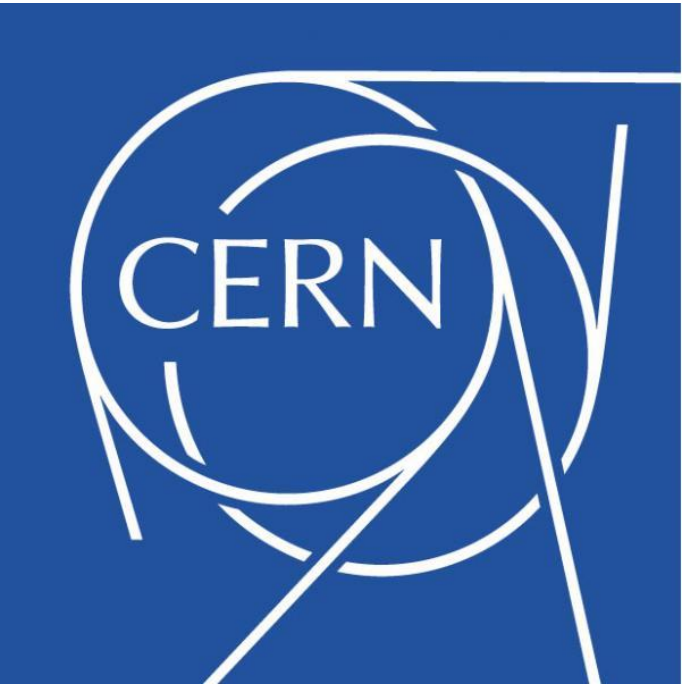
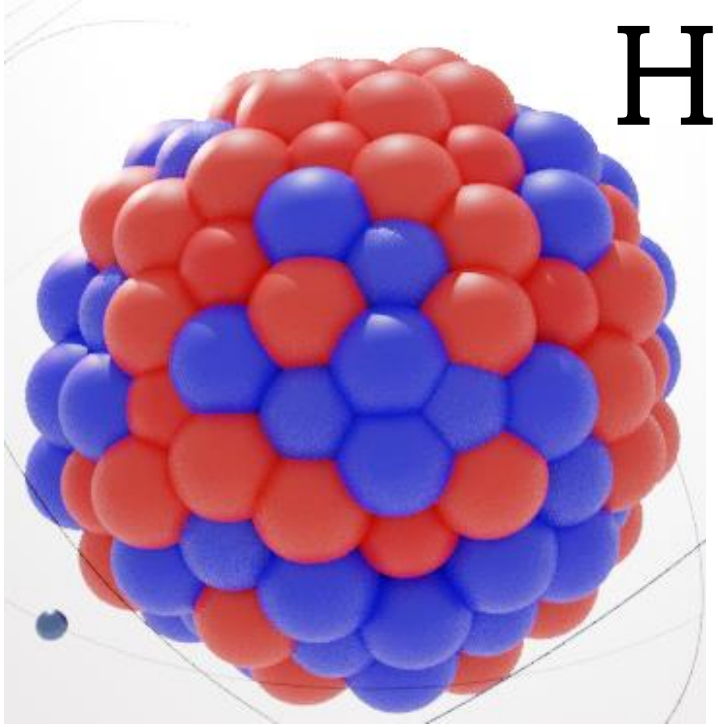
Experiments with cold antimatter at CERN



Dr. Fredrik Parnefjord Gustafsson

How did I end up here?



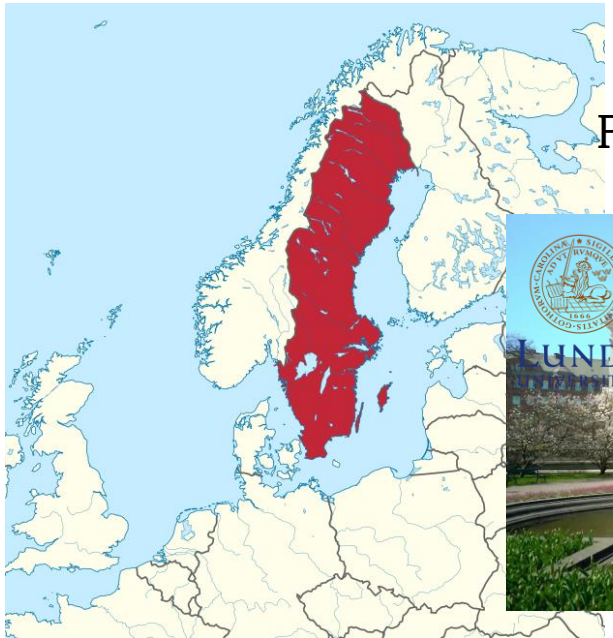
PhD in Nuclear physics,
KU Leuven Belgium (2017-2021)

PostDoc at Stefan Meyer institute in Austria (2021-2022)

Senior fellow at CERN (2023- ..)

AEgIS

CERN



Physics at Lund university,
Sweden (2011-2017)

What is antimatter?

The Dirac equation (1928):

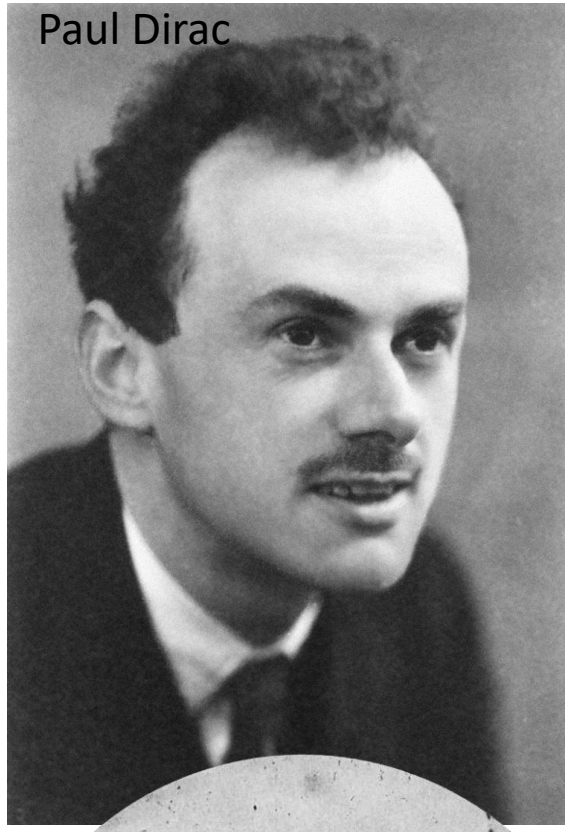
$$(i\gamma^{\mu}\partial_{\mu} - m)\psi = 0$$

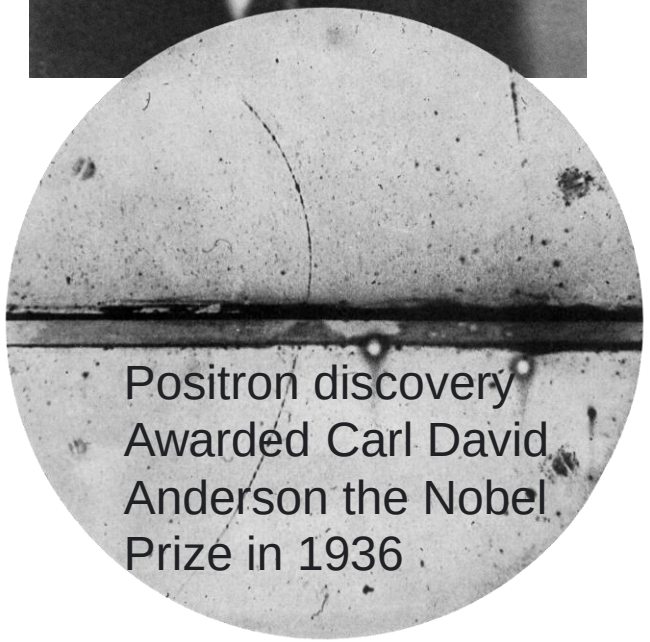
$$X^2 = K$$

Two equally valid solutions:

Positive energy states consitent with matter.

Negative energy states consitent with anti-matter?

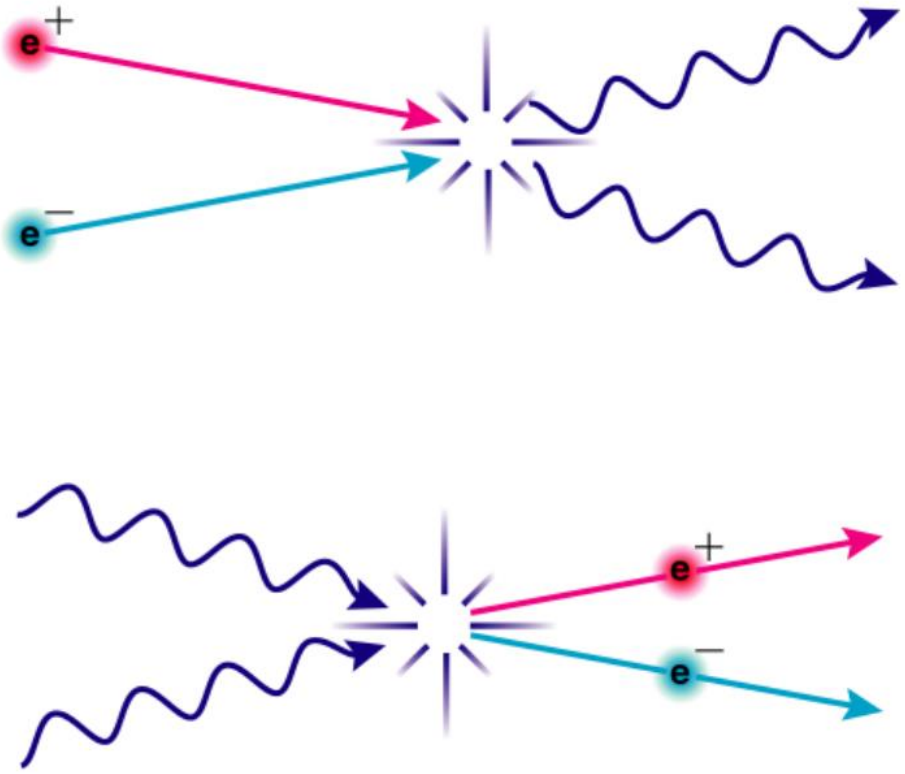


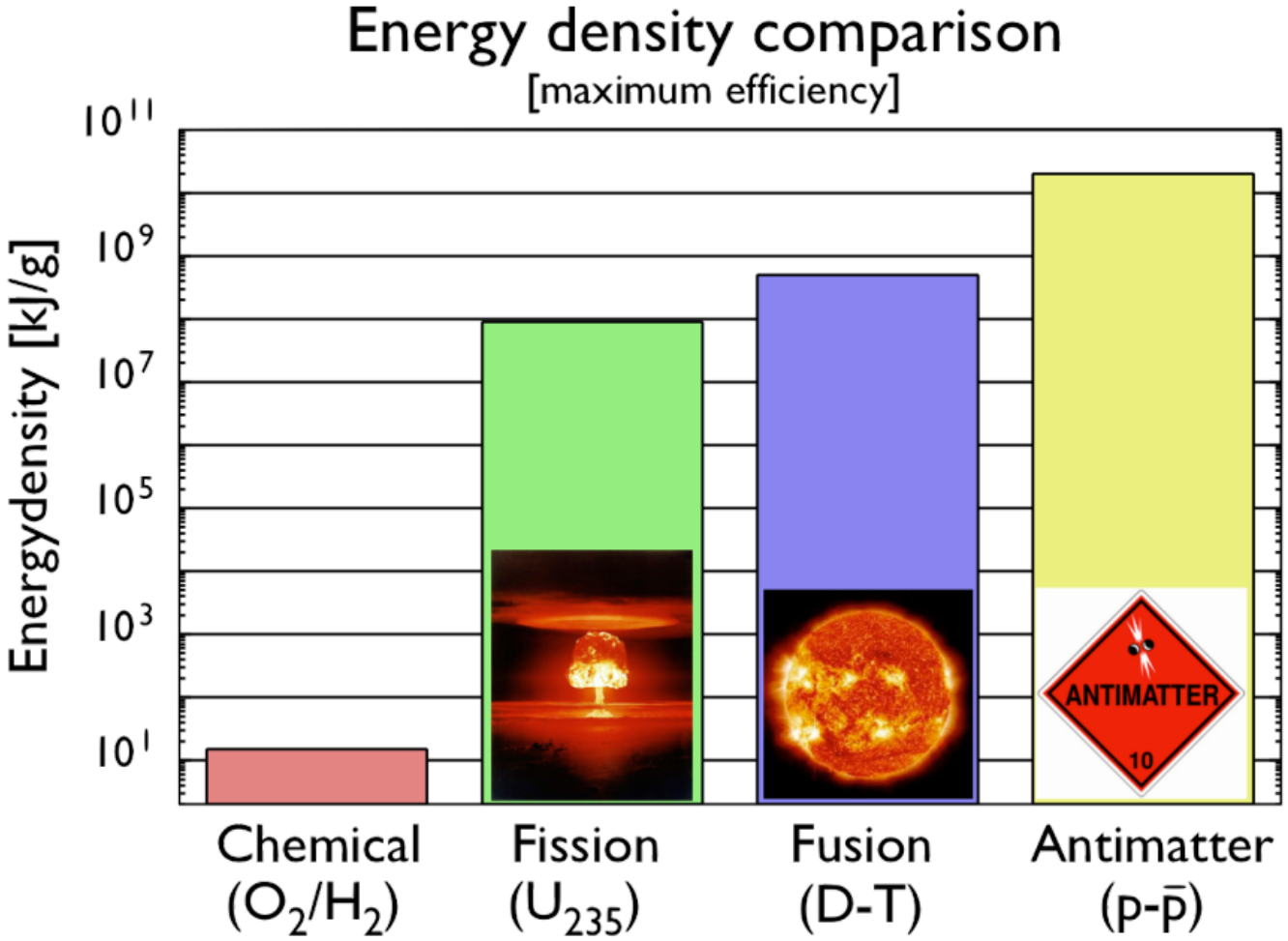


- **Antimatter perfectly cancel matter in energy with an equal mass but opposite charge.**
- **Anti-electron (positron) discovery in 1932 proved the existence of antimatter.**

Antimatter creation and annihilation

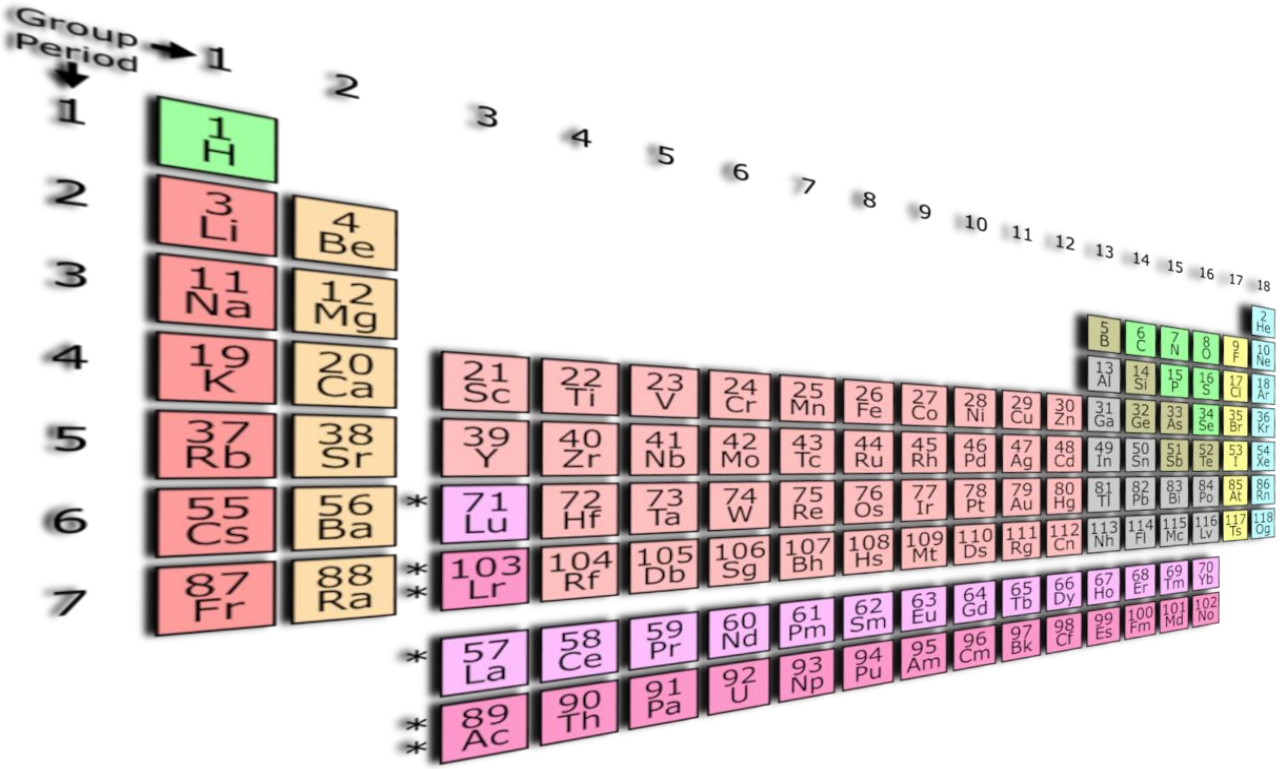
$$E = mc^2$$



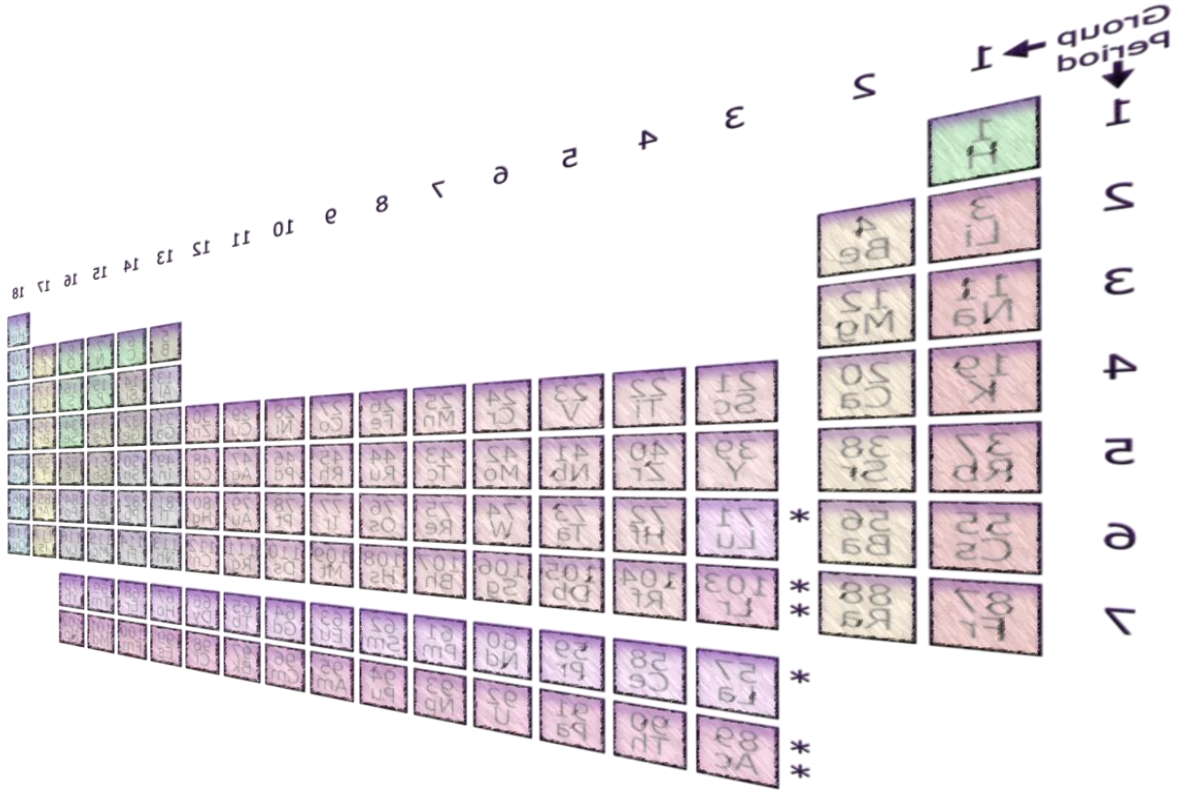


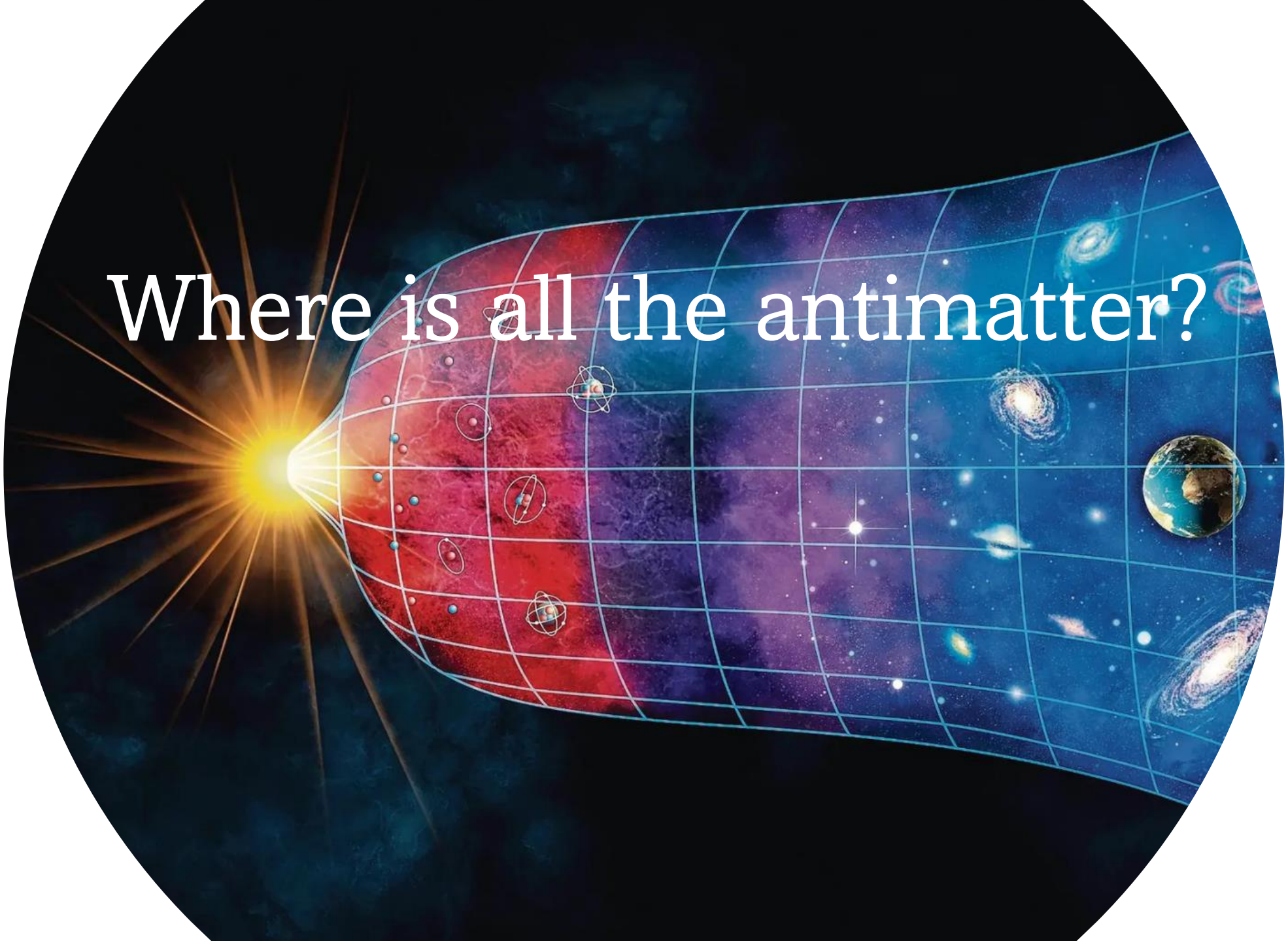
For every matter particle there is an equivalent anti-matter particle…

Elements in our universe



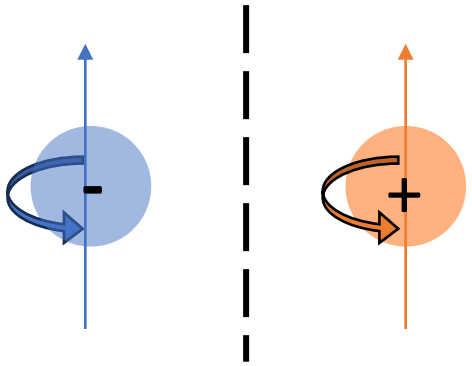
Anti- elements in our universe?




Where is all the antimatter?

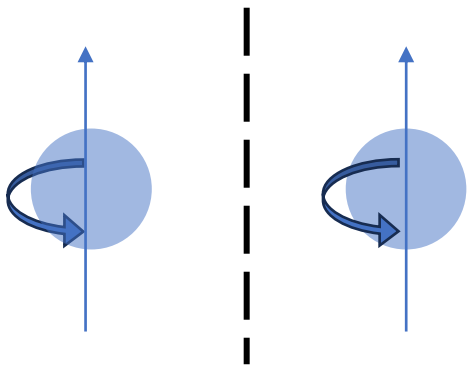
Broken fundamental symmetry?

Charge conjugation



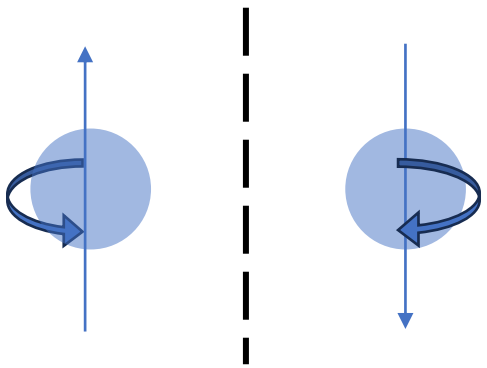
Charge changes sign

Parity inversion



Spatial coordinate change (mirroring)

Time reversal



Spin changes sign

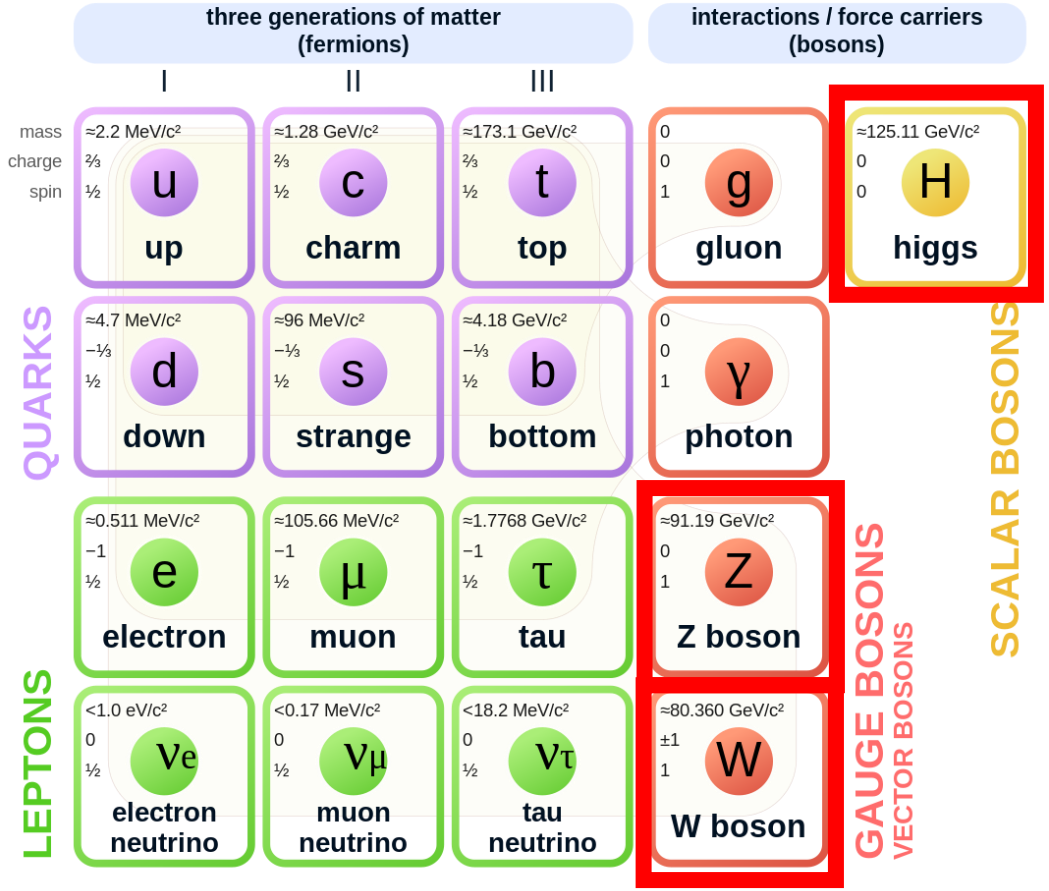
- **C**, **P**, and **CP** are each broken in the standard model (Beta decay, Kaon decay etc..) ..not sufficient to explain antimatter/matter asymmetry…
- No process has been observed to break fundamental **CPT** symmetry yet..

$$\boldsymbol{Example}\text{: } \boldsymbol{CPT} \rightarrow (-\boldsymbol{CP})(-\boldsymbol{T}) \rightarrow \boldsymbol{CPT}\ \textbf{(Invariant)}$$

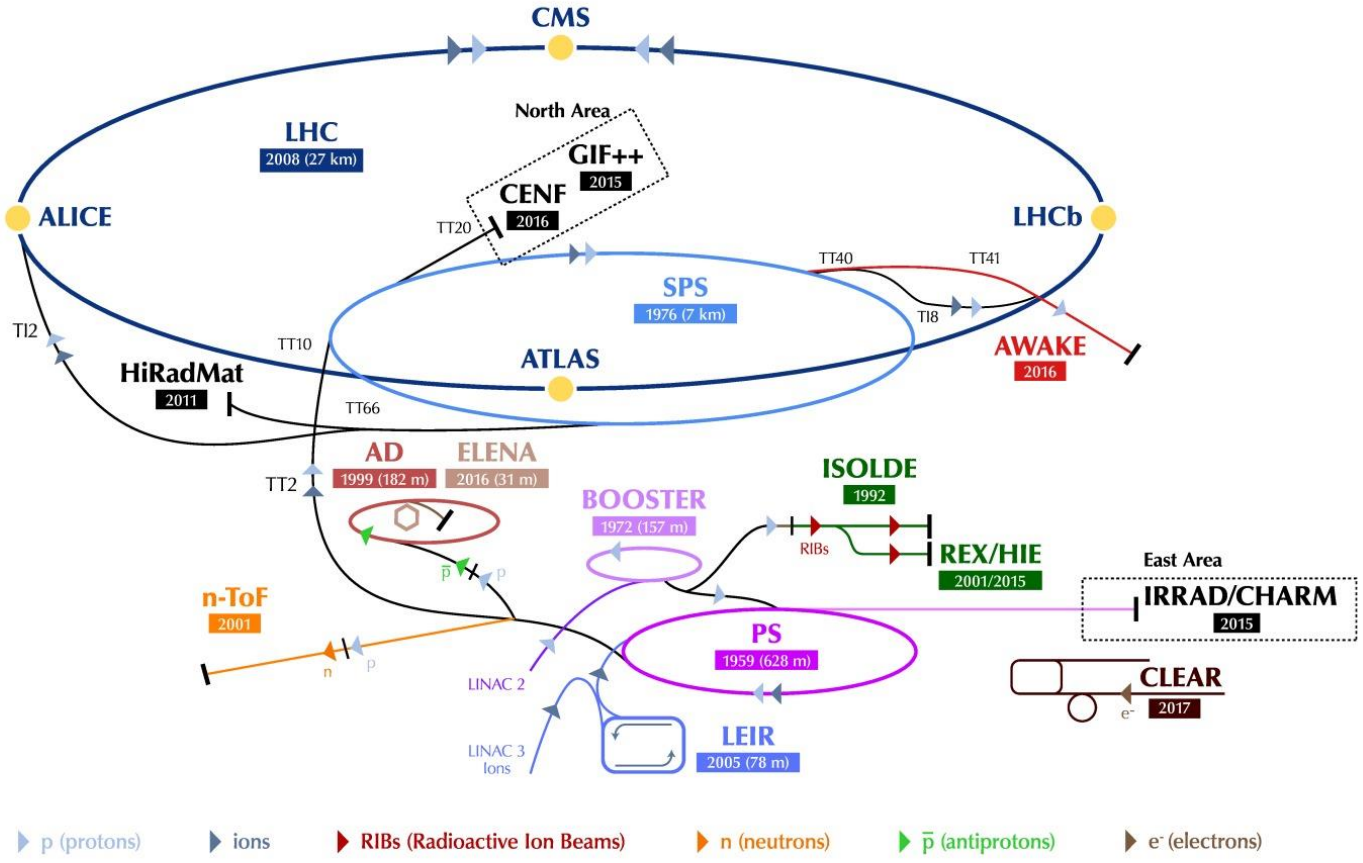
Where do we explore fundamental laws of nature?


CERN
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

Standard Model of Elementary Particles

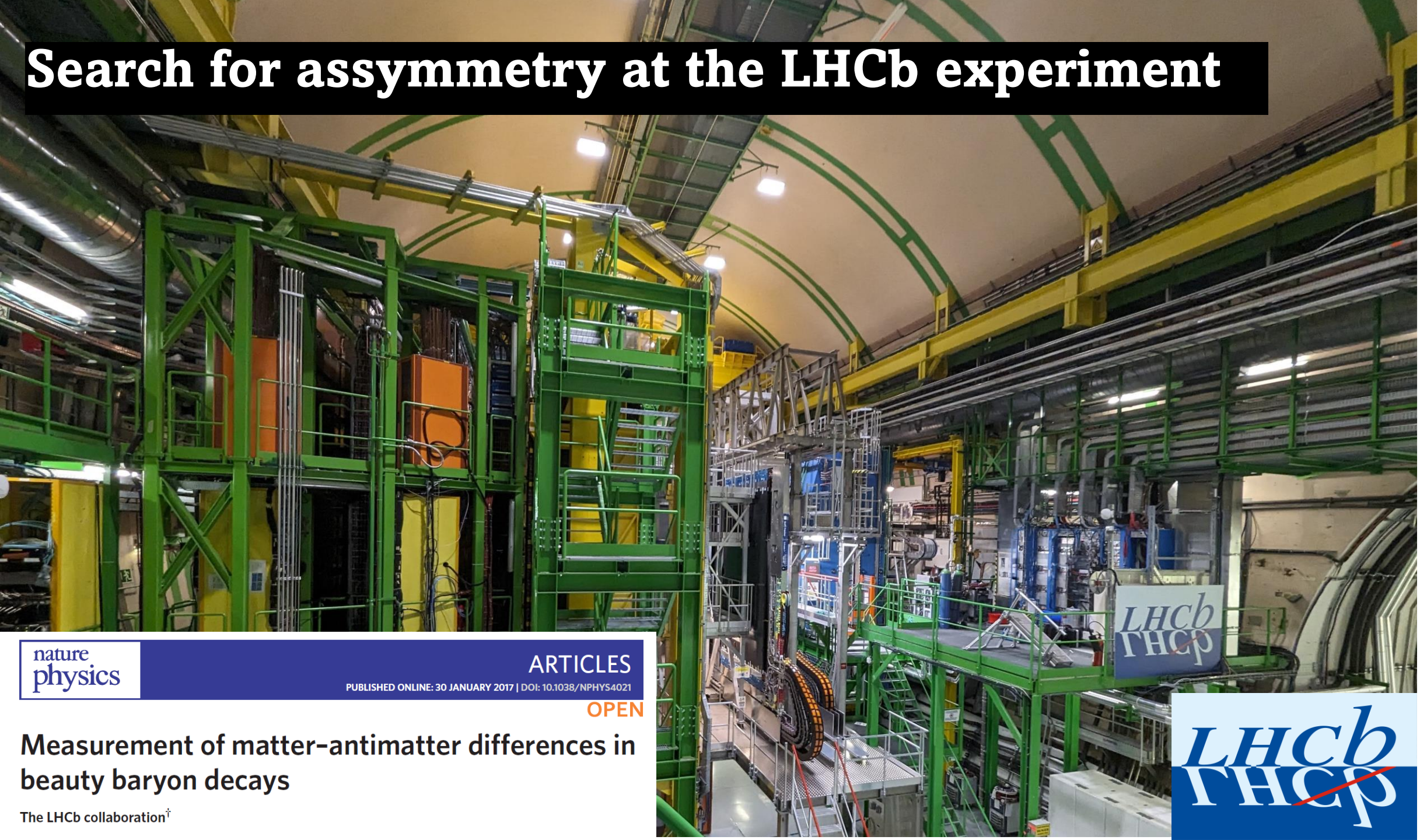


The CERN accelerator complex
Complexe des accélérateurs du CERN



LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n-ToF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // CHARM - Cern High energy AcceleRator Mixed field facility // IRRAD - proton IRRADiation facility // GIF++ - Gamma Irradiation Facility // CENF - CErn Neutrino platForm

Search for assymmetry at the LHCb experiment



nature physics

ARTICLES

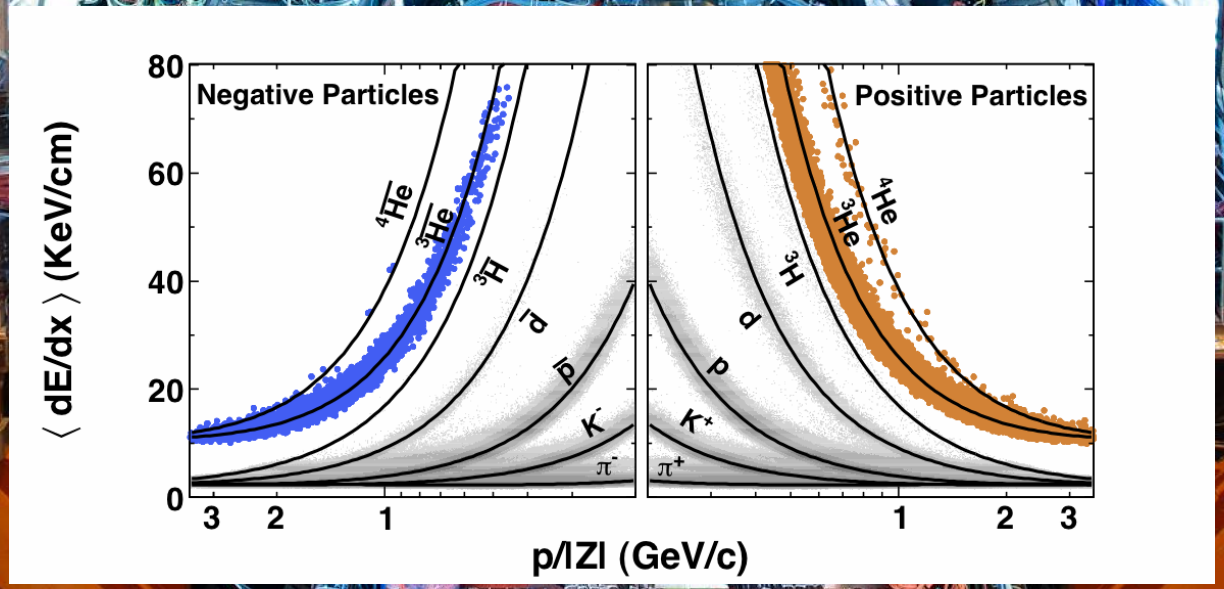
PUBLISHED ONLINE: 30 JANUARY 2017 | DOI: 10.1038/NPHYS4021

OPEN

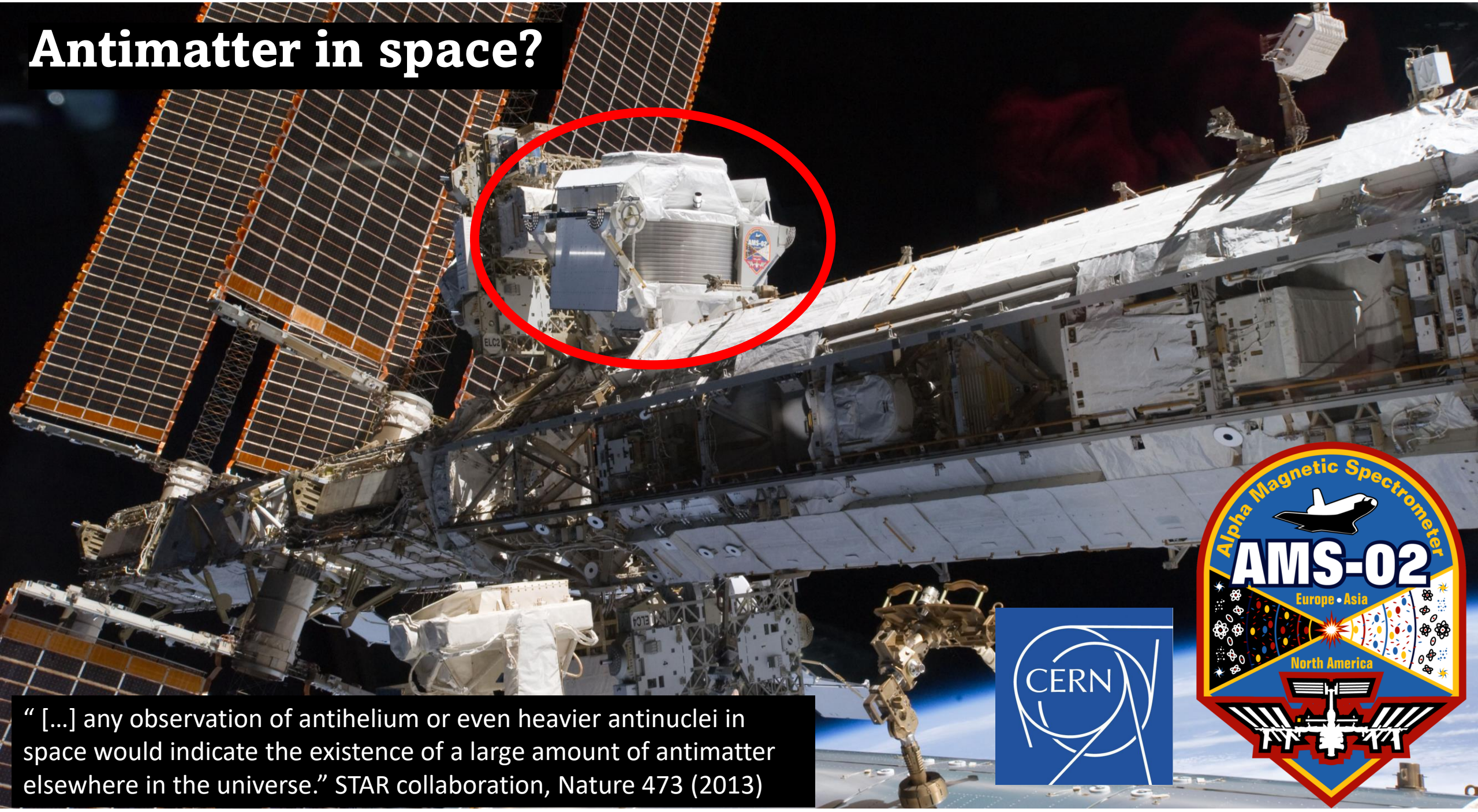
Measurement of matter–antimatter differences in beauty baryon decays

The LHCb collaboration†

Antinuclei production at the ALICE experiment



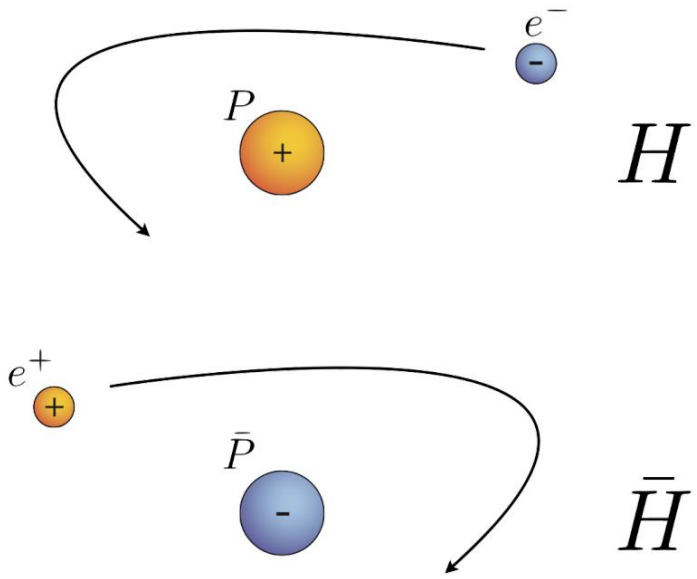
Antimatter in space?

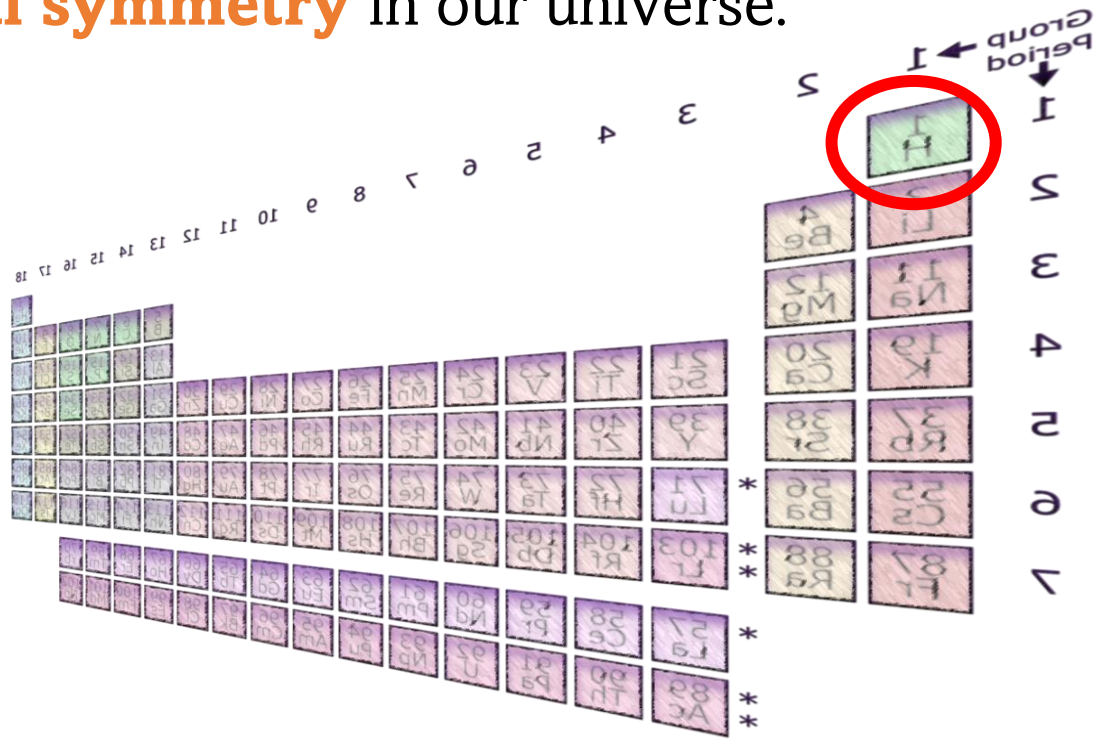


" […] any observation of antihelium or even heavier antinuclei in space would indicate the existence of a large amount of antimatter elsewhere in the universe." STAR collaboration, Nature 473 (2013)

Studying the difference between matter and antimatter

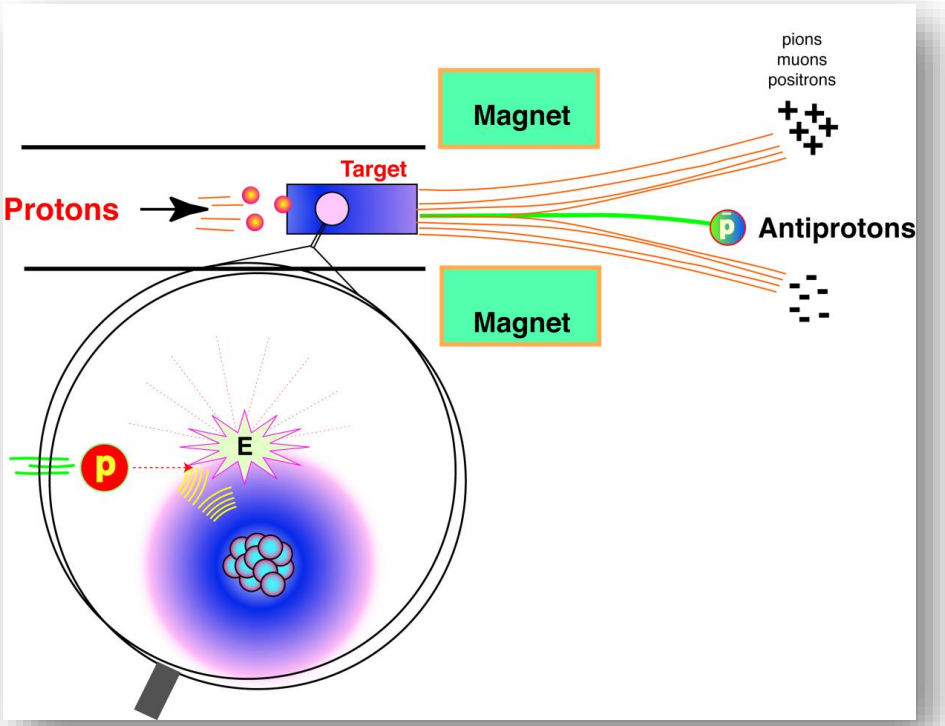
- The hydrogen atom is the **best understood physical system**.
- **A neutral system is** excellent for **testing gravity.**
- **Any observed difference** between the properties of H and $\bar{H}$ would suggest a **broken fundamental symmetry** in our universe.

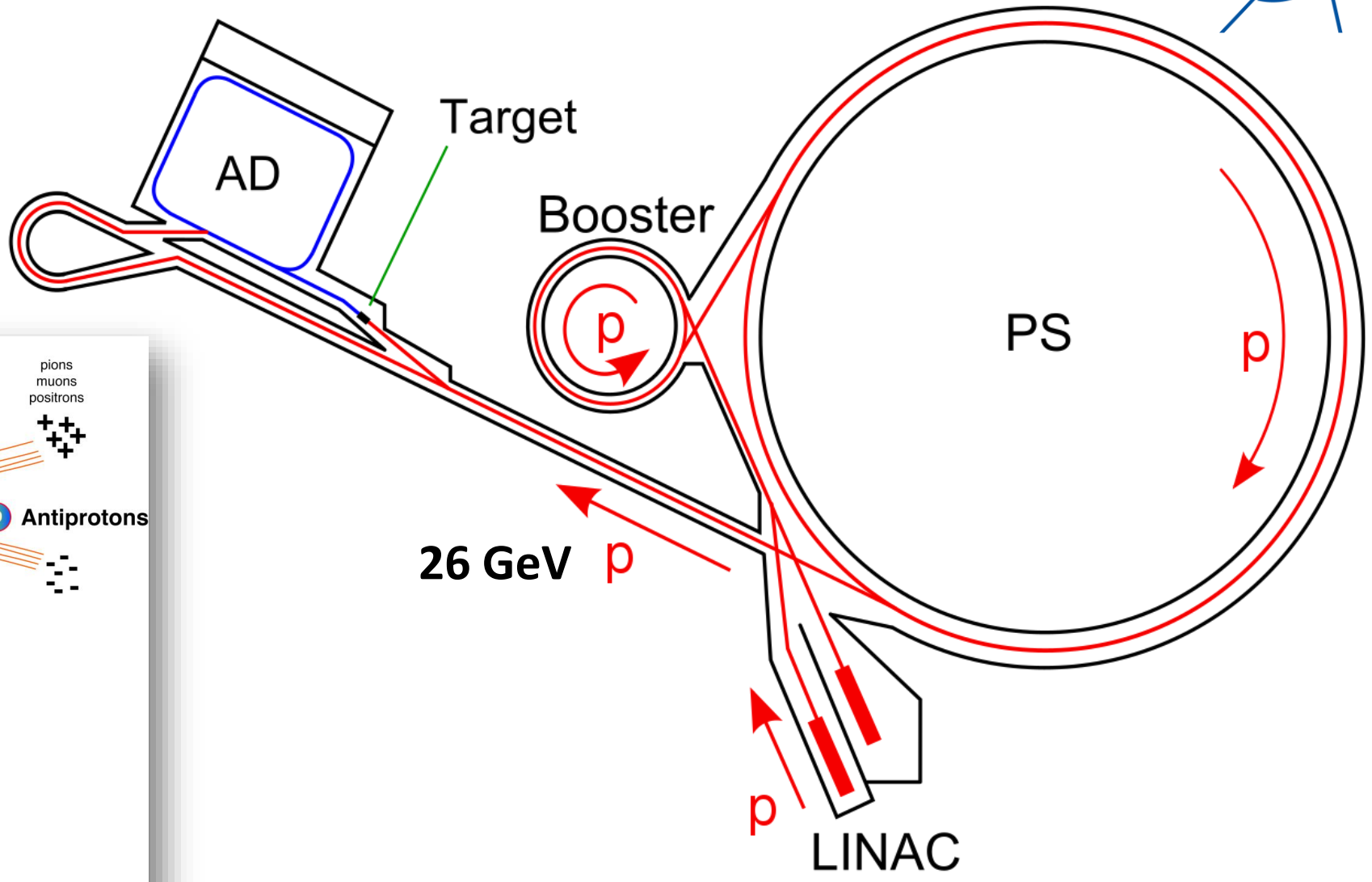




COLD antimatter needed!

The **A**ntiproton **D**ecelerator (**AD**) at CERN





The antimatter factory at CERN

Antiprotons from PS

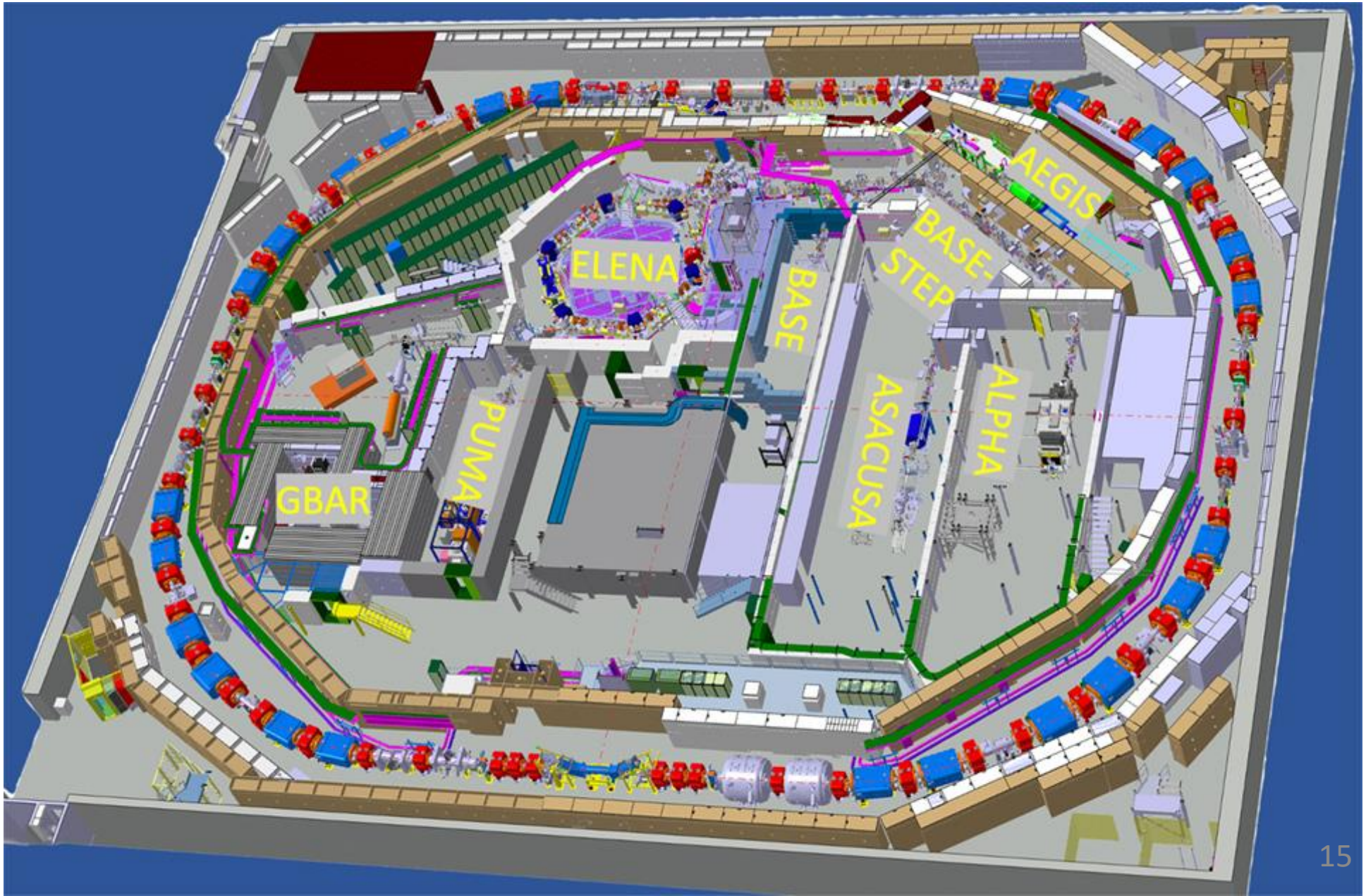
Energy: 3.5 GeV

AD
Antiproton Decelerator

Start: 2000
Length: 182 m
Energy: 5.3 MeV

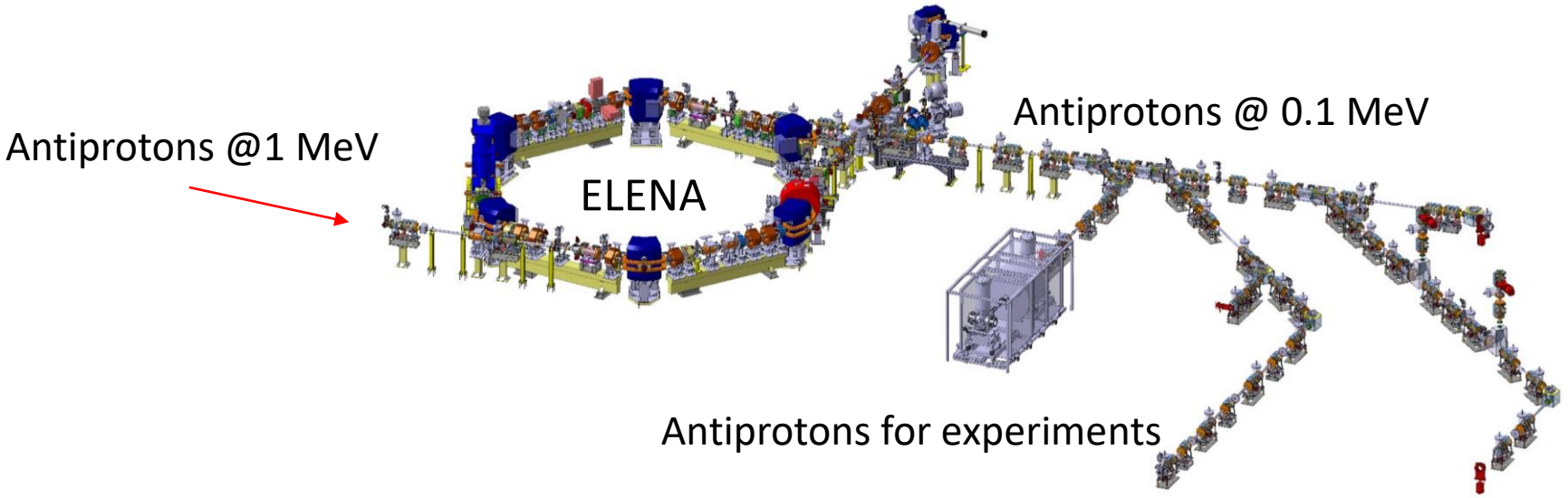
ELENA
Extra Low
ENergy Antiproton

Start: 2021
Length: 30 m
Energy: 0.1 MeV



Inside the antimatter factory at CERN

Six active experiments at AD



ALPHA

Trap
Antihydrogen trapping
Spectroscopy
Gravity

ASACUSA

Beam
Antiprotonic atoms
Collisions
Spectroscopy

AEGIS

Beam
Pulsed production
of antihydrogen
Test of gravity
Antimatter bound states

BASE

Trap
Mass spectroscopy
$\bar{p}$ magnetic moment

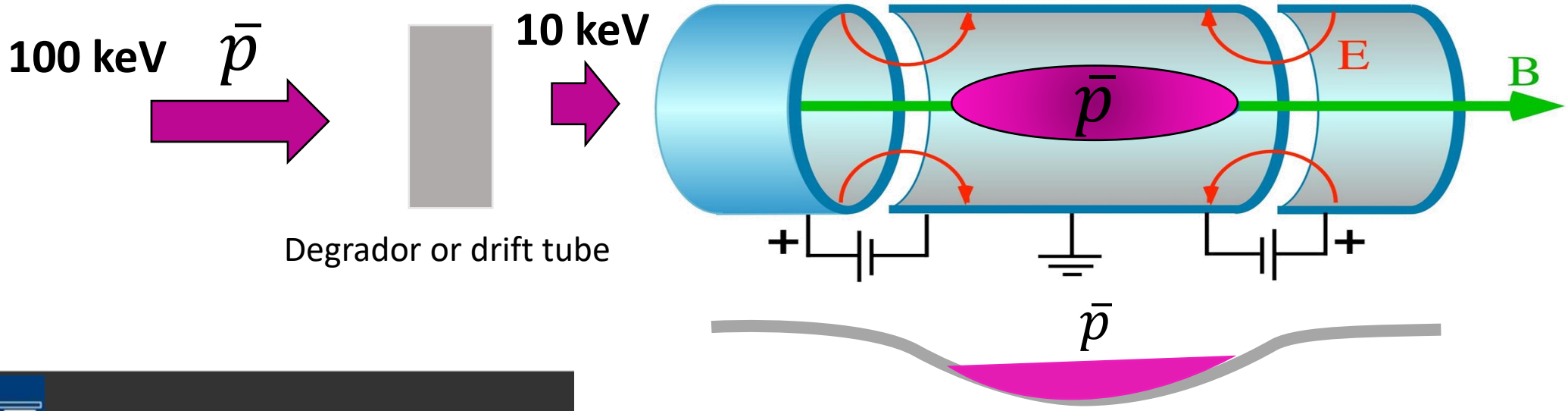
GBAR

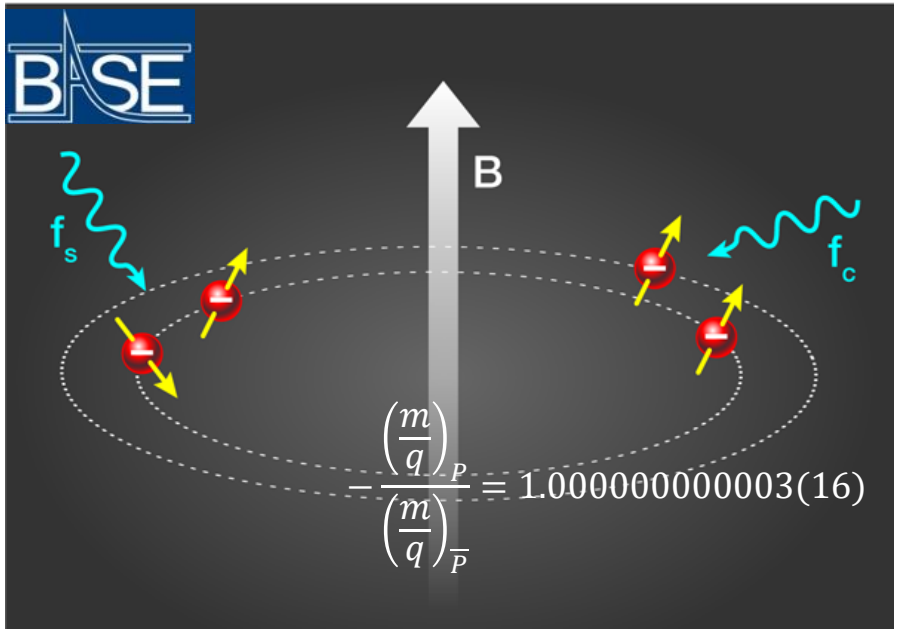
Trap
Antimatter gravity
Lamb-shift

PUMA

Movable trap
for antiprotons
Study of exotic nuclei

Trapping antiprotons





Article

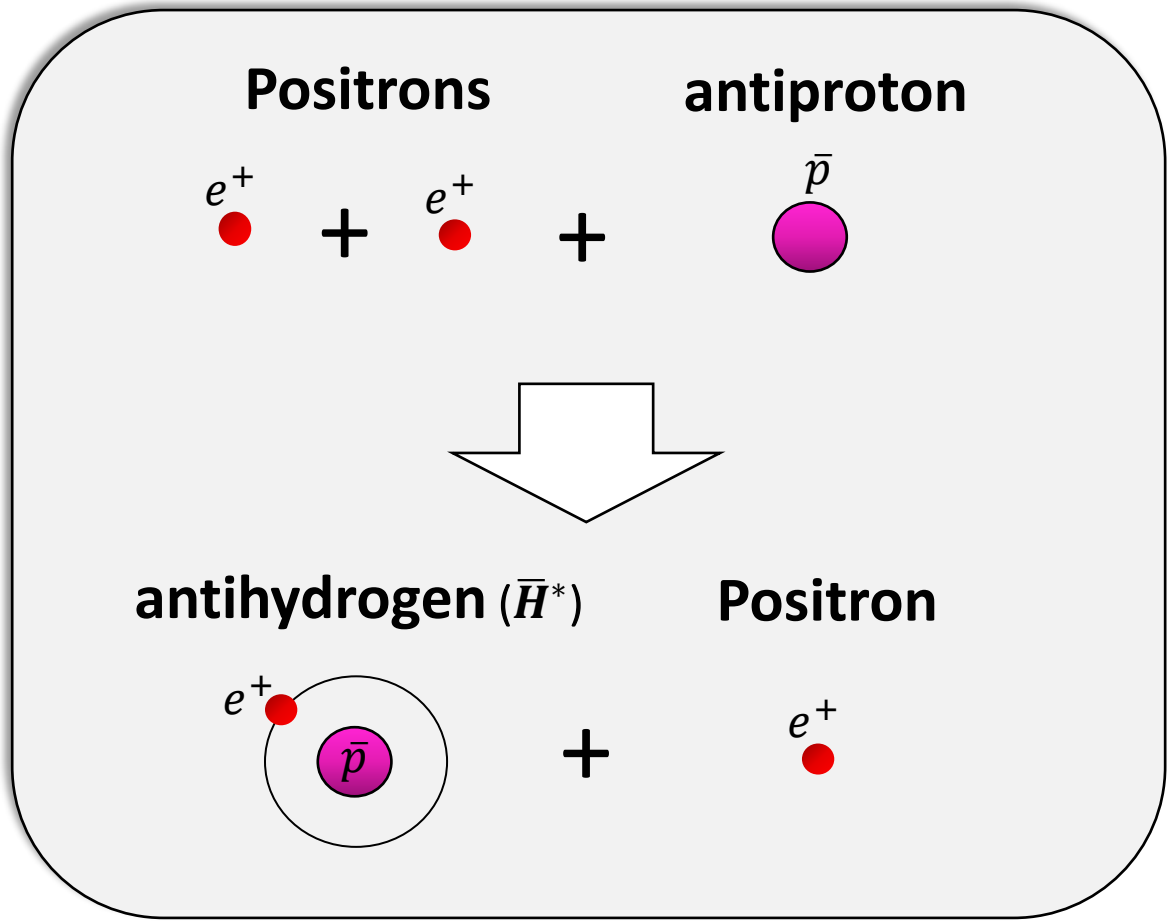
A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio

https://doi.org/10.1038/s41586-021-04203-w
Received: 25 May 2021
Accepted: 3 November 2021
Published online: 5 January 2022

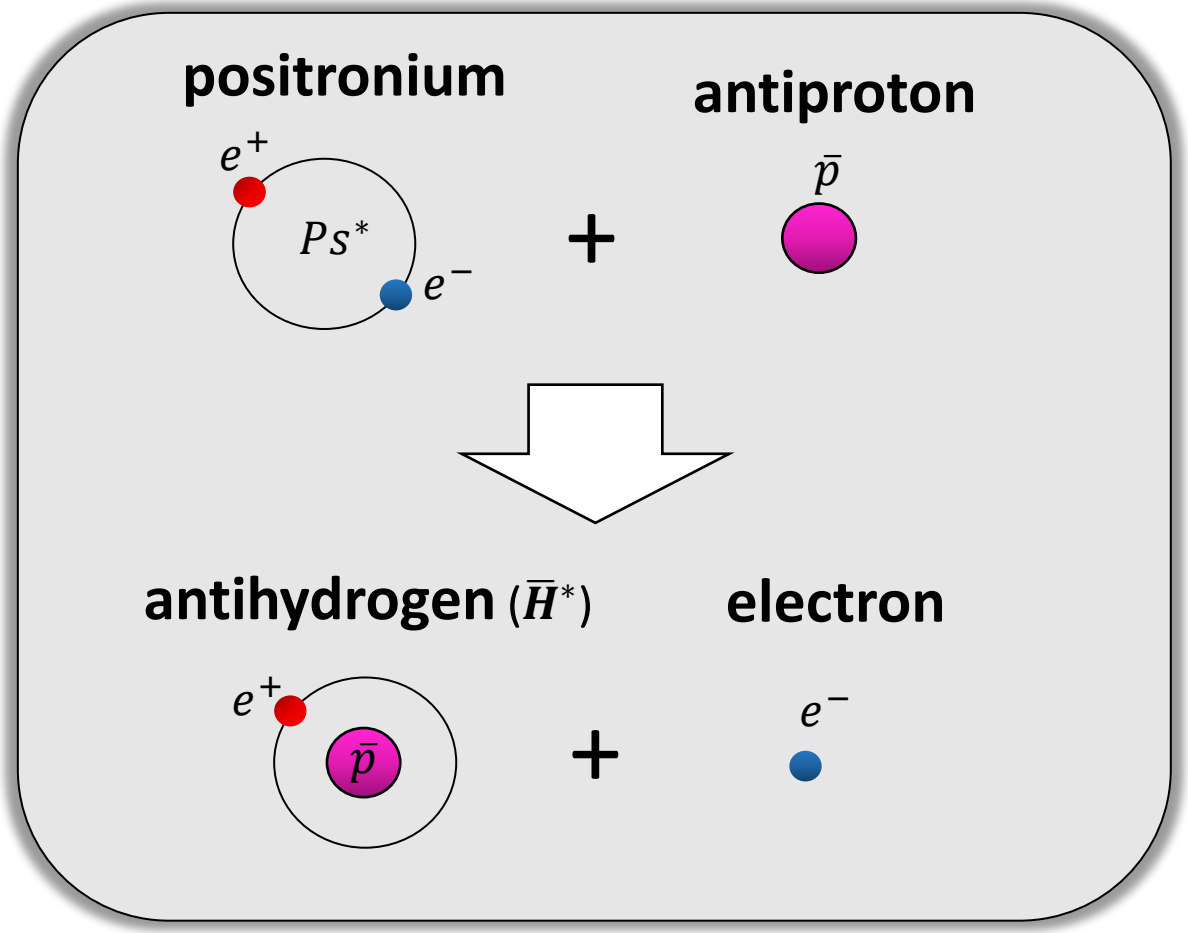
M. J. Borchert[1,2,3], J. A. Devlin[1,4], S. R. Erlewein[1,4,5], M. Fleck[1,6], J. A. Harrington[1,5], T. Higuchi[1,6], B. M. Latacz[1], F. Voelksen[1,7], E. J. Wursten[1,4,5], F. Abbass[8], M. A. Bohman[1,5], A. H. Mooser[5], D. Popper[8], M. Wiesinger[1,5], C. Will[5], K. Blaum[5], Y. Matsuda[6], C. Ospelkaus[2,3], W. Quint[7], J. Walz[8,9], Y. Yamazaki[1], C. Smorra[1,8] & S. Ulmer[1]✉

How do we make antihydrogen?

3-body recombination

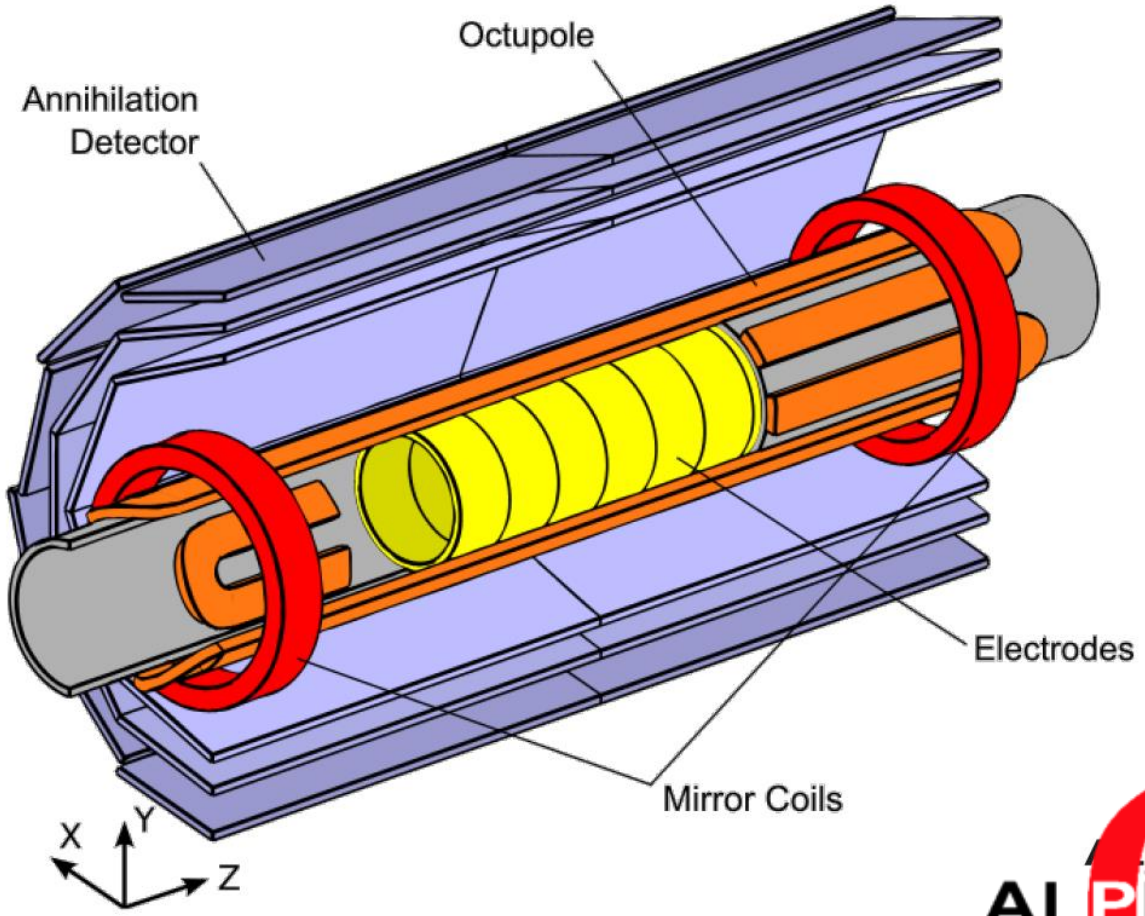


Charge-exchange with positronium



Trapping antihydrogen

Antihydrogen **L**aser **Ph**ysics **A**pparatus

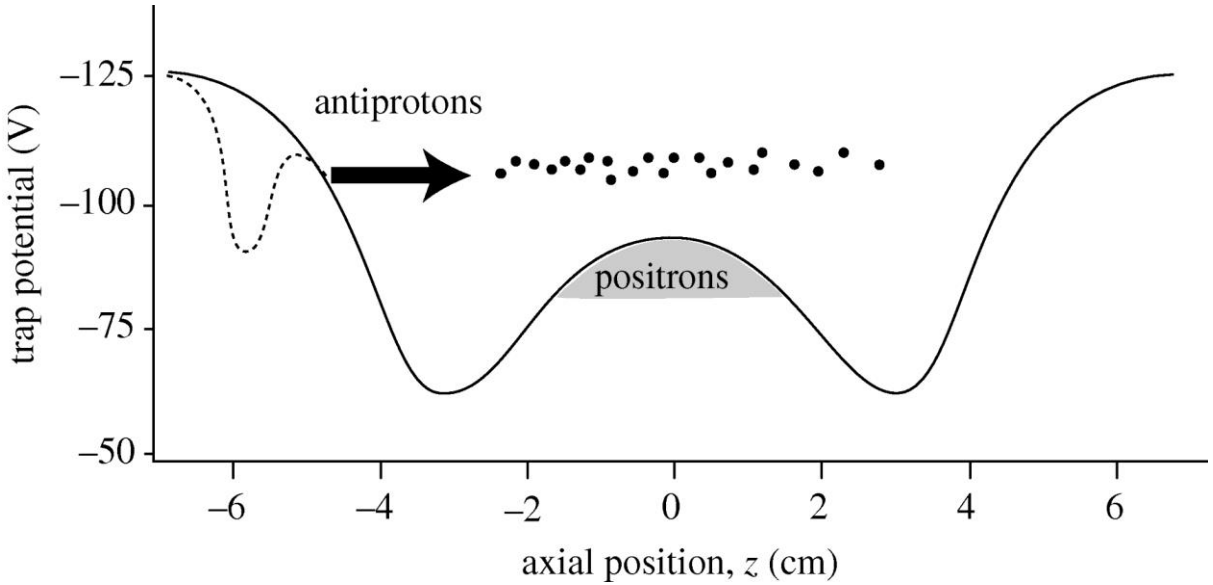


Letter | Published: 17 November 2010

Trapped antihydrogen

G. B. Andresen, M. D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P. D. Bowe, E. Butler, C. L. Cesar, S. Chapman, M. Charlton, A. Deller, S. Eriksson, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, A. J. Humphries, R. Hydomako, M. J. Jenkins, S. Jonsell, L. V. Jørgensen, ... Y. Yamazaki + Show authors

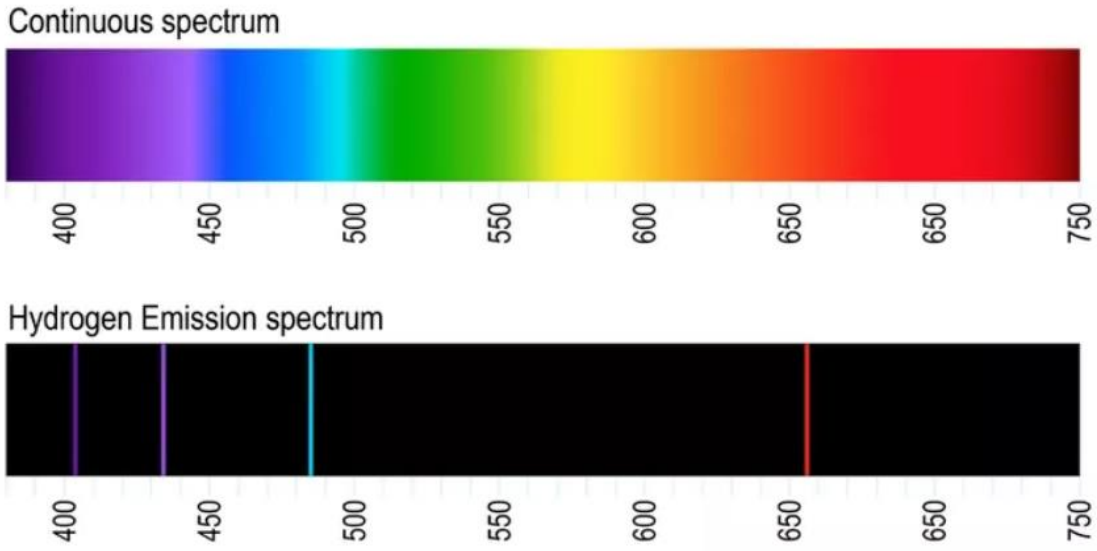
Nature **468**, 673–676 (2010) | Cite this article



ALPHA

Spectroscopy of (anti-)hydrogen

- **1S → 2S**
- **1S → 2P**
- **1S** Hyperfine splitting



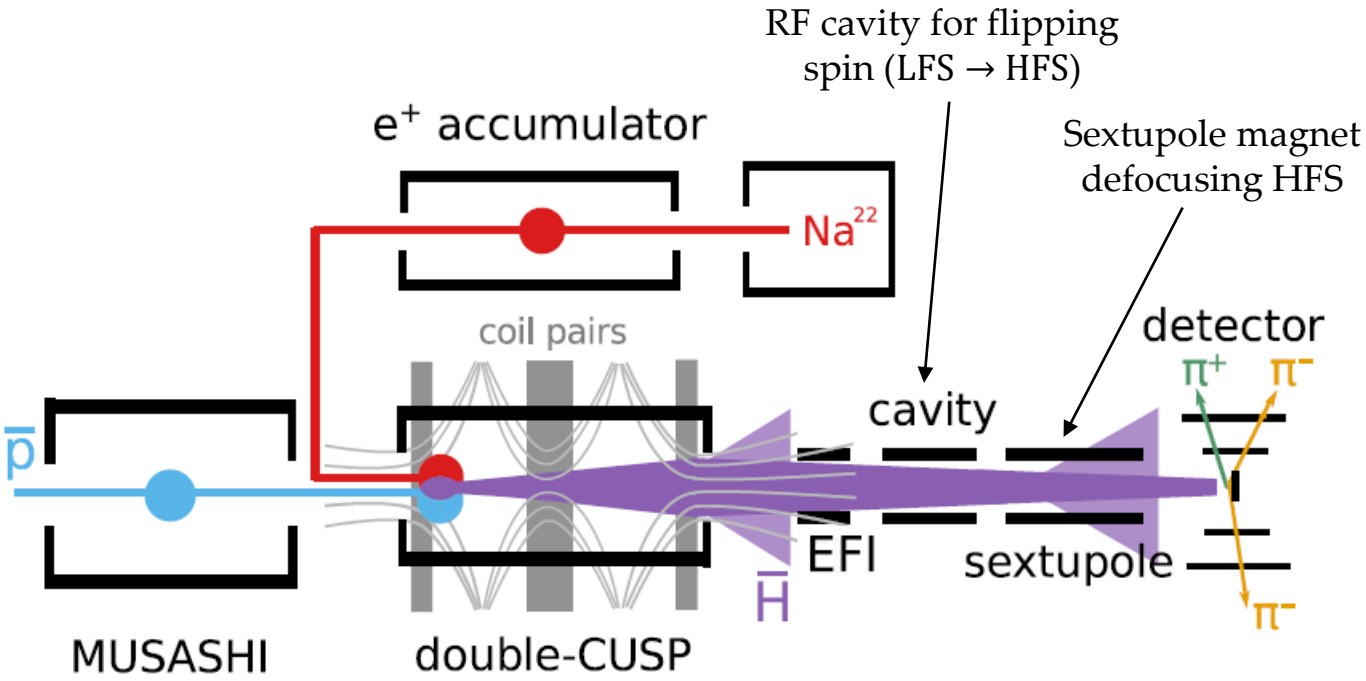
Ahmadi et al., *Nature 548, 66* (**2017**)
Ahmadi et al., *Nature* 557**,** 71 (**2018**)
Ahmadi et al., *Nature* 561**,** 211 (**2018**)
Ahmadi et al., *Nature 578, 375* (**2020**)

$\nu_{HFS}\ (H)$= 1,420.4057513768(1) MHz

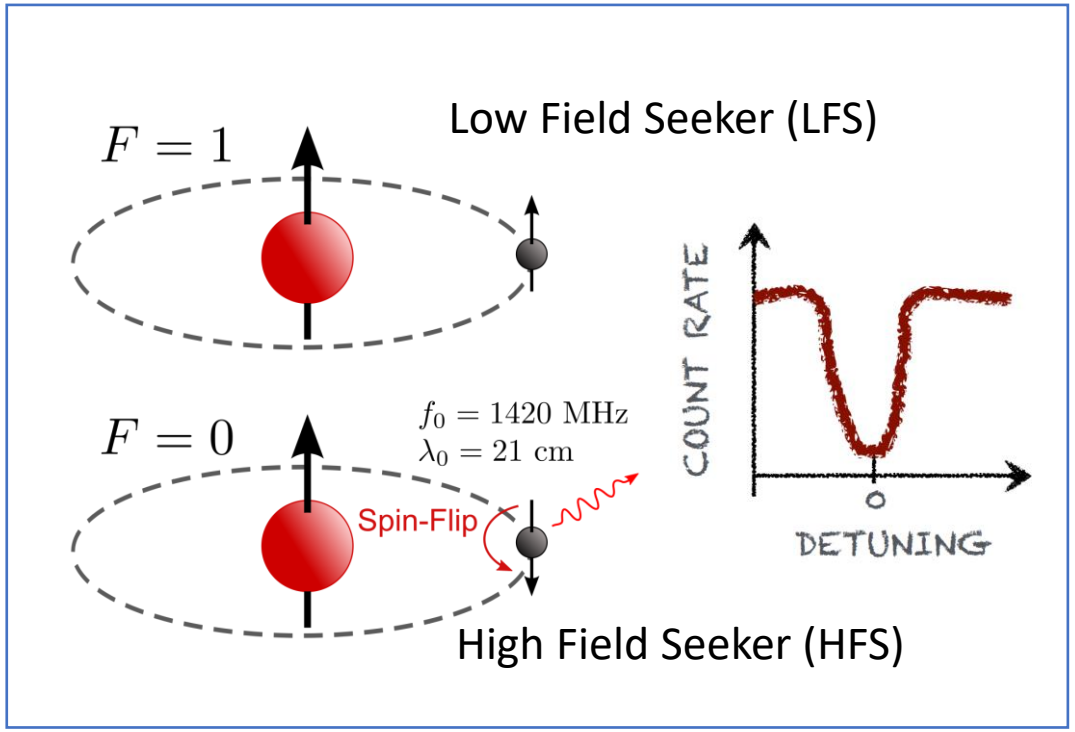
$\nu_{HFS}\ (\bar{H})$= 1,420.4 (5) MHz

Goal: Measuring the ground-state hyperfine splitting in a near field-free region below 1 p.p.m

In-beam GS-HFS spectroscopy at ASACUSA



Production and spin polarization of $\bar{H}$ (LFS)

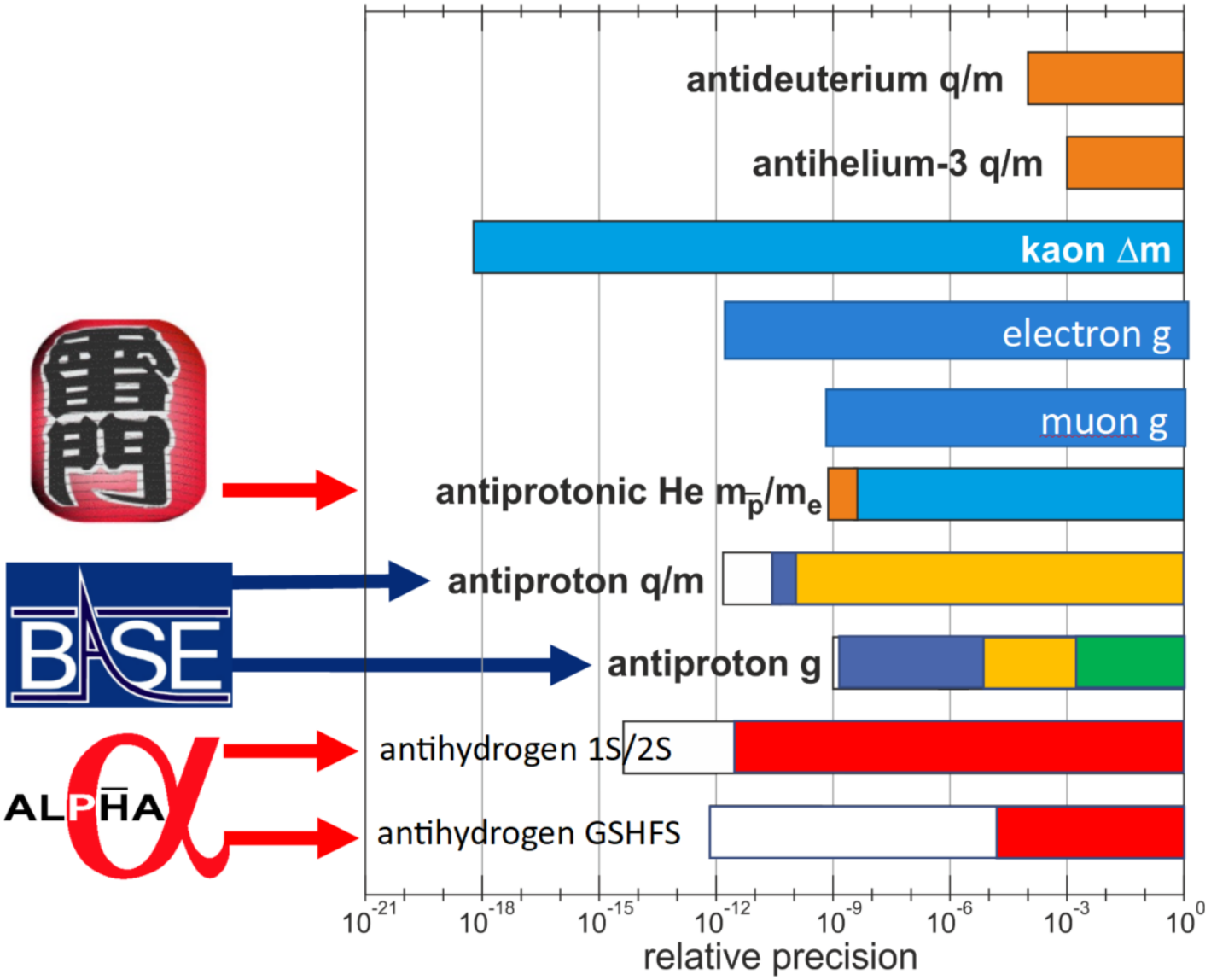


Measurement using proof-of principle setup reached p.p.b accuracy:

In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy

M. Diermaier, C. B. Jepsen, B. Kolbinger, C. Malbrunot, O. Massiczek, C. Sauerzopf, M. C. Simon, J. Zmeskal & E. Widmann

CPT with particle/antiparticle comparisons



CERN ALICE

CERN AD

Anomolous antimatter gravity?

Segregation of matter and antimatter?

Is the Weak Equivalence Principle valid?

Measurement of the gravitational influence on antimatter

$$\bar{g} = 0.75 \pm 0.13\ (stat + sys) \pm 0.16\ (sim)g$$

AEGIS

Article | Open access | Published: 27 September 2023

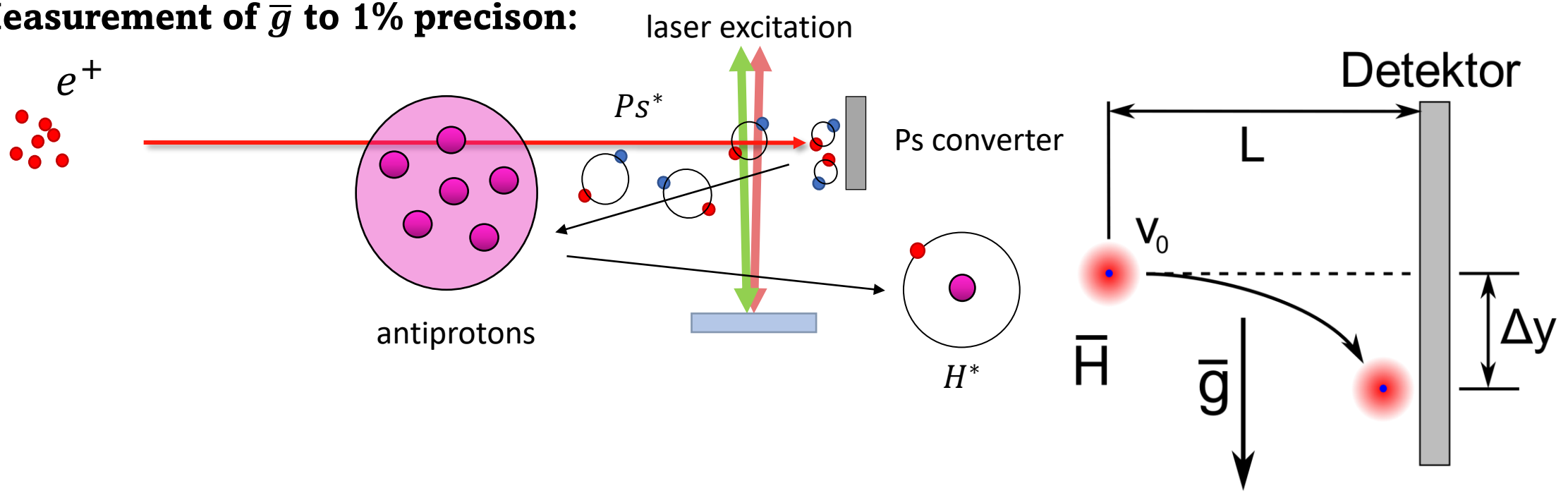
Observation of the effect of gravity on the motion of antimatter

ALPHA

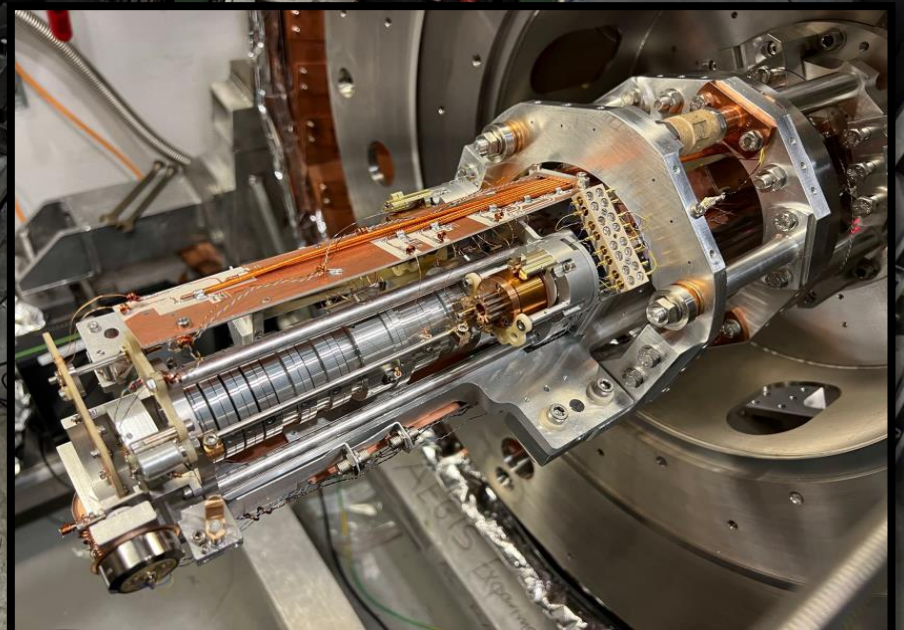
E. K. Anderson, C. J. Baker, W. Bertsche, N. M. Bhatt, G. Bonomi, A. Capra, I. Carli, C. L. Cesar, M. Charlton, A. Christensen, R. Collister, A. Cridland Mathad, D. Duque Quiceno, S. Eriksson, A. Evans, N. Evetts, S. Fabbri, J. Fajans, A. Ferwerda, T. Friesen, M. C. Fujiwara, D. R. Gill, L. M. Golino, M. B. Gomes Gonçalves, ... J. S. Wurtele + Show authors

Nature **621**, 716–722 (2023) | Cite this article

Measurement of $\bar{g}$ to 1% precison:

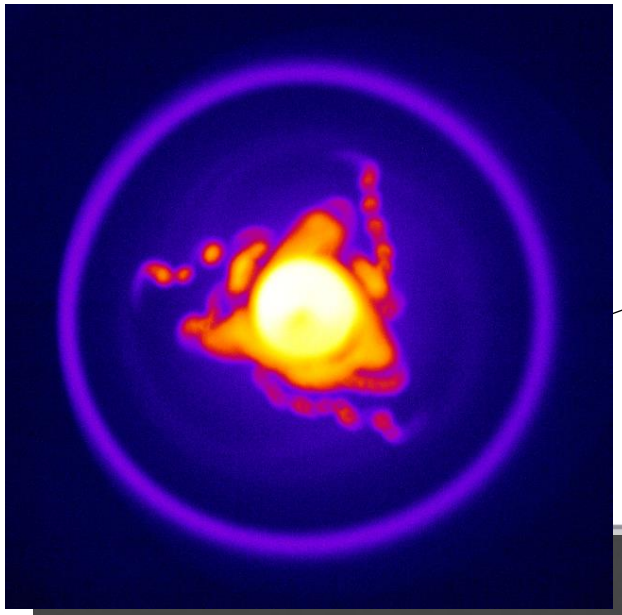


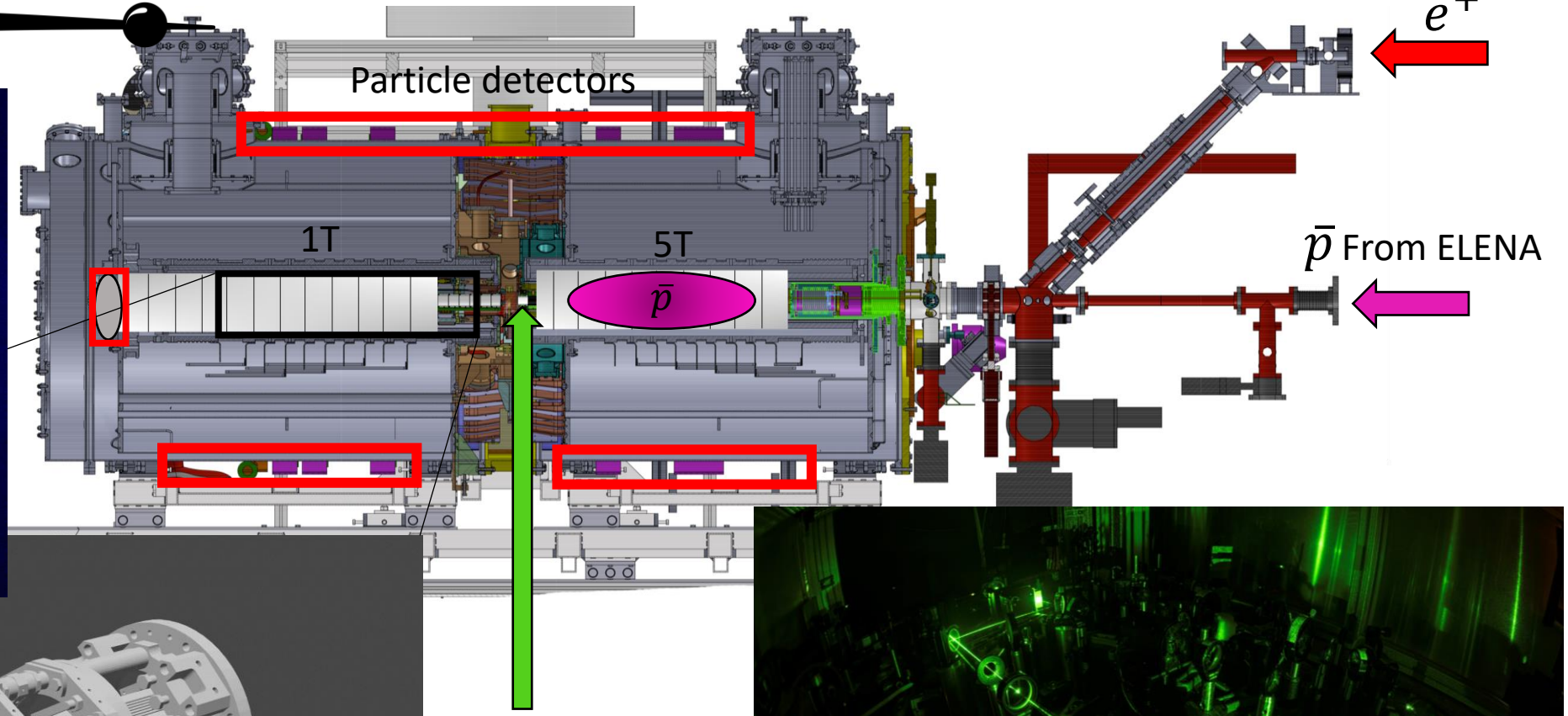
The AEGIS experiment

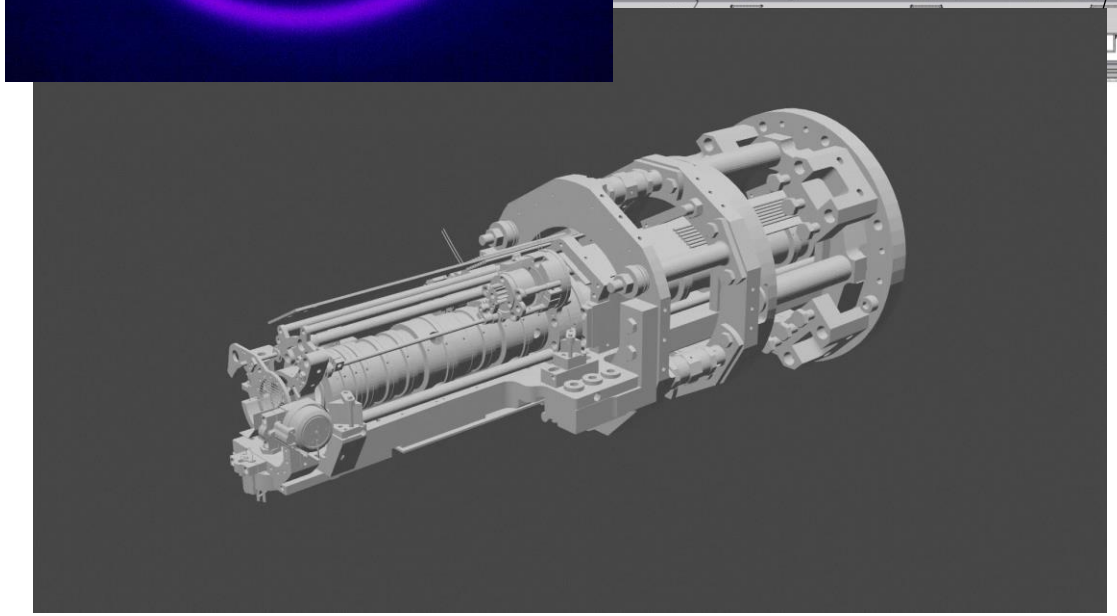


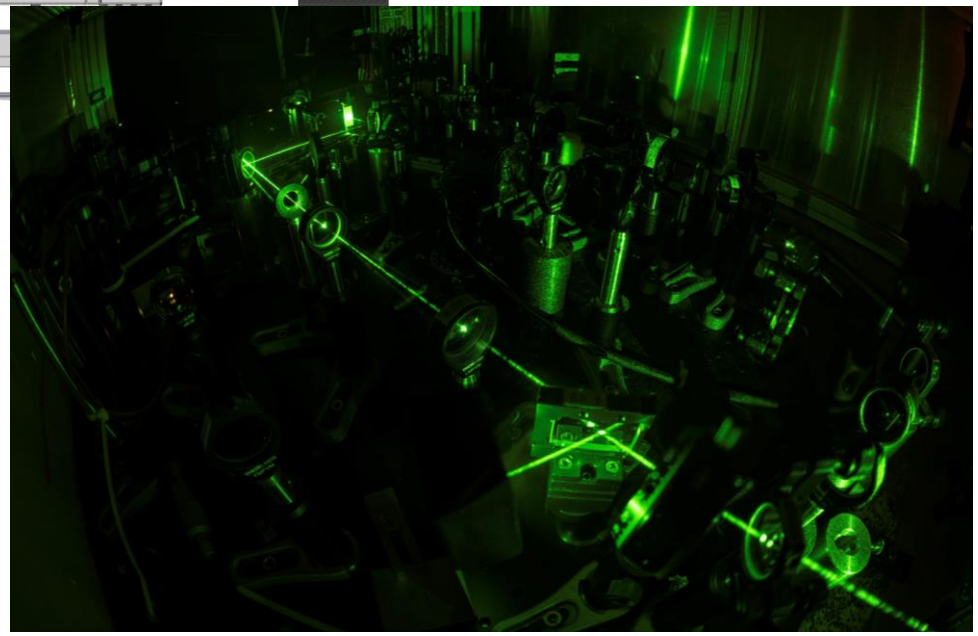
AEgIS

(Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy)









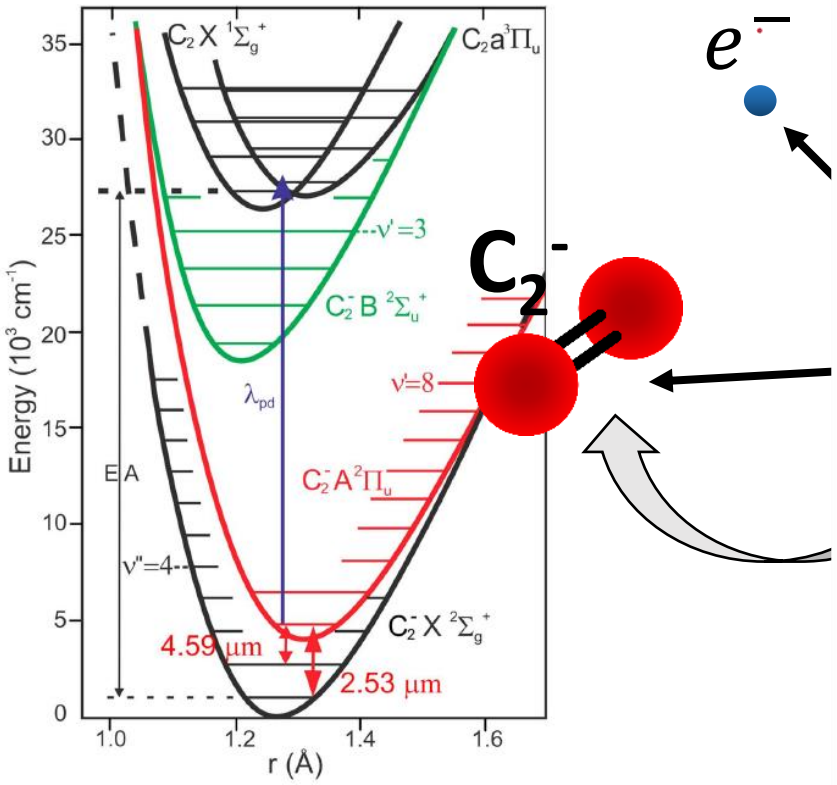
Techniques for pr

Sympathetic cooling

antiprotons:

Using electrons

or laser cooled anio



Yzombard, Pauline, et al. "Laser cooling of mole
anions." *Physical review letters* 114.21 (2015): 2

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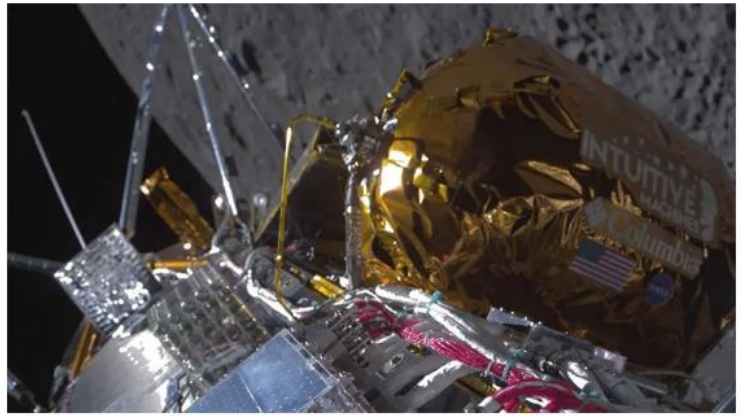
Science

Science & Environment

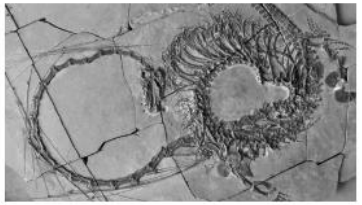


American company makes historic Moon landing

Intuitive Machines completes the first ever lunar touchdown by a privately built spacecraft.

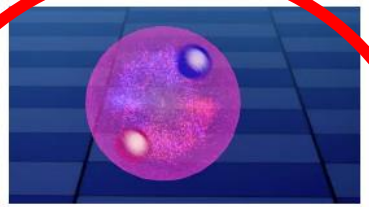
Jonathan Amos
Science correspondent

Science & Environment · 37min



Fossil reveals 240 million year-old 'dragon'

Science & Environment · 3h



Frozen antimatter may reveal origins of Universe

Science & Environment · 16h

Whale song mystery solved by scientists

Science & Environment · 1d

UK quits treaty that lets oil firms sue government

20h · 66
Science & Environment

How AI is helping the search for extraterrestrial life

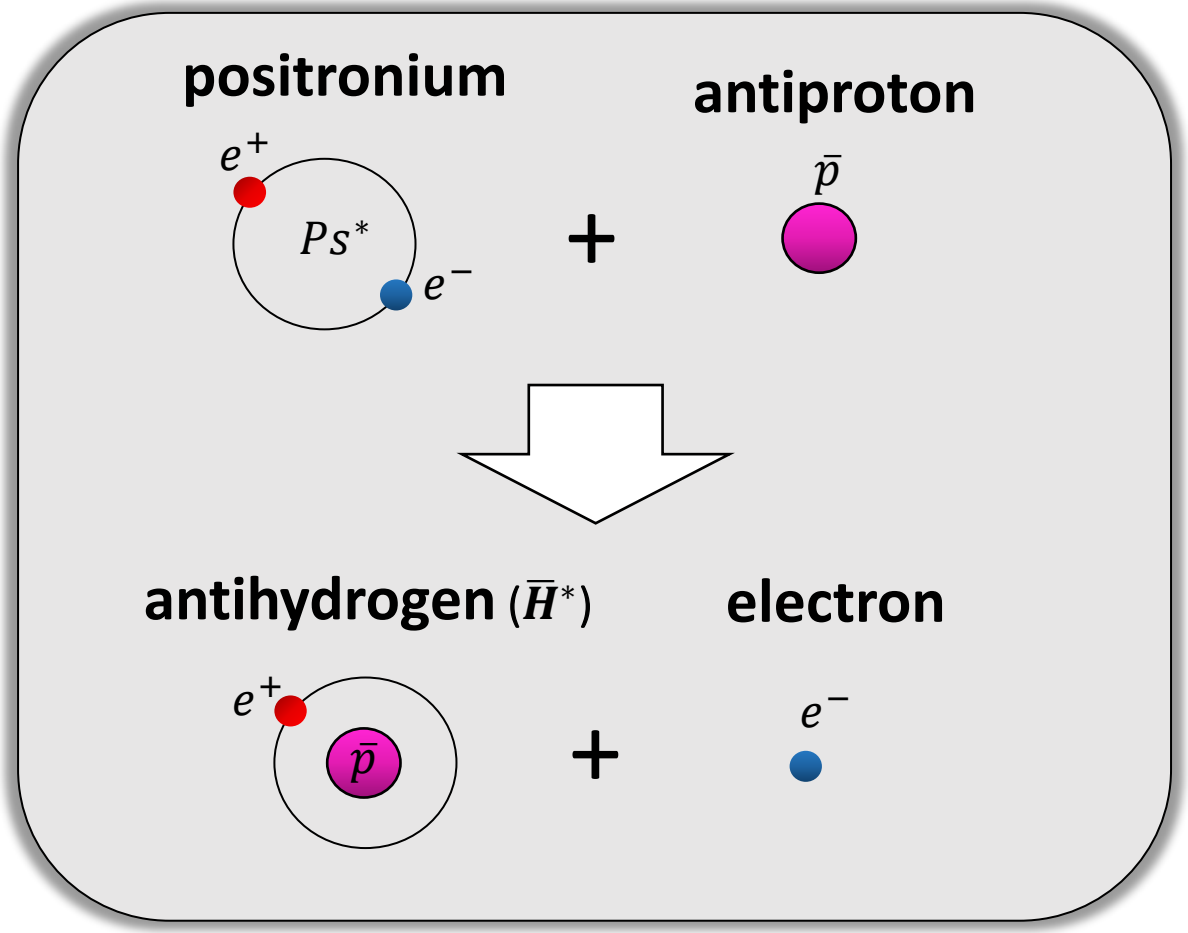
Business · 1d · 285

▶ Moment giant Antarctica drone takes off

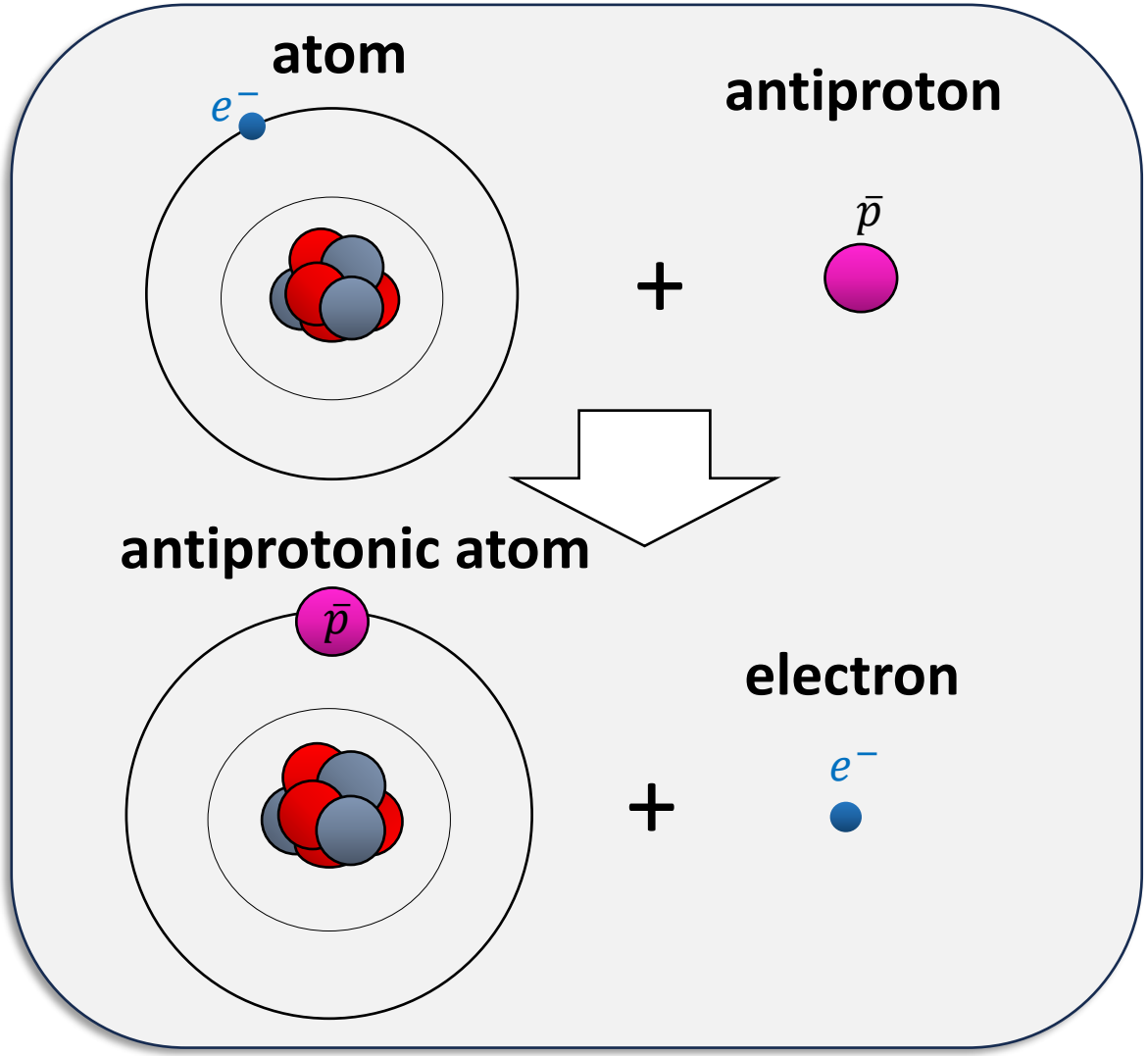
Science & Environment · 1d

Forming matter-antimatter bound states?

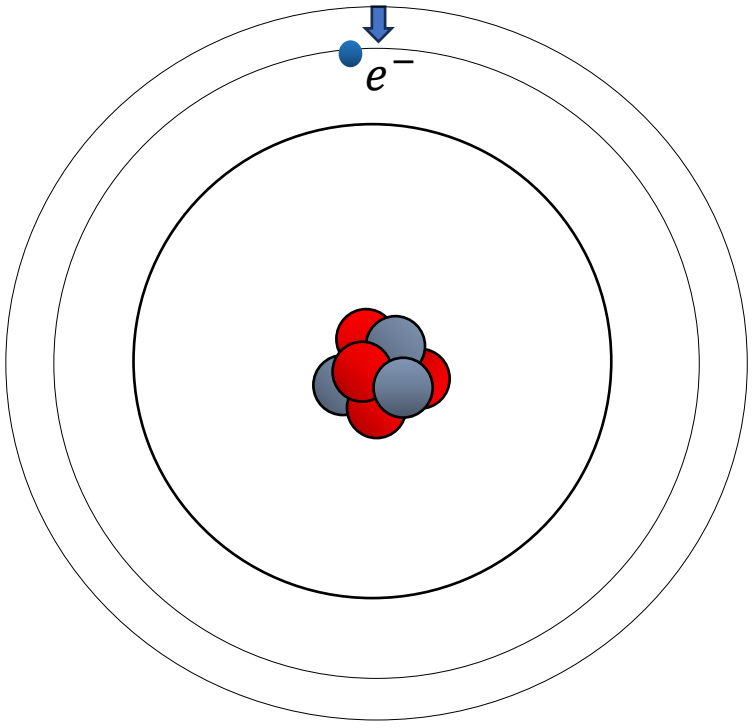
Charge-exchange with positronium



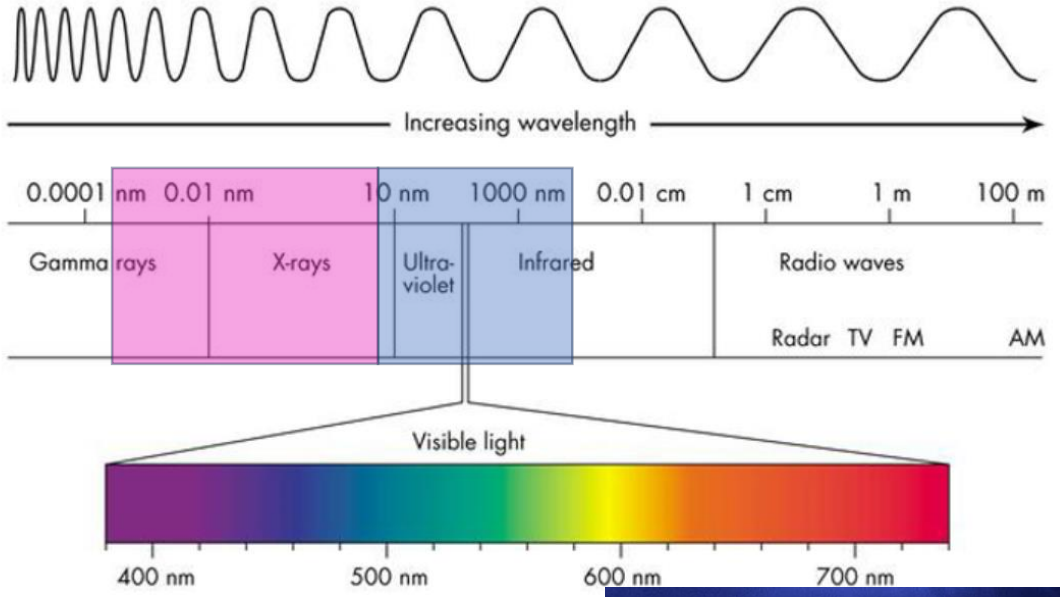
Charge-exchange with atom

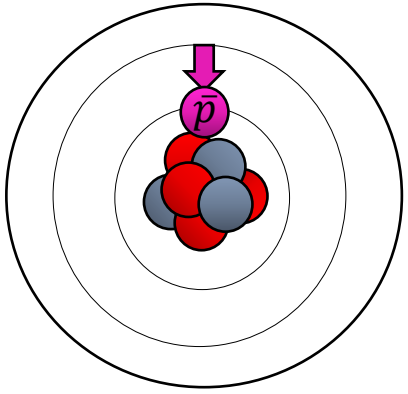


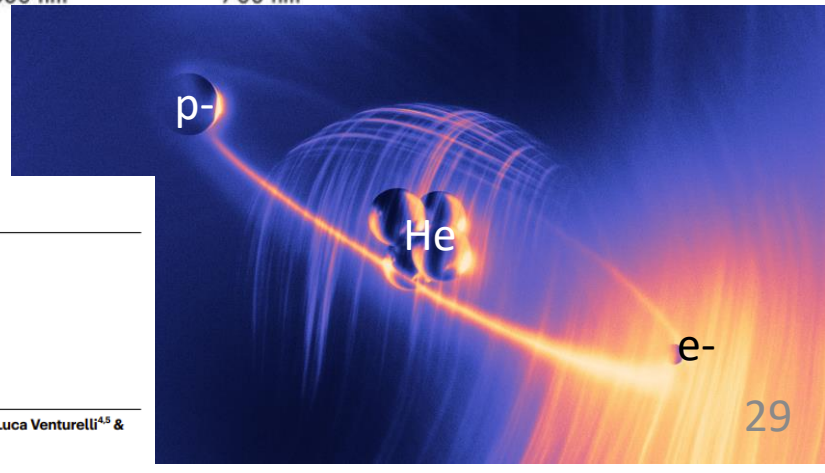
Antiprotonic bound states



$$m_{\bar{p}} = 1836 m_e \quad \Rightarrow \quad r_{\bar{p}} \sim \frac{1}{1836} r_e$$







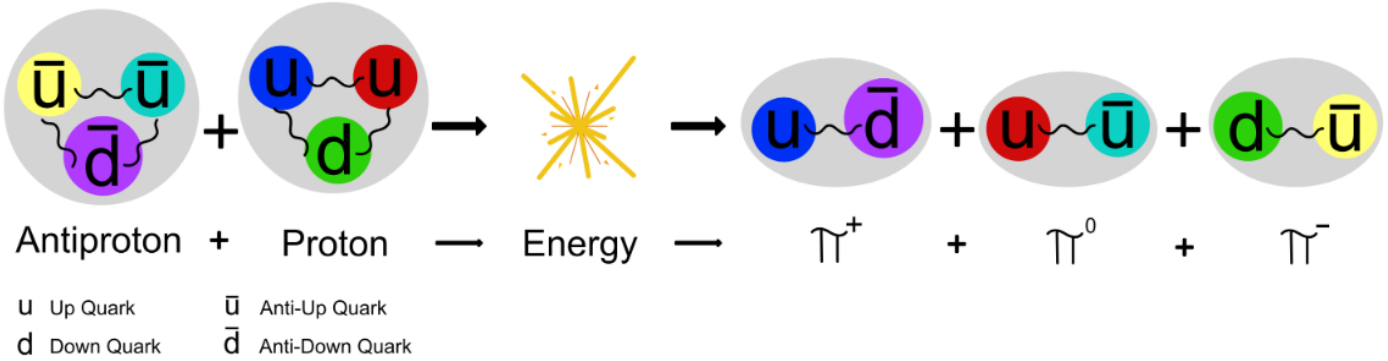
Article

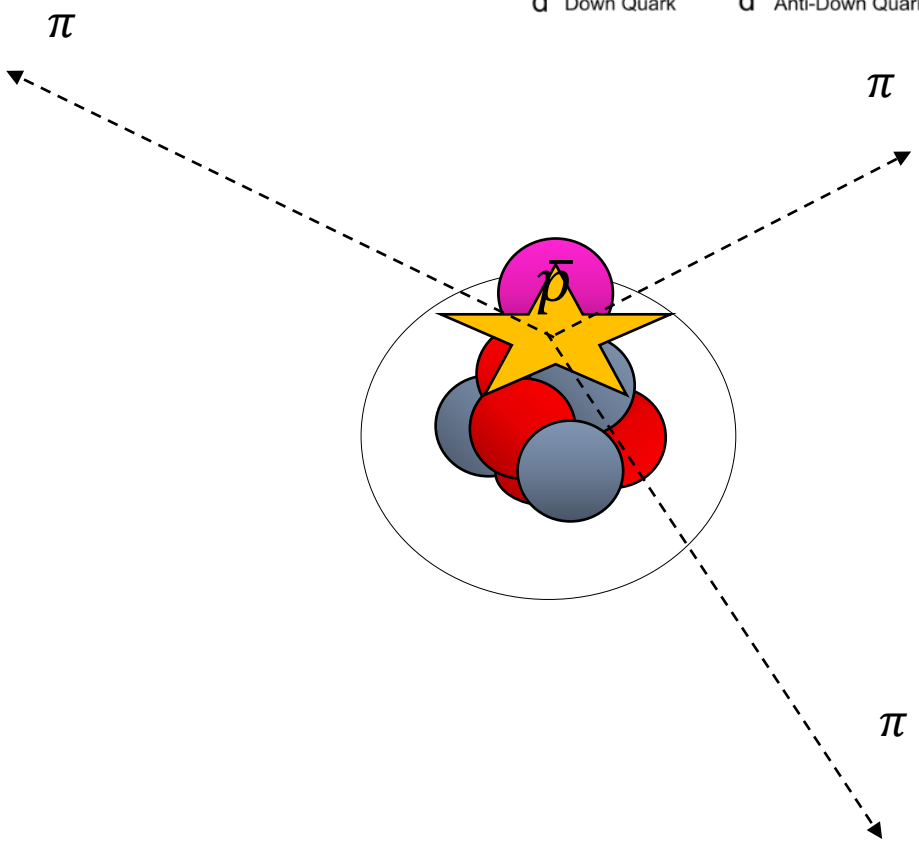
High-resolution laser resonances of antiprotonic helium in superfluid ^{4}He

https://doi.org/10.1038/s41586-022-04440-7
Received: 14 June 2021

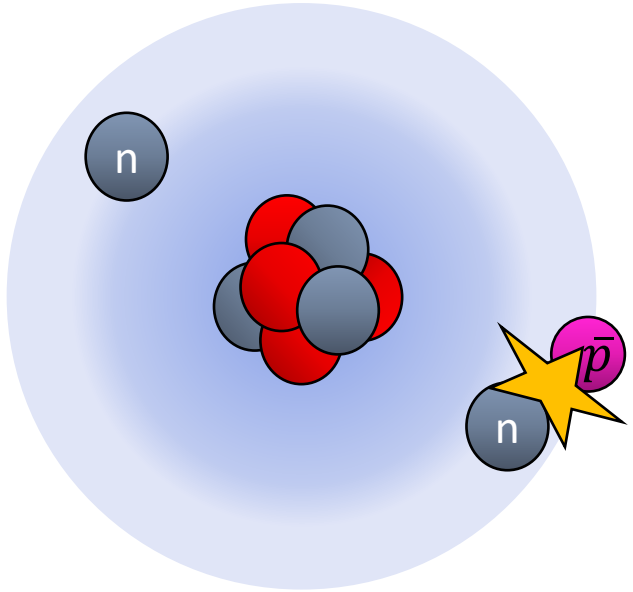
Anna Sótér[1,7], Hossein Aghai-Khozani[1,8], Dániel Barna[2,3], Andreas Dax[2,9], Luca Venturelli[4,5] & Masaki Hori[1,6]

Antiproton annihilation on nucleus



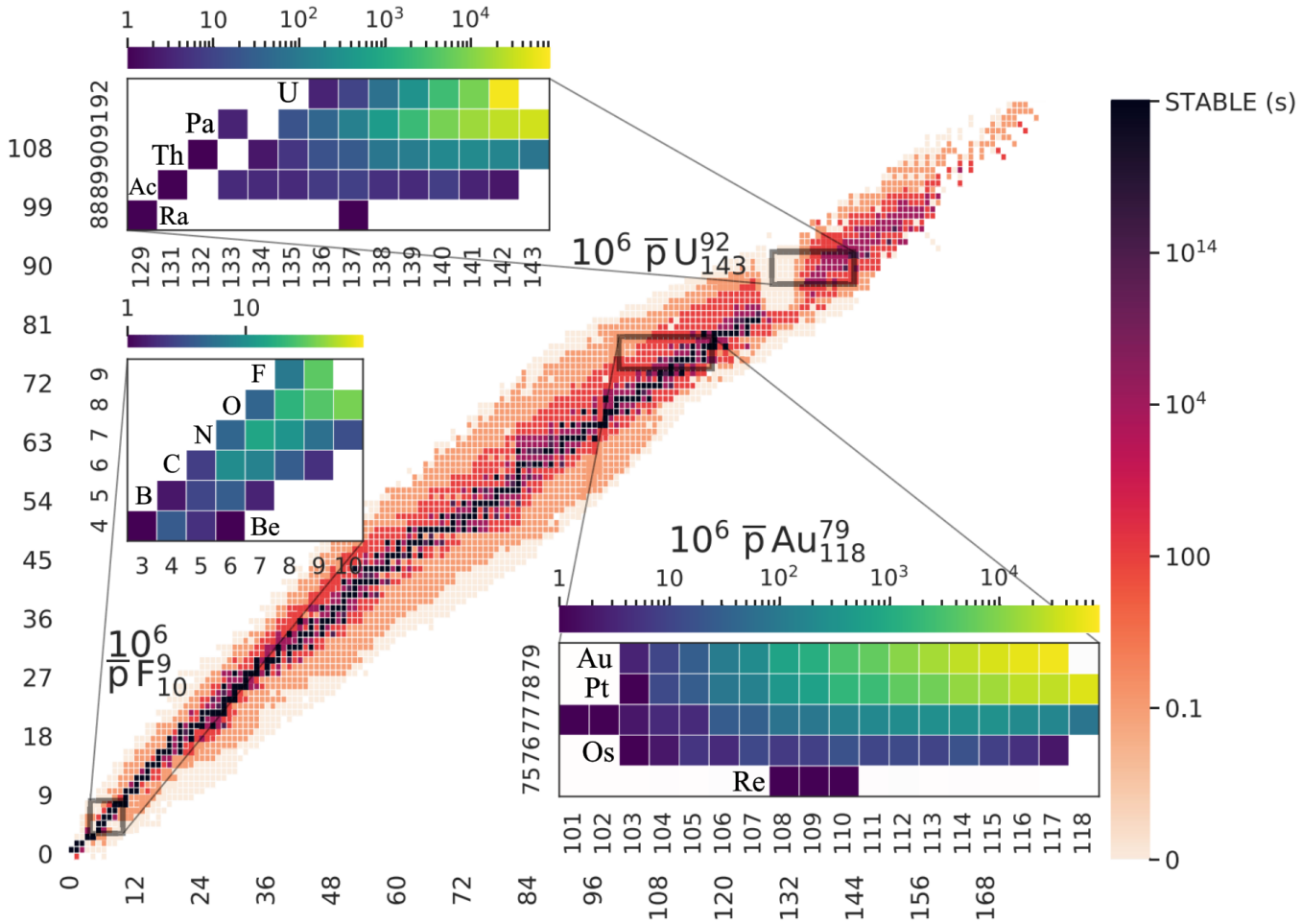


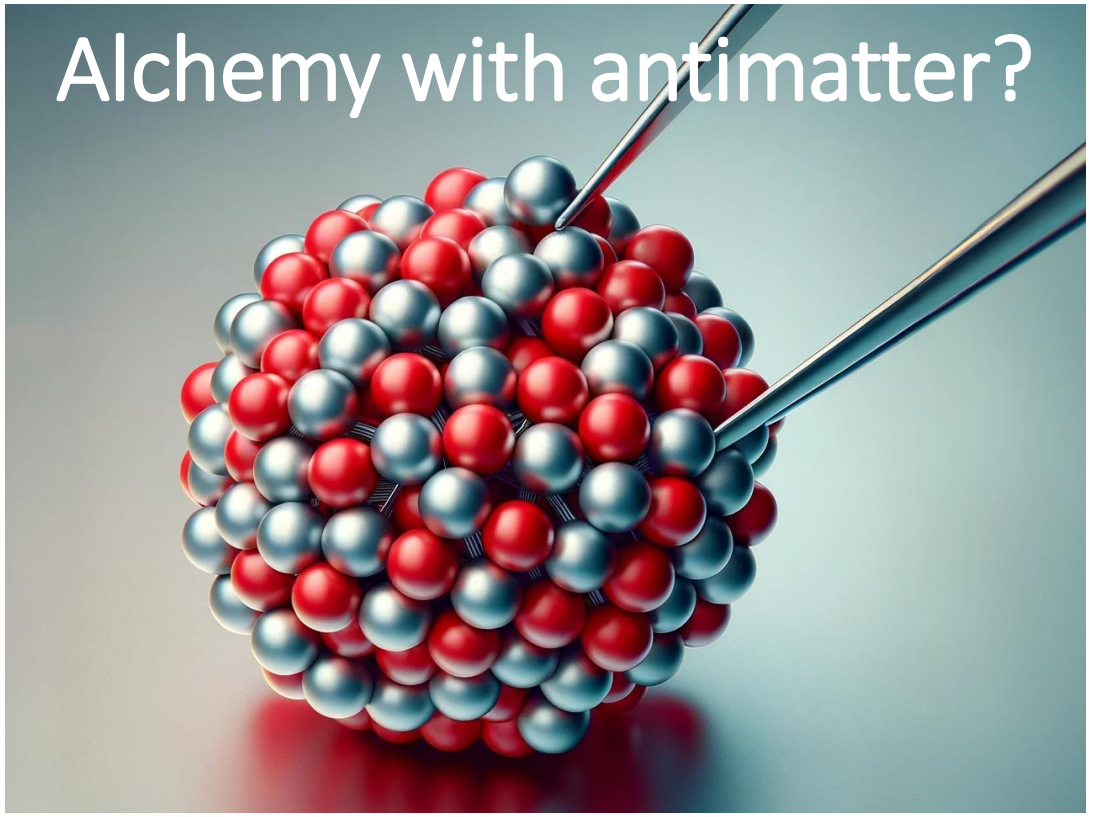
Sensitive approach for studying halo nuclei:



PUMA: antiprotons to probe the surface of radioactive nuclei

Simulation of trappable nuclear recoil fragments

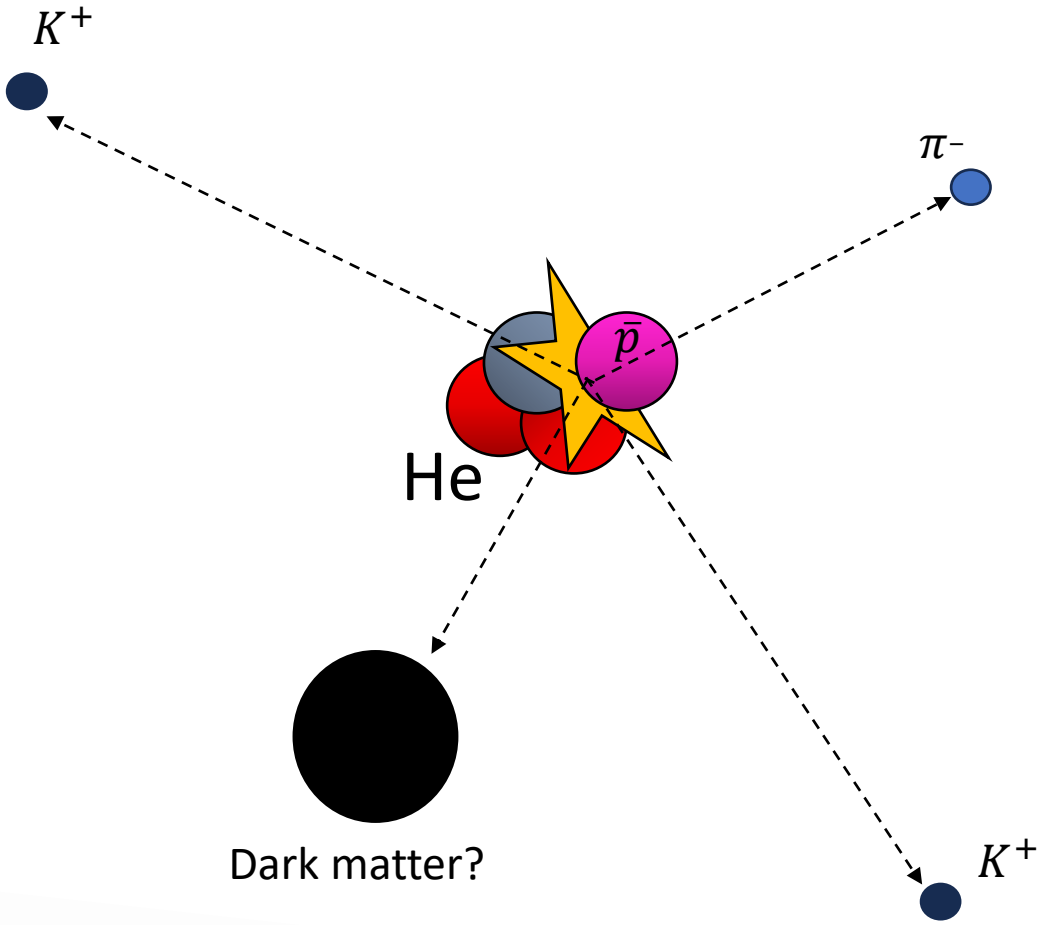


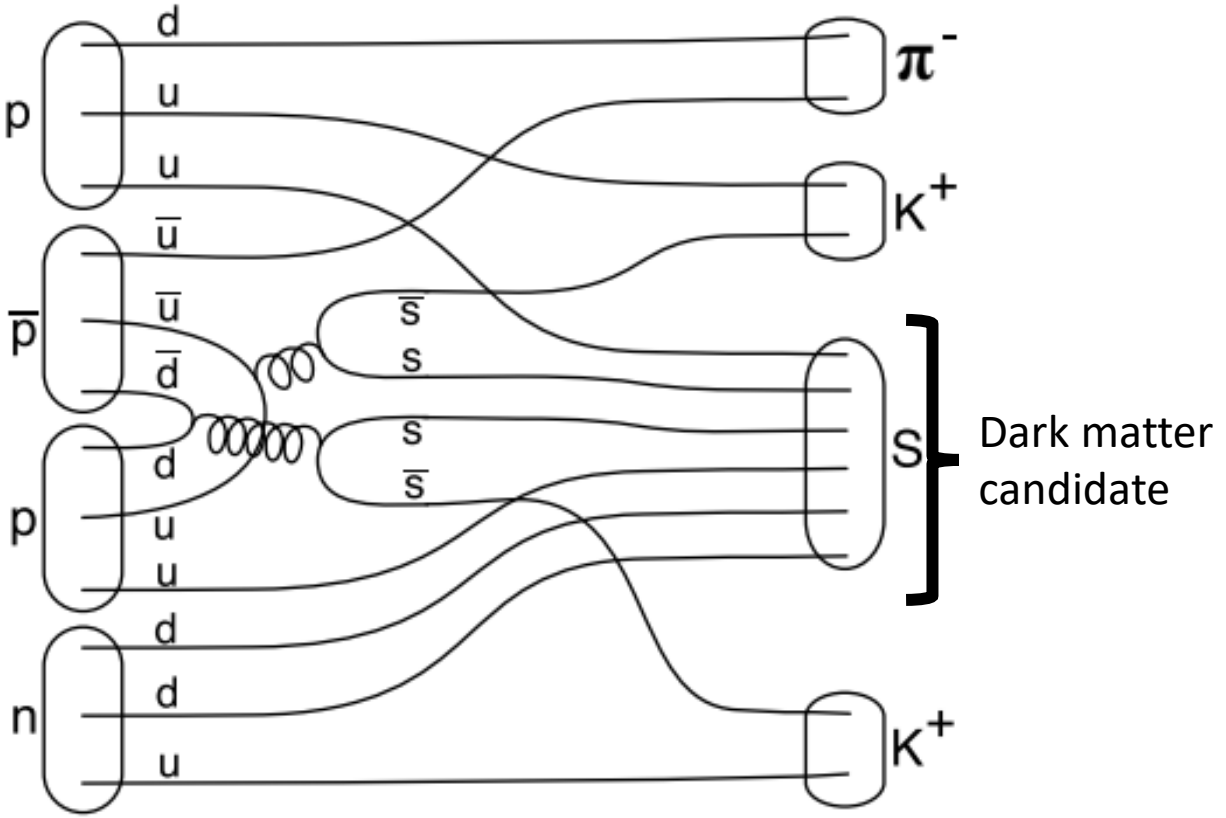


G. Kornakov et al., PRC **107**, 034314 (2023)

Novel technique for making exotic elements..

Searching for dark matter using antiprotons?



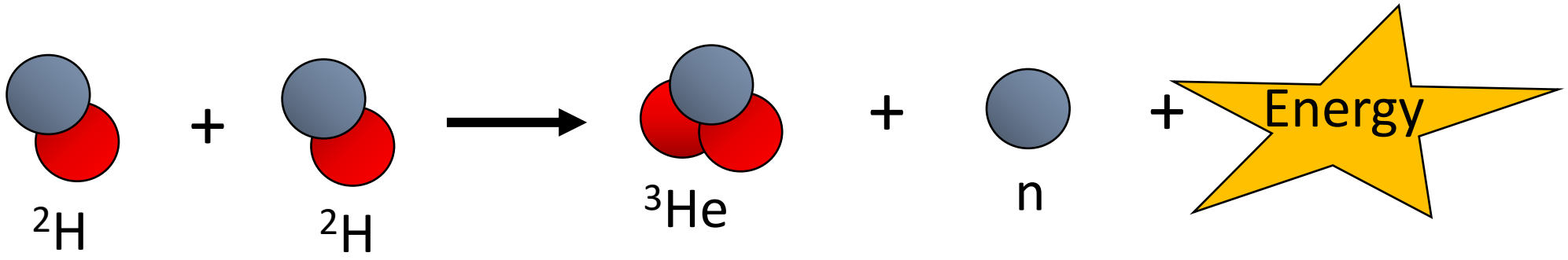


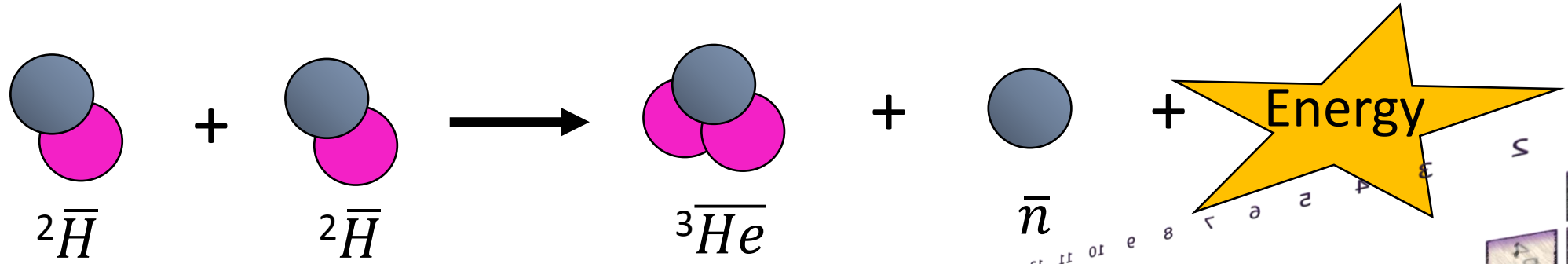
Dark matter candidate

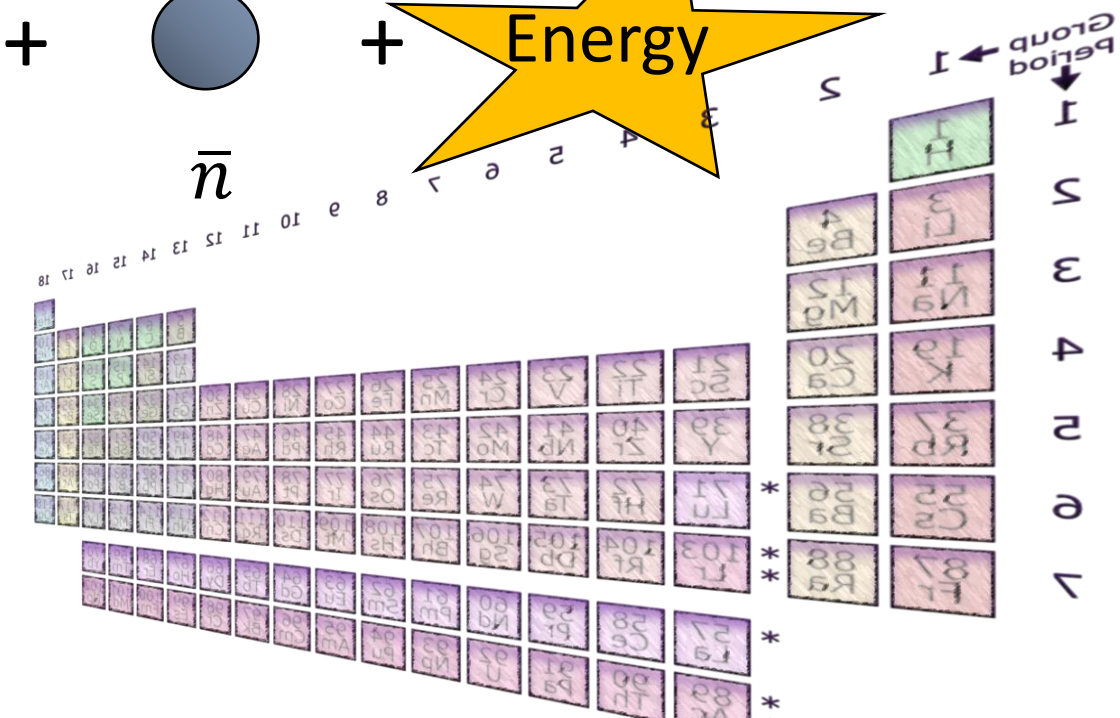
Searching for a dark matter particle with anti-protonic atoms

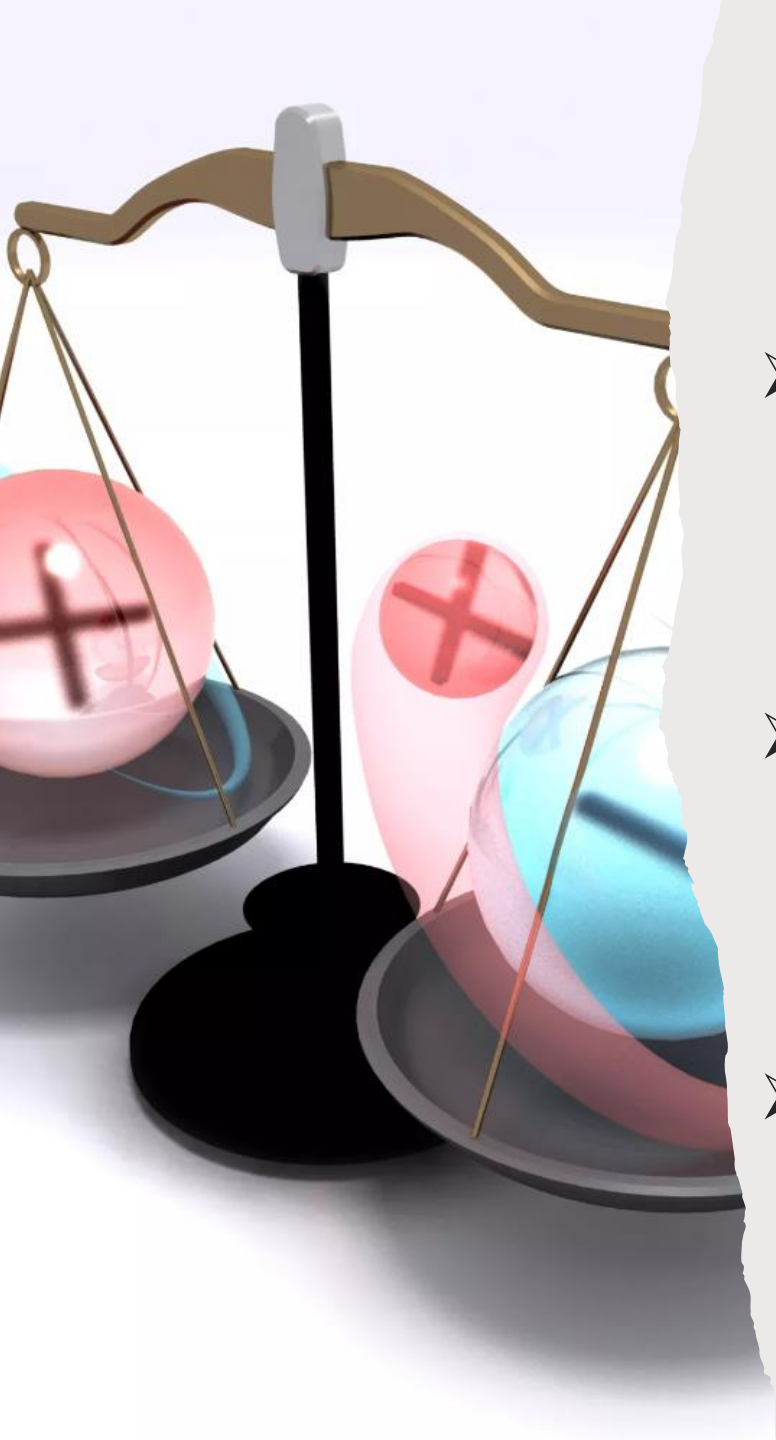
M. Doser[1], G. Farrar[2], and G. Kornakov[3]
[1]CERN, Esplanade des particules 1, 1211 Geneva, Switzerland
[2]Center for Cosmology and Particle Physics, New York University, New York, NY, 10003, USA
[3]Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warsaw, Poland

Antifusion with antideuterons?



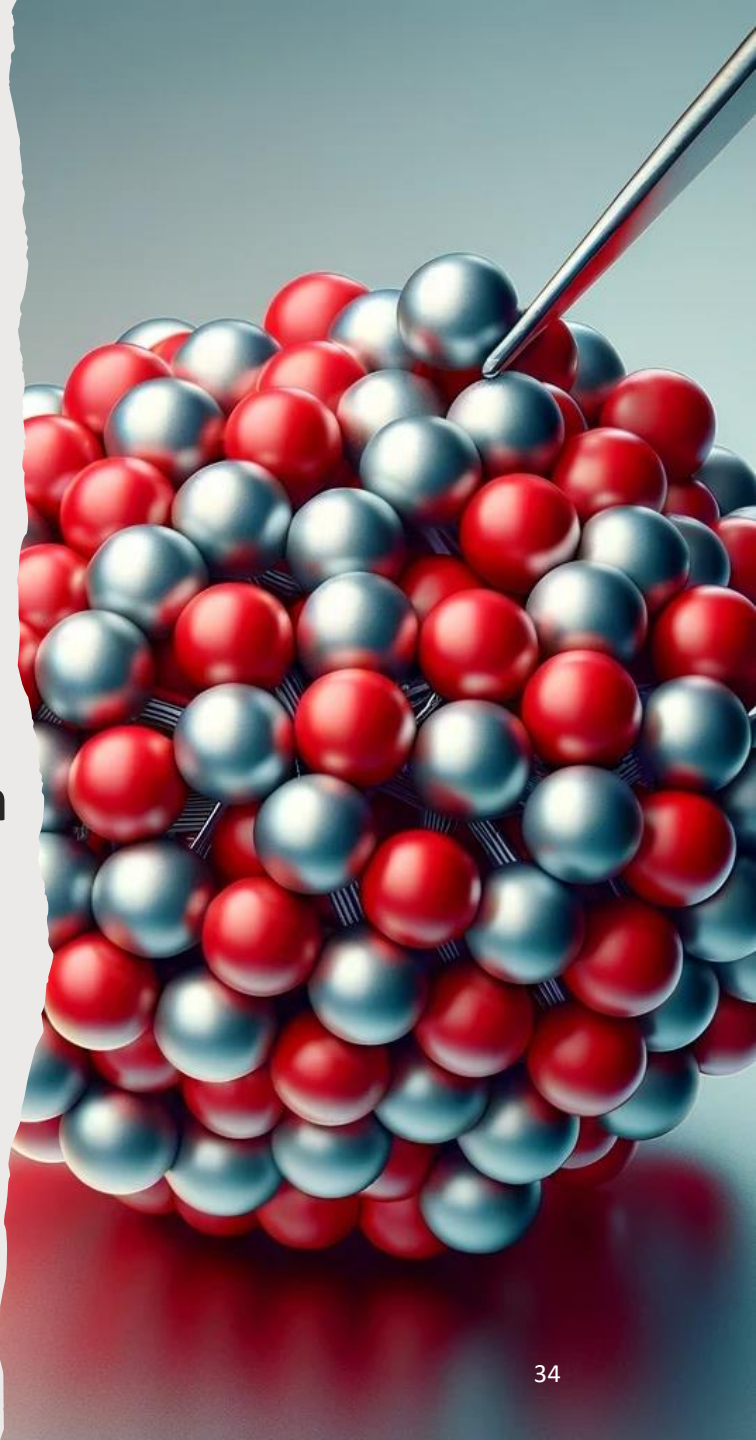






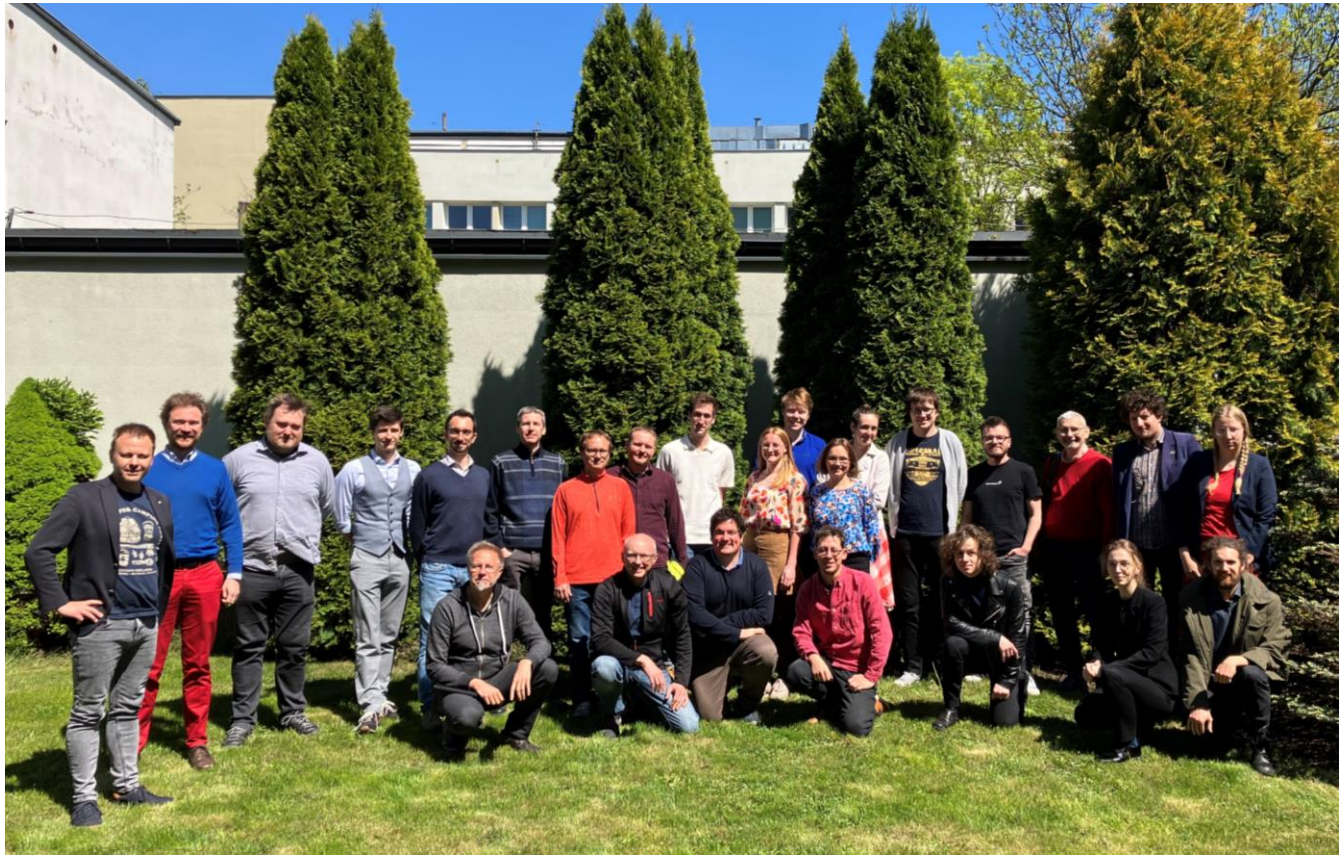
Summary and outlook

- AD is a is currently the **only facility in the world capable of producing cold antiprotons** for precision studies of antihydrogen.
- Multiple experiments are benchmarking the **difference between matter and antimatter**: Fundamental symmetries and gravity.
- **Antiprotonic atoms provide an avenue for precision studies** of nuclear, atomic physics and aid in the search for dark matter candidates.



Thank you for your attention

On behalf of the AEGIS collaboration



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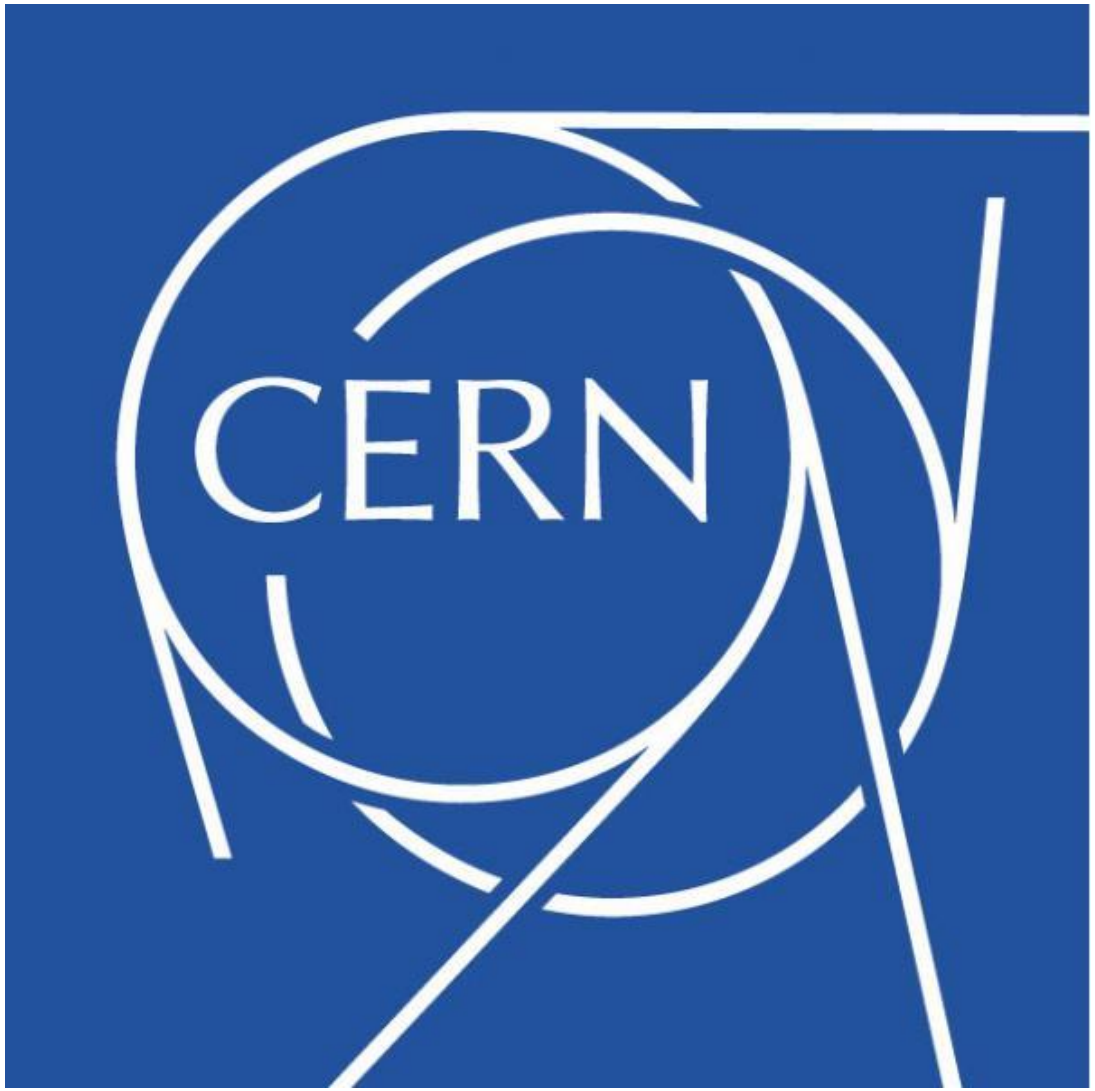
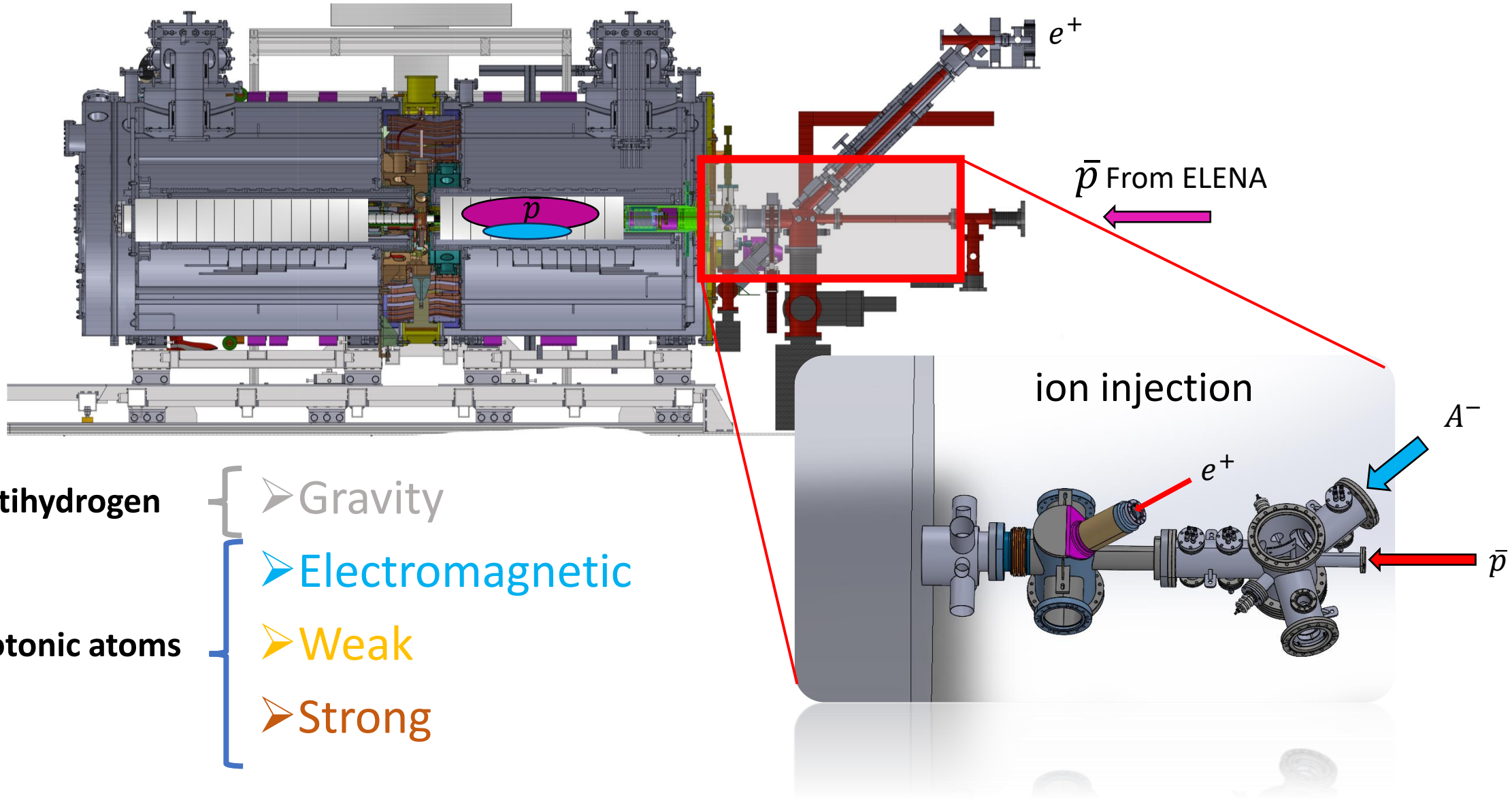

CERN

Ongoing work for antiprotonic atom studies at AEGIS



Antihydrogen
- Gravity

Antiprotonic atoms
- Electromagnetic
- Weak
- Strong

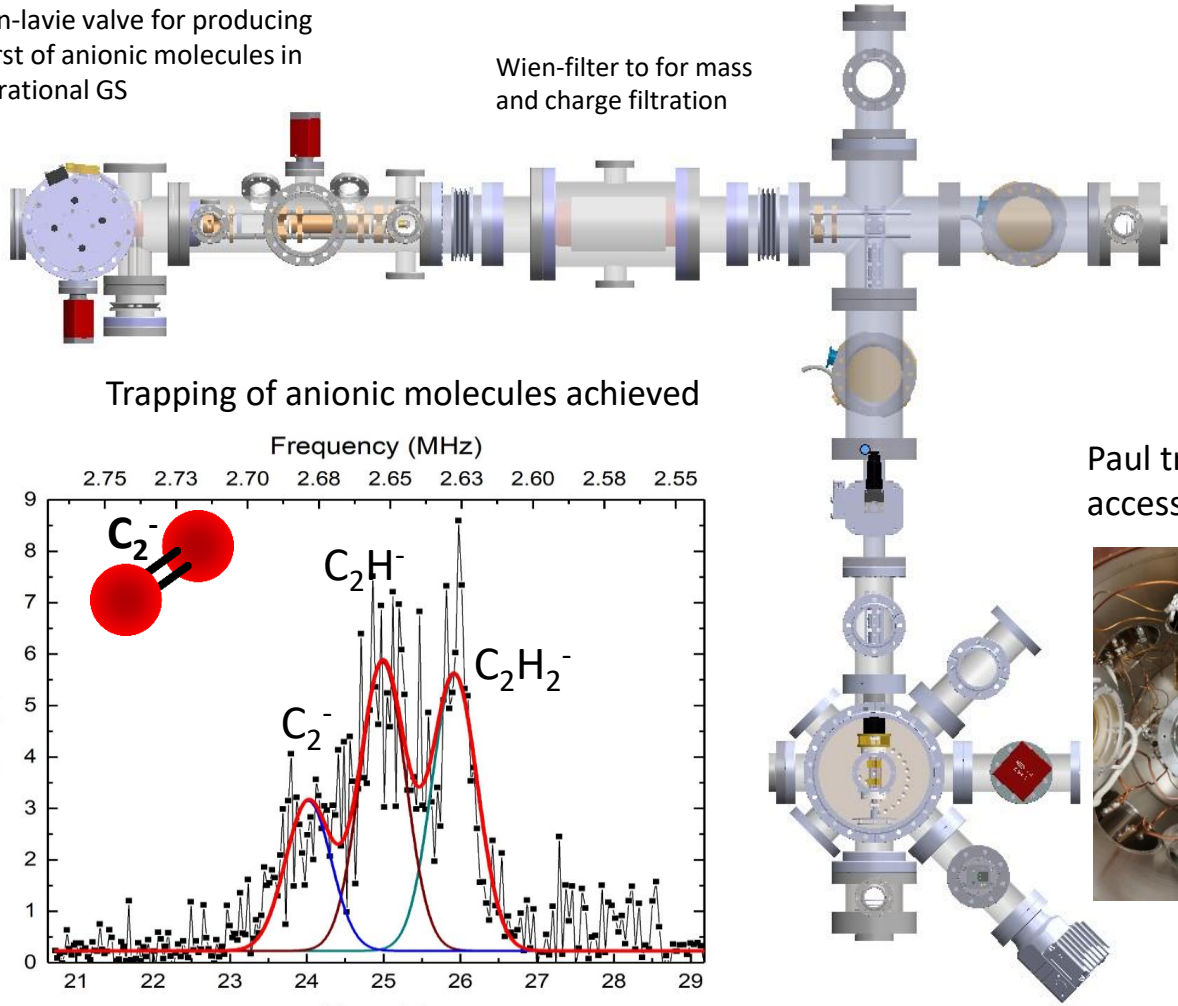
Cooling of antiprotons using anionic molecules?

The BOREALIS experiment

Indirect laser cooling of antiprotons to mK level and below using anionic molecules

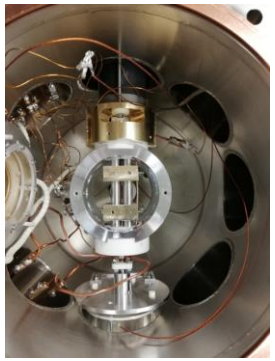
Evin-lavie valve for producing burst of anionic molecules in vibrational GS

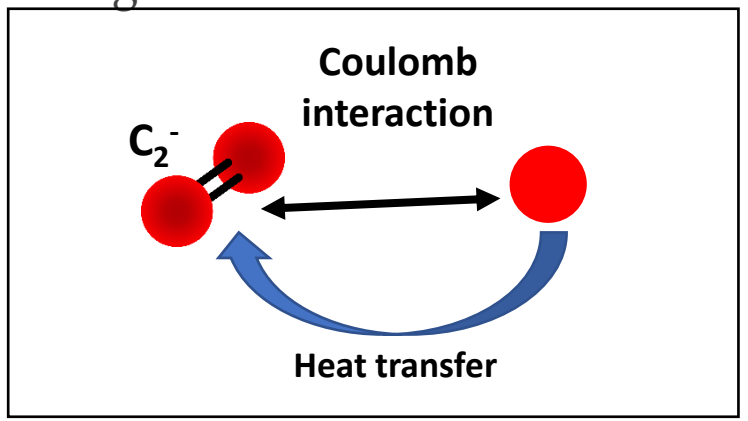
Wien-filter to for mass and charge filtration



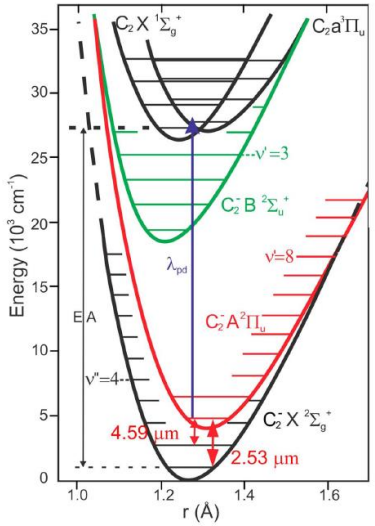
Trapping of anionic molecules achieved

Paul trap with laser access for cooling





Proposed laser cooling scheme:

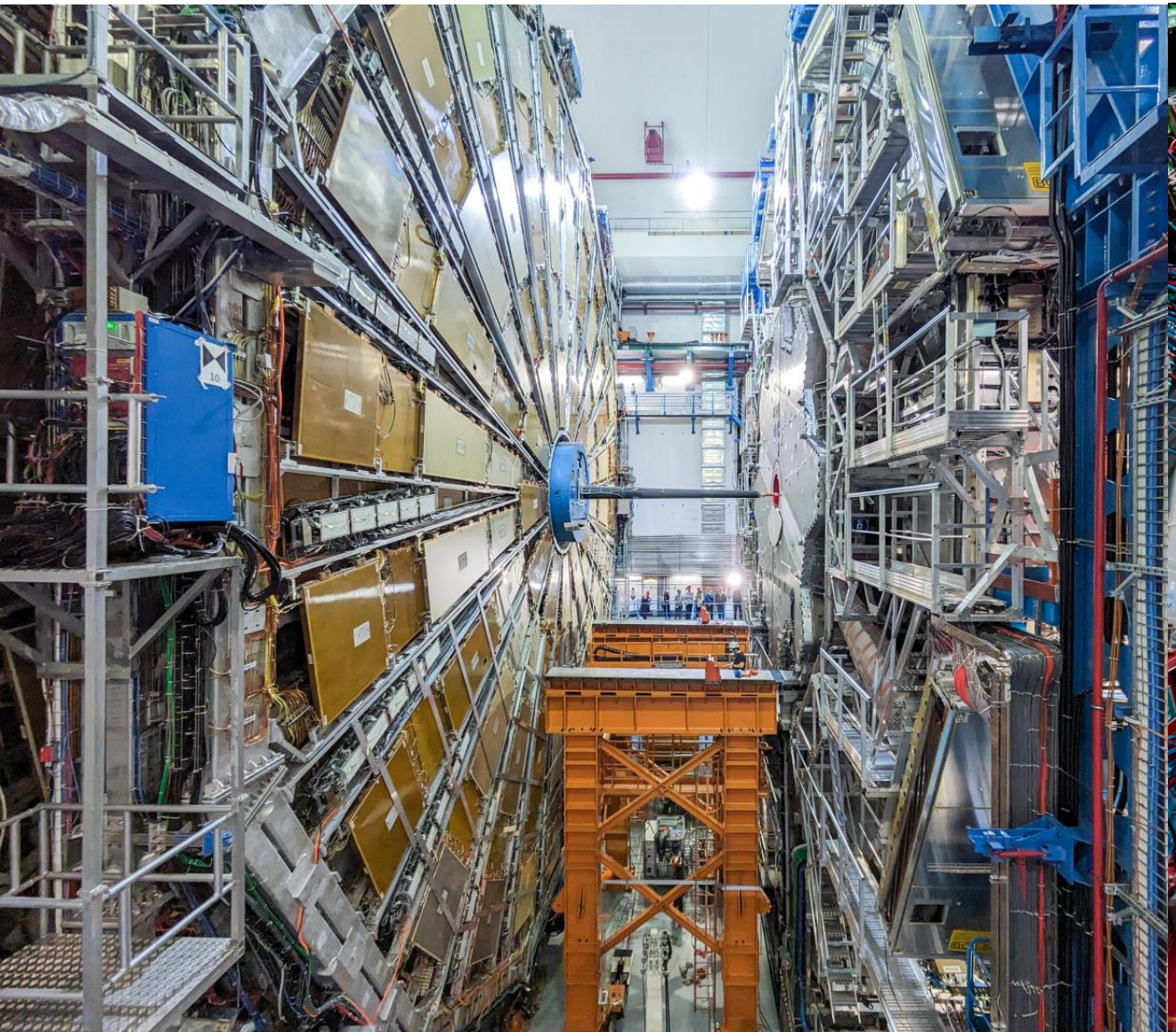


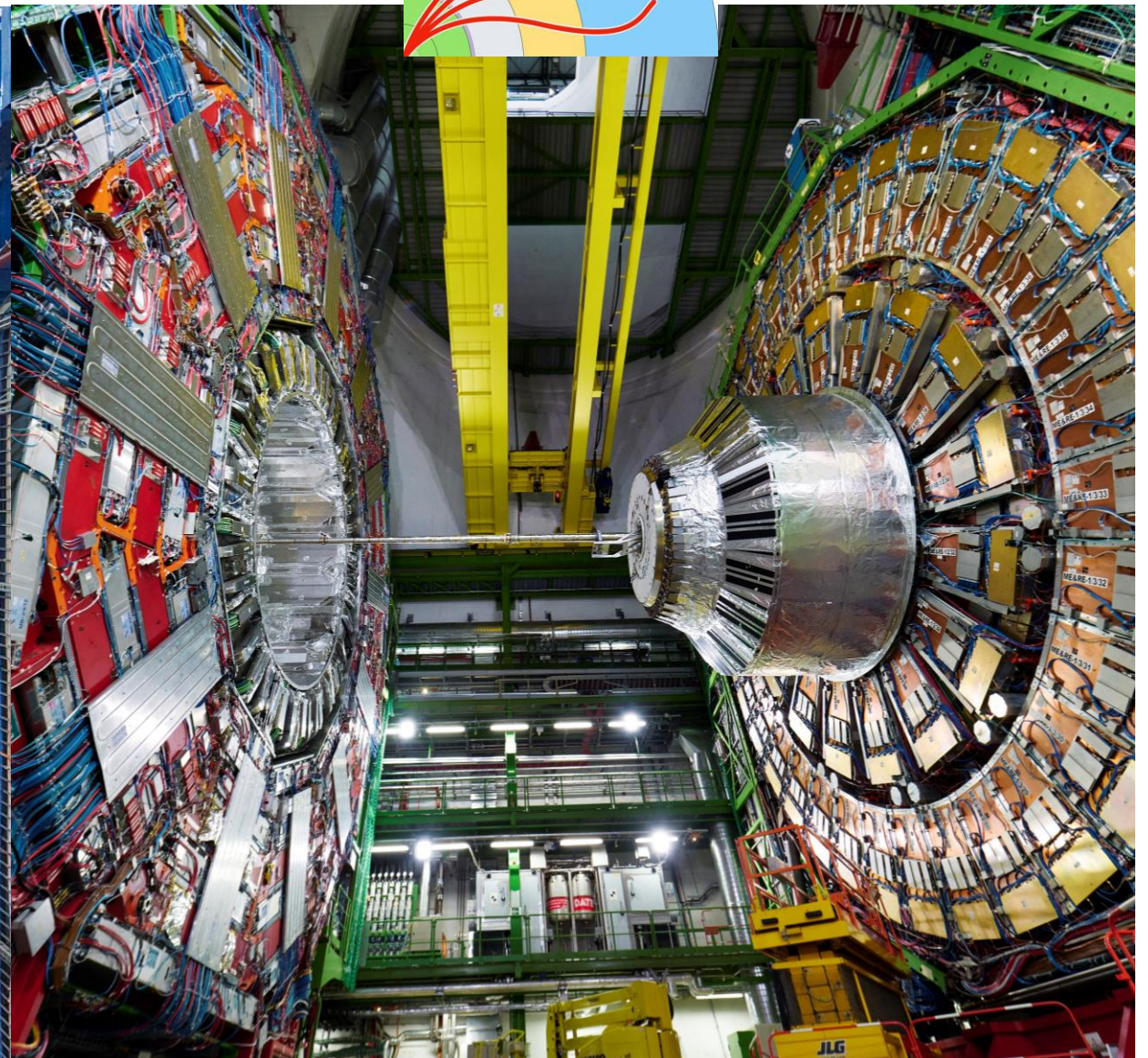
Yzombard, Pauline, et al. "Laser cooling of molecular anions." *Physical review letters* 114.21 (2015): 213001.

The iridium target

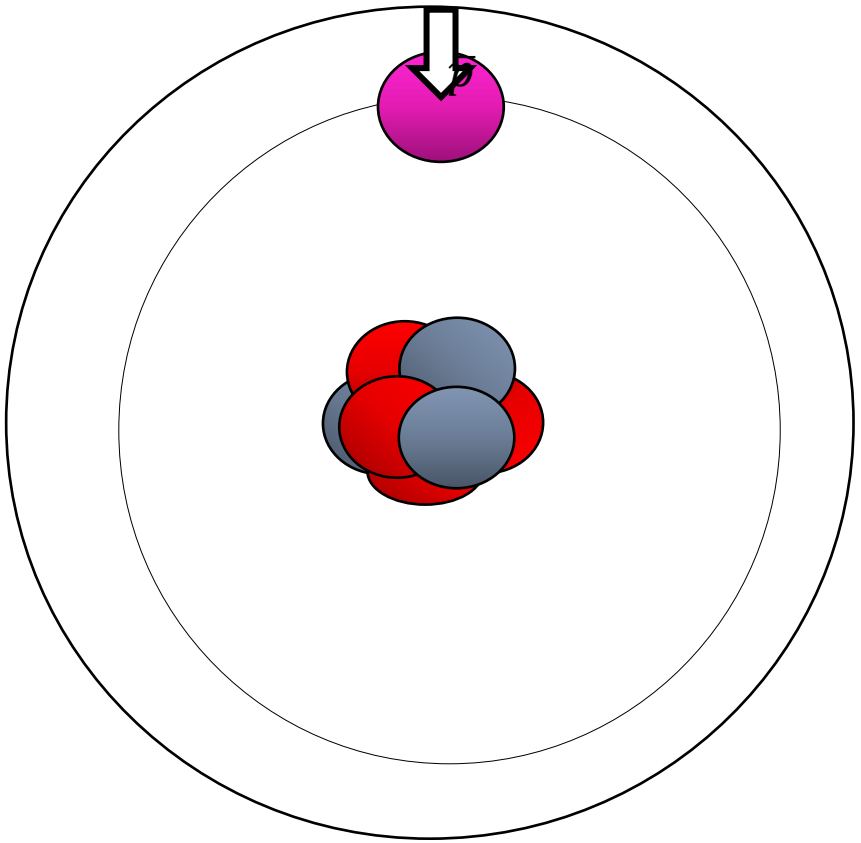
ATLAS EXPERIMENT

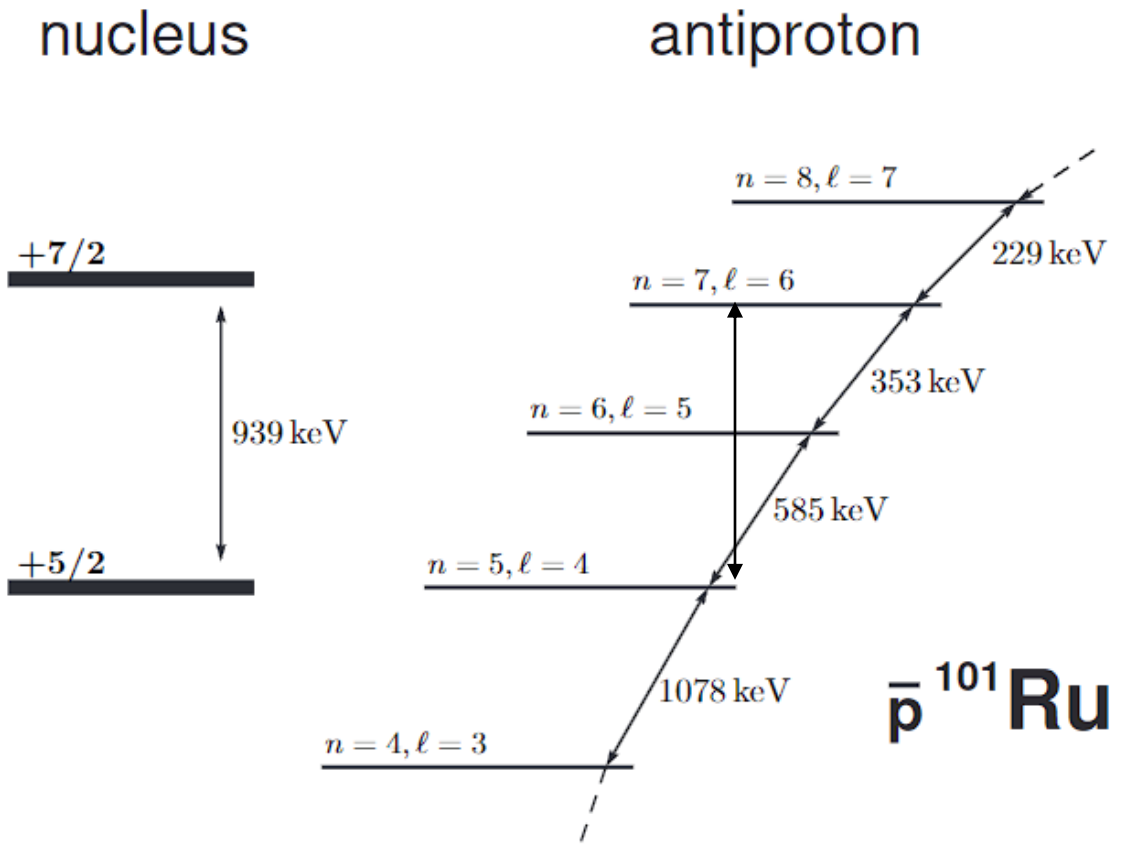
CMS Compact Muon Solenoid





Antiprotonic atom cascade:
Nuclear resonance effects for probing QCD





Gustafsson, Fredrik P., Daniel Pęcak, and Tomasz Sowiński. "The spin-flip-induced quadrupole resonance in odd-$ A $ exotic atoms." *arXiv preprint arXiv:2401.06063* (2024).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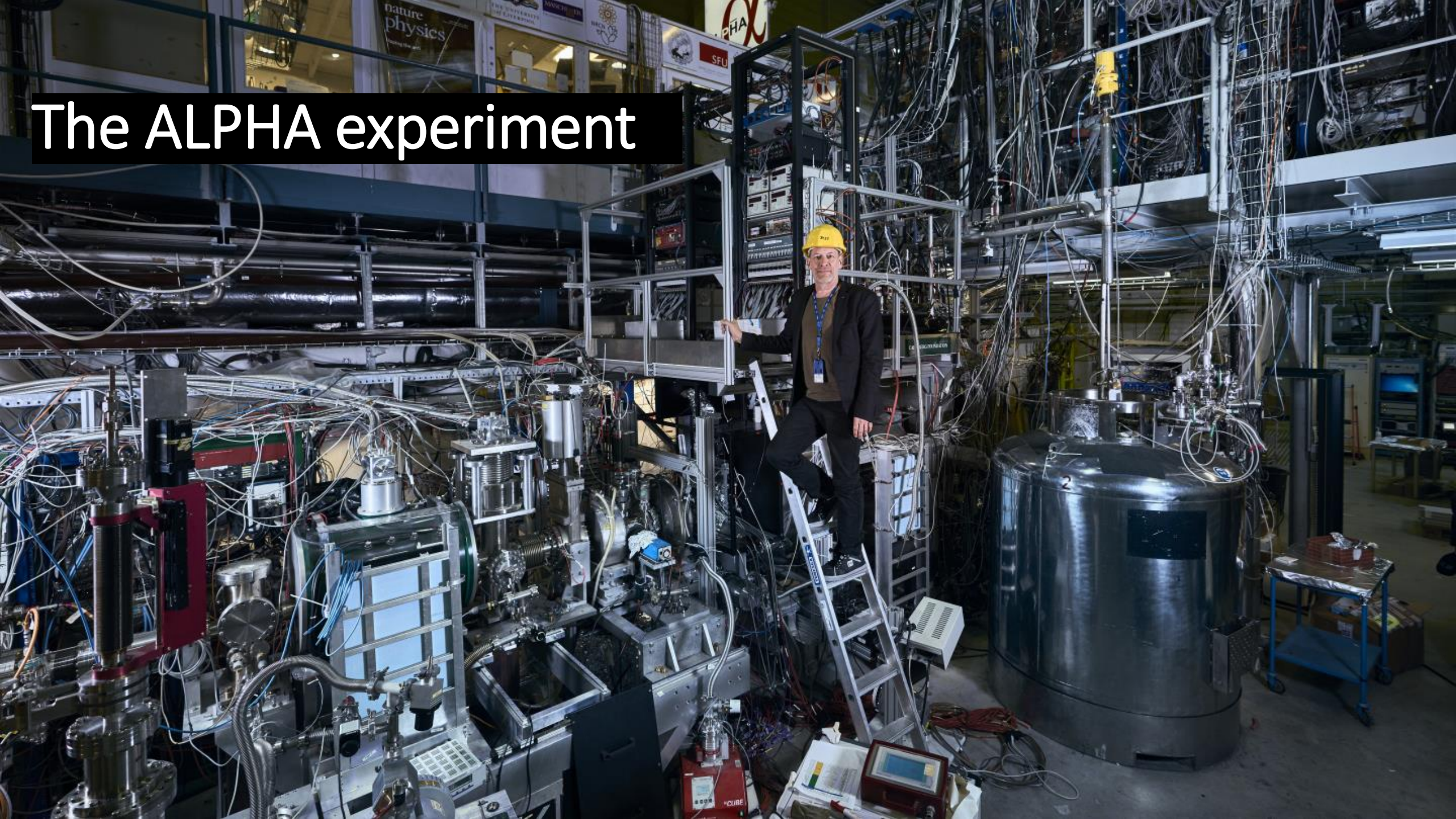
ANTIMATTER
FACTORY
ELENA



The ALPHA experiment

Forming antihydrogen