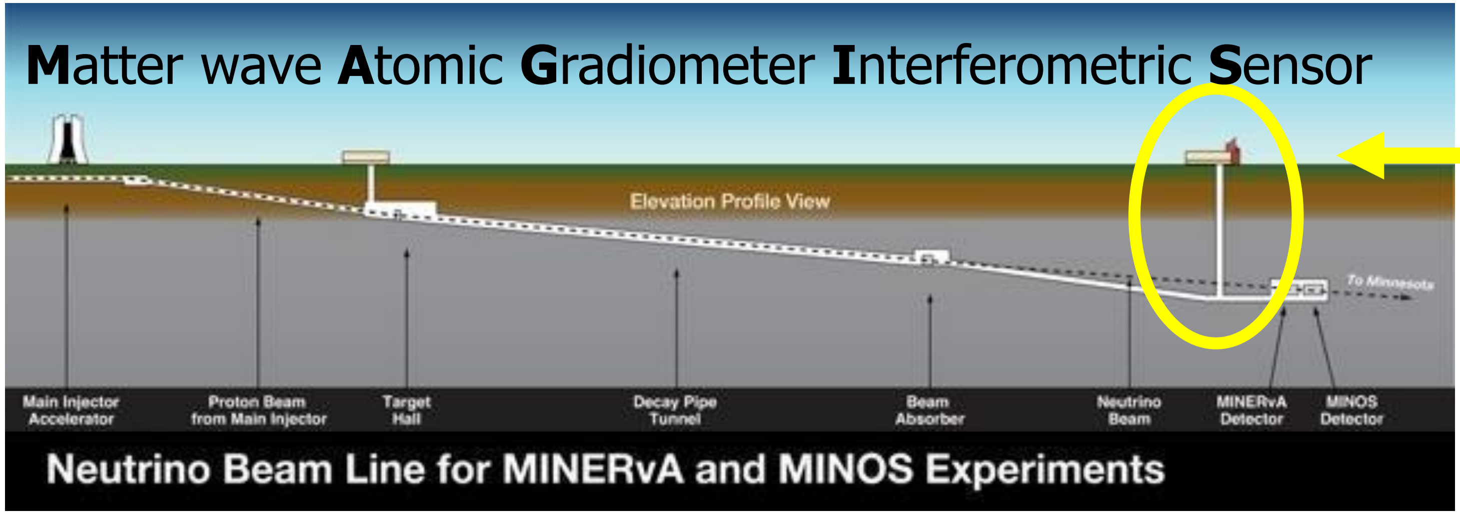


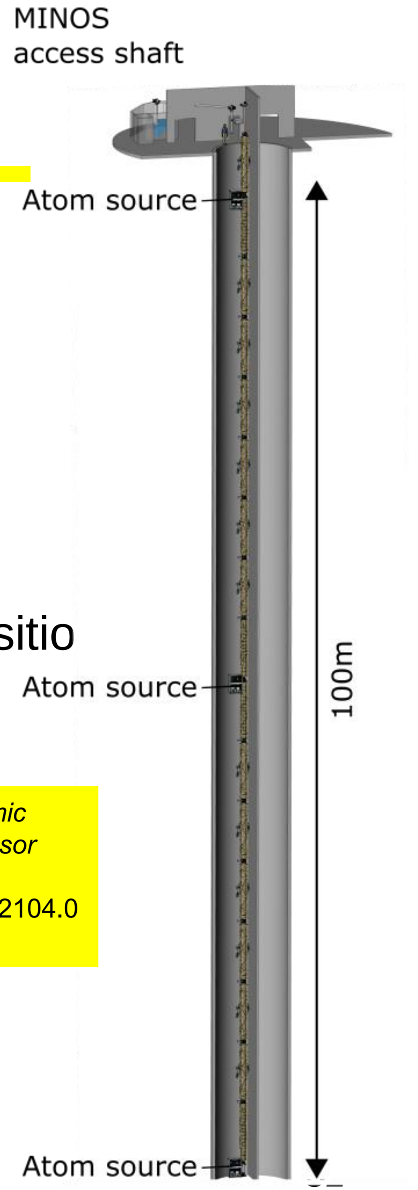


UK QTEP Overview

MAGIS

MAGIS-100 at Fermilab



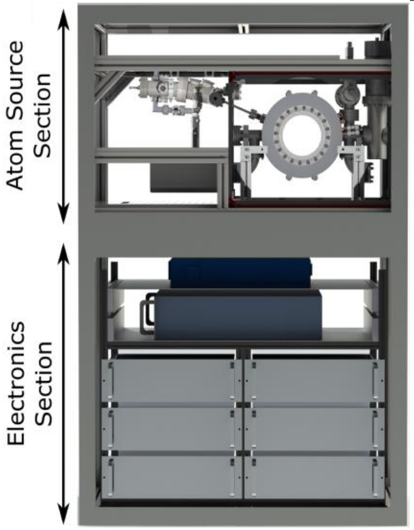


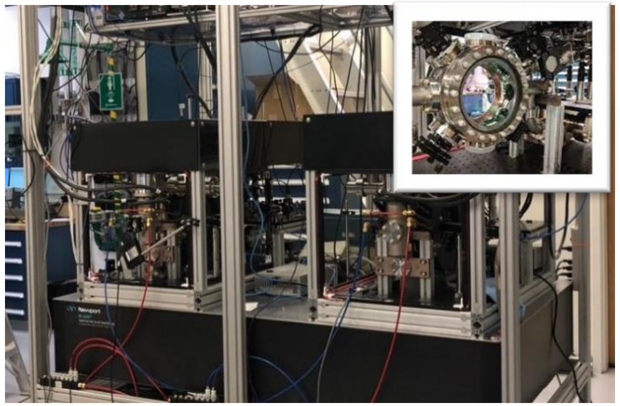
- 100-meter baseline atom interferometry in MINOS shaft at Fermilab
- Gravitational wave detector pathfinder, ultralight dark matter search, extreme quantum superpositio states (> metre wavepacket separation)
- Design and construction underway; commissioning early 2025
- ~ $15M scope (Gordon and Betty 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:2104.02835].

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

MAGIS-100 design and construction



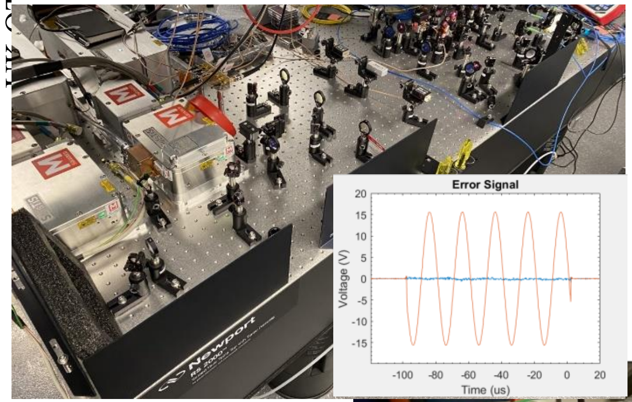


Strontium atom source prototypes & enclosure CAD

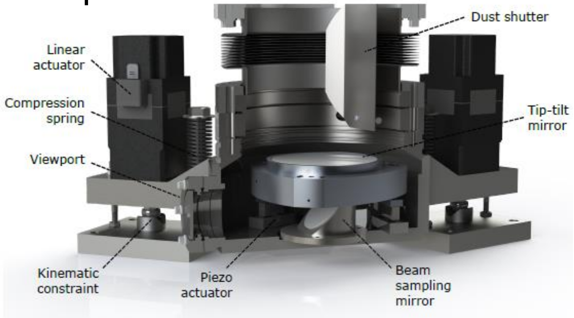
Lasers stabilized to frequency comb

MAGIS-100

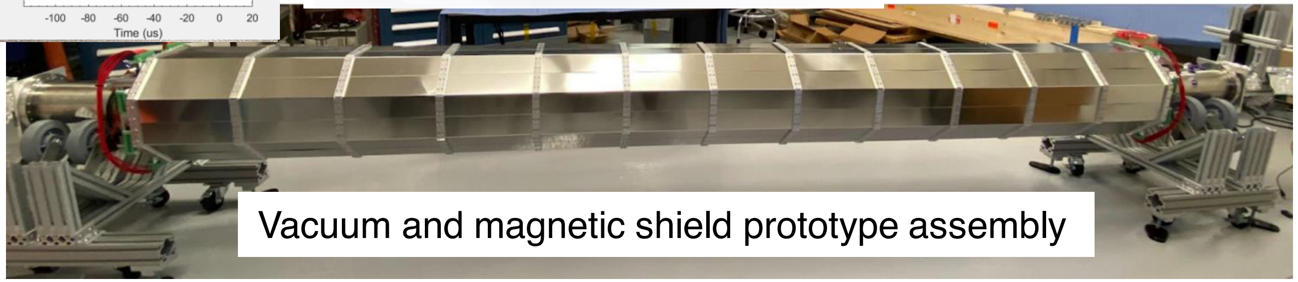
Interferometry laser system



Tip-tilt retro mirror for rotation compensation

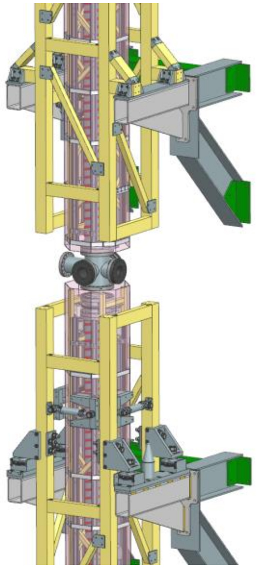


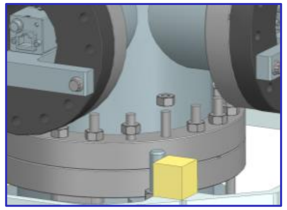
Integrated laser frame



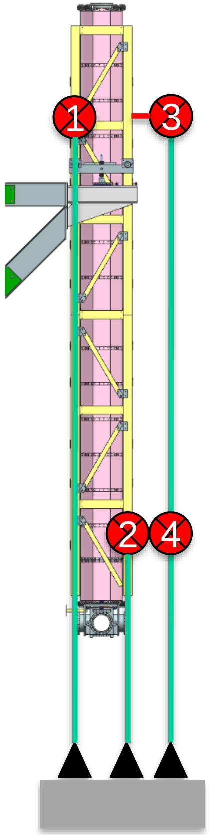
Vacuum and magnetic shield prototype assembly

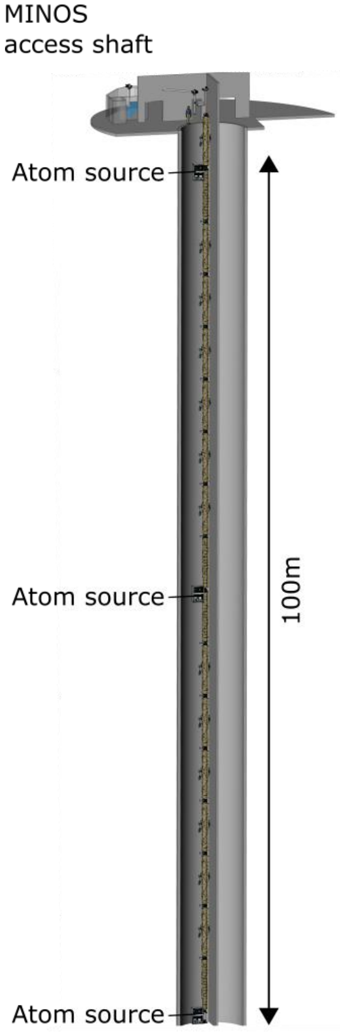
Installation and assembly planning models





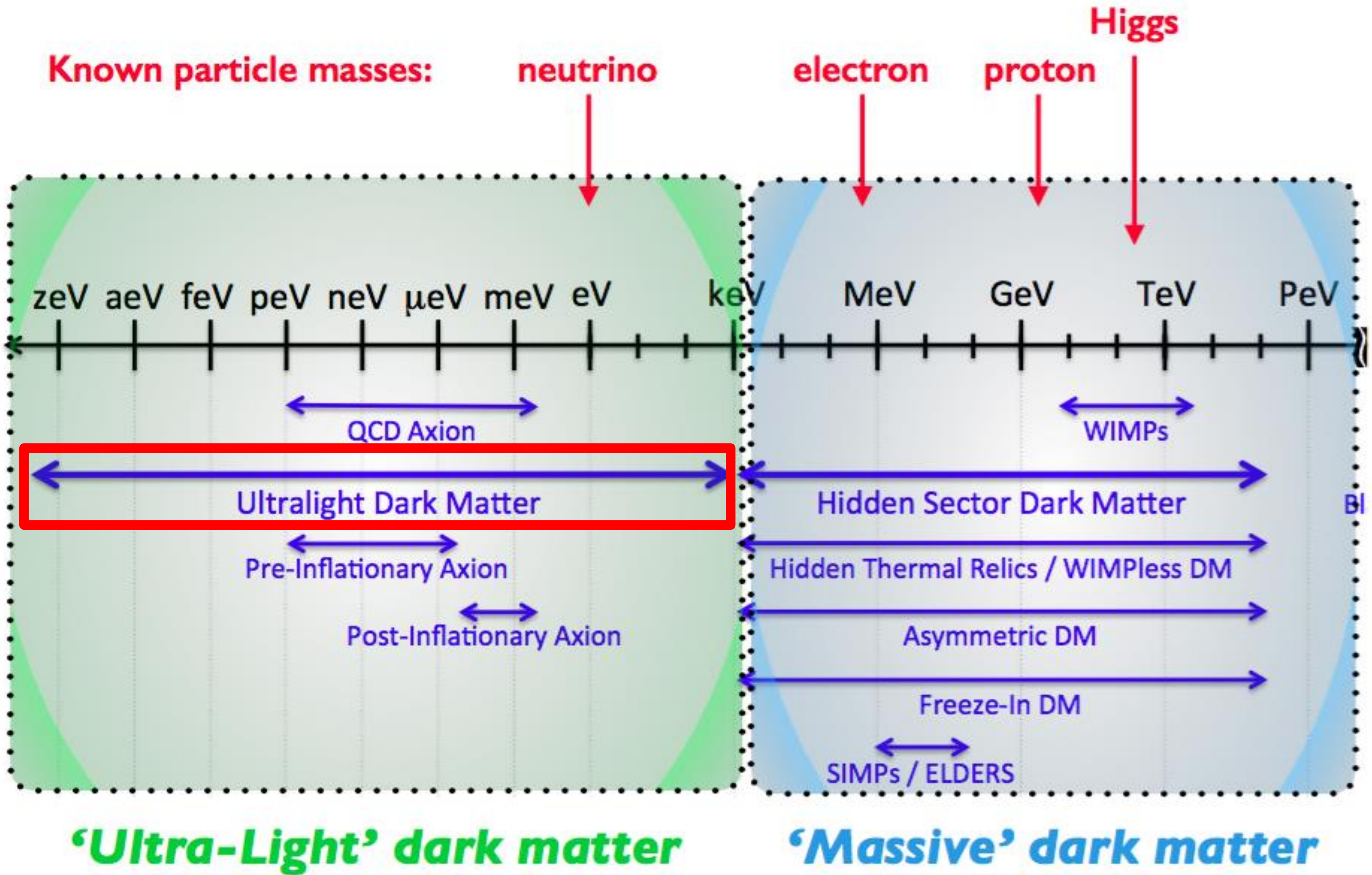
Optical alignment concept





ULTRA-LIGHT DARK MATTER

Search for Ultra-Light Dark Matter



Ultralight scalar dark matter

Ultralight dilaton DM acts as a background field (e.g., mass ~10^{-15} eV)

$$\mathcal{L} = +\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \sqrt{4\pi G_N}\phi\left[d_{m_e}m_e\bar{e}e - \frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}\right] + \ldots$$

DM scalar field

Electron coupling

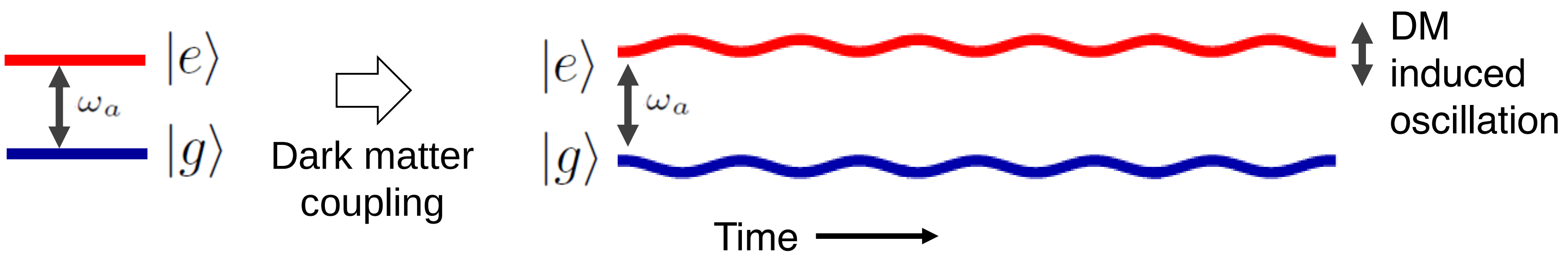
Photon coupling

e.g., QCD

$$\phi(t,\mathbf{x}) = \phi_0\cos\left[m_\phi(t-\mathbf{v}\cdot\mathbf{x})+\beta\right] + \mathcal{O}\left(|\mathbf{v}|^2\right)$$

$$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$ DM mass density

DM coupling causes time-varying atomic energy levels:

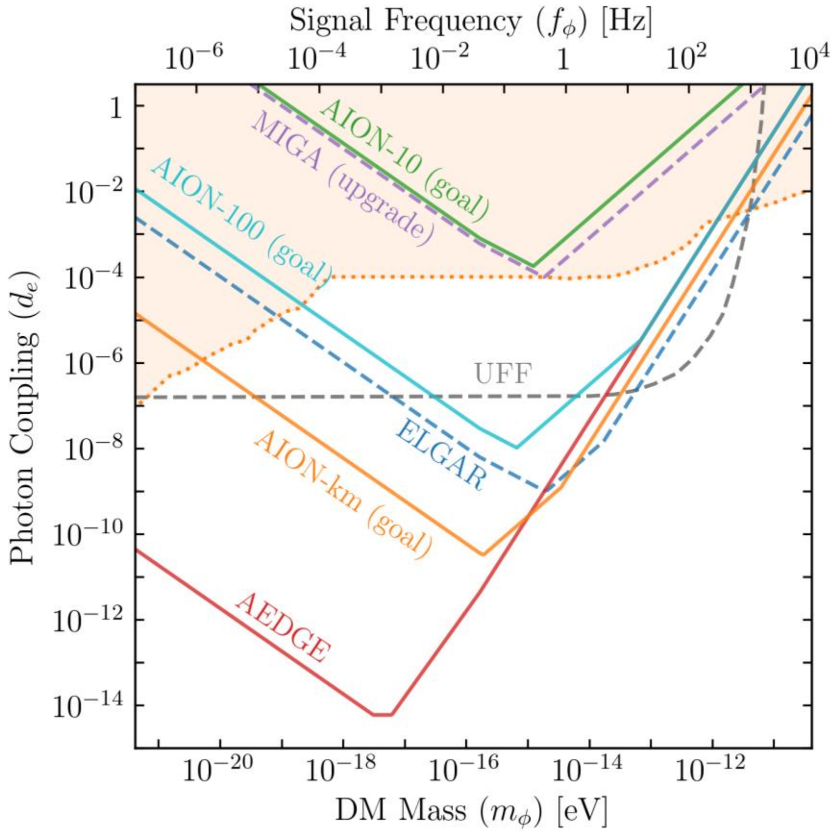


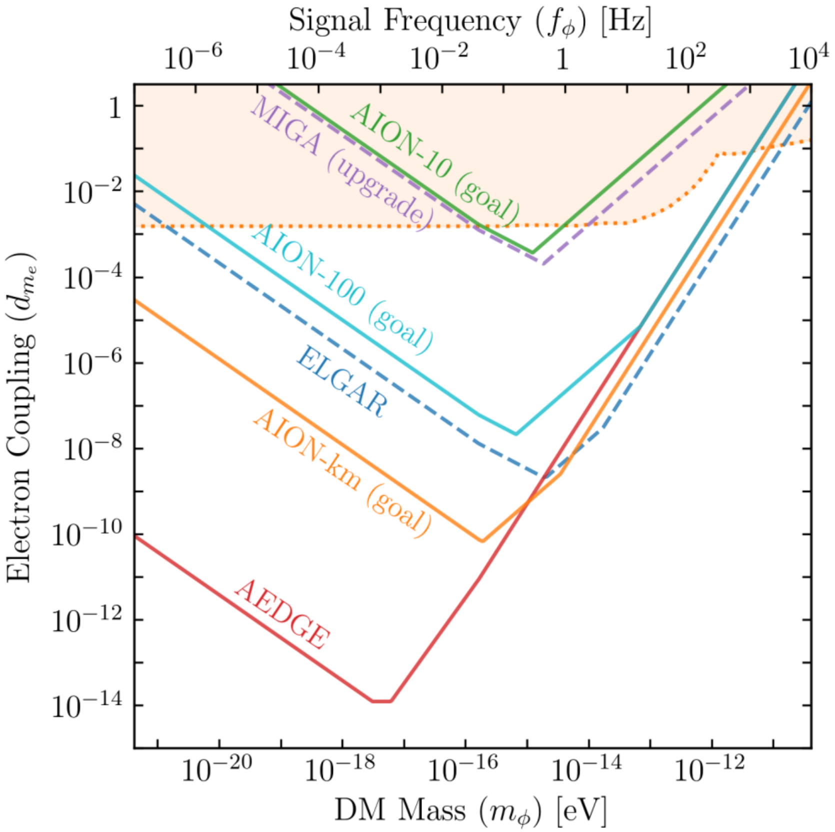
Courtesy of Jason Hogan!

Search for Ultra-Light Dark Matter

Linear couplings to gauge fields and matter fermions

$$\mathcal{L}_{\text{int}\phi} = \kappa\phi \left[+\frac{d_e}{4e^2} F_{\mu\nu}F^{\mu\nu} - \frac{d_g \beta_3}{2g_3} F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right]$$





Orders of magnitude improvement over current sensitivities

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