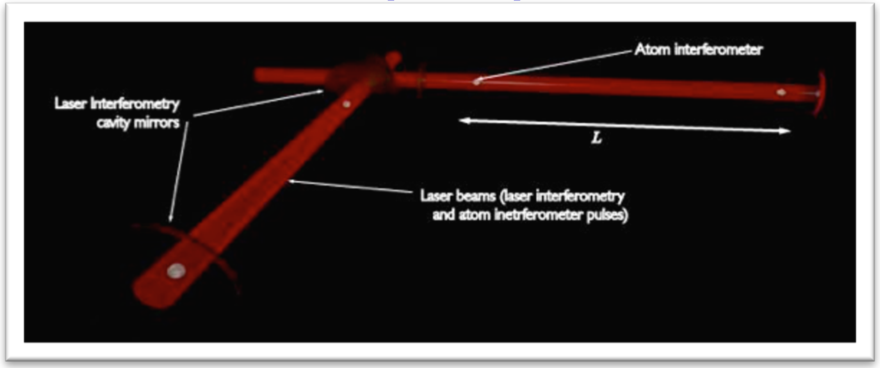
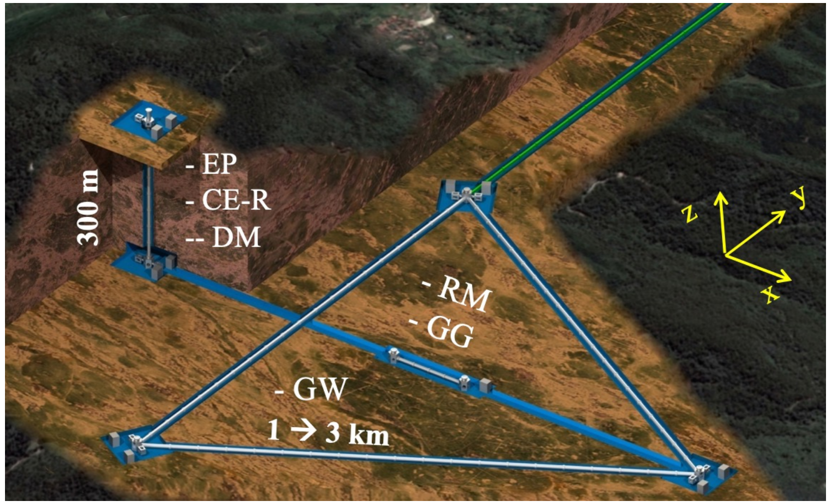
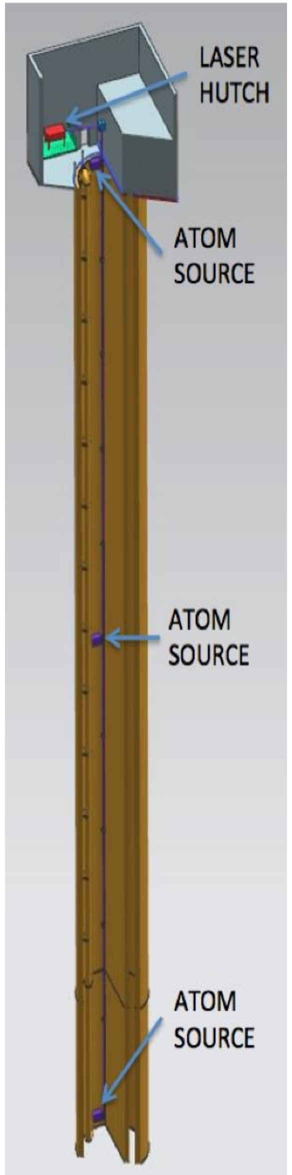
Large Scale Atom Interferometry O(100m) Projects

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

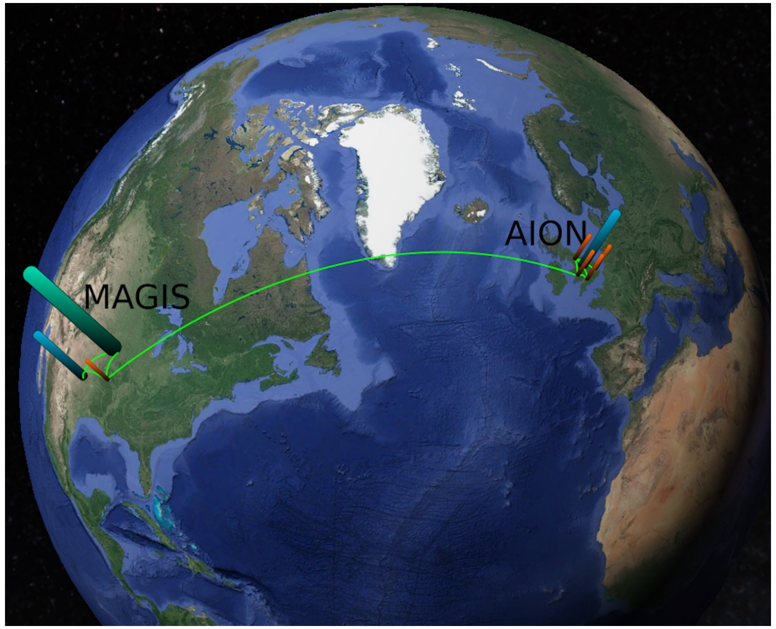


ZIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)
(China)





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

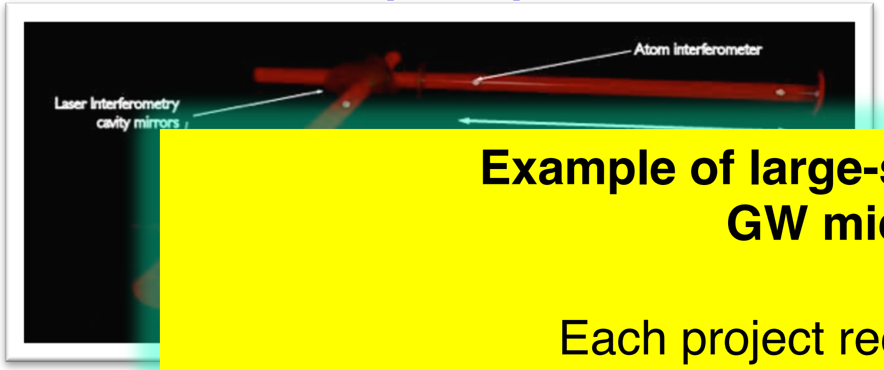


MAGIS: Terrestrial shaft detector using atom interferometer at O(100m)
(US)

Planned network operation

Large Scale Atom Interferometry O(100m) Projects

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

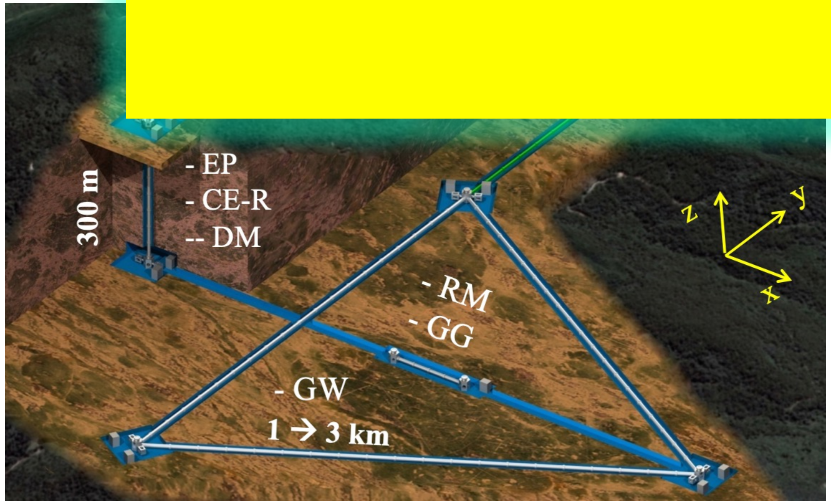


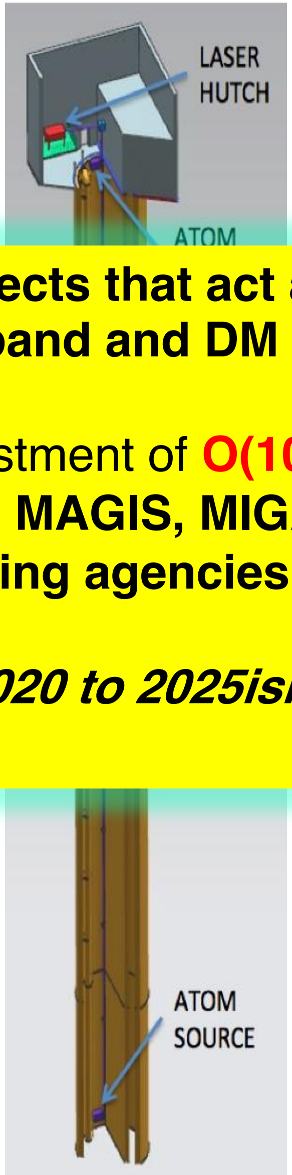
Example of large-scale CA projects that act as demonstrators for GW mid-frequency band and DM detectors.

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

Timeline 2020 to 2025ish

ZIGA:
interf





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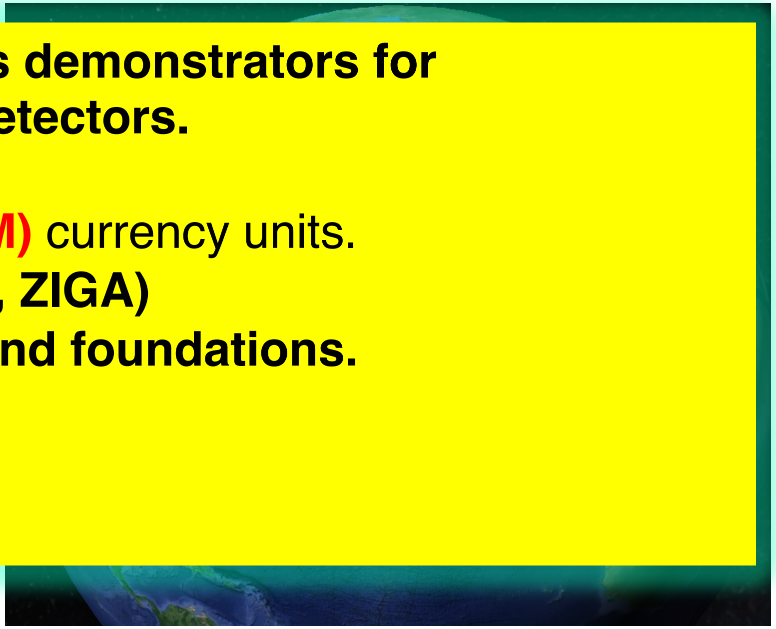
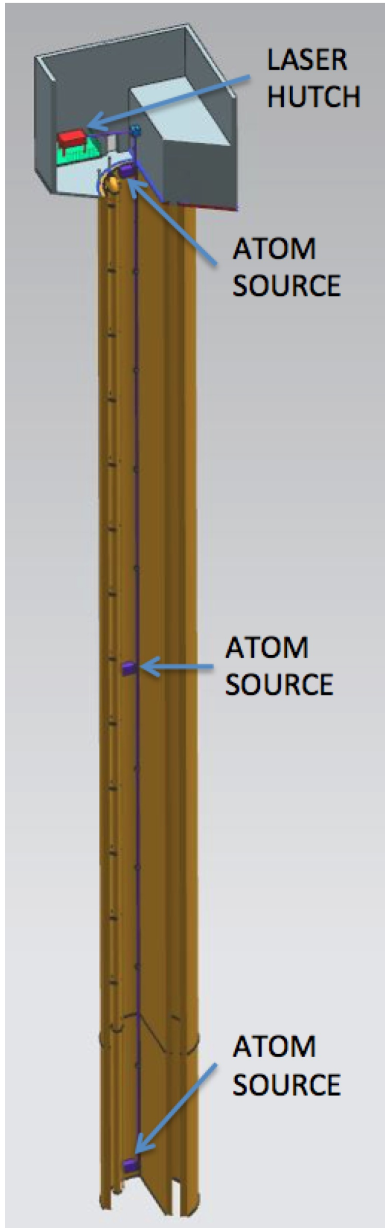


MAGIS: Terrestrial shaft detector using atom interferometer at O(100m)
(US)

Planned network operation

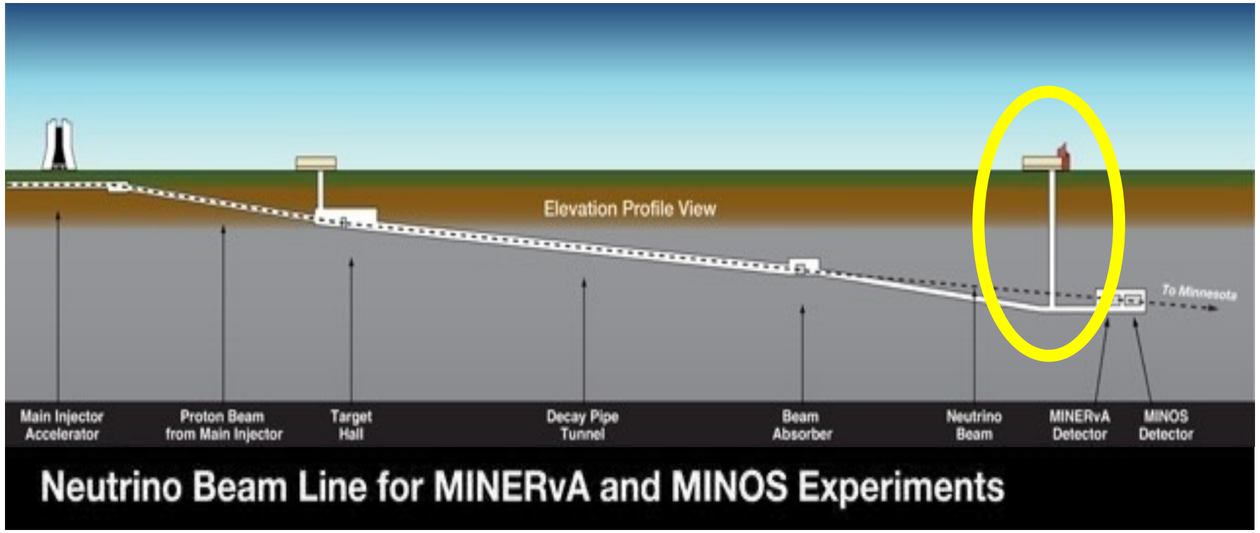
SITES FOR MAGIS & AION

2019 – 2023: MAGIS-100 at Fermilab (100-meterdetector)

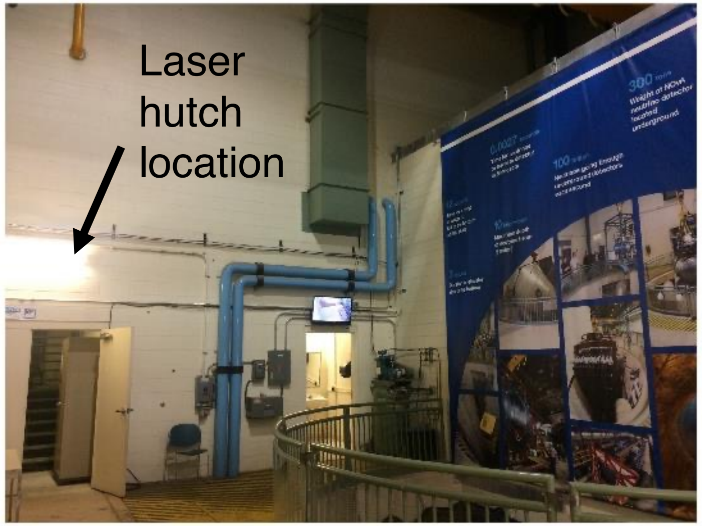


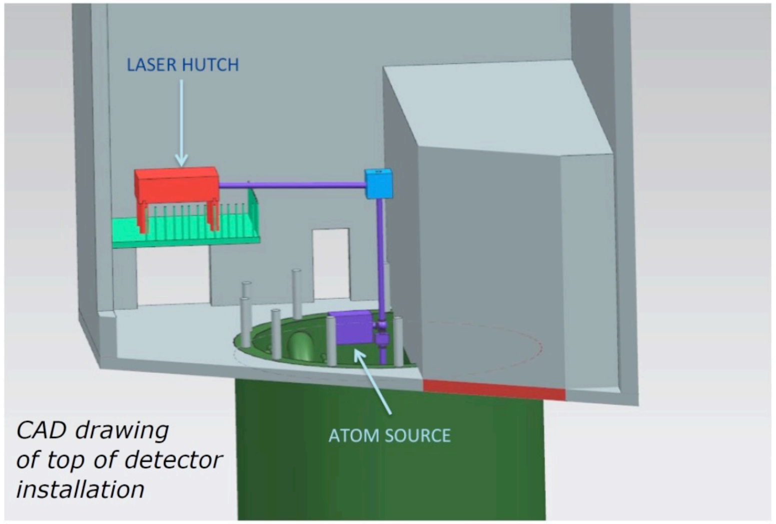
System Components:

- ~90 meter vacuum tube (vertical)
- Atoms sources (three, attached to tube)
- Laser system for implementing atom interferometry (hutch at top)



Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor

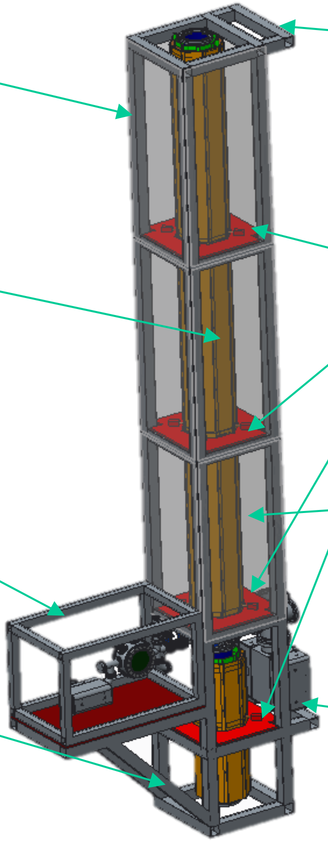




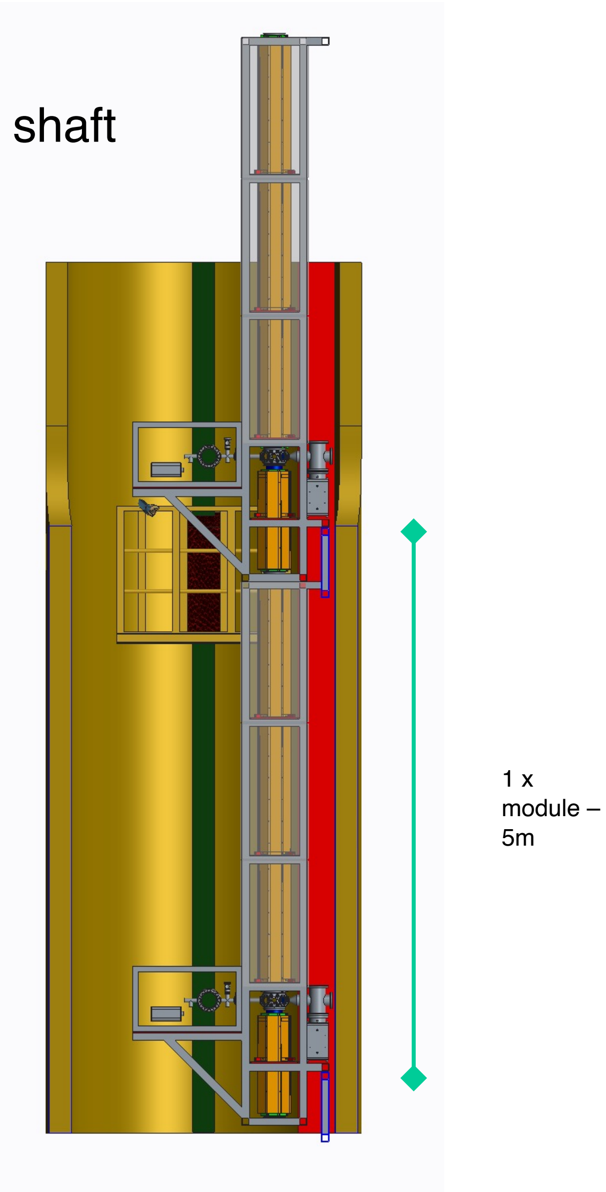
CAD drawing of top of detector installation

- 100-meter baseline atom interferometry at Fermilab (MINOS access shaft)
- Intermediate step to full-scale (km) detector for gravitational waves

AION: Design & Construction: Module Assembly

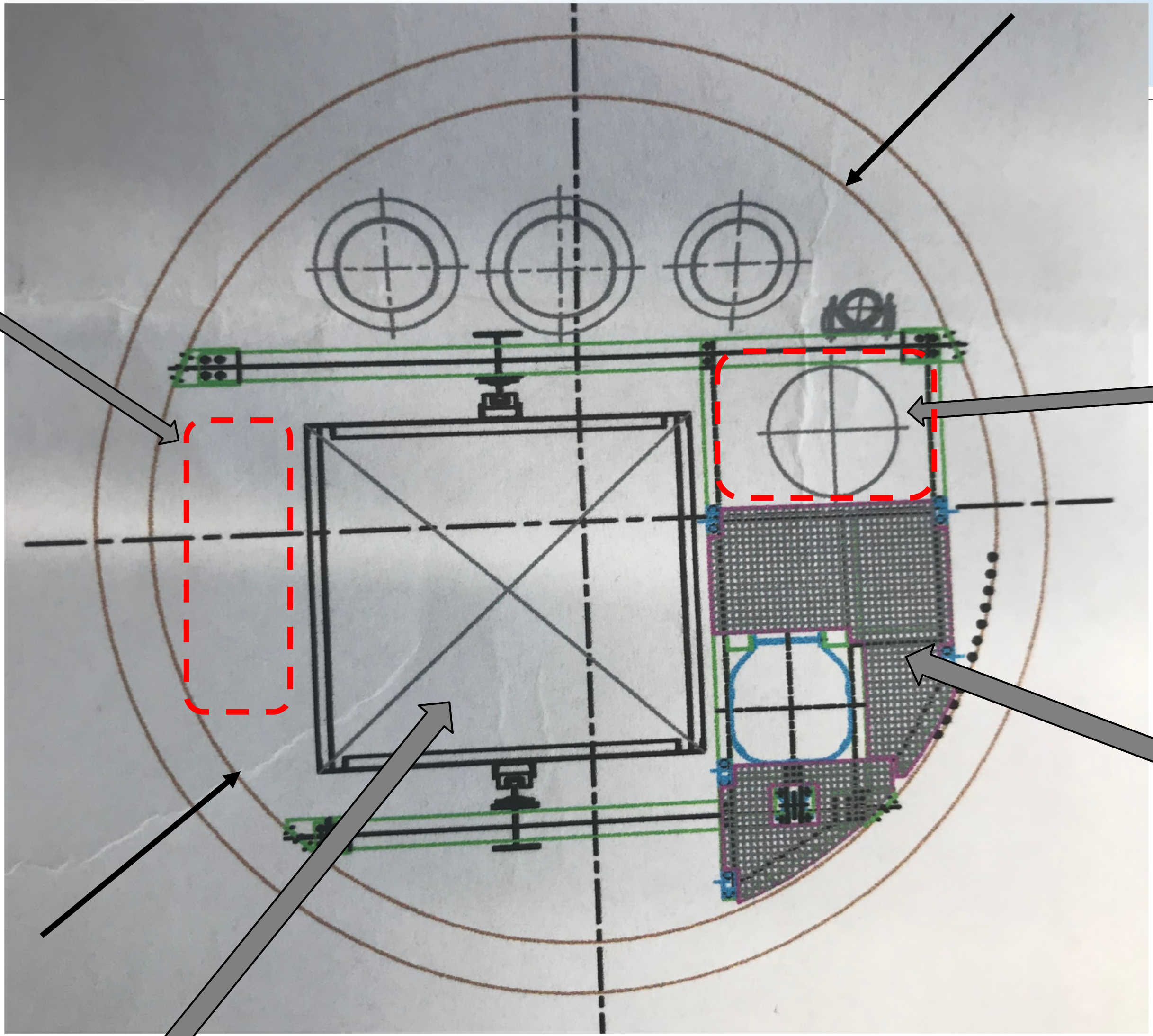


Two modules in shaft



Inner circle diameter : 5m

Possible location for AION-100



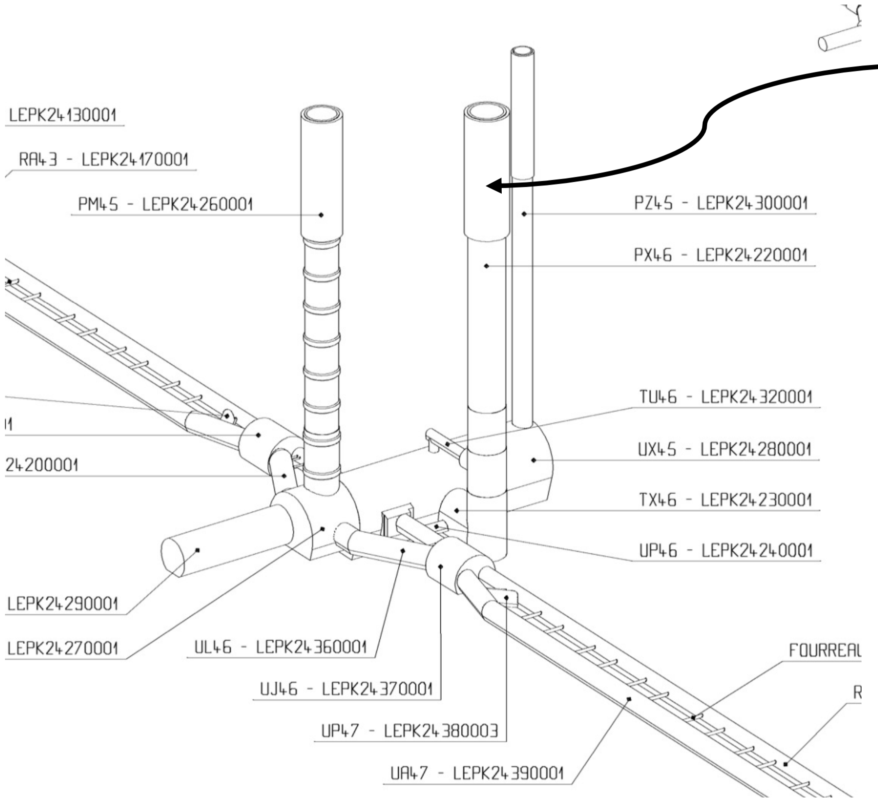
Possible location for AION-100 1.2 m x 0.8 m

Staircase

Working cage 2 m x 2 m

Location of the short shaft at Boulby for AION-100

Possible CERN Site for AION 100m



PX46 – P4 Support shaft

Lengths 143m

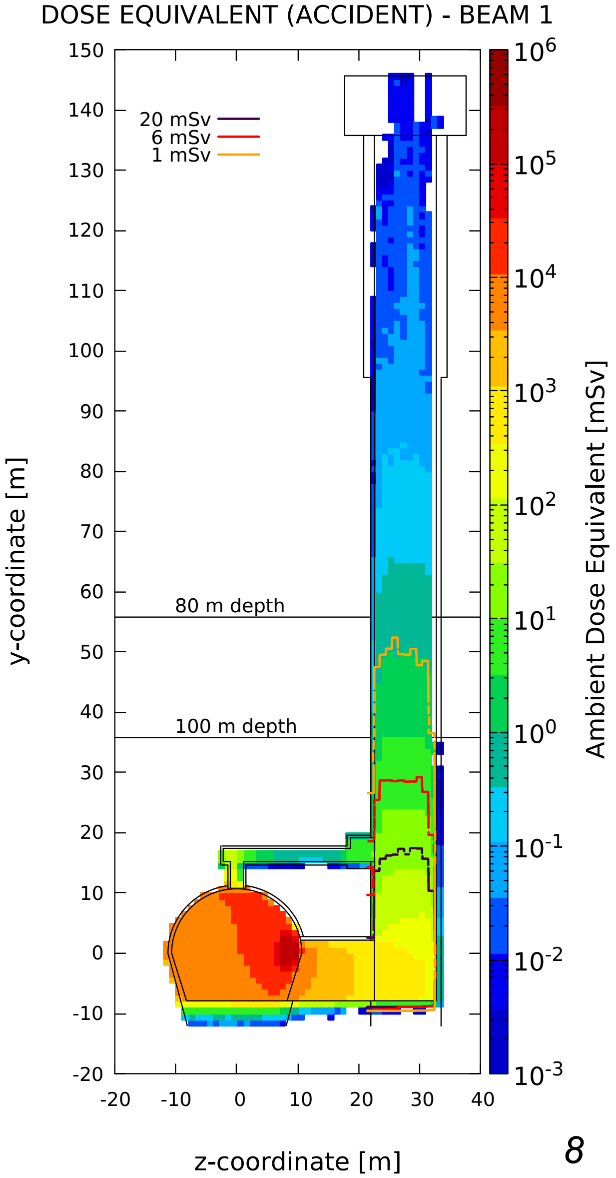
D = 10.10m

➢ **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 (K Balazs and before J. Gall)

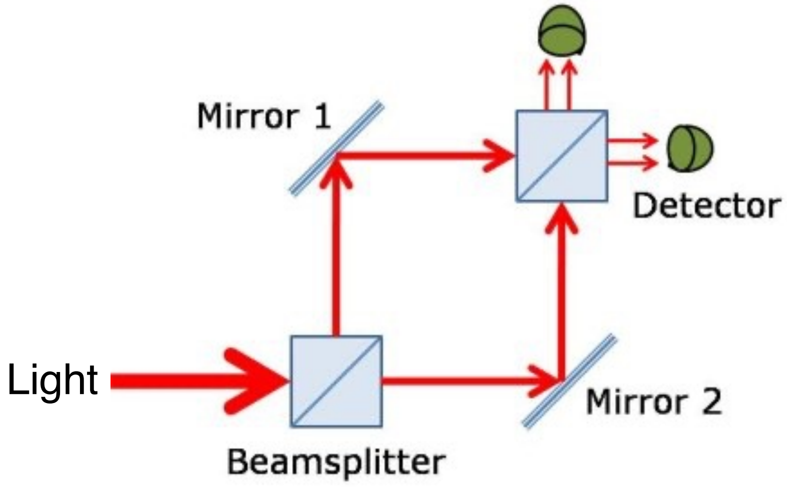
Next step: looking with RP and HE department into the feasibility of the shielding arrangement.

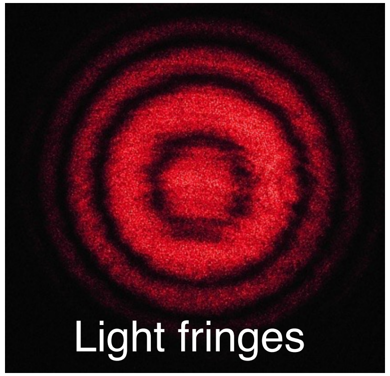


Other site options that are currently investigated are the ***national facility in Boulby and Daresbury (UK).***

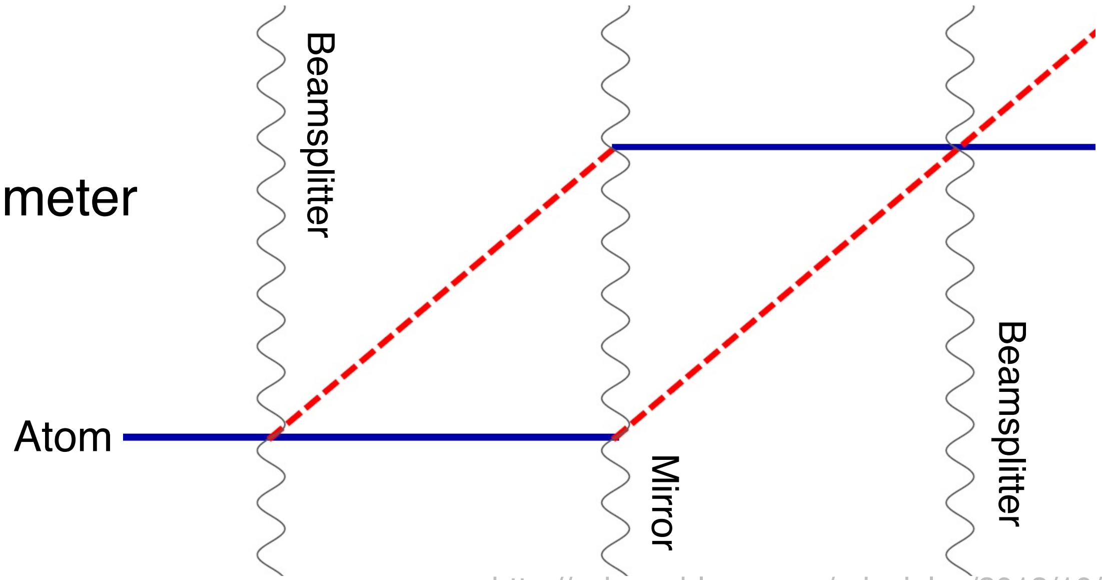
Light vs. Cold Atoms: Atom Interferometry

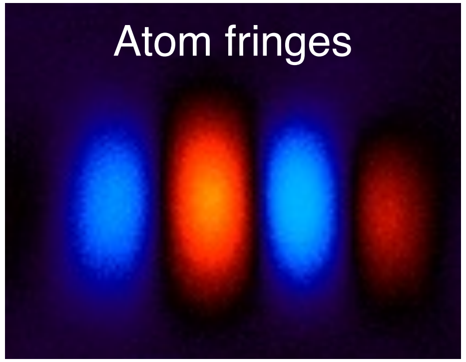
Light interferometer





Atom interferometer





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

BACKUP FOR DISCUSSION – DARK MATTER AND GRAVITATIONAL WAVES

Ultra-Light Spin-0 Dark Matter

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

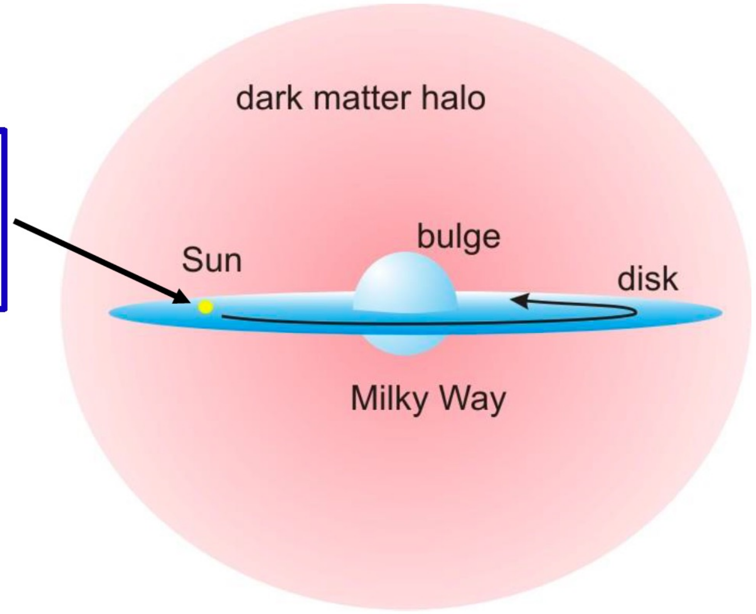
$$\phi(t) = \phi_0 cos(E_\phi t/\hbar)$$

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

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

$\rho_{DM} \approx 0.4$ GeV/cm^3

$v_{DM} \sim 300$ km/s



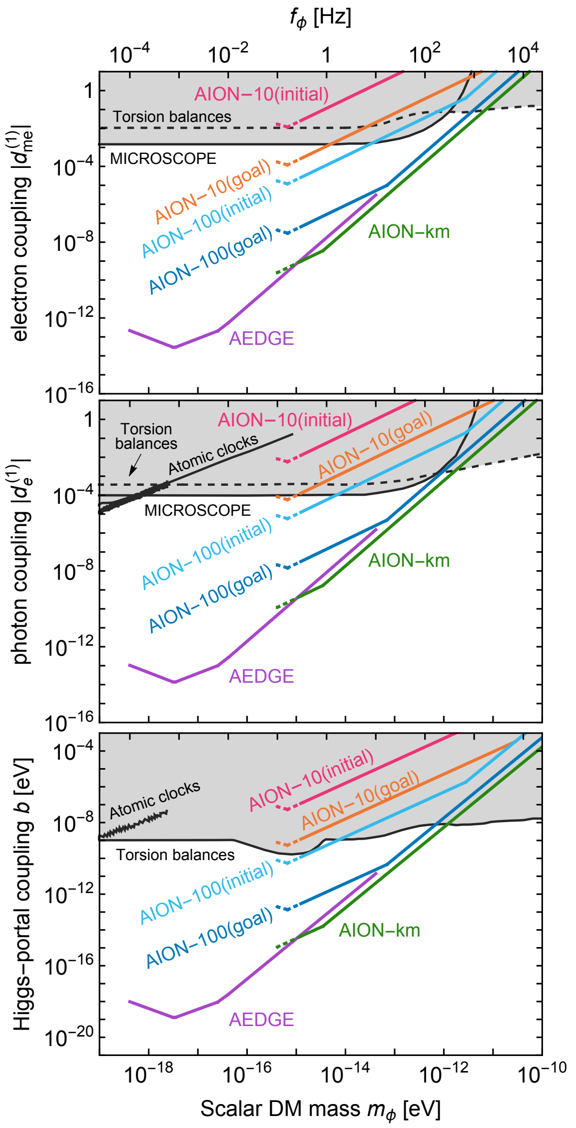
Ultra-Light Scalar Dark Matter

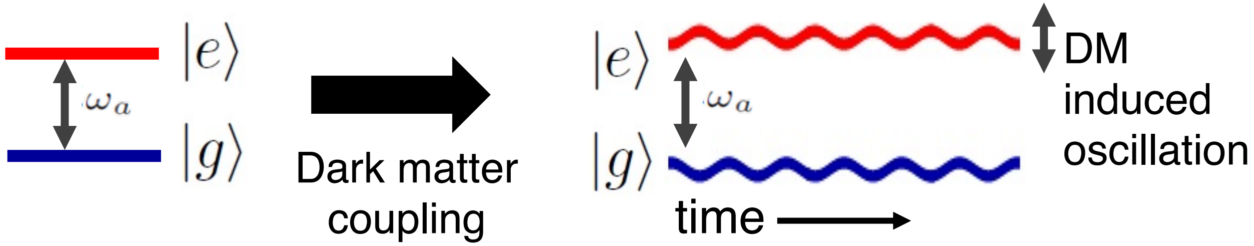
AION Project: SURF Long-Term Vision Workshop

Coupling to electron

Coupling to photon

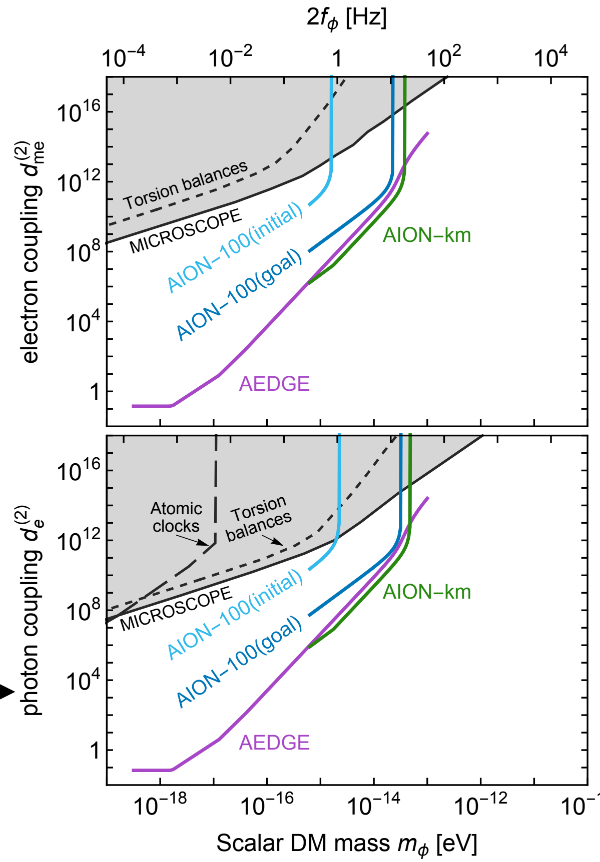
Coupling Higgs-portal





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).

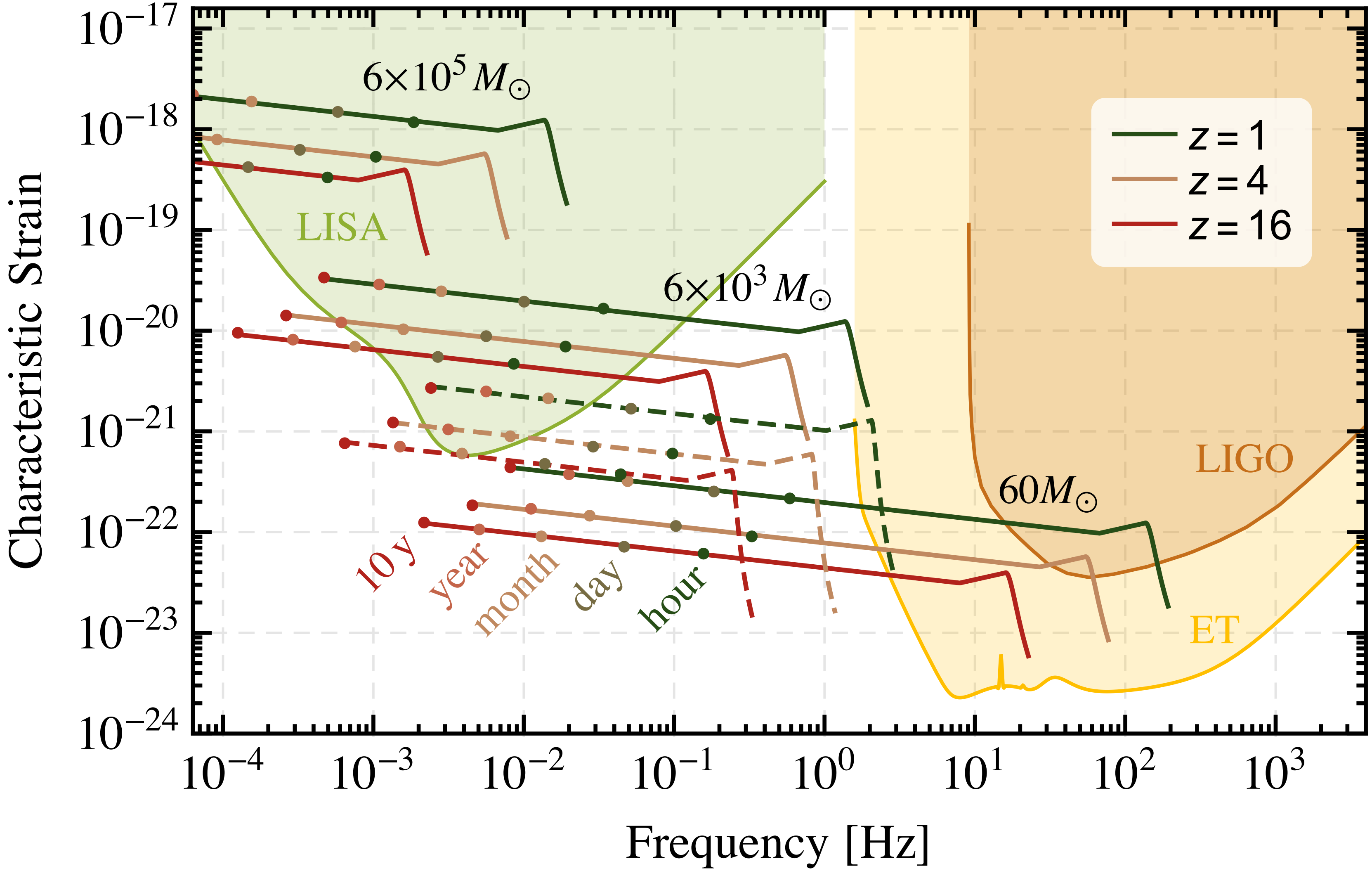


Linear scalar DM interactions

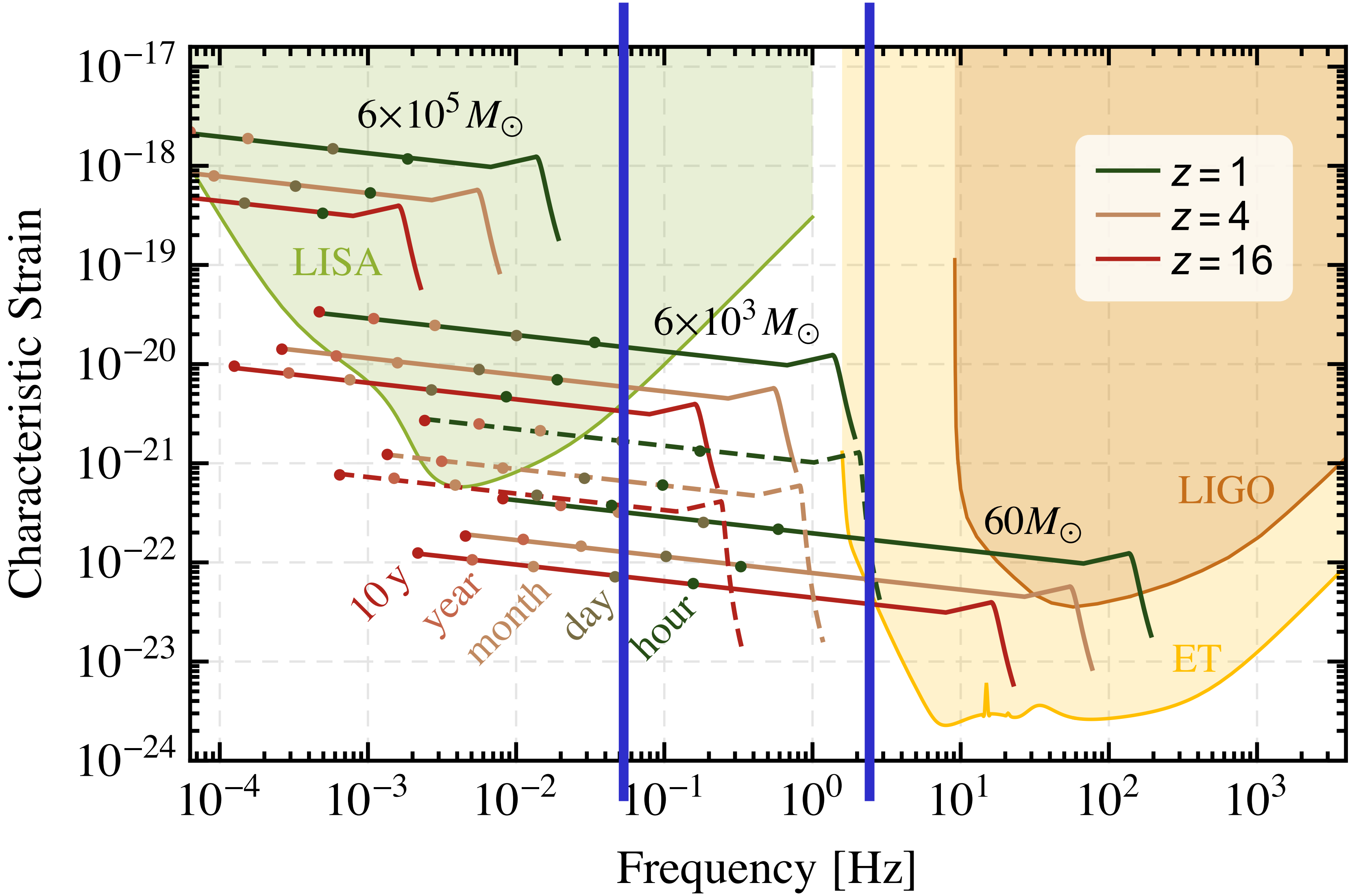
Quadratic scalar DM interactions

UNEXPLORED MID-FREQUENCY GRAVITATIONAL WAVES

Pathway to the GW Mid-(Frequency)



Pathway to the GW Mid-(Frequency)

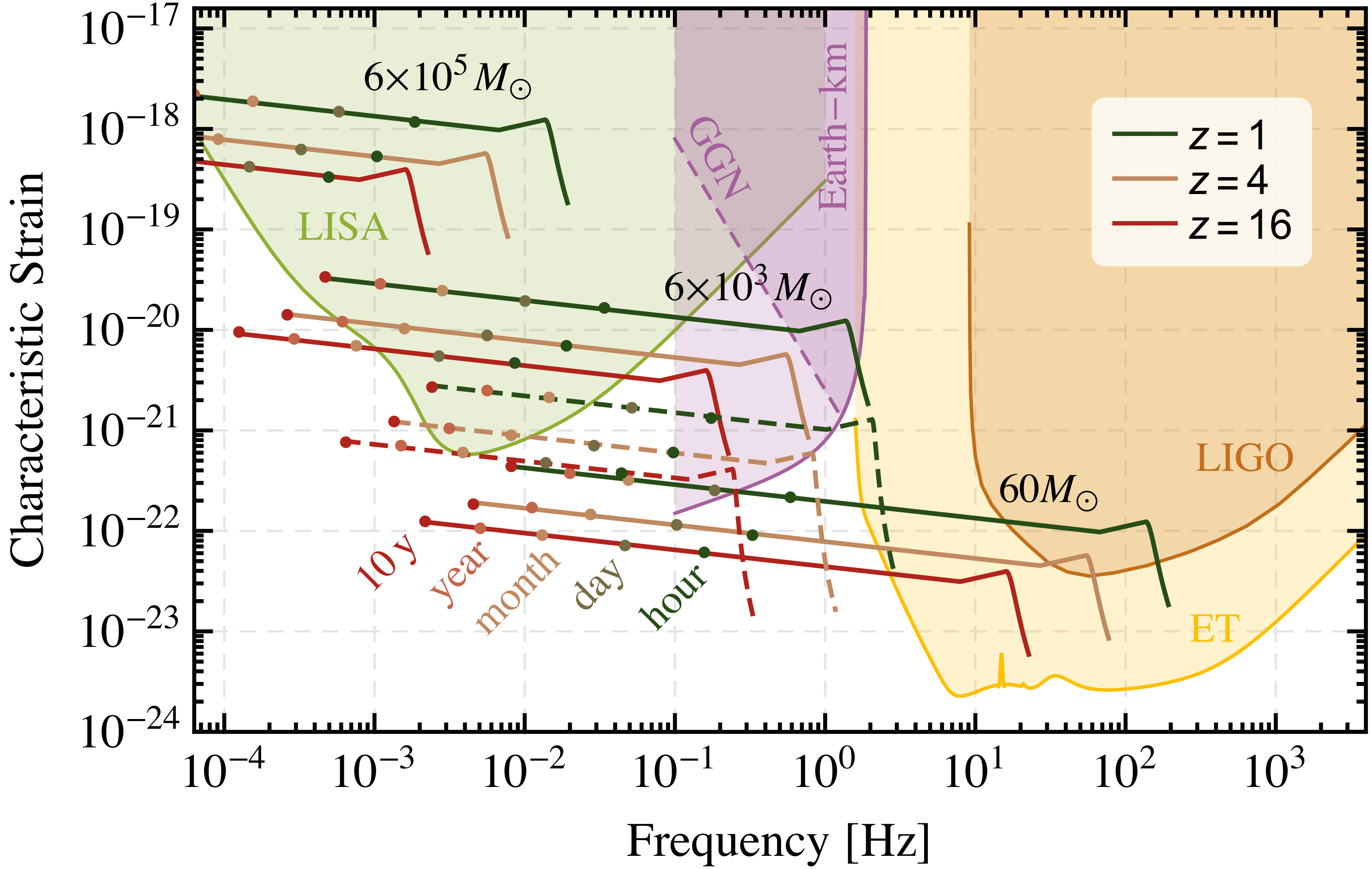


Mid-band science

- 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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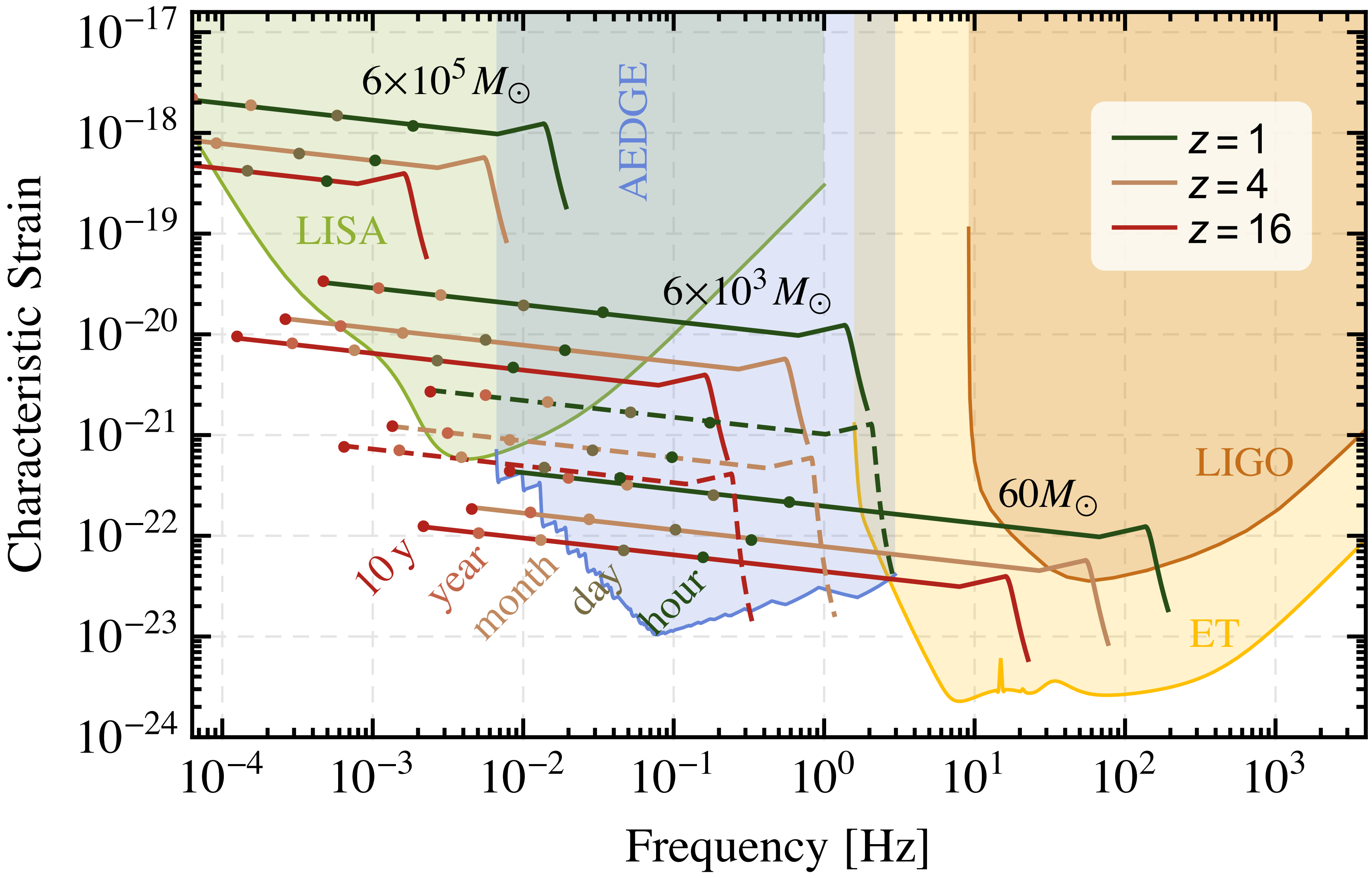
AION: Terrestrial detectors can start filling this gap

AION: Pathway to the GW Mid-(Frequency)



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- Detect sources BEFORE they reach the high frequency band [LIGO, ET]
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AEDGE
Ultimate coverage with a space based detector

Sky position determination

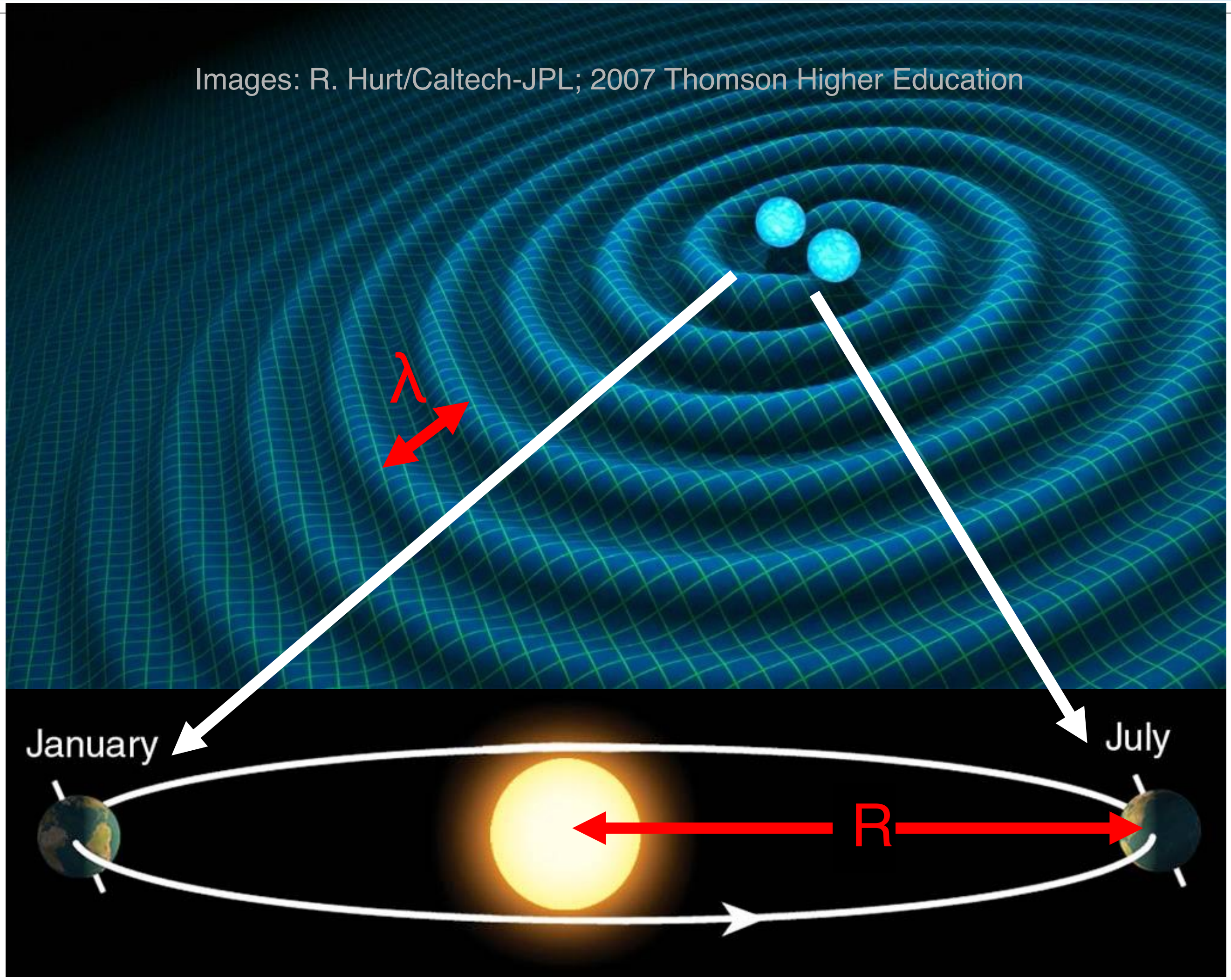
Sky localization precision:

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

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

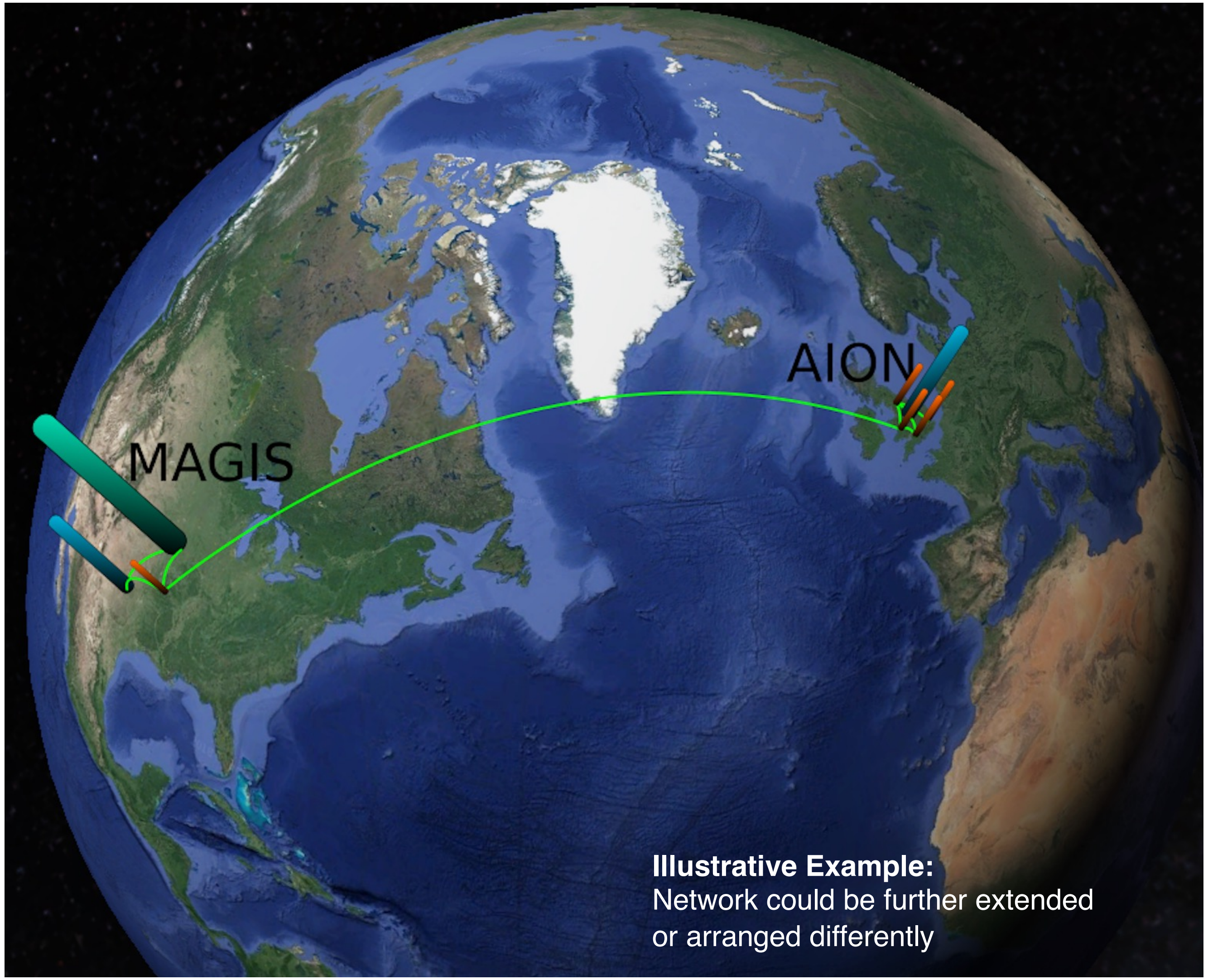
Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19

Courtesy of Jason Hogan!

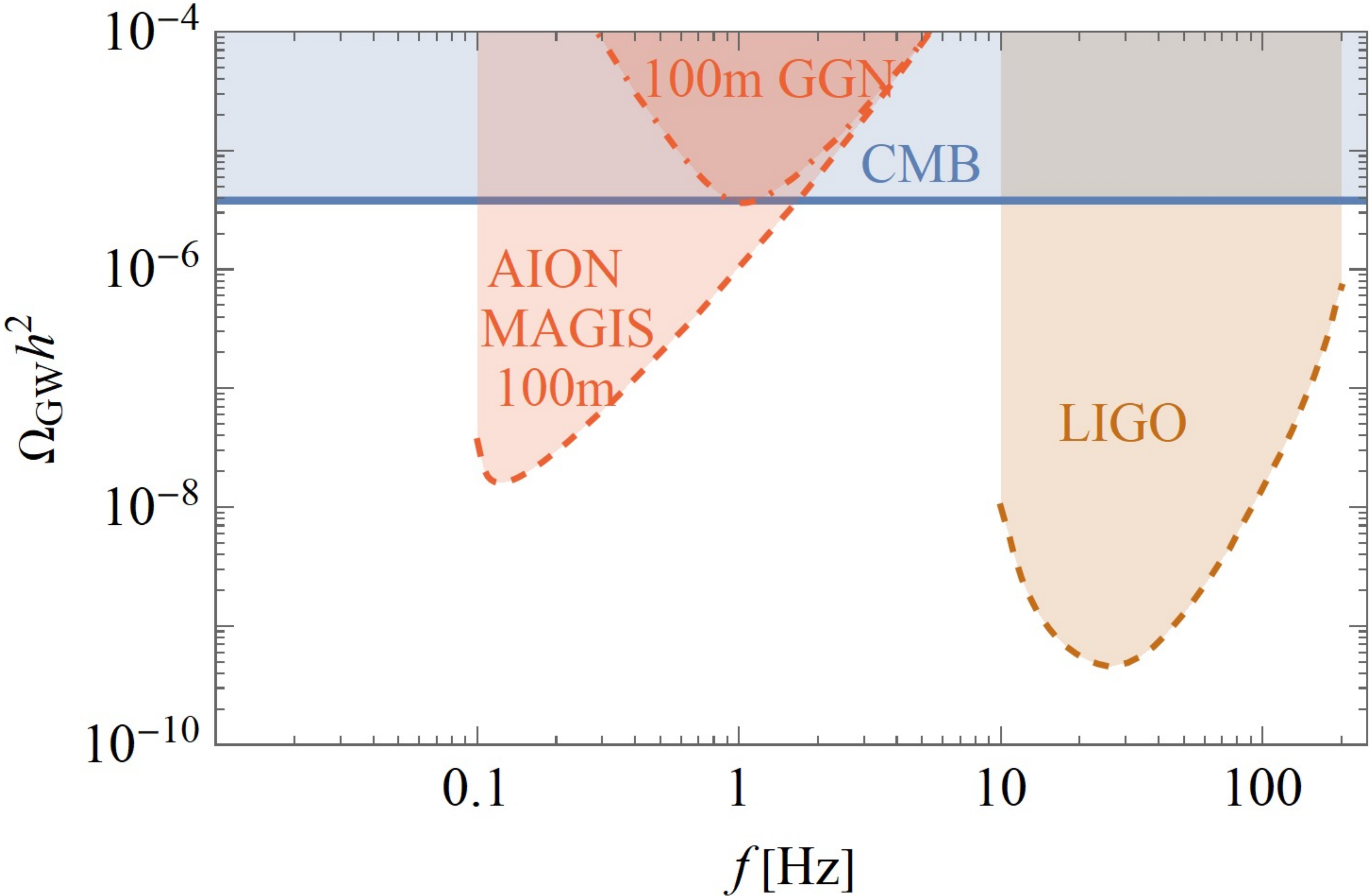


Ultimate sensitivity for terrestrial based detectors is achieved by operating 2 (or more) Detectors in synchronisation mode

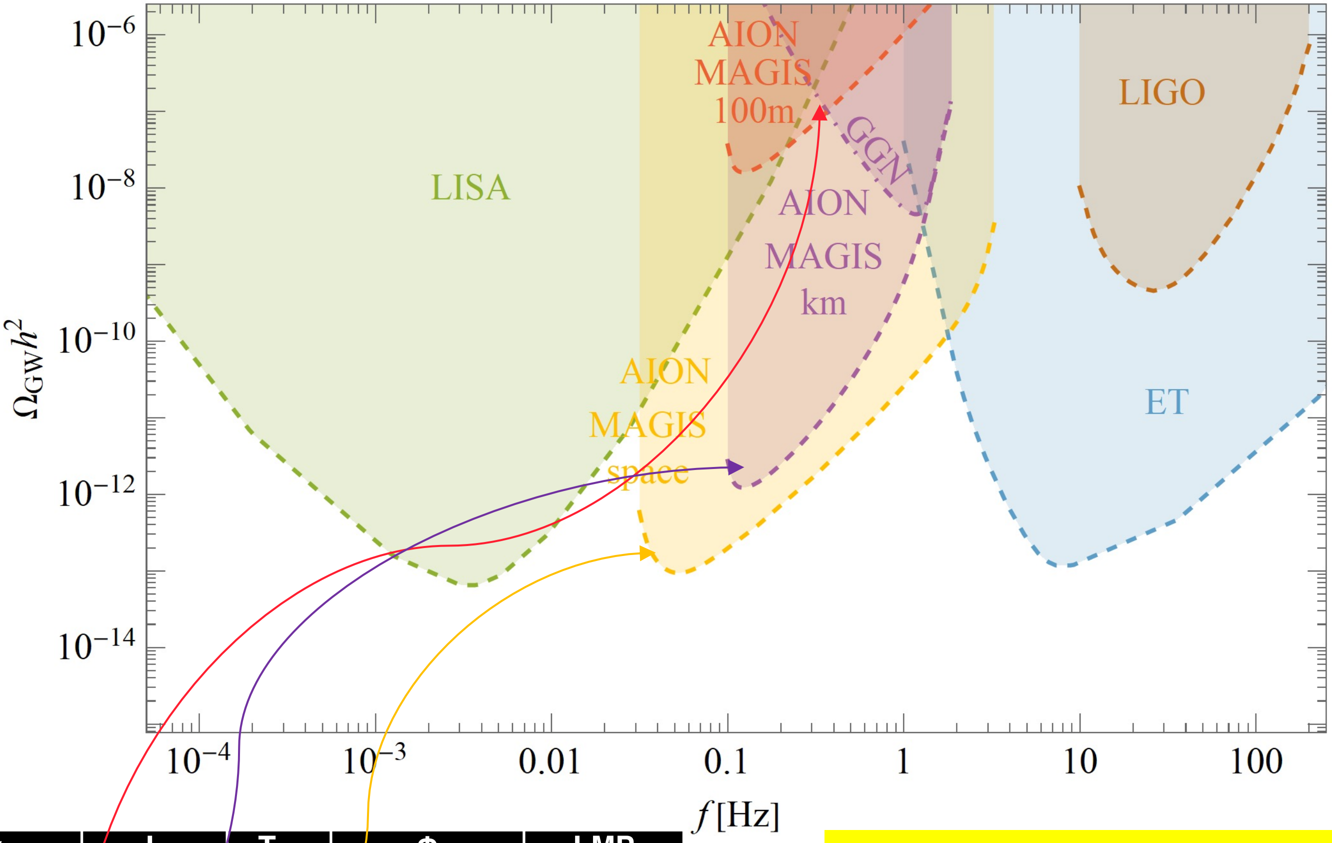
Ultimate Goal: Establish International Network



The GW Experimental Landscape: 2030ish



The GW Experimental Landscape: 2040ish+



Sensitivity Scenario	L [m]	T_{int} [s]	Φ [1/√Hz]	LMP [#]
AION-100-today	100	1.4	10^{-3}	100
AION-100-ultimate	100	1.4	10^{-5}	40000
AION-km	2000	5	0.3×10^{-5}	40000
AION-space	4.4×10^{7}	300	10^{-5}	<1000

List of basic parameters: Lengths of the detector L, interrogation time of the atom interferometer T_{int}, phase noise ϕ, and number of momentum transfers LMP. The choice of these parameters predominately defines the sensitivity of the projection scenarios.

Constraints on Graviton Mass

arXiv:2003.13480

Current LIGO/Virgo limit:

1.76 × 10^{-23} eV

LIGO/Virgo: arXiv:2010.14529

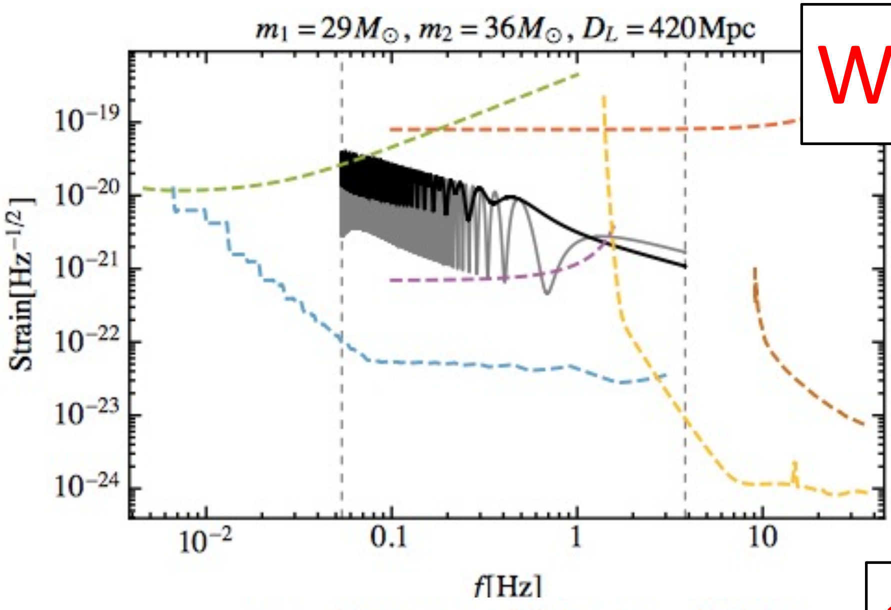
Future sensitivity with LIGO/Virgo-like event?

Longer observations

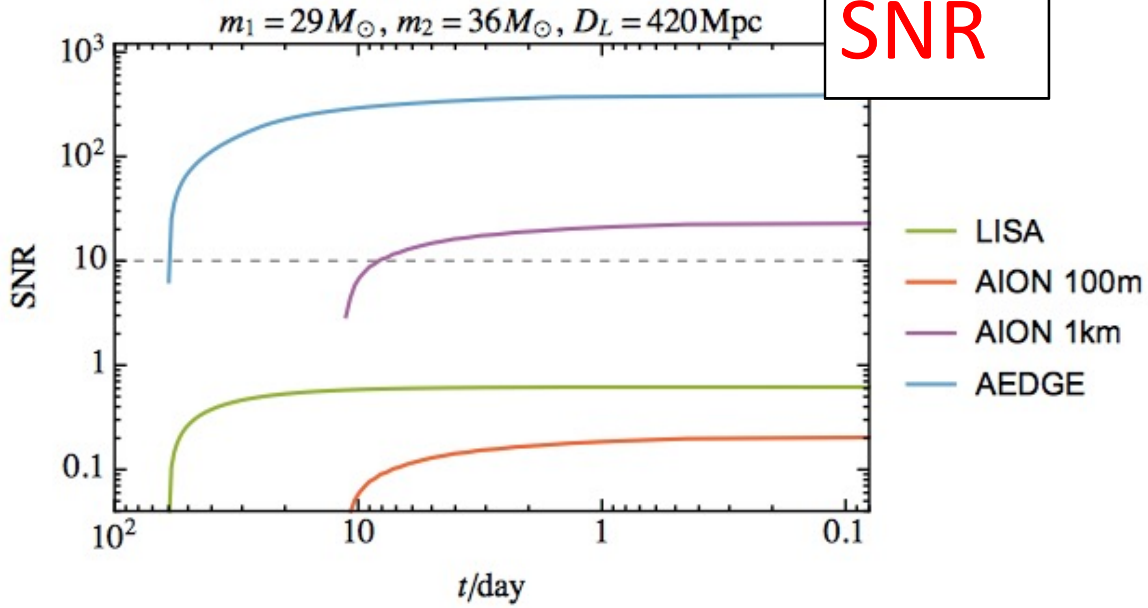
With merger of heavier BHs?

Lower frequencies

GW150914-like BH-BH binary inspiral



Waveforms



SNR

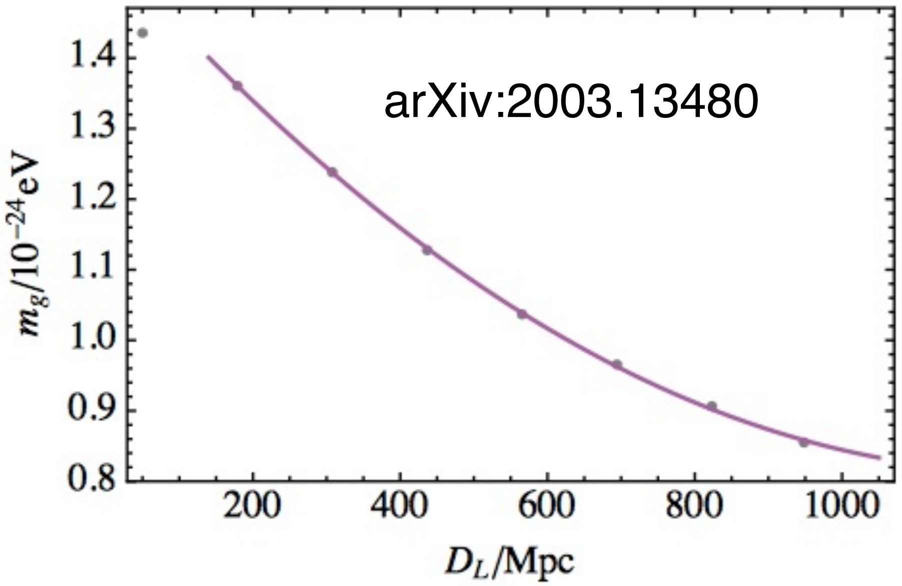
J Ellis & V Vaskonen: arXiv:2003.13480

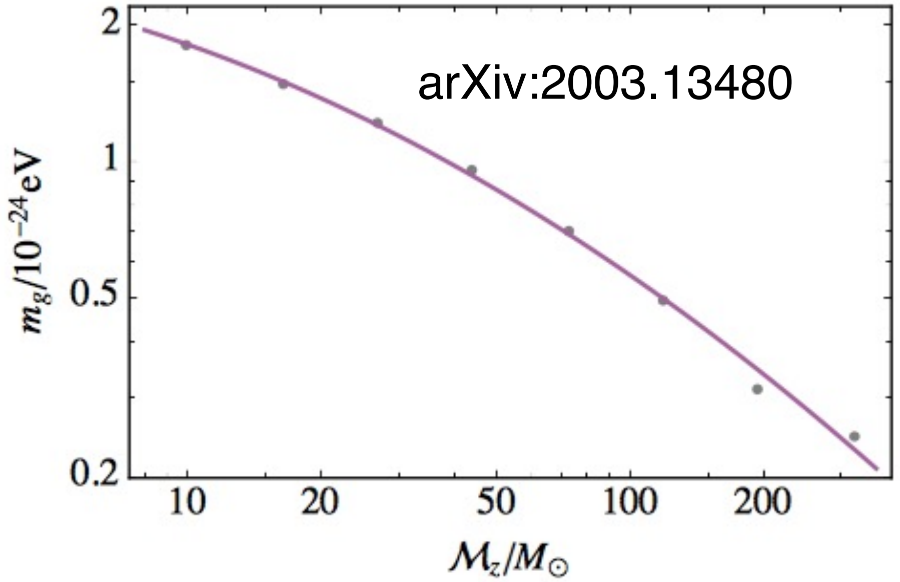
Constraints on Graviton Mass

- LIGO/Virgo: <1.76 × 10^{-23} eV
- AION 1-km: sensitive to 10^{-24} eV
  with LIGO/Virgo-like event
- Sensitive to 2 × 10^{-25} eV
  with heavier BHs
- AEDGE: 8 × 10^{-27} eV
  with BHs 5600 + 4400
  solar masses

AION (and AEDGE) have impressive sensitivity to Graviton Mass

J Ellis & V Vaskonen: arXiv:2003.13480





90% upper bound on the graviton mass for observations of BH-BH binary inspirals as functions of the luminosity distance (upper) and binary chirp mass (lower) for AION 1km

Other Fundamental Physics

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

Examples may include:

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

SITES

Summary

New window on gravitational physics, astrophysics & cosmology using atom interferometers:

- leveraging investment in quantum technologies
- providing new opportunities for science communities
- several large-scale protype projects are currently funded and first results are expected in the next few years
- also very interesting applications for space (see e.g. AEDGE proposal)

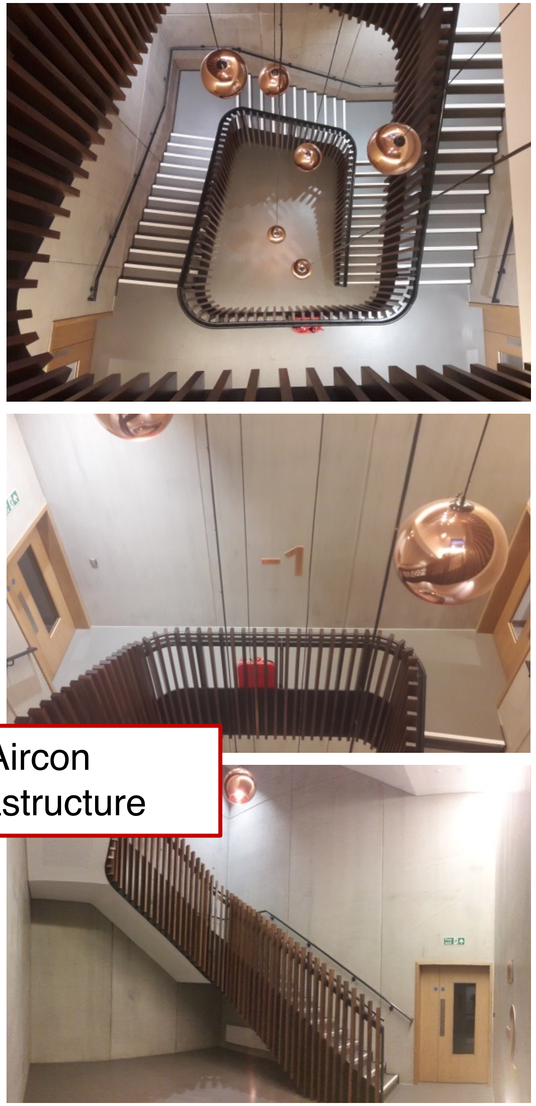
BACKUP

AION 10M PROTOTYPE DETECTOR AT 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

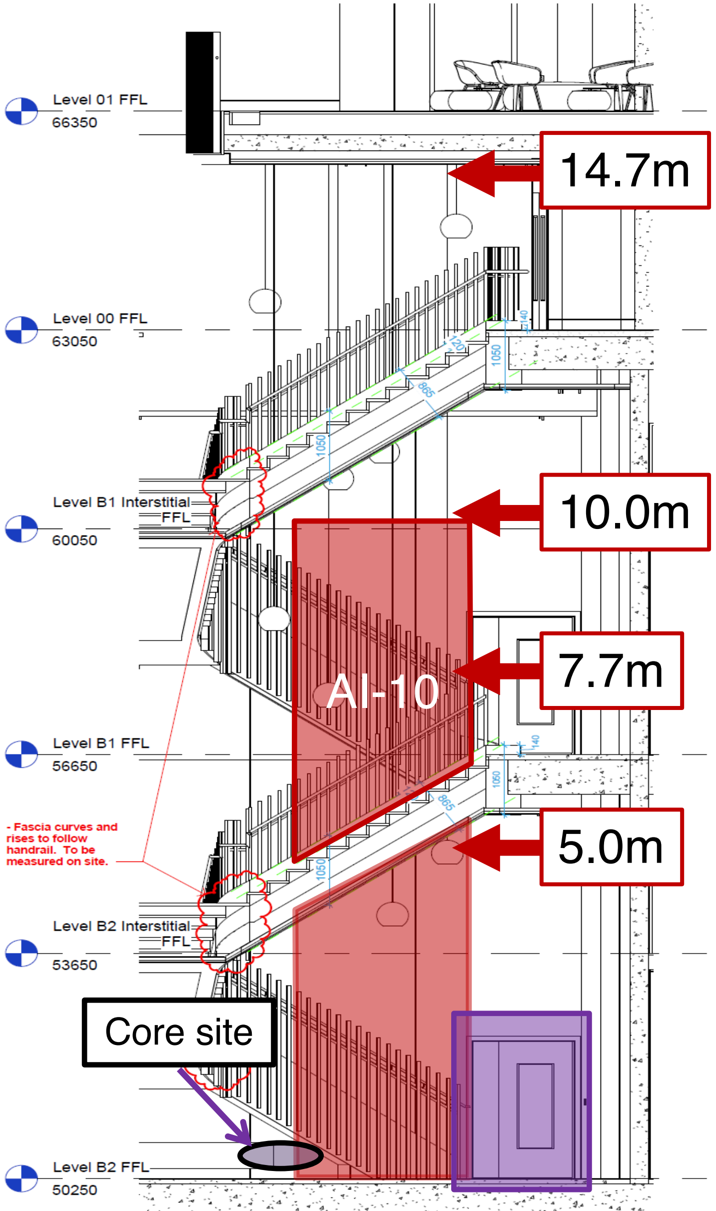
Adjacent laser lab reserved for AION use
- keel slabs
- $\pm 0.1^{\circ}$C stability
- Isolated mains

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

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

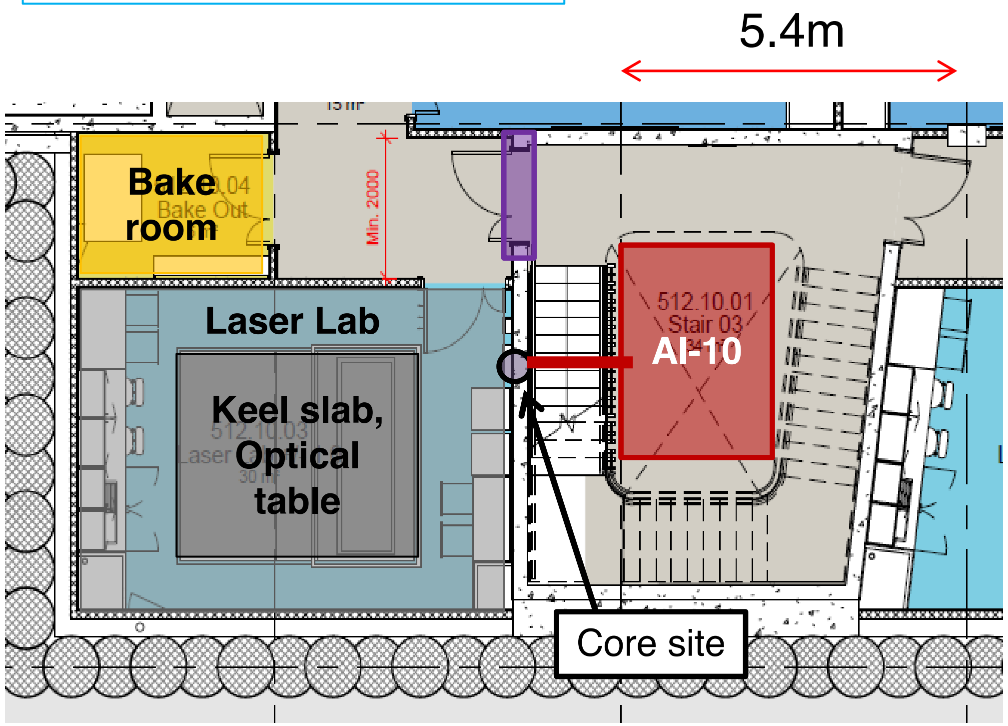
Bakeout room and cleanroom nearby

Beecroft building, Oxford Physics



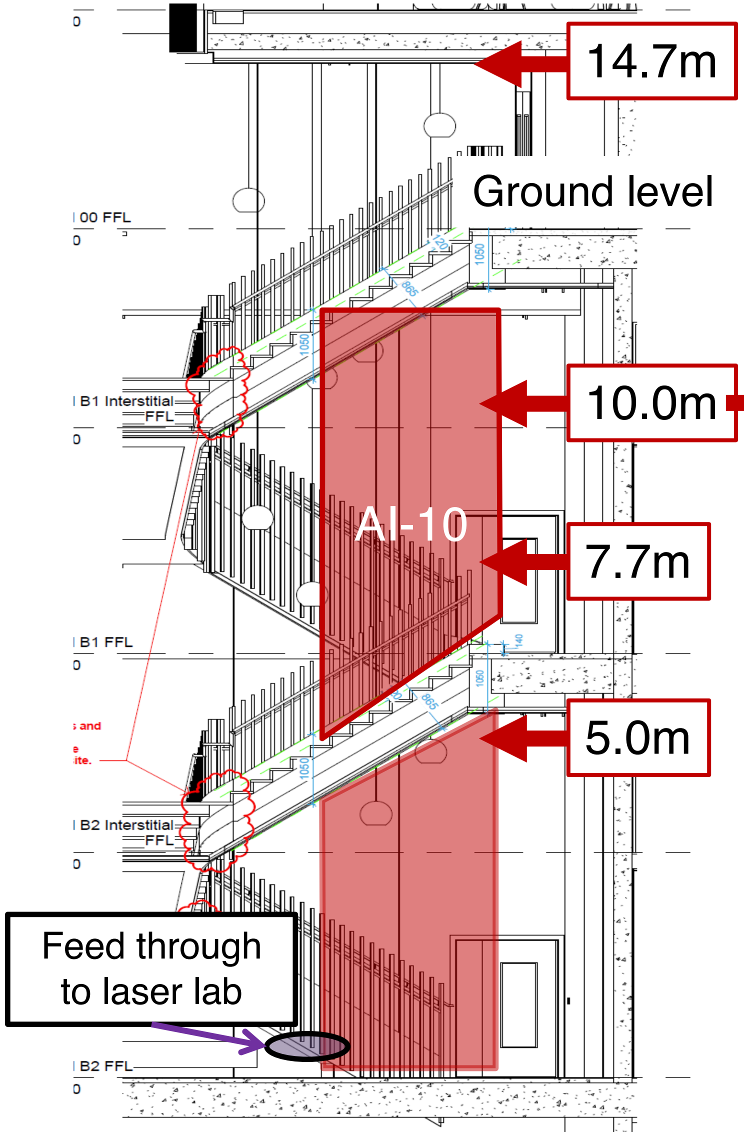
← Side view

↓ Plan view

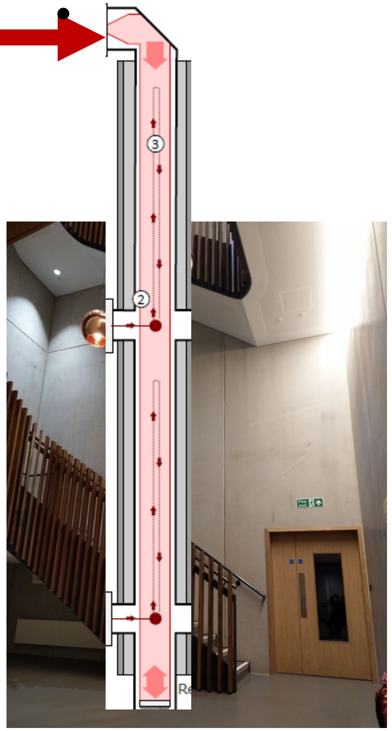


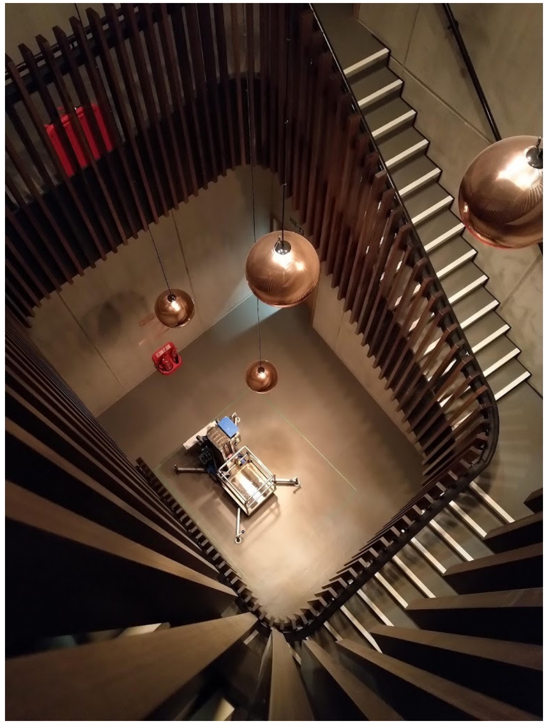
AION-10 site: Beecroft building, Oxford Physics

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



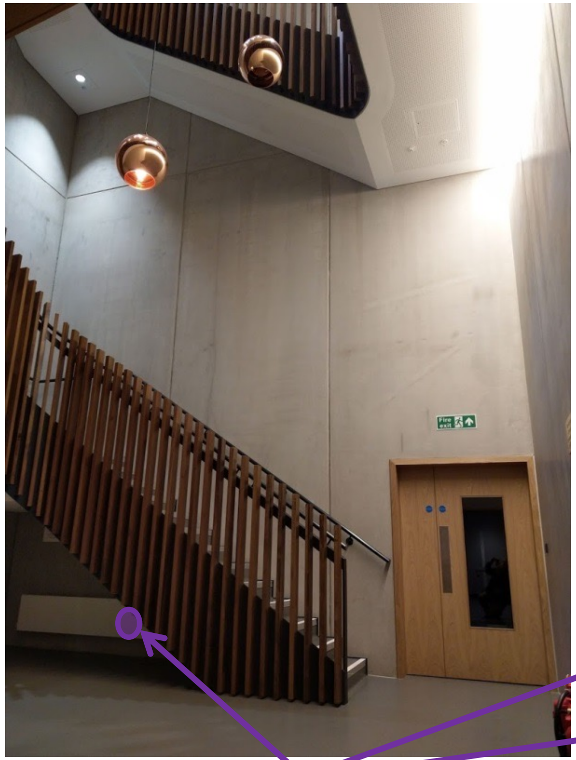
- Detailed planning of support structure by RAL (Engineering), Oxford Physics Technical Services and Liverpool Univ.
- Experienced Project Manager: Roy Preece
- Good site for long-term operation and wide accessibility (also 'visibility' and outreach).

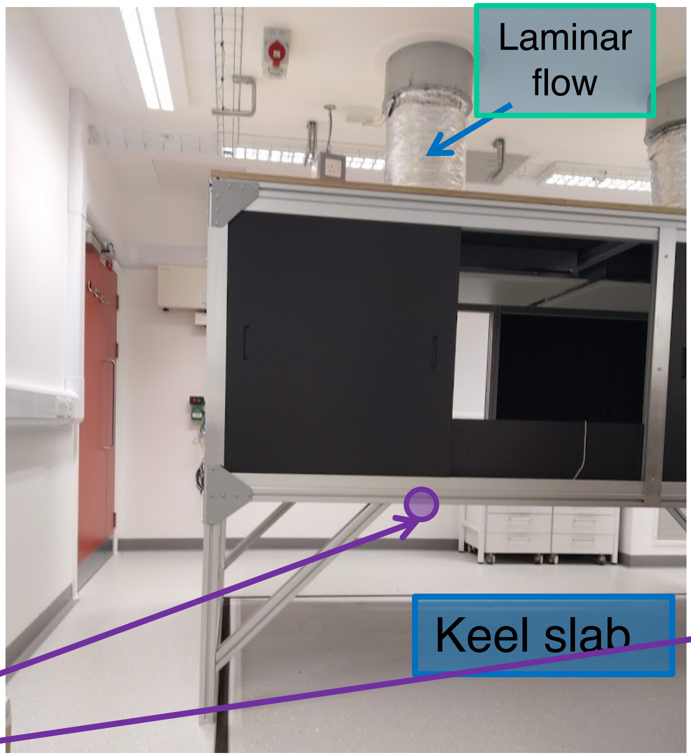


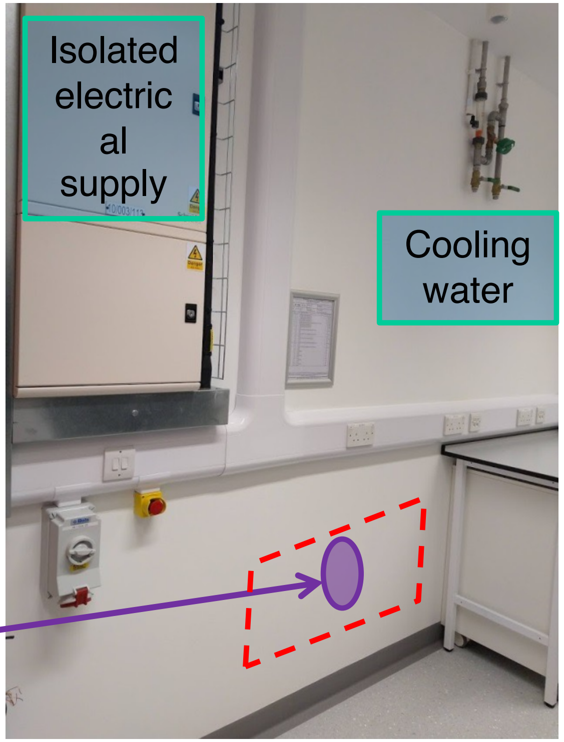


Beecroft building laser lab

Beecroft stairwell: lowest level







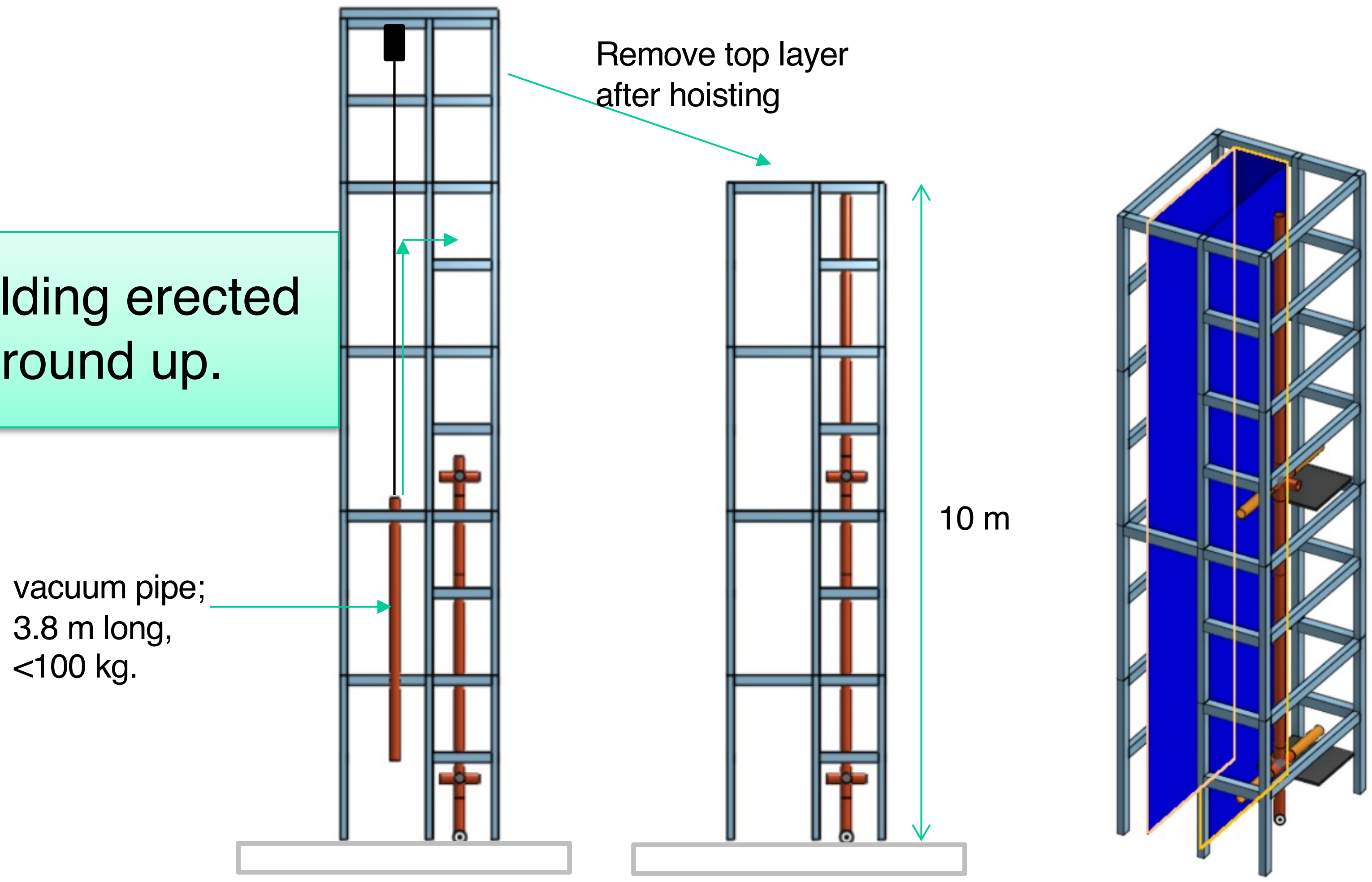
Core site: feed through fibre and cables

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

Bake-out room next door

Assembly: extruded aluminium support structure

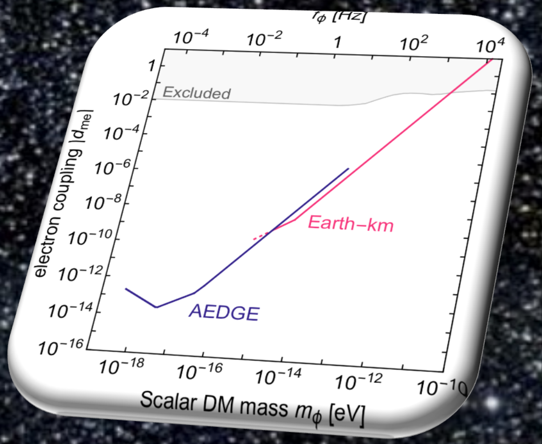
Scaffolding erected from ground up.

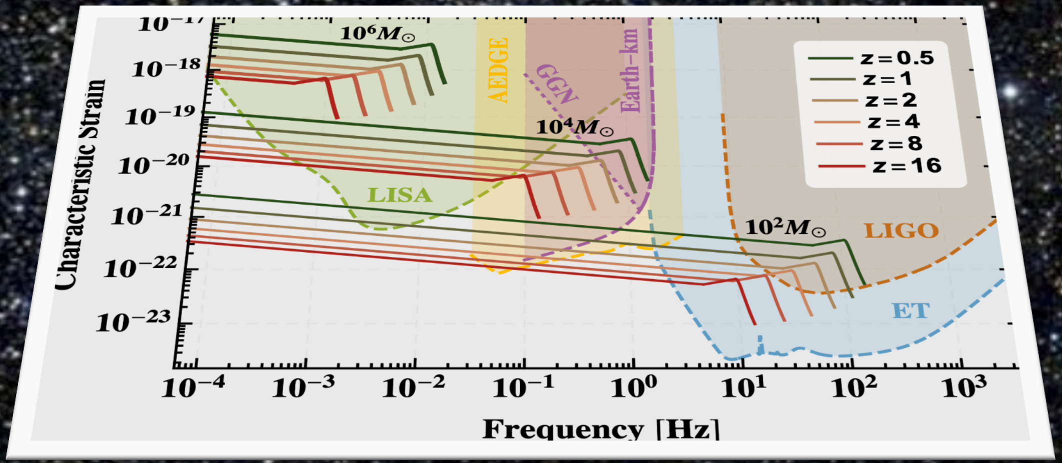


The Space Version of AION – Stage 4 of the Programme

AEDGE

AEDGE:
Atomic Experiment for Dark Matter and Gravity Exploration





Informal Workshop
CERN, July 22/23 2019

Organizers:
Kai Bongs(CA), Philippe Bouyer(CA), Oliver Buchmueller(PP),
Albert De Roeck(PP), John Ellis(PP, Theory), Peter Graham (CA, Theory),
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

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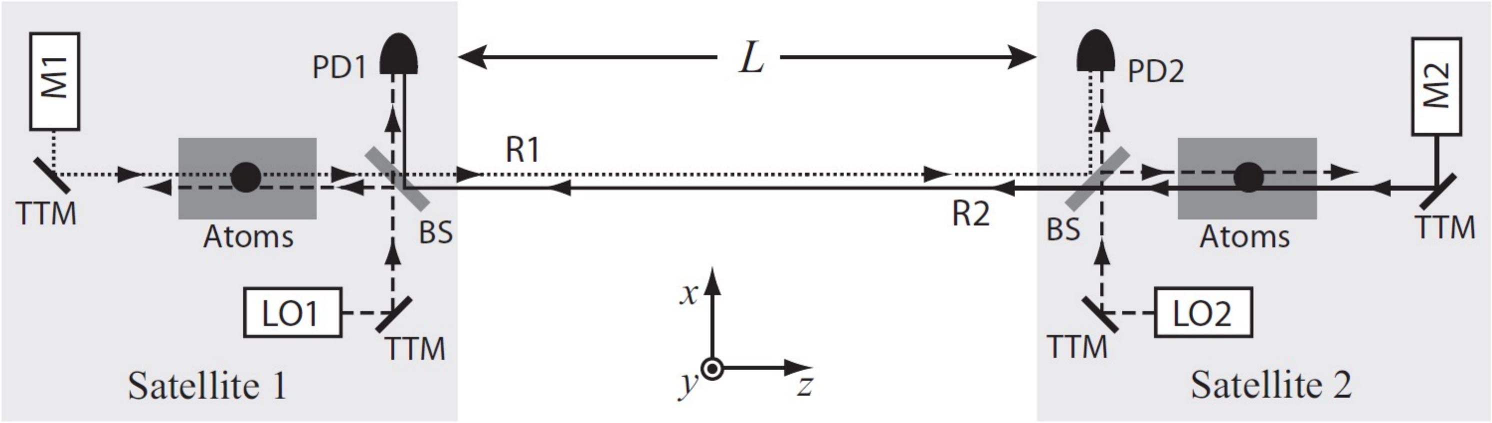
132 Authors, from **70** institutions, based in **23** different counties!

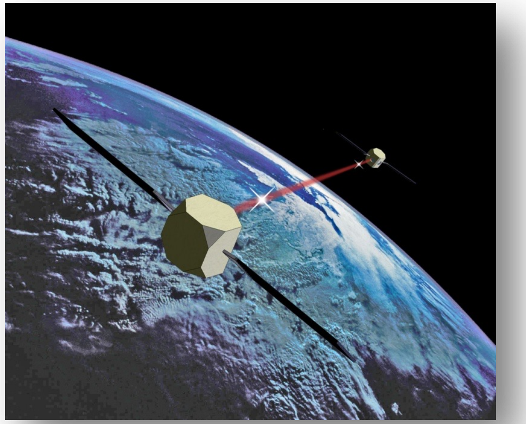
The authors represent several science communities ranging from Cold Atoms, & Gravitational Waves, over Cosmology and Astrophysics to fundamental Particle Physics.

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:

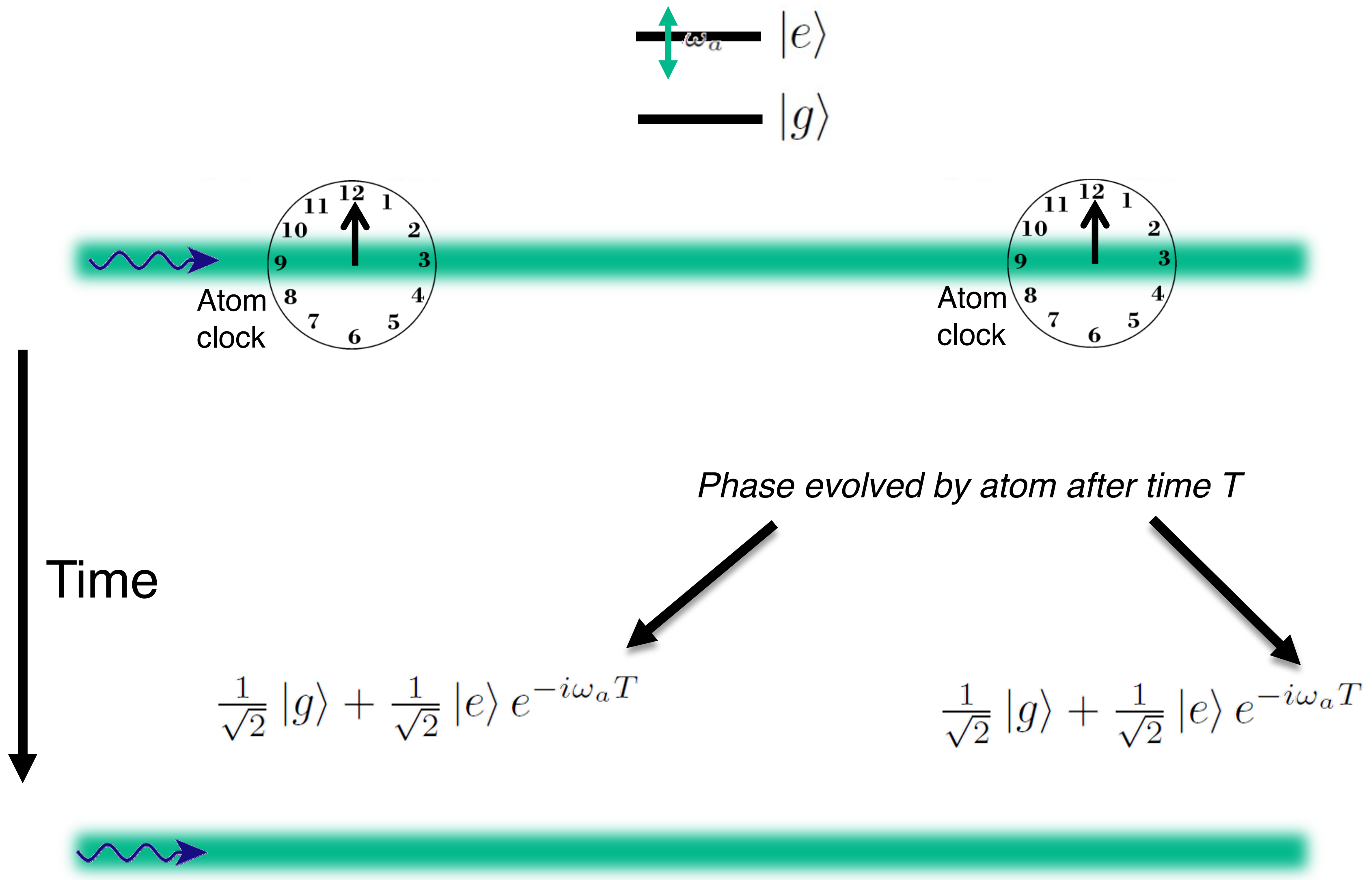
- Pair of satellites in medium earth orbit (MEO)
- Satellite separation L = 4.4 x 10^7 m

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**

ATOM INTERFEROMETER CONCEPT

Simple Example: Two Atomic Clocks



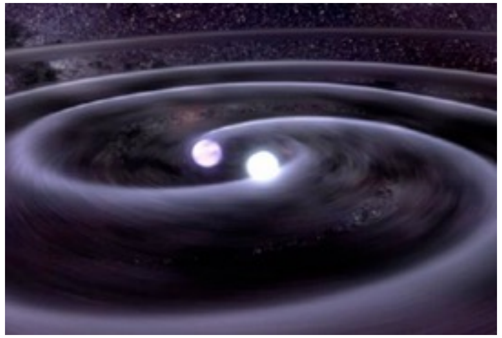
Simple Example: Two Atomic Clocks

ω_a $|e\rangle$

$|g\rangle$

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

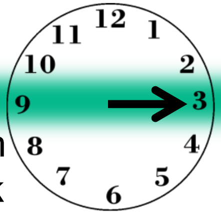
Time



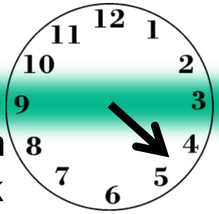
GW changes light travel time

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

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



Atom clock



Atom clock

Phase Noise from the Laser

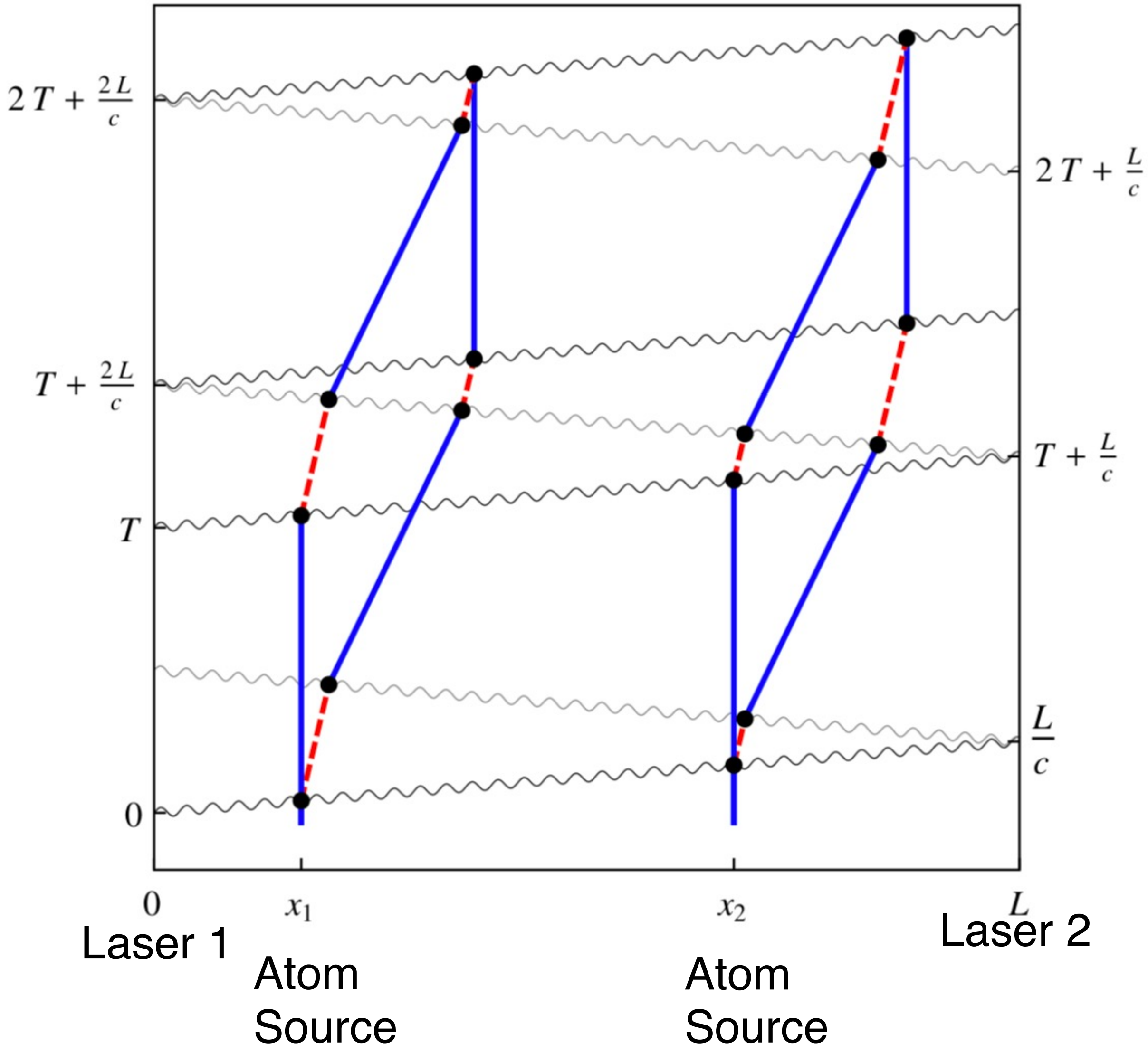
The phase of the laser is imprinted onto the atom.

Laser phase noise, mechanical platform noise, etc.

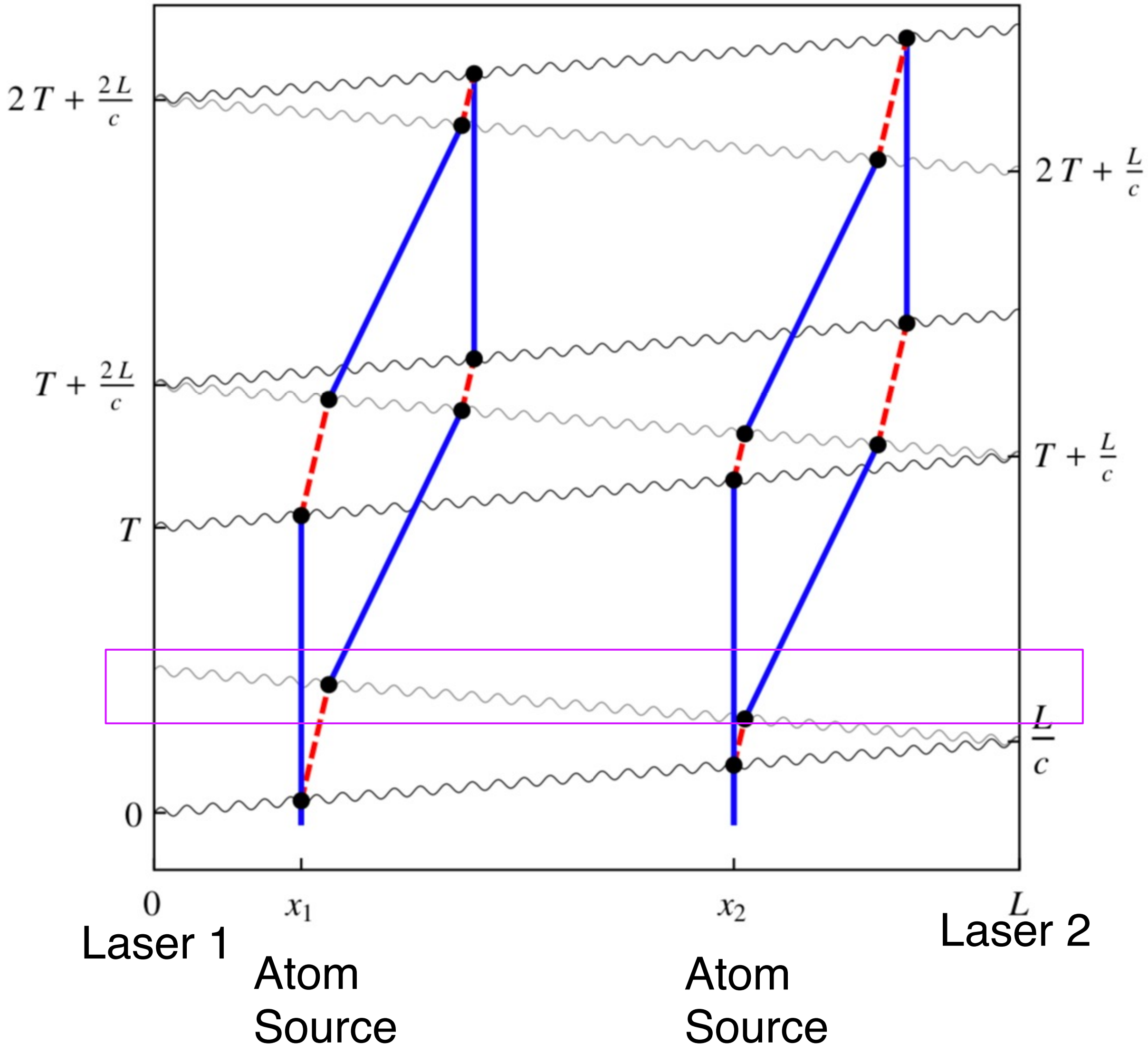
$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle e^{i\phi_L} \qquad\qquad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle e^{i\phi_L}$$

*Laser phase is **common** to both atoms – rejected in a differential measurement.*

Basic Differential Measurement



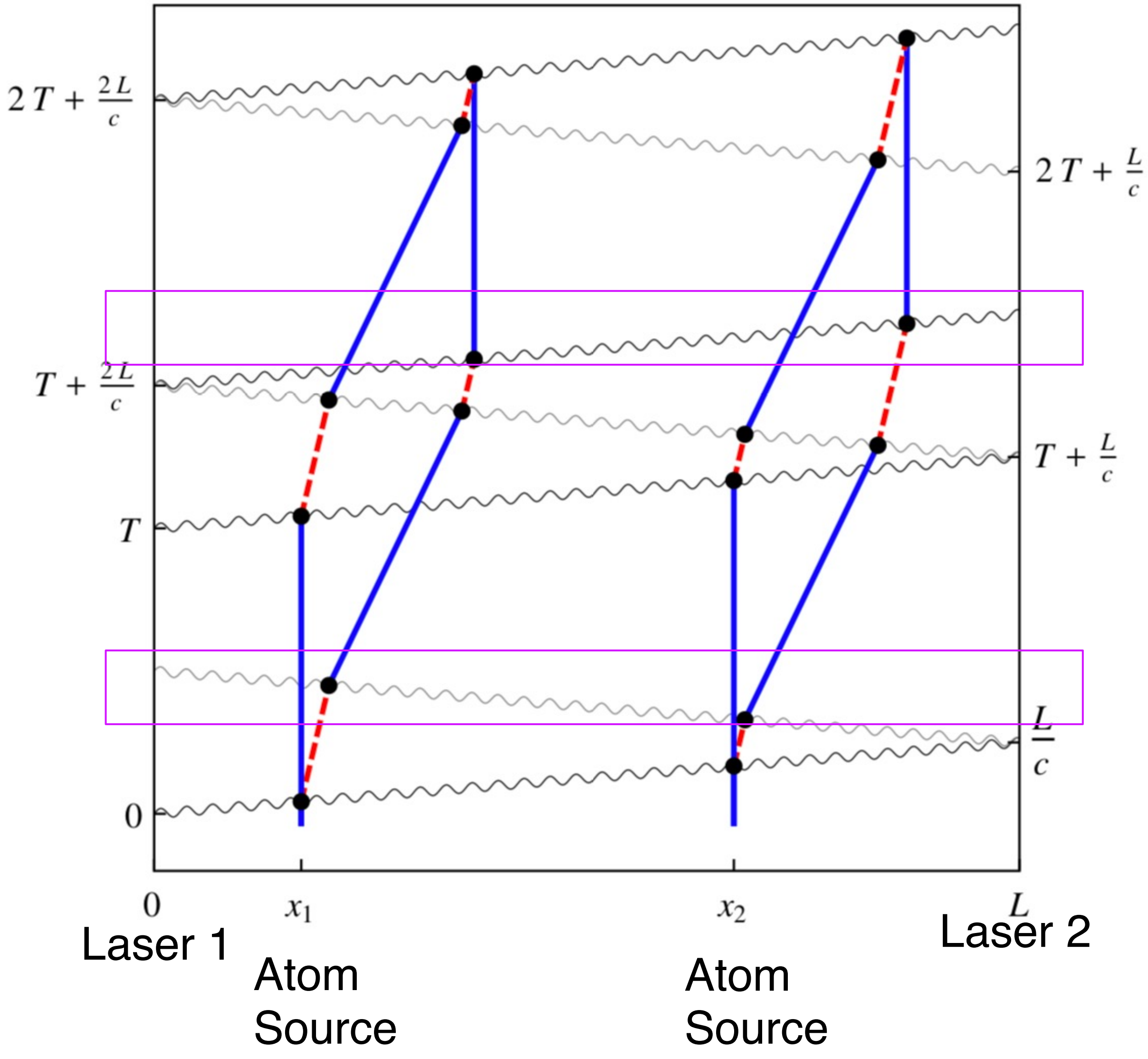
Basic Differential Measurement



Laser 2: π pulse [high p]

Laser 1: π/2 pulse [split]

Basic Differential Measurement

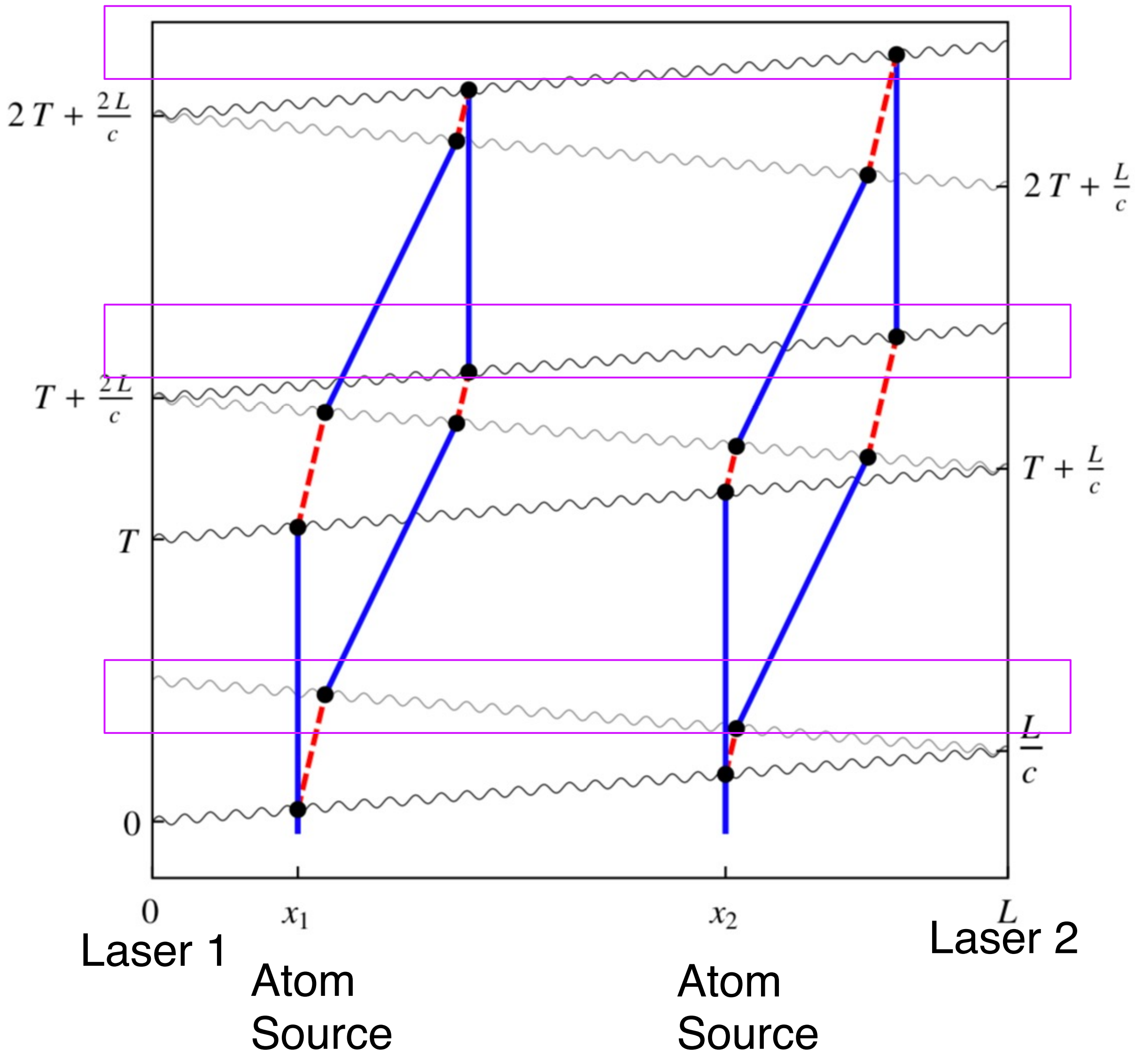


"Mirror"
3π pulse
[low-high/low-high]
[Doppler shift to select]

Laser 2: π pulse [high p]

Laser 1: π/2 pulse [split]

Basic Differential Measurement



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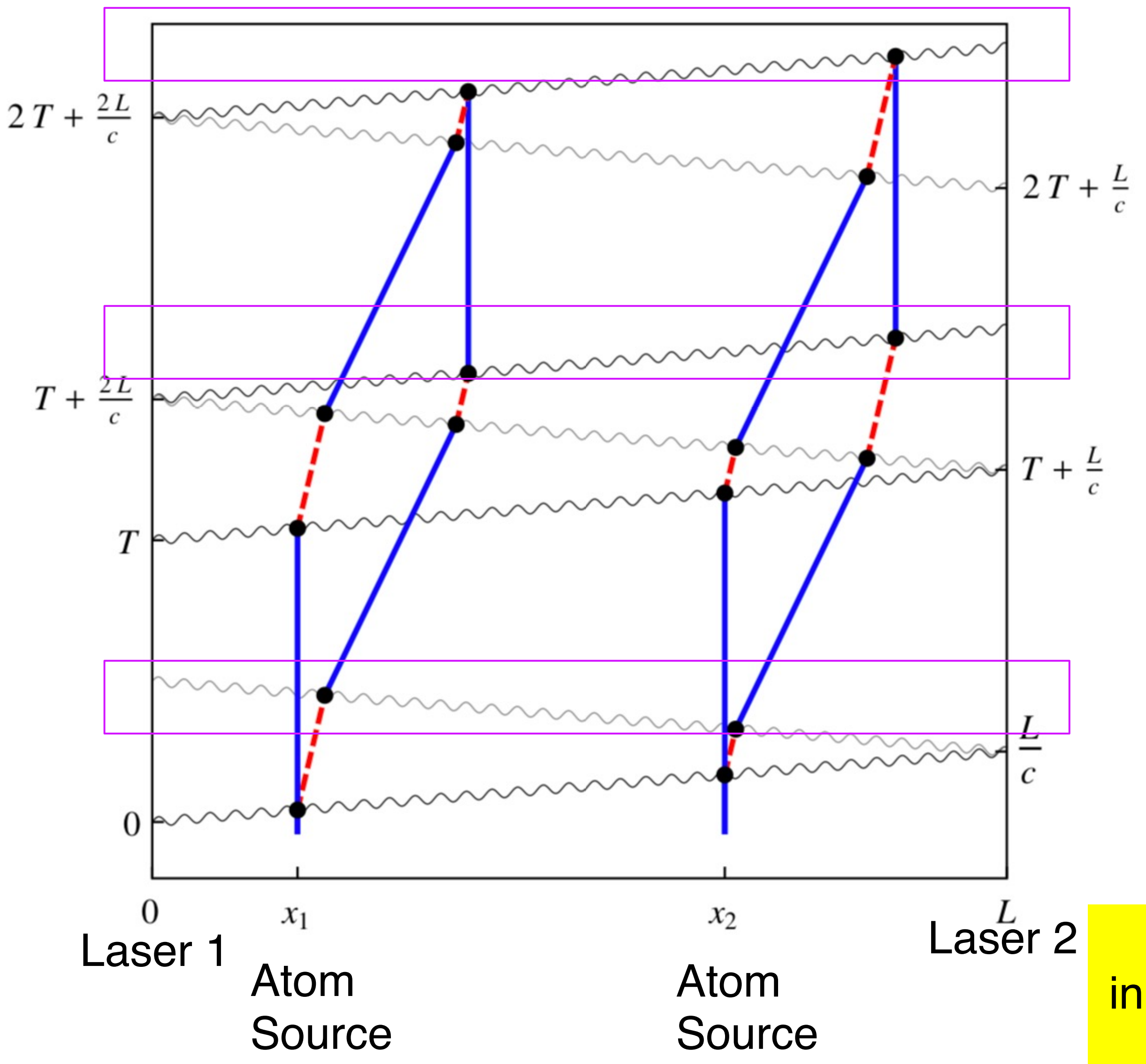
Basic Differential Measurement



Laser 1: π/2 pulse [split]

Laser 2: π pulse [low p]

"Mirror"
3π pulse
[low-high/low-high]
[Doppler shift to select]

Laser 2: π pulse [high p]

Laser 1: π/2 pulse [split]

Each AI spends time L/c in excited state but at different periods in the sequence

Team roles and linkages in AION and MAGIS

MAGIS-100

Joint work includes:-

- Jon Coleman (Liverpool) is a founding member of the MAGIS project: Design and fabrication of key parts by Liverpool Physics.
- Hardware deliverables to MAGIS: Cameras (Oxf.), Electronics (Cam.)
- Assisting in construction, commissioning and data-taking at Fermilab site.
- Participation in date analysis and first results.
- Kavli-funded PDRA (Cam.)

UK laser company: Unique systems for Q Tech. with Sr

King's + Imperial Colleges: Theory and publication office

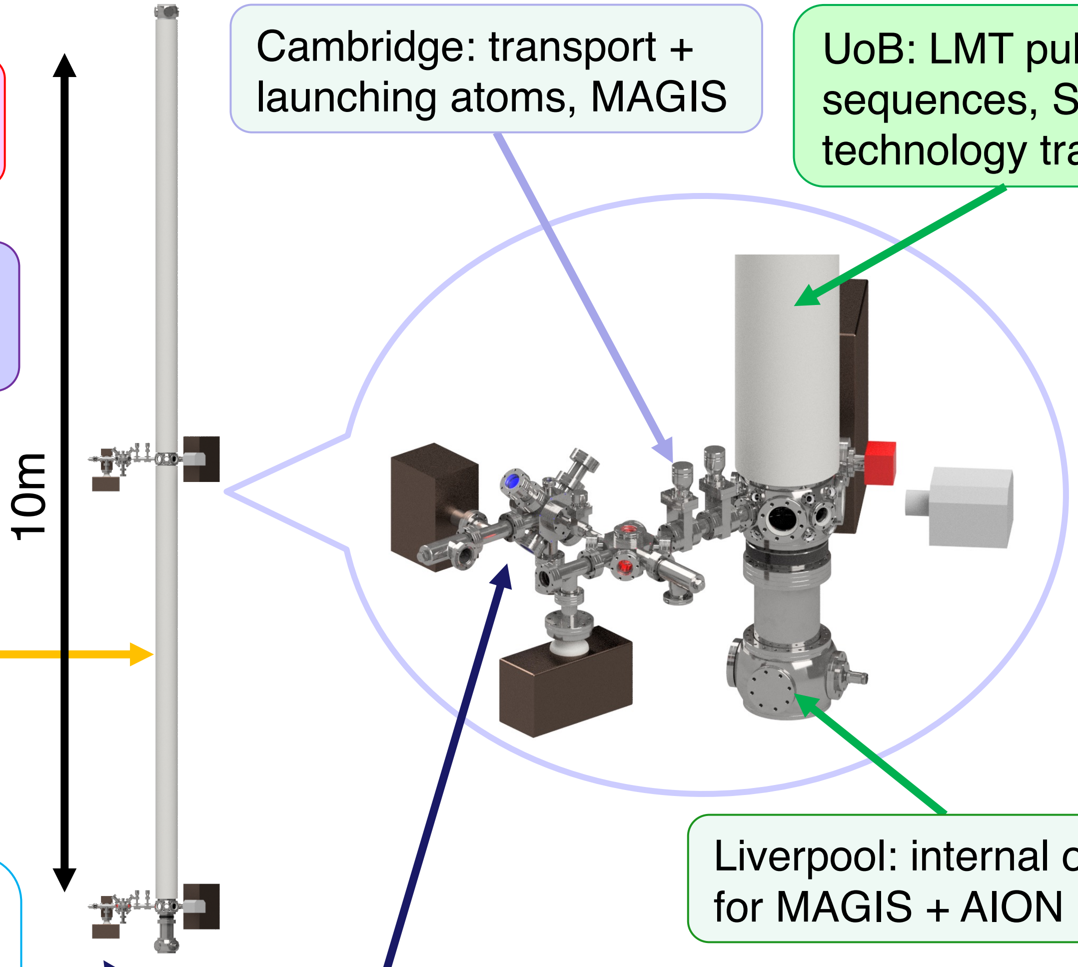
UoB, Cambridge, Imperial: modelling system parameters

Imperial: (clock) laser stabilisation, squeezing

RAL: Vacuum + support structure. Design AION-100

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

- Impact
- Technology transfer



Cambridge: transport + launching atoms, MAGIS

UoB: LMT pulse sequences, Sr technology transfer

Liverpool: internal optics for MAGIS + AION

Oxford: site, cold-atom source, laser lab, construction

THE PHYSICS CASE

Based on DM workshop at KCL:

https://indico.cern.ch/event/797031/timetable/

and AION workshop at Imperial:

https://indico.cern.ch/event/802946/

Using Material from. M. Bauer, J. Hogan, J. March-Russel, C. McCabe, and Y. Stadnik

DARK MATTER PHYSICS @AION

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

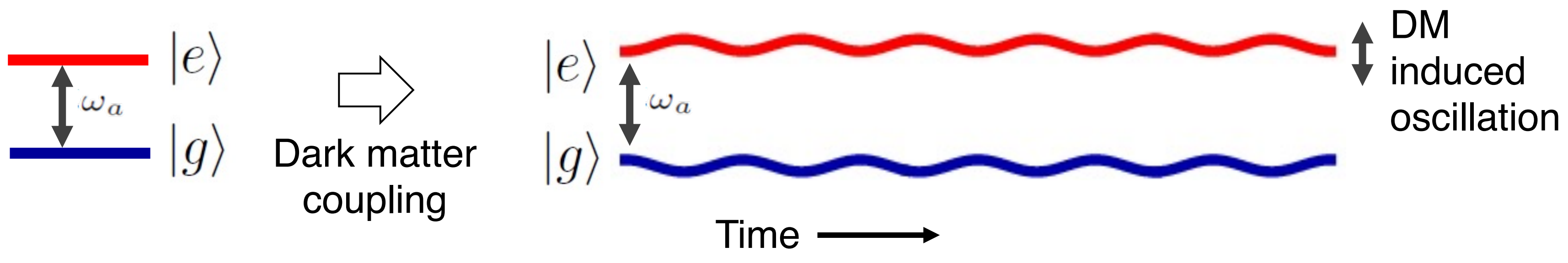
Photon coupling

e.g., QCD

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

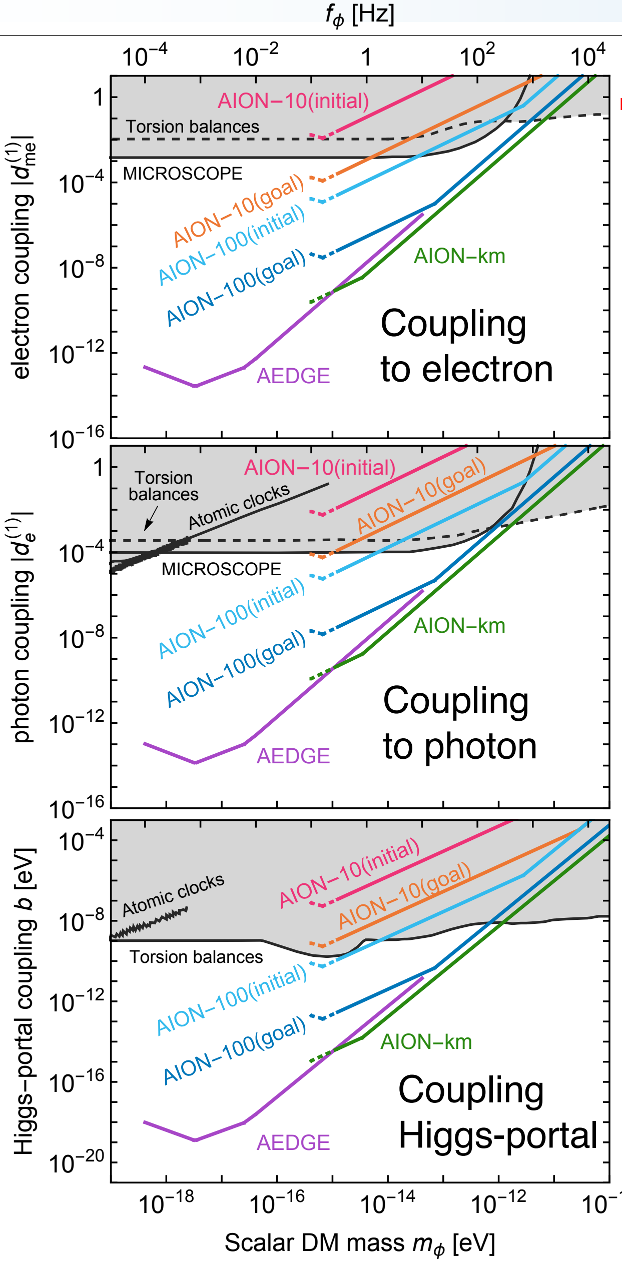
$$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$ DM mass density

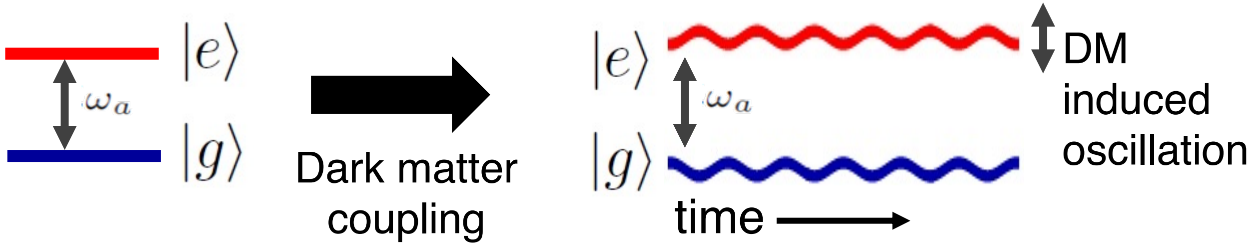
DM coupling causes time-varying atomic energy levels:



Courtesy of Jason Hogan!

Ultra-Light Scalar Dark Matter



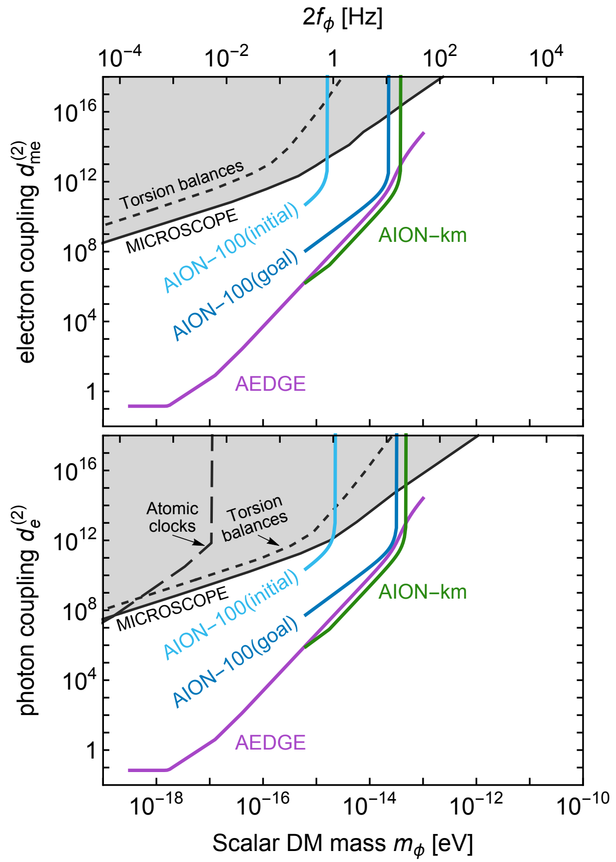


The AION staged programme will have unprecedented sensitivity to DM with scalar couplings to matter, which cause time variation of fundamental constants such as the electron mass.

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

Linear scalar DM interactions

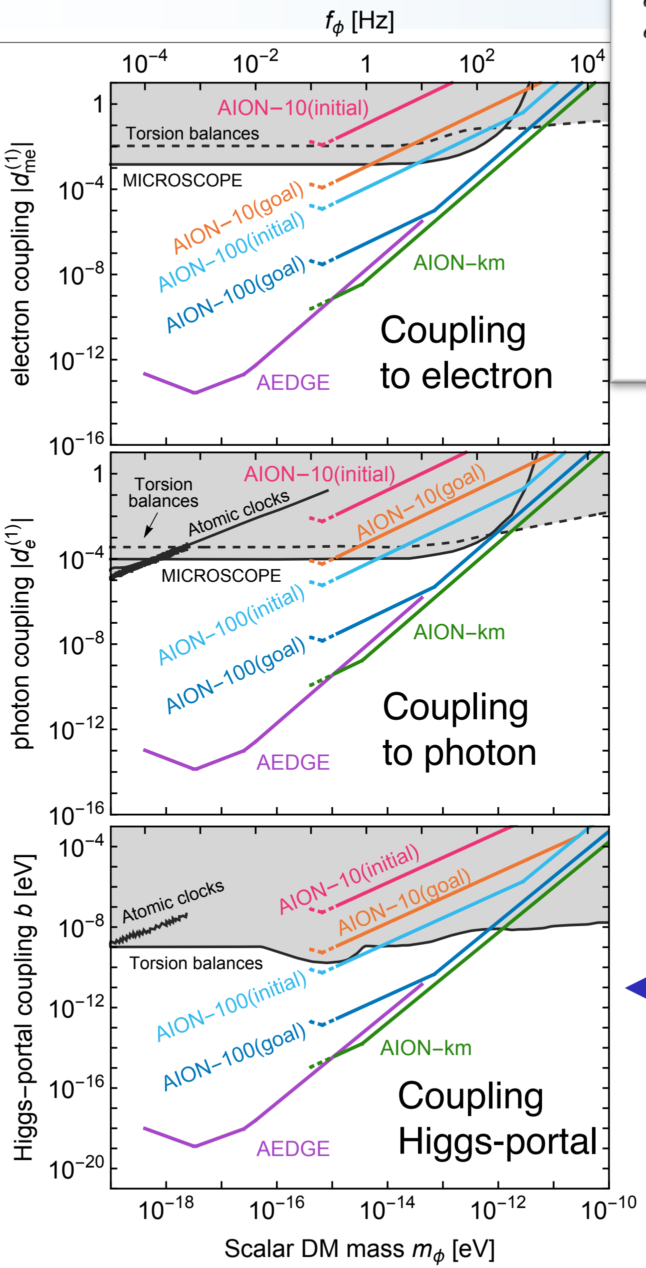
Quadratic scalar DM interactions



Ultra-

Table 1. *List of basic parameters: length of the detector L; interrogation time of the atom interferometer T_{int}; phase noise $\delta\phi_{\rm noise}$; and number of momentum transfers LMT. The choices of these parameters largely determine the sensitivities of the projection scenarios. It should be noted that at a 100m detector it will be conceptually possible to increase the interrogation time of the atom interferometer beyond 1.4 sec.*

Sensitivity Scenario	L [m]	T_{int} [sec]	$\delta\phi_{\rm noise}$ [$1/\sqrt{\rm Hz}$]	LMT [number n]
AION-10 (initial)	10	1.4	10^{-3}	100
AION-10 (goal)	10	1.4	10^{-4}	1000
AION-100 (initial)	100	1.4	10^{-4}	1000
AION-100 (goal)	100	1.4	10^{-5}	40000
AION-km	2000	5	0.3×10^{-5}	40000



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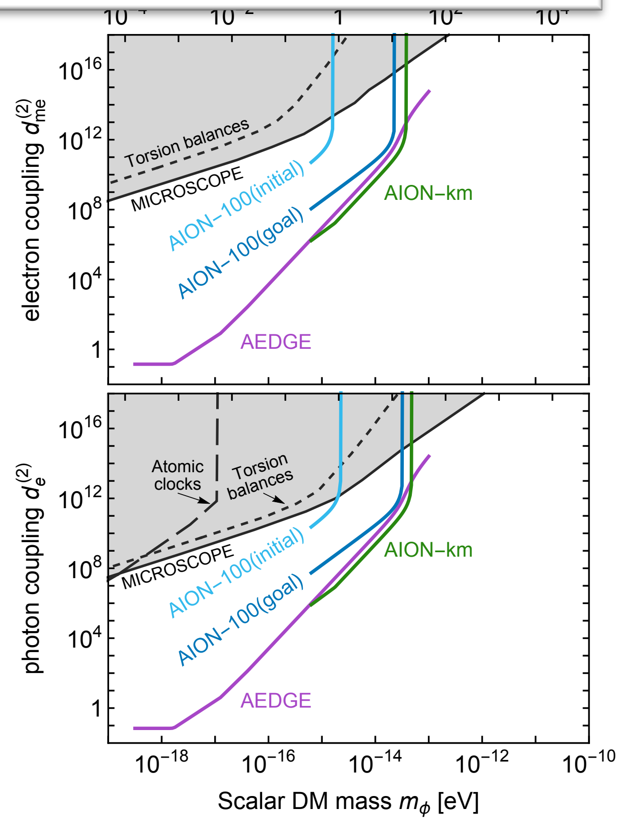
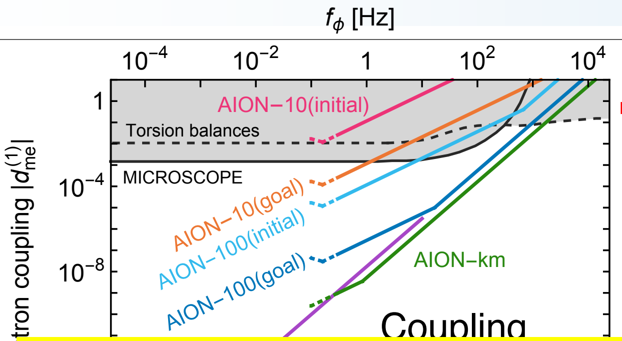
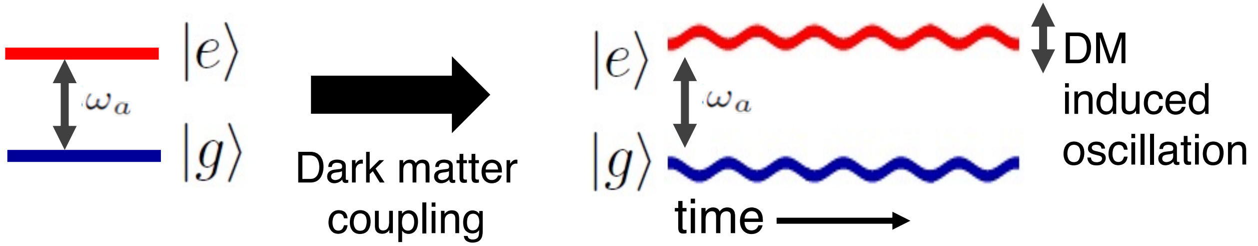
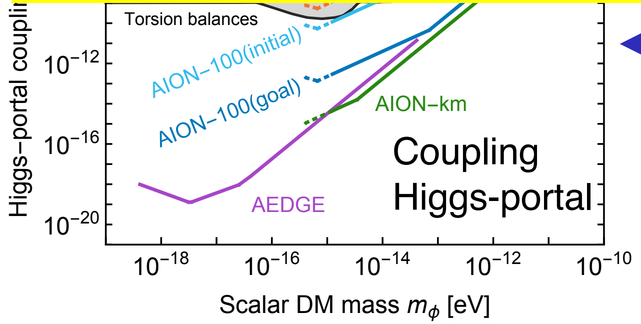


Ultra-Light Scalar Dark Matter



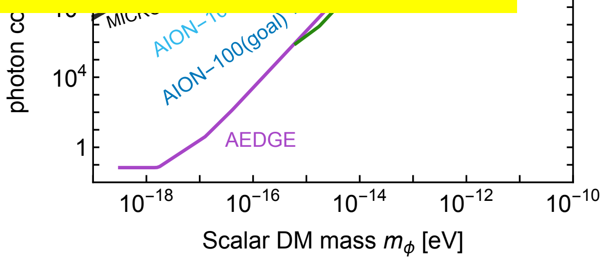


AION will be probing new territory in ULD scalar scenarios.
With different configurations of the Atom Interferometer it will be also possible to search for
Axions (pseudo-scalar) and **Vector** DM candidates!
[studies are ongoing]



Linear scalar DM interactions

Quadratic scalar DM interactions



AION Project: SURF Long-Term Vision Workshop

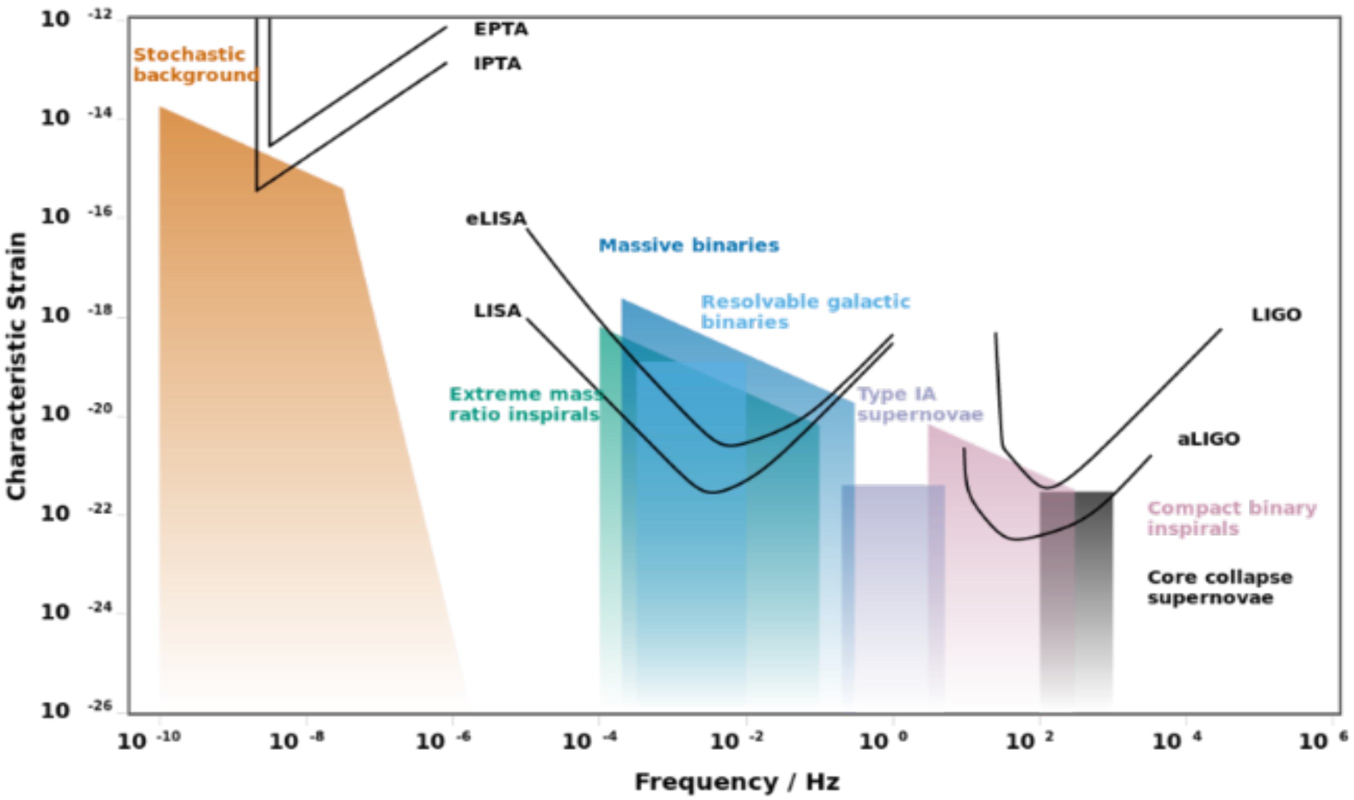
References:

- On the Maximal Strength of a First-Order Electroweak Phase Transition and its Gravitational Wave Signal, 1809.08242
- Cosmic Archaeology with Gravitational Waves from Cosmic Strings, 1711.03104
- Probing the pre-BBN universe with gravitational waves from cosmic strings, 1808.08968
- Formation and Evolution of Primordial Black Hole Binaries in the Early Universe, 1812.01930
- Primordial Black Holes from Thermal Inflation, 1903.09598

GW PHYSICS @ AION

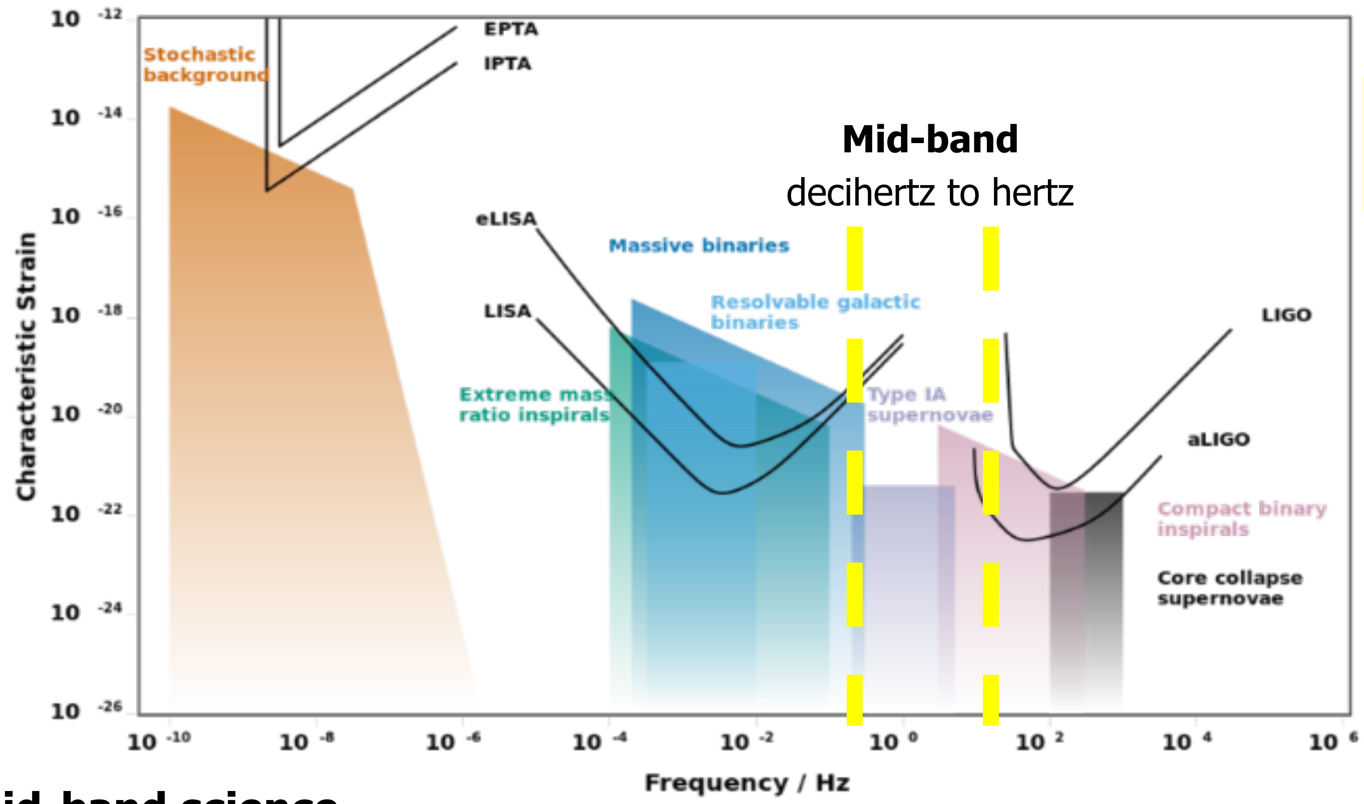
AION: Pathway to the GW Mid-(Frequency) Band

Experimental GW Landscape



AION: Pathway to the GW Mid-(Frequency) Band

Experimental GW Landscape

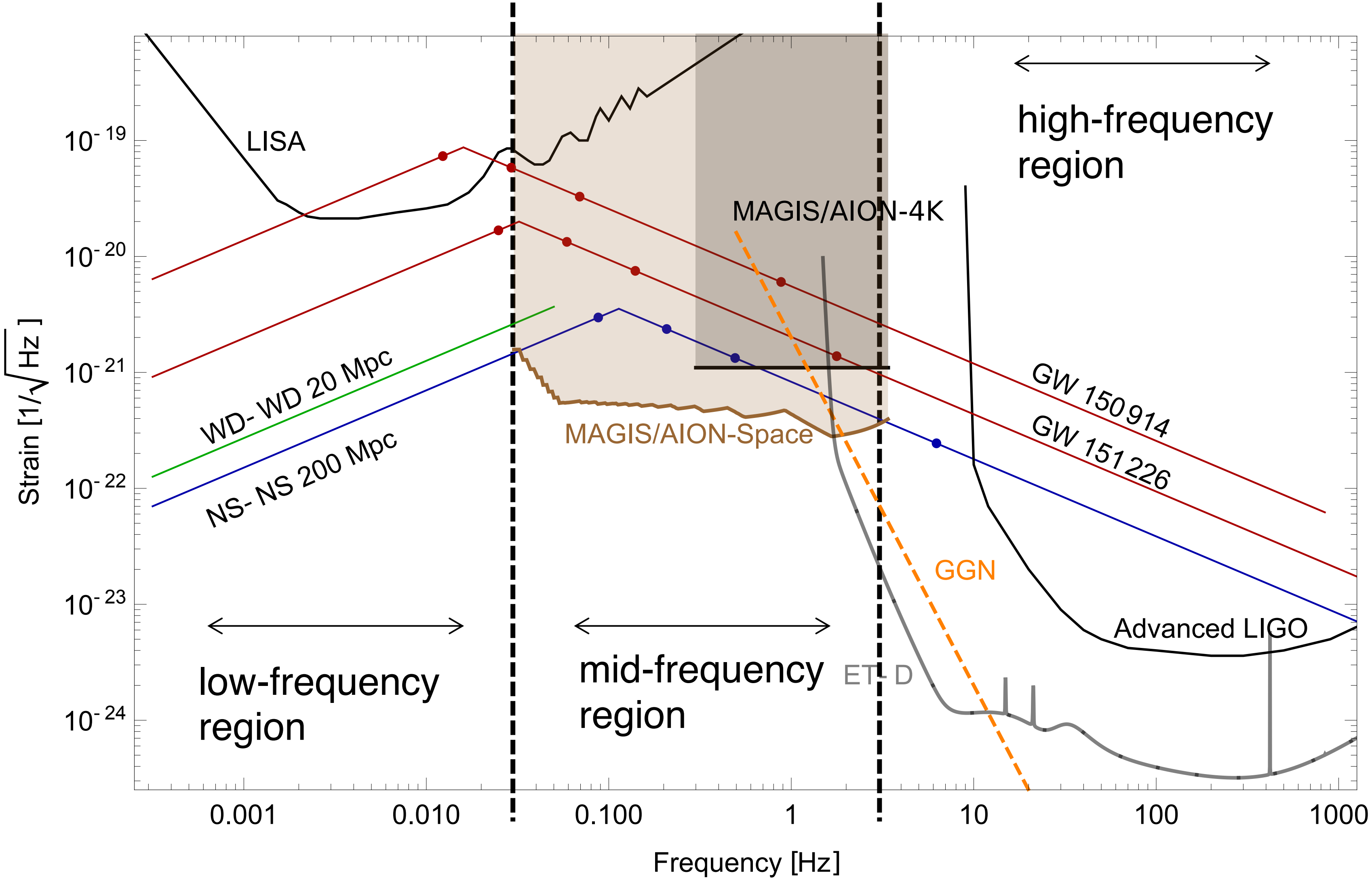


Mid-Band currently NOT covered

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

Gravitational Wave Detection with Atom Interferometry



Sky position determination

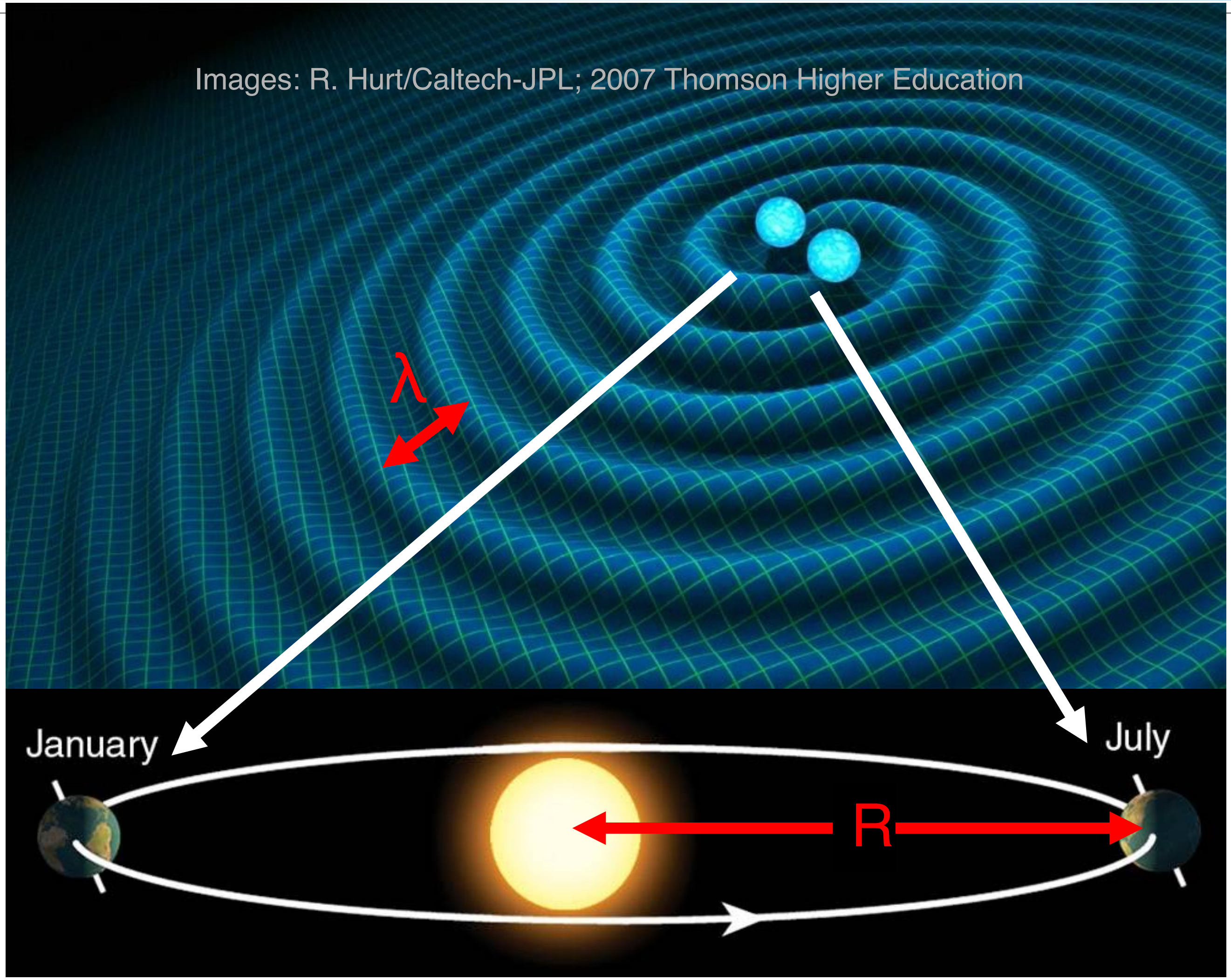
Sky localization precision:

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

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

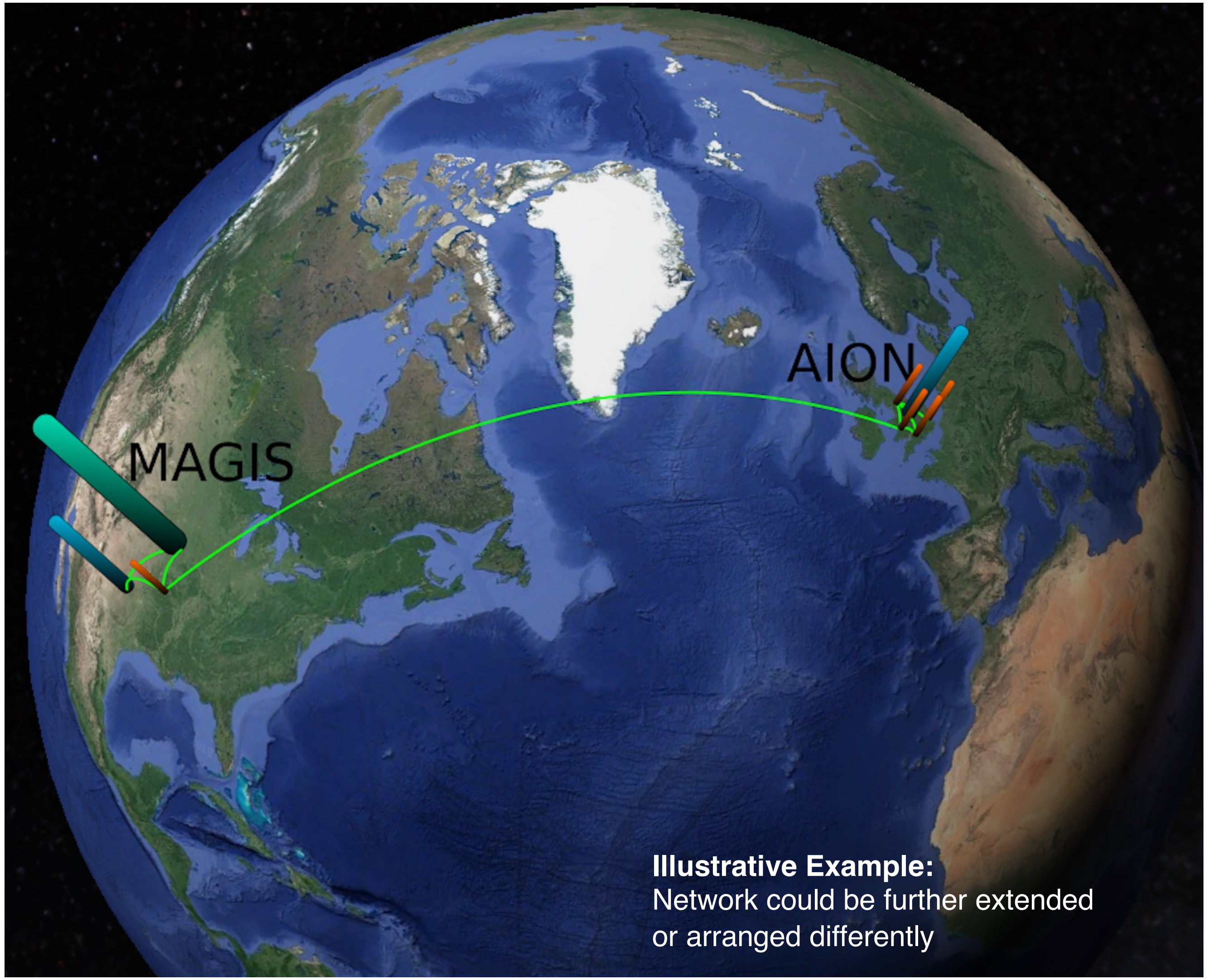
Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19

Courtesy of Jason Hogan!



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

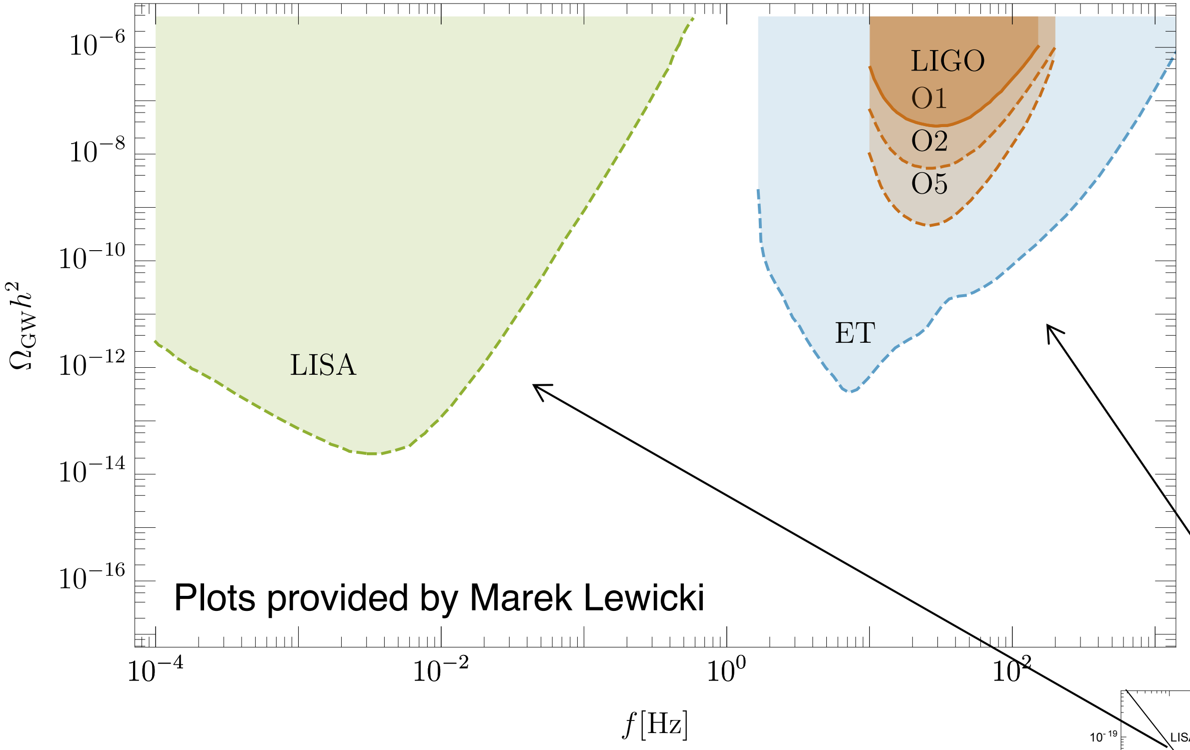
Ultimate Goal: Establish International Network



Illustrative Example:
Network could be further extended or arranged differently

GW Detection & Fundamental Physics - Example

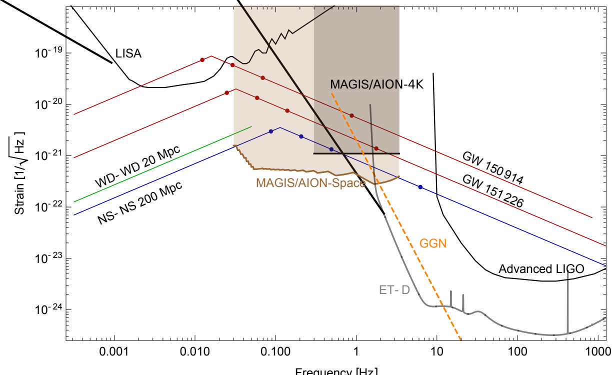
First-Order Electroweak Phase Transition and its Gravitational Wave Signal



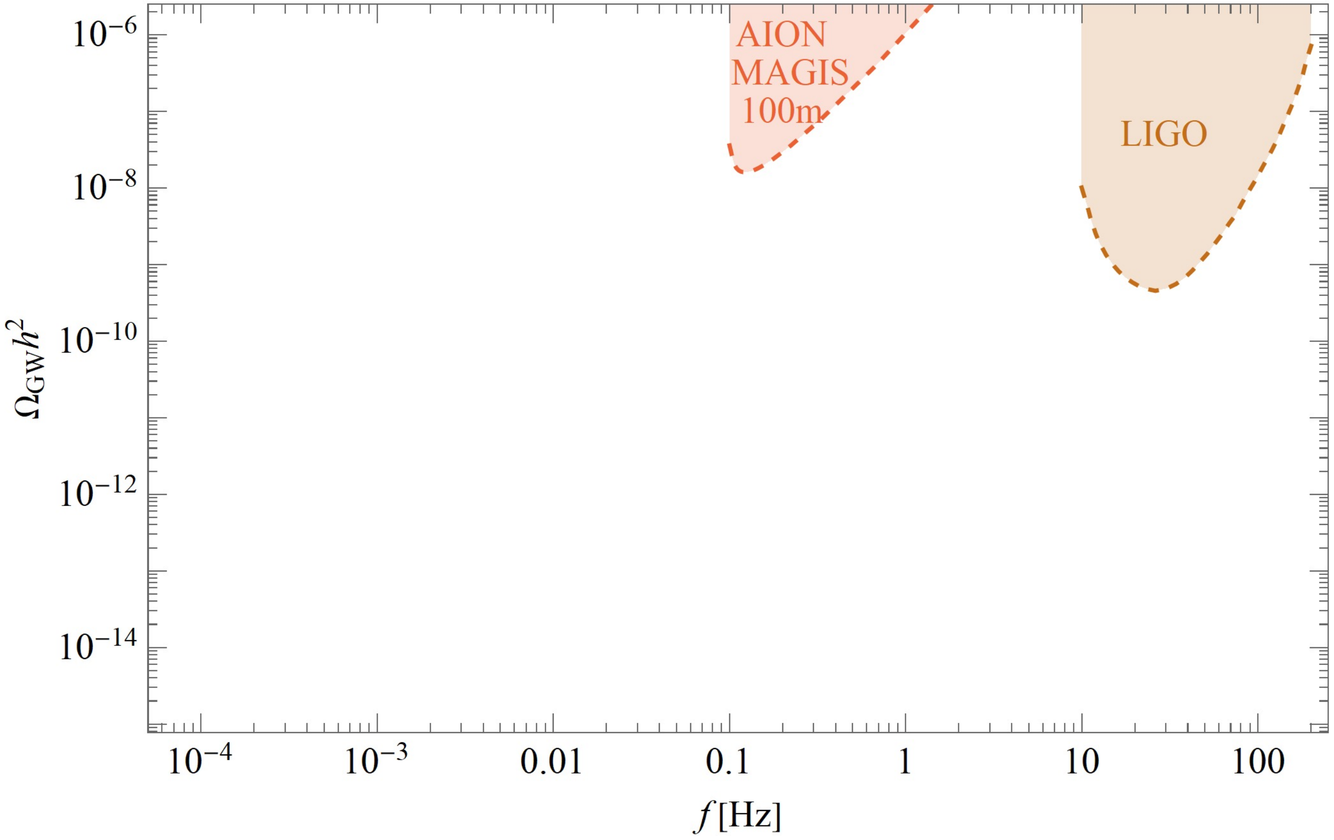
arXiv:1809.08242
John Ellis, Marek Lewicki,
José Miguel No

What is is the GW signal of electroweak phase transition in various theories beyond the Standard Model.

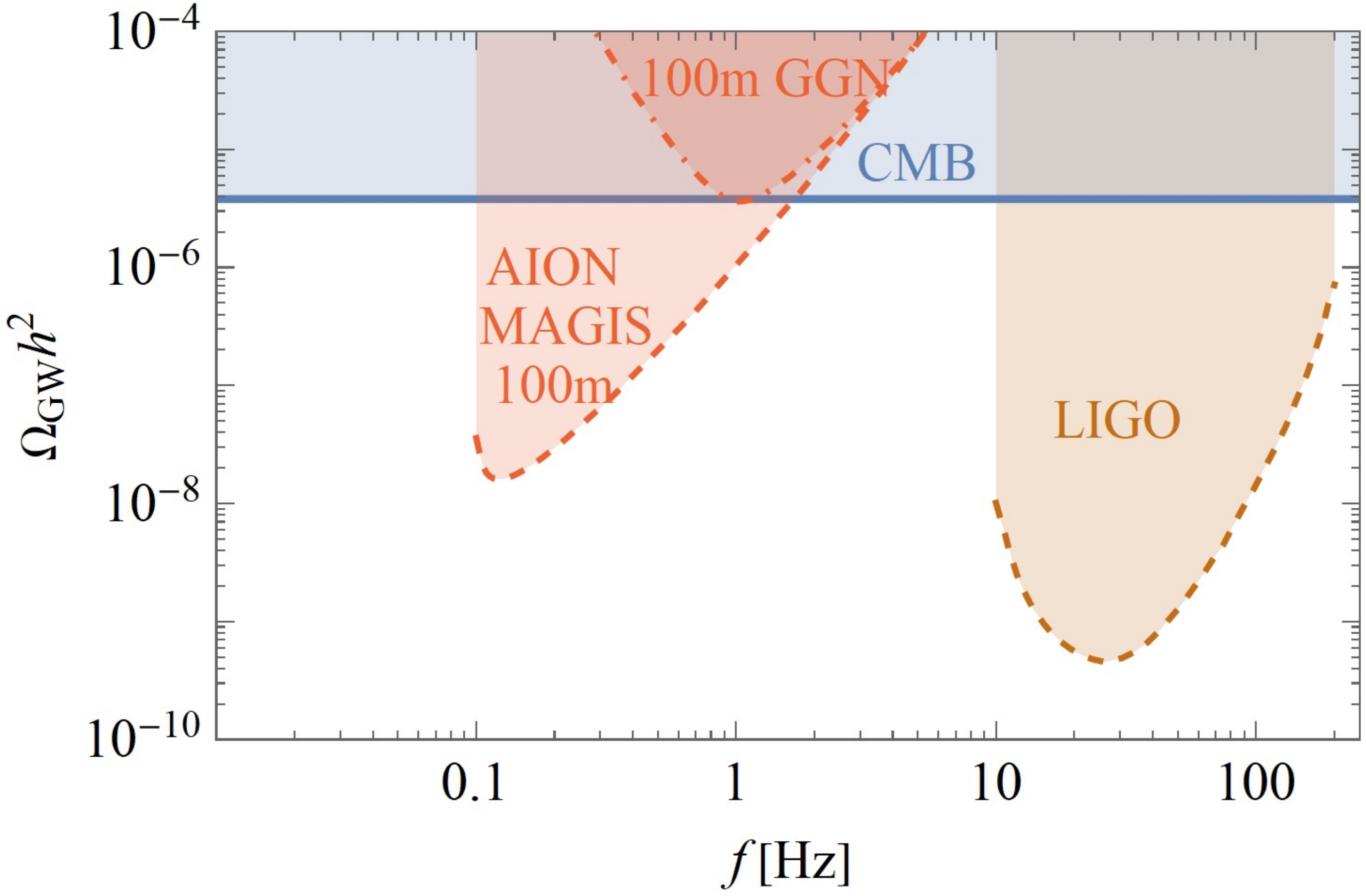
Translate strain into dimensionless energy density $\Omega_{GW}h^2$ in GWs against frequency



The GW Experimental Landscape: 2030ish



The GW Experimental Landscape: 2030ish



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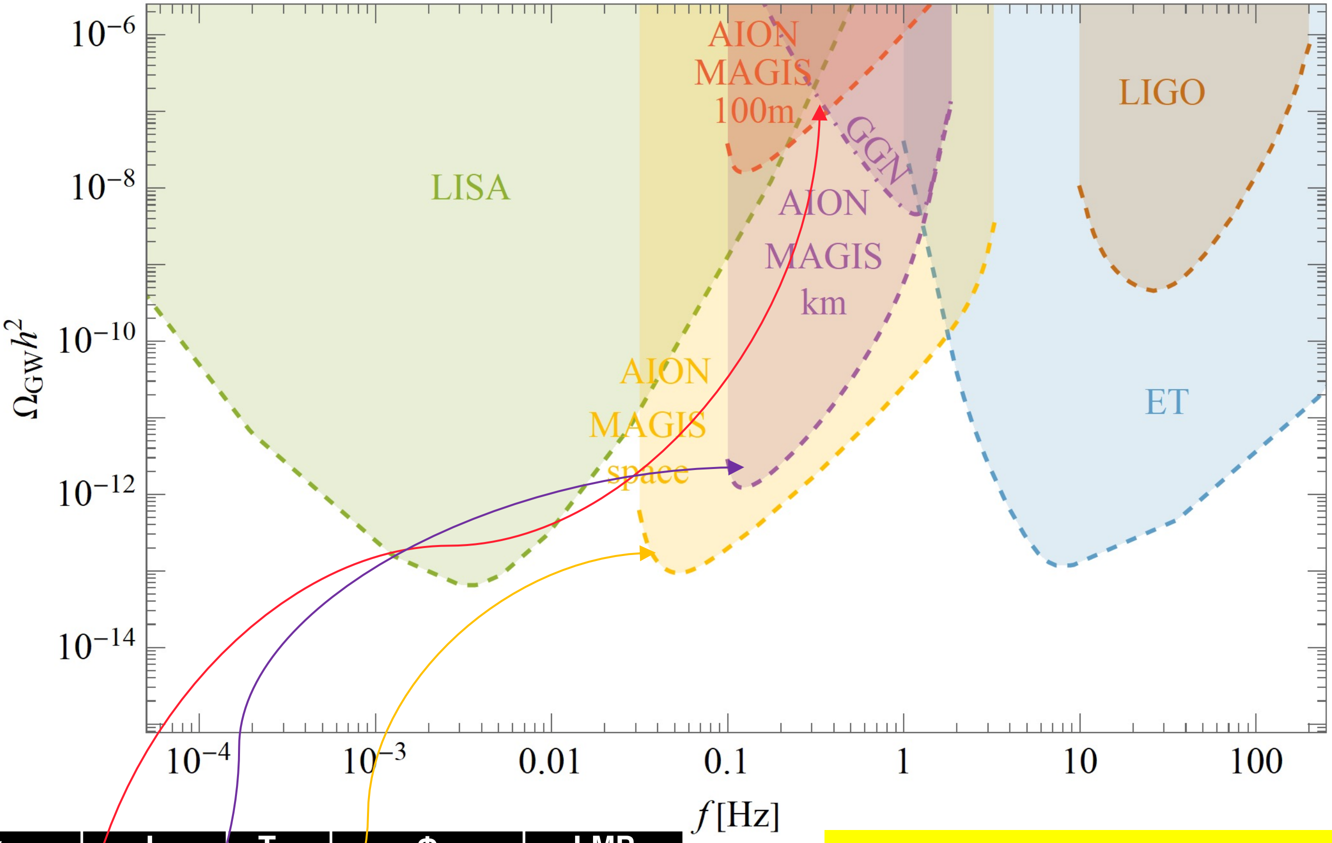


Sensitivity Scenario	L [m]	T_{int} [s]	Φ [1/√Hz]	LMP [#]
AION-100-today	100	1.4	10^{-3}	100
AION-100-ultimate	100	1.4	10^{-5}	40000
AION-km	2000	5	0.3×10^{-5}	40000
AION-space	4.4×10^{7}	300	10^{-5}	<1000

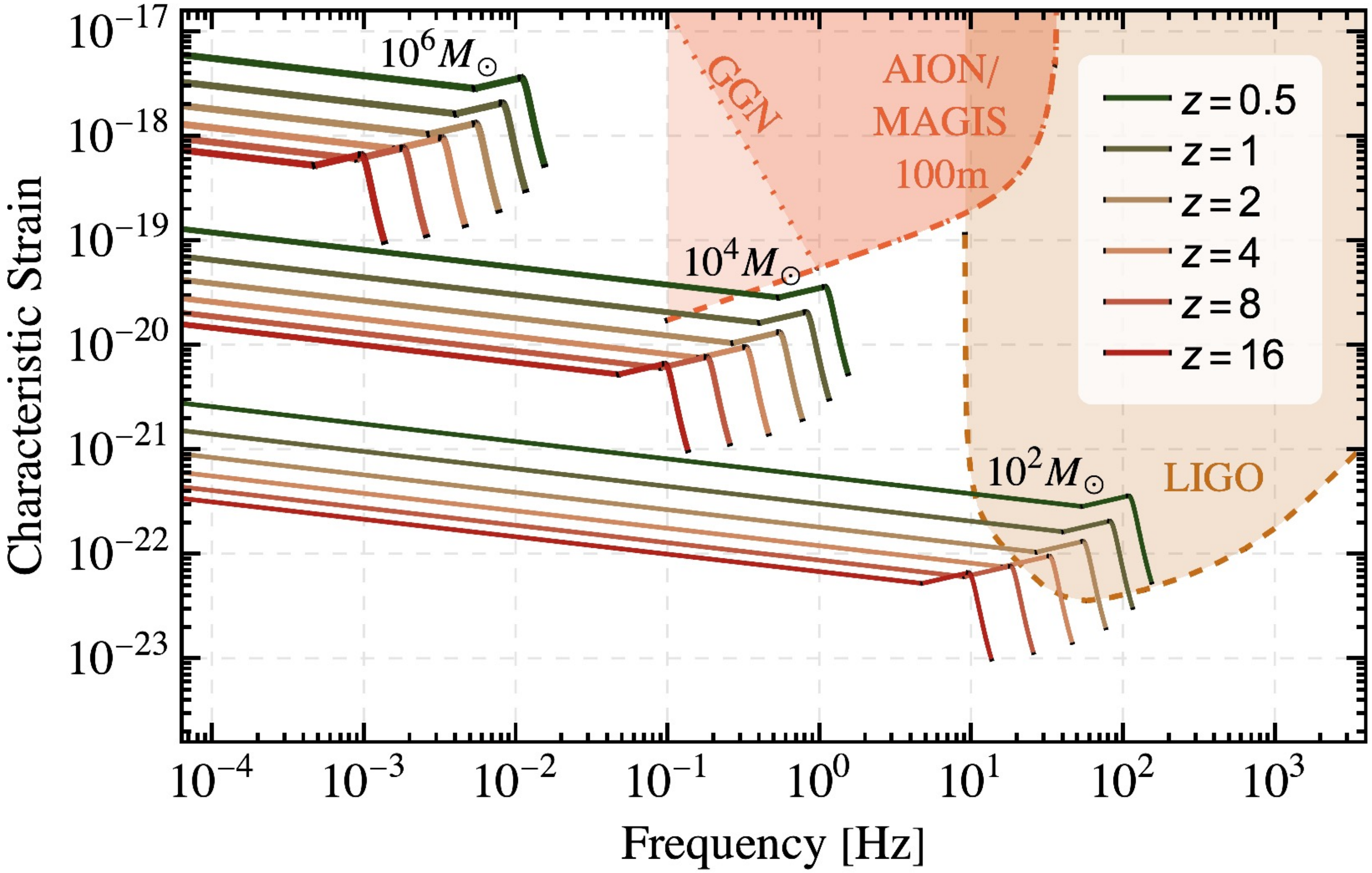
List of basic parameters: Lengths of the detector L, interrogation time of the atom interferometer T_{int}, phase noise ϕ, and number of momentum transfers LMP. The choice of these parameters predominately defines the sensitivity of the projection scenarios.

GW Physics: A Few Examples

- **Astrophysical Sources**
  - The Black Holes (BH) whose mergers were discovered by LIGO and Virgo have masses up to several tens of solar masses. Many galaxies are known to contain super-massive black holes (SMBHs) with masses in the range between 10^6 and billions of solar masses.
  - It is expected that intermediate-mass black holes (IMBHs) with masses in the range 100 to 10^5 solar masses must also exist [6]. There is some observational evidence for IMBHs, and they are thought to have played key roles in the assembly of SMBHs.

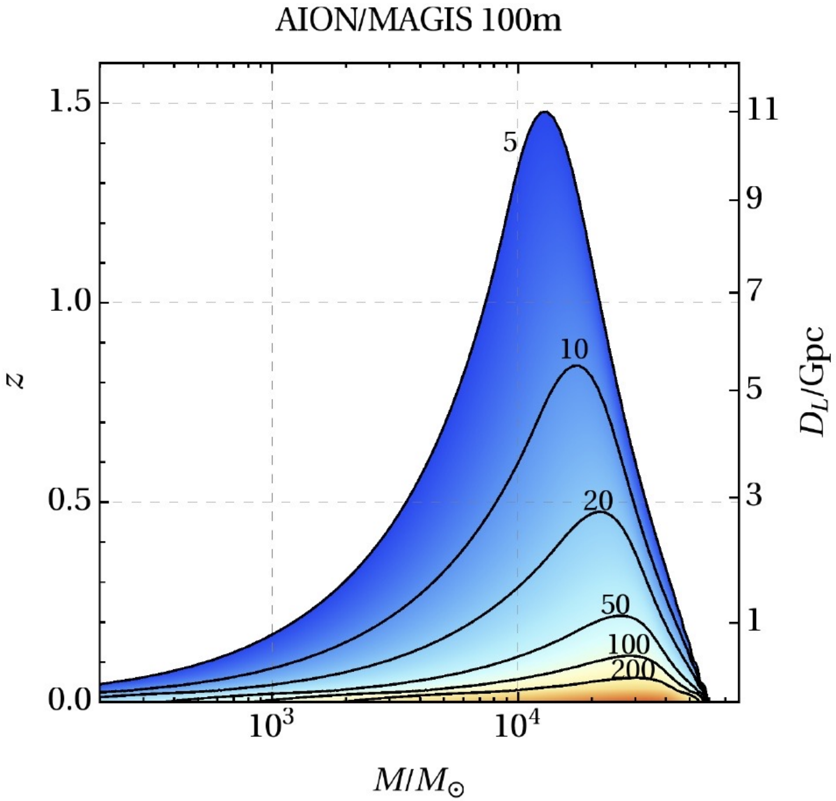
- **Cosmological Sources**
  - Many extensions of the Standard Model (SM) predict first-order phase transitions in the early Universe. Examples include extended electroweak sectors, effective field theories with higher-dimensional operators and hidden sector interactions.
    - Extended electroweak model with a massive Z' boson
    - Cosmic String Model

Strain Sensitivity & BH Mergers: 2030ish

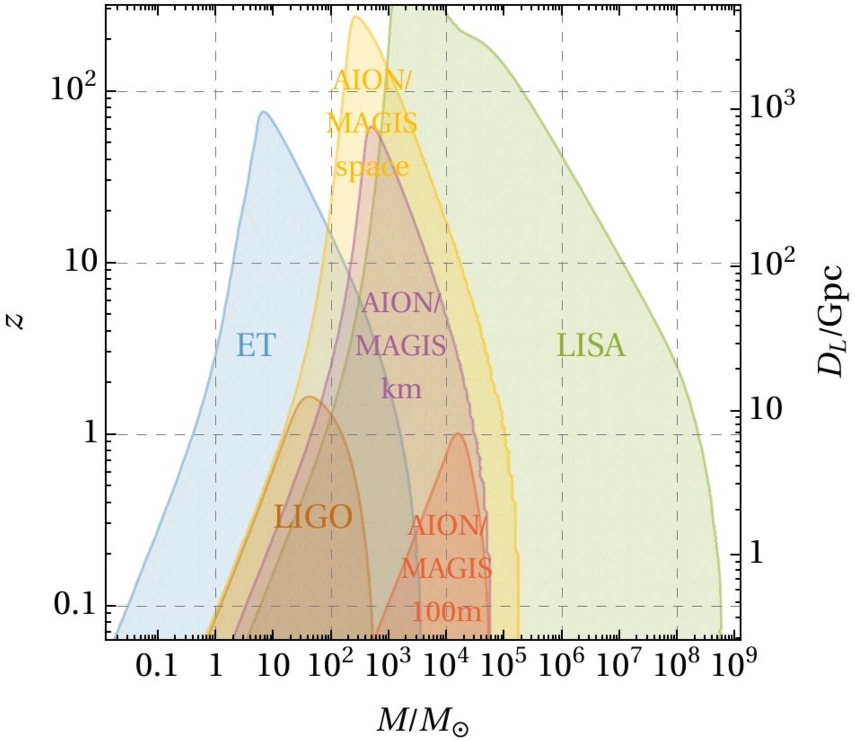


The AION frequency range is ideal for observations of mergers involving IMBHs, to which LISA and the LIGO/Virgo/KAGRA/ET experiments are relatively insensitive.

Strain Sensitivity & BH Mergers

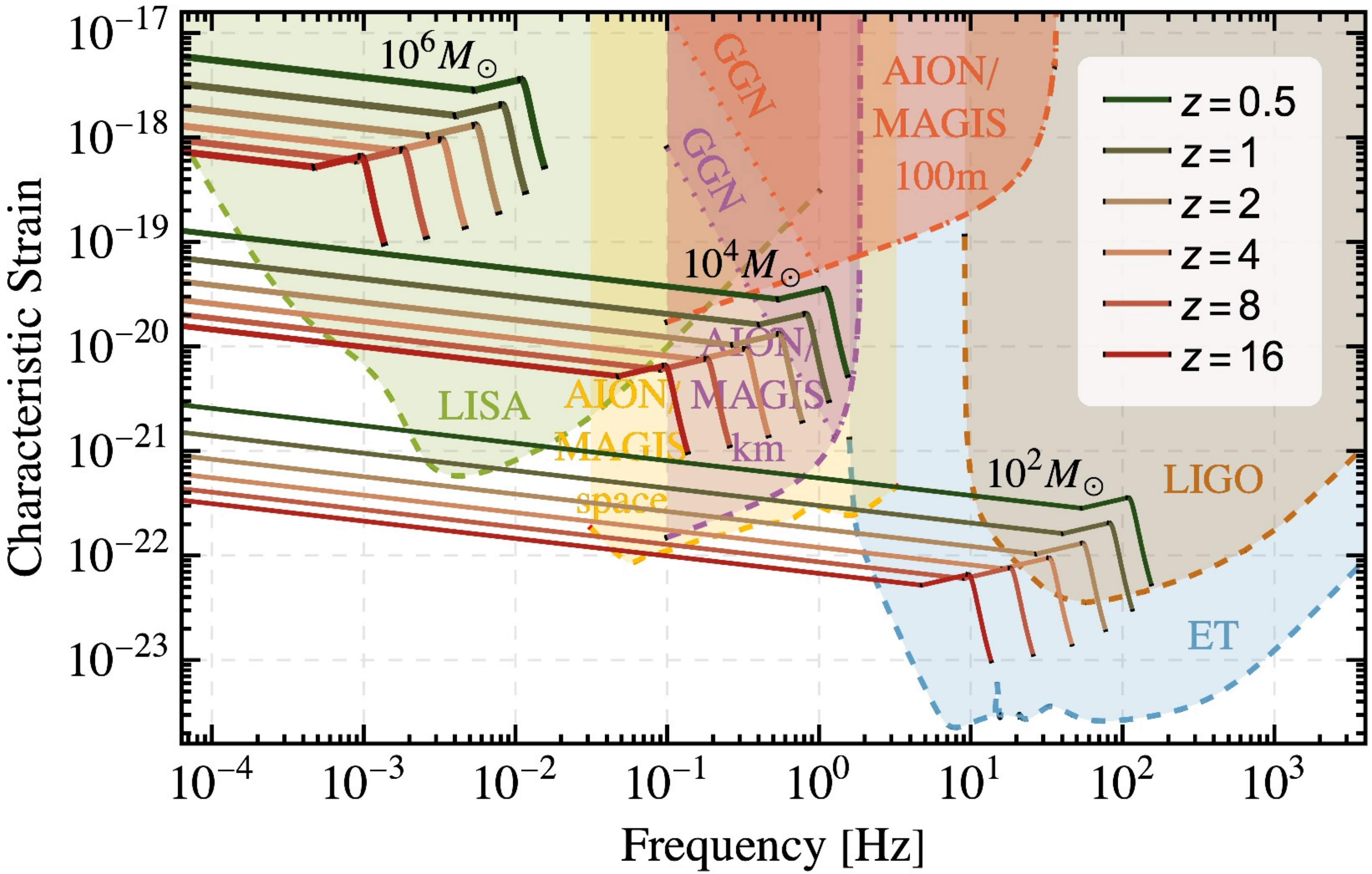


Sensitivity of AION-100m for detecting GWs from the mergers of IMBHs at signal-to-noise (SNR) levels ≥ 5, which extends to redshifts of 1.5 for BHs with masses ~ 10^4 solar masses.



Comparison of the sensitivities of AION and other experiments with threshold SNR = 8.

Strain Sensitivity & BH Mergers: Future

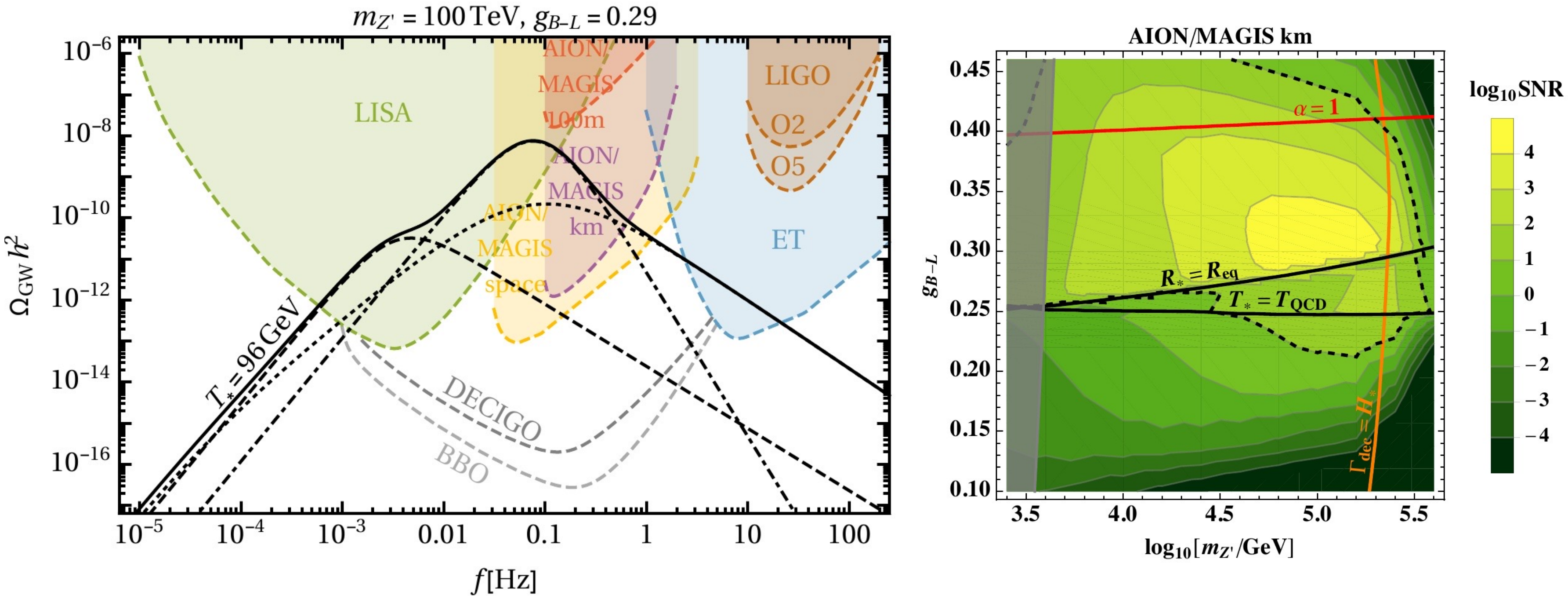


The AION frequency range is ideal for observations of mergers involving IMBHs, to which LISA and the LIGO/Virgo/KAGRA/ET experiments are relatively insensitive.

Cosmological GW Sources: Z' Model

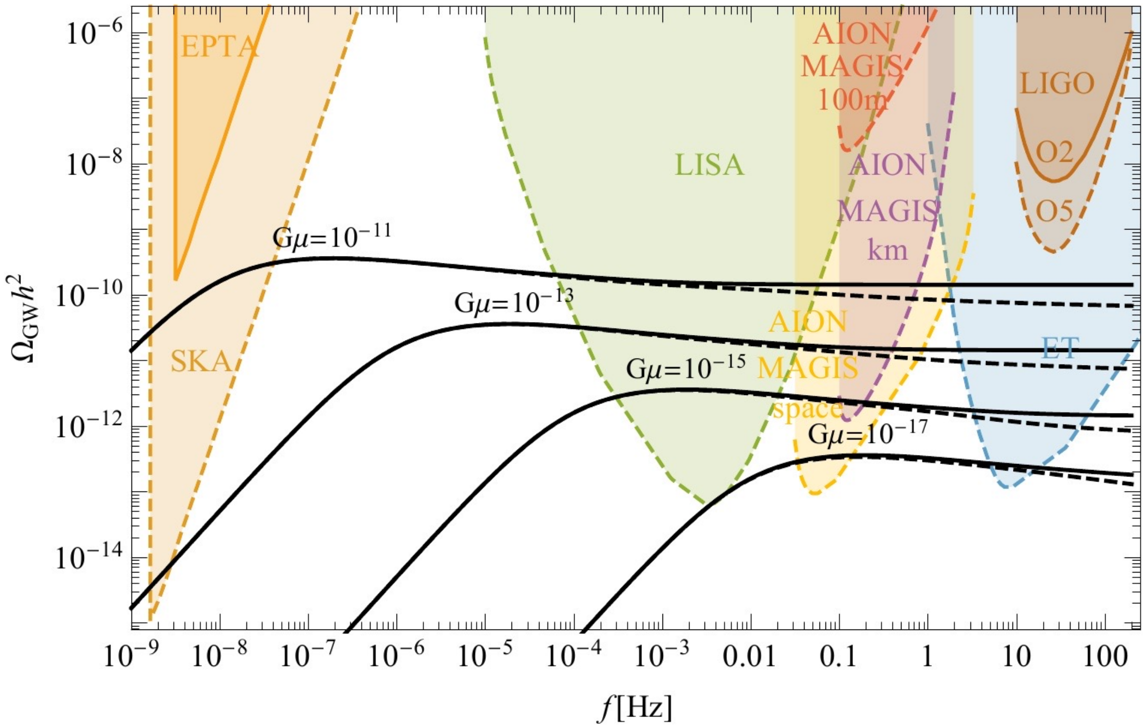
Many extensions of the Standard Model (SM) predict first-order phase transitions in the early Universe.

Example: Extended electroweak model with a massive Z' boson



Example of the GW spectrum in a classical scale-invariant extension of the SM with a massive Z' boson compared with various experimental sensitivities. Right panel: Signal-to-noise ratio (SNR) in the parameter plane of the same model for the AION-1km stage.

Cosmological GW Sources: Cosmic Strings



Other possible cosmological sources of GW signals are cosmic strings. These typically give a very broad frequency spectrum stretching across the ranges to which the LIGO/ET, AION/MAGIS, LISA and SKA experiments are sensitive.

The impact of including the change in the number of degrees of freedom as predicted in the Standard Model and clearly shows that probing the plateau in a wide range of frequencies can give us a significant amount of information not only on strings themselves but also on the evolution of the universe.

This way we could probe both SM processes such as the QCD phase transition and BSM scenarios predicting new degrees of freedom or even more significant cosmological modifications such as early matter domination, which would all leave distinguishable features in the GW background.

Other Fundamental Physics

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

Examples may include:

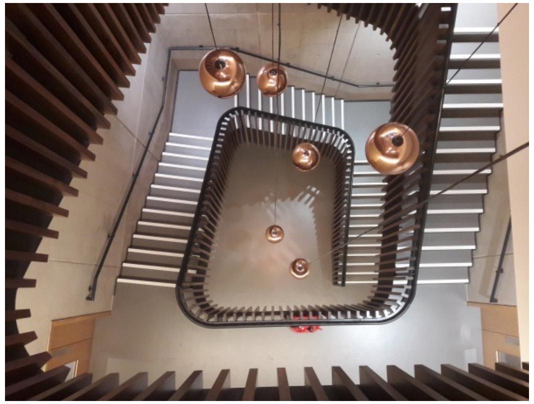
- *The possibility of detecting the astrophysical neutrinos*
- *Probes of long-range fifth forces*.
- *Constraining possible variations in fundamental constants.*
- *Probing dark energy*.
- Probes of basic physical principles such as foundations of quantum mechanics and Lorentz invariance.

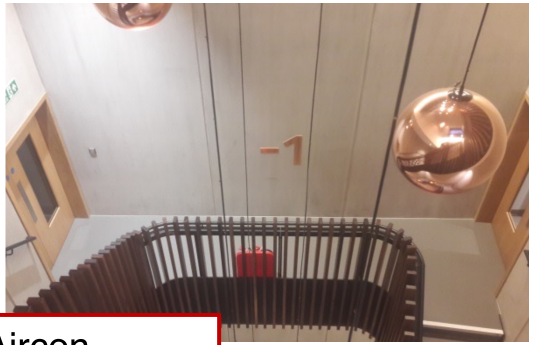
AION-10: 10 METER SIDE CHOSEN TO BE OXFORD

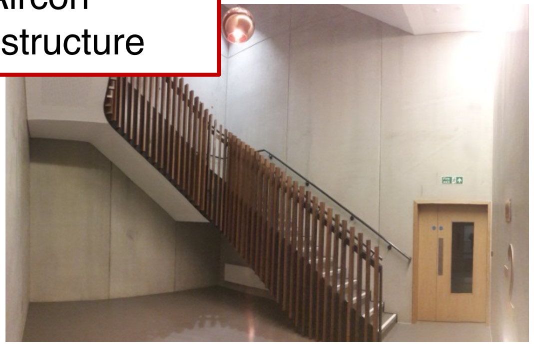
Beecroft building, Oxford Physics

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
- $\pm 0.1^{\circ}$C stability
- Isolated mains

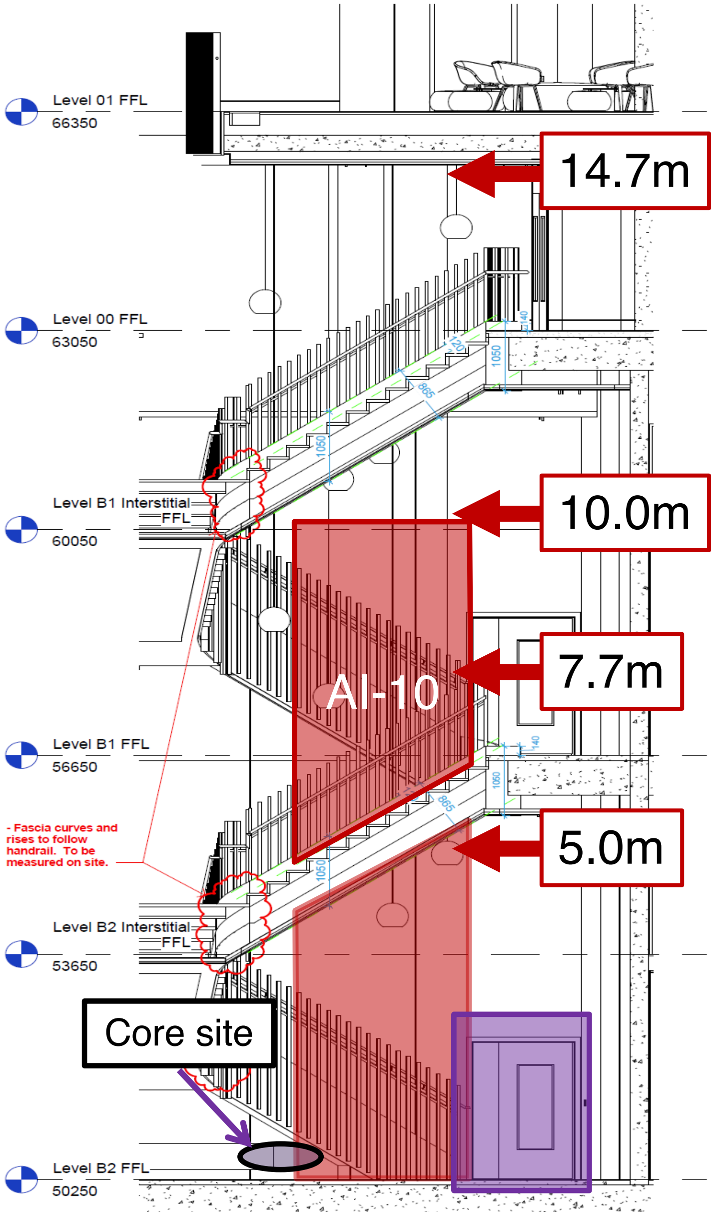
Vertical space

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

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

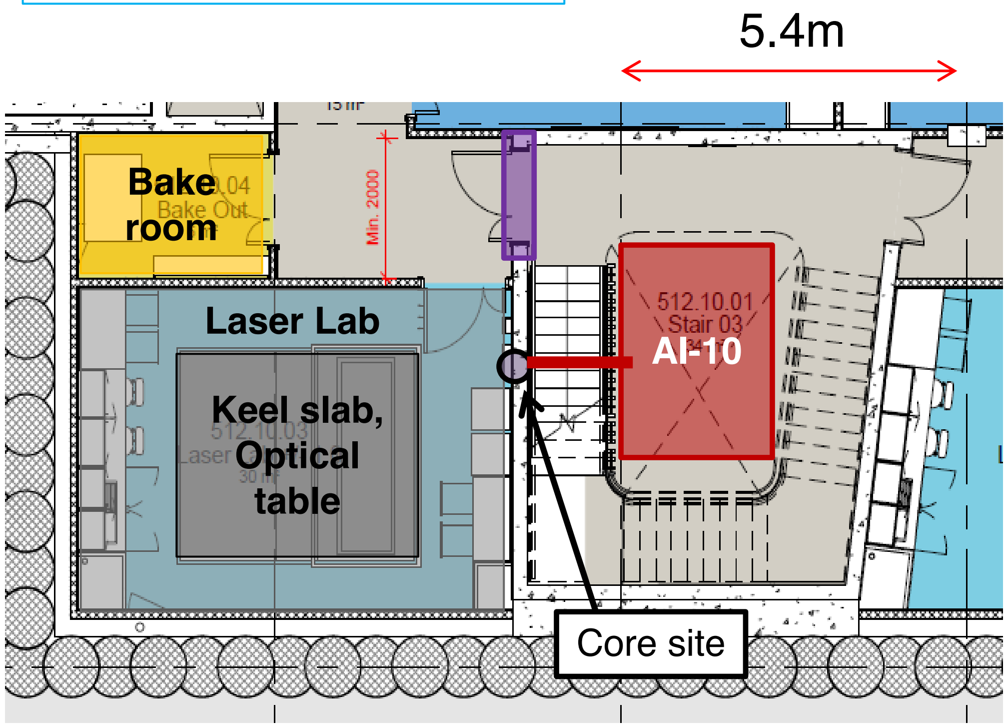
Bakeout room and cleanroom nearby

Beecroft building, Oxford Physics



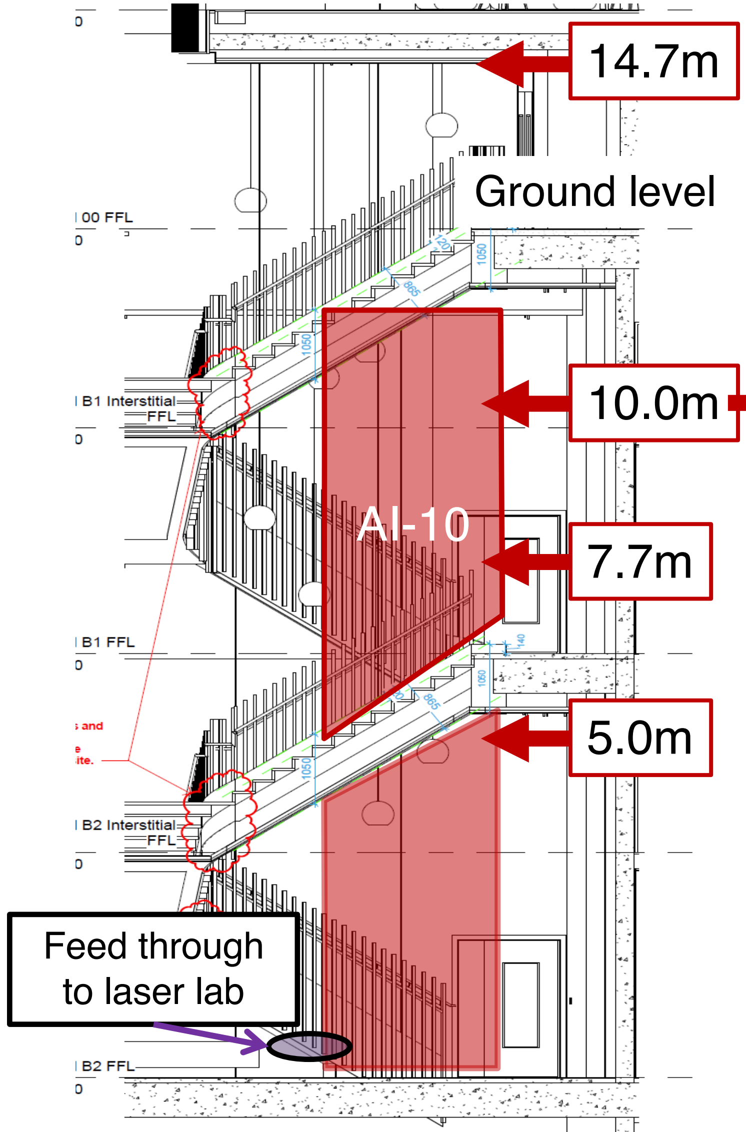
← Side view

↓ Plan view

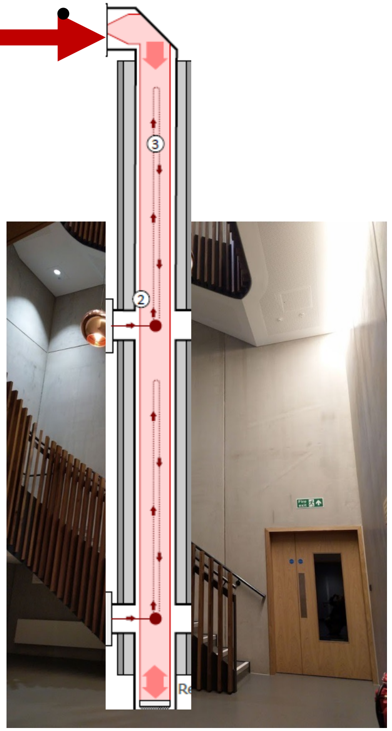


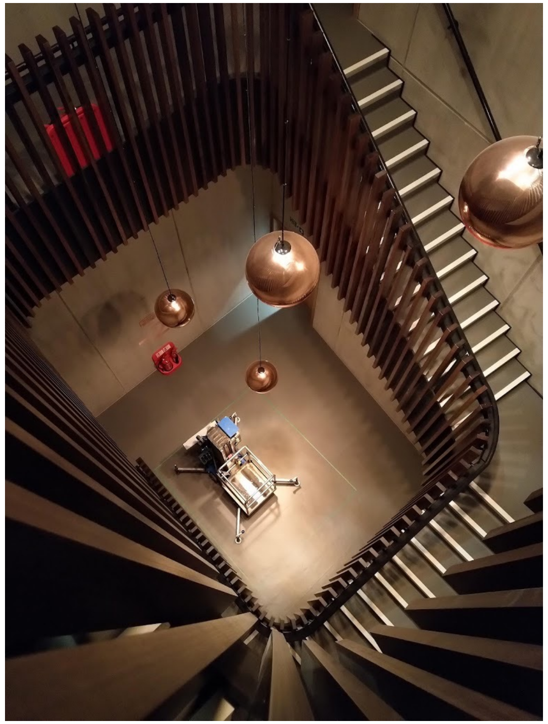
AION-10 site: Beecroft building, Oxford Physics

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



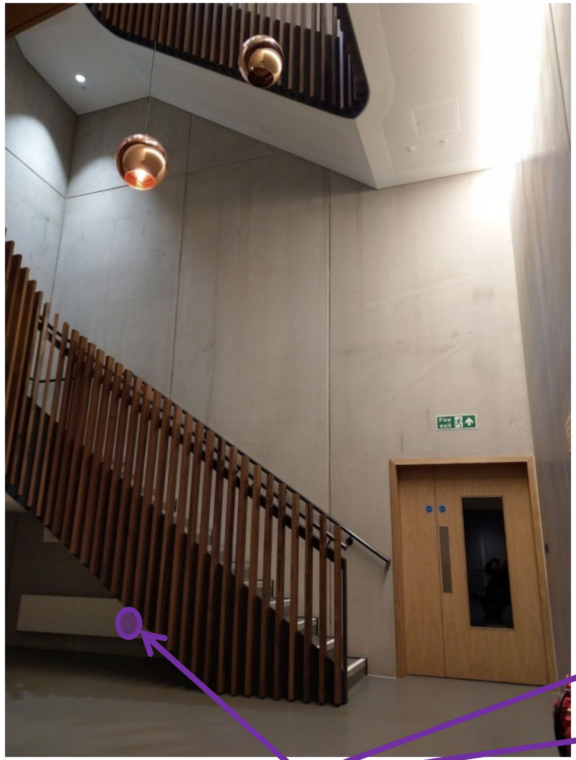
- Detailed planning of support structure by RAL (Engineering), Oxford Physics Technical Services and Liverpool Univ.
- Experienced Project Manager: Roy Preece
- Good site for long-term operation and wide accessibility (also ‘visibility’ and outreach).

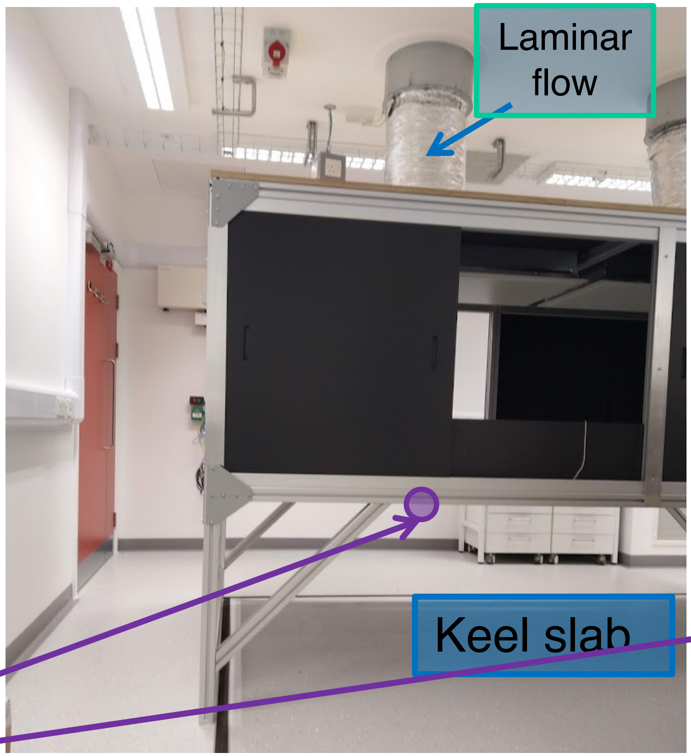


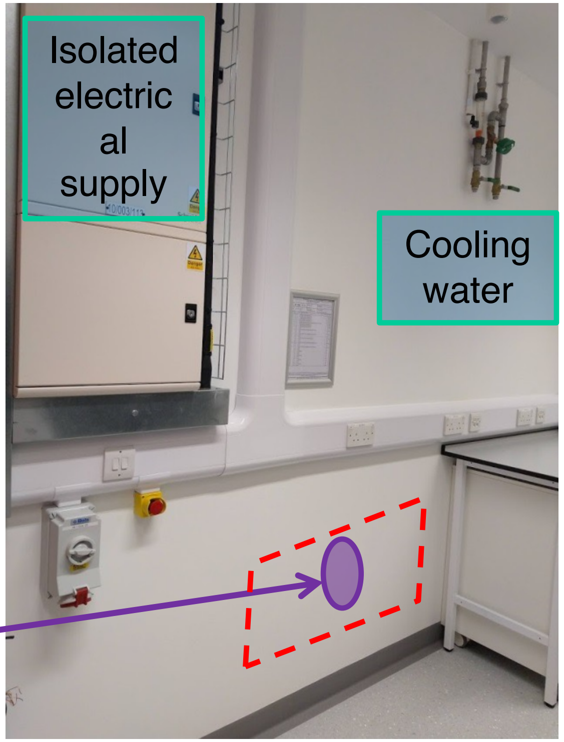


Beecroft building laser lab

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

Scaffolding erected from ground up.