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 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

- Rotation Curves
- Clusters of galaxies
- CMB
- Type Ia Supernovae

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

<table>
<thead>
<tr>
<th>Stage</th>
<th>Scale</th>
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<tbody>
<tr>
<td>1</td>
<td>L ~ 1m to 10m</td>
</tr>
<tr>
<td>2</td>
<td>L ~ 100m</td>
</tr>
<tr>
<td>3, 4</td>
<td>L ~ km-scale</td>
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<tr>
<td></td>
<td>L ~ $10^4$ km</td>
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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
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AION-SPACE: Stage 4 [ after AION-KM ]
- Space based version **outlined in Big Ideas proposal
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
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- Liverpool
- Manchester
- Nottingham
- Open University
- Oxford
- RAL
- Sheffield
- Strathclyde
- Sussex
- Swansea
- NPL

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
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 Atomic Gradiometer Interferometric Sensor**
- 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]

Courtesy of Jason Hogan!
MAGIS-100: GW detector prototype at Fermilab

**Matter wave Atomic Gradiometer Interferometric Sensor**
- 100-meter baseline atom interferometry at Fermilab (MINOS access shaft)
- Interferometers for gravitational waves

**Timeline:**
- 2019-2023: MAGIS-100 at Fermilab (100m)
- 2023-2028: km-scale detector [site still to 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
VISIT TO STANFORD ON 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

Sr gradiometer CAD (atom source detail)

Two assembled Sr atom sources

Trapped Sr atom cloud (Blue MOT)

Atom optics laser (M Squared SolsTiS)

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

More about MAGIS-100 in the talk of Jason Hogan

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

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

- WP-MAGIS
- WP-AI
- WP-Physics
- WP-AION100
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

Experimental GW Landscape

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

Mid-Band currently NOT covered
Gravitational Wave Detection with Atom Interferometry

Frequency [Hz]

Strain [1/Hz]

- LISA
- WD-WD 20 Mpc
- NS-NS 200 Mpc
- MAGIS/AION-4K
- MAGIS/AION-Space
- GW 150914
- GW 151226
- GGN
- Advanced LIGO

Regions:
- Low-frequency region
- Mid-frequency region
- High-frequency region
Sky position determination

Sky localization precision:

\[ \sqrt{\Omega_s} \sim \left( \text{SNR} \cdot \frac{R}{\lambda} \right)^{-1} \]

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

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>( \sqrt{\Omega_s} ) [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW150914</td>
<td>0.16</td>
</tr>
<tr>
<td>GW151226</td>
<td>0.20</td>
</tr>
<tr>
<td>NS-NS (140 Mpc)</td>
<td>0.19</td>
</tr>
</tbody>
</table>

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

\[ \Omega_{GW} h^2 \]

Plots provided by Marek Lewicki

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

arXiv:1809.08242

John Ellis, Marek Lewicki, José Miguel No

What is the GW signal of electroweak phase transition in various theories beyond the Standard Model.
GW Detection & Fundamental Physics - Example

Plots provided by Marek Lewicki

arXiv:1809.08242
GW Detection & Fundamental Physics - Example

\[ \Omega_{GW} h^2 \]

\( \alpha = 0.2, \ \beta/H = 200 \)

- \( T_* = 0.1 \text{ TeV} \)
- \( T_* = 1 \text{ TeV} \)
- \( T_* = 10 \text{ TeV} \)
- \( T_* = 100 \text{ TeV} \)

LISA

MAGIS

AION

Space

MAGIS

AION

4K

LIGO

O1

O2

O5

ET

Plots provided by Marek Lewicki

arXiv:1809.08242
We would more studies like this to further workout the physics case!
The Landscape of Ultra-Light Dark Matter Detection

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

Example: Ultra-Light Dark Matter:

\[
\begin{array}{cccccc}
10^{-22} \text{eV} & 10^{-18} \text{eV} & 10^{-14} \text{eV} & 10^{-10} \text{eV} & 10^{-6} \text{eV} & 10^{-2} \text{eV} \\
10^{-8} \text{Hz} & 10^{-4} \text{Hz} & 1 \text{Hz} & 10^{4} \text{Hz} & 10^{8} \text{Hz} & 10^{12} \text{Hz}
\end{array}
\]

Diagram taken from P. Graham’s talk at HEP Front 2018
The Landscape of Ultra-Light Dark Matter Detection

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\begin{align*}
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& 10^{-8} \text{ Hz} & 10^{-4} \text{ Hz} & 1 \text{ Hz} & 10^4 \text{ Hz} & 10^8 \text{ Hz} & 10^{12} \text{ Hz}
\end{align*}
\]

← atom interferometry →

MAGIS/AION

Diagram taken from P. Graham’s talk at HEP Front 2018
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<tr>
<td></td>
<td>10^{-8} Hz</td>
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<td>1 Hz</td>
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- Torsion balances
- Eot-Wash
- Atom interferometry
- MAGIS/AION
- Atomic magnetometers
- Romalis and Trahms groups
- NMR
- CASPER
- E&M
- DM Radio

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

\[ \langle \rho_\phi \rangle \approx \frac{m_\phi^2 \phi_0^2}{2} \left( \rho_{DM, local} \approx 0.4 \text{ GeV/cm}^3 \right). \]

\( \rho_{DM} \approx 0.4 \text{ GeV/cm}^3 \)

\( v_{DM} \approx 300 \text{ km/s} \)
Ultralight scalar dark matter

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

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

Electron coupling

Photon coupling

e.g., QCD

DM scalar field

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

\[ \phi_0 \propto \sqrt{\rho_{\text{DM}}} \]

DM mass density

DM coupling causes time-varying atomic energy levels:

\[ |g\rangle \leftrightarrow |e\rangle \]

Dark matter coupling

\[ |g\rangle \rightarrow |e\rangle \]

DM induced oscillation

Courtesy of Jason Hogan!
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

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

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!