# AION WORKING MEETING

## JANUARY 25, 2019

Oliver Buchmueller, Imperial College London
and
Jon Coleman, Liverpool University

# Main Discussion Items



- 10 m(ish) Site proposals
- Work Package Breakdown
- Regular Meeting

# 10m(ish) Site Proposals



- We have two concrete proposals for a site top host the 10m(ish) prototype version, which (so far) is the main deliverable of the 3 year funding cycle
  - Oxford (Beecroft)
  - RAL (R72)

# Work Package Breakdown (and Deliverables)



- So far, we only have a high-level WP structure (see next slides) and we will have to refine it in the coming few months. The WPs will form the skeleton for the proposal and thus are the first items we have to define (carefully).

- Along with the WPs we will have define the main deliverables of the project for the first three (2+1) years of funding. This request MUST have the follow-up funding for additional three years in mind. Therefore, we need to plan for a 3+3=6 year period.

- Several discussion have taken place already on scope & structure [see e.g. Email thread] and this now needs to be carefully crafted in WPs.

- We will also have to start to think about WP leaders [IMO we should aim for co-leadership].

# 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

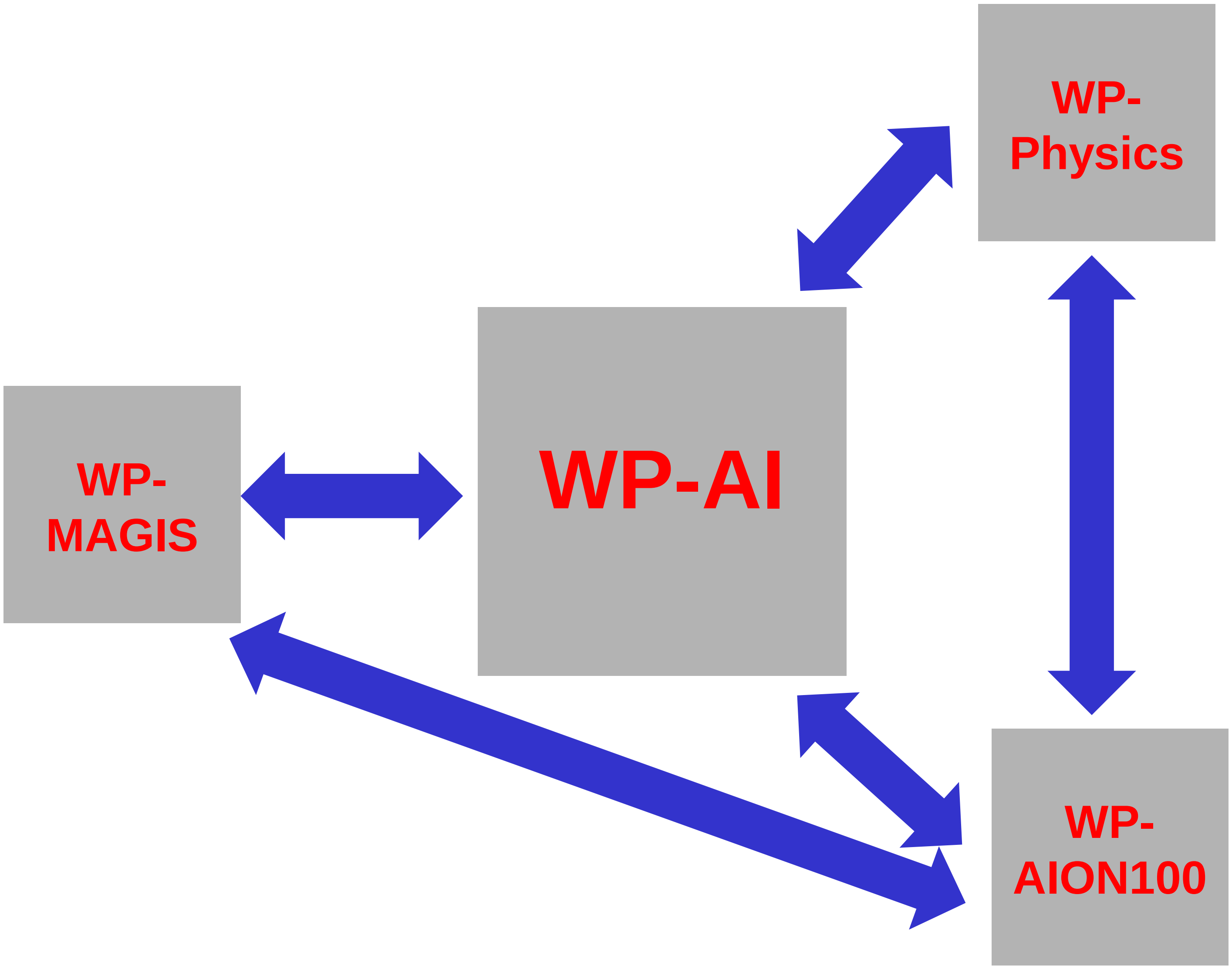
**This will give us the path into the future (next bid)**

## WP-MAGIS

**This will give us MAGIS and US Collaboration**

# AION10 [Stage 1]: Main WP Connections





# Budget Estimate (so far)



| Item | [Year 1 to 3] | [Year 4 to 6] |
|---|---|---|
| **Materials** | £2000K | £3300K |
| **Operation** | £100K | £100K |
| **R&D** | £1900K | £800K |
| **Infrastructure** | £100K | £200K |
| **Network** | £300 | £500K |
| **Computing** | £100K | £300K |
| | | |
| **Total Capital** | **£4500K** | **£5200K** |

***Table 1: Capital cost estimate for 6 years.***

A first estimate for all the work packages suggests that about 8 postdocs and 4 technicians/engineers will be required for the period of the project. This leads to an estimated cost envelope of about £7.2M for RAs and technicians/engineers over the six-year funding period. This will be complemented buy approx. £600K (£100K a year) for travel.

A first preliminary budget estimate, capital plus staff, would amount to £9.7M + £7.8M **= £17.5M.** This total funding envelope is roughly equally distributed over the six-year period, corresponding to about £2.9M per year. With this simple assumption, a 2 year + 1 year + 3 year budgeting allocation would be: **£5.8M (year 1 and 2), £2.9M (year 3), £8.8M (year 4,5, and 6)**. However, we would like to point out that a 2-year period for a first funding milestone is not ideal for an experimental programme, whereas a 3-year period would allow for greater scientific impact and achievements.

# Regular Meeting



As discussed already, we have to start regular Working Meetings in order to prepare for the brutal timeline for the proposal:

Suggestion:

- bi-weekly meetings
  - will circulate doodle to find best slot]
- Use indico to manage agenda and vidyo, etc
  - this requires that people subscribe to indico. It’s a light process and simple. Will circulate instructions before the next meeting.

Slides from Oxford Meeting January 17th

# BACKUP

# A UK ATOM INTERFEROMETER OBSERVATORY AND NETWORK

## QSFP WP3 REPORT, JANUARY 17, 2019

Oliver Buchmueller, Imperial College London

and

Jon Coleman, Liverpool University

# 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:*

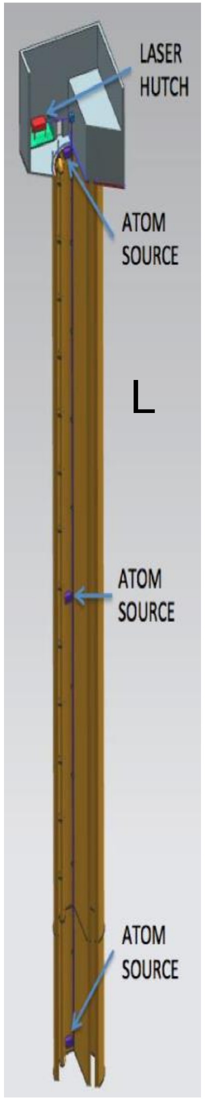
- **The first stage** develops existing technology (Laser systems, vacuum, magnetic shielding etc.) and the infrastructure for the 100m detector and produces detailed plan resulting in an accurate assessment of the expected performance in Stage 2.
- **The second stage** builds, commissions and exploits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

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 |

| | | | |
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| **Flae** | | | |
| **Gol** | | | |
| **Velt** | | | |
| **Hob** | | | |
| **Smi** | | | |
| **Bell** | | | |
| **Ham** | | | |
| **Arau** | | | |
| **Buc** | | | |
| **Has** | | | |
| **Hinc** | | | |
| **Sau** | | | |
| **Sum...** | | | interferometry, atomic clocks, magnetometry |
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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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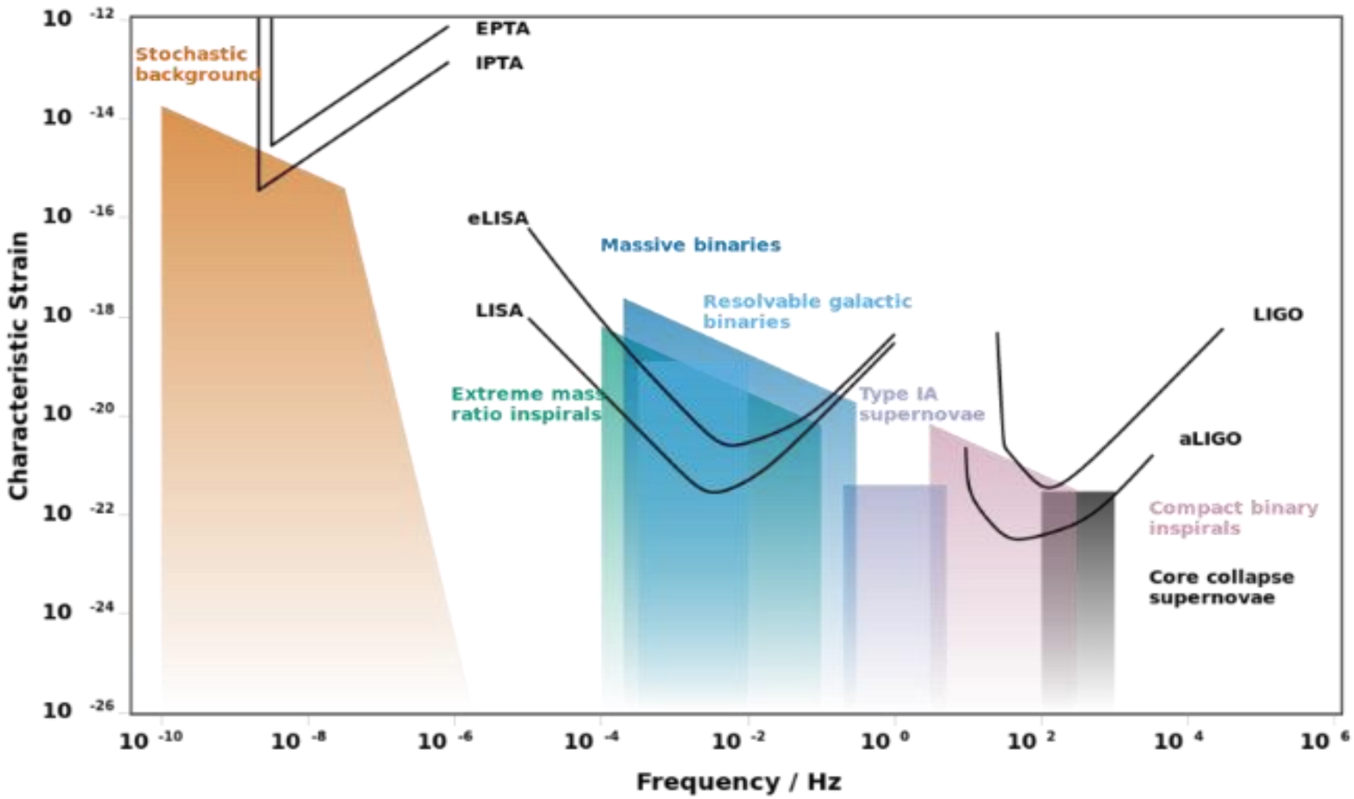
| **Ovchinnikov*** | Atom interferometry / BEC |
| **Godun*** | Ion clocks/ atom interferometry |

# THE PHYSICS CASE

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



Experimental GW Landscape



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

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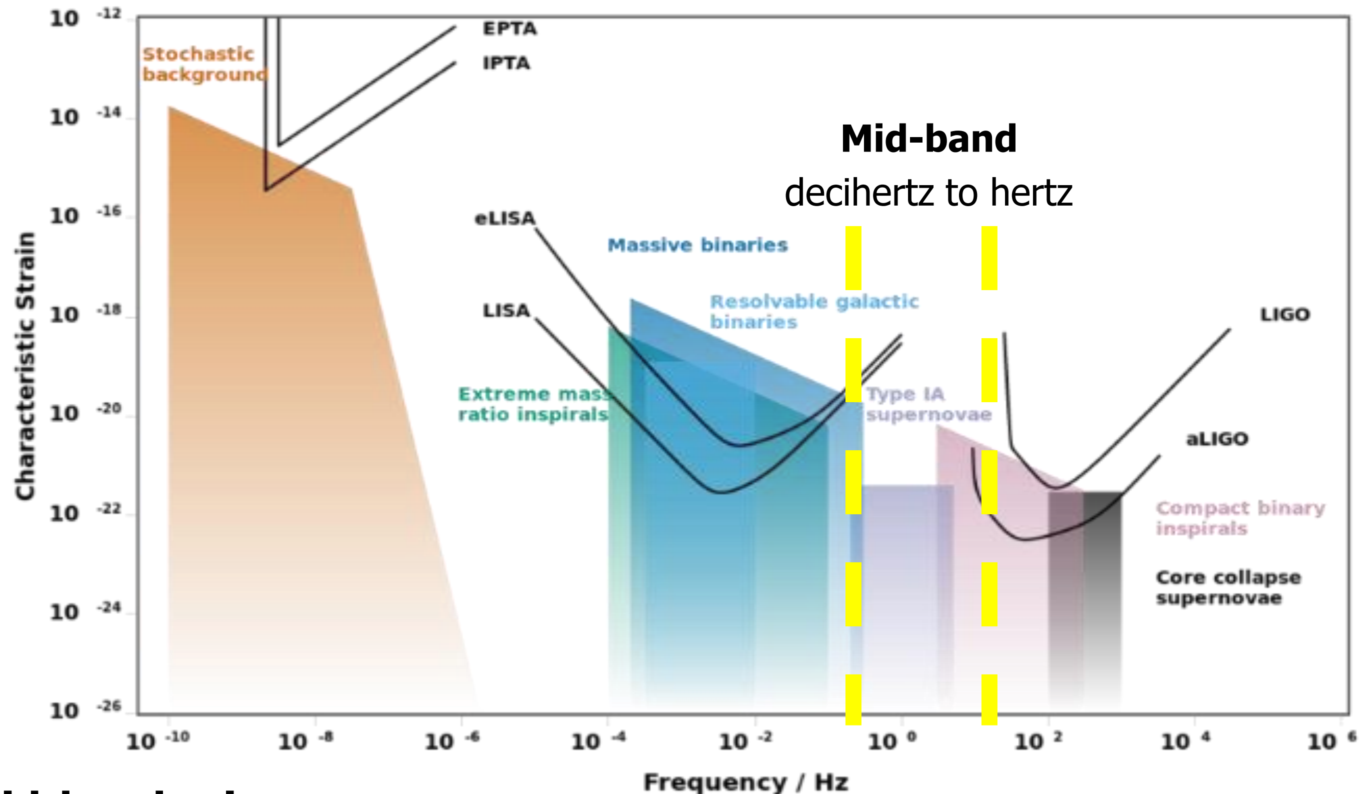


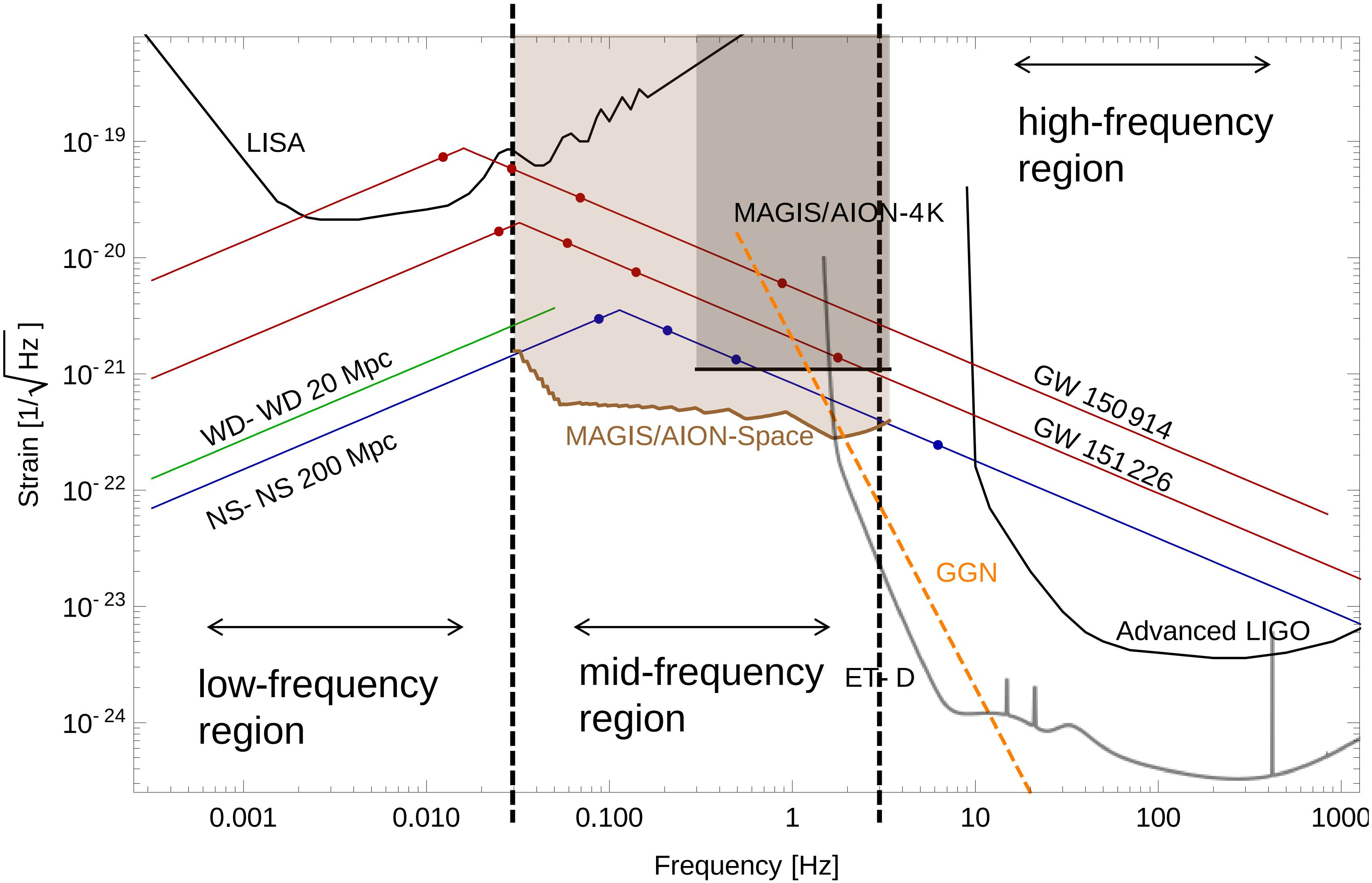

Mid-Band currently NOT covered

**Mid-band science**

- Detect sources BEFORE they reach the high frequency band [LIGO, ET]
- Optimal for sky localization: predict when and where events will occur (for multi-messenger astronomy)
- Search for Ultra-light dark matter in a similar frequency [i.e. mass] range

# Gravitational Wave Detection with Atom Interferometry





# Sky position determination



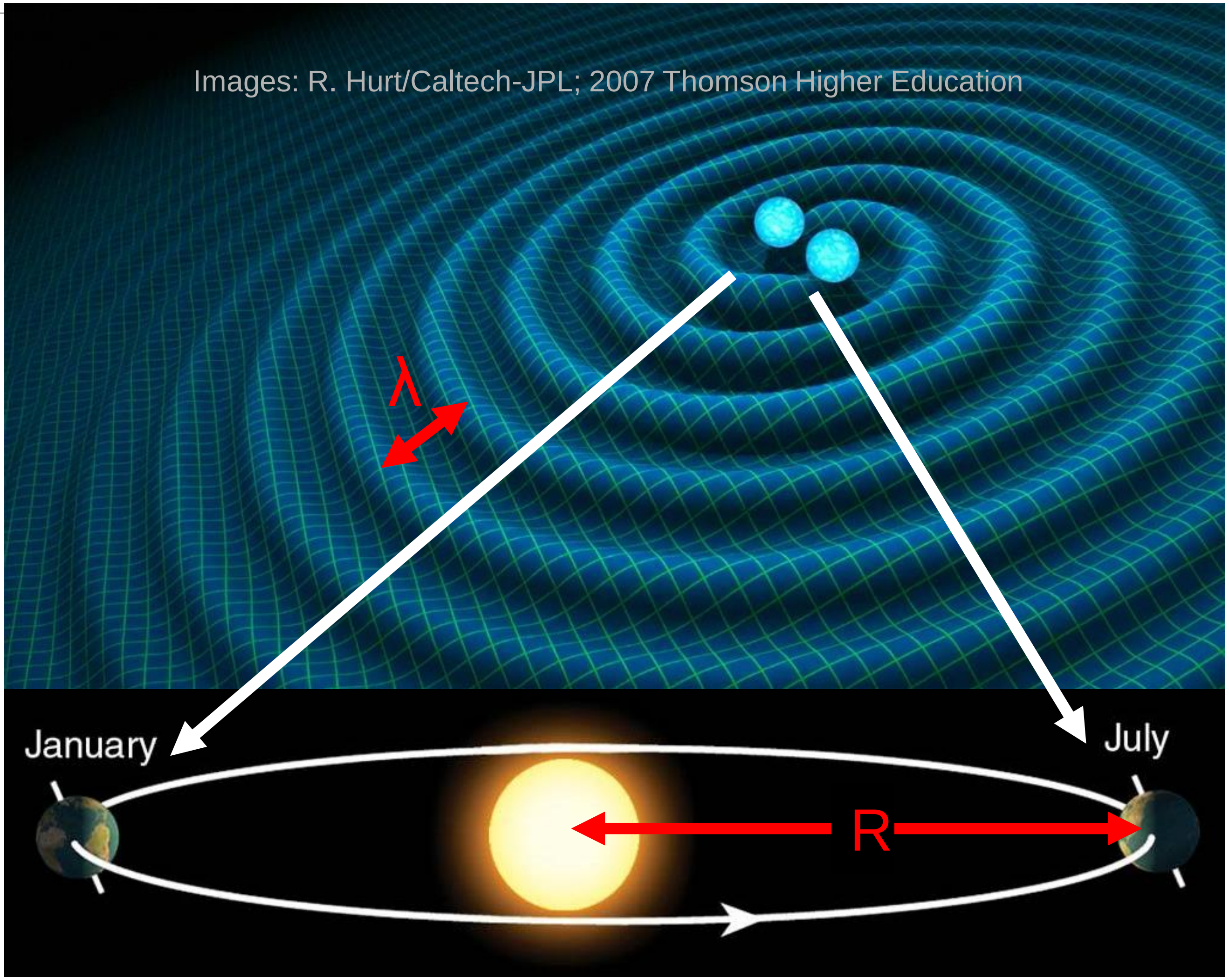
Sky localization precision:

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

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

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

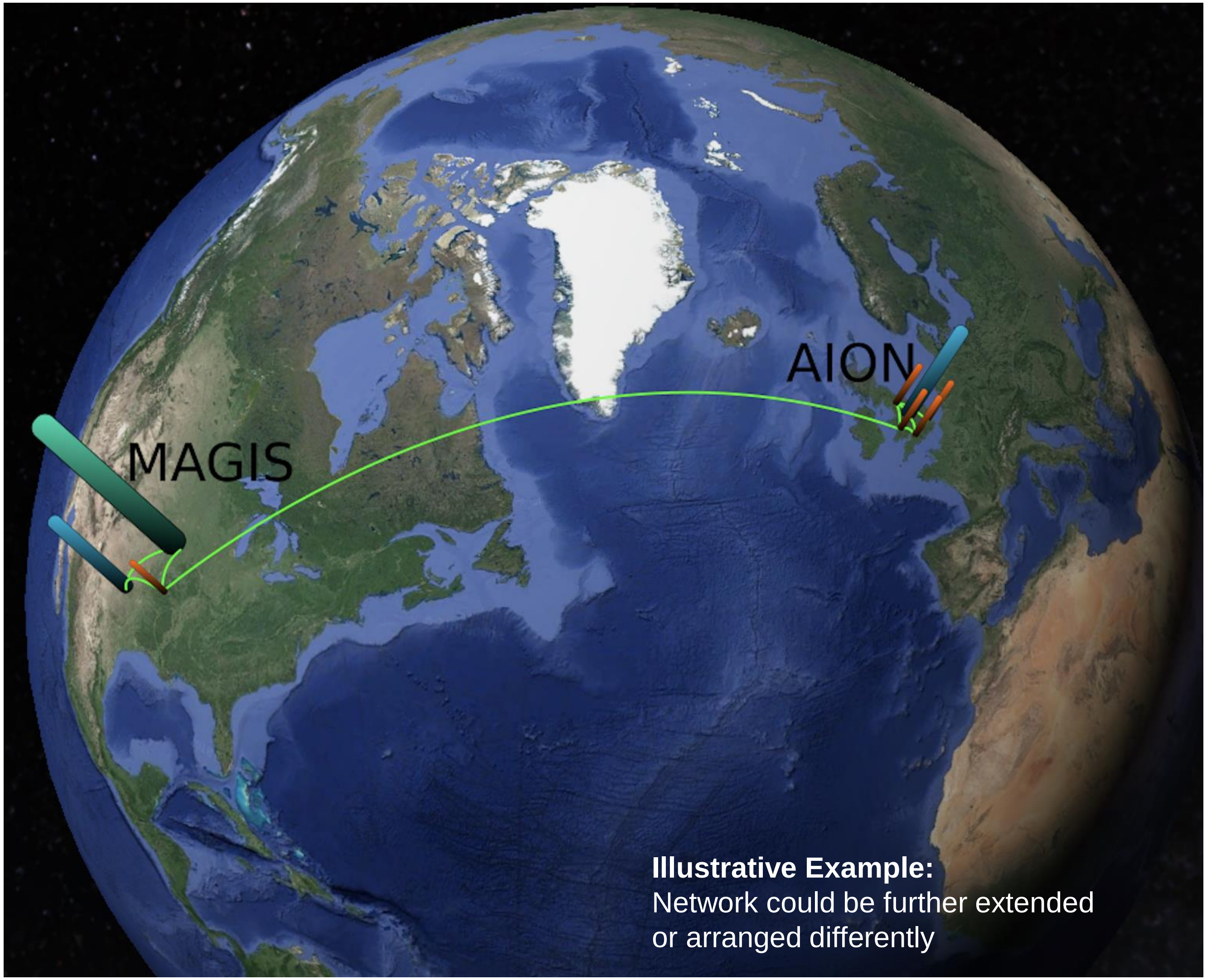
Courtesy of Jason Hogan!




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

# Ultimate Goal: Establish International Network

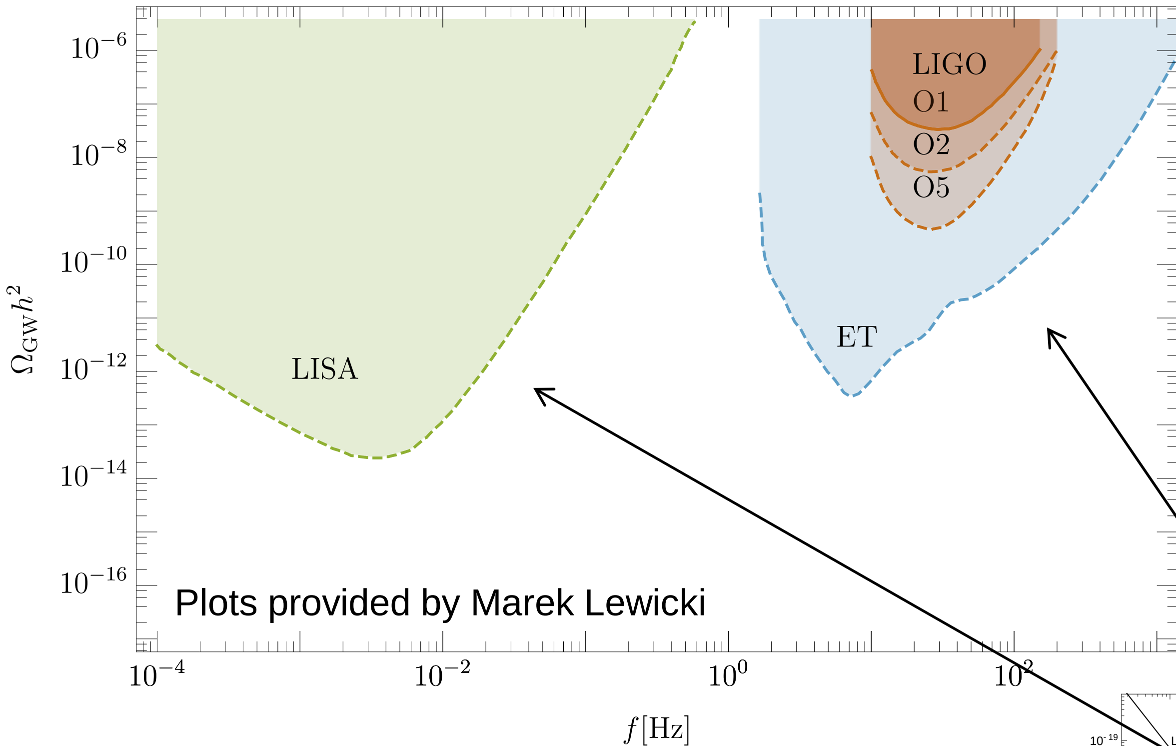





**Illustrative Example:**
Network could be further extended or arranged differently

# GW Detection & Fundamental Physics - Example

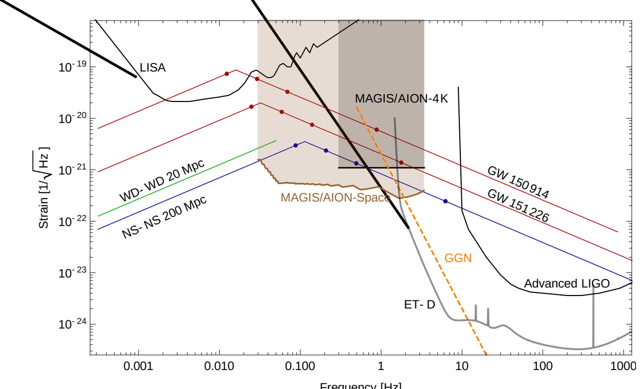
First-Order Electroweak Phase Transition and its Gravitational Wave Signal




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

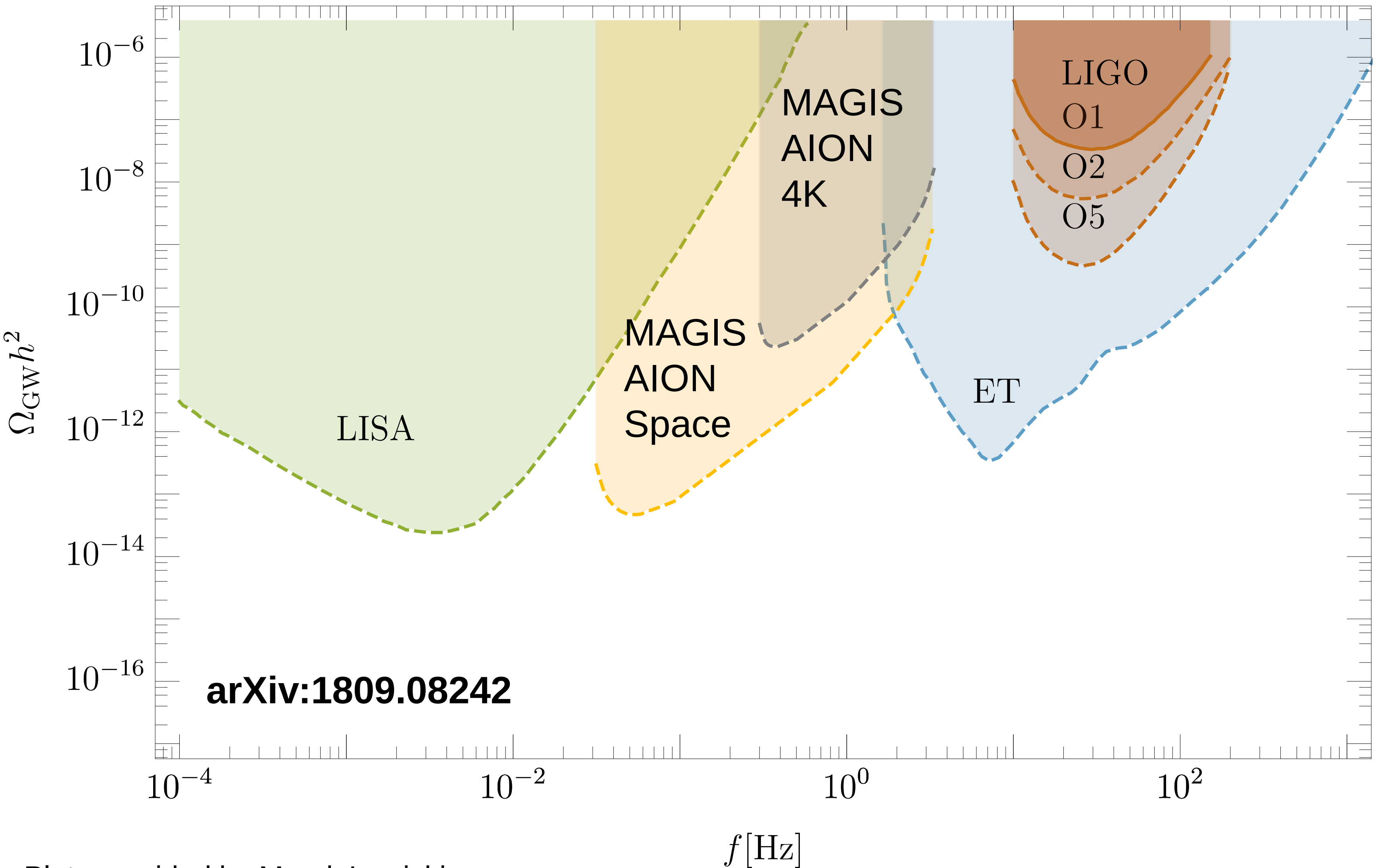
What is is the GW signal of electroweak phase transition in various theories beyond the Standard Model.

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



# GW Detection & Fundamental Physics - Example

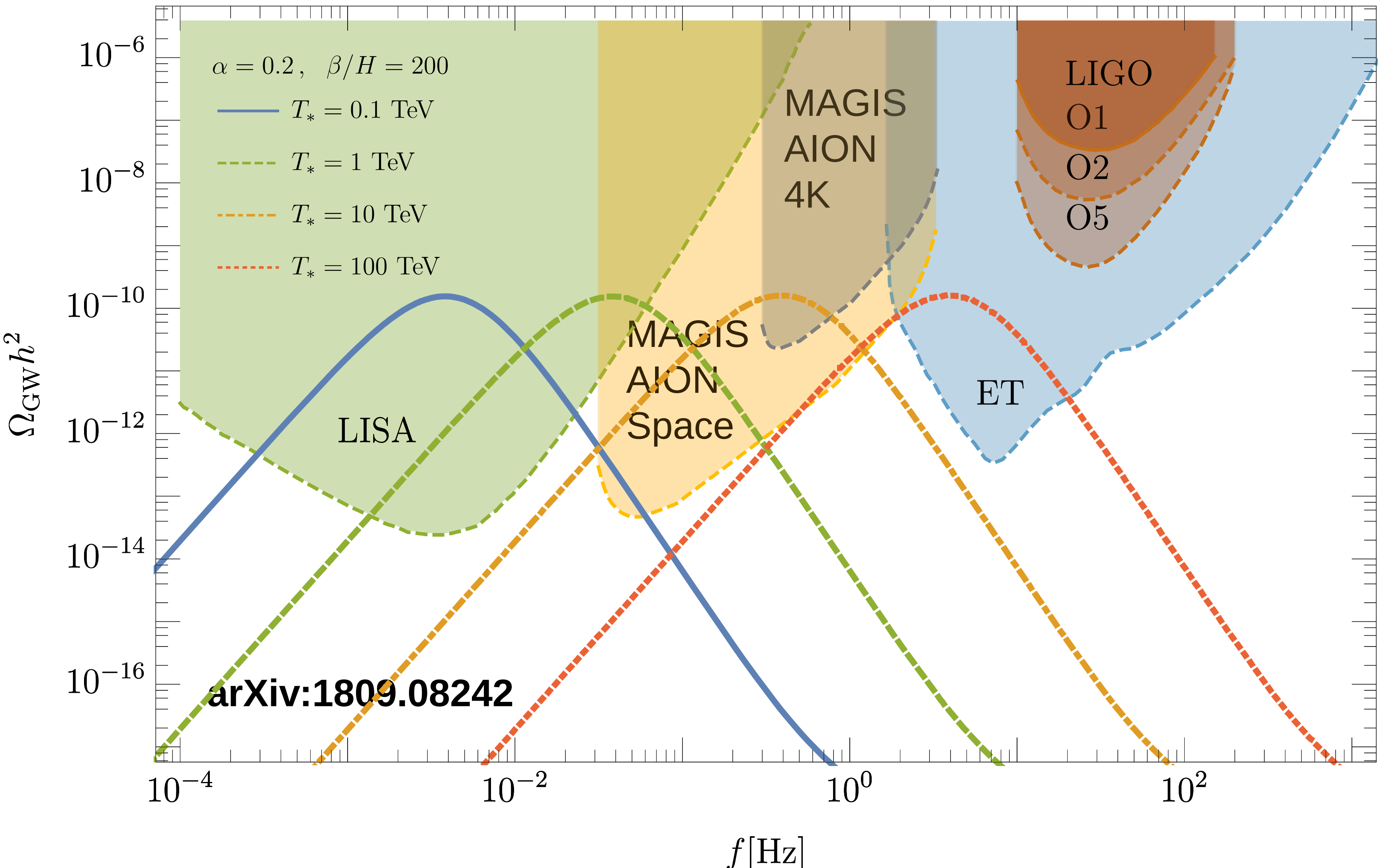





Plots provided by Marek Lewicki

# GW Detection & Fundamental Physics - Example






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:

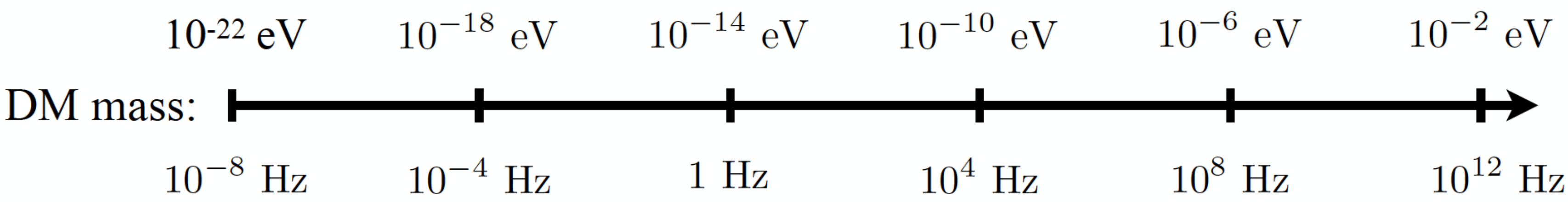



Diagram taken from P. Graham's talk at HEP Front 2018

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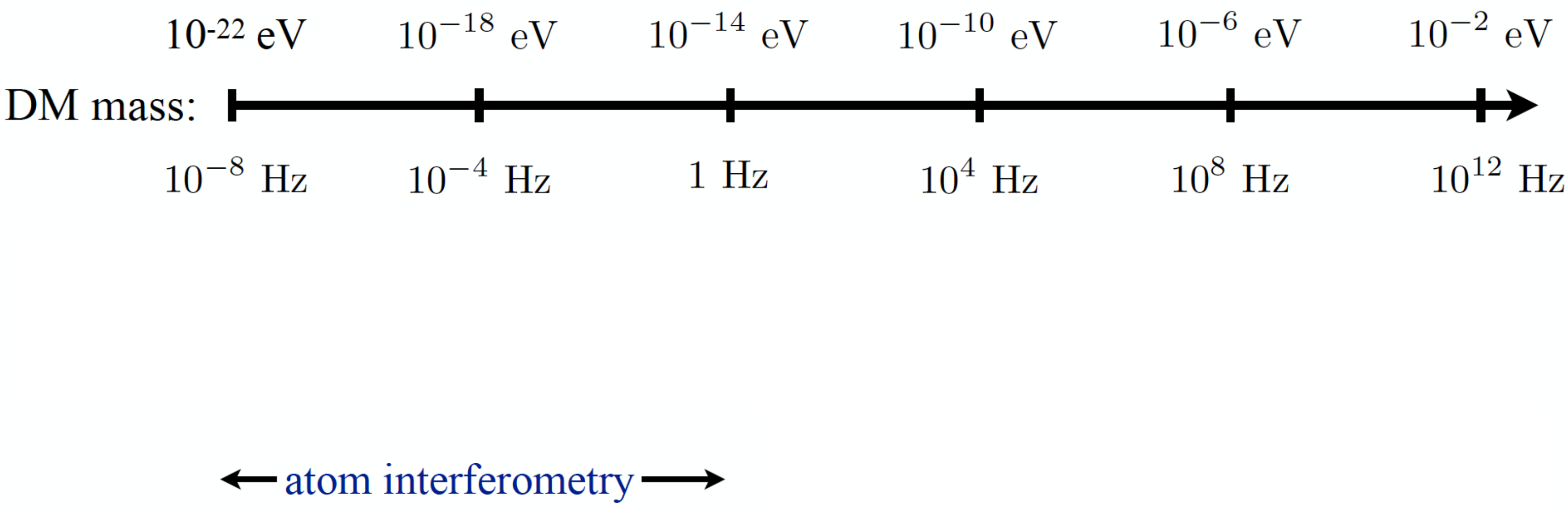


MAGIS/AION

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

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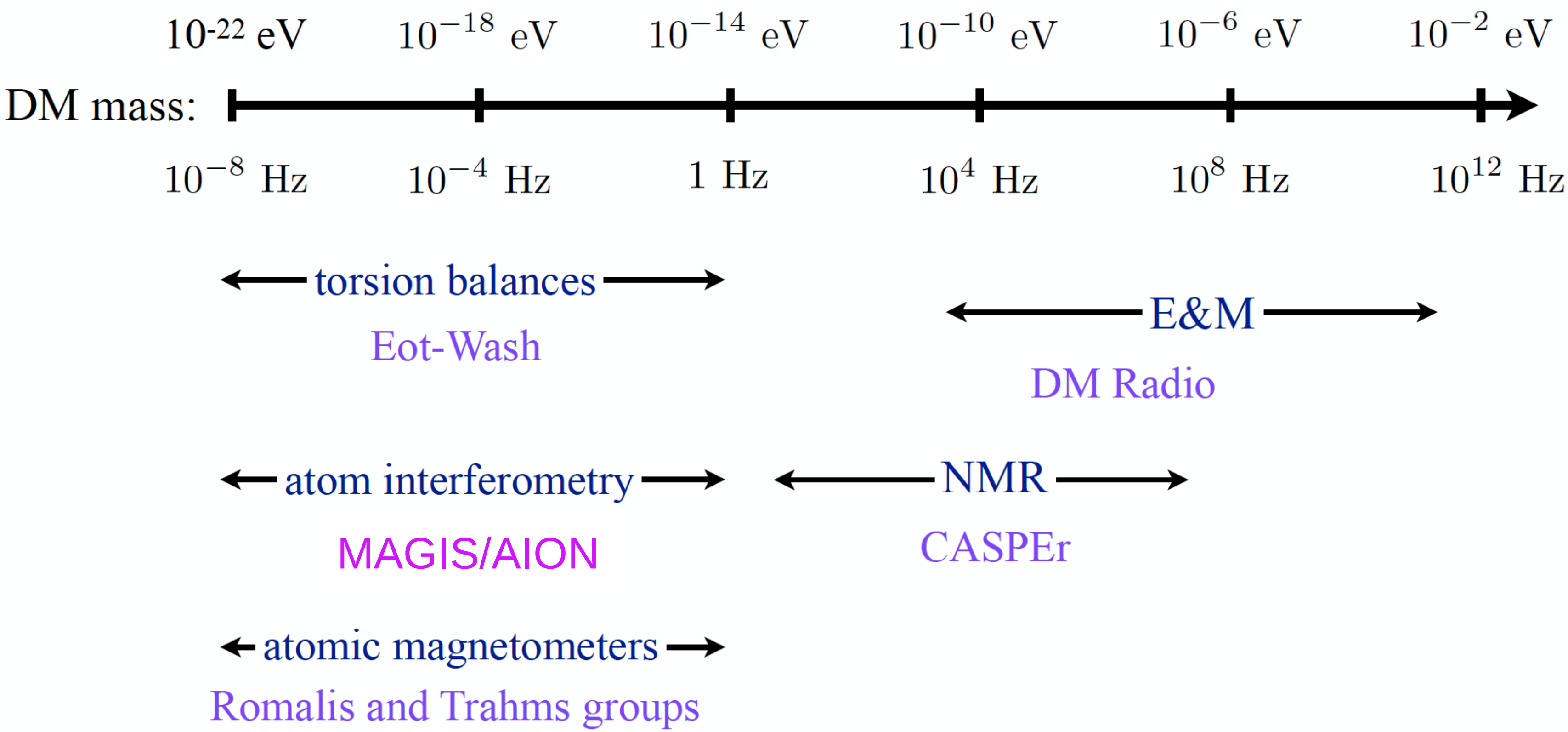



Diagram taken from P. Graham's talk at HEP Front 2018

# 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.

Together with John Ellis (KCL) and Martin Bauer(IPPP, Durham) we plan a
**1-day gathering in London on Feb 1**
to discuss the theory and phenomenology
of Dark Matter/Sector Physics with Quantum Sensors.

Two main categories of Dark Matter that could be probed within the QSFP programme:

- Light DM (< GeV scale) which is hard to see in DD or at the LHC because of negligible nuclear recoil or missing energy, respectively. This could be probed through electron scattering or super-sensitive nuclear scattering experiments. The 3.5 keV sterile neutrino would be a prime candidate for that.

- Ultralight DM (~$10^{-14}$ tto $10^{-22}$ eV) that behaves more like a classical wave and ends up modifying fundamental constants through oscillations. Something like an ultralight axion.

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

# COLLABORATION WITH US (VIA MAGIS)

# International Collaboration

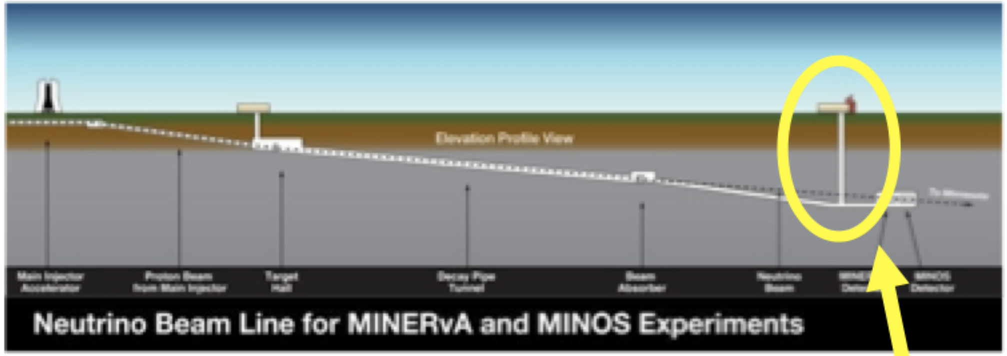


- From the outset this project would greatly benefit from close collaboration on an international level with the US initiative, MAGIS-100, which pursues a similar goal of an eventual km-scale atom interferometer on a comparable timescale.
- The option of operating two AI detectors, one in the UK and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

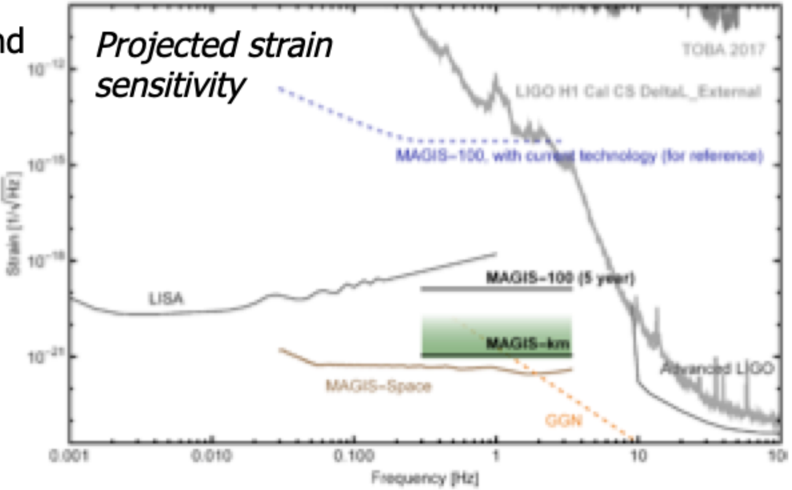
**M**atter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor

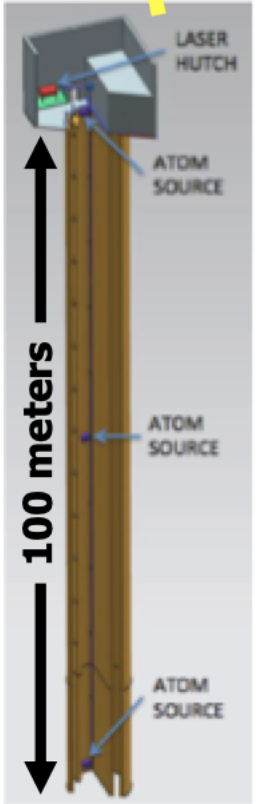
- 100-meter baseline atom interferometry at Fermilab (MINOS access shaft)
- Intermediate step to full-scale (km) detector for gravitational waves




## 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 · Northern Illinois University

Courtesy of Jason Hogan!

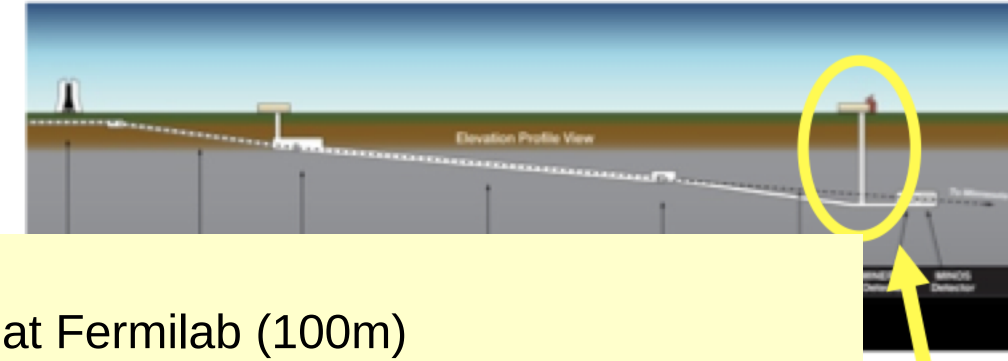
# MAGIS-100: GW detector prototype at Fermilab

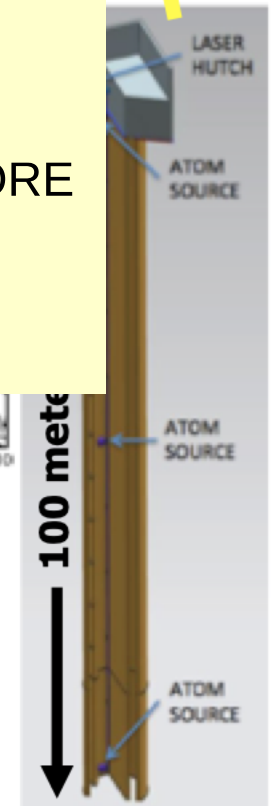
**M**atter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor

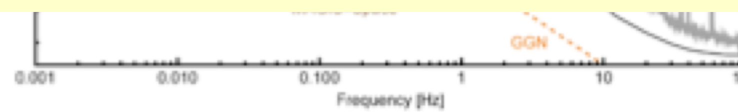
- 100-meter baseline atom interferometry at Fermilab (MINOS access shaft)
- Inte[...] for gra[...]

**Mid-b[...]**

- LIG[...]
- Opt[...] and [...] mu[...]
- BH[...]
- Pro[...]
- Sea[...]
- Ext[...] >meter wavepacket separation, up to 9 seconds duration




**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

**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

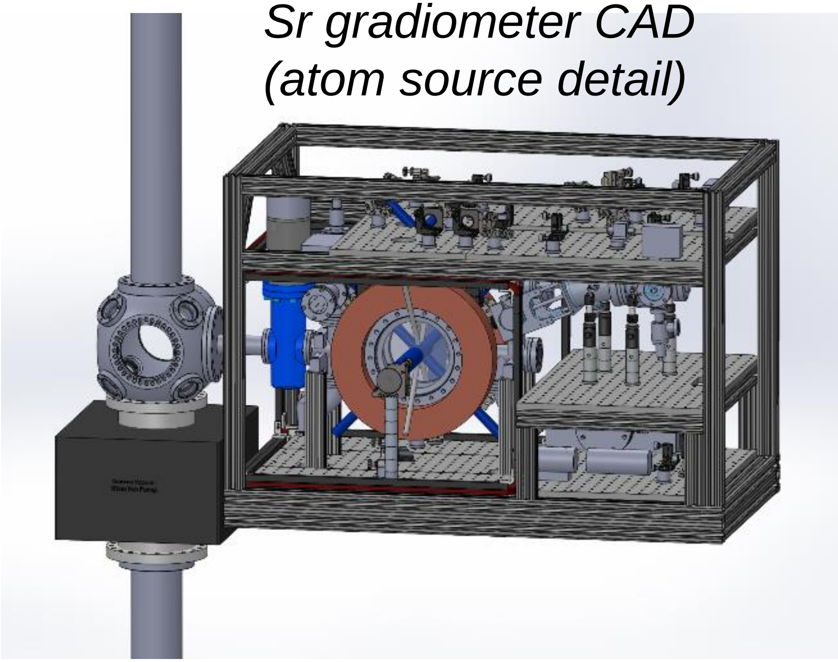
Stanford University · Fermilab · Berkeley · University of Liverpool · Northwestern University · Northern Illinois University

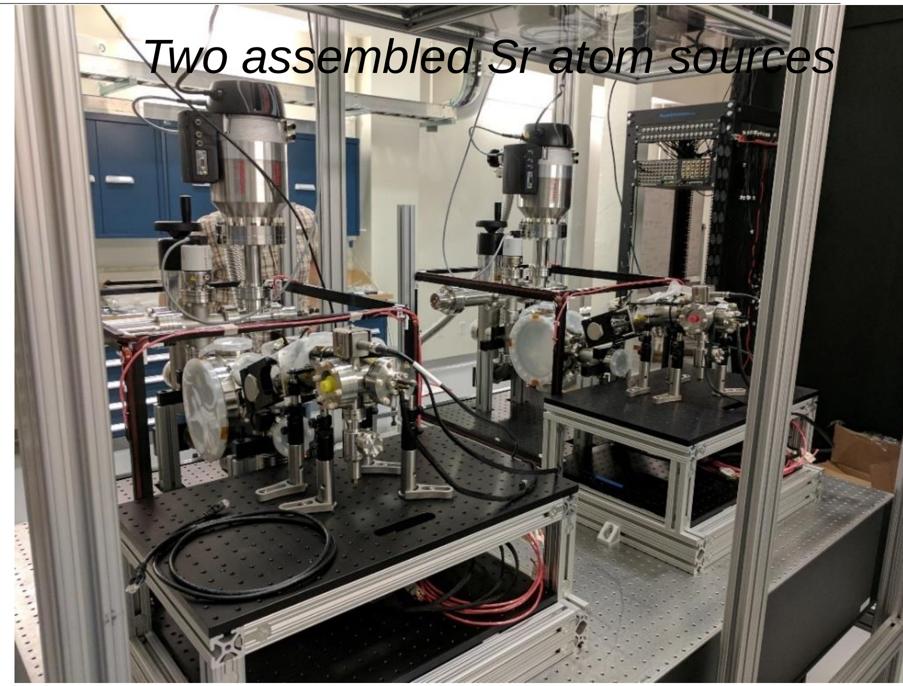
Courtesy of Jason Hogan!

# Stanford MAGIS prototype



*Sr gradiometer CAD (atom source detail)*



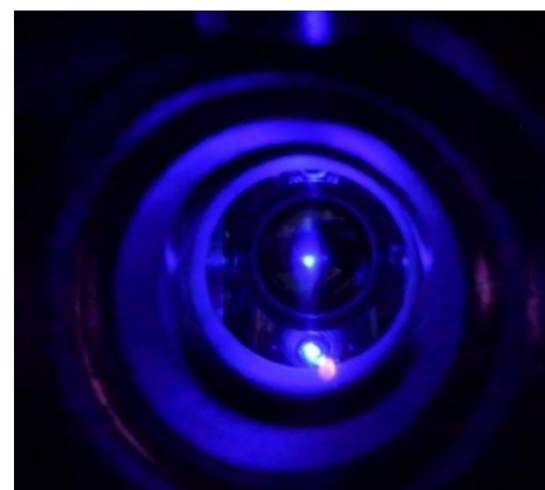


*Two assembled Sr atom sources*


*Atom optics laser (M Squared SolsTiS)*

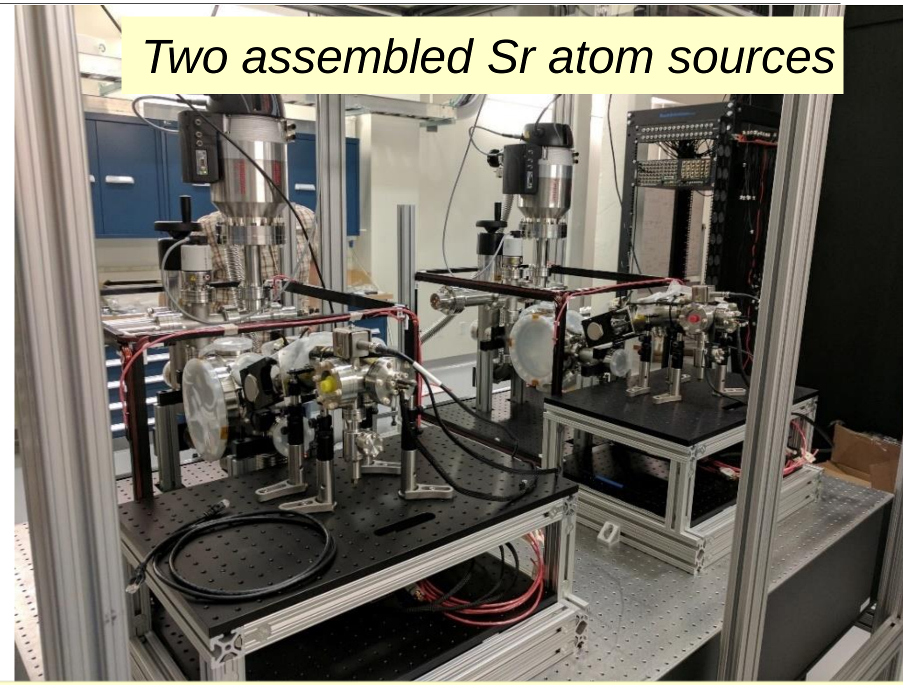
Courtesy of Jason Hogan!

*Trapped Sr atom cloud (Blue MOT)*



# Stanford MAGIS prototype





*Two assembled Sr atom sources*

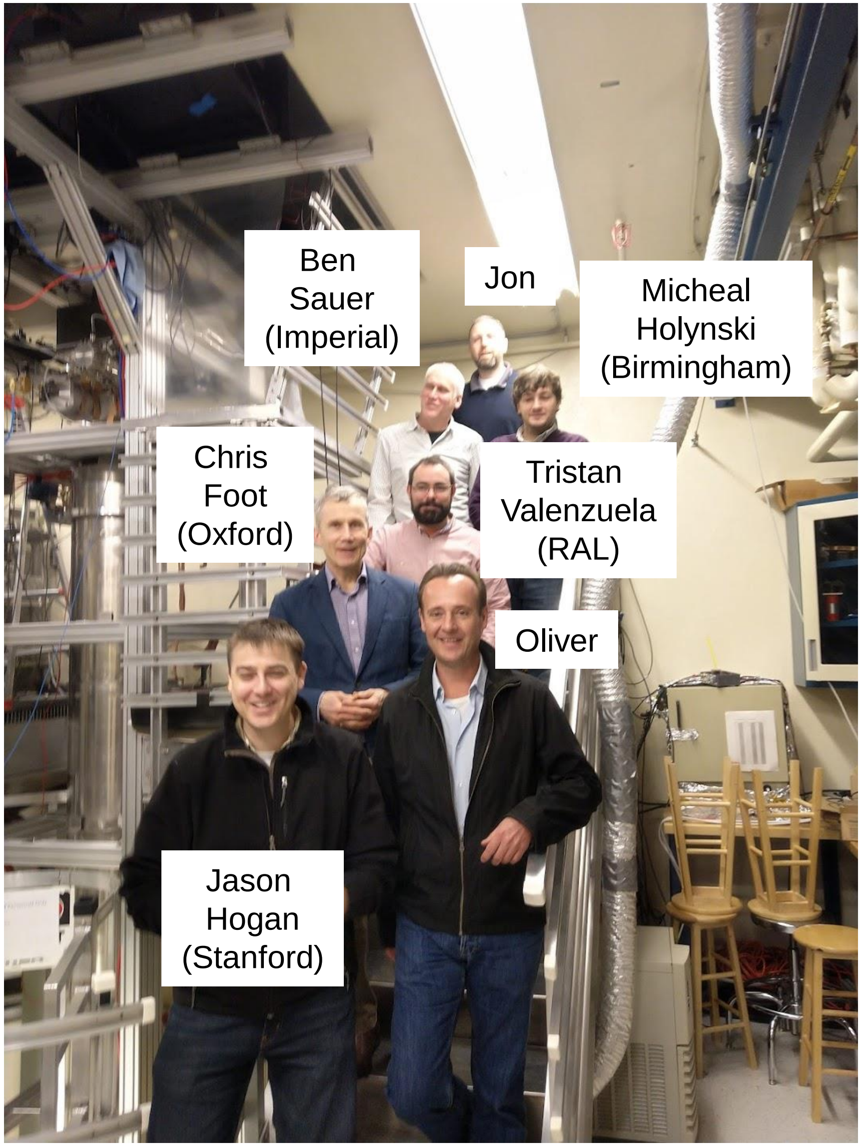
Stanford Lab to host 8 m prototype of the Sr fountain.

It is supposed to be assembled over summer 2019.

# 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:

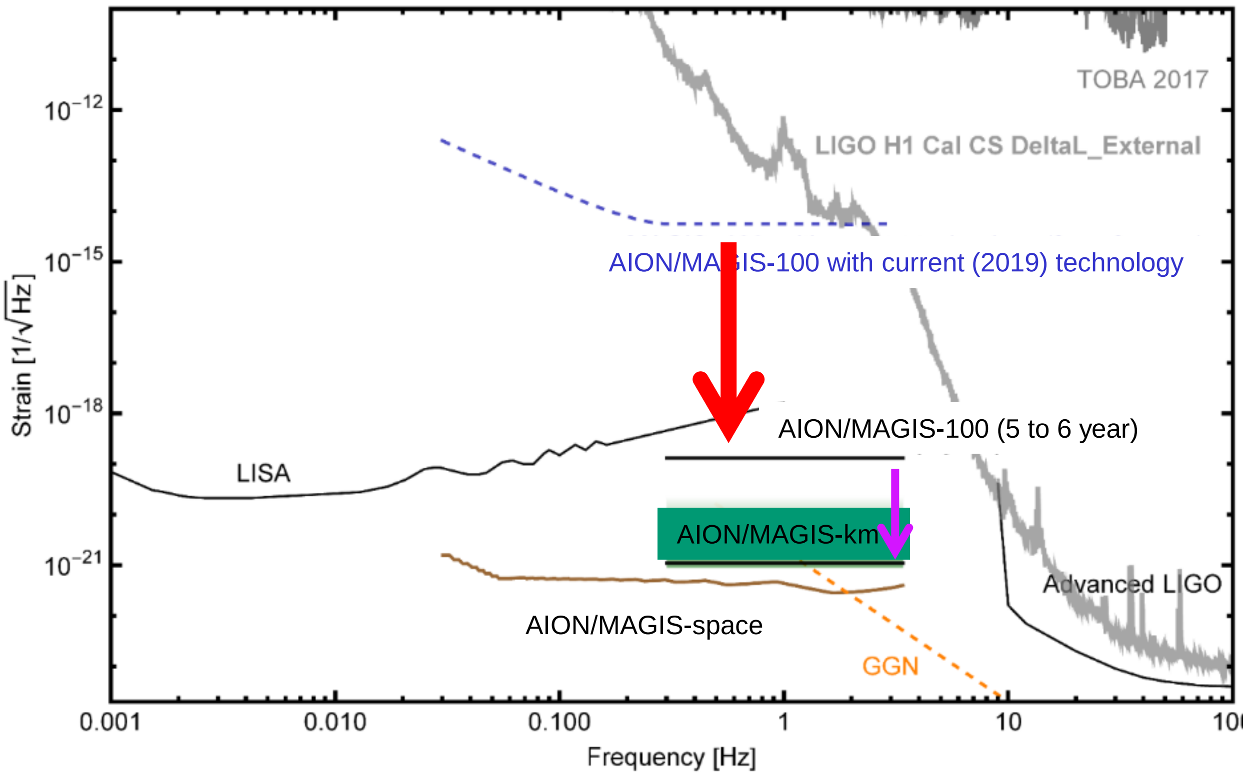
- Establish information exchange and review the Stanford work.
- Strengthen the US-UK collaboration
- Identify synergies and common goals between AION and MAGIS.

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.

# 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 | $10^{-3}/\sqrt{\text{Hz}}$ | $10^{-5}/\sqrt{\text{Hz}}$ | $0.3 \times 10^{-5}/\sqrt{\text{Hz}}$ |
| 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

# 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.

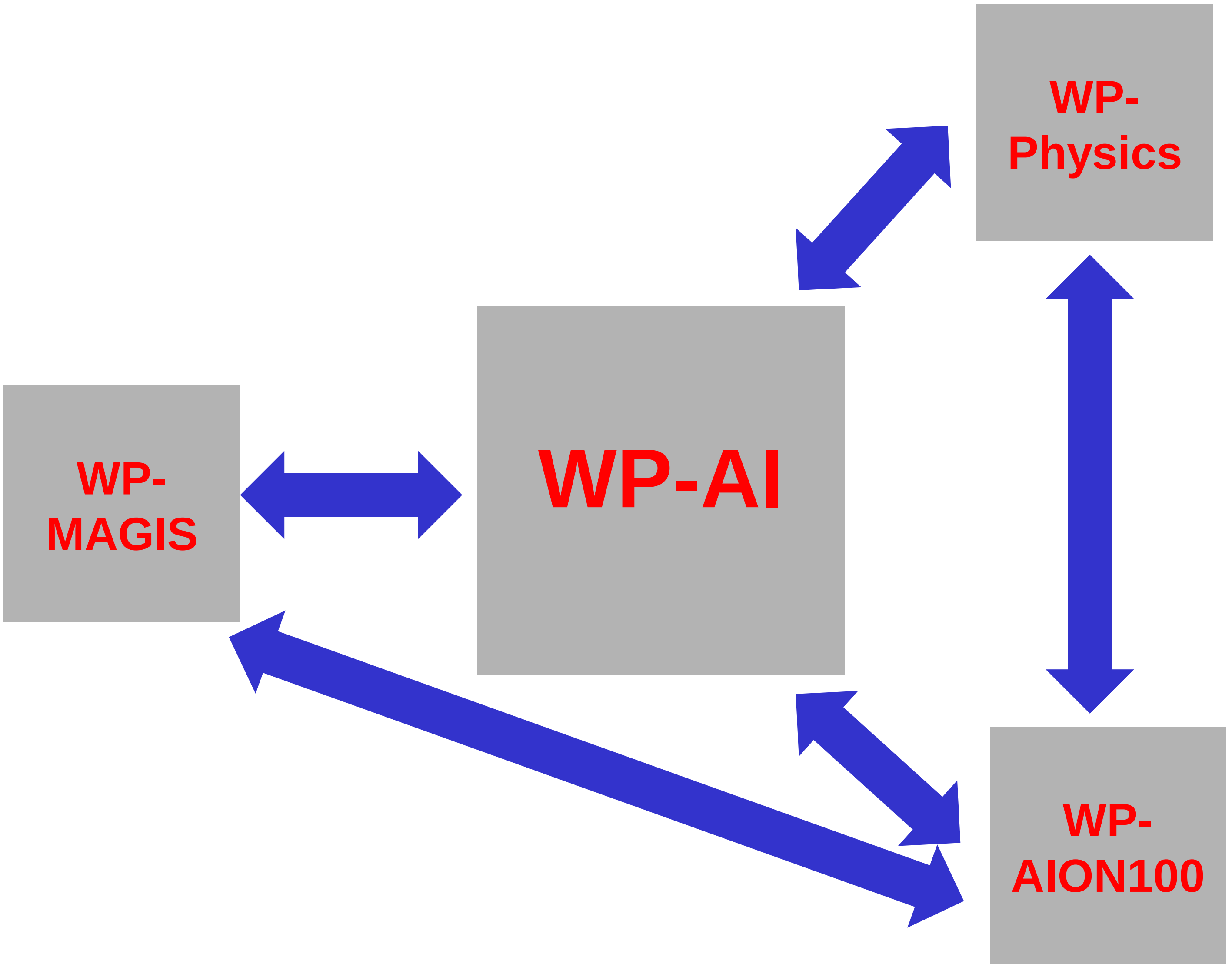
**WP-AION100**

**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



# Budget Estimate (so far)



| Item | [Year 1 to 3] | [Year 4 to 6] |
|---|---|---|
| Materials | £2000K | £3300K |
| Operation | £100K | £100K |
| R&D | £1900K | £800K |
| Infrastructure | £100K | £200K |
| Network | £300 | £500K |
| Computing | £100K | £300K |
| | | |
| **Total Capital** | **£4500K** | **£5200K** |

*Table 1: Capital cost estimate for 6 years.*

A first estimate for all the work packages suggests that about 8 postdocs and 4 technicians/engineers will be required for the period of the project. This leads to an estimated cost envelope of about £7.2M for RAs and technicians/engineers over the six-year funding period. This will be complemented buy approx. £600K (£100K a year) for travel.

A first preliminary budget estimate, capital plus staff, would amount to £9.7M + £7.8M **= £17.5M.** This total funding envelope is roughly equally distributed over the six-year period, corresponding to about £2.9M per year. With this simple assumption, a 2 year + 1 year + 3 year budgeting allocation would be: **£5.8M (year 1 and 2), £2.9M (year 3), £8.8M (year 4,5, and 6)**. However, we would like to point out that a 2-year period for a first funding milestone is not ideal for an experimental programme, whereas a 3-year period would allow for greater scientific impact and achievements.


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

# 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!
- The formation of an AION collaboration is well underway with the next important milestone being the AION workshop in March 25/26

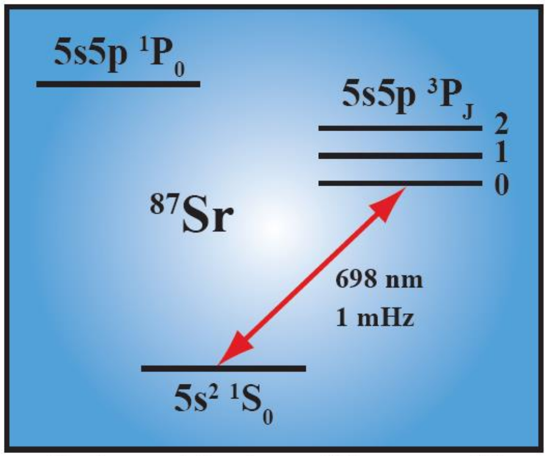
# BACKUP

# A different kind of atom interferometer

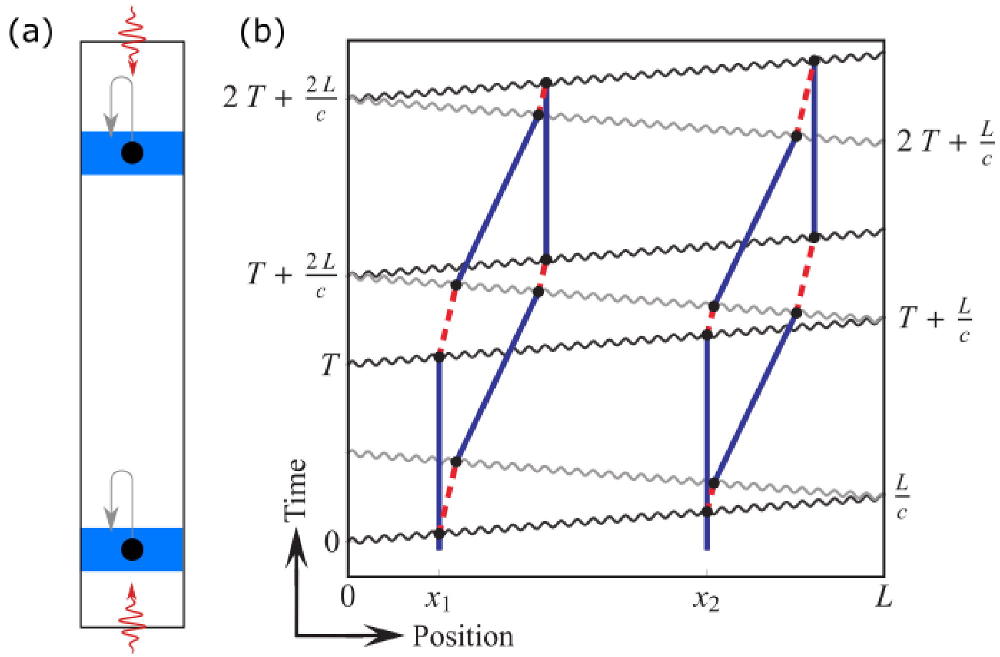


Hybrid "clock accelerometer"

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



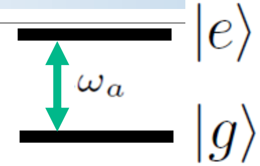

Clock transition in candidate atom ⁸⁷Sr

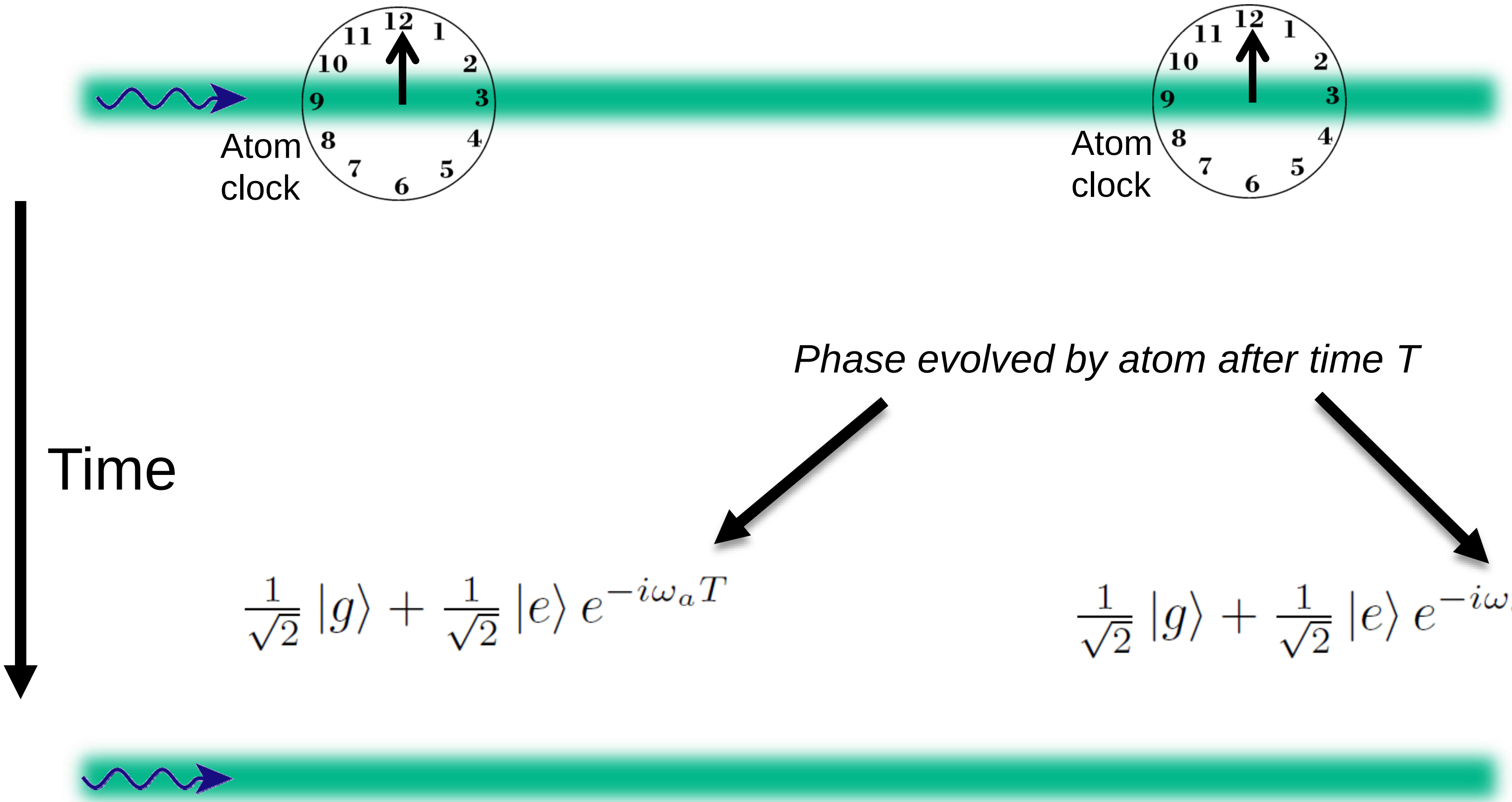



**Clock:** measure light travel time ➜ remove laser noise with *single baseline*

**Accelerometer:** atoms excellent inertial test masses

# Simple Example: Two Atomic Clocks




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

Courtesy of Jason Hogan!

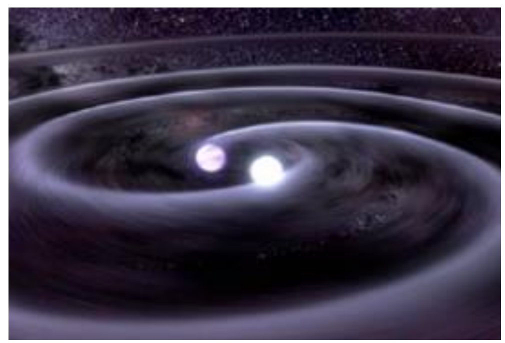
# Simple Example: Two Atomic Clocks

$|e\rangle$

$\omega_a$

$|g\rangle$

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



**GW changes light travel time**

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

Time

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

Atom clock

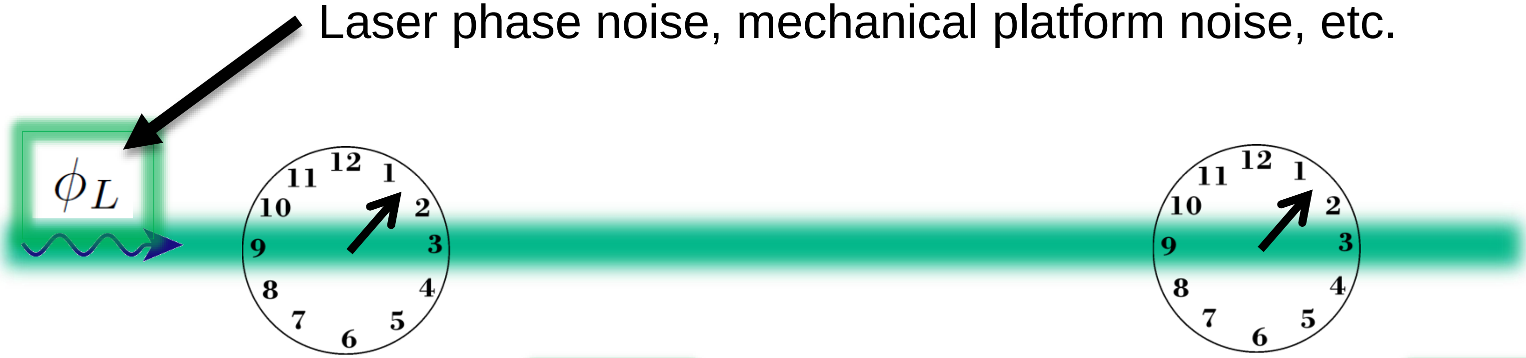
Atom clock

Courtesy of Jason Hogan!

# Phase Noise from the Laser

*The phase of the laser is imprinted onto the atom.*

Laser phase noise, mechanical platform noise, etc.

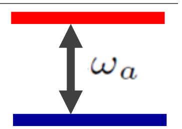



$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle e^{i\phi_L} \qquad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle e^{i\phi_L}$$

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

Courtesy of Jason Hogan!

# Clock gradiometer

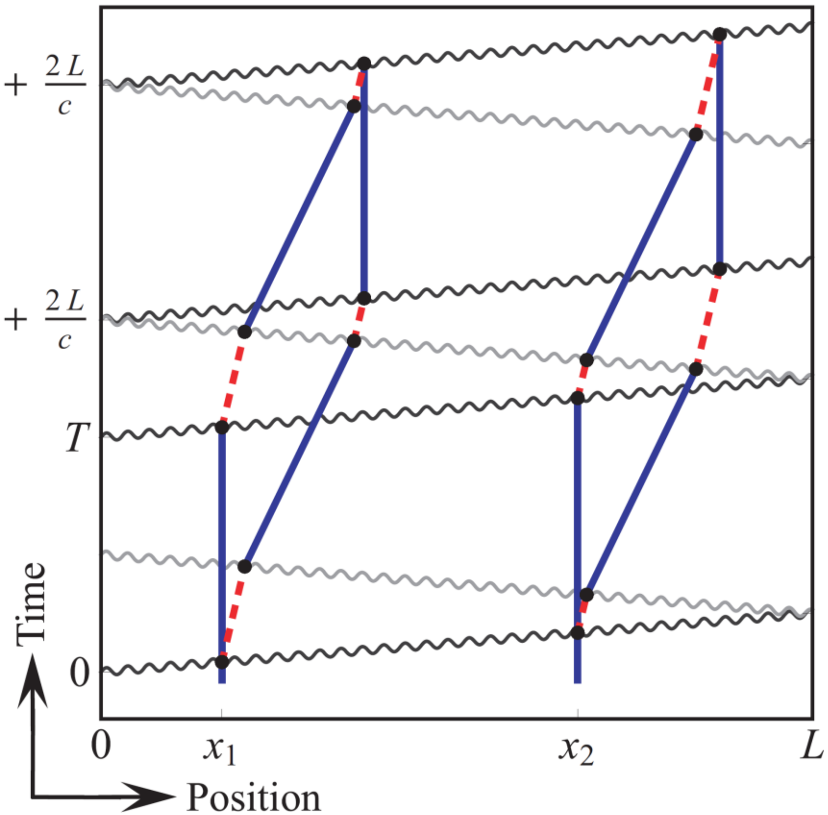



Excited state phase evolution:

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

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

Courtesy of Jason Hogan!

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

# Ultralight scalar dark matter

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

$$\mathcal{L} = +\frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 - \sqrt{4\pi G_N}\phi \left[ d_{m_e} m_e \bar{e} e - \frac{d_e}{4} F_{\mu\nu} F^{\mu\nu} \right] + \ldots$$

DM scalar field

Electron coupling

Photon coupling

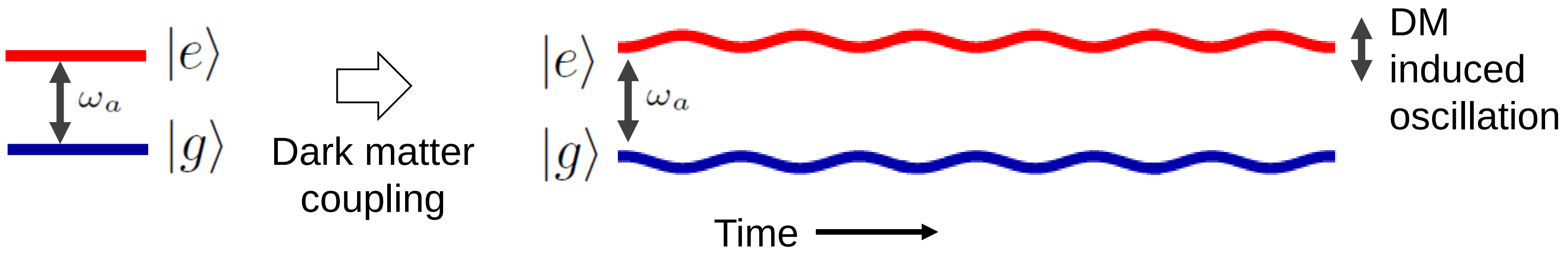
e.g., QCD

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

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

DM mass density

DM coupling causes time-varying atomic energy levels:



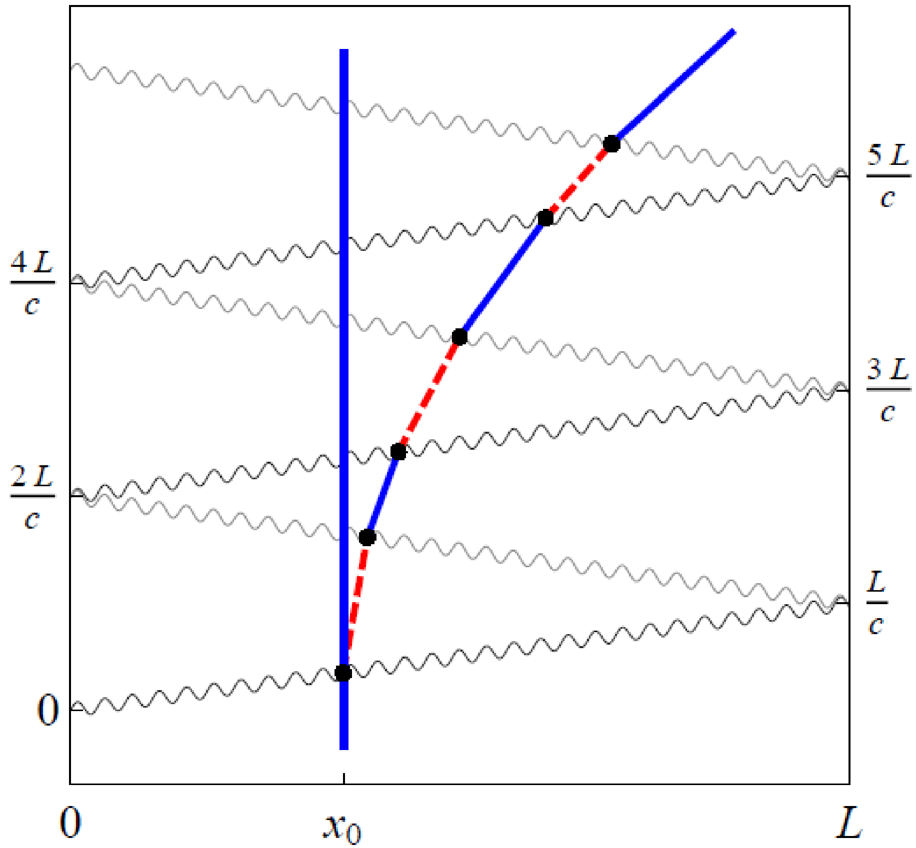

Courtesy of Jason Hogan!

# LMT and Resonant Pulse Sequences



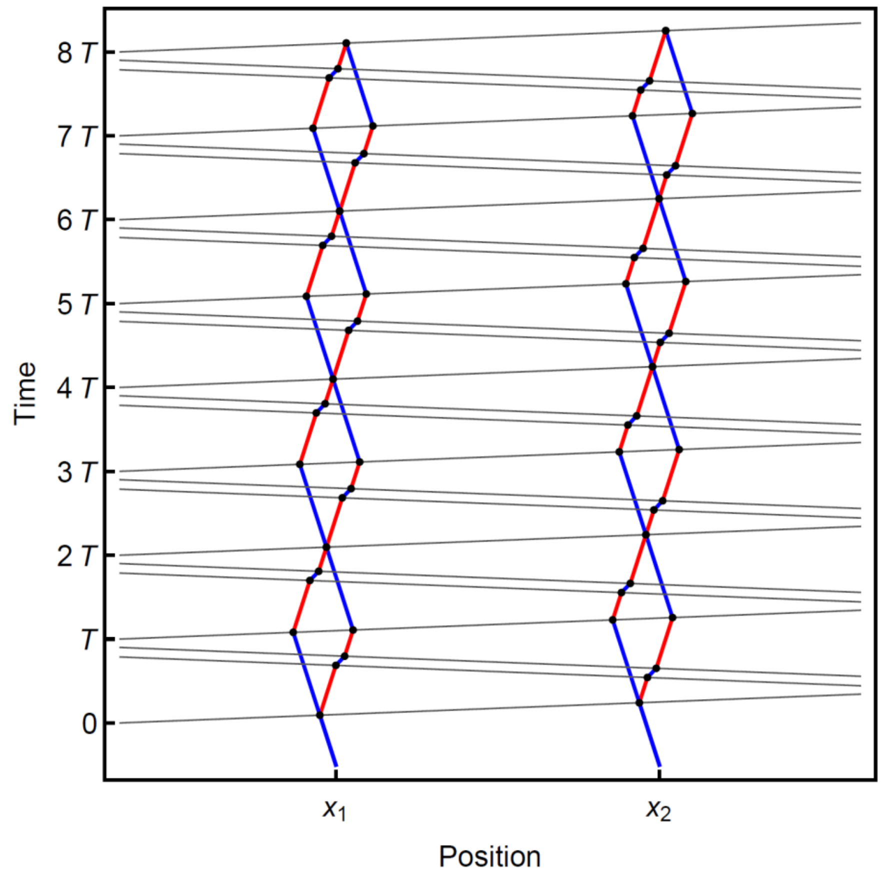
Sequential single-photon transitions remain laser noise immune

**LMT beamsplitter (N = 3)**




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

**Resonant sequence (Q = 4)**




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

Courtesy of Jason Hogan!