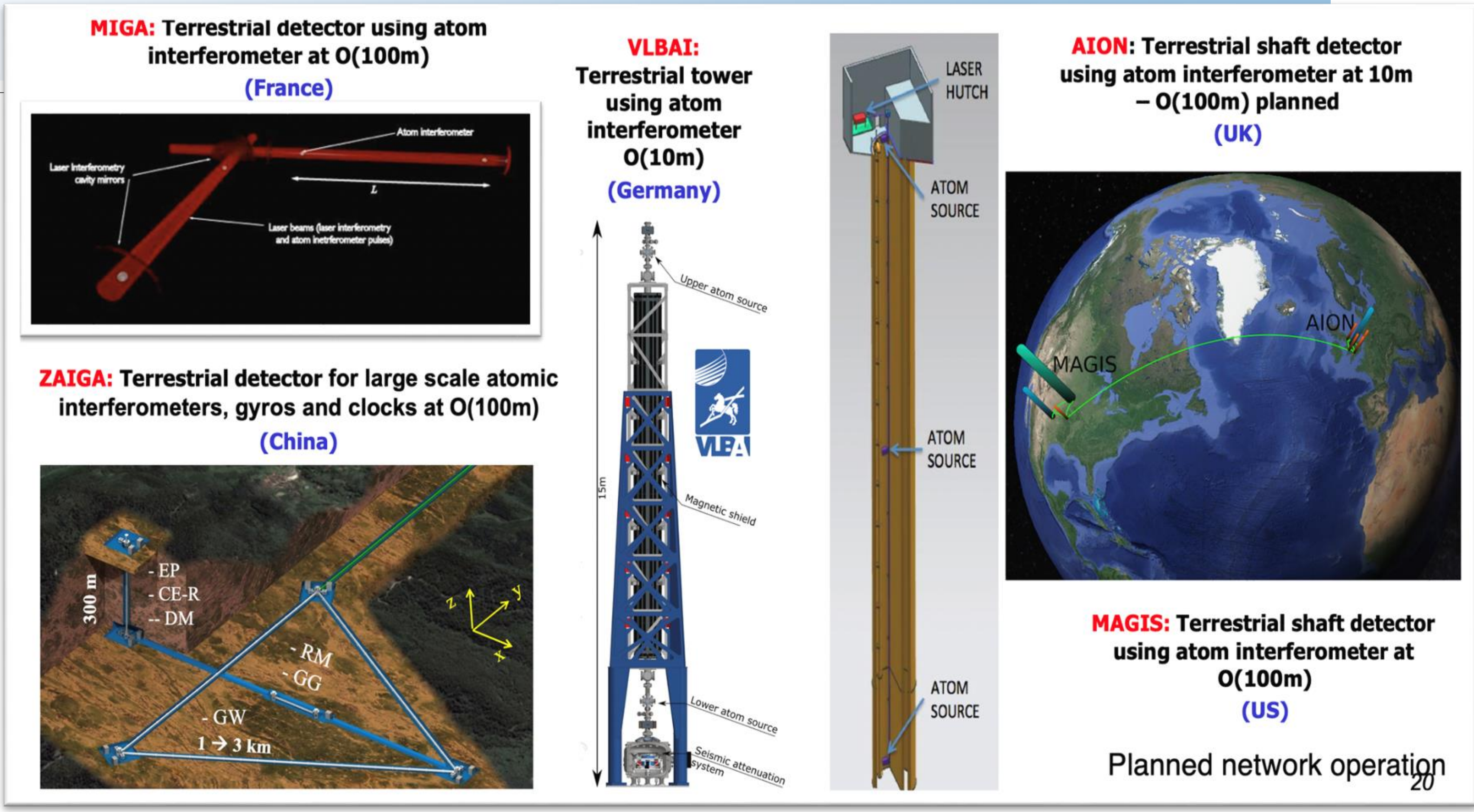
AION

A UK Atom Interferometer Observatory and Network



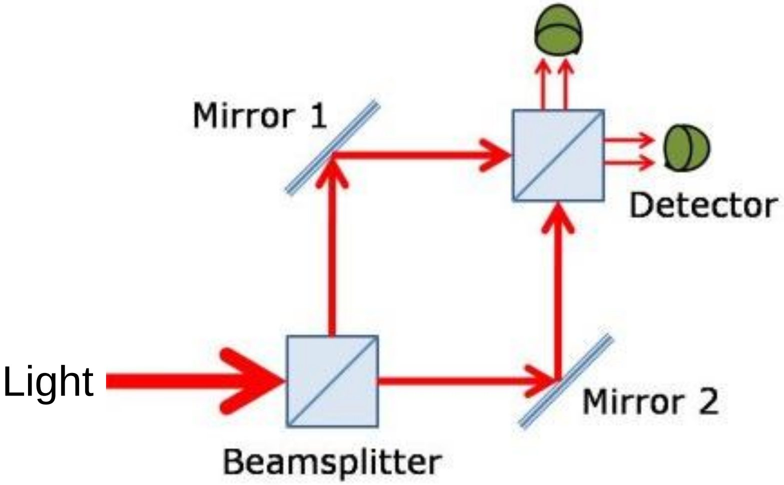
Oliver Buchmueller,

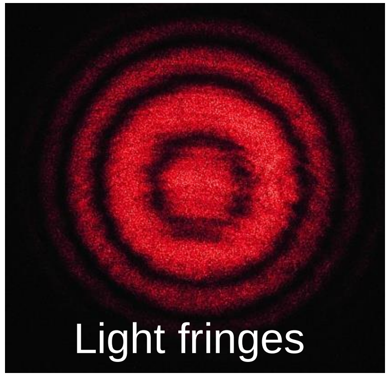
Imperial College London, Oxford University, Royal Society Leverhulme Trust Senior Research Fellow

LARGE SCALE ATOM INTERFEROMETRY TO EXPLORE FUNDAMENTAL PHYSICS

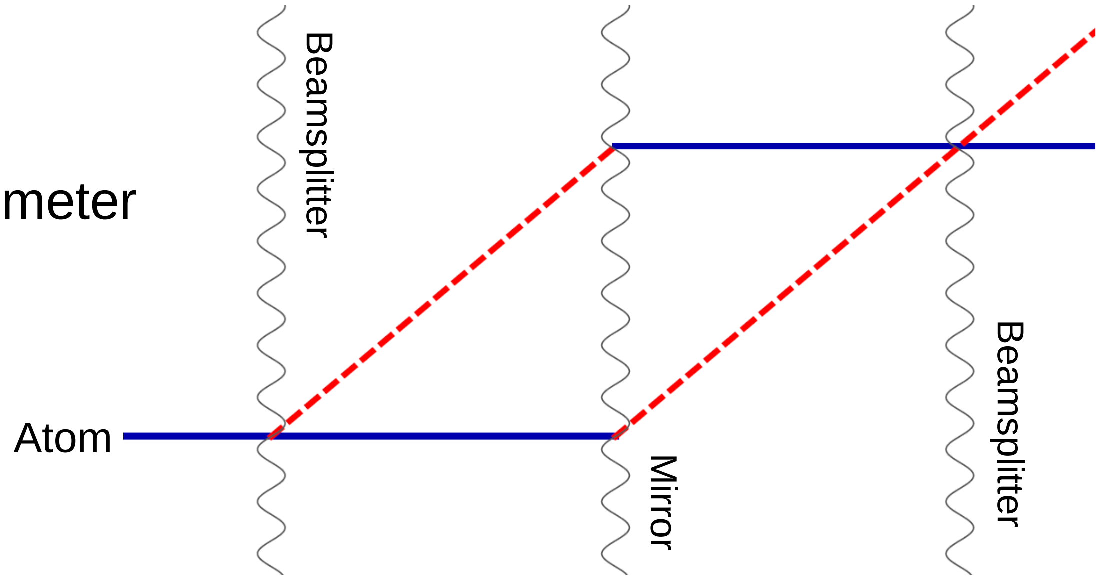
Light vs. Cold Atoms: Atom Interferometry

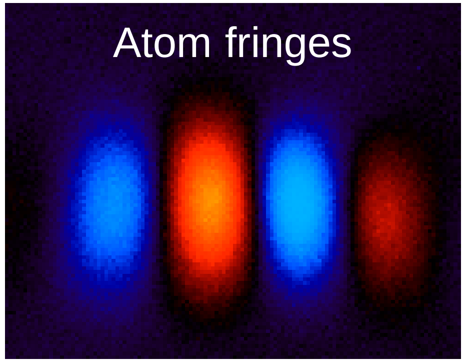
Light interferometer





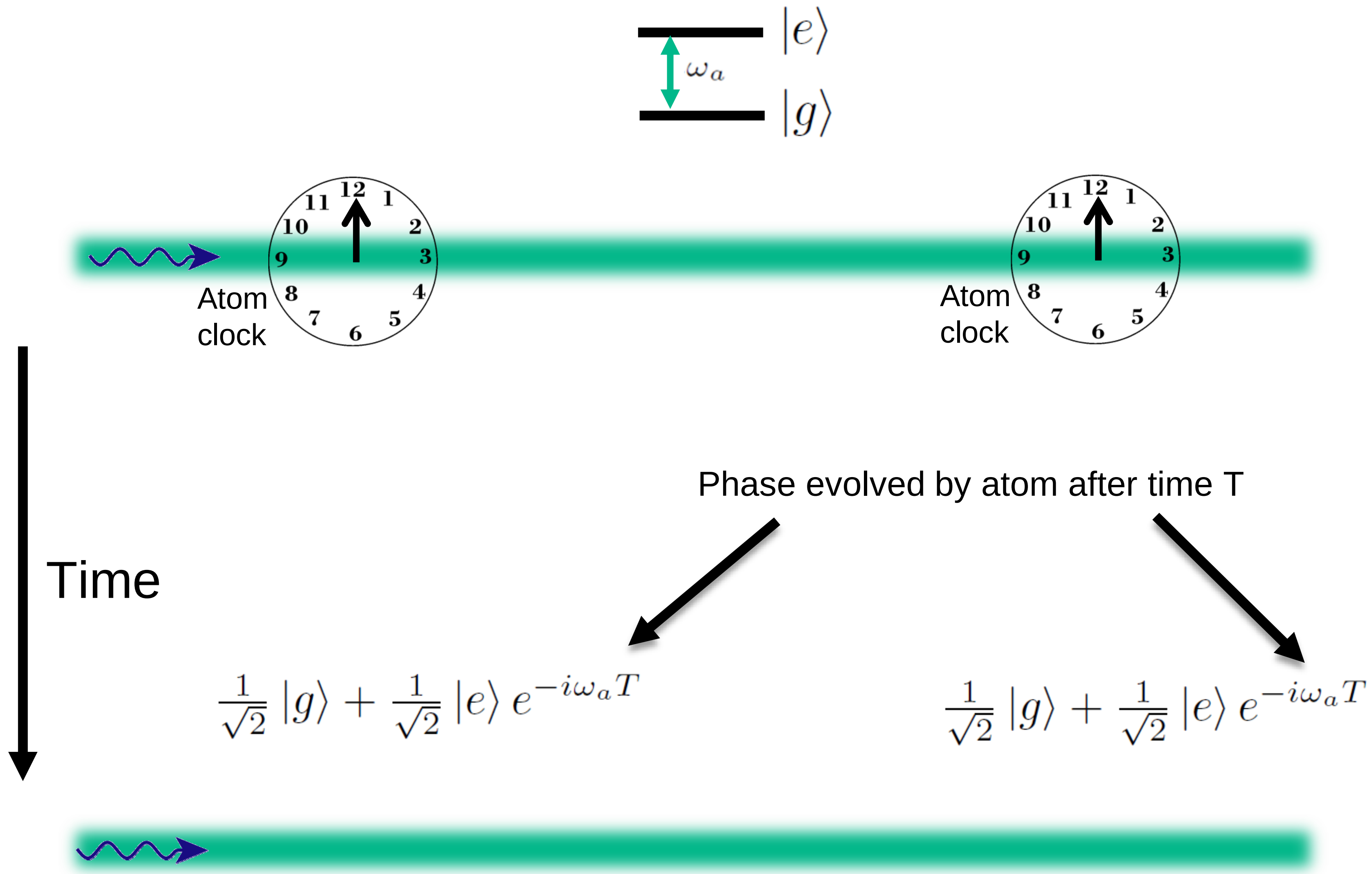
Atom interferometer





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

Simple Example: Two Atomic Clocks



Simple Example: Two Atomic Clocks

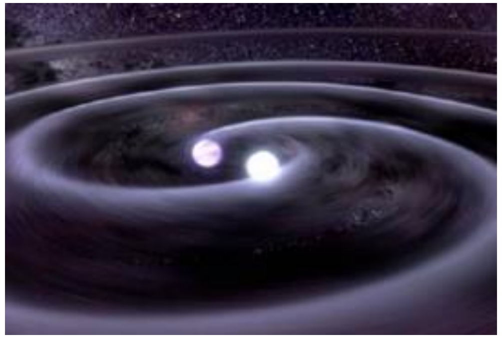
$|e\rangle$

ω_a

$|g\rangle$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle \qquad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$$

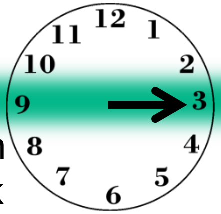
Time



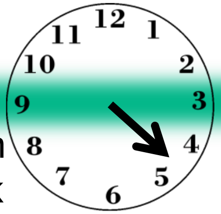
GW changes light travel time

$$\Delta T \sim hL/c$$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a T} \qquad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a (T+\Delta T)}$$



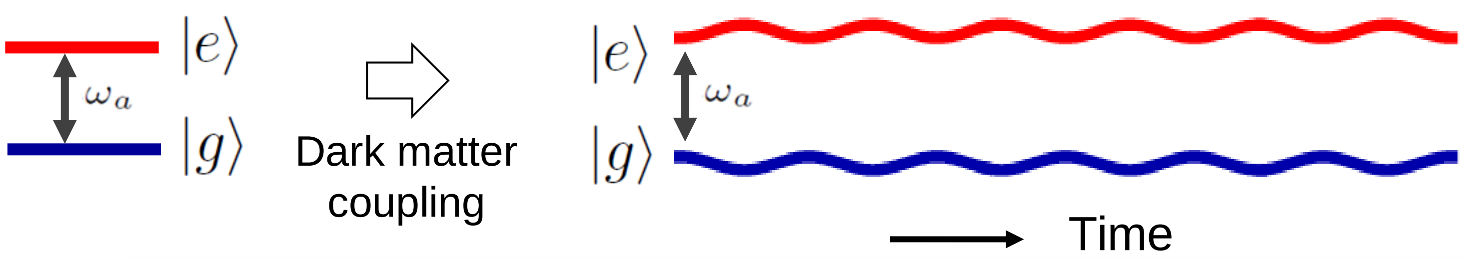
Atom clock



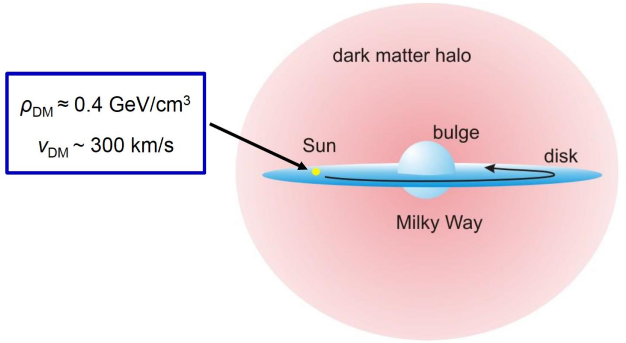
Atom clock

Courtesy of Jason Hogan!

Simple Example: Two Atomic Clocks



DM induced oscillation $\Delta\omega_a^{DM}$



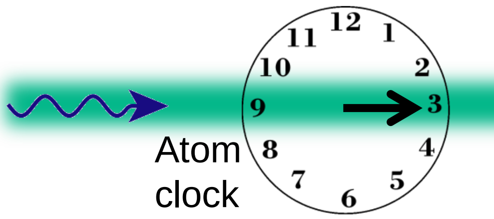
DM cloud changes atom frequency

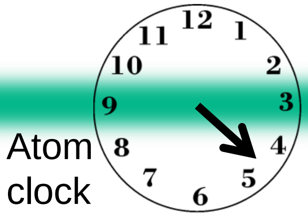
DM coupling causes time-varying atomic energy levels:

Time

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a T}$$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i(\omega_a + \Delta\omega_a^{DM})T}$$





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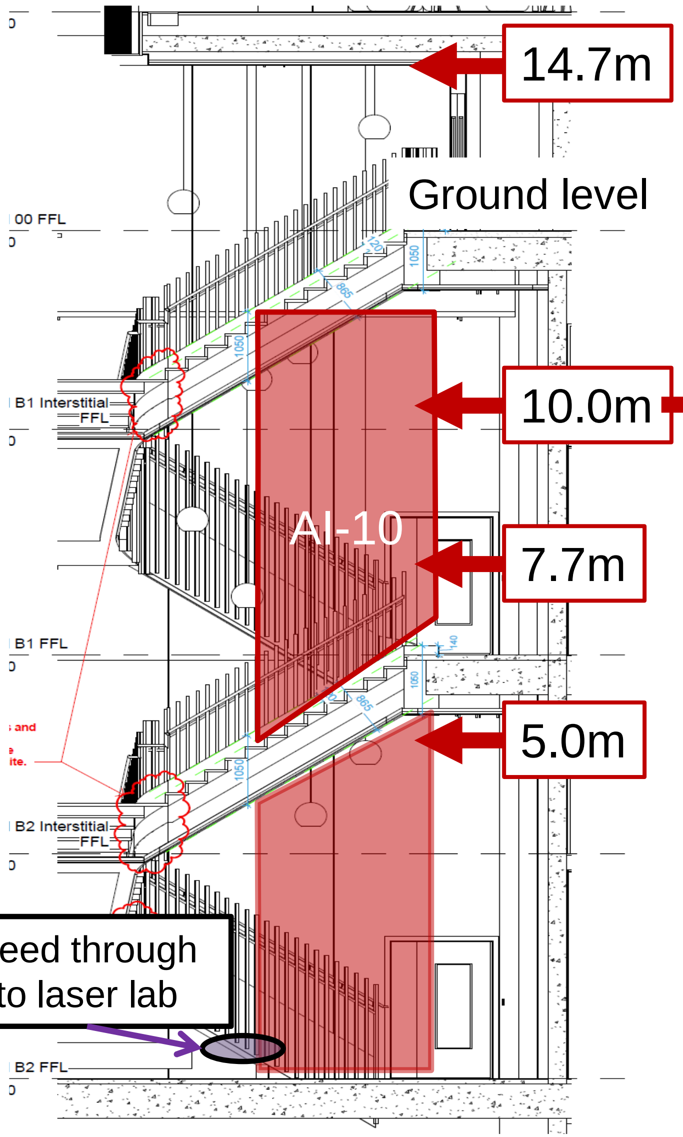
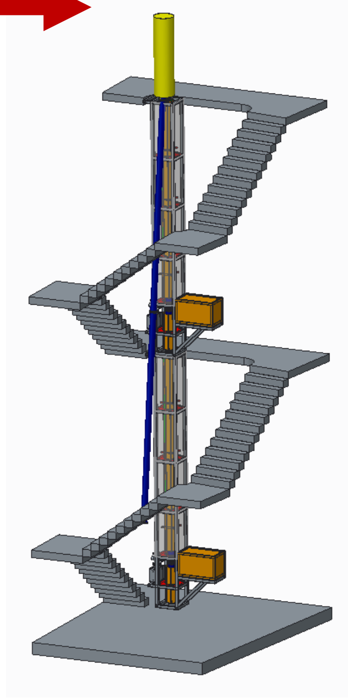
AION Project in the UK

Large Scale AI For Fundamental Physics





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]

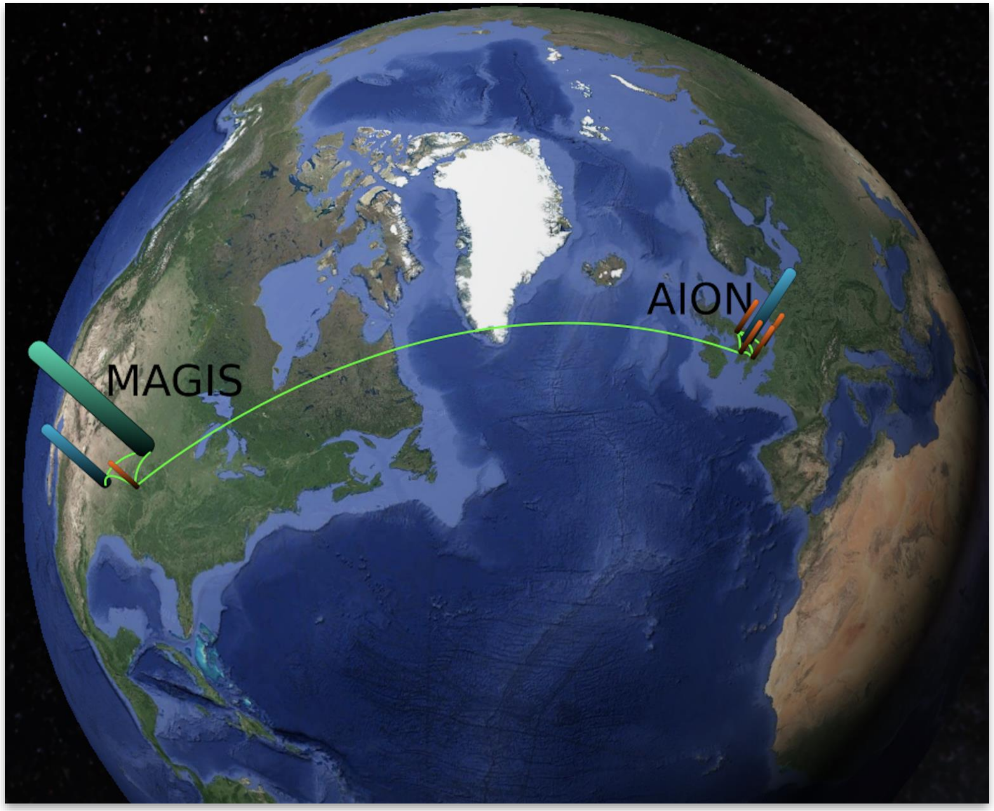
Ongoing Atom Interferometry Projects in UK and US

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.

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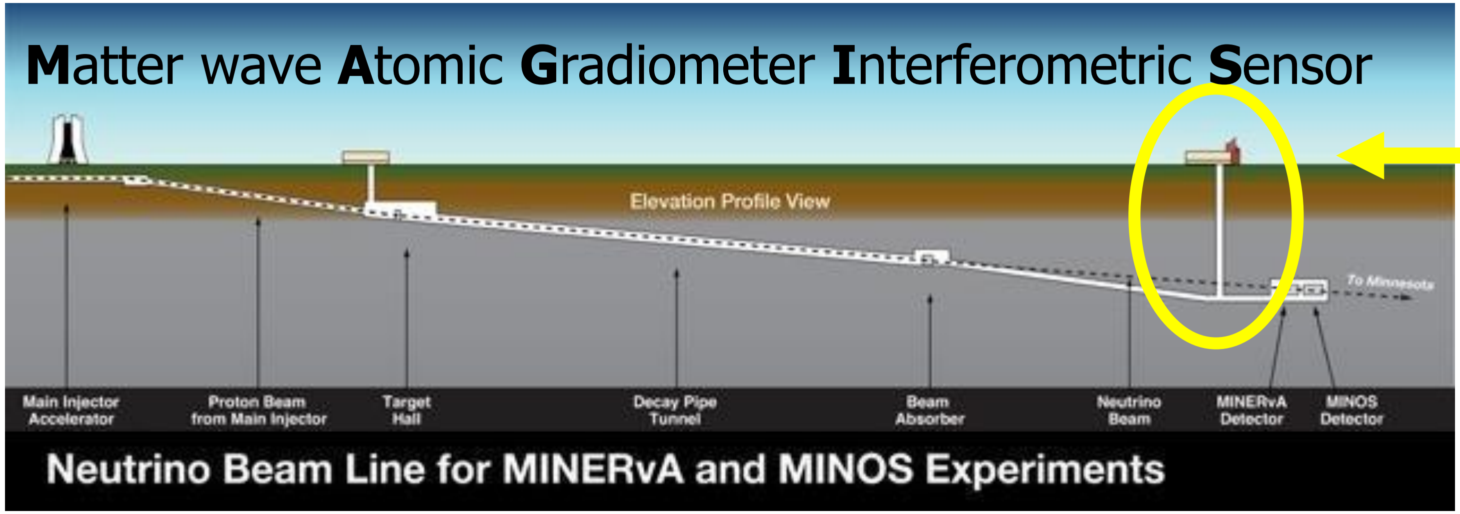
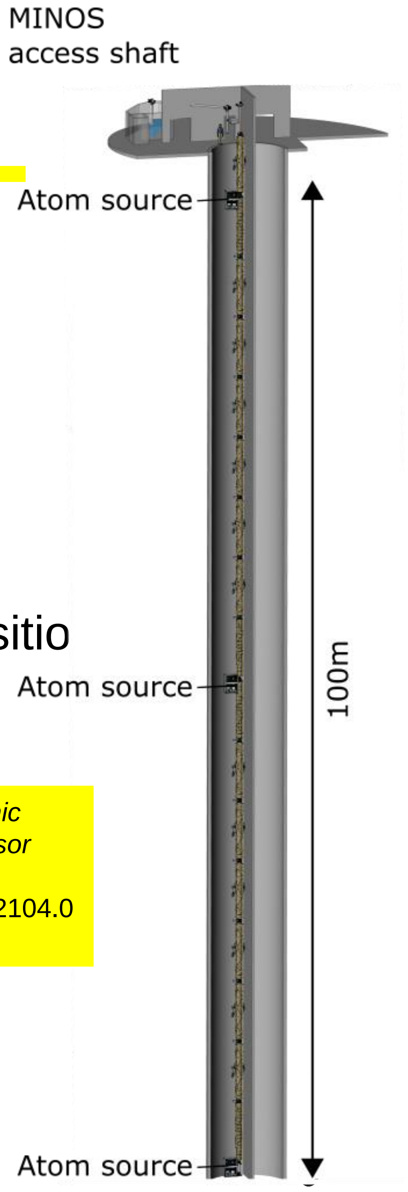
MAGIS-100 ICRADA Ceremony at Fermilab on Nov 16, 2023

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

AION

The AION Programme consists of 4 Stages

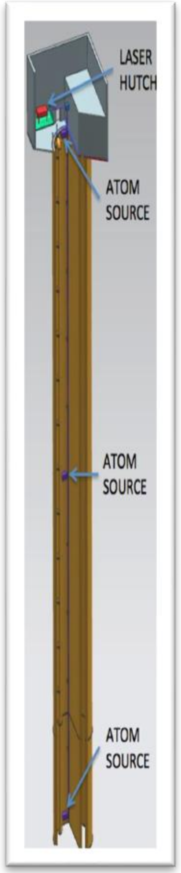
- ❑ **Stage 1:** to build and commission the 10 m detector, develop existing technology and the infrastructure for the 100 m.

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.

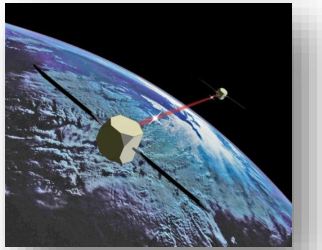


Stage 1 is now funded with about £10M by the QTFP Programme and other sources and Stage 2 could be placed at national facility in Boulby or Daresbury (UK), possibly also at CERN (France/Switzerland).

- ❑ **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).

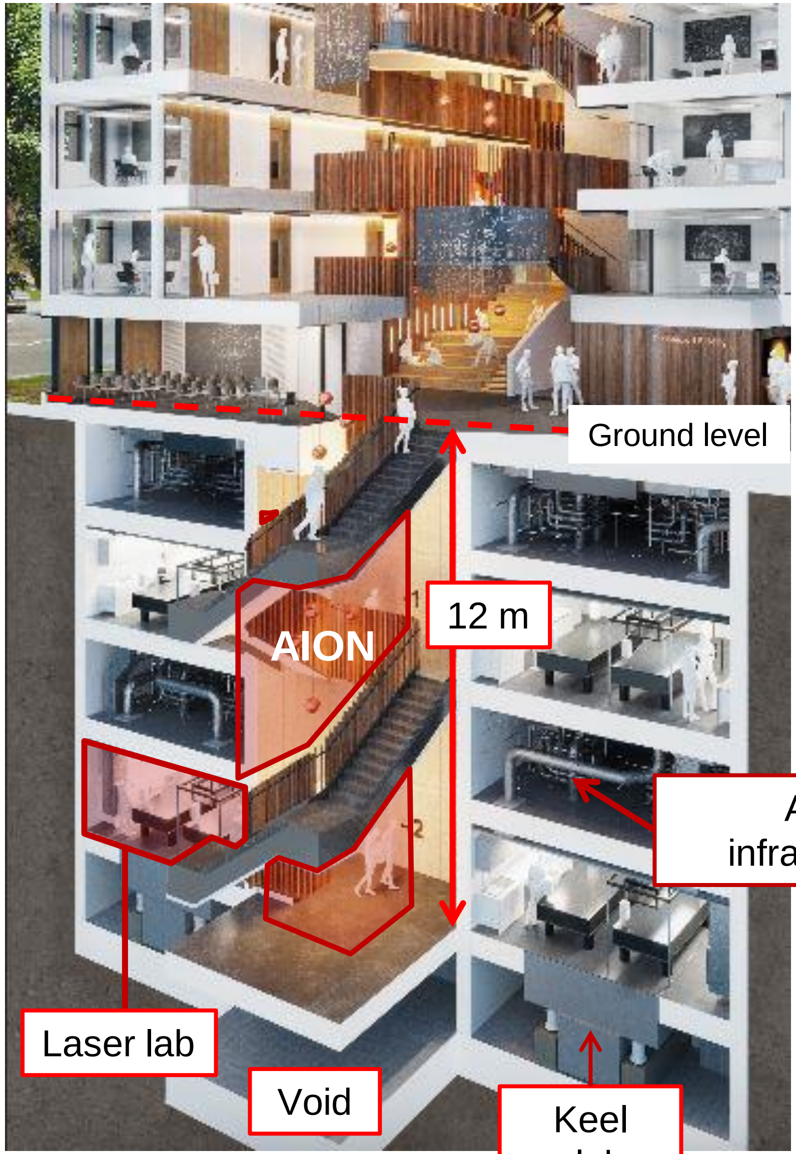


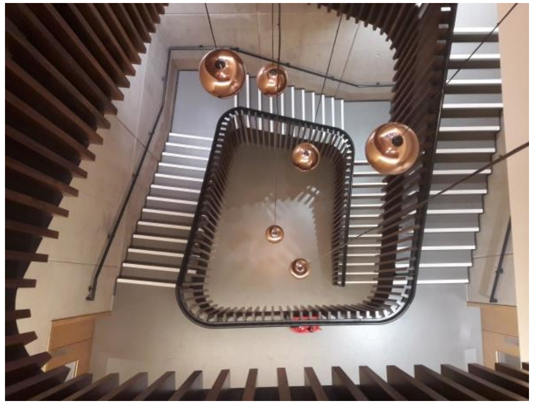
Stage 3 and 4 will likely require funding on international level (ESA, EU, etc) and AION has already started to build the foundation for it.

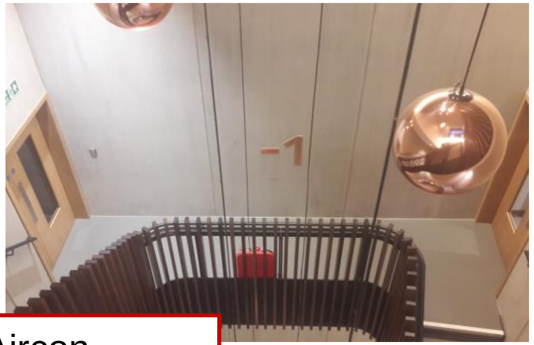
AION Collaboration Days in Oxford: Fall 2021

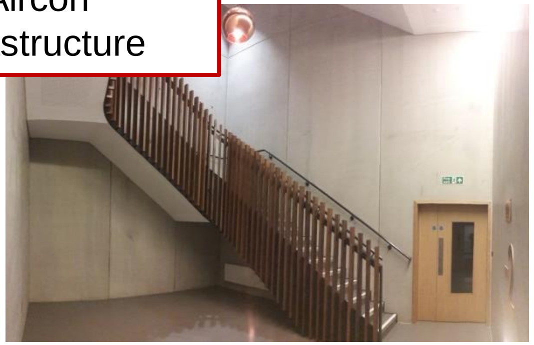
Ratio of Cold Atom : Particle/Fundamental Physics people is 1:1

Beecroft building, Oxford Physics









Ultralow vibration

- All plant isolated
- Thick concrete walls

Adjacent laser lab reserved for AION use

- keel slabs
- ±0.1°C stability
- Isolated mains

Vertical space

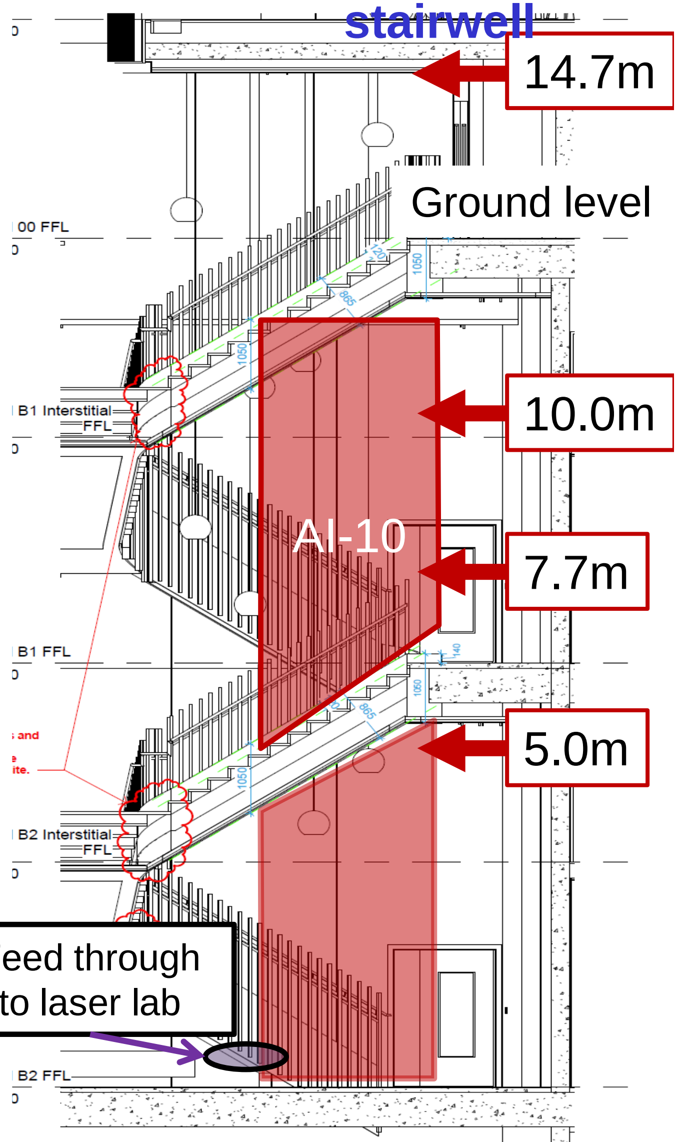
- 12m basement to ground floor
- 14.7m floor to ceiling

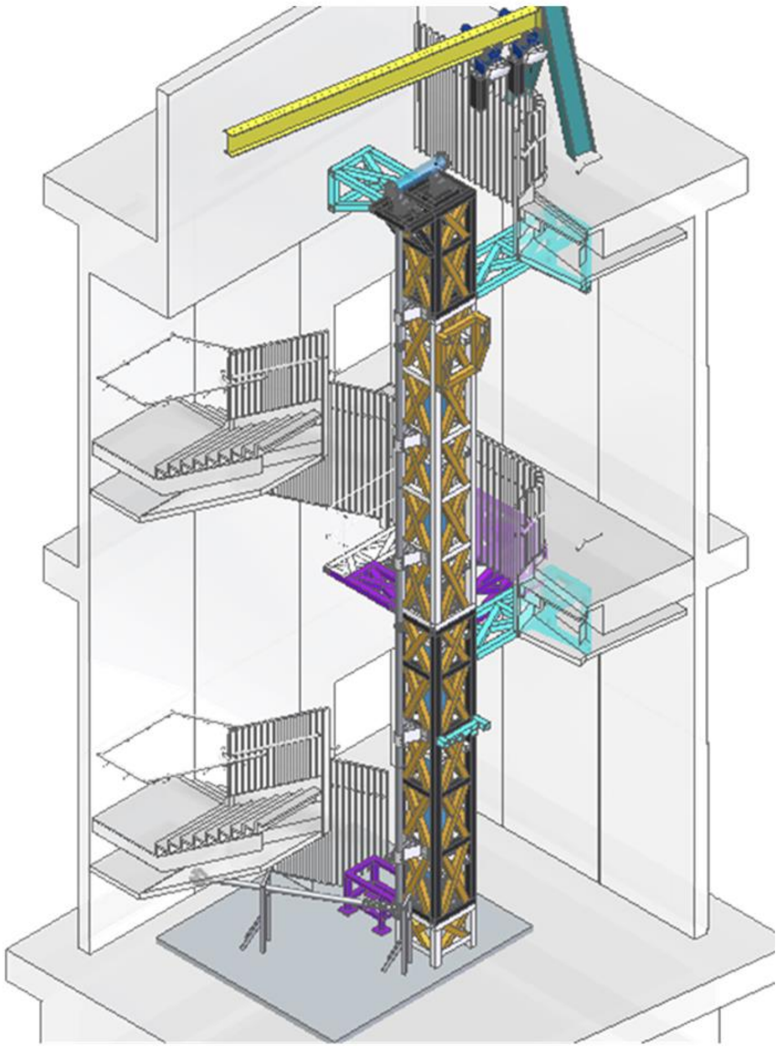
Stairwell is **not** a fire escape route.

Bakeout room and cleanroom nearby

AION-10 site: Beecroft building, Oxford Physics

Beecroft building – brand new, low-vibration laser lab and concrete stairwell





- AION-10 Preliminary Design Review successfully passed,
- Structure stabilisation and support designed and confirmed pending final rounds of analysis and internal component specification,
- Interconnect chambers and atom sources interface designed,
- Retroreflecting mirror stabilisation and cleanliness protection from MAGIS,
  - May be changes slightly as design is progressed,
- Launch lattice and telescope design currently being progressed,
- Magnetic shielding and field bias coils fully designed – credit RAL and MSL.

Construction start expected: Fall 2024, pending final funding decision.

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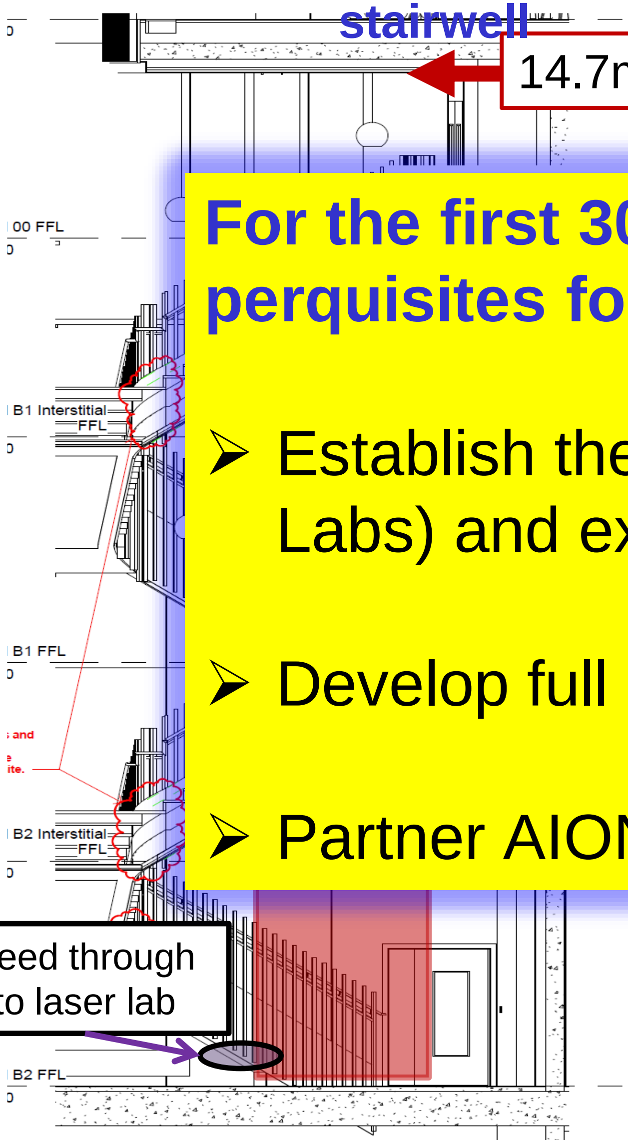
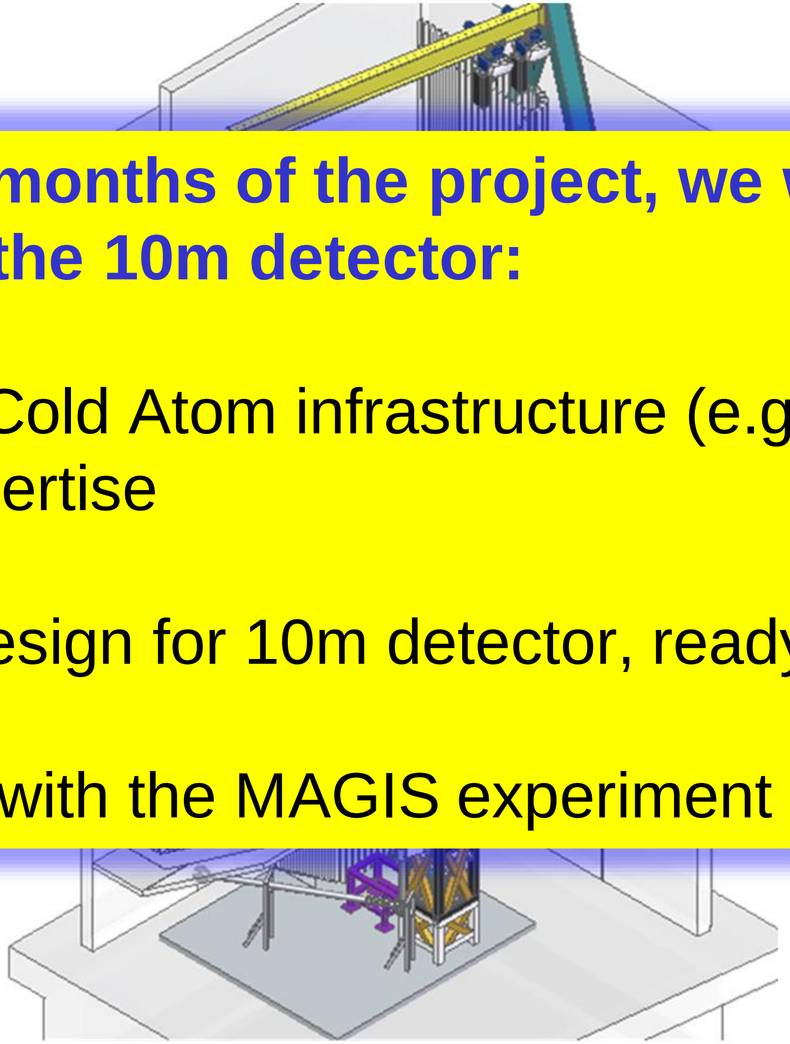
AION-10 site: Beecroft building, Oxford Physics

Beecroft building – brand new, low-vibration laser lab and concrete stairwell

Large Scale AI For Fundamental Physics





- AION-10 Preliminary Design Review successfully passed,
- Structure stabilisation and support designed

ces

n is

fully

For the first 30 months of the project, we will focus on the perquisites for the 10m detector:

➢ Establish the Cold Atom infrastructure (e.g. build UltraCold Sr Laser Labs) and expertise

➢ Develop full design for 10m detector, ready for physics exploitation

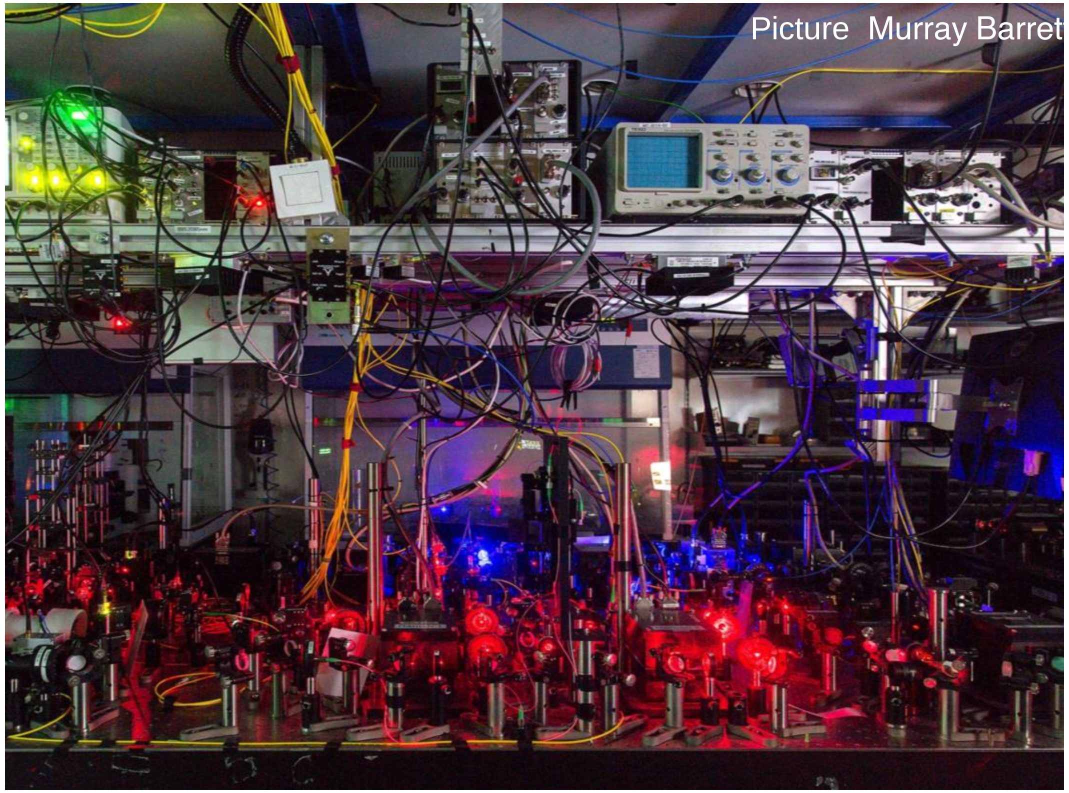
➢ Partner AION with the MAGIS experiment in the US

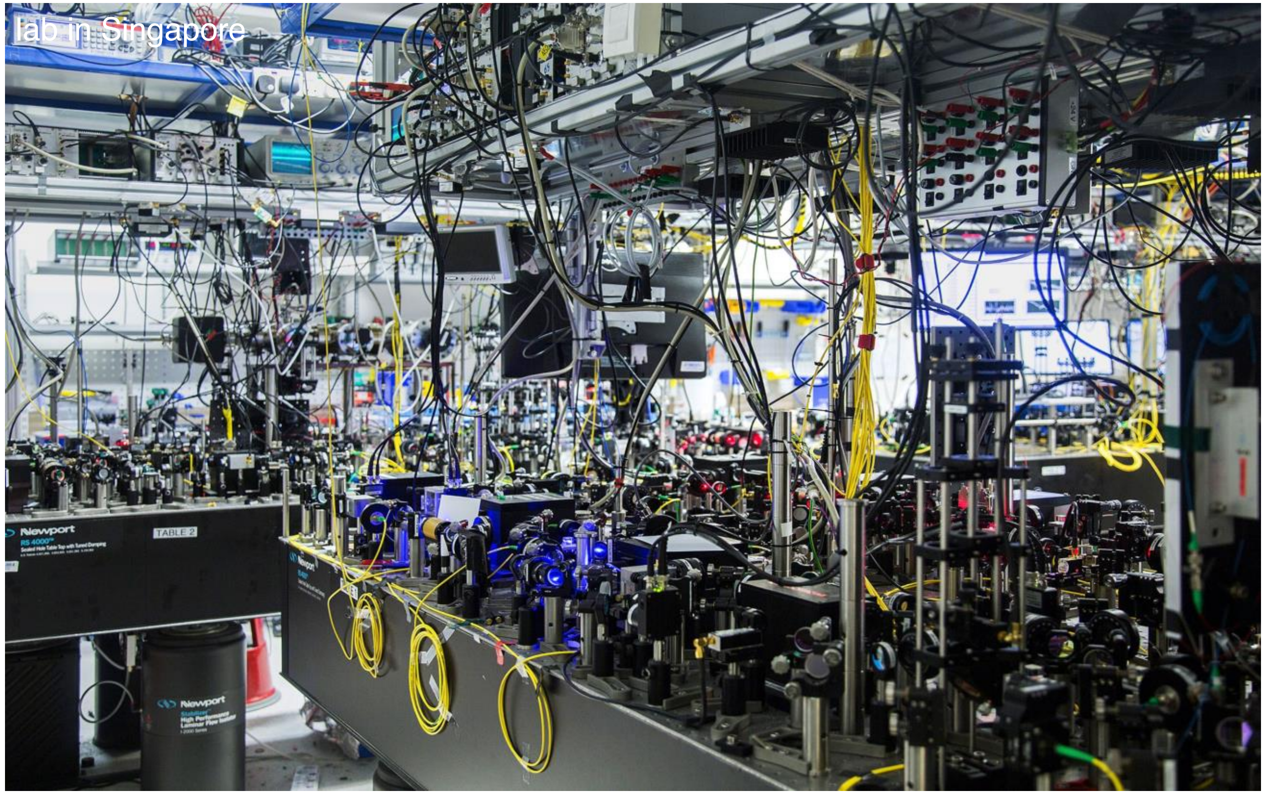
Construction start expected: Summer 2024, pending final funding decision.

Centralized Production of Ultra-Cold Strontium Laboratories

HOW TO BUILD A STATE-OF-THE-ART ULTRA COLD STRONTIUM LAB FOR PROJECT Q IN 24 MONTHS

AION: Ultra-Cold Strontium Laboratories in UK



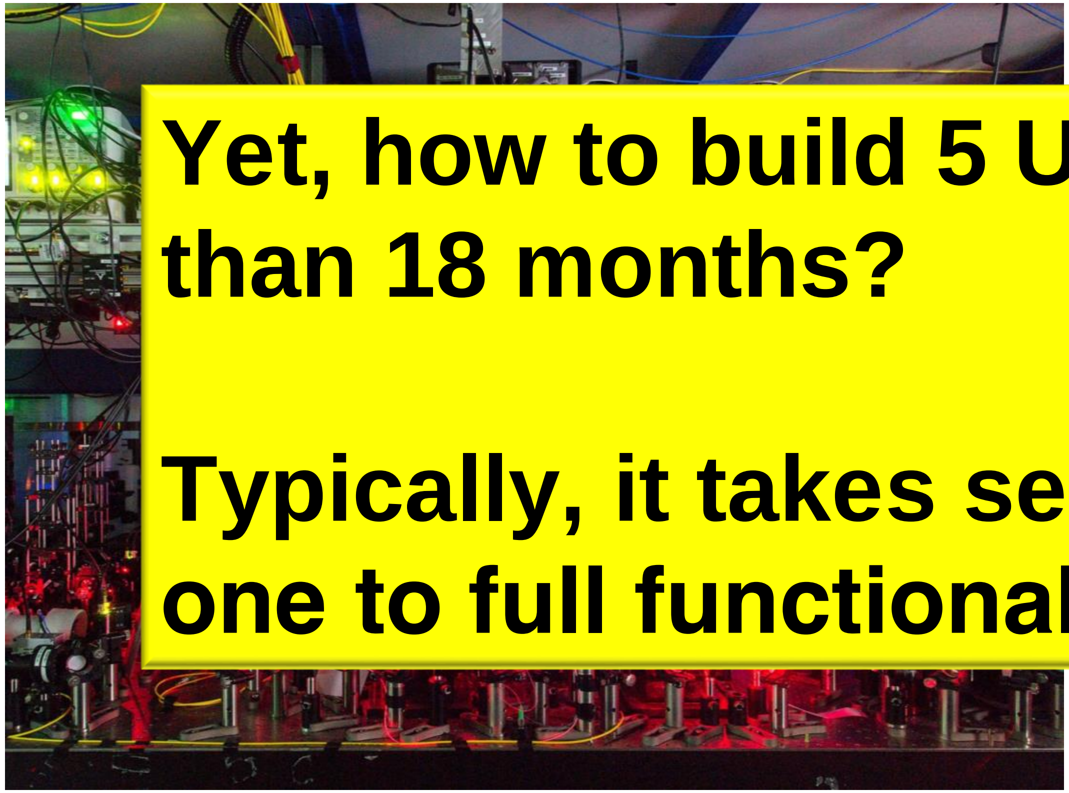
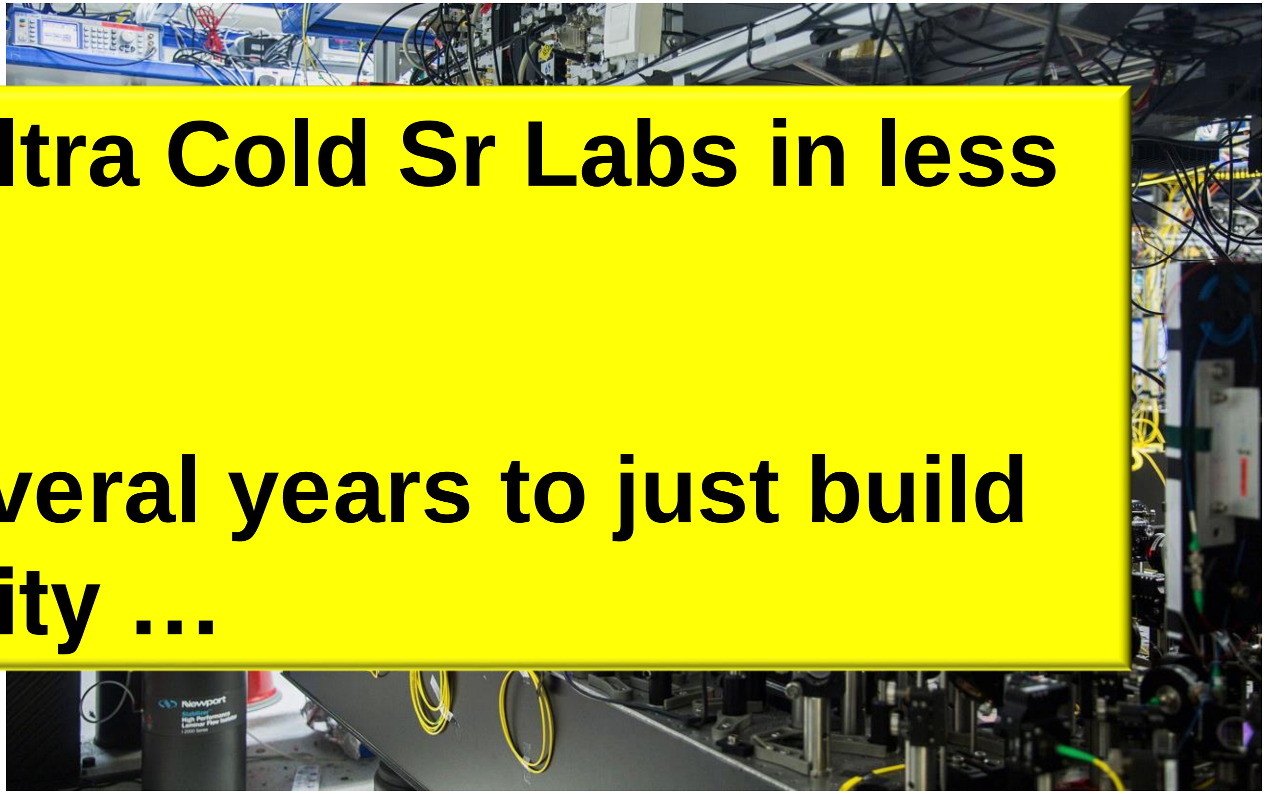


Picture Murray Barrett lab in Singapore

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

Birmingham, Cambridge, Imperial College, Oxford, and RAL

AION: Ultra-Cold Strontium Laboratories in UK

Yet, how to build 5 Ultra Cold Sr Labs in less than 18 months?

Typically, it takes several years to just build one to full functionality …

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 fully operational since summer 2023.

Applying HEP Large Scale Experience to Cold Atom Technology Development

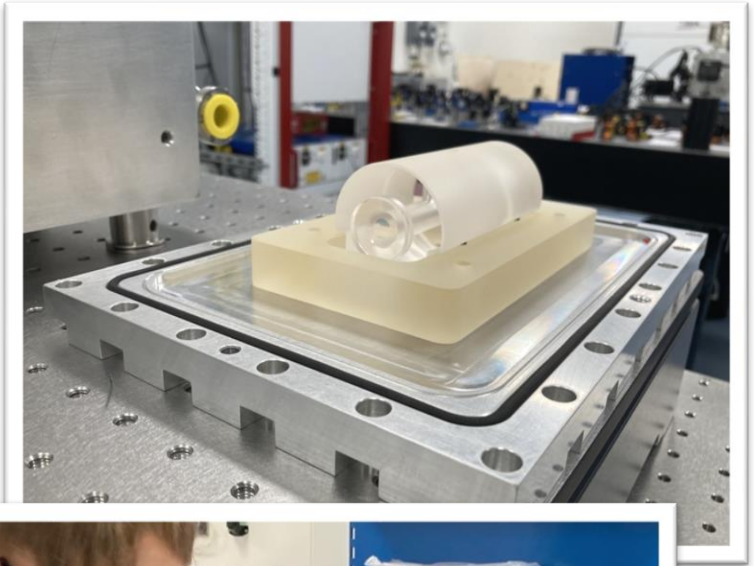
AION – FIRST LESSONS LEARNED AFTER 18 MONTHS IN THE PROJECT

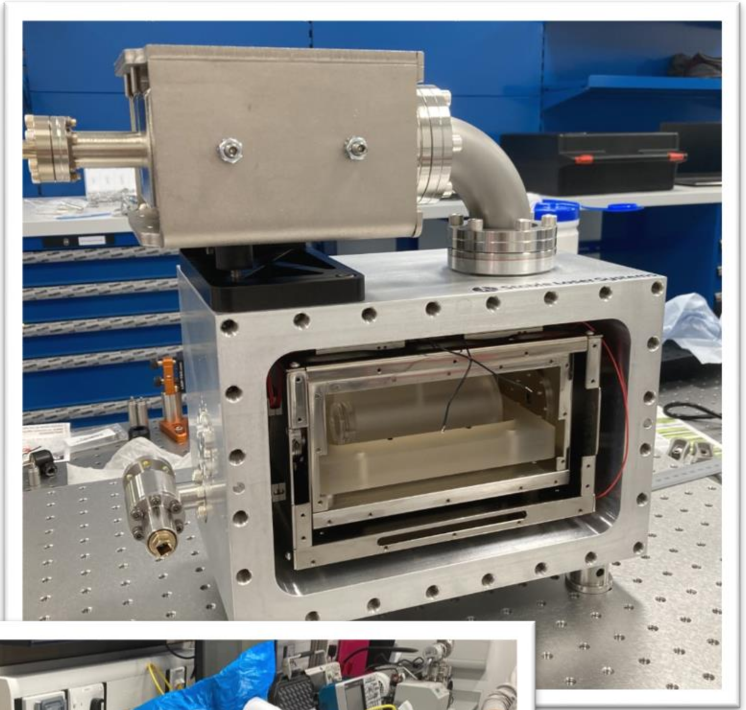
Centralize the design and production of major components:

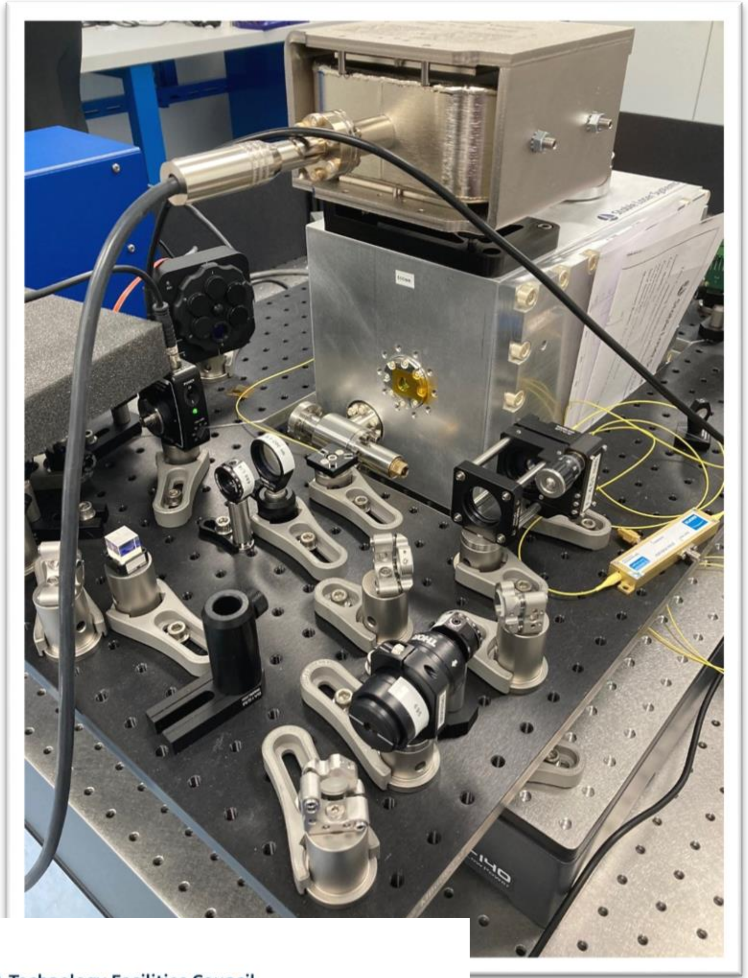
- **Ultra High Vacuum System**
- **Laser Stabilization System**
- **…**

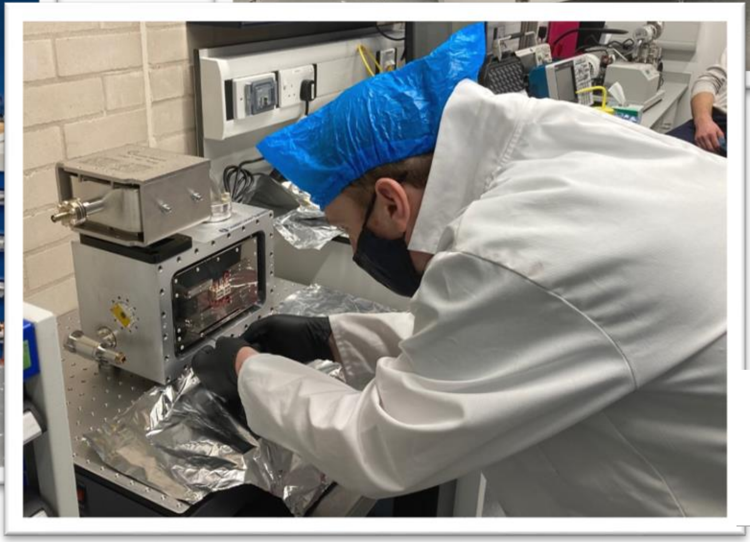
and make use of expertise at National Laboratories like Rutherford Appleton and Daresbury Laboratory!

CENTRAL PRODUCTION OF LASER STABILIZATION SYSTEM









Science & Technology Facilities Council
Rutherford Appleton Laboratory

20

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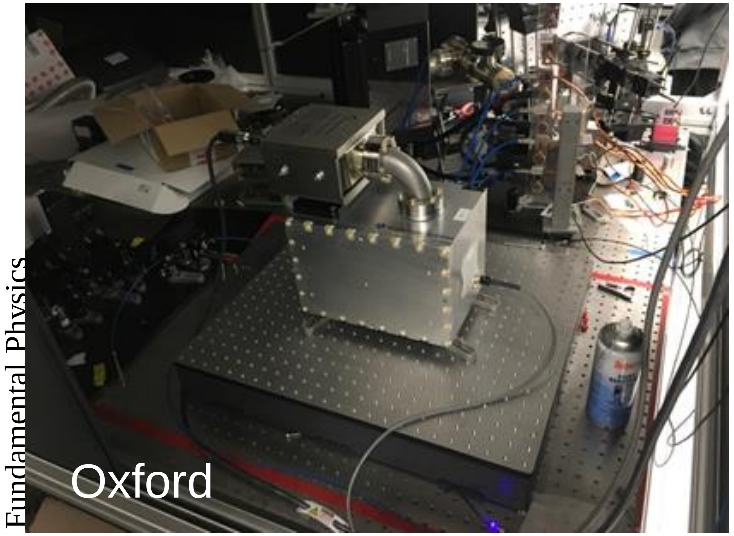
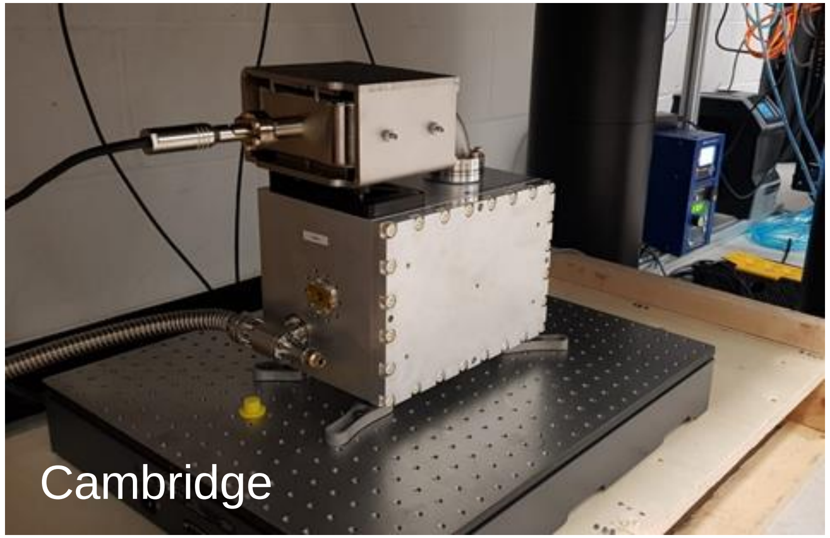
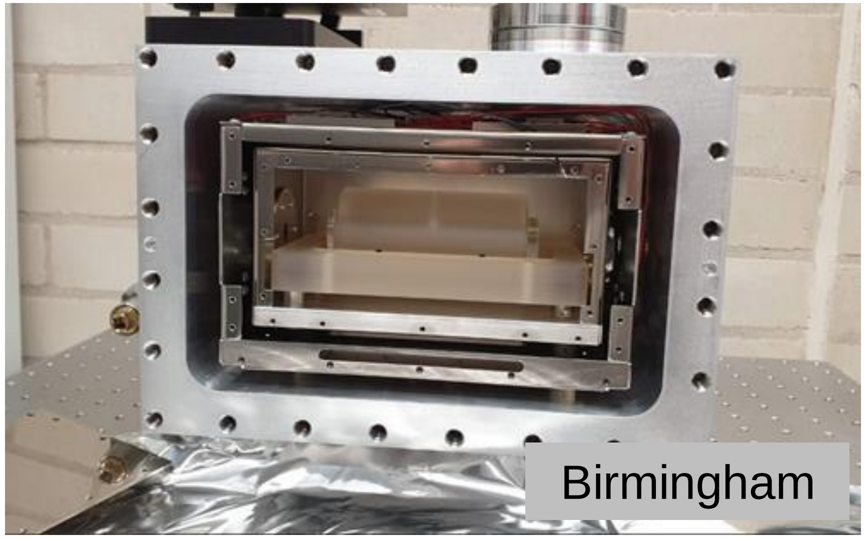
AION

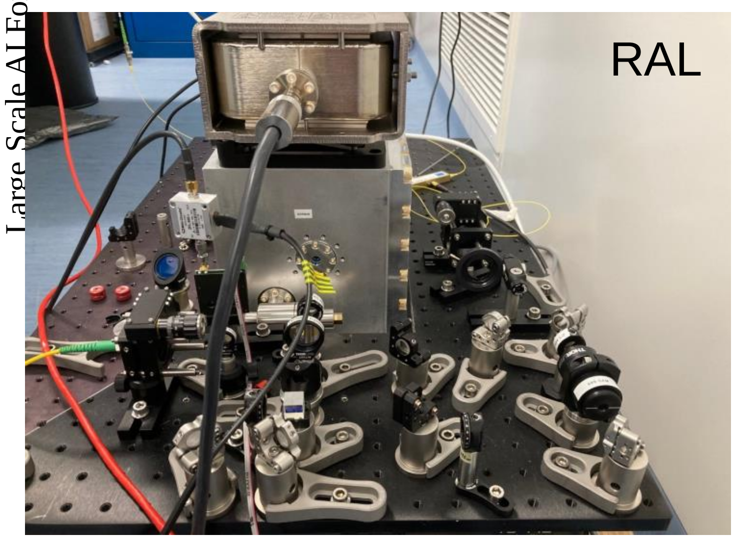
INSTALLATION OF LASER STABILIZATION SYSTEM

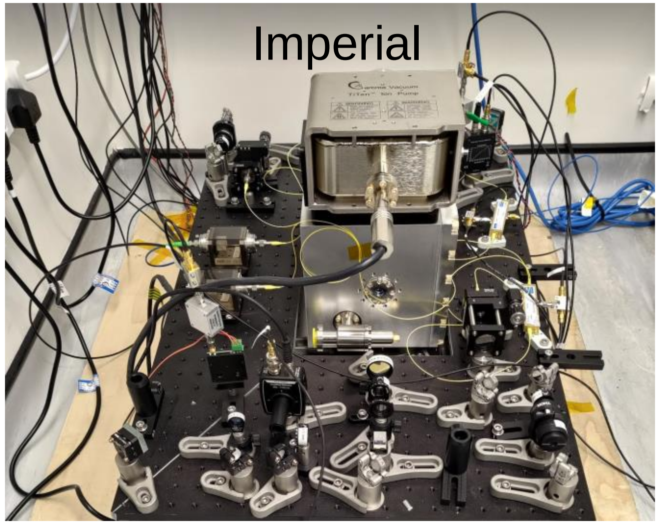
Large Scale AI For Fundamental Physics



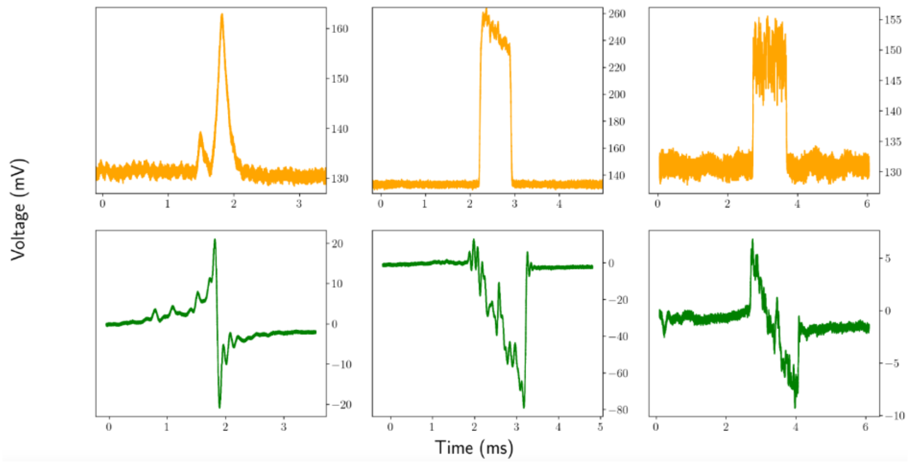






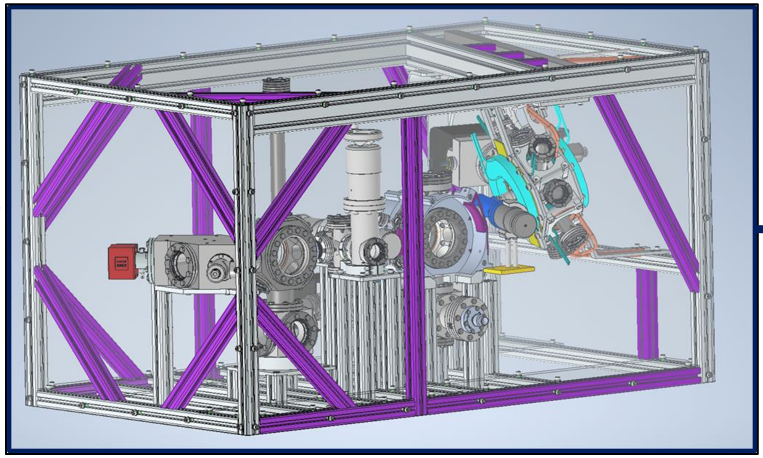


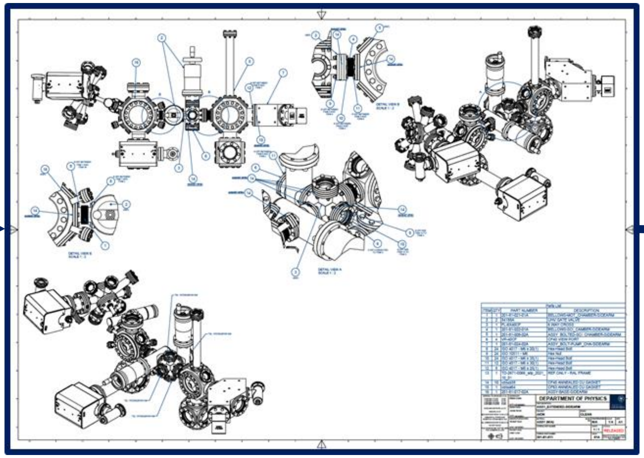
Below: Transmission and error signal data at Imperial
Laser stays locked for several days autonomously

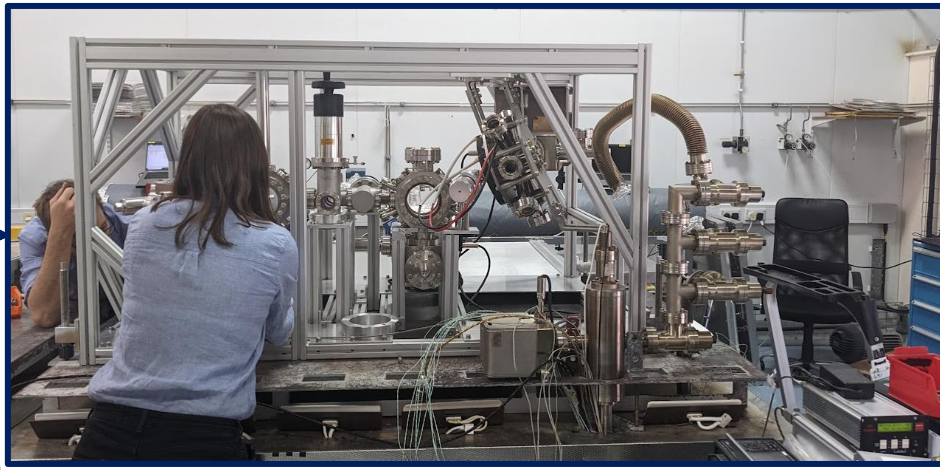


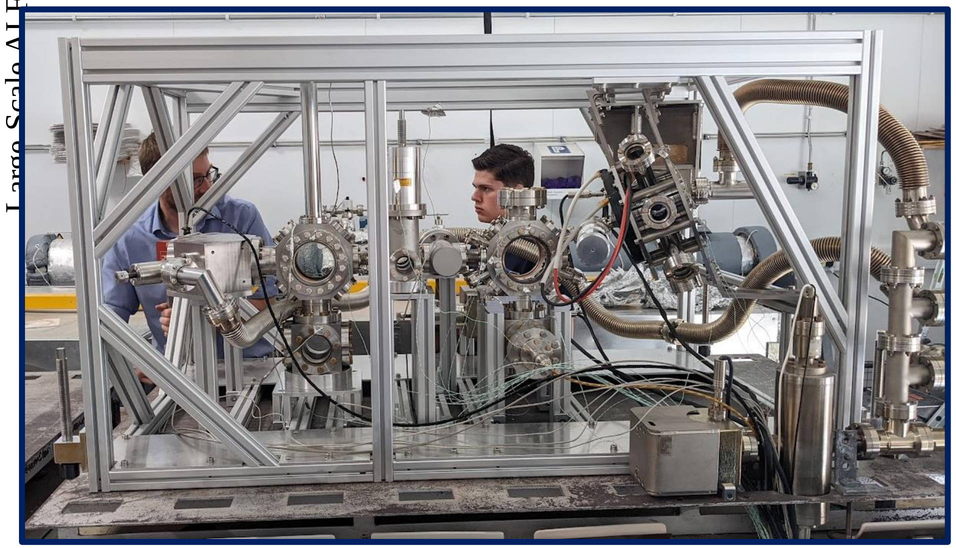
Ultra-High Vacuum System: Centralized Construction

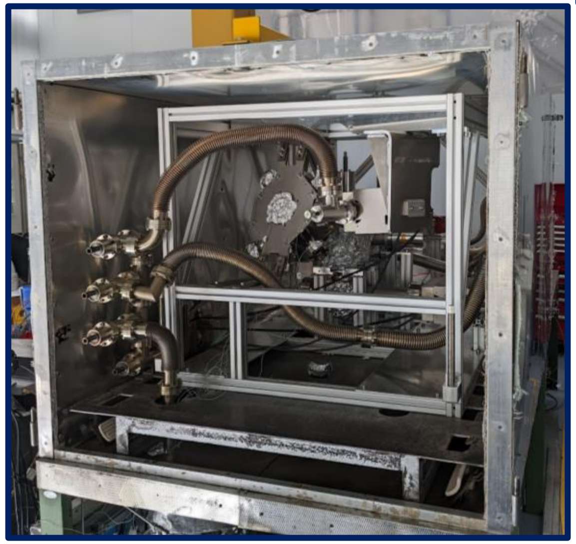
Manufacturing, Assembly and Installation

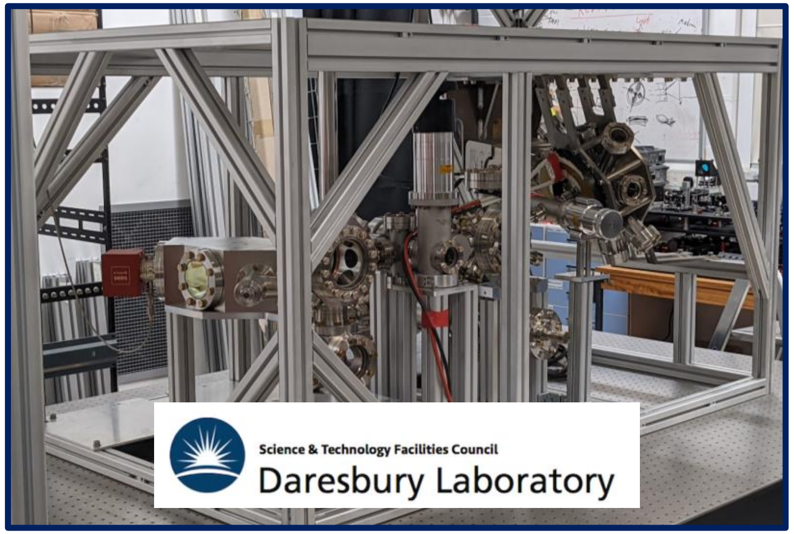












AION: Ultra-Cold Strontium Laboratories in UK

To push the state-of-the-art single photon Sr Atom Interferometry, the AION project built dedicated Ultra-Cold Strontium Laboratories in:
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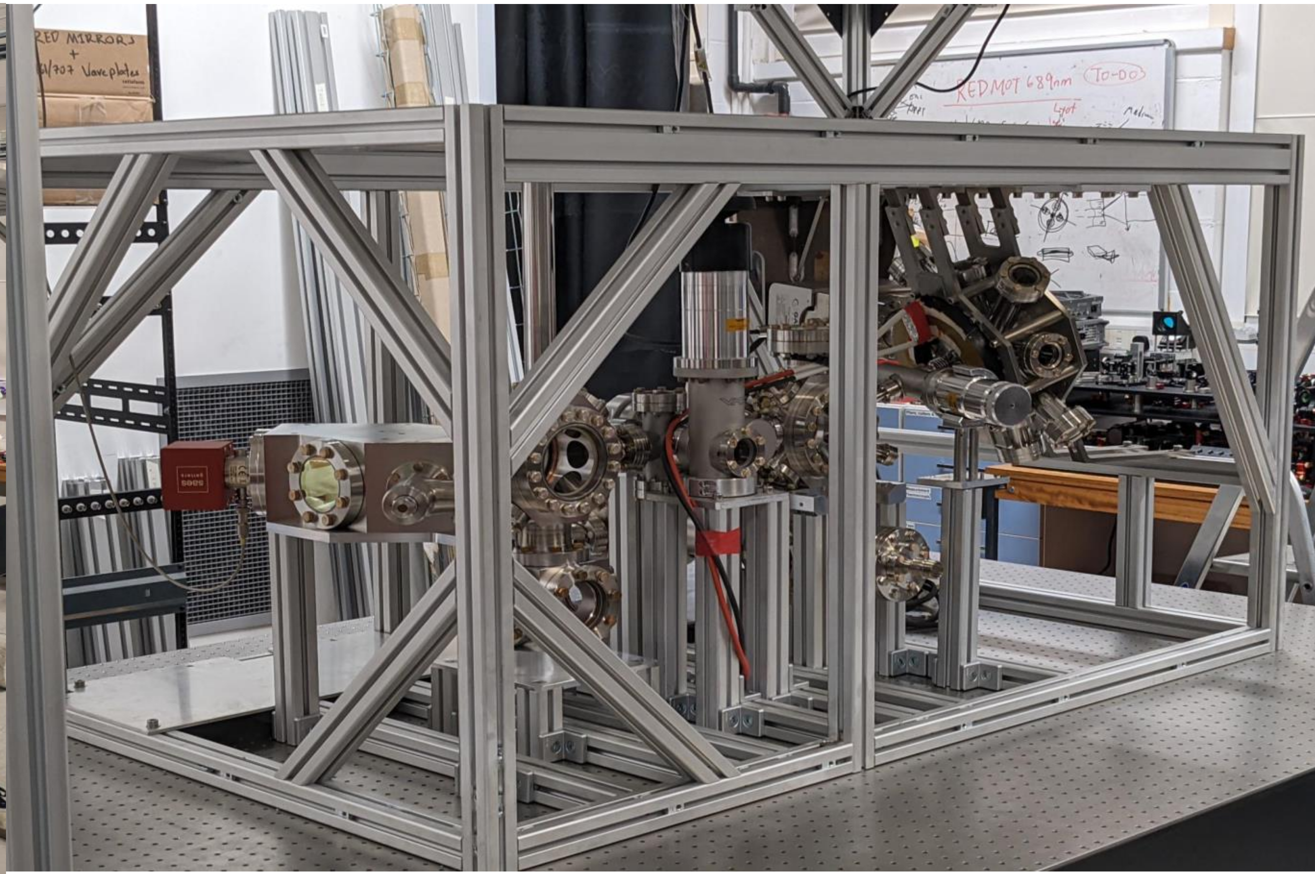
The laboratories are operational since summer 2023.



Large Scal

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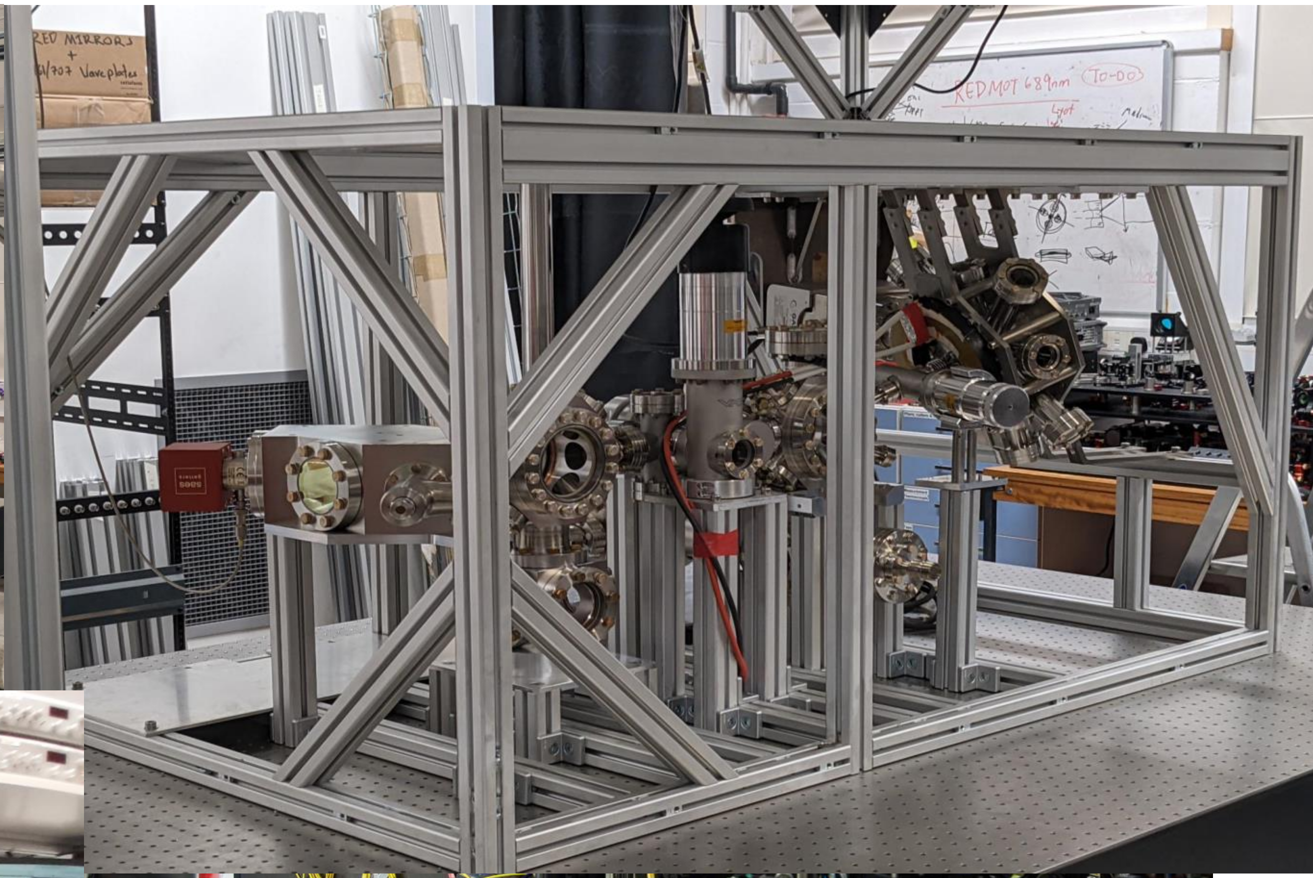

n Sr Atom Interferometry, the AION
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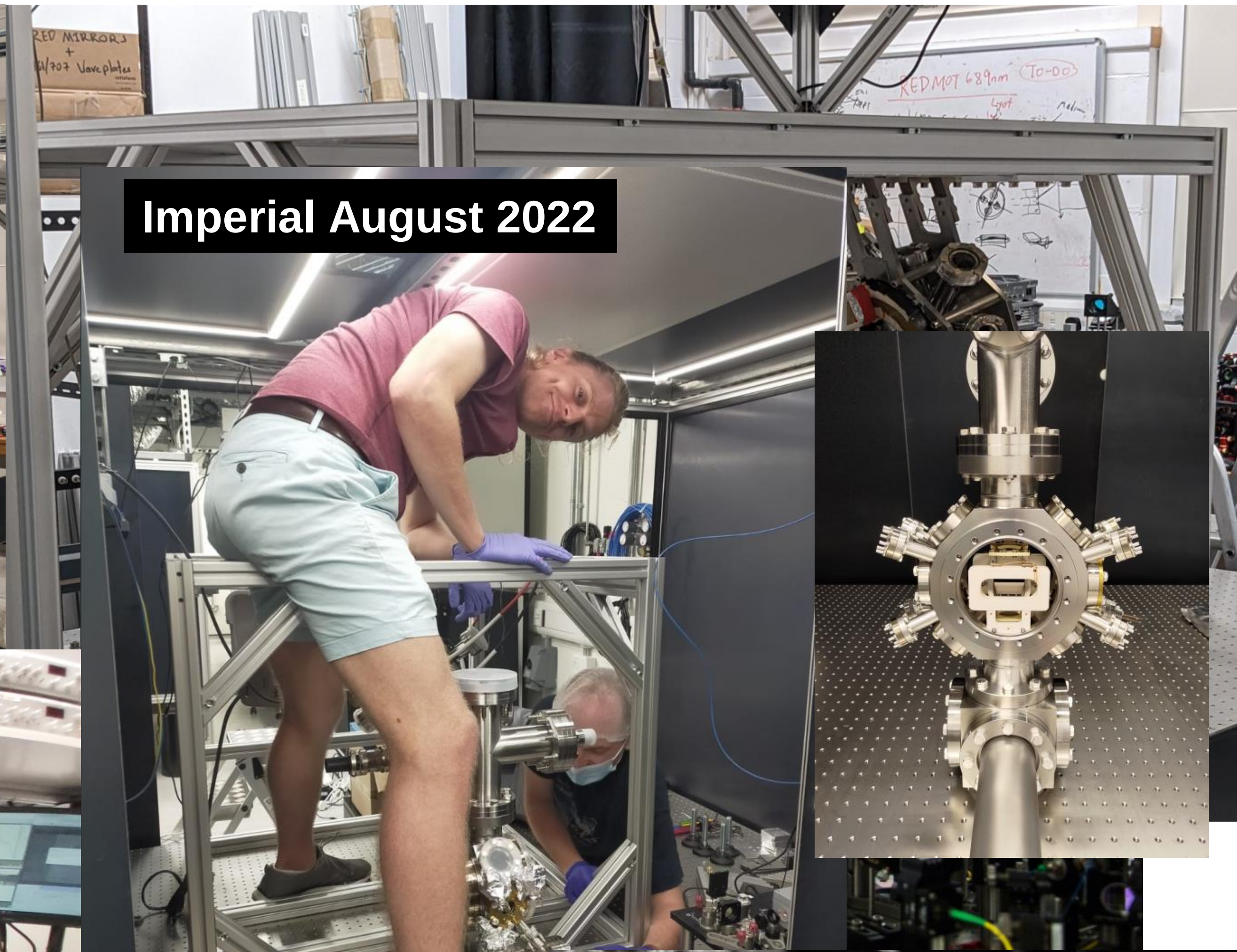
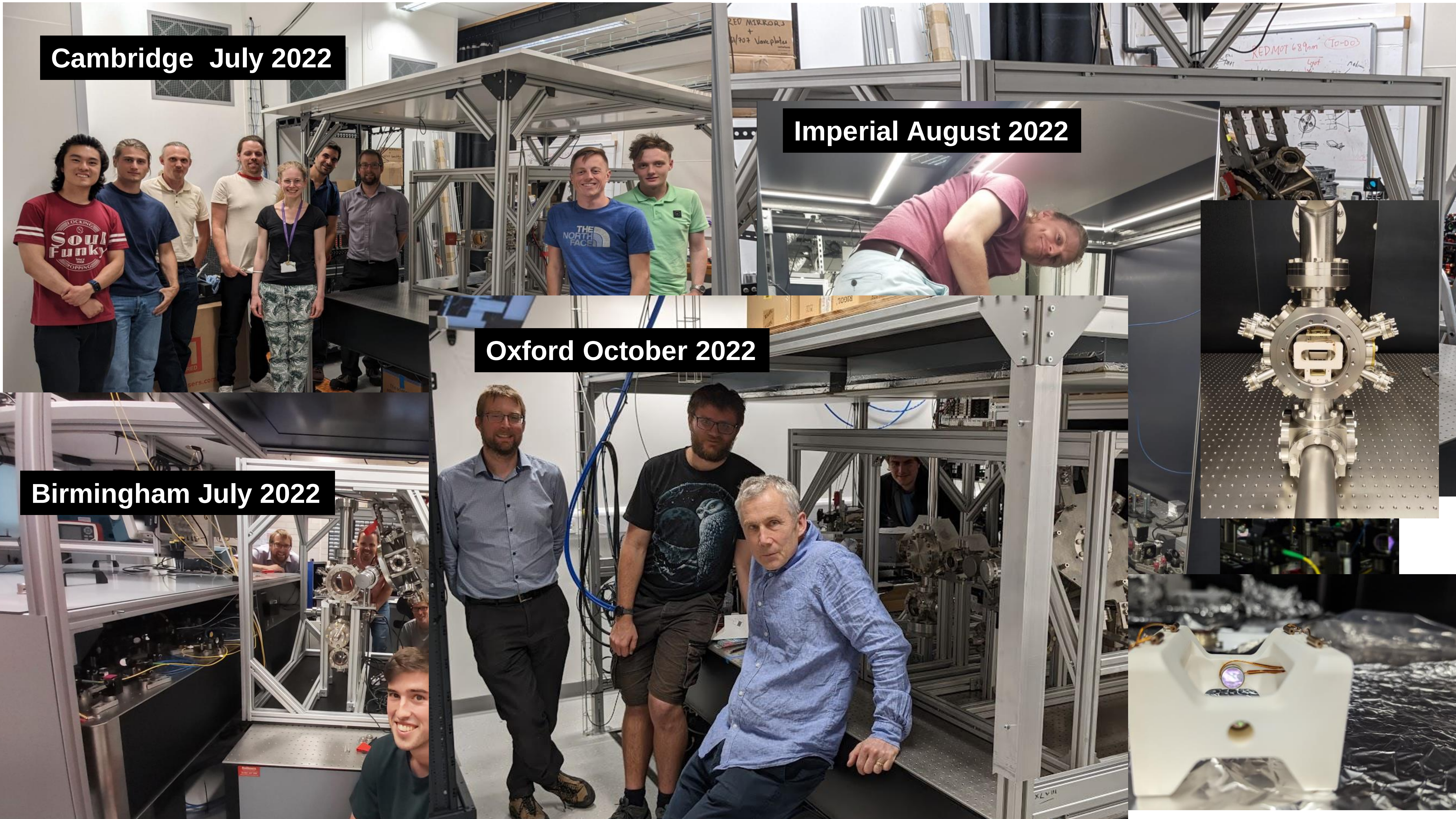
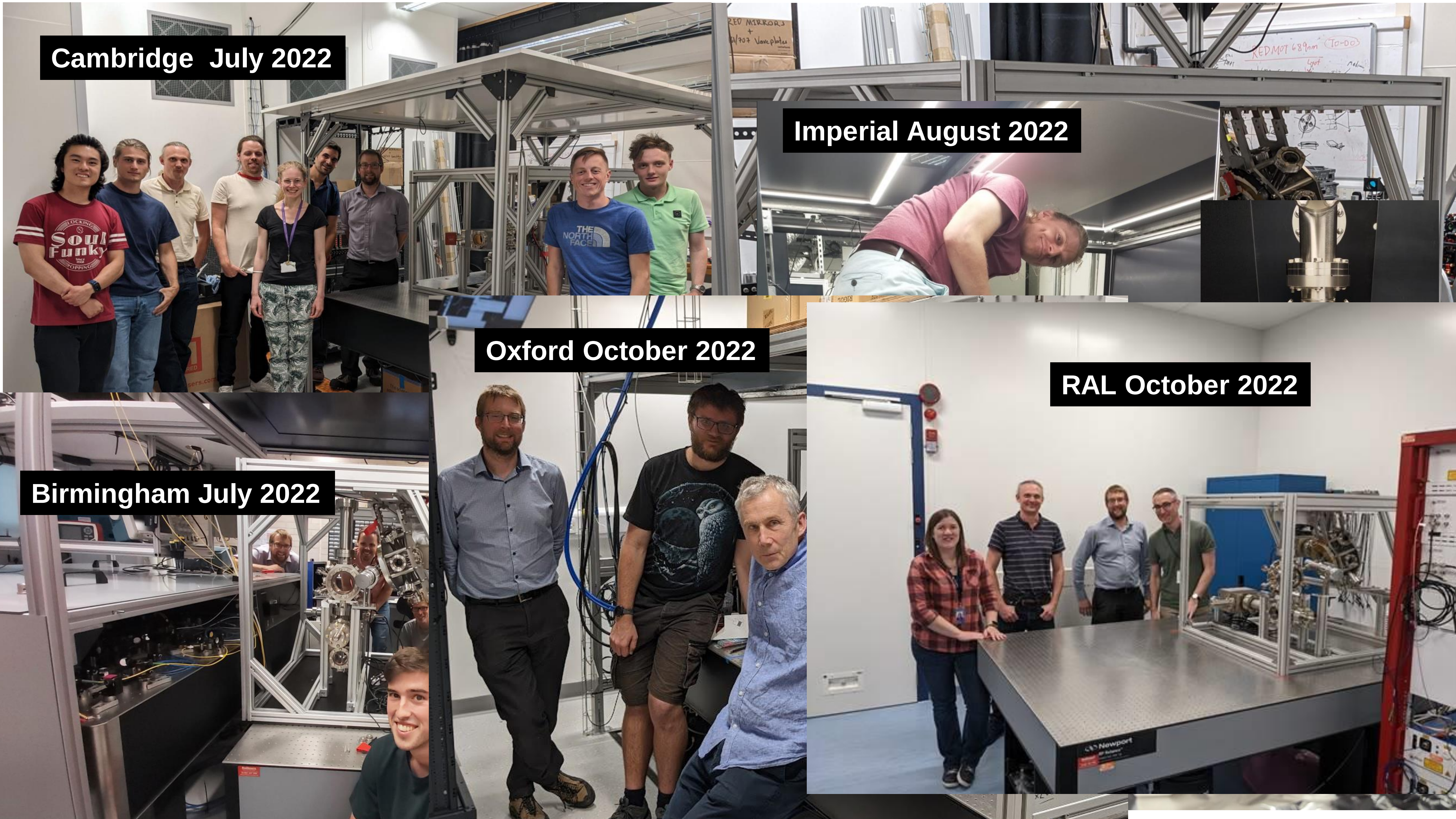


nal since summer


Cambridge July 2022
Imperial August 2022
Oxford October 2022
Birmingham July 2022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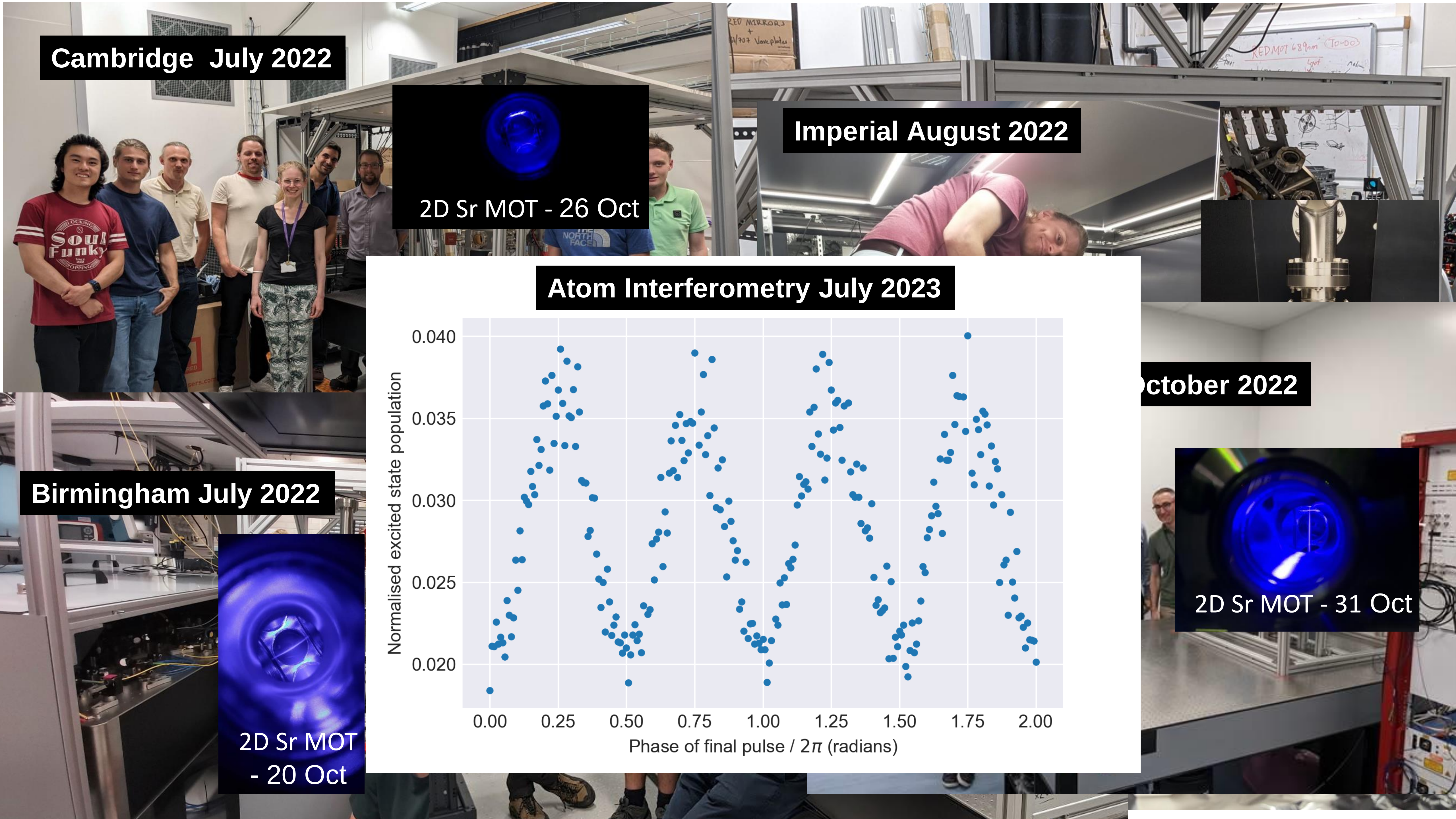
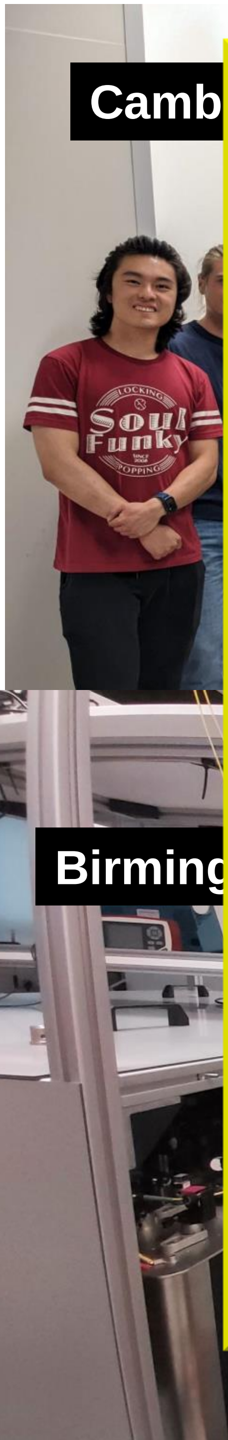
RAL October 2022

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



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!

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

https://arxiv.org/abs/2305.20060
[accepted for publication in AVS journal]

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

Centralised Design and Production of the Ultra-High Vacuum and Laser-Stabilisation Systems for the AION Ultra-Cold Strontium Laboratories

AION Collaboration:

B. Stray, O. Ennis, S. Hedges, S. Dey, M. Langlois, K. Bongs, S. Lellouch, M. Holynski; [a]

B. Bostwick, J. Chen, Z. Eyler, V. Gibson, T. L. Harte, M. Hsu, M. Karzazi, J. Mitchell, N. Mouelle, U. Schneider, Y. Tang, K. Tkalcec, Y. Zhi; [b]

K. Clarke and A. Vick; [c]

K. Bridges, J. Coleman, G. Elertas, L. Hawkins, S. Hindley, K. Hussain, C. Metelko, H. Throssell; [d]

C. F. A. Baynham, O. Buchmüller, D. Evans, R. Hobson, L. Iannizzotto-Venezze, A. Josset, E. Pasatembou, B. E. Sauer, M. R. Tarbutt; [e]

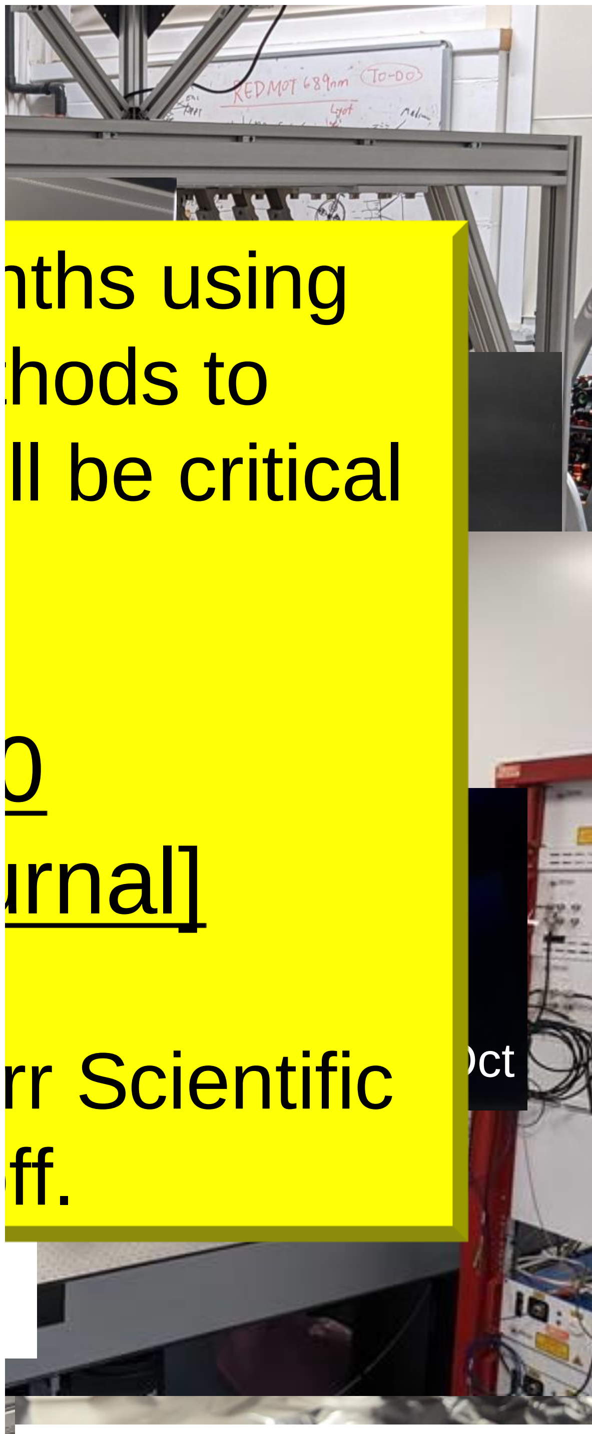
L. Badurina, A. Beniwal, D. Blas, [1] J. Carlton, J. Ellis, C. McCabe; [f]

E. Bentine, M. Booth, D. Bortoletto, C. Foot, C. Gomez, T. Hird, K. Hughes, A. James, A. Lowe, J. March-Russell, J. Schelfhout, I. Shipsey, D. Weatherill, D. Wood; [g]

S. Balashov, M. G. Bason, J. Boehm, M. Courthold, M. van der Grinten, P. Majewski, A. L. Marchant, D. Newbold, Z. Pan, Z. Tam, T. Valenzuela, I. Wilmut [h]

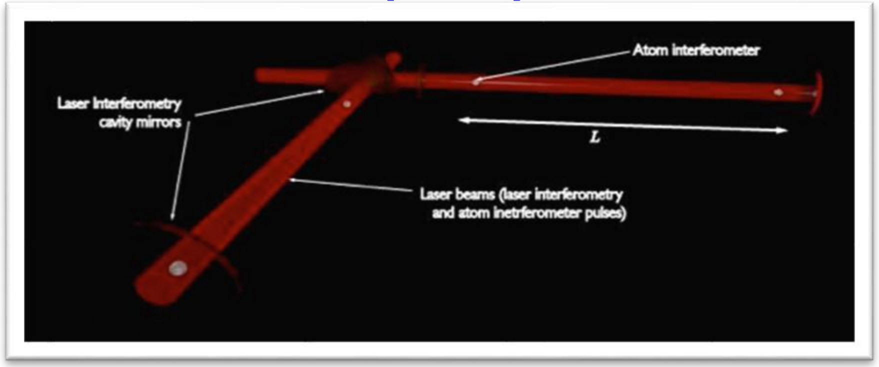
[a] *Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK*
[b] *Cavendish Laboratory, J J Thomson Avenue, University of Cambridge, CB3 0HE, UK*
[c] *ASTeC, STFC Daresbury Laboratory, Warrington, WA4 4AD, UK*
[d] *Department of Physics, University of Liverpool, Merseyside, L69 7ZE, UK*
[e] *Department of Physics, Blackett Laboratory, Imperial College, Prince Consort Road, London, SW7 2AZ, UK*
[f] *Physics Department, King's College London, Strand, London, WC2R 2LS, UK*
[g] *Department of Physics, University of Oxford, Keble Road, Oxford, OX1 2JJ, UK*
[h] *STFC Rutherford Appleton Laboratory, Didcot, OX11 0QX, UK*

[1] Present address: Grup de Física Teòrica, Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain and Institut de Fisica d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain

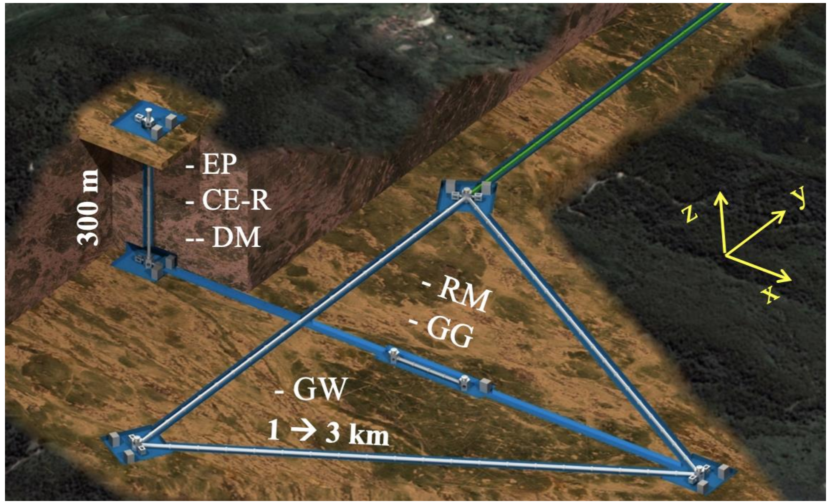


Ground Based Large Scale O(100m) Projects

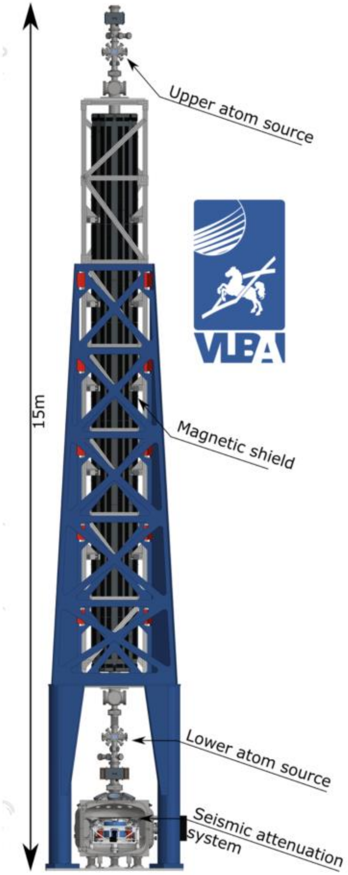
MIGA: Terrestrial detector using atom interferometer at O(100m)
(France)

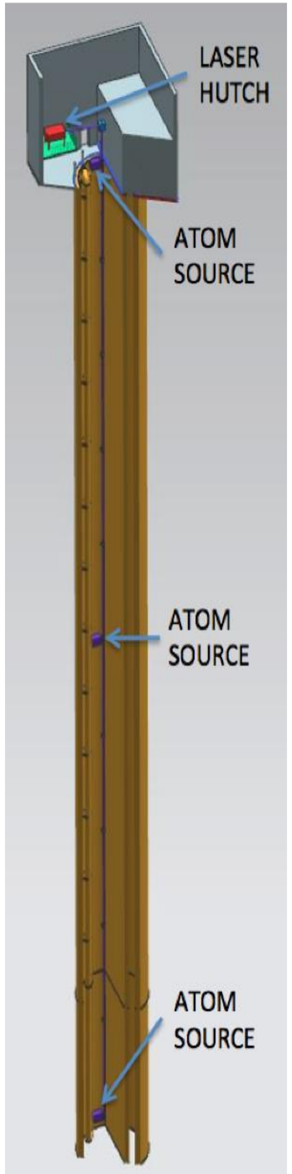


ZAIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)
(China)

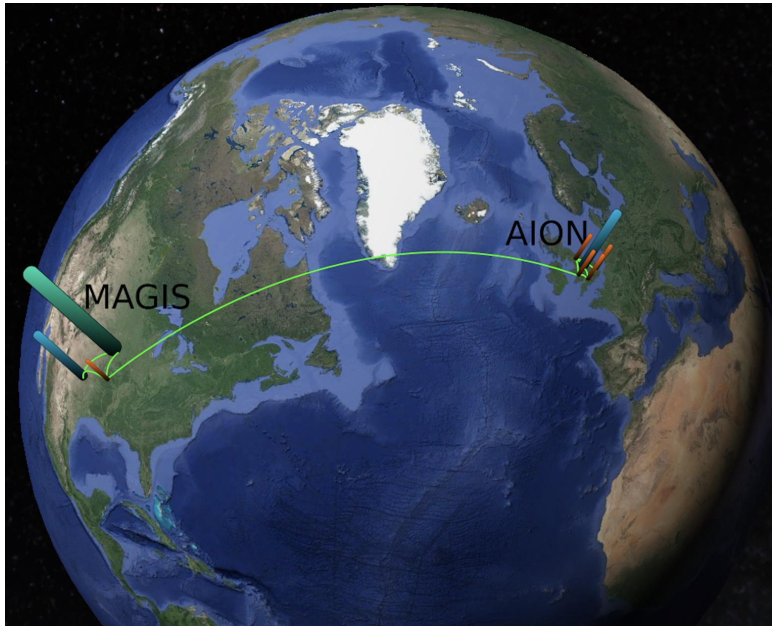


VLBAI: Terrestrial tower using atom interferometer O(10m)
(Germany)



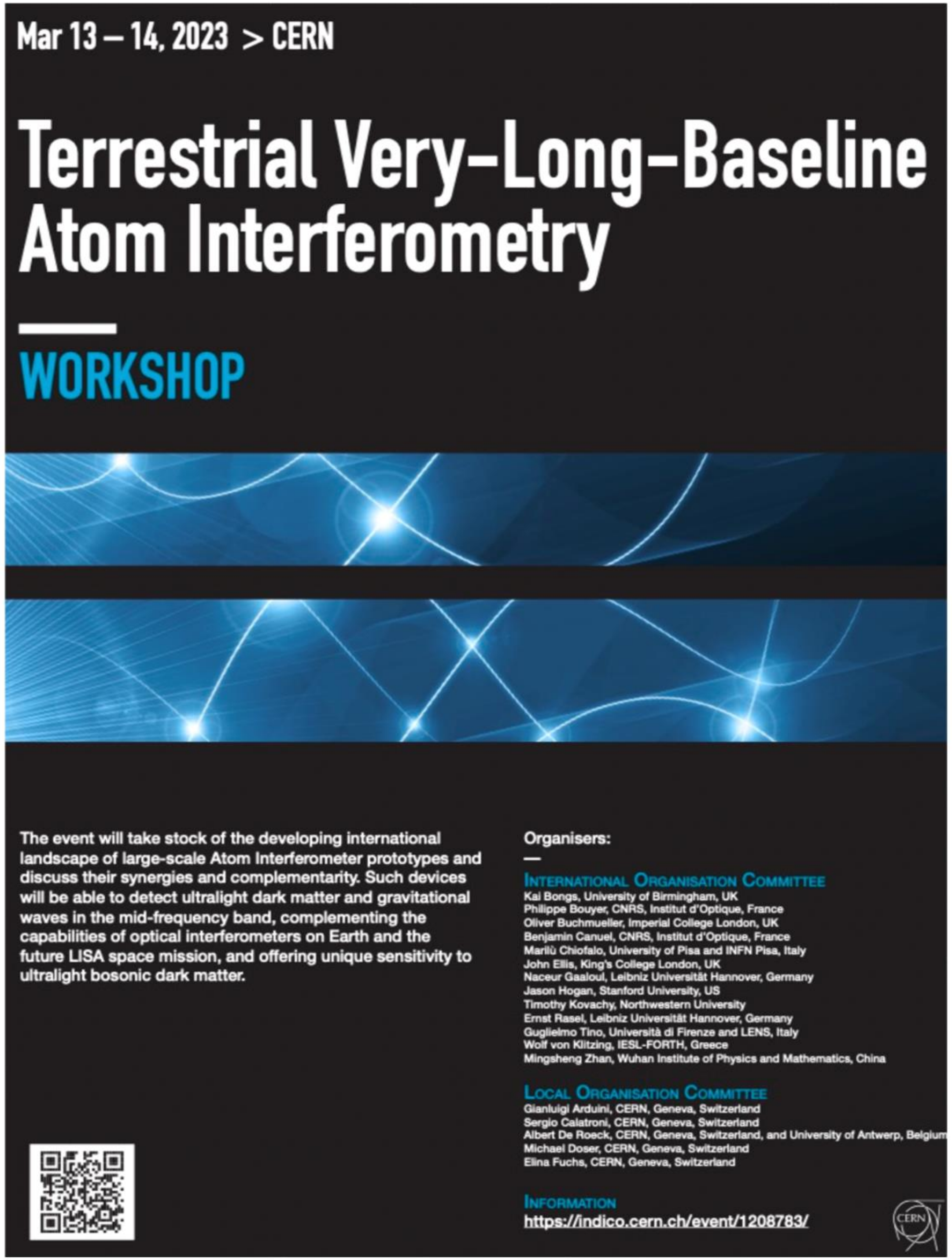


AION: Terrestrial shaft detector using atom interferometer at 10m – O(100m) planned
(UK)

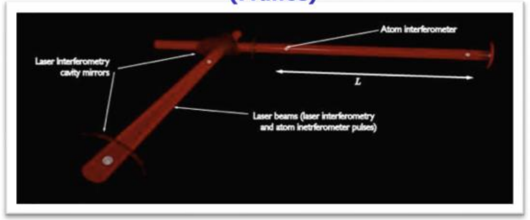


MAGIS: Terrestrial shaft detector using atom interferometer at O(100m)
(US)

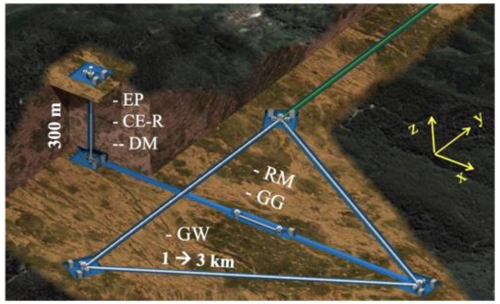
Planned network operation



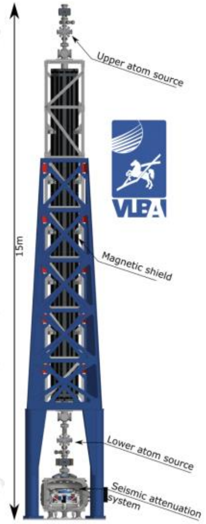
MIGA: Terrestrial detector using atom interferometer at O(100m) (France)

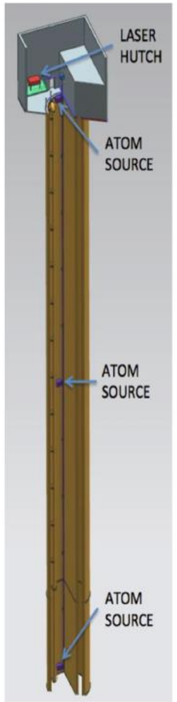


ZIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m) (China)



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

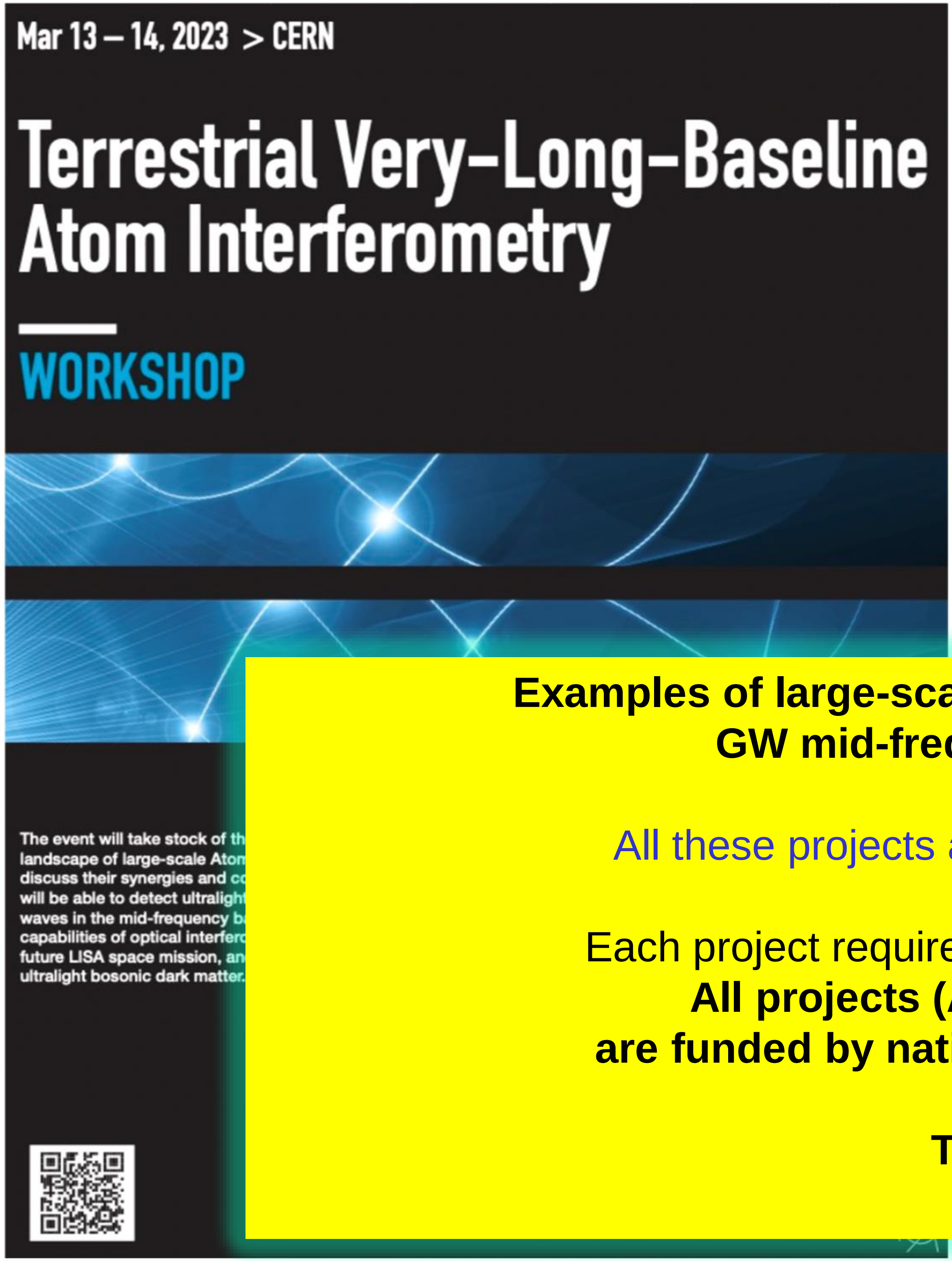
International Organisation Committee
Kai Bongs, University of Birmingham, UK
Philippe Bouyer, CNRS, Institut d'Optique, France
Oliver Buchmueller, Imperial College London, UK
Benjamin Canuel, CNRS, Institut d'Optique, France
Marilù Chiofalo, University of Pisa and INFN Pisa, Italy
John Ellis, King's College London, UK
Naceur Gaaloul, Leibniz Universität Hannover, Germany
Jason Hogan, Stanford University, US
Timothy Kovachy, Northwestern University
Ernst Rasel, Leibniz Universität Hannover, Germany
Guglielmo Tino, Università di Firenze and LENS, Italy
Wolf von Klitzing, IESL-FORTH, Greece
Mingsheng Zhan, Wuhan Institute of Physics and Mathematics, China

Local Organisation Committee
Gianluigi Arduini, CERN, Geneva, Switzerland
Sergio Calatroni, CERN, Geneva, Switzerland
Albert De Roeck, CERN, Geneva, Switzerland, and University of Antwerp, Belgium
Michael Doser, CERN, Geneva, Switzerland
Elina Fuchs, CERN, Geneva, Switzerland

Physics Beyond Colliders

AIP Publishing

IQ QUANTUM TECHNOLOGY INITIATIVE



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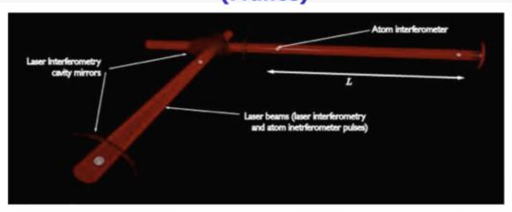
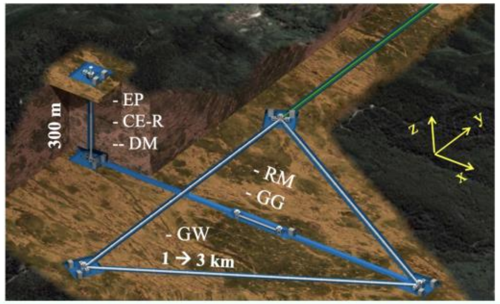
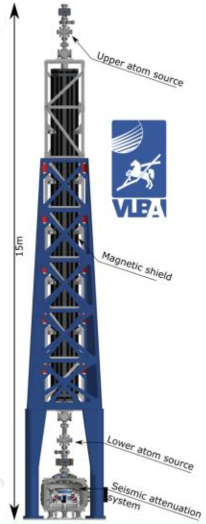
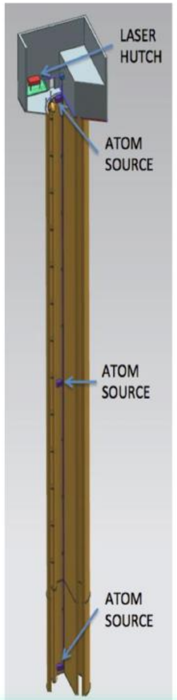


ZIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m) (China)



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

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.

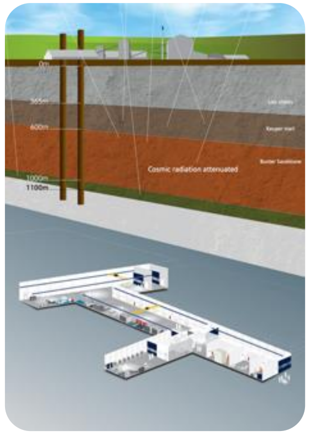
Each project requires an investment of O(10M+) currency units.
All projects (AION, MAGIS, MIGA, VLBAI, ZAIGA) are funded by national funding agencies and foundations.

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

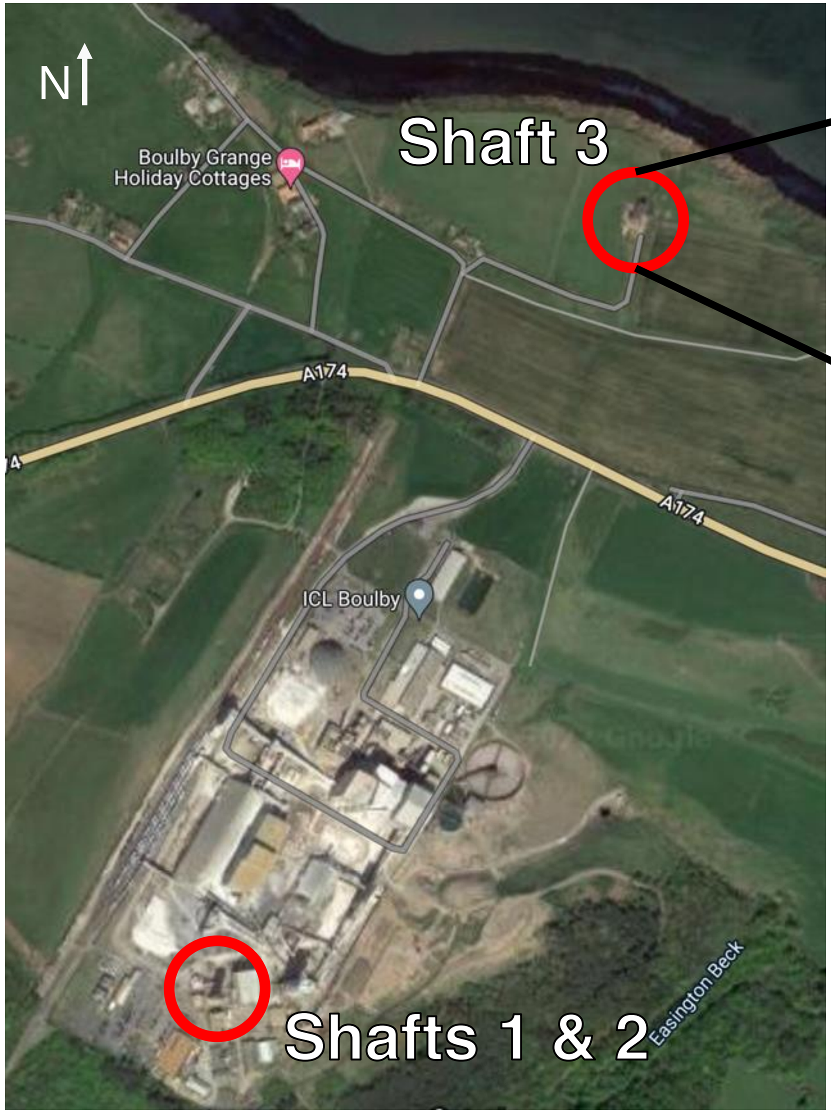
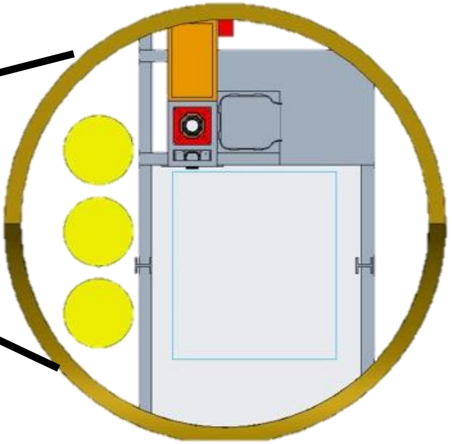
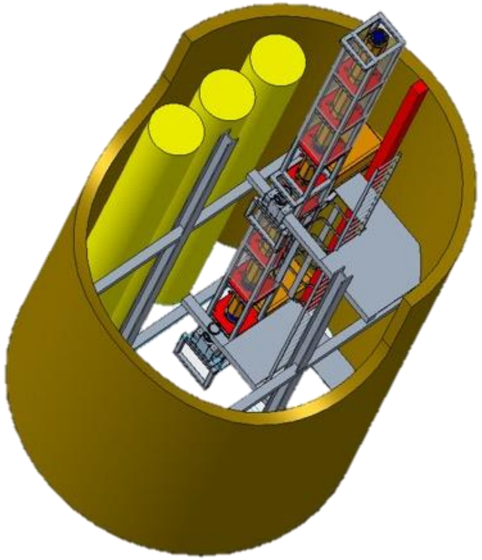


Image: google maps



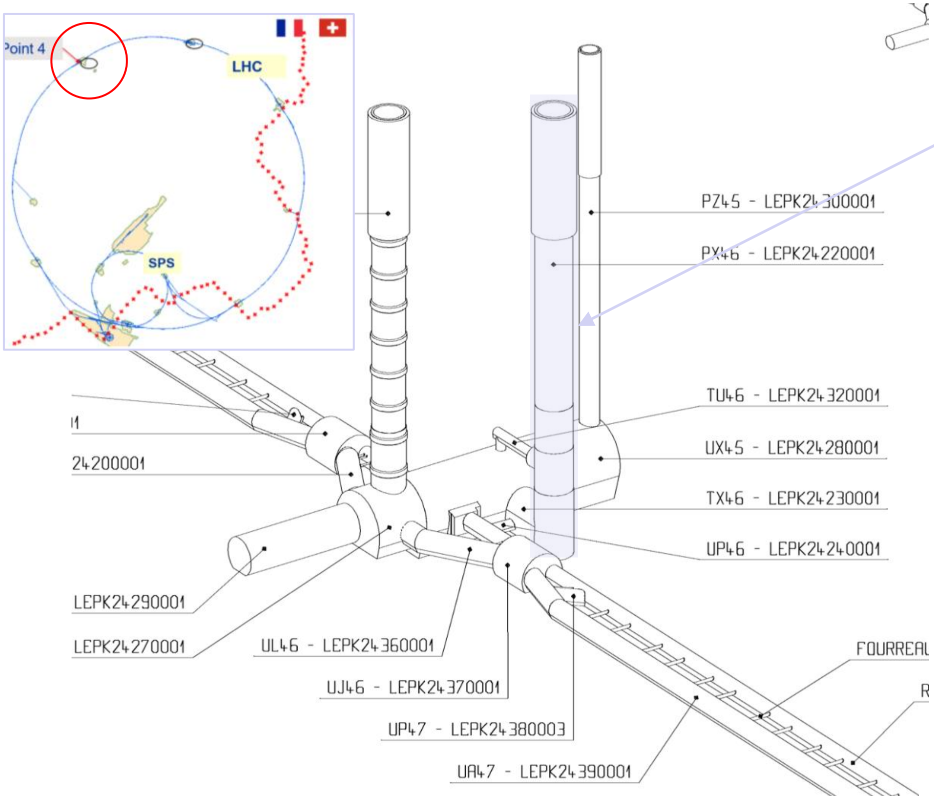
Shaft 3



AION

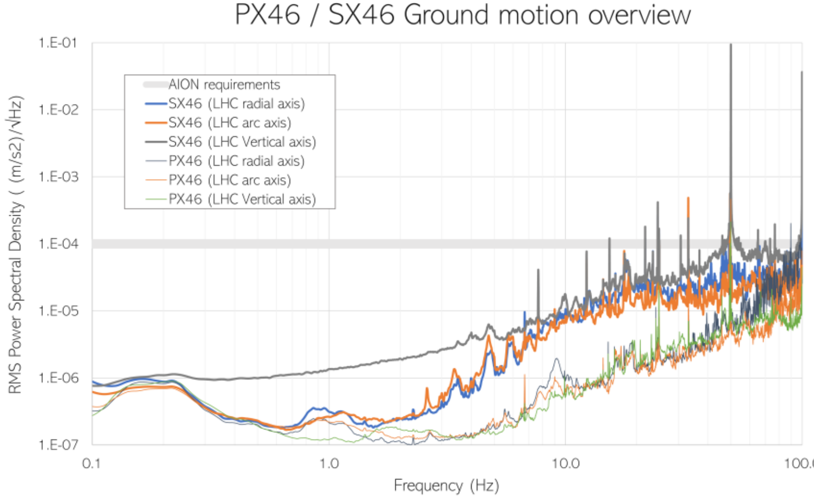
Possible site for a vertical VLBAI at CERN: 140 m deep pit at LHC Pt 4

Large Scale AI For Fundamental Physics

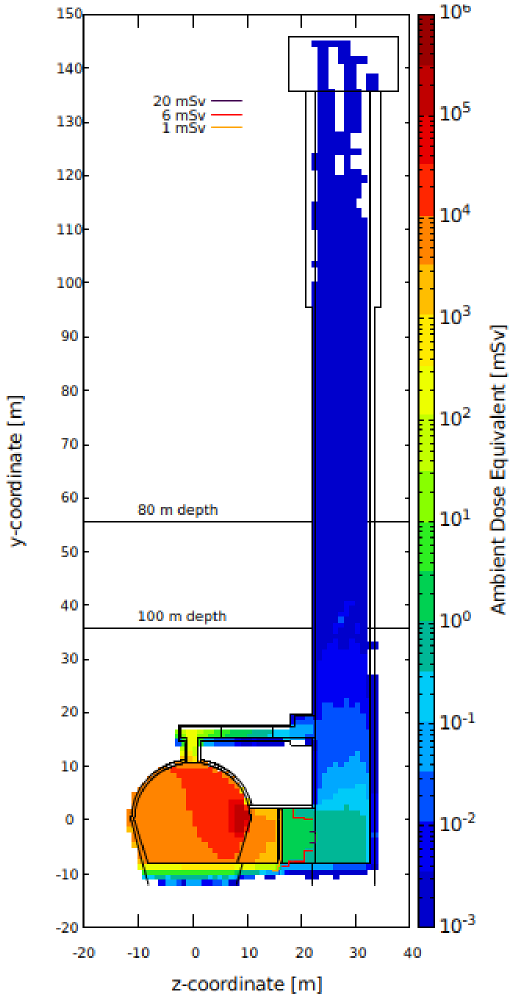


PX46 – P4 Support shaft

Depth 143m, diameter 10.10m

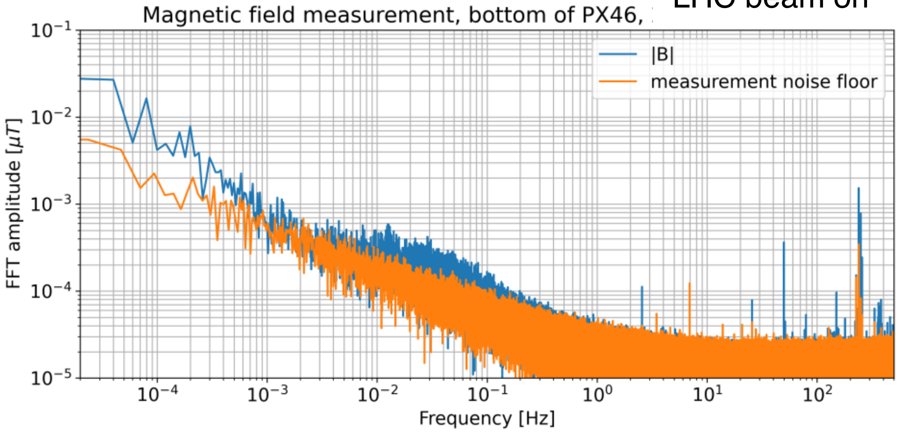


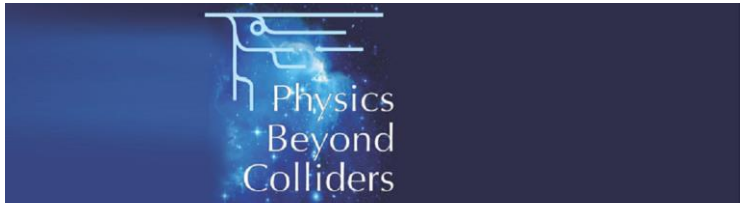
Dose equivalent – case of beam loss
Shielding wall at the bottom of TX46



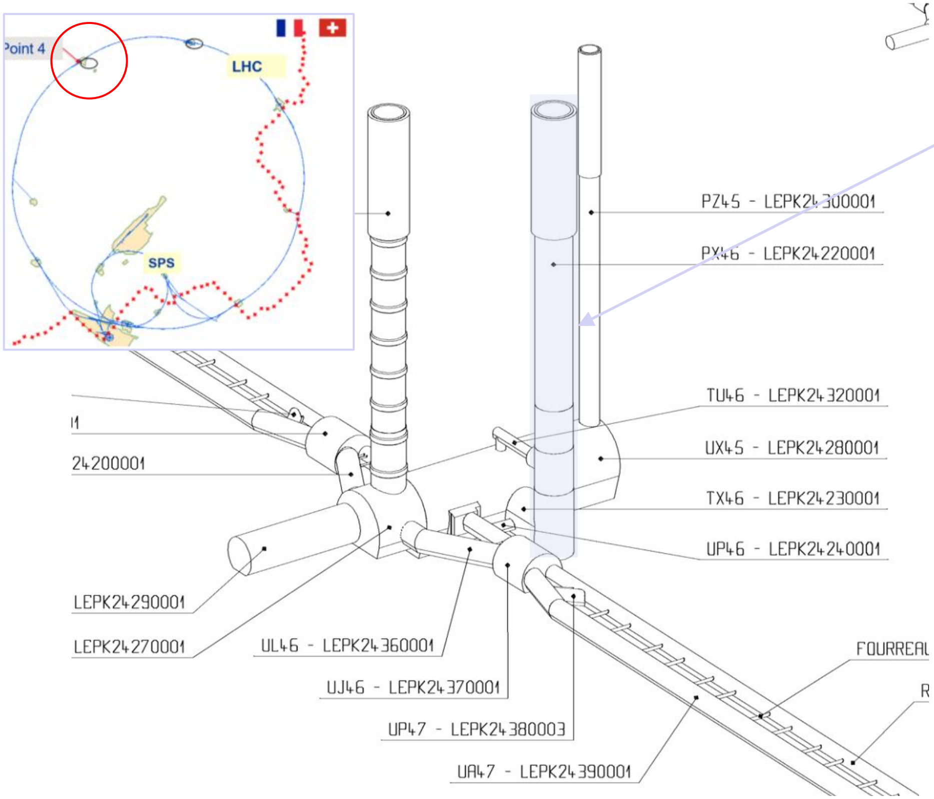
Safety, access, evacuation, etc.: demonstrated feasibility for 365d/y 24h24 access and AION operation, also when the LHC beam is on

LHC beam on

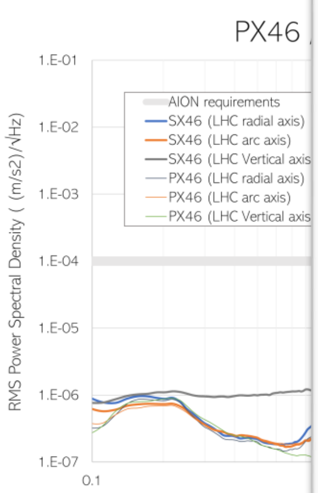


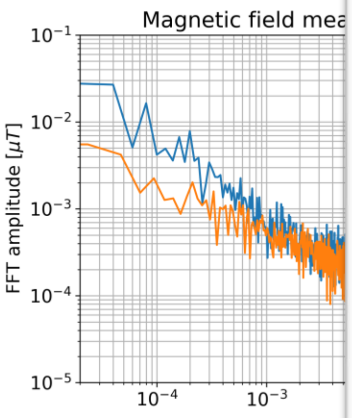


Possible site for a vertical VLBAI a… pt.4

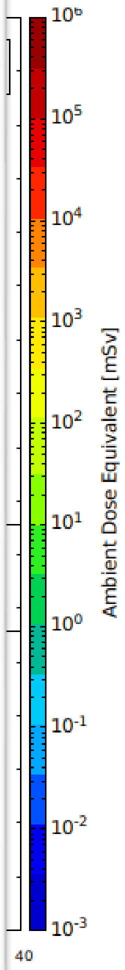


PX46 – P…
Depth 143n…





…eam loss
…of TX46



Safety, access, evacuation, etc.: demonstrated feasibility for 365d/y 24h24 access and AION operation, also when the LHC beam is on

Physics Beyond Colliders

CERN | Physics Beyond Colliders

CERN-PBC Report-2023-002

A Long-Baseline Atom Interferometer at CERN: Conceptual Feasibility Study

G. Arduini[1,], L. Badurina[2], K. Balazs[1], C. Baynham[3], O. Buchmueller[3,4,*], M. Buzio[1], S. Calatroni[1,*], J.-P. Corso[1], J. Ellis[1,2,*], Ch. Gaignant[1], M. Guinchard[1], T. Hakulinen[1], R. Hobson[3], A. Infantino[1], D. Lafarge[1], R. Langlois[1], C. Marcel[1], J. Mitchell[5], M. Parodi[1], M. Pentella[1], D. Valuch[1], H. Vincke[1]*

[1] CERN, [2] King's College London, [3] Imperial College London, [4] University of Oxford, [5] University of Cambridge
[*] Editors

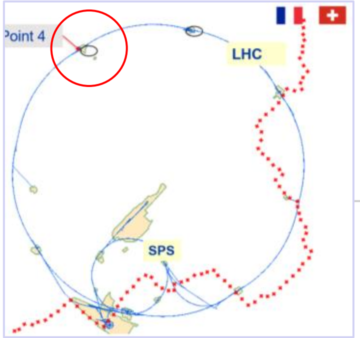
Abstract

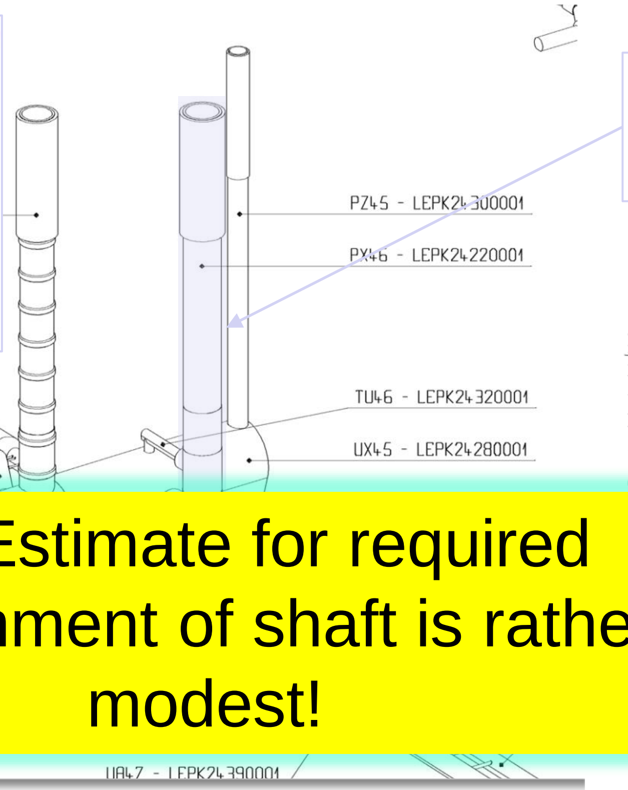
We present results from exploratory studies, supported by the Physics Beyond Colliders (PBC) Study Group, of the suitability of a CERN site and its infrastructure for hosting a vertical atom interferometer (AI) with a baseline of about 100 m. We first review the scientific motivations for such an experiment to search for ultralight dark matter and measure gravitational waves, and then outline the general technical requirements for such an atom interferometer, using the AION-100 project as an example. We present a possible CERN site in the PX46 access shaft to the Large Hadron Collider (LHC), including the motivations for this choice and a description of its infrastructure. We then assess its compliance with the technical requirements of such an experiment and what upgrades may be needed. We analyse issues related to the proximity of the LHC machine and its ancillary hardware and present a preliminary safety analysis and the required mitigation measures and infrastructure modifications. In conclusion, we identify primary cost drivers and describe constraints on the experimental installation and operation schedules arising from LHC operation. We find no technical obstacles: the CERN site is a very promising location for an AI experiment with a vertical baseline of about 100 m.

Geneva, Switzerland

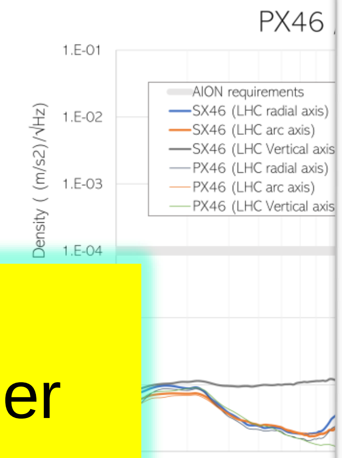
August 7, 2023

Possible site for a vertical VLBAI a... pt.4





PX46 – P...
Depth 143m...

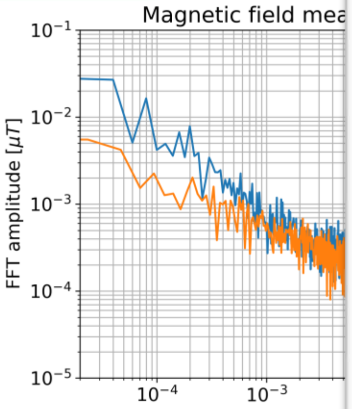


Cost Estimate for required refurbishment of shaft is rather modest!

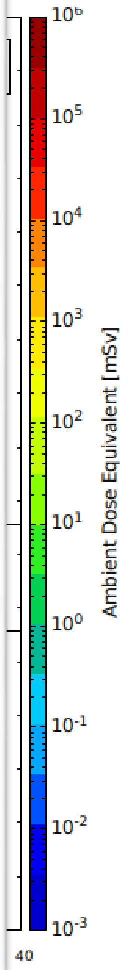
Safet... feasi... opera...

Item	Cost [kCHF]
Shielding	400
Lifting platform	400
Access, safety systems and monitoring	200
General services and utilities	500
Total	**1500**

Physics Beyond Colliders



...eam loss ...of TX46



CERN Physics Beyond Colliders

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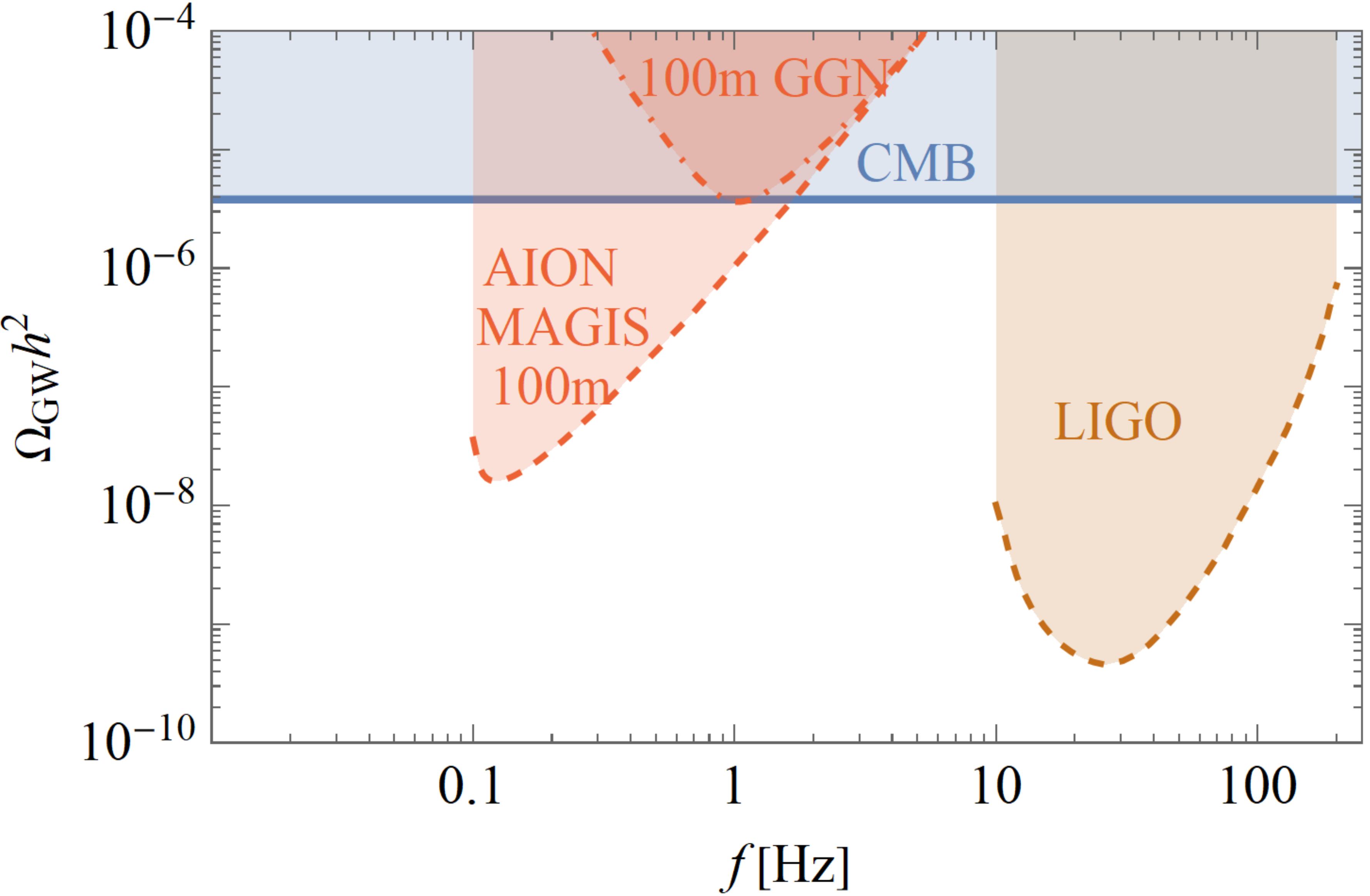
Geneva, Switzerland

August 7, 2023

AION

Possible GW Experimental Landscape: 2030ish

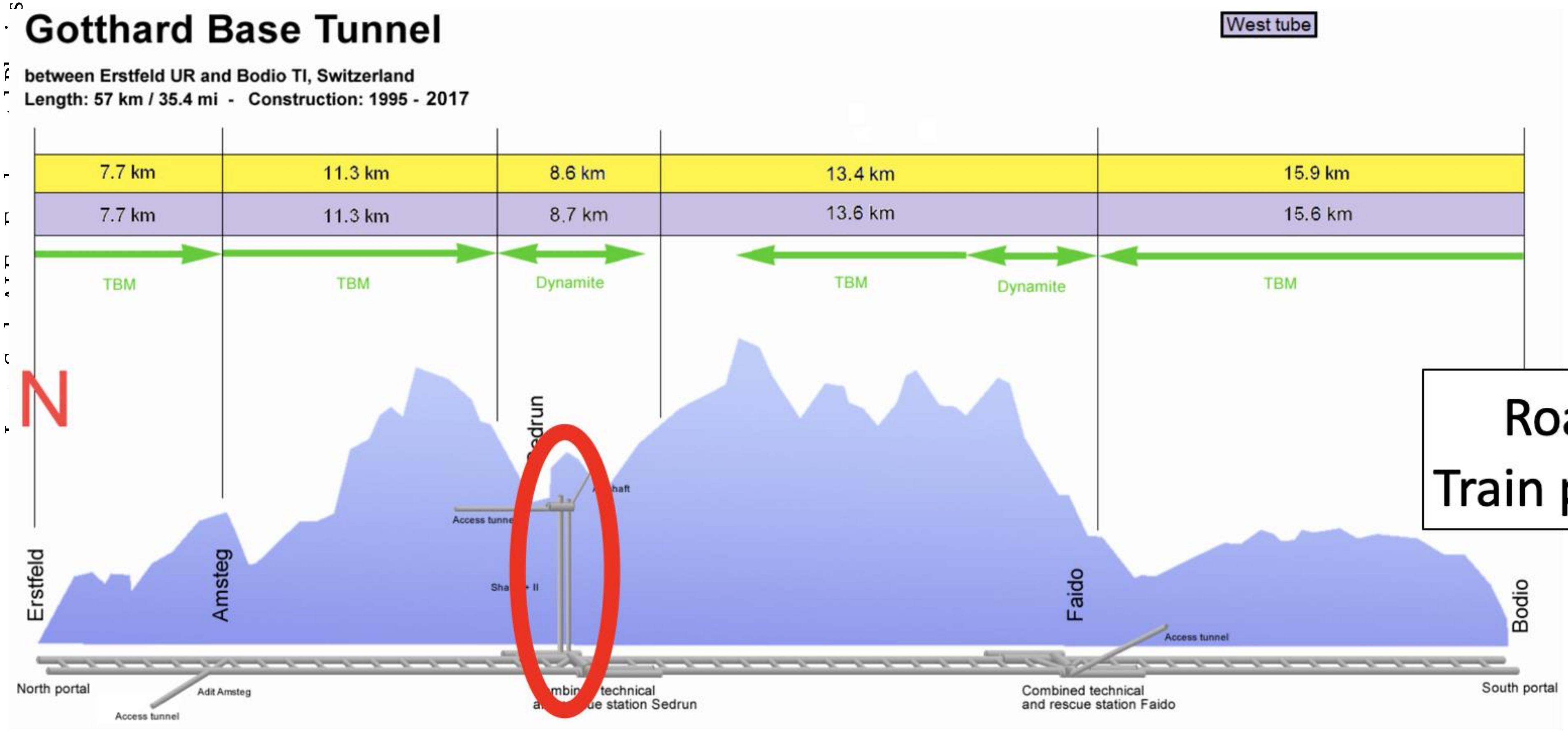


Besides probing a large range of new Ultra-Light DM parameter space, a ~100m experiment could also explore new territory for gravitational waves in a yet unexplored frequency range.

Possible site for an 800m vertical VLBAI in the Swiss Alps

Porta Alpina

A pair of 800m vertical shafts down to the Gotthard base railway tunnel, with a 1km horizontal access tunnel

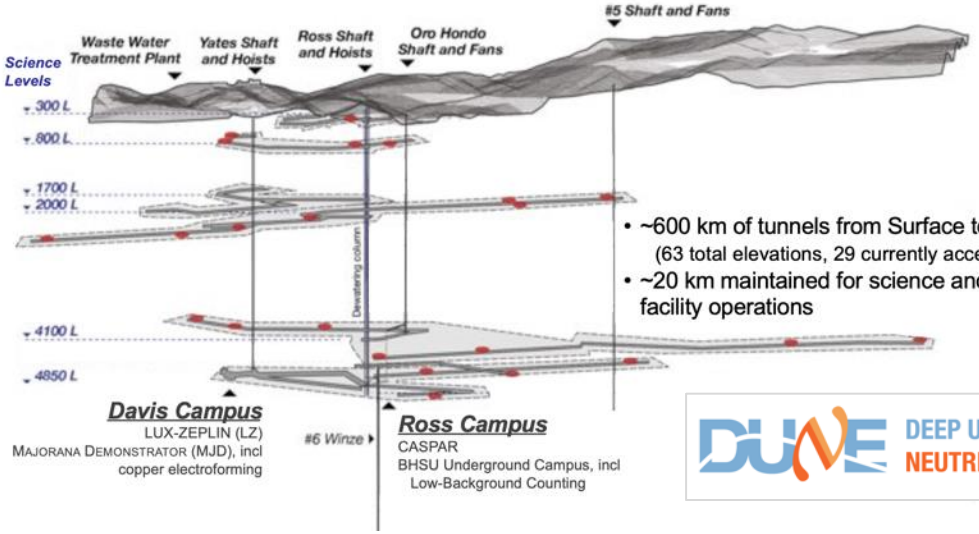


Road access at top

Train platform at bottom

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

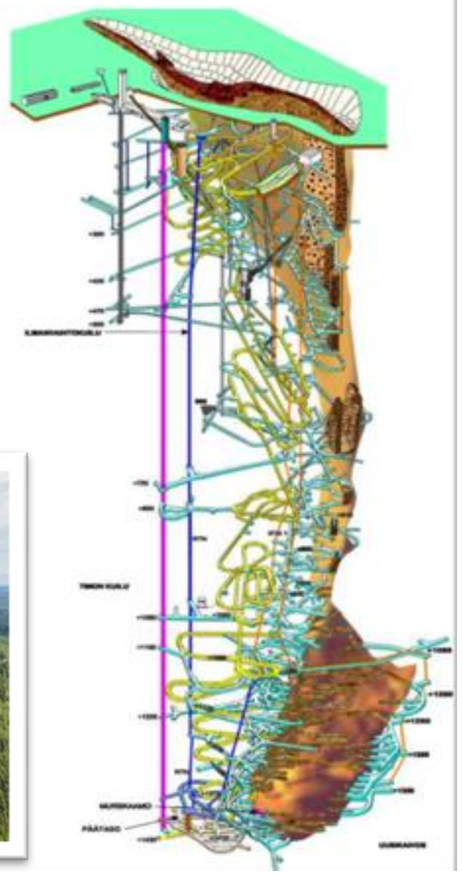
CALLIO LAB
Underground Center for Science and R & D

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
Marilù Chiofalo, University of Pisa and INFN Pisa, Italy
John Ellis, King's College London, UK
Naceur Gaaloul, Leibniz Universität Hannover, Germany
Jason Hogan, Stanford University, US
Timothy Kovachy, Northwestern University
Ernst Rasel, Leibniz Universität Hannover, Germany
Guglielmo Tino, Università di Firenze and LENS, Italy
Wolf von Klitzing, IESL-FORTH, Greece
Mingsheng Zhan, Wuhan Institute of Physics and Mathematics, China

Local Organisation Committee

Gianluigi Arduini, CERN, Geneva, Switzerland
Sergio Calatroni, CERN, Geneva, Switzerland
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
Oliver Buchmueller, Imperial College London, UK
Sergio Calatroni, CERN, Geneva, Switzerland
Benjamin Canuel, CNRS, Institut d'Optique, France
Marilù Chiofalo, University of Pisa and INFN Pisa, Italy
Michael Doser, CERN, Geneva, Switzerland
John Ellis, King's College London, UK
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Local Organisation Committee

Charles Baynham, Imperial College London, UK
Oliver Buchmueller, Imperial College London, UK
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

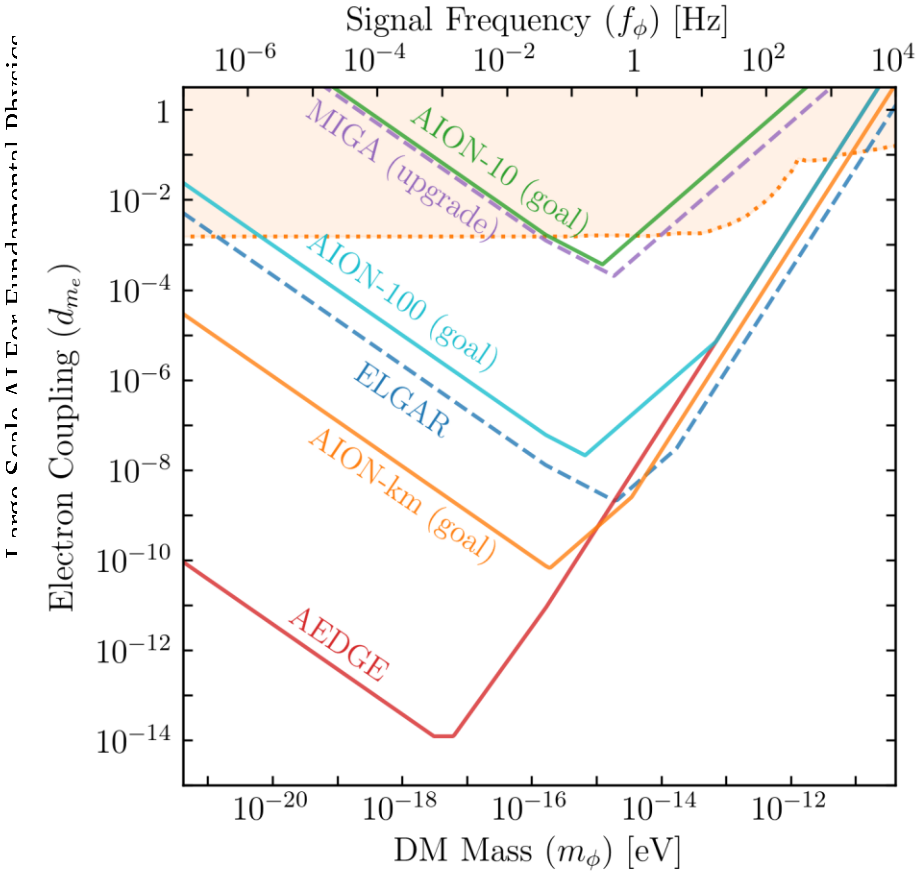
Imperial College London

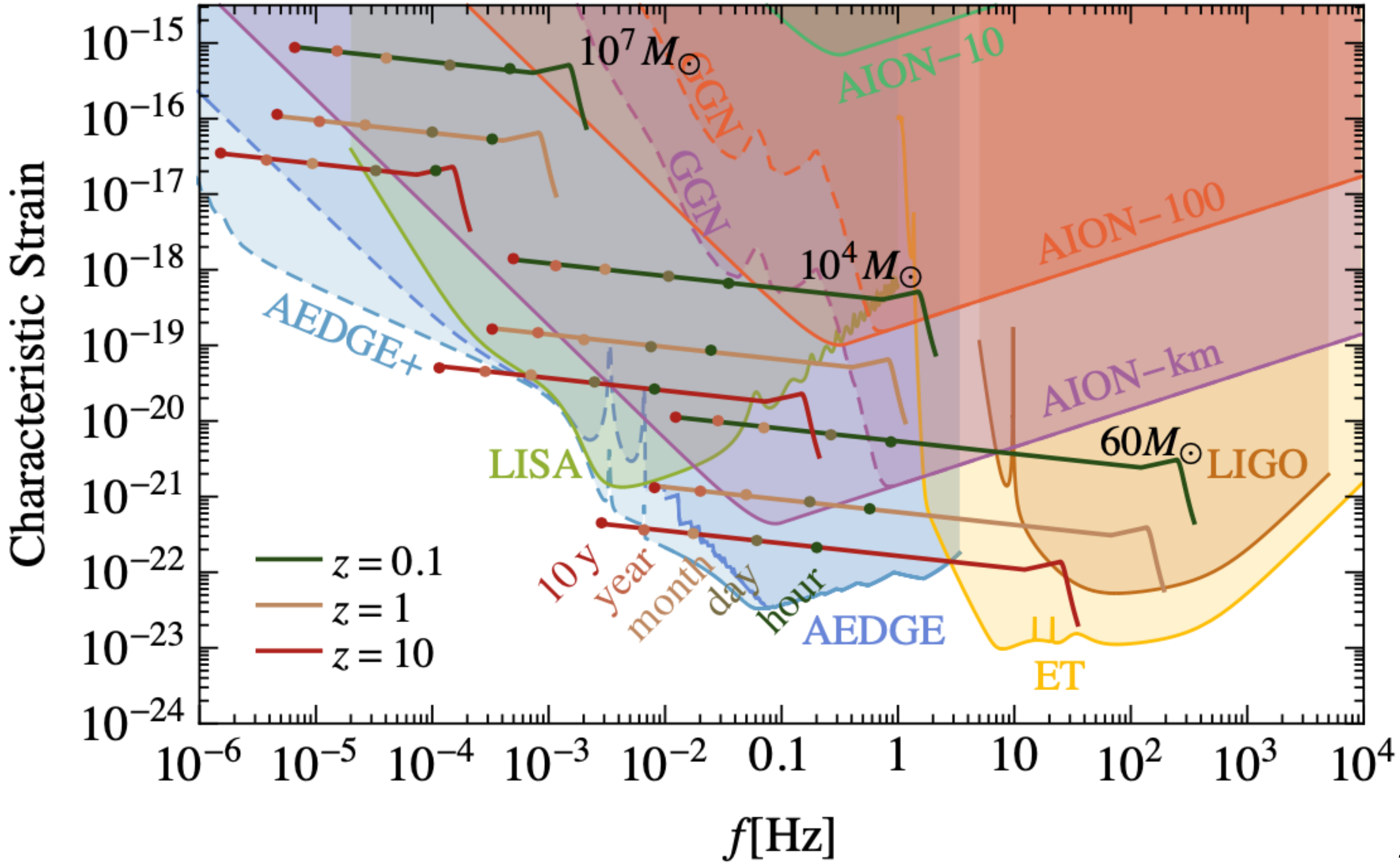
Information

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





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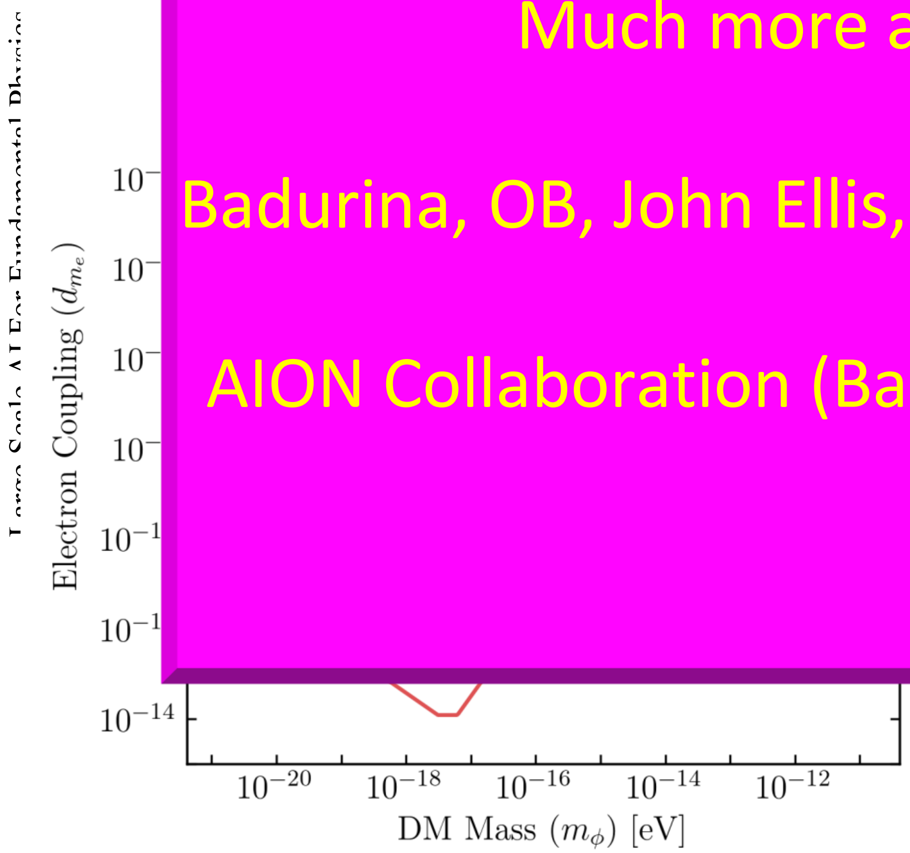
Unlocking the potential for observation of Ultra-Light Dark Matter and Gravitational Waves from cosmological and astrophysical sources in the unexplored mid-frequency band

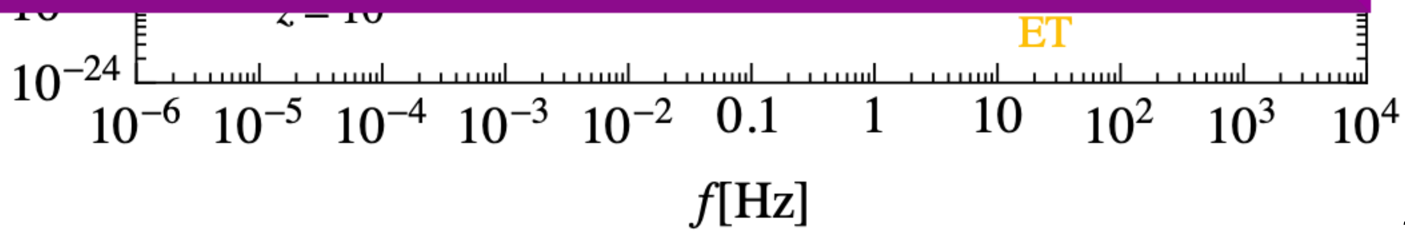
Much more about the general GW science case in:

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

and

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





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.
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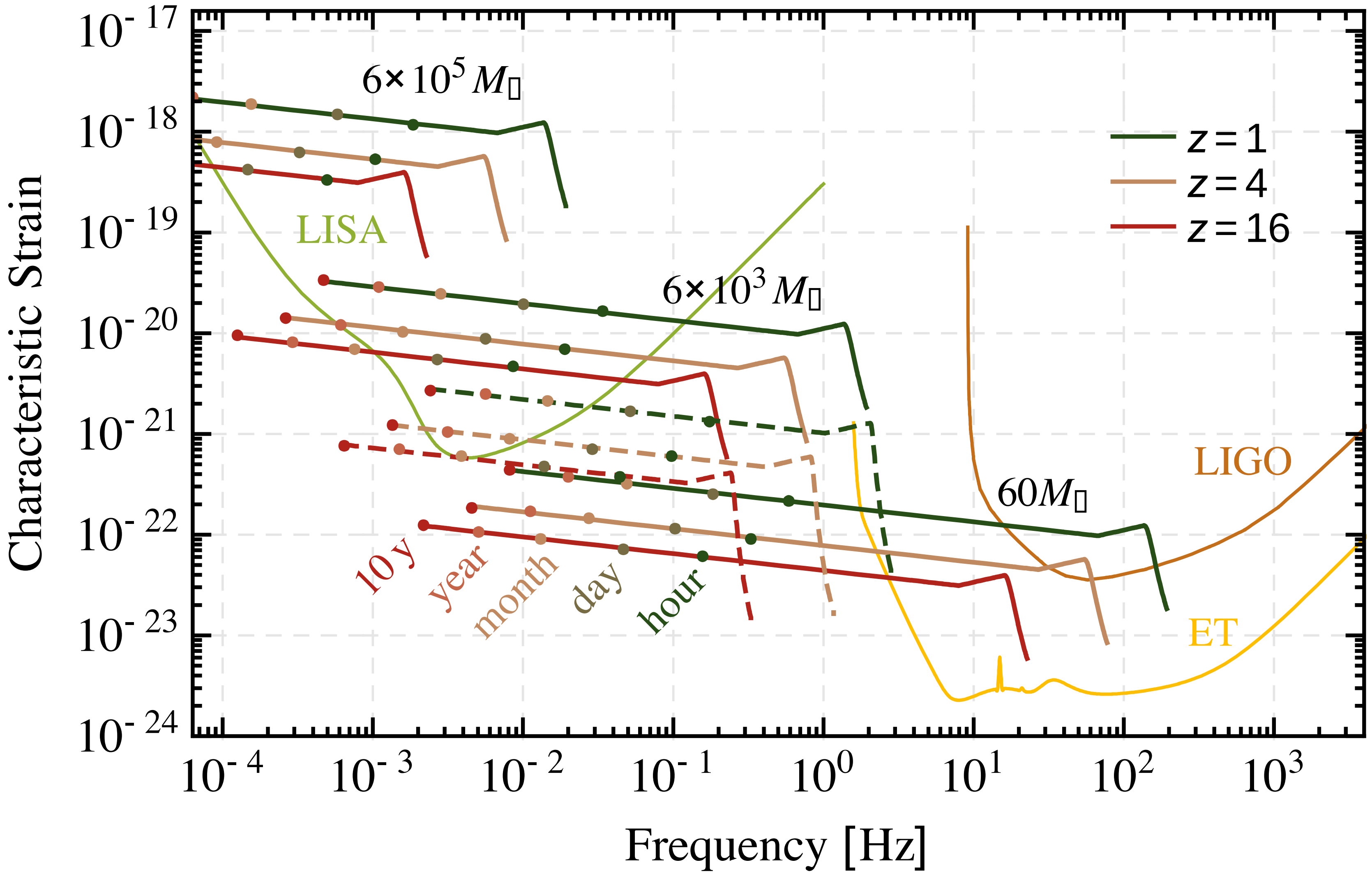
- Probes of basic physical principles such as foundations of quantum mechanics and Lorentz invariance.

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

THE SCIENCE CASE

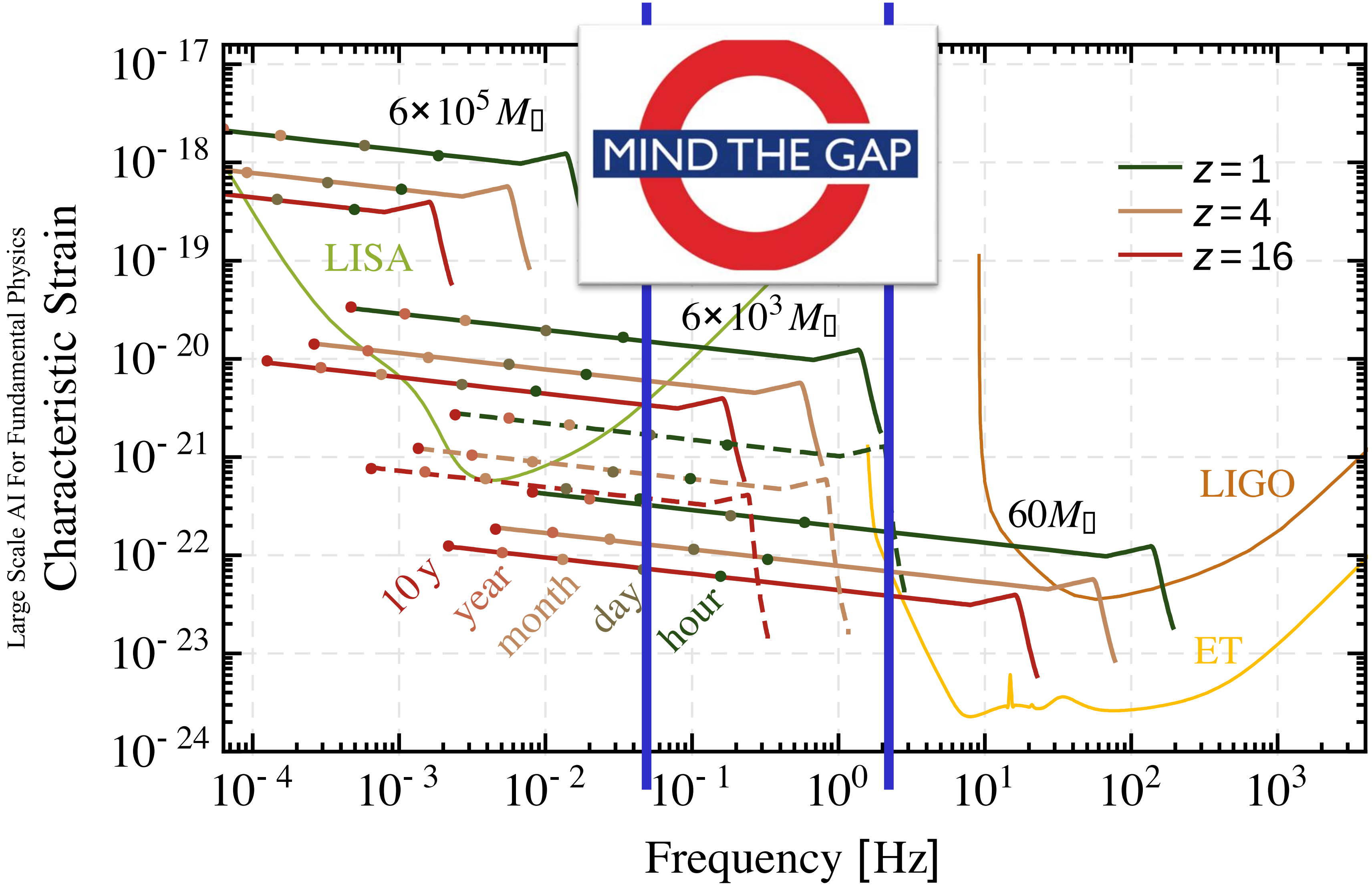
UNEXPLORED MID-FREQUENCY GRAVITATIONAL WAVES

Pathway to the GW Mid-(Frequency)



Large Scale AI For Fundamental Physics

Pathway to the GW Mid-(Frequency)

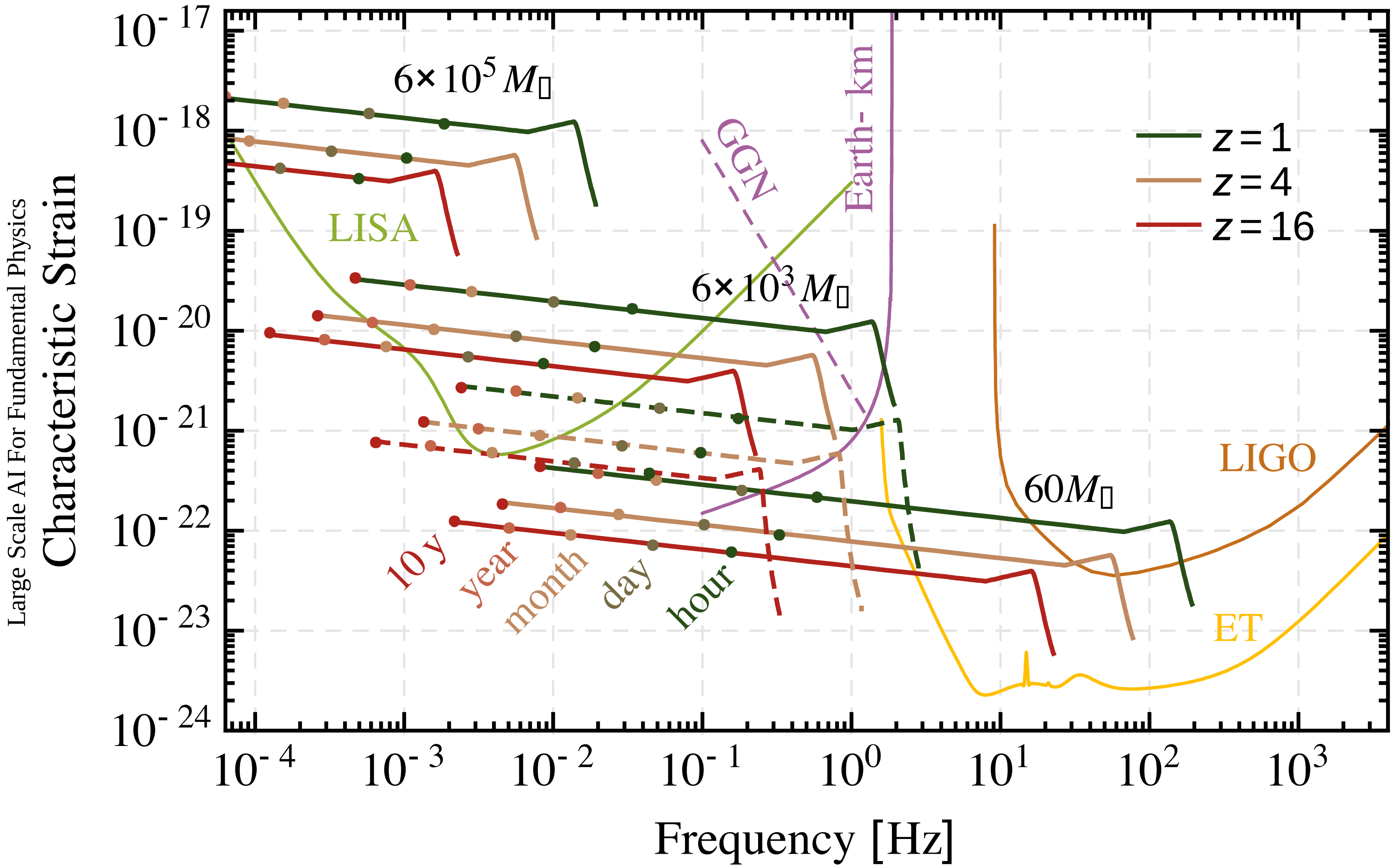


Mid-band science

- 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

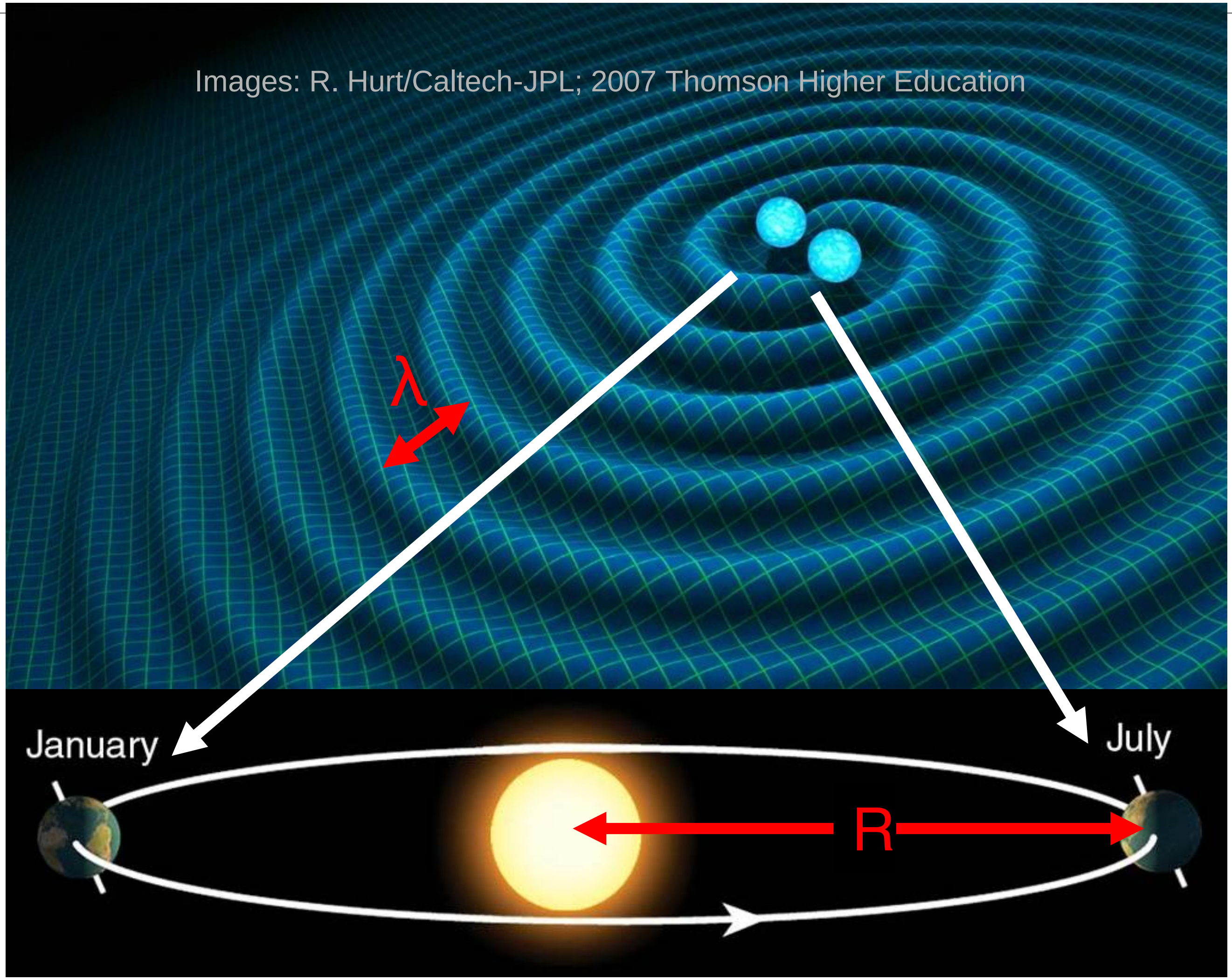
Sky localization precision:

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

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

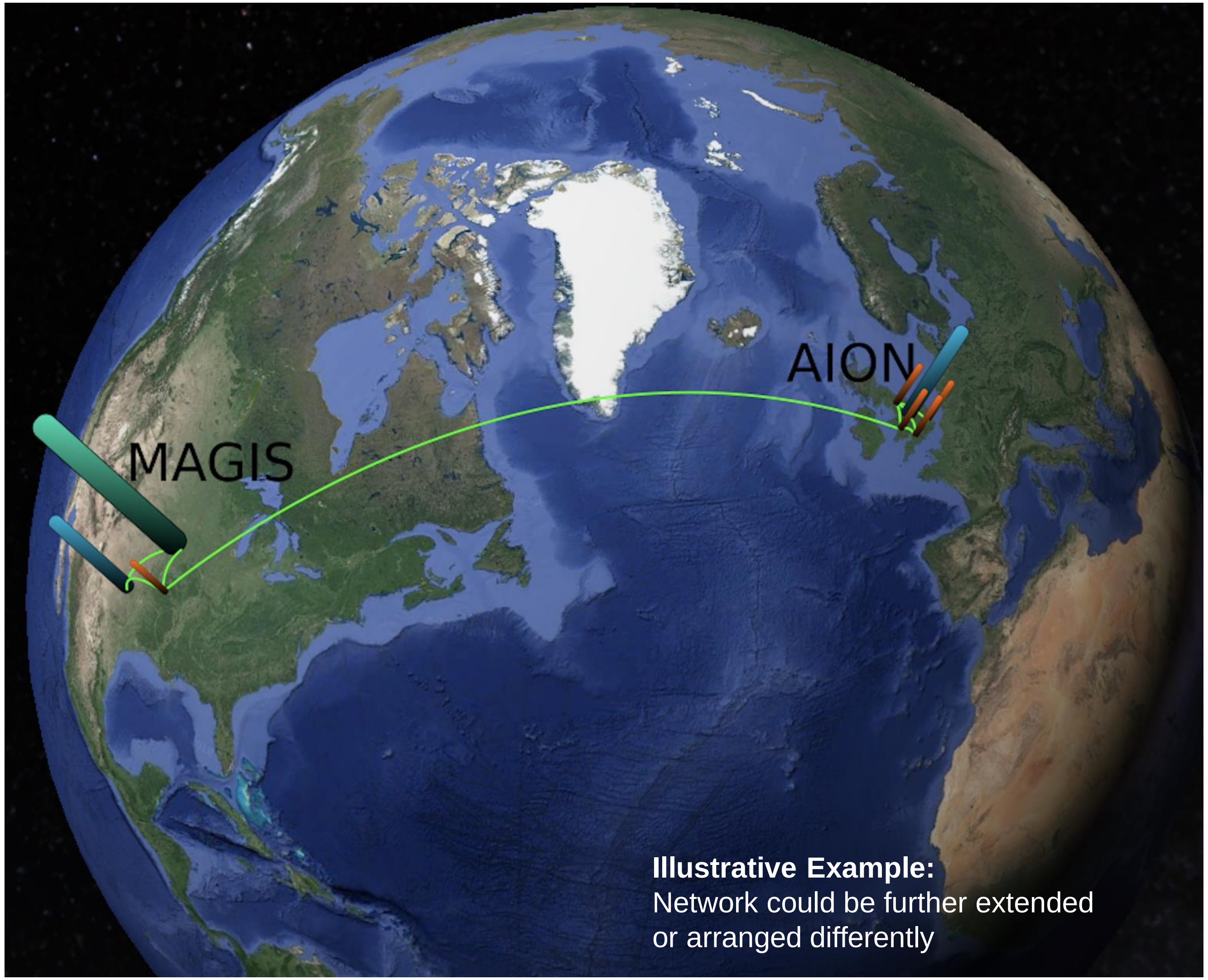
Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19

Courtesy of Jason Hogan!



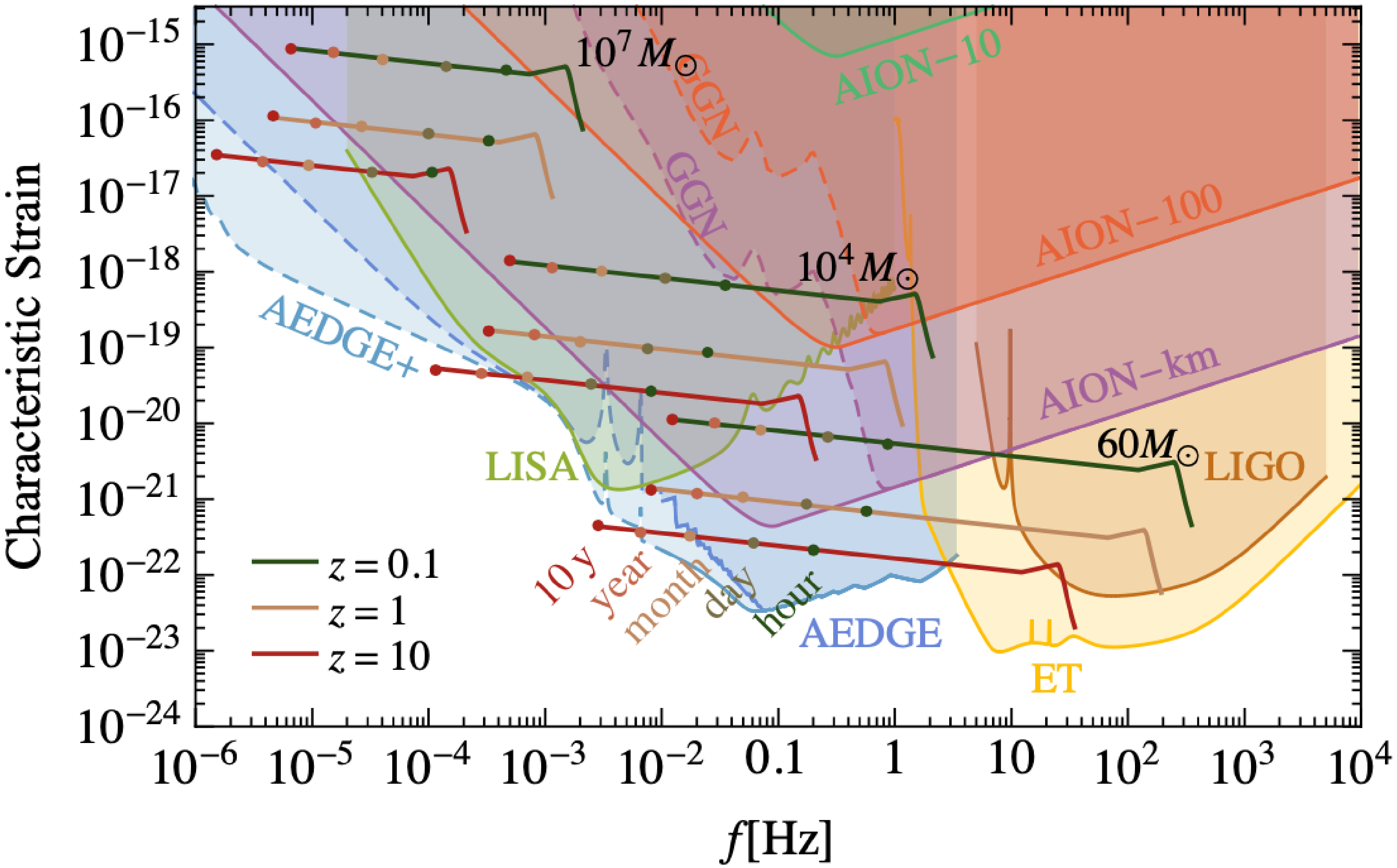
Ultimate sensitivity for terrestrial based detectors is achieved by operating 2 (or more) Detectors in synchronisation mode

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

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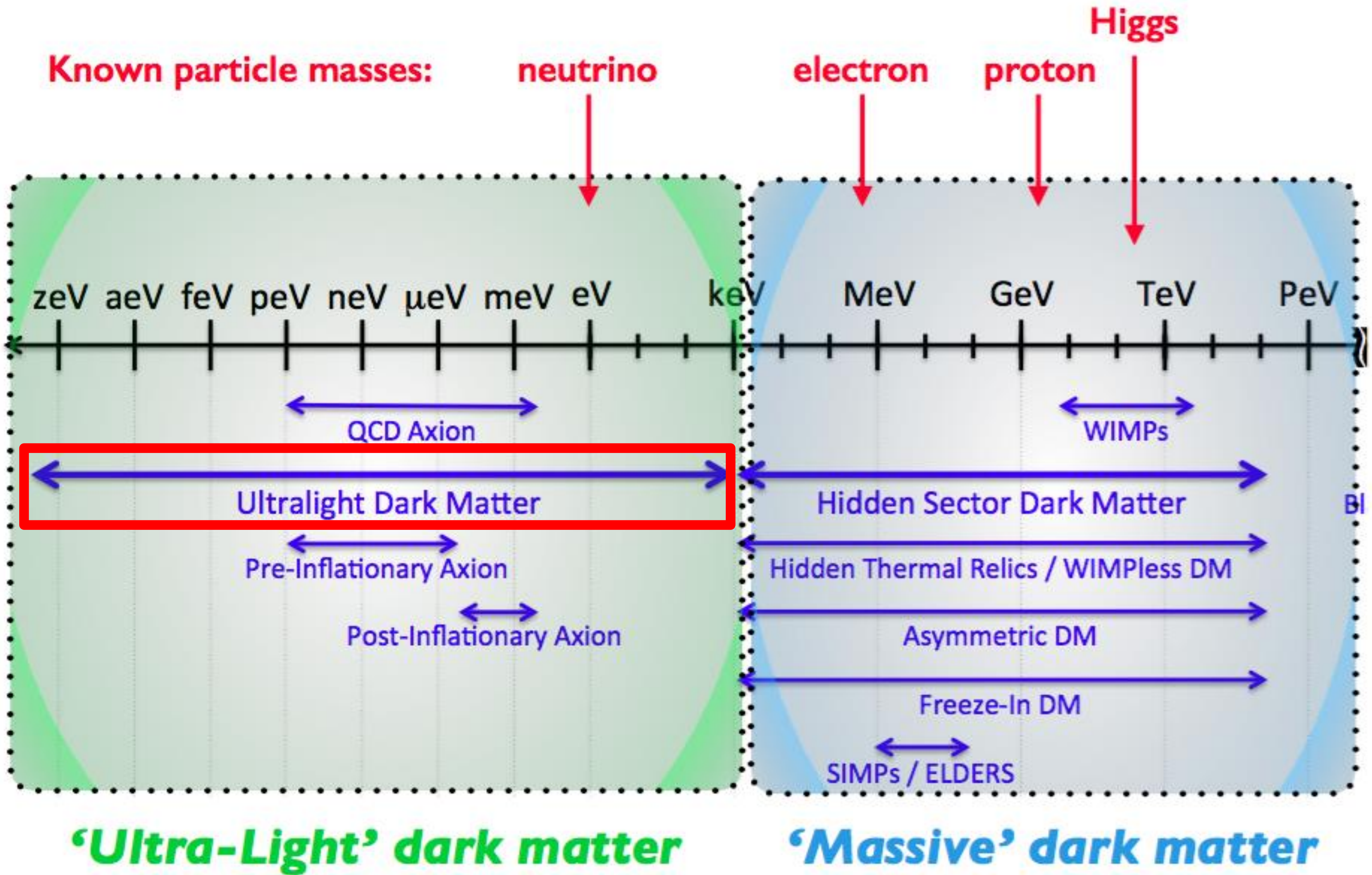
ULTRA-LIGHT DARK MATTER

Search for Ultra-Light Dark Matter



The Landscape of Ultra-Light Dark Matter Detection

Vey light dark matter and gravitational wave detection similar when detecting coherent effects of entire field, not single particles.

Example: Ultra-Light Dark Matter:

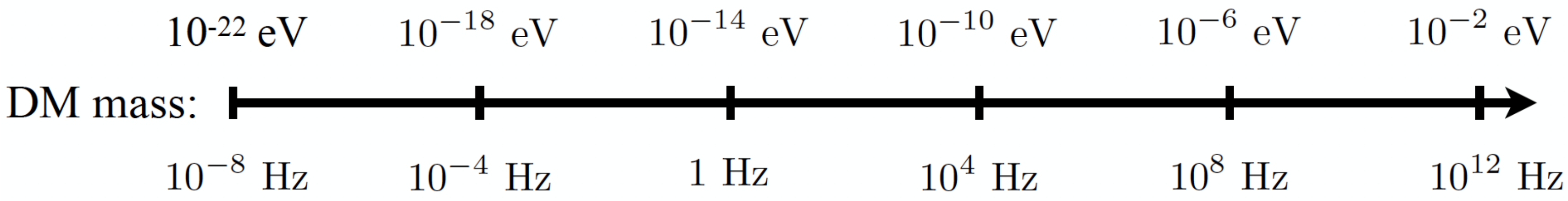


Diagram taken from P. Graham's talk at HEP Front 2018

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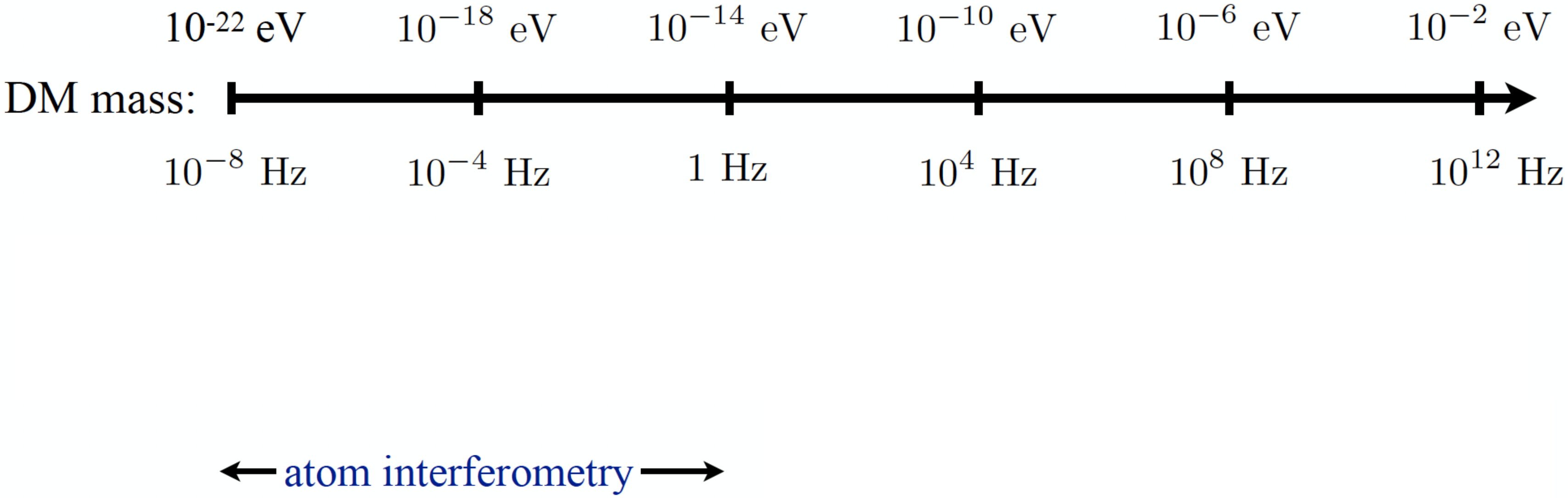

MAGIS/AION

Diagram taken from P. Graham's talk at HEP Front 2018

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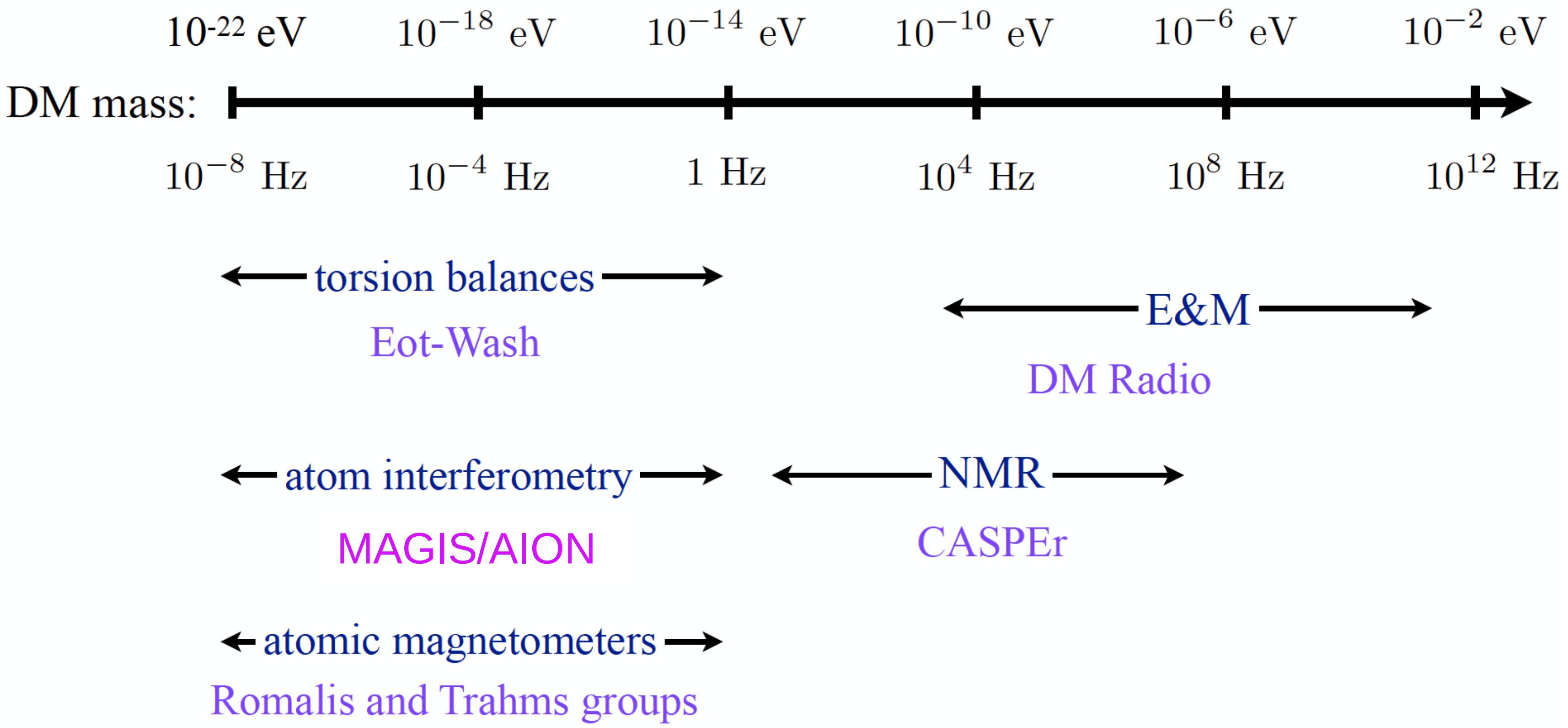


Diagram taken from P. Graham's talk at HEP Front 2018

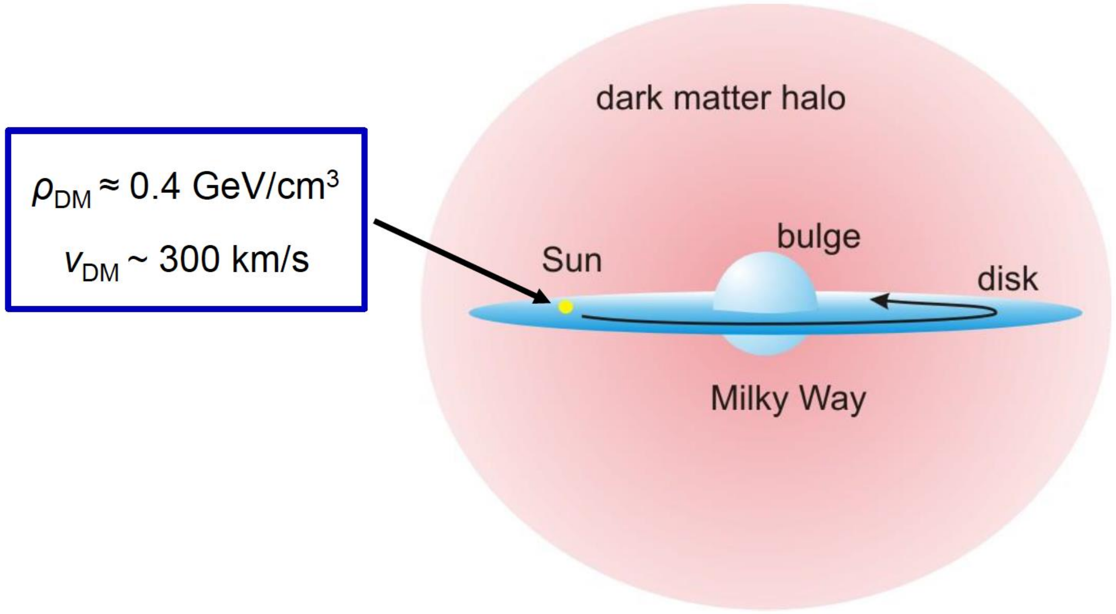
Ultra-Light Spin-0 Dark Matter

Ultra-light spin 0 particles are expected to form a coherently oscillating classical field

$$\phi(t) = \phi_0 cos(E_\phi t/\hbar)$$

as $E_\phi \approx m_\phi c^2$ with an energy density of

$$< \rho_\phi > \approx m_\phi^2 \phi_0^2/2 \; (\rho_{DM,local} \approx 0.4 \text{ GeV}/\text{cm}^3).$$



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

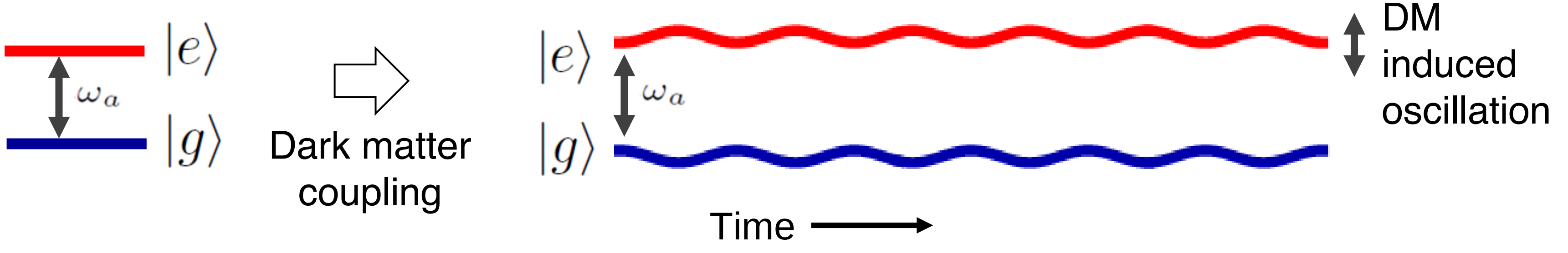
e.g., QCD

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

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

DM mass density

DM coupling causes time-varying atomic energy levels:

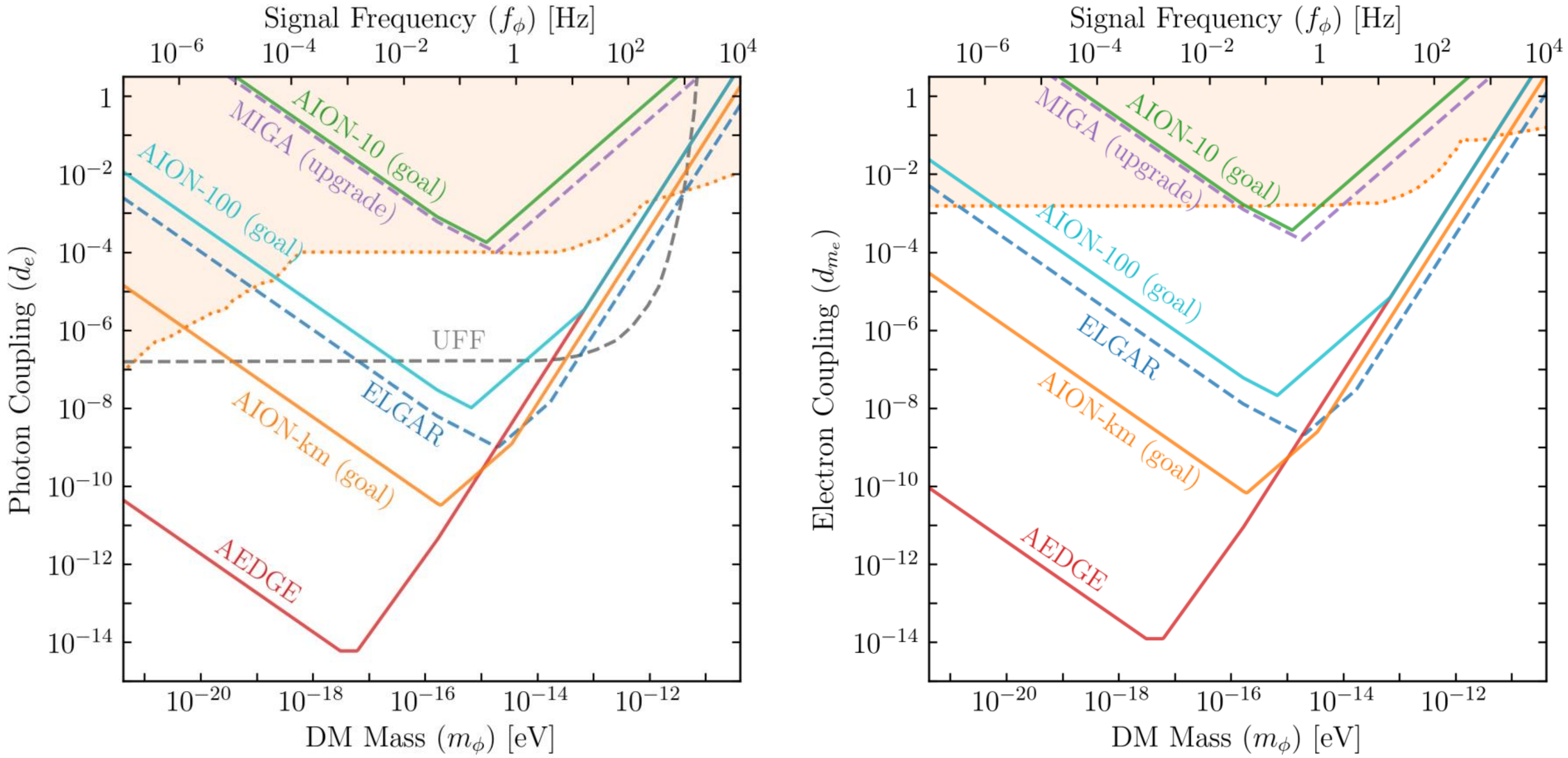


Courtesy of Jason Hogan!

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

GRAVITATIONAL WAVES

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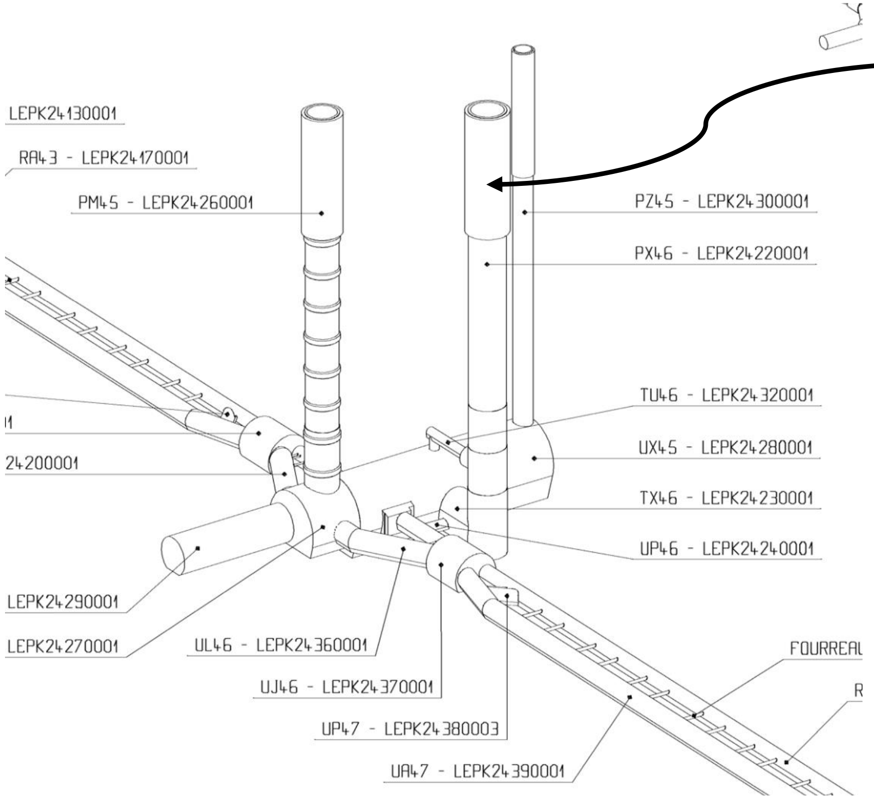
- *Probes of long-range fifth forces*.
- *Constraining possible variations in fundamental constants.*
- *Probing dark energy*.
- Probes of basic physical principles such as foundations of quantum mechanics and Lorentz invariance.

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

BACKUP

Possible CERN Site for AION 100m



PX46 – P4 Support shaft

Lengths 143m

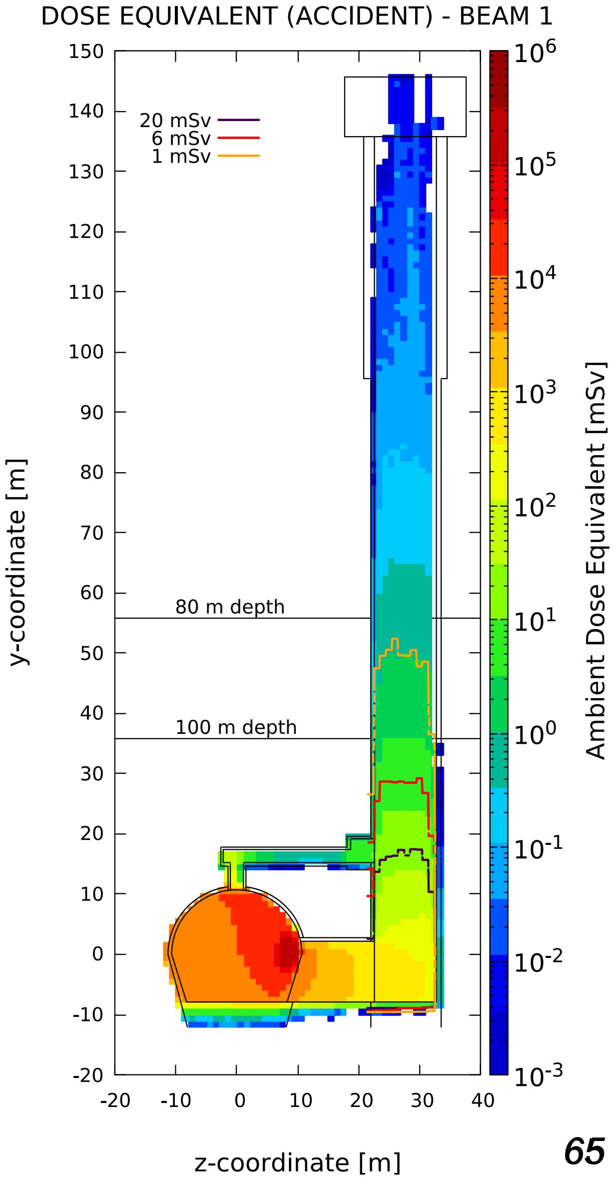
D = 10.10m

- **Ideal basic parameters for AION100**

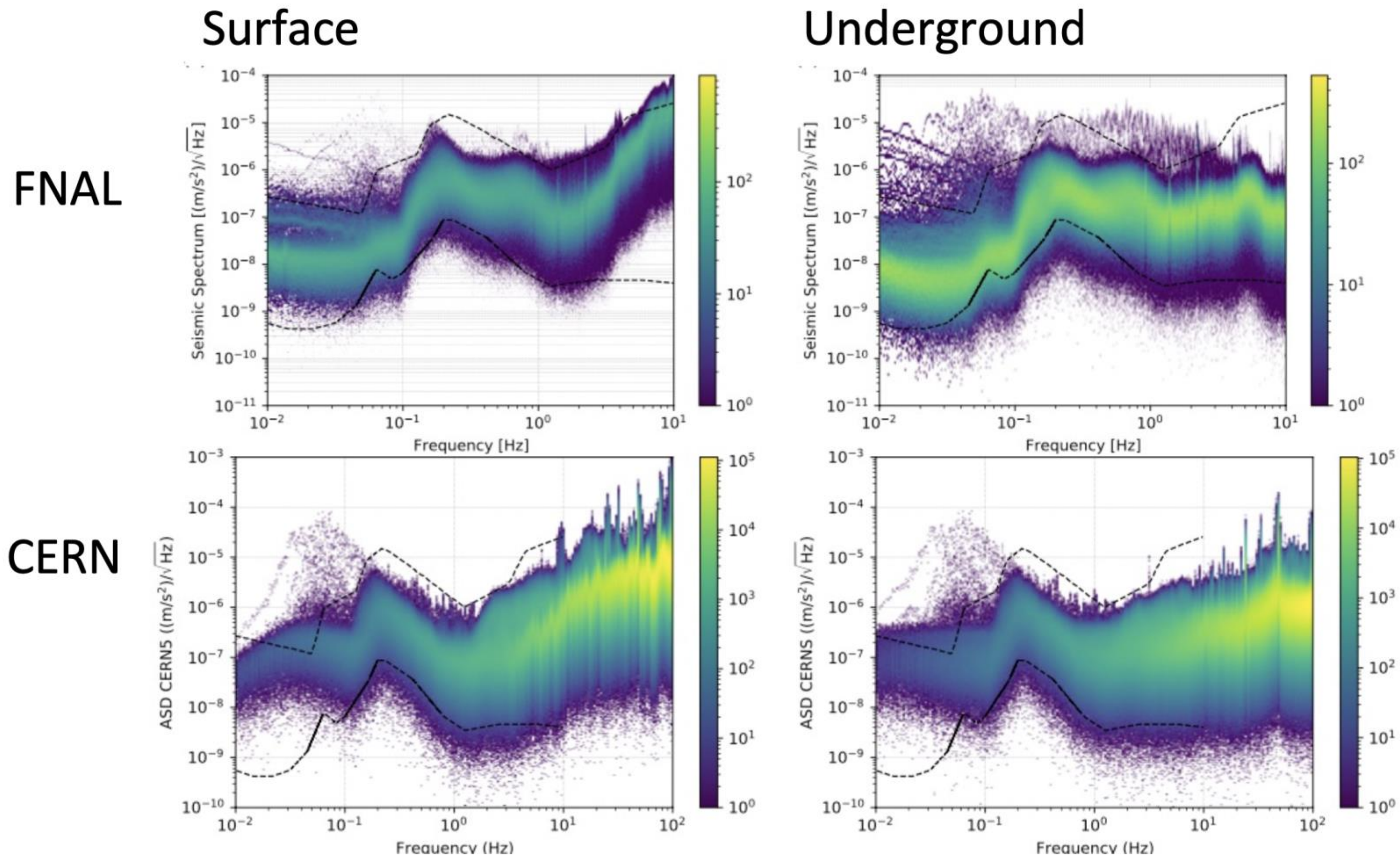
First radiation studies are also Looking promising but more work is needed to determine if PX46 could be a valid option for AION 100.

We are working with PBC Team on this feasibility study

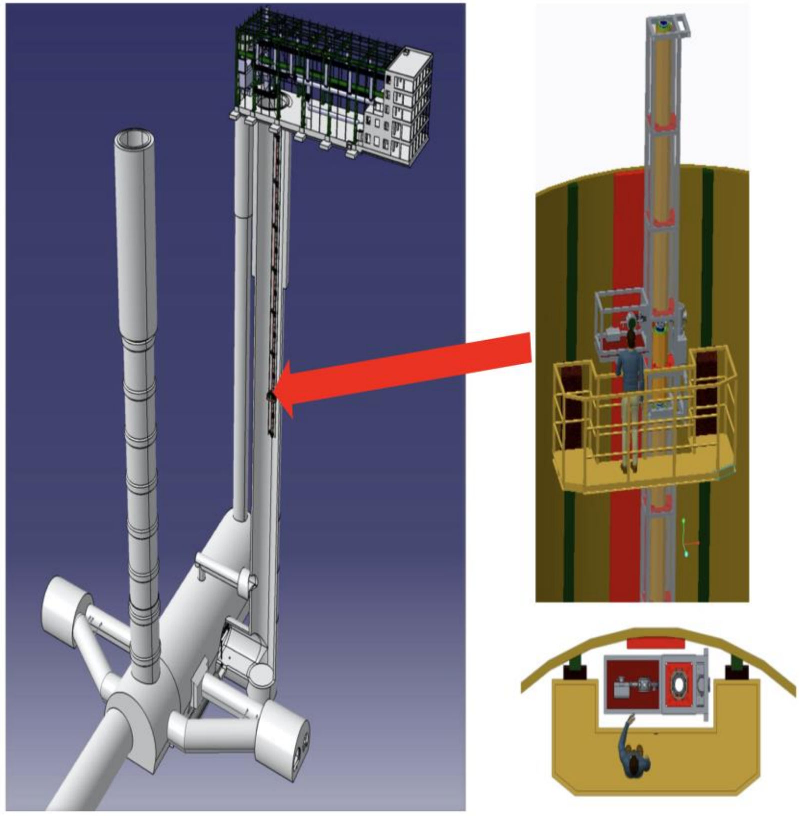
Other site options that are currently investigated are the **national facility in Boulby and Daresbury (UK).**



A 100 Detector at CERN – Site Investigation



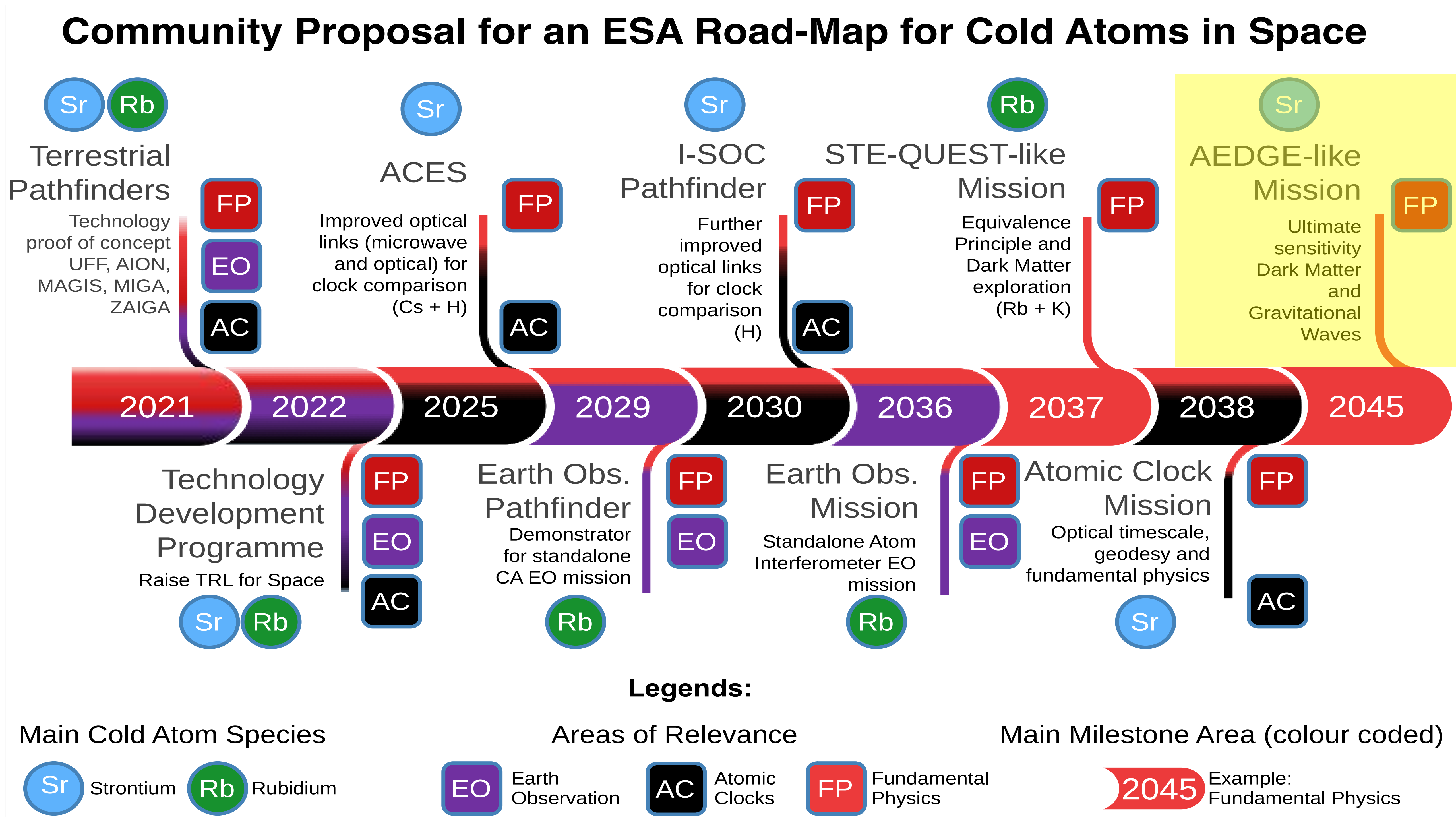
General view of LHC Point 4 Possible layout in PX46 shaft



Spectrum similar to that measured at Fermilab for MAGIS

More about the site investigation in the backup

AEDGE AND STE-QUEST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Main Milestone Area (colour coded)
2045 Example: Fundamental Physics

AEDGE:
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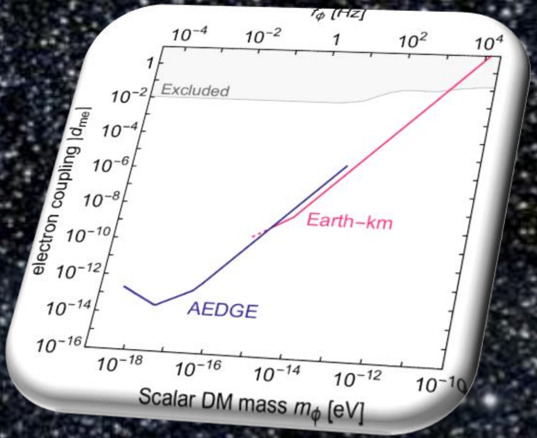

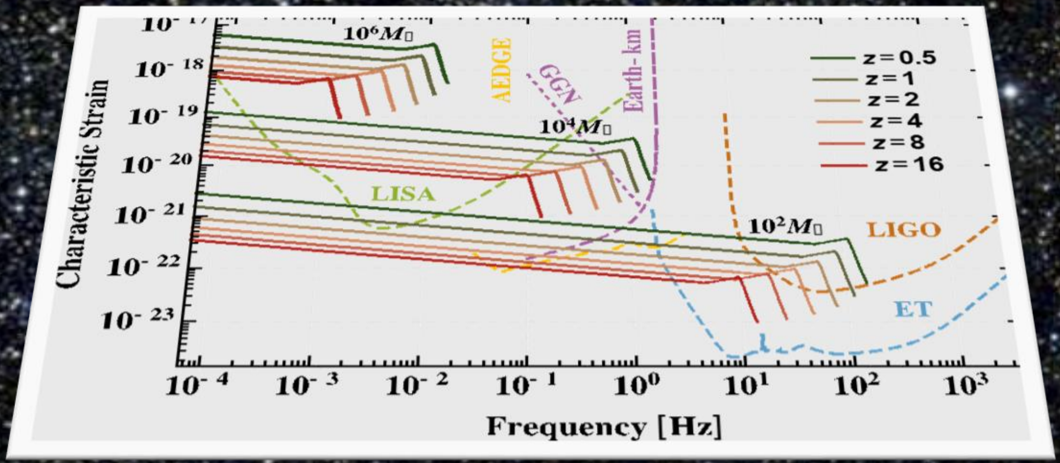

Informal Workshop
CERN, July 22/23 2019

Organizers:
Kai Bongs(CA), Philippe Bouyer(CA), Oliver Buchmueller(PP),
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Jason Hogan (CA), Wolf von Klitzing(CA), Guglielmo Tino(CA), and AtomQT
PP=Particle Physics
CA=Cold Atoms

AEDGE:
Atomic Experiment for Dark Matter and Gravity Exploration

With more than 130 participants the workshop was very well attended!

The full agenda can be accessed via:
https://indico.cern.ch/event/830432/timetable/

The main scope was to review the landscape of Cold Atom experiments on ground AND in space to eventually establish a roadmap for technology readiness for space.

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AEDGE Mission Concept

AEDGE:
Atomic Experiment for Dark Matter and Gravity Exploration in Space

Yousef Abou El-Neaj,[1] Cristiano Alpigiani,[2] Sana Amairi-Pyka,[3] Henrique Araújo,[4] Antun Balaž,[5] Angelo Bassi,[6] Lars Bathe-Peters,[7] Baptiste Battelier,[8] Aleksandar Belić,[5] Elliot Bentine,[9] José Bernabeu,[10] Andrea Bertoldi,[8,*] Robert Bingham,[11] Diego Blas,[12] Vasiliki Bolpasi,[13] Kai Bongs,[14,*] Sougato Bose,[15] Philippe Bouyer,[8,*] Themis Bowcock,[16] William Bowden,[17] Oliver Buchmueller,[4,@] Clare Burrage,[18] Xavier Calmet,[19] Benjamin Canuel,[8,*] Laurentiu-Ioan Caramete,[20,*] Andrew Carroll,[16] Giancarlo Cella,[21,22] Vassilis Charmandaris,[23] Swapan Chattopadhyay,[24,25] Xuzong Chen,[26] Maria Luisa Chiofalo,[21,22] Jonathon Coleman,[16,*] Joseph Cotter,[4] Yanou Cui,[27] Andrei Derevianko,[28] Albert De Roeck,[29,30,*] Goran Djordjevic,[31] Peter Dornan,[4] Michael Doser,[30] Ioannis Drougkakis,[13] Jacob Dunningham,[19] Ioana Dutan,[20] Sajan Easo,[11] Gedminas Elertas,[16] John Ellis,[12,32,33,*] Mai El Sawy,[34] Farida Fassi,[35] Daniel Felea,[20] Chen-Hao Feng,[8] Robert Flack,[15] Chris Foot,[9] Ivette Fuentes,[18] Naceur Gaaloul,[36] Alexandre Gauguet,[37] Remi Geiger,[38] Valerie Gibson,[39] Gian Giudice,[33] Jon Goldwin,[14] Oleg Grachov,[40] Peter W. Graham,[41,*] Dario Grasso,[21,22] Maurits van der Grinten,[11] Mustafa Gündogan,[3] Martin G. Haehnelt,[42,*] Tiffany Harte,[39] Aurélien Hees,[38,*] Richard Hobson,[17] Bodil Holst,[43] Jason Hogan,[41,*] Mark Kasevich,[41] Bradley J. Kavanagh,[44] Wolf von Klitzing,[13,*] Tim Kovachy,[45] Benjamin Krikler,[46] Markus Krutzik,[3,*] Marek Lewicki,[12,47,*] Yu-Hung Lien,[15] Miaoyuan Liu,[26] Giuseppe Gaetano Luciano,[48] Alain Magnon,[49] Mohammed Mahmoud,[50] Sarah Malik,[4] Christopher McCabe,[12,*] Jeremiah Mitchell,[24] Julia Pahl,[3] Debapriya Pal,[13] Saurabh Pandey,[13] Dimitris Papazoglou,[51] Mauro Paternostro,[52] Bjoern Penning,[53] Achim Peters,[3,*] Marco Prevedelli,[54] Vishnupriya Puthiya-Veettil,[55] John Quenby,[4] Ernst Rasel,[36,*] Sean Ravenhall,[9] Haifa Rejeb Sfar,[29] Jack Ringwood,[16] Albert Roura,[56,*] Dylan Sabulsky,[8,*] Muhammed Sameed,[57] Ben Sauer,[4] Stefan Alaric Schäffer,[58] Stephan Schiller,[59,*] Vladimir Schkolnik,[3] Dennis Schlippert,[36] Christian Schubert,[3,*] Armin Shayeghi,[60] Ian Shipsey,[9] Carla Signorini,[21,22] Marcelle Soares-Santos,[53] Fiodor Sorrentino,[61,*] Yajpal Singh,[14,*] Timothy Sumner,[4] Konstantinos Tassis,[13] Silvia Tentindo,[62] Guglielmo Maria Tino,[63,64,*] Jonathan N. Tinsley,[63] James Unwin,[65] Tristan Valenzuela,[11] Georgios Vasilakis,[13] Ville Vaskonen,[12,32,*] Christian Vogt,[66] Alex Webber-Date,[16] André Wenzlawski,[67] Patrick Windpassinger,[67] Marian Woltmann,[66] Michael Holynski,[14] Efe Yazgan,[68] Ming-Sheng Zhan,[69,*] Xinhao Zou,[8] Jure Zupan[70]

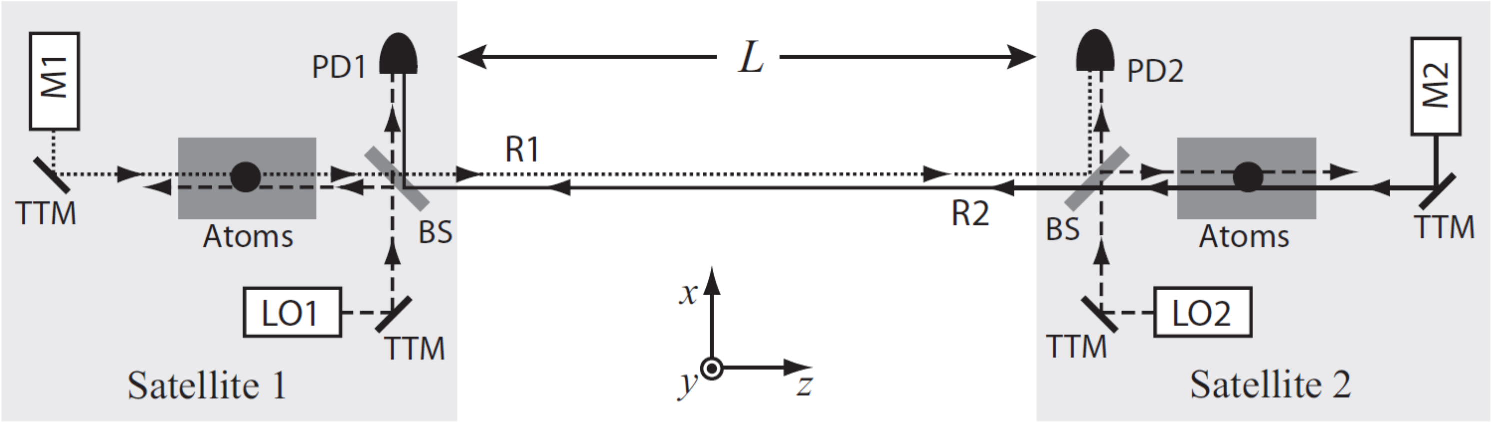
132 Authors, from **70** institutions, based in **23** different counties!

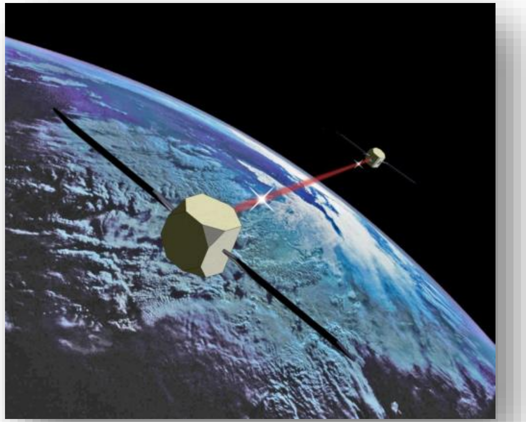
The authors represent several science communities ranging from Cold Atoms, & Gravitational Waves, over Cosmology and Astrophysics to fundamental Particle Physics.

https://arxiv.org/abs/1908.00802

The paper is now published in EPJ Quantum Technology

Potential Mission Design





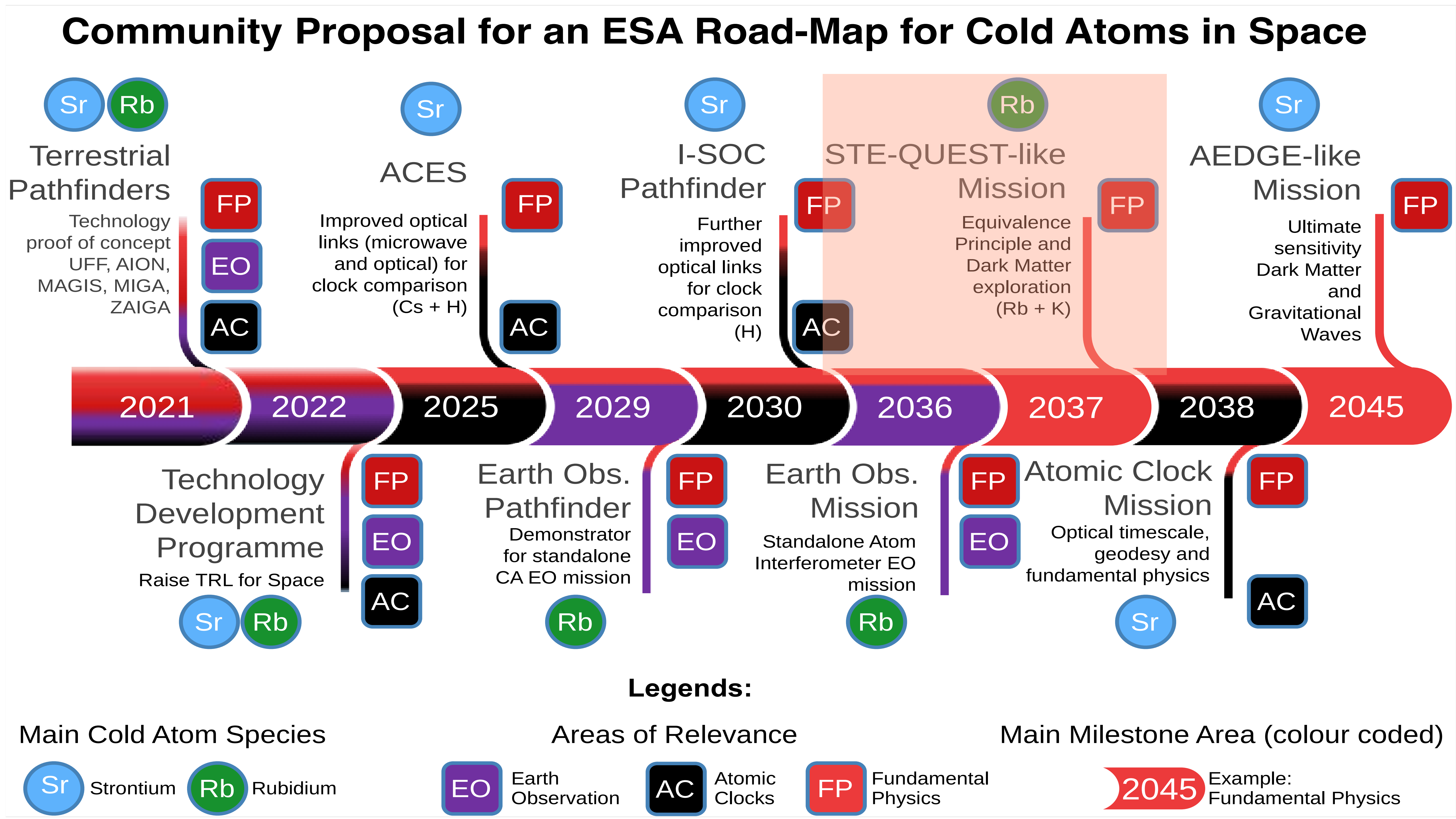
Using two cold-atom interferometers that perform a relative measurement of differential phase shift, a potential mission profile would be using a pair of satellites separated by a very long baseline L.

Assumed basic parameters:

- Pair of satellites in medium earth orbit (MEO)
- Satellite separation L = 4.4×10^7 m

Note: as Laser noise is common-mode suppressed only two satellites are required

A detailed mission outline is provided in: MAGIS collaboration, P. W. Graham et al **arXiv:1711.02225**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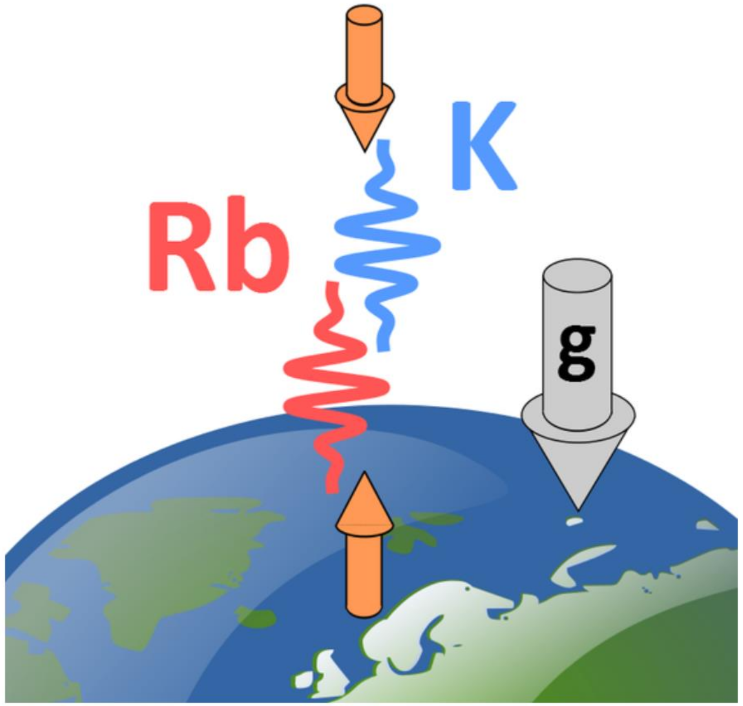
Main Milestone Area (colour coded)
2045 Example: Fundamental Physics

STE-QUEST (M-Class Mission Proposal)

STE-QUEST

Space Time Explorer and QUantum Equivalence principle Space Test

A M-class mission proposal in response to the 2022 call in ESA's science program



Core Team:

- Angelo Bassi, Department of Physics, University of Trieste, and INFN - Trieste Section, *Italy*
- Kai Bongs, Midlands Ultracold Atom Research Centre, School of Physics and Astronomy University of Birmingham, *United Kingdom*
- Philippe Bouyer, LP2N, Université Bordeaux, IOGS, CNRS, Talence, *France*
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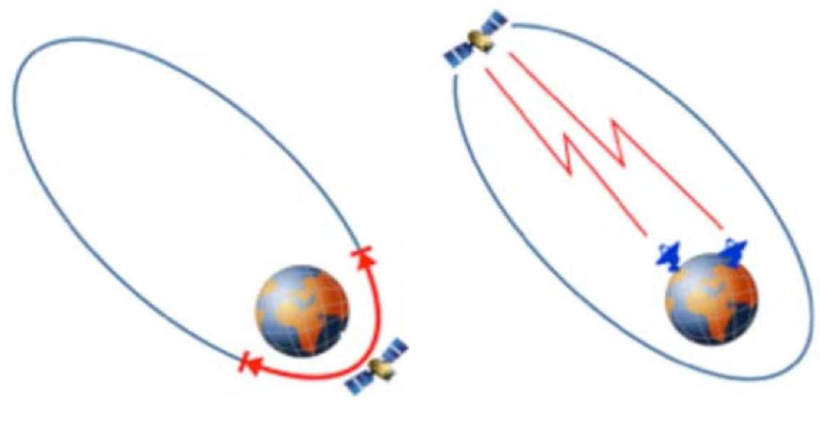
- Martin Zelan, Measurement Science and Technology, RISE Research Institutes of Sweden, Borås, *Sweden*

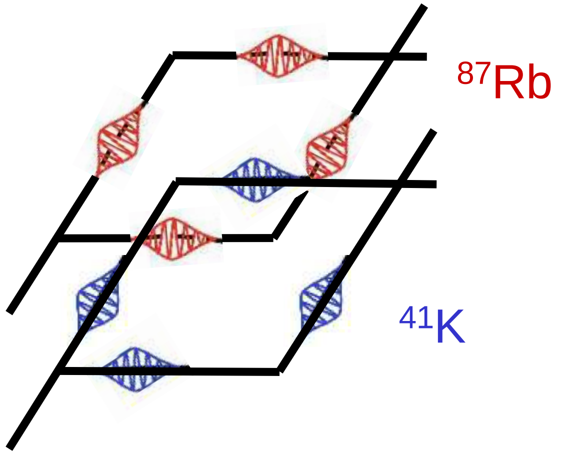
Strong International Team

STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics

Science Goals: Equivalent Principal at 1E-17, Ultra-Light Dark Matter, Test of Quantum Mechanics



(a) (b)

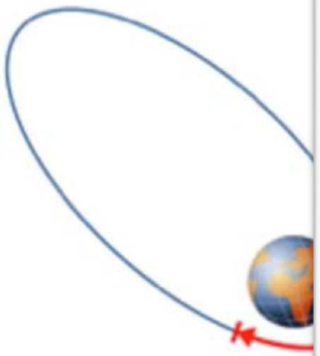


- Based on STE-QUEST proposals (M3, M4).
- Double atom interferometer with Rb and K "test masses" in non-classical states (quantum superpositions).
- Optimized for UFF test. Assume 700 km circular orbit.
- Apply recent results on controlling gravity gradient shifts by offsetting laser frequencies, thus relaxing atom positioning requirements by factor >100.
- **Reaches 1E-17 target after 18 months of operation.**

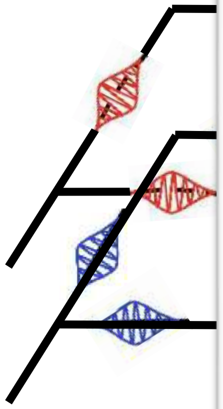
Class	Elements	η	Year [ref]	Comments
Classical	Be - Ti	2×10^{-13}	2008	Torsion balance
	Pt - Ti	1×10^{-14}	2017	MICROSCOPE first results
	Pt - Ti	(10^{-15})	2022+	MICROSCOPE full data
Hybrid	^{133}Cs - CC	7×10^{-9}	2001	Atom Interferometry
	^{87}Rb - CC	7×10^{-9}	2010	and macroscopic corner cube (CC)
Quantum	^{39}K - ^{87}Rb	3×10^{-7}	2020	different elements
	^{87}Sr - ^{88}Sr	2×10^{-7}	2014	same element, fermion vs. boson
	^{85}Rb - ^{87}Rb	3×10^{-8}	2015	same element, different isotopes
	^{85}Rb - ^{87}Rb	3.8×10^{-12}	2020	10 m tower
	^{41}K - ^{87}Rb	(10^{-17})	2037	STE-QUEST
Antimatter	$\overline{\mathrm{H}}$ - H	(10^{-2})	2023+	under construction at CERN

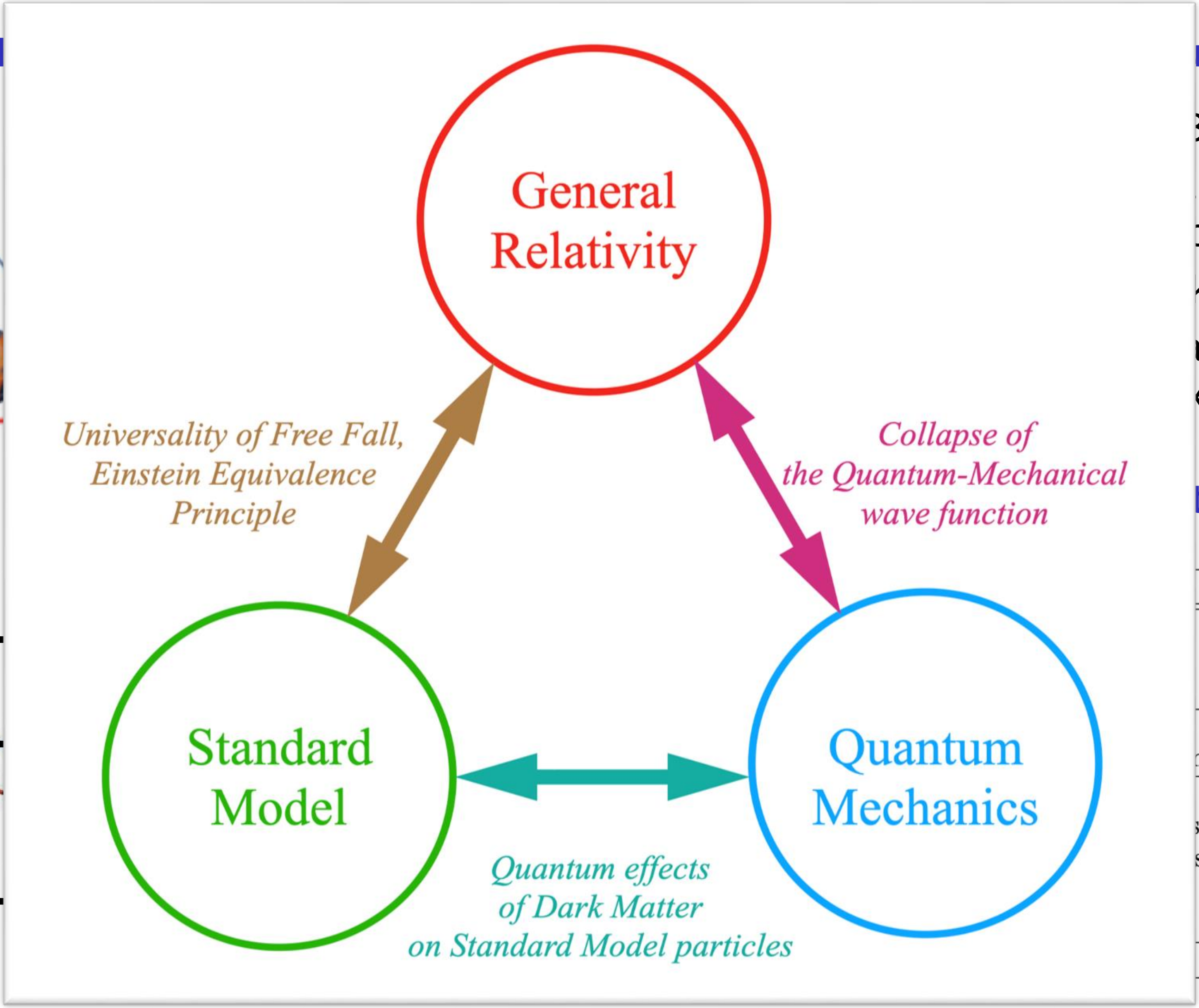
STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics

Science Goals: I … uantum Mechanics



(a)





3, M4).
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Comments
Torsion balance
MICROSCOPE first results
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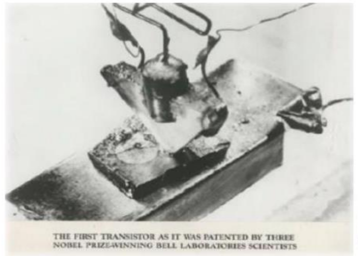
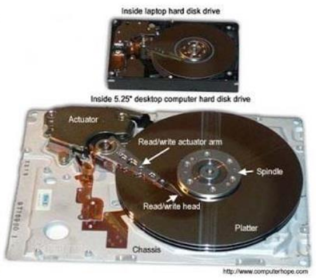
STE-QUEST
under construction at CERN

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


Albert Einstein (1879-1955)


Werner Heisenberg (1901-1976)

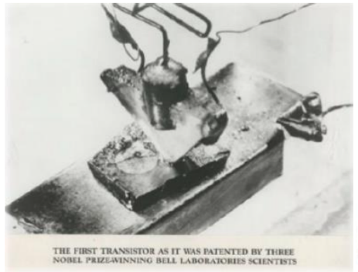

Erwin Schrödinger (1887-1961)

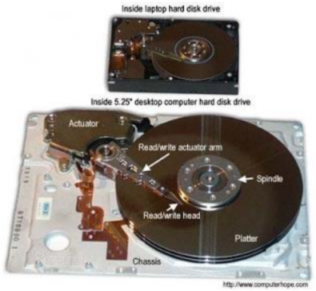
The first quantum revolution

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 — beginning of 20^{th} century

transistor — 1947

hard disk — 1954

laser — 1960

end 20^{th} / beginning 21^{st} — 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…

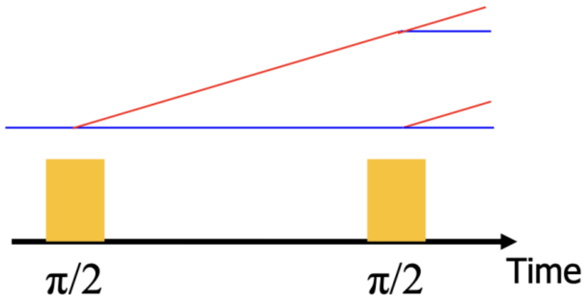
The second quantum revolution

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

MORE ON ATOM INTERFEROMETRY CONCEPT

Possible Phase Shifts

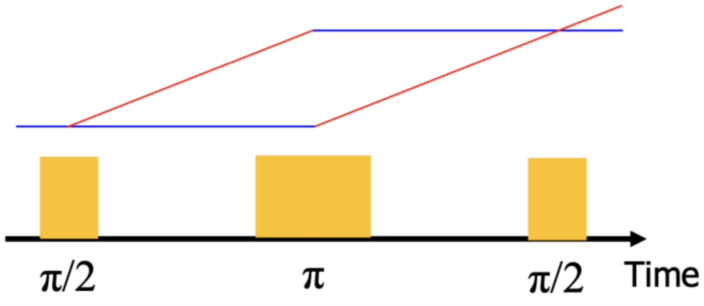
Ramsey sequence (clock)



$$\Delta\phi = \phi_1 - \phi_2 = (\omega - \omega_A)T + kx_1 - kx_2$$
$$= (\omega - \omega_A)T + \underline{kvT}$$

- Measures velocity

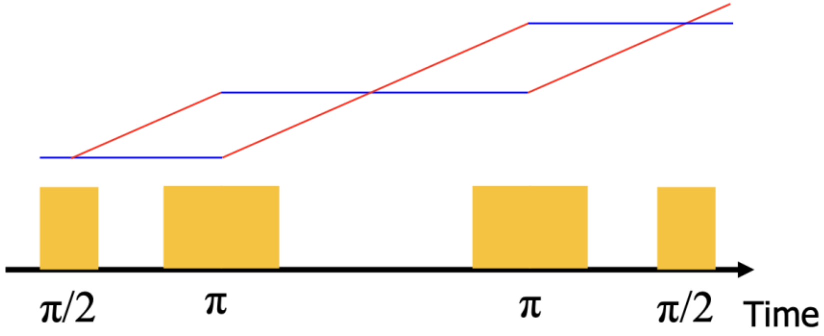
Mach-Zehnder



$$\Delta\phi = (\phi_1 - \phi_2) - (\phi_2 - \phi_3)$$
$$= kv_1T - kv_2T = \underline{kaT^2}$$

- "Difference" of two Ramsey sequences
- Measures acceleration

"Double diamond"



$$\Delta\phi = ka_1T^2 - ka_2T^2 = k\,\delta a\,T^3$$

- Difference of two MZ loops
- Measures acceleration gradient (in space and/or time)

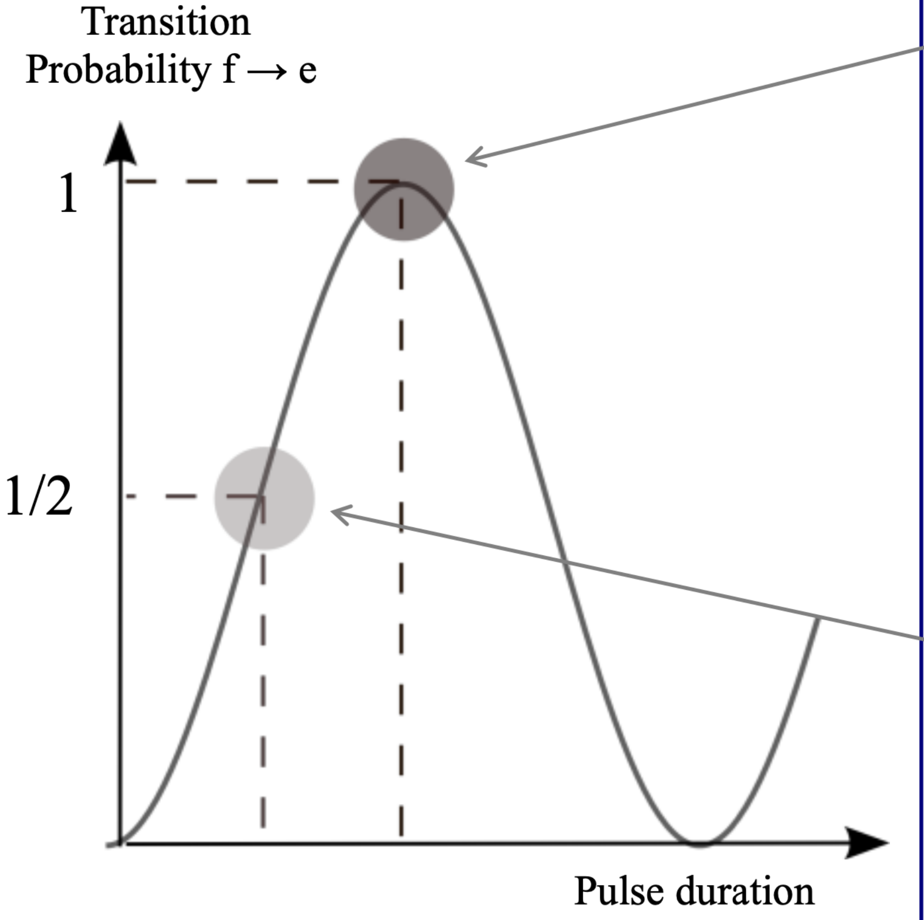
General Relativistic Effects in Atom Interferometry

	GR Phase Shift	Size (rad)	Interpretation	NR Phase Shift
1.	$-k_{\text{eff}}gT^2$	$3. \times 10^8$	Newtonian gravity	$-k_{\text{eff}}gT^2$
2.	$-k_{\text{eff}}(\partial_r g)v_L T^3$	$-2. \times 10^3$	1st gradient	$-k_{\text{eff}}(\partial_r g)v_L T^3$
3.	$-\frac{7}{12}k_{\text{eff}}(\partial_r g)gT^4$	$9. \times 10^2$		$-\frac{7}{12}k_{\text{eff}}(\partial_r g)gT^4$
4.	$-3k_{\text{eff}}g^2T^3$	$-4. \times 10^1$	finite speed of light and	
5.	$-3k_{\text{eff}}gv_L T^2$	$4. \times 10^1$	Doppler shift corrections	
6.	$-\frac{k_{\text{eff}}^2}{2m}(\partial_r g)T^3$	$-7. \times 10^{-1}$	1st gradient recoil	$-\frac{k_{\text{eff}}^2}{2m}(\partial_r g)T^3$
7.	$(\omega_{\text{eff}} - \omega_a)\,gT^2$	$-4. \times 10^{-1}$	detuning	
8.	$(2-2\beta-\gamma)k_{\text{eff}}g\phi T^2$	$-2. \times 10^{-1}$	GR (non-linearity)	
9.	$-\frac{3k_{\text{eff}}^2}{2m}gT^2$	$2. \times 10^{-2}$		
10.	$-\frac{7}{12}k_{\text{eff}}v_L^2(\partial_r^2 g)T^4$	$8. \times 10^{-3}$	2nd gradient	$-\frac{7}{12}k_{\text{eff}}v_L^2(\partial_r^2 g)T^4$
11.	$-\frac{35}{4}k_{\text{eff}}(\partial_r g)gv_L T^4$	$6. \times 10^{-4}$		
12.	$-4k_{\text{eff}}(\partial_r g)v_L^2 T^3$	$-3. \times 10^{-4}$		
13.	$2\omega_a g^2T^3$	$2. \times 10^{-4}$		
14.	$2\omega_a gv_L T^2$	$-2. \times 10^{-4}$		
15.	$-\frac{7k_{\text{eff}}^2}{12m}v_L(\partial_r^2 g)T^4$	$7. \times 10^{-6}$	2nd gradient recoil	$-\frac{7k_{\text{eff}}^2}{12m}v_L(\partial_r^2 g)T^4$
16.	$-12k_{\text{eff}}g^2v_L T^3$	$-7. \times 10^{-6}$		
17.	$-7k_{\text{eff}}g^3T^4$	$4. \times 10^{-6}$		
18.	$-5k_{\text{eff}}gv_L^2T^2$	$3. \times 10^{-6}$	GR (velocity-dependent force)	
19.	$(2-2\beta-\gamma)k_{\text{eff}}\partial_r(g\phi)v_L T^3$	$2. \times 10^{-6}$	GR 1st gradient	
20.	$\frac{7}{12}(4-4\beta-3\gamma)k_{\text{eff}}\phi(\partial_r g)gT^4$	$-2. \times 10^{-6}$	GR	
21.	$(\omega_{\text{eff}} - \omega_a)\,(\partial_r g)v_L T^3$	$2. \times 10^{-6}$		
22.	$\frac{7}{12}\,(\omega_{\text{eff}} - \omega_a)\,(\partial_r g)gT^4$	$-1. \times 10^{-6}$		
23.	$-\frac{7}{12}(2-2\beta-\gamma)k_{\text{eff}}g^3T^4$	$-3. \times 10^{-7}$	GR	
24.	$-\frac{7k_{\text{eff}}^2}{2m}(\partial_r g)v_L T^3$	$-2. \times 10^{-7}$		
25.	$-\frac{27k_{\text{eff}}^2}{8m}(\partial_r g)gT^4$	$2. \times 10^{-7}$		
26.	$\frac{k_{\text{eff}}\omega_a}{m}gT^2$	$-1. \times 10^{-7}$		
27.	$6(2-2\beta-\gamma)k_{\text{eff}}\phi g^2T^3$	$5. \times 10^{-8}$	GR	
28.	$3\,(\omega_{\text{eff}} - \omega_a)\,g^2T^3$	$4. \times 10^{-8}$		
29.	$3\,(\omega_{\text{eff}} - \omega_a)\,gv_L T^2$	$-4. \times 10^{-8}$		
30.	$6(1-\beta)k_{\text{eff}}\phi gv_L T^2$	$3. \times 10^{-8}$	GR	

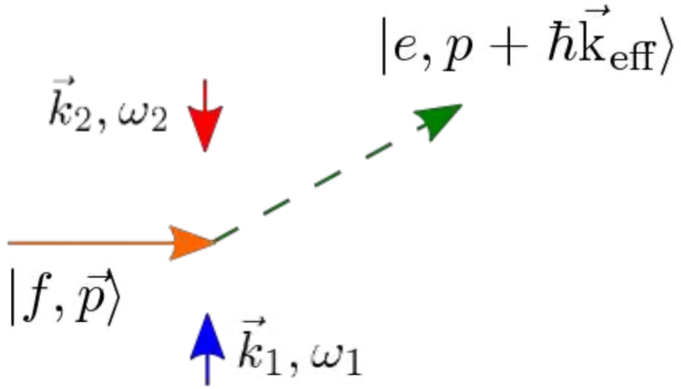
Dimopoulos et al, Phys.Rev.D78:042003,**2008**

Pi and Pi/2 Pluses – Rabi Oscillation

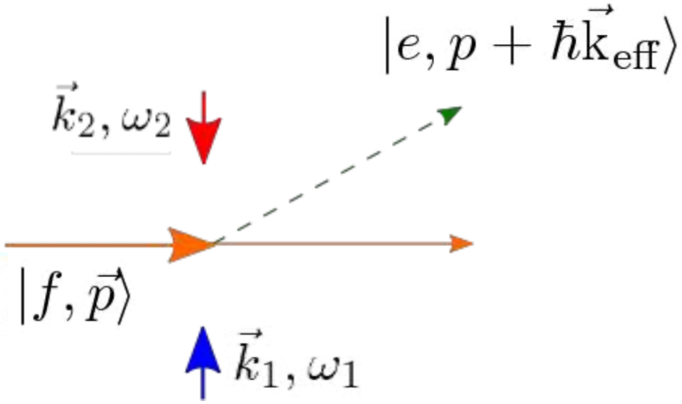
Rabi oscillation between |f> and |e>



"π" pulse = mirror

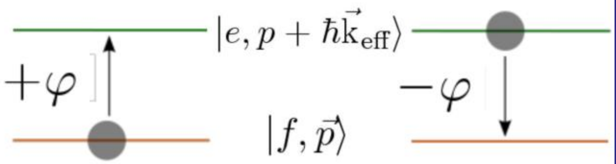


"π/2" pulse = beam splitter



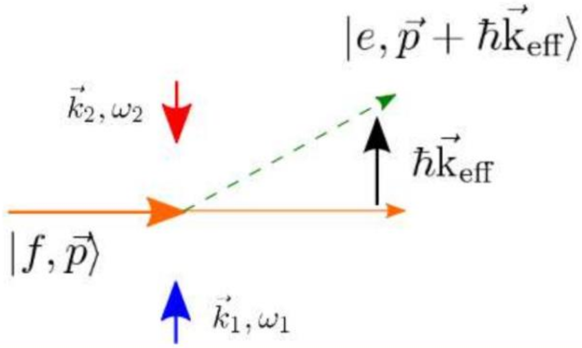
Imprint laser phase on atomic wave-function:

$$\varphi = \phi_1 - \phi_2 = \vec{k}_{\mathrm{eff}} \cdot \vec{r}(t)$$



Momentum tranfser (~1 cm/s)

$$k_{\mathrm{eff}} = k_1 + k_2$$



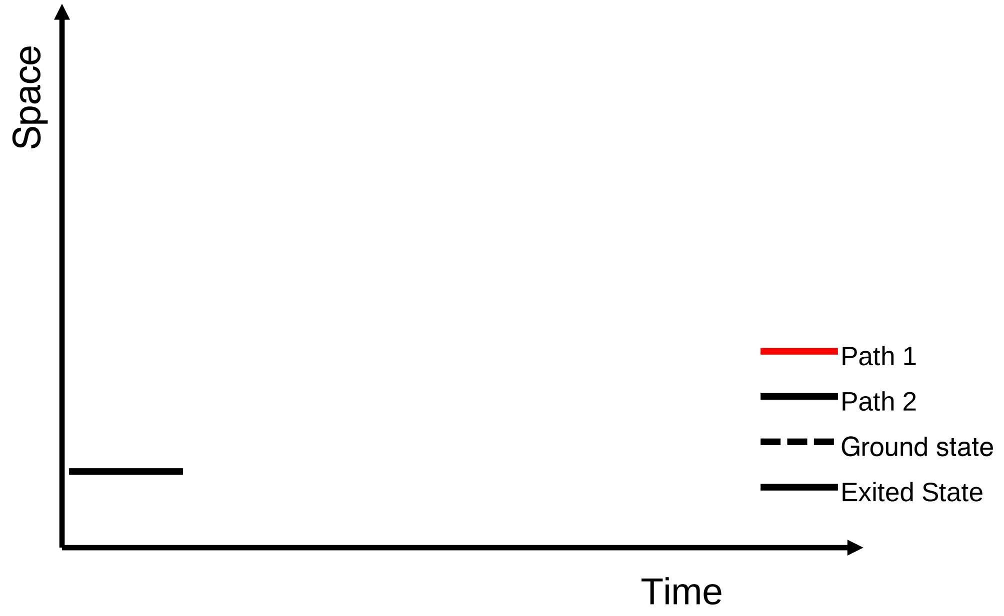
Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.

Atoms at rest:

At time before first Pulse:

$$\Phi_1 = 0, \quad \Phi_2 = 0$$



Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.

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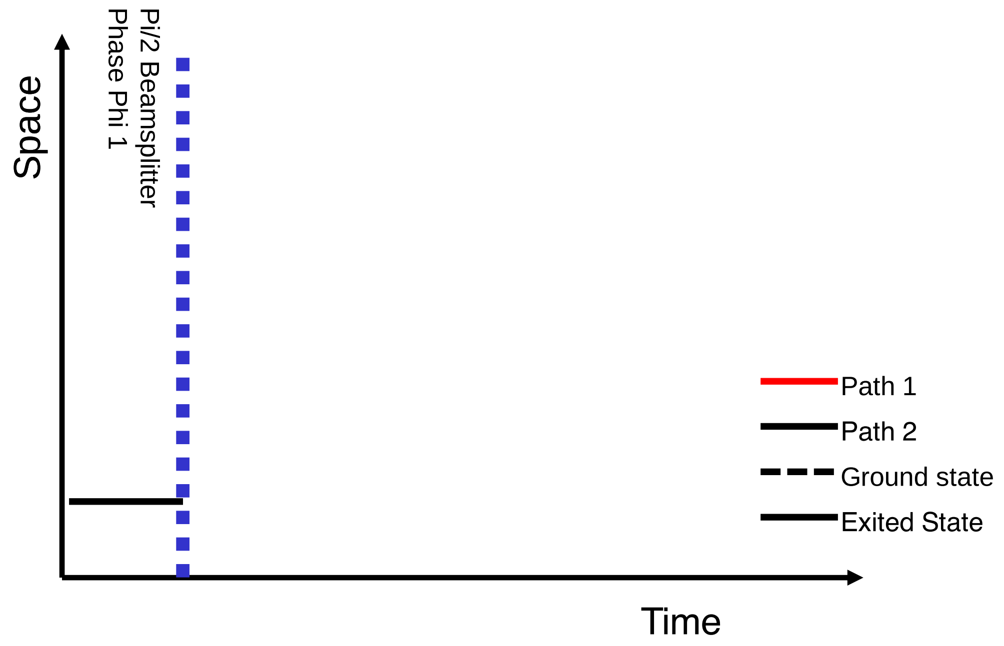
At time before first Pulse:

$$\Phi_1 = 0, \quad \Phi_2 = 0$$

At time $T = 0$ of first $\pi/2$ Pulse:

$$\Phi_1 = \phi_1, \quad \Phi_2 = 0$$



Mach-Zehnder Atom Interferometer – Phase shift

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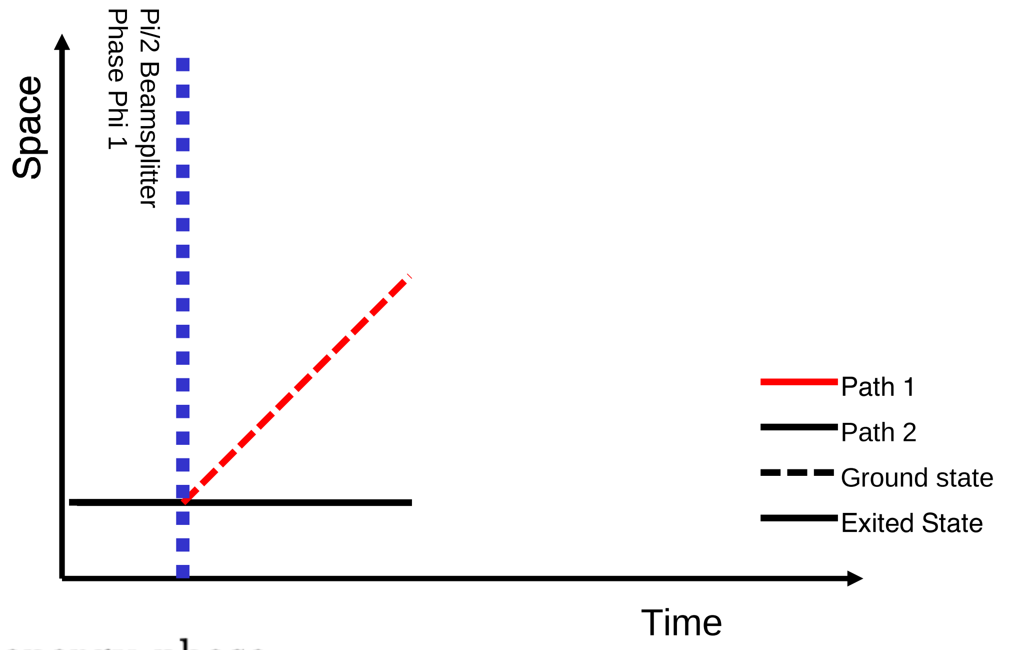


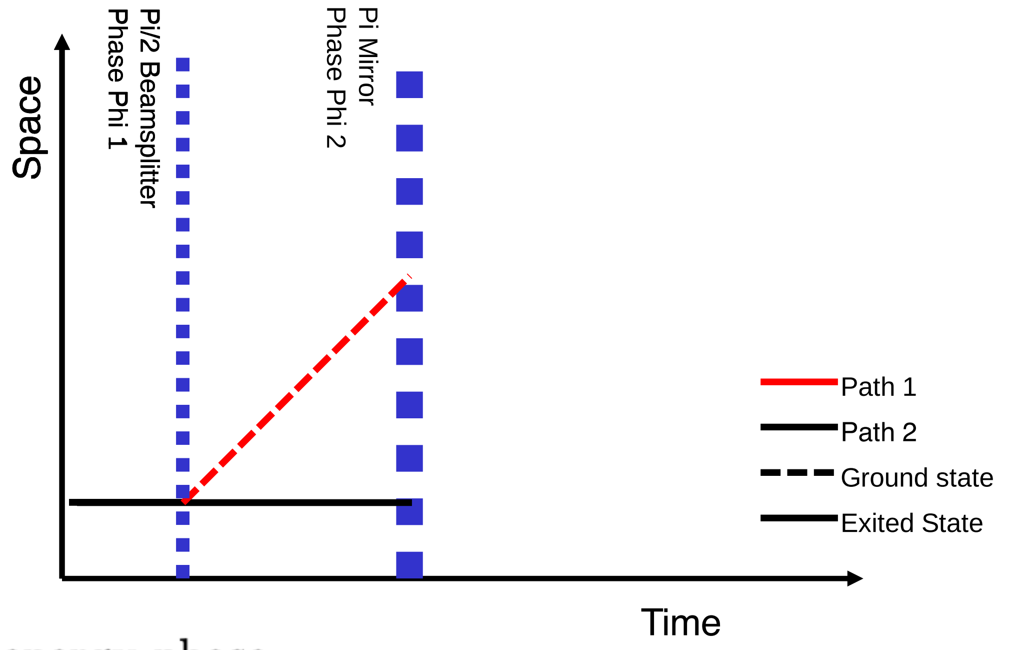
At time $t = T$ just before the π mirror pulse $|1\rangle$ acquired the energy phase $-Et/\hbar = -\omega_a T$

$$\Phi_1 = \phi_1 - ET/\hbar, \quad \Phi_2 = 0$$

Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.

Atoms at rest:



At time before first Pulse:

$$\Phi_1 = 0, \quad \Phi_2 = 0$$

At time $T = 0$ of first $\pi/2$ Pulse:

$$\Phi_1 = \phi_1, \quad \Phi_2 = 0$$

At time $t = T$ just before the π mirror pulse $|1\rangle$ acquired the energy phase $-Et/\hbar = -\omega_a T$

$$\Phi_1 = \phi_1 - ET/\hbar, \quad \Phi_2 = 0$$

At time $t = T$ of the π Pulse:

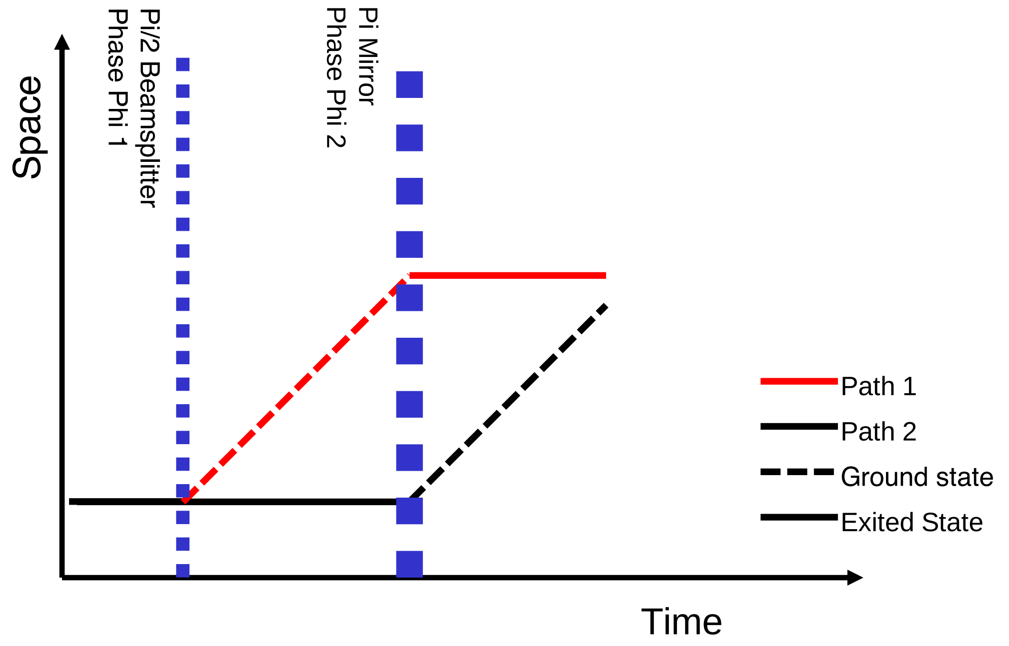
$$\Phi_1 = \phi_1 - ET/\hbar - \phi_2, \quad \Phi_2 = \phi_2$$

Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.

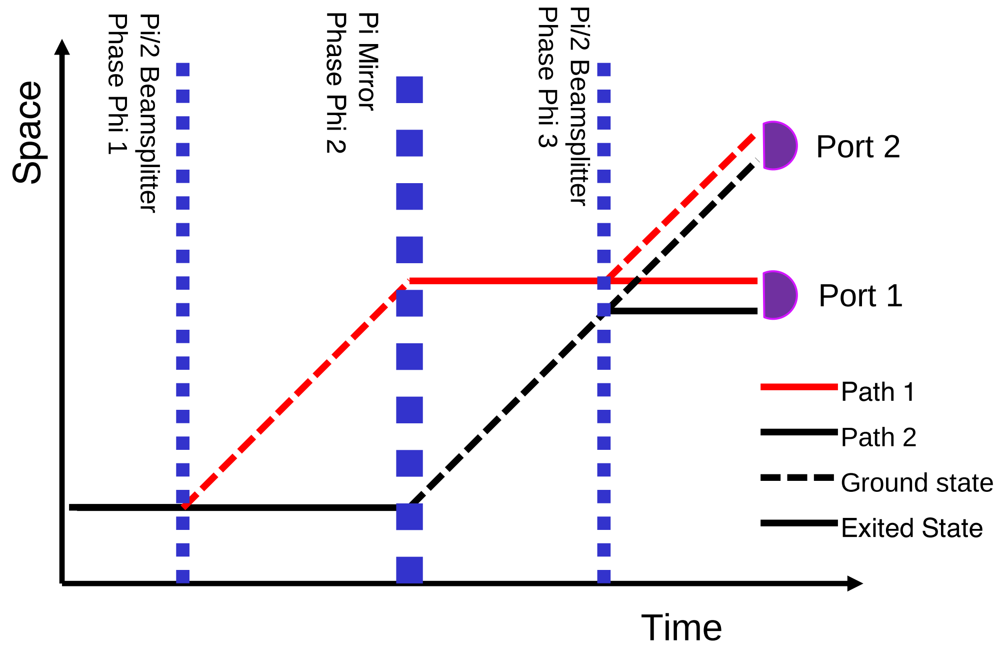
At time $t = 2T$ just before the next $\pi/2$ mirror pulse:

$$\Phi_1 = \phi_1 - ET/\hbar - \phi_2, \quad \Phi_2 = \phi_2 - ET/\hbar$$



Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.



At time $t = 2T$ just before the next $\pi/2$ mirror pulse:

$$\Phi_1 = \phi_1 - ET/\hbar - \phi_2, \quad \Phi_2 = \phi_2 - ET/\hbar$$

At time $t = 2T$ just after the next $\pi/2$ mirror pulse, we actually split in four components:

At $|0\rangle$ port:

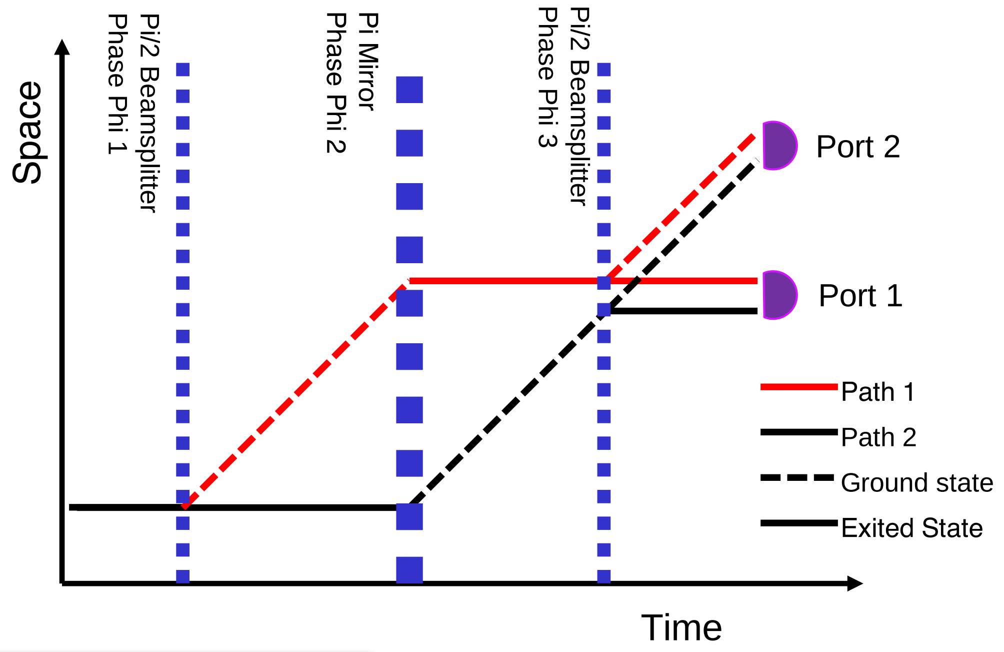
$$\Phi_1 = \phi_1 - ET/\hbar - \phi_2, \quad \Phi_2 = \phi_2 - ET/\hbar - \phi_3$$

At $|1\rangle$ port:

$$\Phi_1 = \phi_1 - ET/\hbar - \phi_2 + \phi_3, \quad \Phi_2 = \phi_2 - ET/\hbar$$

Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.



Therefore, the phase difference $\Delta\phi = \Phi_1 - \Phi_2$ is:

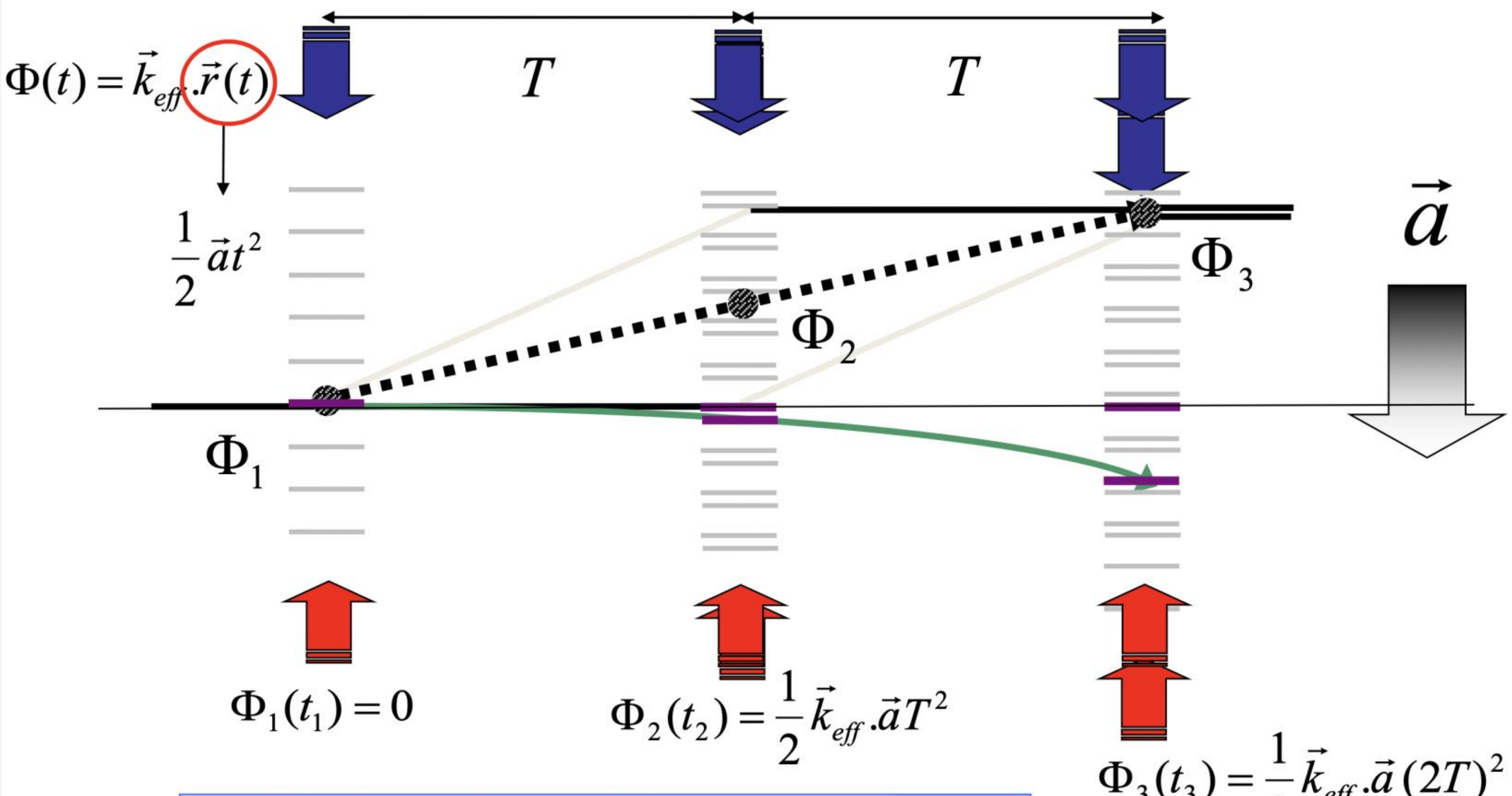
$$\Phi_1 - \Phi_2 = (\phi_1 - ET/\hbar - \phi_2) - (\phi_2 - ET/\hbar - \phi_3) = \phi_1 - 2\phi_2 + \phi_3$$

or

$$\Phi_1 - \Phi_2 = (\phi_1 - ET/\hbar - \phi_2 + \phi_3) - (\phi_2 - ET/\hbar) = \phi_1 + \phi_3 - 2\phi_2$$

MZ Acceleration Phase Shift

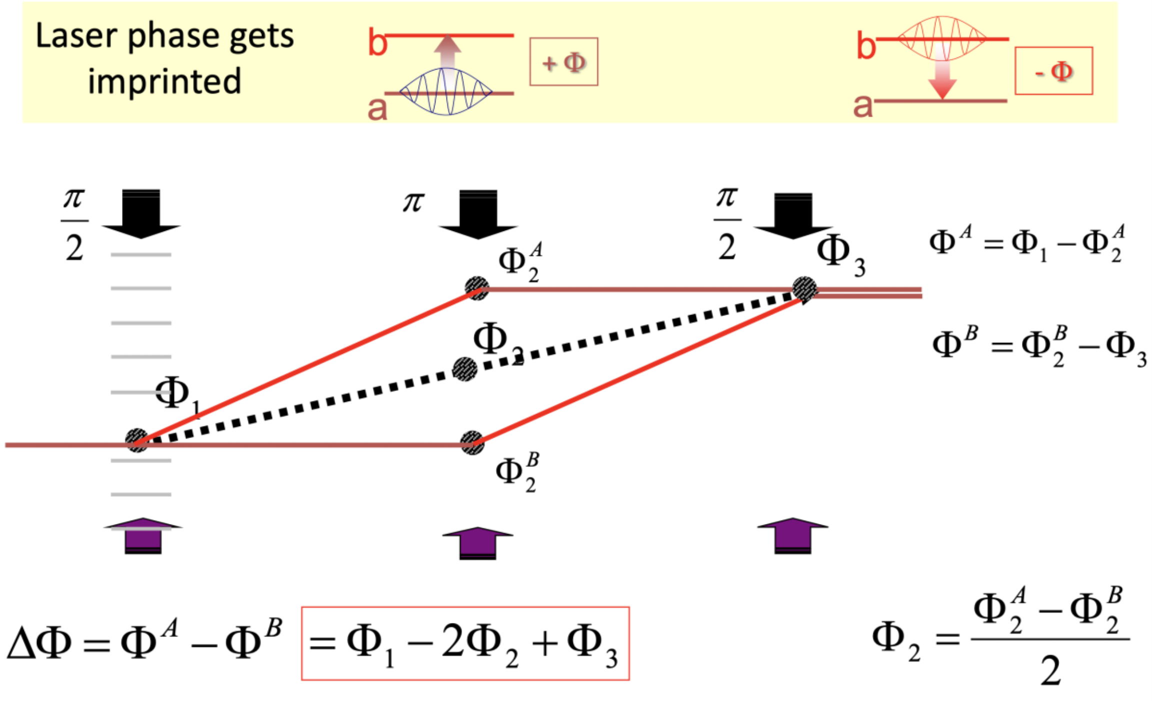
Acceleration phase shift

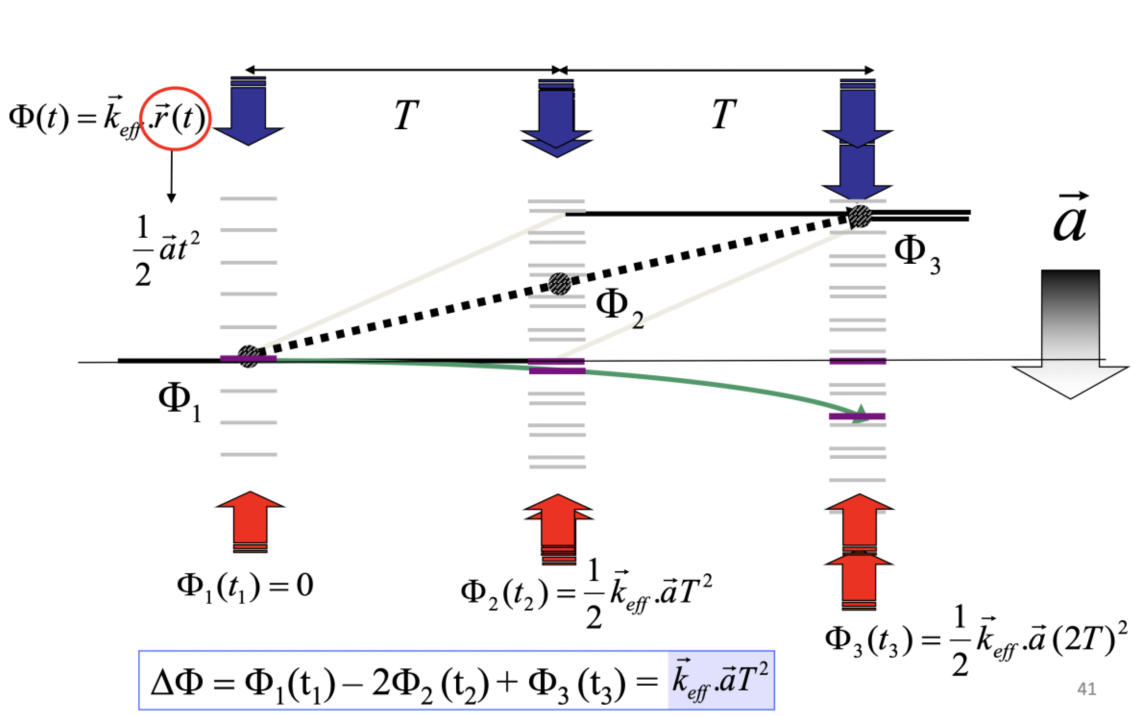


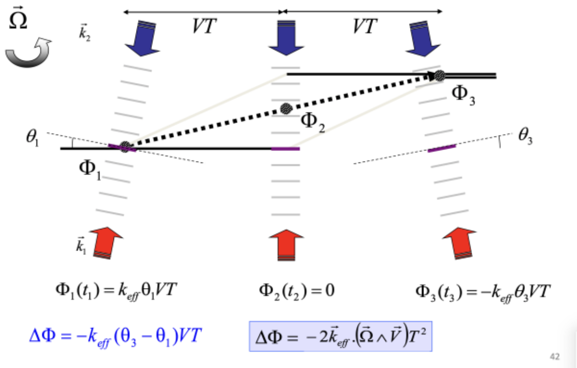
$$\Delta\Phi = \Phi_1(t_1) - 2\Phi_2(t_2) + \Phi_3(t_3) = \vec{k}_{eff}.\vec{a}T^2$$

41

Different Phase Shifts for Different Interactions







$$\Delta\Phi = \Phi_1^{eff} - 2\Phi_2^{eff} + \Phi_3^{eff}$$

$$\Phi_i^{eff}(t) = \vec{k}_i^{eff}\vec{r}_i(t)$$

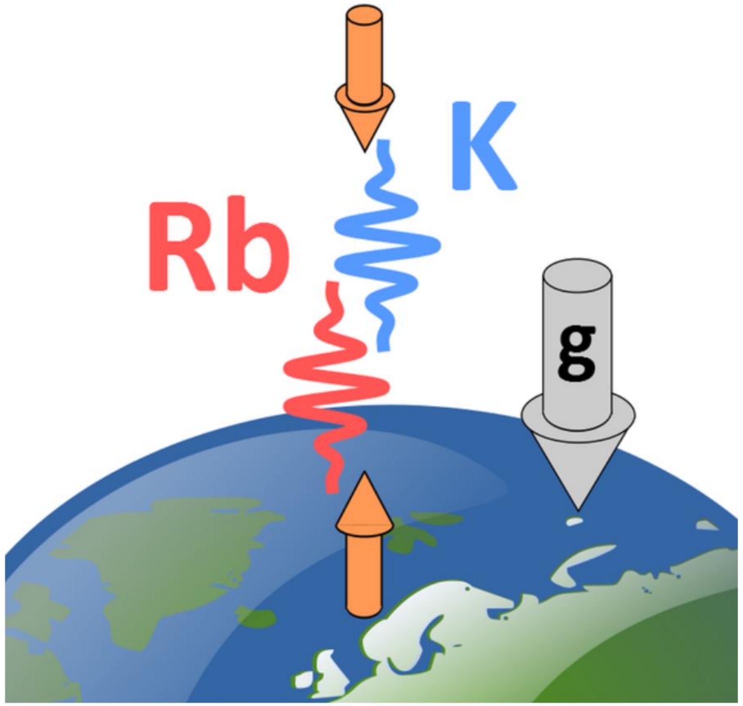
STE-QUEST

STE-QUEST (M-Class Mission Proposal)

STE-QUEST

Space Time Explorer and QUantum Equivalence principle Space Test

A M-class mission proposal in response to the 2022 call in ESA's science program



Core Team:

- Angelo Bassi, Department of Physics, University of Trieste, and INFN - Trieste Section, *Italy*
- Kai Bongs, Midlands Ultracold Atom Research Centre, School of Physics and Astronomy University of Birmingham, *United Kingdom*
- Philippe Bouyer, LP2N, Université Bordeaux, IOGS, CNRS, Talence, *France*
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- Oliver Buchmueller, High Energy Physics Group, Blackett Laboratory, Imperial College London, London, *United Kingdom*
- Maria Luisa (Marilu) Chiofalo, Physics Department "Enrico Fermi" University of Pisa, and INFN-Pisa *Italy*
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- Steve Lecomte, Centre Suisse d'Electronique et de Microtechnique (CSEM), Neuchâtel, *Switzerland*
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- Ernst M. Rasel, Institute of Quantum Optics, Leibniz University of Hanover, *Germany*
- Thilo Schuldt, German Aerospace Center (DLR), Institute of Quantum Technologies, Ulm *Germany*
- Carlos F. Sopuerta, Institute of Space Sciences (ICE, CSIC), Institute of Space Studies of Catalonia (IEEC), *Spain*
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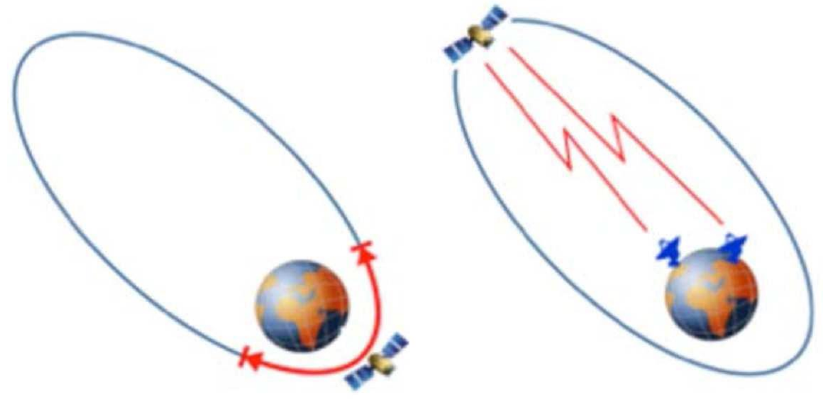
- Nan Yu, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, *USA*
- Martin Zelan, Measurement Science and Technology, RISE Research Institutes of Sweden, Borås, *Sweden*

Strong UK representation in STE-QUEST Core Team.

All are also core members of AION

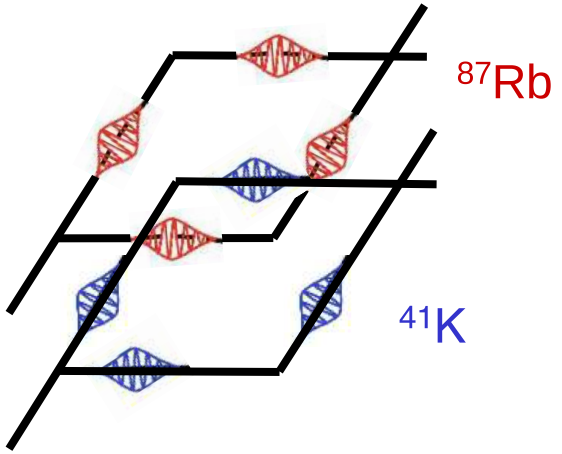
STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics

Science Goals: Equivalent Principal at 1E-17, Ultra-Light Dark Matter, Test of Quantum Mechanics



(a) (b)

- Based on STE-QUEST proposals (M3, M4).
- Double atom interferometer with Rb and K “test masses” in non-classical states (quantum superpositions).
- Optimized for UFF test. Assume 700 km circular orbit.
- Apply recent results on controlling gravity gradient shifts by offsetting laser frequencies, thus relaxing atom positioning requirements by factor >100.
- **Reaches 1E-17 target after 18 months of operation.**



Class	Elements	η	Year [ref]	Comments
Classical	Be - Ti	2×10^{-13}	2008	Torsion balance
	Pt - Ti	1×10^{-14}	2017	MICROSCOPE first results
	Pt - Ti	(10^{-15})	2022+	MICROSCOPE full data
Hybrid	^{133}Cs - CC	7×10^{-9}	2001	Atom Interferometry
	^{87}Rb - CC	7×10^{-9}	2010	and macroscopic corner cube (CC)
Quantum	^{39}K - ^{87}Rb	3×10^{-7}	2020	different elements
	^{87}Sr - ^{88}Sr	2×10^{-7}	2014	same element, fermion vs. boson
	^{85}Rb - ^{87}Rb	3×10^{-8}	2015	same element, different isotopes
	^{85}Rb - ^{87}Rb	3.8×10^{-12}	2020	10 m tower
	^{41}K - ^{87}Rb	(10^{-17})	2037	STE-QUEST
Antimatter	$\overline{\text{H}}$ - H	(10^{-2})	2023+	under construction at CERN

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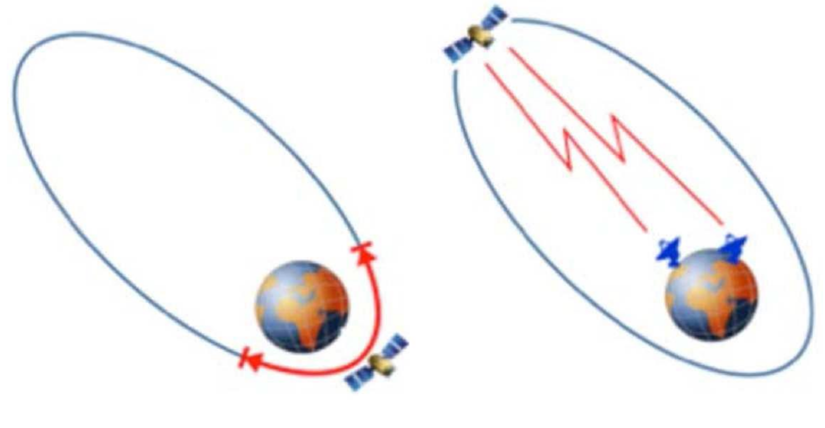

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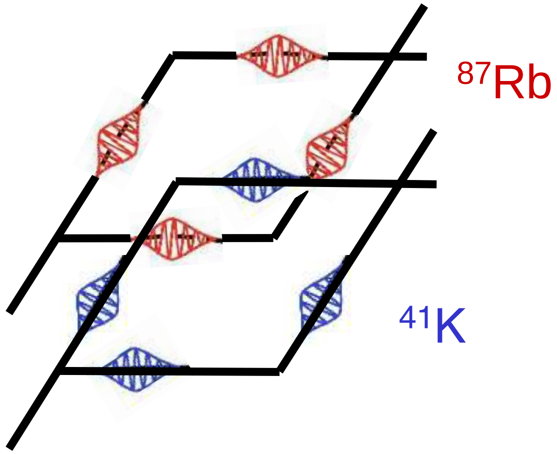

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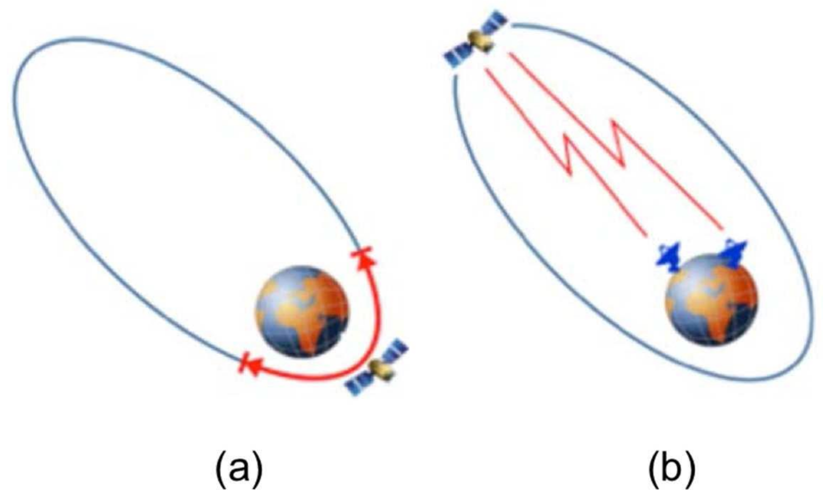

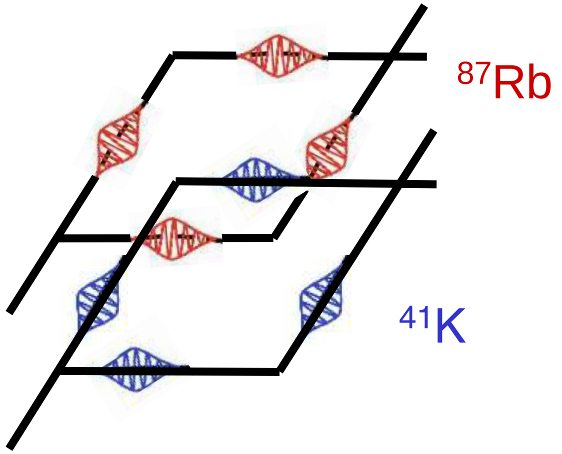

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- Optimized
- Apply rec offsetting requireme
- **Reaches**

State-of-the-art conventional sensors (electrostatic accelerometers) e.g. used for Earth Observation are limited by around eta ~1E-11 (acceleration sensitivity)

Class	Elements	η	Year [ref]	Comments
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STE-QUEST Workshop on May 17/18

STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics is now open at:

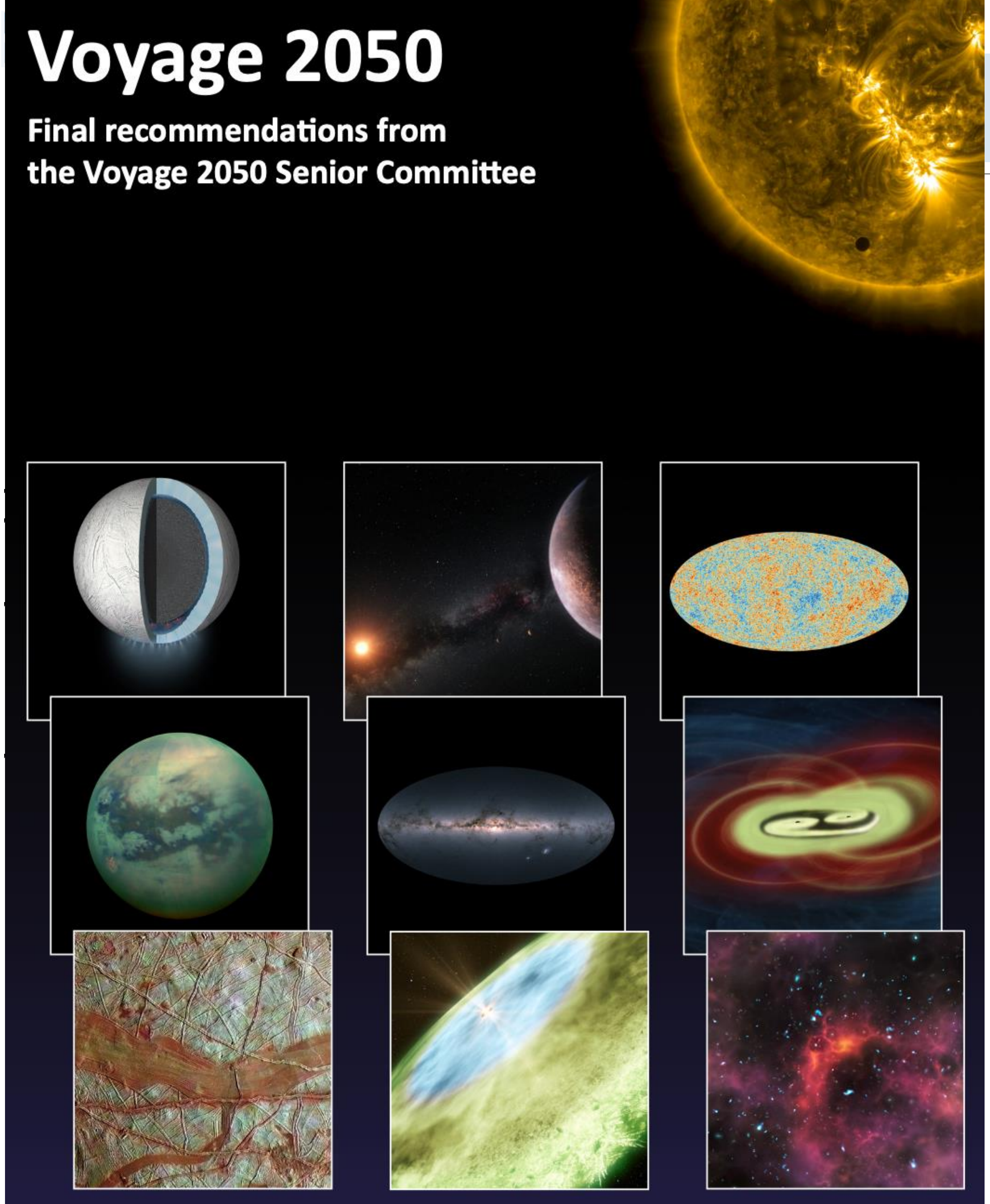
https://indico.cern.ch/event/1138902/registrations/

The workshop will take place as a virtual event on zoom on May 17/18.

https://indico.cern.ch/event/1138902/

- This workshop follows our Community Workshop & Roadmap for Cold Atoms in Space and is the next step in our community building process to define, develop and promote important milestones of our Community Roadmap, specifically the STE-QUEST M-class mission proposal now being considered by ESA.
- This event will bring together the cold atom, astrophysics, cosmology, and fundamental physics communities to discuss the science opportunities of this M-class mission proposal. Further information about the workshop scope is listed below.
- **Registering on the link provided above will enable you to attend the virtual workshop event and to keep informed about the continuing development of a full mission proposal that will follow it.**

ESA SENIOR RECOMMENDATIONS VOYGAE2050



Large missions:

- ➢ Moons of the Giant Planets
- ➢ Exoplanets
- ➢ New Physical Probes of the Early Universe: Fundamental physics and astrophysics

Possible Medium missions:

… QM & GR (cold atoms?)

Technology development recommendations for Cold Atom Interferometry

- for gravitational wave detectors in new wavebands …, detectors for dark matter candidates, sensitive clock tests of general relativity, tests of wave function collapse ….
- must reach high technical readiness level, be superior to classical technologies
- start with atomic clocks, on free-flyer or ISS?

What M-mission to propose?

A coordinated three-fold response of the community to the Voyage 2050 recommendations:

- **A letter to ESA's Director of Science, Guenther Hasinger:**
  - to raise awareness in ESA that the community is prepared to organise itself and to work actively with ESA, as it shapes a roadmap for a Cold Atom technology in space development programme
- **A community workshop in September:**
  - This event brought together the cold atom, astrophysics, cosmology, fundamental physics, and earth observation communities to formulate a road-map for the development programme,.
- **A Workshop Summary and Road-map Document**
  - As input input to ESA and national space agencies on how to structure a Cold atoms in Space programme and what priorities could be established.

CERN AION100 SITE EXPLORATION WITH PBC

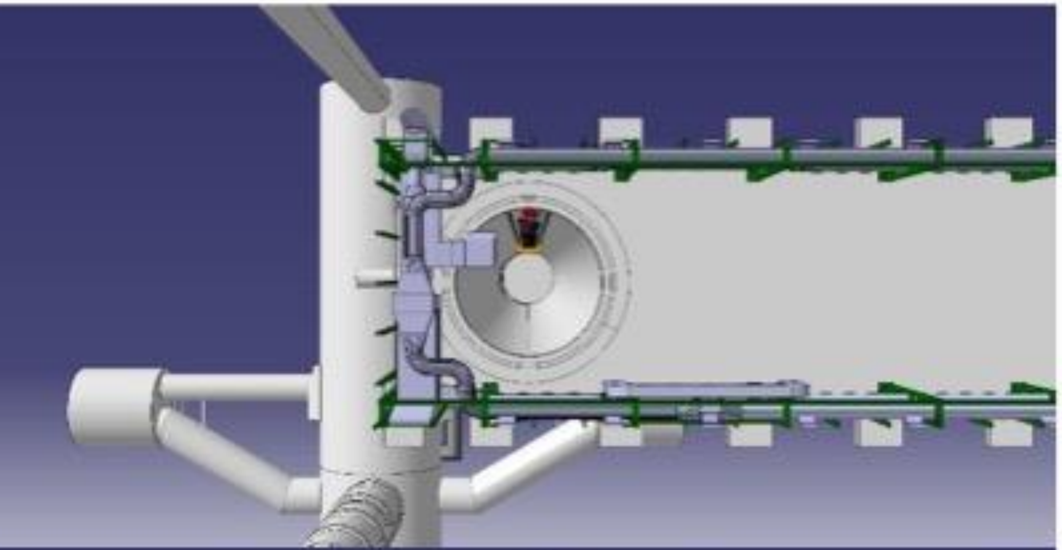
Introduction

EM Noise Levels

Slides from Sergio Calatroni (TE-VSC and PBC)

- **AION-100 experiment is an ion interferometer, proposed to be installed in the PX46 pit**
- **Feasibility study under way, with the support of the Physics Beyond Collider study - Technology Working Group. Aiming for official letter of intent at the end of the year.**
- **For info of other feasibility studies under way for AION-100: https://indi.to/RkZdN**
- **Need to measure EM background noise (1 mHz – 100 kHz) at the top (few meters below the steel lid) and at the bottom of PX46 during machine operation, using fluxgates up to 1-3 kHz, and 3D pick-up coils for the high frequency spectrum**
- **Choice of a closed plastic tube installed in the lid, after drilling, for hosting the probes**
- **Installation procedure approved by LMC: https://edms.cern.ch/document/2710516/1.0**
- **Many thanks to all services and people involved for the support: everybody was fully motivated to help**

AION-100



Location of AION-100

Drilling location

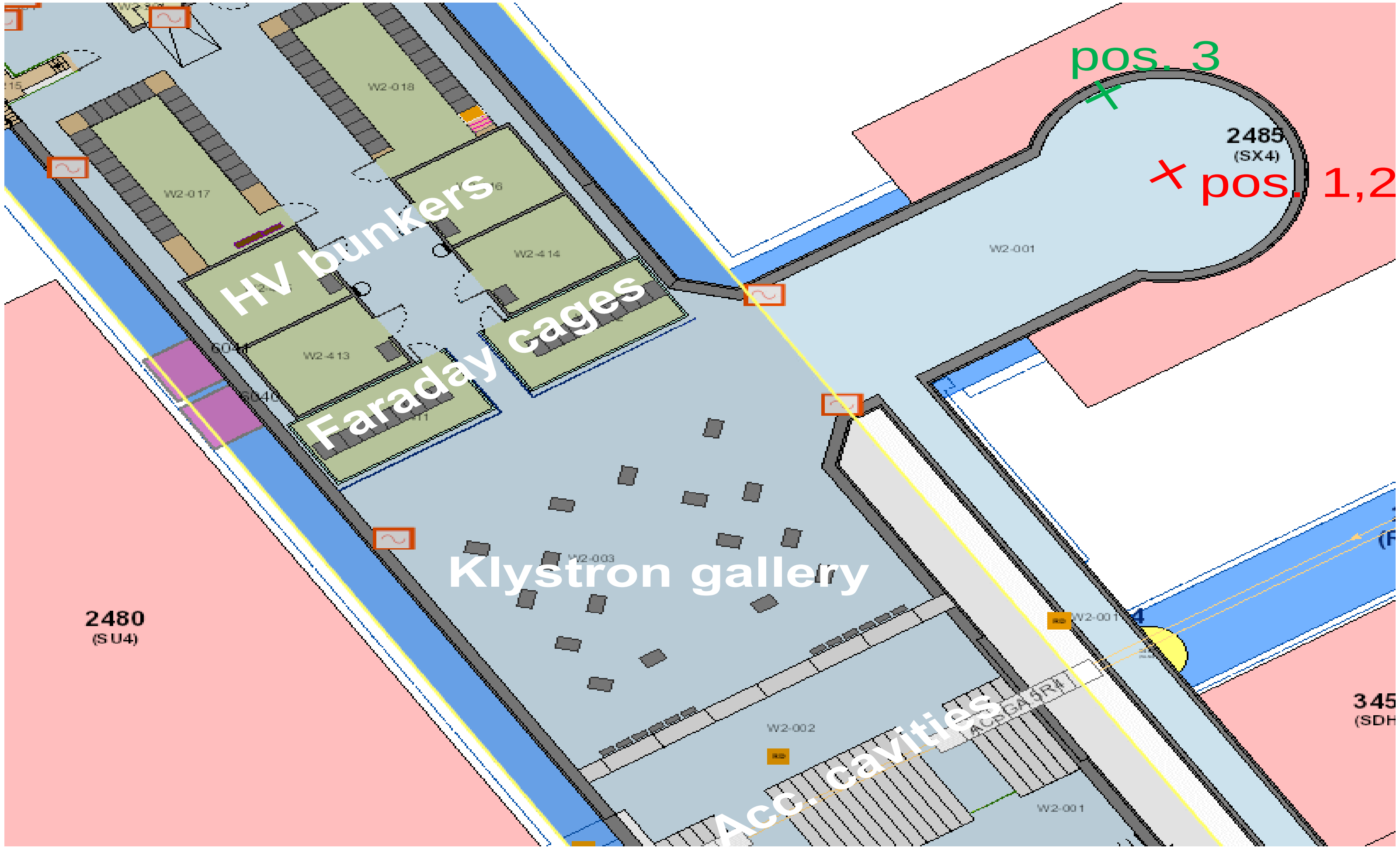
The tube (thanks to EN-MME)

PP plastic, closed at bottom
225 mm outer diameter
199,4 mm inner diameter
5000 mm length
Al flange for support

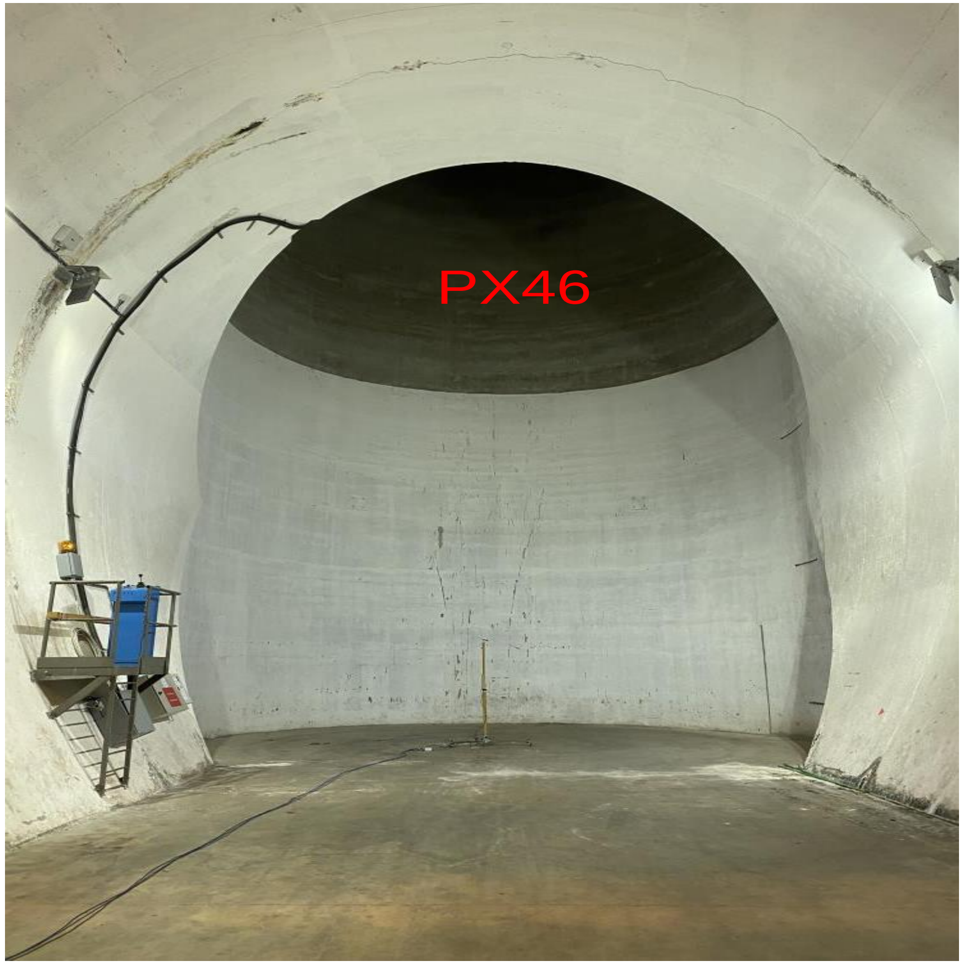
Installation (thanks to EN-ACE, EN-HE, EN-CV)

Measurement location at the bottom of the PX46 shaft, UX45 building

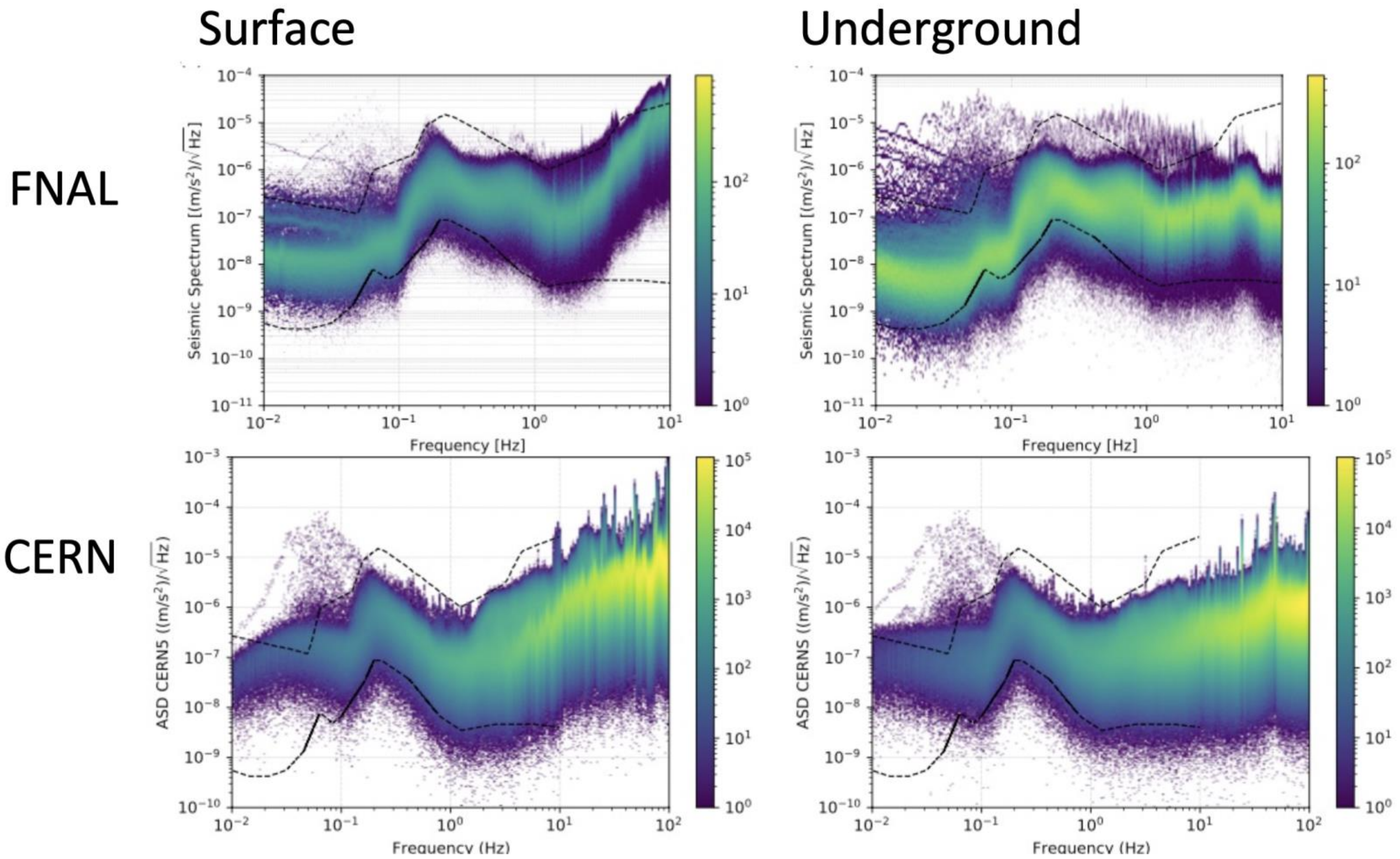
Slides from Marco Buzio, Mariano Pentella, Daniel Valuch

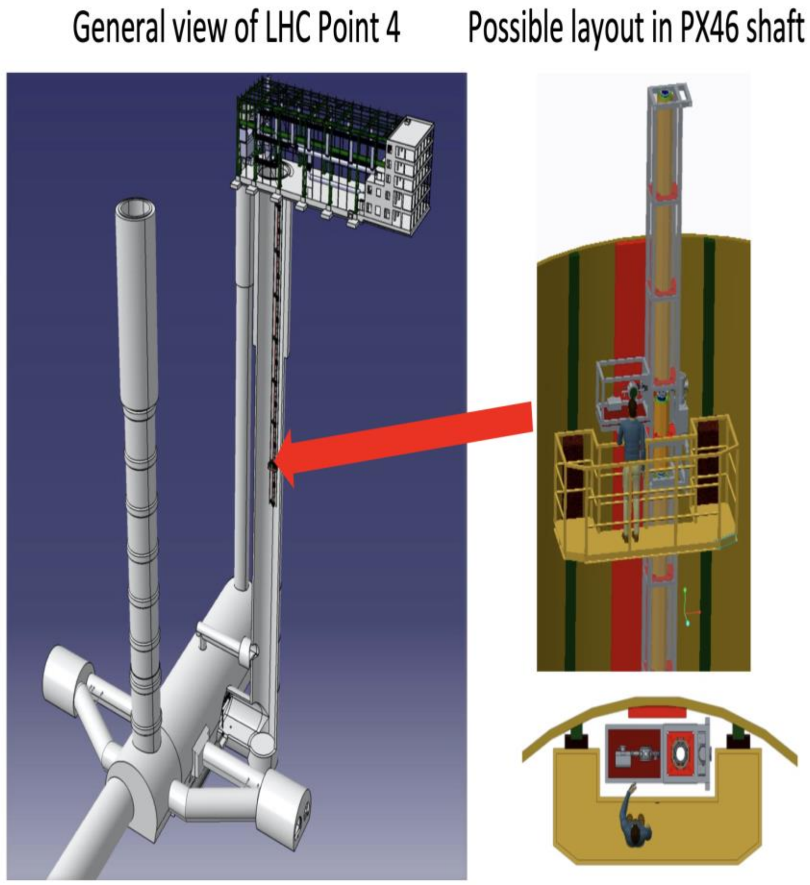


Measurement location at the bottom of the PX46 shaft, UX45 cavern



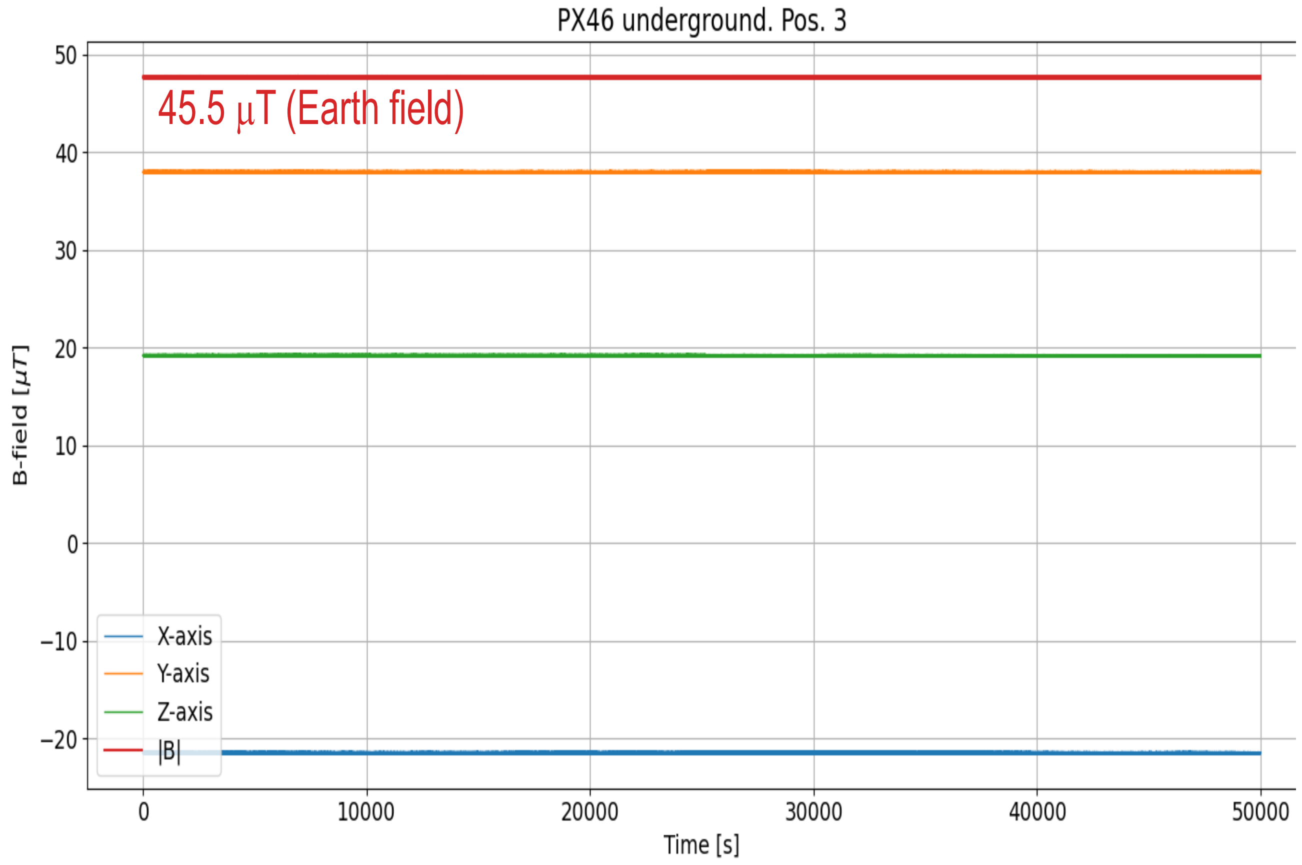
ATION-100 at CERN – Site Investigation





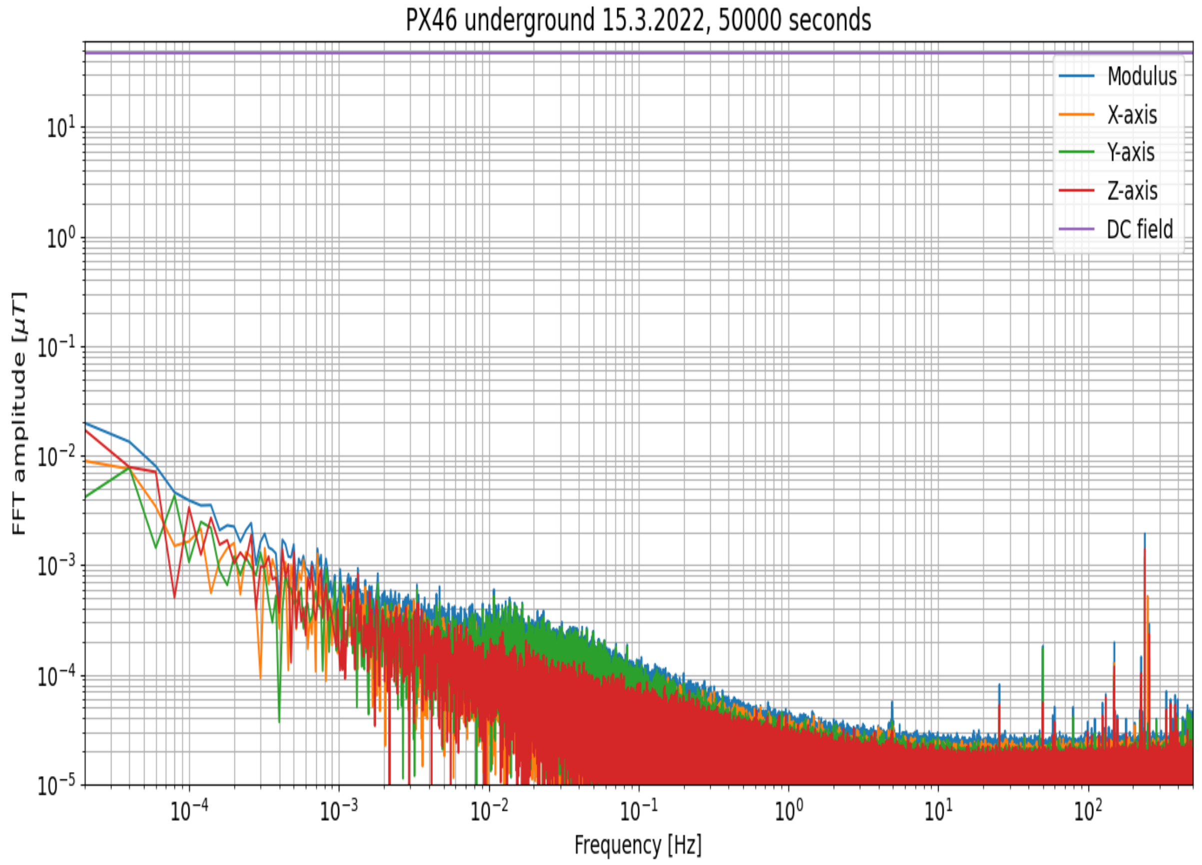
Spectrum similar to that measured at Fermilab for MAGIS

Location: bottom of the PX46 shaft. Systems in UX45 running



Location 3, wall of PX46. Quiet, Earth field for scale

Location: bottom of the PX46 shaft. Systems in UX45 running



Location 3, wall of PX46. Earth (DC) field for scale

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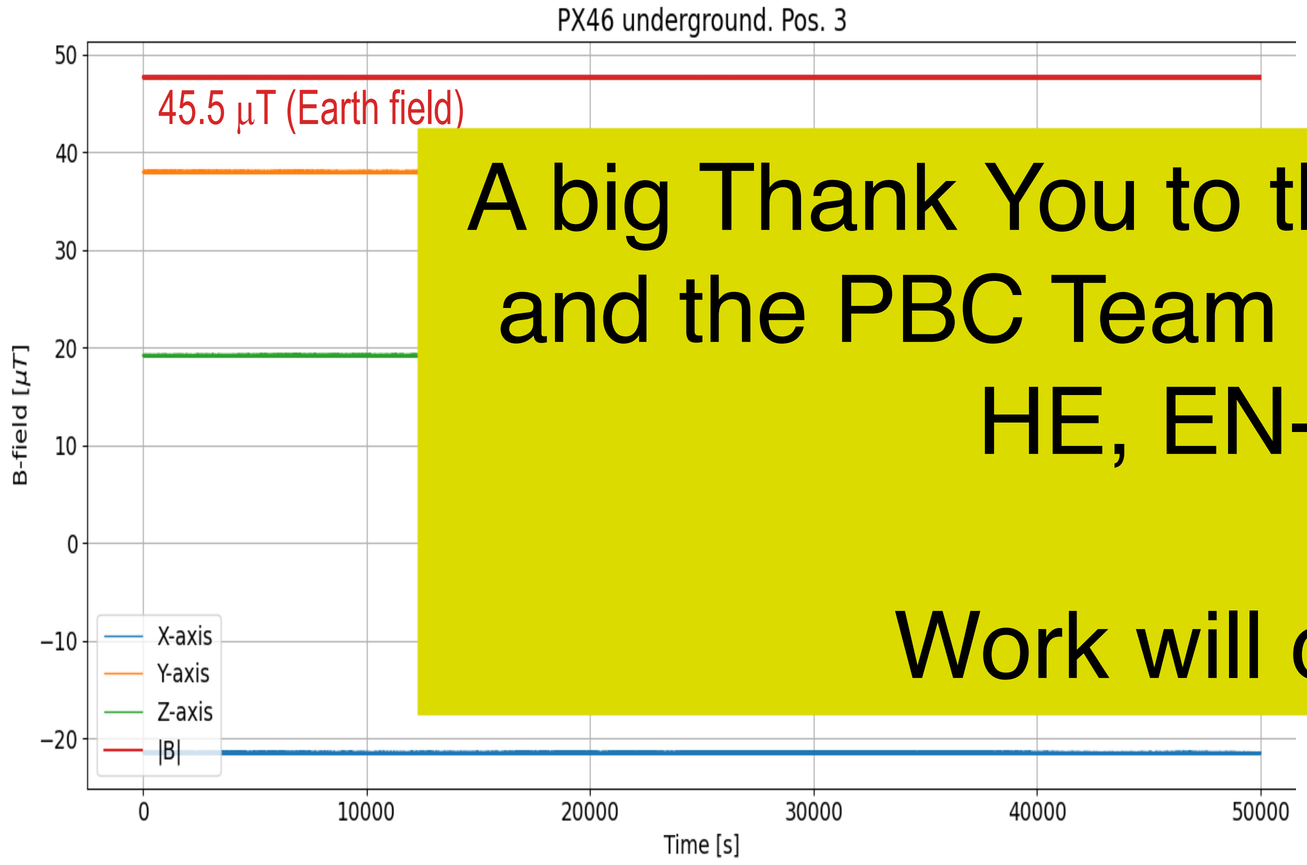
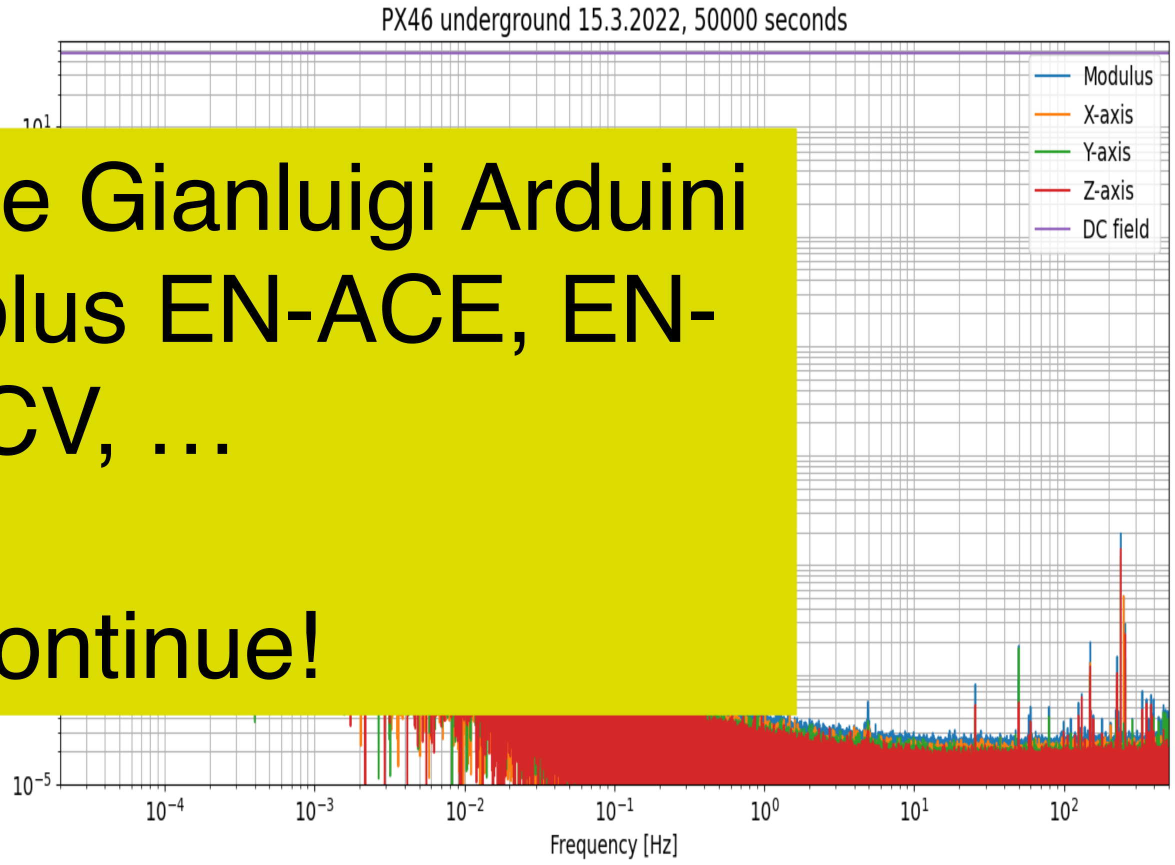


Location 3, wall of PX46. Quiet, Earth field for scale

A big Thank You to the Gianluigi Arduini and the PBC Team plus EN-ACE, EN-HE, EN-CV, …

Work will continue!

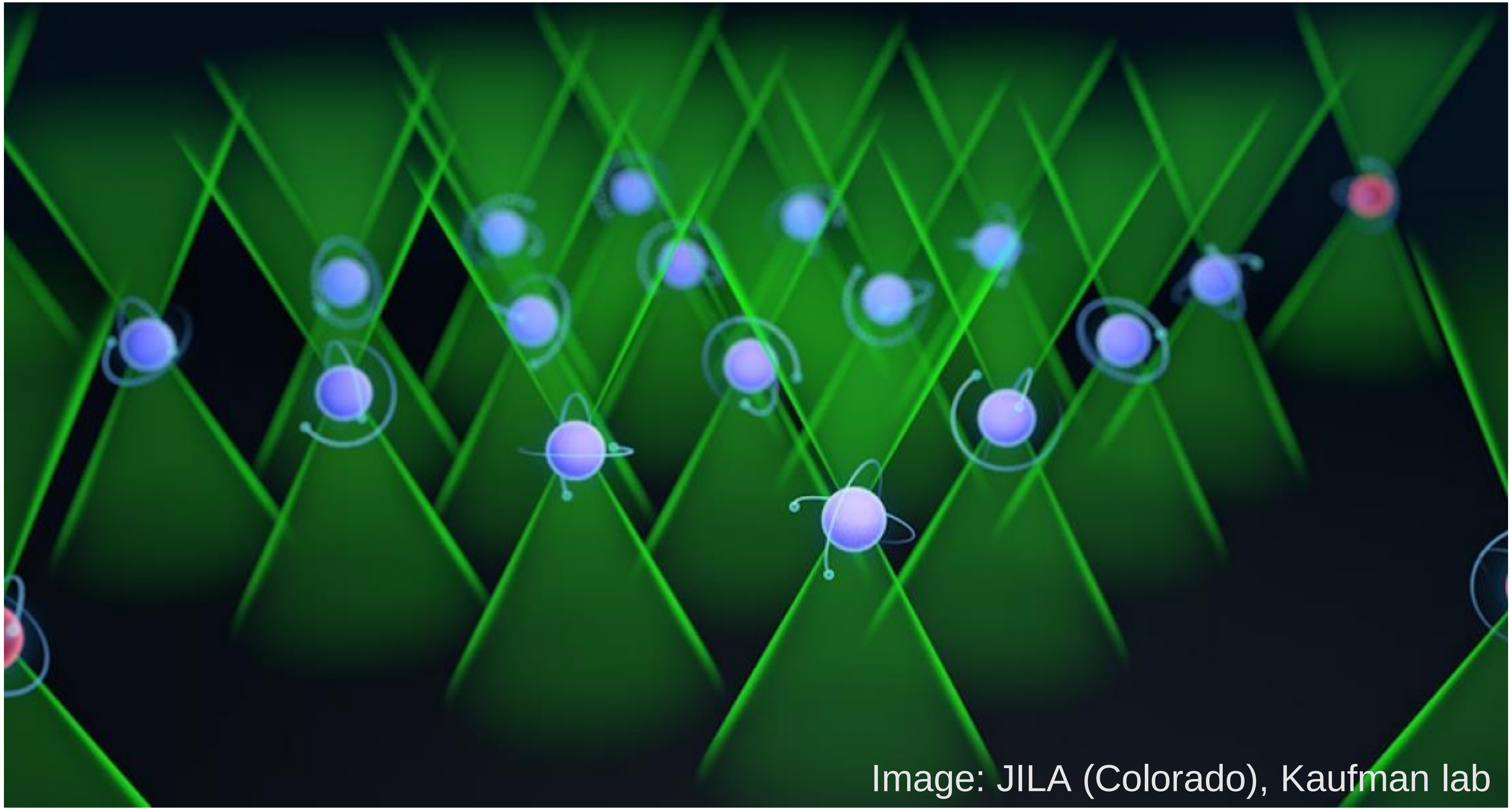
Location: bottom of the PX46 shaft. Systems in UX45 running



Location 3, wall of PX46. Earth (DC) field for scale

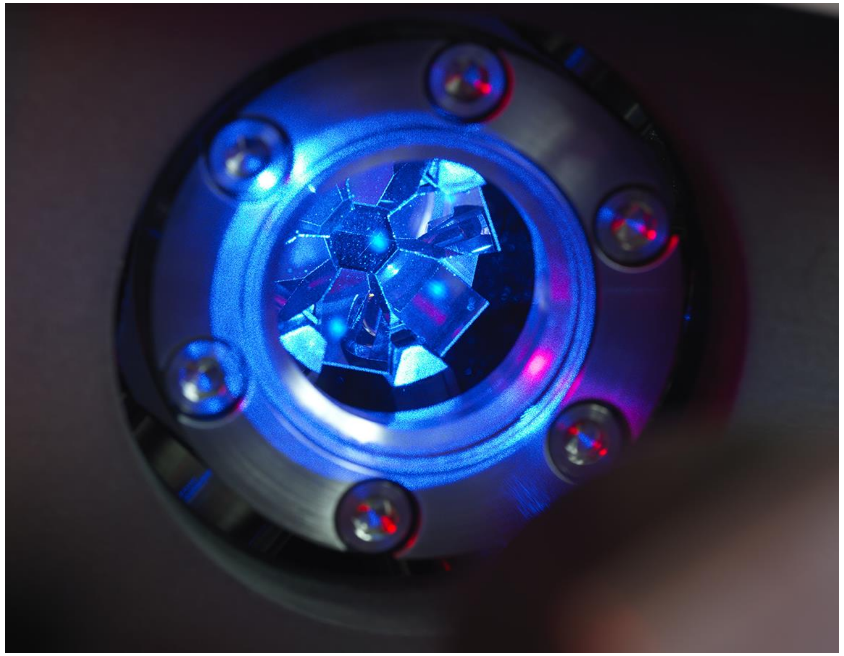
APPLICATIONS IN OTHER FIELDS, SUCH AS QUANTUM COMPUTING.

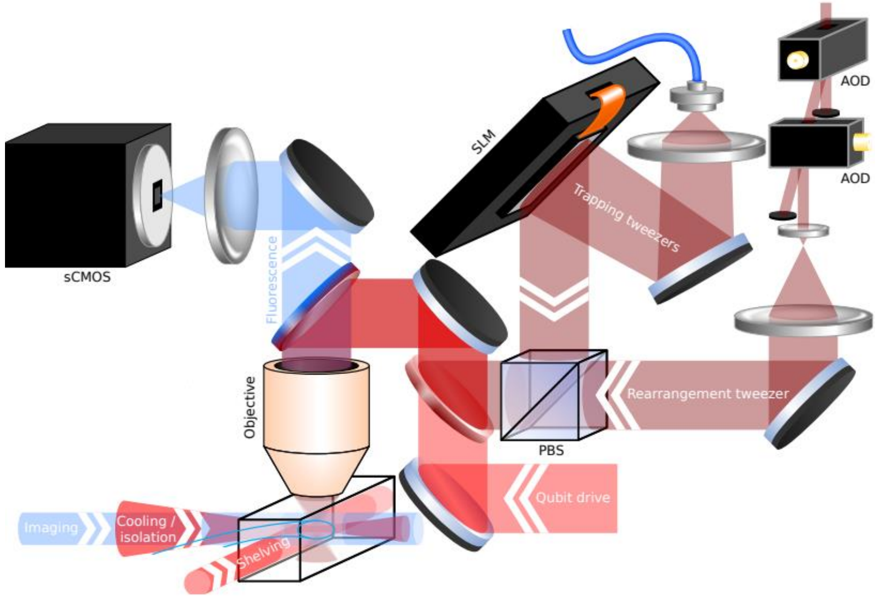
Quantum Computing & AION



Quantum Computing & AION

Existing AION cold Sr system (80%) + New tweezer array (20%) = Quantum computer

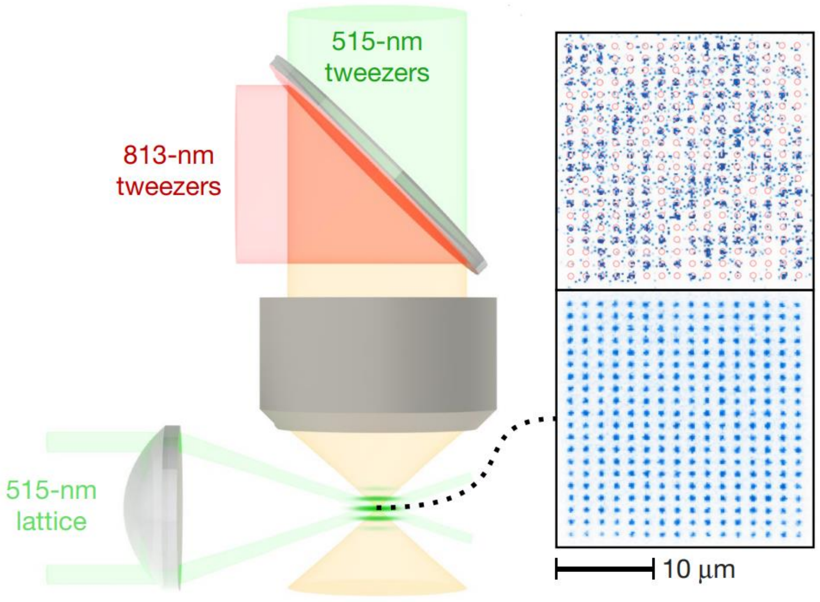




K. Barnes et al, https://arxiv.org/abs/2108.04790 (2021) – Atom Computing

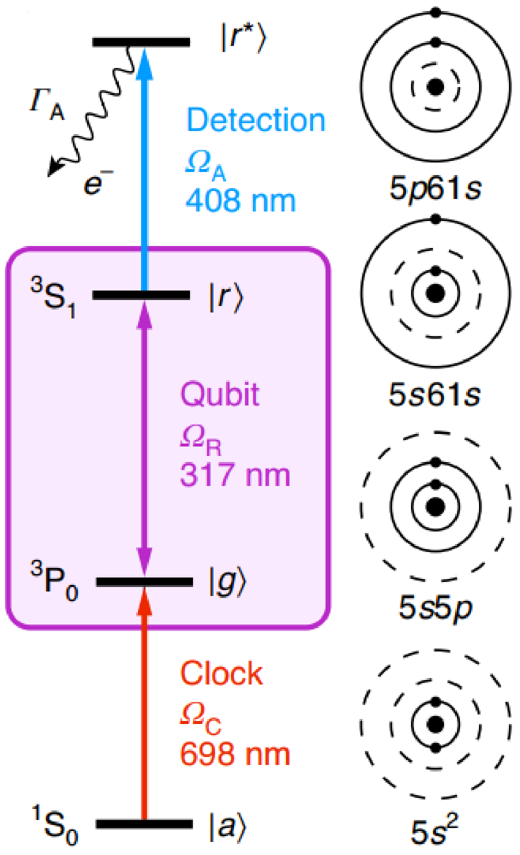
Quantum Computing & AION

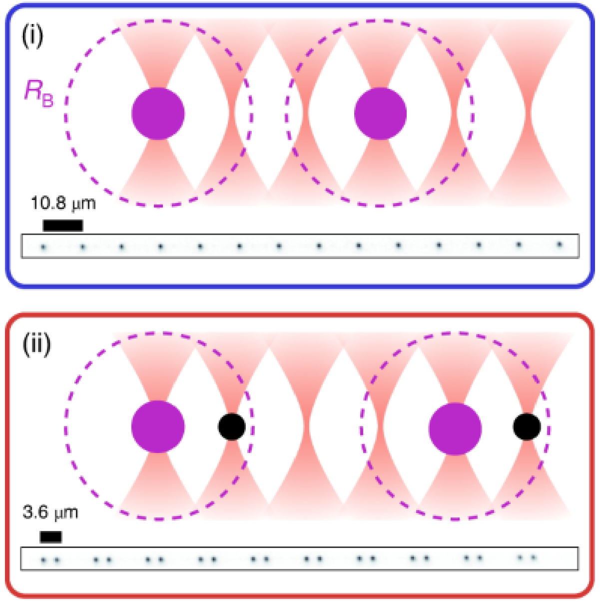
1 qubit = 1 Sr atom



A. W. Young et al, Nature 588, 408-413 (2020)
– JILA Colorado, Kaufman lab

Quantum logic gates (the hard bit!): Rydbergs

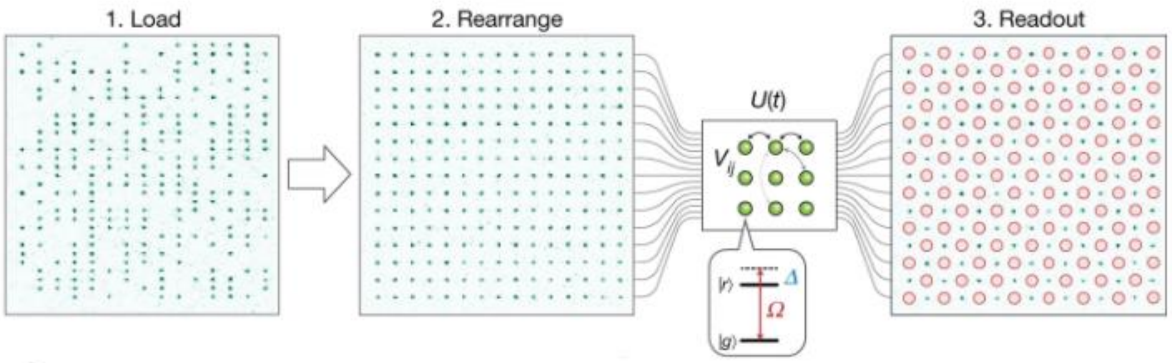




S. Madjarov et al. Nature Physics 16, 857-861 (2020)
– Caltec, Endres lab
99.9(2)% gate fidelity

Quantum Computing & AION

- Trapped-ion or superconducting qubits developed over ~ 20 years
- Tweezer array qubits started to emerge in the last ~ 10 years



Startups in neutral atom computing
https://atom-computing.com/ - $60M funding round, 2022
https://pasqal.io/about
https://coldquanta.com/core-technology/hilbert/
https://www.quera.com/
https://mobile.twitter.com/computingq

Why are we well placed to do this at Imperial?

- Atomic clocks → single qubit operations
- Squeezing → cavities to exchange atom vs photon qubits
- AION → robust, highly engineered Sr systems

Atoms in tweezers – some recent academic results:

S. Ebadi et al, Nature 595, 227-232 (2021) – Harvard, Lukin lab
A. W. Young et al, Nature 588, 408-413 (2020) – JILA, Kaufman lab
S. Madjarov et al. Nature Physics 16, 857-861 (2020) – Caltec, Endres lab
P. Scholl et al, Nature 595, 233-238 (2021) – CNRS, Bronwaes lab

Why Space?

One important argument in favour of Space (vs Earth) is interrogation time T of the atoms in free fall conditions.

To better understand this, it is useful to look at the short-term sensitivity to acceleration of an Atom Interferometer:

$$\delta g = \frac{\delta\phi}{nkT^2} \qquad [\mathrm{m/s^2/\sqrt{Hz}}]$$

where $\delta\phi$ is the atom-phase-resolution of the interferometer, n is the number of Large Momentum Transfer pulses, k is the effective wave-number of the atomic transition and T is the interrogation time between interferometer pulses.

On Earth, many interferometry experiments are limited by their free-fall interrogation times T, achieved through launching or dropping atom clouds at some limited distance above the floor. In space this limitation is removed, leading to potentially large improvements in performance.

Example:
Taking AION-10 goal as reference, we are planning to demonstrate that AION-10 can reach on earth with an interrogation time T ~1s a dg of about 5.7x1E-13 in 2024. In space, we estimate we could reach T~20sec and, thus, reach 3.9x1E-14 (factor ~15 better).

Why Atom Interferometry in Space?

$$\Delta g = \frac{1}{kT^2\sqrt{N}}$$

GRACE reference:
ONERA Superstar
Accelerometer: 10^{-10} m/s^2

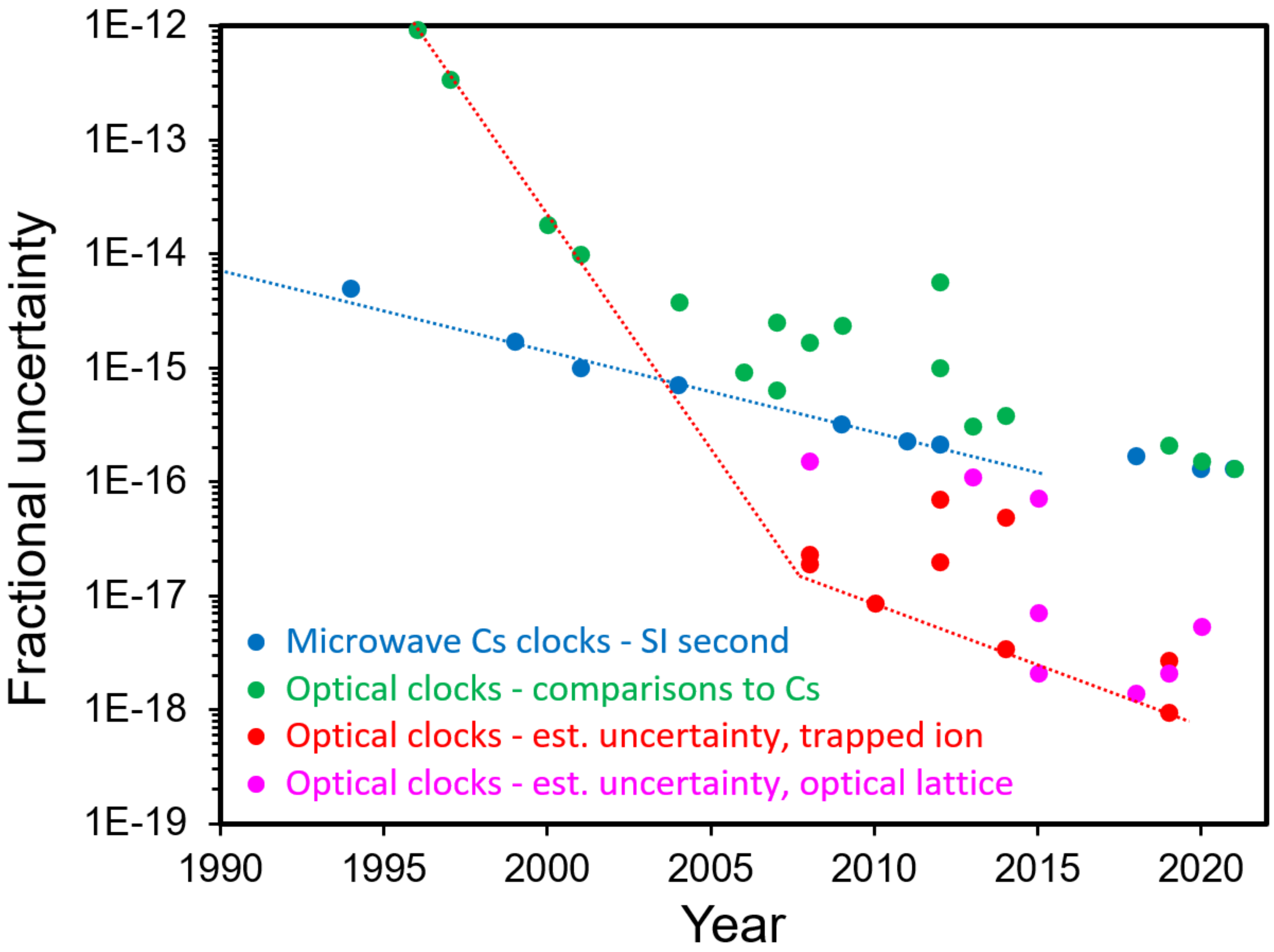
T=100ms N=10^6	T=1s N=10^6	T=10s N=10^6	T=1s N=10^6 100 pulses	T=1s N=10^8 1000 pulses
6 10^{-9} m/s^2	6 10^{-11} m/s^2	**6 10^{-13} m/s^2**	6 10^{-13} m/s^2	3 10^{-14} m/s^2

Large T → large sensitivity

ROADMAP

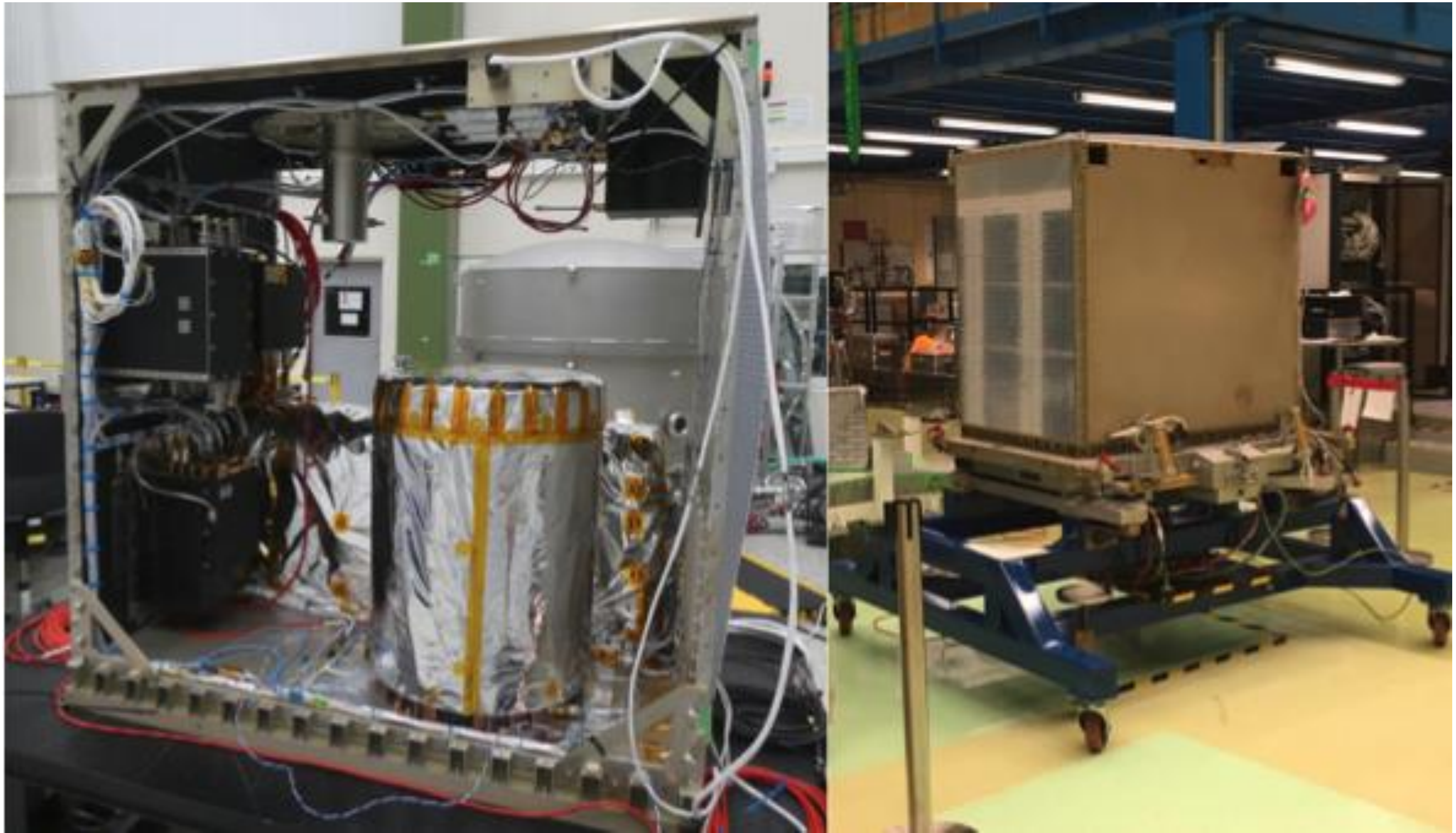
Atomic Clock Progress

use for next-generation SI time standard worldwide?



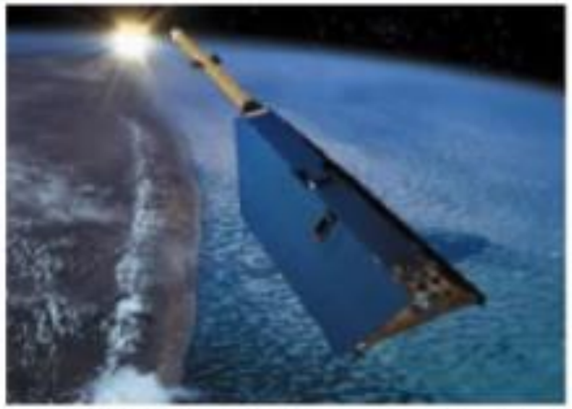
Atomic Clock Progress

ACES atomic clock mission: scheduled launch to ISS 2025

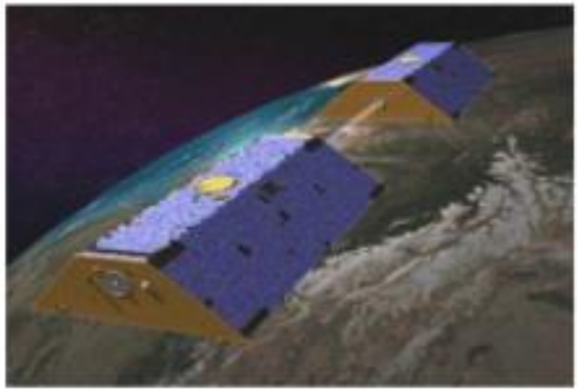


Earth Observation Progress

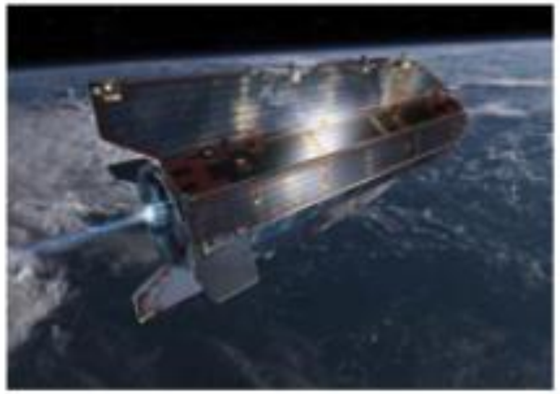
Earth Observation: using classical electrostatic accelerometers & gradiometers



CHAMP : satellite tracking by GNSS + accelerometry



GRACE and GRACE-FO: orbit determination + satellite-to-satellite tracking + accelerometry

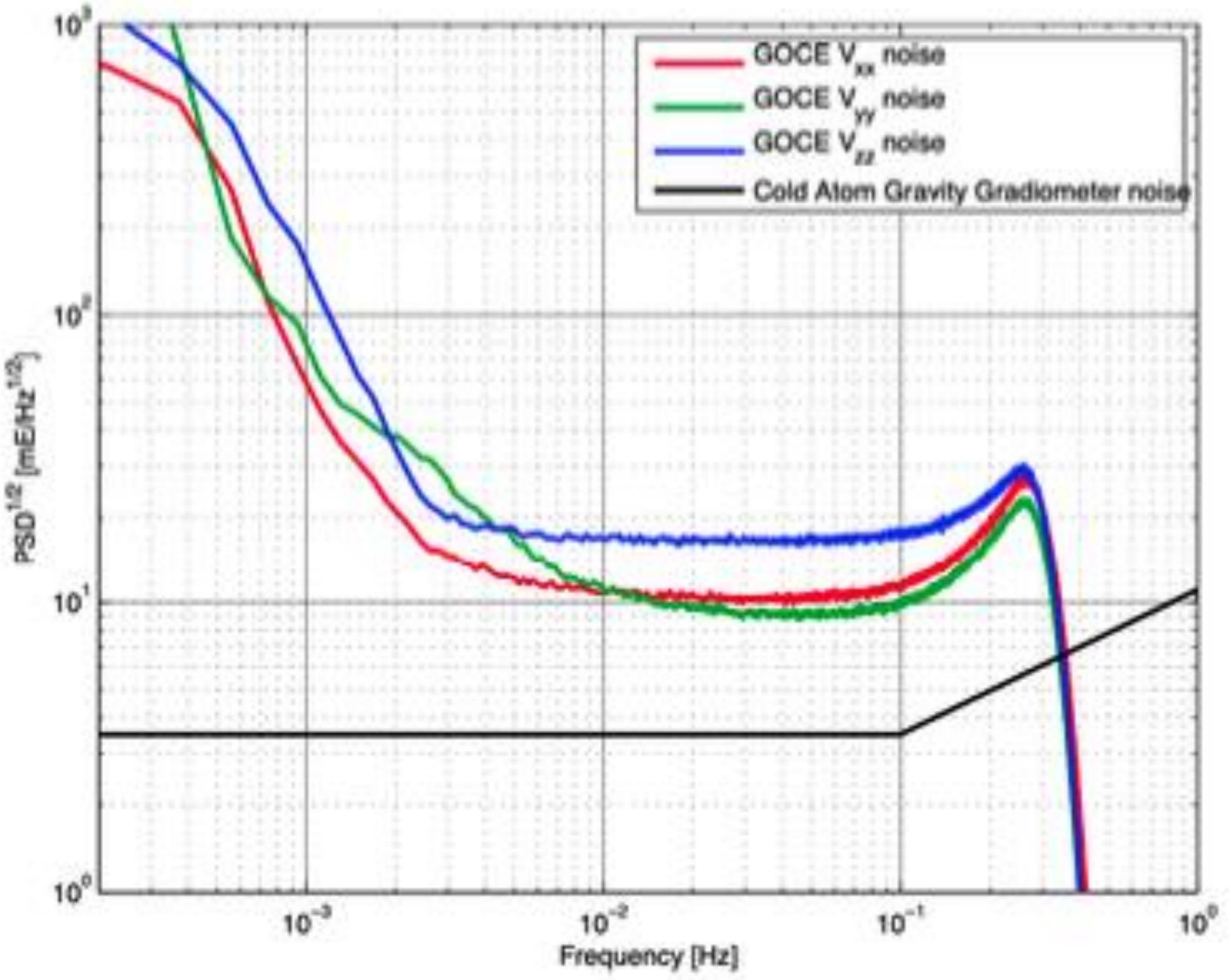


GOCE: orbit determination + gradiometry

	CHAMP 2000 - 2010	GRACE/GRACE-FO 2002 - ongoing	NGGM Launch scheduled 2028	GOCE 2009 - 2013
Measurement type		Monitoring gravity field time variations		Static gravity field
EA accuracy	$\sim 10^{-10}$ m/s^2	$\sim 10^{-11}$ m/s^2	$\sim 10^{-11}$ m/s^2	$\sim 10^{-12}$ m/s^2
Geoid undulations	$\sim$ 10 cm @350 *km*	$\sim$ 10 cm @175 *km*	$\sim$ 1 mm @ 500 km every 3 days $\sim$ 1 mm @ 150 km every 10 days	$\sim$ 1 cm @100 *km*
Gravity anomalies	$\sim$ 0.02 mGal @1000 *km*	$\sim$ 1 mGal @175 *km*		$\sim$ 1 mGal @100 *km*

Earth Observation Progress

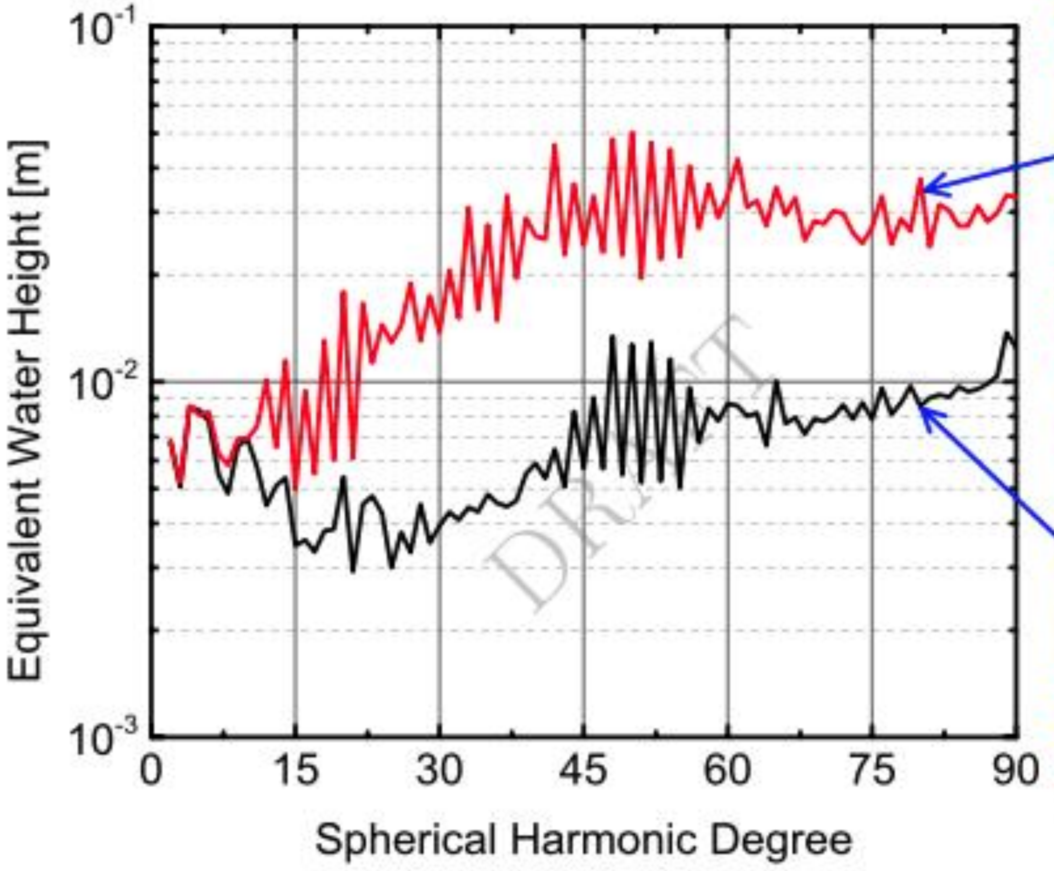
Frequency Sensitivity advantage of cold atom gravity gradiometers at low frequency, no drift

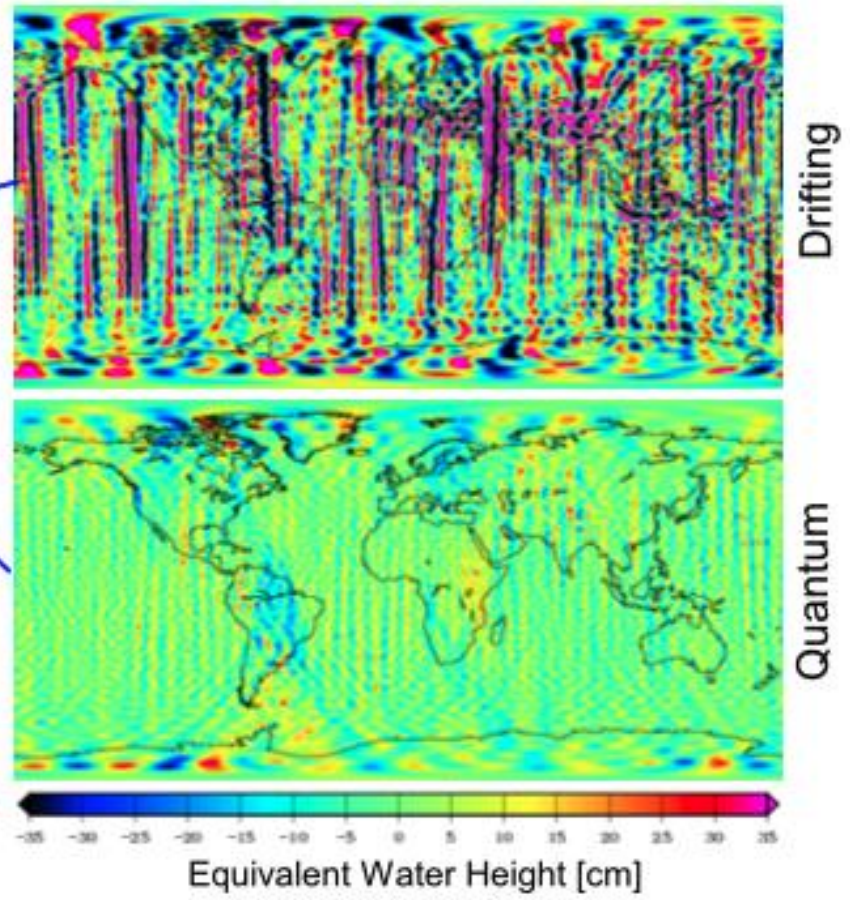


Earth Observation Progress

Sensitivity to Water Height

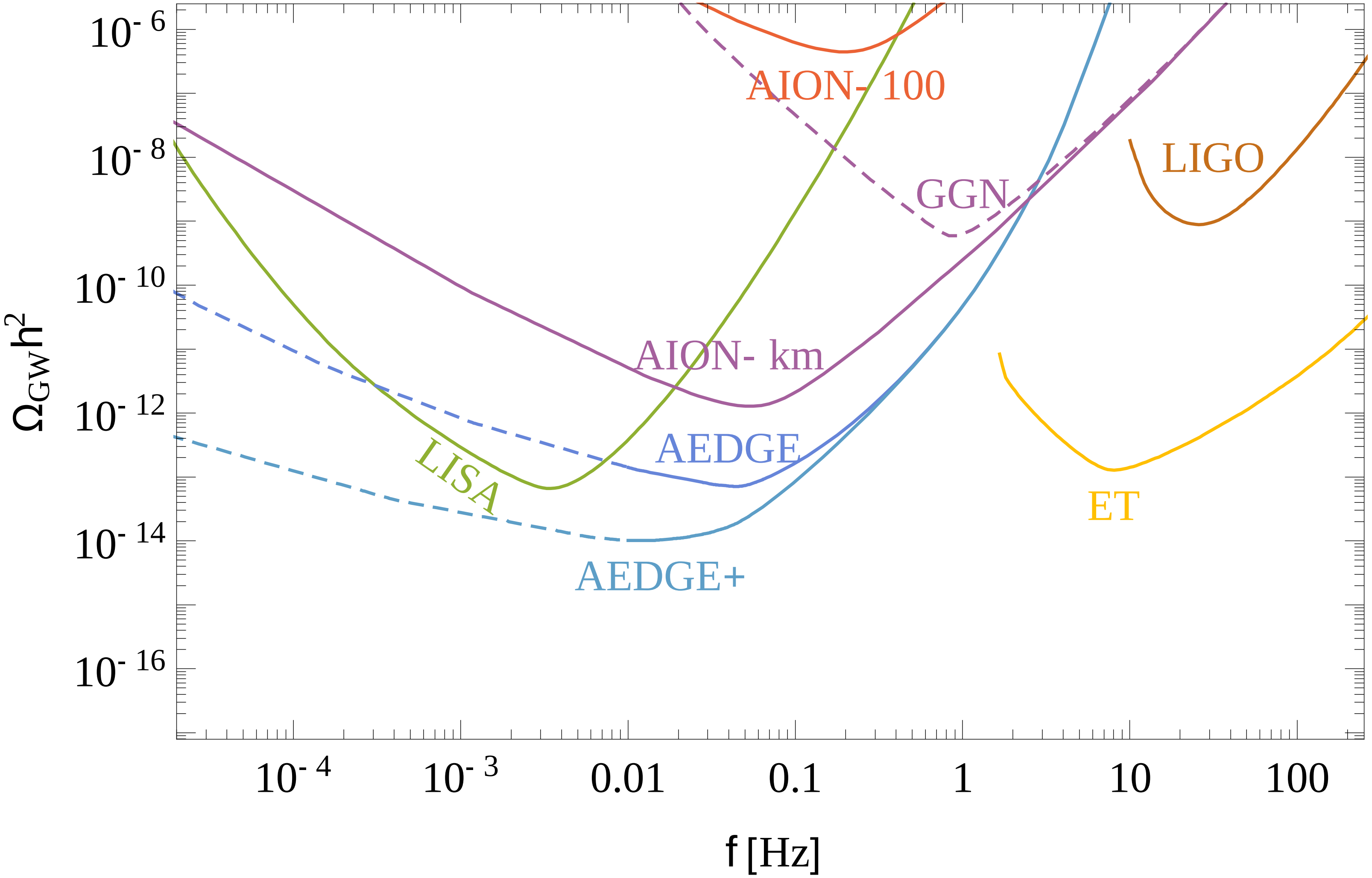
crucial for monitoring climate change





Vision for 2045+

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



Translate Stain sensitivity into the dimensionless energy density of a GW

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

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

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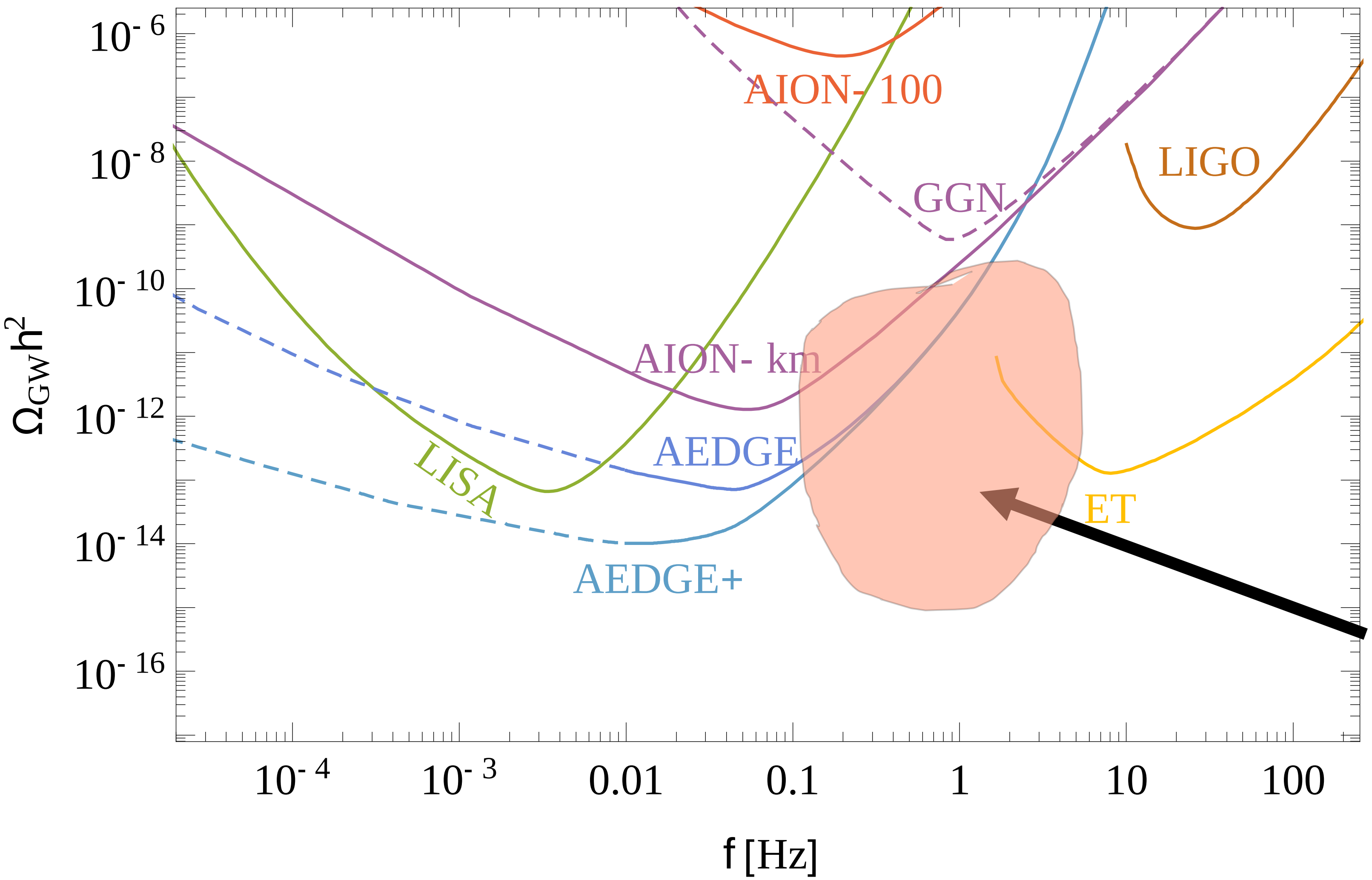


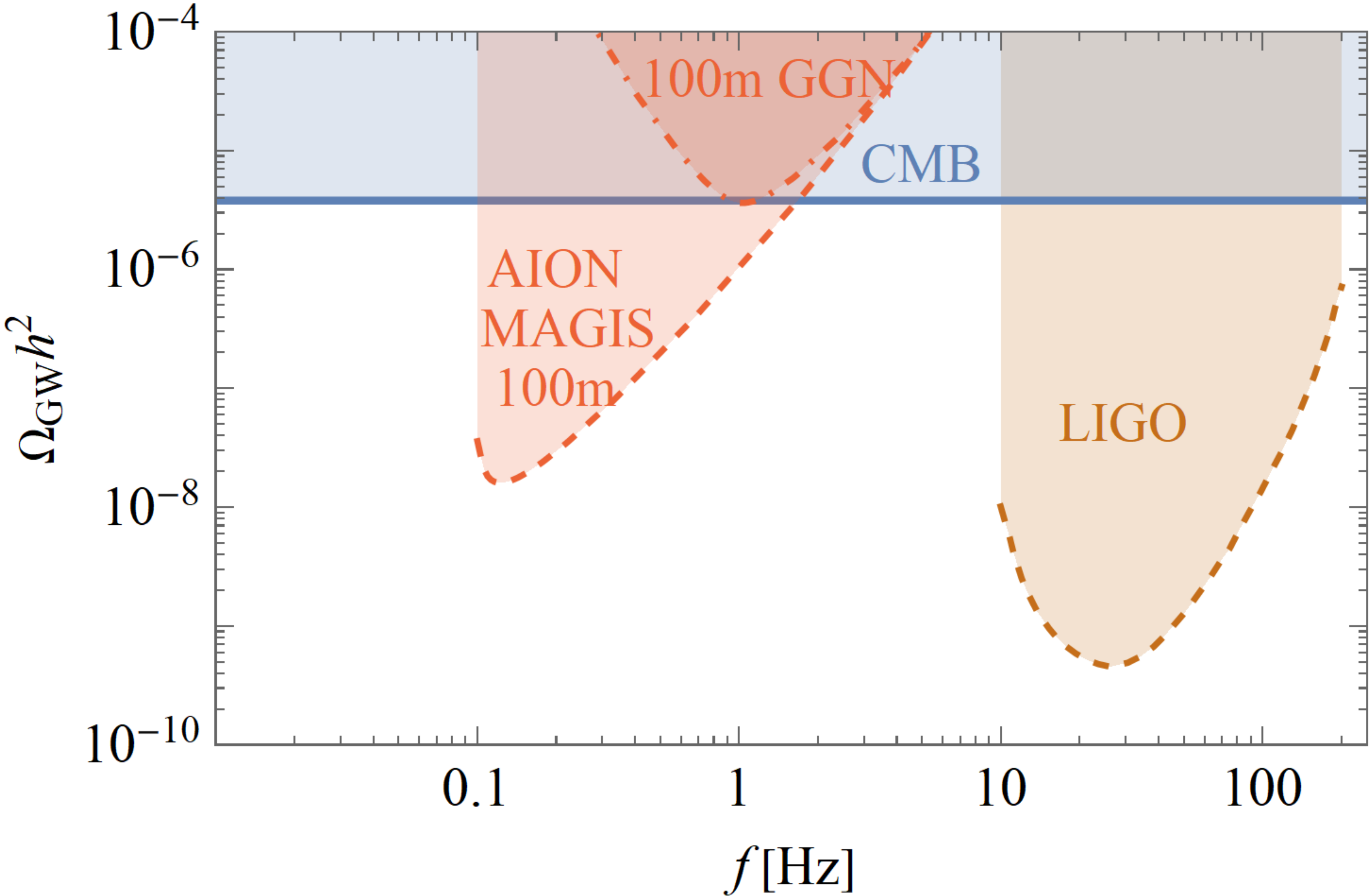
Translate Stain sensitivity into the dimensionless energy density of a GW

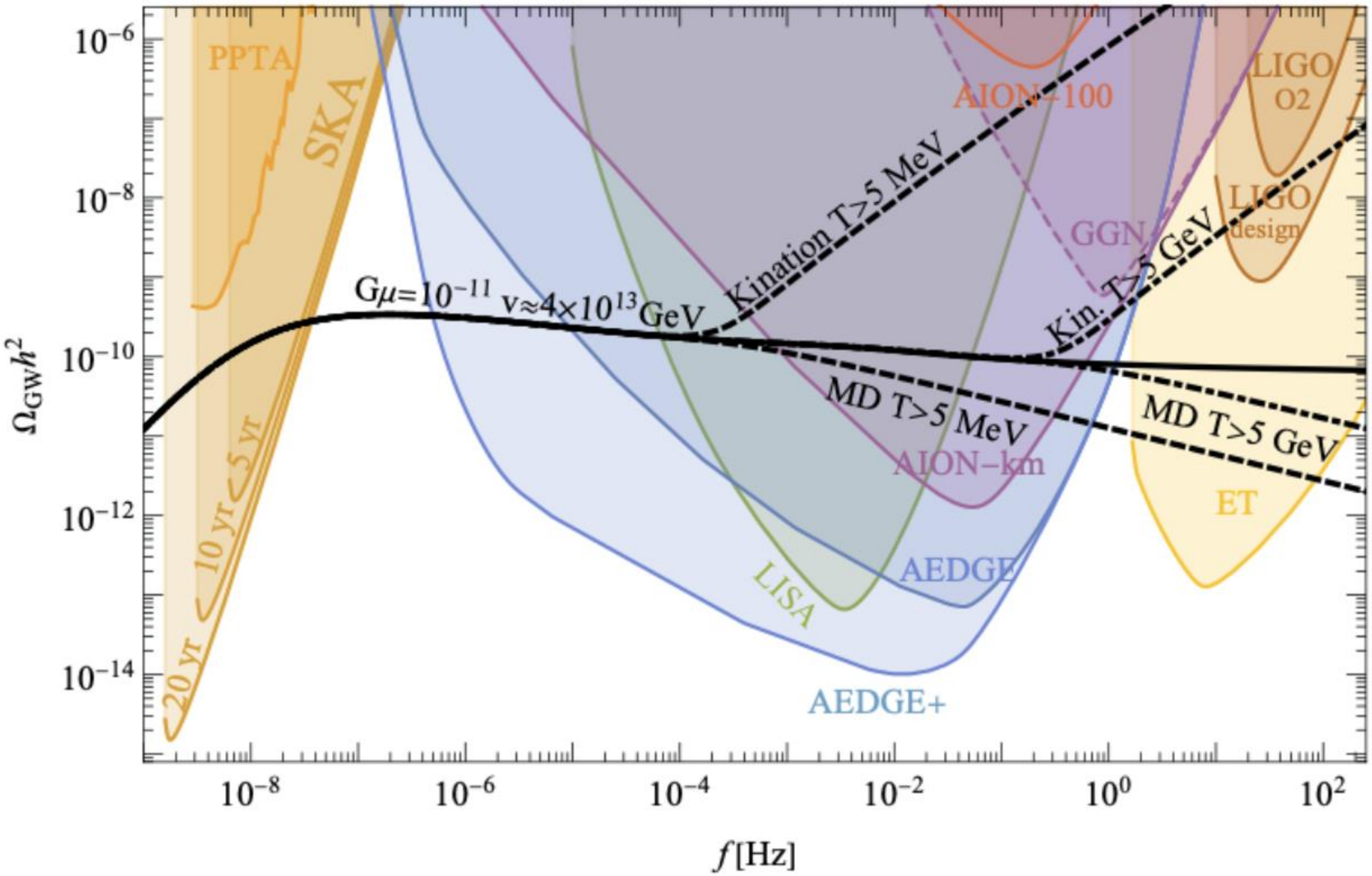
Still a "gap" around 1Hz
Need to find a solution to fill it

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

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

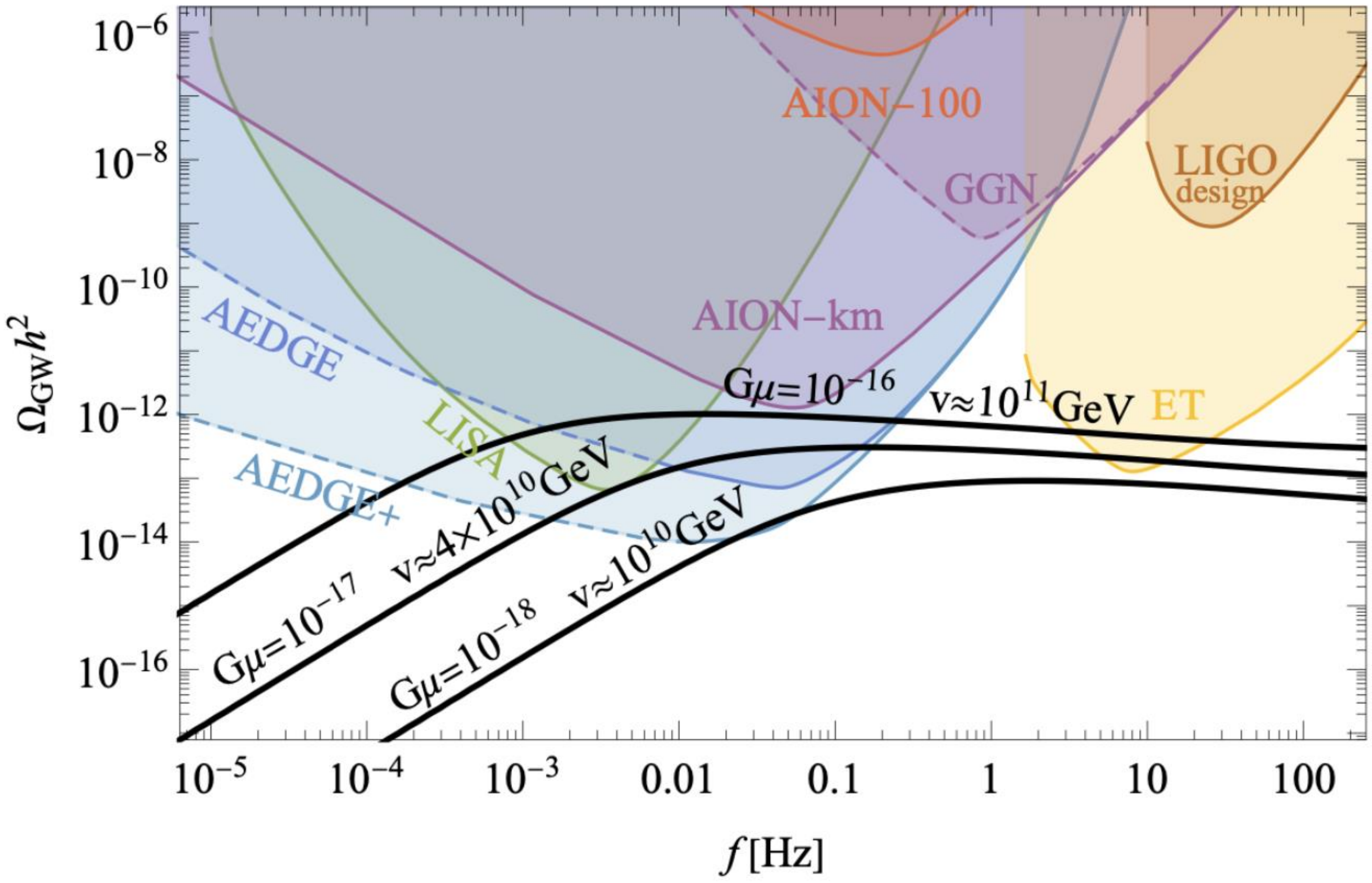
The GW Experimental Landscape: 2030ish





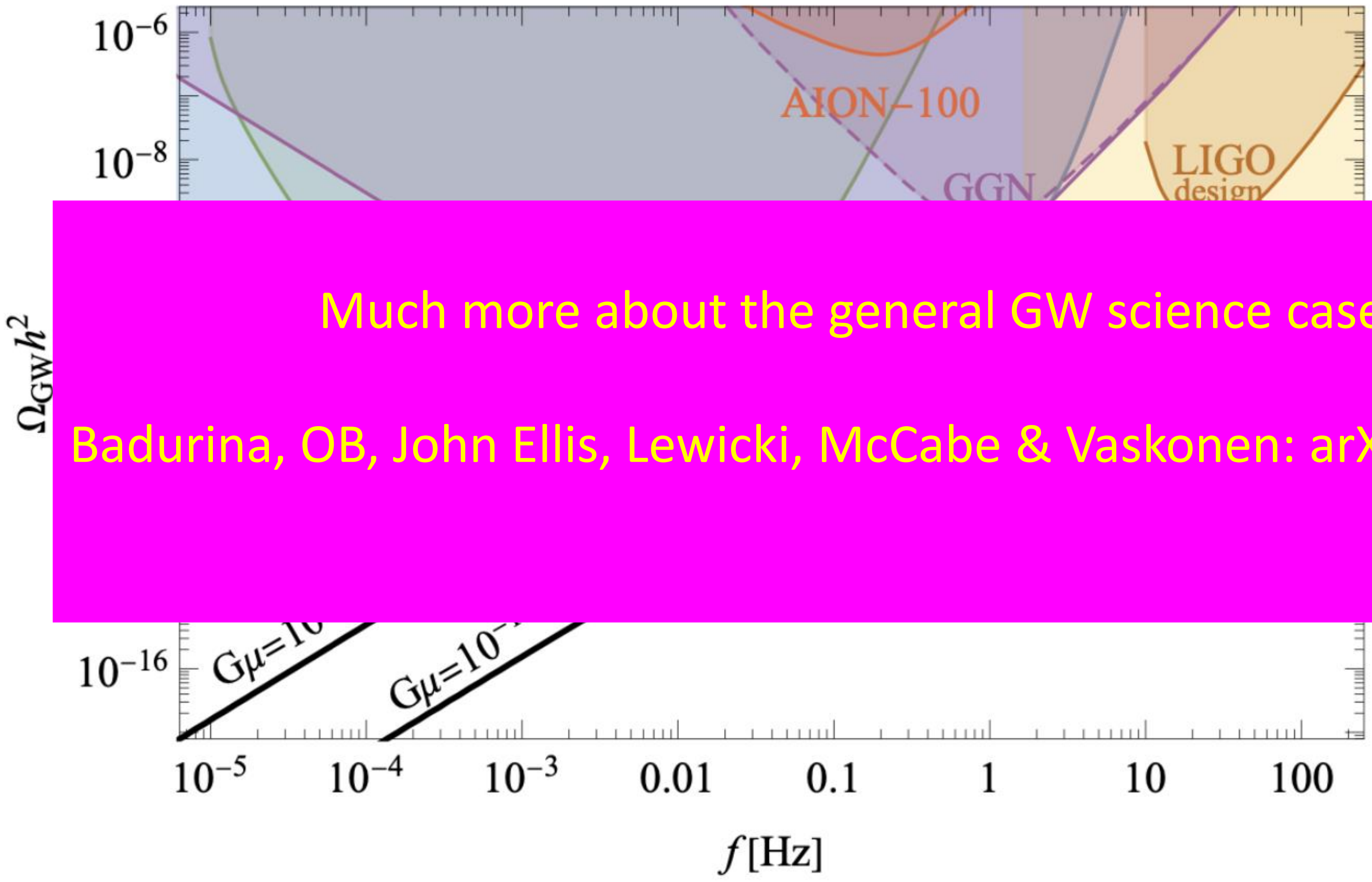
Comparison of the Ω sensitivities to PI spectra of AION-100, AION-km, AEDGE and AEDGE+, LIGO, ET, Pulsar Timing Arrays (PTAs) and SKA.

Sensitivities of cosmic string measurements to modifications of the cosmological expansion rate. Kination or matter dominance (MD) at temperatures T > 5 *MeV or* 5 *GeV.*



Different experiments sensitive to different values of cosmic string tension

Sensitivities to the cosmic strings with tension $G\mu$ of AION-100 and -km, AEDGE and AEDGE+, LIGO, ET and LISA.



Much more about the general GW science case in:

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

Different experiments sensitive ... es of cosmic ... nsion

Sensitivities to the cosmic strings with tension Gμ *of AION-100 and -km, AEDGE and AEDGE+, LIGO, ET and LISA.*

Earth Observation Progress

Requirements & Objectives

Threshold requirements

Spatial resolution	Equivalent water height: Monthly field	Equivalent water height: Long-term trend	Geoid: Monthly field	Geoid: Long-term trend
400 km	5 mm	0.5 mm/yr	50 μm	5 μm/yr
200 km	10 cm	1 cm/yr	0.5 mm	0.05 mm/yr
150 km	50 cm	5 cm/yr	1 mm	0.1 mm/yr
100 km	5 m	0.5 m/yr	10 mm	1 mm/yr

Target objectives

Spatial resolution	Equivalent water height: Monthly field	Equivalent water height: Long-term trend	Geoid: Monthly field	Geoid: Long-term trend
400 km	0.5 mm	0.05 mm/yr	5 μm	0.5 μm/yr
200 km	1 cm	0.1 cm/yr	0.05 mm	5 μm/yr
150 km	5 cm	0.5 cm/yr	0.1 mm	0.01 mm/yr
100 km	0.5 m	0.05 m/yr	1 mm	0.1 mm/yr

Fundamental Physics Part

Tests of Weak Equivalence Principle (Universality of Free Fall)

Class	Elements	η	Year [ref]	Comments
	Be - Ti	2×10^{-13}	2008 [200]	Torsion balance
Classical	Pt - Ti	1×10^{-14}	2017 [179]	MICROSCOPE first results
	Pt - Ti	(10^{-15})	2019+	MICROSCOPE full data
	^{133}Cs - CC	7×10^{-9}	2001 [204]	Atom Interferometry
Hybrid	^{87}Rb - CC	7×10^{-9}	2010 [205]	and macroscopic corner cube
	^{39}K - ^{87}Rb	5×10^{-7}	2014 [206]	different elements
	^{87}Sr - ^{88}Sr	2×10^{-7}	2014 [207]	same element, fermion vs. boson
Quantum	^{85}Rb - ^{87}Rb	3×10^{-8}	2015 [208]	same element, different isotopes
	^{85}Rb - ^{87}Rb	3.8×10^{-12}	2020 [209]	≥ 10 m towers
	^{85}Rb - ^{87}Rb	(10^{-13})	2020+ [210]	
	^{170}Yb - ^{87}Rb	(10^{-13})	2020+ [211]	
	^{41}K - ^{87}Rb	10^{-17}	2035+	STE-QUEST-like mission
Antimatter	$\overline{\text{H}}$ - H	(10^{-2})	2020+ [212]	under construction at CERN