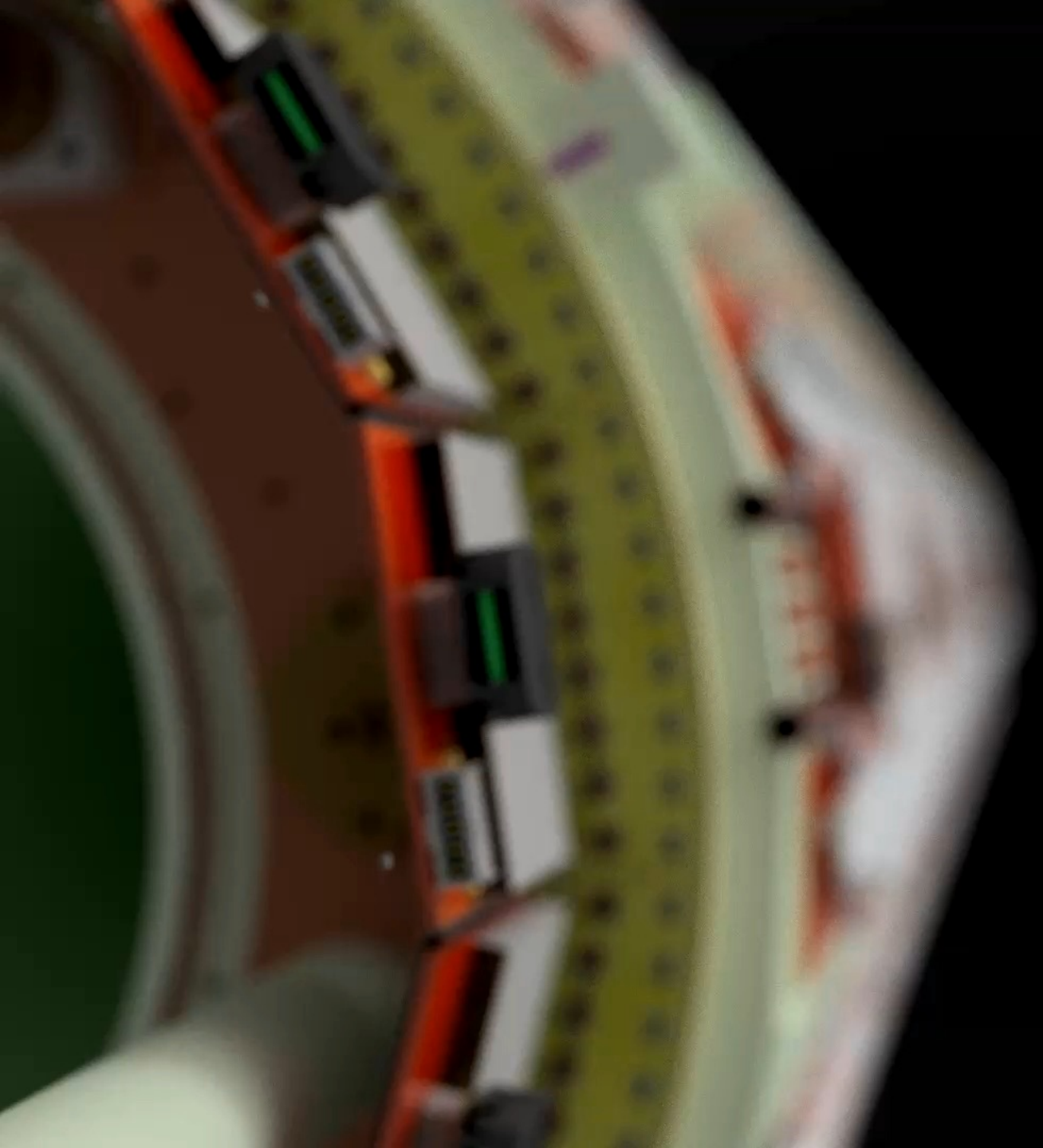


Measuring Antimatter Gravity

Dr Danielle Hodgkinson

http://alpha.web.cern.ch/

Introduction

- MPhys Physics with Theoretical Physics 2014 - 2018

University of Manchester

Introduction

- MPhys Physics with Theoretical Physics 2014 - 2018

University of Manchester

- PhD in antimatter (based at CERN)

University of Manchester

Introduction

- MPhys Physics with Theoretical Physics 2014 - 2018

University of Manchester

- PhD in antimatter (based at CERN)

University of Manchester

- Post-Doc Researcher 2022-present

UC Berkeley

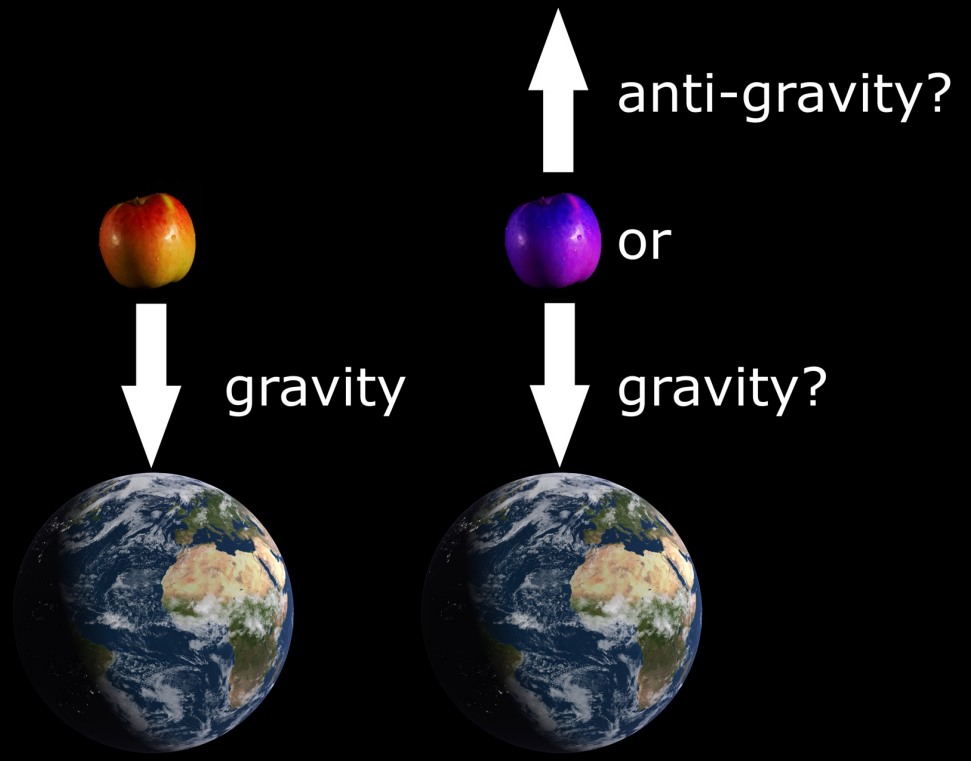
Northwestern Passages
Greenland
Iceland
Norwegian Sea
Sweden
Finland
Norway
Canada
Hudson Bay
Labrador Sea
Denmark
United Kingdom
Ireland
Belarus
Poland
Germany
Ukraine
Austria
Romania
Italy
Spain
Portugal
Greece
Tunisia
Morocco
Algeria
Libya
Egypt
Western Sahara
Mauritania
Mali
Niger
Chad
Sudan
Burkina Faso
North Atlantic Ocean
Gulf of Mexico
Mexico
Cuba
Puerto Rico
Guatemala
Nicaragua
Caribbean Sea
United States
YT
NT
NU
AB
BC
SK
MB
ON
QC
NL
WA
MT
ND
MN
OR
ID
WY
SD
WI
MI
NY
NB
PE
NS
ME
NH
MA
NE
IA
IL
IN
OH
PA
MD
NV
UT
MO
KY
VA
AZ
NM
OK
AR
TN
NC
SC
AL
GA
TX
LA
FL

Point Reyes National Seashore
Novato
Vallejo
Benicia
Martinez
Pittsburg
Antioch
San Rafael
Concord
Richmond
Brentwood
Walnut Creek
Mt Diablo
Berkeley
Golden Gate Bridge
Gulf of the Farallones
San Francisco
San Ramon
Mountain House
Tracy
Dublin
Livermore
Hayward
Carnegie State Vehicular Recreation Area
Fremont
Palo Alto
Milpitas
Mountain View
160
4
580
680
1
24
880
205
92

ANTIMATTER
FACTORY
ELENA

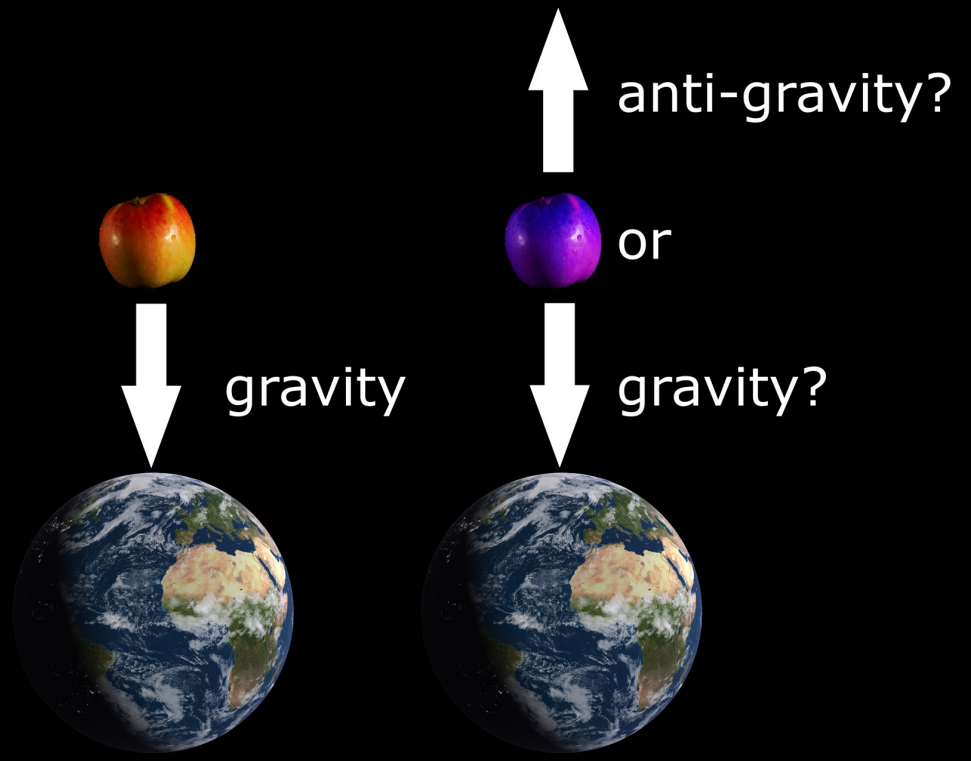
Overview

- What is antimatter?
- Why do we care about antimatter?
- How do we make antimatter?
- How do we test whether anti-gravity exists?

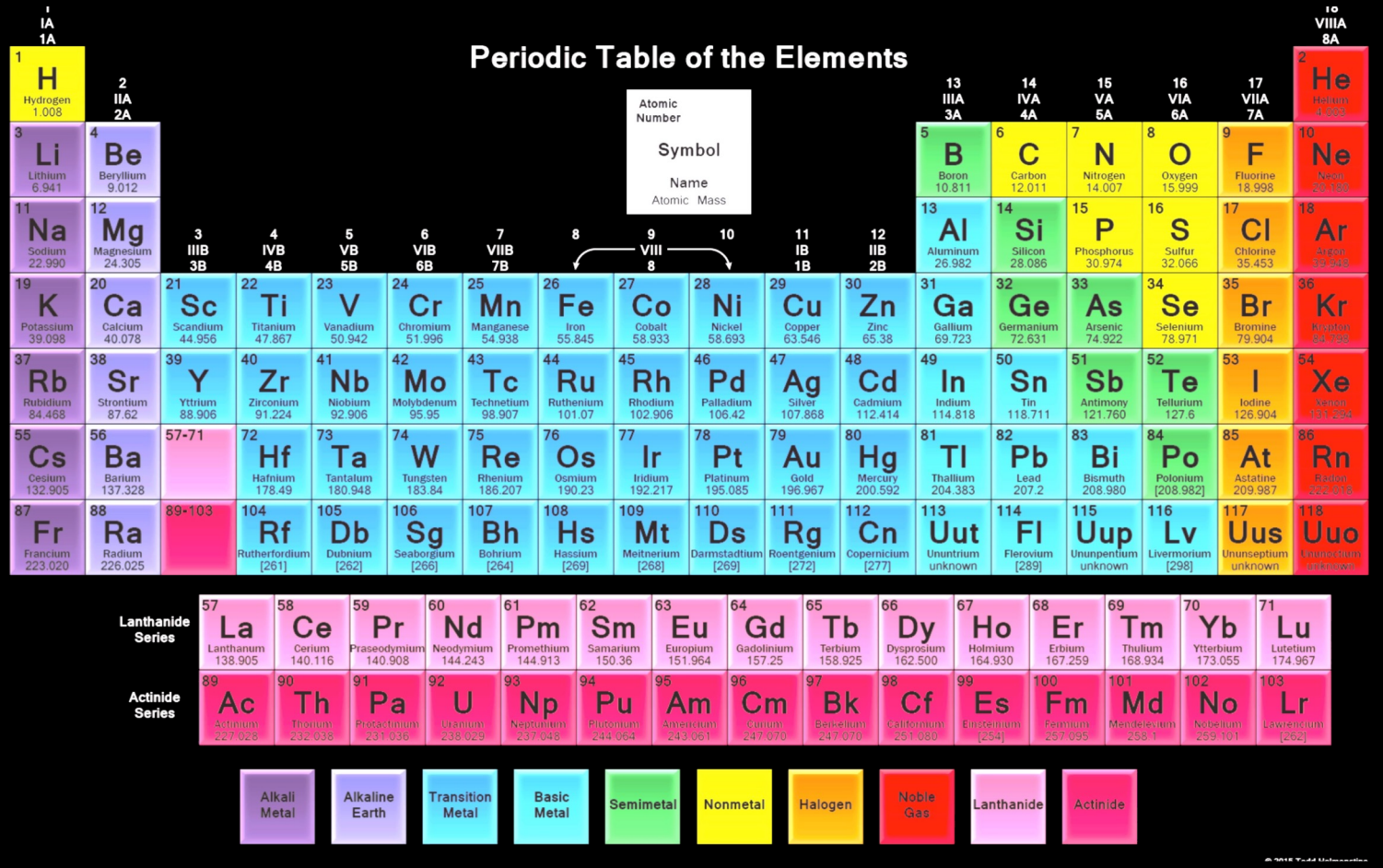


Overview

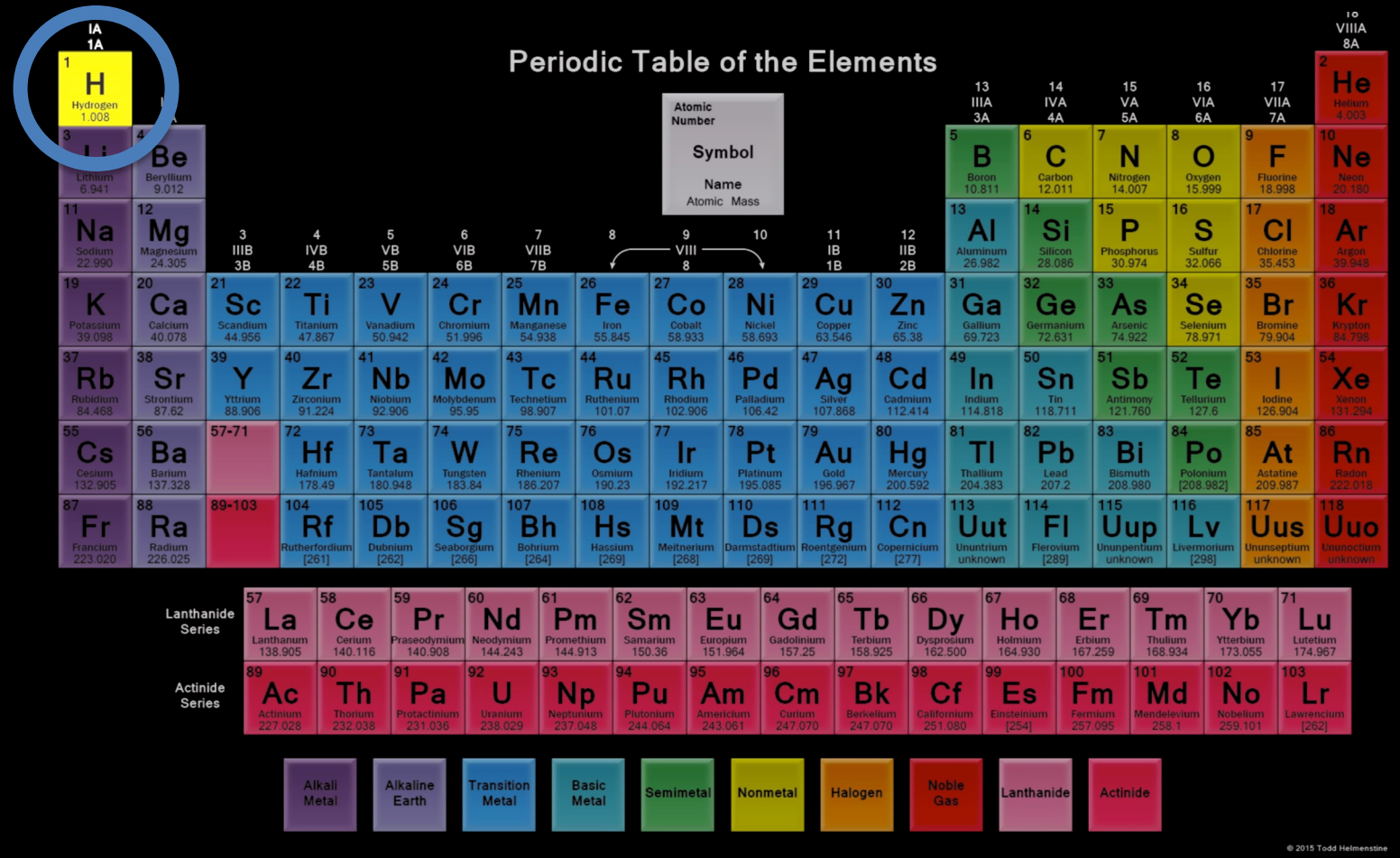
- **What is antimatter?**
- Why do we care about antimatter?
- How do we make antimatter?
- How do we test whether anti-gravity exists?



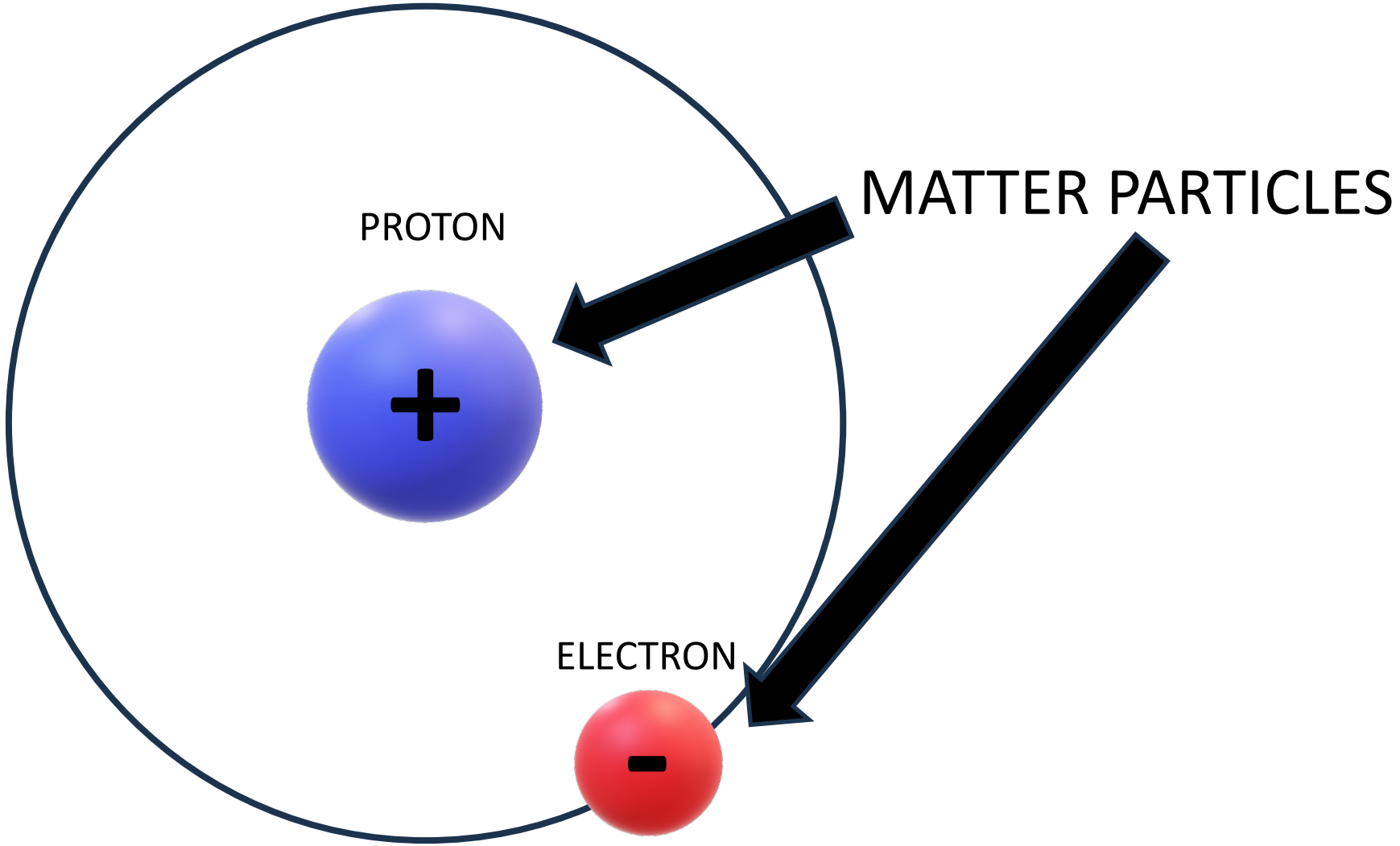
What is matter?



Hydrogen


Periodic Table of the Elements
Atomic Number
Symbol
Name
Atomic Mass
IA 1A
VIIIA 8A
1 H Hydrogen 1.008
2 He Helium 4.003
3 Li Lithium 6.941
4 Be Beryllium 9.012
5 B Boron 10.811
6 C Carbon 12.011
7 N Nitrogen 14.007
8 O Oxygen 15.999
9 F Fluorine 18.998
10 Ne Neon 20.180
11 Na Sodium 22.990
12 Mg Magnesium 24.305
13 Al Aluminum 26.982
14 Si Silicon 28.086
15 P Phosphorus 30.974
16 S Sulfur 32.066
17 Cl Chlorine 35.453
18 Ar Argon 39.948
19 K Potassium 39.098
20 Ca Calcium 40.078
21 Sc Scandium 44.956
22 Ti Titanium 47.867
23 V Vanadium 50.942
24 Cr Chromium 51.996
25 Mn Manganese 54.938
26 Fe Iron 55.845
27 Co Cobalt 58.933
28 Ni Nickel 58.693
29 Cu Copper 63.546
30 Zn Zinc 65.38
31 Ga Gallium 69.723
32 Ge Germanium 72.631
33 As Arsenic 74.922
34 Se Selenium 78.971
35 Br Bromine 79.904
36 Kr Krypton 84.798
37 Rb Rubidium 84.468
38 Sr Strontium 87.62
39 Y Yttrium 88.906
40 Zr Zirconium 91.224
41 Nb Niobium 92.906
42 Mo Molybdenum 95.95
43 Tc Technetium 98.907
44 Ru Ruthenium 101.07
45 Rh Rhodium 102.906
46 Pd Palladium 106.42
47 Ag Silver 107.868
48 Cd Cadmium 112.414
49 In Indium 114.818
50 Sn Tin 118.711
51 Sb Antimony 121.760
52 Te Tellurium 127.6
53 I Iodine 126.904
54 Xe Xenon 131.294
55 Cs Cesium 132.905
56 Ba Barium 137.328
57-71
72 Hf Hafnium 178.49
73 Ta Tantalum 180.948
74 W Tungsten 183.84
75 Re Rhenium 186.207
76 Os Osmium 190.23
77 Ir Iridium 192.217
78 Pt Platinum 195.085
79 Au Gold 196.967
80 Hg Mercury 200.592
81 Tl Thallium 204.383
82 Pb Lead 207.2
83 Bi Bismuth 208.980
84 Po Polonium [208.982]
85 At Astatine 209.987
86 Rn Radon 222.018
87 Fr Francium 223.020
88 Ra Radium 226.025
89-103
104 Rf Rutherfordium [261]
105 Db Dubnium [262]
106 Sg Seaborgium [266]
107 Bh Bohrium [264]
108 Hs Hassium [269]
109 Mt Meitnerium [268]
110 Ds Darmstadtium [269]
111 Rg Roentgenium [272]
112 Cn Copernicium [277]
113 Uut Ununtrium unknown
114 Fl Flerovium [289]
115 Uup Ununpentium unknown
116 Lv Livermorium [298]
117 Uus Ununseptium unknown
118 Uuo Ununoctium unknown
Lanthanide Series
57 La Lanthanum 138.905
58 Ce Cerium 140.116
59 Pr Praseodymium 140.908
60 Nd Neodymium 144.243
61 Pm Promethium 144.913
62 Sm Samarium 150.36
63 Eu Europium 151.964
64 Gd Gadolinium 157.25
65 Tb Terbium 158.925
66 Dy Dysprosium 162.500
67 Ho Holmium 164.930
68 Er Erbium 167.259
69 Tm Thulium 168.934
70 Yb Ytterbium 173.055
71 Lu Lutetium 174.967
Actinide Series
89 Ac Actinium 227.028
90 Th Thorium 232.038
91 Pa Protactinium 231.036
92 U Uranium 238.029
93 Np Neptunium 237.048
94 Pu Plutonium 244.064
95 Am Americium 243.061
96 Cm Curium 247.070
97 Bk Berkelium 247.070
98 Cf Californium 251.080
99 Es Einsteinium [254]
100 Fm Fermium 257.095
101 Md Mendelevium 258.1
102 No Nobelium 259.101
103 Lr Lawrencium [262]
Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Semimetal
Nonmetal
Halogen
Noble Gas
Lanthanide
Actinide
© 2015 Todd Helmenstine

MATTER



HYDROGEN

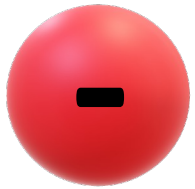
NOT TO SCALE

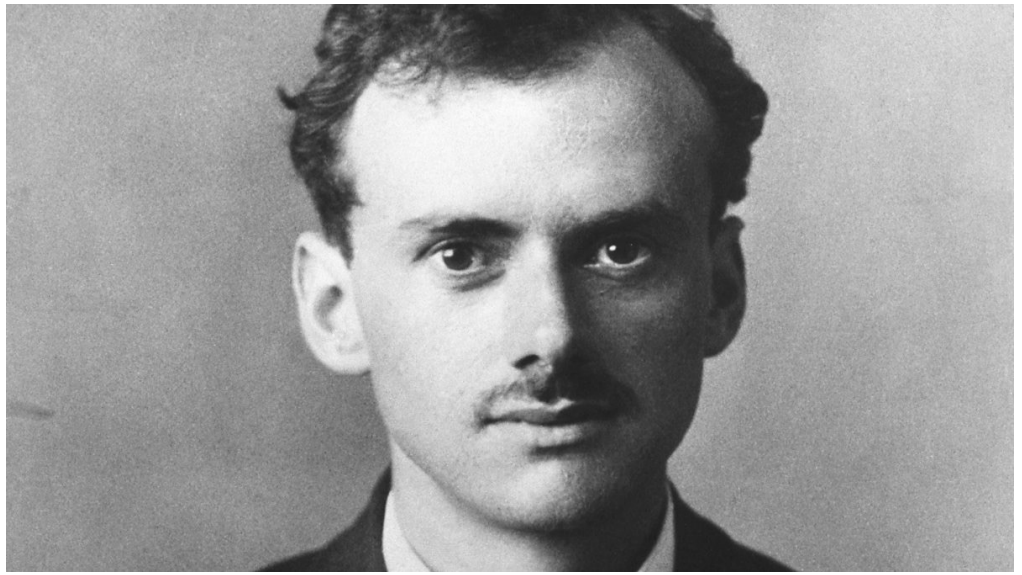
The Discovery of Antimatter

1928

$$\left(\beta mc^2 + c\sum_{n=1}^{3}\alpha_n p_n\right)\psi(x,t) = i\hbar\frac{\partial\psi(x,t)}{\partial t}$$

ELECTRON





Paul Dirac

The Discovery of Antimatter

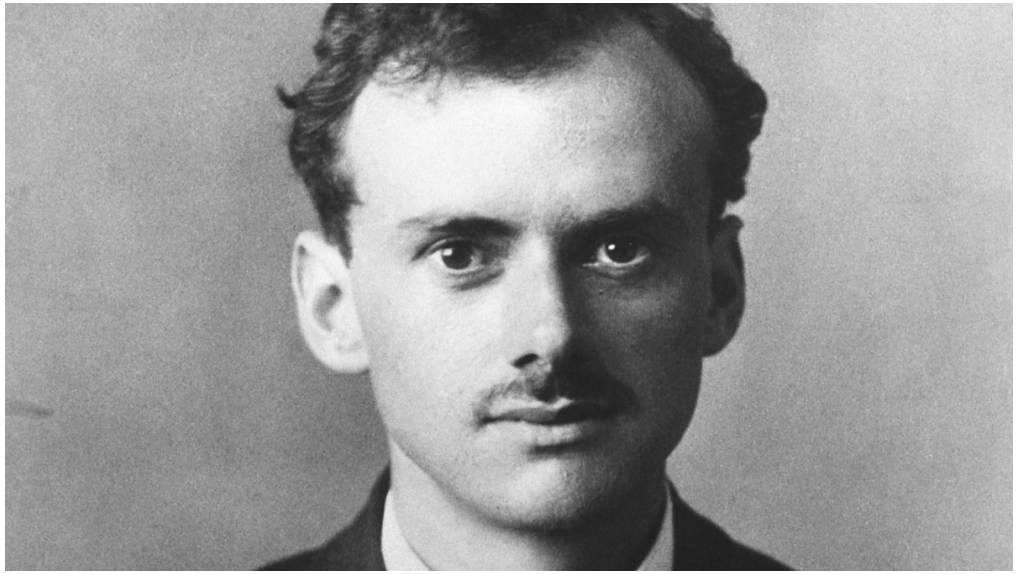
1928

$$\left(\beta mc^2 + c\sum_{n=1}^{3}\alpha_n p_n\right)\psi(x,t) = i\hbar\frac{\partial\psi(x,t)}{\partial t}$$

SOLUTION: contains a square root

$$x^2 = 4$$

$$x = +2 \qquad x = -2$$

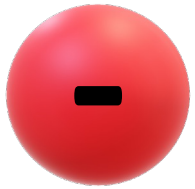


Paul Dirac

The Discovery of Antimatter

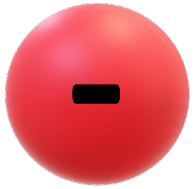
1928

ELECTRON

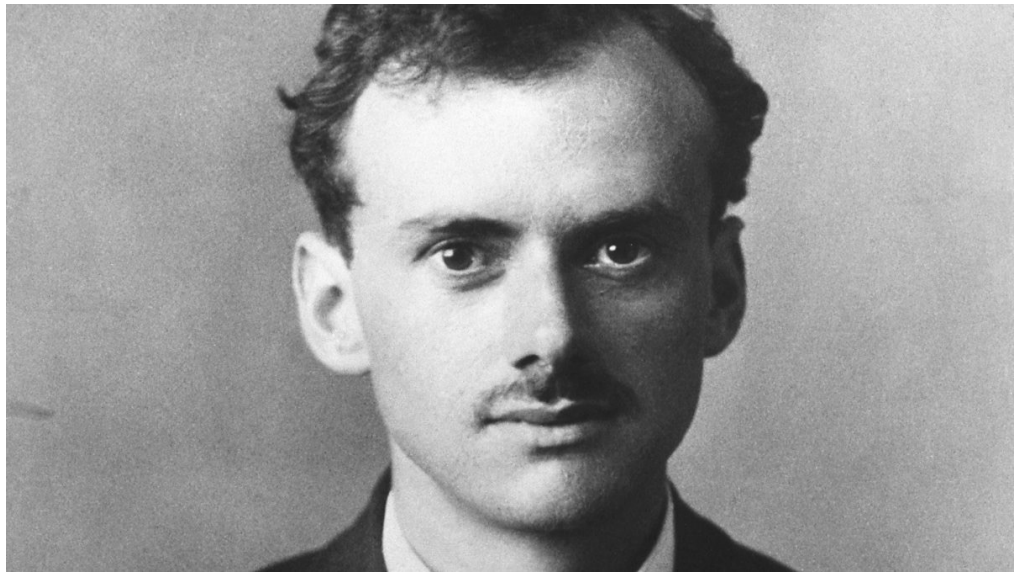


Positive solution:
Positive energy

ELECTRON



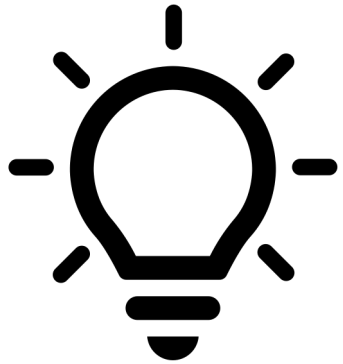
Negative solution:
Negative energy



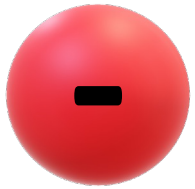
Paul Dirac

The Discovery of Antimatter

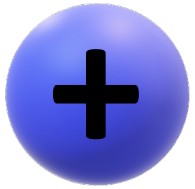
1928

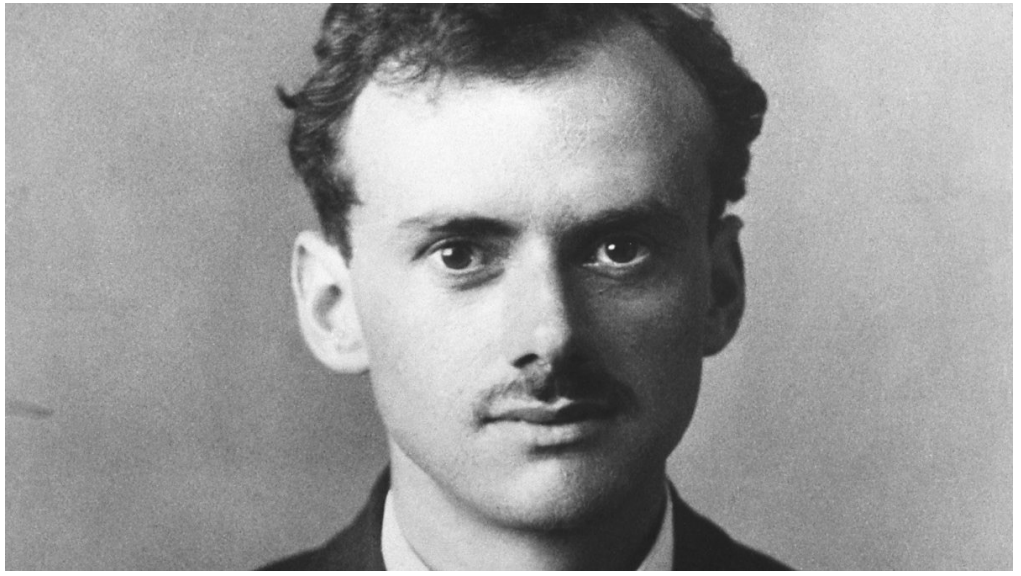


ELECTRON



ANTI - ELECTRON





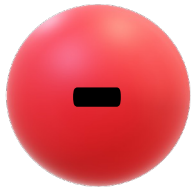
Paul Dirac

Positive solution:
Positive energy

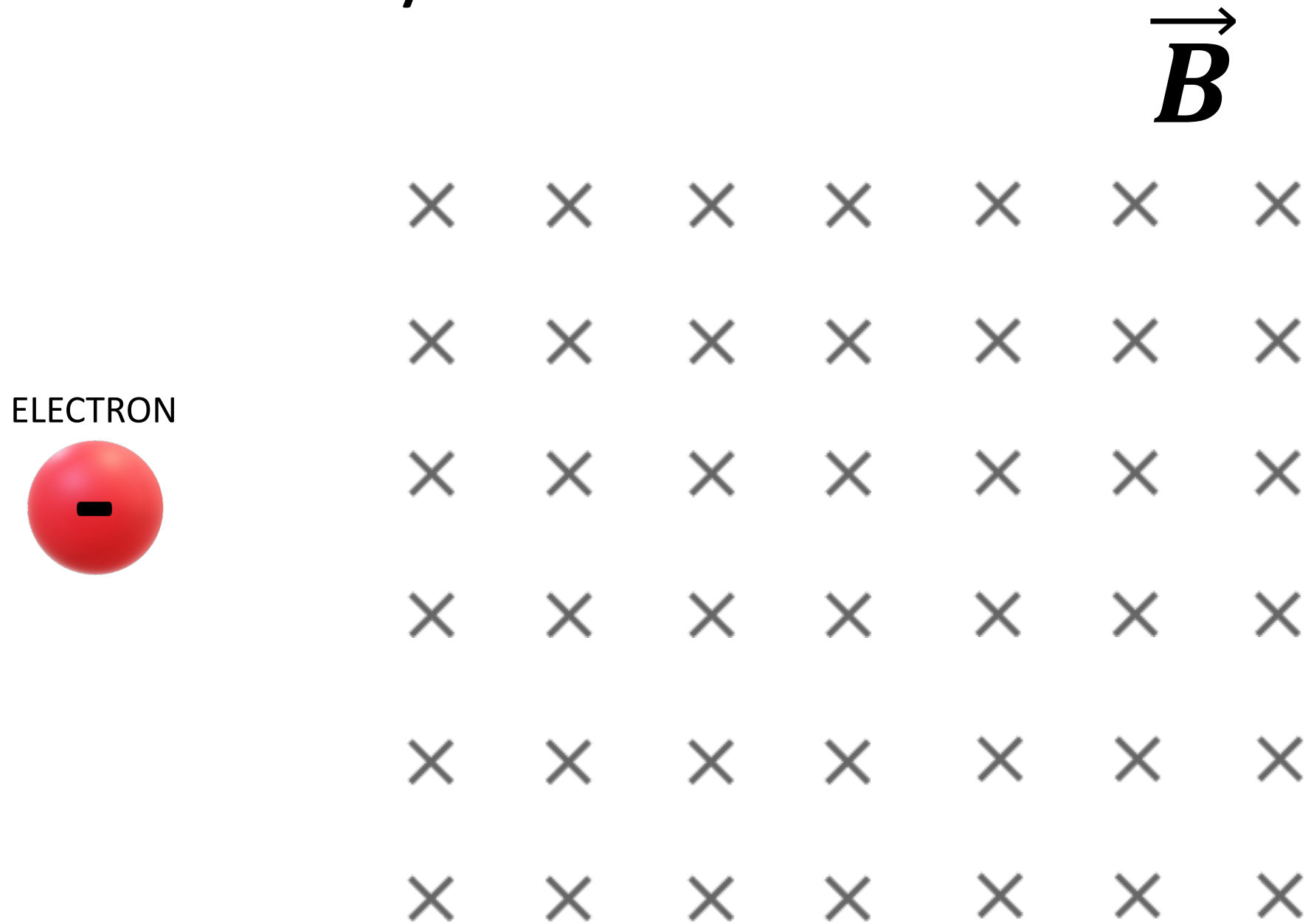
Negative solution:
~~Negative energy~~
Opposite charge (and same mass)

The Discovery of Antimatter

ELECTRON



The Discovery of Antimatter



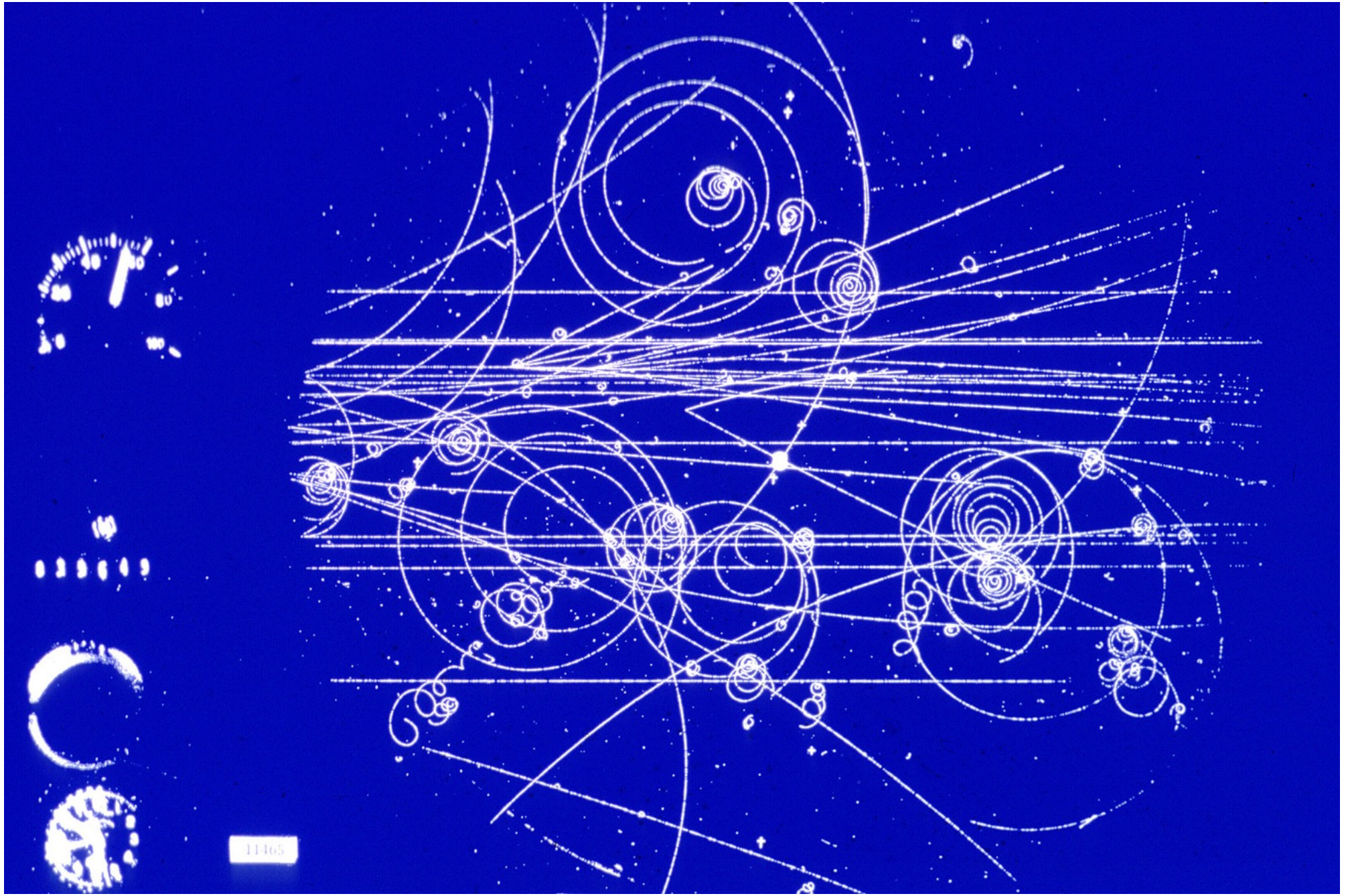
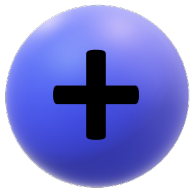


IMAGE: CERN DOCUMENT SERVER

The Discovery of Antimatter

$\vec{B}$

ANTI-ELECTRON



1932 – The ‘positron’ discovery

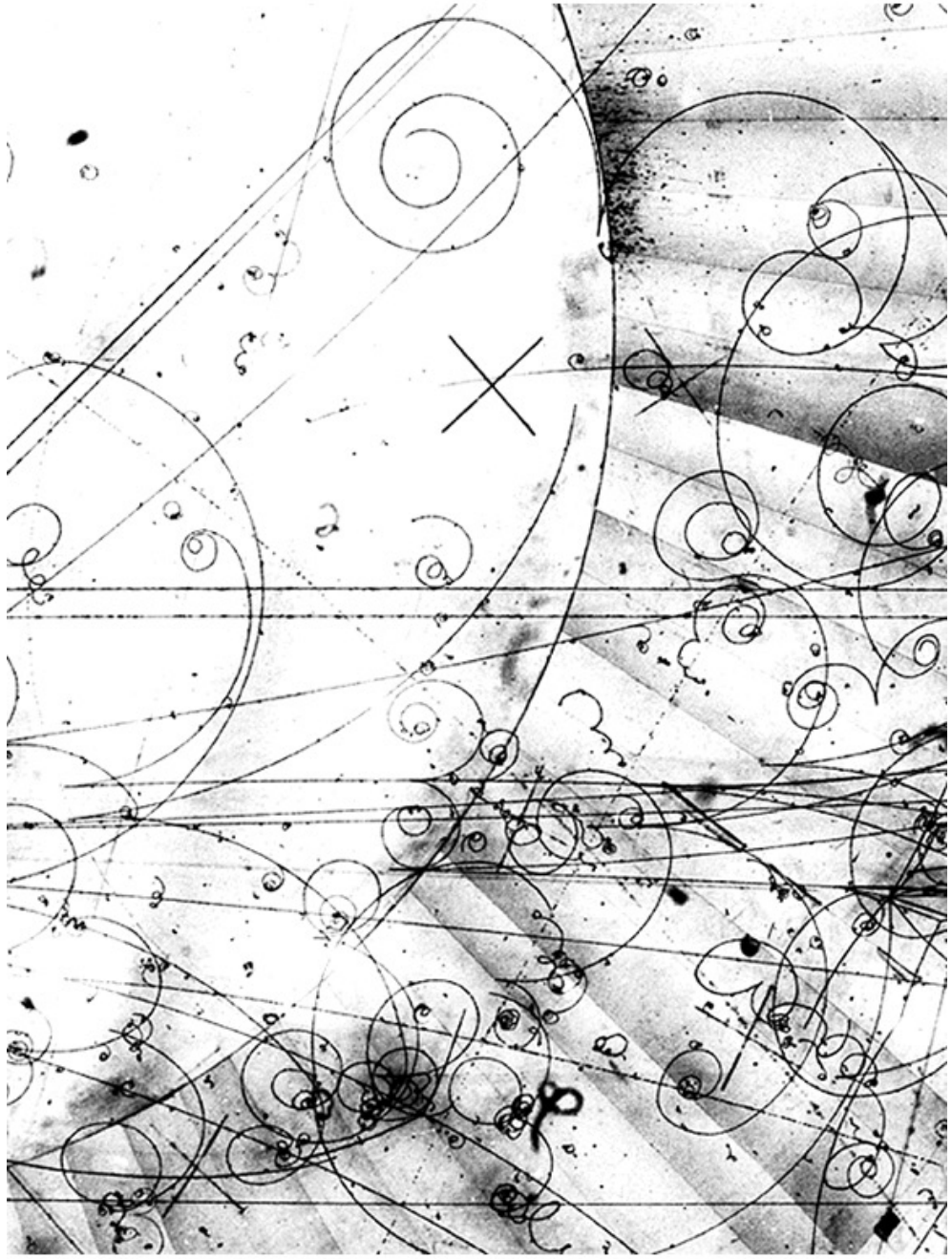
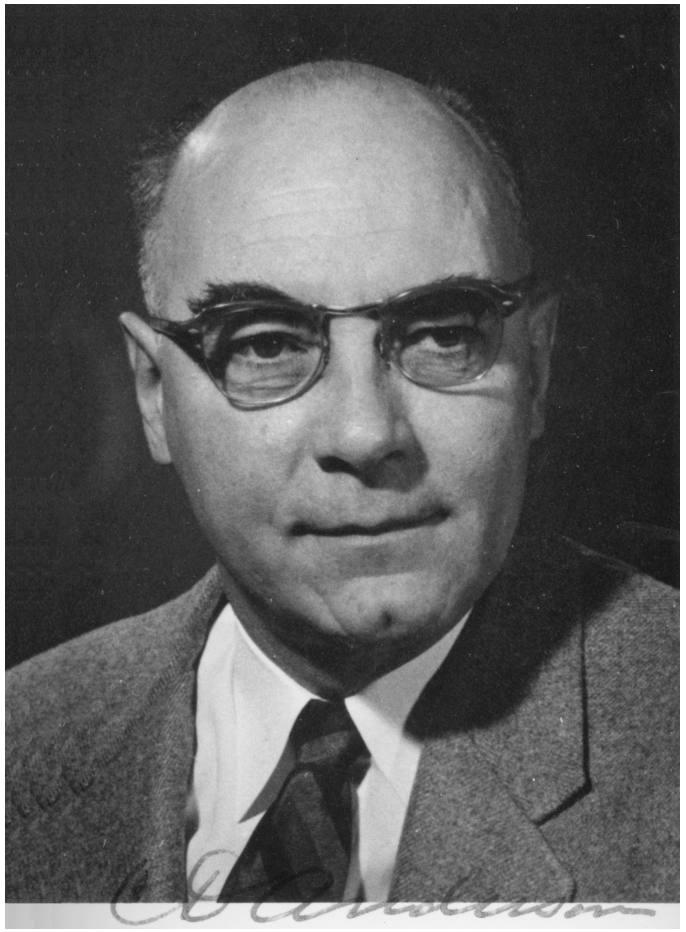


IMAGE: CERN DOCUMENT SERVER



Carl Anderson

MATTER

ANTIMATTER

ANNIHILATION

PROTON

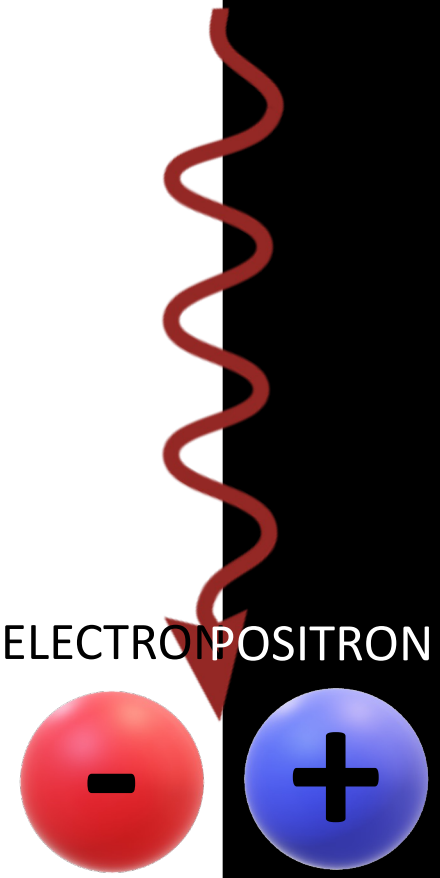
ANTIPROTON

ELECTRON

POSITRON

MATTER

ANTIMATTER



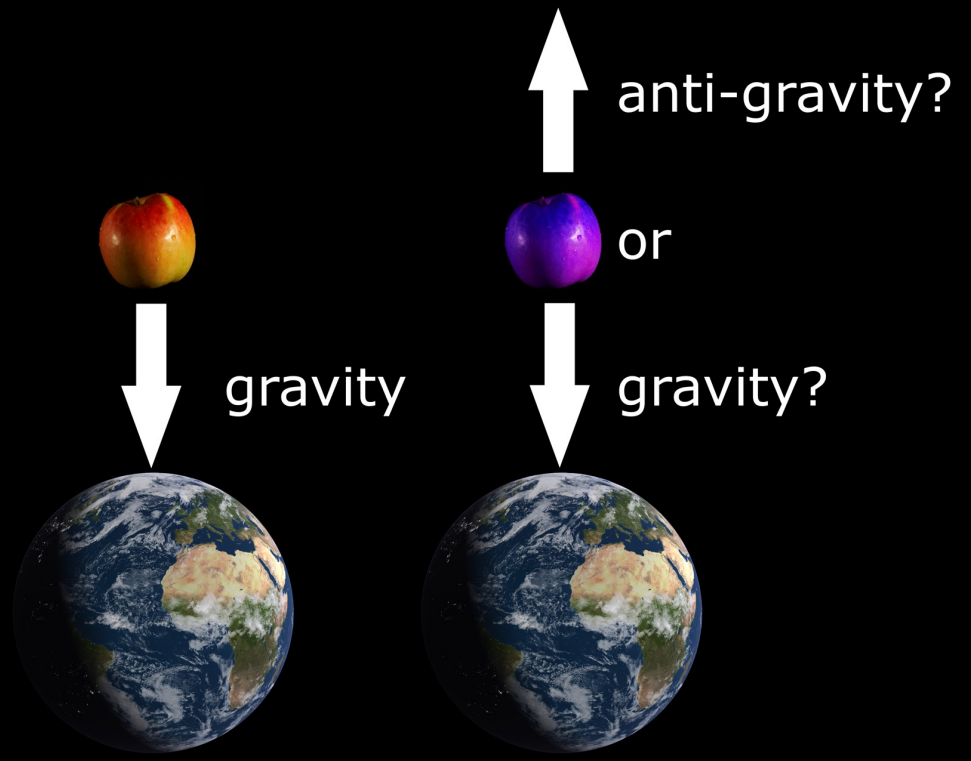
ELECTRON

POSITRON

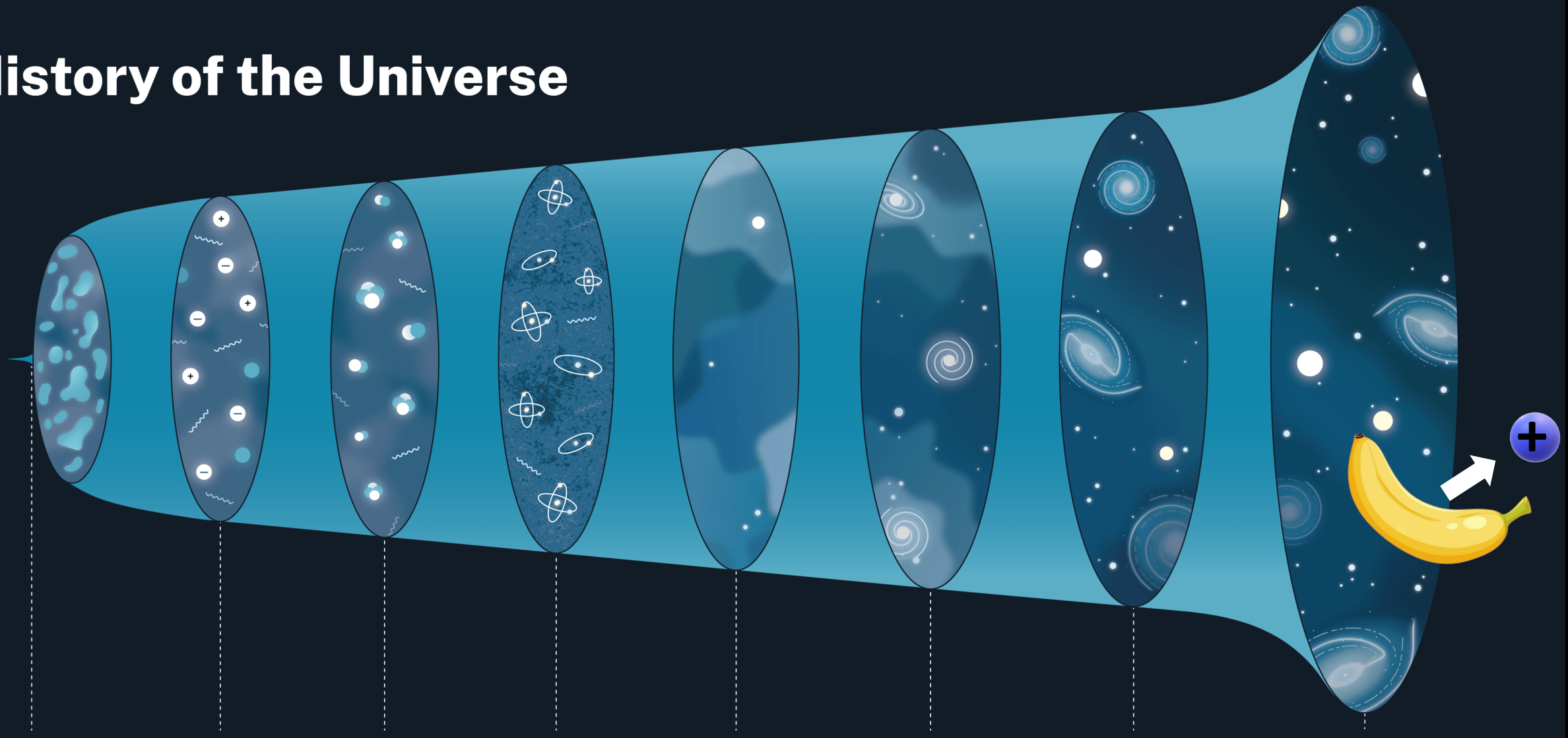
PAIR PRODUCTION

Overview

- What is antimatter?
- **Why do we care about antimatter?**
- How do we make antimatter?
- How do we test whether anti-gravity exists?



History of the Universe

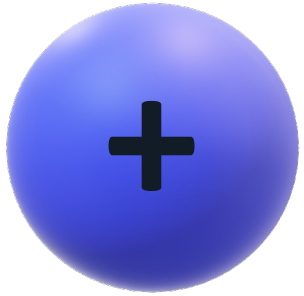


10^{-32} seconds	1 microsecond	3 minutes	380,000 years	200 million years	400 million years	10 billion years	13.8 billion years
Inflation	**First Particles**	**First Nuclei**	**First Light**	**First Stars**	**Galaxies & Dark Matter**	**Dark Energy**	**Today**
Initial expansion	Neutrons, protons, and electrons form	Helium and hydrogen form	The first atoms form	Gas and dust condense into stars	Galaxies form in dark matter cradles	Expansion accelerates	Humans observe the universe

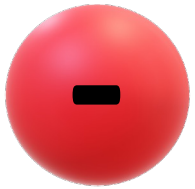
IMAGE CREDIT: NASA (ORIGINAL DOES NOT CONTAIN BANANA)

MATTER

PROTON

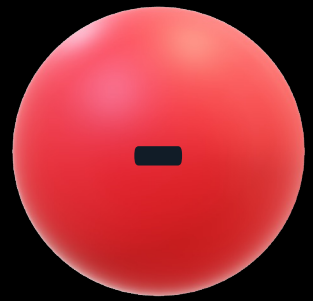


ELECTRON



ANTIMATTER

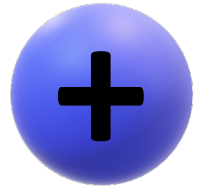
ANTIPROTON



POSITRON

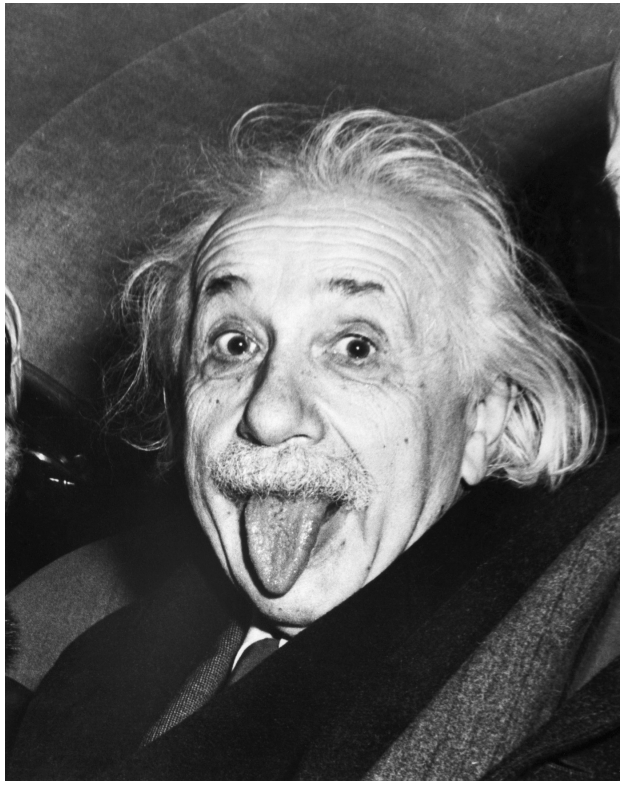
ELECTRON

POSITRON



What is the force between the weight and the Earth?

$$F = \frac{GMm}{r^2}$$



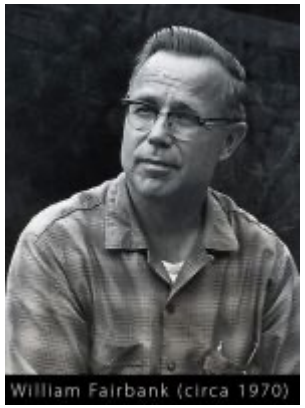
Einstein

What is the acceleration of the weights?

$$F = ma$$

$$a = \frac{GM}{r^2} \approx 9.81 \text{ m/s^2}$$

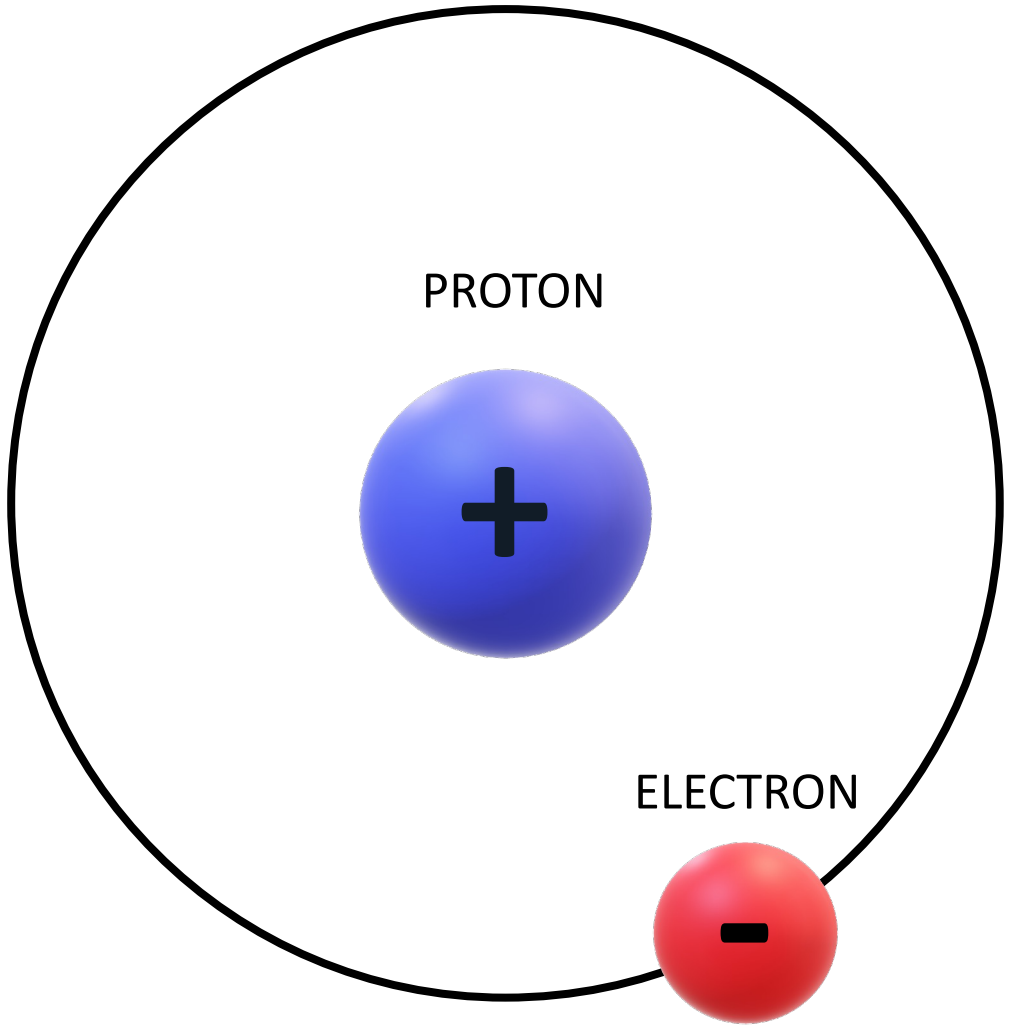
F. C. Witteborn and W. M. Fairbank, Experimental Comparison of the Gravitational Force on Freely Falling Electrons and Metallic Electrons, Phys. Rev. Lett. 19, 1049 (1967).



William Fairbank

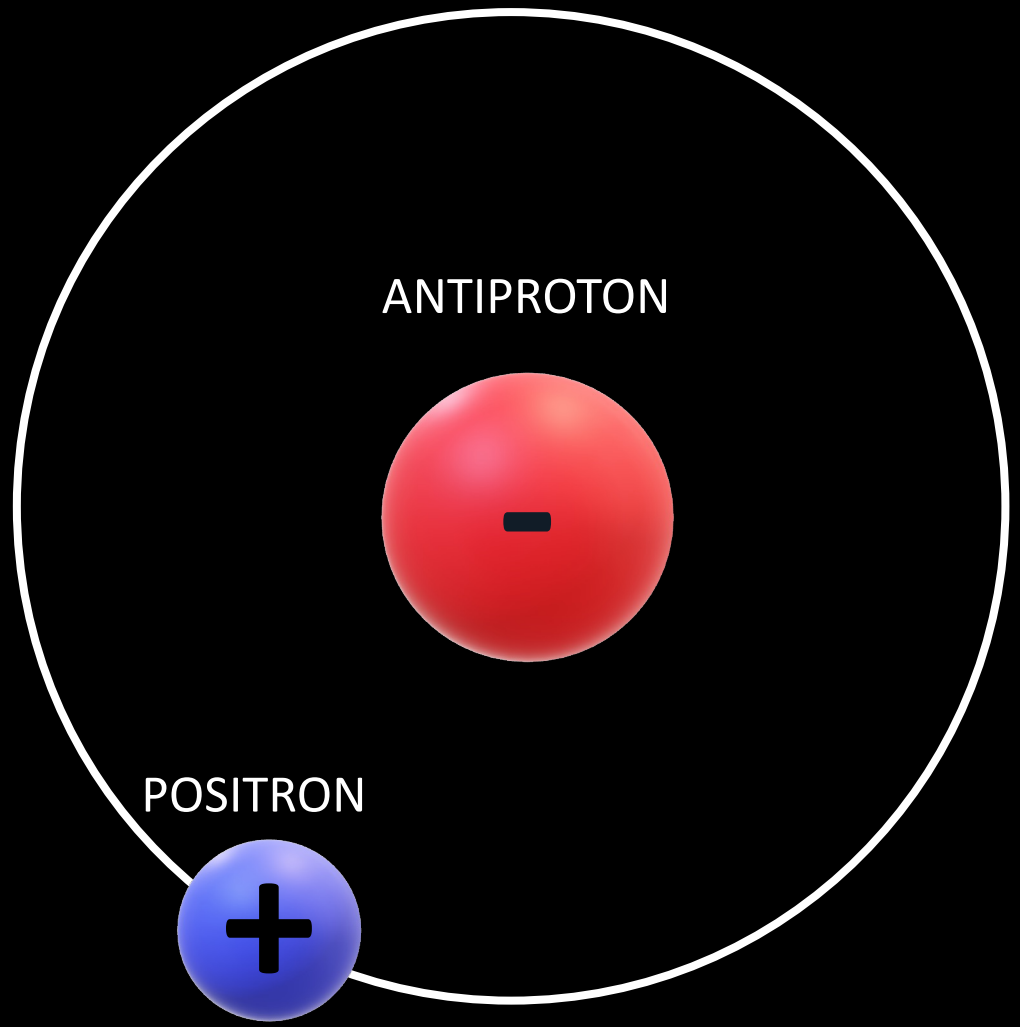
- The Weak Equivalence Principle (WEP) insists antimatter will fall in exactly the same way as normal matter.
- No WEP-breaking process has ever been found.
- WEP violation could solve the matter antimatter asymmetry.

MATTER

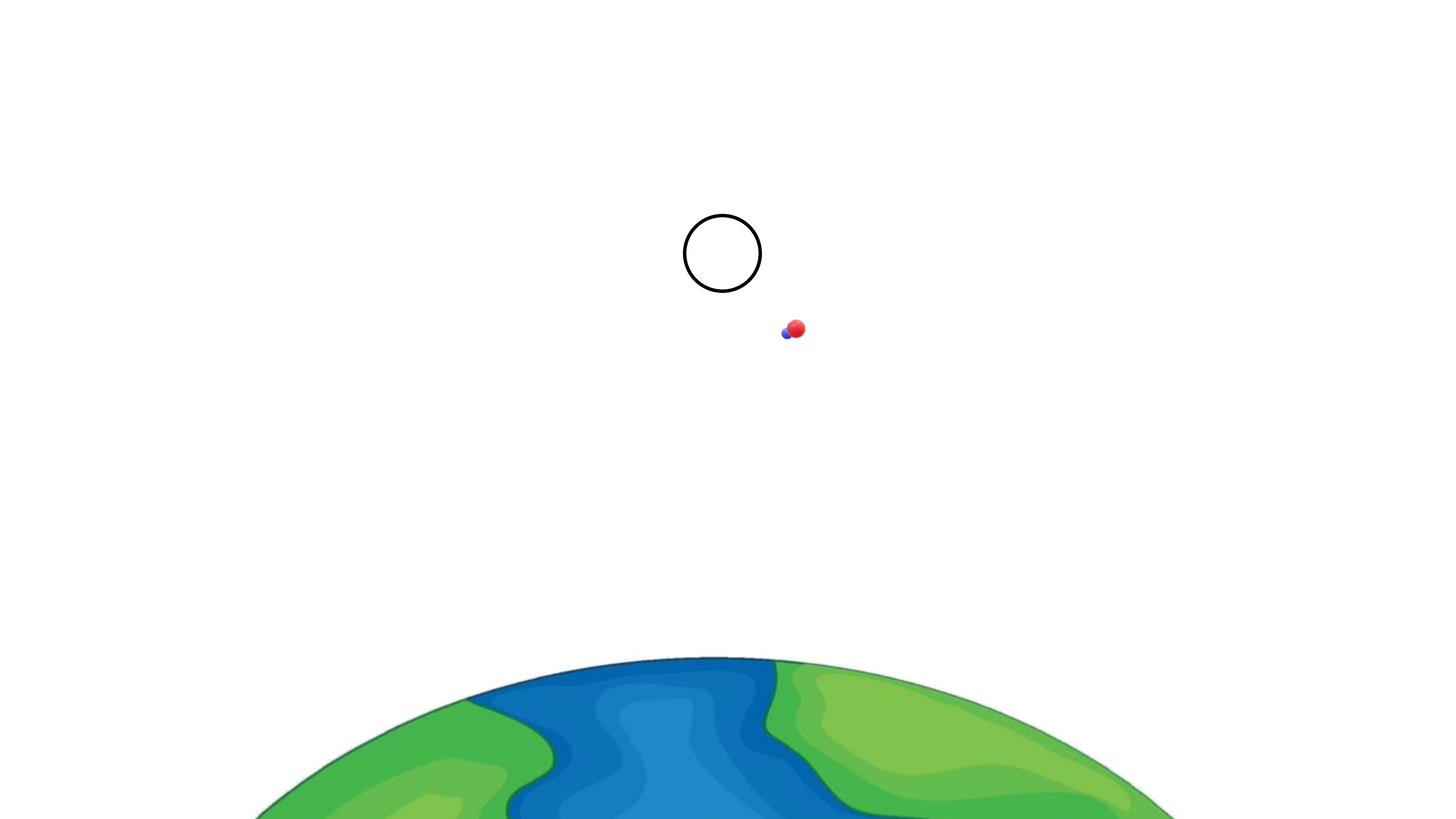


HYDROGEN

ANTIMATTER



ANTIHYDROGEN



nature

The New York Times

motion of

Podcast Episode

Experimenting with Antimatter

NSF's Discovery Files

Oct 2023 · 20 min 50 sec

Episode Description

Timothy Tharp, assistant professor at Marquette University; Danielle Hodgkinson, postdoctoral fellow at University of California, Berkeley; and Andrew Christensen a senior graduate student at UC Berkeley all contributed to the success of the Alpha-g experiment at the European Organization for Nuclear Research (CERN), testing gravity's effect on antimatter. We'll hear about what roles they played, challenges they faced and what's next for the group.

Show less

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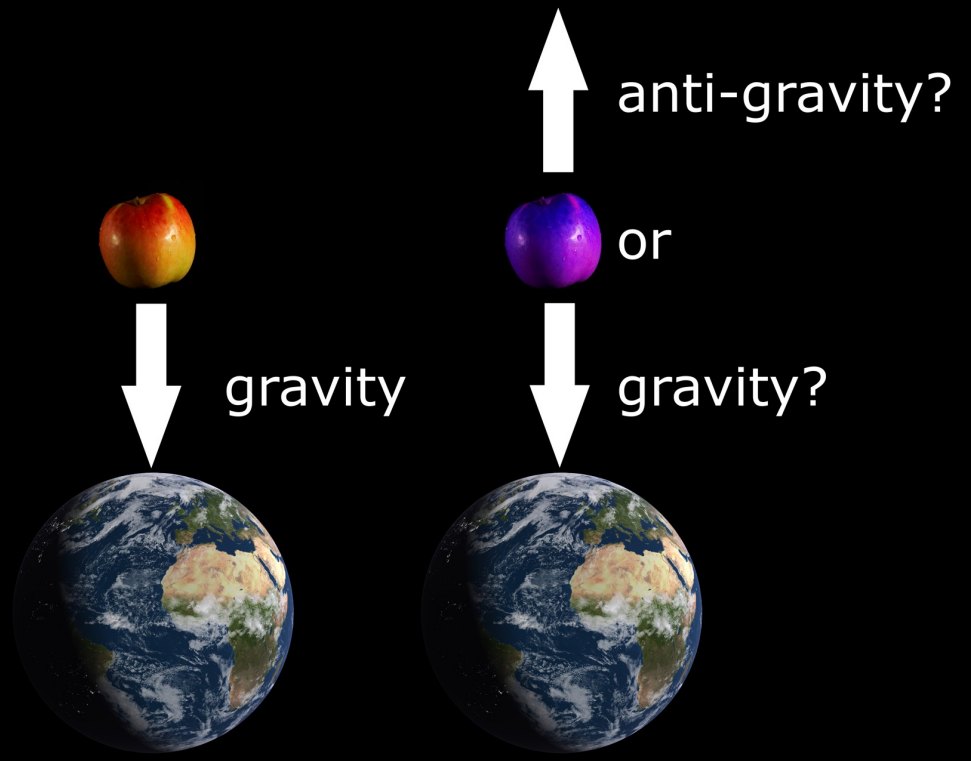
t to

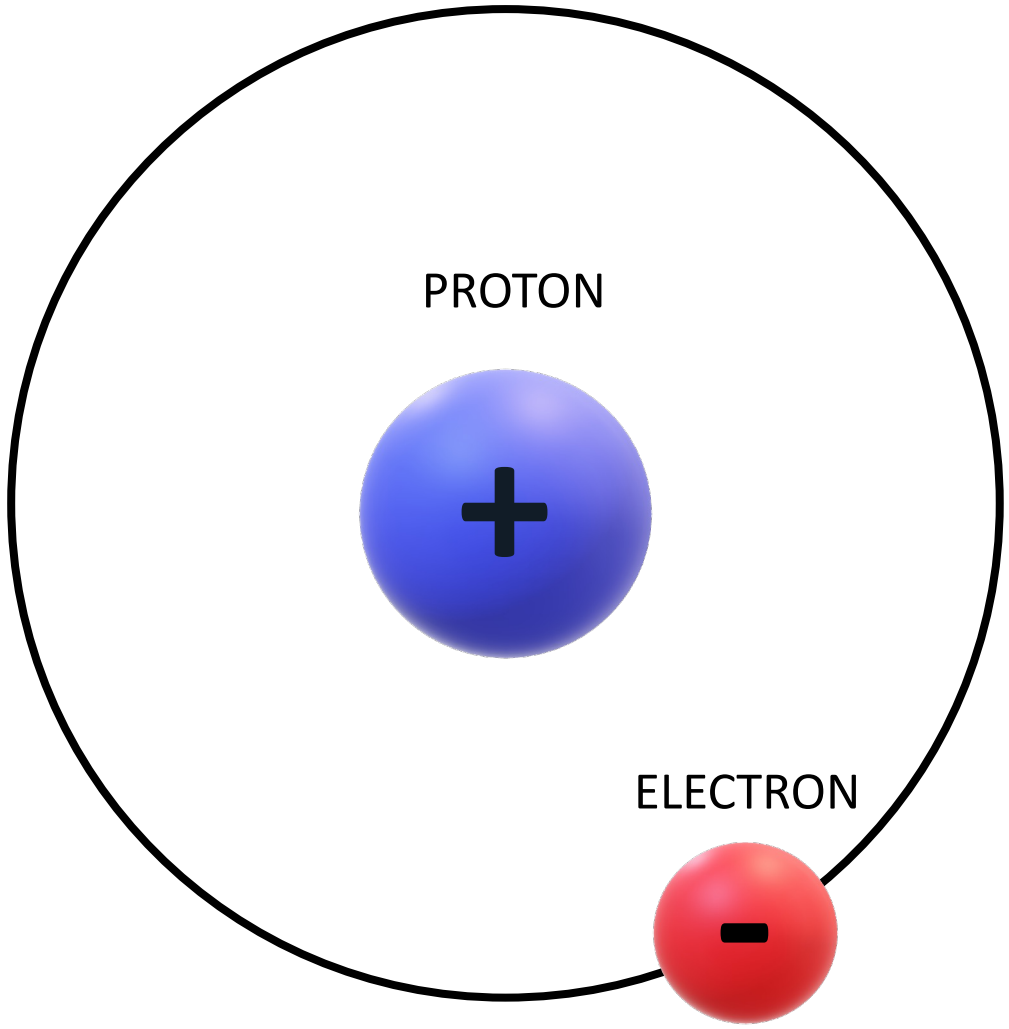
physicsworld TOP 10 BREAKTHROUGH 2023

Overview

- What is antimatter?
- Why do we care about antimatter?
- **How do we make antimatter?**
- How do we test whether anti-gravity exists?

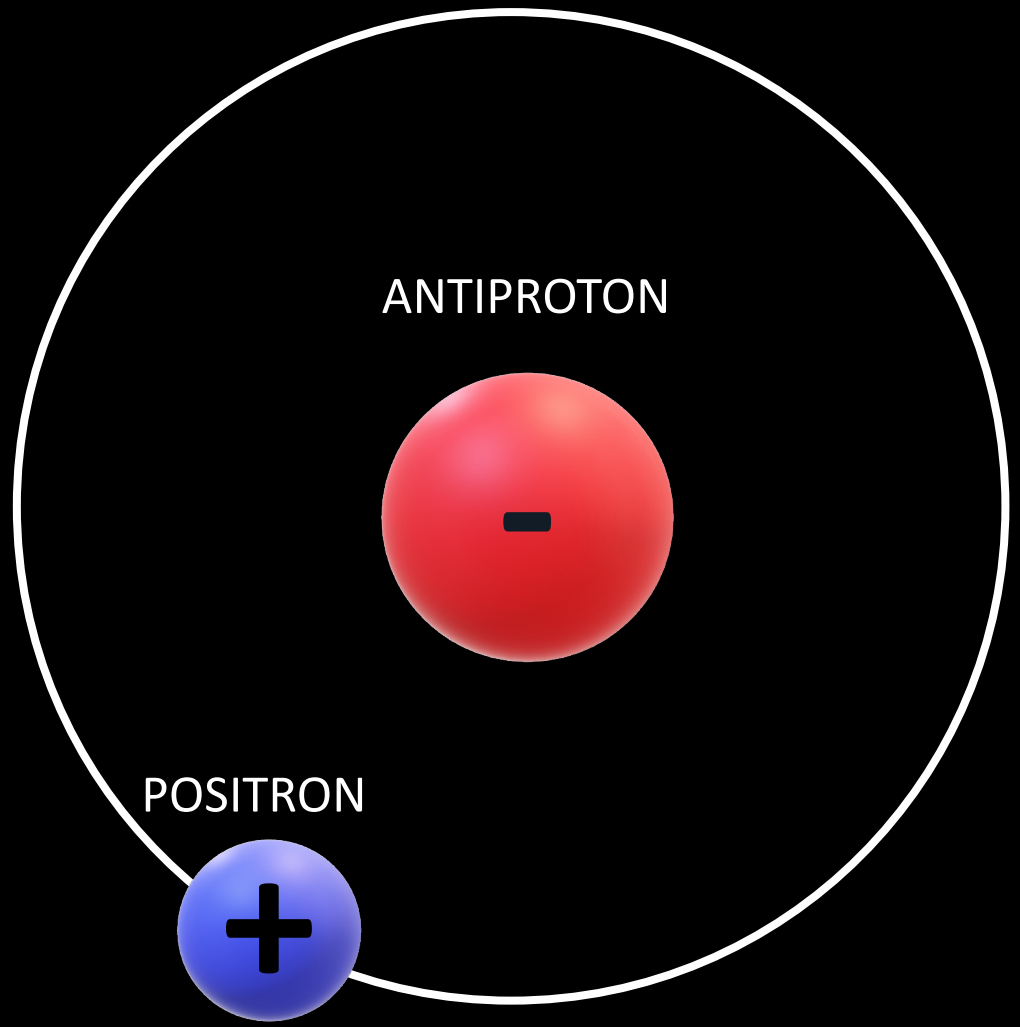


MATTER



HYDROGEN

ANTIMATTER



ANTIHYDROGEN

Where does ALPHA get their positrons from?

Naturally: Radioactivity! Beta plus decay of ^{22}Na

$^{22}Na \rightarrow {}^{22}Ne + Positron$

Proton → Neutron + Positron

Where does ALPHA get their positrons from?

- Positrons come from a really strong radioactive source: 2 Gbq

What does 2 Gbq mean?

2,000,000,000 radio active decays per second…

How many bananas is 2 Gbq?

a) 2 million bananas
b) 2 million tons of bananas
c) 2 billion tons of bananas
d) The weight of the moon in bananas
e) The weight of the sun in bananas

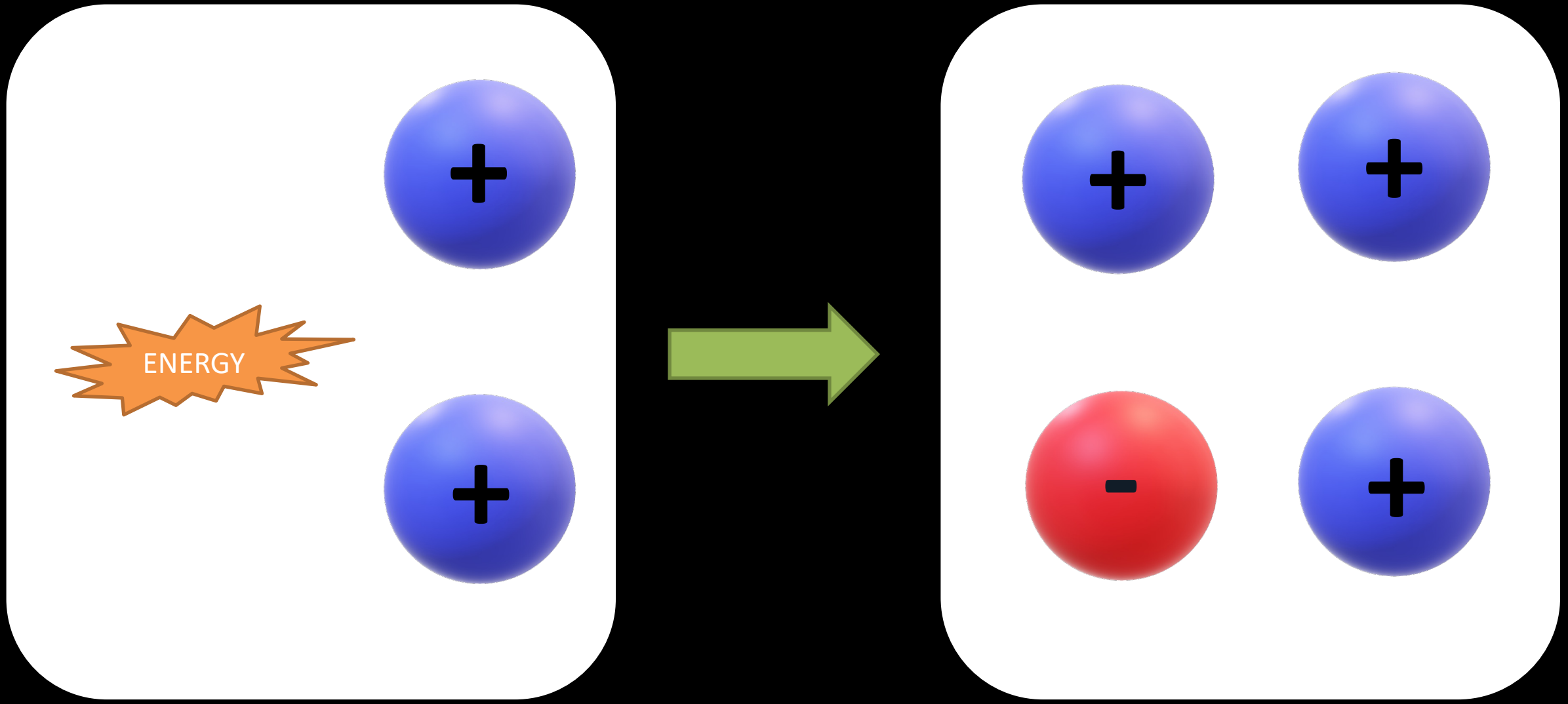
How many bananas is 2 Gbq?

a) 2 million bananas
b) 2 million tons of bananas
c) 2 billion tons of bananas
d) The weight of the moon in bananas
e) The weight of the sun in bananas

c) ~2 billion tons of Bananas [1]

[1] - http://tertiarysource.net/ts.cgi/anti-banana

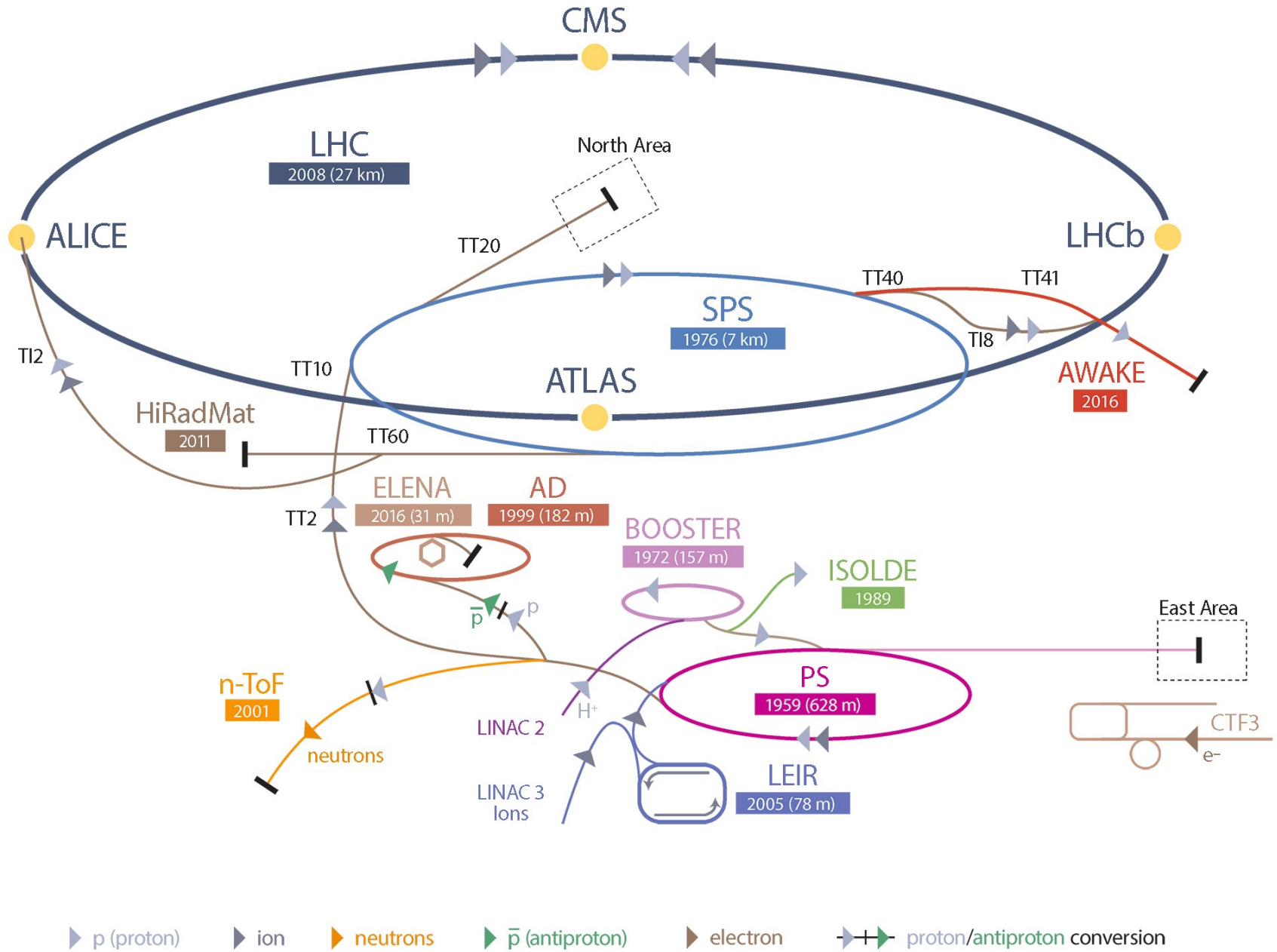
Where does the AD get antiprotons from?



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

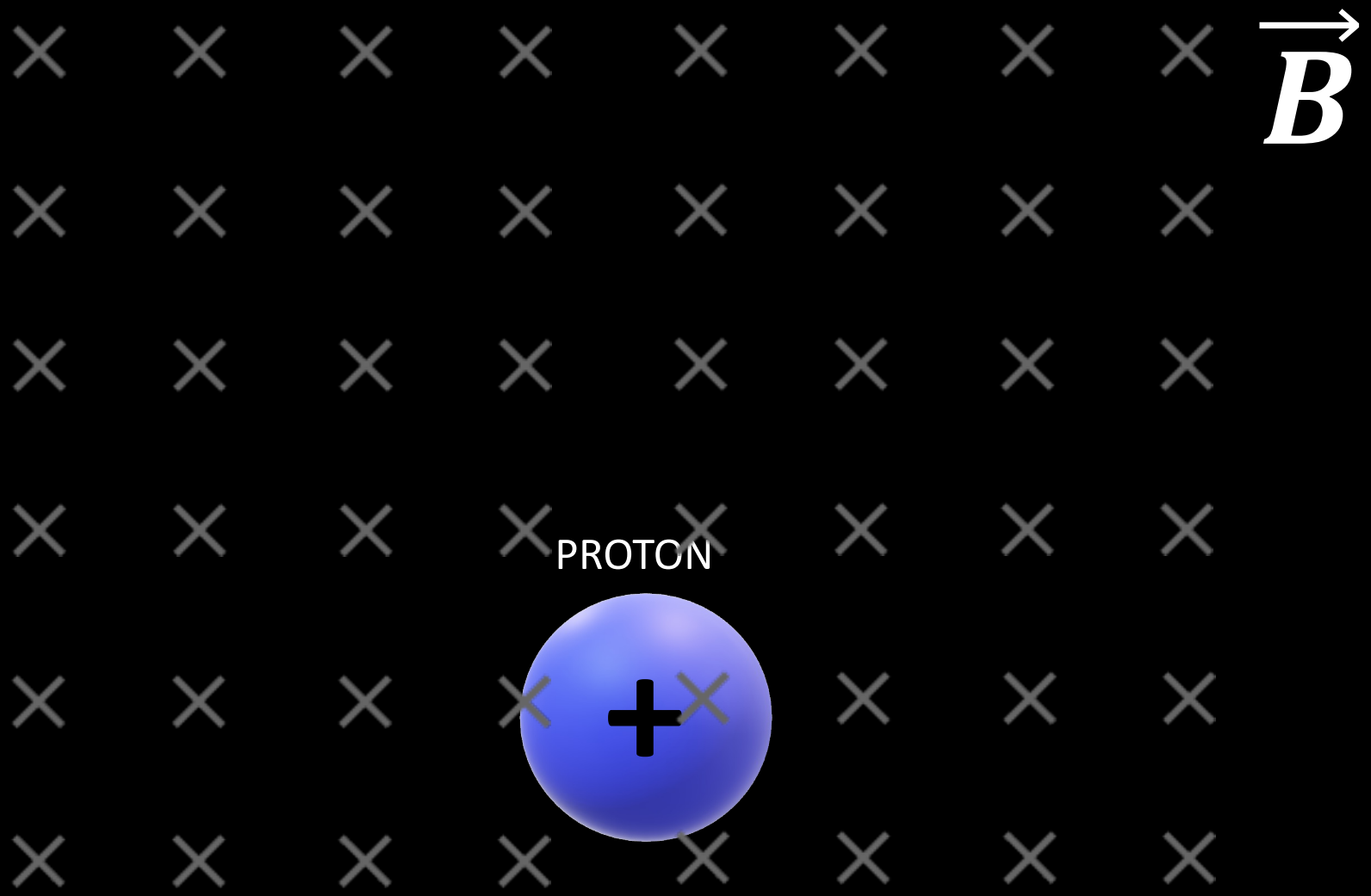
Antiproton Discovery: Chamberlain and Segre 1955

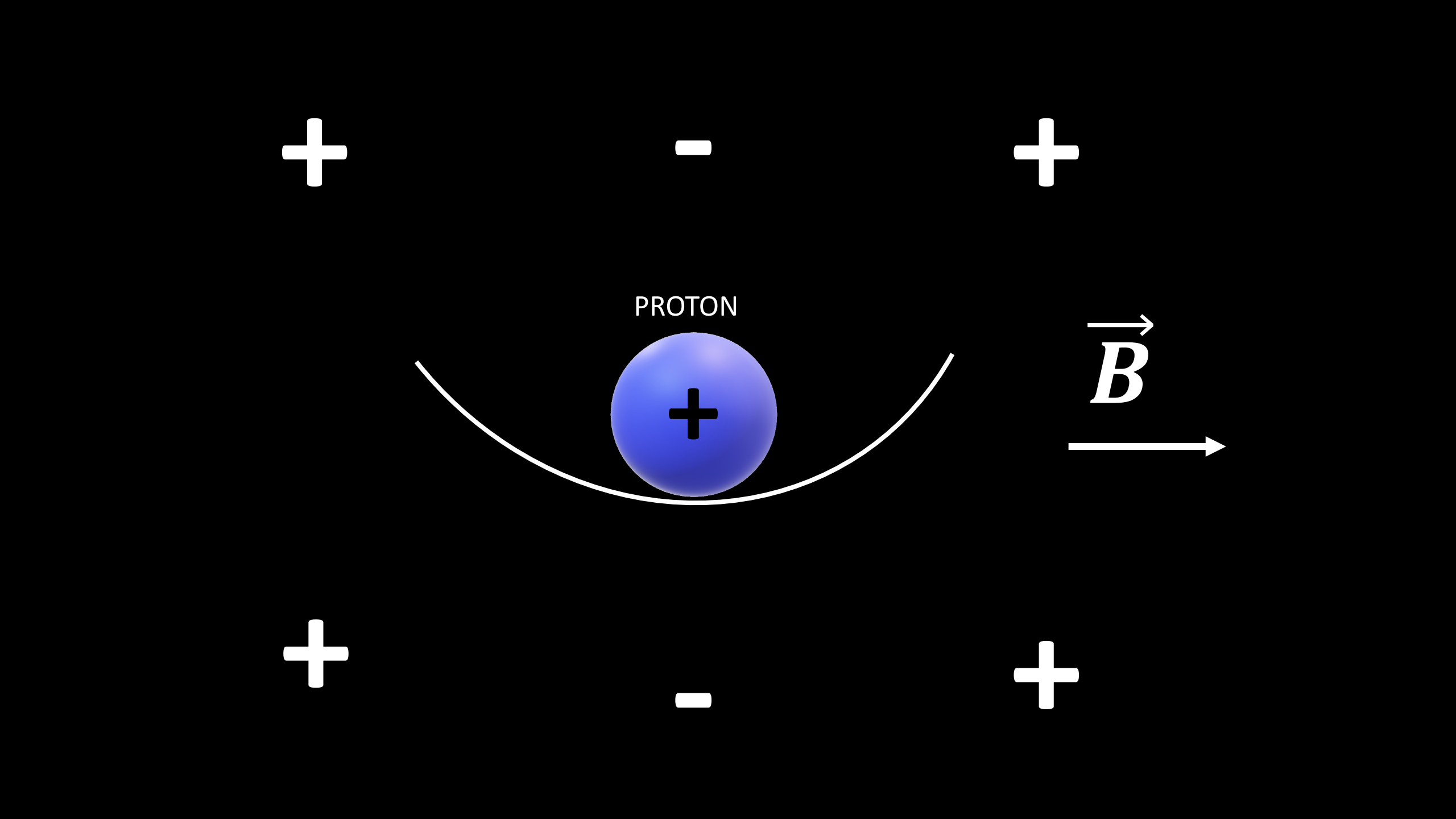
CERN's Accelerator Complex

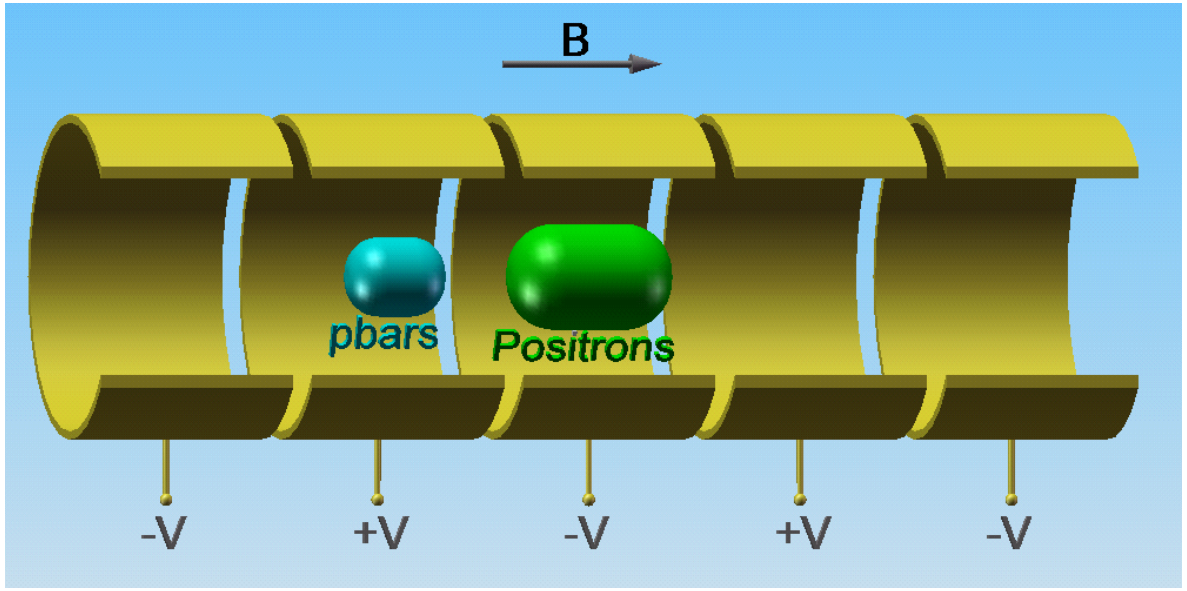


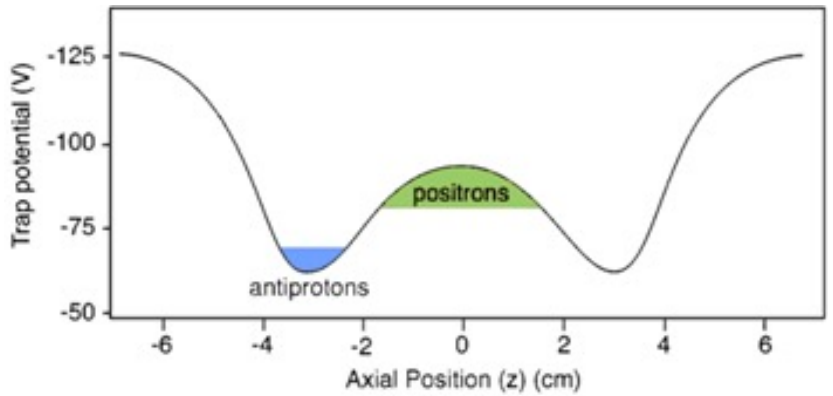
ANTIMATTER
FACTORY
ELENA

Trapping Charged Particles




+
-
+
PROTON
+
$\vec{B}$
+
-
+





Frans Michel Penning

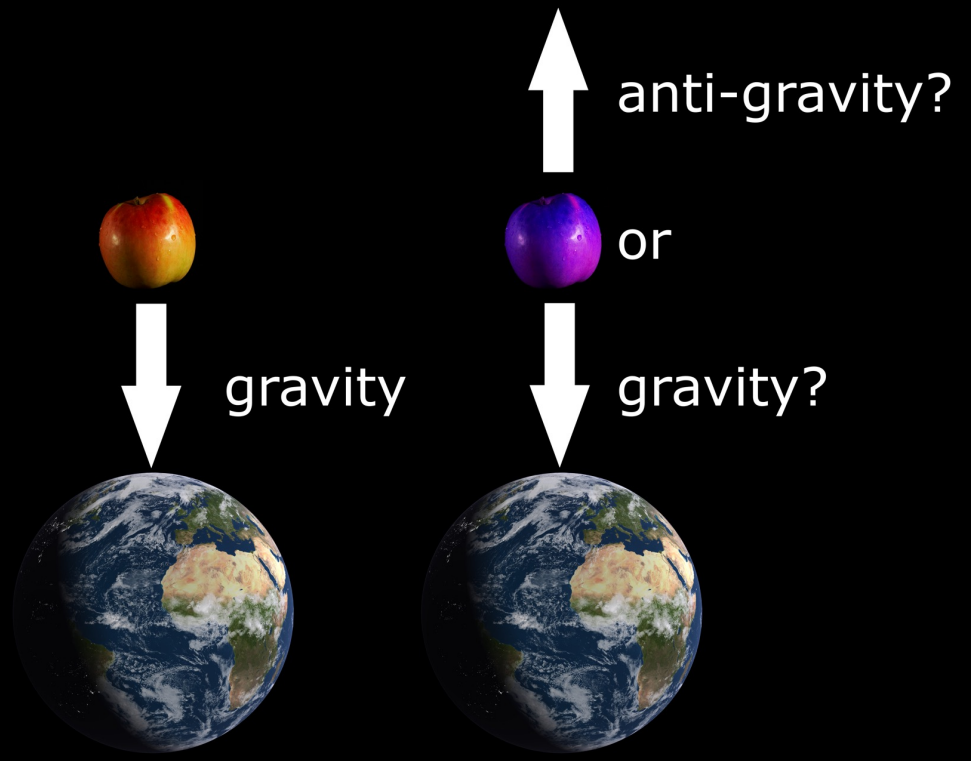
John Malmberg

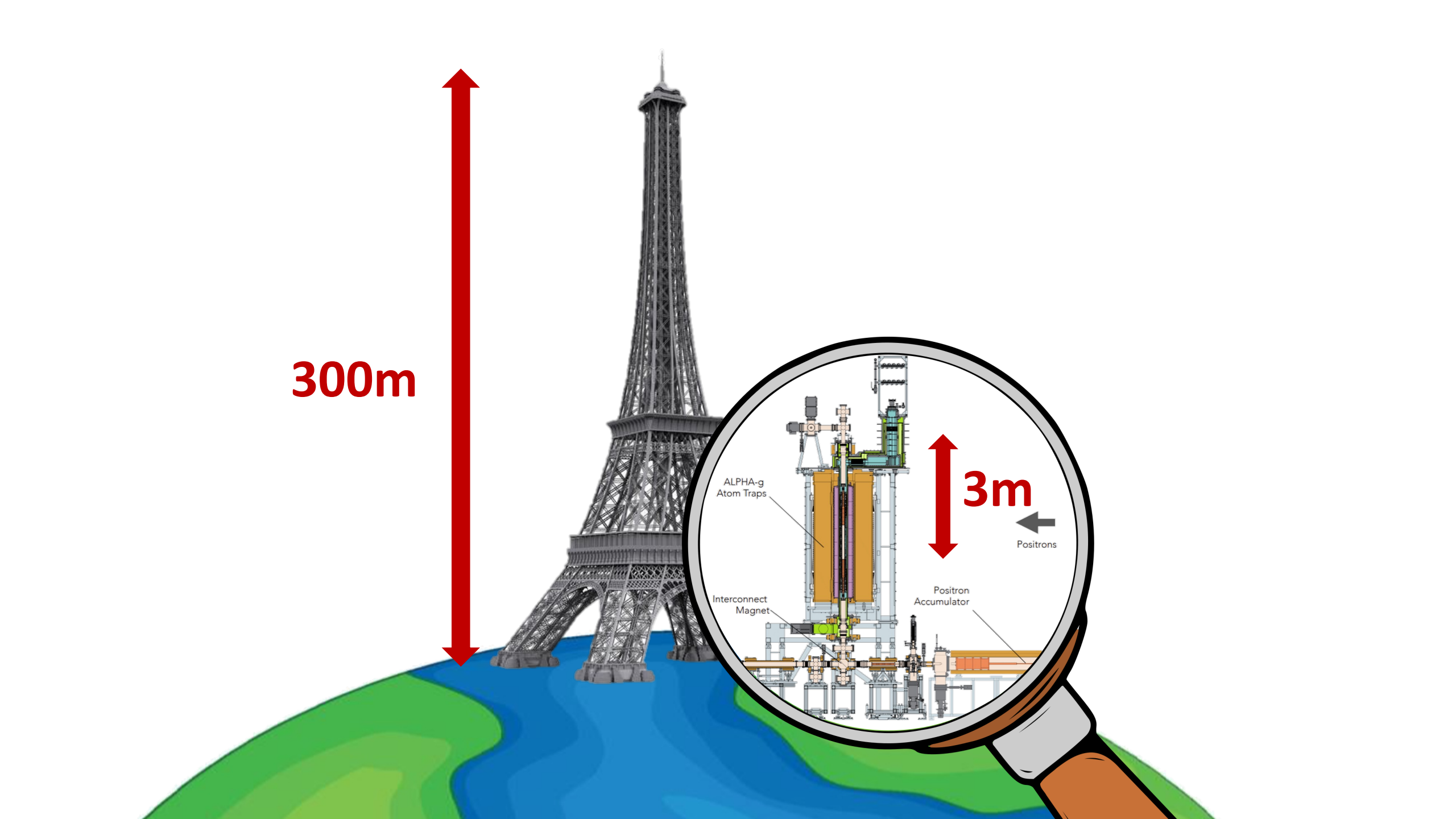
[1] ALPHA, Evaporative Cooling of Antiprotons to Cryogenic Temperatures, *Phys. Rev. Lett.*, **105** 013003, (2010).

ANTIMATTER
FACTORY
ELENA

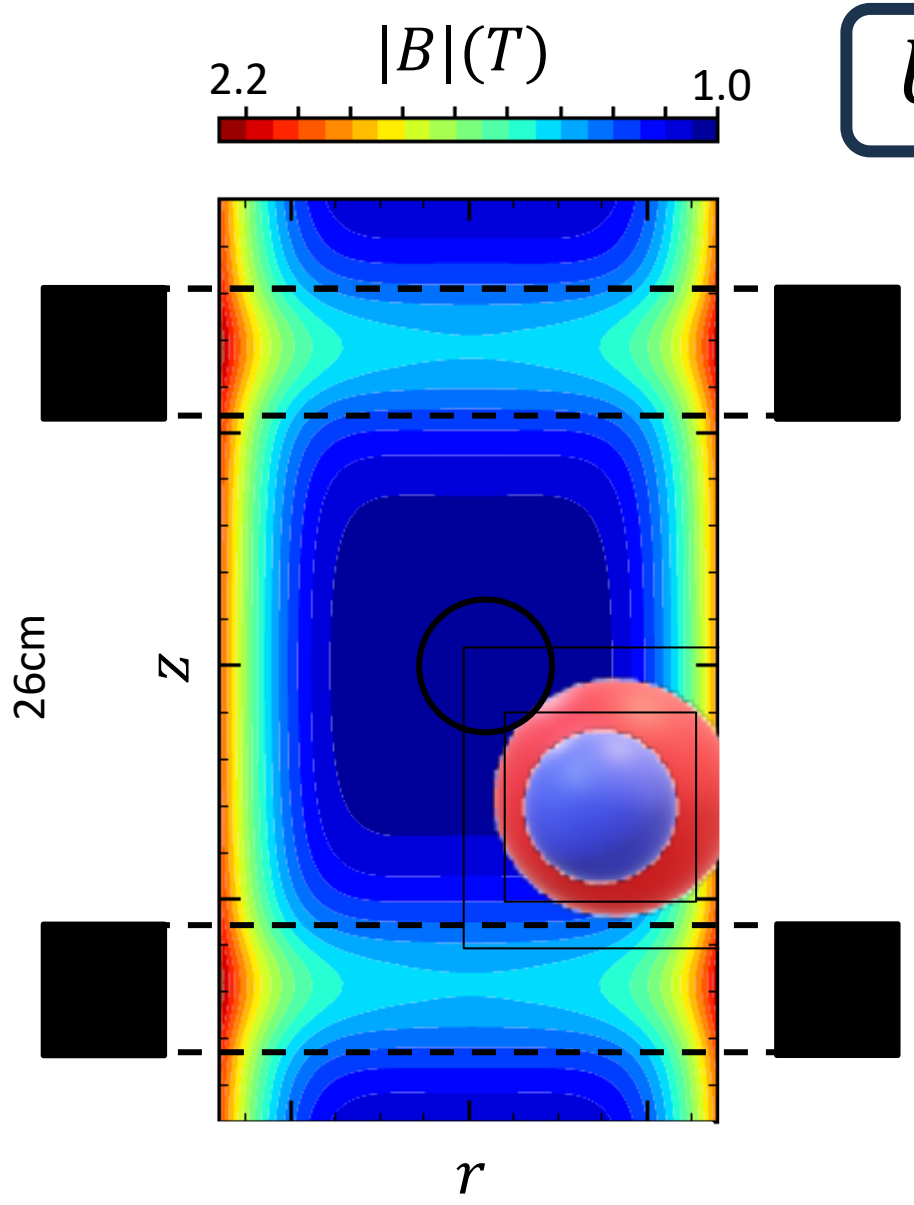
Overview

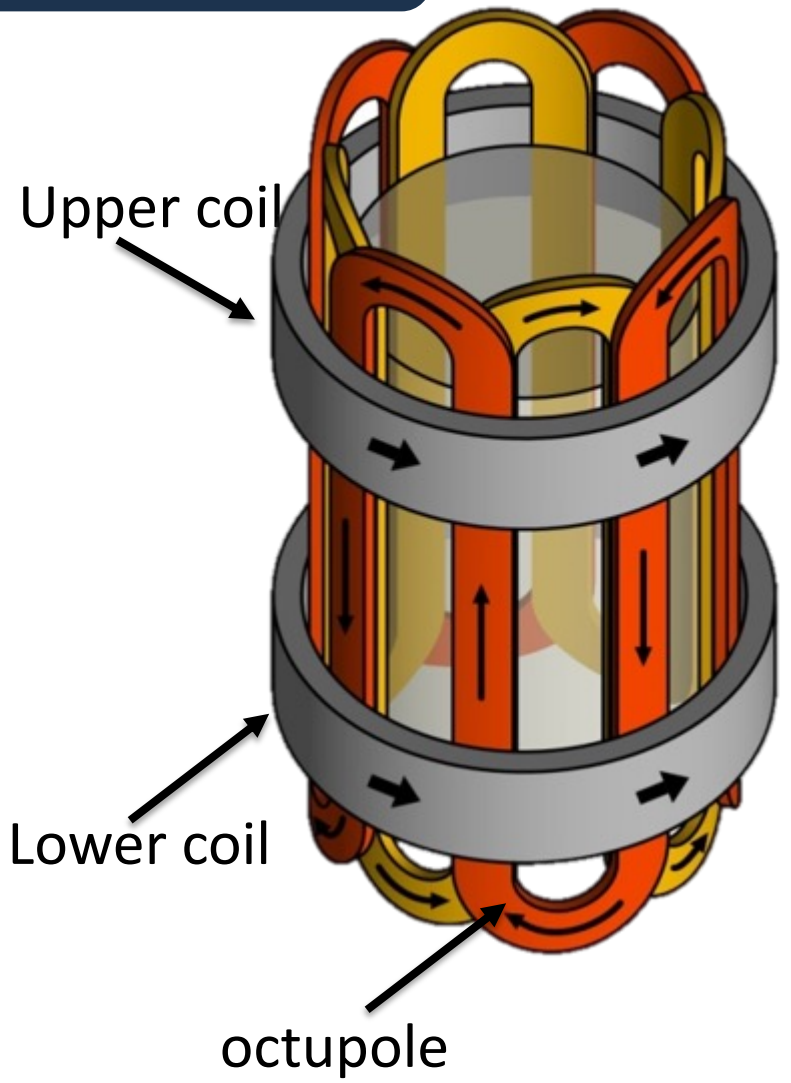
- What is antimatter?
- Why do we care about antimatter?
- How do we make antimatter?
- **How do we test whether anti-gravity exists?**




300m
3m
ALPHA-g
Atom Traps
Positrons
Interconnect
Magnet
Positron
Accumulator

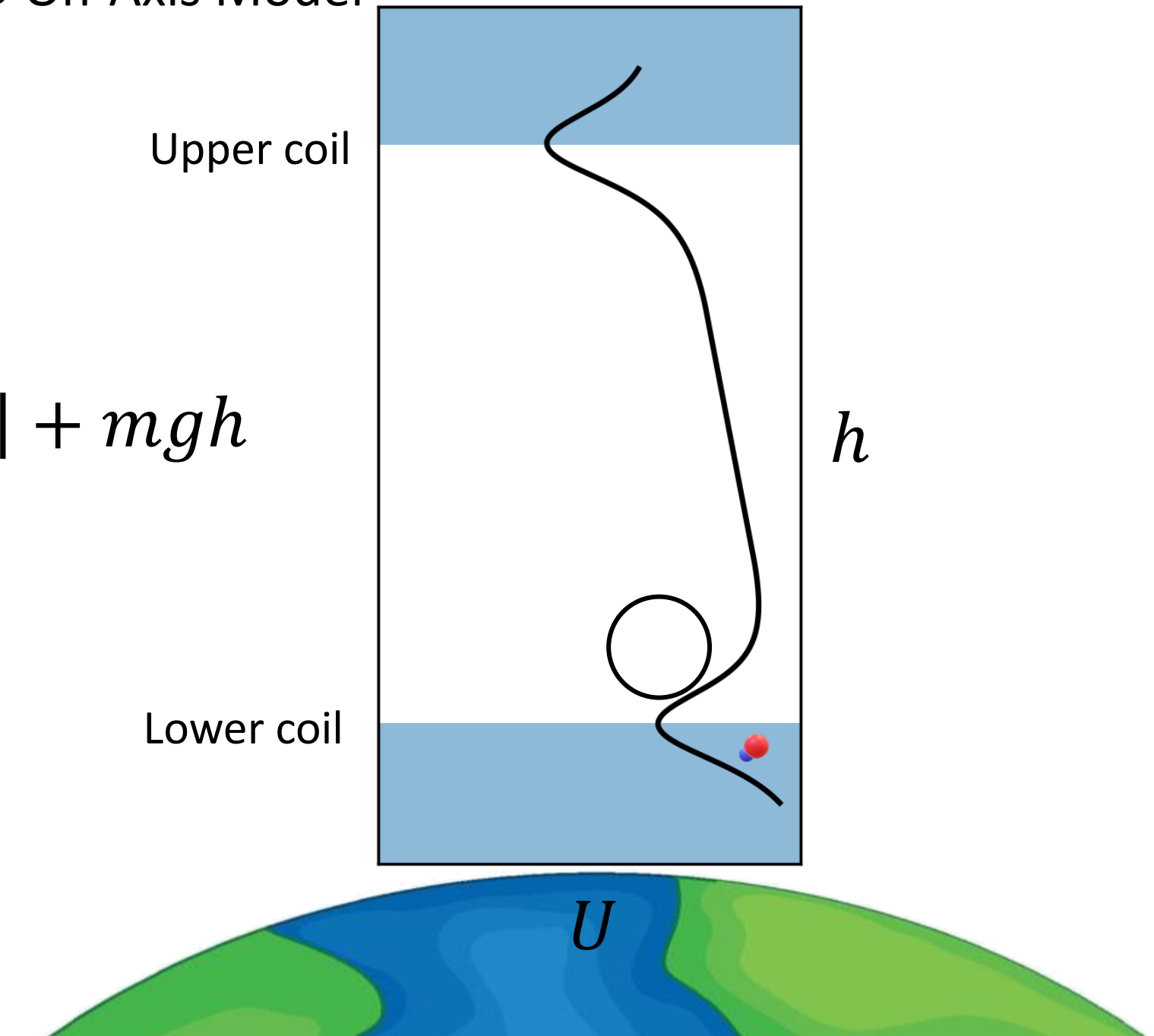
$$U_T = \mu|B|$$





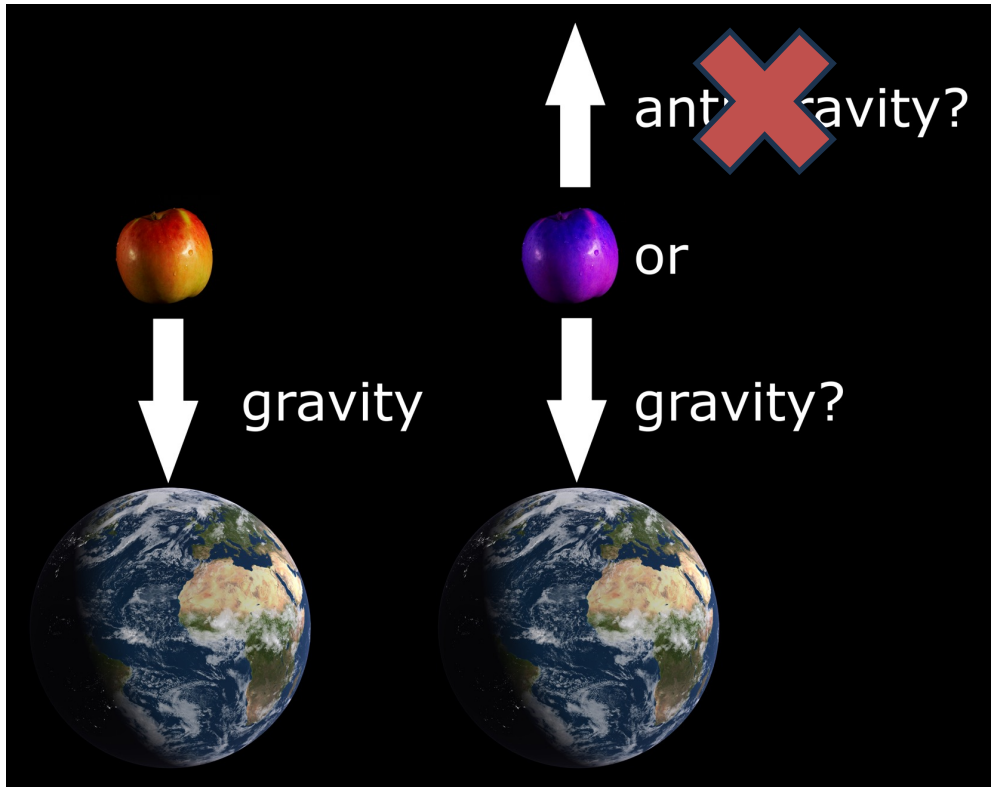
Simplified 1D On-Axis Model

$$U = \mu|B| + mgh$$



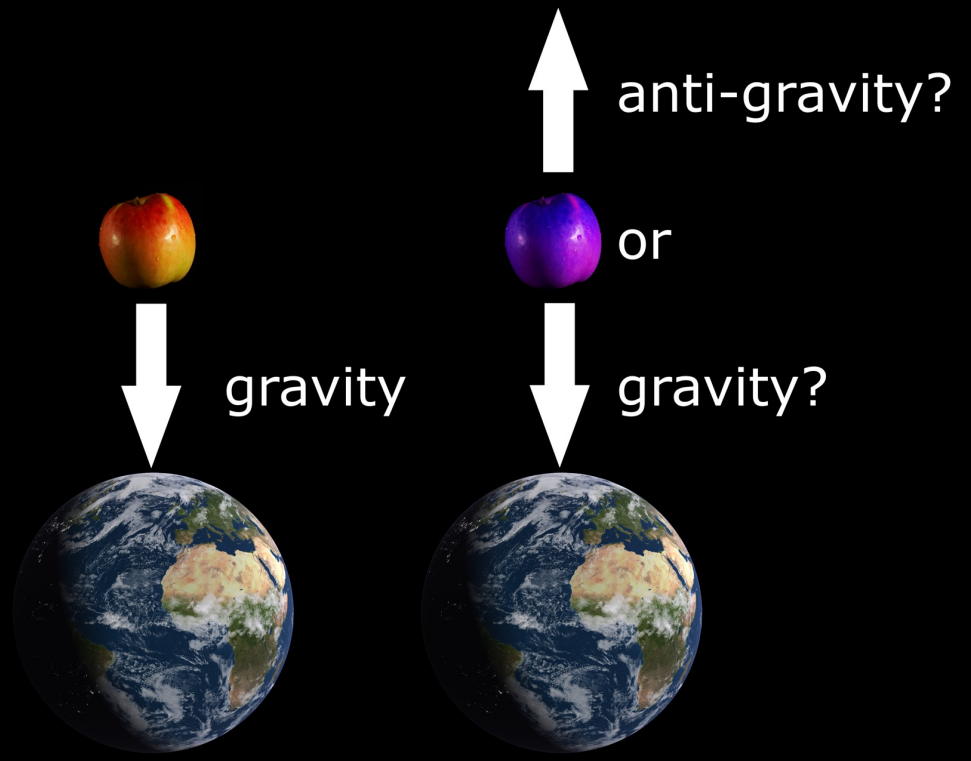
ANTIMATTER
FACTORY
ELENA

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

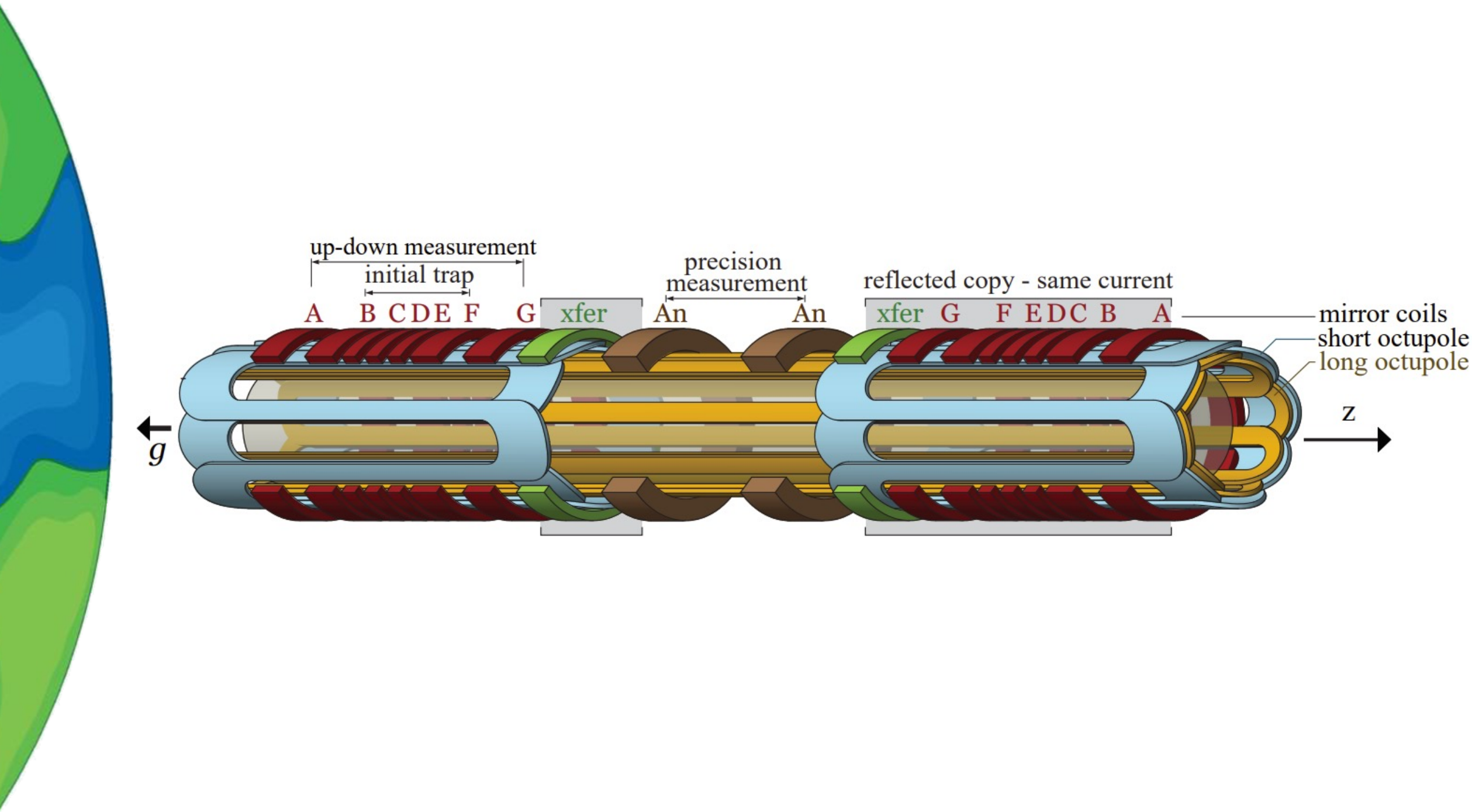


What we have learnt

- What is antimatter?
- Why do we care about antimatter?
- How do we make antimatter?
- How do we test whether anti-gravity exists?



What next?


up-down measurement
initial trap
precision
measurement
reflected copy - same current
A B C D E F G
xfer
An
An
xfer G F E D C B A
mirror coils
short octupole
long octupole
g
z

ANTIMATTER
FACTORY
ELENA