A UK ATOM INTERFEROMETER OBSERVATORY AND NETWORK (AION) FOR THE EXPLORATION OF ULTRA-LIGHT DARK MATTER AND MID-FREQUENCY GRAVITATIONAL WAVES

QUANTUM SENSORS FOR FUNDAMENTAL PHYSICS,
ST. CATHERINE'S COLLEGE, OXFORD, UK
OCTOBER 16/17, 2018

Oliver Buchmueller, Imperial College London

Much more details in the talks of:
Jason Hogan [yesterday]
Jon Coleman [just before me]

What is AION (in a nutshell)?

O. Buchmueller AION Project 17th Oct 2018

- 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 across 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

What is AION (in a nutshell)? Cont

- The outline case was prepared by Themis Bowcock [Liverpool], Oliver Buchmueller [Imperial College, Coordinator], Jonathon Coleman [Liverpool], and Ian Shipsey [Oxford]. It was submitted on September 7th and is now with STFC Executive Board and Science Board for review.
- There is the opportunity to be involved in the design and the R&D for large-scale quantum interferometric experiments to be located in the UK.
- There is also the exciting option to collaborate with the US community, which pursues a similar goal of an eventual km-scale atom interferometer.
- As the programme would reach its ultimate sensitivity by operating two detectors in tandem, one in the UK and one in the US, this collaboration would open not only unique physics opportunities but would also enable important synergies in the design of the experiments.

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
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

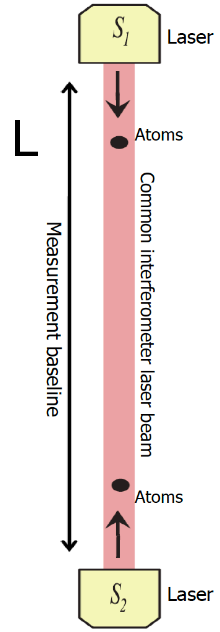
In preparation of this proposal we have broadly consulted with the relevant UK science communities and have received very positive feedback. The support is across several fields, ranging from fundamental particle physics, over atom interferometry to gravitational wave physics. The support also covers both experimental as well as theory communities in the UK. So far, about 70 members from 18 UK institutions have provided explicit support for this proposal:

Birmingham, Bristol, Brunel, Glasgow, Imperial College, Kings College London, University College London, Liverpool, National Physical Laboratory, Nottingham, Oxford, Rutherford Appleton Laboratory, Manchester, Sheffield, Strathclyde, Sussex, Swansea

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

Proposed AION Programme

The proposal contains a 3-stage programme.



- **The first stage** develops existing technology and develops the infrastructure for the 100m detector, and produces detailed plans and assessment of performance before moving to Stage 2. L ~ 1m to 10m
- **The second stage** builds, commissions and exploits the 100m detector and also prepares design studies for the km-scale. L ~ 100m
- **The final stage**, which is not part of the funding request but we outline for completeness, prepares the groundwork for the continuing programme L ~ km-scale

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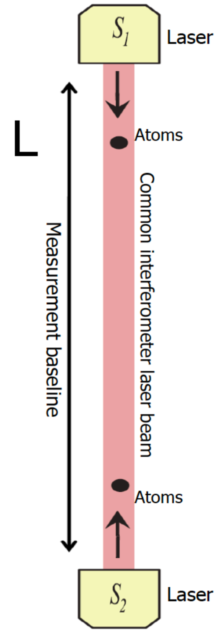

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More details about the individual stages are given in the backup of this talk

Site Options (non-exhaustive)

Site Constraints:

- The site must provide a long vertical shaft/tower (~100m) in which the device will be installed.
- The shaft/tower and its associated areas will, contain the shaft head and provide workspace, unrestricted access along its length, environmental control, ventilation, power, networking, and safety infrastructure.

Site Options (non-exhaustive)

- The cost is strongly dependent on the tower/shaft decision.

Options in the UK are:

- STFC-Daresbury Tower [already existing][
- Shaft at Boulby [would need to be build but extension to a km-scale detector could favour the Boulby mine.

Outside UK:

- CERN; using some of the LHC support shafts (~O(100m)) [currently in discussion with CERN management to evaluate the options]

Bottom line: There are options but further investigations are required to choose an appropriate site to facilitate optimal execution of the programme.

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.

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:

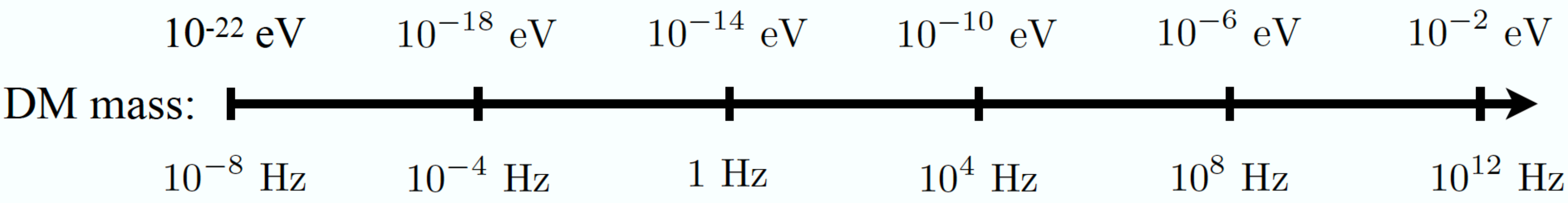

Diagram taken from P. Graham's talk at HEP Front 2018

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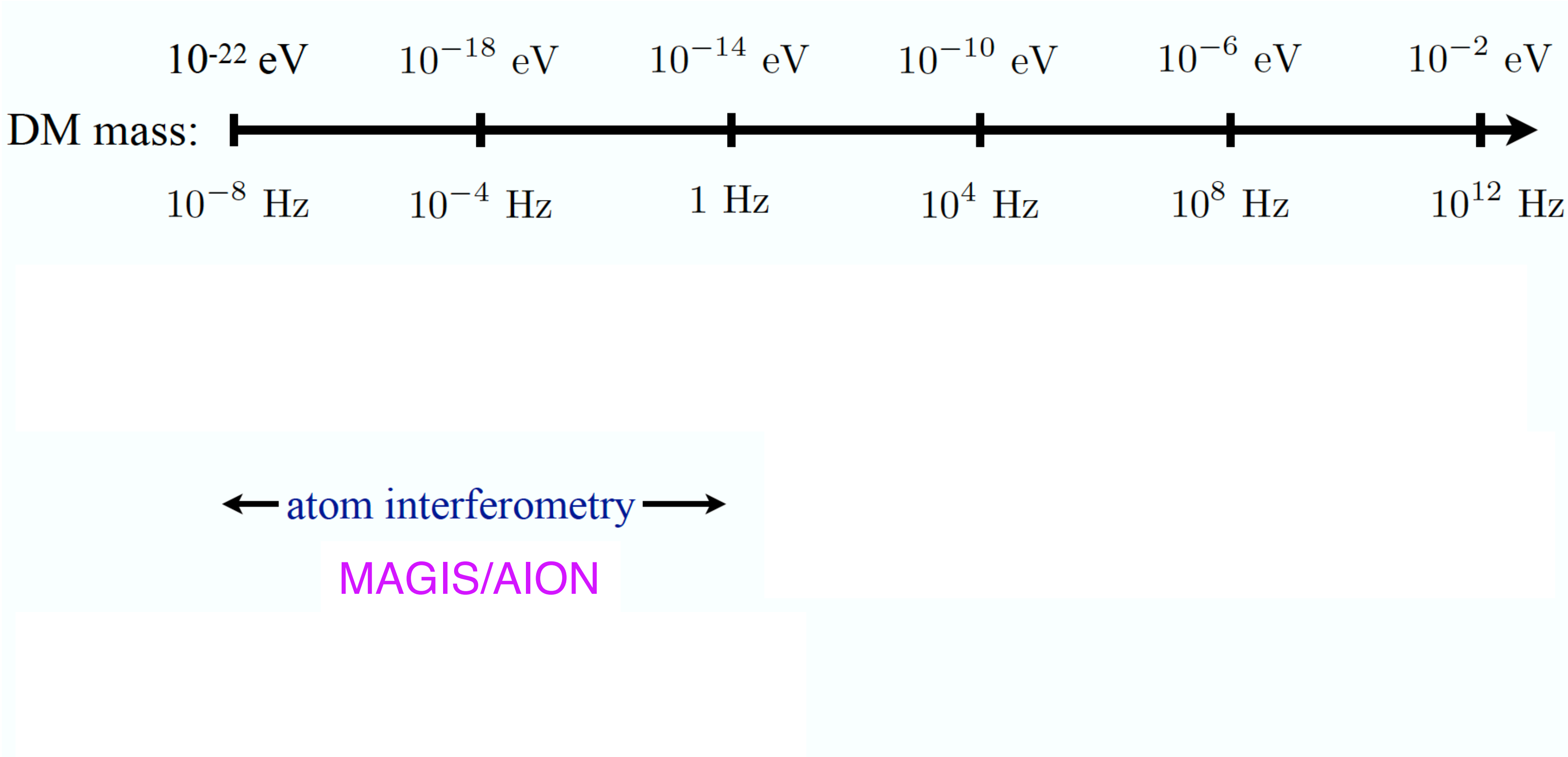

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Imperial College London

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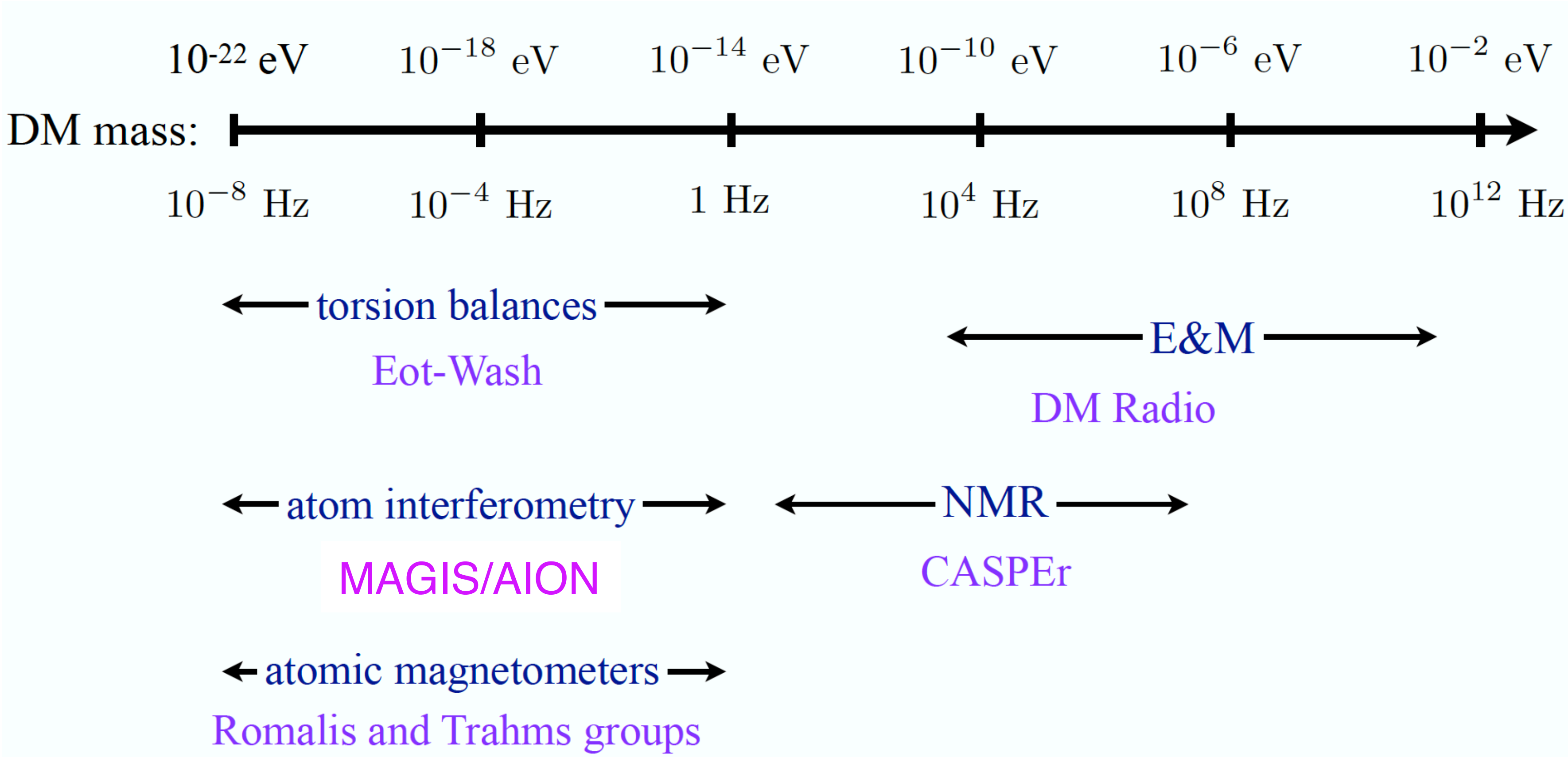

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Gravitational Wave Detection with Atom Interferometry

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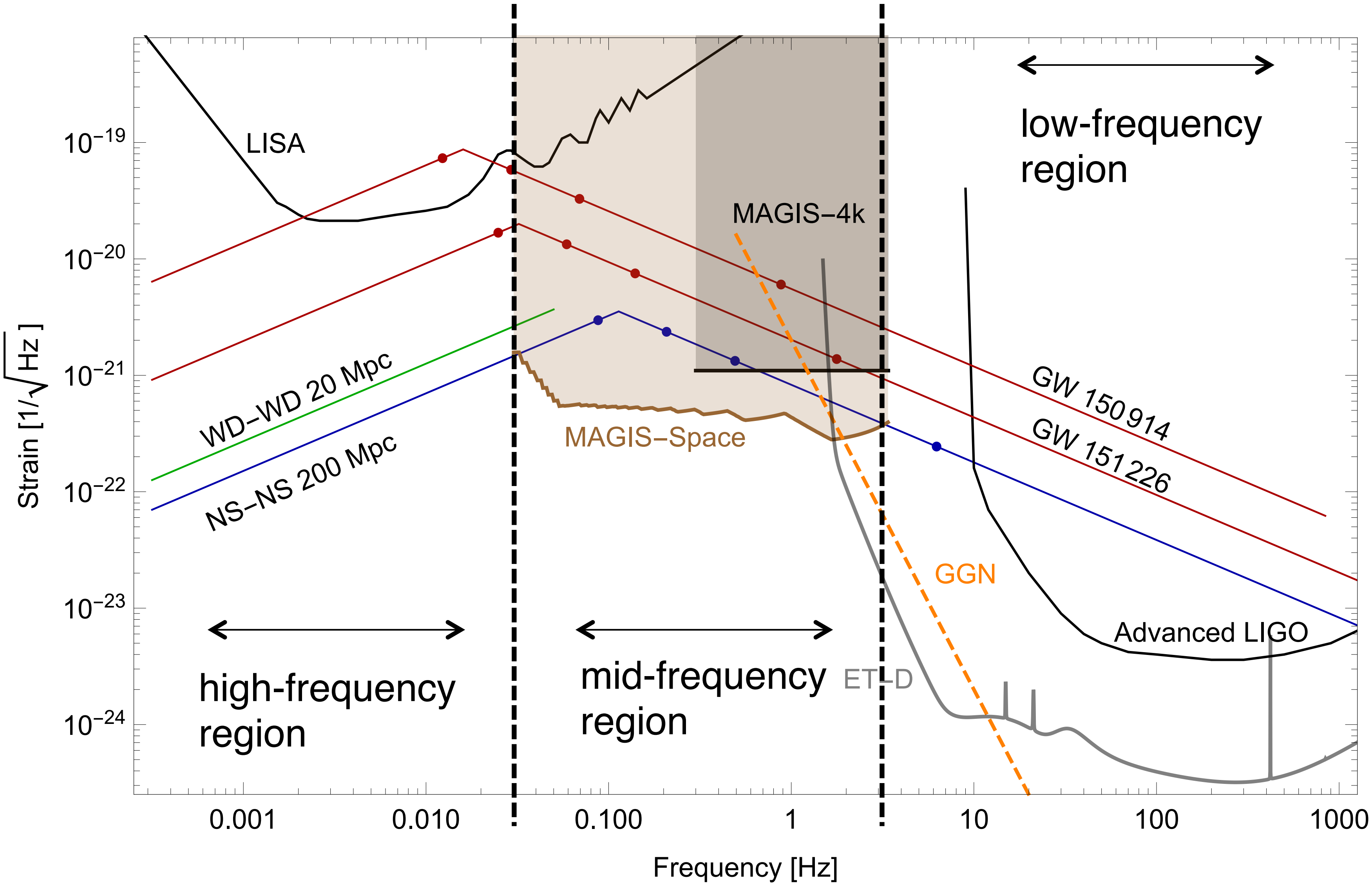
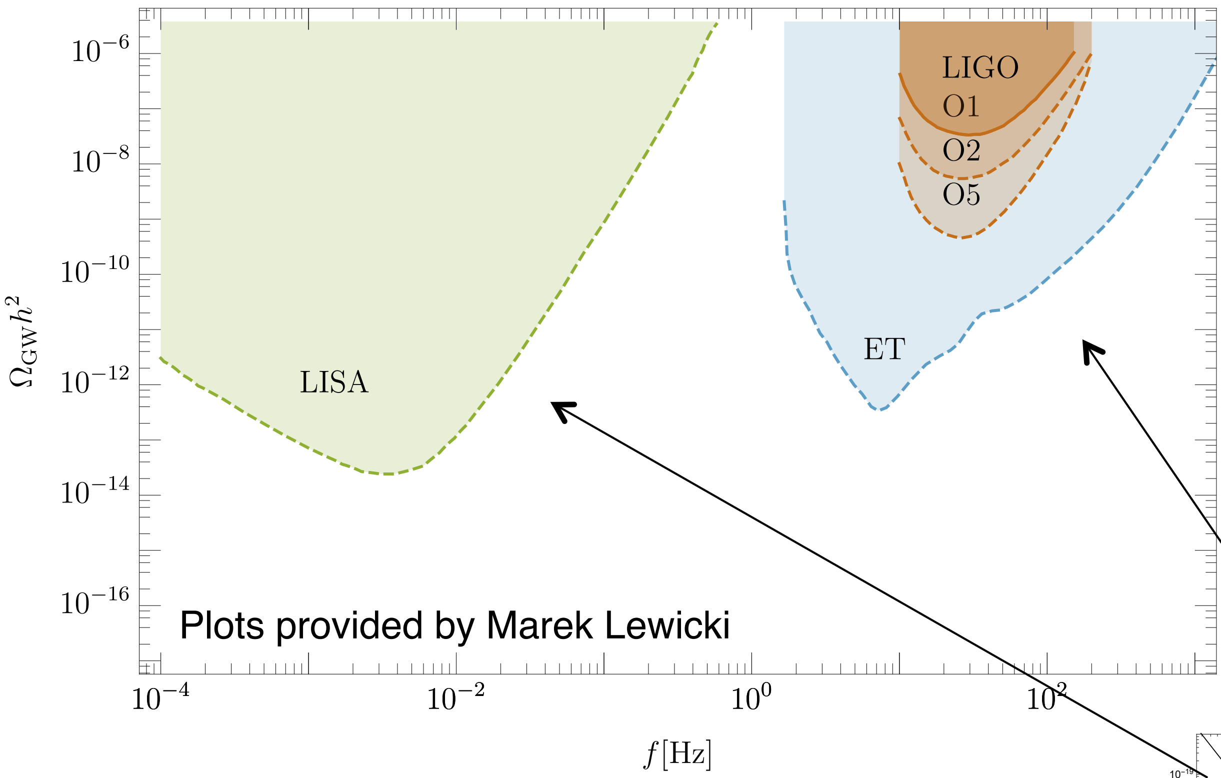


GW Detection & Fundamental Physics - Example

First-Order Electroweak Phase Transition and its Gravitational Wave Signal

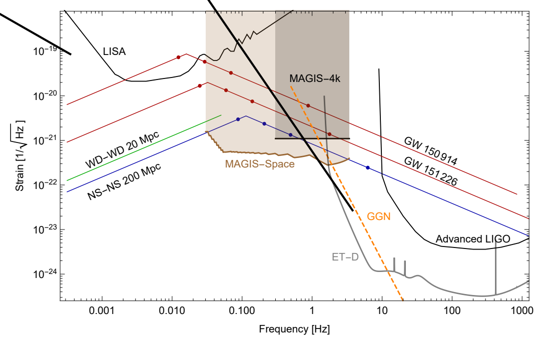


arXiv:1809.08242

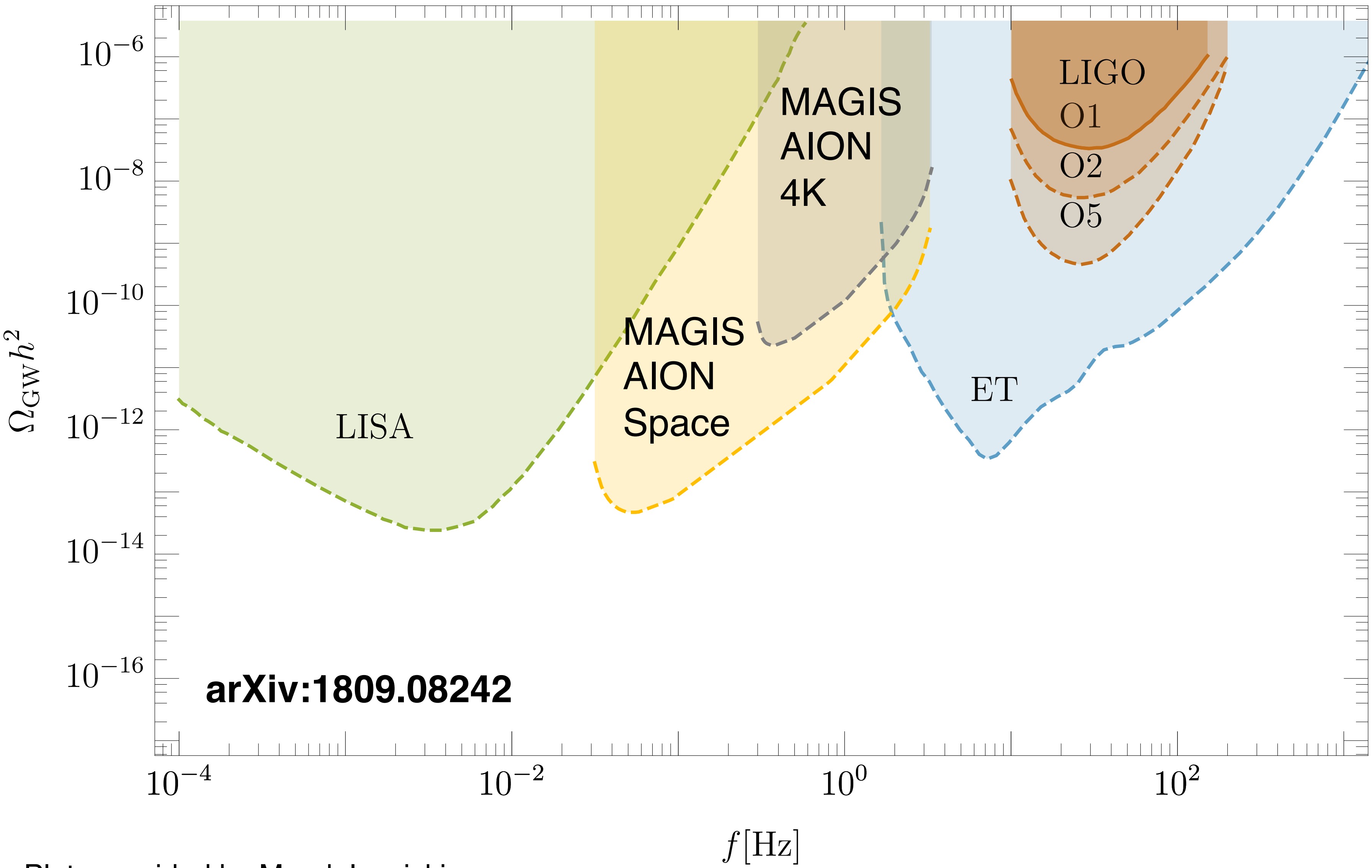
John Ellis, Marek Lewicki, José Miguel No

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

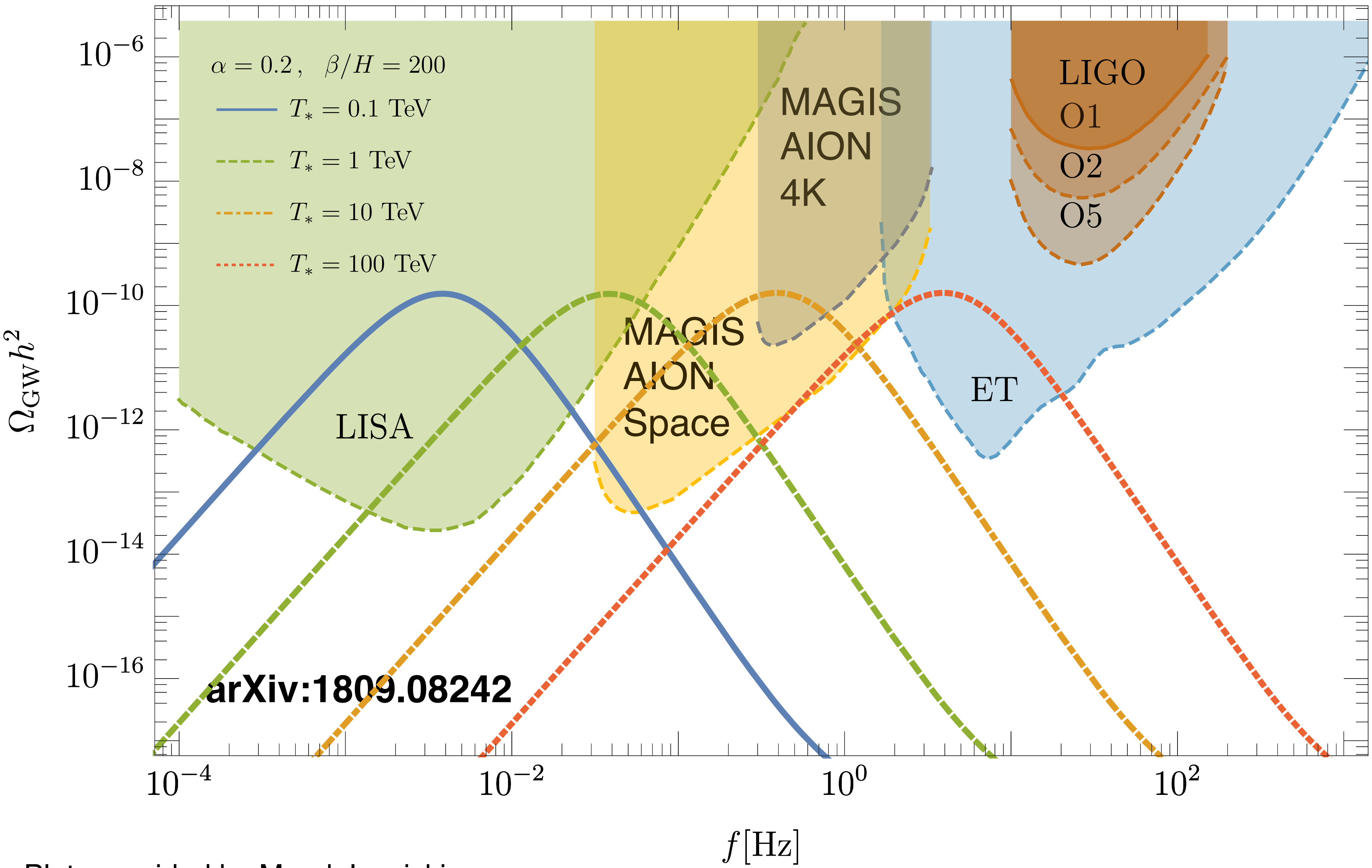


GW Detection & Fundamental Physics - Example



Plots provided by Marek Lewicki

GW Detection & Fundamental Physics - Example



Plots provided by Marek Lewicki

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.

BACKUP

AION: Stage 1

Stage 1 [year 1 to 3 in funding cycle] – 1 & 10 m Interferometers & Site Development for 100m Baseline

- Form UK collaboration to design and construct a 10 m atom interferometer (AI-10) based on AI-1 and MAGIS designs.
- Complete upgrade to an existing 1 m fountain (AI-1) in Liverpool, to deliver benchmark results
- Choose appropriate site to host the programme.
- Collaborate with UK industry to develop the laser system, phase locking cavities, optics and cameras for AI-10.
- Prototype AI-10 to demonstrate the technology and to establish UK expertise and leadership in the field.
- Commission AI-10 with short baseline and compare with AI-1.
- Design work for 100m atom interferometer (AI-100) in a tower or a shaft.
- Complete site development and infrastructure for housing AI-100.

AION: Stage 2

Stage 2 [year 3 to 6 in funding cycle] – 100m Construction & Commissioning

- Build 2nd AI-10 to share expertise and to train people.
- Demonstrate use of two AI-10s working in simultaneously to pave the way for AI-100 and km-scale detector correlation.
- Design study for A-100 and km-stage
- **Final Goal:** build and commission AI-100 based on the AI-10 prototype. This setup would enable competitive searches for ultra-light dark matter and first prototype studies of gravitational wave physics in the mid-frequency band.
- Operation and exploitation of the experiment will begin after Stage2 and is expected to be incorporated in the relevant consolidated grants of participating institutes.

AION: Stage 3 [not part of funding request]

Stage 3 Planning for 1 km & Beyond [not part of funding request]

- A km-scale terrestrial detector for mid-frequency gravitational wave physics and refined sensitivity for Dark Sector physics. Opening a new dimension of multi-signal and multi-messenger physics in the mid-frequency band (and beyond) by correlation with other km devices (e.g. located in the US), as well as experiments in the high- and low-frequency band.