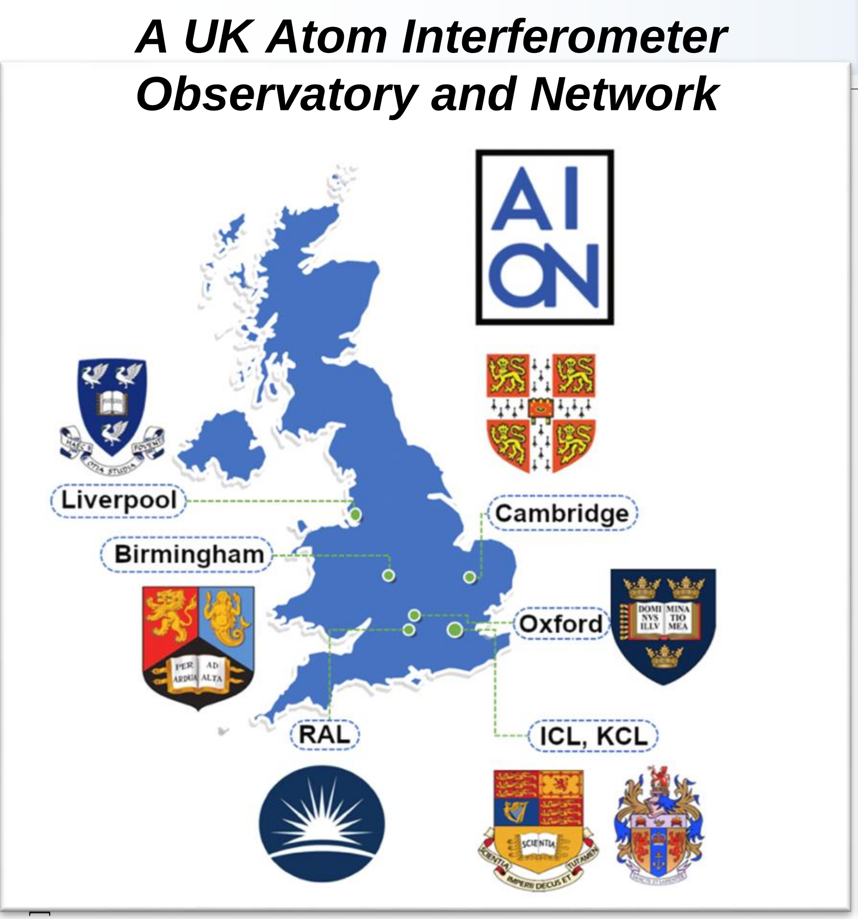
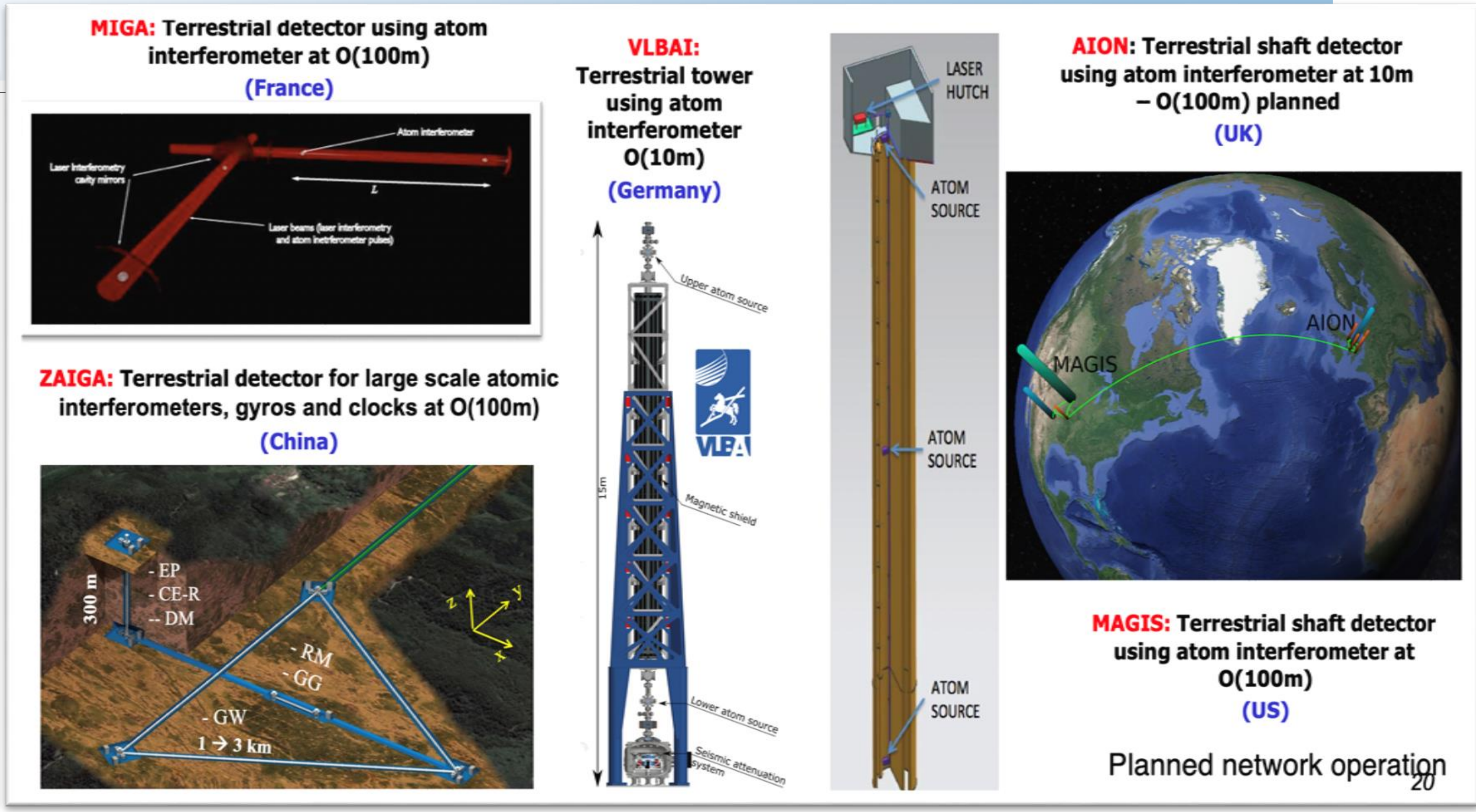


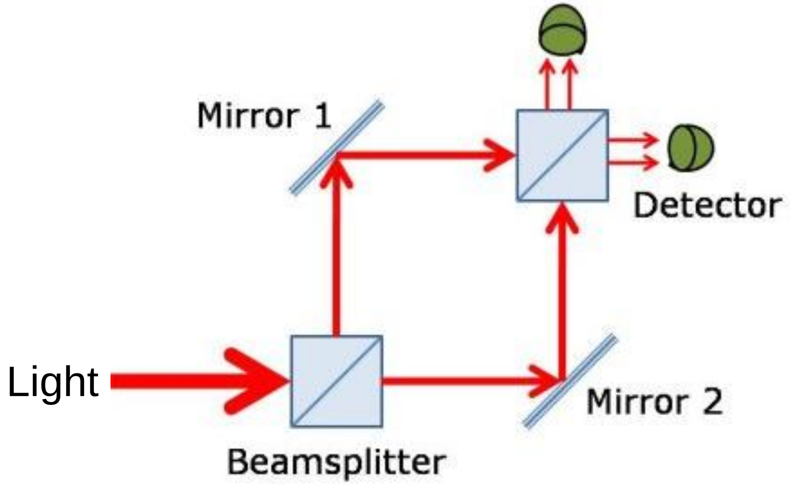

Oliver Buchmueller, Imperial College London

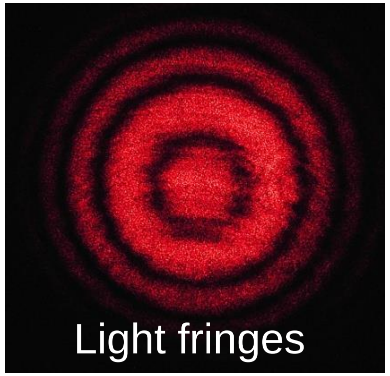
# LARGE SCALE ATOM INTERFEROMETRY TO EXPLORE FUNDAMENTAL PHYSICS

# AION AND MAGIS EXPERIMENTS
# EXAMPLE OF TERRESTRIAL DETECTORS

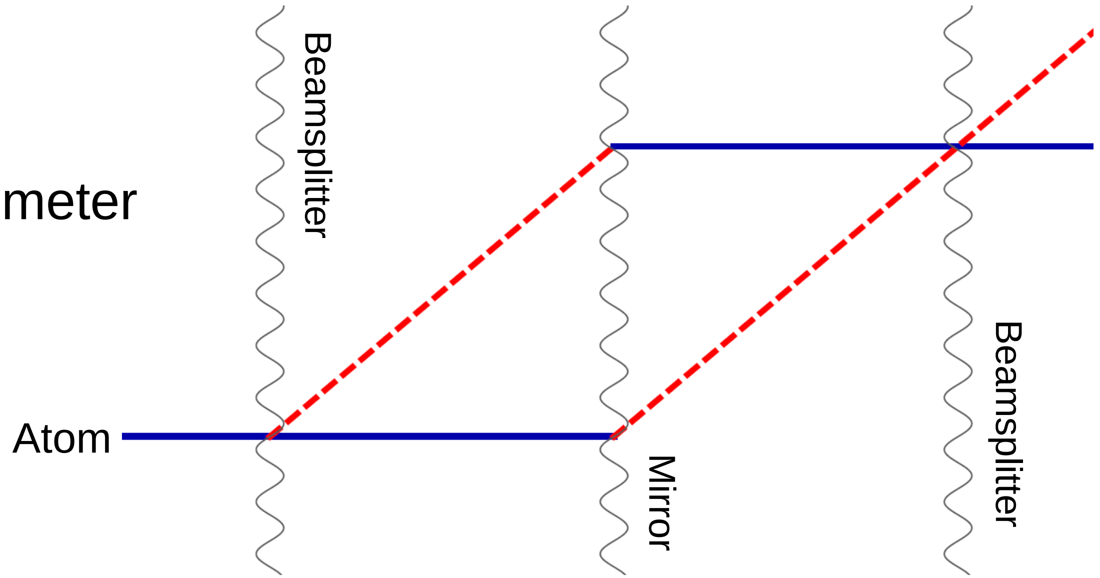
# Light vs. Cold Atoms: Atom Interferometry

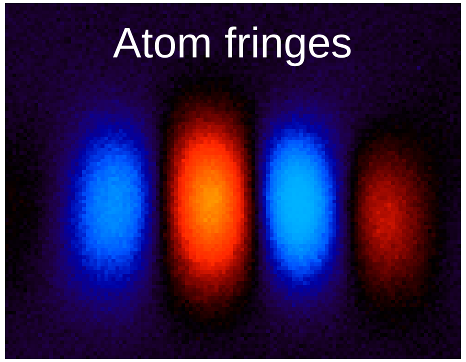
Light interferometer



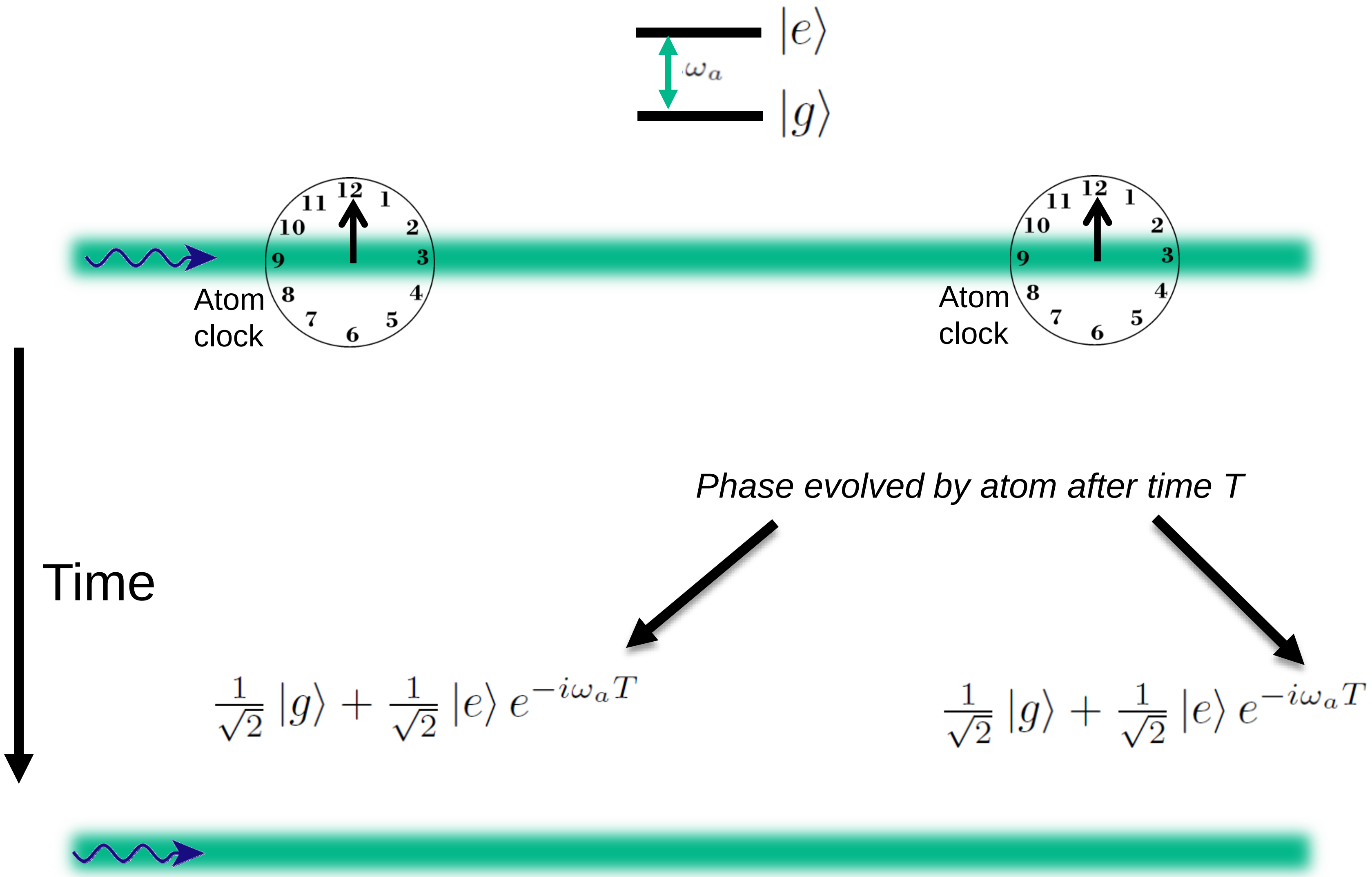

Atom interferometer




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

$|e\rangle$

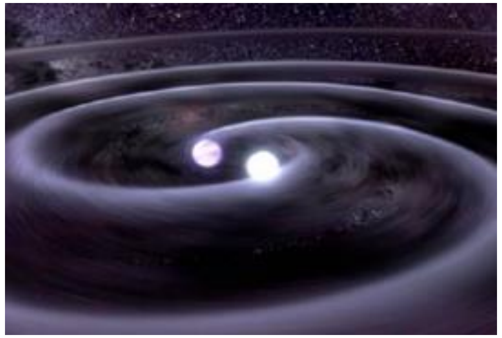
$\omega_a$

$|g\rangle$

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



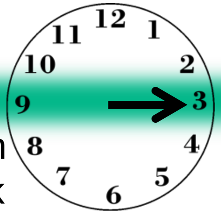
Time



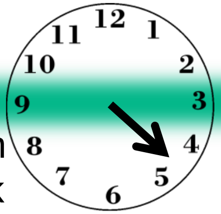
**GW changes light travel time**

$\Delta T \sim hL/c$

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



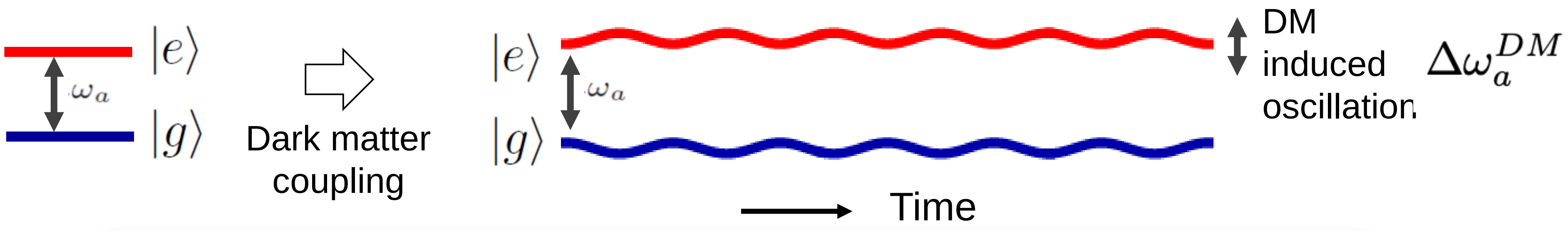

Atom clock



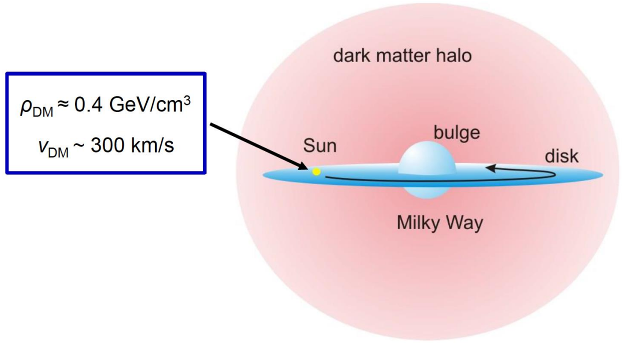

Atom clock

Courtesy of Jason Hogan!

# Simple Example: Two Atomic Clocks




Time




**DM cloud changes atom frequency**

DM coupling causes time-varying atomic energy levels:

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

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


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.

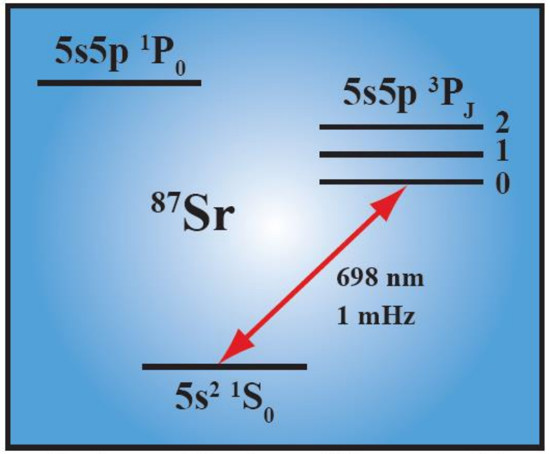

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle e^{i\phi_L} \qquad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle e^{i\phi_L}$$

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

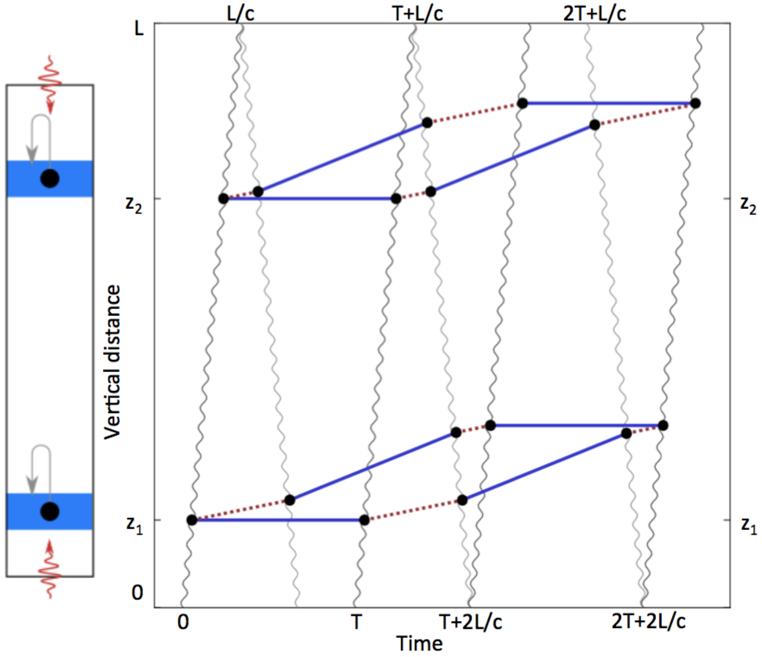
# AION: A Different Kind of Atom Interferometer

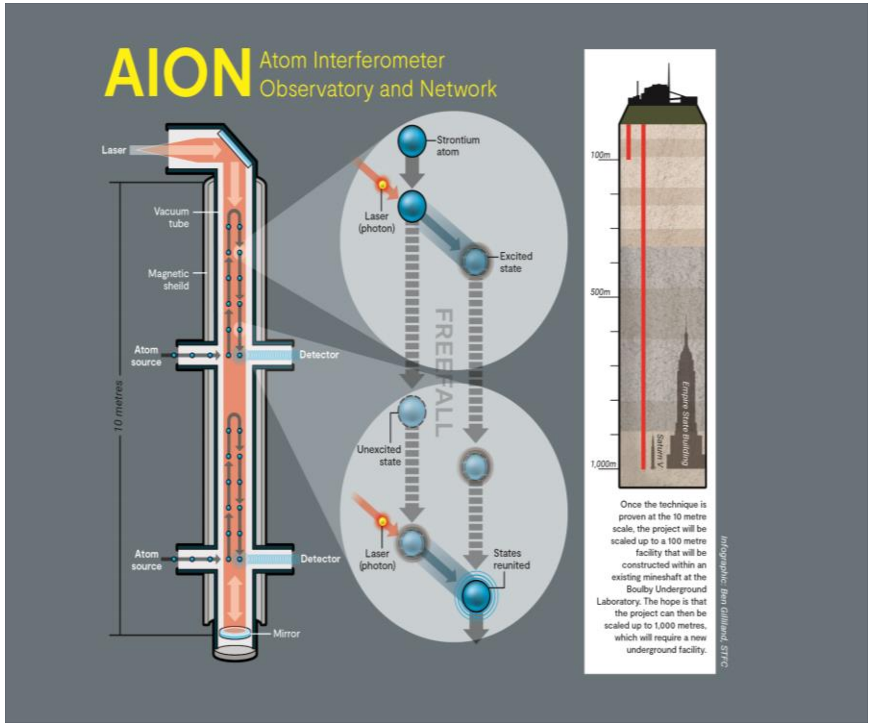


Hybrid “clock accelerometer”




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] | $\delta\phi_{\text{noise}}$ $[1/\sqrt{\text{Hz}}]$ | 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 | $0.3 \times 10^{-5}$ | 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

# 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.

L ~ 10m

L ~ 100m

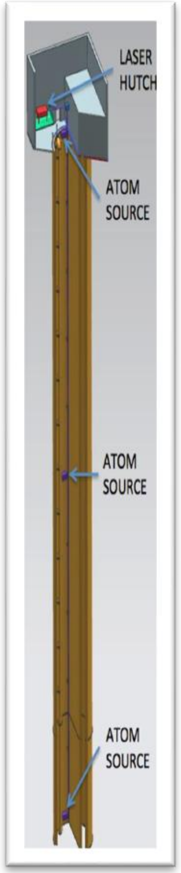
***Stage 1 is now funded with about £10M by the QTFP Programme and other sources and Stage 2 could be placed at national facility in Boulby or Daresbury (UK), possibly also at CERN (France/Switzerland).***

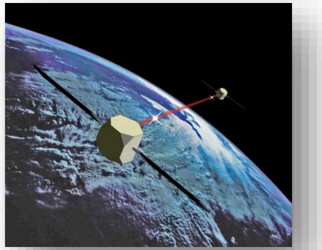
- **Stage 3:** to build a kilometre-scale terrestrial detector.

L ~ 1km

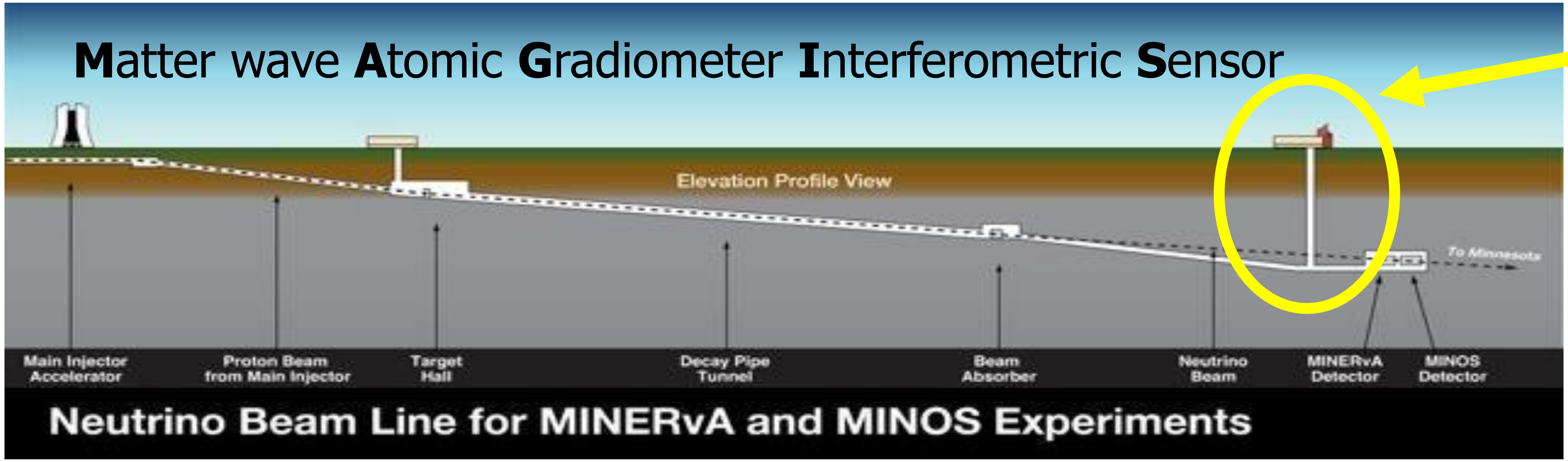
- **Stage 4**: long-term objective a pair of satellite detectors (thousands of kilometres scale) [AEDGE proposal to ESA Voyage2050 call]
  - AION has established science leadership in AEDGE, bringing together collaborators from European and Chinese groups (e.g. MIGA, MAGIA, ELGAR, ZAIGA).

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

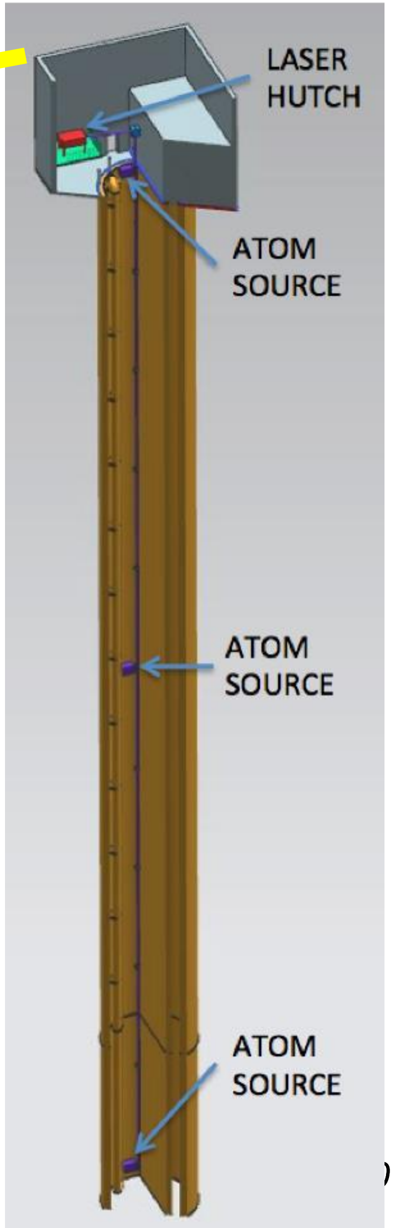


# MAGIS-100: Detector prototype at Fermilab




100 meters




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

STANFORD · Fermilab · JOHNS HOPKINS UNIVERSITY · UNIVERSITY OF LIVERPOOL · Northwestern University · Northern Illinois University

Imperial College London

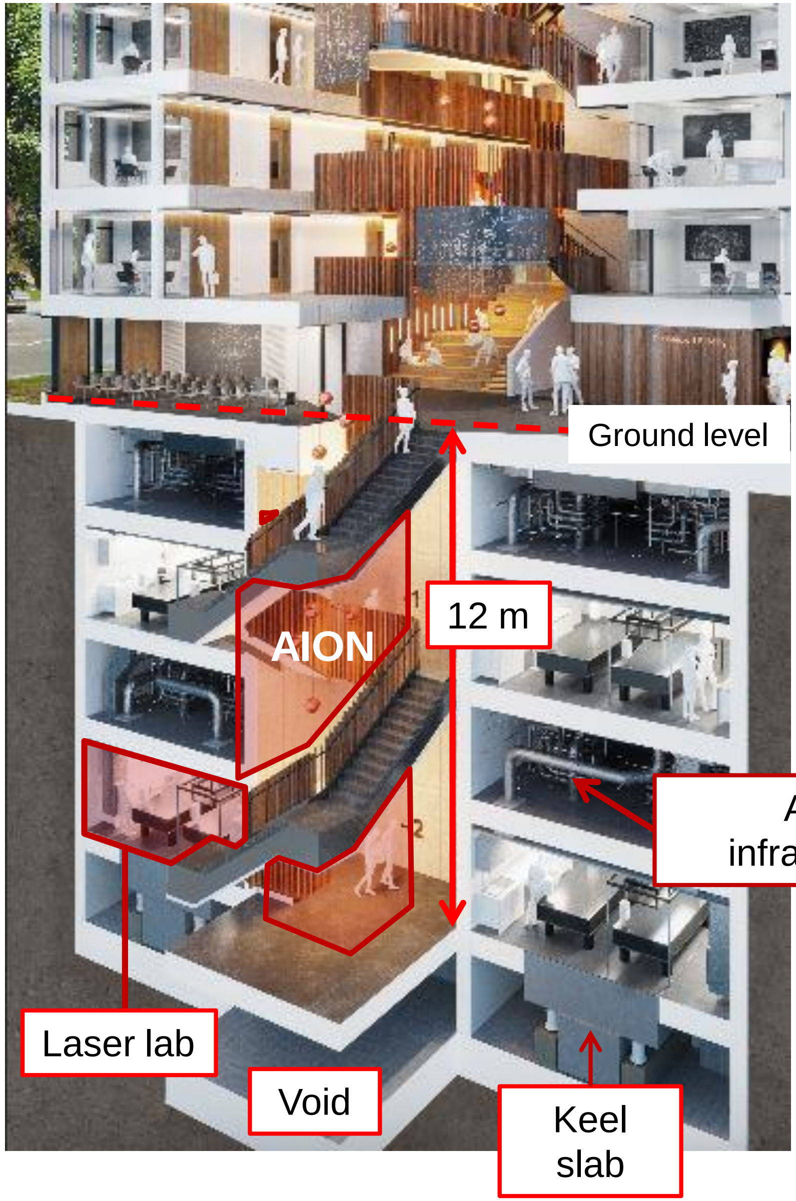
# AION Collaboration Days in Oxford: Fall 2021

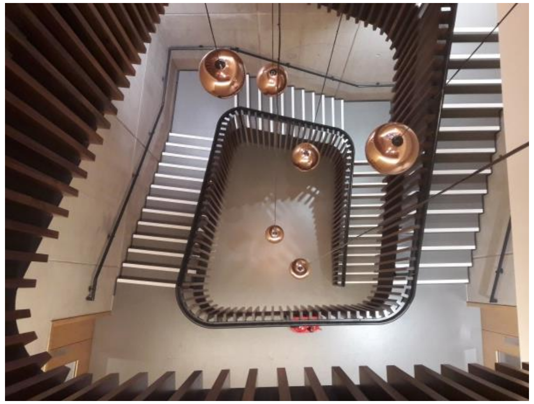


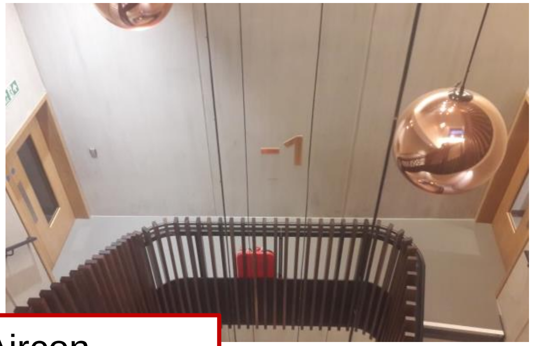
**Ratio of Cold Atom : Particle/Fundamental Physics people is 1:1**

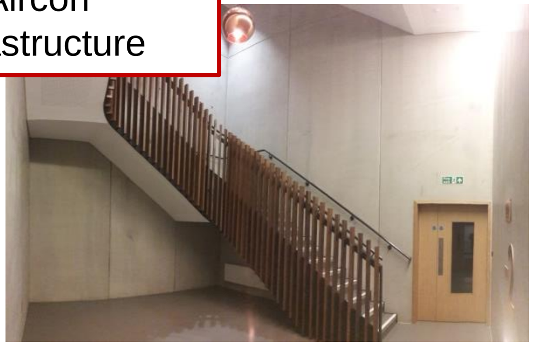
# Beecroft building, Oxford Physics









## Ultralow vibration

- All plant isolated
- Thick concrete walls

## Adjacent laser lab reserved for AION use

- keel slabs
- $\pm 0.1^{\circ}$C stability
- Isolated mains

## Vertical space

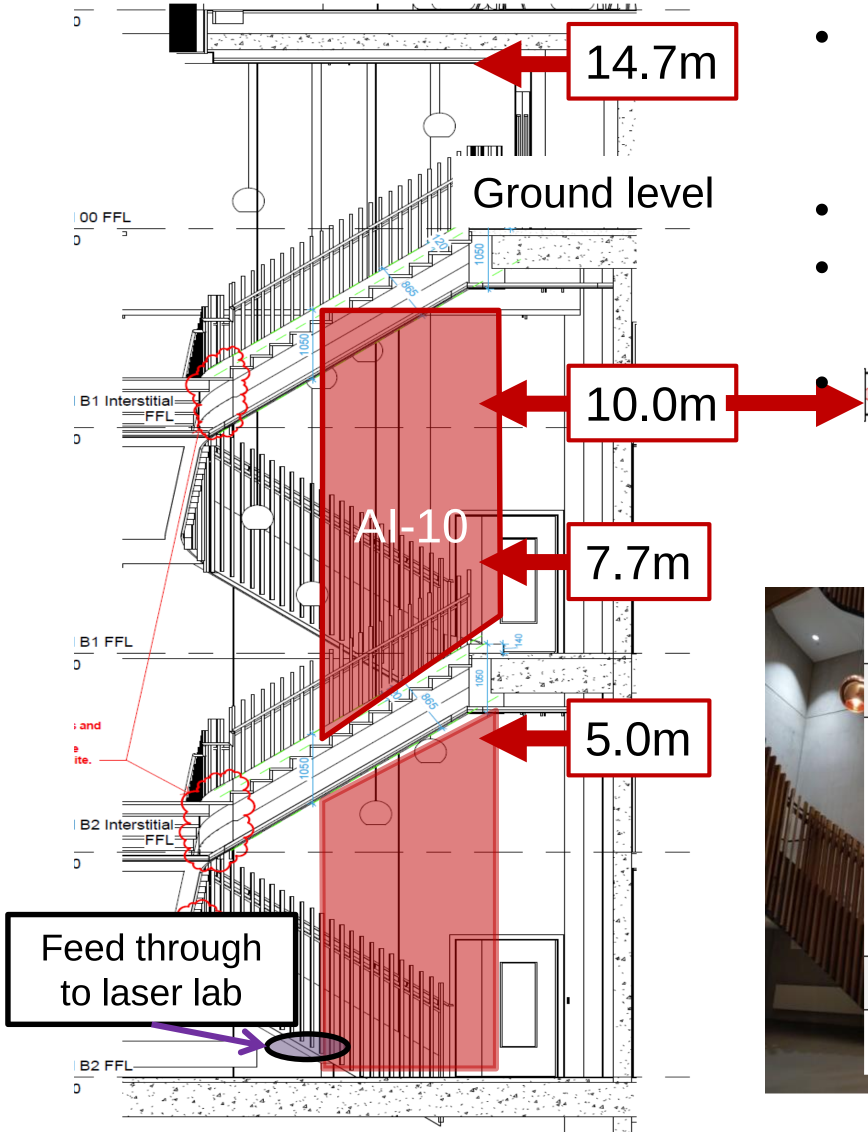
- 12m basement to ground floor
- 14.7m floor to ceiling

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

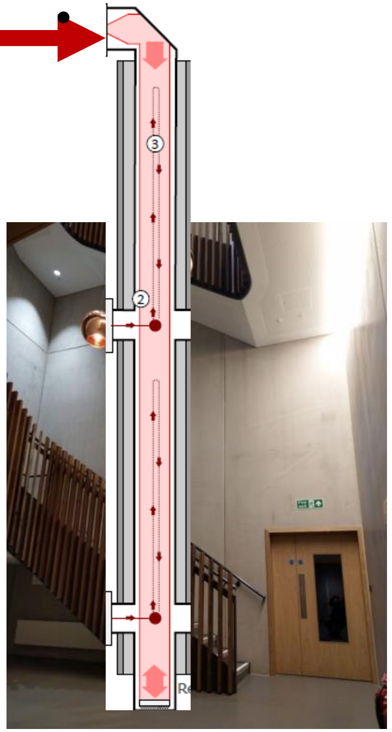
## Bakeout room and cleanroom nearby

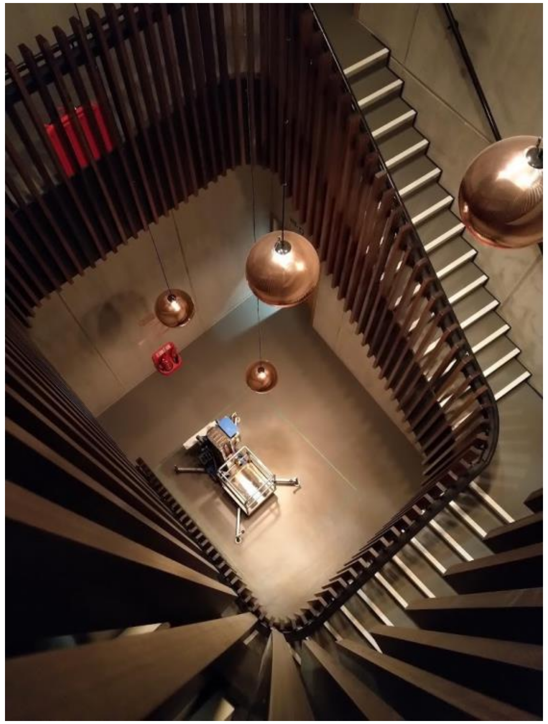
# AION-10 site: Beecroft building, Oxford Physics

## 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: Adam Lowe
- Good site for long-term operation and wide accessibility (also ‘visibility’ and outreach).





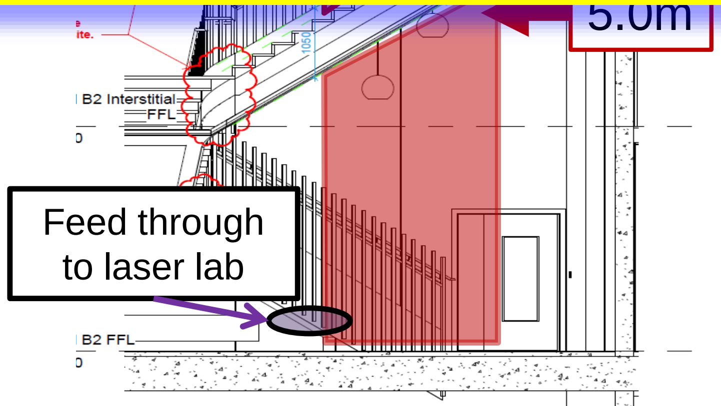
# AION-10 site: Beecroft building, Oxford Physics

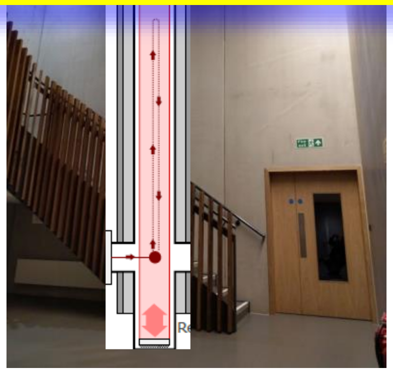


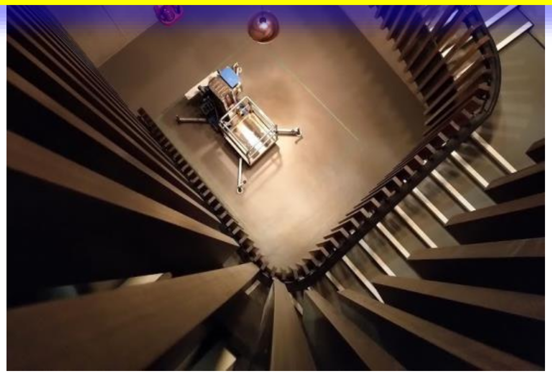
**Beecroft building – brand new, low-vibration laser lab and concrete stairwell**

**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

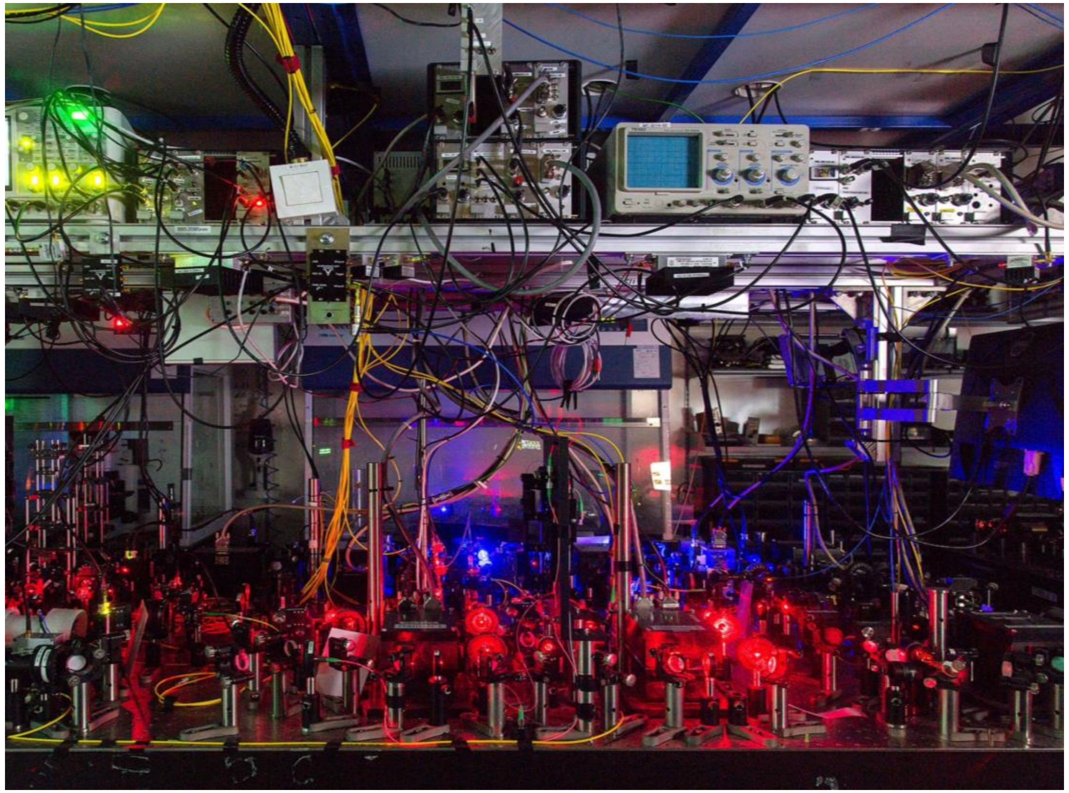


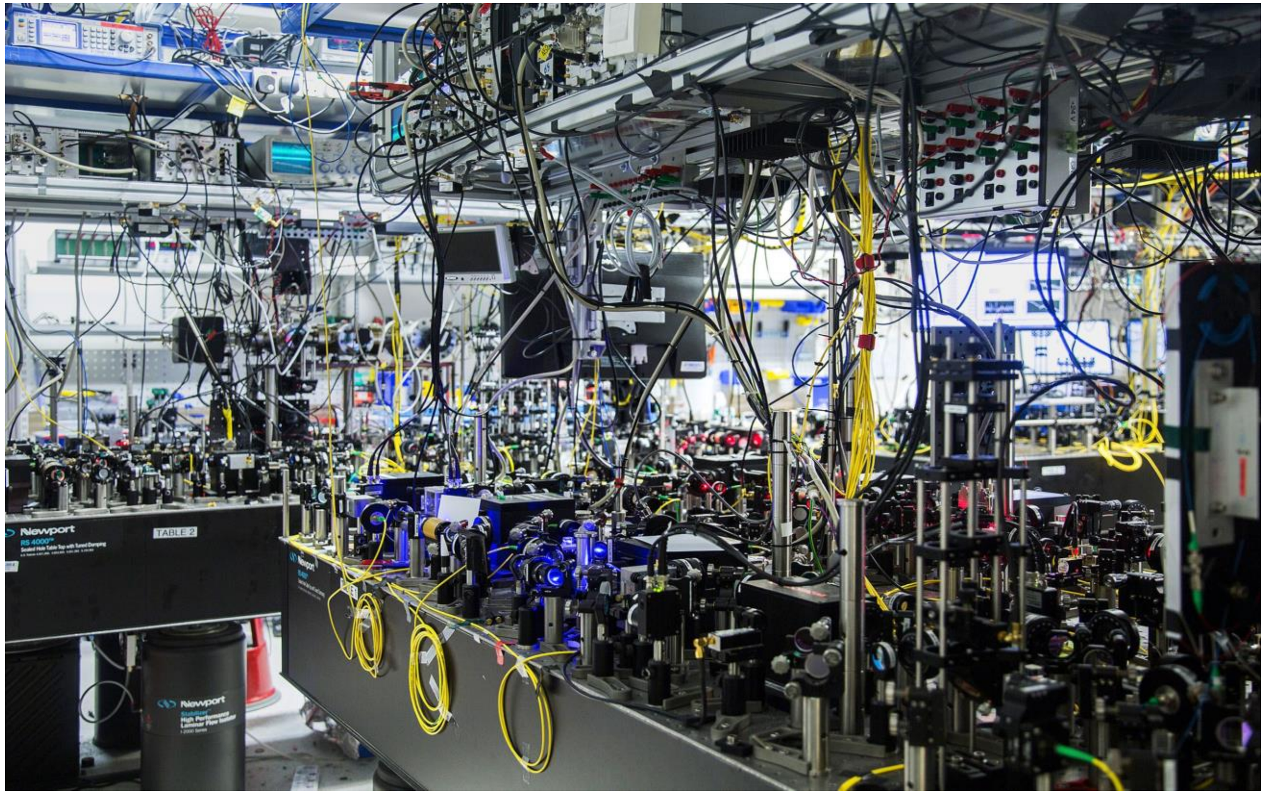





# AION: Ultra-Cold Strontium Laboratories in UK





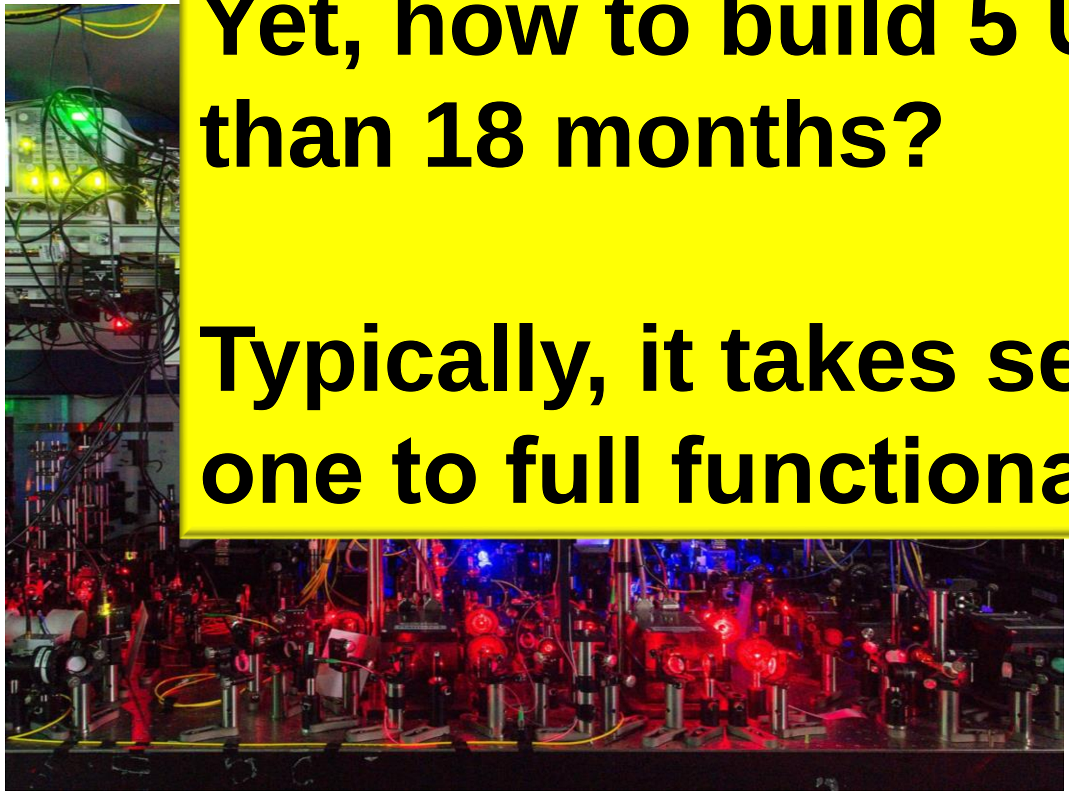


To push the state-of-the-art single photon Sr Atom Interferometry, the AION project builds dedicated Ultra-Cold Strontium Laboratories in:

**Birmingham, Cambridge, Imperial College, Oxford, and RAL**

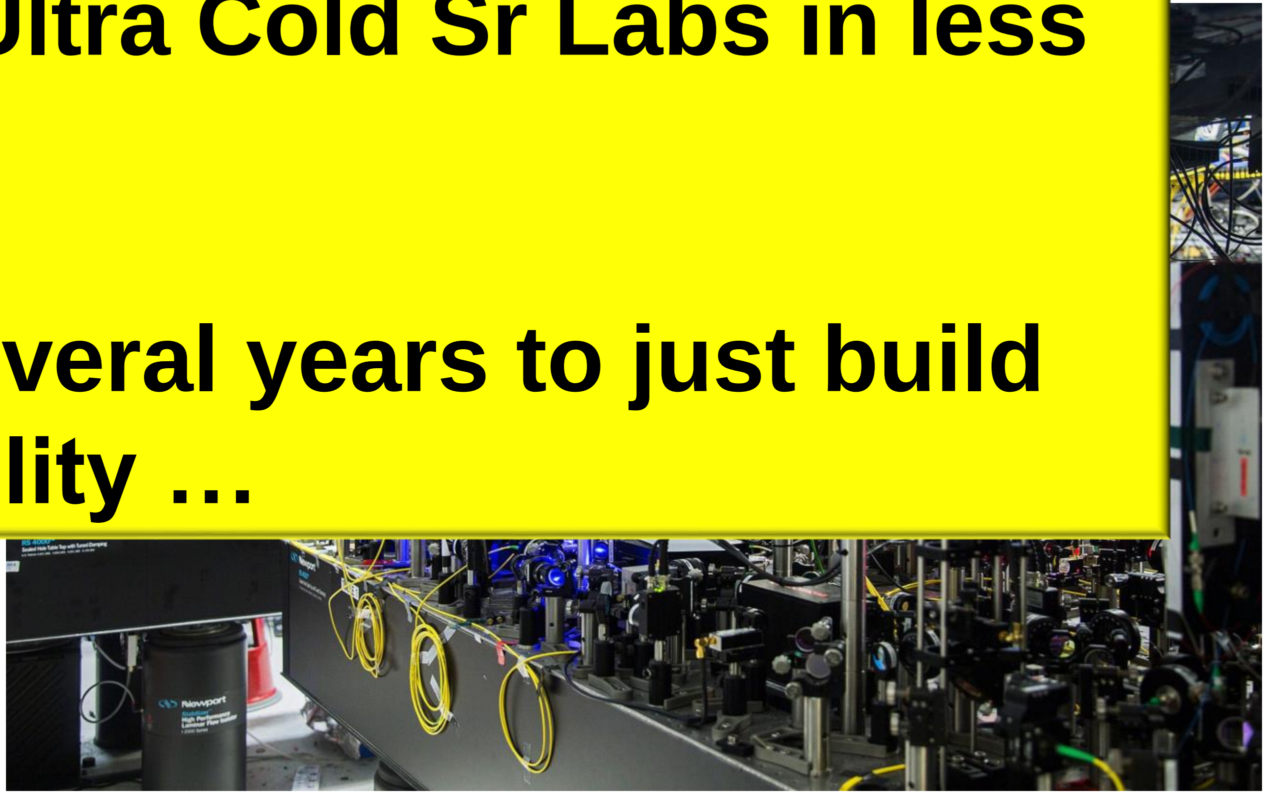
*The laboratories are expected to be fully operational in fall 2022.*

# AION: Ultra-Cold Strontium Laboratories in UK



**Yet, how to build 5 Ultra Cold Sr Labs in less than 18 months?**

**Typically, it takes several years to just build one to full functionality …**



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*The laboratories are expected to be fully operational in fall 2022.*

# HEP4QT ☺

Applying HEP Large Scale Experience to Cold Atom Technology Development

## AION – FIRST LESSON LEARNED AFTER 18 MONTHS IN THE PROJECT

# HEP4QT ☺

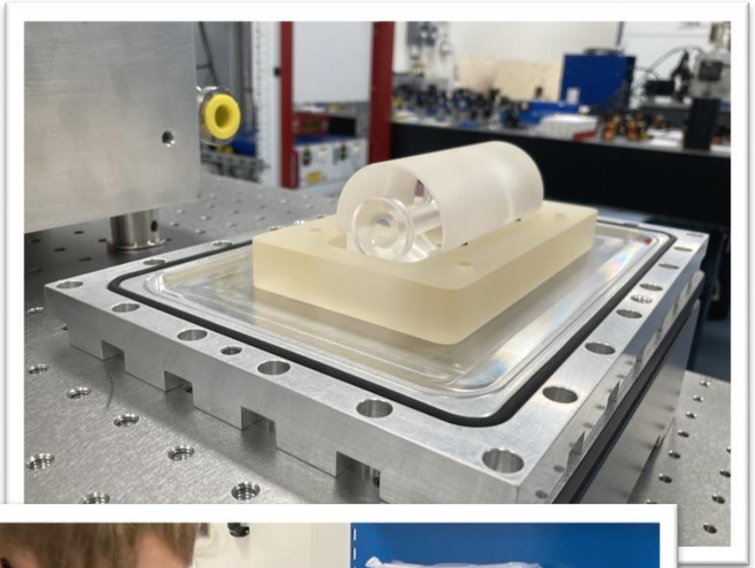
**Centralize the design and production of major components:**

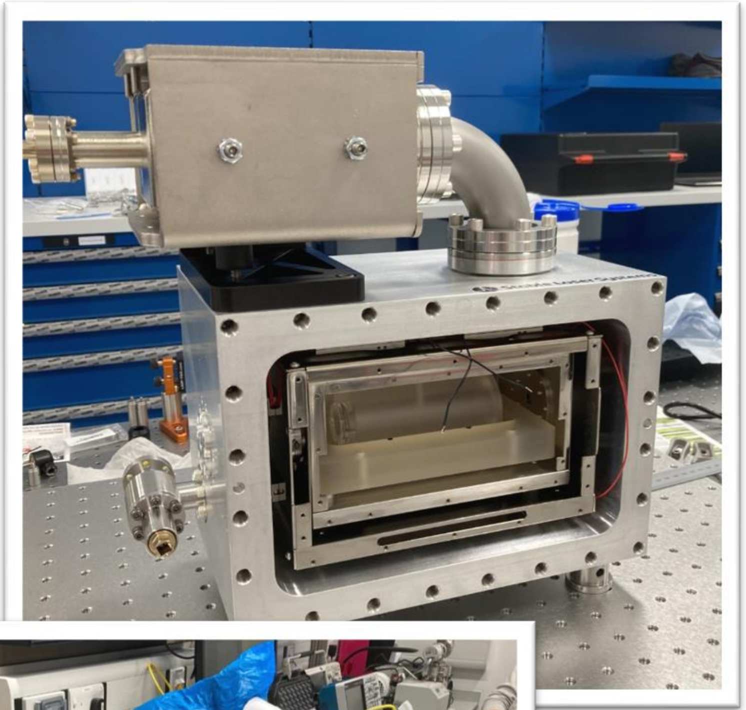
- **Ultra High Vacuum System**
- **Laser Stabilization System**
- **…**

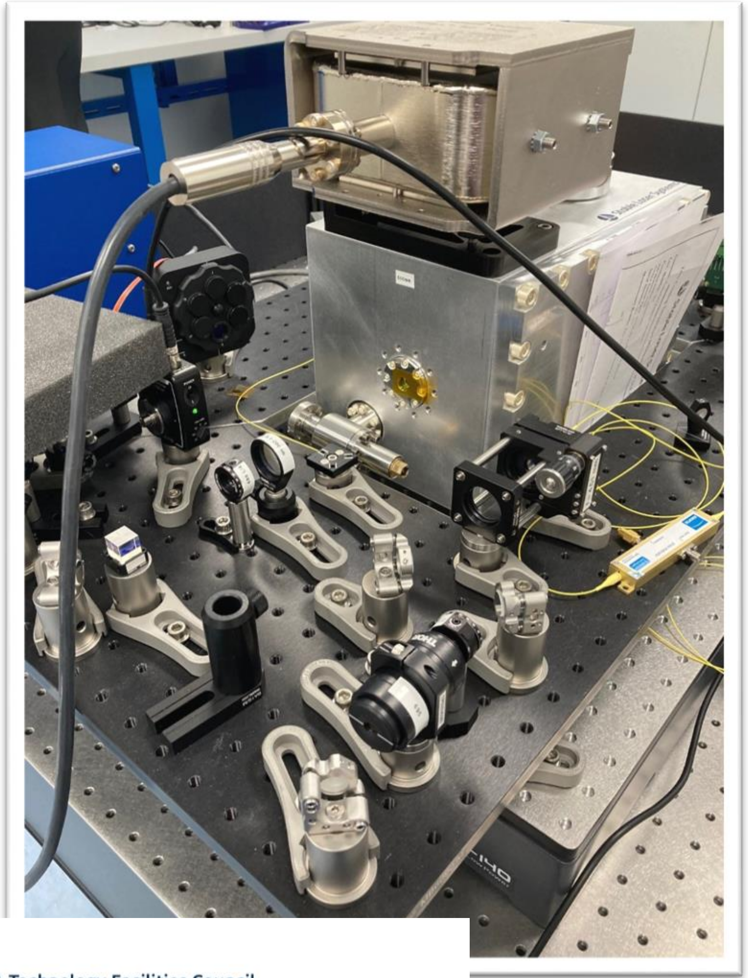
**and make use of expertise at National Laboratories like Rutherford Appleton and Daresbury Laboratory!**

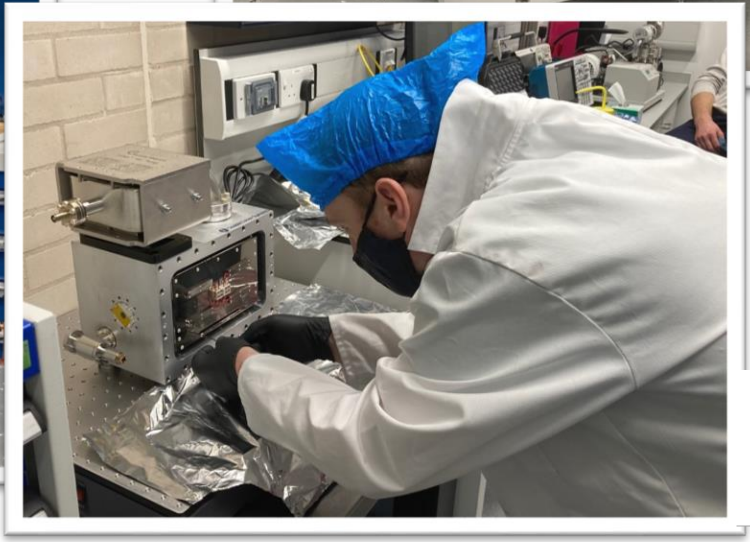
# CENTRAL PRODUCTION OF LASER STABILIZATION SYSTEM











Science & Technology Facilities Council
Rutherford Appleton Laboratory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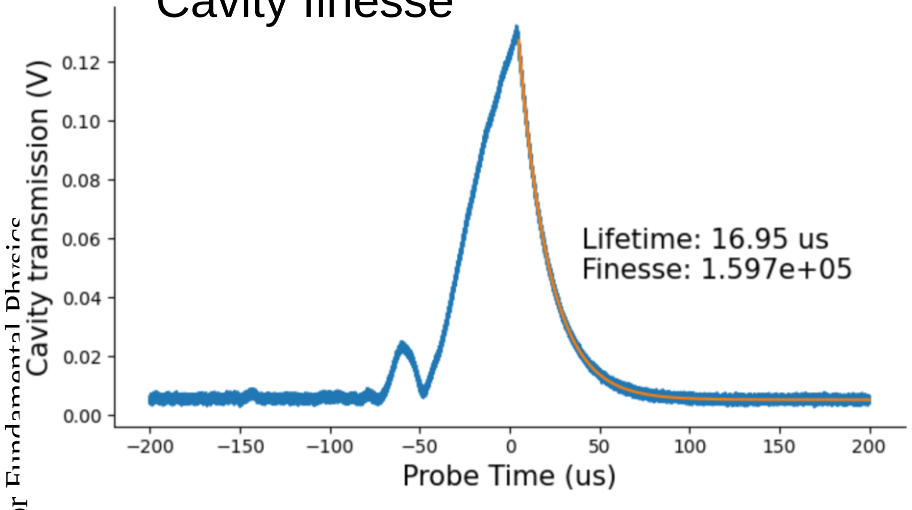
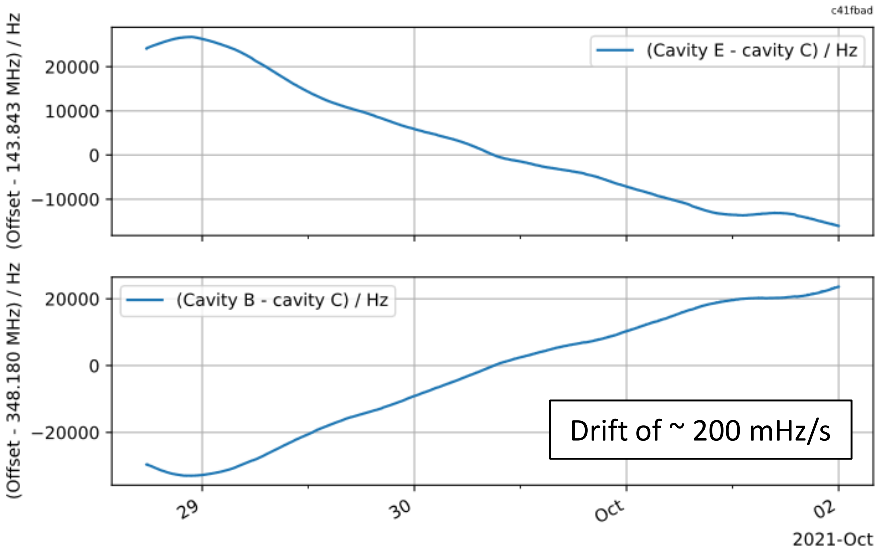
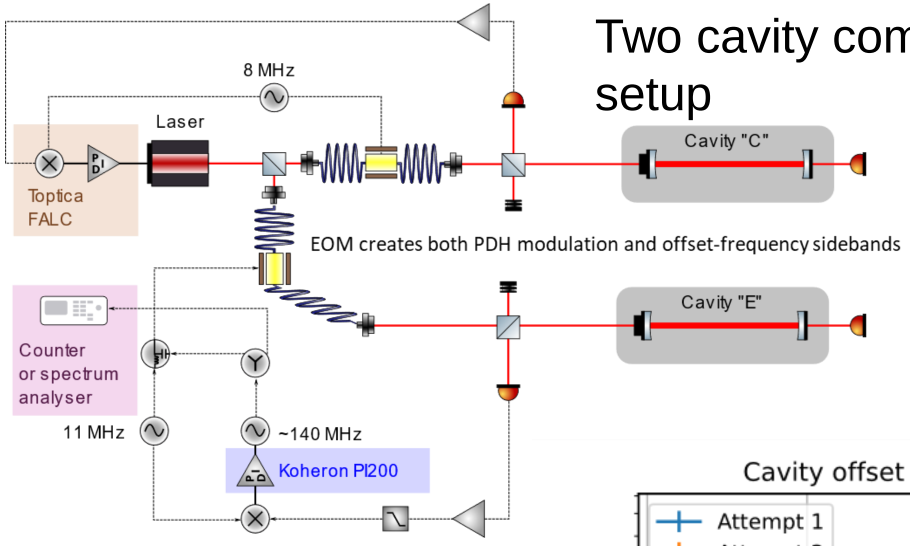
# PERFORMANCE OF LASER STABILIZATION SYSTEM

## Cavity finesse

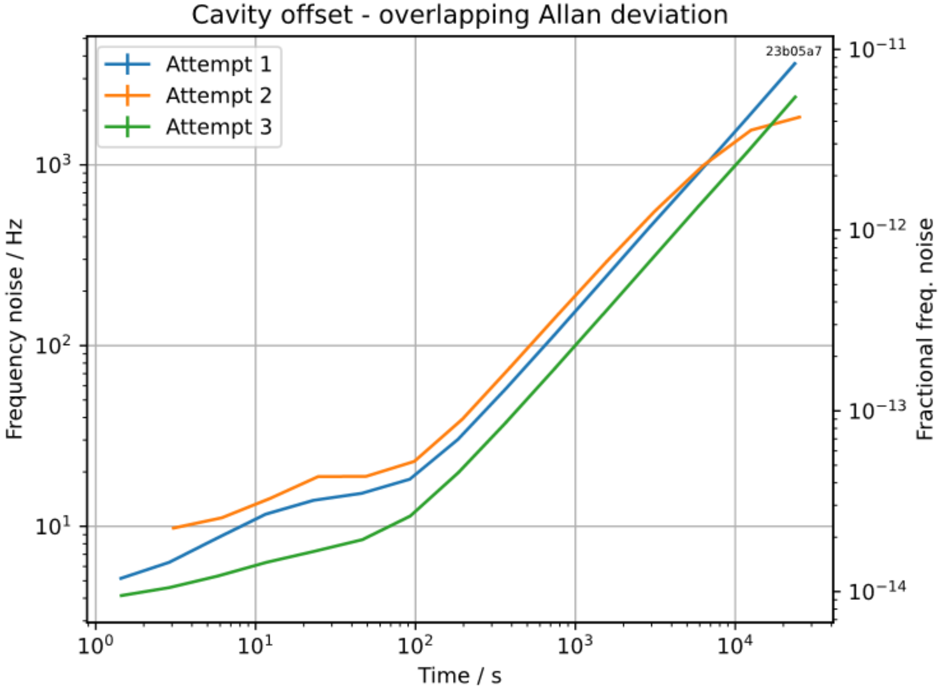



## Two cavity comparison setup

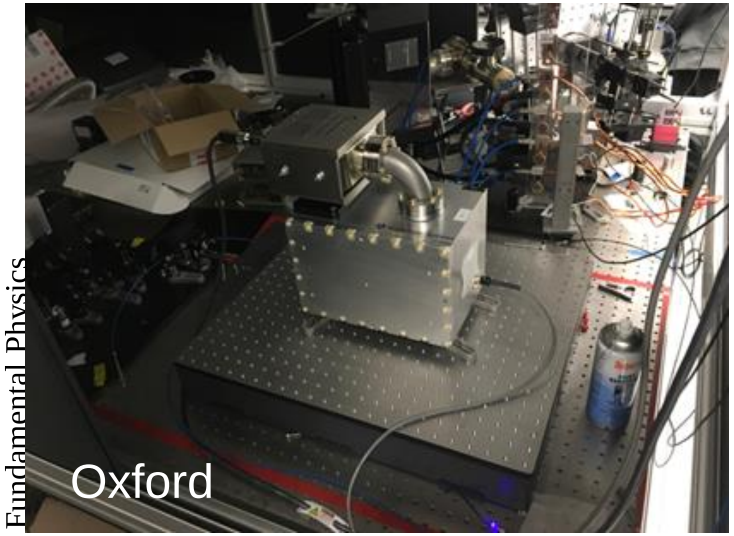


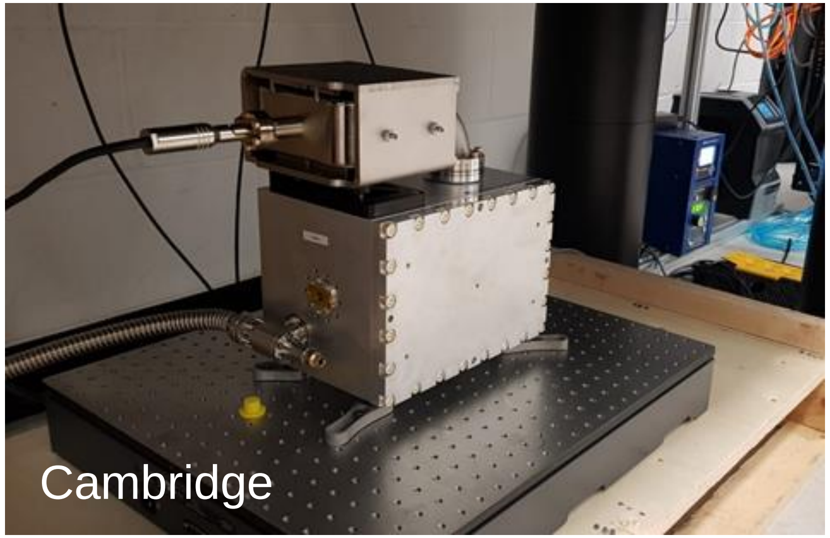

- Noise floor of ~4Hz @ 1s averaging time
- Assuming equal noise on both cavities: ~3 Hz = 7 x $10^{-15}$
- Theoretical limit set by Brownian motion of mirror coating: ~ 1 x $10^{-15}$

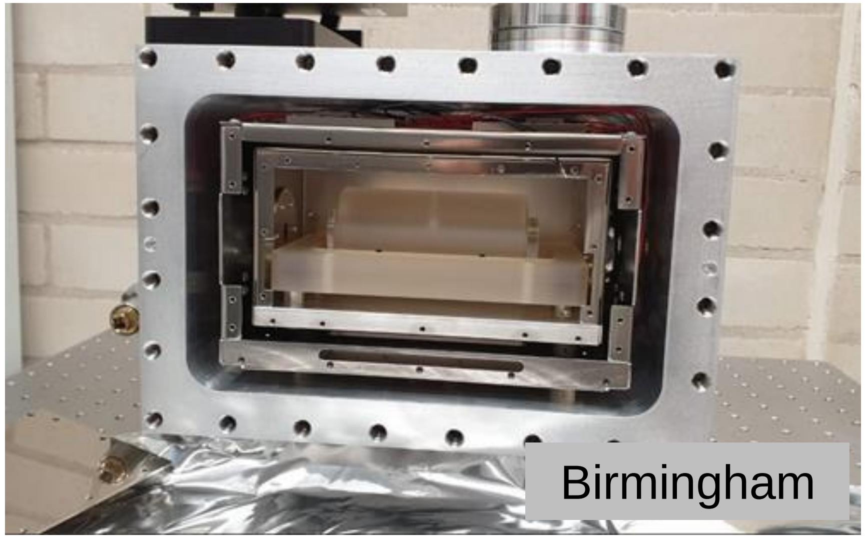


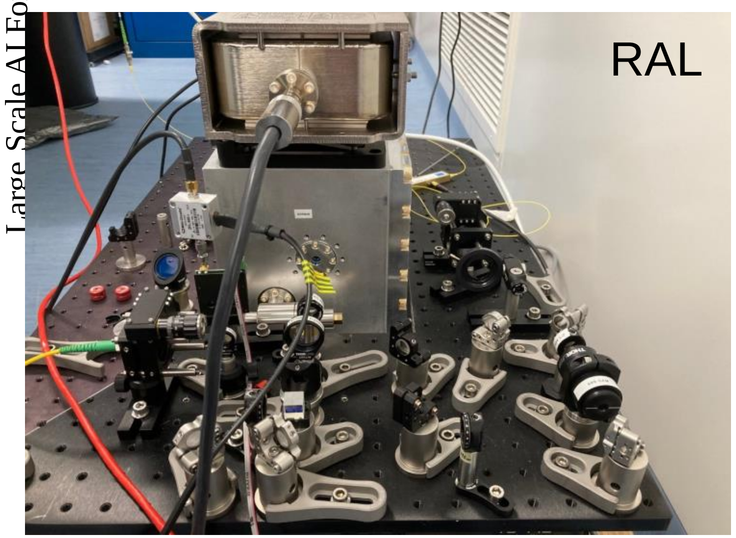
# INSTALLATION OF LASER STABILIZATION SYSTEM

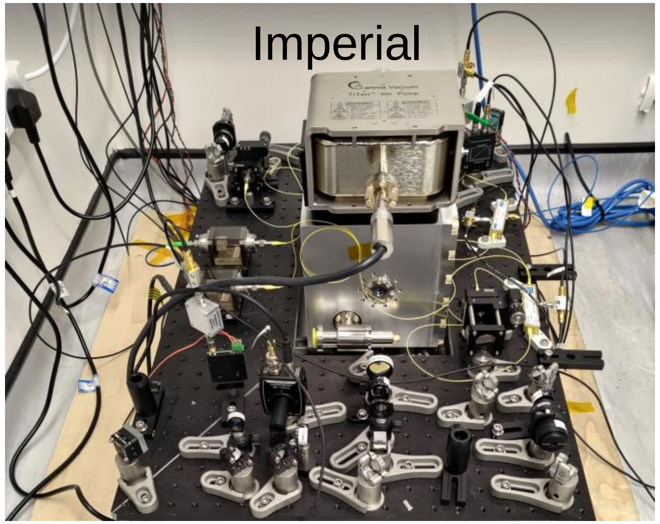




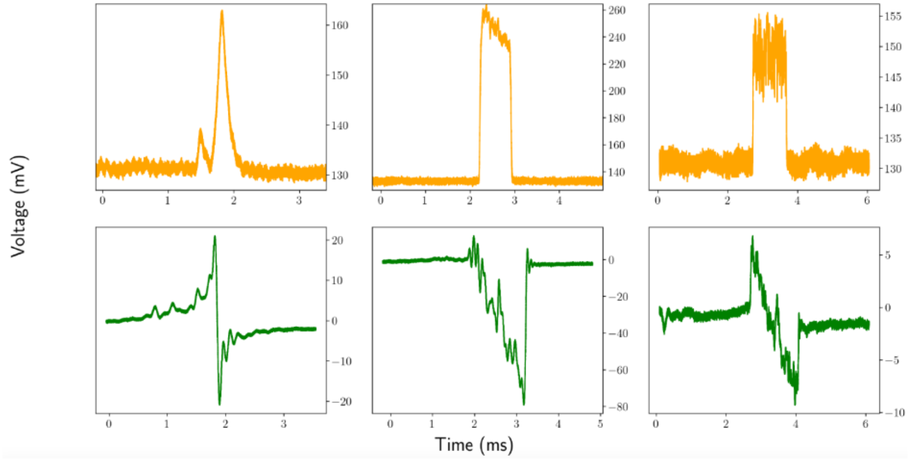



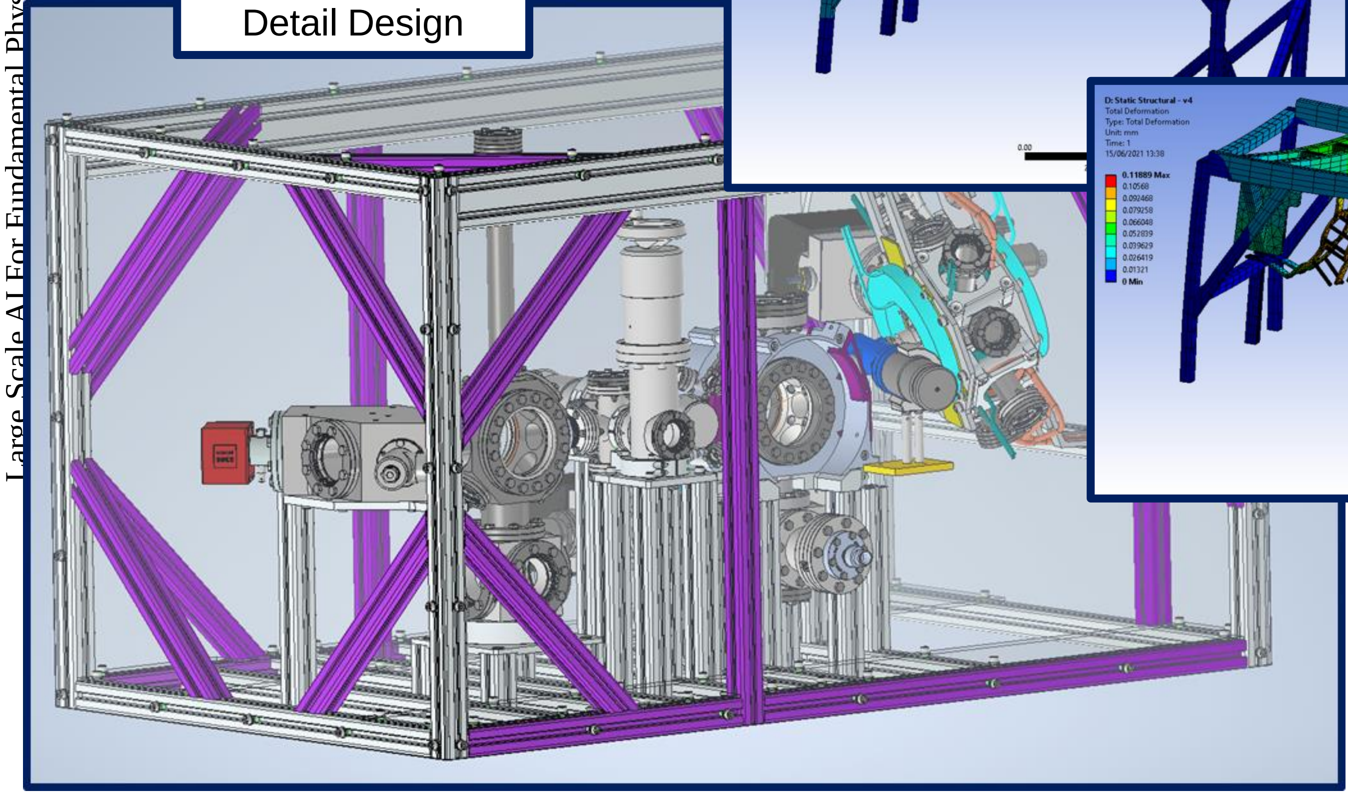

Below: Transmission and error signal data at Imperial
Laser stays locked for several days autonomously



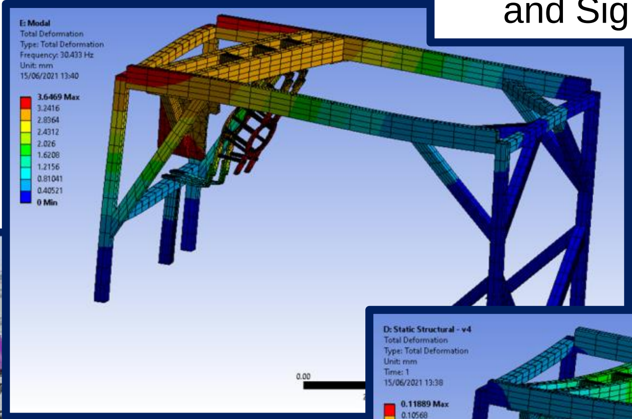
# Ultra-High Vacuum System: Centralized Design

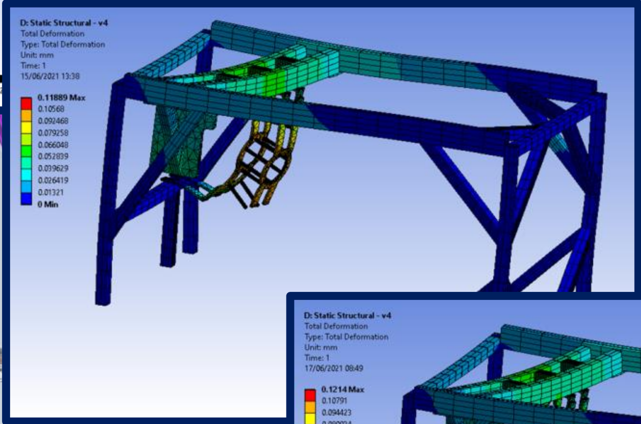
## Design and Analysis

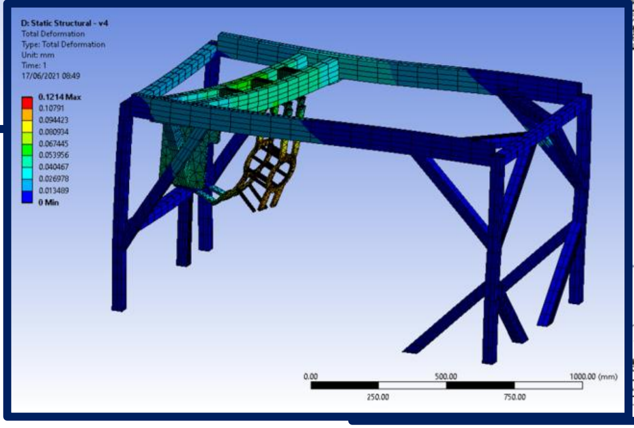
Conceptual – Detail Design



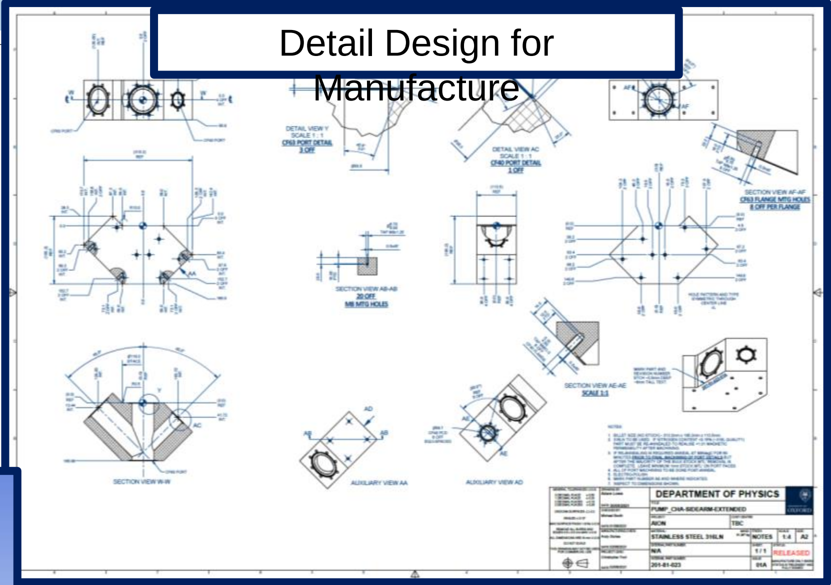
Structural Analysis and Sign Off

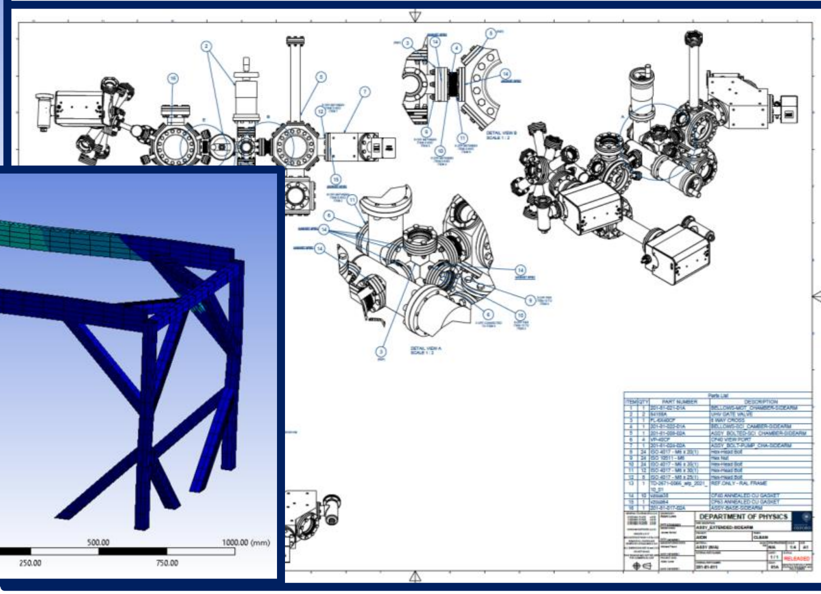



Detail Design for Manufacture



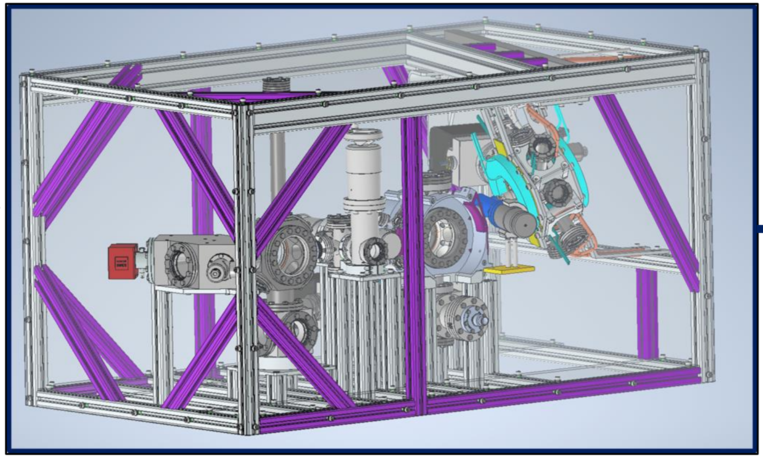



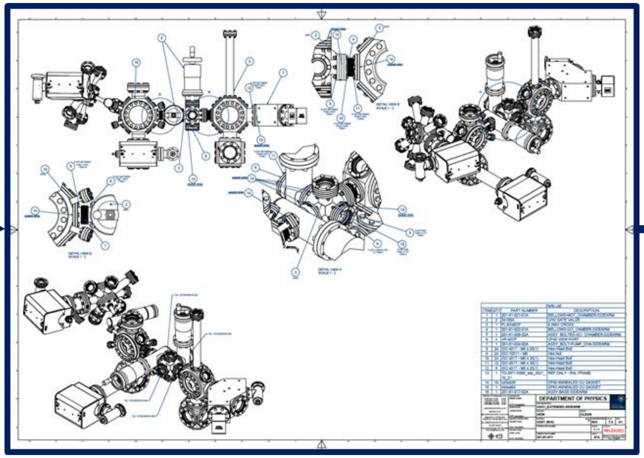

Large Scale AI For Fundamental Physics

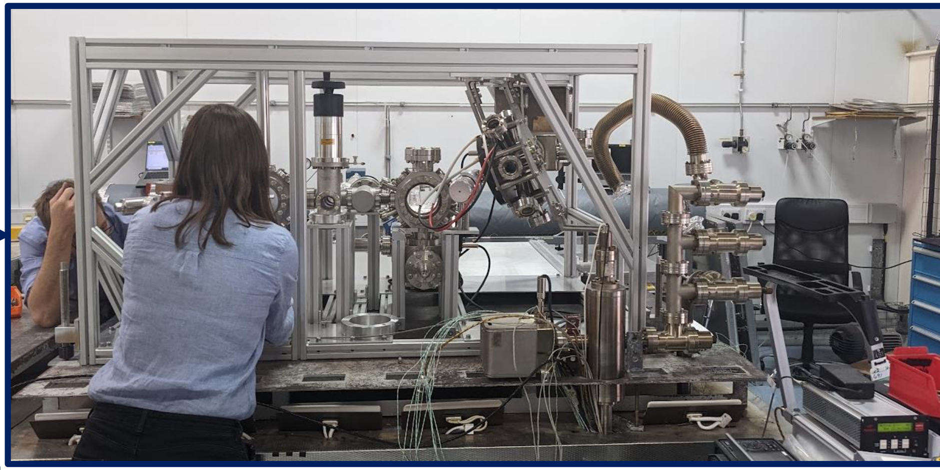
# Ultra-High Vacuum System: Centralized Construction

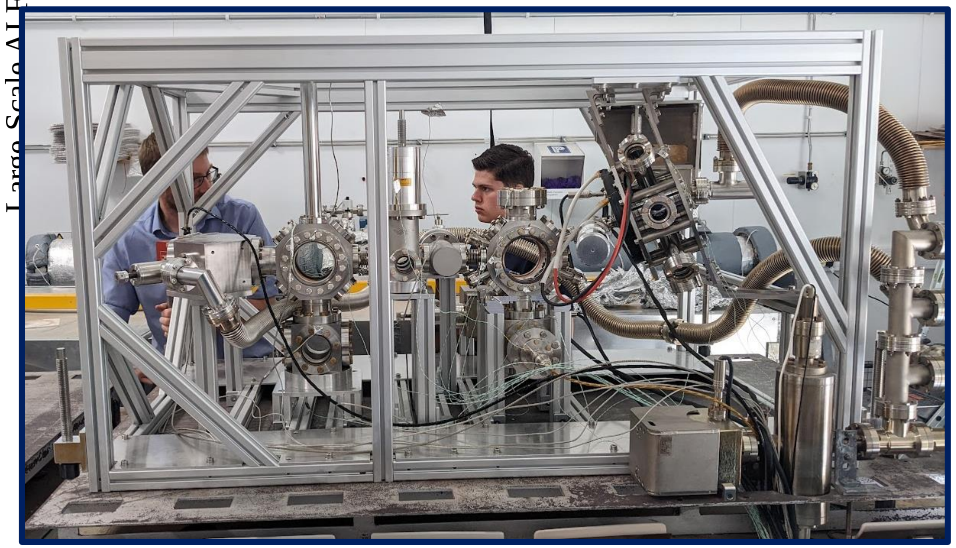
## Manufacturing, Assembly and Installation

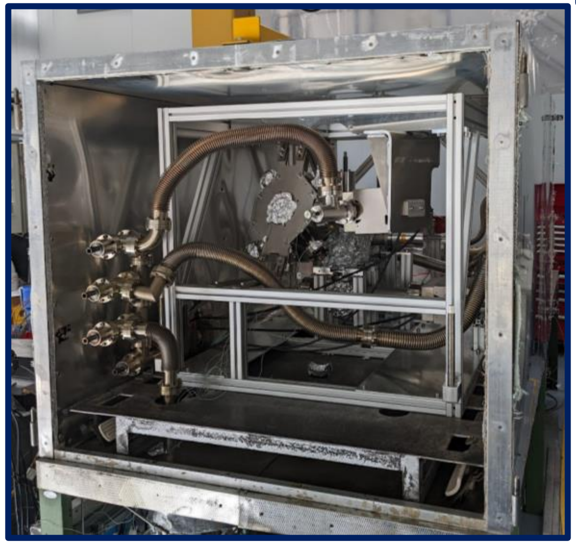


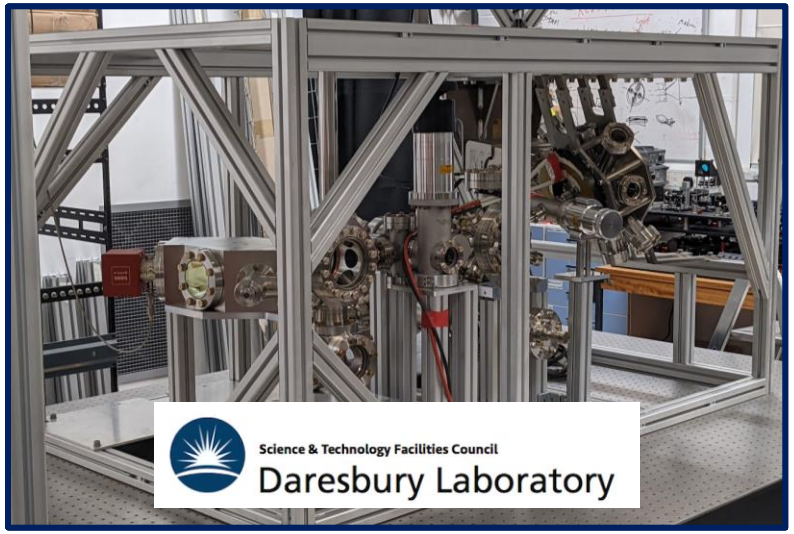










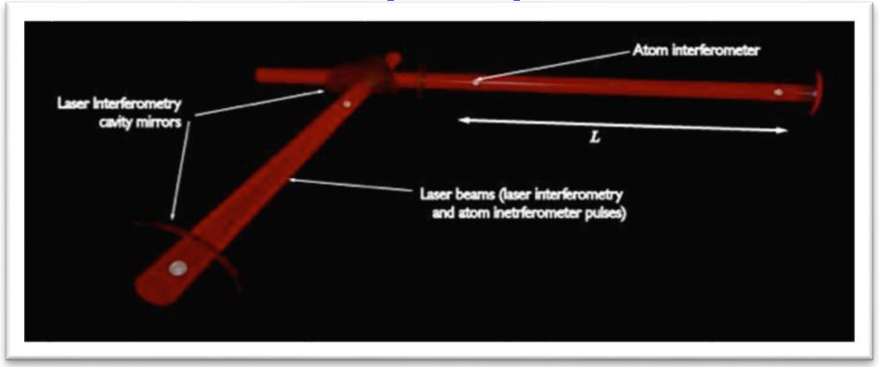



5 Ultra Cold Sr Labs build in less than 18 months using large scale HEP production methods to significantly accelerate the turnaround – this will be critical for future success!

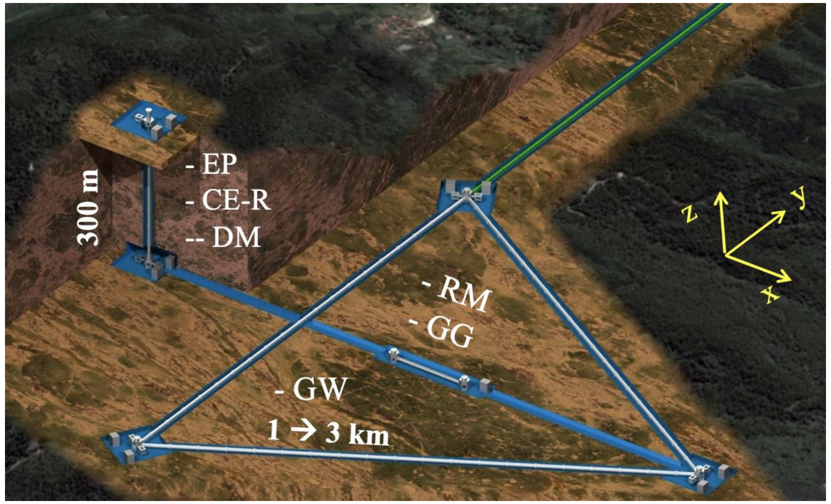
# Ground Based Large Scale O(100m) Projects



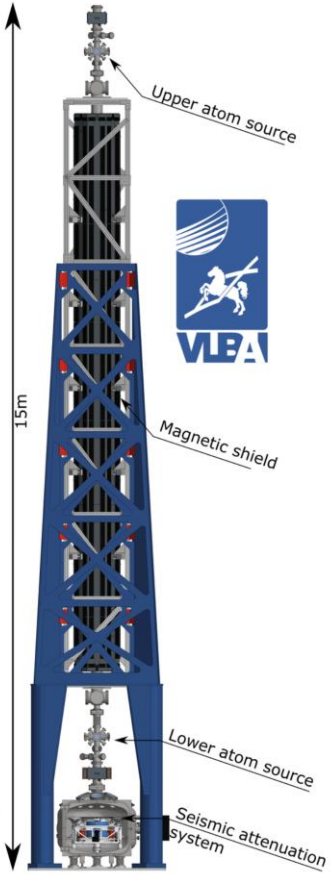
**MIGA: Terrestrial detector using atom interferometer at O(100m)**
**(France)**

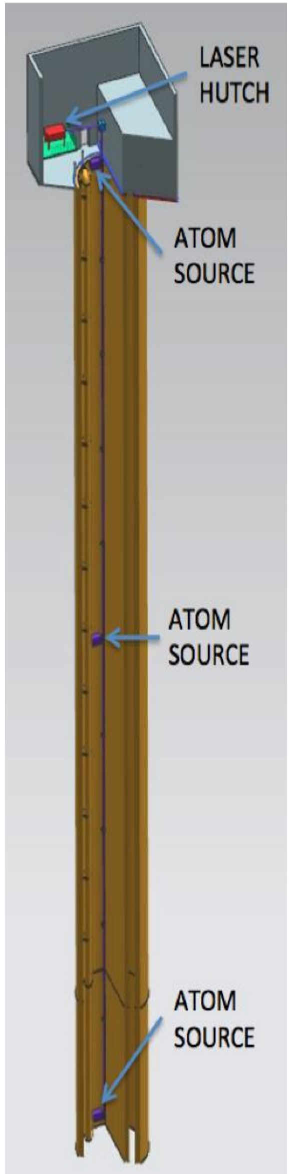



**ZAIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)**
**(China)**

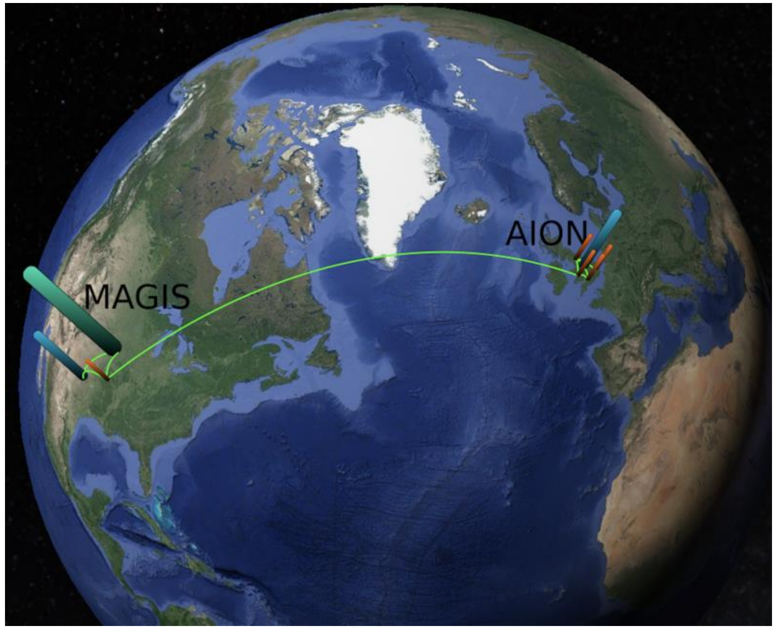



**VLBAI: Terrestrial tower using atom interferometer O(10m)**
**(Germany)**




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




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

Planned network operation

# Ground Based Large Scale O(100m) Projects



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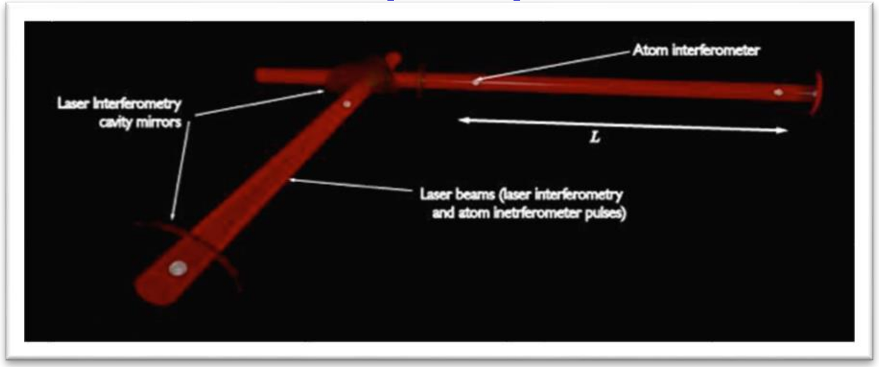


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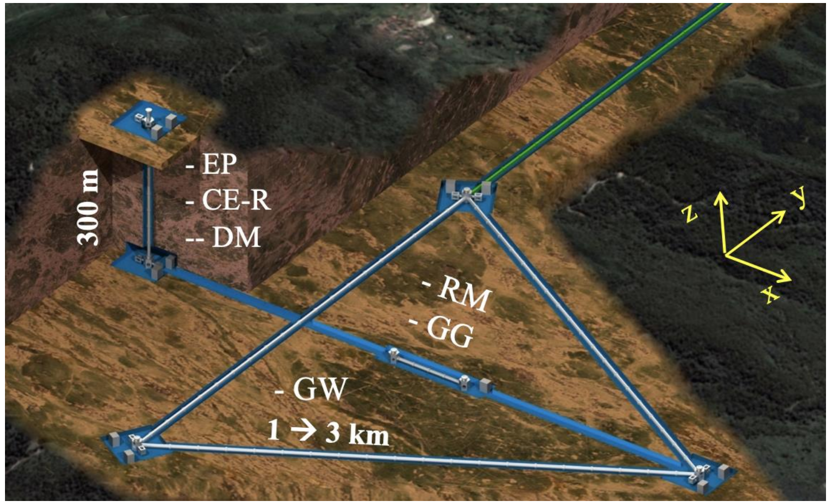


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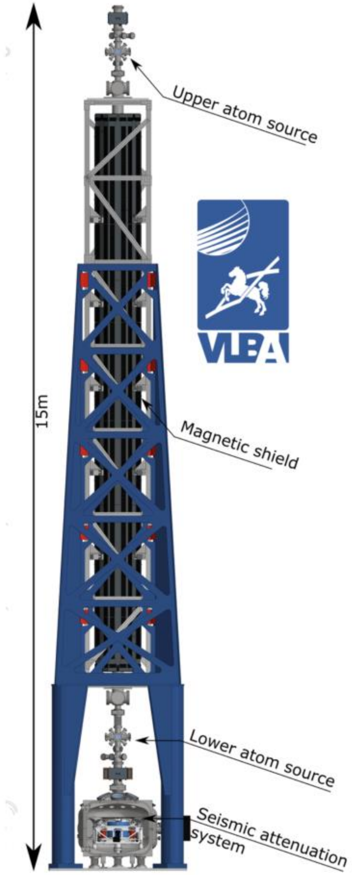


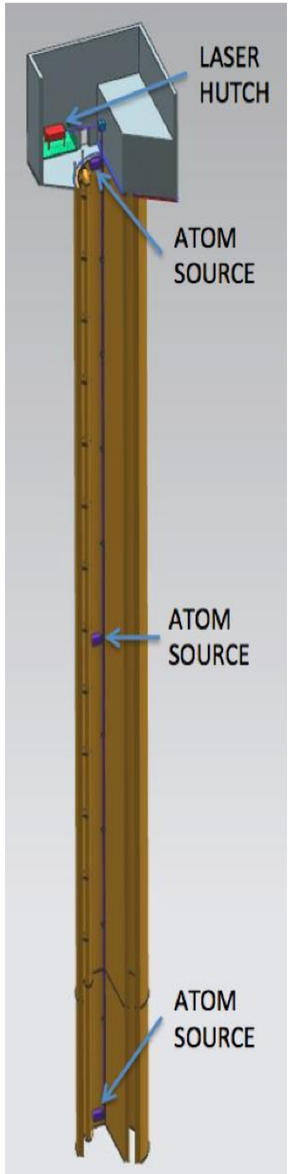


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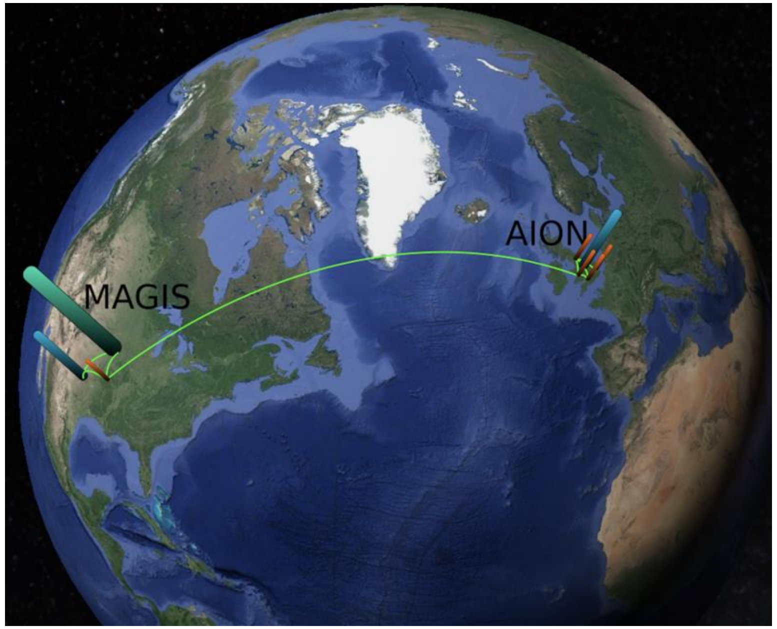


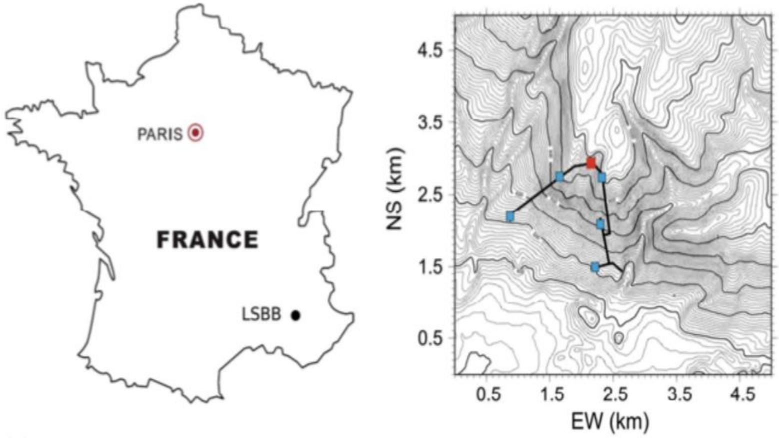

**MAGIS: Terrestrial shaft detector using atom interferometer at O(100m)**
**(US)**

Planned network operation

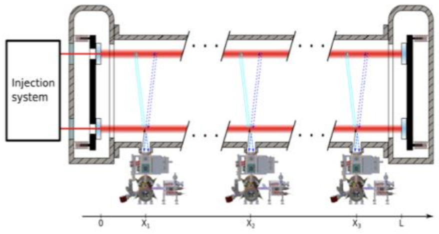
# Horizontal Designs: MIGA, ZAIGA, ELGRA

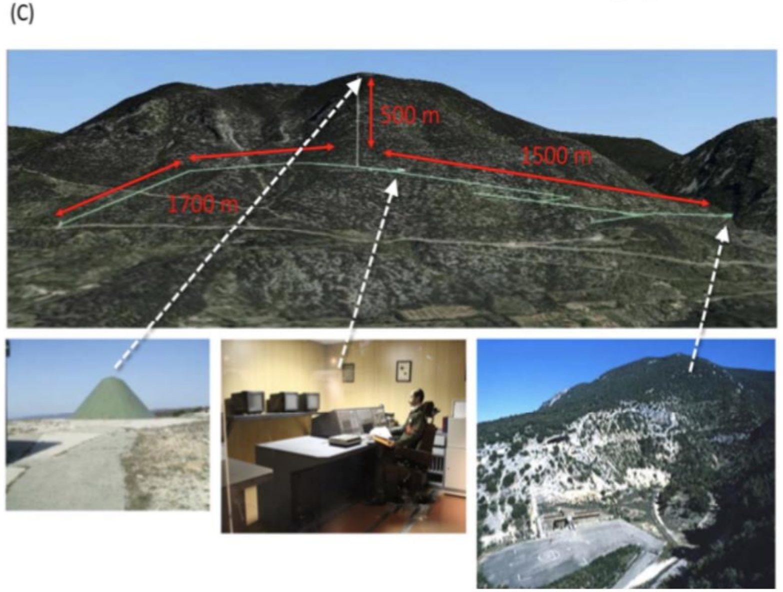
## The MIGA Large-Scale Atom Interferometer

Under construction in former nuclear bunker

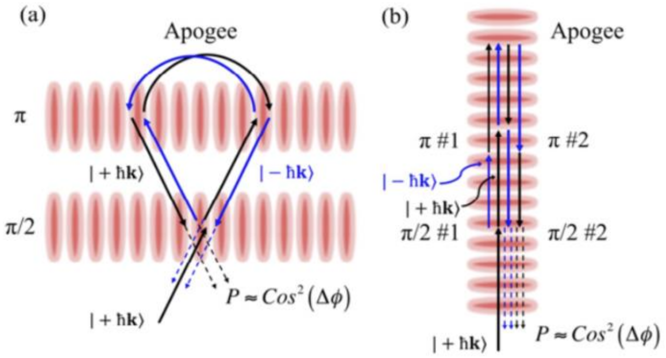


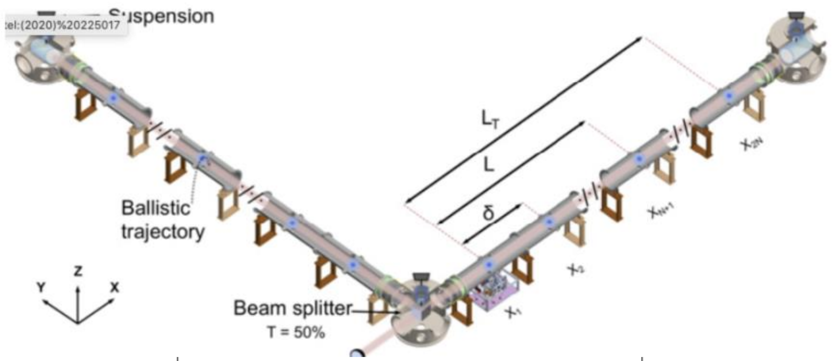

Atomic fountains illuminated by laser beams

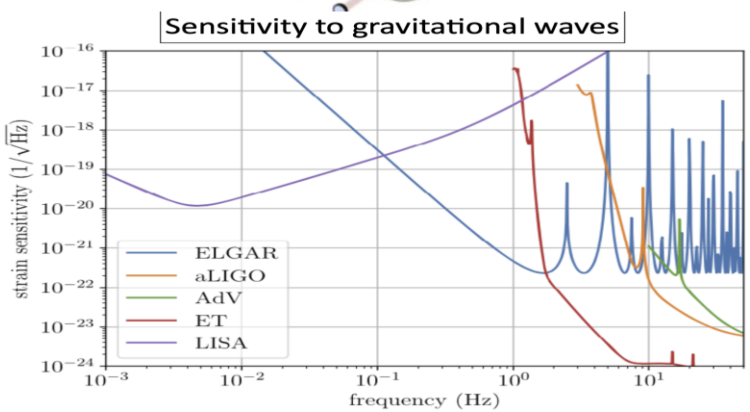



## Design for the ELGAR Atom Interferometer



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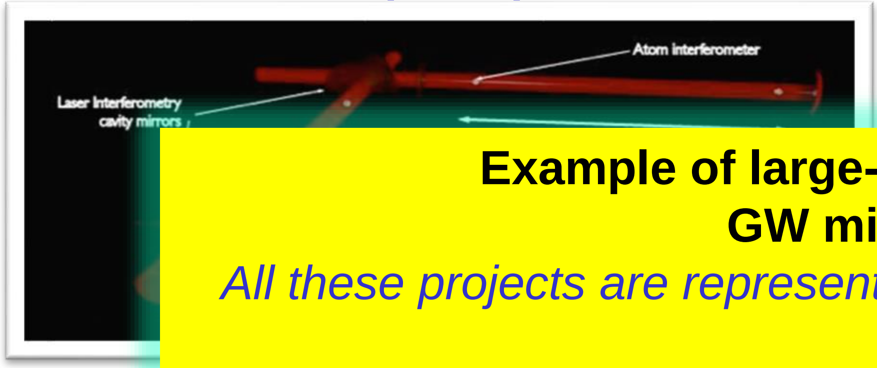


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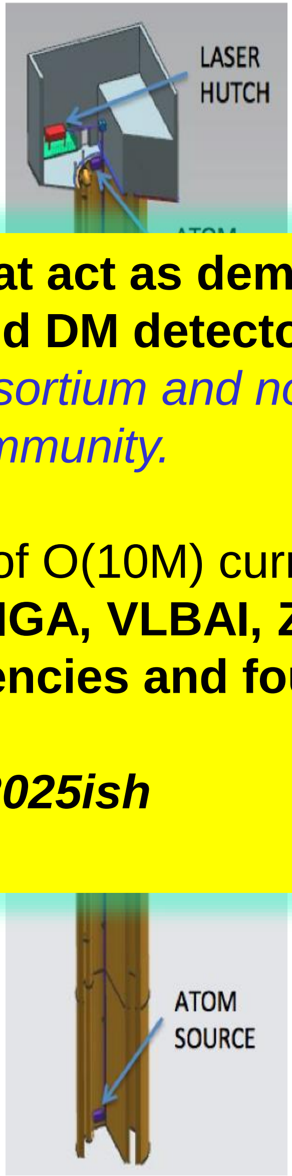


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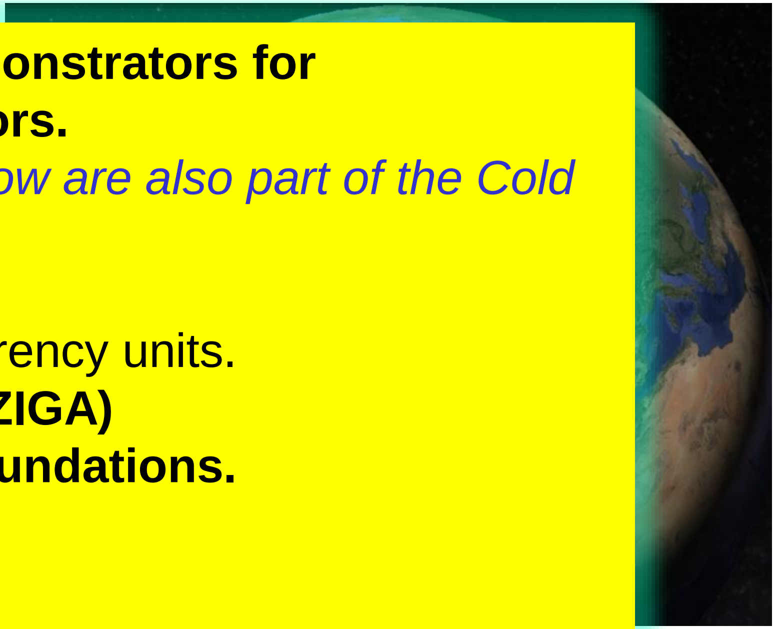


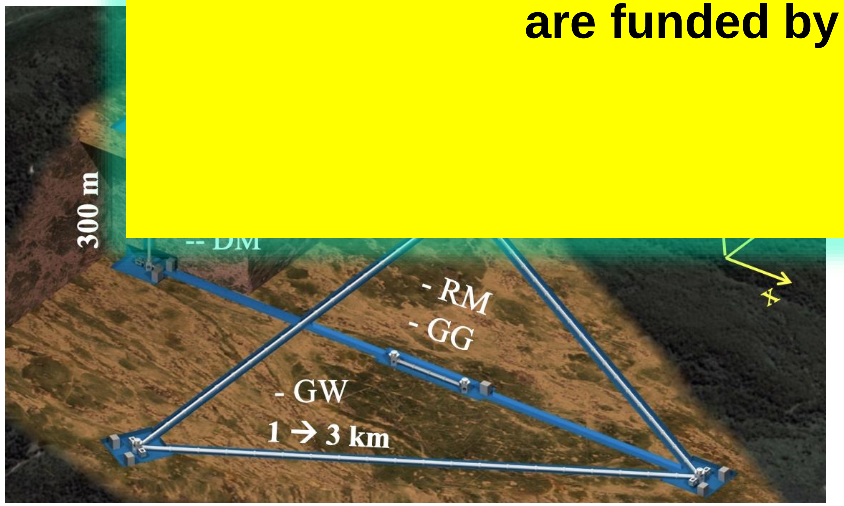
**Example of large-scale CA projects that act as demonstrators for GW mid-frequency band and DM detectors.**

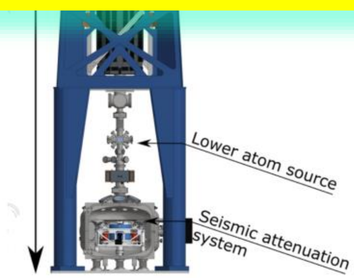
*All these projects are represented in the AEDGE consortium and now are also part of the Cold Atoms in Space Community.*

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***

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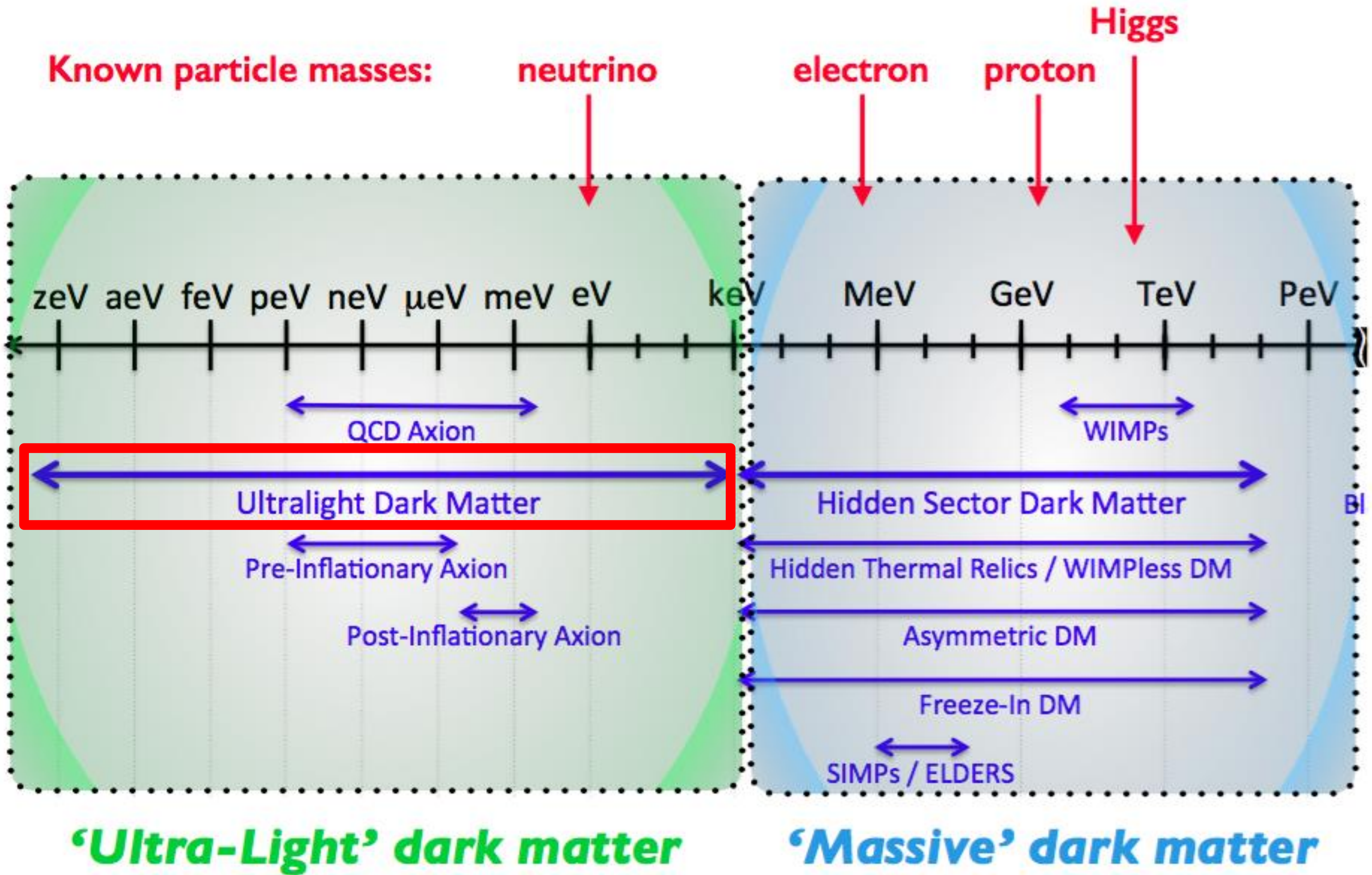
**Workshop will at CERN in the Council Chamber on March 13/14 2023 [announcement coming soon]**

# ULTRA-LIGHT DARK MATTER

# Search for Ultra-Light Dark Matter



# The Landscape of Ultra-Light Dark Matter Detection



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

Example: Ultra-Light Dark Matter:

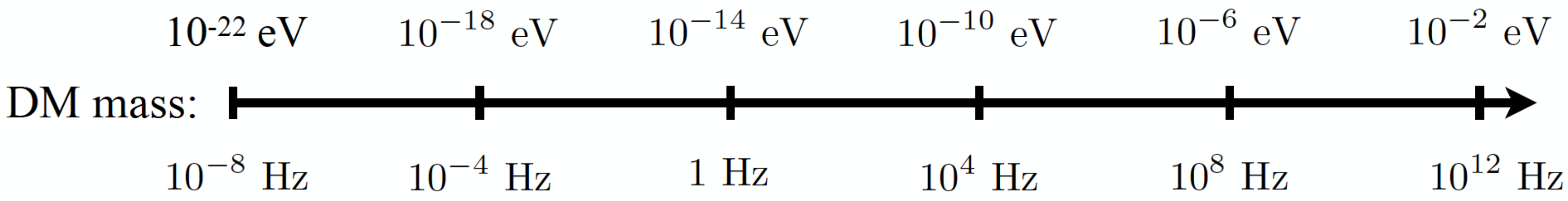



Diagram taken from P. Graham’s talk at HEP Front 2018

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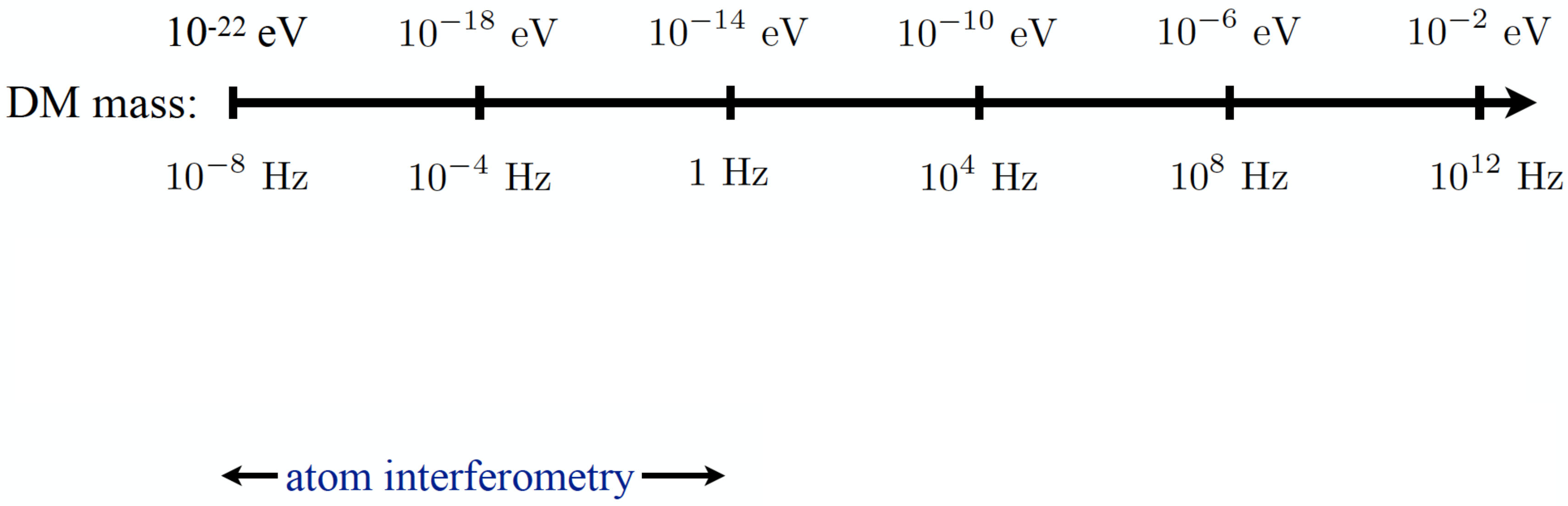


MAGIS/AION

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

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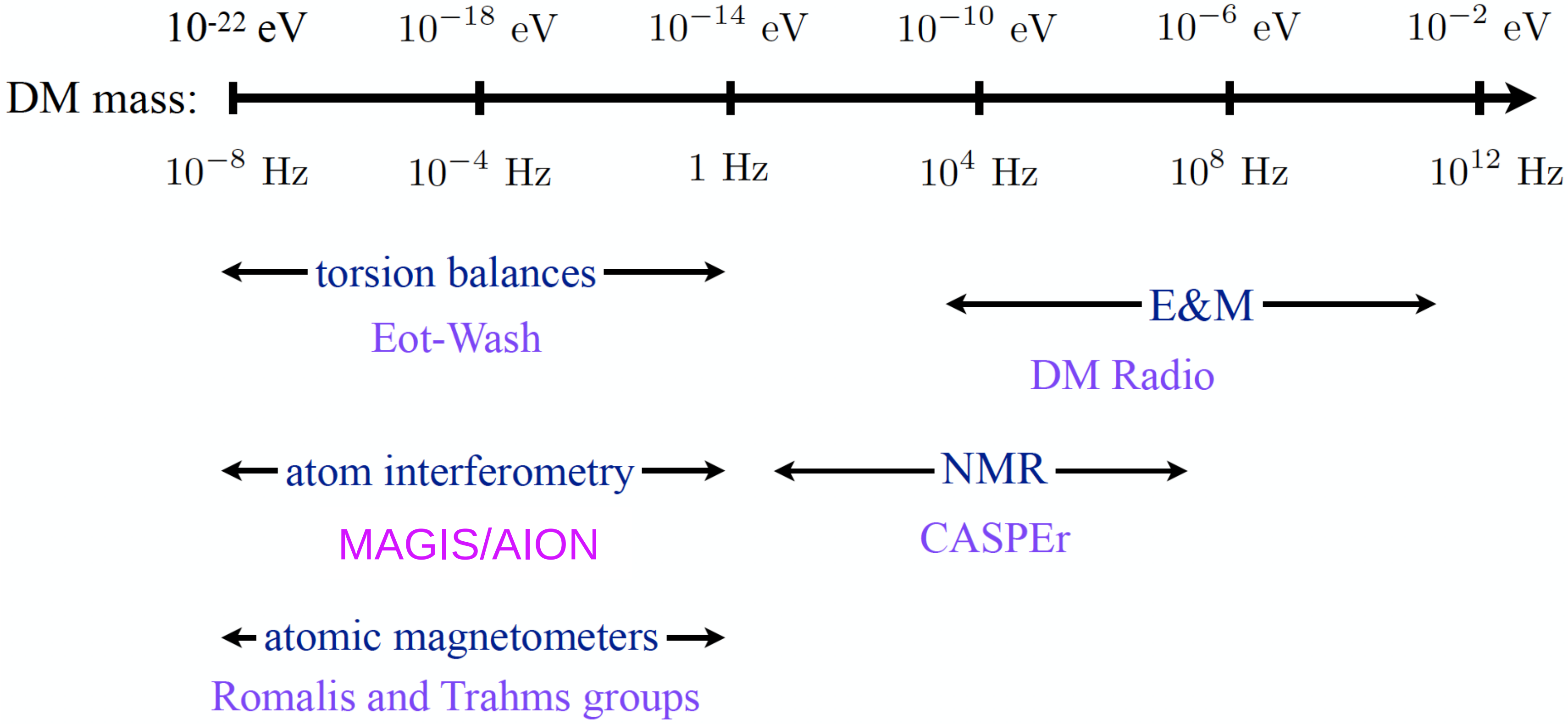



Diagram taken from P. Graham's talk at HEP Front 2018

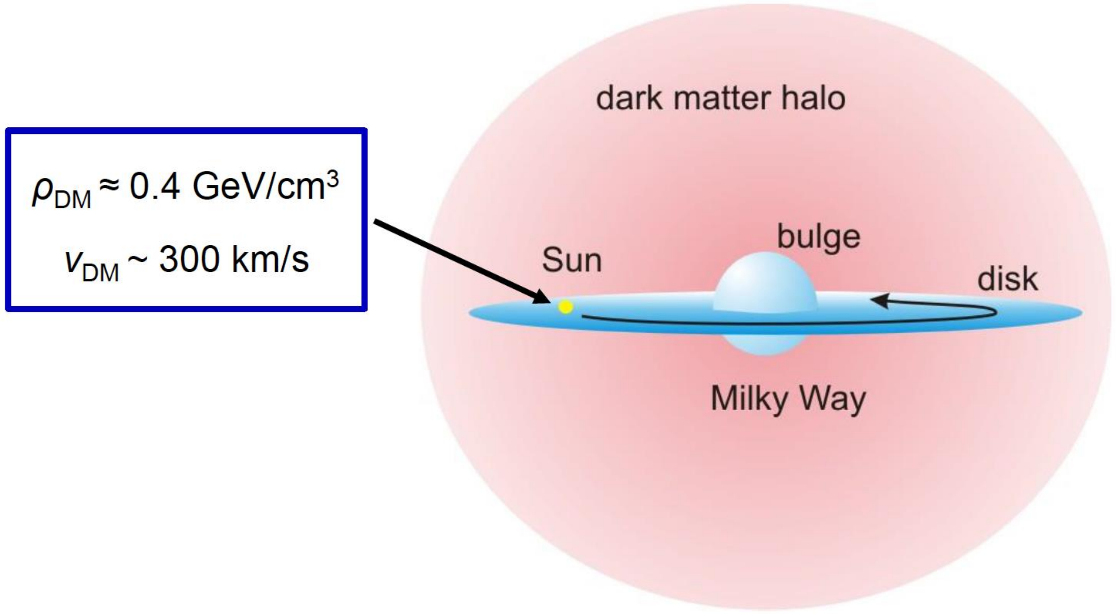
# Ultra-Light Spin-0 Dark Matter

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

$$< \rho_\phi > \approx m_\phi^2 \phi_0^2/2 \ (\rho_{DM,local} \approx 0.4 \ \mathrm{GeV/cm^3}).$$



# Ultralight scalar dark matter

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

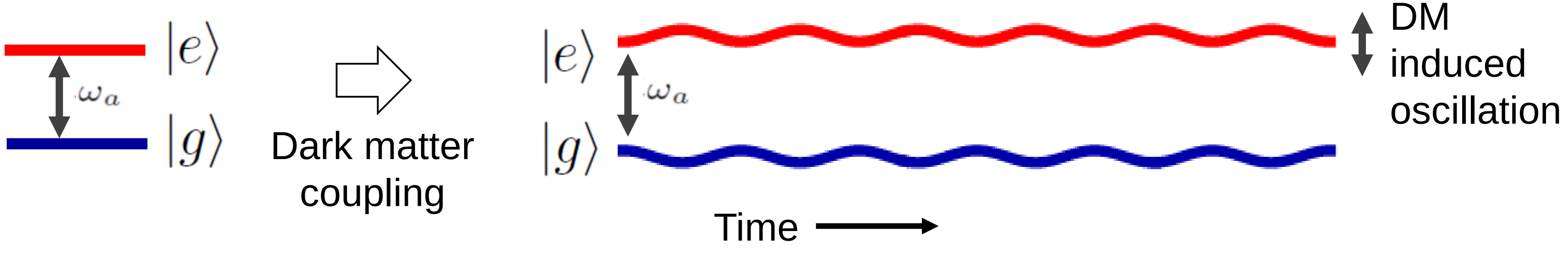
$$\mathcal{L} = +\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \sqrt{4\pi G_N}\phi\left[d_{m_e} m_e \bar{e}e - \frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}\right] + \ldots$$

- $\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2$: DM scalar field
- $d_{m_e} m_e \bar{e}e$: Electron coupling
- $\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}$: Photon coupling
- $\ldots$: 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:



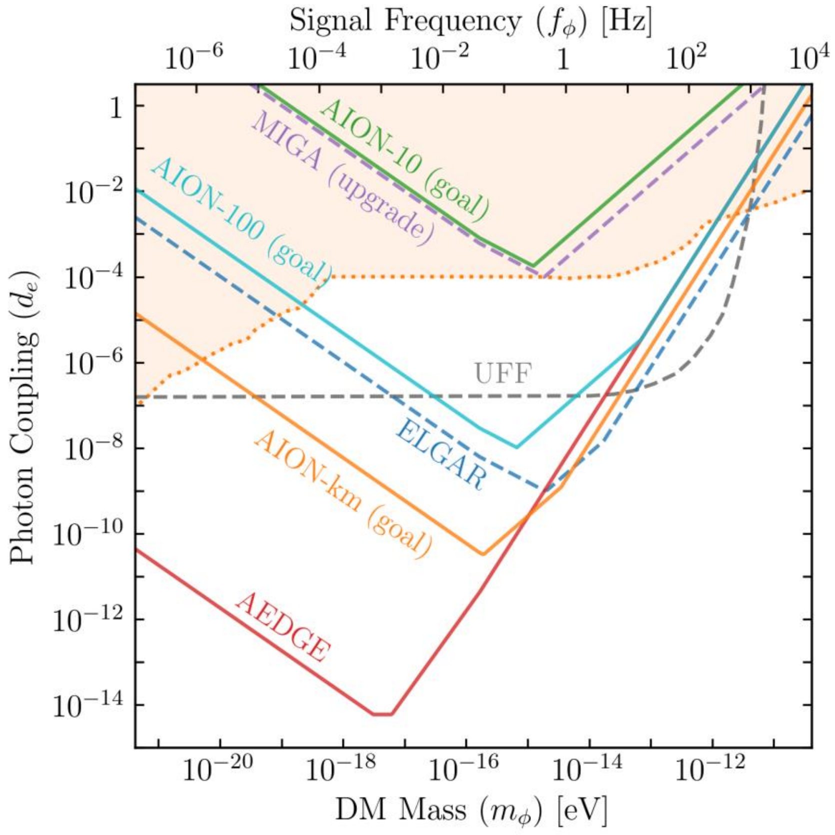

Courtesy of Jason Hogan!

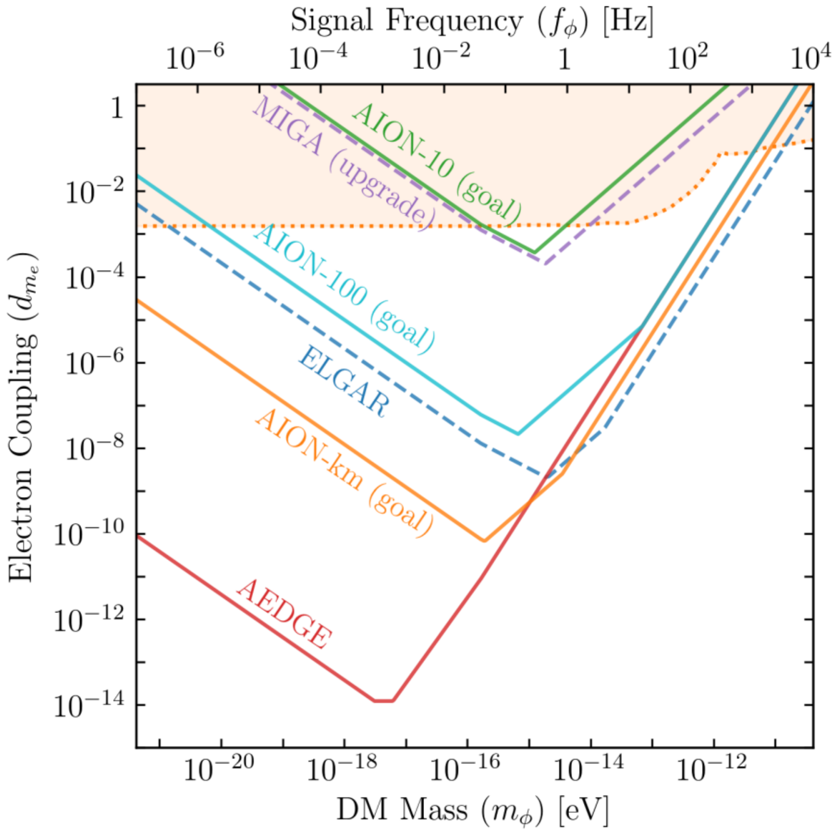
# Search for Ultra-Light Dark Matter



## Linear couplings to gauge fields and matter fermions

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



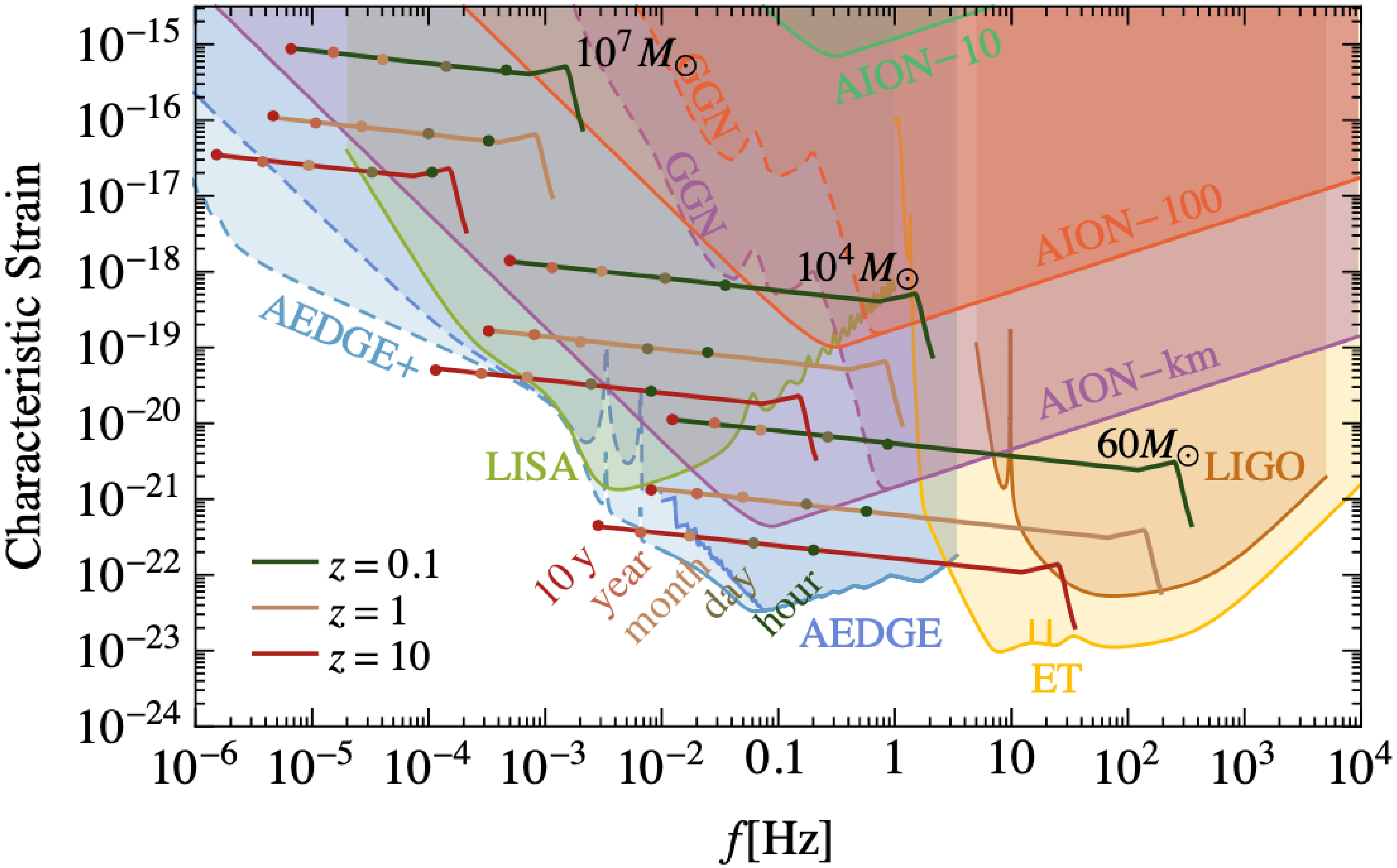

Orders of magnitude improvement over current sensitivities

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

# GRAVITATIONAL WAVES

# Vision for 2045+

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



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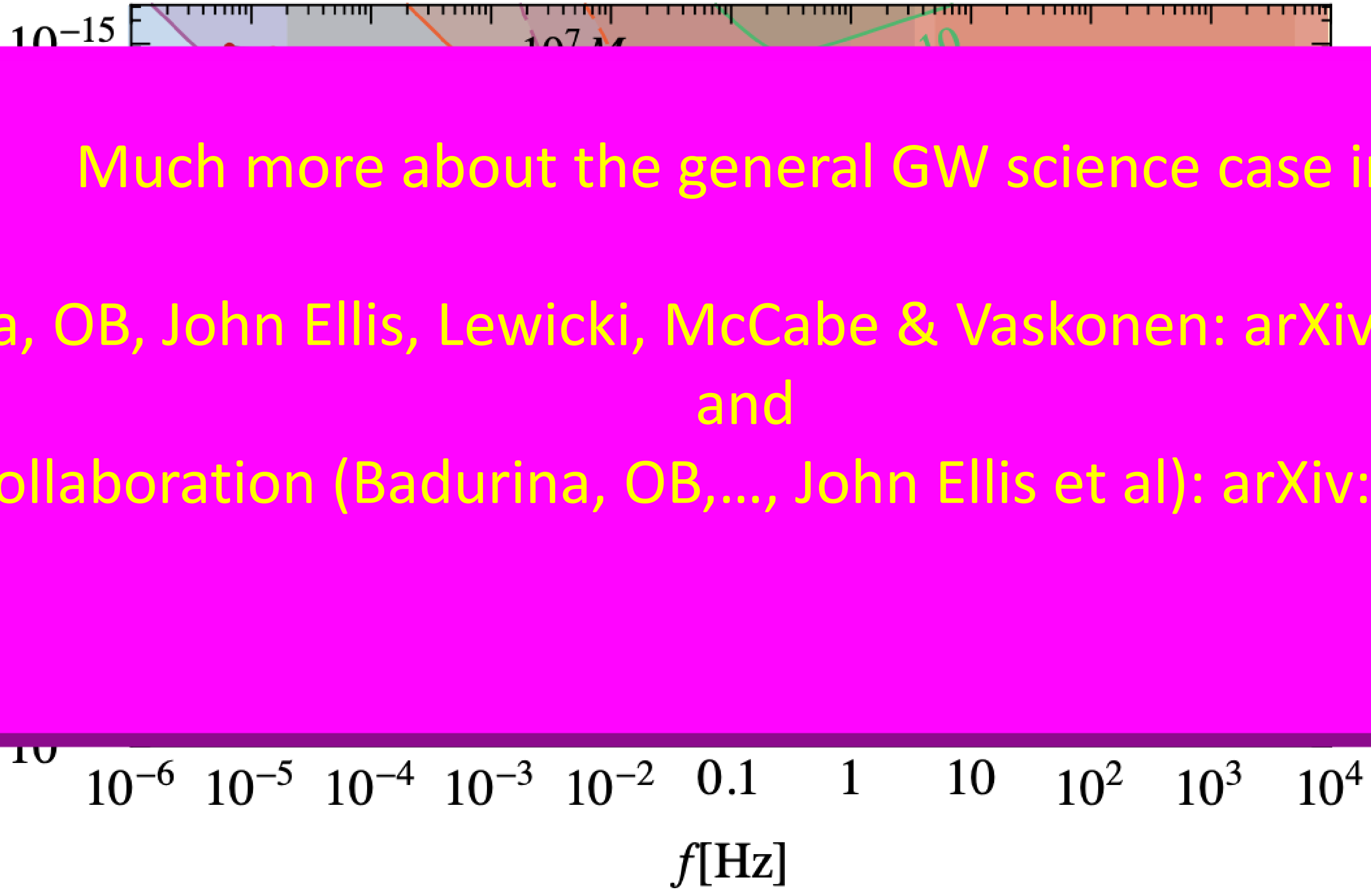



Much more about the general GW science case in:

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

and

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



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

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

# Other Fundamental Physics



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

Examples may include:

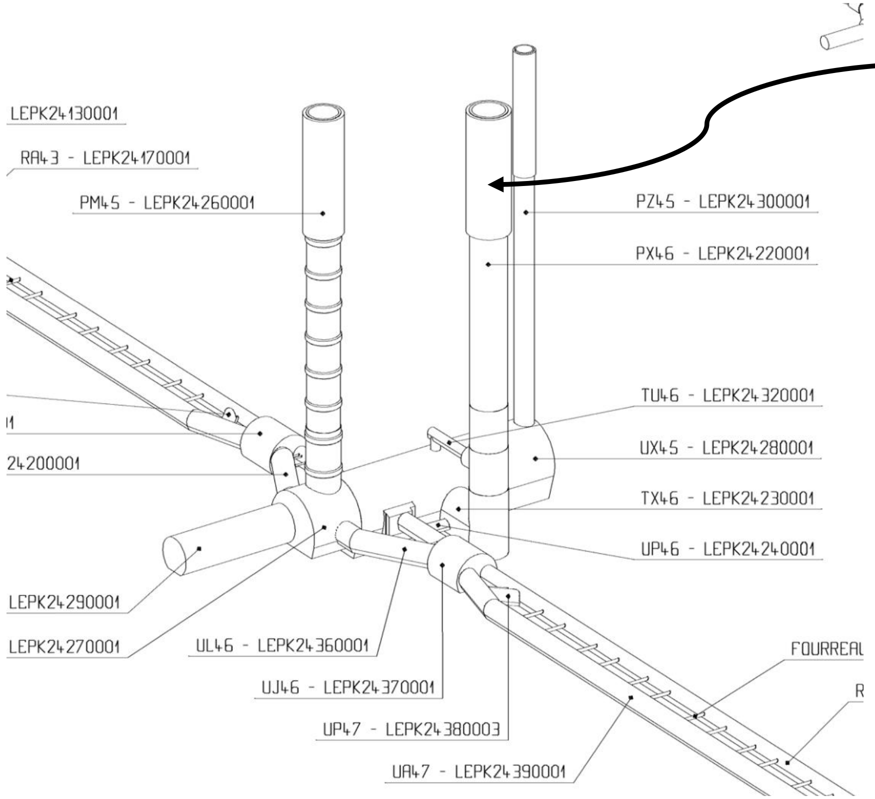
- *The possibility of detecting the astrophysical neutrinos*
- *Probes of long-range fifth forces*.
- *Constraining possible variations in fundamental constants.*
- *Probing dark energy*.
- Probes of basic physical principles such as foundations of quantum mechanics and Lorentz invariance.

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

# BACKUP

# Possible CERN Site for AION 100m






## PX46 – P4 Support shaft

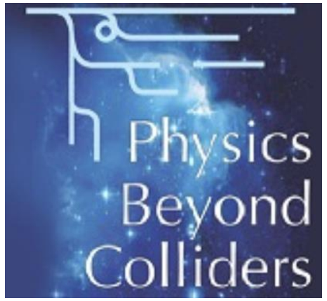
Lengths 143m

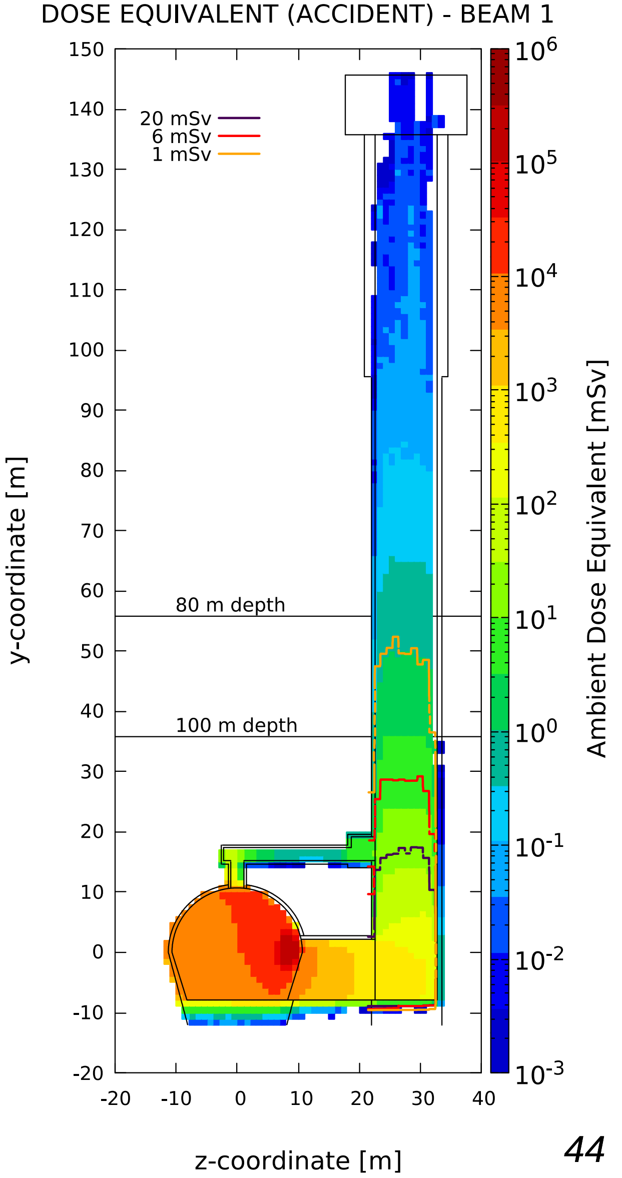
D = 10.10m

- **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.

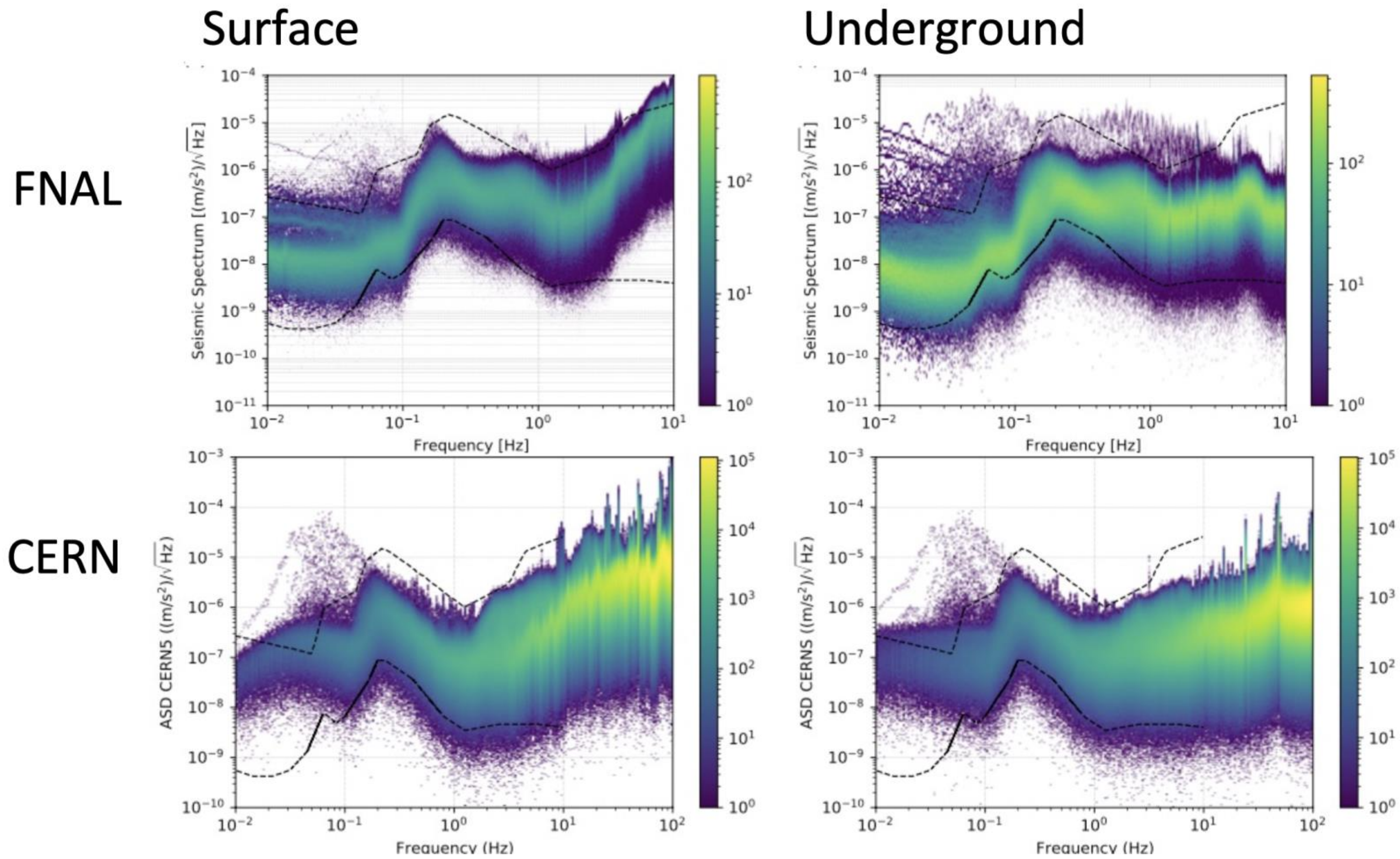
**We are working with PBC Team on this feasibility study**

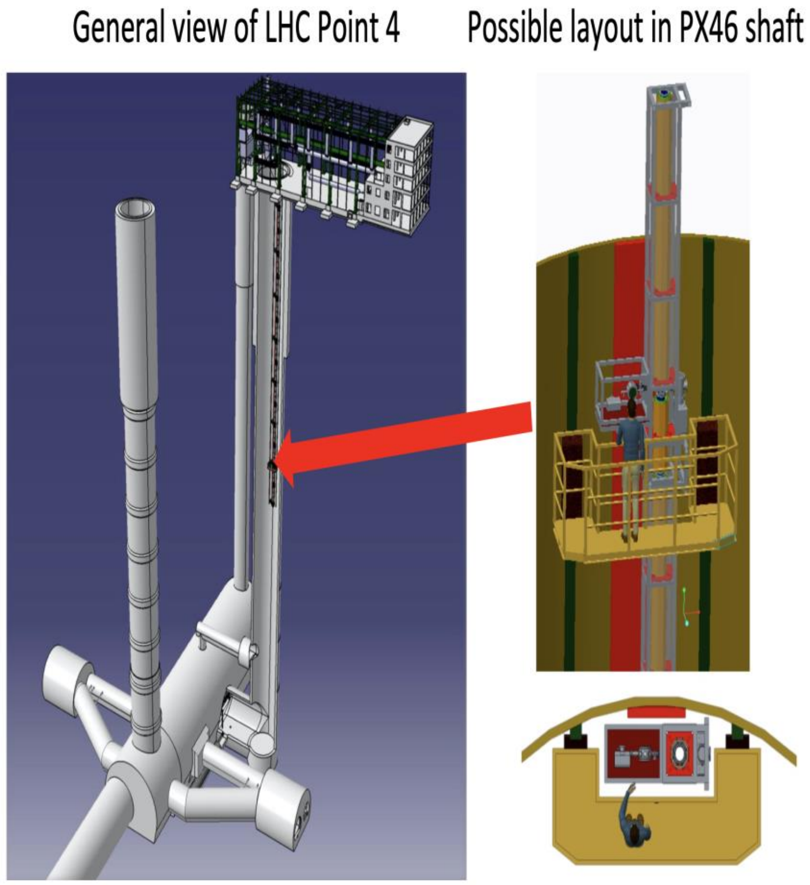



Other site options that are currently investigated are the ***national facility in Boulby and Daresbury (UK).***

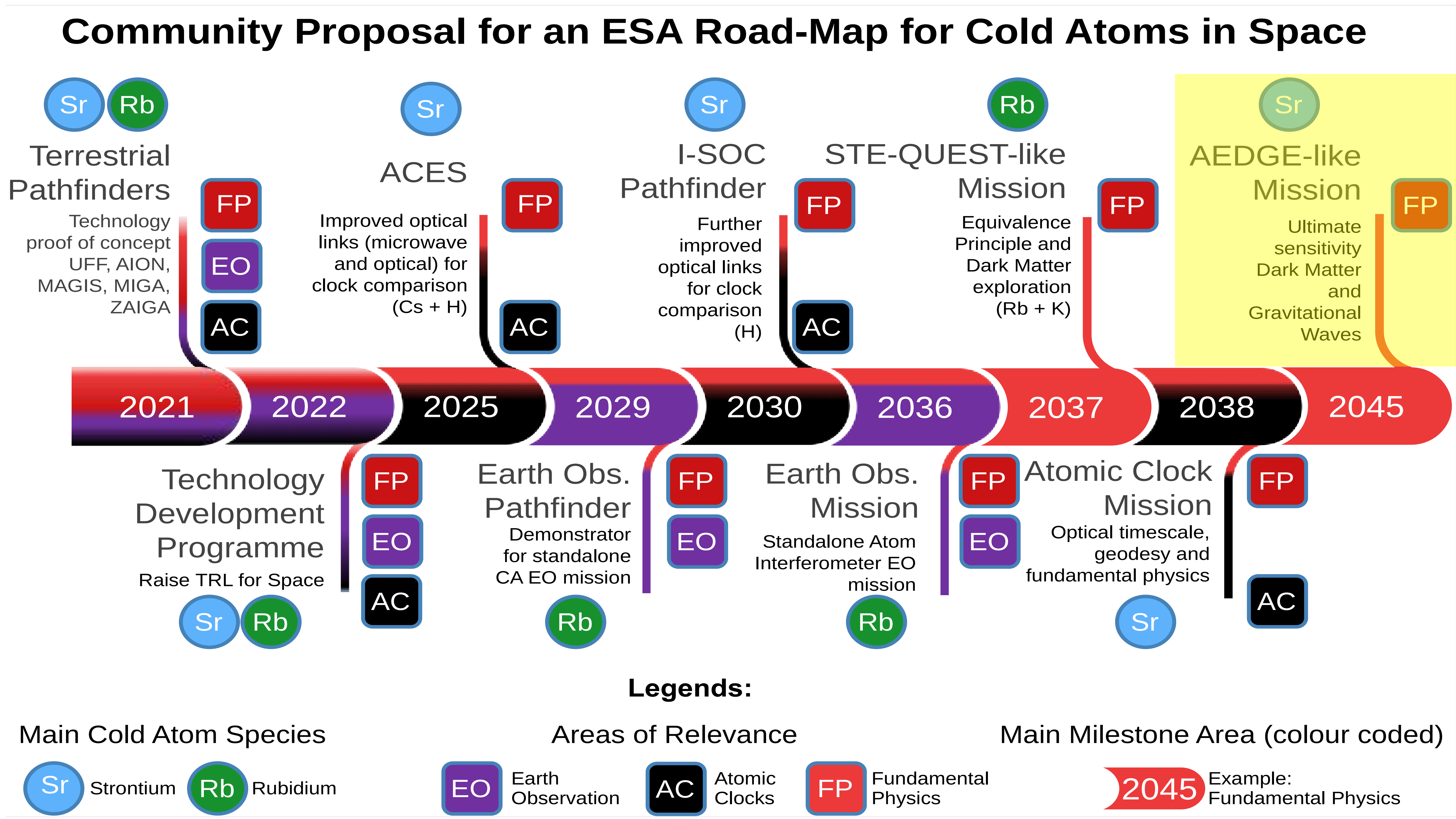
# A 100 Detector at CERN – Site Investigation



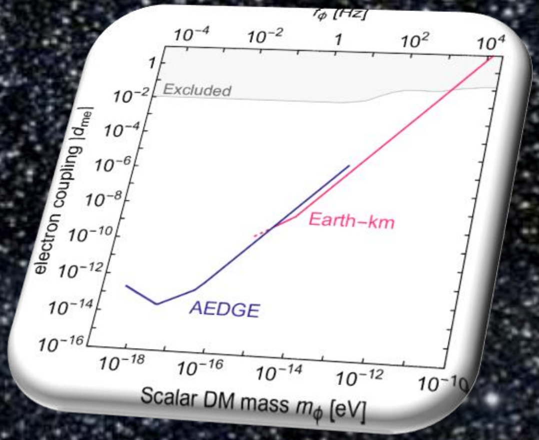

**Spectrum similar to that measured at Fermilab for MAGIS**
**More about the site investigation in the backup**

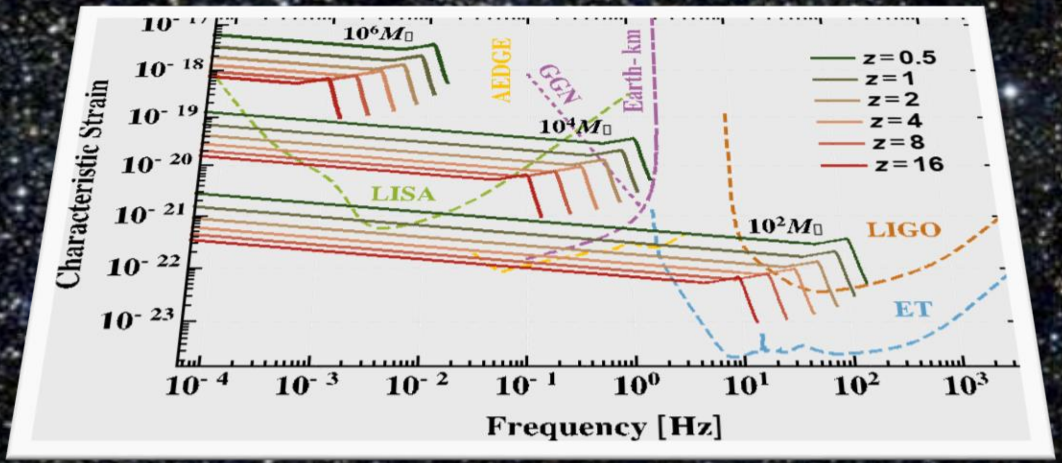
# AEDGE AND STE-QUEST



Community Proposal for an ESA Road-Map for Cold Atoms in Space
Sr
Rb
Terrestrial Pathfinders
Technology proof of concept UFF, AION, MAGIS, MIGA, ZAIGA
FP
EO
AC
Sr
ACES
Improved optical links (microwave and optical) for clock comparison (Cs + H)
FP
AC
Sr
I-SOC Pathfinder
Further improved optical links for clock comparison (H)
FP
AC
Rb
STE-QUEST-like Mission
Equivalence Principle and Dark Matter exploration (Rb + K)
FP
Sr
AEDGE-like Mission
Ultimate sensitivity Dark Matter and Gravitational Waves
FP
2021
2022
2025
2029
2030
2036
2037
2038
2045
Technology Development Programme
Raise TRL for Space
Sr
Rb
FP
EO
AC
Earth Obs. Pathfinder
Demonstrator for standalone CA EO mission
Rb
FP
EO
Earth Obs. Mission
Standalone Atom Interferometer EO mission
Rb
FP
EO
Atomic Clock Mission
Optical timescale, geodesy and fundamental physics
Sr
FP
AC
Legends:
Main Cold Atom Species
Sr Strontium
Rb Rubidium
Areas of Relevance
EO Earth Observation
AC Atomic Clocks
FP Fundamental Physics
Main Milestone Area (colour coded)
2045 Example: Fundamental Physics

# 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.**

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# AEDGE Mission Concept





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

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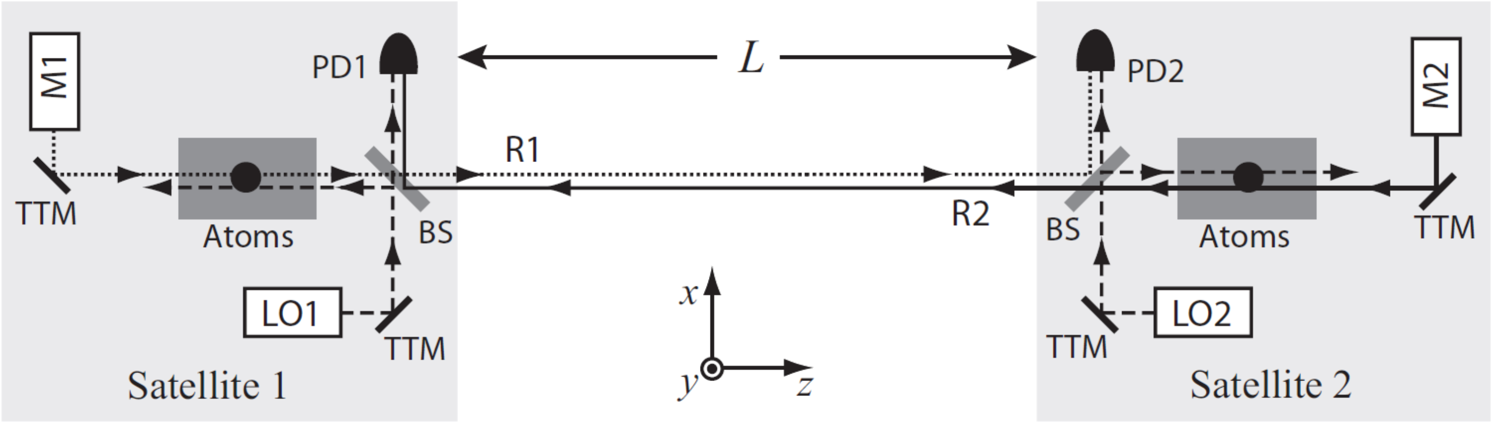
**132** Authors, from **70** institutions, based in **23** different counties!

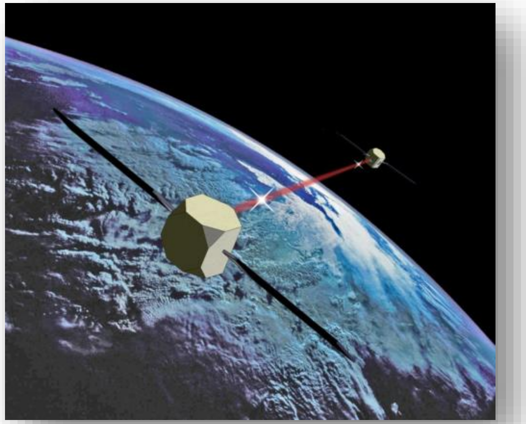
The authors represent several science communities ranging from Cold Atoms, & Gravitational Waves, over Cosmology and  Astrophysics to fundamental Particle Physics.

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.



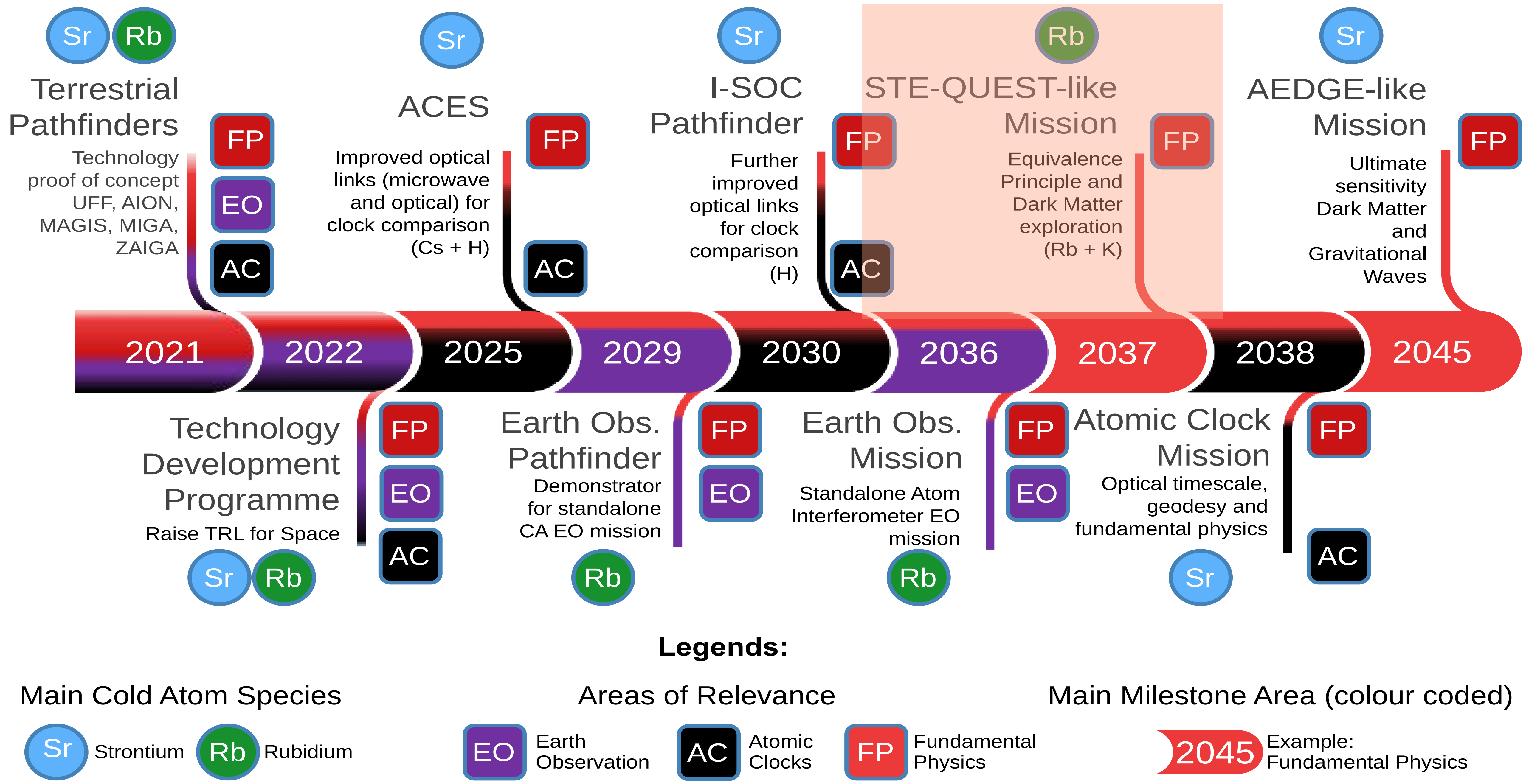
Assumed basic parameters:

- 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)

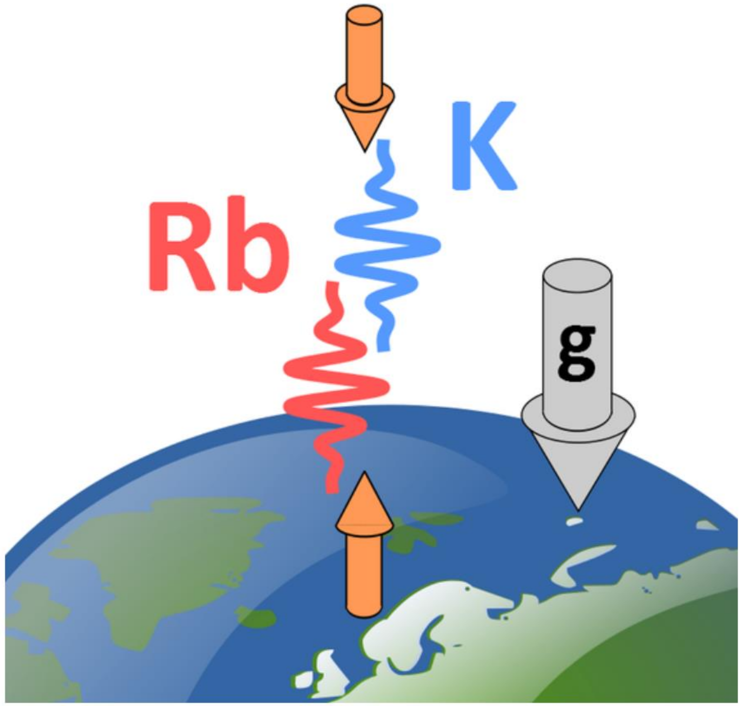




## STE-QUEST

## 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:**

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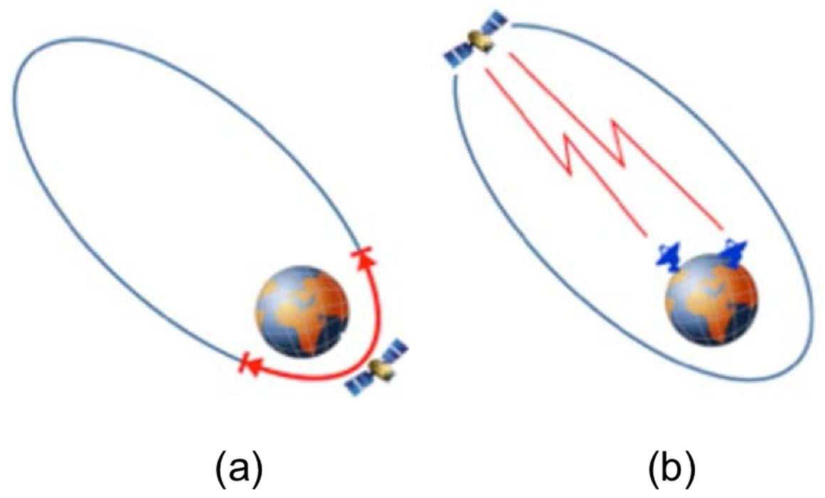
- Martin Zelan, Measurement Science and Technology, RISE Research Institutes of Sweden, Borås, *Sweden*


Strong International Team

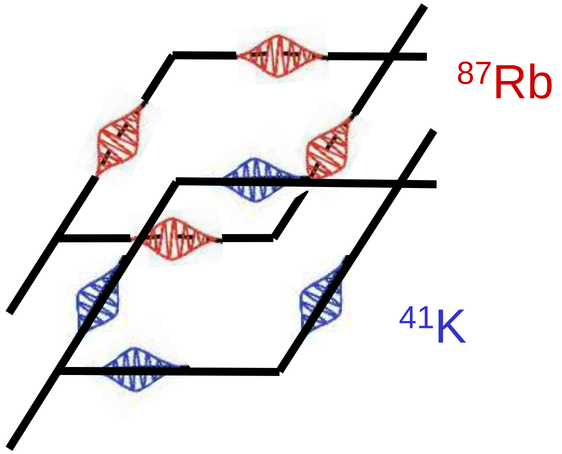
# STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics

## 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 | $\eta$ | Year [ref] | Comments |
|---|---|---|---|---|
| Classical | Be - Ti | $2 \times 10^{-13}$ | 2008 | Torsion balance |
| | Pt - Ti | $1 \times 10^{-14}$ | 2017 | MICROSCOPE first results |
| | Pt - Ti | $(10^{-15})$ | 2022+ | MICROSCOPE full data |
| Hybrid | $^{133}$Cs - CC | $7 \times 10^{-9}$ | 2001 | Atom Interferometry |
| | $^{87}$Rb - CC | $7 \times 10^{-9}$ | 2010 | and macroscopic corner cube (CC) |
| Quantum | $^{39}$K - $^{87}$Rb | $3 \times 10^{-7}$ | 2020 | different elements |
| | $^{87}$Sr - $^{88}$Sr | $2 \times 10^{-7}$ | 2014 | same element, fermion vs. boson |
| | $^{85}$Rb - $^{87}$Rb | $3 \times 10^{-8}$ | 2015 | same element, different isotopes |
| | $^{85}$Rb - $^{87}$Rb | $3.8 \times 10^{-12}$ | 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

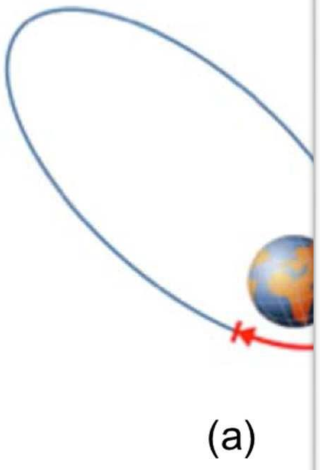
## Science Goals: E… …antum Mechanics

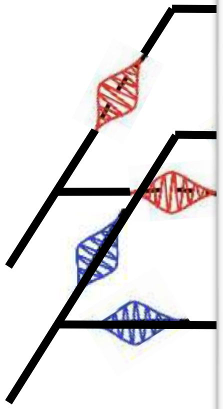
…3, M4).

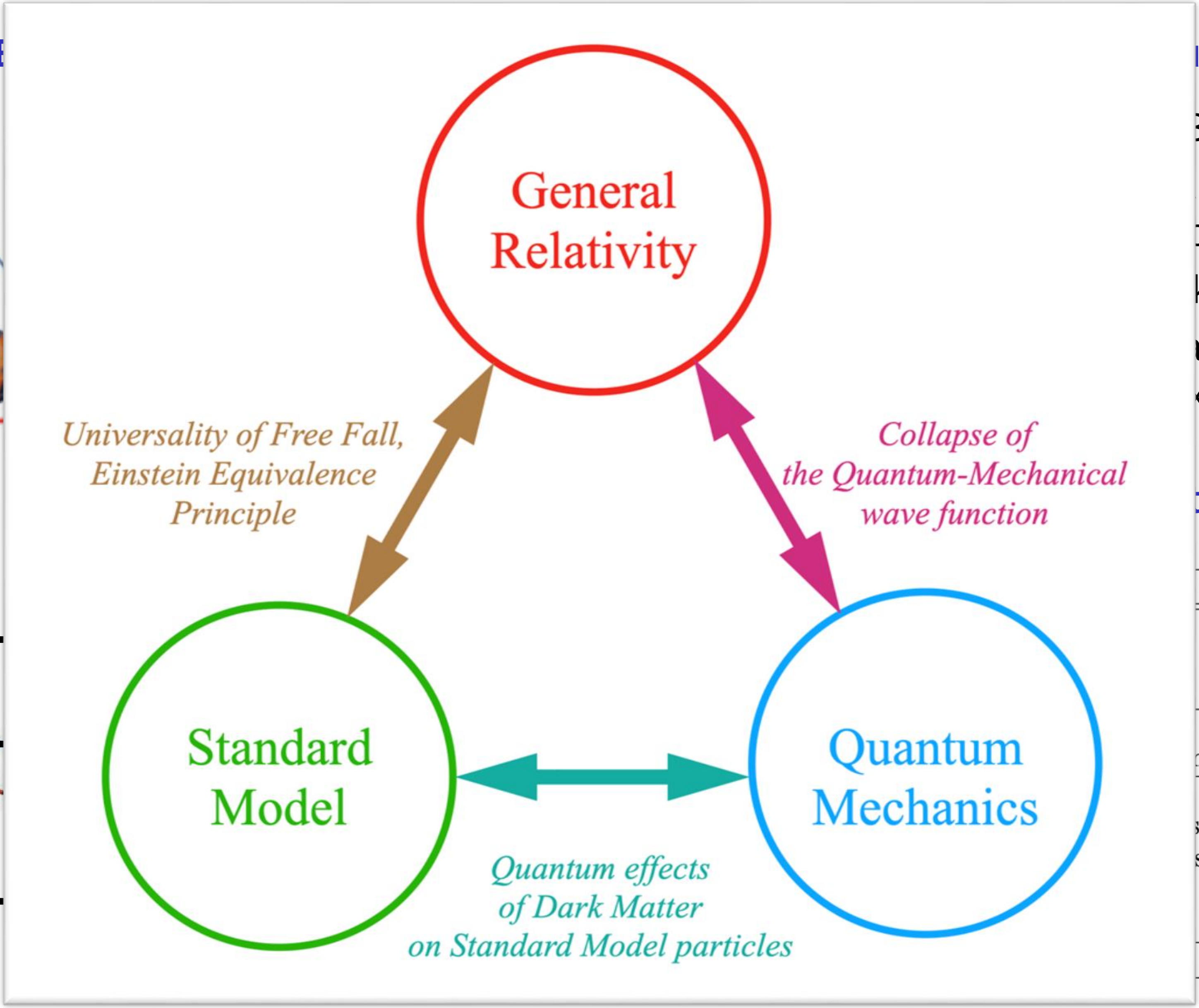
…nd K “test masses” in non-…ons).

…km circular orbit.

…avity gradient shifts by …king atom positioning



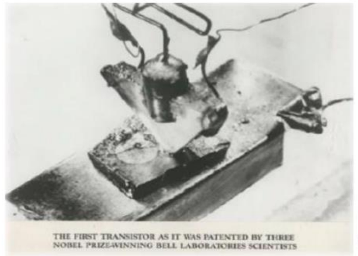


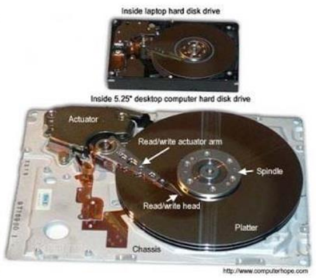

**…ths of operation.**

| 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 $20^{th}$ century

transistor — 1947

hard disk — 1954

laser — 1960

Albert Einstein (1879-1955)

Werner Heisenberg (1901-1976)

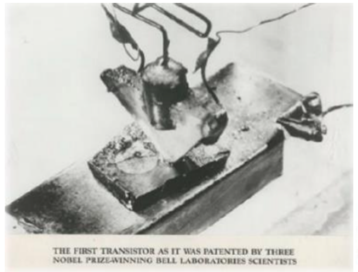
Erwin Schrödinger (1887-1961)

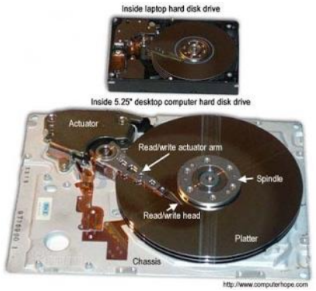
**The first quantum revolution**

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 — transistor — hard disk — laser

beginning of $20^{th}$ century — 1947 — 1954 — 1960 — end $20^{th}$ / beginning $21^{st}$

Richard Feynman
(1918–1988)

Serge Haroche

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

Control of single quantum particles
First quantum algorithms

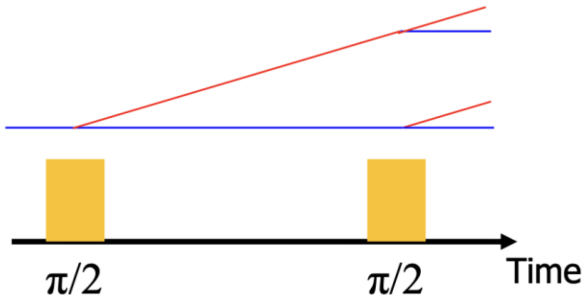
**The second quantum revolution**

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

# MORE ON ATOM INTERFEROMETRY CONCEPT

# Possible Phase Shifts

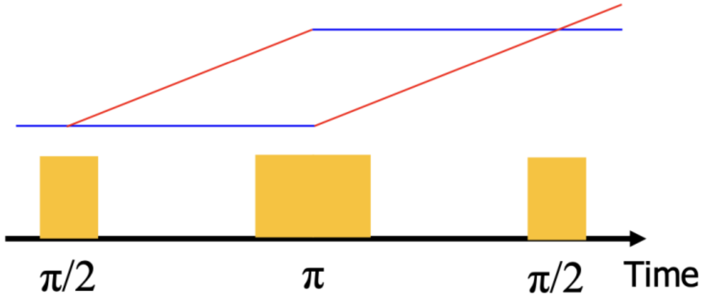
Ramsey sequence (clock)




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

- Measures velocity

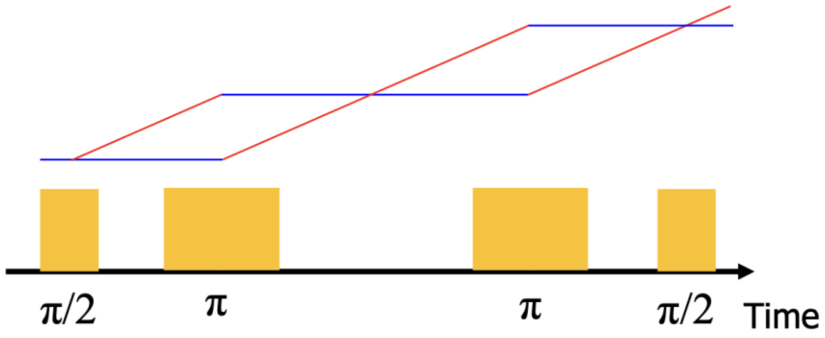
Mach-Zehnder




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

- "Difference" of two Ramsey sequences
- Measures acceleration

"Double diamond"




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

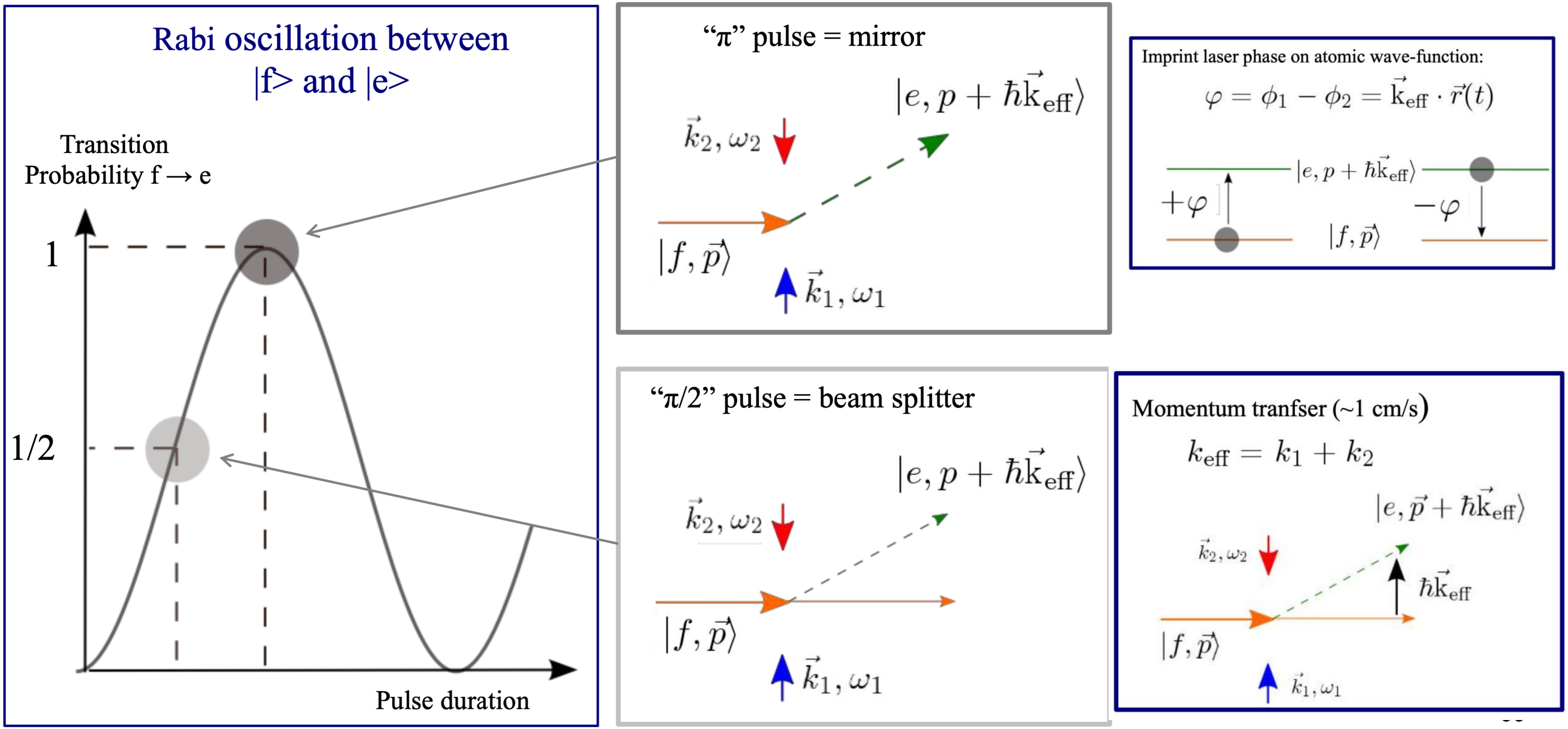
- Difference of two MZ loops
- Measures acceleration gradient (in space and/or time)

## General Relativistic Effects in Atom Interferometry

| | GR Phase Shift | Size (rad) | Interpretation | NR Phase Shift |
|---|---|---|---|---|
| 1. | $-k_{\text{eff}}gT^2$ | $3. \times 10^{8}$ | Newtonian gravity | $-k_{\text{eff}}gT^2$ |
| 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. | $-\frac{7}{12}k_{\text{eff}}(\partial_r g)gT^4$ | $9. \times 10^{2}$ | | $-\frac{7}{12}k_{\text{eff}}(\partial_r g)gT^4$ |
| 4. | $-3k_{\text{eff}}g^2T^3$ | $-4. \times 10^{1}$ | finite speed of light and | |
| 5. | $-3k_{\text{eff}}gv_L T^2$ | $4. \times 10^{1}$ | 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. | $(\omega_{\text{eff}} - \omega_a)\,gT^2$ | $-4. \times 10^{-1}$ | detuning | |
| 8. | $(2 - 2\beta - \gamma)k_{\text{eff}}g\phi T^2$ | $-2. \times 10^{-1}$ | GR (non-linearity) | |
| 9. | $-\frac{3k_{\text{eff}}^2}{2m}gT^2$ | $2. \times 10^{-2}$ | | |
| 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. | $-\frac{35}{4}k_{\text{eff}}(\partial_r g)gv_L T^4$ | $6. \times 10^{-4}$ | | |
| 12. | $-4k_{\text{eff}}(\partial_r g)v_L^2T^3$ | $-3. \times 10^{-4}$ | | |
| 13. | $2\omega_a g^2T^3$ | $2. \times 10^{-4}$ | | |
| 14. | $2\omega_a gv_L T^2$ | $-2. \times 10^{-4}$ | | |
| 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. | $-12k_{\text{eff}}g^2v_L T^3$ | $-7. \times 10^{-6}$ | | |
| 17. | $-7k_{\text{eff}}g^3T^4$ | $4. \times 10^{-6}$ | | |
| 18. | $-5k_{\text{eff}}gv_L^2T^2$ | $3. \times 10^{-6}$ | 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. | $\frac{7}{12}(4 - 4\beta - 3\gamma)k_{\text{eff}}\phi(\partial_r g)gT^4$ | $-2. \times 10^{-6}$ | GR | |
| 21. | $(\omega_{\text{eff}} - \omega_a)\,(\partial_r g)v_L T^3$ | $2. \times 10^{-6}$ | | |
| 22. | $\frac{7}{12}\,(\omega_{\text{eff}} - \omega_a)\,(\partial_r g)gT^4$ | $-1. \times 10^{-6}$ | | |
| 23. | $-\frac{7}{12}(2 - 2\beta - \gamma)k_{\text{eff}}g^3T^4$ | $-3. \times 10^{-7}$ | GR | |
| 24. | $-\frac{7k_{\text{eff}}^2}{2m}(\partial_r g)v_L T^3$ | $-2. \times 10^{-7}$ | | |
| 25. | $-\frac{27k_{\text{eff}}^2}{8m}(\partial_r g)gT^4$ | $2. \times 10^{-7}$ | | |
| 26. | $\frac{k_{\text{eff}}\omega_a}{m}gT^2$ | $-1. \times 10^{-7}$ | | |
| 27. | $6(2 - 2\beta - \gamma)k_{\text{eff}}\phi g^2T^3$ | $5. \times 10^{-8}$ | GR | |
| 28. | $3\,(\omega_{\text{eff}} - \omega_a)\,g^2T^3$ | $4. \times 10^{-8}$ | | |
| 29. | $3\,(\omega_{\text{eff}} - \omega_a)\,gv_L T^2$ | $-4. \times 10^{-8}$ | | |
| 30. | $6(1 - \beta)k_{\text{eff}}\phi gv_L T^2$ | $3. \times 10^{-8}$ | GR | |

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

# Pi and Pi/2 Pluses – Rabi Oscillation



# Mach-Zehnder Atom Interferometer – Phase shift

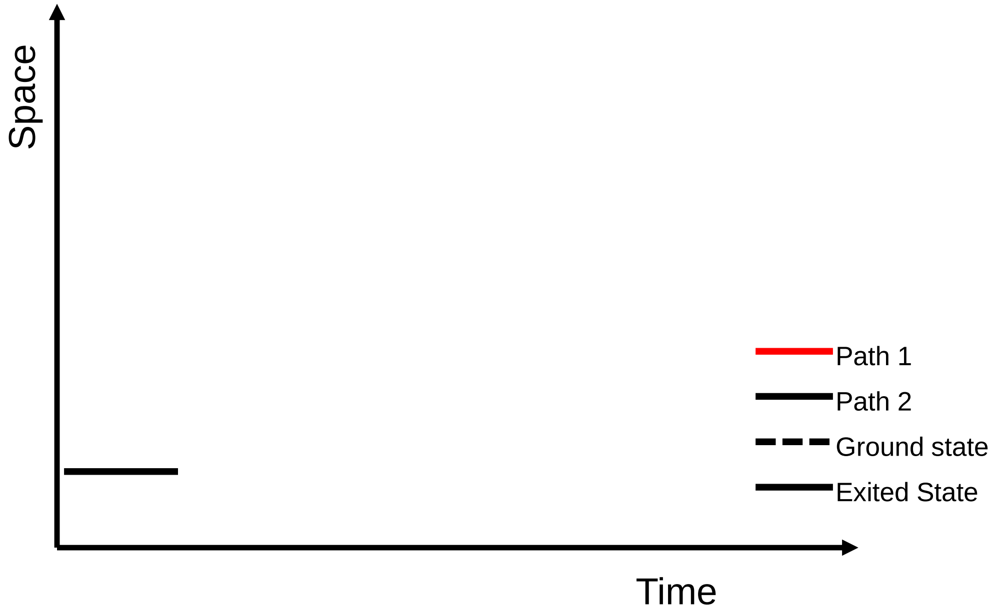


**Assuming no other interactions like gravity, etc.**

**Atoms at rest:**

At time before first Pulse:

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



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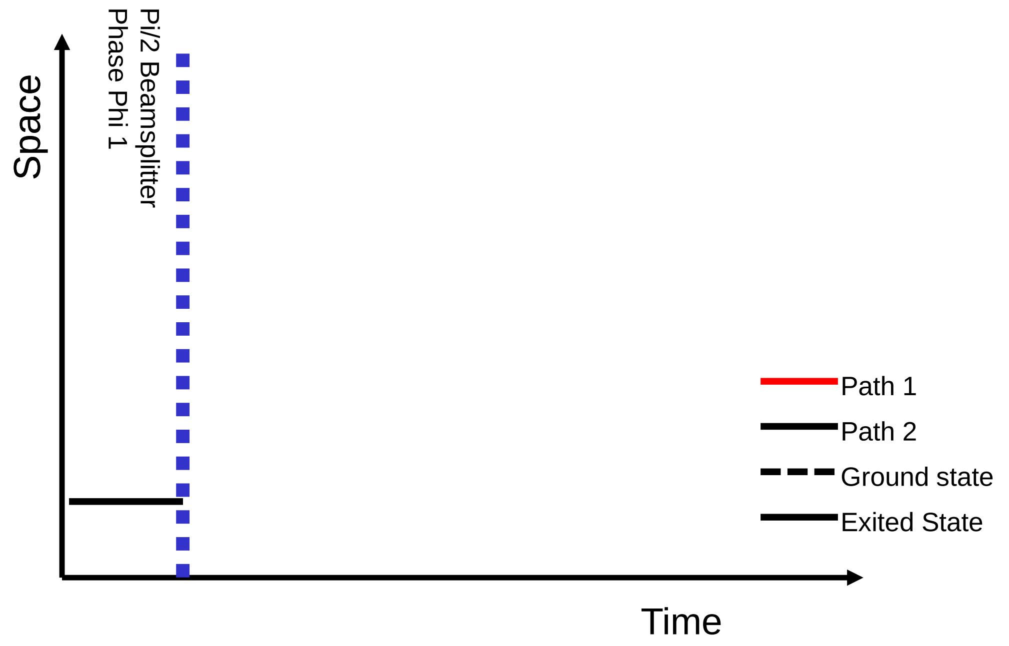
At time $T = 0$ of first $\pi/2$ Pulse:

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



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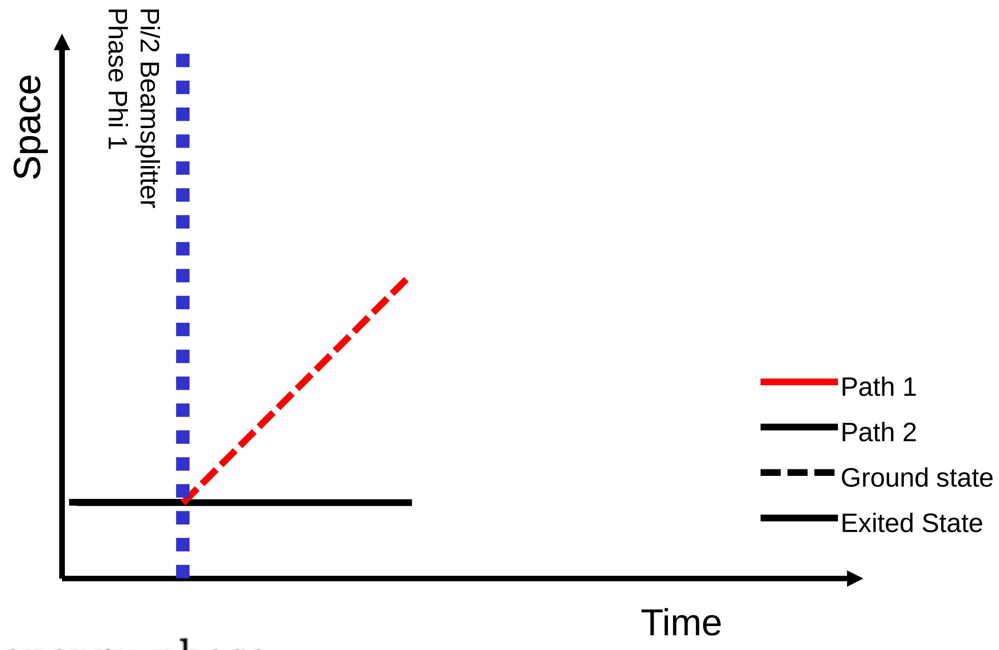



At time $t = T$ just before the $\pi$ mirror pulse $|1\rangle$ acquired the energy phase $-Et/\hbar = -\omega_a T$

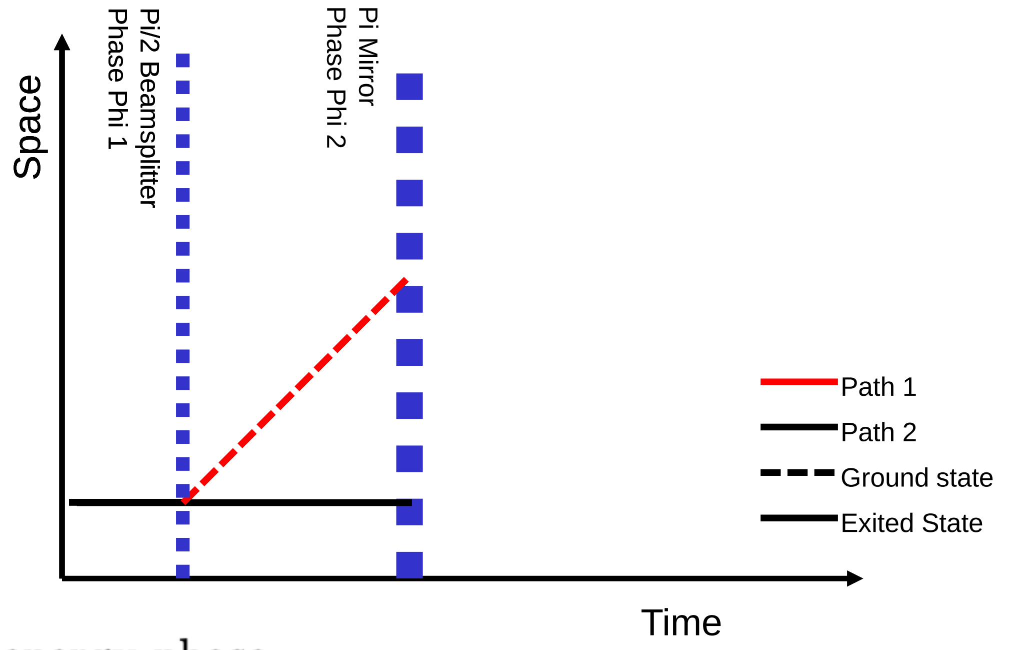
$$\Phi_1 = \phi_1 - ET/\hbar, \quad \Phi_2 = 0$$

# 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 $\pi$ 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 $\pi$ Pulse:

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

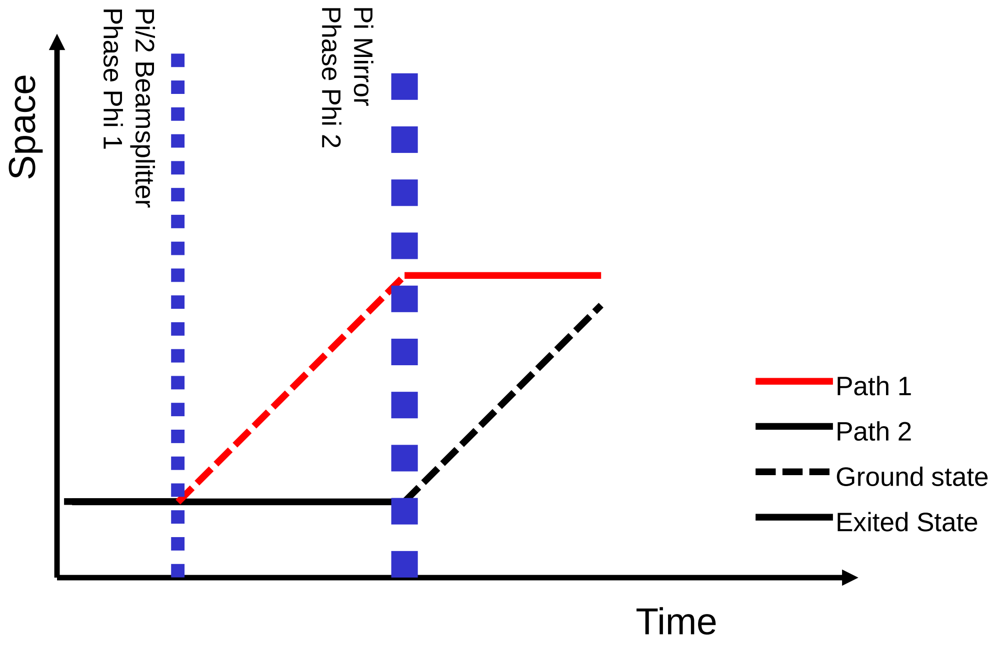
# Mach-Zehnder Atom Interferometer – Phase shift



**Assuming no other interactions like gravity, etc.**

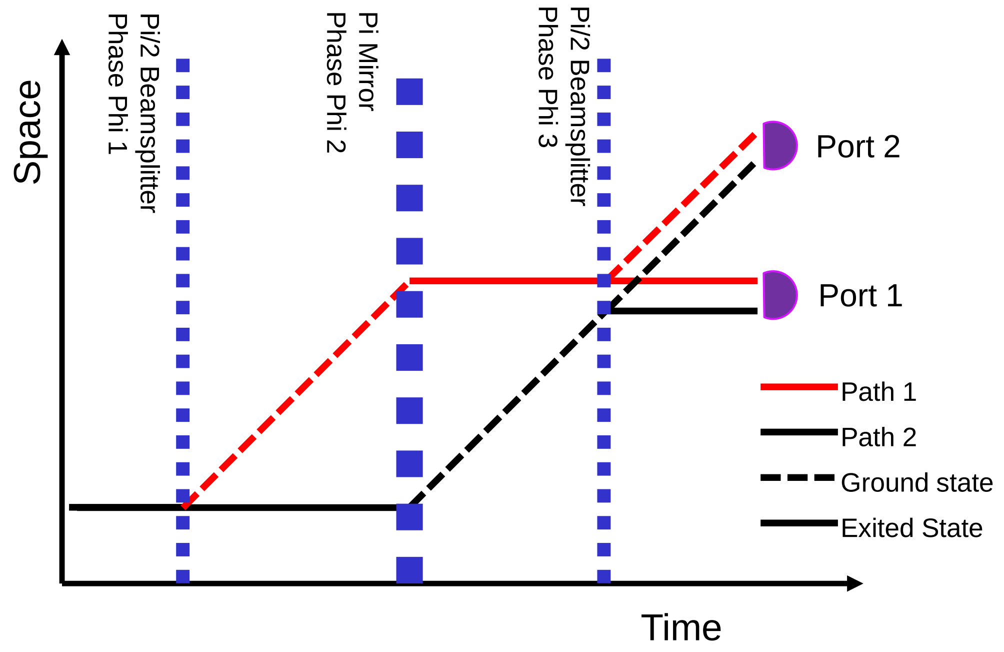
At time $t = 2T$ just before the next $\pi/2$ mirror pulse:

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



# 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:

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

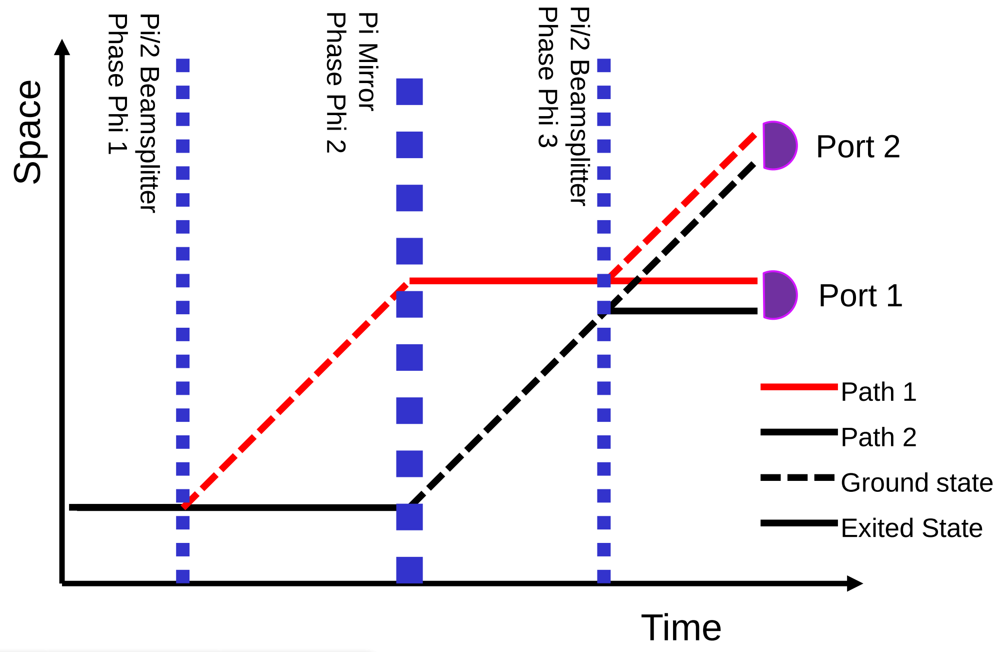
At $|1\rangle$ port:

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

# Mach-Zehnder Atom Interferometer – Phase shift



**Assuming no other interactions like gravity, etc.**




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

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

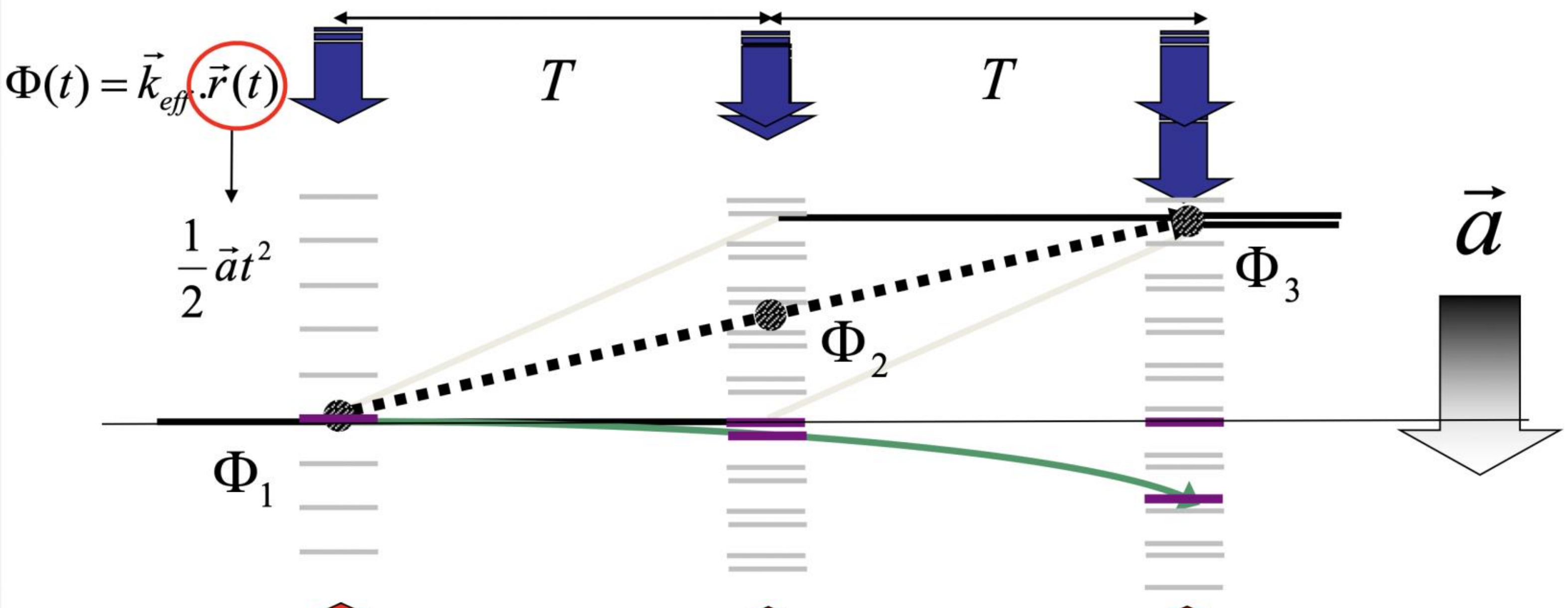
or

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

# MZ Acceleration Phase Shift



## Acceleration phase shift




$\Phi_1(t_1) = 0$

$\Phi_2(t_2) = \frac{1}{2}\vec{k}_{eff}.\vec{a}T^2$

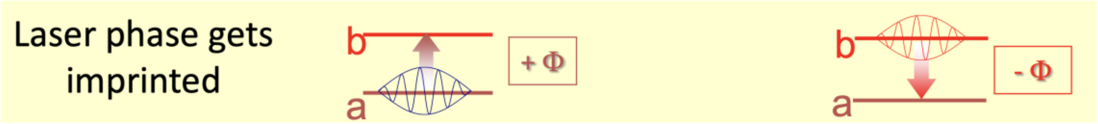
$\Phi_3(t_3) = \frac{1}{2}\vec{k}_{eff}.\vec{a}\,(2T)^2$

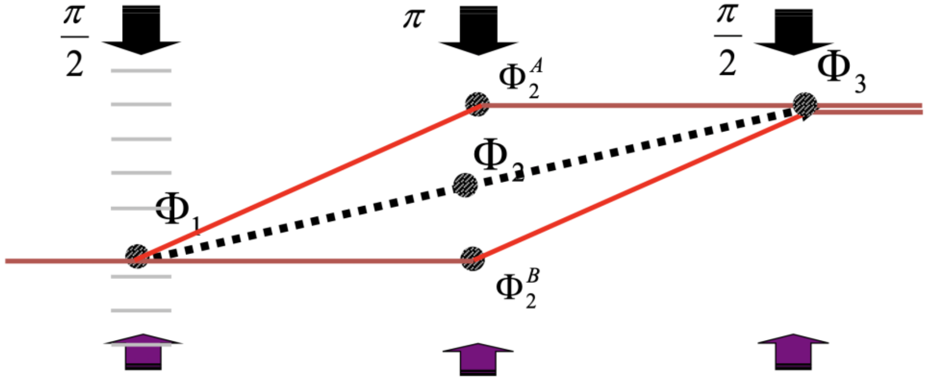
$$\Delta\Phi = \Phi_1(t_1) - 2\Phi_2(t_2) + \Phi_3(t_3) = \vec{k}_{eff}.\vec{a}T^2$$

41

# Different Phase Shifts for Different Interactions





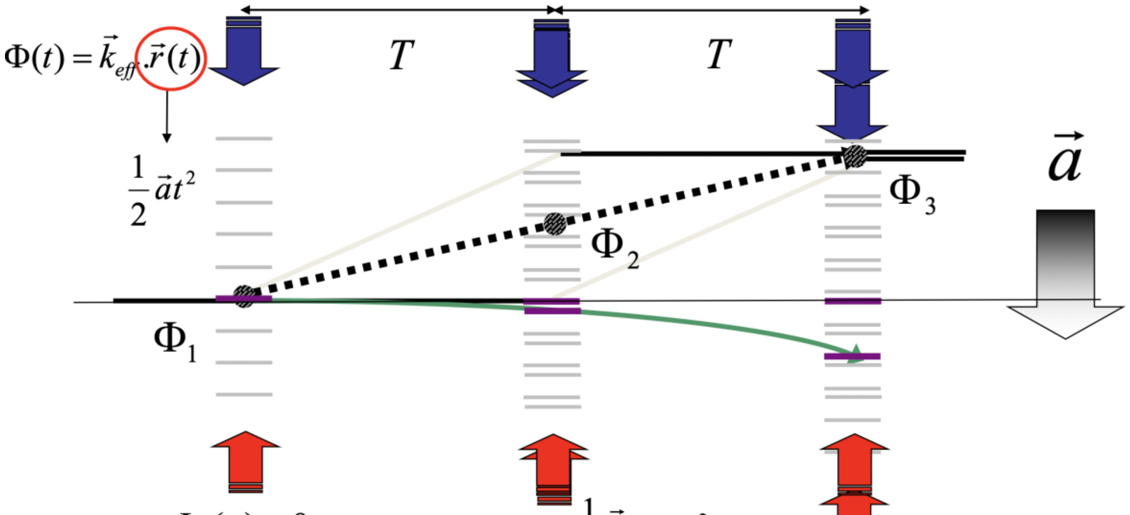




$$\Phi^A = \Phi_1 - \Phi_2^A$$

$$\Phi^B = \Phi_2^B - \Phi_3$$

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

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

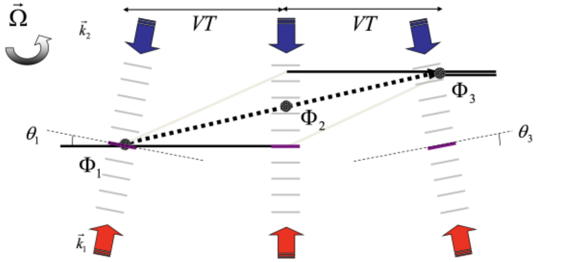



$$\Phi(t) = \vec{k}_{eff}.\vec{r}(t)$$

$$\frac{1}{2}\vec{a}t^2$$

$$\Phi_1(t_1) = 0 \quad \Phi_2(t_2) = \frac{1}{2}\vec{k}_{eff}.\vec{a}T^2 \quad \Phi_3(t_3) = \frac{1}{2}\vec{k}_{eff}.\vec{a}(2T)^2$$

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




$$\Phi_1(t_1) = k_{eff}\theta_1 VT \quad \Phi_2(t_2) = 0 \quad \Phi_3(t_3) = -k_{eff}\theta_3 VT$$

$$\Delta\Phi = -k_{eff}(\theta_3 - \theta_1)VT \qquad \Delta\Phi = -2\vec{k}_{eff}.(\vec{\Omega}\wedge\vec{V})T^2$$

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

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

# STE-QUEST

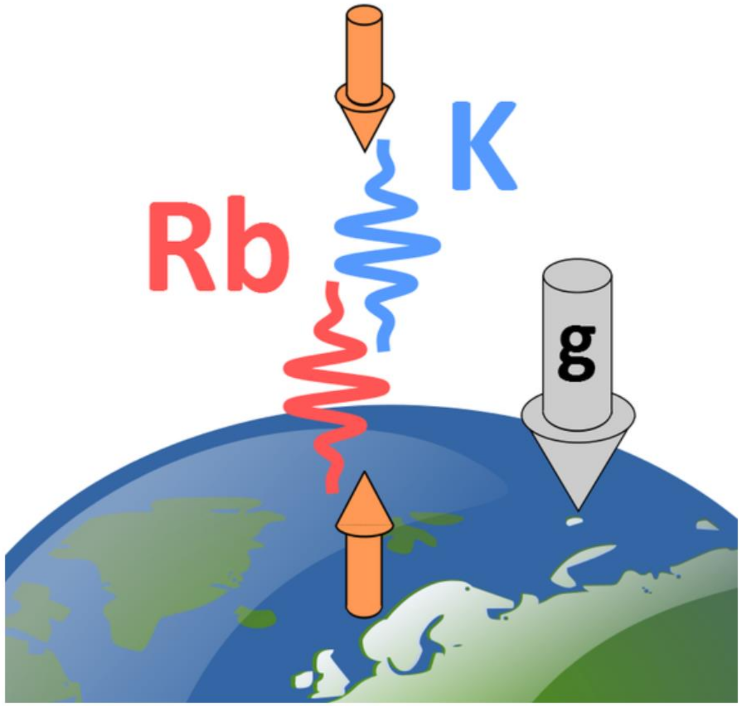
# STE-QUEST (M-Class Mission Proposal)



## 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:**

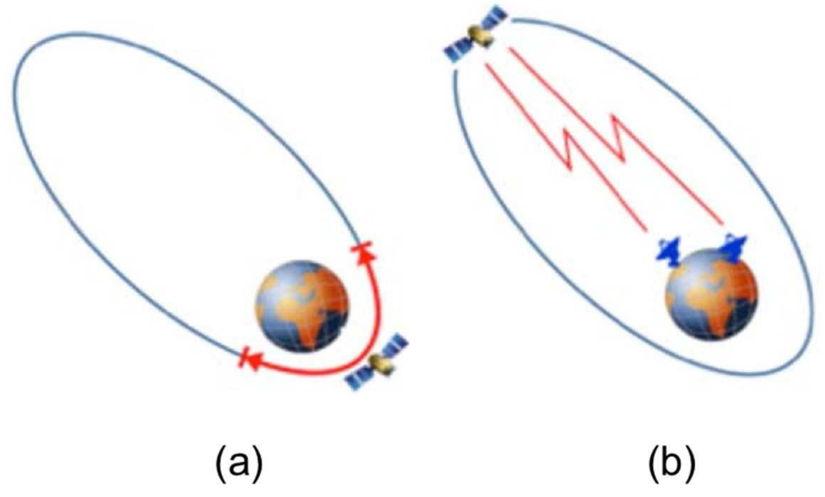
- Angelo Bassi, Department of Physics, University of Trieste, and INFN - Trieste Section, *Italy*
- Kai Bongs, Midlands Ultracold Atom Research Centre, School of Physics and Astronomy University of Birmingham, *United Kingdom*
- Philippe Bouyer, LP2N, Université Bordeaux, IOGS, CNRS, Talence, *France*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

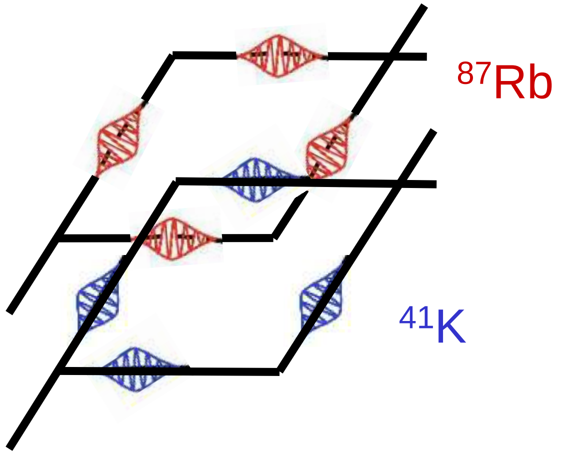
All are also core members of AION

# 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 | $\eta$ | Year [ref] | Comments |
|---|---|---|---|---|
| Classical | Be - Ti | $2 \times 10^{-13}$ | 2008 | Torsion balance |
| | Pt - Ti | $1 \times 10^{-14}$ | 2017 | MICROSCOPE first results |
| | Pt - Ti | $(10^{-15})$ | 2022+ | MICROSCOPE full data |
| Hybrid | $^{133}$Cs - CC | $7 \times 10^{-9}$ | 2001 | Atom Interferometry |
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| | $^{41}$K - $^{87}$Rb | $(10^{-17})$ | 2037 | STE-QUEST |
| Antimatter | $\overline{\text{H}}$ - H | $(10^{-2})$ | 2023+ | under construction at CERN |

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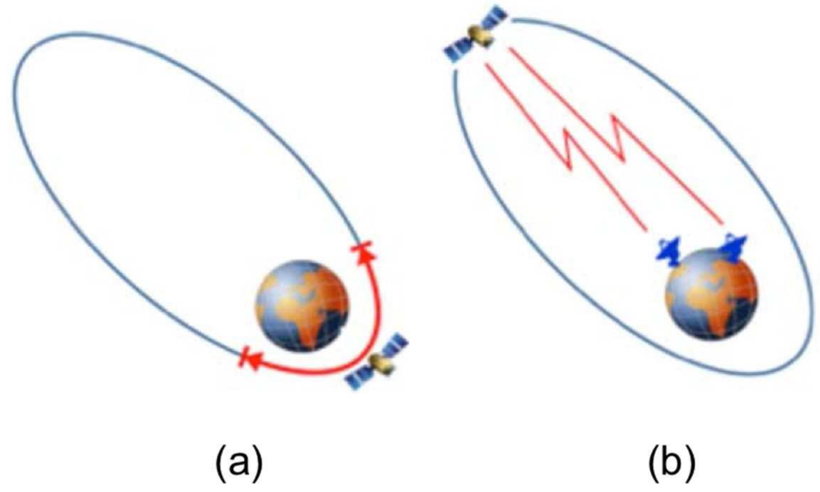
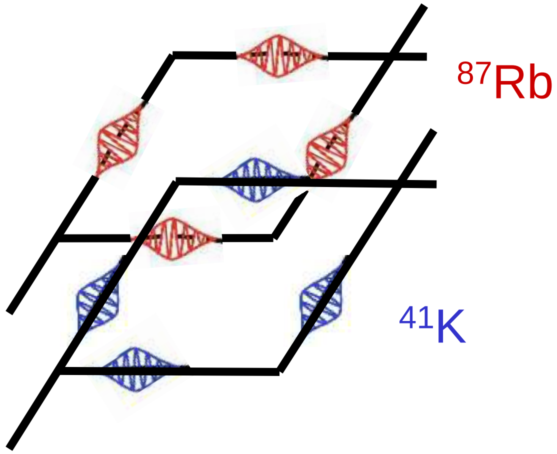
## Science Goals: Equivalent Principal at 1E-17, Ultra-Light Dark Matter, Test of Quantum Mechanics

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| | $^{88}$Sr - $^{88}$Sr | $< 10^{-15}$ | 2030 | AION/MAGIS 100m |
| | $^{41}$K - $^{87}$Rb | $(10^{-17})$ | 2037 | STE-QUEST |
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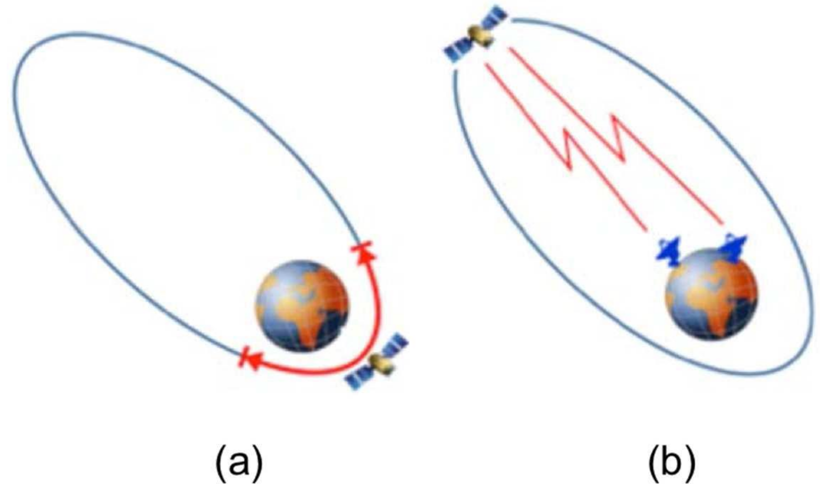
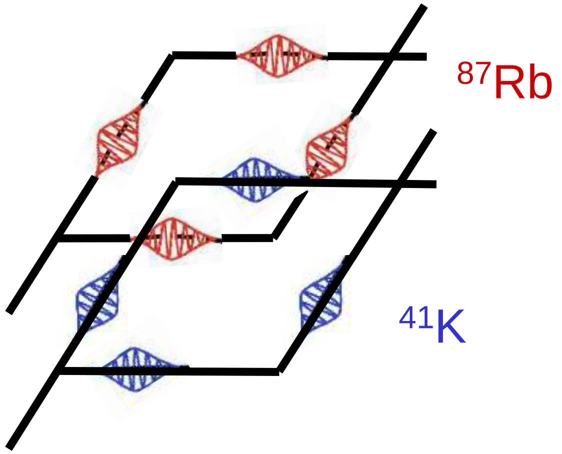
# STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics

## 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 s
- 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)**

| Class | Elements | $\eta$ | Year [ref] | Comments |
|---|---|---|---|---|
| Classical | Be - Ti | $2 \times 10^{-13}$ | 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:

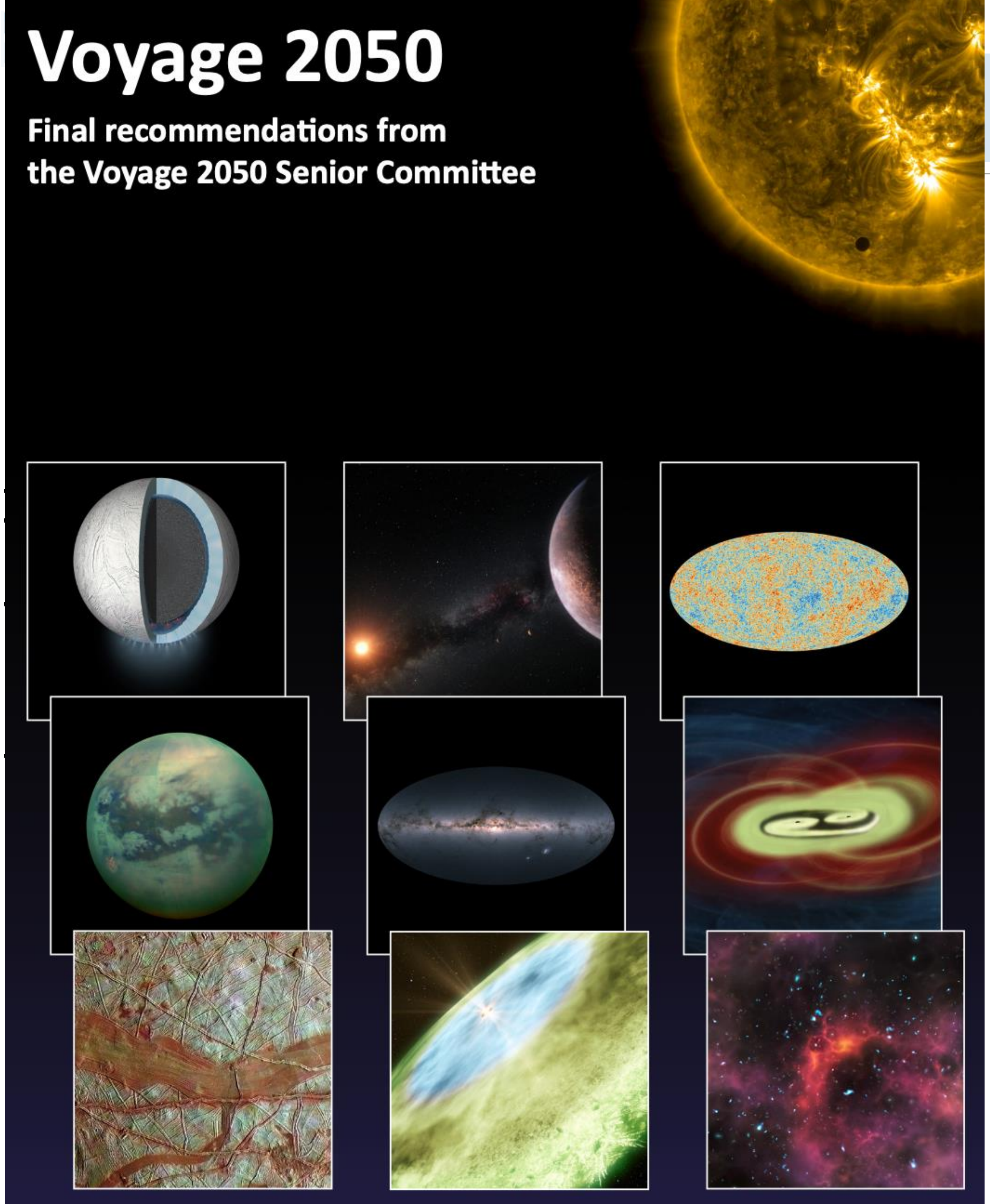
https://indico.cern.ch/event/1138902/registrations/

**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




AION

**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?***

# *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

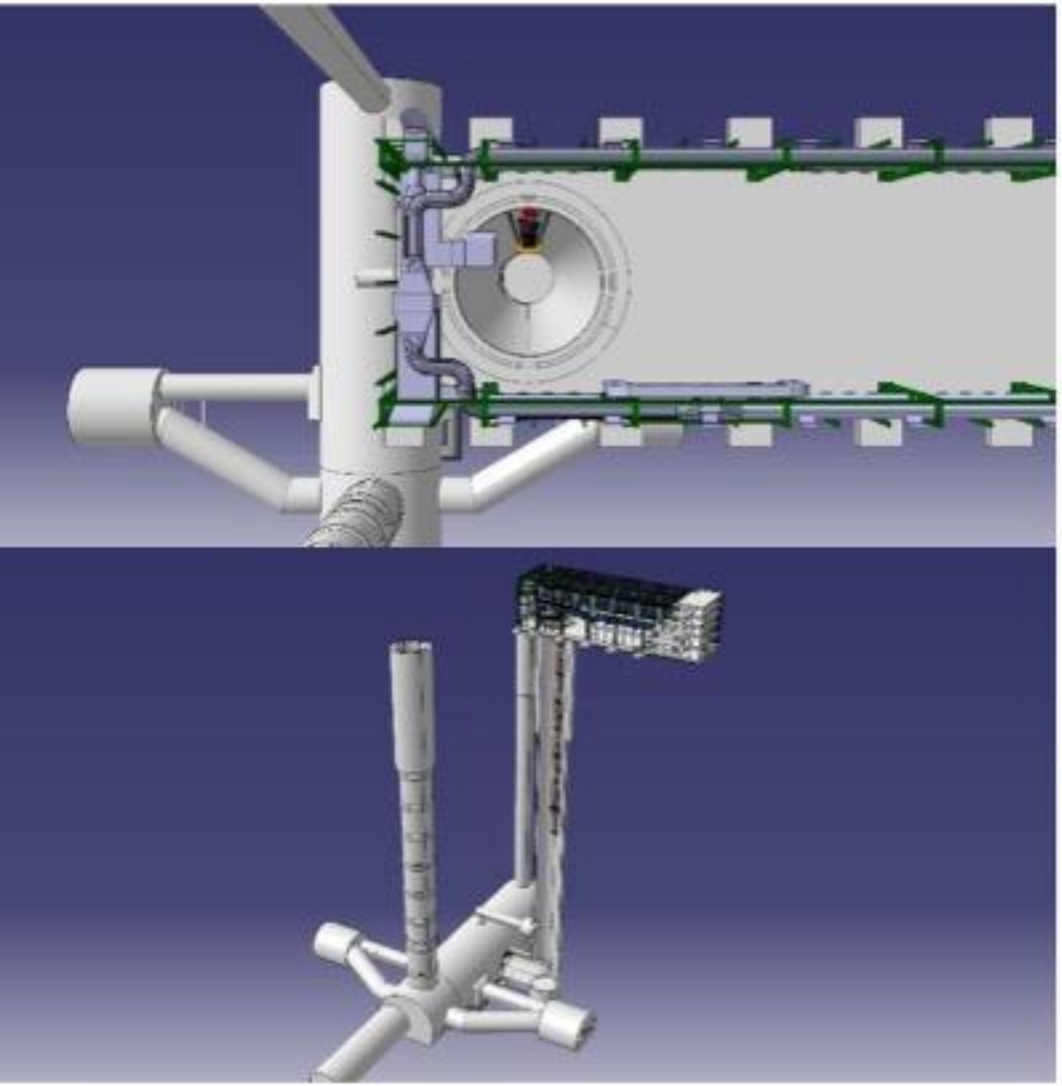
# Introduction

## 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

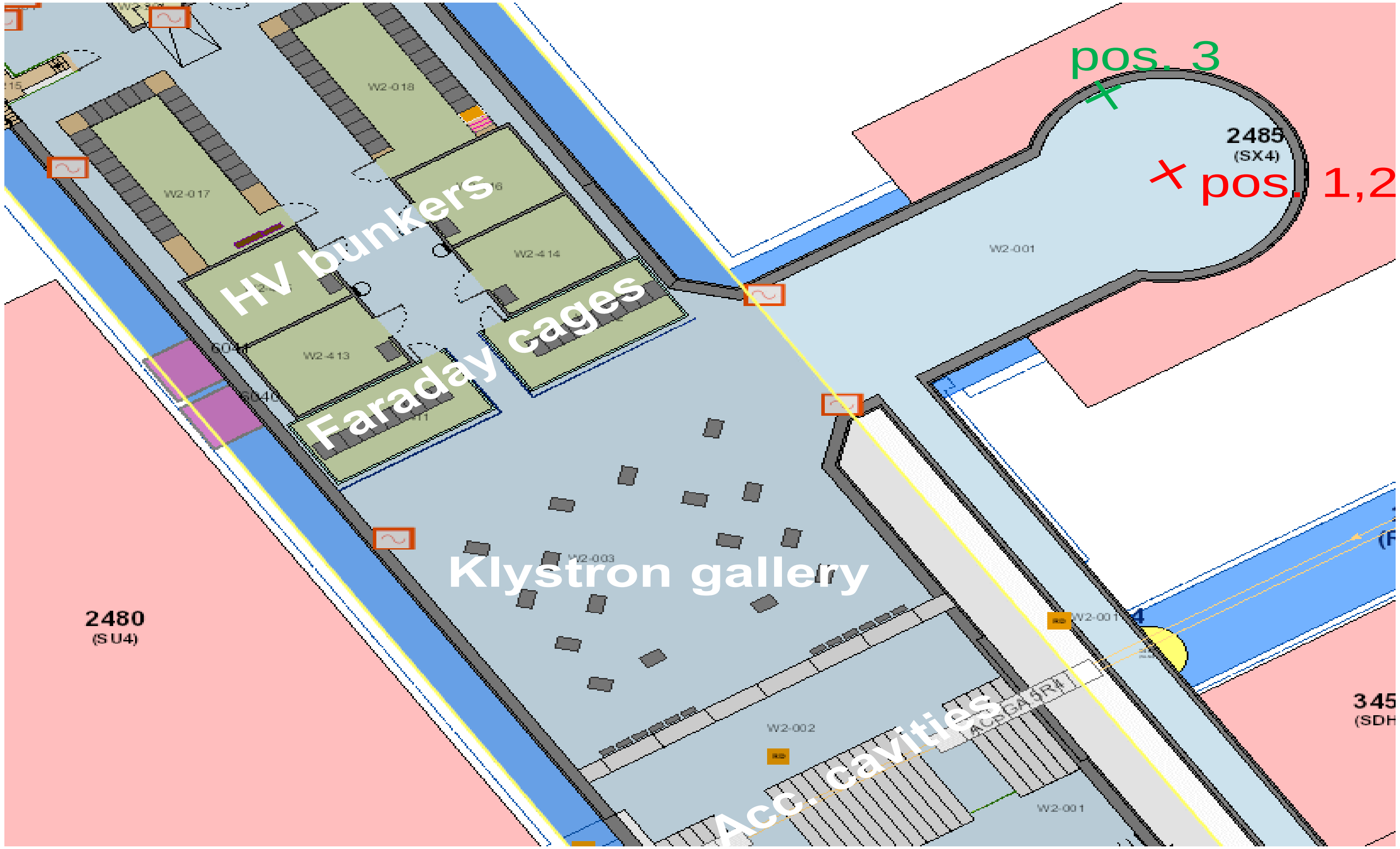
# The tube (thanks to EN-MME)


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

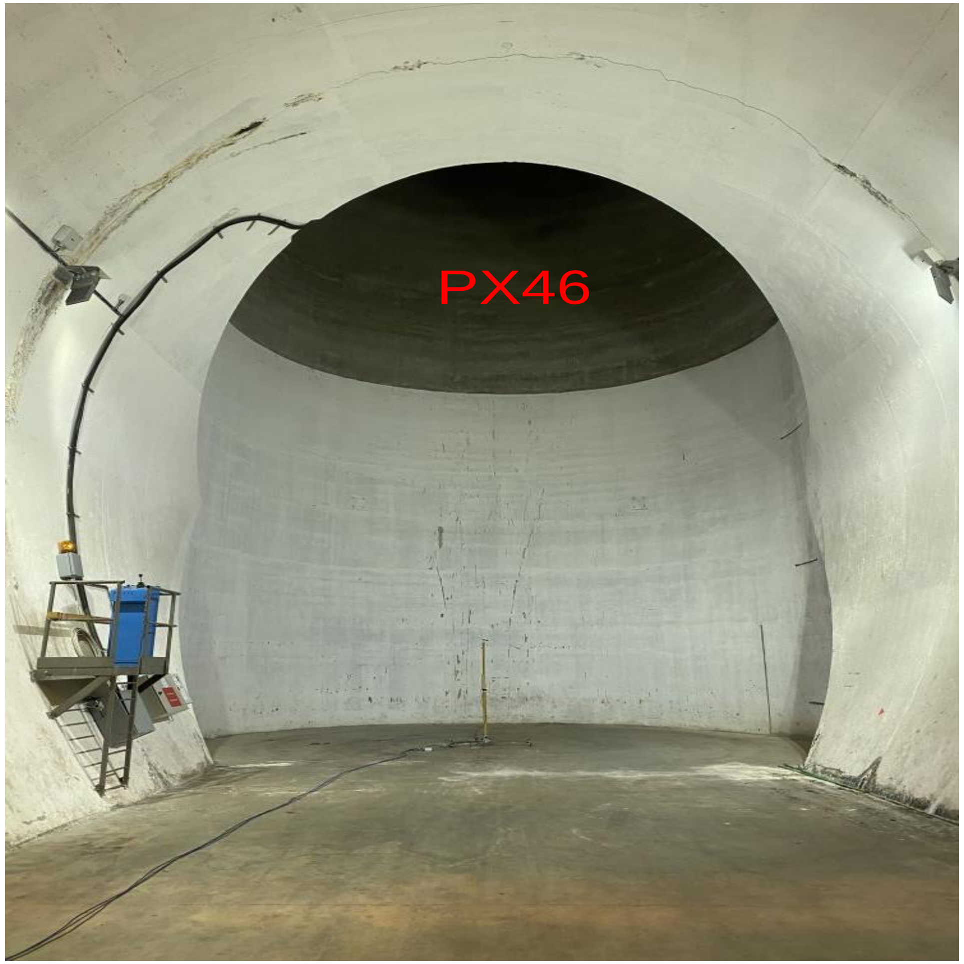
# Installation (thanks to EN-ACE, EN-HE, EN-CV)

# 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

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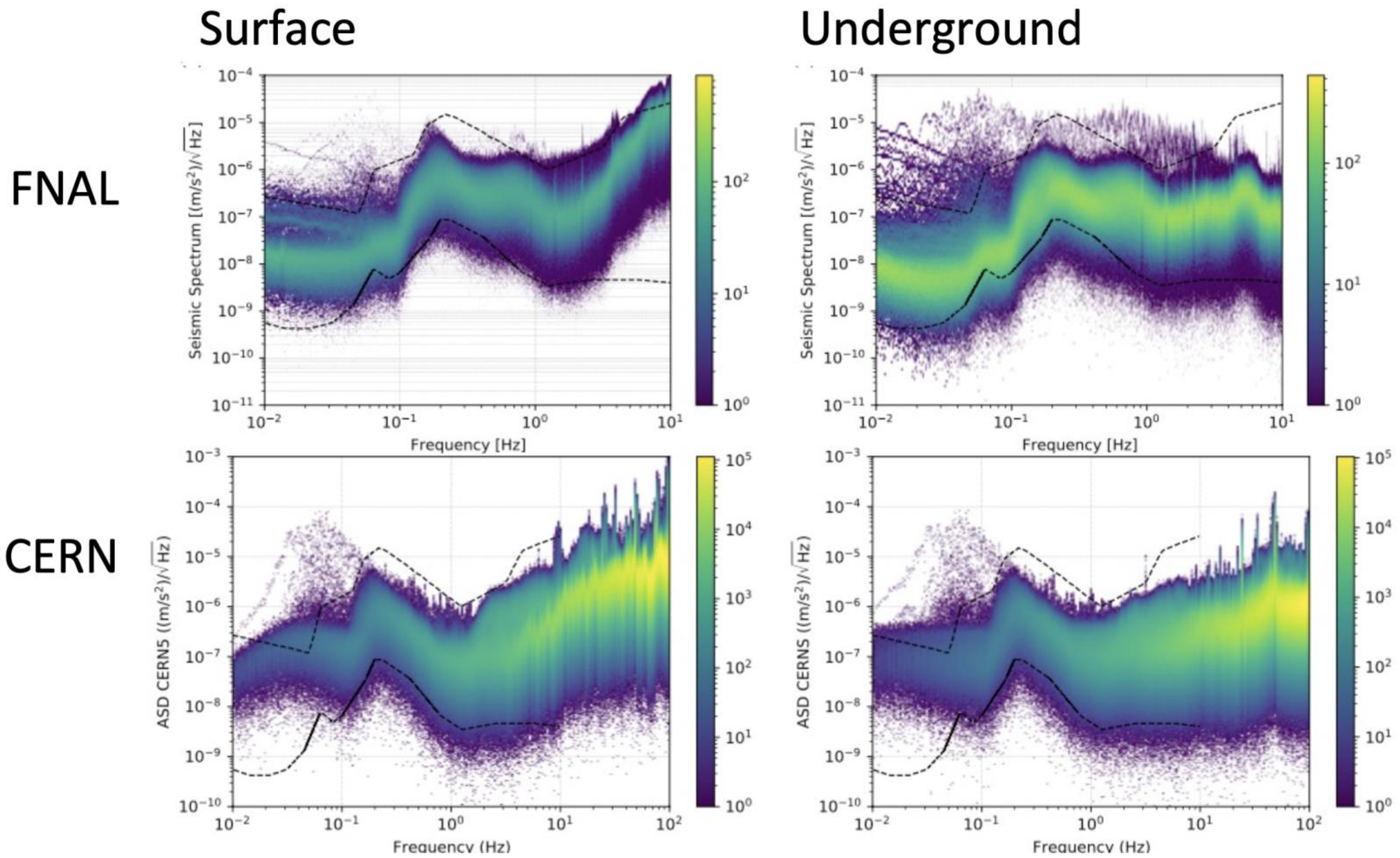
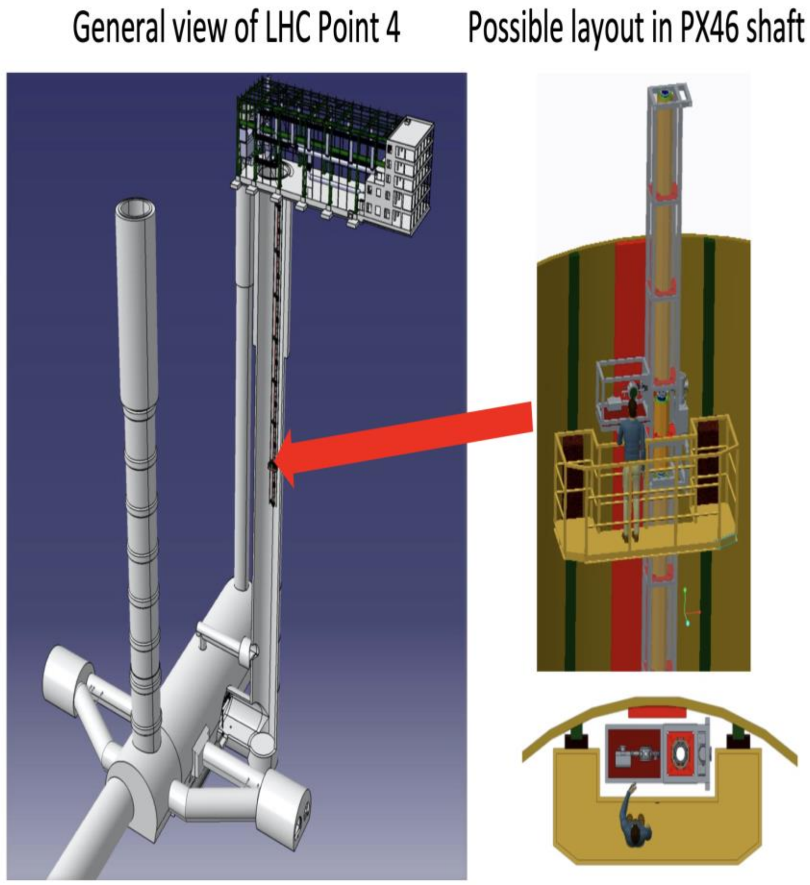
AION

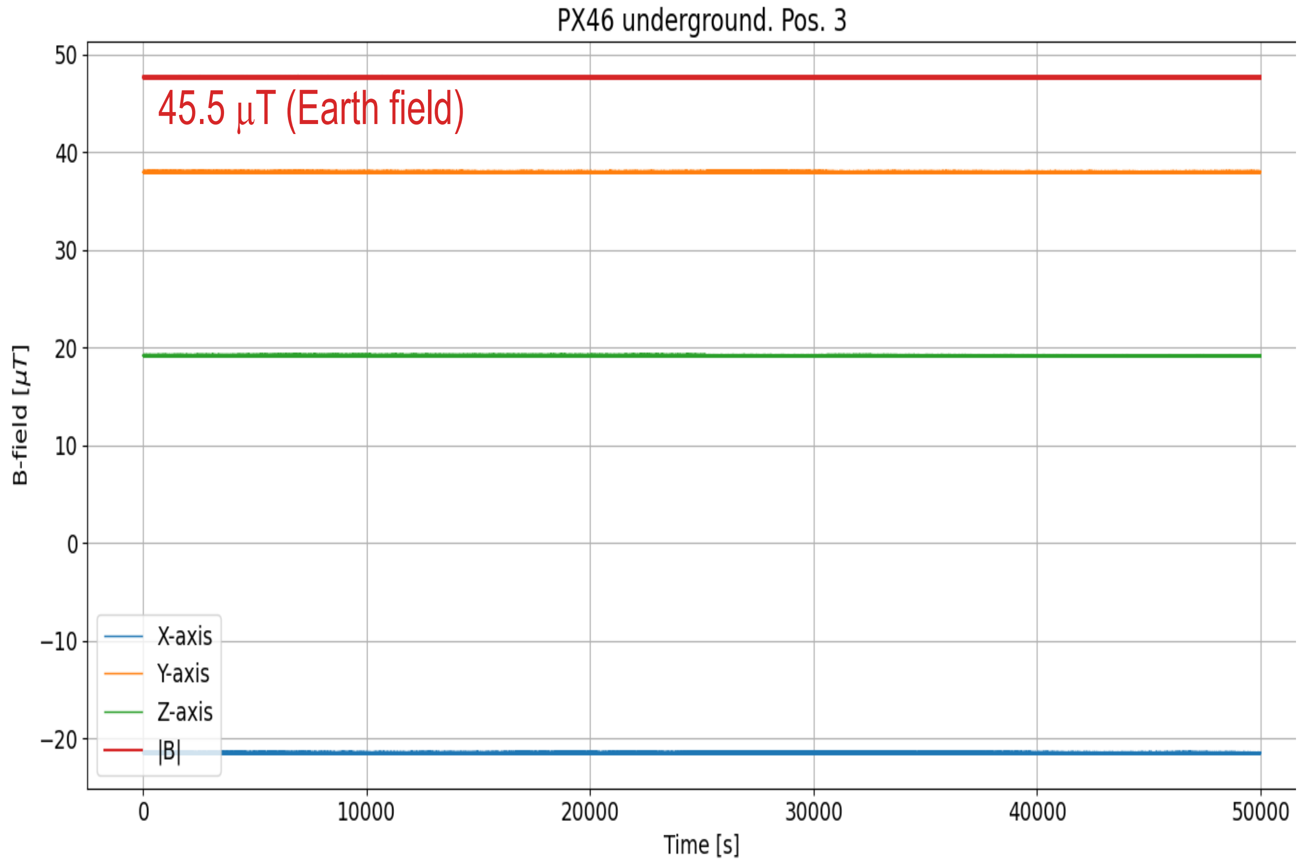
# ATION-100 at CERN – Site Investigation




**Spectrum similar to that measured at Fermilab for MAGIS**

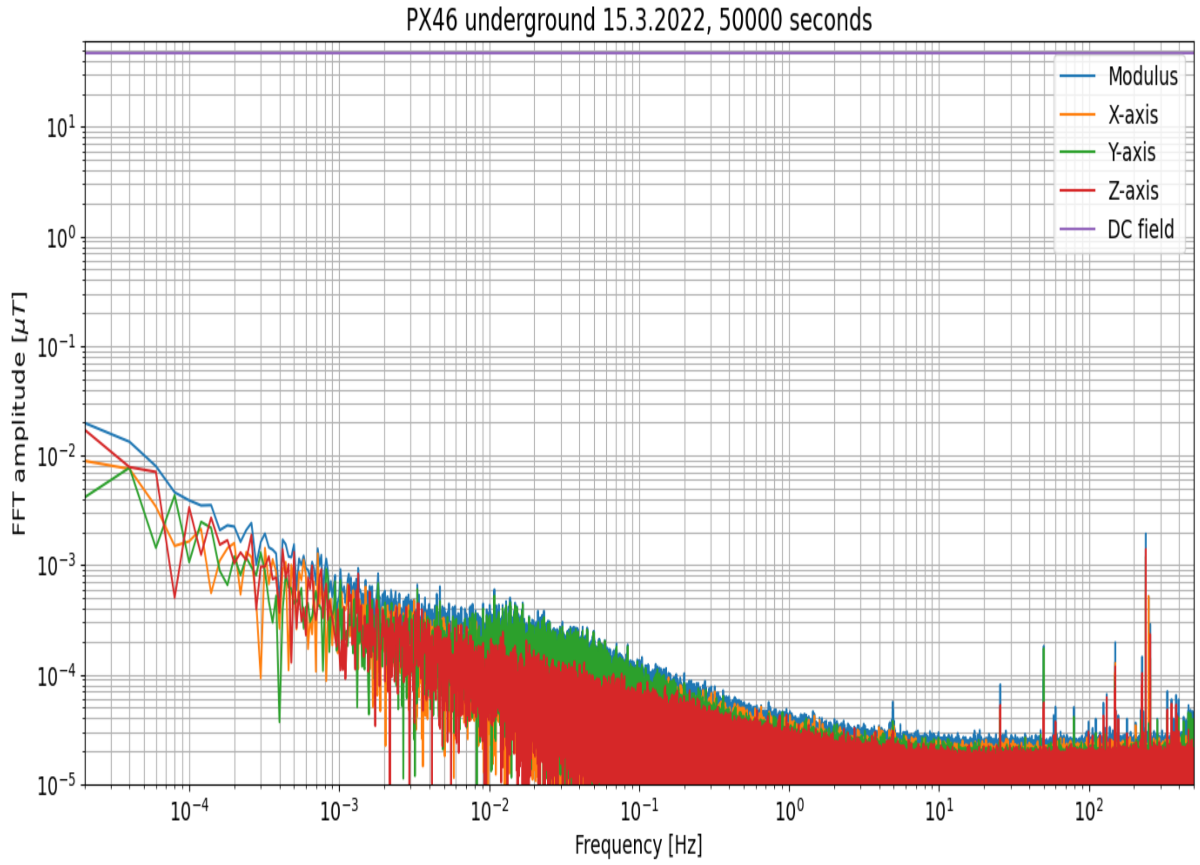
# Location: bottom of the PX46 shaft. Systems in UX45 running




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

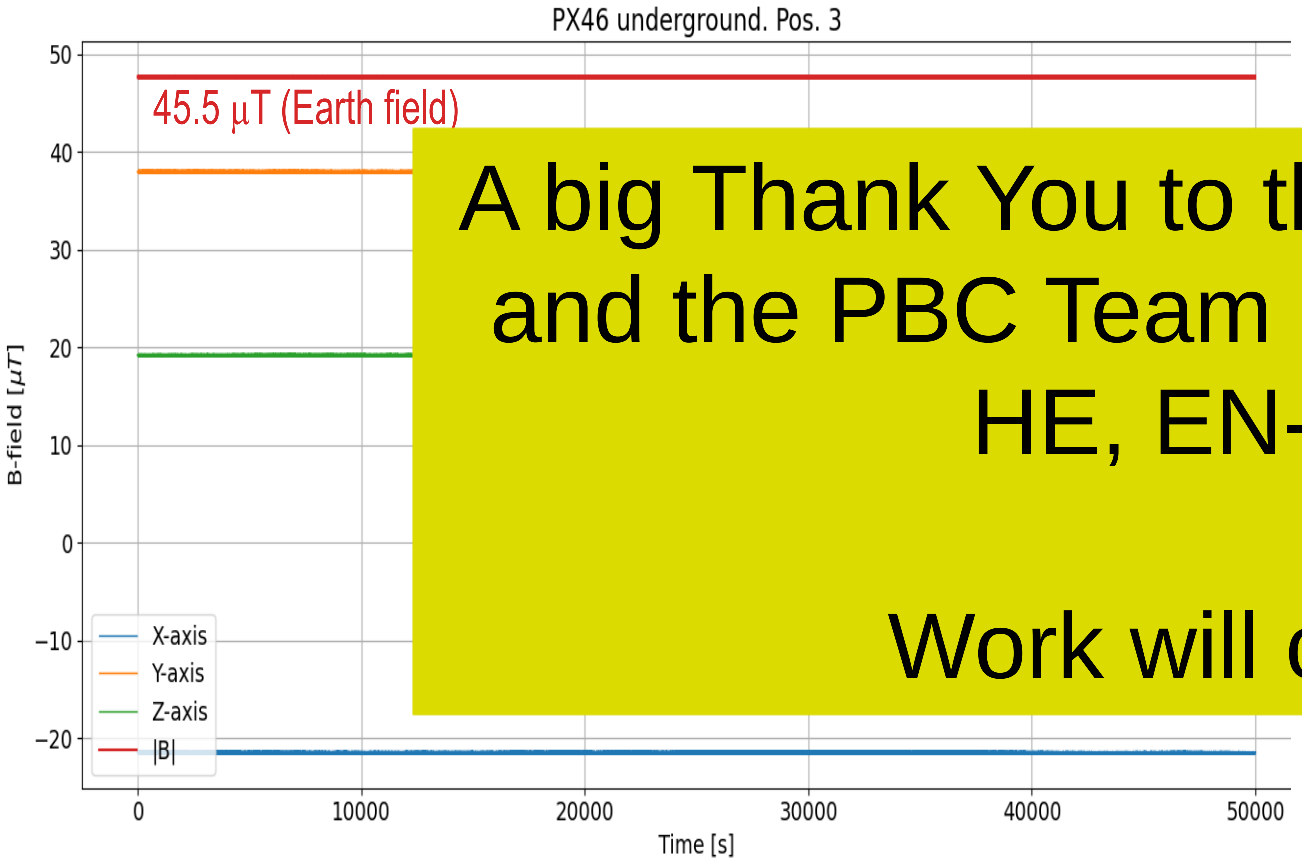


# Location: bottom of the PX46 shaft. Systems in UX45 running




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

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



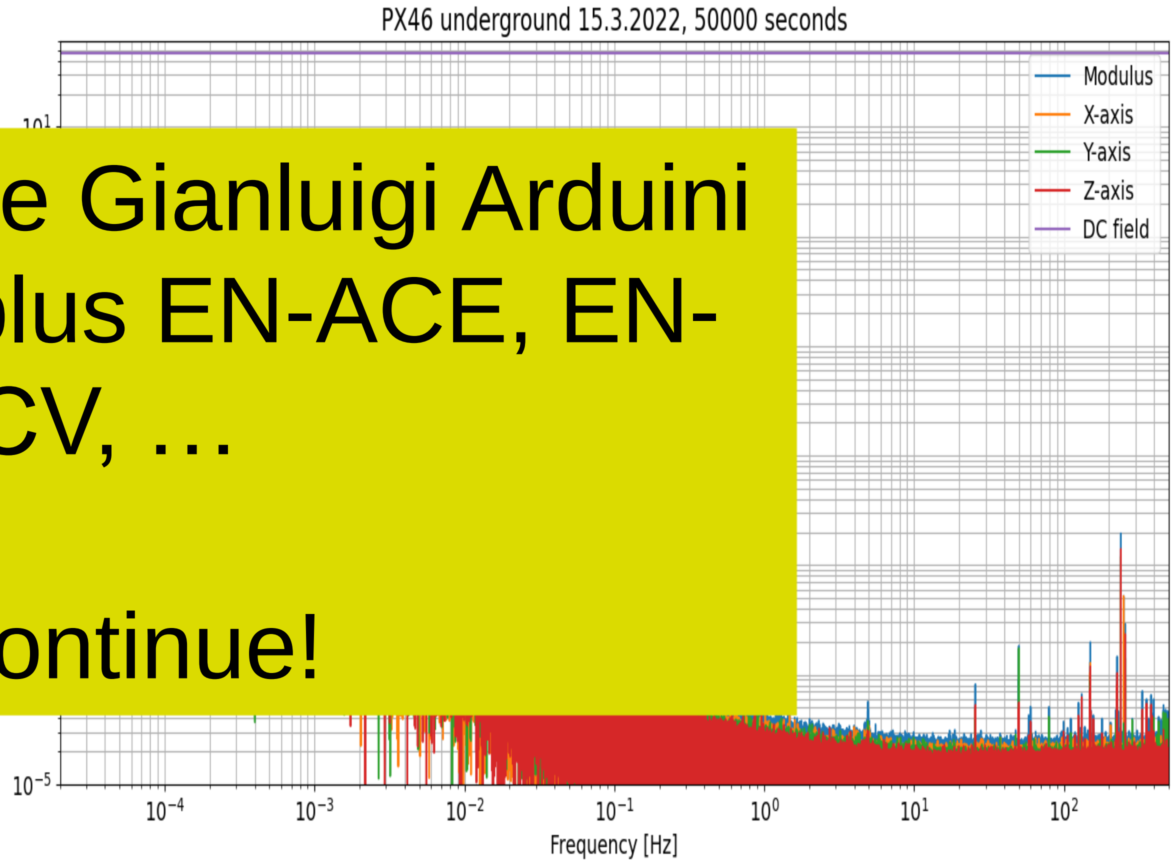

Location 3, wall of PX46. Quiet, Earth field for scale



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

Work will continue!

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



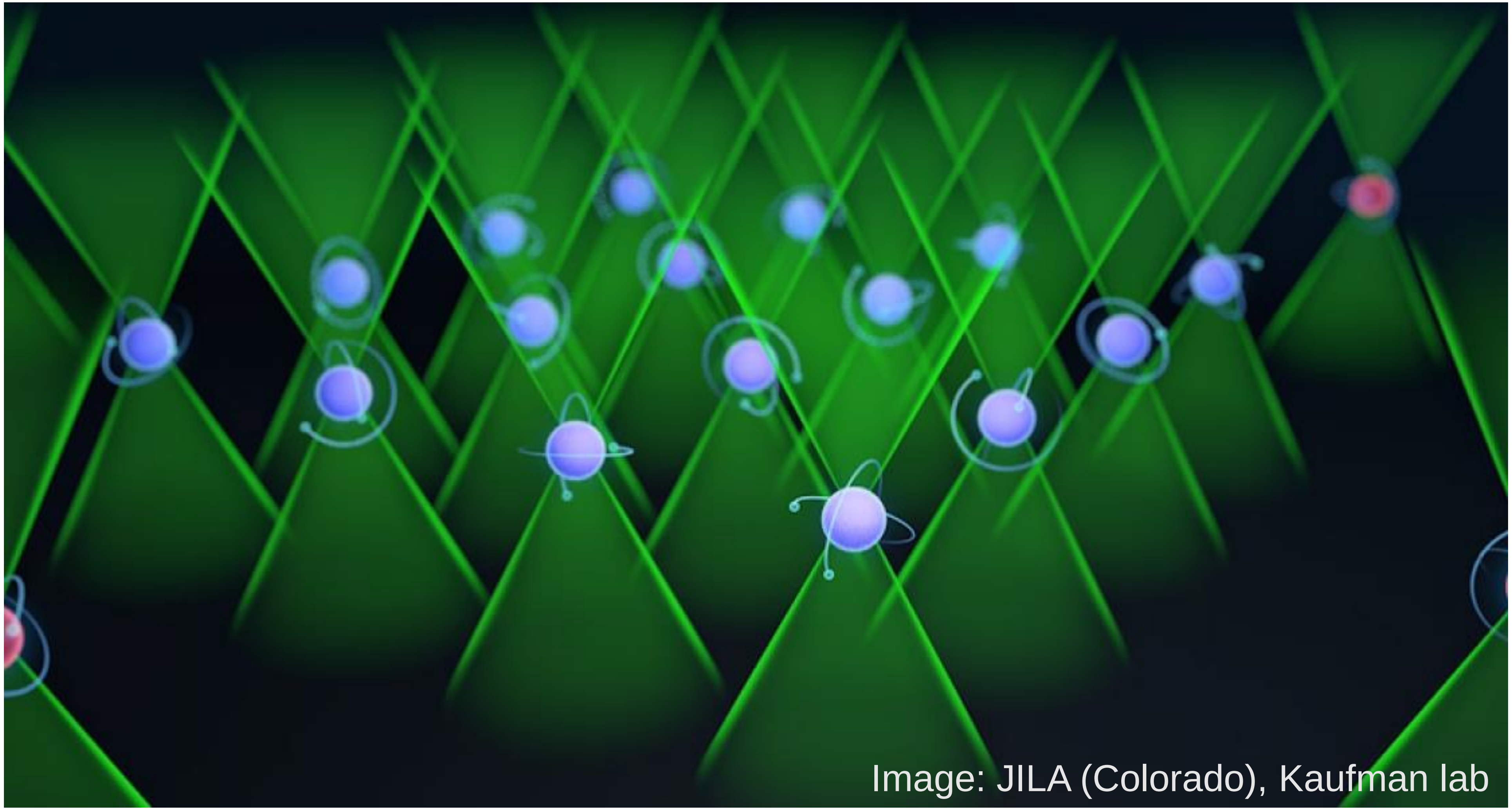

Location 3, wall of PX46. Earth (DC) field for scale

# APPLICATIONS IN OTHER FIELDS, SUCH AS QUANTUM COMPUTING.

# Quantum Computing & AION



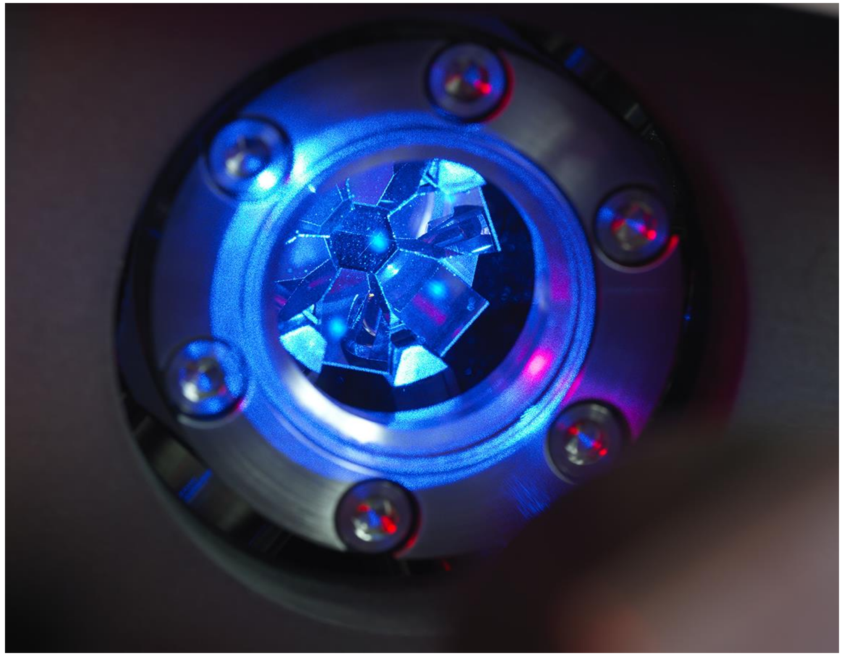


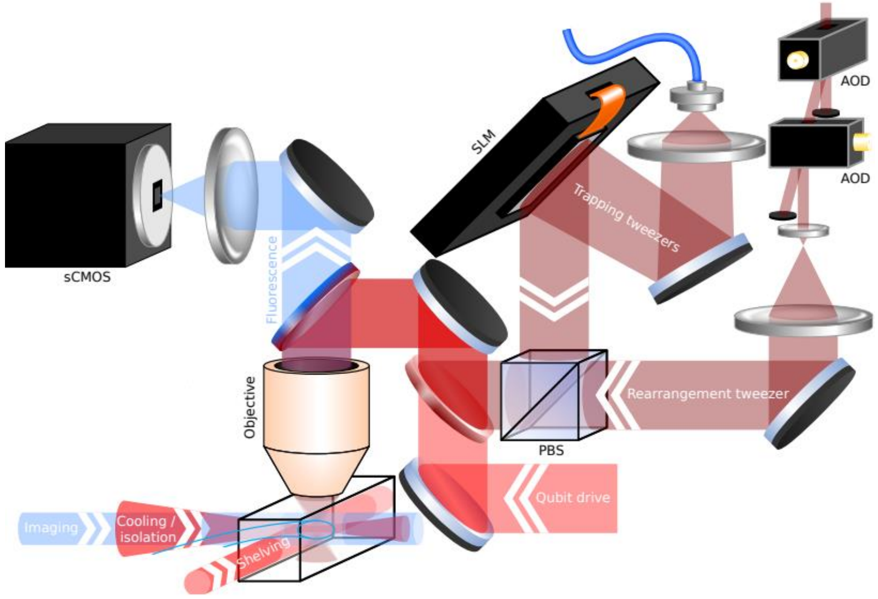


# Quantum Computing & AION



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

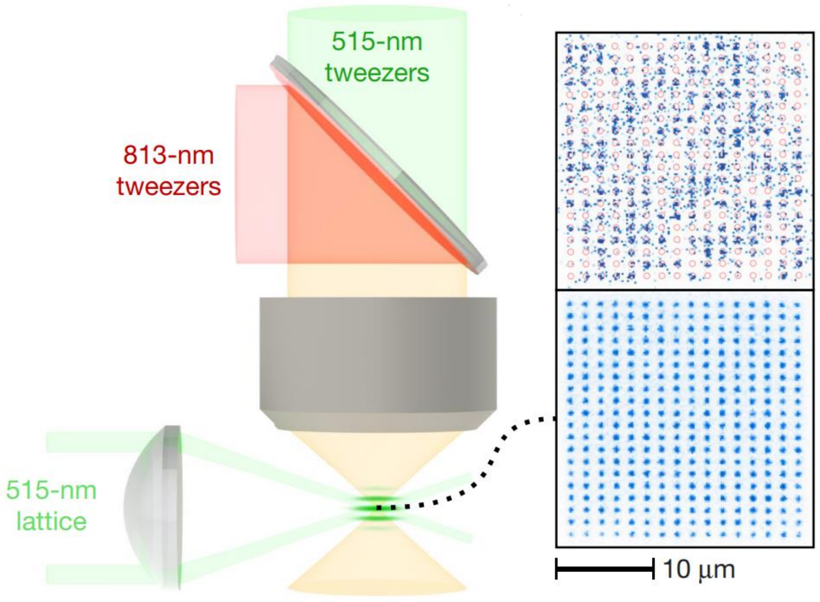





K. Barnes et al, https://arxiv.org/abs/2108.04790 (2021) – Atom Computing

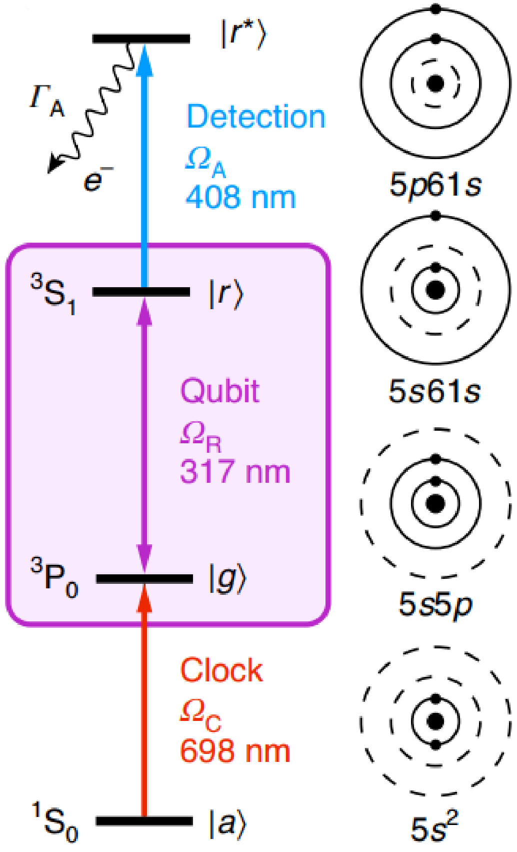
# Quantum Computing & AION

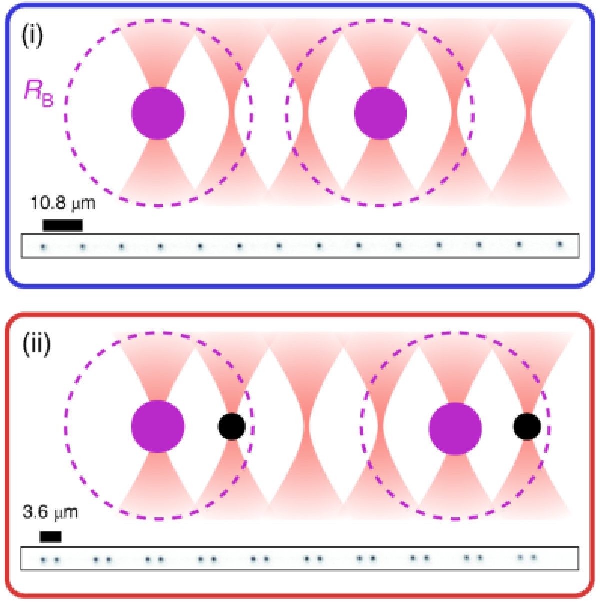
## 1 qubit = 1 Sr atom




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

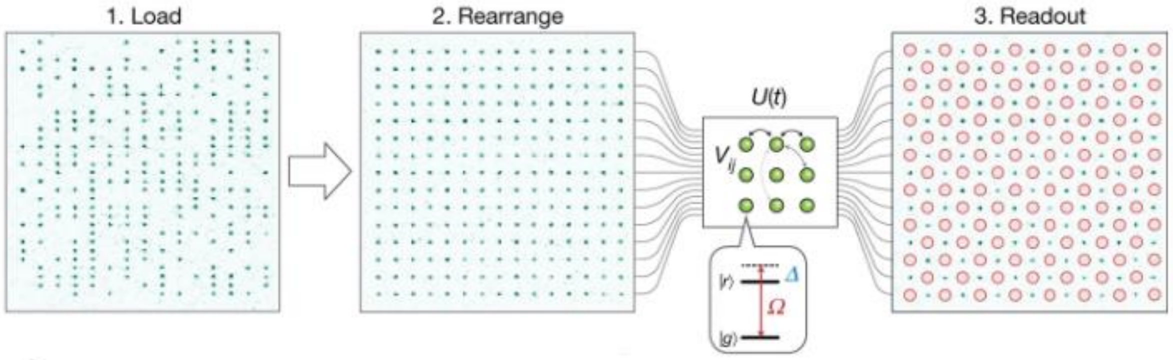
Imperial College London

AION

# 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$^2$**

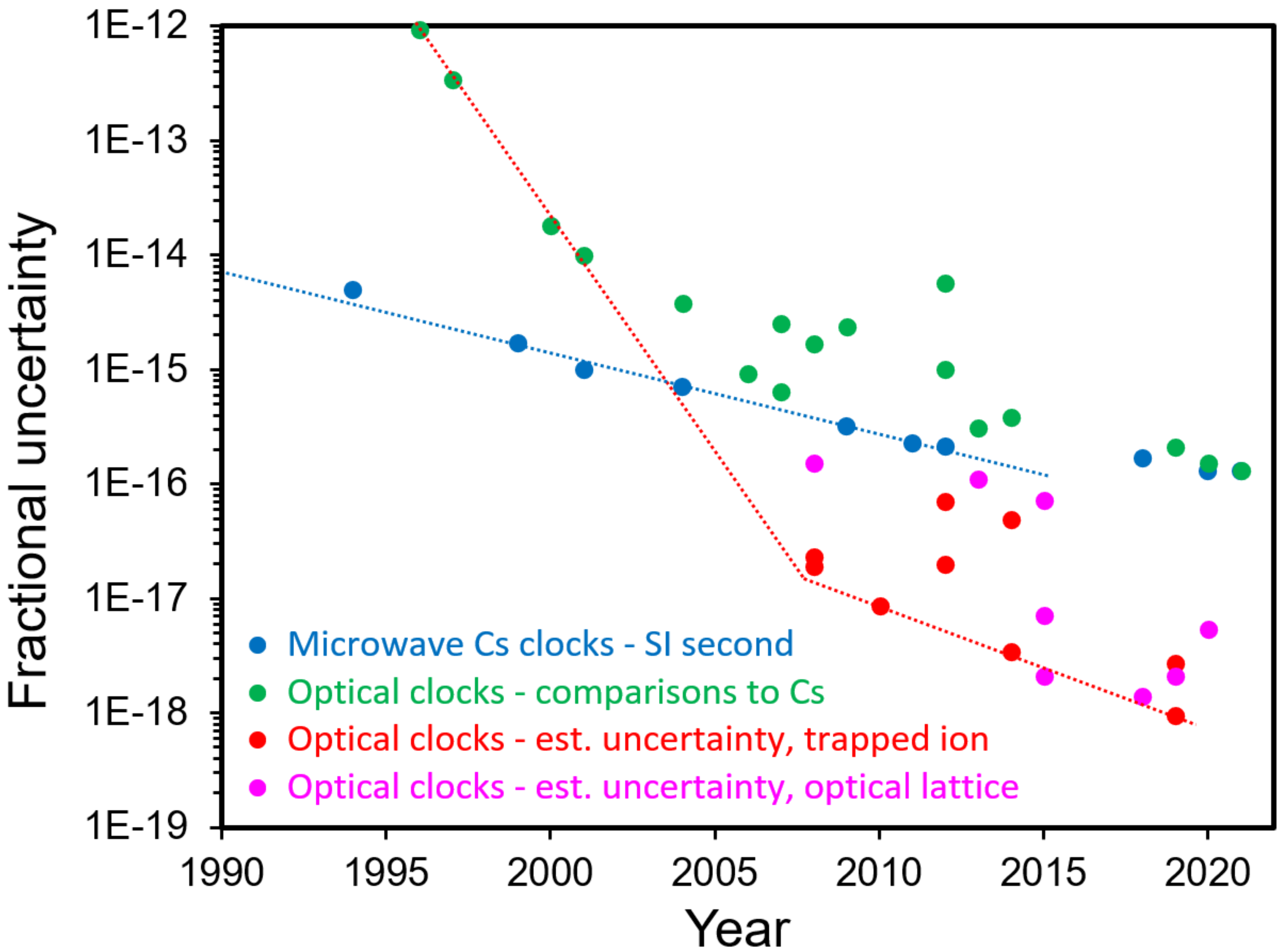
| T=100ms<br>N=$10^6$ | T=1s<br>N=$10^6$ | T=10s<br>N=$10^6$ | T=1s<br>N=$10^6$<br>100 pulses | T=1s<br>N=$10^8$<br>1000 pulses |
|---|---|---|---|---|
| 6 $10^{-9}$ m/s$^2$ | 6 $10^{-11}$ m/s$^2$ | **6 $10^{-13}$ m/s$^2$** | 6 $10^{-13}$ m/s$^2$ | 3 $10^{-14}$ m/s$^2$ |

**Large *T* → large sensitivity**

# ROADMAP

# Atomic Clock Progress

**use for next-generation SI time standard worldwide?**

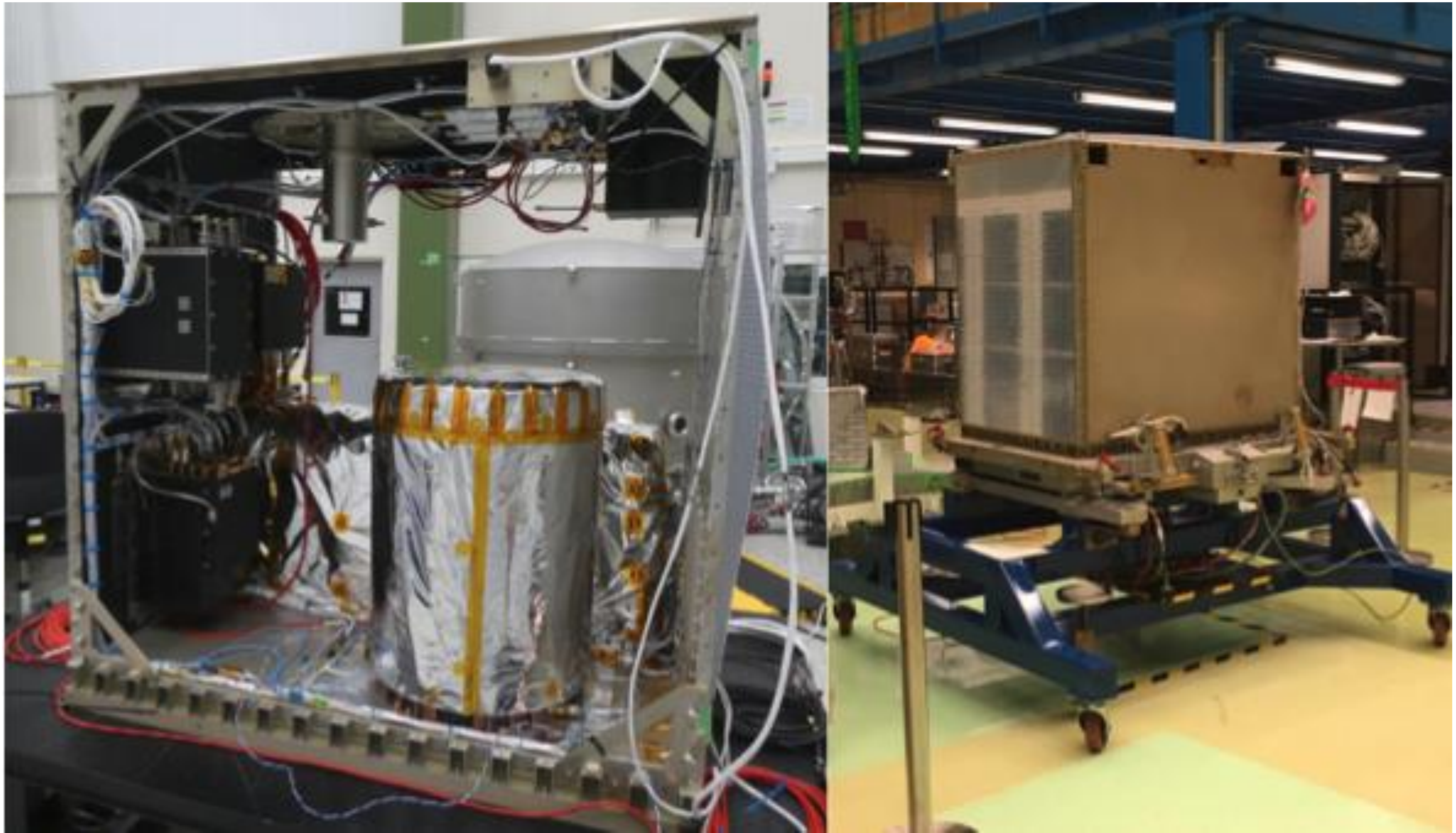


Imperial College London

AION

# Atomic Clock Progress

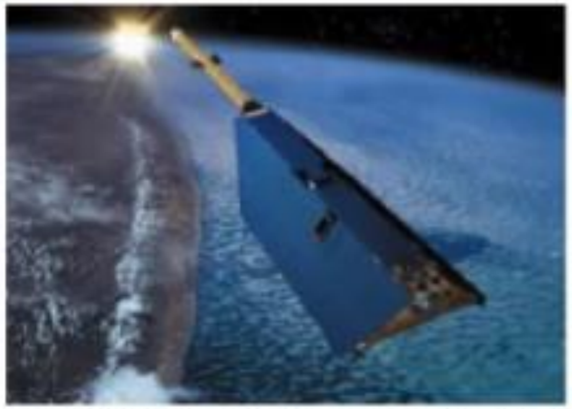
**ACES atomic clock mission: scheduled launch to ISS 2025**



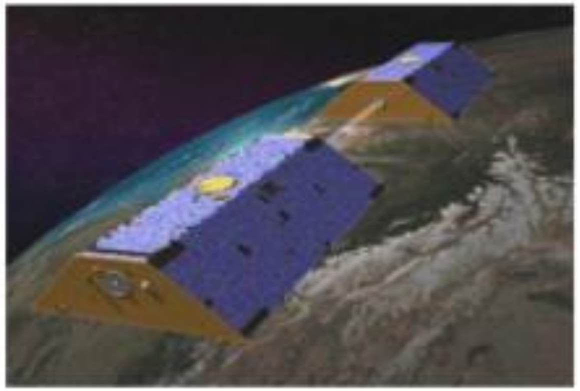
Large Scale AI For Fundamental Physics

# Earth Observation Progress

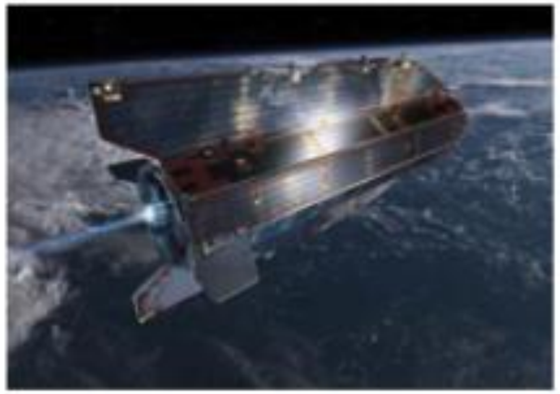
**Earth Observation: using classical electrostatic accelerometers & gradiometers**



CHAMP : satellite tracking by GNSS + accelerometry



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

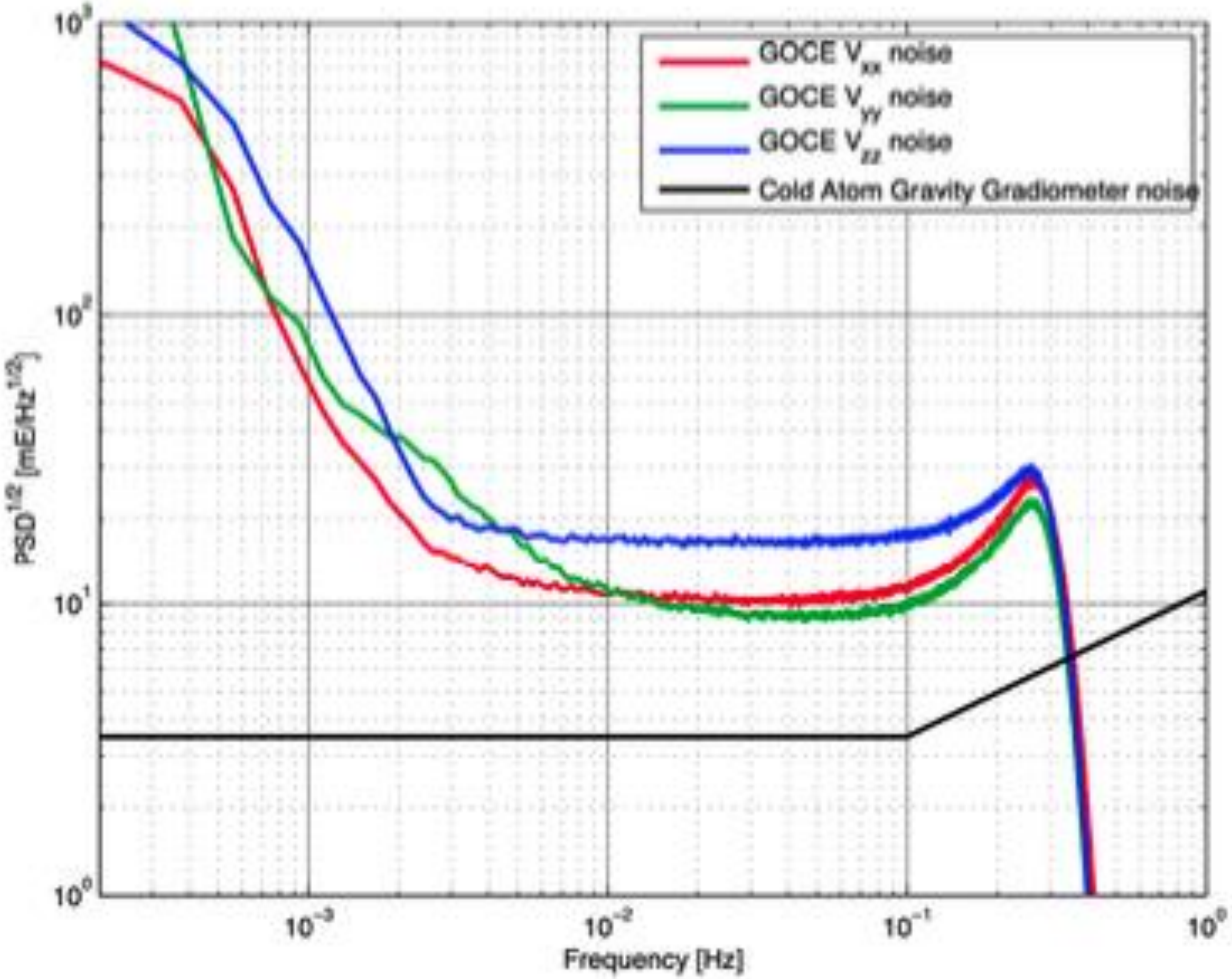


GOCE: orbit determination + gradiometry

| | CHAMP<br>2000 - 2010 | GRACE/GRACE-FO<br>2002 - ongoing | NGGM<br>Launch scheduled 2028 | GOCE<br>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<br>@350 $km$ | $\sim$ 10 cm<br>@175 $km$ | $\sim$ 1 mm @ 500 km<br>every 3 days<br>$\sim$ 1 mm @ 150 km<br>every 10 days | $\sim$ 1 cm<br>@100 $km$ |
| Gravity anomalies | $\sim$ 0.02 mGal<br>@1000 $km$ | $\sim$ 1 mGal<br>@175 $km$ | | $\sim$ 1 mGal<br>@100 $km$ |

# Earth Observation Progress

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

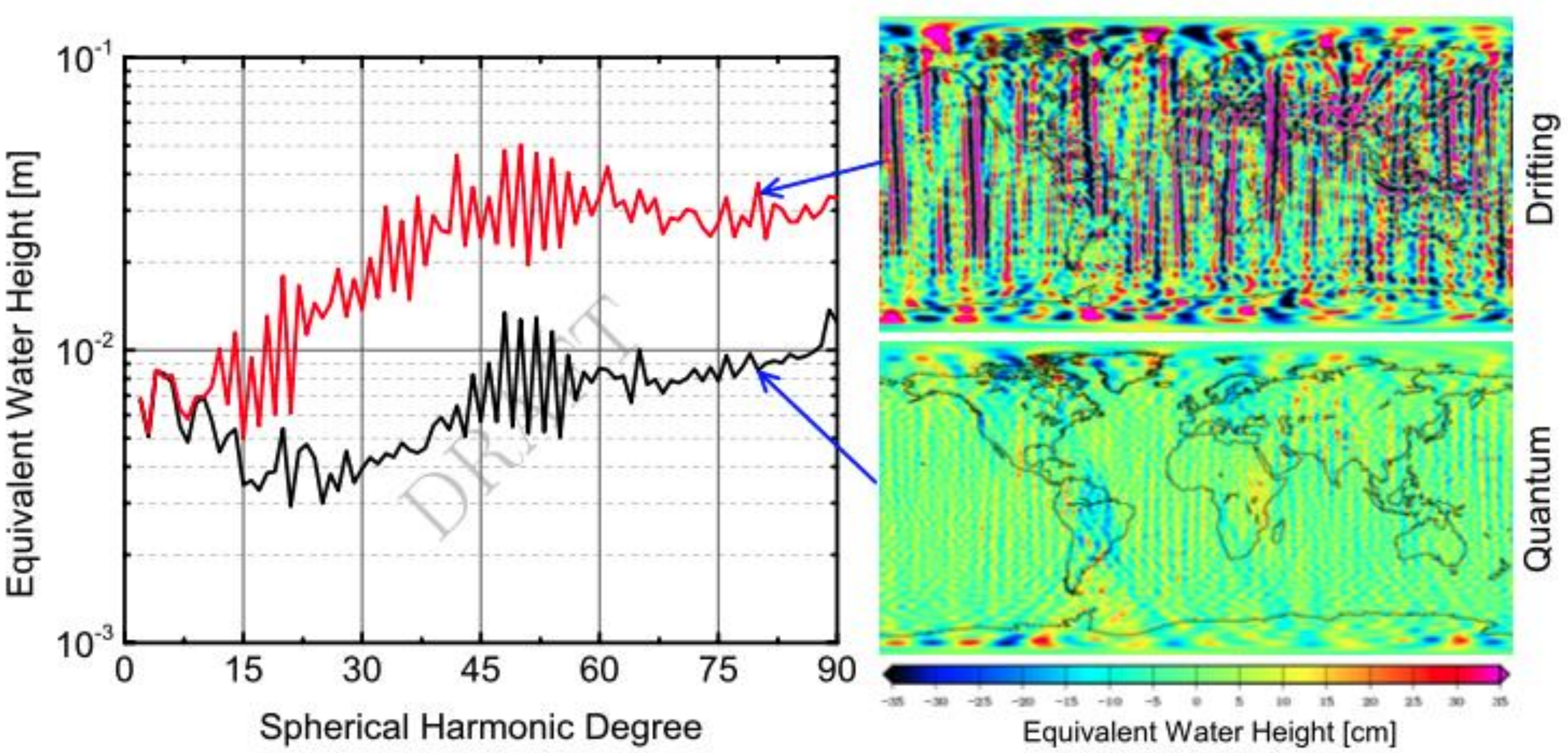


# Earth Observation Progress



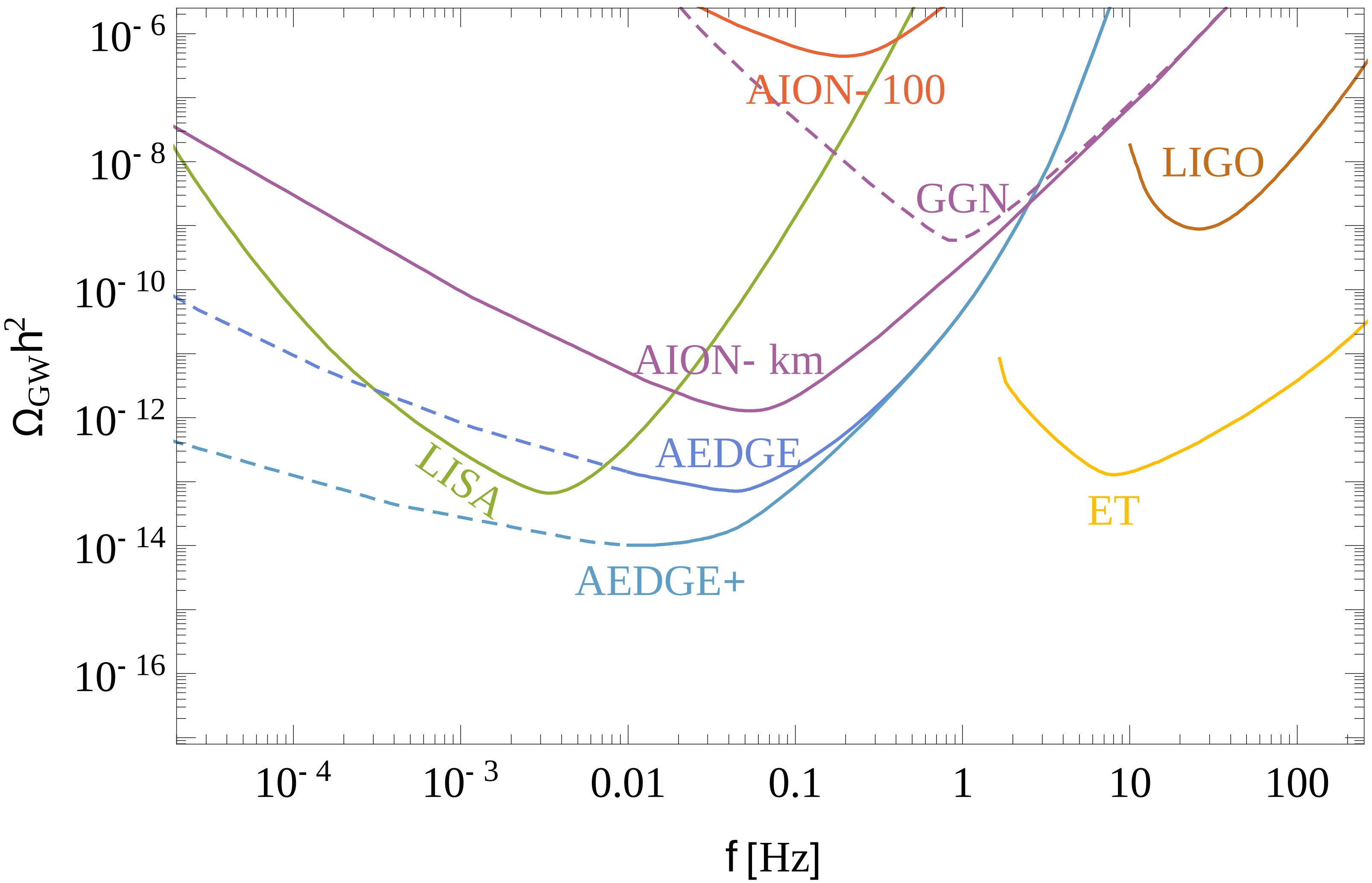
## Sensitivity to Water Height

**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**

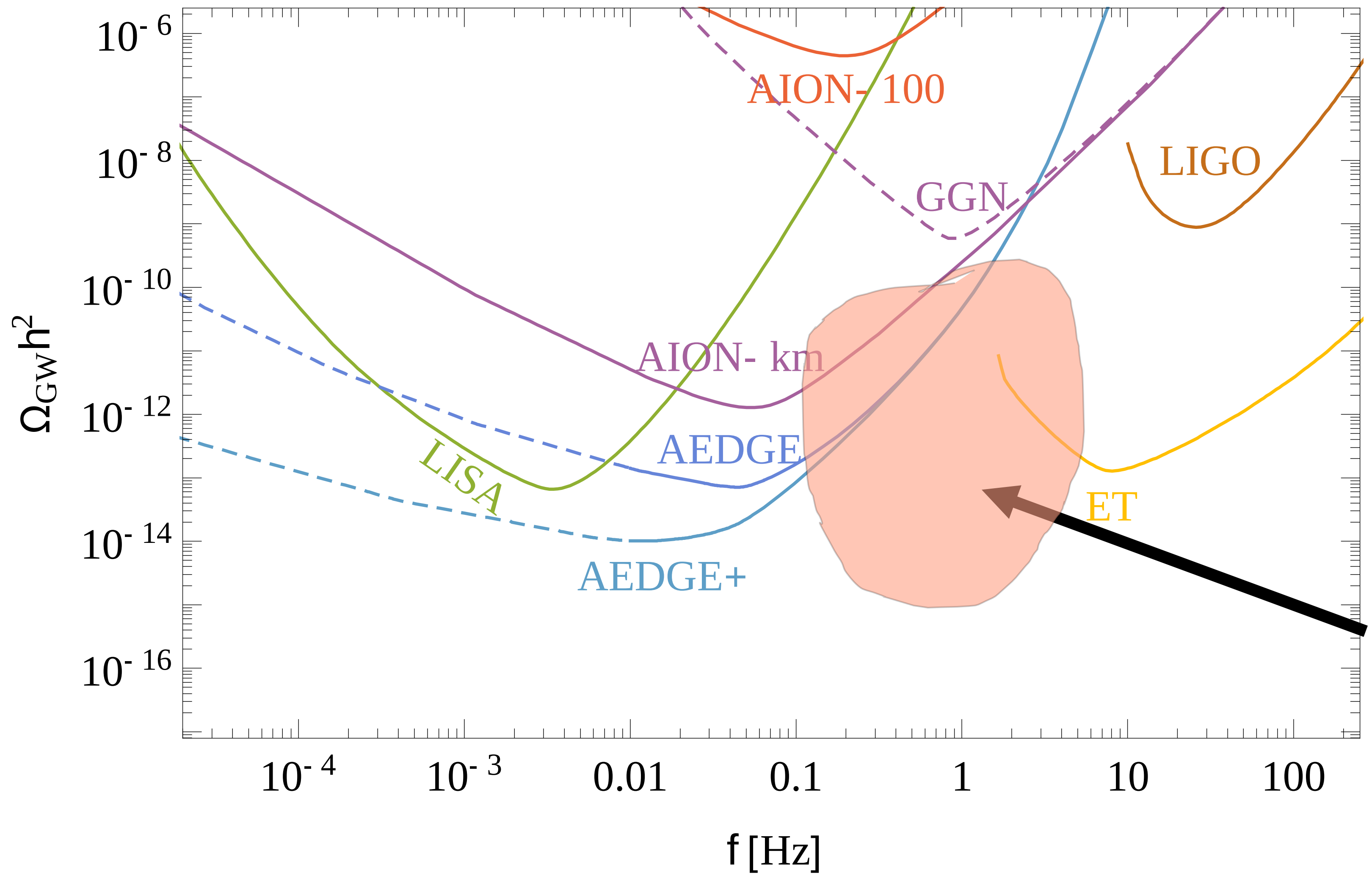


AION Collaboration (Badurina, OB,…, John Ellis et al): arXiv:1911.11755

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

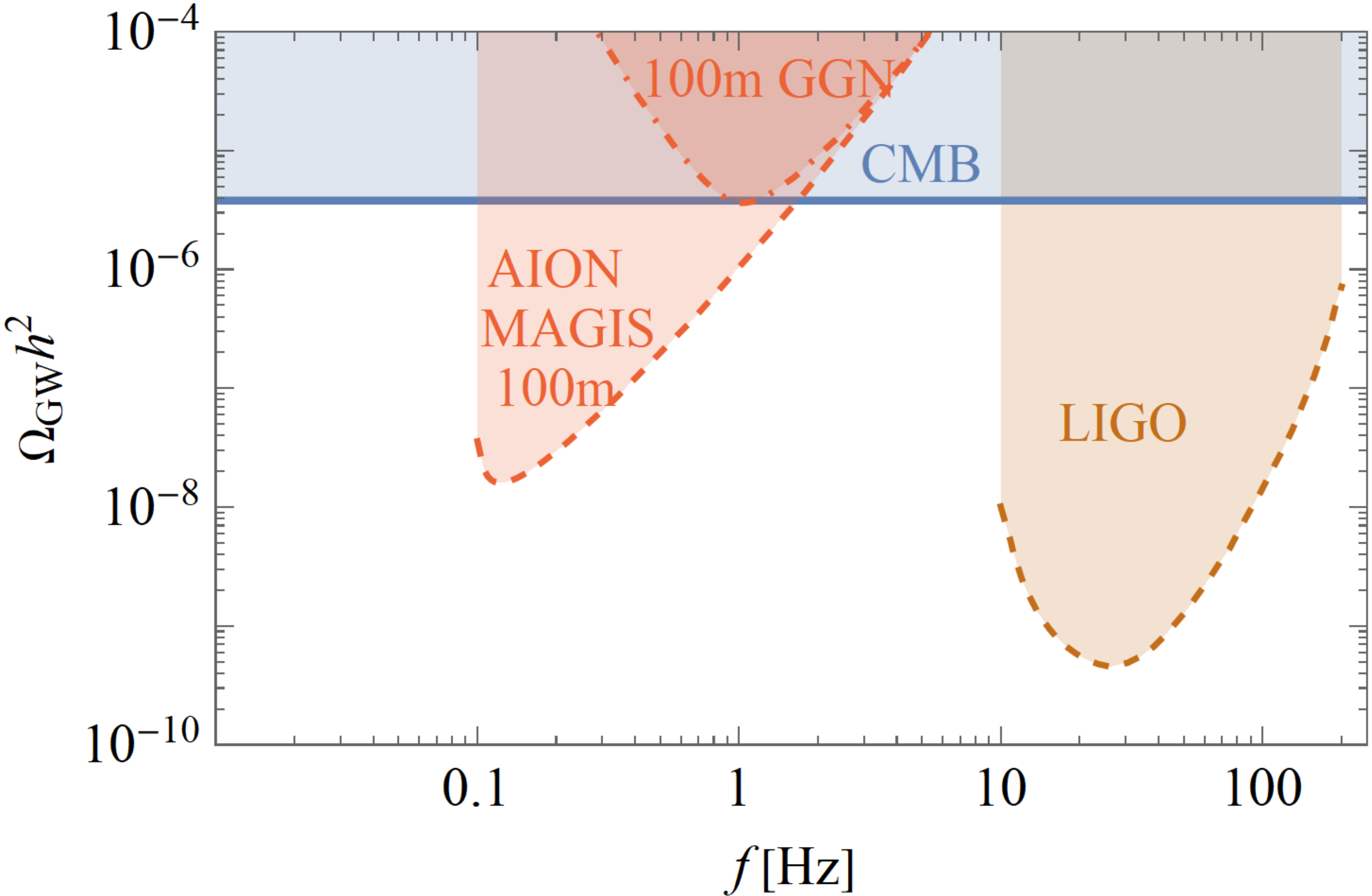


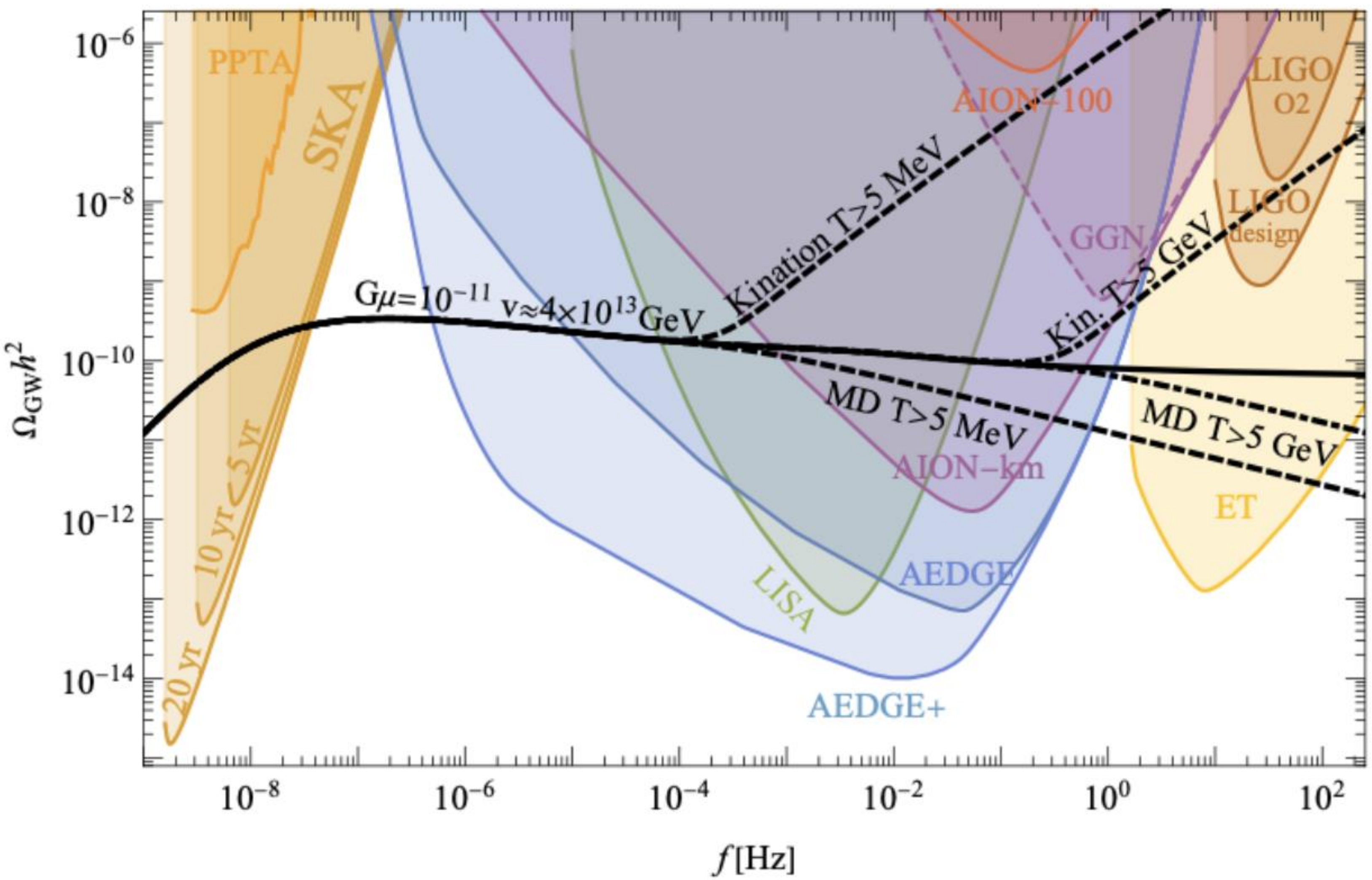
AION Collaboration (Badurina, OB,..., John Ellis et al): arXiv:1911.11755

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

# The GW Experimental Landscape: 2030ish

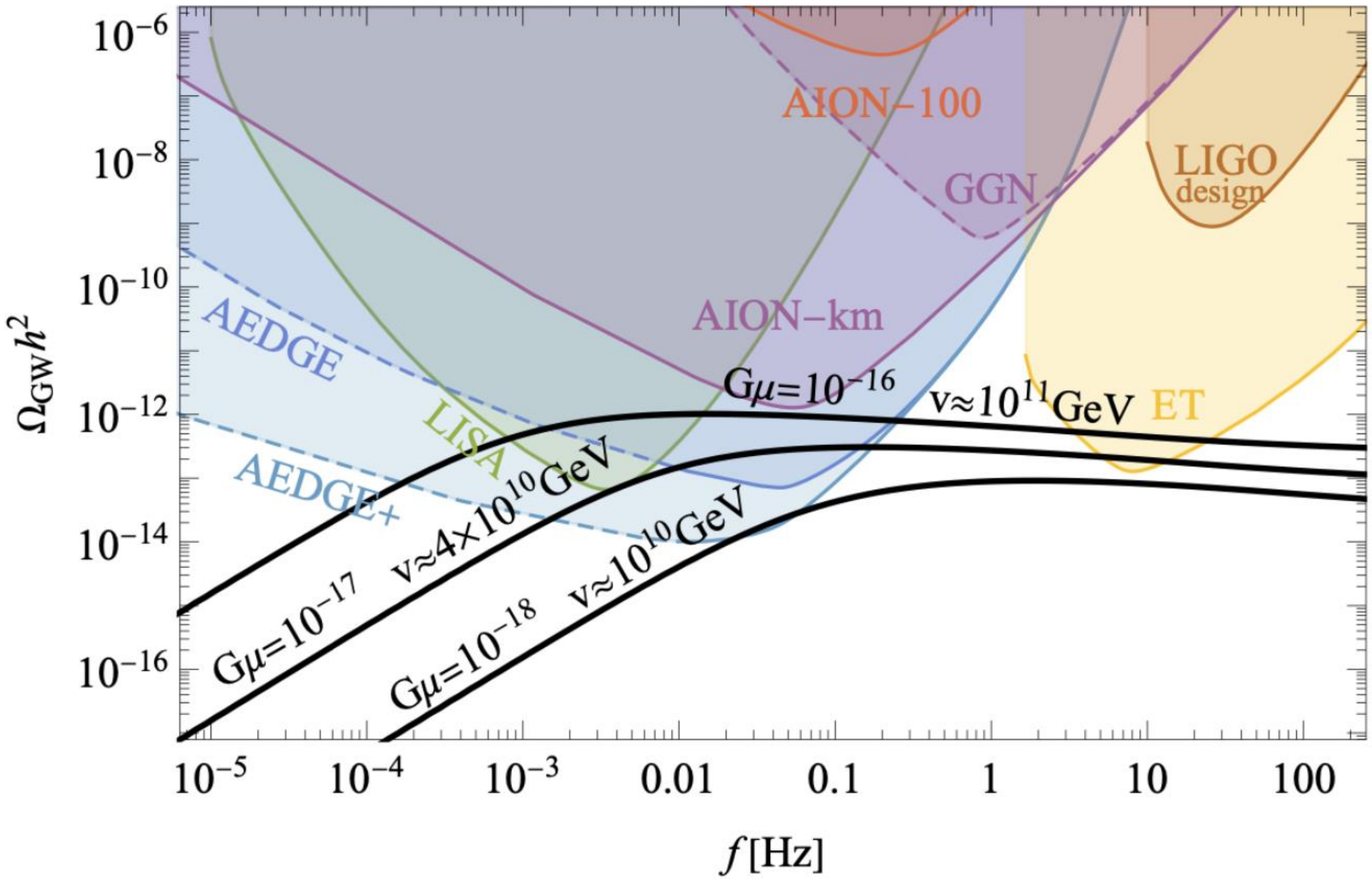






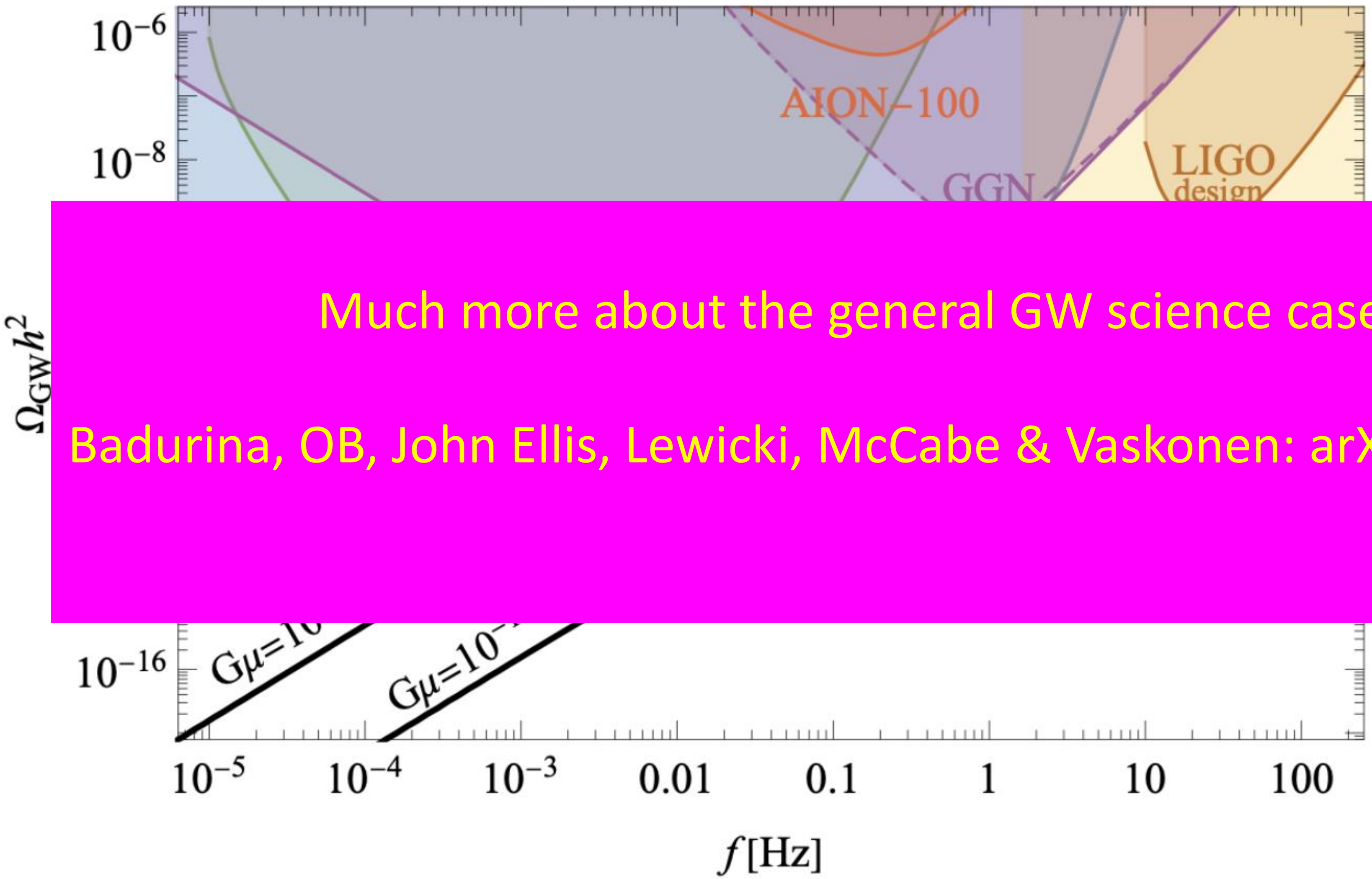

*Comparison of the Ω sensitivities to PI spectra of AION-100, AION-km, AEDGE and AEDGE+, LIGO, ET, Pulsar Timing Arrays (PTAs) and SKA.*

*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.*




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 $\mu$m | 5 $\mu$m/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 $\mu$m | 0.5 $\mu$m/yr |
| 200 km | 1 cm | 0.1 cm/yr | 0.05 mm | 5 $\mu$m/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 | $\eta$ | Year [ref] | Comments |
|---|---|---|---|---|
| Classical | Be - Ti | $2 \times 10^{-13}$ | 2008 [200] | Torsion balance |
| | Pt - Ti | $1 \times 10^{-14}$ | 2017 [179] | MICROSCOPE first results |
| | Pt - Ti | $(10^{-15})$ | 2019+ | MICROSCOPE full data |
| Hybrid | $^{133}$Cs - CC | $7 \times 10^{-9}$ | 2001 [204] | Atom Interferometry |
| | $^{87}$Rb - CC | $7 \times 10^{-9}$ | 2010 [205] | and macroscopic corner cube |
| Quantum | $^{39}$K - $^{87}$Rb | $5 \times 10^{-7}$ | 2014 [206] | different elements |
| | $^{87}$Sr - $^{88}$Sr | $2 \times 10^{-7}$ | 2014 [207] | same element, fermion vs. boson |
| | $^{85}$Rb - $^{87}$Rb | $3 \times 10^{-8}$ | 2015 [208] | same element, different isotopes |
| | $^{85}$Rb - $^{87}$Rb | $3.8 \times 10^{-12}$ | 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 | $\overline{\text{H}}$ - H | $(10^{-2})$ | 2020+ [212] | under construction at CERN |