Large Scale Atom Interferometry to Explore Fundamental Physics

Oliver Buchmueller, Imperial College London
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

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

Phase evolved by atom after time \(T\)

\[ |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i\omega_a T} \]
Simple Example: Two Atomic Clocks

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

\[ \omega_a \]

\[ |g\rangle \]

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

GW changes light travel time

\[ \Delta T \sim \frac{\hbar L}{c} \]

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

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

Courtesy of Jason Hogan!
Simple Example: Two Atomic Clocks

DM cloud changes atom frequency

DM coupling causes time-varying atomic energy levels:

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

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

\( \rho_{DM} = 0.4 \text{ GeV/cm}^2 \)
\( v_{DM} = 300 \text{ km/s} \)

Courtesy of Jason Hogan!
The phase of the laser is imprinted onto the atom.

Laser phase noise, mechanical platform noise, etc.

\[ \frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} e^{i\phi_L} \]

\[ \frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} e^{i\phi_L} \]

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

Courtesy of Jason Hogan!
AION: A Different Kind of Atom Interferometer

Hybrid “clock accelerometer”

Clock: measure light travel time $\rightarrow$ remove laser noise with single baseline

<table>
<thead>
<tr>
<th>Sensitivity Scenario</th>
<th>$L$ [m]</th>
<th>$T_{int}$ [sec]</th>
<th>$\delta \phi_{\text{noise}}$ [1/\sqrt{Hz}]</th>
<th>LMT [number $n$]</th>
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</thead>
<tbody>
<tr>
<td>AION-10 (initial)</td>
<td>10</td>
<td>1.4</td>
<td>$10^{-3}$</td>
<td>100</td>
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<tr>
<td>AION-10 (goal)</td>
<td>10</td>
<td>1.4</td>
<td>$10^{-4}$</td>
<td>1000</td>
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<tr>
<td>AION-100 (initial)</td>
<td>100</td>
<td>1.4</td>
<td>$10^{-4}$</td>
<td>1000</td>
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<tr>
<td>AION-100 (goal)</td>
<td>100</td>
<td>1.4</td>
<td>$10^{-5}$</td>
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<td>2000</td>
<td>5</td>
<td>$0.3 \times 10^{-5}$</td>
<td>40000</td>
</tr>
</tbody>
</table>

Used for sensitivity projections

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: $\sim 1000 \text{ hbar} \times k$
- Squeezing: $\sim 20$ dB 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.

  *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.

- **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.*
• 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
AION Collaboration Days in Oxford: Fall 2021

Start of AION in 2018
~5 people

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

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

Ratio of Cold Atom : Particle/Fundamental Physics people is 1:1
Beecroft building, Oxford Physics

Ultralow vibration
- All plant isolated
- Thick concrete walls

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

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

Stairwell is not a fire escape route.

Bakeout room and cleanroom nearby

Laser lab
Void
Keel slab
Aircon infrastructure

12 m
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).

Ground level

Feed through to laser lab

14.7m
10.0m
7.7m
5.0m
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
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.
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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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
Cavity finesse

- Lifetime: 16.95 us
- Finesse: $1.597 \times 10^5$

Drift of $\sim 200 \text{ mHz/s}$

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

Two cavity comparison setup

Cavity offset - overlapping Allan deviation
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
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

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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

Sensitivity to gravitational waves
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(UK)

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

(Germany)

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**
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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ULTRA-LIGHT DARK MATTER
Search for Ultra-Light Dark Matter

Known particle masses: neutrino, electron, proton, Higgs

QCD Axion

Ultralight Dark Matter

Pre-Inflationary Axion

Post-Inflationary Axion

WIMPs

Hidden Sector Dark Matter

Hidden Thermal Relics / WIMPless DM

Asymmetric DM

freeze-In DM

SIMPs / ELDERS

‘Ultra-Light’ dark matter

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

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

\[ < \rho_\phi > \approx \frac{m_\phi^2 \phi_0^2}{2} \left( \rho_{DM,\text{local}} \approx 0.4 \text{ GeV/cm}^3 \right) \]

\[ \rho_{DM} \approx 0.4 \text{ GeV/cm}^3 \]

\[ v_{DM} \approx 300 \text{ km/s} \]
Ultralight scalar dark matter

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

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

- Electron coupling
- Photon coupling
e.g., QCD

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

DM coupling causes time-varying atomic energy levels:

- Dark matter coupling
- DM induced oscillation

Courtesy of Jason Hogan!
Linear couplings to gauge fields and matter fermions

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

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

Vision for 2045+

AION Collaboration [Badurina, OB, ... John Ellis et al]: arXiv:1911.11755

Vision for 2045+

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

Much more about the general GW science case in:


and

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

Terrestrial Pathfinders
Technology proof of concept
UFF, AION, MAGIS, MIGA, ZAIGA

ACES
Improved optical links (microwave and optical) for clock comparison (Cs + H)

I-SOC Pathfinder
Further improved optical links for clock comparison (H)

STE-QUEST-like Mission
Equivalence Principle and Dark Matter exploration (Rb + K)

AEDGE-like Mission
Ultimate sensitivity
Dark Matter and Gravitational Waves

2021
Technology Development Programme
Raise TRL for Space

2022
Earth Obs. Pathfinder
Demonstrator for standalone CA EO mission

2025

Earth Obs. Mission
Standalone Atom Interferometer EO mission

2029

2030

2036

Atomic Clock Mission
Optical timescale, geodesy and fundamental physics

2037

2038

2045

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

Legends:
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

Informal Workshop
CERN, July 22/23 2019

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PP=Particle Physics
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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.
AEDGE Mission Concept

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
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

A detailed mission outline is provided in: MAGIS collaboration, P. W. Graham et al arXiv:1711.02225
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 Basi, Department of Physics, University of Trieste, and INFN - Trieste Section, Italy
- Kai Bongs, Midlands Ultrahigh Atom Research Centre, School of Physics and Astronomy University of Birmingham, United Kingdom
- Philippe Boger, LIPN, Université Sorbonne, INES, CNRS, Talence, France
- Chia Brodmann, Institute of Microelectronics, Ulm University and Institute of Quantum Technologies, German Aerospace Center (DLR), Germany
- Oliver Buchmeier, High Energy Physics Group, Bldlett Laboratory, Imperial College London, United Kingdom
- Maria Luisa (Marilù) Chiadalo, Physics Department "Ezio Forti" University of Pisa, and INFN-Pisa Italy
- John Ellis, Physics Department, King’s College London, United Kingdom
- Naeem Gashoki, Institute of Quantum Optics, Leibniz University of Hanover, Germany
- Aurélien Buse, SYRTE, Observatoire de Paris-FSL, CNRS, Sorbonne Université, LNE, Paris, France
- Philippe Jetzer, Department of Physics, University of Zurich, Switzerland
- Steve Leconte, Centre Suisse d’Electronique et de Microtechnique (CSEM), Neuchâtel, Switzerland
- Gillia Mitra, Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, BDI, Grasse, France
- Ernst M. Rasel, Institute of Quantum Optics, Leibniz University of Hanover, Germany
- Thilo Schulz, German Aerospace Center (DLR), Institute of Quantum Technologies, Ulm Germany
- Carlos F. Segrèv, 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 Witten, German Aerospace Center (DLR), Institute of Quantum Technologies, Ulm Germany
- Nan Yu, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
- Martin Zordan, Measurement Science and Technology, HSB Research Institute of Sweden, Borås, Sweden

Strong International Team
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.

### Table: Elements and Information

<table>
<thead>
<tr>
<th>Class</th>
<th>Elements</th>
<th>(\eta)</th>
<th>Year [ref]</th>
<th>Comments</th>
</tr>
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<tbody>
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<td>Be - Ti</td>
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<td>2008</td>
<td>Torsion balance</td>
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<td>Pt - Ti</td>
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<td>2017</td>
<td>MICROSCOPE first results</td>
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<td>2022+</td>
<td>MICROSCOPE full data</td>
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<td>2010</td>
<td>and macroscopic corner cube (CC)</td>
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<td>2020</td>
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<td>(10^{-2})</td>
<td>2023+</td>
<td>under construction at CERN</td>
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STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics

Science Goals: I

- Based on STE-QUEST proposals (M3, M4).
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Quantum Mechanics

Science Goals: II

- UNIVERSALITY of FREE FALL, EINSTEIN EQUIVALENCE PRINCIPLE
- COLLAPSE of the QUANTUM-MECHANICAL wave function

- Standard Model
- Quantum Mechanics

- Quantum effects of Dark Matter on Standard Model particles
- Collapse of the Quantum-Mechanical wave function

- General Relativity
- Universality of Free Fall, Einstein Equivalence Principle

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</table>
Example of Open Questions in Fundamental Physics

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

... and many more

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

Planck's quantum theory
beginning of 20th century
1947

transistor
1954

hard disk
1960

laser

The first quantum revolution
Observation and macroscopic manifestation of quantum principles

Albert Einstein (1879-1955)
Erwin Schrödinger (1887-1961)
Werner Heisenberg (1901-1976)
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 20th century  1947  1954  1960  end 20th / beginning 21st

Control of single quantum particles
First quantum algorithms

Richard Feynman (1918–1988)  Serge Haroche

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

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

\[ \Delta \phi = (\phi_1 - \phi_2) - (\phi_2 - \phi_3) = kv_1T - kv_2T = k\alpha T^2 \]

- “Difference” of two Ramsey sequences
- Measures acceleration

“Double diamond”

\[ \Delta \phi = k\alpha_1 T^2 - k\alpha_2 T^2 = k\delta\alpha T^3 \]

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

General Relativistic Effects in Atom Interferometry

<table>
<thead>
<tr>
<th>GR Phase Shift</th>
<th>Size (rad)</th>
<th>Interpretation</th>
<th>NR Phase Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. (-k\omega_0T^3)</td>
<td>-2. \times 10^{-6}</td>
<td>1st gradient</td>
<td>(-k\omega_0T^3)</td>
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<tr>
<td>2. (-\frac{1}{2}k\omega_0T^3)</td>
<td>-9. \times 10^{-6}</td>
<td></td>
<td>(-\frac{1}{2}k\omega_0T^3)</td>
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<tr>
<td>3. (-3k\omega_0^2T^2)</td>
<td>-4. \times 10^{-6}</td>
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<td>(-3k\omega_0^2T^2)</td>
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<tr>
<td>4. (-6k\omega_0T^2)</td>
<td>-7. \times 10^{-7}</td>
<td></td>
<td>(-6k\omega_0T^2)</td>
</tr>
<tr>
<td>5. (-\omega_0^2\theta^2)</td>
<td>-4. \times 10^{-7}</td>
<td>finite speed of light</td>
<td>(-\omega_0^2\theta^2)</td>
</tr>
<tr>
<td>6. (-2\omega_0\theta\omega_0^2)</td>
<td>-2. \times 10^{-7}</td>
<td>Doppler shift corrections</td>
<td>-2\omega_0\theta^2</td>
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<td>7. (10\omega_0^2\theta^2)</td>
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<td>1st gradient recoil</td>
<td>(-10\omega_0^2\theta^2)</td>
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<tr>
<td>8. (2\omega_0^2\theta^2)</td>
<td>-6. \times 10^{-9}</td>
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<td>(-2\omega_0^2\theta^2)</td>
</tr>
<tr>
<td>9. (-\omega_0^2\theta^2)</td>
<td>-3. \times 10^{-9}</td>
<td>2nd gradient</td>
<td>(-\omega_0^2\theta^2)</td>
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<tr>
<td>10. (-10\omega_0\theta\omega_0^2)</td>
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<tr>
<td>11. (-10\omega_0^2\theta^2)</td>
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<td>2nd gradient recoil</td>
<td>(-10\omega_0^2\theta^2)</td>
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<tr>
<td>12. (-3k\omega_0^2T^2)</td>
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<td>13. (-5k\omega_0^2T^2)</td>
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<td>14. (-12k\omega_0^2T^2)</td>
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<td>15. (-26k\omega_0^2T^2)</td>
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<td>16. (-52k\omega_0^2T^2)</td>
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<td>17. (-104k\omega_0^2T^2)</td>
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<td>18. (-208k\omega_0^2T^2)</td>
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<td>19. (2 - 23 - \gamma)k_\alpha T\omega T^2)</td>
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<td>GR (velocity-dependent force)</td>
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<td>(11(4 - 5 - \gamma)k_\alpha T\omega T^2)</td>
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<td>21. (10(4 - 5 - \gamma)k_\alpha T\omega T^2)</td>
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<tr>
<td>30. (-6(1 - \beta)k_\alpha T\omega T^2)</td>
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<td></td>
<td>(-6(1 - \beta)k_\alpha T\omega T^2)</td>
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</table>

Pi and Pi/2 Pluses – Rabi Oscillation

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

Transition Probability $f \rightarrow e$

\[ \begin{align*}
\text{Probability} & \quad \text{Pulse duration} \\
1 & \quad 1/2
\end{align*} \]

“π” pulse = mirror

\[ |e, p + \hbar k_{\text{eff}}\rangle \]

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\[ |e, p + \hbar k_{\text{eff}}\rangle \]

\[ |e, p + \hbar k_{\text{eff}}\rangle \]

Imprint laser phase on atomic wave-function:

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

“π/2” pulse = beam splitter

\[ |f, p\rangle \]

\[ |f, p\rangle \]

\[ |f, p\rangle \]

Momentum transfer (∼1 cm/s)

\[ k_{\text{eff}} = k_1 + k_2 \]

\[ |e, p + \hbar k_{\text{eff}}\rangle \]

\[ |e, p + \hbar k_{\text{eff}}\rangle \]

\[ |f, p\rangle \]

\[ |f, p\rangle \]

\[ |f, p\rangle \]
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:

\[ \Phi_1 = \phi_1, \quad \Phi_2 = 0 \]
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

$$-Et/\hbar = -\omega_\alpha T$$

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

$$\Phi_1 = \phi_1 - ET/\hbar - \phi_2, \quad \Phi_2 = \phi_2$$
Assuming no other interactions like gravity, etc.

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

\[
\Phi_1 = \phi_1 - \frac{ET}{\hbar} - \phi_2, \quad \Phi_2 = \phi_2 - \frac{ET}{\hbar}
\]
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

$$\Phi_1 - \Phi_2 = (\phi_1 - ET/\hbar - \phi_2 + \phi_3) - (\phi_2 - ET/\hbar) = \phi_1 + \phi_3 - 2\phi_2$$
Large Scale AI For Fundamental Physics

**MZ Acceleration Phase Shift**

Acceleration phase shift

\[ \Phi(t) = \bar{k}_{\text{eff}} \Phi(t) \]

\[ \Phi_1(t_1) = 0 \]

\[ \Phi_2(t_2) = \frac{1}{2} \bar{k}_{\text{eff}} \bar{a} T^2 \]

\[ \Phi_3(t_3) = \frac{1}{2} \bar{k}_{\text{eff}} \bar{a} (2T)^2 \]

\[ \Delta \Phi = \Phi_1(t_1) - 2\Phi_2(t_2) + \Phi_3(t_3) = \bar{k}_{\text{eff}} \bar{a} T^2 \]
Different Phase Shifts for Different Interactions

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

\[ \Phi_i^{eff}(t) = \vec{k}_i^{eff} \cdot \vec{r}_i(t) \]
STE-QUEST
STE-QUEST (M-Class Mission Proposal)

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 Rani, Department of Physics, University of Trieste, and INFN - Trieste Section, Italy
- Kai Bongs, Millenage UltraCold Atom Research Centre, School of Physics and Astronomy University of Birmingham, United Kingdom
- Philippe Bouger, LP2N, Université Bourdeaux, IOGS, CNRS, Talence, France
- Chao Brunner, Institute of Microelectronics, Uni University and Institute of Quantum Technologies, German Aerospace Centre (DLR), Germany
- Oliver Buchmuller, High Energy Physics Group, Blackett Laboratory, Imperial College London, United Kingdom
- Maria Luisa (Marilù) Chiodo, Physics Department "Enrico Fermi" University of Pisa, and INFN-Pisa, Italy
- John Ellis, Physics Department, King’s College London, United Kingdom
- Naceur Gasnari, Institute of Quantum Optics, Leibniz University of Hanover, Germany
- Aurélien Boes, SYRTE, Observatoire de Paris-PSL, CNRS, Sorbonne Université, LNE, Paris, France
- Philippe Jetzer, Department of Physics, University of Zurich, Switzerland
- Steve Lovecchio, Centre Suisse d’Electronique et de Microtechnique (CSEM), Neuchâtel, Switzerland
- Gilles Mérini, Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, BDI, Géant, France
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- Carlos F. Segovia, 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
- Lise Wimmer, German Aerospace Centre (DLR), Institute of Quantum Technologies, Ulm Germany
- Nan Yu, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
- Martin Zeban, 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

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<th>Class</th>
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<th>( \eta )</th>
<th>Year [ref]</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>Classical</td>
<td>Be - Ti</td>
<td>( 2 \times 10^{-13} )</td>
<td>2008</td>
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State-of-the-art conventional sensors (electrostatic accelerometers)

e.g. used for Earth Observation are limited by around \( \eta \sim 1 \times 10^{-11} \) (acceleration sensitivity)

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<td>( 3 \times 10^{-9} )</td>
<td>2015</td>
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</tr>
<tr>
<td></td>
<td>(^{65})Rb - (^{87})Rb</td>
<td>( 3.8 \times 10^{-12} )</td>
<td>2020</td>
<td>10 m tower</td>
</tr>
<tr>
<td></td>
<td>(^{88})Sr - (^{88})Sr</td>
<td>( 5.7 \times 10^{-13} )</td>
<td>2024</td>
<td>AION 10m</td>
</tr>
<tr>
<td></td>
<td>(^{88})Sr - (^{88})Sr</td>
<td>(&lt; 10^{-15} )</td>
<td>2030</td>
<td>AION/MAGIS 100m</td>
</tr>
<tr>
<td></td>
<td>(^{41})K - (^{87})Rb</td>
<td>( (10^{-17}) )</td>
<td>2037</td>
<td>STE-QUEST</td>
</tr>
<tr>
<td>Antimatter</td>
<td>H - H</td>
<td>( (10^{-2}) )</td>
<td>2023+</td>
<td>under construction at CERN</td>
</tr>
</tbody>
</table>
STE-QUEST: An M-class Cold Atom mission to probe gravity, dark matter and quantum mechanics is now open at:

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

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

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

➢ This workshop follows our Community Workshop & Roadmap for Cold Atoms in Space and is the next step in our community building process to define, develop and promote important milestones of our Community Roadmap, specifically the STE-QUEST M-class mission proposal now being considered by ESA.

➢ This event will bring together the cold atom, astrophysics, cosmology, and fundamental physics communities to discuss the science opportunities of this M-class mission proposal. Further information about the workshop scope is listed below.

➢ Registering on the link provided above will enable you to attend the virtual workshop event and to keep informed about the continuing development of a full mission proposal that will follow it.
ESA SENIOR RECOMMENDATIONS
VOYGAE2050
Large missions:
- Moons of the Giant Planets
- Exoplanets
- New Physical Probes of the Early Universe: Fundamental physics and astrophysics

Possible Medium missions:
... QM & GR (cold atoms?)

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

What M-mission to propose?
A coordinated three-fold response of the community to the Voyage 2050 recommendations:

• A letter to ESA’s Director of Science, Guenther Hasinger:
  ➢ to raise awareness in ESA that the community is prepared to organise itself and to work actively with ESA, as it shapes a roadmap for a Cold Atom technology in space development programme

• A community workshop in September:
  ➢ This event brought together the cold atom, astrophysics, cosmology, fundamental physics, and earth observation communities to formulate a road-map for the development programme,

• A Workshop Summary and Road-map Document
  ➢ As input input to ESA and national space agencies on how to structure a Cold atoms in Space programme and what priorities could be established.
CERN AION100 SITE EXPLORATION WITH PBC
Introduction

EM Noise Levels

Slides from Sergio Calatroni (TE-VSC and PBC)

- AION-100 experiment is an ion interferometer, proposed to be installed in the PX46 pit.

- Feasibility study under way, with the support of the Physics Beyond Collider study - Technology Working Group. Aiming for official letter of intent at the end of the year.

- For info of other feasibility studies under way for AION-100: https://indi.to/RkZdN

- Need to measure EM background noise (1 mHz – 100 kHz) at the top (few meters below the steel lid) and at the bottom of PX46 during machine operation, using fluxgates up to 1-3 kHz, and 3D pick-up coils for the high frequency spectrum.

- Choice of a closed plastic tube installed in the lid, after drilling, for hosting the probes.

- Installation procedure approved by LMC: https://edms.cern.ch/document/2710516/1.0

- Many thanks to all services and people involved for the support: everybody was fully motivated to help.
AION-100

Location of AION-100

Drilling location
The tube (thanks to EN-MME)

PP plastic, closed at bottom
225 mm outer diameter
199.4 mm inner diameter
5000 mm length
Al flange for support
Installation (thanks to EN-ACE, EN-HE, EN-CV)

Ready for inserting the probes
Measurement location at the bottom of the PX46 shaft, UX45 building

Slides from Marco Buzio, Mariano Pentella, Daniel Valuch
Measurement location at the bottom of the PX46 shaft, UX45 cavern

PX46

UX45
Spectrum similar to that measured at Fermilab for MAGIS
**Location:** bottom of the PX46 shaft.

**Systems in UX45 running**

- Buzio, Pentella, Valuch: Second campaign EM fields characterization at LHC point 4, 18.3.2022

---

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

- 45.5 μT (Earth field)

---

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

- PX46 underground, 15.3.2022, 50000 seconds
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!
APPLICATIONS IN OTHER FIELDS, SUCH AS QUANTUM COMPUTING.
Quantum Computing & AION

Image: JILA (Colorado), Kaufman lab
Existing AION cold Sr system (80%) + New tweezer array (20%) = Quantum computer

– Atom Computing
1 qubit = 1 Sr atom

Quantum logic gates (the hard bit!): Rydbergs


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

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

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/](https://atom-computing.com/) - $60M funding round, 2022
- [https://pasqal.io/about](https://pasqal.io/about)
- [https://coldquanta.com/core-technology/hilbert/](https://coldquanta.com/core-technology/hilbert/)
- [https://www.quera.com/](https://www.quera.com/)
- [https://mobile.twitter.com/computingq](https://mobile.twitter.com/computingq)

Atoms in tweezers – some recent academic results:

- S. Madjarov et al. Nature Physics 16, 857-861 (2020) – Caltech, Endres lab
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 dg of about $5.7 \times 10^{-13}$ in 2024. In space, we estimate we could reach $T \sim 20\text{sec}$ and, thus, reach $3.9 \times 10^{-14}$ (factor $\sim 15$ better).
Why Atom Interferometry in Space?

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

<table>
<thead>
<tr>
<th>T=100ms N=10^6</th>
<th>T=1s N=10^6</th>
<th>T=10s N=10^6</th>
<th>T=1s N=10^6 100 pulses</th>
<th>T=1s N=10^8 1000 pulses</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 \times 10^{-9} \text{ m/s}^2</td>
<td>6 \times 10^{-11} \text{ m/s}^2</td>
<td>6 \times 10^{-13} \text{ m/s}^2</td>
<td>6 \times 10^{-13} \text{ m/s}^2</td>
<td>3 \times 10^{-14} \text{ m/s}^2</td>
</tr>
</tbody>
</table>

Large $T \rightarrow$ large sensitivity

GRACE reference: ONERA Superstar Accelerometer: $10^{-10}$ m/s$^2$
ROADMAP
Atomic Clock Progress

use for next-generation SI time standard worldwide?

Fractional uncertainty vs. Year

- Microwave Cs clocks - SI second
- Optical clocks - comparisons to Cs
- Optical clocks - est. uncertainty, trapped ion
- Optical clocks - est. uncertainty, optical lattice
Atomic Clock Progress

**ACES** atomic clock mission: scheduled launch to ISS 2025
Earth Observation Progress

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

<table>
<thead>
<tr>
<th></th>
<th>CHAMP 2000 - 2010</th>
<th>GRACE/GRACE-FO 2002 - ongoing</th>
<th>NGGM Launch scheduled 2028</th>
<th>GOCE 2009 - 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measurement type</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EA accuracy</td>
<td>$\sim 10^{-10}$ m/s$^2$</td>
<td>$\sim 10^{-11}$ m/s$^2$</td>
<td>$\sim 10^{-11}$ m/s$^2$</td>
<td>$\sim 10^{-12}$ m/s$^2$</td>
</tr>
<tr>
<td>Geoid undulations</td>
<td>$\sim 10$ cm @350 km</td>
<td>$\sim 10$ cm @175 km</td>
<td>$\sim 1$ mm @ 500 km every 3 days</td>
<td>$\sim 1$ cm @100 km</td>
</tr>
<tr>
<td>Gravity anomalies</td>
<td>$\sim 0.02$ mGal @1000 km</td>
<td>$\sim 1$ mGal @175 km</td>
<td>$\sim 1$ mm @ 150 km every 10 days</td>
<td>$\sim 1$ mGal @100 km</td>
</tr>
</tbody>
</table>
Earth Observation Progress

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

\( \Omega_{GW}/h^2 \) vs. \( f [\text{Hz}] \)

- 100m GGN
- CMB
- AION
- MAGIS 100m
- LIGO
Sensitivities of cosmic string measurements to modifications of the cosmological expansion rate. Kination or matter dominance (MD) at temperatures $T > 5\text{ MeV}$ or $5\text{ GeV}$.

Comparison of the $\Omega$ sensitivities to PI spectra of AION-100, AION-km, AEDGE and AEDGE+, LIGO, ET, Pulsar Timing Arrays (PTAs) and SKA.
Different experiments sensitive to different values of cosmic string tension.
Different experiments sensitive to different values of cosmic string tension.

Much more about the general GW science case in:


*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

<table>
<thead>
<tr>
<th>Spatial resolution</th>
<th>Equivalent water height</th>
<th>Geoid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monthly field</td>
<td>Long-term trend</td>
</tr>
<tr>
<td>400 km</td>
<td>5 mm</td>
<td>0.5 mm/yr</td>
</tr>
<tr>
<td>200 km</td>
<td>10 cm</td>
<td>1 cm/yr</td>
</tr>
<tr>
<td>150 km</td>
<td>50 cm</td>
<td>5 cm/yr</td>
</tr>
<tr>
<td>100 km</td>
<td>5 m</td>
<td>0.5 m/yr</td>
</tr>
</tbody>
</table>

#### Target objectives

<table>
<thead>
<tr>
<th>Spatial resolution</th>
<th>Equivalent water height</th>
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<td>0.5 m</td>
<td>0.05 m/yr</td>
</tr>
</tbody>
</table>
# Fundamental Physics Part

## Tests of Weak Equivalence Principle (Universality of Free Fall)

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