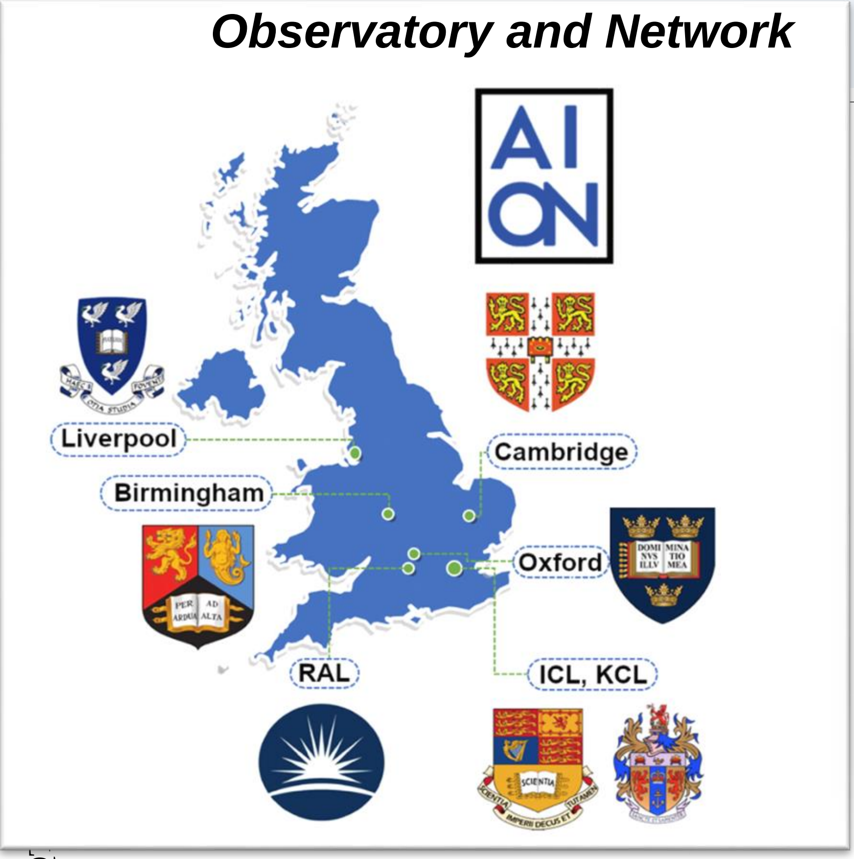
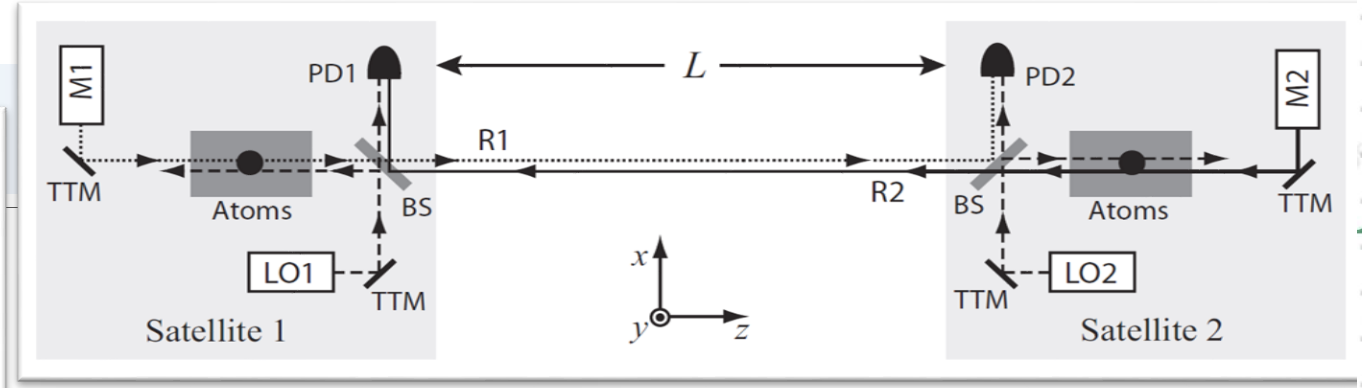
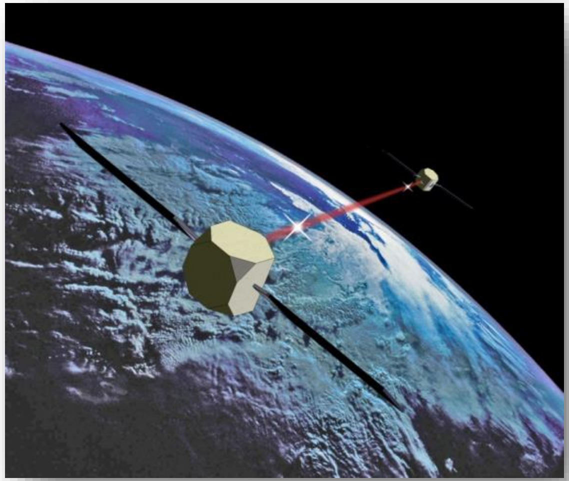
Imperial College London

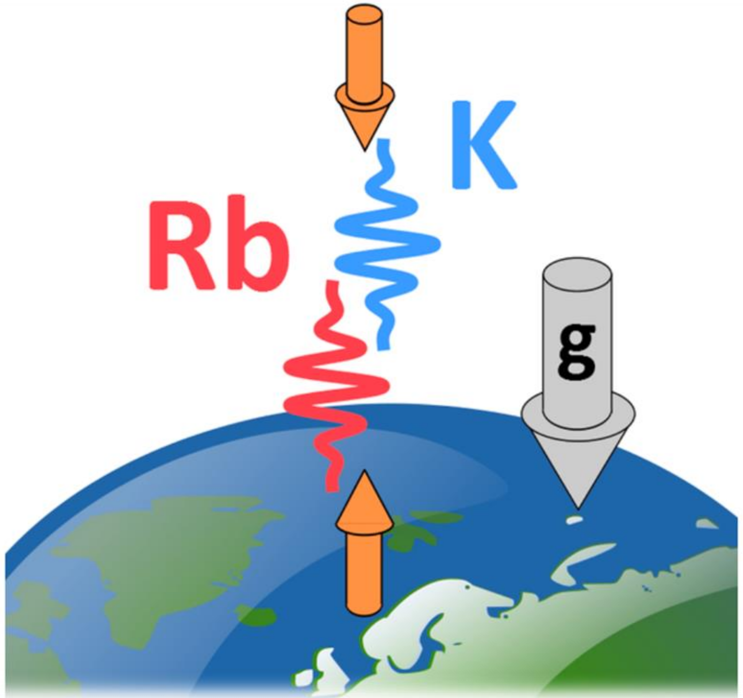
A UK Atom Interferometer Observatory and Network







Atomic Experiment for Dark Matter and Gravity Exploration



STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics

Oliver Buchmueller, Imperial College London

COLD ATOM QUANTUM TECHNOLOGY TO EXPLORE FUNDAMENTAL PHYSICS

SCIENCE CASE

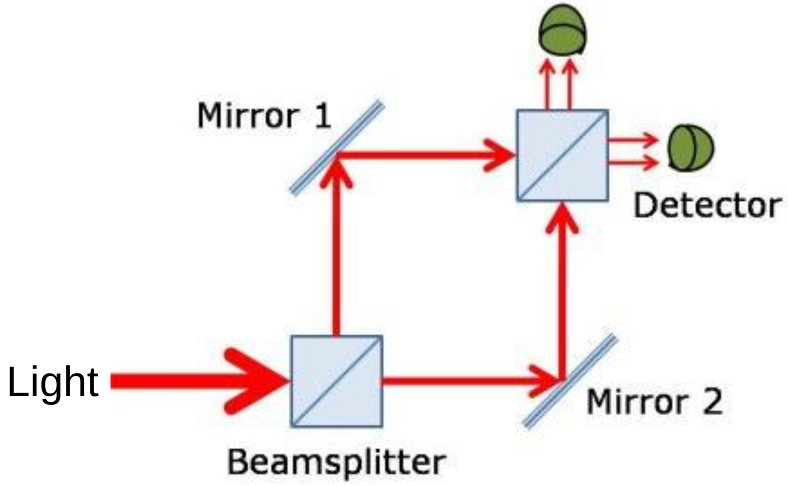
Example of Open Questions in Fundamental Physics

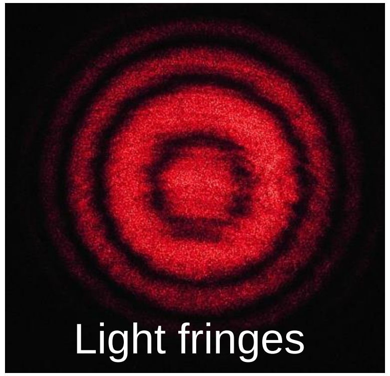
- What is dark matter made of?
- What is dark energy made of?
- Why is there more matter than antimatter in the universe?
- How heavy are the neutrinos? What was their role in the formation of the universe?
- Is there a quantum theory of gravity that can describe the universe we live in?
- What is the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

AION AND MAGIS EXPERIMENTS EXAMPLE OF TERRESTRIAL DETECTOR

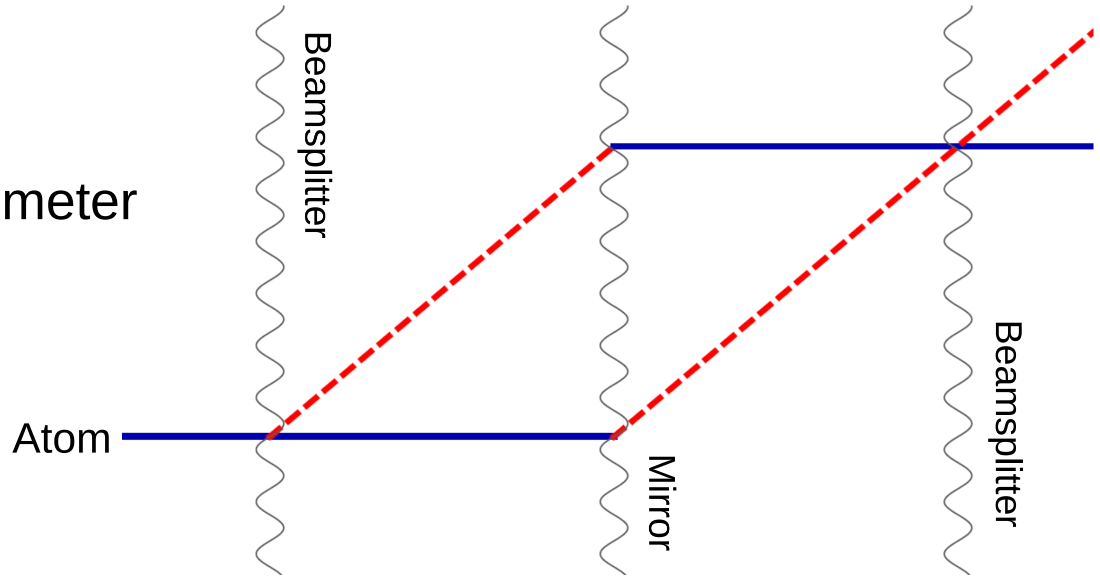
Light vs. Cold Atoms: Atom Interferometry

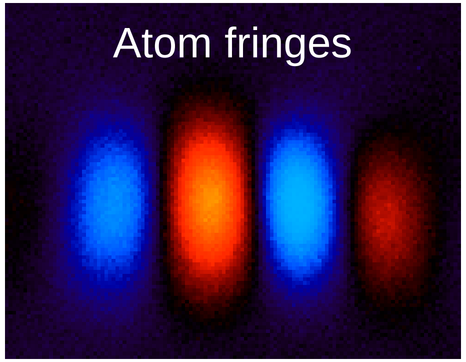
Light interferometer





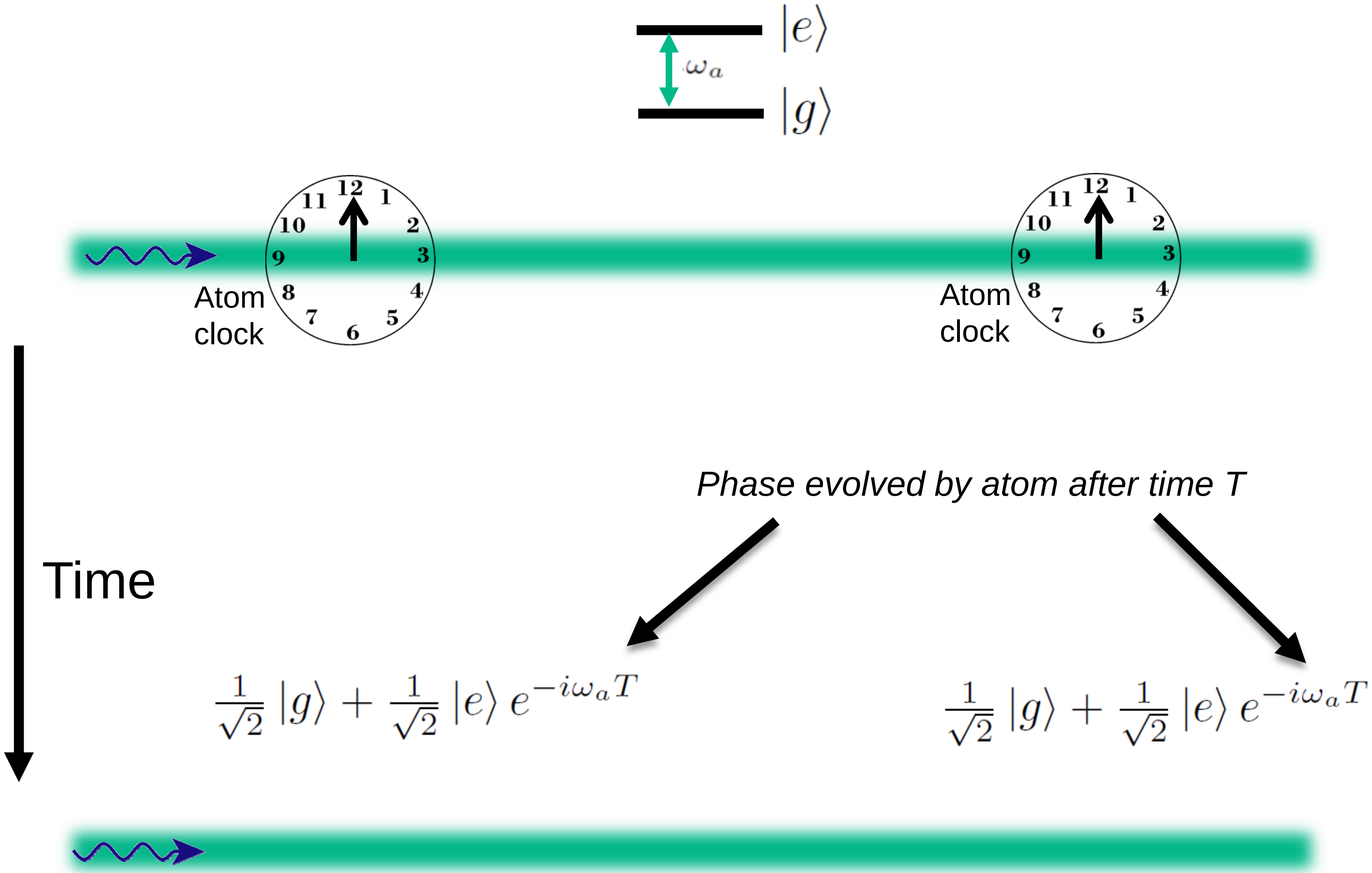
Atom interferometer





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

Simple Example: Two Atomic Clocks



Courtesy of Jason Hogan!

Simple Example: Two Atomic Clocks

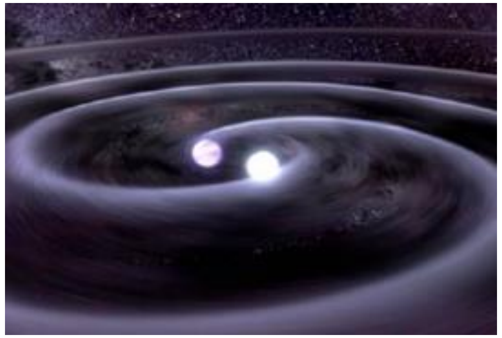
$|e\rangle$

ω_a

$|g\rangle$

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

Time

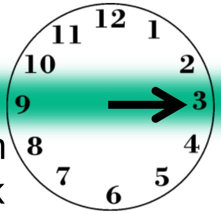


GW changes light travel time

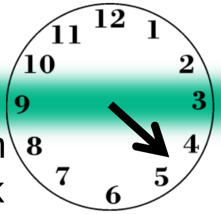
$\Delta T \sim hL/c$

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

Atom clock



Atom clock



Courtesy of Jason Hogan!

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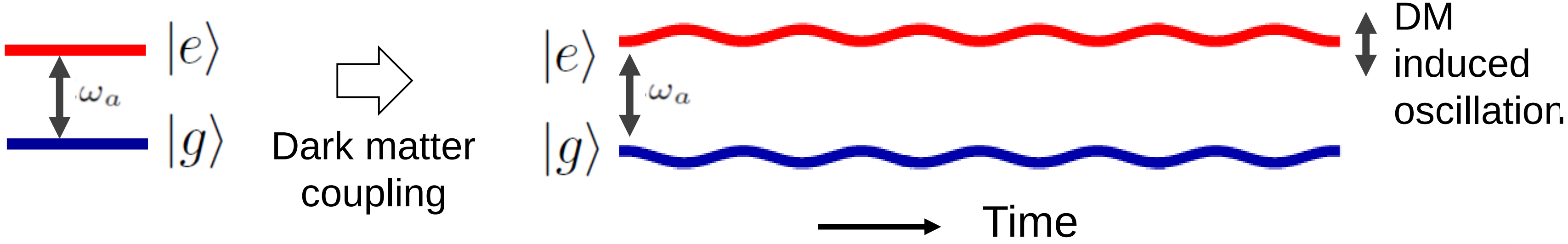
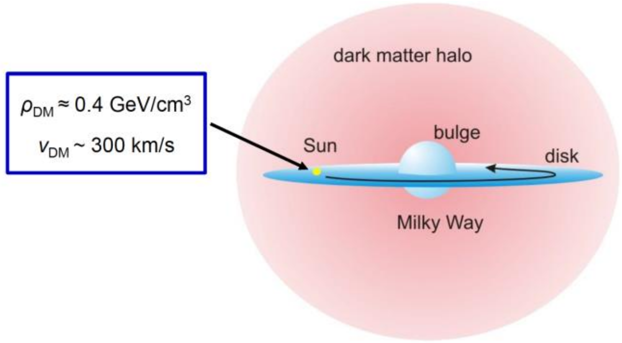


$\Delta\omega_a^{DM}$



DM cloud changes atom frequency

DM coupling causes time-varying atomic energy levels:

Time

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

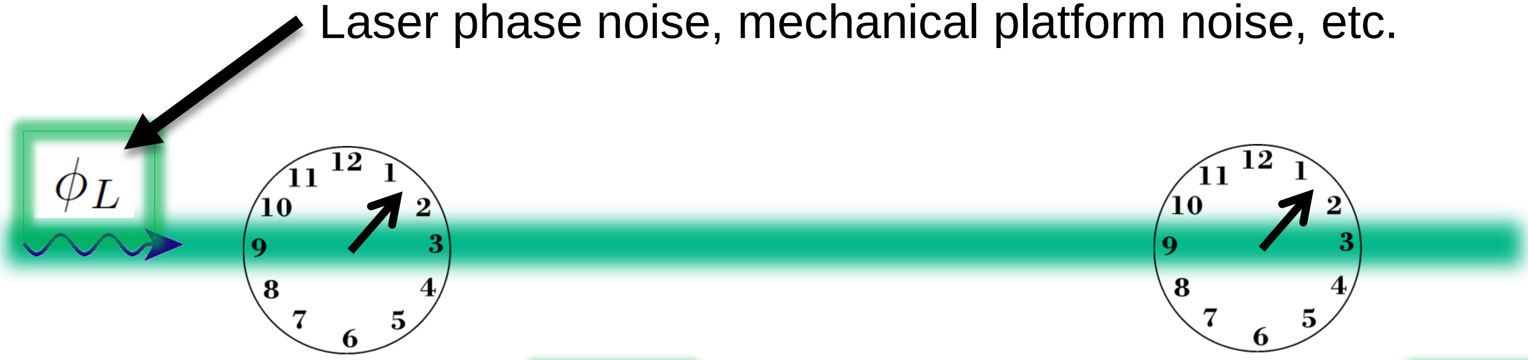
$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle \quad e^{-i(\omega_a+\Delta\omega_a^{DM})T}$$

Courtesy of Jason Hogan!

Phase Noise from the Laser

The phase of the laser is imprinted onto the atom.

Laser phase noise, mechanical platform noise, etc.



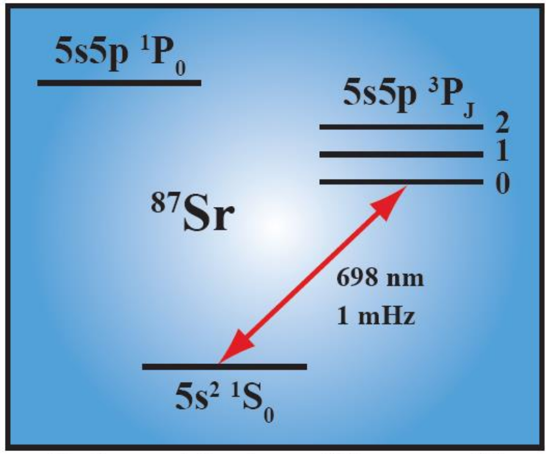
$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle e^{i\phi_L} \qquad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle e^{i\phi_L}$$

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

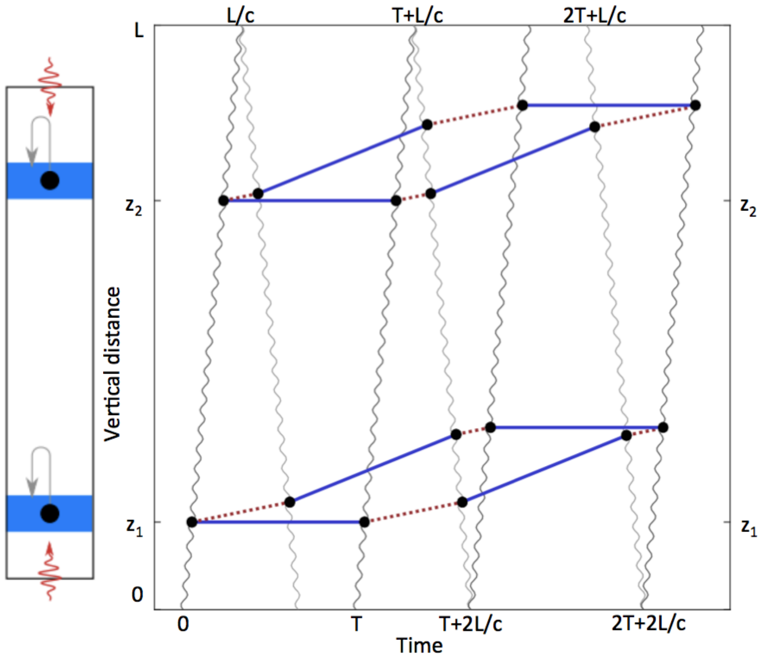
Courtesy of Jason Hogan!

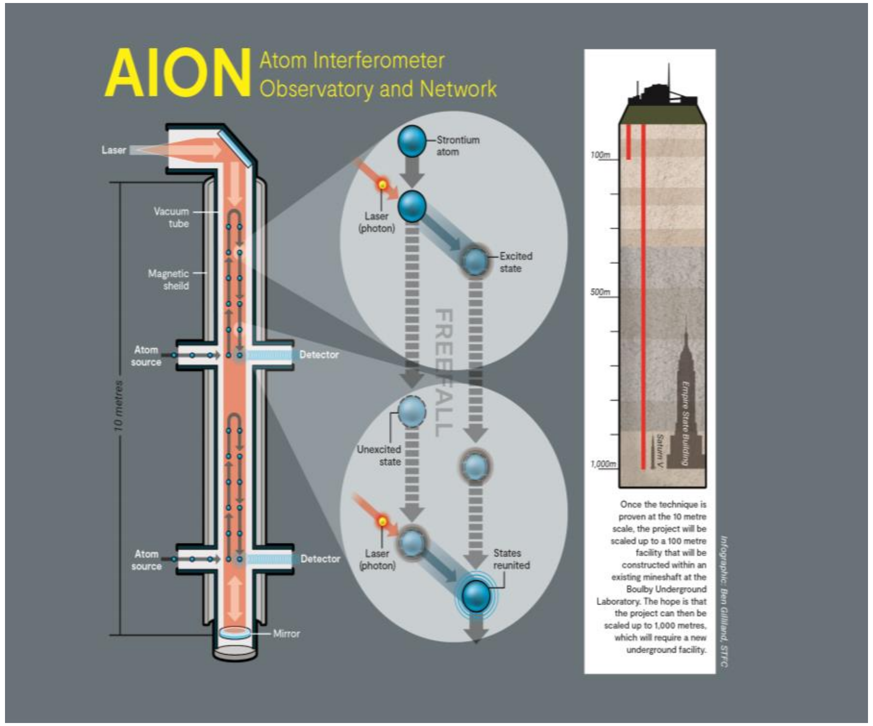
AION: A Different Kind of Atom Interferometer

Hybrid "clock accelerometer"



Clock transition in candidate atom ^{87}Sr





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

Sensitivity Scenario	L [m]	T_{int} [sec]	$\delta\phi_{\rm noise}$ $[1/\sqrt{\rm Hz}]$	LMT [number n]
AION-10 (initial)	10	1.4	10^{-3}	100
AION-10 (goal)	10	1.4	10^{-4}	1000
AION-100 (initial)	100	1.4	10^{-4}	1000
AION-100 (goal)	100	1.4	10^{-5}	40000
AION-km	2000	5	0.3×10^{-5}	40000

Used for sensitivity projections

For ultimate sensitivity we need to push each basic parameter by ~O(10).

The project aims to demonstrate in funding period e.g.

- LMT: ~1000 hbar*k
- Squeezing ~ 20dB for > 1e6 Atoms

AION

The AION Programme consists of 4 Stages

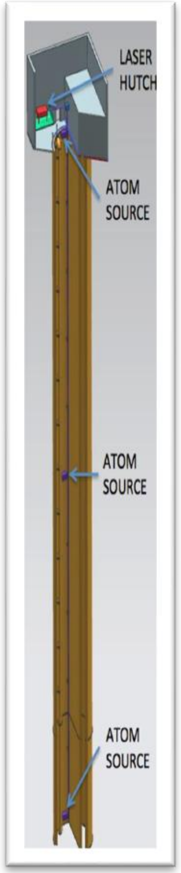
- **Stage 1:** to build and commission the 10 m detector, develop existing technology and the infrastructure for the 100 m.
- **Stage 2:** to build, commission and exploit the 100 m detector and carry out a design study for the km-scale detector.
  - AION was selected in 2018 by STFC as a high-priority 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 now funded with about £10M 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).

L ~ 10m

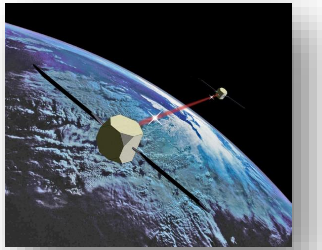
L ~ 100m

L ~ 1km



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



AION Collaboration Days in Oxford: Fall 2021

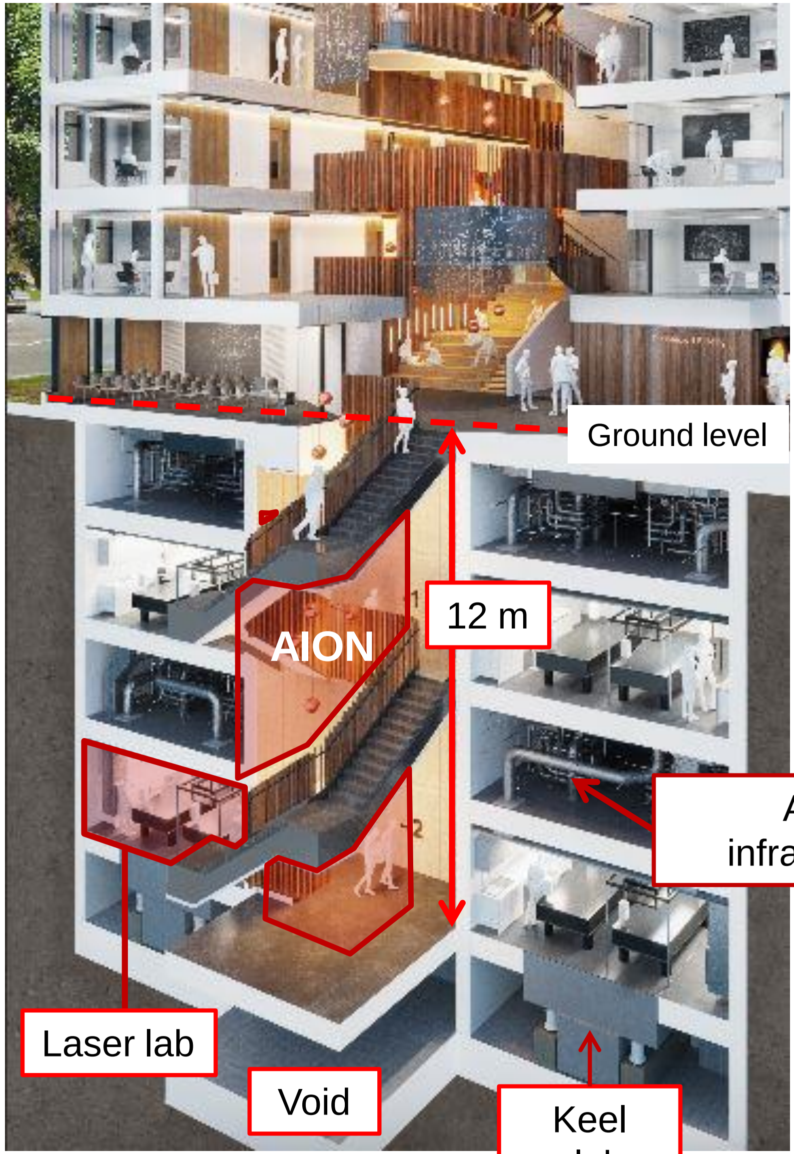
Start of AION in 2018
~5 people

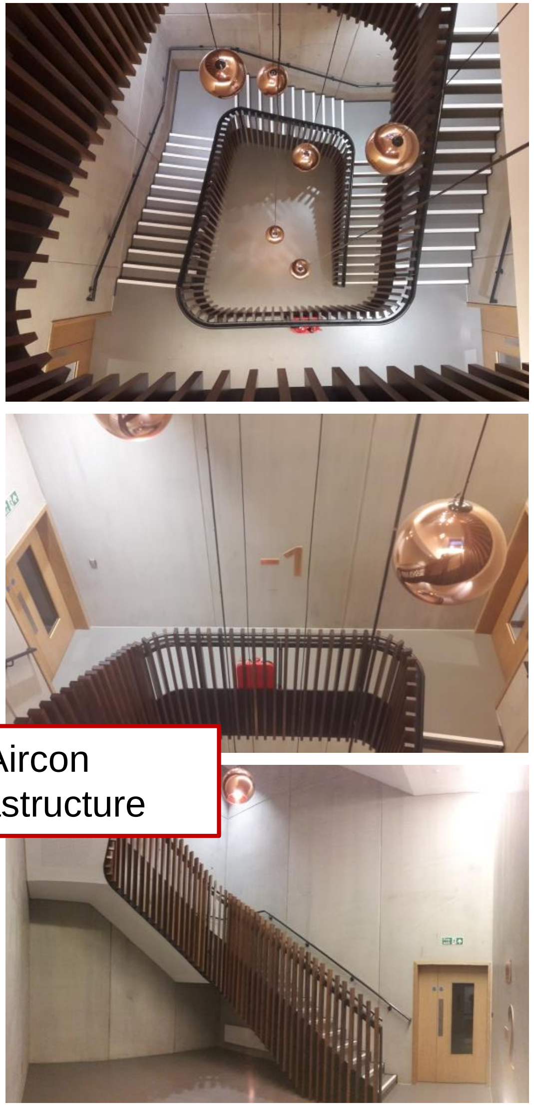
Today, AION
~60 people
(52 came to Oxford)

https://aion-project.web.cern.ch

Ratio of Cold Atom : Particle/Fundamental Physics people is 1:1

Beecroft building, Oxford Physics





Ultralow vibration
- All plant isolated
- Thick concrete walls

Adjacent laser lab reserved for AION use
- keel slabs
- ±0.1°C stability
- Isolated mains

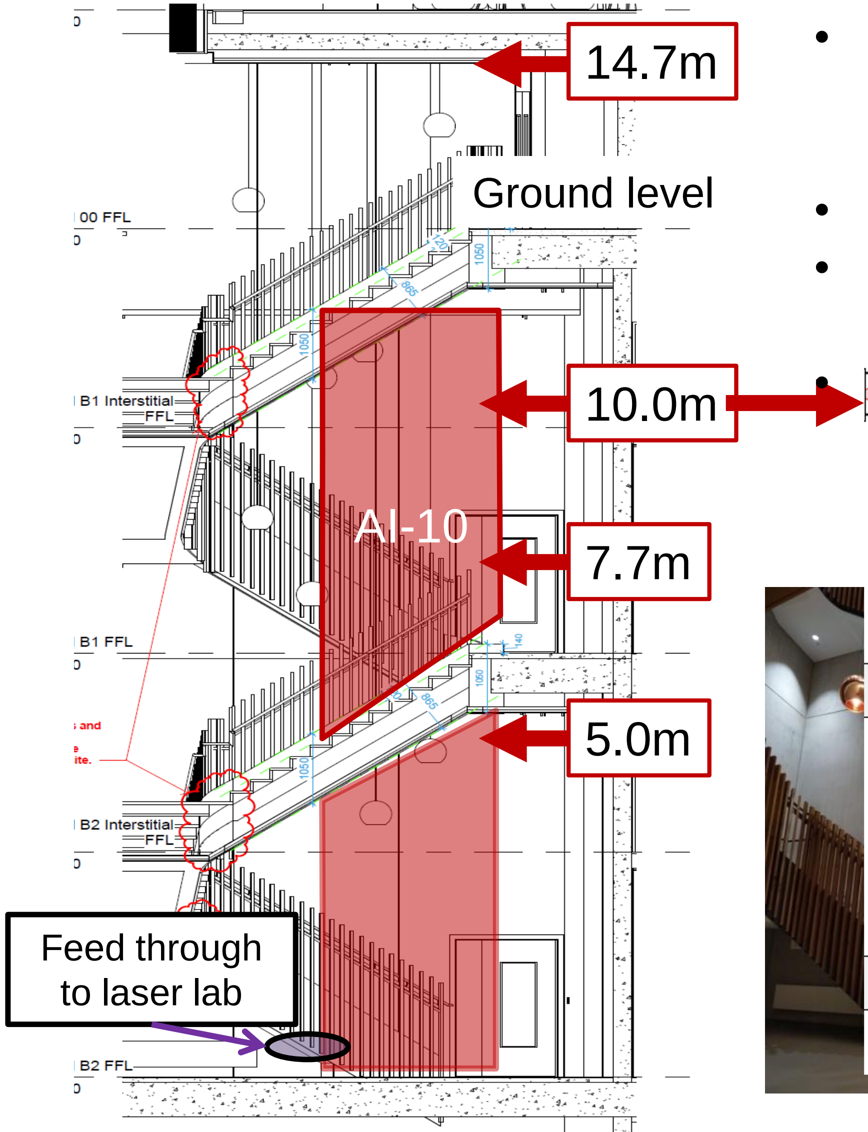
Vertical space
- 12m basement to ground floor
- 14.7m floor to ceiling

Stairwell is **not** a fire escape route.

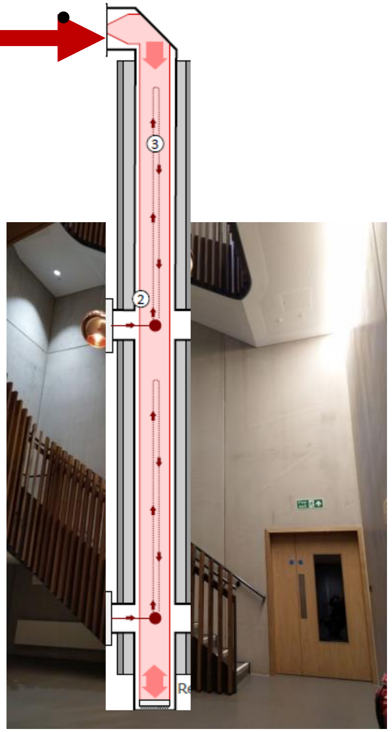
Bakeout room and cleanroom nearby

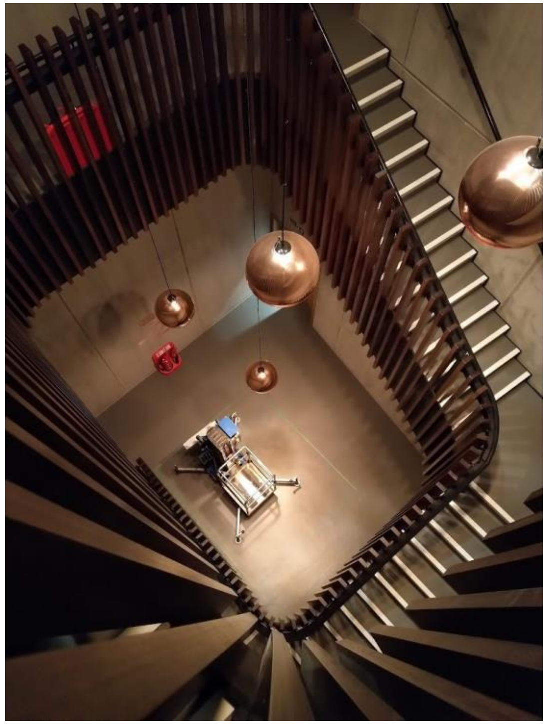
AION-10 site: Beecroft building, Oxford Physics

Beecroft building – brand new, low-vibration laser lab and concrete stairwell



- Detailed planning of support structure by RAL (Engineering), Oxford Physics Technical Services and Liverpool Univ.
- Experienced Project Manager: Roy Preece
- Good site for long-term operation and wide accessibility (also 'visibility' and outreach).



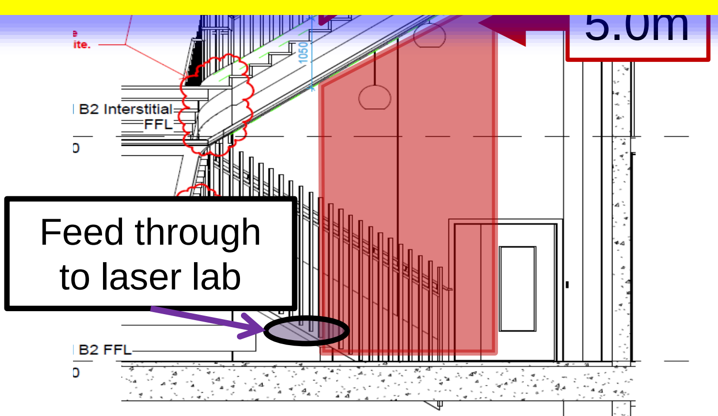


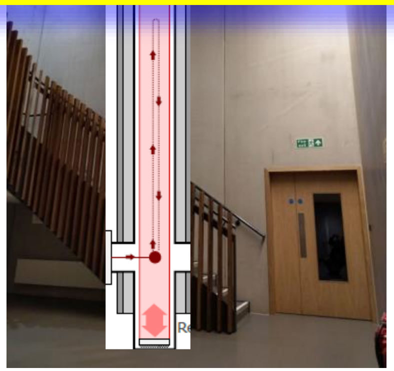
AION-10 site: Beecroft building, Oxford Physics

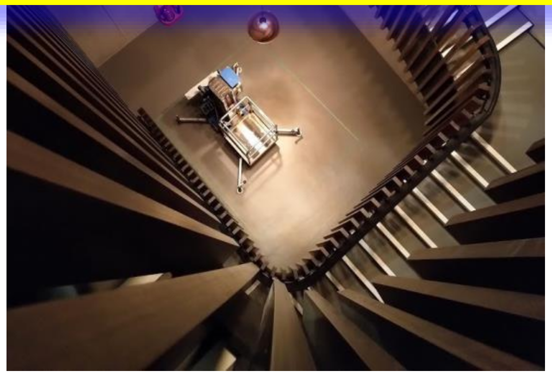
Beecroft building – brand new, low-vibration laser lab and concrete stairwell

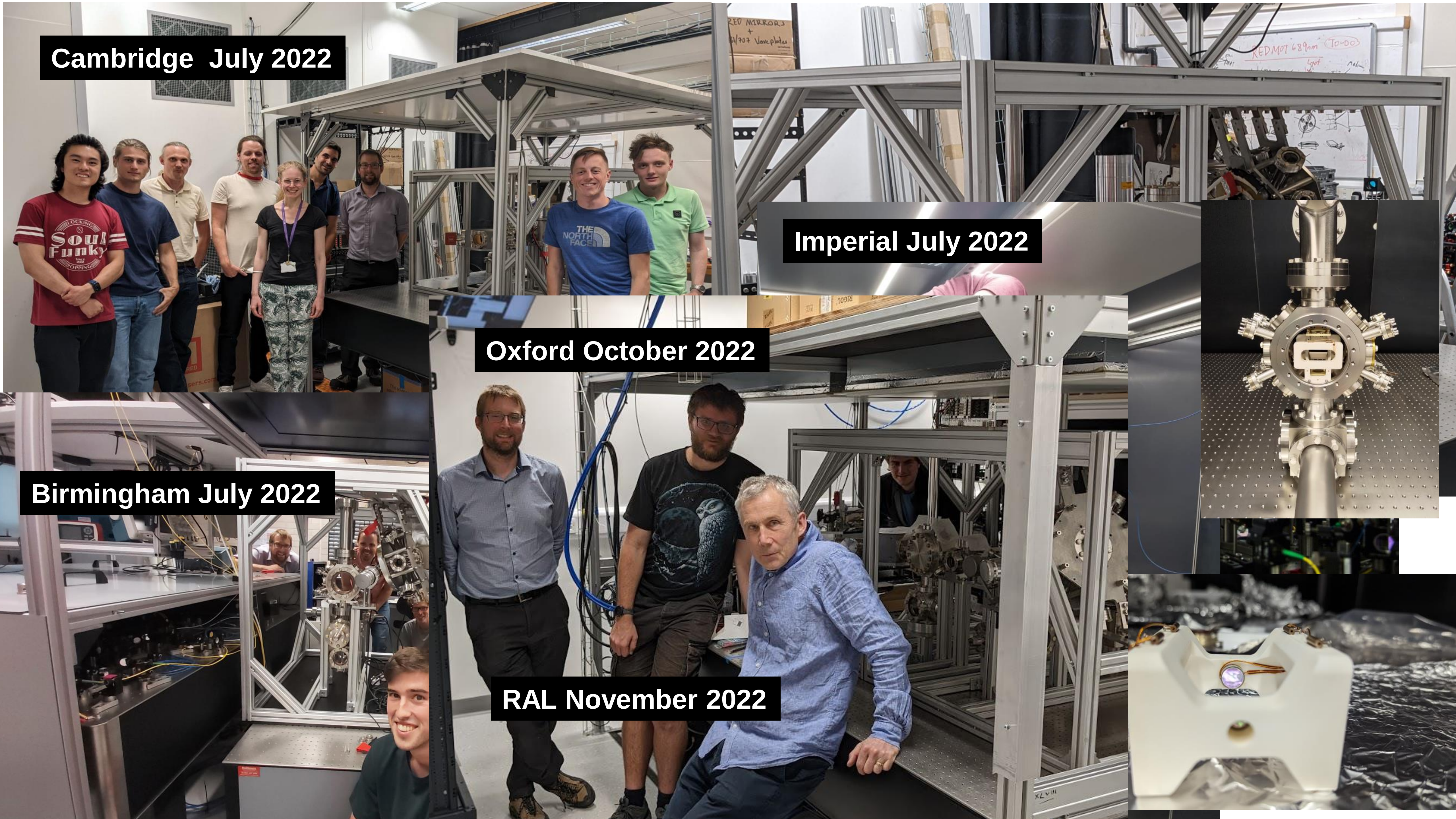
For the first 30 months of the project, we will focus on the perquisites for the 10m detector:

- Establish the Cold Atom infrastructure (e.g. build UltraCold Sr Laser Labs) and expertise
- Develop full design for 10m detector, ready for physics exploitation
- Partner AION with the MAGIS experiment in the US



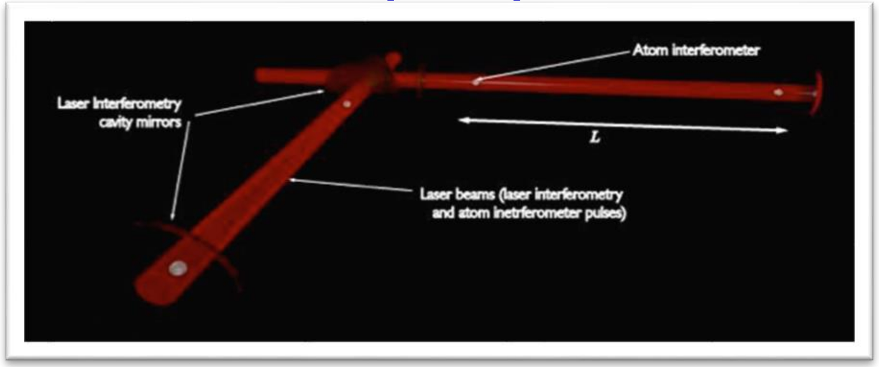




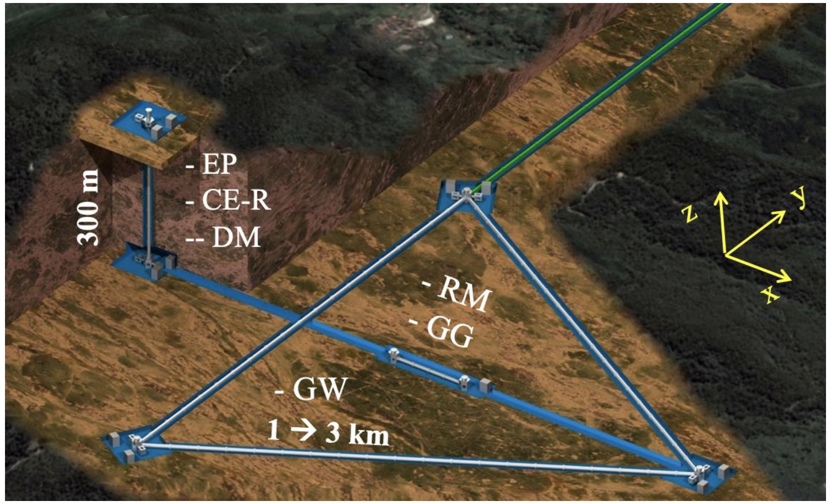

Cambridge July 2022
Imperial July 2022
Oxford October 2022
Birmingham July 2022
RAL November 2022

Ground Based Large Scale O(100m) Projects

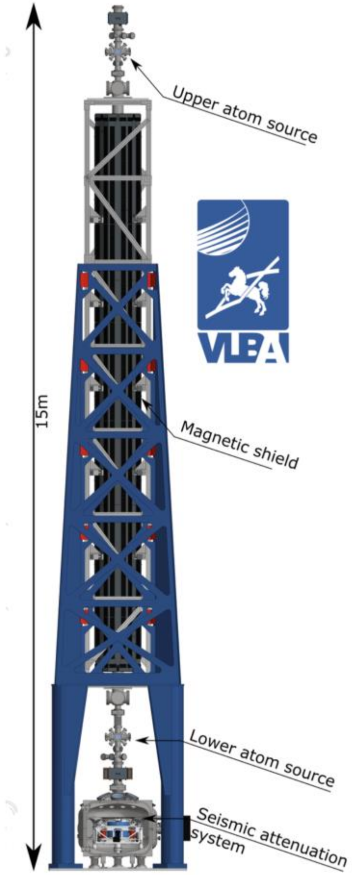
MIGA: Terrestrial detector using atom interferometer at O(100m)
(France)

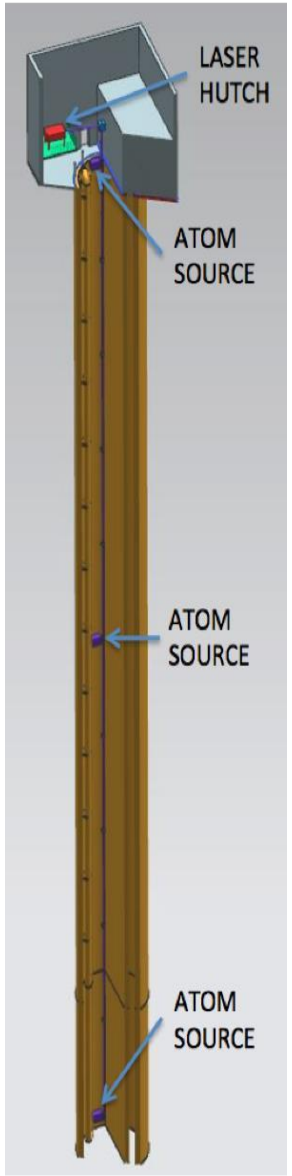


ZIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)
(China)

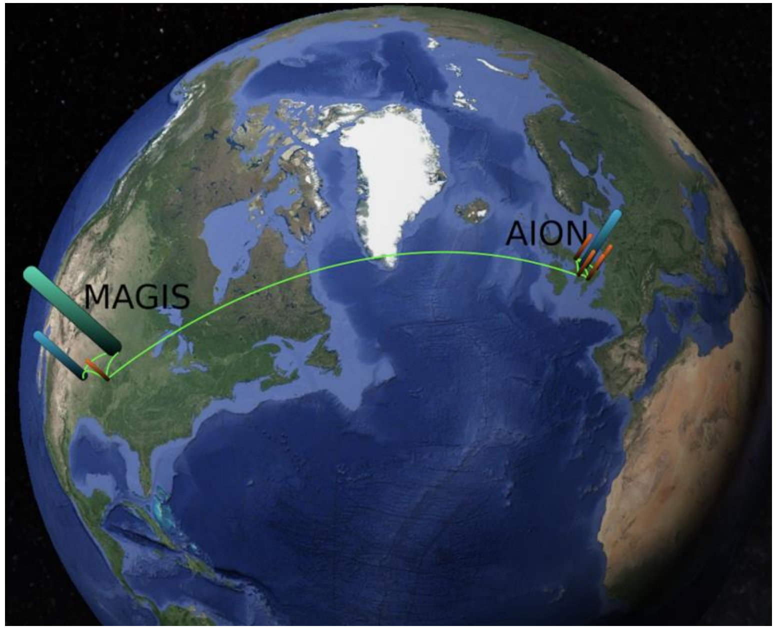


VLBAI: Terrestrial tower using atom interferometer O(10m)
(Germany)





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

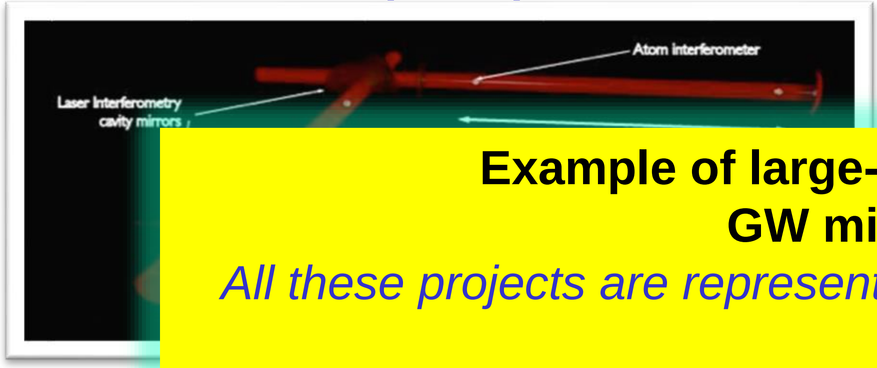


MAGIS: Terrestrial shaft detector using atom interferometer at O(100m)
(US)

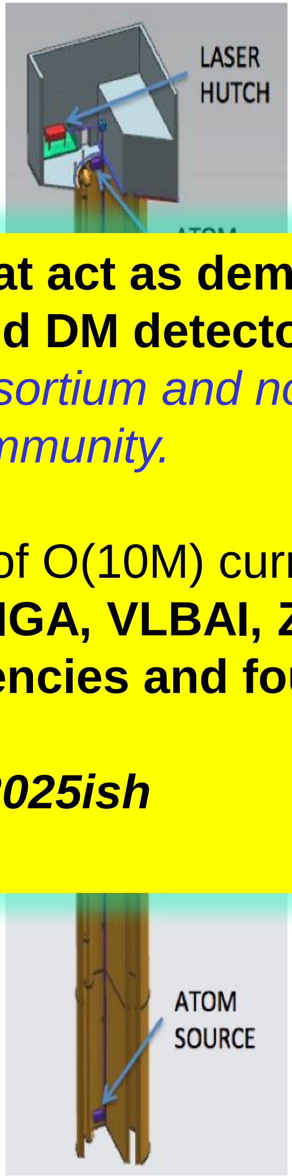
Planned network operation

Ground Based Large Scale O(100m) Projects

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



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



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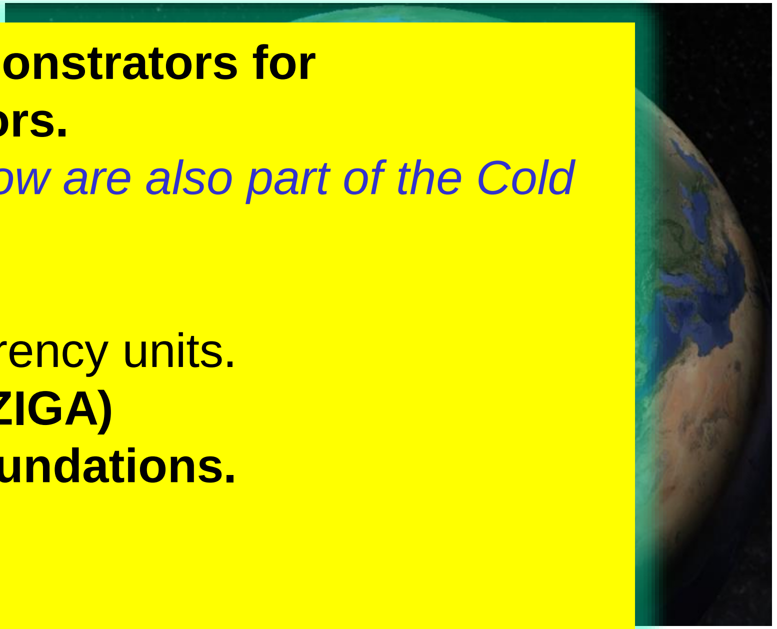


Example of large-scale CA projects that act as demonstrators for GW mid-frequency band and DM detectors.

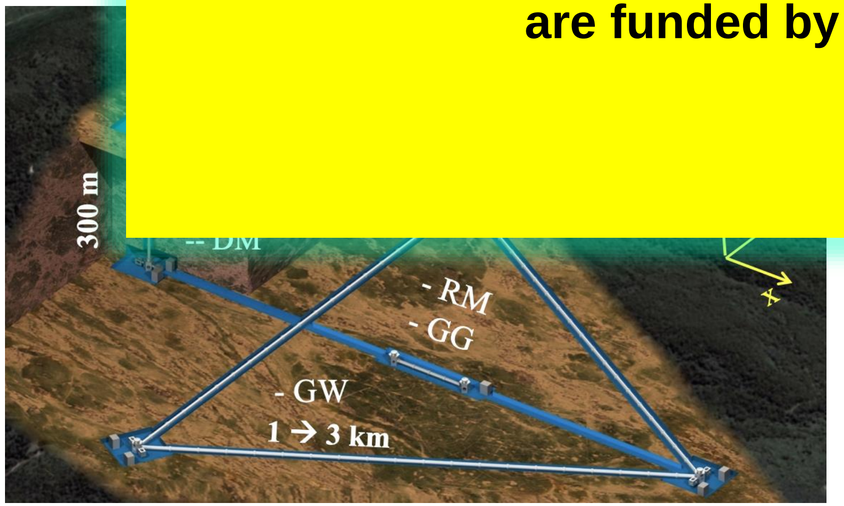
All these projects are represented in the AEDGE consortium and now are also part of the Cold Atoms in Space Community.

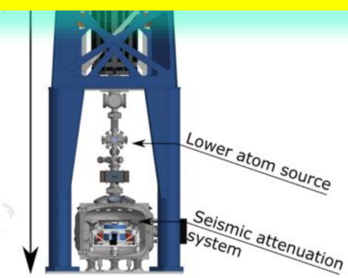
Each project requires an investment of O(10M) currency units.

All projects (AION, MAGIS, MIGA, VLBAI, ZIGA) are funded by national funding agencies and foundations.

Timeline 2020 to 2025ish

ZIGA: interf





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

Planned network operation

Terrestrial Long-Baseline Atom Interferometer Workshop at CERN

- Organise a Workshop in early 2023 to discuss **"Terrestrial Long-baseline Atoms Interferometry for Fundamental Physics"** and the option for building international facilities/experiments.
- The aim is to engage and organise the community and have all the national big players present.
- The Physics Beyond Collider Team and the Quantum Initiative Team at CERN kindly agree to help us to host this event at CERN.
- We are planning for a 2-day in-person workshop with the option to connect remotely to the event via zoom.
- Although the focus will be on terrestrial long-baseline detectors, we believe there are important synergies with our Cold Atom Community activity in Space.

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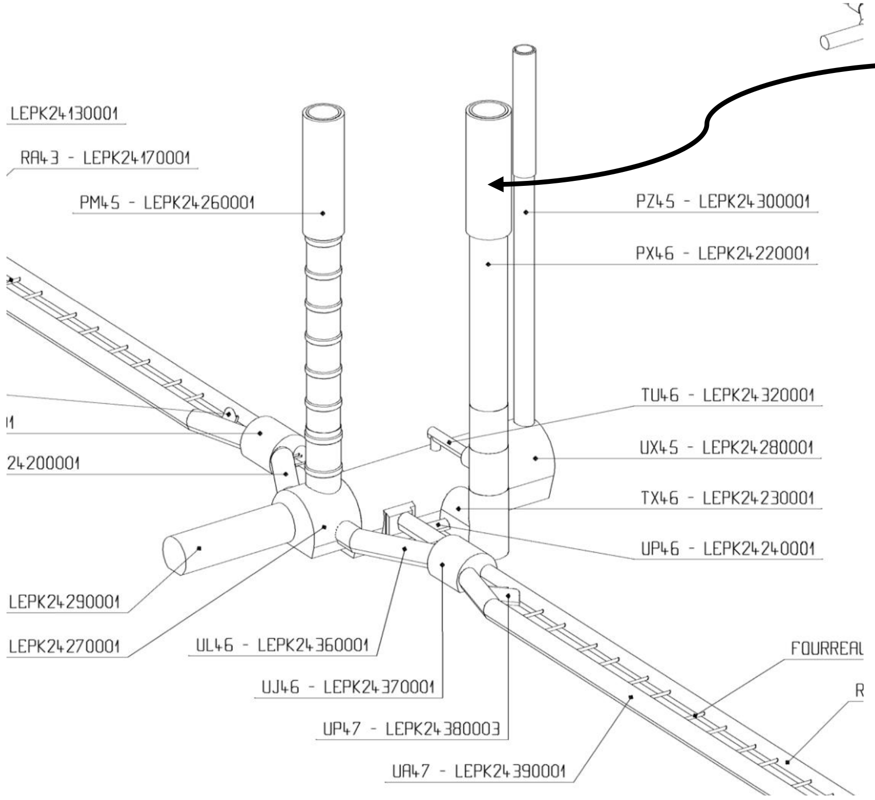
Workshop will at CERN
in the Council Chamber
on March 13/14 2023
[announcement coming soon]

Possible CERN Site for AION 100m



PX46 – P4 Support shaft

Lengths 143m

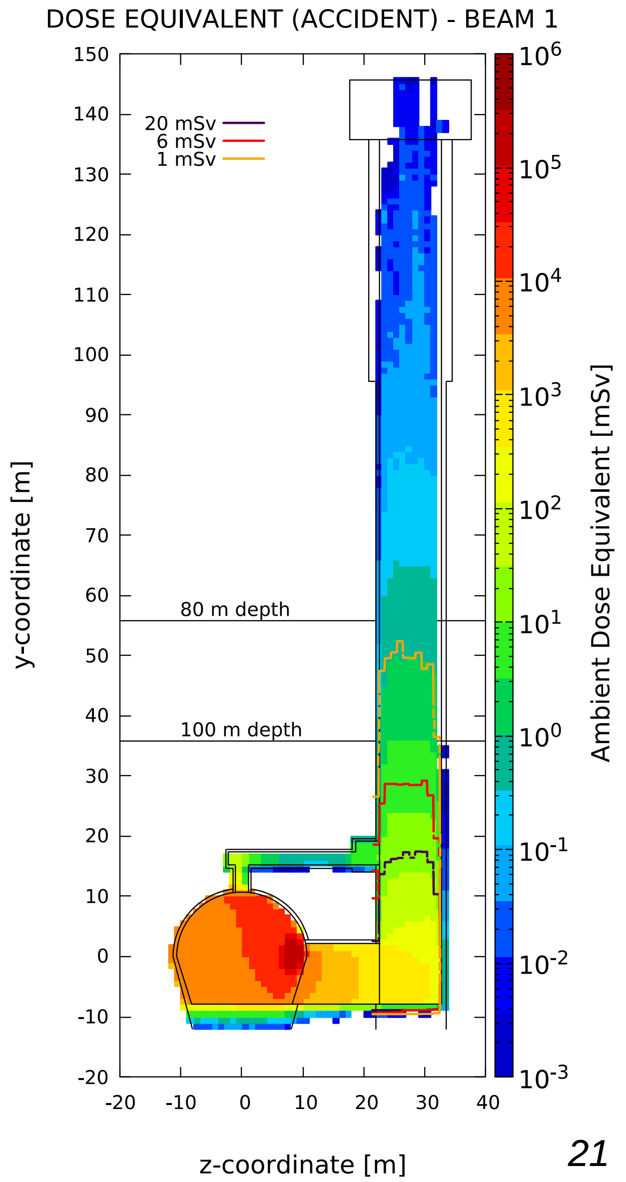
D = 10.10m

- **Ideal basic parameters for AION100**

First radiation studies are also Looking promising but more work is needed to determine if PX46 could be a valid option for AION 100.

We are working with PBC Team on this feasibility study

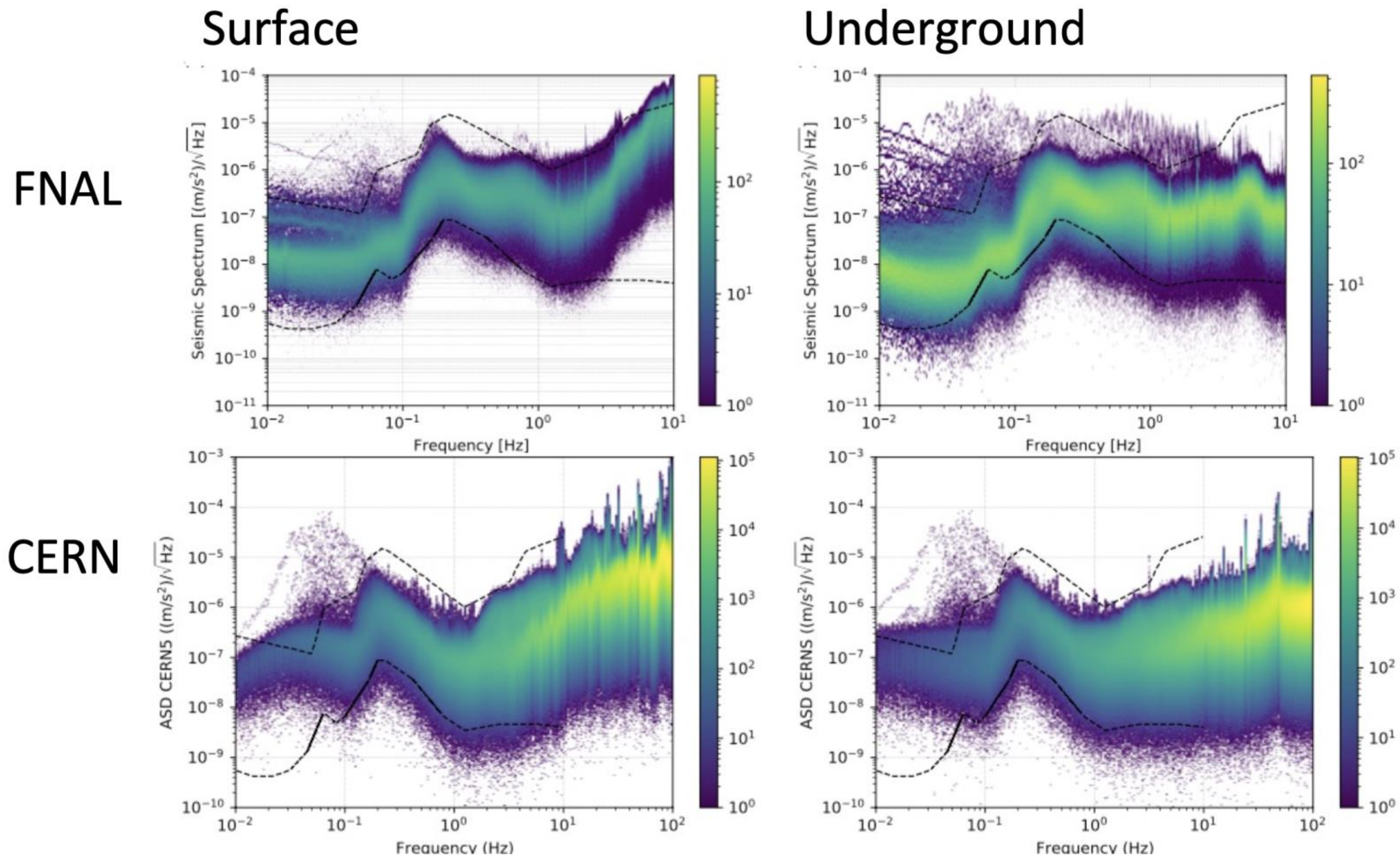
Physics Beyond Colliders

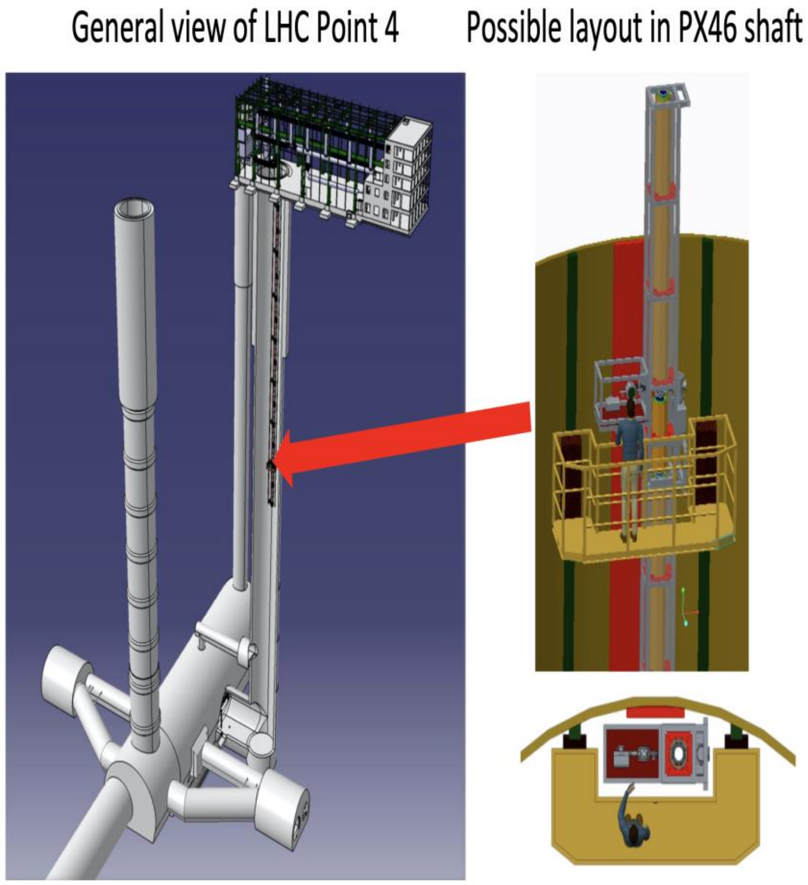


Other site options that are currently investigated are the ***national facility in Boulby and Daresbury (UK).***

CA QT For Fundamental Physics – FIPs 2022

A 100 Detector at CERN – Site Investigation

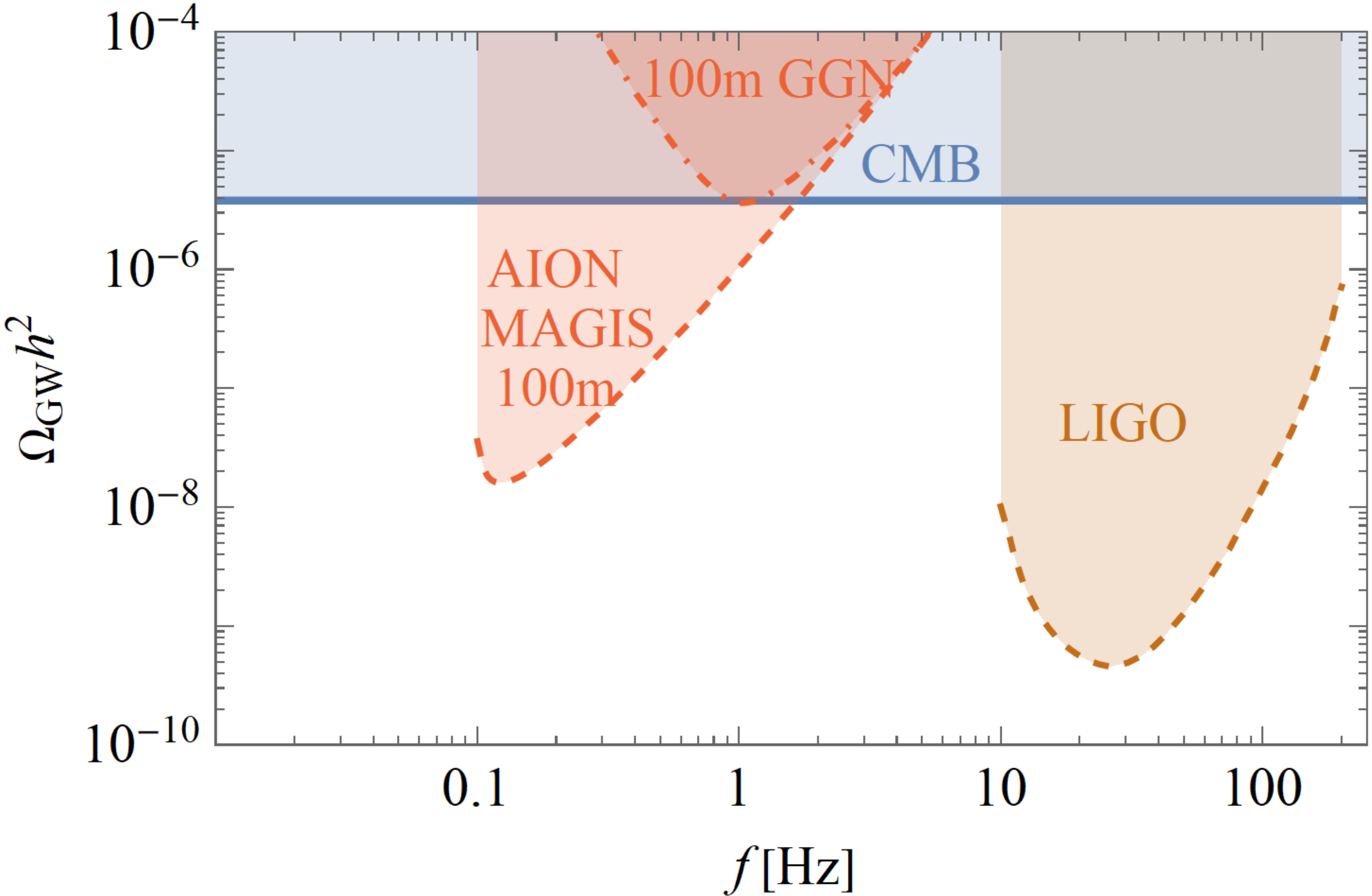




Spectrum similar to that measured at Fermilab for MAGIS

More about the site investigation in the backup

The GW Experimental Landscape: 2030ish



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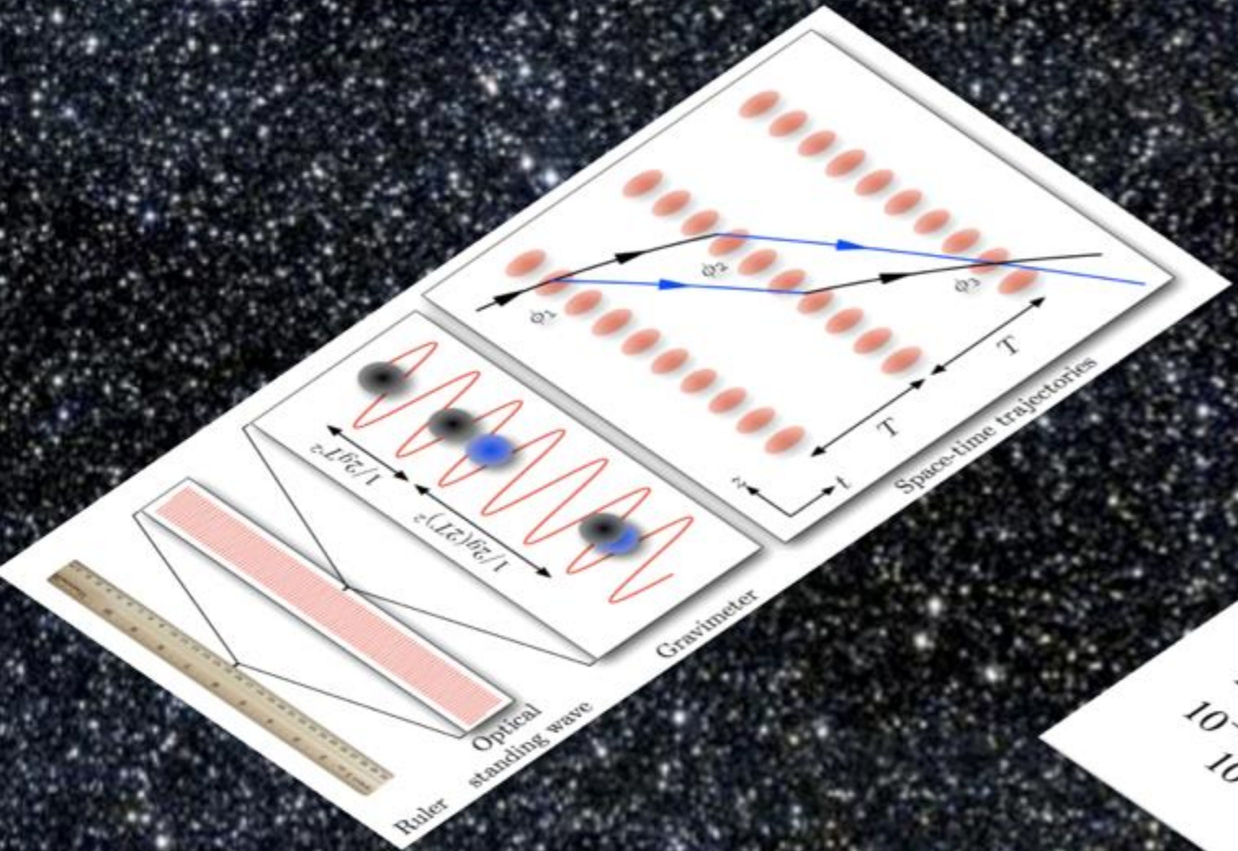
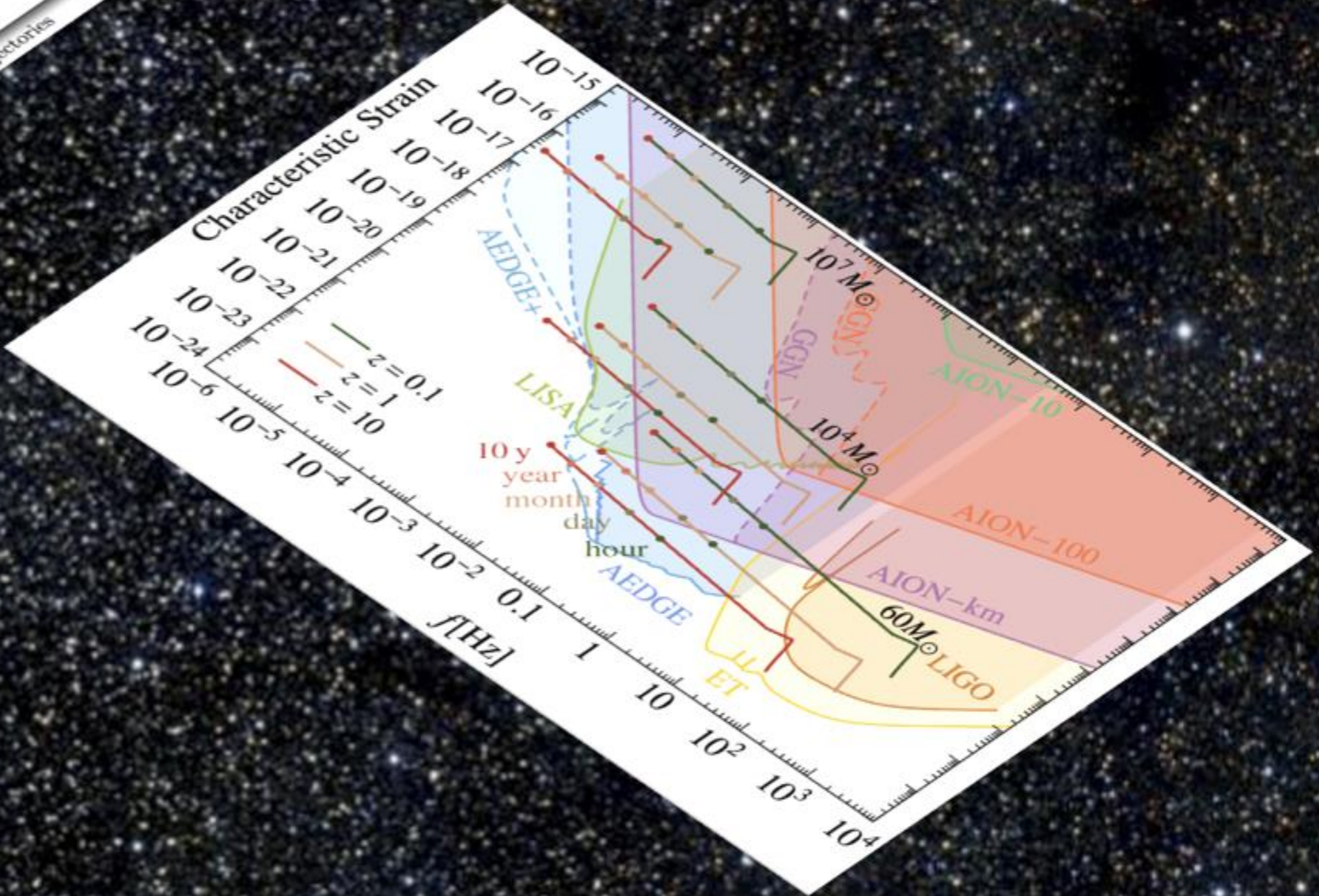
COMMUNITY WORKSHOP FOR COLD ATOMS IN SPACE

Community Workshop on Cold Atoms in Space



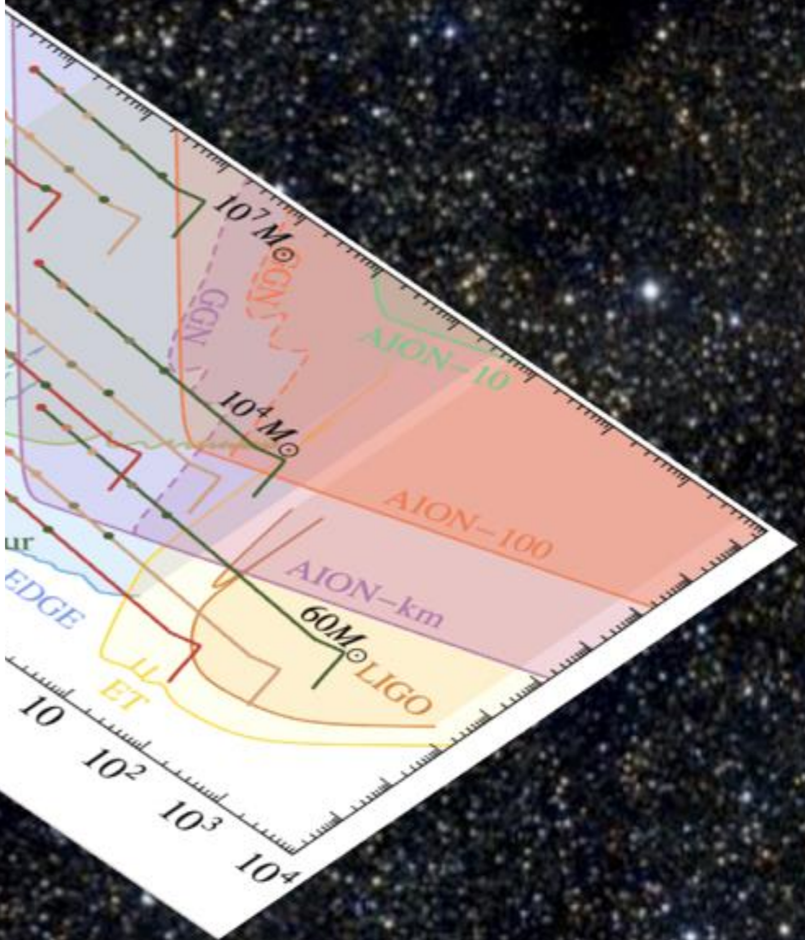


Virtual Workshop
September 23/24 2021

Supported by CERN Quantum Technology Initiative

Community Workshop
toms in Space

Angelo Bassi, University of Trieste, Italy
Kai Bongs, University of Birmingham, UK
Philippe Bouyer, CNRS, Institut d'Optique, France
Oliver Buchmueller, Imperial College London, UK
Luigi Cacciapuoti, European Space Agency
Marilù Chiofalo, University of Pisa and INFN Pisa, Italy
Albert De Roeck, CERN, Geneva, Switzerland, and University of Antwerp, Belgium
Michael Doser, CERN, Geneva, Switzerland
John Ellis, King's College London, UK
Rene Forsberg, DTU Space, Denmark
Thomas Lévèque, Centre National d'Etudes Spatiales, France
Christian Lisdat, Physikalisch-Technische Bundesanstalt, Germany
Federica Migliaccio, DICA, Politecnico di Milano, Italy
Ernst Rasel, Leibniz Universität Hannover, Germany
Stephan Schiller, Heinrich-Heine-Universität Düsseldorf, Germany
Christian Schubert, Leibniz Universität Hannover, Germany
Carla Signorini, INFN Pisa, Italy
Guglielmo Tino, Università di Firenze and LENS, Italy
Wolf von Klitzing, IESL-FORTH, Greece
Peter Wolf, *CNRS, Observatoire de Paris-PSL, Paris, France*



Supported by CERN Quantum Technology Initiative

Community Workshop for Cold Atoms in space

09:00 → 10:10 Workshop Introduction

- 09:00 **Introduction** (10m) — Speaker: Oliver Buchmueller and John Ellis — Workshop ...
- 09:10 **Senior Committee Recommendations for Voyage 2050** (30m) — Speaker: Mike Cruise — Voyage 20...
- 09:40 **ESA Perspective on Cold Atoms in Space** (30m) — Speaker: Olivier Carraz — ESA Persp...

10:10 → 11:00 Voyage2050 White Paper Reviews

- 10:10 **Exploring the Foundations of the Physical Universe with Space Tests of the Equivalence Principle** (10m) — Speaker: Peter Wolf — Wolf_UFF-t...
- 10:20 **AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration** (10m) — Speaker: John Ellis — CAIS-AED...
- 10:30 **Quantum Technologies in Space** (10m) — Speaker: Mauro Paternostro — Communit...
- 10:40 **The Missing Link in Gravitational-Wave Astronomy** (10m) — Speaker: Shimon Kolkowitz — Cold_Atom...
- 10:50 **The local dark sector** (10m) — Speaker: Joel Berge — jberge_dar...

11:00 → 12:30 Atomic Clock Reviews

- 11:00 **Space Clock Projects China** (15m) — Speaker: Yu-Ao Chen
- 11:15 **Space Clock Projects US** (15m) — Speaker: Kurt Gibble — Gibble FOC...
- 11:30 **Atomic Clocks Review** (15m) — Speaker: Sebastien Bize — ESA works...
- 11:45 **Atomic Clocks for SI Second Redefinition** (15m) — Speaker: Helen Margolis — Optical clo...
- 12:00 **Atomic Clocks for Geodesy** (15m) — Speaker: Hu Wu — CERN_Hu...
- 12:15 **Space Clock Projects Europe** (15m) — Speaker: Kai Bongs — 210617_Cl...

12:30 → 13:00 Break with Virtual Breakout Rooms for Discussion

13:00 → 14:30 Earth Observation Reviews

- 13:00 **User requirements as a basis for a future quantum space gravimetry mission** (15m) — Speaker: Federica Migliaccio — User_Requi...
- 13:15 **Methods for atom interferometry in space in the context of earth observation** (15m) — Speaker: Christian Schubert
- 13:30 **Quantum space gravimetry at European Commission** (15m) — Speaker: Frederic Domps — QSG@FC... QSG@FC...
- 13:45 **Earth Observation: ESA perspective** (15m) — Speaker: Olivier Carraz — QT_2021_E...
- 14:00 **CAI and GRICE Studies** (15m) — Speaker: Franck Pereira dos Santos — Communit...

14:30 → 15:00 Break with Virtual Breakout Rooms for Discussion

15:00 → 16:30 Fundamental Science Review

- 15:00 **Wave Function Collapse** (20m) — Speaker: Sandro Donadi — Wave Func...
- 15:15 **Atom interferometry for testing the equivalence principle in space** (20m) — Speaker: Naceur Gaaloul — Communit...
- 15:30 **Dark Matter and Gravitational Waves** (20m) — Speaker: Oliver Buchmueller — GW and D...
- 15:45 **Dark Energy** (20m) — Speaker: Nan Yu — ECWCAP2...

16:30 → 17:00 Break with Virtual Breakout Rooms for Discussion

09:00 → 10:30 Towards a Community Roadmap: Review of Pathfinders on Earth and in Space

- 09:00 **Large Scale Strontium Pathfinder Projects** (20m) — Speaker: Richard Hobson — Sr pathfind... Sr pathfind...
- 09:20 **Large Scale Rubidium Pathfinder Projects** (20m) — Speaker: Benjamin Canuel — Large_Scal...
- 09:40 **MAIUS and related activities** (20m) — Speaker: Ernst Rasel — Communit...
- 10:00 **Technology Perspective** (20m) — Speaker: Kai Bongs — Cold_Atom...

10:30 → 11:00 Break with Virtual Breakout Rooms for Discussion

11:00 → 12:45 Towards a Community Roadmap: Space Agency Perspectives

- 11:00 **ESA** (30m) — Speaker: Eamonn Murphy & Eric Wille & Pierre Waller — Presentati...
- 11:30 **ASI** (15m) — Speaker: Marco Di Clemente — quantum_...
- 11:45 **CNES** (15m) — Speaker: Thomas Leveque — Workshop_...
- 12:00 **DLR** (15m) — Speaker: Karin Kiewisch — 20210923_...
- 12:15 **UKSA** (15m) — Speaker: Benjamin Wells — UKSA Pres...
- 12:30 **NASA** (15m) — Speaker: Ulf Israelsson — NASA Cold... NASA Cold...

12:45 → 13:15 Break with Virtual Breakout Rooms for Discussion

13:15 → 14:45 Community Roadmap Discussion

- 13:15 **Report from Atomic Clocks Breakout Sessions** (10m) — Speaker: Christian Lisdat — Summary ...
- 13:25 **Report from Earth Observation Breakout Sessions** (10m) — Speaker: Federica Migliaccio, Rene Forseberg — Summary_...
- 13:35 **Report from Fundamental Physics Breakout Sessions** (10m) — Speaker: John Ellis — TowardsR...
- 13:45 **Report from General Perspectives Breakout Sessions** (10m) — Speaker: Marilù Chiofalo, Rosa Poggiani
- 13:55 **Discussion** (30m) — Speaker: ALL

15:00 → 16:00 Community Roadmap Writeup [closed session]

Community Workshop for Cold Atoms in space

Closely related to FP

Interest from space agencies

Other interesting space applications of cold atoms

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- 13:55 Discussion — Speaker: ALL (30m)

15:00 → 16:00 Community Roadmap Writeup [closed session]

Community Workshop Summary & Road-map

Cold Atoms in Space:

Community Workshop Summary and Proposed Road-Map

https://arxiv.org/abs/2201.07789

Iván Alonso,[1] Cristiano Alpigiani,[2] Brett Altschul,[3] Henrique Araújo,[4] Gianluigi Arduini,[5]
Jan Arlt,[6] Leonardo Badurina,[7] Antun Balaž,[8] Satvika Bandarupally,[9,10] Barry C Barish,[11]
Michele Barone,[12] Michele Barsanti,[13] Steven Bass,[14] Angelo Bassi,[15,16,*] Baptiste Battelier,[17]
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Jose Bernabeu,[20,21] Andrea Bertoldi,[17] Robert Bingham,[22,23] Sébastien Bize,[18] Diego Blas,[24,25]
Kai Bongs,[26,*] Philippe Bouyer,[17,*] Carla Braitenberg,[15] Christian Brand,[27] Claus Braxmaier,[28,27]
Alexandre Bresson,[19] Oliver Buchmueller,[4,29,*,@] Dmitry Budker,[30,31] Luís Bugalho,[32]
Sergey Burdin,[33] Luigi Cacciapuoti,[34,*] Simone Callegari,[35] Xavier Calmet,[36] Davide Calonico,[37]
Benjamin Canuel,[17] Laurentiu-Ioan Caramete,[38] Olivier Carraz,[34,*] Donatella Cassettari,[40]
Pratik Chakraborty,[41] Swapan Chattopadhyay,[42,43,31] Upasna Chauhan,[44] Xuzong Chen,[45]
Yu-Ao Chen,[46,47,48] Maria Luisa Chiofalo,[13,49,*] Jonathon Coleman,[33] Robin Corgier,[18]
J. P. Cotter,[4] A. Michael Cruise,[26,*] Yanou Cui,[50] Gavin Davies,[4] Albert De Roeck,[51,5,*]
Marcel Demarteau,[52] Andrei Derevianko,[53] Marco Di Clemente,[54] Goran S. Djordjevic,[55]
Sandro Donadi,[16] Olivier Doré,[56] Peter Dornan,[4] Michael Doser,[5,*] Giannis Drougakis,[57]
Jacob Dunningham,[36] Sajan Easo,[22] Joshua Eby,[58] Gedminas Elertas,[33] John Ellis,[7,5,*,@]
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Marco Fattori,[9] Michael A. Fedderke,[61] Daniel Felea,[38] Chen-Hao Feng,[17] Jorge Ferreras,[22]
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Barry M. Garraway,[36] Maria Georgousi,[57] Andrew Geraci,[66] Kurt Gibble,[67] Valerie Gibson,[68]
Patrick Gill,[69] Gian F. Giudice,[5] Jon Goldwin,[26] Oliver Gould,[65] Oleg Grachov,[70]
Peter W. Graham,[43] Dario Grasso,[49] Paul F. Griffin,[23] Christine Guerlin,[71] Mustafa Gündoğan,[72]
Ratnesh K Gupta,[73] Martin Haehnelt,[68] Ekim T. Hanımeli,[74] Leonie Hawkins,[33] Aurélien Hees,[18]
Victoria A. Henderson,[72] Waldemar Herr,[41] Sven Herrmann,[74] Thomas Hird,[29]
Richard Hobson,[4,*] Vincent Hock,[74] Jason M. Hogan,[43] Bodil Holst,[75] Michael Holynski,[26]
Ulf Israelsson,[56] Peter Jeglič,[76] Philippe Jetzer,[77] Gediminas Juzeliūnas,[78] Rainer Kaltenbaek,[79]
Jernej F. Kamenik,[79] Alex Kehagias,[80] Teodora Kirova,[81] Marton Kiss-Toth,[82]
Sebastian Koke,[35,*] Shimon Kolkowitz,[83] Georgy Kornakov,[84] Tim Kovachy,[66] Markus Krutzik,[72]
Mukesh Kumar,[85] Pradeep Kumar,[86] Claus Lämmerzahl,[74] Greg Landsberg,[87]
Christophe Le Poncin-Lafitte,[18] David R. Leibrandt,[88] Thomas Lévèque,[89,*] Marek Lewicki,[90]
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Sina Loriani,[93] Jorma Louko,[65] Giuseppe Gaetano Luciano,[94] Nathan Lundblad,[95]
Steve Maddox,[82] M. A. Mahmoud,[96] Azadeh Maleknejad,[5] John March-Russell,[29]
Didier Massonnet,[89] Christopher McCabe,[7] Matthias Meister,[27] Tadej Mežnaršič,[76]
Salvatore Micalizio,[37] Federica Migliaccio,[97,*] Peter Millington,[65] Milan Milosevic,[55]
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Igor Pikovski,[107,108] Apostolos Pilaftsis,[109] Alexandra Pinto,[110] Marco Prevedelli,[111]
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Marianna Safronova,[115] Ippocratis D. Saltas,[116] Leonardo Salvi,[9,10,117] Muhammed Sameed,[109]
Pandey Saurabh,[58] Stefan Schäffer,[118] Stephan Schiller,[119,*] Manuel Schilling,[41]
Vladimir Schkolnik,[72] Dennis Schlippert,[41] Piet O. Schmidt,[35,41] Harald Schnatz,[35]
Jean Schneider,[120] Ulrich Schneider,[68] Florian Schreck,[118] Christian Schubert,[41,*]
Armin Shayeghi,[121] Nathaniel Sherrill,[36] Ian Shipsey,[29] Carla Signorini,[13,49,*] Rajeev Singh,[122]
Yeshpal Singh,[26] Constantinos Skordis,[123] Augusto Smerzi,[124,10] Carlos F. Sopuerta,[125,126]
Fiodor Sorrentino,[127] Paraskevas Sphicas,[128,5] Yevgeny V. Stadnik,[129] Petruta Stefanescu,[38]
Marco G. Tarallo,[37] Silvia Tentindo,[130] Guglielmo M. Tino,[9,10,117,124,*] Jonathan N. Tinsley,[9,10]
Vincenza Tornatore,[97] Philipp Treutlein,[131] Andrea Trombettoni[15] Yu-Dai Tsai,[132]
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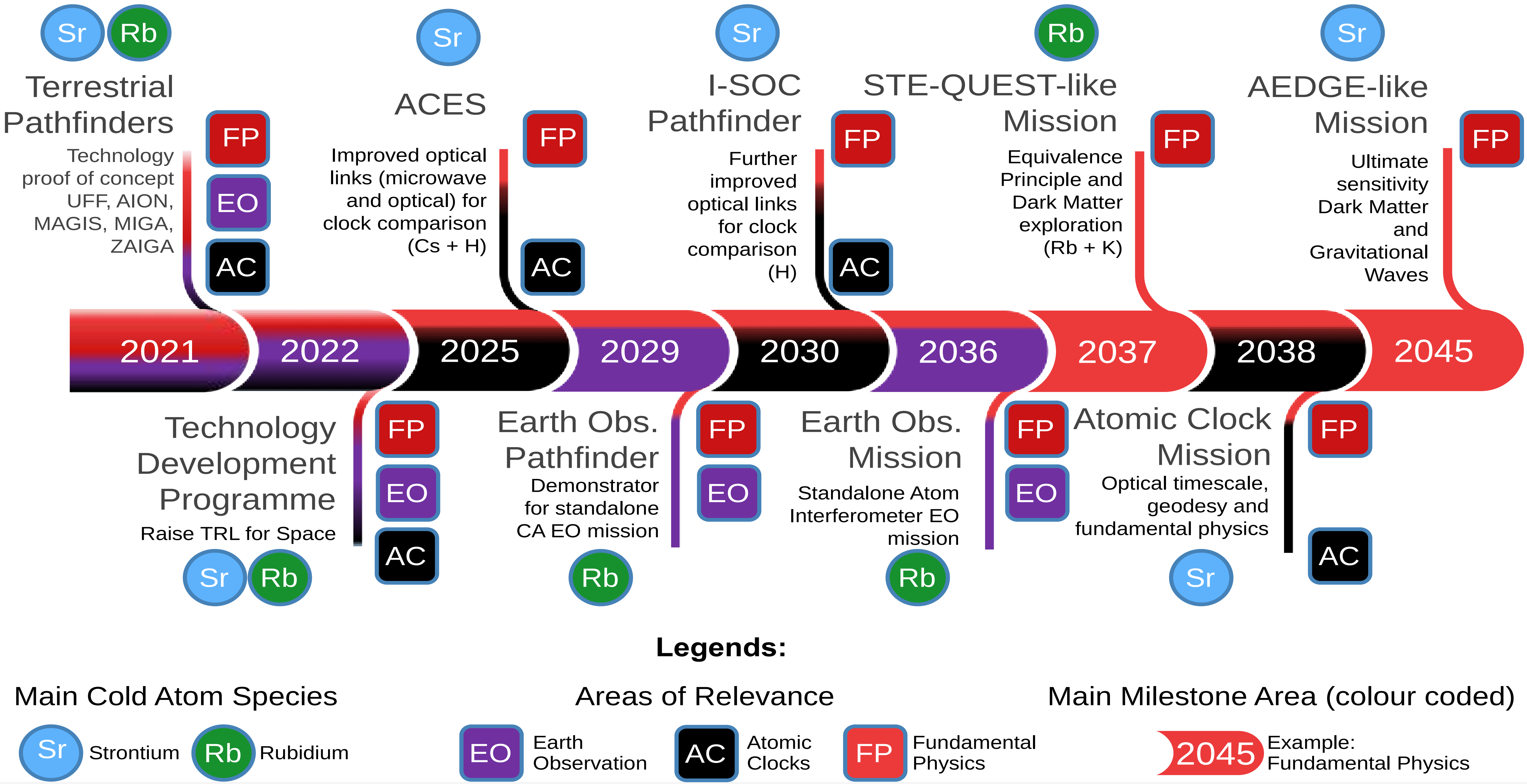
Nassim Zahzam,[19] Emmanuel Zambrini Cruzeiro,[32] Mingsheng Zhan,[142] Xinhao Zou,[17]
Jure Zupan,[143] Erik Zupanič[76]

[@] *Contact Person*
[*] *Section Editor and/or Workshop Organiser*

This document has been signed by more than **250 scientists**, representing the cold atom, astrophysics, cosmology, fundamental physics, geodesy and earth observation communities.

Community Proposal for an ESA Road-Map for Cold Atoms in Space



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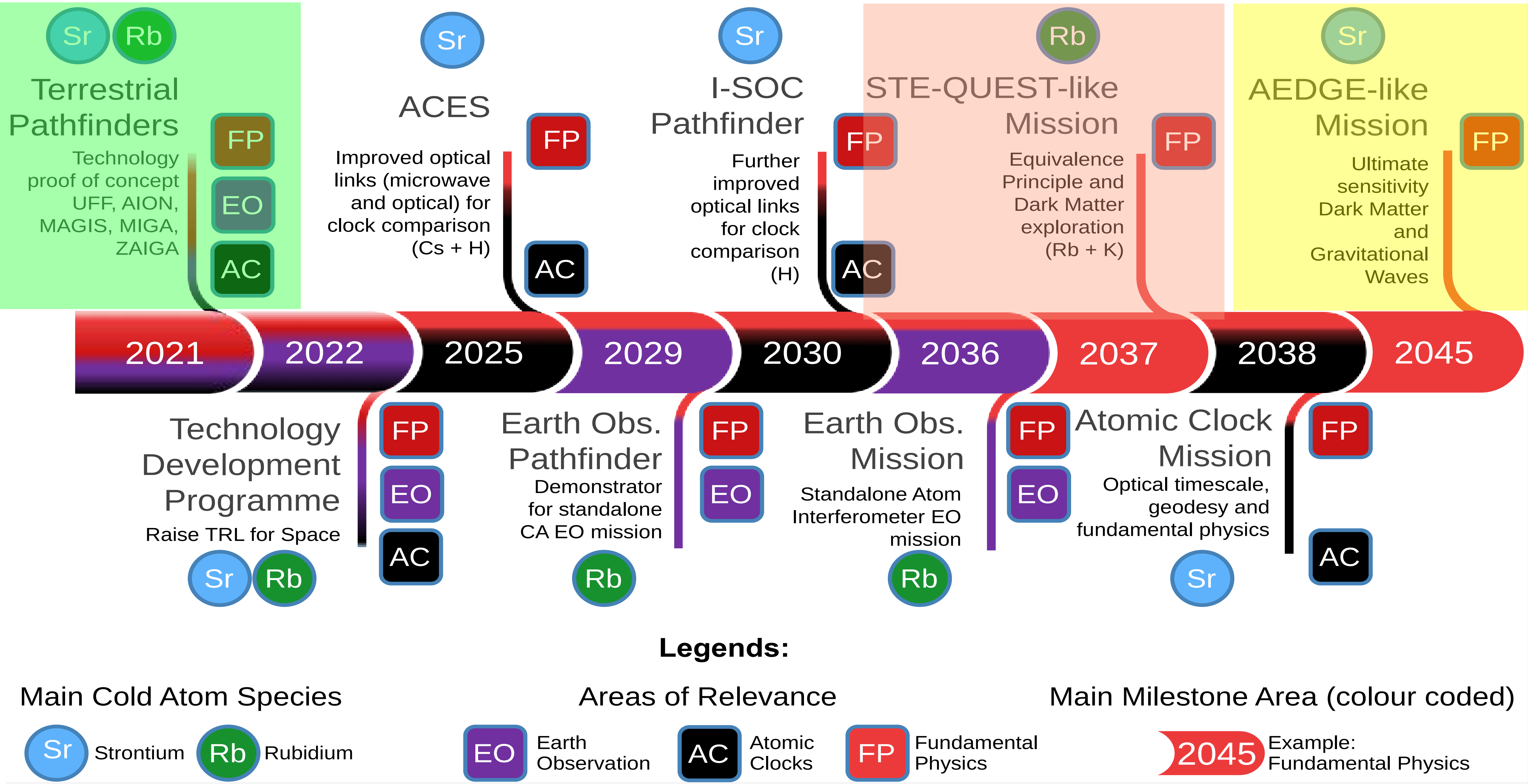
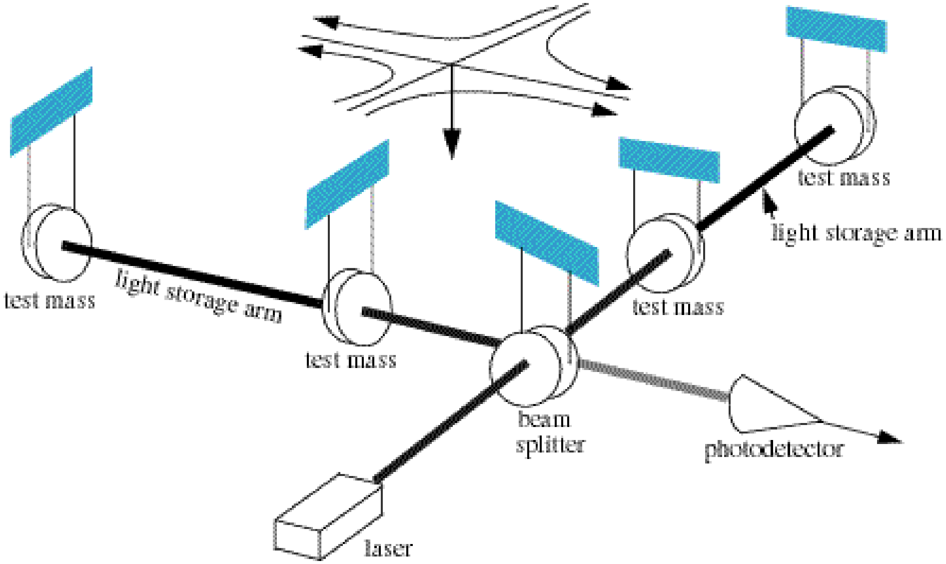


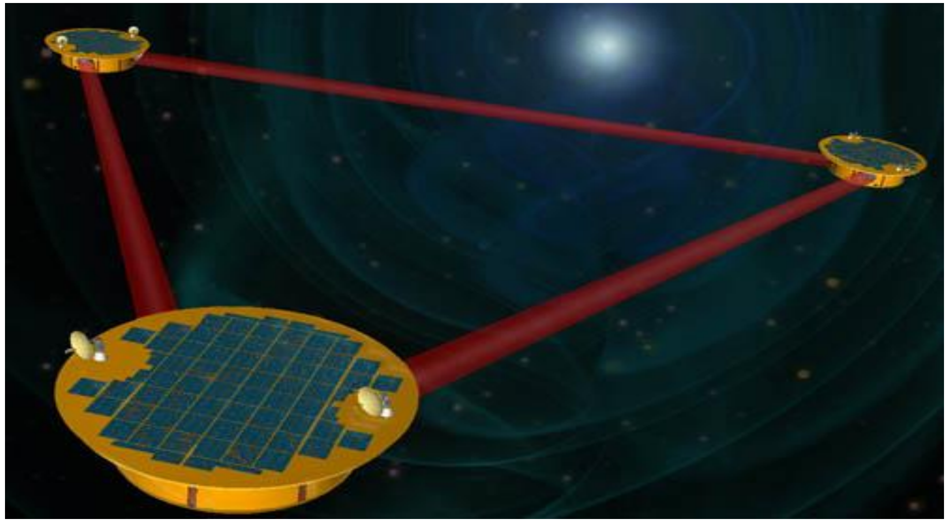
THE SCIENCE CASE

UNEXPLORED MID-FREQUENCY GRAVITATIONAL WAVES

Laser Interferometer Detectors



Gound-based detectors: LIGO, VIRGO, GEO (> 10 Hz)



Space-based detector concept: planned LISA mission (1 mHz – 100 mHz), also proposals to extend LISA concept to higher frequencies

Imperial College London

AION

GW Detection 2016

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

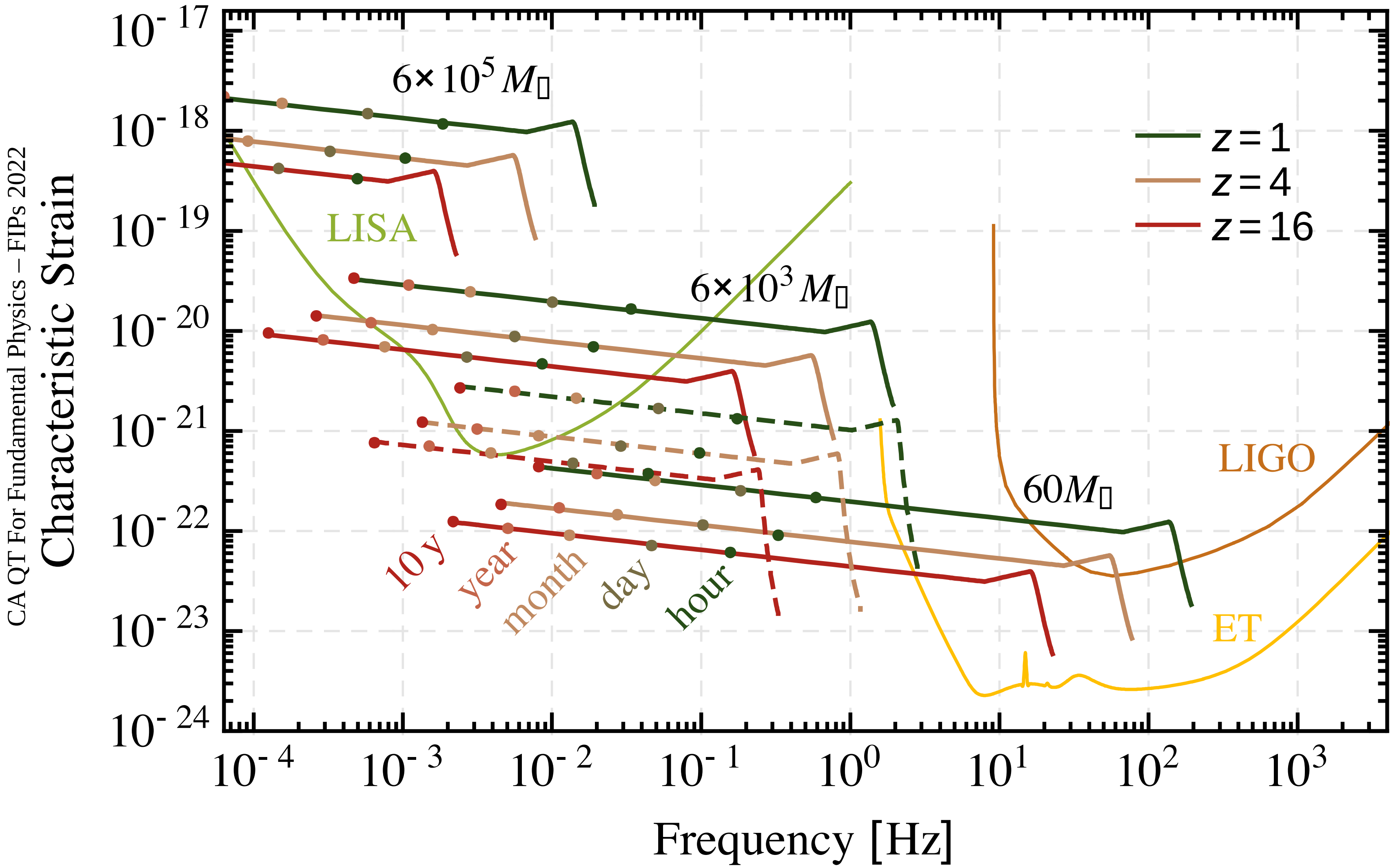
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

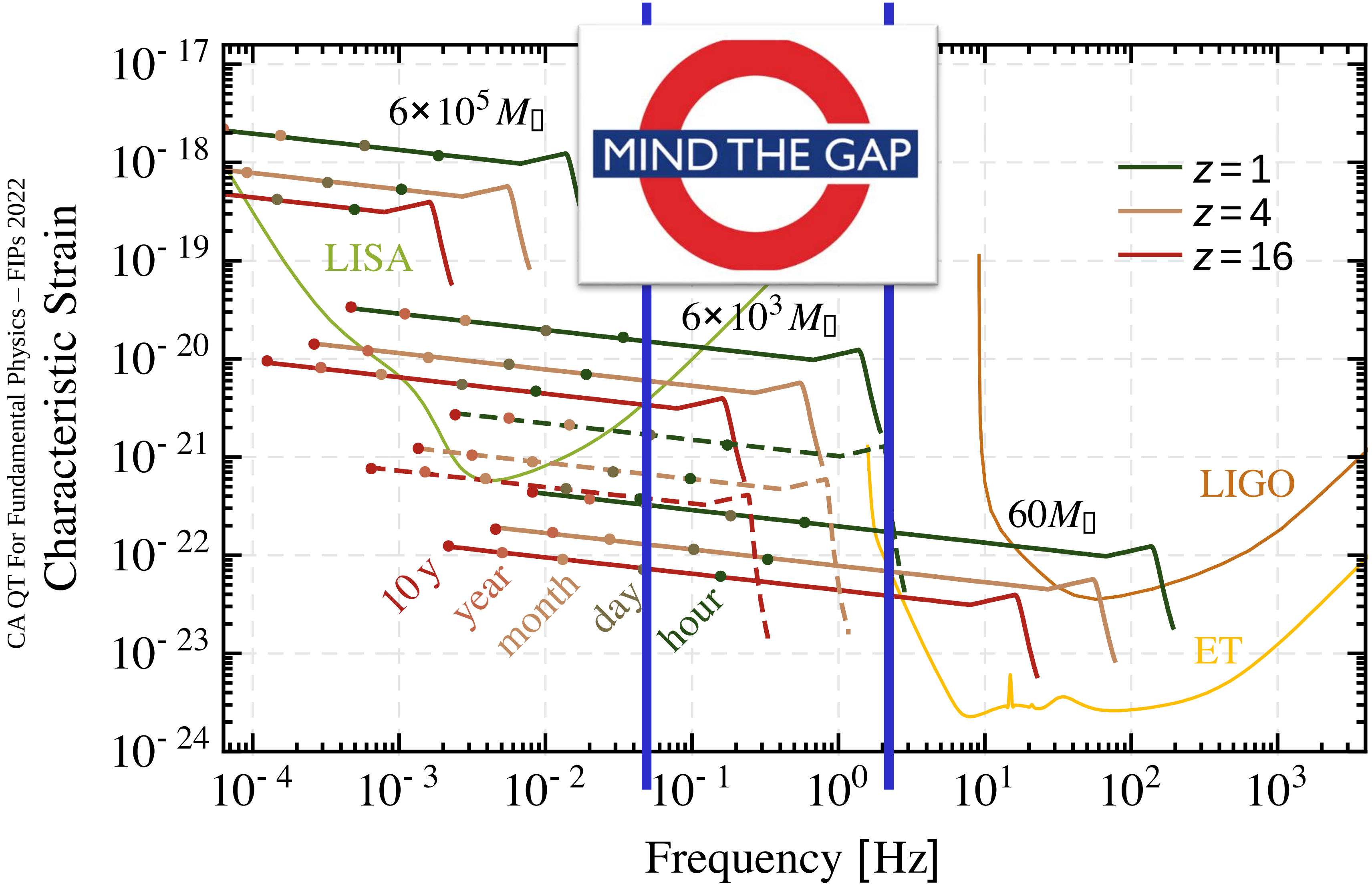
DOI: 10.1103/PhysRevLett.116.061102

CA QT For Fundamental Physics – FIPs 2022

Pathway to the GW Mid-(Frequency)



Pathway to the GW Mid-(Frequency)

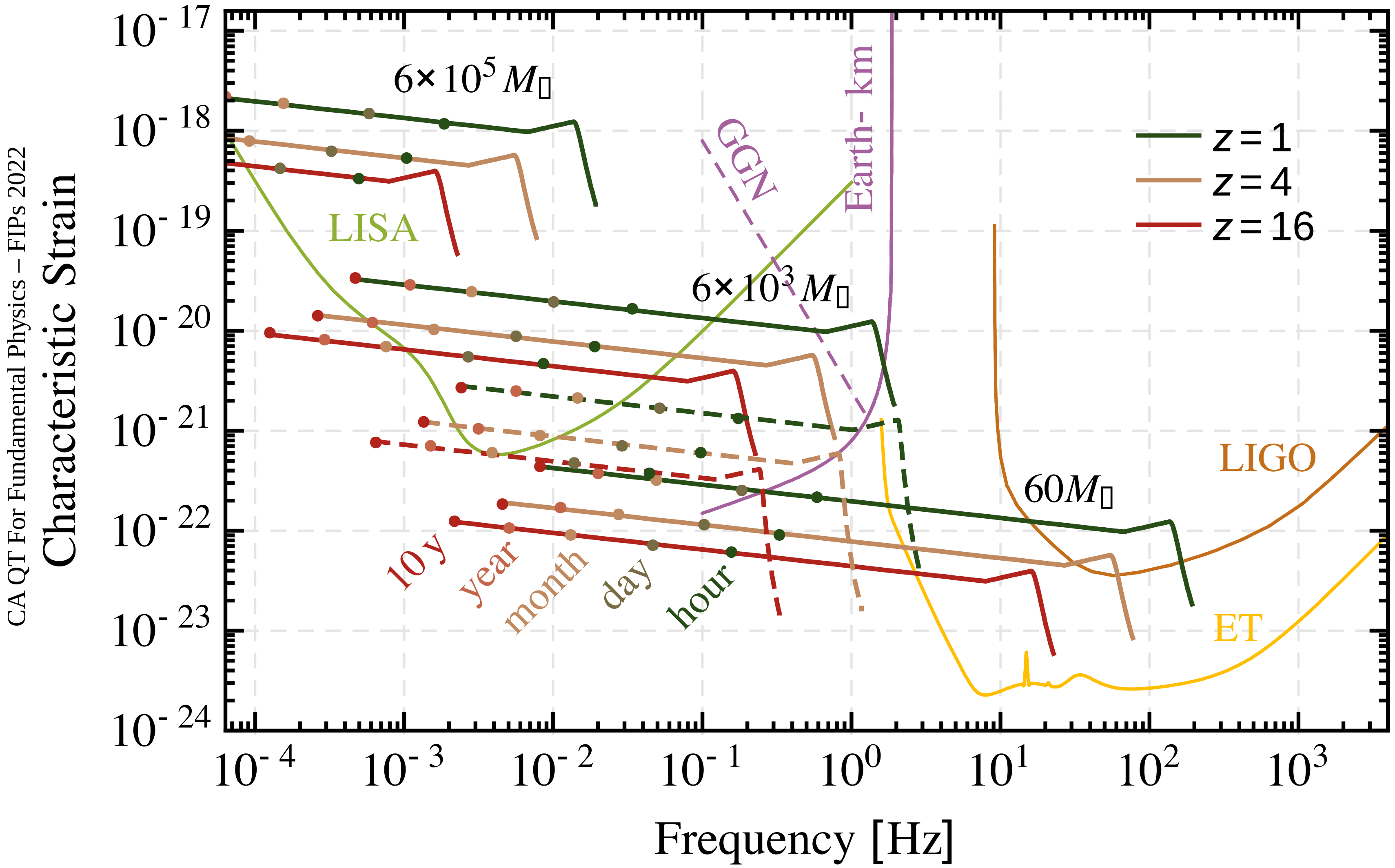


Mid-band science

- 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

AION: Pathway to the GW Mid-(Frequency)



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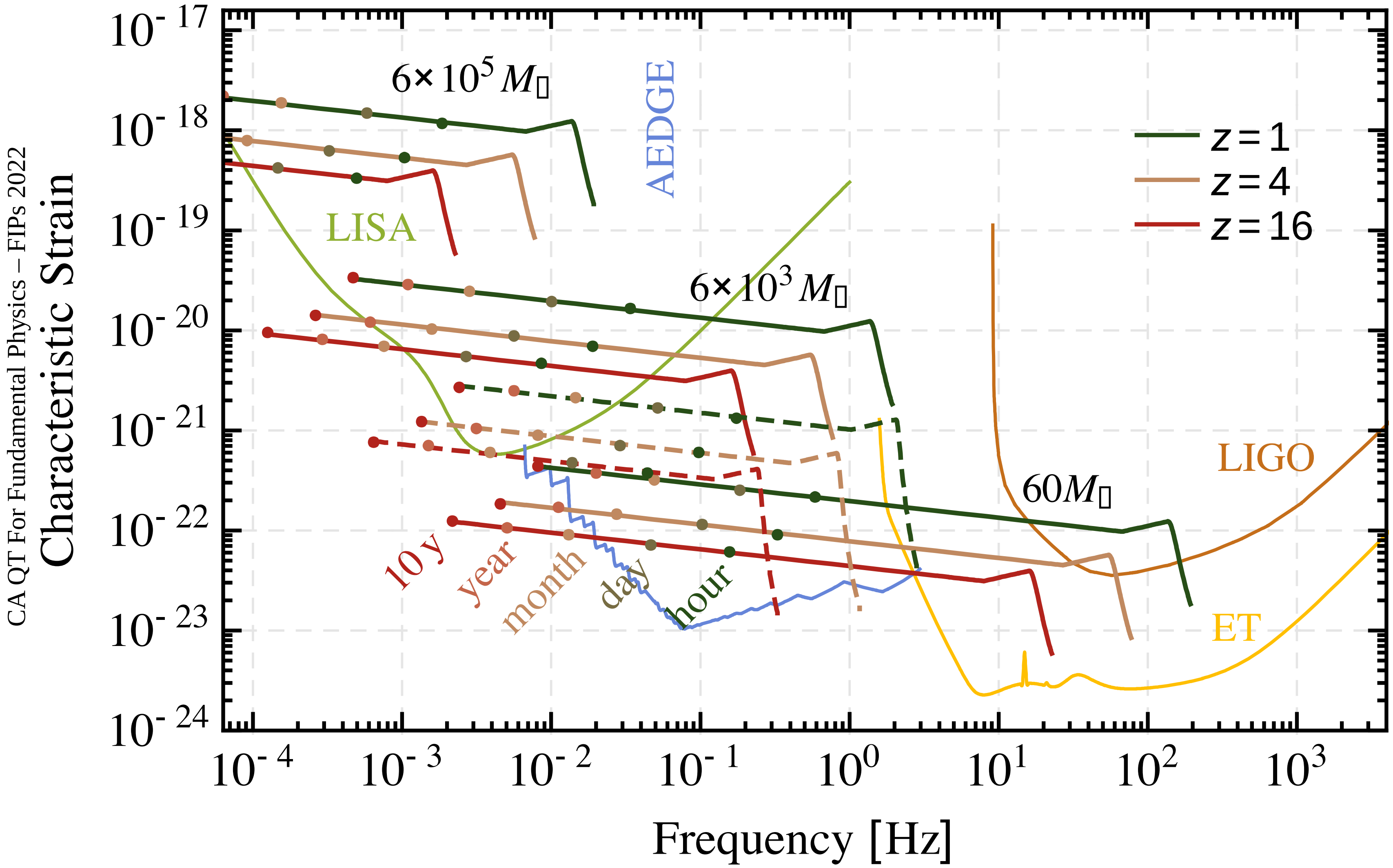
AION: Terrestrial detectors can start filling this gap

AION & AEDGE: Pathway to the GW Mid-(Frequency)



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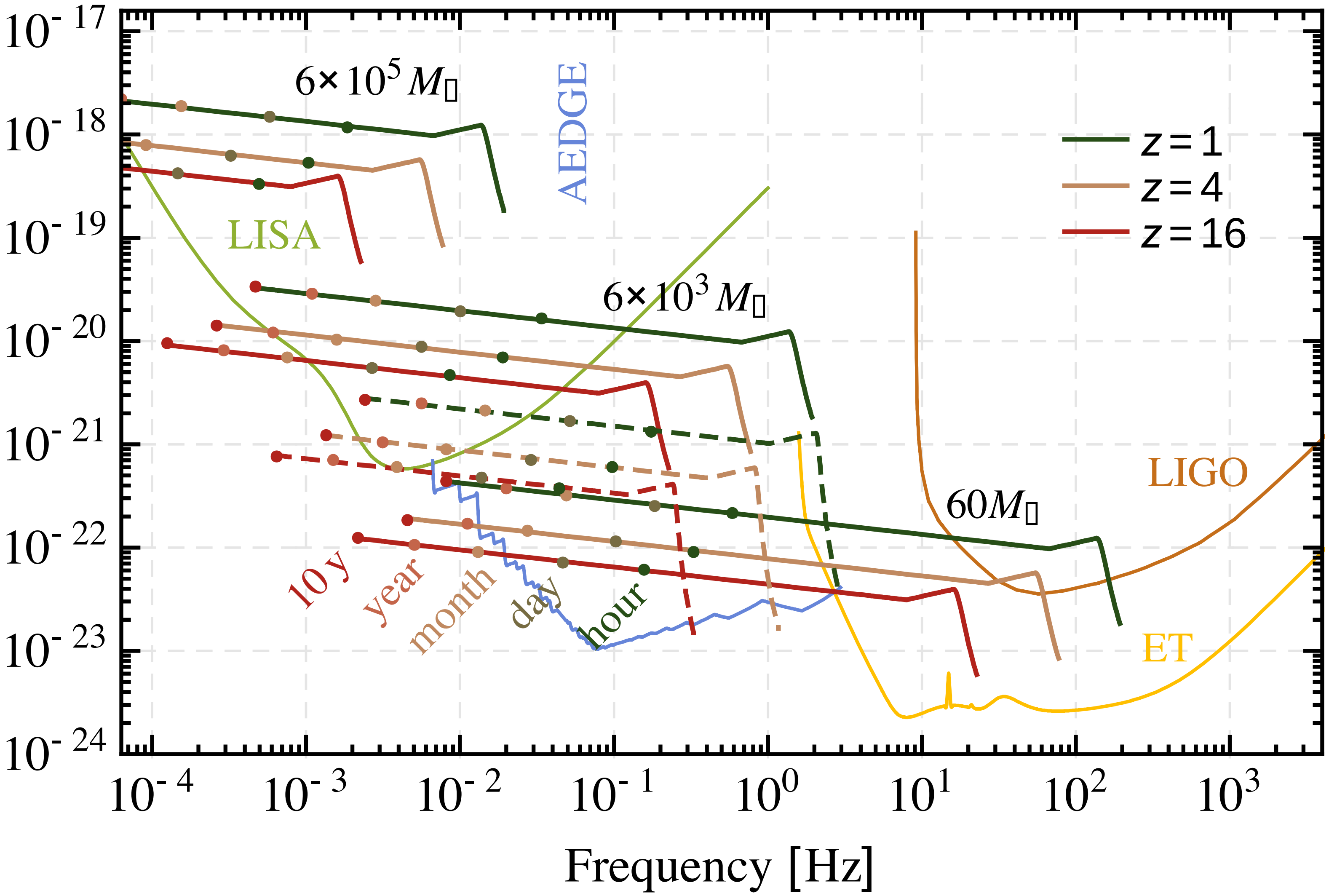
AEDGE
Ultimate coverage with a space based detector

AION & AEDGE: Pathway to the GW Mid-(Frequency)



CA QT For Fundamental Physics – FIPs 2022

Mid-band science

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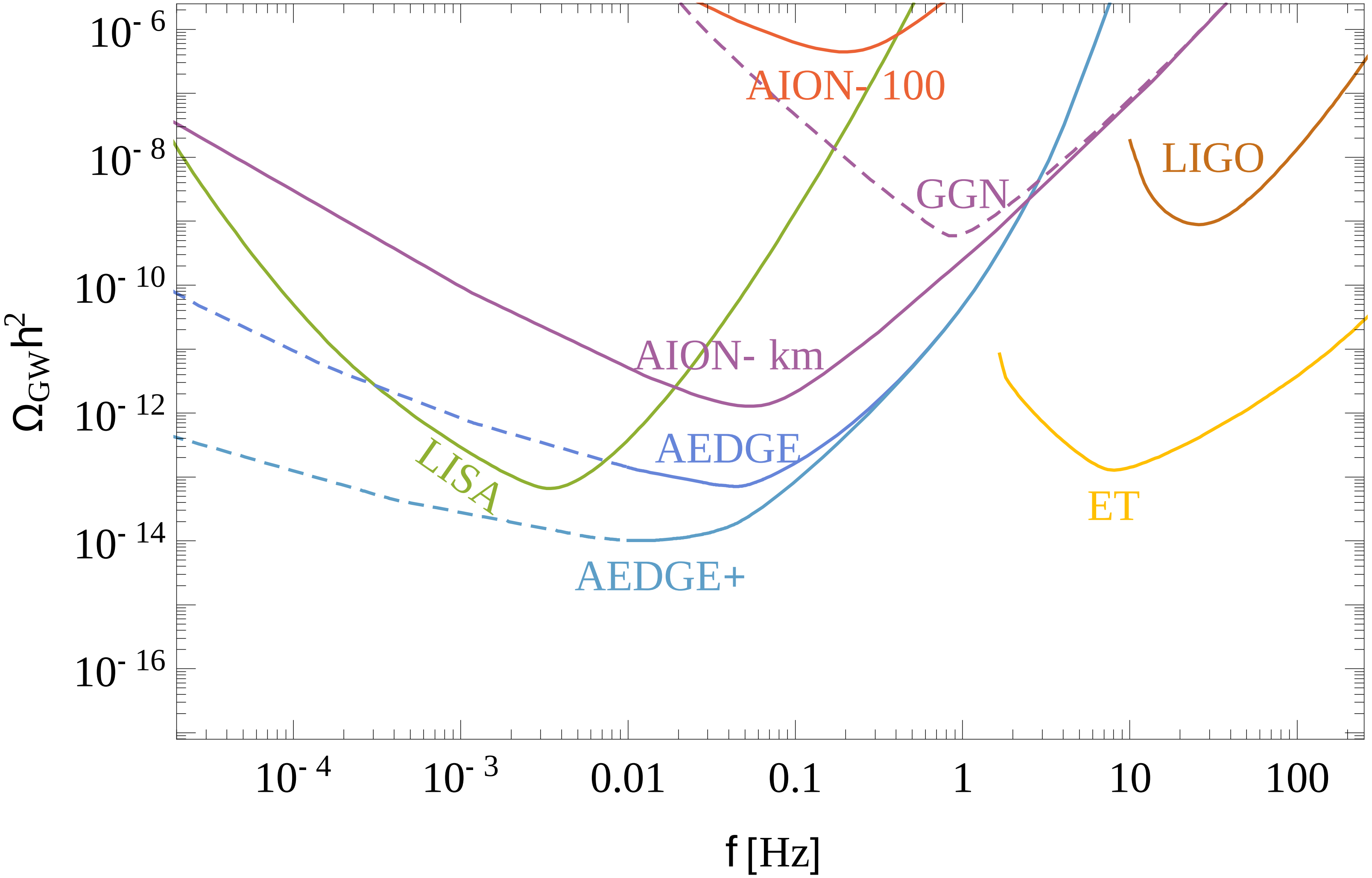
AEDGE
Ultimate coverage with a space based detector

Vision for 2045+

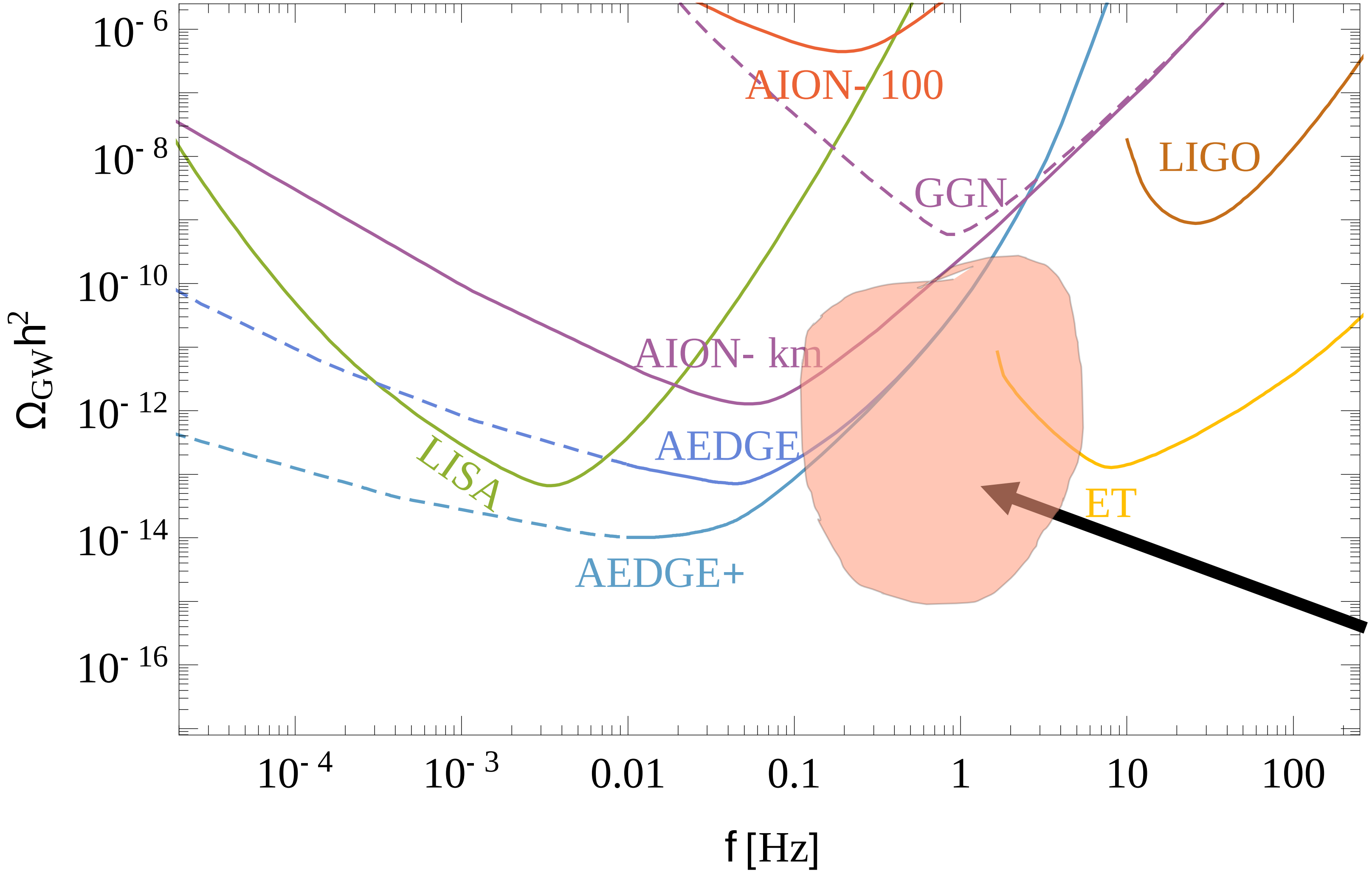
Probe formation of SMBHs: Synergies with other GW experiments (LIGO, LISA), test GR



Translate Stain sensitivity into the dimensionless energy density of a GW

Vision for 2045+

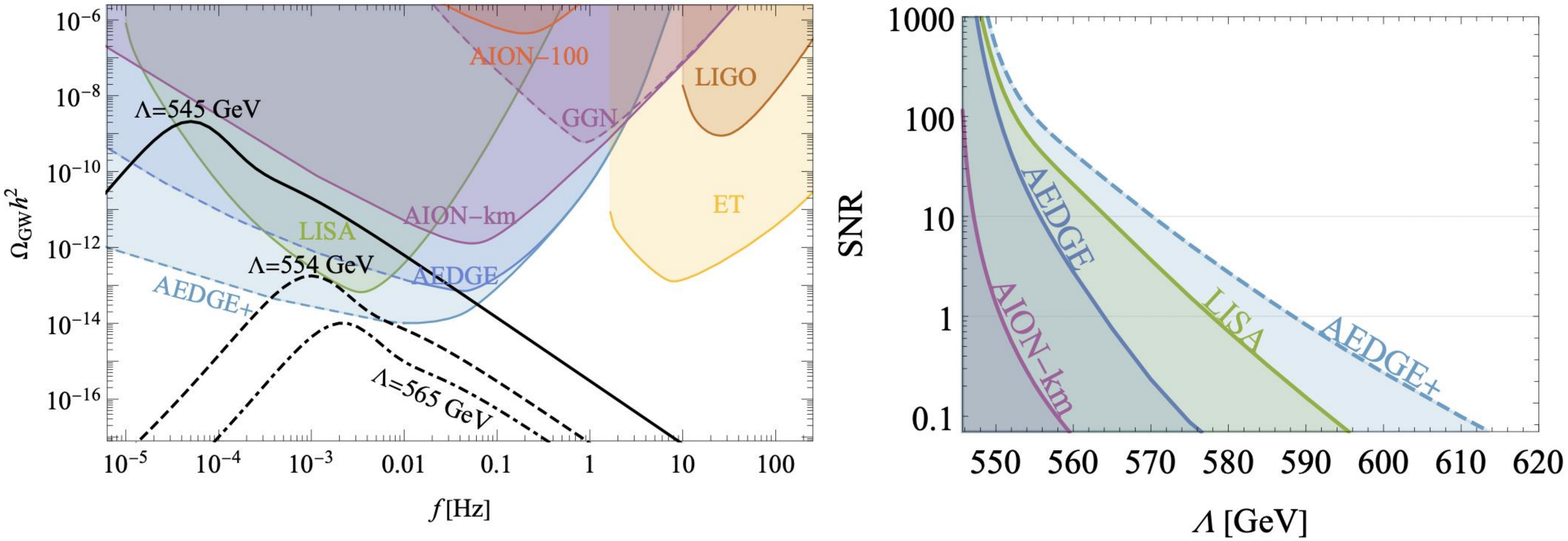
Probe formation of SMBHs: Synergies with other GW experiments (LIGO, LISA), test GR



Translate Stain sensitivity into the dimensionless energy density of a GW

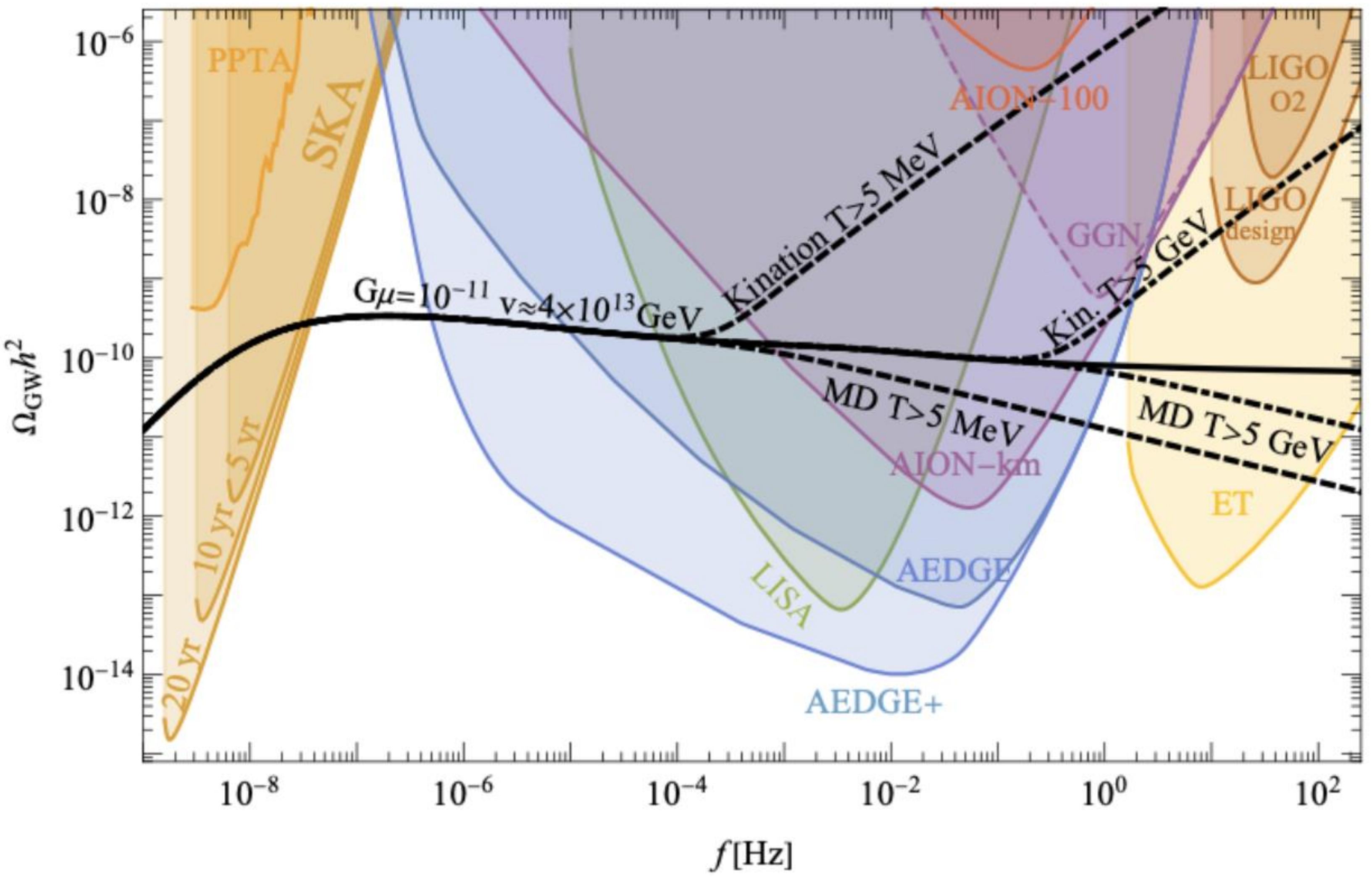
Still a "gap" around 1Hz
Need to find a solution to fill it

Fundamental Physics: First Order Phase Transition Models



Sensitivities to the mass scale parameter Λ in an extension of the Standard Model using a simplified first order phase transition model

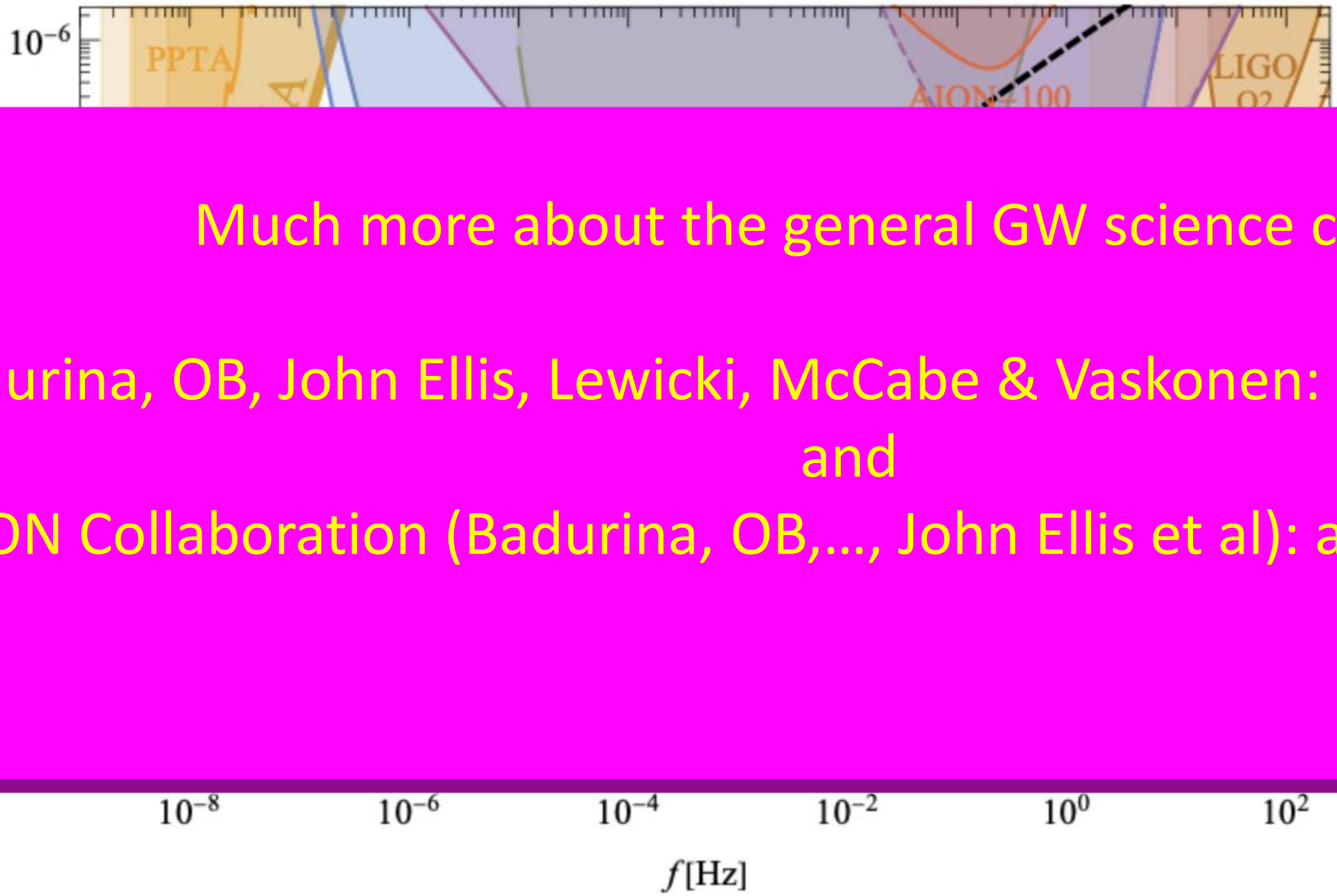
Fundamental Physics: Sensitivities of cosmic string measurements



Comparison of the Ω sensitivities to PI spectra of AION-100, AION-km, AEDGE and AEDGE+, LIGO, ET, Pulsar Timing Arrays (PTAs) and SKA.

Sensitivities of cosmic string measurements to modifications of the cosmological expansion rate. Kination or matter dominance (MD) at temperatures T > 5 *MeV or* 5 *GeV.*

Fundamental Physics: Sensitivities of cosmic string measurements



Much more about the general GW science case in:

Badurina, OB, John Ellis, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

and

AION Collaboration (Badurina, OB,…, John Ellis et al): arXiv:1911.11755

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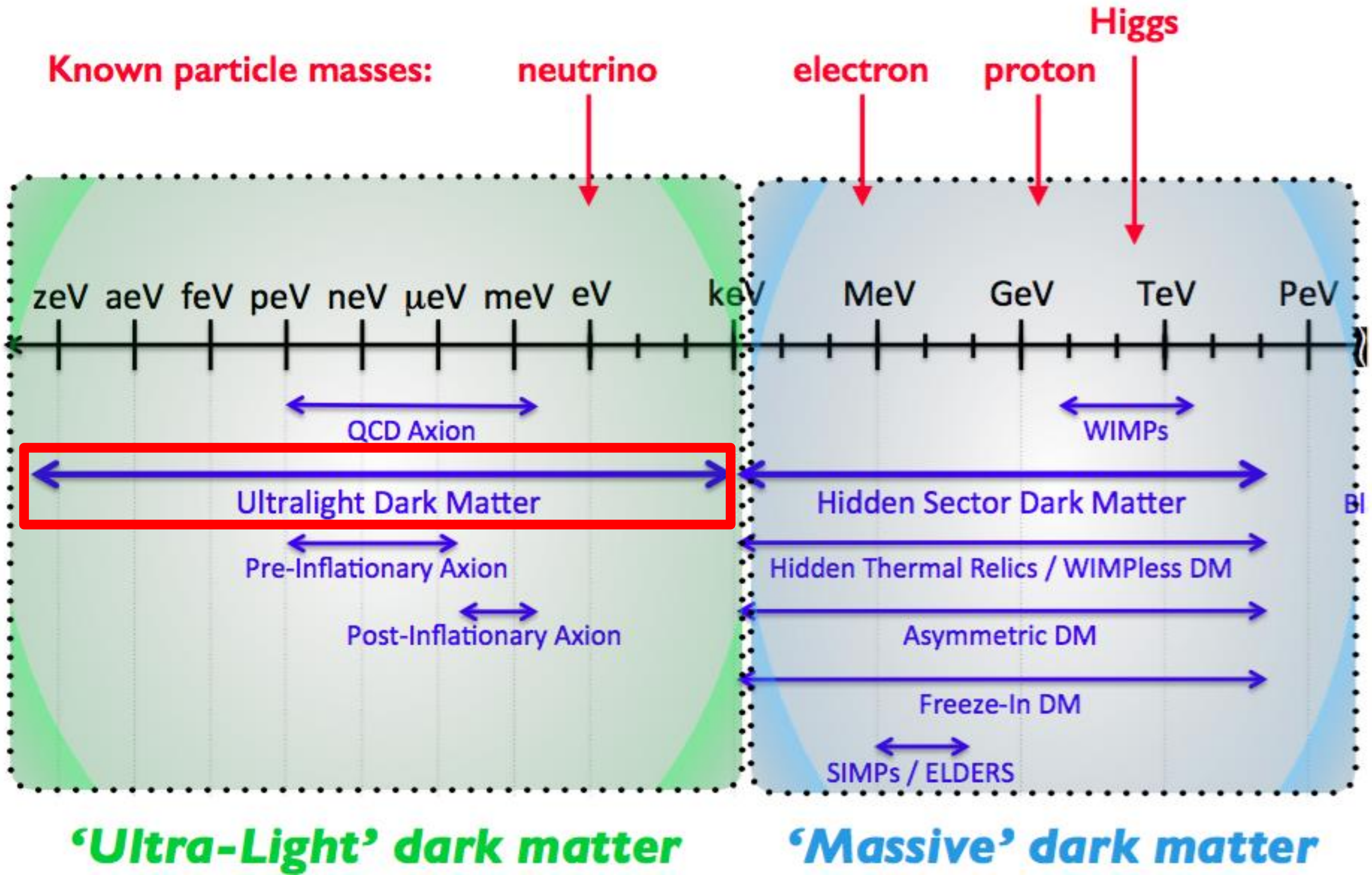
Sensitivities of cosmic string measurements to modifications of the cosmological expansion rate. Kination or matter dominance (MD) at temperatures T > 5 *MeV or* 5 *GeV.*

ULTRA-LIGHT DARK MATTER

AION

Search for Ultra-Light 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

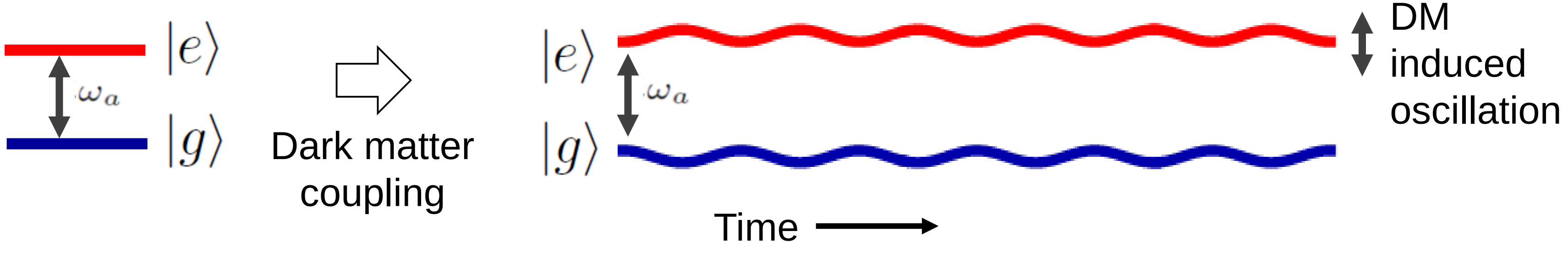
e.g., QCD

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

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

DM mass density

DM coupling causes time-varying atomic energy levels:

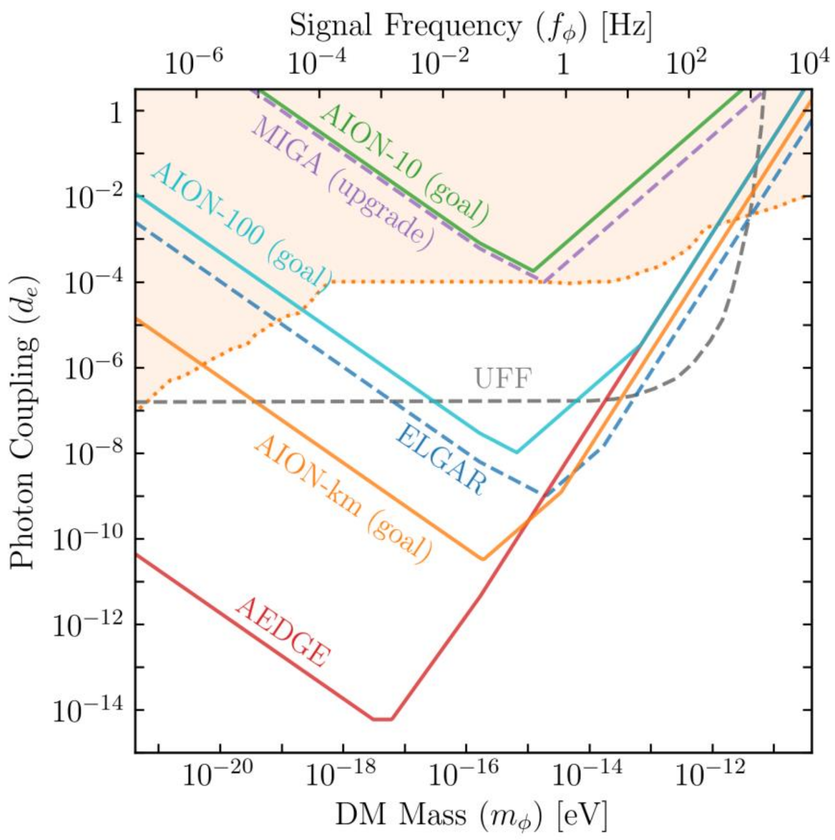


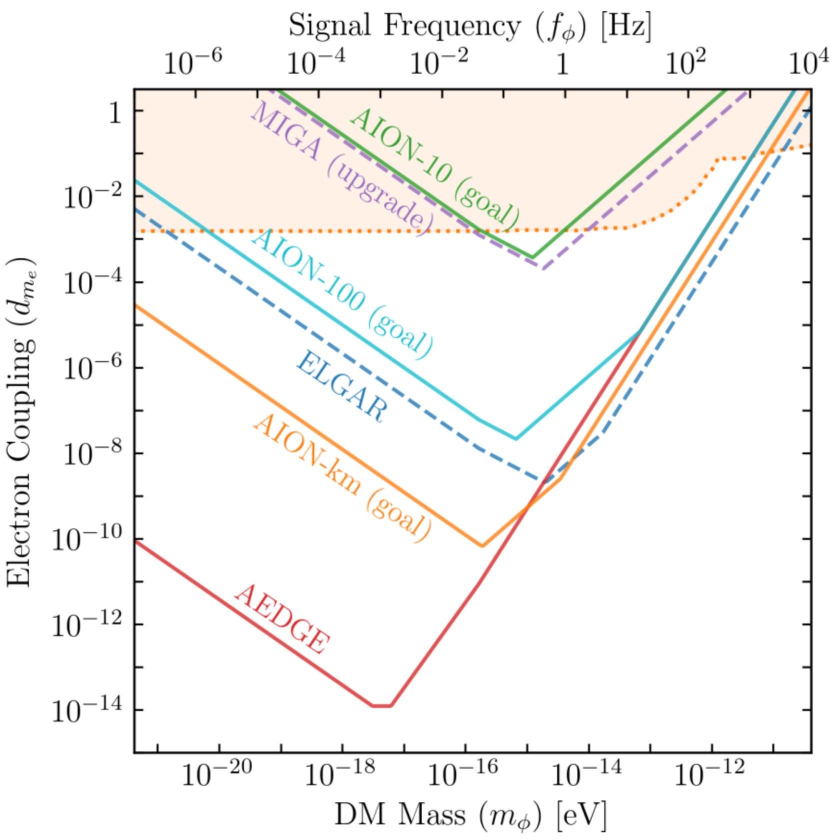
Courtesy of Jason Hogan!

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.

Summary

The first stage of the *UK Atom Interferometer Observatory and Network (AION)* project was recently funded in the UK with about £9.6M

- AION opens a new window on gravitational physics, astrophysics & cosmology using ultra-cold atom interferometers, leveraging UK investment in quantum technologies, providing new opportunities for UK science communities.
- To push the state-of-the-art single photon atom interferometry, the AION project builds dedicated ultra-cold strontium laboratories in **Birmingham, Cambridge, Imperial College, Oxford, and RAL**

AION: An Atom Interferometer Observatory and Network, JCAP05(2020) 011,[1911.11755].

The Atomic Experiment for Dark Matter and Gravity Exploration (AEDGE) mission proposal was summitted in the Voyage2050 White Paper call.

- AEDGE propose to use ultra-cold atom technology to explore gravitational physics, astrophysics & cosmology and to search for ultra-light dark matter. The underlying technology concept is identical to the one AION pursues.
- AEDGE is supported by an international consortium of almost 200 scientists from 70 institutions, based in 23 different counties.
- The AEDGE consortium includes leading members of the **AION (UK), MAGIS (US), MIGA (France),** and **ZIGA (China)** large-scale terrestrial ultra-cold atom interferometry projects. Each project is funded by national agencies with about 10M dollar (or more).

AEDGE: Atomic Experiment for Dark Matter And Gravity Exploration in Space, arXiv:1908.00802, *EPJ Quantum Technol.* 7, 6 (2020).

The Community Workshop on Cold Atoms in Space and its Road-Map

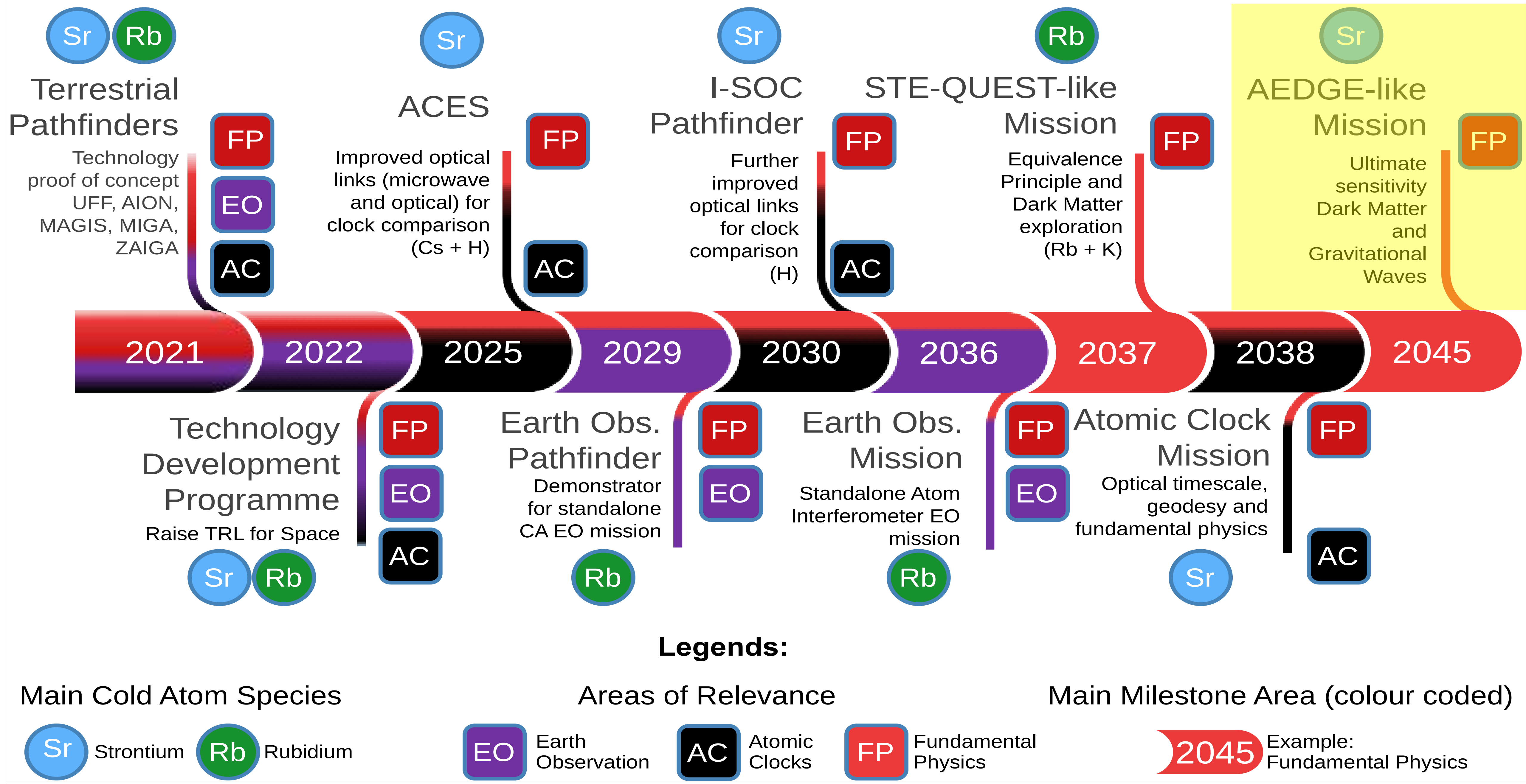
- The purpose of this community workshop was to discuss options for a quantum technology development programme coordinated at the Europe-wide level and to develop a community roadmap and milestones to demonstrate the readiness of cold atom technologies in space, as proposed in the Voyage 2050 recommendations, and in synergy with EU programmes.
- This event brought together the cold atom, astrophysics, cosmology, fundamental physics, and earth observation communities to shape this development programme.

Writeup: Cold Atoms in Space: Community Workshop Summary and Proposed Road-Map, arXiv:2201.07789, submitted to *EPJ Quantum Technology*

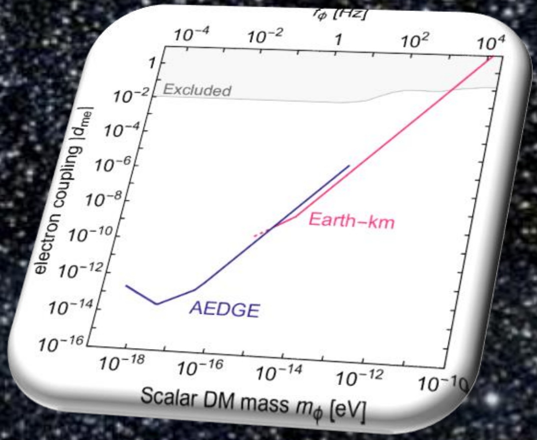
BACKUP

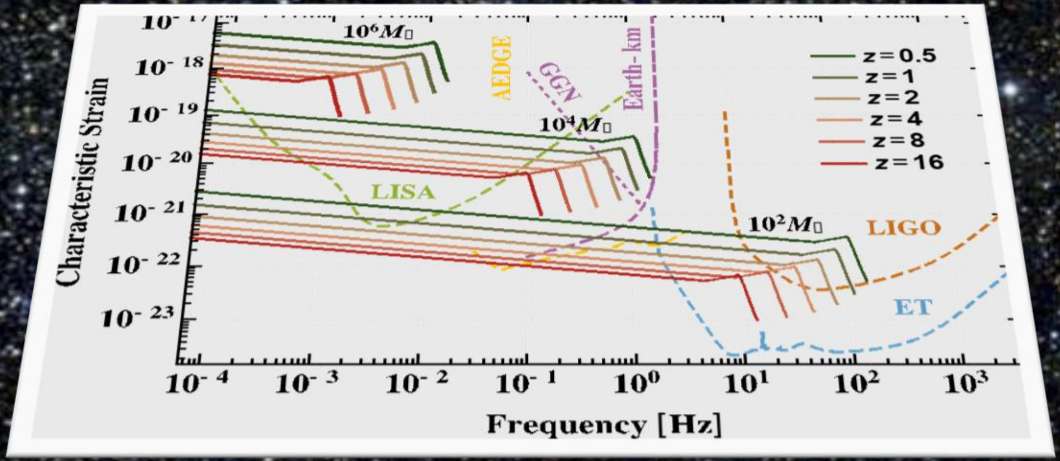
AEDGE AND STE-QUEST

Community Proposal for an ESA Road-Map for Cold Atoms in Space



AEDGE:
Atomic Experiment for Dark Matter and Gravity Exploration





Informal Workshop
CERN, July 22/23 2019

Organizers:
Kai Bongs(CA), Philippe Bouyer(CA), Oliver Buchmueller(PP),
Albert De Roeck(PP), John Ellis(PP, Theory), Peter Graham (CA, Theory),
Jason Hogan (CA), Wolf von Klitzing(CA), Guglielmo Tino(CA), and AtomQT
PP=Particle Physics
CA=Cold Atoms

AEDGE:
Atomic Experiment for Dark Matter and Gravity Exploration

With more than 130 participants the workshop was very well attended!

The full agenda can be accessed via:
https://indico.cern.ch/event/830432/timetable/

The main scope was to review the landscape of Cold Atom experiments on ground AND in space to eventually establish a roadmap for technology readiness for space.

Informal Workshop
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PP=Particle Physics
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AEDGE Mission Concept

CA QT For Fundamental Physics – FIPs 2022

arXiv:1908.00802v2 [gr-qc] 10 Oct 2019

AEDGE:
Atomic Experiment for Dark Matter and Gravity Exploration in Space

Yousef Abou El-Neaj,[1] Cristiano Alpigiani,[2] Sana Amairi-Pyka,[3] Henrique Araújo,[4] Antun Balaž,[5] Angelo Bassi,[6] Lars Bathe-Peters,[7] Baptiste Battelier,[8] Aleksandar Belić,[5] Elliot Bentine,[9] José Bernabeu,[10] Andrea Bertoldi,[8,*] Robert Bingham,[11] Diego Blas,[12] Vasiliki Bolpasi,[13] Kai Bongs,[14,*] Sougato Bose,[15] Philippe Bouyer,[8,*] Themis Bowcock,[16] William Bowden,[17] Oliver Buchmueller,[4,@] Clare Burrage,[18] Xavier Calmet,[19] Benjamin Canuel,[8,*] Laurentiu-Ioan Caramete,[20,*] Andrew Carroll,[16] Giancarlo Cella,[21,22] Vassilis Charmandaris,[23] Swapan Chattopadhyay,[24,25] Xuzong Chen,[26] Maria Luisa Chiofalo,[21,22] Jonathon Coleman,[16,*] Joseph Cotter,[4] Yanou Cui,[27] Andrei Derevianko,[28] Albert De Roeck,[29,30,*] Goran Djordjevic,[31] Peter Dornan,[4] Michael Doser,[30] Ioannis Drougkakis,[13] Jacob Dunningham,[19] Ioana Dutan,[20] Sajan Easo,[11] Gedminas Elertas,[16] John Ellis,[12,32,33,*] Mai El Sawy,[34] Farida Fassi,[35] Daniel Felea,[20] Chen-Hao Feng,[8] Robert Flack,[15] Chris Foot,[9] Ivette Fuentes,[18] Naceur Gaaloul,[36] Alexandre Gauguet,[37] Remi Geiger,[38] Valerie Gibson,[39] Gian Giudice,[33] Jon Goldwin,[14] Oleg Grachov,[40] Peter W. Graham,[41,*] Dario Grasso,[21,22] Maurits van der Grinten,[11] Mustafa Gündogan,[3] Martin G. Haehnelt,[42,*] Tiffany Harte,[39] Aurélien Hees,[38,*] Richard Hobson,[17] Bodil Holst,[43] Jason Hogan,[41,*] Mark Kasevich,[41] Bradley J. Kavanagh,[44] Wolf von Klitzing,[13,*] Tim Kovachy,[45] Benjamin Krikler,[46] Markus Krutzik,[3,*] Marek Lewicki,[12,47,*] Yu-Hung Lien,[15] Miaoyuan Liu,[26] Giuseppe Gaetano Luciano,[48] Alain Magnon,[49] Mohammed Mahmoud,[50] Sarah Malik,[4] Christopher McCabe,[12,*] Jeremiah Mitchell,[24] Julia Pahl,[3] Debapriya Pal,[13] Saurabh Pandey,[13] Dimitris Papazoglou,[51] Mauro Paternostro,[52] Bjoern Penning,[53] Achim Peters,[3,*] Marco Prevedelli,[54] Vishnupriya Puthiya-Veettil,[55] John Quenby,[4] Ernst Rasel,[36,*] Sean Ravenhall,[9] Haifa Rejeb Sfar,[29] Jack Ringwood,[16] Albert Roura,[56,*] Dylan Sabulsky,[8,*] Muhammed Sameed,[57] Ben Sauer,[4] Stefan Alaric Schäffer,[58] Stephan Schiller,[59,*] Vladimir Schkolnik,[3] Dennis Schlippert,[36] Christian Schubert,[3,*] Armin Shayeghi,[60] Ian Shipsey,[9] Carla Signorini,[21,22] Marcelle Soares-Santos,[53] Fiodor Sorrentino,[61,*] Yajpal Singh,[14,*] Timothy Sumner,[4] Konstantinos Tassis,[13] Silvia Tentindo,[62] Guglielmo Maria Tino,[63,64,*] Jonathan N. Tinsley,[63] James Unwin,[65] Tristan Valenzuela,[11] Georgios Vasilakis,[13] Ville Vaskonen,[12,32,*] Christian Vogt,[66] Alex Webber-Date,[16] André Wenzlawski,[67] Patrick Windpassinger,[67] Marian Woltmann,[66] Michael Holynski,[14] Efe Yazgan,[68] Ming-Sheng Zhan,[69,*] Xinhao Zou,[8] Jure Zupan[70]

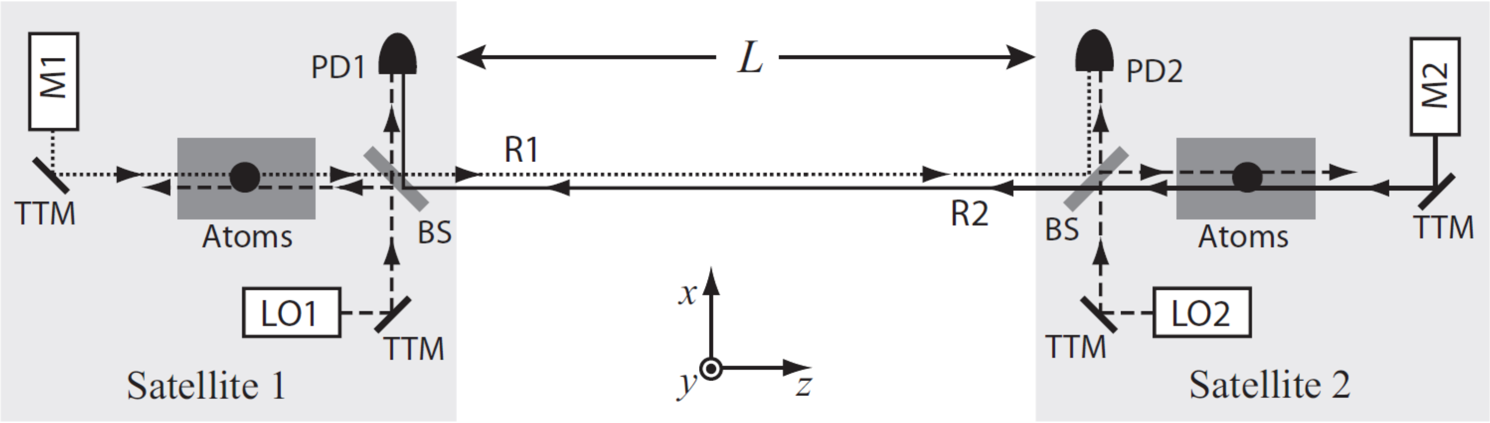
132 Authors, from **70** institutions, based in **23** different counties!

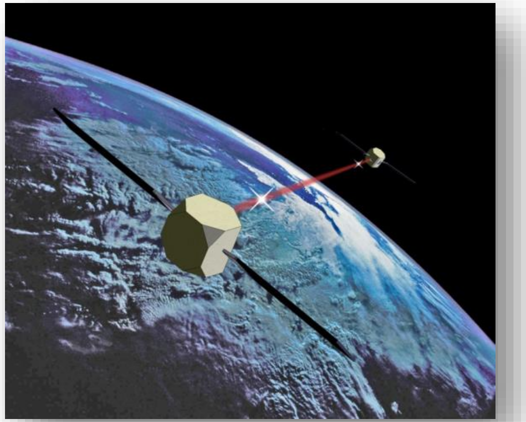
The authors represent several science communities ranging from Cold Atoms, & Gravitational Waves, over Cosmology and Astrophysics to fundamental Particle Physics.

https://arxiv.org/abs/1908.00802

The paper is now published in EPJ Quantum Technology

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.

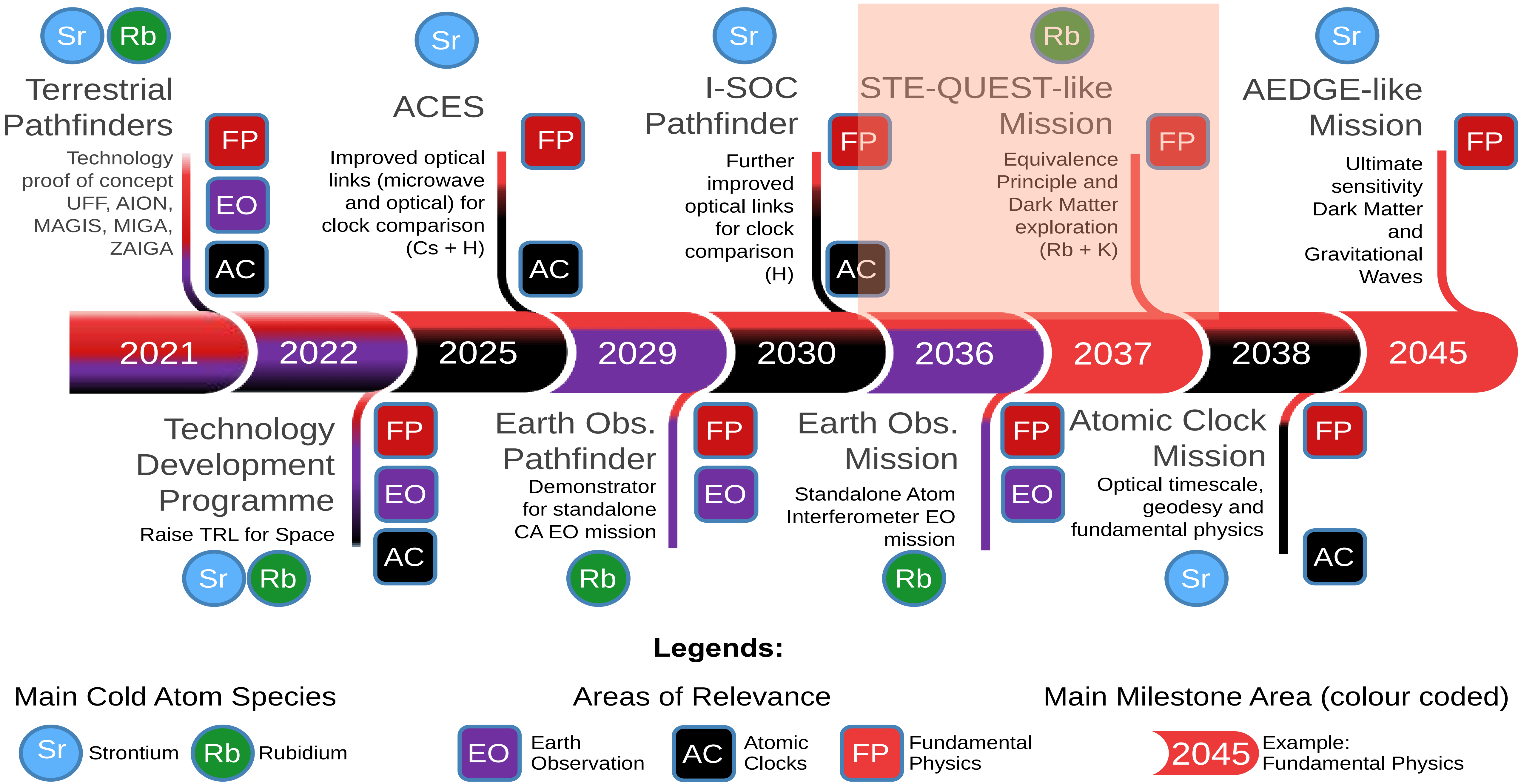
Assumed basic parameters:

- 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: MAGIS collaboration, P. W. Graham et al **arXiv:1711.02225**

Community Proposal for an ESA Road-Map for Cold Atoms in Space

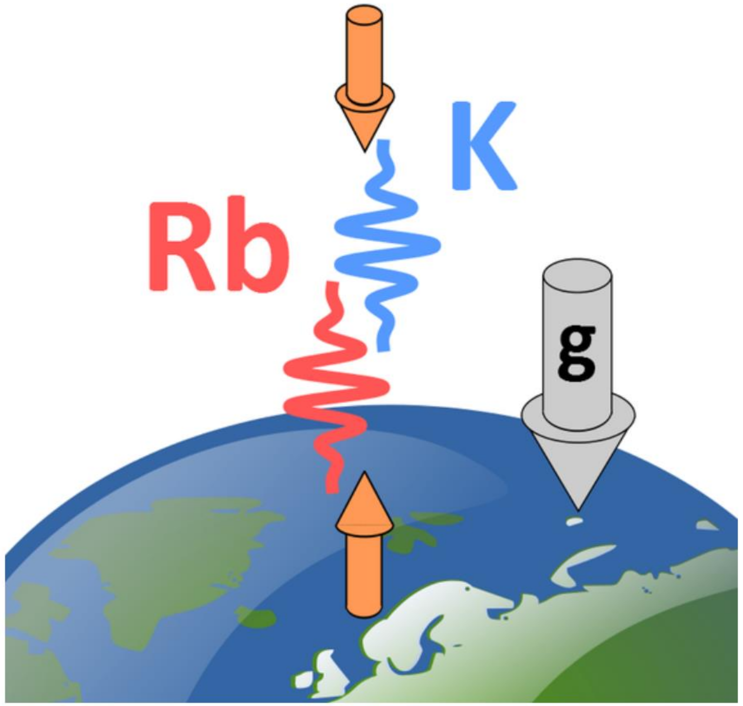


STE-QUEST (M-Class Mission Proposal)

STE-QUEST

Space Time Explorer and QUantum Equivalence principle Space Test

A M-class mission proposal in response to the 2022 call in ESA's science program



Core Team:

- Angelo Bassi, Department of Physics, University of Trieste, and INFN - Trieste Section, *Italy*
- Kai Bongs, Midlands Ultracold Atom Research Centre, School of Physics and Astronomy University of Birmingham, *United Kingdom*
- Philippe Bouyer, LP2N, Université Bordeaux, IOGS, CNRS, Talence, *France*
- Claus Braxmaier, Institute of Microelectronics, Ulm University and Institute of Quantum Technologies, German Aerospace Center (DLR), *Germany*
- Oliver Buchmueller, High Energy Physics Group, Blackett Laboratory, Imperial College London, London, *United Kingdom*
- Maria Luisa (Marilu) Chiofalo, Physics Department "Enrico Fermi" University of Pisa, and INFN-Pisa *Italy*
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- Philippe Jetzer, Department of Physics, University of Zurich, *Switzerland*
- Steve Lecomte, Centre Suisse d'Electronique et de Microtechnique (CSEM), Neuchâtel, *Switzerland*
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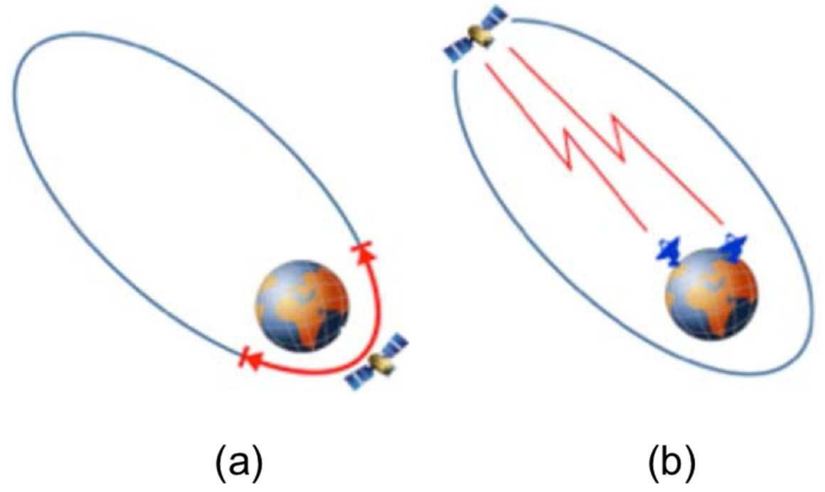
- Martin Zelan, Measurement Science and Technology, RISE Research Institutes of Sweden, Borås, *Sweden*

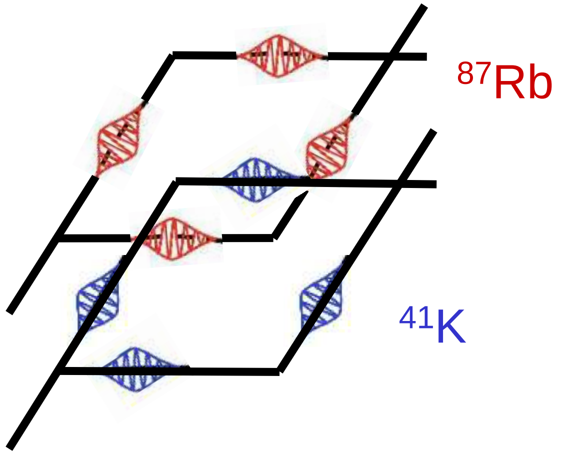
Strong International Team

STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics

Science Goals: Equivalent Principal at 1E-17, Ultra-Light Dark Matter, Test of Quantum Mechanics



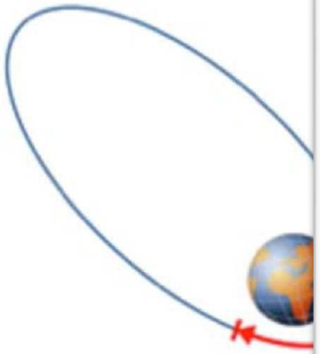
- Based on STE-QUEST proposals (M3, M4).
- Double atom interferometer with Rb and K "test masses" in non-classical states (quantum superpositions).
- Optimized for UFF test. Assume 700 km circular orbit.
- Apply recent results on controlling gravity gradient shifts by offsetting laser frequencies, thus relaxing atom positioning requirements by factor >100.
- **Reaches 1E-17 target after 18 months of operation.**



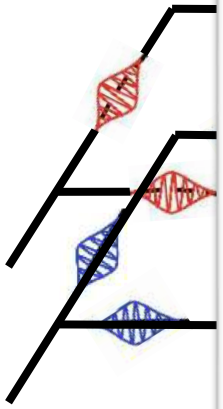
Class	Elements	η	Year [ref]	Comments
Classical	Be - Ti	2×10^{-13}	2008	Torsion balance
	Pt - Ti	1×10^{-14}	2017	MICROSCOPE first results
	Pt - Ti	(10^{-15})	2022+	MICROSCOPE full data
Hybrid	^{133}Cs - CC	7×10^{-9}	2001	Atom Interferometry
	^{87}Rb - CC	7×10^{-9}	2010	and macroscopic corner cube (CC)
Quantum	^{39}K - ^{87}Rb	3×10^{-7}	2020	different elements
	^{87}Sr - ^{88}Sr	2×10^{-7}	2014	same element, fermion vs. boson
	^{85}Rb - ^{87}Rb	3×10^{-8}	2015	same element, different isotopes
	^{85}Rb - ^{87}Rb	3.8×10^{-12}	2020	10 m tower
	^{41}K - ^{87}Rb	(10^{-17})	2037	STE-QUEST
Antimatter	$\overline{\text{H}}$ - H	(10^{-2})	2023+	under construction at CERN

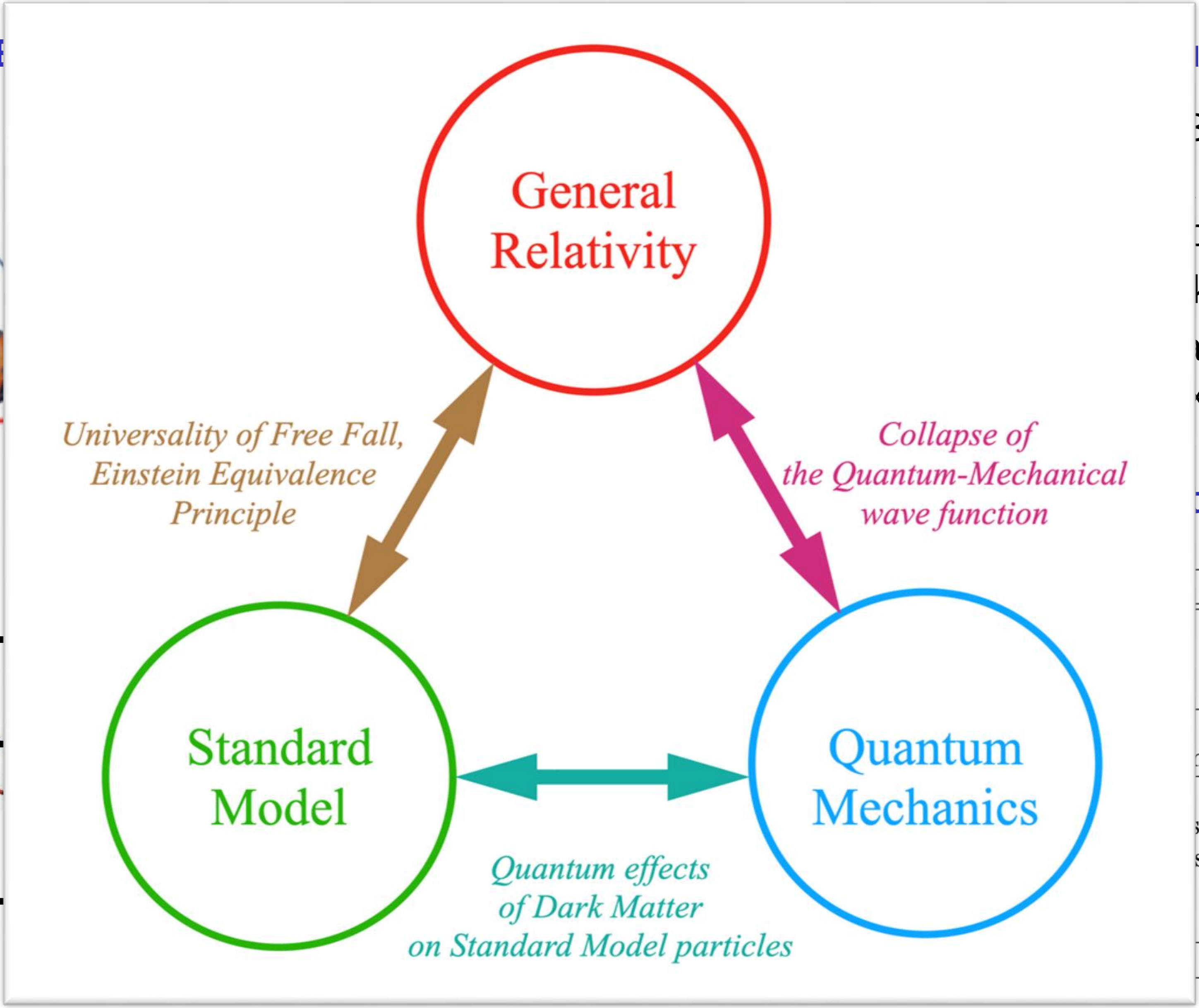
STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics

Science Goals: E … antum Mechanics



(a)





…3, M4).

…nd K “test masses” in non-…ons).

…km circular orbit.

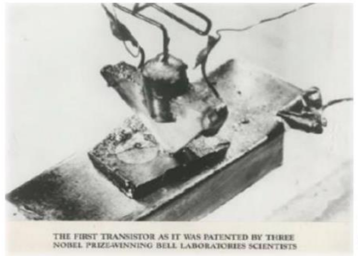
…avity gradient shifts by …king atom positioning

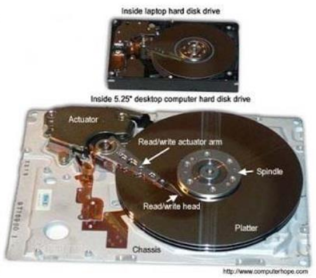
…ths of operation.

Comments
Torsion balance
MICROSCOPE first results
MICROSCOPE full data
Atom Interferometry
…nd macroscopic corner cube (CC)
different elements
…ame element, fermion vs. boson
same element, different isotopes
10 m tower
STE-QUEST
under construction at CERN

Example of Open Questions in Fundamental Physics

… 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)

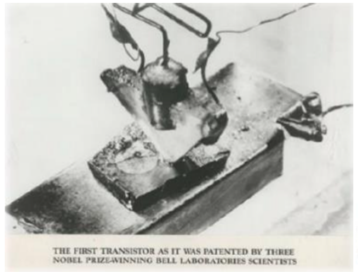
Erwin Schrödinger (1887-1961)

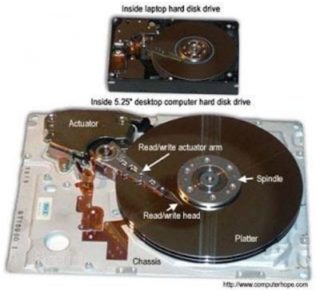
The first quantum revolution

Observation and macroscopic manifestation of quantum principles

Example of Open Questions in Fundamental Physics

… and how the Quantum Revolutions could help addressing them





Planck's quantum theory — beginning of 20^{th} century

transistor — 1947

hard disk — 1954

laser — 1960

end 20^{th} / beginning 21^{st} — 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…

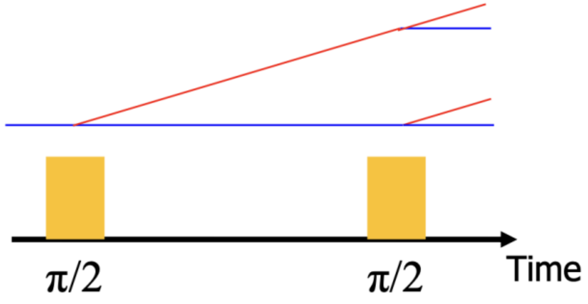
The second quantum revolution

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

MORE ON ATOM INTERFEROMETRY CONCEPT

Possible Phase Shifts

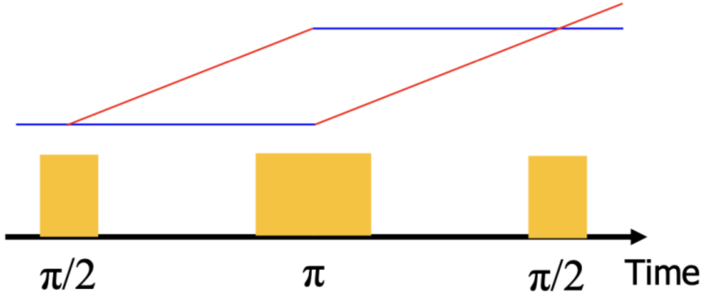
Ramsey sequence (clock)



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

- Measures velocity

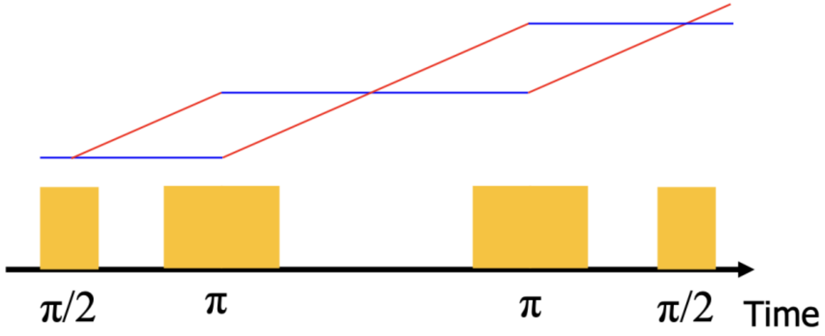
Mach-Zehnder



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

- “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.	$-k_{\rm eff}gT^2$	$3. \times 10^{8}$	Newtonian gravity	$-k_{\rm eff}gT^2$
2.	$-k_{\rm eff}(\partial_r g)v_LT^3$	$-2. \times 10^{3}$	1st gradient	$-k_{\rm eff}(\partial_r g)v_LT^3$
3.	$-\frac{7}{12}k_{\rm eff}(\partial_r g)gT^4$	$9. \times 10^{2}$		$-\frac{7}{12}k_{\rm eff}(\partial_r g)gT^4$
4.	$-3k_{\rm eff}g^2T^3$	$-4. \times 10^{1}$	finite speed of light and	
5.	$-3k_{\rm eff}gv_LT^2$	$4. \times 10^{1}$	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.	$(\omega_{\rm eff} - \omega_a)\,gT^2$	$-4. \times 10^{-1}$	detuning	
8.	$(2-2\beta-\gamma)k_{\rm eff}g\phi T^2$	$-2. \times 10^{-1}$	GR (non-linearity)	
9.	$-\frac{3k_{\rm eff}^2}{2m}gT^2$	$2. \times 10^{-2}$		
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.	$-\frac{35}{4}k_{\rm eff}(\partial_r g)gv_LT^4$	$6. \times 10^{-4}$		
12.	$-4k_{\rm eff}(\partial_r g)v_L^2T^3$	$-3. \times 10^{-4}$		
13.	$2\omega_a g^2T^3$	$2. \times 10^{-4}$		
14.	$2\omega_a gv_LT^2$	$-2. \times 10^{-4}$		
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.	$-12k_{\rm eff}g^2v_LT^3$	$-7. \times 10^{-6}$		
17.	$-7k_{\rm eff}g^3T^4$	$4. \times 10^{-6}$		
18.	$-5k_{\rm eff}gv_L^2T^2$	$3. \times 10^{-6}$	GR (velocity-dependent force)	
19.	$(2-2\beta-\gamma)k_{\rm eff}\partial_r(g\phi)v_LT^3$	$2. \times 10^{-6}$	GR 1st gradient	
20.	$\frac{7}{12}(4-4\beta-3\gamma)k_{\rm eff}\phi(\partial_r g)gT^4$	$-2. \times 10^{-6}$	GR	
21.	$(\omega_{\rm eff} - \omega_a)\,(\partial_r g)v_LT^3$	$2. \times 10^{-6}$		
22.	$\frac{7}{12}\,(\omega_{\rm eff} - \omega_a)\,(\partial_r g)gT^4$	$-1. \times 10^{-6}$		
23.	$-\frac{7}{12}(2-2\beta-\gamma)k_{\rm eff}g^3T^4$	$-3. \times 10^{-7}$	GR	
24.	$-\frac{7k_{\rm eff}^2}{2m}(\partial_r g)v_LT^3$	$-2. \times 10^{-7}$		
25.	$-\frac{27k_{\rm eff}^2}{8m}(\partial_r g)gT^4$	$2. \times 10^{-7}$		
26.	$\frac{k_{\rm eff}\omega_a}{m}gT^2$	$-1. \times 10^{-7}$		
27.	$6(2-2\beta-\gamma)k_{\rm eff}\phi g^2T^3$	$5. \times 10^{-8}$	GR	
28.	$3\,(\omega_{\rm eff} - \omega_a)\,g^2T^3$	$4. \times 10^{-8}$		
29.	$3\,(\omega_{\rm eff} - \omega_a)\,gv_LT^2$	$-4. \times 10^{-8}$		
30.	$6(1-\beta)k_{\rm eff}\phi gv_LT^2$	$3. \times 10^{-8}$	GR	

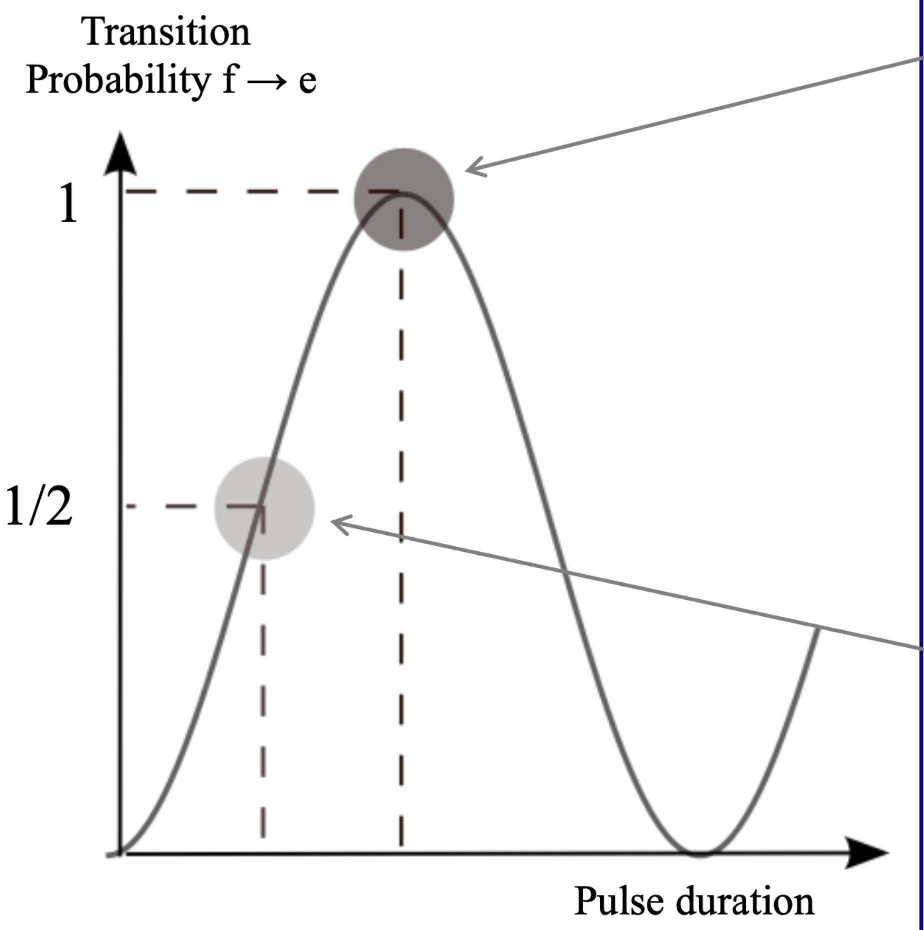
Dimopoulos et al, Phys.Rev.D78:042003,**2008**

Imperial College London

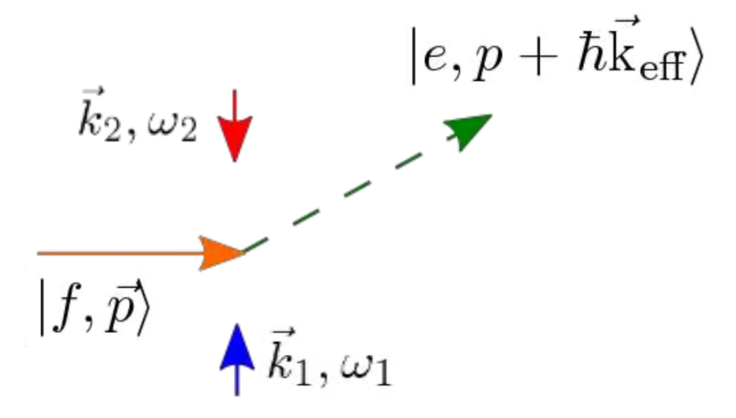
AION

Pi and Pi/2 Pluses – Rabi Oscillation

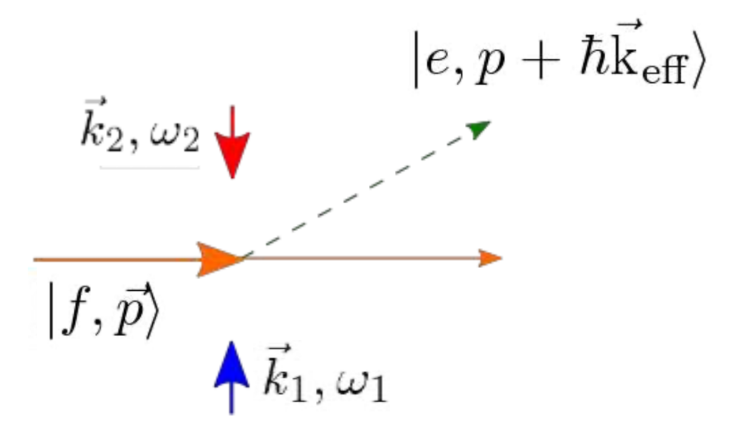
Rabi oscillation between |f> and |e>



"π" pulse = mirror

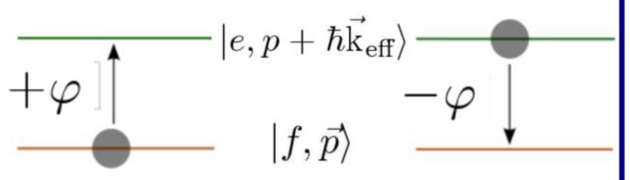


"π/2" pulse = beam splitter



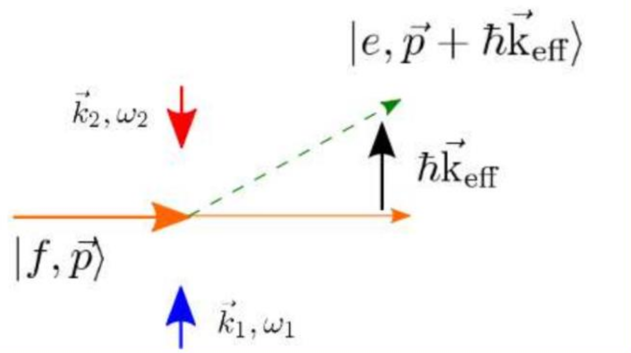
Imprint laser phase on atomic wave-function:

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



Momentum tranfser (~1 cm/s)

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



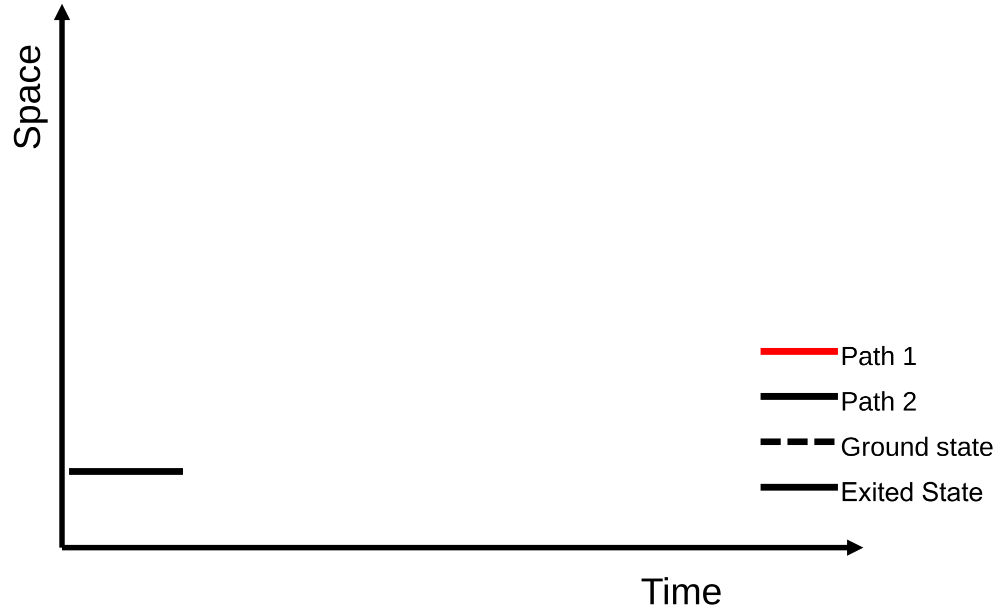
Mach-Zehnder Atom Interferometer – Phase shift

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.

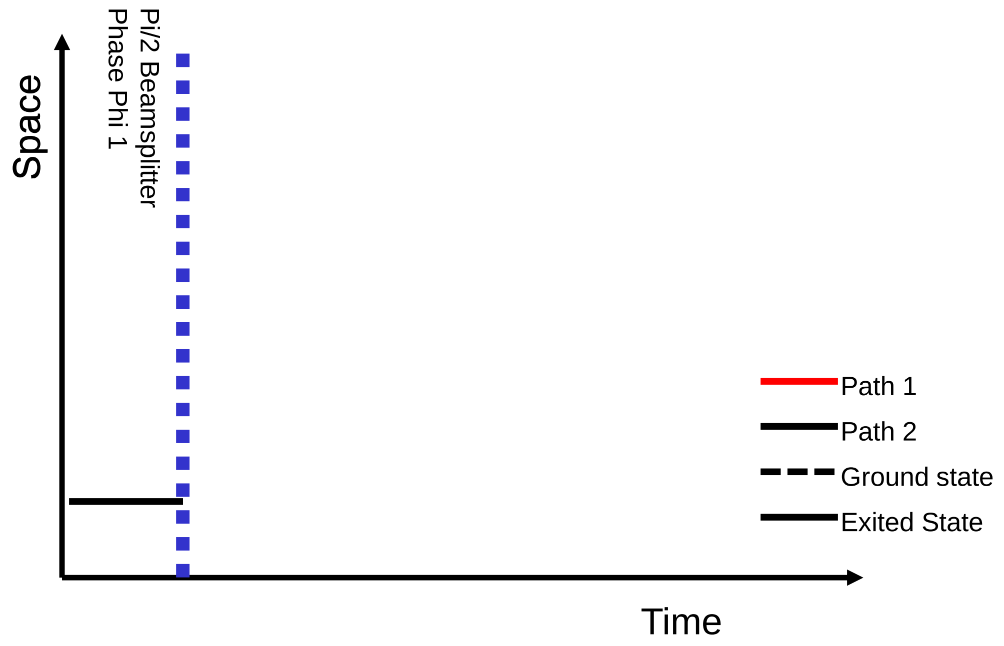
Atoms at rest:

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

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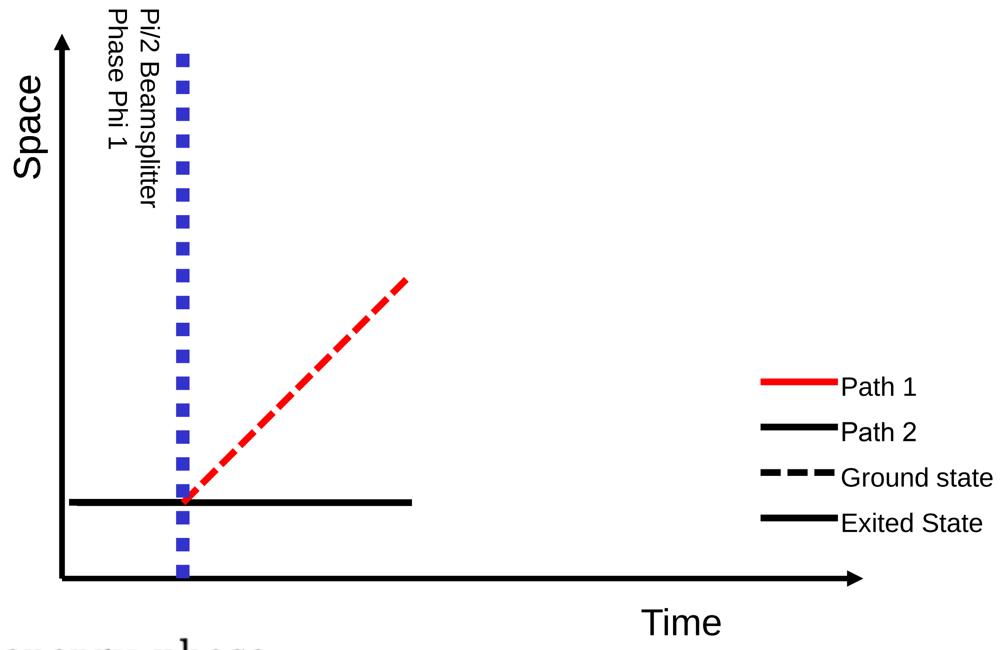


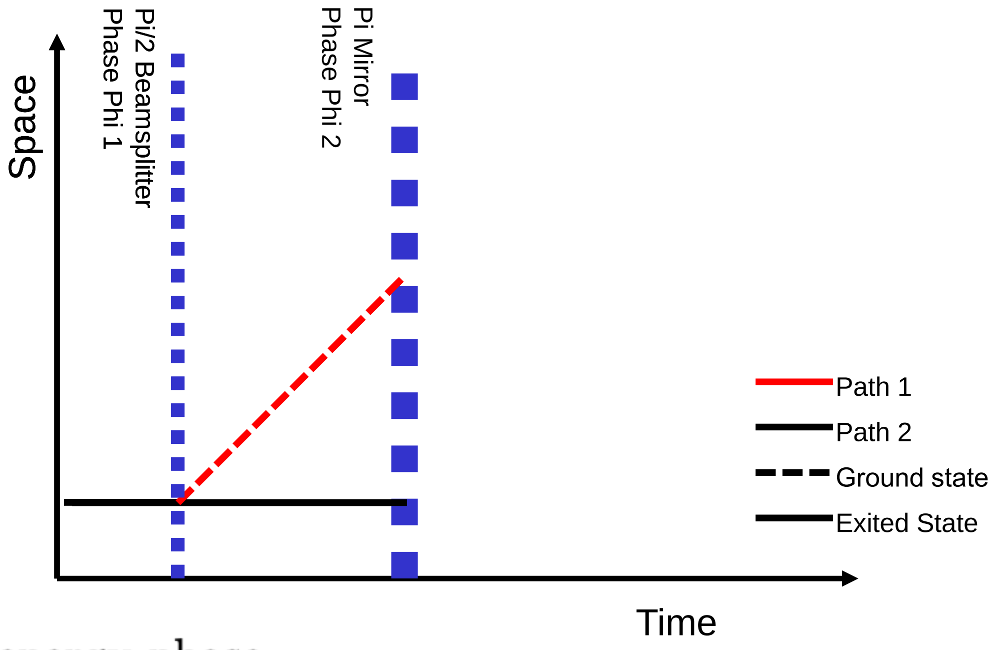
At time $t = T$ just before the π mirror pulse $|1\rangle$ acquired the energy phase $-Et/\hbar = -\omega_a T$

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

Mach-Zehnder Atom Interferometer – Phase shift

AION

Assuming no other interactions like gravity, etc.



Atoms at rest:

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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:

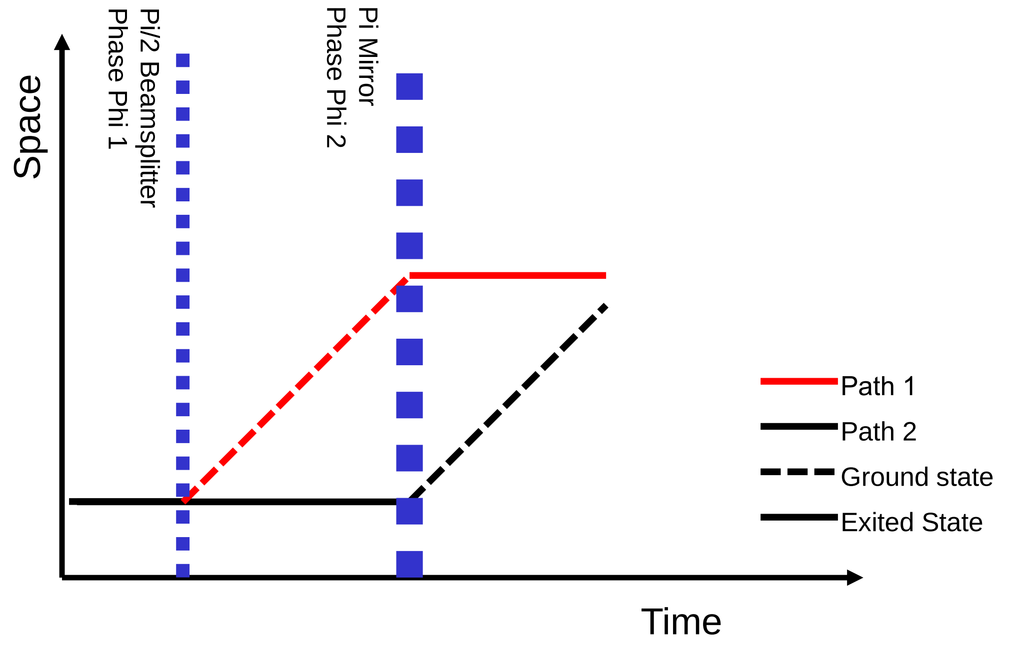
$$\Phi_1 = \phi_1 - ET/\hbar - \phi_2, \quad \Phi_2 = \phi_2$$

Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.

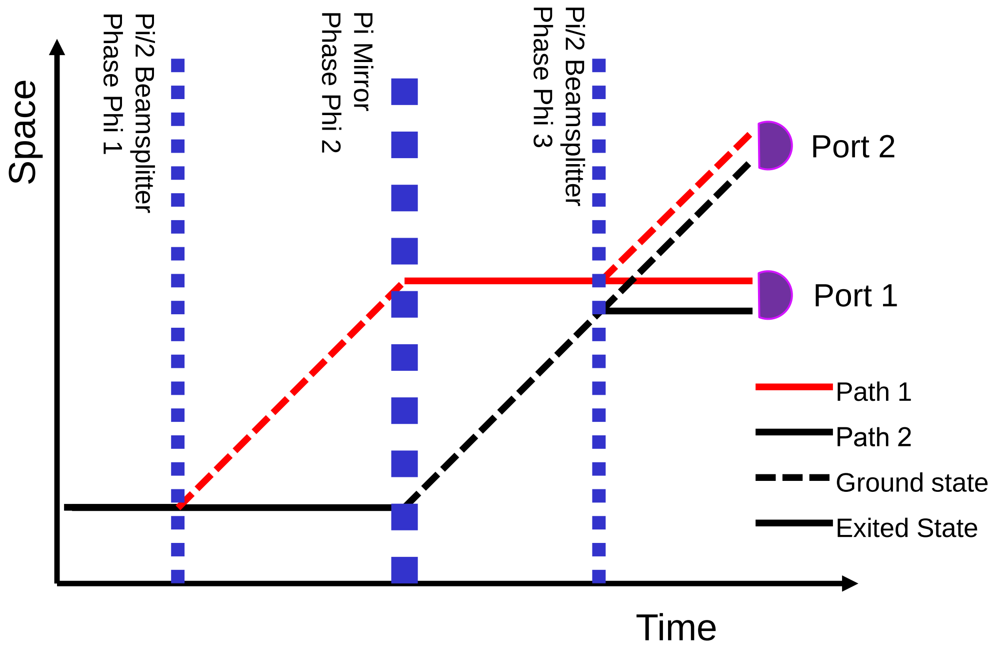
At time $t = 2T$ just before the next $\pi/2$ mirror pulse:

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



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:

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

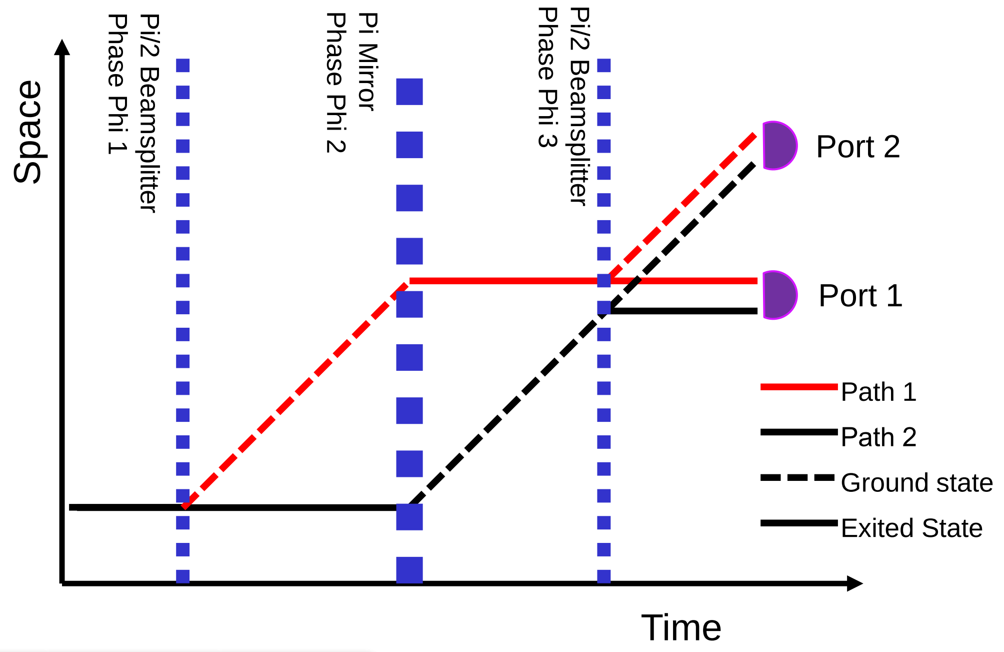
At $|1\rangle$ port:

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

Mach-Zehnder Atom Interferometer – Phase shift

CA QT For Fundamental Physics – FIPs 2022

Assuming no other interactions like gravity, etc.



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

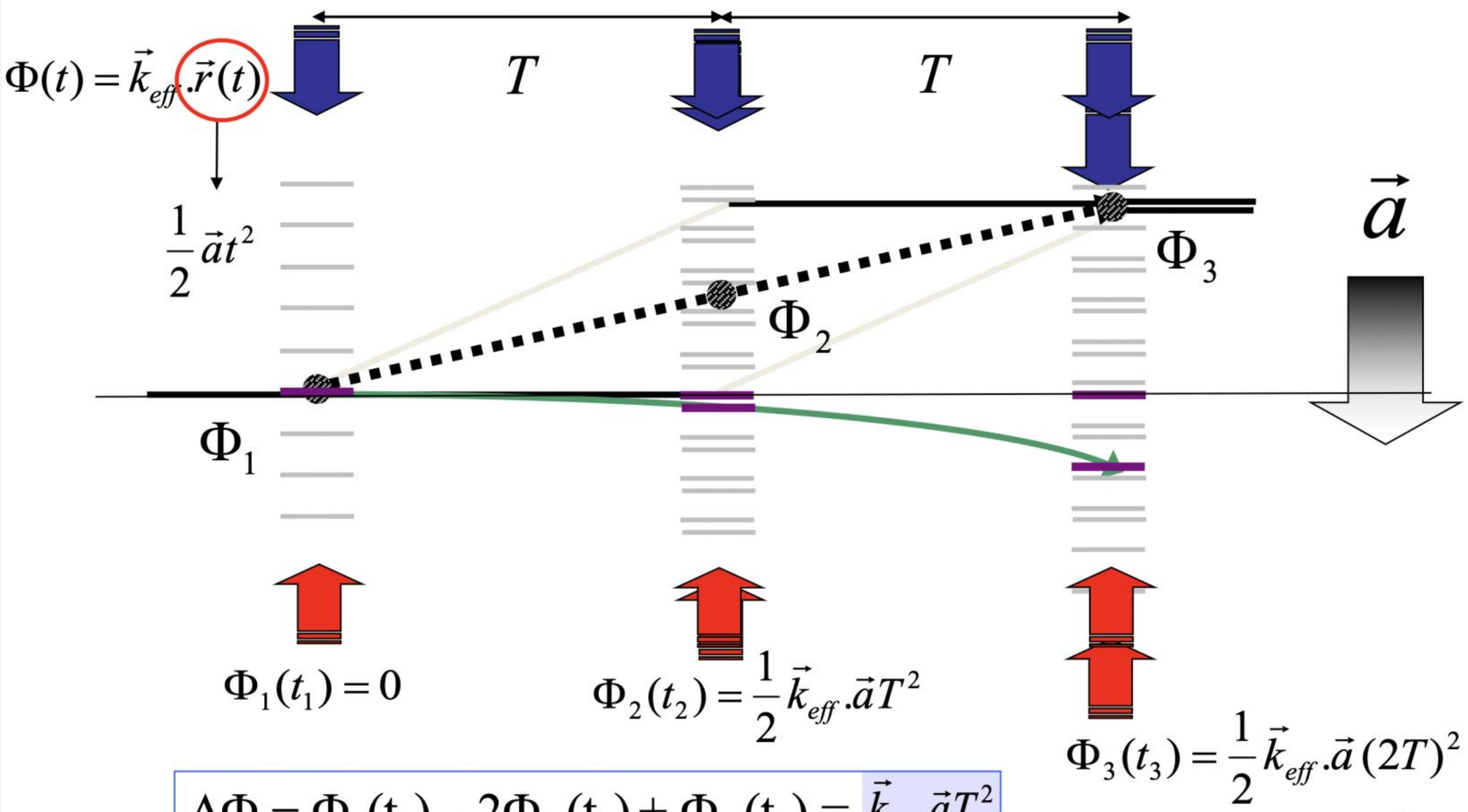
$$\Phi_1 - \Phi_2 = (\phi_1 - ET/\hbar - \phi_2) - (\phi_2 - ET/\hbar - \phi_3) = \phi_1 - 2\phi_2 + \phi_3$$

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

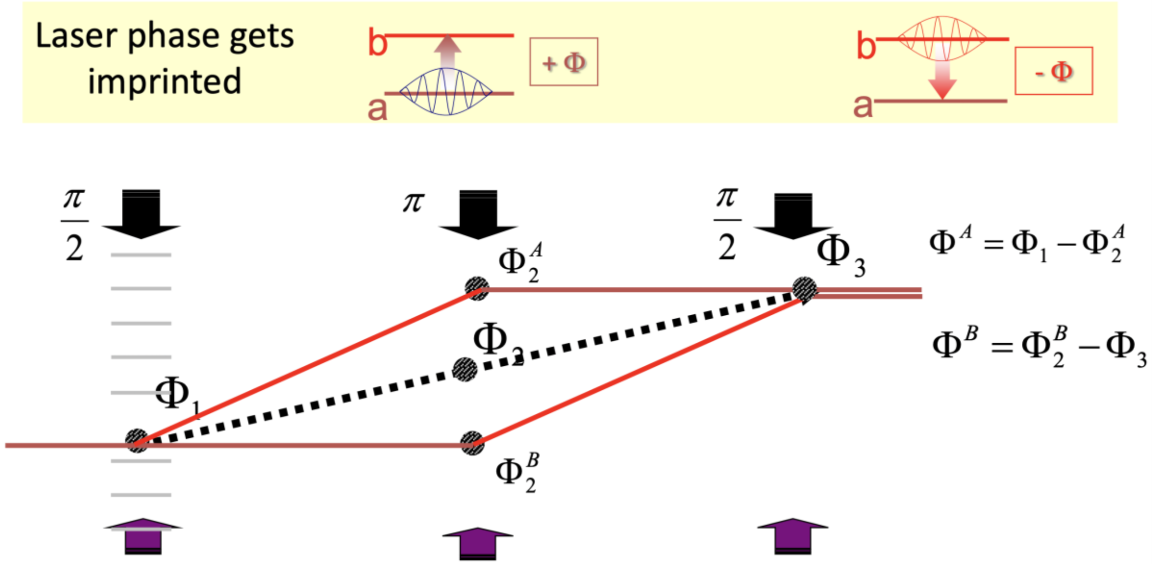
Acceleration phase shift



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

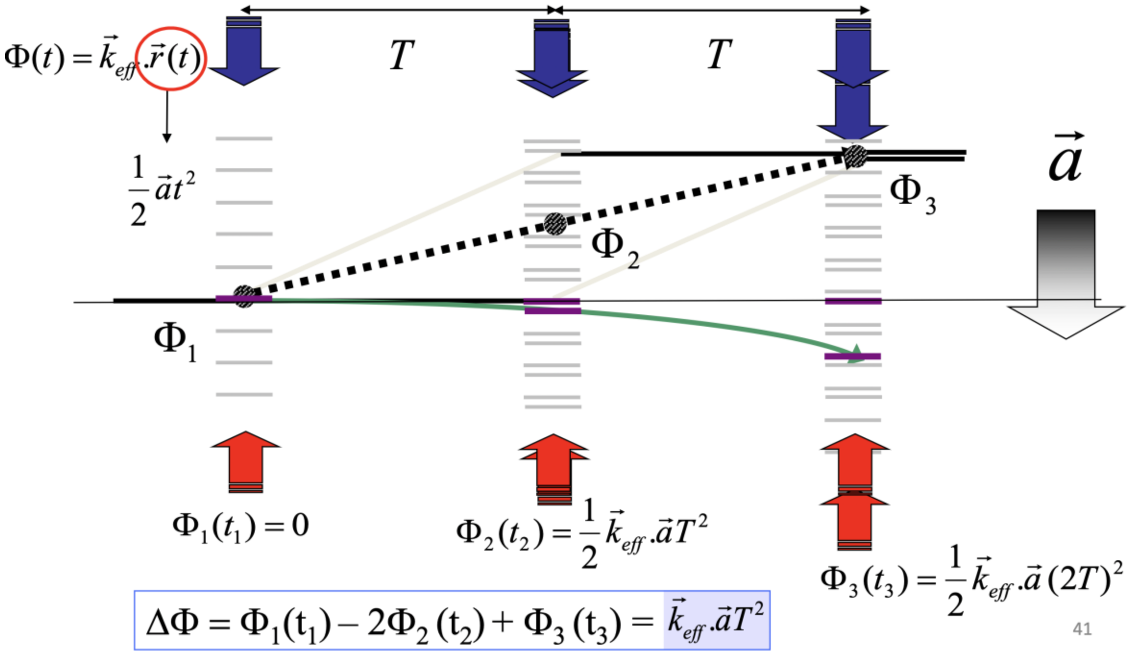
41

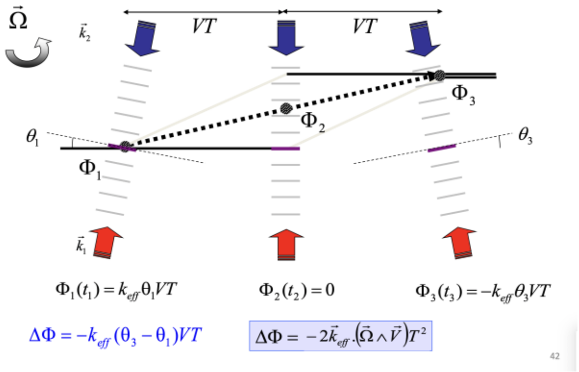
Different Phase Shifts for Different Interactions



$$\Delta\Phi = \Phi^A - \Phi^B = \Phi_1 - 2\Phi_2 + \Phi_3$$

$$\Phi_2 = \frac{\Phi_2^A - \Phi_2^B}{2}$$





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

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

STE-QUEST

Imperial College London

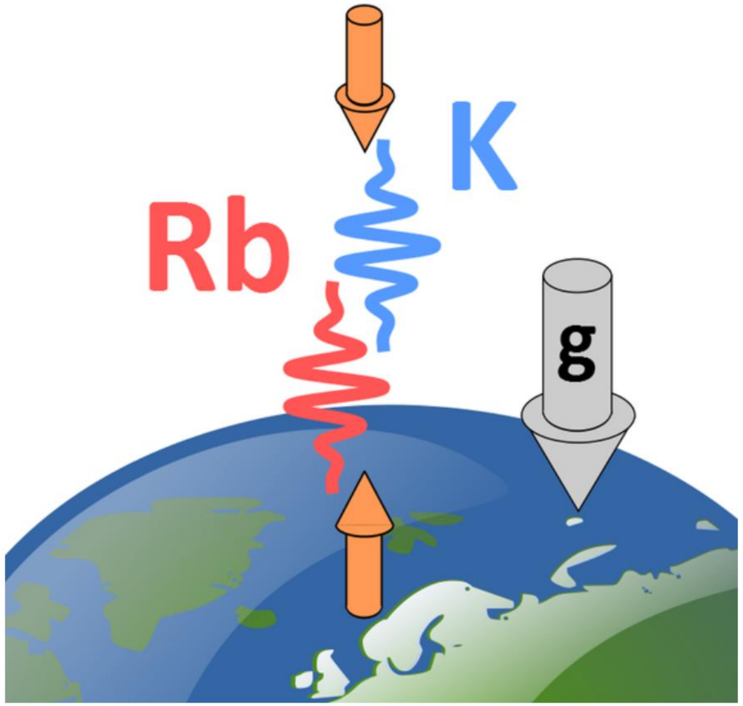
AION

STE-QUEST (M-Class Mission Proposal)

STE-QUEST

Space Time Explorer and QUantum Equivalence principle Space Test

A M-class mission proposal in response to the 2022 call in ESA's science program



Core Team:

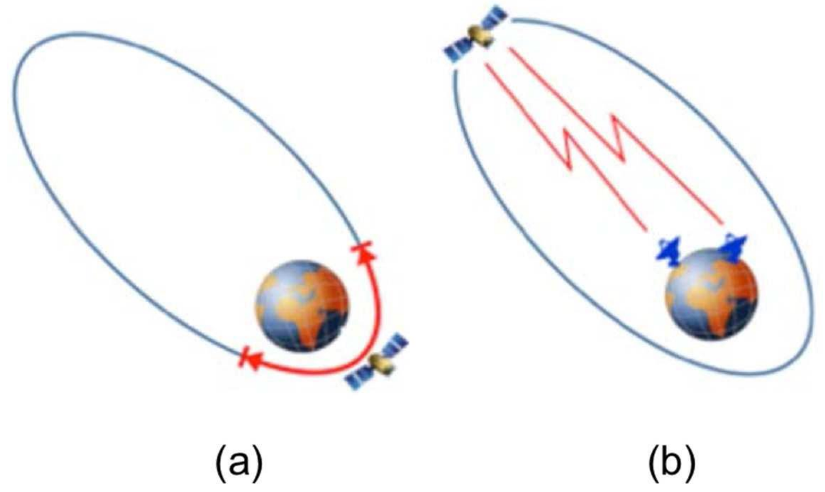
- Angelo Bassi, Department of Physics, University of Trieste, and INFN - Trieste Section, *Italy*
- Kai Bongs, Midlands Ultracold Atom Research Centre, School of Physics and Astronomy University of Birmingham, *United Kingdom*
- Philippe Bouyer, LP2N, Université Bordeaux, IOGS, CNRS, Talence, *France*
- Claus Braxmaier, Institute of Microelectronics, Ulm University and Institute of Quantum Technologies, German Aerospace Center (DLR), *Germany*
- Oliver Buchmueller, High Energy Physics Group, Blackett Laboratory, Imperial College London, London, *United Kingdom*
- Maria Luisa (Marilu) Chiofalo, Physics Department "Enrico Fermi" University of Pisa, and INFN-Pisa *Italy*
- John Ellis, Physics Department, King's College London, *United Kingdom*
- Naceur Gaaloul, Institute of Quantum Optics, Leibniz University of Hanover, *Germany*
- Aurélien Hees, SYRTE, Observatoire de Paris-PSL, CNRS, Sorbonne Université, LNE, Paris, *France*
- Philippe Jetzer, Department of Physics, University of Zurich, *Switzerland*
- Steve Lecomte, Centre Suisse d'Electronique et de Microtechnique (CSEM), Neuchâtel, *Switzerland*
- Gilles Métris, Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur, *France*
- Ernst M. Rasel, Institute of Quantum Optics, Leibniz University of Hanover, *Germany*
- Thilo Schuldt, German Aerospace Center (DLR), Institute of Quantum Technologies, Ulm *Germany*
- Carlos F. Sopuerta, Institute of Space Sciences (ICE, CSIC), Institute of Space Studies of Catalonia (IEEC), *Spain*
- Guglielmo M. Tino, Dipartimento di Fisica e Astronomia and LENS, Università di Firenze, INFN, CNR *Italy*
- Wolf von Klitzing, Institute of Electronic Structure and Laser, Foundation for Research and Technology Hellas, *Greece*
- Lisa Wörner, German Aerospace Center (DLR), Institute of Quantum Technologies, Ulm *Germany*
- Nan Yu, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, *USA*
- Martin Zelan, Measurement Science and Technology, RISE Research Institutes of Sweden, Borås, *Sweden*

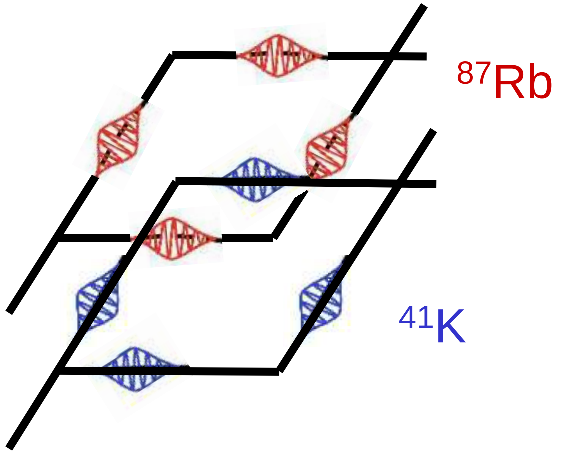
Strong UK representation in STE-QUEST Core Team.

All are also core members of AION

STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics

Science Goals: Equivalent Principal at 1E-17, Ultra-Light Dark Matter, Test of Quantum Mechanics





- Based on STE-QUEST proposals (M3, M4).
- Double atom interferometer with Rb and K “test masses” in non-classical states (quantum superpositions).
- Optimized for UFF test. Assume 700 km circular orbit.
- Apply recent results on controlling gravity gradient shifts by offsetting laser frequencies, thus relaxing atom positioning requirements by factor >100.
- **Reaches 1E-17 target after 18 months of operation.**

Class	Elements	η	Year [ref]	Comments
Classical	Be - Ti	2×10^{-13}	2008	Torsion balance
	Pt - Ti	1×10^{-14}	2017	MICROSCOPE first results
	Pt - Ti	(10^{-15})	2022+	MICROSCOPE full data
Hybrid	^{133}Cs - CC	7×10^{-9}	2001	Atom Interferometry
	^{87}Rb - CC	7×10^{-9}	2010	and macroscopic corner cube (CC)
Quantum	^{39}K - ^{87}Rb	3×10^{-7}	2020	different elements
	^{87}Sr - ^{88}Sr	2×10^{-7}	2014	same element, fermion vs. boson
	^{85}Rb - ^{87}Rb	3×10^{-8}	2015	same element, different isotopes
	^{85}Rb - ^{87}Rb	3.8×10^{-12}	2020	10 m tower
	^{41}K - ^{87}Rb	(10^{-17})	2037	STE-QUEST
Antimatter	$\overline{\text{H}}$ - H	(10^{-2})	2023+	under construction at CERN

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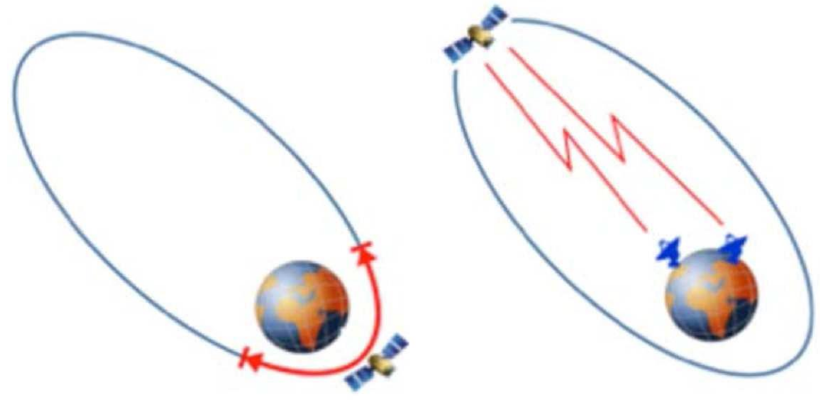
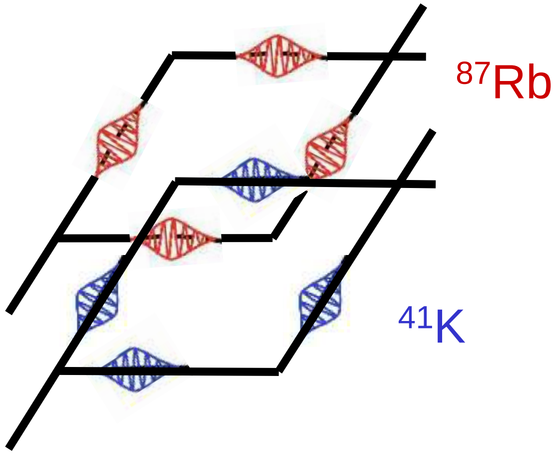


(a) (b)



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	^{88}Sr - ^{88}Sr	$< 10^{-15}$	2030	AION/MAGIS 100m
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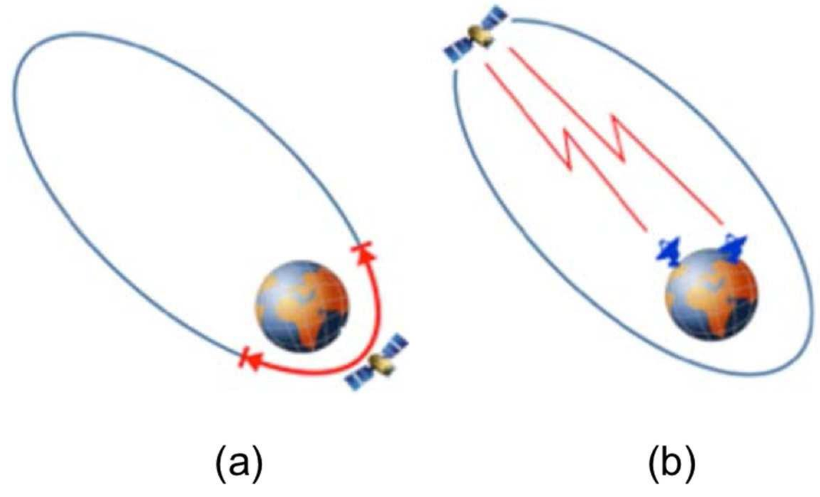

- Based on STE-QUEST proposals (M3, M4).
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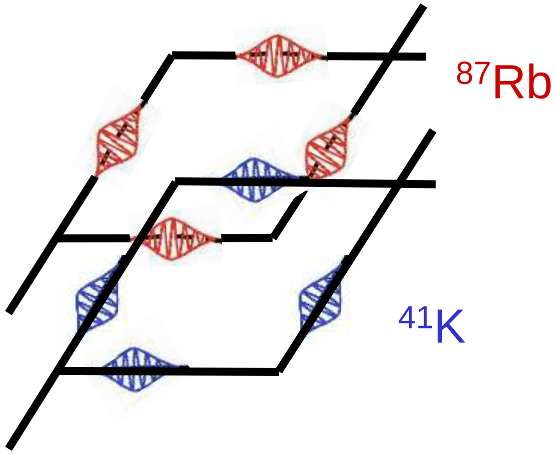
- Optimized
- Apply rec offsetting requireme
- **Reaches**

State-of-the-art conventional sensors (electrostatic accelerometers) e.g. used for Earth Observation are limited by around eta ~1E-11 (acceleration sensitivity)



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STE-QUEST Workshop on May 17/18

STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics is now open at:

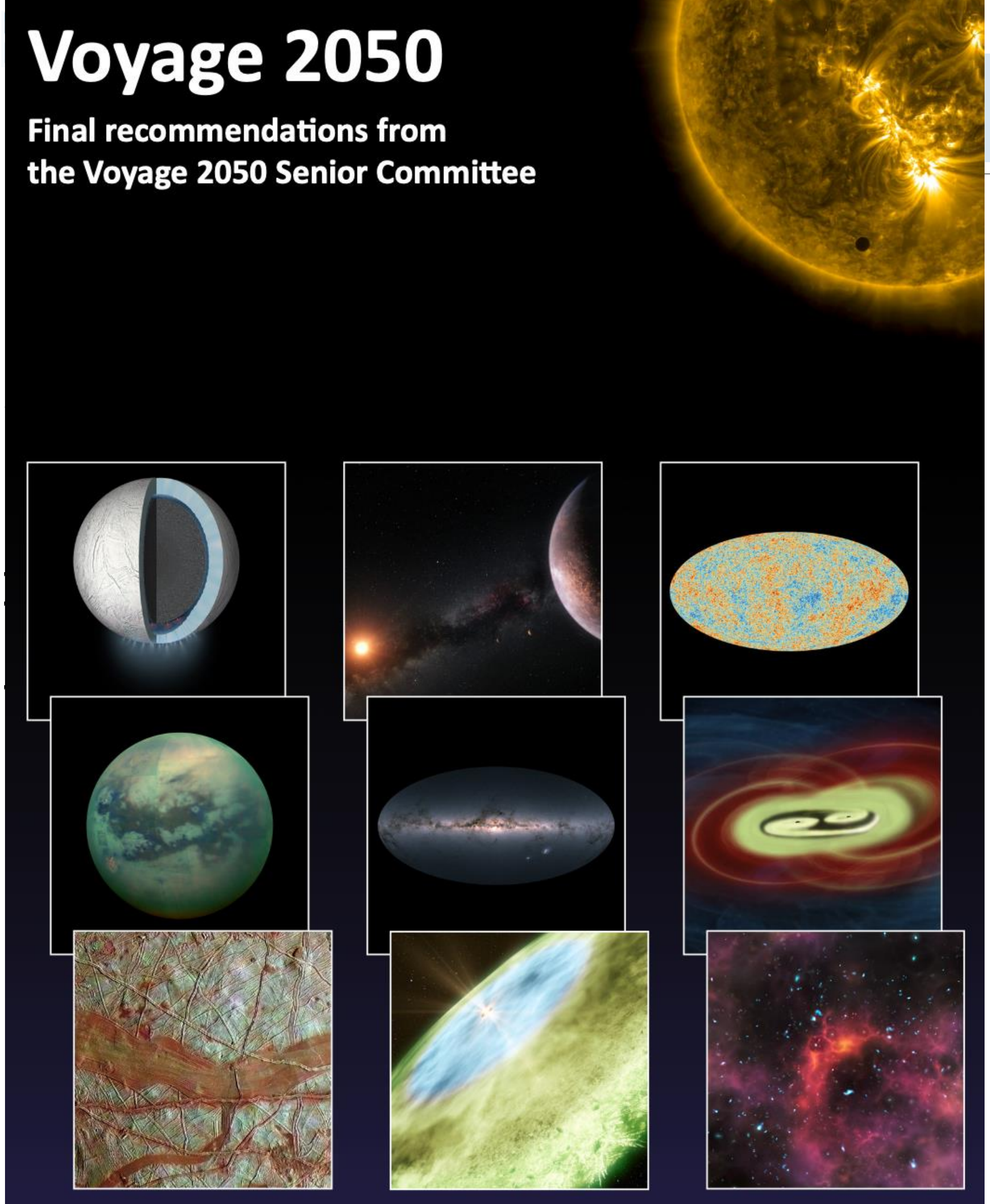
https://indico.cern.ch/event/1138902/registrations/

The workshop will take place as a virtual event on zoom on May 17/18.

https://indico.cern.ch/event/1138902/

- This workshop follows our Community Workshop & Roadmap for Cold Atoms in Space and is the next step in our community building process to define, develop and promote important milestones of our Community Roadmap, specifically the STE-QUEST M-class mission proposal now being considered by ESA.
- This event will bring together the cold atom, astrophysics, cosmology, and fundamental physics communities to discuss the science opportunities of this M-class mission proposal. Further information about the workshop scope is listed below.
- **Registering on the link provided above will enable you to attend the virtual workshop event and to keep informed about the continuing development of a full mission proposal that will follow it.**

ESA SENIOR RECOMMENDATIONS VOYGAE2050



Large missions:

- Moons of the Giant Planets
- Exoplanets
- New Physical Probes of the Early Universe: Fundamental physics and astrophysics

Possible Medium missions:

… QM & GR (cold atoms?)

Technology development recommendations for Cold Atom Interferometry

- for gravitational wave detectors in new wavebands …, detectors for dark matter candidates, sensitive clock tests of general relativity, tests of wave function collapse ….
- must reach high technical readiness level, be superior to classical technologies
- start with atomic clocks, on free-flyer or ISS?

What M-mission to propose?

AION

A coordinated three-fold response of the community to the Voyage 2050 recommendations:

- **A letter to ESA's Director of Science, Guenther Hasinger:**
  - ➢ to raise awareness in ESA that the community is prepared to organise itself and to work actively with ESA, as it shapes a roadmap for a Cold Atom technology in space development programme
- **A community workshop in September:**
  - ➢ This event brought together the cold atom, astrophysics, cosmology, fundamental physics, and earth observation communities to formulate a road-map for the development programme,.
- **A Workshop Summary and Road-map Document**
  - ➢ As input input to ESA and national space agencies on how to structure a Cold atoms in Space programme and what priorities could be established.

CERN AION100 SITE EXPLORATION WITH PBC

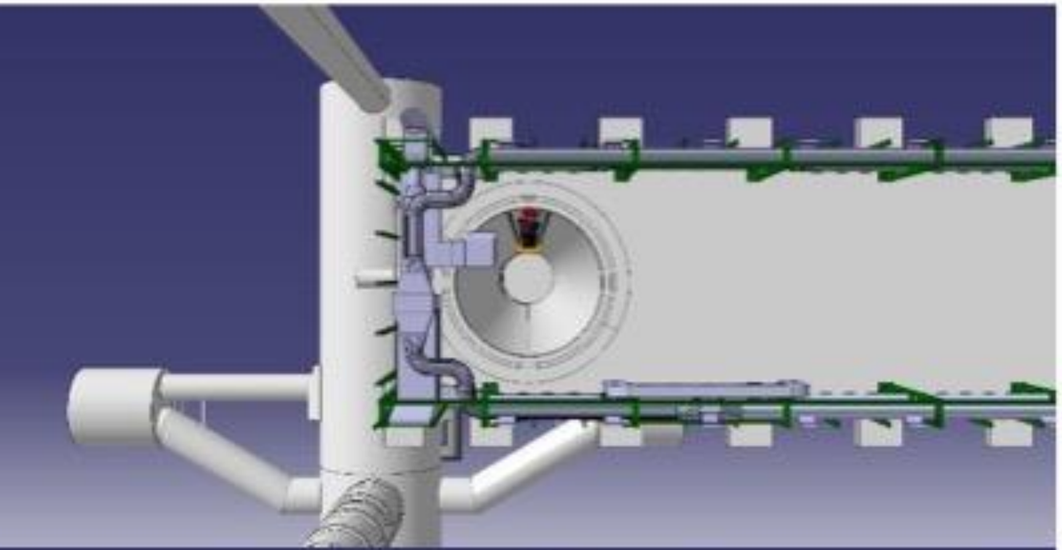
Introduction

EM Noise Levels

Slides from Sergio Calatroni (TE-VSC and PBC)

- **AION-100 experiment is an ion interferometer, proposed to be installed in the PX46 pit**
- **Feasibility study under way, with the support of the Physics Beyond Collider study - Technology Working Group. Aiming for official letter of intent at the end of the year.**
- **For info of other feasibility studies under way for AION-100: https://indi.to/RkZdN**
- **Need to measure EM background noise (1 mHz – 100 kHz) at the top (few meters below the steel lid) and at the bottom of PX46 during machine operation, using fluxgates up to 1-3 kHz, and 3D pick-up coils for the high frequency spectrum**
- **Choice of a closed plastic tube installed in the lid, after drilling, for hosting the probes**
- **Installation procedure approved by LMC: https://edms.cern.ch/document/2710516/1.0**
- **Many thanks to all services and people involved for the support: everybody was fully motivated to help**

AION-100



Location of AION-100

Drilling location

The tube (thanks to EN-MME)

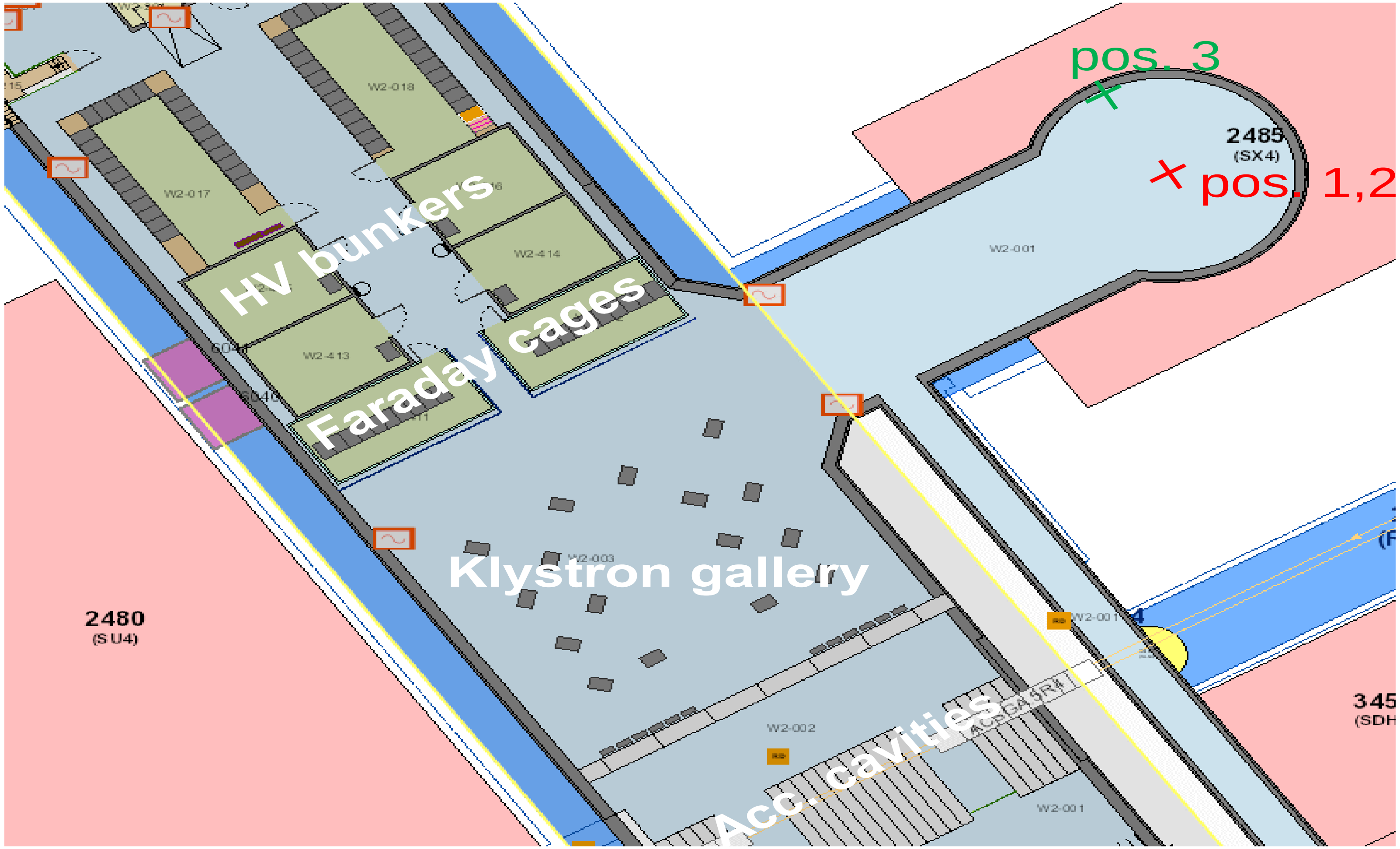
PP plastic, closed at bottom
225 mm outer diameter
199,4 mm inner diameter
5000 mm length
Al flange for support

Installation (thanks to EN-ACE, EN-HE, EN-CV)

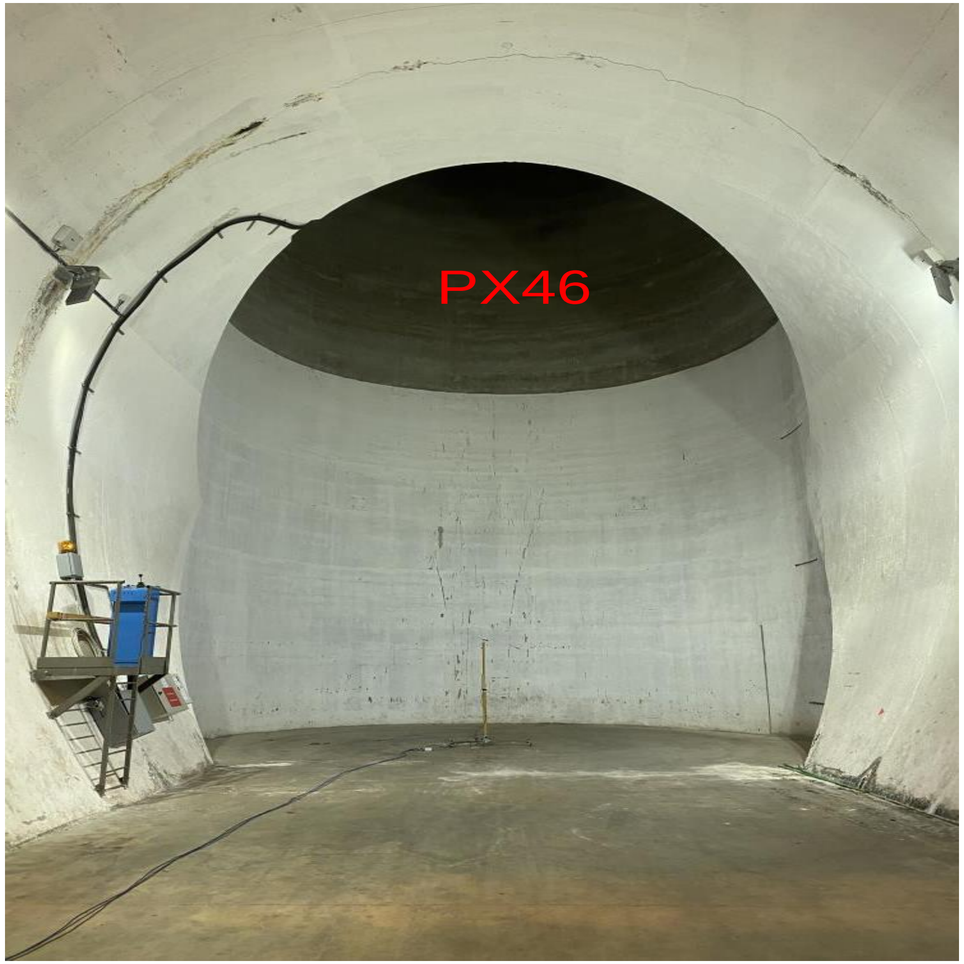
Ready for inserting the probes

Measurement location at the bottom of the PX46 shaft, UX45 building

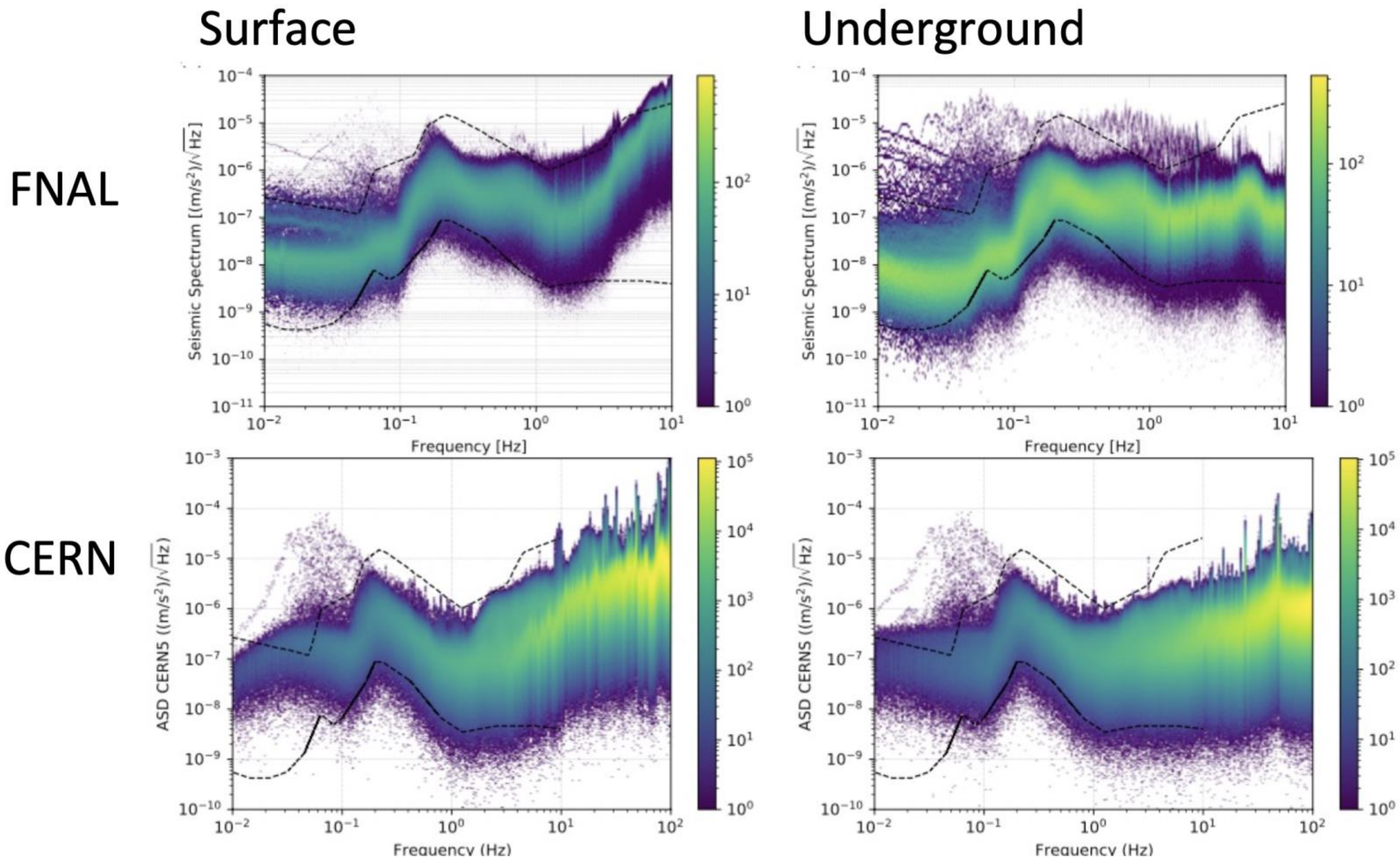
Slides from Marco Buzio, Mariano Pentella, Daniel Valuch

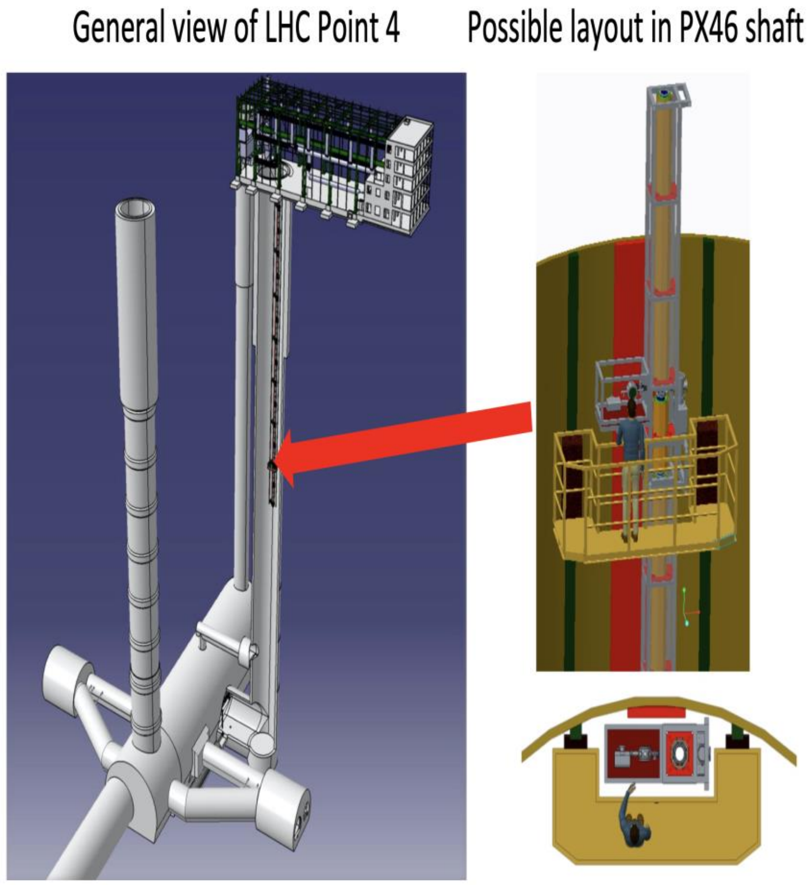


Measurement location at the bottom of the PX46 shaft, UX45 cavern



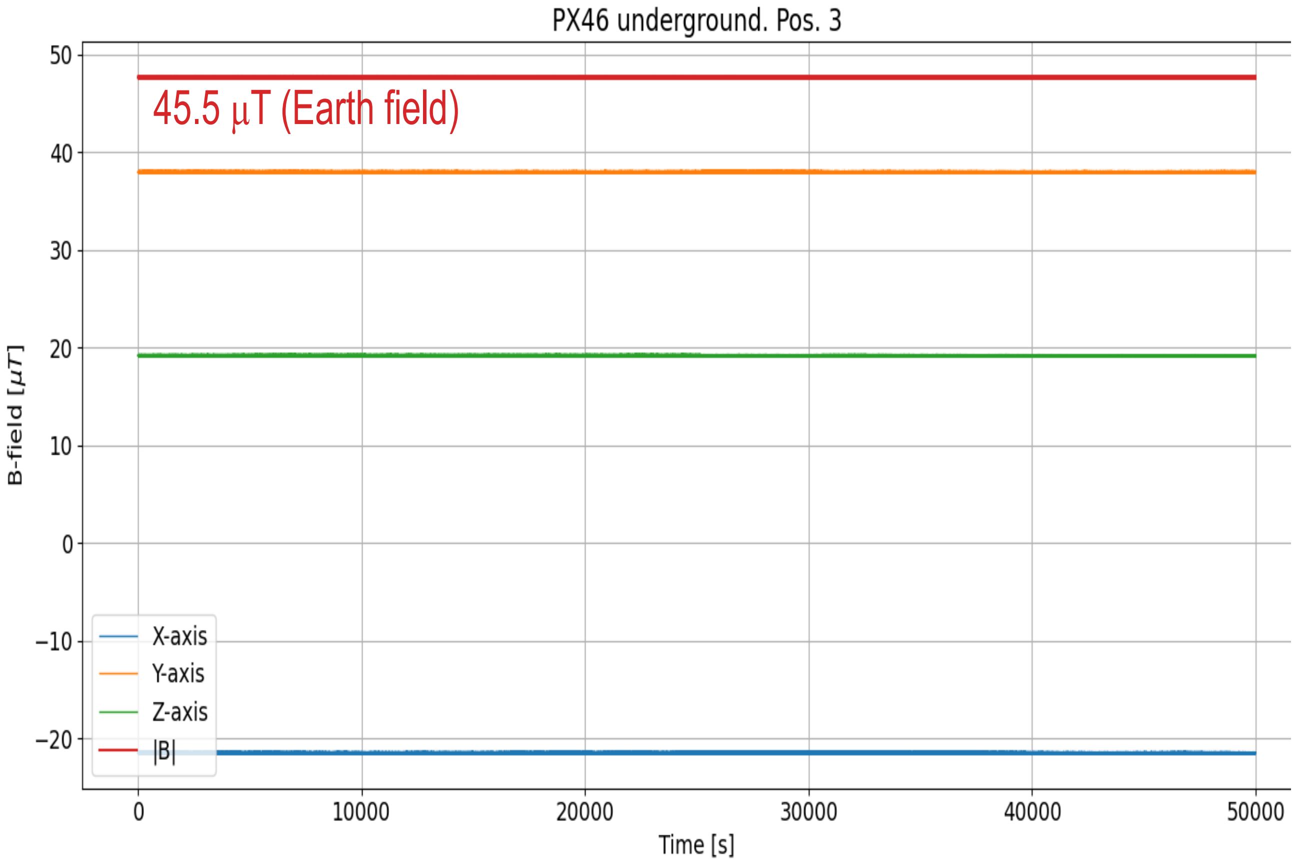
ATION-100 at CERN – Site Investigation





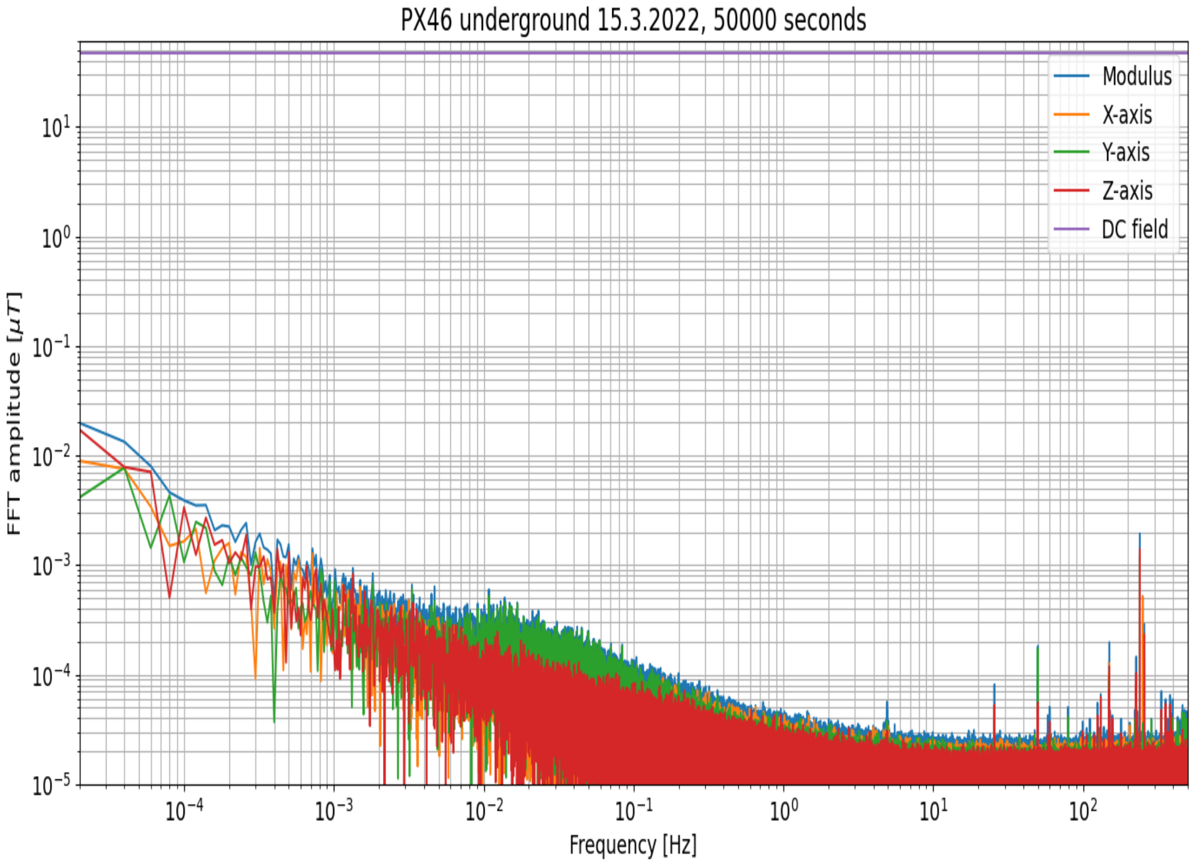
Spectrum similar to that measured at Fermilab for MAGIS

Location: bottom of the PX46 shaft. Systems in UX45 running



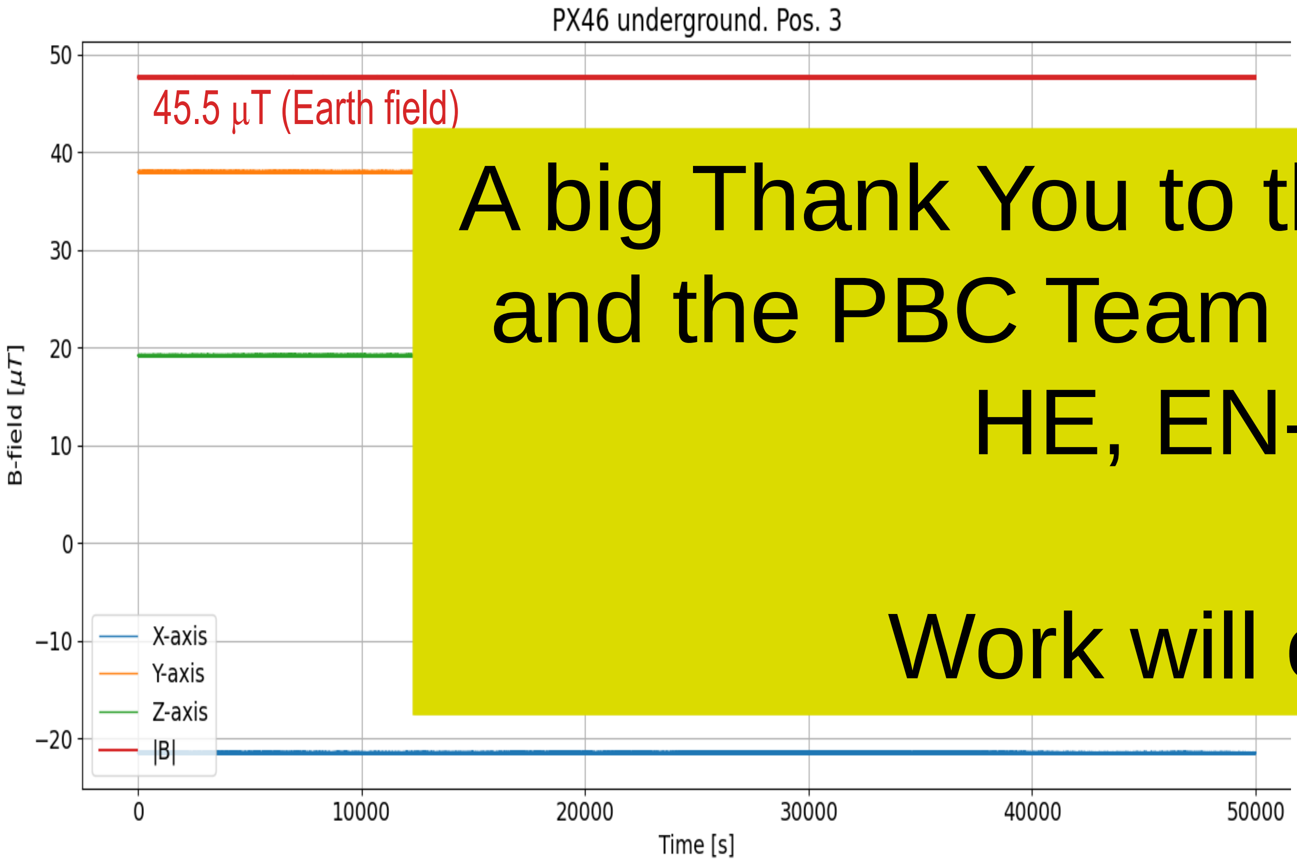
Location 3, wall of PX46. Quiet, Earth field for scale

Location: bottom of the PX46 shaft. Systems in UX45 running



Location 3, wall of PX46. Earth (DC) field for scale

Location: bottom of the PX46 shaft. Systems in UX45 running



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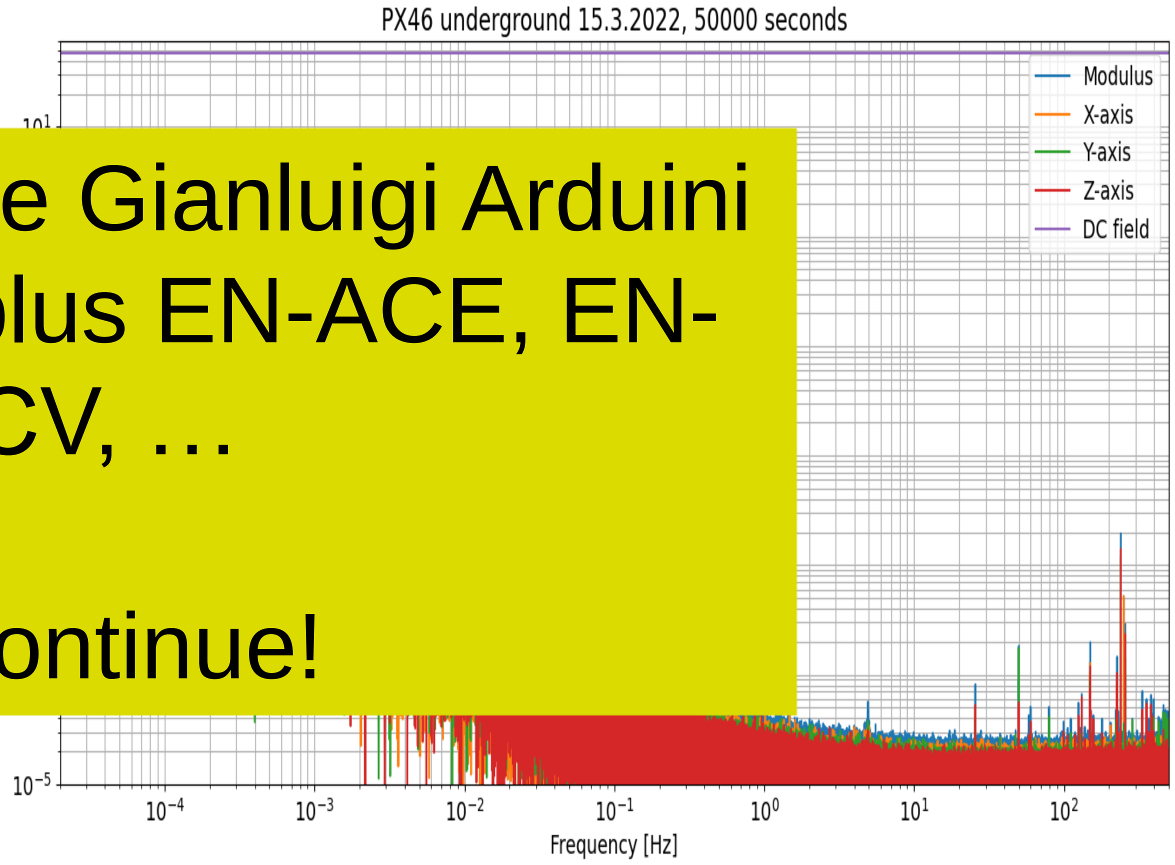


Location 3, wall of PX46. Earth (DC) field for scale

A big Thank You to the Gianluigi Arduini and the PBC Team plus EN-ACE, EN-HE, EN-CV, …

Work will continue!

APPLICATIONS IN OTHER FIELDS, SUCH AS QUANTUM COMPUTING.

Quantum Computing & AION

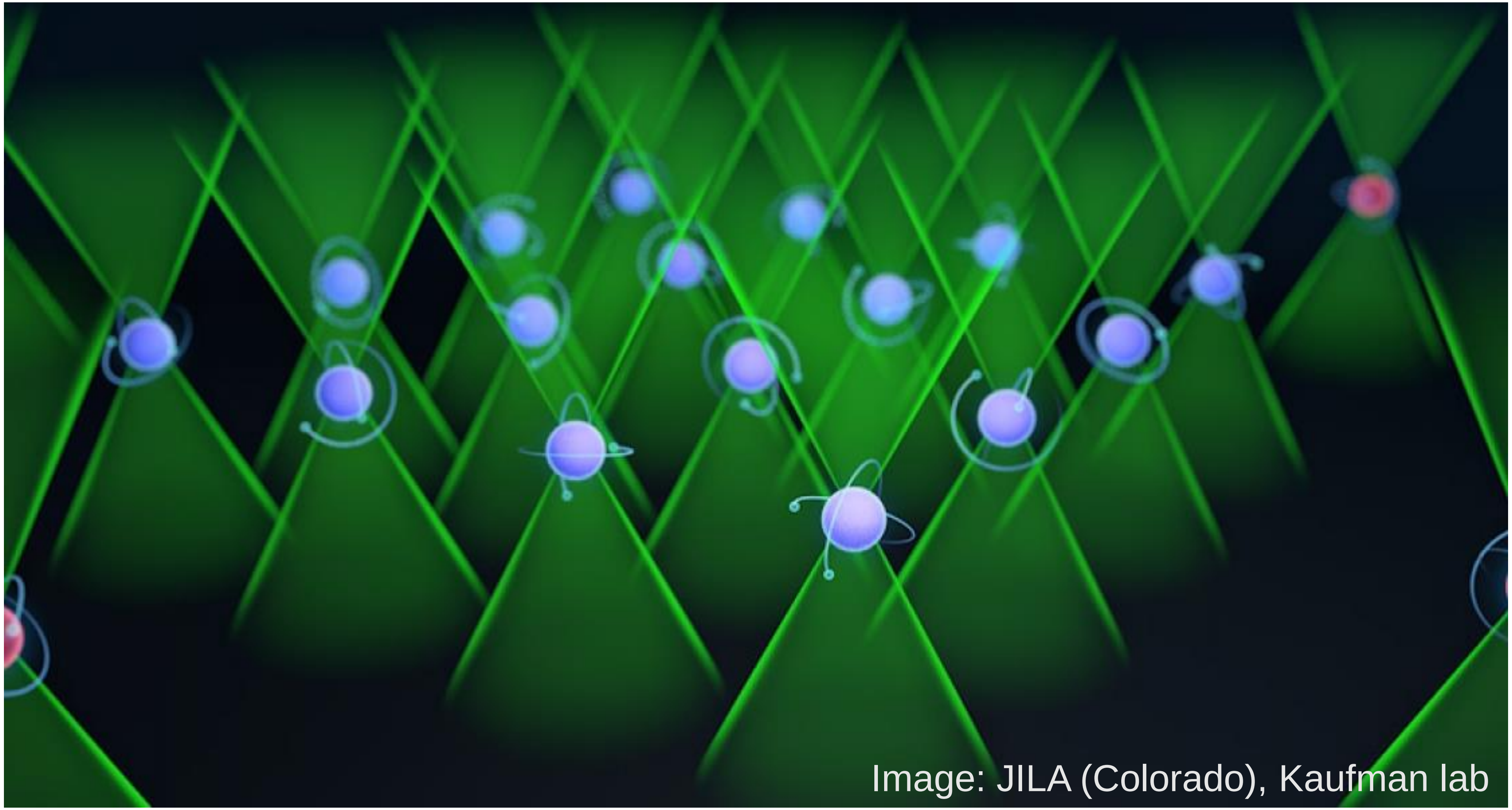
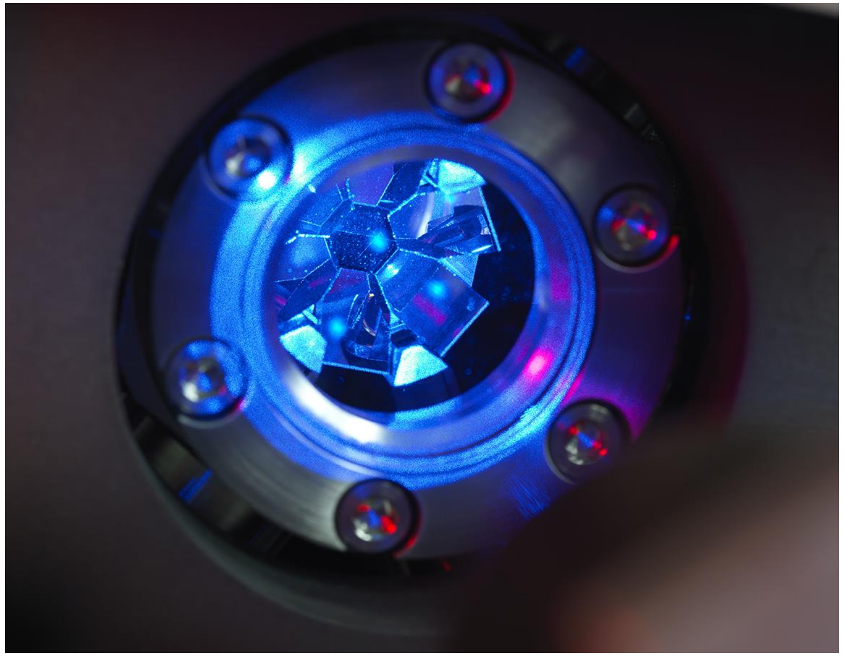
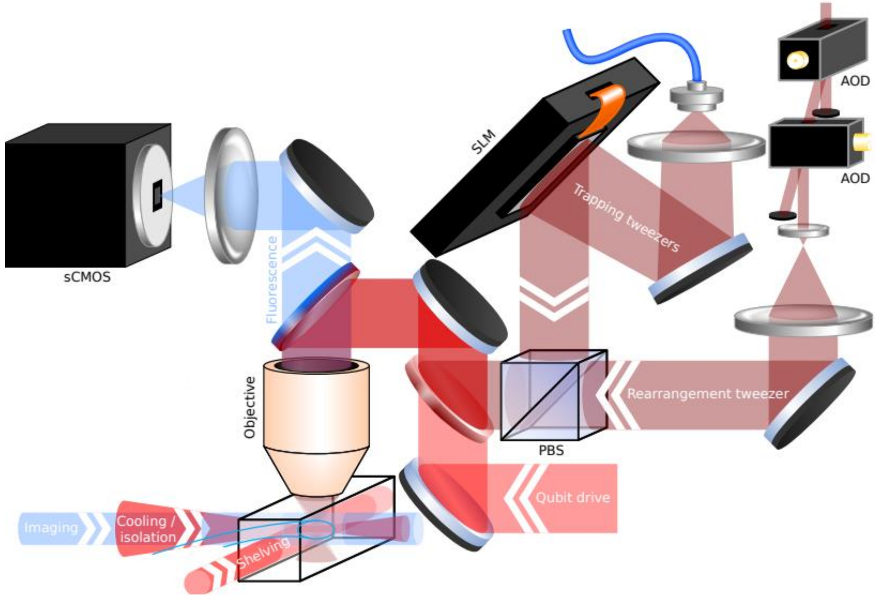


Image: JILA (Colorado), Kaufman lab

Quantum Computing & AION

Existing AION cold Sr system (80%) + New tweezer array (20%) = Quantum computer

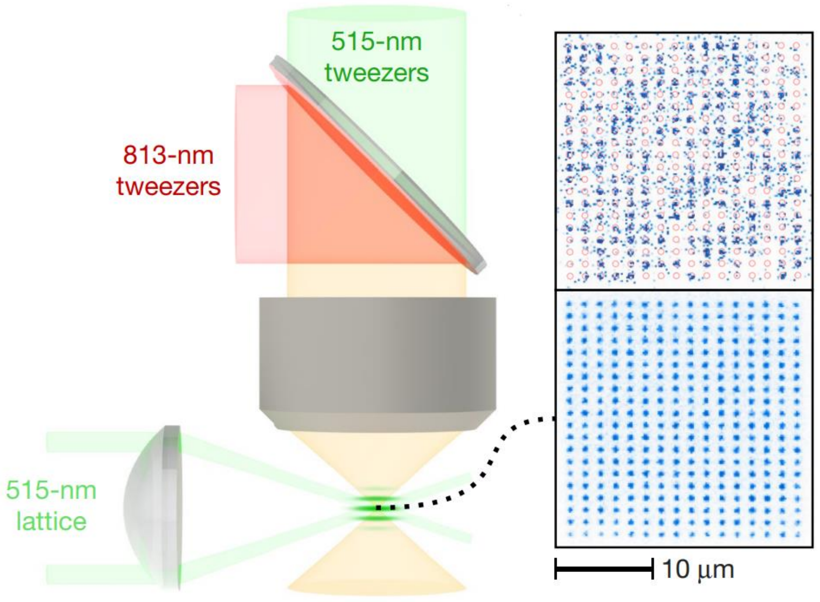




K. Barnes et al, https://arxiv.org/abs/2108.04790 (2021) – Atom Computing

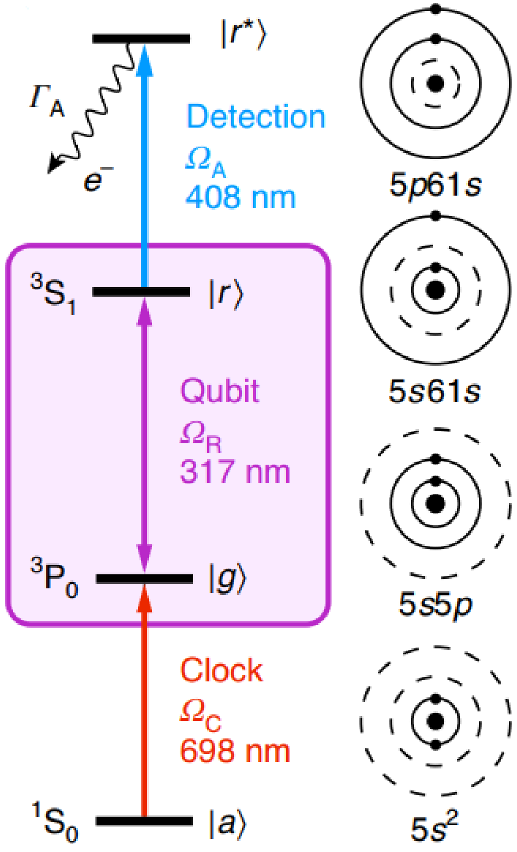
Quantum Computing & AION

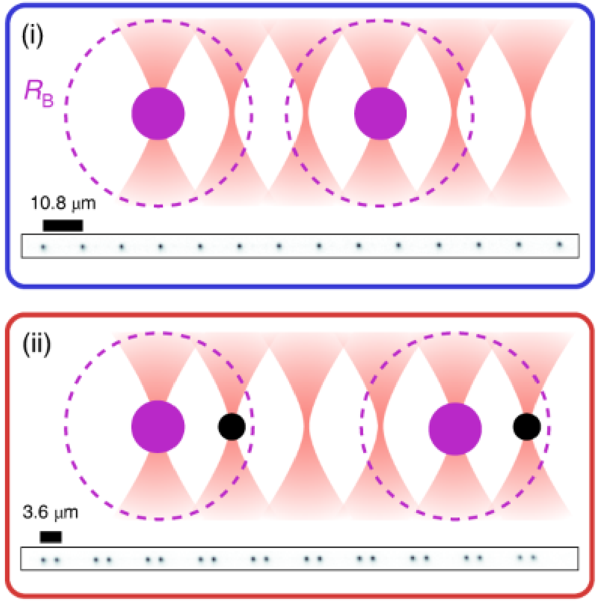
1 qubit = 1 Sr atom



A. W. Young et al, Nature 588, 408-413 (2020)
– JILA Colorado, Kaufman lab

Quantum logic gates (the hard bit!): Rydbergs

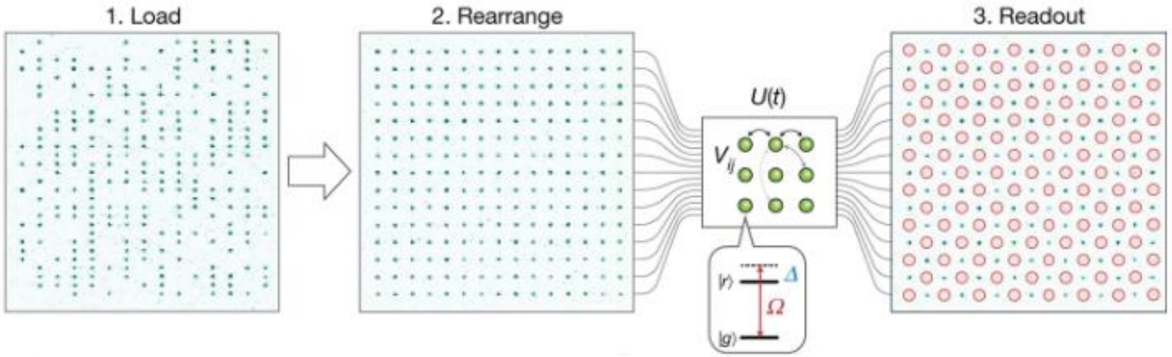




S. Madjarov et al. Nature Physics 16, 857-861 (2020)
– Caltec, Endres lab
99.9(2)% gate fidelity

Quantum Computing & AION

- Trapped-ion or superconducting qubits developed over ~ 20 years
- Tweezer array qubits started to emerge in the last ~ 10 years



Startups in neutral atom computing
https://atom-computing.com/ - $60M funding round, 2022
https://pasqal.io/about
https://coldquanta.com/core-technology/hilbert/
https://www.quera.com/
https://mobile.twitter.com/computingq

Why are we well placed to do this at Imperial?

- Atomic clocks → single qubit operations
- Squeezing → cavities to exchange atom vs photon qubits
- AION → robust, highly engineered Sr systems

Atoms in tweezers – some recent academic results:

S. Ebadi et al, Nature 595, 227-232 (2021) – Harvard, Lukin lab
A. W. Young et al, Nature 588, 408-413 (2020) – JILA, Kaufman lab
S. Madjarov et al. Nature Physics 16, 857-861 (2020) – Caltec, Endres lab
P. Scholl et al, Nature 595, 233-238 (2021) – CNRS, Bronwaes lab

Why Space?

One important argument in favour of Space (vs Earth) is interrogation time T of the atoms in free fall conditions.

To better understand this, it is useful to look at the short-term sensitivity to acceleration of an Atom Interferometer:

$$\delta g = \frac{\delta\phi}{nkT^2} \qquad [\mathrm{m/s^2/\sqrt{Hz}}]$$

where $\delta\phi$ is the atom-phase-resolution of the interferometer, n is the number of Large Momentum Transfer pulses, k is the effective wave-number of the atomic transition and T is the interrogation time between interferometer pulses.

On Earth, many interferometry experiments are limited by their free-fall interrogation times T, achieved through launching or dropping atom clouds at some limited distance above the floor. In space this limitation is removed, leading to potentially large improvements in performance.

Example:
Taking AION-10 goal as reference, we are planning to demonstrate that AION-10 can reach on earth with an interrogation time T ~1s a dg of about 5.7x1E-13 in 2024. In space, we estimate we could reach T~20sec and, thus, reach 3.9x1E-14 (factor ~15 better).

Why Atom Interferometry in Space?

$$\Delta g = \frac{1}{kT^2\sqrt{N}}$$

GRACE reference: ONERA Superstar Accelerometer: 10^{-10} m/s^2

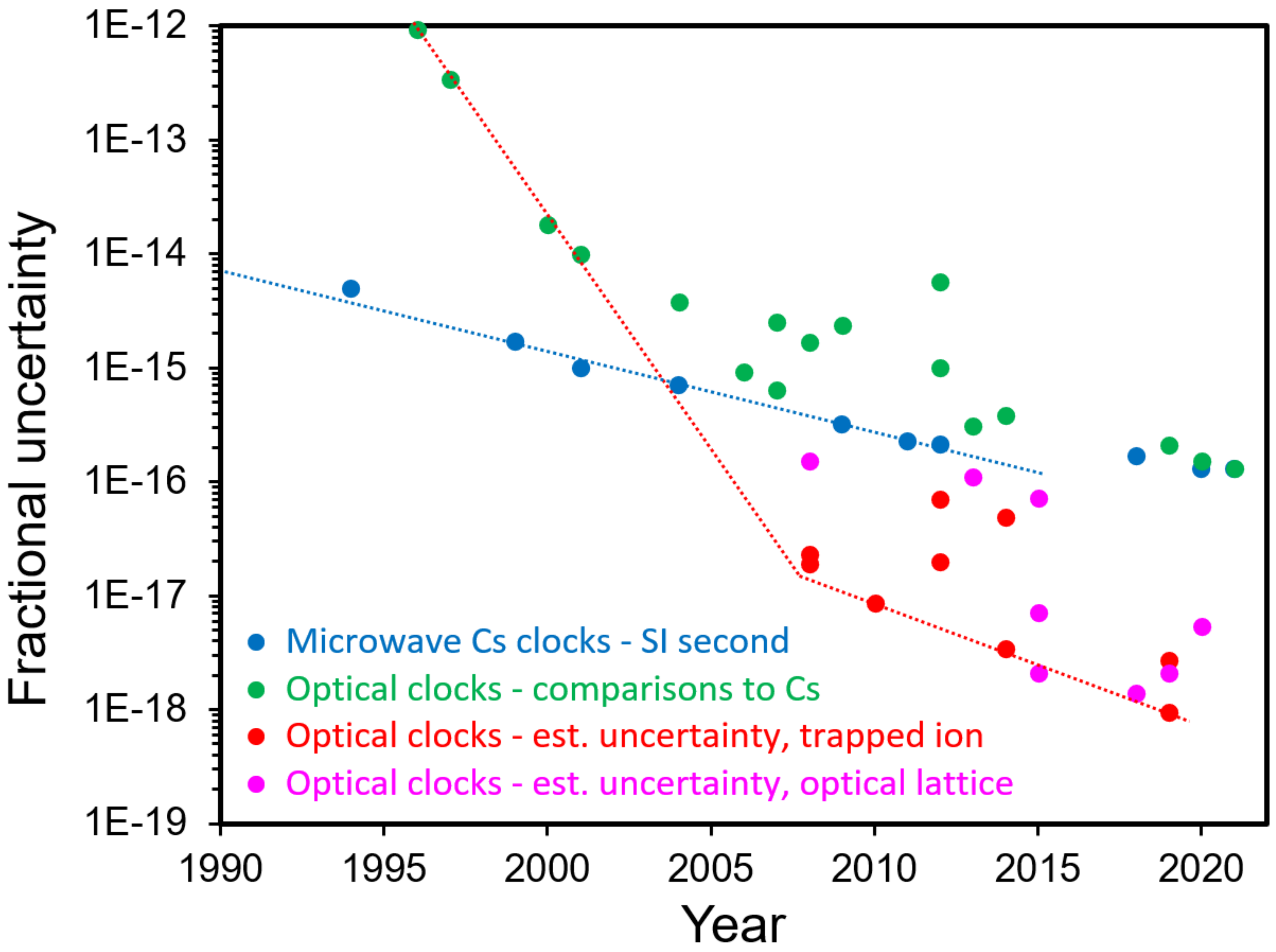
T=100ms N=10^6	T=1s N=10^6	T=10s N=10^6	T=1s N=10^6 100 pulses	T=1s N=10^8 1000 pulses
6 10^{-9} m/s^2	6 10^{-11} m/s^2	**6 10^{-13} m/s^2**	6 10^{-13} m/s^2	3 10^{-14} m/s^2

Large T → large sensitivity

ROADMAP

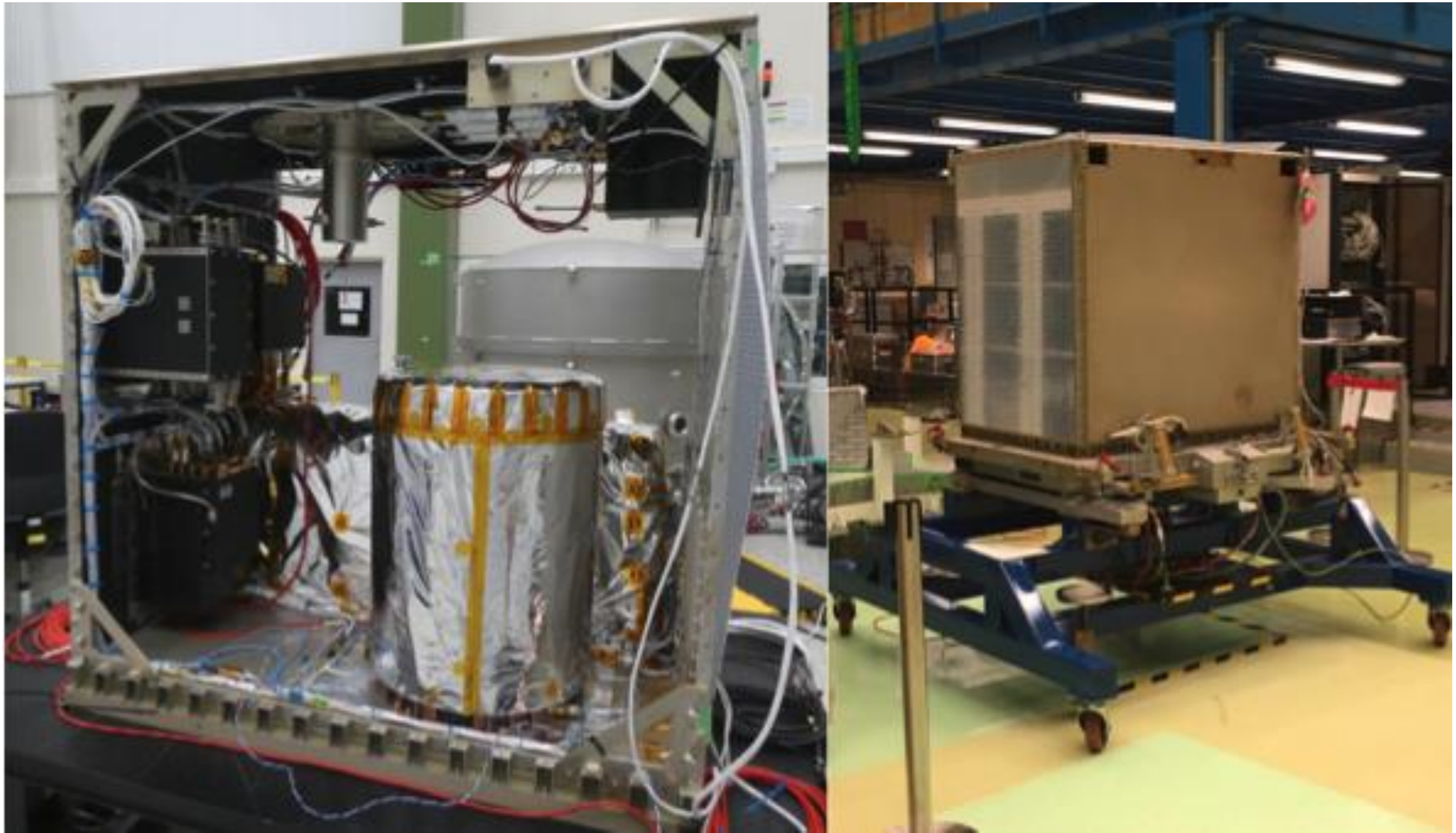
Atomic Clock Progress

use for next-generation SI time standard worldwide?



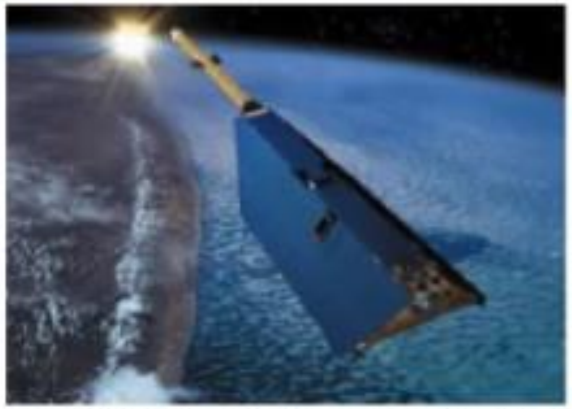
Atomic Clock Progress

ACES atomic clock mission: scheduled launch to ISS 2025

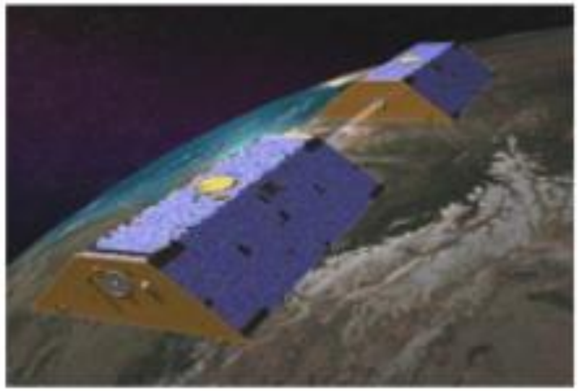


Earth Observation Progress

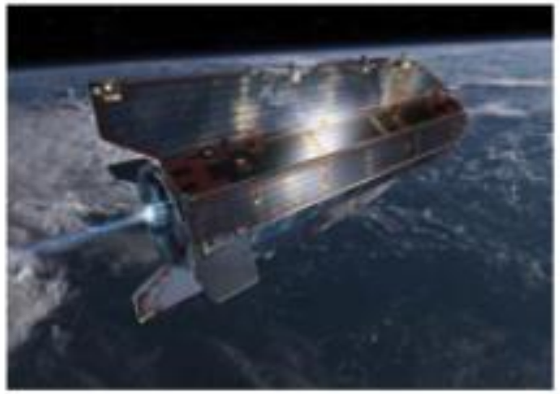
Earth Observation: using classical electrostatic accelerometers & gradiometers



CHAMP : satellite tracking by GNSS + accelerometry



GRACE and GRACE-FO: orbit determination + satellite-to-satellite tracking + accelerometry



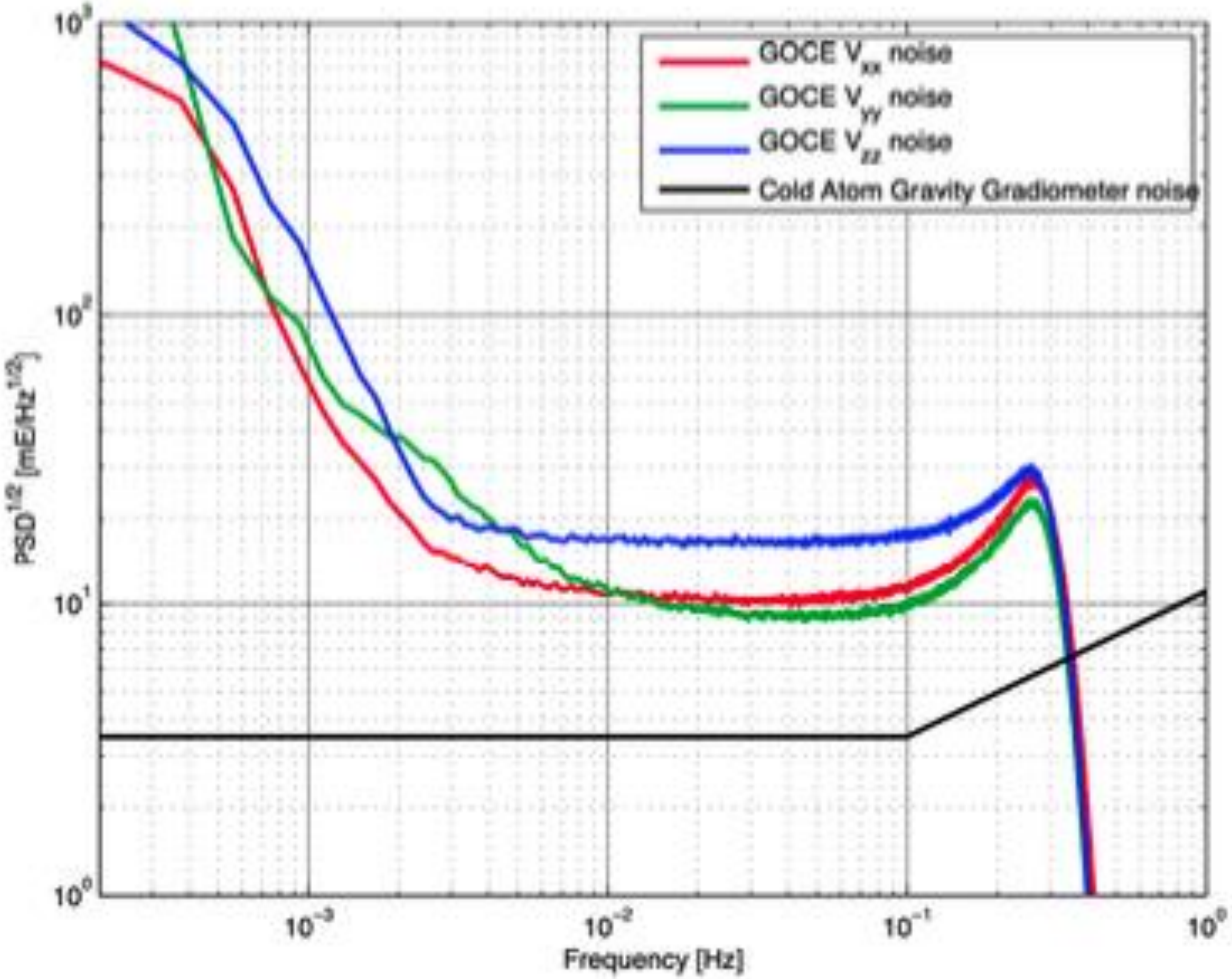
GOCE: orbit determination + gradiometry

	CHAMP 2000 - 2010	GRACE/GRACE-FO 2002 - ongoing	NGGM Launch scheduled 2028	GOCE 2009 - 2013
Measurement type		Monitoring gravity field time variations		Static gravity field
EA accuracy	$\sim 10^{-10}$ m/s^2	$\sim 10^{-11}$ m/s^2	$\sim 10^{-11}$ m/s^2	$\sim 10^{-12}$ m/s^2
Geoid undulations	$\sim$ 10 cm @350 km	$\sim$ 10 cm @175 km	$\sim$ 1 mm @ 500 km every 3 days $\sim$ 1 mm @ 150 km every 10 days	$\sim$ 1 cm @100 km
Gravity anomalies	$\sim$ 0.02 mGal @1000 km	$\sim$ 1 mGal @175 km		$\sim$ 1 mGal @100 km

AION

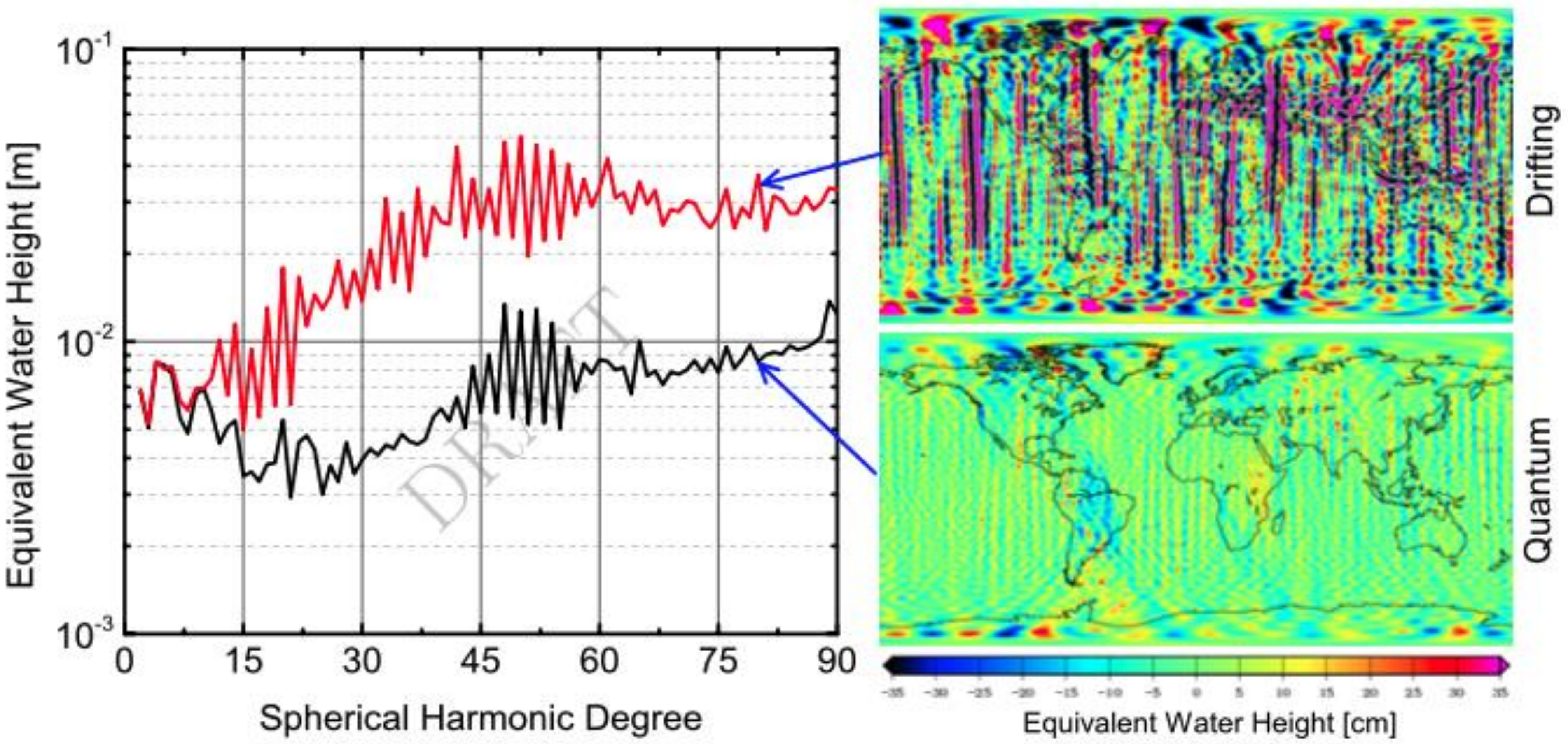
Earth Observation Progress

Frequency Sensitivity advantage of cold atom gravity gradiometers at low frequency, no drift



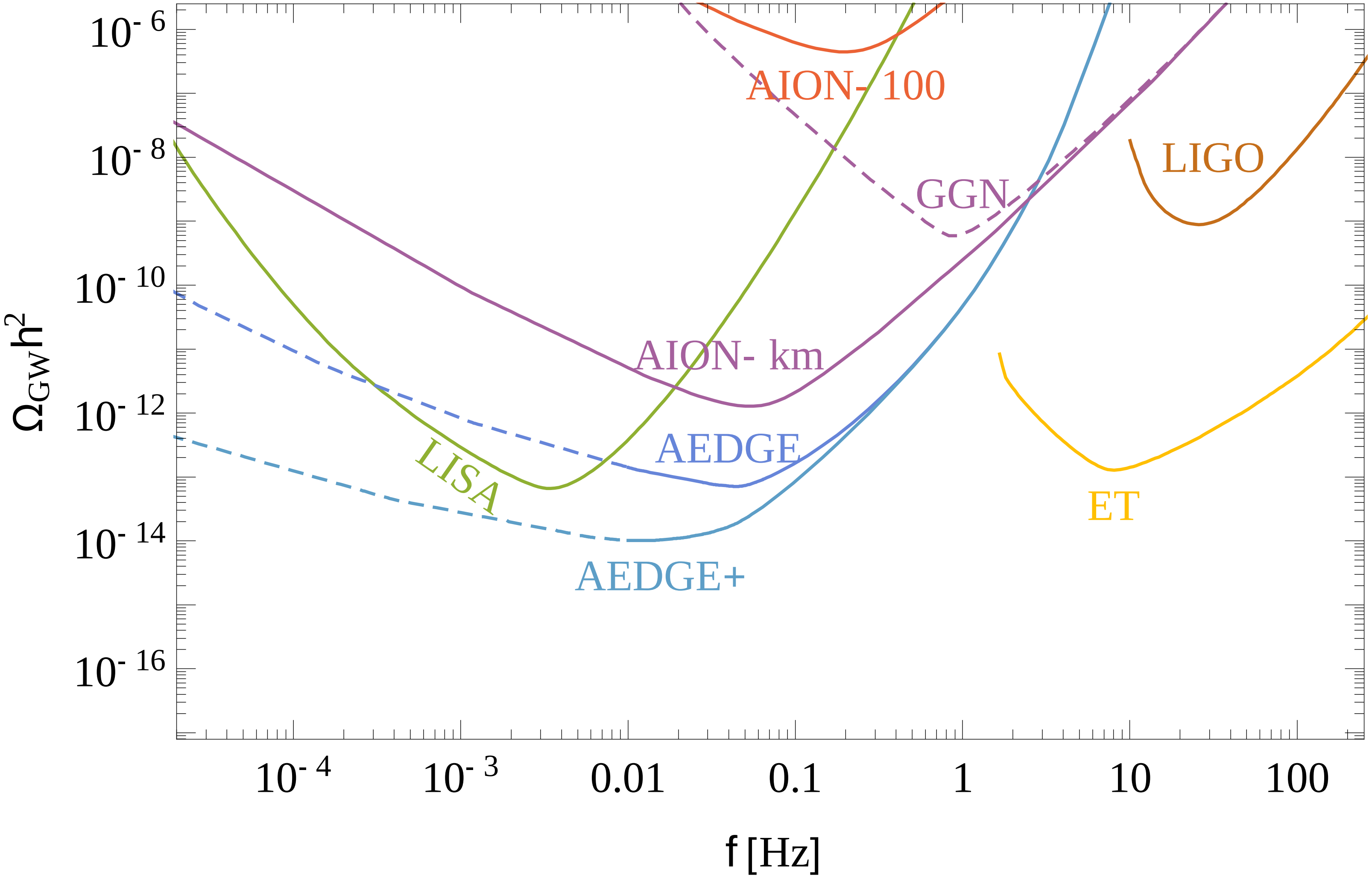
Earth Observation Progress

Sensitivity to Water Height
crucial for monitoring climate change



Vision for 2045+

Probe formation of SMBHs: Synergies with other GW experiments (LIGO, LISA), test GR



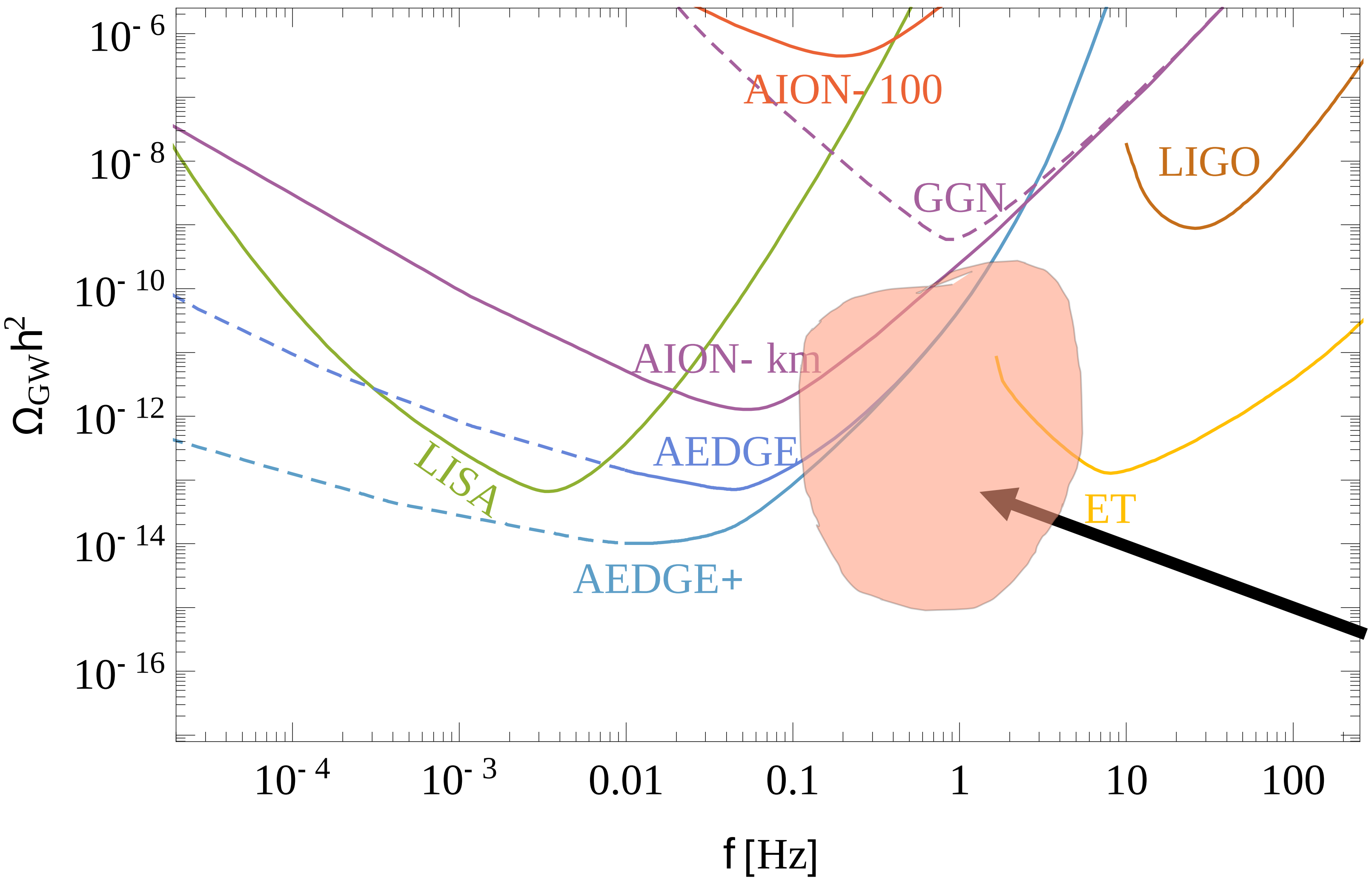
Translate Stain sensitivity into the dimensionless energy density of a GW

AION Collaboration (Badurina, OB,…, John Ellis et al): arXiv:1911.11755

Badurina, OB, John Ellis, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

Vision for 2045+

Probe formation of SMBHs: Synergies with other GW experiments (LIGO, LISA), test GR



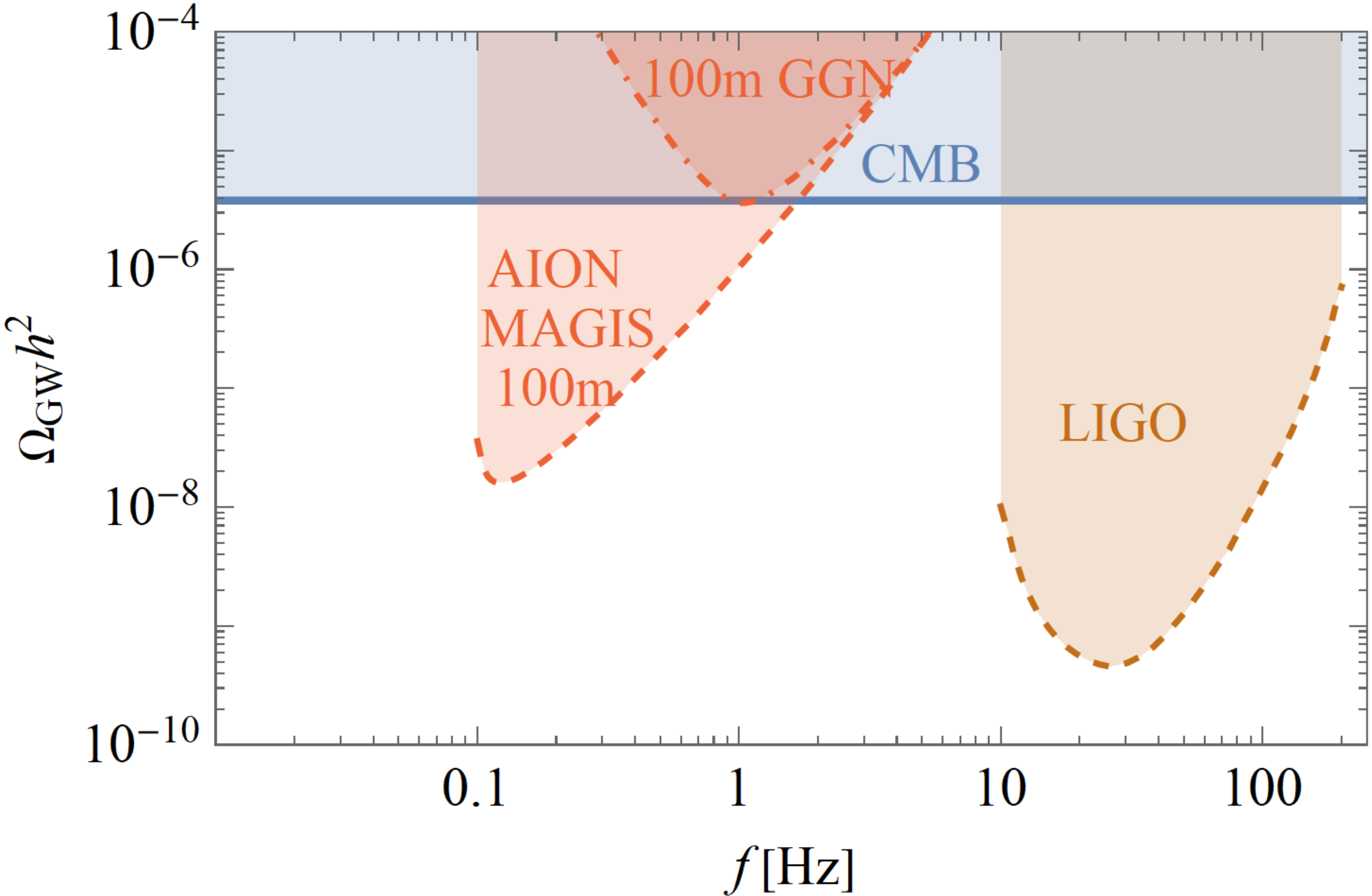
Translate Stain sensitivity into the dimensionless energy density of a GW

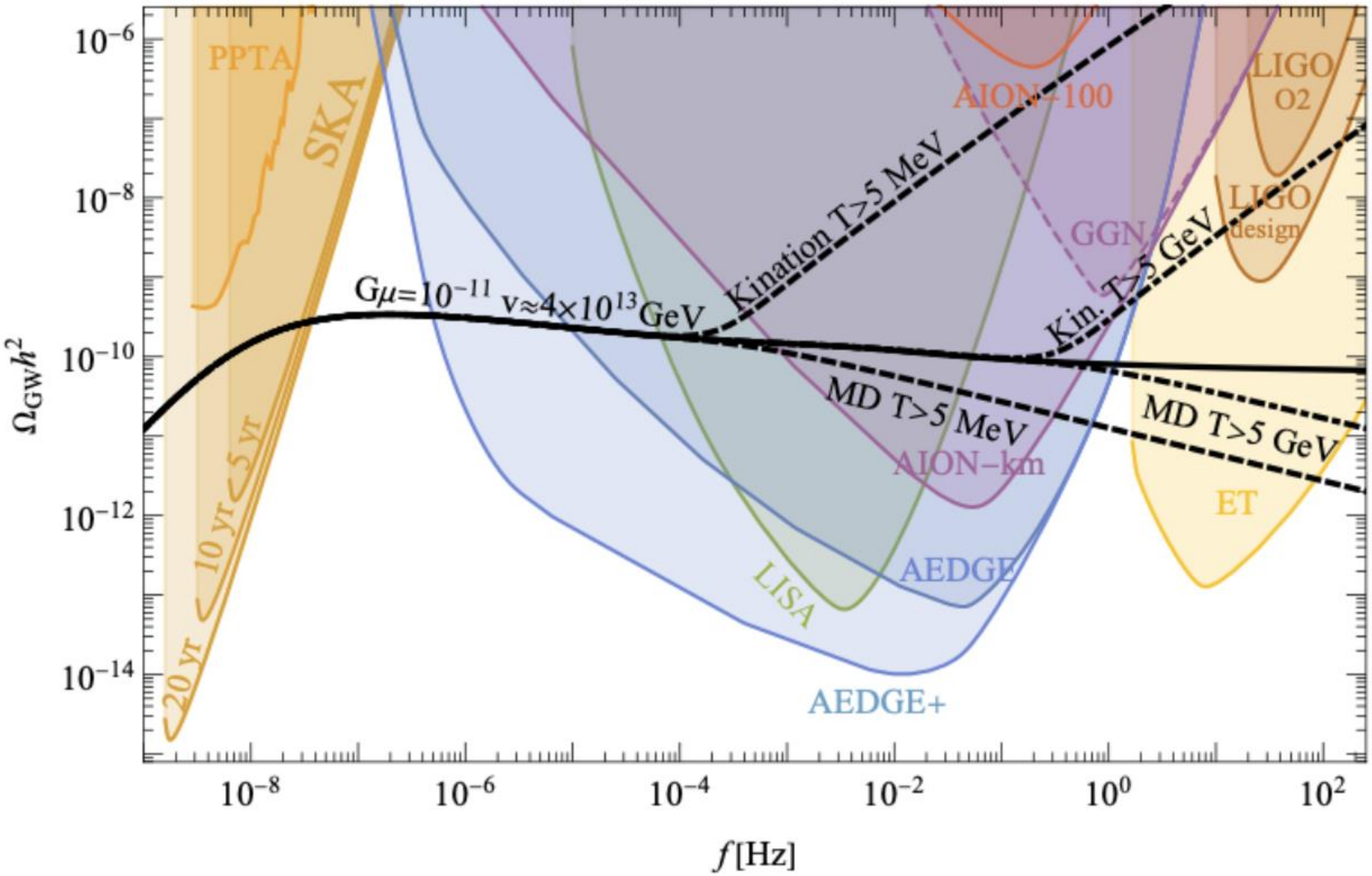
Still a "gap" around 1Hz
Need to find a solution to fill it

AION Collaboration (Badurina, OB,…, John Ellis et al): arXiv:1911.11755

Badurina, OB, John Ellis, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

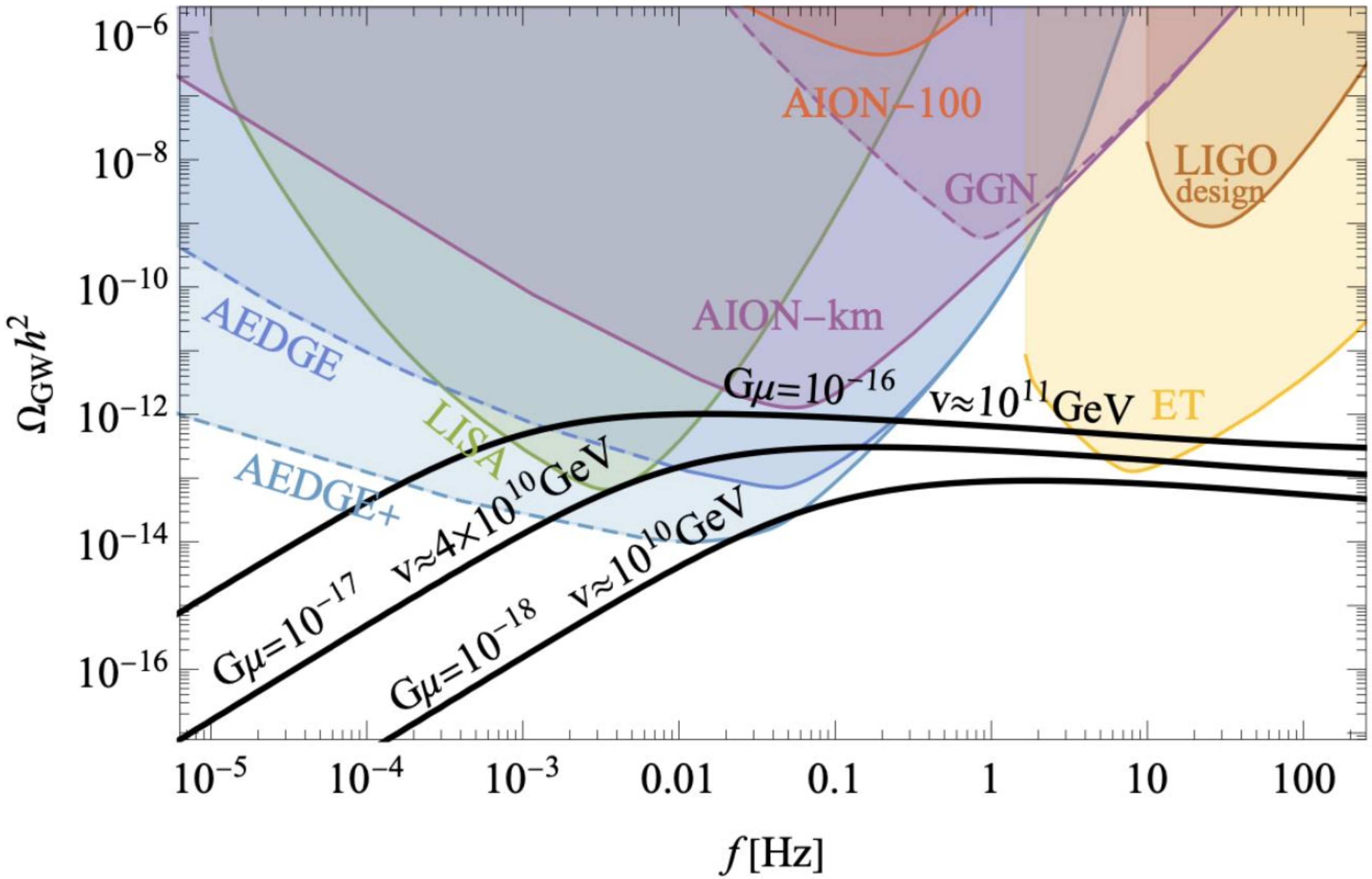
The GW Experimental Landscape: 2030ish





Comparison of the Ω sensitivities to PI spectra of AION-100, AION-km, AEDGE and AEDGE+, LIGO, ET, Pulsar Timing Arrays (PTAs) and SKA.

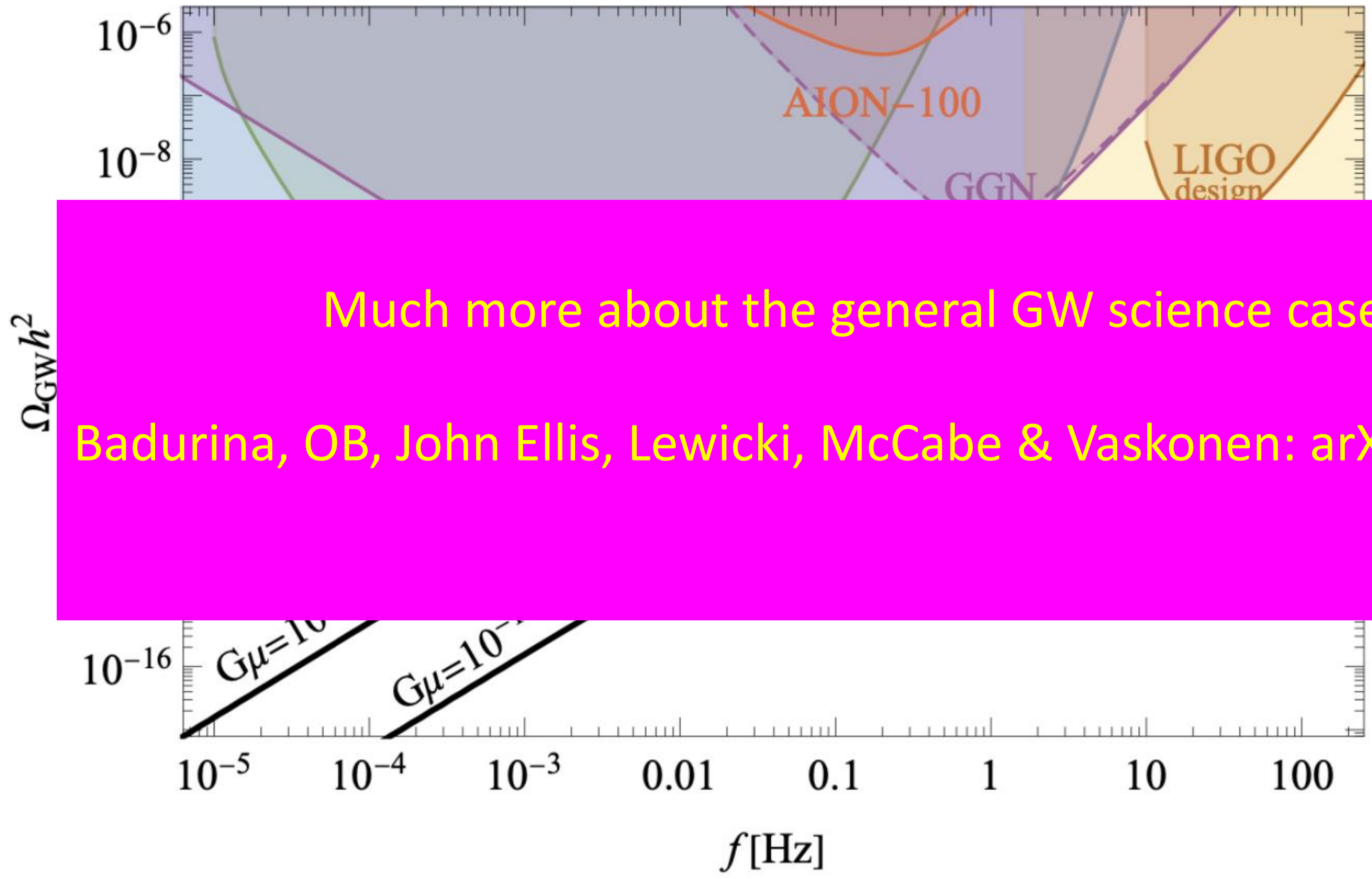
Sensitivities of cosmic string measurements to modifications of the cosmological expansion rate. Kination or matter dominance (MD) at temperatures T > 5 *MeV or* 5 *GeV.*



Different experiments sensitive to different values of cosmic string tension

Sensitivities to the cosmic strings with tension Gμ *of AION-100 and -km, AEDGE and AEDGE+, LIGO, ET and LISA.*

AION



Much more about the general GW science case in:

Badurina, OB, John Ellis, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

Different experiments sensitive
es of cosmic
nsion

Sensitivities to the cosmic strings with tension Gμ *of AION-100 and -km, AEDGE and AEDGE+, LIGO, ET and LISA.*

Earth Observation Progress

Requirements & Objectives

Threshold requirements

Spatial resolution	Equivalent water height		Geoid	
	Monthly field	Long-term trend	Monthly field	Long-term trend
400 km	5 mm	0.5 mm/yr	50 μm	5 μm/yr
200 km	10 cm	1 cm/yr	0.5 mm	0.05 mm/yr
150 km	50 cm	5 cm/yr	1 mm	0.1 mm/yr
100 km	5 m	0.5 m/yr	10 mm	1 mm/yr

Target objectives

Spatial resolution	Equivalent water height		Geoid	
	Monthly field	Long-term trend	Monthly field	Long-term trend
400 km	0.5 mm	0.05 mm/yr	5 μm	0.5 μm/yr
200 km	1 cm	0.1 cm/yr	0.05 mm	5 μm/yr
150 km	5 cm	0.5 cm/yr	0.1 mm	0.01 mm/yr
100 km	0.5 m	0.05 m/yr	1 mm	0.1 mm/yr

Fundamental Physics Part

Tests of Weak Equivalence Principle (Universality of Free Fall)

Class	Elements	η	Year [ref]	Comments
Classical	Be - Ti	2×10^{-13}	2008 [200]	Torsion balance
	Pt - Ti	1×10^{-14}	2017 [179]	MICROSCOPE first results
	Pt - Ti	(10^{-15})	2019+	MICROSCOPE full data
Hybrid	^{133}Cs - CC	7×10^{-9}	2001 [204]	Atom Interferometry
	^{87}Rb - CC	7×10^{-9}	2010 [205]	and macroscopic corner cube
Quantum	^{39}K - ^{87}Rb	5×10^{-7}	2014 [206]	different elements
	^{87}Sr - ^{88}Sr	2×10^{-7}	2014 [207]	same element, fermion vs. boson
	^{85}Rb - ^{87}Rb	3×10^{-8}	2015 [208]	same element, different isotopes
	^{85}Rb - ^{87}Rb	3.8×10^{-12}	2020 [209]	$\geq$ 10 m towers
	^{85}Rb - ^{87}Rb	(10^{-13})	2020+ [210]	
	^{170}Yb - ^{87}Rb	(10^{-13})	2020+ [211]	
	^{41}K - ^{87}Rb	10^{-17}	2035+	STE-QUEST-like mission
Antimatter	$\overline{\mathrm{H}}$ - H	(10^{-2})	2020+ [212]	under construction at CERN