



Angels&Demons

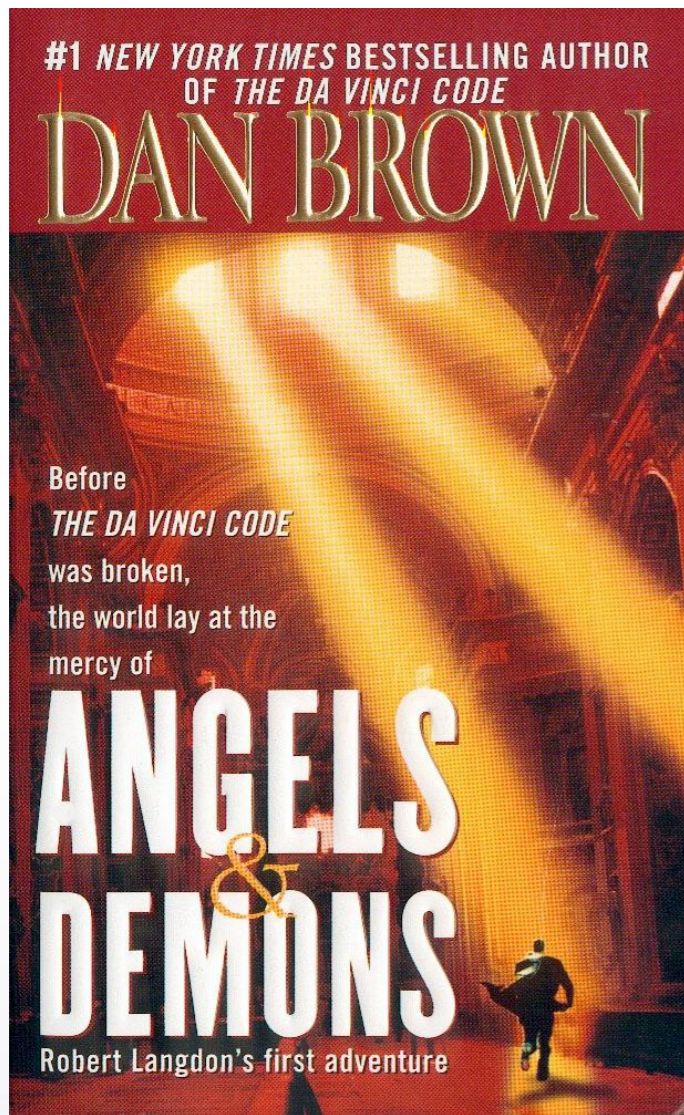
The Physics Behind the Movie

Rolf Landua

CERN

Angels & Demons - The Physics behind the Movie

Dan Brown's "Angels + Demons"



Wuminati



... steal 1 g of antimatter from a physicist at the 'LHC' in a place called "CERN" ...

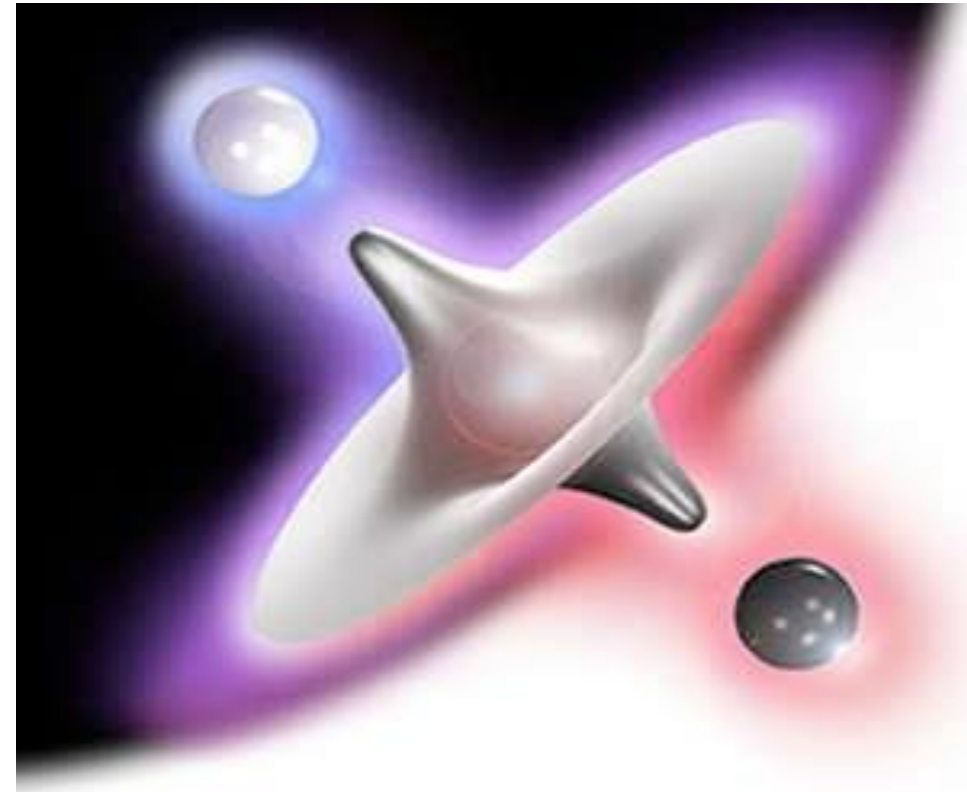


... to blow up the Vatican, an old "enemy of science and CERN".

What's true ? What's false ? Antimatter seems mysterious ...

Angels & Demons - The Physics behind the Movie

Antimatter Questions



Many questions

What is antimatter ?

Antimatter in the LHC ?

The mystery of antimatter ?

How to study antimatter ?

Energy source? A bomb ? Anything useful ?

Angels & Demons: The Director

In 2007, to prepare his movie, Ron Howard visited CERN to find out more about antimatter traps.

What did he say after his guided tour at CERN?



A That's how much I understood from this nerd guiding me around ...

B This much science will be in the "Angels and Demons" movie ...

C That's the budget of my new movie "Angels and Demons"

D This is what Dan Brown understands about antimatter

Who wants to be a millionaire ?

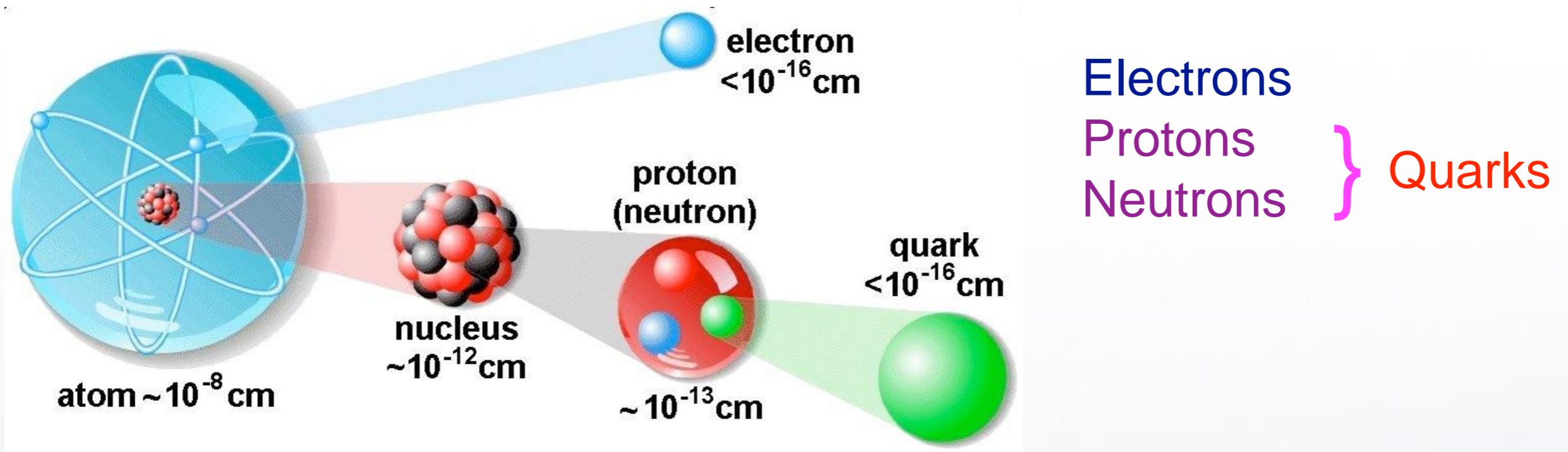
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1 What is antimatter ?

1 What is antimatter ?

Everything is made of matter
(We, animals, plants, rocks)

Hierarchy of matter



Matter is made of **particles**

The whole (visible) Universe is made of 3 building blocks

1 What is antimatter ?

Particles have specific **masses** and **charges**

Name	Electric Charge [e]	Mass [GeV*]
Electron	- 1	0.0005
Proton	+ 1	0.938
Neutron	0	0.941

*GeV = Giga-Electron Volt = 1,000,000,000 Electron-Volt = $1.8 \cdot 10^{-27}$ kg

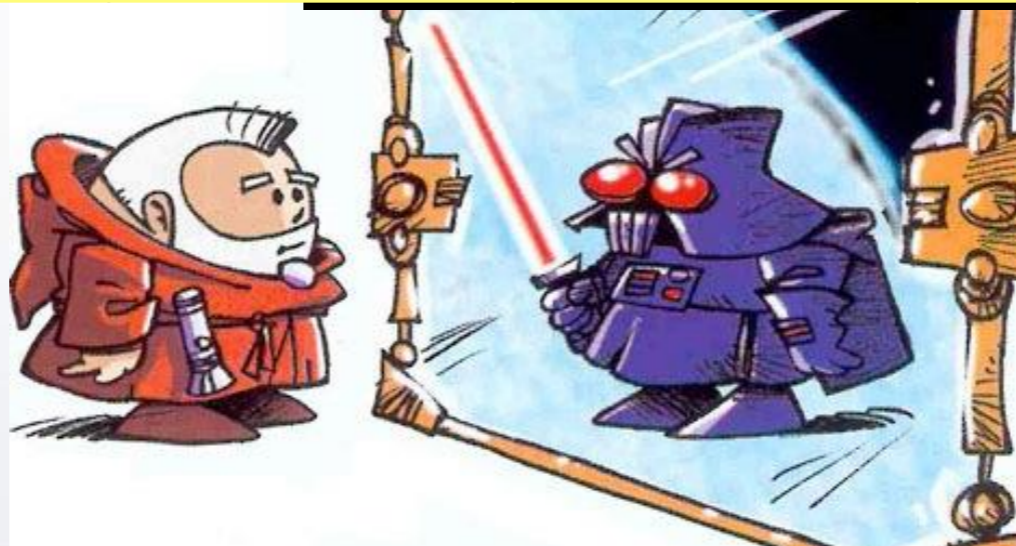
1 What is antimatter ?

Anti-particles have the **same mass**, but **opposite charge**

Name	Electric Charge [e]	Mass	Electric Charge [e]	Name
Electron	- 1	0.0005	+ 1	Positron
Proton	+ 1	0.938	- 1	Antiproton
Neutron	0	0.941	0	Antineutron



Particles

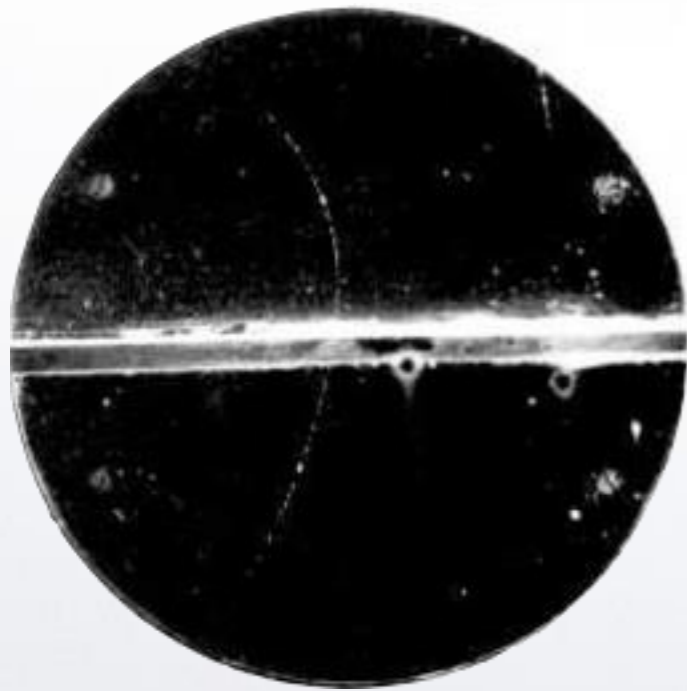
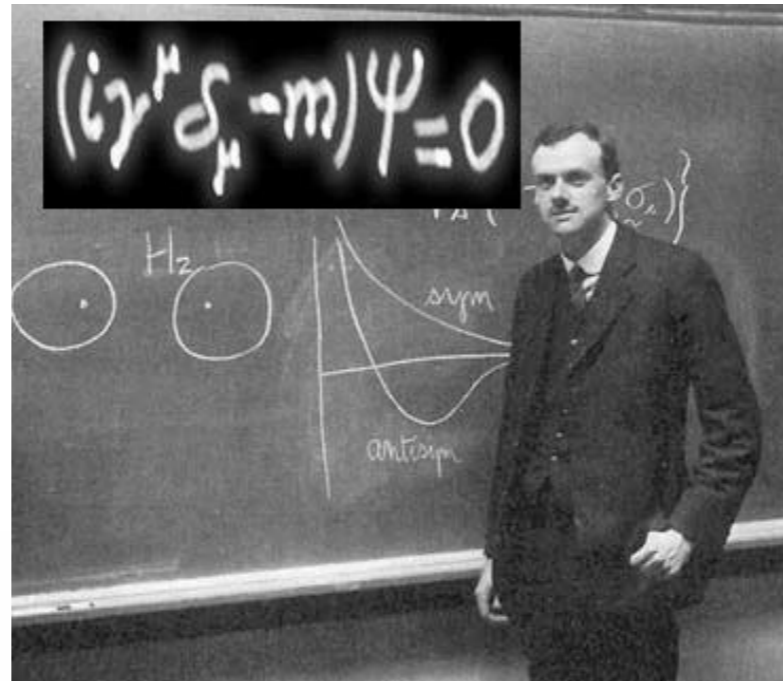


Anti-particles

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1 What is antimatter ?

Predicted by
Paul Dirac (1928) ...



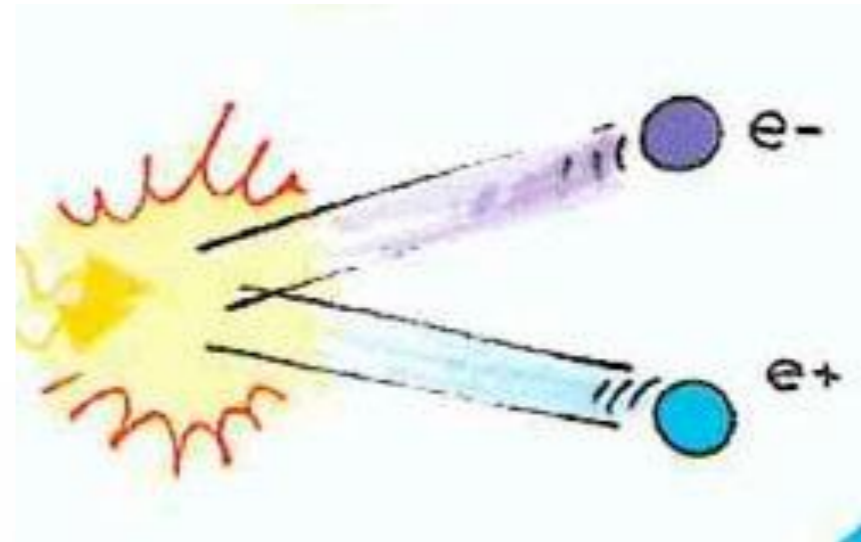
... first antiparticle (positron)
found by Carl Anderson (1932)

1 What is antimatter ?

Particles and anti-particles are always **created in pairs** ...

$$E=mc^2$$

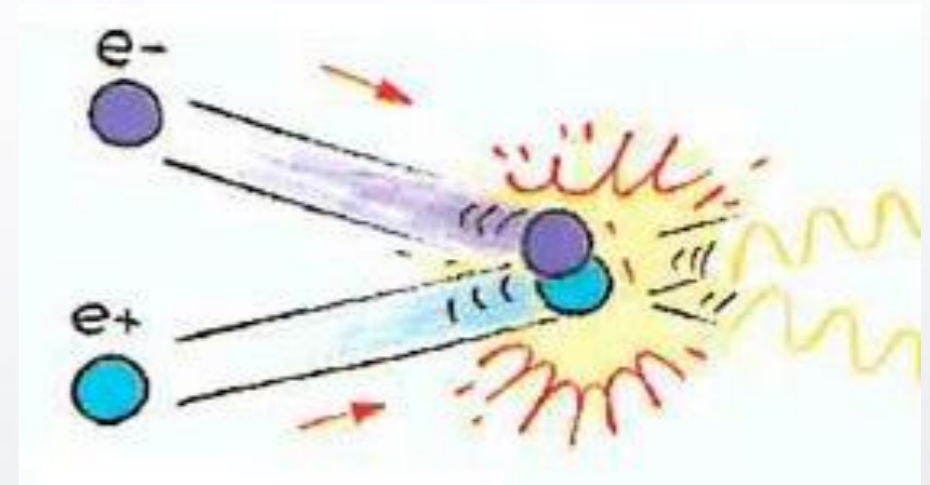
Energy to
mass:



... and they can also **annihilate** each other

$$E=mc^2$$

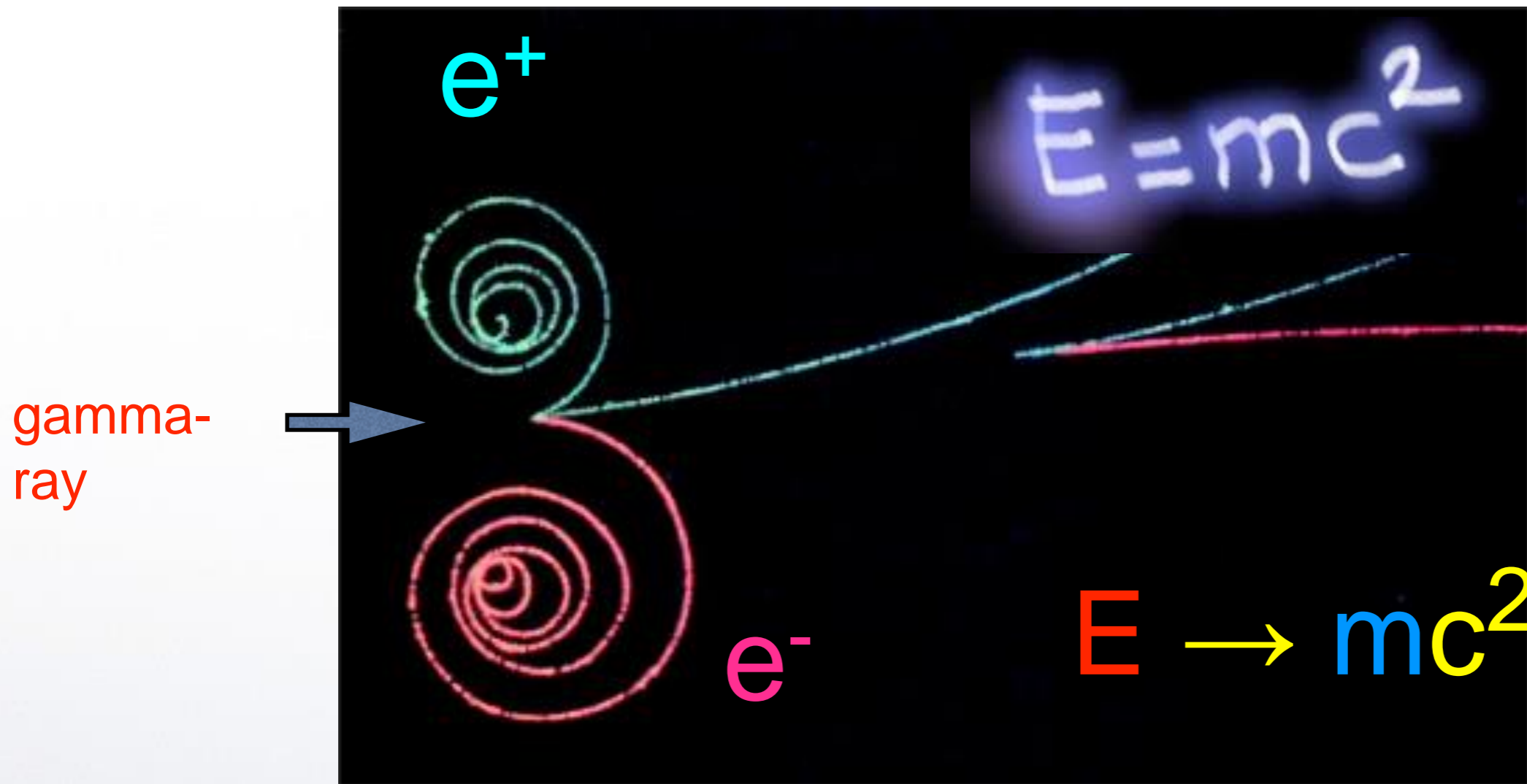
Mass to energy:



1 What is antimatter ?

When Energy is converted to **mass**

an equal amount of matter and antimatter particles are created



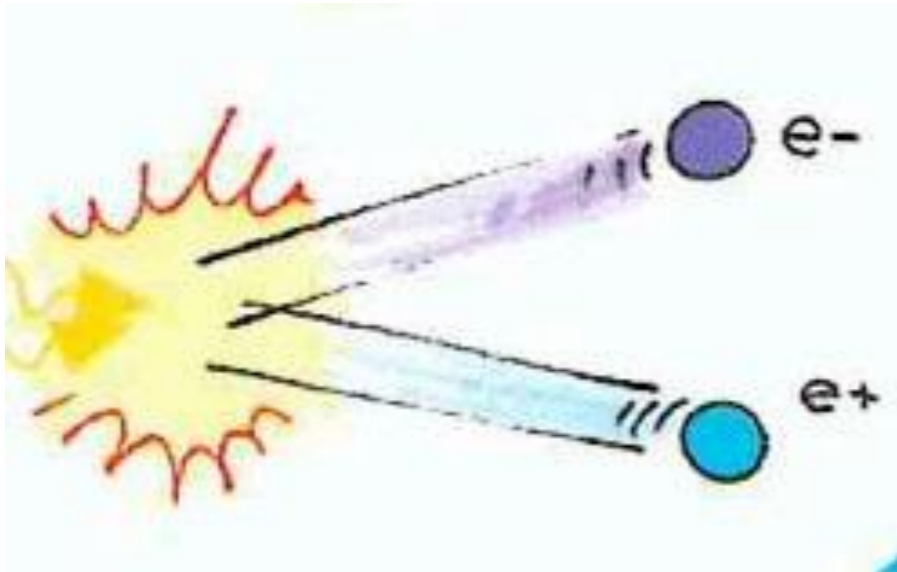
Key: high energy **density**

1 What is antimatter ?

Metaphors for the relation between particles and anti-particles



1 What is antimatter ?



Anti-particles are **as real as particles**



Matter becomes antimatter

A world made of antiparticles would look the same as our world.

1 What is antimatter ?

Careful with “antimatter E.T.” !



2 Antimatter in the LHC ?

2 Antimatter in the LHC ?



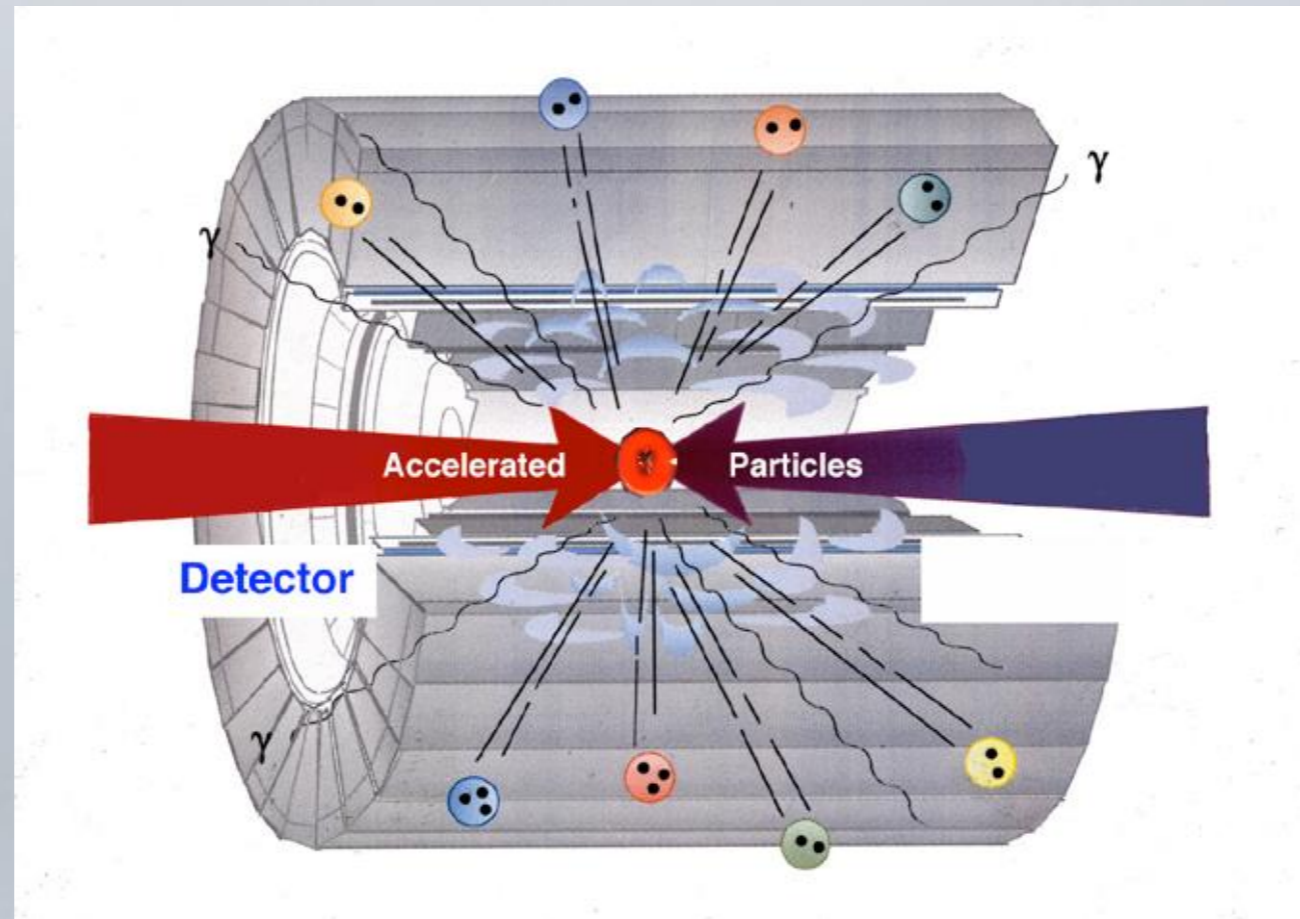
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2 Antimatter in the LHC ?



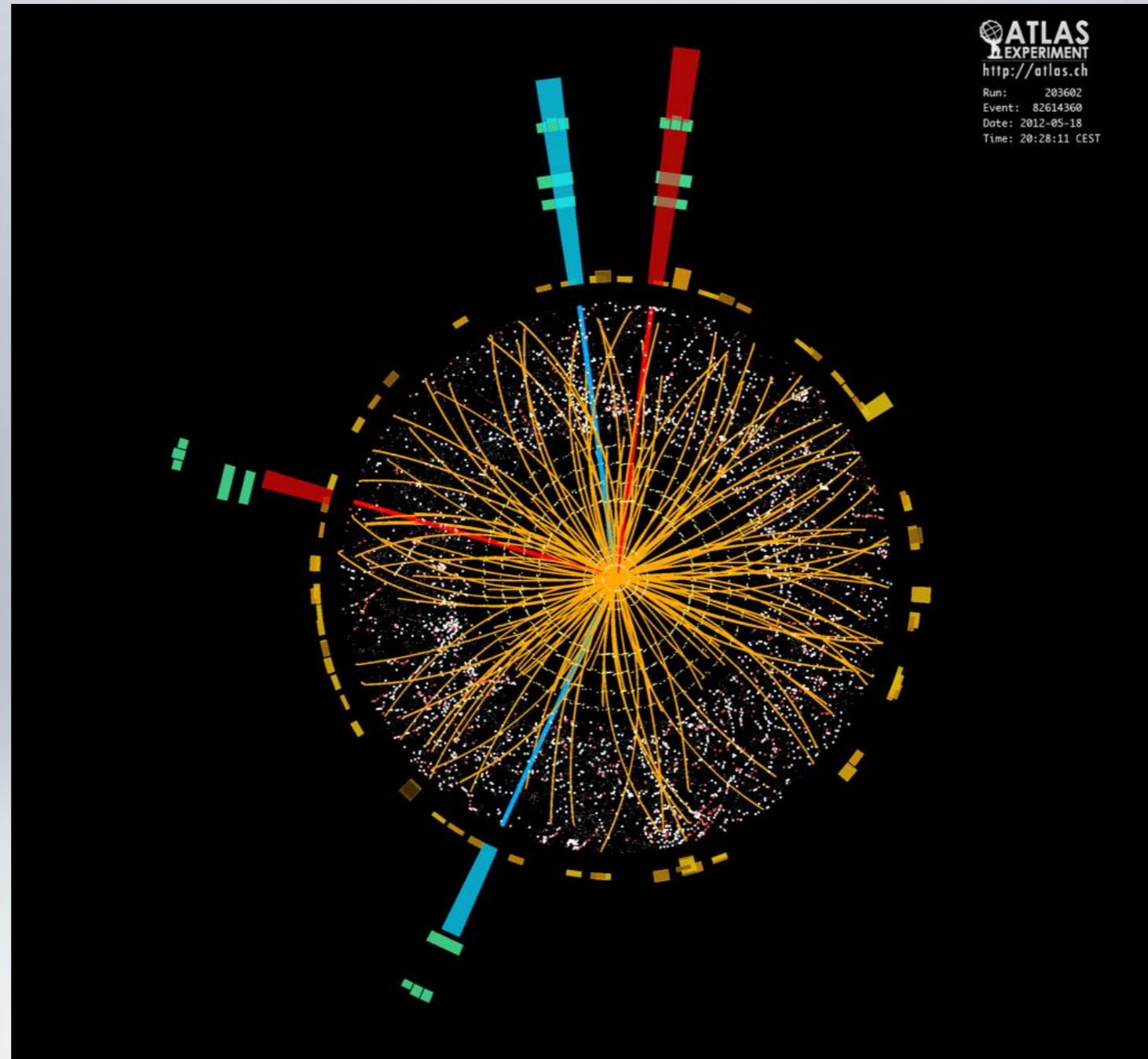
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Movie

2 Antimatter in the LHC ?



Proton-proton collision at 8,000,000,000,000 eV
300-800 new particles ... and antiparticles (1:1)

2 Antimatter in the LHC ?



For example: 400 new particles - average energy 20 GeV

2 Antimatter in the LHC ?

New particles and antiparticles are produced in collisions



The real ATLAS cavern - 100 m underground



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The noisy Hollywood version of antimatter production

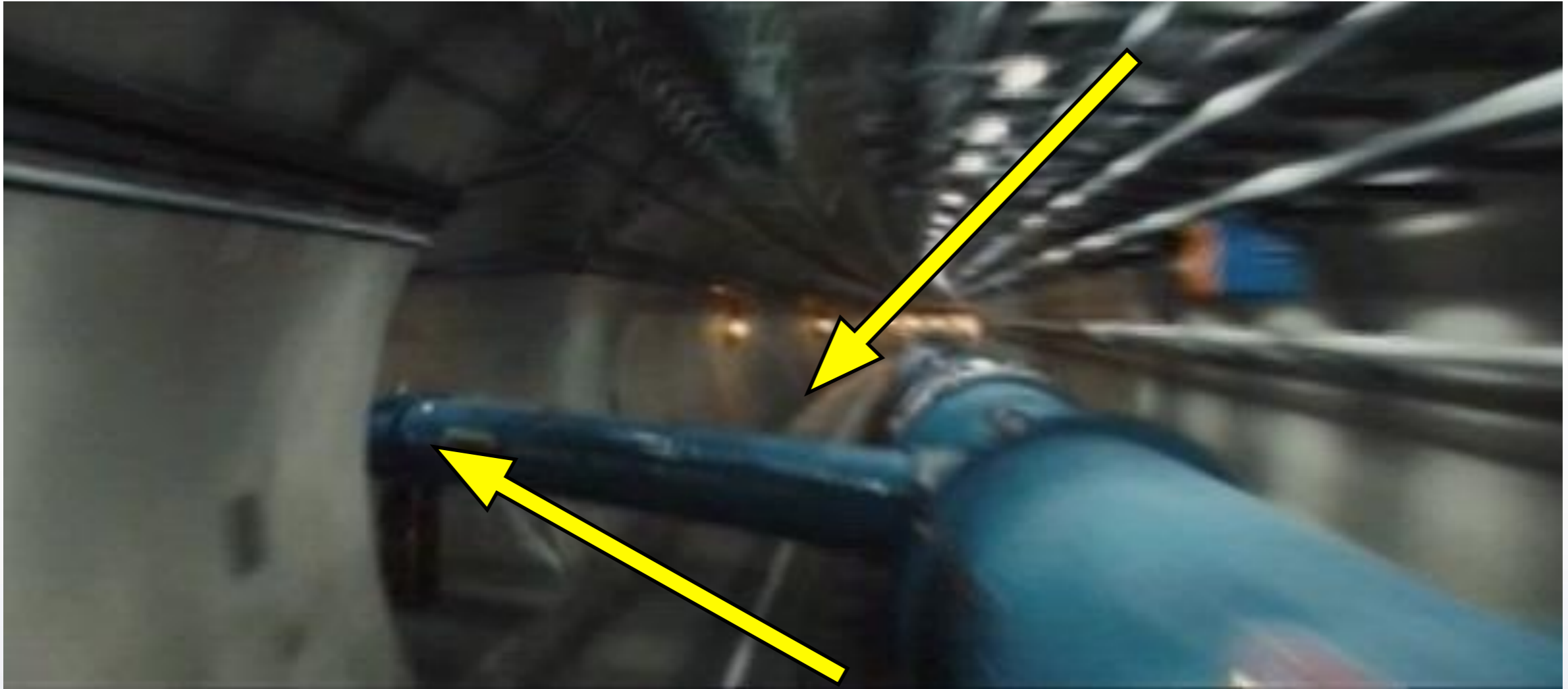


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2 Antimatter in the LHC ?

Bend 20 GeV antiprotons around 5 m radius?

$$B = E [\text{GeV}] / 0.3 / R[\text{m}] = 20/0.3/5 \sim \mathbf{13\ T} (?)$$



Decelerate 20 GeV antiprotons within 100 m?

$$\text{Gradient} = 20000 \text{ MeV}/100 \text{ m} = \mathbf{200\ MeV/m}$$

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3 The mystery of

2009:
Pre-premiere of
Angels+Demons at
CERN



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3 The mystery of antimatter



Tom Hanks explains the research at CERN

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3 The mystery of antimatter

Antimatter and ...

God particle ?? No.

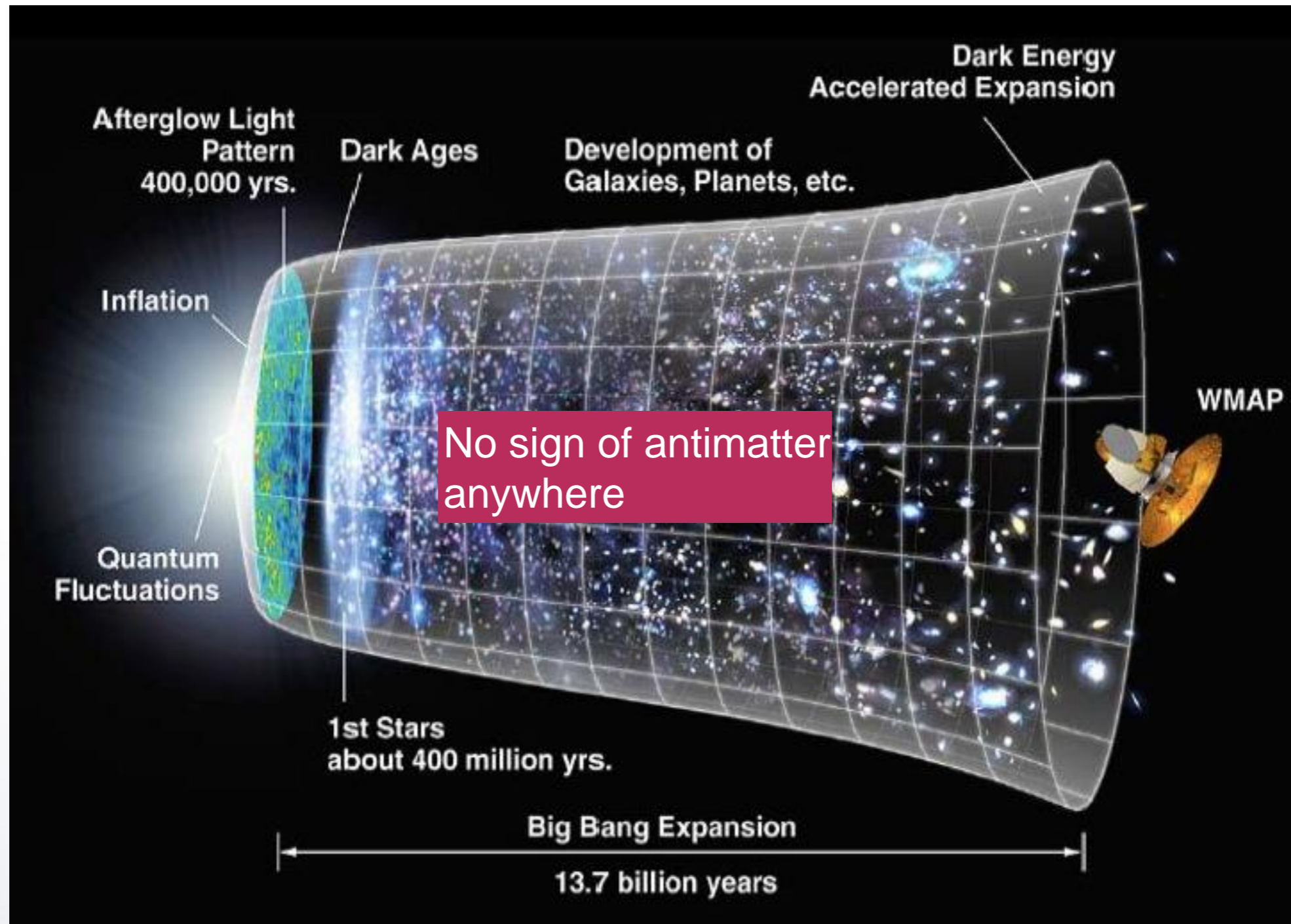
Implications for energy research ? Hmmm.

Combustible substance ? May be.

An airtight nanocomposite container with magnets

The moment of creation ... yes!!

3 The mystery of antimatter



Big Bang model: the evolution of the Universe

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3 The mystery of antimatter

Where has the antimatter gone
?

Solar System ? No !

3 The mystery of antimatter

Where has the antimatter gone

?

In galaxies far, far away ? No.

There seems to be no antimatter in the Universe

!

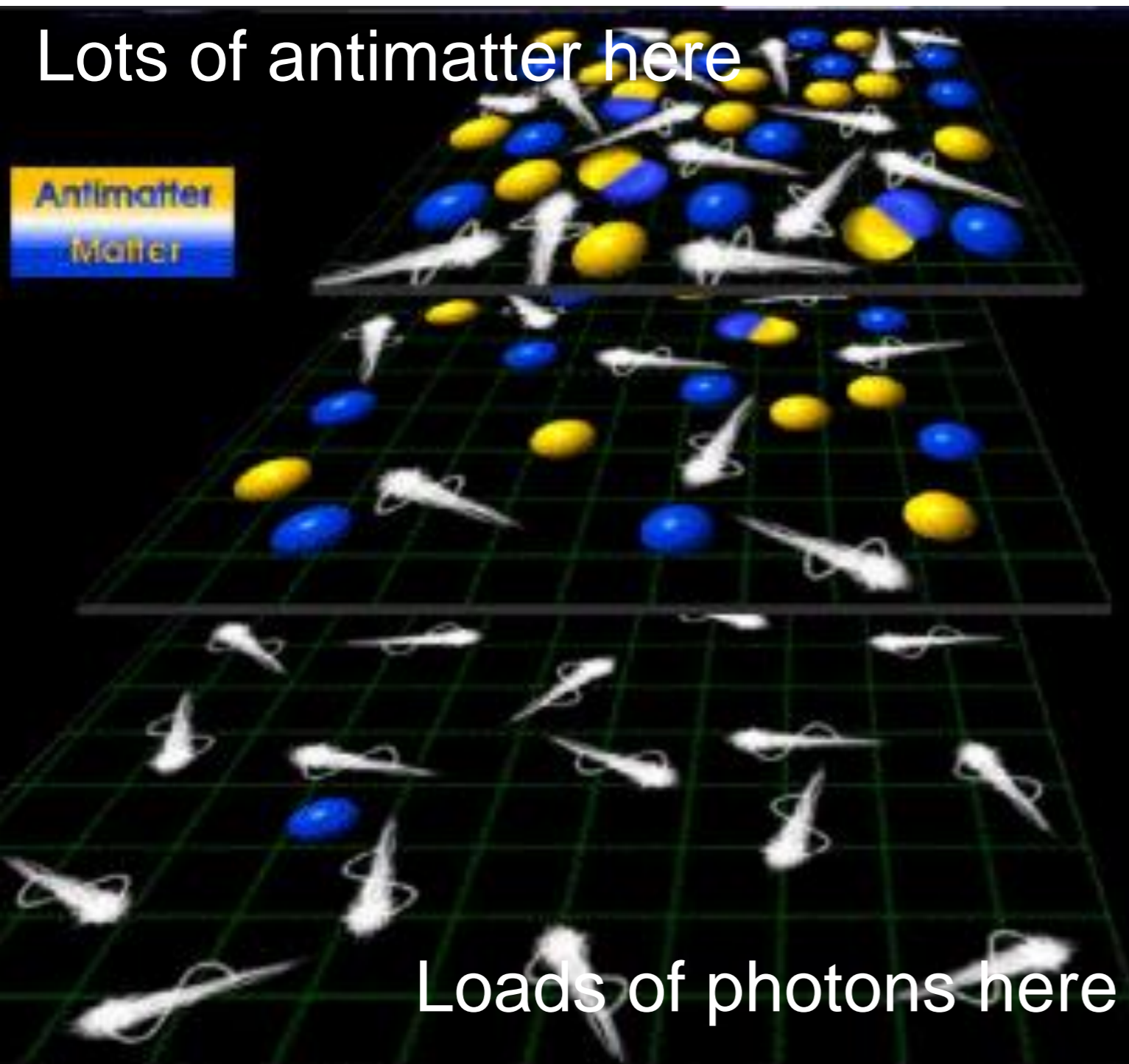
3 The mystery of antimatter

No antimatter in the Universe ?

Why not ????

3 The mystery of antimatter

Lots of antimatter here



Cosmic CSI

Big Bang:

Energy transforms to mass

$< 1 \mu\text{s}$: matter = antimatter

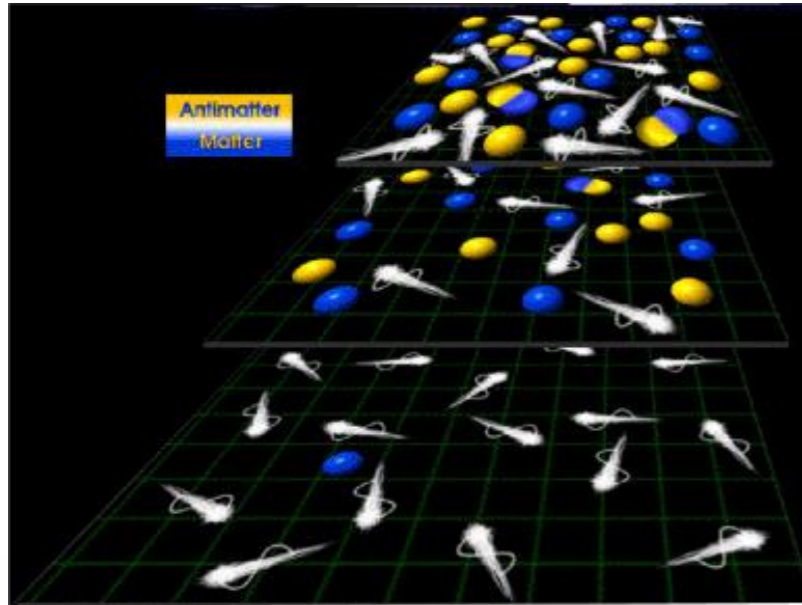
Annihilation battle

1 s: all antimatter has disappeared,

some particles left (all stars/planets)
loads of 'photons' (left from annihilation)

Universe filled with light (cosmic microwave backg.)

3 The mystery of antimatter



Why did all antimatter disappear,
but a little bit of matter was left?

Matter and antimatter must have (very slightly) different properties!

But where do we have to look ?

Mass, charge, magnetic moment (CERN: AD experiments)

CP violation (CERN: LHCb experiment)

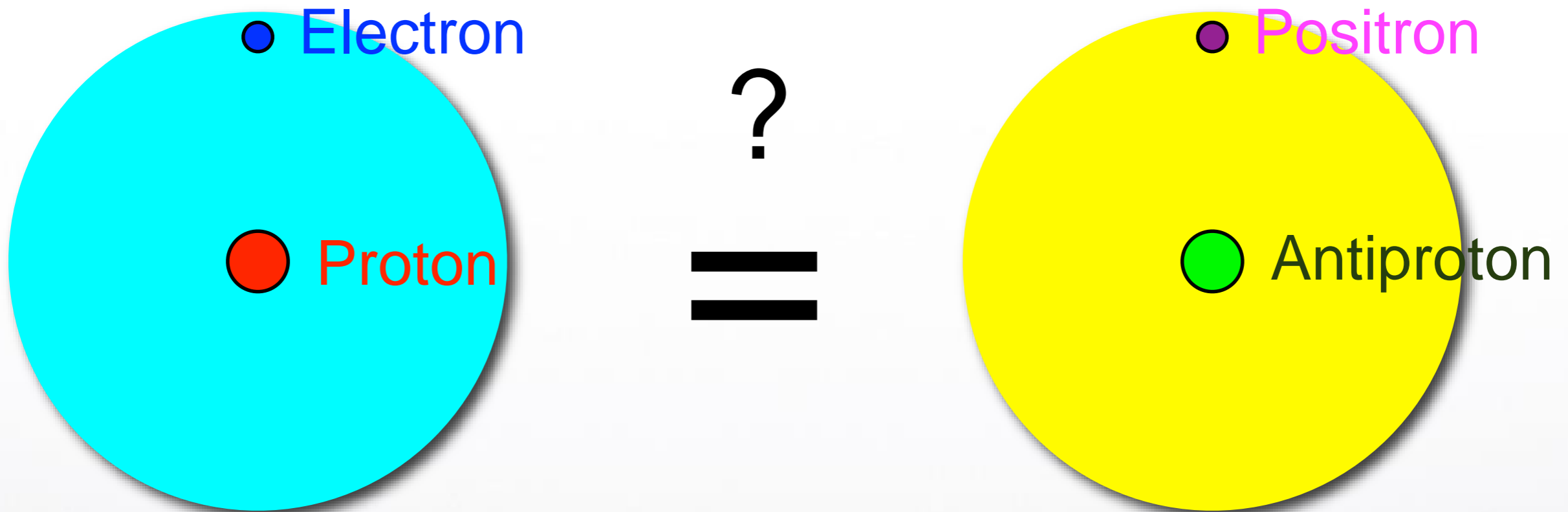
4 How to study antimatter ?

The antihydrogen route

...

4 How to study antimatter ?

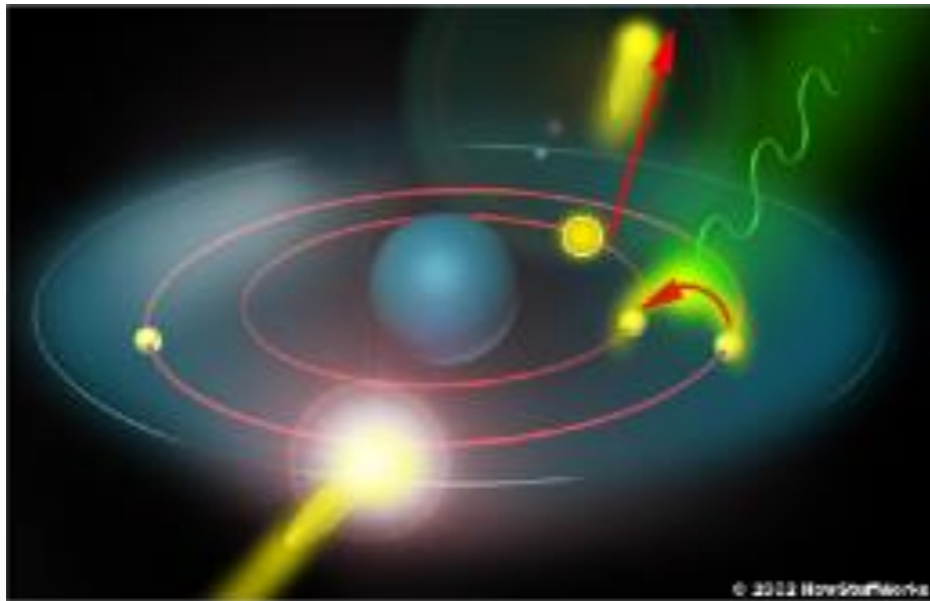
Make antihydrogen + compare with hydrogen atom



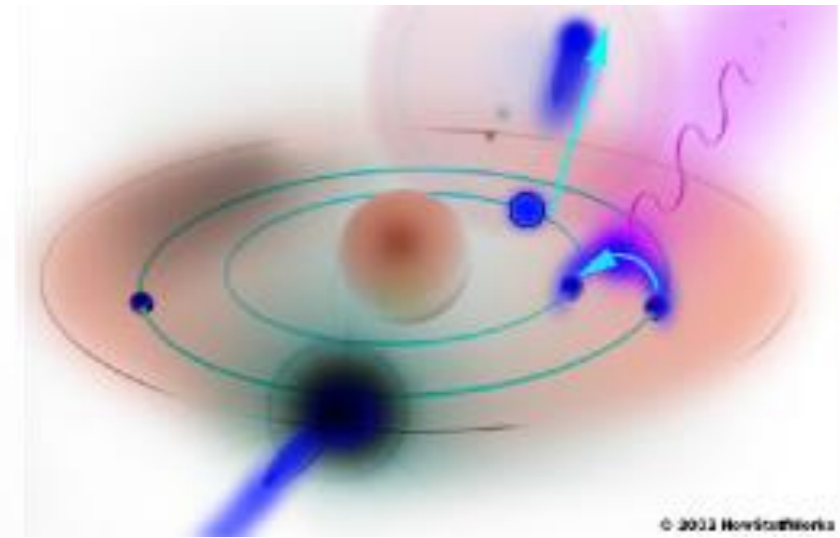
Measure differences to a precision of
0.000 000 000 000 001 %

4 How to study antimatter ?

Same energy levels (1S-2S)?



Hydrogen



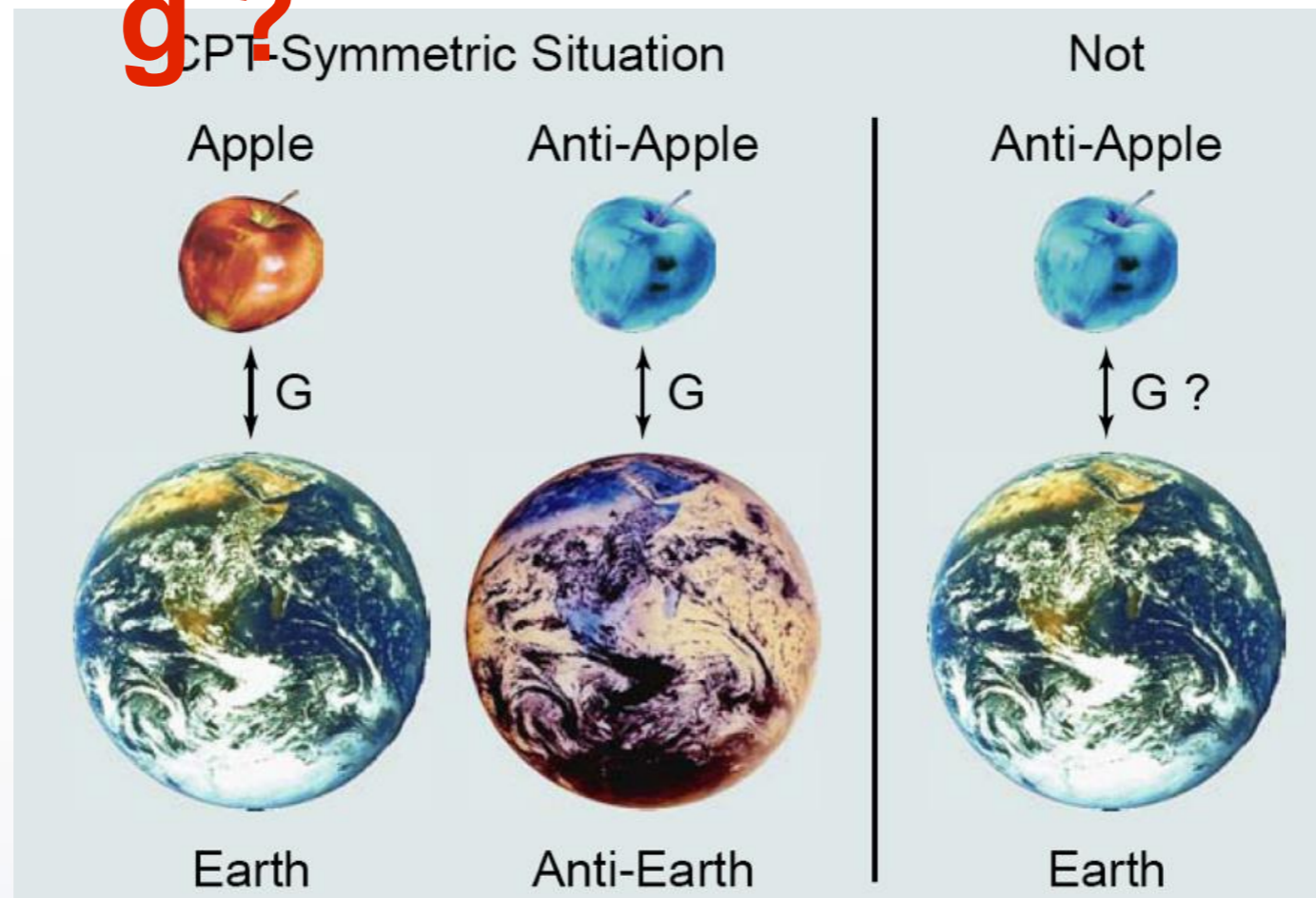
Anti-Hydrogen

AD experiments: ALPHA, ATRAP, ASACUSA

4 How to study antimatter ?

Same gravity: $g \equiv$

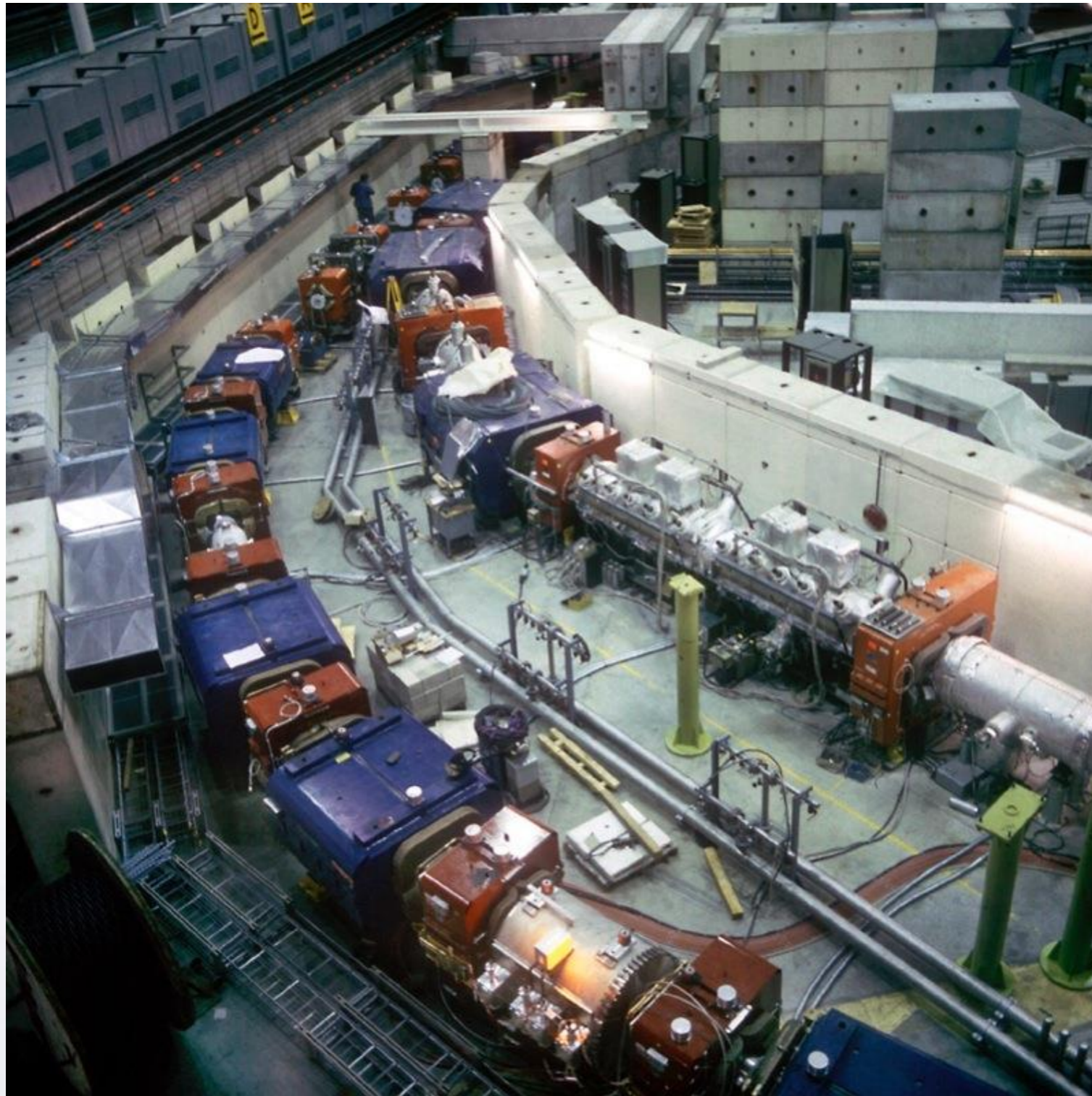
g ?



AD experiments: Aegis, Gbar

Antiproton Decelerator at CERN

4 How to study antimatter ?

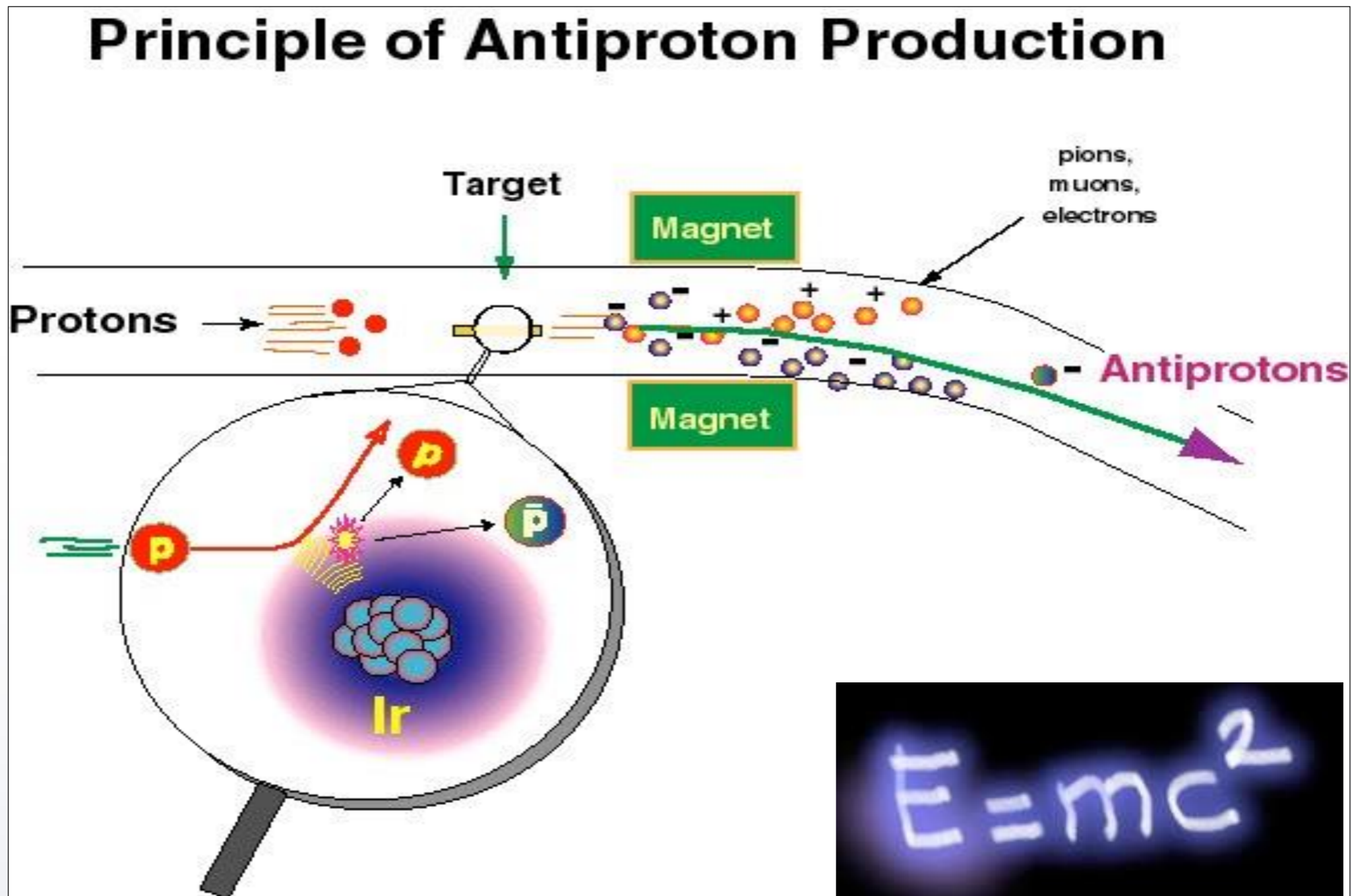


Antiproton Decelerator

produces 100,000,000
antiprotons per minute

Slows them down to 10
% of the speed of light

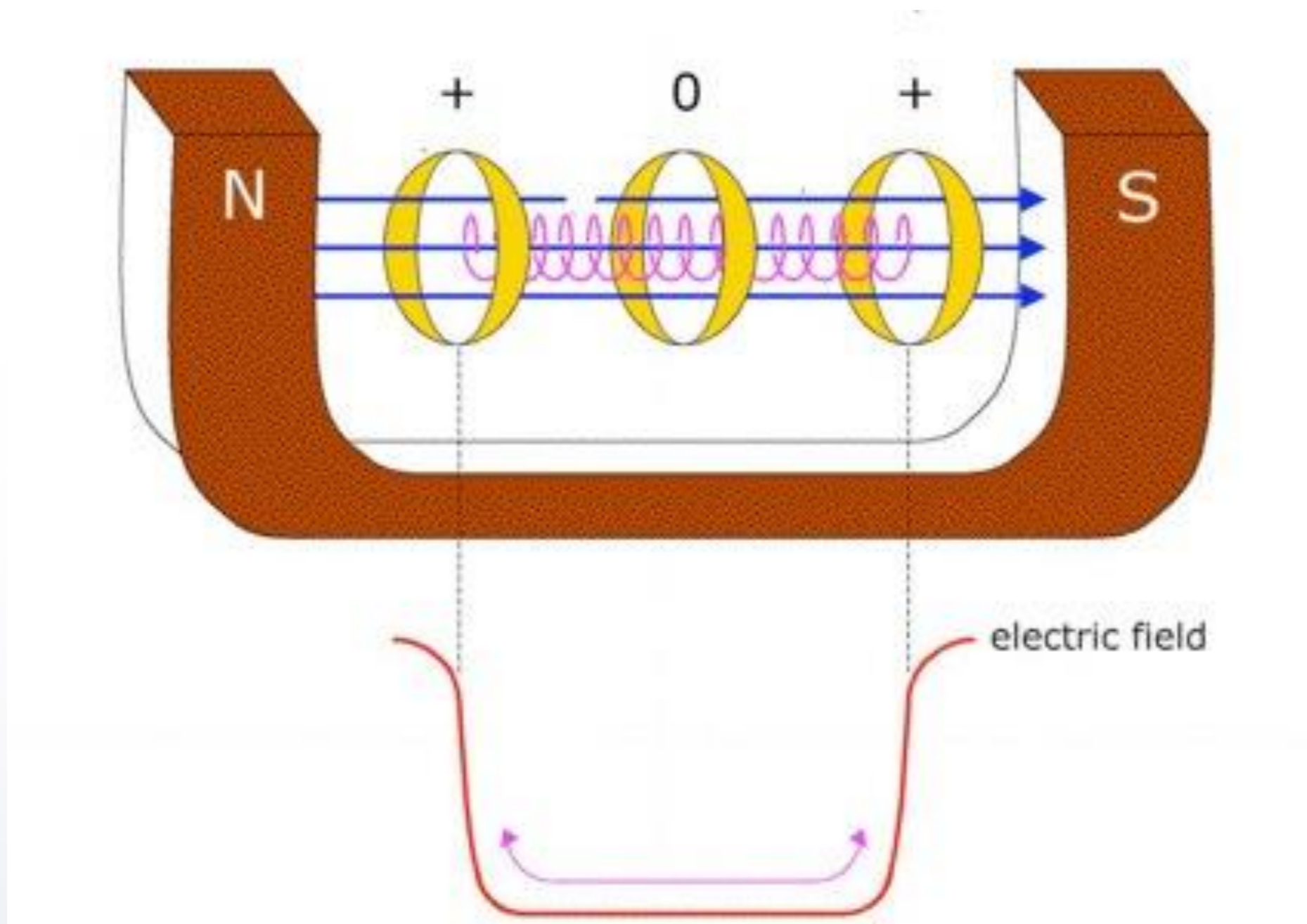
4 How to study antimatter ?



Antiprotons are made in collisions of protons with nuclei

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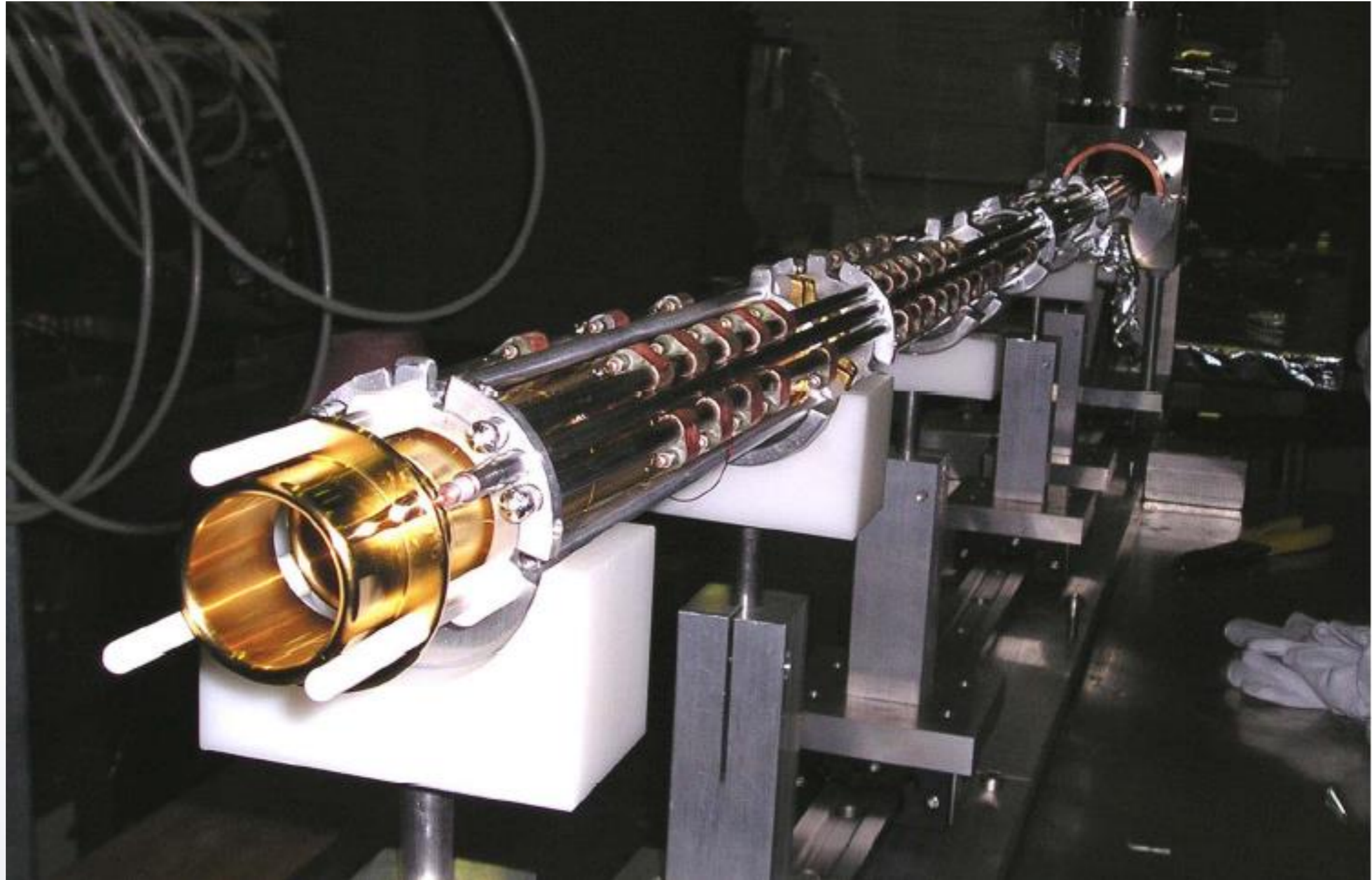
4 How to study antimatter ?



Principle of antiparticle trapping

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4 How to study antimatter ?



A real antimatter trap at CERN

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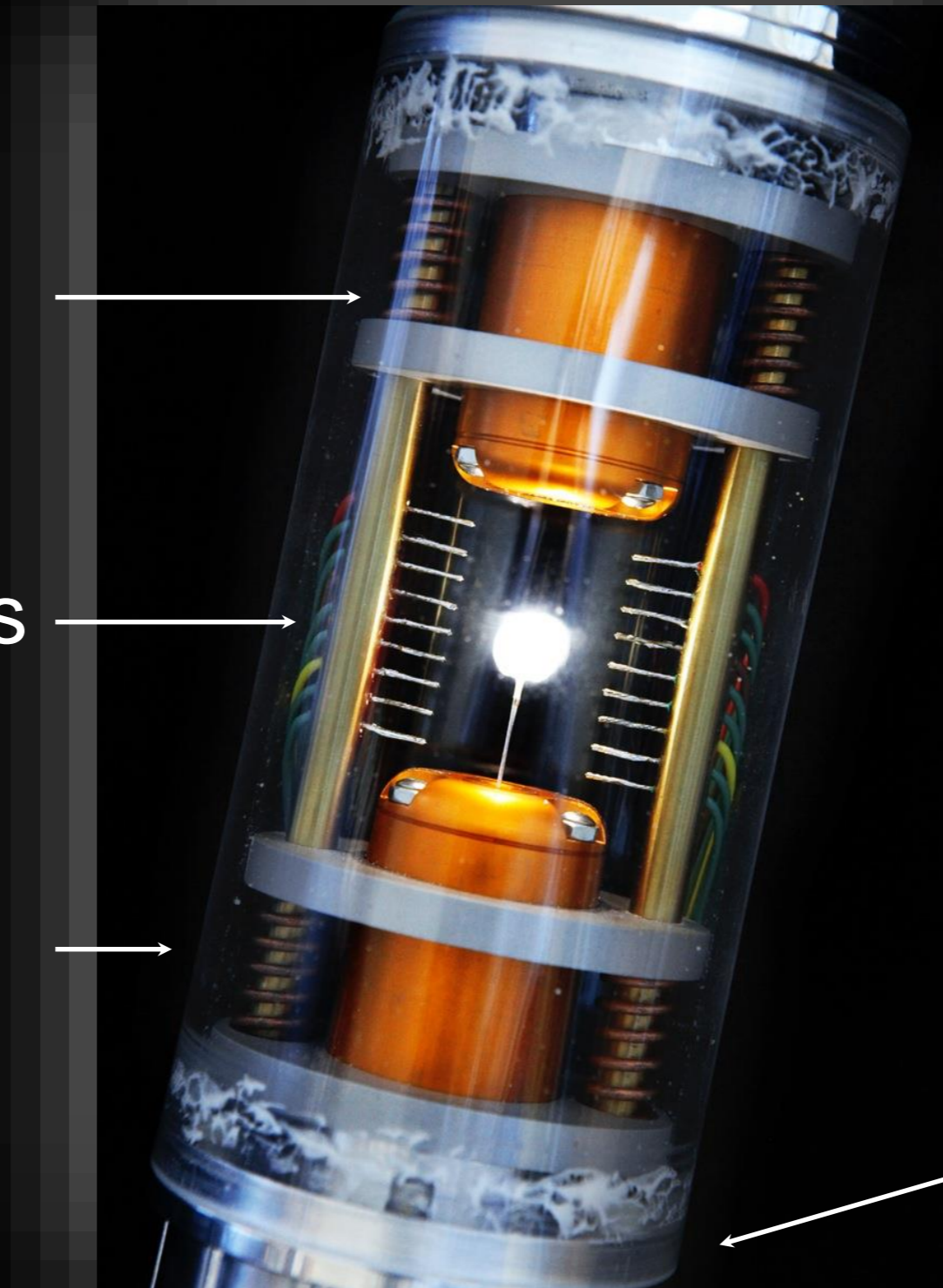
Magnets

Electrodes

Magnets

Ultra-high
vacuum

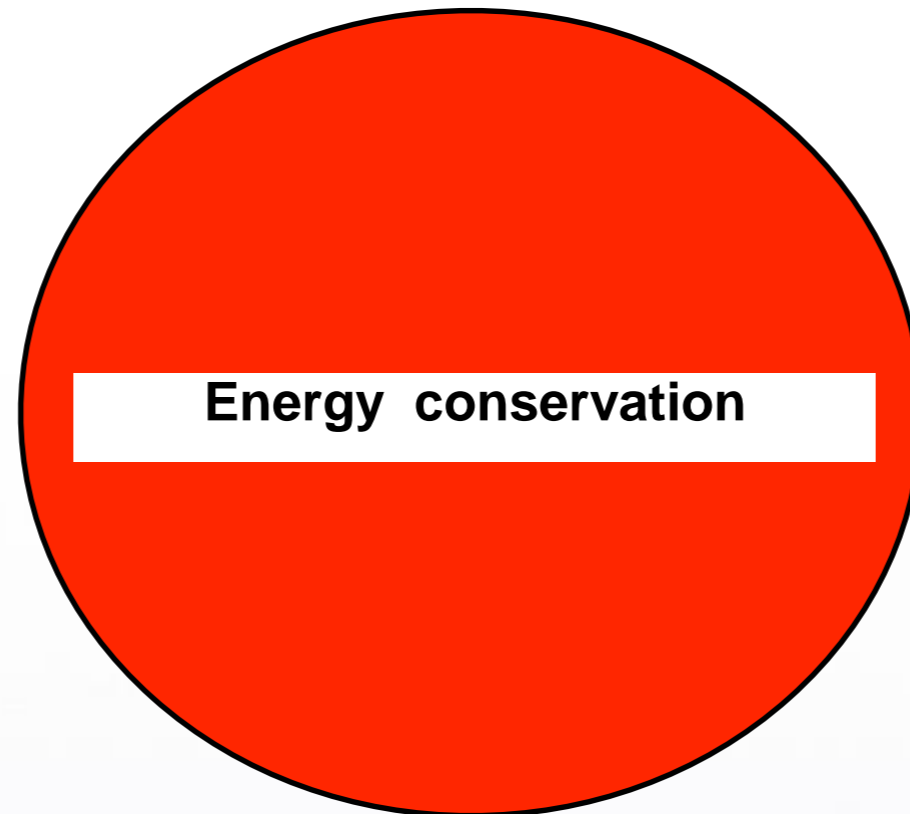
The “Angels & Demons” version



5 An energy source? A bomb?

5 An energy source? A bomb?

Dan Brown: “Antimatter is the energy source of the future” !



No

Antimatter production **requires energy**

**1,000,000,000 times more energy invested
than released by annihilation**



Antimatter explosion in “Angels & Demons”

5 An energy source? A bomb?



Dan Brown:

“0.5 g antimatter makes a powerful bomb”

$$E=mc^2$$

**22 kt TNT = $9 \cdot 10^{13}$ J =
0.5 g antimatter + 0.5 g matter**

So this is correct, but

Hiroshima - 20 kt TNT equivalent

5 An energy source? A bomb?



0.5 g antimatter = $4.5 \cdot 10^{13}$ J

Total energy needed (efficiency = 10^{-9}) : $4.5 \cdot 10^{22}$ J

Even with electricity discount price CERN by EDF
[1 kWh = $3.6 \cdot 10^6$ J = 0.1 €]

Price **1,000,000,000,000,000 €**

Delivery time **1 000 000 000 years**

Anything useful ??

Yes - the PET scanner can save lifes!

Positron Emission Tomography

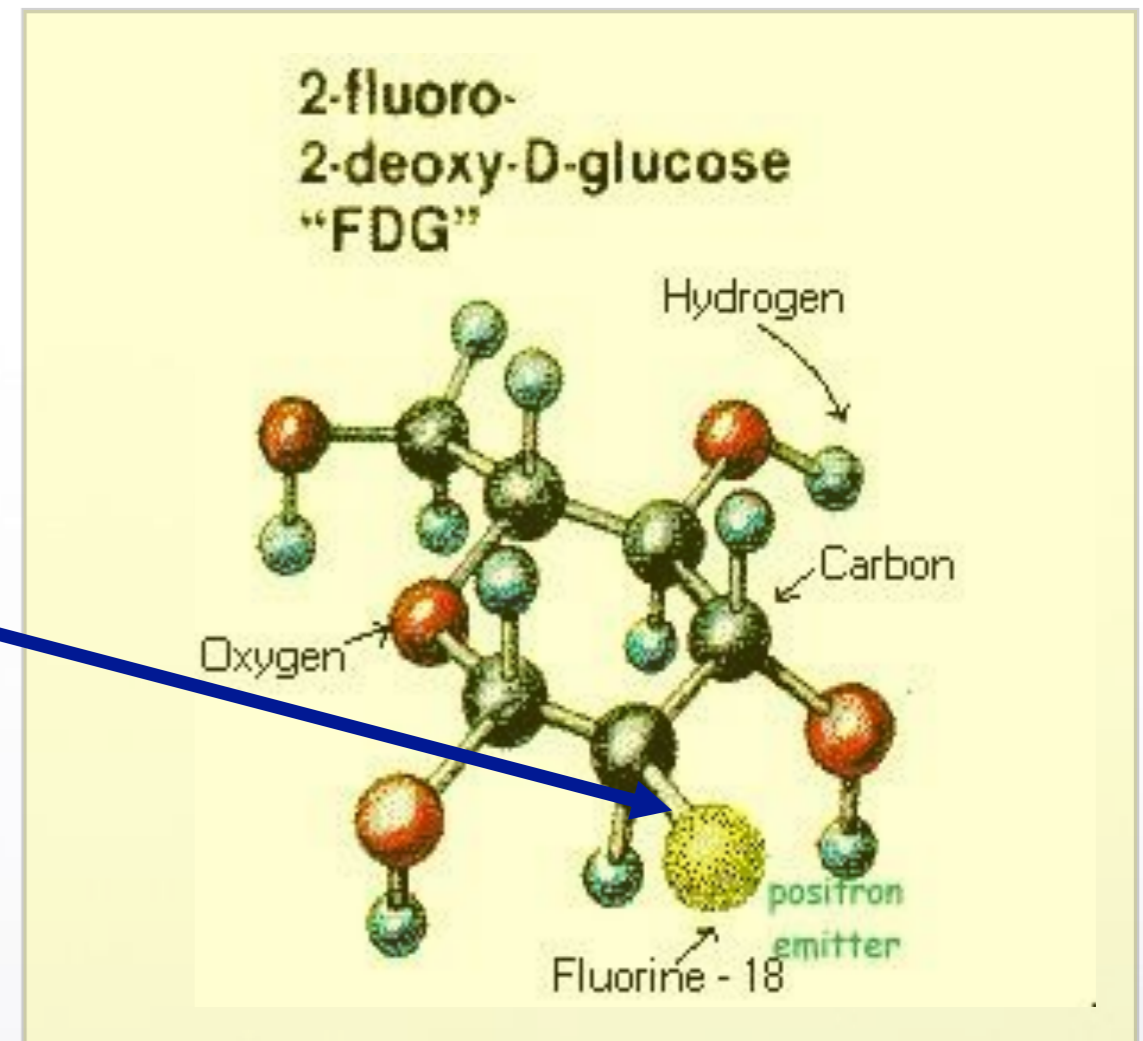
Glucose supplies energy

Add **positron** emitting isotopes (e.g. F-18) to glucose

Inject into blood stream

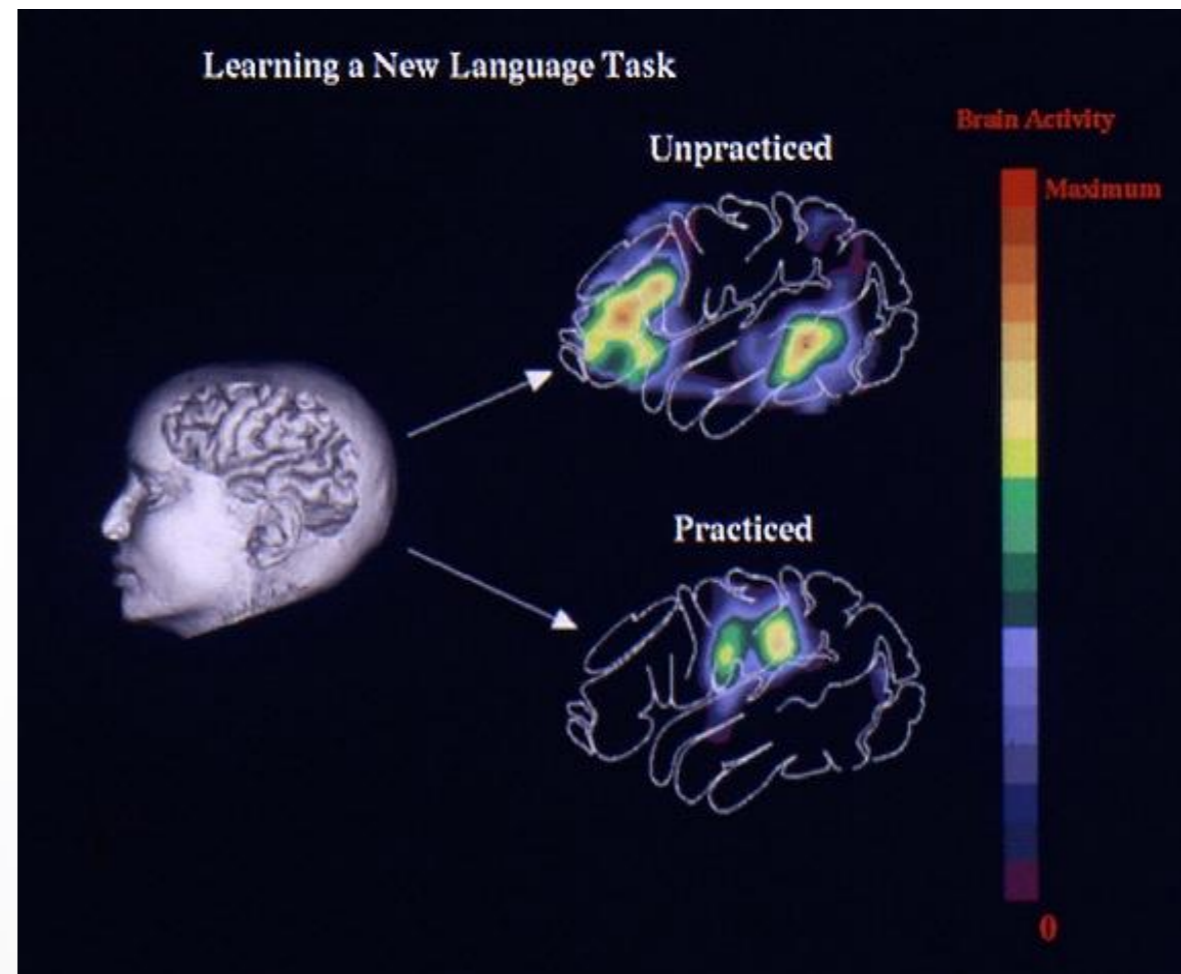
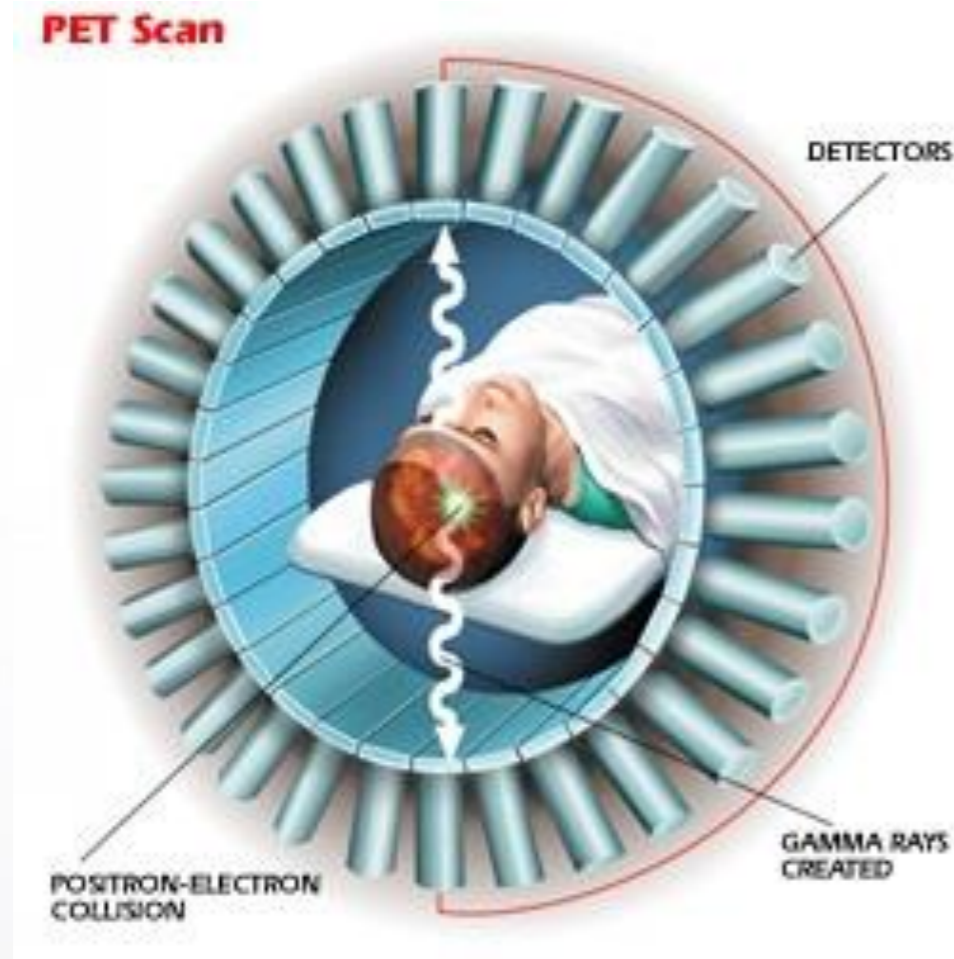
Glucose accumulates where energy is needed

Positron emission and annihilation - detect where the glucose is !



5 Antimatter in daily life

Positron Emission Tomography (“PET Scan”)



Antimatter helps

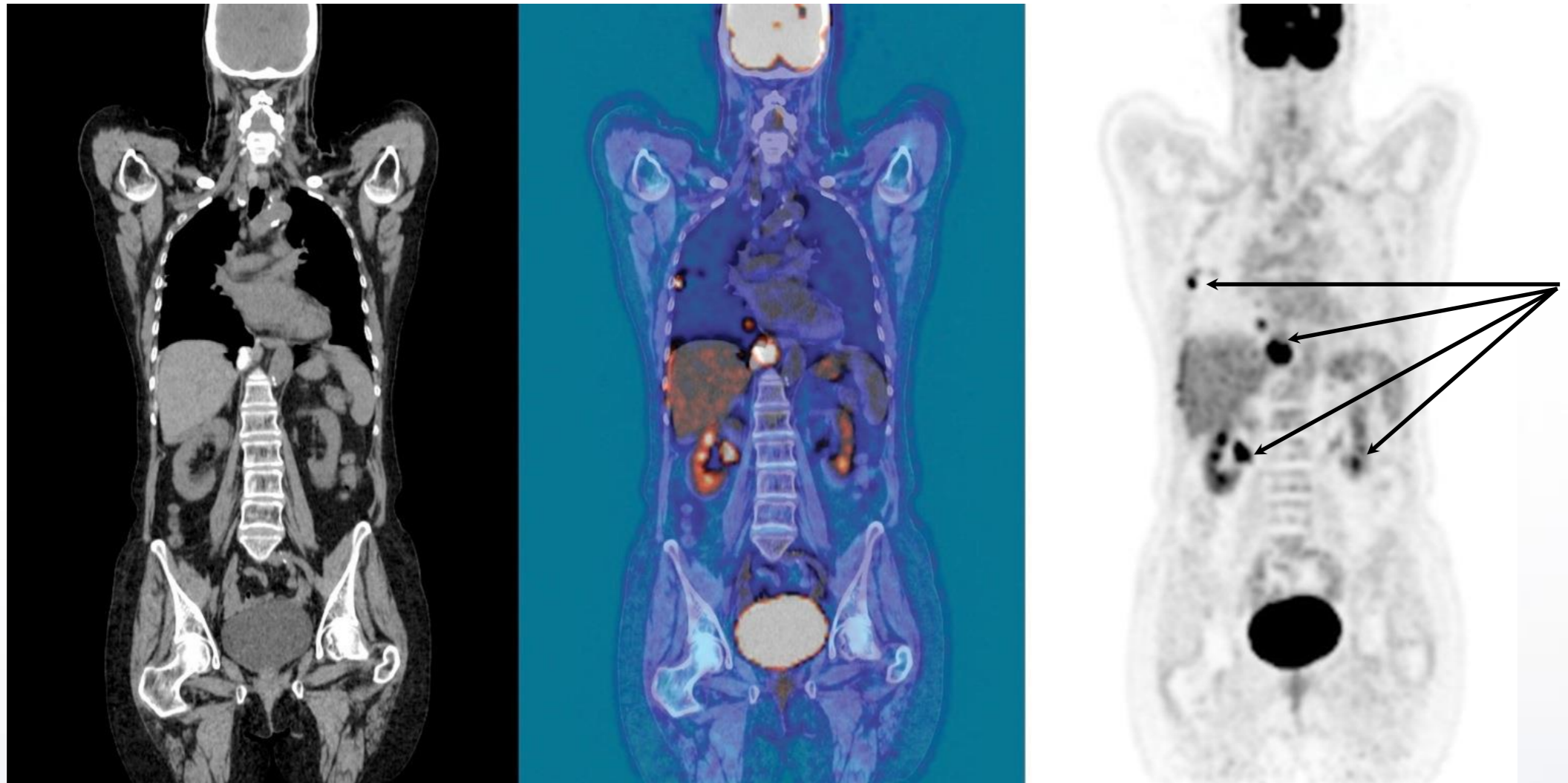
- to understand how the brain works

- to find tumours

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5 Antimatter in daily life ?

Positron Emission Tomography (“PET Scan”)



CT Scan only

Combination

PET scan only

**Antimatter helps to find
tumours**

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Movie

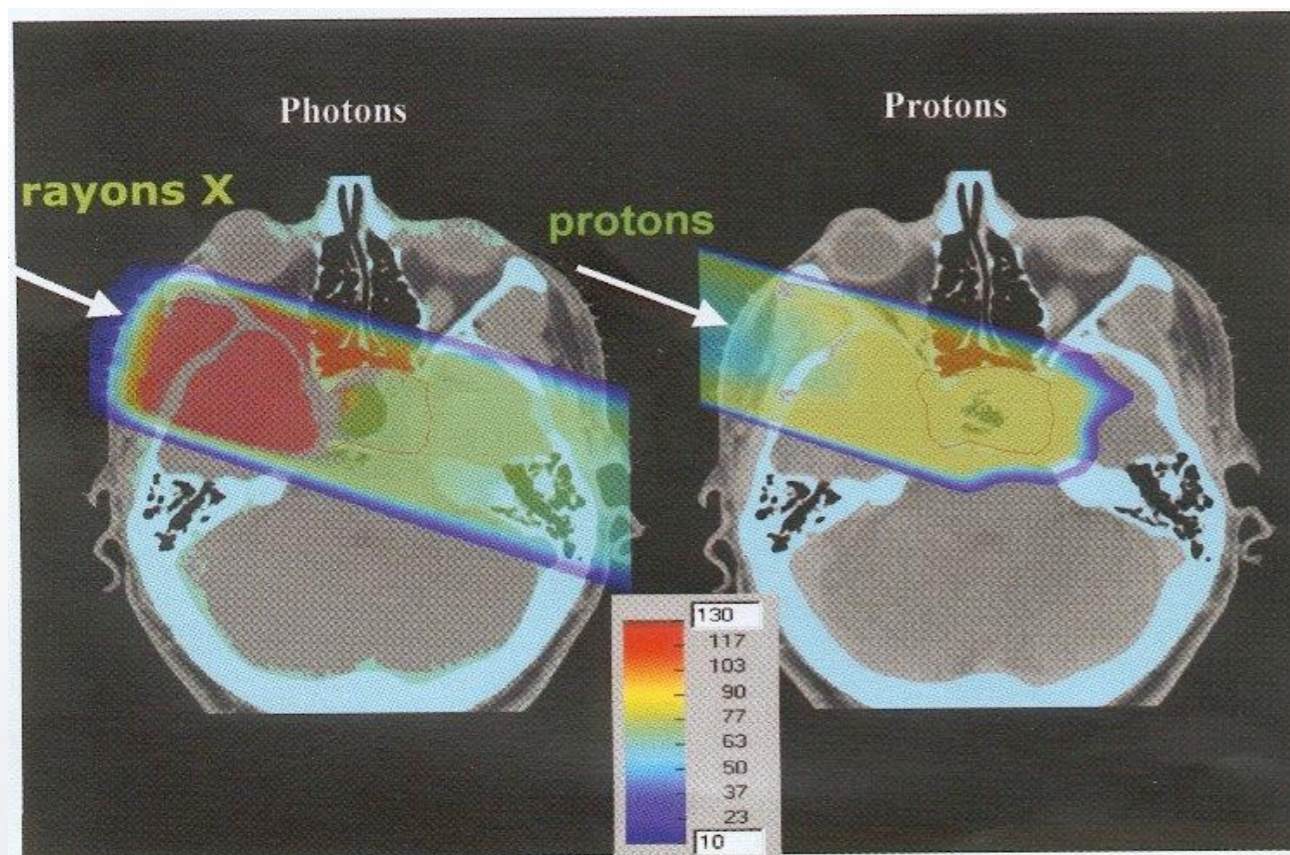
5 Antimatter in daily life ?

Tumour therapy with antiprotons ?

Gamma radiation destroys many healthy cells

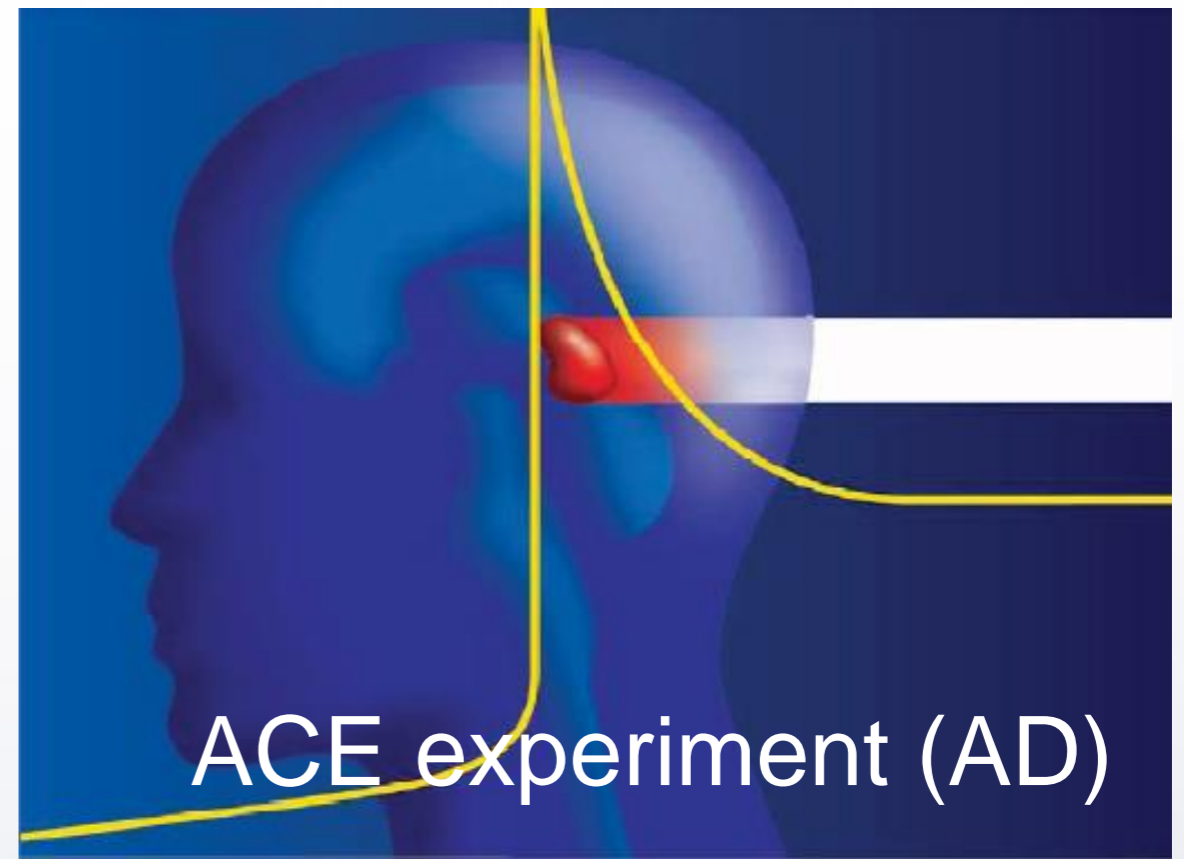
Protons deliver radiation more specifically to tumour cells

Antiprotons would be 3 x more efficient than protons (annihilation!)



Gamma radiation

Protons

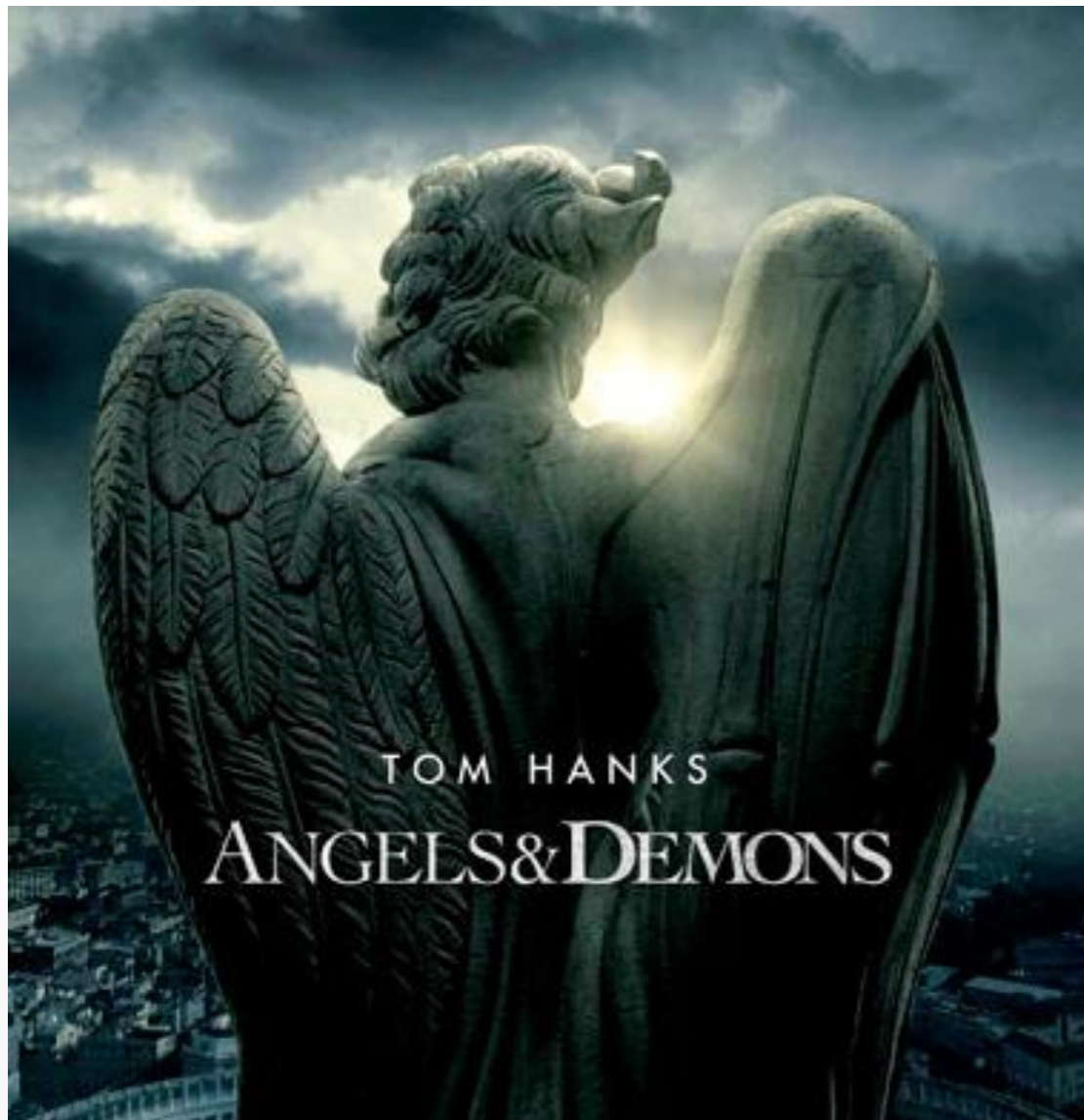


Antiprotons

What did Ron Howard say ?



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Angels&Demons

The Physics Behind the Movie

<http://ed.ted.com/lessons/what-happened-to-antimatter-rolf-landua>

<http://www.youtube.com/watch?v=CtR5EkvLNfg>

Thank you for your attention.

Antimatter @ School

For Teaching

Antimatter Teaching Module
NEW

CERN

Particle Physics

Cosmology

Principles of Experimental
Physics

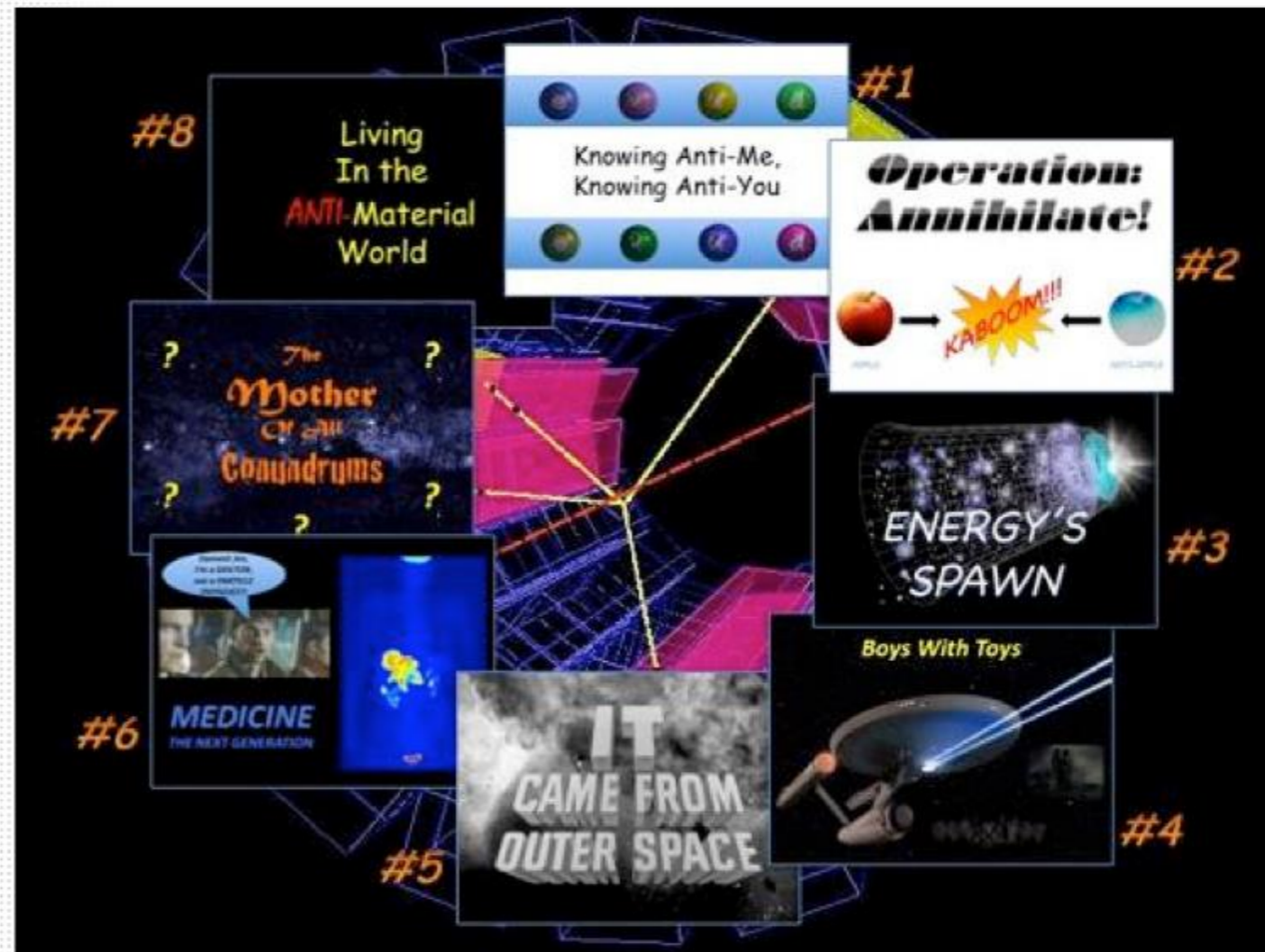
Introduction to Accelerators

Applications of CERN
research

Multimedia material

Teaching Resources - Antimatter Teaching Module

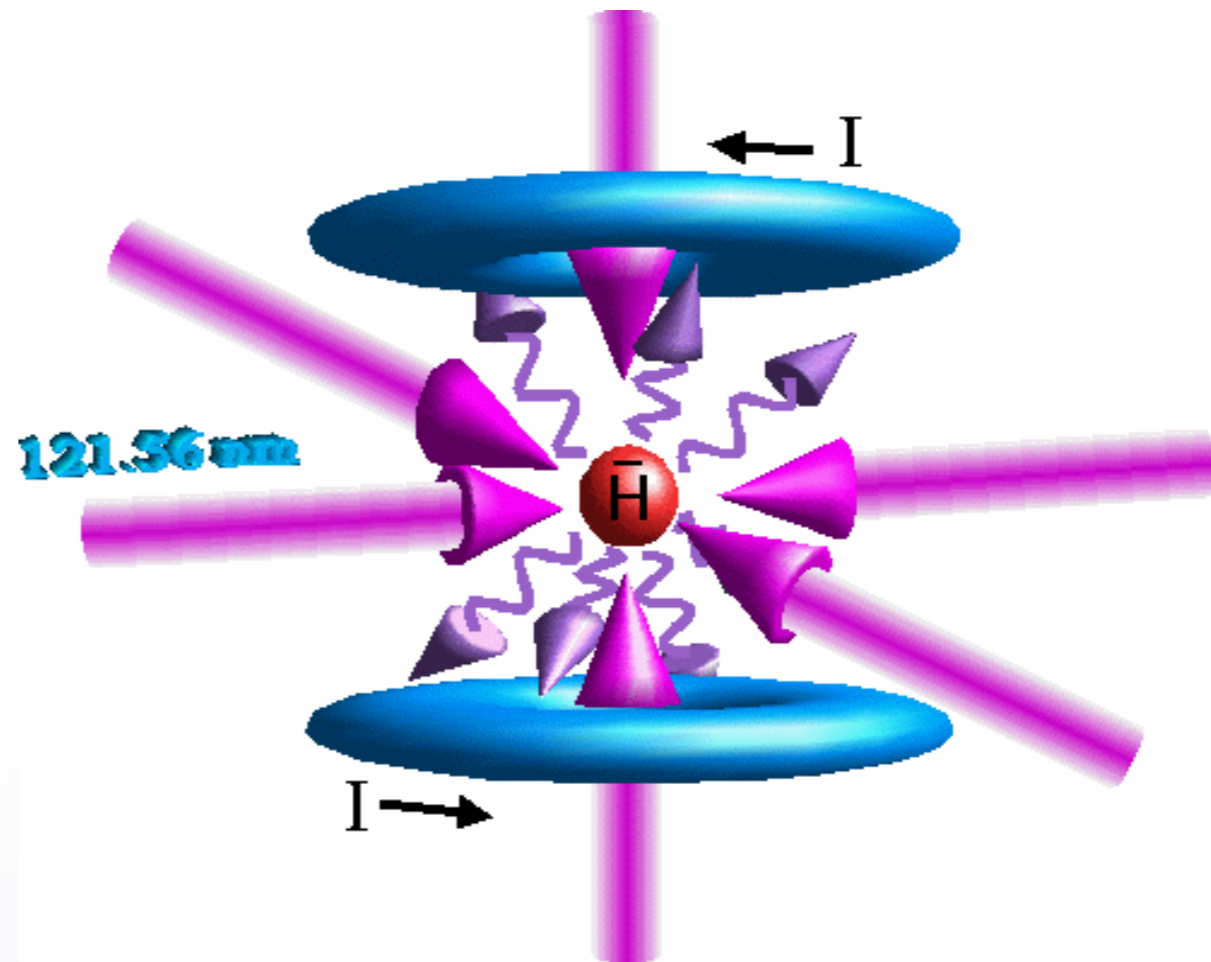
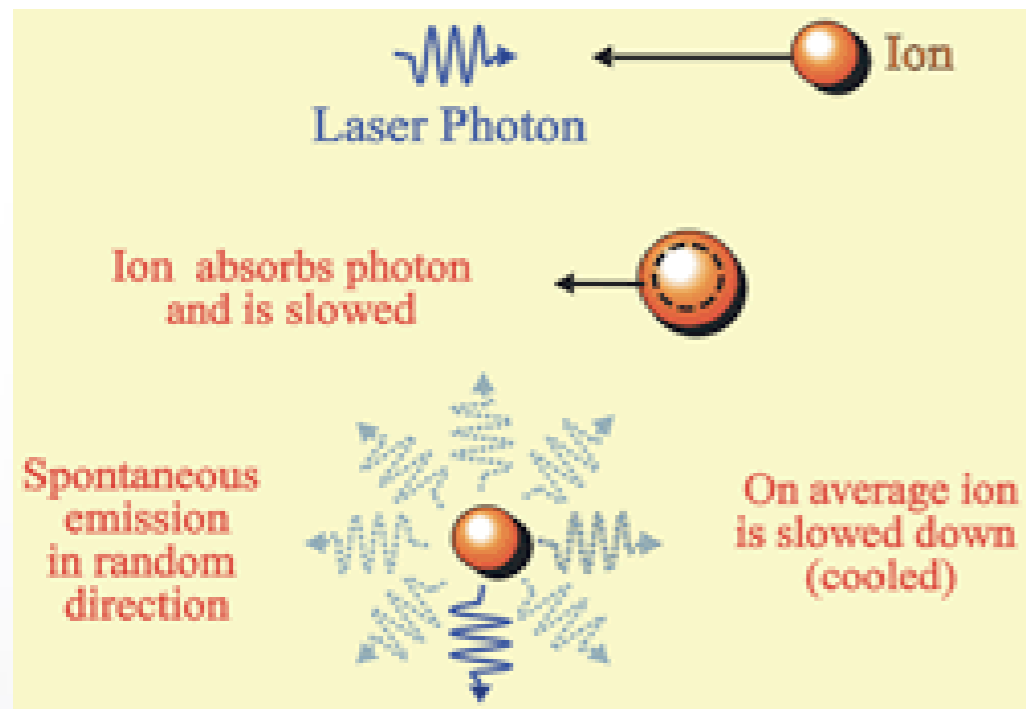
>> Lesson Plans



Back to [Antimatter Teaching Module](#)

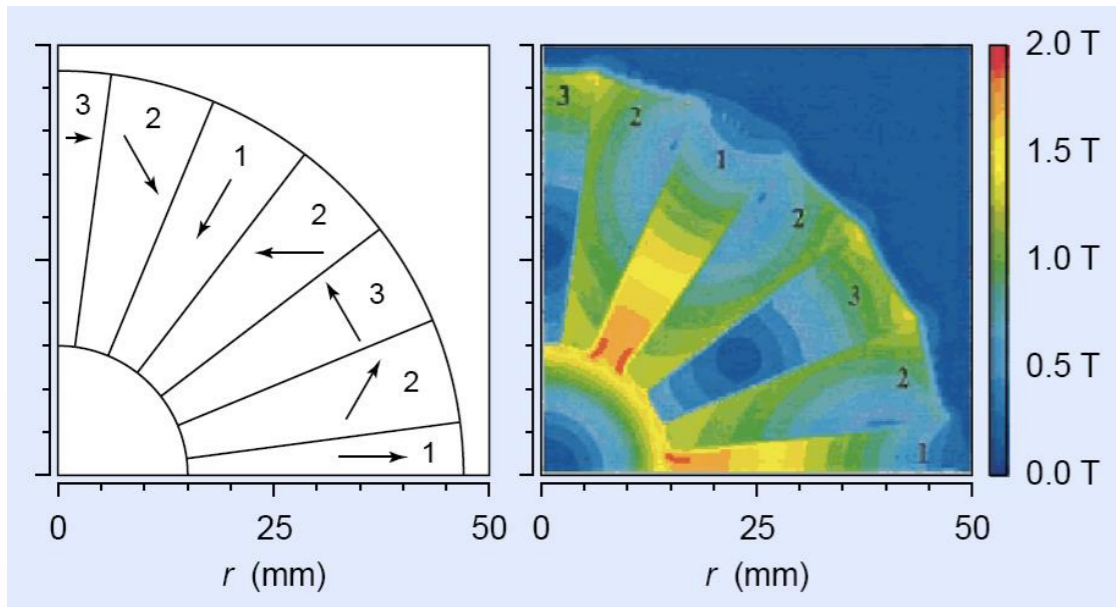
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Movie

Laser cooling



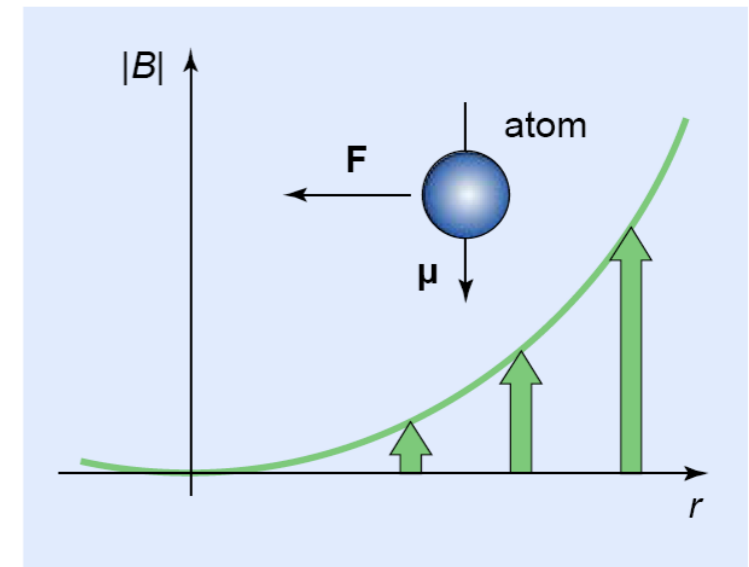
121 nm laser needed
Prototype at MPI Munich
... only 50 nW

Magnetic multipole traps ?



$$U = -\vec{\mu} \cdot \vec{B}$$

$$\vec{F} = -\vec{\nabla} U$$



Low field seeking atoms (50%) at $r=0$

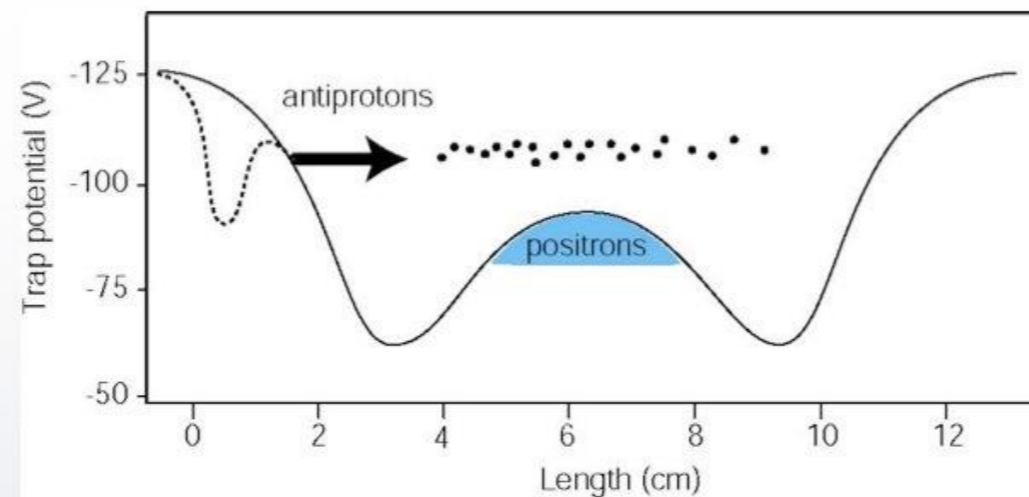
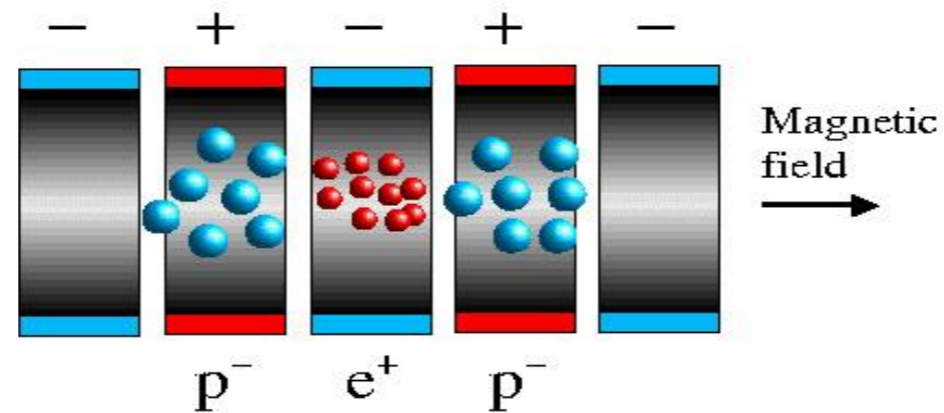
BUT: Very shallow potential (~ 0.07 meV/T)

Realistic $\Delta B \sim 0.2-0.3$ T \Leftrightarrow **$E < 0.02$ meV**

(reminder: produced antihydrogen has $E_{\text{kin}} \sim 1-200$ meV)

Trap antihydrogen from low energy 'Boltzmann tail' ?

Example: Sextupole magnet



- More than 1 million antihydrogen atoms produced
- Small kinetic energy (< 0.01 eV)
- Next step (in progress): trap antihydrogen atoms

p^- and e^+ in mixing trap (cooling)

Antihydrogen formation

AD

p^- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (meV)

$10^4 p^-$

$10^8 e^+$

Na-22

e^+ Production (MeV)

Moderation

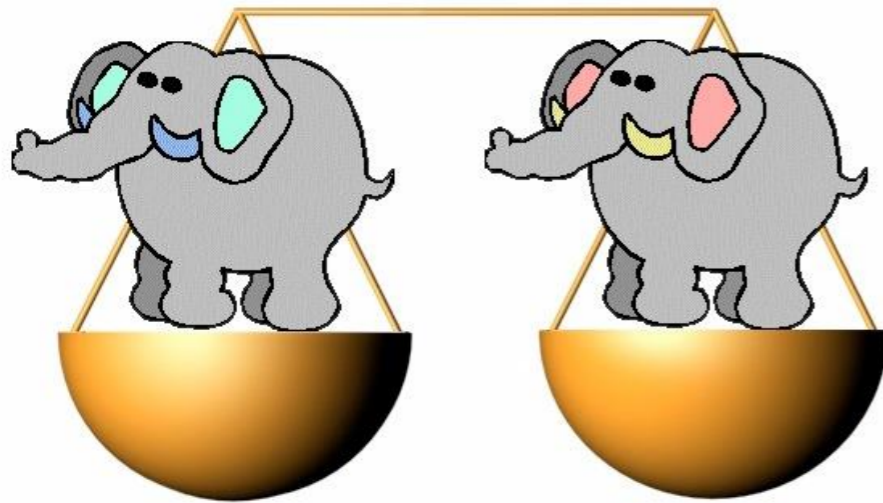
Accumulation (eV)



Detection of annihilation

Antihydrogen milestones

Is that true? Make very precise comparisons!



difference less than one dust grain

Mass of proton and antiproton ?

Present result: $\Delta M/M < 0.000\,000\,000\,000\,1$



Magnetic moment of electron and positron ?

Present result: $\Delta\mu/\mu < 0.000\,000\,000\,001$

Present status: excellent agreement !

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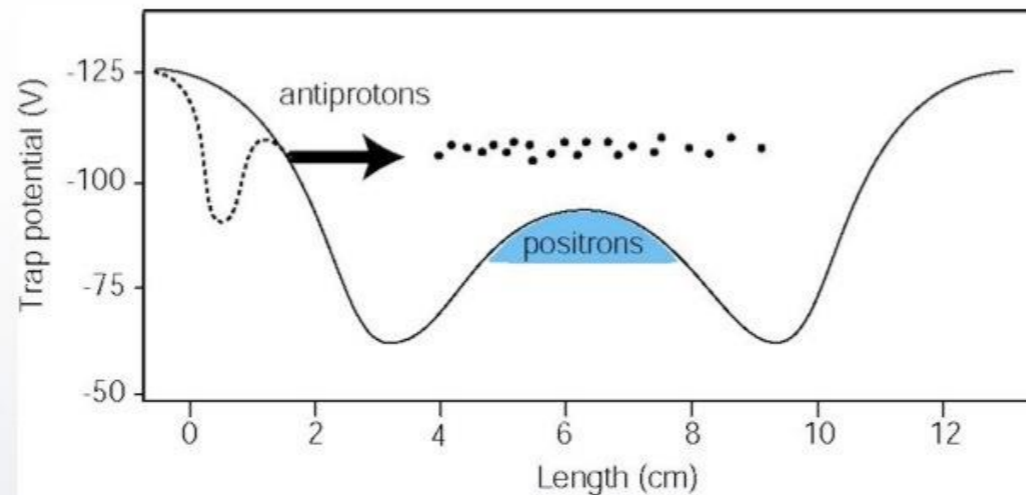
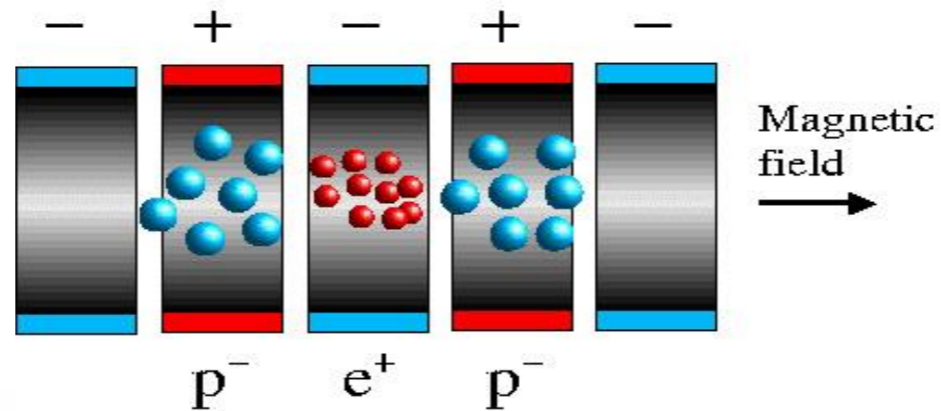
ATHENA Experiment (2002), at the AD facility



- More than 1 million antihydrogen atoms produced
- Small kinetic energy (< 0.01 eV)
- Next step (in progress): trap antihydrogen atoms

2002: 'Cold' antihydrogen production by AD experiments*

Recombination



- More than 1 million antihydrogen atoms produced
- Small kinetic energy (< 0.01 eV)
- Next step (in progress): trap antihydrogen atoms

Next step: Trapping antihydrogen

Neutral (anti-) atoms escape from Penning trap

