THE AION PROJECT

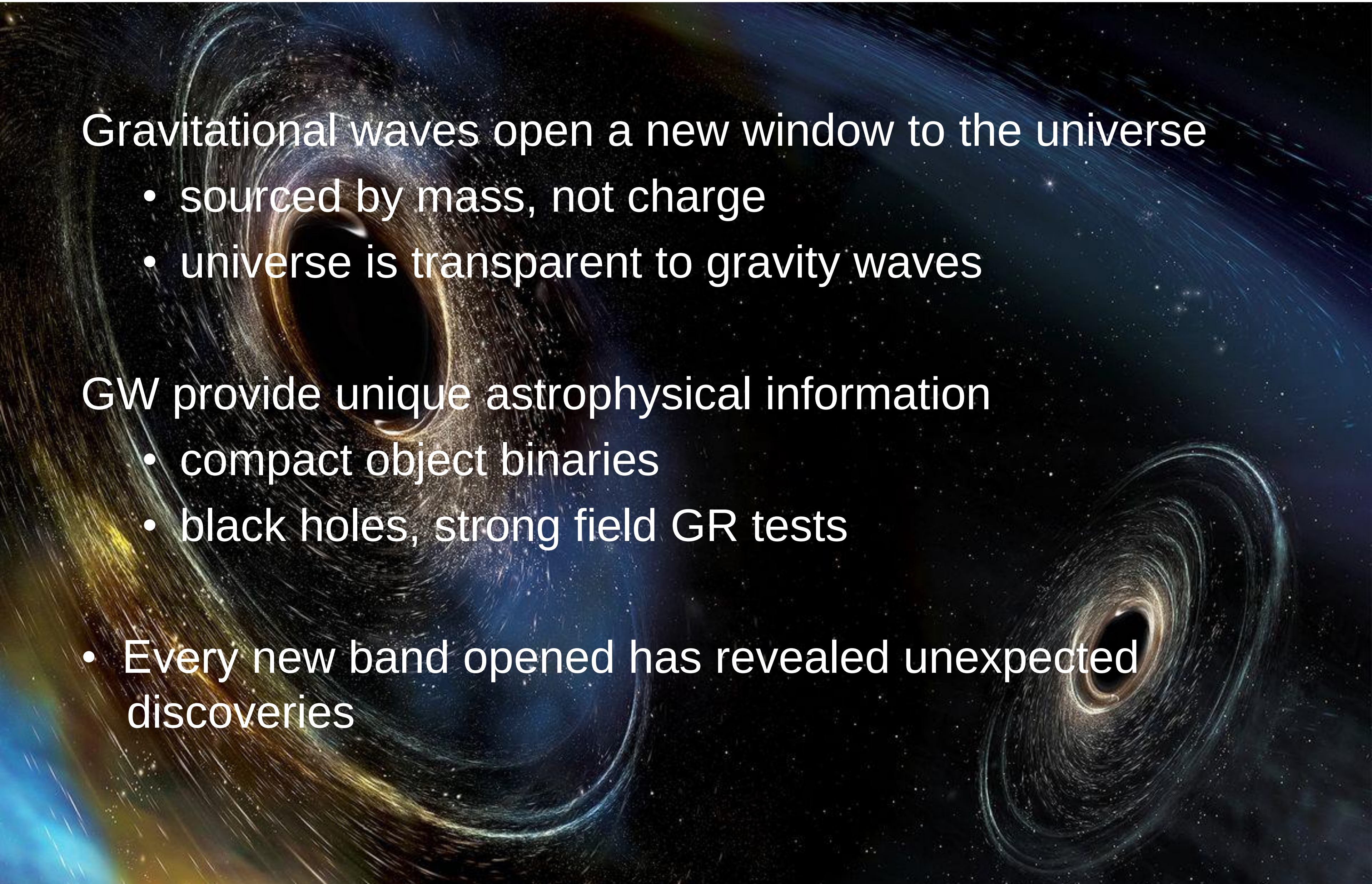
A UK ATOM INTERFEROMETER OBSERVATORY AND NETWORK

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

AION WORKSHOP, MARCH 25, 2019

Oliver Buchmueller, Imperial College London

Gravitational Waves



Gravitational waves open a new window to the universe

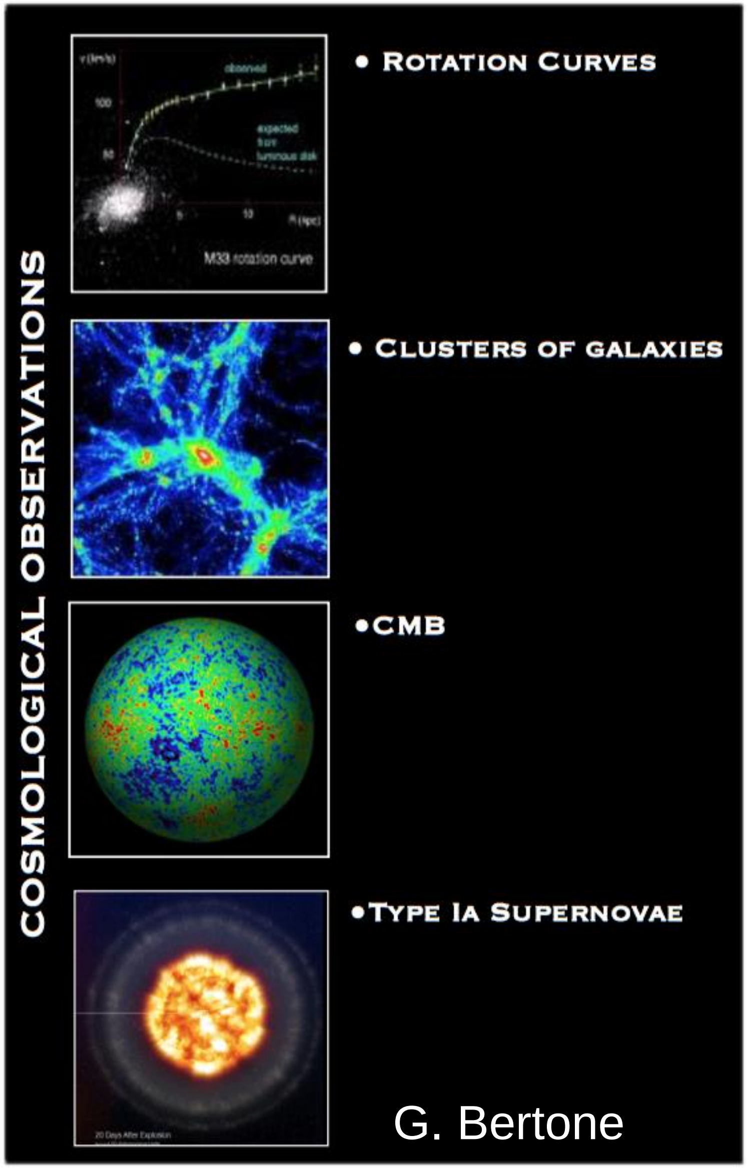
- sourced by mass, not charge
- universe is transparent to gravity waves

GW provide unique astrophysical information

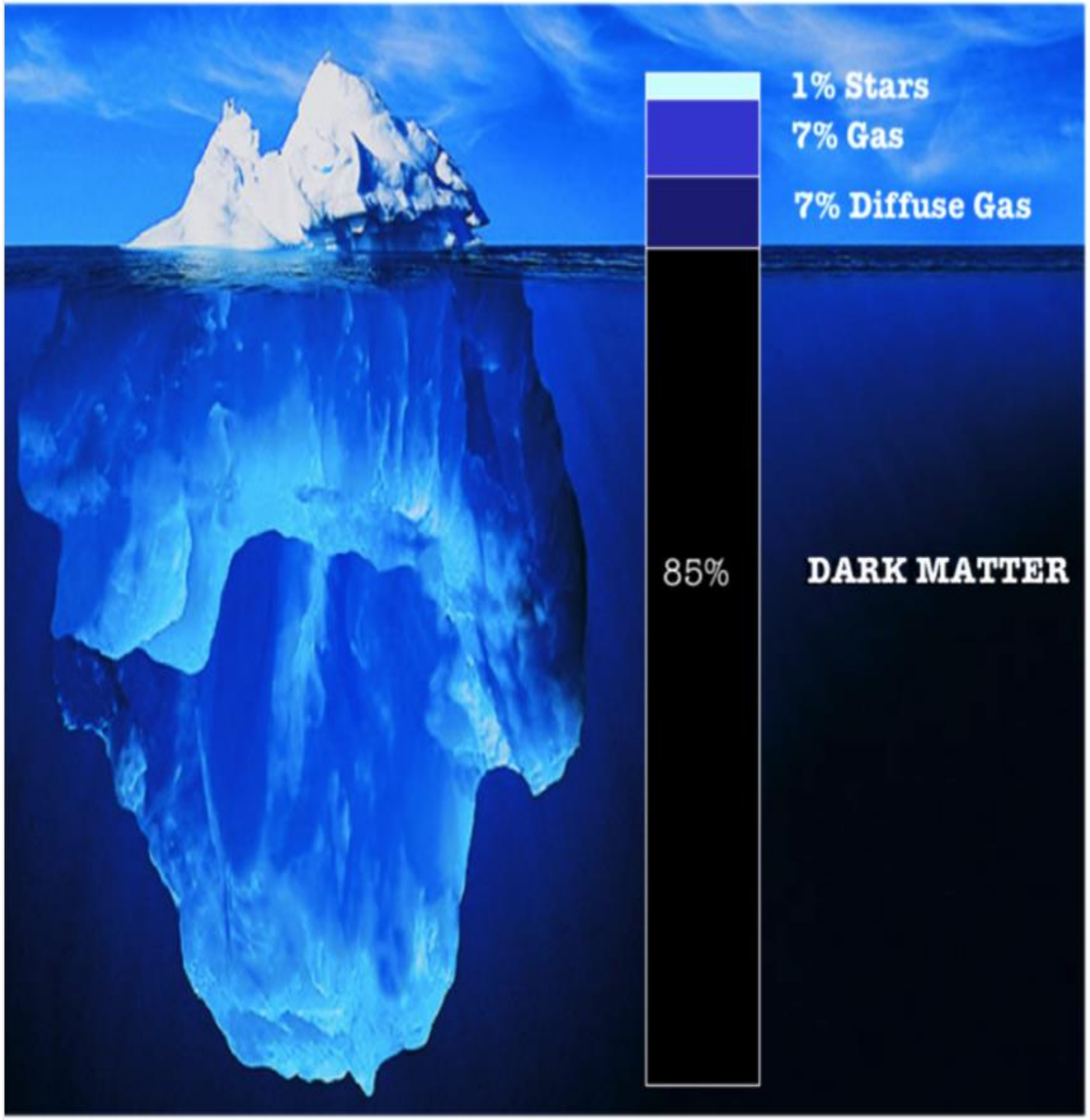
- compact object binaries
- black holes, strong field GR tests

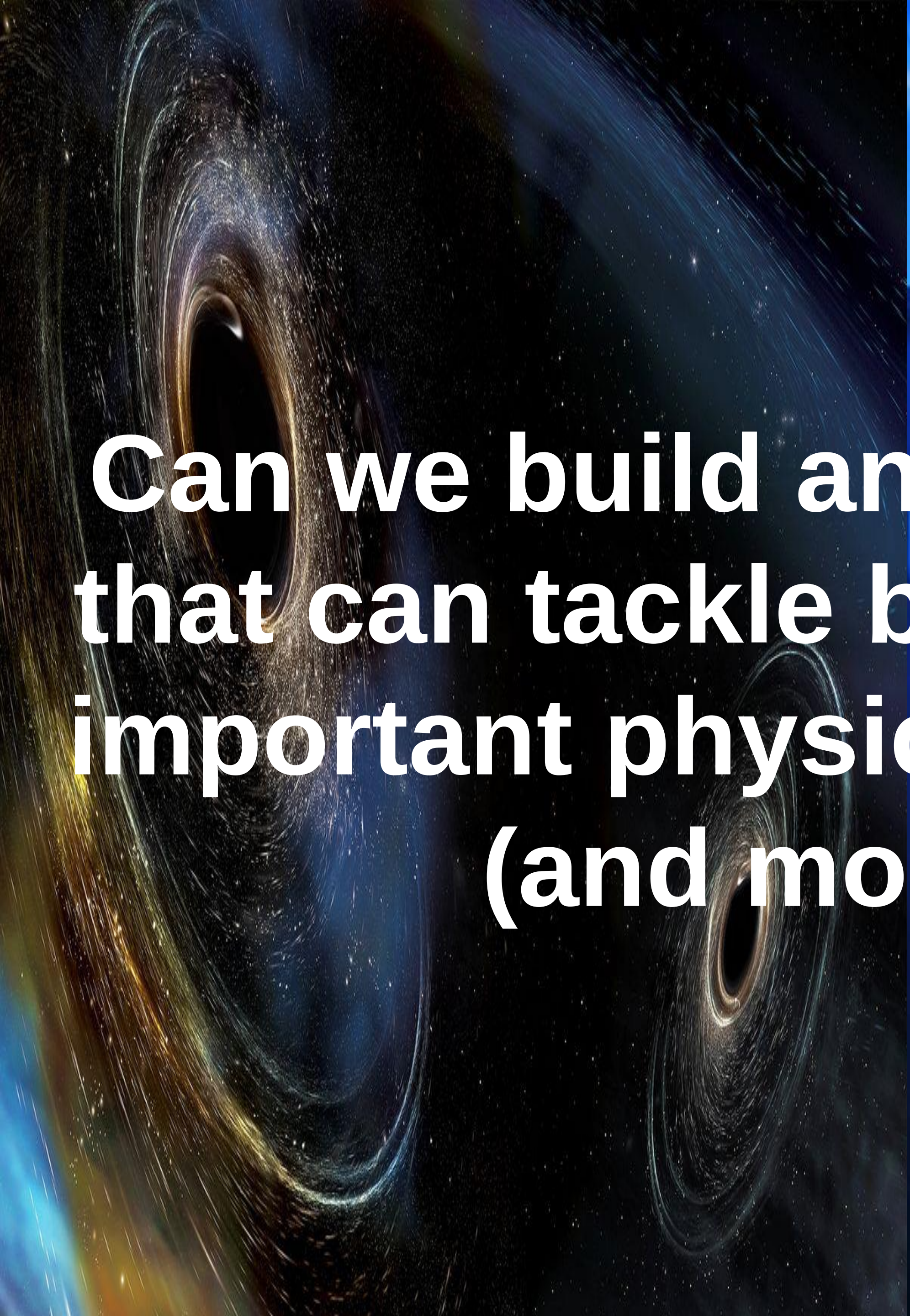
- Every new band opened has revealed unexpected discoveries

(Very Strong) Evidence for Dark Matter



G. Bertone





Can we build an experiment that can tackle both of these important physics questions (and more)?

Outline

- What is AION
- Collaboration of AION with the US effort MAGIS
- The Physics Case

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 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:

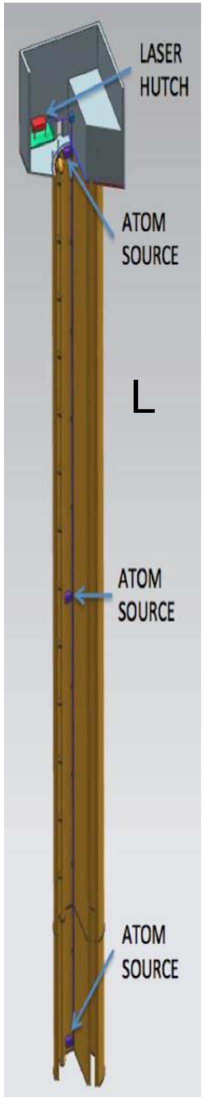
- **The first stage** develops existing technology (Laser systems, vacuum, magnetic shielding etc.) and the infrastructure for the 100m detector and produces detailed plan resulting in an accurate assessment of the expected performance in Stage 2.
- **The second stage** builds, commissions and exploits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

- 100m Construction & Commissioning

AION-KM: Stage 3 [> year 6]

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

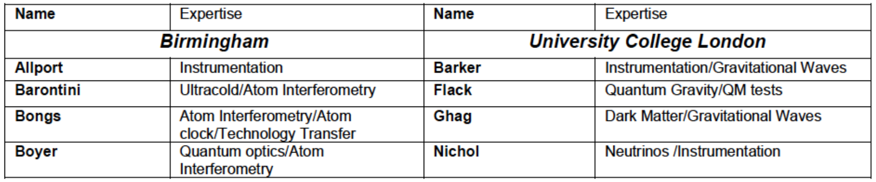
AION-SPACE: Stage 4 [after AION-KM]

- Space based version

**outlined in Big Ideas proposal

Freise	GW/ Instrumentation
Guarrera	Ultracold/Atom Interferometry
Holynsky	Atom Interferometry/Technology Transfer
Lien	Atom Interferometry
Newman	QCD/ DIS / Forward Instrumentation
Nikolopoulos	Light Dark Matter/Higgs
Singh	Atom clock/Technology Transfer
Worm	Dark Matter
Bristol	
Brooke	Energy frontier/BSM/Instrumentation
Flaecher	Energy frontier/BSM/Dark Matter
Goldstein	Energy frontier/Instrumentation
Velthuis	Instrumentation/Technology Transfer
Brunel	
Hobson	Energy Frontier/Instrumentation
Smith	Spaceborne Instrumentation/Technology Transfer
Glasgow	
Bell	GW/ Instrumentation
Hammond	GW/ Instrumentation
Imperial College	
Araujo	Dark Matter/Instrumentation
Buchmueller	Energy frontier/BSM/Dark Matter/GW
Hassard	Instrumentation/Technology Transfer
Hinds	EDM/Atom Interferometry/ultracold
Sauer	EDM/Atom Interferometry/ultracold
Sumner	GW/ Instrumentation
Tarbutt	EDM/Atom Interferometry/ultracold
Kings College London	
Acharya%	DM & GW Theory
Blas%	DM & GW Theory
Ellis%	DM & GW Theory
Fairbairn%	DM & GW Theory
Lim%	GW Theory
Mavromatos%	GW Theory
Sakellariado%	GW Theory
Witek%	GW Theory
Millen	Quantum Optomechanics

Saakyan	Neutrinos/Dark Matter/Instrumentation
Waters	Neutrinos/Dark Matter/Instrumentation
Liverpool	
Coleman	Atom Interferometry
Bowcock	EDMs/instrumentation/Quantum Foam
Burdin	Dark Matter
Rompotis	Muons/Relic neutrinos
Nottingham	
Burrage%	GW Theory
Sotiriou%	GW Theory
Oxford	
Kraus	Dark Matter
March-Russel%	BSM Theory
Randall%	BSM Theory
Shipsey	Higgs/muons/darkenergy/ instrumentation
Rutherford Appleton Laboratory	
Valenzuela	Head of Quantum Sensors Group, RAL Space
Vick	Head of the Disruptive Space Technology Centre, RAL Space
Waltham	Chief Technologist, RAL Space
Shepherd-Themistocleous	Contact for Particle Physics at RAL
Sheffield	
Dolan%	GW Theory
Strathclyde	
Arnold	Ultra-cold atoms, BEC, matterwave interferometry, atomic clocks
Griffin	Ultra-cold atoms, BEC, matterwave interferometry, atomic clocks, magnetometry
Riis	Ultra-cold atoms, BEC, matterwave interferometry, atomic clocks, magnetometry
Sussex	
Calmet%	GW Theory
Dunningham%	Theory of atom interferometry
Hindmarsh%	GW Theory
Huber%	GW Theory
Krueger	Quantum Systems and BEC, AI
Swansea	
Tasinato%	GW Theory
National Physical Laboratory*	
Gill*	Cold atom & ion clocks/ ultrastable cavities & lasers/ precision timing/ atom interferometry
Margolis*	Cold atom & ion clocks/ frequency combs/ precision timing
Barwood*	Ultrastable cavities & lasers / ion clocks

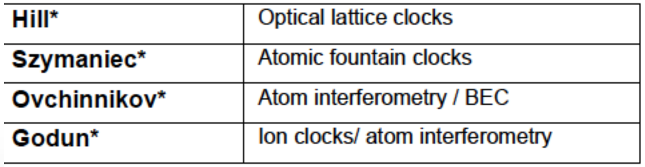


Name	Expertise	**Name**	Expertise
Birmingham		***University College London***	
Allport	Instrumentation	**Barker**	Instrumentation/Gravitational Waves
Barontini	Ultracold/Atom Interferometry	**Flack**	Quantum Gravity/QM tests
Bongs	Atom Interferometry/Atom clock/Technology Transfer	**Ghag**	Dark Matter/Gravitational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

Status “Big Ideas Call”
Will be updated in March 2019

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

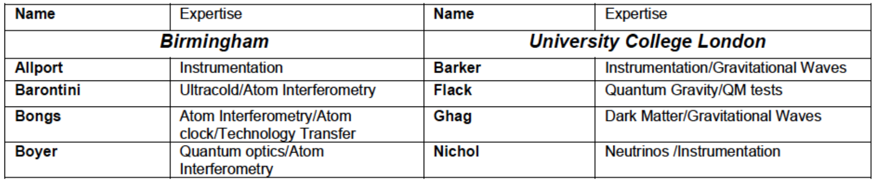


Hill*	Optical lattice clocks
Szymaniec*	Atomic fountain clocks
Ovchinnikov*	Atom interferometry / BEC
Godun*	Ion clocks/ atom interferometry

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

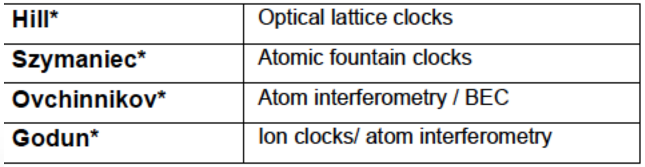
via:
https://mailman.ic.ac.uk/mailman/listinfo/aion-project

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	**Sotiriou%**	GW Theory
Flae			
Gol			
Velt			
Hob			
Smi			
Bell			
Ham			
Arau			
Buc			
Has			
Hind			
Sau			
Sum			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
Ellis%	DM & GW Theory	**Huber%**	GW Theory
Fairbairn%	DM & GW Theory	**Krueger**	Quantum Systems and BEC, AI
Lim%	GW Theory		***Swansea***
Mavromatos%	GW Theory	**Tasinato%**	GW Theory
Sakellariado%	GW Theory		***National Physical Laboratory****
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
		Barwood*	Ultrastable cavities & lasers / ion clocks



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

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

COLLABORATION WITH US (VIA MAGIS)

International Collaboration

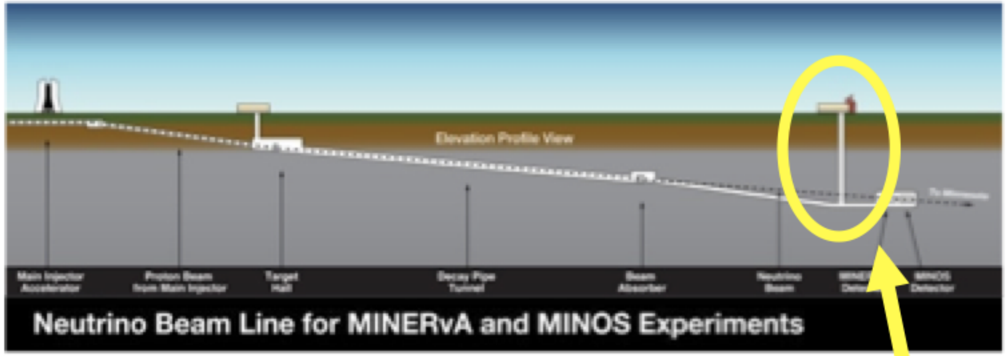
- From the outset this project would greatly benefit from close collaboration on an international level with the US initiative, MAGIS-100, which pursues a similar goal of an eventual km-scale atom interferometer on a comparable timescale.
- The option of operating two AI detectors, one in the UK and 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.

O. Buchmueller AION Project

MAGIS-100: GW detector prototype at Fermilab

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

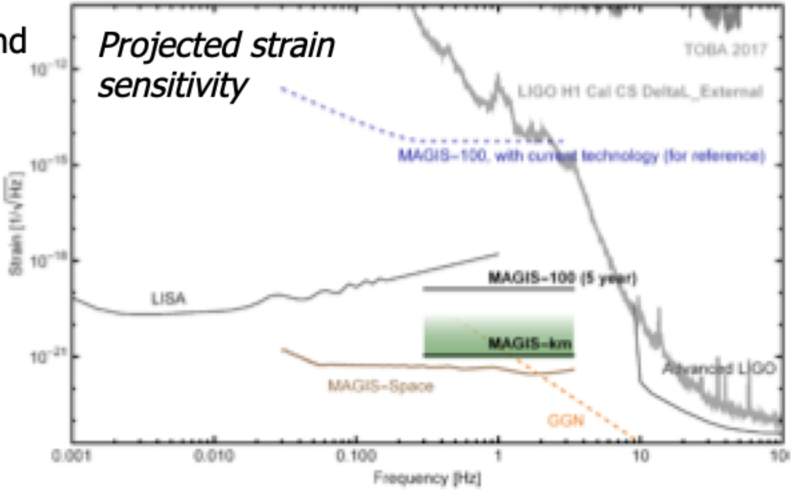
- 100-meter baseline atom interferometry at Fermilab (MINOS access shaft)
- Intermediate step to full-scale (km) detector for gravitational waves

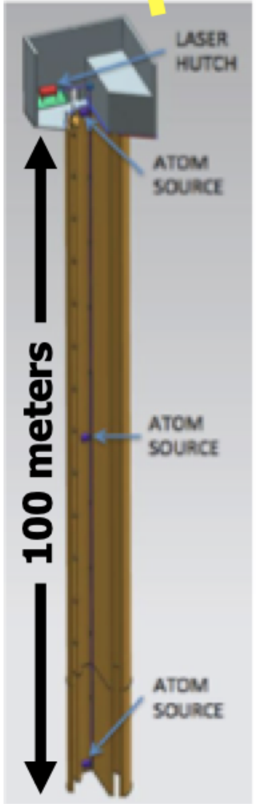


Neutrino Beam Line for MINERvA and MINOS Experiments

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

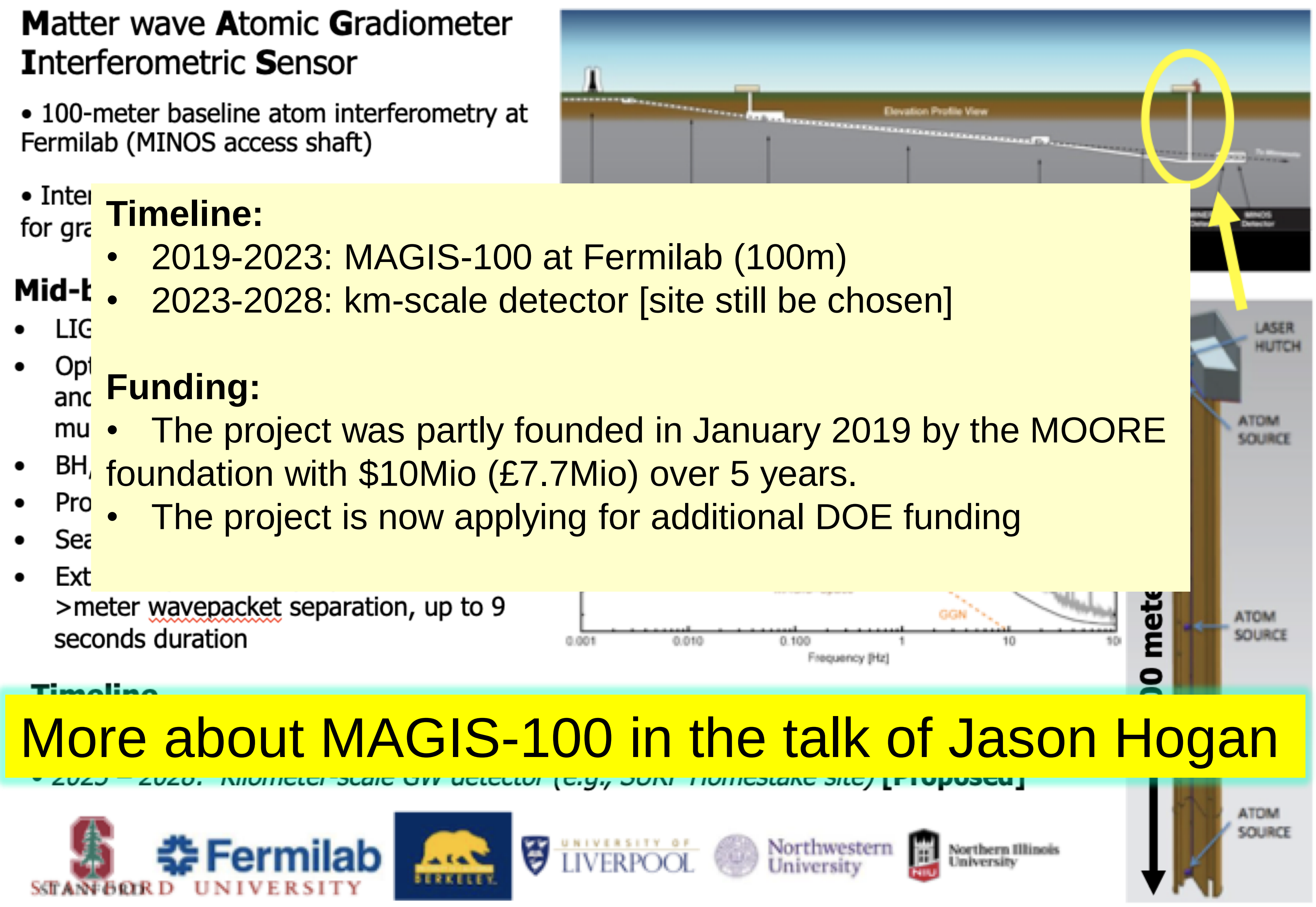
UNIVERSITY OF LIVERPOOL

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

- 100-meter baseline atom interferometry at Fermilab (MINOS access shaft)

- Inter
for gra

Mid-b
- LIG
- Opt
anc
mu
- BH
- Pro
- Sea
- Ext
>meter wavepacket separation, up to 9 seconds duration

Timeline

- 2023 – 2028: Kilometer-scale GW detector (e.g., SURF Homestake site) [Proposed]

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

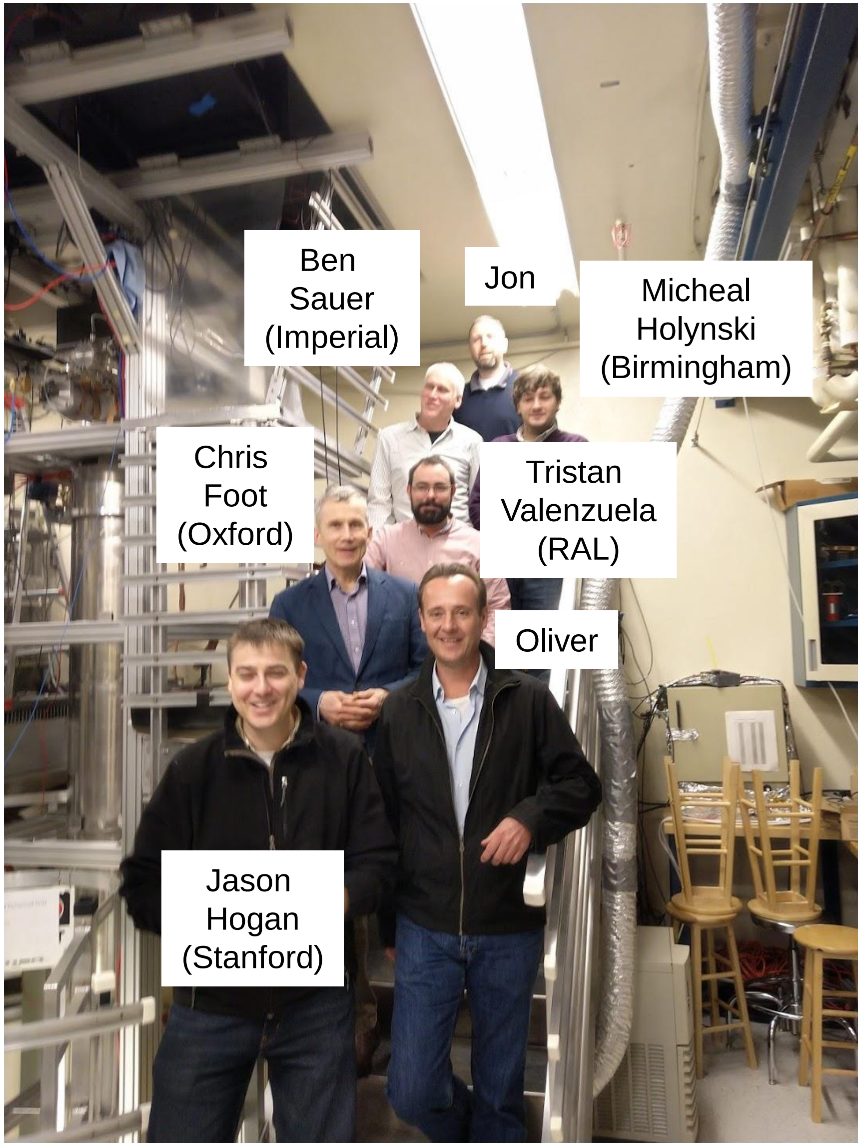
Funding:
- The project was partly founded in January 2019 by the MOORE foundation with $10Mio (£7.7Mio) over 5 years.
- The project is now applying for additional DOE funding

More about MAGIS-100 in the talk of Jason Hogan

Courtesy of Jason Hogan!

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:

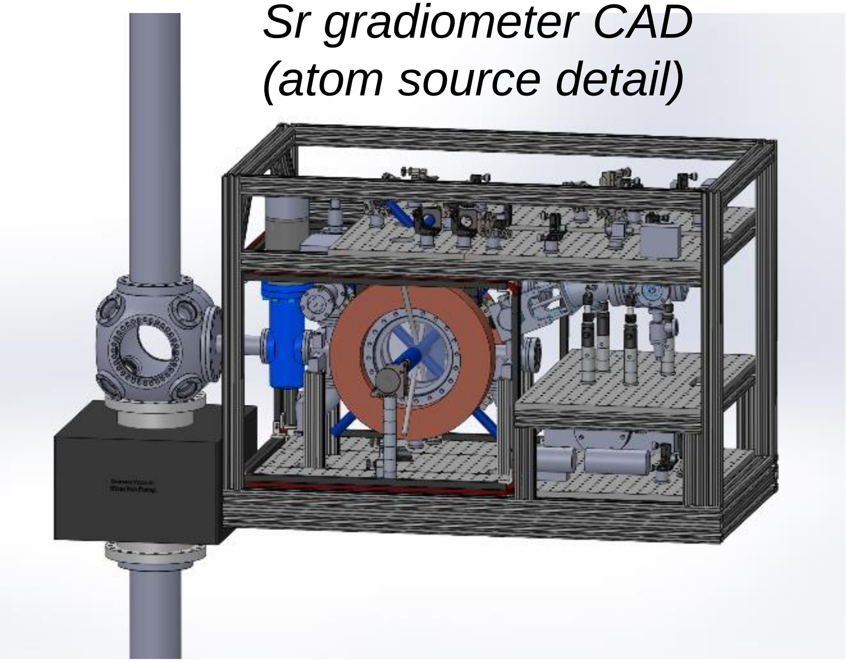
- Stanford/MAGIS is very open to closer collaboration with the UK/AION and they very much welcome another activity working towards the mid-band with AIs.
- There are several challenges where the UK expertise can help to achieve the design goals of the programme [see next slide].
- We agreed to include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

Imperial College London

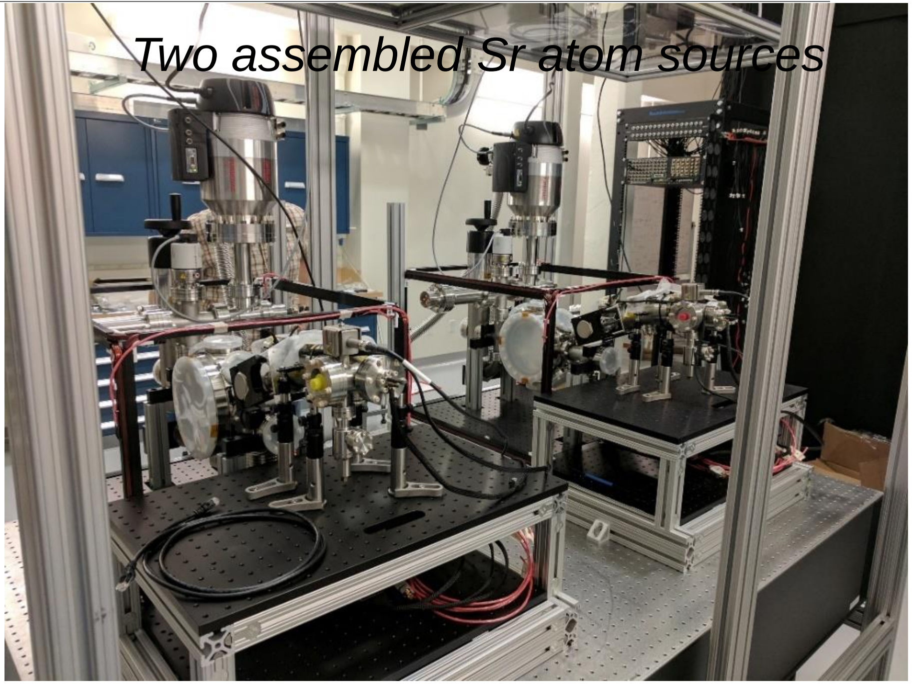
Stanford MAGIS prototype

O. Buchmueller AION Project

Sr gradiometer CAD
(atom source detail)

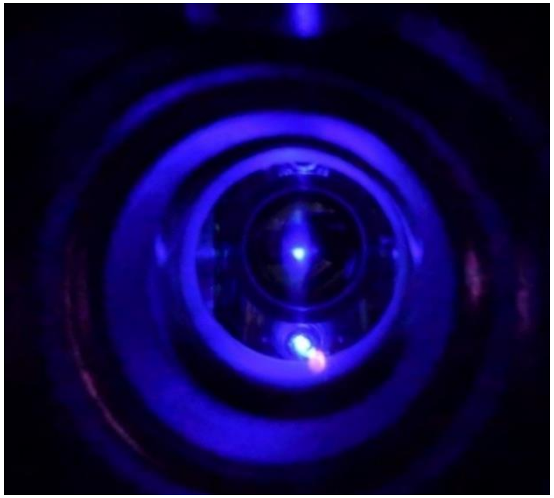


Two assembled Sr atom sources



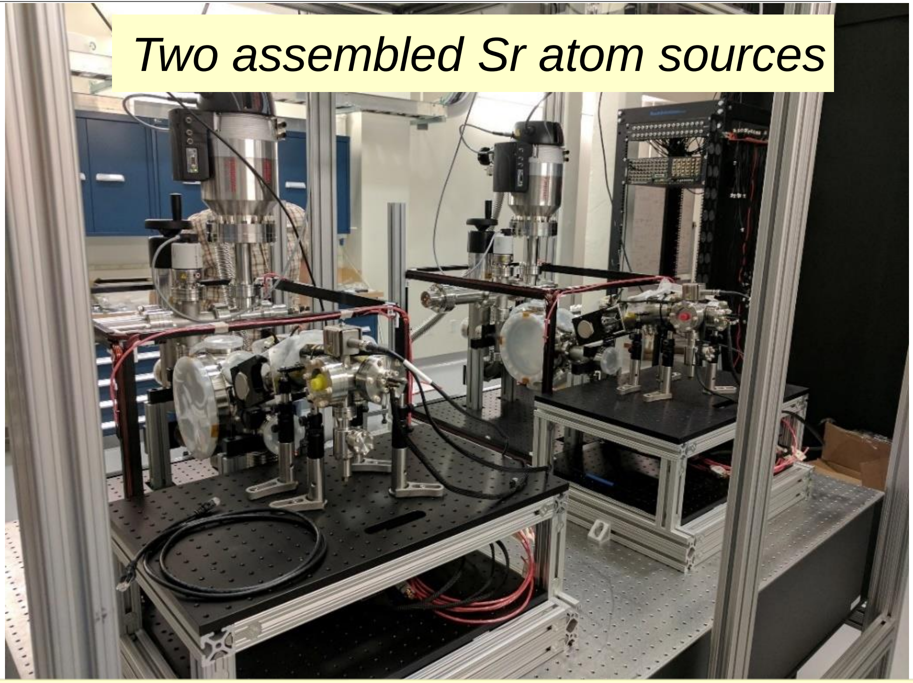
Atom optics laser
(M Squared SolsTiS)

Trapped Sr atom cloud
(Blue MOT)



Courtesy of Jason Hogan!

Stanford MAGIS prototype

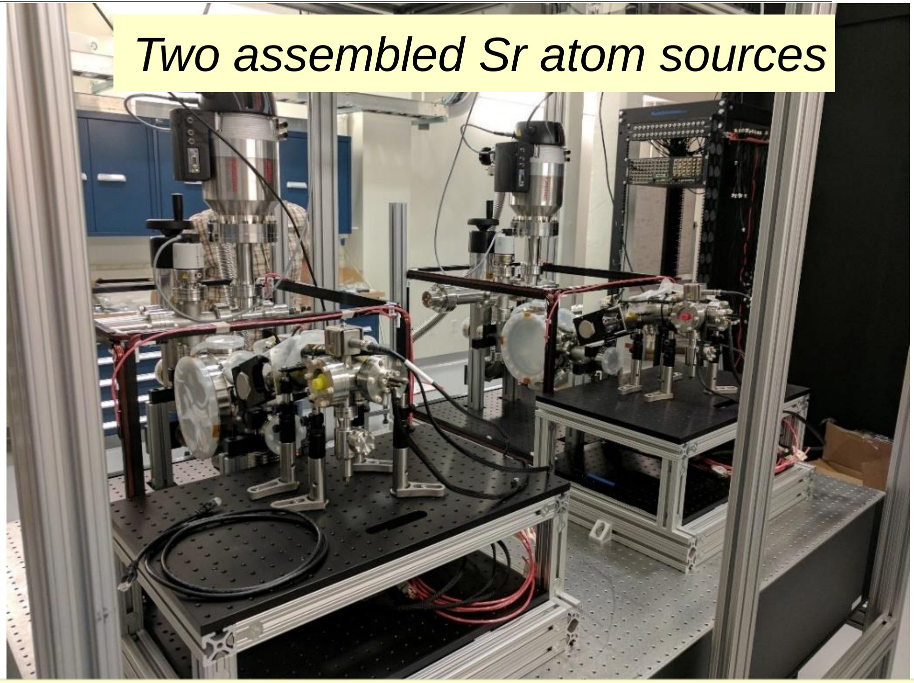


Two assembled Sr atom sources

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

It is supposed to be assembled over summer 2019.

Stanford MAGIS prototype



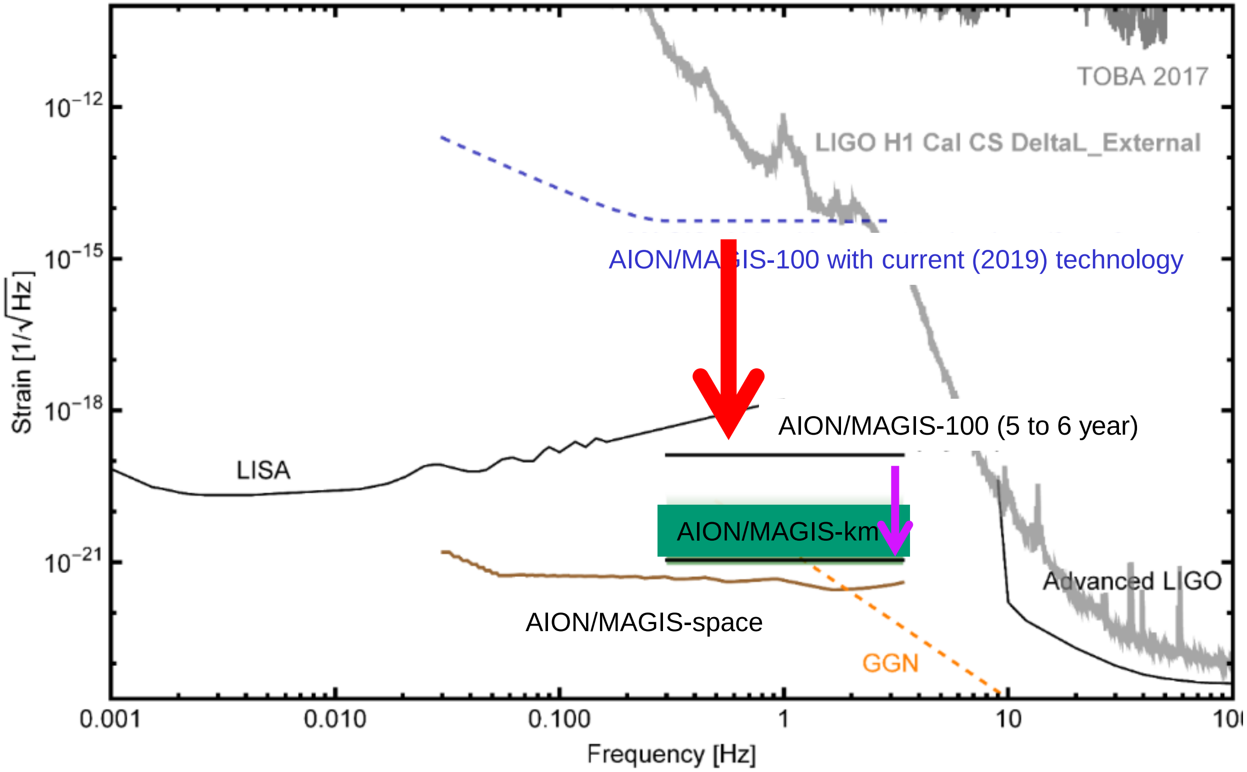
Two assembled Sr atom sources

Stanford Lab to host 8 m prototype of the Sr fountain

More about MAGIS-100 in the talk of Jason Hogan

It is supposed to be assembled over summer 2019.

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

AION PROJECT WORK PACKAGES

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

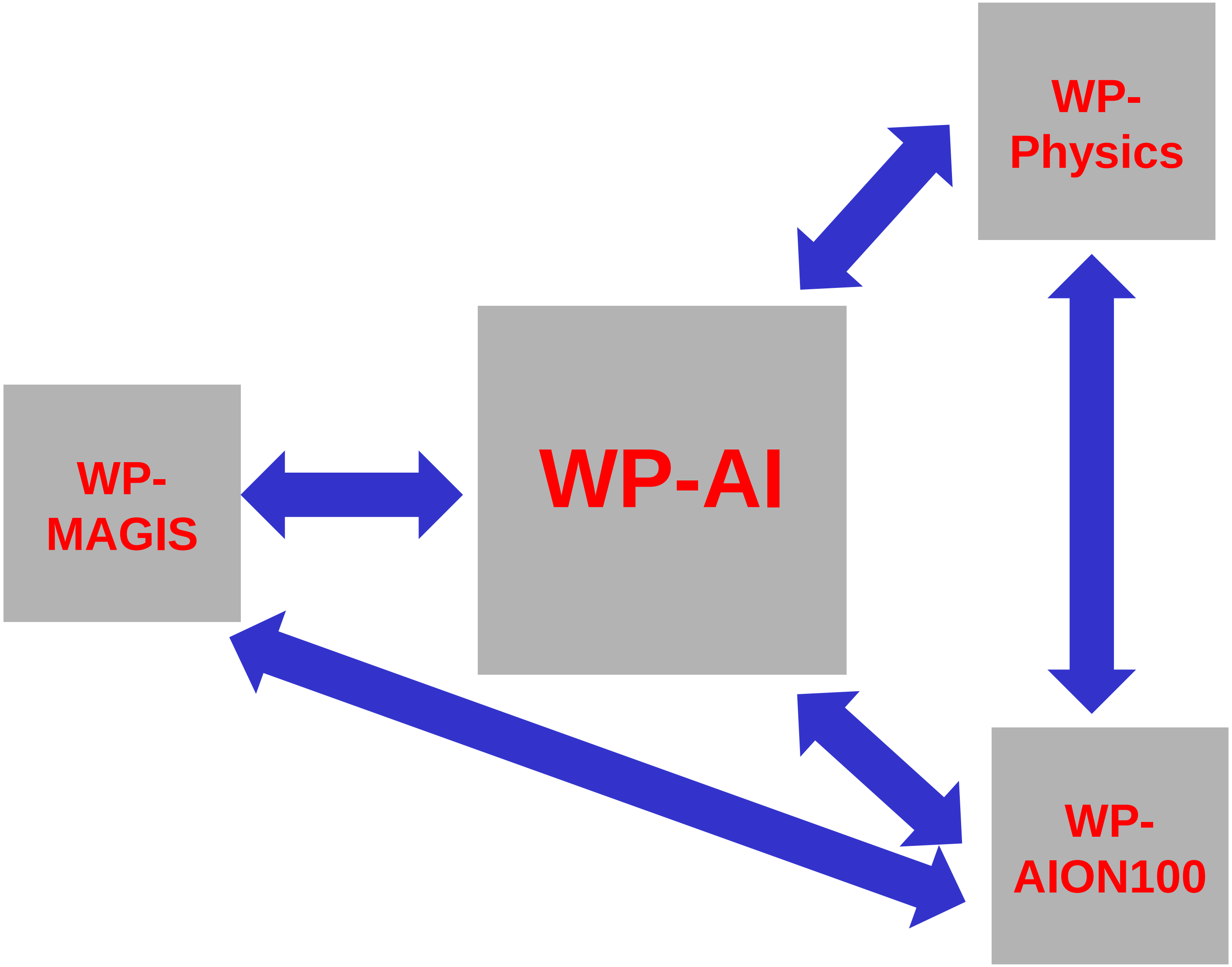
WP-AION100

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

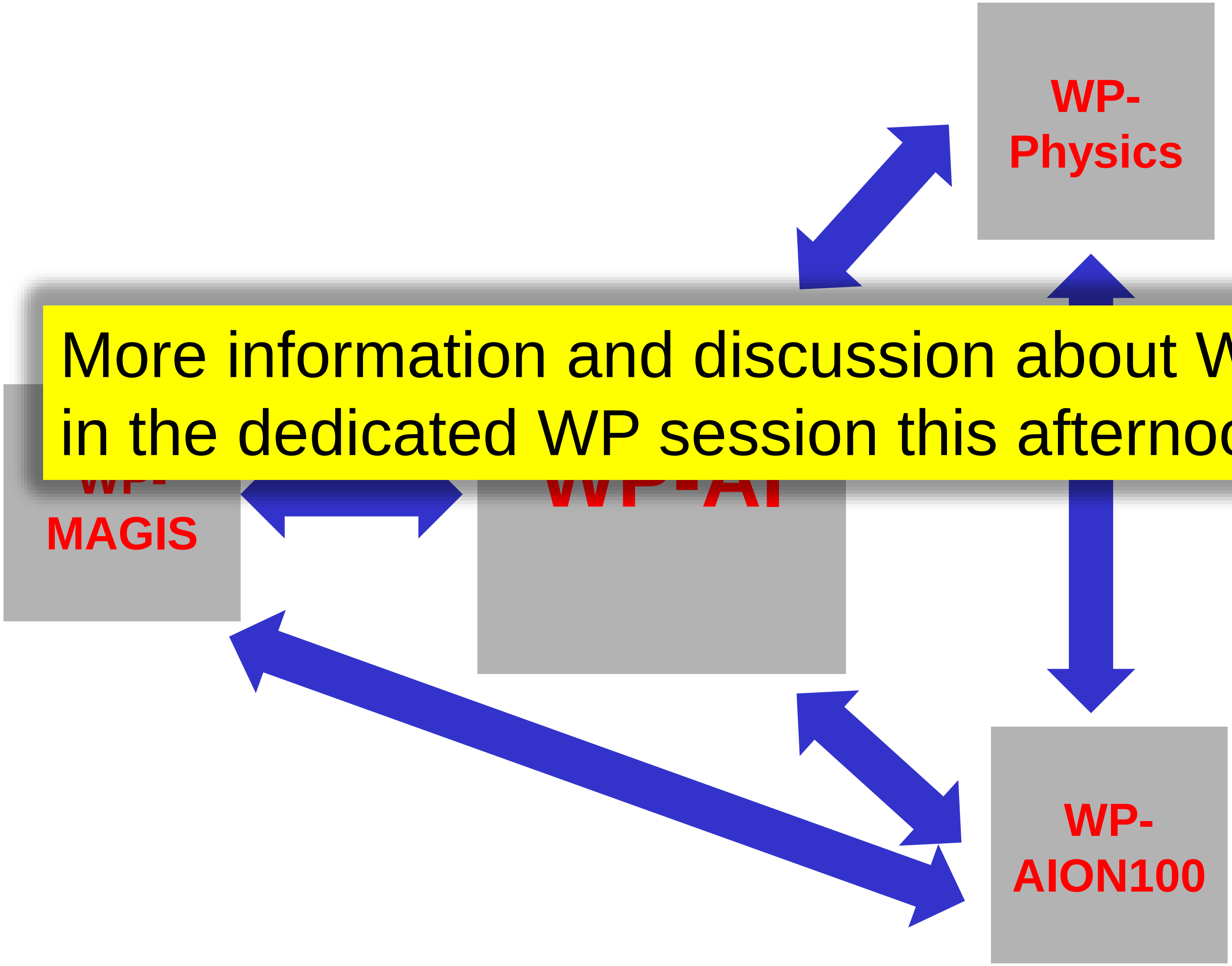
WP-MAGIS

This will give us MAGIS and US Collaboration

AION10 [Stage 1]: Main WP Connections



AION10 [Stage 1]: Main WP Connections

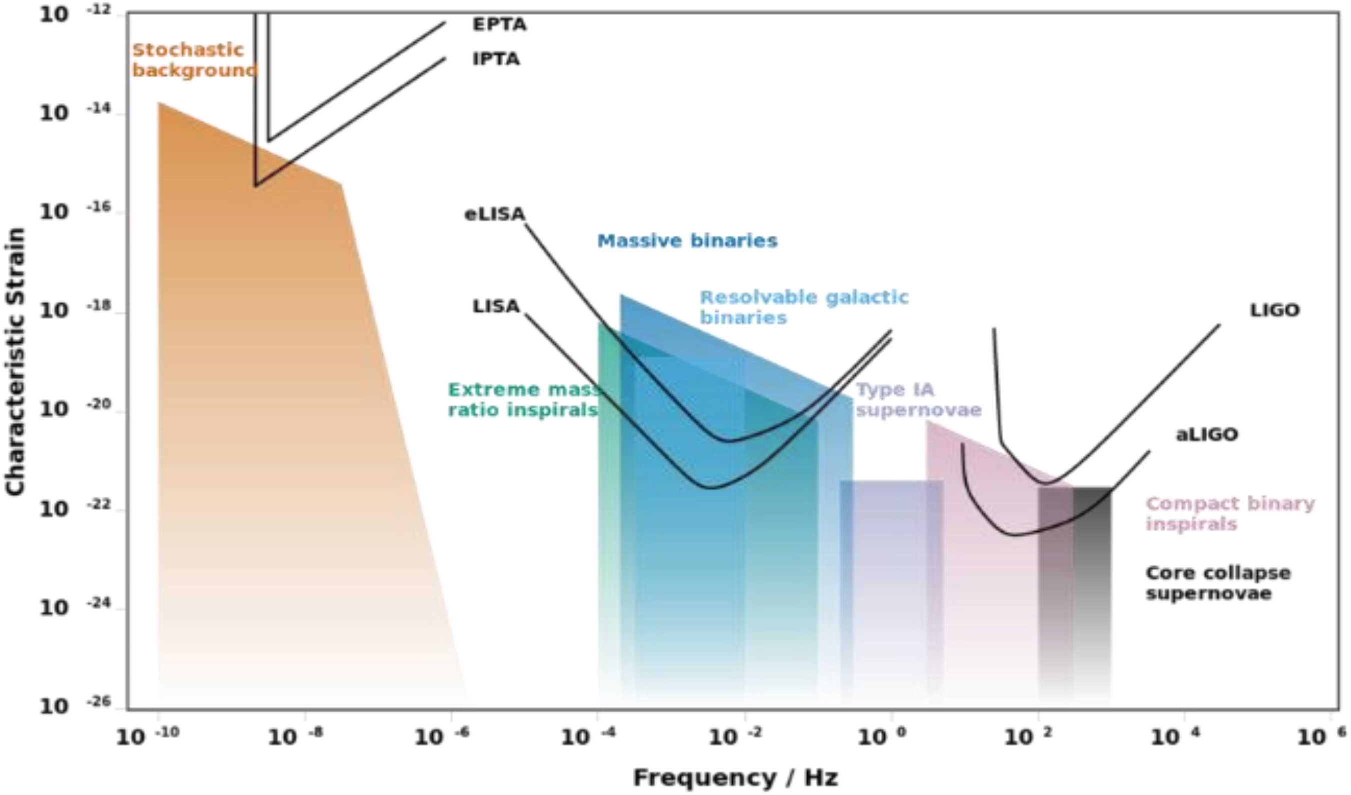


More information and discussion about WPs in the dedicated WP session this afternoon!

THE PHYSICS CASE

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

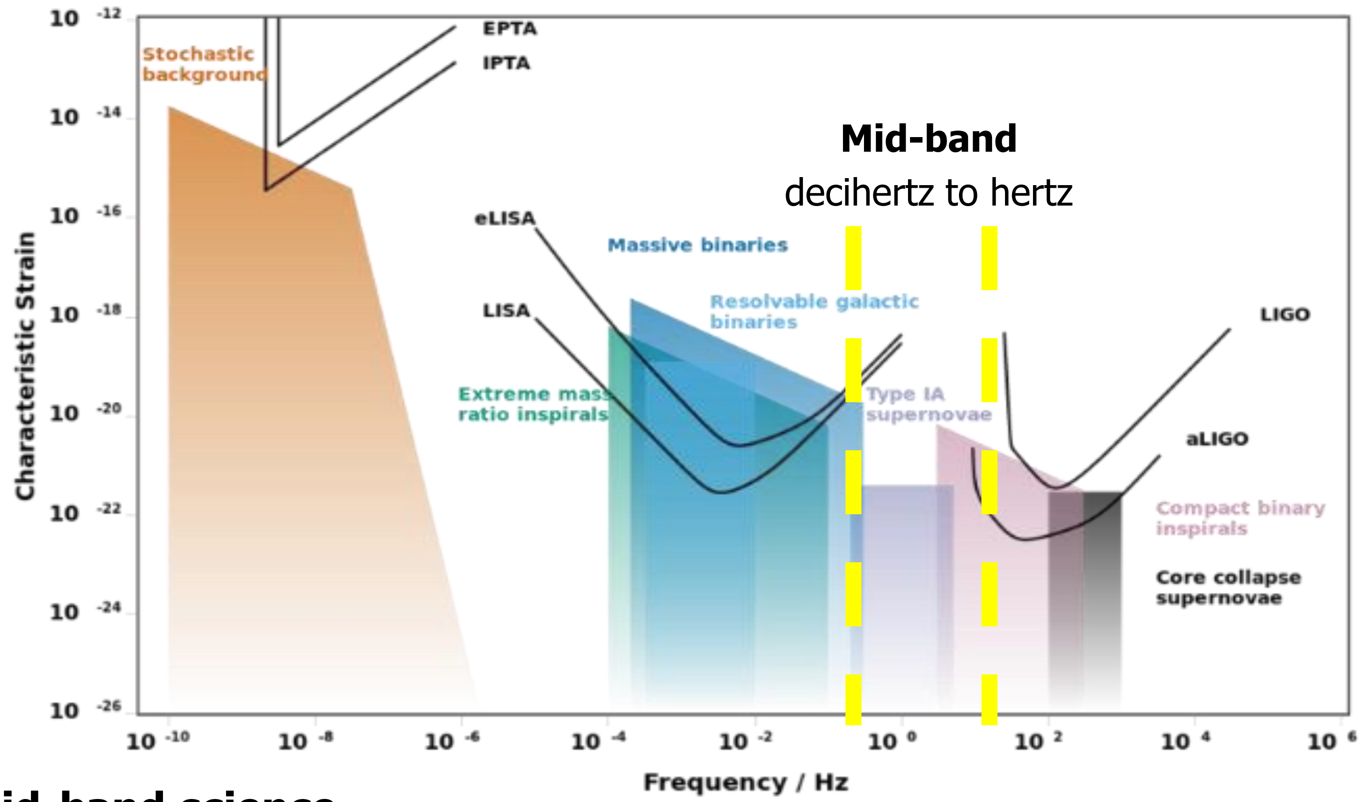
Experimental GW Landscape



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

O. Buchmueller AION Project

Experimental GW Landscape



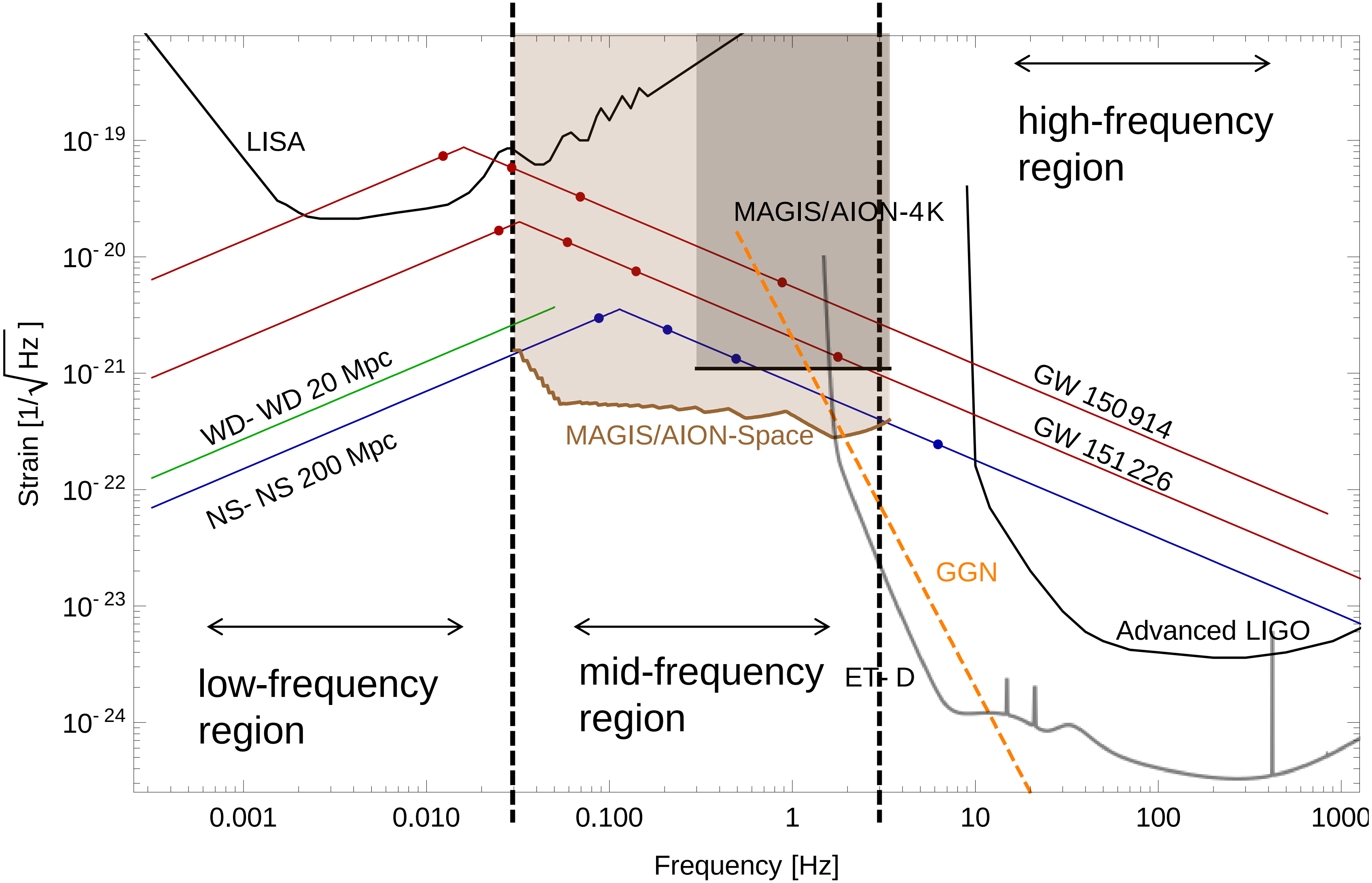
Mid-Band currently NOT covered

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

O. Buchmueller AION Project



Sky position determination

Sky localization precision:

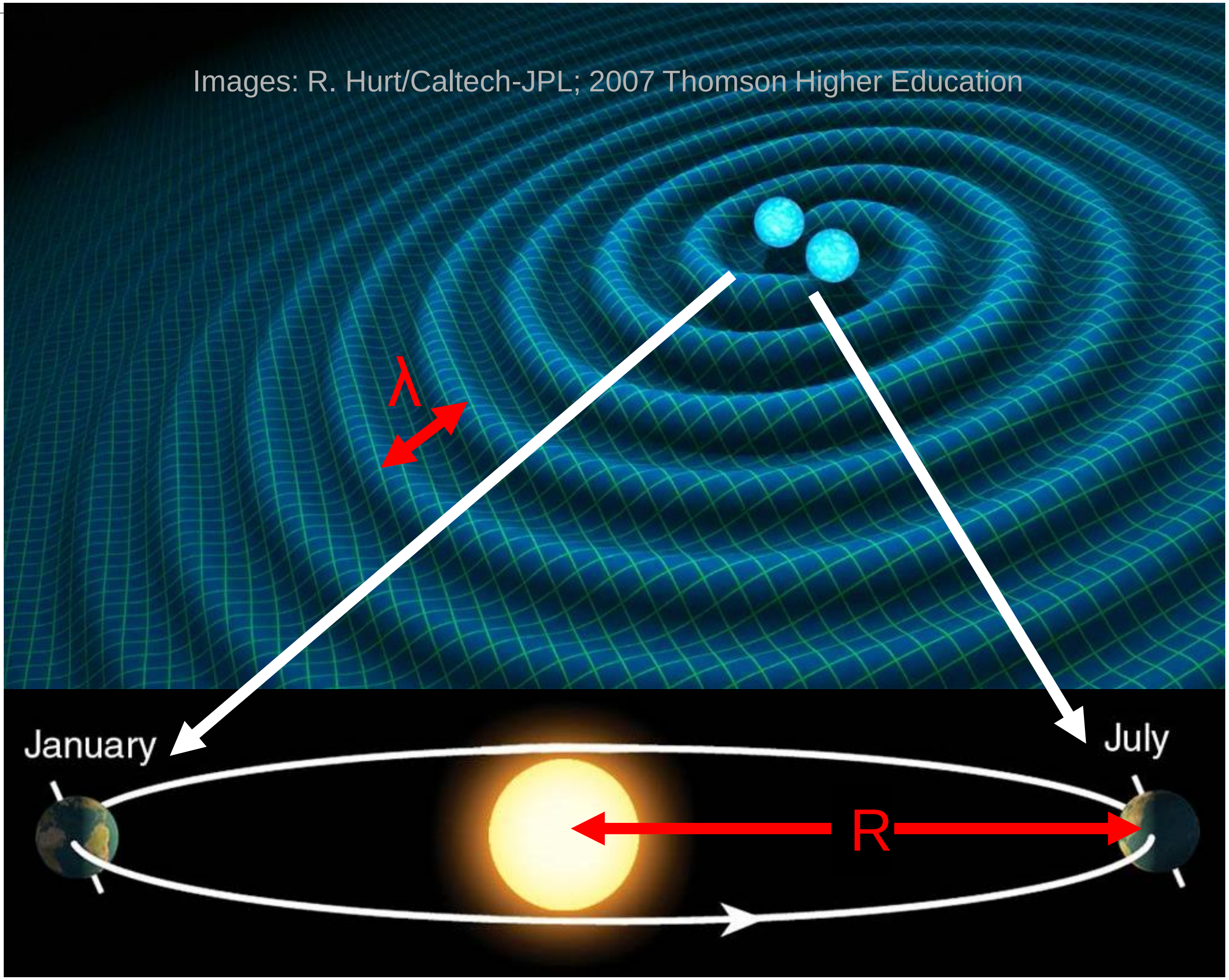
$$\sqrt{\Omega_s} \sim \left(\mathrm{SNR} \cdot \frac{R}{\lambda}\right)^{-1}$$

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

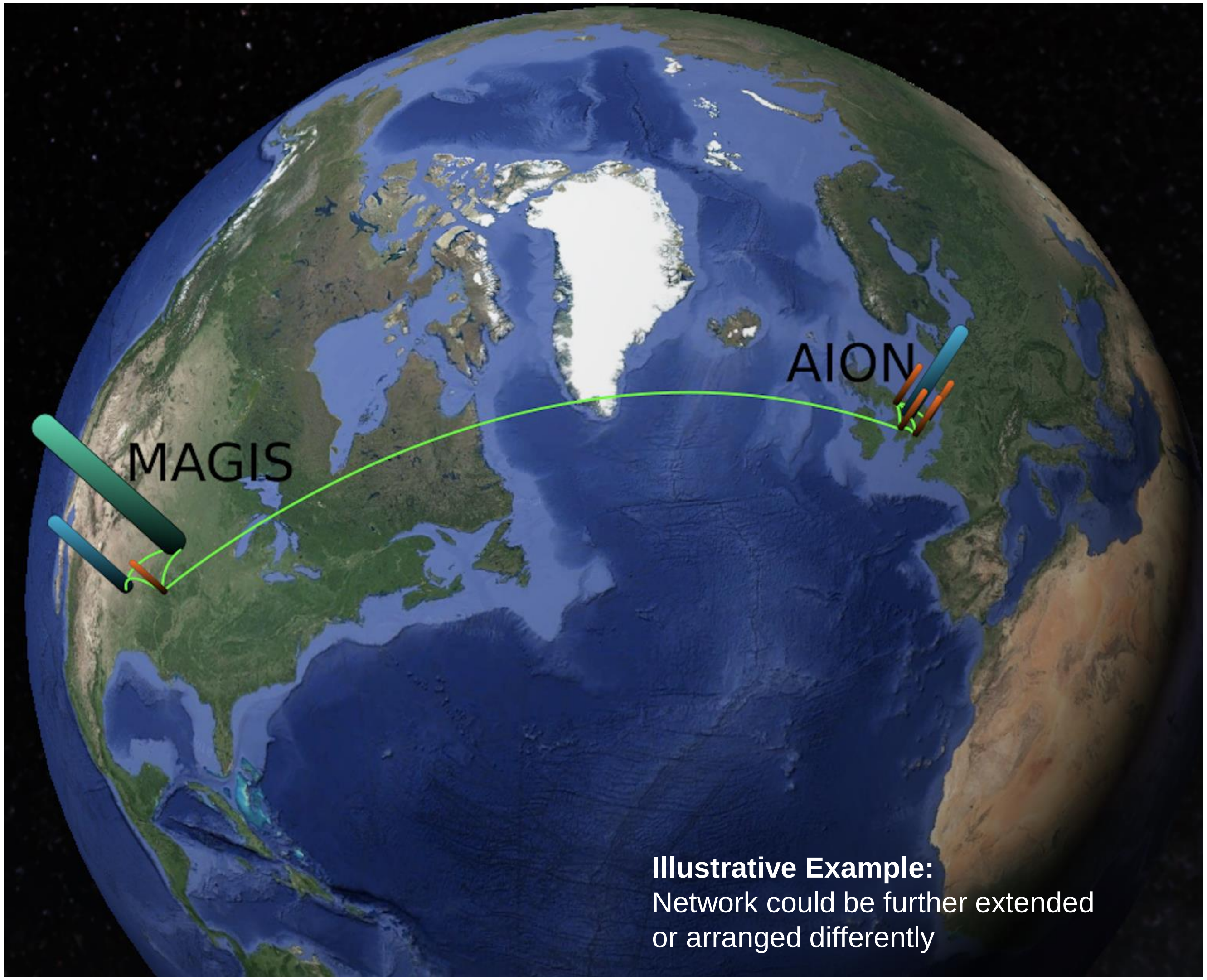
Courtesy of Jason Hogan!



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

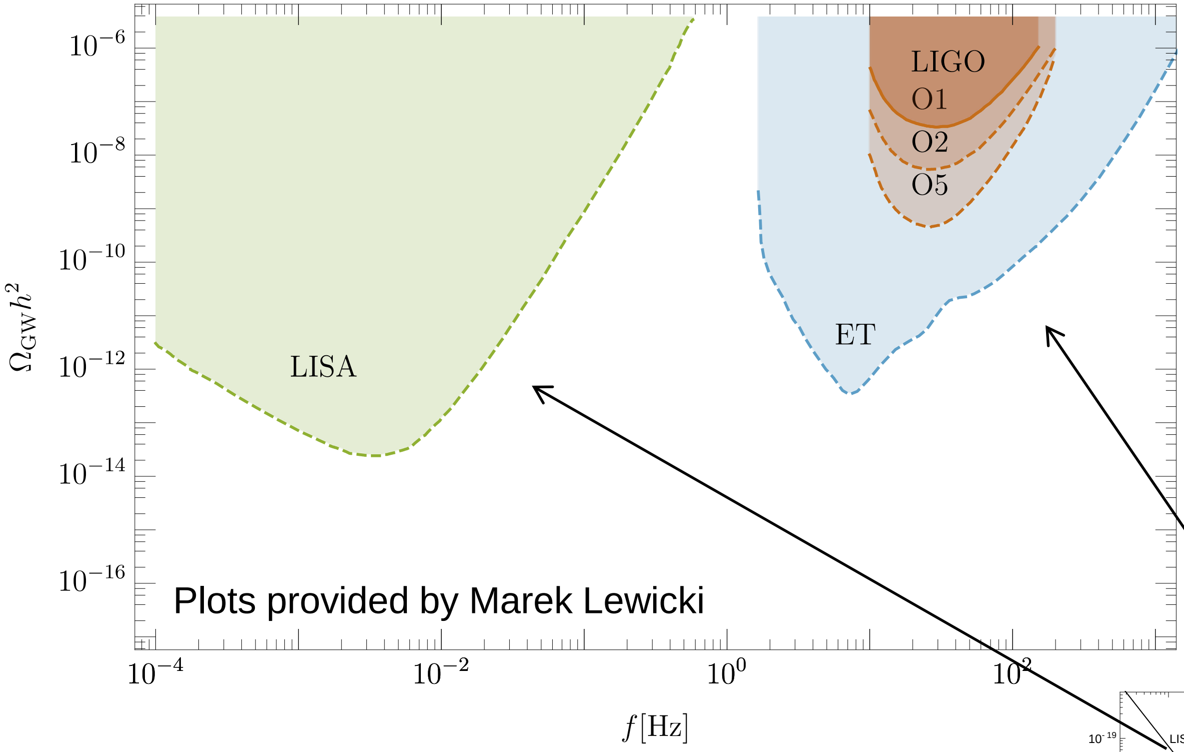
Ultimate Goal: Establish International Network



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

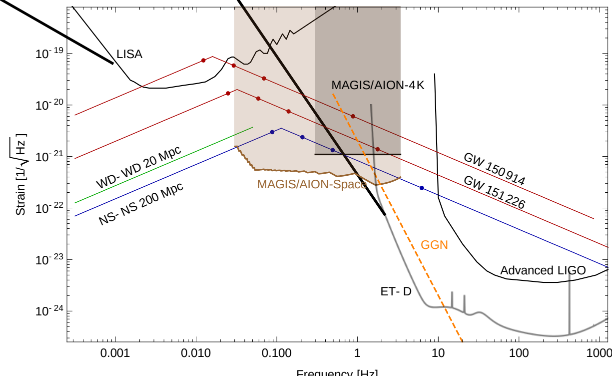


Plots provided by Marek Lewicki

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

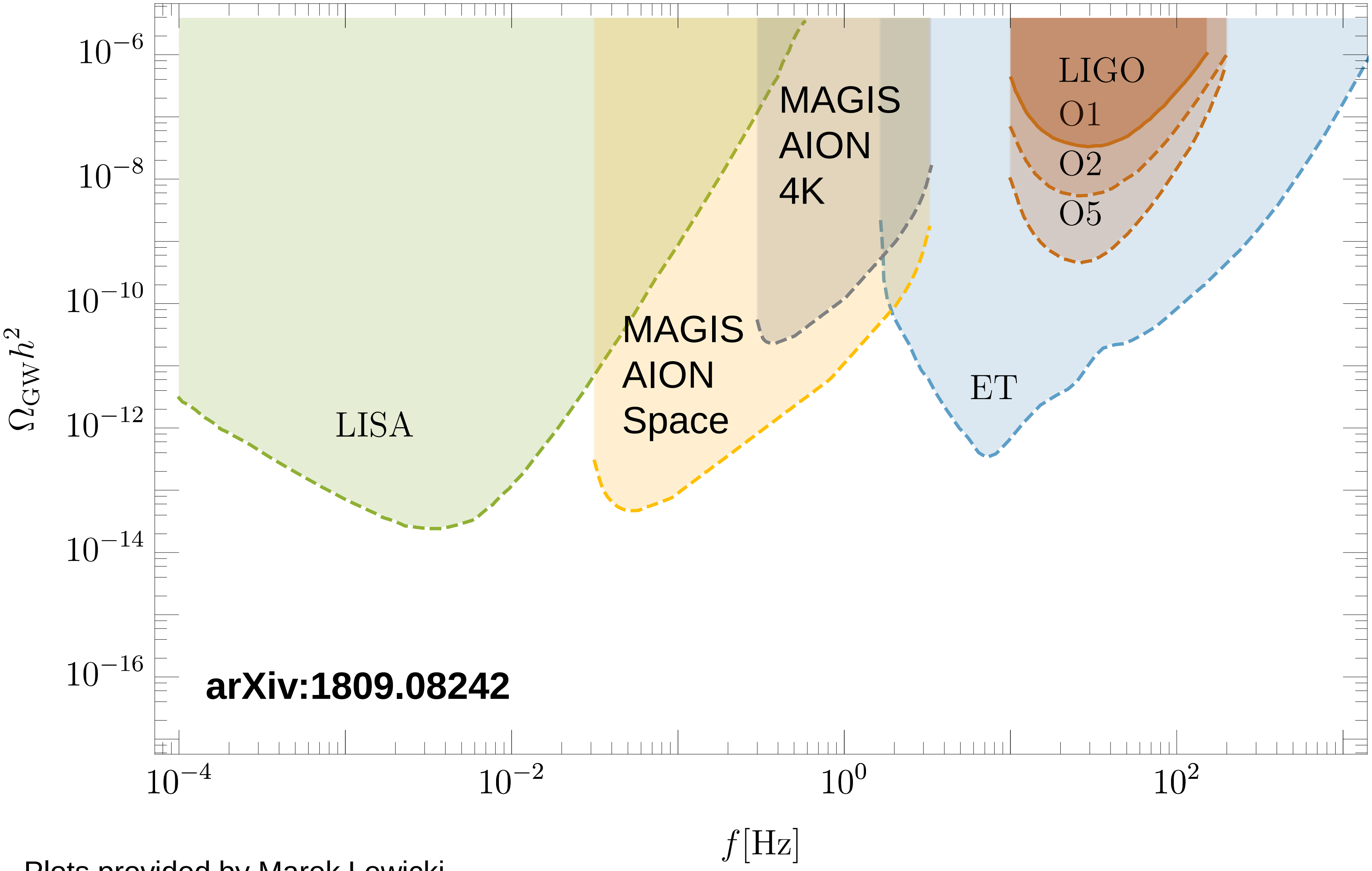
What is is the GW signal of electroweak phase transition in various theories beyond the Standard Model.

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



GW Detection & Fundamental Physics - Example

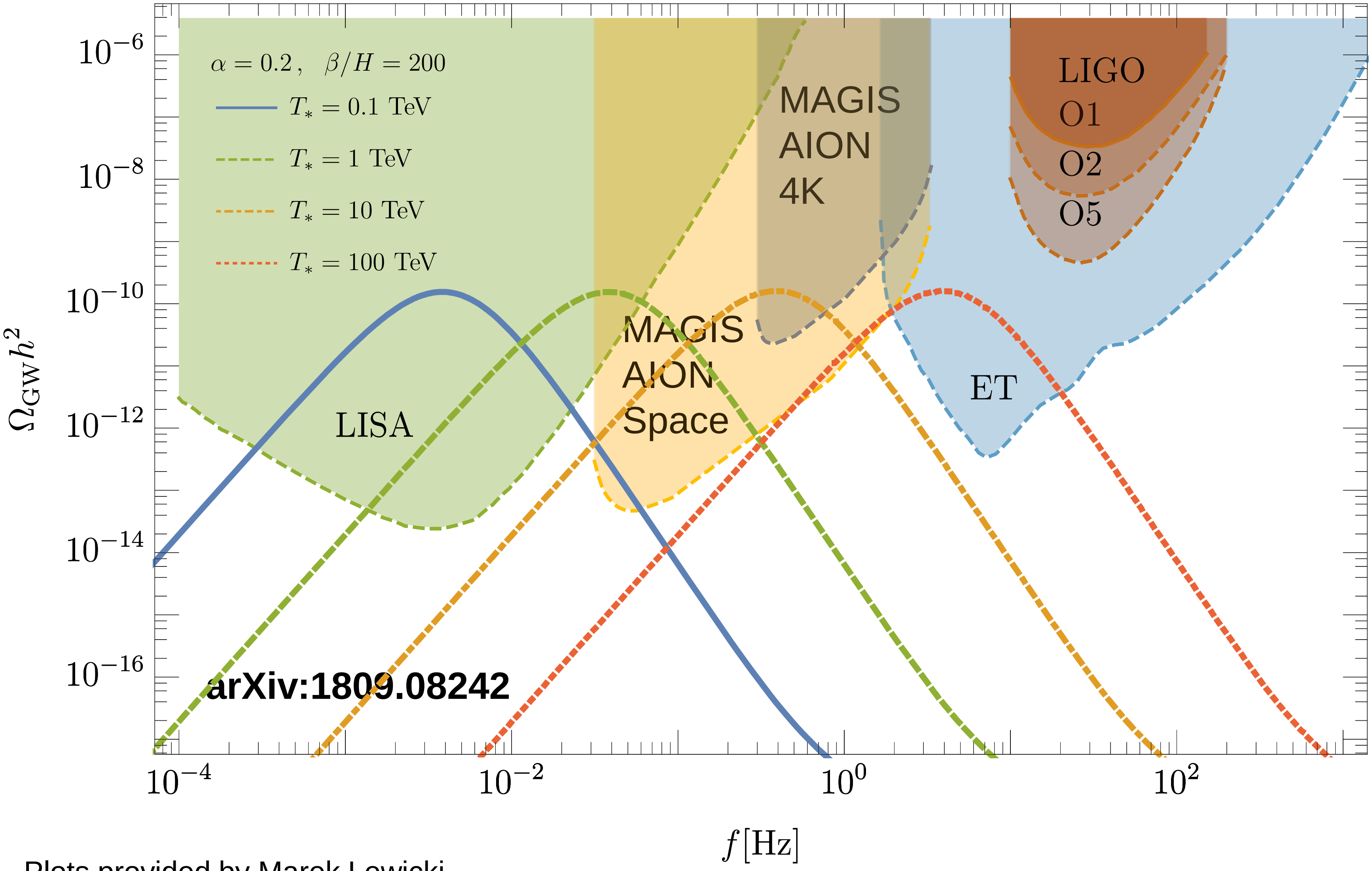
O. Buchmueller AION Project



Plots provided by Marek Lewicki

GW Detection & Fundamental Physics - Example

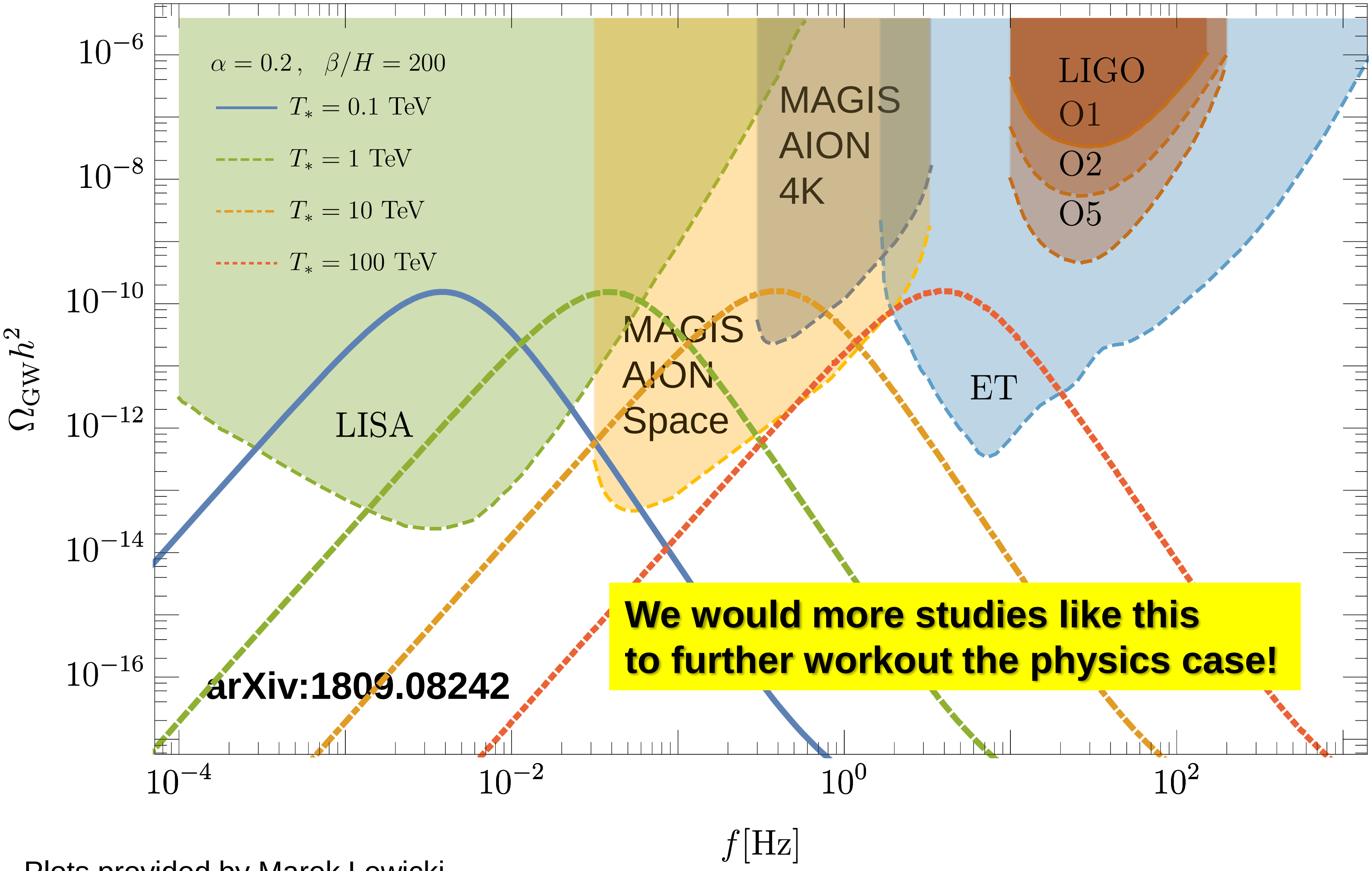
O. Buchmueller AION Project



Plots provided by Marek Lewicki

GW Detection & Fundamental Physics - Example

O. Buchmueller AION Project



arXiv:1809.08242

We would more studies like this to further workout the physics case!

Plots provided by Marek Lewicki

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:

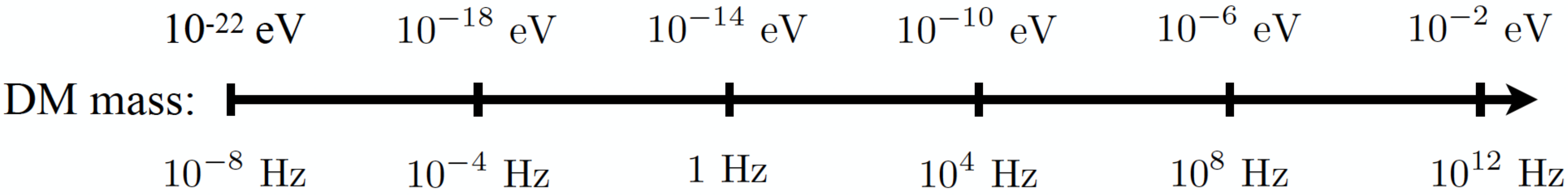
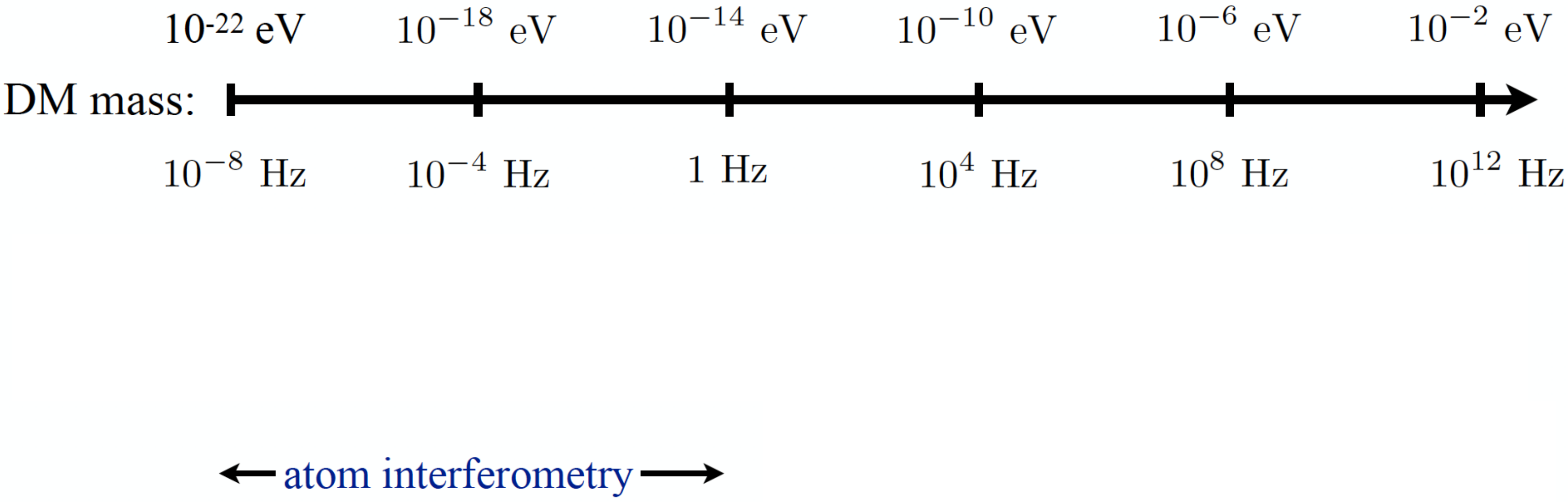


Diagram taken from P. Graham's
talk at HEP Front 2018

The Landscape of Ultra-Light Dark Matter Detection

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

Example: Ultra-Light Dark Matter:



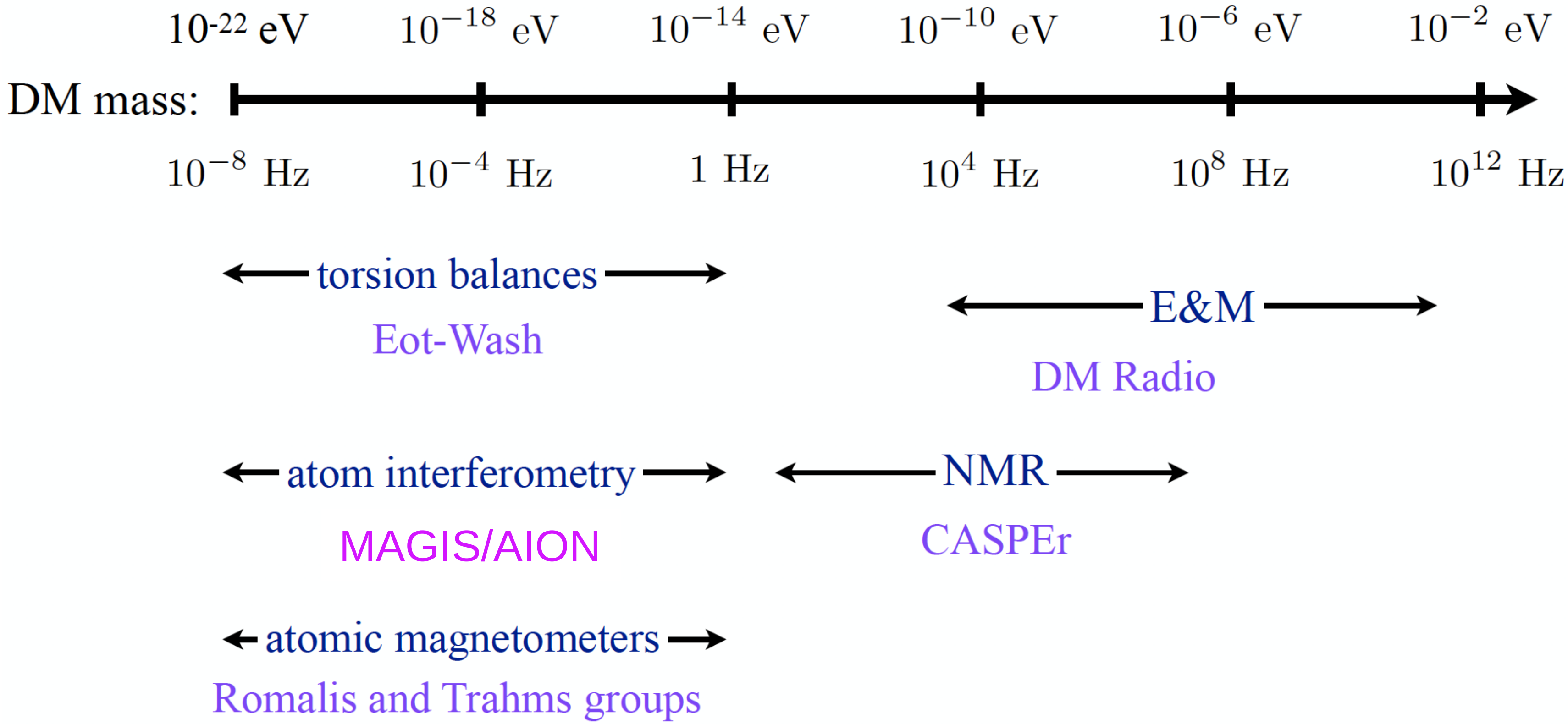
MAGIS/AION

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

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:



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

Imperial College London

Ultra-Light Spin-0 Dark Matter

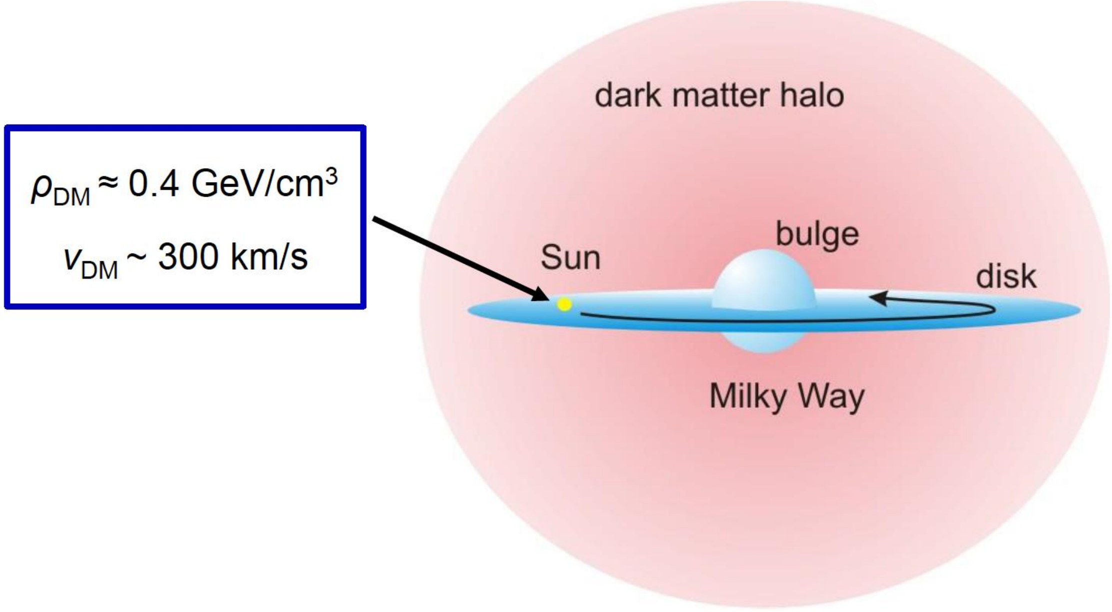
O. Buchmueller AION Project

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

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

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

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



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

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

Ultralight scalar dark matter

Ultralight dilaton DM acts as a background field (e.g., mass ~10^{-15} eV)

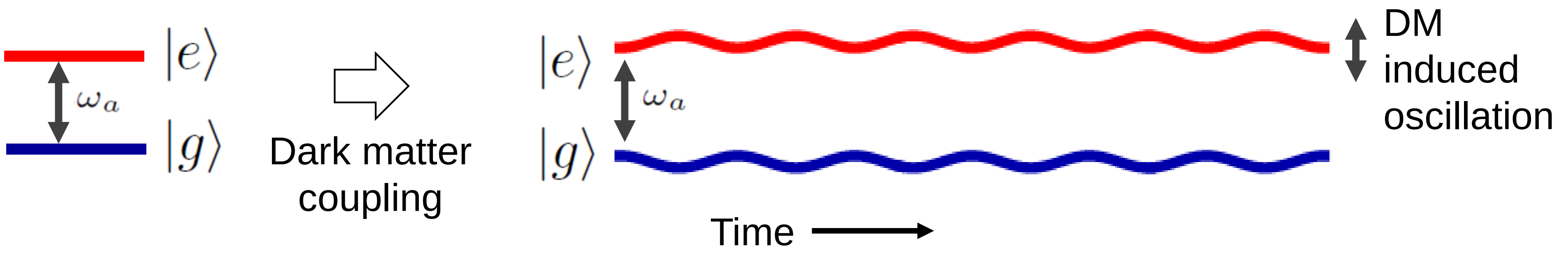
O. Buchmueller AION Project

$$\mathcal{L} = \underbrace{+\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2}_{\text{DM scalar field}} - \sqrt{4\pi G_N}\phi\left[\underbrace{d_{m_e} m_e \bar{e}e}_{\text{Electron coupling}} - \underbrace{\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Photon coupling}}\right] + \underbrace{\ldots}_{\text{e.g., QCD}}$$

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

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

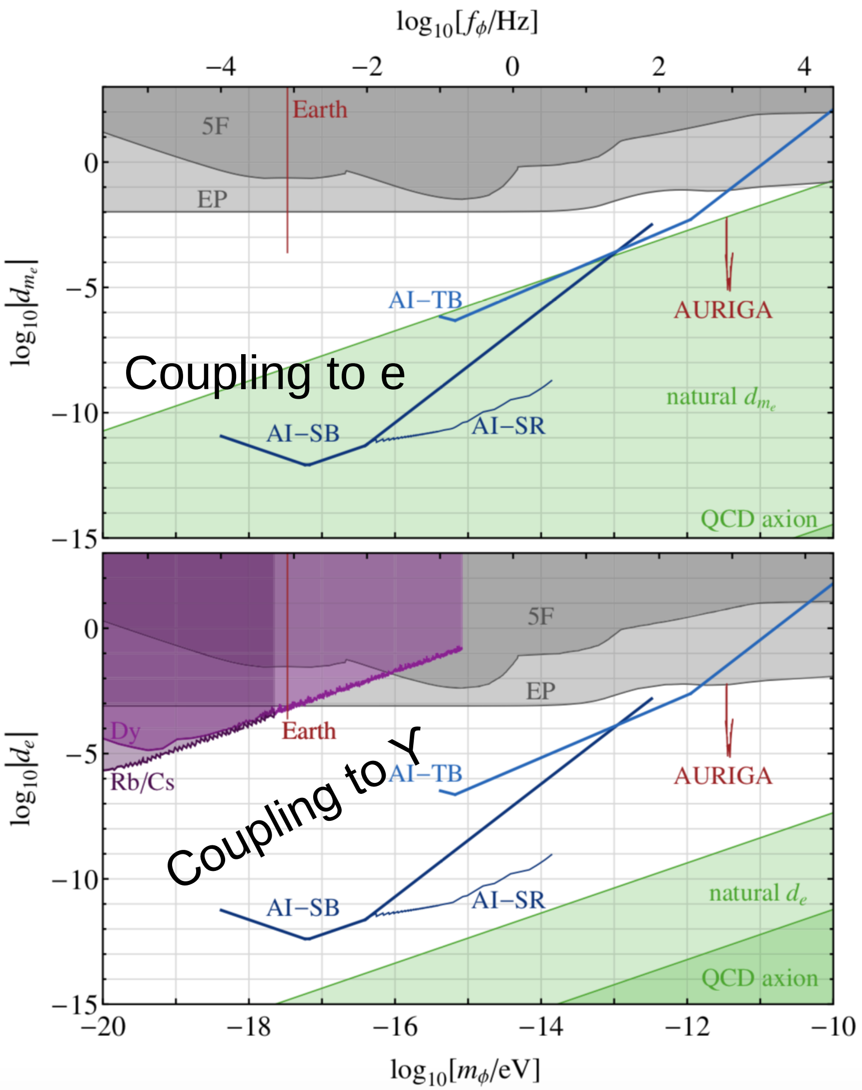
DM coupling causes time-varying atomic energy levels:

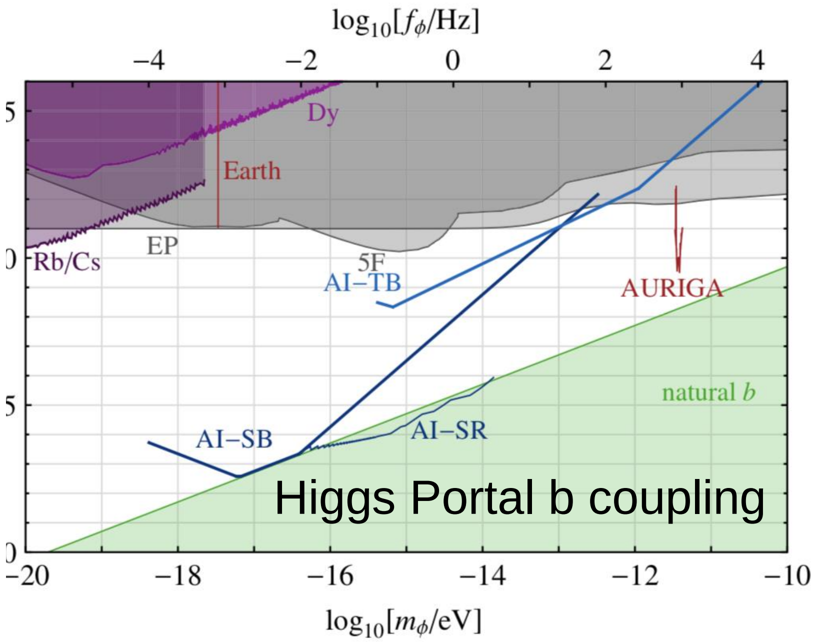


Courtesy of Jason Hogan!

Sensitivity for DM with Scalar Couplings to Matter

O. Buchmueller AION Project

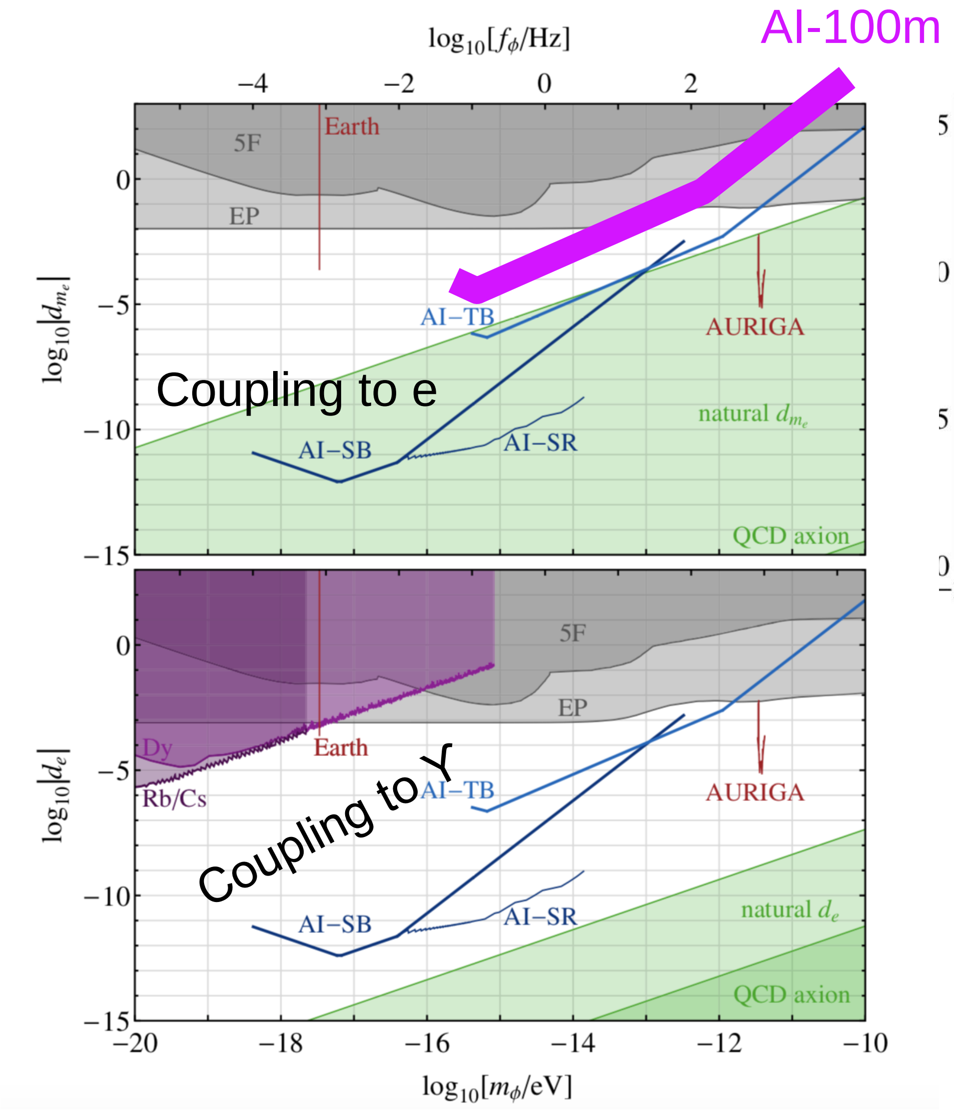


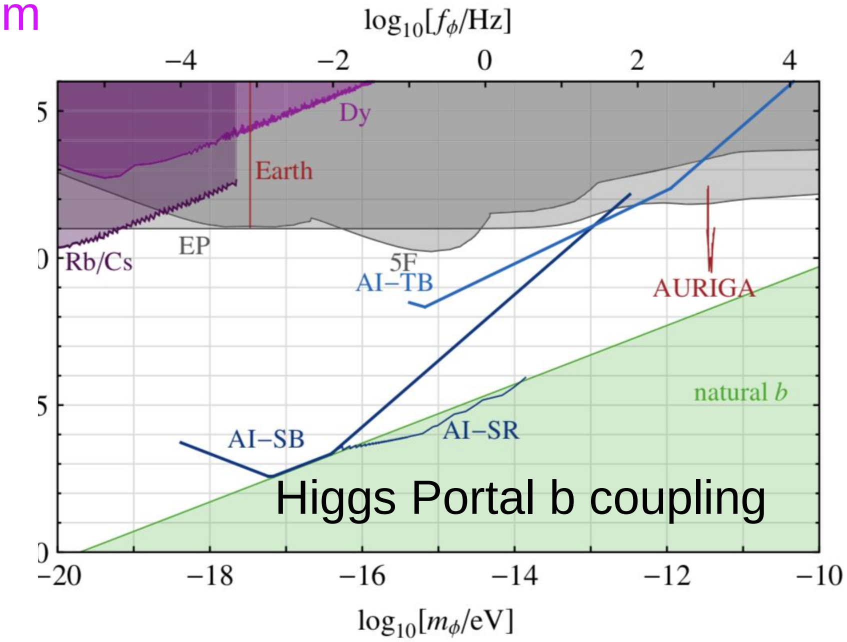


DM with scalar couplings to matter, which cause time variation of fundamental constants such as the electron mass

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

Sensitivity for DM with Scalar Couplings to Matter





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

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

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 AION project will closely collaborate 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 detectors, one in the UK and one in the US, in tandem enables new exciting physics opportunities not accessible to either detector alone.
  - To accomplish the ultimate sensitivity required to study the Mid-Frequency Band of the GW spectrum, the basic parameters of the Atom Interferometer have to be significantly improved. This requires significant effort and ingenuity, and the UK community can play an important role in it!