AION - DARK MATTER SEARCHES WITH ATOM INTERFEROMETRY

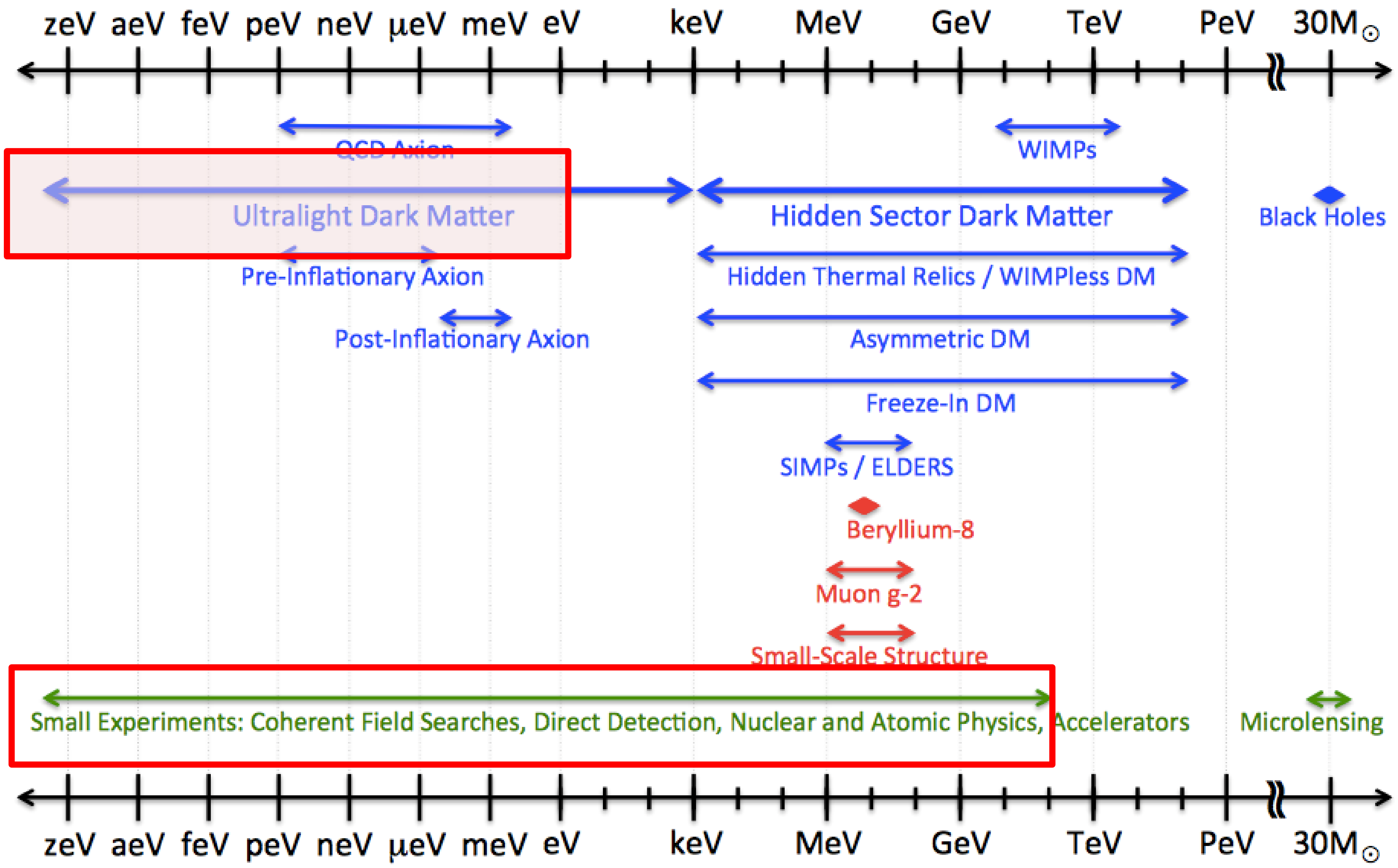
Jon Coleman On behalf of the AION & MAGIS collaborations

UNIVERSITY OF LIVERPOOL

THE ROYAL SOCIETY

Wide Range of Candidate Dark Matter Particles

Dark Sector Candidates, Anomalies, and Search Techniques



QCD Axion

WIMPs

Ultralight Dark Matter

Hidden Sector Dark Matter

Black Holes

Pre-Inflationary Axion

Hidden Thermal Relics / WIMPless DM

Post-Inflationary Axion

Asymmetric DM

Freeze-In DM

SIMPs / ELDERS

Beryllium-8

Muon g-2

Small-Scale Structure

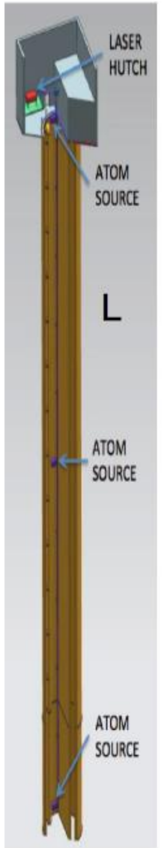
Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators

Microlensing

Searches for Light Dark Matter

Dark matter could be coherent waves of light bosons

Many detection techniques, **e.g. atom interferometers**

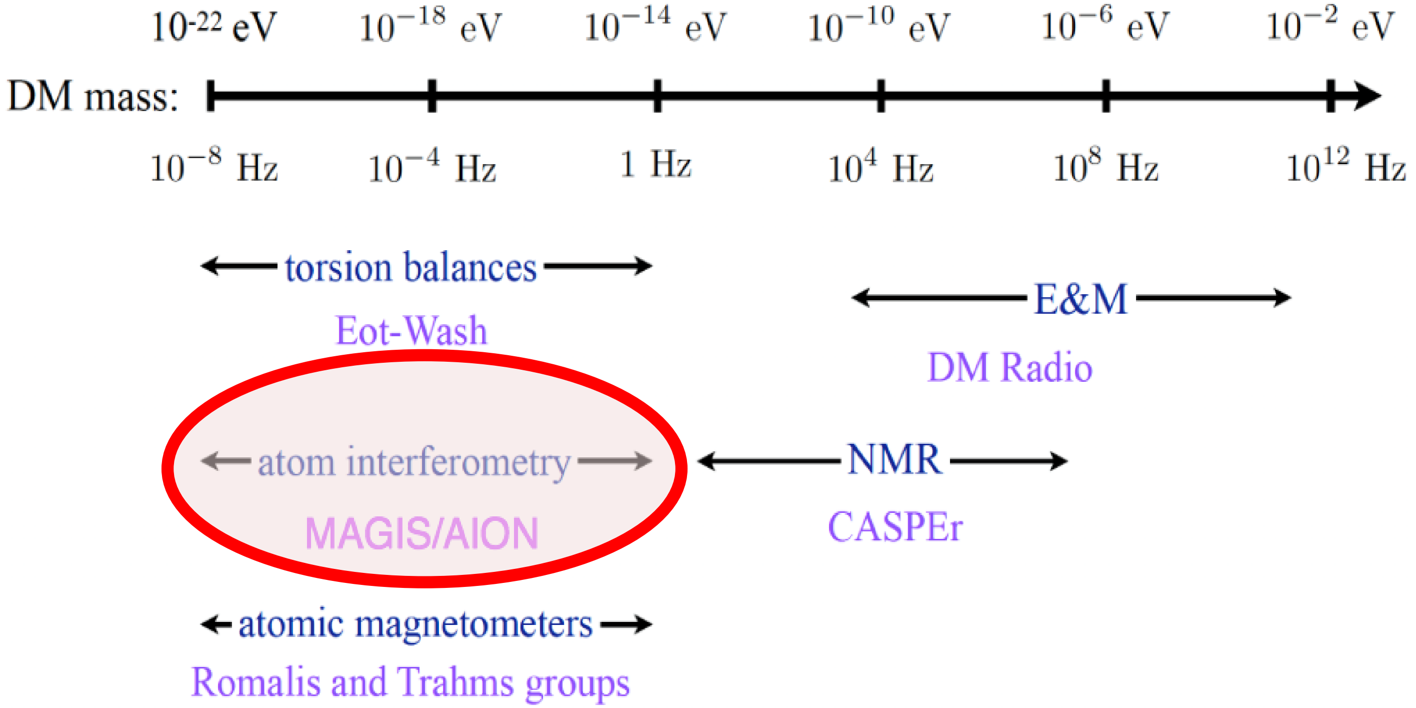


L ~ 1m to 10m

L ~ 100m

L ~ km-scale

L ~ 10^4 km



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

also interesting for gravitational waves

Science Case – See Fermilab ‘Letter of Intent’

A new ‘telescope’ for Unexplored Phase Space

“Ultralight” dark matter (e.g., axions, dilatons, etc.)

- Mass ~10^{-15} eV
- Would act like a **classical field**

Gravitational waves in the mid-band

Tests of quantum mechanics at long time / length scales

Equivalence principle tests (‘spin dependent gravity’)

Lorentz invariance tests

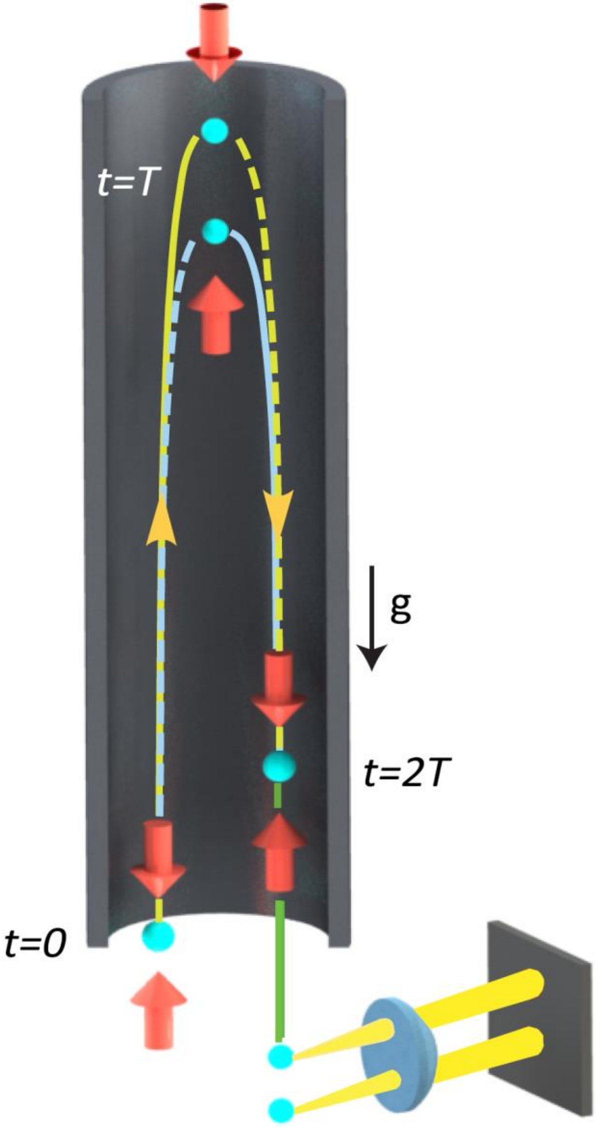
Multiple ways to detect ultralight DM (axions, dilatons, moduli, etc)

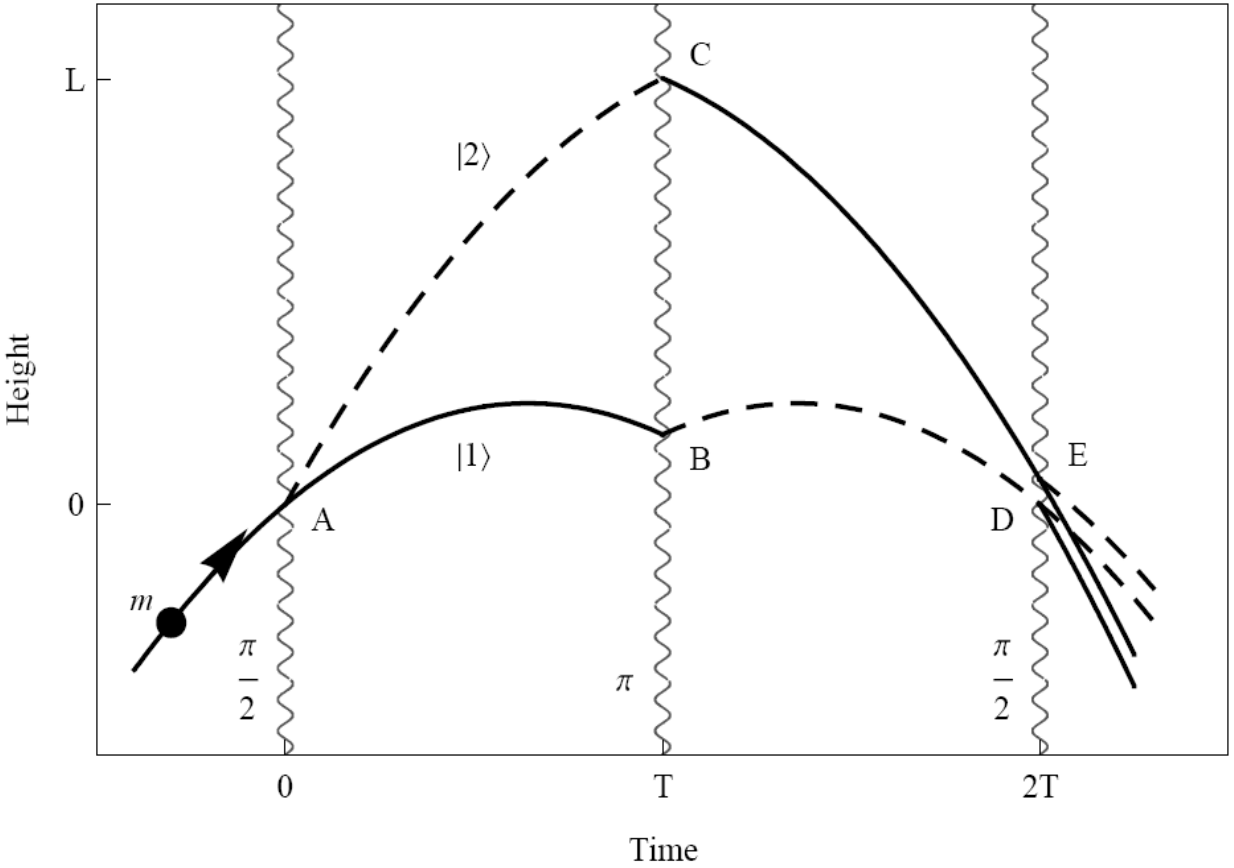
1. affects fundamental constants such as the electron mass or fine structure constant, which changes the energy levels of the quantum states used in the interferometer

2. causes accelerations: can be searched for by comparing the accelerometer signals from two simultaneous quantum interferometers run with different Sr isotopes

3. affects precession of nuclear spins, such as general axions. Searched for by comparing simultaneous, co-located interferometers with the Sr atoms in different quantum states with differing nuclear spins

Light Pulse Atom Interferometry

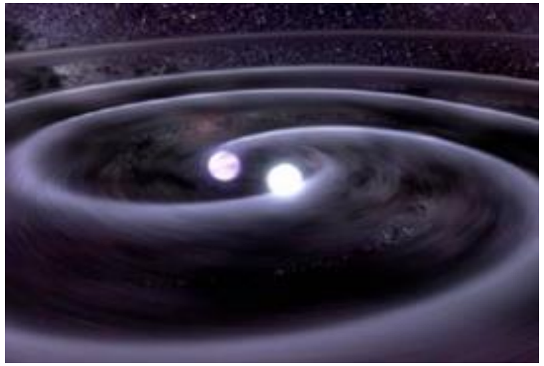




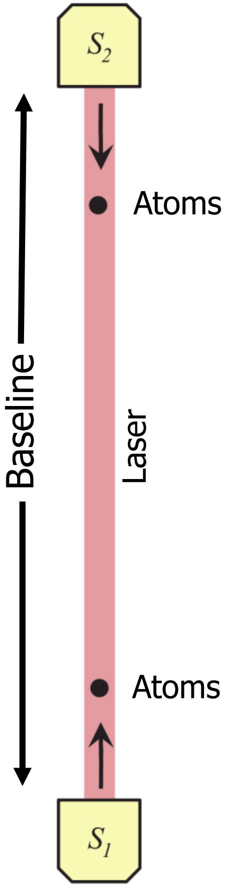
Long duration

Large wavepacket separation

Gradiometer detector concept



GW source (e.g., black hole binary inspiral)



Gradiometer

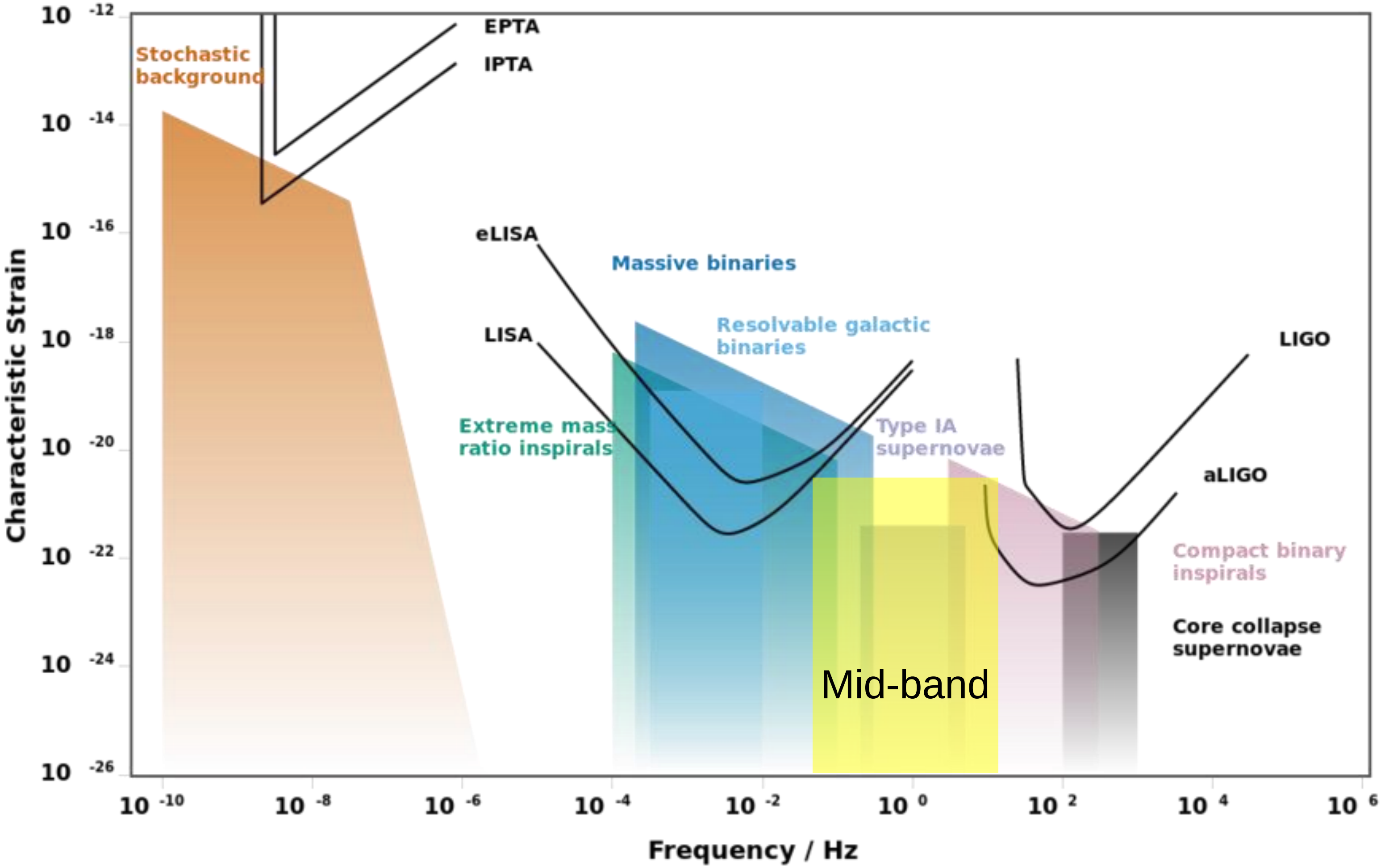
Compare two (or more) atom ensembles separated by a **large baseline**

Science signal is **differential phase** between interferometers

Differential measurement suppresses many sources of common noise and systematic errors

Science signal strength is proportional to baseline length (DM, GWs).

Gravitational wave frequency bands



There is a gap between the LIGO and LISA detectors (0.1 Hz – 10 Hz).

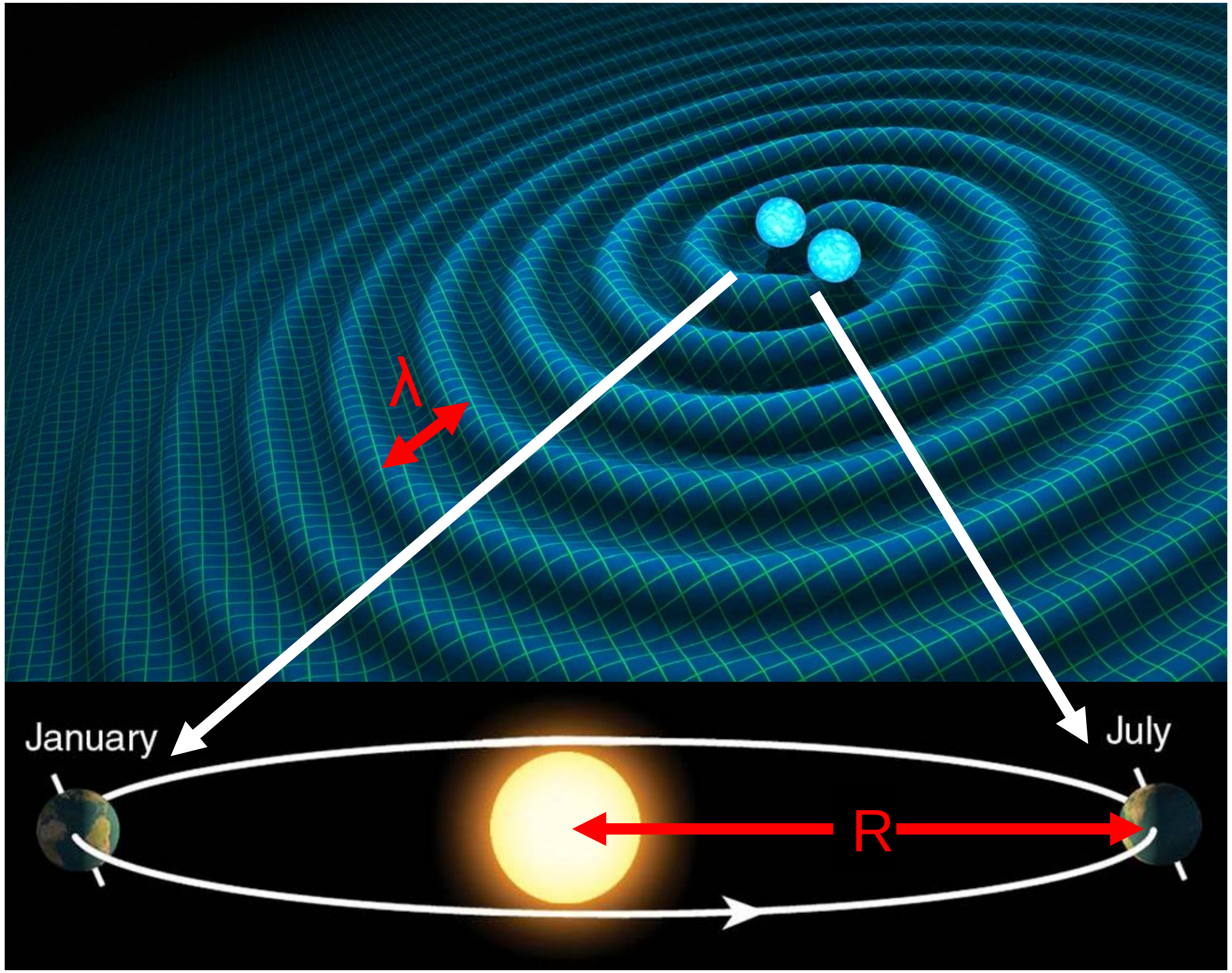
Moore et al., CQG **32**, 015014 (2014)

Sky position determination

Sky localization precision ~λ/R

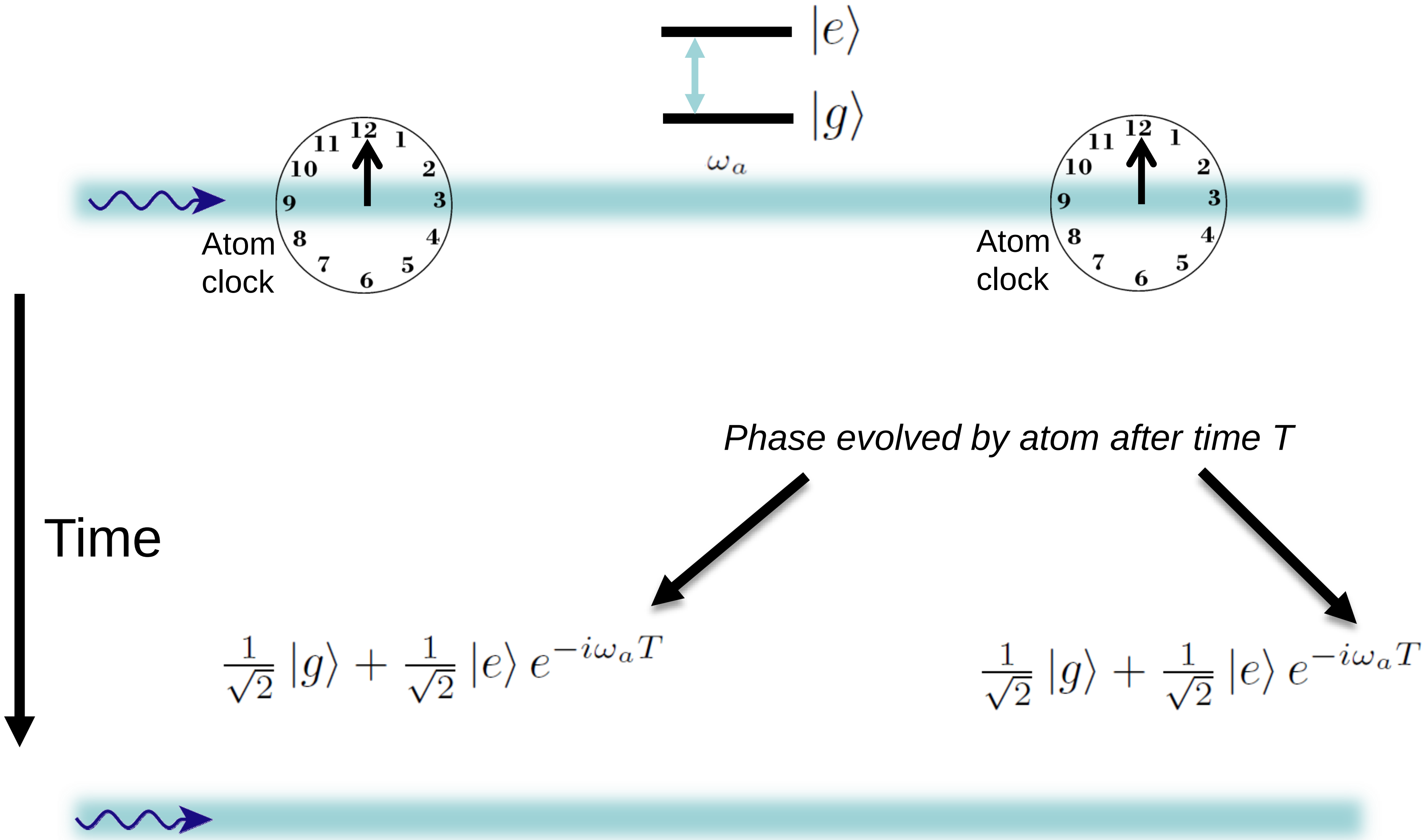
Mid-band advantages

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



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

Simple Example: Two Atomic Clocks



Atom clock

Atom clock

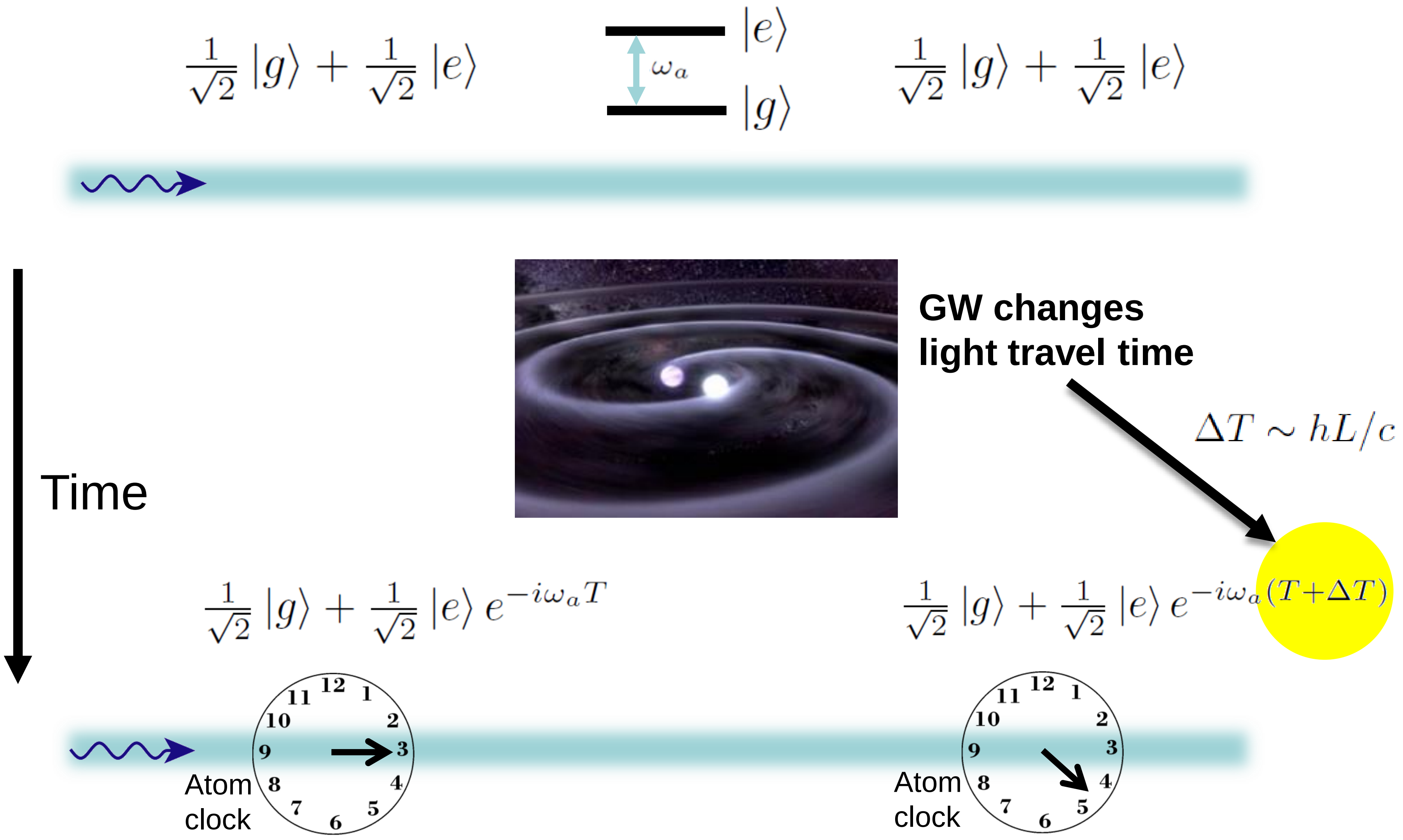
Time

Phase evolved by atom after time T

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

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

Simple Example: Two Atomic Clocks



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

$|e\rangle$

ω_a

$|g\rangle$

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

Time

GW changes light travel time

$\Delta T \sim hL/c$

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

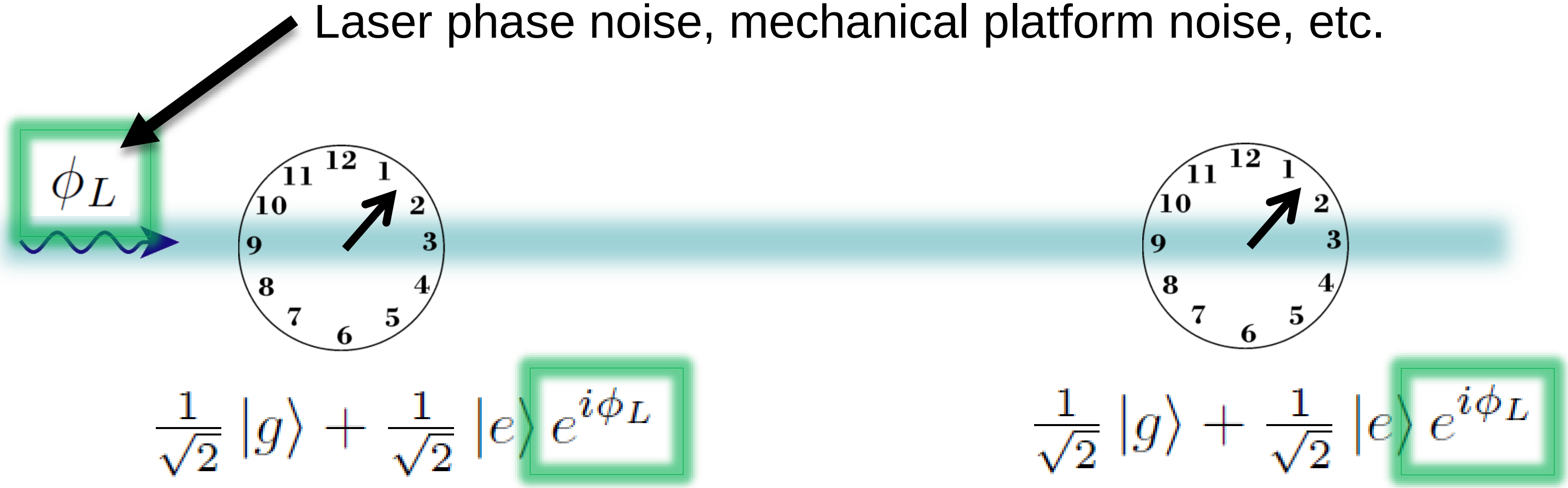
$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle e^{-i\omega_a (T+\Delta T)}$$

Atom clock

Atom clock

Phase Noise from the Laser

The phase of the laser is imprinted onto the atom.



Laser phase noise, mechanical platform noise, etc.

$\boxed{\phi_L}$

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

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

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

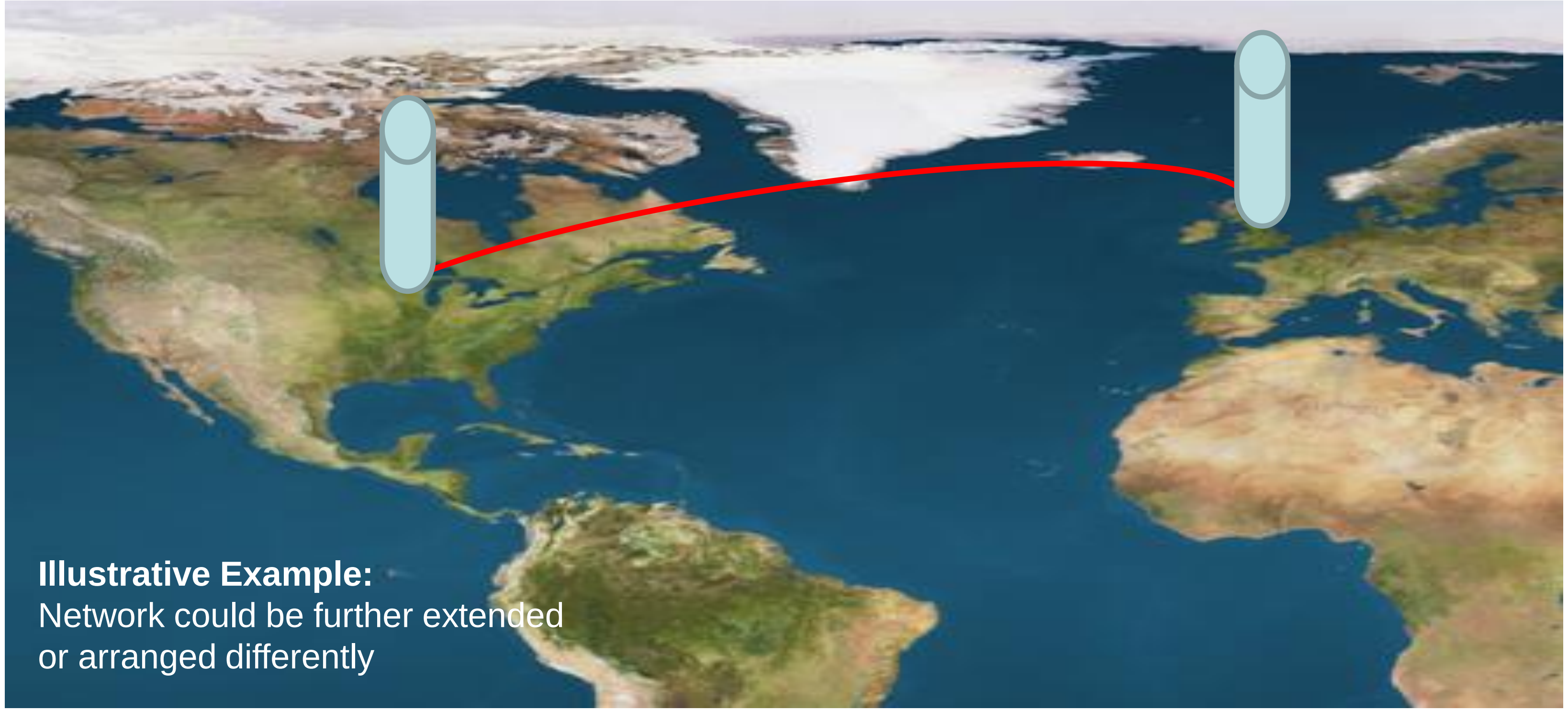
AION - Proposal

- Networking atom interferometers for fundamental physics
- The goal is to build a detector networked with MAGIS
  - a’la LIGO and VIRGO
- The AION program was conceived in Summer 2018, it has been designed to be complimentary to MAGIS
  - Using similar technologies
- Subsequently this has become a work-package in the UK Quantum Sensors for Fundamental Physics Programme (QSFP) see previous talk.
- Providing Non-common background mode rejection
  - unequivocal proof of any observation

What is AION?

- Construction and operation of a next generation Atomic Interferometric Observatory and Network (AION) in the UK with similar physics goals to MAGIS
  - enable the exploration of properties of dark matter as well as searches for new fundamental interactions
  - provide a pathway for detecting gravitational waves in the mid-frequency band
- project spans across several science areas
  - fundamental particle physics, atomic physics, astrophysics & cosmology
  - connects communities.
- opportunity to be involved in the design and the R&D for large-scale quantum interferometric experiments to be located in the UK.
- the programme would reach its ultimate sensitivity by operating two detectors in tandem
  - one in the UK and one in the US

Ultimate Goal: Establish International Network



Illustrative Example:
Network could be further extended
or arranged differently

International Collaboration

- AION greatly benefits from close collaboration on an international level with MAGIS-100
  - goal of an eventual km-scale atom interferometer on comparable timescales
- operating two detectors, one in the UK and one in the US in tandem enables new physics opportunities
- MAGIS experiment and Fermilab endorsed collaboration with AION
- US-UK collaboration serves as a testbed for full-scale terrestrial (kilometer-scale) and satellite-based (thousands of kilometres scale) detectors and builds the framework for global scientific endeavor

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. Construct a 'proof-of-principle, 10m scale device. Produces a 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

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

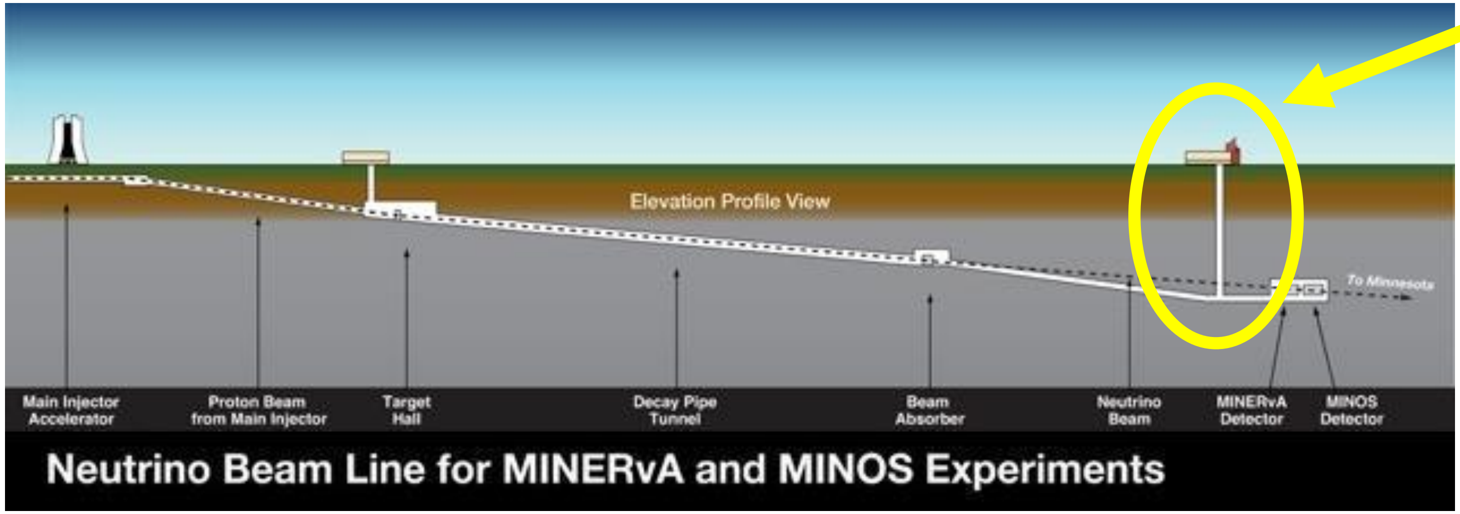
If you like to participate or require further information please contact:
fundamental-physics-admin@imperial.ac.uk
with "AION" in title.

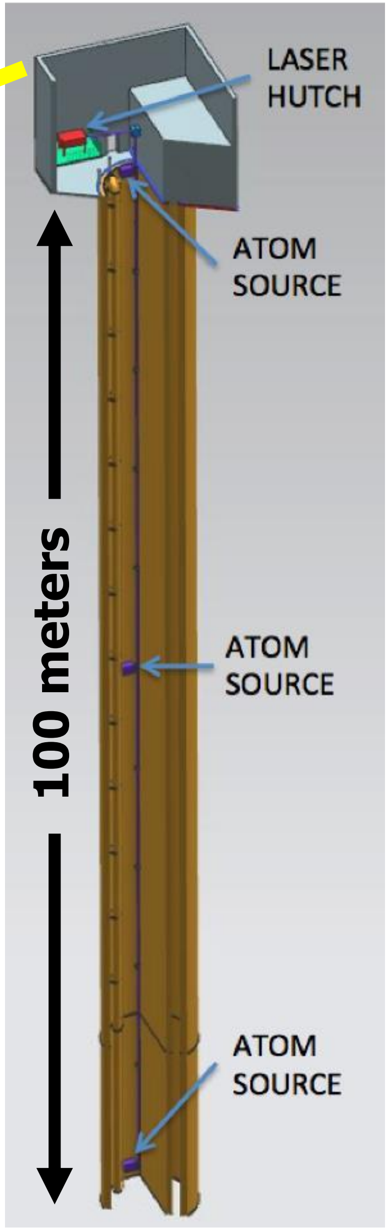
Proto-collaboration

- Interested parties include (no particular order):
- IPPP - Durham, The Open University, UCL, University of Strathclyde, Brunel - University of London, University of Birmingham, University of Bristol, University of Sheffield, National Physical Laboratory, University of Glasgow, University of Liverpool, King's College London, University of Nottingham, Imperial College London, STFC - RAL Space, University of Sussex, University of Aberdeen, Royal Holloway - University of London, STFC RAL, University of Cambridge, Swansea University, University of Glasgow, University of Oxford, + others.

MAGIS-100: GW detector prototype at Fermilab

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

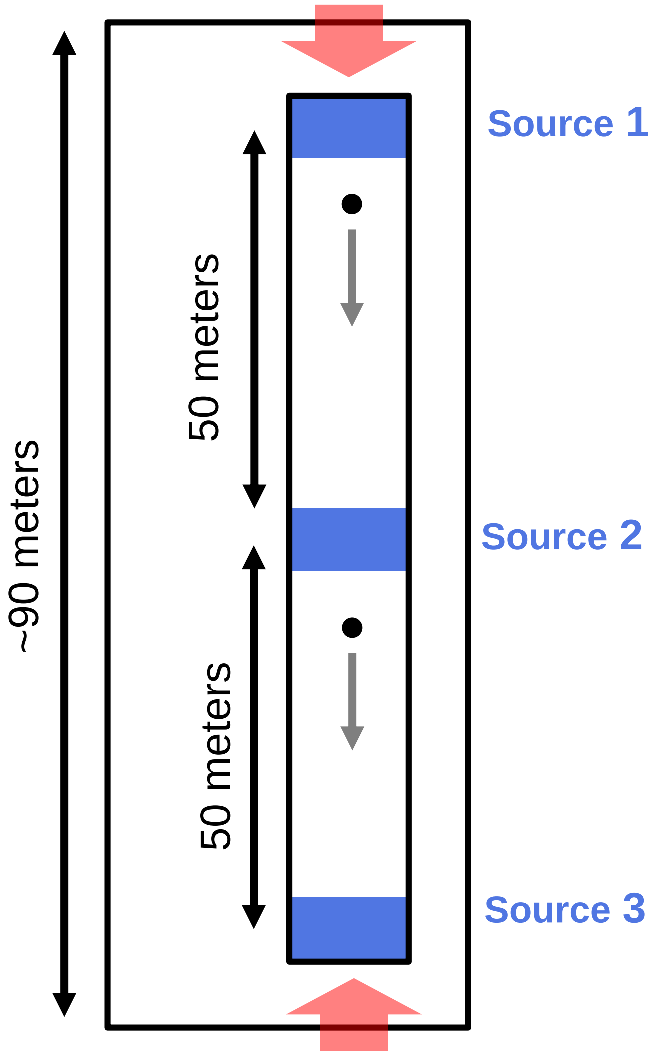




- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration

STANFORD   Fermilab   BERKELEY   UNIVERSITY OF LIVERPOOL   Northwestern University   Northern Illinois University

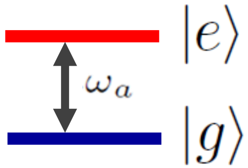
MAGIS-100 Configuration

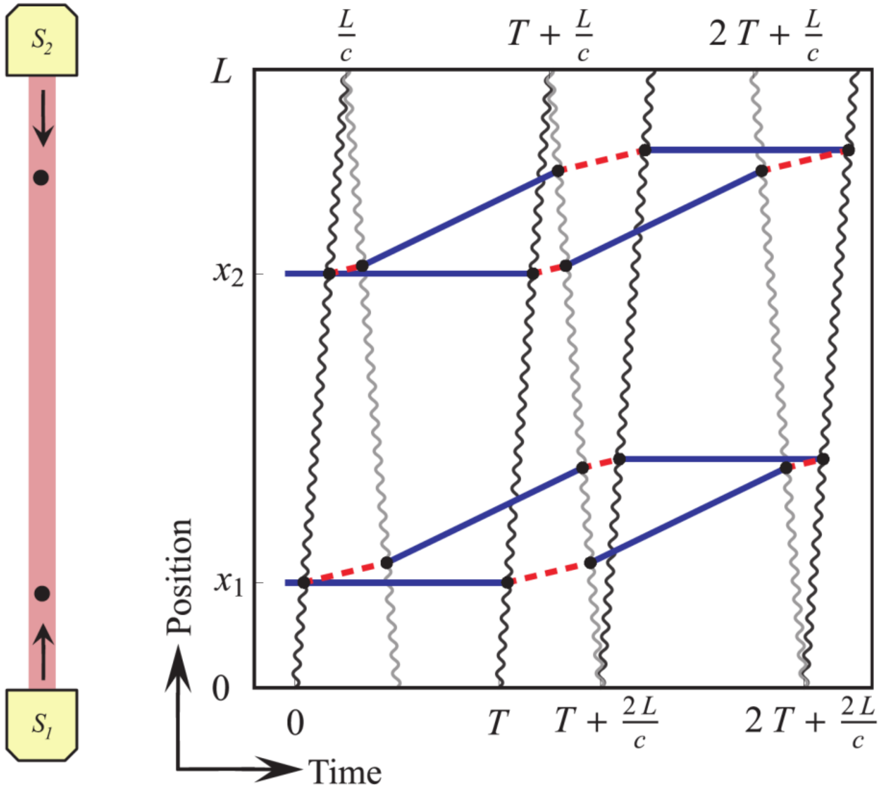


Detector modes of operation

I. Max drop time >3 seconds (sources 1,2)
II. Max free fall with launch (sources 2,3)
III. Max baseline (sources 1,3)
IV. Newtonian noise rejection (sources 1,2,3)
V. Extreme QM, 4 - 9 s (drop 1 or launch 3)

Differential atom interferometer response





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

Graham et al., PRL **110**, 171102 (2013).
Arvanitaki et al., arXiv:1606.04541 (2016).

Ultralight scalar dark matter

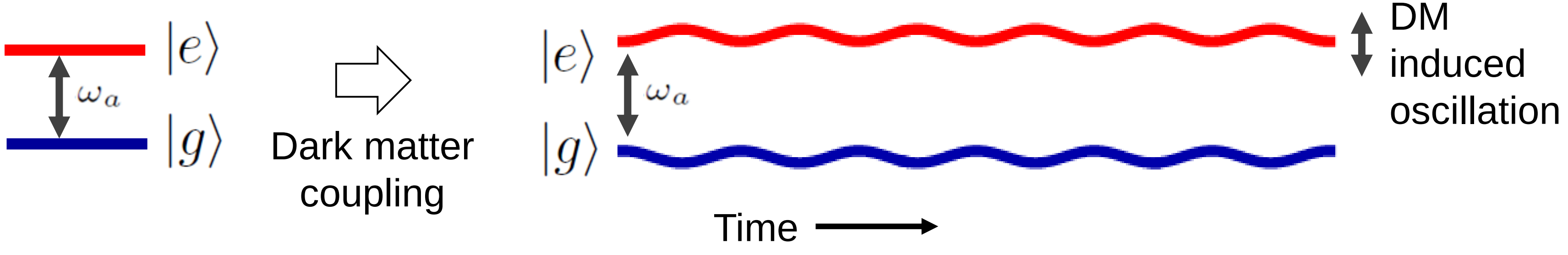
Ultralight dilaton DM acts as a background field (e.g., mass ~10^{-15} eV)

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

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

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

DM coupling causes time-varying atomic energy levels:

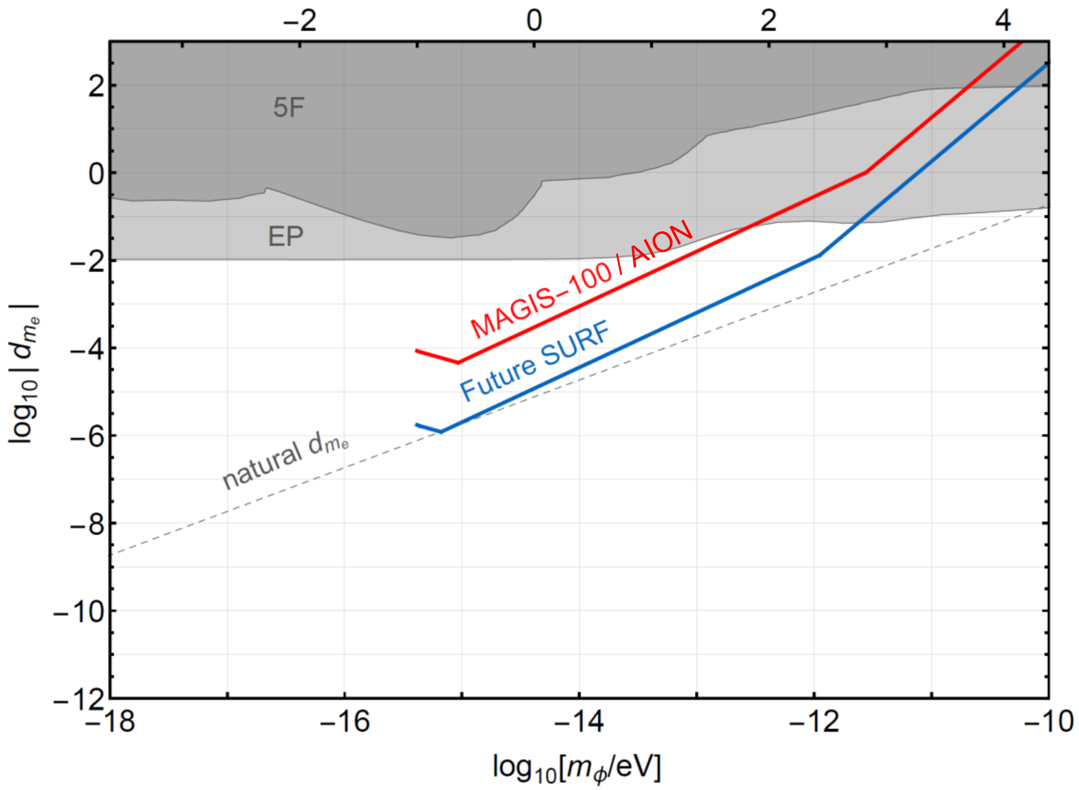


Dark matter coupling

Time

DM induced oscillation

Via coupling to the electron mass

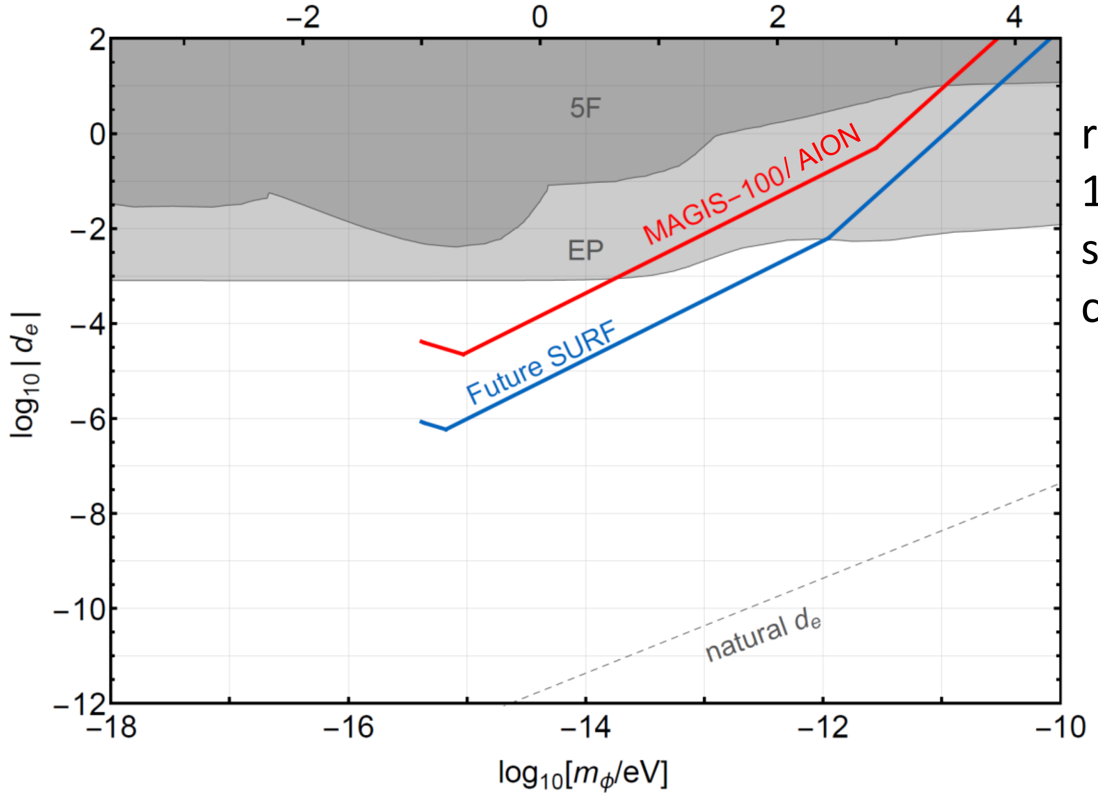


red curve:
10^{15} dropped atoms
shot-noise limited phase resolution
corresponds to 1 year of data taking

Sensitivity to ultralight dark matter field coupling to the electron mass
with strength d_{me},
shown as a function of the mass of the scalar field *m*
(or alternatively the frequency of the field - top scale)

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

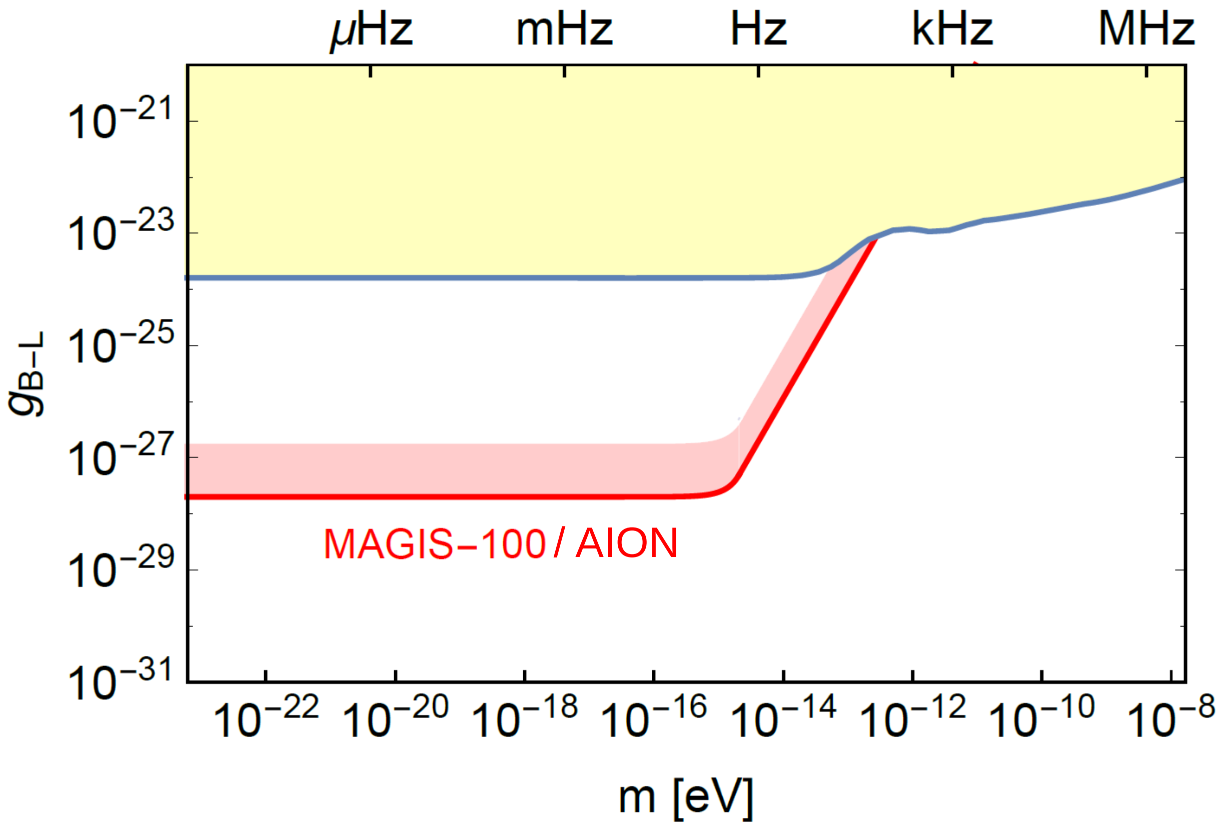
Sensitivity via coupling to α



red curve:
10^{15} dropped atoms
shot-noise limited phase resolution
corresponds to 1 year of data taking

Sensitivity to dark matter via coupling to the fine structure constant
with strength d_e,
shown as a function of the mass of the scalar field *m*
(or alternatively the frequency of the field - top scale).

B-L Coupled Forces

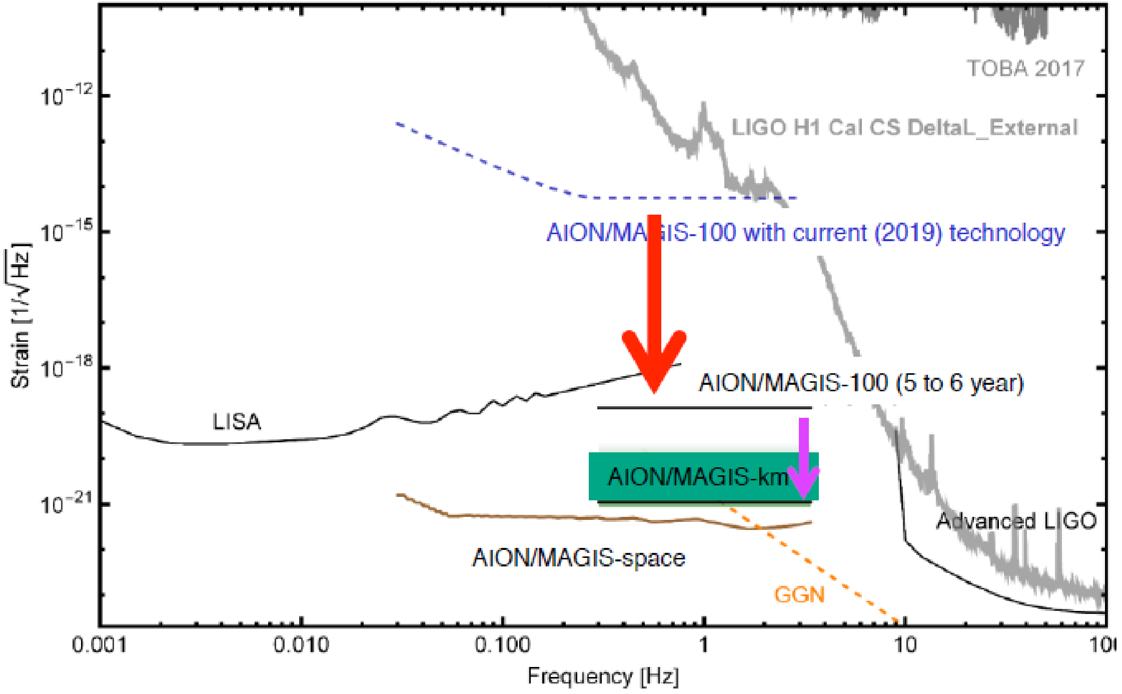


Assumes:
50 m launch,
1000 ~ħ*k* atom optics
10^8 atoms/s flux
shot noise limited

Sensitivity to a B-L coupled new force, with $10^{-16} g/\sqrt{Hz}$ acceleration sensitivity

Graham et al. PRD **93**, 075029 (2016).

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

Summary

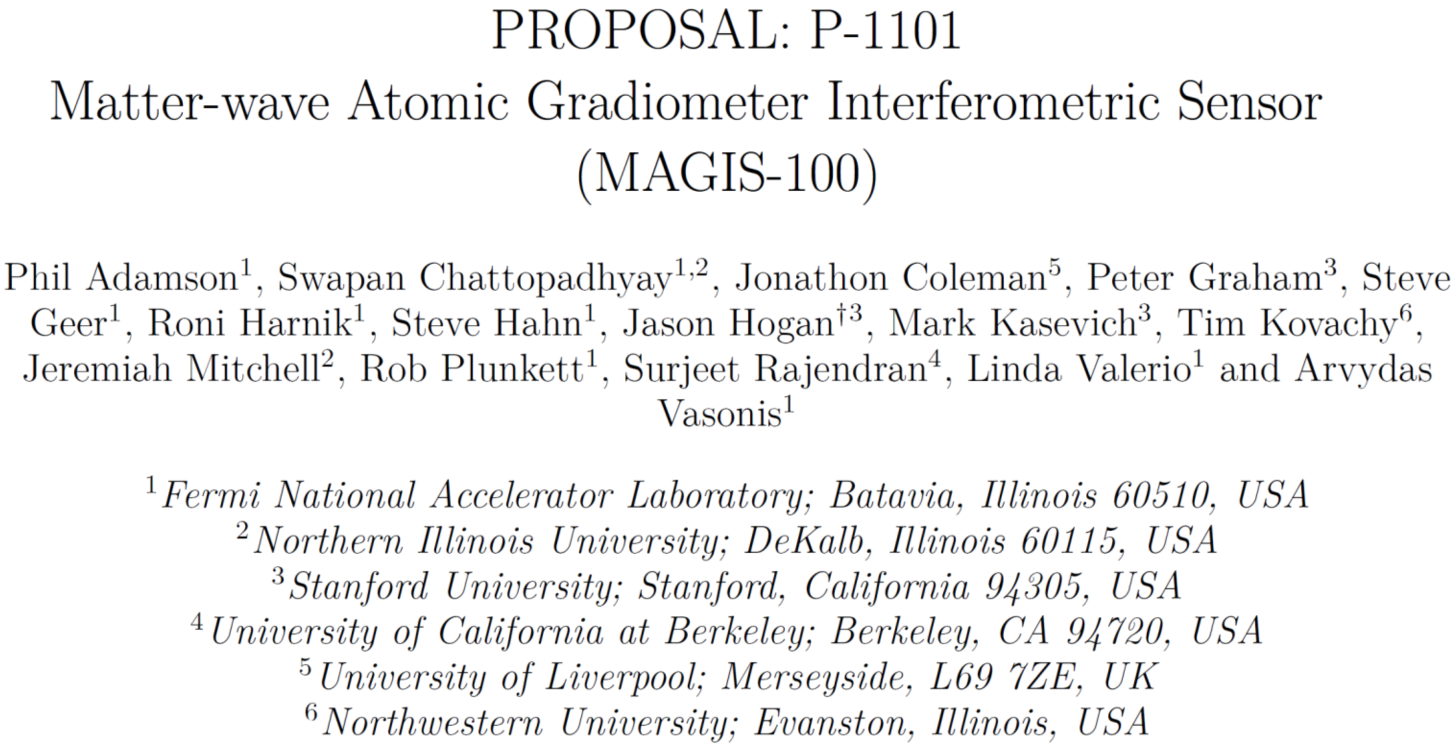
- Using Atom Interferometry as a macroscopic quantum probe of the ‘early universe’ through:
  - gravitational waves
  - and the ‘dark sector’
- AION is new UK initiative to network another detector with MAGIS
  - Allows for increased sensitivity
  - Non-common mode background rejection
  - Unequivocal proof of any signal in the dark sector or gravitational waves

- MAGIS-100 is a new experiment at Fermilab
  - potential to scale much larger to SURF
- Proposal currently given stage-1 approval by the Fermilab PAC
- MAGIS-100 has been funded through the Gordon and Betty Moore Foundation

GORDON AND BETTY
MOORE
FOUNDATION

- Many thanks to all members of the MAGIS and AION collaborations for help and contributions to the presentation

MAGIS Collaboration



PROPOSAL: P-1101

Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)

Phil Adamson[1], Swapan Chattopadhyay[1,2], Jonathon Coleman[5], Peter Graham[3], Steve Geer[1], Roni Harnik[1], Steve Hahn[1], Jason Hogan[†3], Mark Kasevich[3], Tim Kovachy[6], Jeremiah Mitchell[2], Rob Plunkett[1], Surjeet Rajendran[4], Linda Valerio[1] and Arvydas Vasonis[1]

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[5] *University of Liverpool; Merseyside, L69 7ZE, UK*
[6] *Northwestern University; Evanston, Illinois, USA*

Part of the proposed Fermilab Quantum Initiative:

http://www.fnal.gov/pub/science/particle-detectors-computing/quantum.html#magis

MAGIS-100 Location: MINOS building

Ground level of MINOS building

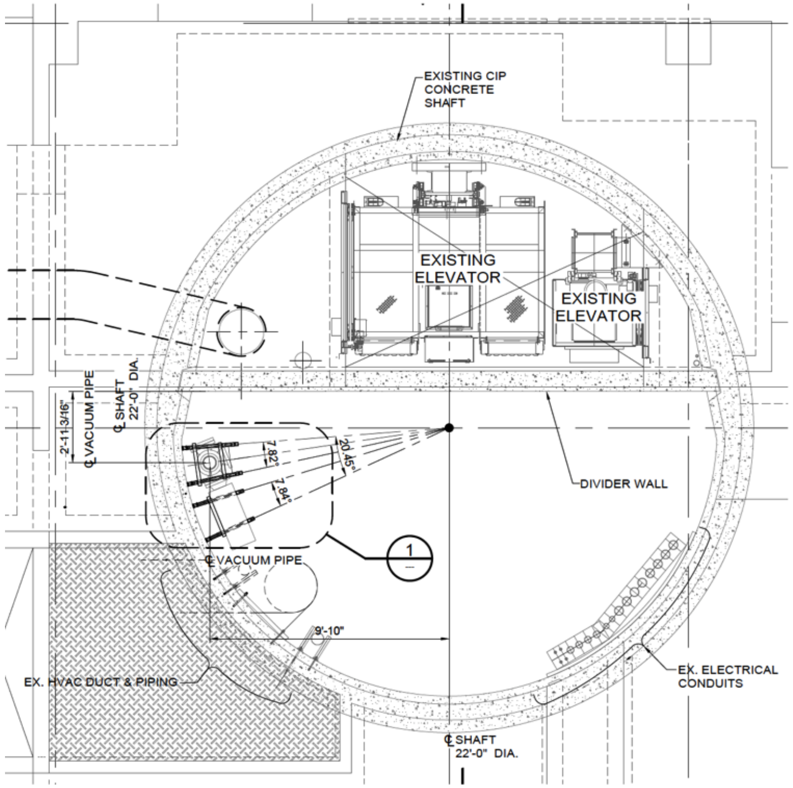
From: L. Valerio (Fermilab), MAGIS Project Engineer

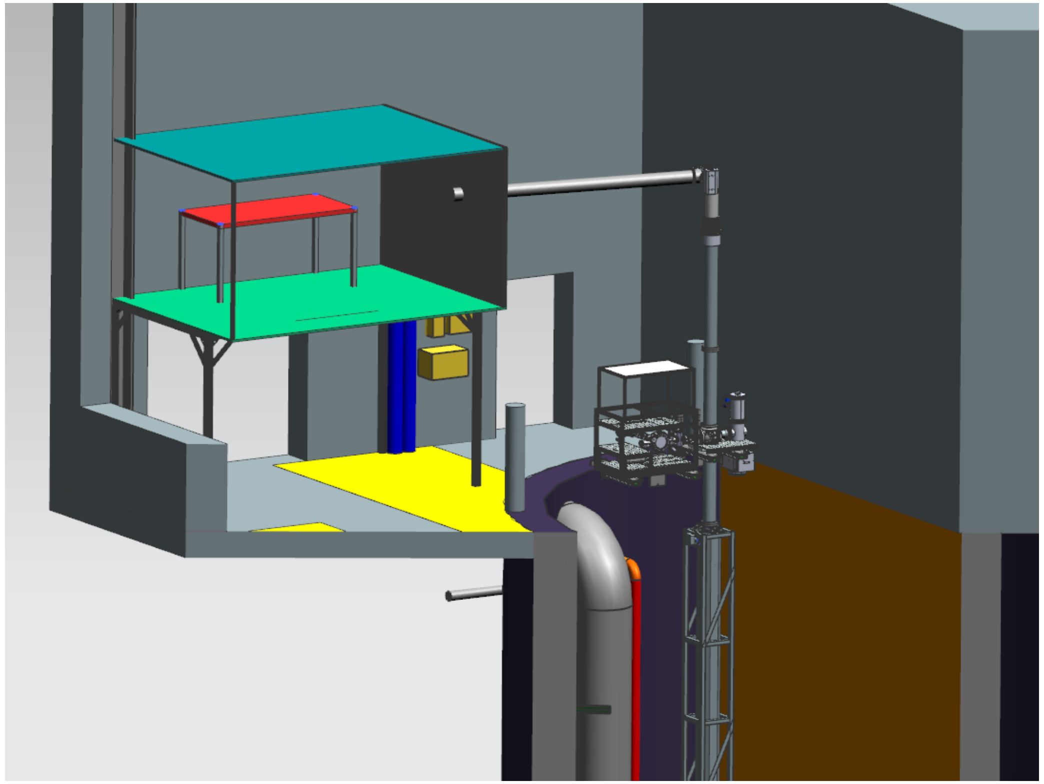
MAGIS-100 Location: Shaft in MINOS building

Top and bottom of ~100m shaft.

From: L. Valerio (Fermilab), MAGIS Project Engineer

Preliminary designs – 3D model





Civil engineering drawing of shaft and proposed location of mounting brackets.
Cutaway view of laser platform and top of shaft.

From: L. Valerio (Fermilab), MAGIS Project Engineer

Quantum science

Realizing macroscopic quantum mechanical superposition states

Distance: Wave packets are expected to be separated by distances of up to 10 meters (current state-of-art 0.5 meters, demonstrated at Stanford University)

Time: Support record breaking matter wave interferometer durations, up to 9 seconds (current state-of-art 2 seconds)

Entanglement: 20 dB spin squeezed Sr atom sources takes advantage of quantum correlations to reduce sensor noise below the standard quantum limit (shot noise)

What is QSFP?

- QSFP - Quantum Sensors for Fundamental Physics
- To take advantage of the extraordinary science opportunities and UK capabilities and to exploit this science in a world-class program
- An initiative in response to the UKRI ‘umbrella-council’ era
- To develop genuinely new *interdisciplinary* partnerships between physicists from multiple domains
    - Including, atomic, particle, space, astronomy, cosmology, etc
    - working with the quantum hubs, and NPL and US partners
    - we anticipate entirely new and exciting science will emerge
- a major attractor for creative, original young experimentalists and theorists