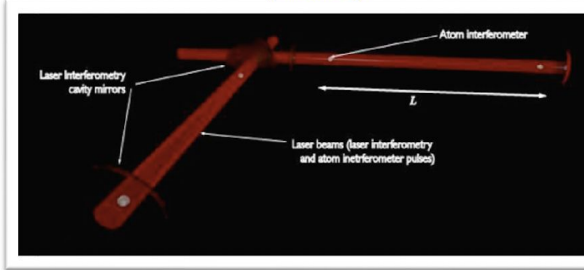


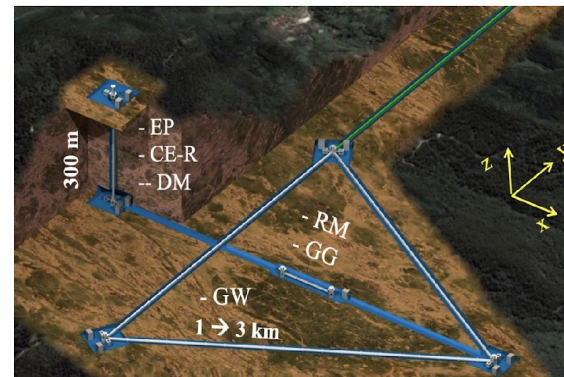
A UK Atom Interferometer Observatory and Network



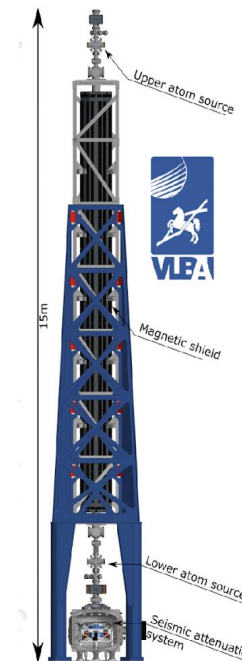
MIGA: Terrestrial detector using atom interferometer at $O(100\text{m})$
(France)



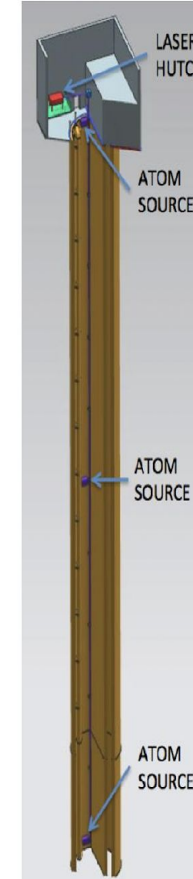
ZAIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at $O(100\text{m})$
(China)



VLBAI: Terrestrial tower using atom interferometer $O(10\text{m})$
(Germany)



AION: Terrestrial shaft detector using atom interferometer at 10m – $O(100\text{m})$ planned
(UK)



MAGIS: Terrestrial shaft detector using atom interferometer at $O(100\text{m})$
(US)

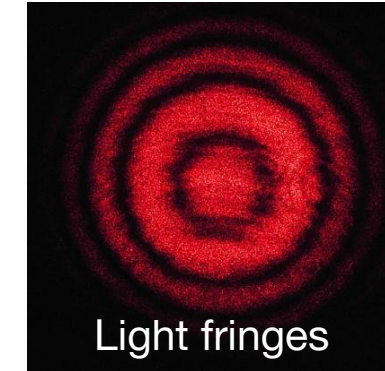
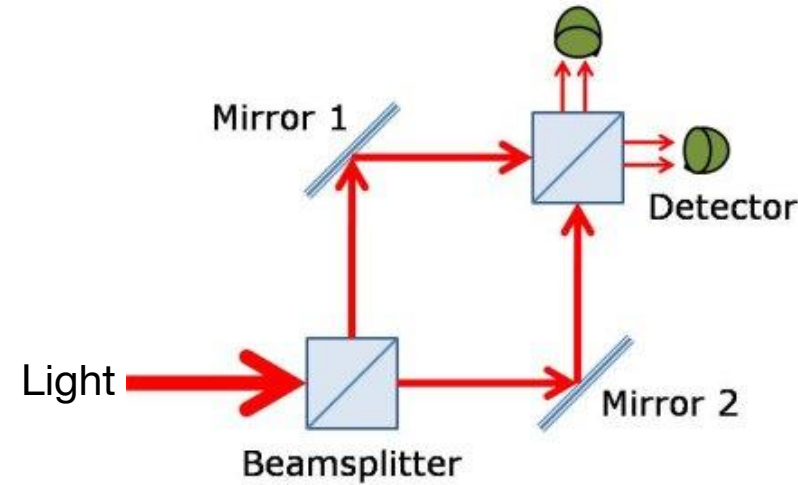
Planned network operation

Oliver Buchmueller, Imperial College London

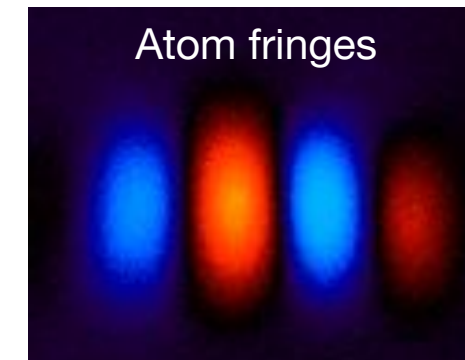
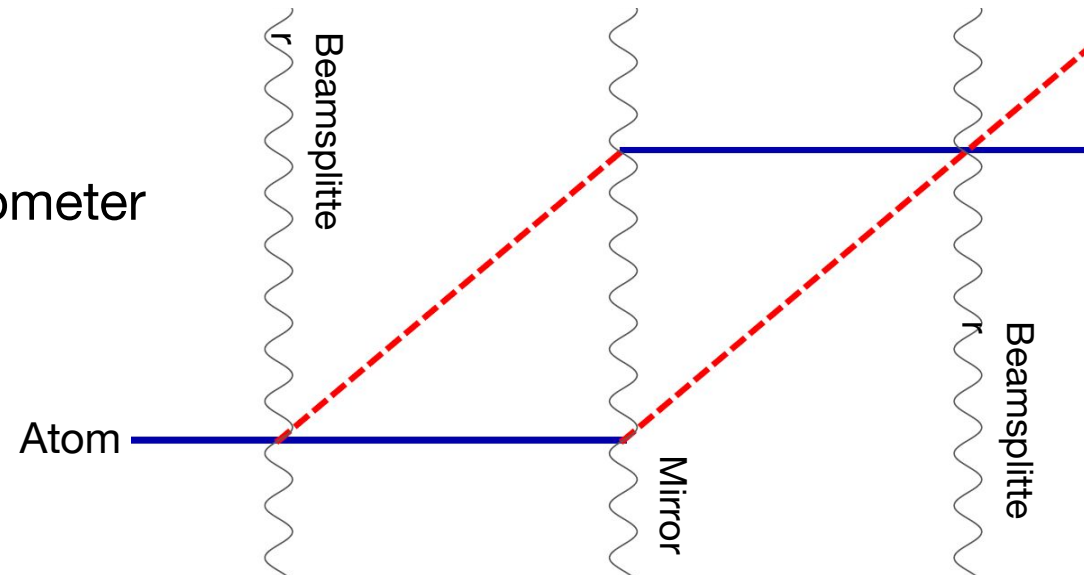
LARGE SCALE ATOM INTERFEROMETRY TO EXPLORE FUNDAMENTAL PHYSICS

Light vs. Cold Atoms: Atom Interferometry

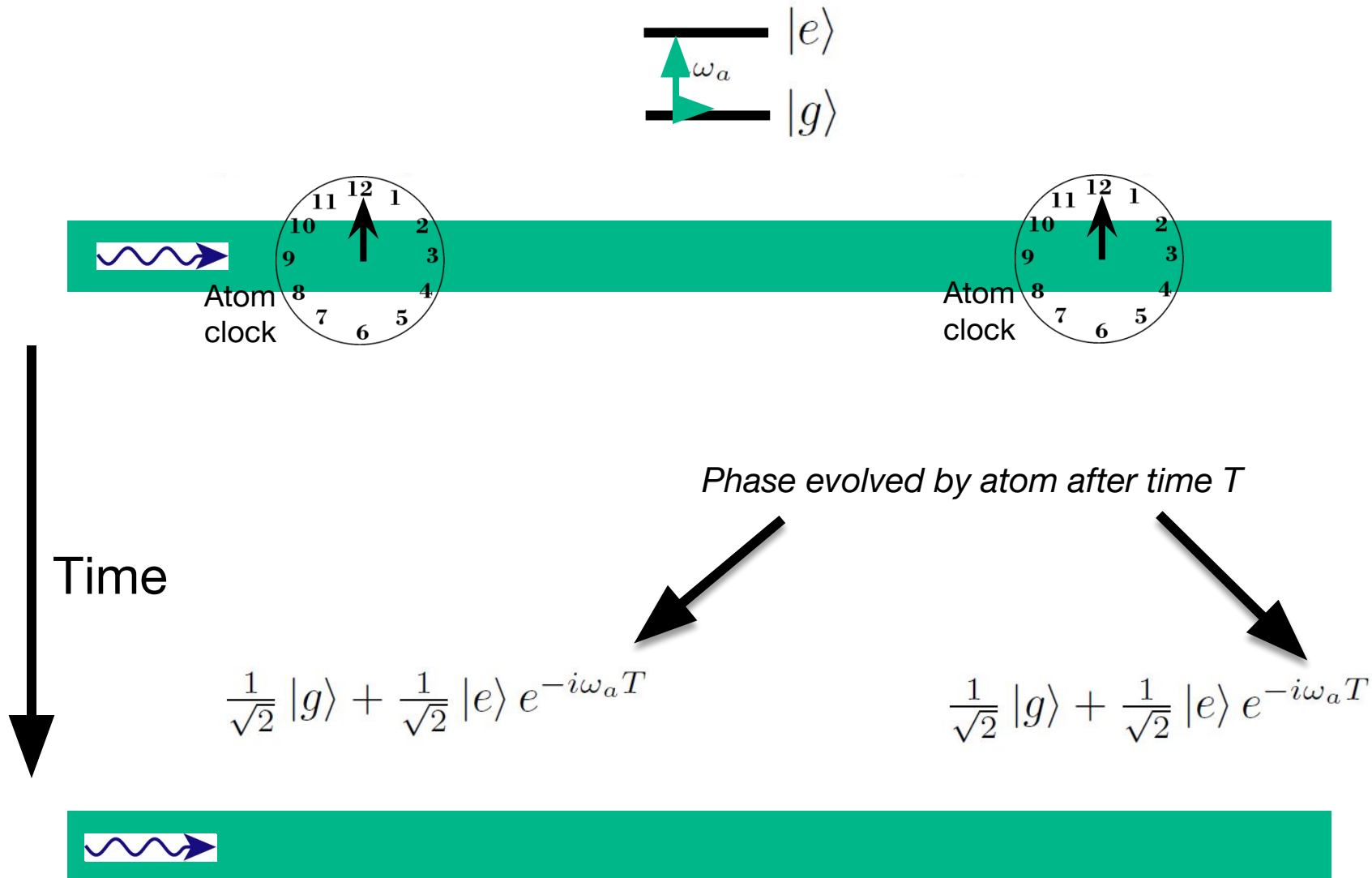
Light
interferometer



Atom
interferometer

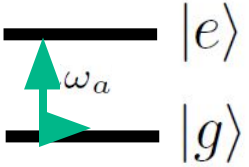


Simple Example: Two Atomic Clocks



Simple Example: Two Atomic Clocks

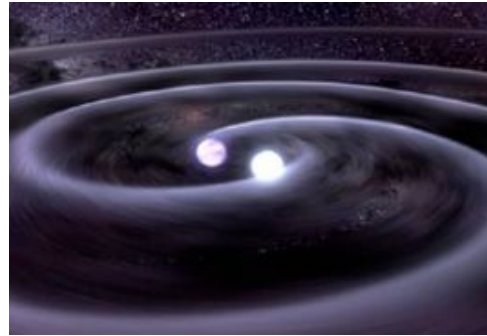
$$\frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle$$



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

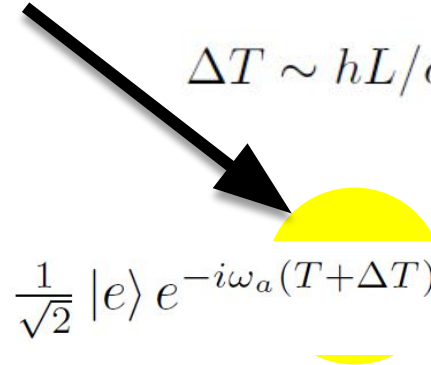


Time



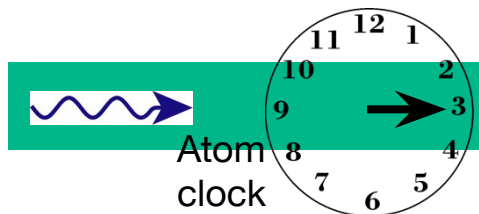
**GW changes
light travel time**

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

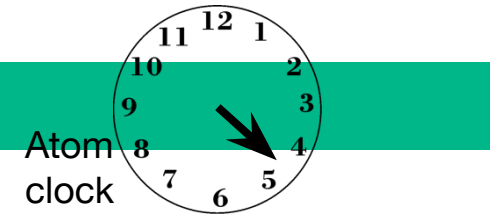


$$\frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i\omega_a T}$$

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

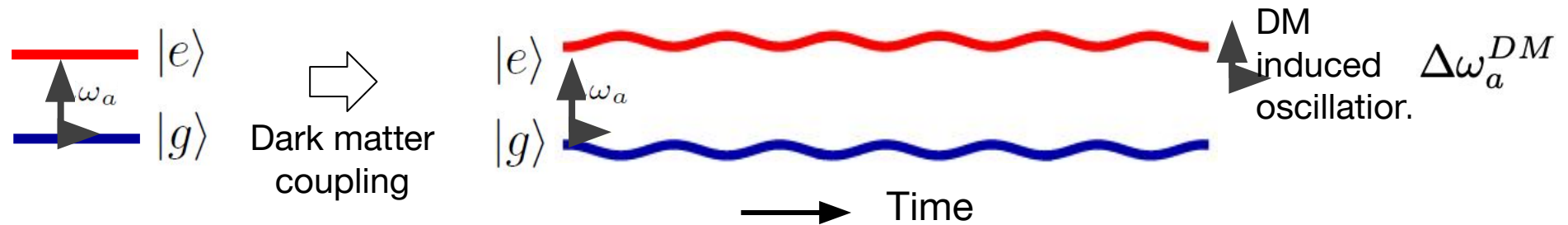


Atom
clock

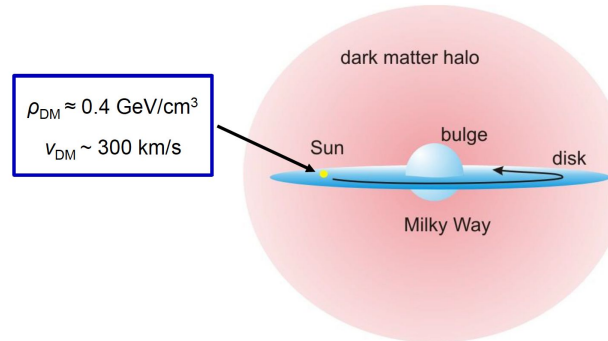


Atom
clock

Simple Example: Two Atomic Clocks



Time

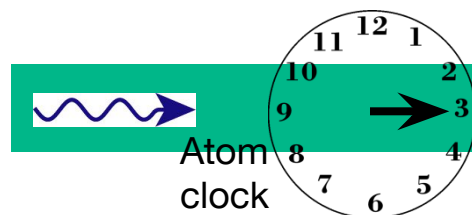


DM cloud changes atom frequency

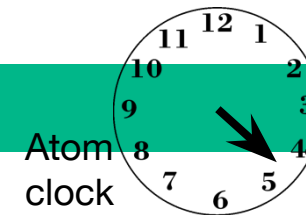
DM coupling causes time-varying atomic energy levels:

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

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



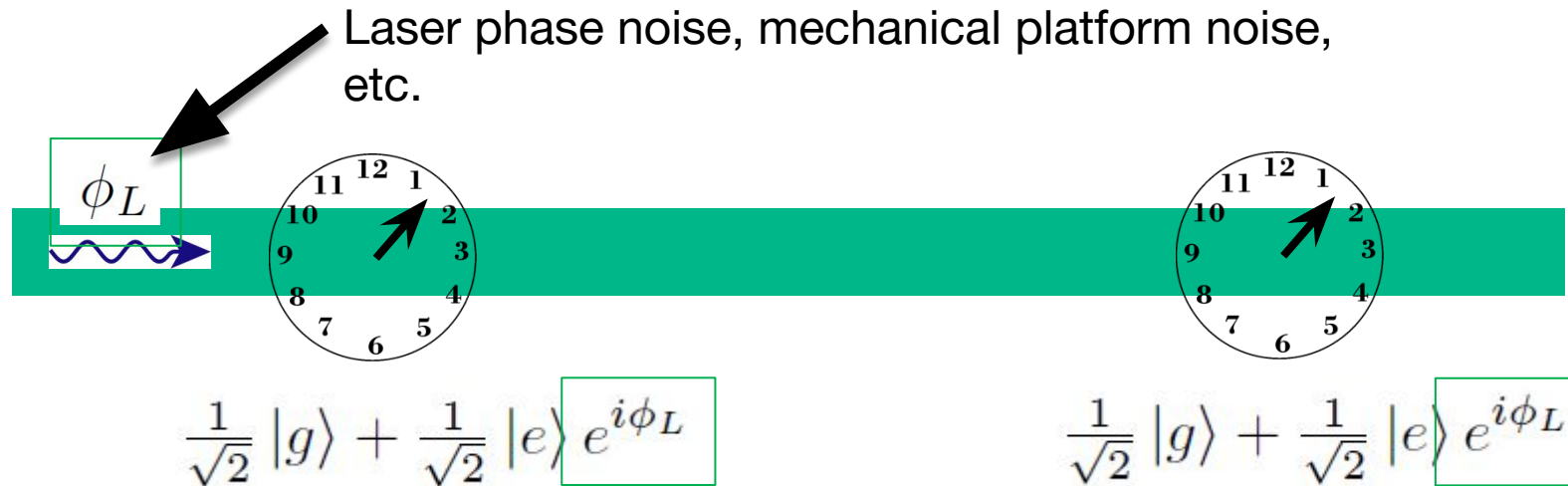
Atom clock



Atom clock

Phase Noise from the Laser

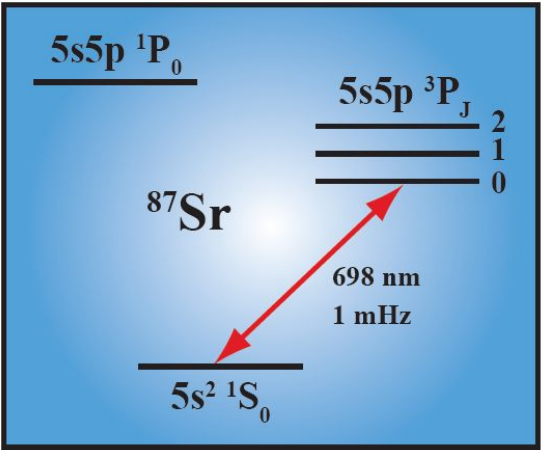
The phase of the laser is imprinted onto the atom.



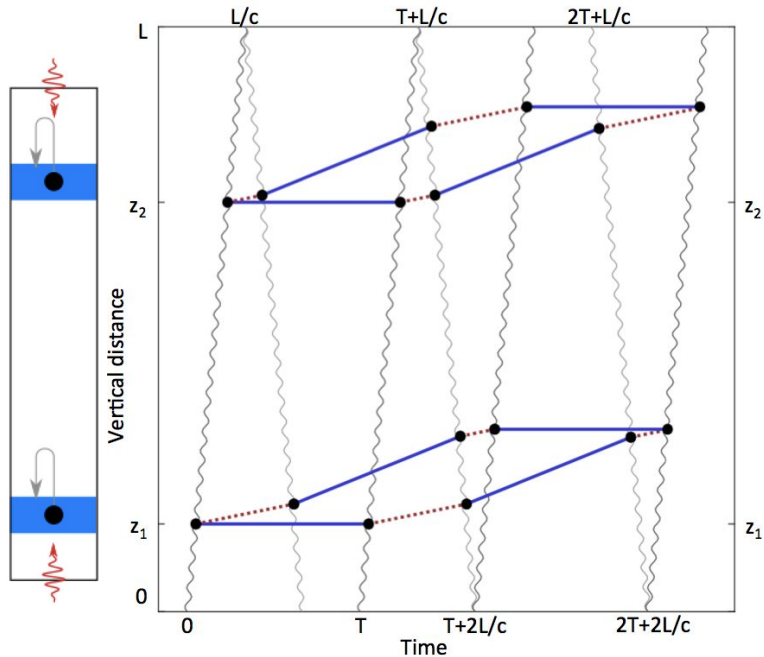
*Laser phase is **common** to both atoms – rejected in a differential measurement.*

AION: A Different Kind of Atom Interferometer

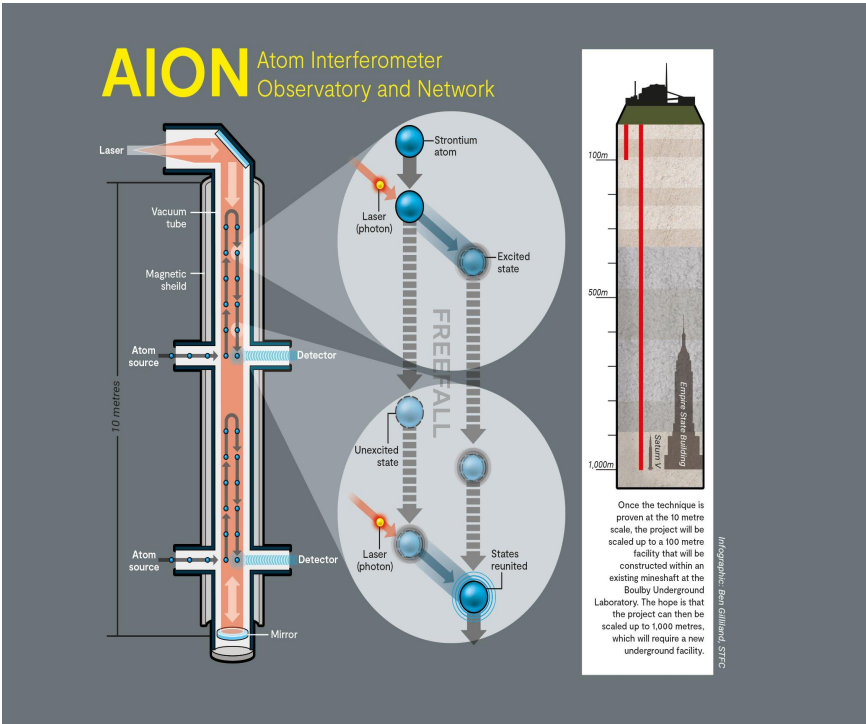
Hybrid “clock accelerometer”



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]	$\delta\phi_{noise}$ [$1/\sqrt{\text{Hz}}$]	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

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

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

- LMT: $\sim 1000 \text{ hbar} \cdot \text{k}$
- Squeezing $\sim 20\text{dB}$ for $> 1\text{e6}$ Atoms

Used for sensitivity

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.

$L \sim 10\text{m}$

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

$L \sim 100\text{m}$

❑ 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).

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

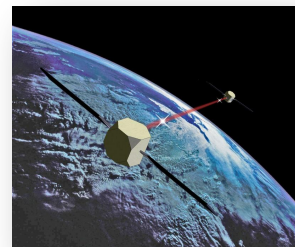
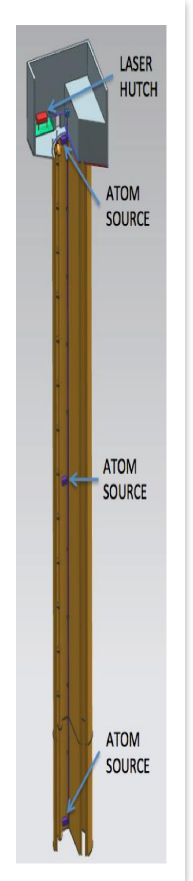
$L \sim$

❑ **Stage 4:** long-term objective a pair of satellite detectors (thousands of kilometres scale) [AEDGE proposal to ESA Voyage2050 call]

1km

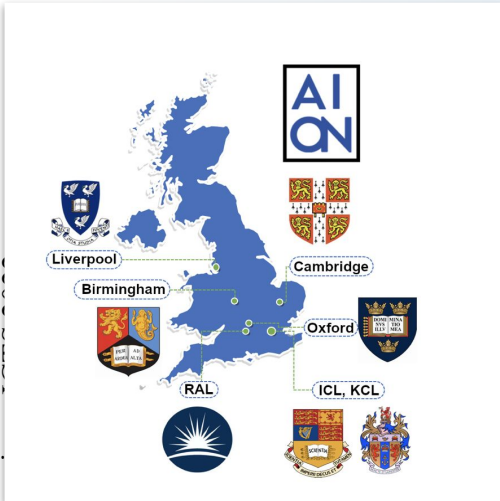
❑ AION has established science leadership in AEDGE, bringing together collaborators from European and Chinese groups (e.g. MIGA, MAGIA, ELGAR, ZAIGA).

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

Atom Interferometry For Fundamental Physics



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

FIRST LESSONS LEARNED AFTER 18 MONTHS

**There is, of course, QT4HEP,
but there is also **HEP4QT****

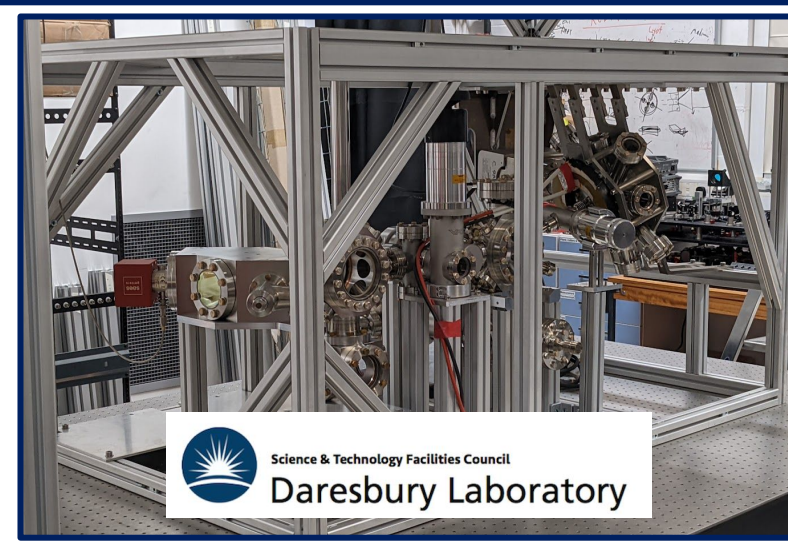
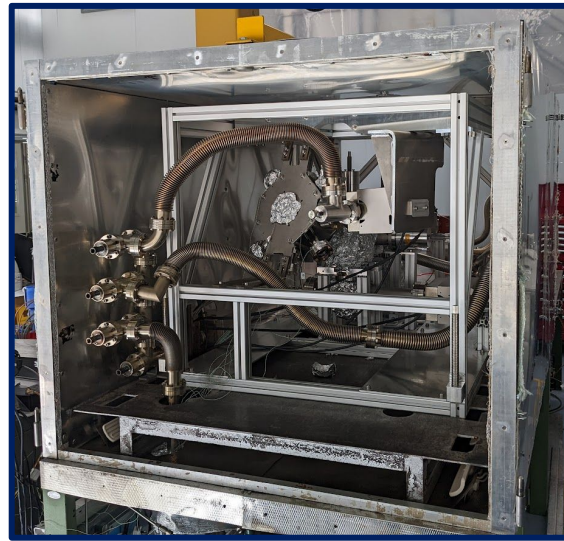
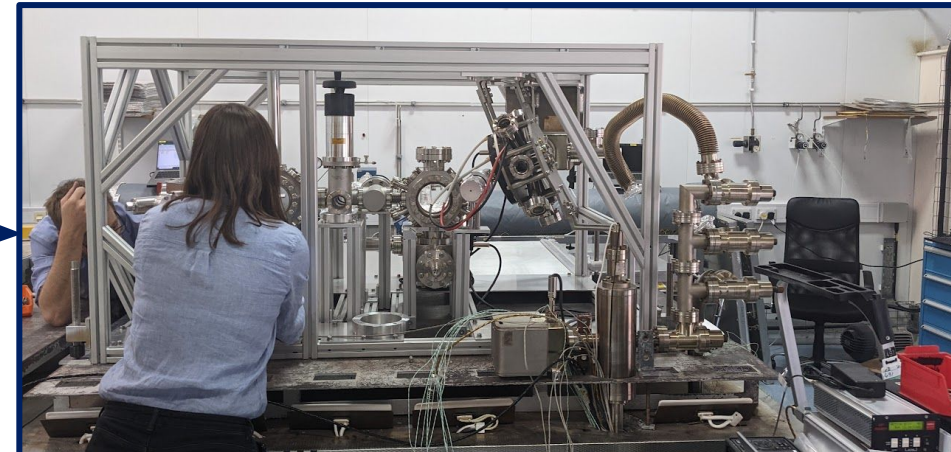
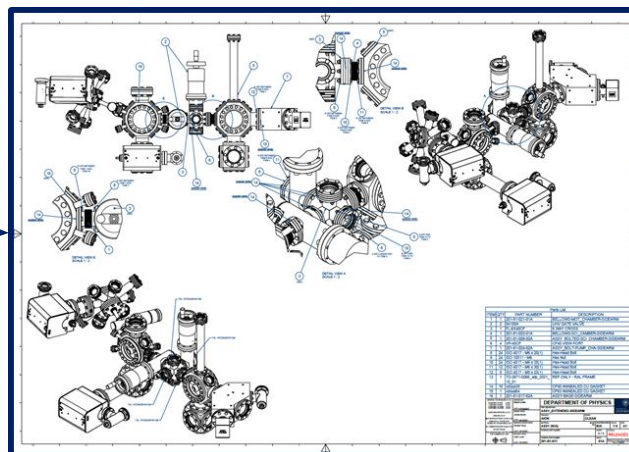
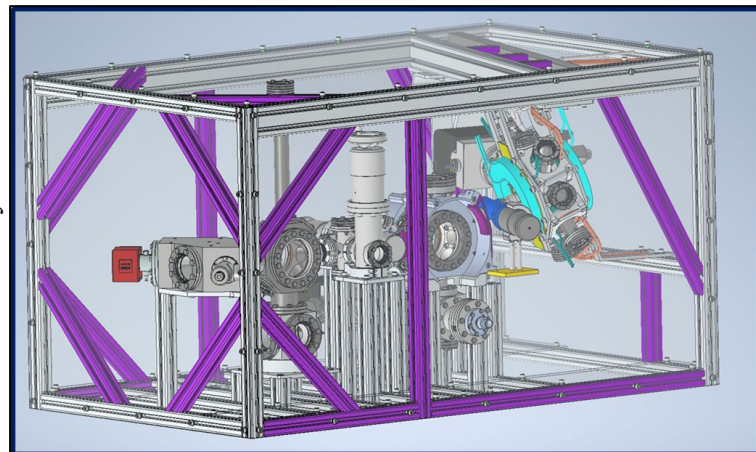
**Centralize the design and production of major
components:**

- **Ultra High Vacuum System**
- **Laser Stabilization System**
- **...**

**and make use of expertise at National Laboratories like
Rutherford Appleton and Daresbury Laboratory!**

Ultra-High Vacuum System: Centralized Construction

Manufacturing, Assembly and Installation



Science & Technology Facilities Council

Daresbury Laboratory

Cambridge July 2022



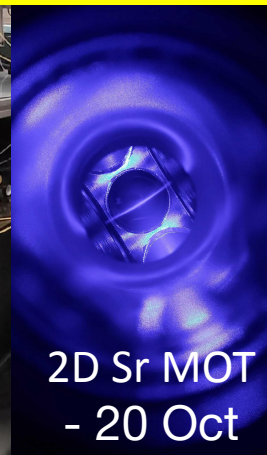
2D Sr MOT - 26 Oct

Imperial August 2022



5 Ultra Cold Sr Labs build in less than 18 months using large scale HEP production methods to significantly accelerate the turnaround – this will be critical for future success!

Birmin



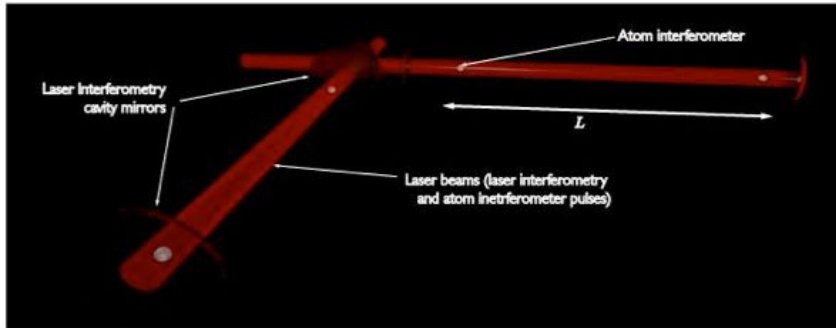
2D Sr MOT
- 20 Oct



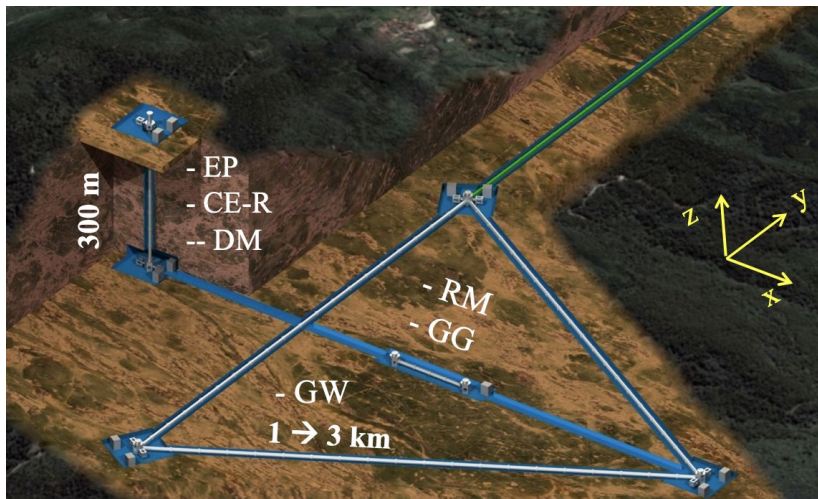
2D Sr MOT - 31 Oct

Ground Based Large Scale O(100m) Projects

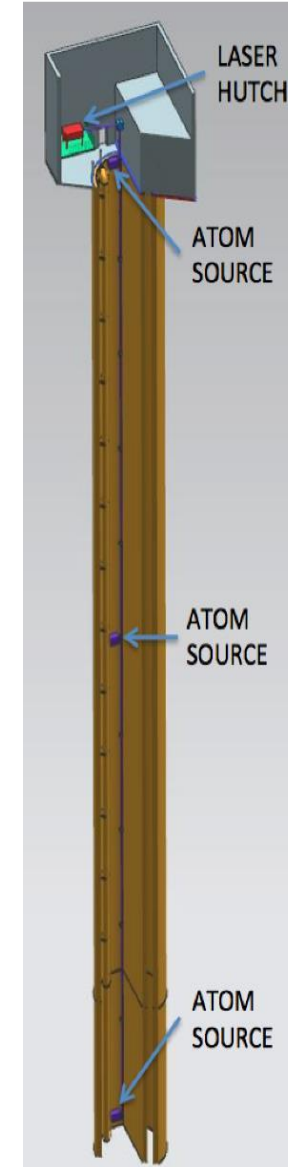
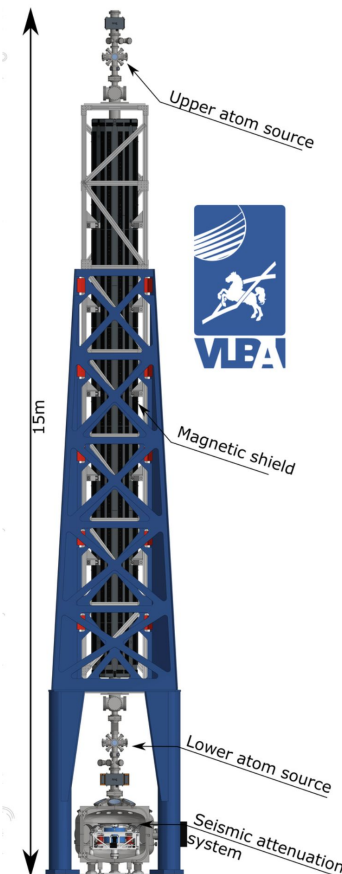
MIGA: Terrestrial detector using atom interferometer at O(100m)
(France)



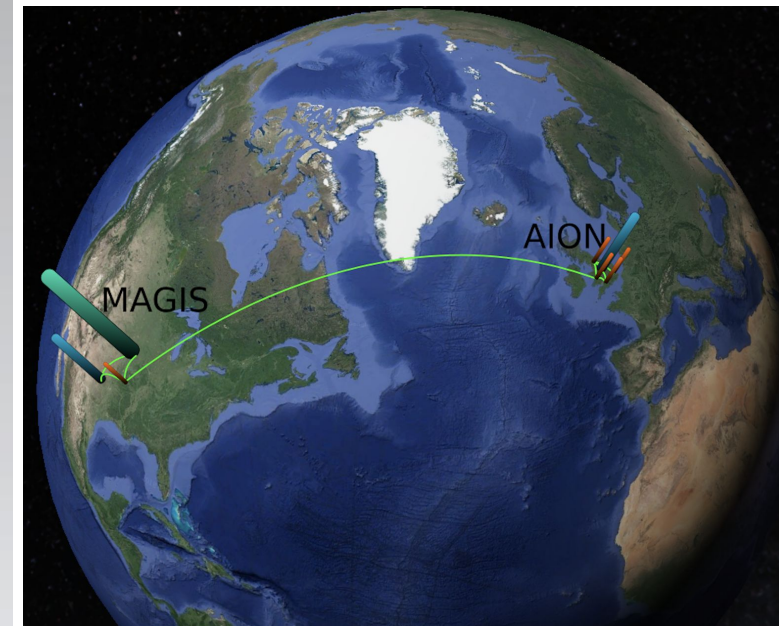
ZIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)
(China)



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



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



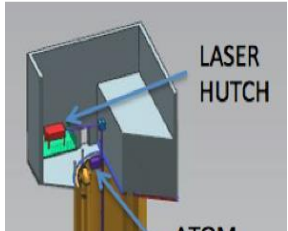
MAGIS: Terrestrial shaft detector using atom interferometer at O(100m)
(US)

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)
(Germany)



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

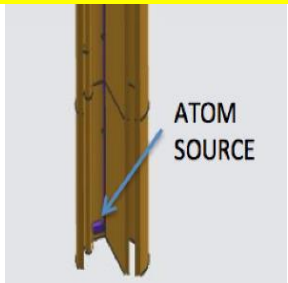
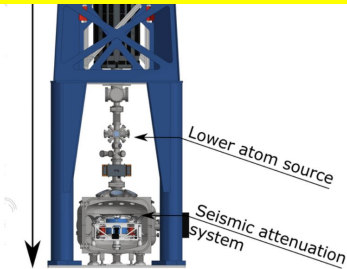
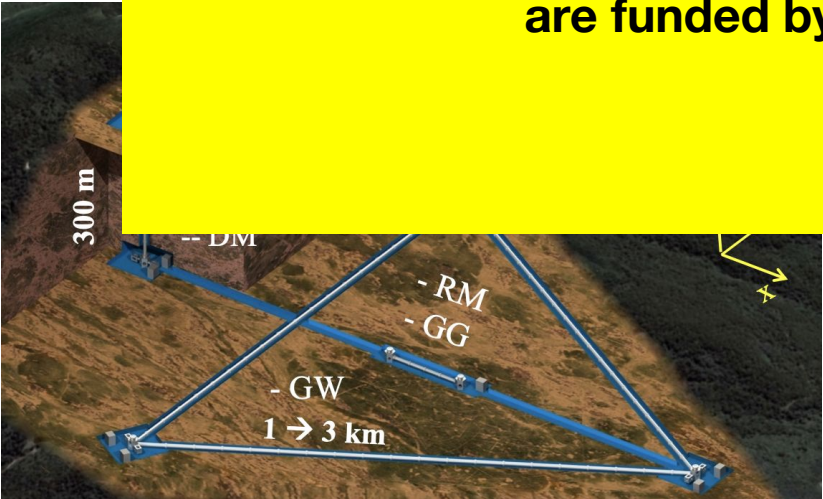
Example of large-scale CA projects that act as demonstrators for GW mid-frequency band and DM detectors.

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.

Terrestrial Long-Baseline Atom Interferometer Workshop at CERN

- Organise a Workshop in early 2023 to discuss “**Terrestrial**

**Workshop will at CERN
in the Council Chamber
on **March 13/14 2023****

Workshop:

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

Register here:

<https://indico.cern.ch/event/1208783/registrations/>

- We
- con

- Alth

believe there are important synergies with our Cold Atom
Community activity in Space.

Possible CERN Site for AION 100m

PX46 – P4 Support shaft

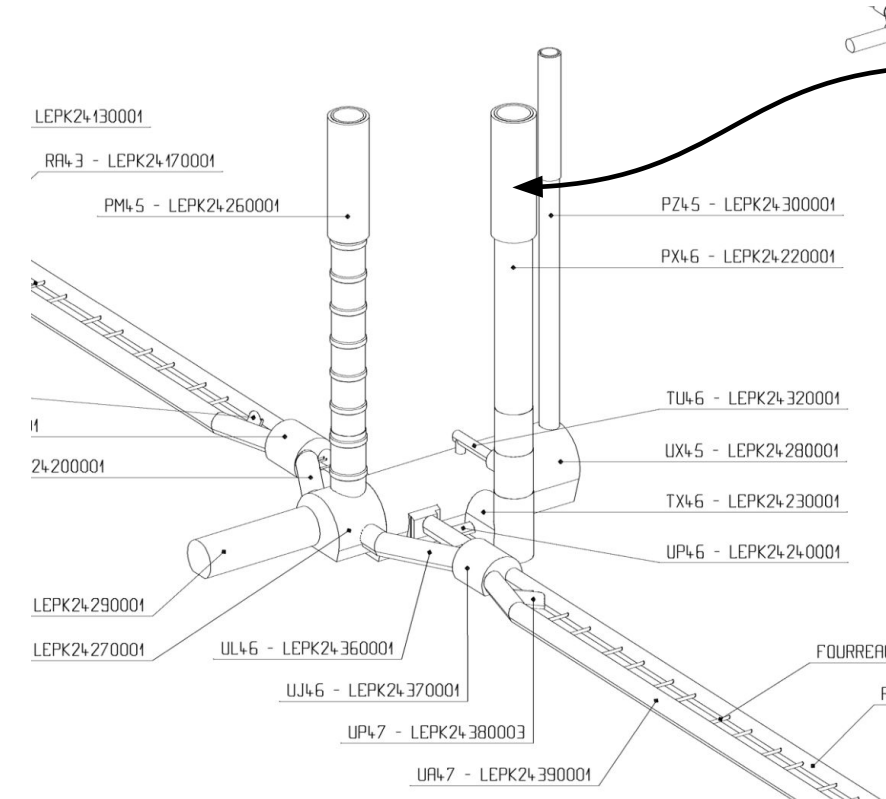
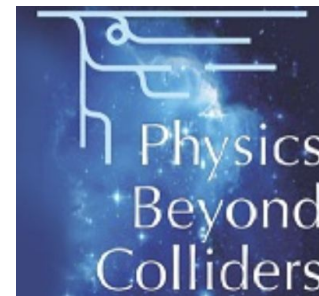
Lengths 143m

D = 10.10m

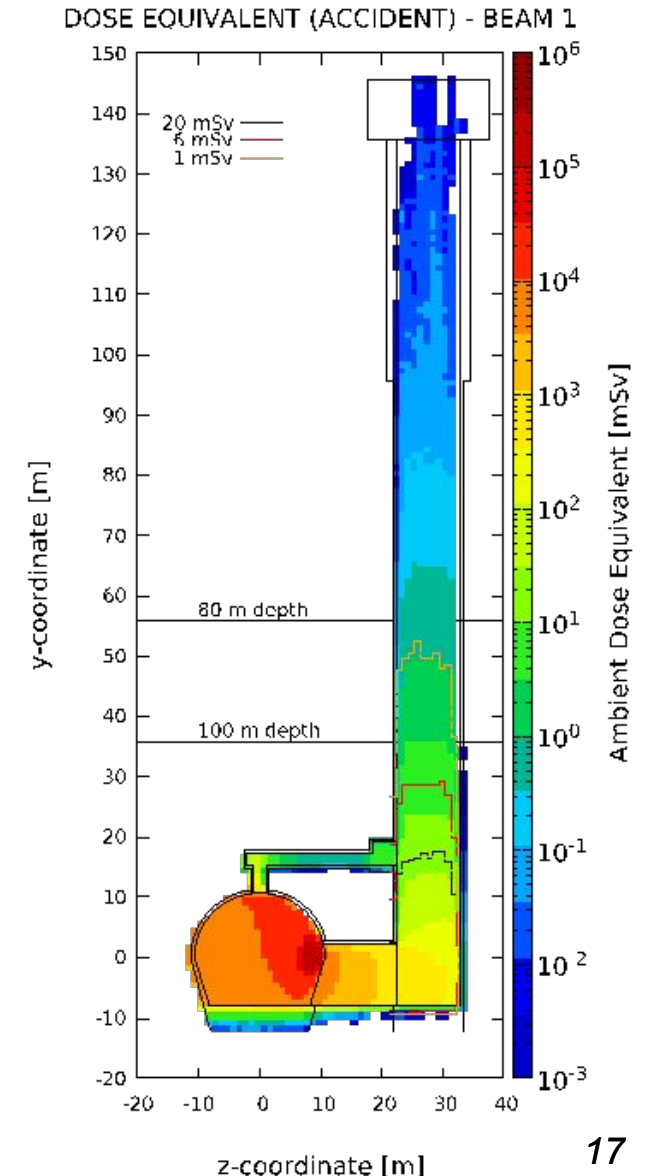
□ Ideal basic parameters for
AION100

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

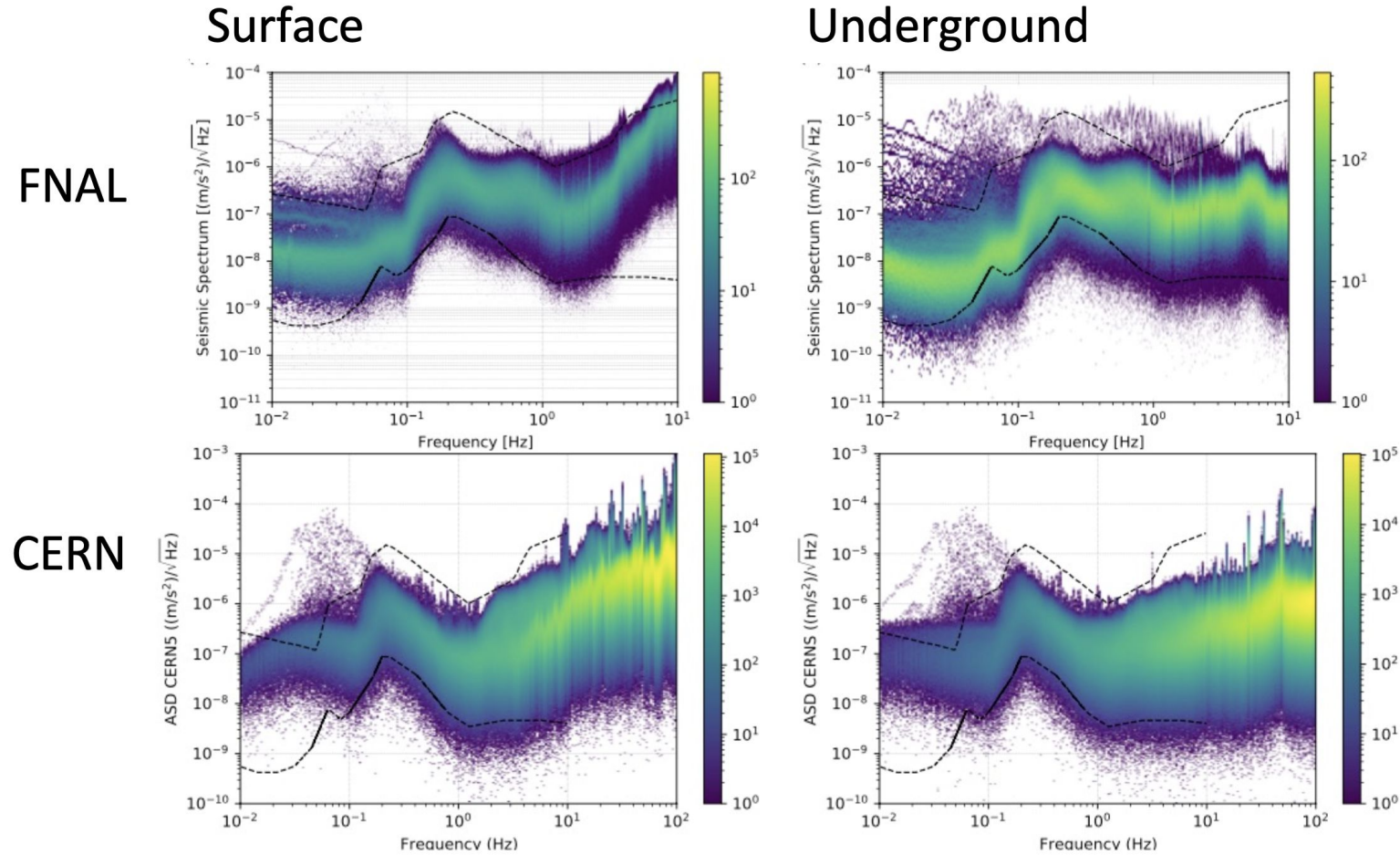
We are working with PBC Team on
this feasibility study



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

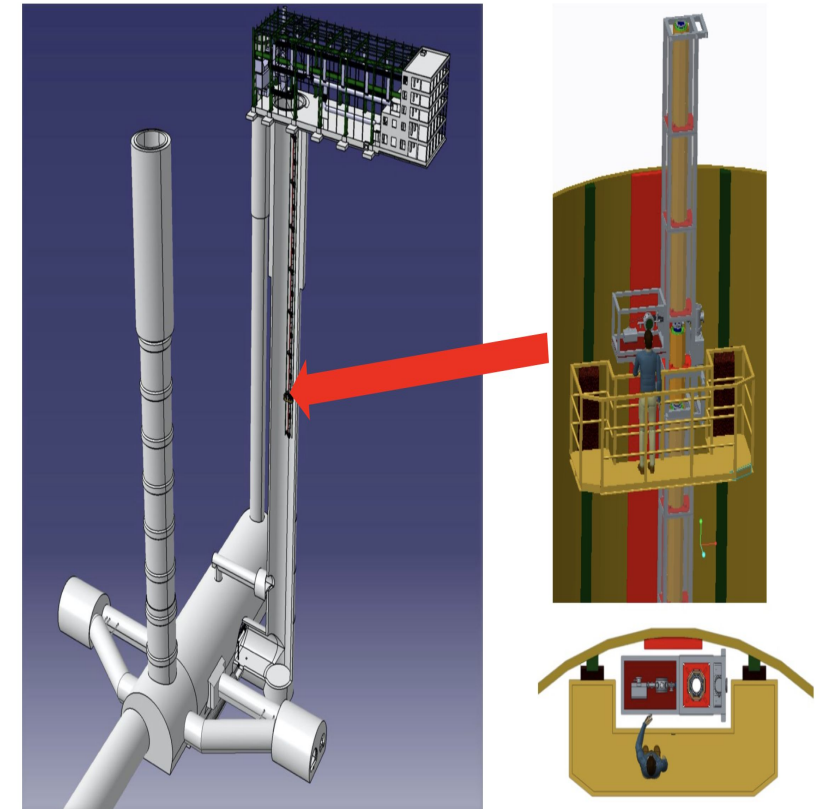


A 100 Detector at CERN – Site Investigation



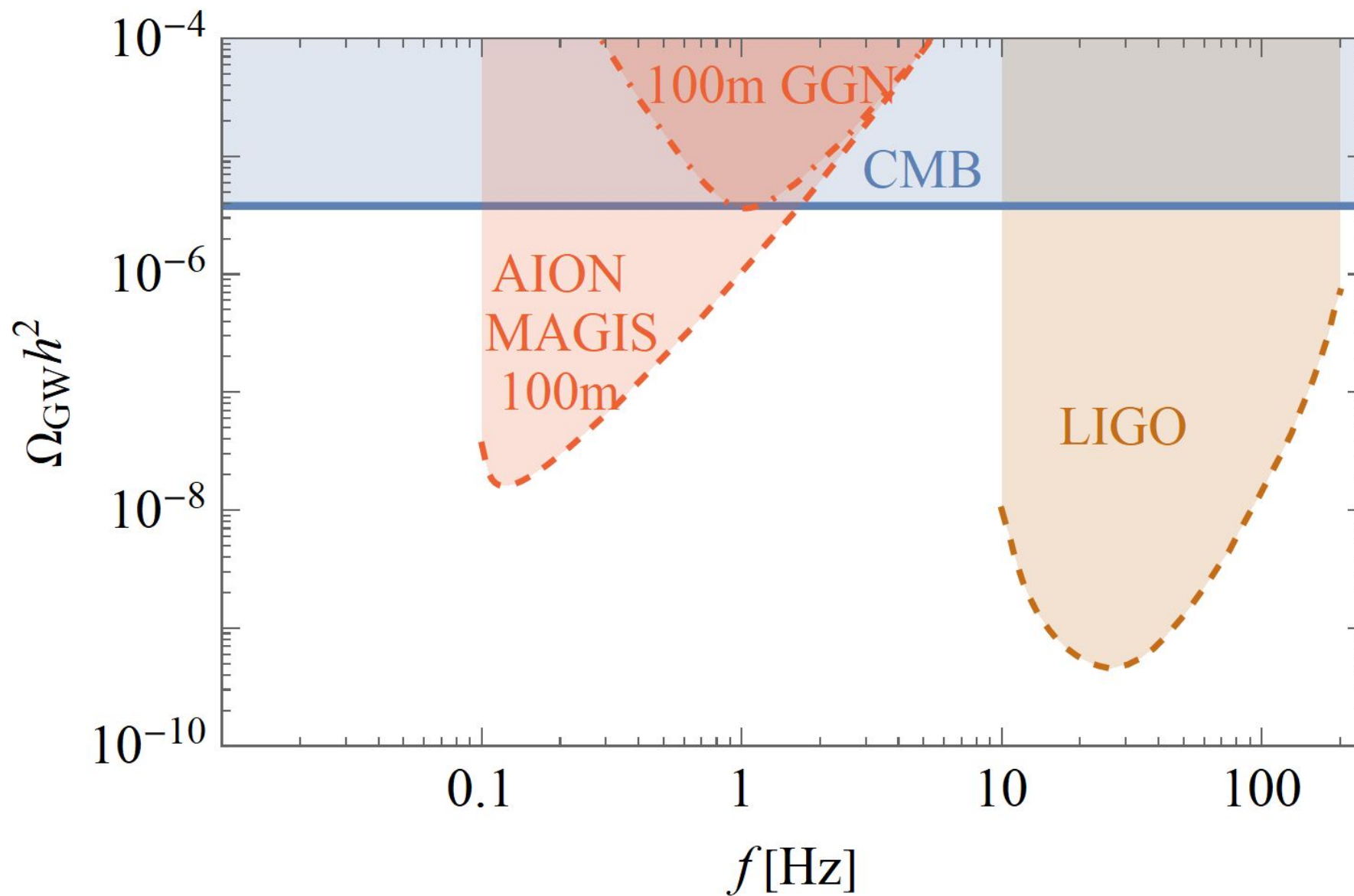
General view of LHC Point 4

Possible layout in PX46 shaft



Spectrum similar to that measured at Fermilab for MAGIS
More about the site investigation in the backup

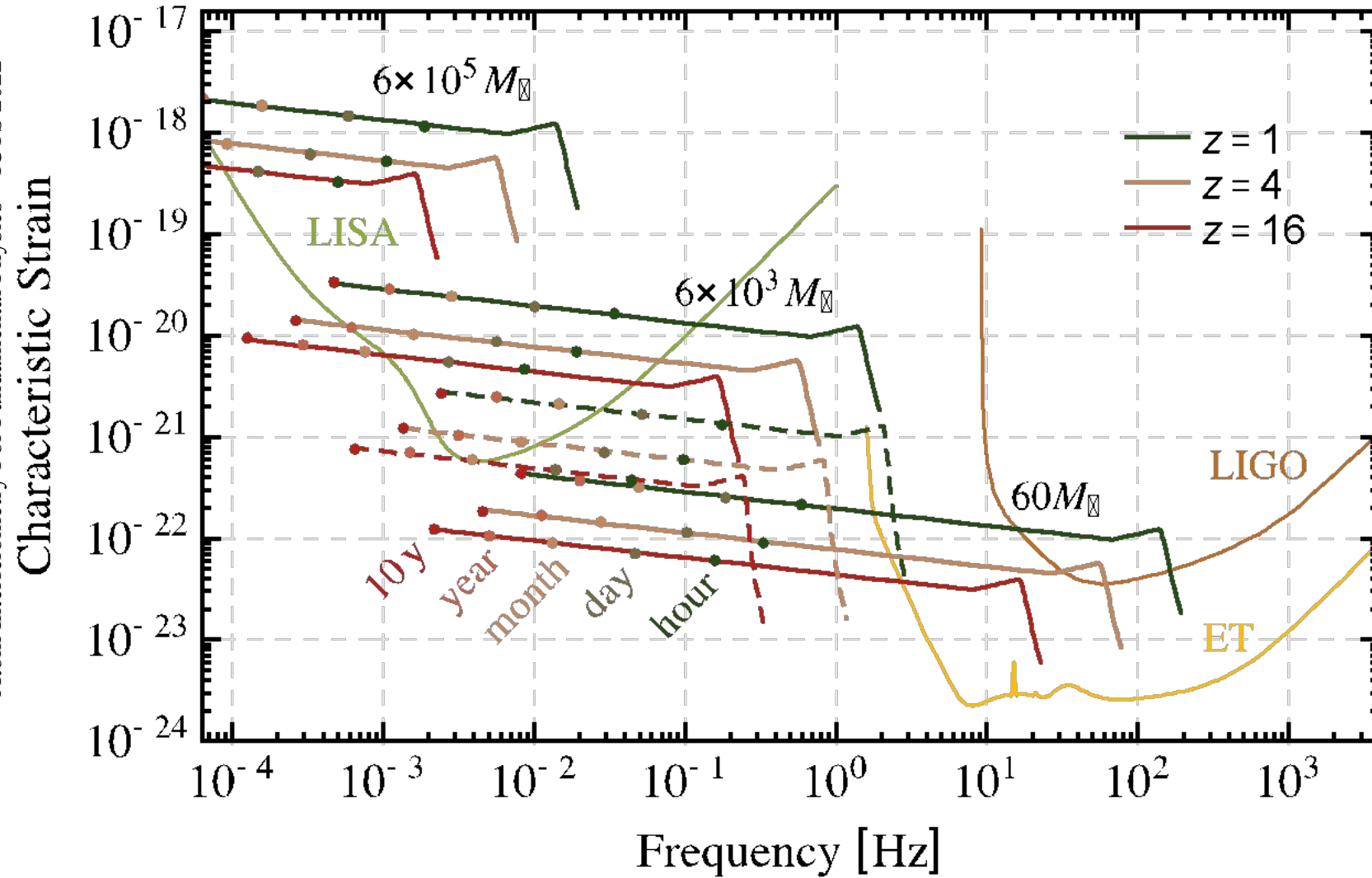
The GW Experimental Landscape: 2030ish



THE SCIENCE CASE

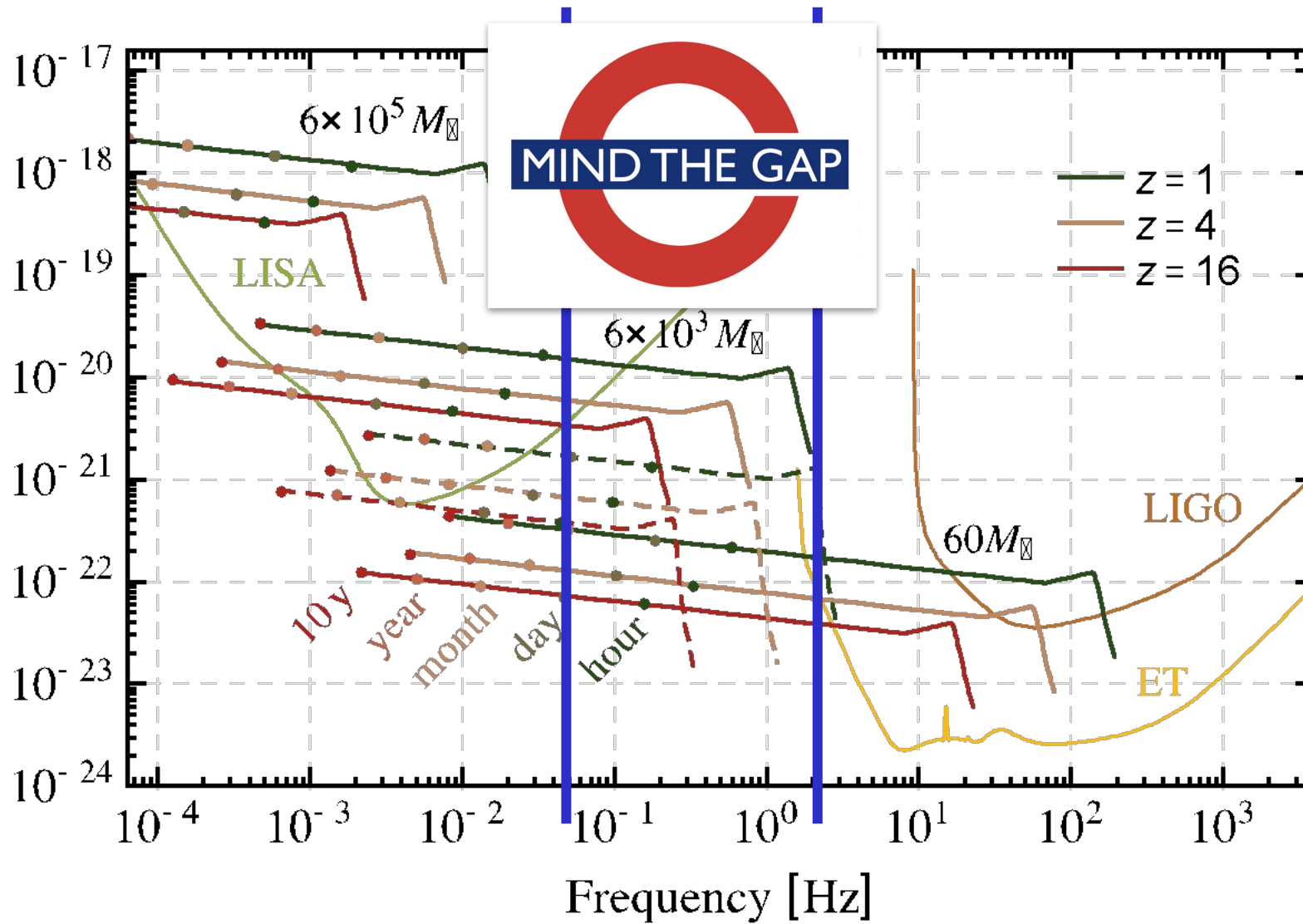
UNEXPLORED MID-FREQUENCY GRAVITATIONAL WAVES

Pathway to the GW Mid-(Frequency)



Pathway to the GW Mid-(Frequency)

Atom Interferometry For Fundamental Physics – ICTS 2022

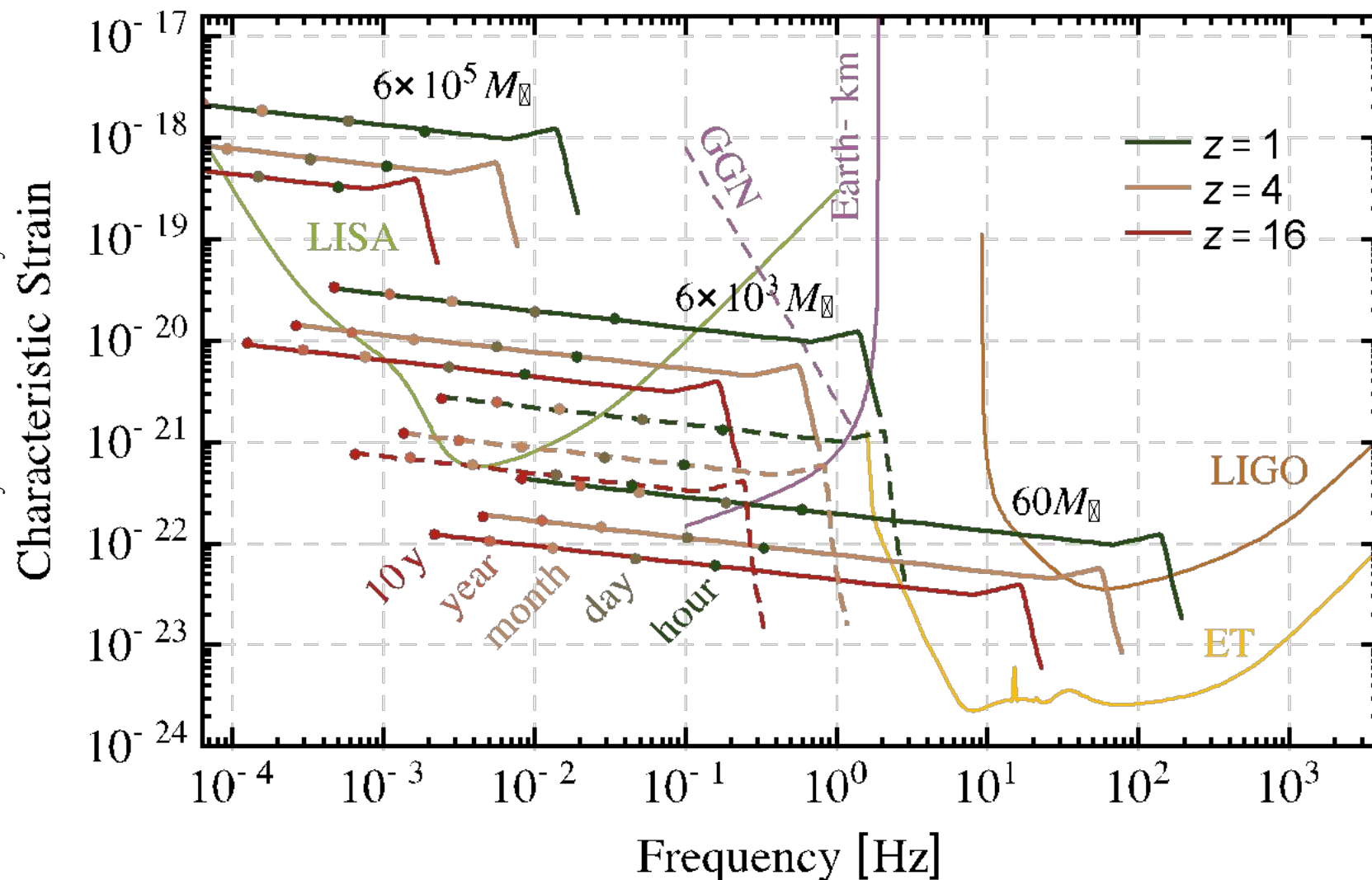


Mid-band science

- 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)



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

AION:
Terrestrial detectors
can start filling this
gap

Sky position determination

Sky localization
precision:

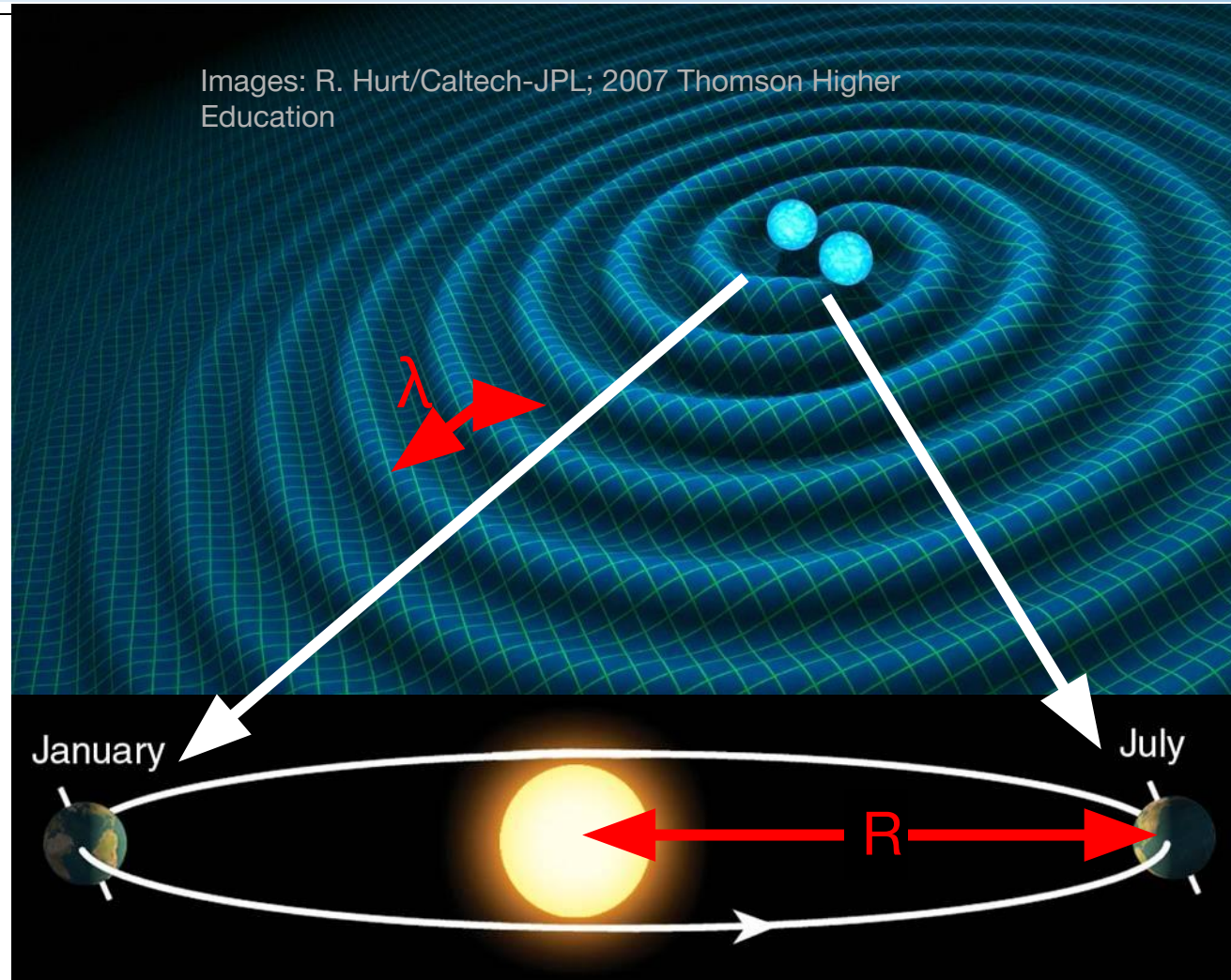
$$\sqrt{\Omega_s} \sim \left(\text{SNR} \cdot \frac{R}{\lambda} \right)^{-1}$$

Mid-band advantages

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

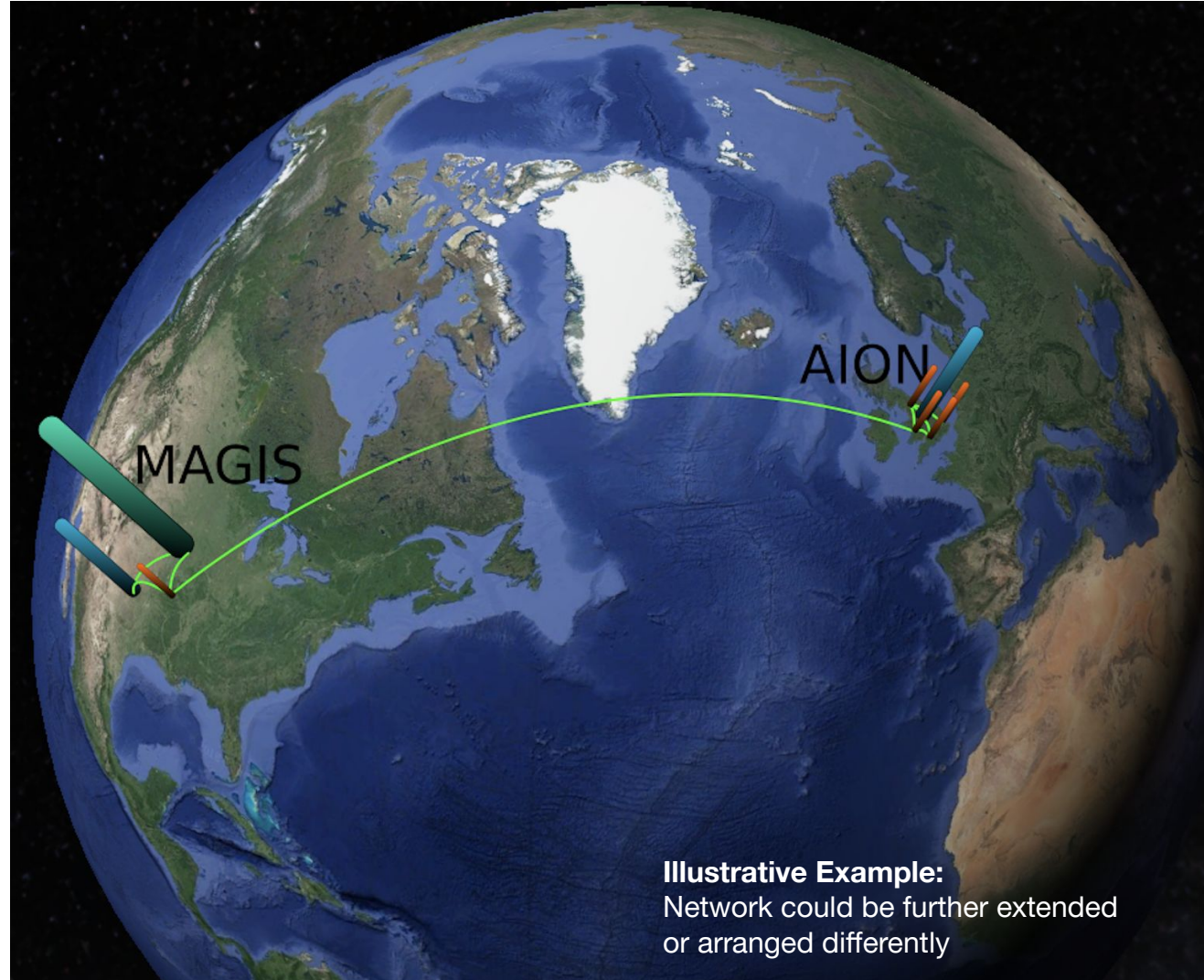
Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19

Courtesy of Jason Hogan!

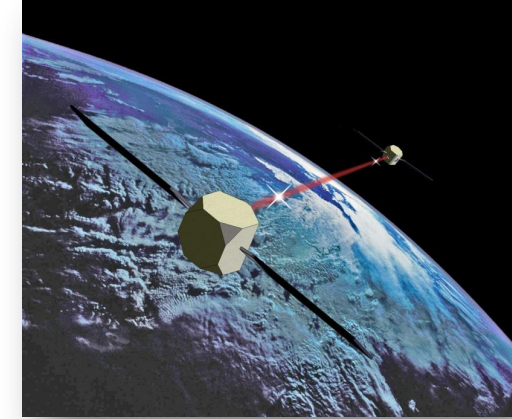
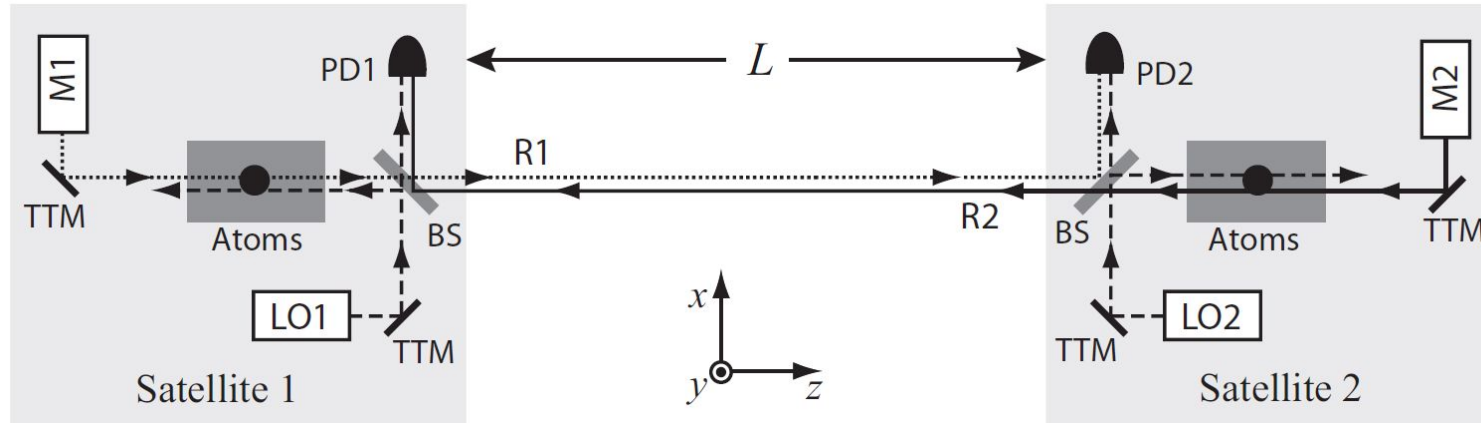


Ultimate sensitivity for terrestrial based detectors is achieved by operating 2 (or more) Detectors in synchronisation mode

Ultimate Goal: Establish International Network



AEDGE: Potential Mission Design



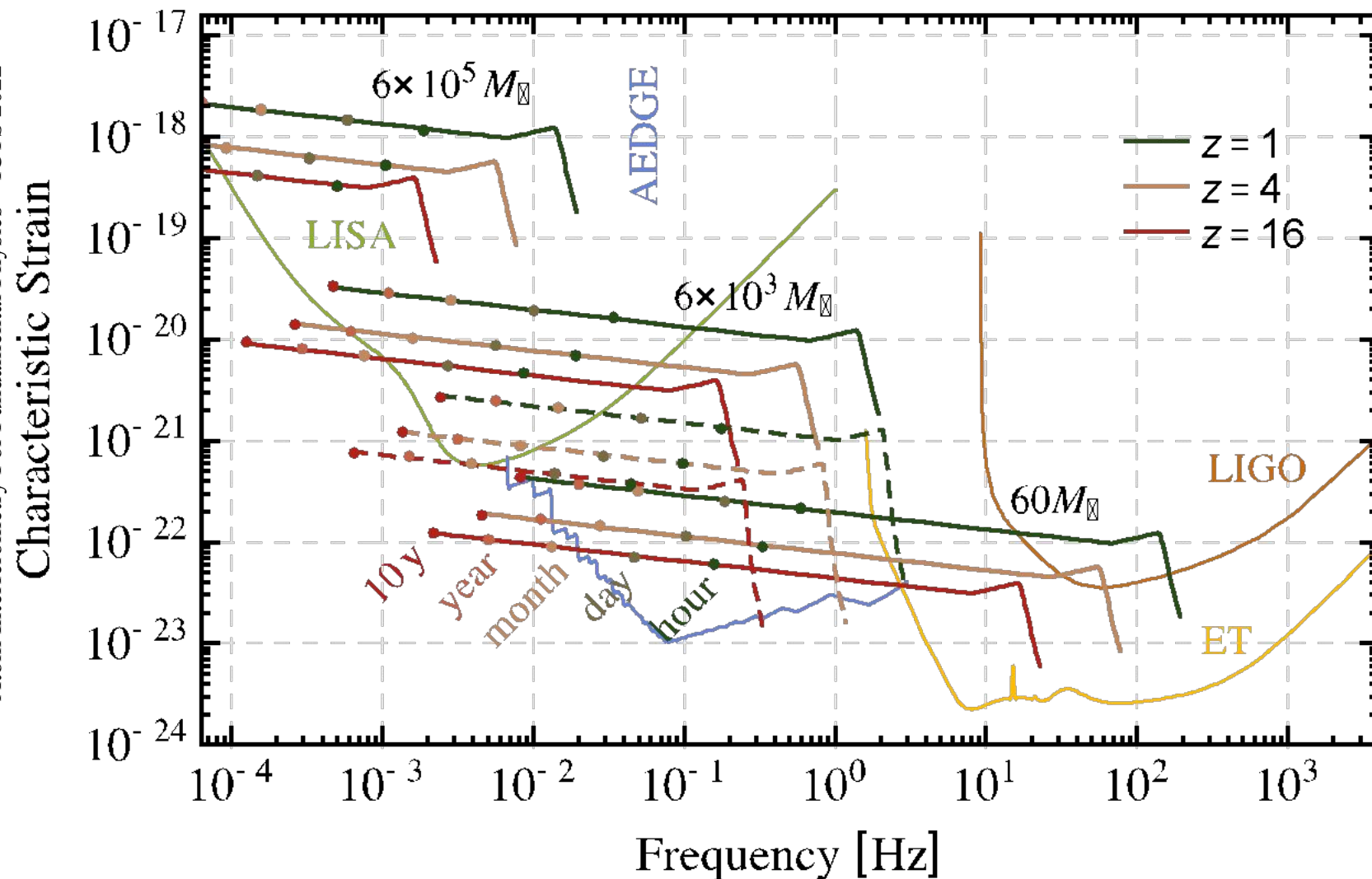
Using two cold-atom interferometers that perform a relative measurement of differential phase shift, a potential mission profile would be using a pair of satellites separated by a very long baseline L .

Assumed basic parameters:

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

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

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



Mid-band science

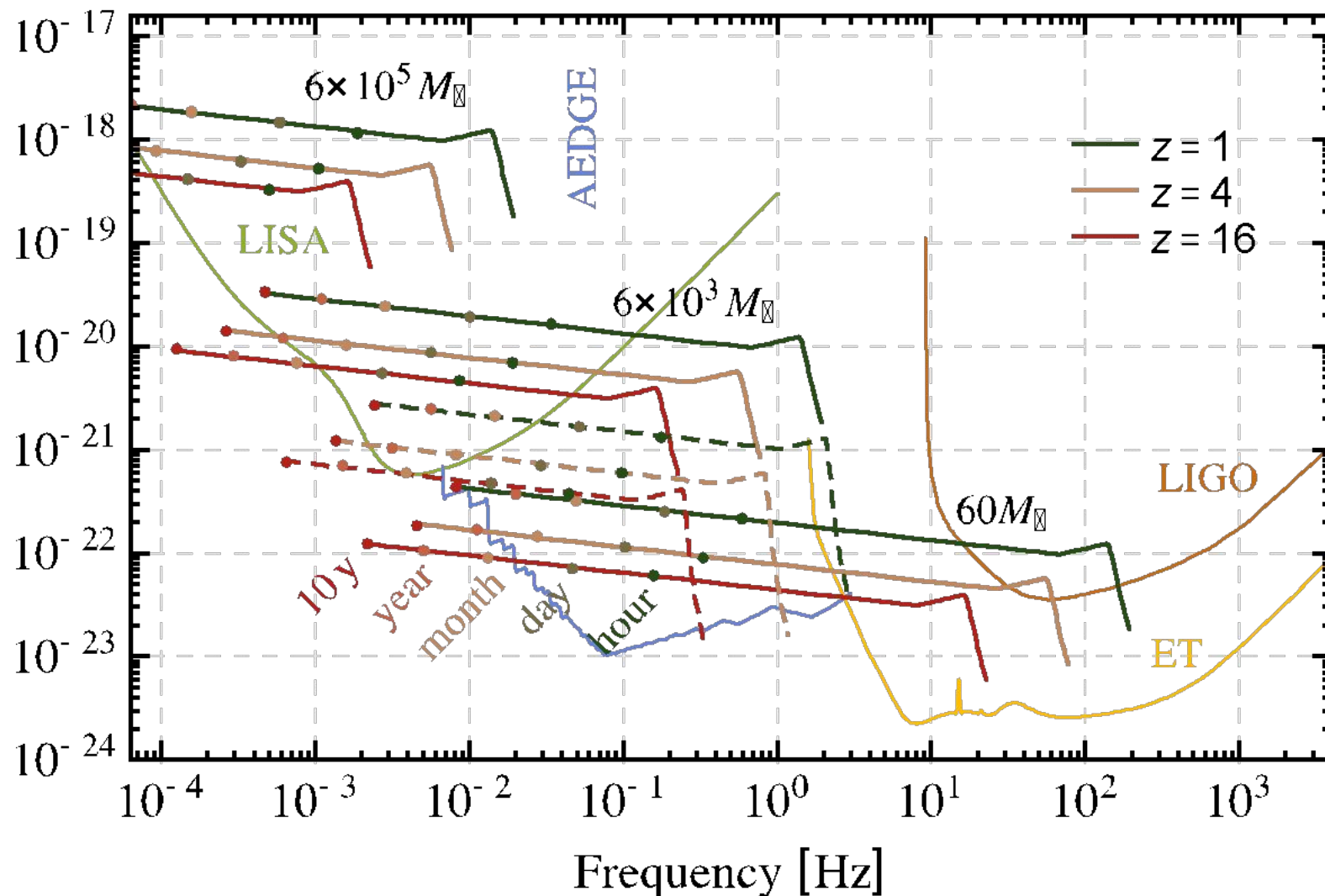
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- Search for Ultra-light dark matter in a similar frequency [i.e. mass] range

AEDGE
Ultimate coverage
with a space based
detector

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

Atom Interferometry For Fundamental Physics – ICTS 2022

Characteristic Strain



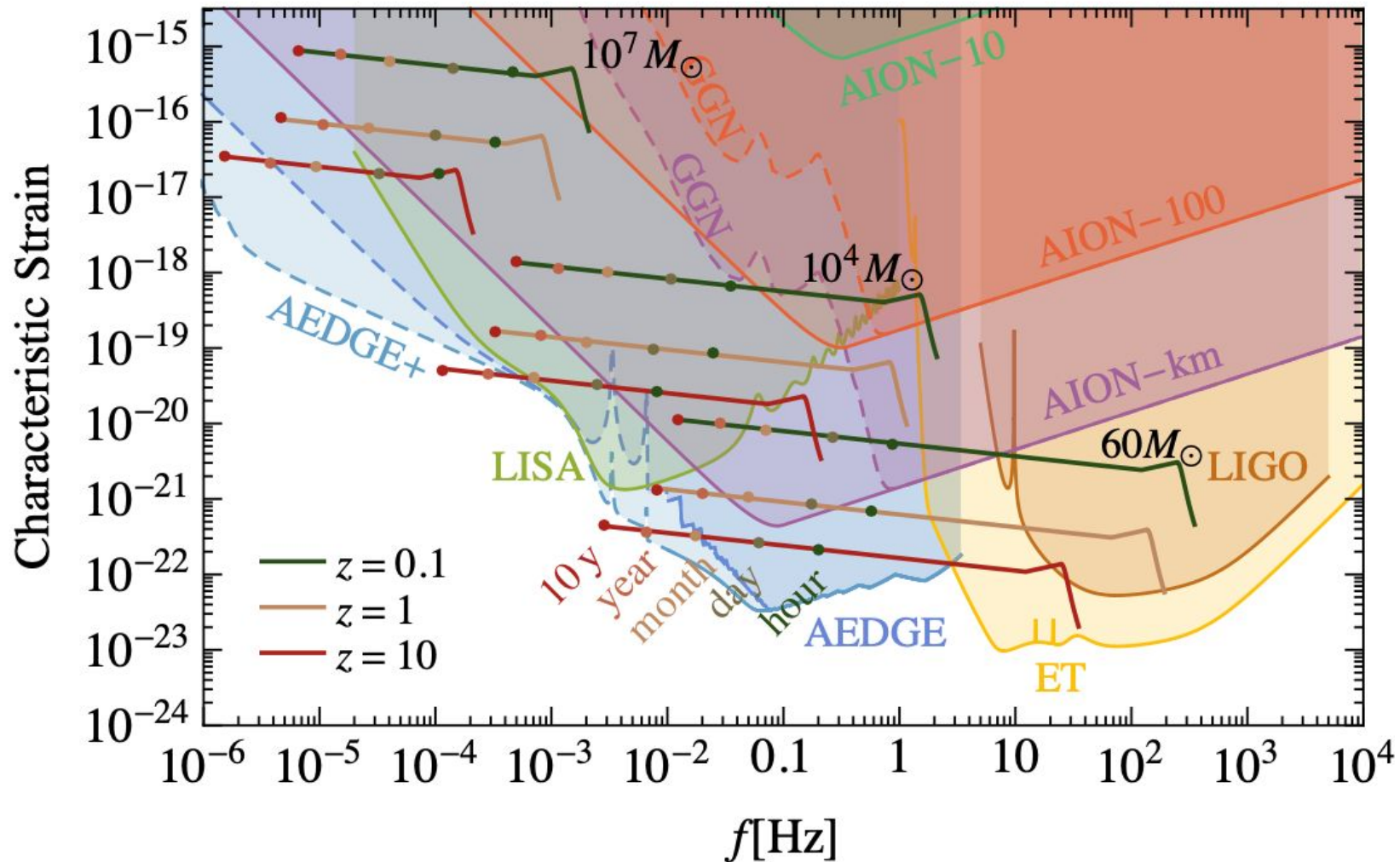
Mid-band science

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AEDGE
Ultimate coverage
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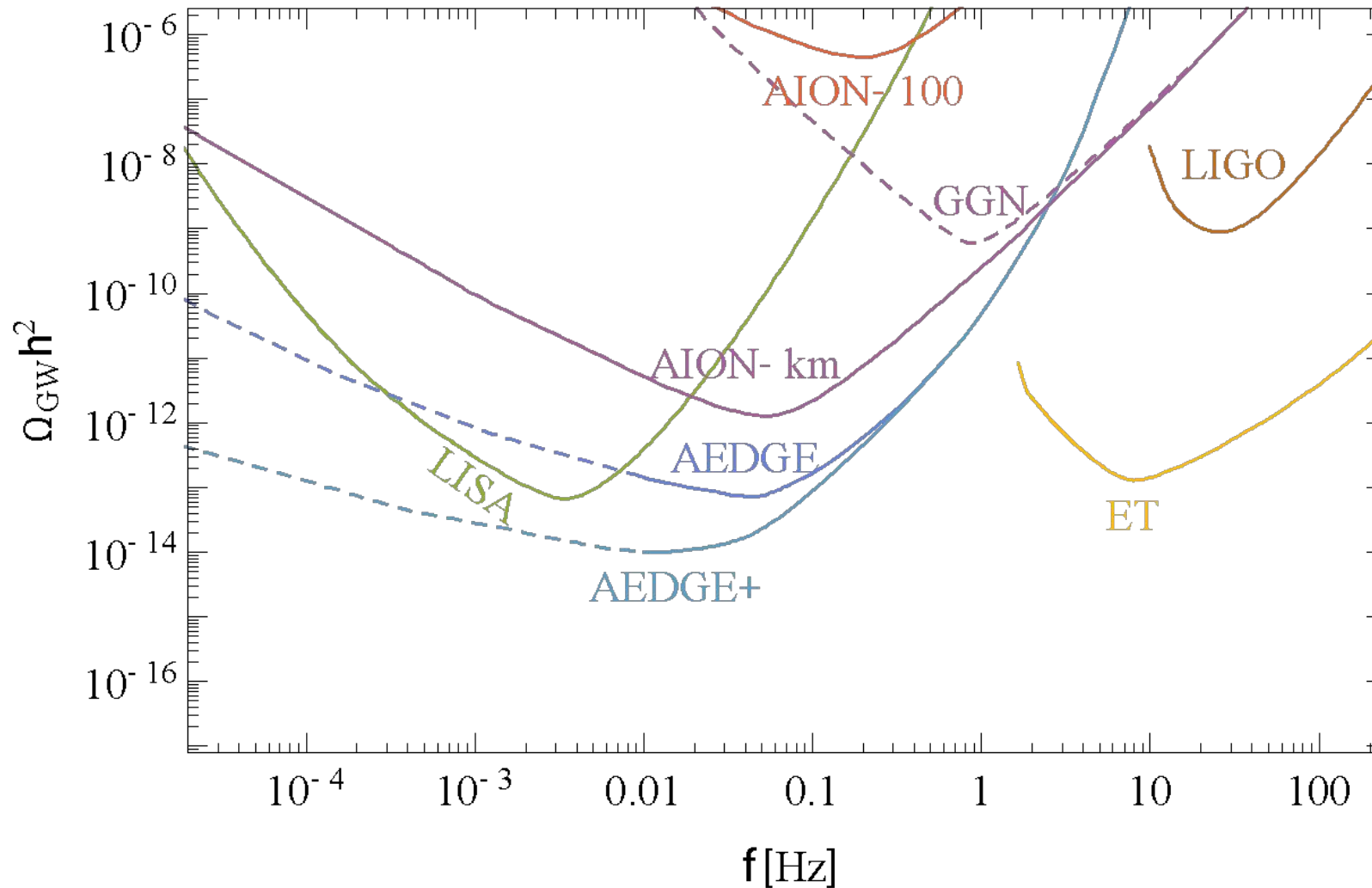
Vision for 2045+

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



Vision for 2045+

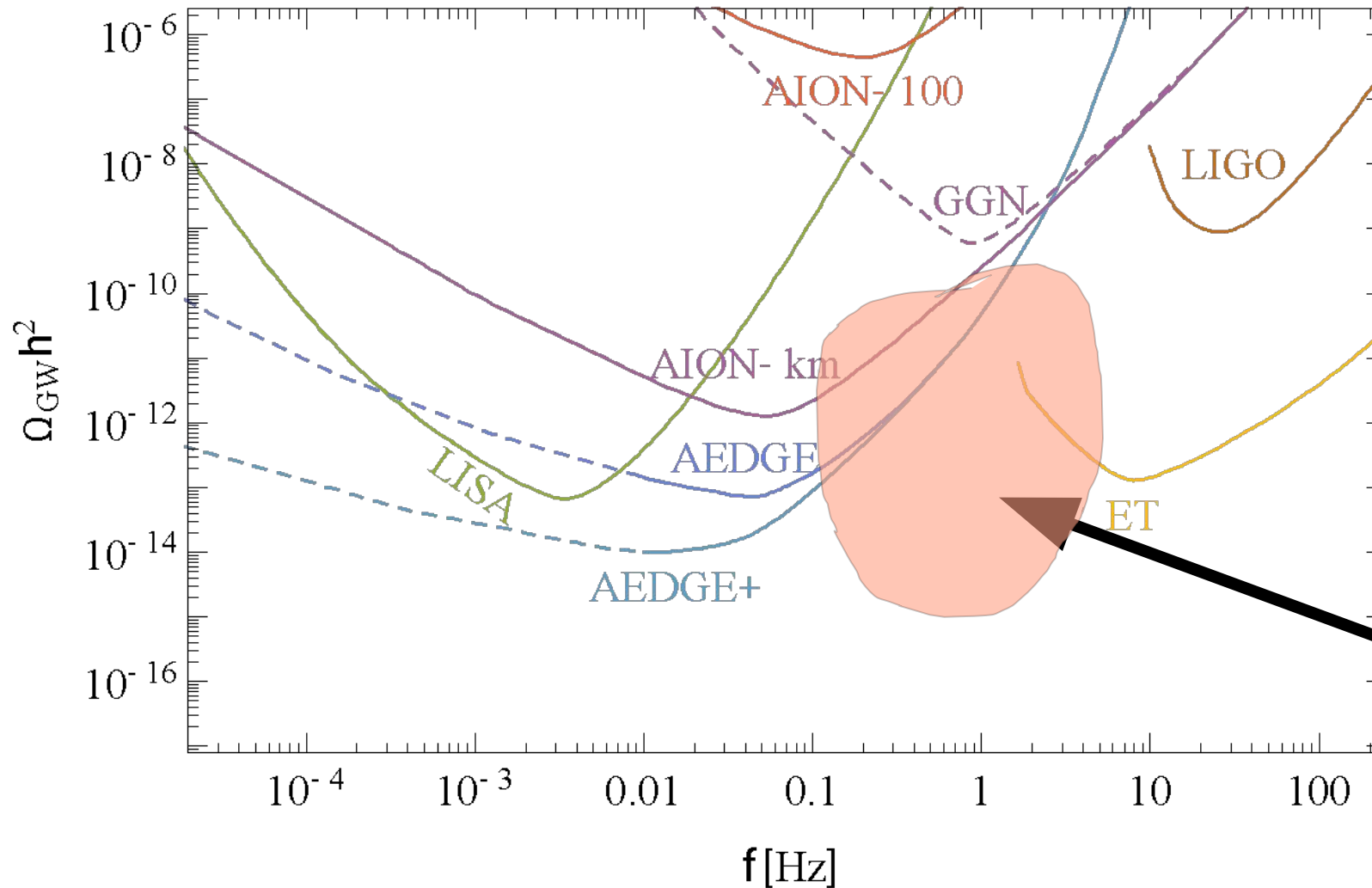
Probe formation of SMBHs: Synergies with other GW experiments (LIGO, LISA), test GR



**Translate Stain
sensitivity into the
dimensionless
energy density of a
GW**

Vision for 2045+

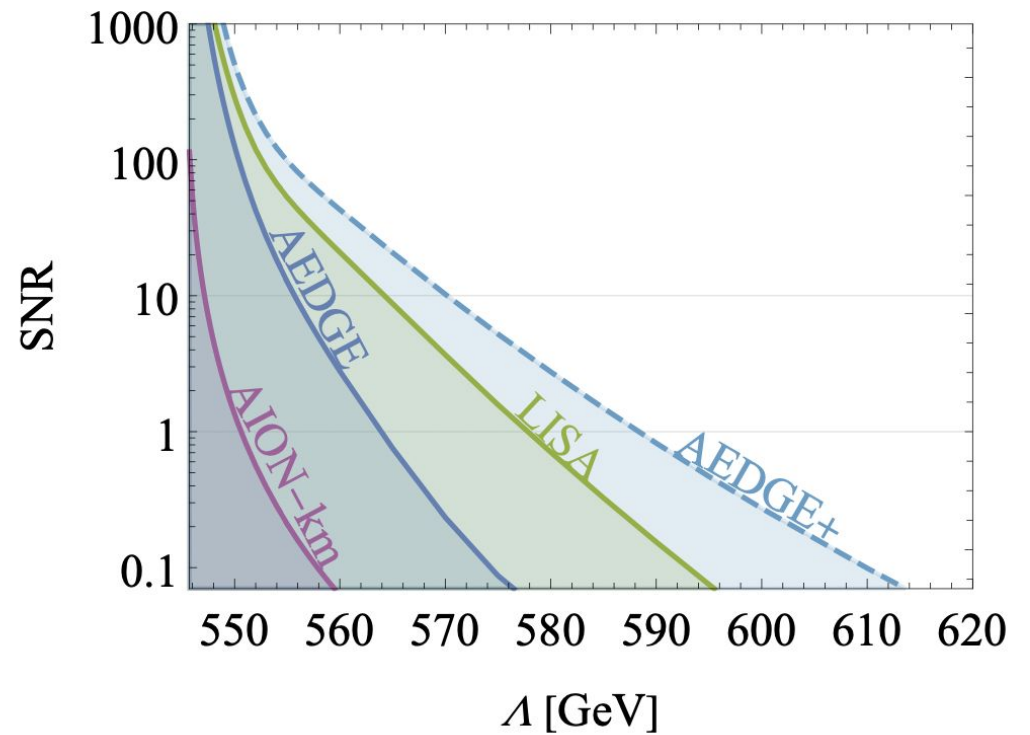
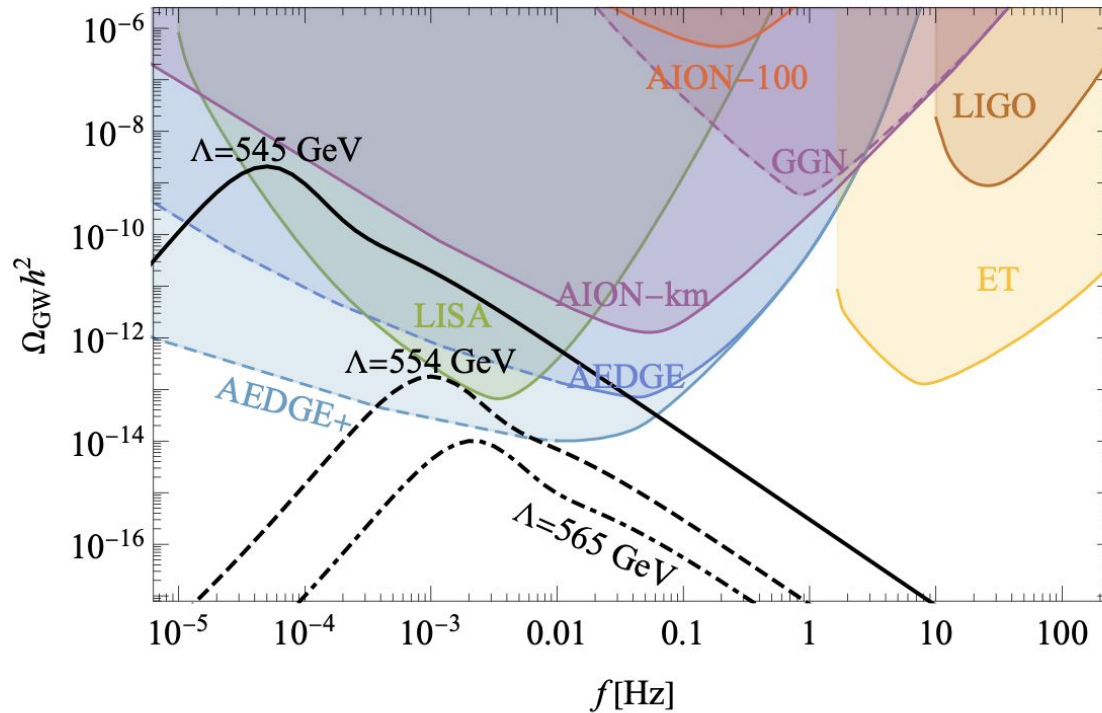
Probe formation of SMBHs: Synergies with other GW experiments (LIGO, LISA), test GR



**Translate Stain
sensitivity into the
dimensionless
energy density of a
GW**

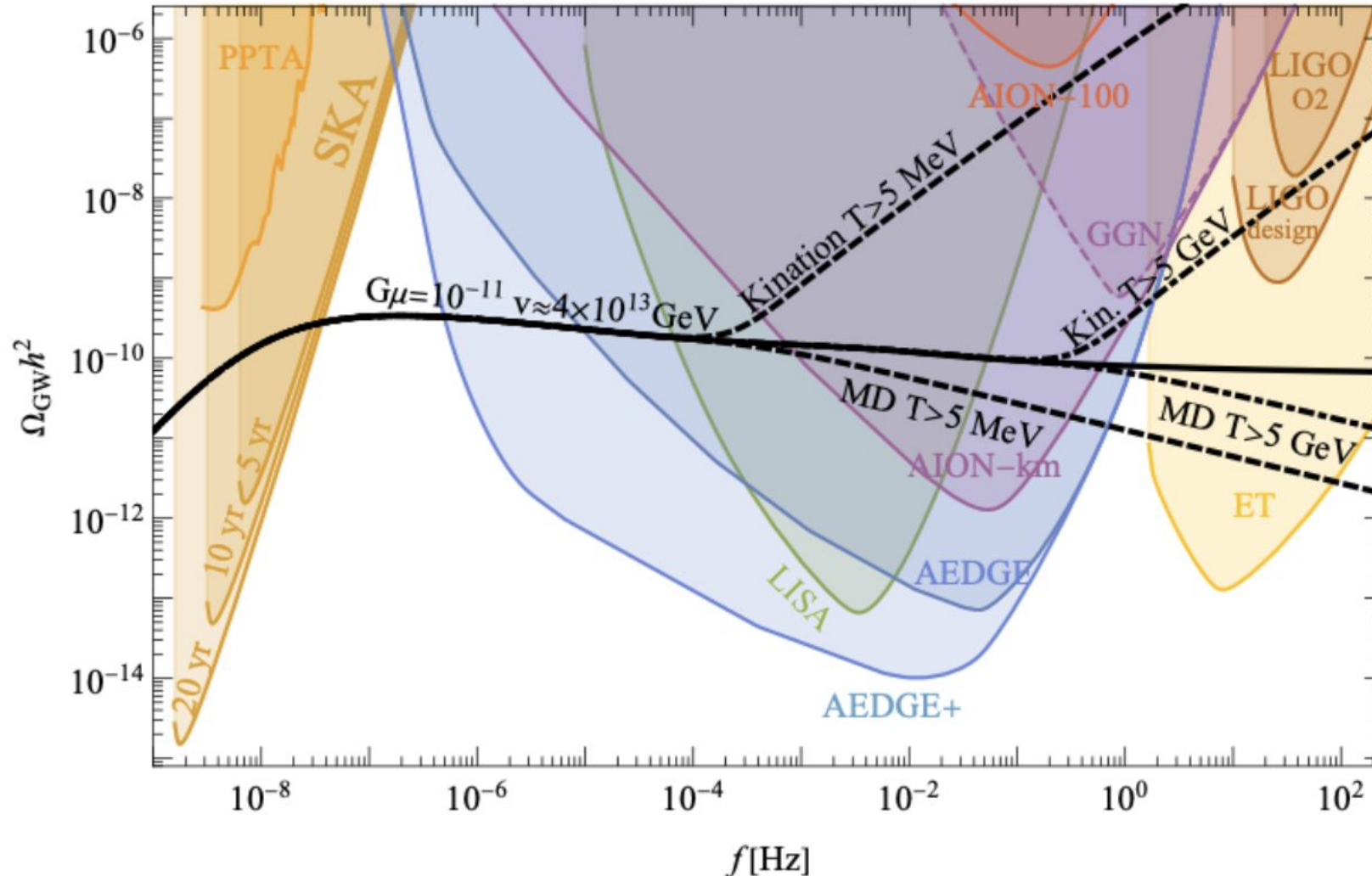
Still a "gap" around 1Hz
Need to find a solution
to fill it

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:

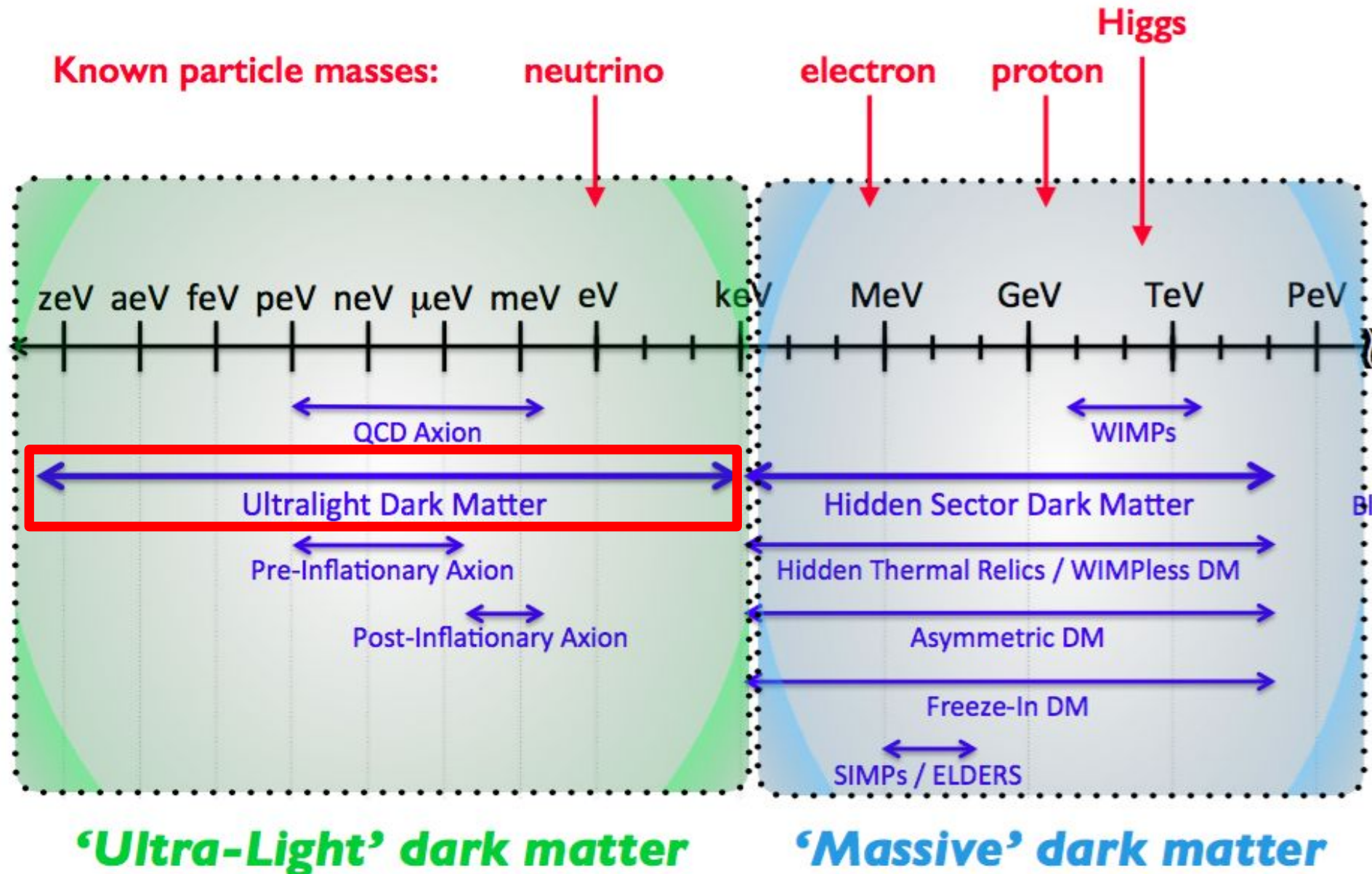
Badurina, OB, John Ellis, Lewicki, McCabe & Vaskonen: arXiv:2108.02468
and

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

$f[\text{Hz}]$

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

Search for Ultra-Light Dark Matter



The Landscape of Ultra-Light Dark Matter Detection

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

Example: Ultra-Light Dark Matter:

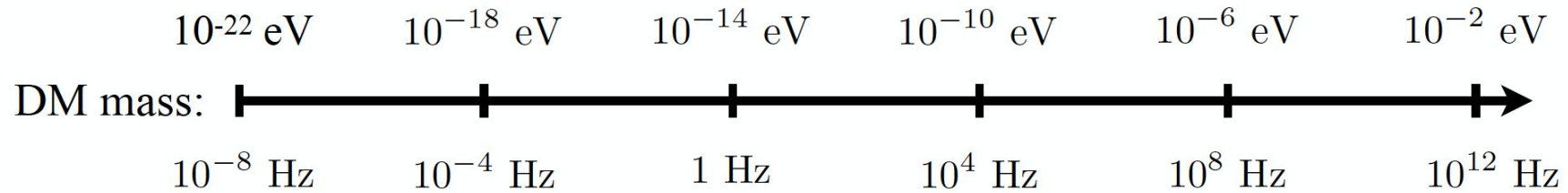


Diagram taken from P. Graham's
talk at HEP Front 2018

The Landscape of Ultra-Light Dark Matter Detection

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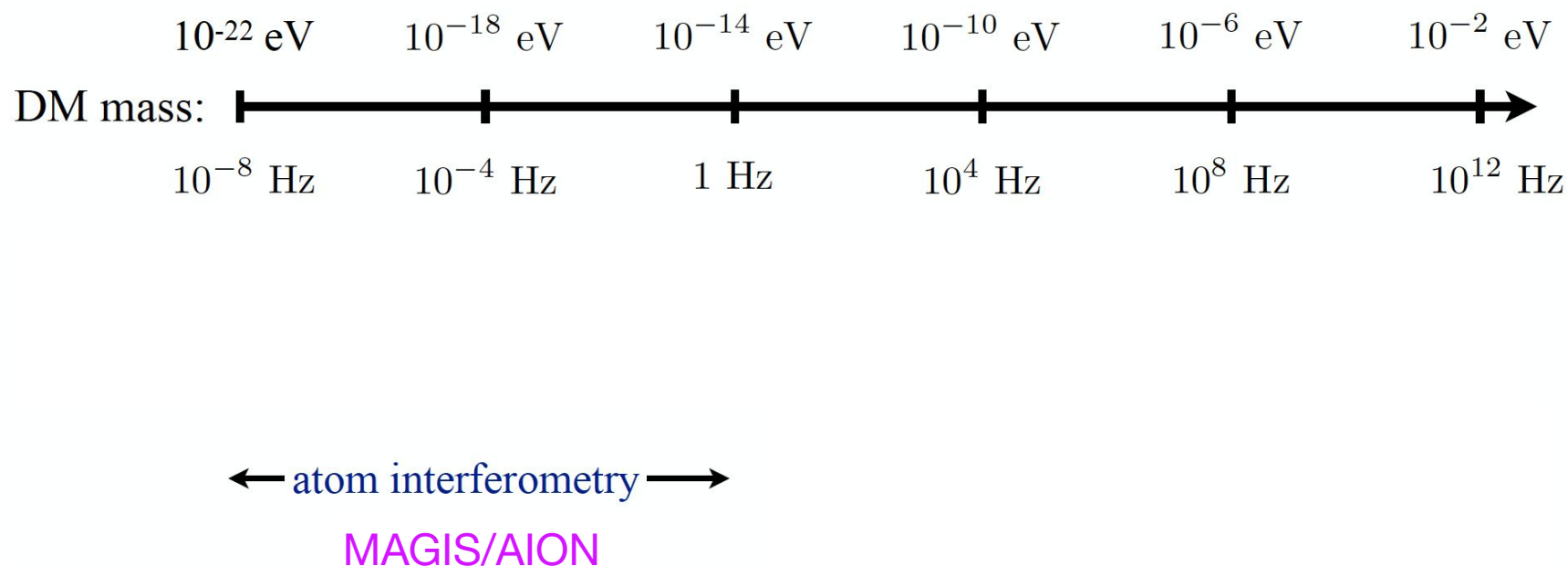


Diagram taken from P. Graham's
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The Landscape of Ultra-Light Dark Matter Detection

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Example: Ultra-Light Dark Matter:

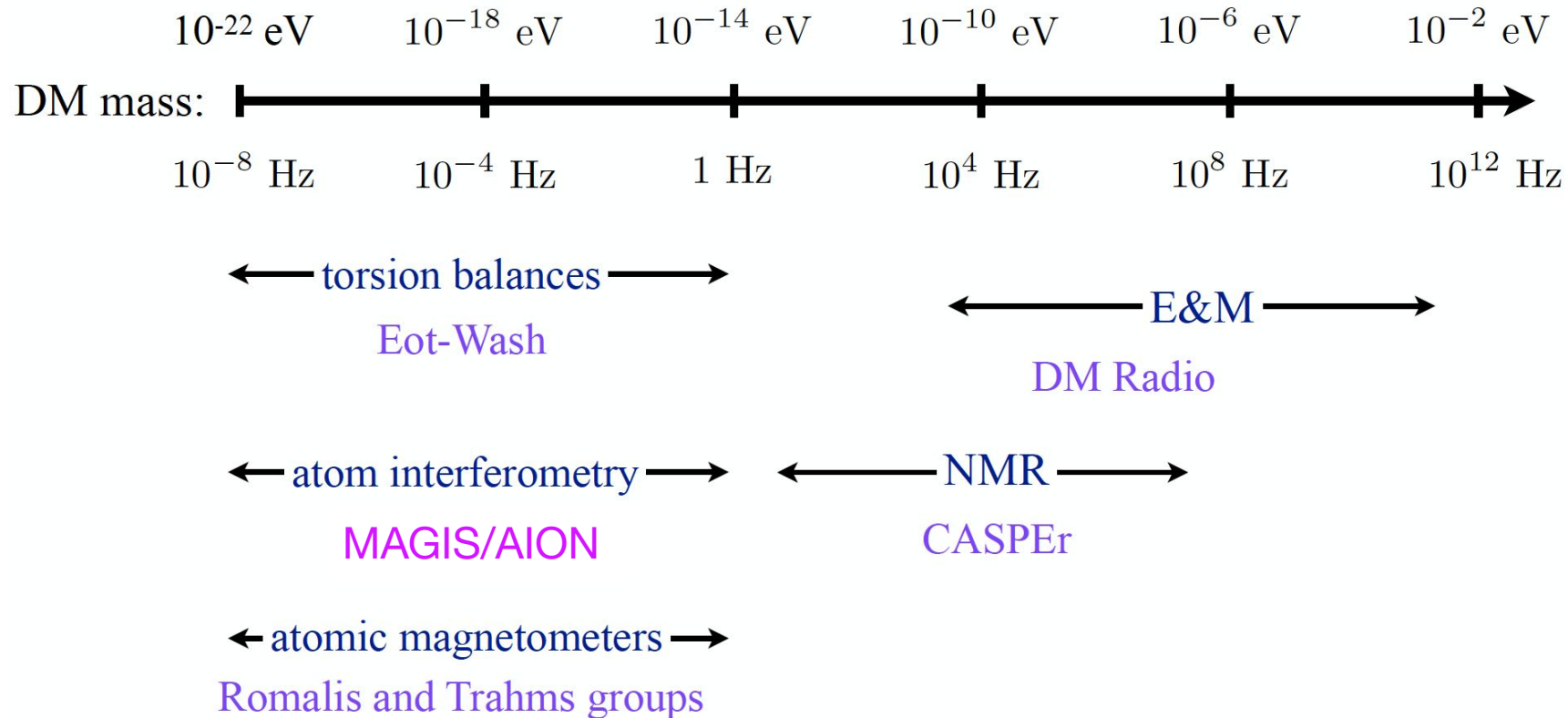


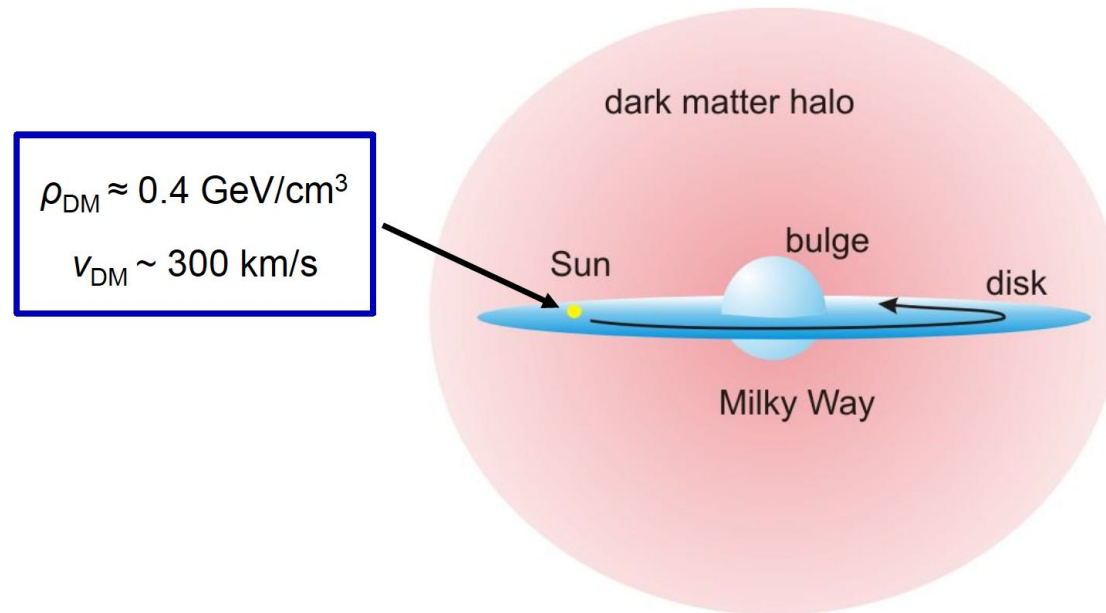
Diagram taken from P. Graham's
talk at HEP Front 2018

Ultra-Light Spin-0 Dark Matter

Ultra-light spin 0 particles are expected to form a coherently oscillating classical field

$$\phi(t) = \phi_0 \cos(E_\phi t / \hbar)$$

as $E_\phi \approx m_\phi c^2$ with an energy density of
 $\langle \rho_\phi \rangle \approx m_\phi^2 \phi_0^2 / 2$ ($\rho_{DM,local} \approx 0.4 \text{ GeV/cm}^3$).



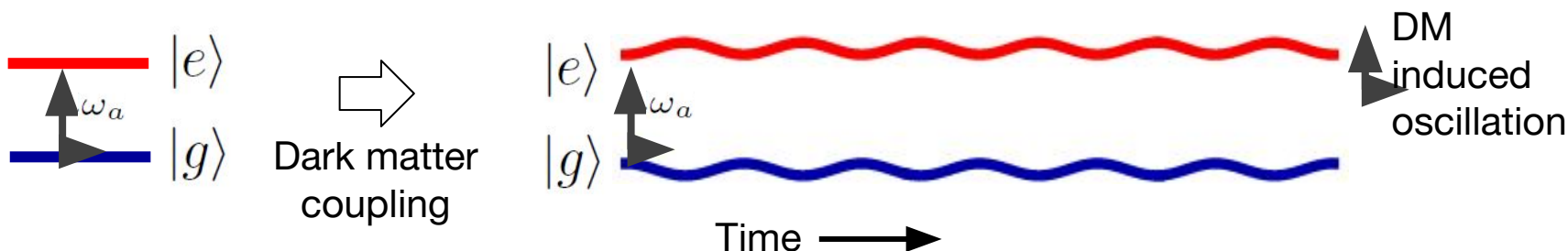
Ultralight scalar dark matter

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

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

$$\phi(t, \mathbf{x}) = \phi_0 \cos[m_\phi(t - \mathbf{v} \cdot \mathbf{x}) + \beta] + \mathcal{O}(|\mathbf{v}|^2) \quad \phi_0 \propto \sqrt{\rho_{\text{DM}}} \quad \text{DM mass density}$$

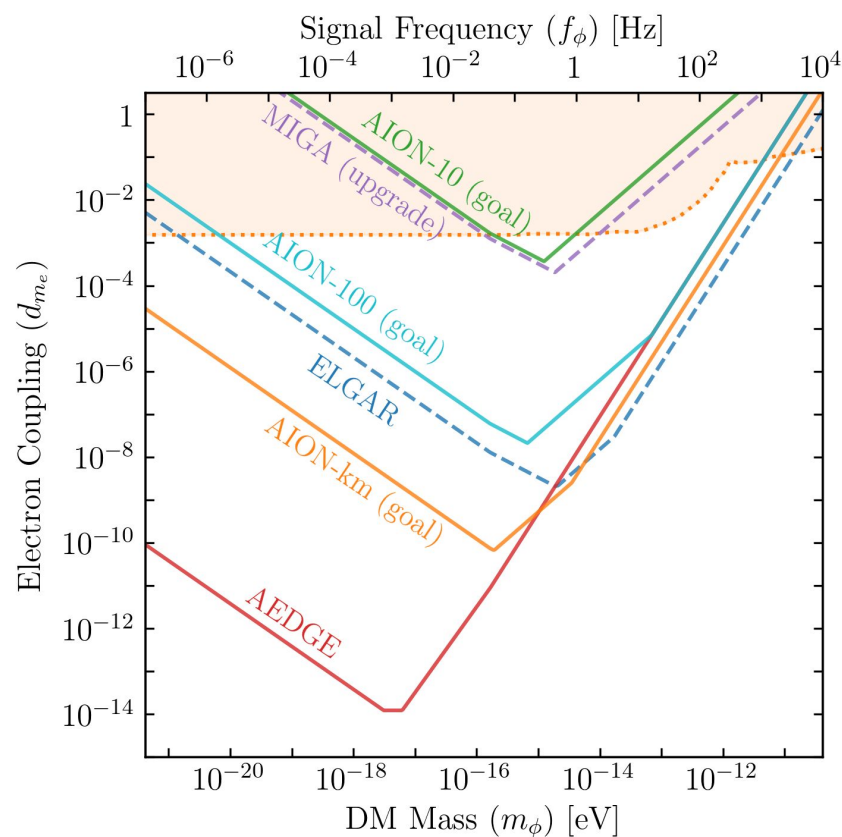
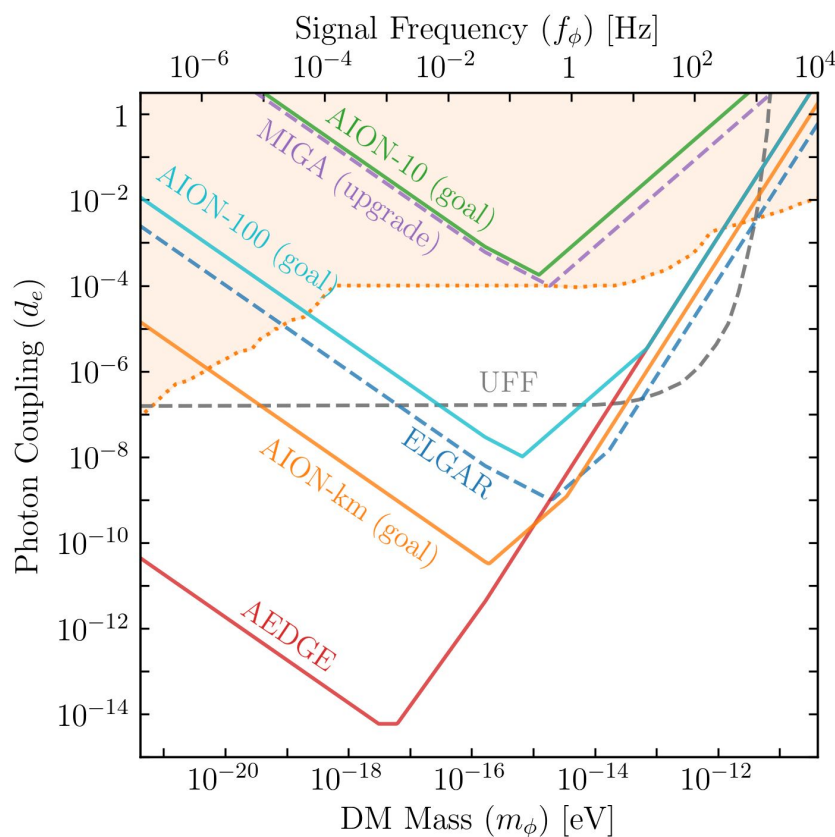
DM coupling causes time-varying atomic energy levels:



Search for Ultra-Light Dark Matter

Linear couplings to gauge fields and matter fermions

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



Orders of
magnitude
improvement
over current
sensitivities

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:

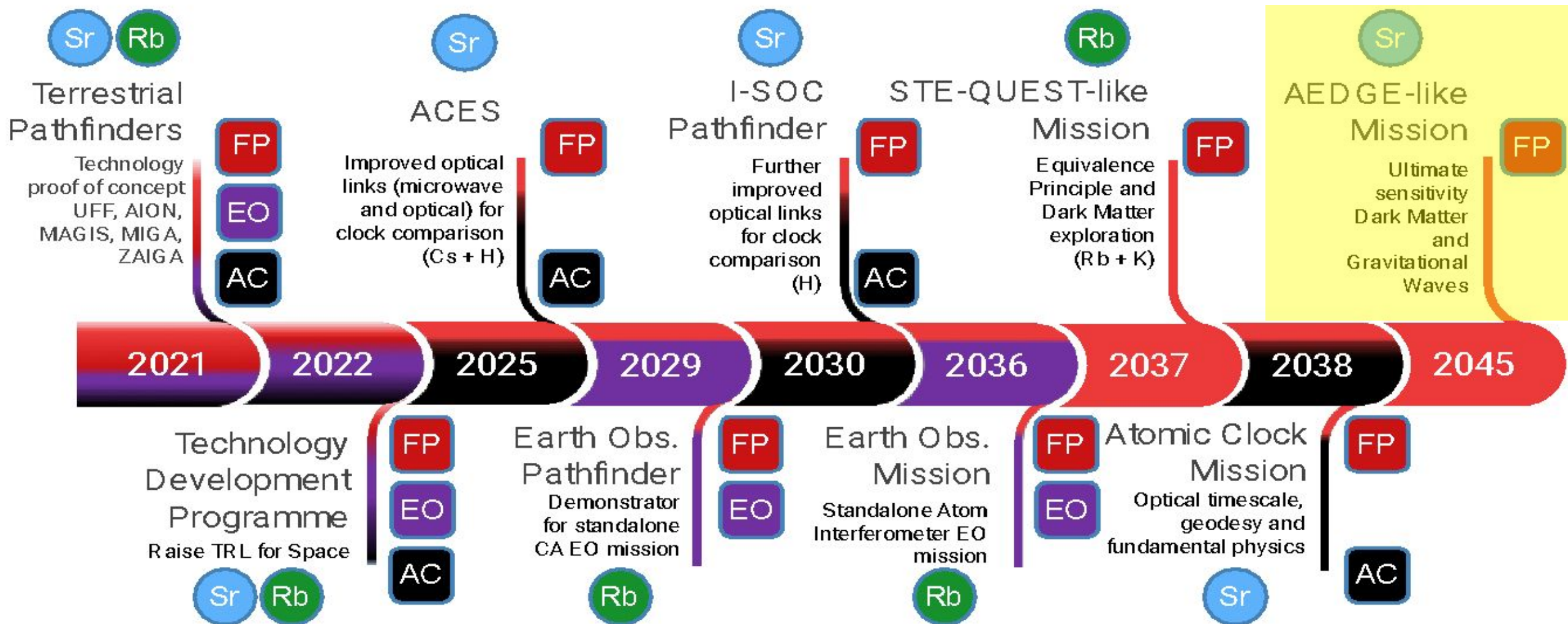
- *The possibility of detecting the astrophysical neutrinos*
- *Probes of long-range fifth forces.*
- *Constraining possible variations in fundamental constants.*
- *Probing dark energy.*
- Probes of basic physical principles such as foundations of quantum mechanics and Lorentz invariance.

A very exciting new research avenue is ahead of us

BACKUP

AEDGE AND STE-QUEST

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



Legends:

Main Cold Atom Species



Areas of Relevance

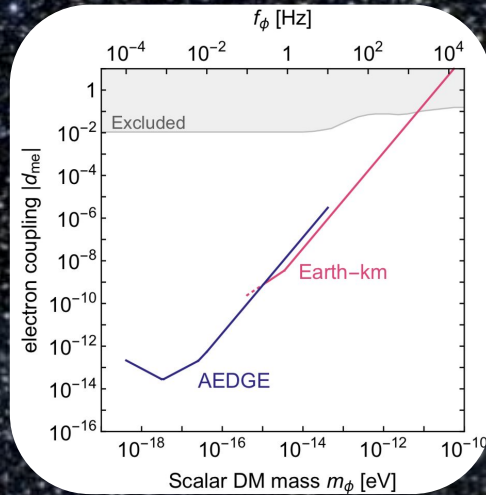


Main Milestone Area (colour coded)



AEDGE:

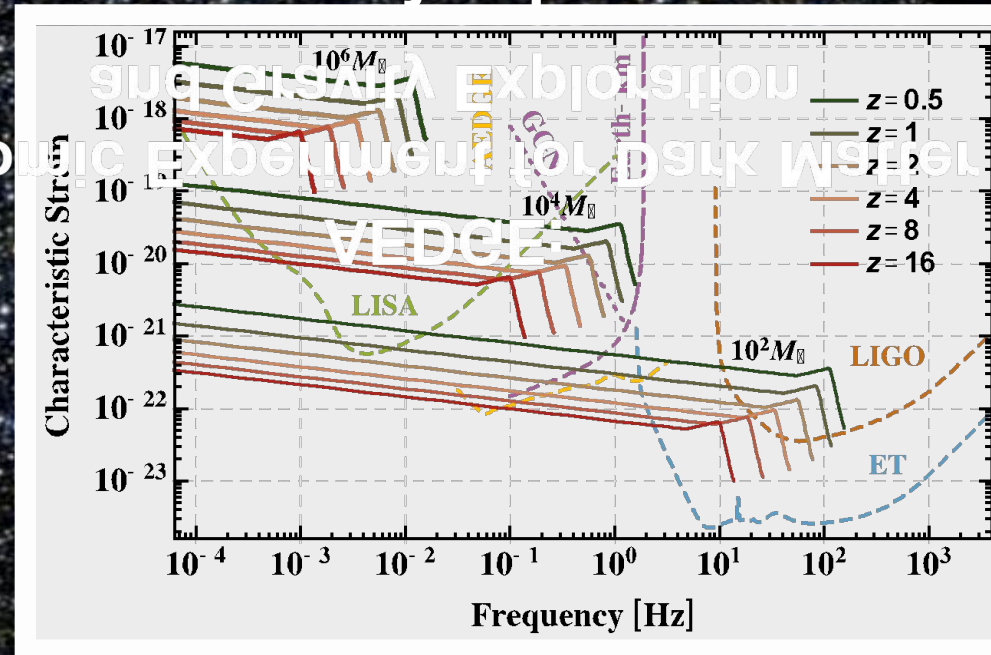
Atomic Experiment for Dark Matter and Gravity Exploration



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
CERN, July 22/23 2019**

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PP=Particle Physics
CA=Cold Atoms

AEDGE Mission Concept

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 Sajjan 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 Gauguier,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 Gundogan,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 Kriker,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-Veetil,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 Zupan⁷⁰

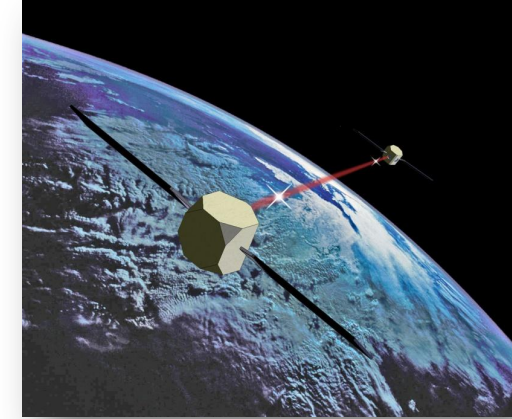
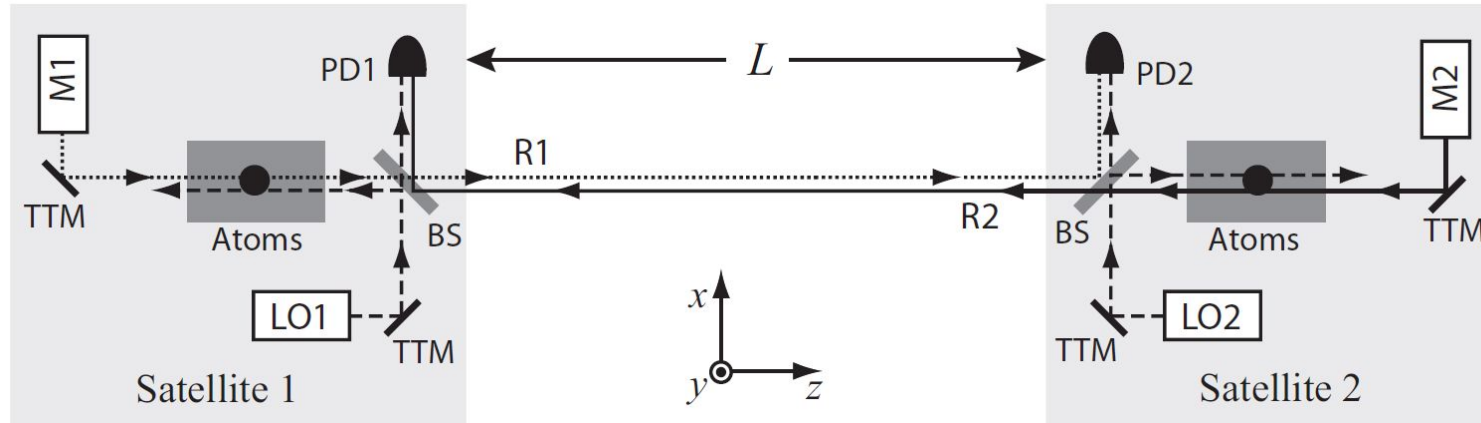
132 Authors, from **70** institutions,
based in **23** different counties!

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



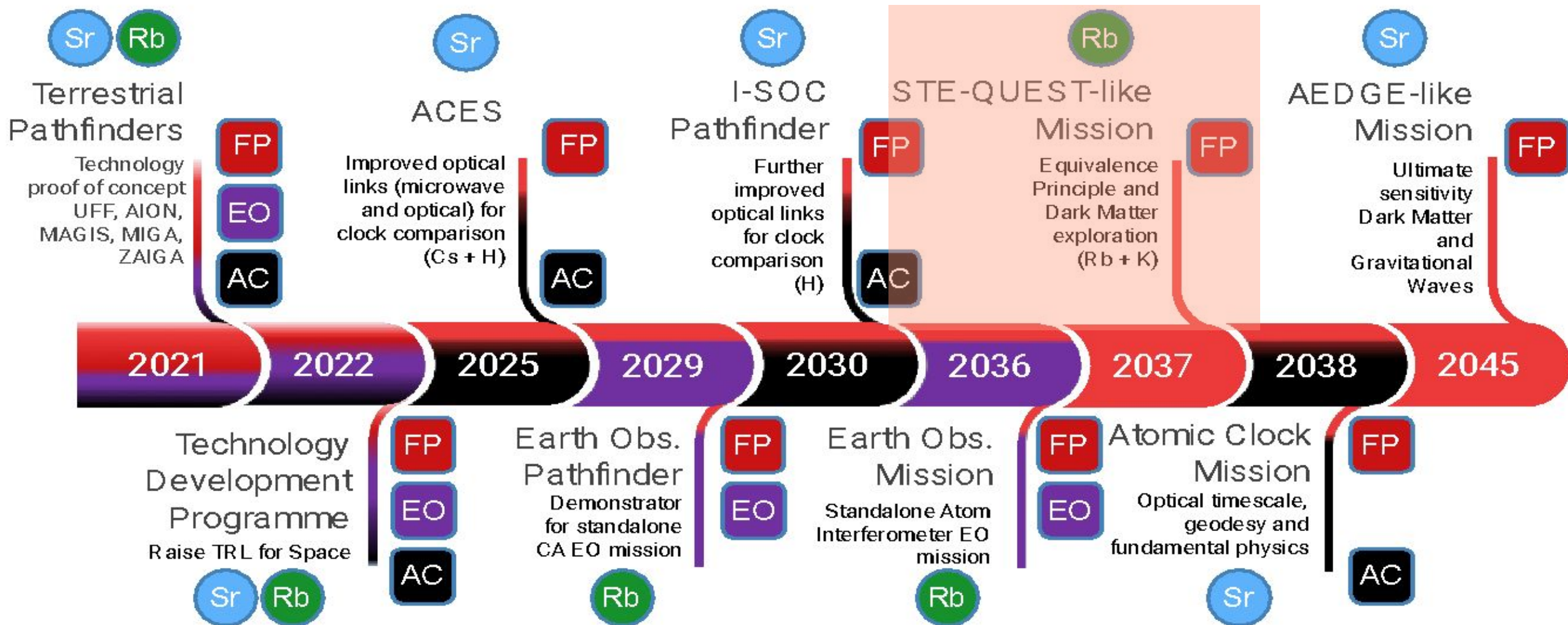
Using two cold-atom interferometers that perform a relative measurement of differential phase shift, a potential mission profile would be using a pair of satellites separated by a very long baseline L .

Assumed basic parameters:

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

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

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



Legends:

Main Cold Atom Species



Areas of Relevance



Main Milestone Area (colour coded)



STE-QUEST (M-Class Mission Proposal)

STE-QUEST

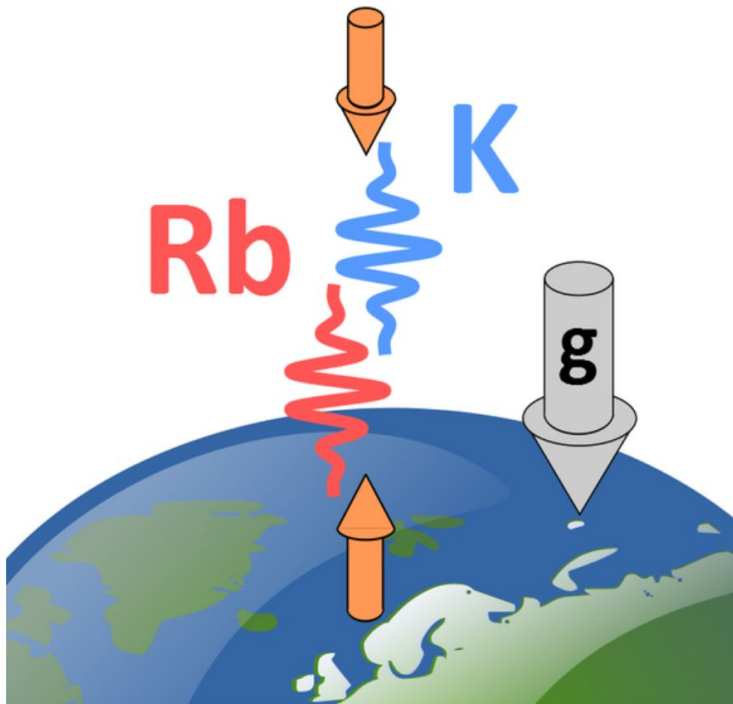
Space Time Explorer and QUantum Equivalence principle Space Test

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

Core Team:

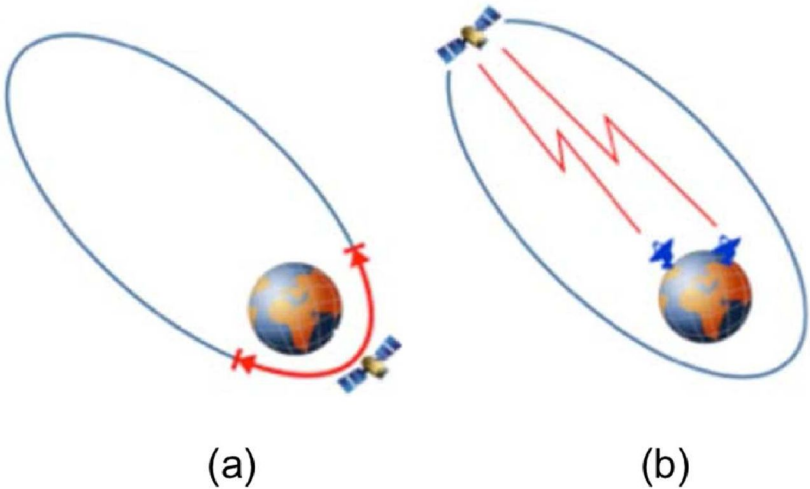
- Angelo Bassi, Department of Physics, University of Trieste, and INFN - Trieste Section, *Italy*
- Kai Bongs, Midlands Ultracold Atom Research Centre, School of Physics and Astronomy University of Birmingham, *United Kingdom*
- Philippe Bouyer, LP2N, Université Bordeaux, IOGS, CNRS, Talence, *France*
- 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 (Marilyn) 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 Schuoldt, 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
International Team**

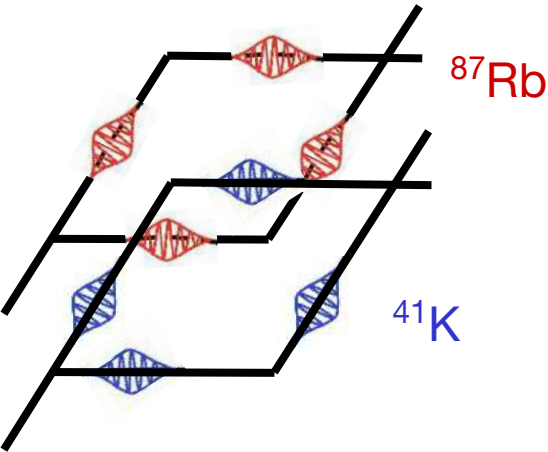


STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics

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



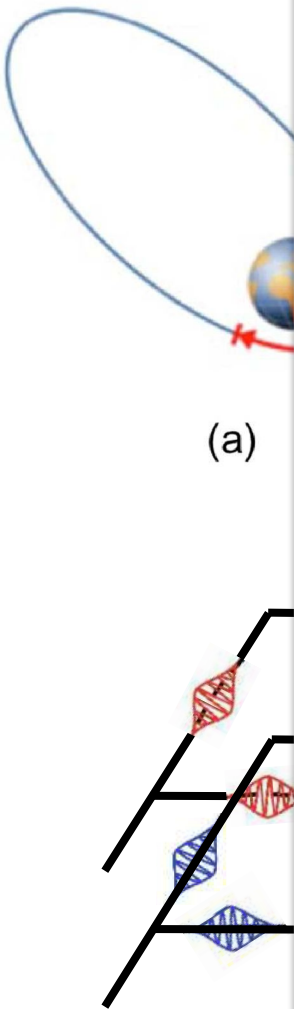
- Based on STE-QUEST proposals (M3, M4).
- Double atom interferometer with Rb and K “test masses” in non-classical states (quantum superpositions).
- Optimized for UFF test. Assume 700 km circular orbit.
- Apply recent results on controlling gravity gradient shifts by offsetting laser frequencies, thus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



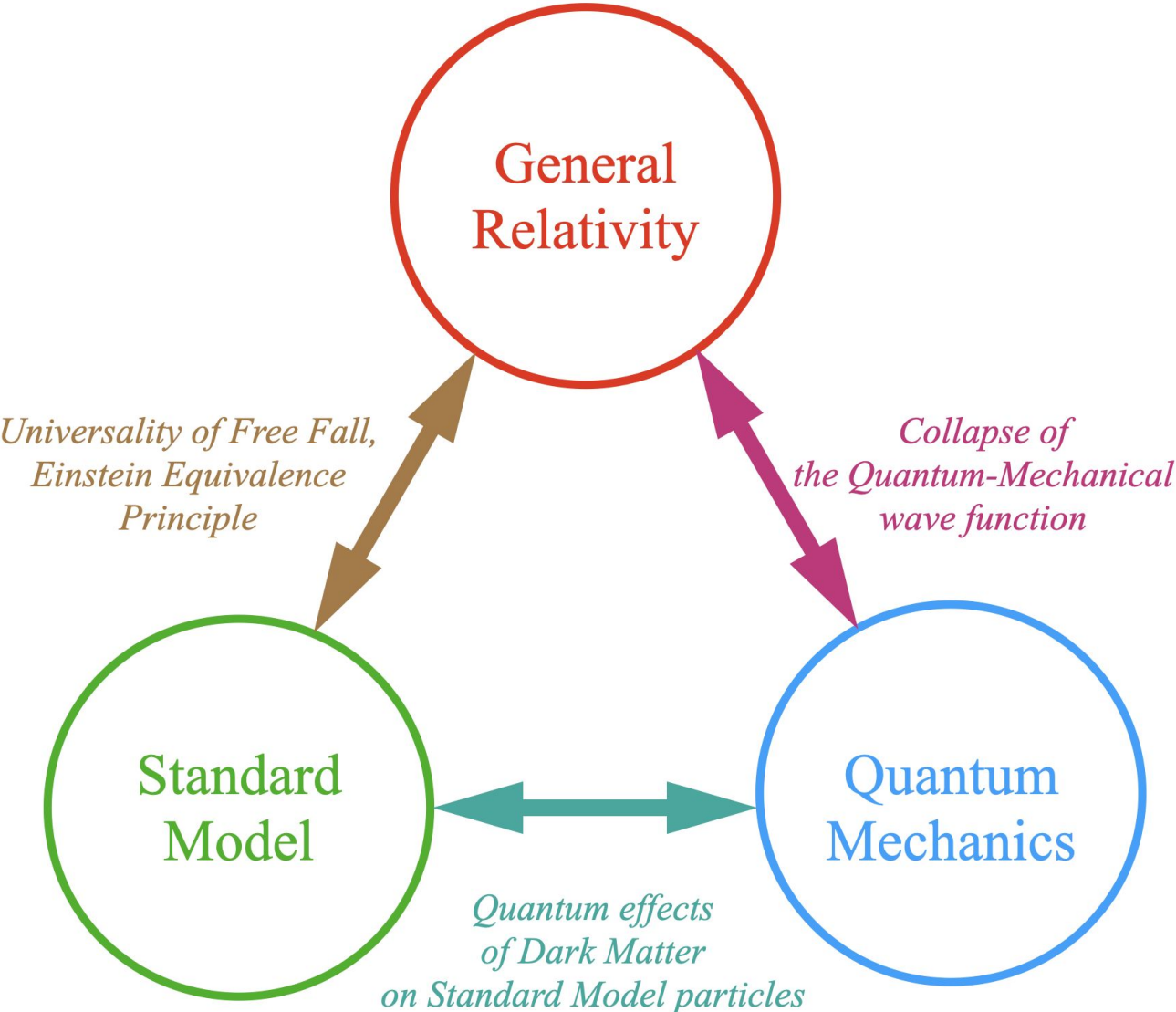
Class	Elements	η	Year [ref]	Comments
Classical	Be - Ti	2×10^{-13}	2008	Torsion balance
	Pt - Ti	1×10^{-14}	2017	MICROSCOPE first results
	Pt - Ti	(10^{-15})	2022+	MICROSCOPE full data
Hybrid	^{133}Cs - CC	7×10^{-9}	2001	Atom Interferometry
	^{87}Rb - CC	7×10^{-9}	2010	and macroscopic corner cube (CC)
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	$\bar{\text{H}}$ - 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:



(a)



Quantum Mechanics

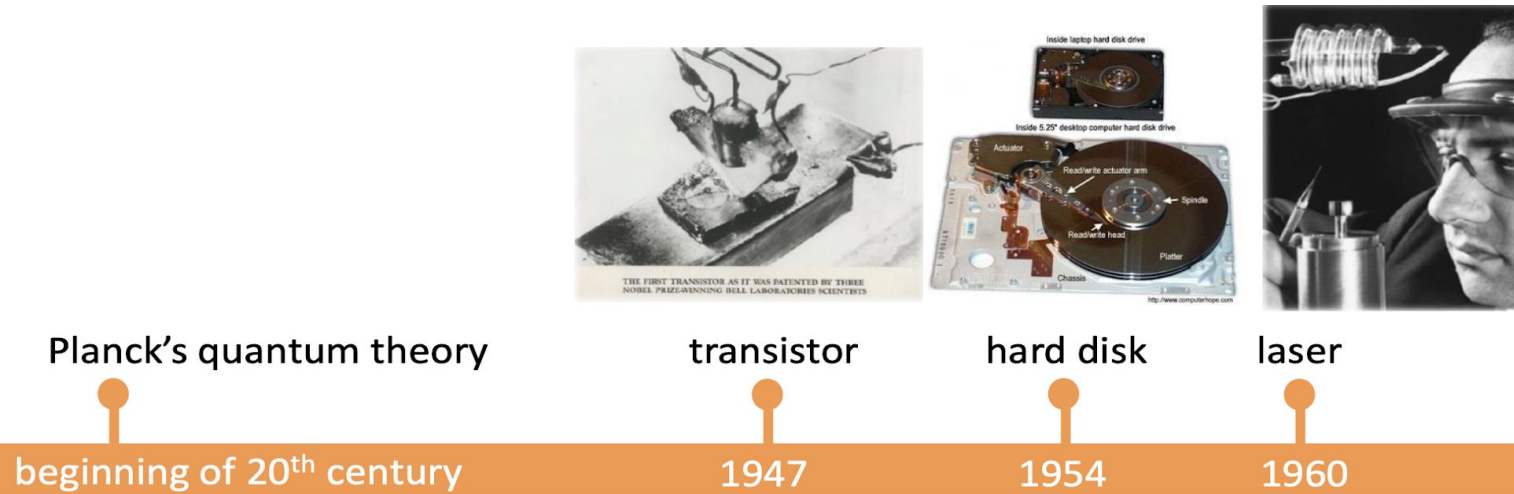
M4).
nd K “test masses” in
ositions).
m circular orbit.
vity gradient shifts by
ing atom positioning

hs of operation.

Comments
Torsion balance
MICROSCOPE first results
MICROSCOPE full data
Atom Interferometry
l macroscopic corner cube (CC)
different elements
me element, fermion vs. boson
ame 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



Albert Einstein (1879-1955)



Werner Heisenberg (1901-1976)

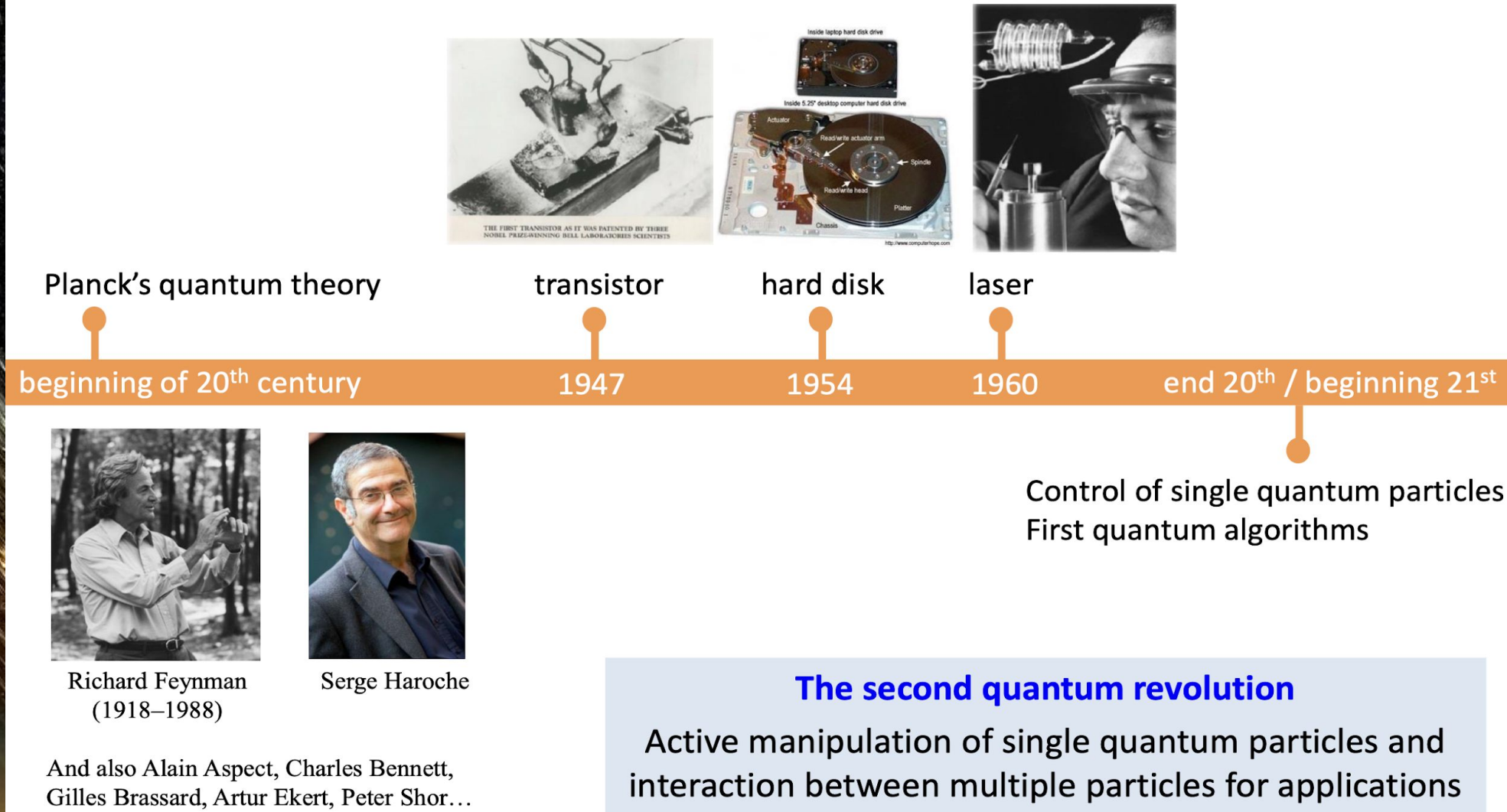


Erwin Schrödinger (1887-1961)

The first quantum revolution
Observation and macroscopic
manifestation of quantum principles

Example of Open Questions in Fundamental Physics

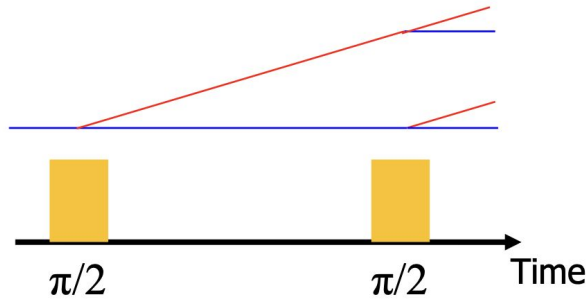
... and how the Quantum Revolutions could help addressing them



MORE ON ATOM INTERFEROMETRY CONCEPT

Possible Phase Shifts

Ramsey
sequence
(clock)

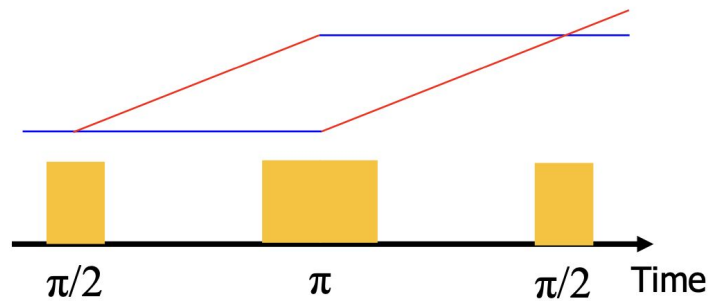


$$\Delta\phi = \phi_1 - \phi_2 = (\omega - \omega_A)T + kx_1 - kx_2$$

$$= (\omega - \omega_A)T + \underline{k v T}$$

- Measures velocity

Mach-
Zehnder

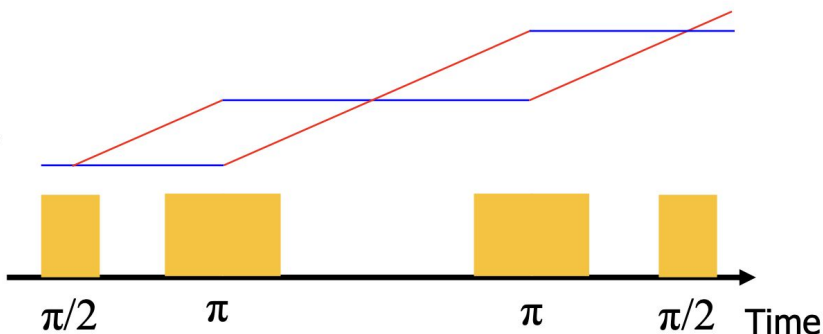


$$\Delta\phi = (\phi_1 - \phi_2) - (\phi_2 - \phi_3)$$

$$= k v_1 T - k v_2 T = \underline{k a T^2}$$

- "Difference" of two Ramsey sequences
- Measures acceleration

"Double
diamond"



$$\Delta\phi = k a_1 T^2 - k a_2 T^2 = k \delta a T^3$$

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

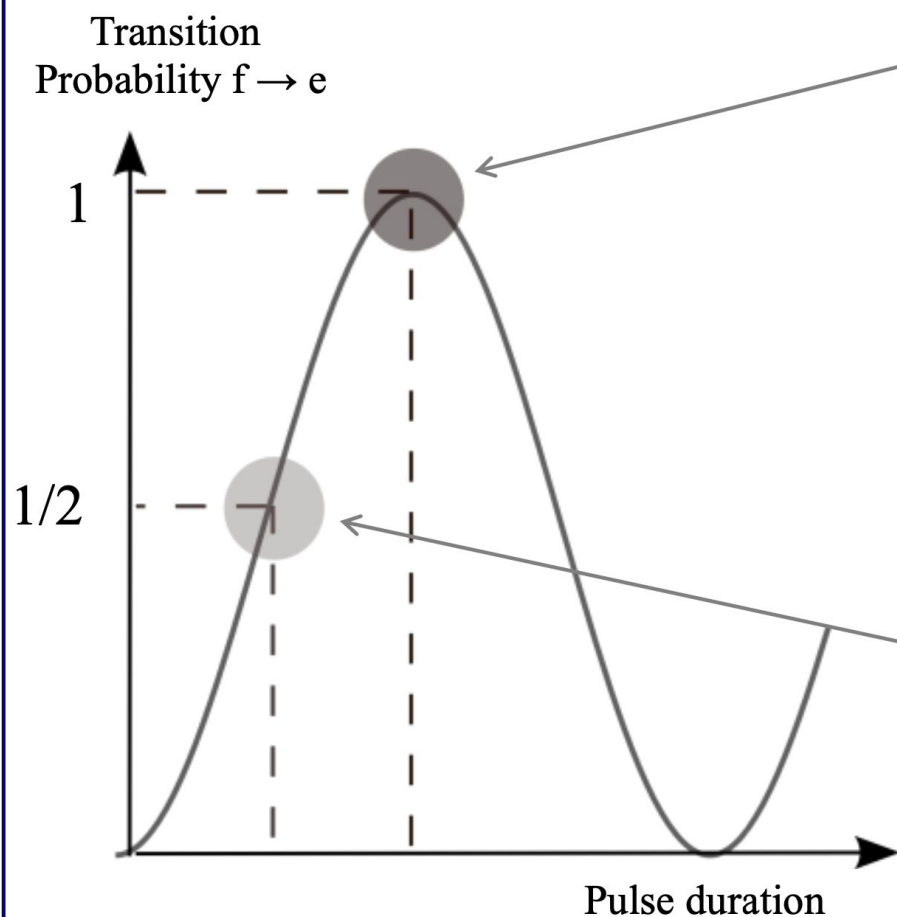
General Relativistic Effects in Atom Interferometry

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

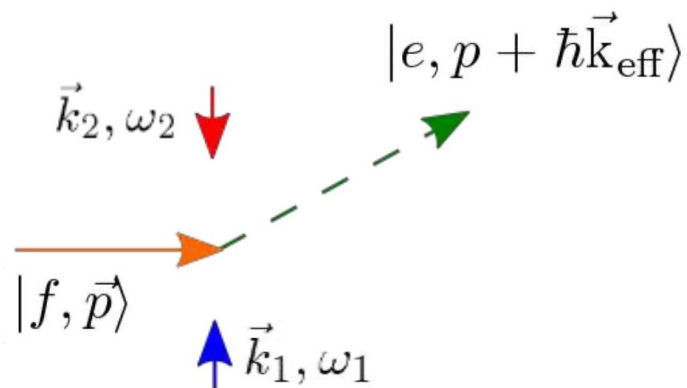
Dimopoulos et al,
Phys.Rev.D78:042003,2008

Pi and Pi/2 Pluses – Rabi Oscillation

Rabi oscillation between $|f\rangle$ and $|e\rangle$

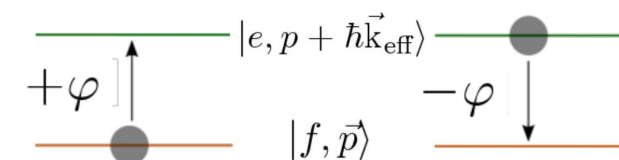


“ π ” pulse = mirror

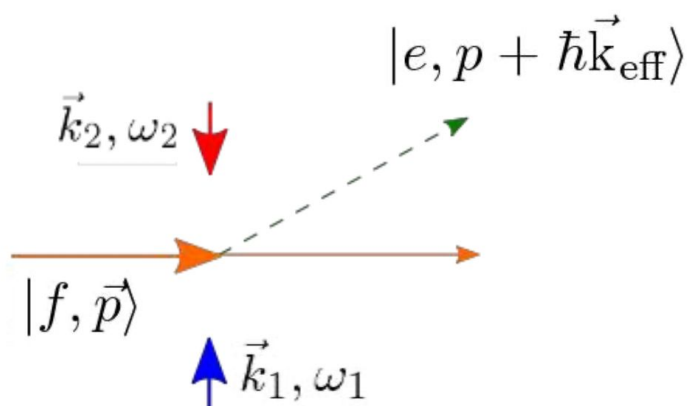


Imprint laser phase on atomic wave-function:

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

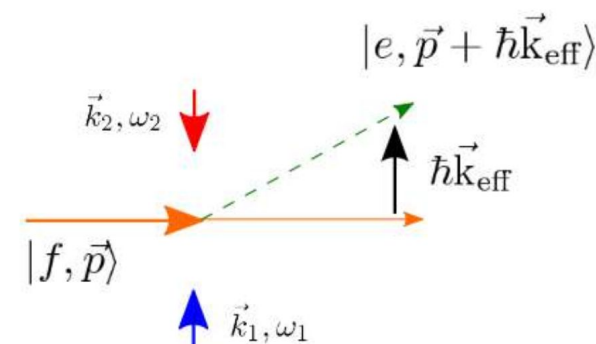


“ $\pi/2$ ” pulse = beam splitter



Momentum transfer (~ 1 cm/s)

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



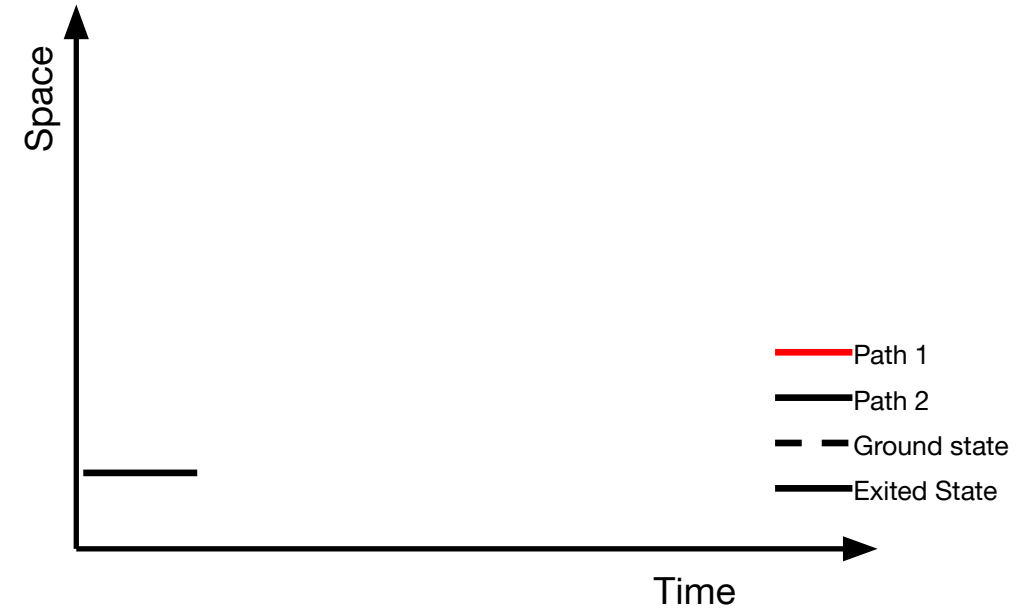
Mach-Zehnder Atom Interferometer – Phase shift

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.

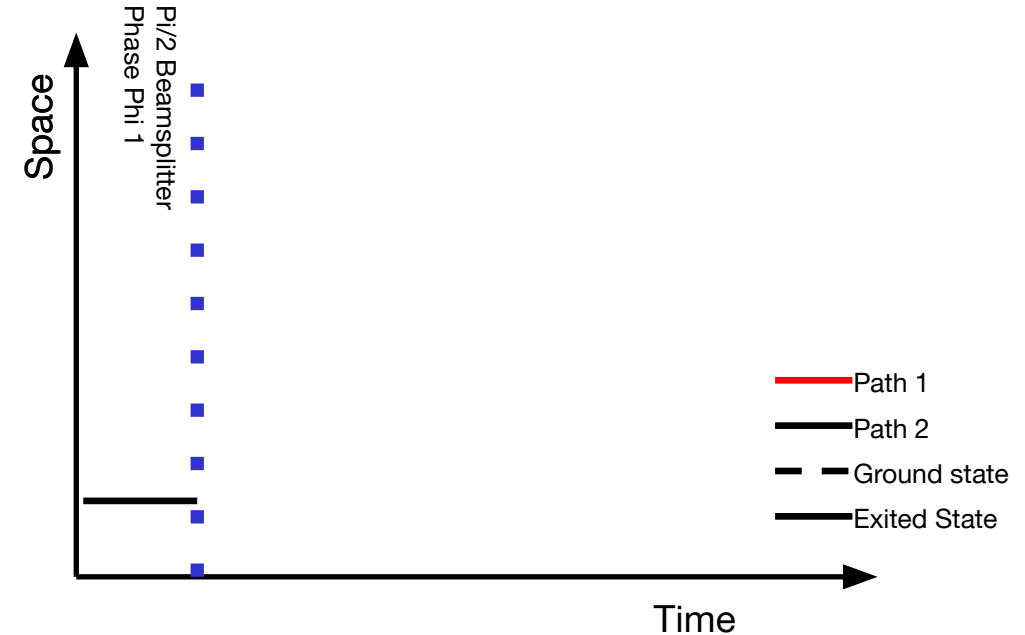
Atoms at rest:

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:

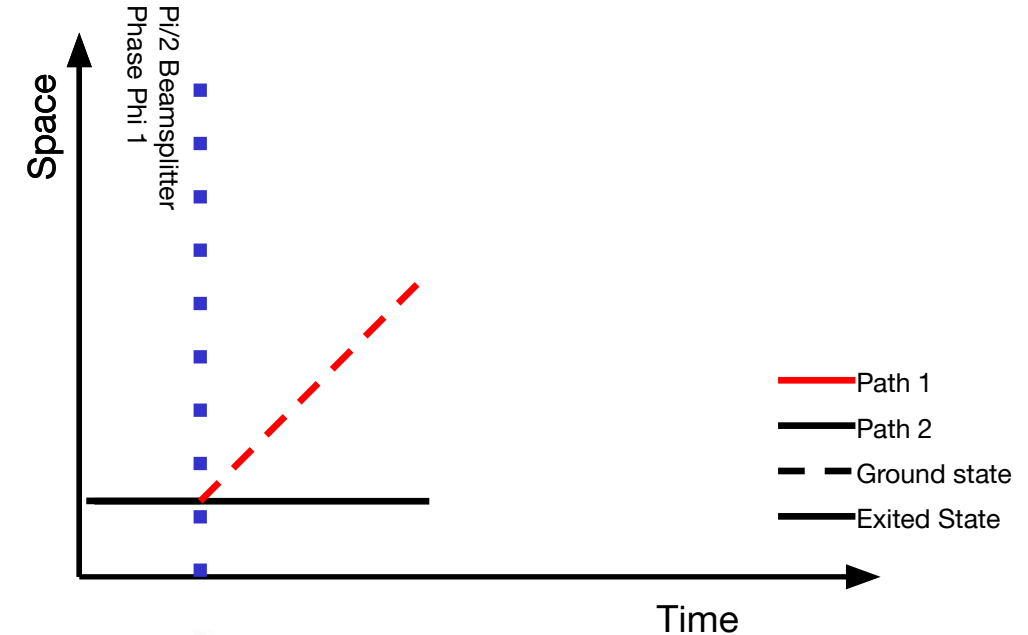
$$\Phi_1 = 0, \quad \Phi_2 = 0$$

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:

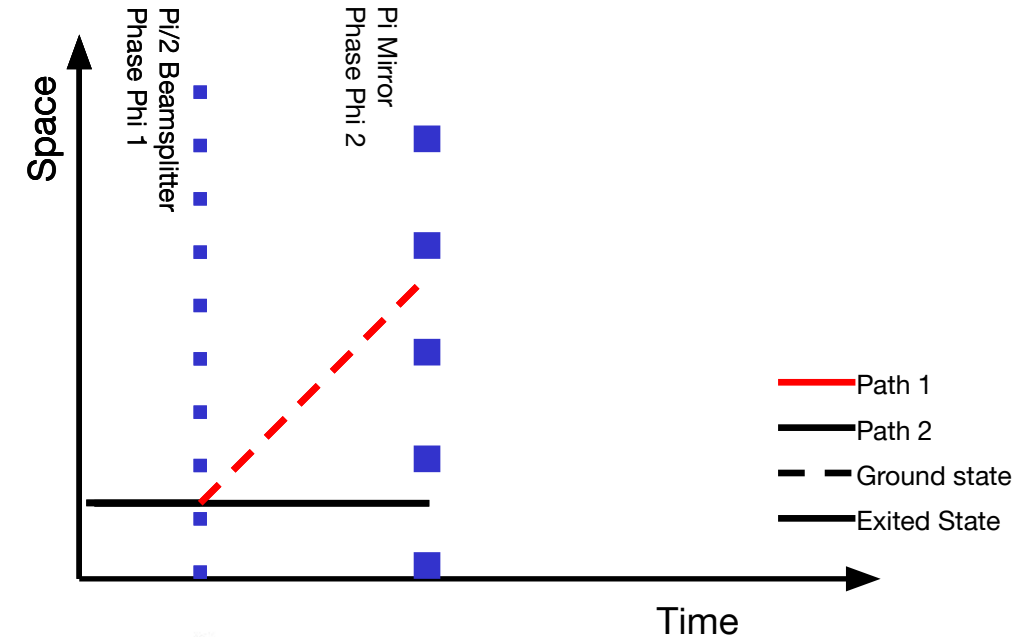
$$\Phi_1 = \phi_1, \quad \Phi_2 = 0$$

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:

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

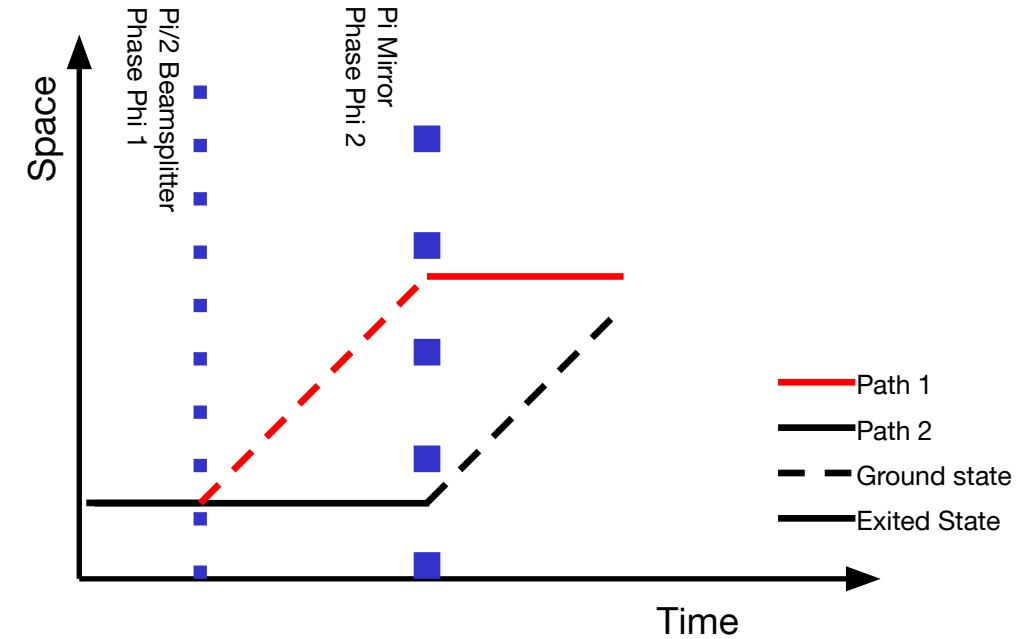


Mach-Zehnder Atom Interferometer – Phase shift

Assuming no other interactions like gravity, etc.

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

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

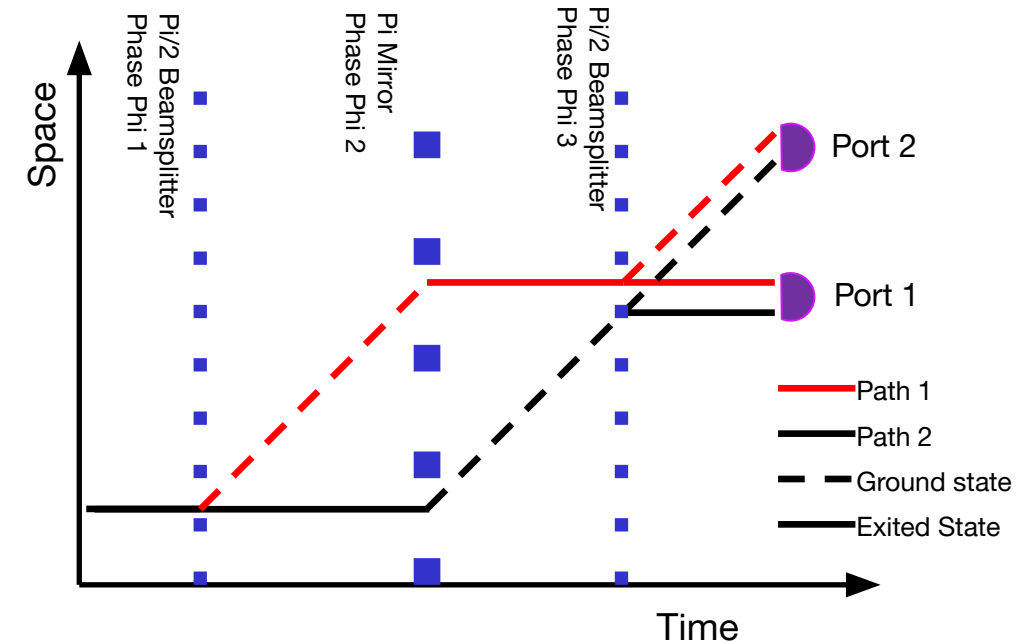


Mach-Zehnder Atom Interferometer – Phase shift

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:

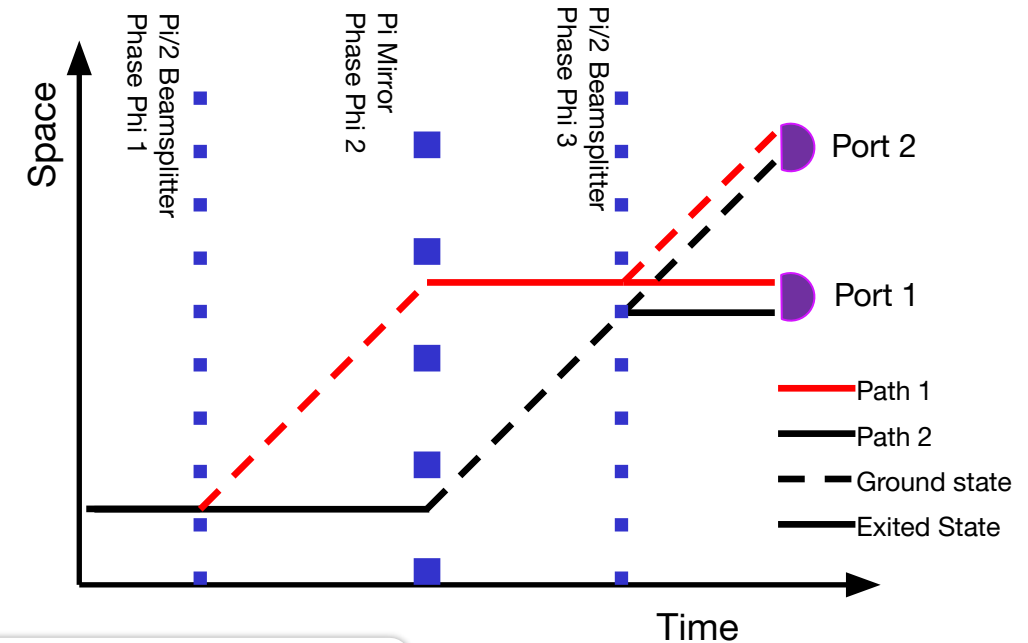
$$\Phi_1 = \phi_1 - ET/\hbar - \phi_2, \quad \Phi_2 = \phi_2 - ET/\hbar - \phi_3$$

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:

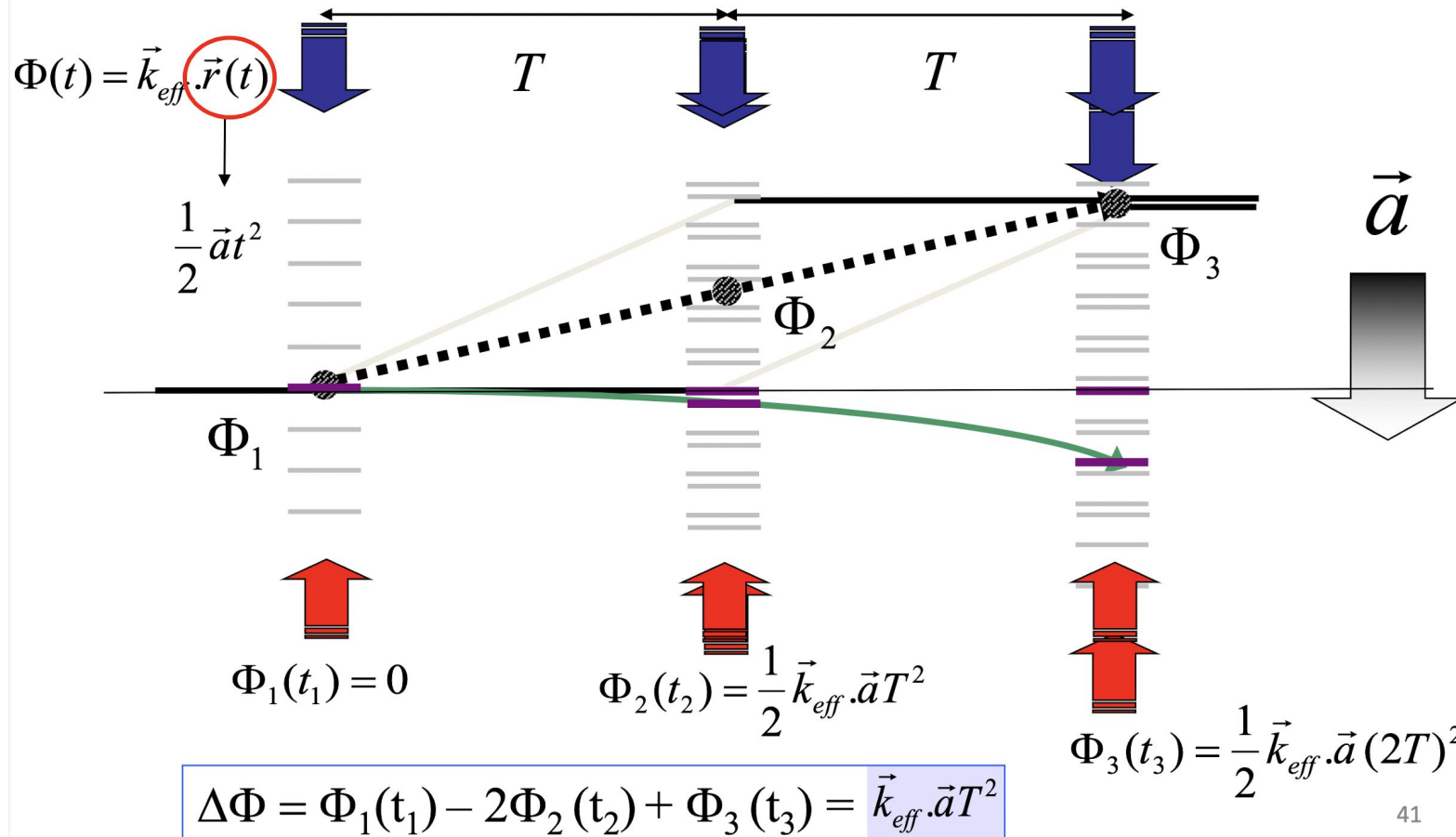
$$\Phi_1 - \Phi_2 = (\phi_1 - ET/\hbar - \phi_2) - (\phi_2 - ET/\hbar - \phi_3) = \phi_1 - 2\phi_2 + \phi_3$$

or

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

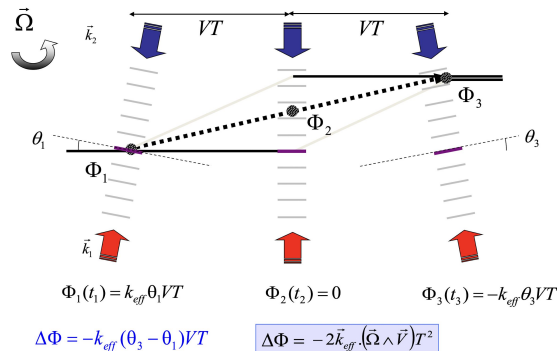
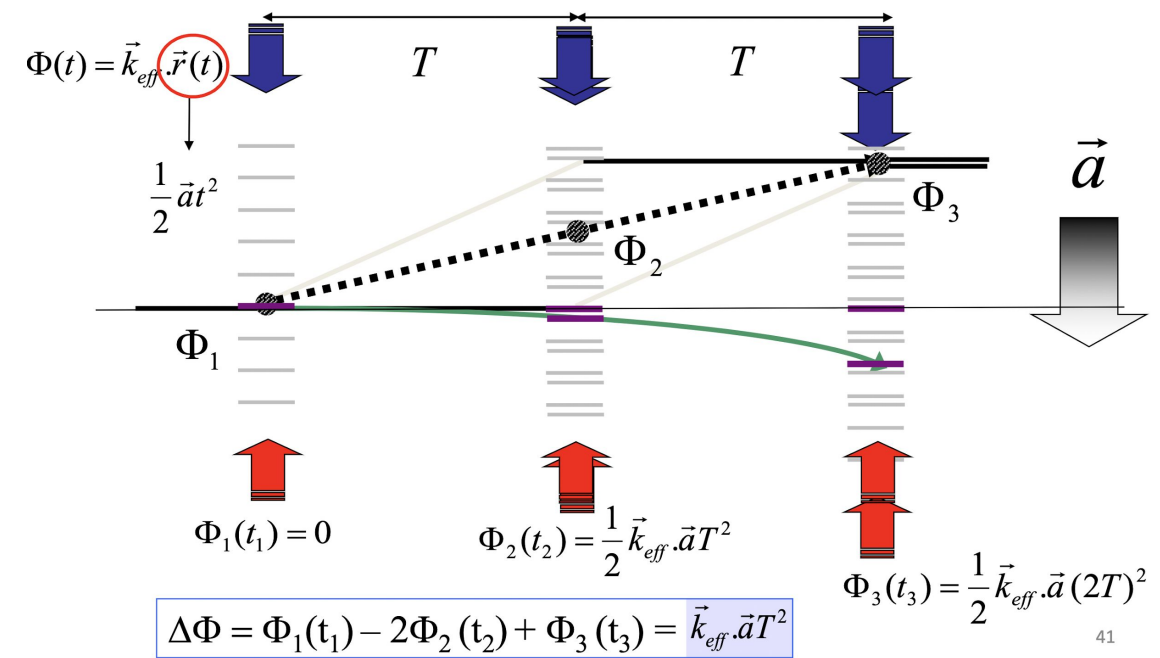
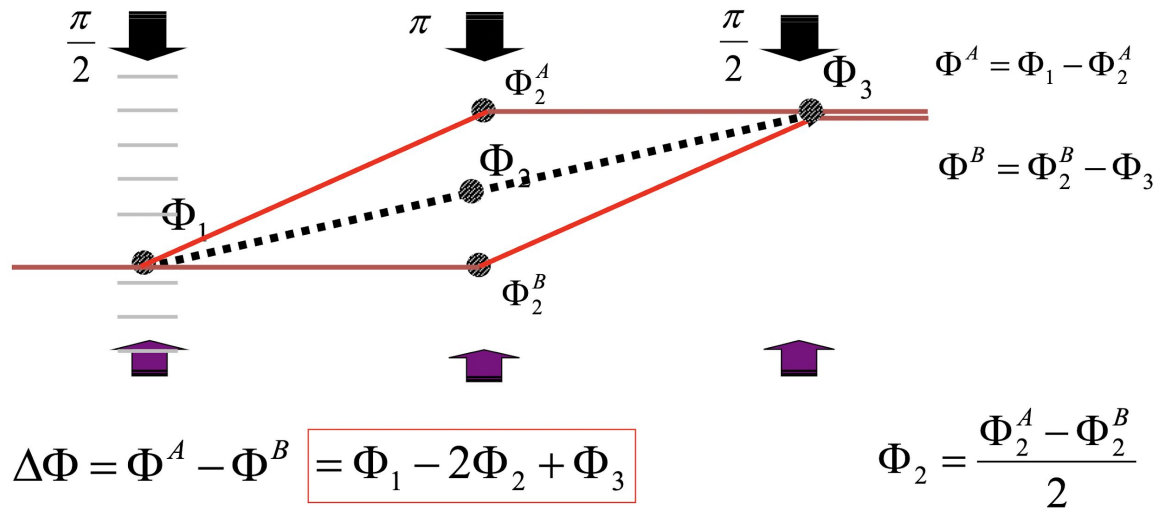
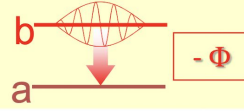
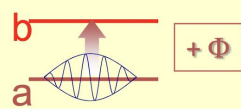
MZ Acceleration Phase Shift

Acceleration phase shift



Different Phase Shifts for Different Interactions

Laser phase gets imprinted



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

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

STE-QUEST

STE-QUEST (M-Class Mission Proposal)

STE-QUEST

Space Time Explorer and QUantum Equivalence principle Space Test

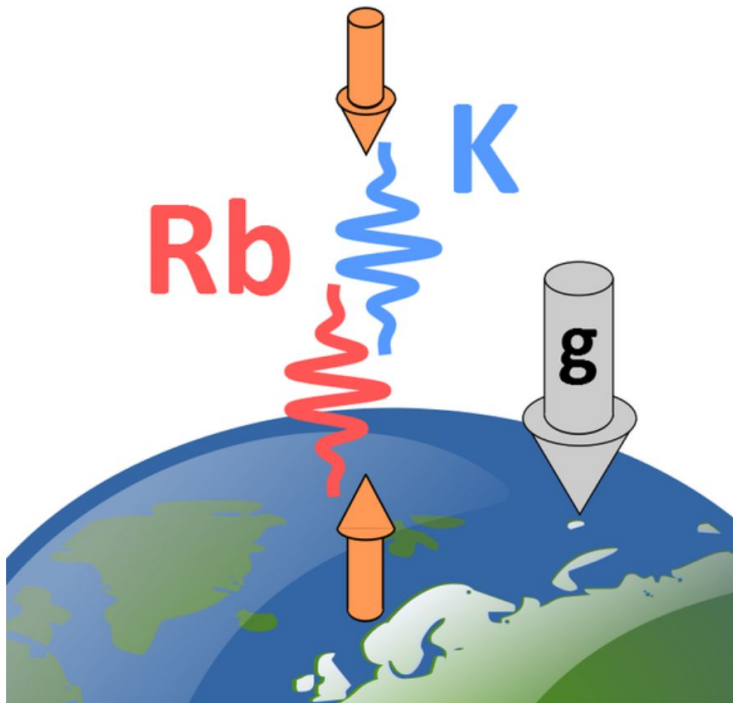
A M-class mission proposal in response to the 2022 call in ESA's science program

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 Schuoldt, 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*

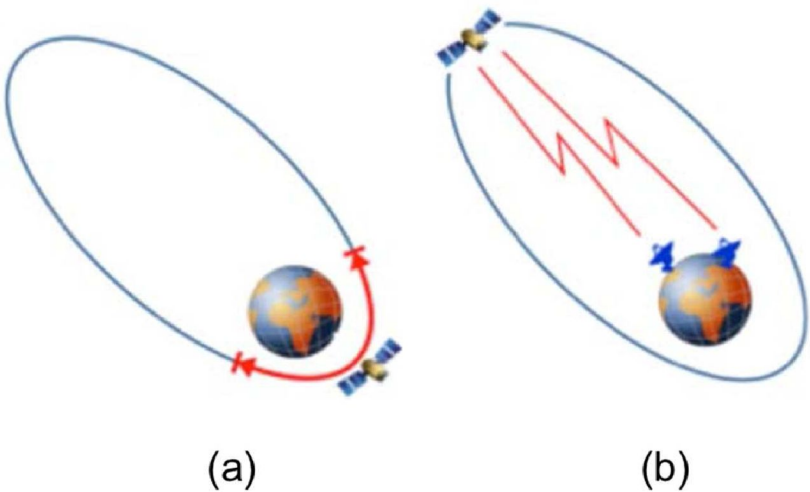
Strong UK representation
in STE-QUEST Core Team.

All are also core
members of AION

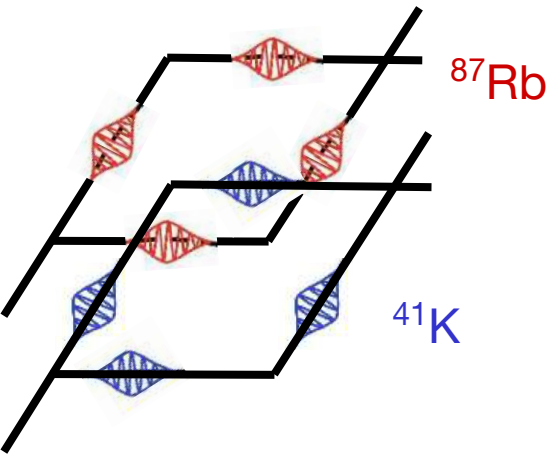


STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics

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



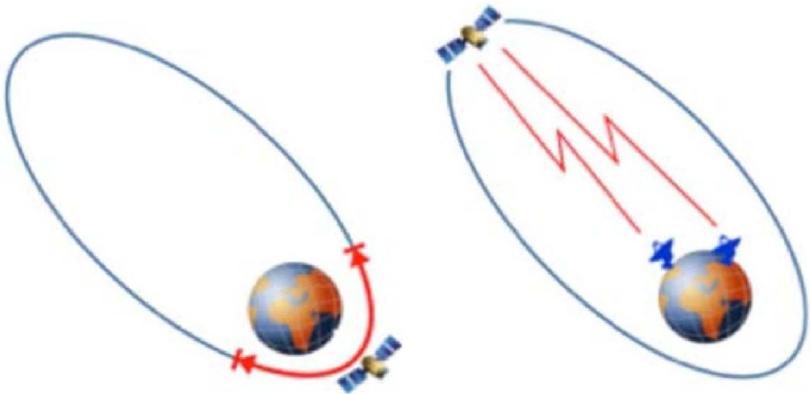
- Based on STE-QUEST proposals (M3, M4).
- Double atom interferometer with Rb and K “test masses” in non-classical states (quantum superpositions).
- Optimized for UFF test. Assume 700 km circular orbit.
- Apply recent results on controlling gravity gradient shifts by offsetting laser frequencies, thus 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	$\bar{\text{H}}$ - H	(10^{-2})	2023+	under construction at CERN

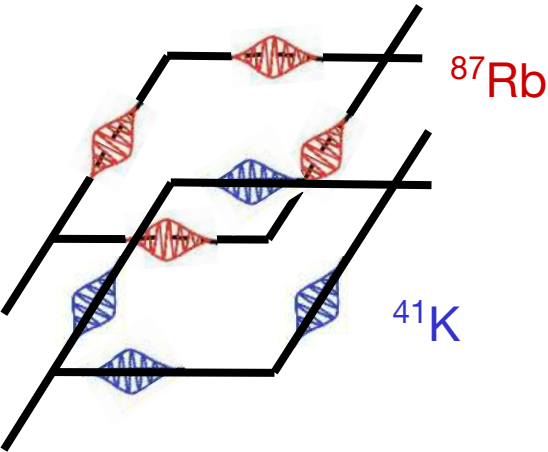
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Science Goals: Equivalent Principal at 1E-17, Ultra-Light Dark Matter, Test of Quantum Mechanics



(a)

(b)

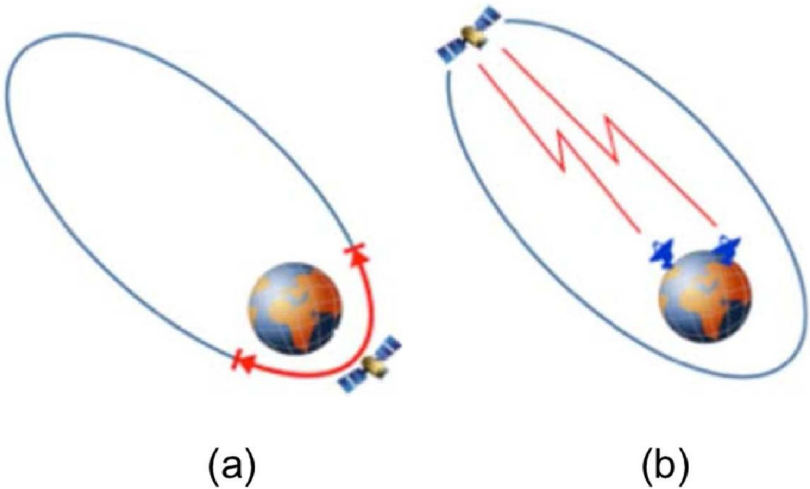


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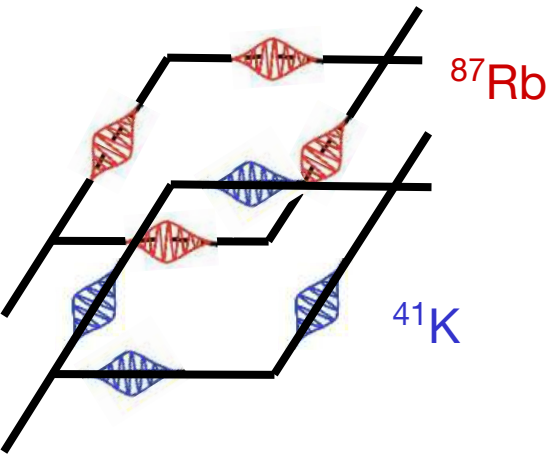
Science Goals: Equivalent Principal at 1E-17, Ultra-Light Dark Matter, Test of Quantum Mechanics



- Based on STE-QUEST proposals (M3, M4).
- Double atom interferometer with Rb and K “test masses” in non-classical states
- Optimized for dark matter detection
- Apply receding orbit to offsetting requirements

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

• **Reaches**



Class	Elements	η	Year [ref]	Comments
Classical	Be - Ti	2×10^{-13}	2008	Torsion balance
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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

Voyage 2050

Final recommendations from
the Voyage 2050 Senior Committee

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?

“Per audacia ad astra”

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

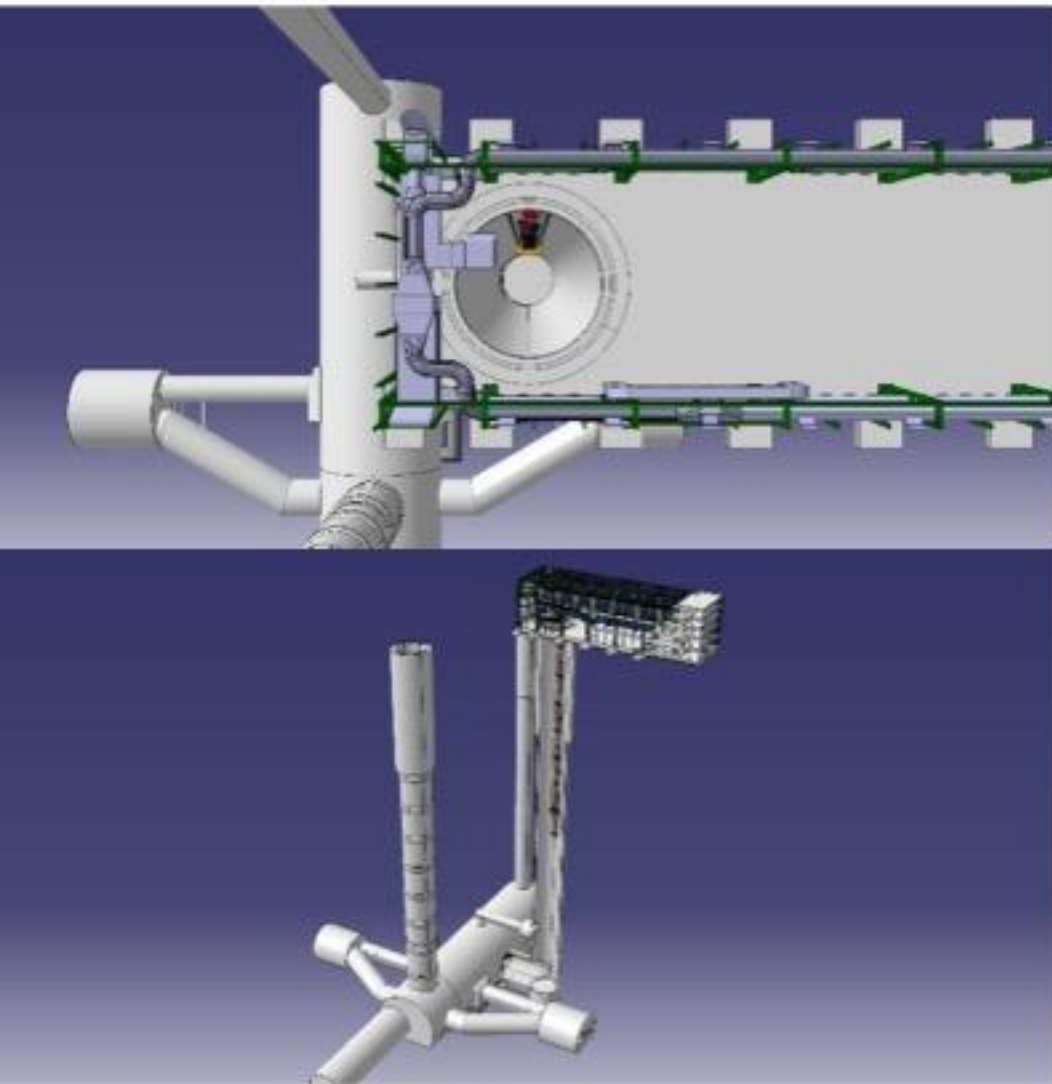
Introduction

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

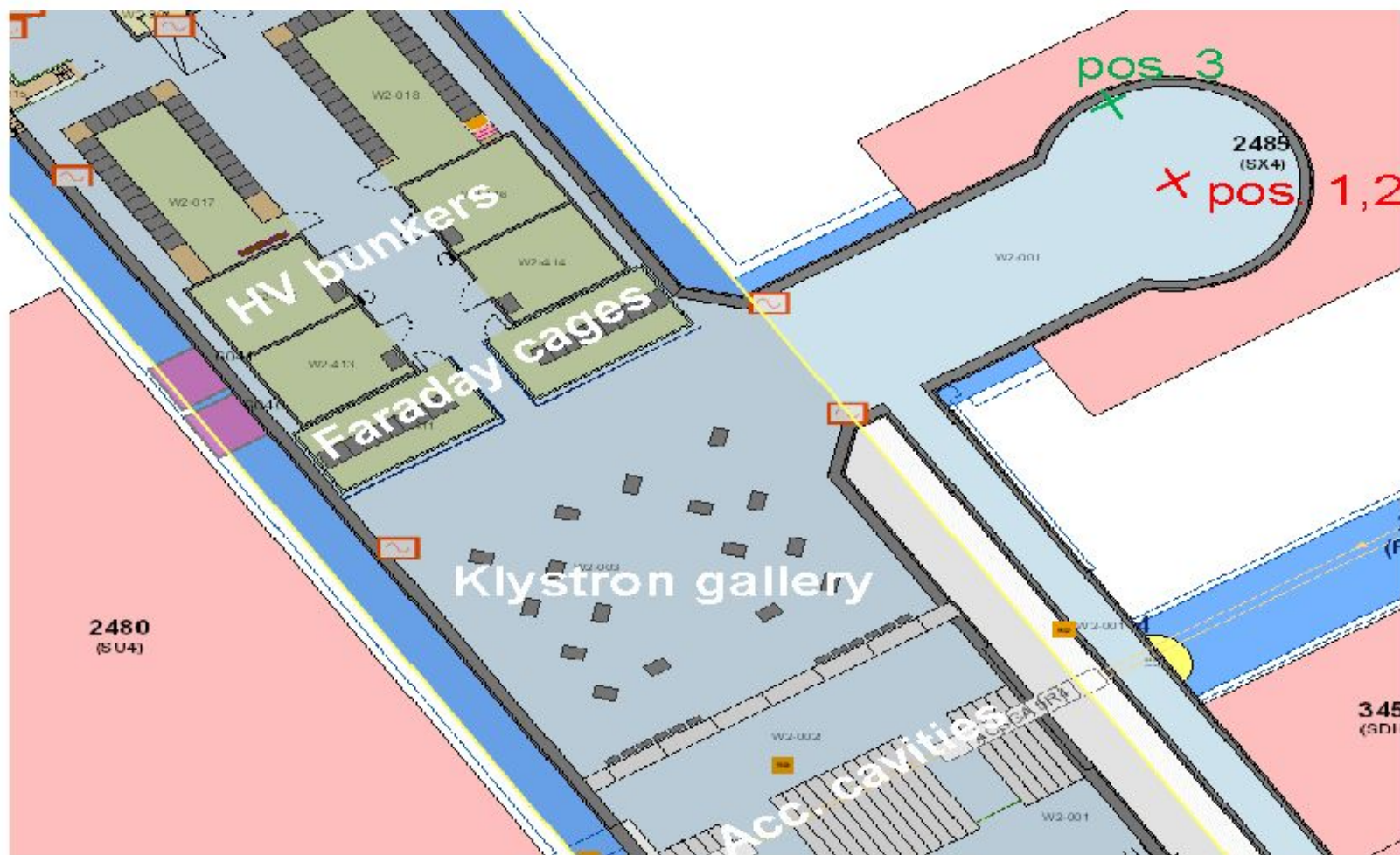


Installation (thanks to EN-ACE, EN-HE, EN-CV)



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

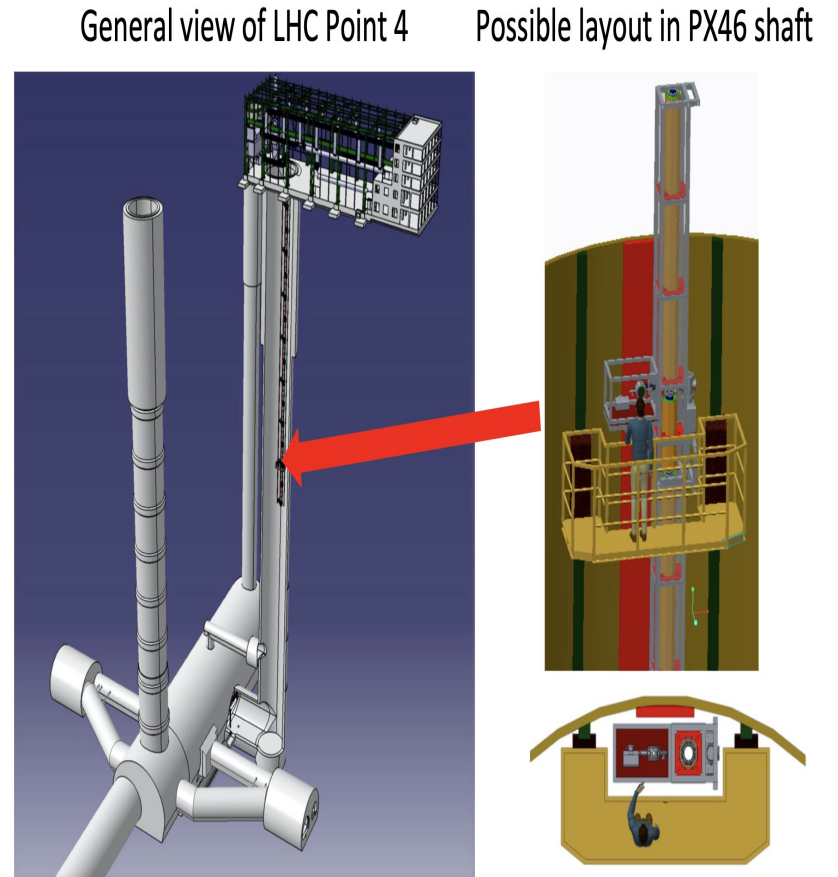
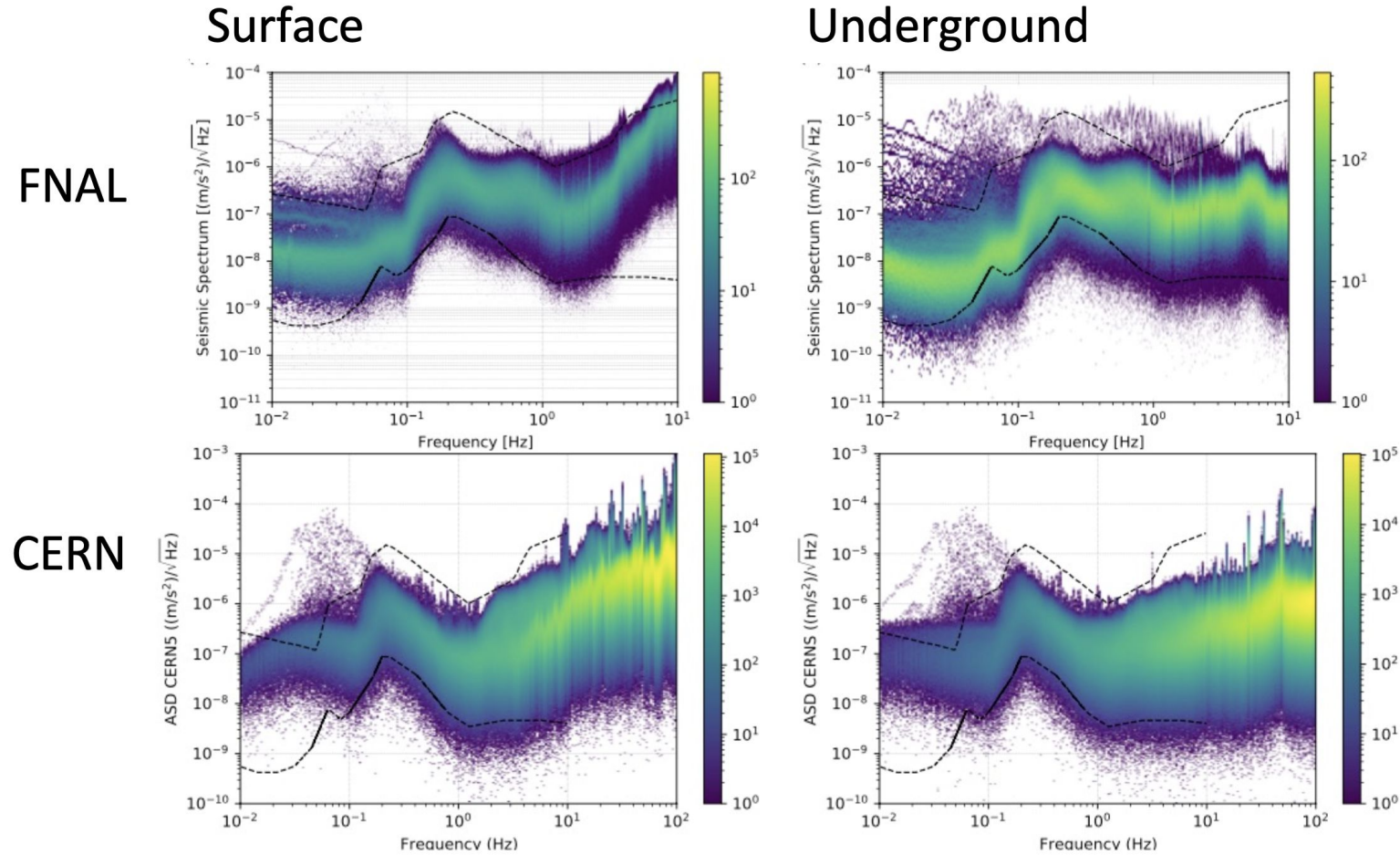
Slides from Marco Buzio, Mariano Pentella, Daniel Valuch



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

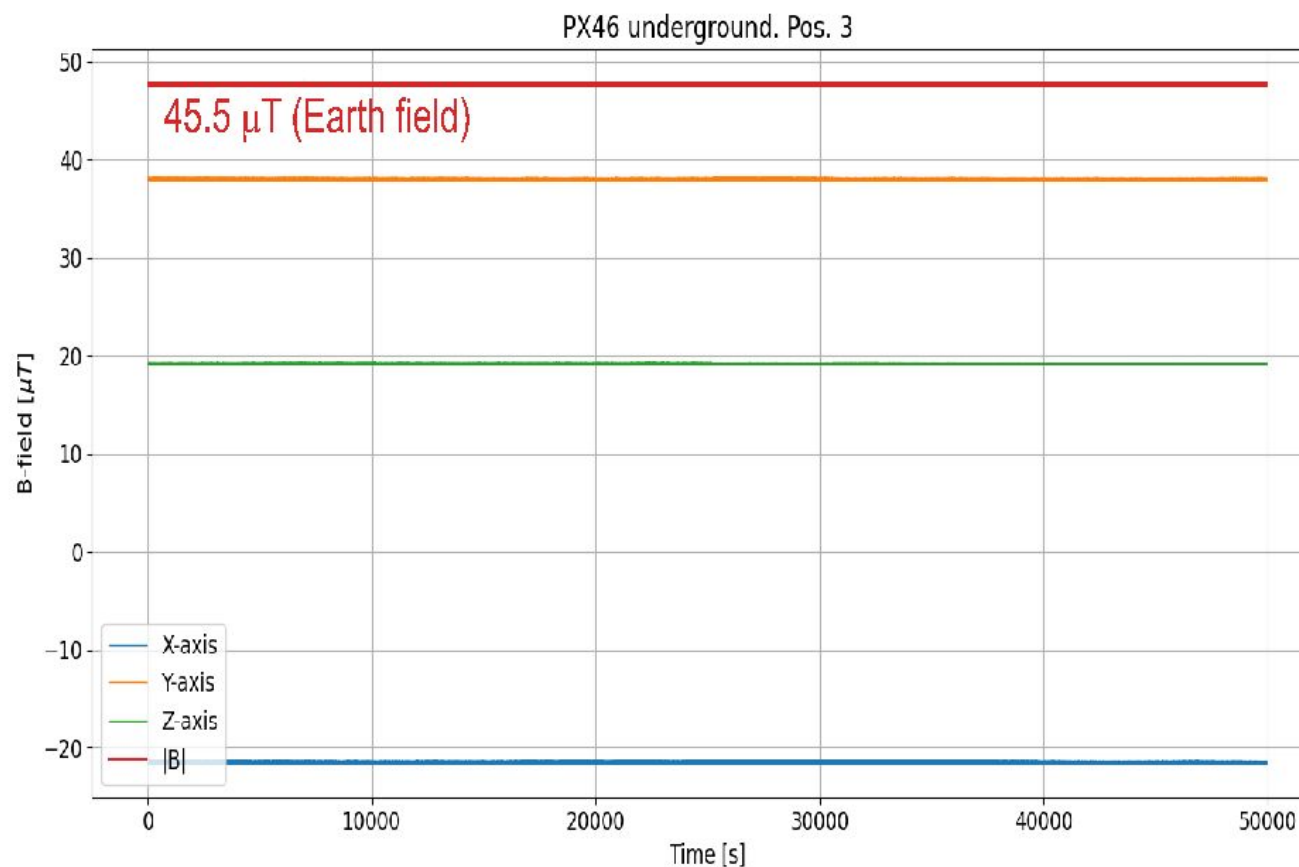


ATION-100 at CERN – Site Investigation



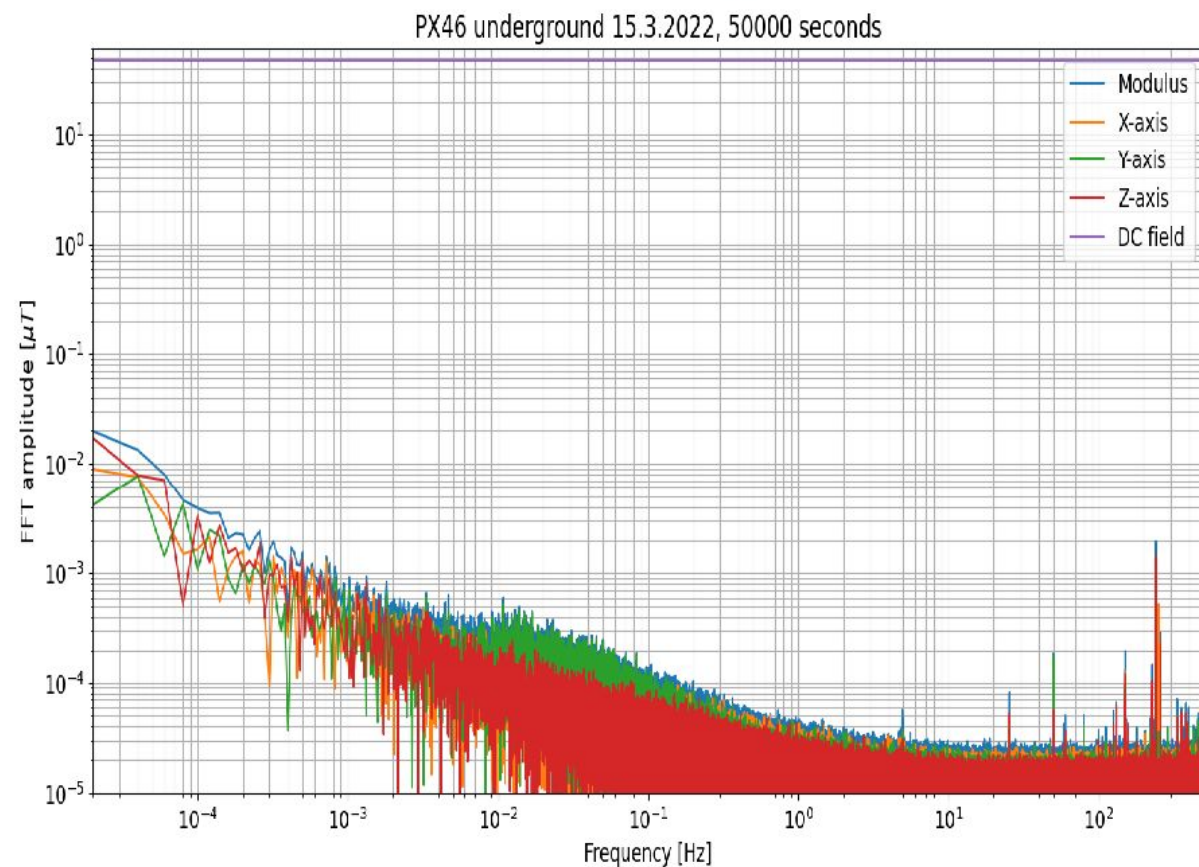
Spectrum similar to that measured at Fermilab for MAGIS

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



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

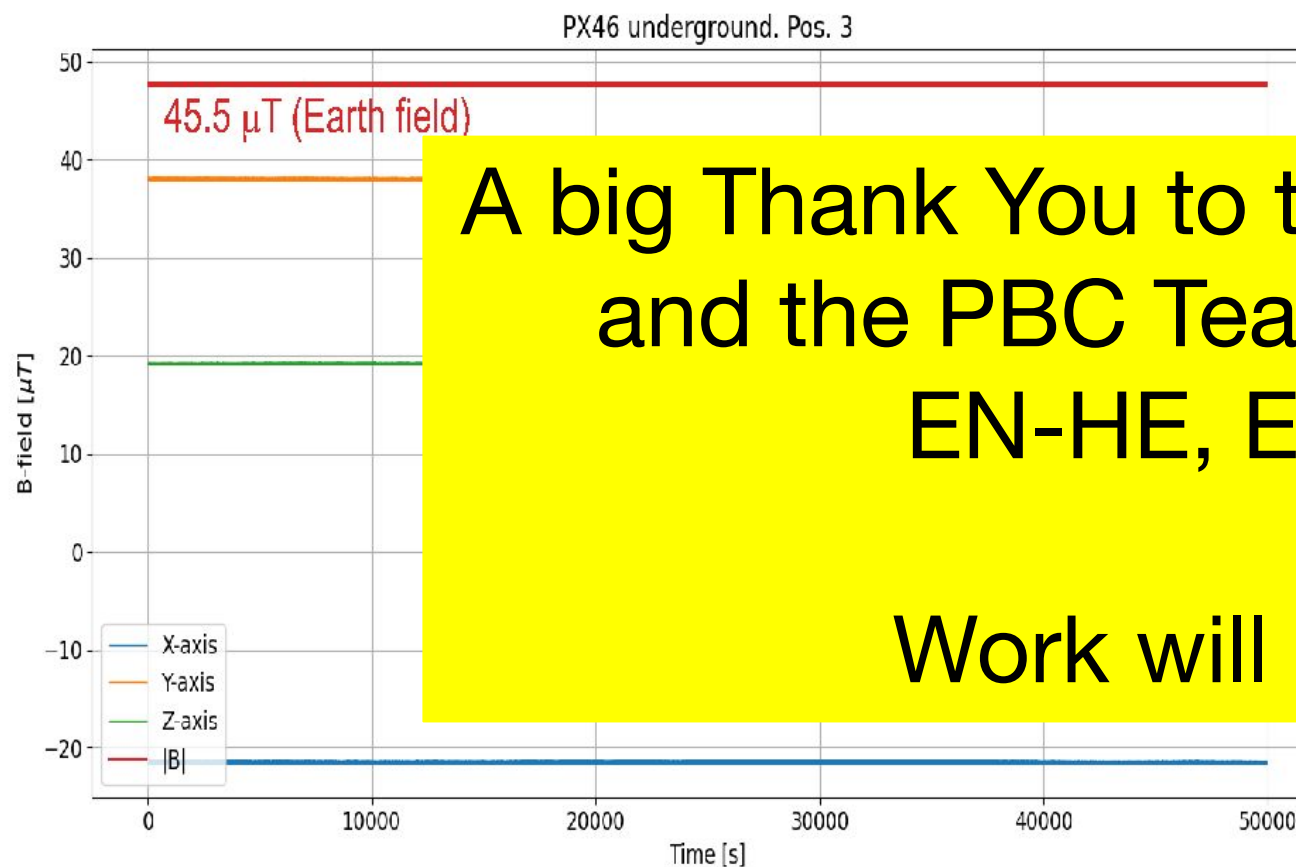
Location: bottom of the PX46 shaft. Systems in UX45 running



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

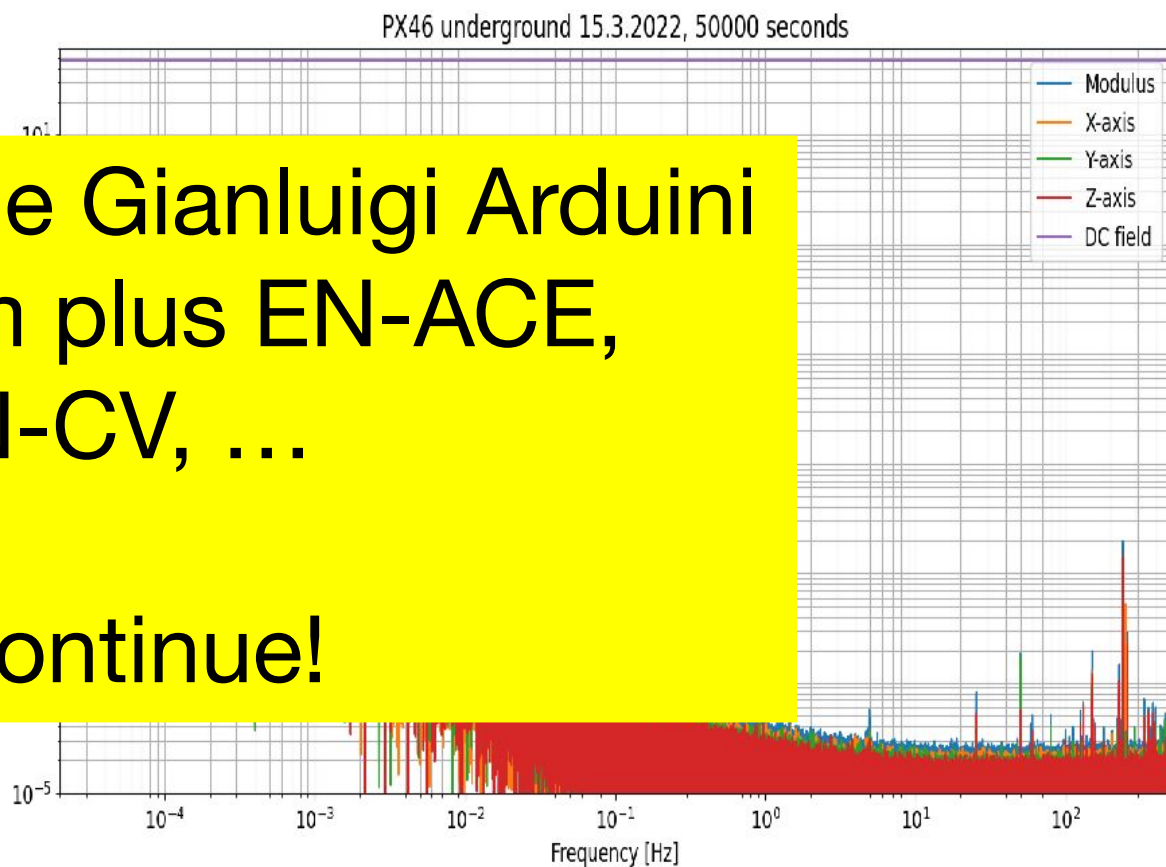
Location: bottom of the PX46 shaft.
Systems in UX45 running

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



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

Work will continue!



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

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

**APPLICATIONS IN OTHER FIELDS, SUCH AS
QUANTUM COMPUTING.**

Quantum Computing & AION

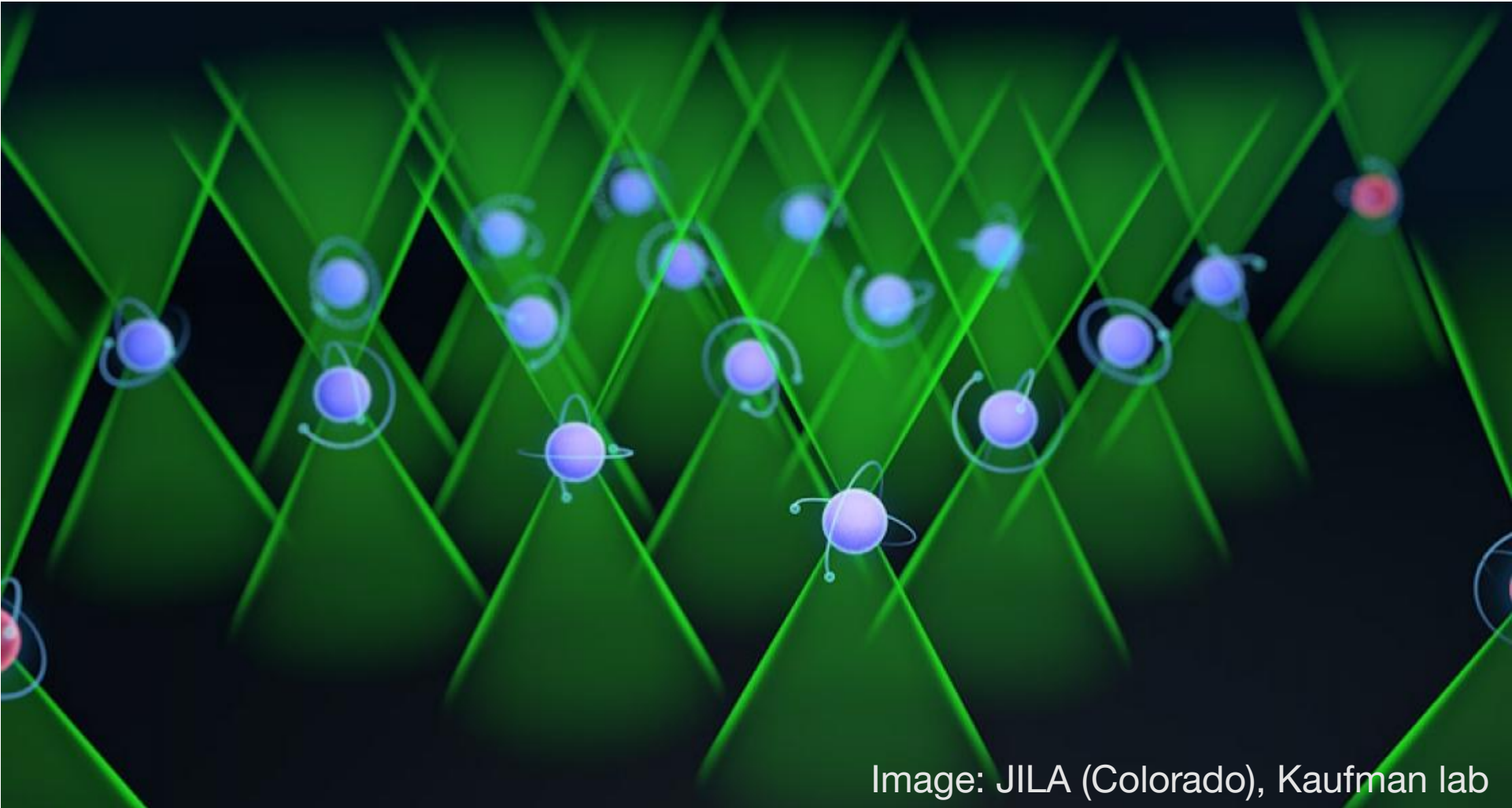
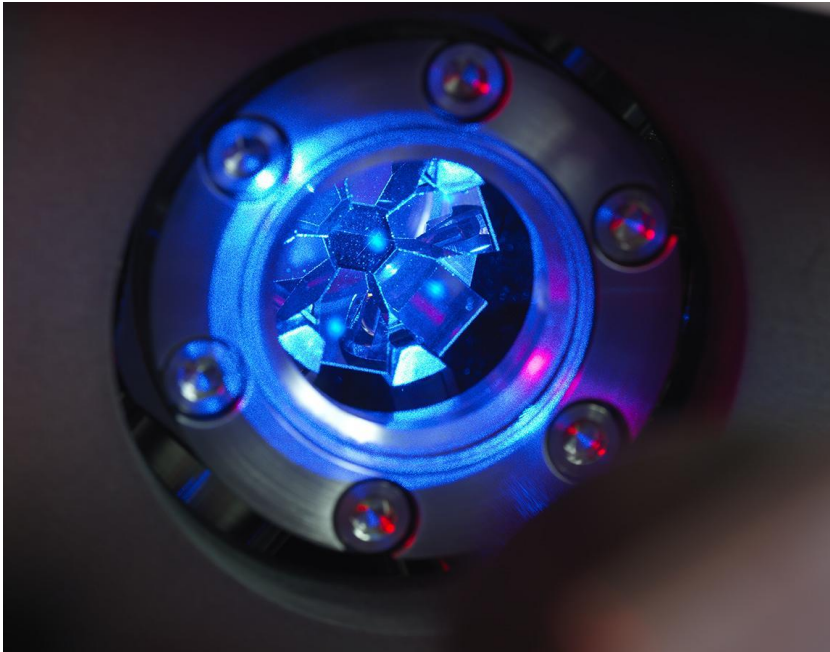


Image: JILA (Colorado), Kaufman lab

Quantum Computing & AION

Existing AION cold Sr system (80%)

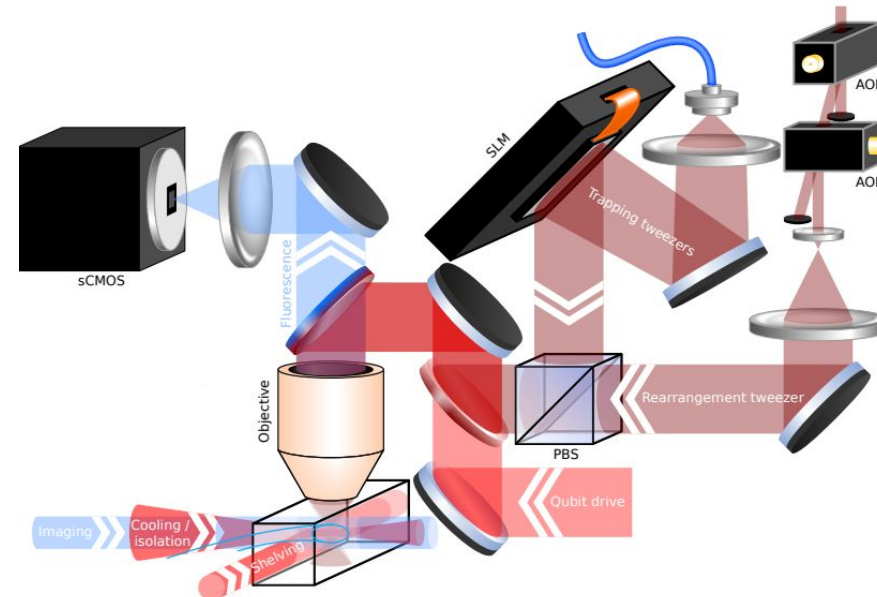


+

New tweezer array (20%)

=

Quantum computer

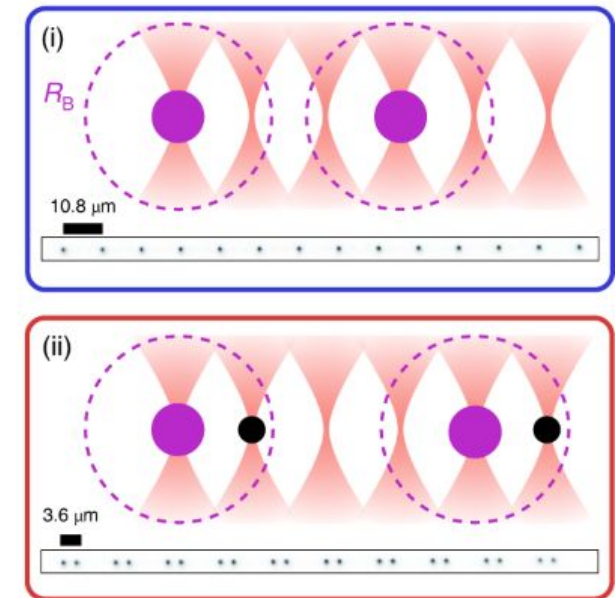
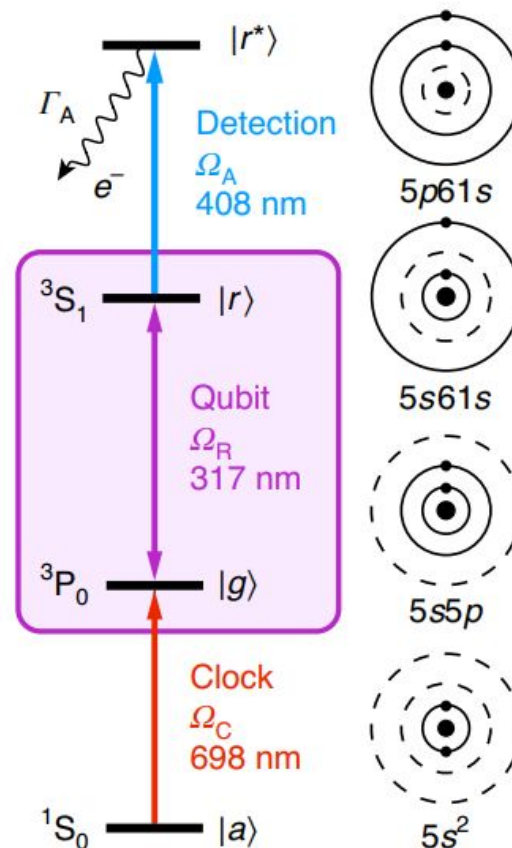
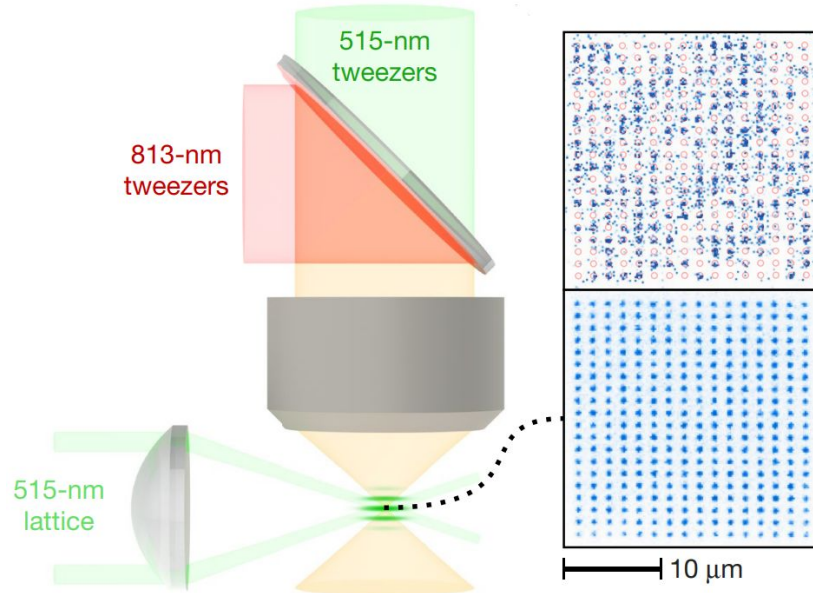


K. Barnes et al, <https://arxiv.org/abs/2108.04790> (2021)
– Atom Computing

Quantum Computing & AION

1 qubit = 1 Sr atom

Quantum logic gates (the hard bit!): Rydbergs

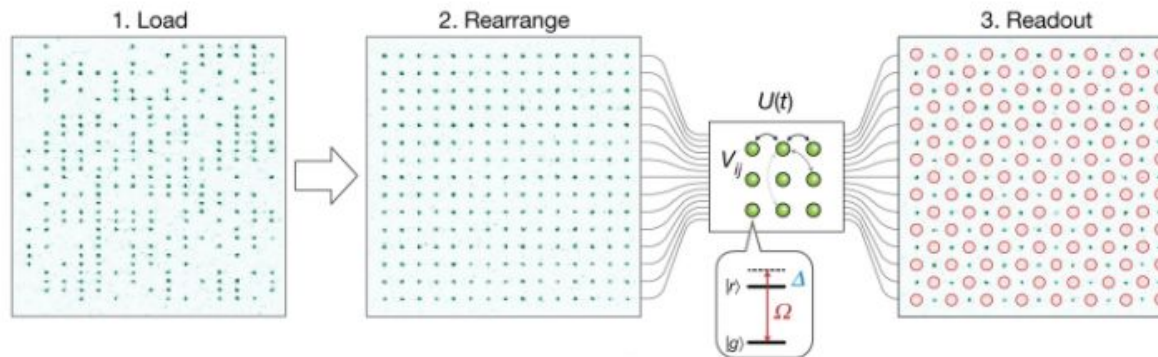


A. W. Young et al, Nature 588, 408-413 (2020)
– JILA Colorado, Kaufman lab

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



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

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>

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:

$$\delta g = \frac{\delta \phi}{n k T^2} \quad [\text{m/s}^2 / \sqrt{\text{Hz}}]$$

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 $T \sim 1\text{s}$ a δg of about 5.7×10^{-13} in 2024. In space, we estimate we could reach $T \sim 20\text{sec}$ and, thus, reach 3.9×10^{-14} (factor ~ 15 better).

Why Atom Interferometry in Space?

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

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

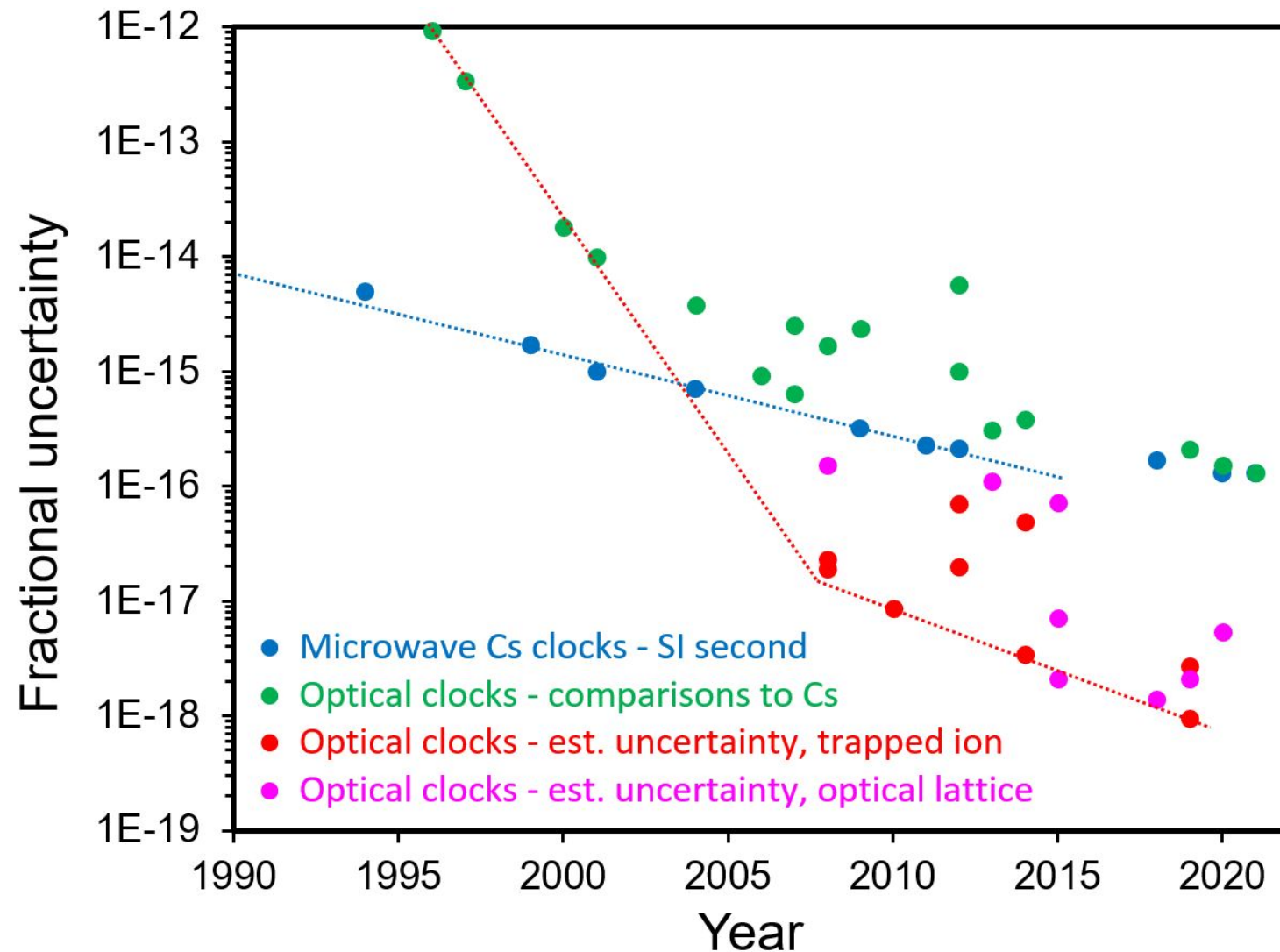
T=100ms N=10 ⁶	T=1s N=10 ⁶	T=10s N=10 ⁶	T=1s N=10 ⁶ 100 pulses	T=1s N=10 ⁸ 1000 pulses
6 10 ⁻⁹ m/s ²	6 10 ⁻¹¹ m/s ²	6 10 ⁻¹³ m/s ²	6 10 ⁻¹³ m/s ²	3 10 ⁻¹⁴ m/s ²

Large T $\square$ large sensitivity

ROADMAP

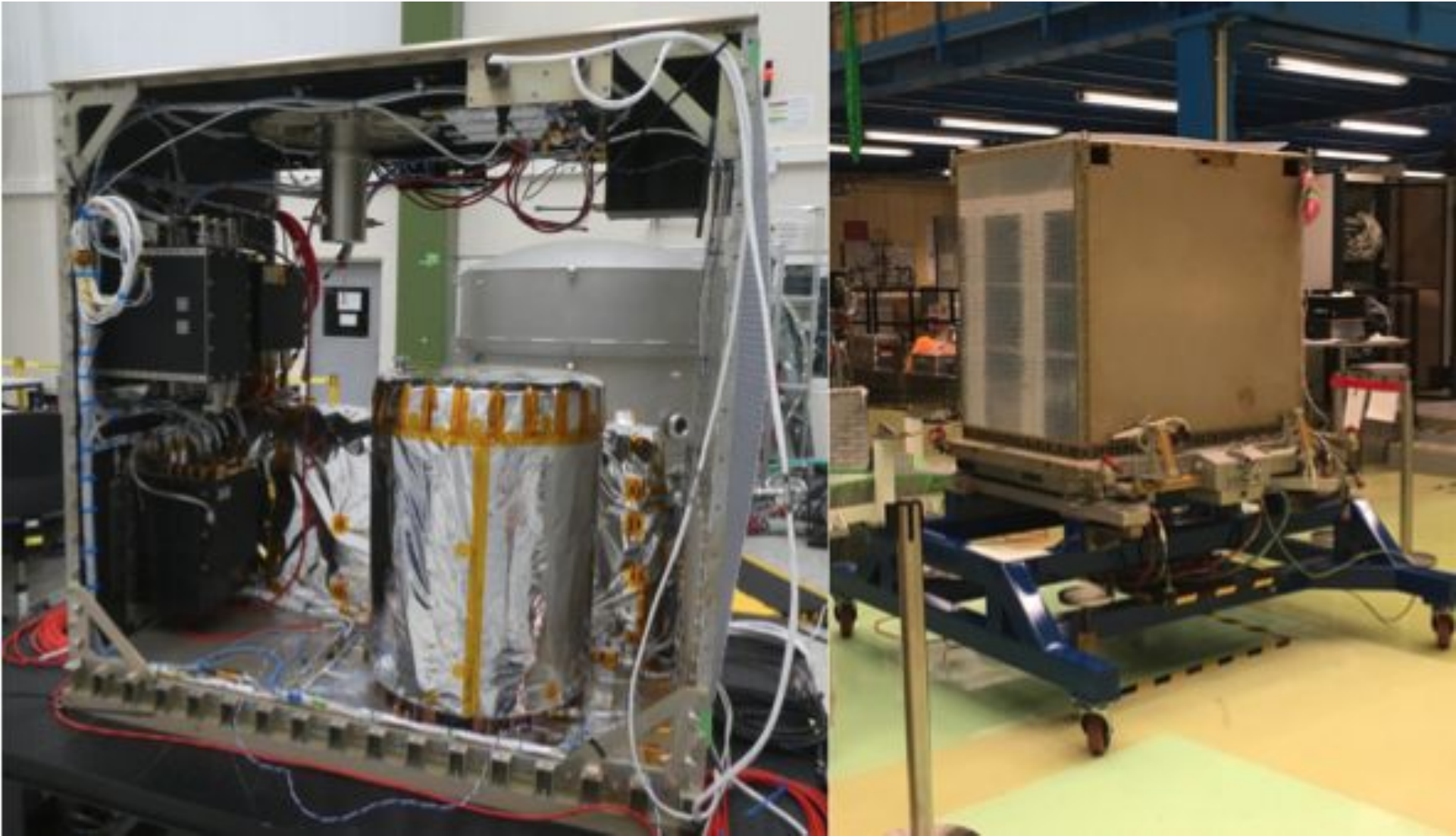
Atomic Clock Progress

use for next-generation SI time standard worldwide?



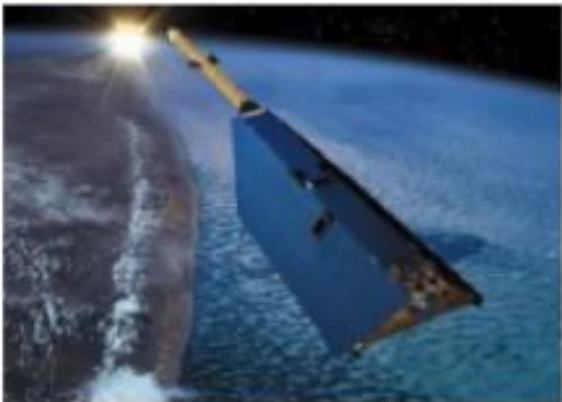
Atomic Clock Progress

ACES atomic clock mission: scheduled launch to ISS 2025

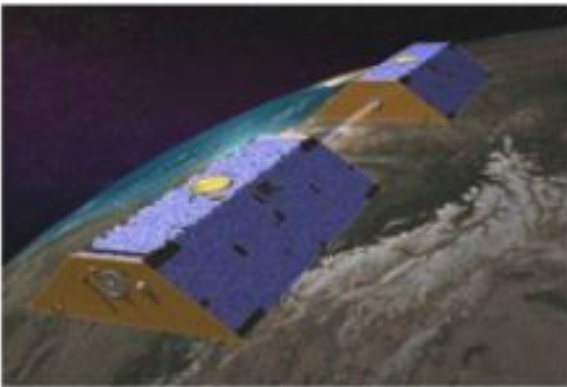


Earth Observation Progress

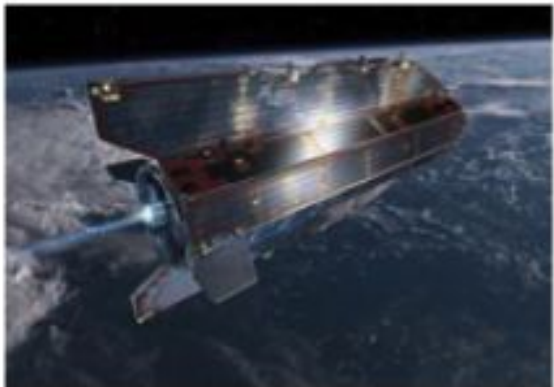
Earth Observation: using classical electrostatic accelerometers & gradiometers



CHAMP : satellite tracking by GNSS + accelerometry



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

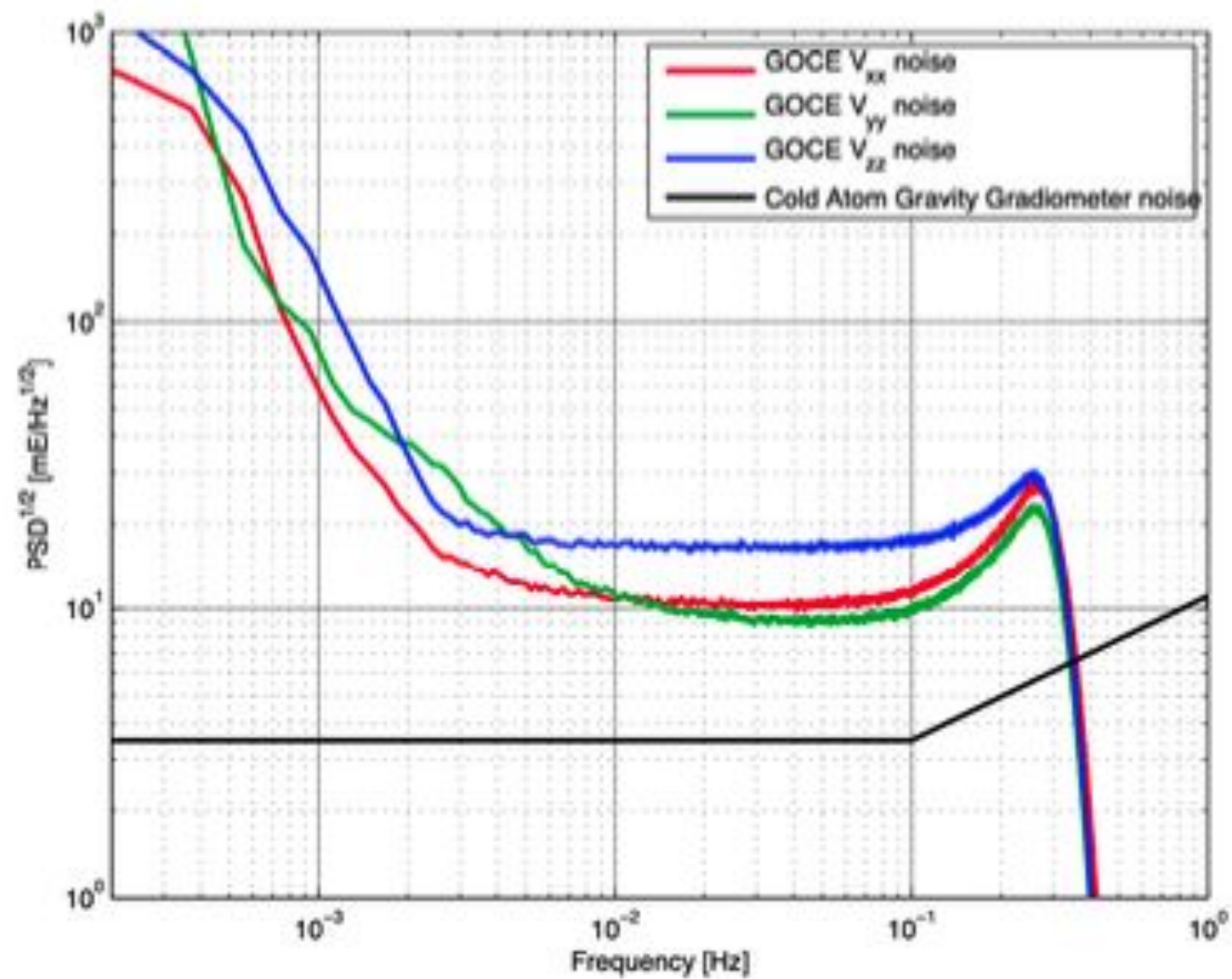


GOCE: orbit determination + gradiometry

	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	$\sim 10^{-10} \text{ m/s}^2$	$\sim 10^{-11} \text{ m/s}^2$	$\sim 10^{-11} \text{ m/s}^2$	$\sim 10^{-12} \text{ m/s}^2$
Geoid undulations	$\sim 10 \text{ cm}$ @350 km	$\sim 10 \text{ cm}$ @175 km	$\sim 1 \text{ mm}$ @ 500 km every 3 days $\sim 1 \text{ mm}$ @ 150 km every 10 days	$\sim 1 \text{ cm}$ @100 km
Gravity anomalies	$\sim 0.02 \text{ mGal}$ @1000 km	$\sim 1 \text{ mGal}$ @175 km		$\sim 1 \text{ mGal}$ @100 km

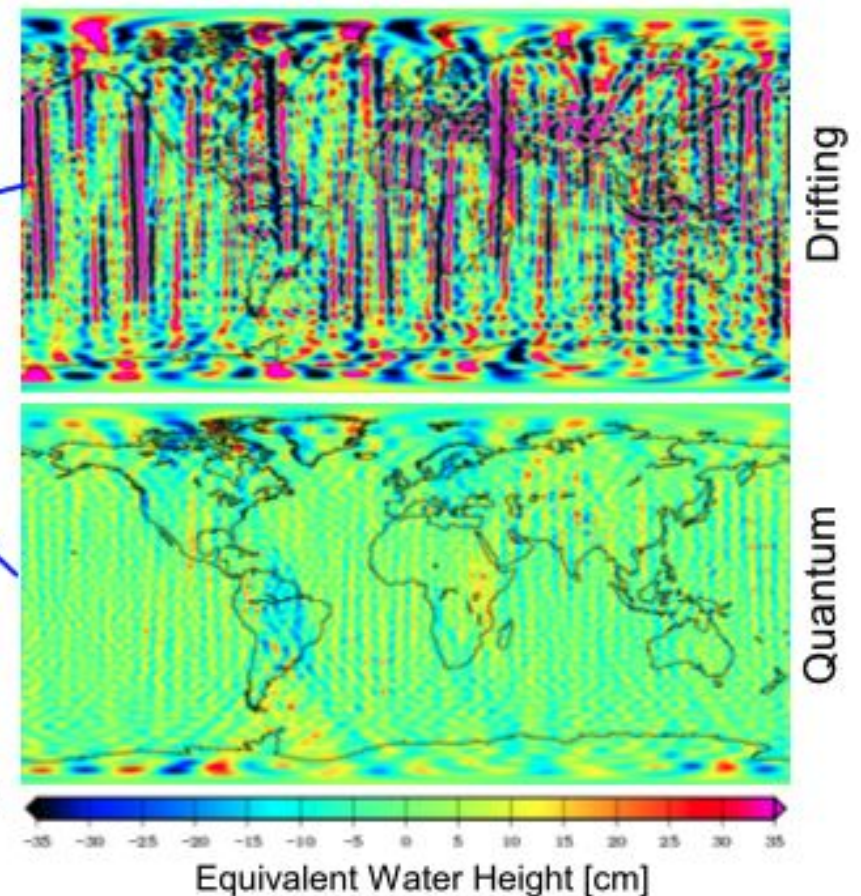
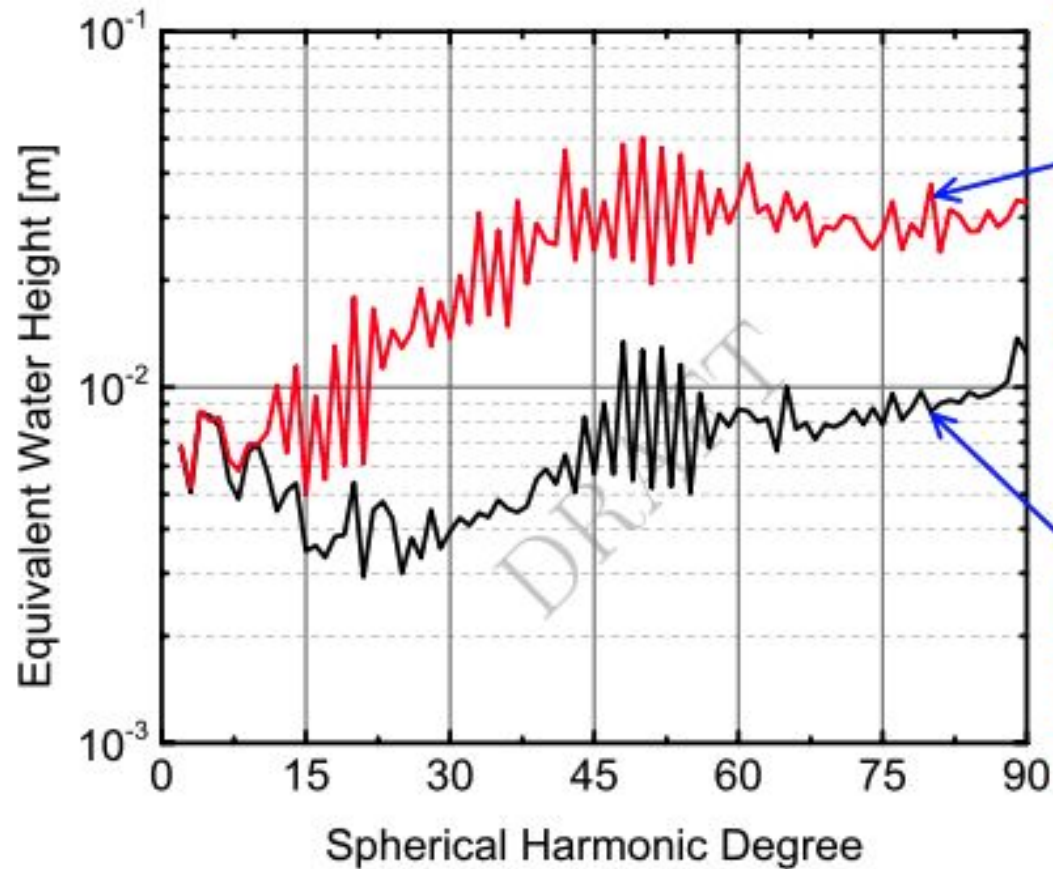
Earth Observation Progress

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



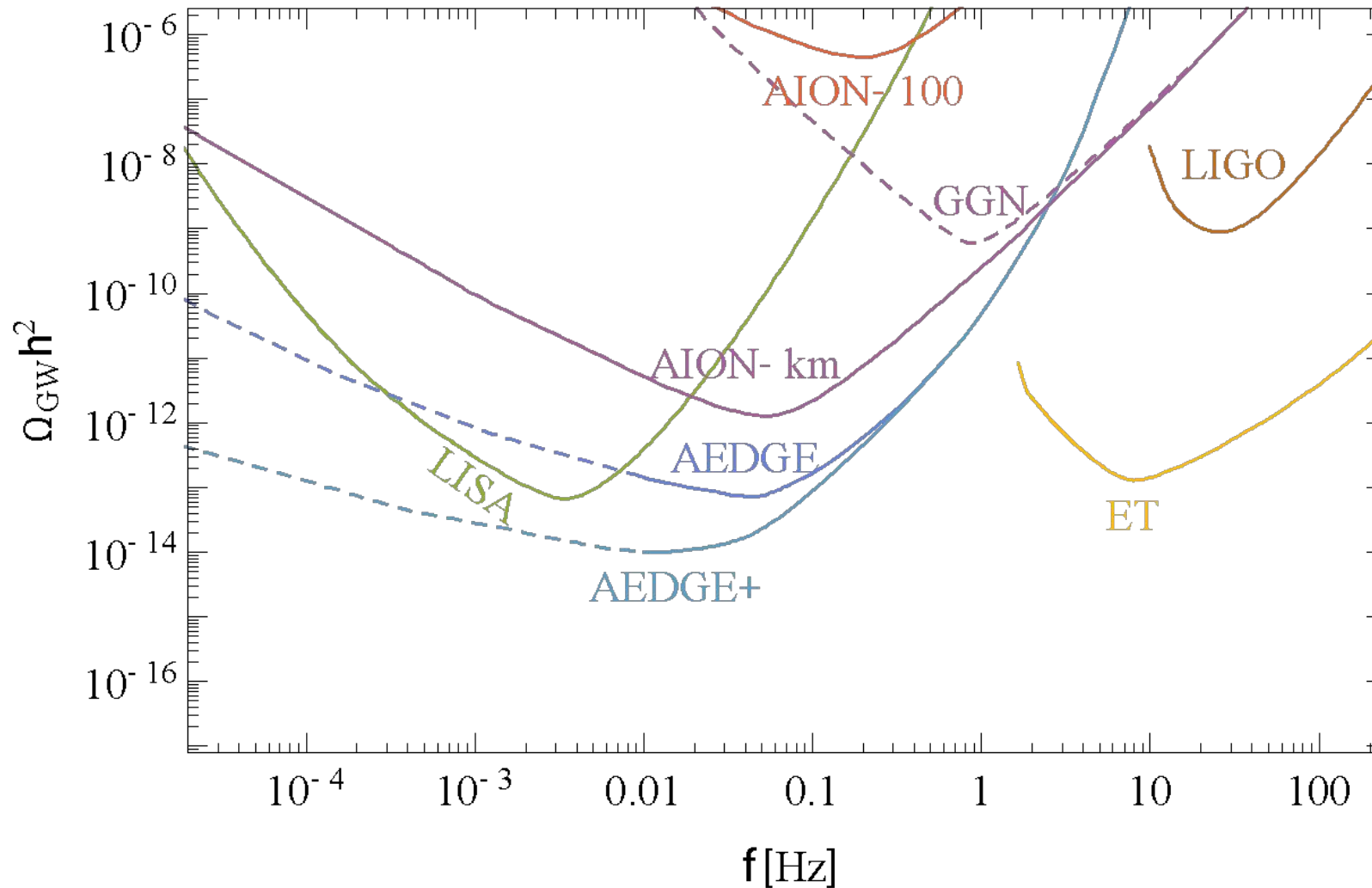
Earth Observation Progress

Sensitivity to Water Height
crucial for monitoring climate change



Vision for 2045+

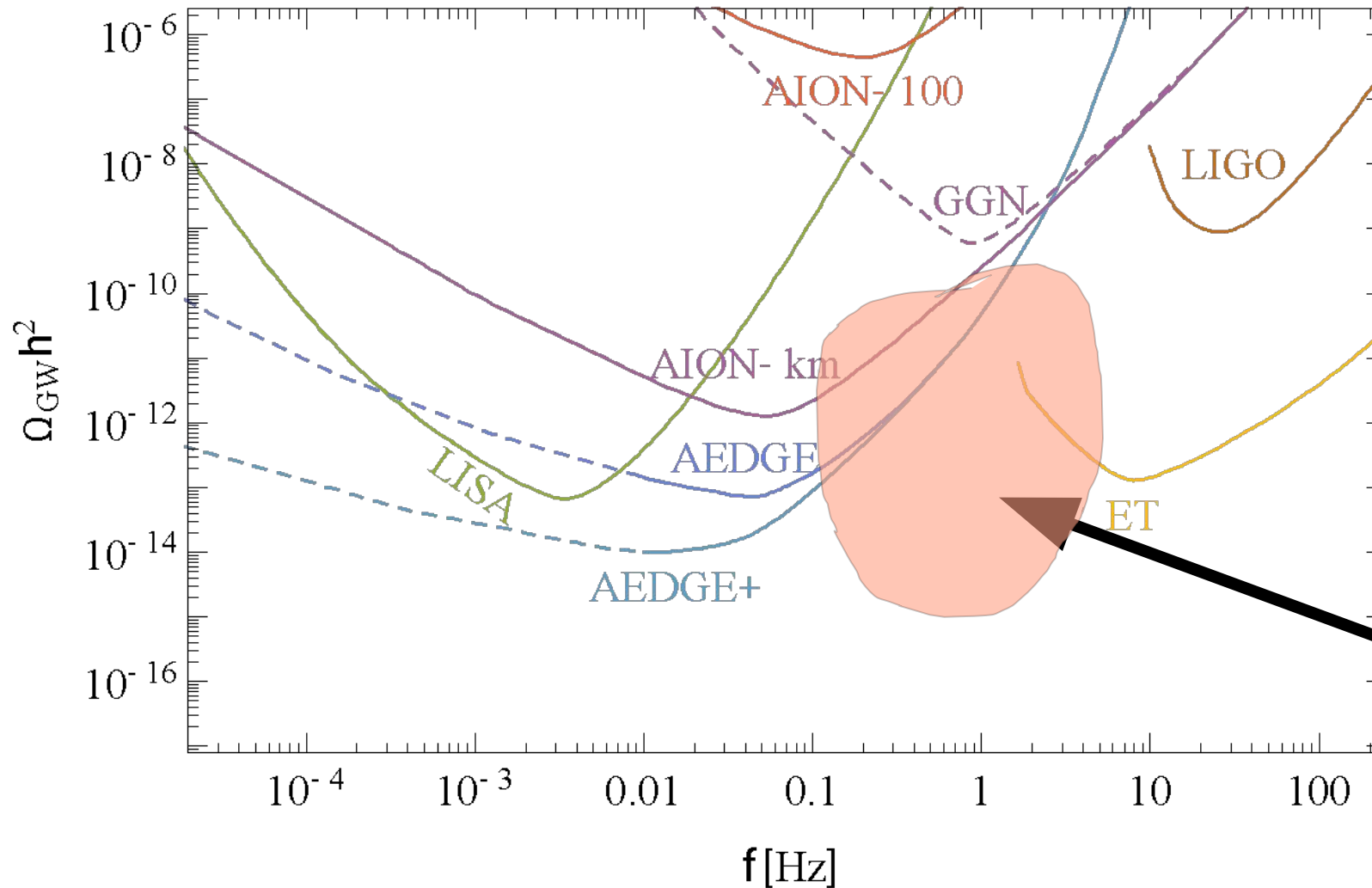
Probe formation of SMBHs: Synergies with other GW experiments (LIGO, LISA), test GR



**Translate Stain
sensitivity into the
dimensionless
energy density of a
GW**

Vision for 2045+

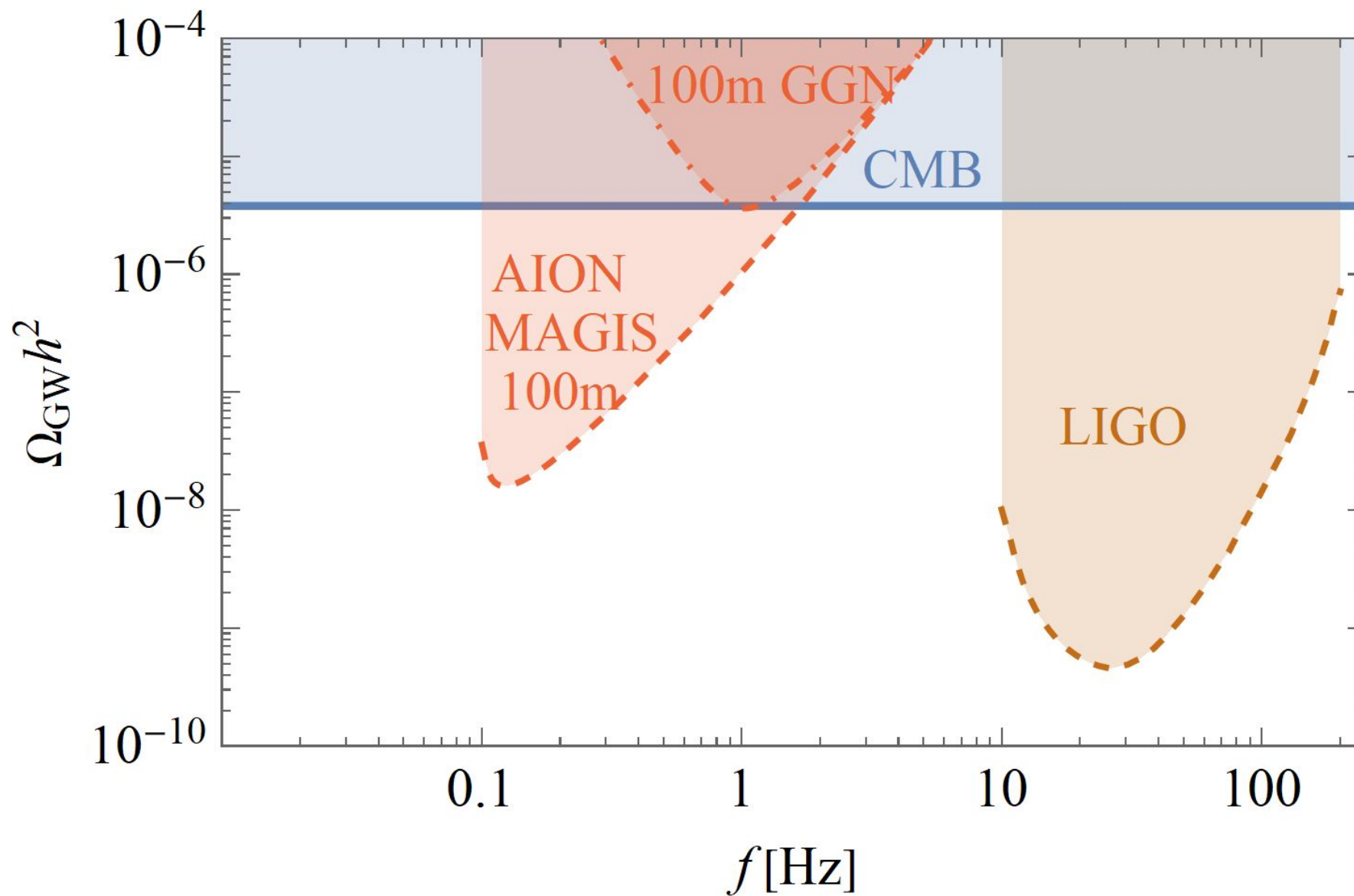
Probe formation of SMBHs: Synergies with other GW experiments (LIGO, LISA), test GR

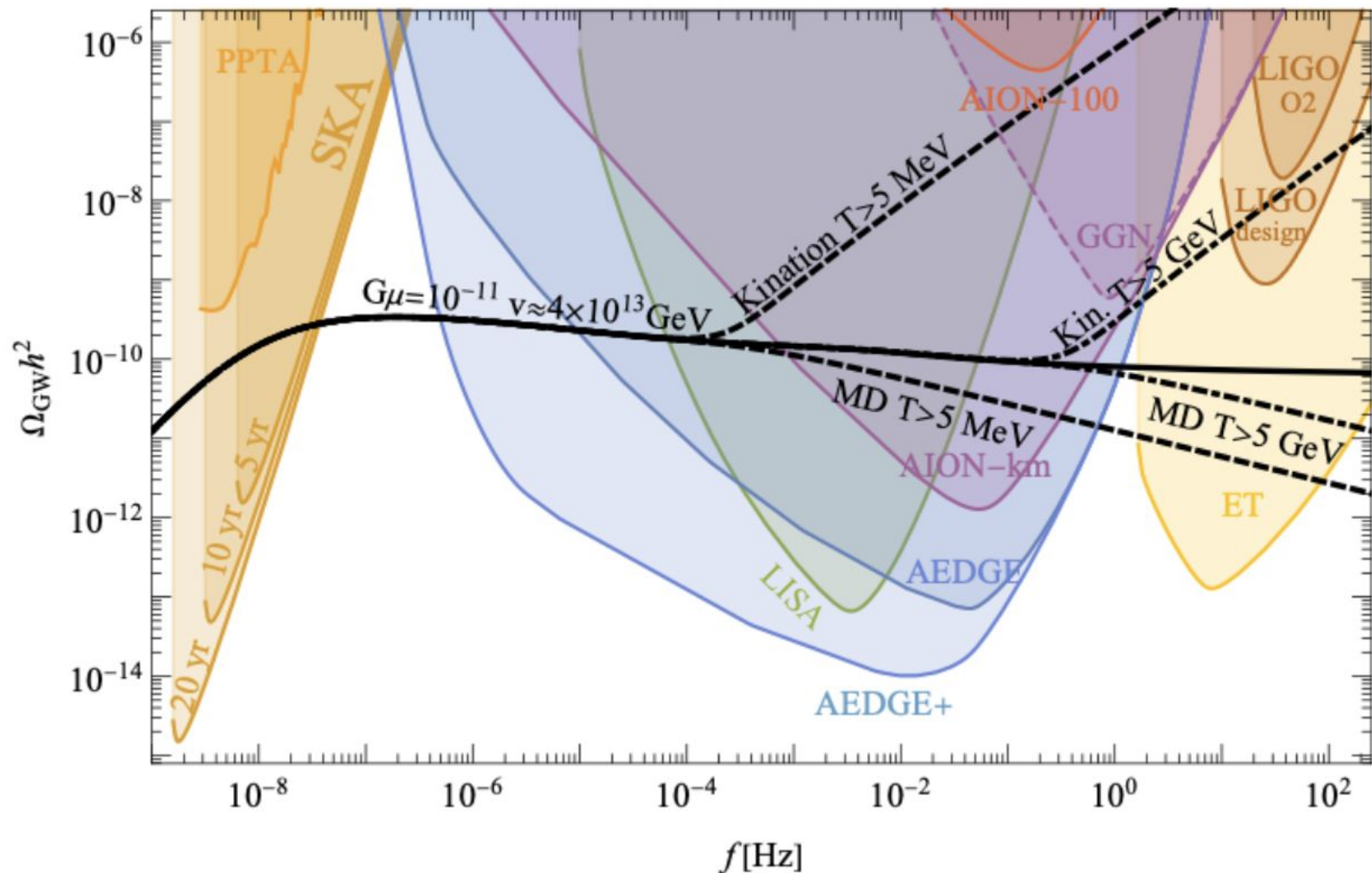


**Translate Stain
sensitivity into the
dimensionless
energy density of a
GW**

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

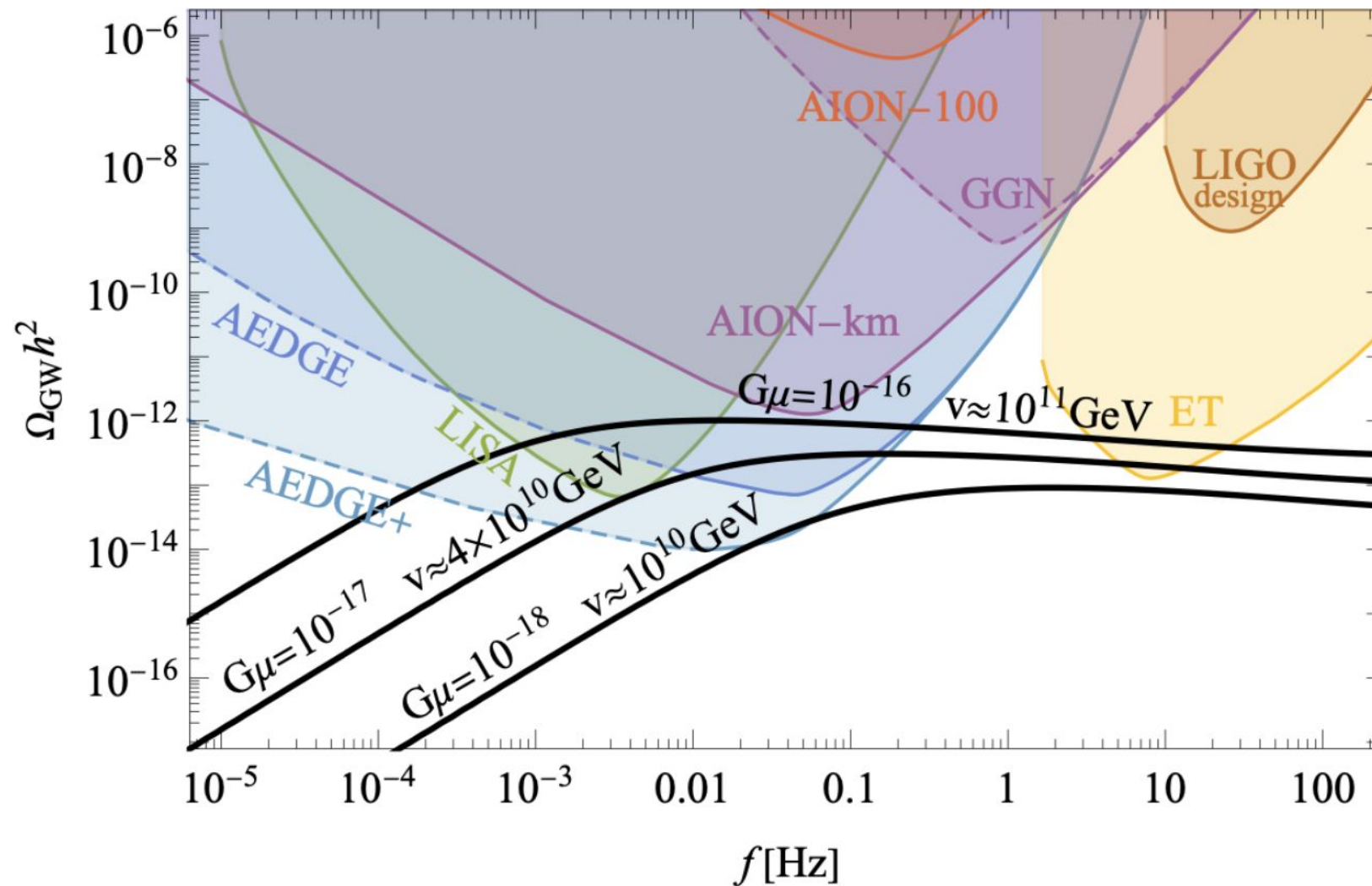
The GW Experimental Landscape: 2030ish





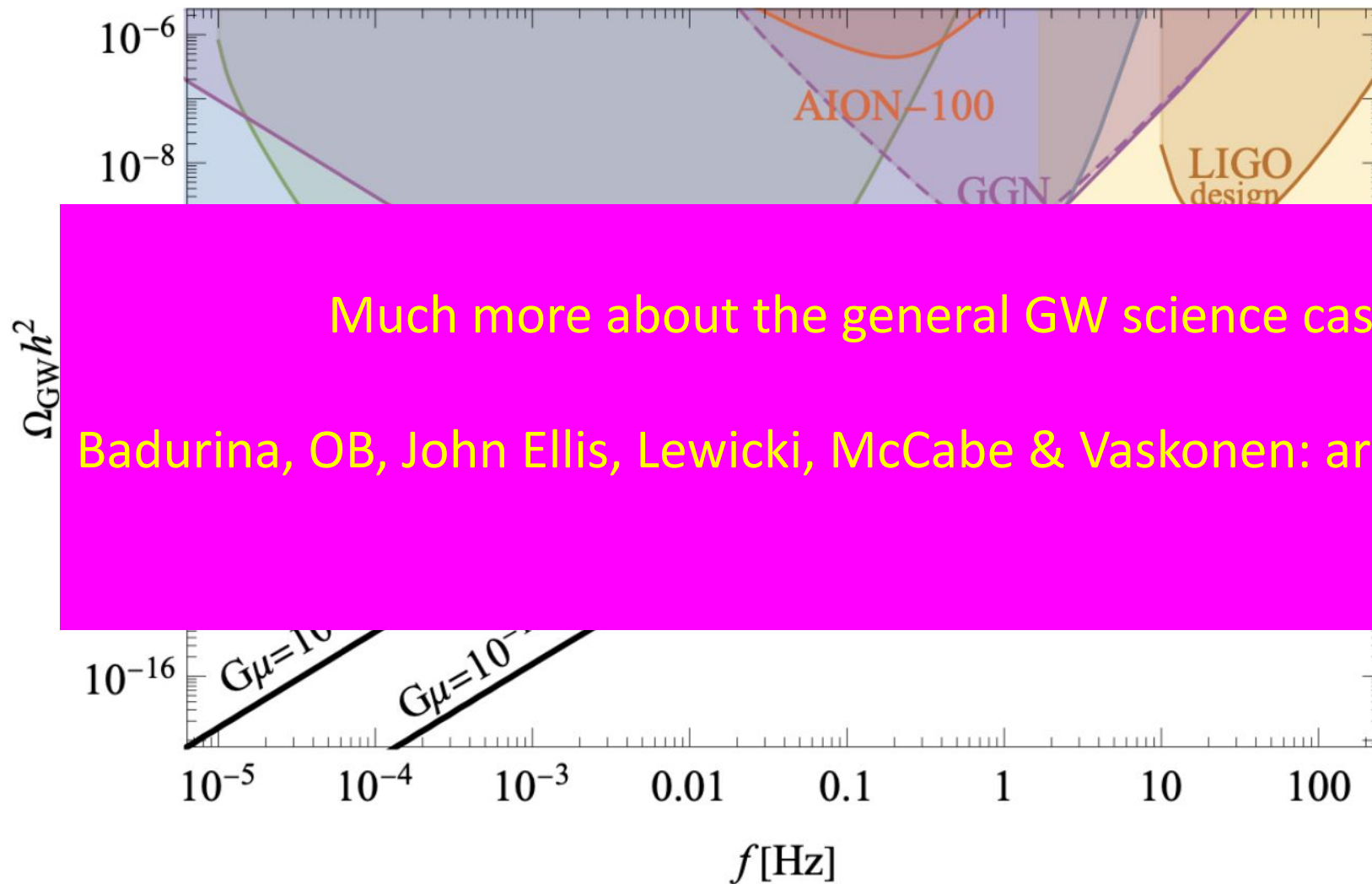
Comparison of the Ω sensitivities to PI spectra of AION-100, AION-km, AEDGE and AEDGE+, LIGO, ET, Pulsar Timing Arrays (PTAs) and SKA.

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 $G\mu$ of AION-100 and -km, AEDGE and AEDGE+, LIGO, ET and LISA.



Different experiments sensitive to different frequencies of cosmic strings

Much more about the general GW science case in:

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

Sensitivities to the cosmic strings with tension $G\mu$ 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 $\mu\text{m}/\text{yr}$
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 $\mu\text{m}/\text{yr}$
200 km	1 cm	0.1 cm/yr	0.05 mm	5 $\mu\text{m}/\text{yr}$
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 and macroscopic corner cube
	^{87}Rb - CC	7×10^{-9}	2010 [205]	
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]	≥ 10 m towers
	^{85}Rb - ^{87}Rb	(10^{-13})	2020+ [210]	
	^{170}Yb - ^{87}Rb	(10^{-13})	2020+ [211]	
Antimatter	^{41}K - ^{87}Rb	10^{-17}	2035+	STE-QUEST-like mission
	$\bar{\text{H}}$ - H	(10^{-2})	2020+ [212]	under construction at CERN