Physics Beyond Colliders

New projects supported by the Technologies Working group

Sergio Calatroni

21.1.2025

The Universe ☺

- Only a minor fraction of the universe, as we know it, is made of “ordinary matter”
- What are Dark Energy and Dark Matter?
- Is their study part of CERN plans?
- And how is the PBC helping?

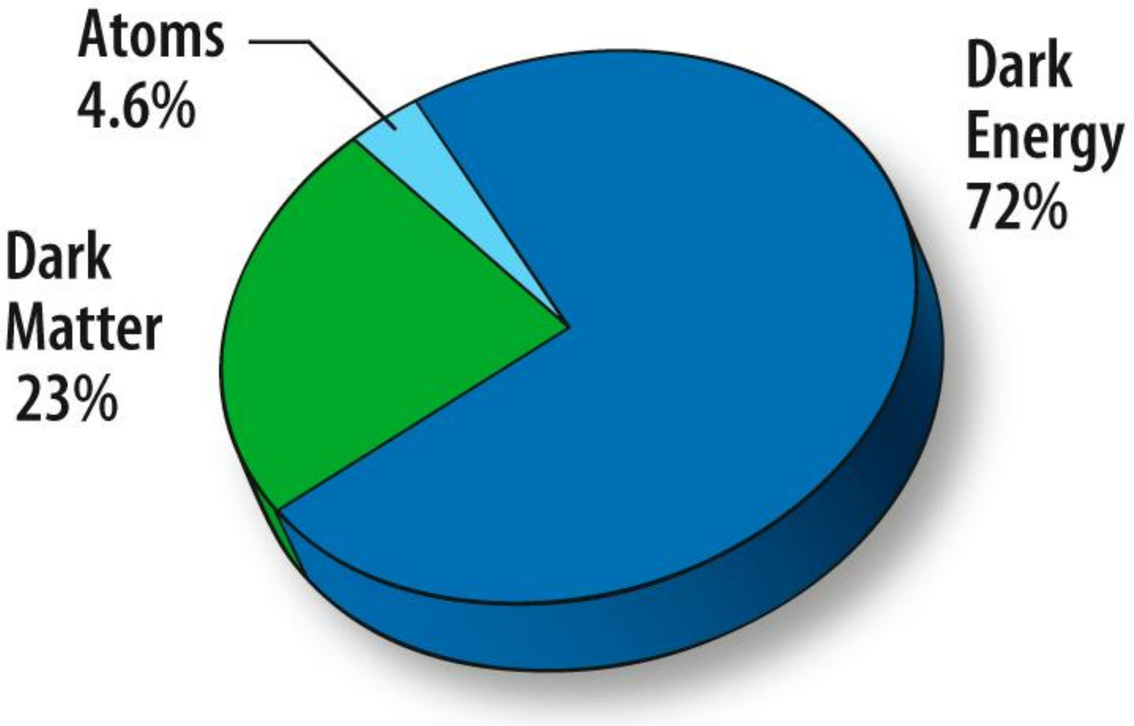


Image source: NASA / WMAP Science Team

All experiments & proposals linked with Tech WG
(mostly about Dark Matter and Dark Energy)

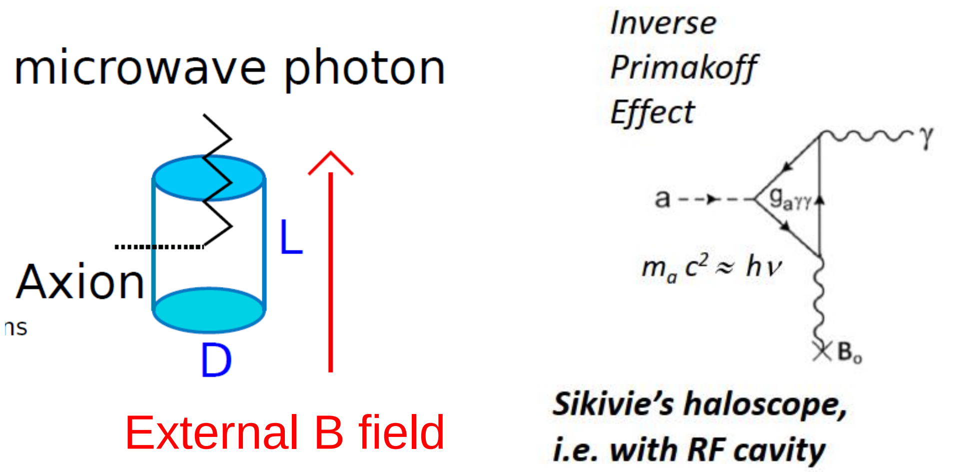
- ALPS-II (Joern Schaffran) -> axion search light-shining-through-wall with lasers
- BabyIAXO (Igor Garcia Irastorza) -> axion search from the Sun and the Galaxy halo

- Advanced-KWISP (Giovanni Cantatore) -> search for Short Range Interactions (DE)
- AION-100 @ CERN (Oliver Buchmuller) -> vertical atom interferometer (GW and DM)
- Axion Heterodyne Detection (Alick Macpherson) -> axion search with two-mode RF cavities
- FLASH (Claudio Gatti) - > axion search with RF cavities
- GrAHal (Pierre Pugnat) -> axion search with RF cavities
- RADES/HTS (Babette Döbrich) -> axion search with HTS RF cavities

RADES: Relic Axion Detector Exploratory Setup Study

Using RF cavities (normal conducting and superconducting – HTS based) to detect axions

Axion detection: a cavity in a magnetic field



$$\mathcal{F} \sim g_{A\gamma}^4 \, \boldsymbol{Q} \, T_{sys}^{-2} V^2 G^4 m_A^2 \, \boldsymbol{B}^4$$

Increase Q
copper coating → superconducting coating

Requirement: High quality factor in a high magnetic field

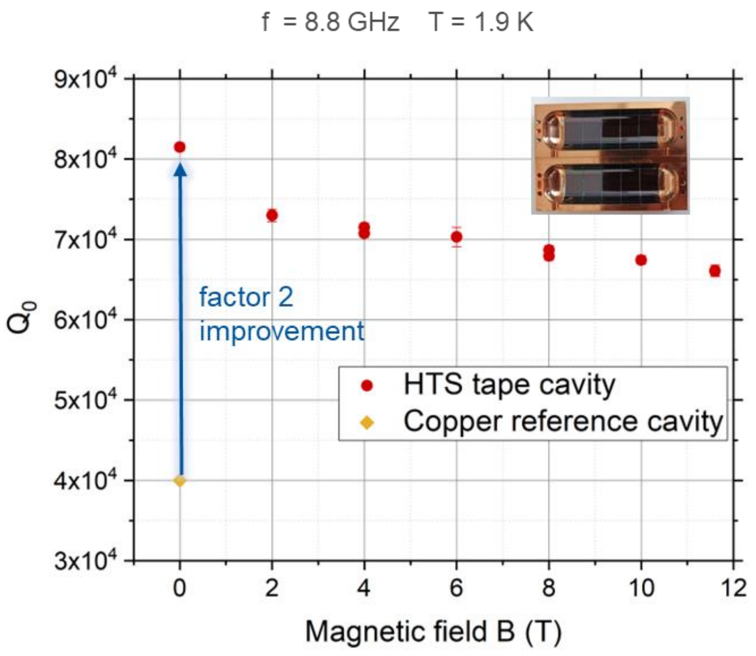
An axion can shift the frequency of a photon.
In this case, from 0 Hz to ν Hz. Proportional to axion mass m_a

Sensitivity is proportional to cavity Q, cavity volume V^2 and to the external magnetic field B^4

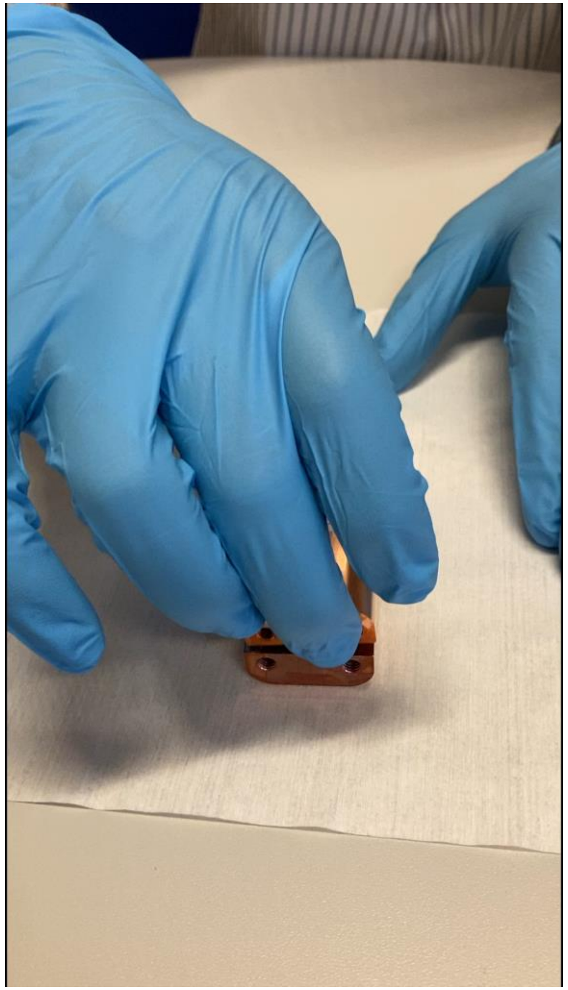
J. Golm, CERN

RADES HTS-coated cavities

First-generation HTS Cavities - 2021



J. Golm et al., IEEE TAS, Vol. 32, No. 4, (2022) 1500605

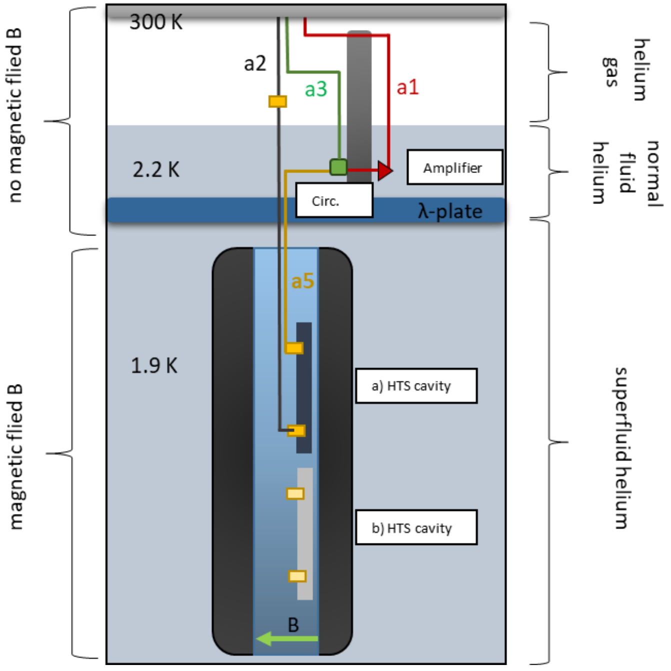


Second-generation HTS Cavities - 2024

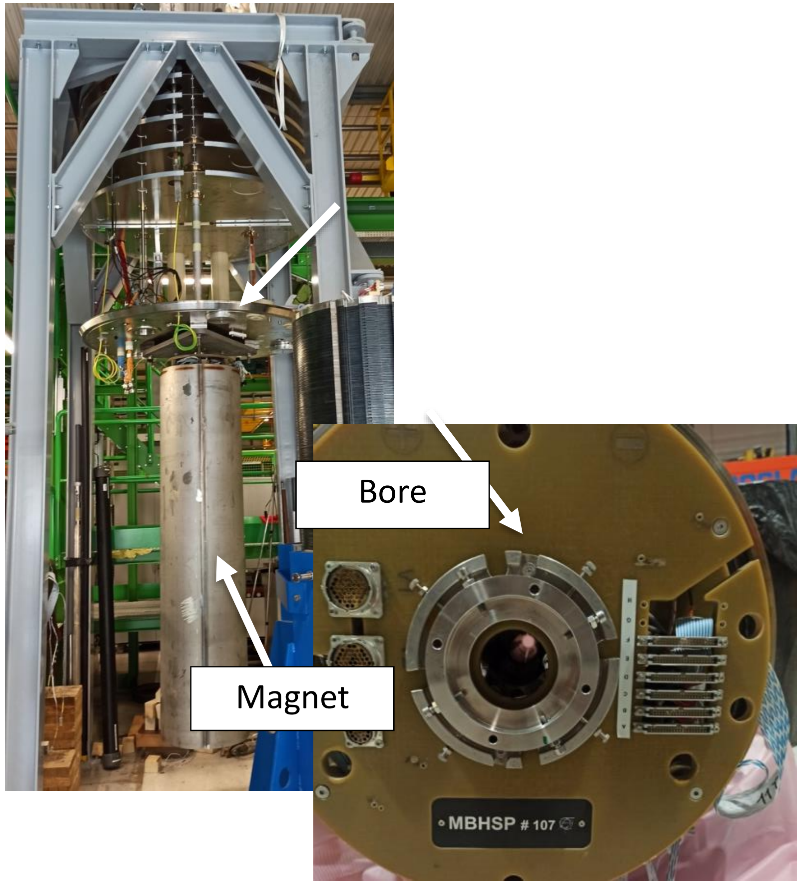
		B = 0T	B= 11T
HTS A	Q_0	~ 2.2 x 10^5	~ 1.1 x10^5
	$Q_{0(HTS)}$ / $Q_{0(Cu)}$	5.5	3
HTS B	Q_0	~ 2 x 10^5	~ 1.4 x 10^5
	$Q_{0(HTS)}$ / $Q_{0(Cu)}$	5	3.5

J. Golm, CERN

RADES data-taking experiment in SM18: 11.2024



J. Golm, CERN

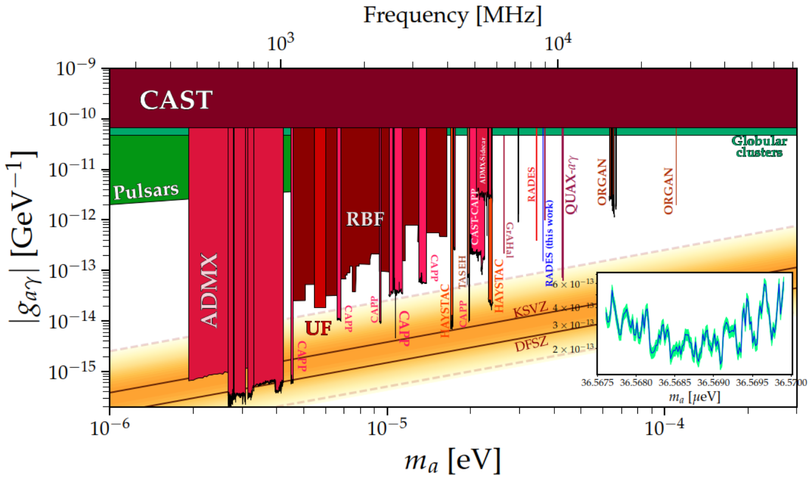


Two weeks of coordinated effort:

CERN – MPI – Mainz . U – ICMAB

Supported by PBC

Thanks to TE-CRG, TE-MSC

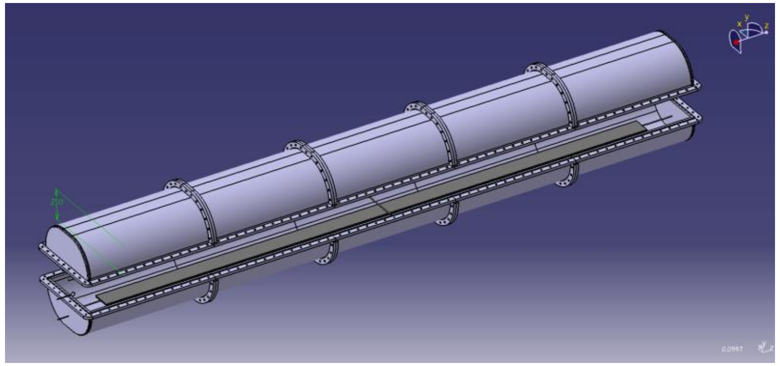


arXiv:2403.07790

BabyIAXO and RADES

- **Axion helioscope**: pointing to the Sun to measure solar axions
- Will make use of directional photon detectors like CAST

- **Axion haloscope**: non-directional, to detect axions from the Galaxy halo
- Will make use of **RADES cavities**
- Marco Morrone has studied the effect of quenches (eddy current stresses) on cavities inside the magnet bores



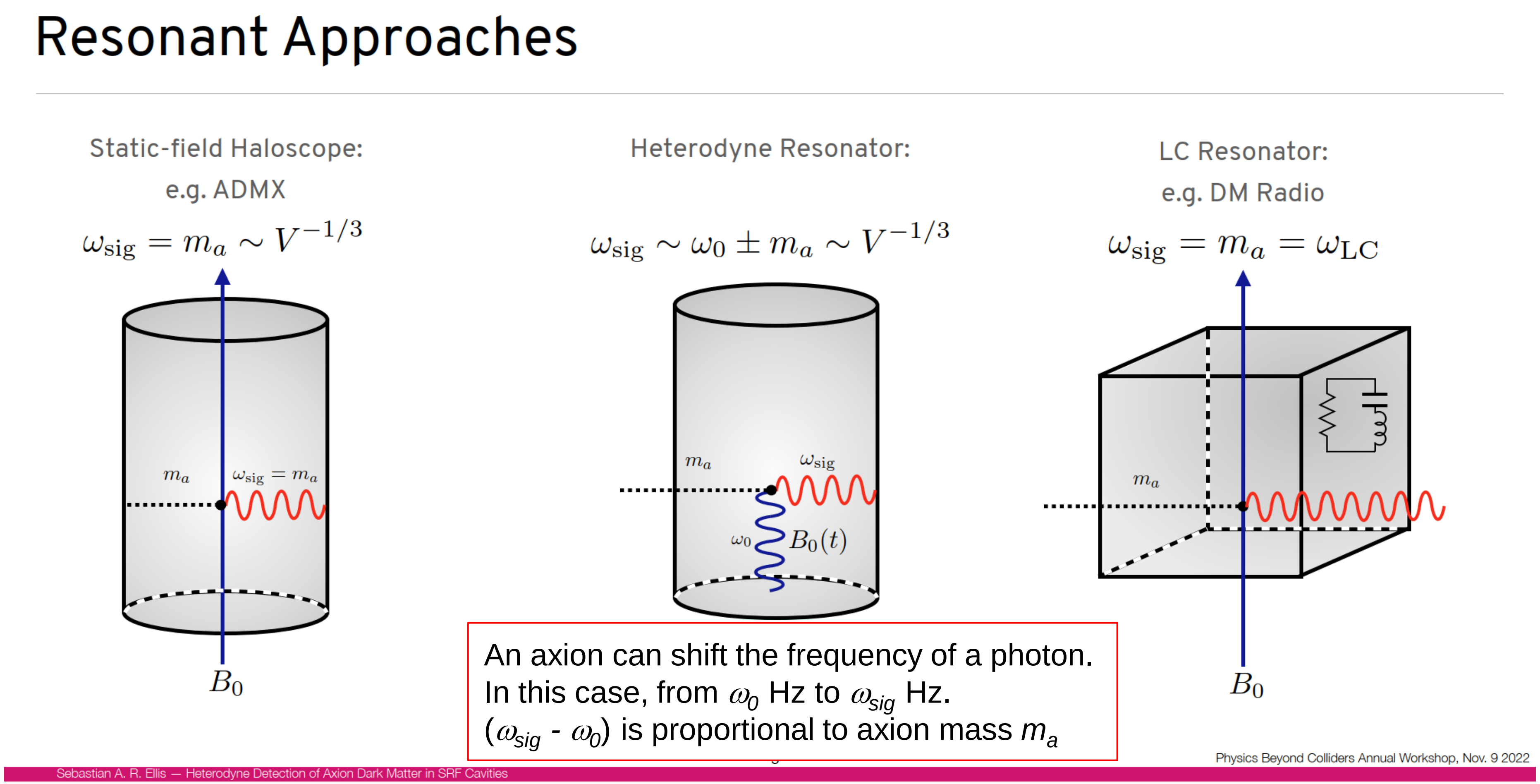
I. Garcia Irastorza, Zaragoza

Heterodyne Axion Detection

Using two-mode SRF cavities to detect ultra-light axions

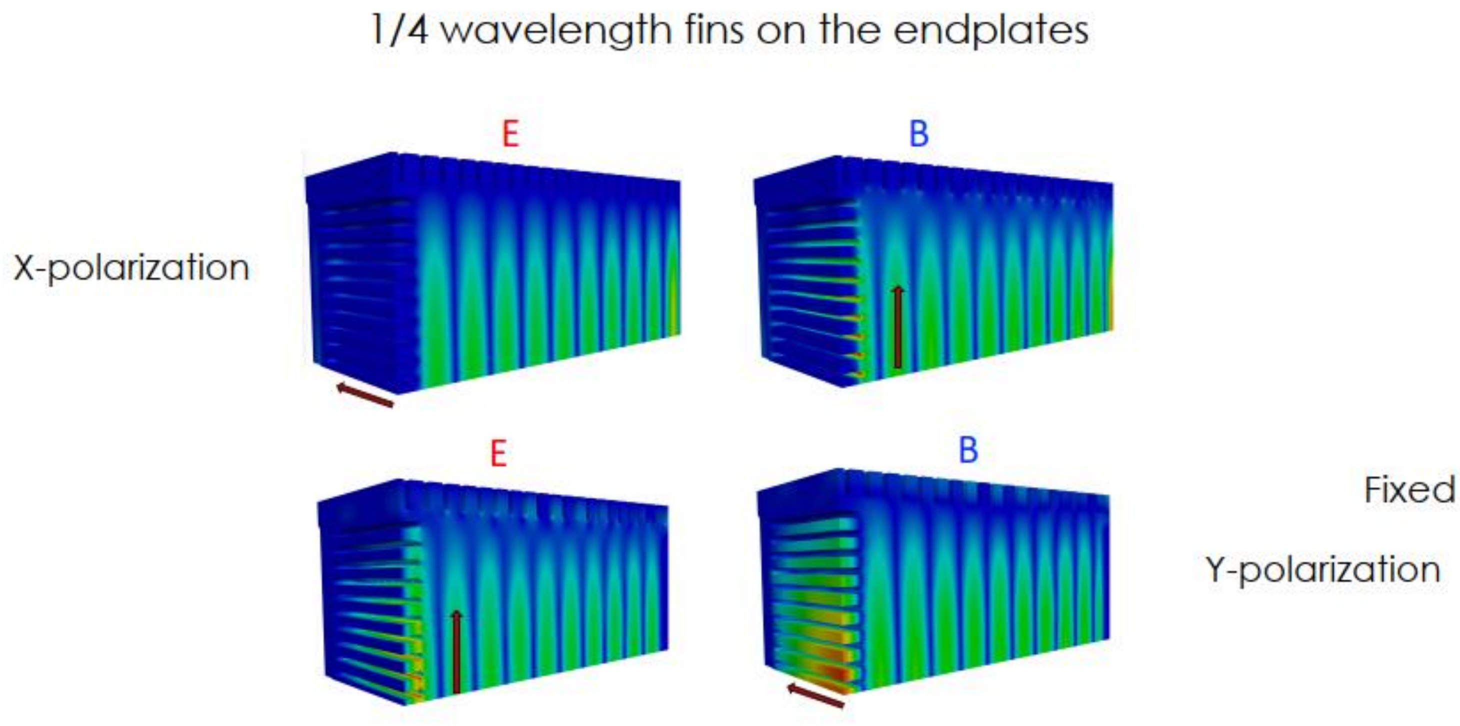
Axion Heterodyne detection status

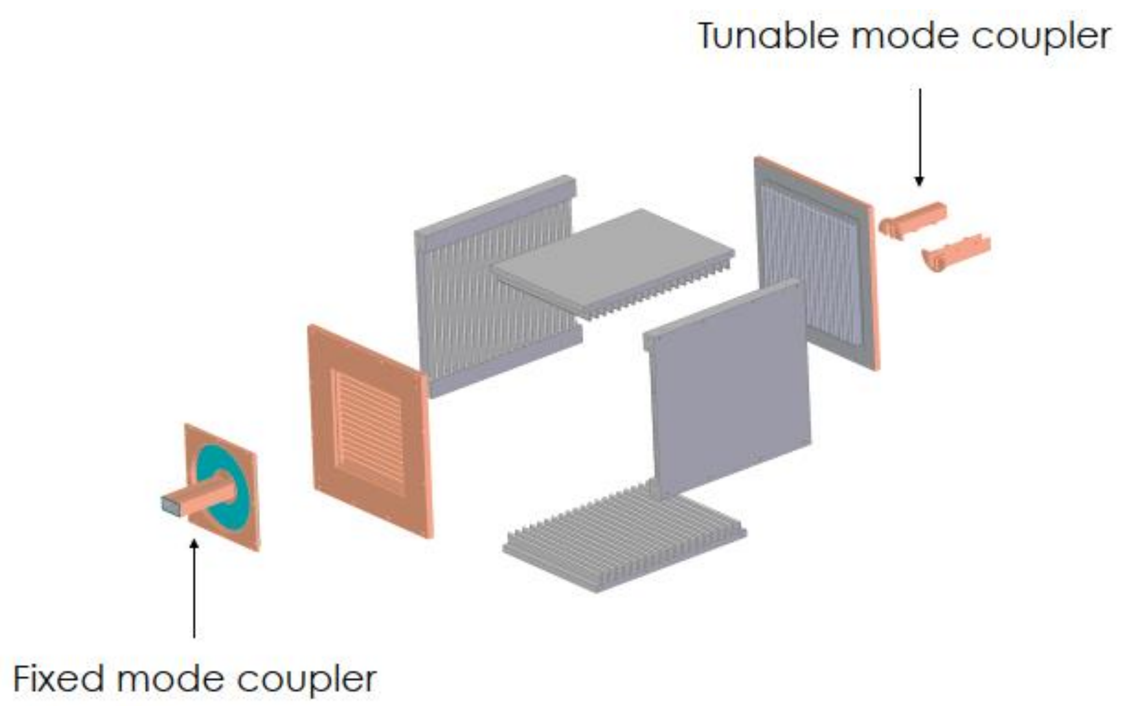
First presented to PBC management in 2021



An axion can shift the frequency of a photon.
In this case, from ω_0 Hz to ω_{sig} Hz.
(ω_{sig} - ω_0) is proportional to axion mass m_a

Progress from SLAC





Zenghai Li, SLAC

Progress from SLAC

(*) loaded non-tunable mode

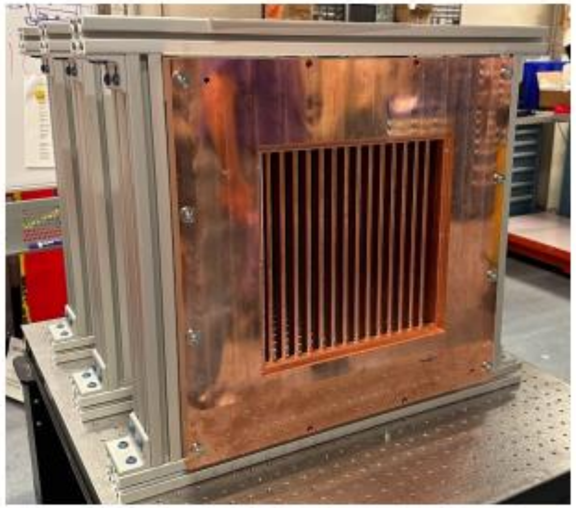
(*) $Q \simeq 3.5 \times 10^4$

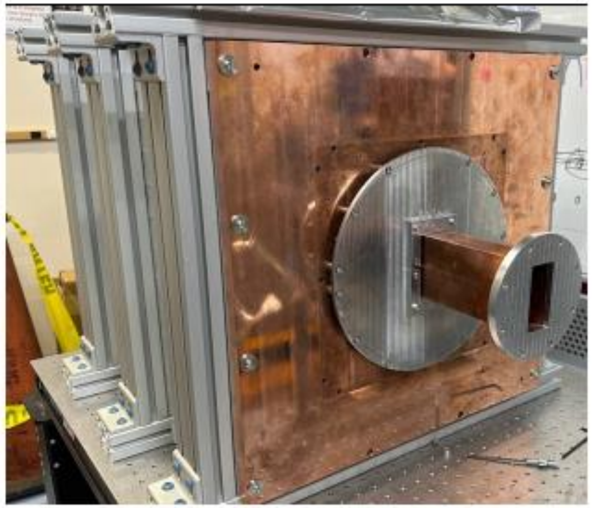
$V \simeq (0.48 \times 0.46 \times 0.46)\,\mathrm{m}^3$

$T \simeq 300\,\mathrm{K}$

$\epsilon_{1d} \simeq 10^{-3}$

$\omega \simeq 3\,\mathrm{GHz}$





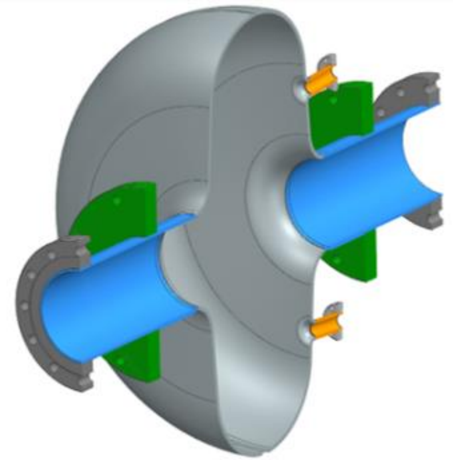
Zenghai Li, SLAC

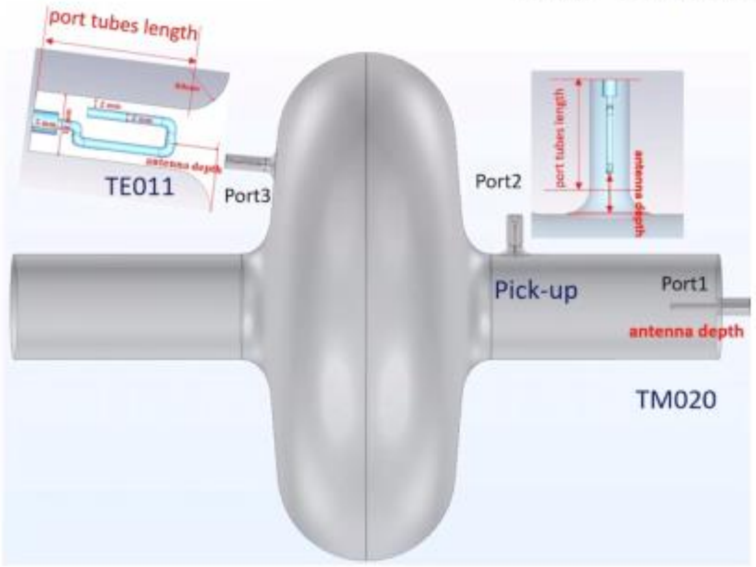
Progress from Fermilab

SQMS Team

Parameters based on informal conversations

VERY PRELIMINARY!





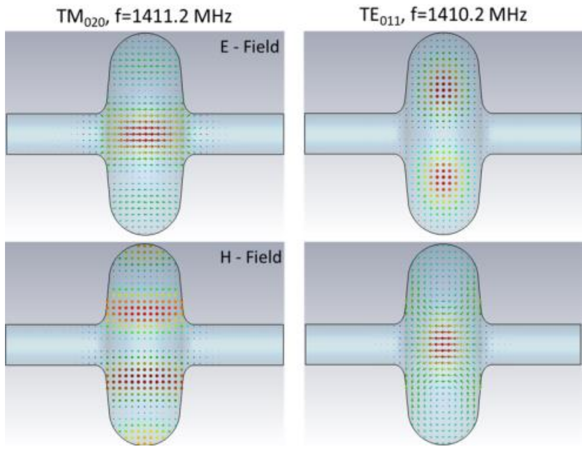
$$Q \simeq 10^{10} \quad \text{(loaded)}$$

$$V \simeq 10\ \mathrm{L}$$

$$\omega_0 \gtrsim \mathrm{GHz}$$

$$T \simeq 4\ \mathrm{K}$$

$$\epsilon_d \simeq ?$$

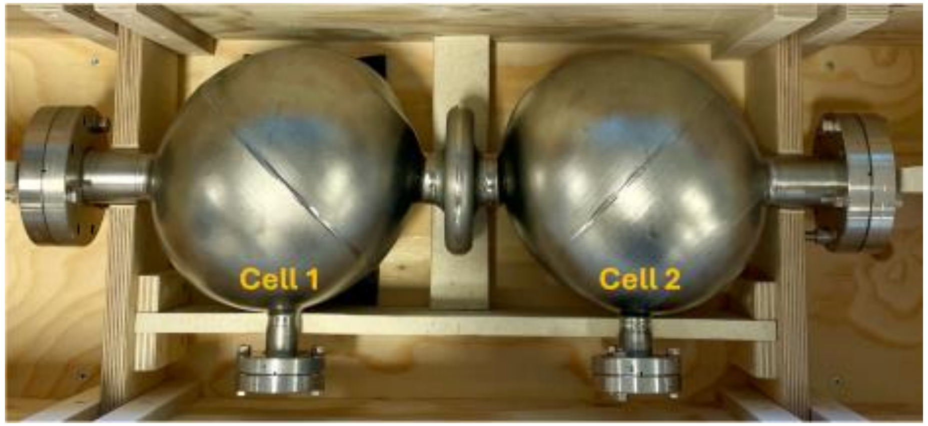


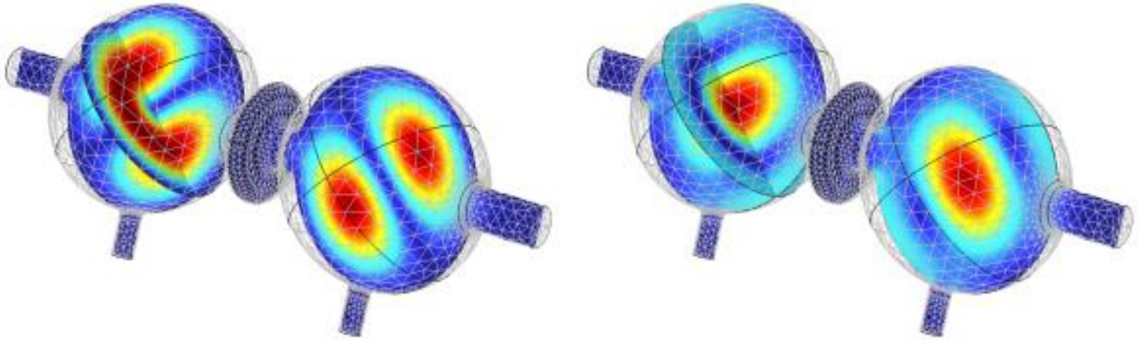
The potential sensitivity is beyond current bounds

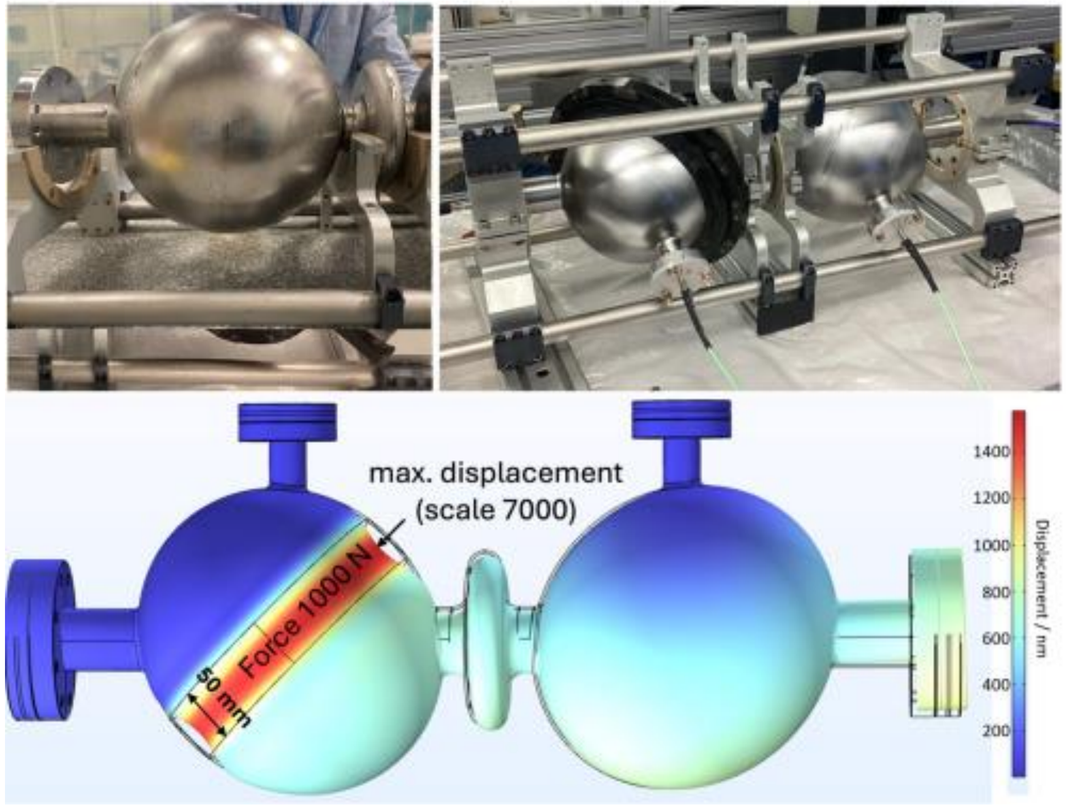
B. Giaccone, FNAL

https://arxiv.org/abs/2207.11346

Progress from FNAL: MAGO cavity







Mechanical tuning and first tests at room temperature, collaboration FNAL – DESY https://arxiv.org/abs/2411.18346

Axion Heterodyne @ CERN status:
CERN Quantum Technology Initiative 2.0 (QTI) 2024-2028

Centre of Competence: Quantum Platforms Demonstrators

Activities

- Exotic atoms and ions as qubits and Dark Matter sensors
- Atomic and nuclear clocks as sensors for new, feeble interactions
- Cryogenics and RF cavities for axion and Gravitational Wave searches
- Development and characterisation of (prototype) multi-qubit systems with superconducting cavities, ion traps and isotopes
- Quantum sensors for millicharged particles and for HEP
- Quantum data acquisition

Expected impact

- Accelerate the development and adoption of quantum technology and classic “enabling” technologies based on unique, existing facilities and technologies at CERN
- Establish visible, efficient mechanisms for impactful co-development and knowledge sharing
- Work with labs and companies to further exploit the technologies beyond CERN (many expression of interest from companies to work with and learn from CERN)

QUANTUM TECHNOLOGY INITIATIVE 13/09/2023 CERN QTI 2 Kick-Off 14

S. Vallecorsa, M. Doser

Axion Heterodyne @ CERN: started !

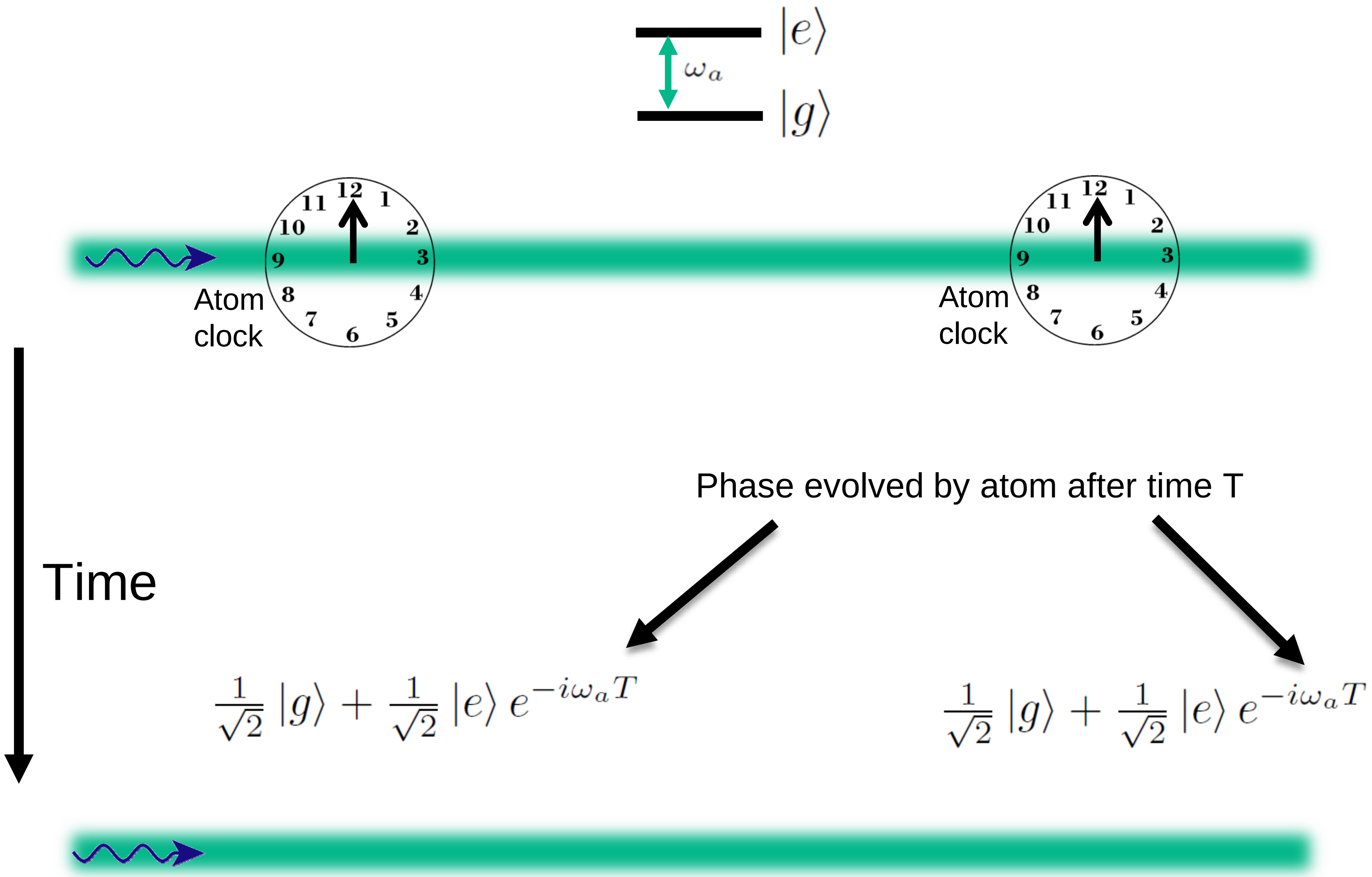
- Dedicated **Staff and Fellows both in TE and SY** departments, and **funds for investments** have been allocated by QTI
  - **Staff (5y)** in SY/RF, for supervision of cavity design and measurements – **hired**
  - **GRAD-Quest (3y)** in SY/RF for cavity design **on PBC funds** – **VN open**
  - **Staff (5y)** in TE/CRG, for design and construction of sub-K cryogenics – **hired**
  - **GRAD-Origin (3y)** in TE/VSC for cavity surface treatments – **VN open**
  - **Allocated funds** in SY/RF for cavity fabrication and in TE/CRG for Sub-K cryogenics
- Program is in **synergy between PBC and QTI**
- **Ideal platform for quantum sensing technologies**
- **Quantum sensing <-> detecting signals of one single photon**, avoiding noise from traditional electronic DAQ chains

AION: Atom Interferometer Observatory and Network

TVLBAI: Terrestrial Very-Long-Baseline Atom Interferometer

Using atom clocks to measure Dark Matter and low-frequency Gravitational Waves

Simple Example: Two Atomic Clocks



Simple Example: Two Atomic Clocks

$|e\rangle$

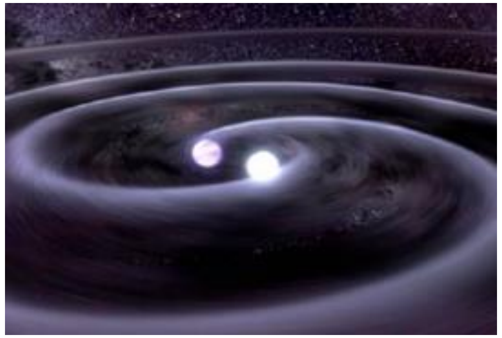
ω_a

$|g\rangle$

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

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

Time

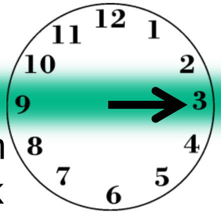


GW changes light travel time

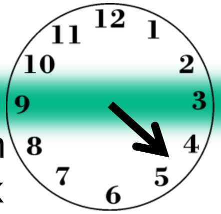
$\Delta T \sim hL/c$

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

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

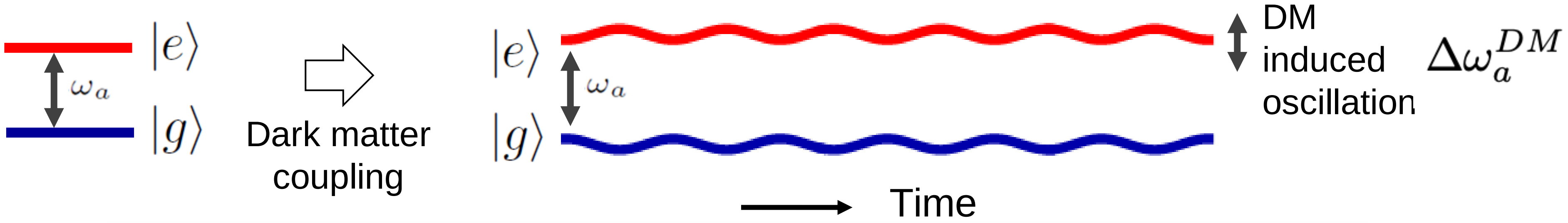


Atom clock

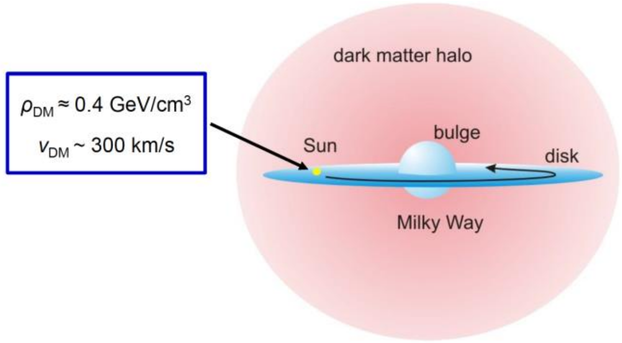


Atom clock

Simple Example: Two Atomic Clocks



Time

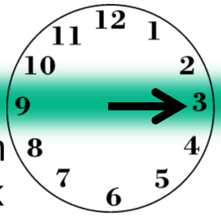


DM cloud changes atom frequency

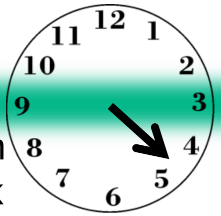
DM coupling causes time-varying atomic energy levels:

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

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



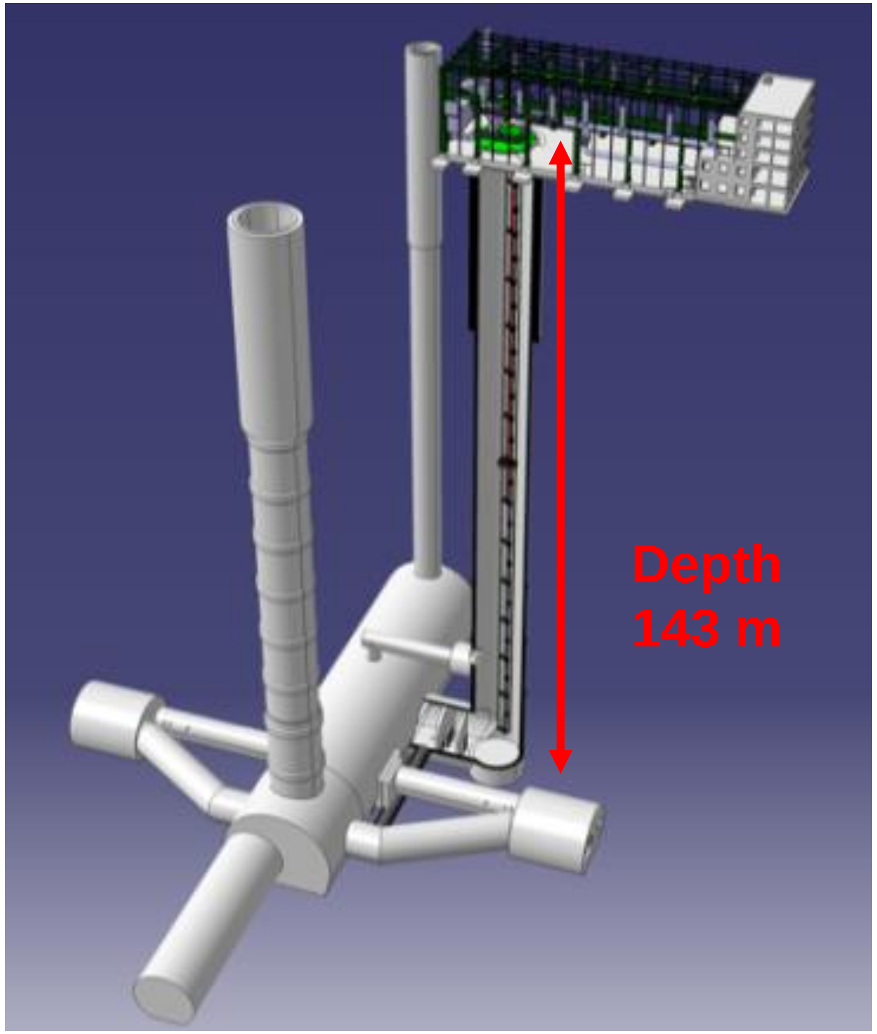
Atom clock

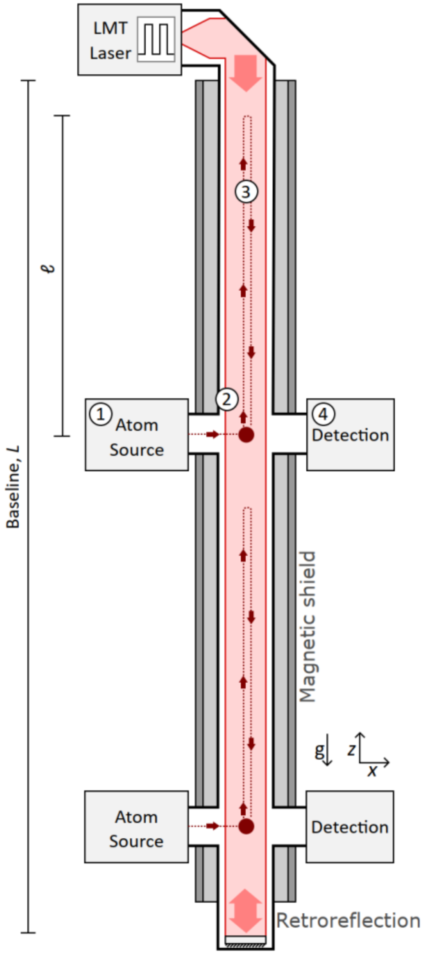


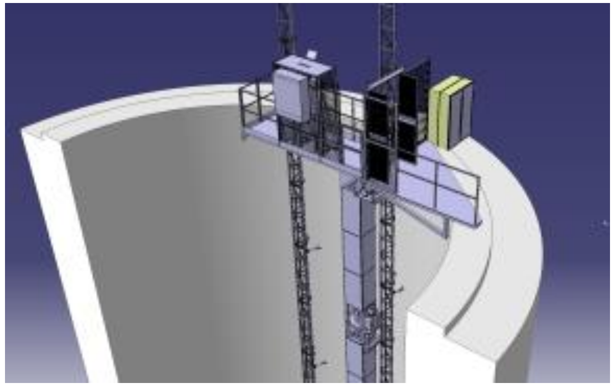
Atom clock

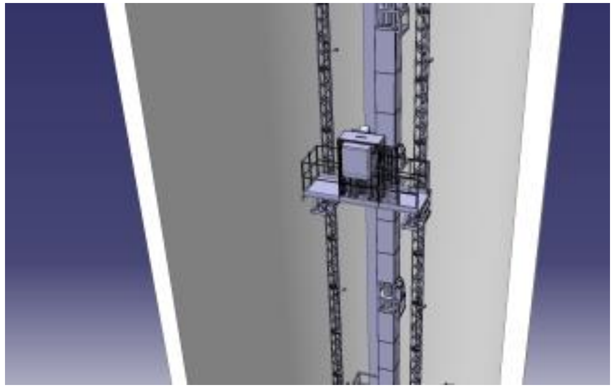
AION-100 @ CERN status

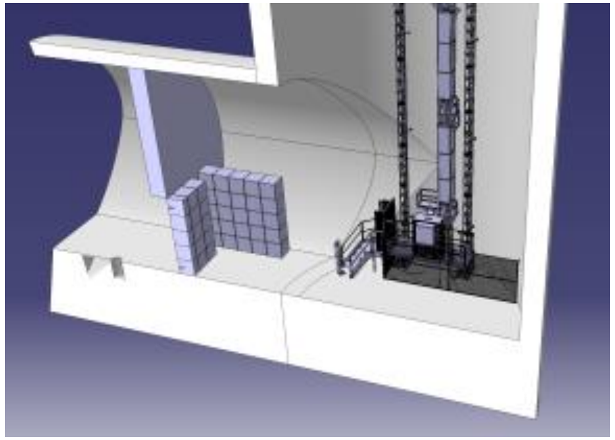
Feasibility study report https://arxiv.org/abs/2304.00614











AION-100 @ CERN

From feasibility study in 2023 to MoU of TVLBAI collaboration in 2024

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

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

March 30, 2023

→

Memorandum of Understanding for the Terrestrial Very Long Baseline Atom Interferometer Study

THE INSTITUTES, LABORATORIES, UNIVERSITIES, FUNDING AGENCIES SIGNATORIES OF THIS MEMORANDUM OF UNDERSTANDING ("the Participants")

Whereas

The scientific community wishes to draft a framework for the development and realization of Terrestrial Very-Long-Baseline Atom Interferometry (TVLBAI) experiments, with a view to executing a Conceptual Design Study for a TVLBAI (the "TVLBAI Study"),

53 participants from Europe and America

Signed by:

The Chair of the Terrestrial Very-Long-Baseline Atom Interferometry (TVLBAI) Study	For the European Organization for Nuclear Research (CERN)
Signed by: Oliver Buchmueller 9784927EEEBB4B6...	DocuSigned by: Mike Lamont 3FE200FFB3CF46F...
Prof. Oliver Buchmueller TVLBAI Study Chair	Mike Lamont Director of CERN Accelerator and Technology Sector
Date: 9/18/2024	Date: 9/18/2024

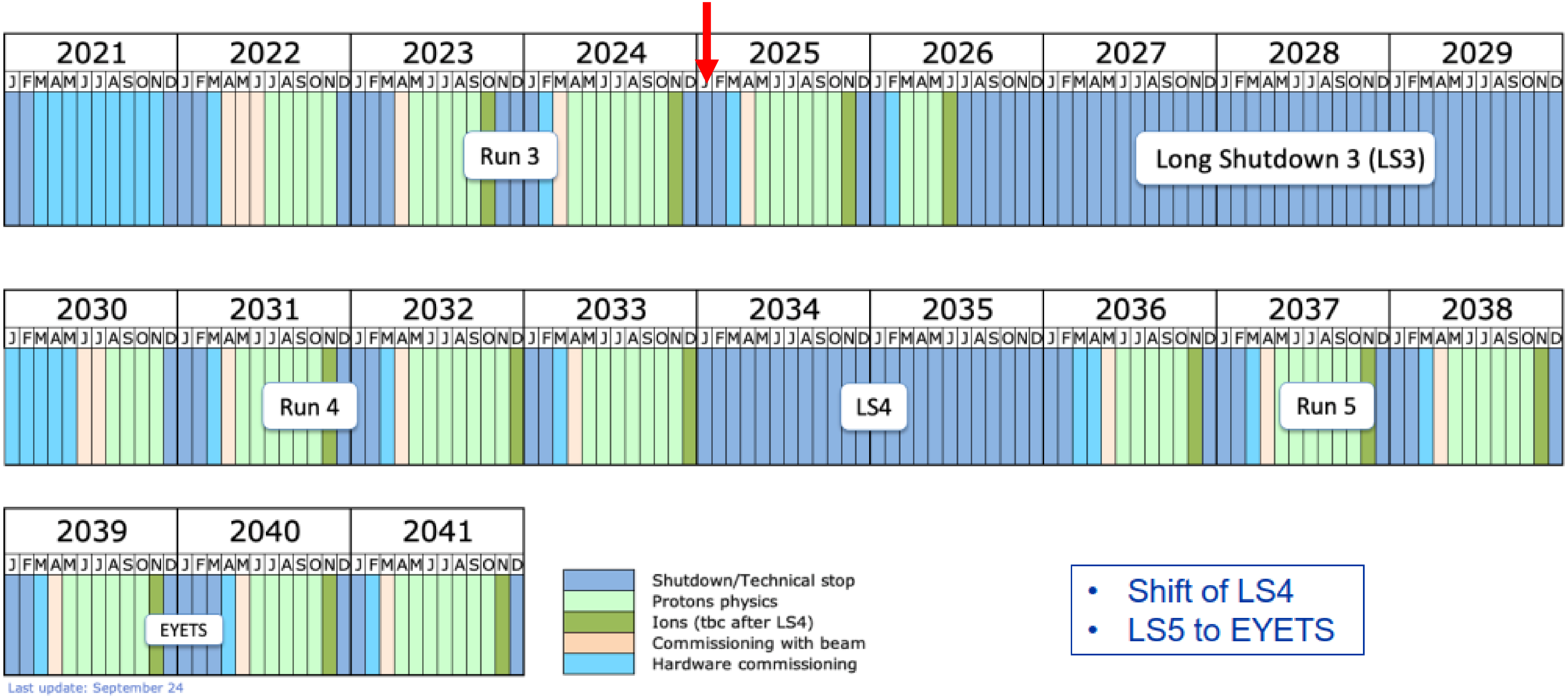
AION-100 @ CERN: Next steps

- **Conceptual technical design, construction timeline and cost estimates for making PX46 available to the AI community for a future installation of an experiment**

- **In particular -> Mandate received from Mike Lamont**
  - Design of the shielding wall, in coordination between RP and CE with input from HE and AA
  - Access control, alarms and ODH design, in coordination with HSE
  - Verification of CV requirements (ventilation of the bottom of the shaft if confined area)
  - Assessment of the requirements for the installation of the elevator platform
  - Any further needs from CV and EL

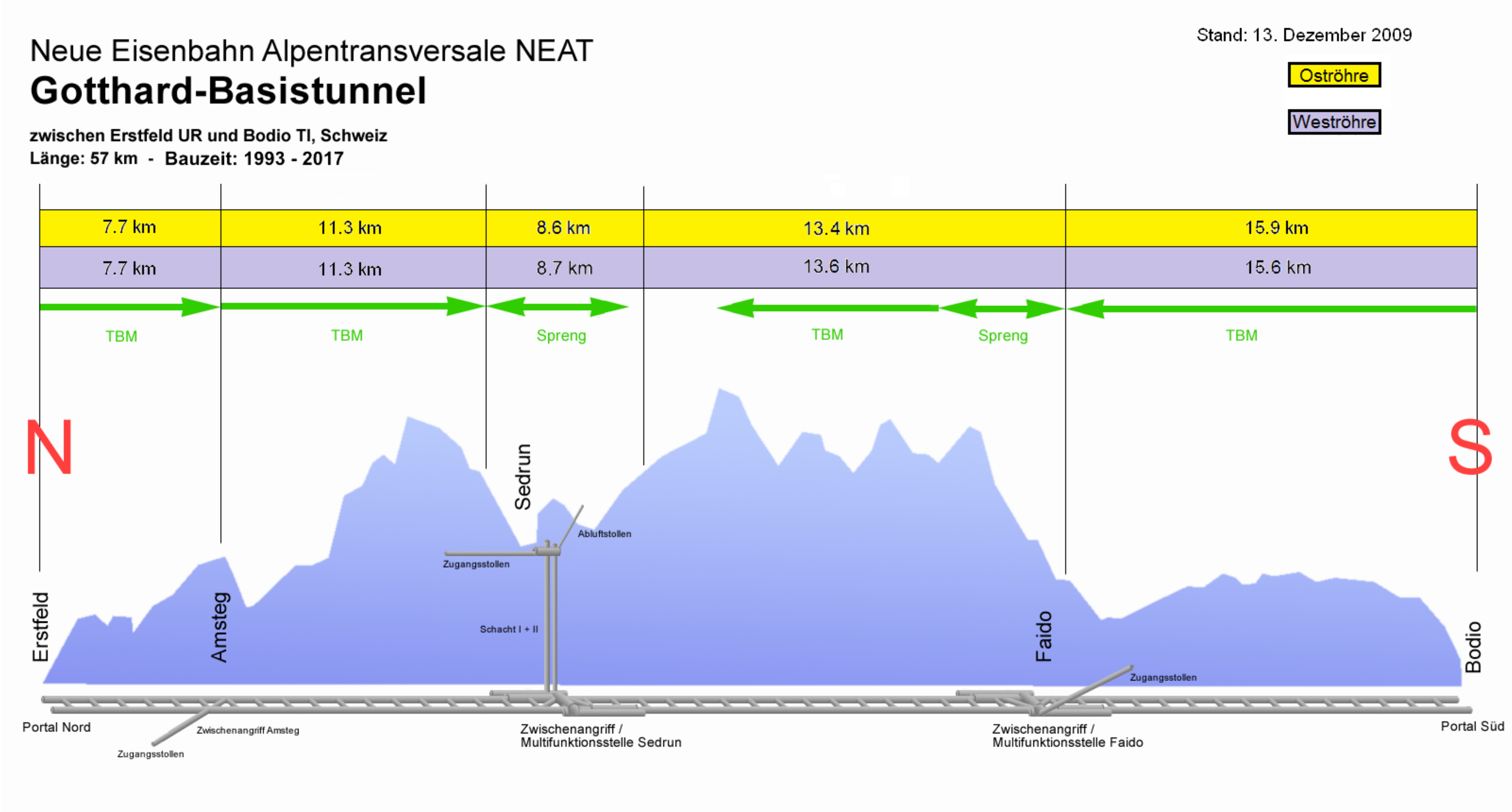
- **Assess the time-line required and the associated cost for technical and execution design and for the construction and installation works: is LS3 a possible option?**

Proposed Long Term LHC Schedule

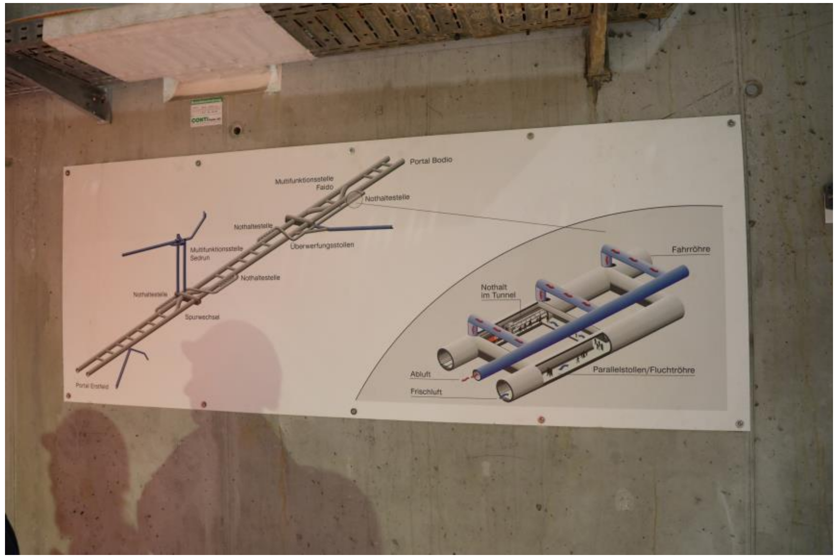


- Shift of LS4
- LS5 to EYETS

New AI initiative: Porta Alpina, a km-scale AI



Porta Alpina, visit on 7.11.2024: 850m deep shaft



Porta Alpina, outcome of the visit

Jointly organized by SBB, UniGE, UniNE, UniZH, FHS Graubünden, FHS Luzern and CERN

CERN-EDMS3195246

Proposal for Environmental Measurements in the Sedrun Sector of the Gotthard Base Tunnel

S. Calatroni[1], *J. Ellis*[1,2], *M. Guinchard*[1,*], *L. Lombriser*[3]

[1] CERN, [2] King's College London, [3] University of Geneva, [*] Editors

- **Visit by SBB delegation** (Head of Region South and collaborators) **to CERN** is scheduled for 29.1.2025 (next week), to visit LHC tunnel and share work experience

The PBC Technology Working Group

Mandate (highlights):

- …explore and evaluate **possible technological contributions of CERN** primarily to non-accelerator-related experimental physics initiatives and projects that may also be hosted elsewhere
- …**survey technologies** that could become relevant to CERN accelerator and non-accelerator projects
- …favour the **exchange of experience and expertise** in technological domains such as superconducting and normal conducting magnet and RF technology, cryogenics, optics, vacuum and surface technology
- …**support the development of new physics experiments** and detection methods like quantum sensing and new (accelerator and non-accelerator) experiment proposals

Objectives:

- Contribution to **advancing conceptual designs** where appropriate
- Identification and **promotion of synergies** with **Quantum Sensing Initiatives at CERN** and with **other PBC Working Groups**
- Documentation of identified and undertaken initiatives and benefits for the experimental community

~~Mini~~-workshops

- The **mix of technologies** in the initiatives considered in the PBC is **very varied**
- The technology WG mini-workshop series is aimed at providing users with an overview of possibilities/expertise at CERN and – in turn – to provide CERN experts with an overview of the ideas "out there"

- **1st PBC technology mini workshop: superconducting RF**
- **2nd PBC technology mini workshop: lasers & optics**
- **3rd PBC technology mini workshop: vacuum, coating and surface technologies**
- **4th PBC technology mini workshop: cryogenics technologies**
- **5th PBC technology mini workshop: Superconductivity Technologies**

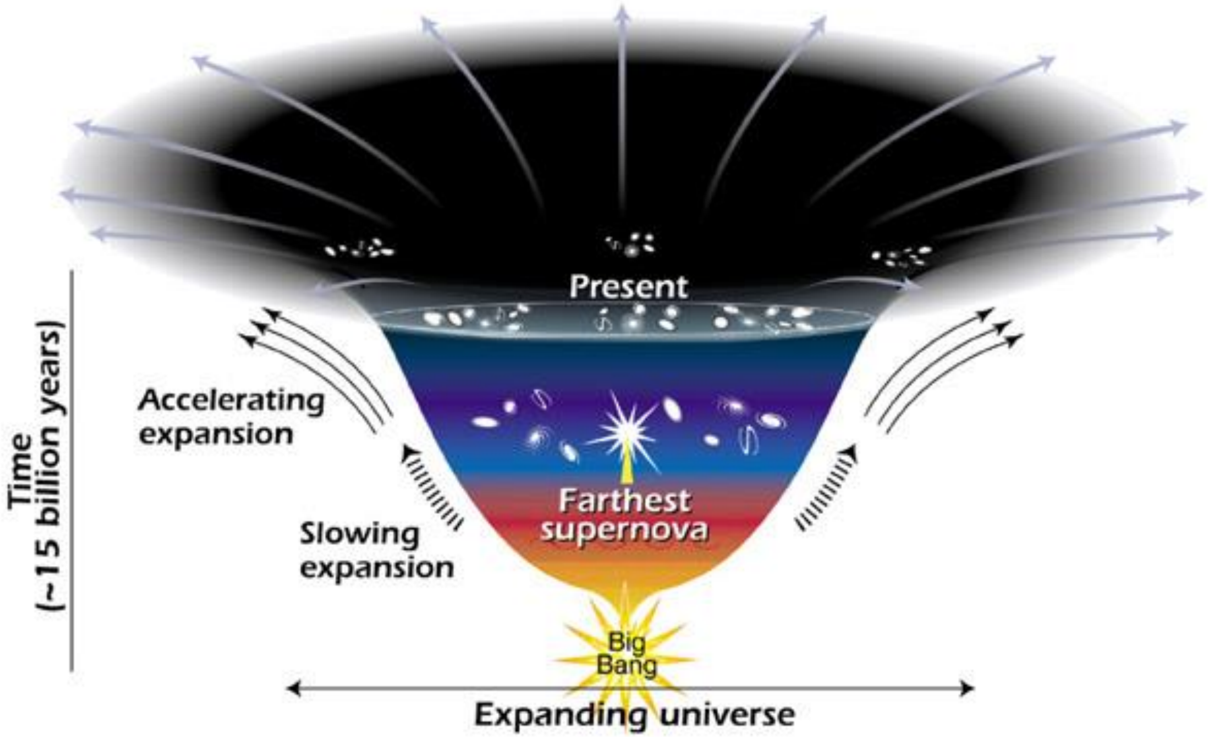
- Future workshop
  - Mechanical, design and fabrication technologies, goal before summer 2025 (Michael Guinchard)

CERN Quantum Technology Initiative

home.cern

Dark energy

- **The expansion of the universe is accelerating.**
- **This could be (main hypothesis):**
  - a property of space (Einstein general relativity);
  - or due to “quantum properties” of vacuum;
  - or to a new unknown field (“quintessence”) that fills the universe.
- **The main fact is: we do not know.**



This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.

Image source: NASA/STSci/Ann Feild

Dark matter

How it should appear | How it is in reality

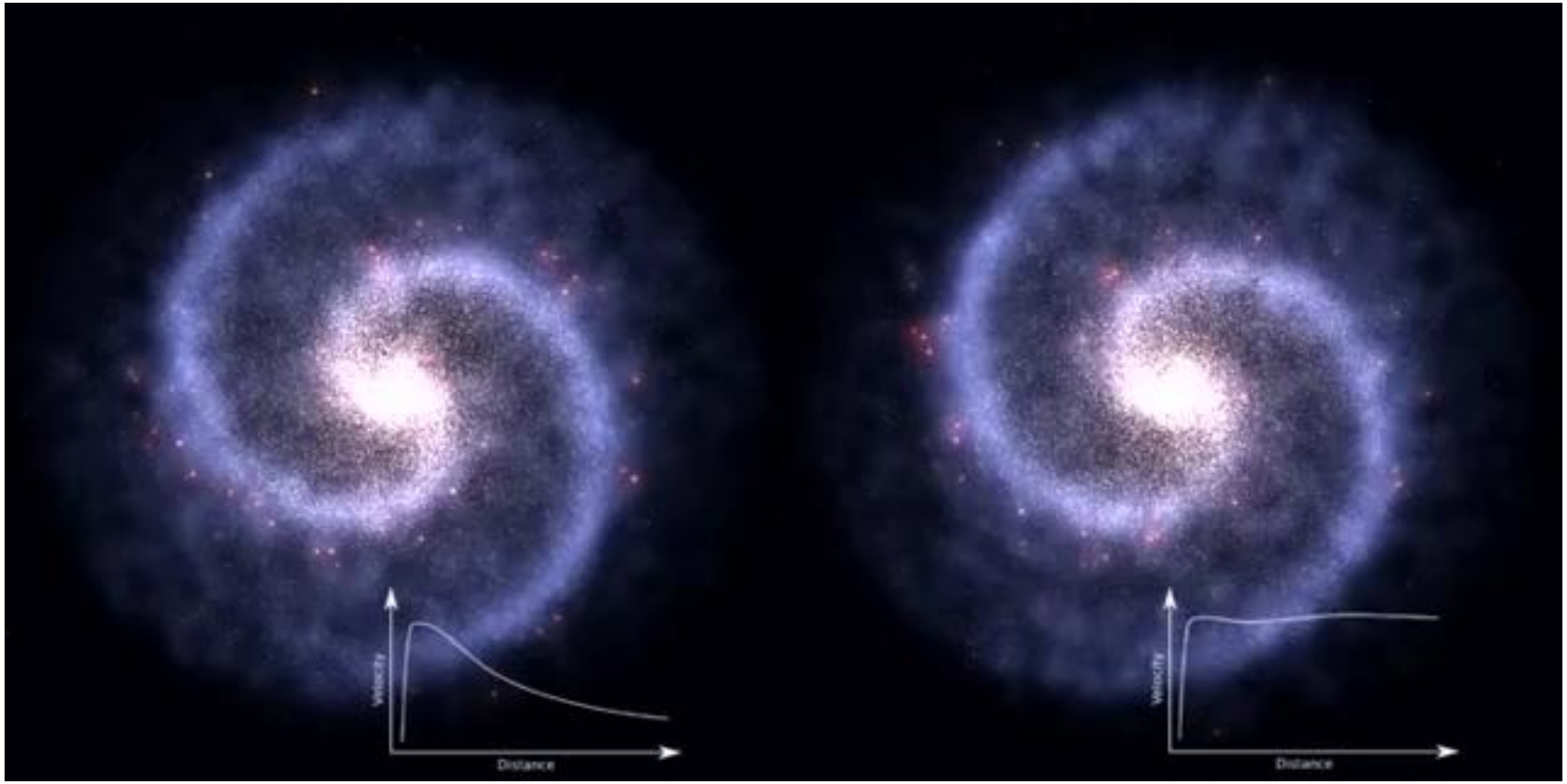
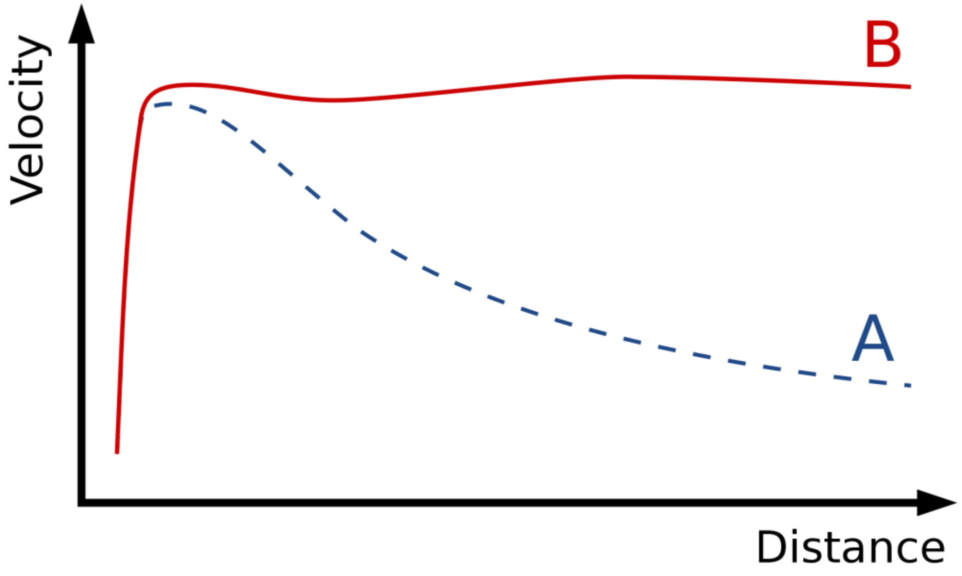


Image source: Wikipedia

Dark matter

- **Dark matter IS NOT:**
  - is not in the form of stars and planets that we see;
  - it is not in the form of dark clouds of normal matter;
  - it is not antimatter;
  - it is not large galaxy-sized black holes.
- **Dark matter MAY BE:**
  - MACHOs (MAssive Compact Halo Objects): small black holes, neutron stars, or brown dwarfs (max 20% of dark matter)
  - WIMPs (Weakly Interacting Massive Particles): subatomic particles which are not made up of ordinary matter. Axions are the best candidate

Rotation curve of a typical spiral galaxy



A predicted from the visible mass
B observed : due to dark matter?

Image source: Wikipedia

BabyIAXO and RADES

- BabyIAXO, now under construction
- Axion helioscope + option as halosc