MEASURING ANTIMATTER GRAVITY

5th World Summit on Exploring the Dark Side of the Universe (EDSU-Tools 2024)

Danielle Hodgkinson (UC Berkeley, USA)

on behalf of the ALPHA Collaboration

Work supported by:
DOE OFES and the NSF/DOE Partnership in Basic Plasma Science

Also supported by CNPq, FINEP/RENAFAE (Brazil), ISF (Israel), MEXT (Japan), FNU and the Carlsberg Foundation (Denmark), VR (Sweden), NSERC, NRC/TRIUMF AIF FQRNT(Canada), and EPSRC, the Royal Society and the Leverhulme Trust (UK).

nature

Observation of the effect of gravity on the motion of antimatter

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

Overview

1. Motivation
2. Our recent observation of the effect of gravity on antimatter
3. Future plans

Overview

1. **Motivation**

2. Our recent observation of the effect of gravity on antimatter

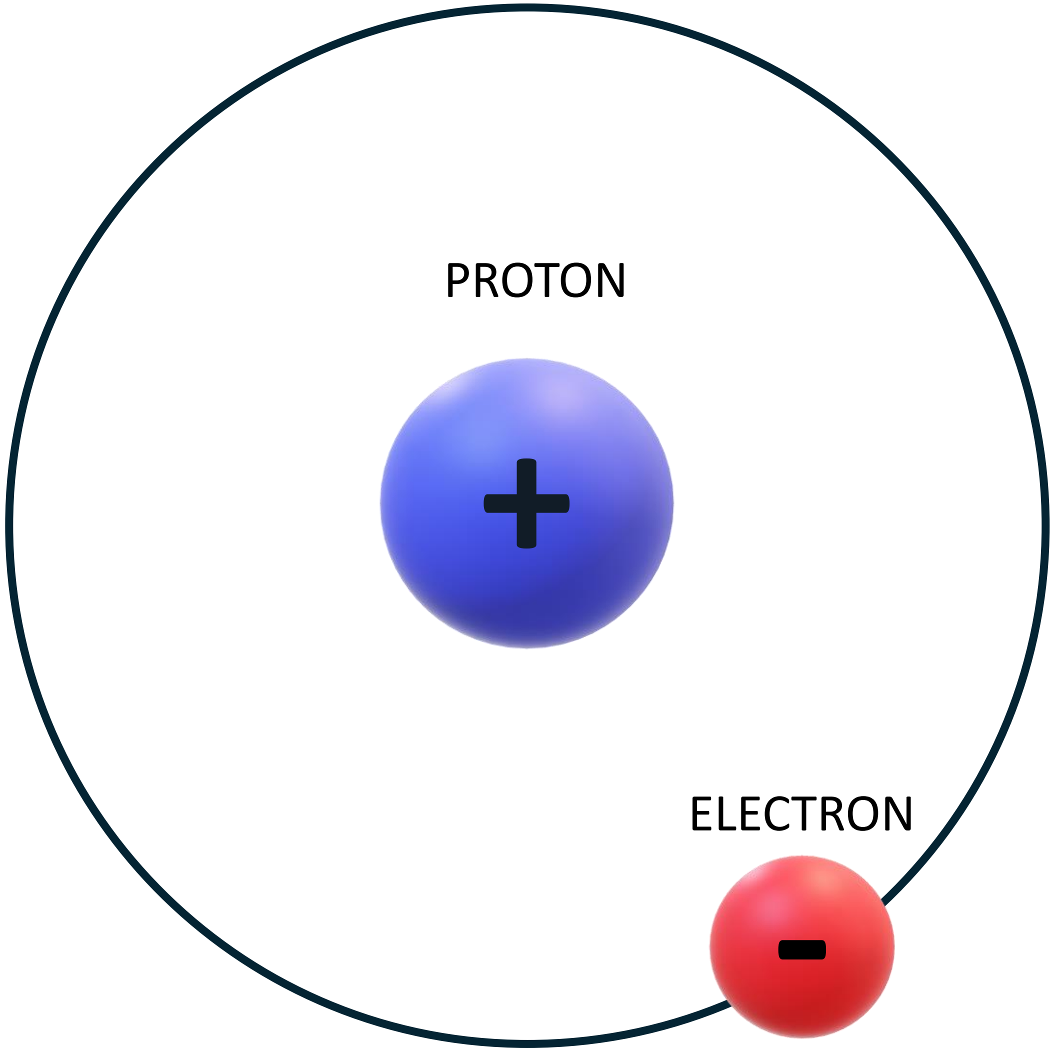
3. Future plans

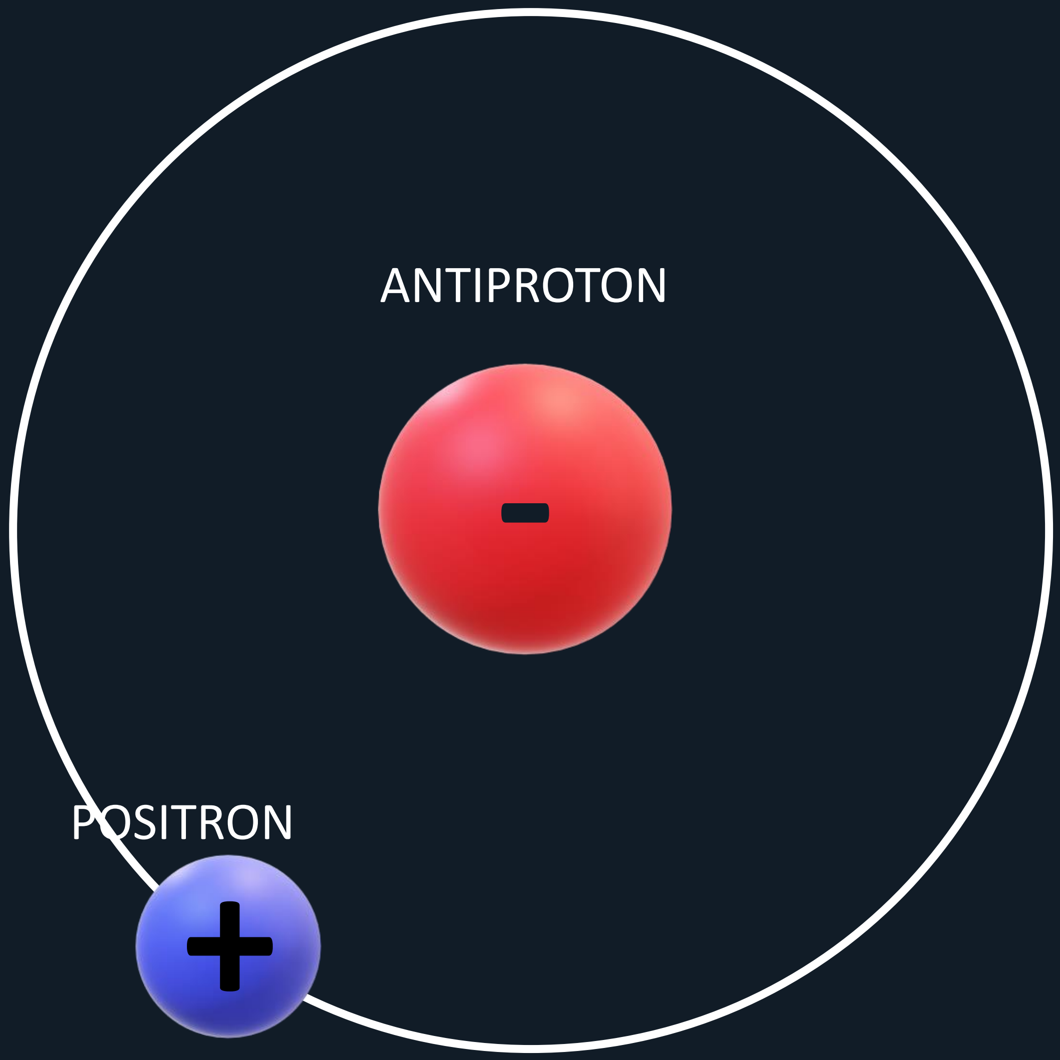
The ALPHA Experiment

- Motivated by the **baryon asymmetry problem**
- Measure the **fundamental properties** of antimatter
- Since the Standard Model (SM) cannot explain the matter dominated Universe, it makes sense to seek explanations **beyond the SM**
- **Charge-Parity-Time (CPT) invariance** – a cornerstone of the SM – requires that antimatter atoms have the **same spectroscopic energy levels** as their matter equivalents
- We reproduce **atomic physics** results in antihydrogen

MATTER

ANTIMATTER





HYDROGEN

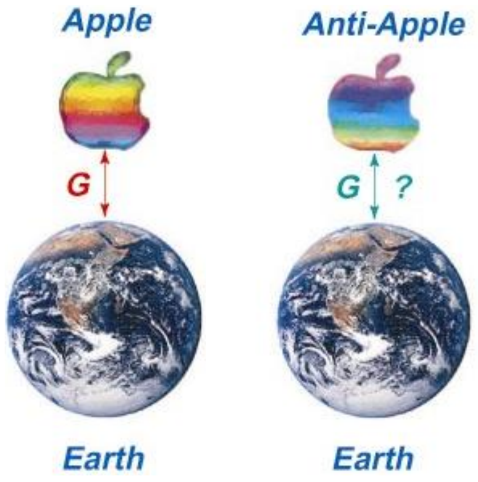
ANTIHYDROGEN

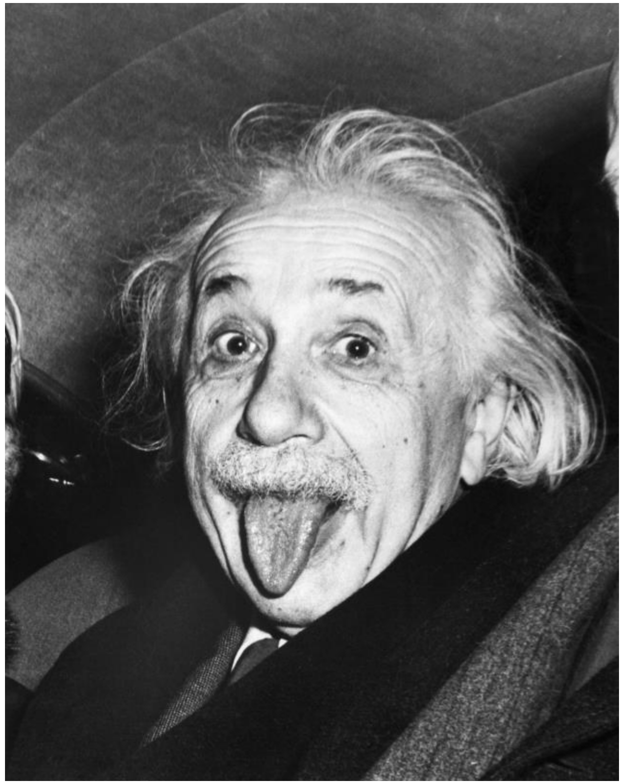
The ALPHA Experiment

- Measured the 1S-2S transition to about 2ppt [1]
- Measured the hyperfine structure to about 1kHz [2]
- Measured the 1S-2P Lyman-alpha transition [3]
- Demonstrated laser cooling of antihydrogen [4]
- Set the bound on the antihydrogen charge to 1ppb [5]

[1] ALPHA, Characterization of the 1S-2S transition in antihydrogen, *Nature* **548**, 66 (2017).
[3] ALPHA, Observation of the 1S-2P Lyman-α transition in antihydrogen *Nature* **557**, 71 (2018).
[2] ALPHA, Observation of the hyperfine structure of *Nature* **561** 211 (2018).
[4] ALPHA, Laser cooling of antihydrogen atoms, *Nature* **592**, 211 (2021).
[5] ALPHA, An experimental limit on the charge of antihydrogen, *Nature Comm*, **5**, 3955 (2014).

Why measure antimatter gravity?





Einstein

- It is Einstein's Weak Equivalence Principle (WEP) that insists antimatter will fall in exactly the same way as normal matter.

- No WEP-breaking process has ever been found.

- WEP violation could shed light on the baryon asymmetry problem.

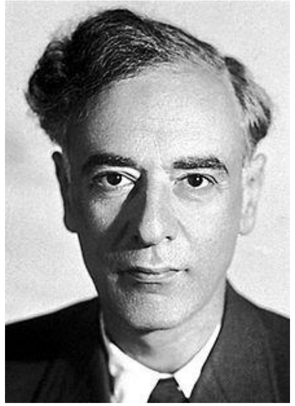
Why measure antimatter gravity?

- In addition to the WEP, there are many **other theoretical arguments** that argue **against** ‘weird’ antimatter gravity [1].

- There are **indirect experiments** that argue **against** ‘weird’ antimatter gravity [1].

- On the other hand, respectable theoretical physicists have considered the effect of **repulsive antimatter gravity** [2-5].

- There is **much to be learned** about gravity.



Lev Landau

“If CP is violated, I will hang myself.”

[1] Nieto, M. M. & Goldman, Physics Reports (1991): doi.org/10.1016/0370-1573(91)90138-C
[2] Kowitt, M. (1996). "Gravitational repulsion and Dirac antimatter". International Journal of Theoretical Physics. 35 (3): 605 631. Bibcode:1996IJTP...35..605K. doi:10.1007/BF02082828. S2CID 120473463.
[3] Santilli, R. M. (1999). "A classical isodual theory of antimatter and its prediction of antigravity". International Journal of Modern Physics A. 14 (14): 2205–2238. Bibcode:1999IJMPA..14.2205S. doi:10.1142/S0217751X99001111.
[4] Villata, M. (2011). "CPT symmetry and antimatter gravity in general relativity". EPL. 94 (2): 20001. arXiv:1103.4937. Bibcode:2011EL.....9420001V. doi:10.1209/0295-5075/94/20001. S2CID 36677097.
[5] Cabbolet, M. J. T. F. (2010). "Elementary Process Theory: a formal axiomatic system with a potential application as a foundational framework for physics supporting gravitational repulsion of matter and antimatter". Annalen der Physik. 522 (10): 699–738. Bibcode:2010AnP...522..699C. doi:10.1002/andp.201000063. S2CID 123136646.

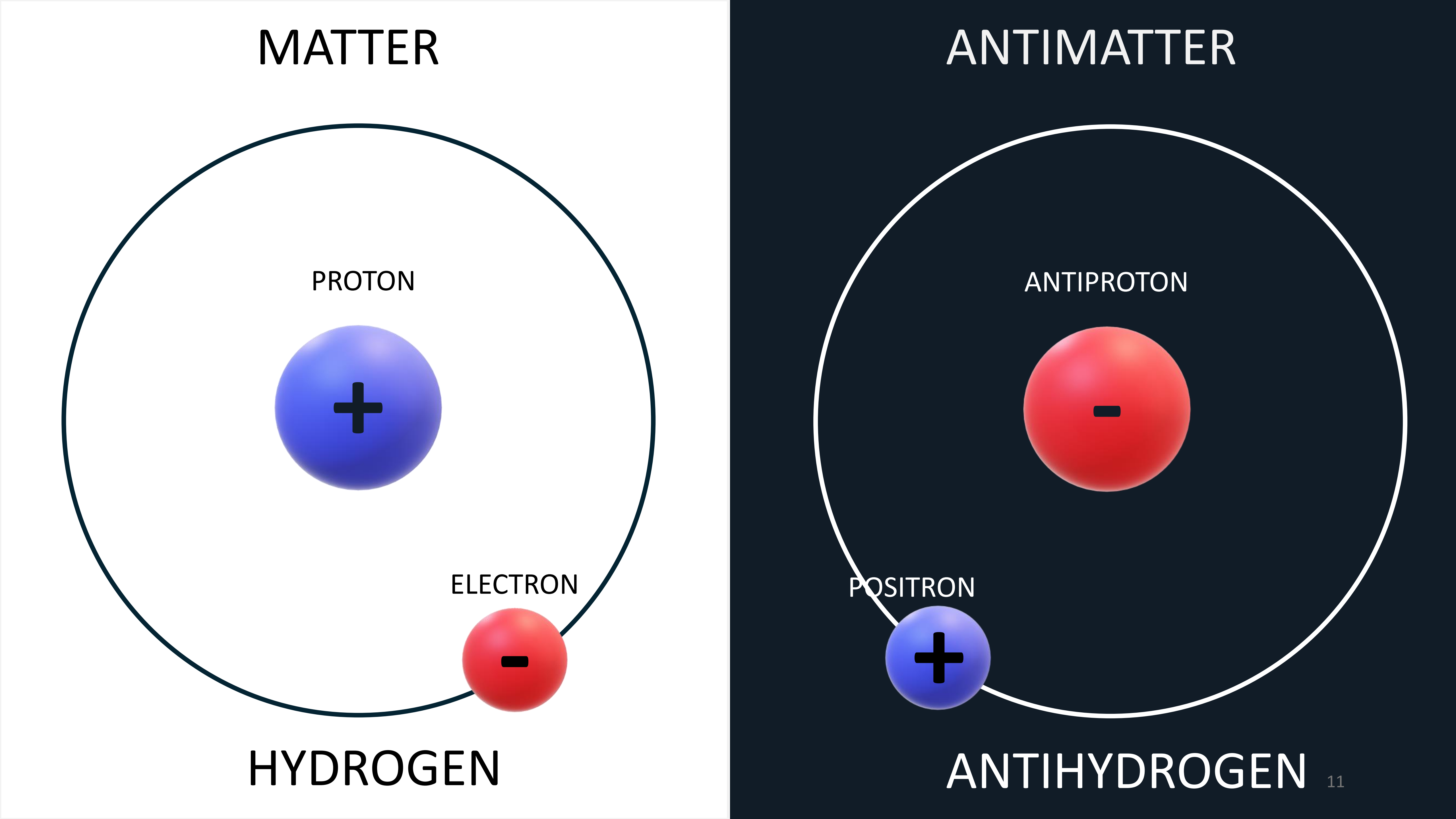
nature

Observation of the effect of gravity on the motion of antimatter

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

DIRECT


MATTER
ANTIMATTER
PROTON
ANTIPROTON
ELECTRON
POSITRON
HYDROGEN
ANTIHYDROGEN

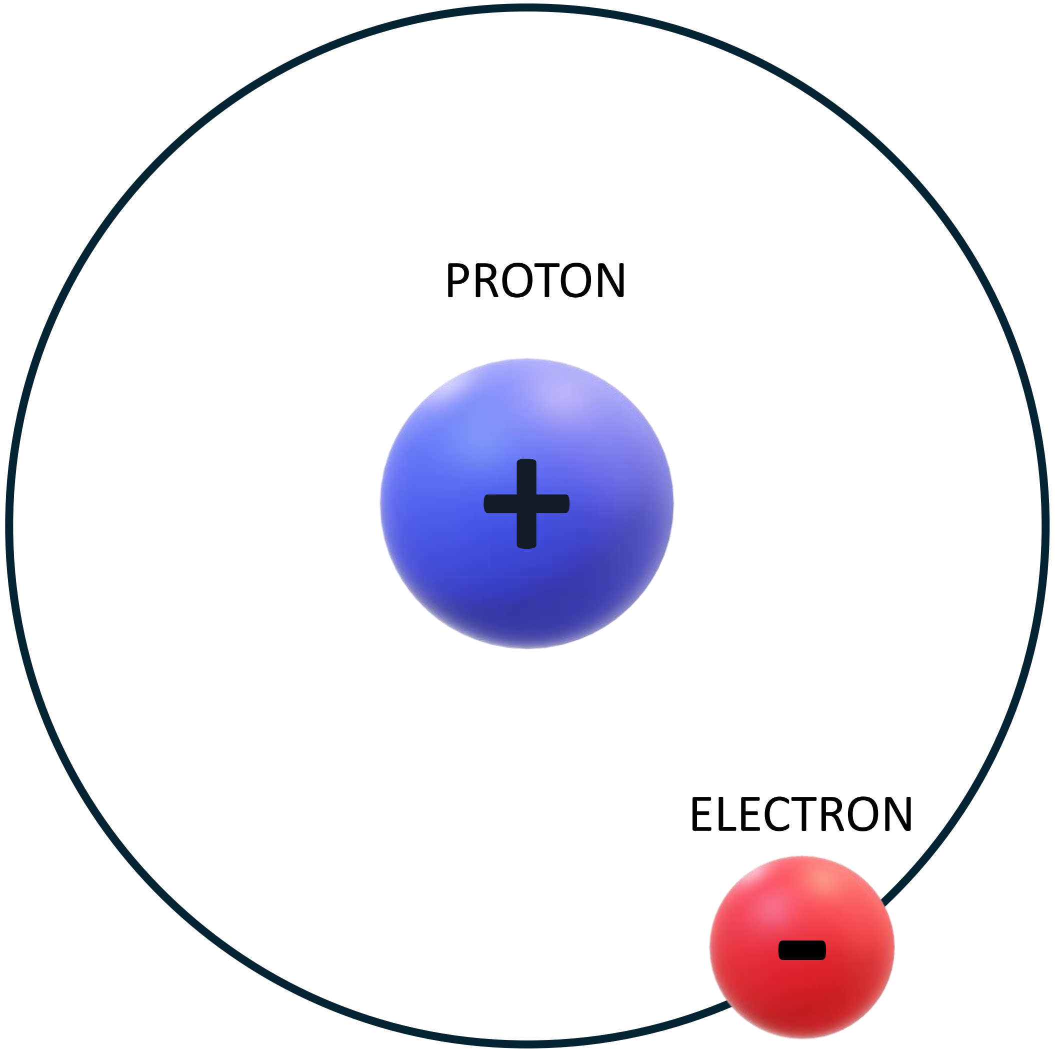
Overview

1. Motivation

2. **Our recent observation of the effect of gravity on antimatter**

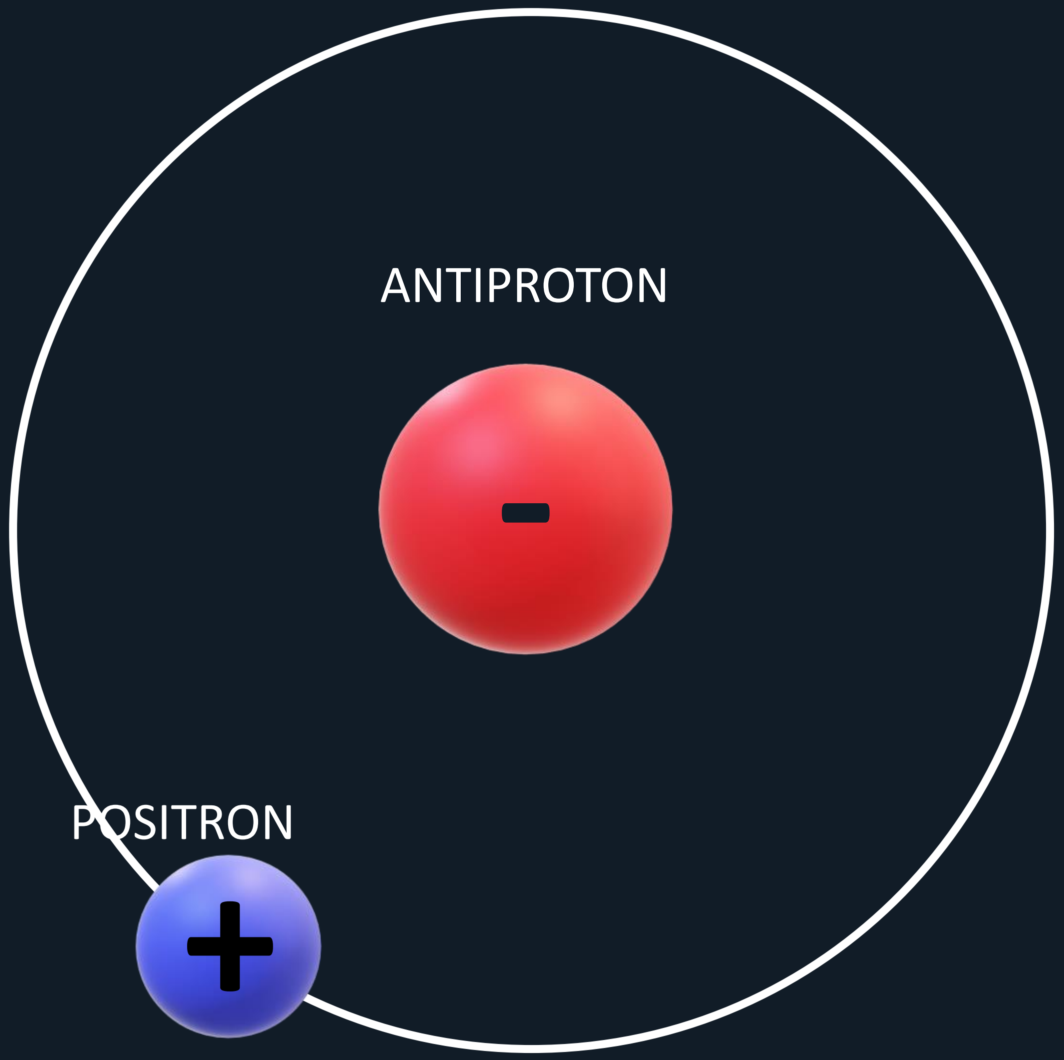
3. Future plans

MATTER



HYDROGEN

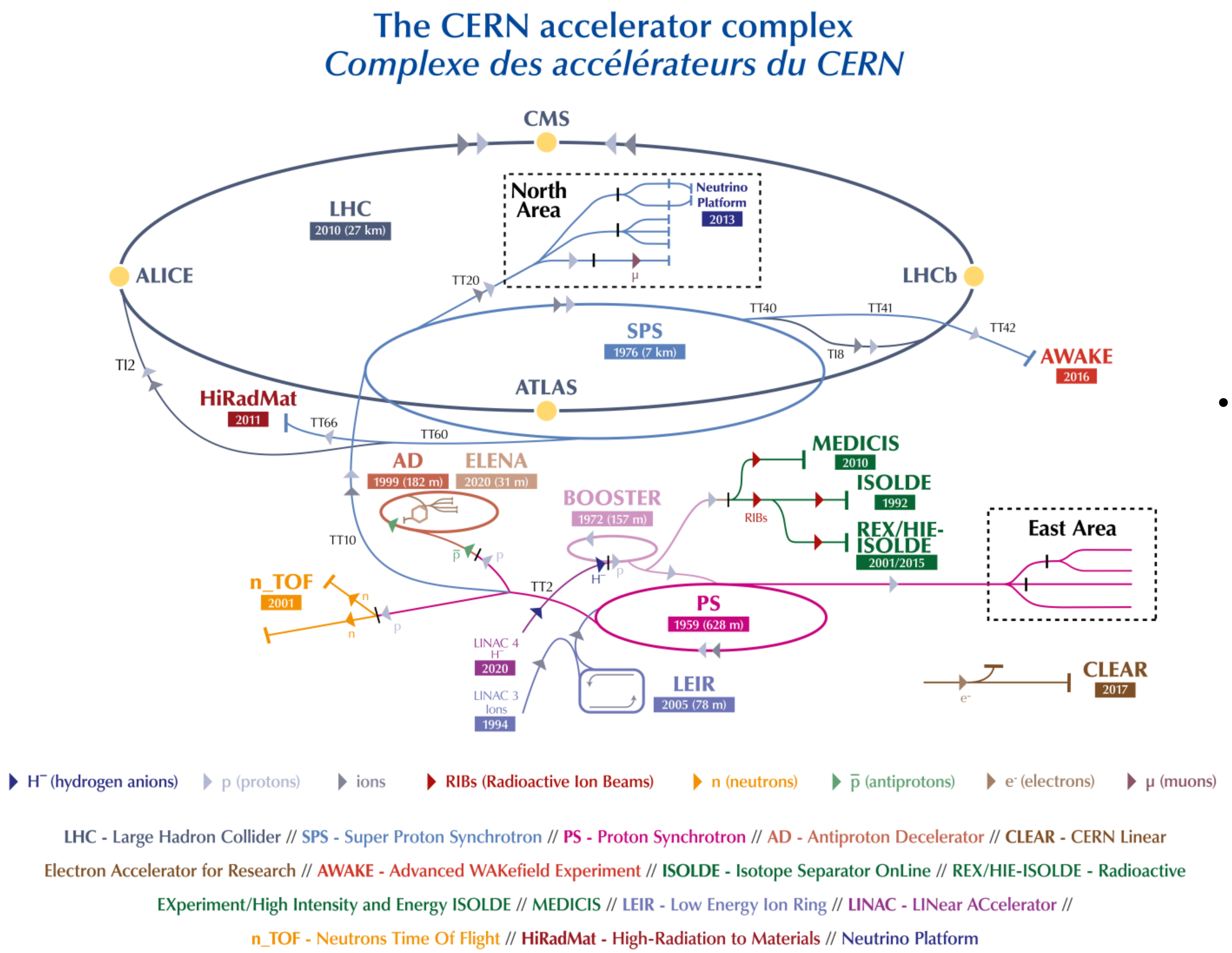
ANTIMATTER



ANTIHYDROGEN

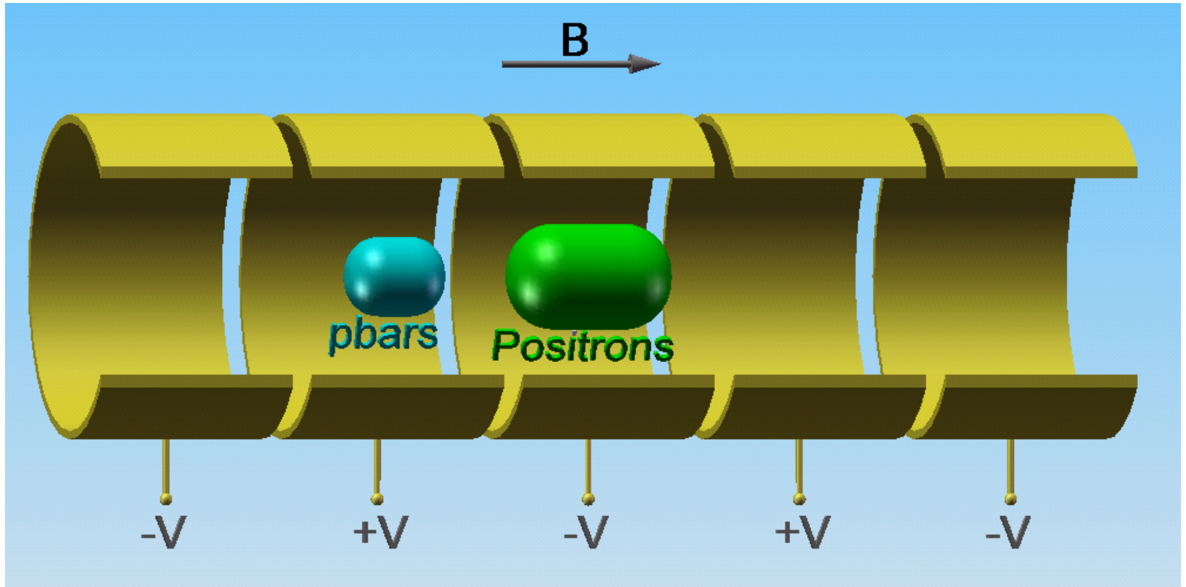
The Bevatron in 1958 (Image: Lawrence Berkeley National Laboratory)

Antiproton Discovery: Chamberlain and Segre 1955



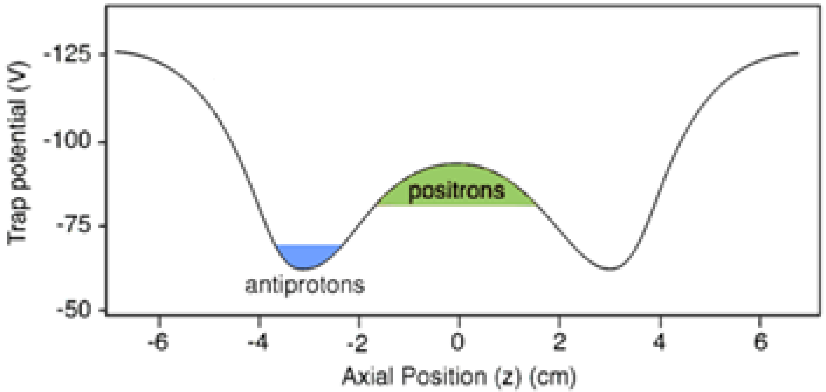
- AD and Elena typically delivers 10^7 antiprotons at 100keV every 2 minutes.


ANTIMATTER
FACTORY
ELENA



- Positrons cool via cyclotron cooling, producing around **3M** positrons at **~20K** with radius **1mm** [1].

- Antiprotons are sympathetically cooled with electrons, producing around **100,000** at **~100K** with radius **1mm** [1].

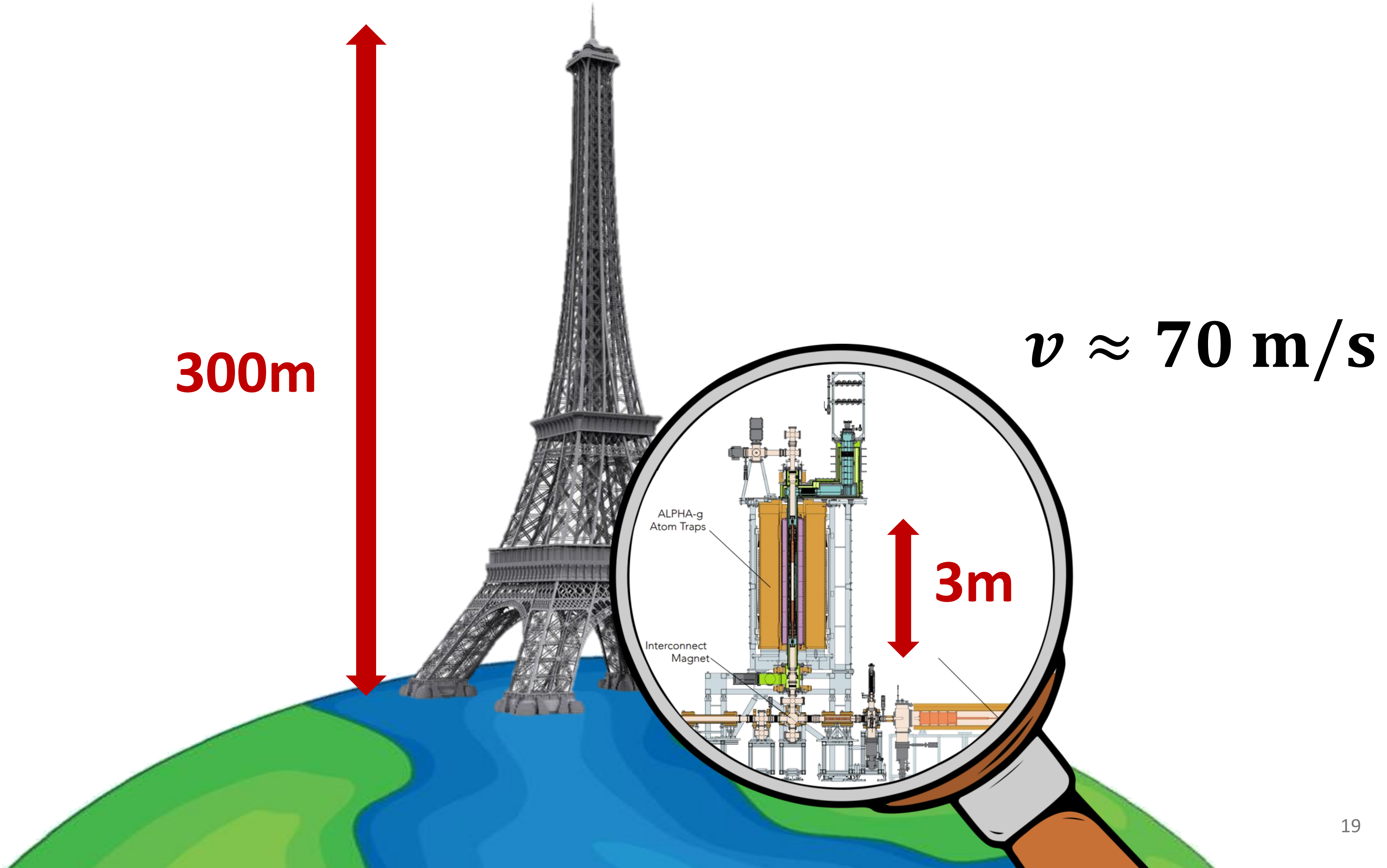


Frans Michel Penning

John Malmberg

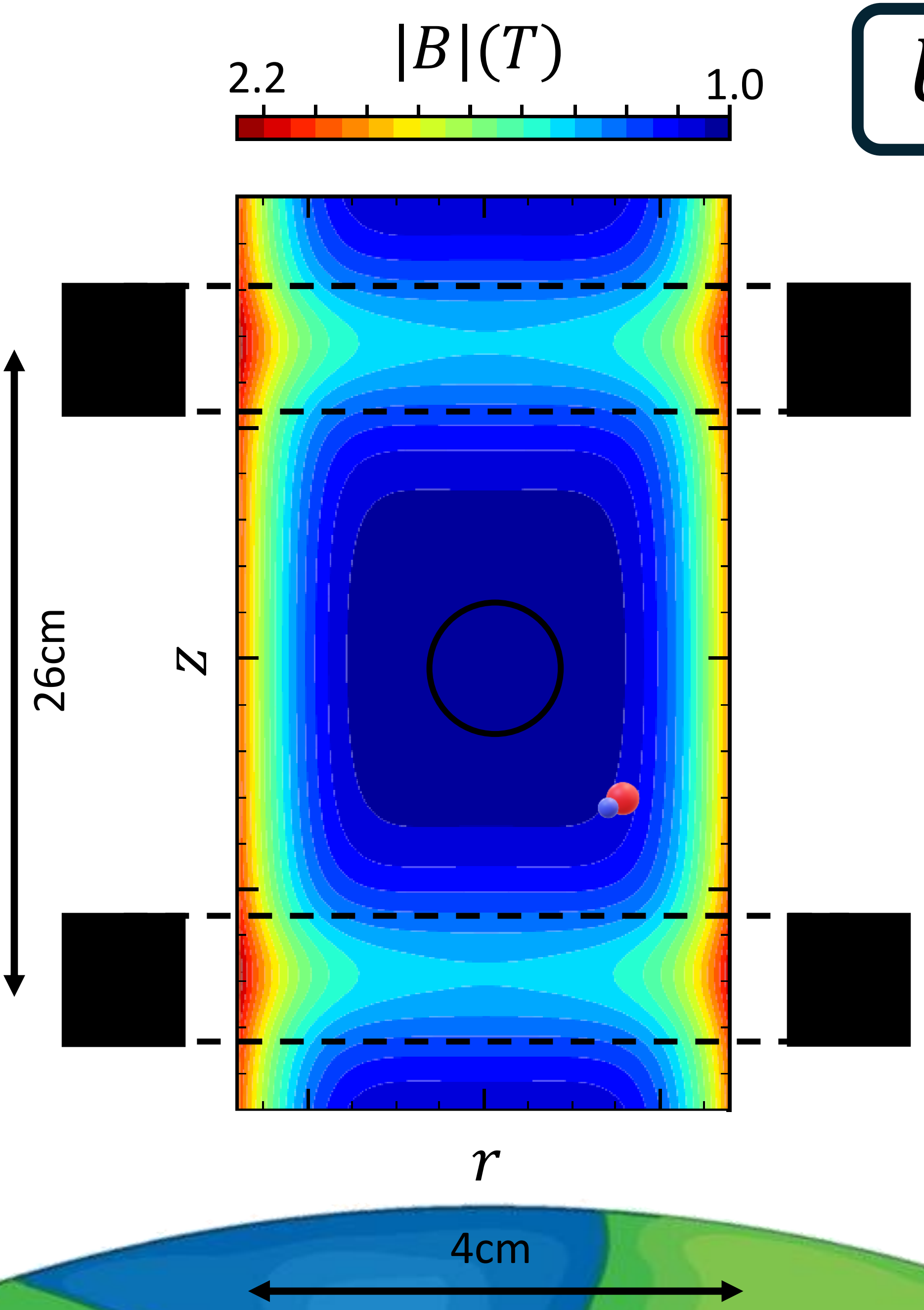
[1] ALPHA, Evaporative Cooling of Antiprotons to Cryogenic Temperatures, *Phys. Rev. Lett.*, **105** 013003, (2010).

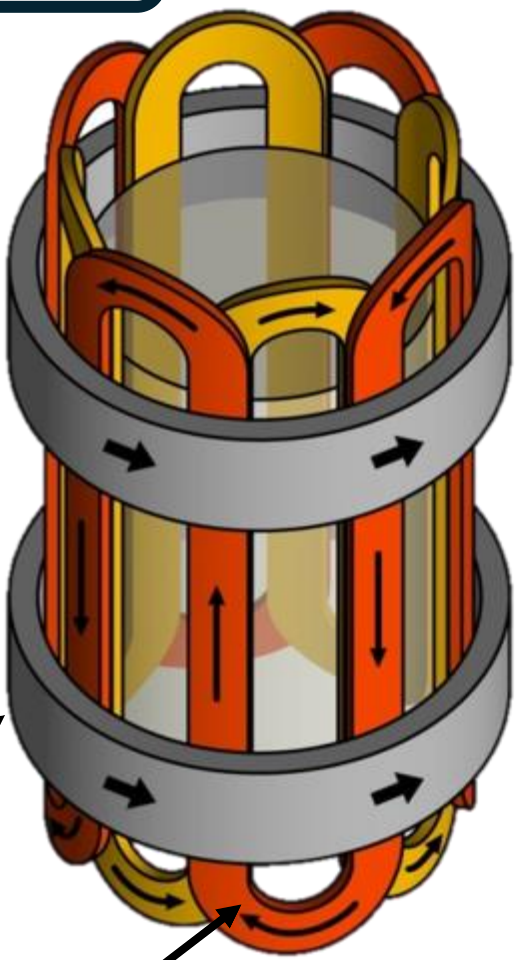

ANTIMATTER
FACTORY
ELENA


300m
ALPHA-g
Atom Traps
3m
Interconnect
Magnet
$v \approx 70\ \mathrm{m/s}$

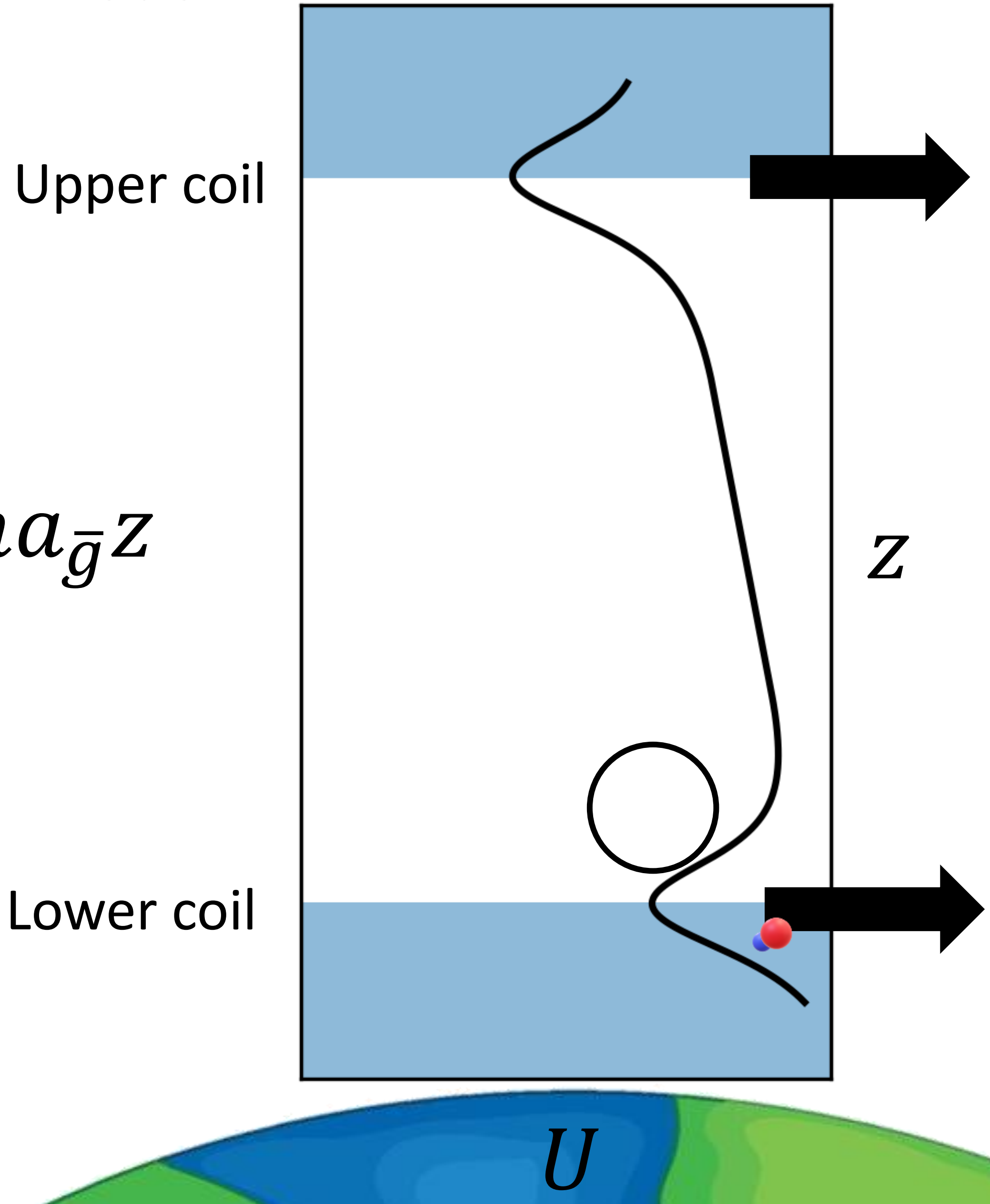
$$U_T = \mu|B|$$

- Magnetic moment of $\overline{\mathrm{H}}$ is small, so **trap depth is only ~0.5K**.
- Antihydrogen is formed around the temp of the e+ (~20K), only trap a **few atoms per mixing**
- Each mixing happens every 4min, so we **stack for hours** to obtain hundreds of atoms.
- Radial bounce time about 1ms, axial bounce time about 10ms





Simplified 1D On-Axis Model



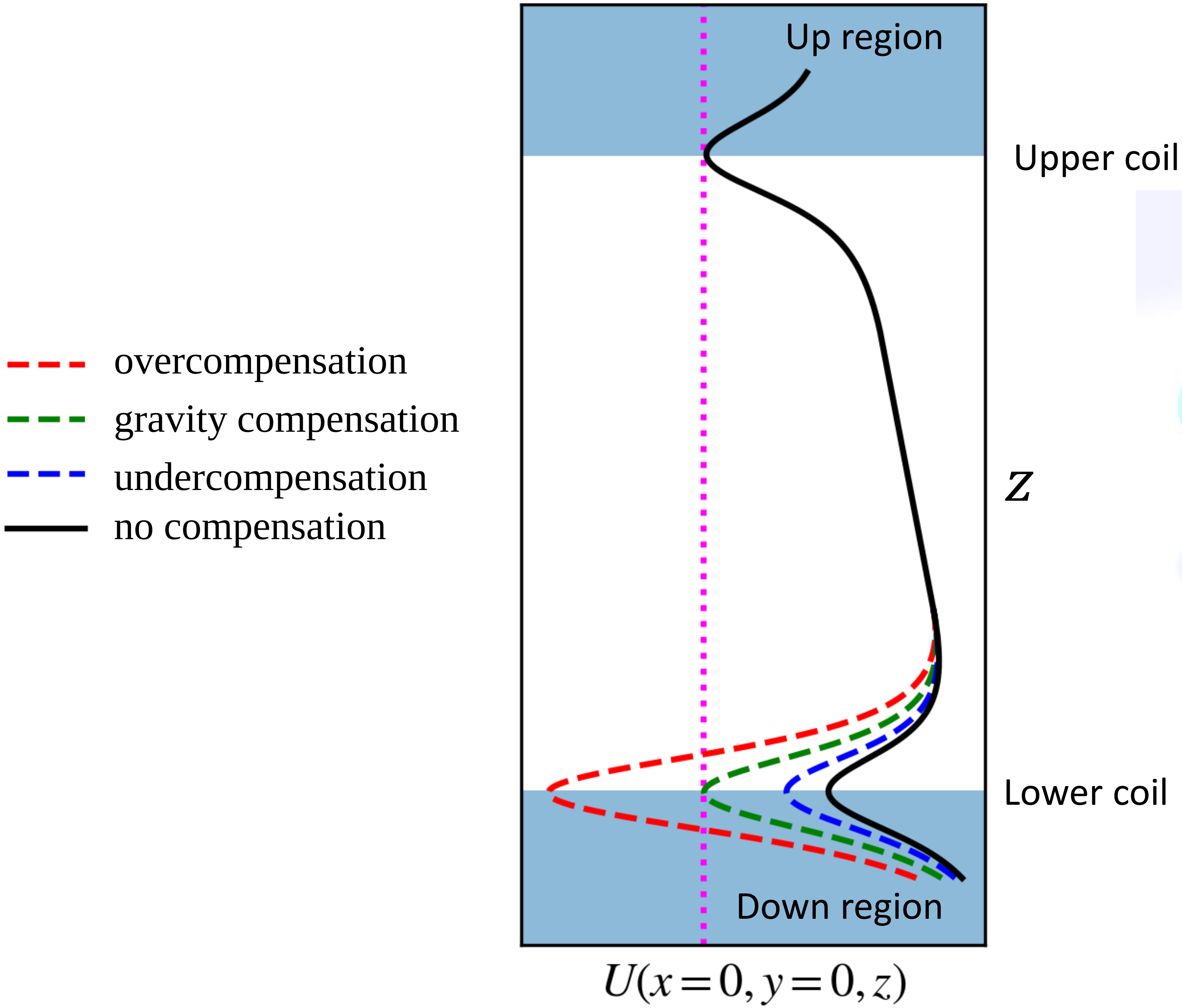
$$U = \mu|B| + m a_{\bar{g}} z$$

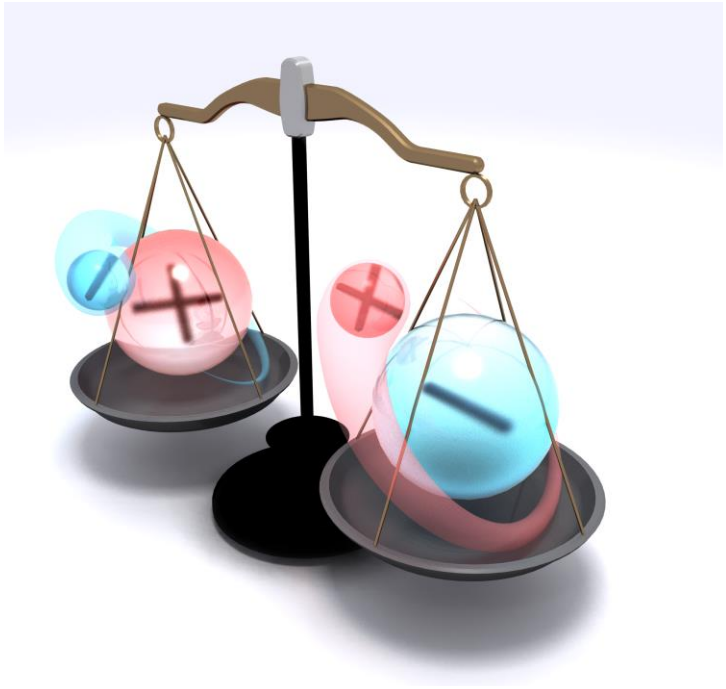
- A field difference of 4×10^{-4} T would mimic the force of gravity over the length of the trap.
- We perform **on-axis** online and offline **magnetometry** using plasma techniques [1,2].
- Superconducting magnetic fields do not follow a linear relationship with current due to **persistent fields**.
- 3D simulations model these persistent currents.

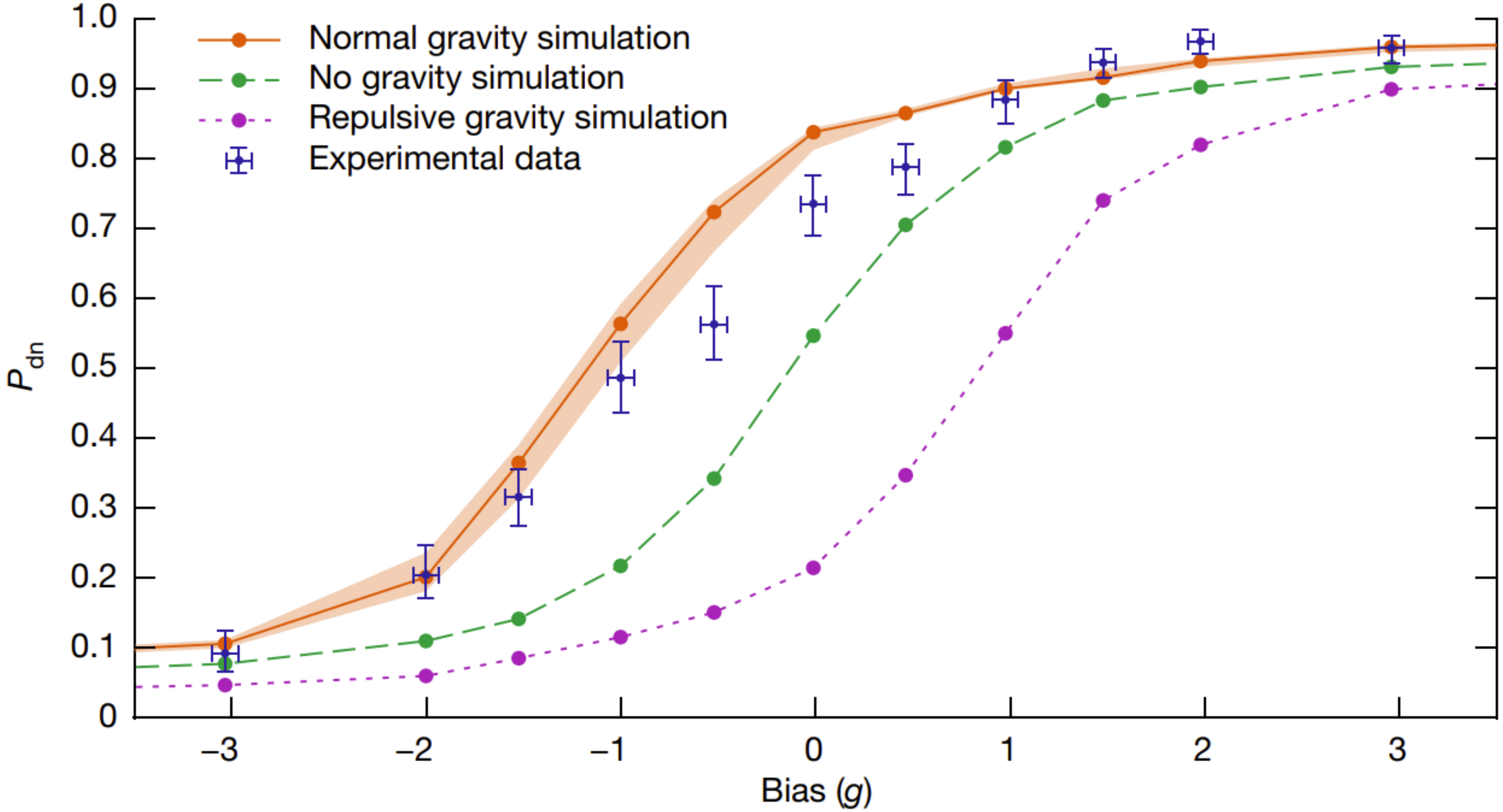
[1] ALPHA. In situ electromagnetic field diagnostics with an electron plasma in a Penning–Malmberg trap. New J. Phys. 16, 013037 (2014).
[2] A. Christensen et al., Measurements of Penning-Malmberg Trap Patch Potentials and Associated Performance Degradation, *Physical Review Research, L012008, (2024)*


AD
ANTIMATTER
FACTORY
ELENA

Simplified 1D On-Axis Model







$$a_{\bar{g}} = (0.75 \pm 0.13 \text{ (statistical + systematic)} \pm 0.16 \text{ (simulation)})g, \text{ where } g = 9.81 \text{ m s}^{-2}$$

- Dominant uncertainty from our ability to model the magnetic fields, in particular **off-axis**
- We set limits on off-axis persistent fields using critical current of superconductors

Overview

1. Motivation

2. Our recent observation of the effect of gravity on antimatter

3. **Future plans**

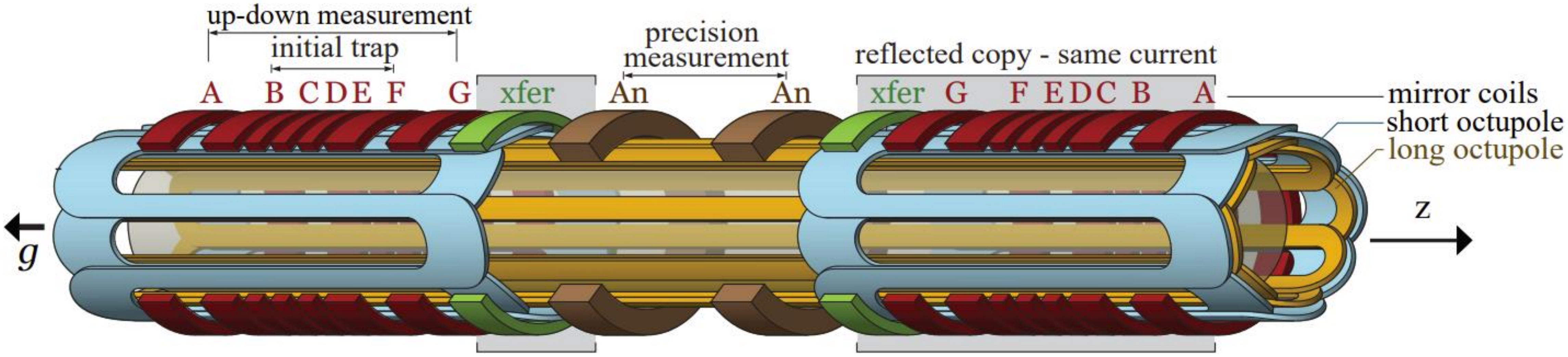
Future Plans: achieving higher precision

1. **Off-axis magnetometry**

2. Antihydrogen **phase-space measurements** and comparison to simulation

3. Transfer to the **precision region**

[1] ALPHA, Laser cooling of antihydrogen atoms, *Nature* **592**, 211 (2021).
[2] Hodgkinson, D. *On the Dynamics of Adiabatically Cooled Antihydrogen in an Octupole-Based Ioffe-Pritchard Magnetic Trap*. PhD thesis, Univ. of Manchester (2022).
[3] Hamilton, P. et al. Antimatter interferometry for gravity measurements. Phys. Rev. Lett. 112, 121102 (2014).
[4] Jones, S.A. An ion trap source of cold atomic hydrogen via photodissociation of the BaH+ molecular ion. *New J. Phys.* **24** 023016 (2022),
[5] Cesar, C.L. *A platform for trapped cryogenic electrons, anions and cations for fundamental physics and chemical studies,* arXiv:2301.13248 (2023).
[6] W. A. Bertsche *et al*. A Low Energy H^- Beamline for the ALPHA Antihydrogen Experiment *J. Phys.: Conf. Ser.* **2244** 012080 (2022).
[7] Baker, C. J. et al. Sympathetic cooling of positrons to cryogenic temperatures for antihydrogen production. *Nat. Commun.* **12**, 6139 (2021).



- The precision region is significantly further from the octupole end turns.
- Magnetic confinement is weaker
- A reflected copy of the up-down measurement trap enables symmetry cancellation of persistent currents.

Future Plans: achieving higher precision

1. **Off-axis magnetometry**

2. Antihydrogen **phase-space measurements** and comparison to simulation

3. Transfer to the **precision region**

4. **Cooling** techniques (laser cooling [1] and adiabatic cooling [2]), ultimately leading to antihydrogen fountain measurements predicting precision of 10^{-6} in determining $a_{\bar{g}}$ [3].

5. Measuring the gravitational acceleration of **hydrogen** in ALPHA-g [4,5,6]

6. Sympathetic cooling of positrons [7]

[1] ALPHA, Laser cooling of antihydrogen atoms, *Nature* **592**, 211 (2021).
[2] Hodgkinson, D. *On the Dynamics of Adiabatically Cooled Antihydrogen in an Octupole-Based Ioffe-Pritchard Magnetic Trap*. PhD thesis, Univ. of Manchester (2022).
[3] Hamilton, P. et al. Antimatter interferometry for gravity measurements. Phys. Rev. Lett. 112, 121102 (2014).
[4] Jones, S.A. An ion trap source of cold atomic hydrogen via photodissociation of the BaH+ molecular ion. *New J. Phys.* **24** 023016 (2022),
[5] Cesar, C.L. *A platform for trapped cryogenic electrons, anions and cations for fundamental physics and chemical studies,* arXiv:2301.13248 (2023).
[6] W. A. Bertsche *et al*. A Low Energy H^- Beamline for the ALPHA Antihydrogen Experiment *J. Phys.: Conf. Ser.* **2244** 012080 (2022).
[7] Baker, C. J. et al. Sympathetic cooling of positrons to cryogenic temperatures for antihydrogen production. *Nat. Commun.* **12**, 6139 (2021).

Joel Fajans

Jonathan Wurtele

Will Bertsche

Thank you for listening!

Contact: danielle.louise.hodgkinson@cern.ch