The antimatter factory at CERN: experiments with antimatter systems

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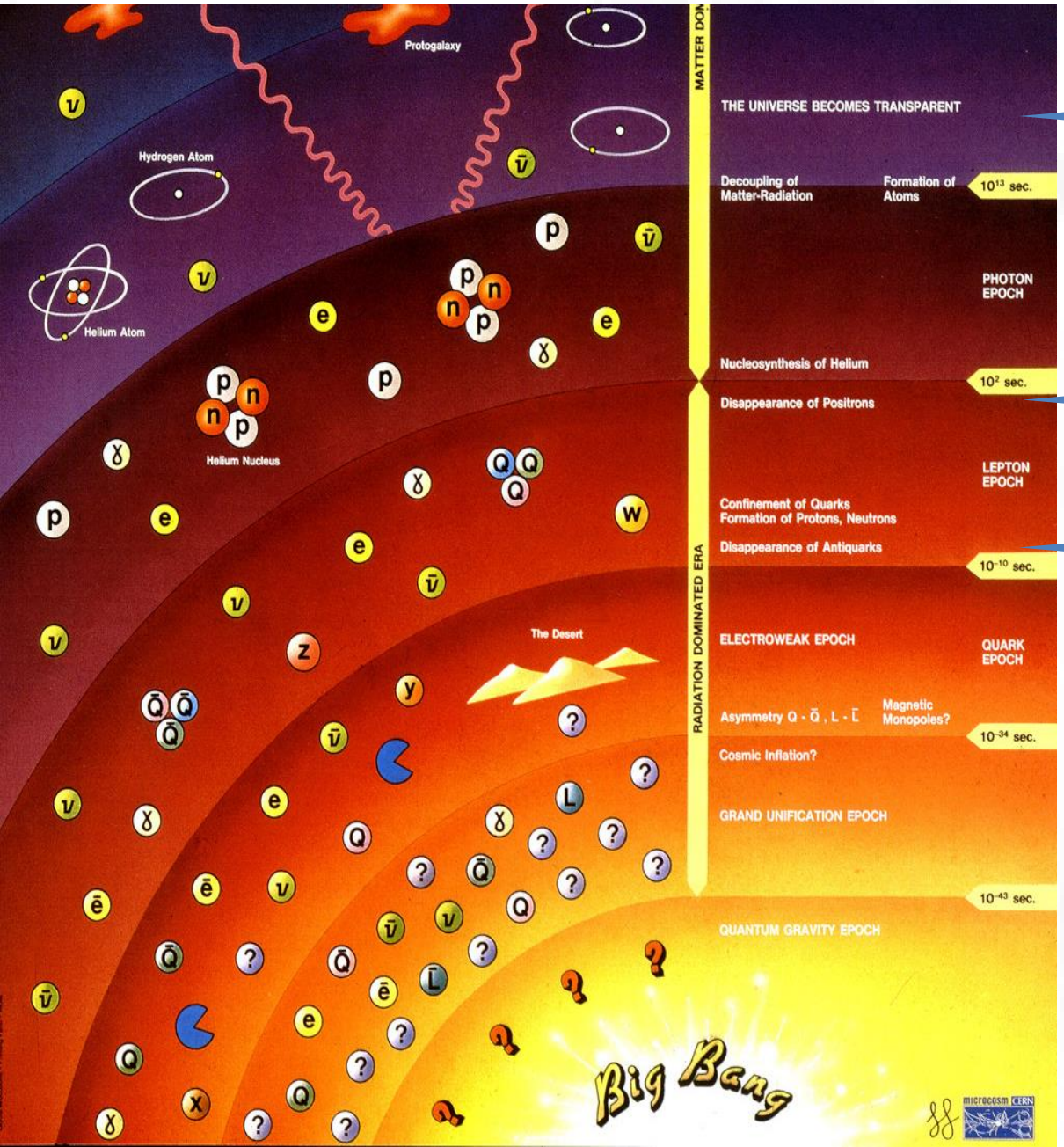
UNIVERSITÀ
DI TRENTO

Introduction: matter/antimatter asymmetry



Imbalance in matter and antimatter in the observable universe

The disappearance of anti matter is not fully understood neither from theory or experiment

Violation of CPT?
Weak equivalence principle (WEP)?

Production of antimatter systems

ANTIPROTON

The proton's antimatter counterpart is produced in high-energy collisions and needs heavy deceleration.

POSITRON

This lower-mass particle, the electron's antimatter counterpart, is produced in radioactive decays.

POSITRONIUM

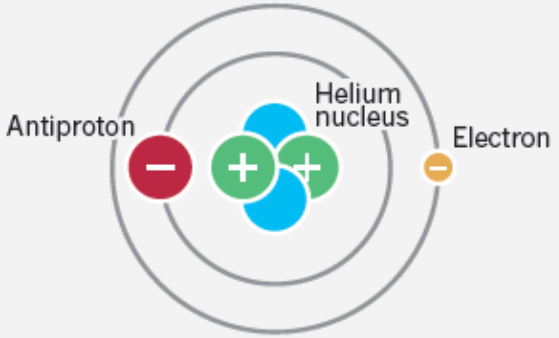
An electron and a positron can be combined to make positronium

ANTIHYDROGEN

An antiproton and a positron can be combined to make antihydrogen, opening up opportunities to study new properties.

ANTIPROTONIC HELIUM

Researchers also build this exotic hybrid, in which an antiproton takes the place of an electron in a helium atom.

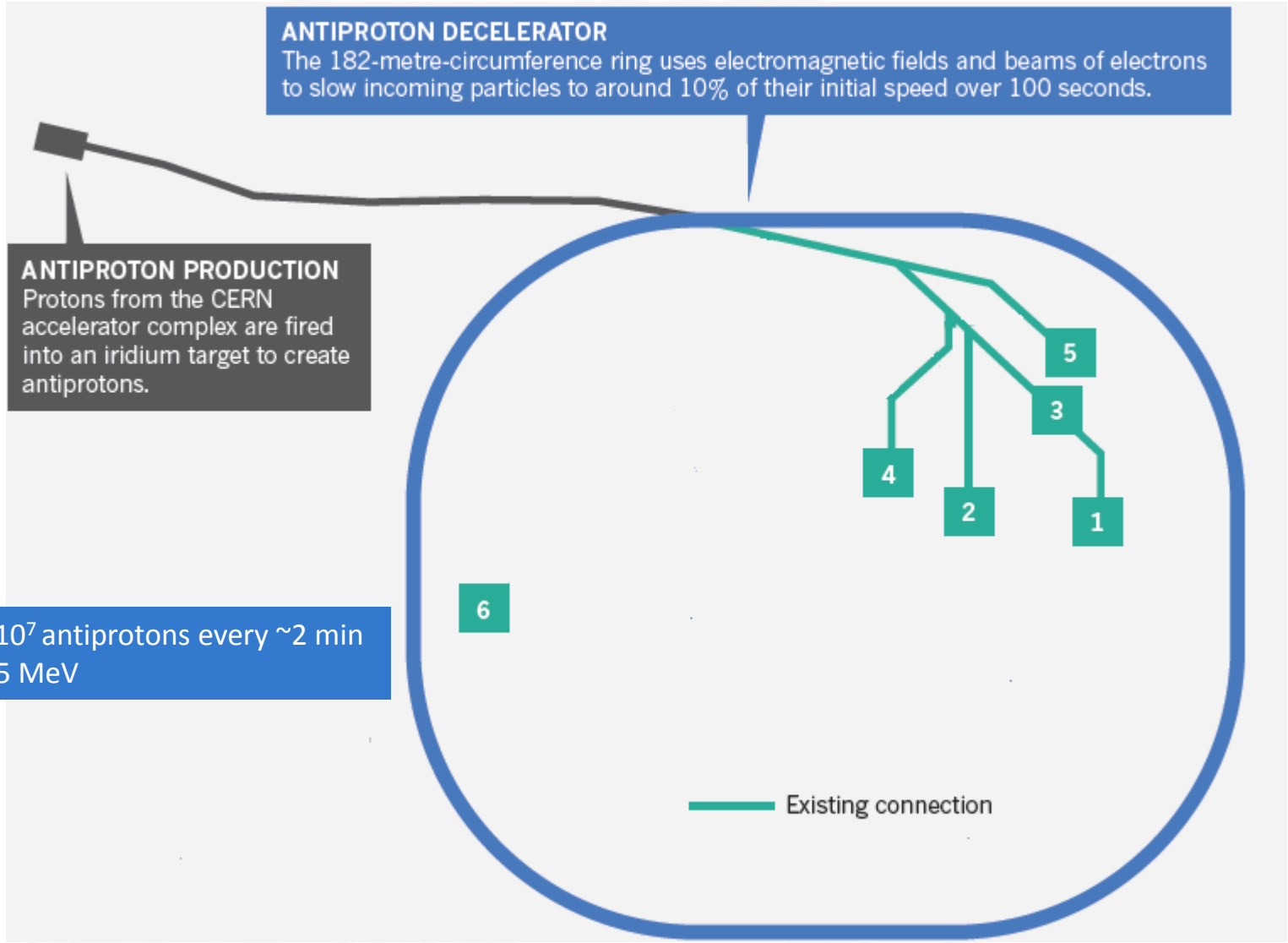


Gibney, E Nature **548**, 20 (2017)

Antiproton production (before 2021)

ANTIPROTON

The proton's antimatter counterpart is produced in high-energy collisions and needs heavy deceleration.

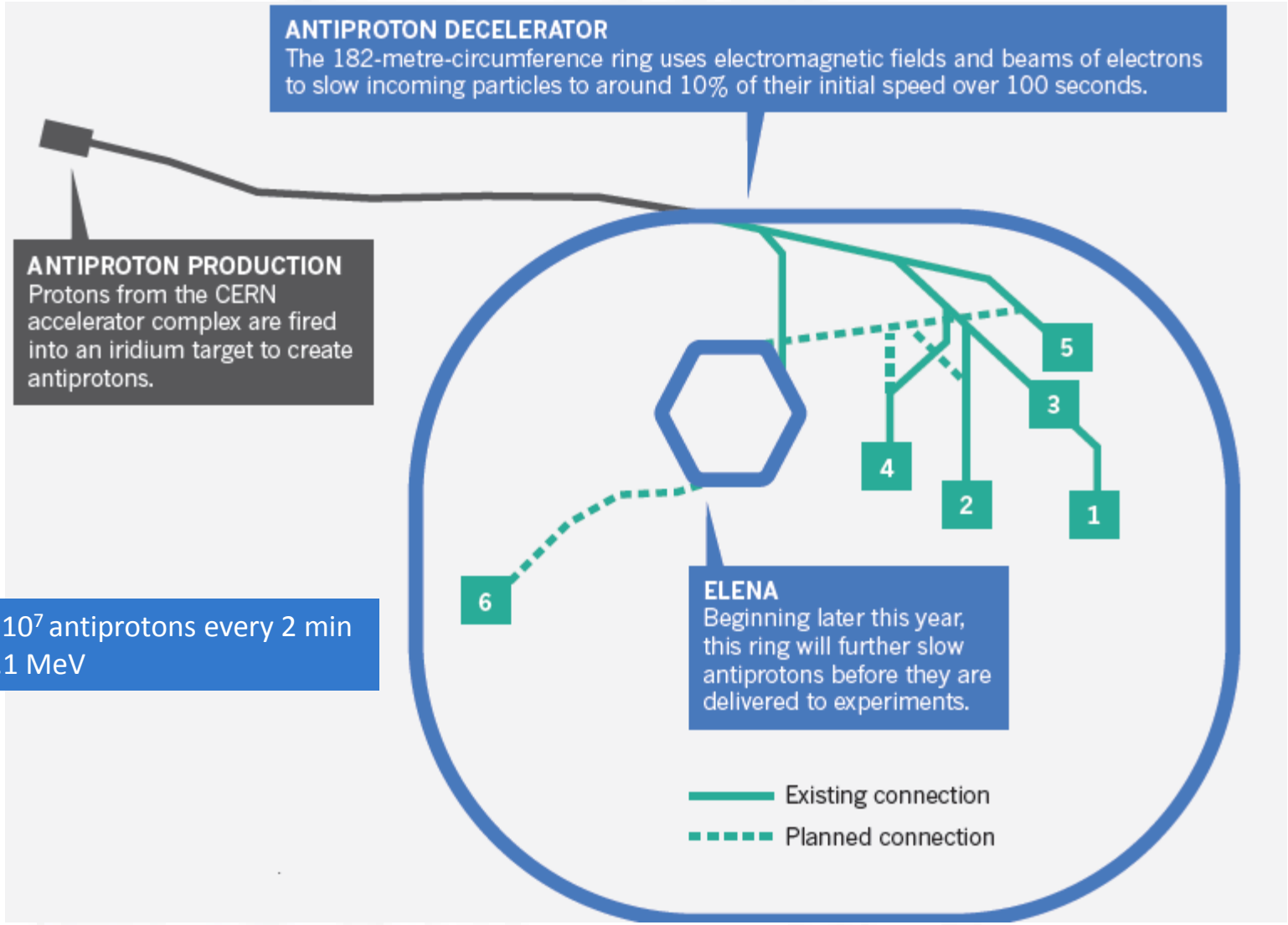


2 10^7 antiprotons every ~2 min
3.5 MeV

Antiproton production (from 2021)

ANTIPROTON

The proton's antimatter counterpart is produced in high-energy collisions and needs heavy deceleration.



2 10^7 antiprotons every 2 min
0.1 MeV

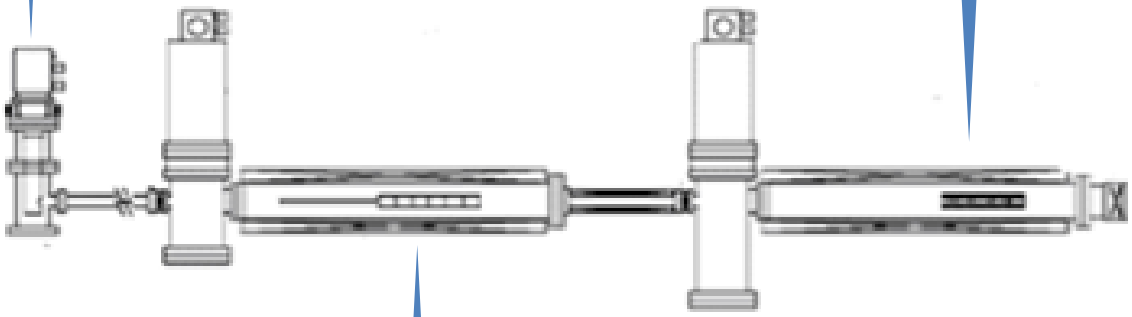
Positron production

POSITRON

This lower-mass particle, the electron's antimatter counterpart, is produced in radioactive decays.

Beta$^+$ source + solid Ne moderator
For the production of few eV positrons

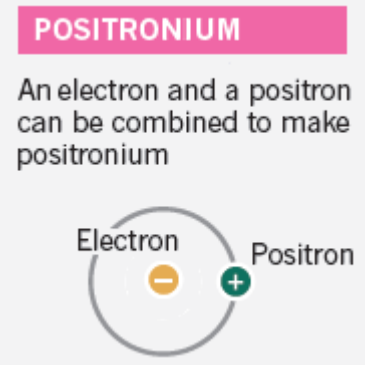
Penning-Malmberg accumulator to store up to 10^8 positrons with lifetime of several minutes. Positrons can then bunched in ~20 ns.

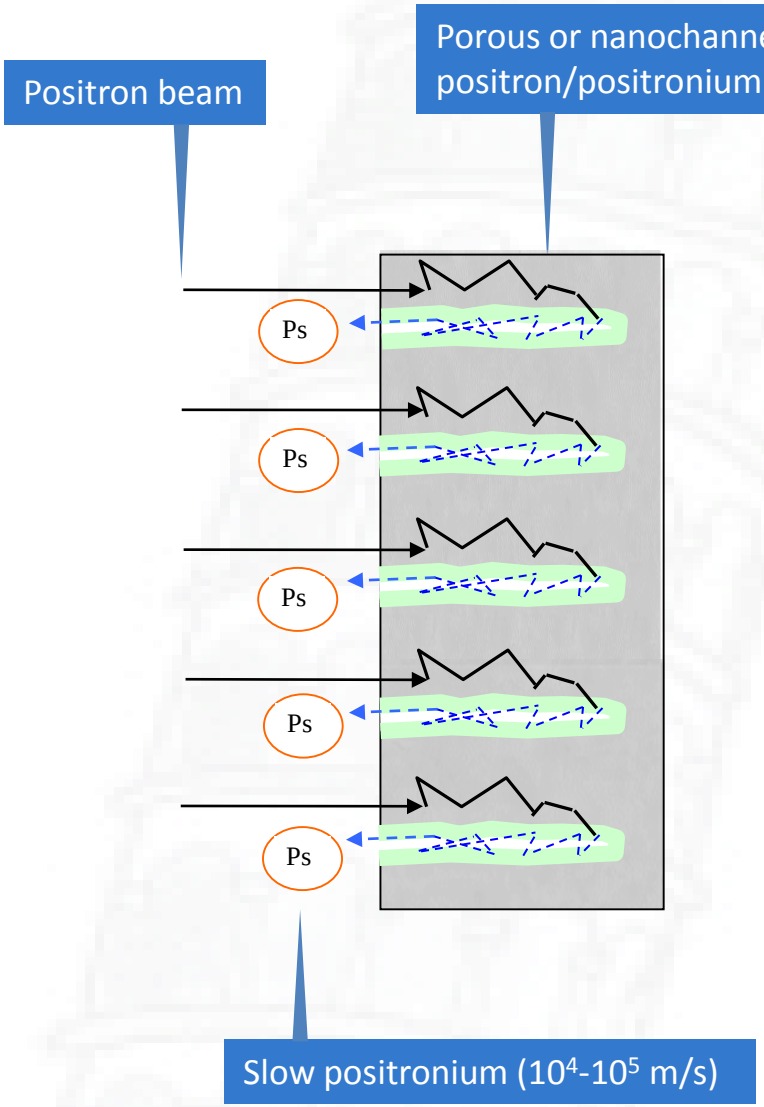


Buffer gas positron trap. Around 15% of incoming positrons are trapped in a Penning-Malmberg trap to produce bunches of up to some 10^5 positron/s

Danielson, JR... Surko, CM *Rev Mod Phys* **87**, 247 (2015)

Positronium production



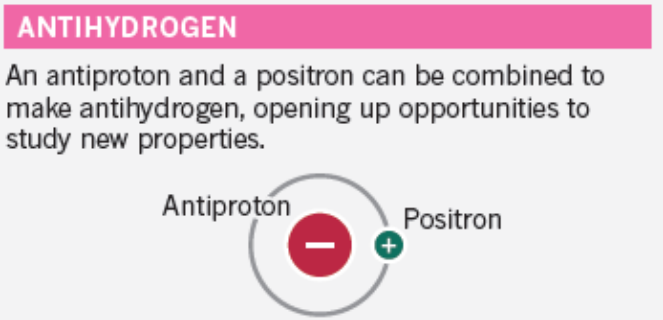


The lifetime of emitted positronium in the 1^3S ground state is 142 ns. Its lifetime can be extended to μs or ms via laser excitation to metastable levels.

Cassidy DB et al., *Phys Rev Lett* **108**, 043401 (2012)

Cassidy DB et al., *Phys Rev A* 81, 012715 (2010)
Mariazzi S et al., *Phys Rev Lett* **104**, 243401 (2010)

Antihydrogen production



Antihydrogen formation via mixing

$$\bar{p} + e^+ + e^+ \rightarrow \bar{H}^* + e^+$$

Positron carrying away the binding energy

Amoretti M et al., (ATHENA collaboration) *Nature* **419**, 456 (2002)

Gabrielse G et al., (ATRAP collaboration) *Phys Rev Lett* **89**, 213401 (2002)

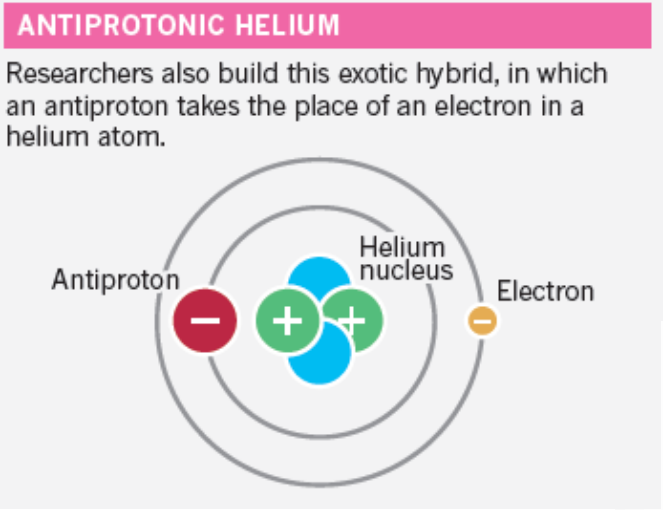
Antihydrogen formation via charge exchange reaction

$$\bar{p} + Ps^* \rightarrow \bar{H}^* + e^-$$

Storry C et al., (ATRAP collaboration) *Phys Rev Lett* **93**, 263401 (2004)

To maximize the cross section:
- Cold Ps (10^4-10^5 m/s)
- Ps in Rydberg states

Antiprotonic helium production



Antiprotonic helium formation

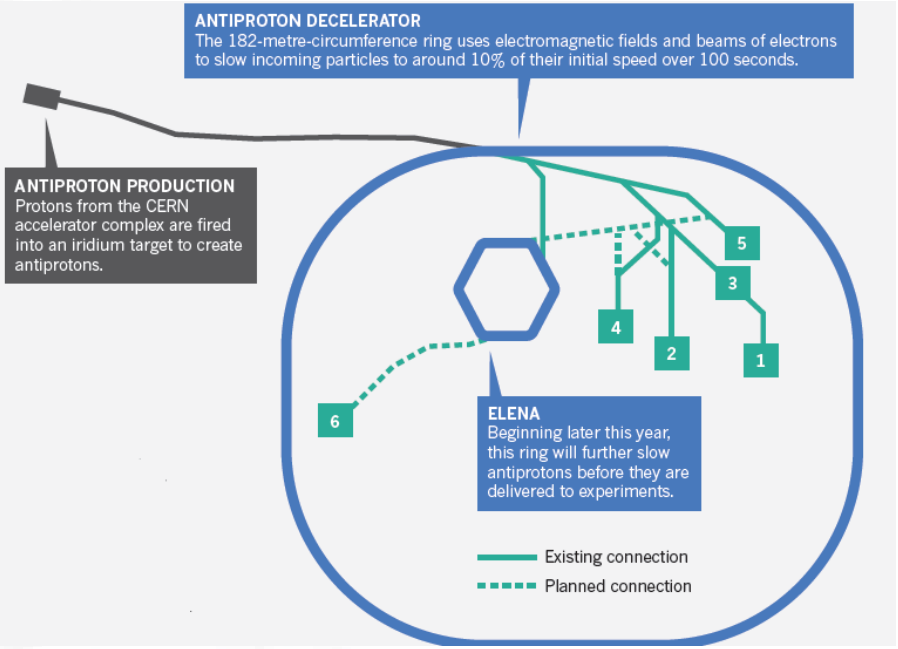
$$\bar{p} + He \rightarrow \bar{p}He$$

Around 3% of implanted antiprotons form antiprotonic helium in a Rydberg state (n>38 and L>35) with a lifetime longer than 1 μs.

One of the He 's two electrons is knocked out and replaced by antiproton

Iwasaki M et al., *Phys Rev Lett* **67**, 1246 (1991)

AD experiments



1 ALPHA

Started: 2005

Studies: Charge, spectroscopy and acceleration under gravity of antihydrogen.

2 ASACUSA

Started: 2000

Studies: Mass of antiproton (relative to the electron), spectroscopy of antihydrogen and antiprotonic helium.

3 ATRAP

Started: 2000

Studies: Magnetic moment and charge-to-mass ratio of antiprotons; plans to study the spectroscopy of antihydrogen.

4 BASE

Started: 2014

Studies: Charge-to-mass ratio and magnetic moment of antiprotons.

5 AEGIS

Started: 2015

Studies: Gravitational acceleration of antihydrogen atoms.

6 GBAR

Started: 2017

Studies: Gravitational acceleration of antihydrogen atoms.

ALPHA experiment

1 ALPHA

Started: 2005

Studies: Charge, spectroscopy and acceleration under gravity of antihydrogen.

Antihydrogen Laser PHysics Apparatus

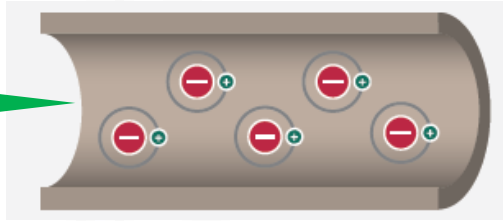
Antihydrogen produced via mixing

$$\bar{p} + e^+ + e^+ \rightarrow \bar{H}^* + e^+$$

Antihydrogen trapped in a magnetic Ioffe trap (antihydrogen temperature ~0.5 K)

Andresen G B et al., (ALPHA collaboration) *Nature* **468**, 673 (2010)

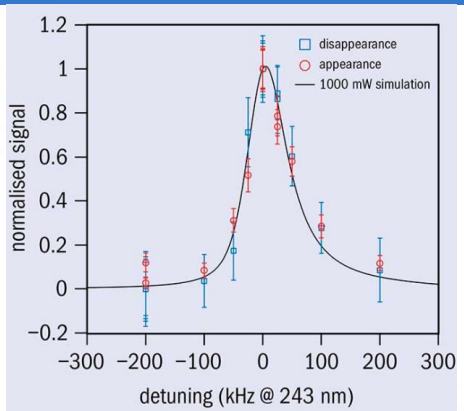
Test of CPT invariance: spectroscopy of 1S-2S



Only some S sublevels with specific magnetic quantum number m are trapped.

2S→1S spontaneous decay populates all the S sublevels. A fraction of antihydrogen atoms is lost after each excitation.

Ahmadi M et al., (ALPHA collaboration) *Nature* **557**, 71 (2018)



CPT invariance at the precision of 2×10^{-12}

ALPHA experiment

1 ALPHA

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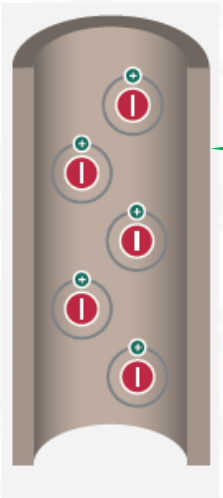


Test of WEP

Removal of the confining magnetic field and count of the antihydrogen annihilations on the two trap sides.

Amole C et al., (ALPHA collaboration) *Nature Comm* **4**, 1785 (2013)

No Italian institutes currently involved

ASACUSA experiment

2 ASACUSA

Started: 2000

Studies: Mass of antiproton (relative to the electron), spectroscopy of antihydrogen and antiprotonic helium.

Atomic Spectroscopy And Collisions Using Slow Antiprotons

Antiprotonic helium formation

$$\bar{p} + He \rightarrow \bar{p}He$$

Laser spectroscopy for antiproton-to-electron mass ratio measurement

Antiprotonic helium cooled at 1.5-1.7 K in He gas

Laser induced transition to lower levels with short lifetime

Cherenkov detector to detect the pions and reveal the resonance conditions

Comparison of the measured and calculated frequencies to extract the antiproton-to-electron mass ratio

In agreement within 8 10^{-10} with experimental proton-to-electron mass ratio

Hori M et al., *Science* **354, 610** (2016)

Hori M et al., *Nature* **475**, 484 (2011)

ASACUSA experiment

2 ASACUSA

Started: 2000

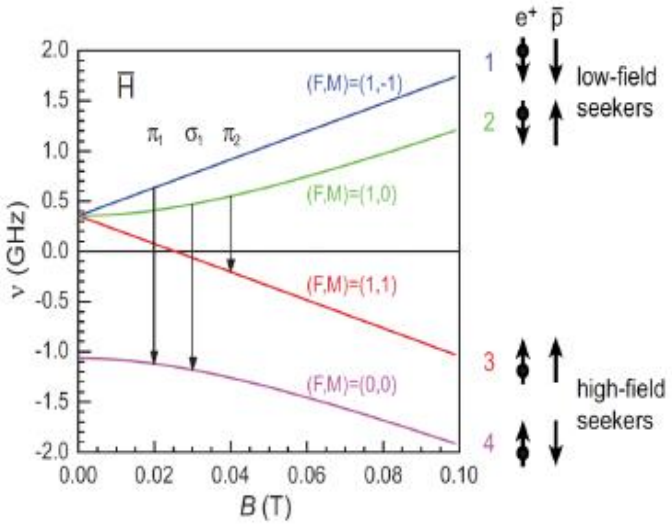
Studies: Mass of antiproton (relative to the electron), spectroscopy of antihydrogen and antiprotonic helium.

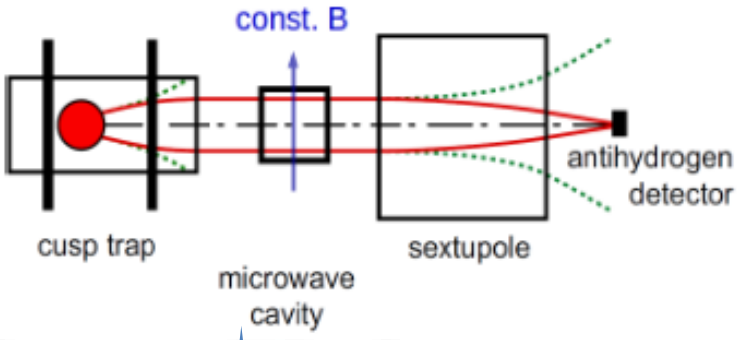
Atomic Spectroscopy And Collisions Using Slow Antiprotons

Antihydrogen produced via mixing

$$\bar{p} + e^+ + e^+ \rightarrow \bar{H}^* + e^+$$

Production of an antihydrogen beam for HFS studies





Lfs-hfs flipper

Kuroda N et al., (ASACUSA collaboration) *Nature Comm* **5**, 3089 (2014)

Antiproton-nucleous annihilation cross section

Aghai-Khozani H et al., (ASACUSA collaboration) *Nucl Phys A 970*, 266 (2018)

UNIBS-INFN Pavia ~9 people
UNIMI-POLIMI-INFN Milano

ATRAP experiment

Antihydrogen TRAP experiment

Activity closed

3 ATRAP

Started: 2000

Studies: Magnetic moment and charge-to-mass ratio of antiprotons; plans to study the spectroscopy of antihydrogen.

Antihydrogen produced via mixing

$$\bar{p} + e^+ + e^+ \rightarrow \bar{H}^* + e^+$$

Gabrielse G et al., (ATRAP collaboration) *Phys Rev Lett* **89**, 213401 (2002)

Antihydrogen formation via double charge exchange reaction

$$Cs^* + e^+ \rightarrow Ps^* + Cs^+$$

$$\bar{p} + Ps^* \rightarrow \bar{H}^* + e^-$$

Storry C et al., (ATRAP collaboration) *Phys Rev Lett* **93**, 263401 (2004)

Antihydrogen trapped in a magnetic Ioffe trap

Gabrielse G et al., (ATRAP collaboration) *Phys Rev Lett* **108**, 113002 (2012)

No Italian institutes involved

BASE experiment

4 BASE

Started: 2014

Studies: Charge-to-mass ratio and magnetic moment of antiprotons.

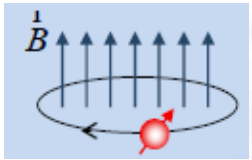
Barion Antibarion Simmetry Experiment

Measurement of antiproton-to-proton charge-to-mass ratio

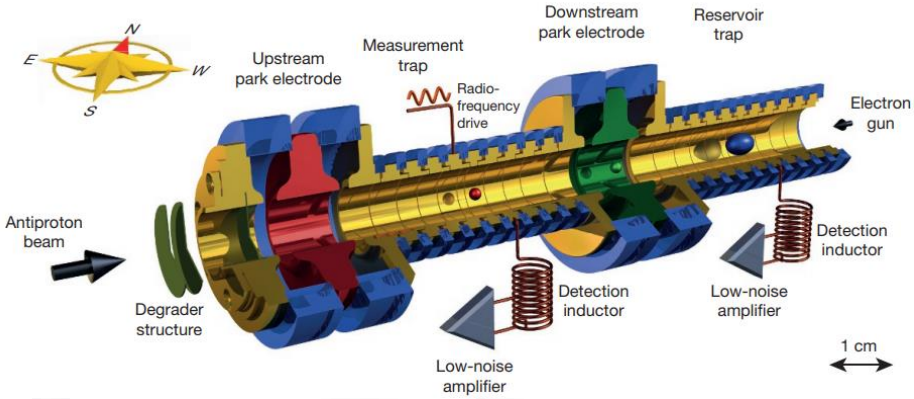
Antiprotons trapped in cryogenic Penning traps (antiproton lifetime >1 y)

Measurement trap (homogeneous magnetic field)

Measurement of cyclotron frequency



$$\omega_c = \frac{q}{m} B$$



Ulmer S et al., (BASE collaboration) *Nature* **524**, 196 (2015)

$$\frac{(q/m)_{\bar{p}}}{(q/m)_p} - 1 = 1 \times 10^{-12}$$

No Italian institutes currently involved

AEGIS experiment

5 AEGIS

Started: 2015

Studies: Gravitational acceleration of antihydrogen atoms.

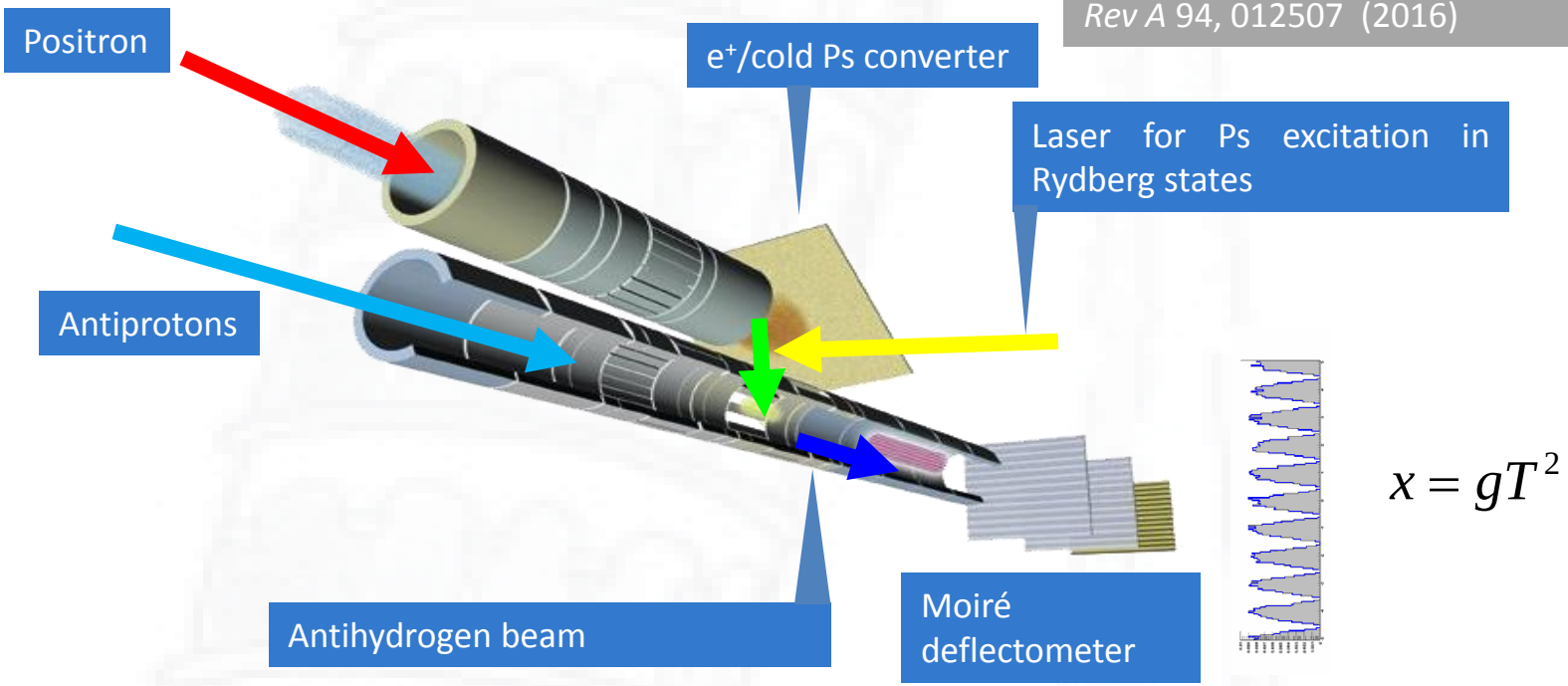
Antimatter Experiment: Gravity, Interferometry, Spectroscopy

Antihydrogen formation via charge exchange reaction

$$\bar{p} + Ps^* \rightarrow \bar{H}^* + e^-$$

Production of an antihydrogen beam for measurements of gravitational interaction

Aghion S et al., (AEGIS collaboration) *Phys Rev A* 94, 012507 (2016)



$$x = gT^2$$

Aghion S et al., (AEGIS collaboration) *Nature comm* 5, 4538 (2014)

AEGIS experiment

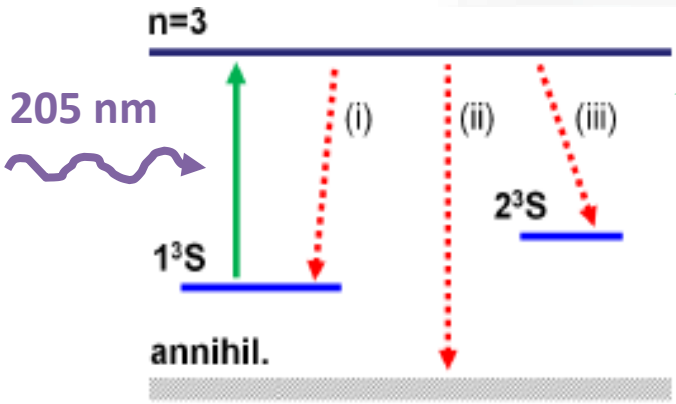
5 AEGIS

Started: 2015

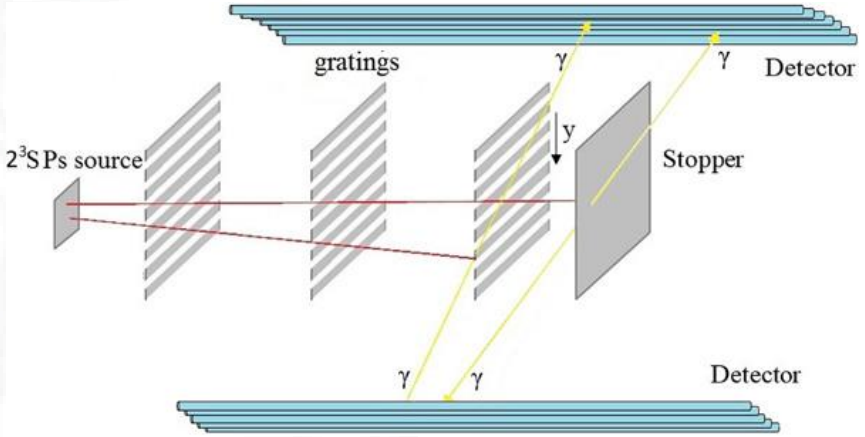
Studies: Gravitational acceleration of antihydrogen atoms.

Antimatter Experiment: Gravity, Interferometry, Spectroscopy

Laser excitation of Ps to metastable levels



Production of metastable positronium for inertial sensing measurements



Antonello M et al., (AEGIS collaboration) *Phys Rev A* 100, 063414 (2019)

Aghion S et al., (AEGIS collaboration) *Phys Rev A* 99, 033405 (2019)

Aghion S et al., (AEGIS collaboration) *Phys Rev A* 98, 013402 (2018)

Mariazzi S et al., (AEGIS collaboration) *Europ Phys J D* 74, 79 (2020)

INFN/TIFPA	~10 people
INFN-Pavia	
INFN-Milano	
INFN-Padova	

GBAR experiment

6 GBAR

Started: 2017

Studies: Gravitational acceleration of antihydrogen atoms.

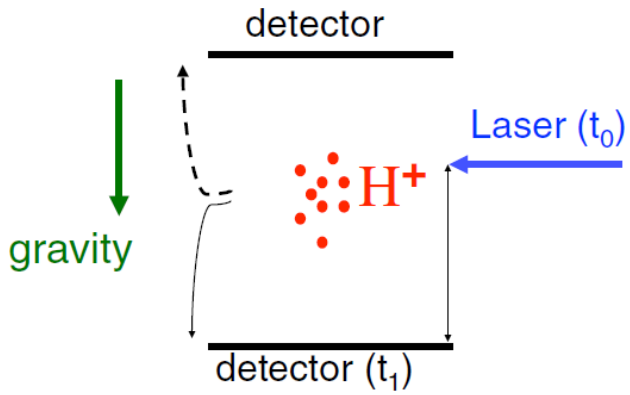
Gravitational Behaviour of Antihydrogen at Rest

Antihydrogen formation via charge exchange reaction

$$\bar{p} + Ps^* \rightarrow \bar{H}^* + e^-$$

Antihydrogen positive ion formation via charge exchange reaction

$$Ps^* + \bar{H} \rightarrow \bar{H}^+ + e^-$$



Production of antihydrogen ions for trapping, cooling and photodetachment

Use of the produced cold antihydrogen for gravitational acceleration measurement

Very high number of Ps atoms needed, 10^{12} Ps/cm^3 (positron production via pair production)

Very cold antihydrogen ions needed, 10 μK.

Debu P et al., (GBAR collaboration) *Hyperfine Int.* **212**, 51 (2012)

Dufour G et al., *Phys. Rev. A* **87**, 022506 (2013)

No Italian institutes currently involved

Conclusion

Antimatter systems for matter/antimatter symmetry studies

Activity of the AD experiments

New antiproton decelerator available for all the AD experiments from middle 2021