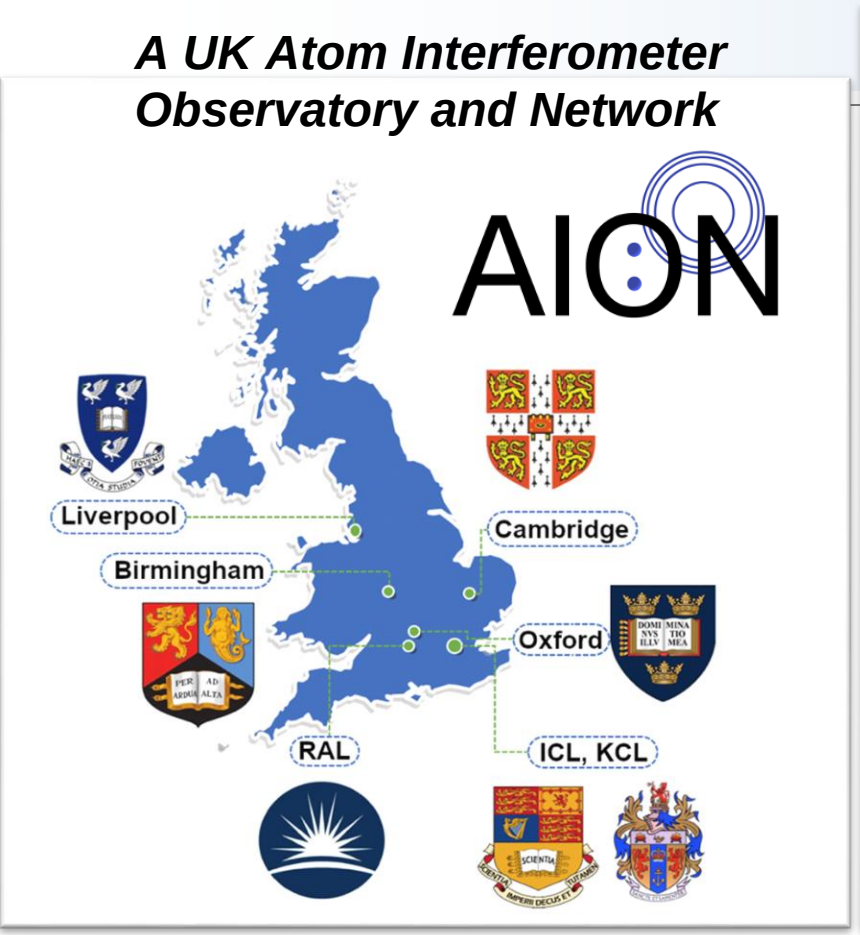
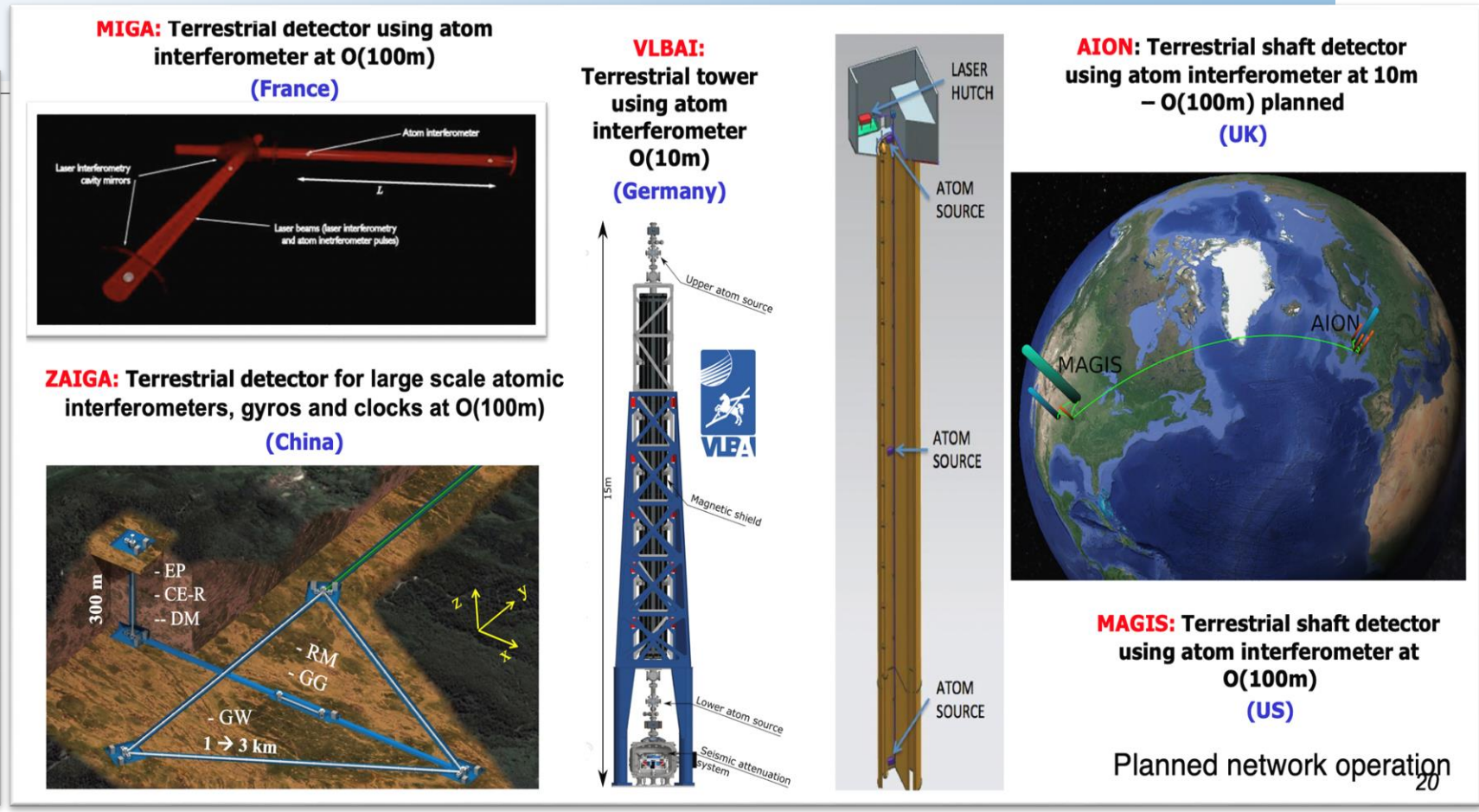




Oliver Buchmueller,

Imperial College London, Oxford University, Royal Society Leverhulme Trust Senior Research Fellow

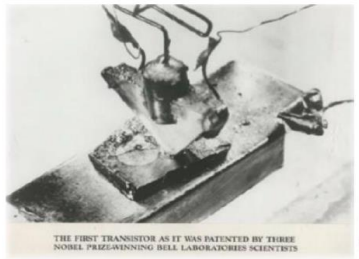
COLD ATOM QUANTUM TECHNOLOGY TO EXPLORE FUNDAMENTAL PHYSICS

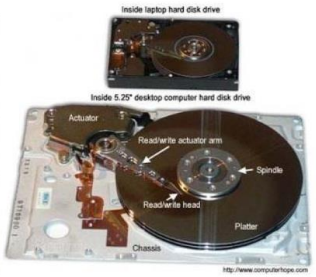
Example of Open Questions in Fundamental Physics

- What is dark matter made of?
- What is dark energy made of?
- Why is there more matter than antimatter in the universe?
- How heavy are the neutrinos? What was their role in the formation of the universe?
- Is there a quantum theory of gravity that can describe the universe we live in?
- What is the number of dimensions in a fundamental theory of nature?
- … and many more

The Centenary of Quantum Mechanics (1925–2025)

… and how the Quantum Revolutions could help addressing them





Planck's quantum theory — beginning of 20th century

transistor — 1947

hard disk — 1954

laser — 1960

Albert Einstein (1879-1955)

Werner Heisenberg (1901-1976)

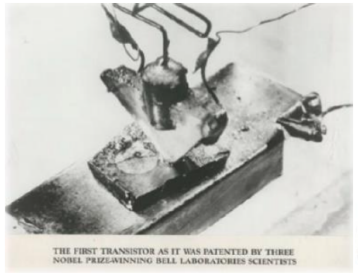
Erwin Schrödinger (1887-1961)

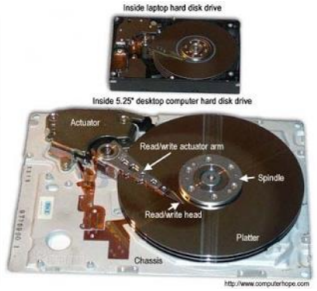
The first quantum revolution

Observation and macroscopic manifestation of quantum principles

The Centenary of Quantum Mechanics (1925–2025)

… and how the Quantum Revolutions could help addressing them





Planck's quantum theory — beginning of 20th century

transistor — 1947

hard disk — 1954

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end 20th / beginning 21st — Control of single quantum particles; First quantum algorithms

Richard Feynman
(1918–1988)

Serge Haroche

And also Alain Aspect, Charles Bennett, Gilles Brassard, Artur Ekert, Peter Shor…

The second quantum revolution

Active manipulation of single quantum particles and interaction between multiple particles for applications

Example of Open Questions in Fundamental Physics

- What is dark matter made of?
- What is dark energy made of?
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- What can gravitational waves tell us about the universe and its fundamental laws?
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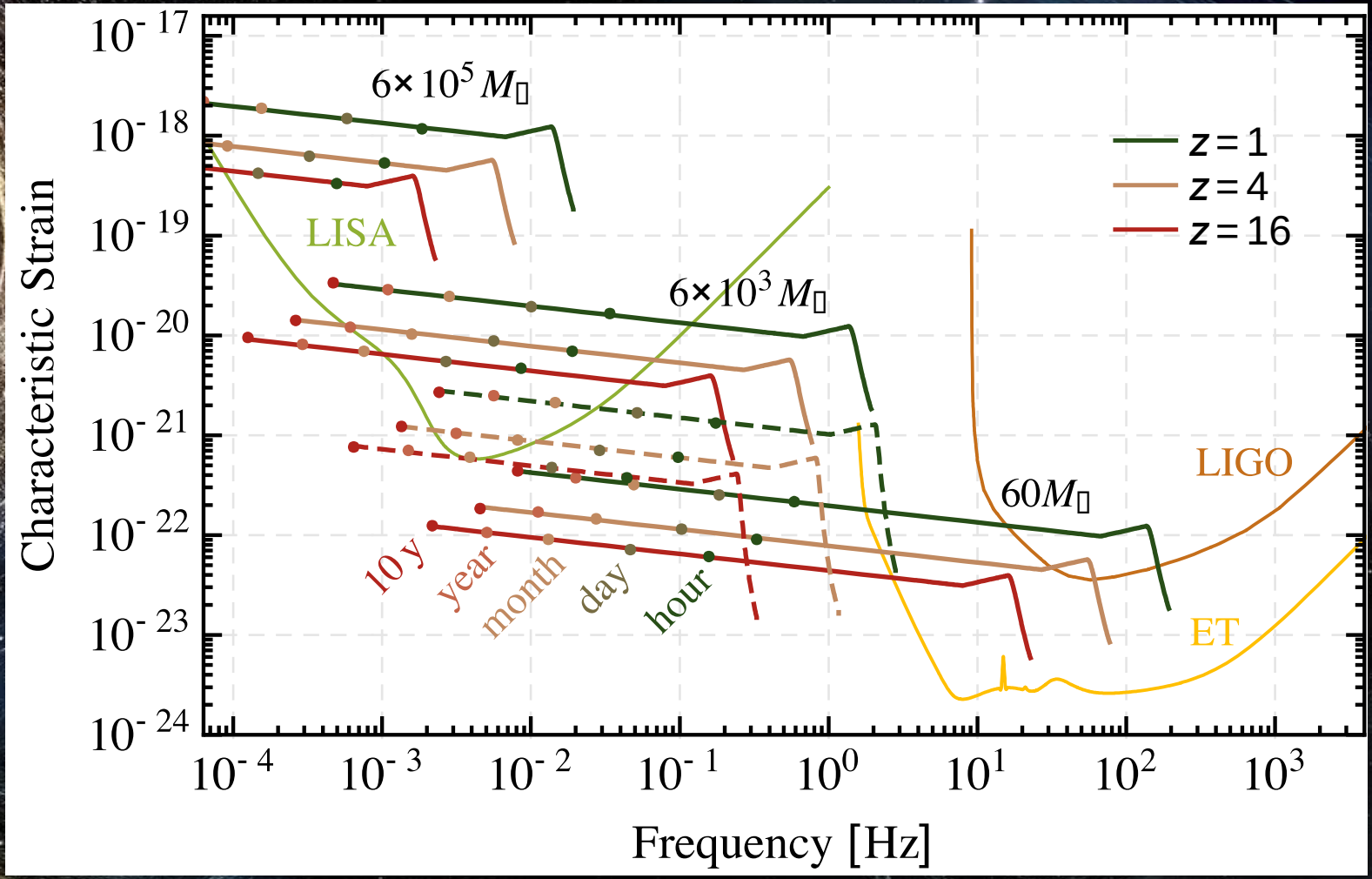
- … and many more

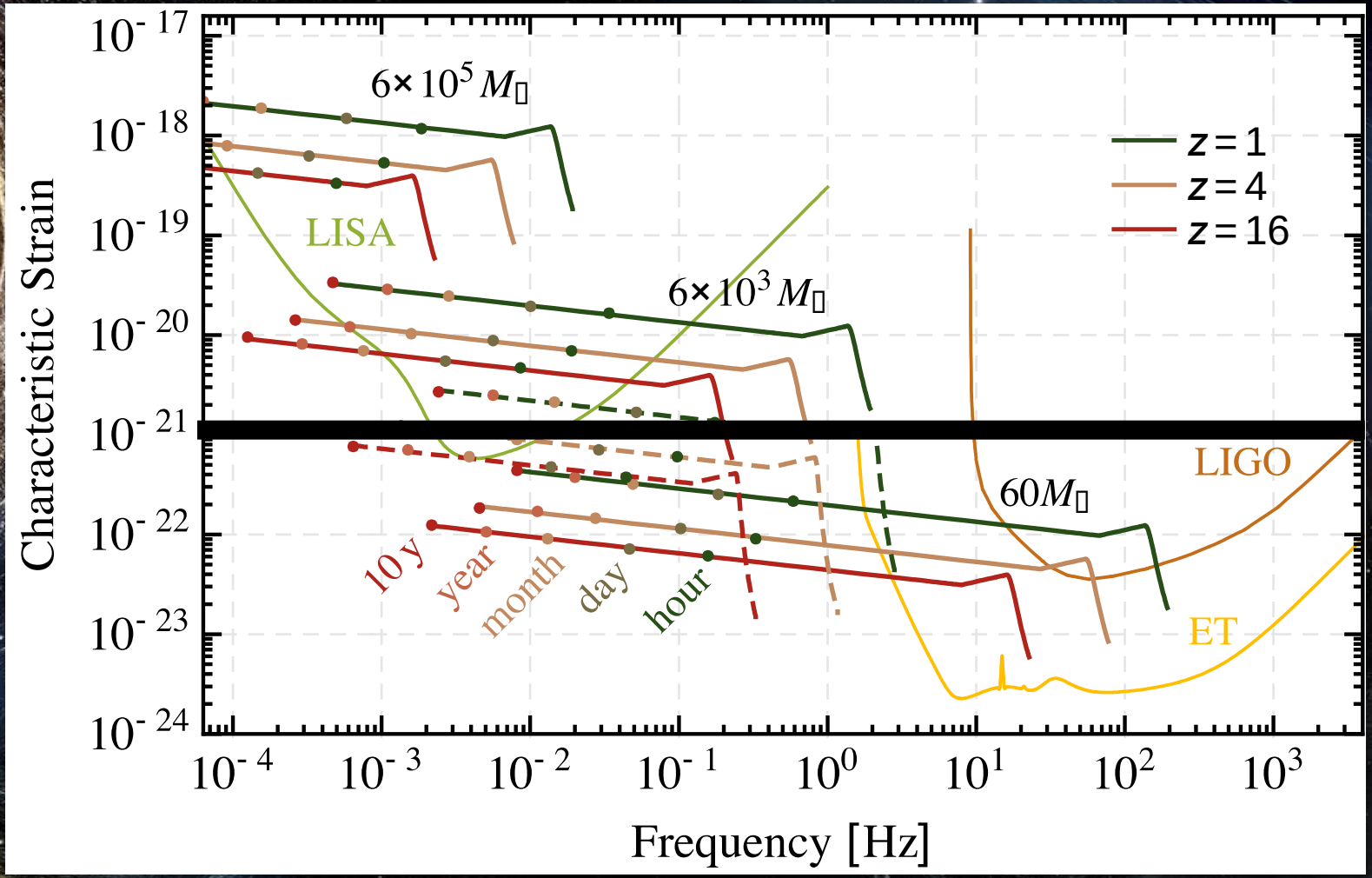
Laser Interferometer Experimental Landscape



KAGRA

GW detection requires enormous precision

Strain sensitivity
$h = \Delta L/L \sim 10^{-21}$



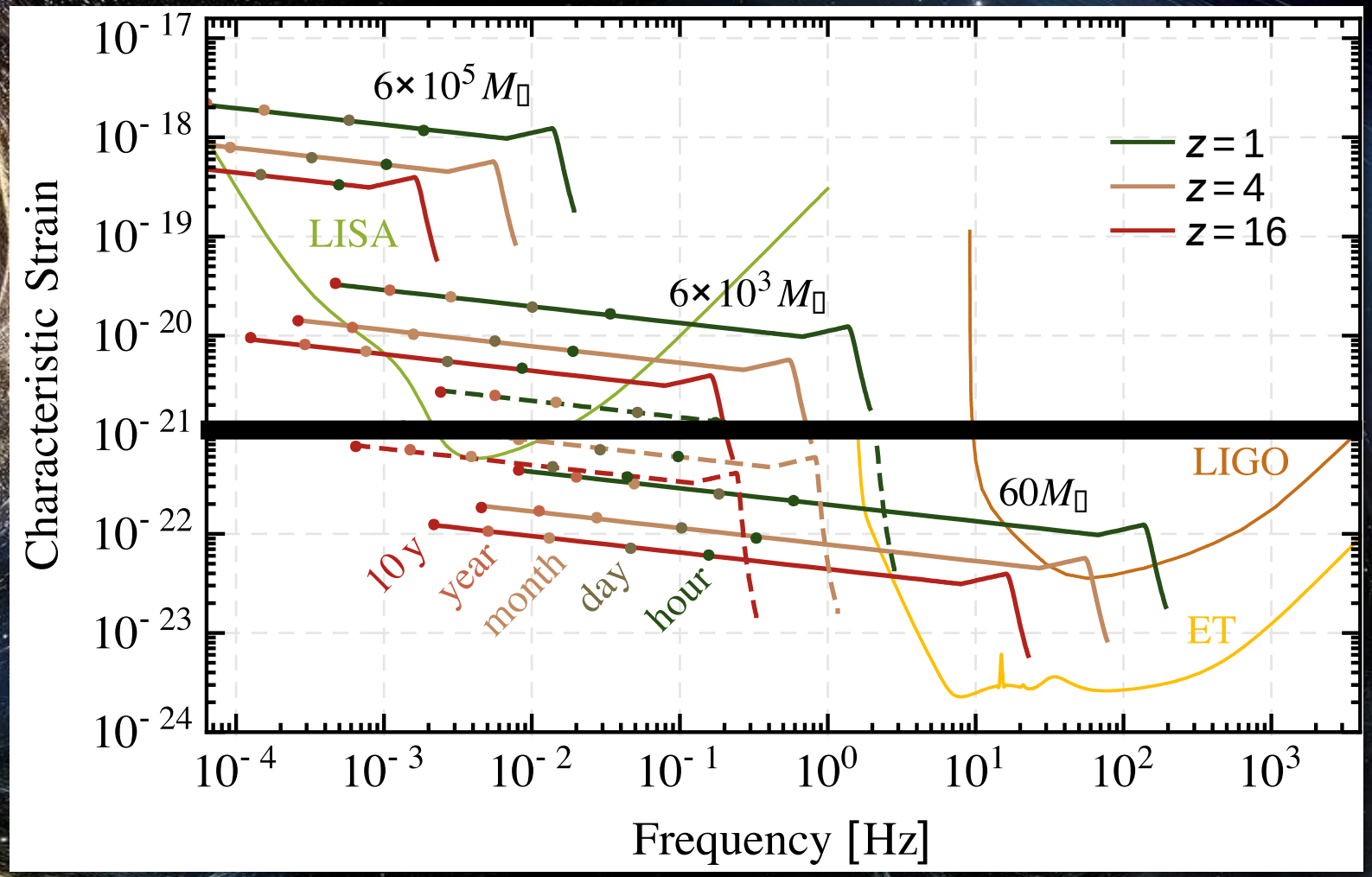
Virgo

KAGRA

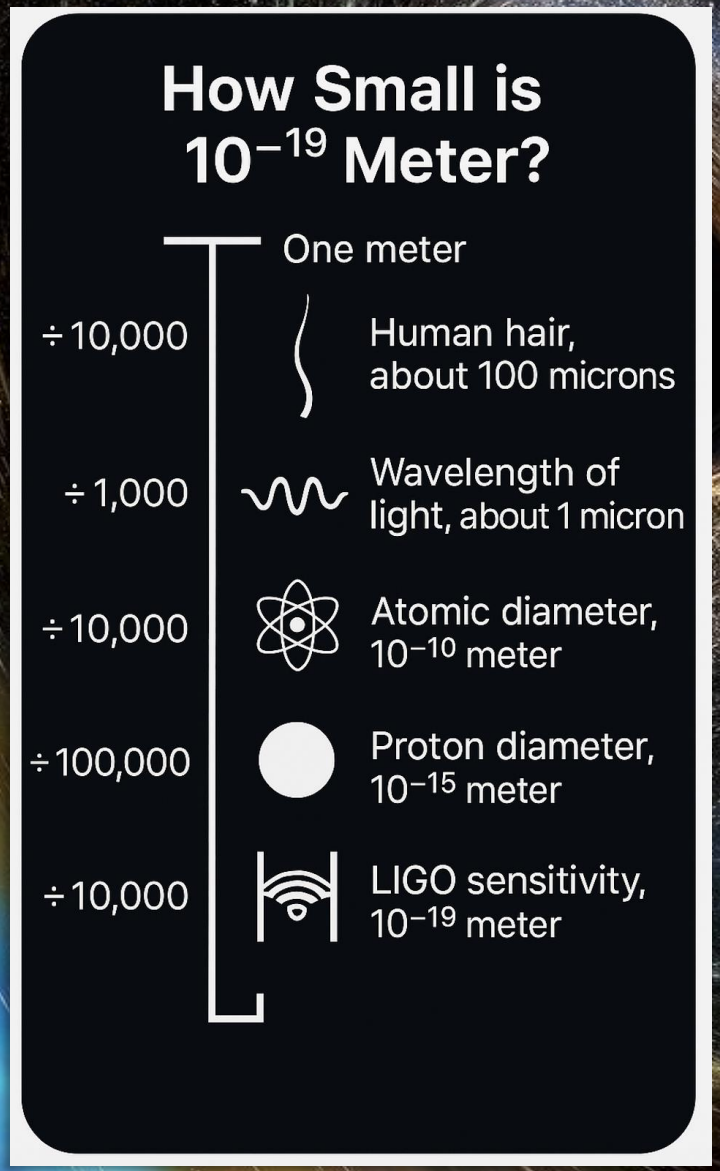
GW detection requires enormous precision

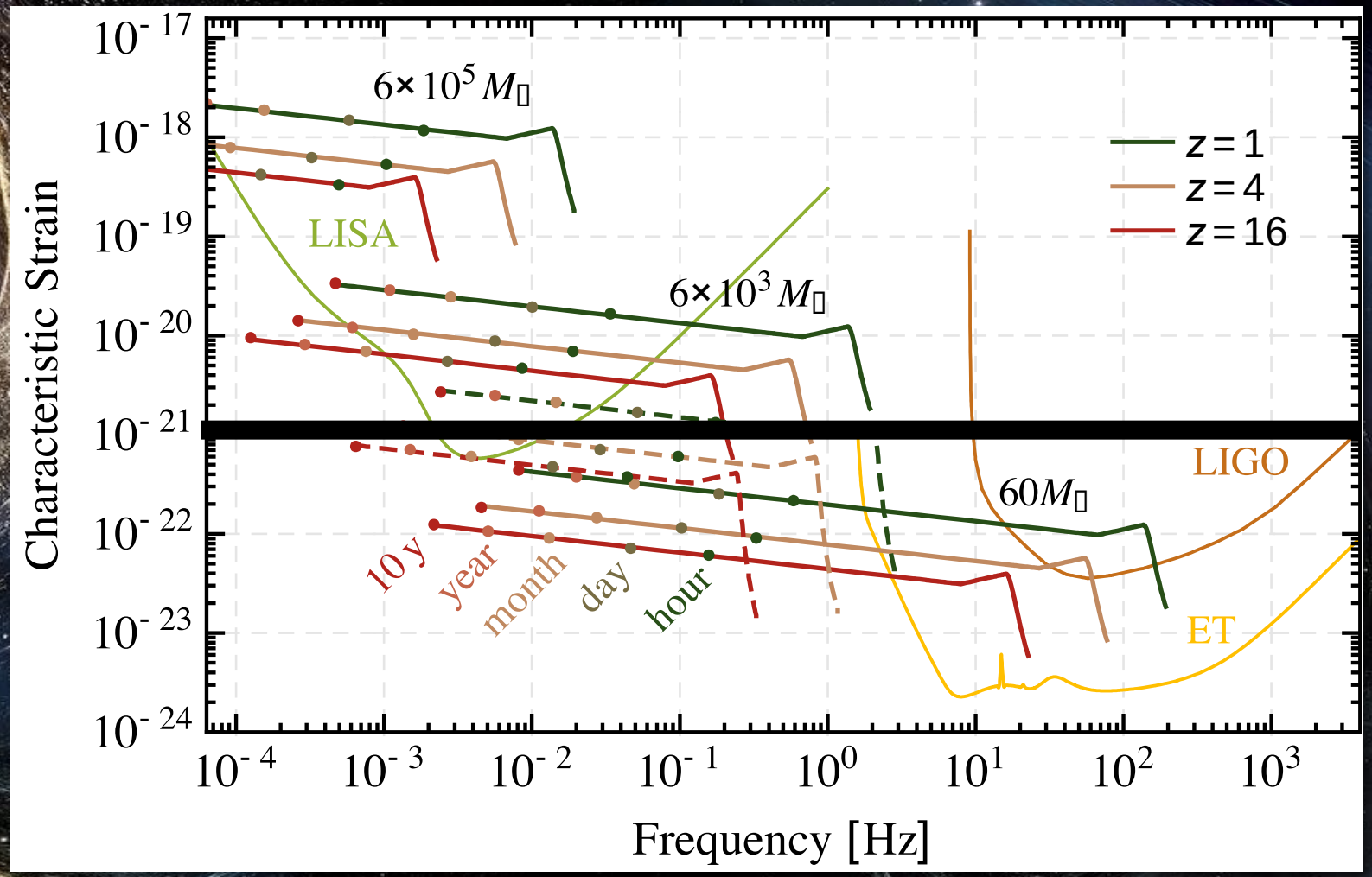
Strain sensitivity
$h = \Delta L/L \sim 10^{-21}$

So, $h=10^{-21}$ implies about 10^{-19} m change for a GW detector like Ligo/Virgo (km scale)



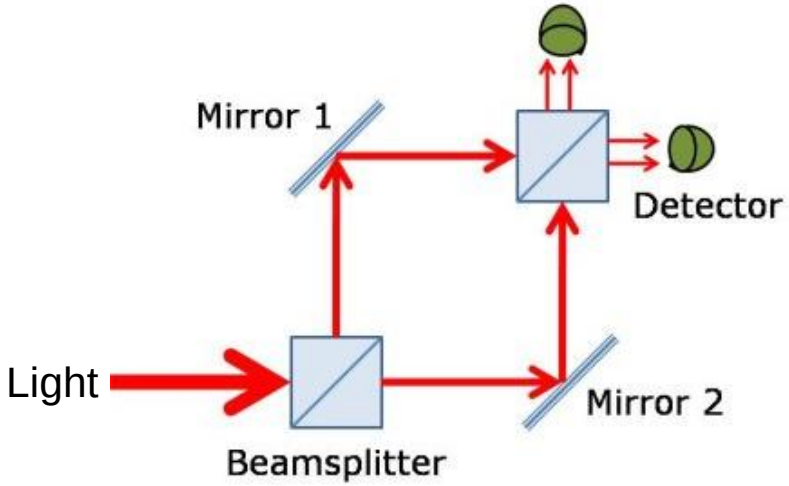
GW detection requires enormous precision

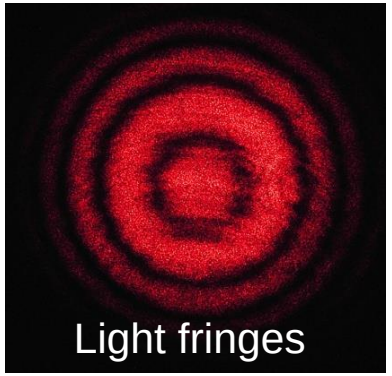




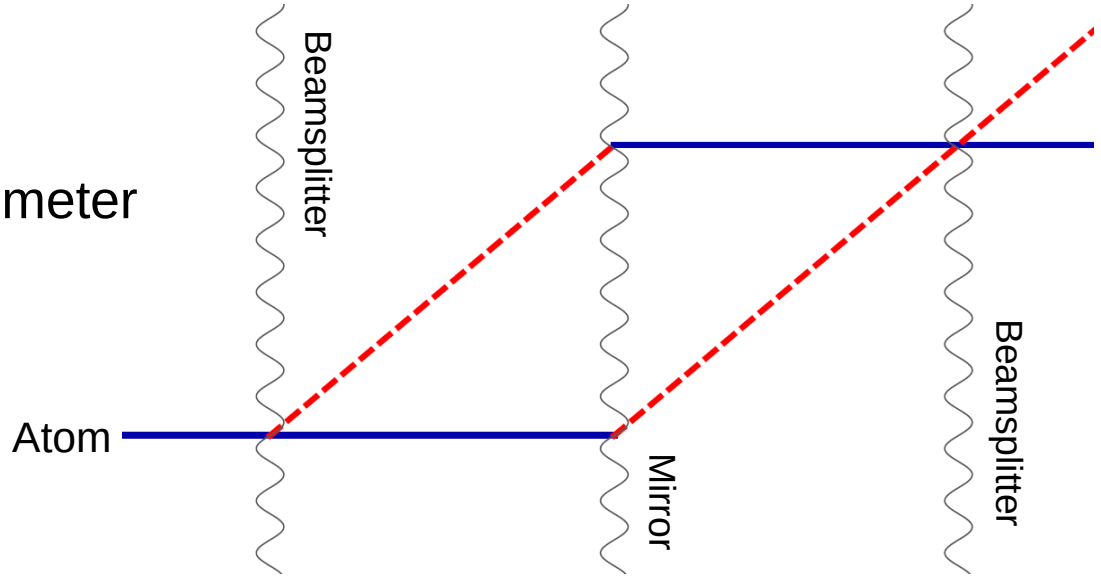
Light vs. Cold Atoms: Atom Interferometry

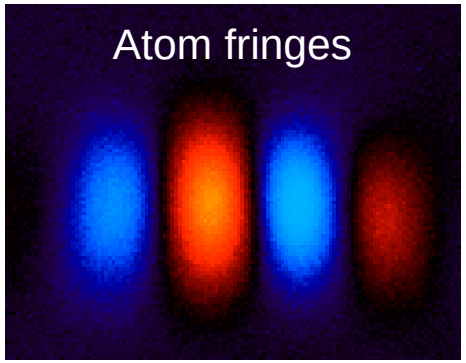
Light interferometer





Atom interferometer

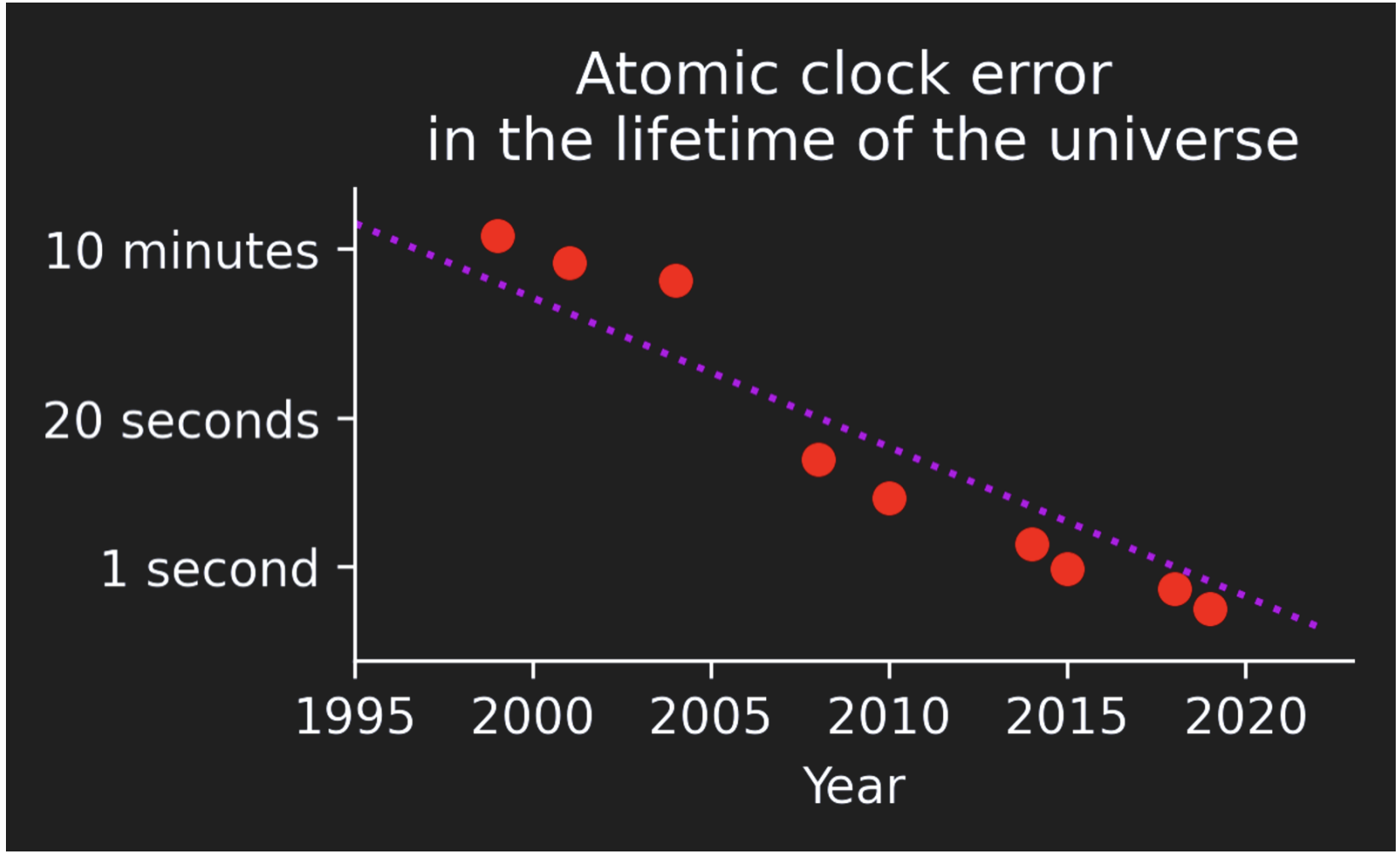




http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

Atom Interferometry and Atomic Clocks

- **Atomic clocks are incredibly precise.**
- **Their precision is equivalent to losing only 0.5 seconds over the entire 13.7-billion-year lifespan of the Universe.**
- **We harness this unparalleled atomic precision and combine it with atom interferometry to achieve the highest possible accuracy and sensitivity.**



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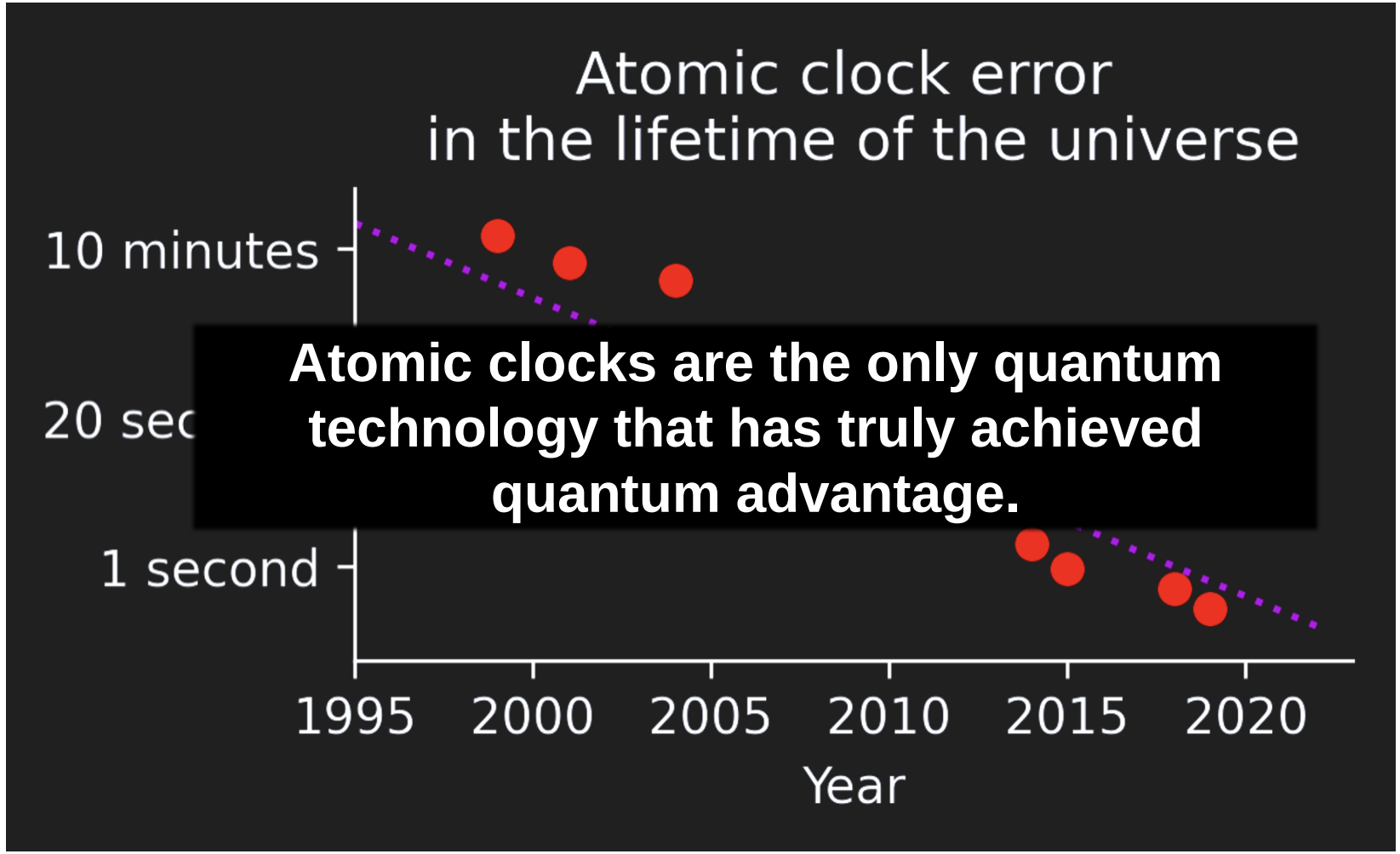

Atomic clocks are the only quantum technology that has truly achieved quantum advantage.

Atom Interferometry and Atomic Clocks

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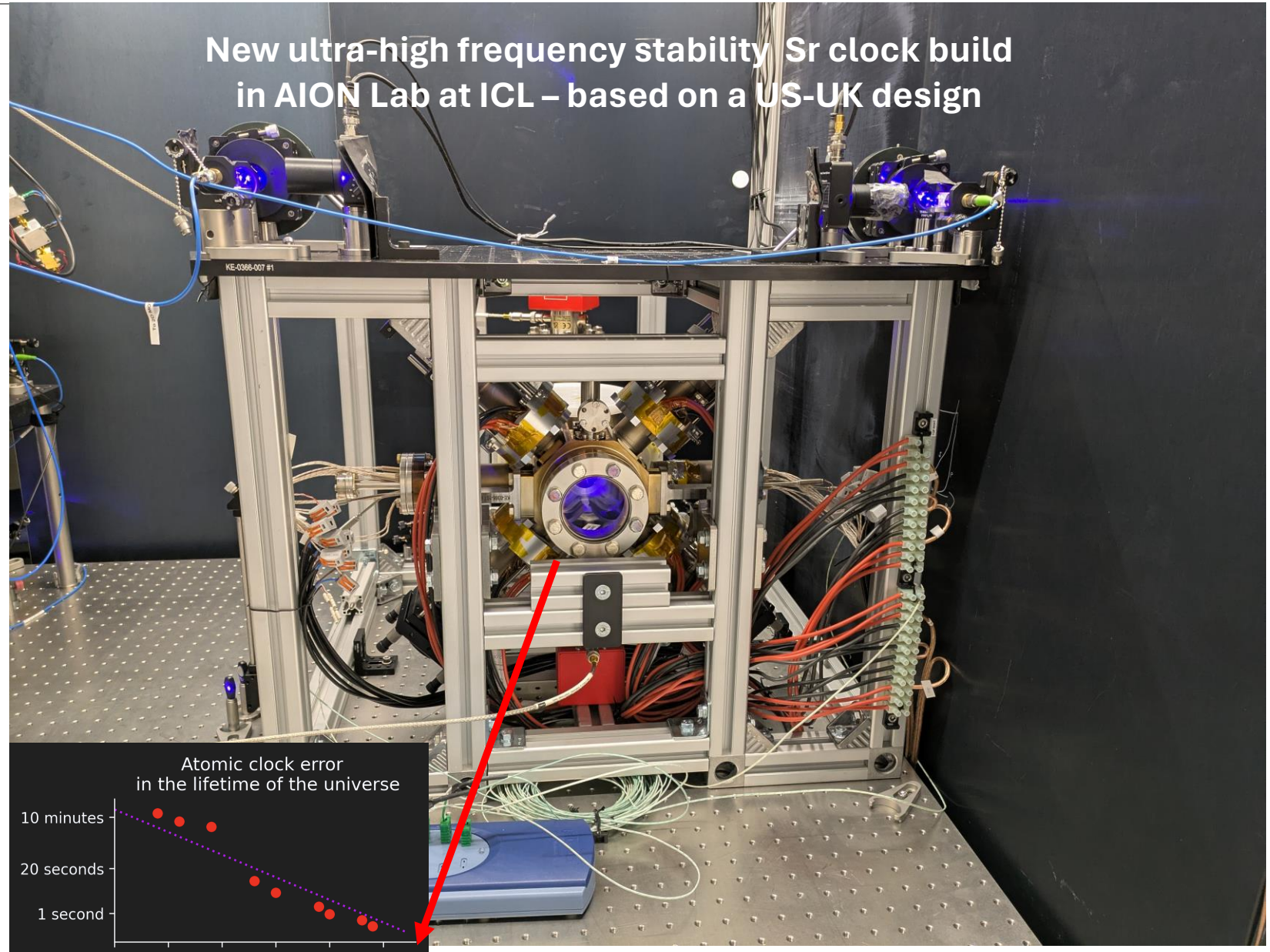
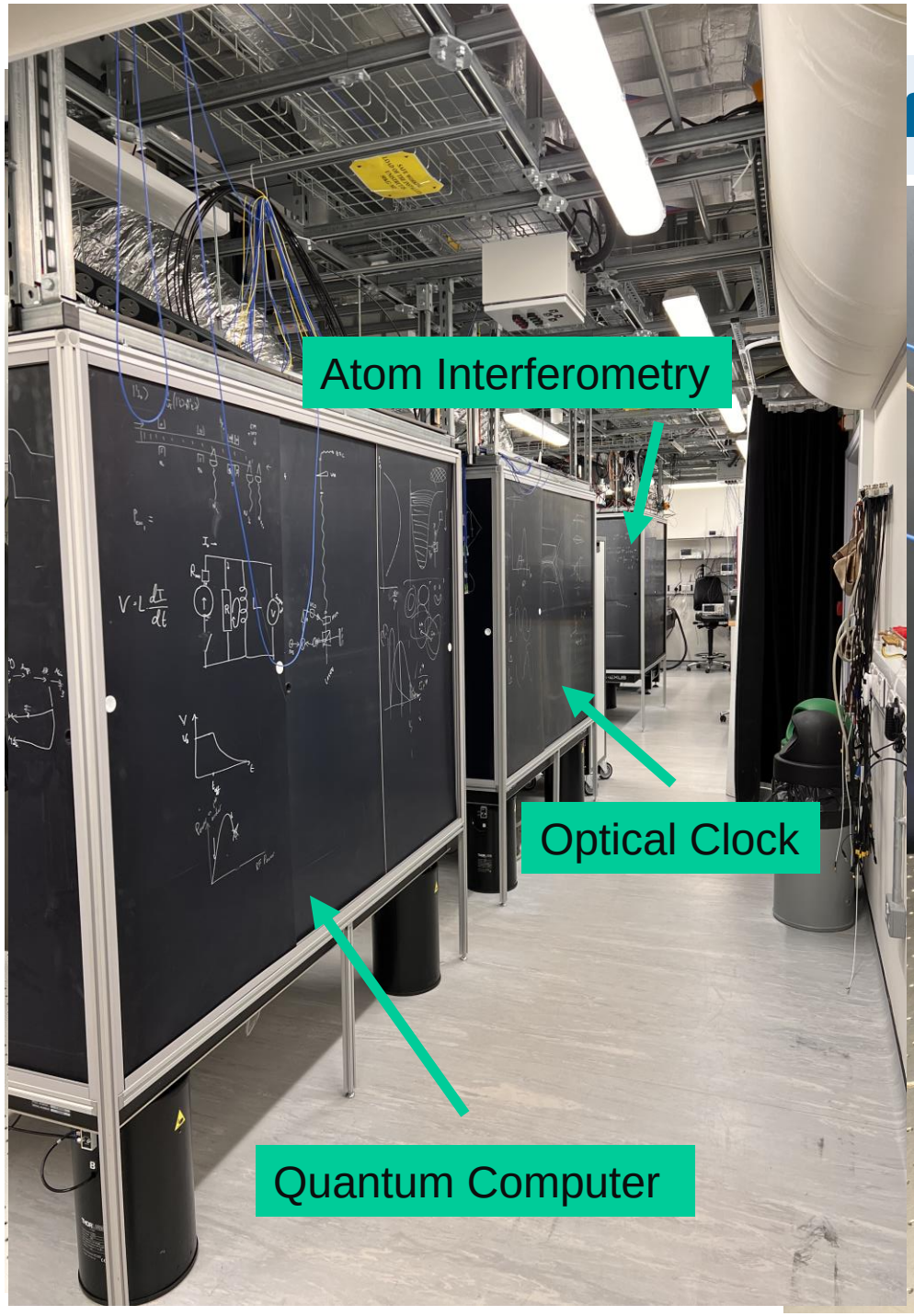
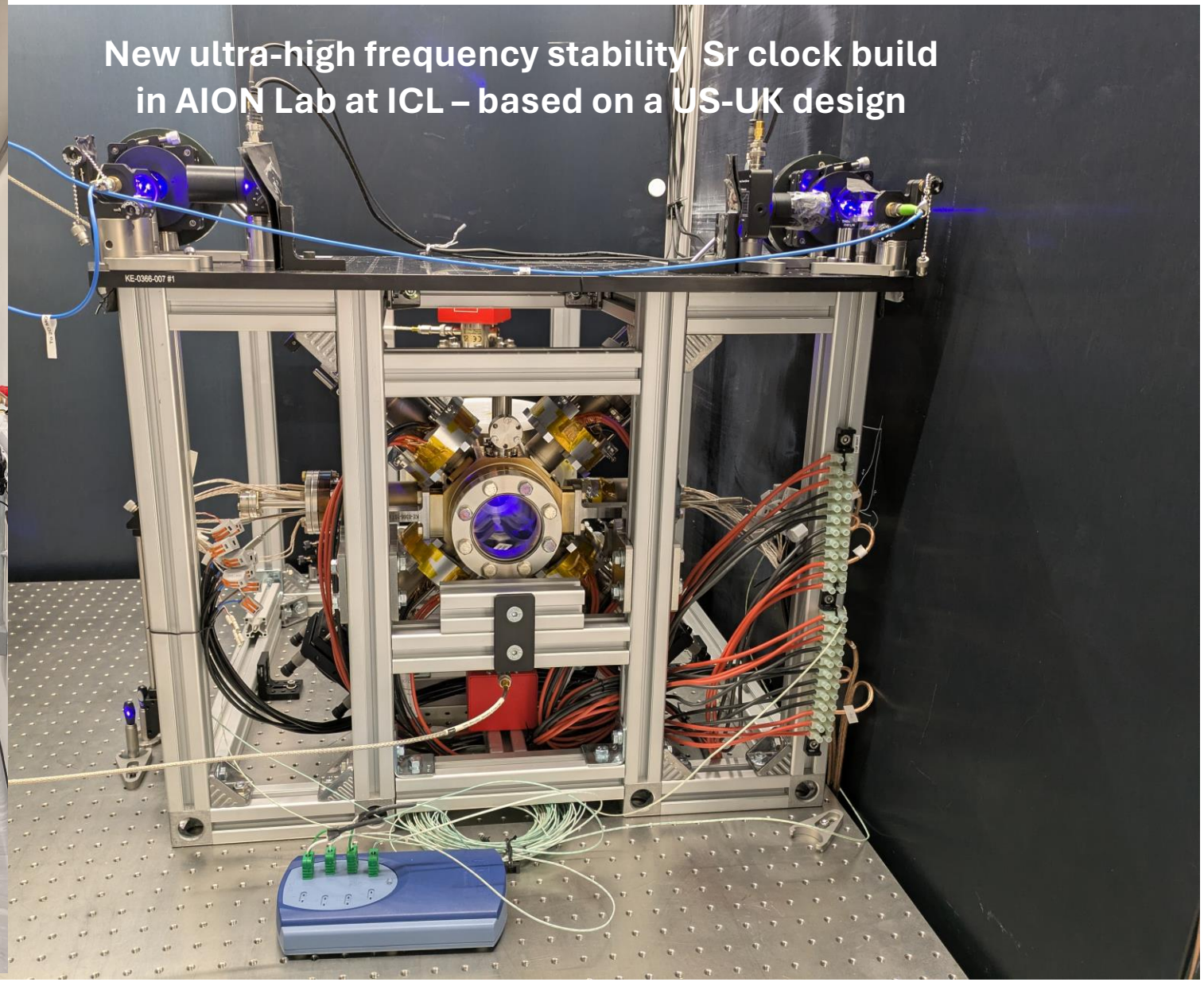
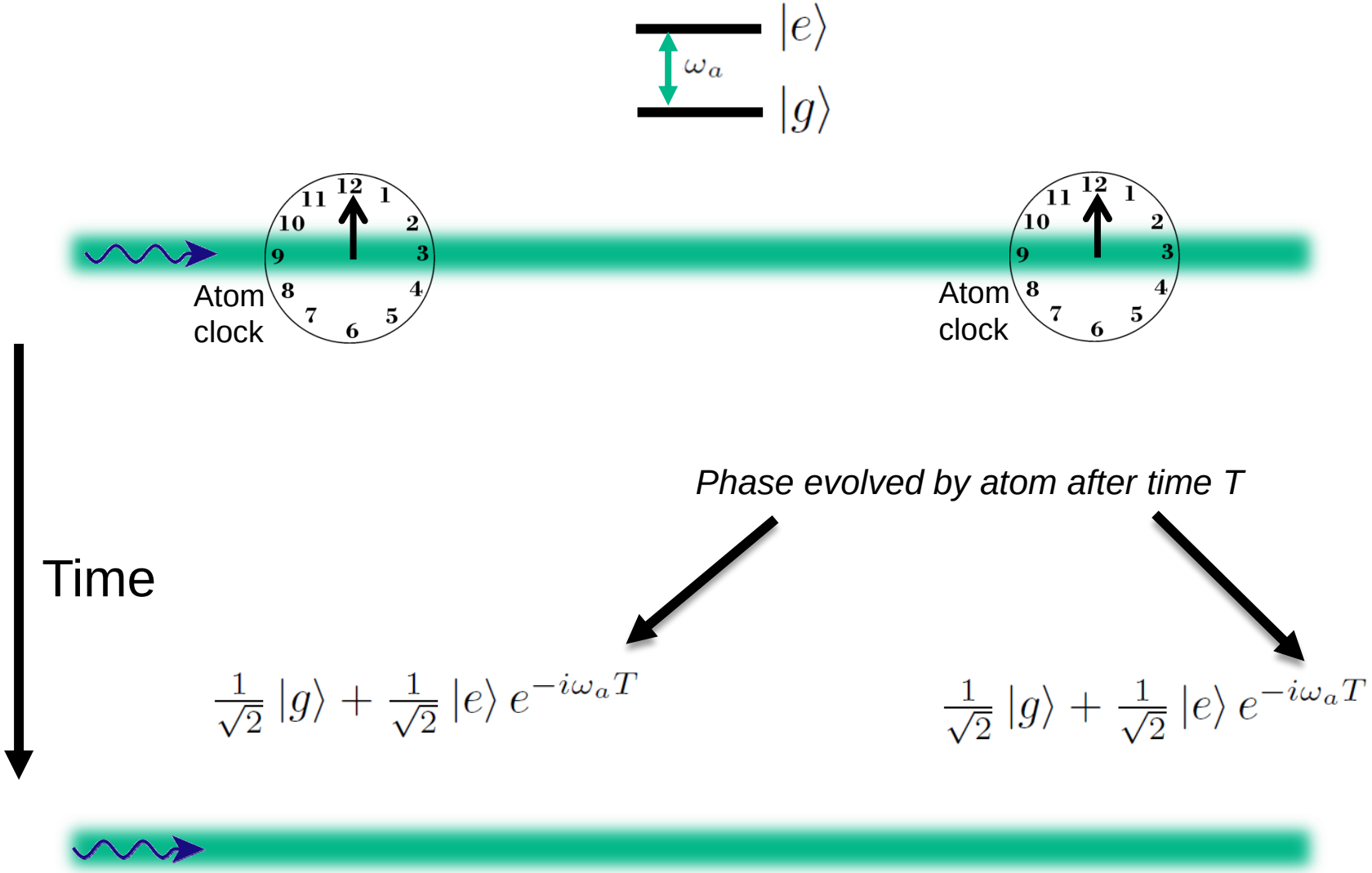


ferometry and Atomic Clocks

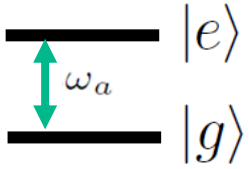




Simple Example: Two Atomic Clocks



Simple Example: Two Atomic Clocks



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

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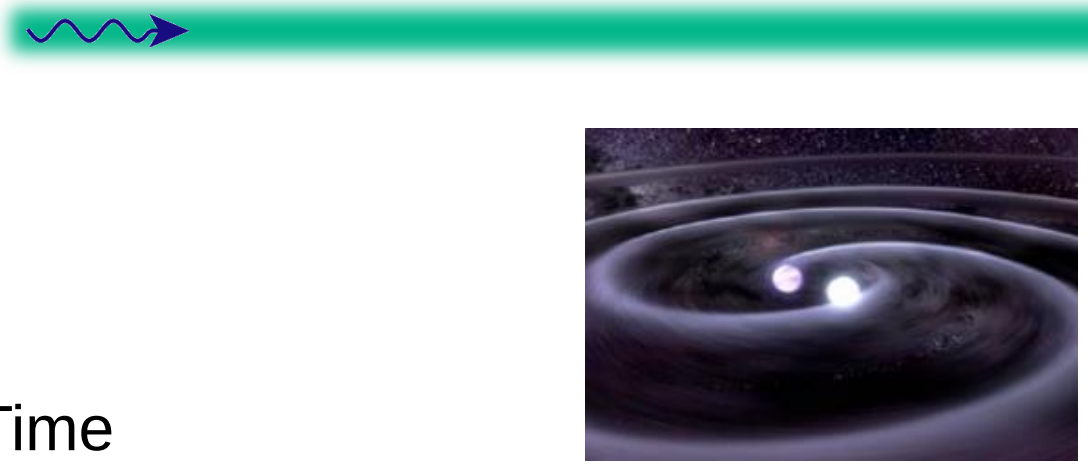


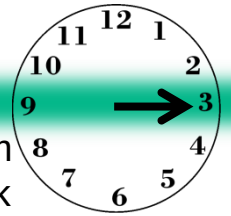
GW changes light travel time

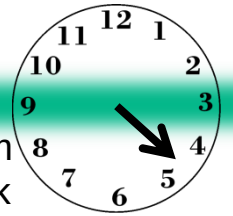
$$\Delta T \sim hL/c$$

Time

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

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





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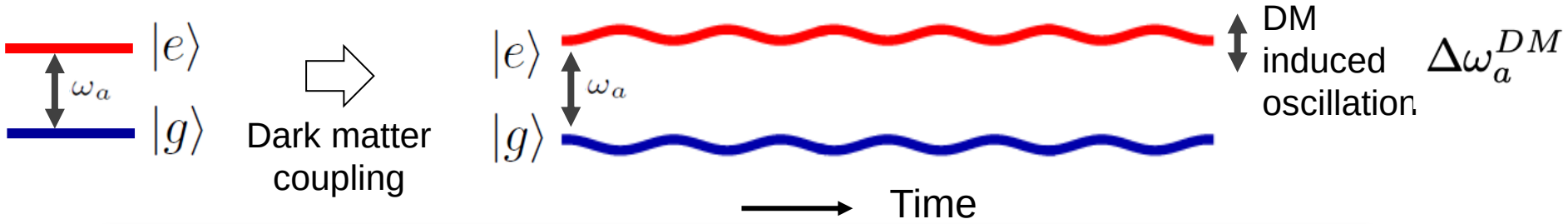
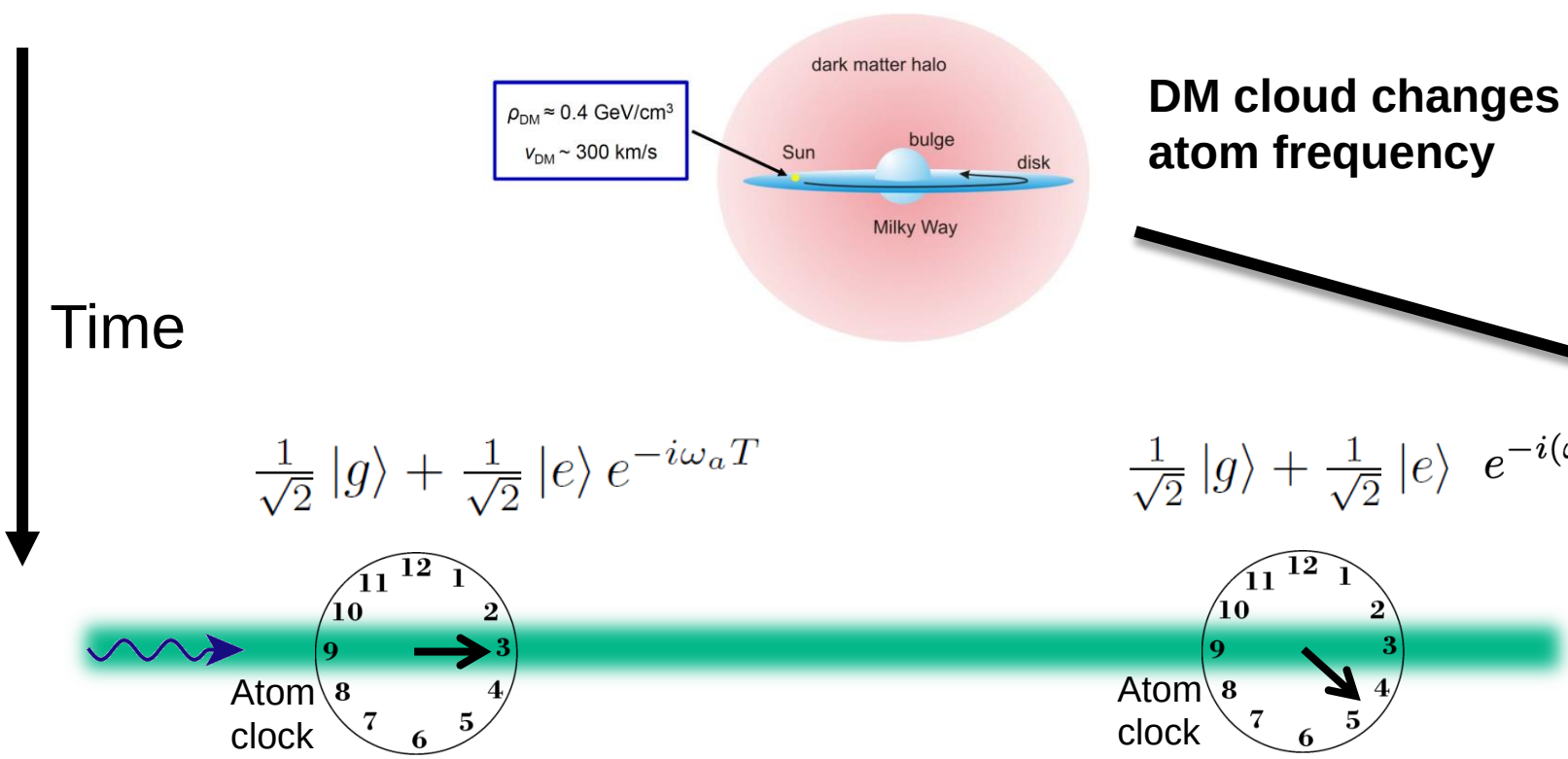
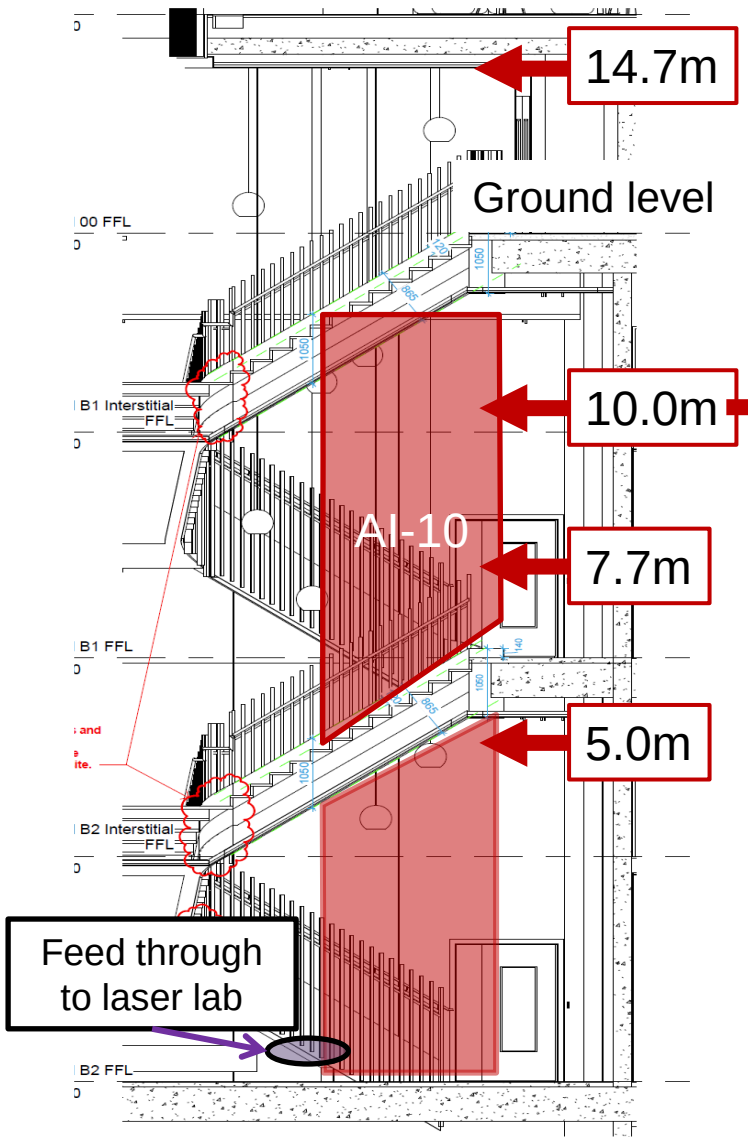


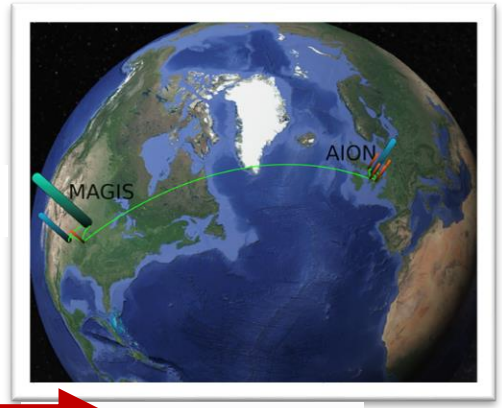


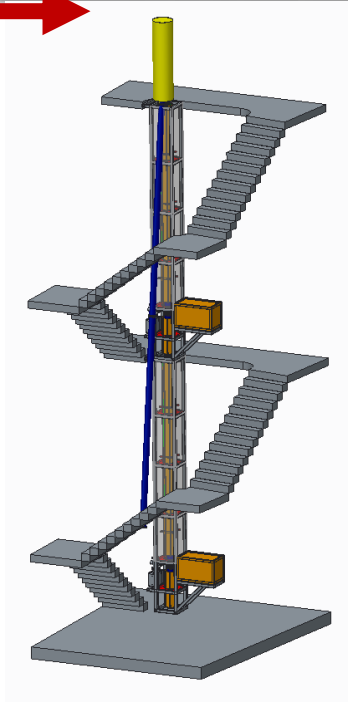
DM cloud changes atom frequency

DM coupling causes time-varying atomic energy levels:

AION Project in the UK







Project executed in national partnership with **UK National Quantum Technology Hub in Sensors and Timing, Birmingham, UK,** and international partnership with **The MAGIS Collaboration and The Fermi National Laboratory, US**

To push the state-of-the-art single photon Sr Atom Interferometry, the AION project builds dedicated Ultra-Cold Strontium Laboratories in: **Birmingham, Cambridge, Imperial College, Oxford, and RAL**
The laboratories are expected to be fully operational in summer 2023.

L. Badurina et al., *AION: An Atom Interferometer Observatory and Network*, *JCAP* **05** (2020) 011, [arXiv:1911.11755]

The AION Programme consists of 4 Stages

- **Stage 1:** to build and commission the 10 m detector, develop existing technology and the infrastructure for the 100 m.

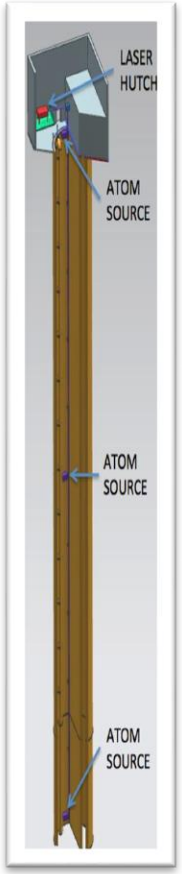
L ~ 10m

- **Stage 2:** to build, commission and exploit the 100 m detector and carry out a design study for the km-scale detector.

L ~ 100m

  - AION was selected in 2018 by STFC as a high-priority medium-scale project.
  - AION will work in equal partnership with MAGIS in the US to form a "LIGO/Virgo-style" network & collaboration, providing a pathway for UK leadership.

Stage 1 is funded with more £15M by the QTFP Programme and other sources and Stage 2 could be placed at national facility in Boulby or Daresbury (UK), possibly also at CERN (France/Switzerland).

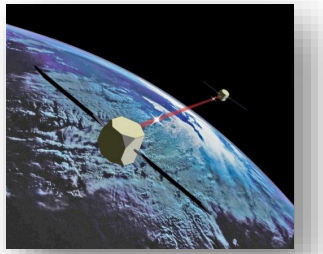


- **Stage 3:** to build a kilometre-scale terrestrial detector.

L ~ 1km

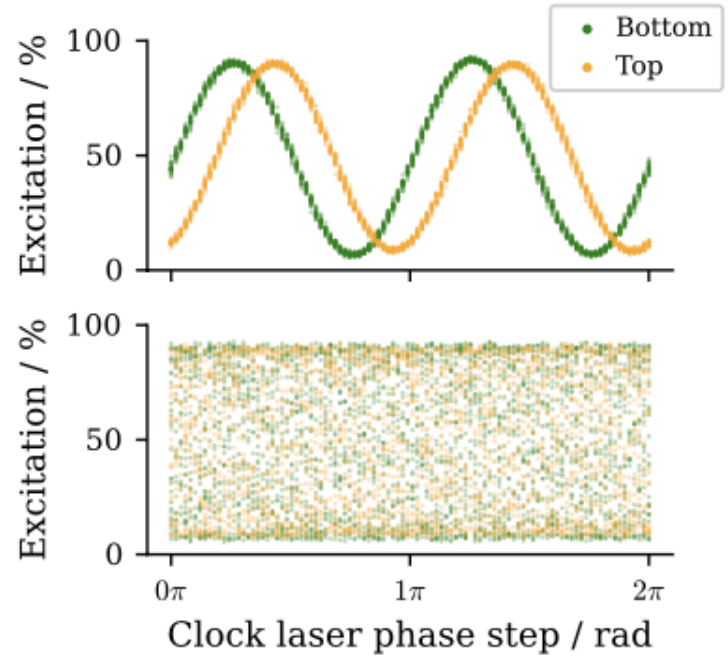
- **Stage 4**: long-term objective a pair of satellite detectors (thousands of kilometres scale) [AEDGE proposal to ESA Voyage2050 call]
  - AION has established science leadership in AEDGE, bringing together collaborators from European and Chinese groups (e.g. MIGA, MAGIA, ELGAR, ZAIGA).

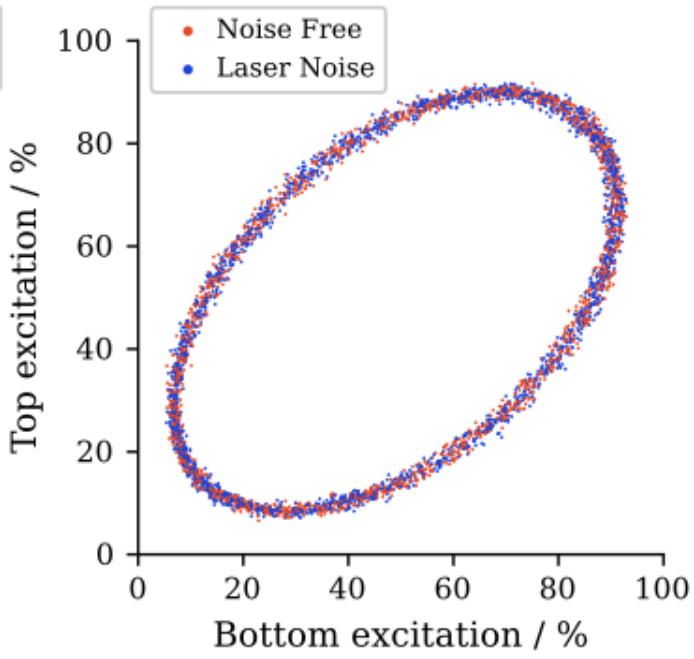
Stage 3 and 4 will likely require funding on international level (ESA, EU, etc) and AION has already started to build the foundation for it.

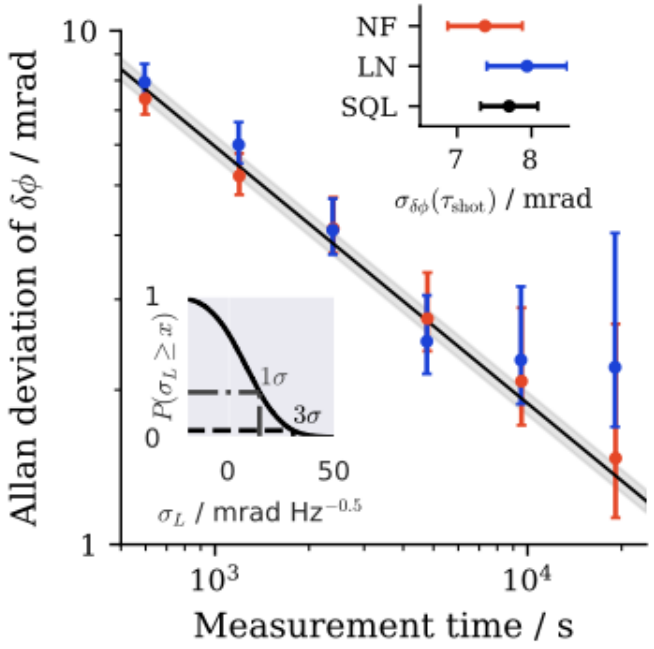


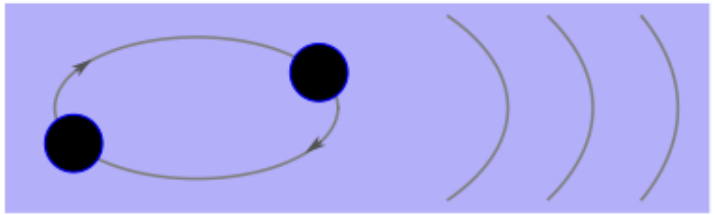
Centralised design and production [AVS Quantum Sci. 6, 014409 (2024)]

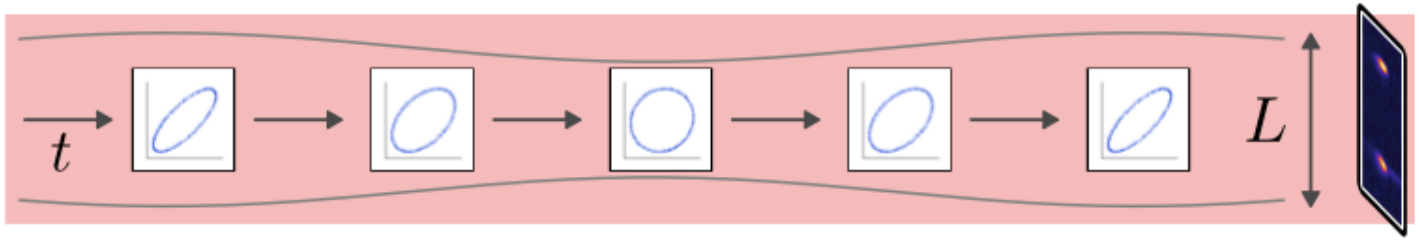
First prototype demonstration of differential measurement technique with free falling Sr87 Atoms - Fall 2024
-- Another World First --









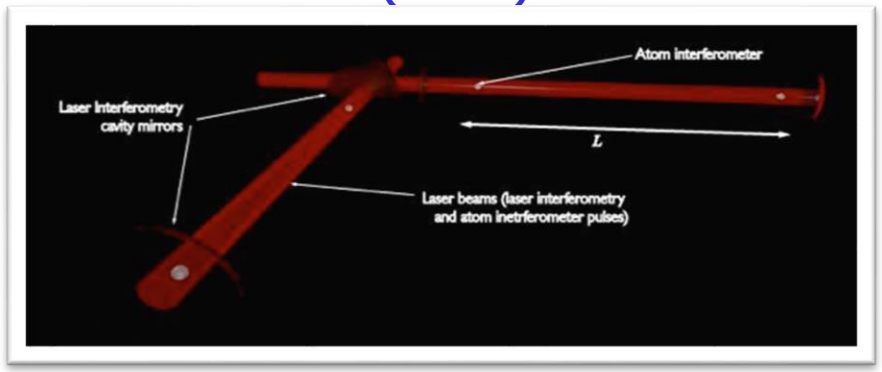


Atomic Clock + Atom Interferometry = Ultimate Precision

Ground Based Large Scale O(100m) Projects

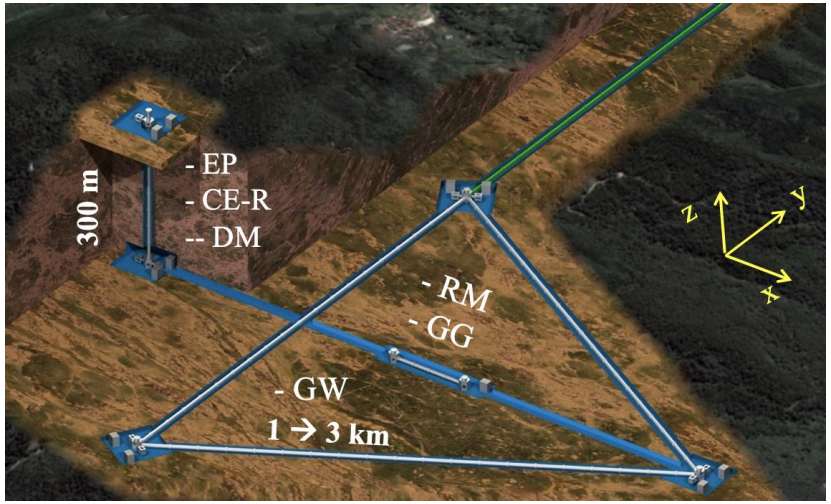
MIGA: Terrestrial detector using atom interferometer at O(100m)

(France)



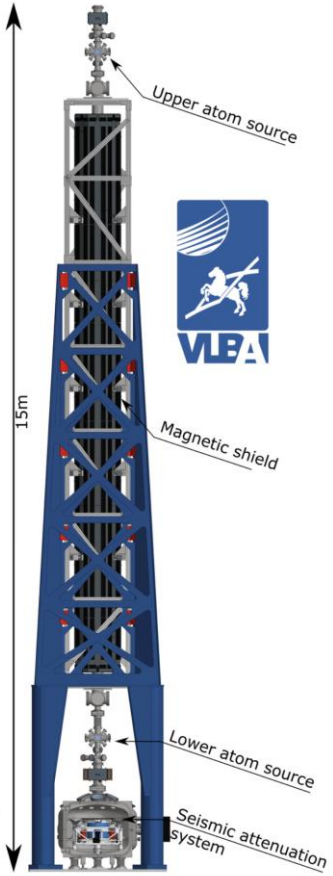
ZAIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)

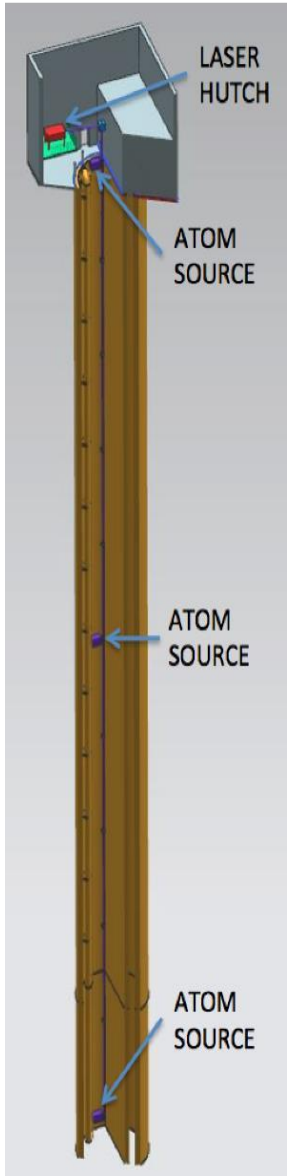
(China)



VLBAI: Terrestrial tower using atom interferometer O(10m)

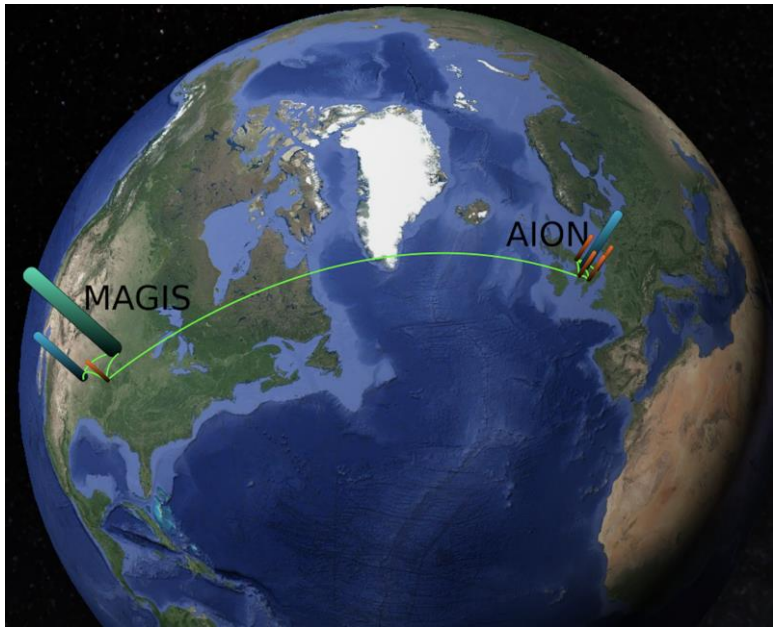
(Germany)





AION: Terrestrial shaft detector using atom interferometer at 10m – O(100m) planned

(UK)



MAGIS: Terrestrial shaft detector using atom interferometer at O(100m)

(US)

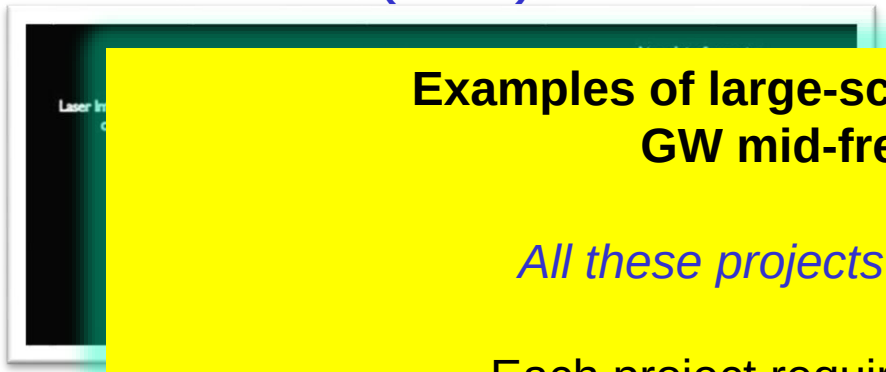
Planned network operation

Ground Based Large Scale O(100m) Projects

MIGA: Terrestrial detector using atom interferometer at O(100m)
(France)

VLBAI: Terrestrial tower using atom interferometer

AION: Terrestrial shaft detector using atom interferometer at 10m – O(100m) planned



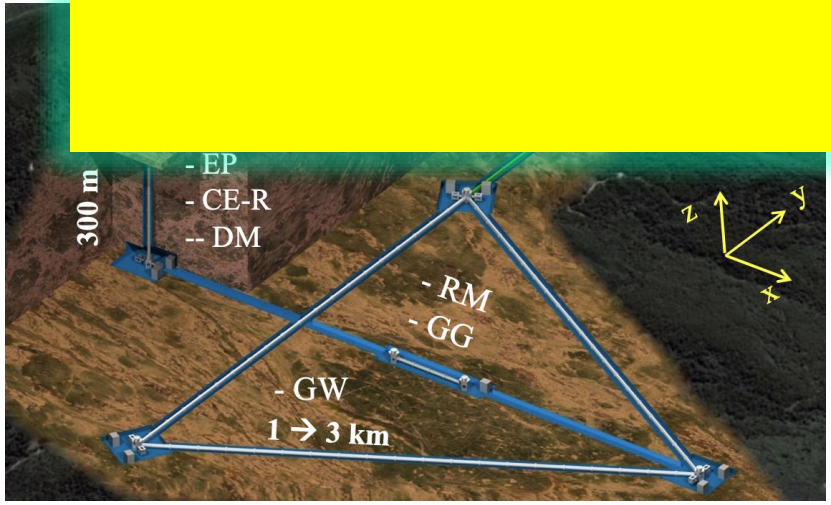
ZAI
in

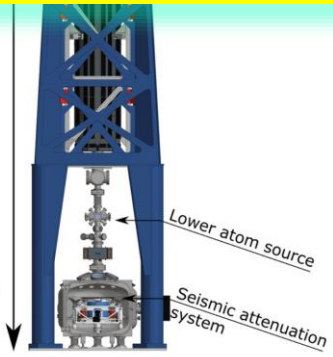
Examples of large-scale CA projects that act as demonstrators for GW mid-frequency band and ULDM detectors.

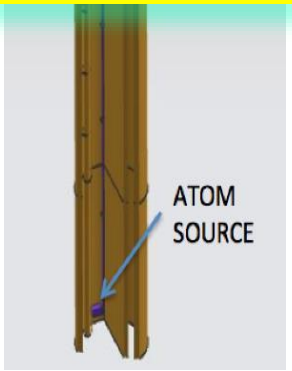
All these projects are represented in the TVLBAI Community.

Each project requires an investment of O(10M+) currency units.
All projects (AION, MAGIS, MIGA, VLBAI, ZAIGA) are funded by national funding agencies and foundations.

Timeline 2020 to 2030ish







MAGIS: Terrestrial shaft detector using atom interferometer at O(100m)
(US)

Planned network operation

Mar 13 – 14, 2023 > CERN

Terrestrial Very-Long-Baseline Atom Interferometry

WORKSHOP

The event will take stock of the developing international landscape of large-scale Atom Interferometer prototypes and discuss their synergies and complementarity. Such devices will be able to detect ultralight dark matter and gravitational waves in the mid-frequency band, complementing the capabilities of optical interferometers on Earth and the future LISA space mission, and offering unique sensitivity to ultralight bosonic dark matter.

Organisers:

International Organisation Committee

Kai Bongs, University of Birmingham, UK
Philippe Bouyer, CNRS, Institut d'Optique, France
Oliver Buchmueller, Imperial College London, UK
Benjamin Canuel, CNRS, Institut d'Optique, France
Marilù Chiofalo, University of Pisa and INFN Pisa, Italy
John Ellis, King's College London, UK
Naceur Gaaloul, Leibniz Universität Hannover, Germany
Jason Hogan, Stanford University, US
Timothy Kovachy, Northwestern University
Ernst Rasel, Leibniz Universität Hannover, Germany
Guglielmo Tino, Università di Firenze and LENS, Italy
Wolf von Klitzing, IESL-FORTH, Greece
Mingsheng Zhan, Wuhan Institute of Physics and Mathematics, China

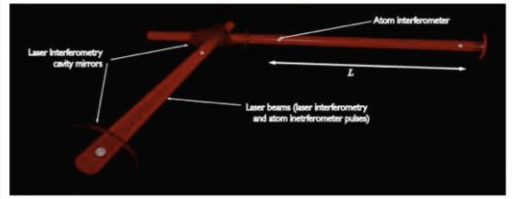
Local Organisation Committee

Gianluigi Arduini, CERN, Geneva, Switzerland
Sergio Calatroni, CERN, Geneva, Switzerland
Albert De Roeck, CERN, Geneva, Switzerland, and University of Antwerp, Belgium
Michael Doser, CERN, Geneva, Switzerland
Elina Fuchs, CERN, Geneva, Switzerland

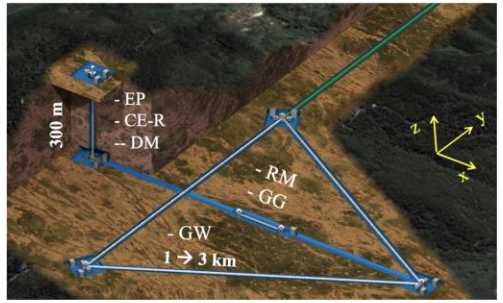
Information

https://indico.cern.ch/event/1208783/

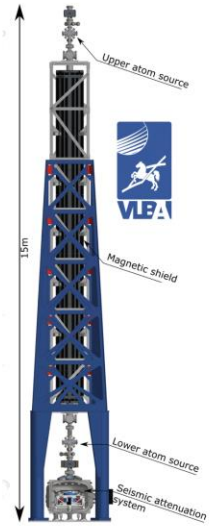
MIGA: Terrestrial detector using atom interferometer at O(100m) (France)

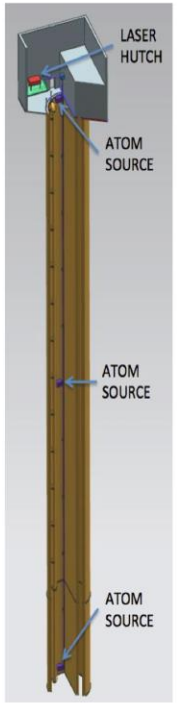


ZIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m) (China)

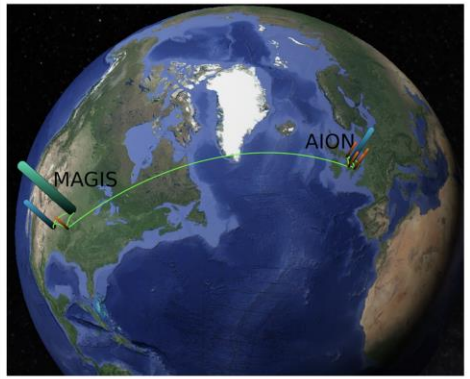


VLBAI: Terrestrial tower using atom interferometer O(10m) (Germany)





AION: Terrestrial shaft detector using atom interferometer at 10m – O(100m) planned (UK)



MAGIS: Terrestrial shaft detector using atom interferometer at O(100m) (US)

Planned network operation

International Organisation Committee

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Michael Doser, CERN, Geneva, Switzerland
Elina Fuchs, CERN, Geneva, Switzerland

Physics Beyond Colliders

AIP Publishing

QUANTUM TECHNOLOGY INITIATIVE

TVLBAI Proto-Collaboration

Austria
•Institute of Science and Technology Austria
Bosnia and Herzegovina
•University of Sarajevo - Faculty of Science
Denmark
•Aarhus University - Department of Physics and Astronomy
Estonia
•National Institute of Chemical Physics and Biophysics (KBFI)

France
•University of Toulouse III – Paul Sabatier
•École Normale Supérieure
Germany
•Technische Universität Darmstadt
•Leibniz University Hannover
•Ulm University

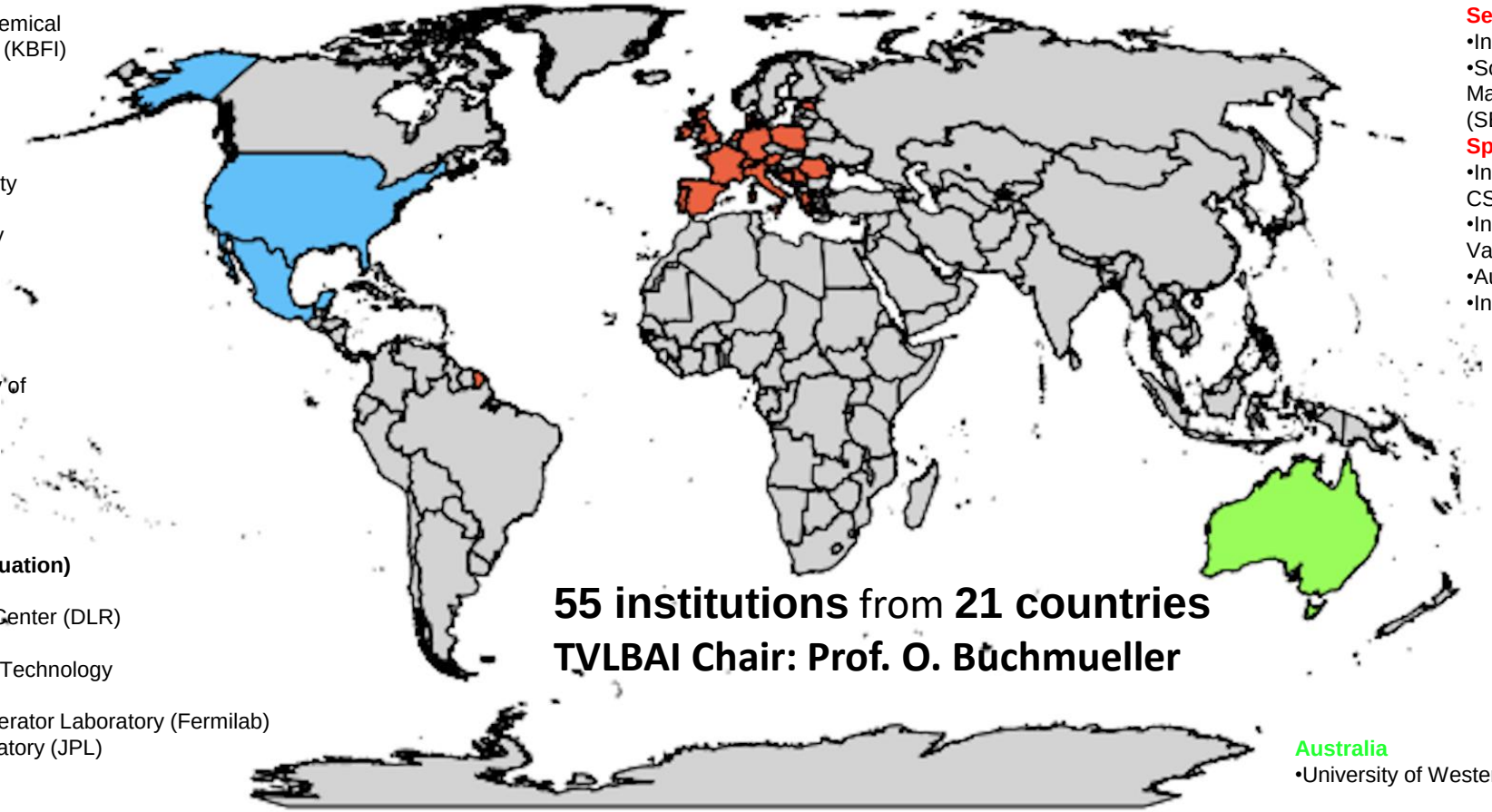
Greece
•Laboratory of Theoretical and Computational Physics, National Technical University of Athens (LThCP)
•Foundation for Research and Technology – Hellas (FORTH)
•Laboratory of Astronomy, Aristotle University of Thessaloniki (AUTH)
Ireland
•Tyndall National Institute

Italy
•University of Florence – DFA
•LENS Laboratory
•University of Pisa
Malta
•University of Malta
Netherlands
•University of Amsterdam

Poland
•Space Technology Centre, AGH University of Science and Technology, Krakow
•Center for Theoretical Physics, Polish Academy of Sciences (CTP PAS)
•University of Warsaw
Portugal
•Instituto de Telecomunicações
Romania
•Institute of Space Science
Serbia
•Institute of Physics Belgrade (IPB)
•South East European Network for Mathematical and Theoretical Physics (SEENET-MTP) Centre
Spain
•Institute of Theoretical Physics (IFT UAM-CSIC)
•Institute of Corpuscular Physics (IFIC), Valencia
•Autonomous University of Madrid (UAM)
•Institut de Fisica d'Altes Energies (IFAE)

United States
•University of Arizona
•Johns Hopkins University
•Stanford University
•Northwestern University
•University of Delaware
•University of Kentucky
•Bates College, Maine

Mexico
•Autonomous University of Aguascalientes (UAA)



55 institutions from **21 countries**
TVLBAI Chair: Prof. O. Buchmueller

Switzerland
•University of Geneva
•CERN
•University of Neuchâtel
•University of Zurich
United Kingdom
•Imperial College London
•King's College London
•University College London (UCL)
•University of Birmingham
•University of Liverpool
•University of Manchester
•University of Oxford
•University of Southampton
•University of Sussex
•University of Warwick
•UKRI-STFC RAL

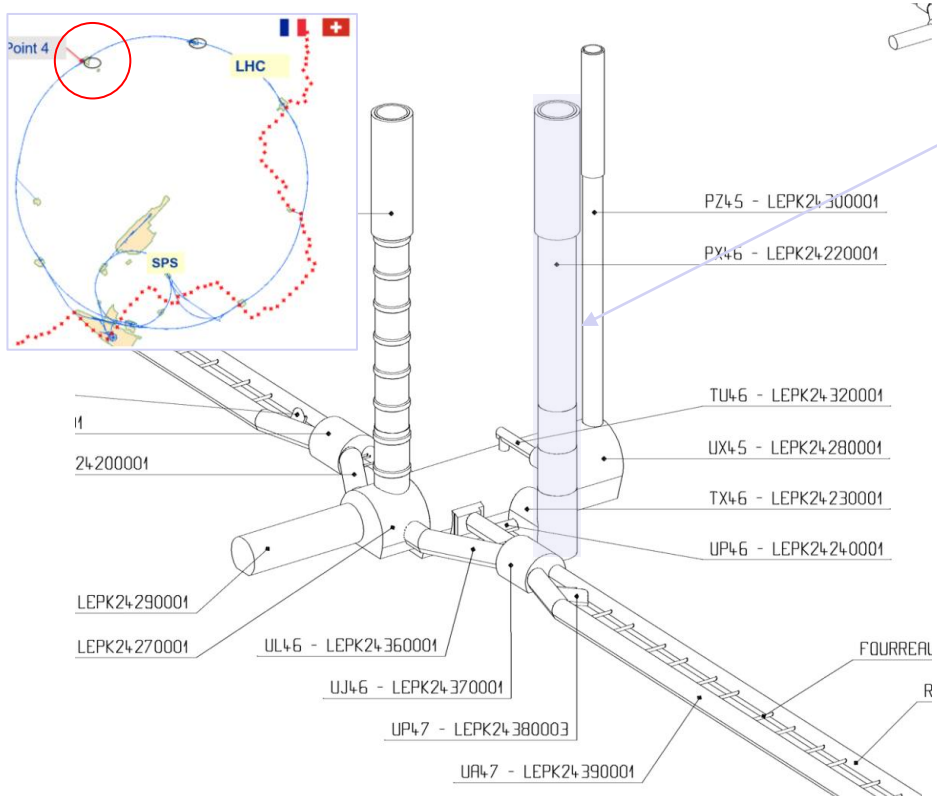
Australia
•University of Western Australia

Observers (Under Evaluation)
Germany
- German Aerospace Center (DLR)

Iran
- Isfahan University of Technology

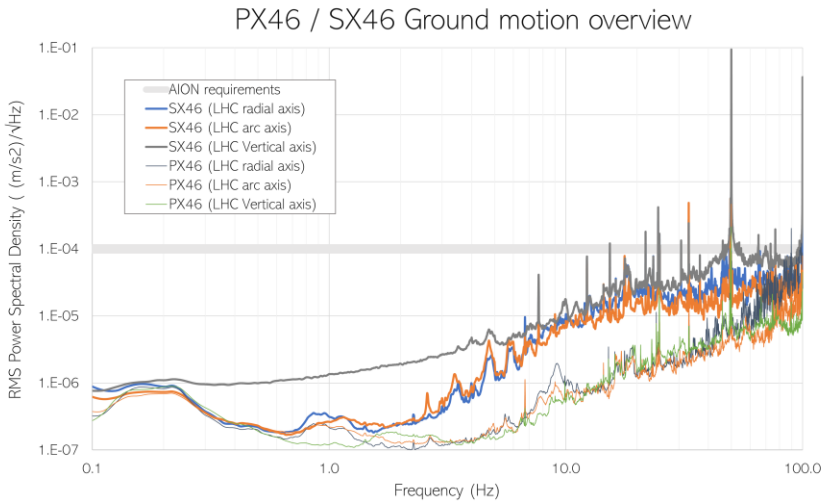
United States
- Fermi National Accelerator Laboratory (Fermilab)
- Jet Propulsion Laboratory (JPL)

Possible site for a vertical VLBAI at CERN: 140 m deep pit at LHC Pt 4

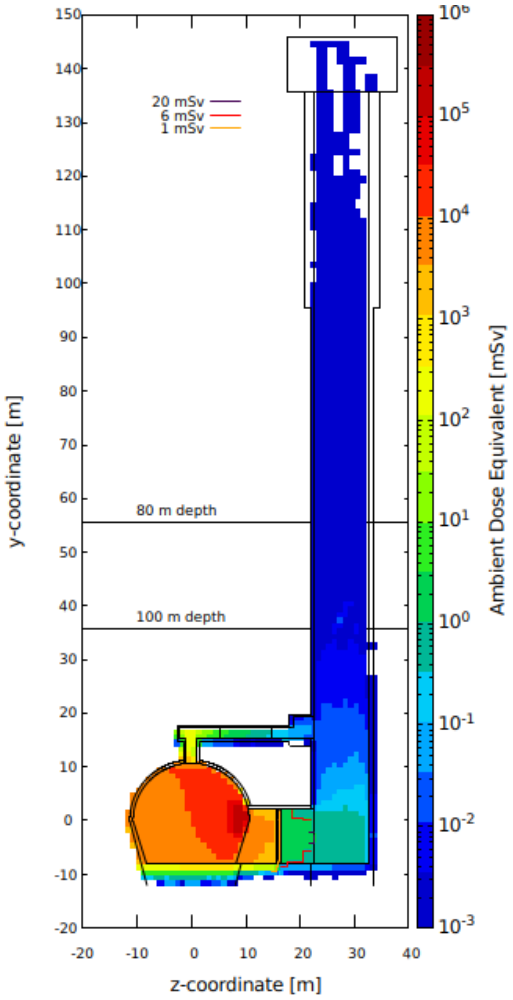


PX46 – P4 Support shaft

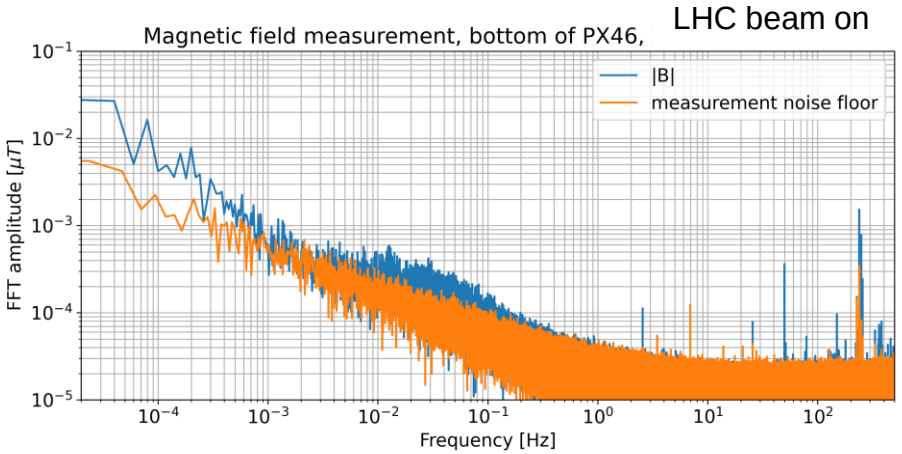
Depth 143m, diameter 10.10m

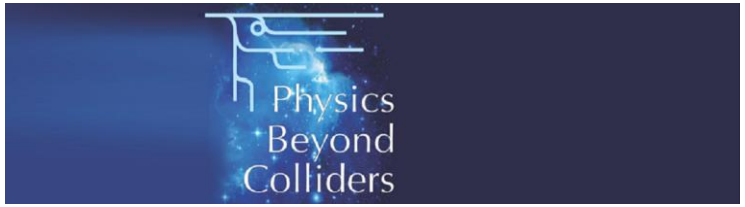


Dose equivalent – case of beam loss
Shielding wall at the bottom of TX46



Safety, access, evacuation, etc.: demonstrated feasibility for 365d/y 24h24 access and AION operation, also when the LHC beam is on





Imperial College London

AION

CERN-PBC Report-2023-002

A Long-Baseline Atom Interferometer at CERN: Conceptual Feasibility Study

G. Arduini[1,], L. Badurina[2], K. Balazs[1], C. Baynham[3], O. Buchmueller[3,4,*], M. Buzio[1], S. Calatroni[1,*], J.-P. Corso[1], J. Ellis[1,2,*], Ch. Gaignant[1], M. Guinchard[1], T. Hakulinen[1], R. Hobson[3], A. Infantino[1], D. Lafarge[1], R. Langlois[1], C. Marcel[1], J. Mitchell[5], M. Parodi[1], M. Pentella[1], D. Valuch[1], H. Vincke[1]*

[1] CERN, [2] King's College London, [3] Imperial College London, [4] University of Oxford, [5] University of Cambridge

[*] Editors

2023: https://arxiv.org/abs/2304.00614

Abstract

We present results from exploratory studies, supported by the Physics Beyond Colliders (PBC) Study Group, of the suitability of a CERN site and its infrastructure for hosting a vertical atom interferometer (AI) with a baseline of about 100 m. We first review the scientific motivations for such an experiment to search for ultralight dark matter and measure gravitational waves, and then outline the general technical requirements for such an atom interferometer, using the AION-100 project as an example. We present a possible CERN site in the PX46 access shaft to the Large Hadron Collider (LHC), including the motivations for this choice and a description of its infrastructure. We then assess its compliance with the technical requirements of such an experiment and what upgrades may be needed. We analyse issues related to the proximity of the LHC machine and its ancillary hardware and present a preliminary safety analysis and the required mitigation measures and infrastructure modifications. In conclusion, we identify primary cost drivers and describe constraints on the experimental installation and operation schedules arising from LHC operation. We find no technical obstacles: the CERN site is a very promising location for an AI experiment with a vertical baseline of about 100 m.

Geneva, Switzerland

August 7, 2023

CERN-PBC Report-2025-004

A Long-Baseline Atom Interferometer at CERN LHC Point 4: Implementation Study

G. Arduini[1], O. Buchmueller[2,3], T.A. Bud[1], S. Calatroni[1,], O. Crespo-Lopez[1], A. Devienne[1], J. Ellis[1,4], T. Hakulinen[1], A. Infantino[1], D. Lafarge[1], A.P. Marion[1]*

[1] CERN, [2] Imperial College London, [3] University of Oxford, [4] King's College London

[*] Editor

2025: https://www.arxiv.org/abs/2508.09694

Abstract

Building on the feasibility study in [1], this report supported by the Physics Beyond Colliders (PBC) Study Group describes the technical implementation of modifications to the PX46 shaft at LHC Point 4 during LS3 (June 2026 – June 2030) that would enable it to accommodate the installation and operation of a vertical long-baseline Atom Interferometer during Run 4 without affecting LHC operations. We specify in detail the necessary civil-engineering work, installation of bespoke radiation shielding, deployment of access-control systems and safety alarms, and design of a mobile elevator platform. Our comprehensive technical assessment identifies no fundamental obstacles or showstoppers to implementation. Refined cost estimates and a critical-path schedule confirm that, from formal approval, all interventions can be completed within a 1.5-year window. These preparations would ensure seamless, concurrent operation of the Atom Interferometer experiment and the HL-LHC, with all technical challenges successfully addressed through established engineering solutions.

Geneva, Switzerland

August 16, 2025

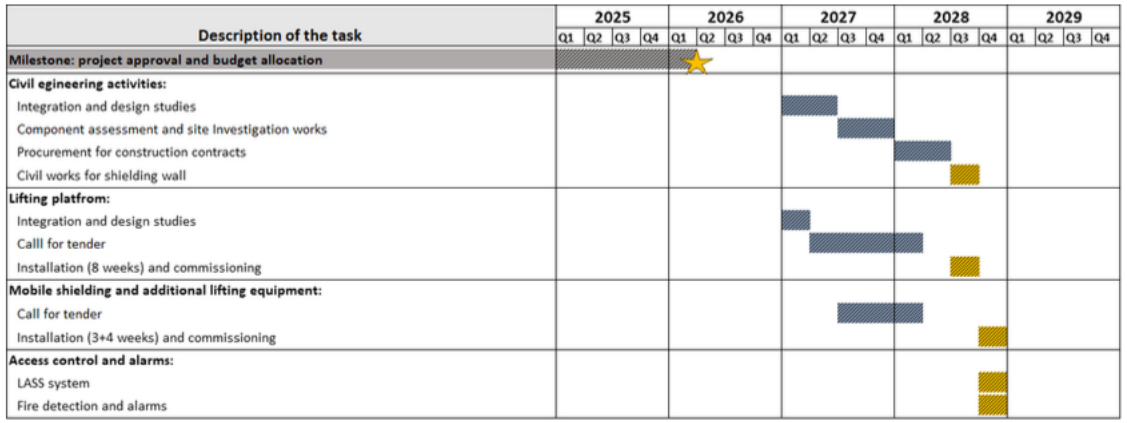
Safety
feasibi
operat

beam loss
n of TX46

Ambient Dose Equivalent [mSv]

Possible site for a vertical VLBAI at C

Description	Cost (CHF)
Civil engineering design services	130’000
Civil engineering works (including concrete blocks and door rails)	260’000
LHC Access Safety System (LASS)	65’000
Fire detection, alarms, emergency communications	30’000
RP monitor	20’000
Lifting platform	400’000
Movable shielding door (structure)	100’000
Modifications of shaft top plug (including ventilation room)	75’000
Additional hoist in SX4	130’000
Grand total	**1’210’000**



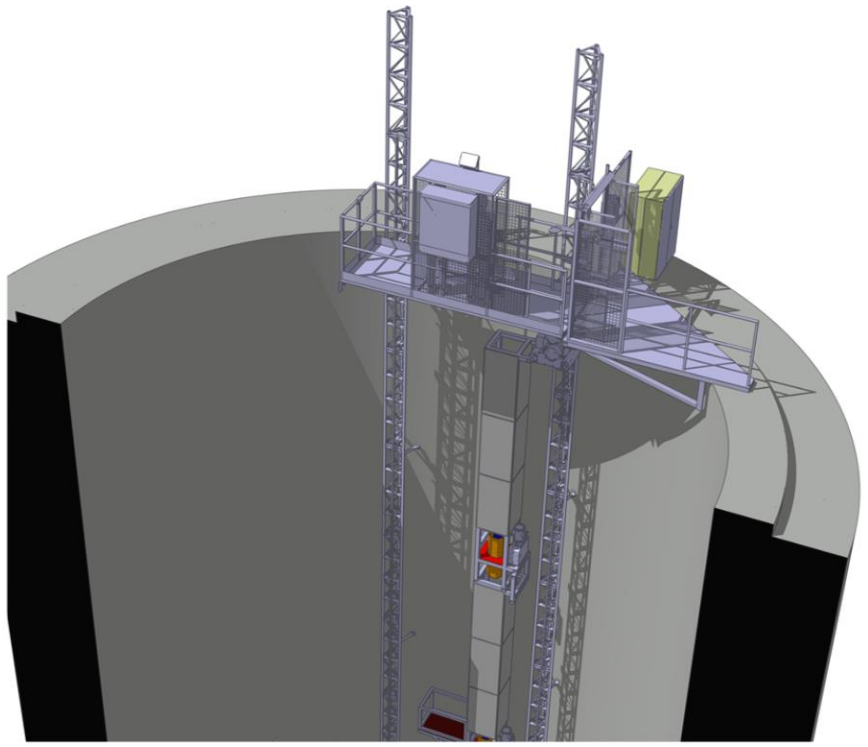
We have defined a reliable budget and timeline to make the shaft ready for a vertical 100 m atom interferometer project

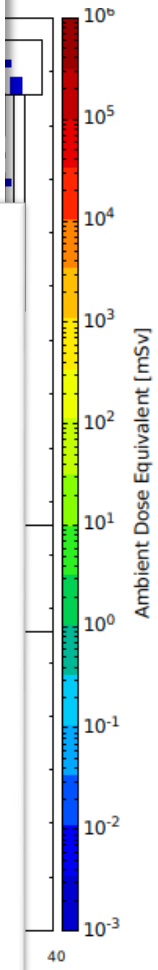
Physics Beyond Colliders

CERN-PBC Report-2025-004

A Long-Baseline Atom Interferometer at CERN LHC Point 4: Implementation Study

G. Arduini[1], O. Buchmueller[2,3], T.A. Bud[1], S. Calatroni[1,], O. Crespo-Lopez[1], A. Devienne[1], J. Ellis[1,4], T. Hakulinen[1], A. Infantino[1], D. Lafarge[1], A.P. Marion[1]*





AICE: 100m Atom Interferometer Experiment at CERN

Letter of Intent:
AICE - Atom Interferometer CERN Experiment

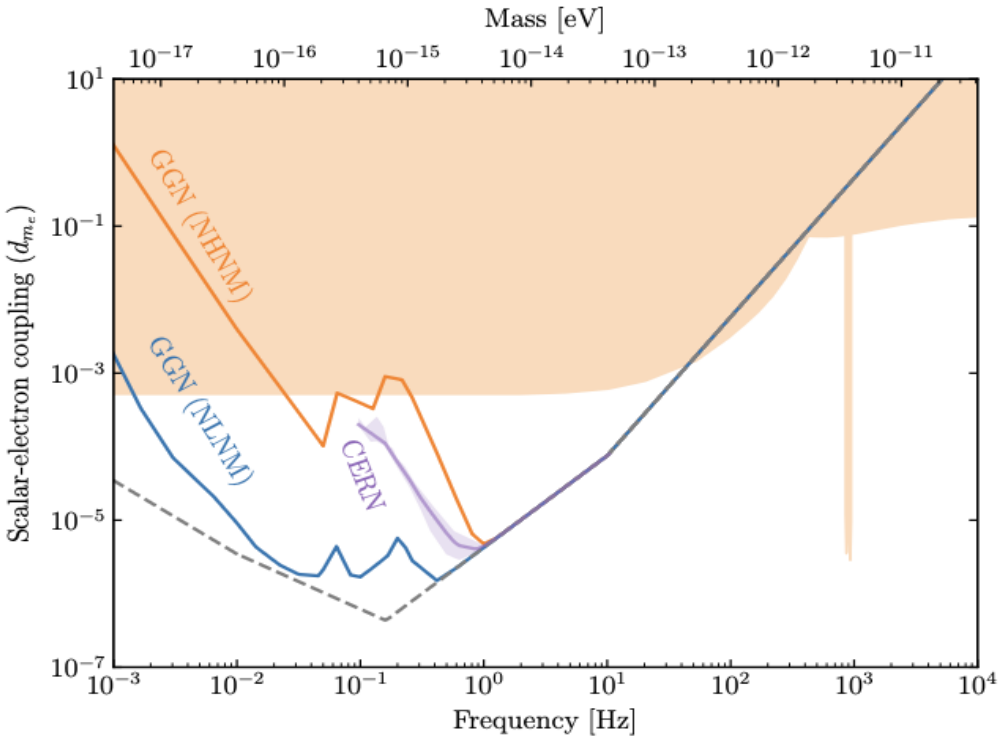
Charles Baynham,[1] Andrea Bertoldi,[2] Diego Blas,[3] Oliver Buchmueller*,[1,4] Sergio Calatroni,[5] Vassilis Charmandaris,[6] Maria Luisa (Marilù) Chiofalo,[7] Pierre Cladé,[8] Jonathon Coleman,[9] Fabio Di Pumpo,[10] John Ellis*,[11] Naceur Gaaloul,[12] Saïda Guellati-Khelifa,[8] Tiffany Harte,[13] Richard Hobson,[1] Michael Holynski,[14] Samuel Lellouch,[14,15] Lucas Lombriser,[16,17] Elias Lopez Asamar,[18] Michele Maggiore,[17,19] Christopher McCabe,[11] Jeremiah Mitchell,[13] Ernst M. Rasel,[12] Federico Sanchez Nieto,[17,19] Wolfgang Schleich,[20] Dennis Schlippert,[12] Ulrich Schneider,[13] Steven Schramm,[17,19] Marcelle Soares-Santos,[21] Guglielmo M. Tino,[22] Jonathan N. Tinsley,[9] Tristan Valenzuela,[23] Maurits van der Grinten,[24] Wolf von Klitzing,[25]

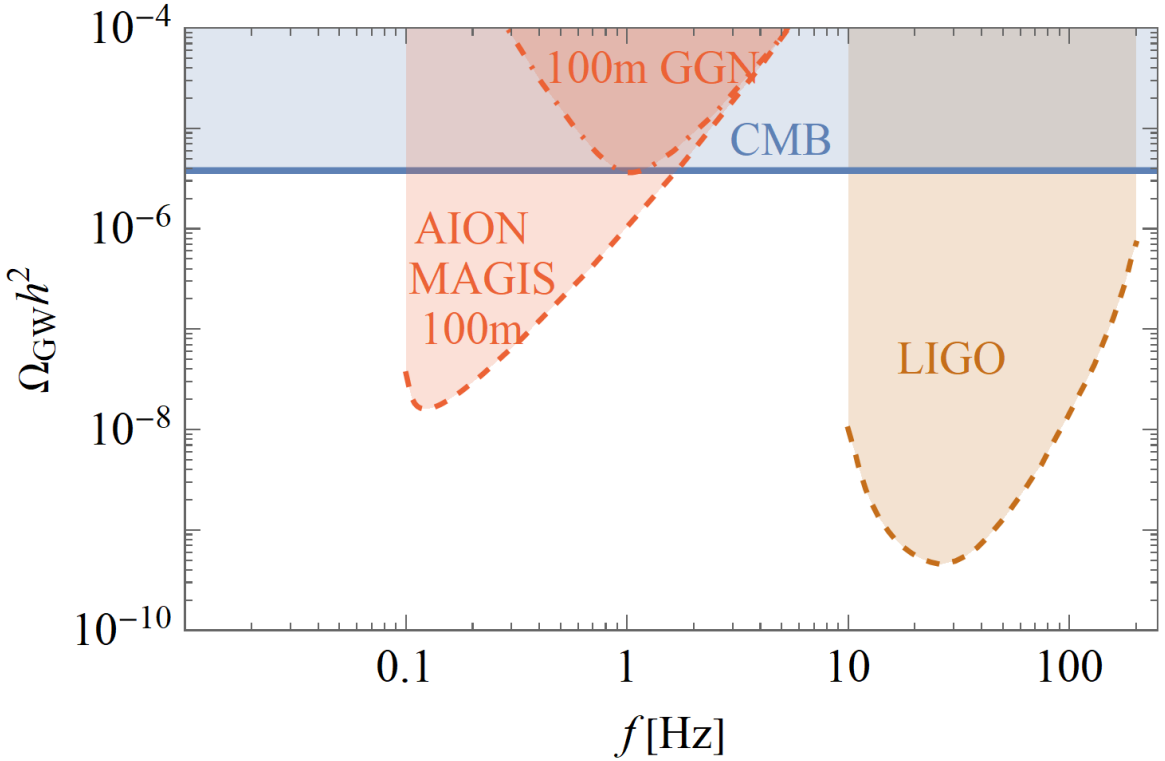
[1] *High Energy Physics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London, SW7 2AZ, UK*
[2] *IOGS, LP2N, Université Bordeaux, CNRS, UMR 5298, F-33400 Talence, France*
[3] *Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain; Institució Catalana de Recerca i Estudis Avançats (ICREA), Passeig Lluís Companys 23, 08010 Barcelona, Spain*
[4] *University of Oxford, South Parks Road, Oxford OX1 3PU, UK*
[5] *CERN, 1211 Geneva 23, Switzerland*
[6] *Chairman, Board of Directors, Foundation for Research and Technology – Hellas (FORTH), Vassilika Vouton, 70013 Heraklion, Creta, Greece*
[7] *Department of Physics, University of Pisa, Largo Bruno Pontecorvo 3 56126 Pisa, Italy; INFN-Pisa, Largo Bruno Pontecorvo 3 56126 Pisa, Italy*
[8] *Laboratoire Kastler Brossel, Sorbonne Université PSL, Collège de France, 75005 Paris, France*
[9] *Department of Physics, University of Liverpool, Merseyside, L69 7ZE, UK*
[10] *Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, Albert-Einstein-Allee 11, 89081 Ulm, Germany*
[11] *Physics Department, King's College London, Strand, London, WC2R 2LS, UK*
[12] *Leibniz Universität Hannover, Institut für Quantenoptik, Welfengarten 1, 30167 Hannover, Germany*
[13] *Cavendish Laboratory, University of Cambridge, J J Thomson Avenue, Cambridge, CB3 0US, UK*
[14] *School of Physics and Astronomy, University of Birmingham, B152TT Edgbaston, UK*
[14] *School of Engineering, University of Birmingham, B152TT Edgbaston, UK*
[16] *Department of Applied Future Technologies, University of Applied Sciences of the Grisons, Pulvermühlestrasse 57, 7000 Chur, Switzerland*
[17] *Département de Physique Théorique, Université de Genève, 24 quai Ernest Ansermet, 1211 Genève 4, Switzerland*
[18] *Departamento de Física Teórica, Universidad Autonoma de Madrid, 28049 Madrid, Spain; Instituto de Física Teórica UAM-CSIC, 28049 Madrid, Spain*
[19] *Gravitational Wave Science Centre, Université de Genève, Genève, Switzerland*

arXiv:2509.11867v2 [hep-ex] 16 Sep 2025

- **Physics goal:** 100 m single-photon atom interferometer to probe **ultralight dark matter** and open the **0.1–10 Hz mid-band** for gravitational waves.
- **Concept:** Vertical UHV tube in PX46; laser lab in SX4; 2→10 atom sources enabling multigradiometer readout and strong noise suppression.
- **Feasibility & cost:** Engineering and safety studies confirm **PX46 is fully viable**. Required CERN-side works (civil, shielding wall, access/ODH/fire systems, shaft-top upgrades) estimated at **≈1.2 M CHF**, well within CERN's infrastructure mandate.
- **Community strength:** LoI backed by the **TVLBAI proto-collaboration** (55 institutes / 20 countries). AICE positioned as the **European 100 m node** toward a global long-baseline network.
- **CERN alignment:** Fits the **Physics Beyond Colliders** roadmap and the **CERN Quantum Technology Initiative**; no interference with HL-LHC operations.
- **Urgency:** All PX46 civil-engineering must be scheduled in **LS3 (2026–2028)**.
- **Decision needed in 2025** to secure inclusion in LS3 planning.
- **Status:** LoI submitted to LHCC; waiting for feedback — **informal signals are positive so far**.

Physics Potential in a Nutshell





Besides probing a large range of new Ultra-Light DM parameter space, a ~100m experiment could also explore new territory for gravitational waves in a yet unexplored frequency range.

Terrestrial Very-Long-Baseline Atom Interferometry

4th WORKSHOP

February 2-4, 2026 > Canfranc

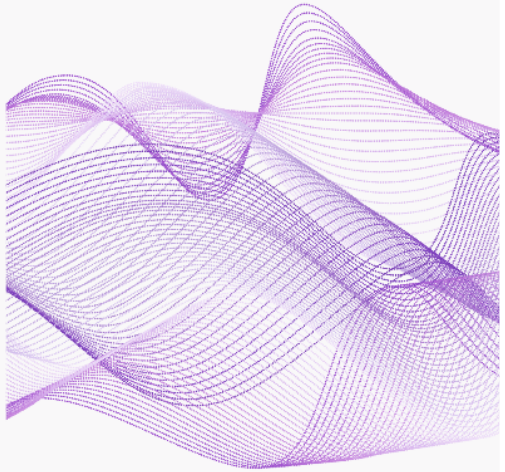
The 4th Terrestrial Very-Large-Baseline Atom Interferometry (TVLBAI) Workshop in Canfranc (Spain) follows the three successful editions held previously in Geneva (March 2023), London (April 2024) and Hannover (August 2025).

This workshop will gather international experts from several scientific and technological areas of relevance to TVLBAI, with the primary objective of progressing towards the realisation of kilometre-scale experiments planned to become operational in the mid-2030s.

Besides reviewing the scientific and technological advancements in the field since the previous meetings, this workshop will also dedicate time to discuss the activities of the various Work Packages of the TVLBAI Proto-Collaboration.

The workshop will be hosted at Canfranc underground laboratory (Laboratorio Subterráneo de Canfranc, LSC), that offers exceptional low-noise conditions for fundamental physics experiments. Participants will have the opportunity to visit this facility and its experiments.

In the same spirit as in the previous editions, this workshop intends to strengthen the sense of community among participants and will help to consolidate the international network of experts and enthusiasts in atom interferometry for fundamental physics.



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Kai Bongs, DLR Institute for Quantum Technologies, Germany
Philippe Bouyer, University of Amsterdam, Netherlands
Diego Blas, Institut de Física d'Altes Energies, Spain
Oliver Buchmueller, Imperial College London, UK
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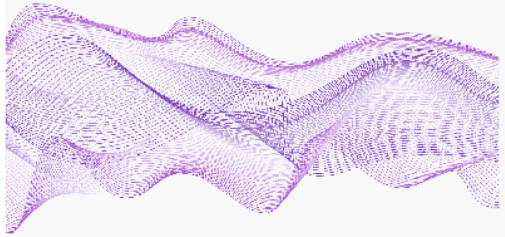
Local Organisation Committee

Diego Blas, Institut de Física de Altes Energies (IFAE), Spain
David Cerdeño, Instituto de Física Teórica (IFT), Spain
David Keitel, Universitat de les Illes Balears (UIB), Spain
Yolanda Labarta, Laboratorio Subterráneo de Canfranc (LSC), Spain
Elias Lopez Asamar, Universidad Autonoma de Madrid, Spain
María Moreno Llacer, Instituto de Física Corpuscular (IFIC), Spain



LSC
Laboratorio Subterráneo Canfranc

Information
https://indico.cern.ch/event/1599454/

4th TVLBAI Workshop February 2-4, 2026

The workshop will take place from **2–4 February 2026** at the Laboratorio Subterraneo de Canfranc (LSC) in Canfranc, Spain:
https://indico.cern.ch/event/1599454/

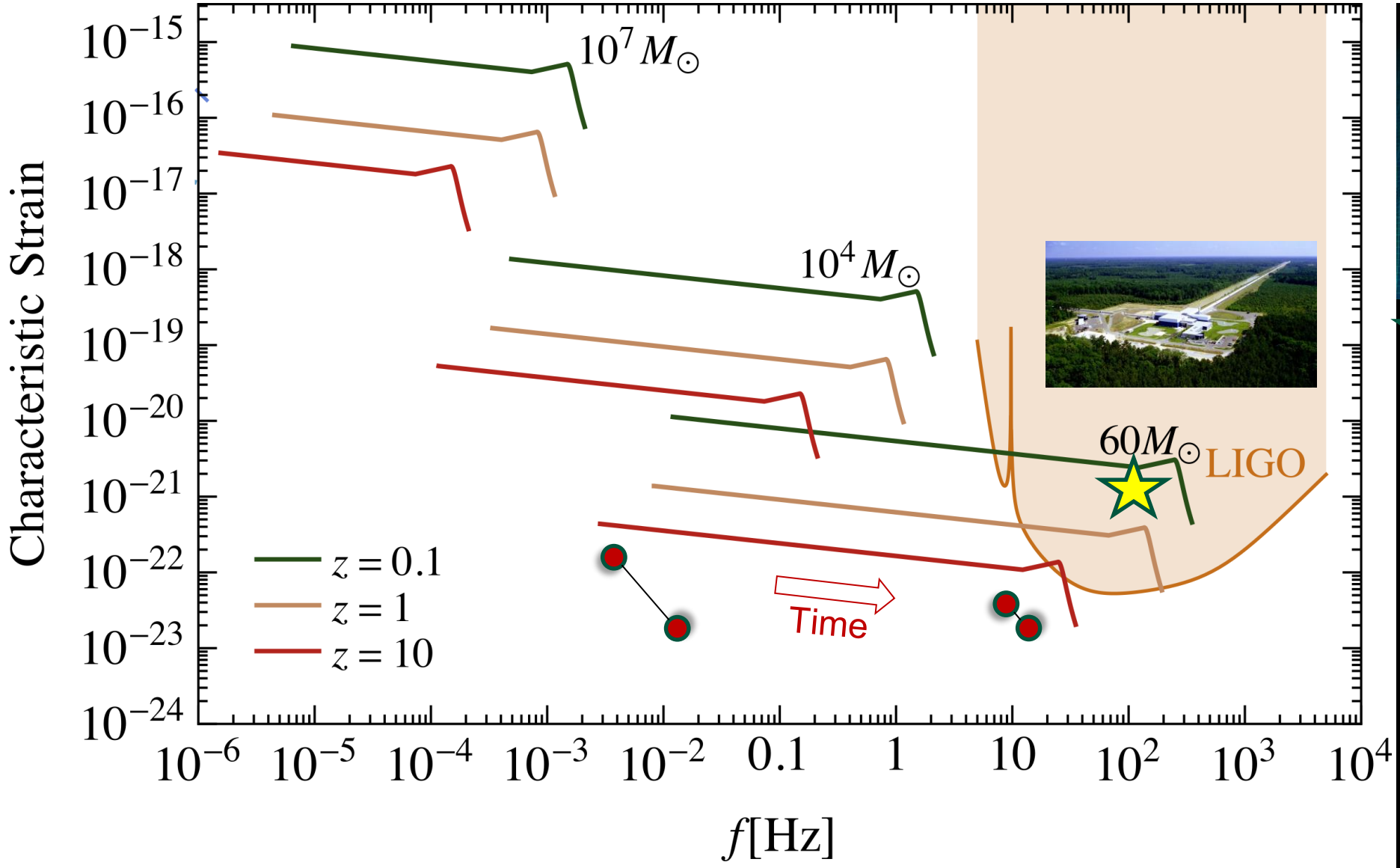
If you are interested in attending this event in person, please register before January 19th, 2026 at:
https://indico.cern.ch/event/1599454/registrations/

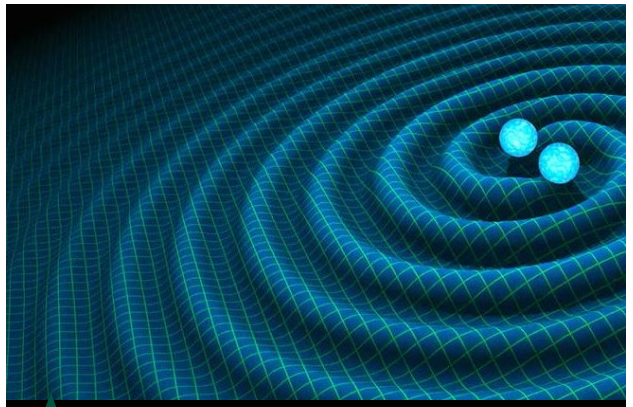
The event will be in a hybrid format, allowing for both in-person and remote participation via Zoom.

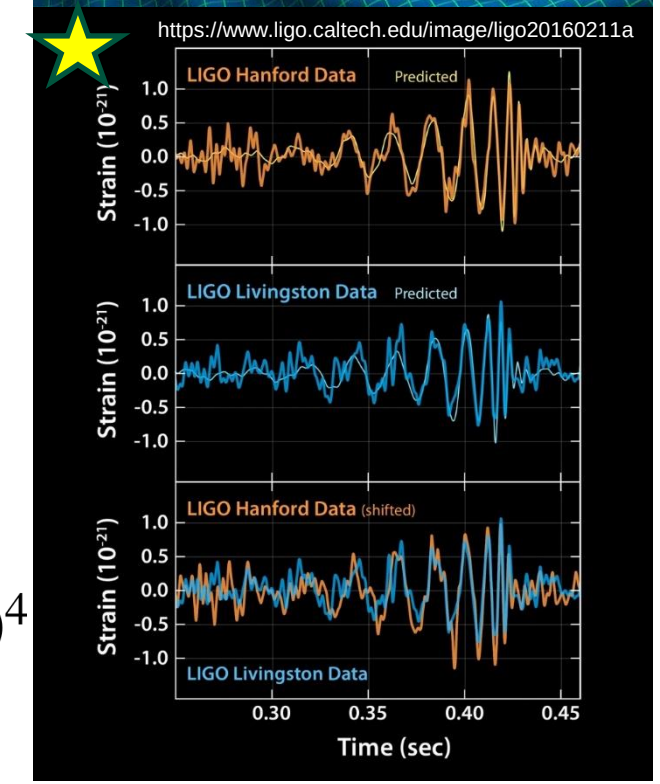
THE SCIENCE CASE

UNEXPLORED MID-FREQUENCY GRAVITATIONAL WAVES

Gravitational wave detectors



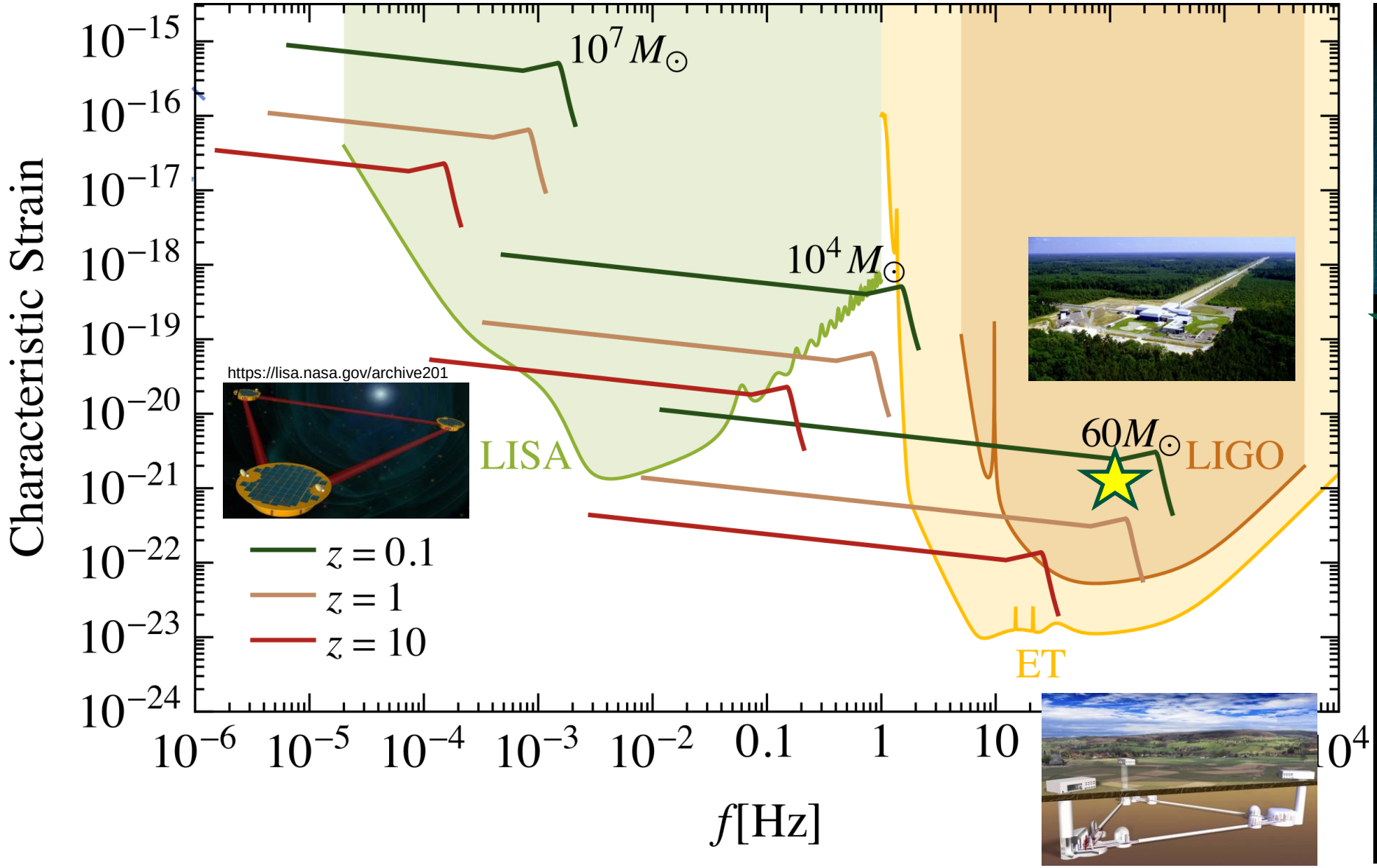




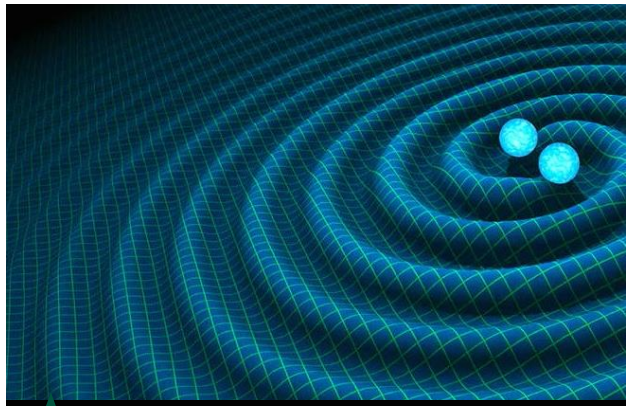
Imperial College London

Gravitational wave detectors

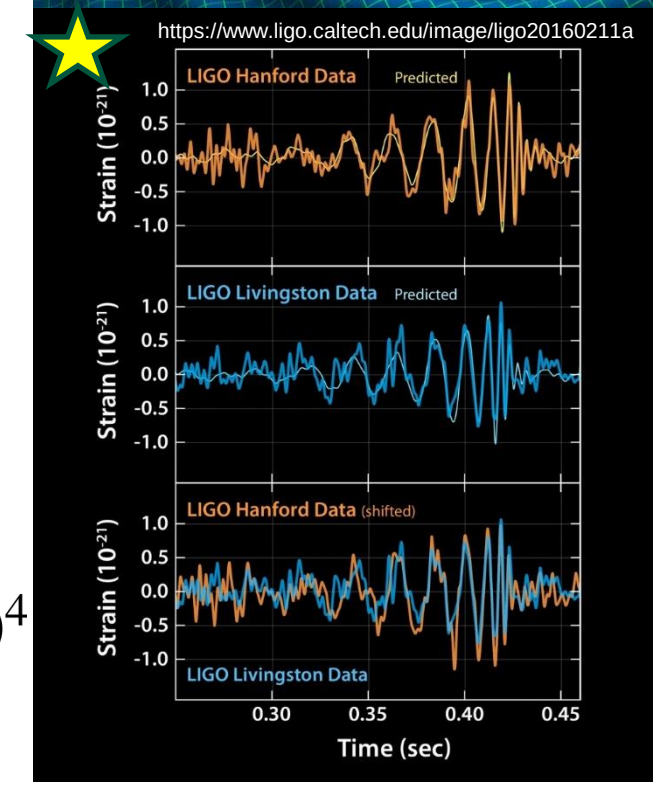
AION



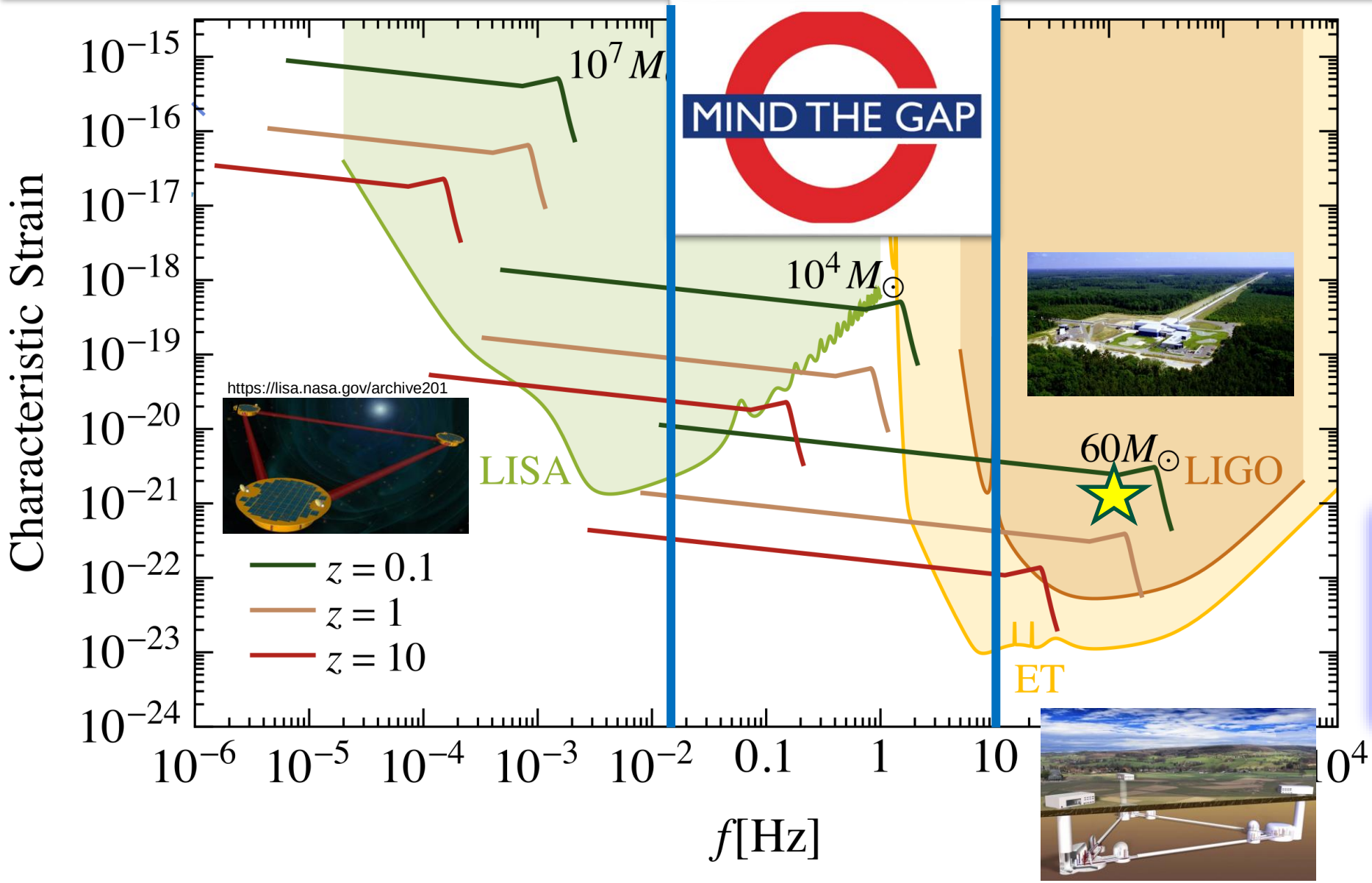
https://lisa.nasa.gov/archive201



https://www.ligo.caltech.edu/image/ligo20160211a



Gravitational wave detectors

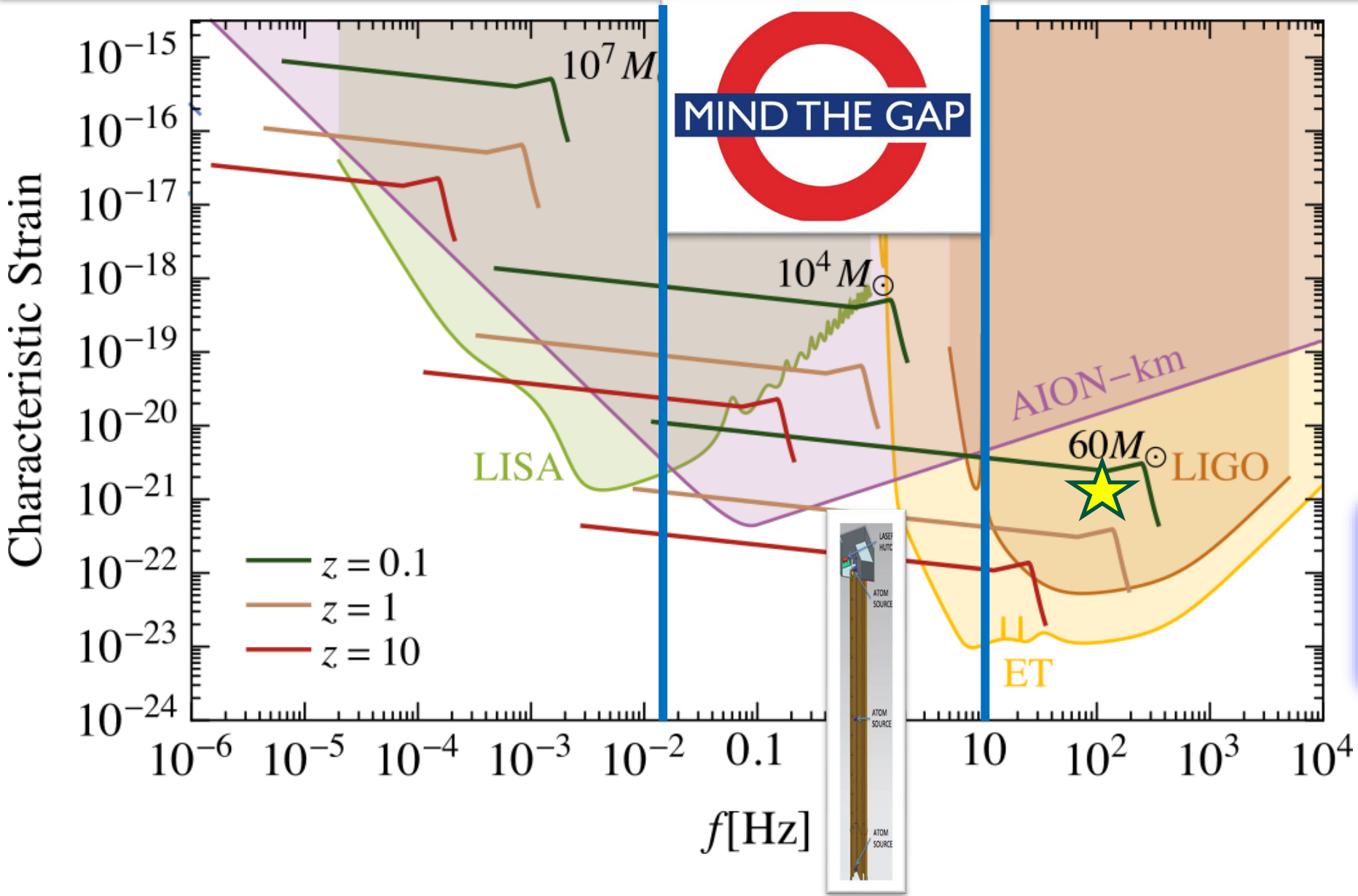


Mid-band science

- 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 detectors



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➢ **Multi-100m to km-scale Atom Interferometer (QT) experiments like AION can cover this gap.**

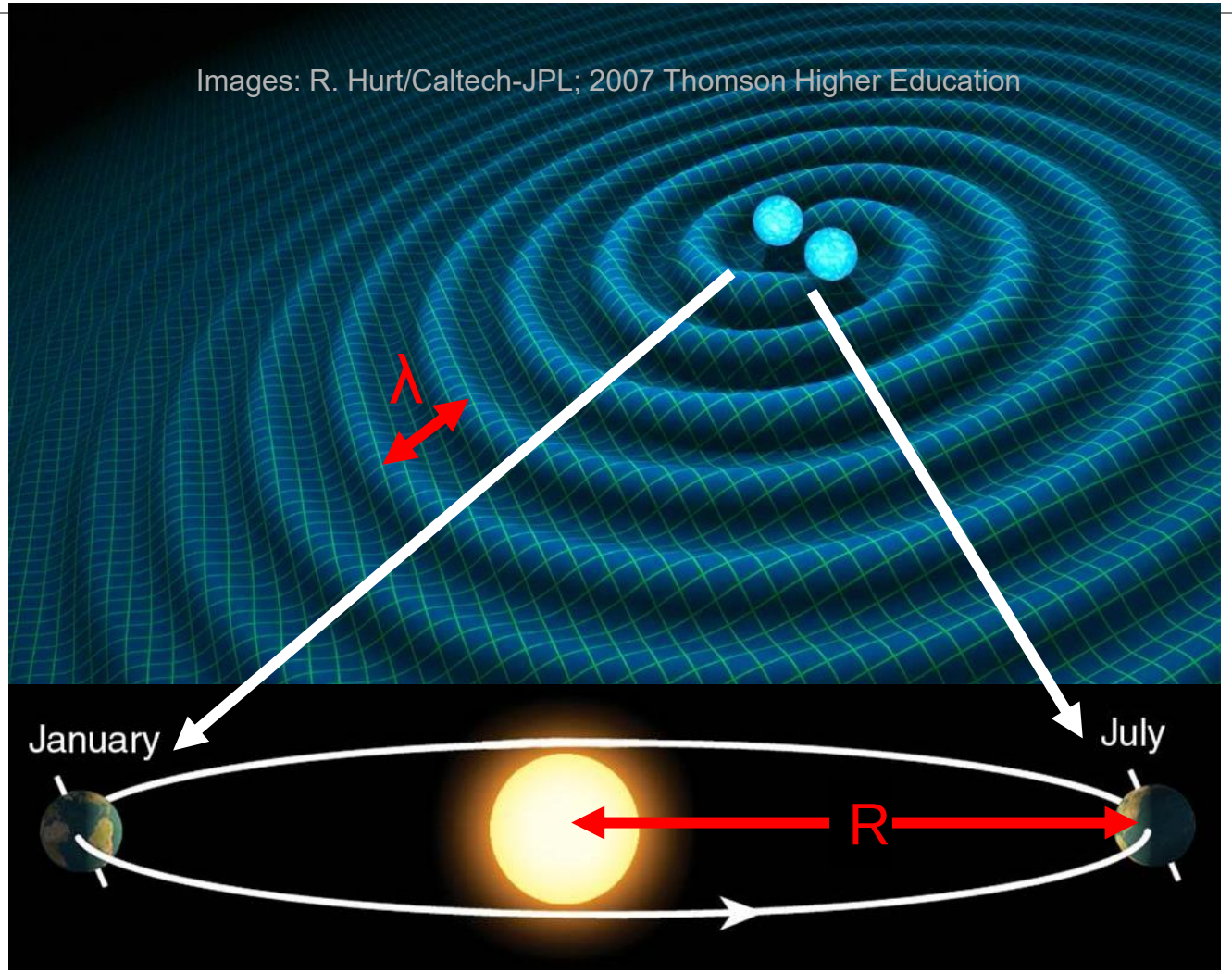
Sky position determination

Sky localization precision:

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

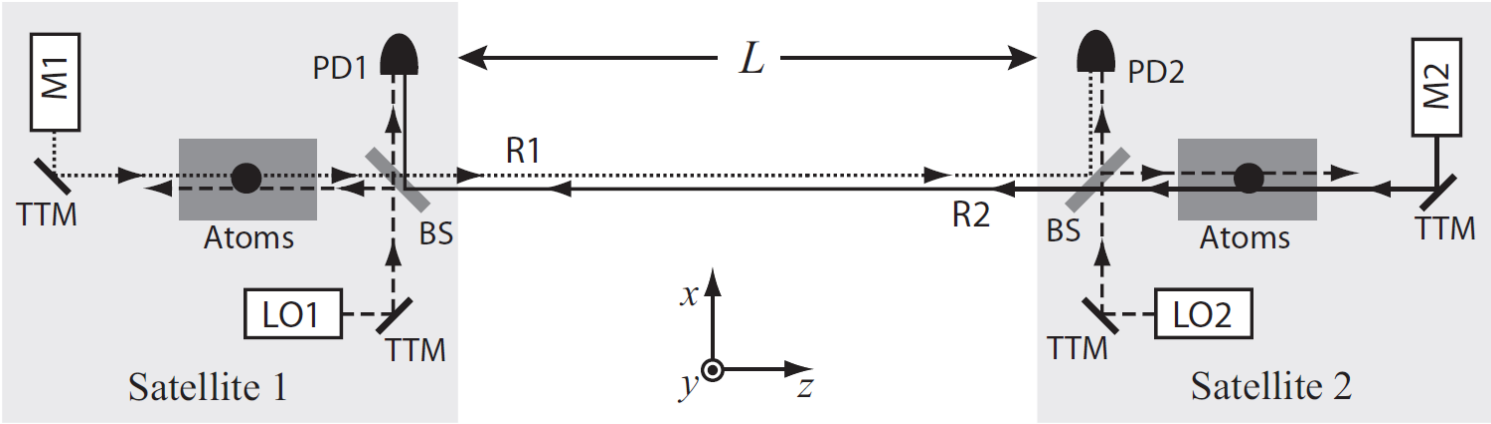
Mid-band advantages
- Small wavelength λ
- Long source lifetime (~months) maximizes effective R

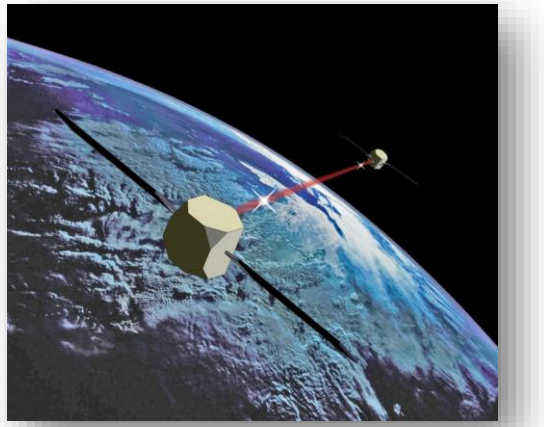
Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19



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

AEDGE: Potential Mission Design





Using two cold-atom interferometers that perform a relative measurement of differential phase shift, a potential mission profile would be using a pair of satellites separated by a very long baseline L.

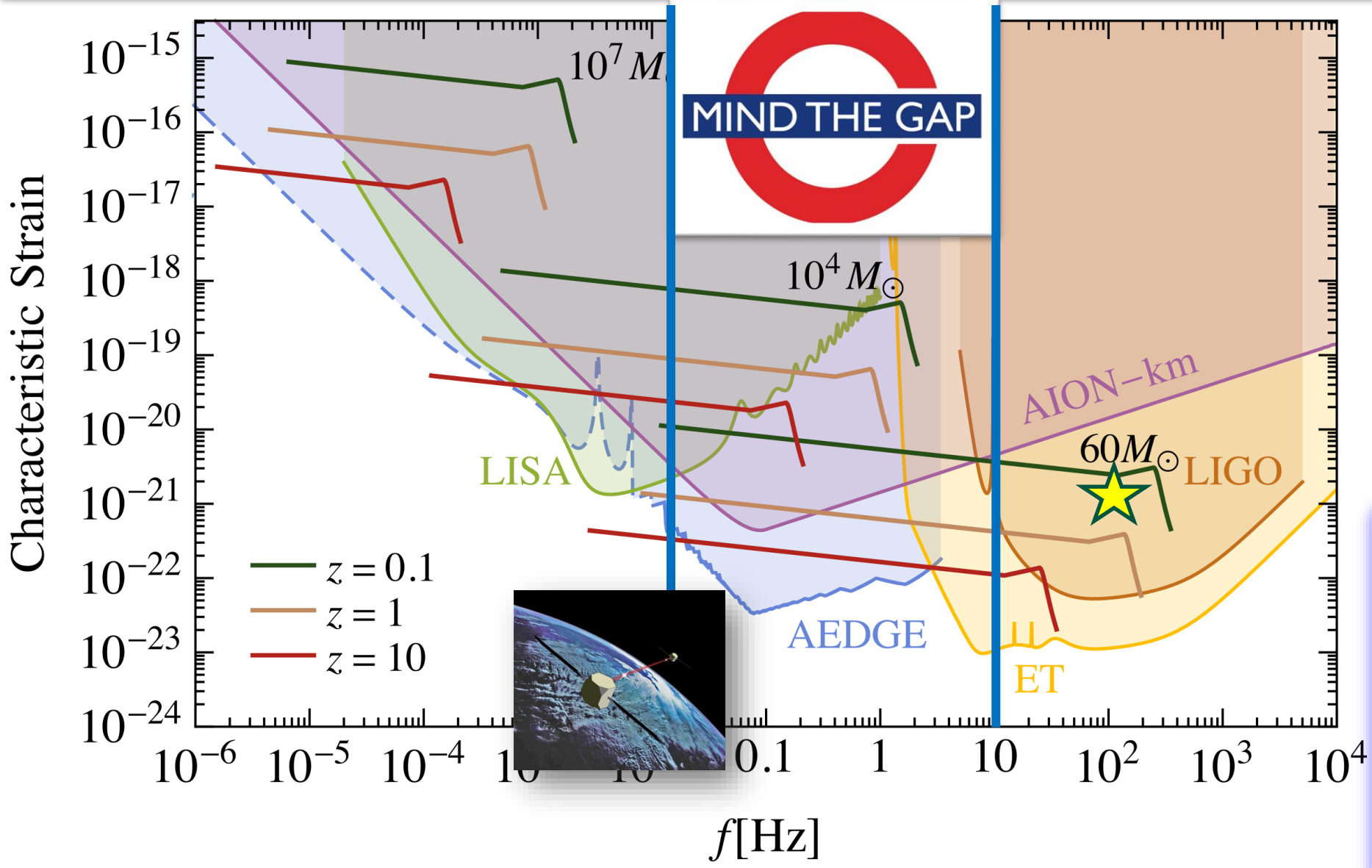
Assumed basic parameters:

- Pair of satellites in medium earth orbit (MEO)
- Satellite separation L = 4.4 x 10^7 m

Note: as Laser noise is common-mode suppressed only two satellites are required

A detailed mission outline is provided in:
https://epjquantumtechnology.springeropen.com/articles/10.1140/epjqt/s40507-020-0080-0
and P. W. Graham et al **arXiv:1711.02225**

Gravitational wave detectors



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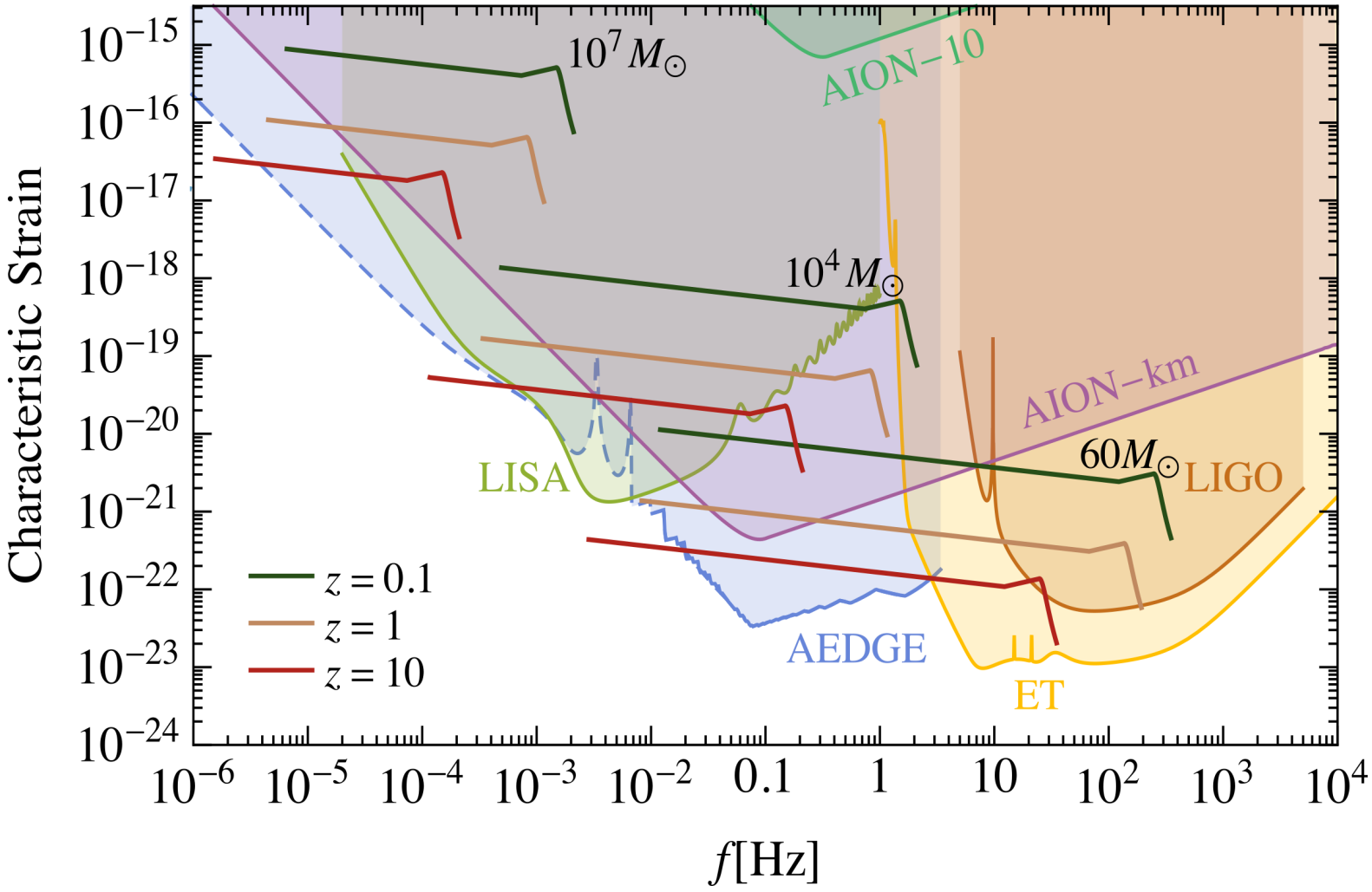
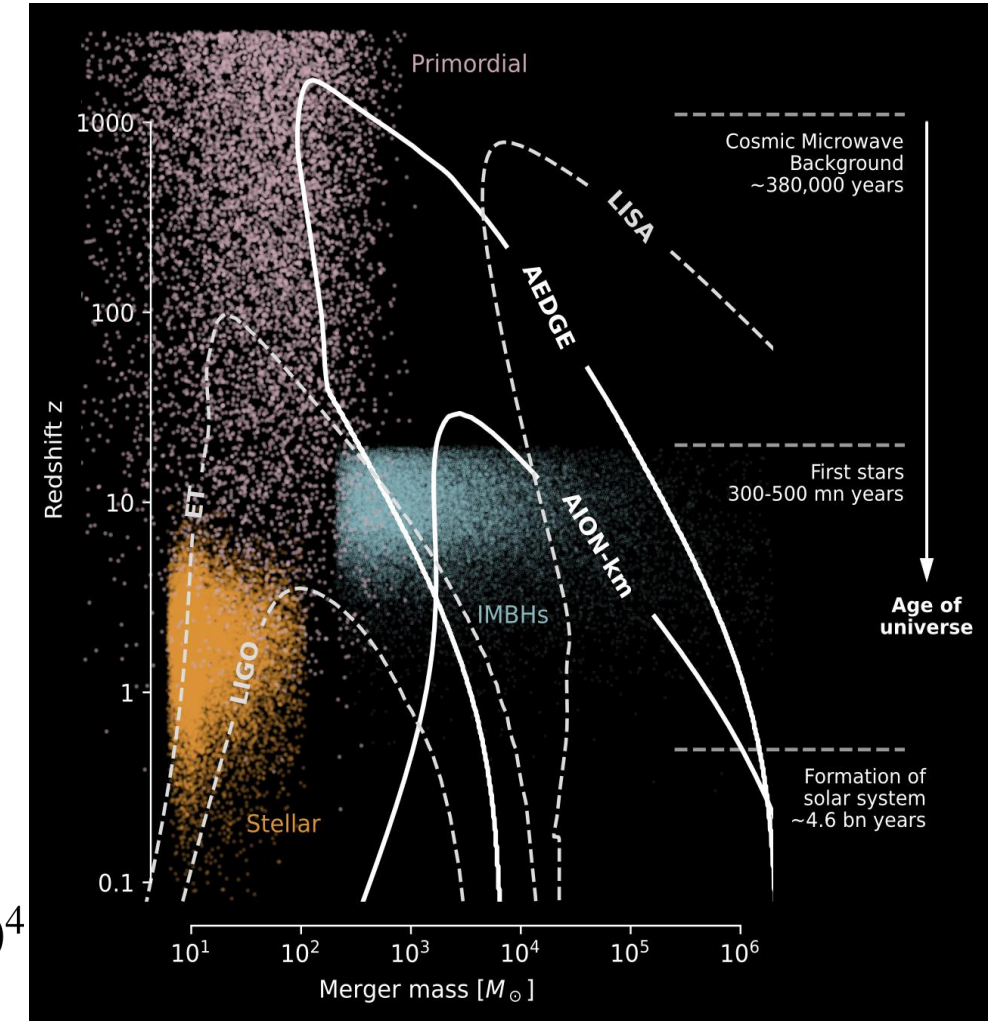
- **Multi-100m to km-scale Atom Interferometer (QT) experiments like AION can cover this gap.**
- **Experiments that bring QT to space, like AEDGE, can further extend our coverage of this region and beyond.**

What does this imply?





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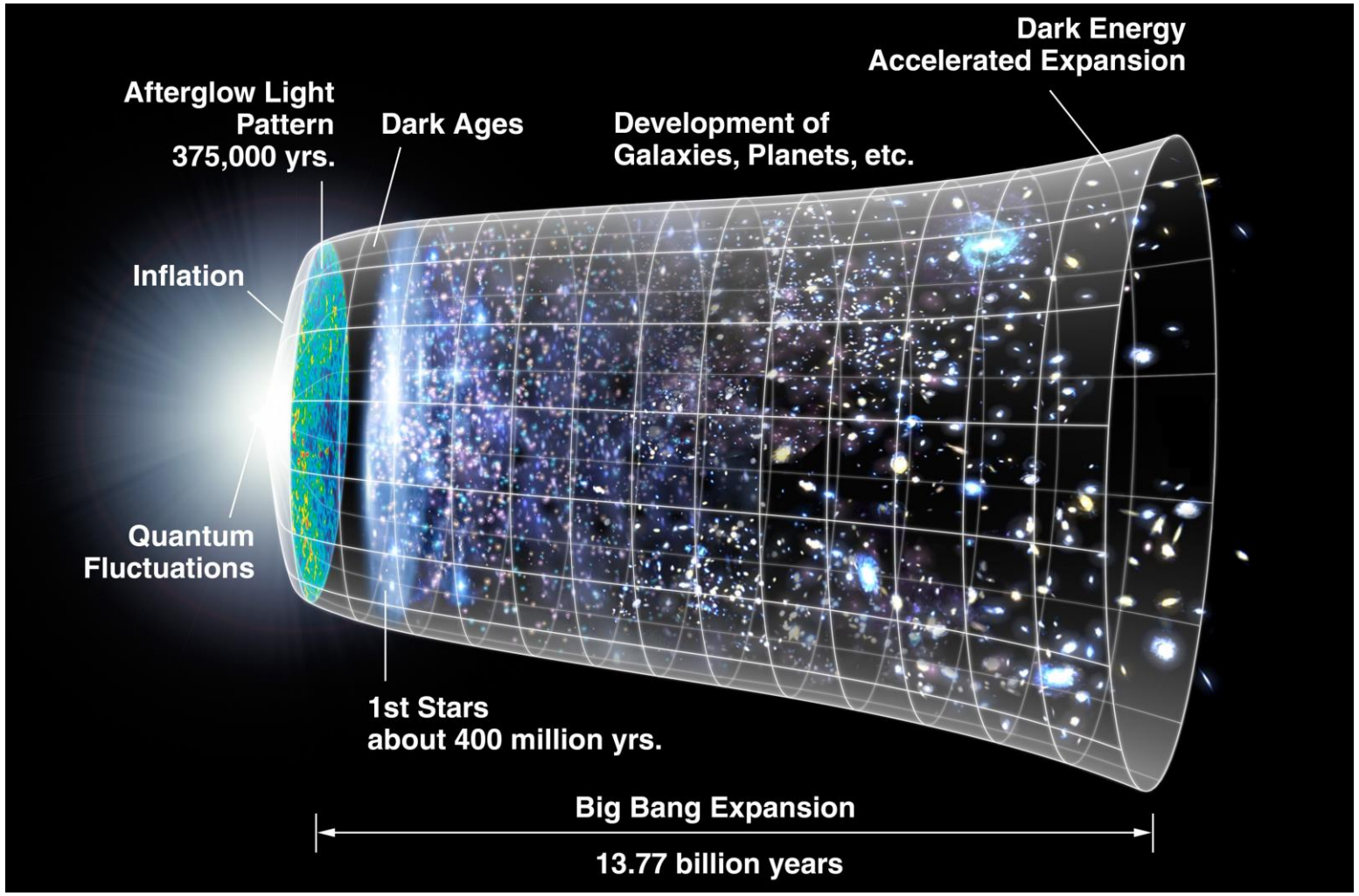

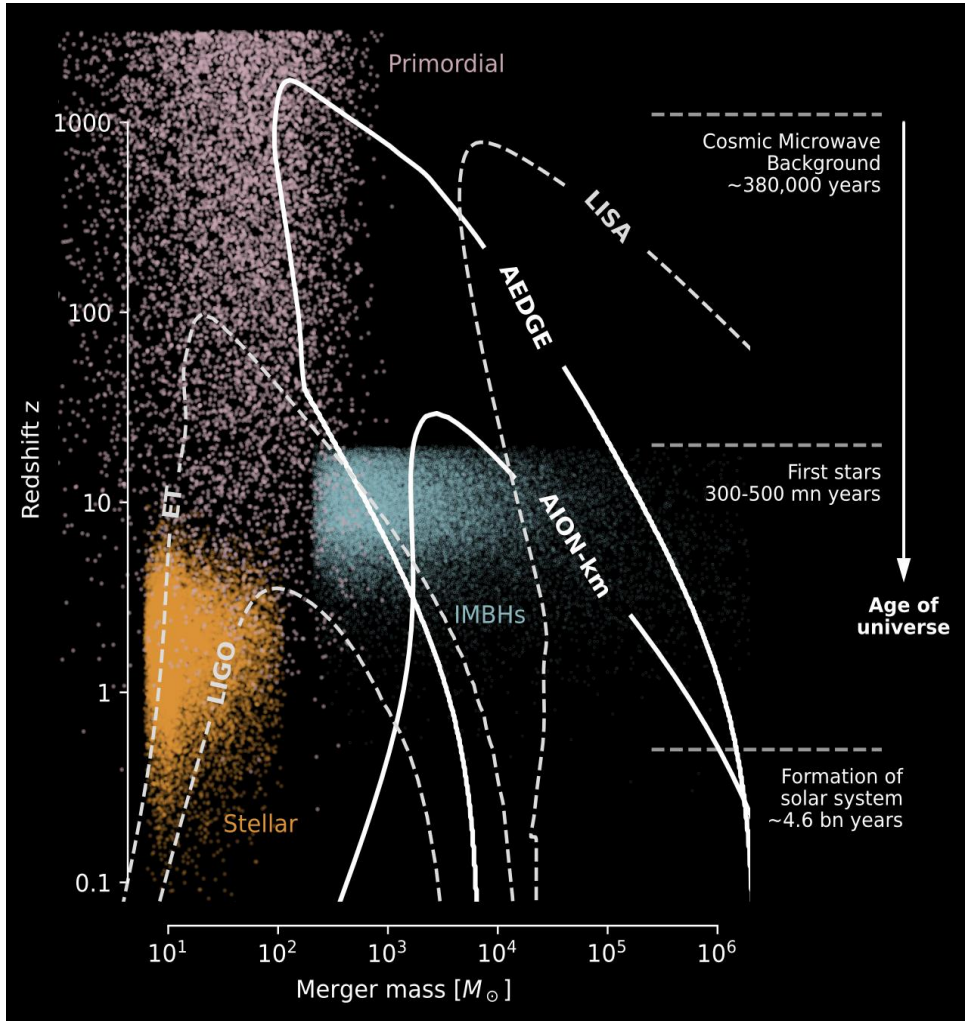

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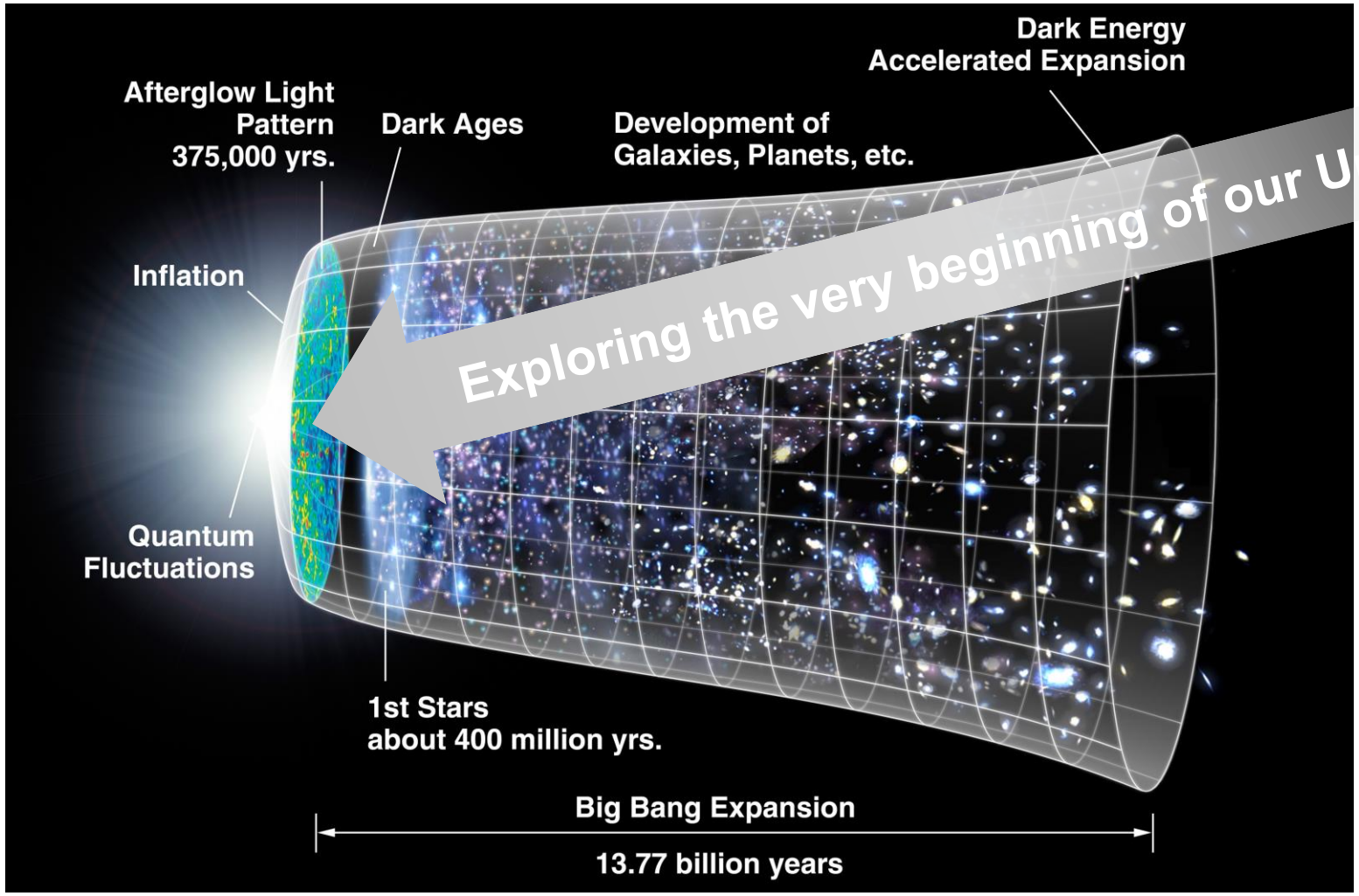
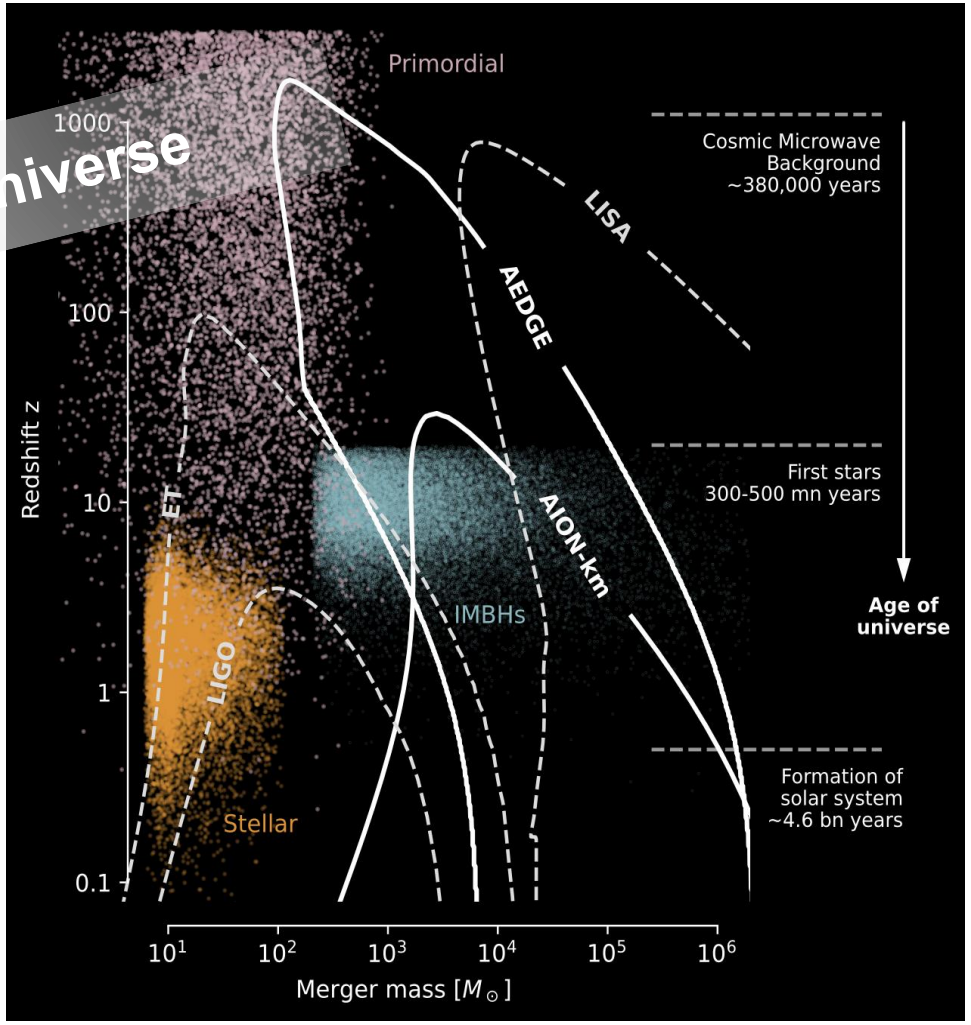
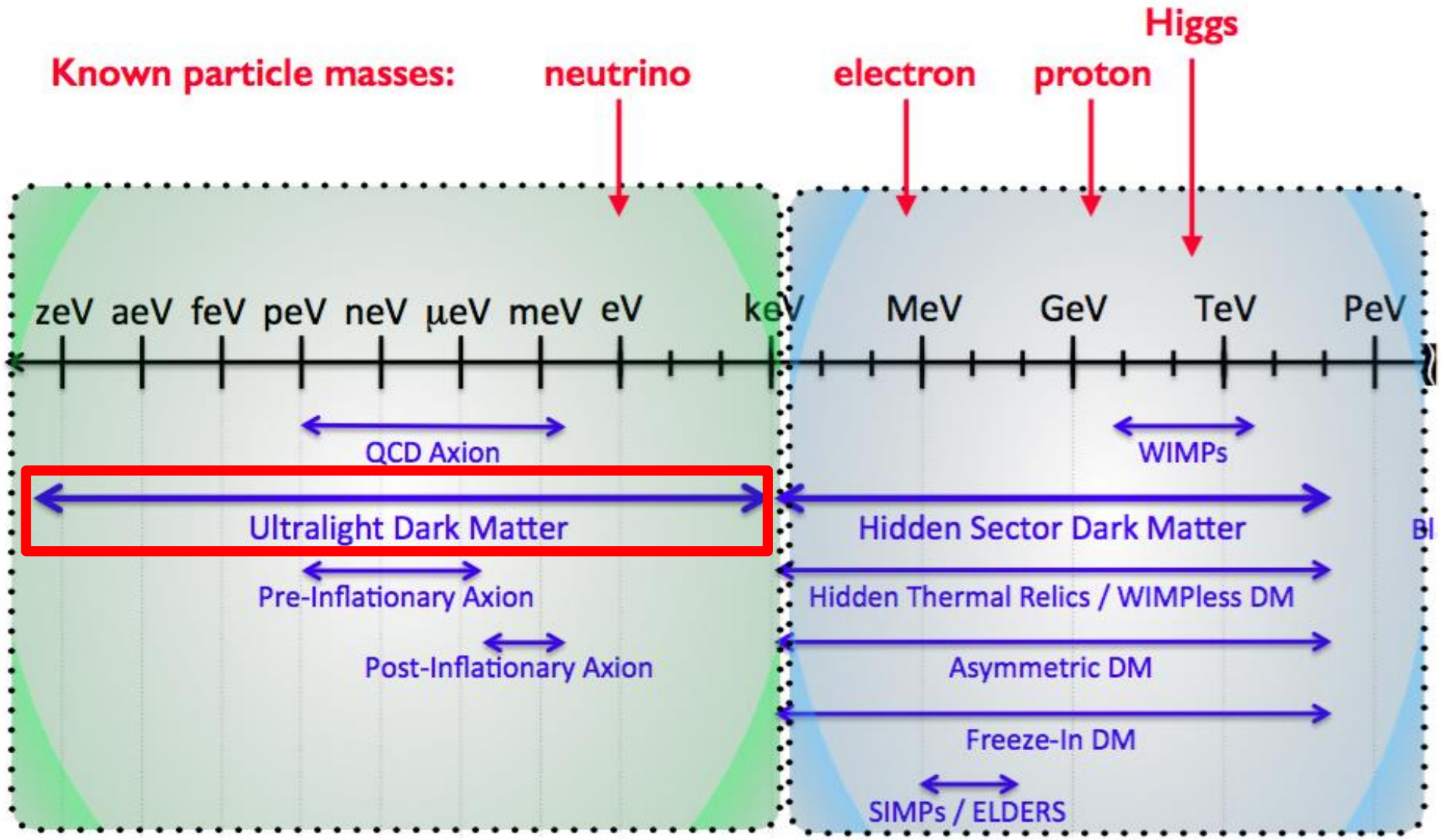


Exploring the very beginning of our Universe



Search for Ultra-Light Dark Matter



'Ultra-Light' dark matter **'Massive' dark matter**

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

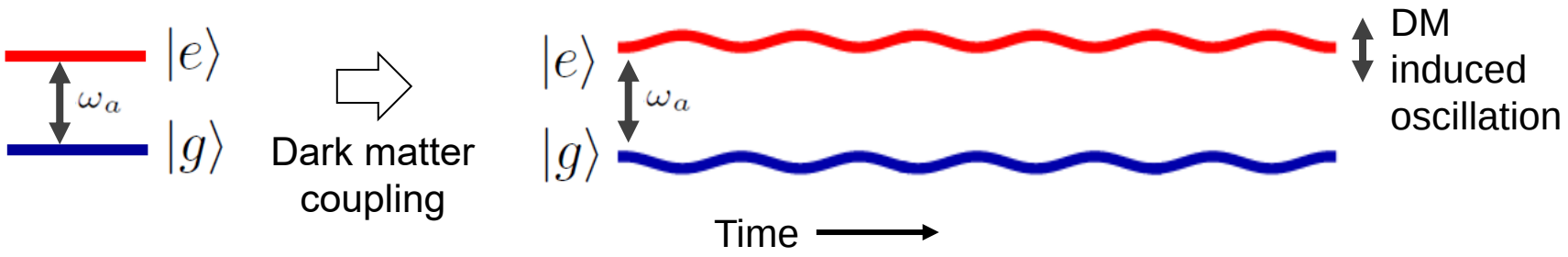
e.g., QCD

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

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

DM mass density

DM coupling causes time-varying atomic energy levels:

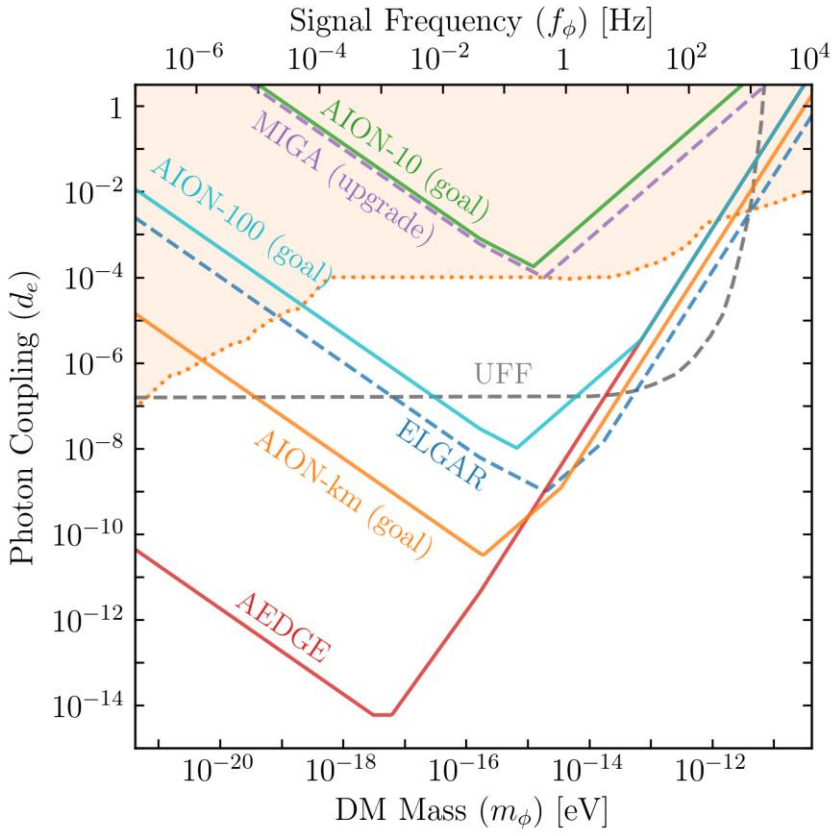


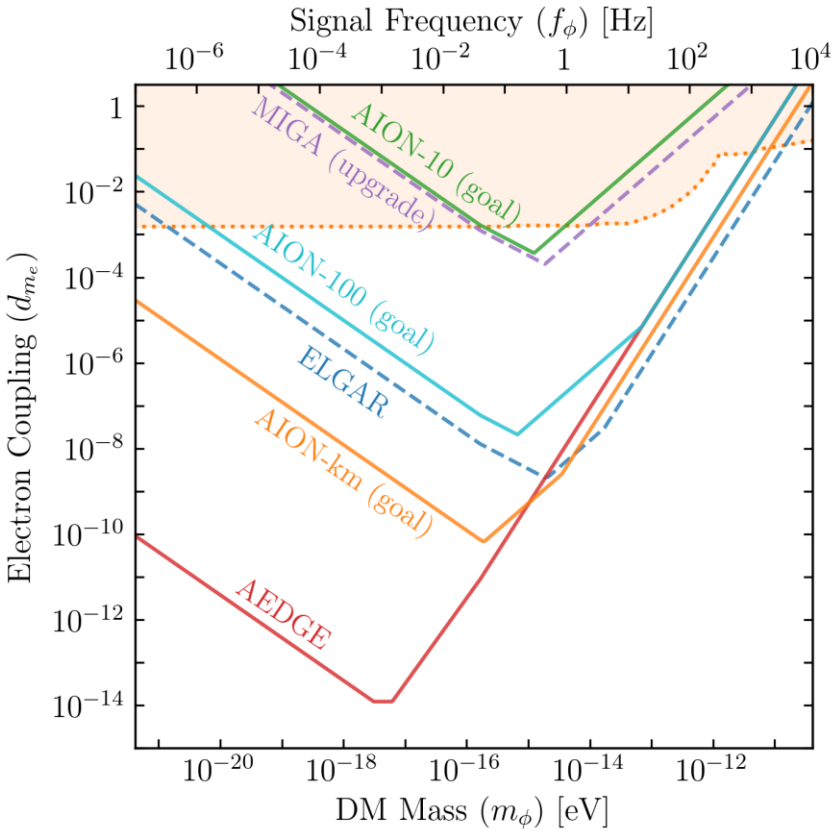
Courtesy of Jason Hogan!

Search for Ultra-Light Dark Matter

Linear couplings to gauge fields and matter fermions

$$\mathcal{L}_{\mathrm{int}\phi} = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$





Orders of magnitude improvement over current sensitivities

AION Collaboration (Badurina, ..., JE et al): arXiv:1911.11755; Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

Other Fundamental Physics

Ultra-high-precision atom interferometry may also be sensitive to other aspects of fundamental physics beyond dark matter and GWs, though studies of such possibilities are still at exploratory stages.

Examples may include:

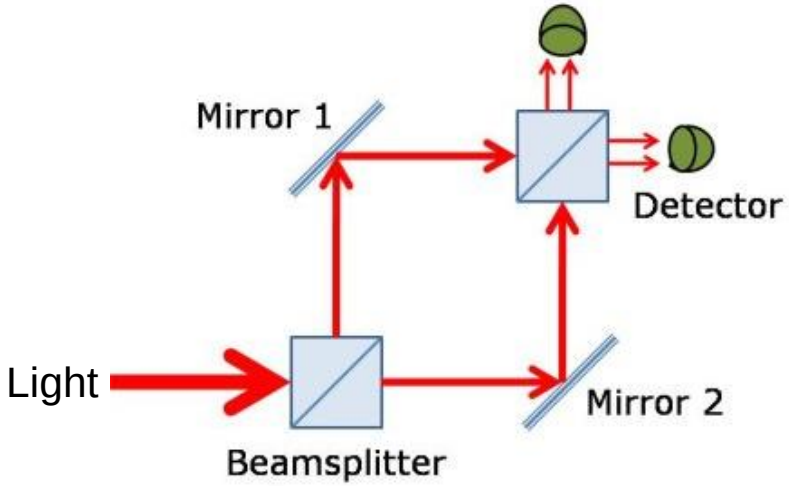
- *The possibility of detecting the astrophysical neutrinos*
- *Probes of long-range fifth forces*.
- *Constraining possible variations in fundamental constants.*
- *Probing dark energy*.
- Probes of basic physical principles such as foundations of quantum mechanics and Lorentz invariance.

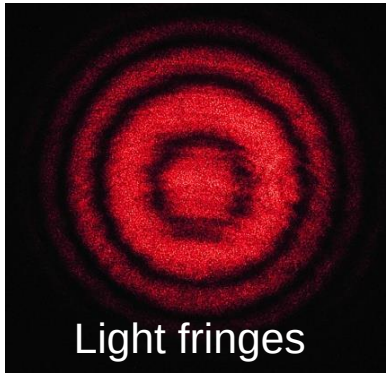
A very exciting new research avenue is ahead of us ….

MORE ON ATOM INTERFEROMETRY CONCEPT

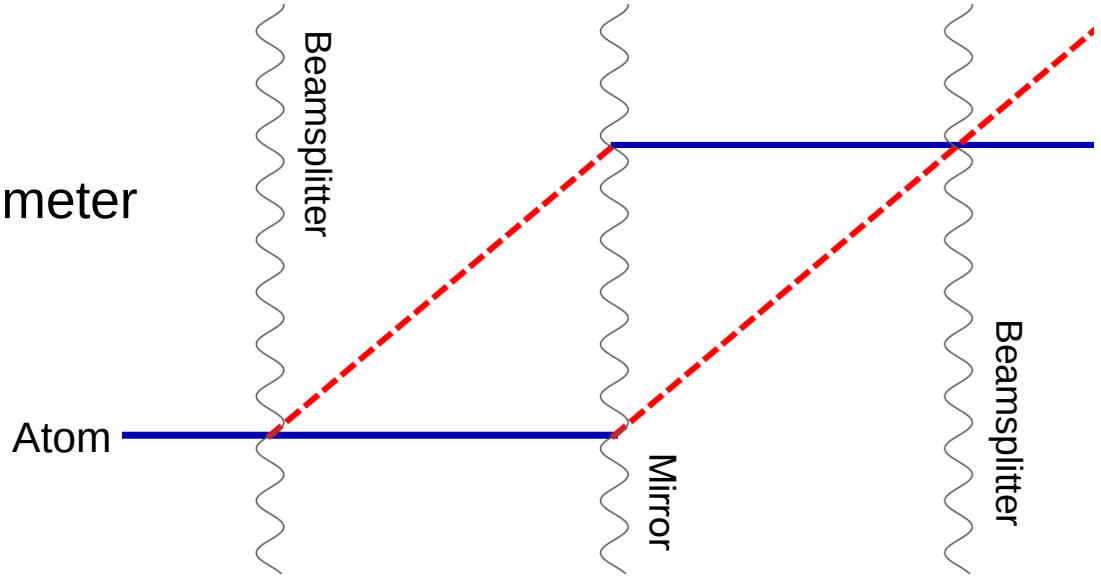
Light vs. Cold Atoms: Atom Interferometry

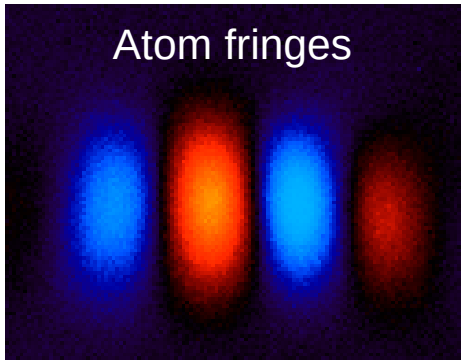
Light interferometer





Atom interferometer

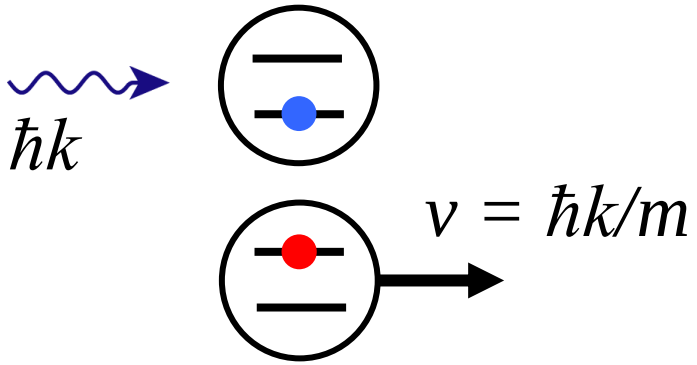




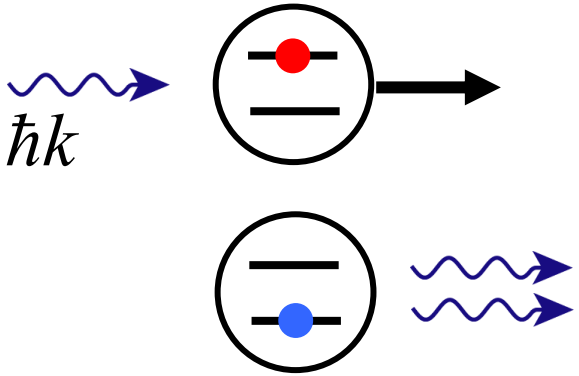
http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

Atom Interferometry Optics using Light

(1) Light absorption:



(2) Stimulated emission:



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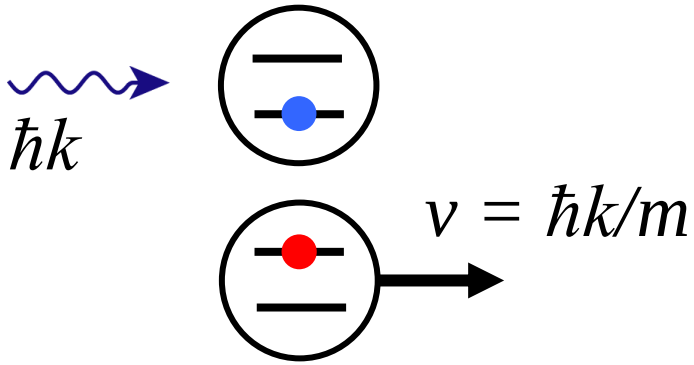

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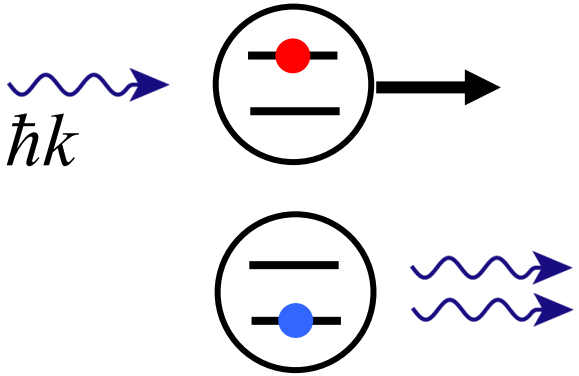
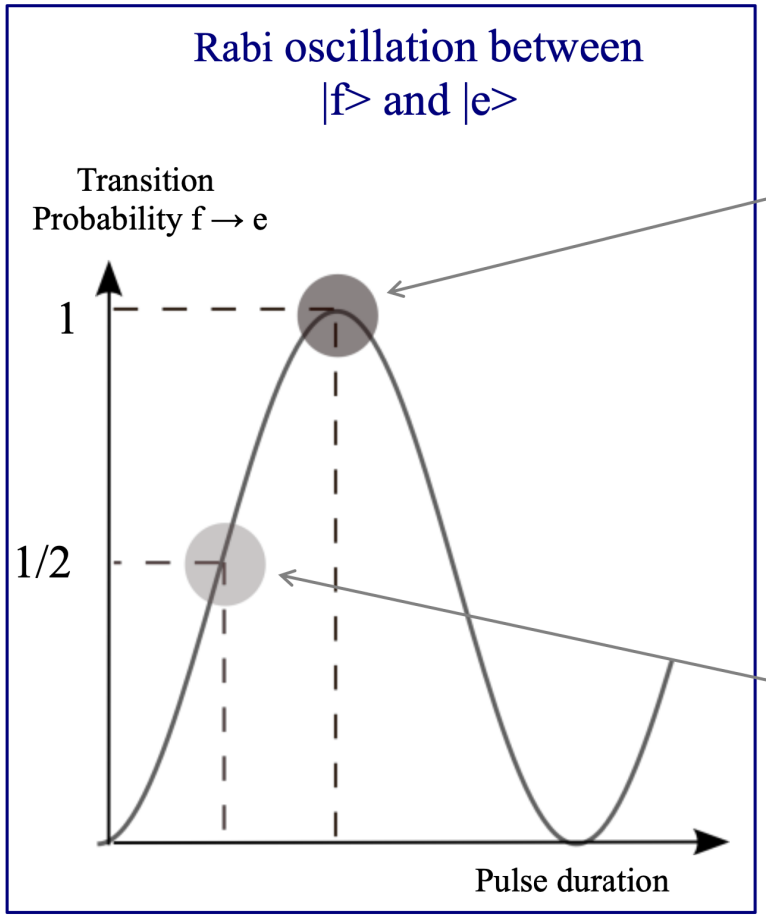
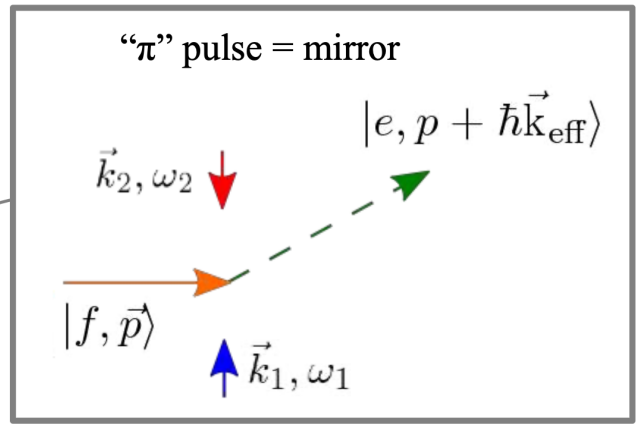
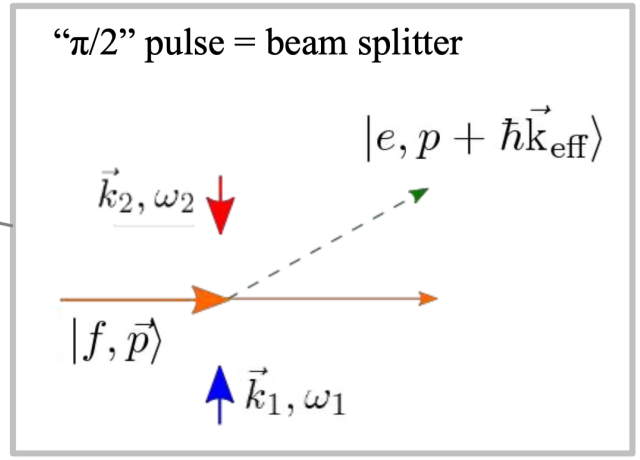








Light Pulse Atom Interferometry

$$|\text{atom}\rangle = |p\rangle$$

π/2 pulse "beamsplitter"

$$\frac{1}{\sqrt{2}}(|p\rangle + e^{i\Delta\phi}|p + \hbar k\rangle)$$

π pulse "mirror"

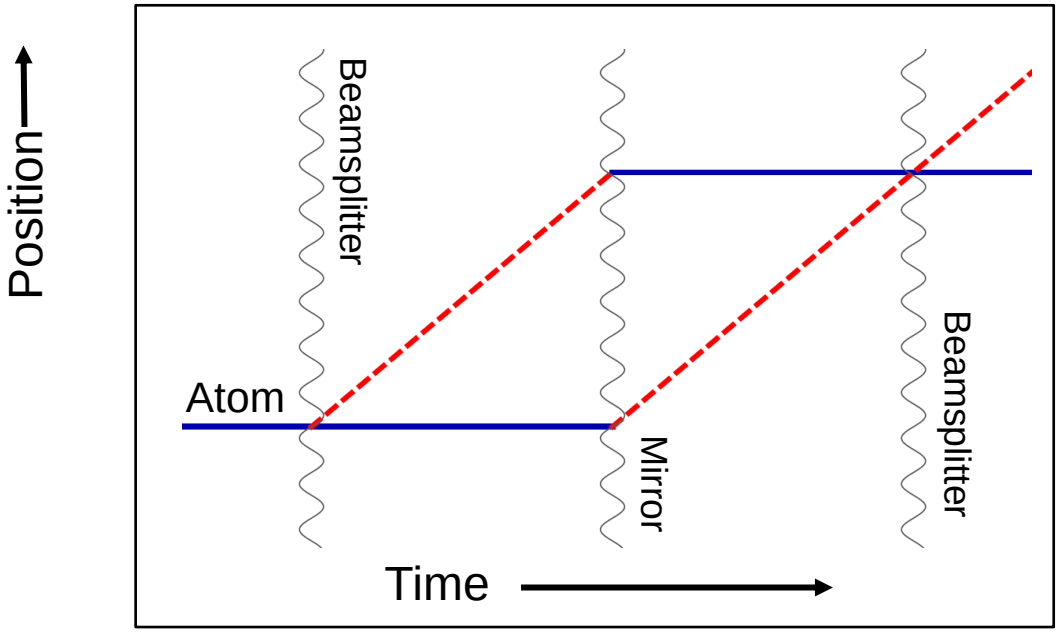
$$\frac{1}{\sqrt{2}}(|p + \hbar k\rangle + e^{i\Delta\phi}|p\rangle)$$

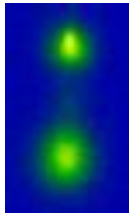
π/2 pulse "beamsplitter"

$$\frac{1}{2}((1 + e^{i\Delta\phi})|p\rangle + ((1 - e^{i\Delta\phi}))|p + \hbar k\rangle)$$

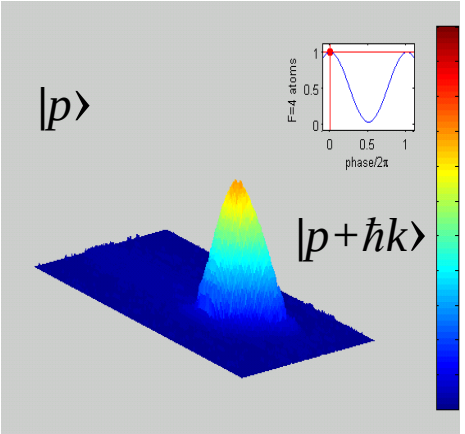
$$\text{Probability in State } |p\rangle = \cos^2\left(\frac{\Delta\phi}{2}\right)$$

$$\text{Probability in State } |\hbar k + k\rangle = \sin^2\left(\frac{\Delta\phi}{2}\right)$$

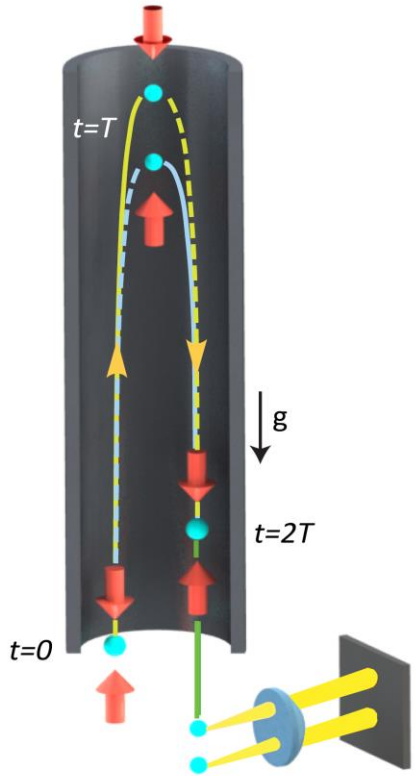


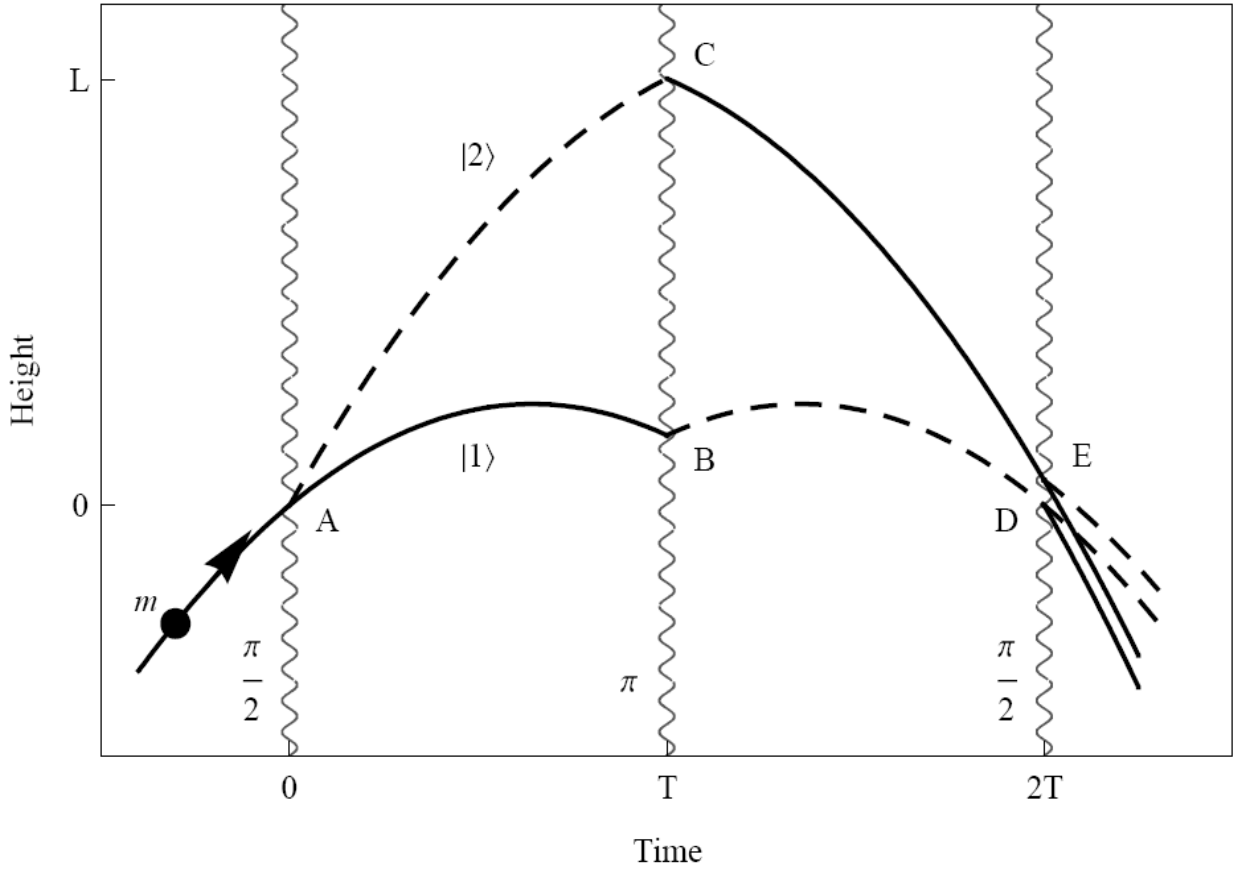


$$\Delta\Phi = \Phi_1^{eff} - 2\Phi_2^{eff} + \Phi_3^{eff} \qquad \Phi_i^{eff}(t) = \vec{k}_i^{eff}\vec{r}_i(t)$$



Light Pulse Atom Interferometry





$$\Delta\phi = k_{\text{eff}} g T^2$$

Proportional to spacetime area enclosed.

$$\frac{\delta g}{g} \sim \frac{\delta\phi}{k_{\text{eff}} g T^2}$$

Sensitivity

$$\delta\phi \sim \frac{1}{\sqrt{N}}$$

Shot noise

T : Long duration

k_{eff} : Large wavepacket separation

$\delta\phi$: High flux, spin squeezing

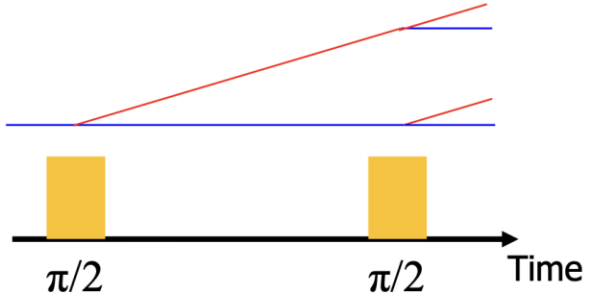
Three contributions:

- Laser phase at each node
- Propagation phase along each path
- Separation phase at end of interferometer

$$\Delta\phi_{\text{total}} = \Delta\phi_{\text{prop}} + \Delta\phi_{\text{laser}} + \Delta\phi_{\text{sep}}$$

Possible Phase Shifts

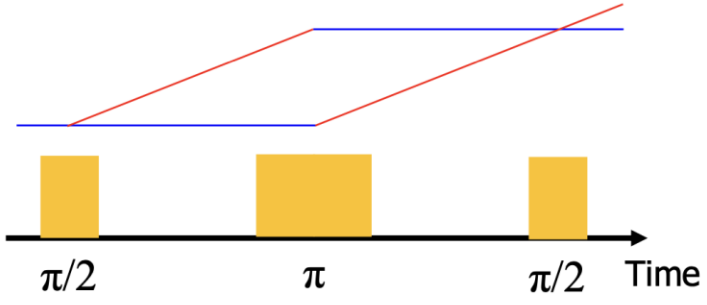
Ramsey sequence (clock)



$$\Delta\phi = \phi_1 - \phi_2 = (\omega - \omega_A)T + kx_1 - kx_2$$
$$= (\omega - \omega_A)T + kvT$$

- Measures velocity

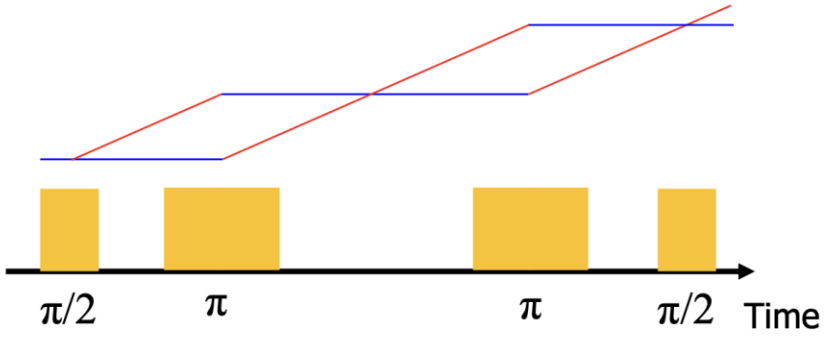
Mach-Zehnder



$$\Delta\phi = (\phi_1 - \phi_2) - (\phi_2 - \phi_3)$$
$$= kv_1T - kv_2T = kaT^2$$

- "Difference" of two Ramsey sequences
- Measures acceleration

"Double diamond"



$$\Delta\phi = ka_1T^2 - ka_2T^2 = k\,\delta a\,T^3$$

- Difference of two MZ loops
- Measures acceleration gradient (in space and/or time)

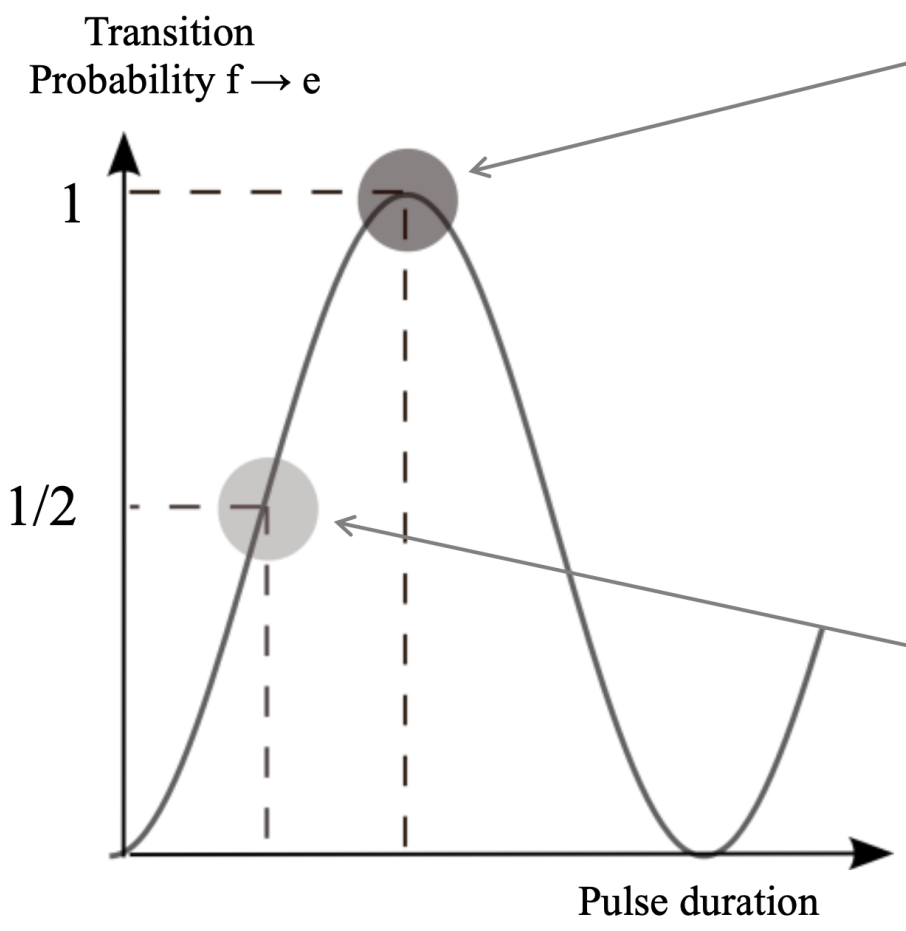
General Relativistic Effects in Atom Interferometry

	GR Phase Shift	Size (rad)	Interpretation	NR Phase Shift
1.	$-k_{\rm eff} g T^2$	$3.\times 10^{8}$	Newtonian gravity	$-k_{\rm eff} g T^2$
2.	$-k_{\rm eff}(\partial_r g) v_L T^3$	$-2.\times 10^{3}$	1st gradient	$-k_{\rm eff}(\partial_r g) v_L T^3$
3.	$-\frac{7}{12} k_{\rm eff}(\partial_r g) g T^4$	$9.\times 10^{2}$		$-\frac{7}{12} k_{\rm eff}(\partial_r g) g T^4$
4.	$-3 k_{\rm eff} g^2 T^3$	$-4.\times 10^{1}$	finite speed of light and	
5.	$-3 k_{\rm eff} g v_L T^2$	$4.\times 10^{1}$	Doppler shift corrections	
6.	$-\frac{k_{\rm eff}^2}{2m}(\partial_r g) T^3$	$-7.\times 10^{-1}$	1st gradient recoil	$-\frac{k_{\rm eff}^2}{2m}(\partial_r g) T^3$
7.	$(\omega_{\rm eff} - \omega_a)\, g T^2$	$-4.\times 10^{-1}$	detuning	
8.	$(2 - 2\beta - \gamma) k_{\rm eff} g \phi T^2$	$-2.\times 10^{-1}$	GR (non-linearity)	
9.	$-\frac{3k_{\rm eff}^2}{2m} g T^2$	$2.\times 10^{-2}$		
10.	$-\frac{7}{12} k_{\rm eff} v_L^2 (\partial_r^2 g) T^4$	$8.\times 10^{-3}$	2nd gradient	$-\frac{7}{12} k_{\rm eff} v_L^2 (\partial_r^2 g) T^4$
11.	$-\frac{35}{4} k_{\rm eff}(\partial_r g) g v_L T^4$	$6.\times 10^{-4}$		
12.	$-4 k_{\rm eff}(\partial_r g) v_L^2 T^3$	$-3.\times 10^{-4}$		
13.	$2\omega_a g^2 T^3$	$2.\times 10^{-4}$		
14.	$2\omega_a g v_L T^2$	$-2.\times 10^{-4}$		
15.	$-\frac{7k_{\rm eff}^2}{12m} v_L (\partial_r^2 g) T^4$	$7.\times 10^{-6}$	2nd gradient recoil	$-\frac{7k_{\rm eff}^2}{12m} v_L (\partial_r^2 g) T^4$
16.	$-12 k_{\rm eff} g^2 v_L T^3$	$-7.\times 10^{-6}$		
17.	$-7 k_{\rm eff} g^3 T^4$	$4.\times 10^{-6}$		
18.	$-5 k_{\rm eff} g v_L^2 T^2$	$3.\times 10^{-6}$	GR (velocity-dependent force)	
19.	$(2 - 2\beta - \gamma) k_{\rm eff} \partial_r (g\phi) v_L T^3$	$2.\times 10^{-6}$	GR 1st gradient	
20.	$\frac{7}{12}(4 - 4\beta - 3\gamma) k_{\rm eff} \phi (\partial_r g) g T^4$	$-2.\times 10^{-6}$	GR	
21.	$(\omega_{\rm eff} - \omega_a)(\partial_r g) v_L T^3$	$2.\times 10^{-6}$		
22.	$\frac{7}{12}(\omega_{\rm eff} - \omega_a)(\partial_r g) g T^4$	$-1.\times 10^{-6}$		
23.	$-\frac{7}{12}(2 - 2\beta - \gamma) k_{\rm eff} g^3 T^4$	$-3.\times 10^{-7}$	GR	
24.	$-\frac{7k_{\rm eff}^2}{2m}(\partial_r g) v_L T^3$	$-2.\times 10^{-7}$		
25.	$-\frac{27k_{\rm eff}^2}{8m}(\partial_r g) g T^4$	$2.\times 10^{-7}$		
26.	$\frac{k_{\rm eff}\omega_a}{m} g T^2$	$-1.\times 10^{-7}$		
27.	$6(2 - 2\beta - \gamma) k_{\rm eff} \phi g^2 T^3$	$5.\times 10^{-8}$	GR	
28.	$3(\omega_{\rm eff} - \omega_a) g^2 T^3$	$4.\times 10^{-8}$		
29.	$3(\omega_{\rm eff} - \omega_a) g v_L T^2$	$-4.\times 10^{-8}$		
30.	$6(1 - \beta) k_{\rm eff} \phi g v_L T^2$	$3.\times 10^{-8}$	GR	

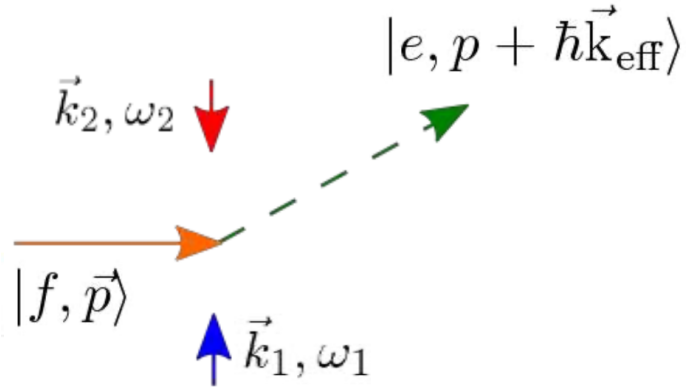
Dimopoulos et al, Phys.Rev.D78:042003,**2008**

Pi and Pi/2 Pluses – Rabi Oscillation

Rabi oscillation between |f> and |e>

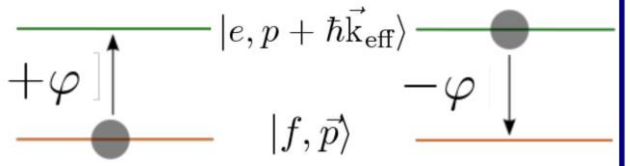


"π" pulse = mirror

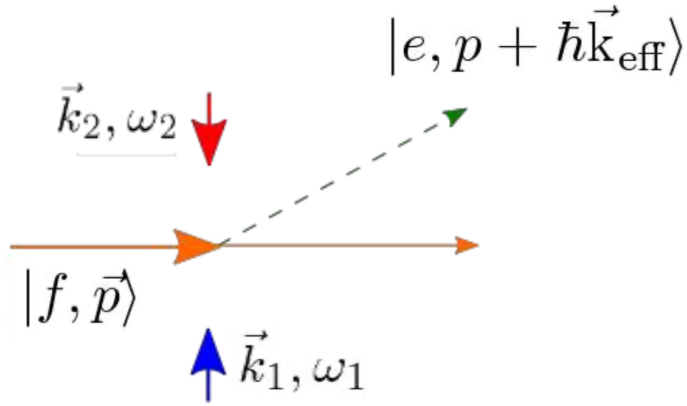


Imprint laser phase on atomic wave-function:

$$\varphi = \phi_1 - \phi_2 = \vec{k}_{\text{eff}} \cdot \vec{r}(t)$$

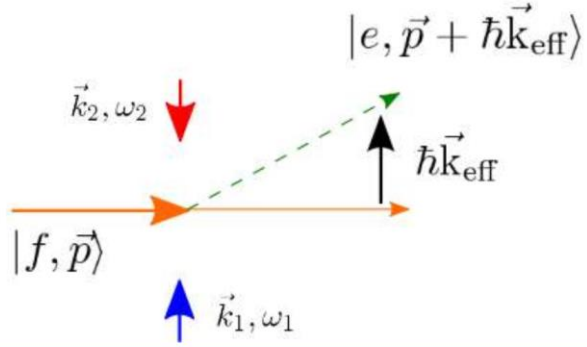


"π/2" pulse = beam splitter



Momentum tranfser (~1 cm/s)

$$k_{\text{eff}} = k_1 + k_2$$



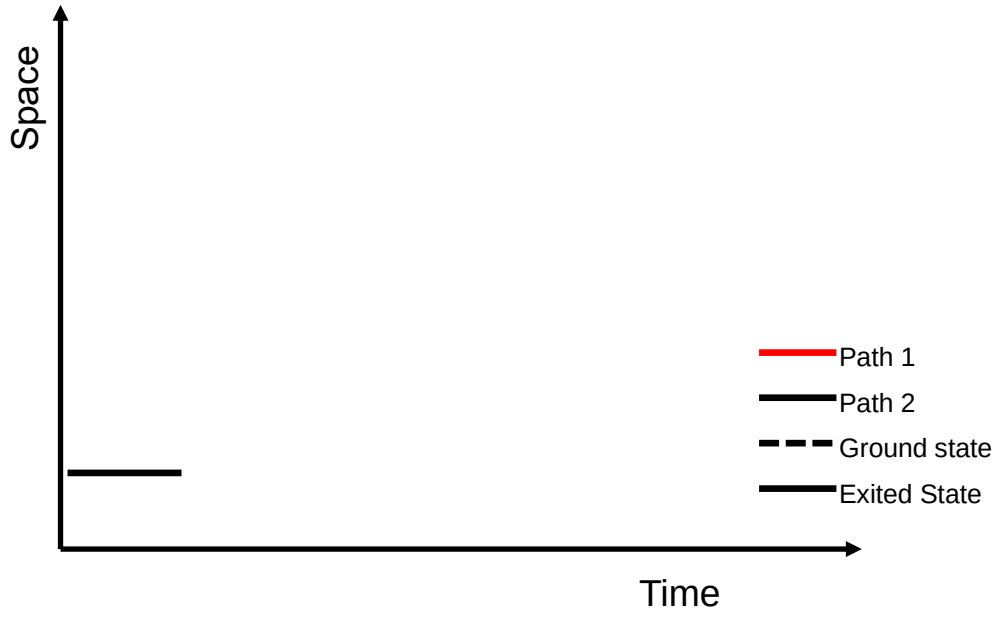
Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.

Atoms at rest:

At time before first Pulse:

$$\Phi_1 = 0, \quad \Phi_2 = 0$$



Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.

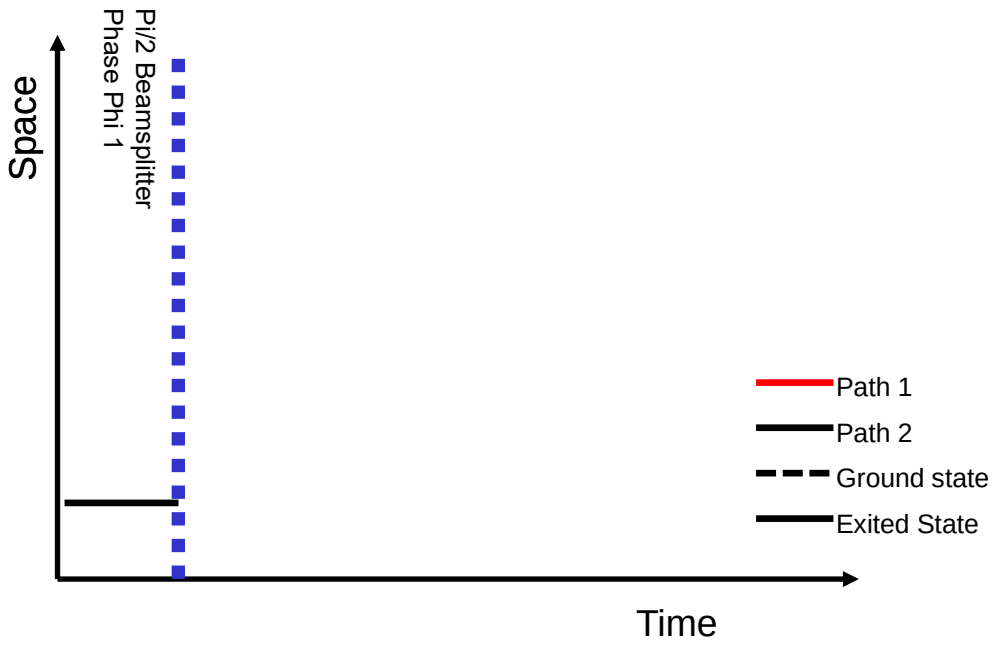
Atoms at rest:

At time before first Pulse:

$$\Phi_1 = 0, \quad \Phi_2 = 0$$

At time $T = 0$ of first $\pi/2$ Pulse:

$$\Phi_1 = \phi_1, \quad \Phi_2 = 0$$



Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.

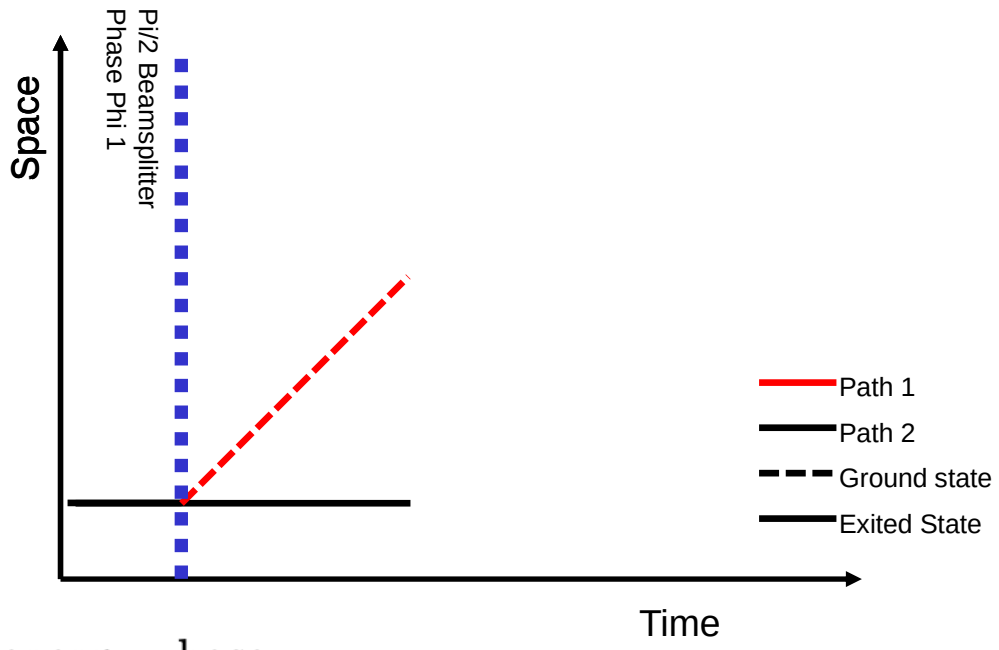
Atoms at rest:

At time before first Pulse:

$$\Phi_1 = 0, \quad \Phi_2 = 0$$

At time $T = 0$ of first $\pi/2$ Pulse:

$$\Phi_1 = \phi_1, \quad \Phi_2 = 0$$



At time $t = T$ just before the π mirror pulse $|1\rangle$ acquired the energy phase $-Et/\hbar = -\omega_a T$

$$\Phi_1 = \phi_1 - ET/\hbar, \quad \Phi_2 = 0$$

Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.

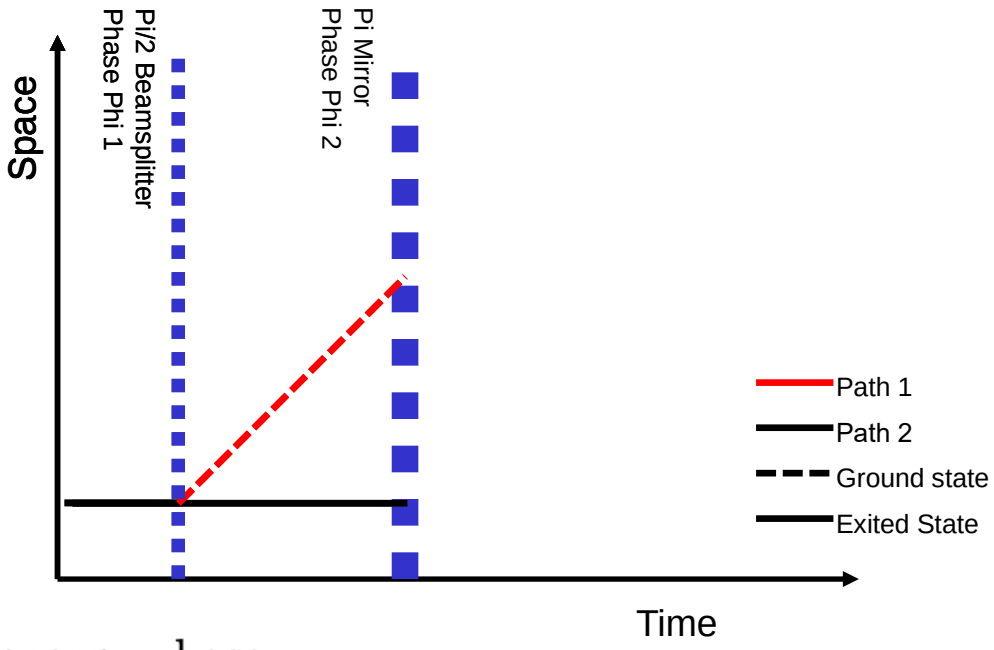
Atoms at rest:

At time before first Pulse:

$$\Phi_1 = 0, \quad \Phi_2 = 0$$

At time $T = 0$ of first $\pi/2$ Pulse:

$$\Phi_1 = \phi_1, \quad \Phi_2 = 0$$



At time $t = T$ just before the π mirror pulse $|1\rangle$ acquired the energy phase $-Et/\hbar = -\omega_a T$

$$\Phi_1 = \phi_1 - ET/\hbar, \quad \Phi_2 = 0$$

At time $t = T$ of the π Pulse:

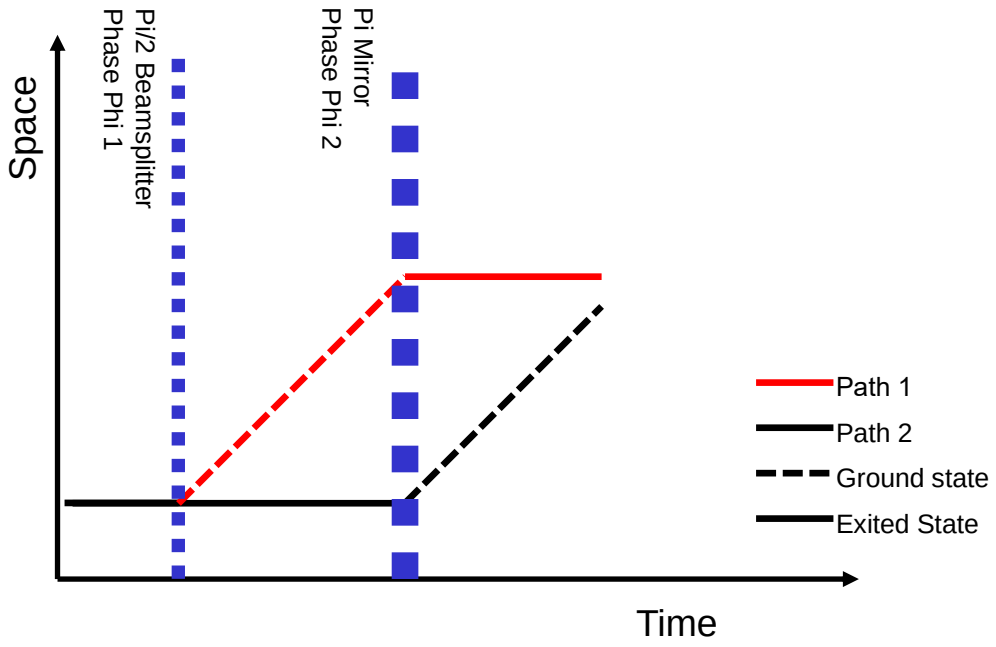
$$\Phi_1 = \phi_1 - ET/\hbar - \phi_2, \quad \Phi_2 = \phi_2$$

Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.

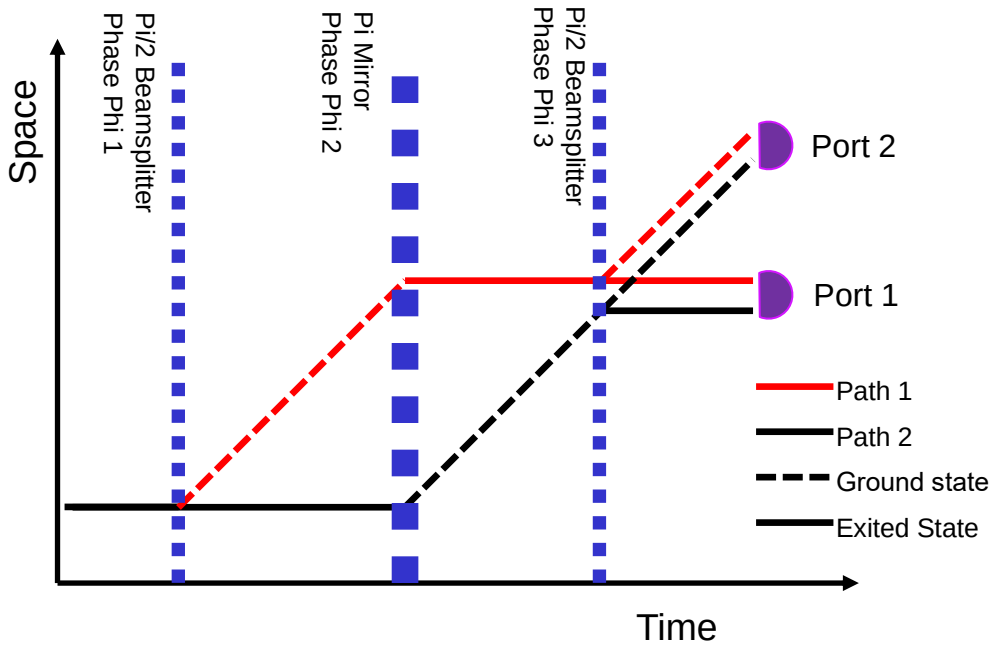
At time $t = 2T$ just before the next $\pi/2$ mirror pulse:

$$\Phi_1 = \phi_1 - ET/\hbar - \phi_2, \quad \Phi_2 = \phi_2 - ET/\hbar$$



Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.



At time $t = 2T$ just before the next $\pi/2$ mirror pulse:

$$\Phi_1 = \phi_1 - ET/\hbar - \phi_2, \quad \Phi_2 = \phi_2 - ET/\hbar$$

At time $t = 2T$ just after the next $\pi/2$ mirror pulse, we actually split in four components:

At $|0\rangle$ port:

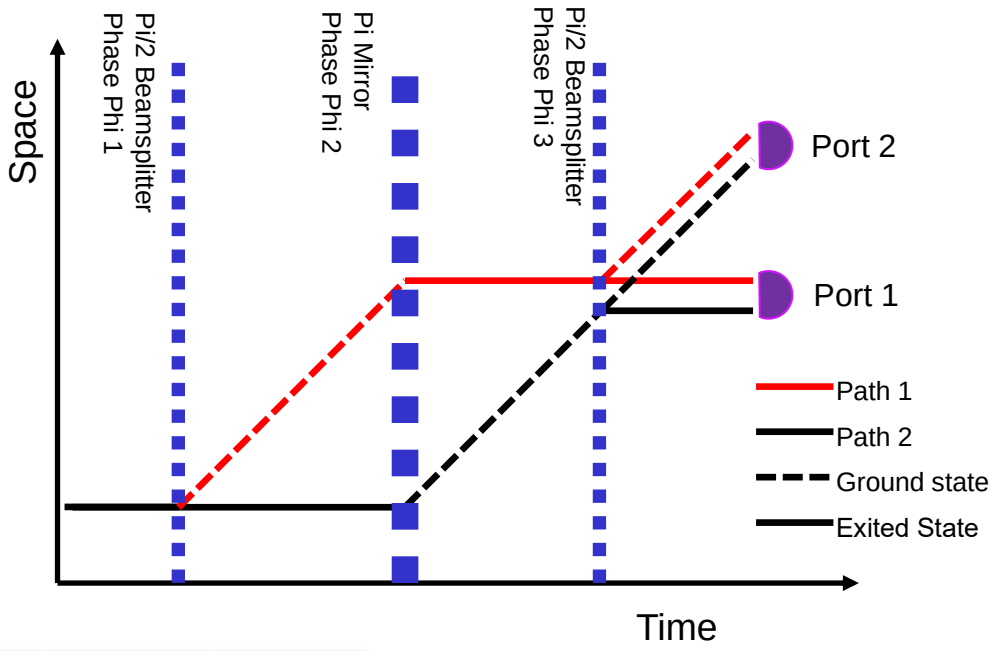
$$\Phi_1 = \phi_1 - ET/\hbar - \phi_2, \quad \Phi_2 = \phi_2 - ET/\hbar - \phi_3$$

At $|1\rangle$ port:

$$\Phi_1 = \phi_1 - ET/\hbar - \phi_2 + \phi_3, \quad \Phi_2 = \phi_2 - ET/\hbar$$

Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.



Therefore, the phase difference $\Delta\phi = \Phi_1 - \Phi_2$ is:

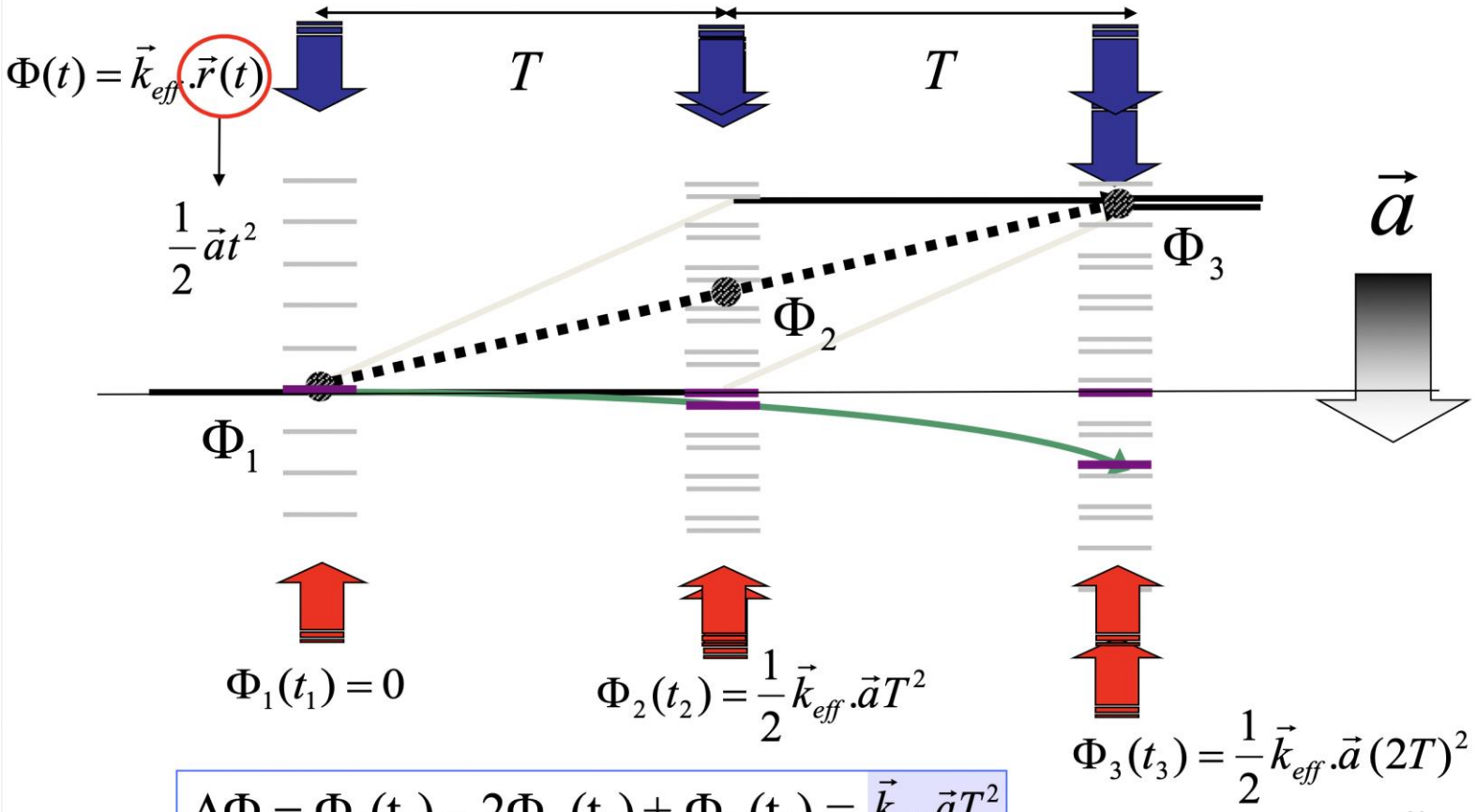
$$\Phi_1 - \Phi_2 = (\phi_1 - ET/\hbar - \phi_2) - (\phi_2 - ET/\hbar - \phi_3) = \phi_1 - 2\phi_2 + \phi_3$$

or

$$\Phi_1 - \Phi_2 = (\phi_1 - ET/\hbar - \phi_2 + \phi_3) - (\phi_2 - ET/\hbar) = \phi_1 + \phi_3 - 2\phi_2$$

MZ Acceleration Phase Shift

Acceleration phase shift



$$\Delta\Phi = \Phi_1(t_1) - 2\Phi_2(t_2) + \Phi_3(t_3) = \vec{k}_{eff}.\vec{a}T^2$$

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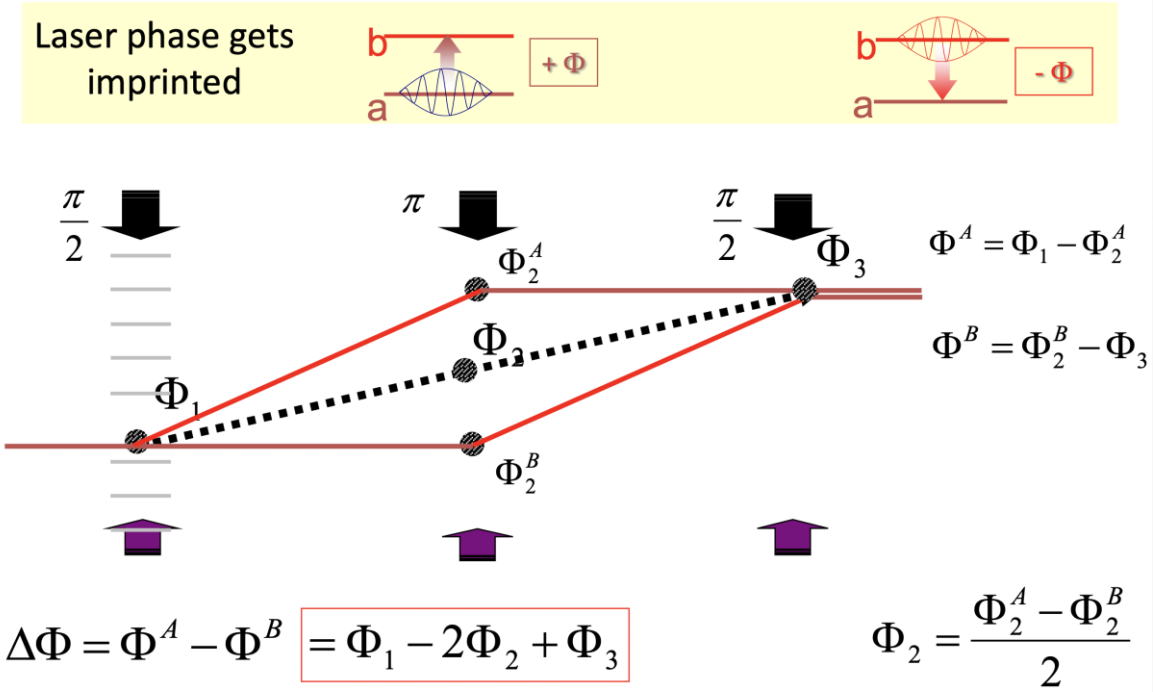
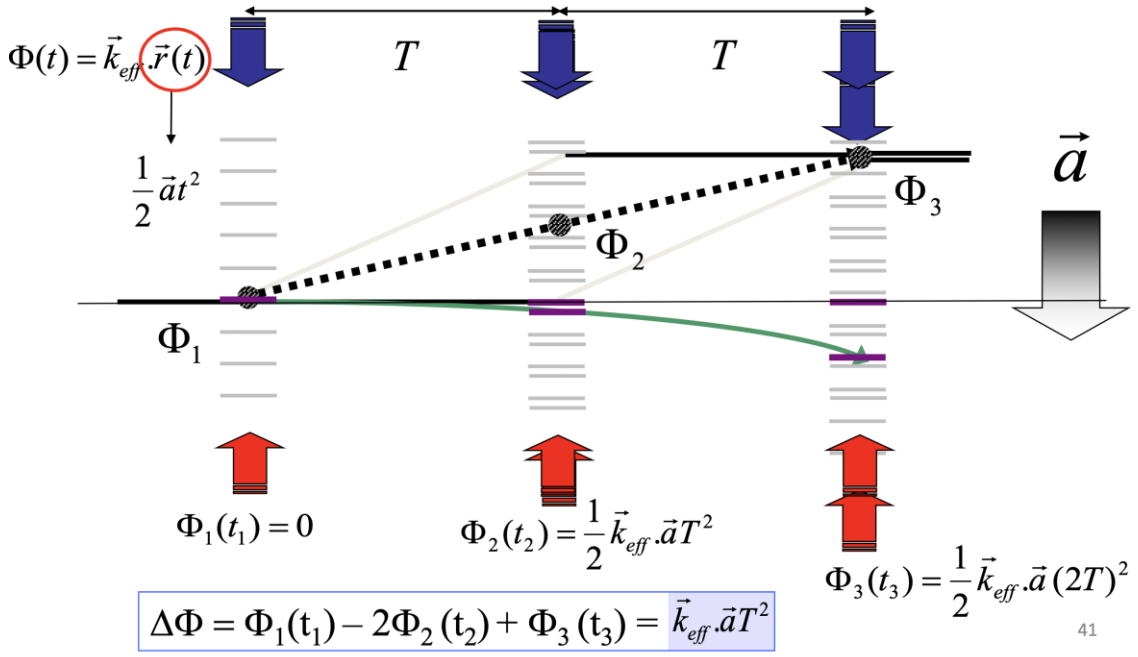
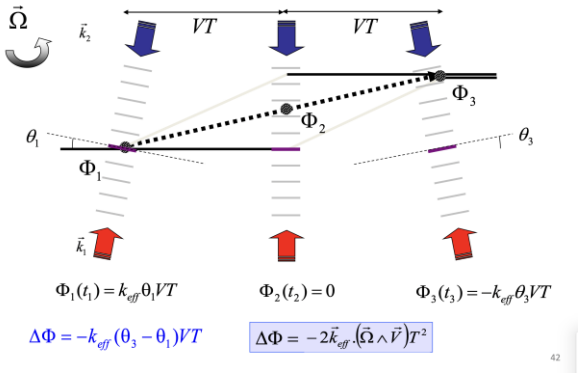
Different Phase Shifts for Different Interactions







$$\Delta\Phi = \Phi_1^{eff} - 2\Phi_2^{eff} + \Phi_3^{eff}$$

$$\Phi_i^{eff}(t) = \vec{k}_i^{eff}\vec{r}_i(t)$$