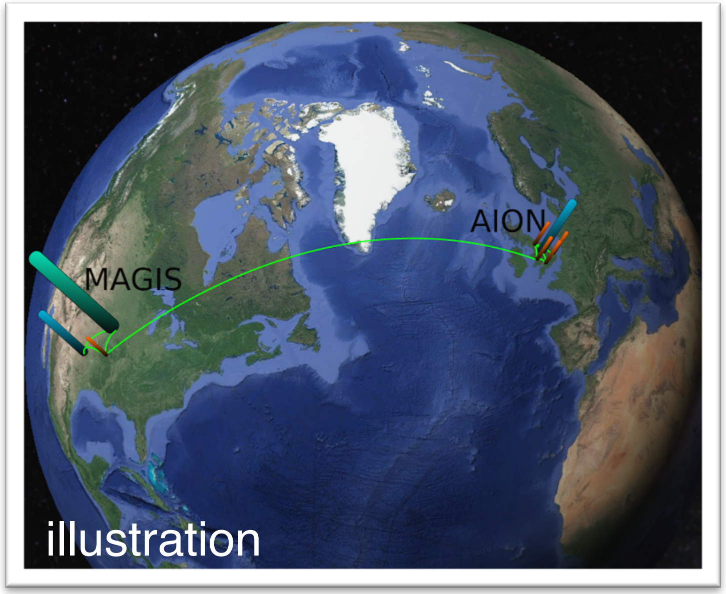


The AION Project

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**

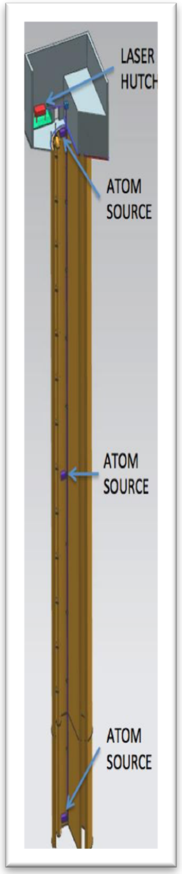
The AION Programme consists of 4 Stages

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

L ~ 10m

L ~ 100m

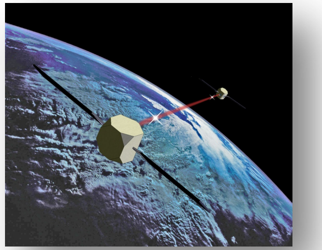
Stage 1 is now funded with about £9M by the QTFP Programme and other sources and Stage 2 (~£10M) could be placed at national facility in Boulby or Daresbury (UK), possibly also at CERN (France/Switzerland).



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

L ~ 1km

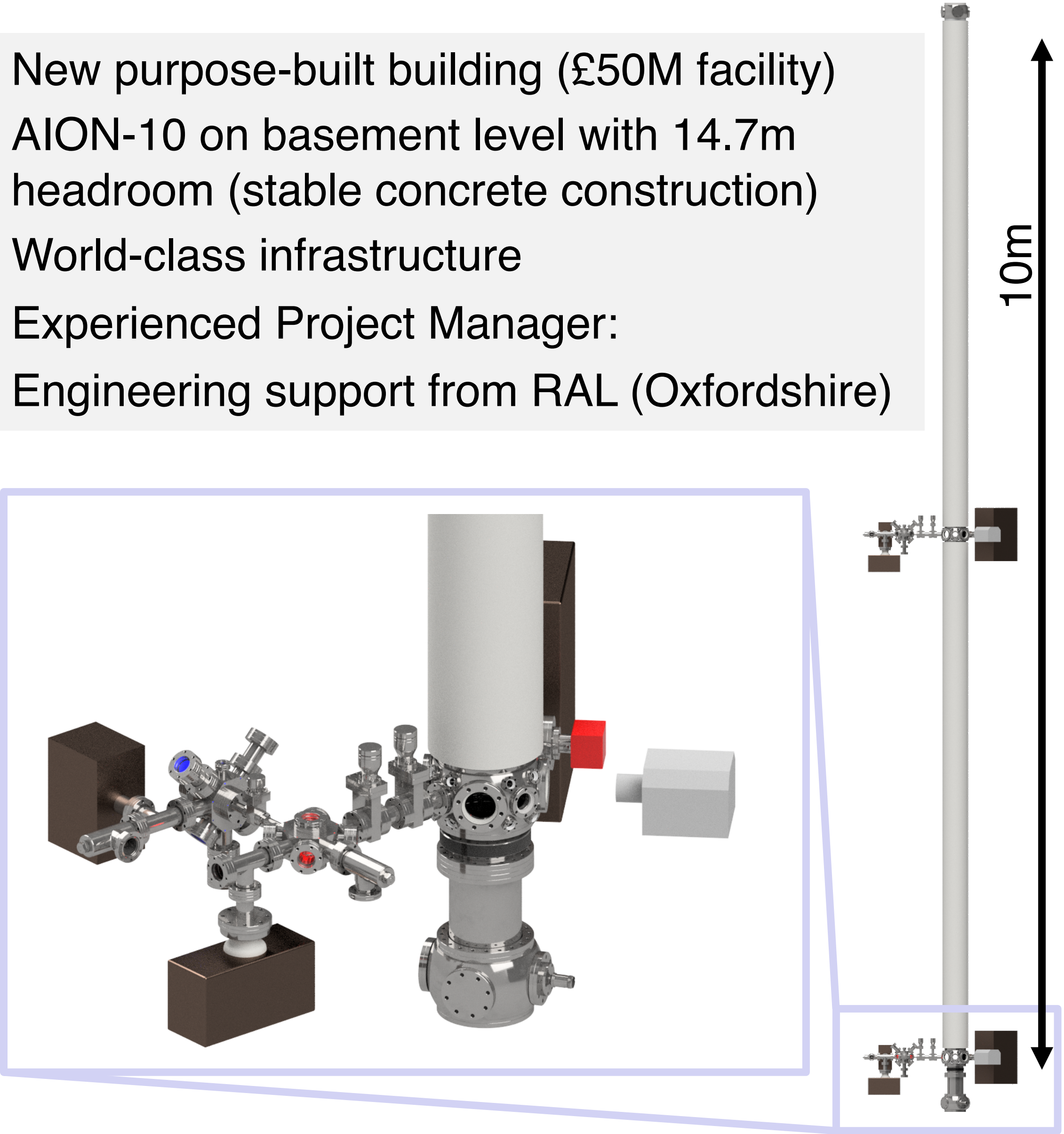
- **Stage 4**: long-term objective a pair of satellite detectors (thousands of kilometres scale) [AEDGE proposal to ESA Voyage2050 call]
  - AION has established science leadership in AEDGE, bringing together collaborators from European and Chinese groups (e.g. MIGA, MAGIA, ELGAR, ZAIGA).



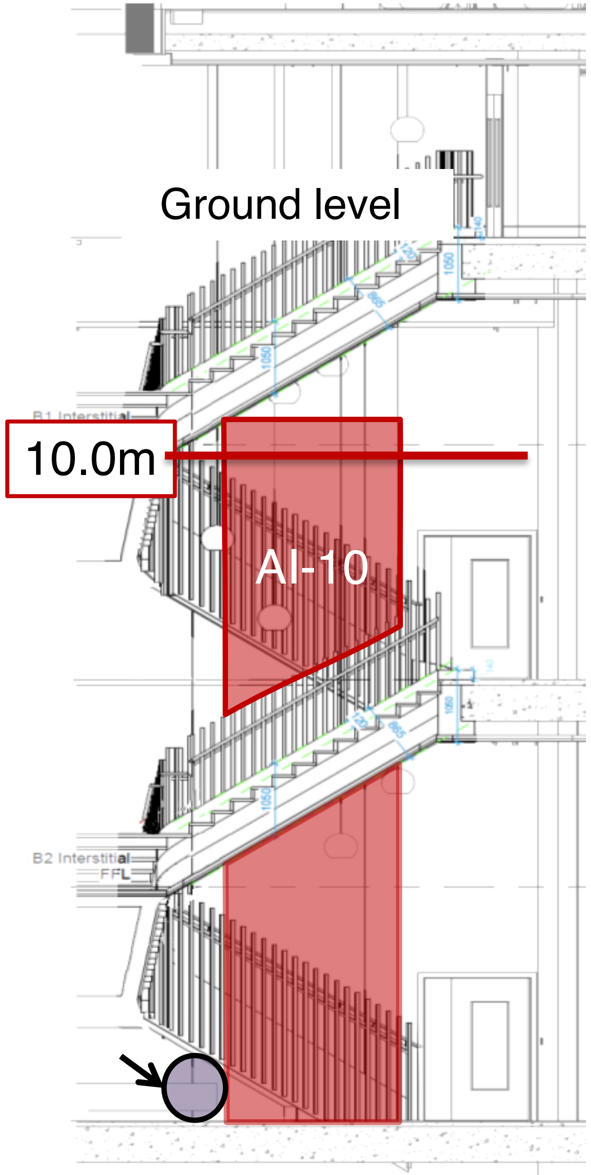
Stage 3 and 4 will likely require funding on international level (ESA, EU, etc) and AION has already started to build the foundation for it.

AION-10 @ Beecroft building, Oxford Physics

- New purpose-built building (£50M facility)
- AION-10 on basement level with 14.7m headroom (stable concrete construction)
- World-class infrastructure
- Experienced Project Manager:
- Engineering support from RAL (Oxfordshire)



Laser lab for AION
vibration criterion, VC-G = 10nm@10Hz. Temperature (22±0.1)° C



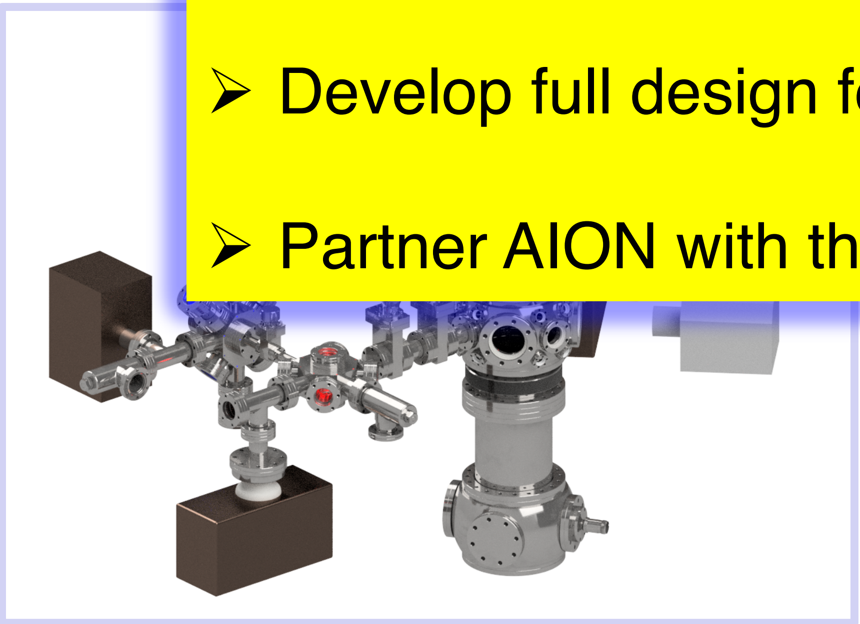
AION-10 @ Beecroft building, Oxford Physics

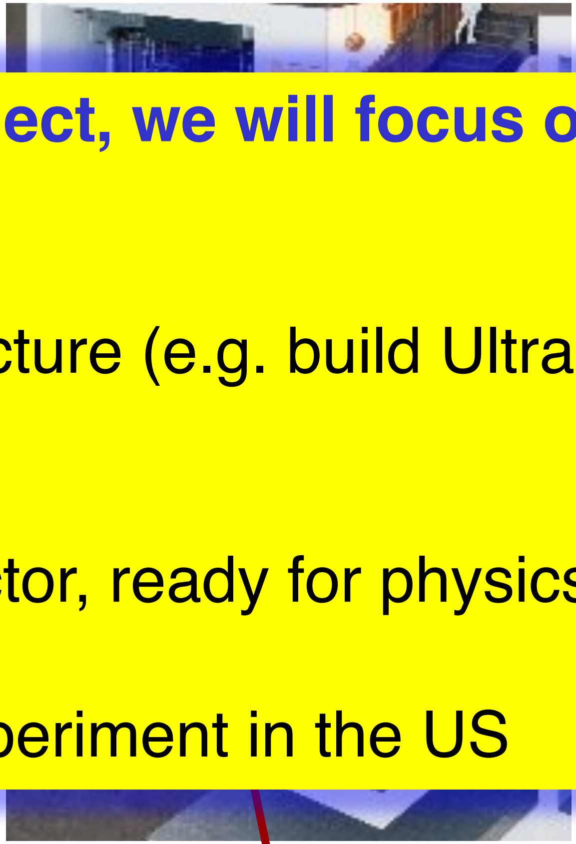
- New purpose-built building (£50M facility)
- AION-1(
  headroo
- World-cl
- Experier
- Enginee

AION Projec

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

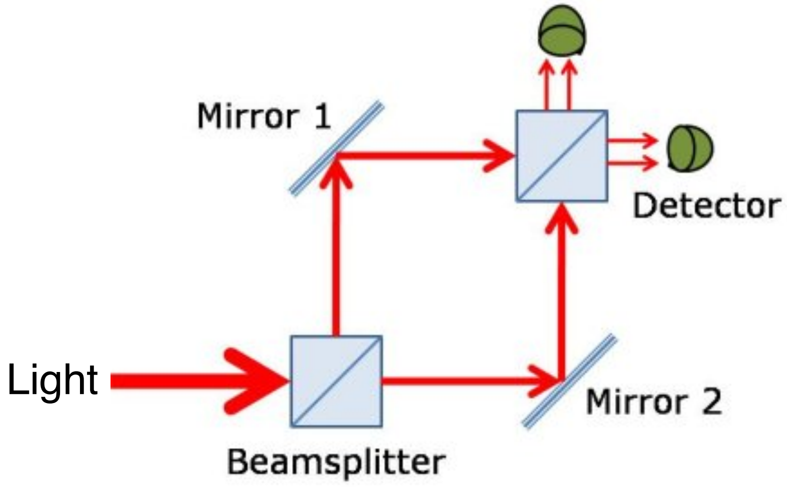


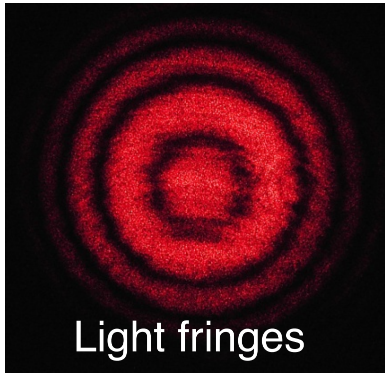


Laser lab for AION
vibration criterion, VC-G = 10nm@10Hz. Temperature (22±0.1)˚ C

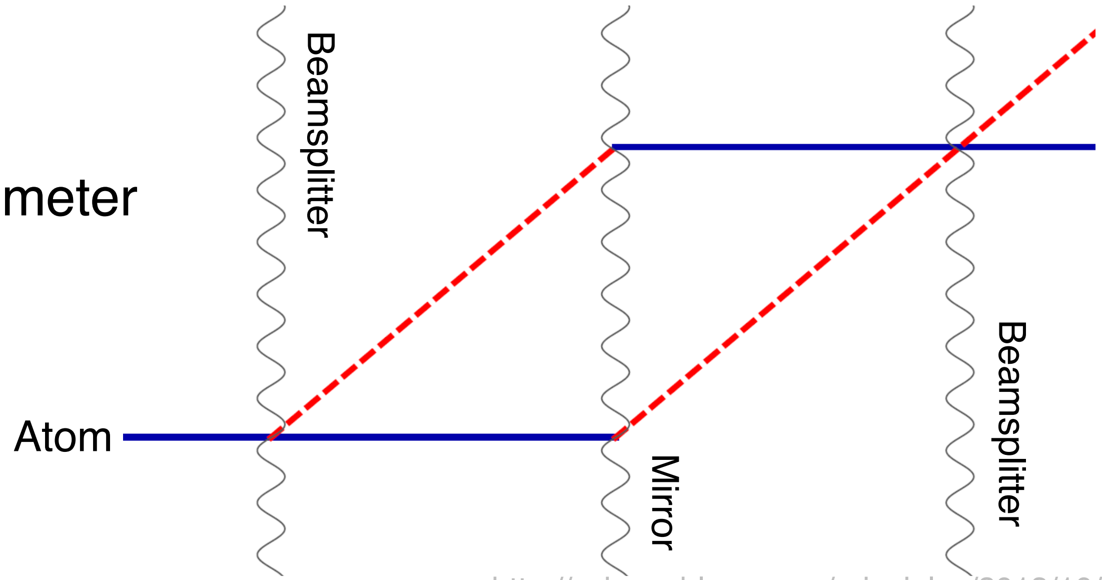
Light vs. Cold Atoms: Atom Interferometry

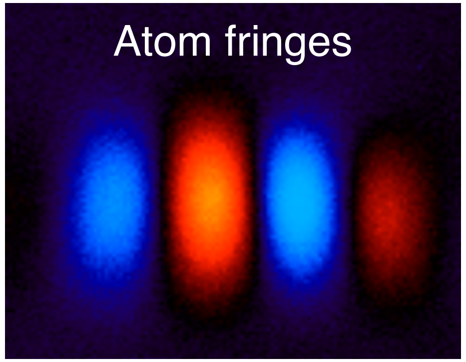
Light interferometer





Atom interferometer

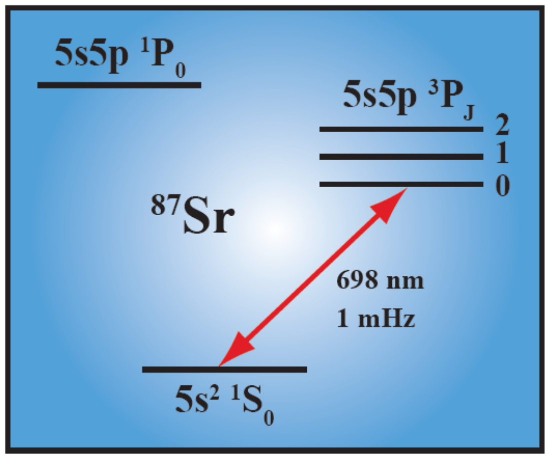




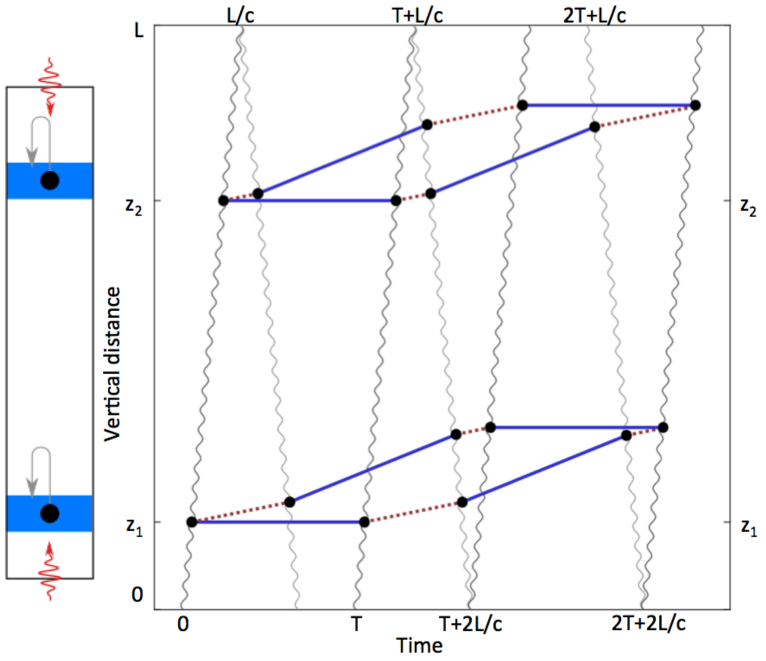
http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

AION: A Different Kind of Atom Interferometer

Hybrid "clock accelerometer"



Clock transition in candidate atom ^{87}Sr



Excited state phase evolution:

$|e\rangle$, $|g\rangle$, ω_a

$$\Delta\phi \sim \omega_A \, (2L/c)$$

Two ways for phase to vary:

$\delta\omega_A$	*Dark matter*
$\delta L = hL$	*Gravitational wave*

Clock: measure light travel time ➜ remove laser noise with *single baseline*

Sensitivity Scenario	L [m]	T_{int} [sec]	$\delta\phi_{noise}$ [$1/\sqrt{\mathrm{Hz}}$]	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

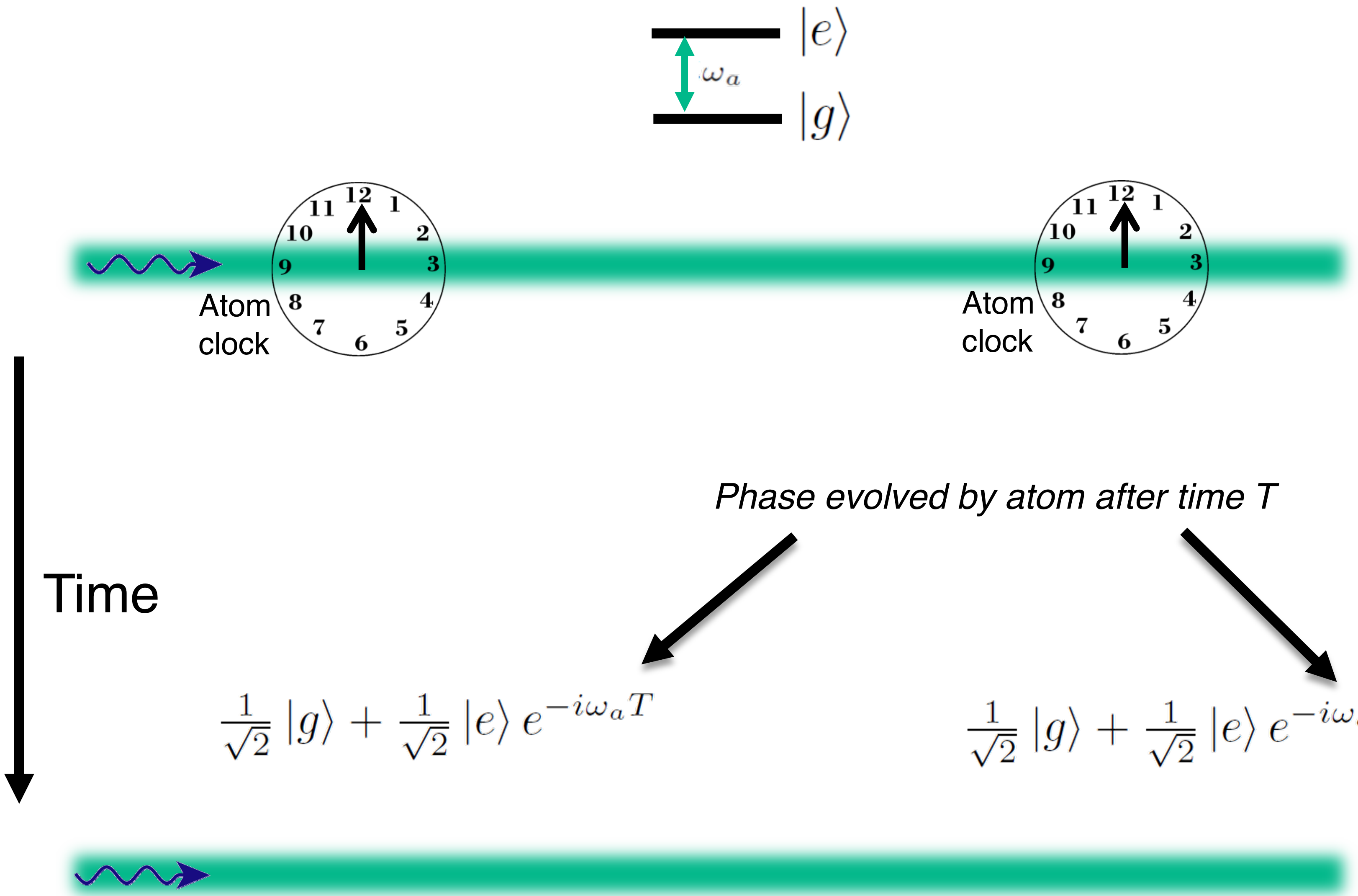
Used for sensitivity projections

For ultimate sensitivity we need to push each basic parameter by ~O(10).

The project aims to demonstrate in funding period e.g.

- LMT: ~1000 hbar*k
- Squeezing ~ 20dB for > 1e6 Atoms

Simple Example: Two Atomic Clocks



Phase evolved by atom after time T

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

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

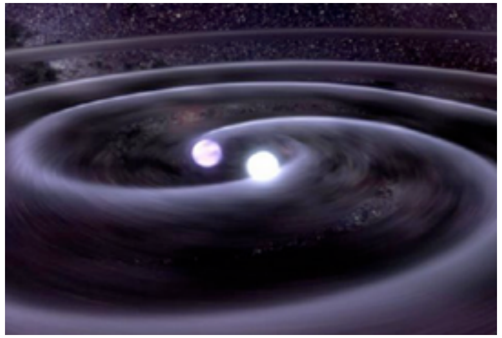
Simple Example: Two Atomic Clocks

$|e\rangle$

ω_a

$|g\rangle$

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



GW changes light travel time

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

Time

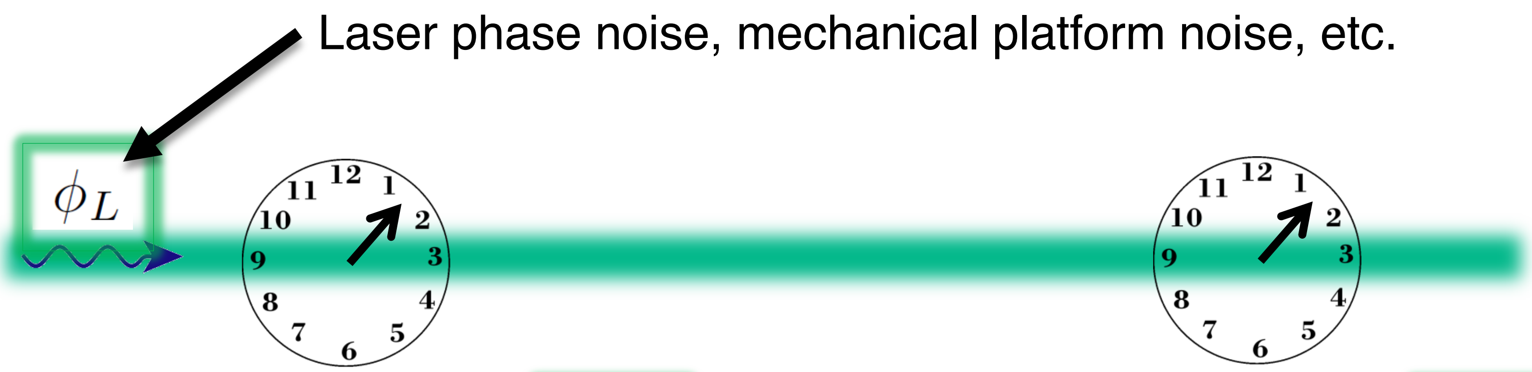
$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a T} \qquad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a (T+\Delta T)}$$

Atom clock

Atom clock

Phase Noise from the Laser

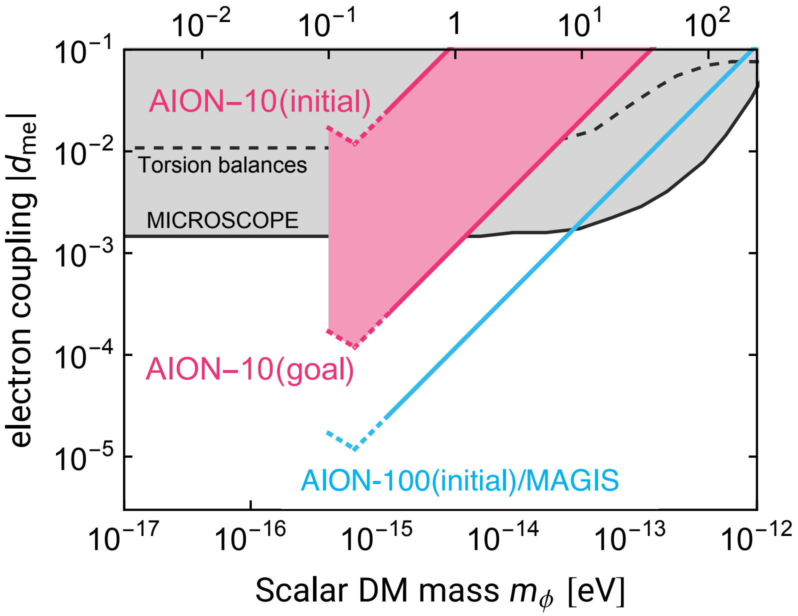
The phase of the laser is imprinted onto the atom.



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

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

Main AION Physics Goals: Dark Matter and Gravitational Waves



AION Project: UK HEP FORUM 2020

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

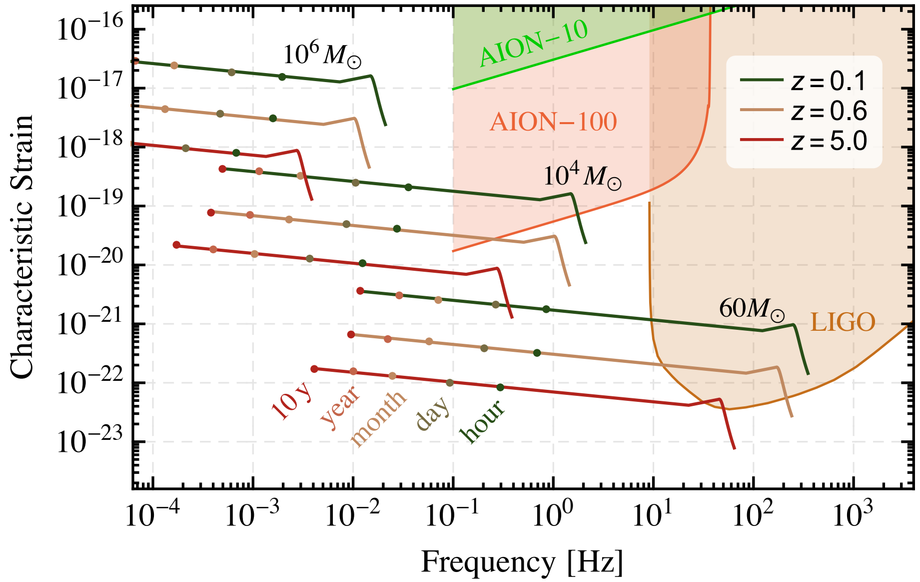
Y. El-Neaj, …, O. Buchmueller *et al.*
AEDGE: Atomic Experiment for Dark Matter And Gravity Exploration in Space, arXiv:1908.00802, *EPJ Quantum Technol.* 7, 6 (2020).
[Submitted to ESA Voyage2050 call]

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



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:

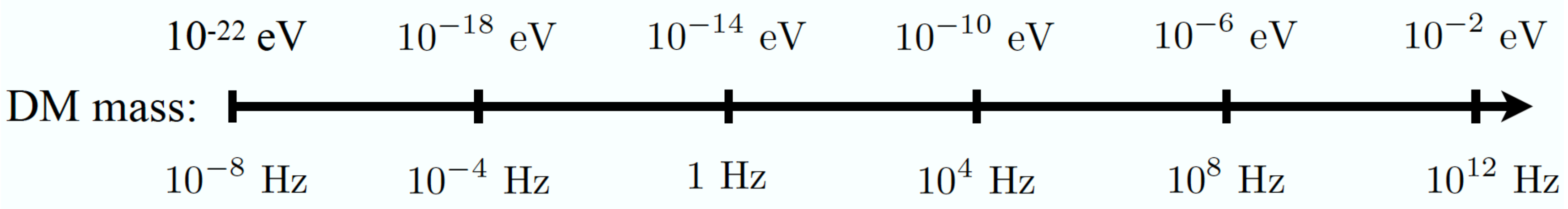


Diagram taken from P. Graham's talk at HEP Front 2018

The Landscape of Ultra-Light Dark Matter Detection

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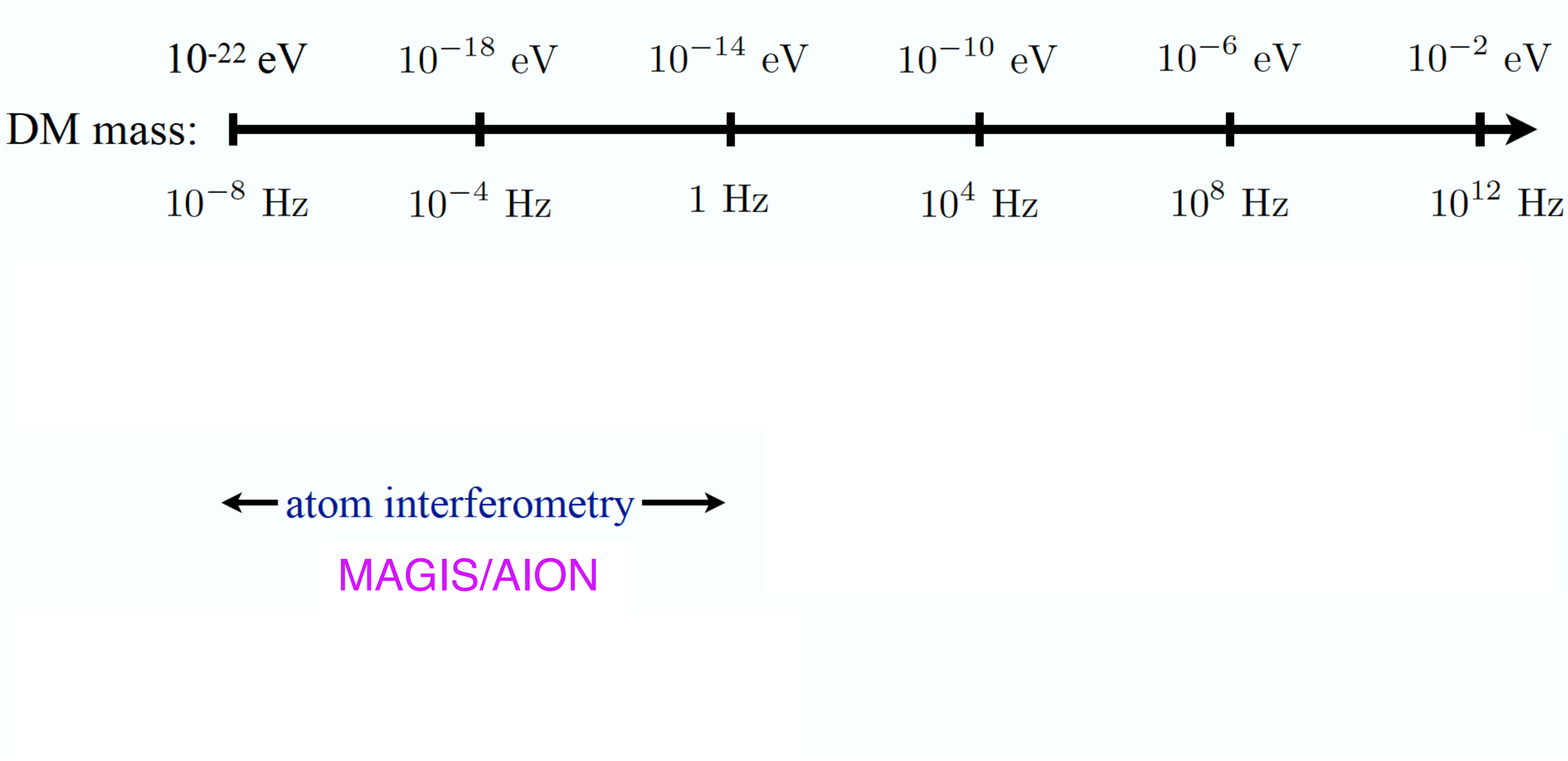

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The Landscape of Ultra-Light Dark Matter Detection

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Example: Ultra-Light Dark Matter:

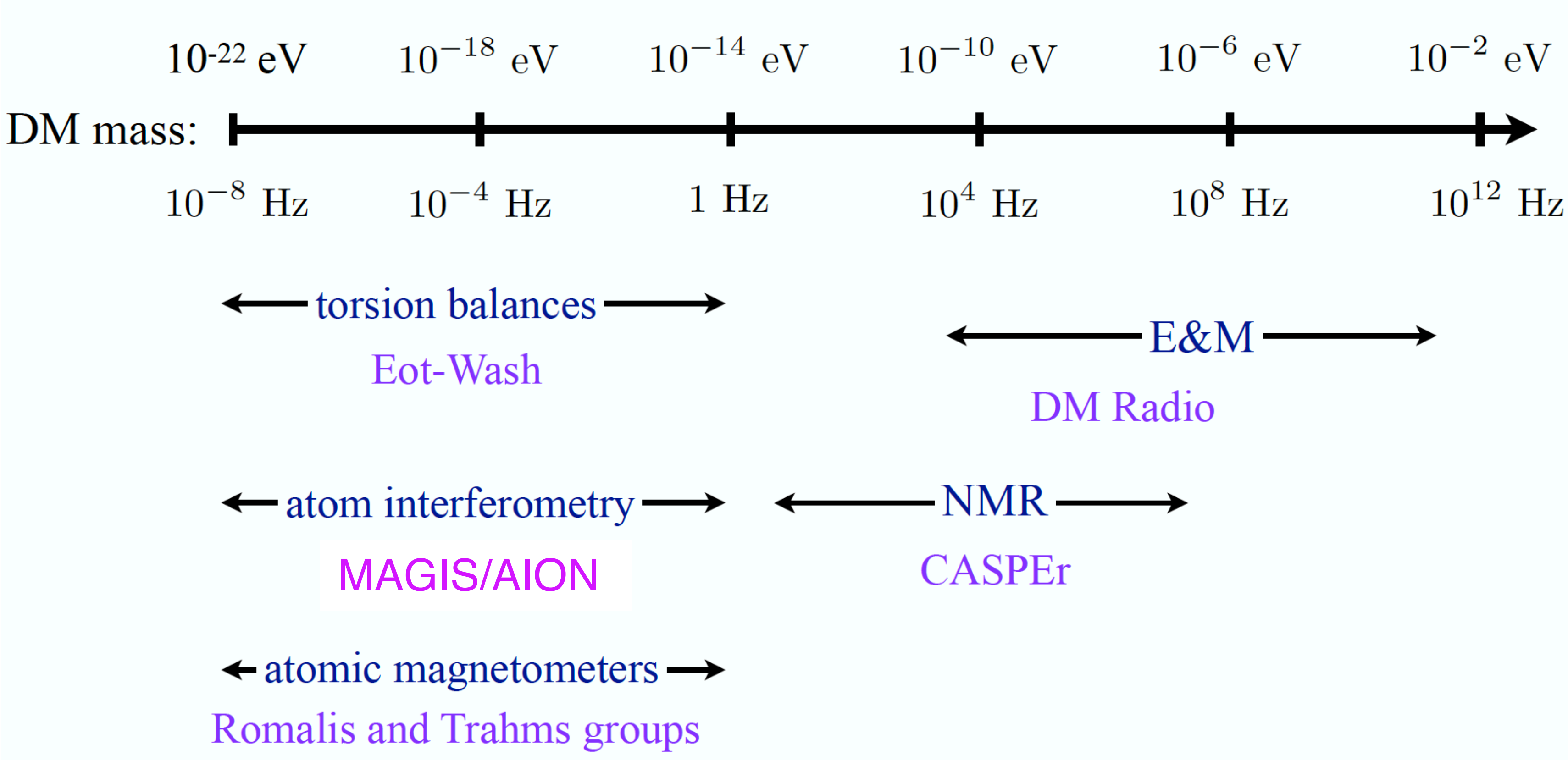


Diagram taken from P. Graham's talk at HEP Front 2018

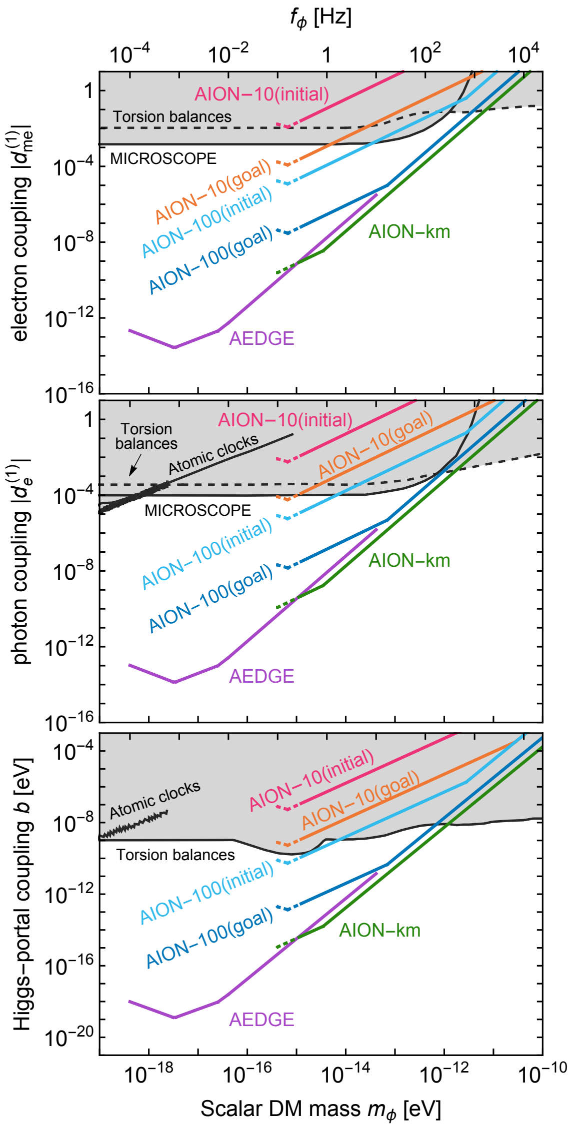
Ultra-Light Scalar Dark Matter

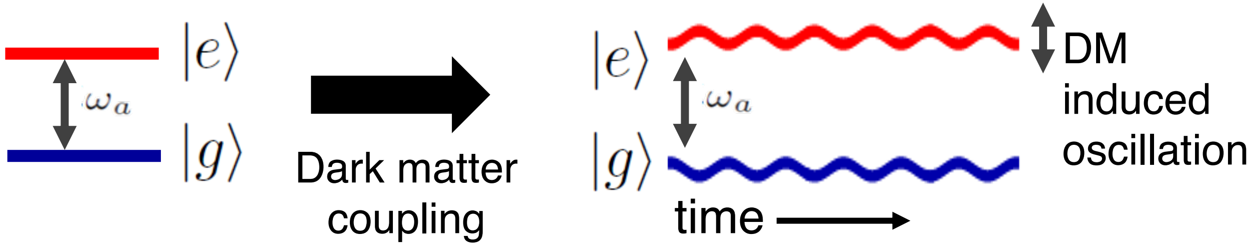
AION Project: UK HEP FORUM 2020

Coupling to electron

Coupling to photon

Coupling Higgs-portal



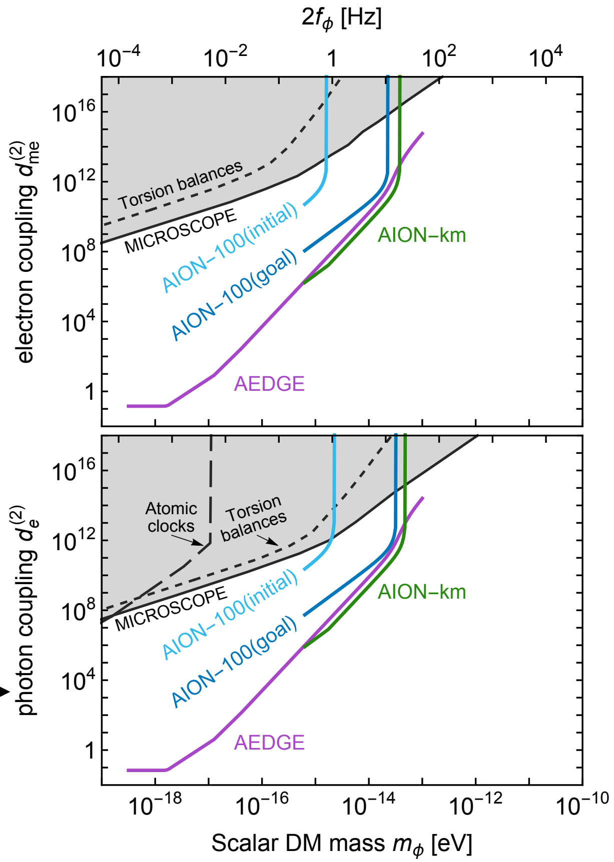


The AION staged programme will have unprecedented sensitivity to DM with scalar couplings to matter, which cause time variation of fundamental constants such as the electron mass.

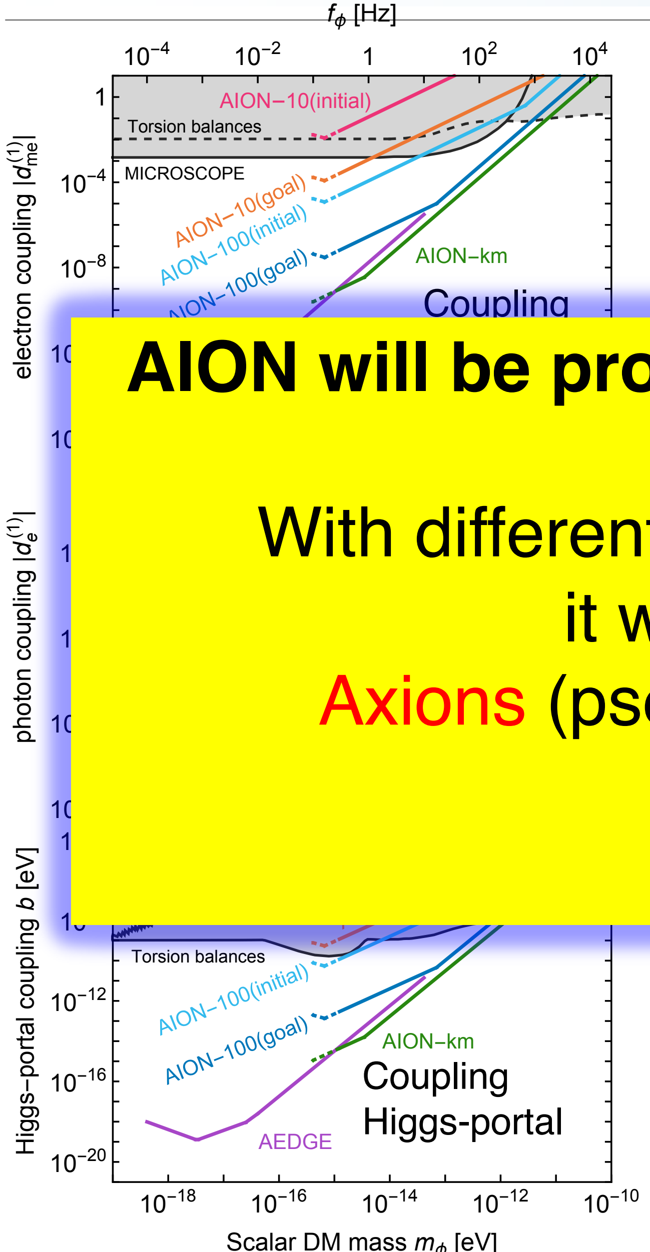
Based on: Arvanitaki et al., PRD **97**, 075020 (2018).

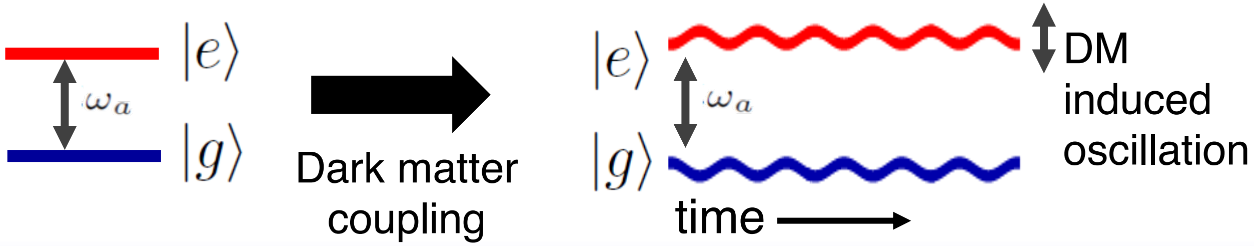
Linear scalar DM interactions

Quadratic scalar DM interactions



Ultra-Light Scalar Dark Matter



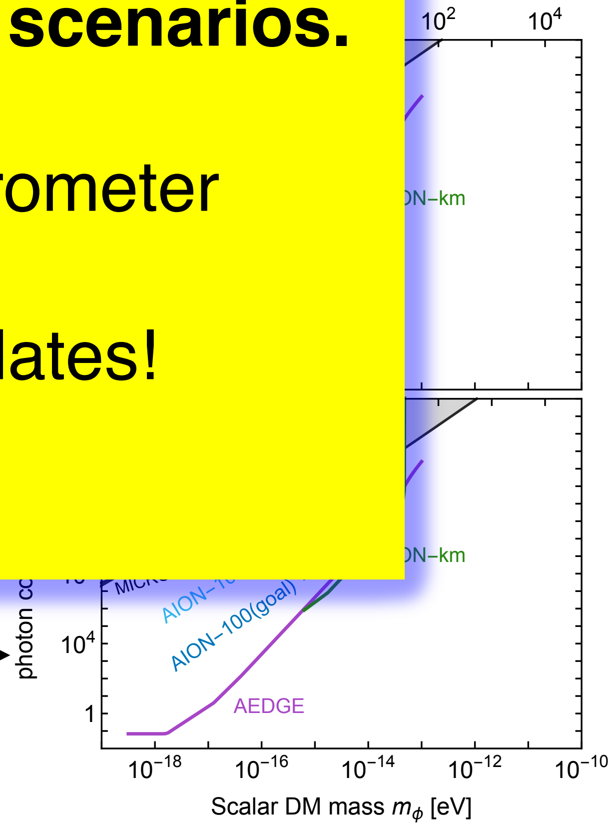


AION will be probing new territory in ULD scalar scenarios.

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



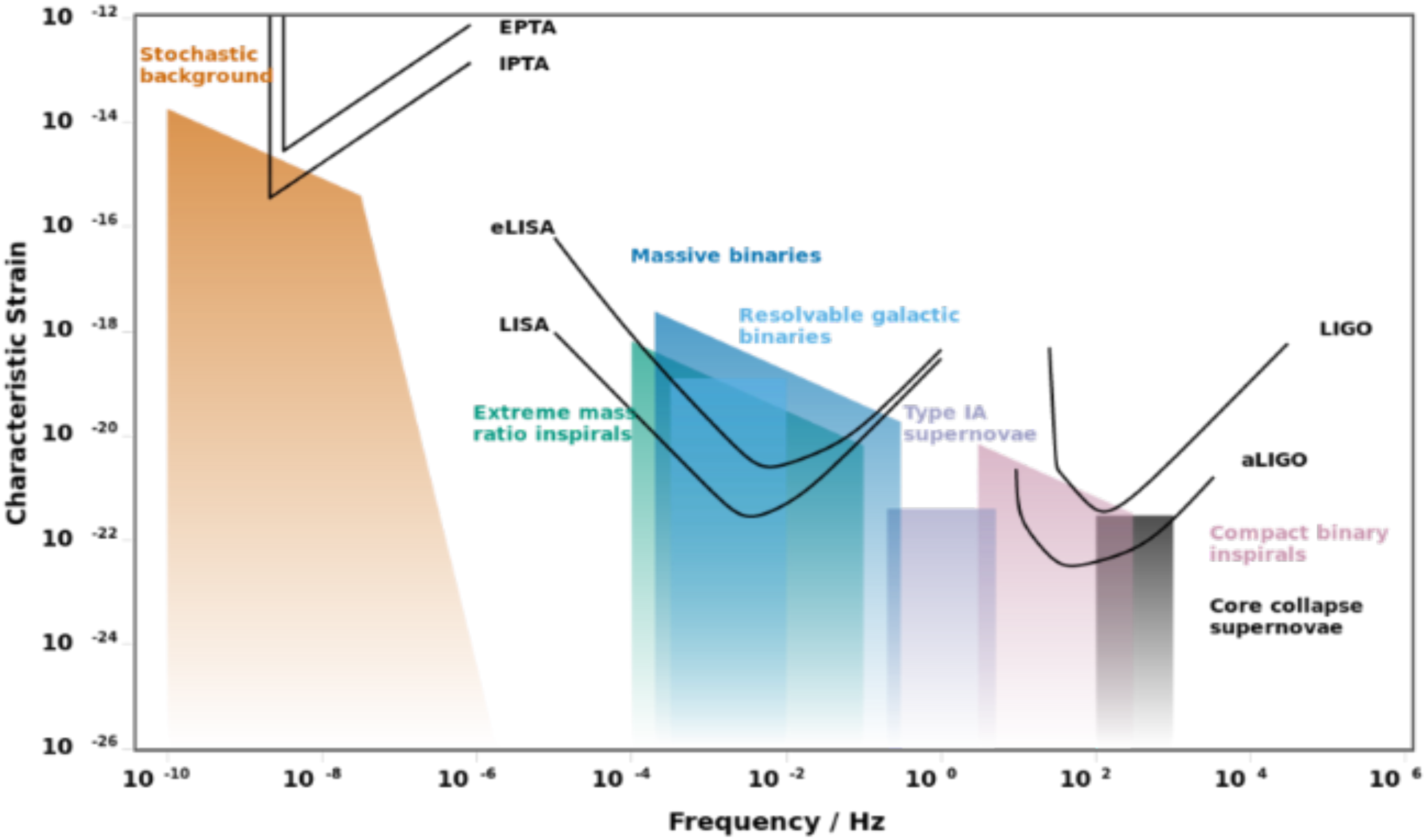
References:

- 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

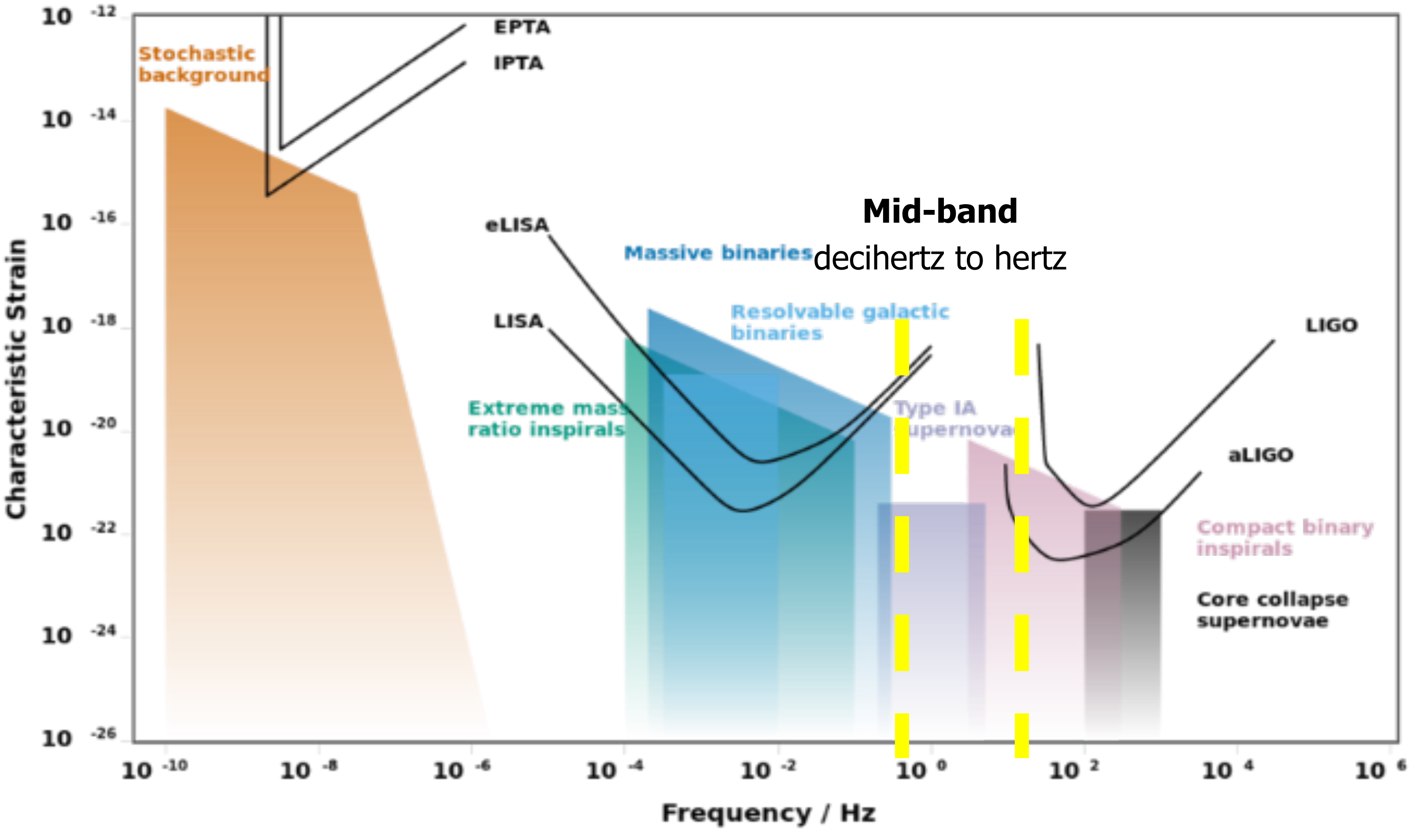
AION: Pathway to the GW Mid-(Frequency) Band

Experimental GW Landscape



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

Experimental GW Landscape



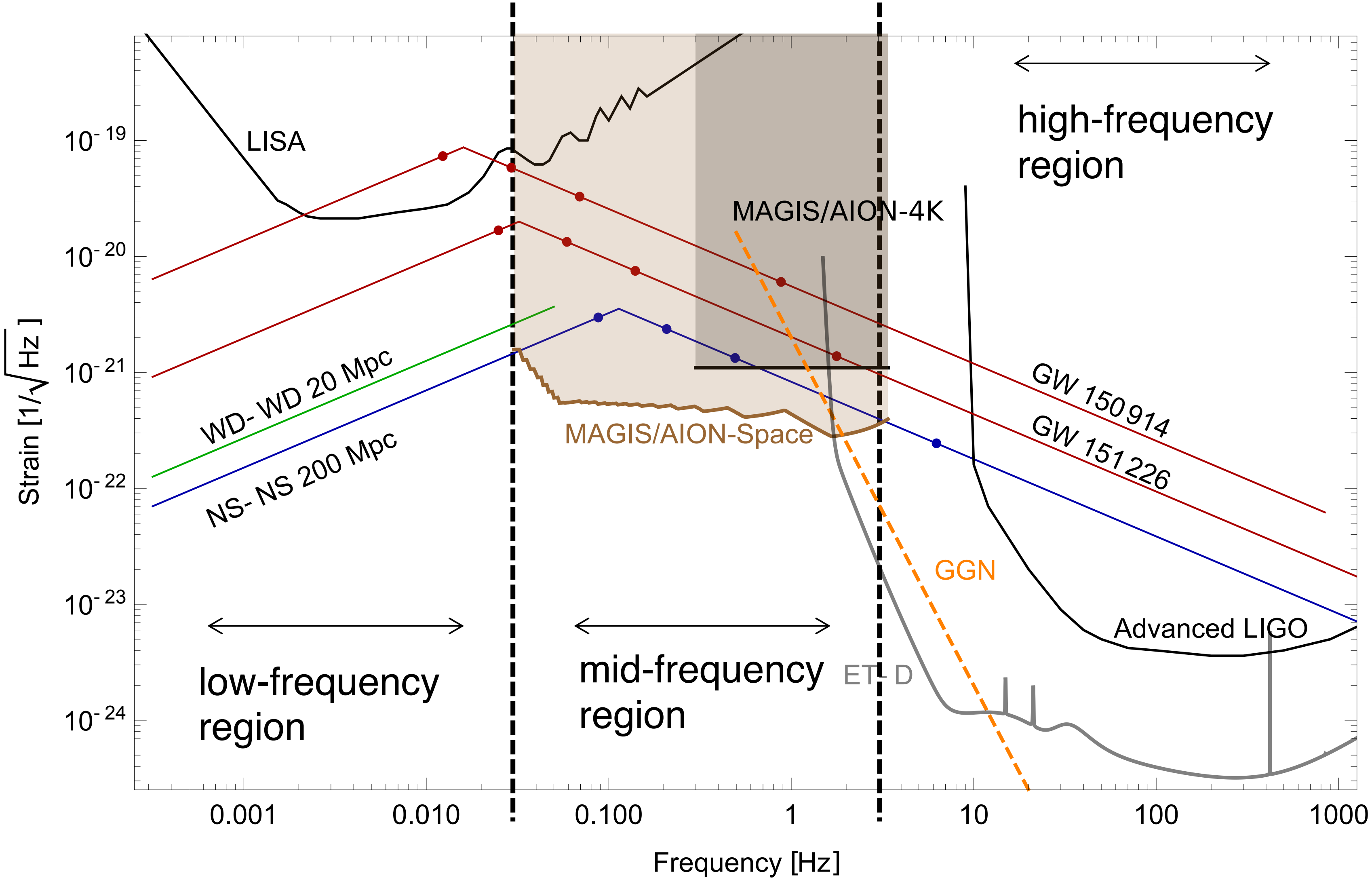
AION Project: UK HEP FORUM 2020

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

Gravitational Wave Detection with Atom Interferometry



Sky position determination

Sky localization precision:

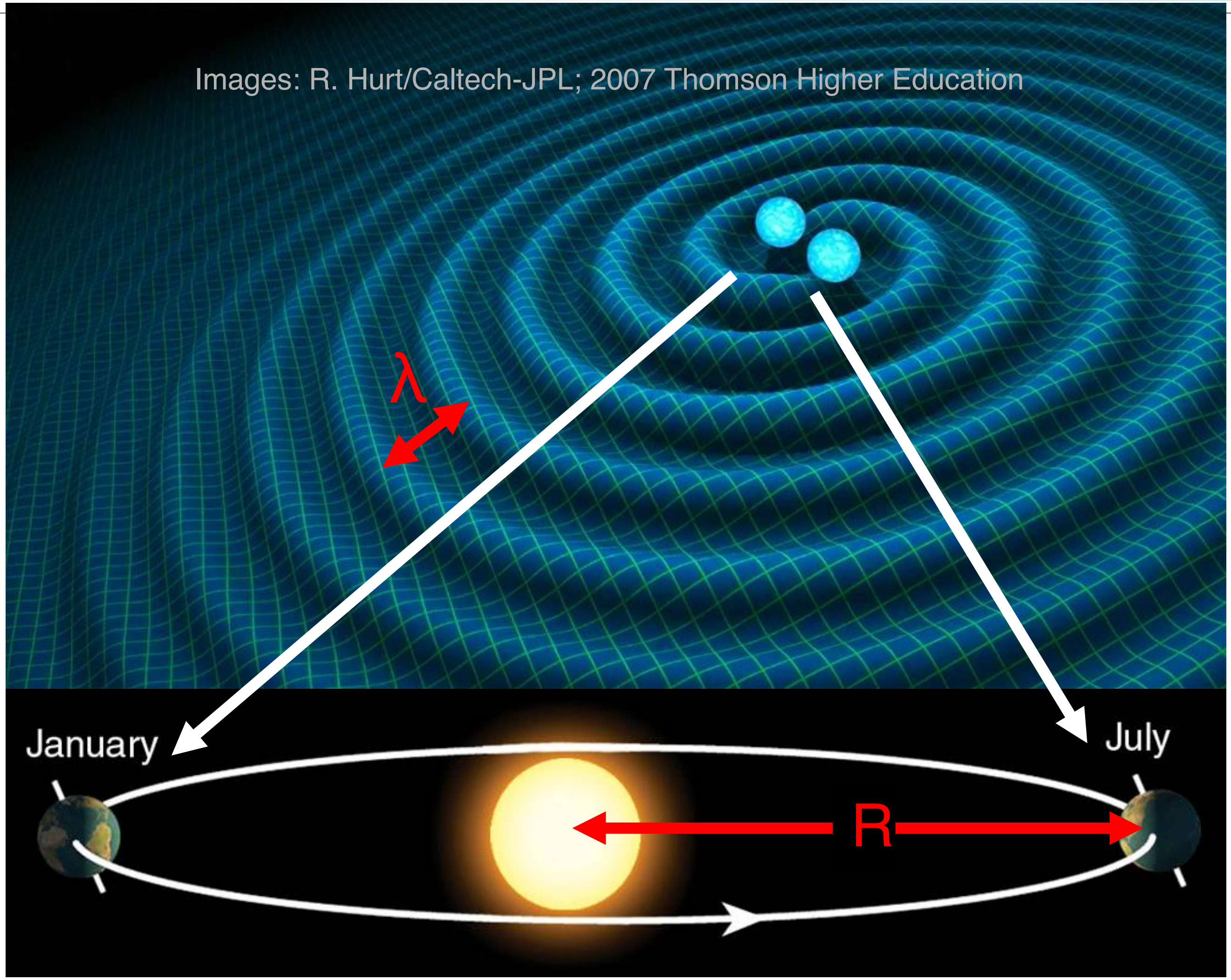
$$\sqrt{\Omega_s} \sim \left(\mathrm{SNR} \cdot \frac{R}{\lambda}\right)^{-1}$$

Mid-band advantages

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

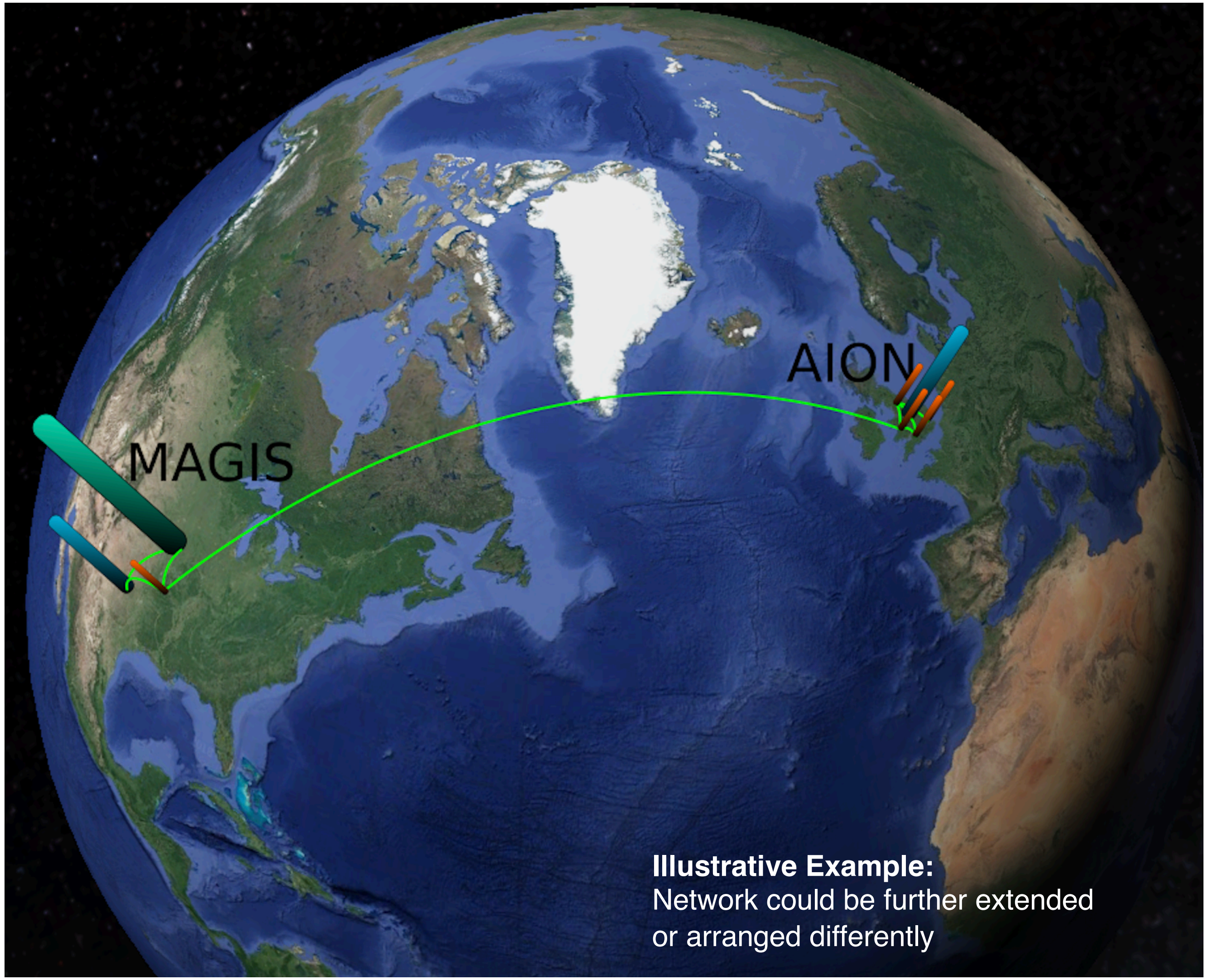
Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19

Courtesy of Jason Hogan!

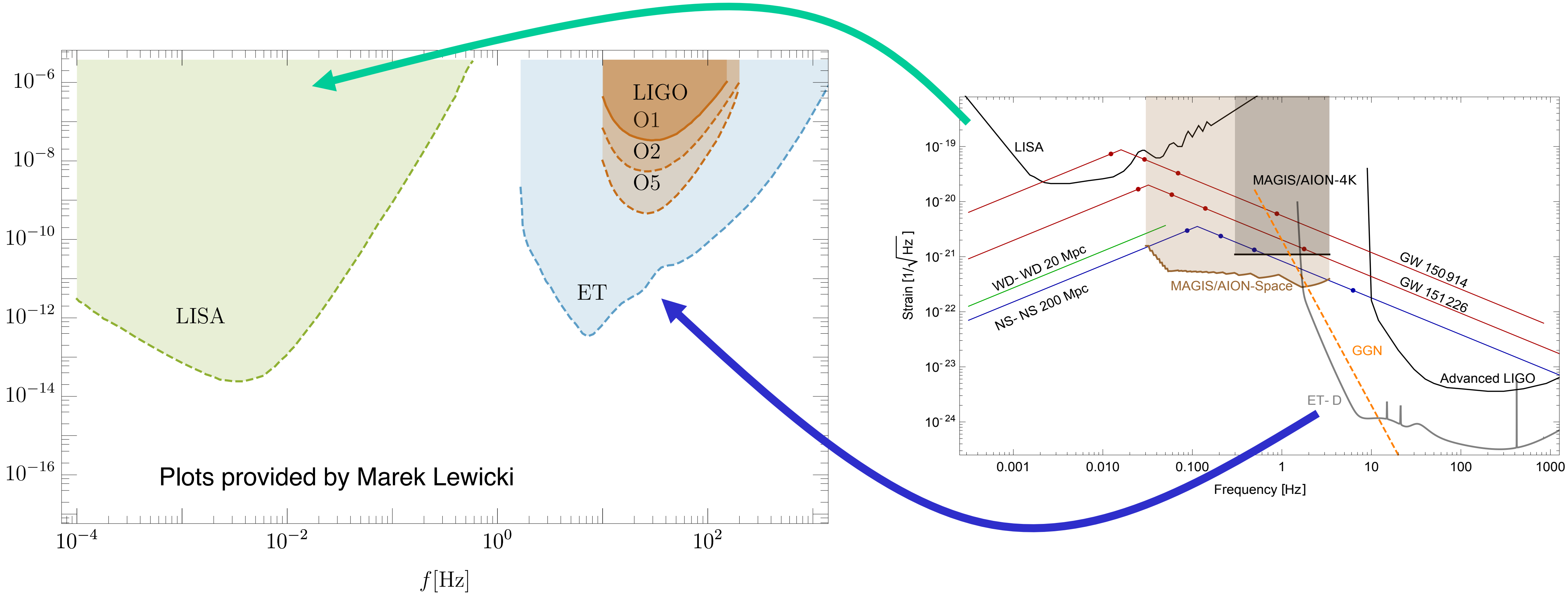


Ultimate sensitivity for terrestrial based detectors is achieved by operating 2 (or more) Detectors in synchronisation mode

Ultimate Goal: Establish International Network

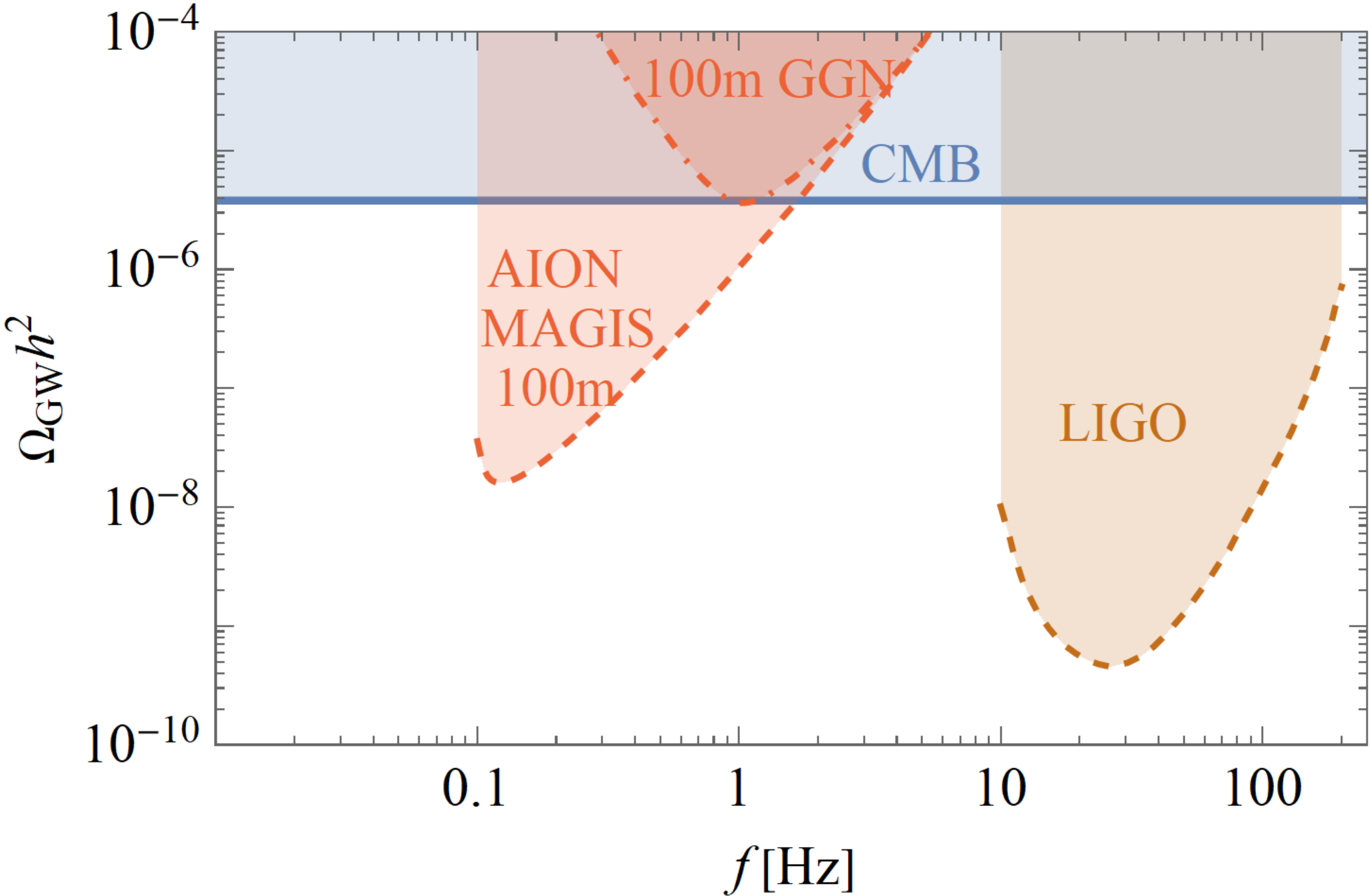


GW Detection & Fundamental Physics - Example

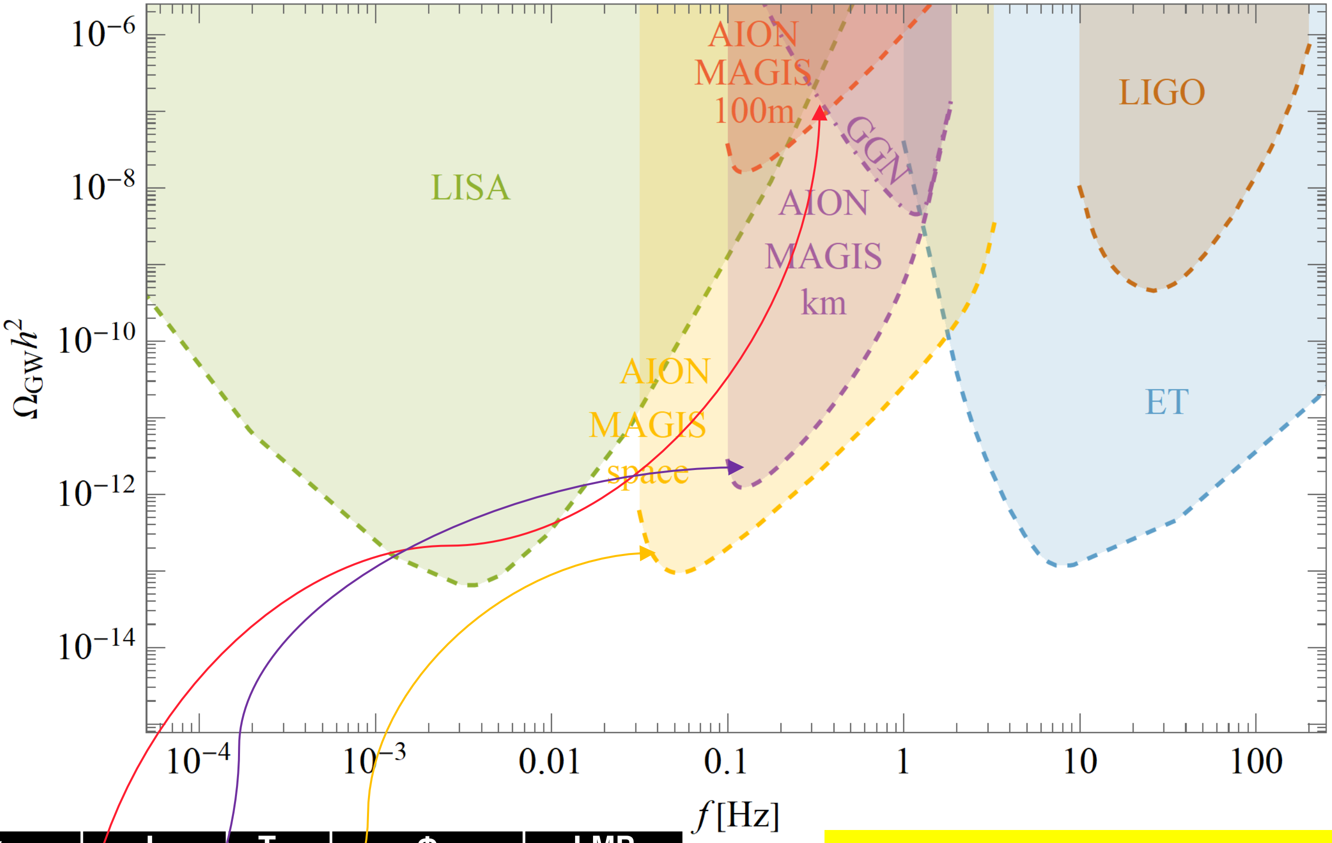


To facilitate comparison, translate strain into dimensionless energy density $\Omega_{GW}h^2$ in GWs against frequency.

The GW Experimental Landscape: 2030ish



The GW Experimental Landscape: 2030ish



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

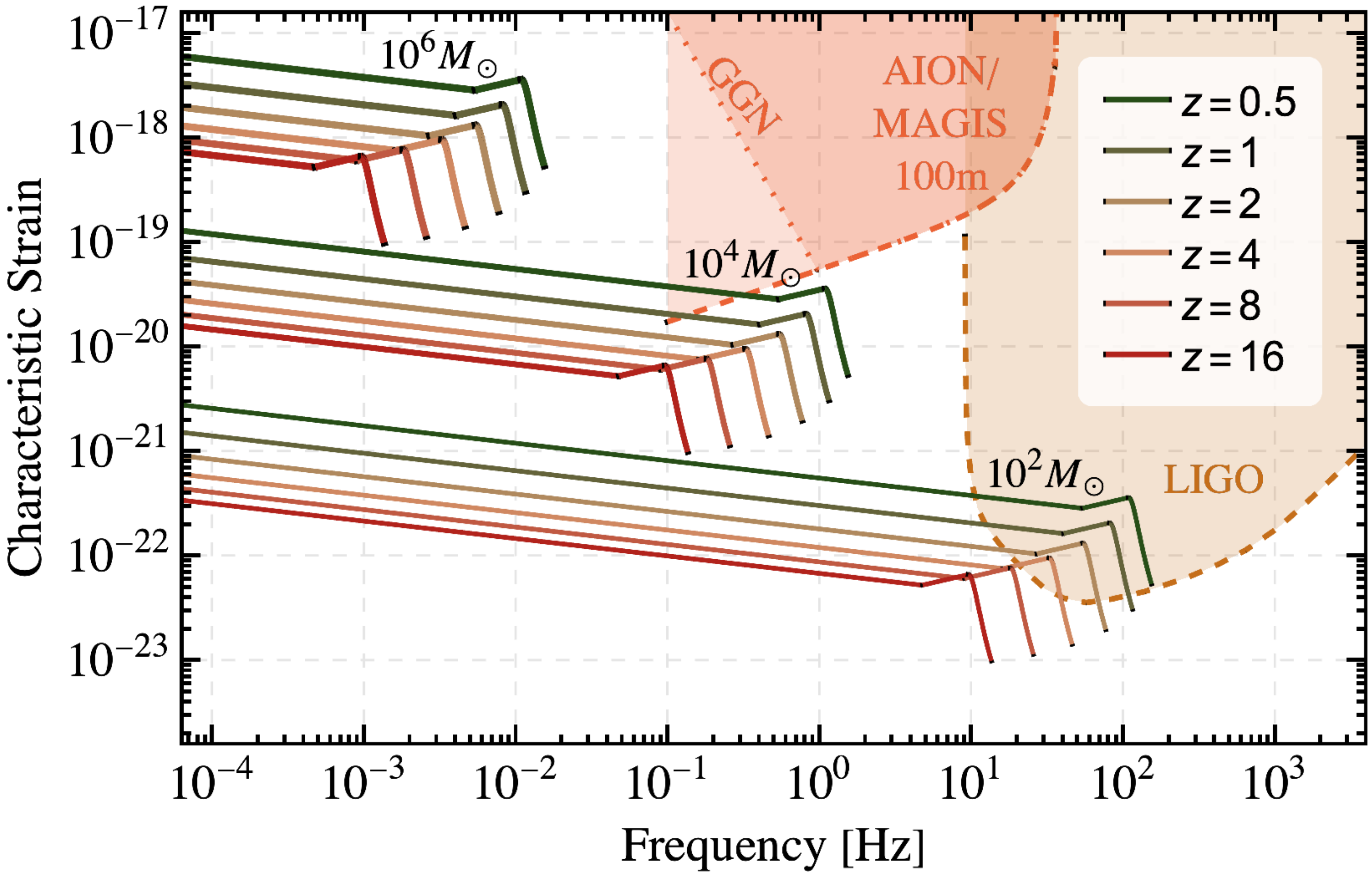
List of basic parameters: Lengths of the detector L, interrogation time of the atom interferometer T_{int} , phase noise ϕ, and number of momentum transfers LMP. The choice of these parameters predominately defines the sensitivity of the projection scenarios.

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.

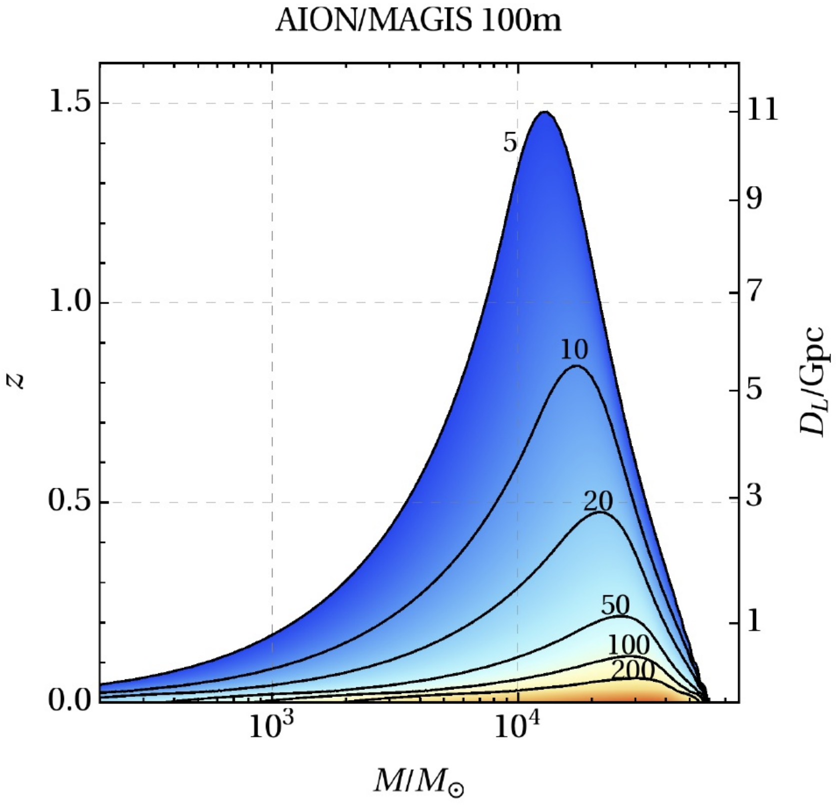
- **Cosmological Sources**
  - Many extensions of the Standard Model (SM) predict first-order phase transitions in the early Universe. Examples include extended electroweak sectors, effective field theories with higher-dimensional operators and hidden sector interactions.
    - Extended electroweak model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

Strain Sensitivity & BH Mergers: 2030ish

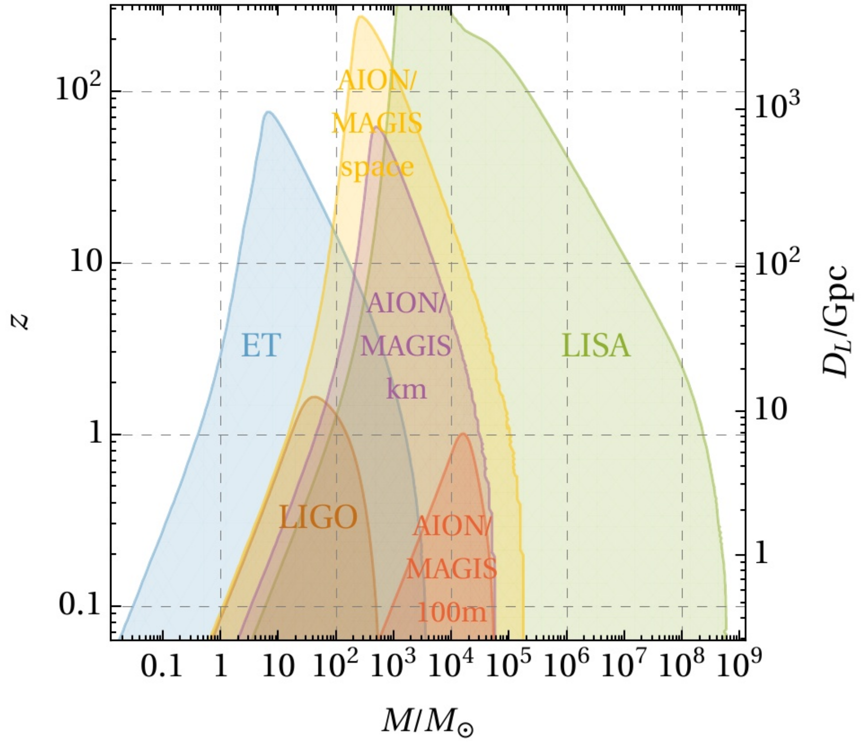


The AION frequency range is ideal for observations of mergers involving IMBHs, to which LISA and the LIGO/Virgo/KAGRA/ET experiments are relatively insensitive.

Strain Sensitivity & BH Mergers

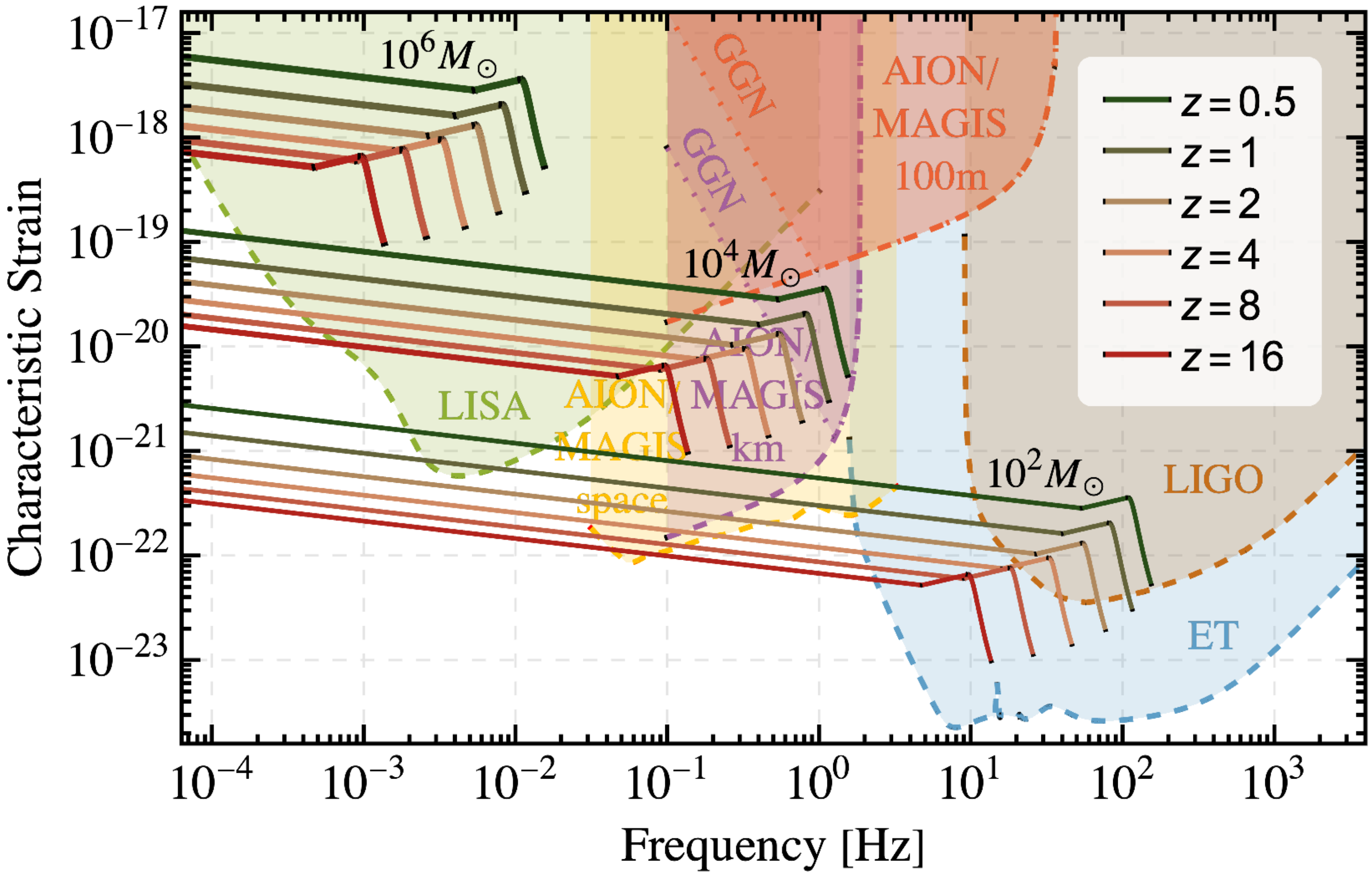


Sensitivity of AION-100m for detecting GWs from the mergers of IMBHs at signal-to-noise (SNR) levels ≥ 5, which extends to redshifts of 1.5 for BHs with masses ~ 10^4 solar masses.



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

Strain Sensitivity & BH Mergers: Future

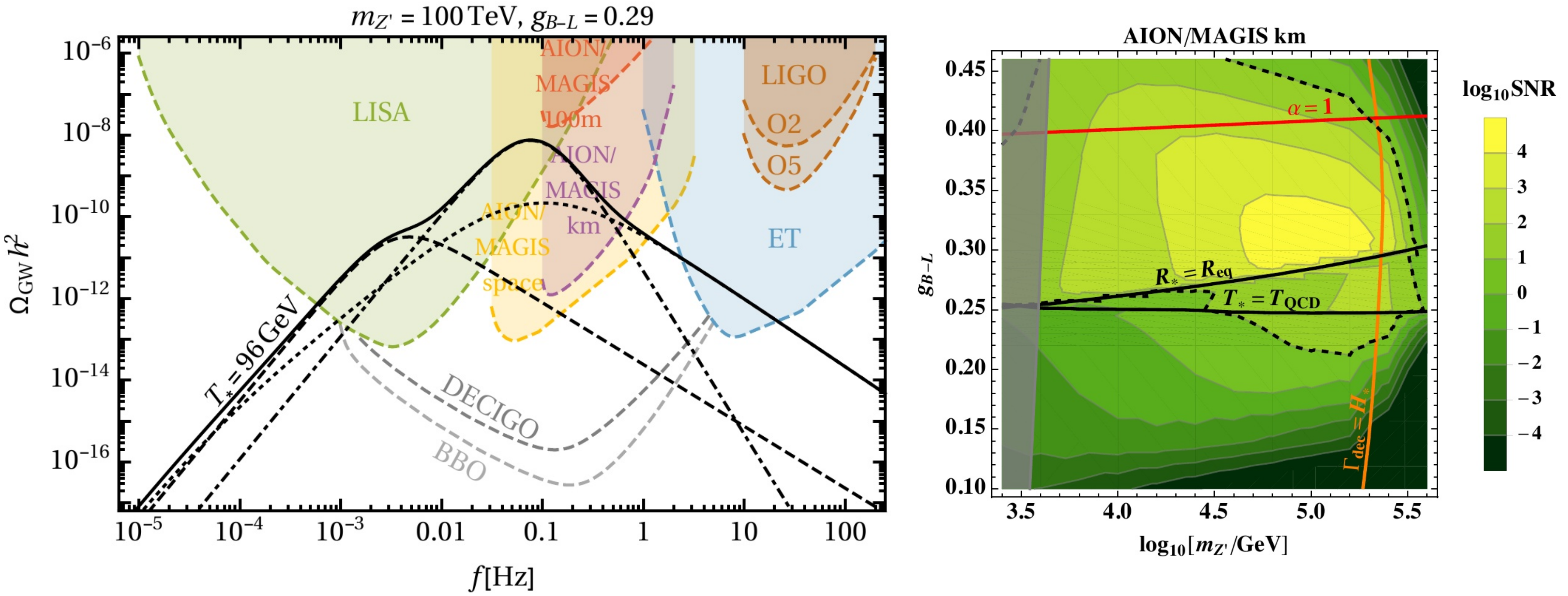


The AION frequency range is ideal for observations of mergers involving IMBHs, to which LISA and the LIGO/Virgo/KAGRA/ET experiments are relatively insensitive.

Cosmological GW Sources: Z' Model

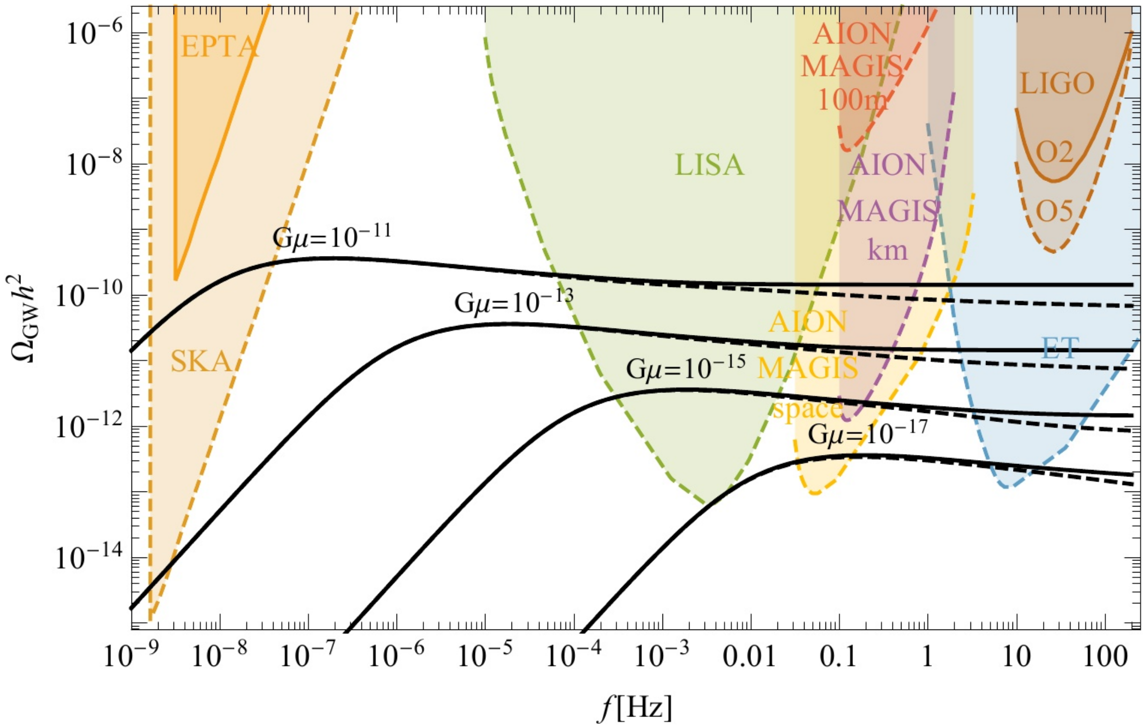
Many extensions of the Standard Model (SM) predict first-order phase transitions in the early Universe.

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.

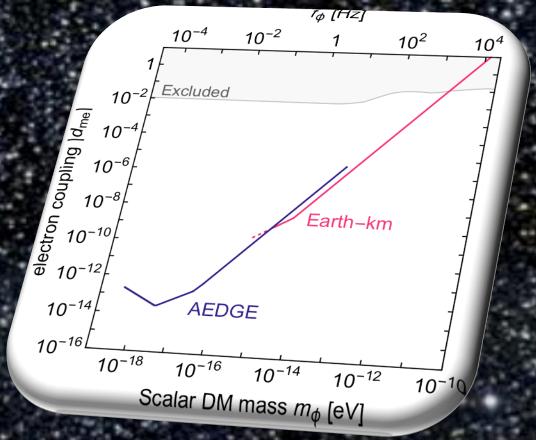
Examples may include:

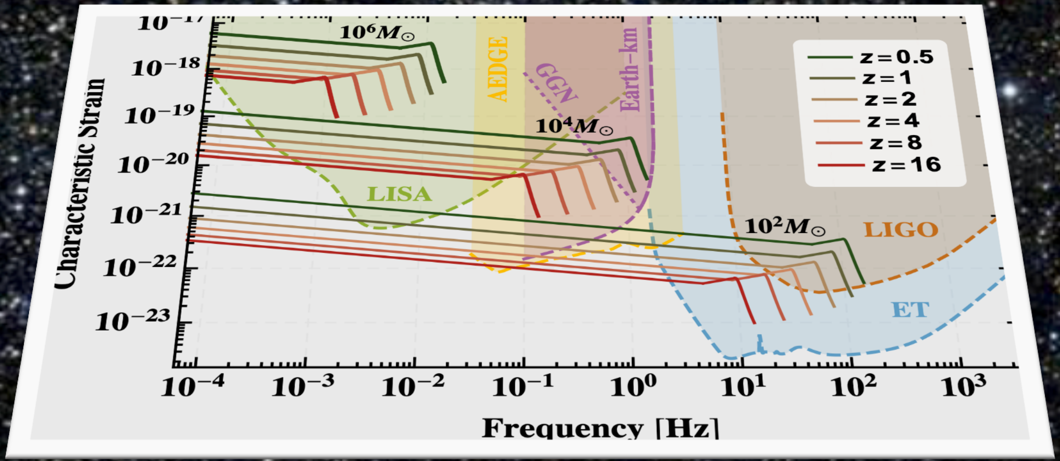
- *The possibility of detecting the astrophysical neutrinos*
- *Probes of long-range fifth forces*.
- *Constraining possible variations in fundamental constants.*
- *Probing dark energy*.
- Probes of basic physical principles such as foundations of quantum mechanics and Lorentz invariance.

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.

Informal Workshop
CERN, July 22/23 2019

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PP=Particle Physics
CA=Cold Atoms

AEDGE Mission Concept

AION Project: UK HEP FORUM 2020

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]

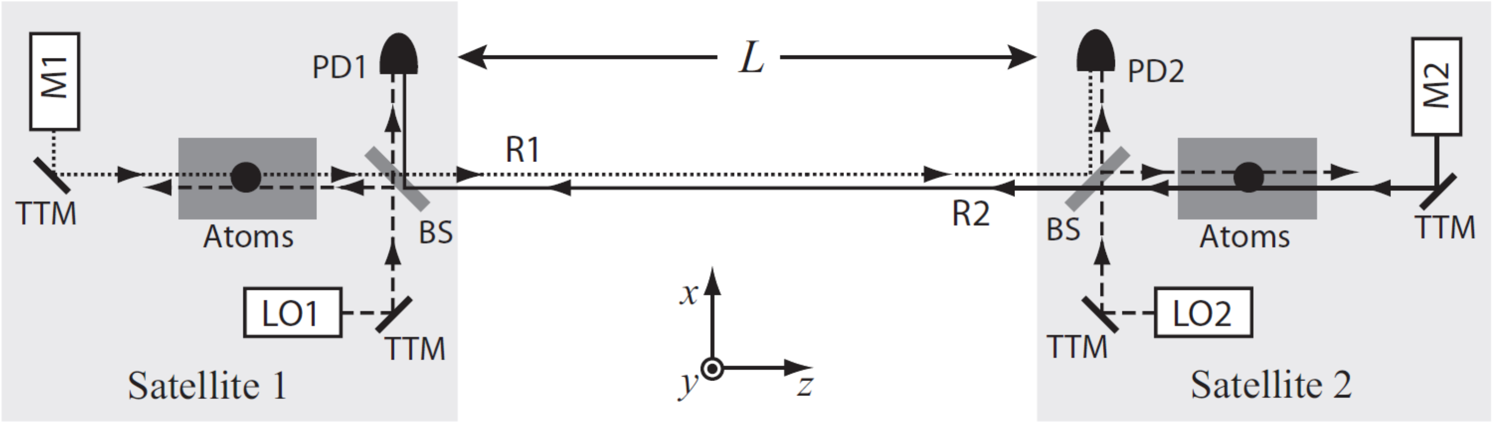
132 Authors, from **70** institutions, based in **23** different counties!

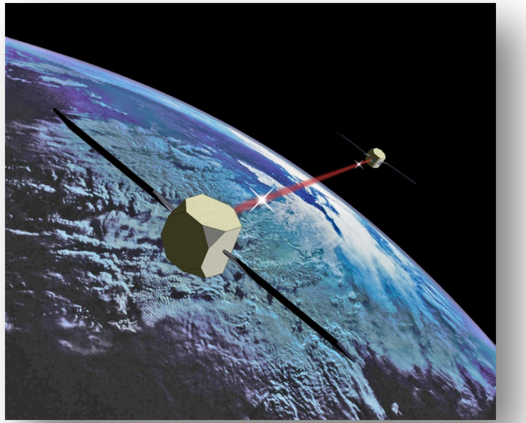
The authors represent several science communities ranging from Cold Atoms, & Gravitational Waves, over Cosmology and Astrophysics to fundamental Particle Physics.

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 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**

Summary: AION & AEDGE

- New window on gravitational physics, astrophysics & cosmology using atom interferometers, leveraging UK investment in quantum technologies, providing new opportunities for UK science communities.

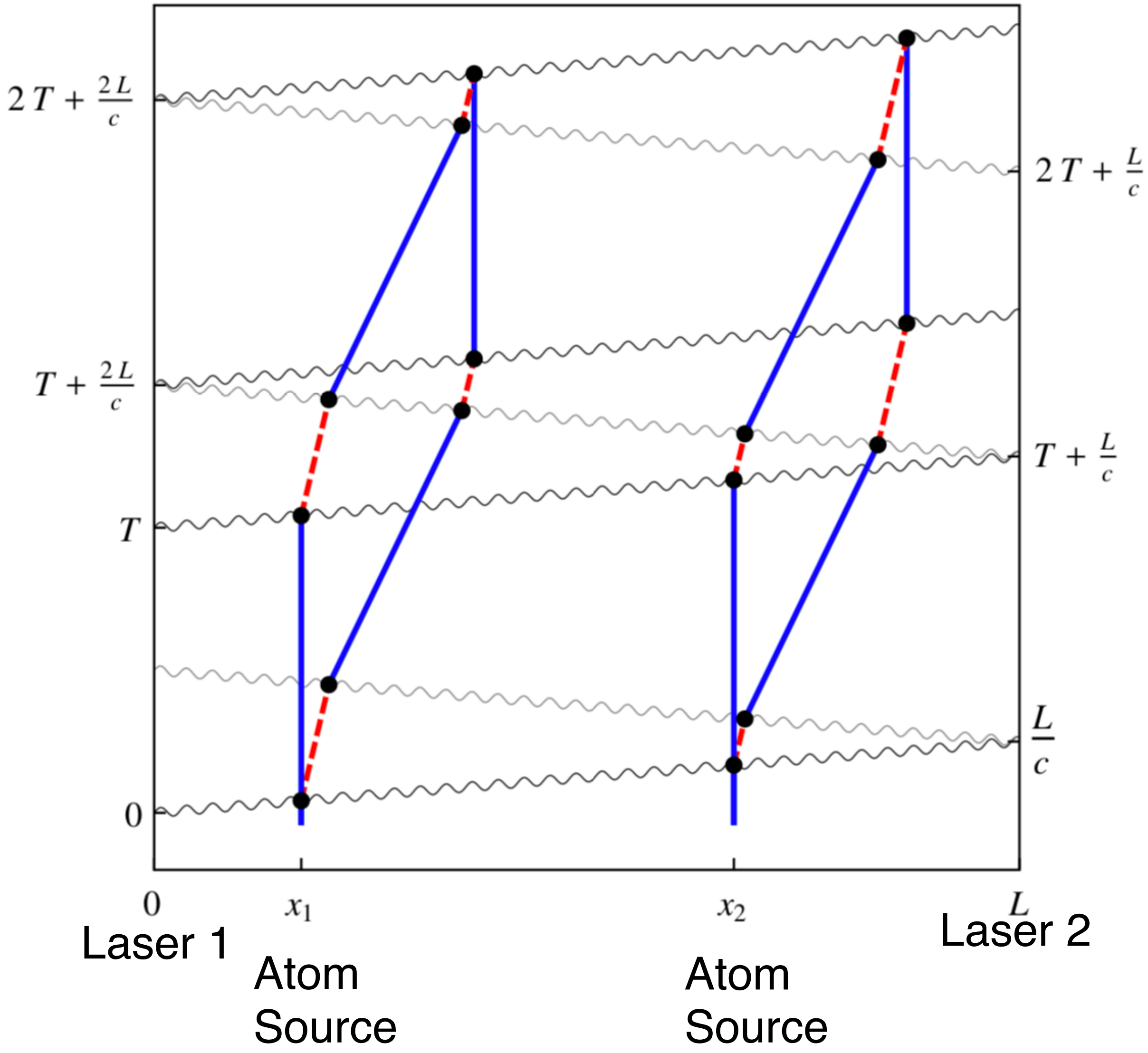
- AION-10 was funded by the QTFP programme and will explore parameter space **of ultra-light dark matter (ULDM)** models, partnership with MAGIS in US.

- Preparation for AION-100 (km-scale) with **unique capabilities for detecting gravitational waves** is key deliverable.
  - ➢ Funding required would be similar to that for AION-10, assuming a suitable site.
  - ➢ Possible 100m sites under investigation: Boulby, Daresbury (UK), CERN (France/Switzerland).

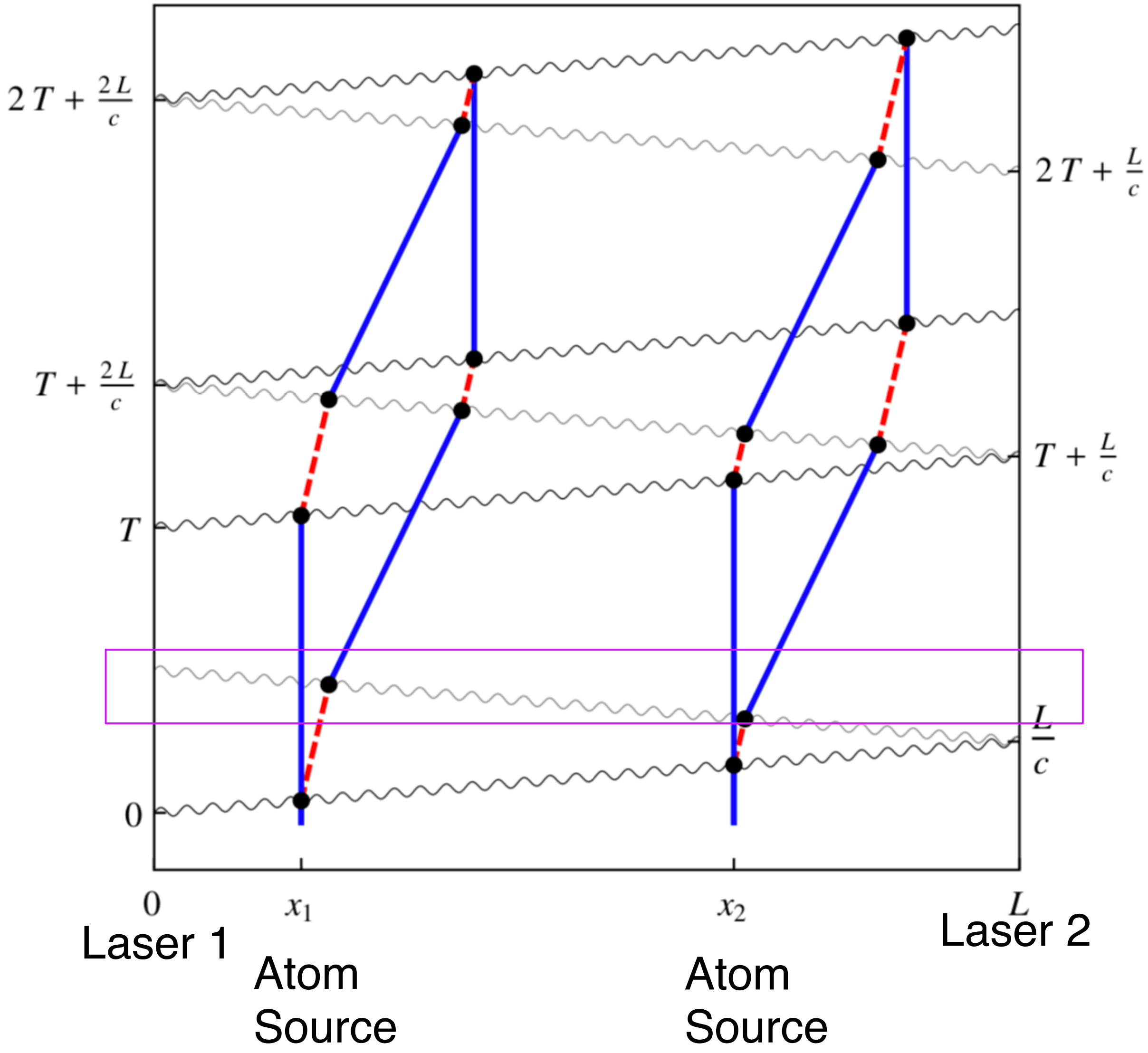
- AEDGE is a uniquely interdisciplinary mission that will harness cold atom technologies, as developed for AION, to address key issues in fundamental physics, astrophysics and cosmology that can be realized within the Voyage 2050 Science Programme of ESA.
  - ➢ AEDGE is currently under review by ESA and we are planning to host another AEDGE workshop when the results of the review are available.

BACKUP

Basic Differential Measurement



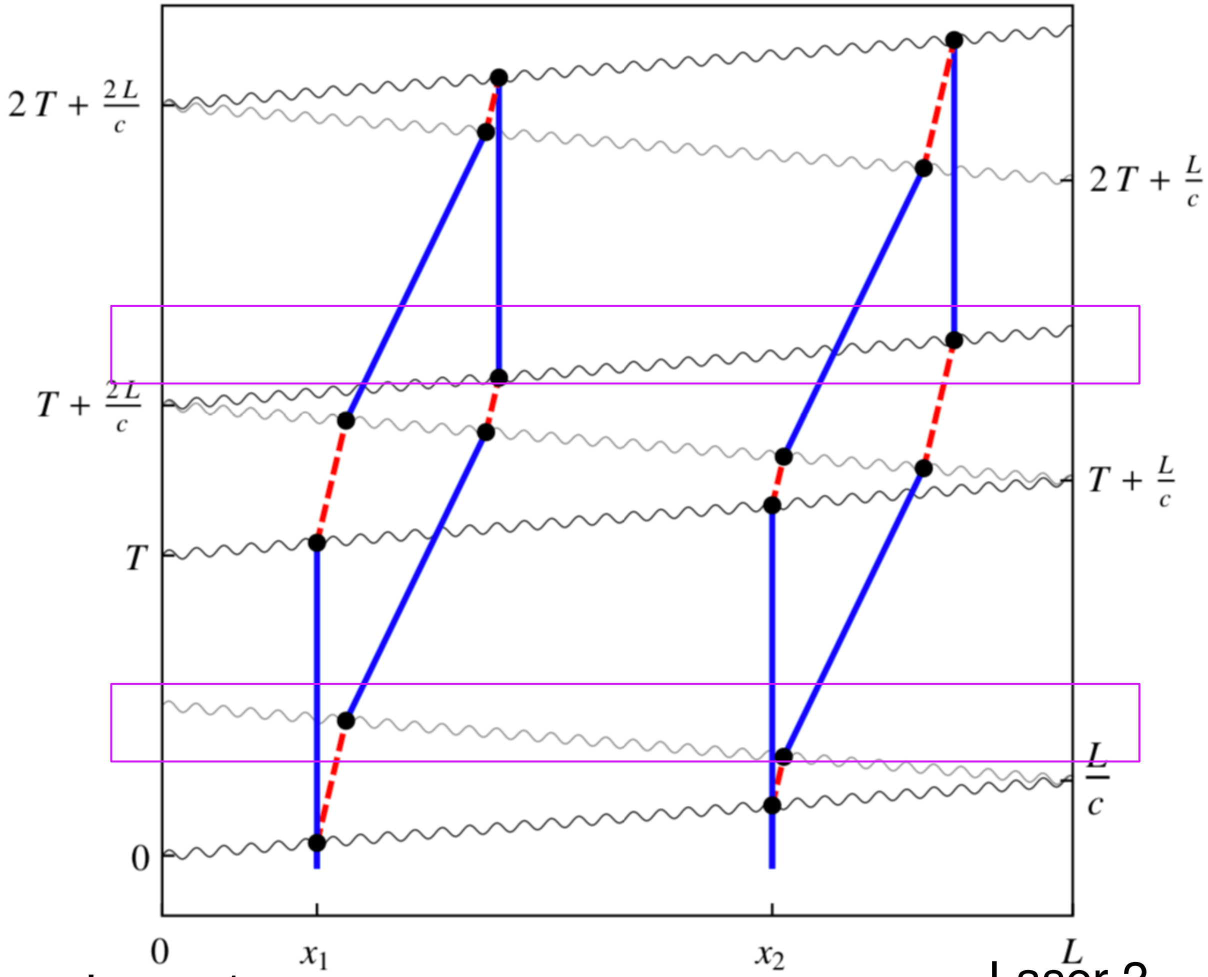
Basic Differential Measurement



Laser 2: π pulse [high p]

Laser 1: π/2 pulse [split]

Basic Differential Measurement

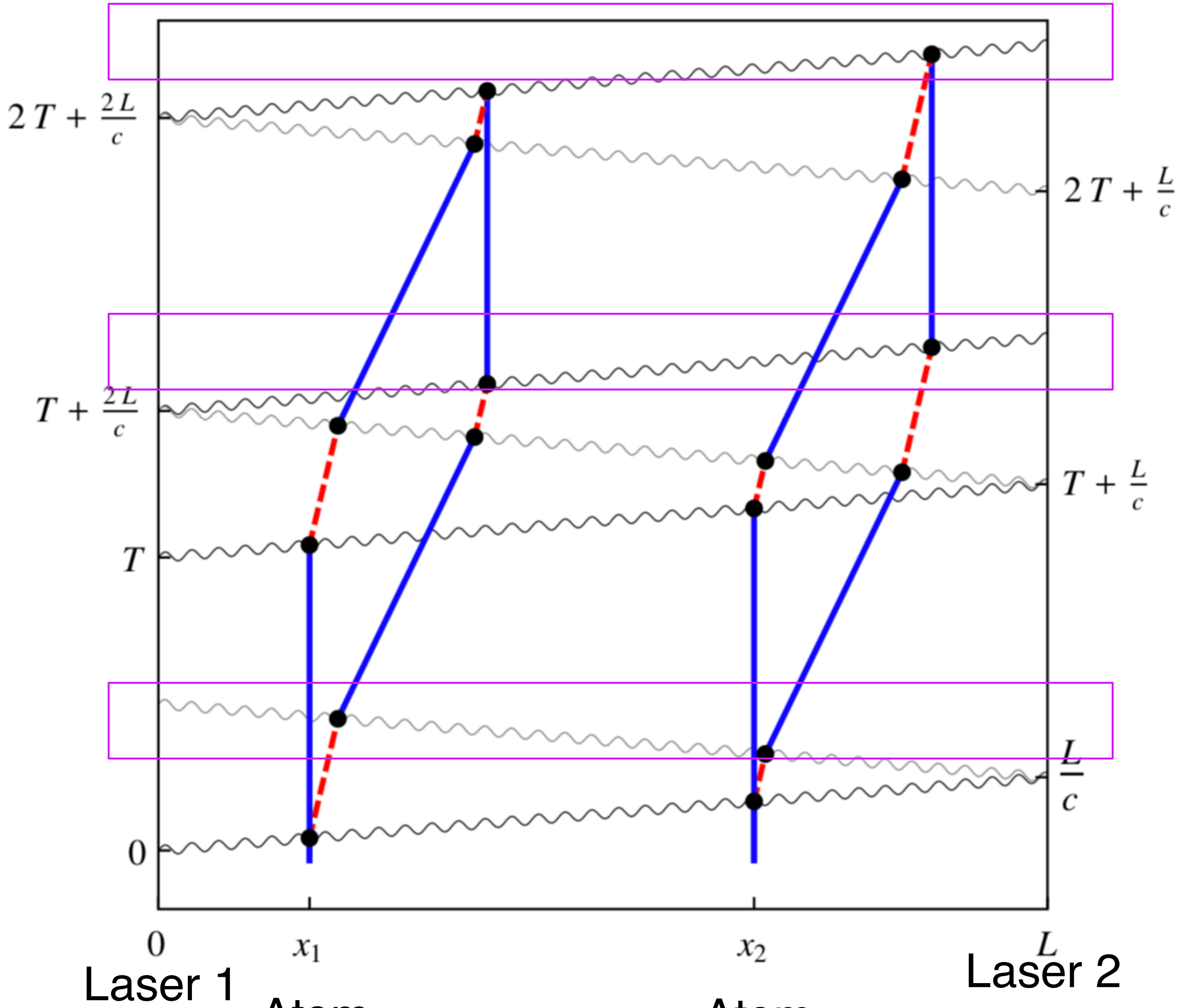


"Mirror"
3π pulse
[low-high/low-high]
[Doppler shift to select]

Laser 2: π pulse [high p]

Laser 1: π/2 pulse [split]

Basic Differential Measurement



Laser 1: π/2 pulse [split]

Laser 2: π pulse [low p]

"Mirror"
3π pulse
[low-high/low-high]
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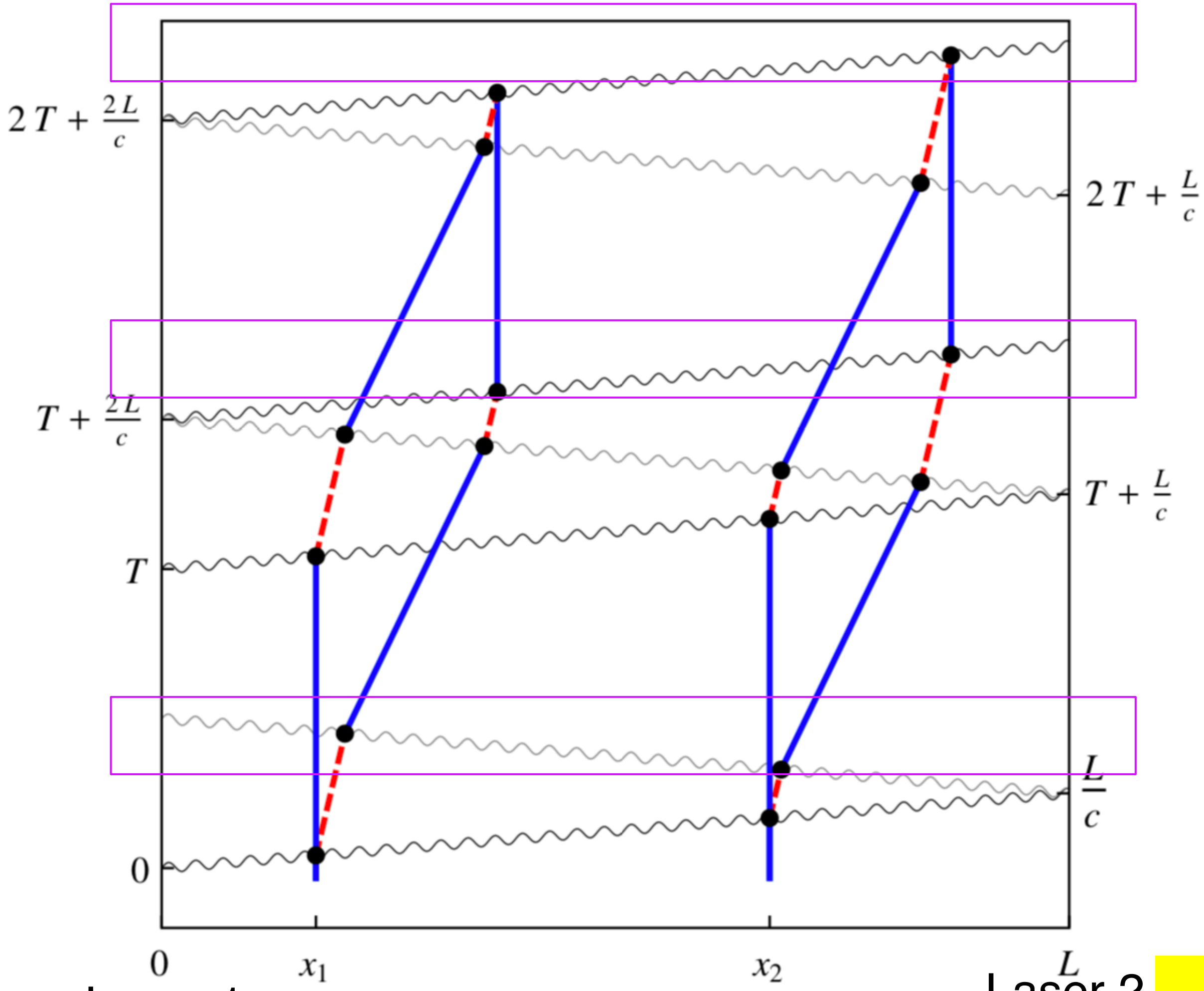
Laser 2: π pulse [high p]

Laser 1: π/2 pulse [split]

Basic Differential Measurement



Laser 1 Atom Source Atom Source Laser 2

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.)

SQUARED

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

King's + Imperial Colleges: Theory and publication office

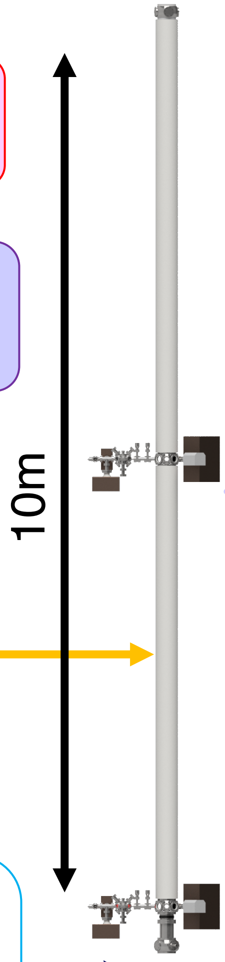
UoB, Cambridge, Imperial: modelling system parameters

Imperial: (clock) laser stabilisation, squeezing

RAL: Vacuum + support structure. Design AION-100

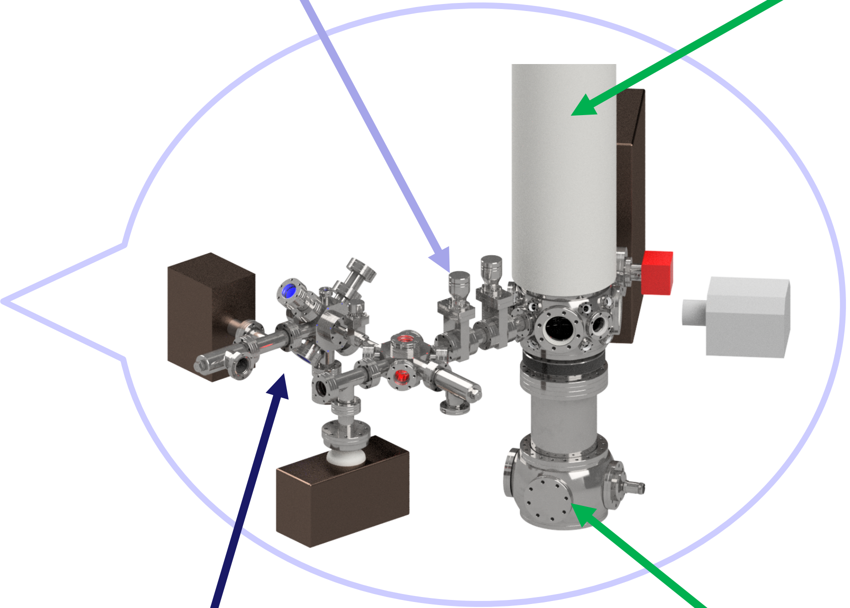
UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

- Impact
- Technology transfer



Cambridge: transport + launching atoms, MAGIS

UoB: LMT pulse sequences, Sr technology transfer



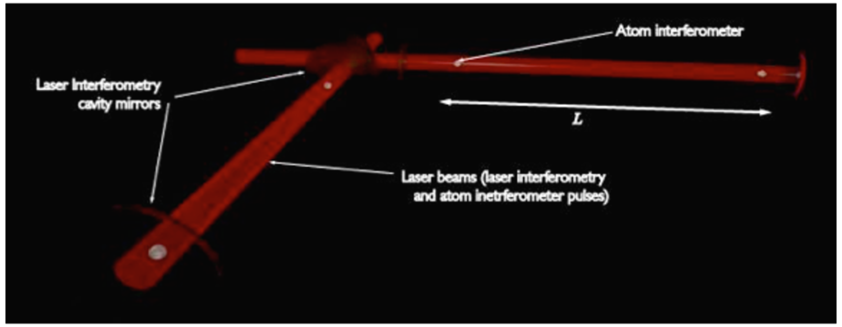
Liverpool: internal optics for MAGIS + AION

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

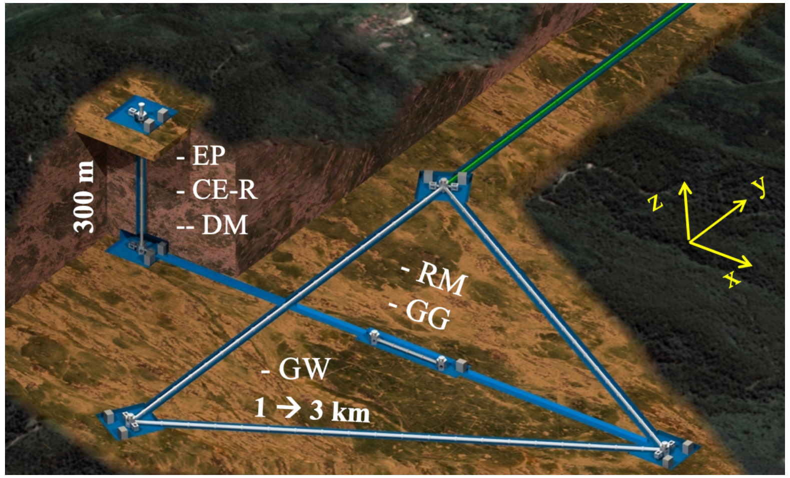
EXPERIMENTAL LANDSCAPE

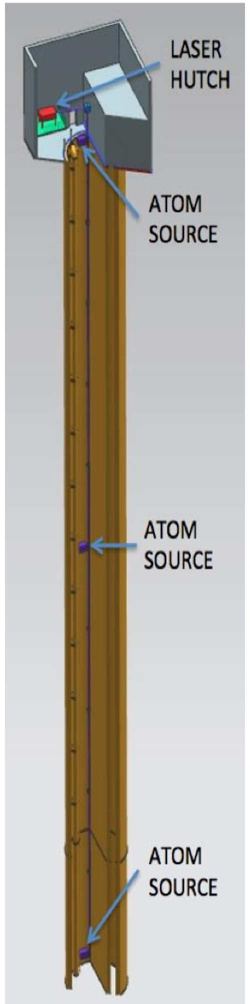
Ground Based Large Scale O(100m) Projects

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



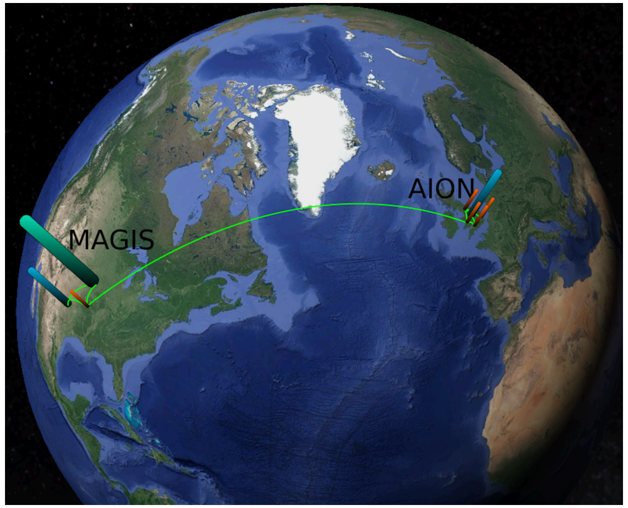
ZIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100M)
(China)





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

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



Planned network operation

STATE-OF-THE-ART DESIGN SPESIFICATIONS

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

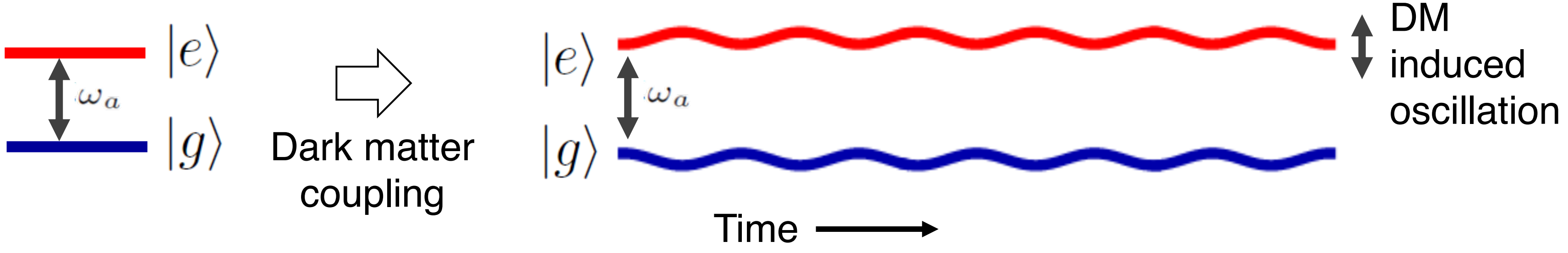
e.g., QCD

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

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

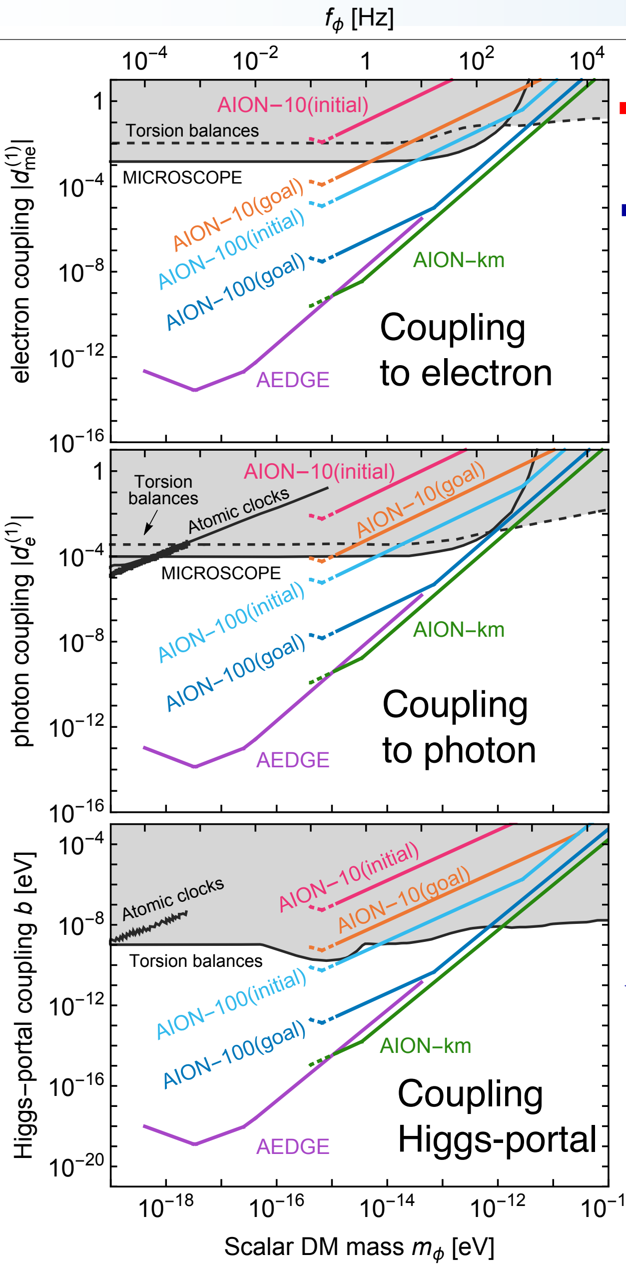
DM mass density

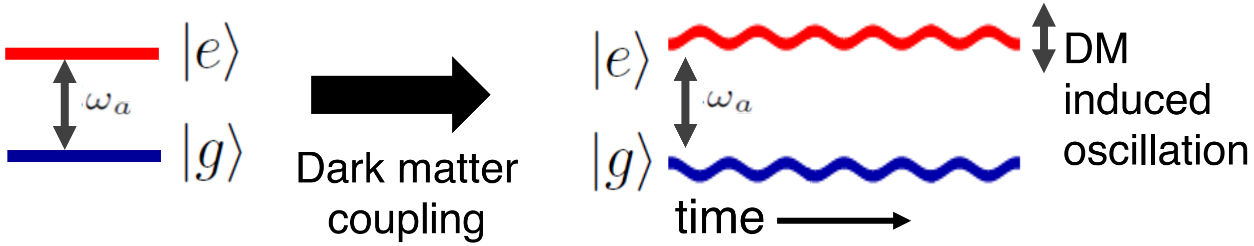
DM coupling causes time-varying atomic energy levels:



Courtesy of Jason Hogan!

Ultra-Light Scalar Dark Matter



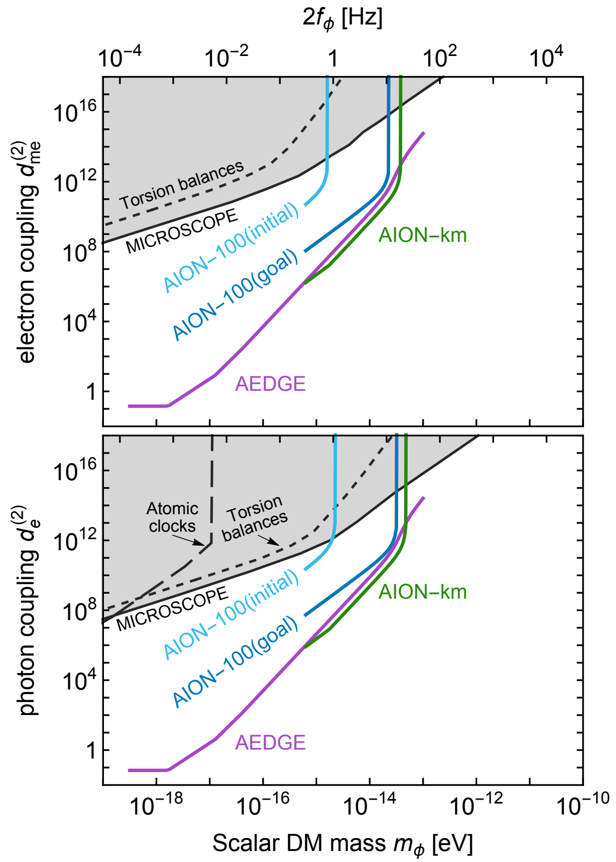


The AION staged programme will have unprecedented sensitivity to DM with scalar couplings to matter, which cause time variation of fundamental constants such as the electron mass.

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

Linear scalar DM interactions

Quadratic scalar DM interactions



Ultra-

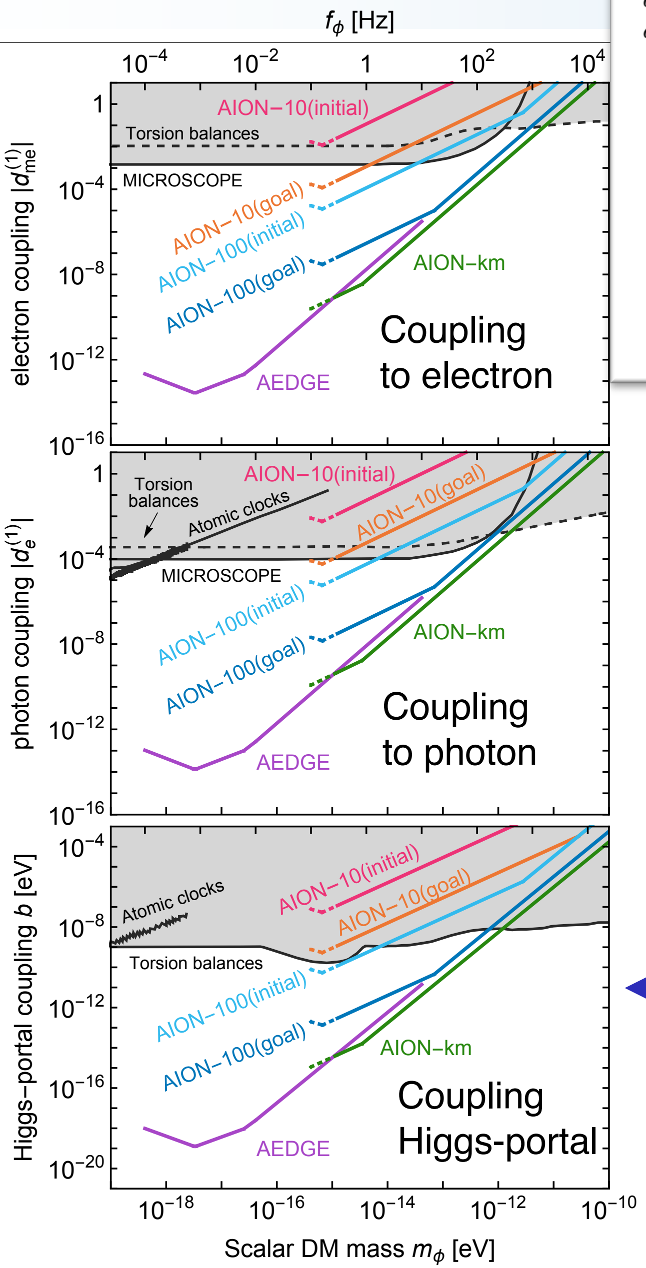


Table 1. *List of basic parameters: length of the detector L; interrogation time of the atom interferometer T_{int}; phase noise $\delta\phi_{noise}$; and number of momentum transfers LMT. The choices of these parameters largely determine the sensitivities of the projection scenarios. It should be noted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

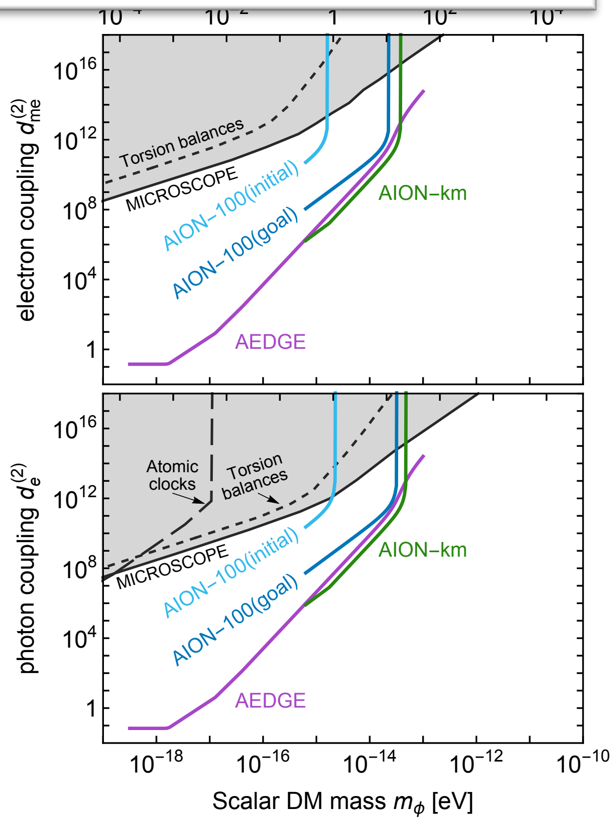
Sensitivity Scenario	L [m]	T_{int} [sec]	$\delta\phi_{noise}$ [$1/\sqrt{Hz}$]	LMT [number n]
AION-10 (initial)	10	1.4	10^{-3}	100
AION-10 (goal)	10	1.4	10^{-4}	1000
AION-100 (initial)	100	1.4	10^{-4}	1000
AION-100 (goal)	100	1.4	10^{-5}	40000
AION-km	2000	5	0.3×10^{-5}	40000

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

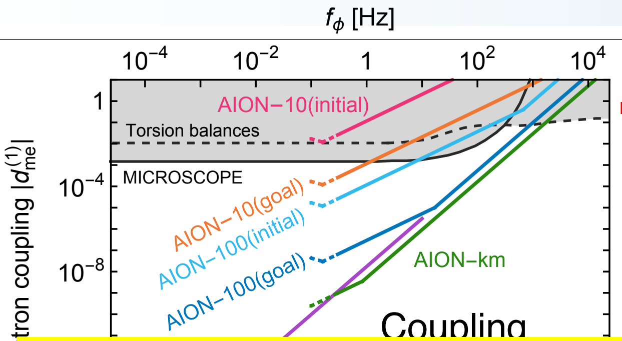
Based on: Arvanitaki et al., PRD **97**, 075020 (2018).

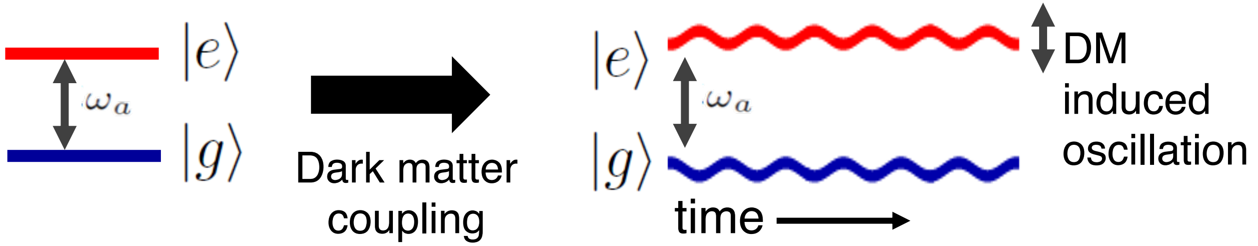
Linear scalar DM interactions

Quadratic scalar DM interactions

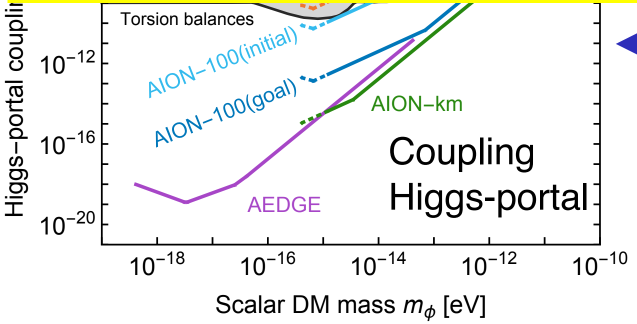


Ultra-Light Scalar Dark Matter



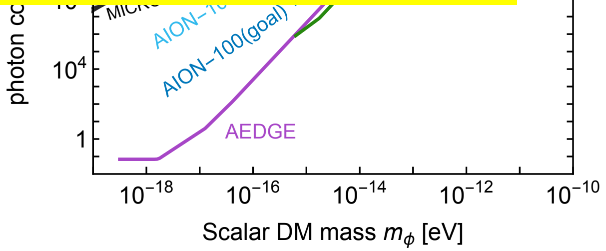


AION will be probing new territory in ULD scalar scenarios.
With different configurations of the Atom Interferometer it will be also possible to search for
Axions (pseudo-scalar) and Vector DM candidates!
[studies are ongoing]



Linear scalar DM interactions

Quadratic scalar DM interactions



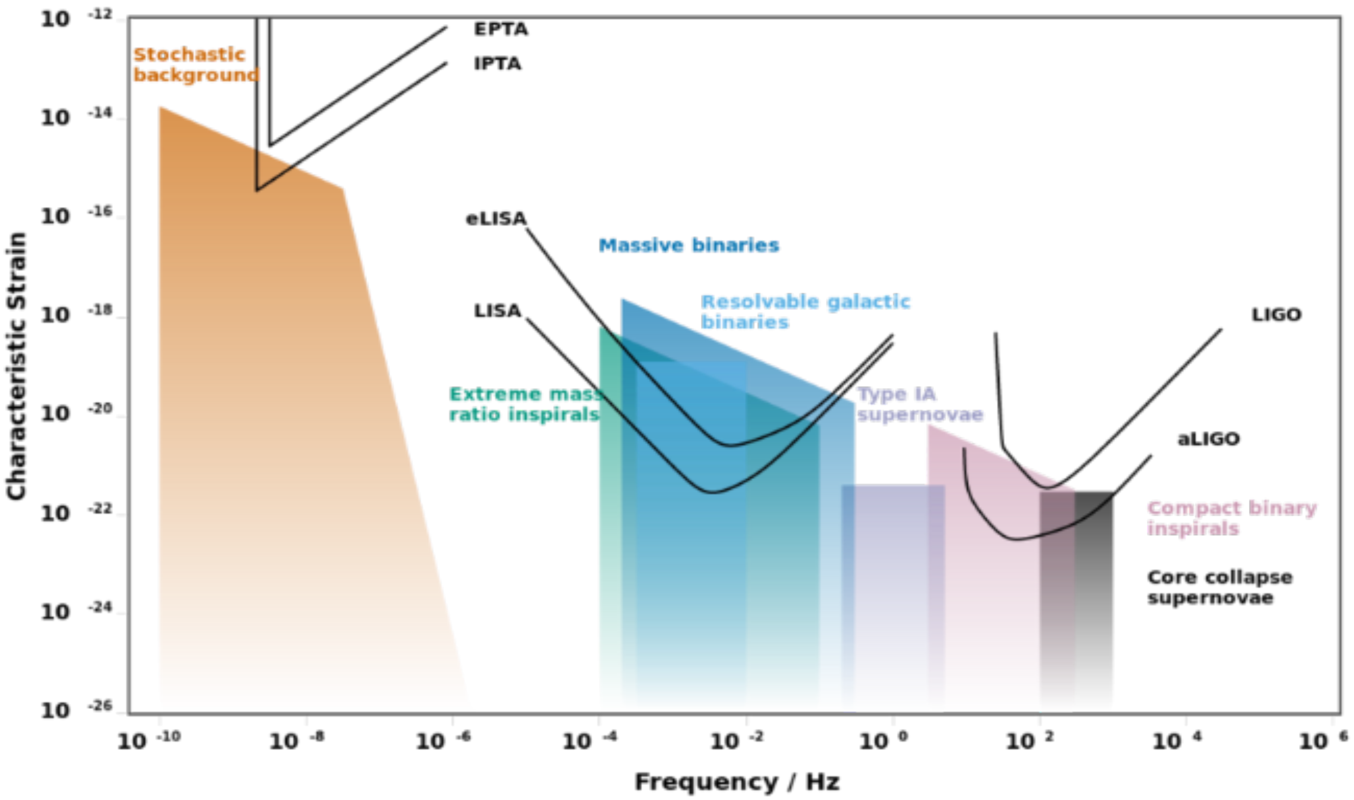
References:

- 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

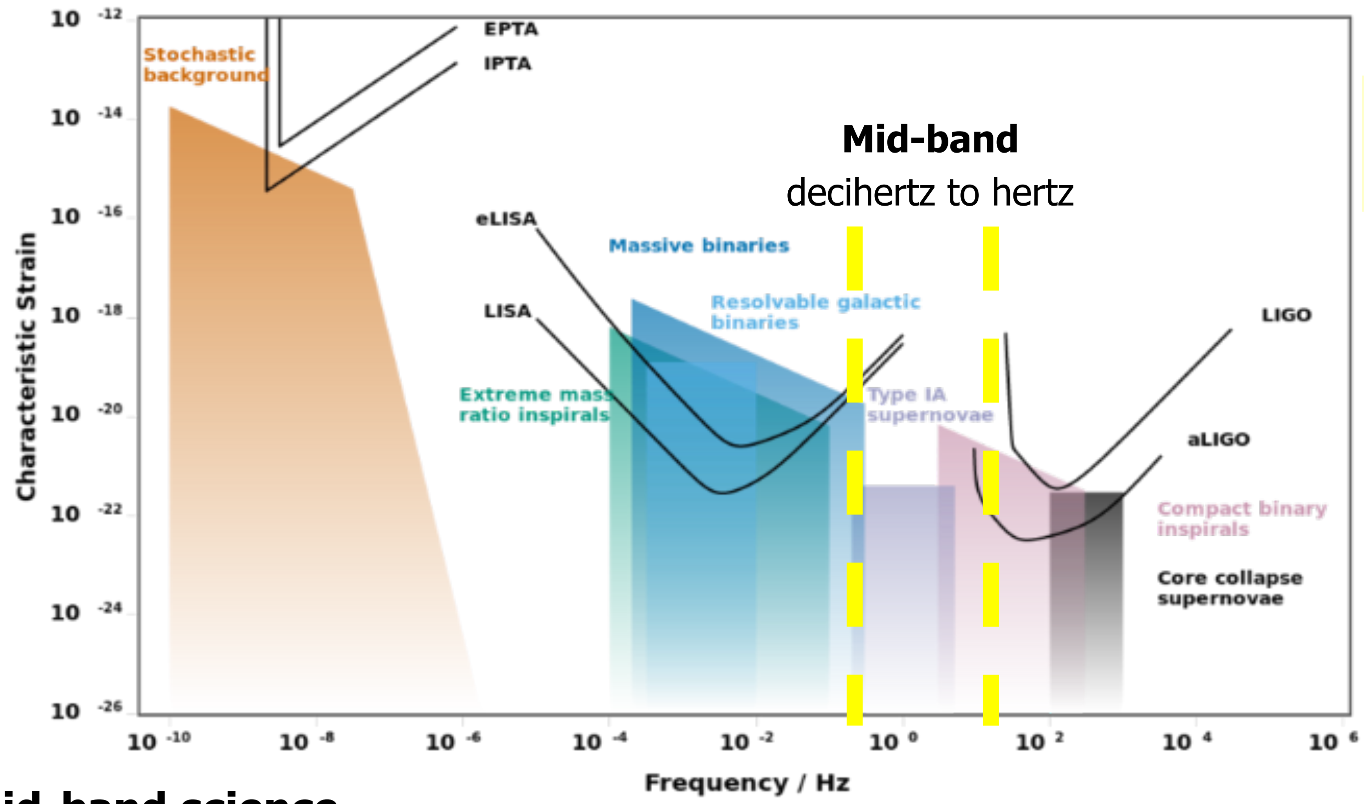
AION: Pathway to the GW Mid-(Frequency) Band

Experimental GW Landscape



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

Experimental GW Landscape

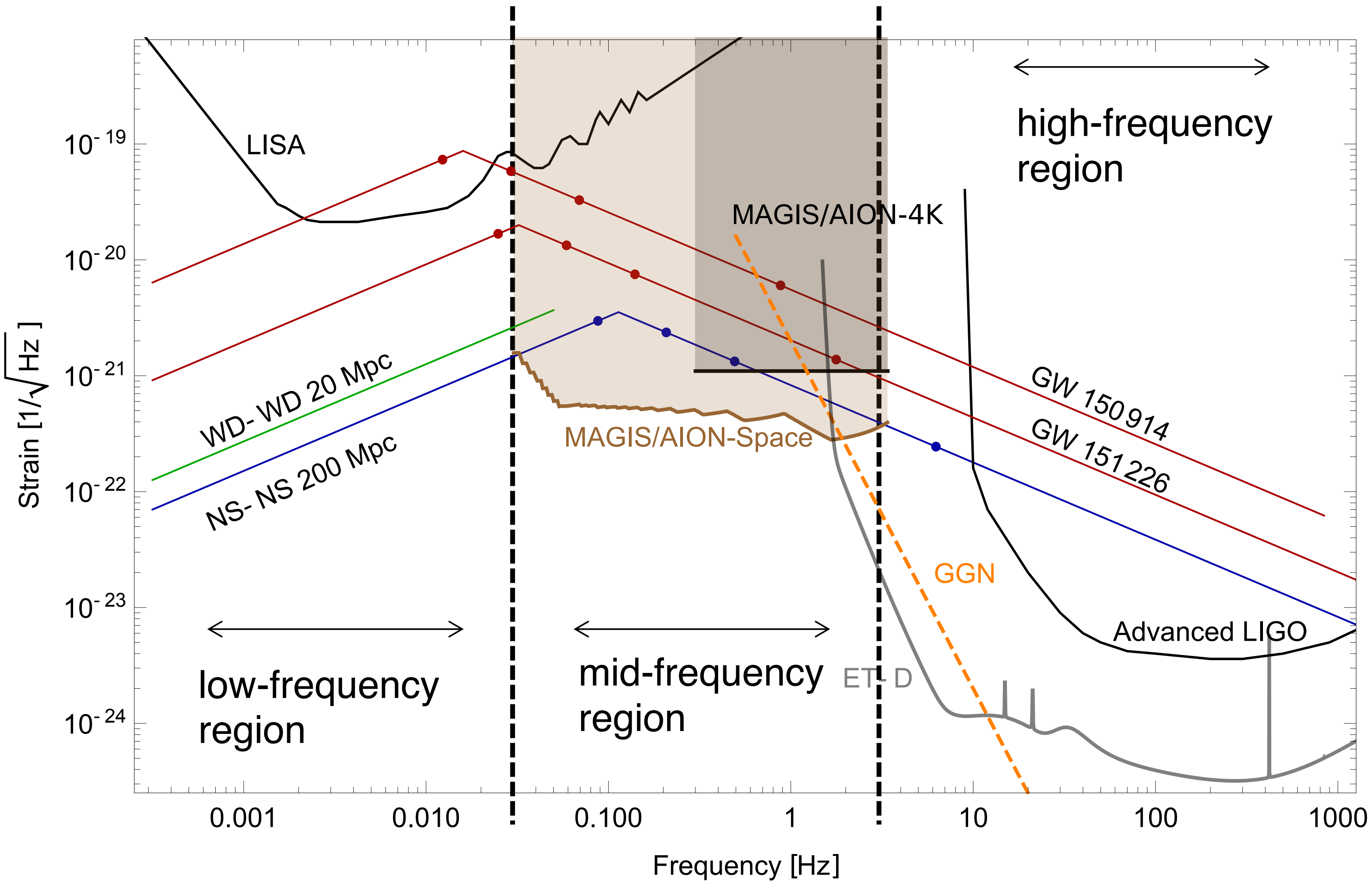


Mid-Band currently NOT covered

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

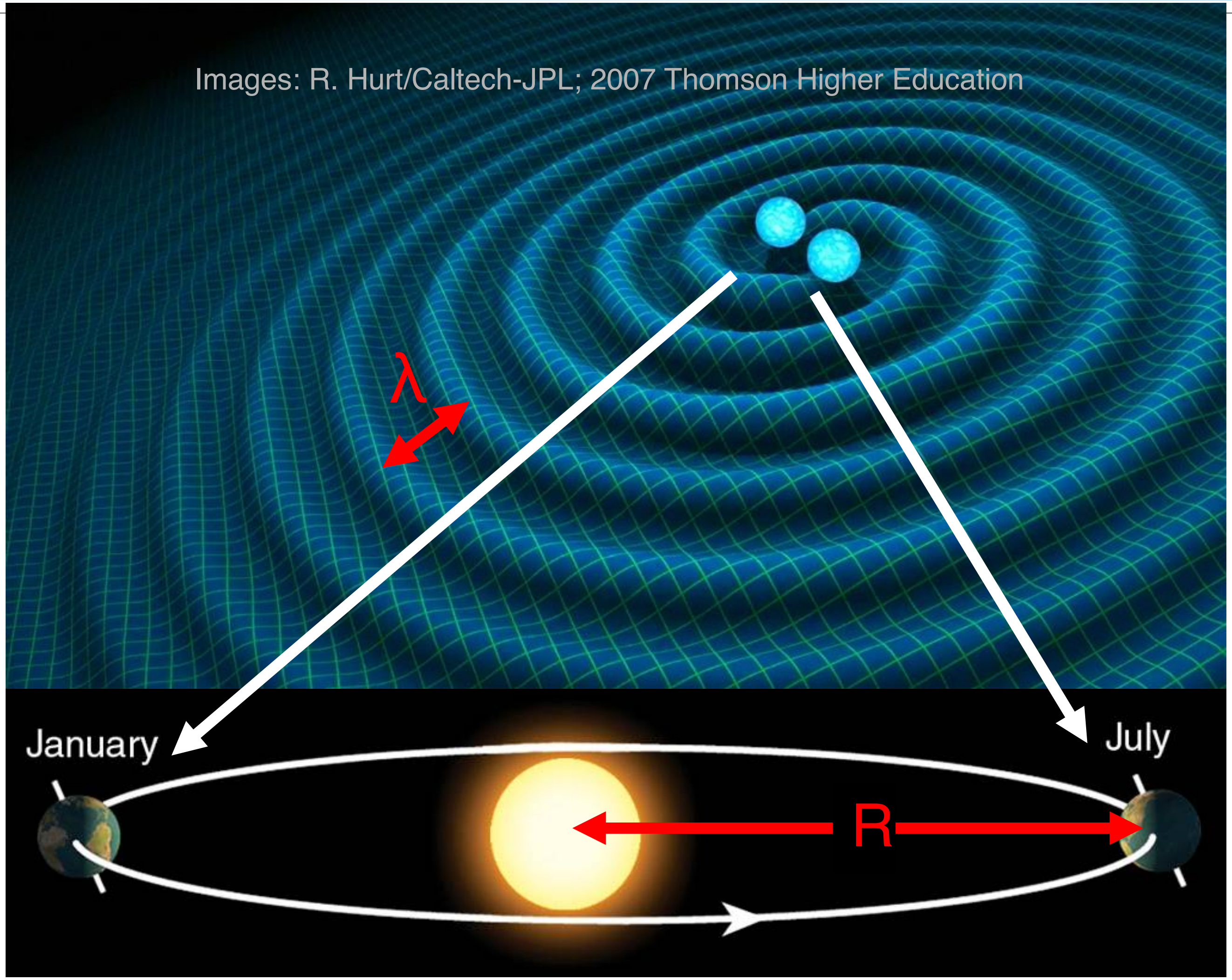
Sky localization precision:

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

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

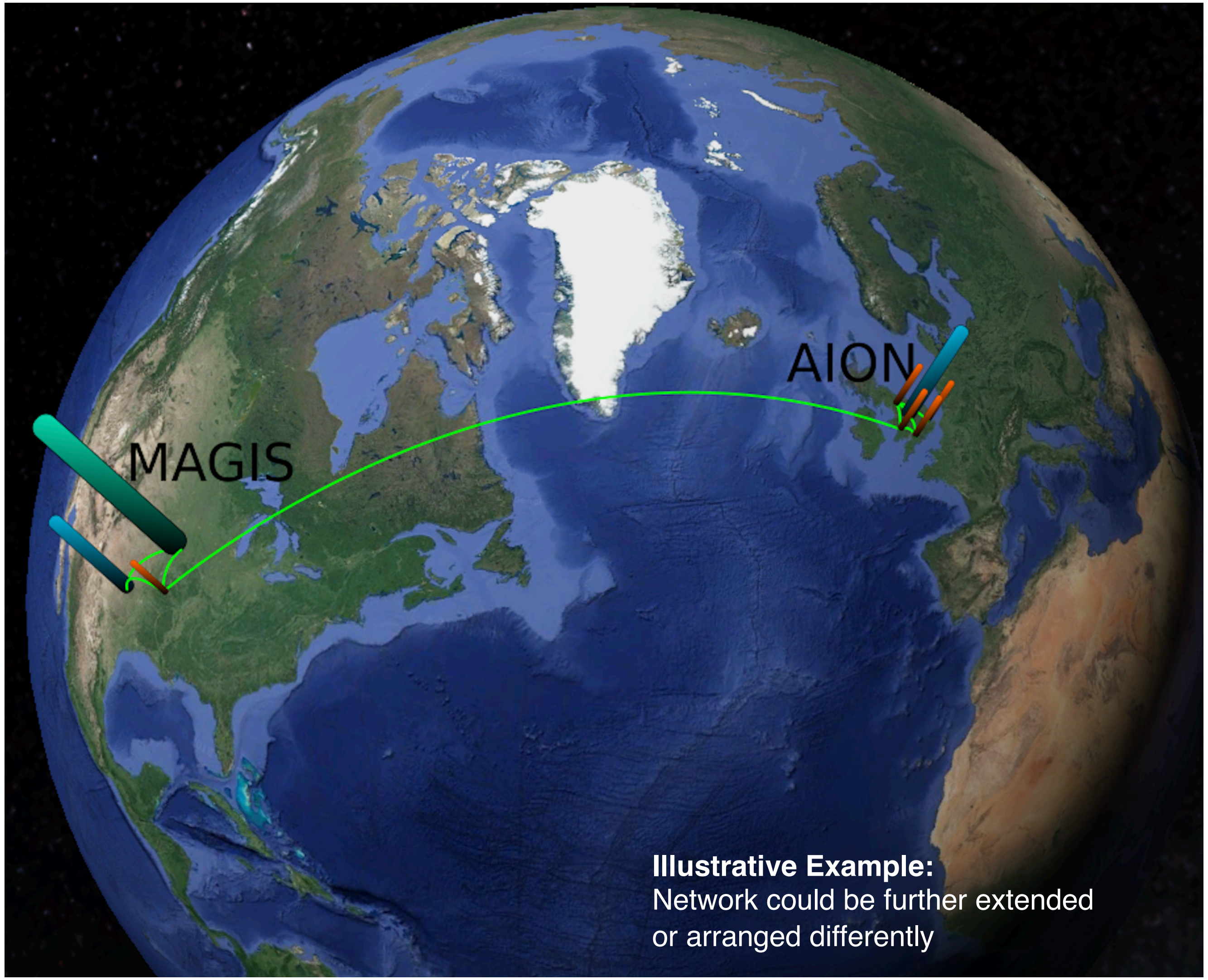
Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19

Courtesy of Jason Hogan!



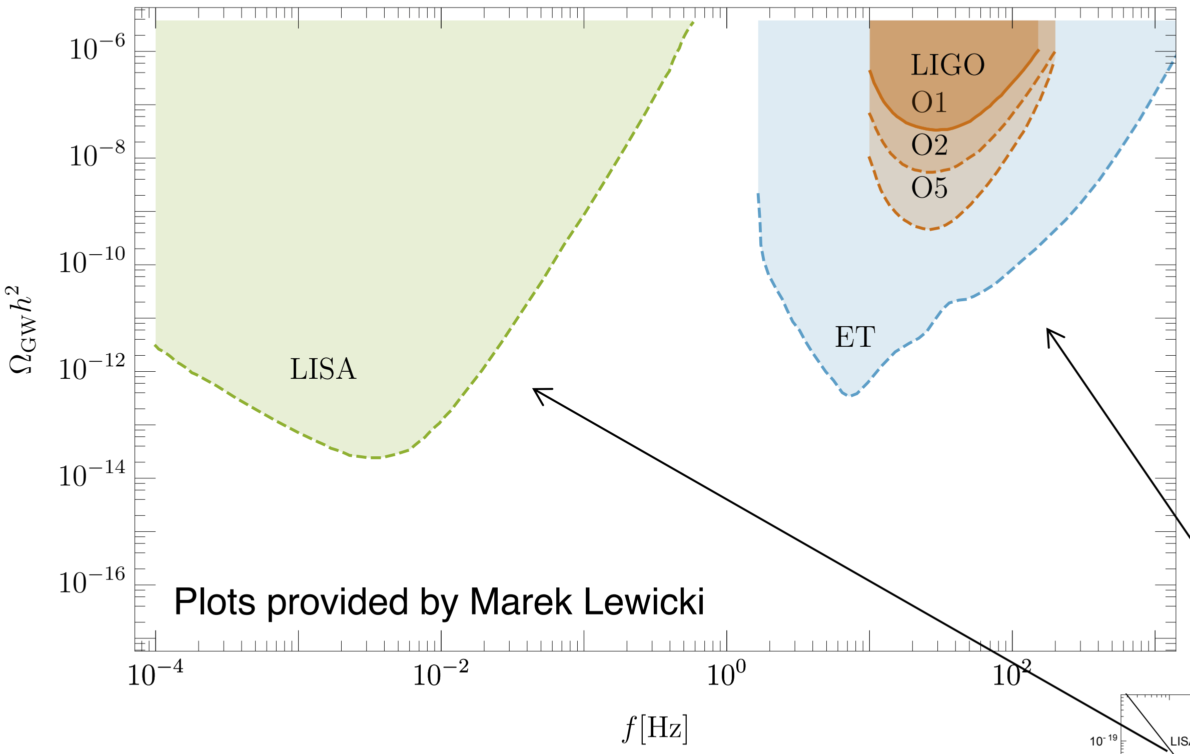
Ultimate sensitivity for terrestrial based detectors is achieved by operating 2 (or more) Detectors in synchronisation mode

Ultimate Goal: Establish International Network



GW Detection & Fundamental Physics - Example

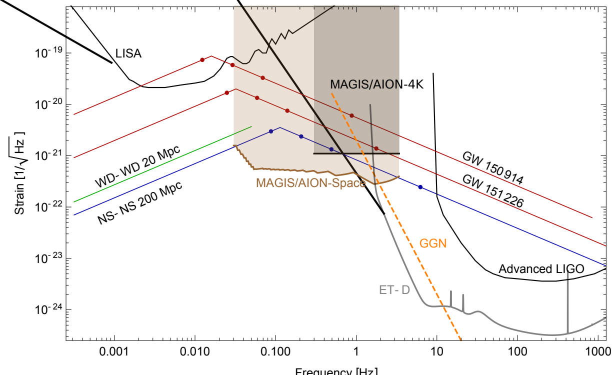
First-Order Electroweak Phase Transition and its Gravitational Wave Signal



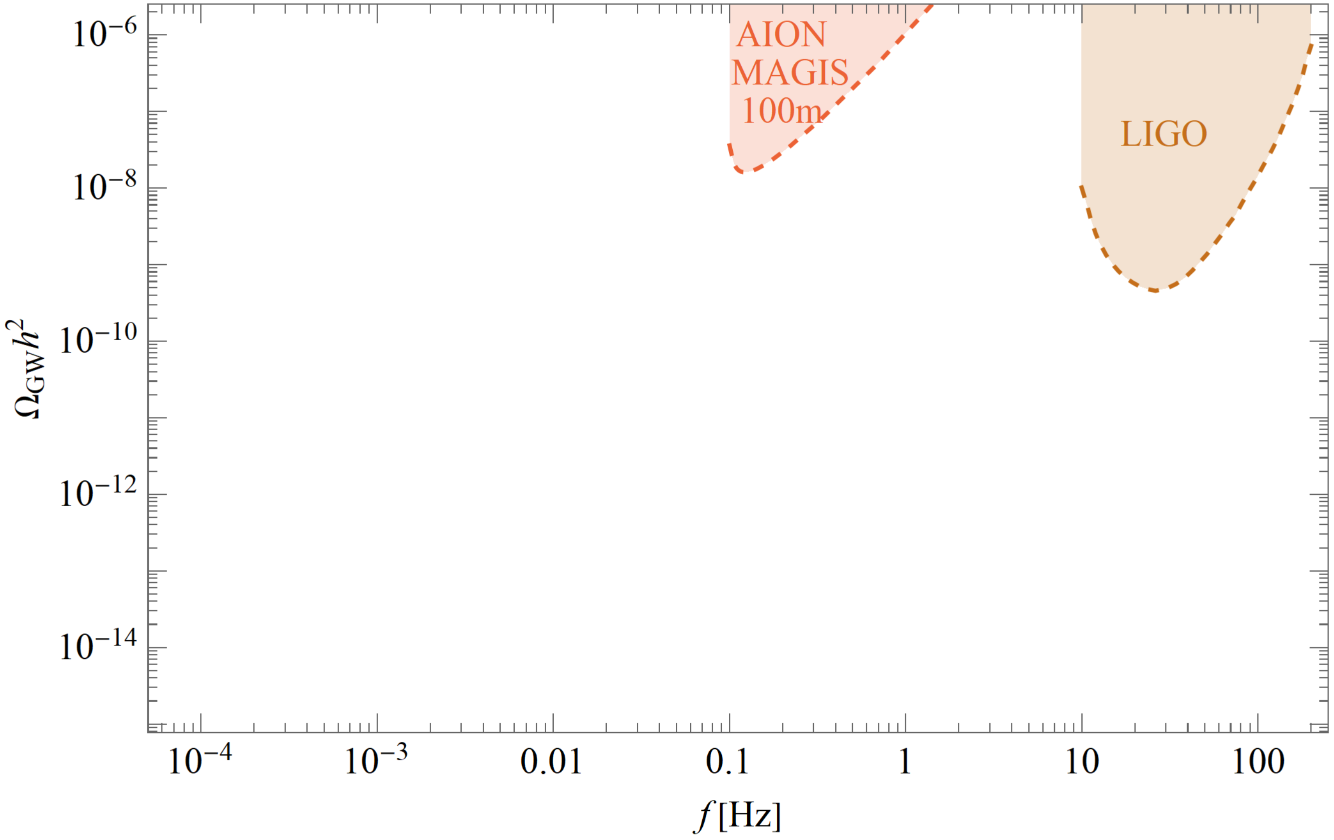
arXiv:1809.08242
John Ellis, Marek Lewicki, José Miguel No

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

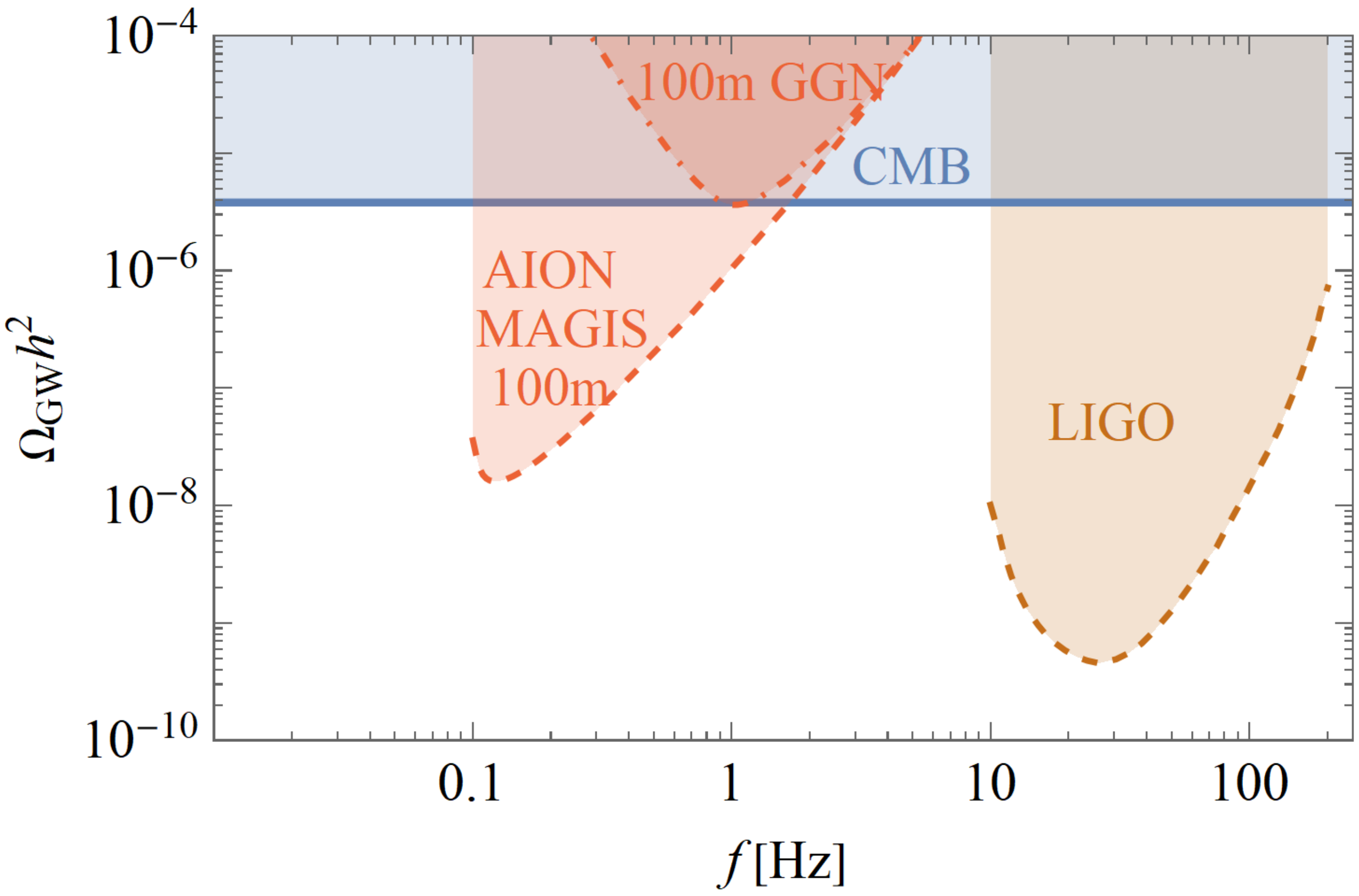
Translate strain into dimensionless energy density $\Omega_{GW}h^2$ in GWs against frequency



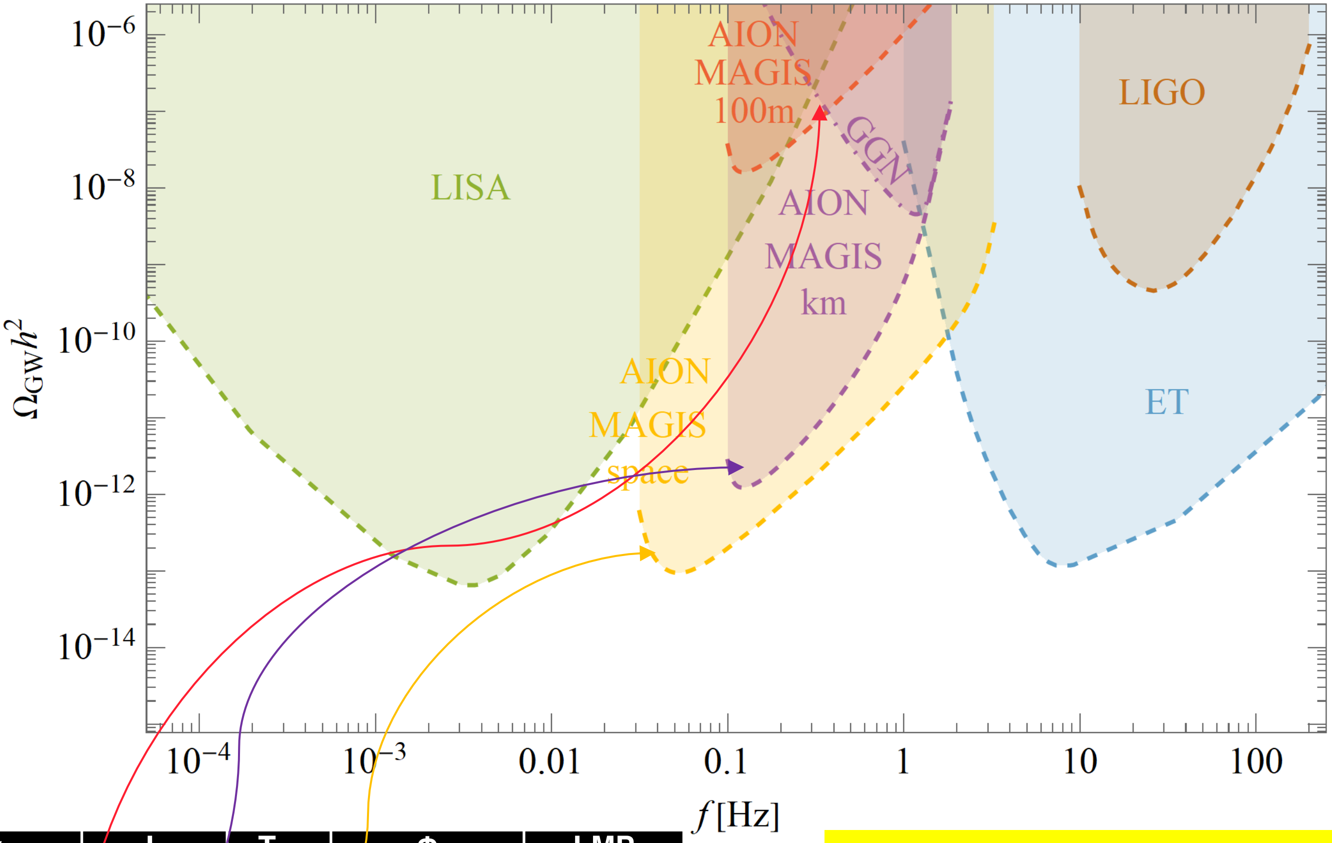
The GW Experimental Landscape: 2030ish



The GW Experimental Landscape: 2030ish



The GW Experimental Landscape: 2030ish



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

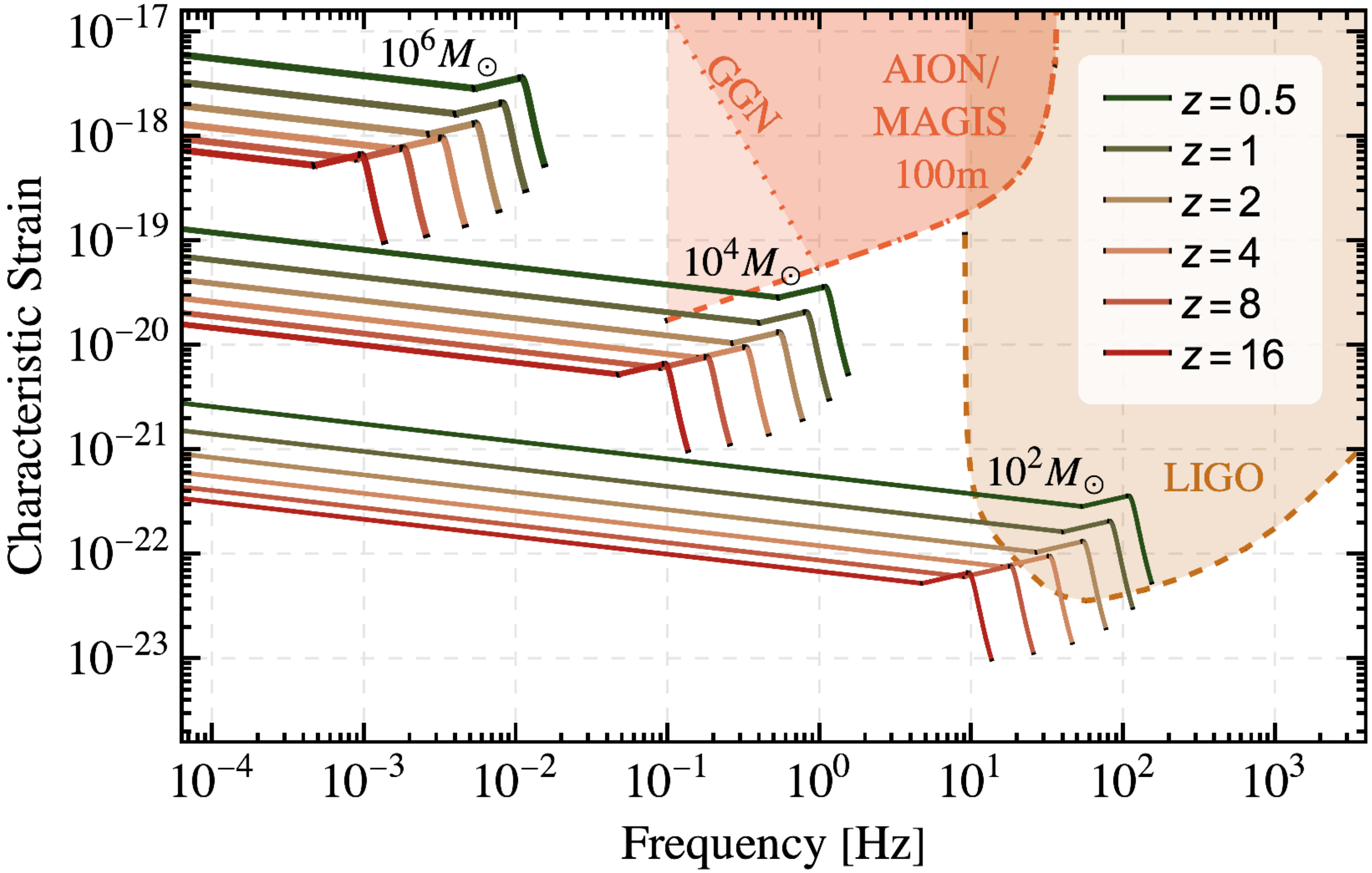
List of basic parameters: Lengths of the detector L, interrogation time of the atom interferometer T_{int} , phase noise ϕ, and number of momentum transfers LMP. The choice of these parameters predominately defines the sensitivity of the projection scenarios.

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.

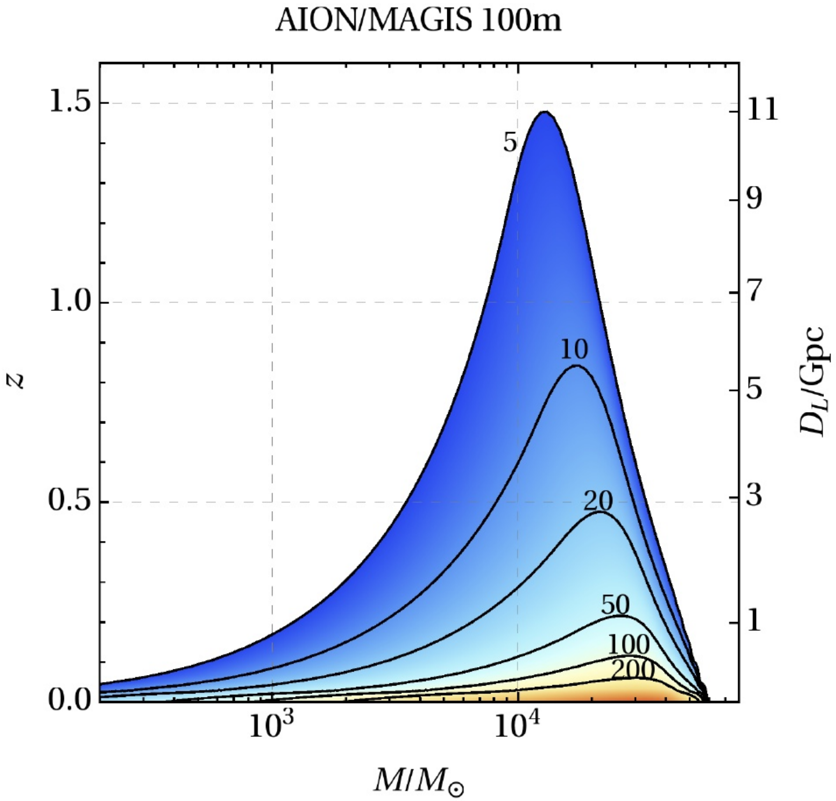
- **Cosmological Sources**
  - Many extensions of the Standard Model (SM) predict first-order phase transitions in the early Universe. Examples include extended electroweak sectors, effective field theories with higher-dimensional operators and hidden sector interactions.
    - Extended electroweak model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

Strain Sensitivity & BH Mergers: 2030ish

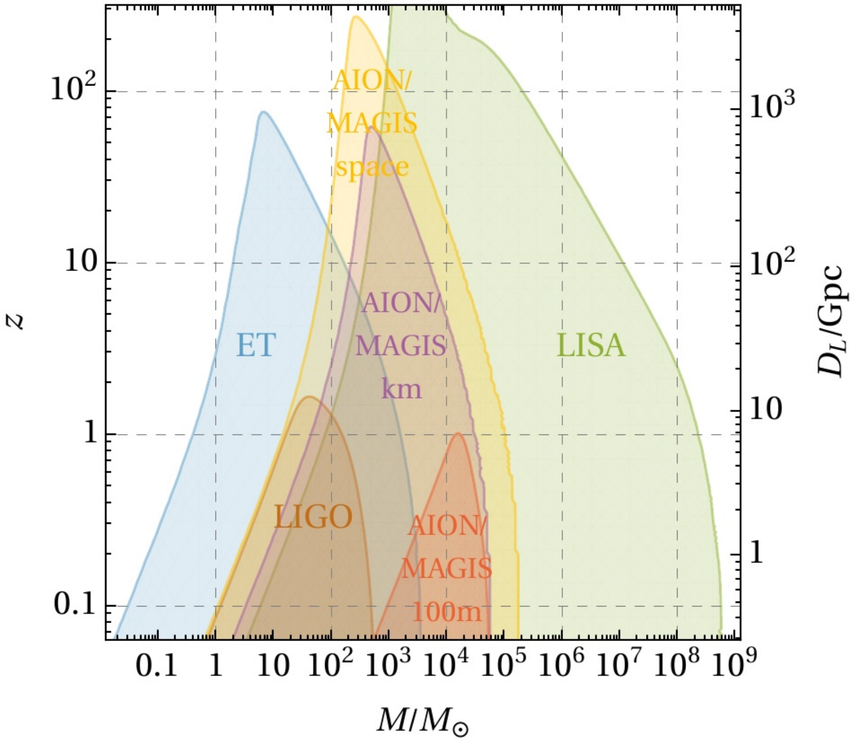


The AION frequency range is ideal for observations of mergers involving IMBHs, to which LISA and the LIGO/Virgo/KAGRA/ET experiments are relatively insensitive.

Strain Sensitivity & BH Mergers

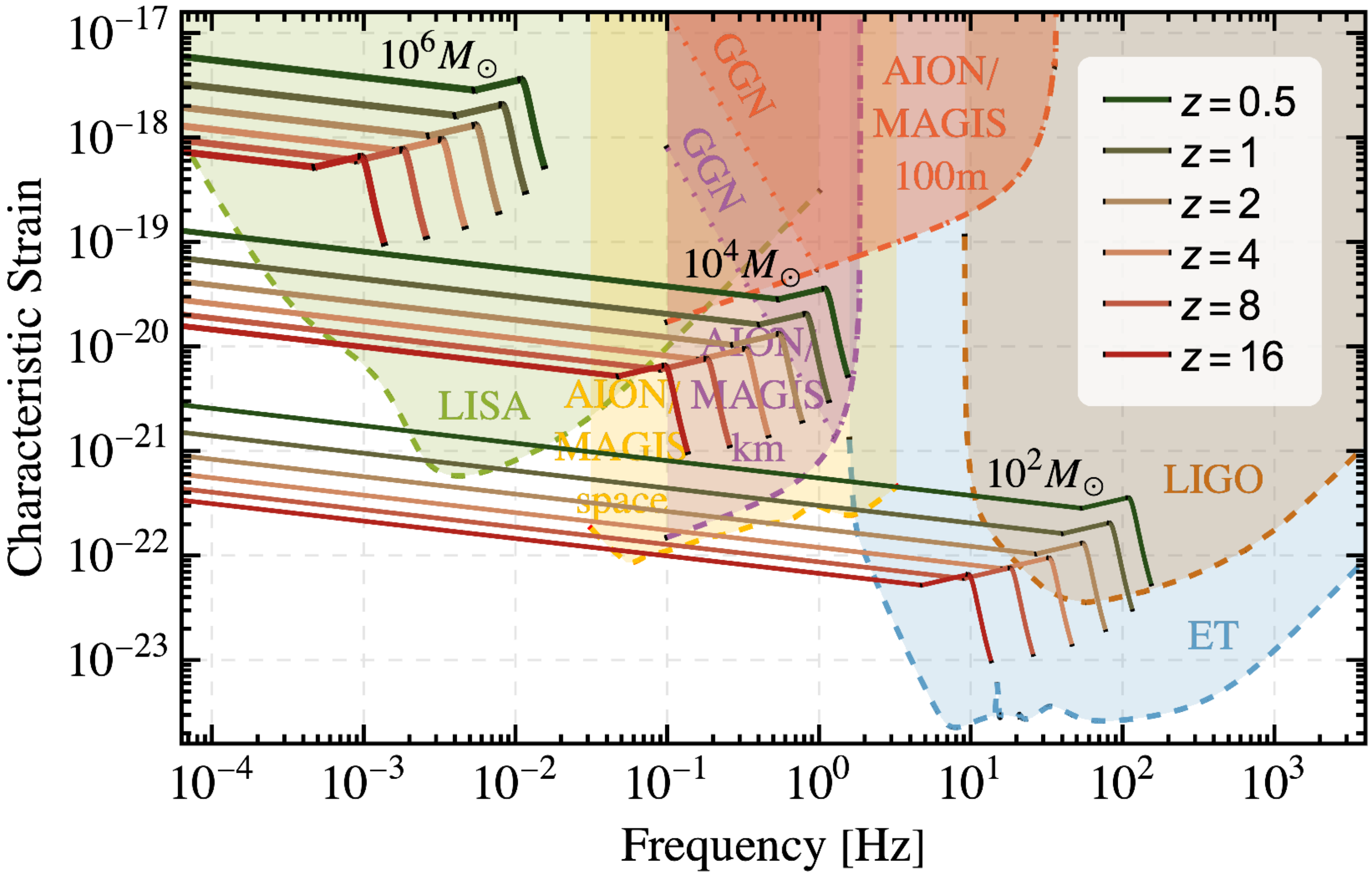


Sensitivity of AION-100m for detecting GWs from the mergers of IMBHs at signal-to-noise (SNR) levels ≥ 5, which extends to redshifts of 1.5 for BHs with masses ~ 10^4 solar masses.



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

Strain Sensitivity & BH Mergers: Future

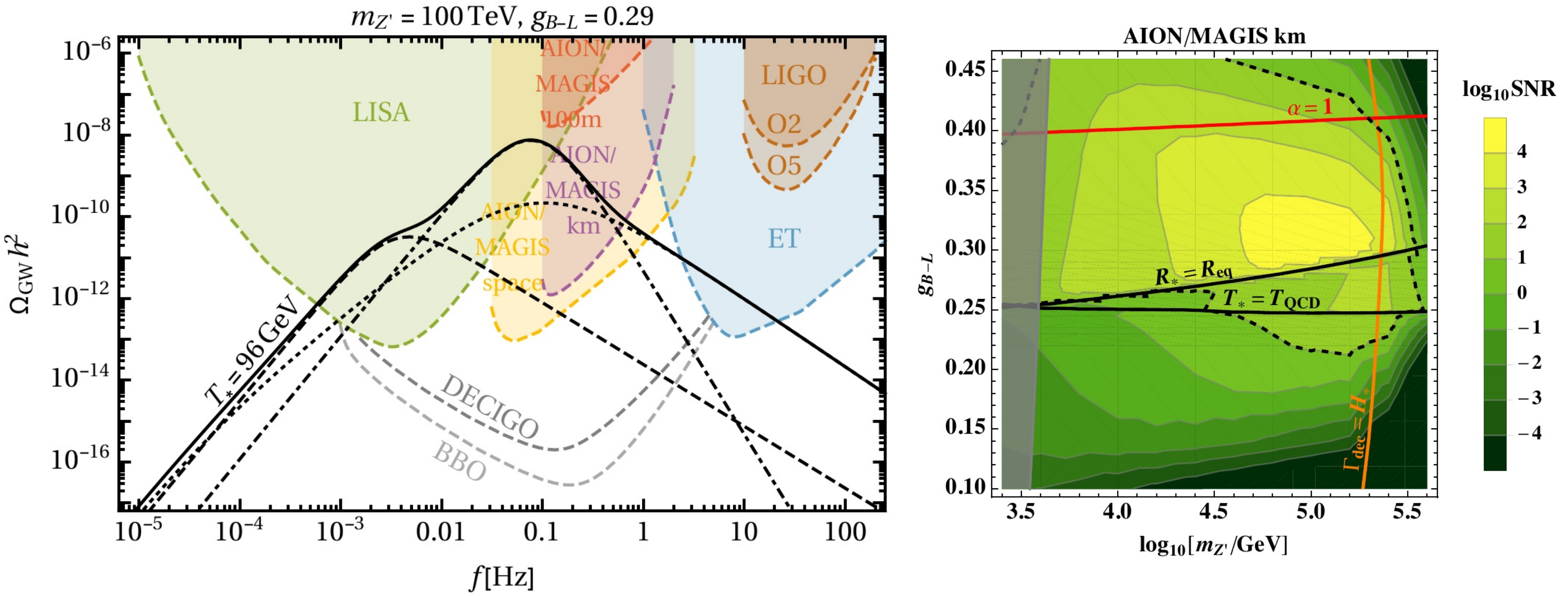


The AION frequency range is ideal for observations of mergers involving IMBHs, to which LISA and the LIGO/Virgo/KAGRA/ET experiments are relatively insensitive.

Cosmological GW Sources: Z' Model

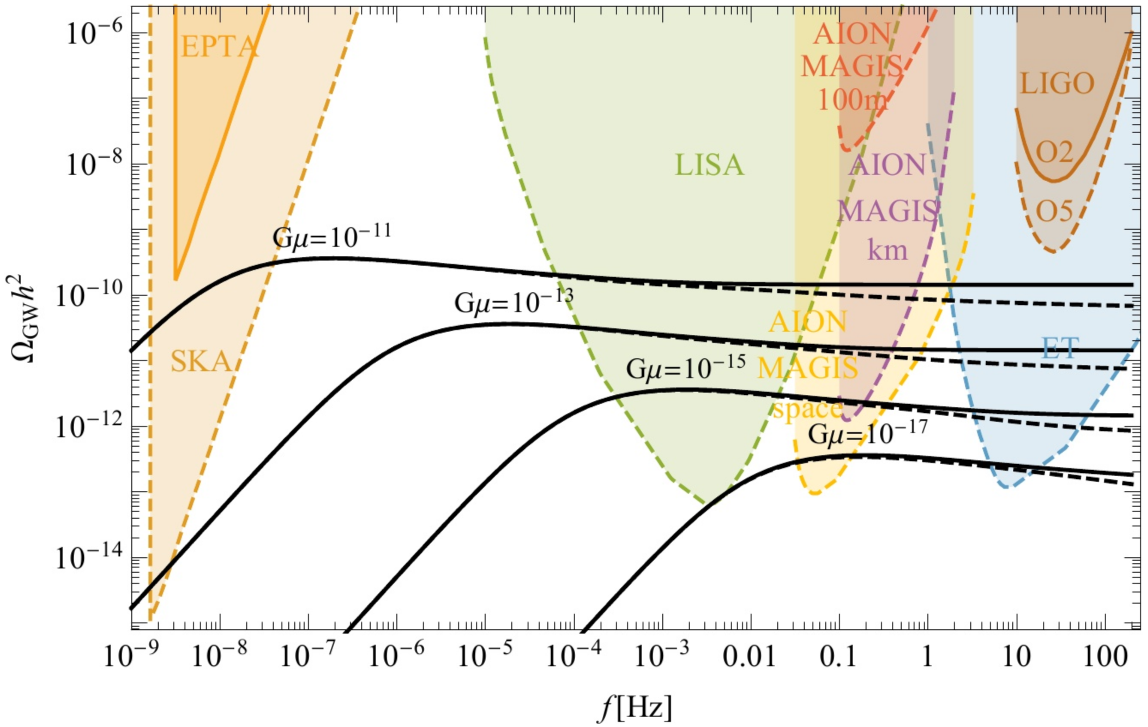
Many extensions of the Standard Model (SM) predict first-order phase transitions in the early Universe.

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:

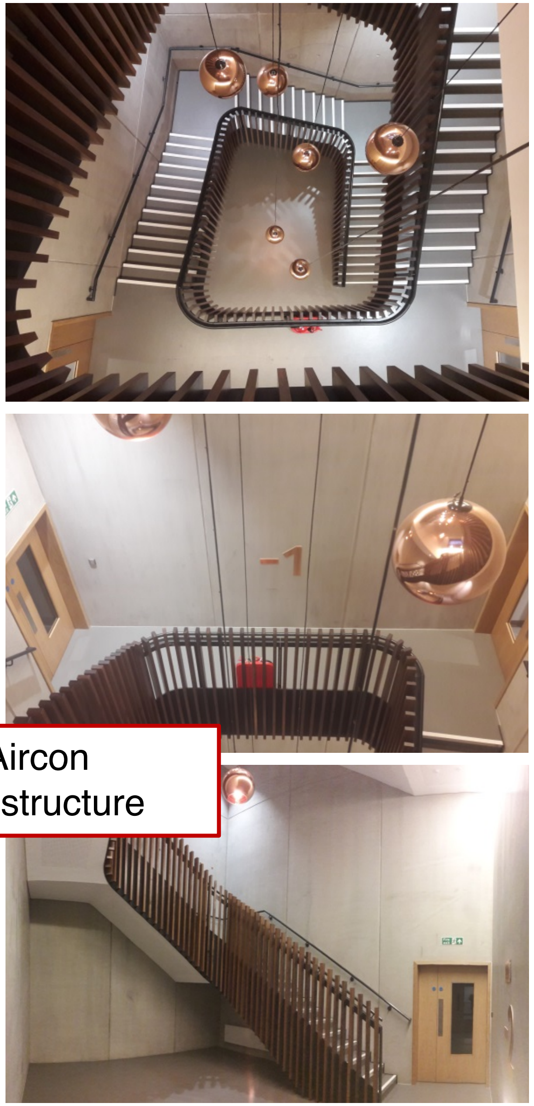
- *The possibility of detecting the astrophysical neutrinos*
- *Probes of long-range fifth forces*.
- *Constraining possible variations in fundamental constants.*
- *Probing dark energy*.
- Probes of basic physical principles such as foundations of quantum mechanics and Lorentz invariance.

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

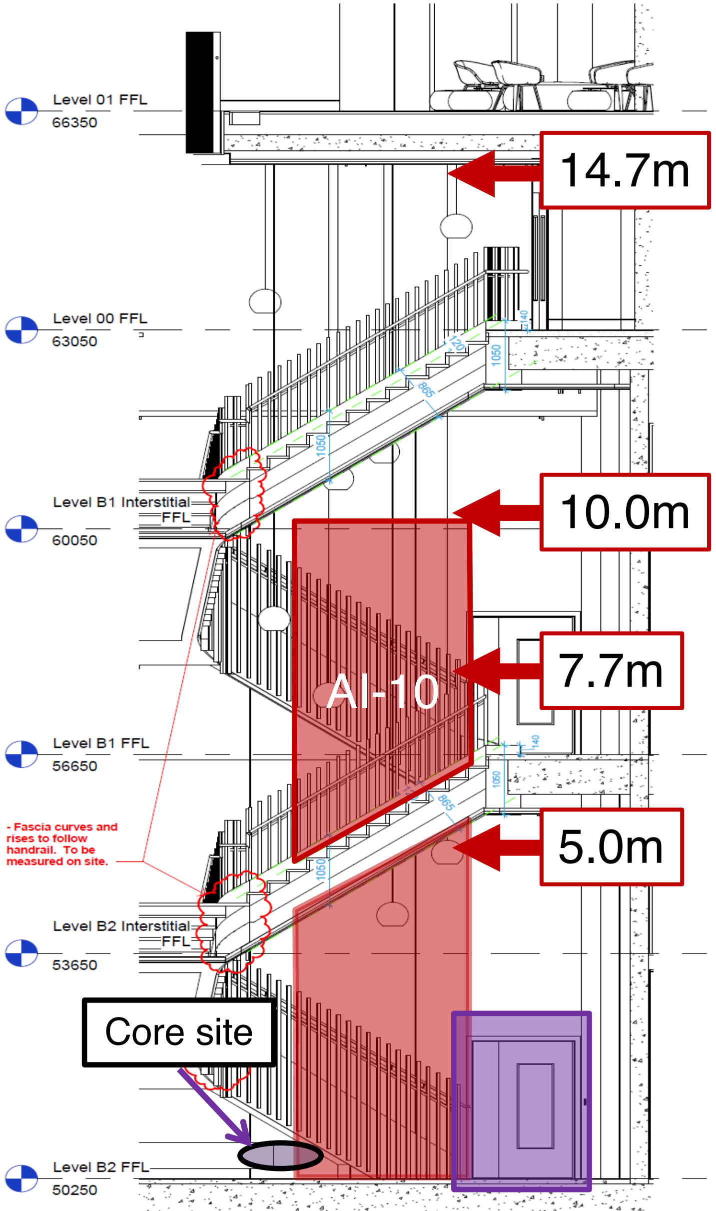
Adjacent laser lab reserved for AION use
- keel slabs
- $\pm 0.1^{\circ}$C stability
- Isolated mains

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

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

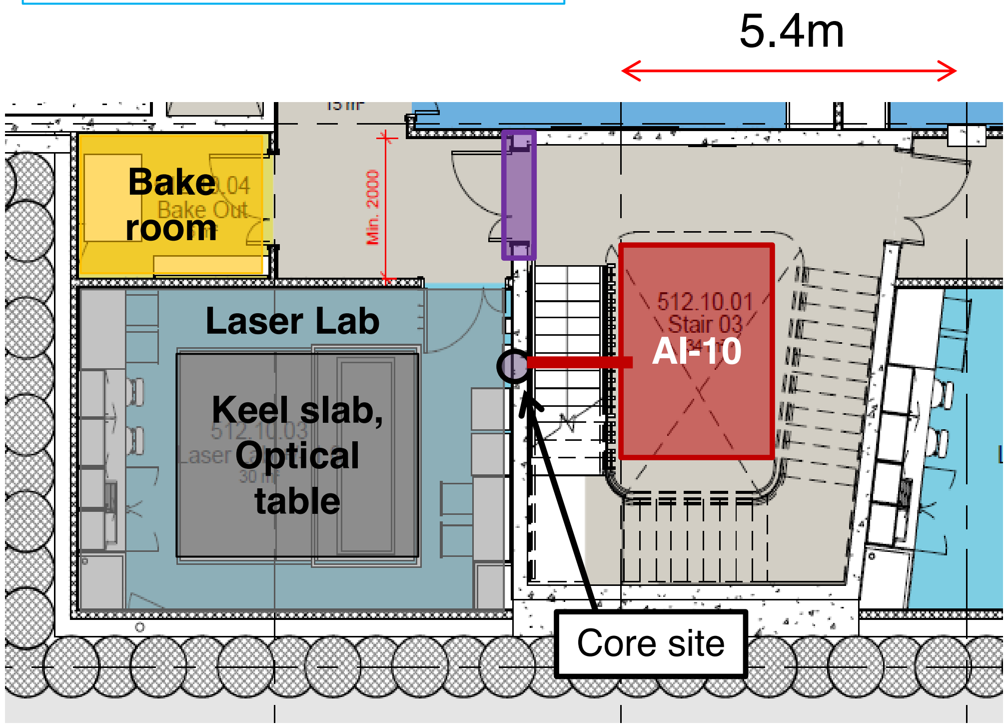
Bakeout room and cleanroom nearby

Beecroft building, Oxford Physics



← Side view

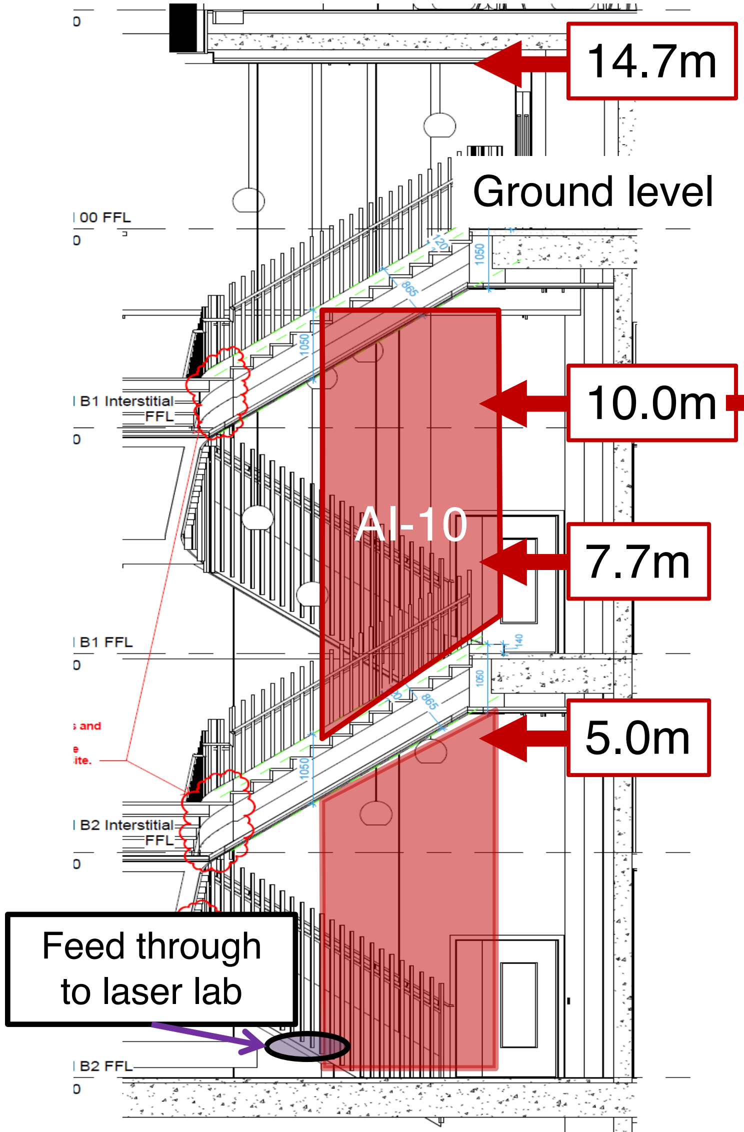
↓ Plan view



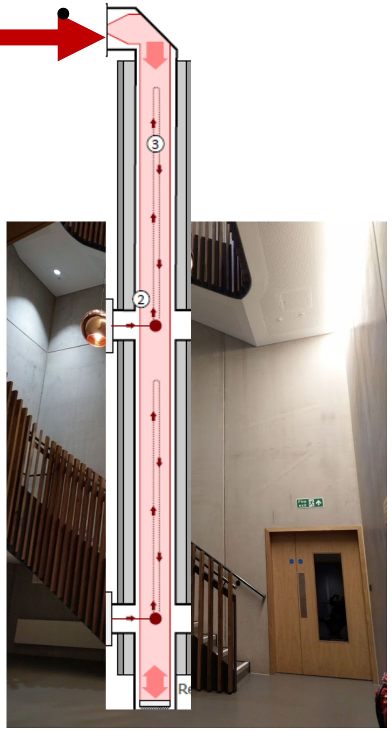
Imperial College London

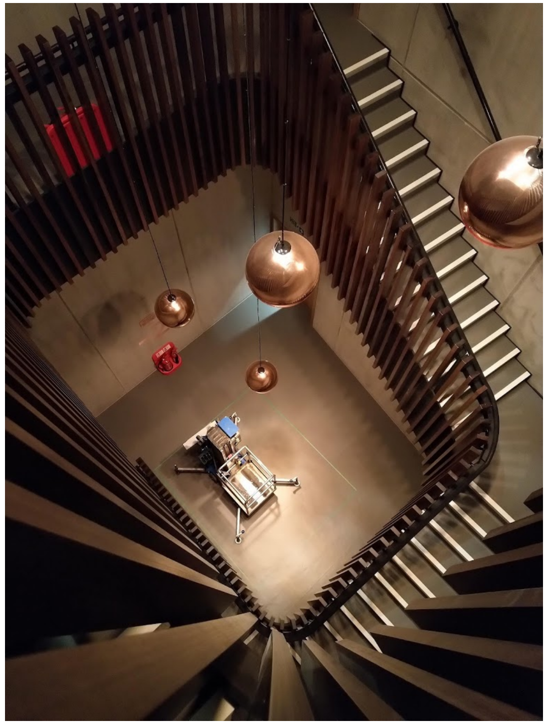
AION-10 site: Beecroft building, Oxford Physics

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



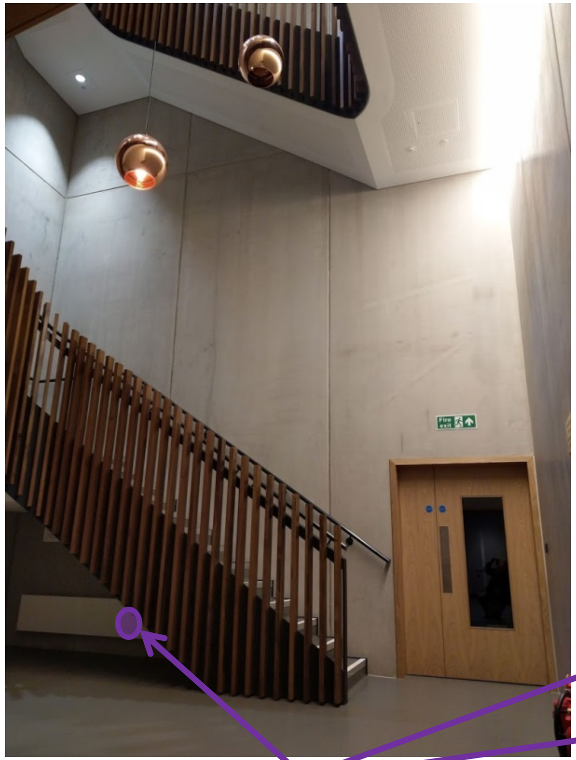
- Detailed planning of support structure by RAL (Engineering), Oxford Physics Technical Services and Liverpool Univ.
- Experienced Project Manager: Roy Preece
- Good site for long-term operation and wide accessibility (also 'visibility' and outreach).

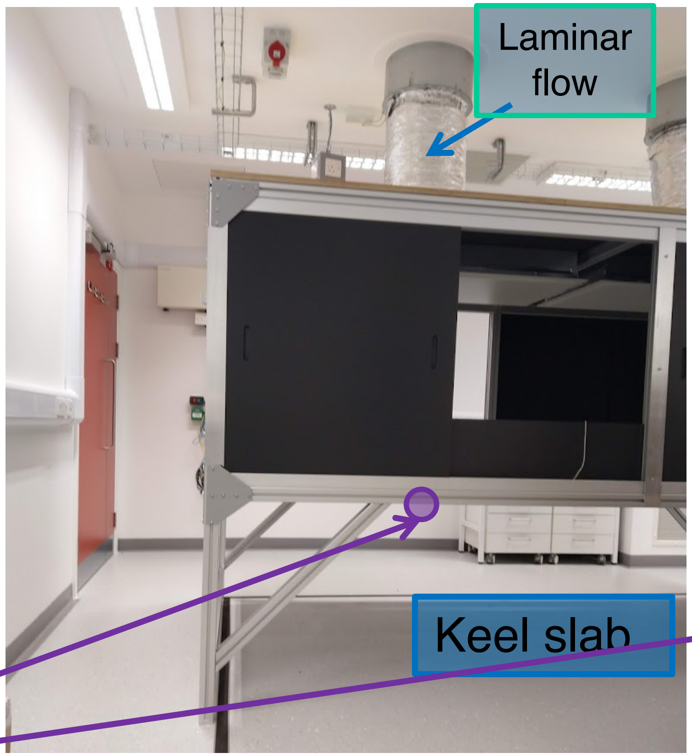


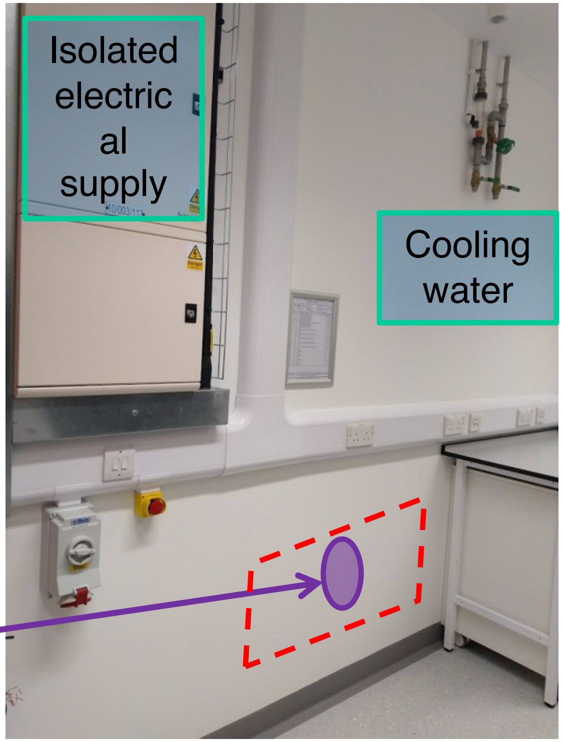


Beecroft building laser lab

Beecroft stairwell: lowest level







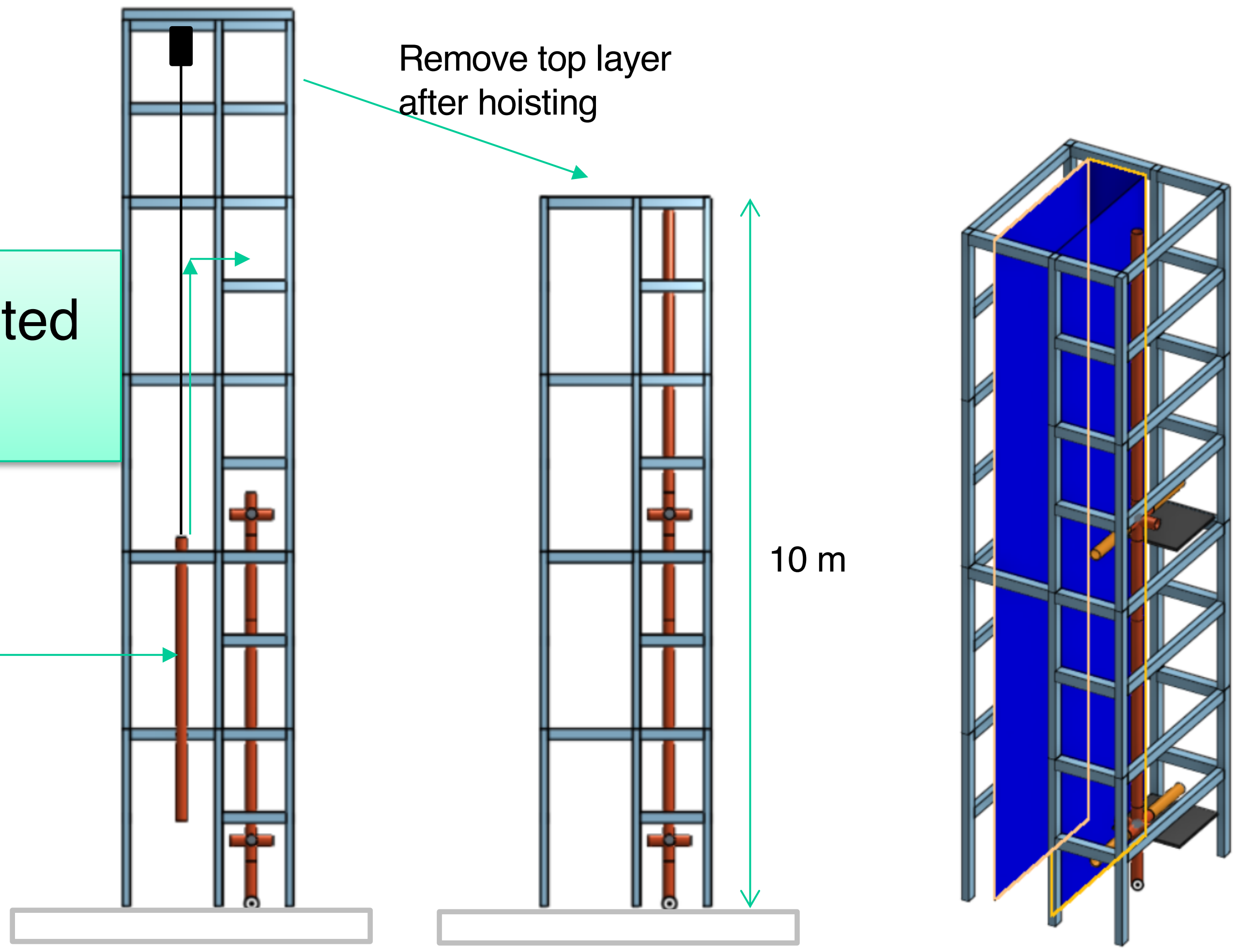
Core site: feed through fibre and cables

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

Bake-out room next door

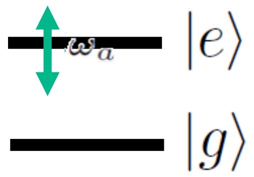
Assembly: extruded aluminium support structure

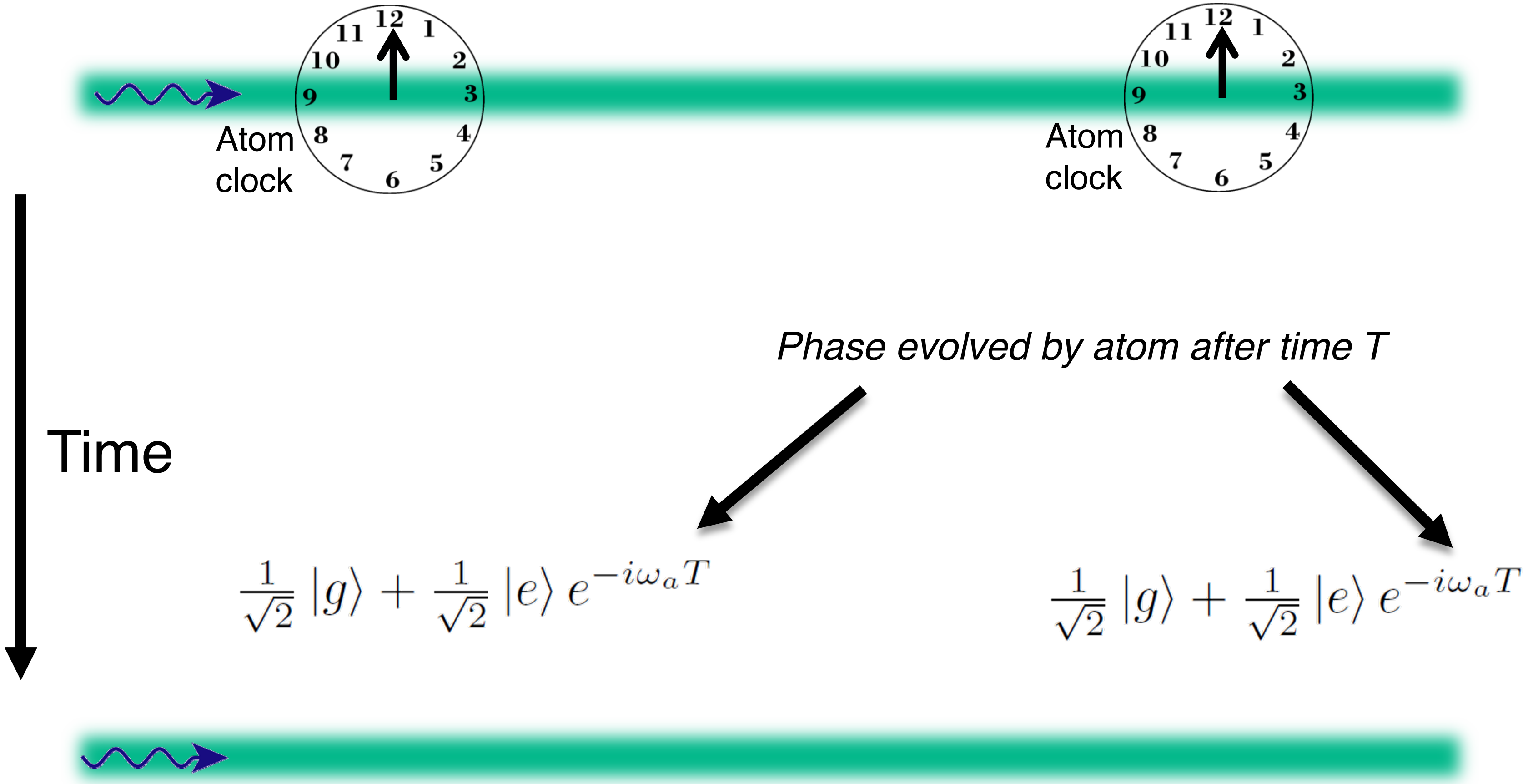
Scaffolding erected from ground up.



ATOM INTERFEROMETER CONCEPT

Simple Example: Two Atomic Clocks





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

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

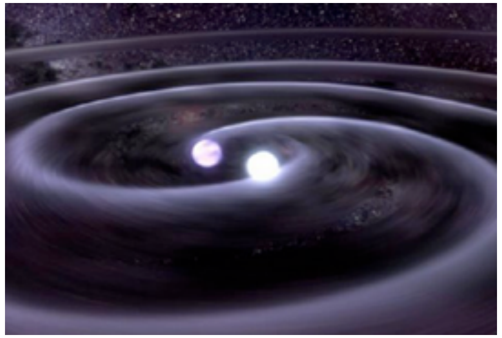
Simple Example: Two Atomic Clocks

$|e\rangle$ ω_a

$|g\rangle$

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

Time



GW changes light travel time

$\Delta T \sim hL/c$

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

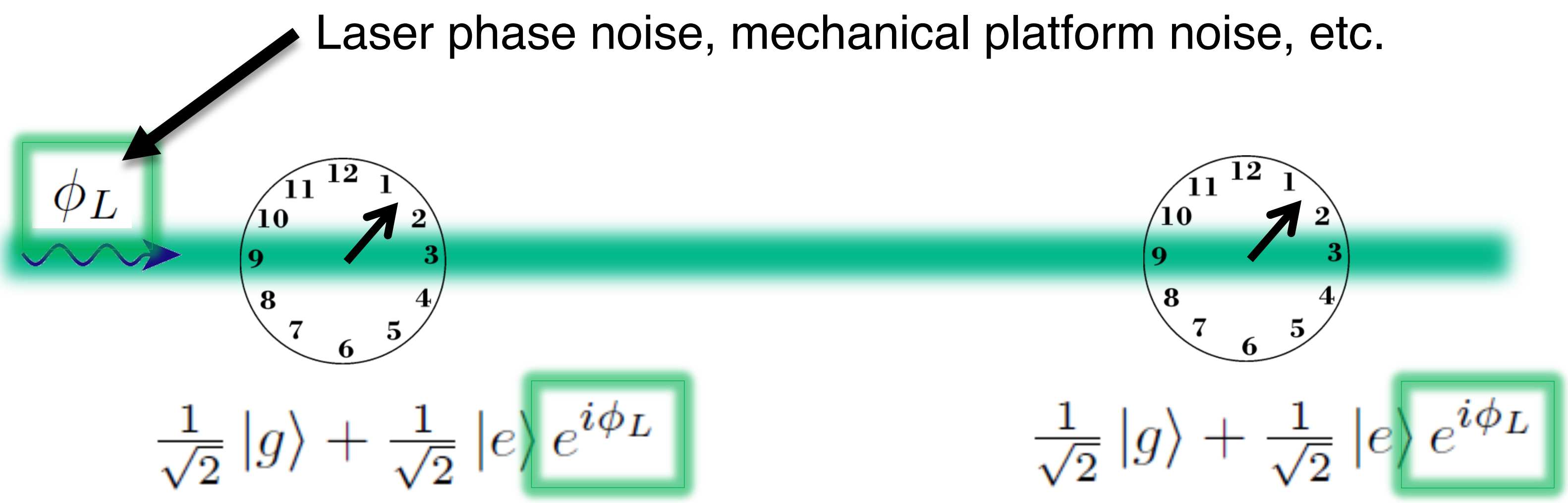
$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a (T+\Delta T)}$

Atom clock

Atom clock

Phase Noise from the Laser

The phase of the laser is imprinted onto the atom.



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