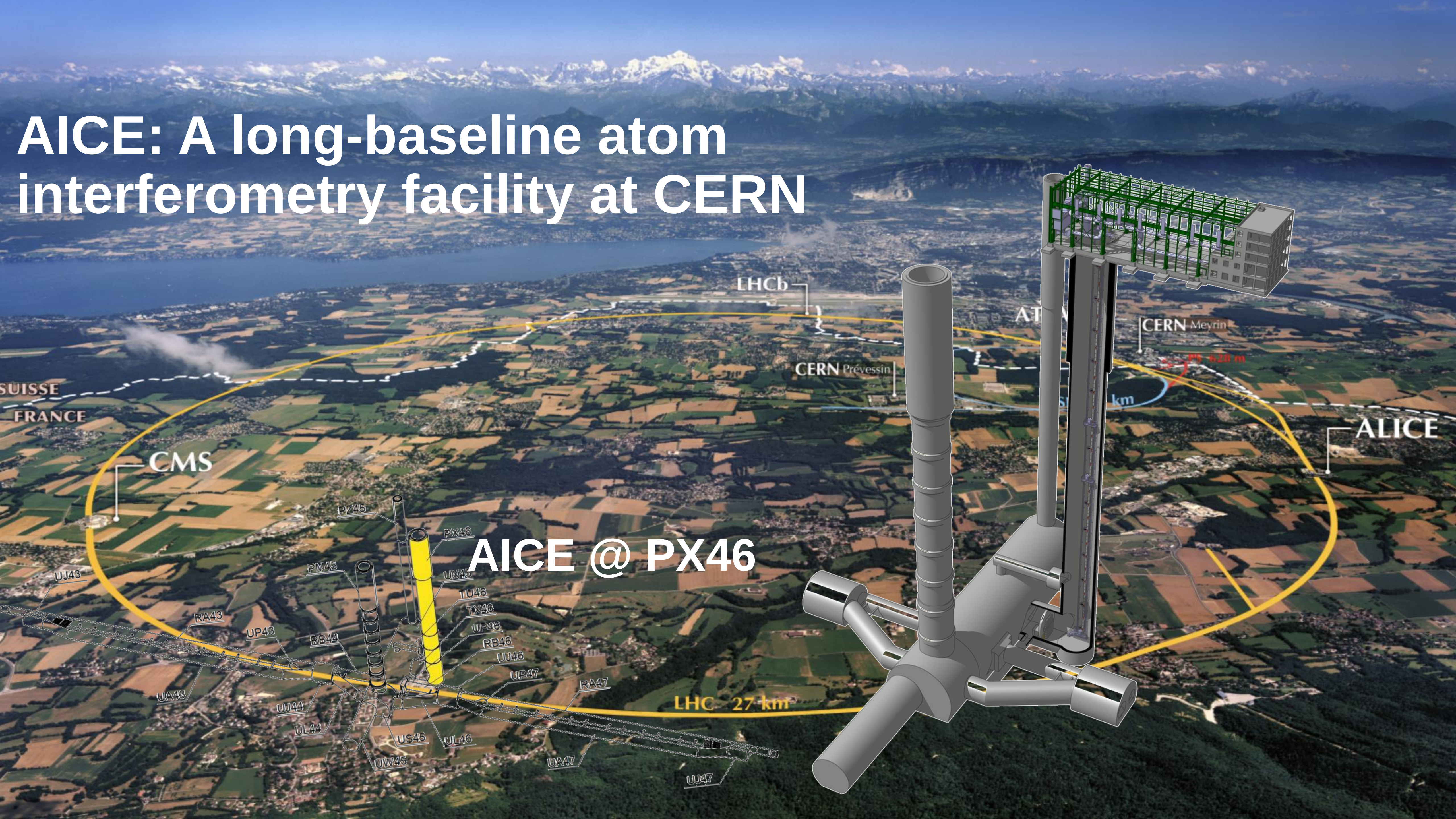
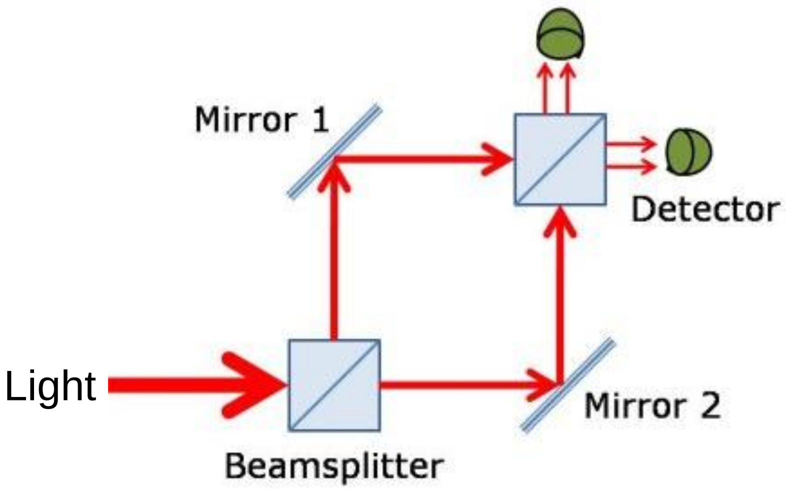
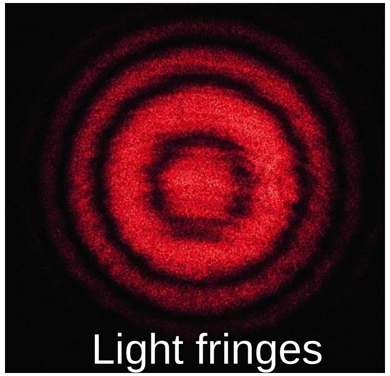
AICE: A long-baseline atom interferometry facility at CERN



Light vs. Cold Atoms: Atom Interferometry

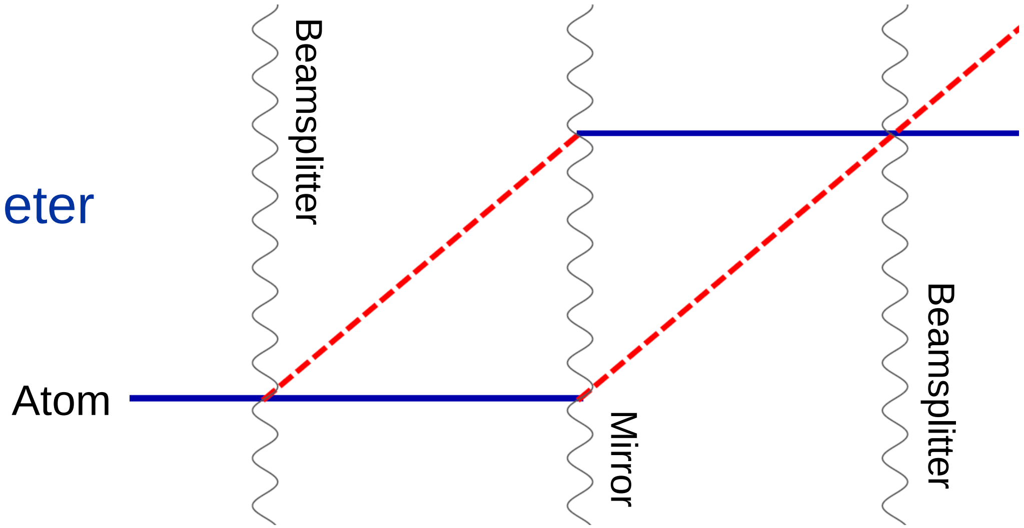
Light interferometer

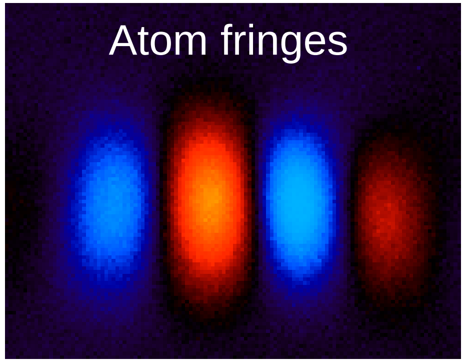




http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
https://hubner-photonics.com/applications/lasers-for-interferometry/

Atom interferometer

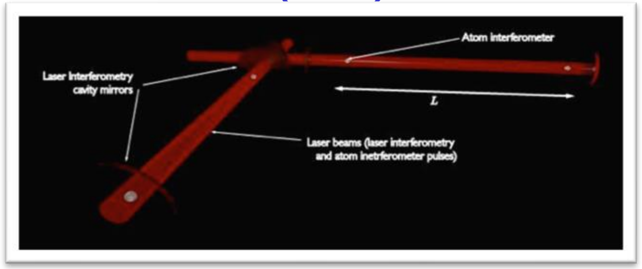




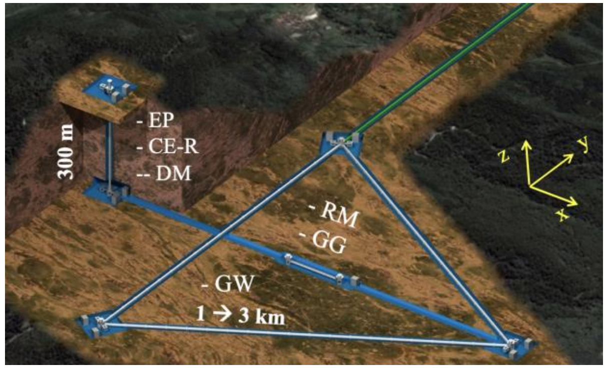
https://arxiv.org/abs/2105.00992

Long baseline atom interferometer

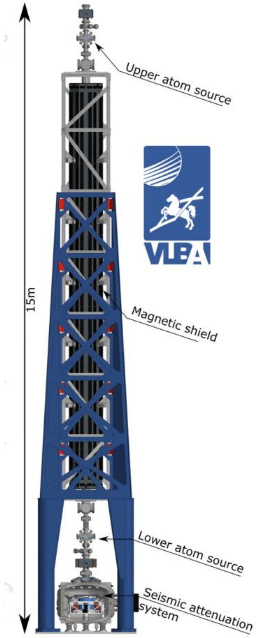
MIGA: Terrestrial detector using atom interferometer at O(100m)
(France)

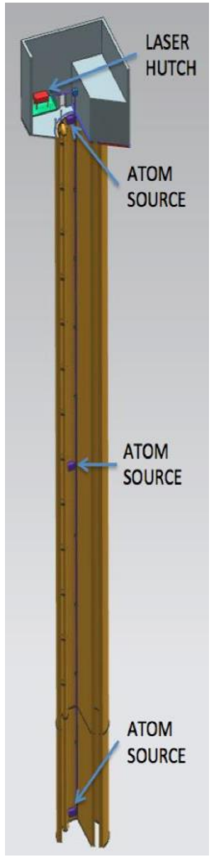


ZAIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)
(China)

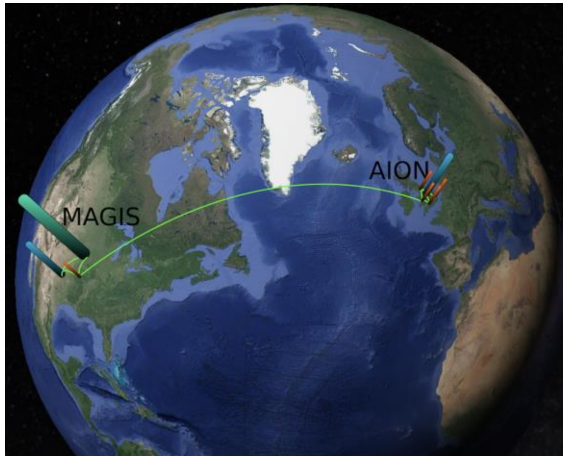


VLBAI: Terrestrial tower using atom interferometer O(10m)
(Germany)



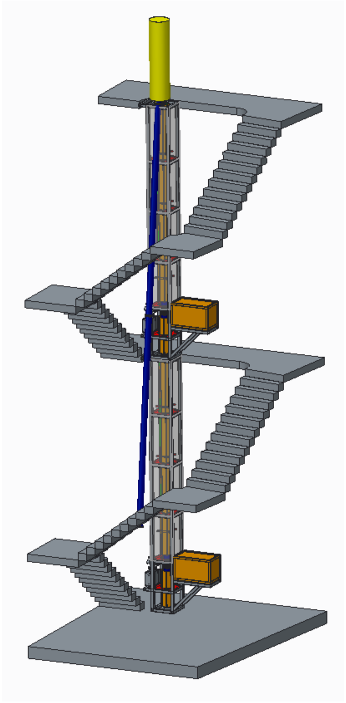


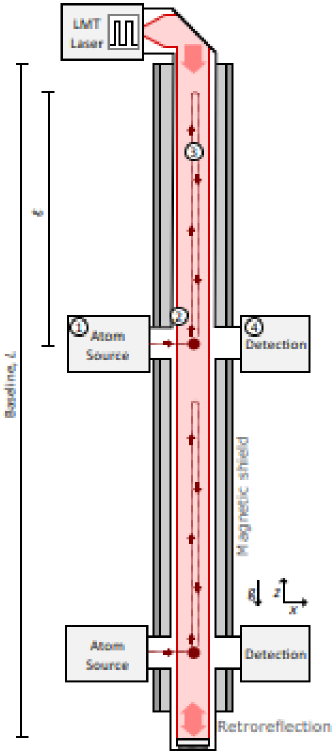
AION: Terrestrial shaft detector using atom interferometer at 10m – O(100m) planned
(UK)



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

Planned network operation

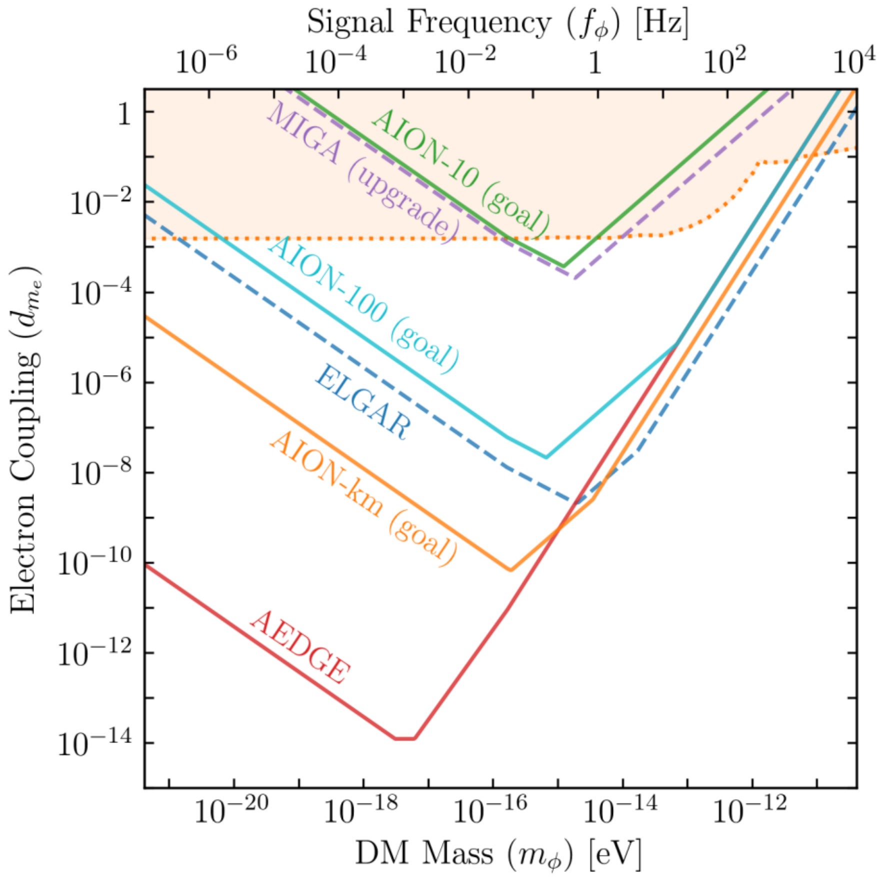


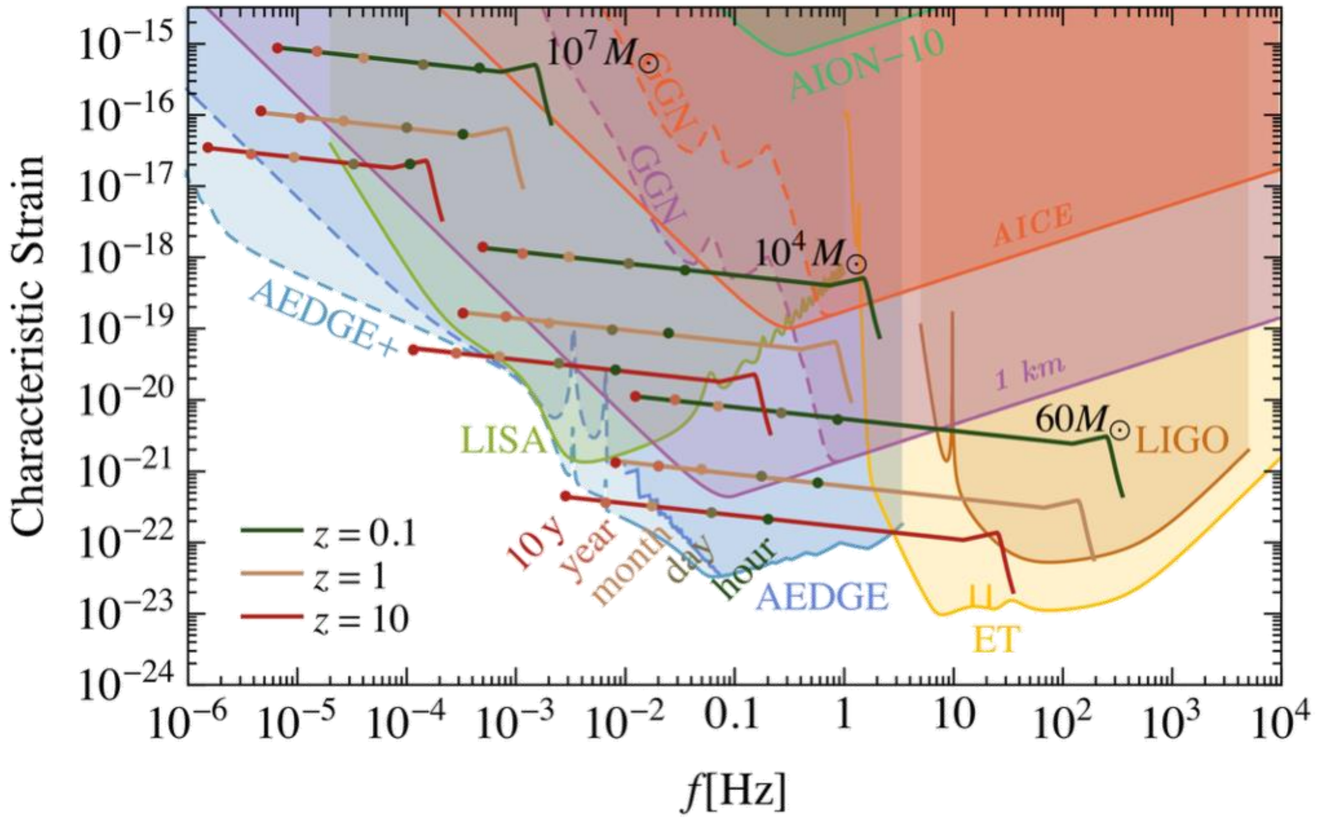


Coupled atom sources have a larger potential for measurement of Gravitational Waves and Dark Matter. AION-10 in Oxford

Motivation for atom interferometer

Unlocking the potential for observation of Ultra-Light Dark Matter and Gravitational Waves from cosmological and astrophysical sources in the unexplored mid-frequency band





AICE Facility at PX46

What is AICE?

- 140 m vertical atom interferometer infrastructure in PX46
- Based on clock-transition interferometry (Sr baseline, but also others)
- Designed as an **upgradable long-baseline facility**

Core Physics Programme

Dark Matter & Fundamental Physics

- Ultralight dark matter (coherent field searches)
- New interactions / B–L couplings
- Precision tests (e.g. alpha, equivalence pri. in multi-species mode)

Exploratory Extension

- Mid-frequency gravitational waves (0.01–10 Hz)
- Pathfinder towards km-scale detectors

Facility Philosophy

- Staged commissioning → baseline → upgrades
- Multi-source configuration along the baseline
- Species flexibility (Sr → Yb → dual-species)
- Infrastructure intended for evolving cold-atom programmes

LETTER OF INTENT: 100M ATOM INTERFEROMETER EXPERIMENT AT CERN

Letter of Intent:
AICE - Atom Interferometer CERN Experiment

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

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

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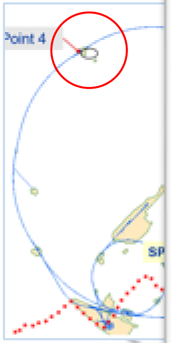
Poss... at



CERN | Physics Beyond Colliders

CERN-PBC Report-2023-002

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

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

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

* Editors

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

Abstract

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

Geneva, Switzerland

August 7, 2023

CERN | Physics Beyond Colliders

CERN-PBC Report-2025-004

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

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

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

* Editor

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

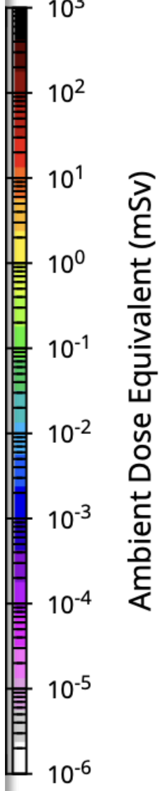
Abstract

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

Geneva, Switzerland

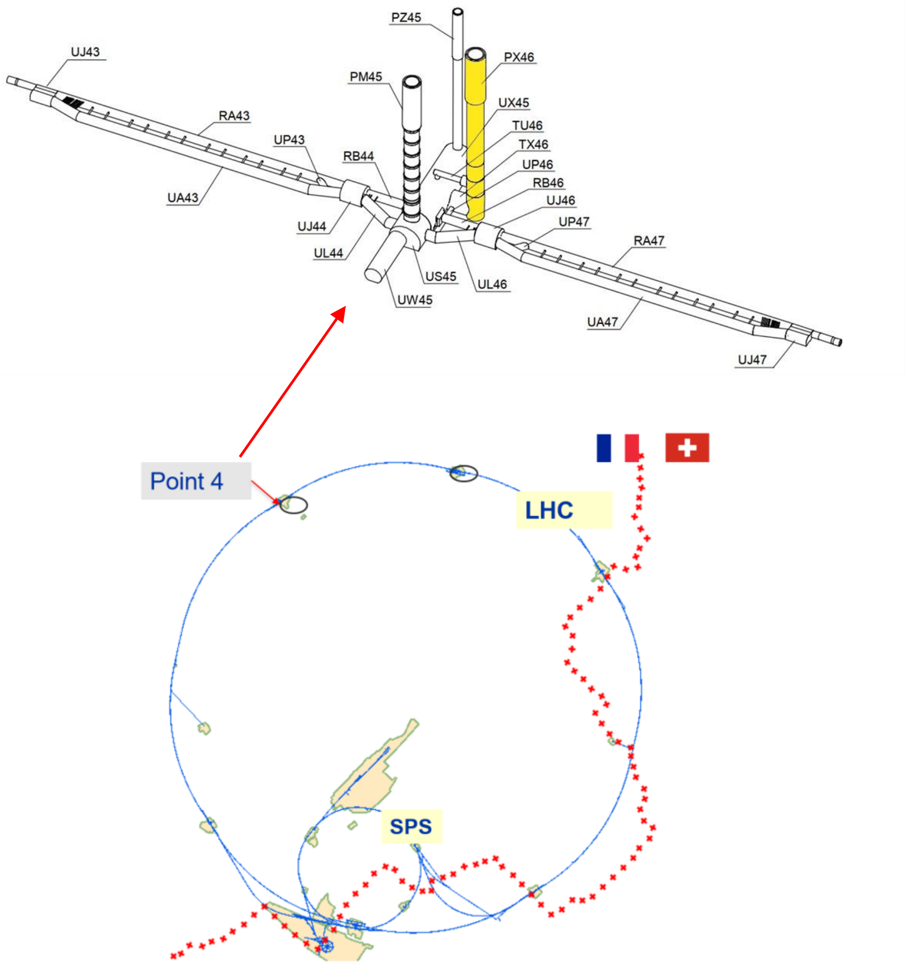
August 16, 2025

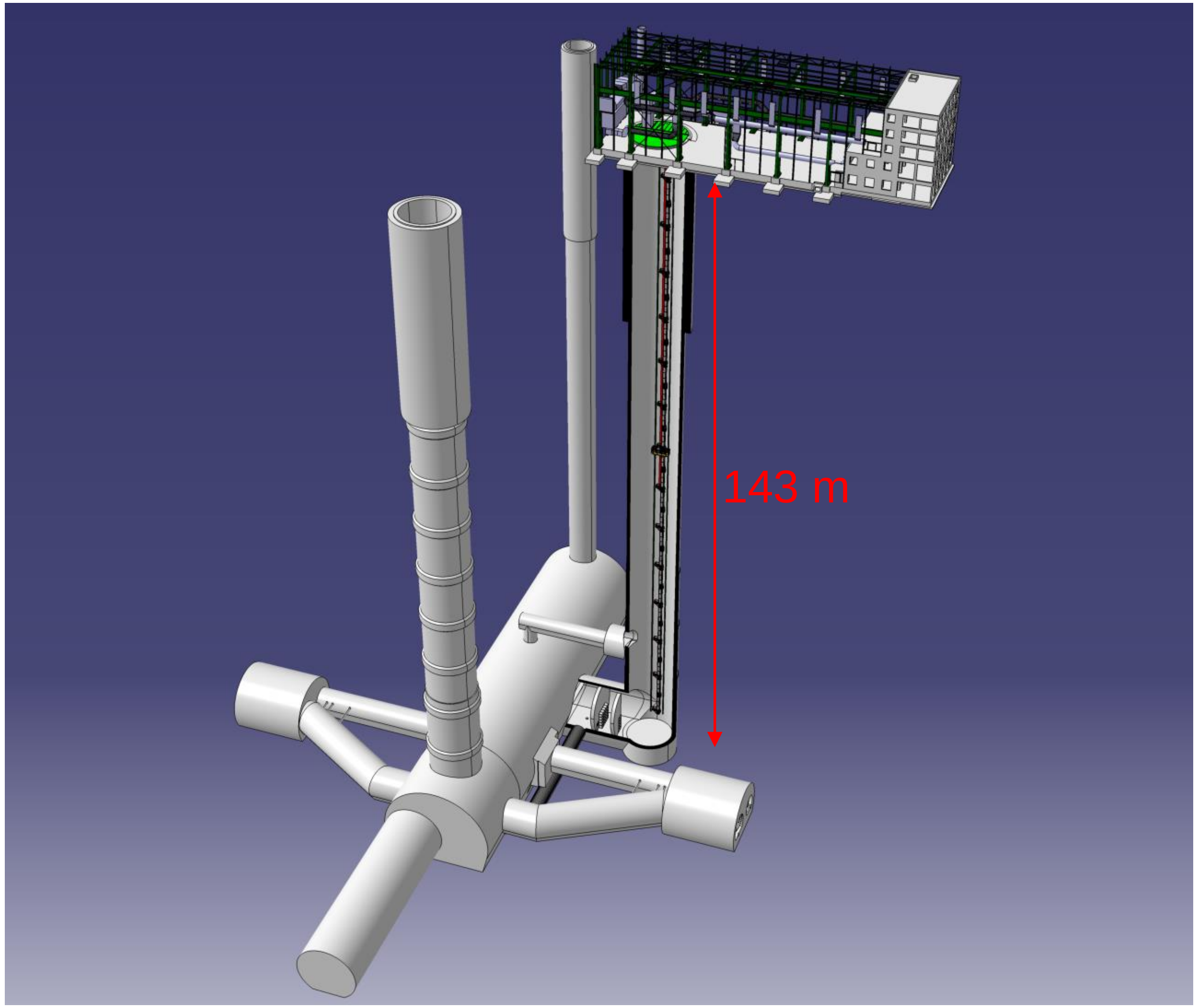
beam loss
n of TX46



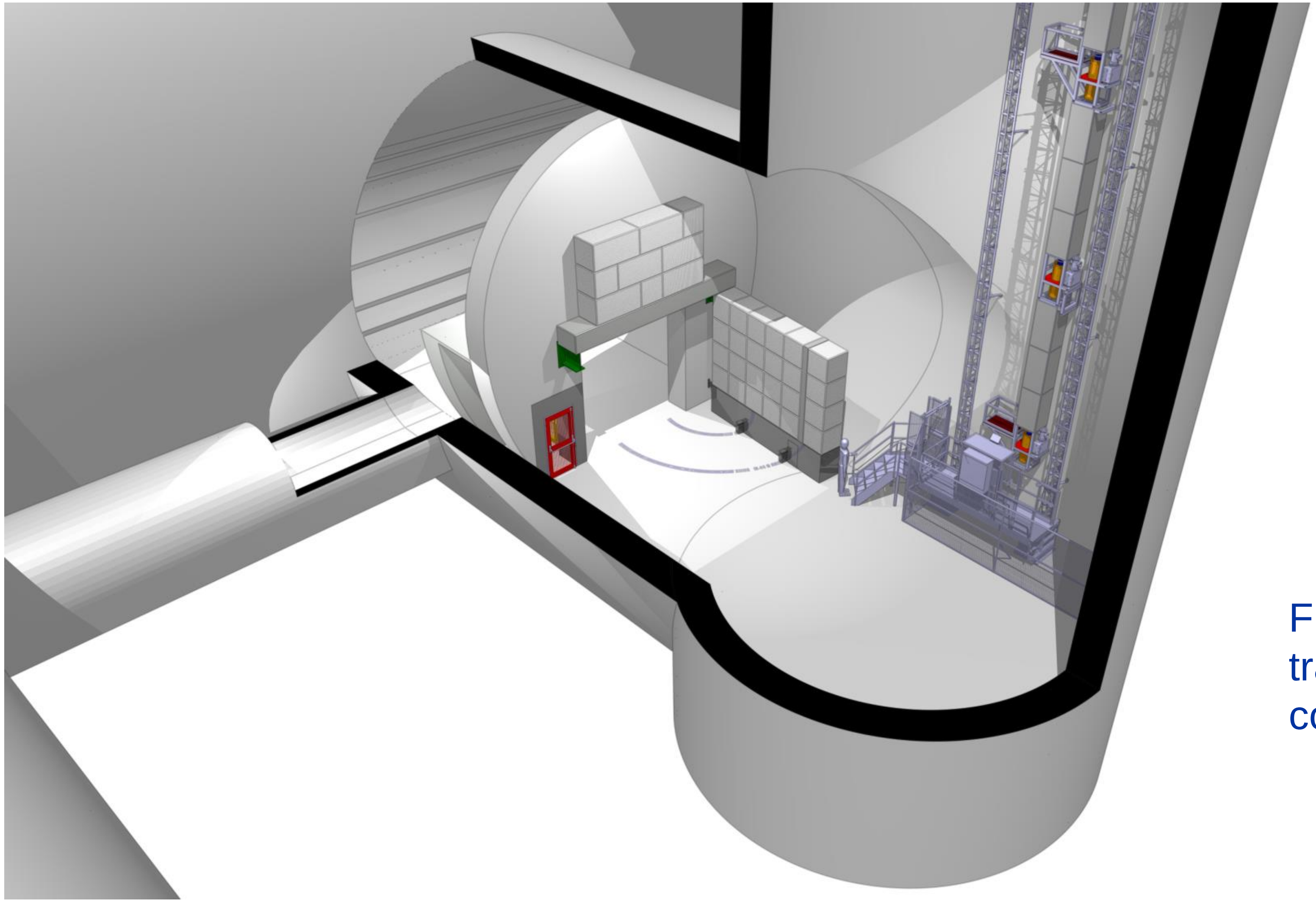
Safety
feasibi
operat

General layout and location of the site



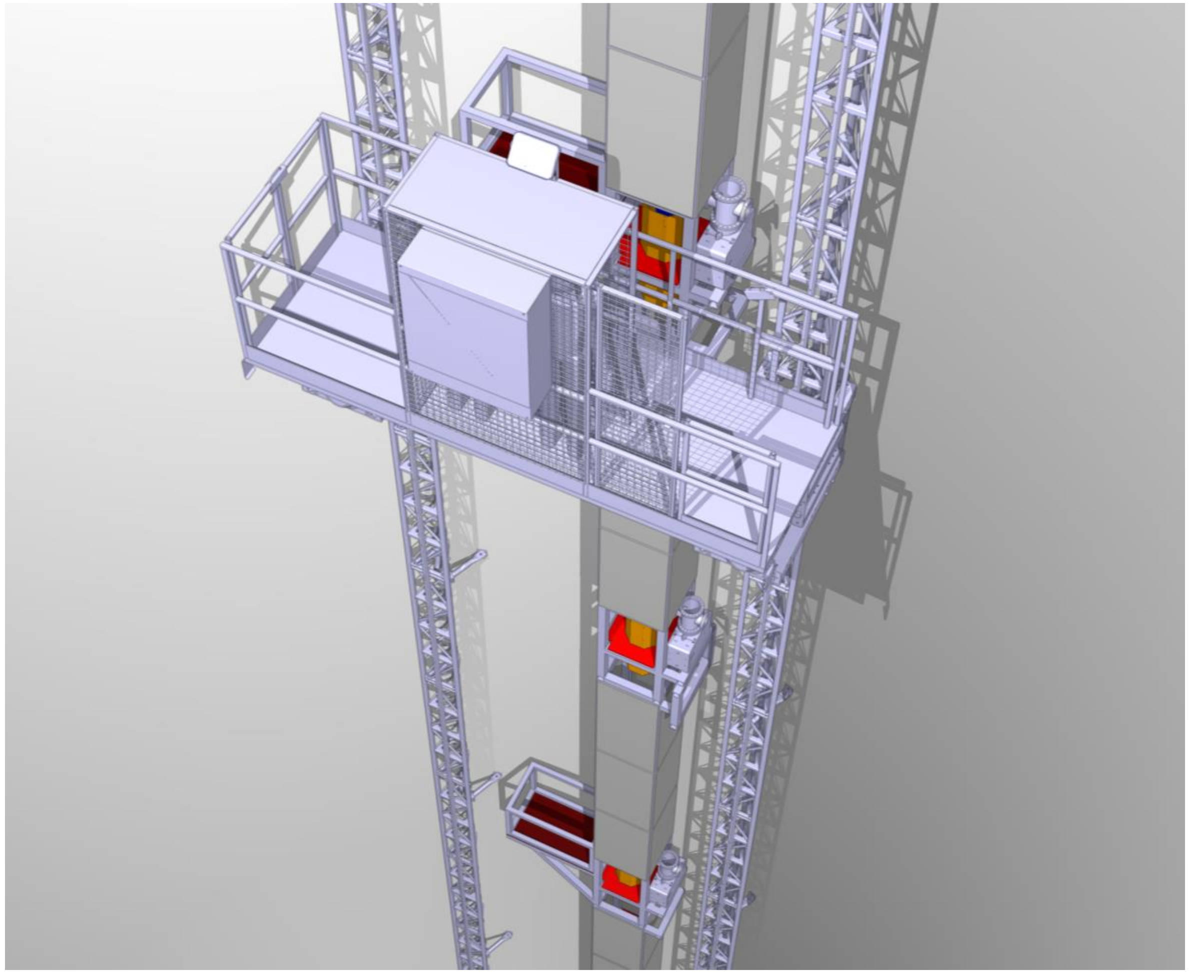


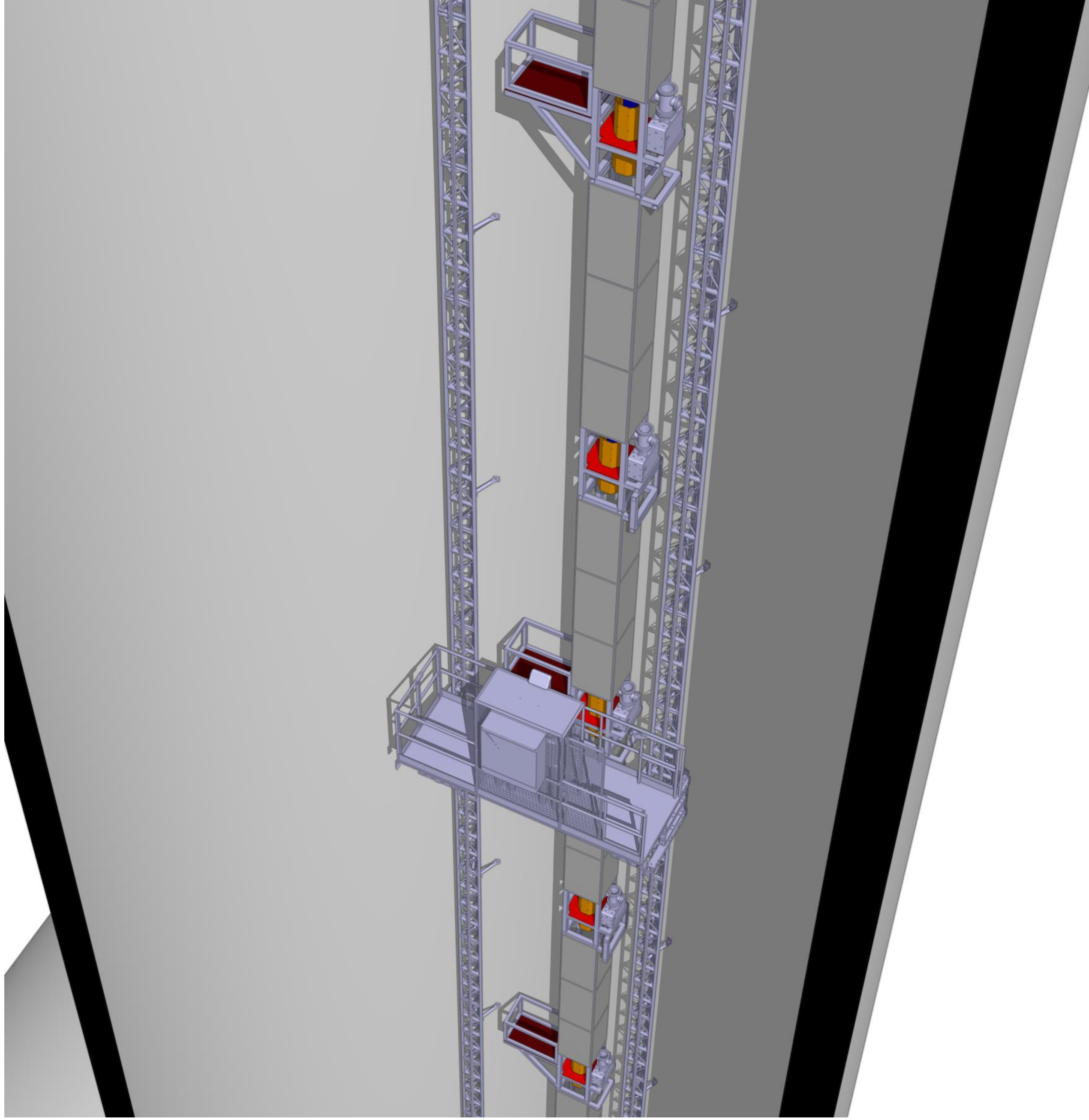
Shielding wall



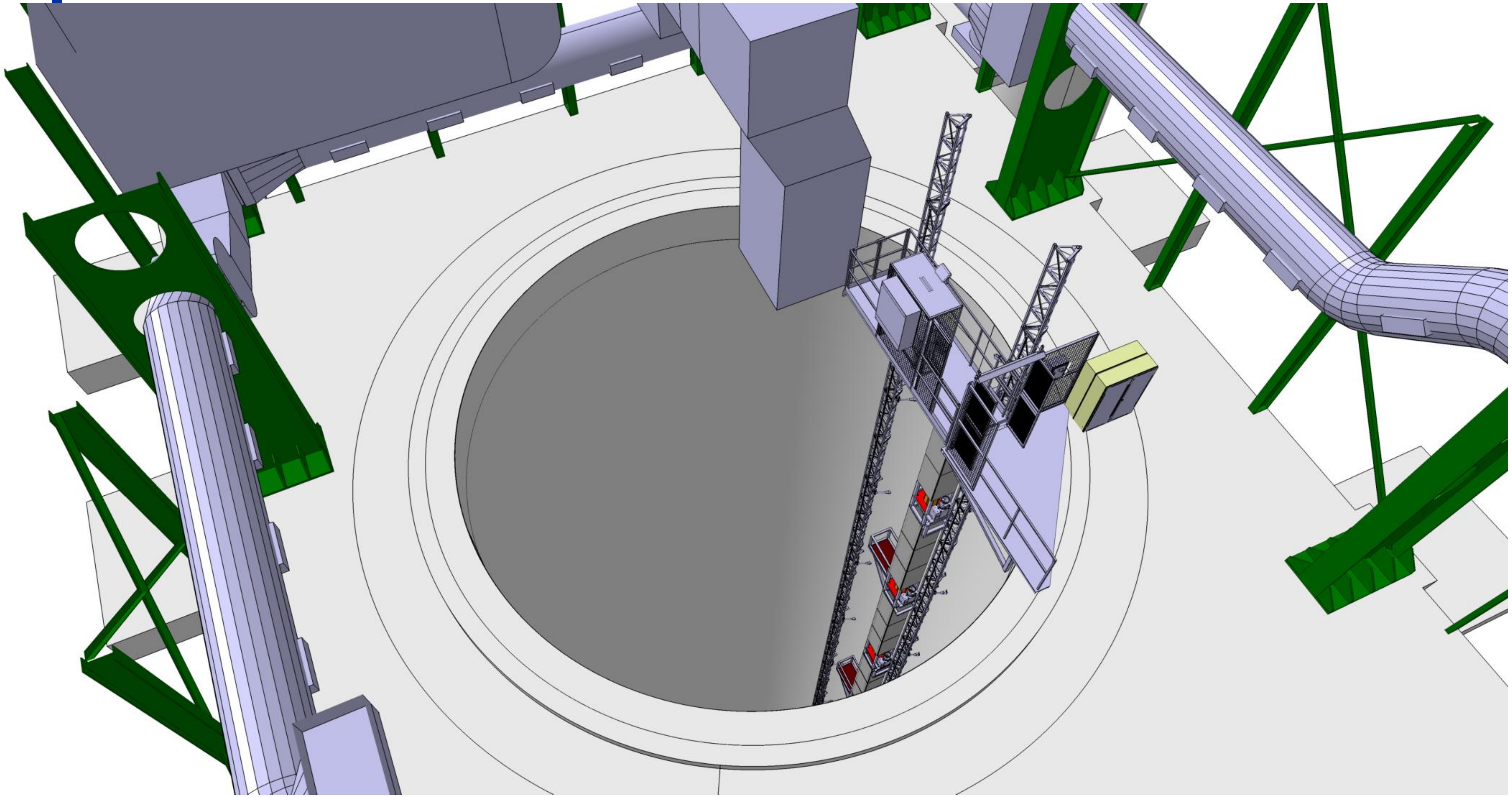
Free passageway for transport of LHC components

Along the shaft

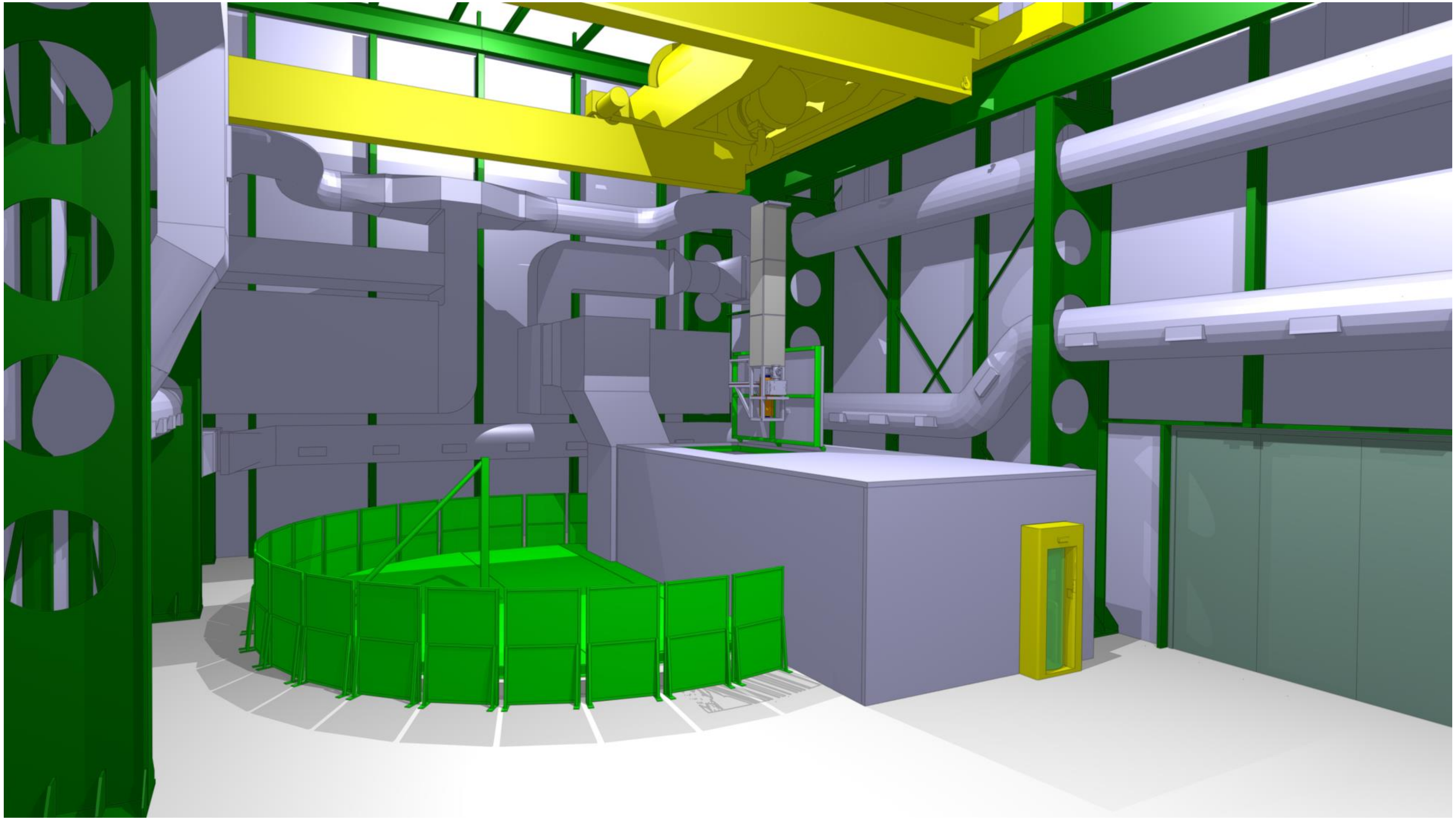




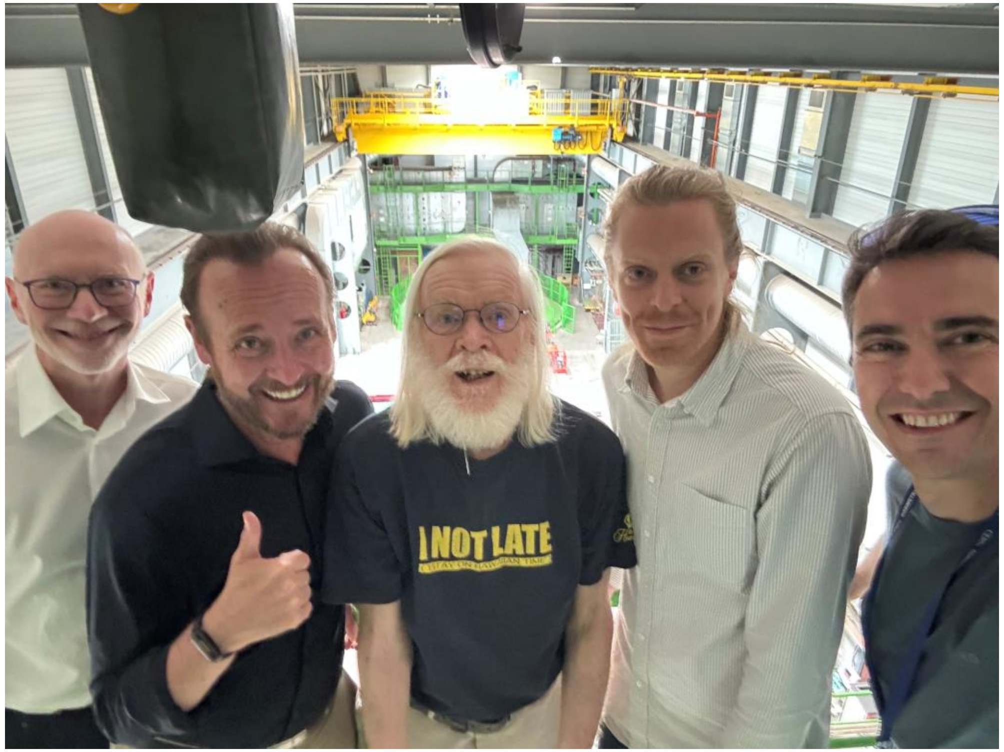
Elevator platform



Ventilation room / laser lab – and components handling

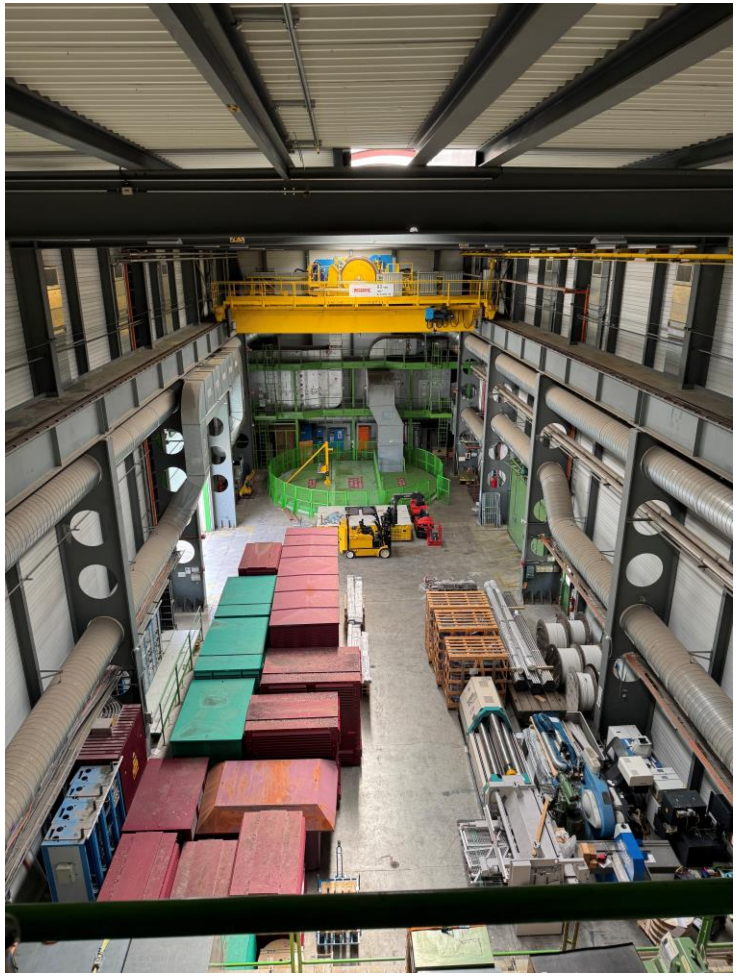


Present status



SC John Ellis Eduardo Granados

Oliver Buchmüller Richard Hobson

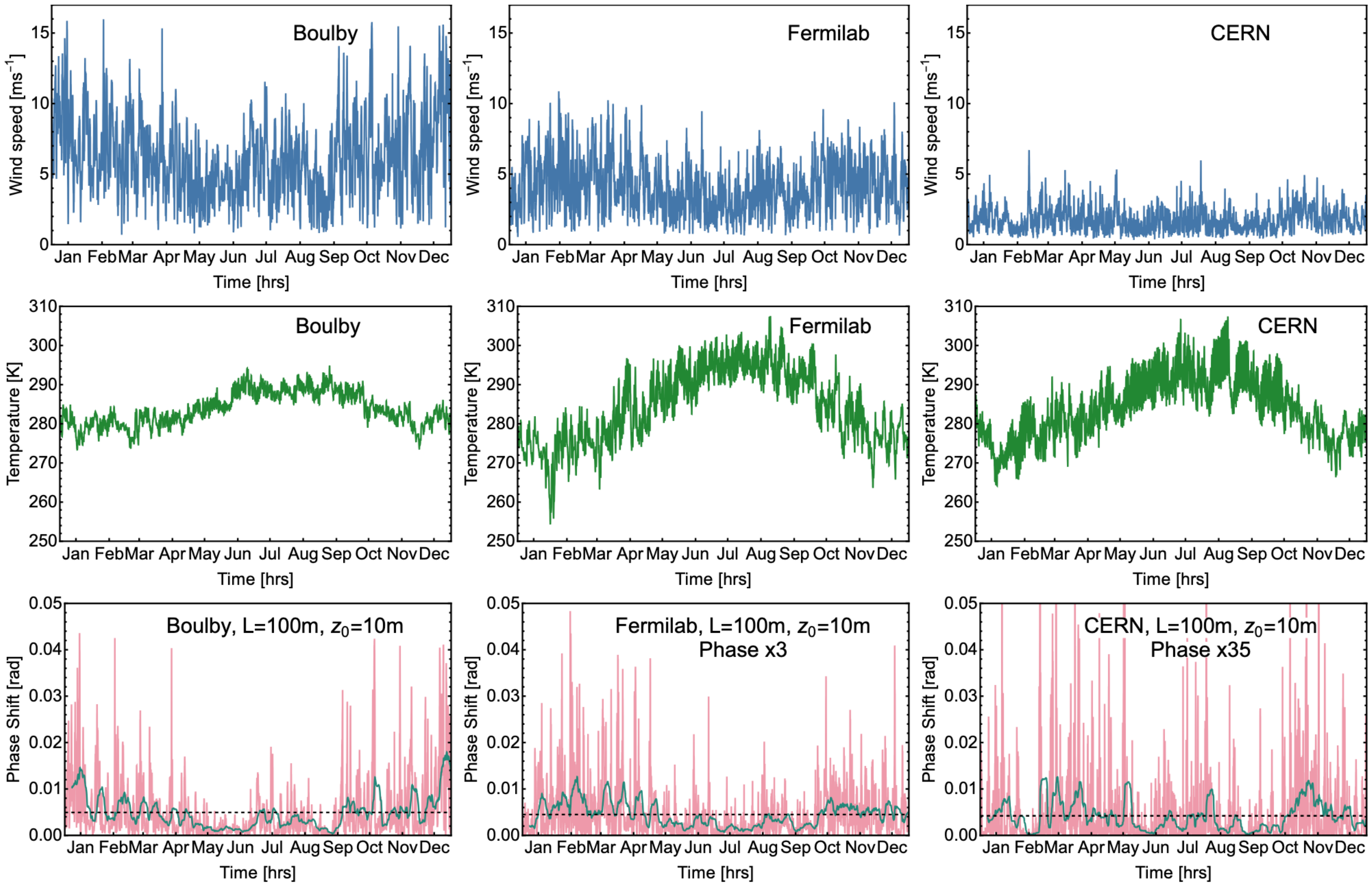


Site selection – many studies done already

Temperature GGN is much more variable and harder to characterise

However integrated weather data shows that CERN is by far the quietest for this noise source compared to similar sites like Boulby and Fermilab

This is mainly due to the lower average windspeeds



Revised "Class 4" cost estimates

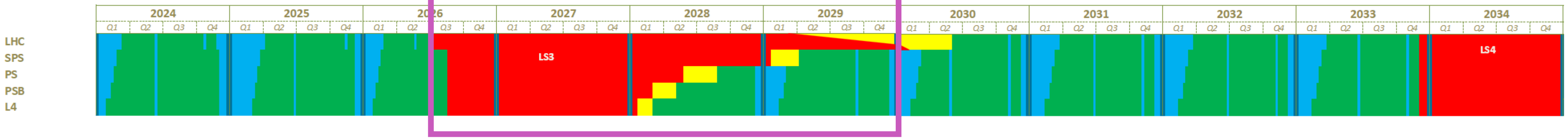
- Class 4: low margin from -15% to -30%; high margin from +20% to +50% (from DOE G 413.3-21A, Cost Estimating Guide)

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

- Lower than Class 5 estimate of 2023 (1.5 MCHF), however non-essential ancillaries (chilling water production and distribution system and electrical and service cabling for the experiment) no longer included

Tentative planning

Long-term CERN accelerator schedule

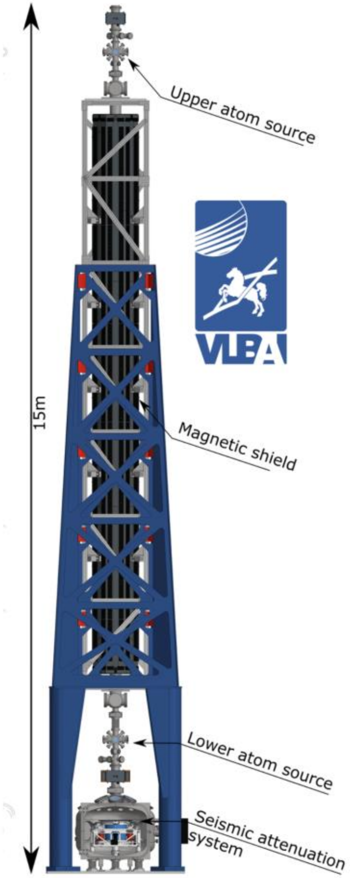


	Description of the task	2026				2027				2028				2029			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
SCE-TOD	**Civil engineering activities: radiation shielding wall**																
	Integration and design studies																
	Component assessment and site Investigation works																
	Procurement for construction contracts																
	Civil works for shielding wall - including rails for mobile shielding door													3M			
EN-THE	**Mobile shielding and additional lifting equipment:**																
	Call for tender																
	Installation and commissioning														4W		
EN-THE	**Lifting platfrom:**																
	Integration and design studies																
	Call for tender																
	Installation and commissioning														3W		
SCE-TOD	**Civil engineering activities: ventilation room**																
	Integration and design studies																
	(Modifications of shaft top plug)																
	Construction of ventilation room														2W		
EN-AA	**Access control and alarms:**																
	Preparations and design, programming																
	LASS trunk cabling from LASS racks and junction box installation									1W							
	Fire detection, evacuation, red telephones cabling from the surface racks to the PX46 top of pit									1W							
	LASS equipment installation and local cabling from junction box															1W	
	Fire detection, evacuation, red telephones equipment															2W	
	Access control system for ventilation room (no LASS)																2W
HSE-RP	**Radiation monitoring**																
	Installation and test of IG5-H20 detector in TX46													3W			
EN-EL	Electrical installations (excluding AA, RP)																
	Integration and design studies																
	Preliminary works (installation of a new switchboard to power the new complex)							1W									
	Works in the shaft and building (installation of new power outlets and cables)															2W	
	Works in the laboratory (lighting, power outlets, and cable installation)															1W	

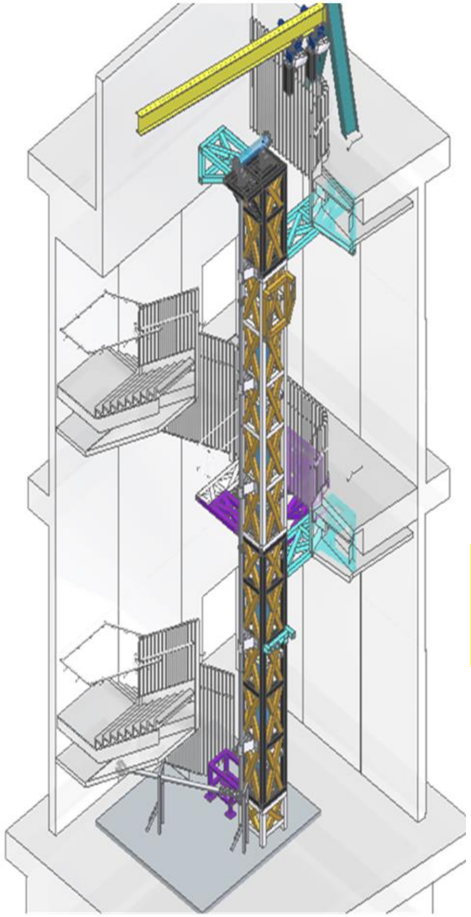
Prototyping – AICE is based on many years of dedicated R&D

MAGIS: 10-Protyotype
@ Stanford
- starting operation -

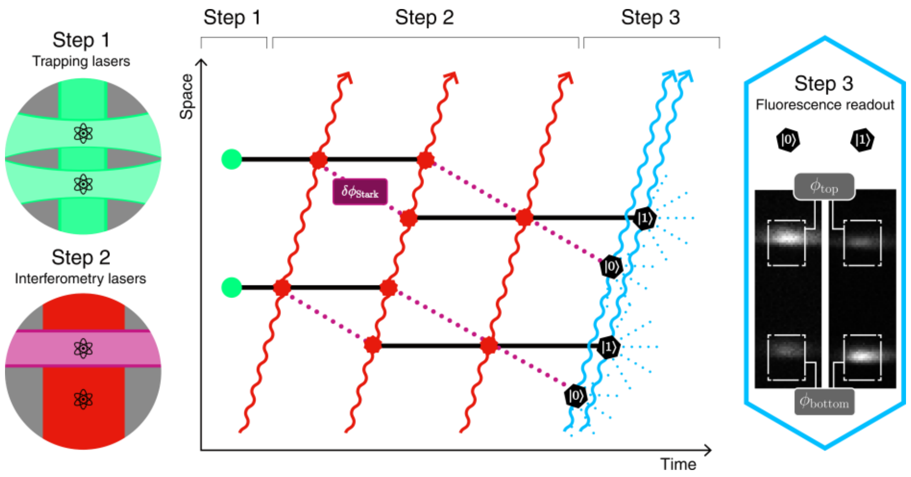
VLBAI: 10-Protyotype
@ Hannover
Dual-species
-staring operation-



AION 10m
@ UK
- Full TDR Level Design



AION Tabletop
@ UK
- Fully demonstrated -



First ever ^{87}Sr differential clock interferometer, in the DM/GW detector configuration

And several other projects that are currently ongoing on national level ….

From Oliver Buchmüller

Facility Roadmap Parameters

Parameter	Tabletop to 10 m	100 m (Initial)	100 m (Baseline)	100 m (Stretch Goal)	1 km
Programme phase	Prototype	Commissioning / Fund. Phys.	Baseline	Stretch Goal	Future Facility
Interrogation time T [s]	1–4	2–5	2–5	2–5	5–10
N_{pulse}	$\mathcal{O}(10^2\text{–}10^3)$	$\mathcal{O}(10^3)$	$\mathcal{O}(10^3\text{–}10^4)$	$\mathcal{O}(4 \times 10^4)$	$\mathcal{O}(10^5)$
N_{source}	2	3	5–10	10–20	$\mathcal{O}(100)$
$\delta\phi_{\text{noise}}$ [rad/$\sqrt{\text{Hz}}$]	$\sim 10^{-3}$	$\sim 10^{-3}\text{–}10^{-4}$	$\sim 10^{-4}$	few $\times 10^{-5}$	$\leq 10^{-5}$

From Oliver Buchmüller

Facility Roadmap Parameters

Prototype Demonstration

AICE@CERN

Future Facility

Parameter	Tabletop to 10 m	100 m (Initial)	100 m (Baseline)	100 m (Stretch Goal)	1 km
Programme phase	Prototype	Commissioning / Fund. Phys.	Baseline	Stretch Goal	Future Facility
Interrogation time T [s]	1–4	2–5	2–5	2–5	5–10
N_{pulse}	$\mathcal{O}(10^2\text{–}10^3)$	$\mathcal{O}(10^3)$	$\mathcal{O}(10^3\text{–}10^4)$	$\mathcal{O}(4 \times 10^4)$	$\mathcal{O}(10^5)$
N_{source}	2	3	5–10	10–20	$\mathcal{O}(100)$
$\delta\phi_{\text{noise}}$ [rad/$\sqrt{\text{Hz}}$]	$\sim 10^{-3}$	$\sim 10^{-3}\text{–}10^{-4}$	$\sim 10^{-4}$	few $\times 10^{-5}$	$\lesssim 10^{-5}$

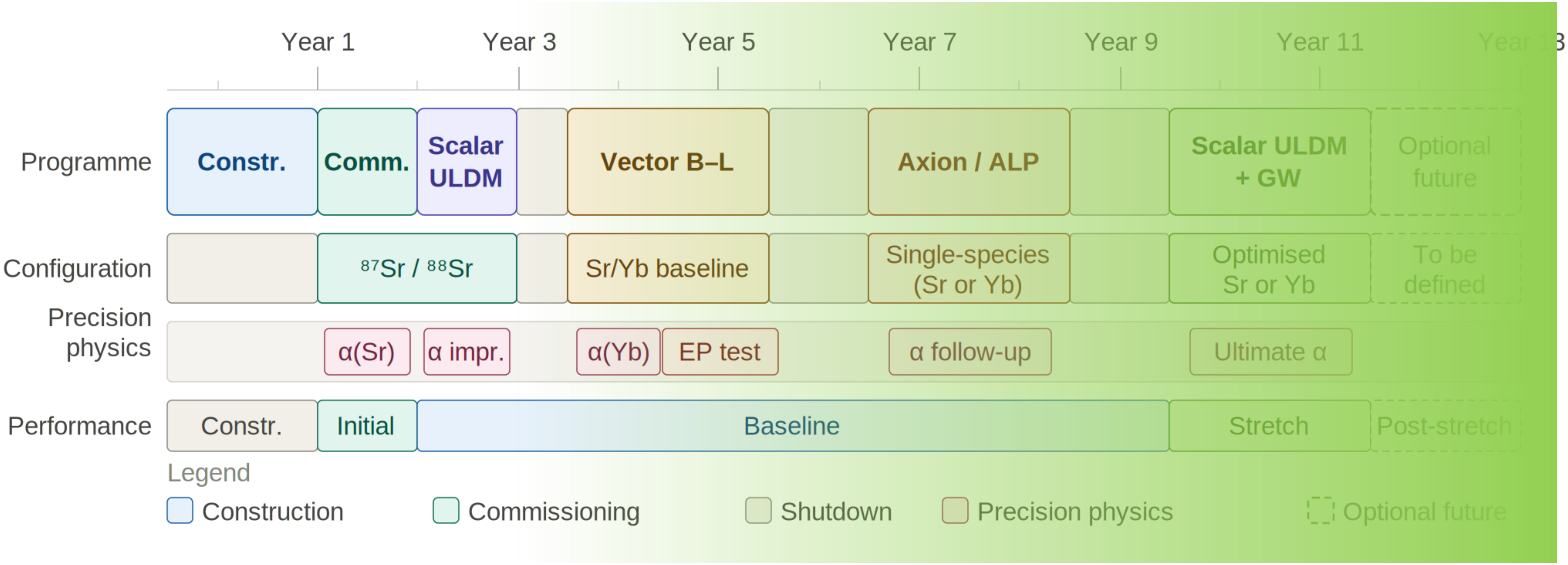
Programme currently ongoing at AION prototype (UK), MAGIS-10 Stanford, US and VLBAI Hannover, Germany

AICE facility programme of different stages. Baseline is used for most DM results

Several sites under active consideration, e.g. Porta Alpina, Boulby, SURF, etc

From Oliver Buchmüller

Possible timeline of AICE facility



Needless to say, uncertainties grow as we project further out.

AICE: A Staged Facility for Three Sciences

Dark Matter

- Scalar and vector B–L: up to two orders of magnitude beyond current bounds.
- Axion couplings: nucleon-spin (g_{aN}) and QCD gluon ($1/f_a$) channels.
- Beyond ULDM: dilatonic and non-standard models.

Precision Physics

- Fine-structure constant α: sub-ppb, resolving the >5σ Cs–Rb tension
- Equivalence Principle: η reach few × 10^{-16}, one decade beyond Microscope.

Gravitational Waves

Pioneers terrestrial access to the mid-frequency band (~0.03–3 Hz), bridging LIGO/Virgo and LISA and extending toward 10 Hz in future concepts.

FACILITY CONCEPT

- **Vertical baseline.** 140 m shaft, ultra-high vacuum, flexible atom source installation .
- **Dual-species design.** Cold ^{87}Sr and ^{171}Yb fountains share the same vertical baseline.
- **Three running modes.** Phase 1 gradiometer, Phase 2 dual-species comparison, Phase 3 full-shaft single cloud.

STRATEGIC POSITIONING

- **Terrestrial bridge.** AICE is the natural step between current 10 m prototypes and future km-scale TVLBAI facilities, and a terrestrial complement to space missions.
- **Cost-effective scale.** A single facility delivers science that would otherwise require several separate experiments.

AICE: Path to Technical Proposal (Q3 2026)

WE ARE HERE
- **Mid-June 2026**

Mar – April	May – June	Summer	Sep	Q3 2026
Define structure & assign sections	Draft TP (physics + technical)	Write TP & prepare workshop	Submit TP Workshop @ CERN	LHCC Review

Critical Path

- Coordination across institutes
- Technical design maturity
- Funding narrative

Key Milestones Ahead

- Jun '26 — Draft TP outline circulated
- Jul '26 — Internal review of TP draft
- Sep '26 — Community workshop at CERN
- Q3 '26 — Submission to LHCC

AICE is fully embedded in the TVLBAI Proto-Collaboration

Austria
- Institute of Science and Technology Austria

Bosnia and Herzegovina
- University of Sarajevo - Faculty of Science

Denmark
- Aarhus University - Department of Physics and Astronomy

Estonia
- National Institute of Chemical Physics and Biophysics (KBFI)

France
- University of Toulouse III – Paul Sabatier
- École Normale Supérieure

Germany
- Technische Universität Darmstadt
- Leibniz University Hannover
- Ulm University

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

Ireland
- Tyndall National Institute

Italy
- University of Florence – DFA
- LENS Laboratory
- University of Pisa

Malta
- University of Malta

Netherlands
- University of Amsterdam

Poland
- Space Technology Centre, AGH University of Science and Technology, Krakow
- Center for Theoretical Physics, Polish Academy of Sciences (CTP PAS)
- University of Warsaw

Portugal
- Instituto de Telecomunicações

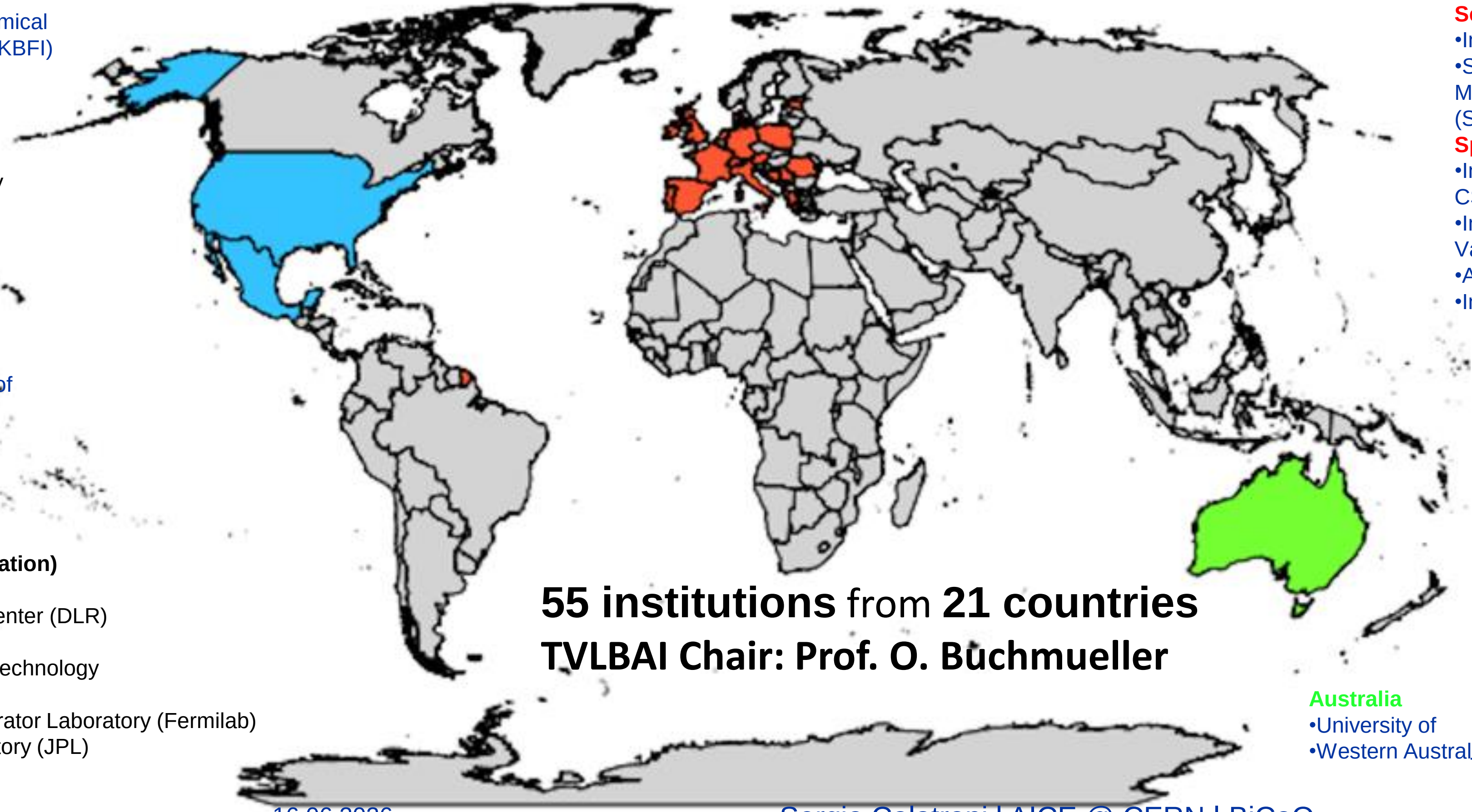
Romania
- Institute of Space Science

Serbia
- Institute of Physics Belgrade (IPB)
- South East European Network for Mathematical and Theoretical Physics (SEENET-MTP) Centre

Spain
- Institute of Theoretical Physics (IFT UAM-CSIC)
- Institute of Corpuscular Physics (IFIC), Valencia
- Autonomous University of Madrid (UAM)
- Institut de Fisica d'Altes Energies (IFAE)

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

Mexico
- Autonomous University of Aguascalientes (UAA)



55 institutions from **21 countries**

TVLBAI Chair: Prof. O. Buchmueller

Switzerland
- University of Geneva
- CERN
- University of Neuchâtel
- University of Zurich

United Kingdom
- Imperial College London
- King's College London
- University College London (UCL)
- University of Birmingham
- University of Cambridge
- University of Liverpool
- University of Manchester
- University of Oxford
- University of Southampton
- University of Sussex
- University of Warwick
- UKRI-STFC RAL

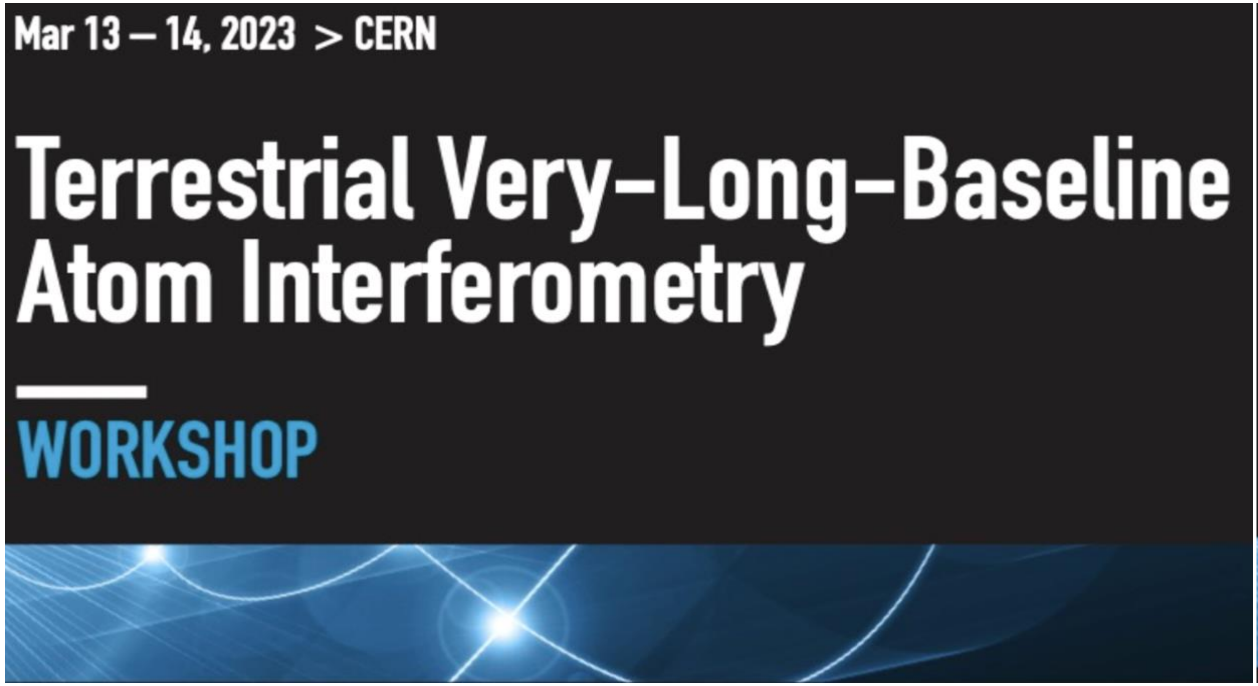
Australia
- University of
- Western Australia

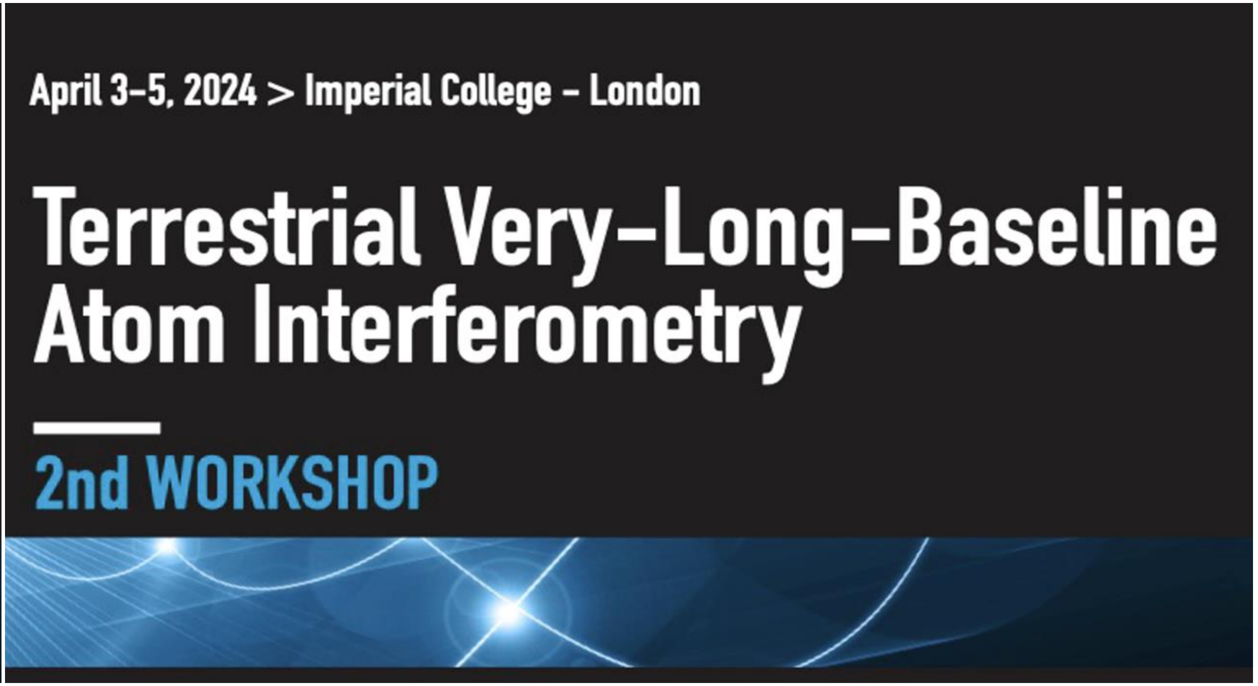
Observers (Under Evaluation)

Germany
- German Aerospace Center (DLR)

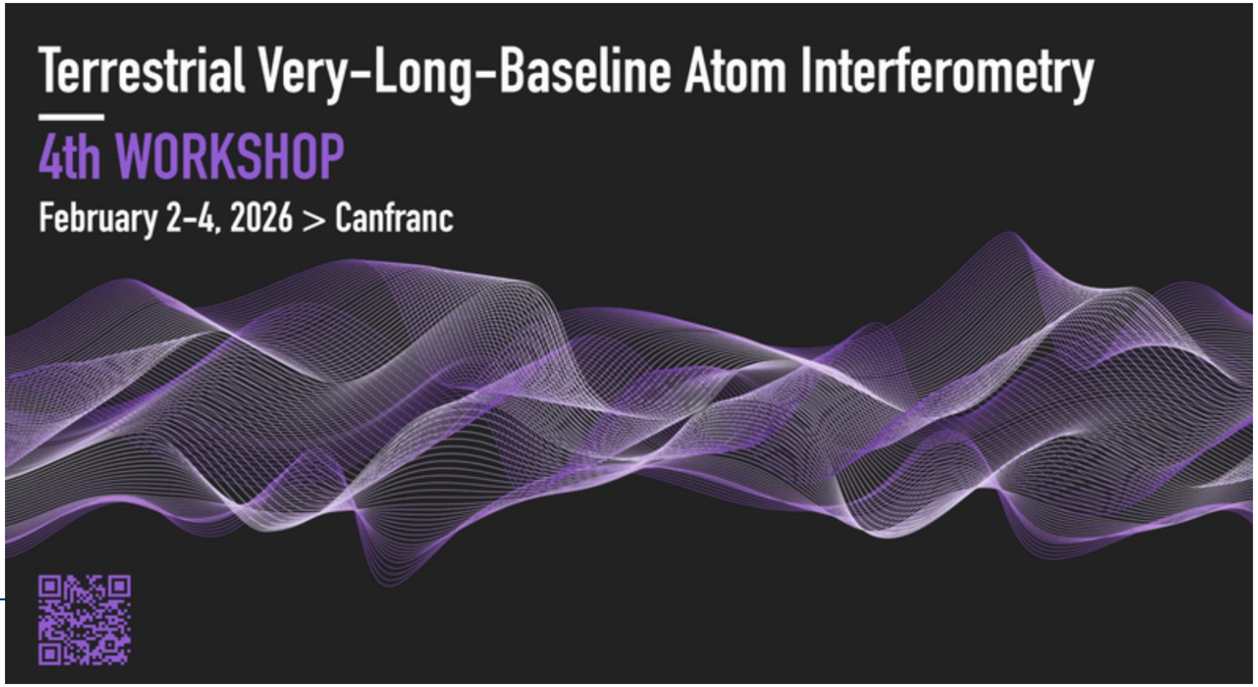
Iran
- Isfahan University of Technology

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


Mar 13 – 14, 2023 > CERN
Terrestrial Very-Long-Baseline Atom Interferometry
WORKSHOP


April 3-5, 2024 > Imperial College - London
Terrestrial Very-Long-Baseline Atom Interferometry
2nd WORKSHOP


Terrestrial Very-Long-Baseline Atom Interferometry
3rd WORKSHOP
August 20-22, 2025 > Leibniz University – Hannover
Leibniz
Universität
Hannover


Terrestrial Very-Long-Baseline Atom Interferometry
4th WORKSHOP
February 2-4, 2026 > Canfranc

AICE Community Workshop - CERN, 1-3 September 2026

Coinciding with the submission of the AICE Technical Proposal to CERN

REGISTRATION NOW OPEN

indico.cern.ch/event/1687915/registrations/

Workshop page: indico.cern.ch/event/1687915/

Hybrid event, but **in-person participation strongly encouraged.**

Organisers: Oliver Buchmueller · John Ellis · Sergio Calatroni: Contact: sergio.calatroni@cern.ch · oliver.buchmuller@cern.ch

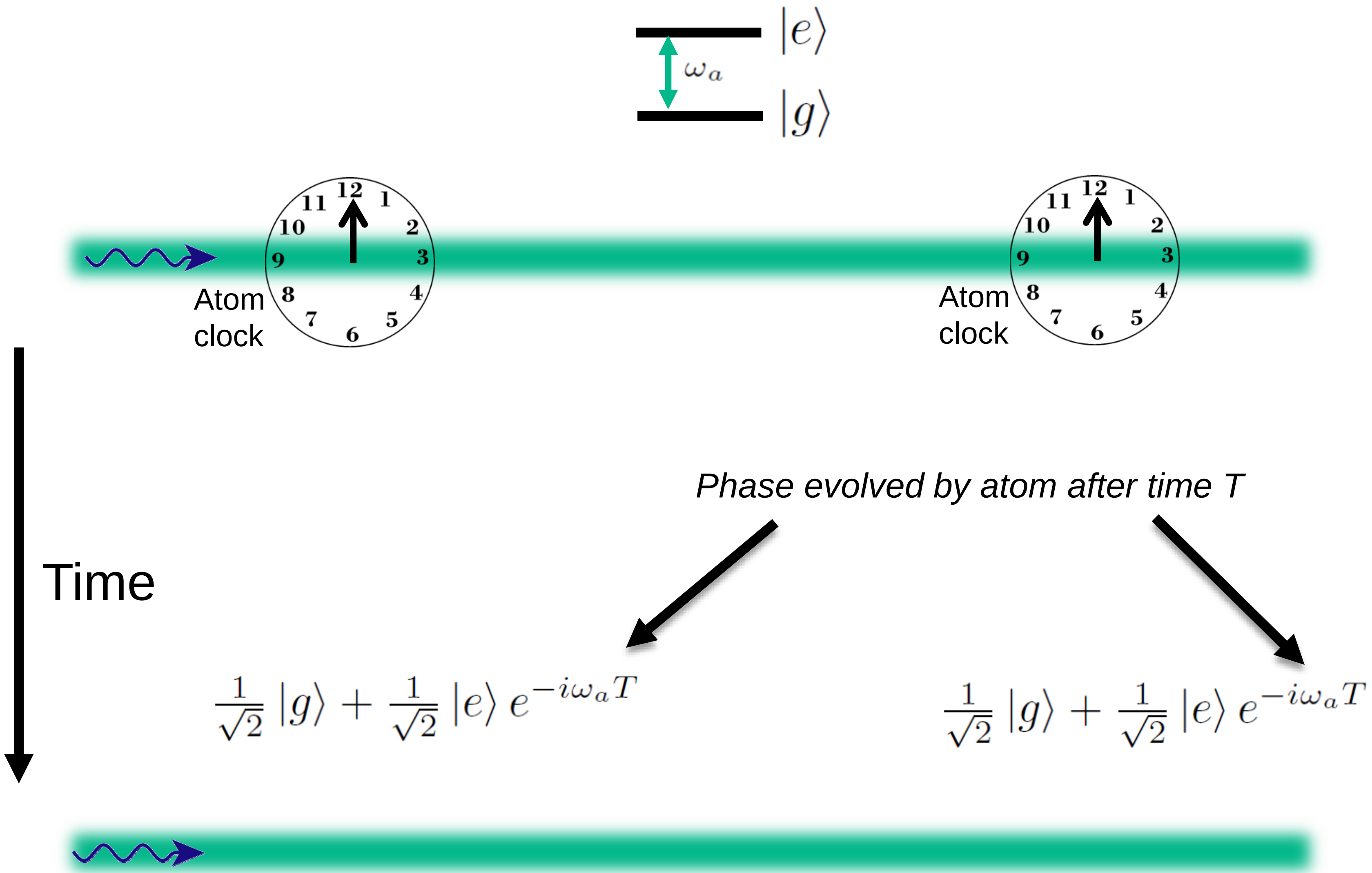
Summary

- **AICE:** long-term atom-interferometer facility planned at CERN in PX46.
- **Technical Proposal:** in advanced preparation, following the invitation from the LHCC and the CERN Research Board.
- **Ultralight dark matter:** broad programme with sensitivity across a wide mass range and many dark-matter scenarios.
- **Precision tests of fundamental physics:** equivalence principle and variations of fundamental constants such as α, all in the same apparatus.
- **Gravitational-wave pathfinder:** opening the mid-frequency band between LISA and ground-based interferometers.
- **Aligned with CERN's physics mission:** flagship quantum-technology experiment with diverse science output, attracting new communities & new funding.


BENVENUTI, SIGNORE E SIGNORI! HO L'ONORE DI PRESENTARVI IL GRAVIMETRO QUANTISTICO AD ATOMI FREDDI!
TOPOLINO
IP-3654-2

home.cern

Simple Example: Two Atomic Clocks



Courtesy of Jason Hogan!

Simple Example: Two Atomic Clocks

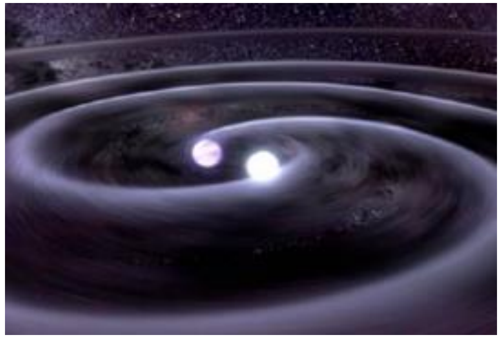
$|e\rangle$

ω_a

$|g\rangle$

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

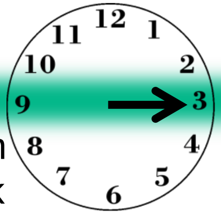
Time



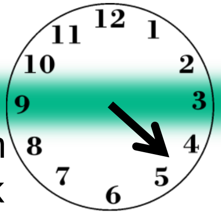
GW changes light travel time

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

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

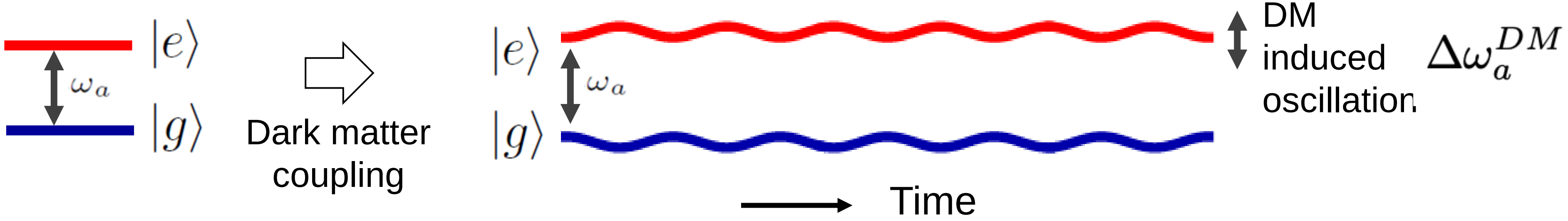


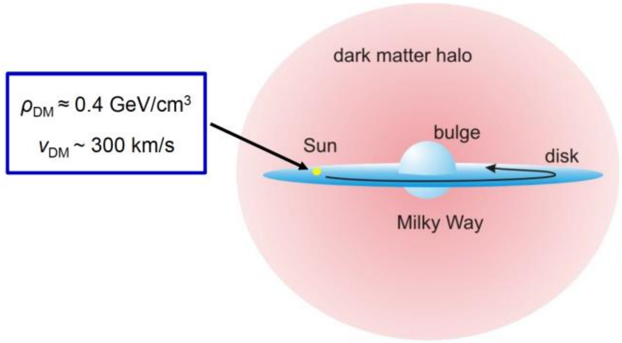
Atom clock



Atom clock

Simple Example: Two Atomic Clocks





DM cloud changes atom frequency

DM coupling causes time-varying atomic energy levels:

Time

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

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

Courtesy of Jason Hogan!