A ATOM INTERFEROMETER OBSERVATORY AND NETWORK (AION)

FOR THE EXPLORATION OF ULTRA-LIGHT DARK MATTER AND MID-FREQUENCY GRAVITATIONAL WAVES.

WORKSHOP ON ATOMIC EXPERIMENTS FOR DARK MATTER AND GRAVITY EXPLORATION

CERN, JULY 22/23, 2019

Oliver Buchmueller, Imperial College London

WHAT IS AION

What is AION (in a nutshell)?

- The proposal is to construct and operate a next generation Atomic Interferometric Observatory and Network (AION) in the UK (and world wide) that will enable the exploration of properties of dark matter as well as searches for new fundamental interactions.
- It will provide a pathway for detecting gravitational waves from the very early universe in the, as yet mostly unexplored, mid-frequency band, ranging from several milliHertz to a few Hertz.
- The proposed project spans several science areas ranging fundamental particle physics over astrophysics to cosmology and, thus, connects these communities.
- Following the “Big Ideas” call, the project was selected by PAAP and STFC as a high priority for the community. It was provisionally classified as a medium scale project.
- AION is also a Work Package of the QSFP proposal

Proposed AION Programme

The AION Project is foreseen as a 4-stage programme:

- **The first stage** develops existing technology (Laser systems, vacuum, magnetic shielding etc.) and the infrastructure for the 100m detector and produces detailed plan resulting in an accurate assessment of the expected performance in Stage 2.

- **The second stage** builds, commissions and exploits the 100m detector and also prepares design studies for the km-scale.

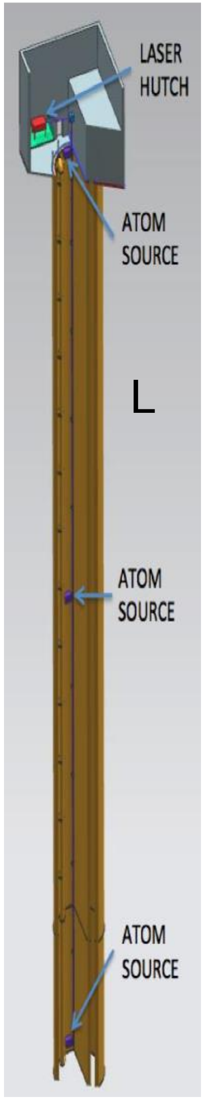
- **The third and fourth stage** prepare the groundwork for the continuing programme:
  - Stage 3: Terrestrial km-scale detector
  - Stage 4: space based detector

L ~ 1m to 10m

L ~ 100m

L ~ km-scale

L ~ 10^4 km



AION – A Staged Programme**

AION-10: Stage 1 [year 1 to 3]

- 1 & 10 m Interferometers & Site Development for 100m Baseline

AION-100: Stage 2 [year 3 to 6]

- 100m Construction & Commissioning

AION-KM: Stage 3 [> year 6]

- Operating AION-100 and planning for 1 km & Beyond

AION-SPACE: Stage 4 [after AION-KM]

- Space based version

**outlined in Big Ideas proposal

AION – A Staged Programme**

AION-10: Stage 1 [year 1 to 3]

- 1 & 10 m Interferometers & Site Development for 100m Baseline

AION-100: Stage 2 [year 3 to 6]

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AION-KM: Stage 3 [> year 6]

- Operating AION-100 and planning for 1 km & Beyond

AION-SPACE: Stage 4 [after AION-KM]

- Space based version

**outlined in Big Ideas proposal

AION Project: Core Team

Birmingham
Kai Bongs*
M. Holynski*
Y. Singh*

Cambridge
V. Gibson**
U. Schneider*

Imperial College London
O. Buchmueller** [co-coord.]
M. Tarbutt*
B. Sauer*

Kings College London
J. Ellis**
C. McCabe**

Liverpool
T. Bowcock**
J. Coleman** [co-coord.]

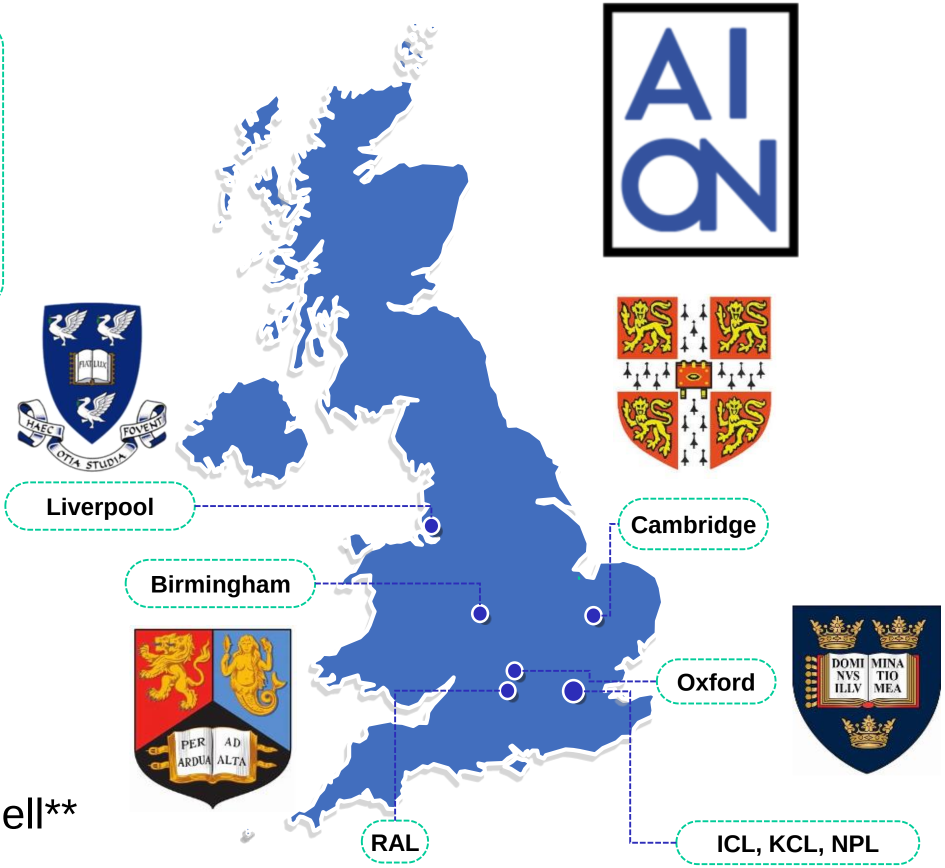
National Physical Lab.
W. Bowden***
P. Gill***
R. Hobson***

UK

- 8 Institutes
- 22 Core Members
- Many Associates

Oxford
E. Bentine*
C. Foot*
J. March-Russell**
I. Shipsey**

Rutherford Appleton Lab.
P. Majewski**
T. Valenzuela**
I. Willmut**



Main UK funding source:
**EPSRC; **STFC, ***NMS*

Freise	GW/ Instrumentation	**Saakyan**	Neutrinos/Dark Matter/Instrumentation
Guarrera	Ultracold/Atom Interferometry	**Waters**	Neutrinos/Dark Matter/Instrumentation
Holynsky	Atom Interferometry/Technology Transfer	***Liverpool***	
Lien	Atom Interferometry	**Coleman**	Atom Interferometry
Newman	QCD/ DIS / Forward Instrumentation	**Bowcock**	EDMs/instrumentation/Quantum Foam
Nikolopoulos	Light Dark Matter/Higgs	**Burdin**	Dark Matter
Singh	Atom clock/Technology Transfer	**Rompotis**	Muons/Relic neutrinos
Worm	Dark Matter	***Nottingham***	
Bristol		**Burrage%**	GW Theory
Brooke	Energy frontier/BSM/Instrumentation	**Sotiriou%**	GW Theory
Flaecher	Energy frontier/BSM/Dark Matter	***Oxford***	
Goldstein	Energy frontier/Instrumentation	**Kraus**	Dark Matter
Velthuis	Instrumentation/Technology Transfer	**March-Russel%**	BSM Theory
Brunel		**Randall%**	BSM Theory
Hobson	Energy Frontier/Instrumentation	**Shipsey**	Higgs/muons/darkenergy/ instrumentation
Smith	Spaceborne Instrumentation/Technology Transfer	***Rutherford Appleton Laboratory***	
Glasgow		**Valenzuela**	Head of Quantum Sensors Group, RAL Space
Bell	GW/ Instrumentation	**Vick**	Head of the Disruptive Space Technology Centre, RAL Space
Hammond	GW/ Instrumentation	**Waltham**	Chief Technologist, RAL Space
Imperial College		**Shepherd-Themistocleous**	Contact for Particle Physics at RAL
Araujo	Dark Matter/Instrumentation	***Sheffield***	
Buchmueller	Energy frontier/BSM/Dark Matter/GW	**Dolan%**	GW Theory
Hassard	Instrumentation/Technology Transfer	***Strathclyde***	
Hinds	EDM/Atom Interferometry/ultracold	**Arnold**	Ultra-cold atoms, BEC, matterwave interferometry, atomic clocks
Sauer	EDM/Atom Interferometry/ultracold	**Griffin**	Ultra-cold atoms, BEC, matterwave interferometry, atomic clocks, magnetometry
Sumner	GW/ Instrumentation	**Riis**	Ultra-cold atoms, BEC, matterwave interferometry, atomic clocks, magnetometry
Tarbutt	EDM/Atom Interferometry/ultracold	***Sussex***	
Kings College London		**Calmet%**	GW Theory
Acharya%	DM & GW Theory	**Dunningham%**	Theory of atom interferometry
Blas%	DM & GW Theory	**Hindmarsh%**	GW Theory
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Witek%	GW Theory	**Gill***	Cold atom & ion clocks/ ultrastable cavities & lasers/ precision timing/ atom interferometry
Millen	Quantum Optomechanics	**Margolis***	Cold atom & ion clocks/ frequency combs/ precision timing
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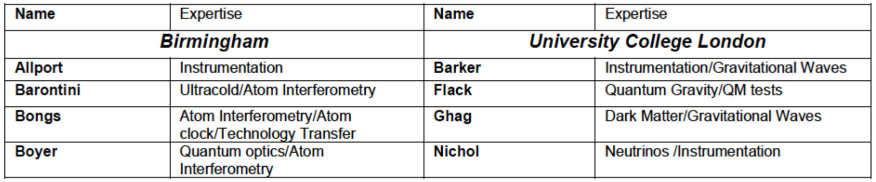
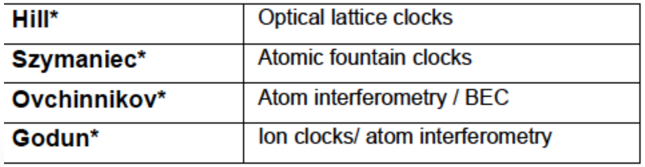


Name	Expertise	**Name**	Expertise
Birmingham		***University College London***	
Allport	Instrumentation	**Barker**	Instrumentation/Gravitational Waves
Barontini	Ultracold/Atom Interferometry	**Flack**	Quantum Gravity/QM tests
Bongs	Atom Interferometry/Atom clock/Technology Transfer	**Ghag**	Dark Matter/Gravitational Waves
Boyer	Quantum optics/Atom Interferometry	**Nichol**	Neutrinos /Instrumentation

Status “Big Ideas Call”

In preparation of this proposal we have broadly consulted with the relevant UK science communities and have received very positive feedback. The support is across several fields, ranging from fundamental particle physics, over atom interferometry to gravitational wave physics. The support also covers both experimental as well as theory communities in the UK. So far, more than 70 members from 20 UK institutions have provided explicit support for this proposal:

Aberdeen, Birmingham, Bristol, Brunel, Durham, Glasgow, Imperial College, Kings College London, University College London, Liverpool, Nottingham, Open University, Oxford, RAL, Sheffield, Strathclyde, Sussex, Swansea and NPL



Hill*	Optical lattice clocks
Szymaniec*	Atomic fountain clocks
Ovchinnikov*	Atom interferometry / BEC
Godun*	Ion clocks/ atom interferometry

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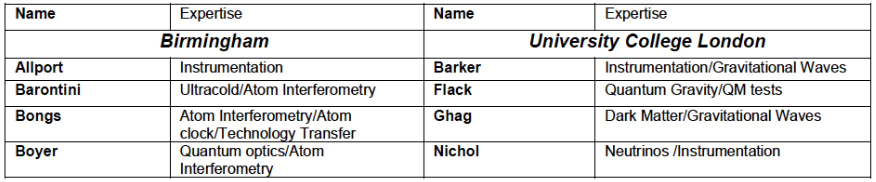

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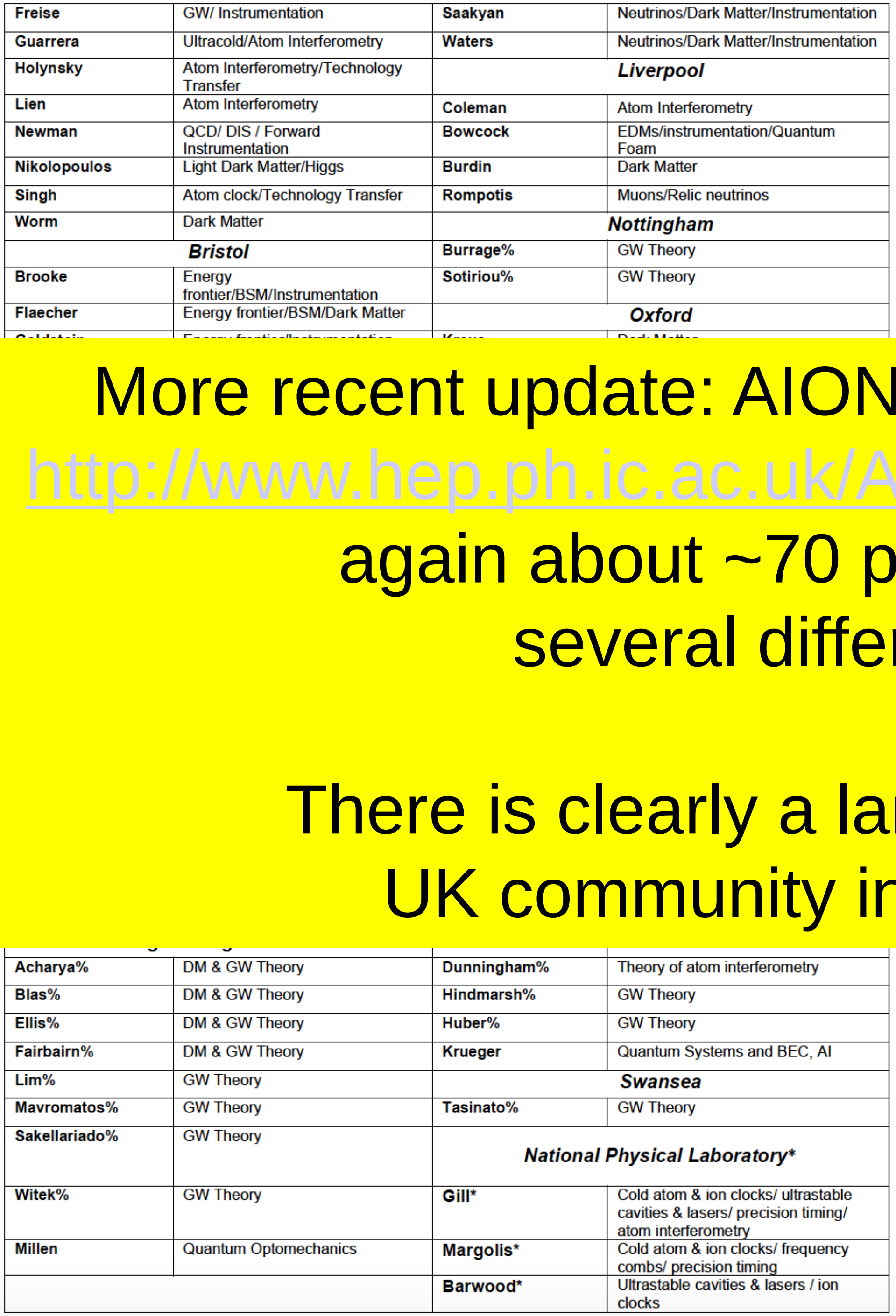
More recent update: AION Workshop March 2019:

http://www.hep.ph.ic.ac.uk/AION2019/participants.html

again about ~70 participants from several different areas!

There is clearly a large interest in the UK community in AION Project!

Nottingham, Open University, Oxford, RAL, Sheffield, Strathclyde, Sussex, Swansea and NPL



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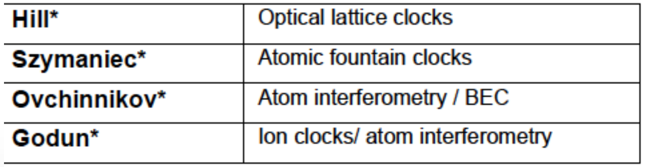

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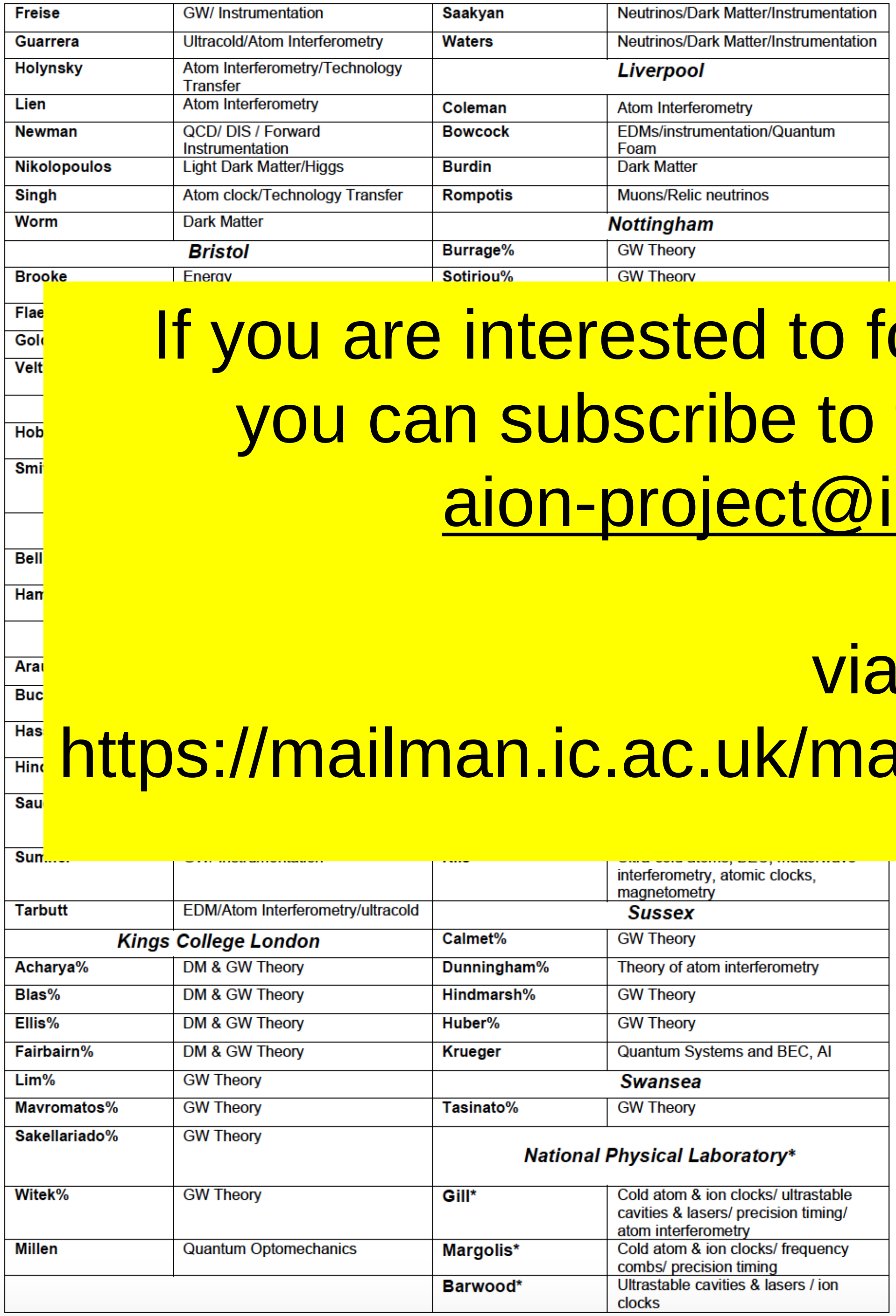

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Hob			
Smi			
Bell			
Ham			
Arau			
Buc			
Has			
Hinc			
Sau			
Sum			interferometry, atomic clocks, magnetometry
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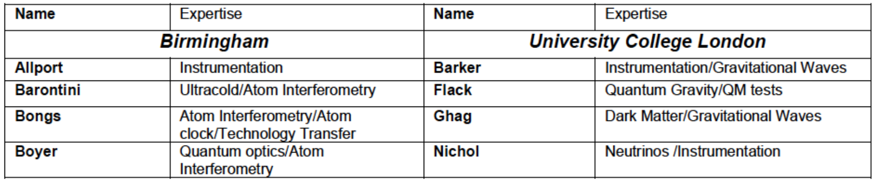

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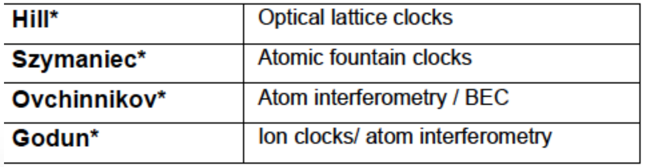
If you are interested to follow the AION activity you can subscribe to the AION Email list:
aion-project@imperial.ac.uk

via:
https://mailman.ic.ac.uk/mailman/listinfo/aion-project

Glasgow, Imperial College, Kings College London, University College London, Liverpool, Nottingham, Open University, Oxford, RAL, Sheffield, Strathclyde, Sussex, Swansea and NPL



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First AION Workshop at Imperial College London March 25/26 2019

Organised by:
T. Bowcock,
O. Buchmueller [Coord.],
J. Coleman,
J. Ellis [Theory],
I. Shipsey

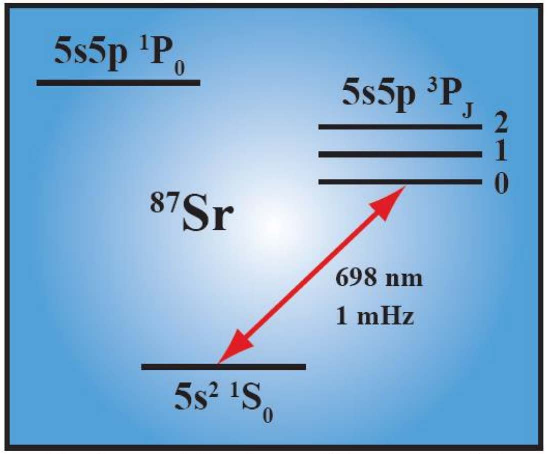
2-Day Workshop:
Day 1: Instrumentation
Day 2: Physics case

If you like to participate or require further information please contact:
fundamental-physics-admin@imperial.ac.uk
with “AION” in title.

THE PHYSICS CASE

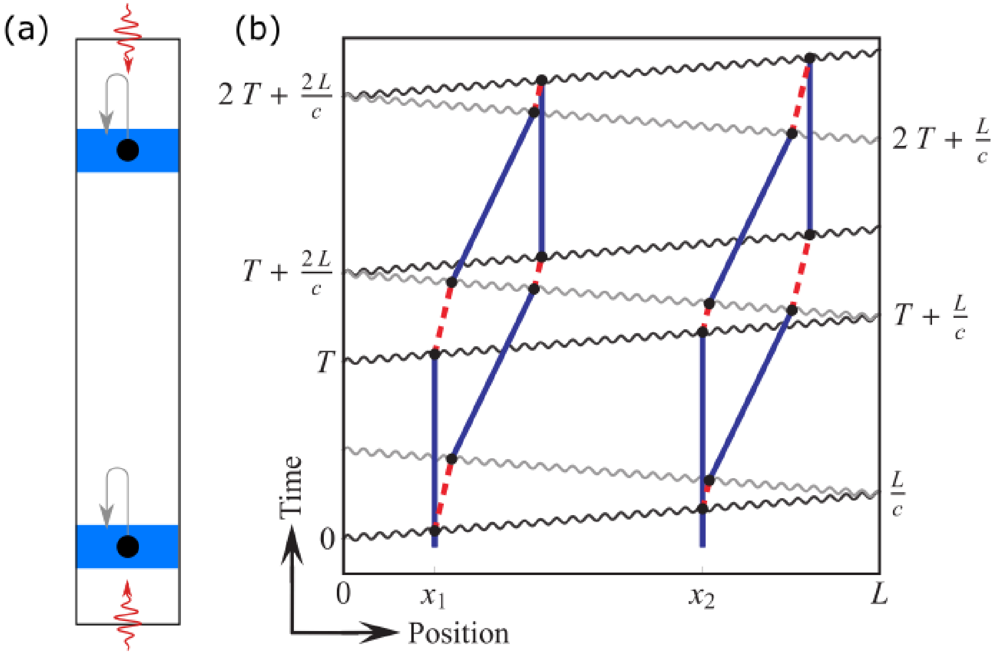
A different kind of atom interferometer

Hybrid “clock accelerometer”



Clock transition in candidate atom ^{87}Sr

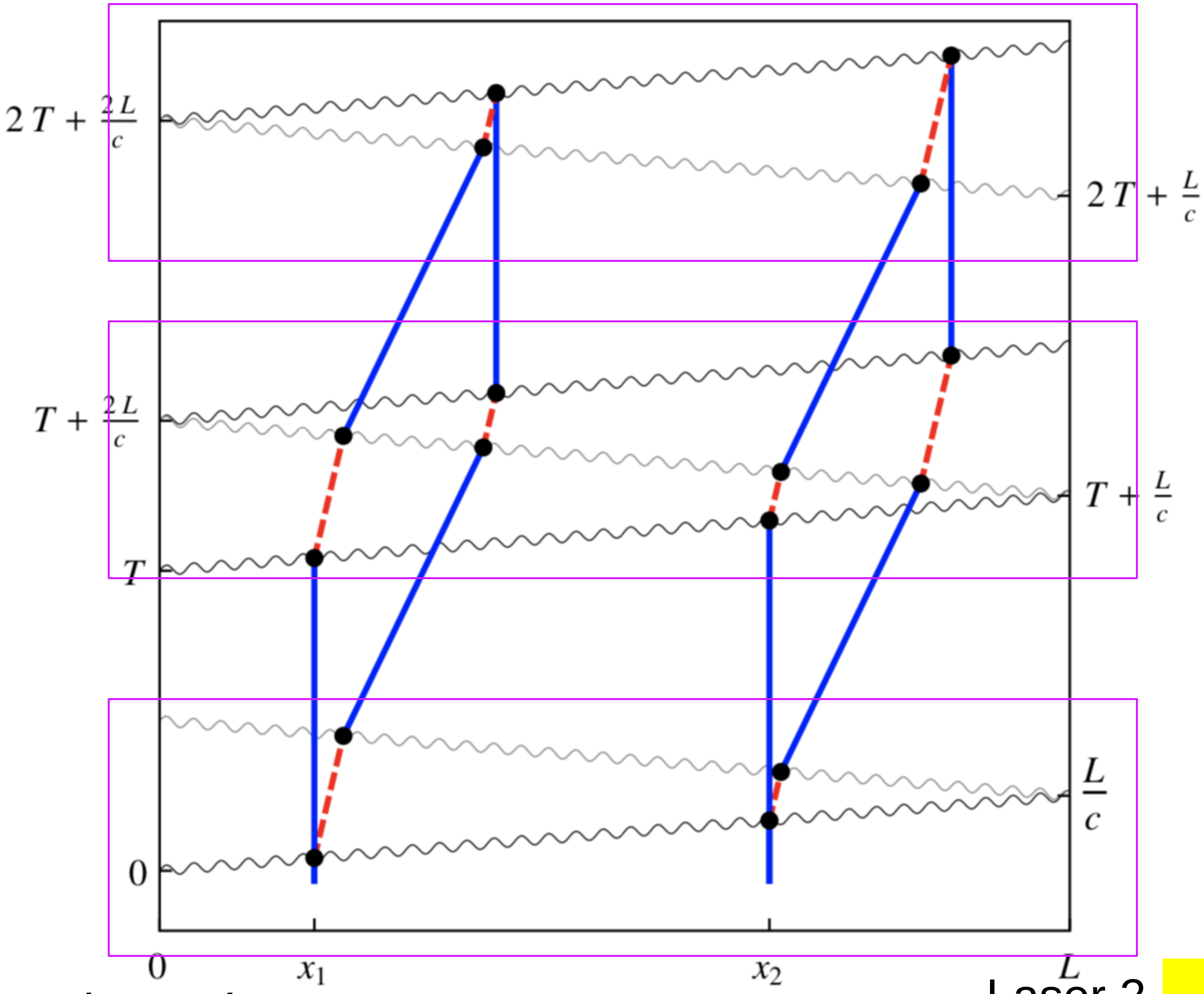
Graham et al., PRL **110**, 171102 (2013).



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

Accelerometer: atoms excellent inertial test masses

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

References:

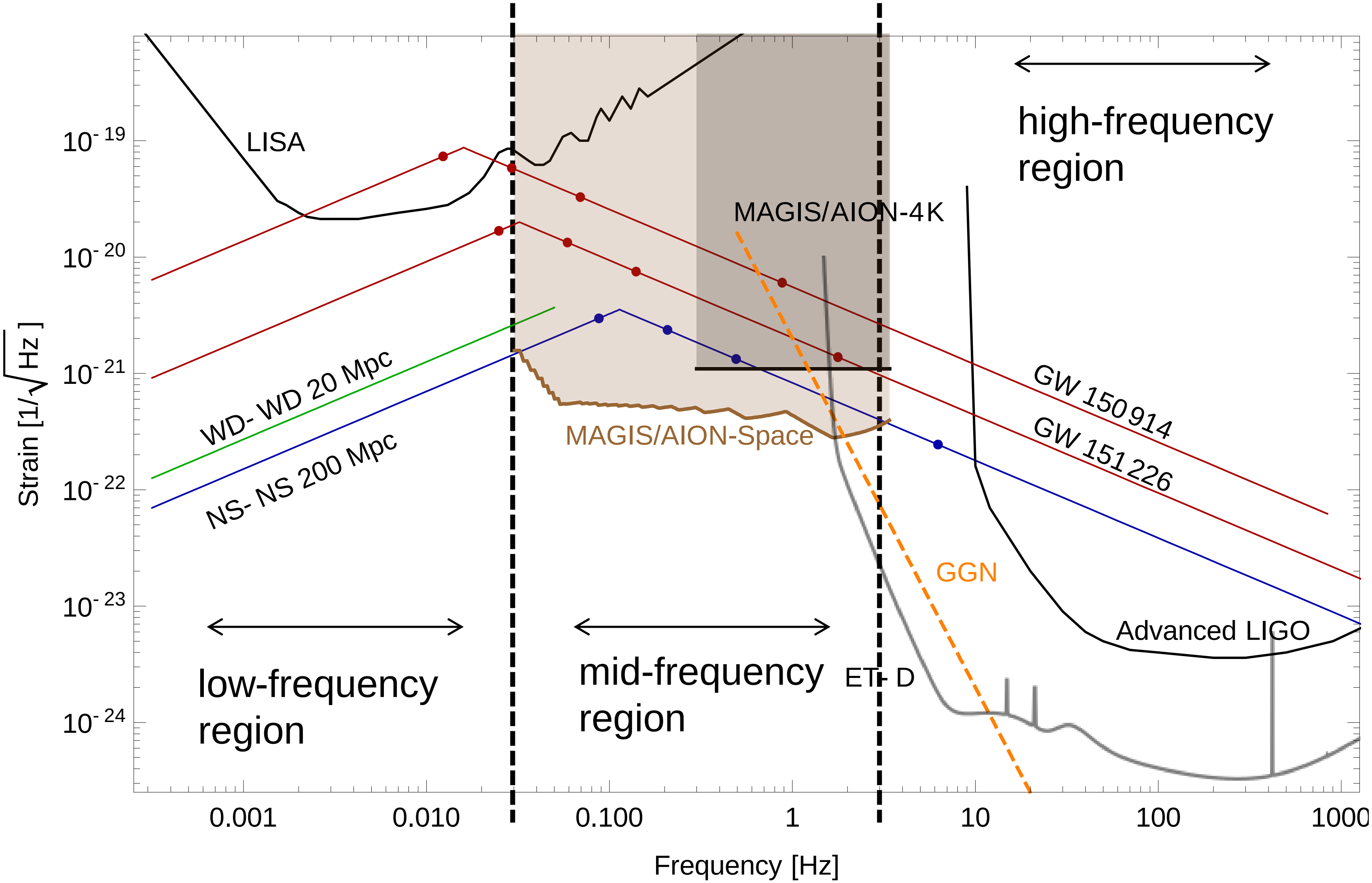
- On the Maximal Strength of a First-Order Electroweak Phase Transition and its Gravitational Wave Signal, 1809.08242
- Cosmic Archaeology with Gravitational Waves from Cosmic Strings, 1711.03104
- Probing the pre-BBN universe with gravitational waves from cosmic strings, 1808.08968
- Formation and Evolution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

GW PHYSICS @ AION

NOTE: Much more in tomorrow’s talk by Marek Lewiki

Gravitational Wave Detection with Atom Interferometry

O. Buchmueller The AION Project



Sky position determination

Sky localization precision:

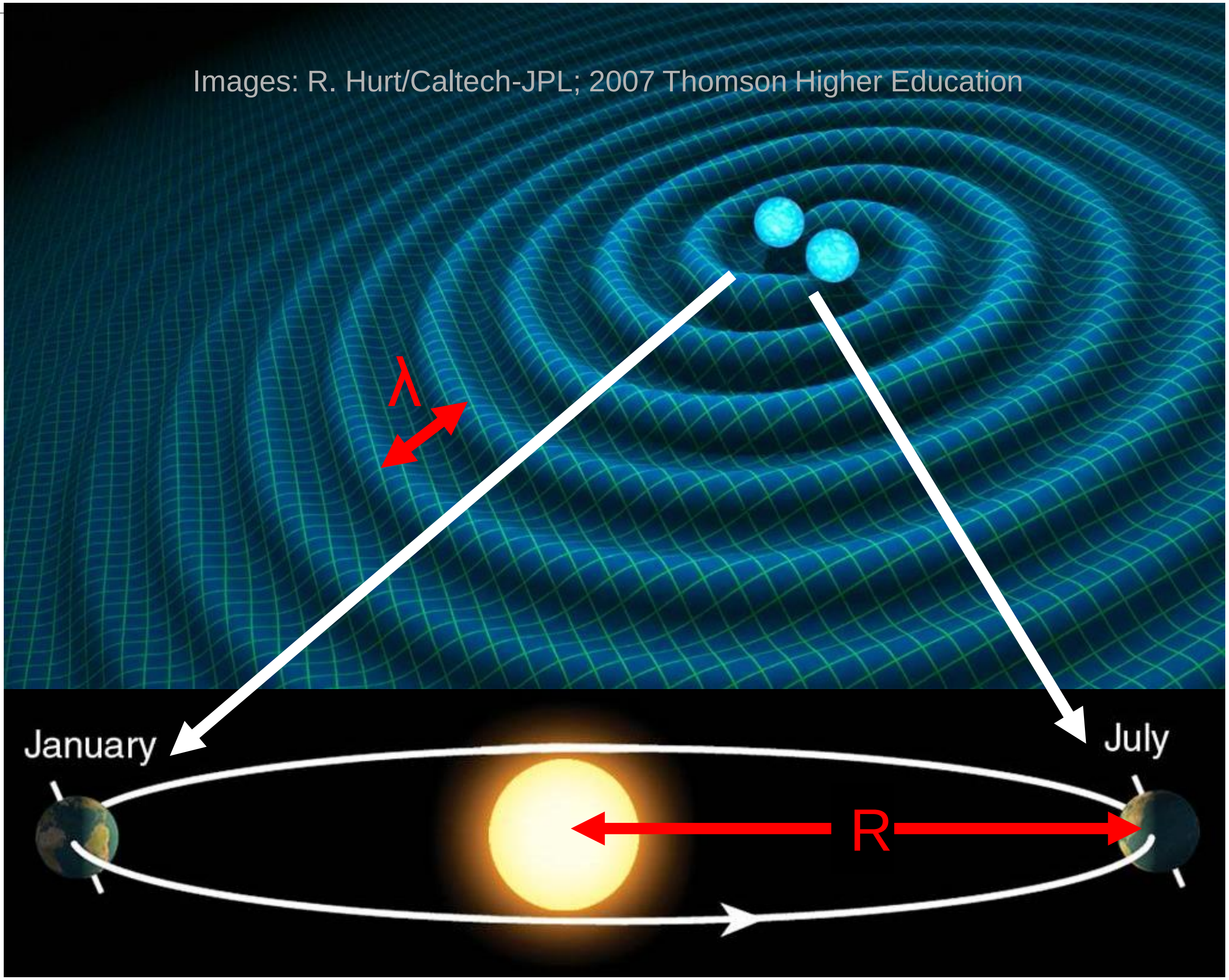
$$\sqrt{\Omega_s} \sim \left(\mathrm{SNR} \cdot \frac{R}{\lambda}\right)^{-1}$$

Mid-band advantages

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

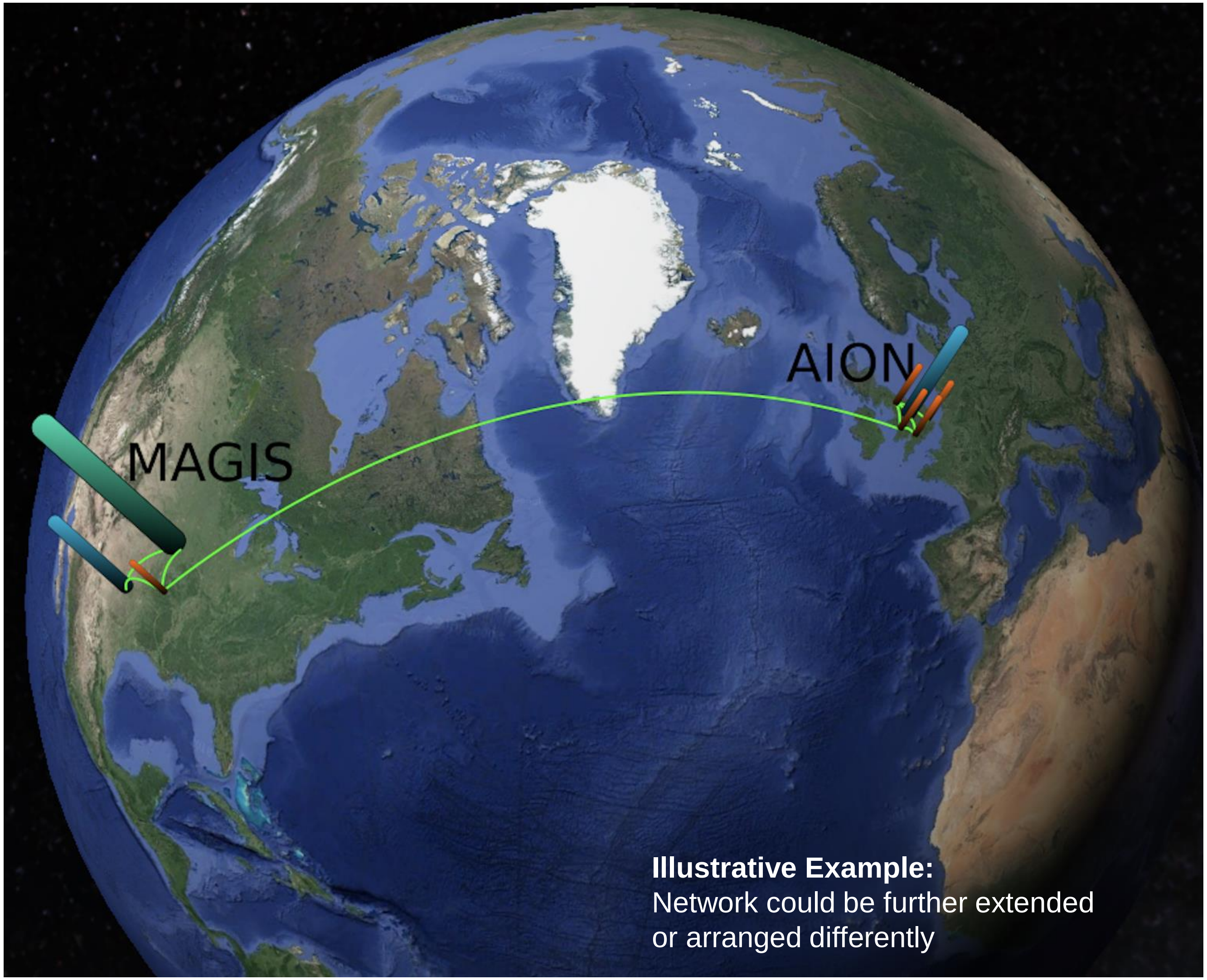
Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19

Courtesy of Jason Hogan!


Images: R. Hurt/Caltech-JPL; 2007 Thomson Higher Education

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

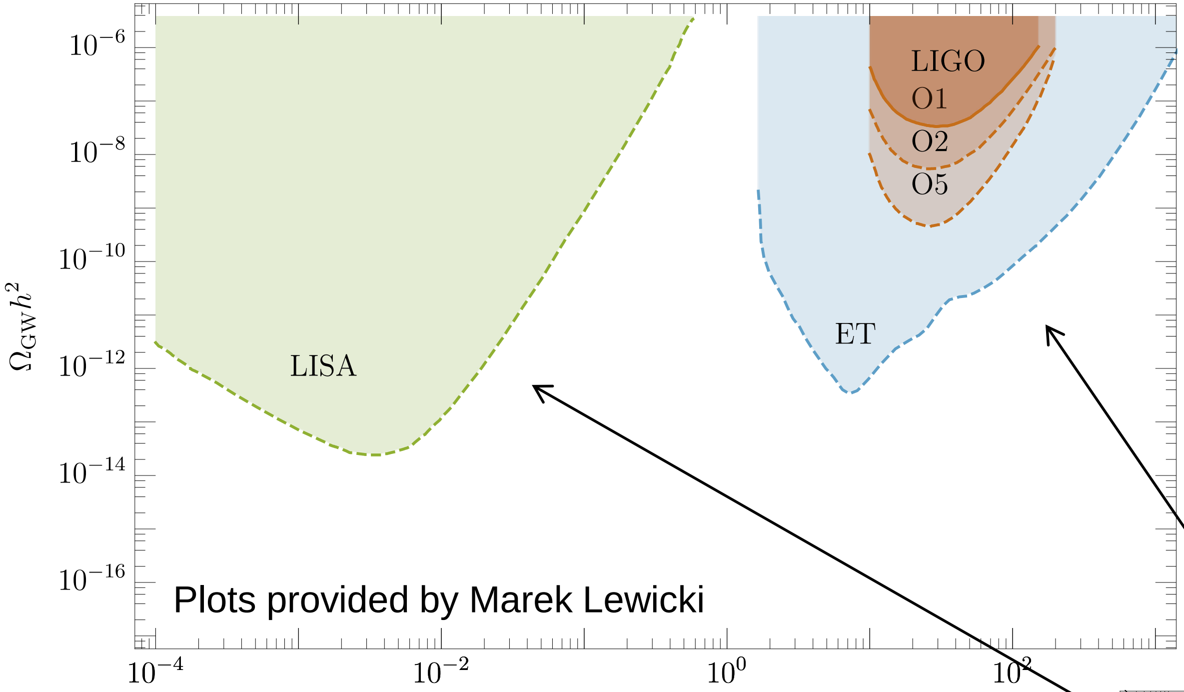
Ultimate Goal: Establish International Network



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

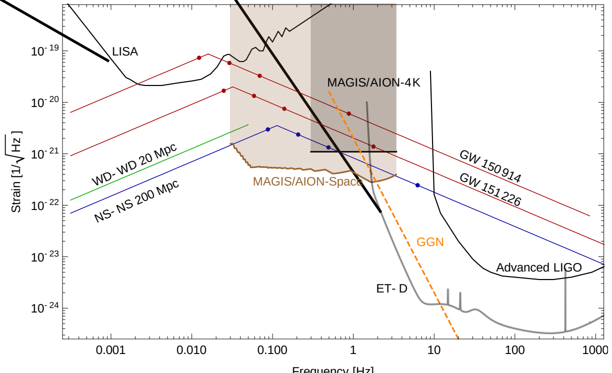


Plots provided by Marek Lewicki

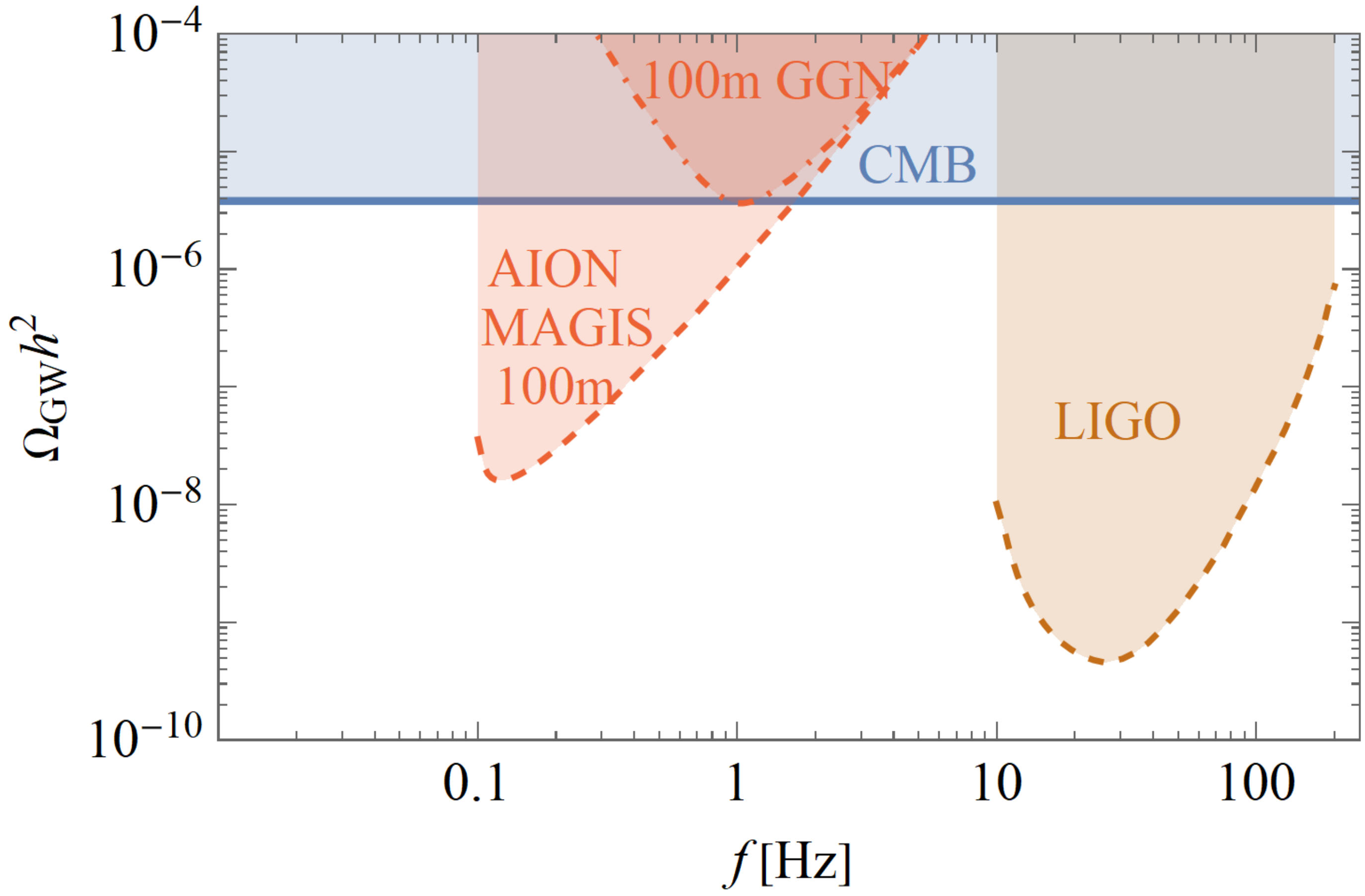
arXiv:1809.08242
John Ellis, Marek Lewicki,
José Miguel No

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



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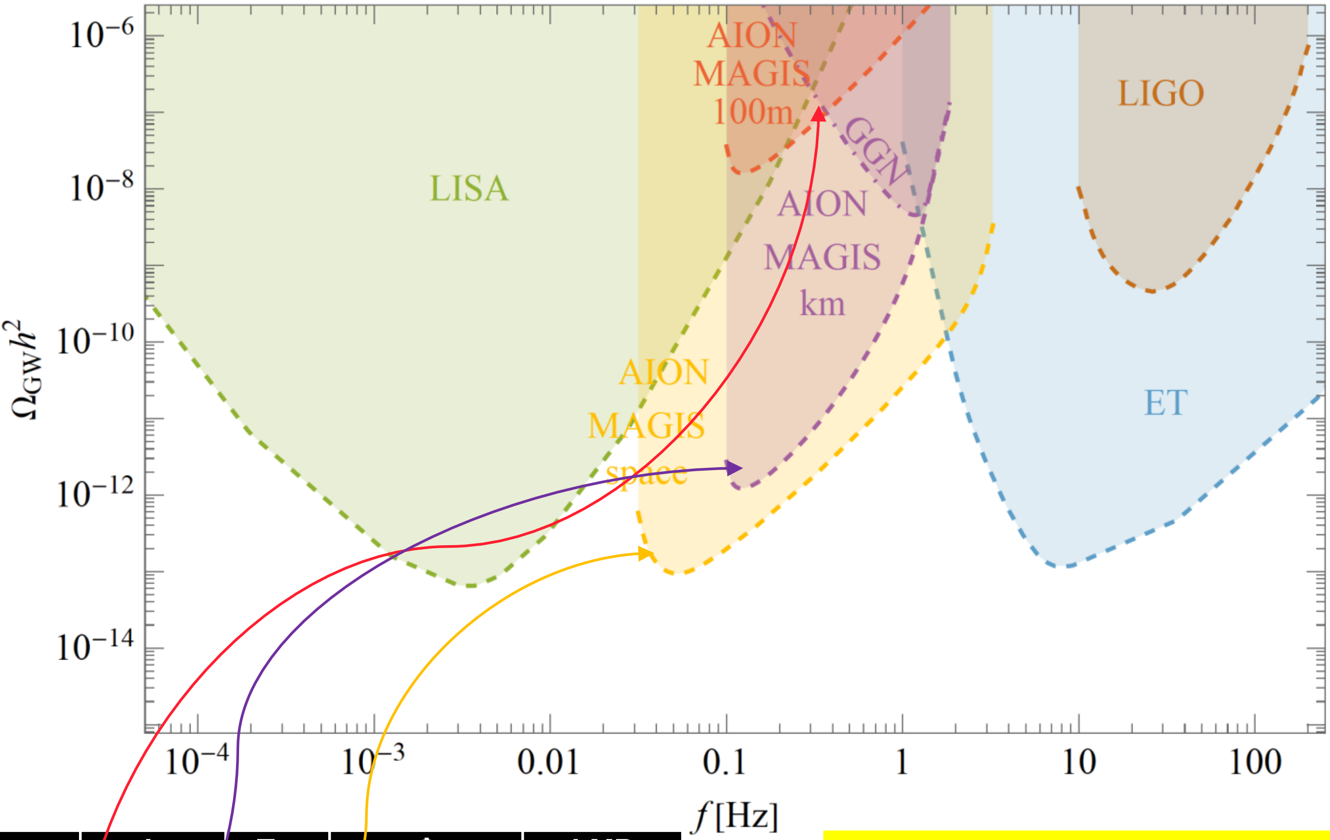
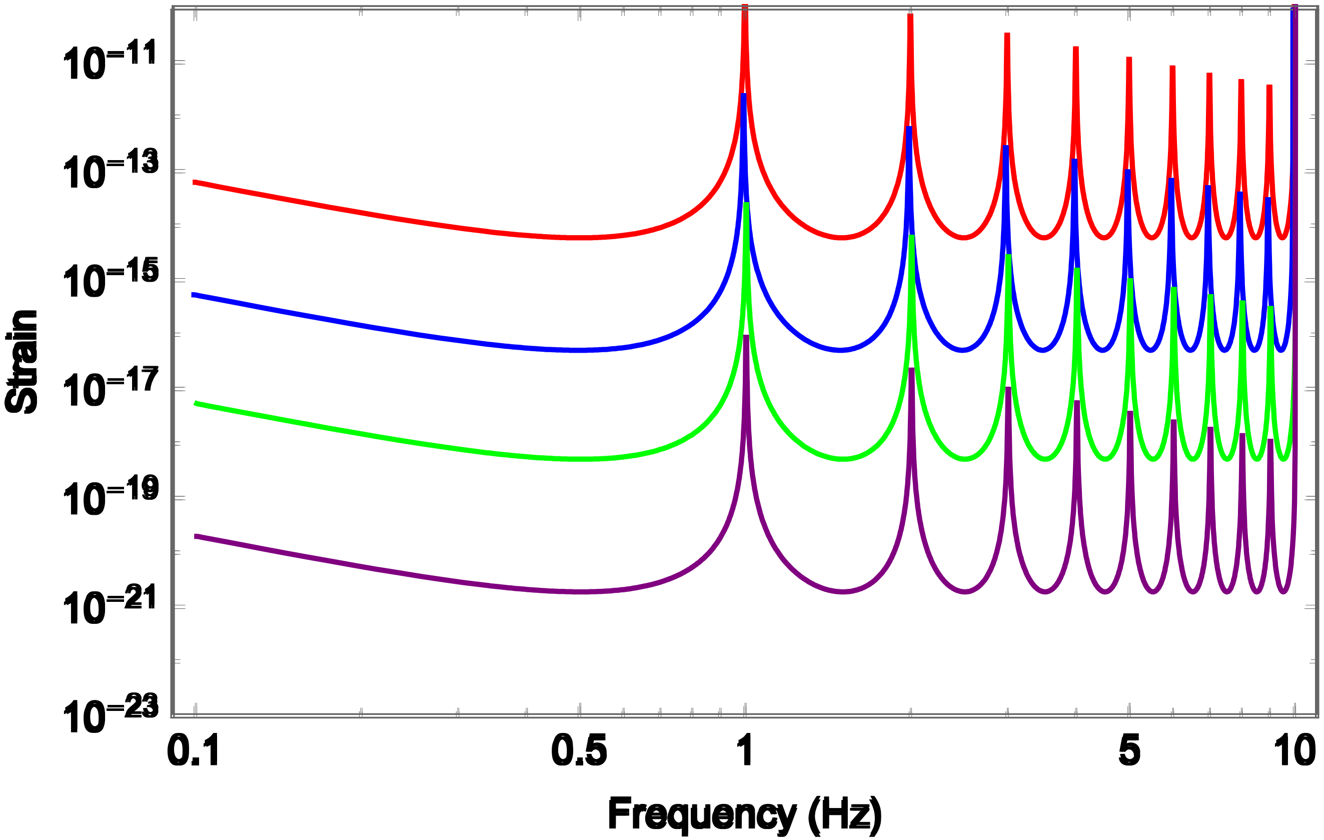


Sensitivity Scenario	L [m]	T_{int} [s]	Φ [1/√Hz]	LMP [#]
AION-100-today	100	1.4	10^{-3}	100
AION-100-ultimate	100	1.4	10^{-5}	40000
AION-km	2000	5	0.3×10^{-5}	40000
AION-space	4.4×10^{7}	300	10^{-5}	<1000

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.

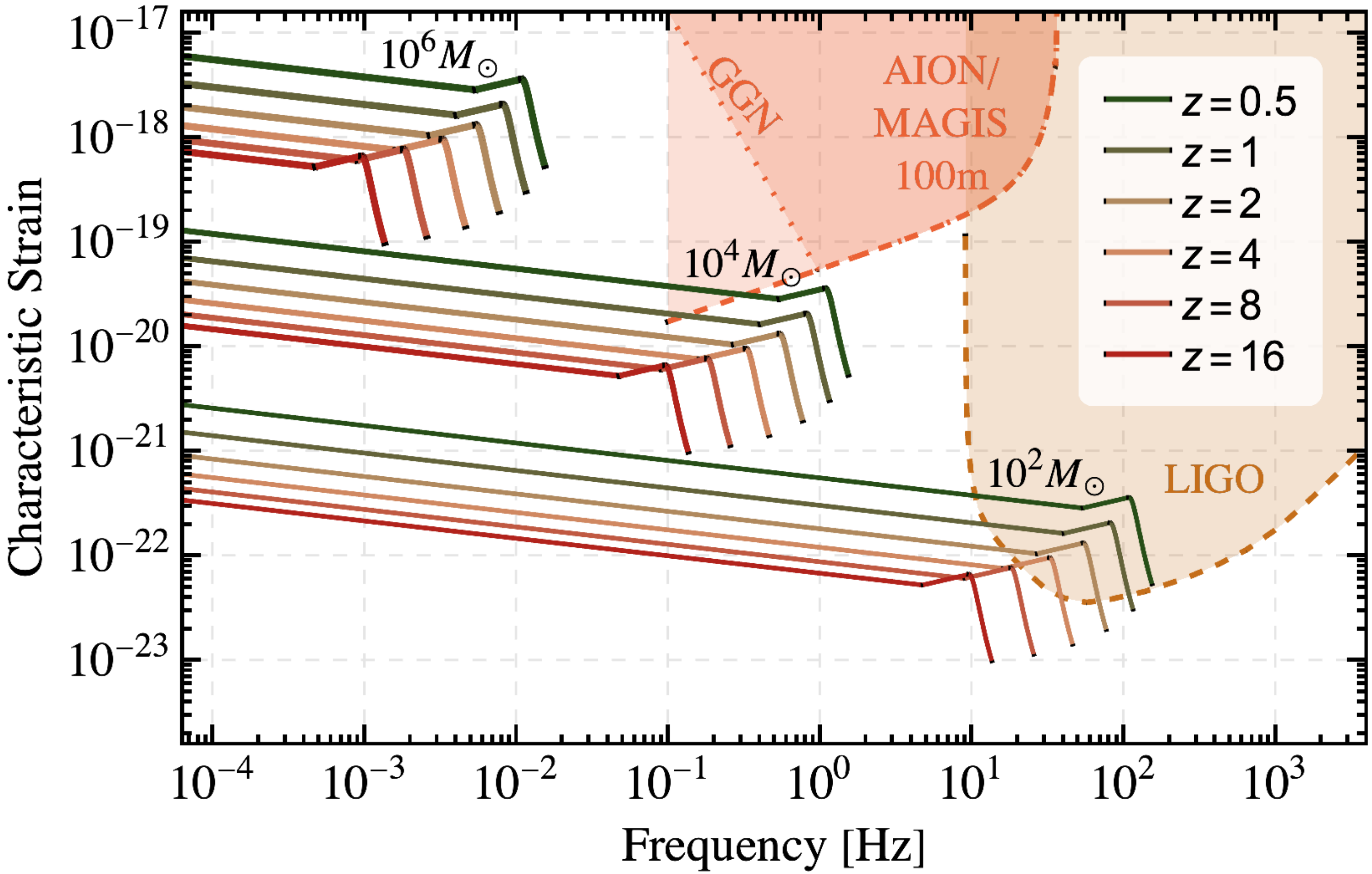
How does Sensitivity Scale in Strain

Question asked today



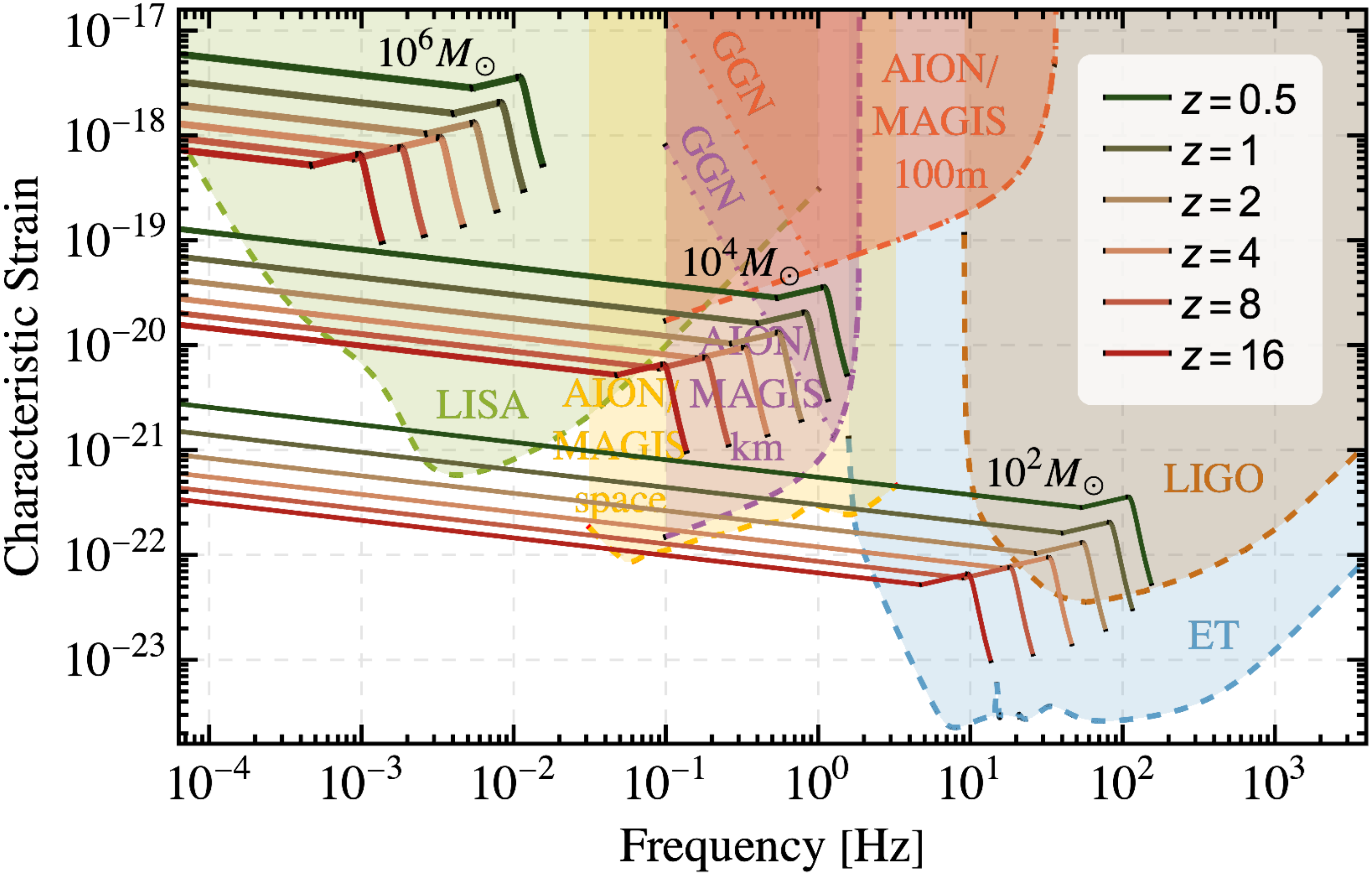
L [m]	LMT	NA
1E2	1E2	1E6
1E4	1E2	1E6
1E4	1E4	1E6
1E4	1E4	1E11

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: 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.

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

NOTE: Much more in tomorrow’s talk by Chris McCabe

The Landscape of Ultra-Light Dark Matter Detection

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

Example: Ultra-Light Dark Matter:

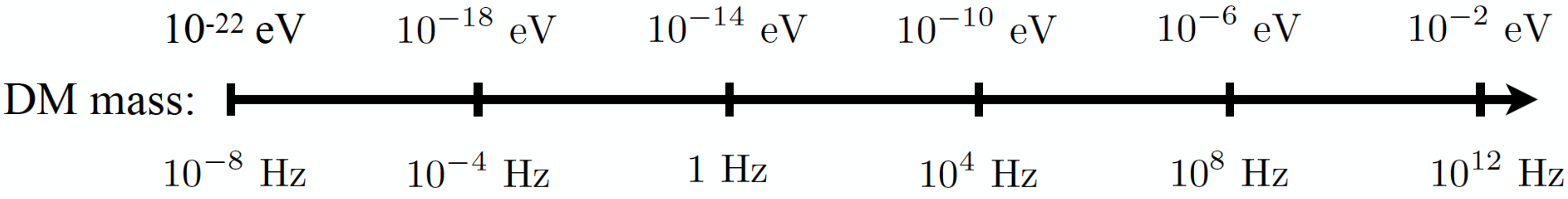


Diagram taken from P. Graham's talk at HEP Front 2018

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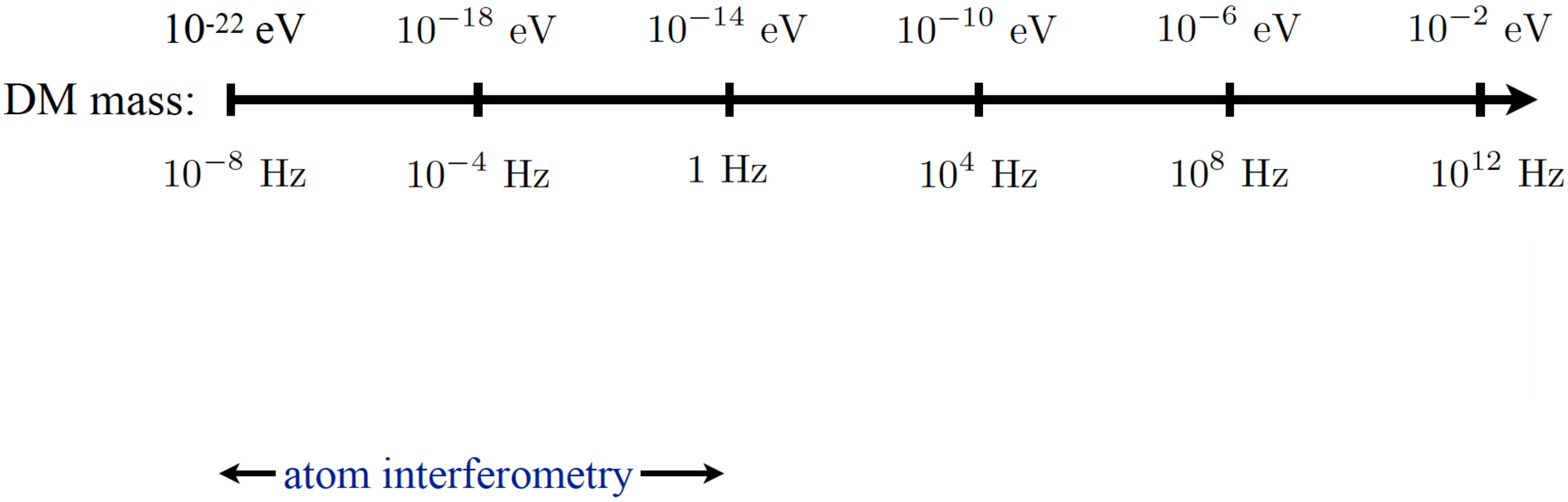

MAGIS/AION

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

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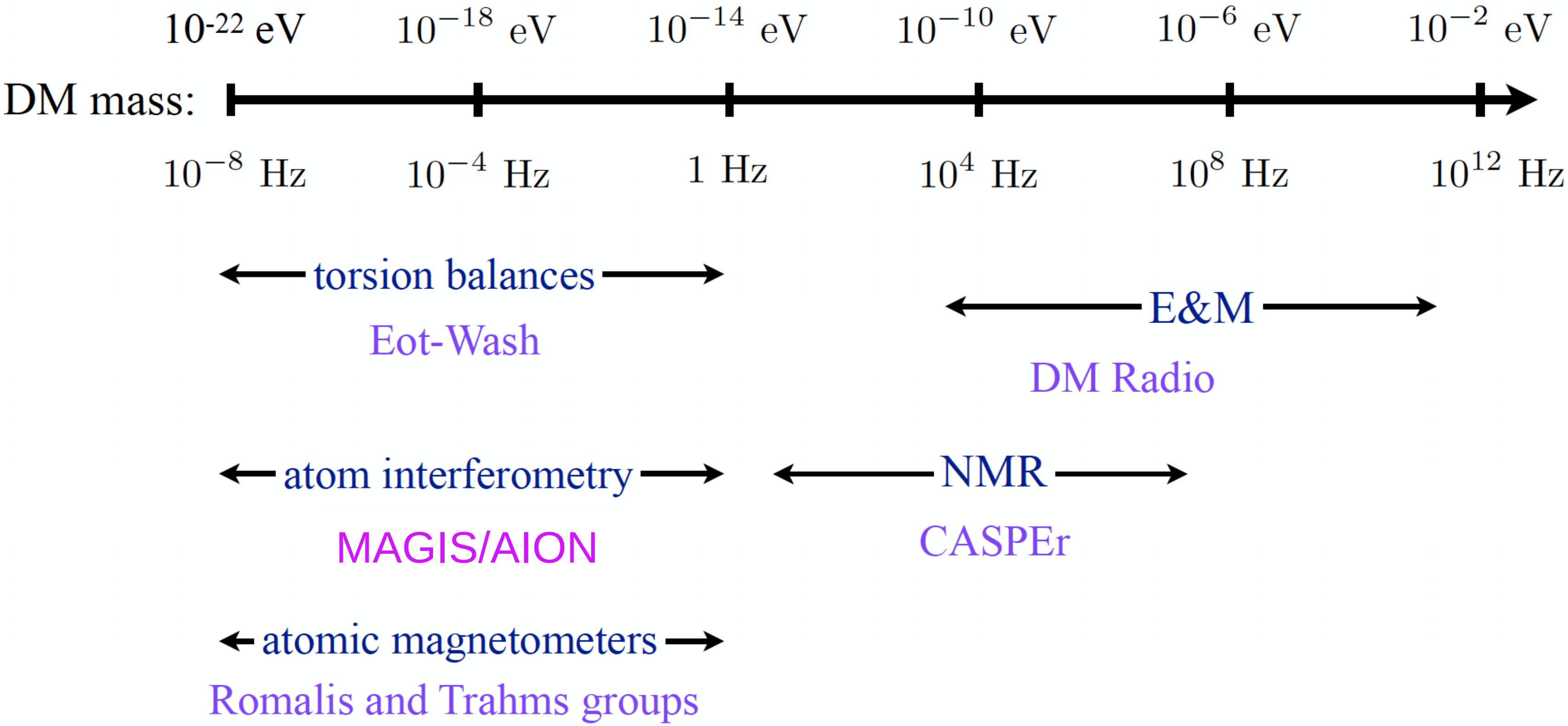


10^{-22} eV 10^{-18} eV 10^{-14} eV 10^{-10} eV 10^{-6} eV 10^{-2} eV

DM mass:

10^{-8} Hz 10^{-4} Hz 1 Hz 10^{4} Hz 10^{8} Hz 10^{12} Hz

← torsion balances →

Eot-Wash

← E&M →

DM Radio

← atom interferometry →

MAGIS/AION

← NMR →

CASPEr

← atomic magnetometers →

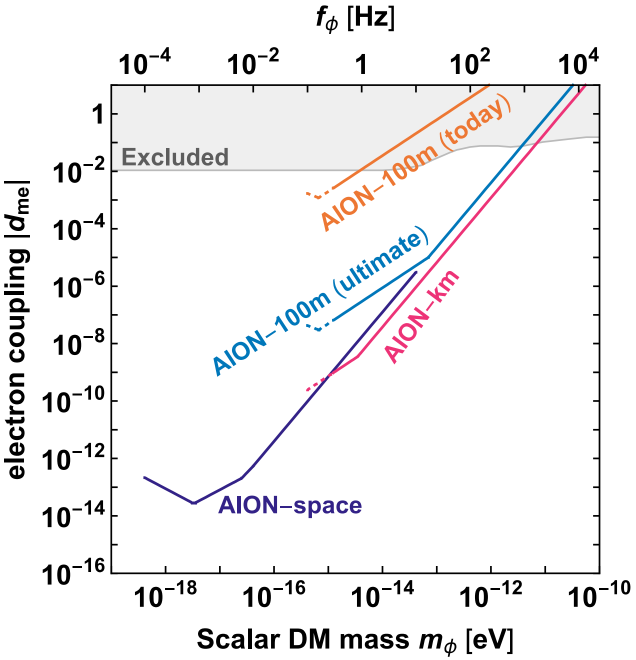
Romalis and Trahms groups

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

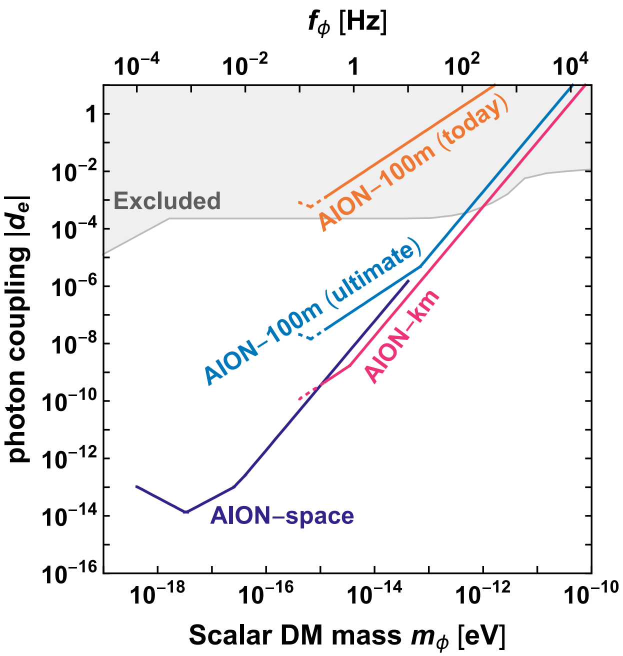
Sensitivity for DM with Scalar Couplings to Matter

O. Buchmueller The AION Project

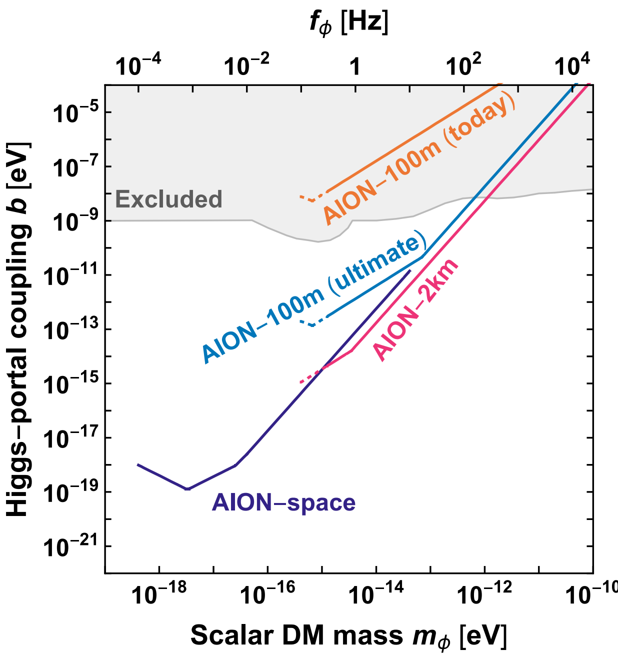
Coupling to e



Coupling to photon



Higgs Portal b coupling

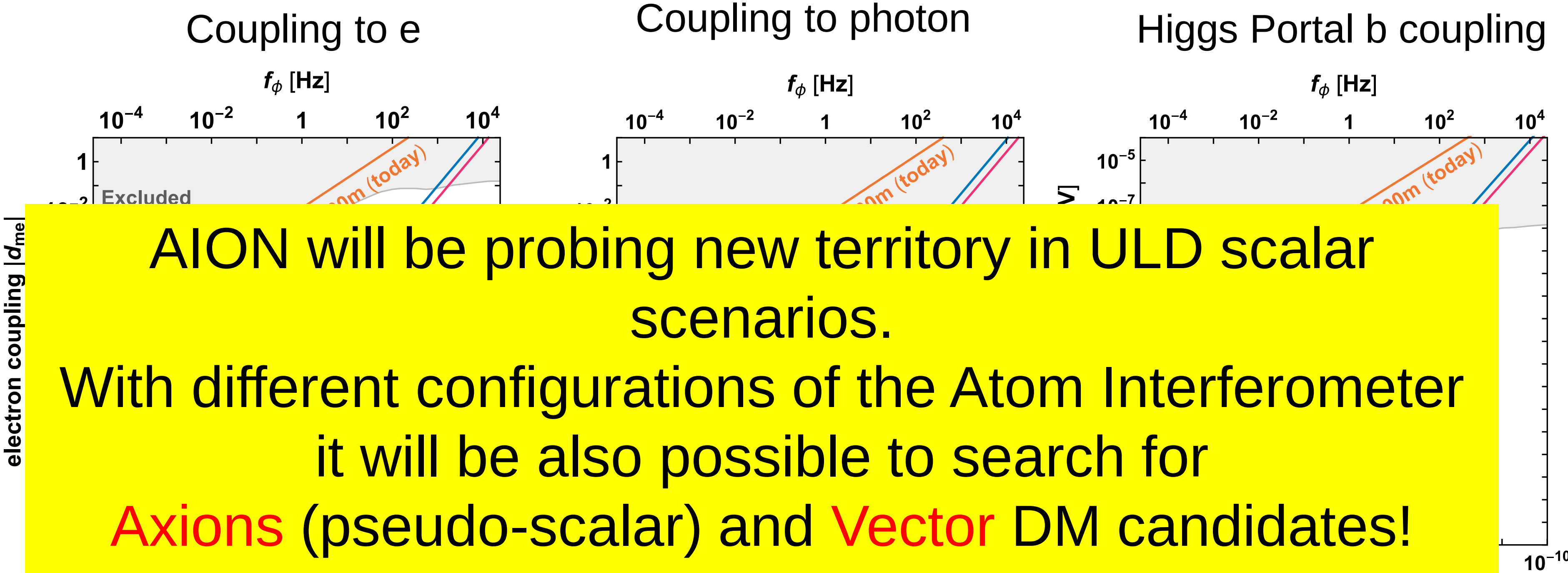


DM with scalar couplings to matter, which cause time variation of fundamental constants such as the electron mass

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

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 x 10^{-5}	40000
AION-space	4.4x10^{7}	300	10^{-5}	<1000

Sensitivity for DM with Scalar Couplings to 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]

which cause time variation of fundamental constants such as the electron mass

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

Scenario	[m]	[s]	[1/√Hz]	[#]
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Other Fundamental Physics

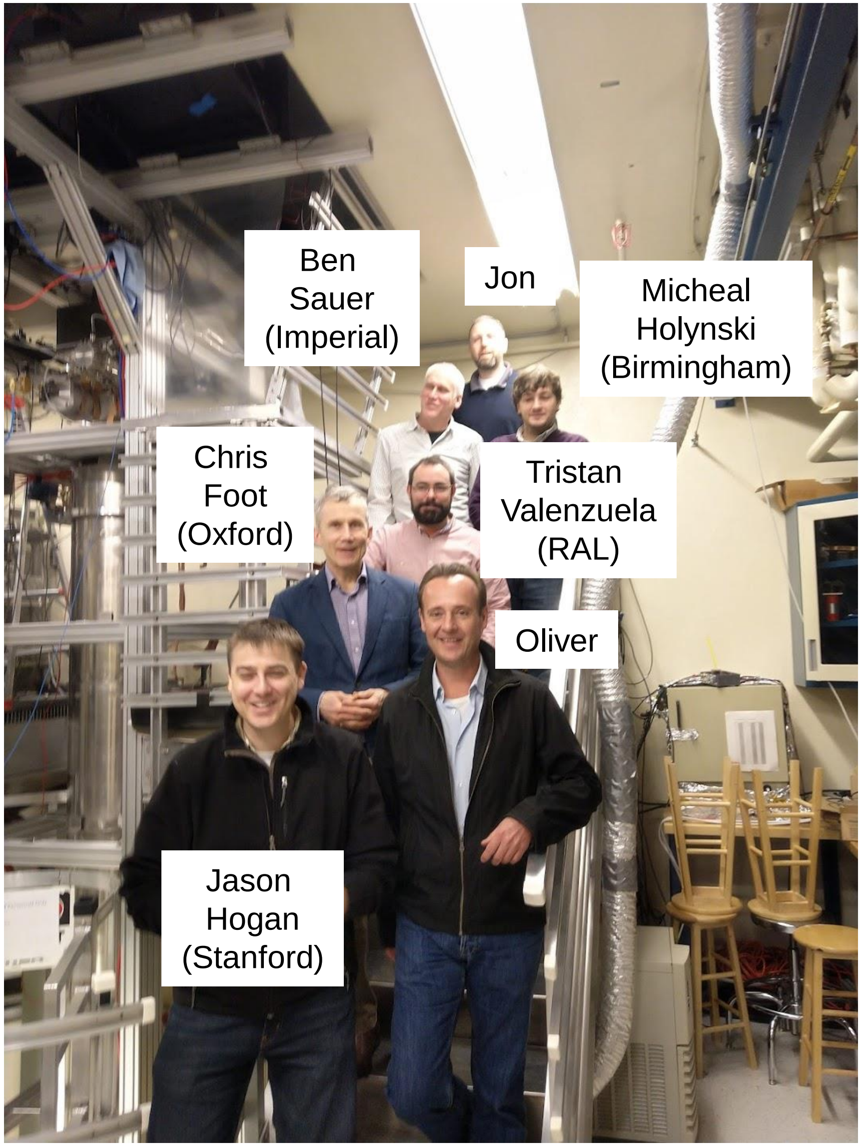
Ultra-high-precision atom interferometry may also be sensitive to other aspects of fundamental physics beyond dark matter and GWs, though studies of such possibilities are still at exploratory stages.

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.

VISIT TO STANFORD ON 10/11 JANUARY 2019

Stanford Visit 10/11 January 2019



We had a very fruitful visit to Stanford!

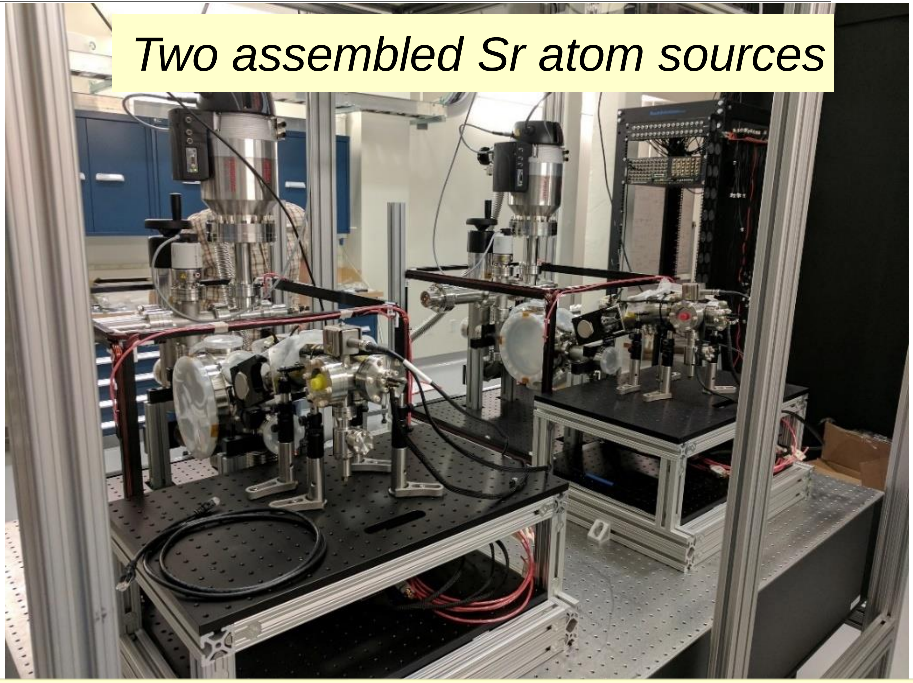
Main goals of the visit:

- Establish information exchange and review the Stanford work.
- Strengthen the US-UK collaboration
- Identify synergies and common goals between AION and MAGIS.

Outcome:

- Stanford/MAGIS is very open to closer collaboration with the UK/AION and they very much welcome another activity working towards the mid-band with AIs.
- There are several challenges where the UK expertise can help to achieve the design goals of the programme [see next slide].
- We agreed to include the synchronised operation of 10m prototype versions (later 100m) in the programme of MAGIS and AION.

Stanford MAGIS prototype



Two assembled Sr atom sources

Stanford Lab to host 8 m prototype of the Sr fountain.

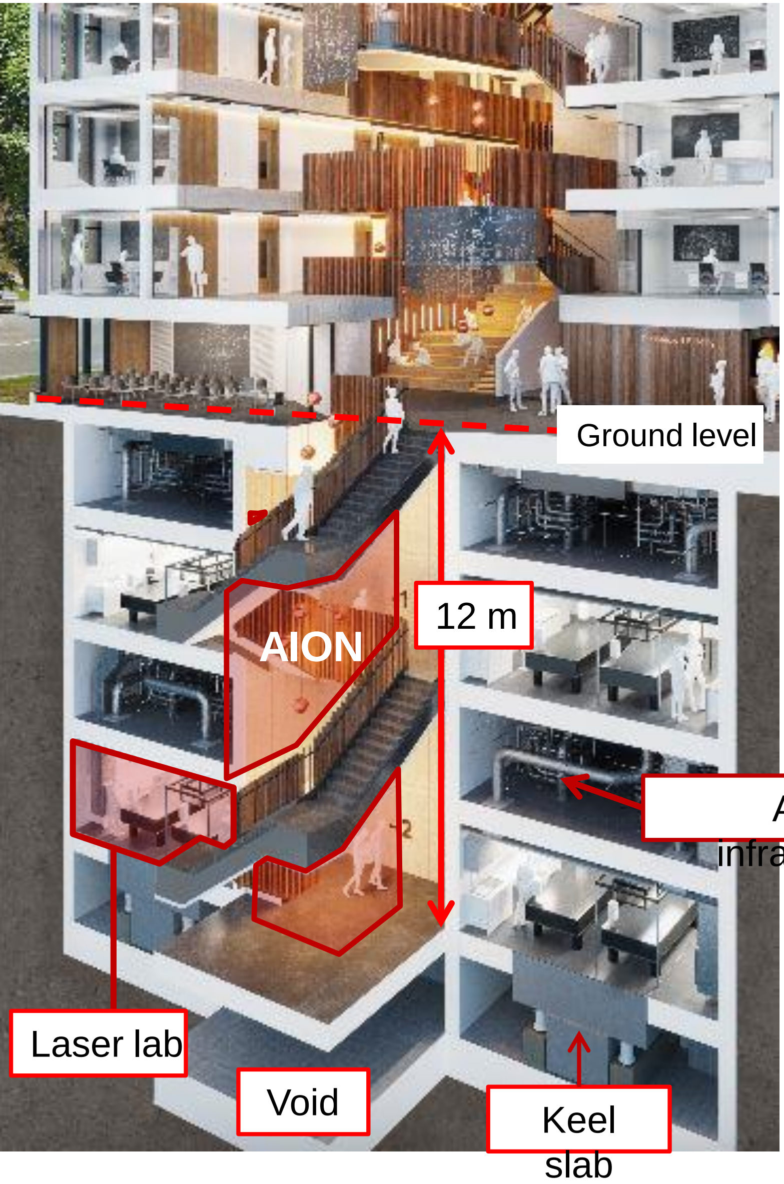
It is supposed to be assembled over summer 2019.

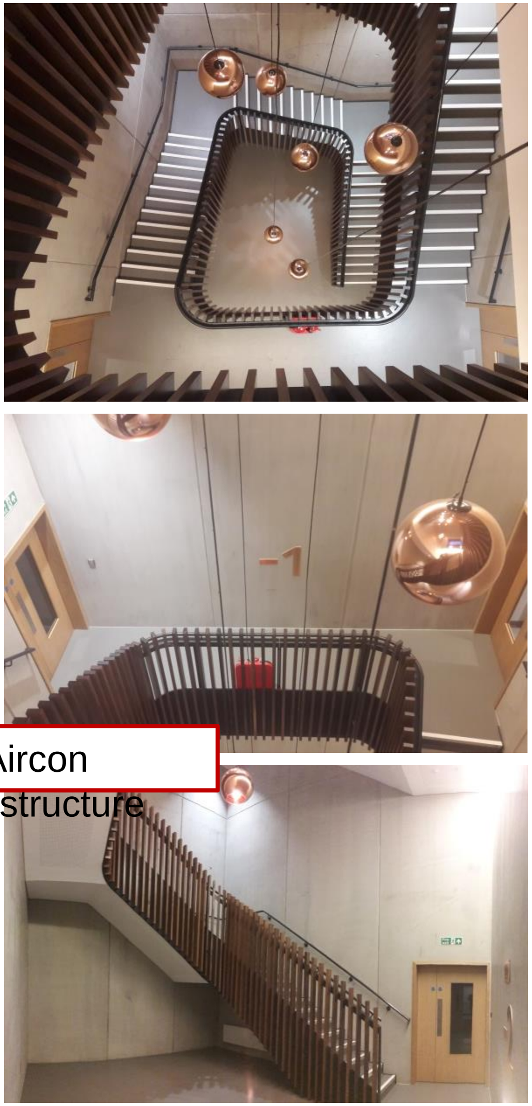
AION-10: 10 METER SIDE CHOSEN TO BE OXFORD

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
- ±0.1°C stability
- Isolated mains

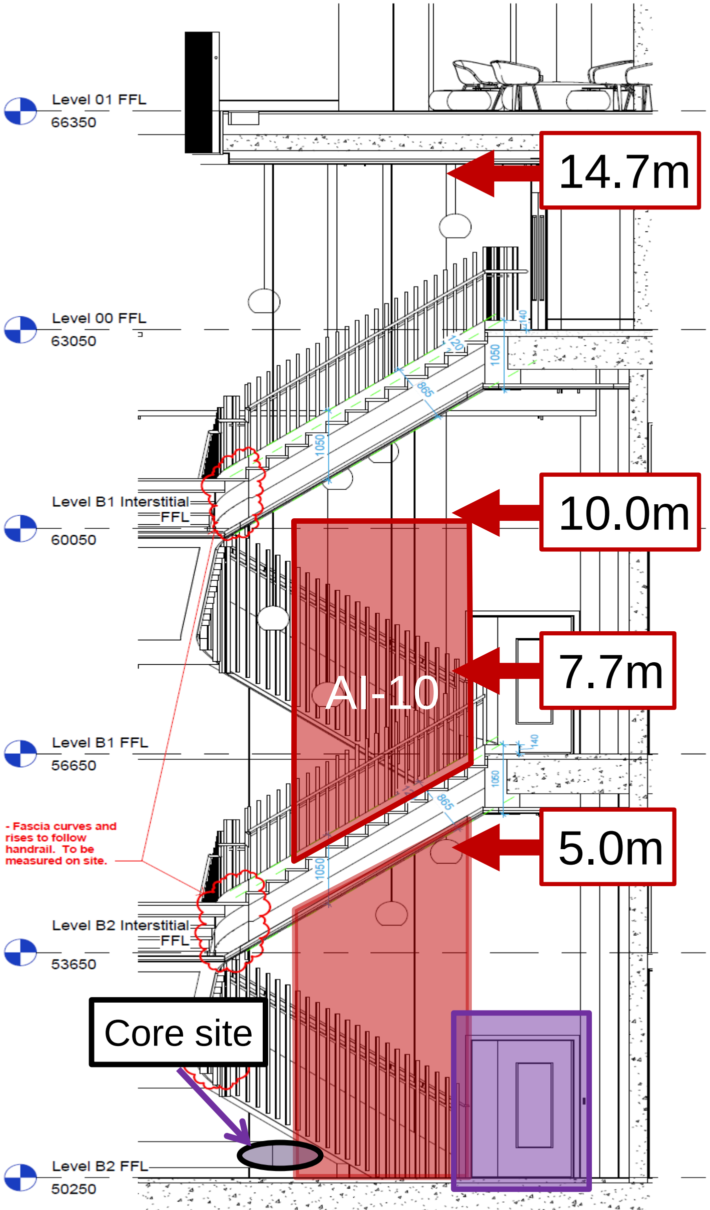
Vertical space

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

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

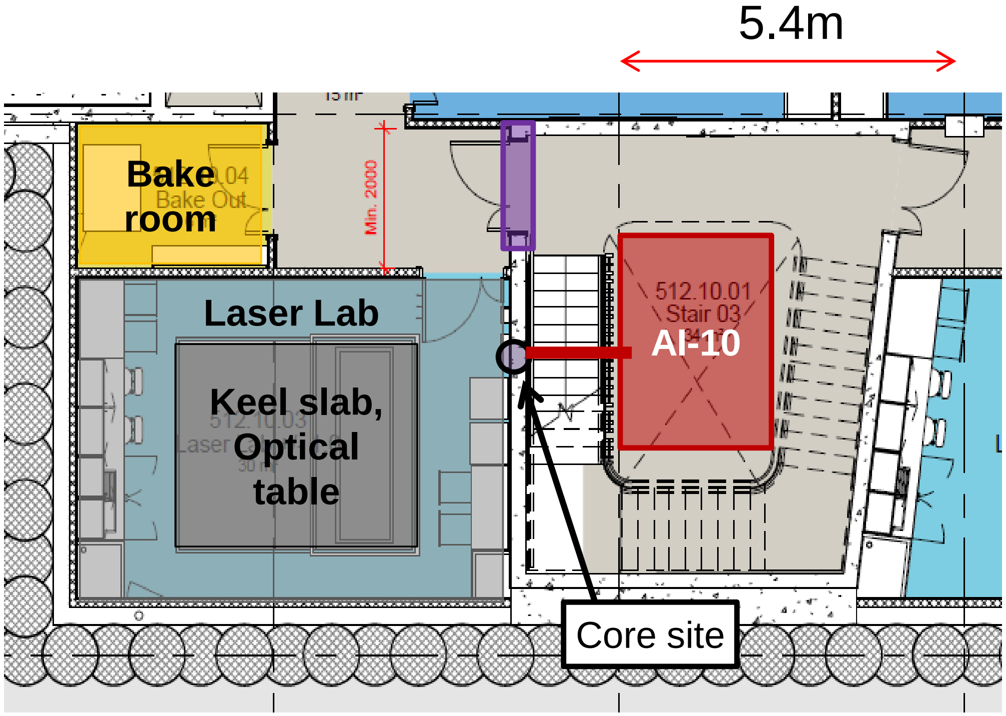
Bakeout room and cleanroom nearby

Beecroft building, Oxford Physics



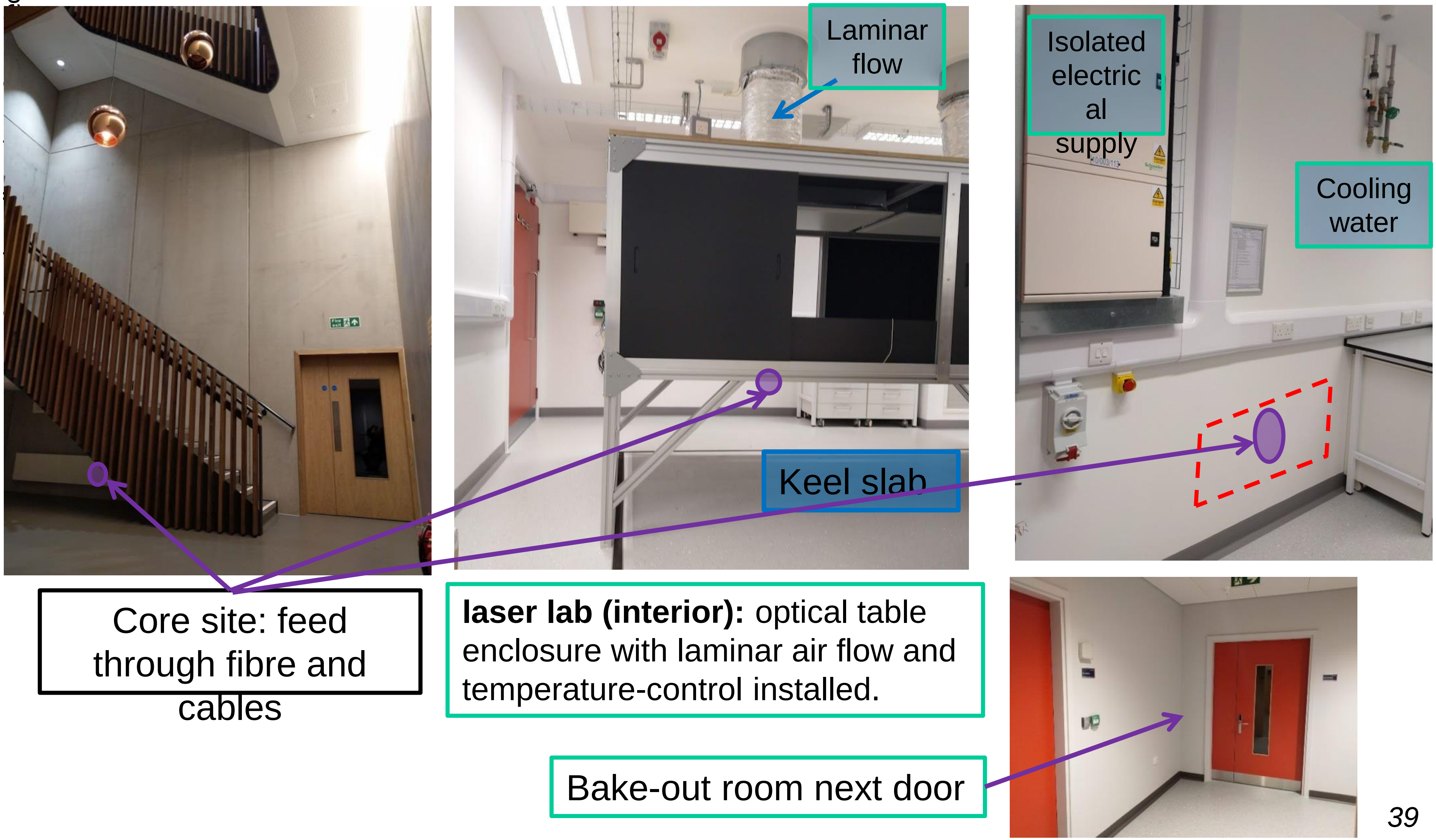
← Side view

↓ Plan view



Beecroft building laser lab

Beecroft stairwell: lowest level

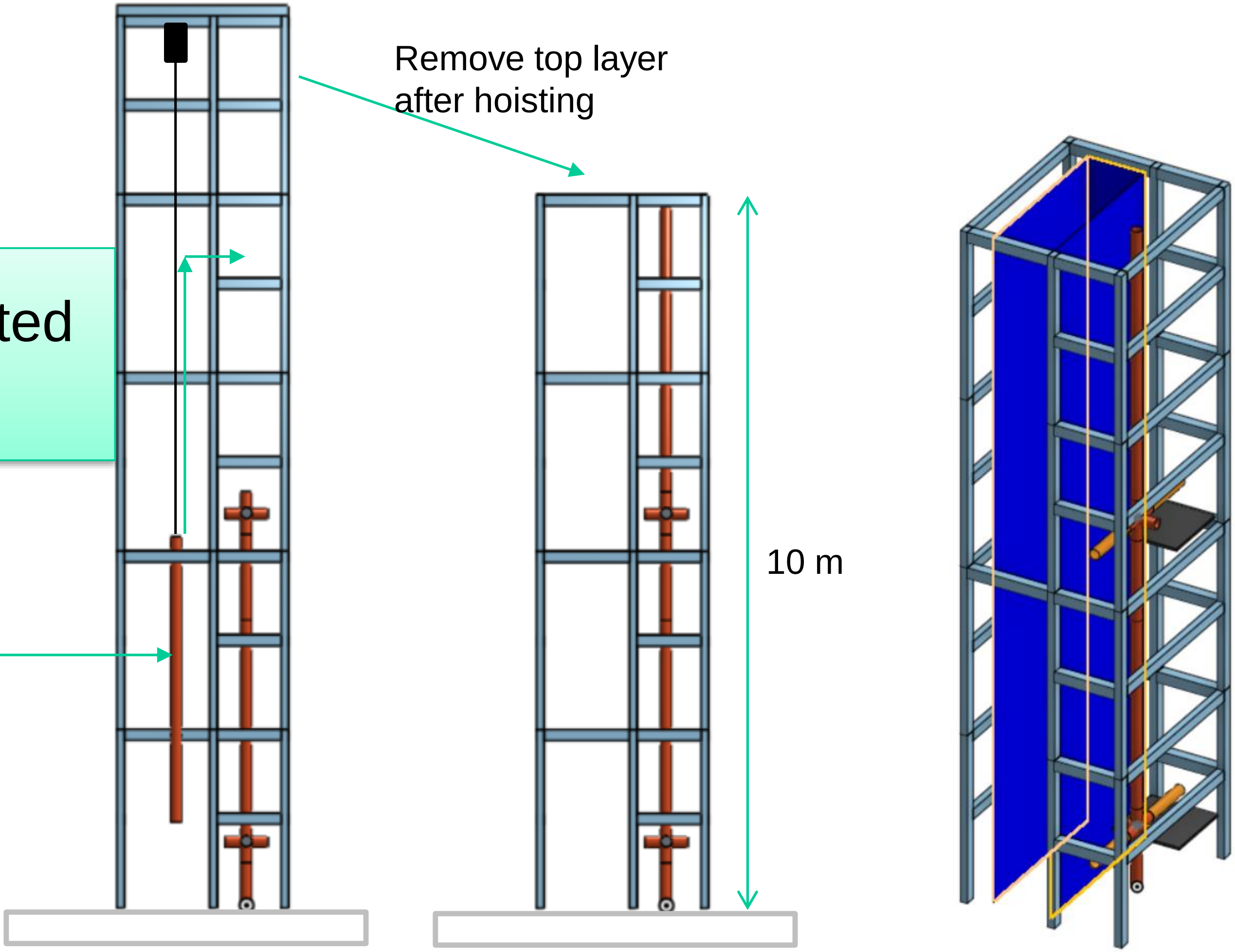


Core site: feed through fibre and cables

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.

vacuum pipe;
3.8 m long,
<100 kg.

Remove top layer
after hoisting

Summary

- The AION programme is driven by a well-defined and ambitious physics case to explore the Mid-Frequency Band of the GW spectrum.
  - In addition, it will enable the exploration of properties of dark matter as well as searches for new fundamental interactions
- AION foreseen as a staged programme: AION-10, AION-100, AION-KM and AION-SPACE.
  - AION-10 [year 1 to 3] and AION-100 [year 3 to 6] are part of the QSFP WP3
  - AION-KM and AION-SPACE are the pathway to the future and achieving ultimate sensitivity
- The formation of an AION collaboration is well underway with the next important milestone to finalize a full funding proposal.
  - At present, only the first three [AION-10] are subject of the proposal with the option to extended for additional three years towards AION-100.
  - No concrete plans for “Earth-km” or even “space” are developed yet.

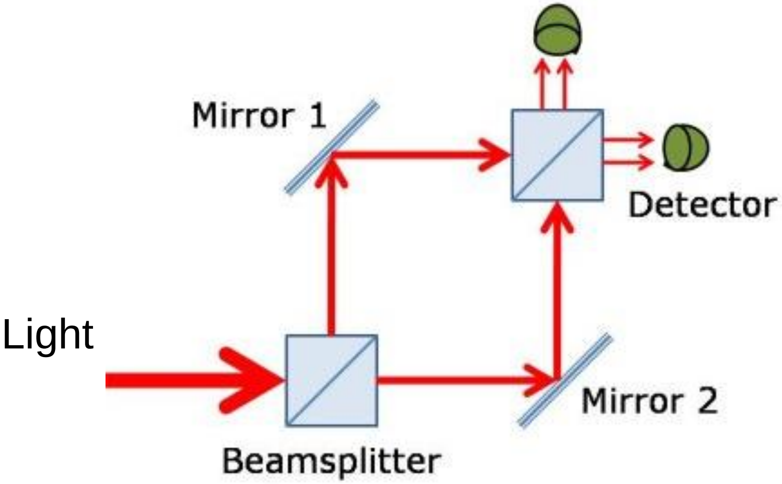
➢ The AION project is very interested in establishing synergies and close collaboration with other European and international initiatives, which pursue similar goals of km-scale (and space) atom interferometer on a comparable timescale.

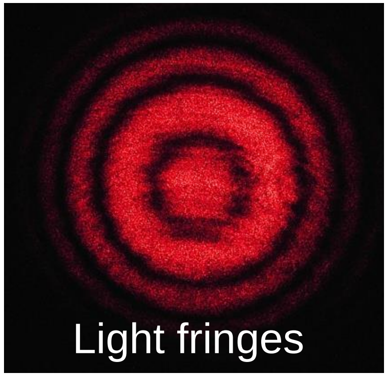
BACKUP

ATOM INTERFEROMETER CONCEPT

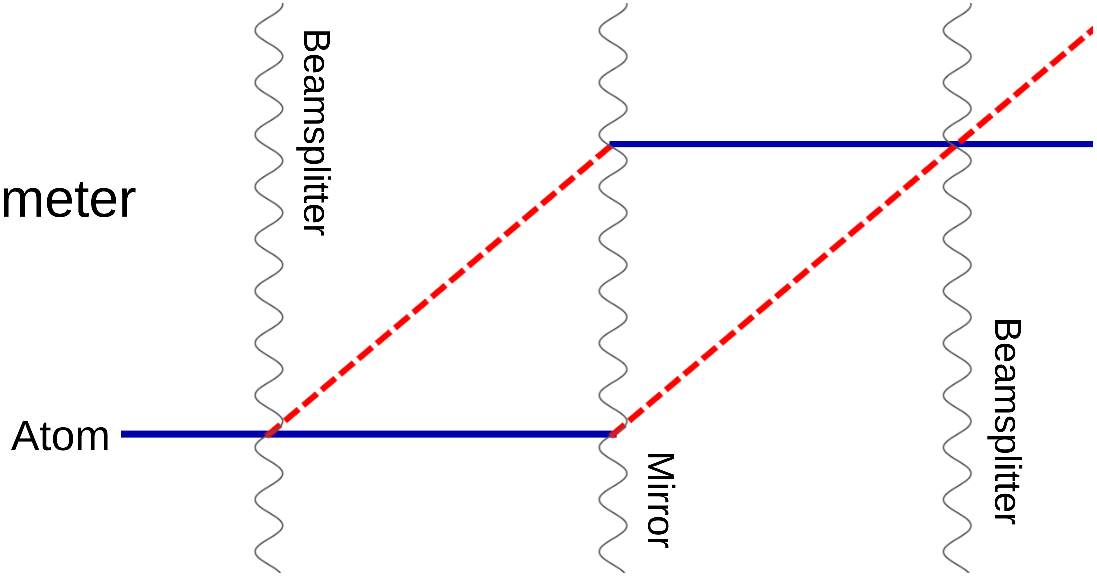
Atom interference

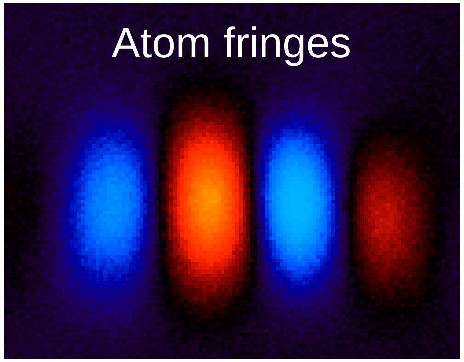
Light interferometer





Atom interferometer

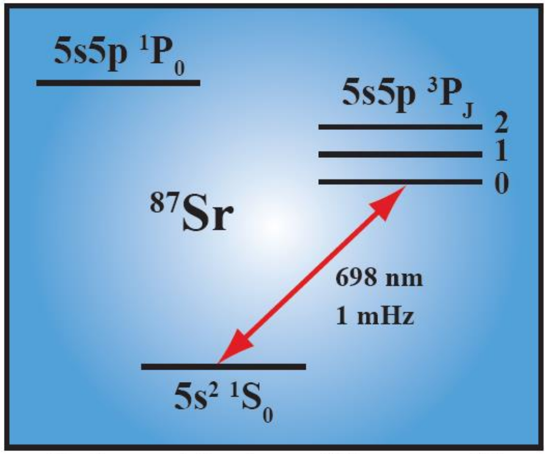




http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

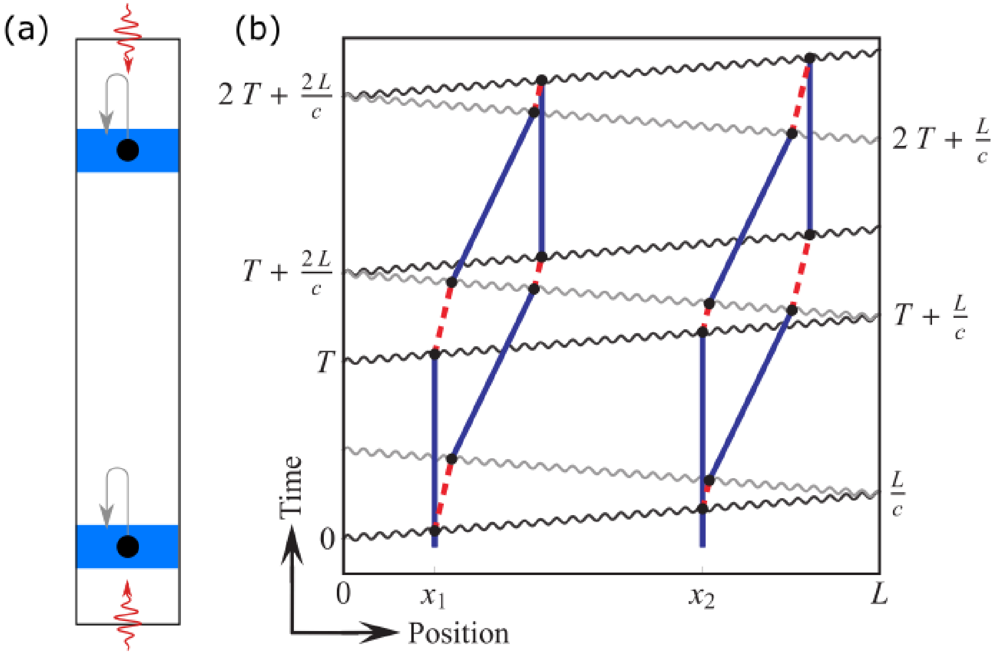
A different kind of atom interferometer

Hybrid “clock accelerometer”



Clock transition in candidate atom ^{87}Sr

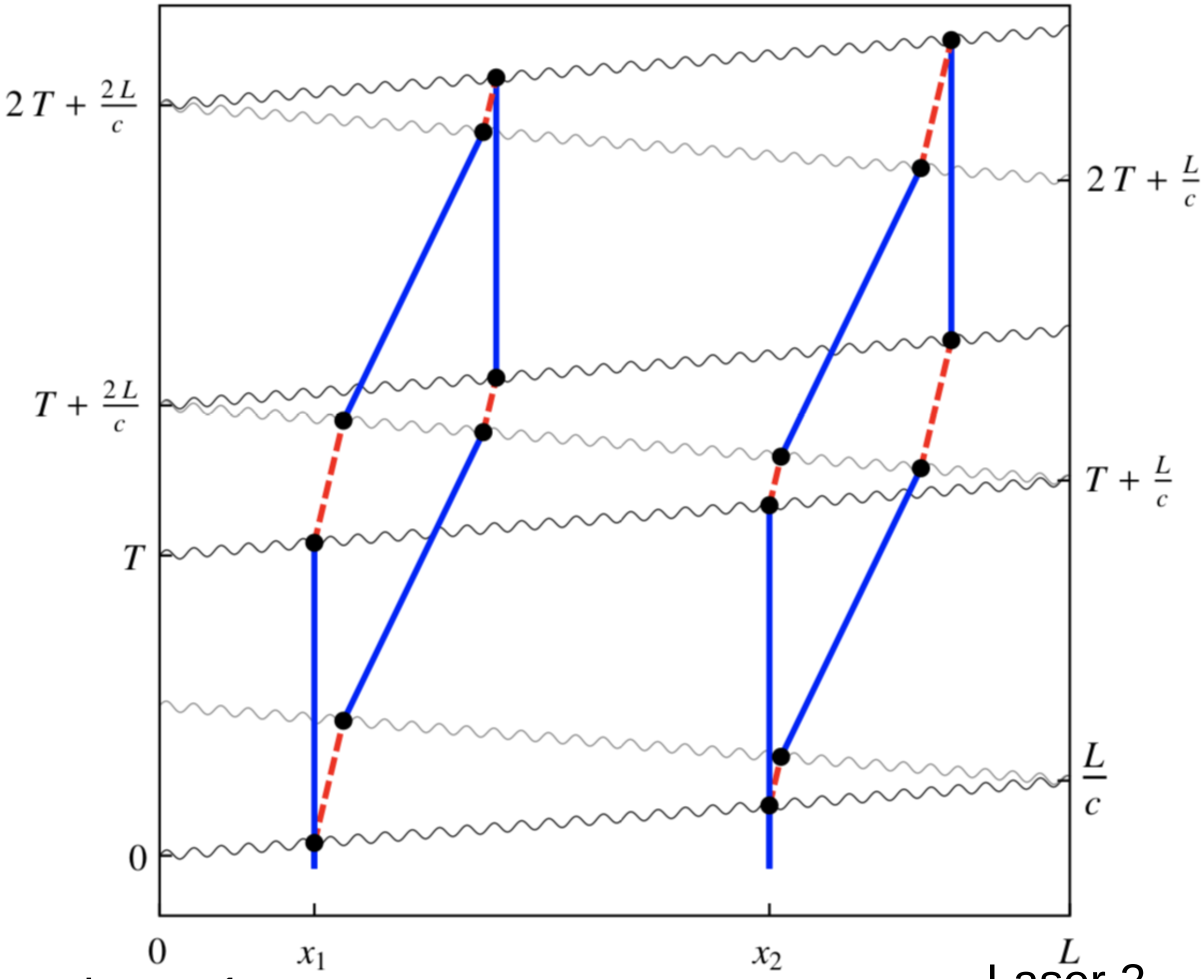
Graham et al., PRL **110**, 171102 (2013).



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

Accelerometer: atoms excellent inertial test masses

Basic Differential Measurement



Laser 1

Atom Source

Atom Source

Laser 2

Basic Differential Measurement

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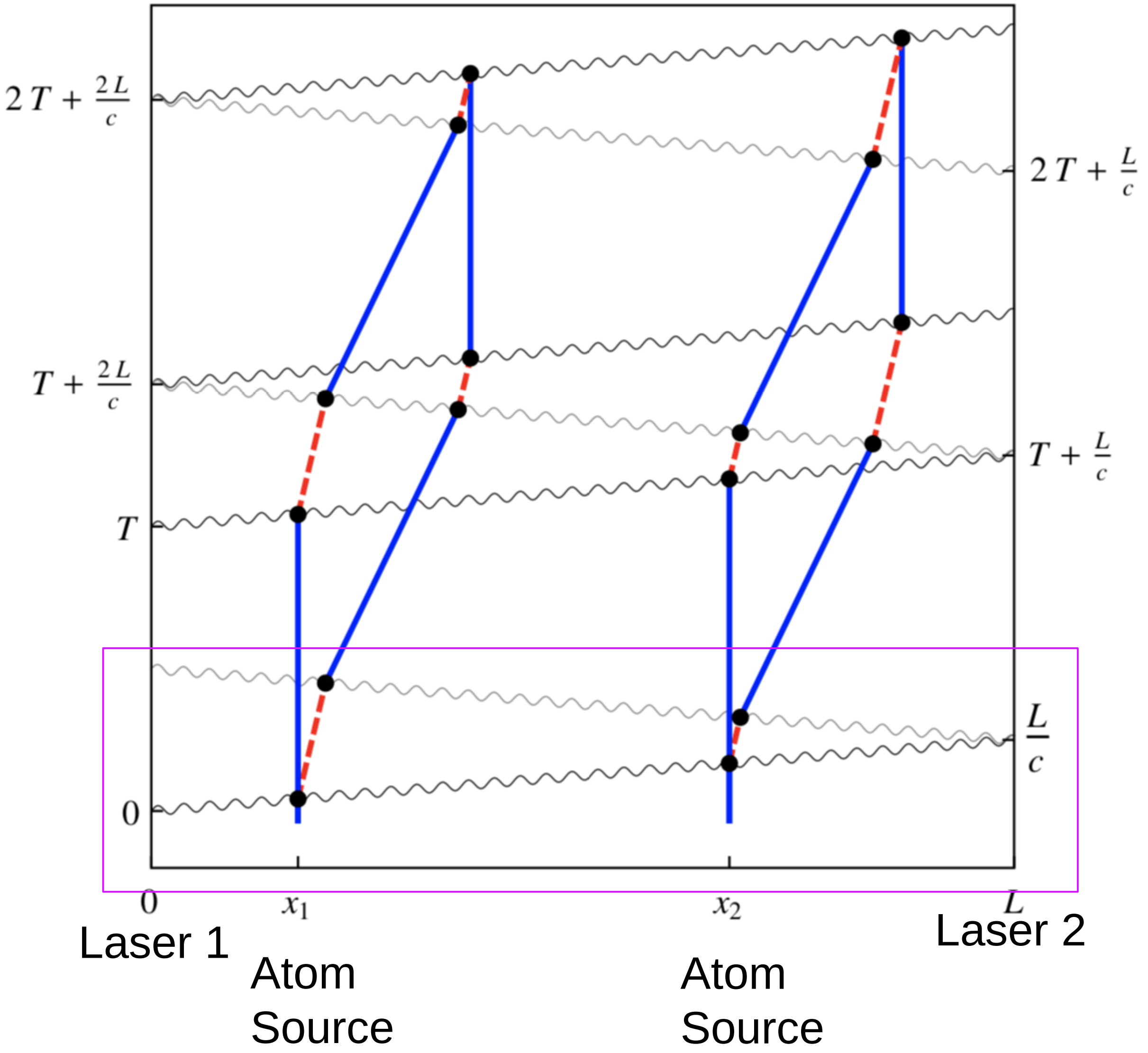
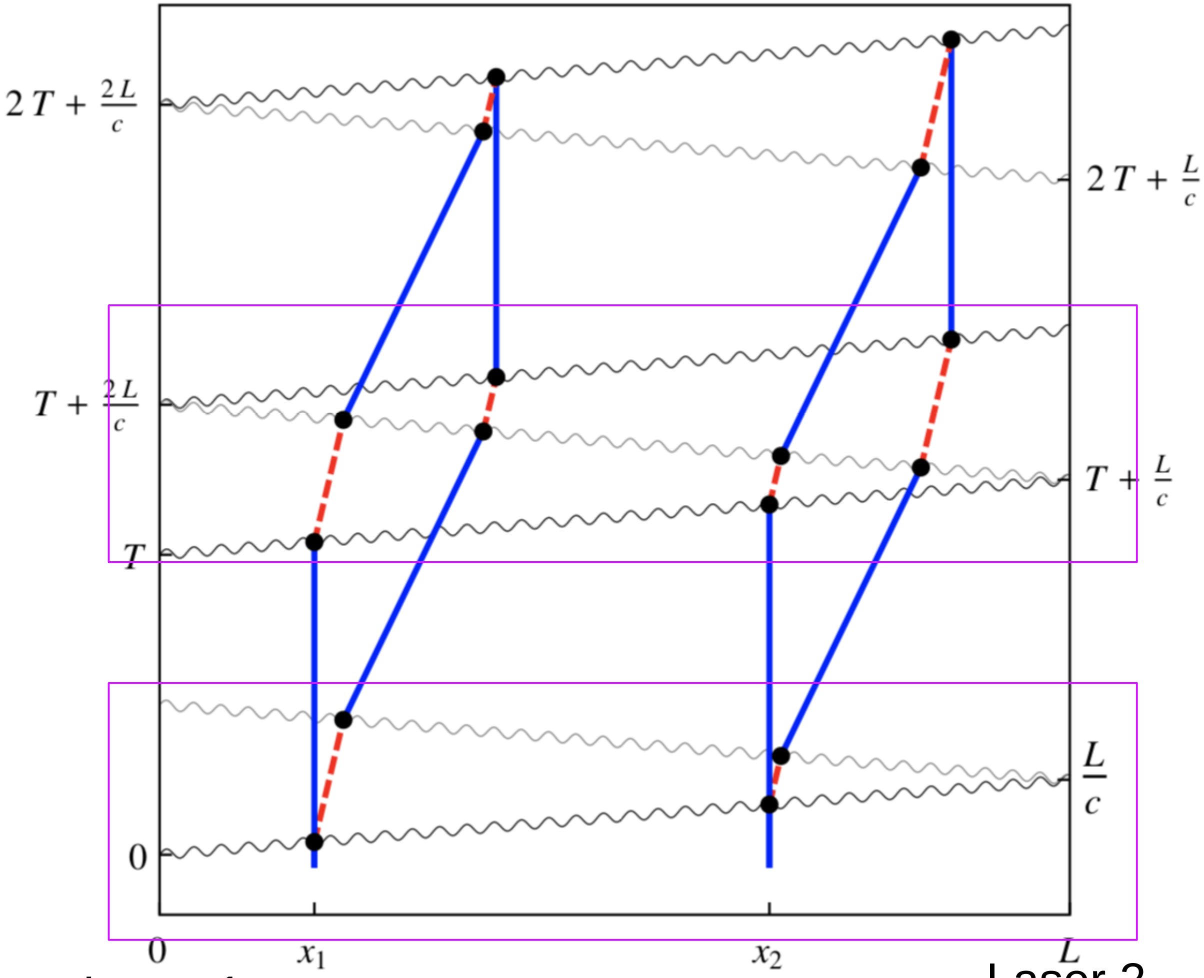


Laser 2: π pulse [high p]

Laser 1: π/2 pulse [split]

Basic Differential Measurement



Laser 1

Atom
Source

Atom
Source

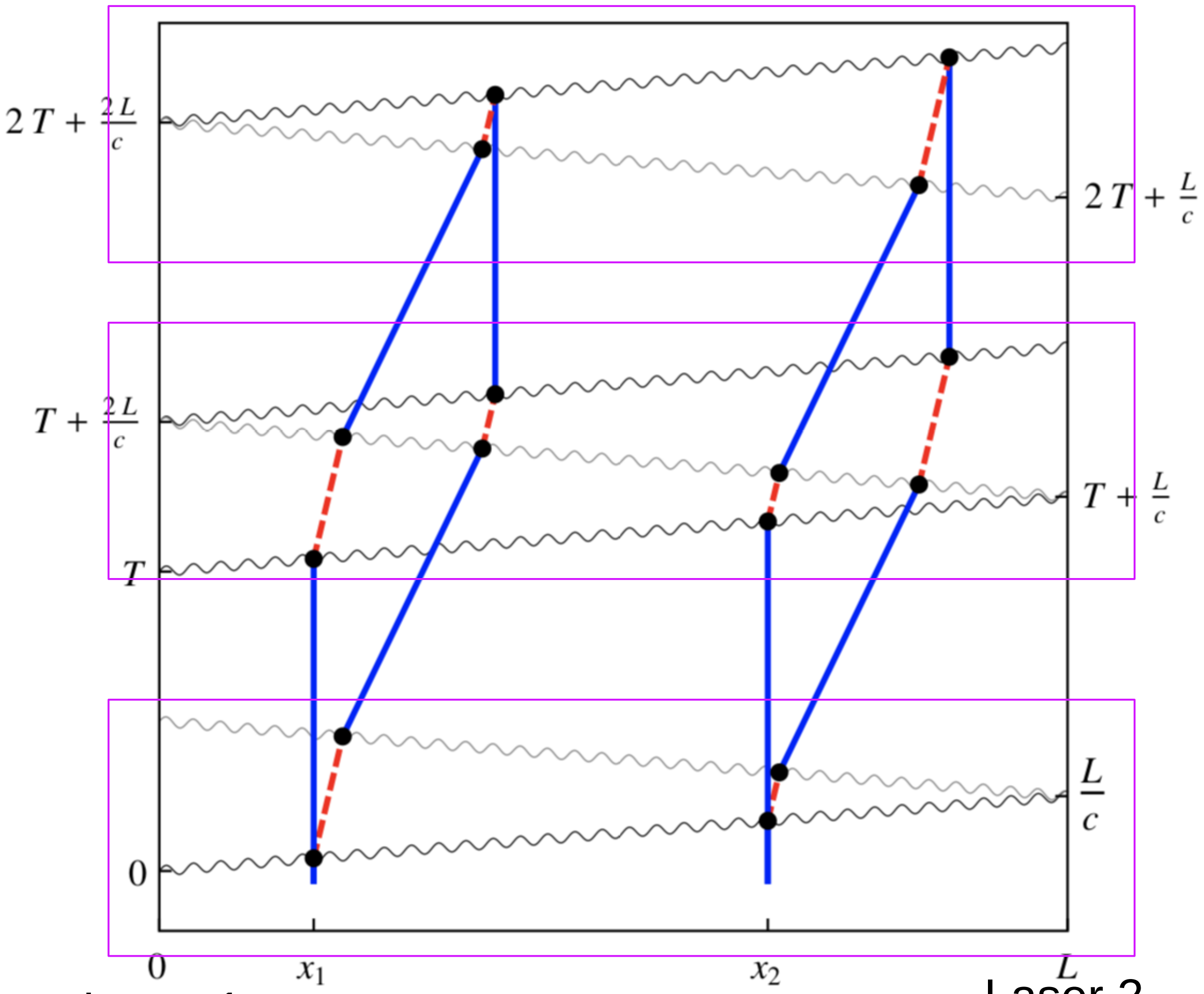
Laser 2

“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

Atom Source

Atom Source

Laser 2

Laser 1: π/2 pulse [split]

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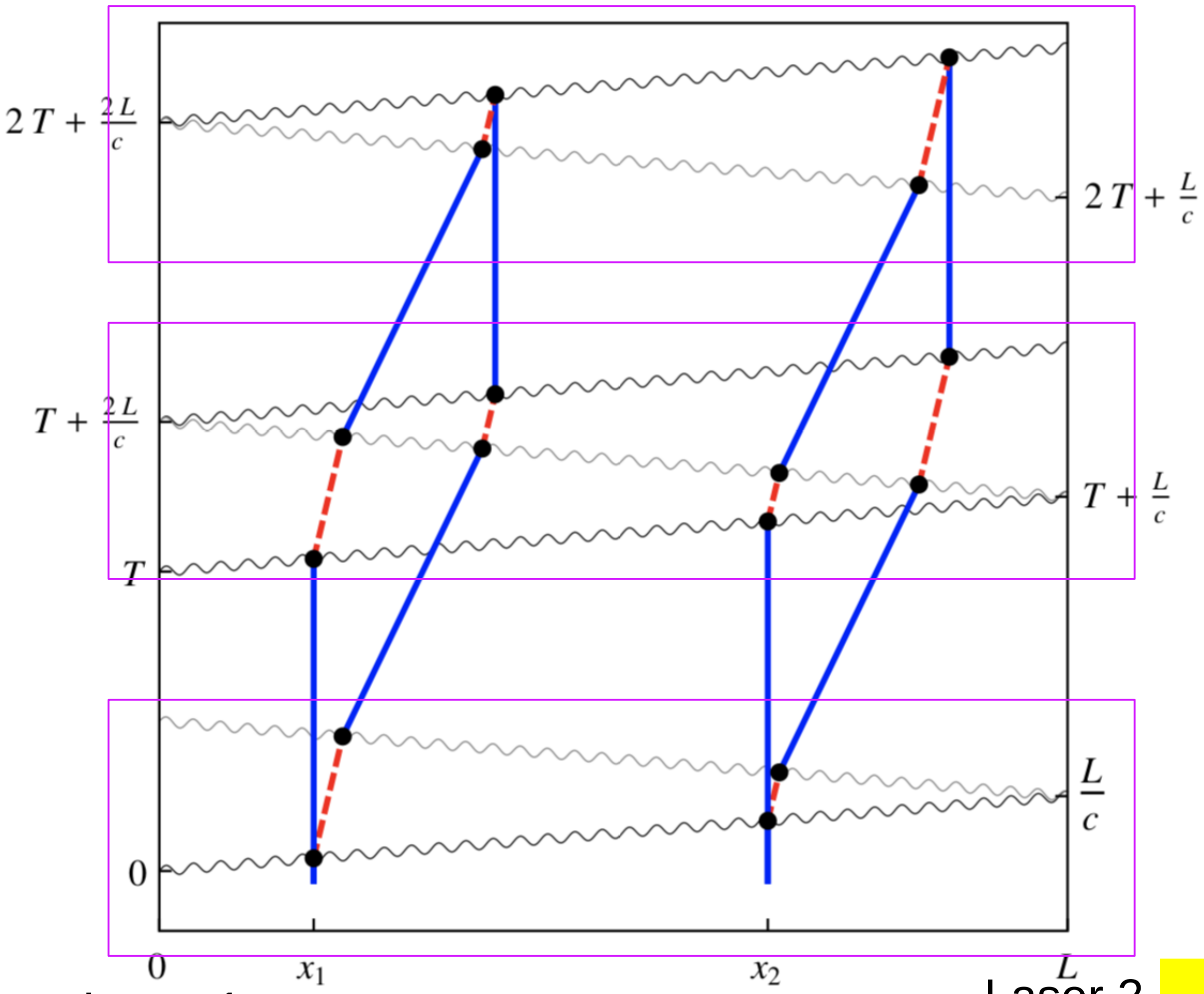

Laser 1: π/2 pulse [split]

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Laser 2: π pulse [high p]

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Laser 1

Atom Source

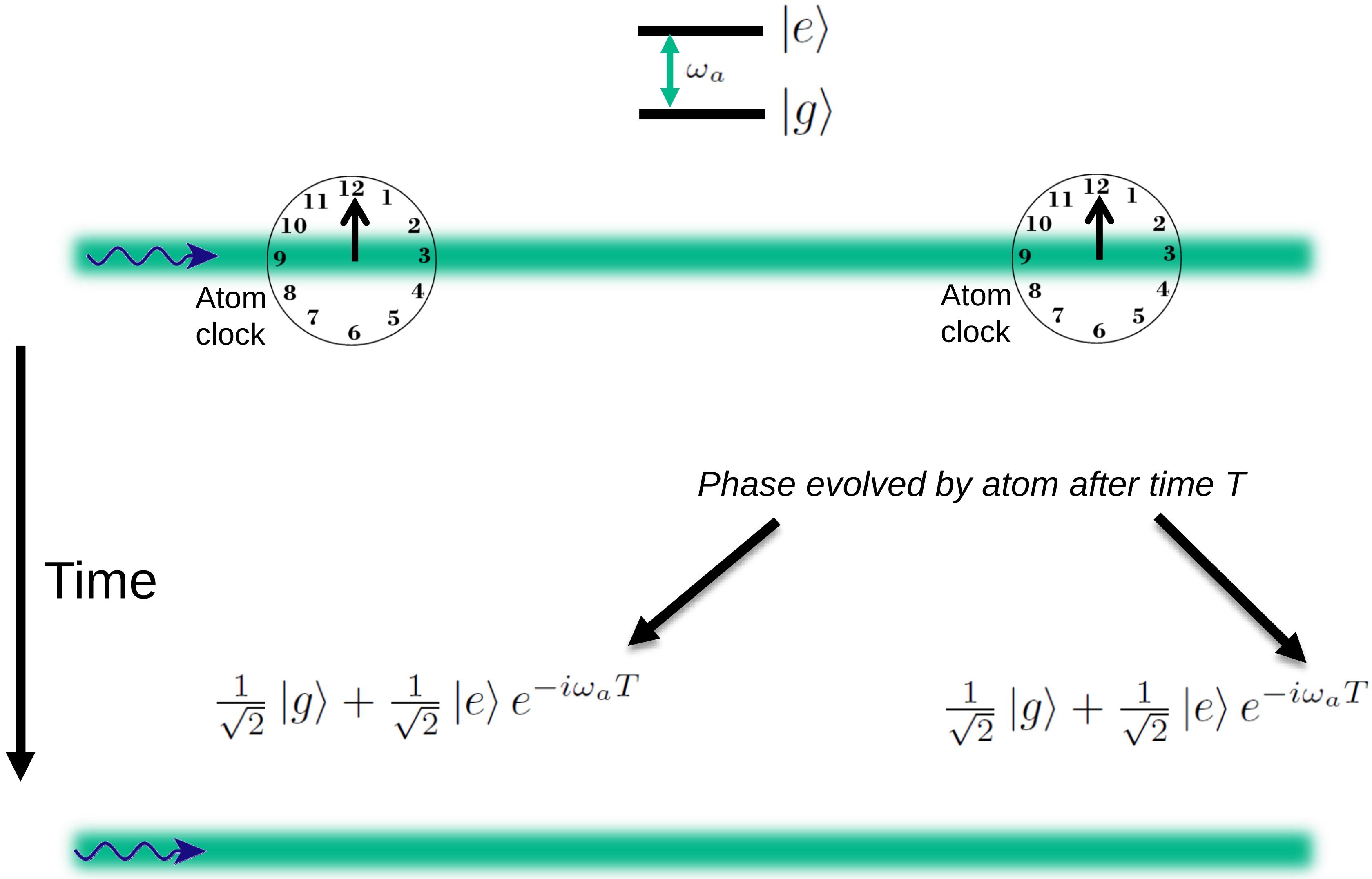
Atom Source

Laser 2

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

Simple Example: Two Atomic Clocks

O. Buchmueller The AION Project

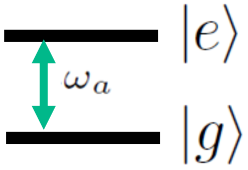


Phase evolved by atom after time T

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

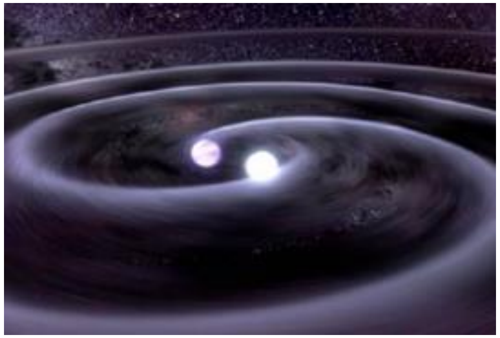
$$\frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle\,e^{-i\omega_a T}$$

Simple Example: Two Atomic Clocks



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

Time



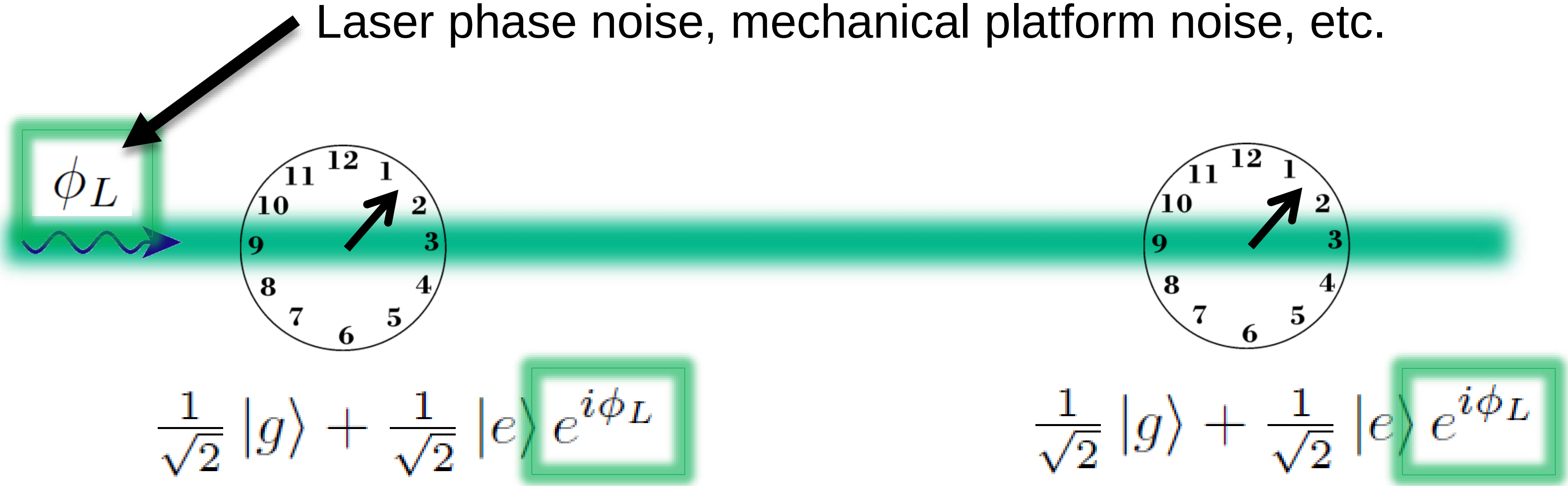
GW changes light travel time

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

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

Phase Noise from the Laser

The phase of the laser is imprinted onto the atom.



Laser phase noise, mechanical platform noise, etc.

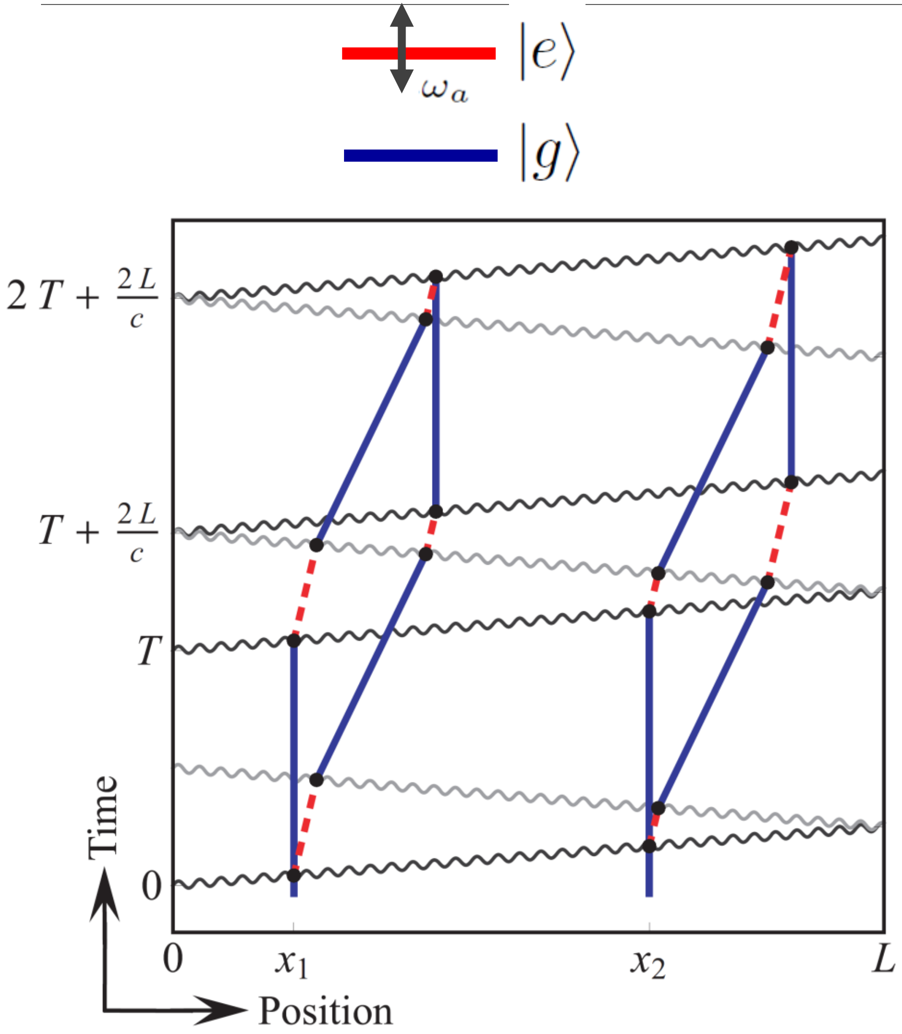
ϕ_L

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

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

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

Clock gradiometer



Excited state phase evolution:

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

Two ways for phase to vary:

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

Each interferometer measures the change over time T

Laser noise is common-mode suppressed in the gradiometer

Graham et al., PRL **110**, 171102 (2013).
Arvanitaki et al., PRD **97**, 075020 (2018).

COLLABORATION WITH US (VIA MAGIS)

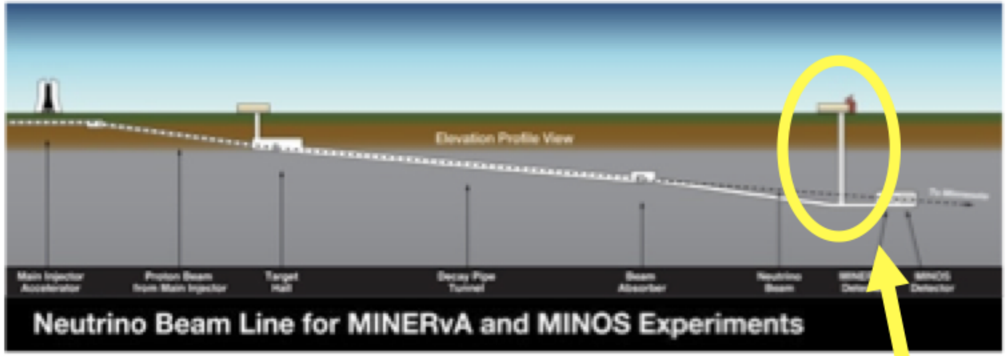
International Collaboration

- From the outset this project would greatly benefit from close collaboration on an international level with the US initiative, MAGIS-100, which pursues a similar goal of an eventual km-scale atom interferometer on a comparable timescale.
- The option of operating two AI detectors, one in the UK and one in the US, in tandem enables new exciting physics opportunities not accessible to either AI detector alone.
- A collaboration with AION by the MAGIS experiment has already been endorsed by the community at Fermilab, presenting the UK with an immediate window of scientific opportunity.
- This US-UK collaboration will serve as the testbed for full-scale terrestrial (kilometre-scale) and satellite-based (thousands of kilometres scale) detectors and build the framework for global scientific leadership in this area.

MAGIS-100: GW detector prototype at Fermilab

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

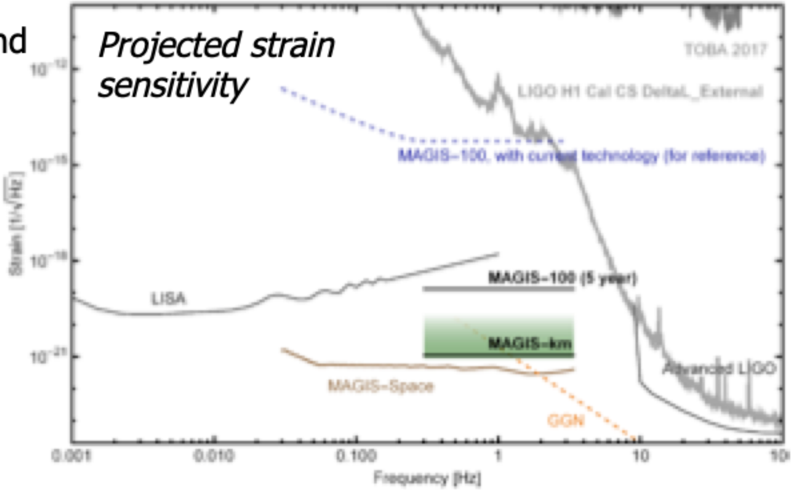
- 100-meter baseline atom interferometry at Fermilab (MINOS access shaft)
- Intermediate step to full-scale (km) detector for gravitational waves

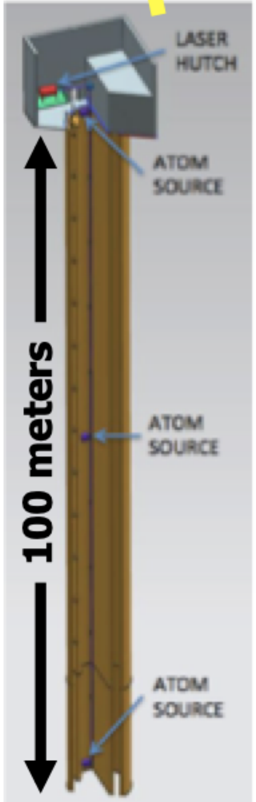


Neutrino Beam Line for MINERvA and MINOS Experiments

Mid-band science

- LIGO sources before they reach LIGO band
- Optimal for sky localization: predict when and where inspiral events will occur (for multi-messenger astronomy)
- BH, NS, WD binaries
- Probe for studying cosmology
- Search for dark matter (dilaton, ALP, …)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration





Timeline

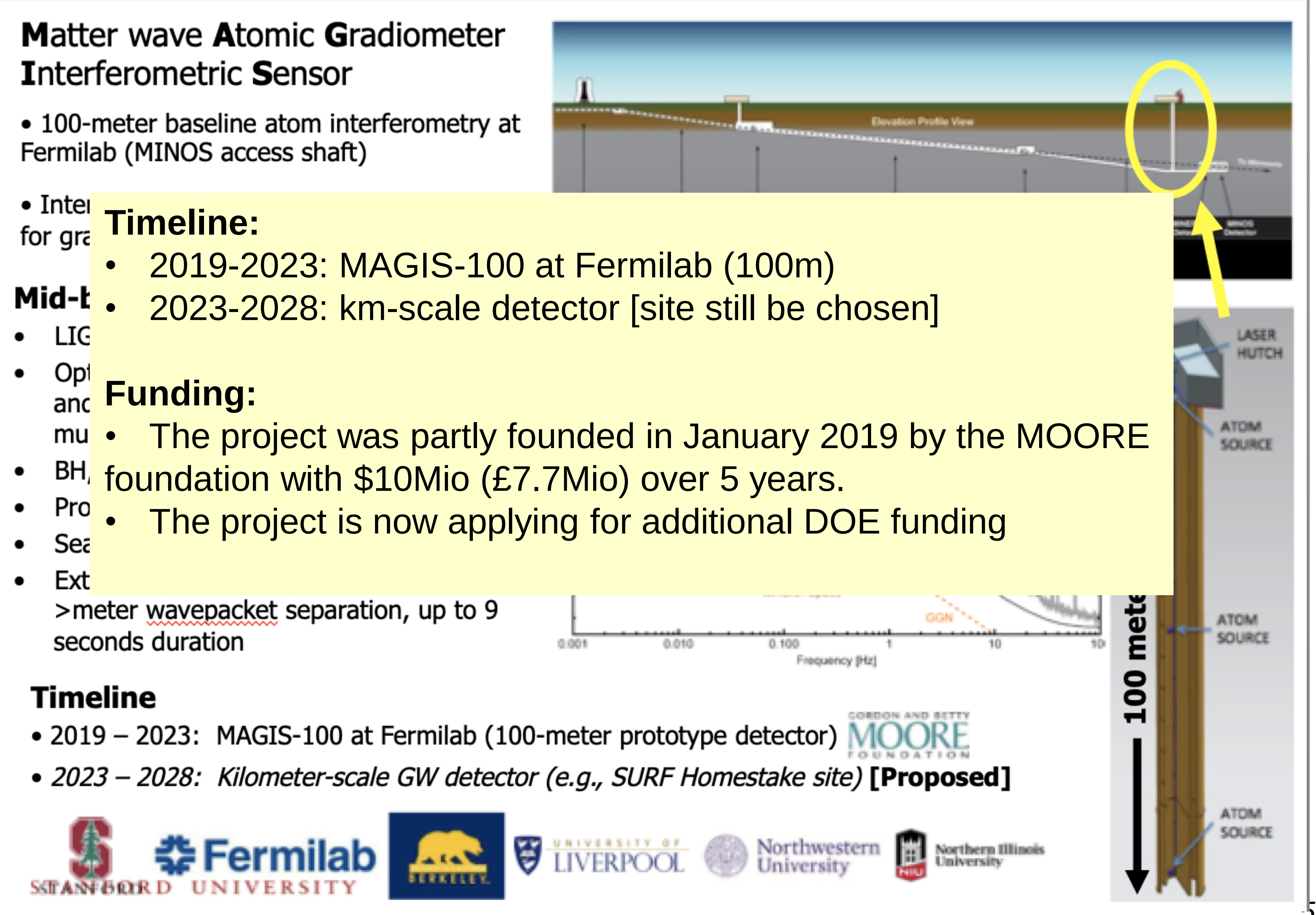
- 2019 – 2023: MAGIS-100 at Fermilab (100-meter prototype detector)
- *2023 – 2028: Kilometer-scale GW detector (e.g., SURF Homestake site)* **[Proposed]**

GORDON AND BETTY MOORE FOUNDATION

STANFORD UNIVERSITY Fermilab BERKELEY UNIVERSITY OF LIVERPOOL Northwestern University NIU Northern Illinois University

Courtesy of Jason Hogan!

MAGIS-100: GW detector prototype at Fermilab



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

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- Inte for gra

Mid-b

- LIG
- Opt and mu
- BH,
- Pro
- Sea
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Timeline:

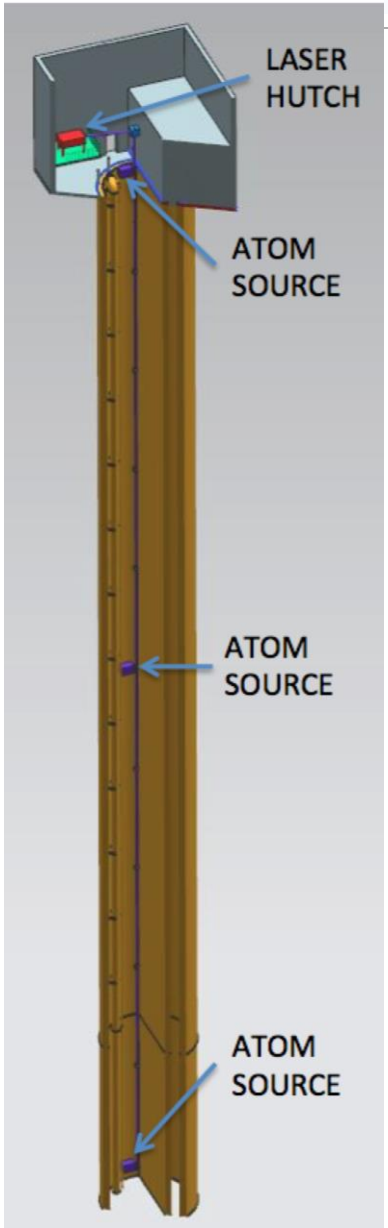
- 2019-2023: MAGIS-100 at Fermilab (100m)
- 2023-2028: km-scale detector [site still be chosen]

Funding:

- The project was partly founded in January 2019 by the MOORE foundation with $10Mio (£7.7Mio) over 5 years.
- The project is now applying for additional DOE funding

Courtesy of Jason Hogan!

MAGIS-100 Design

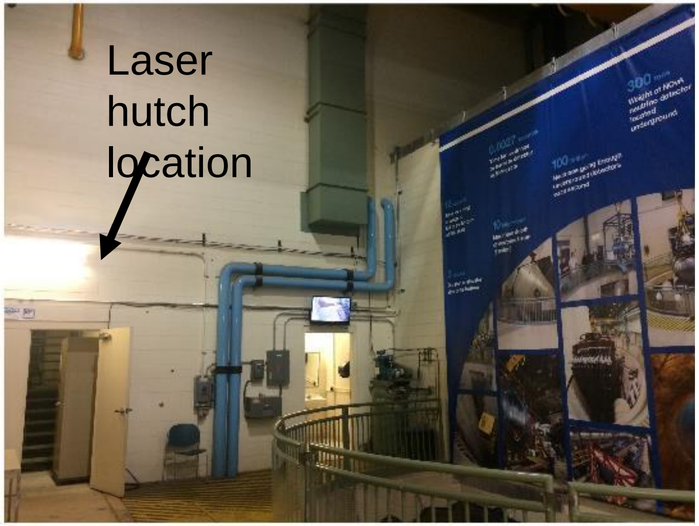


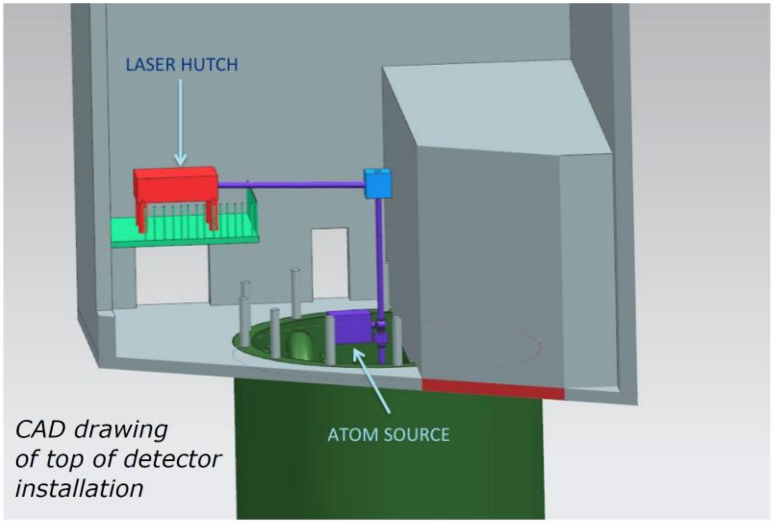
System Components:

~90 meter vacuum tube (vertical)

Atoms sources (three, attached to tube)

Laser system for implementing atom interferometry (hutch at top)

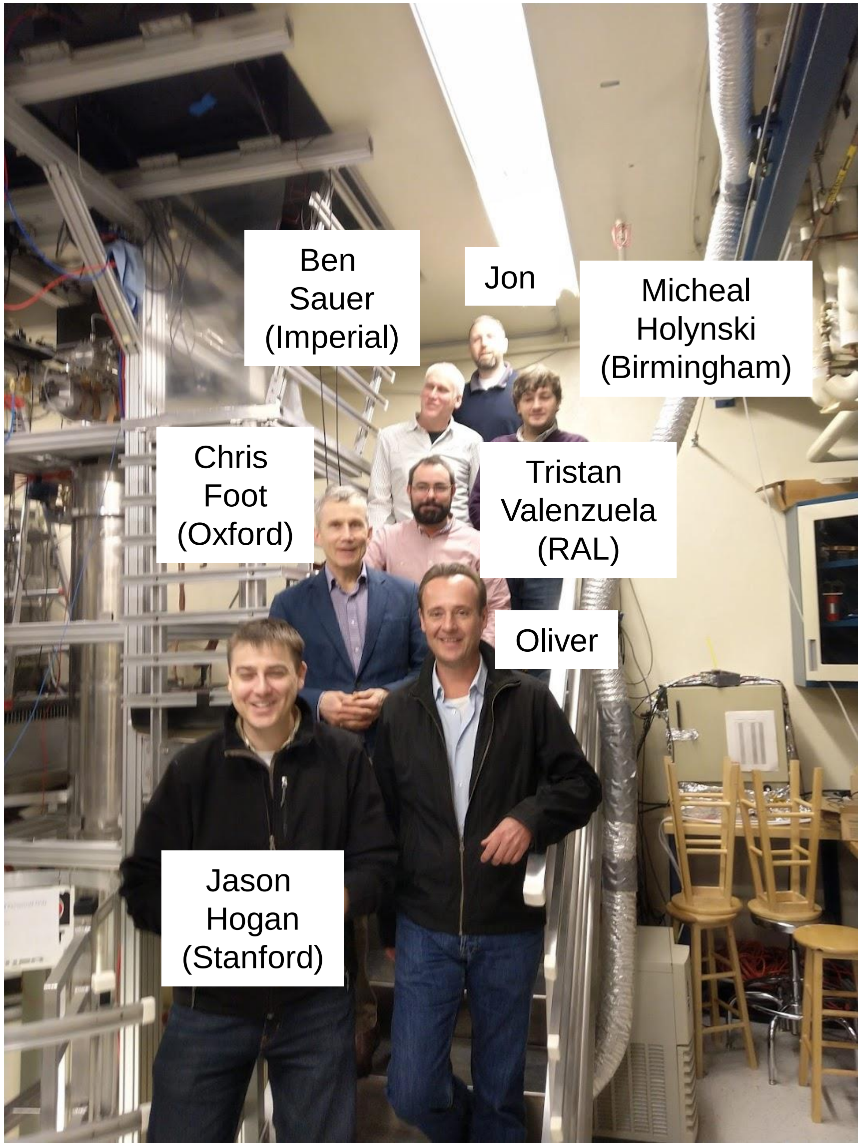




CAD drawing of top of detector installation

VISIT TO STANFORD ON 10/11 JANUARY 2019

Stanford Visit 10/11 January 2019



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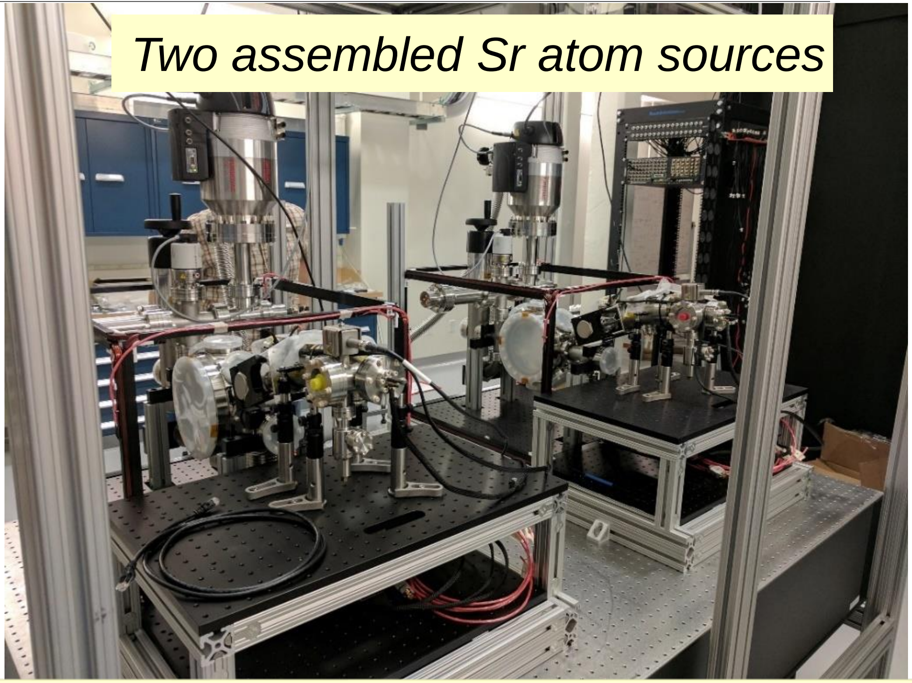
Stanford MAGIS prototype



Two assembled Sr atom sources

Stanford Lab to host 8 m prototype of the Sr fountain.

It is supposed to be assembled over summer 2019.

AION FUNDING PROPOSAL: WORK PACKAGES

First AION Workshop at Imperial College London March 25/26 2019

AI
ON

Organised by:
T. Bowcock,
O. Buchmueller [Coord.],
J. Coleman,
J. Ellis [Theory],
I. Shipsey

2-Day Workshop:
Day 1: Instrumentation
Day 2: Physics case

If you like to participate or require further information please contact: fundamental-physics-admin@imperial.ac.uk with “AION” in title.

Please register at:
http://www.hep.ph.ic.ac.uk/AION2019/

AION10 [Stage 1]: Work Packages in a Nutshell

WP-AI

- Form UK collaboration to design and construct AION1 and AION10 and establish a first UK AION Network by building AION-1 in selected places.
- Prototype AION-10 to demonstrate the technology and to establish UK expertise and leadership in the field.
- Commission AION-10, compare with AION-1 Network and perform synchronised measurement campaigns with MAGIS.
- Connect to UK QTH to develop techniques and technology required to reach performance for realising science goals, in collaboration with developments in the MAGIS consortium.

WP-Physics

- Establish physics programme for AION-1/10 Network.
- Physics exploitation of AION-1/10 Network
- Contribute to work establishing the physics case for AION-100 and beyond.
- Support phenomenology for AION physics case.

WP-AION100

- Work towards AION-100 including design work for AION-100 in a tower or a shaft and establish the physics case.

WP-MAGIS

- Collaborate with MAGIS-100 to contribute to experiment & exploitation
- Build the foundation of a strong and lasting collaboration with US.

AION10 [Stage 1]: Work Packages in a Nutshell

WP-AI

Pathway to technology and expertise and will form a first network of AI's in the UK.

WP-Physics

This will give us physics & phenomenology

Support phenomenology both for AI in general and AION physics case.

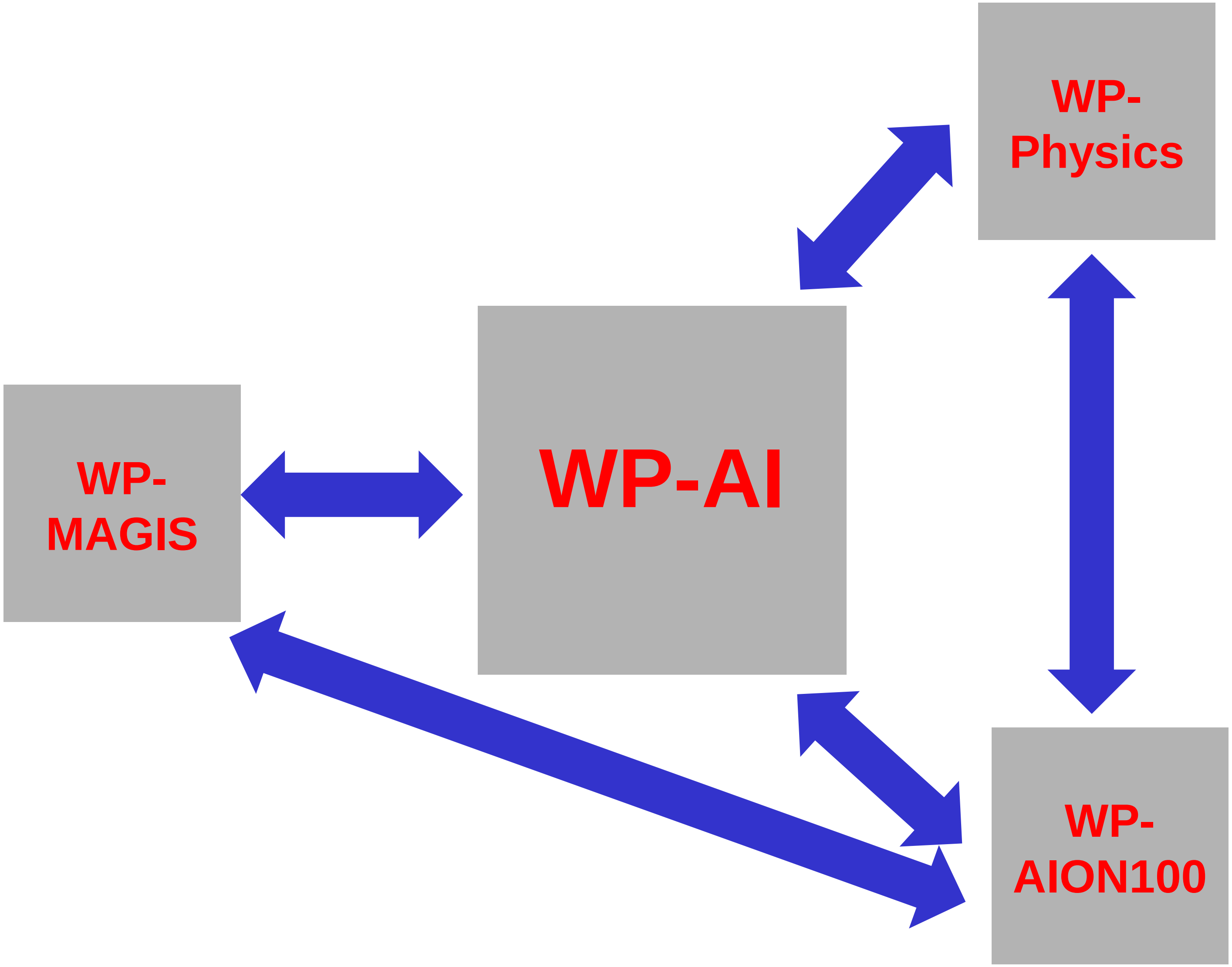
WP-AION100

This will give us the path into the future (next bid)

WP-MAGIS

This will give us MAGIS and US Collaboration

AION10 [Stage 1]: Main WP Connections



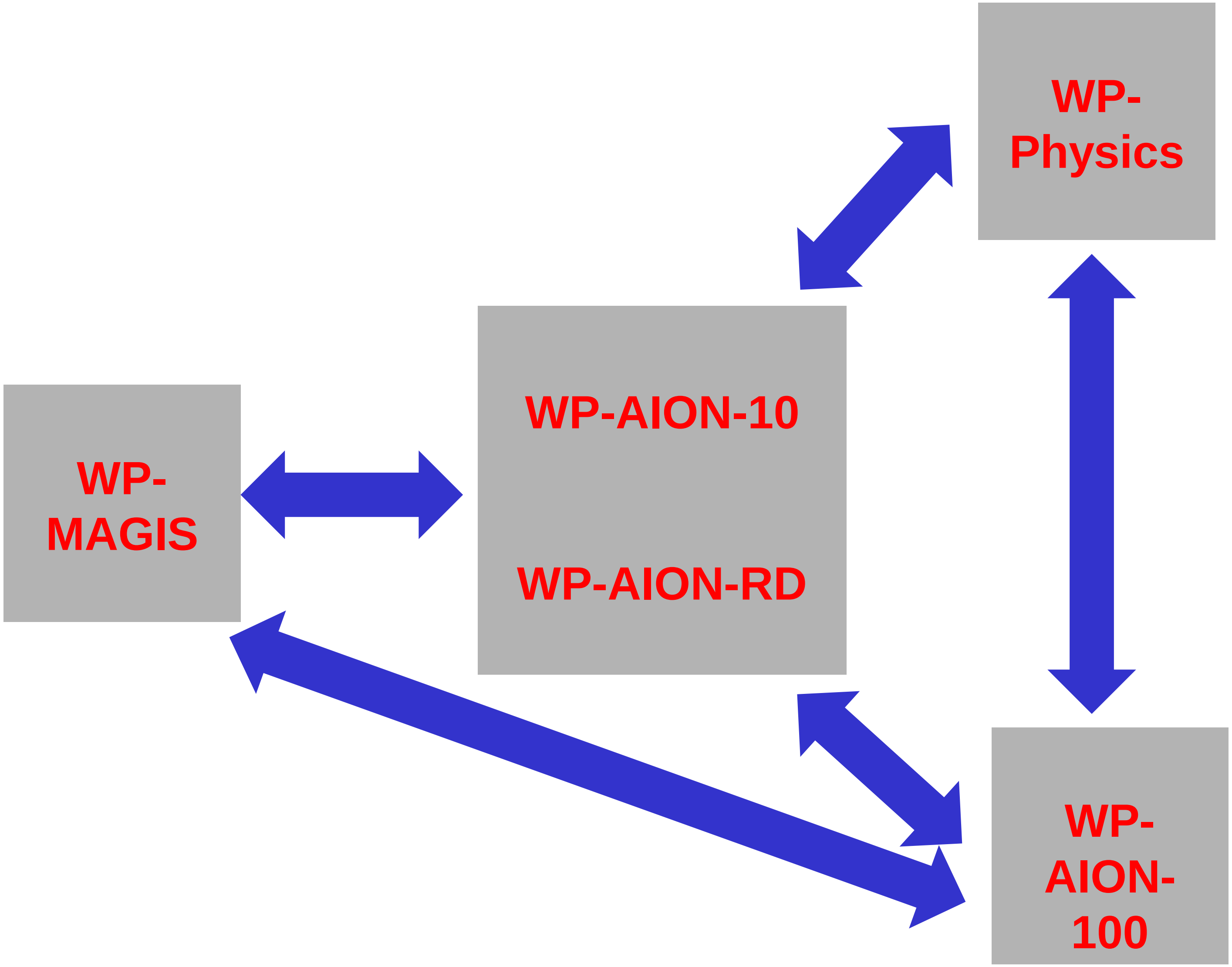
WP-Physics

WP-MAGIS

WP-AI

WP-AION100

AION10 [Stage 1]: Main WP Connections



WP-Physics

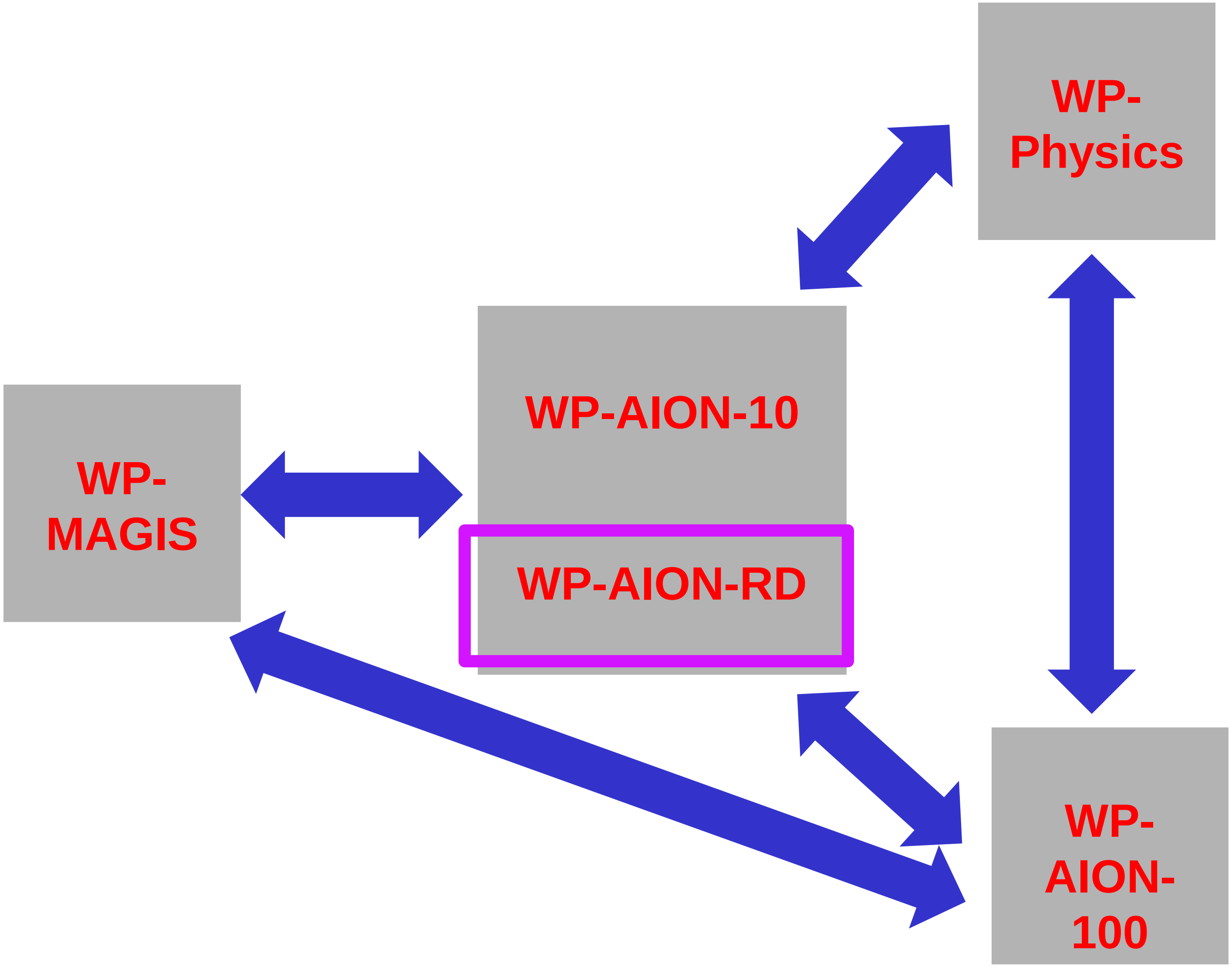
WP-AION-10

WP-AION-RD

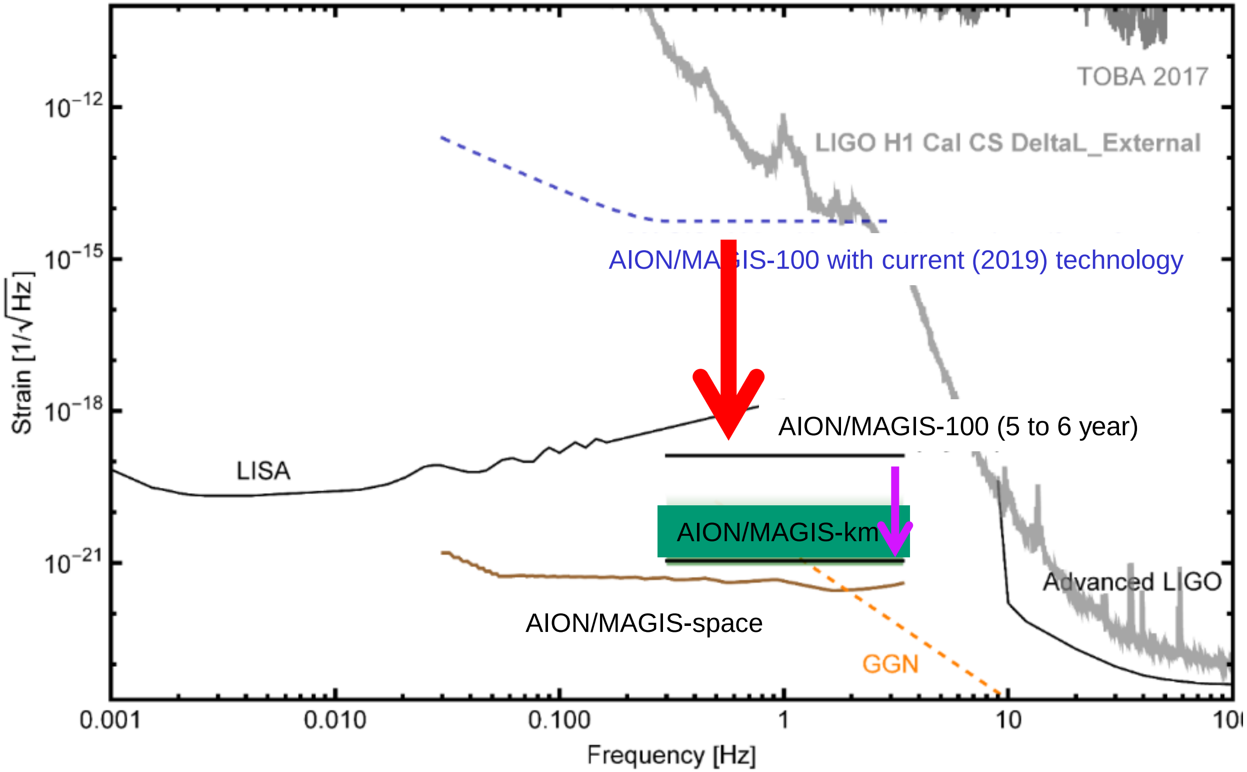
WP-MAGIS

WP-AION-100

AION10 [Stage 1]: Main WP Connections



What are the challenges?



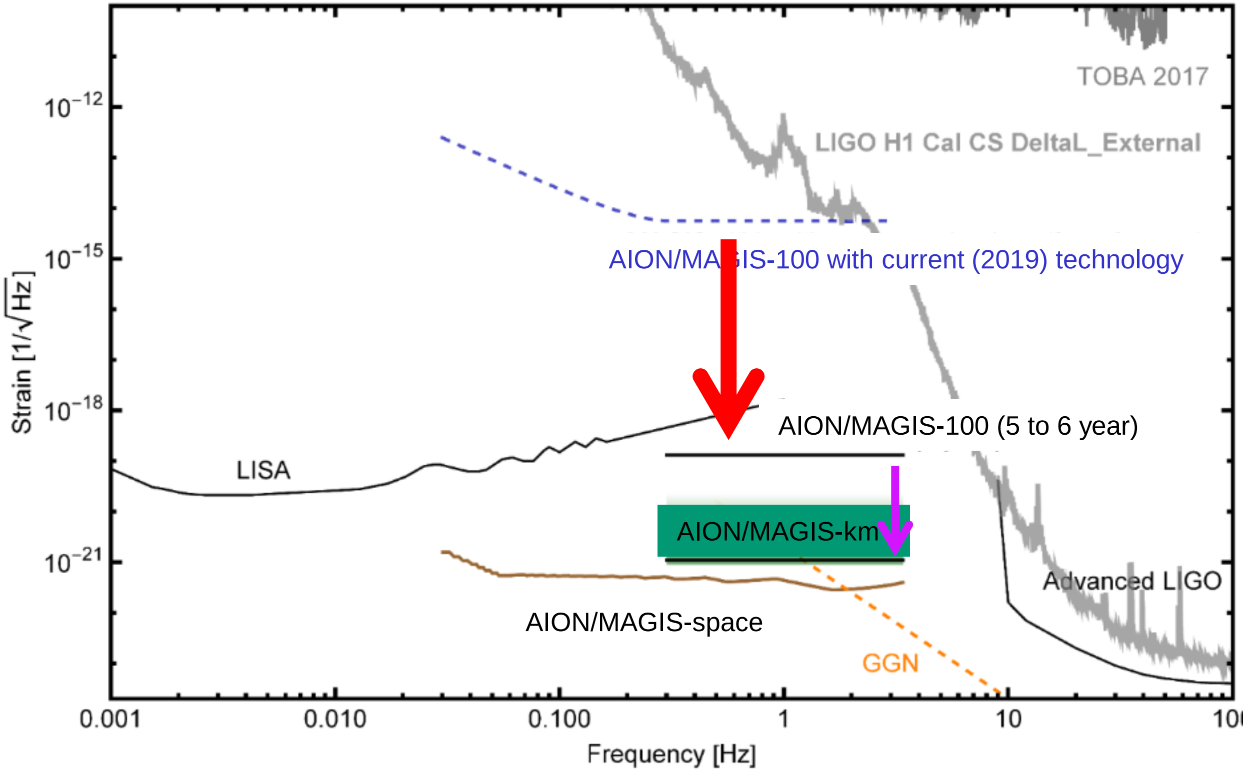
Still several orders of Magnitude away in sensitivity required to be sensitive to Mid-band GW physics!

Need to push the basic parameters to accomplish this goal! Although there is a clear path forward this won't be a free lunch and it will require effort and ingenuity!

	AION/MAGIS-100 current	AION/MAGIS-100 5/6 year	AION/MAGIS-km
Baseline	100 m	100 m	2 km
Phase noise	$10^{-3}/\sqrt{\mathrm{Hz}}$	$10^{-5}/\sqrt{\mathrm{Hz}}$	$0.3 \times 10^{-5}/\sqrt{\mathrm{Hz}}$
LMT	100	4e4	4e4
Atom sources	3	3	30

The UK community could play an important role to accomplish this goal, which, in turn, can accelerate the schedule and minimize the risk of failure

What are the challenges?



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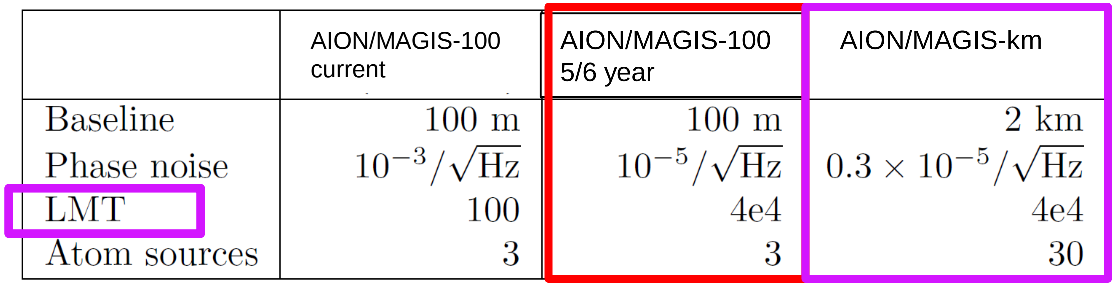

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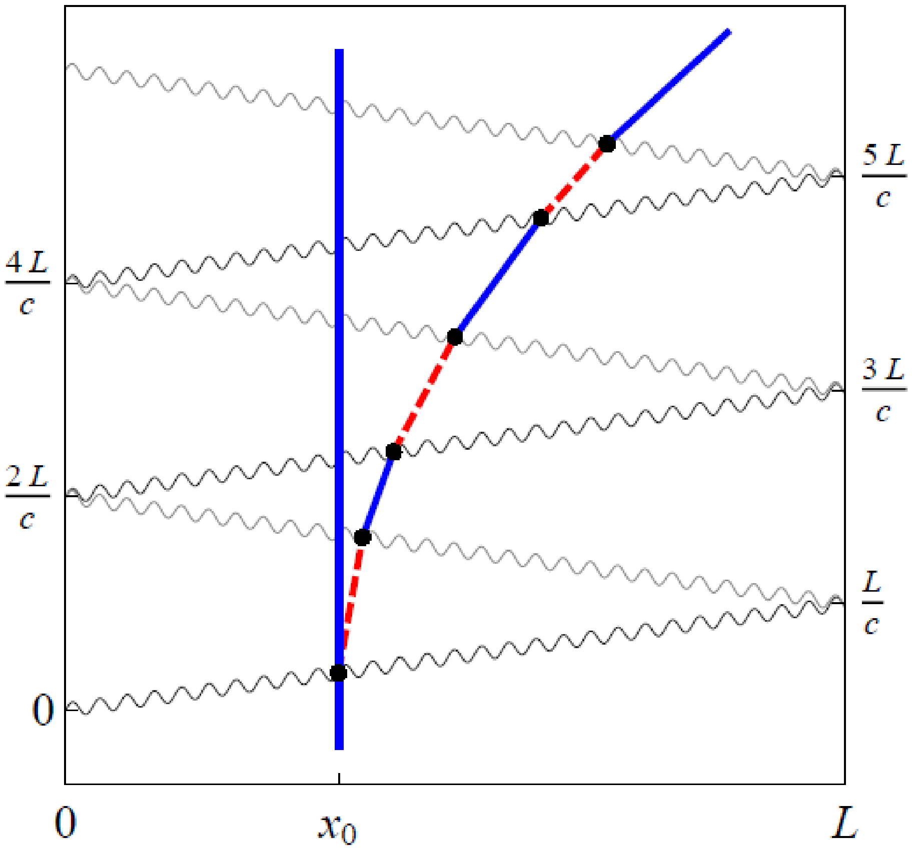
LMT and Resonant Pulse Sequences

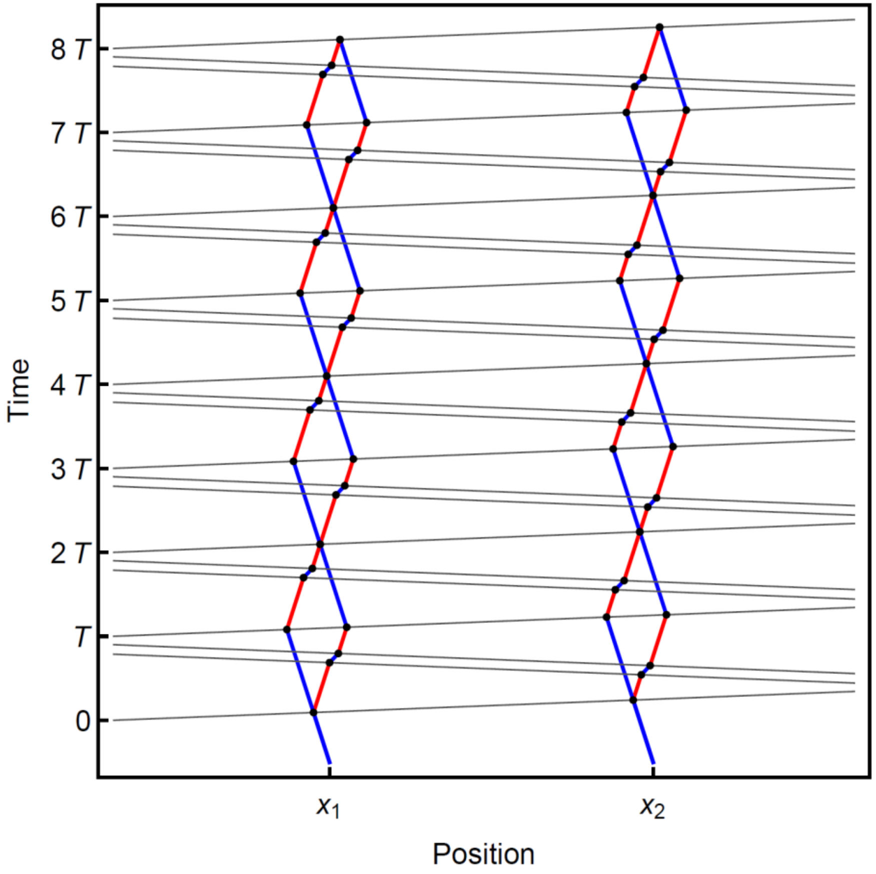
Large Momentum Transfer (LMT): Sequential single-photon transitions remain laser noise immune

LMT beamsplitter (N = 3)



Graham, *et al.*, PRL (2013)

Resonant sequence (Q = 4)



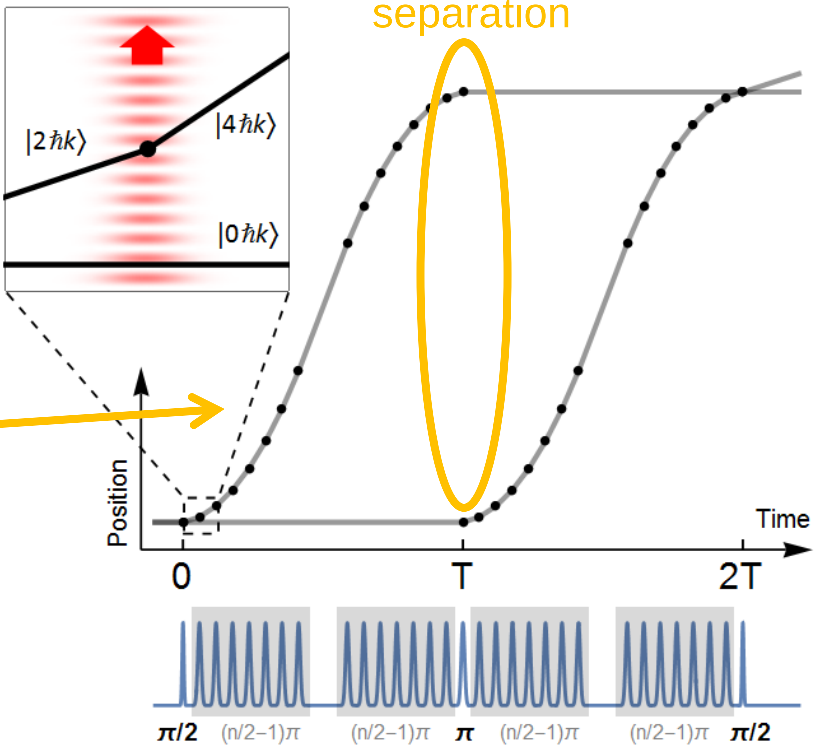
Graham, *et al.*, PRD (2016)

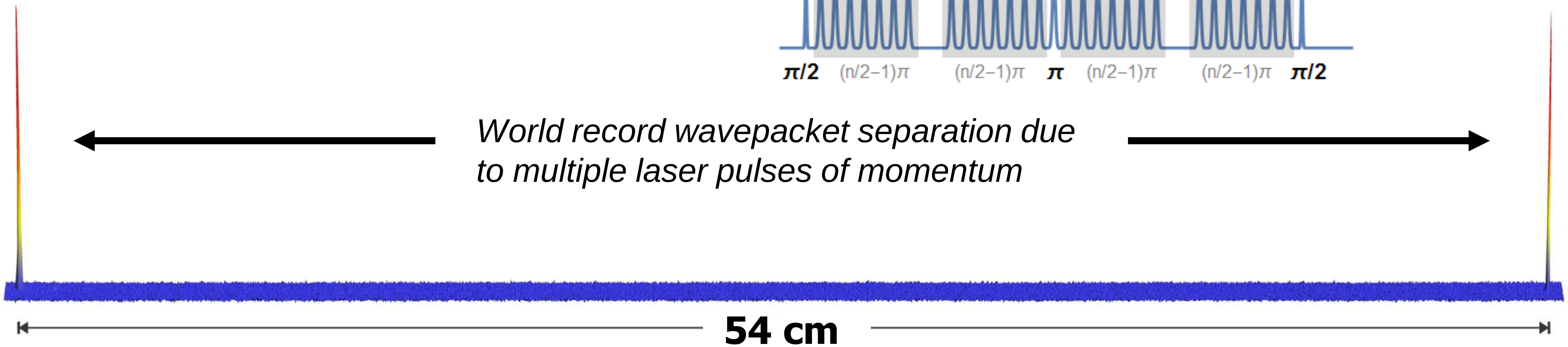
Large space-time area atom interferometry

O. Buchmueller The AION Project

Long duration (2 seconds), large separation (>0.5 meter) matter wave interferometer

90 photons worth of momentum



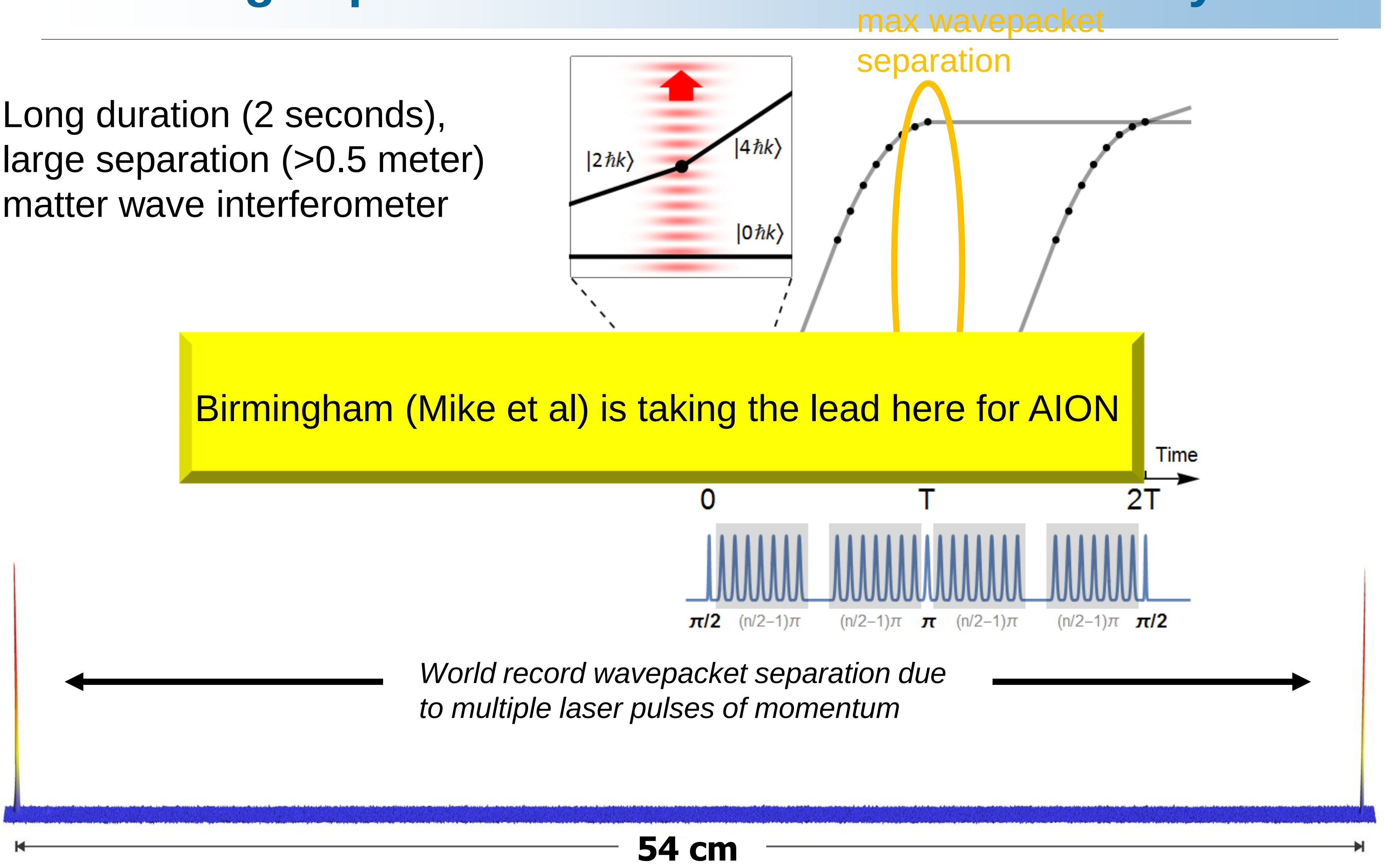


World record wavepacket separation due to multiple laser pulses of momentum

Kovachy et al., *Nature* 2015

Large space-time area atom interferometry

Long duration (2 seconds), large separation (>0.5 meter) matter wave interferometer



Birmingham (Mike et al) is taking the lead here for AION

World record wavepacket separation due to multiple laser pulses of momentum

Kovachy et al., *Nature* 2015

AION PHYSICS CASE

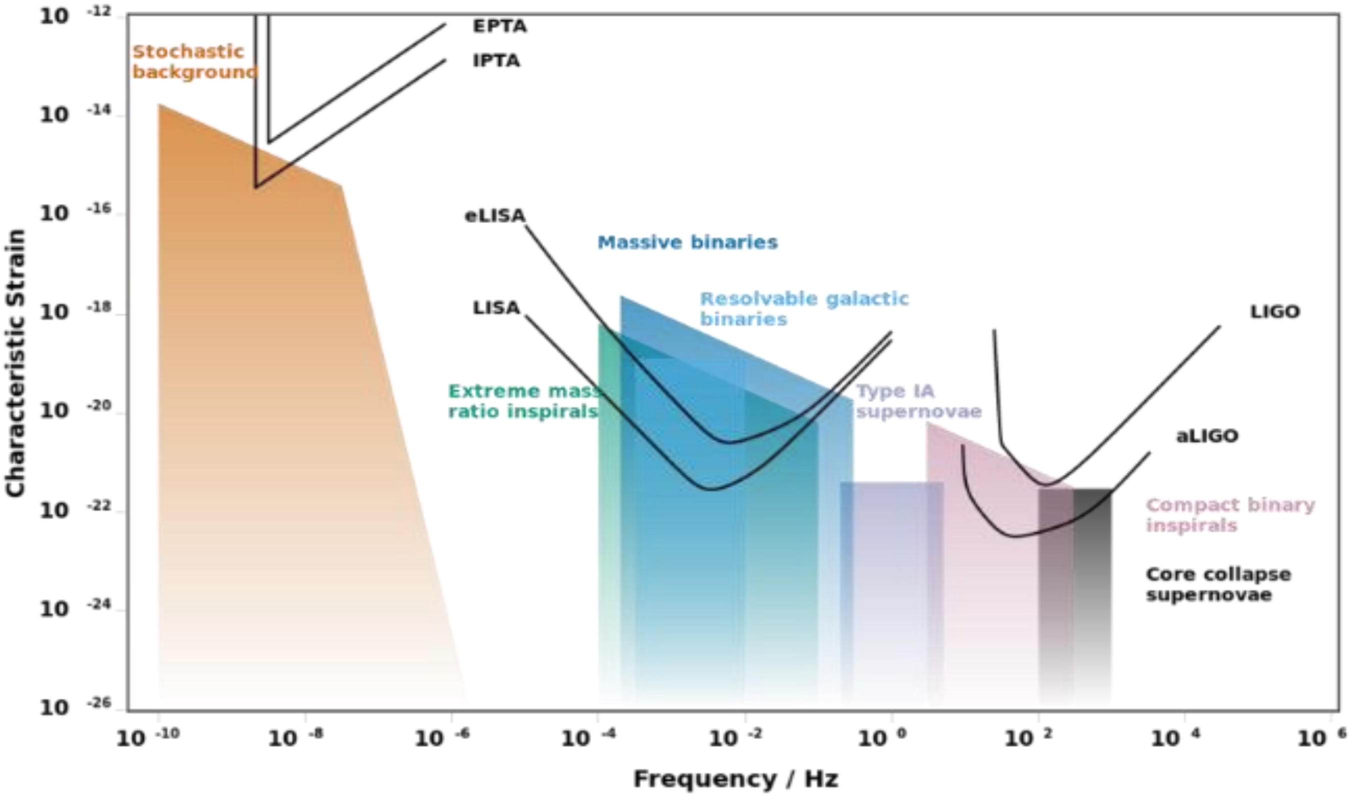
References:

- 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



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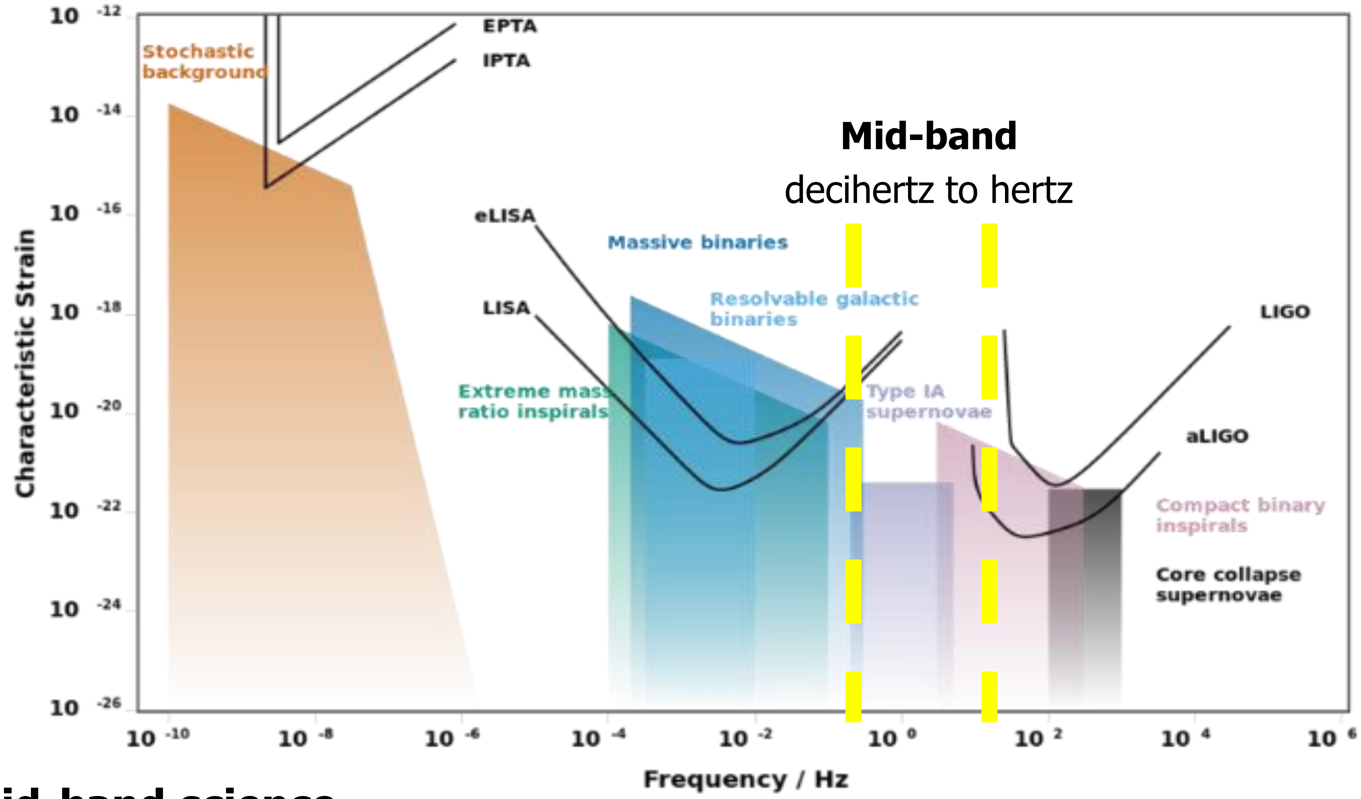


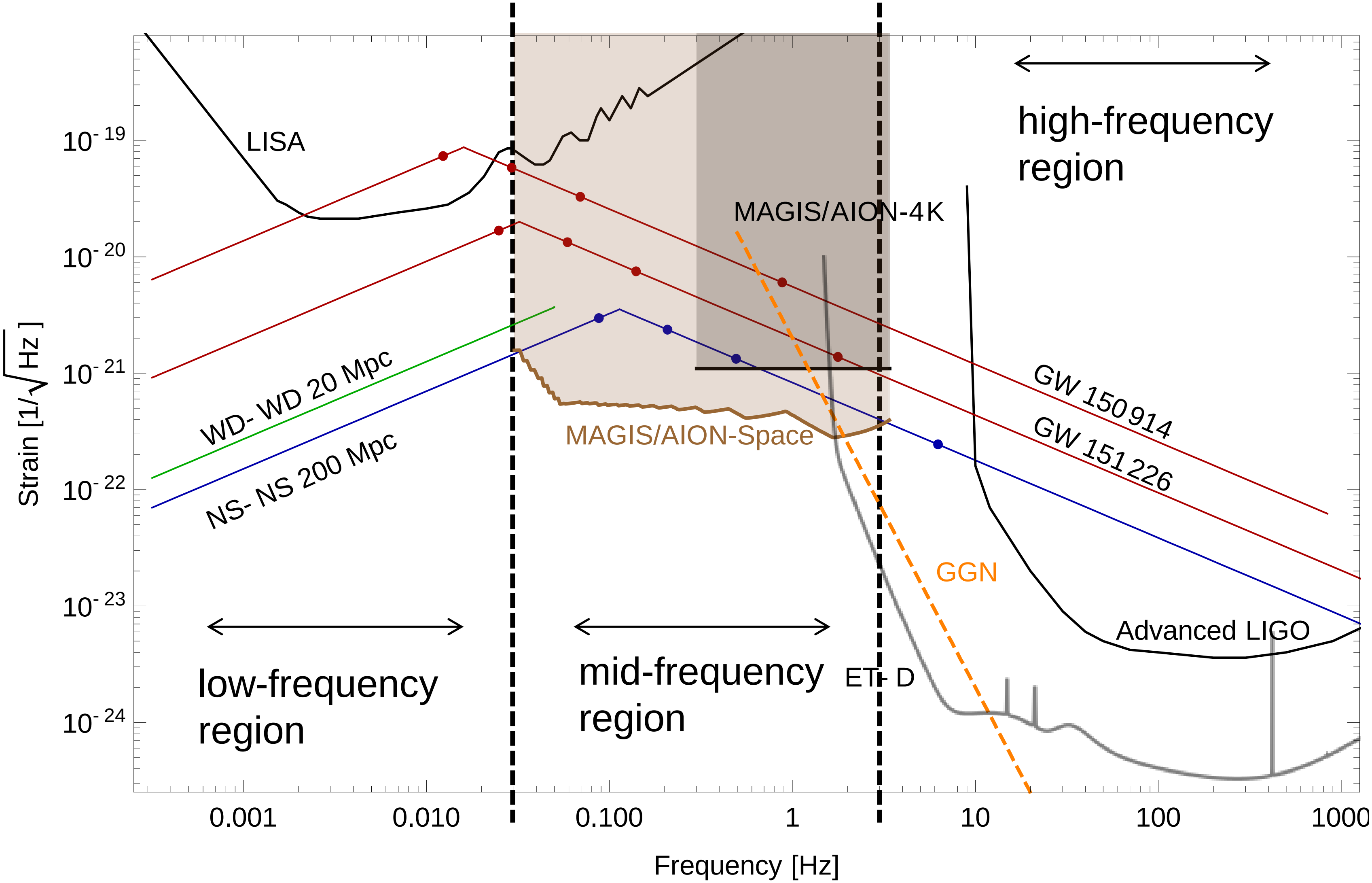
Mid-band
decihertz to hertz

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



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Sky position determination

Sky localization precision:

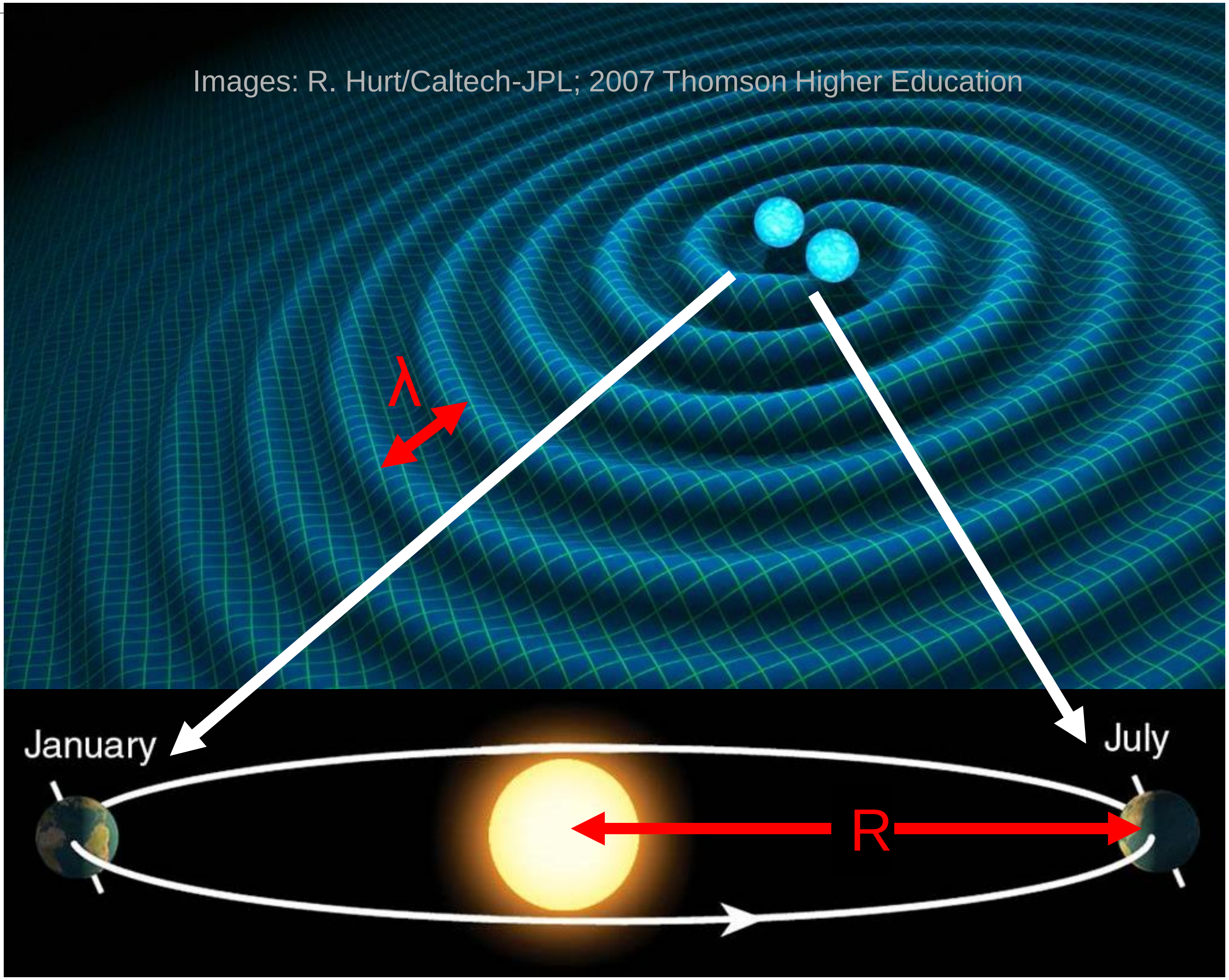
$$\sqrt{\Omega_s} \sim \left(\mathrm{SNR} \cdot \frac{R}{\lambda}\right)^{-1}$$

Mid-band advantages

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

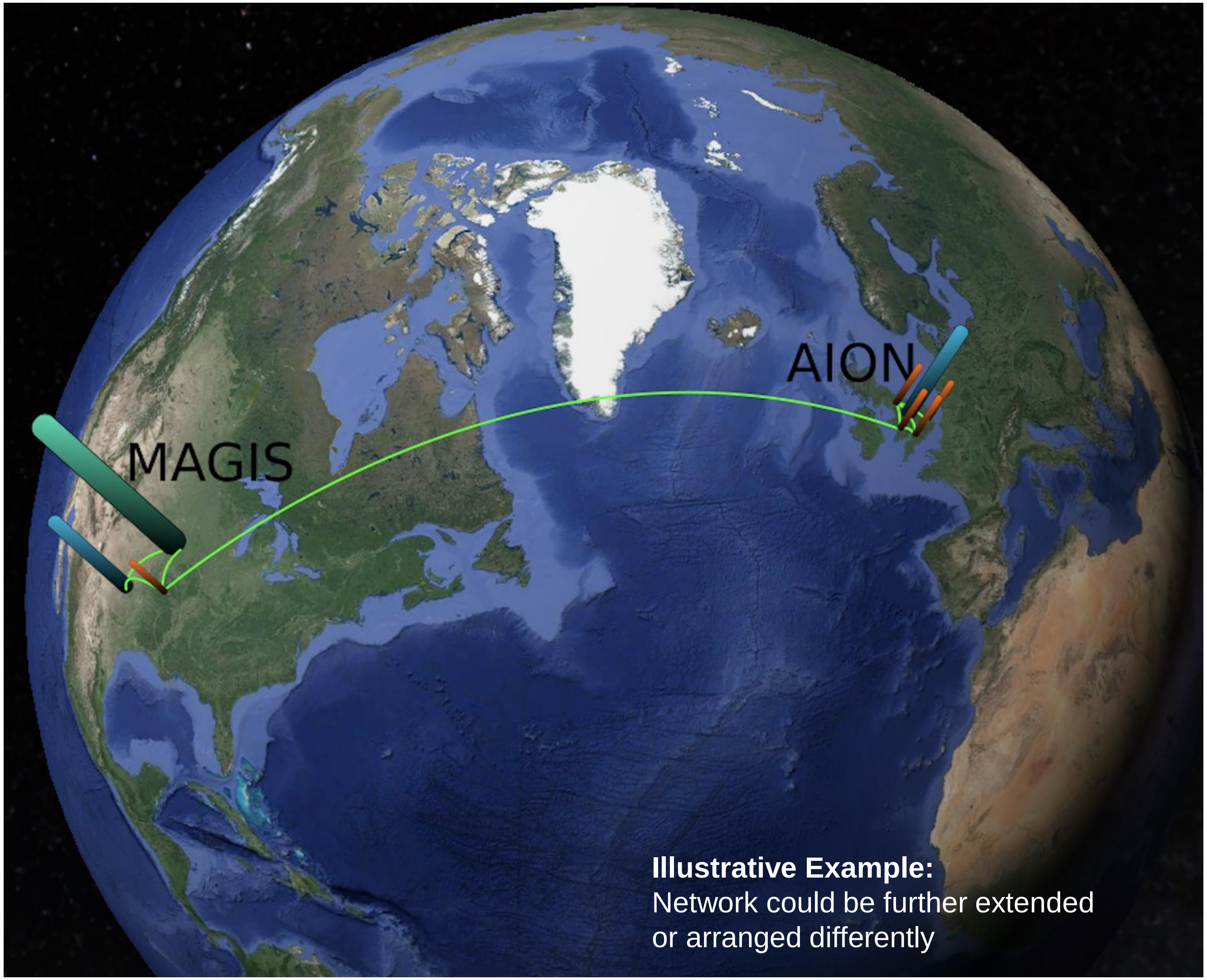
Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19

Courtesy of Jason Hogan!


Images: R. Hurt/Caltech-JPL; 2007 Thomson Higher Education

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

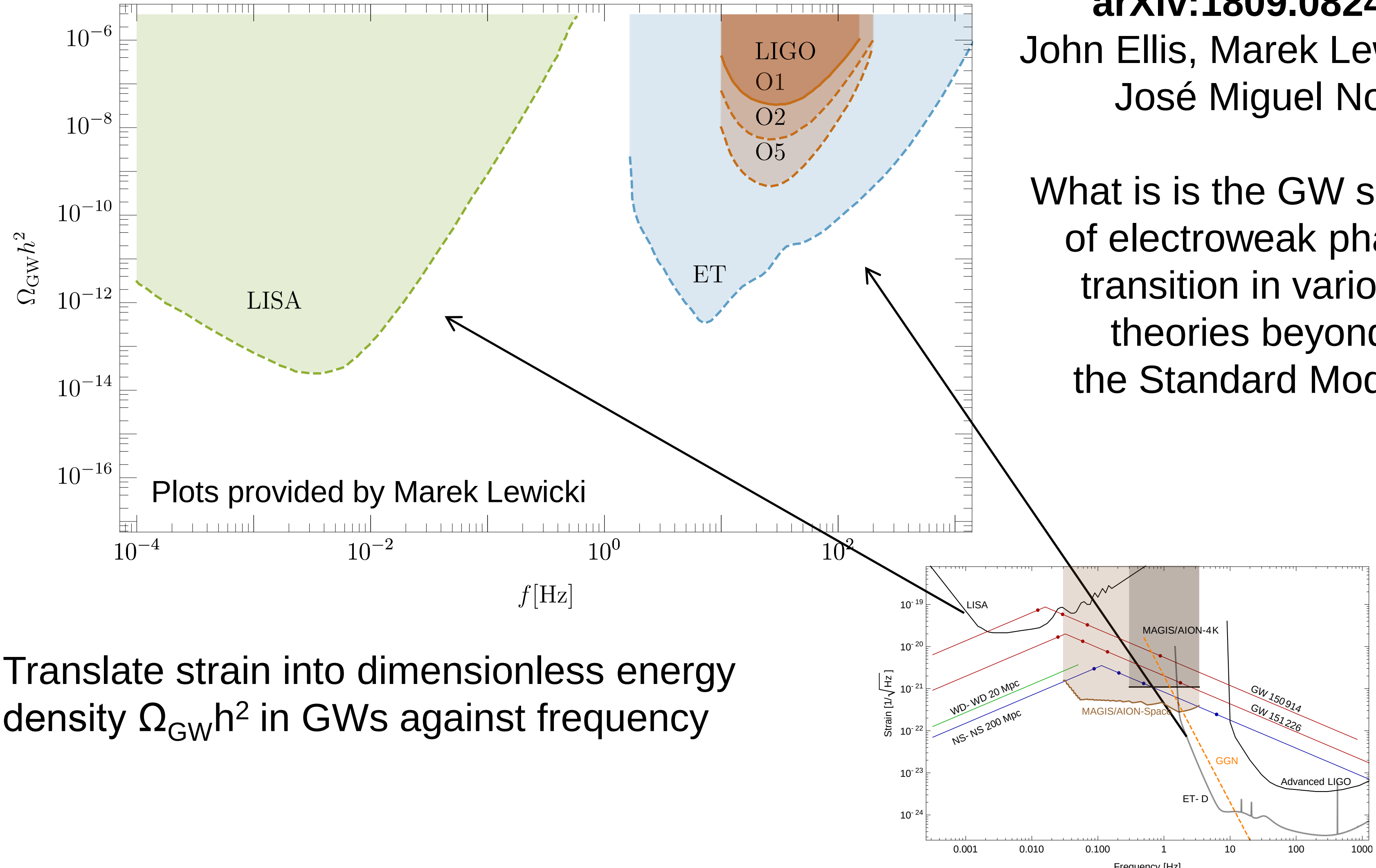
Ultimate Goal: Establish International Network



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



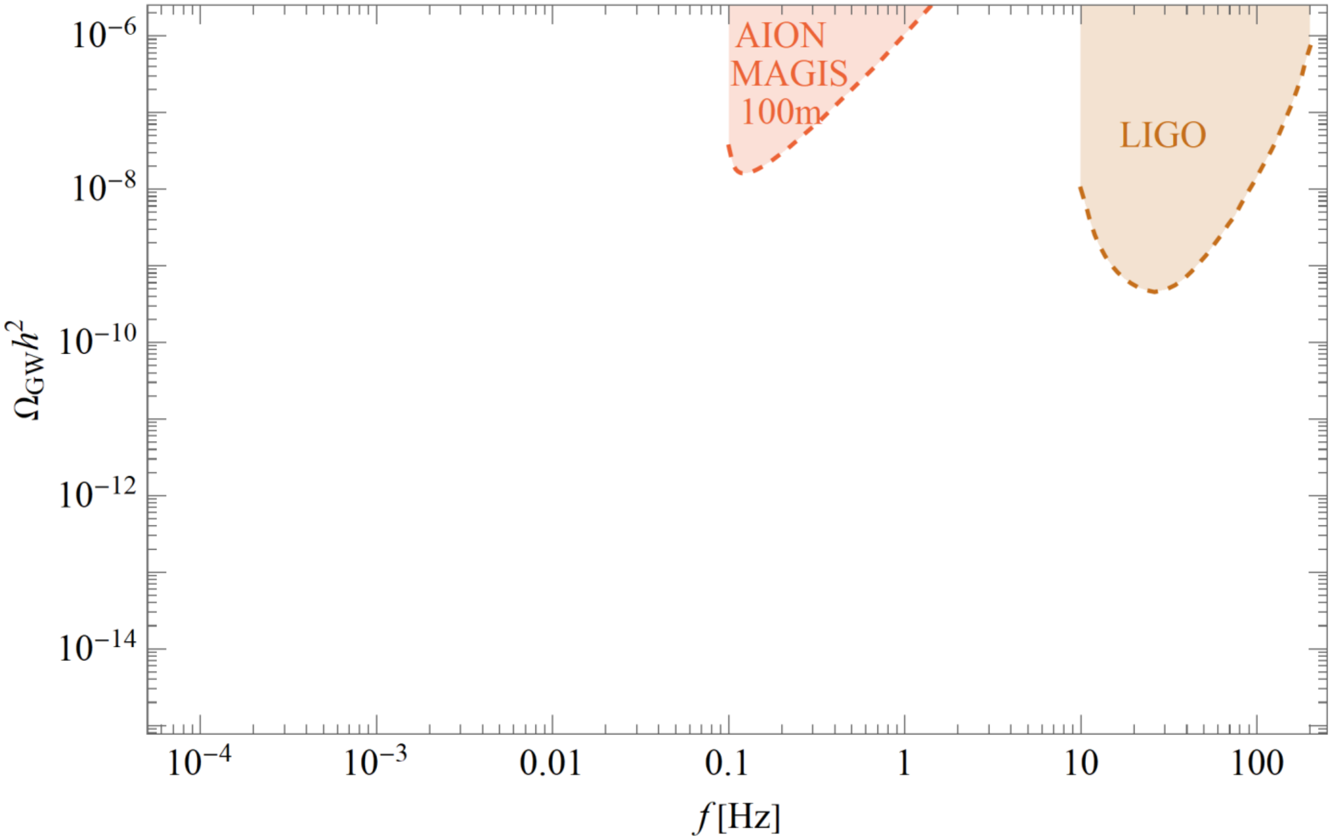
Plots provided by Marek Lewicki

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

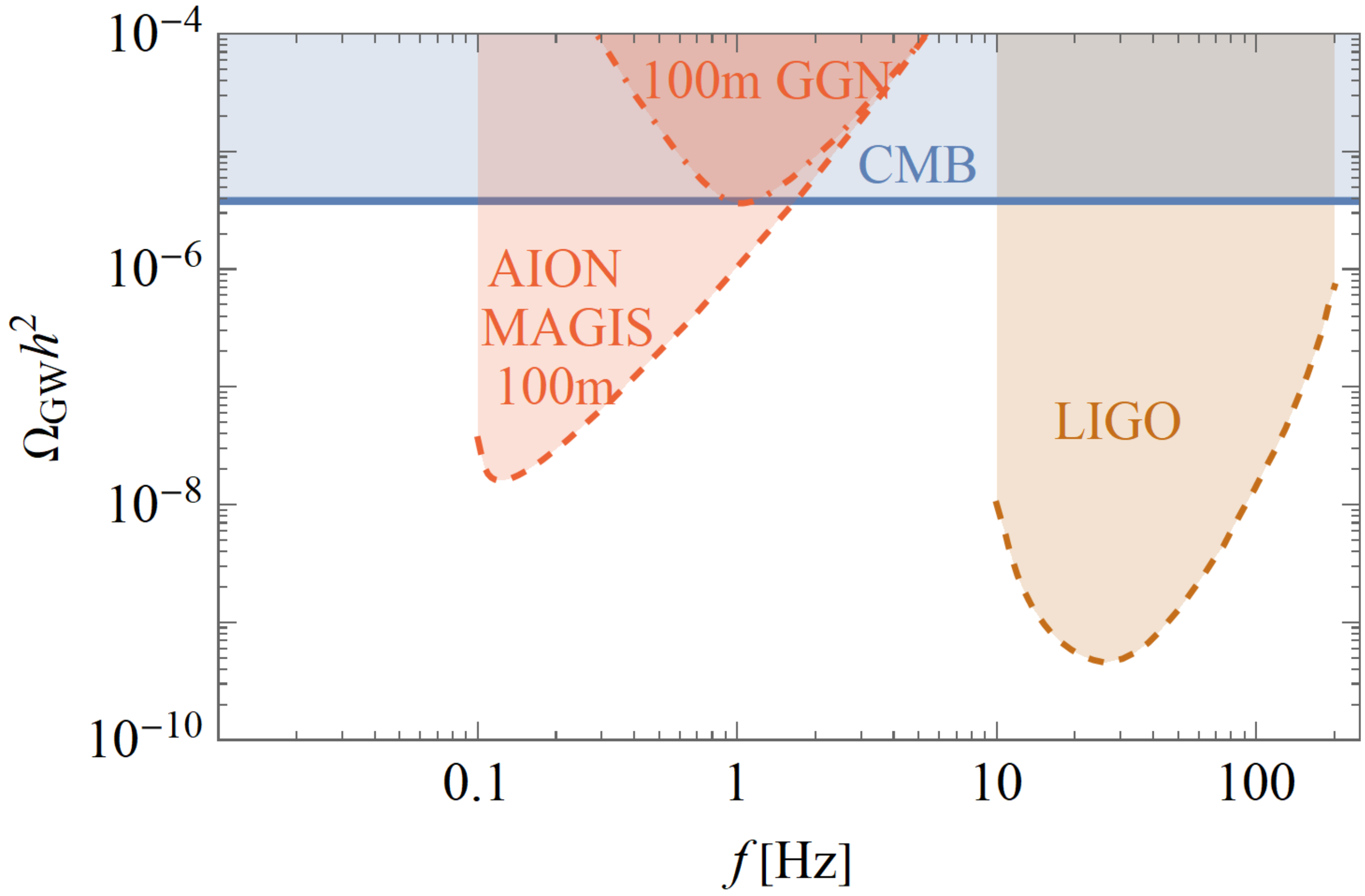
What is is the GW signal of electroweak phase transition in various theories beyond the Standard Model.

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

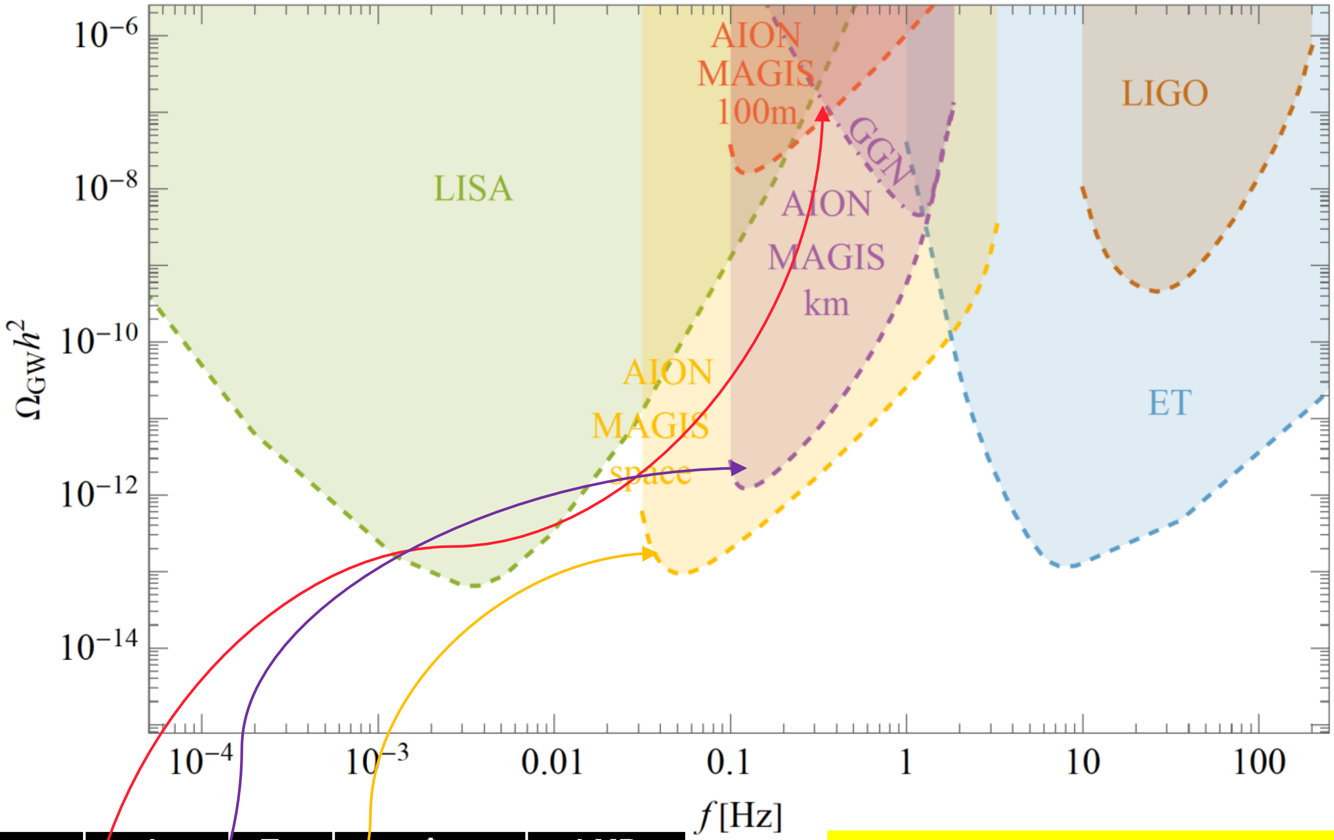
The GW Experimental Landscape: 2030ish



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 x 10^{-5}	40000
AION-space	4.4x10^{7}	300	10^{-5}	<1000

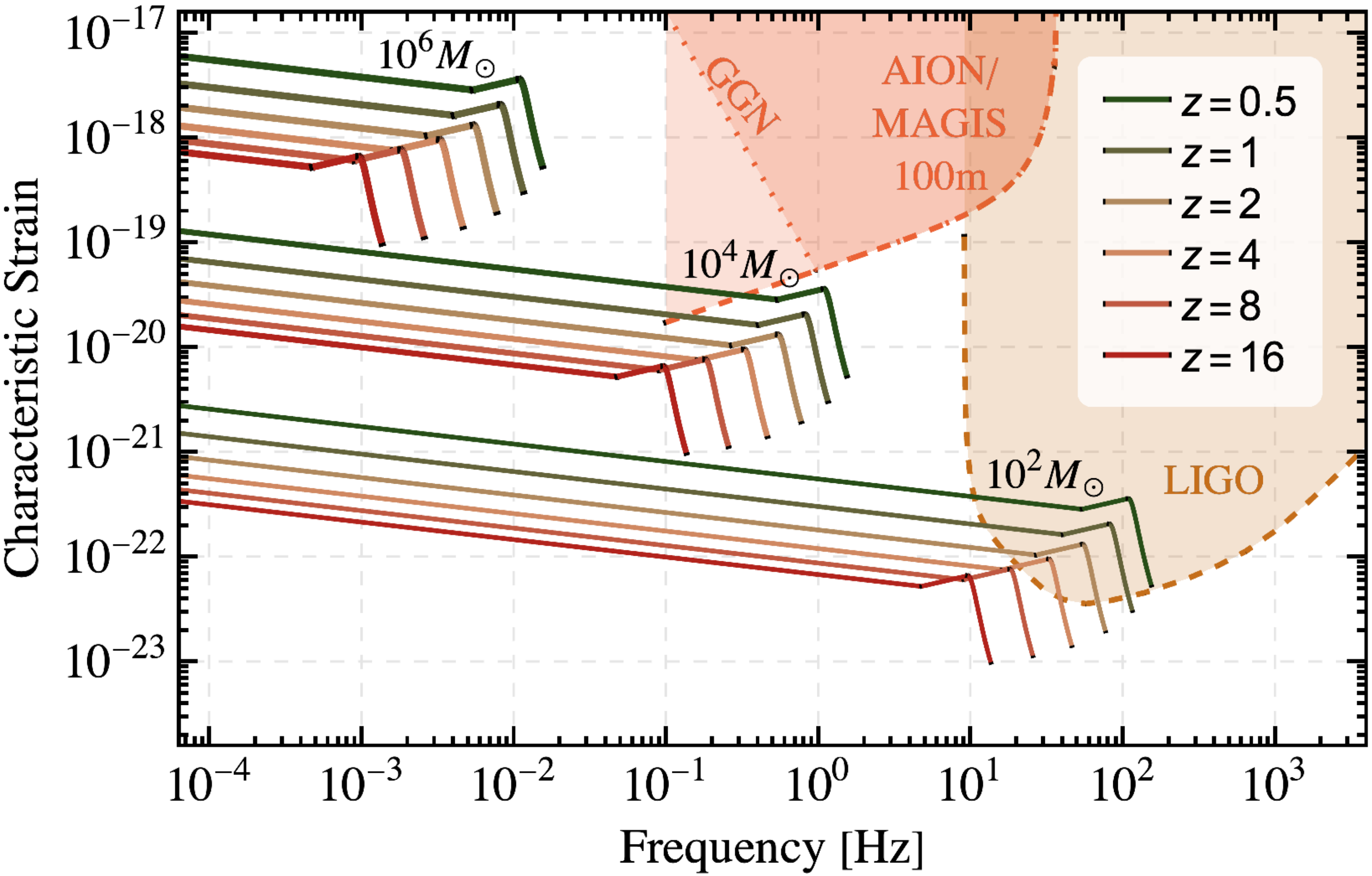
List of basic parameters: Lengths of the detector L, interrogation time of the atom interferometer T_{int} , phase noise ϕ, and number of momentum transfers LMP. The choice of these parameters predominately defines the sensitivity of the projection scenarios.

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.

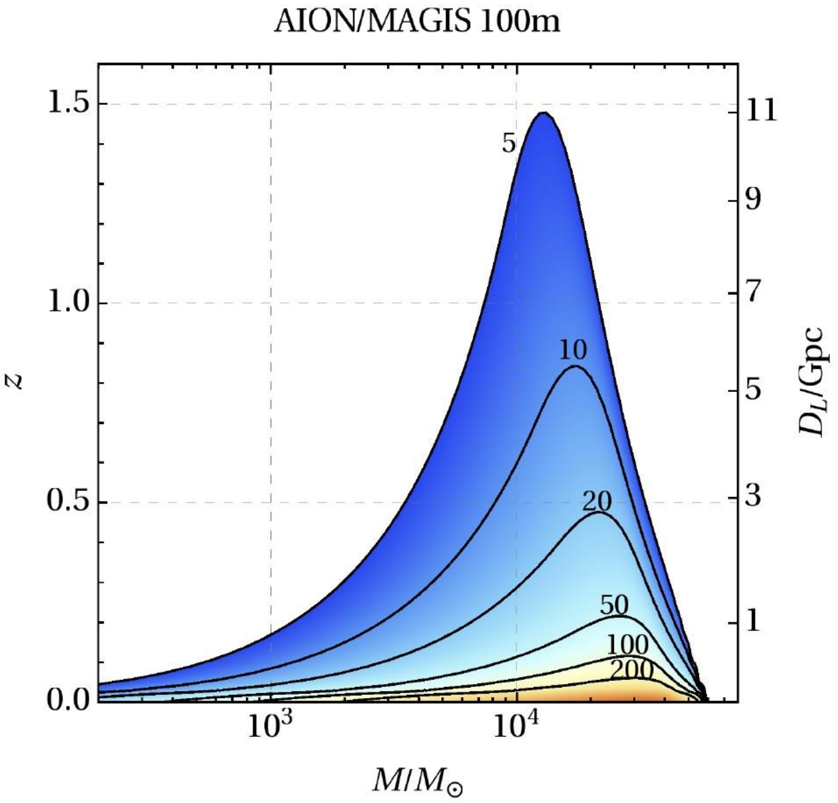
- **Cosmological Sources**
  - Many extensions of the Standard Model (SM) predict first-order phase transitions in the early Universe. Examples include extended electroweak sectors, effective field theories with higher-dimensional operators and hidden sector interactions.
    - Extended electroweak model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

Strain Sensitivity & BH Mergers: 2030ish

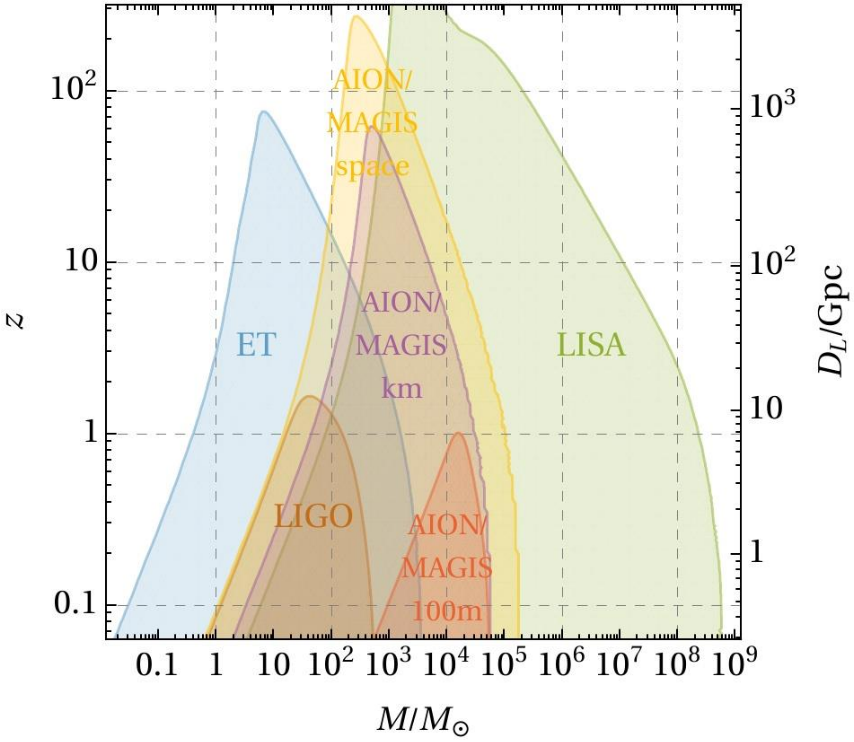


The AION frequency range is ideal for observations of mergers involving IMBHs, to which LISA and the LIGO/Virgo/KAGRA/ET experiments are relatively insensitive.

Strain Sensitivity & BH Mergers

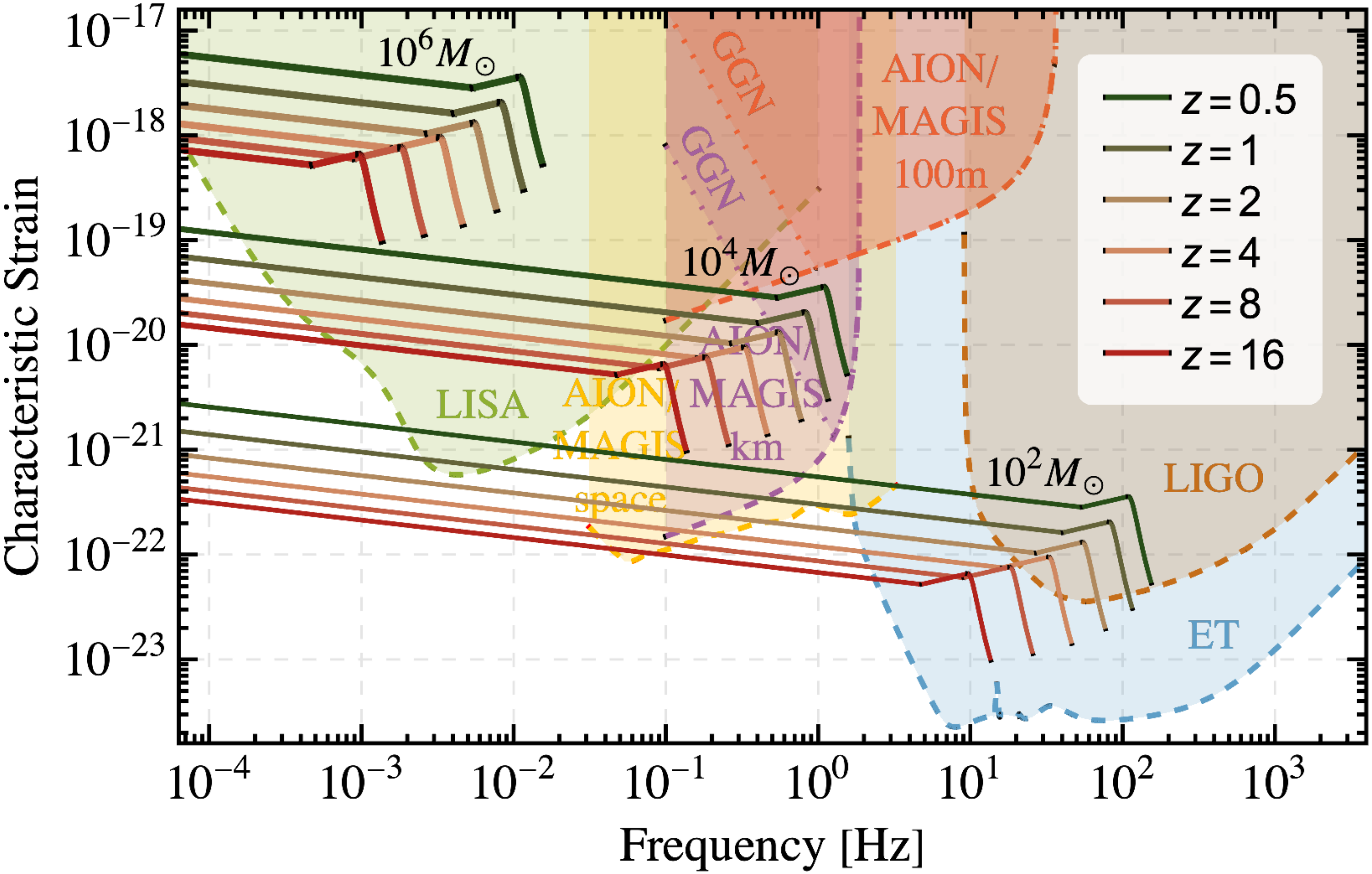


Sensitivity of AION-100m for detecting GWs from the mergers of IMBHs at signal-to-noise (SNR) levels ≥ 5, which extends to redshifts of 1.5 for BHs with masses ~ 10^4 solar masses.



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

Strain Sensitivity & BH Mergers: Future

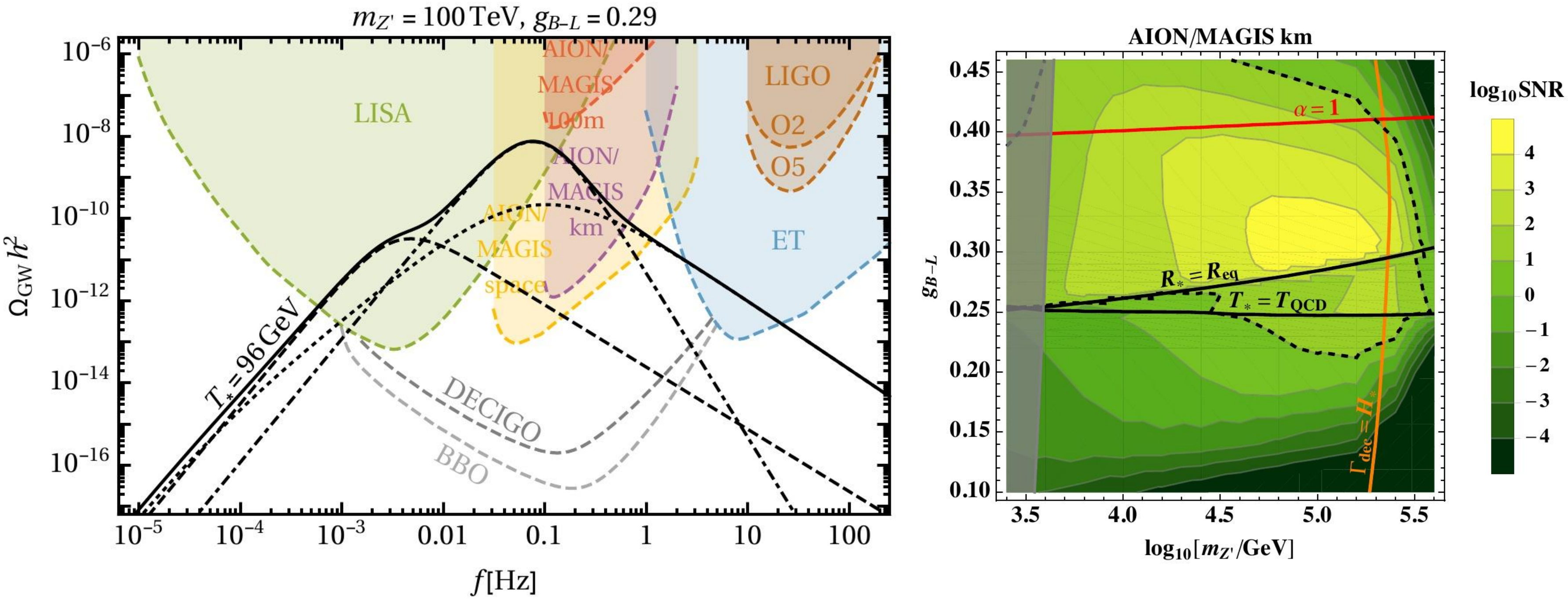


The AION frequency range is ideal for observations of mergers involving IMBHs, to which LISA and the LIGO/Virgo/KAGRA/ET experiments are relatively insensitive.

Cosmological GW Sources: Z’ Model

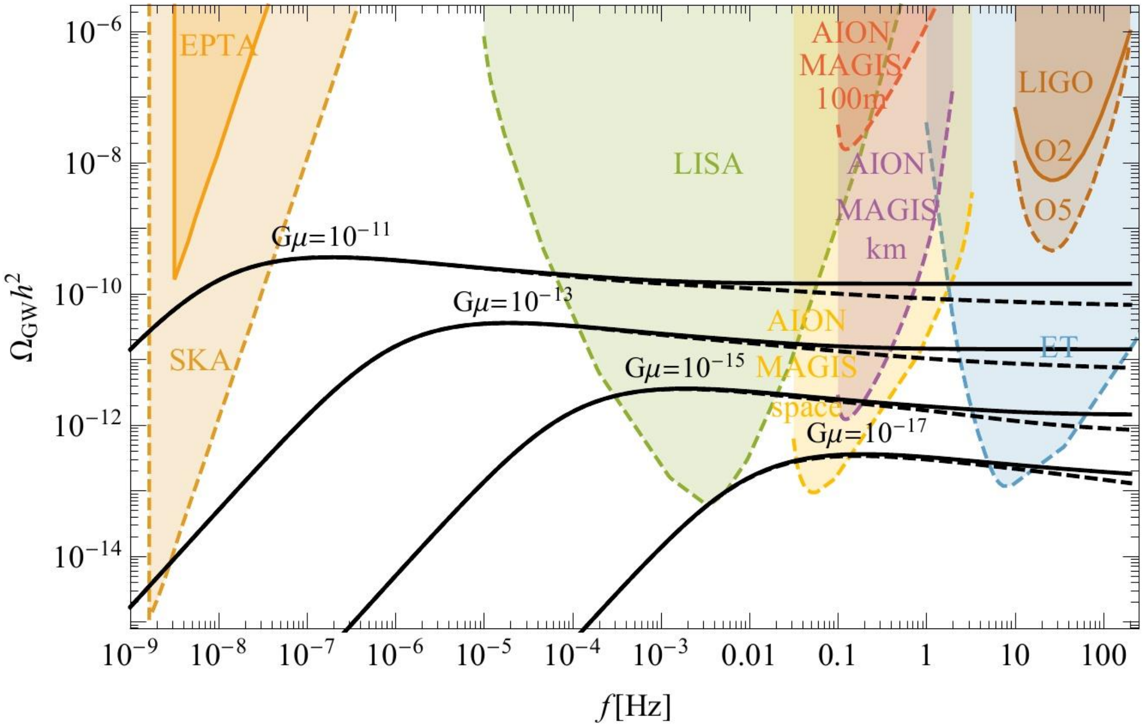
Many extensions of the Standard Model (SM) predict first-order phase transitions in the early Universe.

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.

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

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:

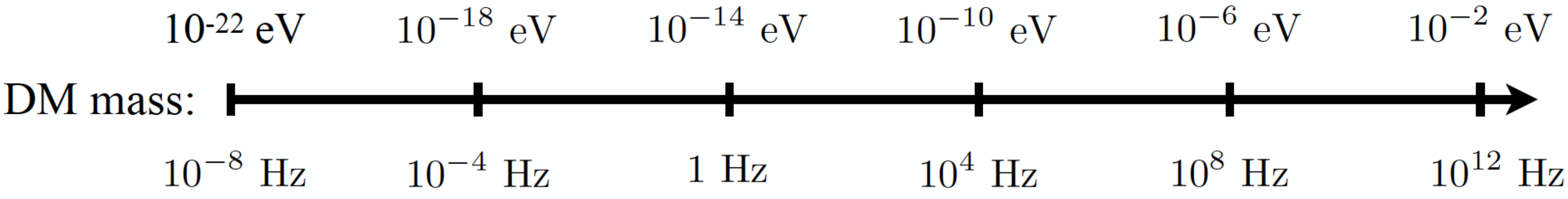


Diagram taken from P. Graham's
talk at HEP Front 2018

O. Buchmueller The AION Project

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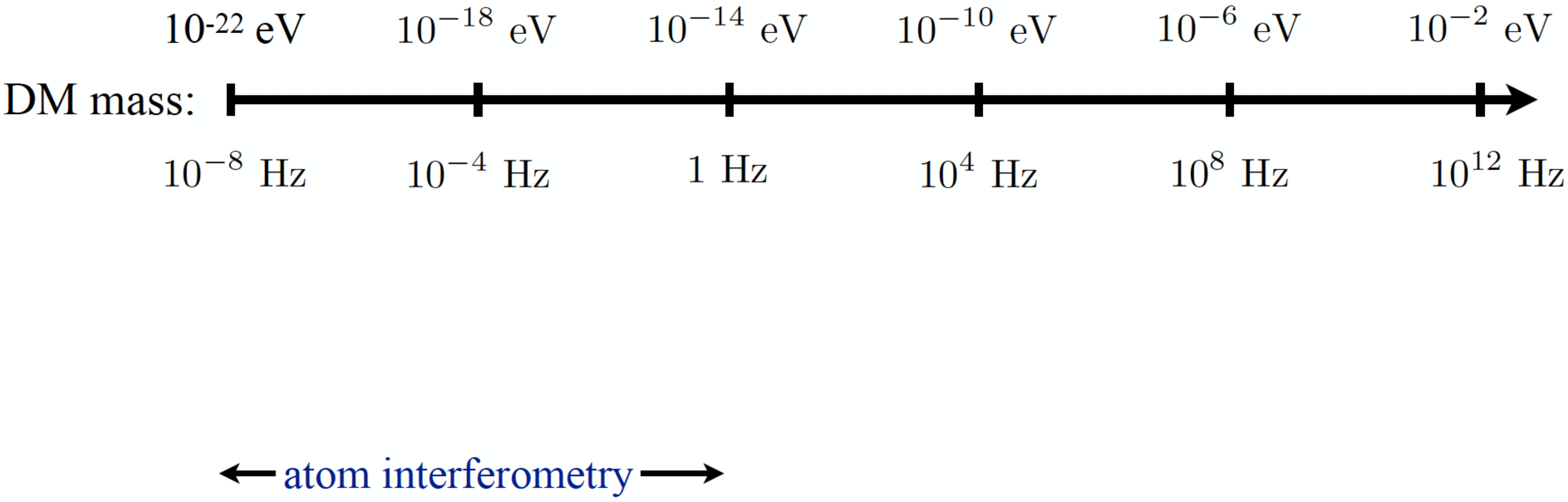

10^{-22} eV 10^{-18} eV 10^{-14} eV 10^{-10} eV 10^{-6} eV 10^{-2} eV

DM mass:

10^{-8} Hz 10^{-4} Hz 1 Hz 10^{4} Hz 10^{8} Hz 10^{12} Hz

← atom interferometry →

MAGIS/AION

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

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O. Buchmueller The AION Project

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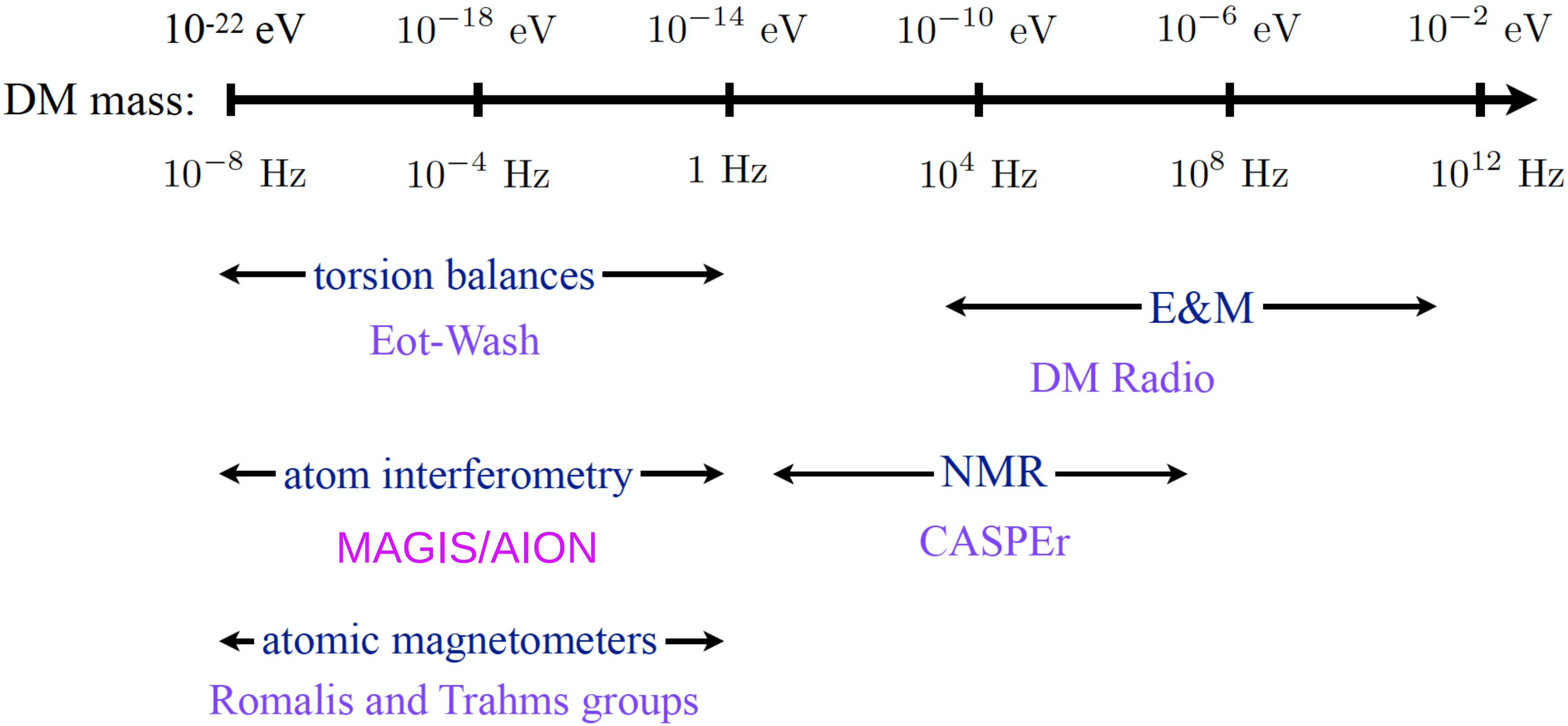

10^{-22} eV 10^{-18} eV 10^{-14} eV 10^{-10} eV 10^{-6} eV 10^{-2} eV

DM mass:

10^{-8} Hz 10^{-4} Hz 1 Hz 10^{4} Hz 10^{8} Hz 10^{12} Hz

torsion balances

Eot-Wash

E&M

DM Radio

atom interferometry

MAGIS/AION

NMR

CASPEr

atomic magnetometers

Romalis and Trahms groups

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

Ultra-Light Spin-0 Dark Matter

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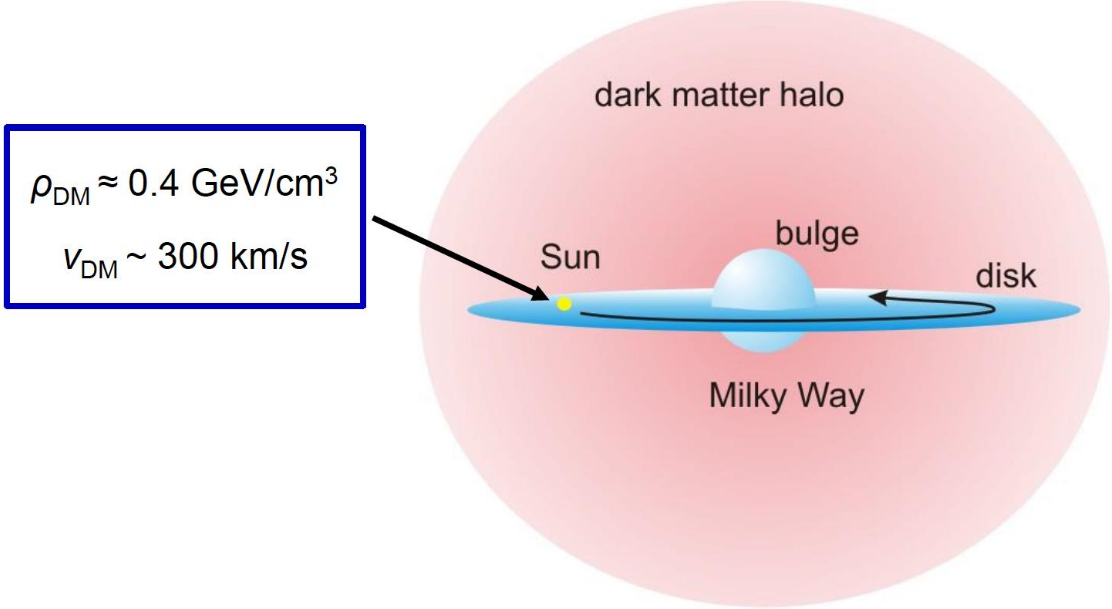
Ultra-light spin 0 particles are expected to form a coherently oscillating classical field

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

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

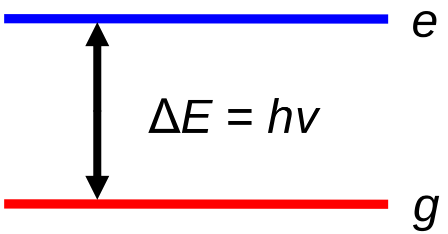
$$< \rho_\phi > \approx m_\phi^2 \phi_0^2/2 \; (\rho_{DM,local} \approx 0.4 \text{ GeV}/\text{cm}^3).$$



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

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

Ultra-Light Spin-0 Dark Matter



Atomic spectroscopy (clocks)

$\delta(v_1/v_2) \propto \cos(m_\varphi t)$

10^{-23} eV $< m_\varphi <$ 10^{-16} eV

Imperial College London

Ultra-Light Spin-0 Dark Matter

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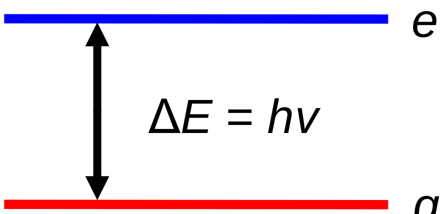

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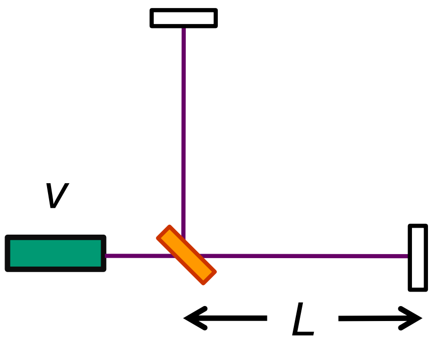
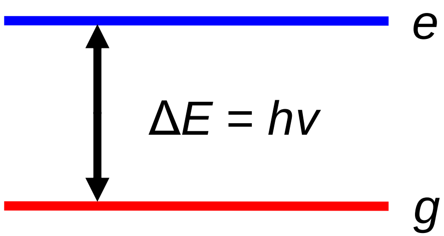


Laser interferometry (cavities)

$\delta\Phi \propto \delta(vL) \propto \cos(m_\varphi t)$ $10^{-20}\ \mathrm{eV} < m_\varphi < 10^{-15}\ \mathrm{eV}$

Ultra-Light Spin-0 Dark Matter



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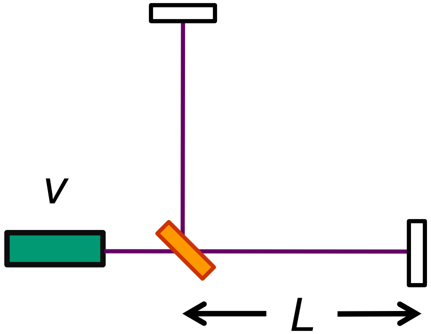

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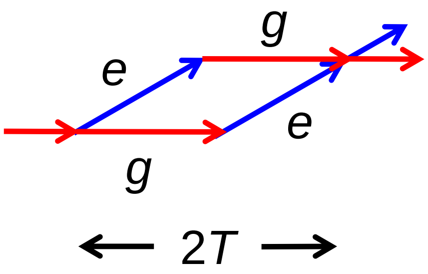
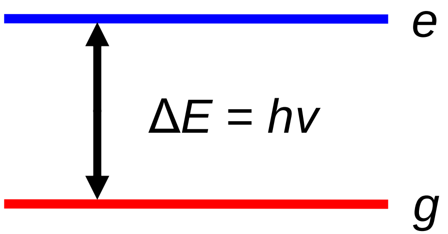


Atom interferometry

$F(t) \propto p_\varphi \sin(m_\varphi t)$

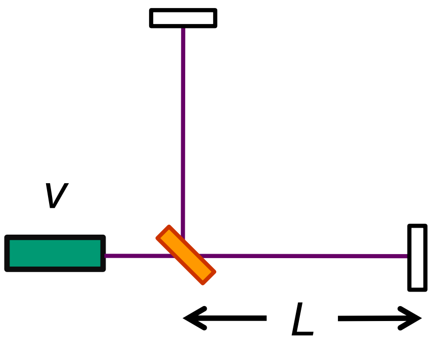
10^{-23} eV $< m_\varphi <$ 10^{-16} eV

Ultra-Light Spin-0 Dark Matter



Atomic spectroscopy (clocks)

$\delta(\nu_1/\nu_2) \propto \cos(m_\varphi t)$ 10^{-23} eV < m_φ < 10^{-16} eV



Laser interferometry (cavities)

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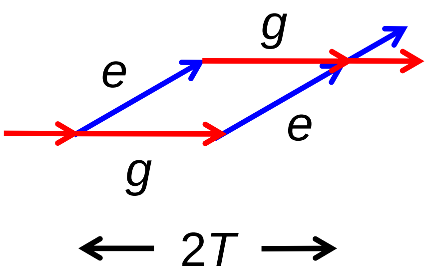
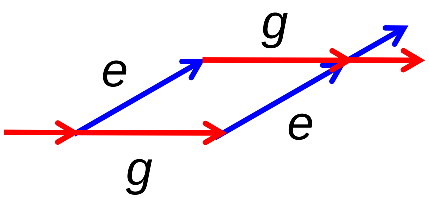


Atom interferometry

$F(t) \propto p_\varphi \sin(m_\varphi t)$ 10^{-23} eV < m_φ < 10^{-16} eV

$\delta\Phi(T,L)$ = max. for $2\pi/m_\varphi \sim 2T$



10^{-17} eV < m_φ < 10^{-15} eV

Courtesy of Yevgeny Stadnik!

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

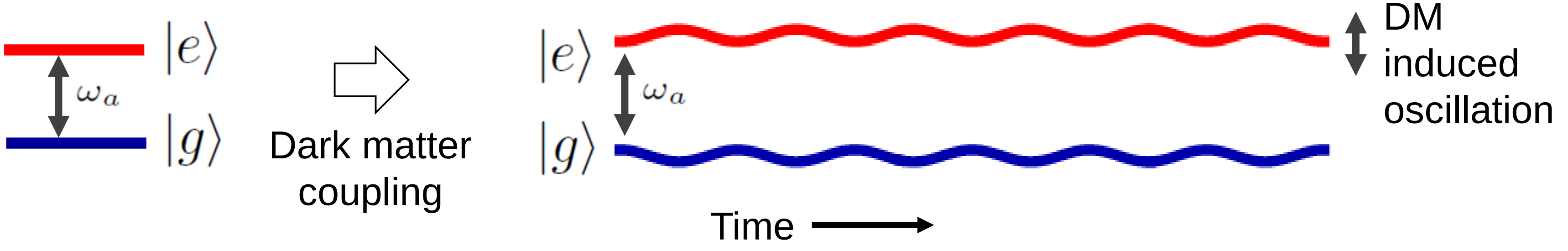
Photon coupling

e.g., QCD

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

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

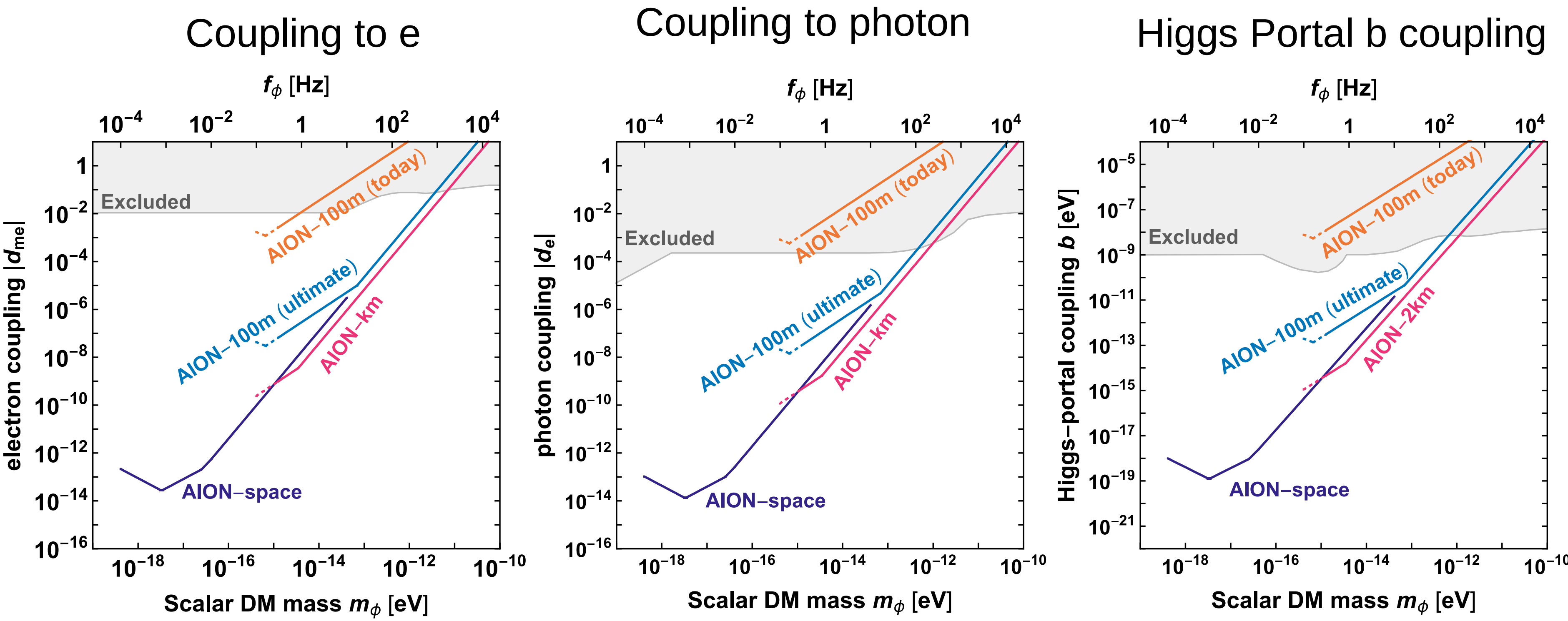
DM coupling causes time-varying atomic energy levels:



Courtesy of Jason Hogan!

Sensitivity for DM with Scalar Couplings to Matter

O. Buchmueller The AION Project

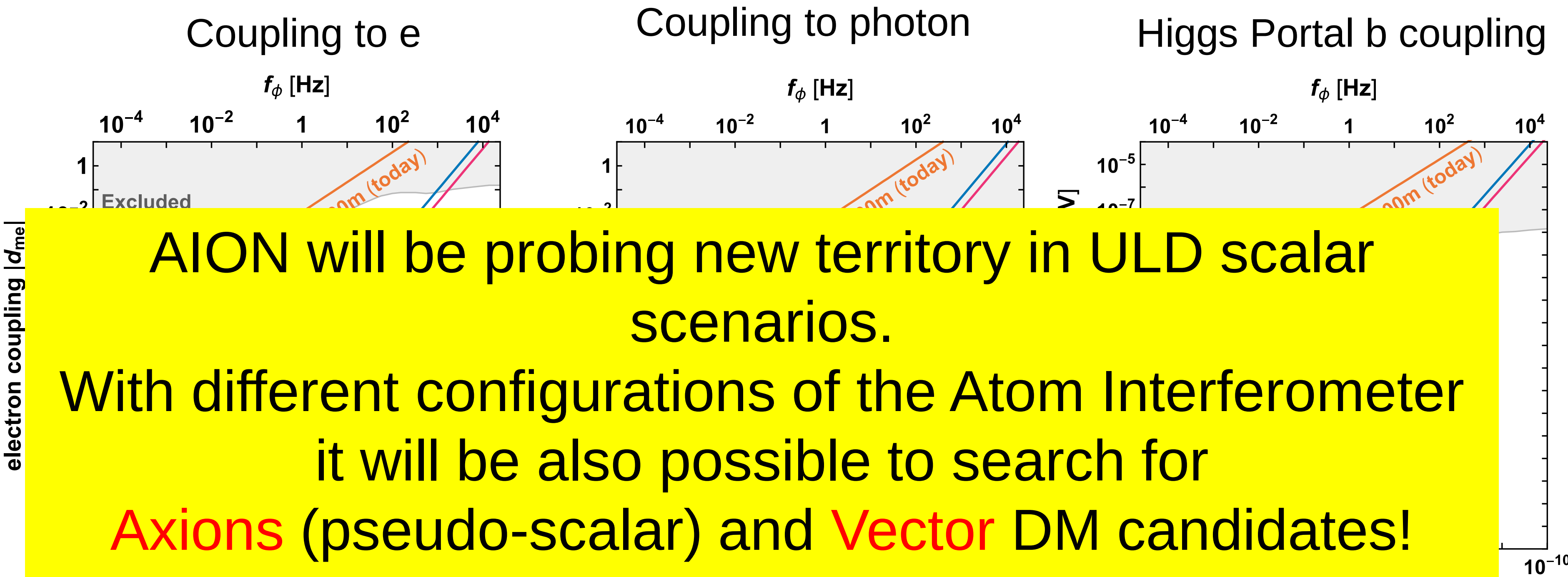


DM with scalar couplings to matter, which cause time variation of fundamental constants such as the electron mass

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

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 x 10^{-5}	40000
AION-space	4.4x10^{7}	300	10^{-5}	<1000

Sensitivity for DM with Scalar Couplings to 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]

which cause time variation of fundamental constants such as the electron mass

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

Scenario	[m]	[s]	[1/√Hz]	[#]
AION-100-today	100	1.4	10^{-3}	100
AION-100-ultimate	100	1.4	10^{-5}	40000
AION-km	2000	5	0.3 x 10^{-5}	40000
AION-space	4.4x10^{7}	300	10^{-5}	<1000

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.