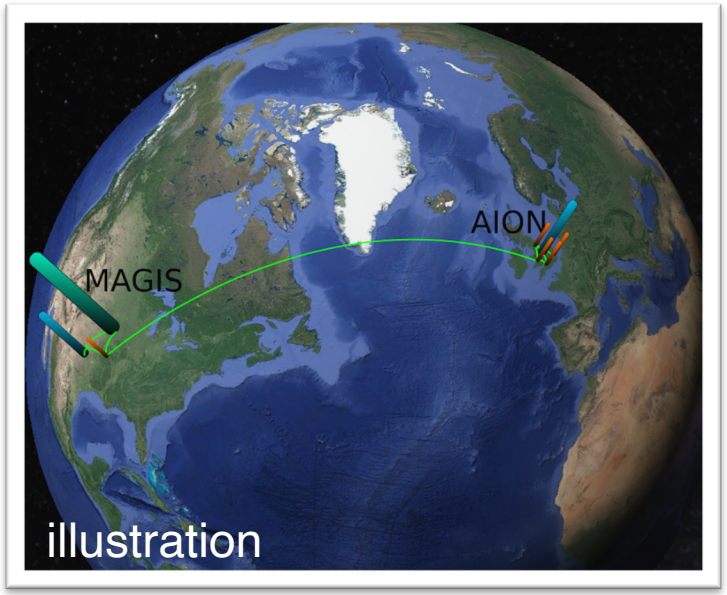
Imperial College London



The AION Project

A UK Atom Interferometer Observatory and Network

to explore Ultra-Light Dark Matter and Mid-Frequency Gravitational Waves.

O. Buchmueller, Imperial College London on behalf of the AION Collaboration

L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4], D. Bortoletto[3], T. Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman[5], G. Elertas[5], J. Ellis[1,$,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*], M. Holynski[4], A. Khazov[2], M. Langlois[4], S. Lellouch[4], Y.H. Lien[4], R. Maiolino[7], P. Majewski[2], S. Malik[6], J. March-Russell[3], C. McCabe[1], D. Newbold[2], R. Preece[3], B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. Singh[4], M. Tarbutt[6], M. A. Uchida[7], T. V-Salazar[2], M. van der Grinten[2], J. Vossebeld[4], D. Weatherill[3], I. Wilmut[7], J. Zielinska[6]

[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge

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**

Progressive Expansion of Quantum Detector in Length

Stage Expansion of Detector Length**

Stage 1: 2021 to 2025

- 10m detector protype to be build in Oxford (see backup).

Stage 2: 2023 to 2030

100m detector: Site options are *Boulby or Daresbury (UK), possibly also at CERN (France/Switzerland).*

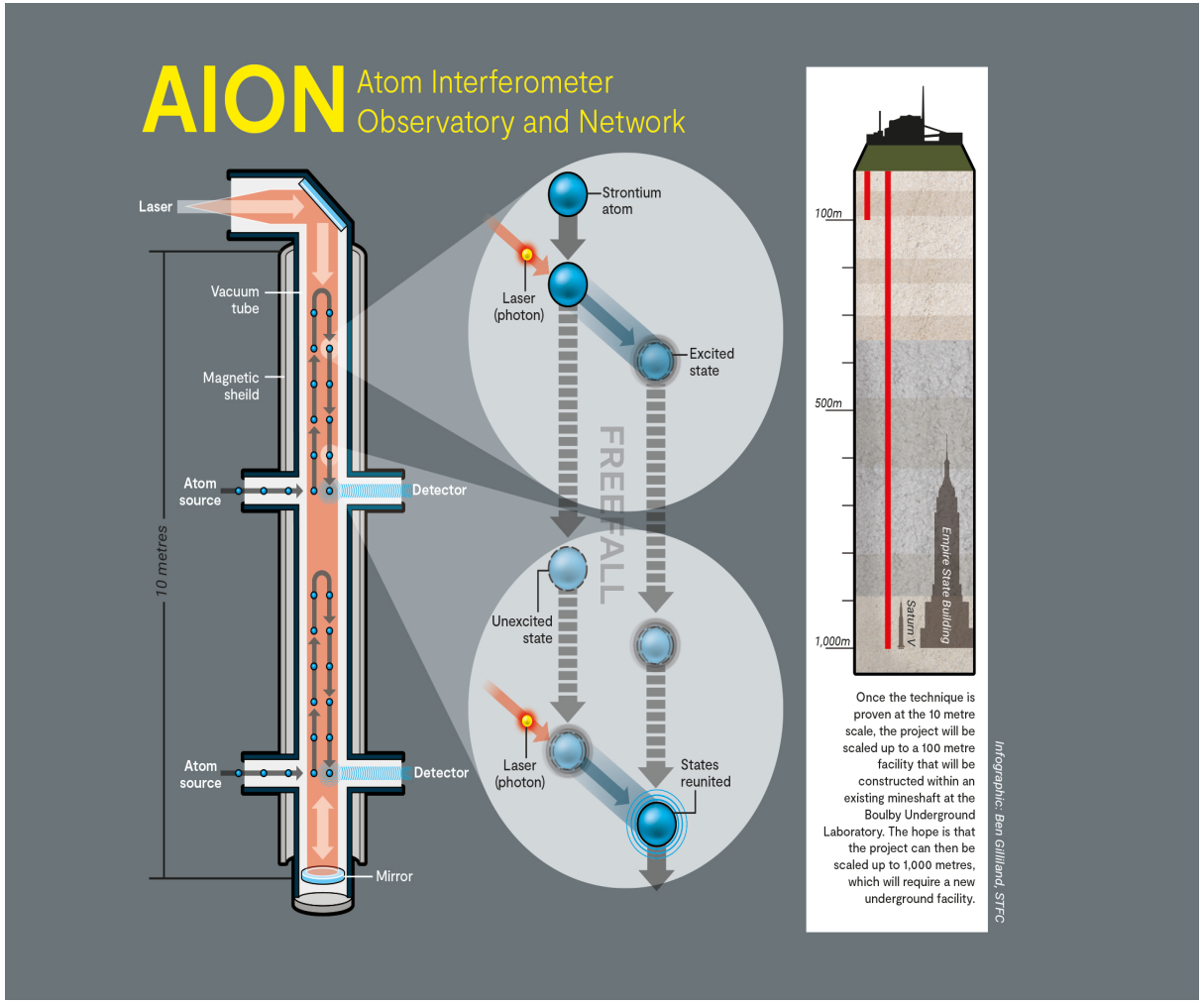
We agreed to do survey measurements at Boulby in summer

Stage 3: 2030 onwards

- Km-scale detector: Site options are *Boulby (so far).*
- Submitted for IAG Future Projects.

** Sensitivity scales with length of detector

Illustration of different Stages



Preliminary Activity Submission for the IAC (UKRI Infrastructure)

In the solicited Preliminary Activity Submission to the IAC in 2020 we proposed two options for km-scale

- ***Building the km-scale detector in an existing mine shaft (e.g. in one of the two 1.1km vertical shafts at the Boulby mine);***
- ***Building the km-scale detector in a new km-deep vertical shaft excavated at a facility like Boulby.***

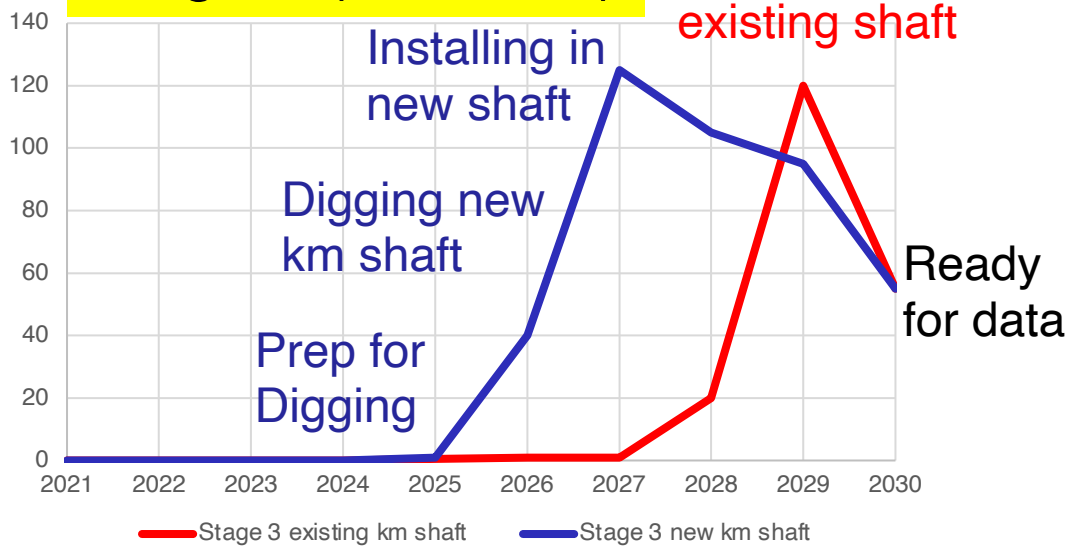
Depending on the scenario, we estimated budgets and timelines, where the "new shaft option" estimate includes a provision of £175M** to build a dedicated new km-deep shaft.

Remark: As a major international facility, we would expect to follow the conventional model of attracting buy-in (via cash, in-kind contributions or reciprocal access agreements) by international partners in return for rights to data exploitation. In past projects at this scale, the host nation has typically contributed between 25-50% of the total cost.

** this number needs further scrutiny

Very Preliminary: Timeline and "Activity Profile"**

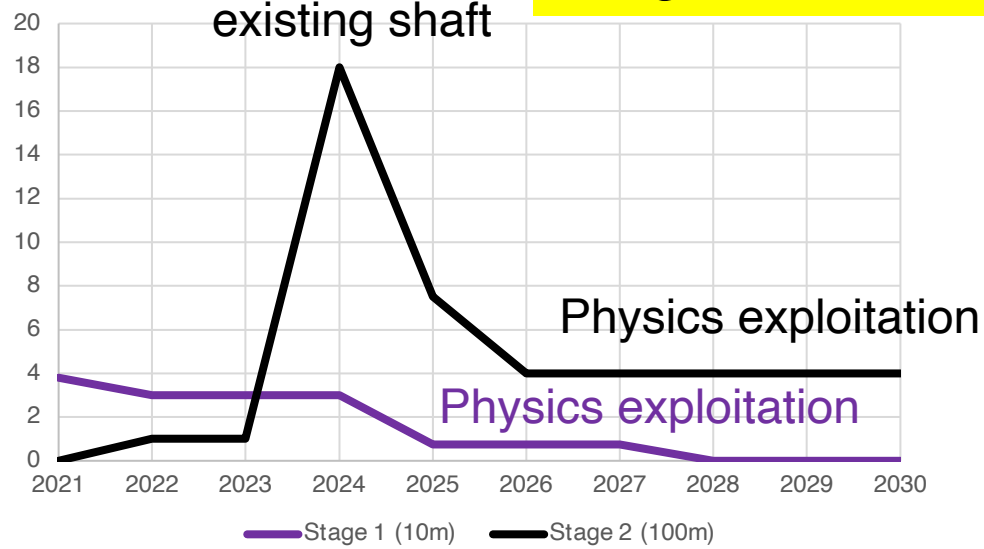
Stage 3 (km scale)



New Shaft:
Prepare for Digging 2025
Digging New shaft 2026/27
Installation 2027/28
Commissioning 2029
Ready for data 2030/31

Existing Shaft:
Installation 2027/28
Commissioning 2029
Ready for data 2030/31

Stage 1 and 2

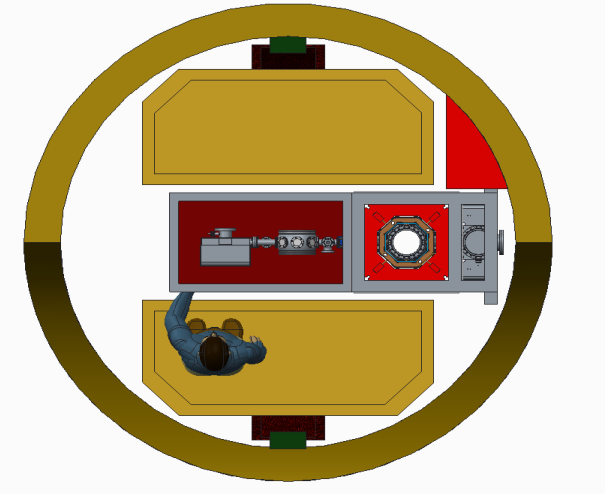


Stage 1 (10m):
Prepare 10m 2021/22
Installation 10m 2023
Commissioning 2023
Physics 2024 to 2027

Stage 2 (100m):
Prepare 100m 2022/23
Installation 2023/24
Commissioning 2025
Physics 2026 to 2030

** activity profile is obtained from a very preliminary spending profile

A new “Science Shaft” at Boulby



- Stage 3 od the AION programme (km-scale detector) would represent a new national/international infrastructure, complementary to existing UK ‘big science’ facilities.
  - Therefore, considering the option of a new dedicated km-shaft for AION does not seem unrealistic.

What are the minimal constraints to host AION in a shaft:

Shaft

2.4m diameter shaft

Round

Perfectly vertical – any incline or bend will require a larger shaft

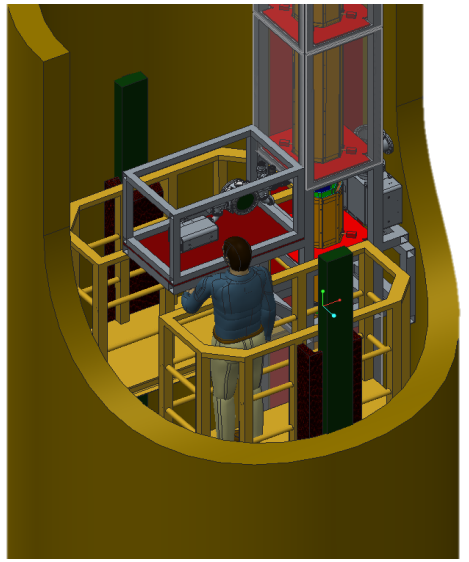
Platforms

2 independent access platforms in shaft

Each platform large enough for 2 people

Platforms to be able to carry atom sources, ion pumps up and down etc.

NOT free hanging, needs rails (avoids swinging cage colliding with detector



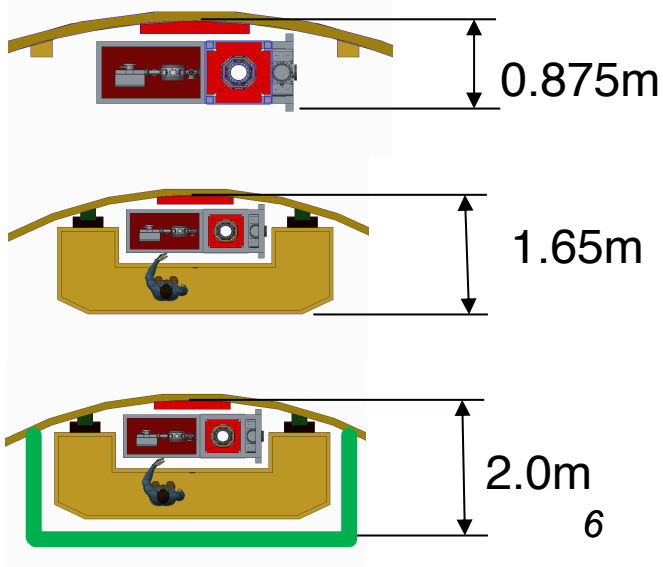
A new "Science Shaft" at Boulby Cont.

- Stage 3 od the AION programme (km-scale detector) would represent a new national/international infrastructure, complementary to existing UK 'big science' facilities.
  - Therefore, considering the option of a new dedicated km-shaft for AION does not seem unrealistic.

There is also the option to consider a (much) larger shaft

- Hosting AION in a much larger shaft is also an option, as the experiment is not requiring much space.
- A larger shaft could have the option to exploit synergies with other experiments that require "space" for lowering equipment and detector components into the Boulby caverns (e.g. 3G)
- As long as shaft access requirements are infrequent and scheduled in advance this could be made part of AION operation.

Example 20m diameter shaft



AION Proposal: Include "science shaft" in scope of Feasibility Study

- We believe that it would be beneficial to extend the current scope of the Boulby feasibility study to include also the option of a dedicated "science shaft".
  - *There are several ways to do this inclusion, and we should discuss options that fit best the timeline of the activity.*

- The case for AION to be hosted in a new national / international research infrastructure at the STFC Boulby underground laboratory alone would warrant the consideration of a dedicated new shaft. This case could be further strengthened if synergies for a science shaft with other underground experience could be identified.

SLIDES FROM 1ST BOULBY FEASIBILITY STUDY MEETING

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.

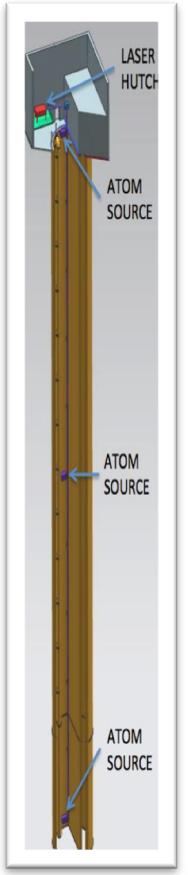
L ~ 10m

- **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 £9.6M 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).



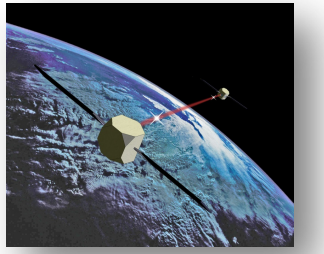
- **Stage 3:** to build a kilometre-scale terrestrial detector.

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



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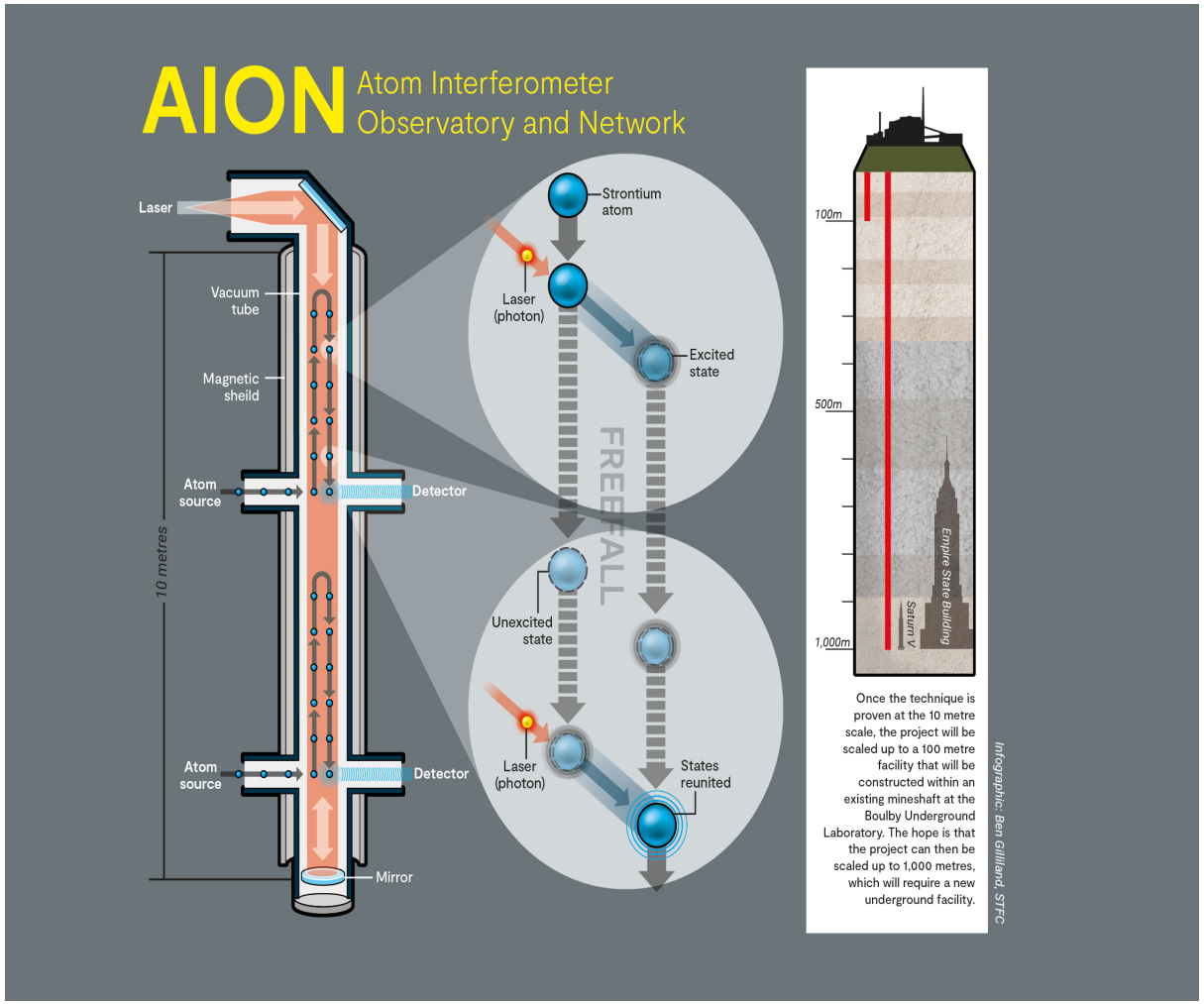


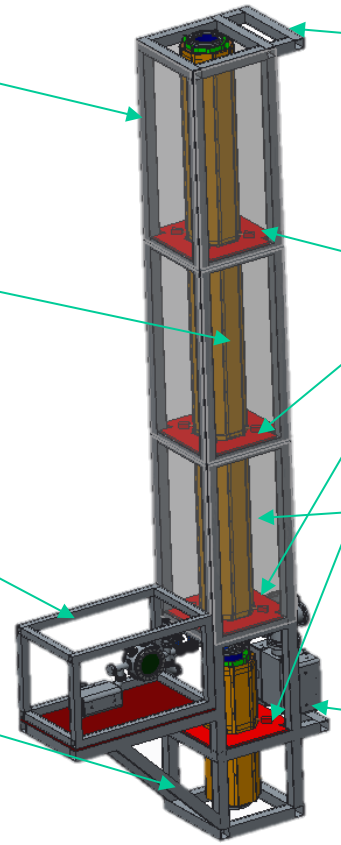
AION: Design & Construction: Module Assembly

Welded steel (or SS) frame

Segmented Shielding (2 layers)

Atom source in removable cage

Side platform for atom source



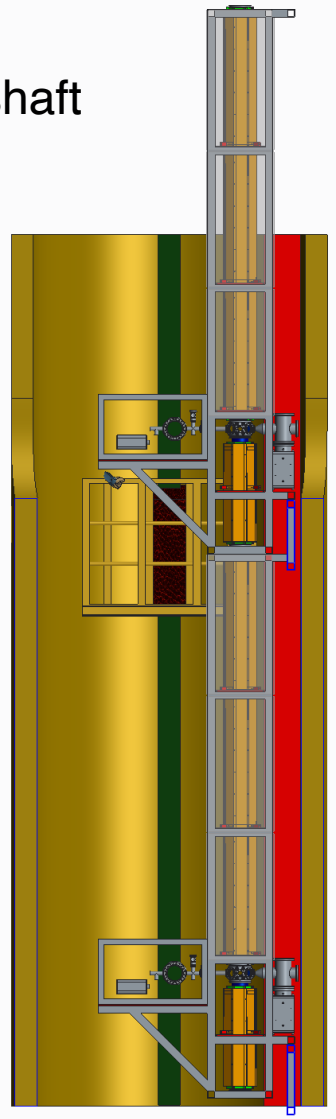
Interface to attach to shaft brackets

4x supports along 5m length

Structure has closure panels to help keep things clean

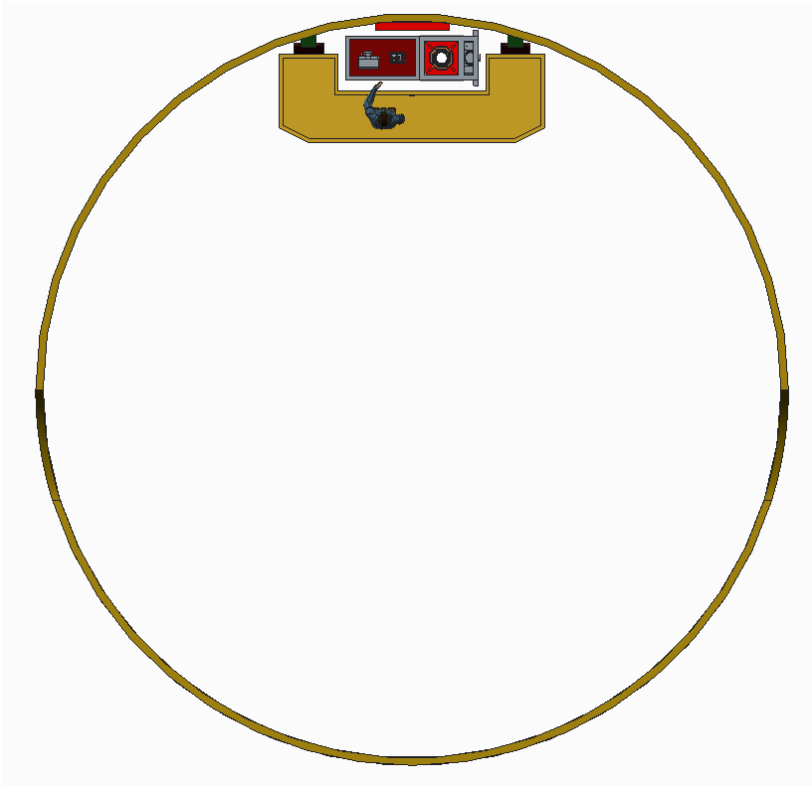
Removable Ion pump

Two modules in shaft



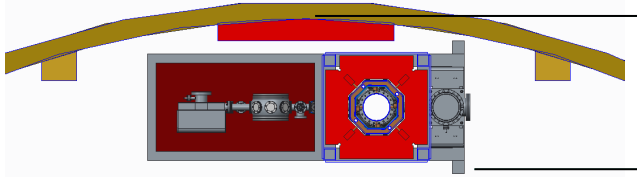
1 x module – 5m

Larger Shafts Design (relevant for Boulby and CERN)

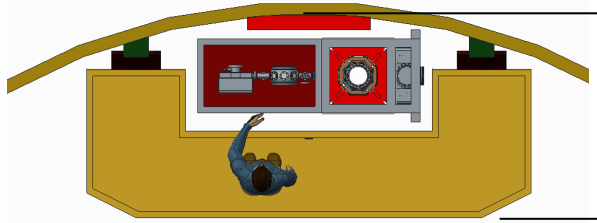


20m diameter shaft with AION installed and access platform in place

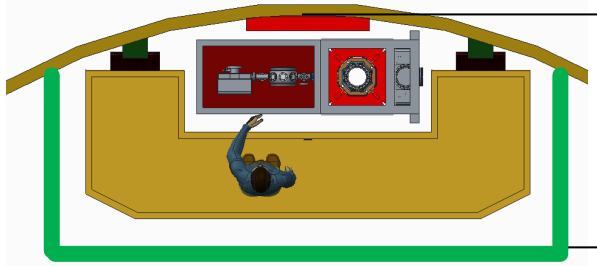
Incursion into shaft of experiment



Incursion into shaft of experiment and access platform



Incursion into shaft of experiment and access platform and cage



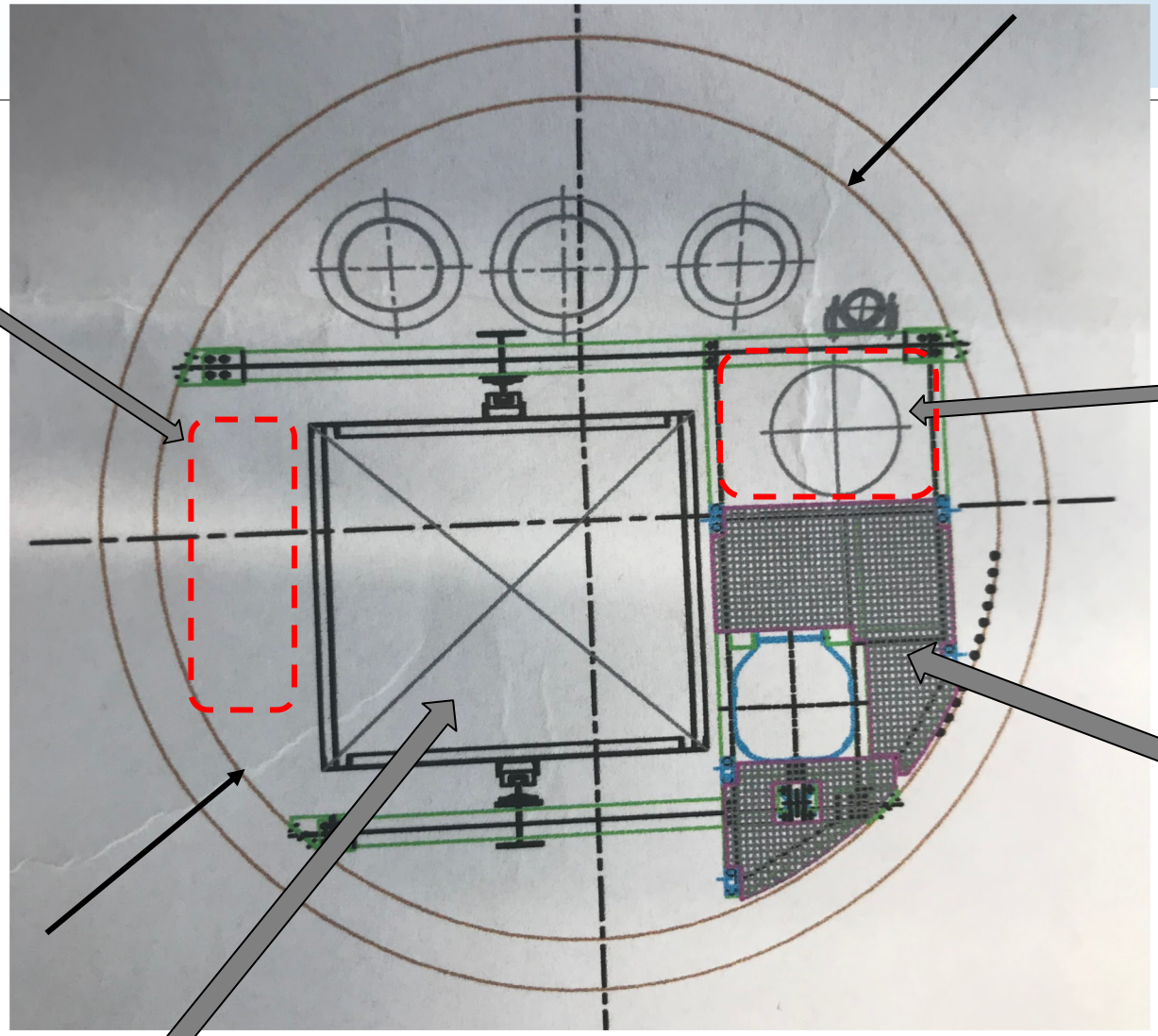
Location of a possible short shaft at Boulby for AION-100

Length 143m
Inner circle diameter 5 m

Two possible locations for AION-100
- next to the staircase : ~ 1.2 m x ~ 0.8 m
- on the other side of the cage - more space but no access from the staircase

Inner circle diameter : 5m

Possible location for AION-100



Possible location for AION-100
1.2 m x 0.8 m

Staircase

Working cage
2 m x 2 m

Summary as submitted in the 2020 Infrastructure Call to IAG & UKRI

- **Stage 1 (10m):** which has received initial funding by an STFC / ESPRC grant (total £9.6M), will provide proof-of-principle of the basic technology and examine the scalability from lab-based to purpose-built infrastructure. A 10m interferometer will be constructed in the low-vibration Beecroft building in Oxford, which also includes a high-specification laser laboratory. The performance and scalability of this device will be fully characterized.

- **Stage 2 (100m):** Construction is planned to commence in late 2023, with a goal of device operation by 2025 and observation and exploitation of GW signals through to the end of the decade. **Two potential UK sites for a 100m device are under study, at Boulby and Daresbury, each taking advantage of existing unique facilities within national laboratory campuses.** This stage of the project will address fundamental engineering challenges for the construction of a large detector 'in the field'.

- **Stage 3 (1km):** Construction could start in 2025/6 and be completed in 2029/30, with a target of reaching the ultimate terrestrial sensitivity for GW / DM observation in the early 2030s. **This stage would represent a new national / international infrastructure, complementary to existing UK 'big science' facilities. Boulby laboratory is under study as a potential UK site for the detector, building on already-announced investment in other science activities.**

  i. Building the km-scale detector in an existing mine shaft (e.g. in one of the two 1.1km vertical shafts at the Boulby mine);
  ii. Building the km-scale detector in a new km-deep vertical shaft excavated at a facility like Boulby.

Summary

Boulby could be an ideal location to host Stage 2 and Stage 3 of the AION project.

- This would make the UK a centre of future international activities in the area of mid- frequency band studies of dark matter and gravitational physics, capable of hosting world-leading experiments at UK sites, e.g., STFC's Boulby facilities The long-term objective of the programme is to give the UK international leadership of a future km-scale atom interferometry observatory.

- This km-scale terrestrial quantum detector for mid-frequency gravitational wave physics and refined sensitivity for ultra-light dark matter physics will open a new dimension of multi-signal and multi-messenger physics in the mid-frequency band (and beyond), capable of networking with other km devices (located, e.g., in the US or China), as well as with experiments in the high- and low-frequency bands.

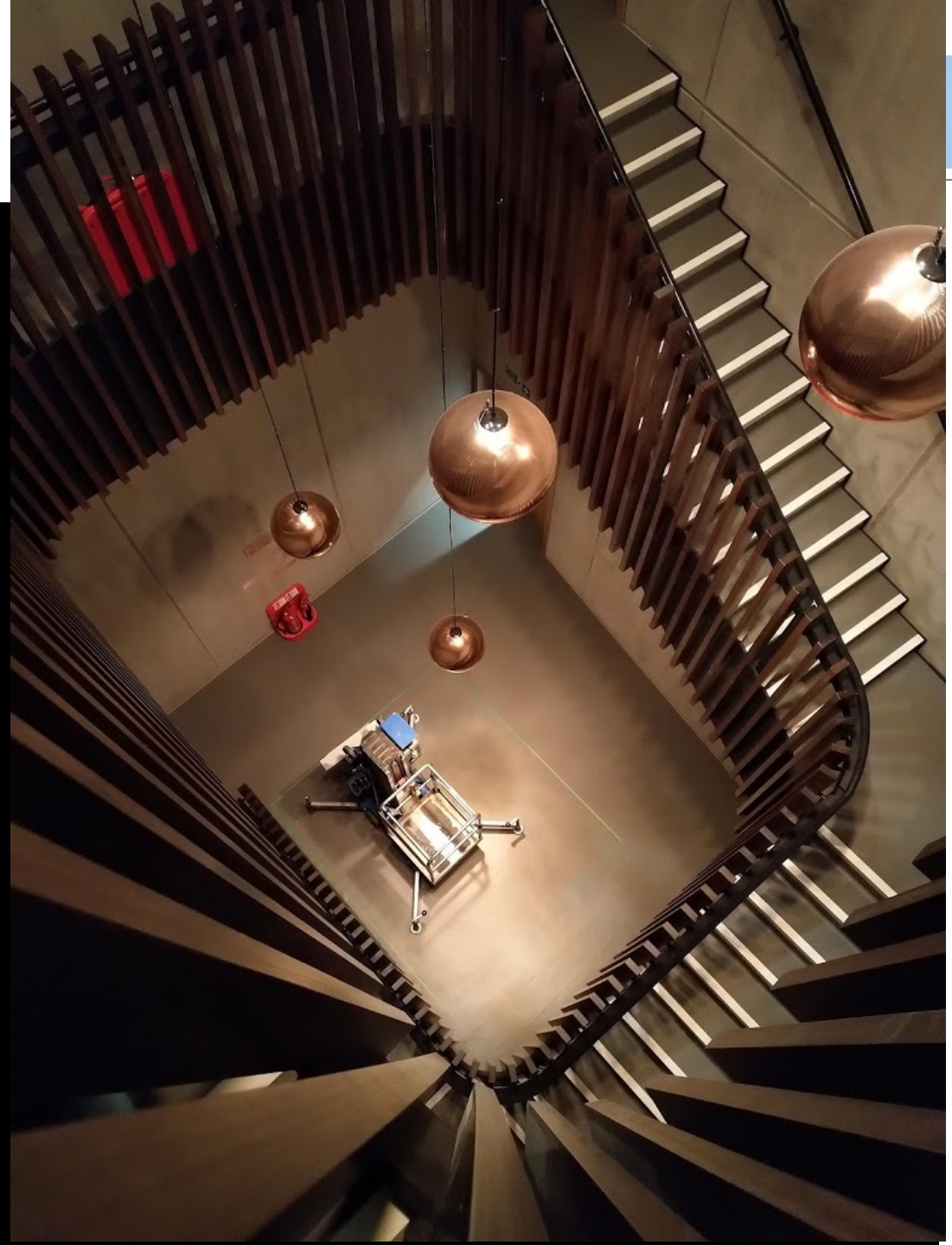
- This stage will represent a new national / international research infrastructure, complementary to existing UK 'big science' facilities. The STFC Boulby underground laboratory is under study as a potential UK site for the detector, building on already-announced investment in other science activities, and on a proposed expansion of the laboratory.

BACKUP MATERIAL

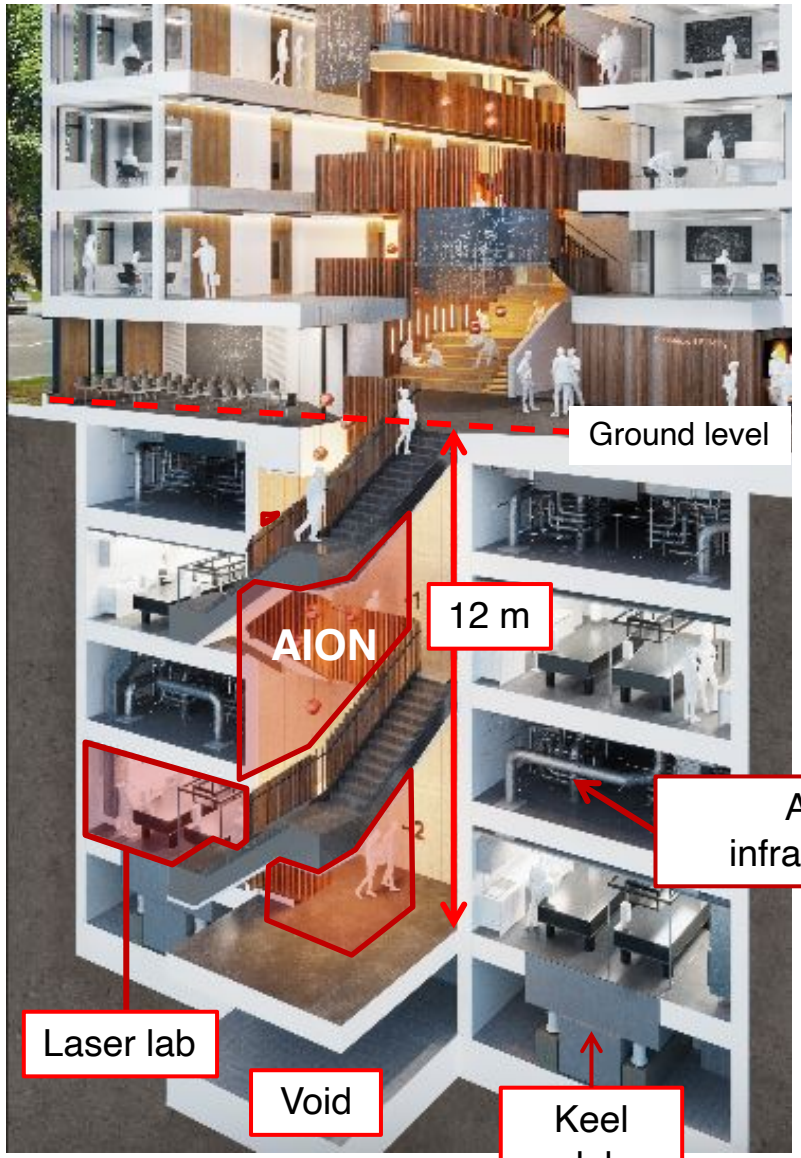
10M DETECTOR IN OXFORD

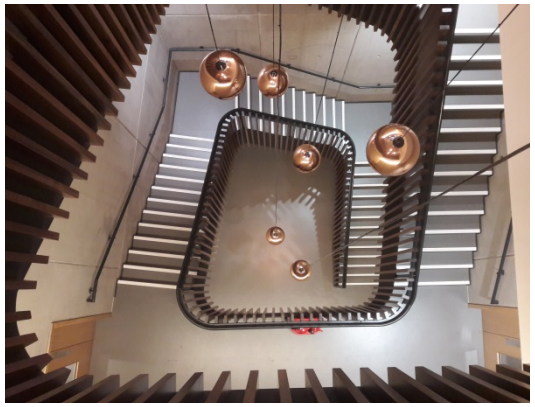
Beecroft building, Oxford Physics

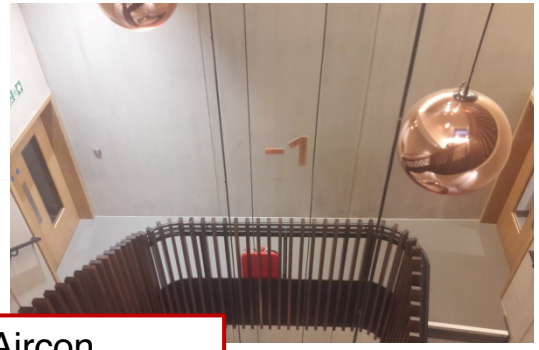
The Beecroft in Oxford is the proposed site, with a backup at RAL (MICE Hall) in case show-stoppers are encountered.

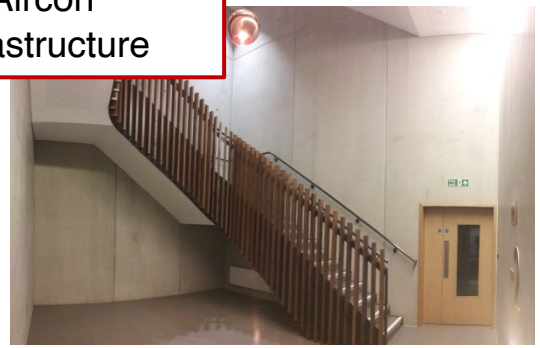


Beecroft building, Oxford Physics









Ultralow vibration

- All plant isolated
- Thick concrete walls

Adjacent laser lab reserved for AION use

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

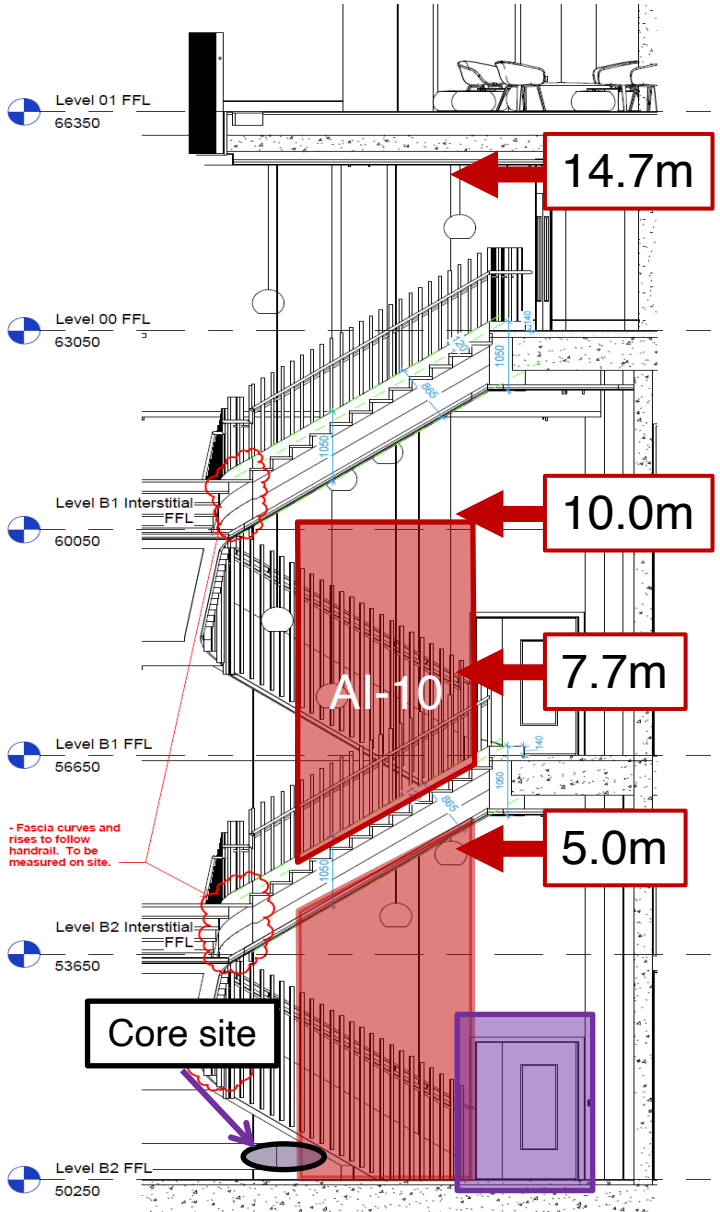
Vertical space

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

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

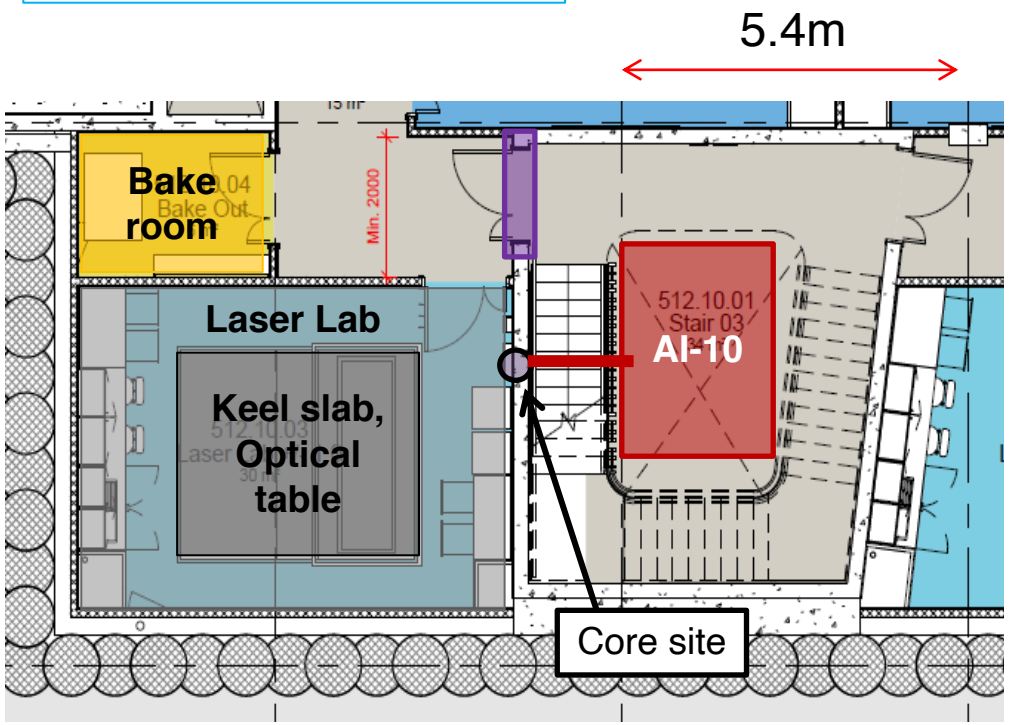
Bakeout room and cleanroom nearby

Beecroft building, Oxford Physics



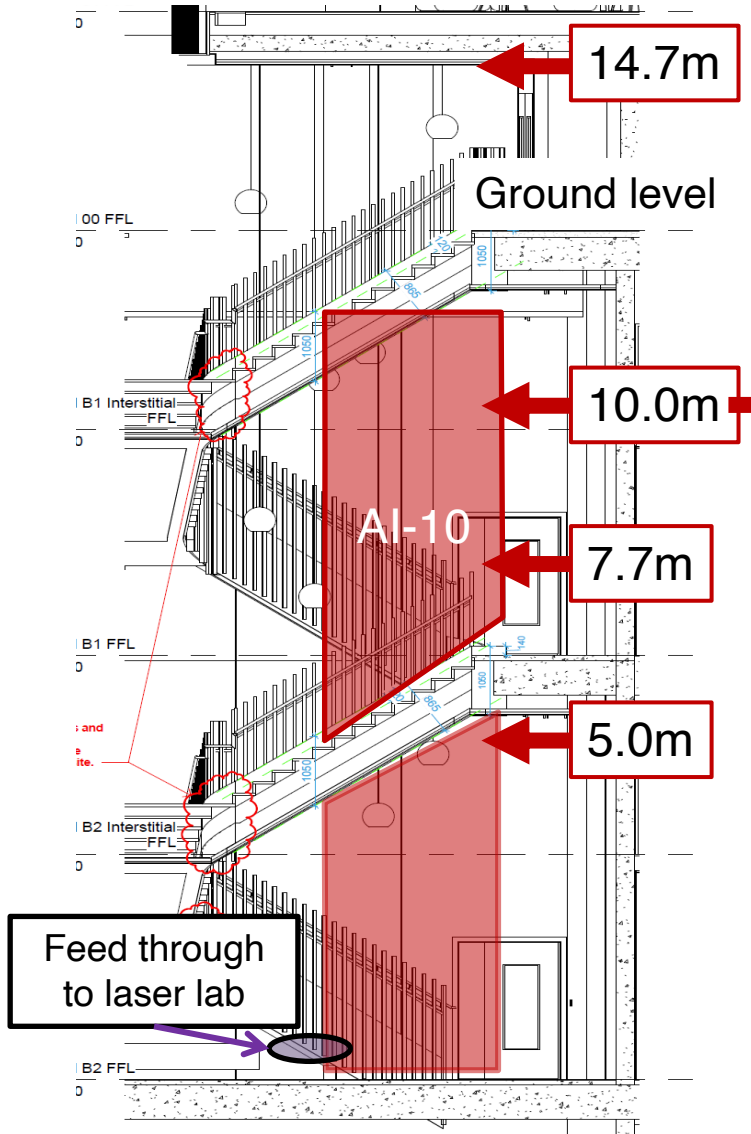
← Side view

↓ Plan view

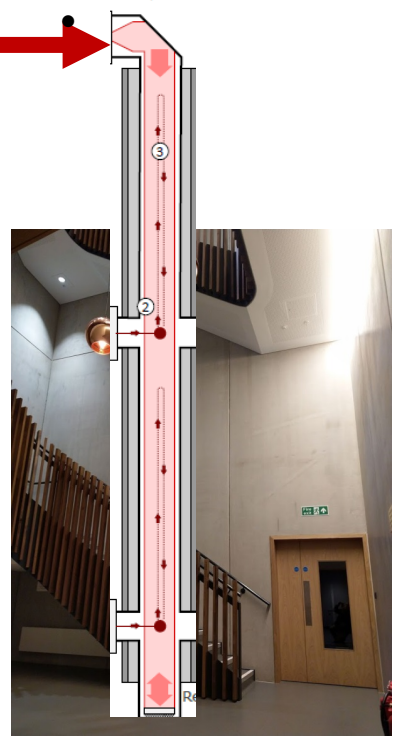


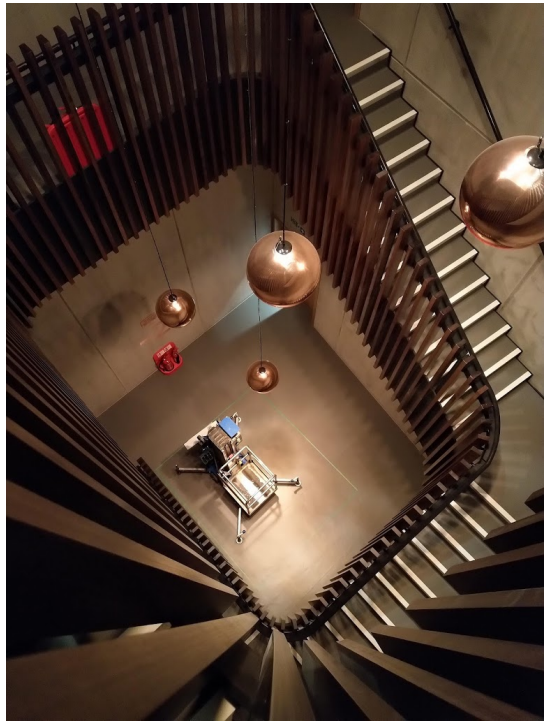
AION-10 site: Beecroft building, Oxford Physics

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



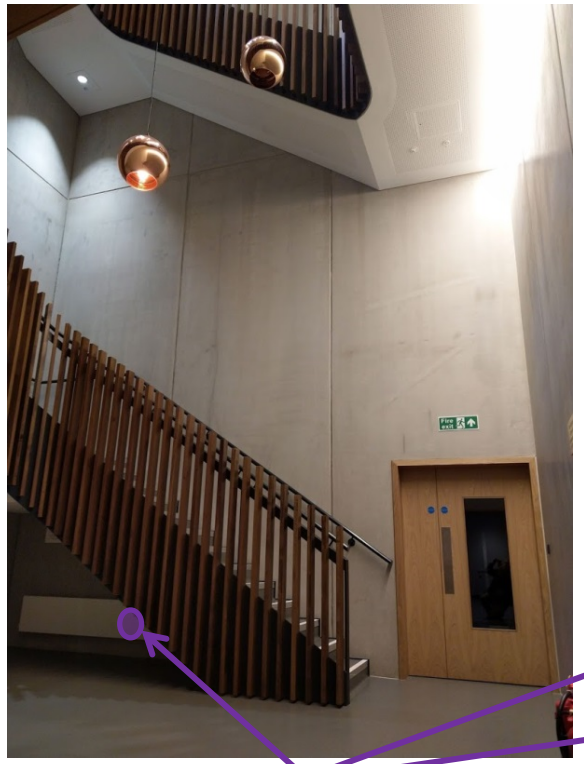
- Detailed planning of support structure by RAL (Engineering), Oxford Physics Technical Services and Liverpool Univ.
- Experienced Project Manager: Roy Preece
- Good site for long-term operation and wide accessibility (also ‘visibility’ and outreach).

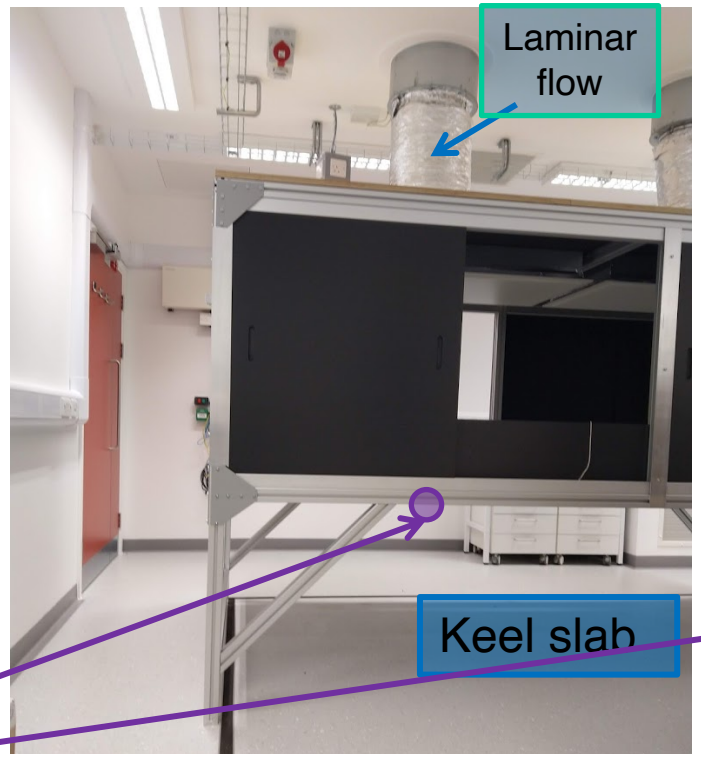


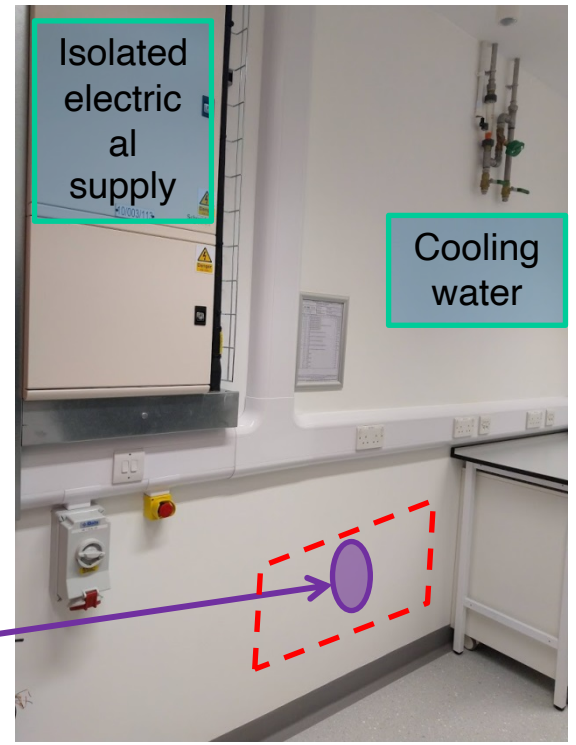


Beecroft building laser lab

Beecroft stairwell: lowest level





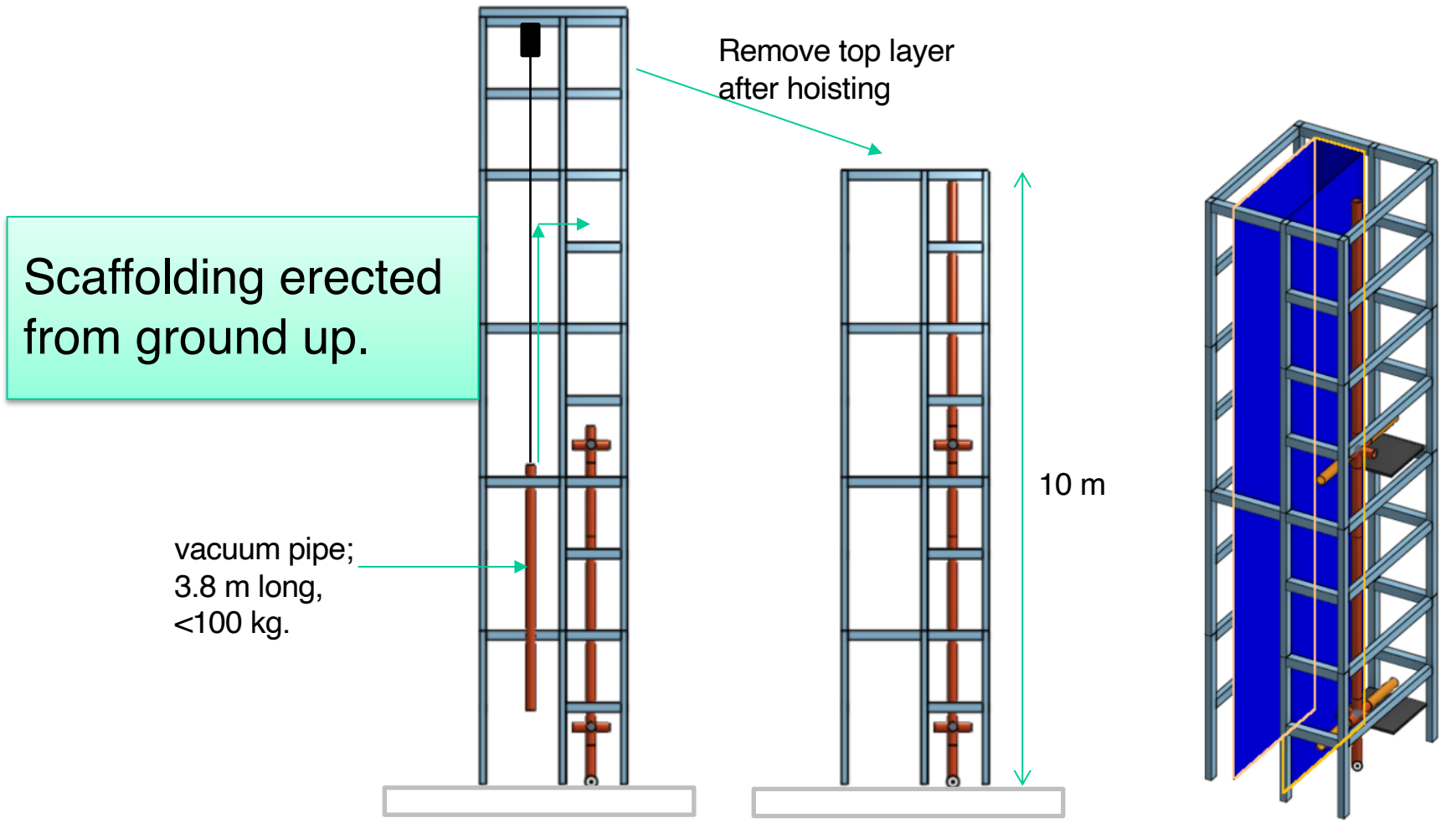


Core site: feed through fibre and cables

laser lab (interior): optical table enclosure with laminar air flow and temperature-control installed.

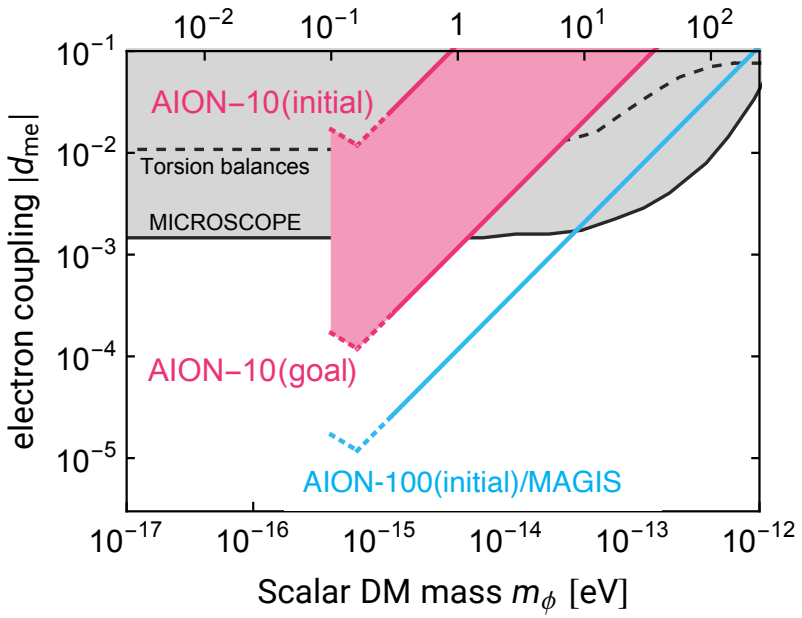
Bake-out room next door

Assembly: extruded aluminium support structure



THE SCIENCE CASE IN A NUTSHELL

Main AION Physics Goals: Dark Matter and Gravitational Waves



Scientific Leadership in phenomenology already established:

The AION Physics Case:

AION Collaboration, AION: An Atom Interferometer Observatory and Network, arXiv:1911.11755. [accepted for publication in JCAP]

AEDGE

Y. El-Neaj, …, O. Buchmueller *et al.* AEDGE: Atomic Experiment for Dark Matter And Gravity Exploration in Space, arXiv:1908.00802, *EPJ Quantum Technol.* 7, 6 (2020). [Submitted to ESA Voyage2050 call]

Working with leading theorists:

J. Ellis, M. Haehnelt, C. McCabe,
J. March-Russell (AION), C. Burrage, …

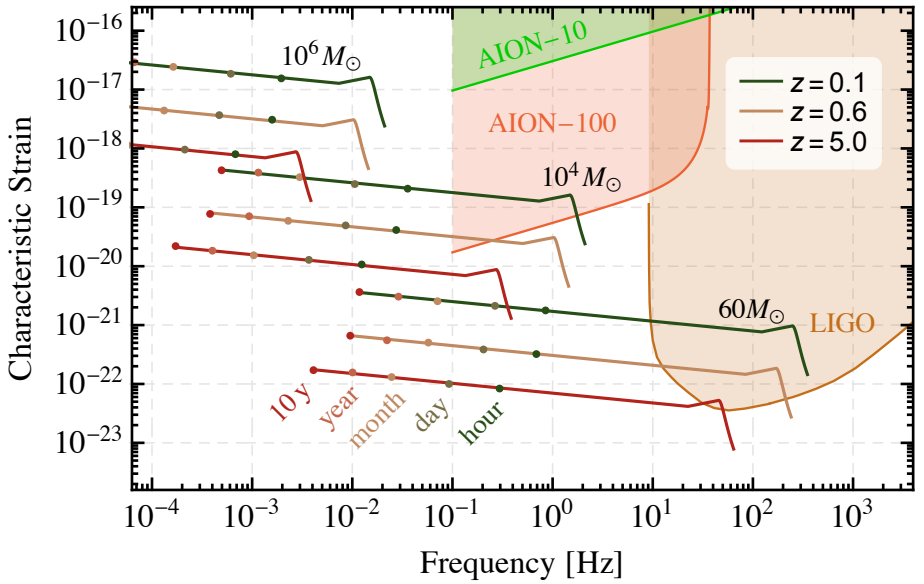
Main Physics Goals:

➢ Search for Ultra-Light Dark Matter

- Explore new parameter space and complement other searches.
- Focus on Scalar DM with Vector and Peudoscalar DM also under study.

➢ Gravitational Waves in mid-frequency band

- Explore frequencies between LISA and LIGO/VIRGO, KAGRA and Einstein Telescope
- Targets: Black hole mergers, phase transitions and cosmic string collisions



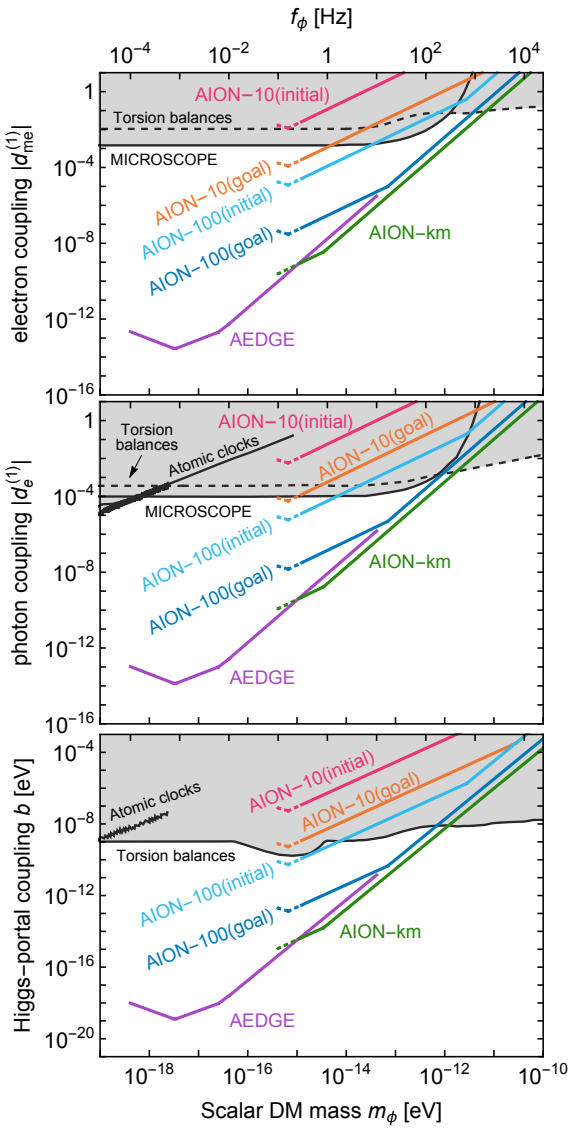
SEARCHES FOR ULTRA-LIGHT DARK MATTER

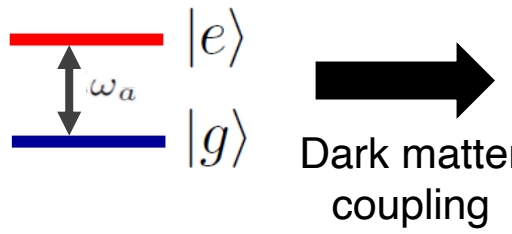
Ultra-Light Scalar Dark Matter

Coupling to electron

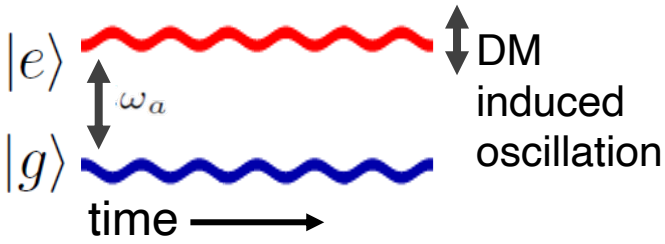
Coupling to photon

Coupling Higgs-portal





Dark matter coupling



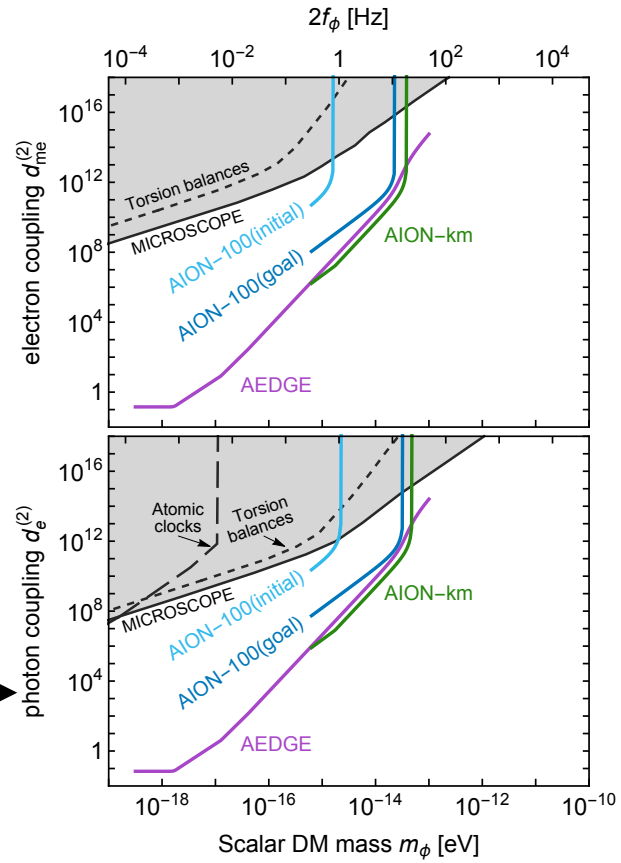
DM induced oscillation

The AION staged programme will have unprecedented sensitivity to DM with scalar couplings to matter, which cause time variation of fundamental constants such as the electron mass.

Based on: Arvanitaki et al., PRD **97**, 075020 (2018).

Linear scalar DM interactions

Quadratic scalar DM interactions

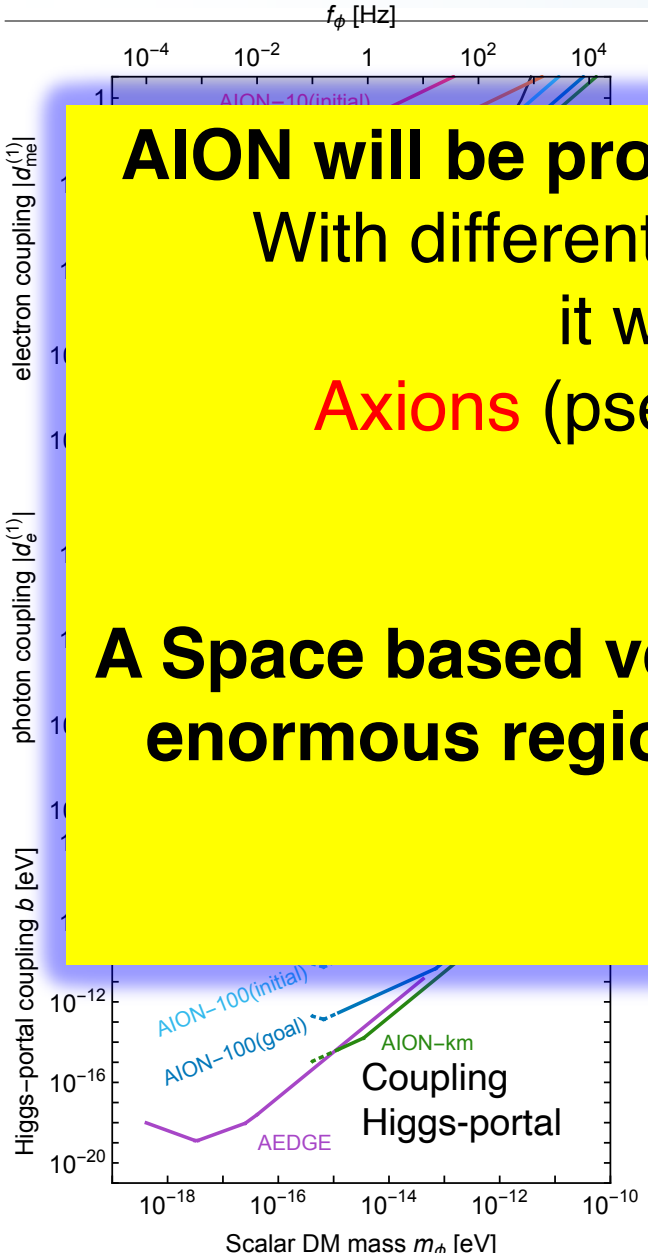


Ultra-Light Scalar Dark Matter

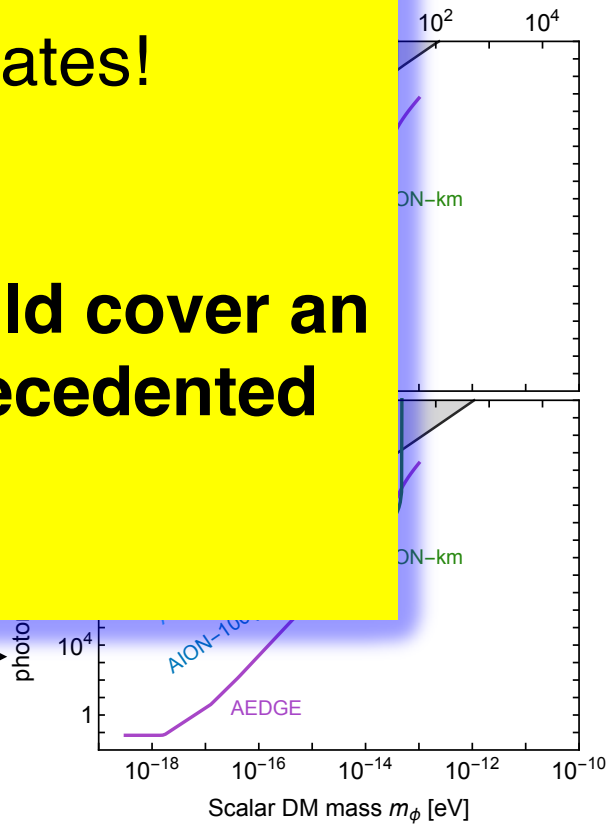
AION will be probing new territory in ULD scalar scenarios.

With different configurations of the Atom Interferometer
it will be also possible to search for
Axions (pseudo-scalar) and Vector DM candidates!
[studies are ongoing]

A Space based version of AION (i.e. AEDGE), would cover an enormous region of parameter space with unprecedented discovery potential!

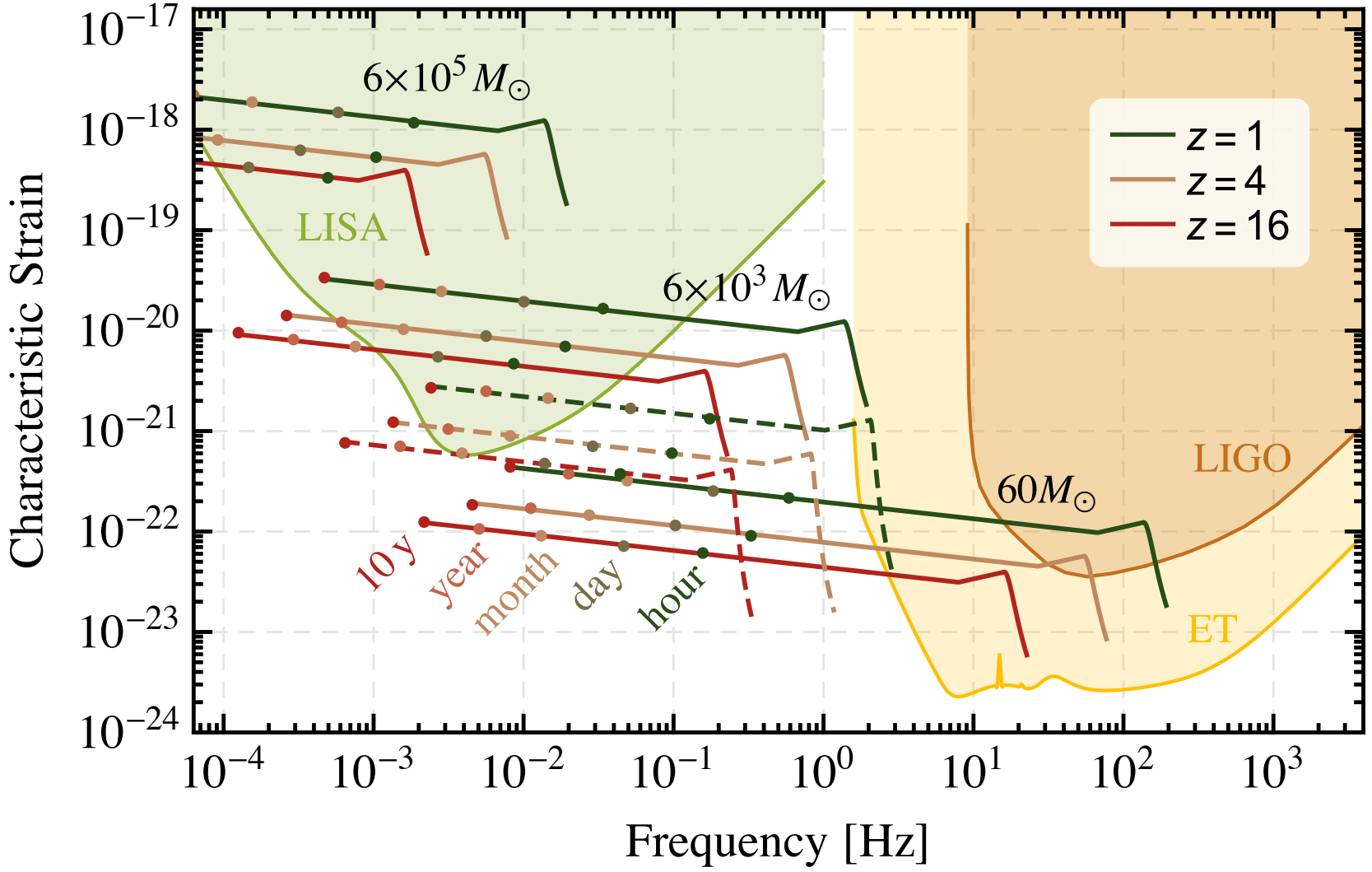


Quadratic scalar DM interactions →

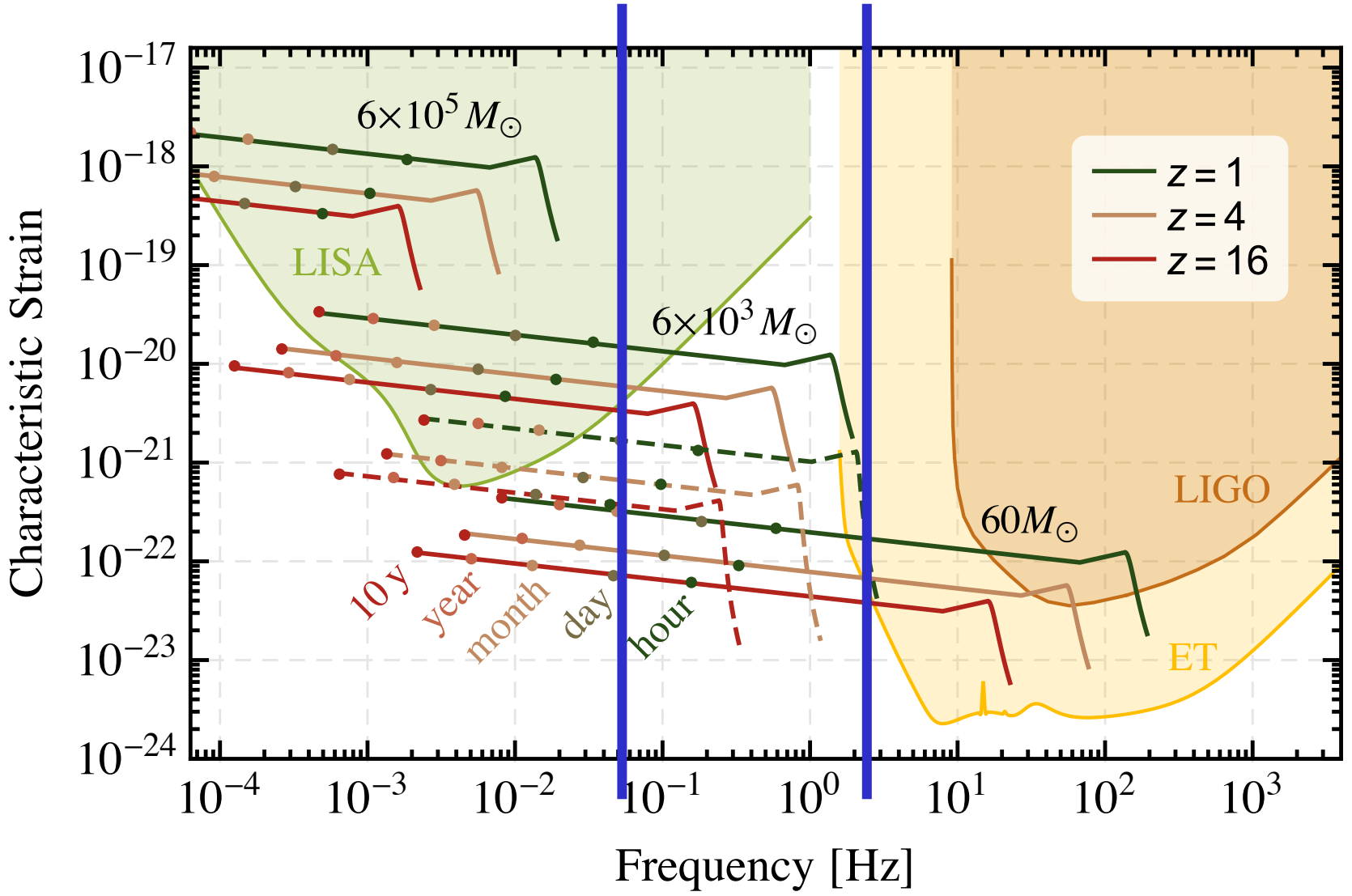


UNEXPLORED MID-FREQUENCY GRAVITATIONAL WAVES

Pathway to the GW Mid-(Frequency)



Pathway to the GW Mid-(Frequency)

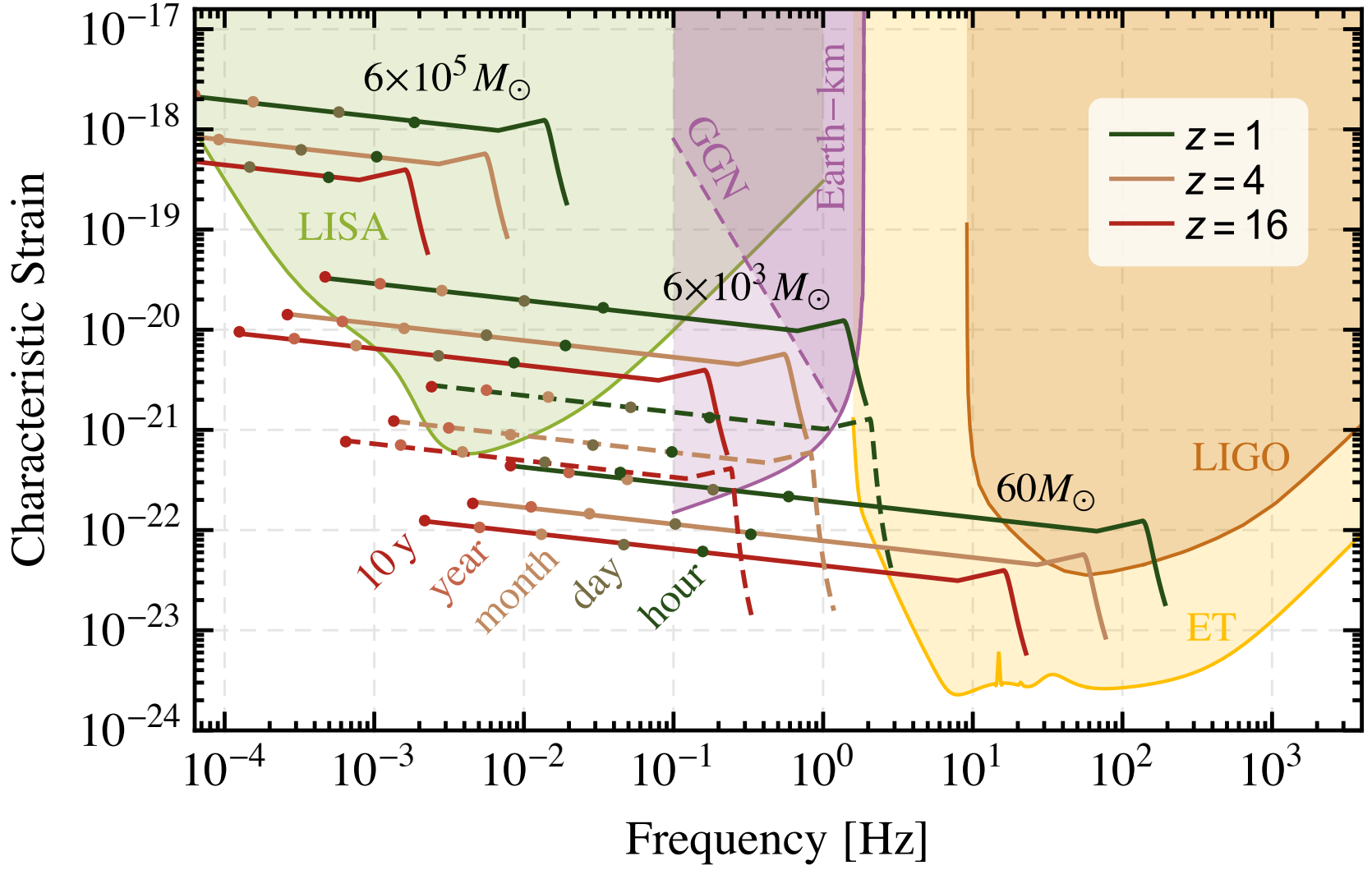


Mid-band science

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

Mid-Band currently NOT covered

AION: Pathway to the GW Mid-(Frequency)



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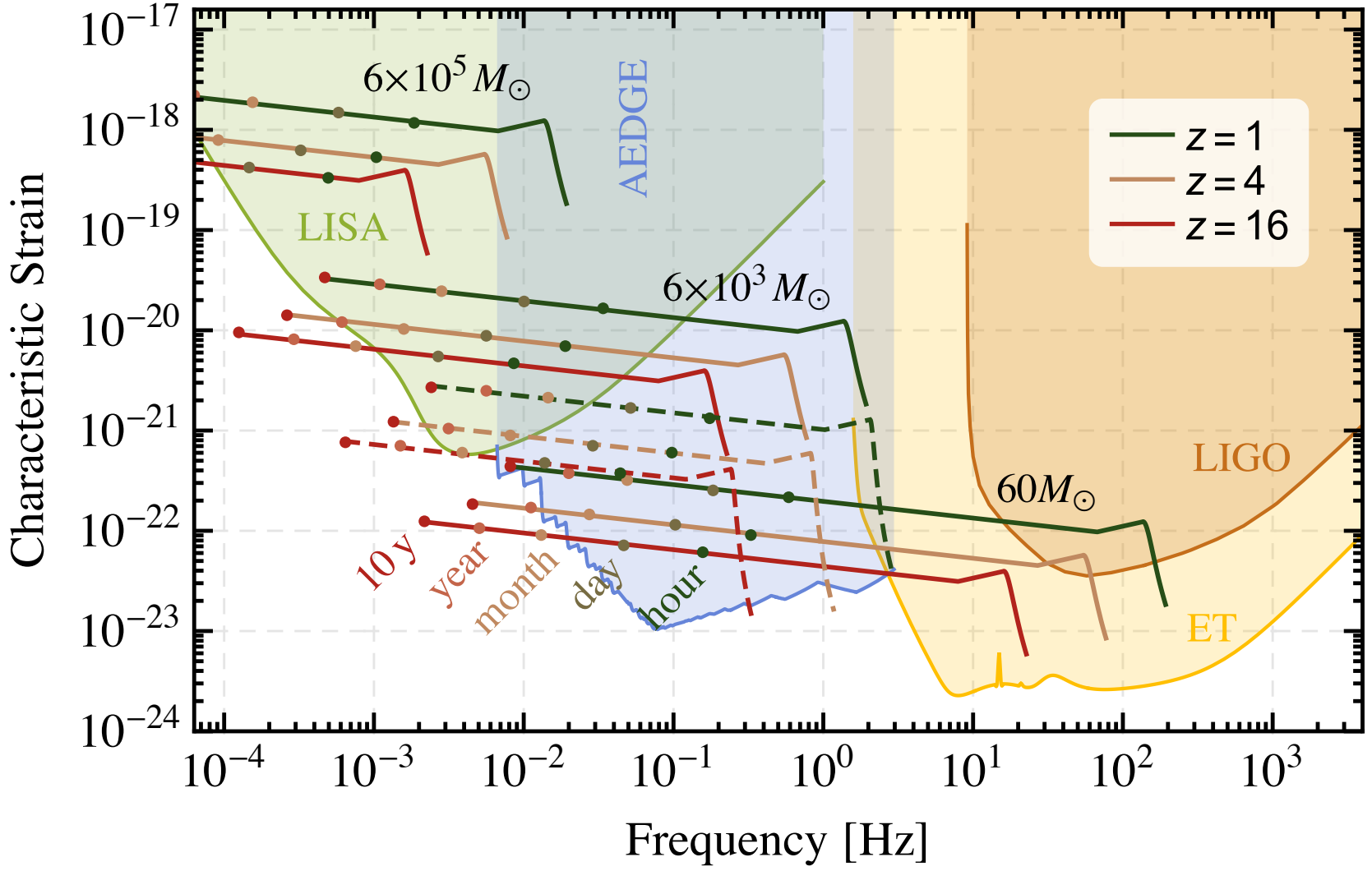
AION: Terrestrial detectors can start filling this gap

AION: Pathway to the GW Mid-(Frequency)



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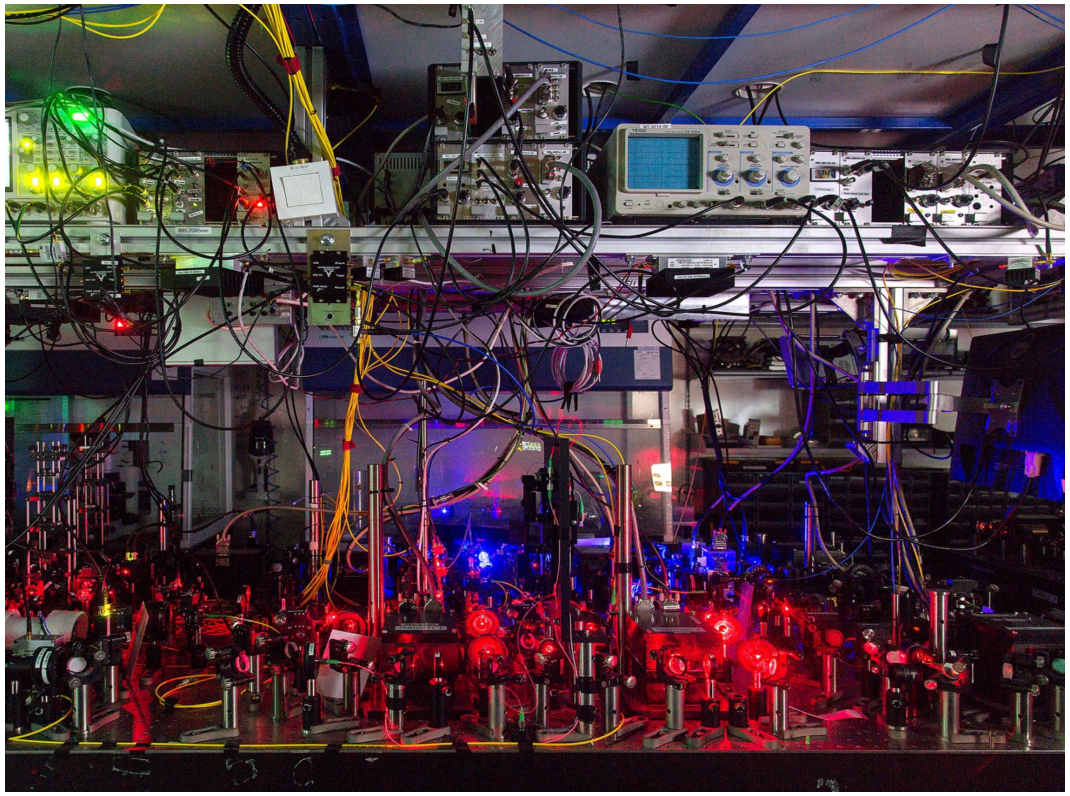
AEDGE
Ultimate coverage with a space based detector

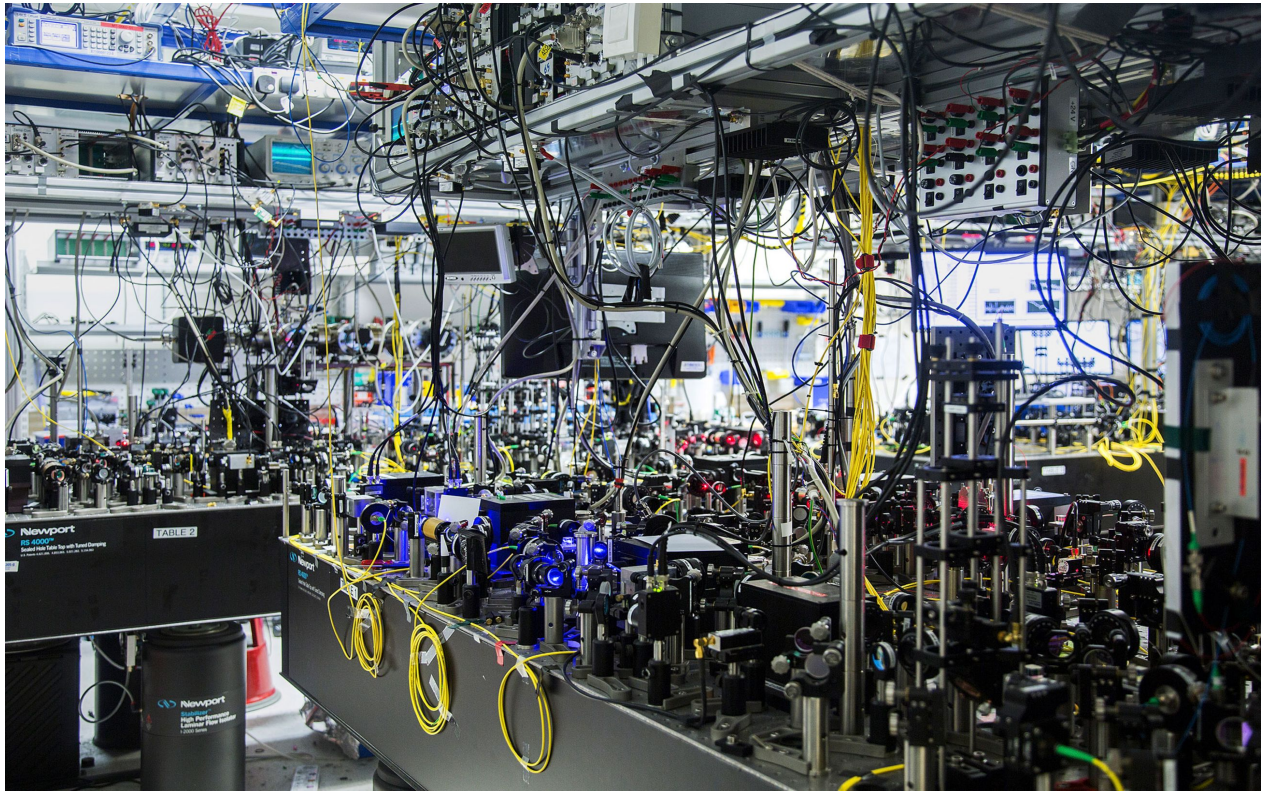
Science Case

- AION & AEDGE provide a new window on gravitational physics, astrophysics & cosmology using atom interferometers, leveraging UK and international investment in quantum technologies, providing new opportunities for technology and science communities.

- The programme will enable the exploration of properties of dark matter, gravitation waves, as well as searches for new fundamental interactions with unprecedented sensitivity, opening many ground breaking discovery opportunities!

AION: Ultra-Cold Strontium Laboratories in UK





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

Birmingham, Cambridge, Imperial College, Oxford, and RAL

The laboratories are expected to be fully operational in fall 2021.