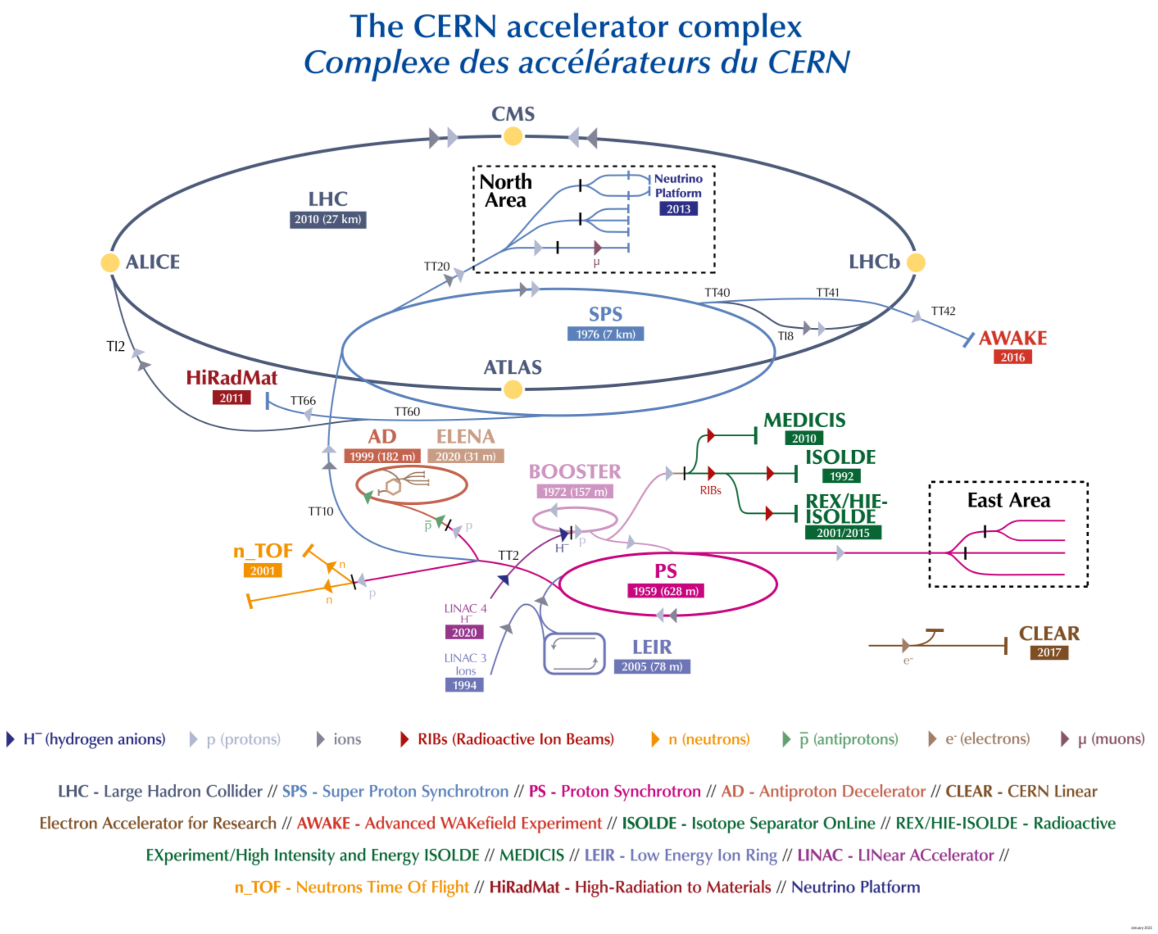
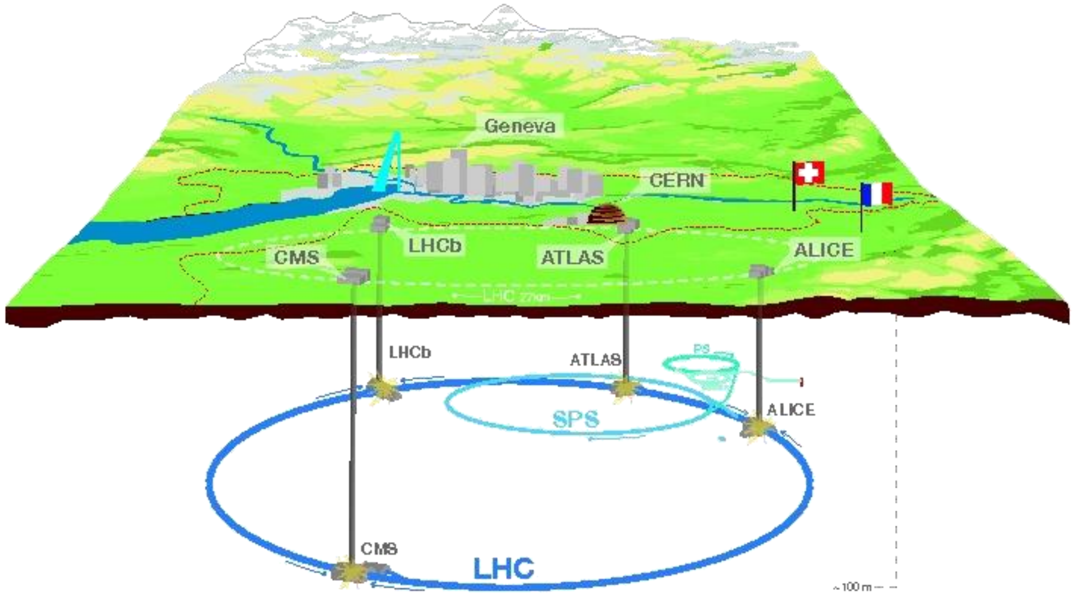
Opportunities in Physics Beyond Colliders

The CERN accelerator complex





Ordinary matter

and the problems of the standard model

- **Phenomena not explained**
  - Gravity
  - Neutrino masses
  - Matter–antimatter asymmetry
- **Experimental results not explained**
  - Anomalous magnetic dipole moment of the muon
  - B meson decay
- **Theoretical problems**
  - Strong CP problem

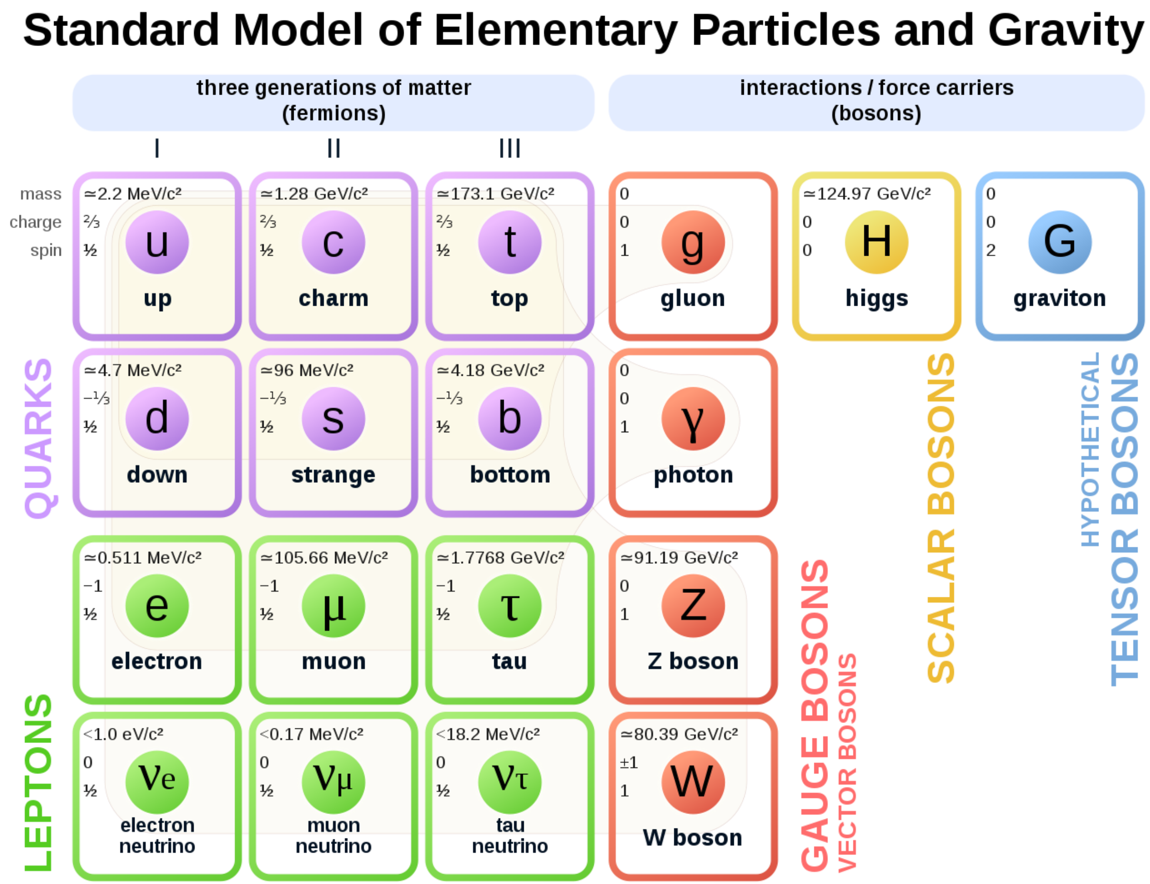


Image source: Wikipedia

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?**

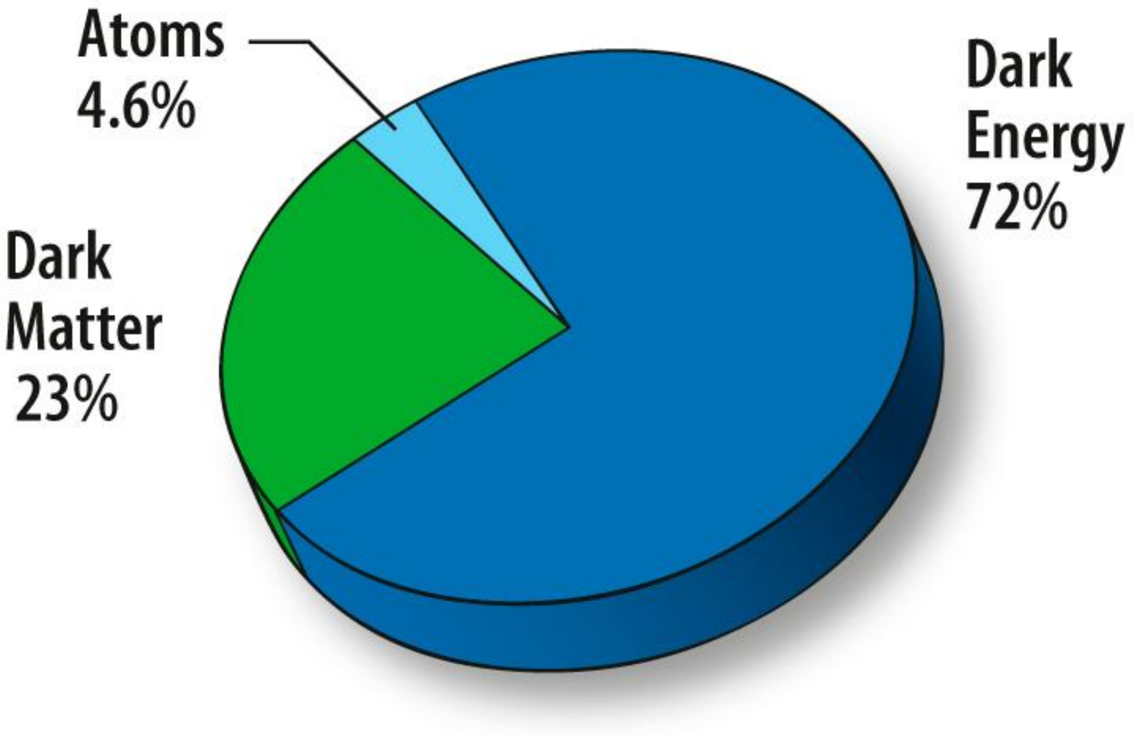
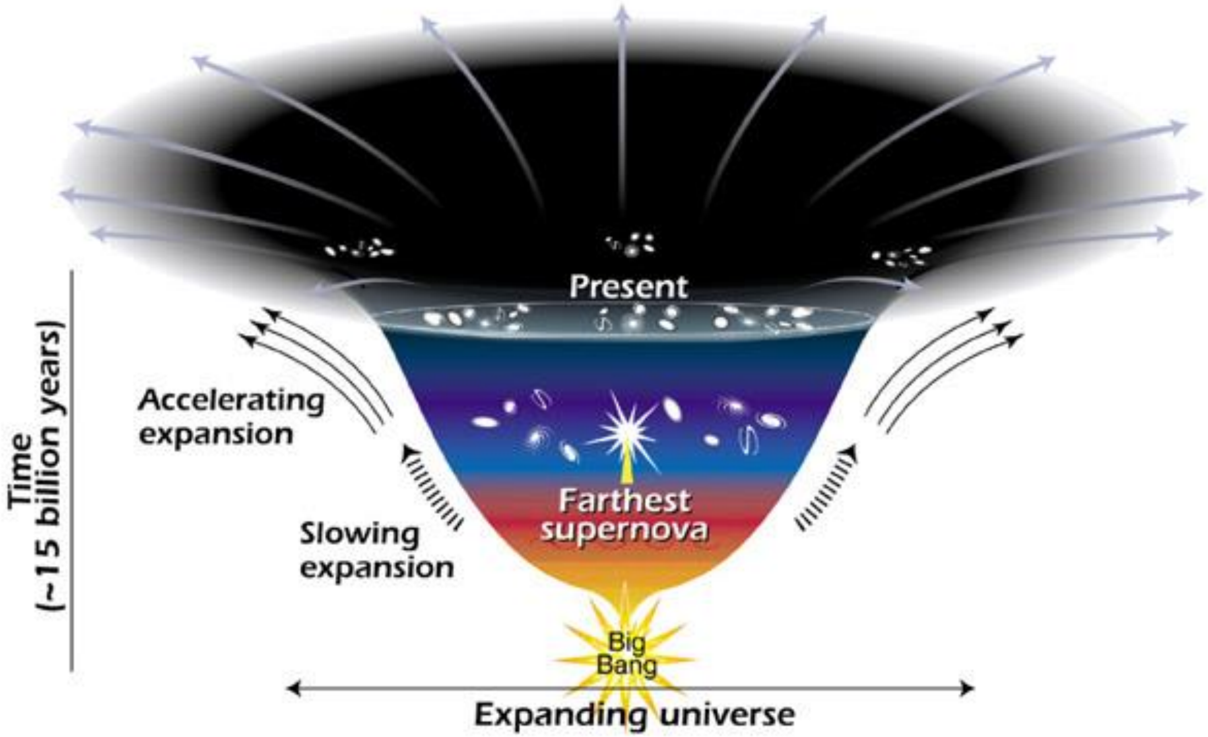


Image source: NASA / WMAP Science Team

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

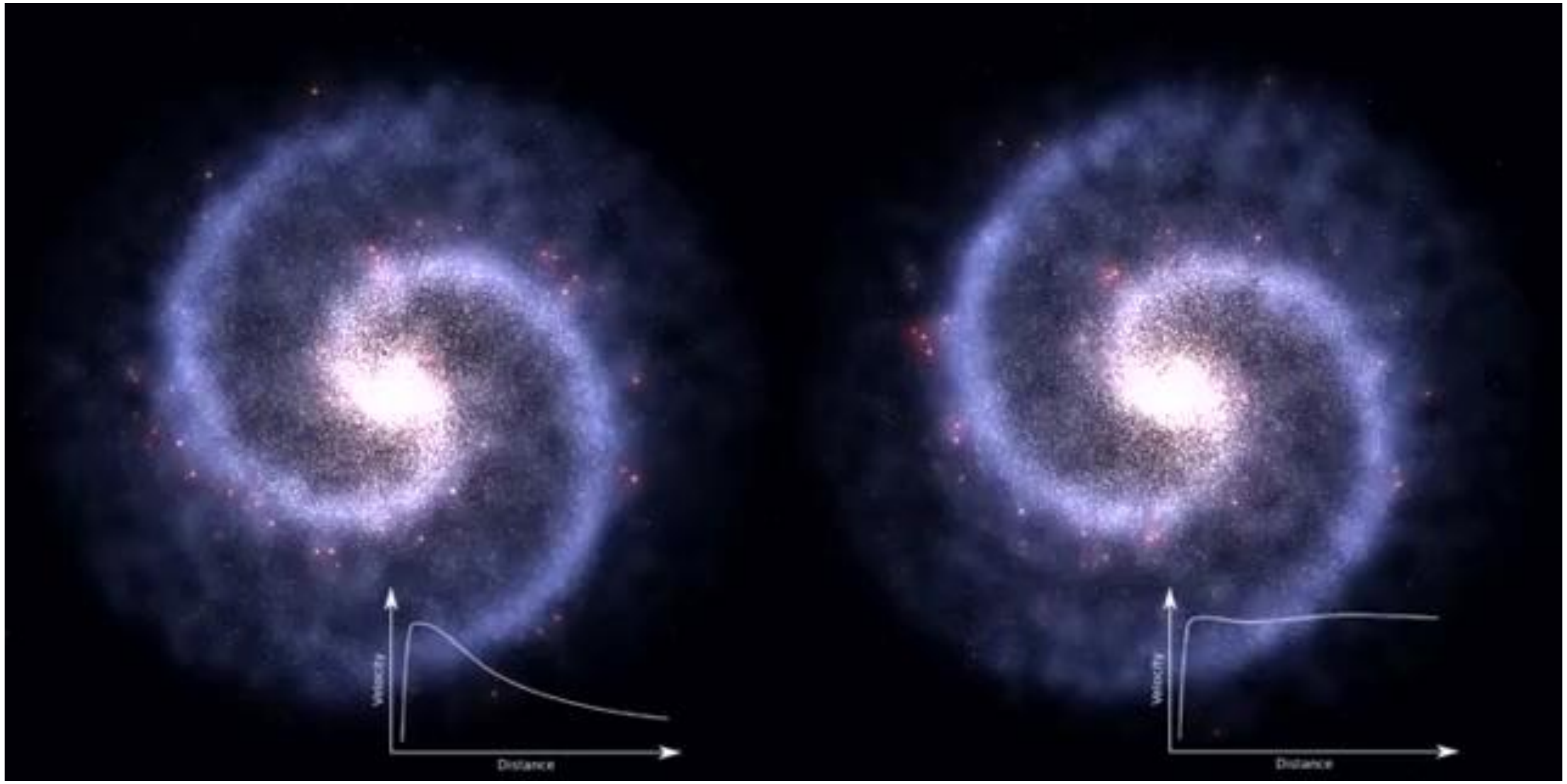
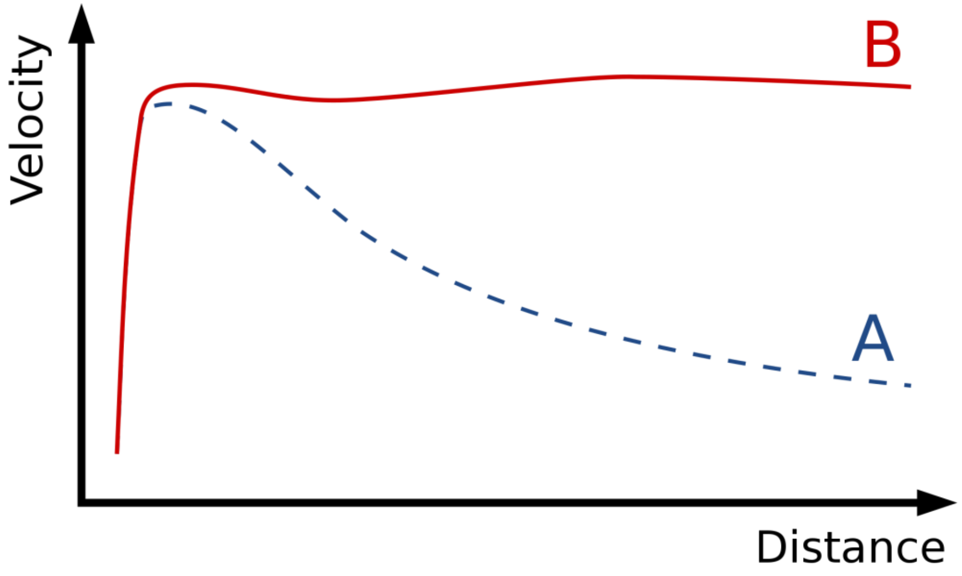


Image source: Wikipedia

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

Physics Beyond Colliders

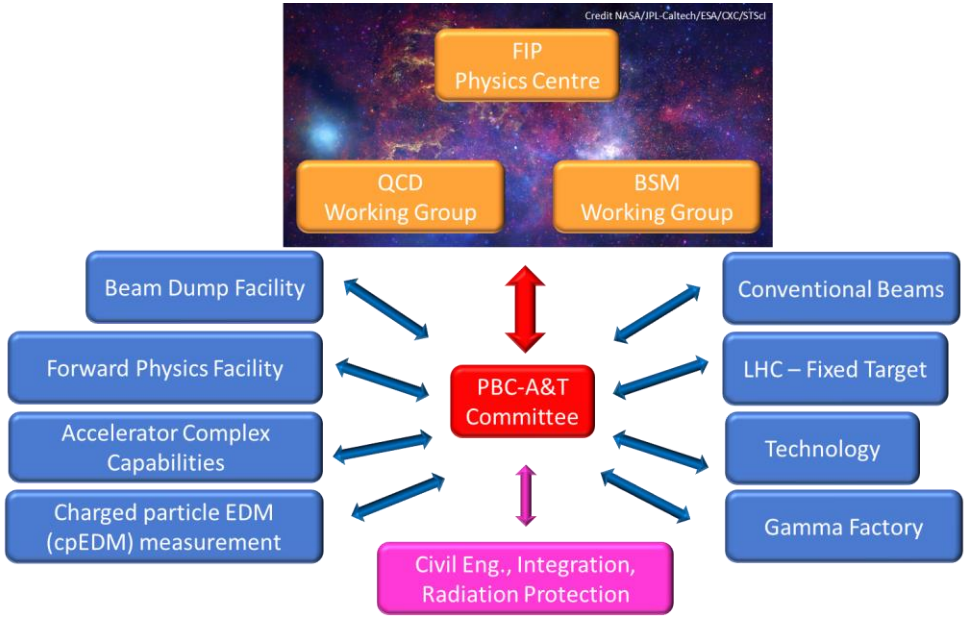
More info: Website, Workshops

From the PBC mandate

- … to address today's outstanding questions in particle physics...
- ... physics objectives include dedicated experiments for studies of rare processes and searches for feebly interacting particles...
- ... physics objectives also include projects aimed at addressing fundamental particle physics questions...
- ... PBC projects complement the goals of the main experiments of the Laboratory's collider programme (...) but require different types of beams and experiments

PBC Organization

- Focus is on using CERN accelerators and technologies for innovative experiments with high physics impact



A&T working groups

- **Accelerator Complex Capabilities**
- **Conventional Beams**

Improvement of existing accelerators for fixed target experiments, with protons, ions etc.

- **Beam Dump Facility**

Novel fixed target experiments at high intensity

- **Forward (and transverse) Physics Facility**
- **LHC fixed target**

Additions to existing LHC experiments allowing higher physics potential

- **Gamma Factory**
- **Charged particle Electric Dipole Moment (cpEDM) measurement**

Novel accelerator ideas

- **Technology**

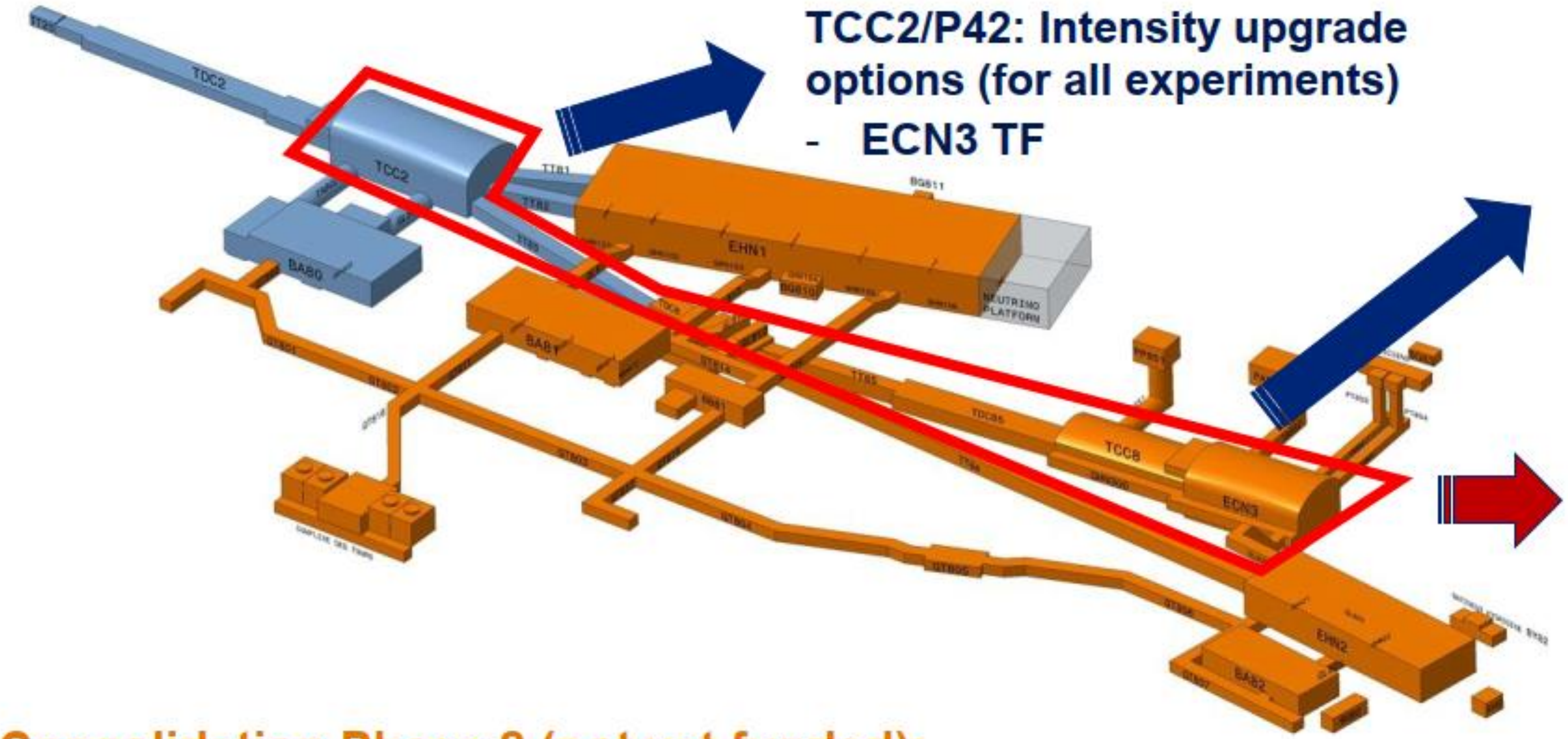
Mostly non-accelerator experiments, based on accelerator technologies

Beam dump facility and ECN3 intensity upgrade

UHV

Consolidation Phase 1 (funded):
2019 – 2028: primary areas, BA80 & beamlines towards EHN1 & TDC8

TCC2/P42: Intensity upgrade options (for all experiments)
- ECN3 TF



TCC8/ECN3: Experiment specific:
- BDF/SHiP WG
- CBWG

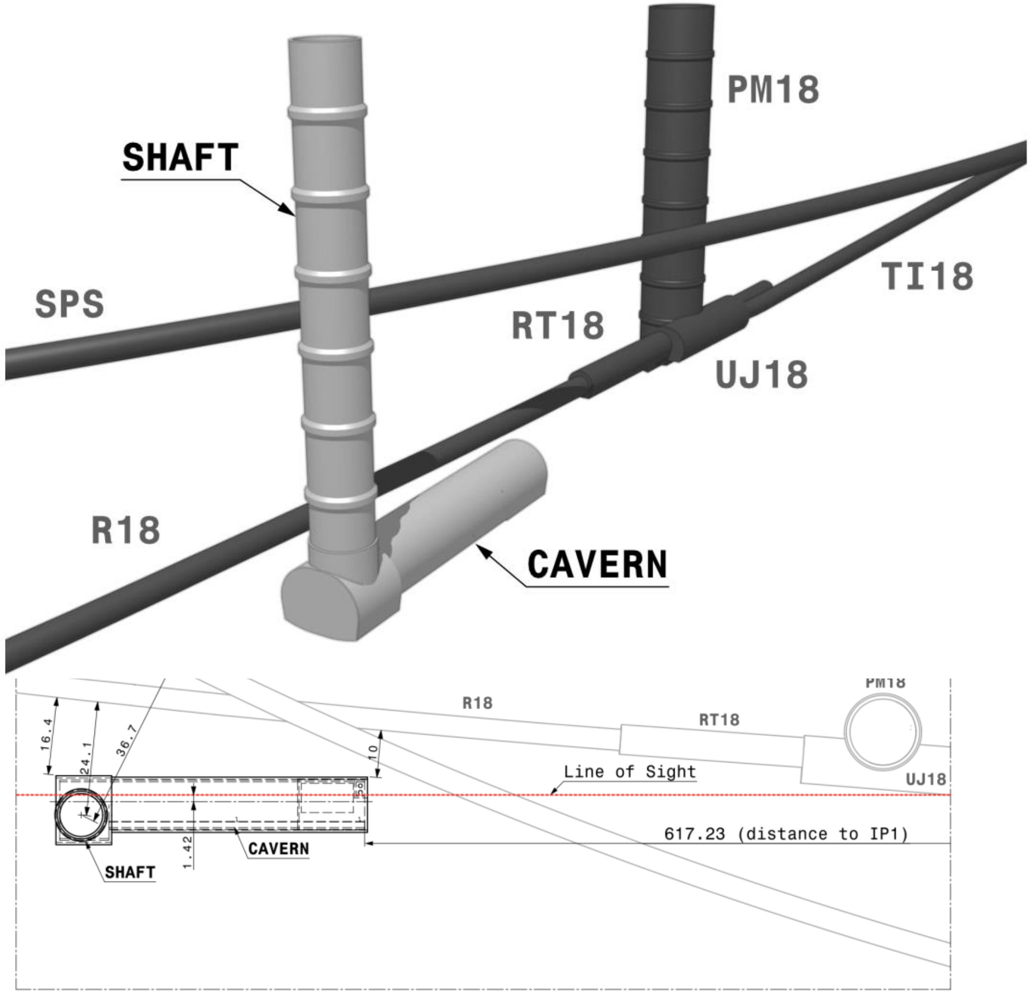
Beam Areas concerned with the upgrade of ECN3 to a high intensity facility

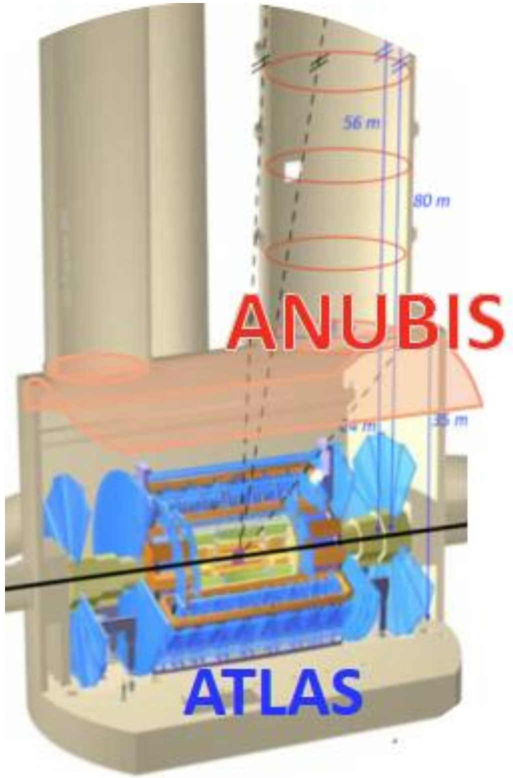
Consolidation Phase 2 (not yet funded):
2029 – 2034: BA81, BA82, EHN1, EHN2, ECN3 & associated beamlines

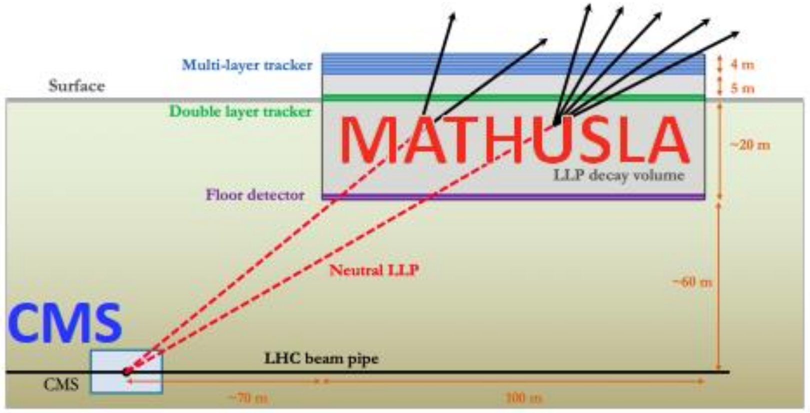
Image source: M. Brugger, M.A. Fraser

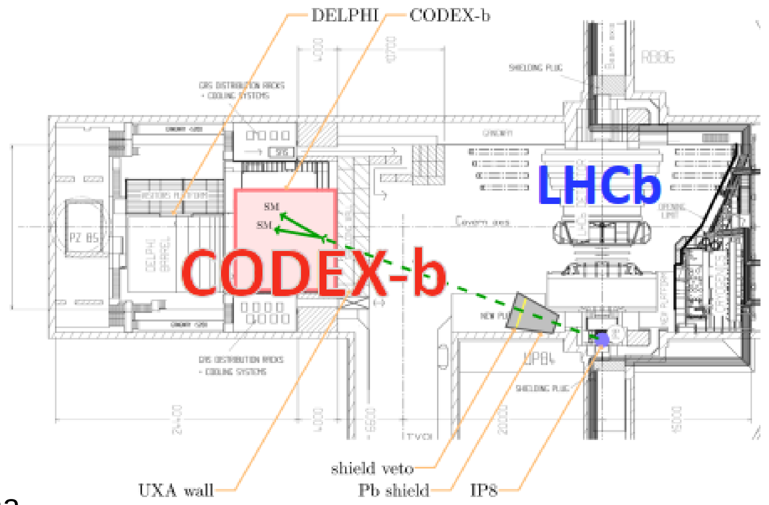
Forward and transverse Physics Facility

Search for long-lived particles



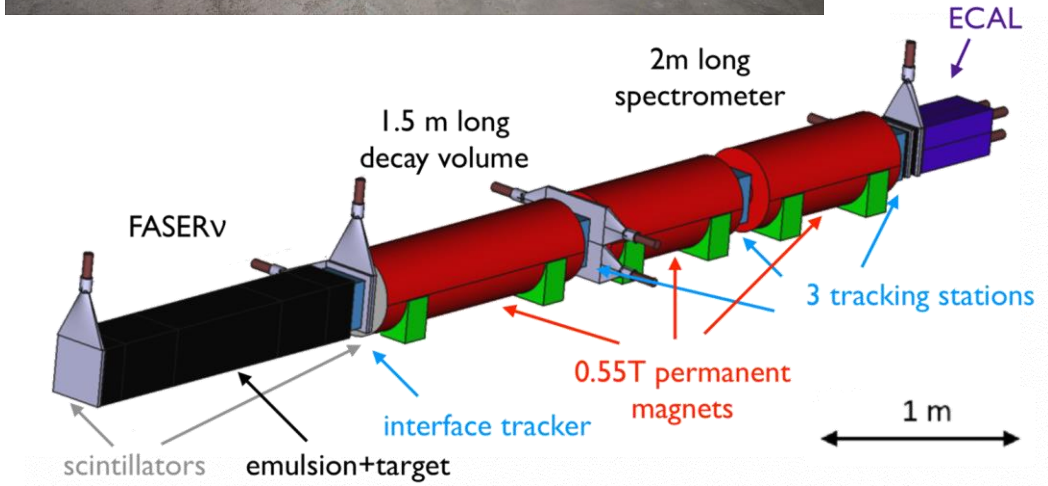






Images sources: J. Boyd, J. Alimena

Today: the FASER experiment

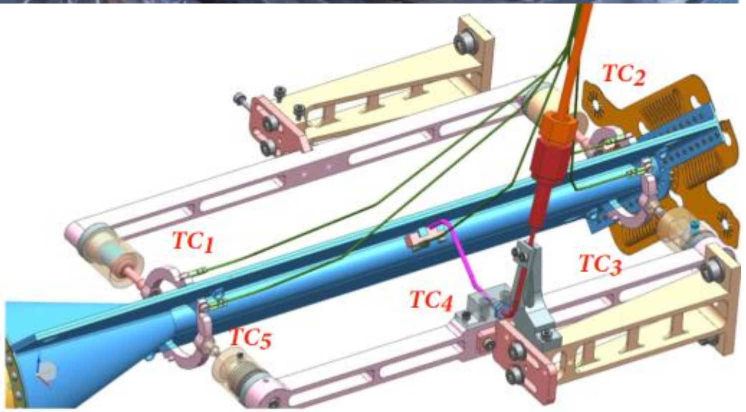


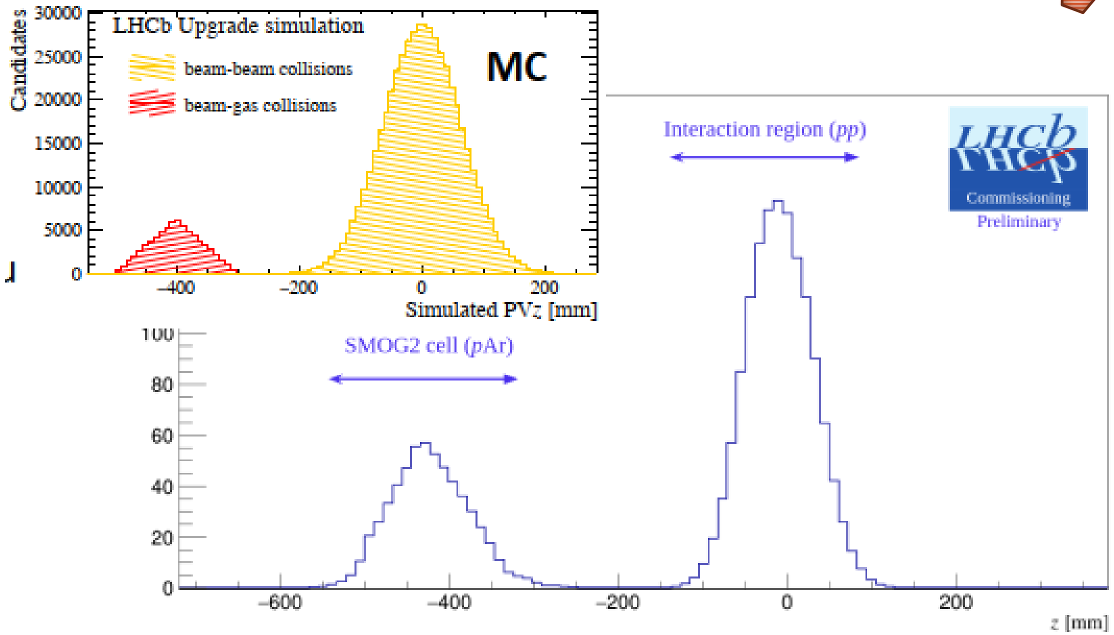
Images source: CERN

LHC fixed target: SMOG2

Deep inelastic scattering

UHV





- The two interaction regions are clearly visible and well separated!
- PV distributions consistent with simulations
- **LHCb is now the first (unique) LHC experiment with two simultaneous interaction regions!**

Images source: L.Pappalardo

From SMOG2 to LHCspin: polarized gas target

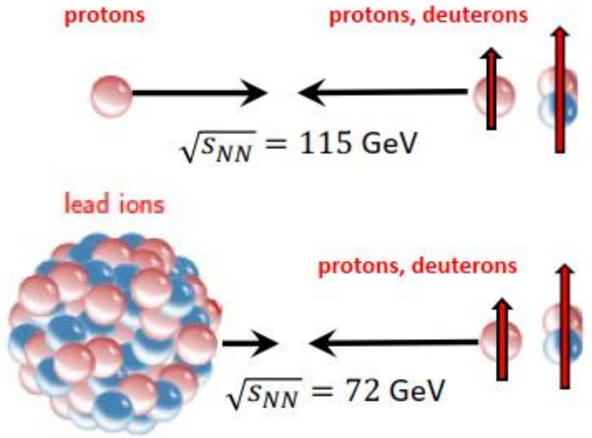
The LHCspin project

SMOG2 is not only a unique project by itself, but also a fantastic playground for the development of a future polarized gas target for LHCb (**LHCspin project**)

UHV

Run 2 → **SMOG** | Run 3 → **SMOG2** | Run 4 (proposed) → **LHCspin**

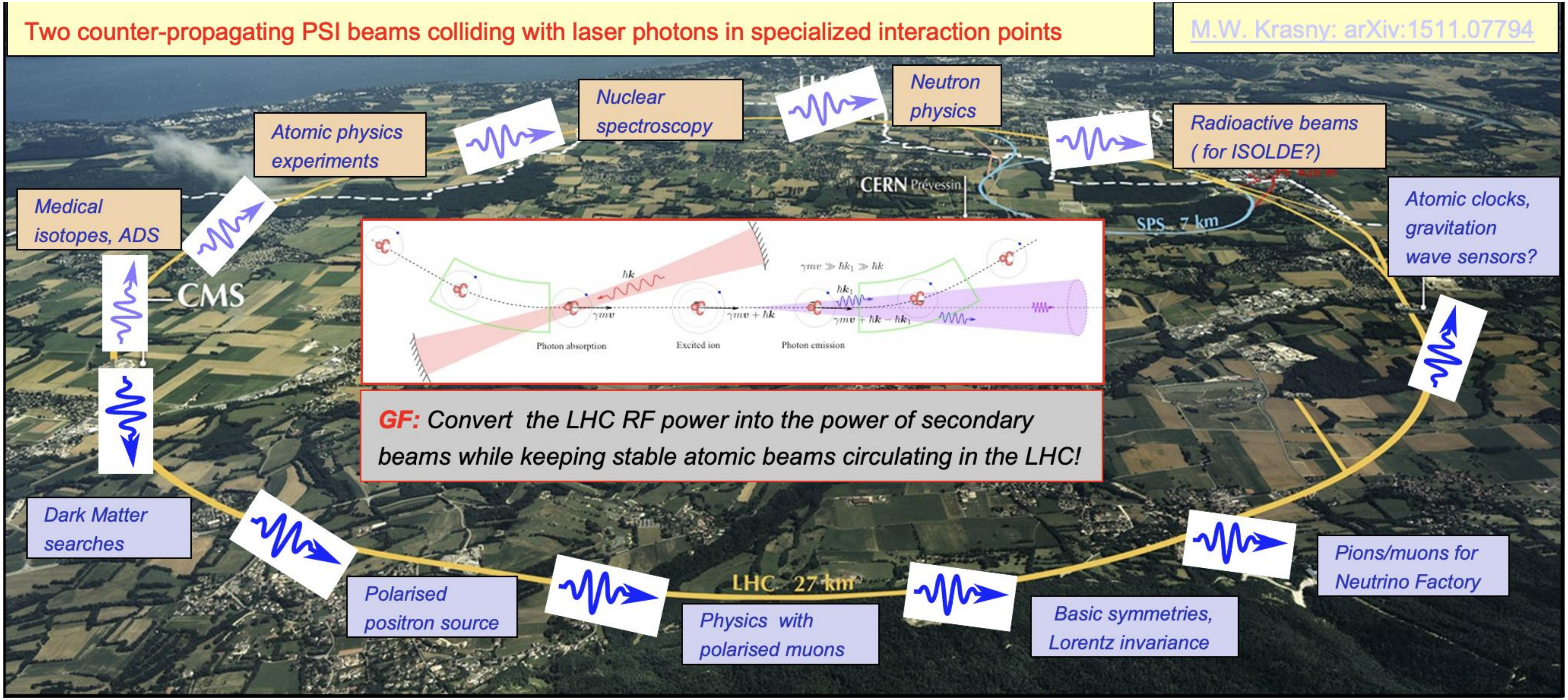
LHCspin is an R&D project aimed to implement a **new-generation HERMES-like polarized gaseous fixed target** in the **LHCb** spectrometer.



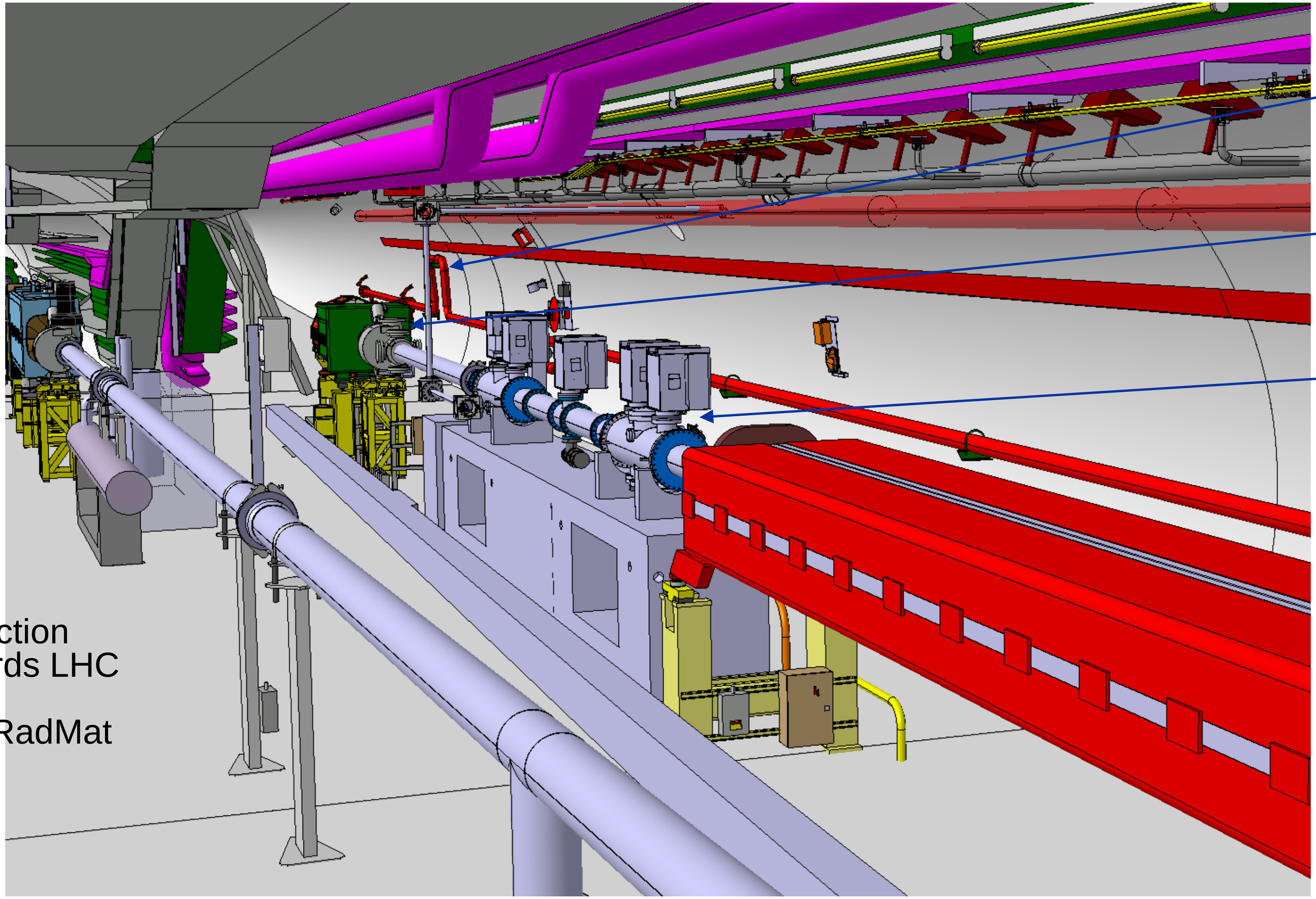
L. L. Pappalardo PBC Annual Meeting - CERN - 7-9/11/2022 28

Gamma Factory
(more info here)

2022 ~ 100 physicists form 40 institutions have contributed so far to the Gamma Factory studies



SPS Proof-of-Principle: preparation in LS3 for Run 4



Laser transport line

X-rays detector

Laser cavity

UHV

Upstream dipole

SPS extraction towards LHC and HighRadMat

Source: Y. Dutheil

The PBC Technology Working Group

More information: Website , Workshops

From the Technology WG mandate

- …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

Experiments & proposals linked with Tech WG

- **ALPS-II / Jura → Data taking at DESY**
- **babyIAXO → Experiment at DESY, collaboration agreement with CERN**
- **Grenoble Haloscope (GrAHal) → will apply to REC**
- **VMB@CERN → will apply to SPSC**
- **DarkSide**
- **Ptolemy- Carbon NanoTubes**
- **STAX**
- **Advanced-KWISP**

(DarkSide, Ptolemy- Carbon NanoTubes, STAX, Advanced-KWISP:) In development in other laboratories with CERN support

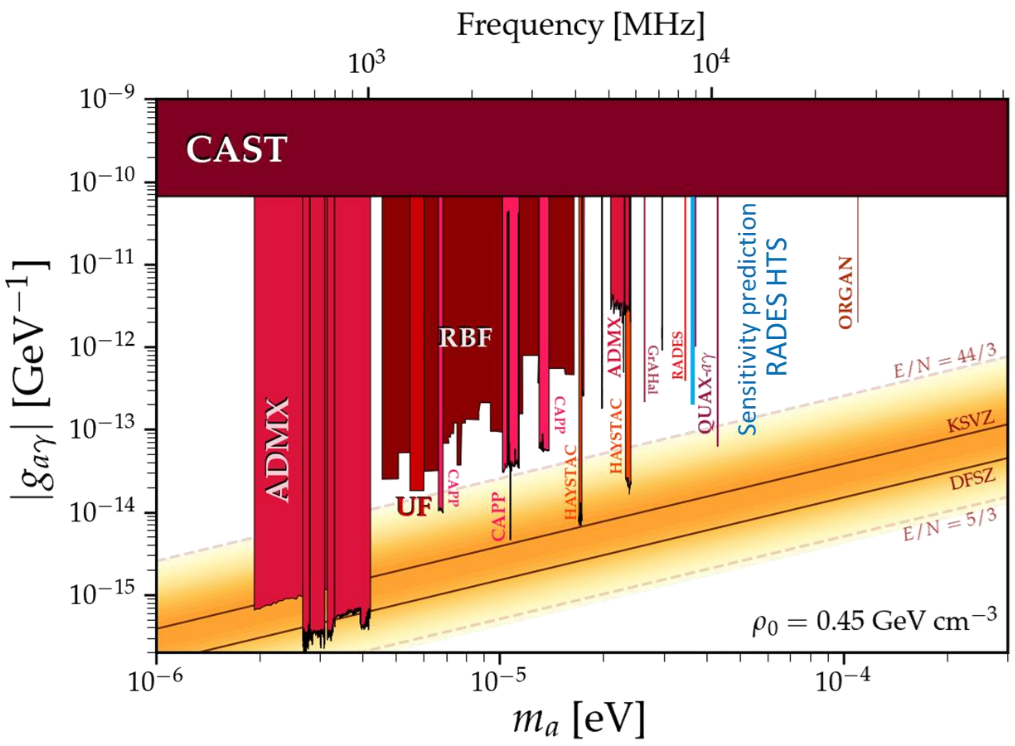
- **RADES/HTS**
- **Axion Heterodyne Detection**
- **AION-100 @ CERN**

(RADES/HTS, Axion Heterodyne Detection, AION-100 @ CERN:) In development at CERN

Axion as dark matter candidate

Electron mass = 511 keV
Proton mass = 938 MeV
Axion mass = … ?? …

- **Many candidates, many theories.**
  - Interaction mainly by gravity
  - Very weak interactions with all other types of particles (baryons, electrons, photons…)
- **Axion is the best dark matter candidate**
- **Axion are also the solution to the strong CP problem**



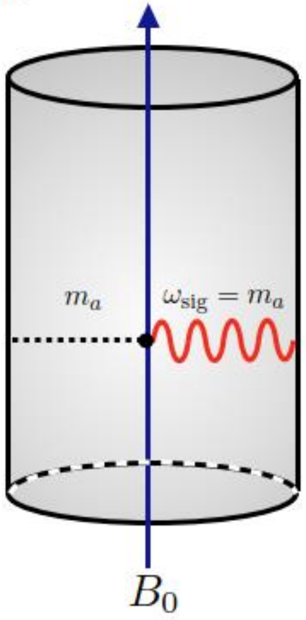
Modified from C. O'HARE. Axion limits.
https://github.com/cajohare/AxionLimits/

Two major types of experiments at CERN

Static-field Haloscope:

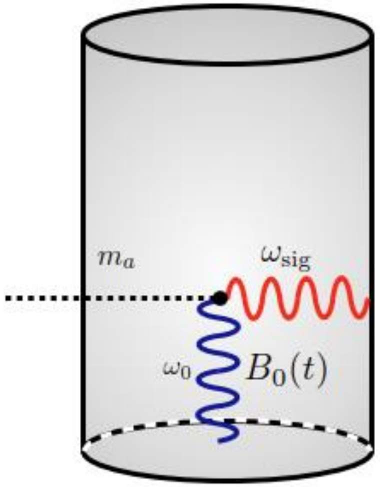
e.g. ADMX

$$\omega_{\text{sig}} = m_a \sim V^{-1/3}$$



Heterodyne Resonator:

$$\omega_{\text{sig}} \sim \omega_0 \pm m_a \sim V^{-1/3}$$



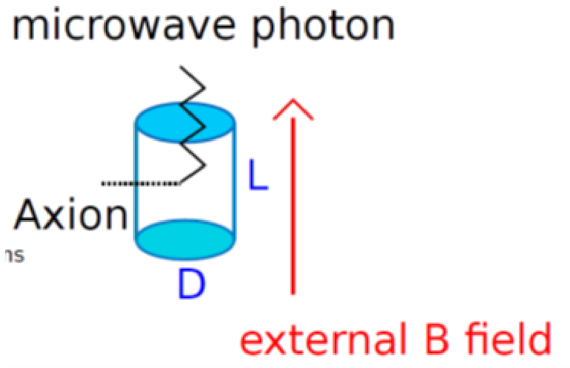
JHEP 07 (2020) 088, hep-ph/1912.11048
A. Berlin, R. T. D'Agnolo, SARE, P. Schuster, N. Toro, C. Nantista, J. Neilson, S. Tantawi, K. Zhou

Cavity immersed in a magnetic field

Cavity excited in one resonant mode

Source: S. Ellis

The RADES experiment
RADES: Relic Axion Detector Exploratory Setup



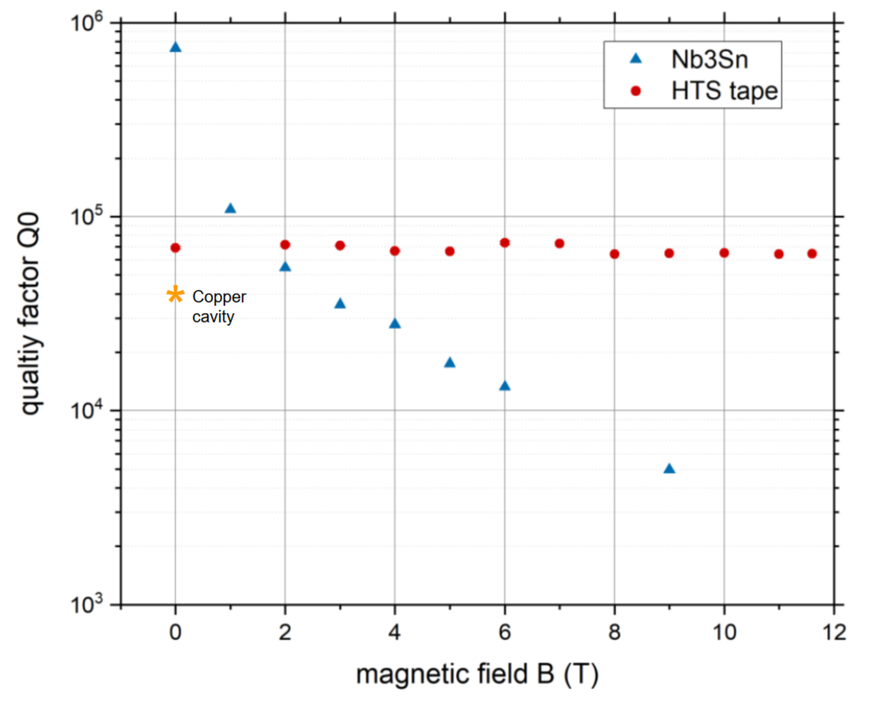
Nb_3Sn ≈ 2 µm layer

Coated at CERN by G. Rosaz and C. Pereira Carlos

HTS tape

Tape attached at ICMAB by G. Telles, N. Lamas, X. Granados, T. Puig, J. Gutierrez

Tested in SM18 in 11.5 T dipole



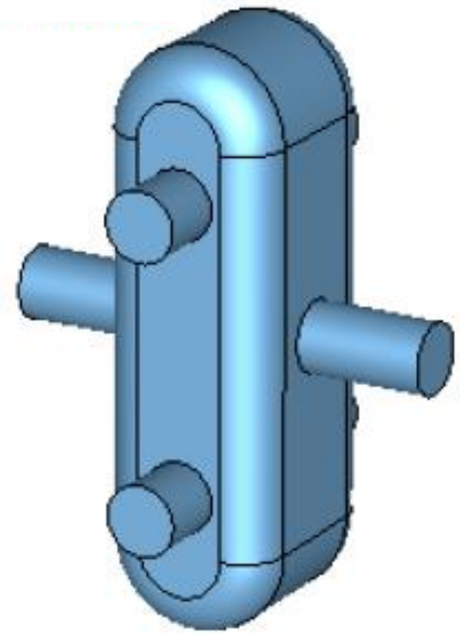
Source: J. Golm

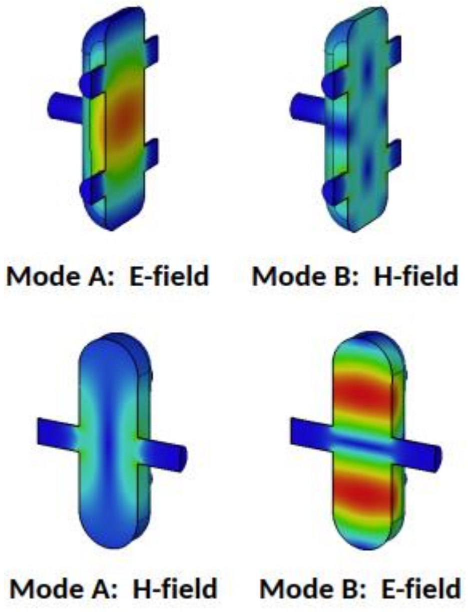
Cavity designs: pushing SRF technology to its limit
Nb/Cu coating? Nb bulk? EP?

UHV

Strong ties with the CERN Quantum Initiative

- **Will have to be cooled at millikelvin temperatures**
- **Make use of quantum sensing devices for signal detection**
- **Critical surface treatments for high performance in novel geometry**

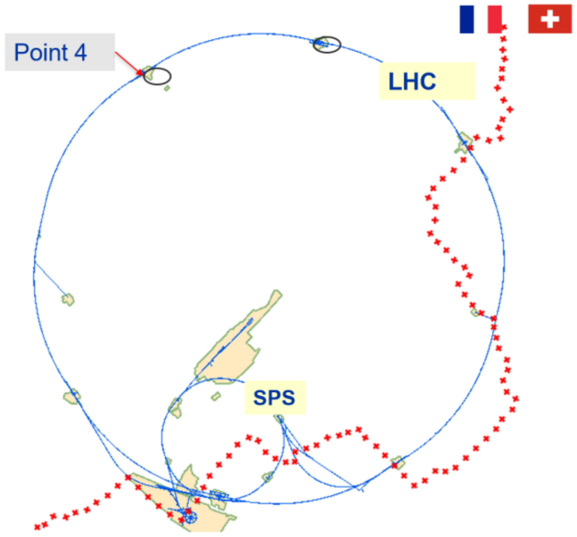


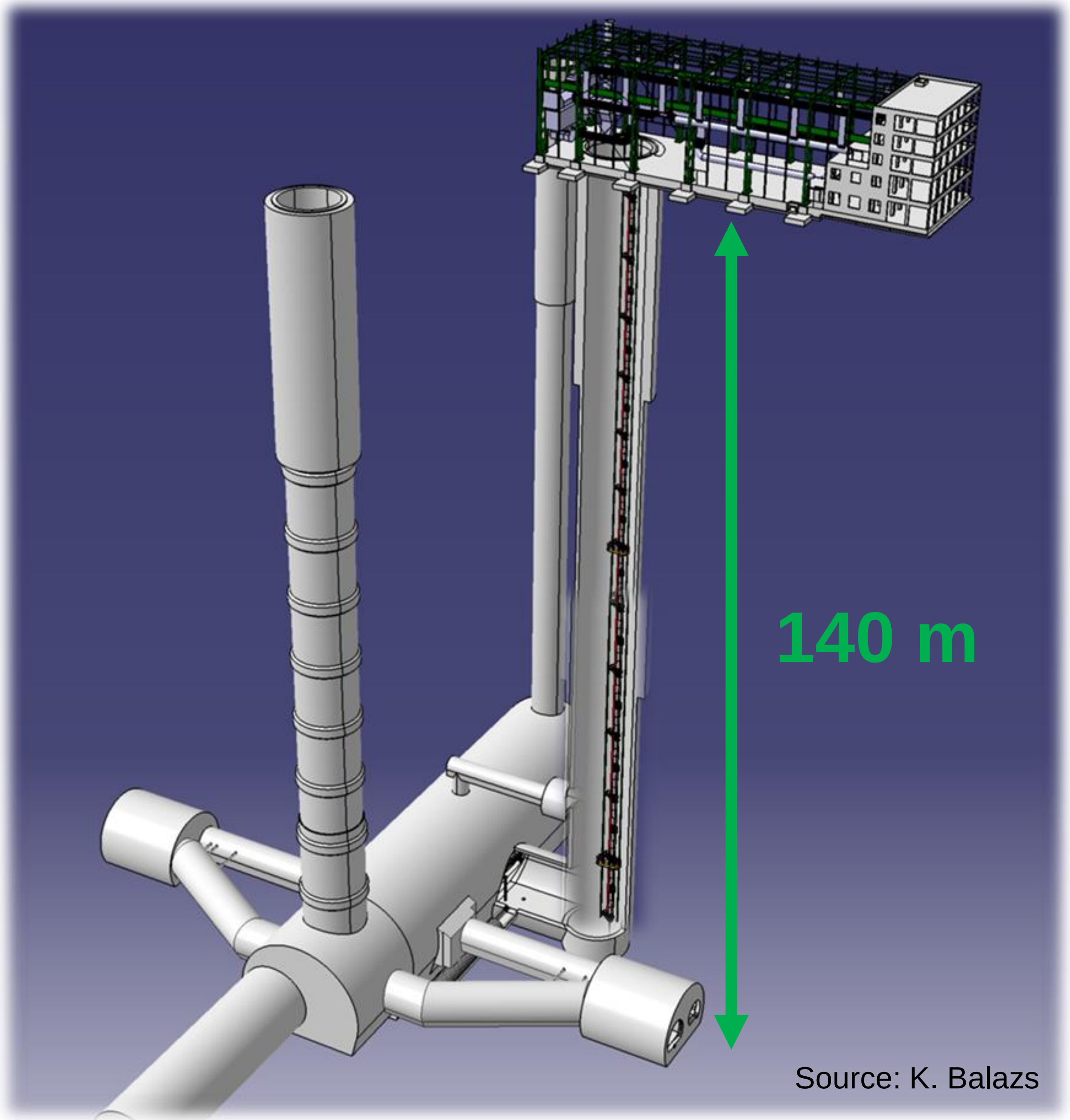


Source: A. Macpherson

Long-baseline atom interferometry in PX 46

- **AION-100 @ CERN proposal**
  - Dark matter detection
  - Gravitational waves detection
  - A 140 m tall UHV system in LHC point 4

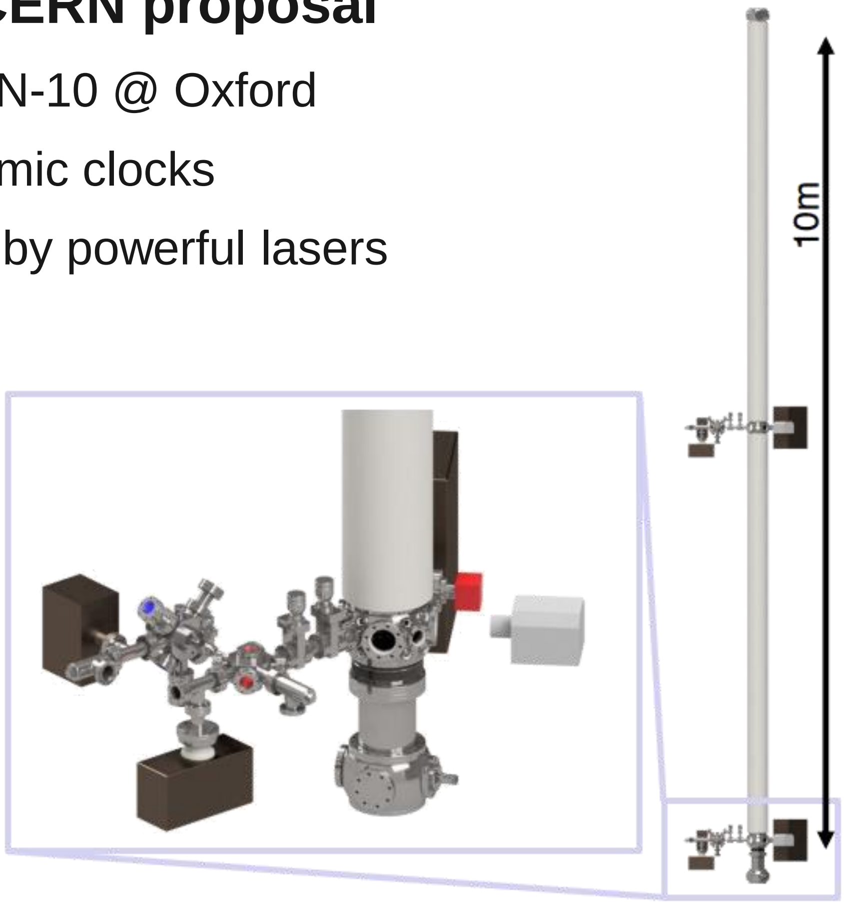


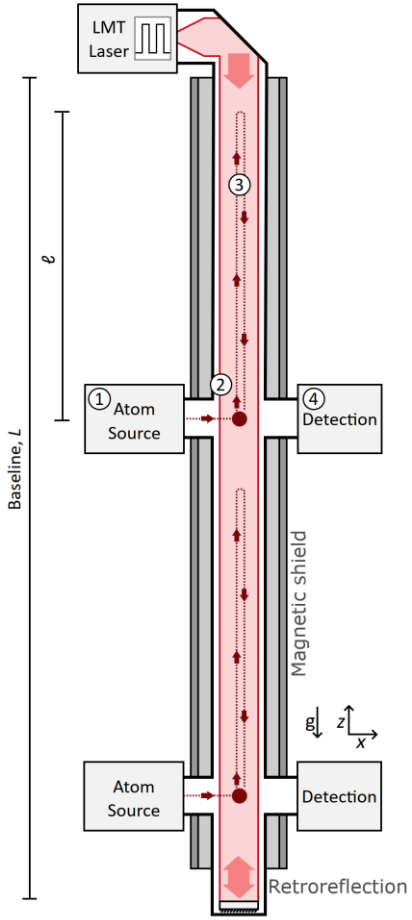


Long-baseline atom interferometry in PX 46

UHV

- **AION-100 @ CERN proposal**
  - Based on AION-10 @ Oxford
  - Interfering atomic clocks
  - Synchronized by powerful lasers
  - In UHV





Source: J. Ellis

Conclusions and opportunities

- **The Physics Beyond Collider activity aims at using the huge potential of CERN infrastructure, technologies, and peoples' competencies, to promote novel experiments at the frontier of particle physics**
- **These experiments have often a great trade off in terms of cost versus physics potential**
- **All the spectrum of accelerator technologies are involved in the PBC activities:**
  - UHV, material and surface engineering, cryogenics, mechanical engineering, civil engineering, controls, low-power and high-power electronics (DC and RF), data acquisition, …
- **PBC helps moving from the idea and feasibility stage to being CERN recognized projects or experiments. Many succeeded already, several are in the pipeline. Stay tuned!**

home.cern