



# Angels&Demons

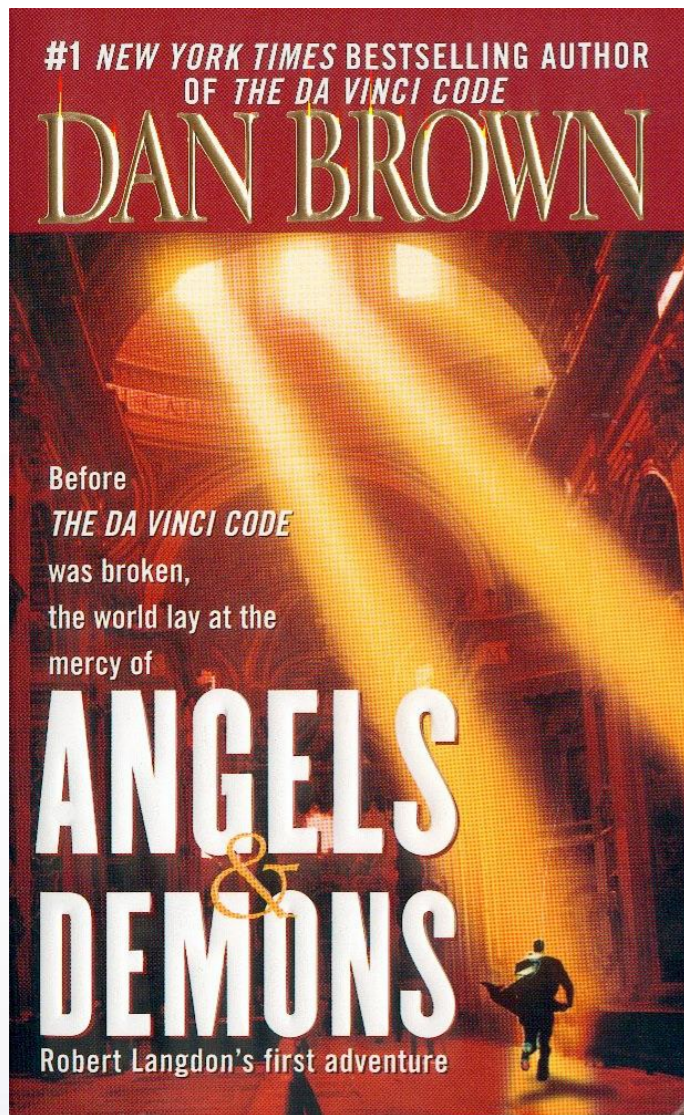
The Physics Behind the Movie

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" ...

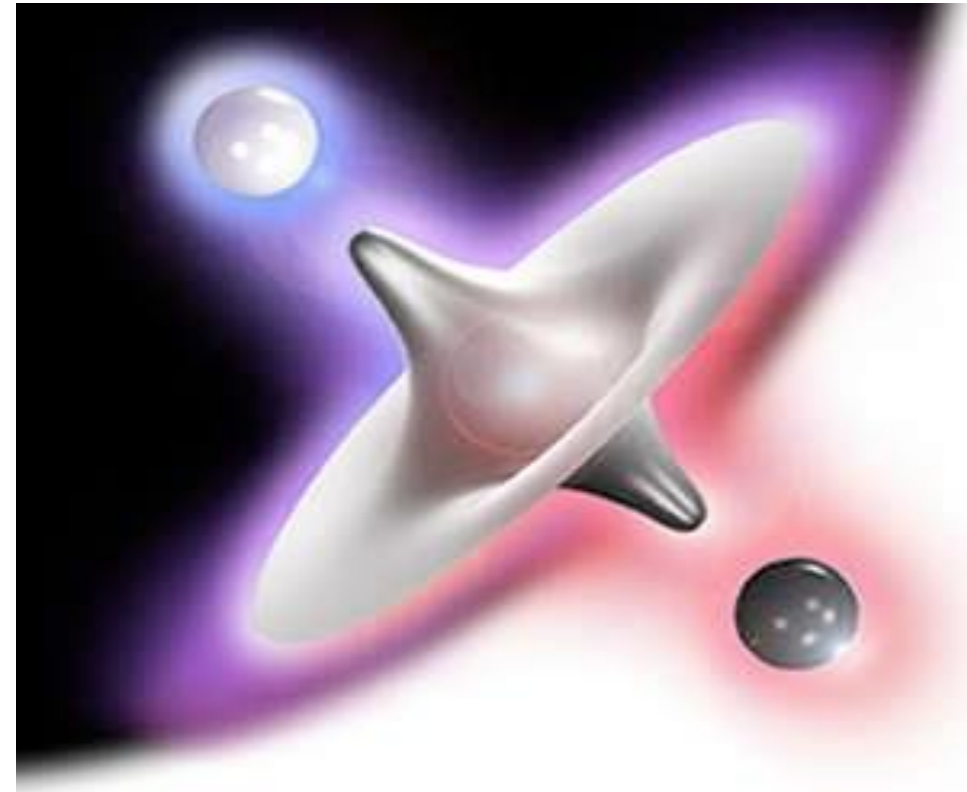


... to blow up the Vatican, an old "enemy of science and CERN".

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 ?

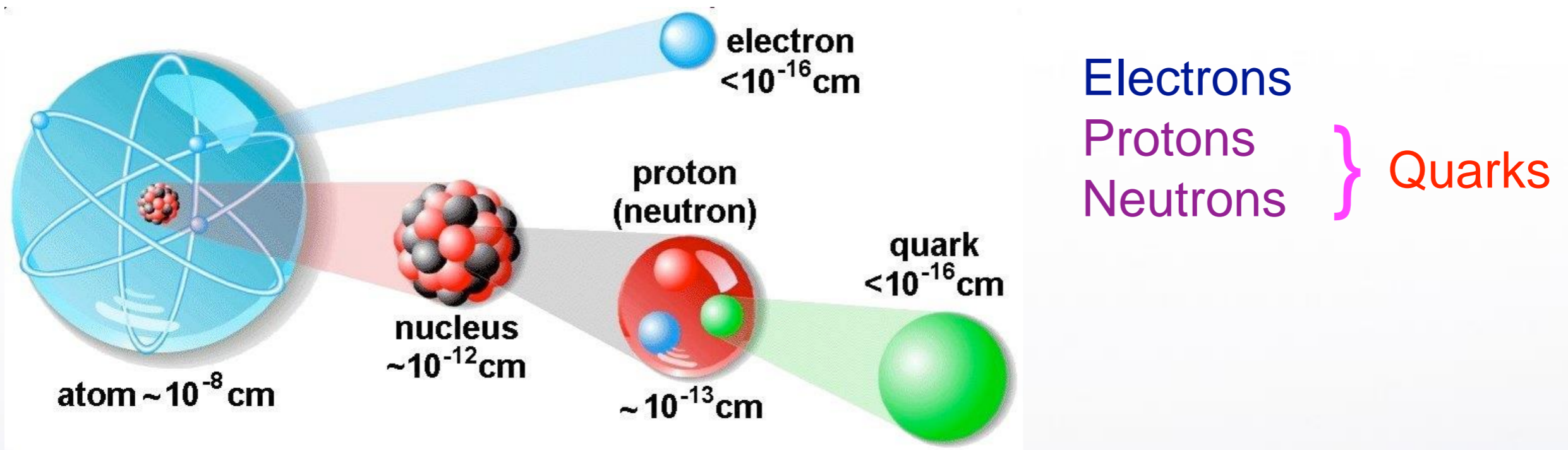
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# 1 What is antimatter ?

# 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

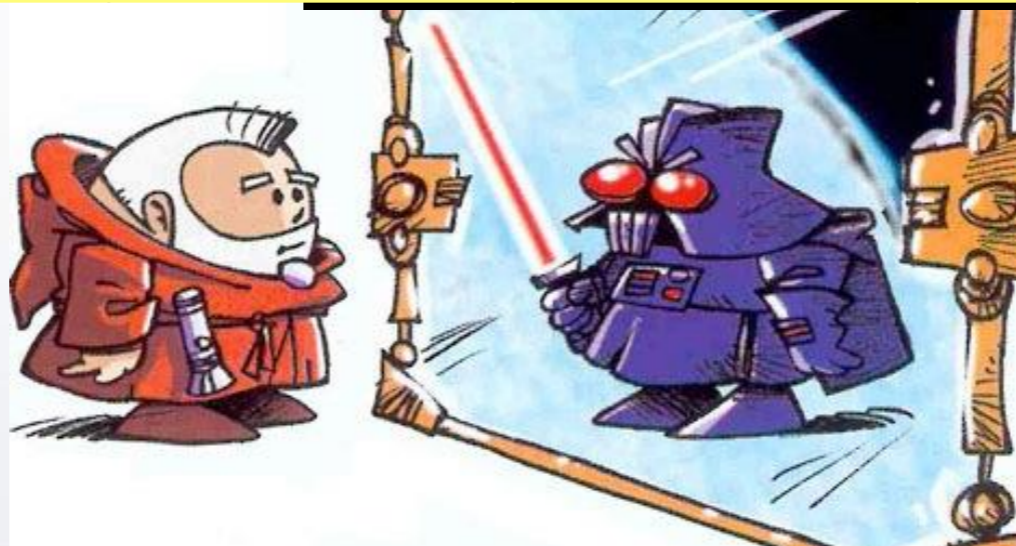
# 1 What is antimatter ?

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



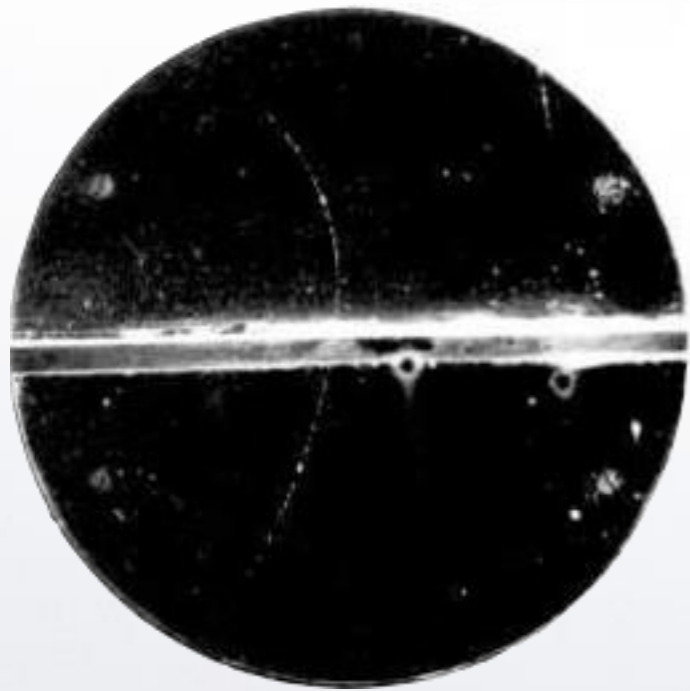
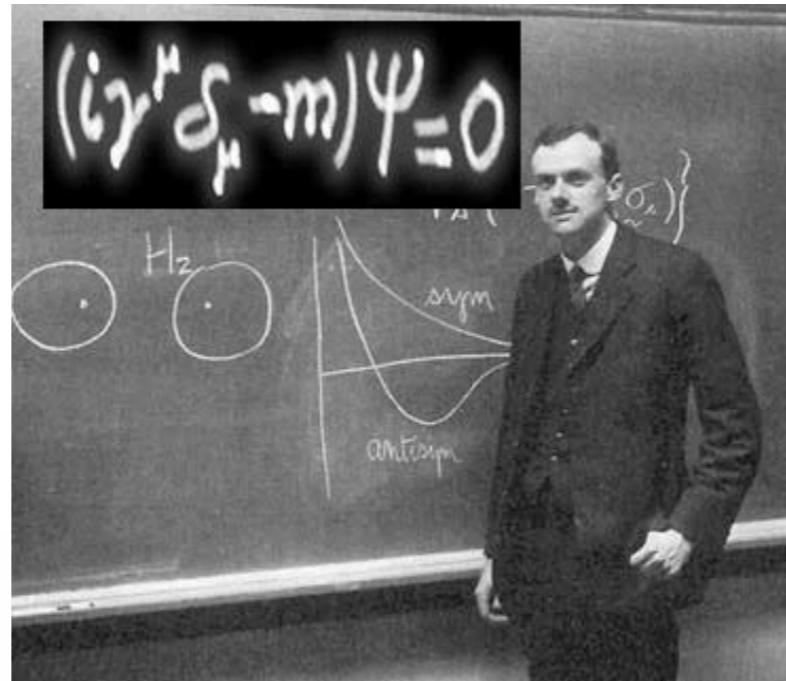
Anti-particles

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# 1 What is antimatter ?

Predicted by  
Paul Dirac (1928) ...



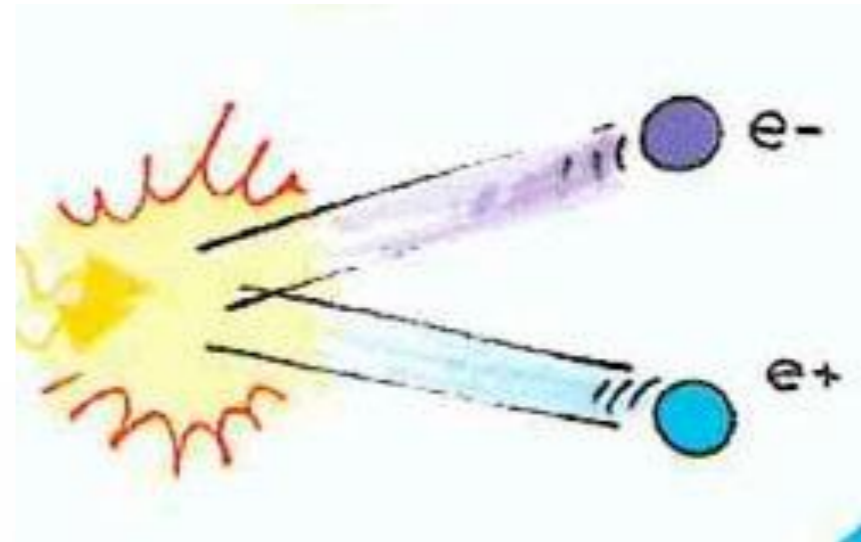
... first antiparticle (positron)  
found by Carl Anderson (1932)

# 1 What is antimatter ?

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

$$E=mc^2$$

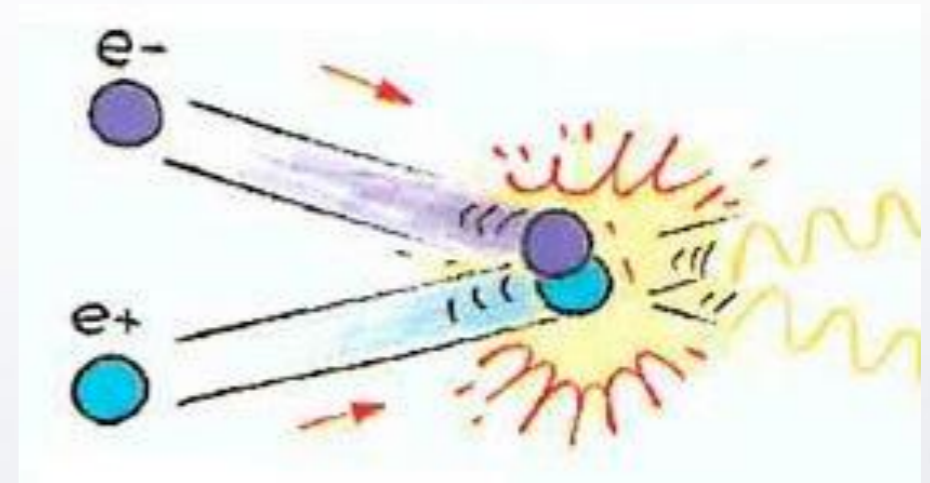
Energy to  
mass:



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

$$E=mc^2$$

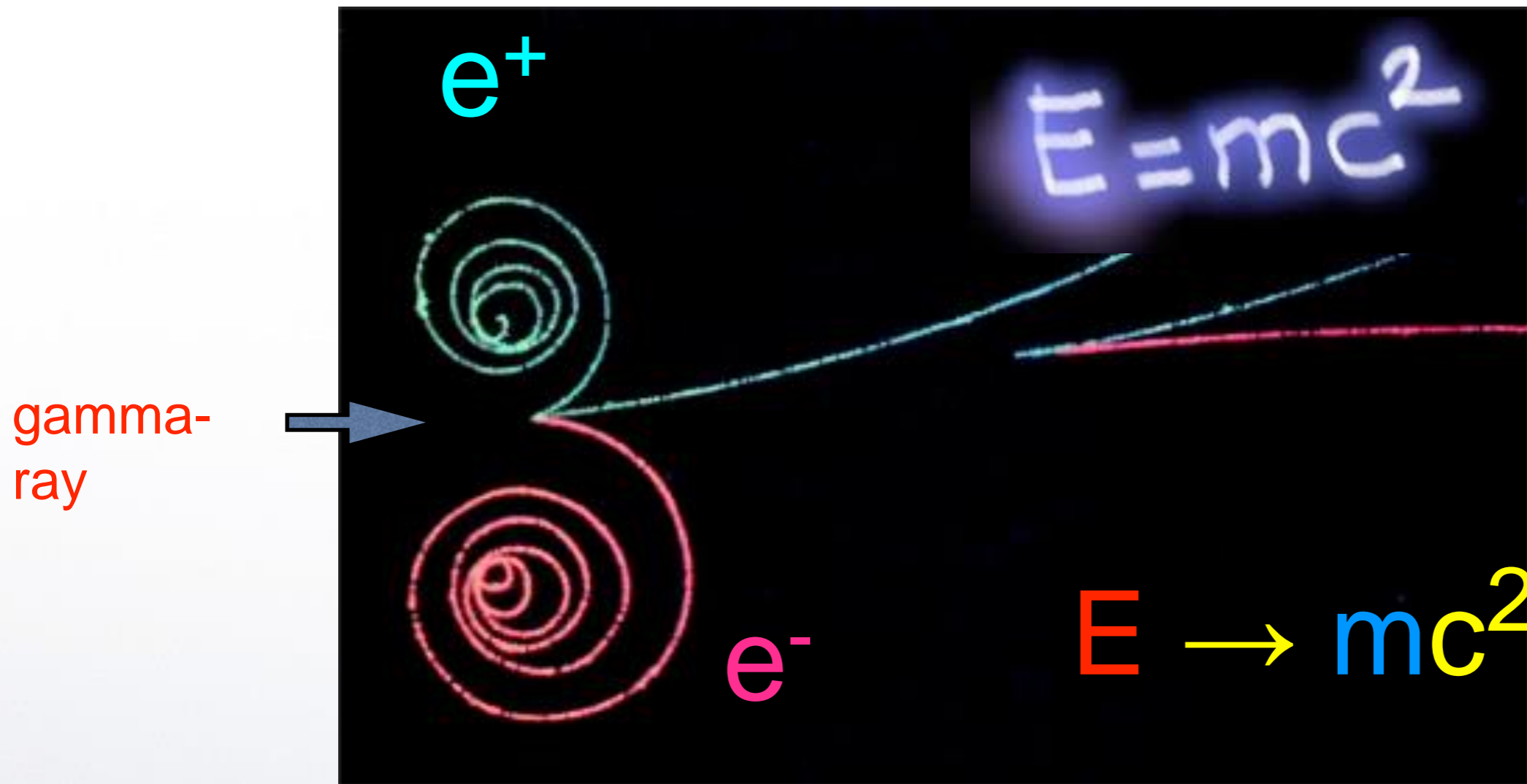
Mass to energy:



# 1 What is antimatter ?

**When Energy** is converted to **mass**

an equal amount of matter and antimatter particles are created



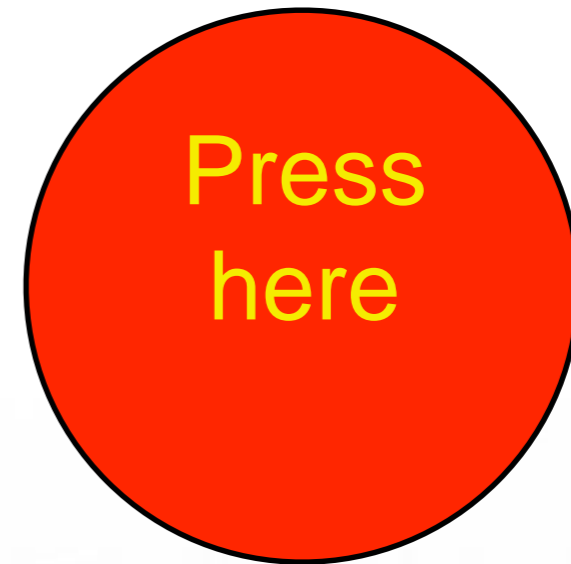
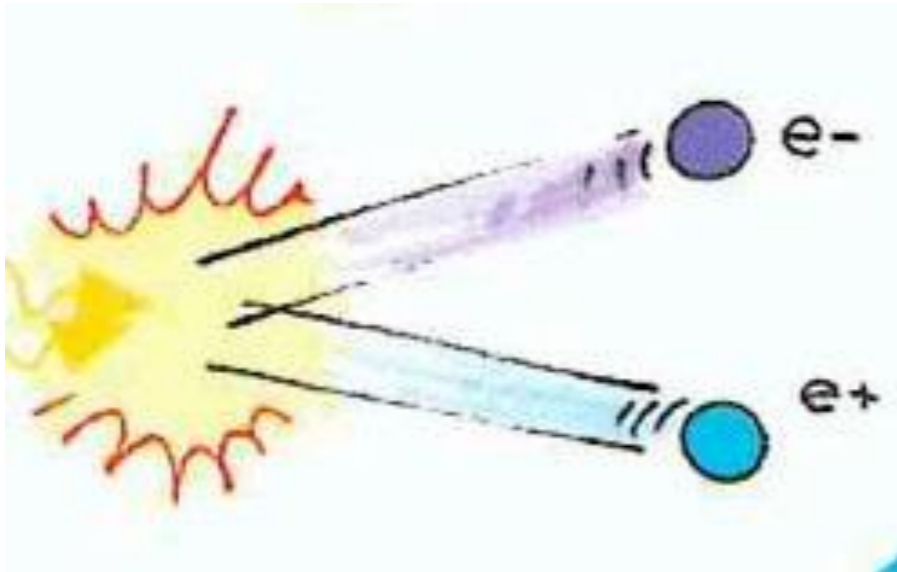
Key: high energy **density**

# 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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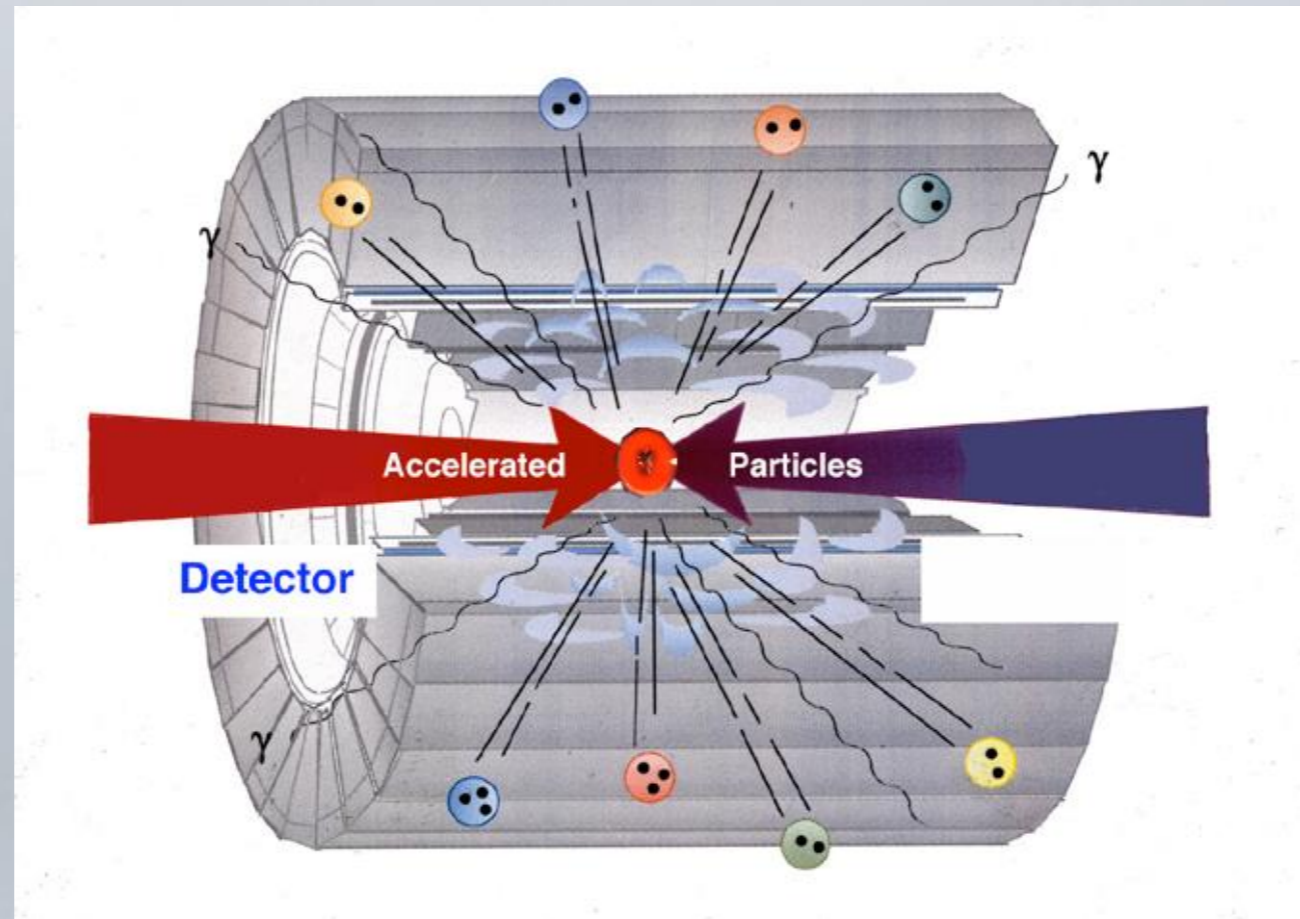


## 2 Antimatter in the LHC ?



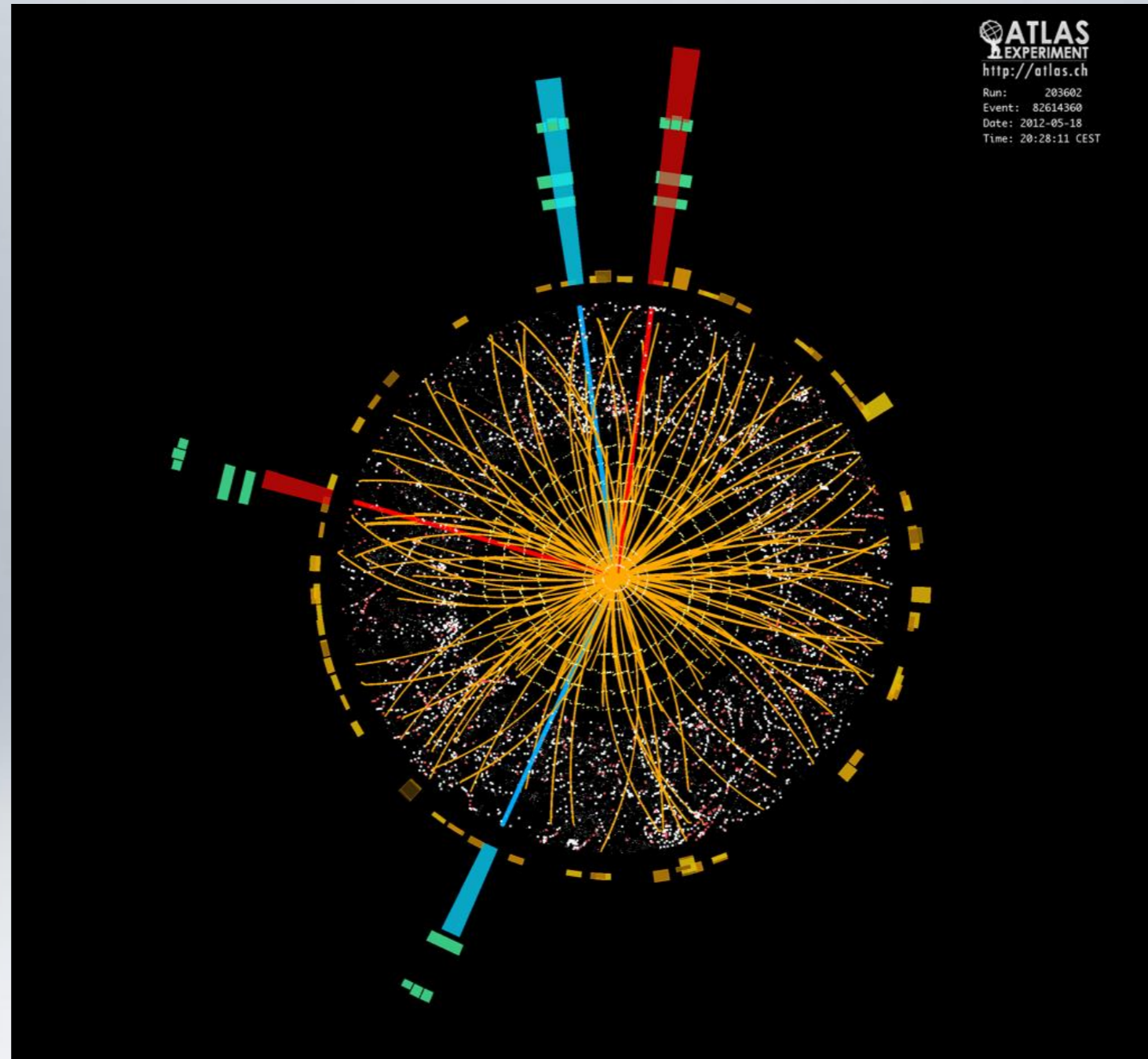
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Movie

## 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

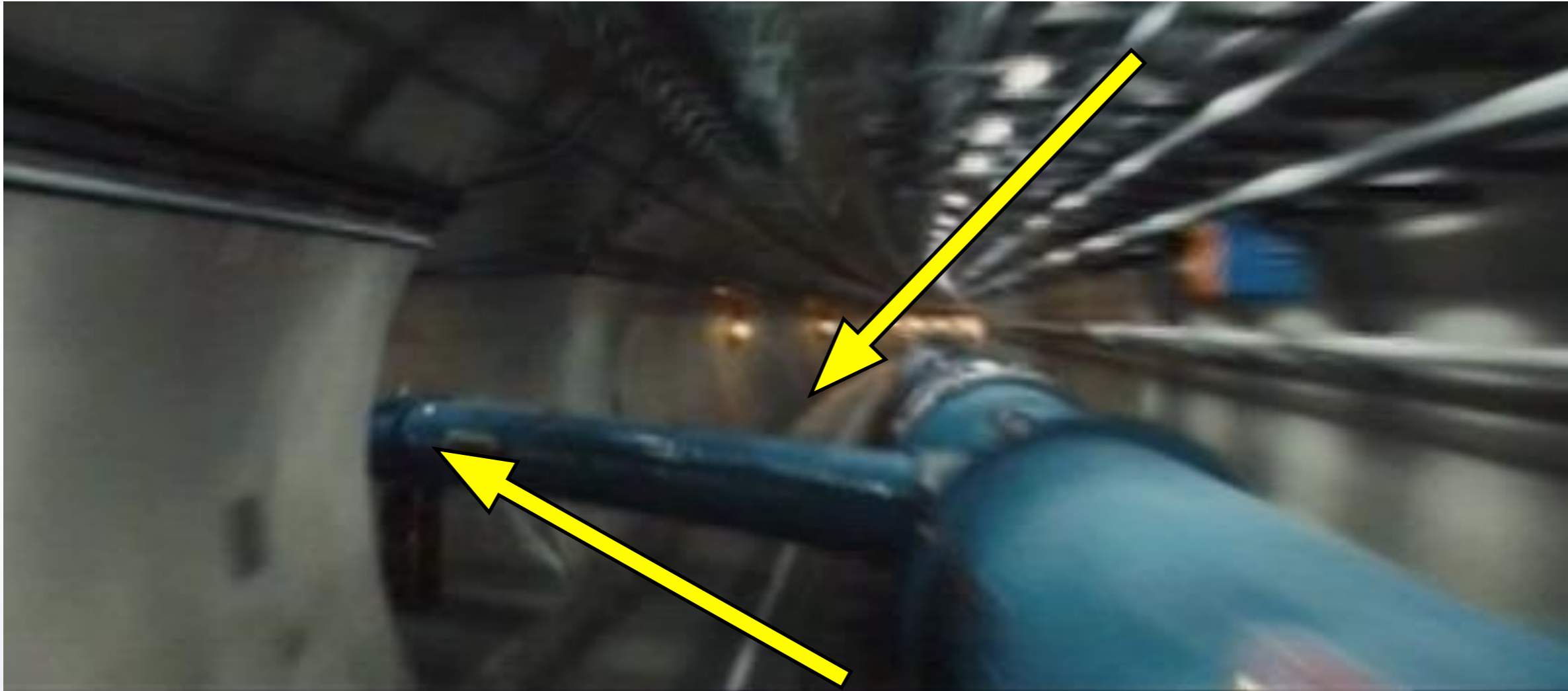


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## 2 Antimatter in the LHC ?

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.

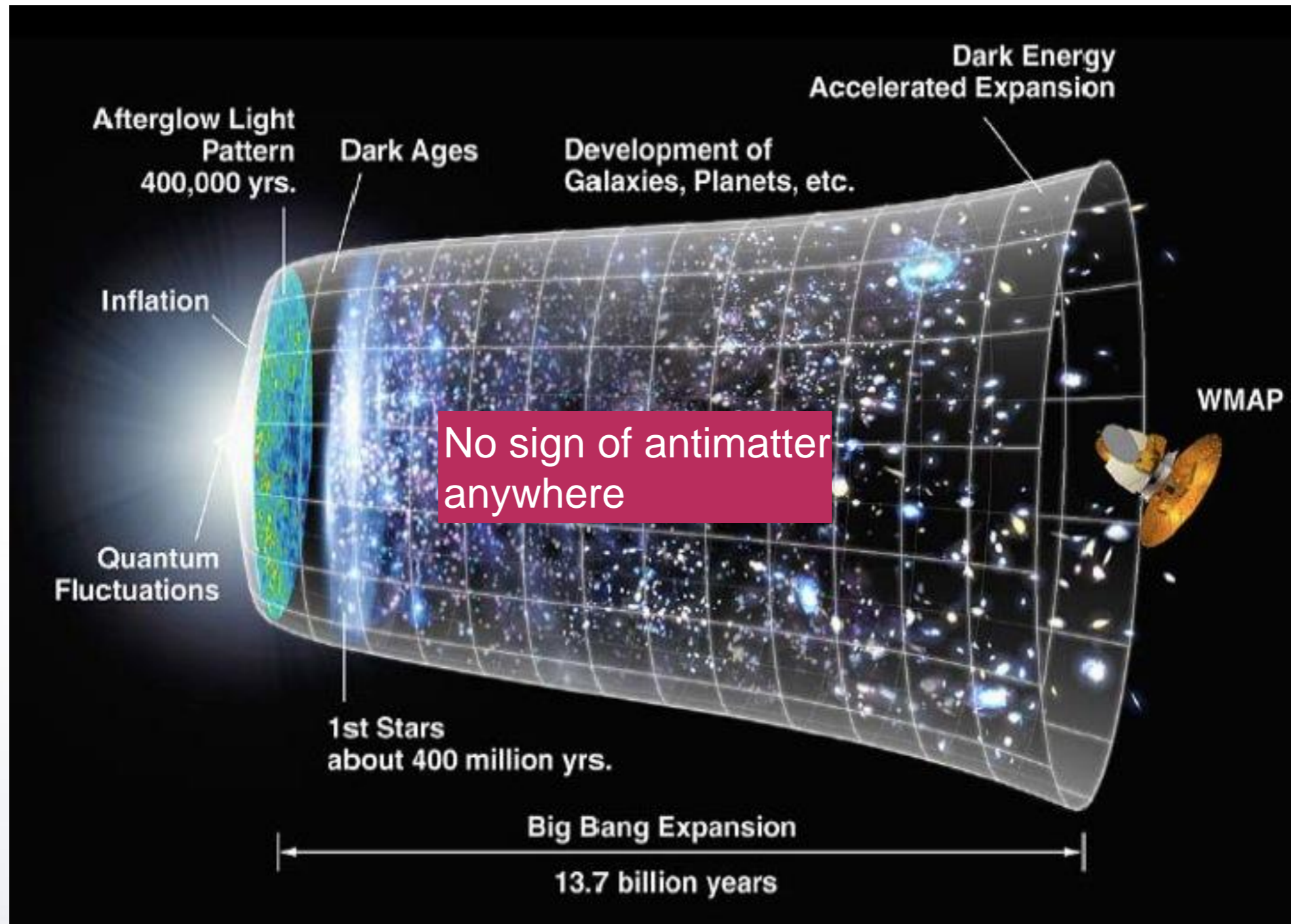
Combustible substance ? May be.

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

!

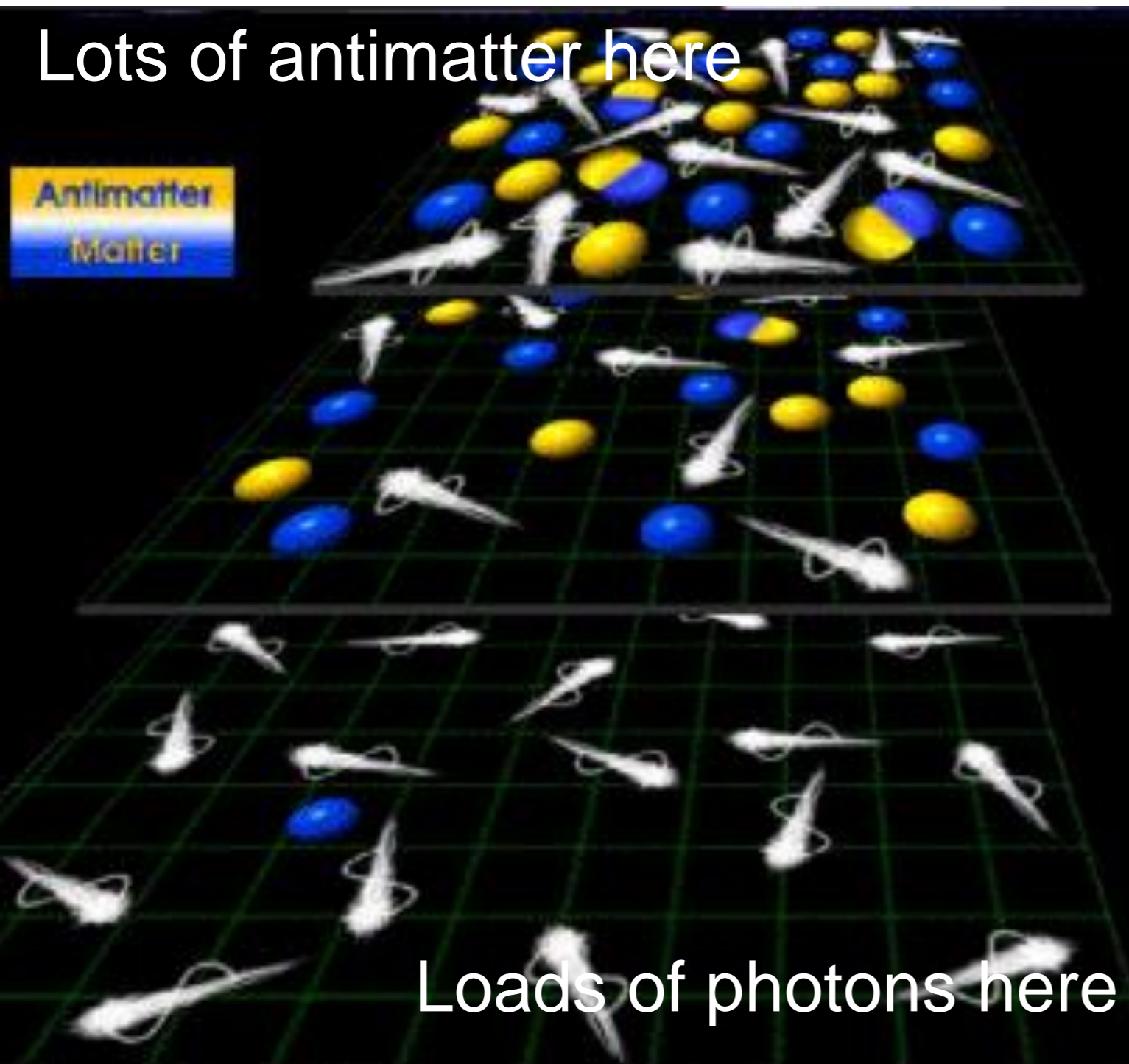
## 3 The mystery of antimatter

**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

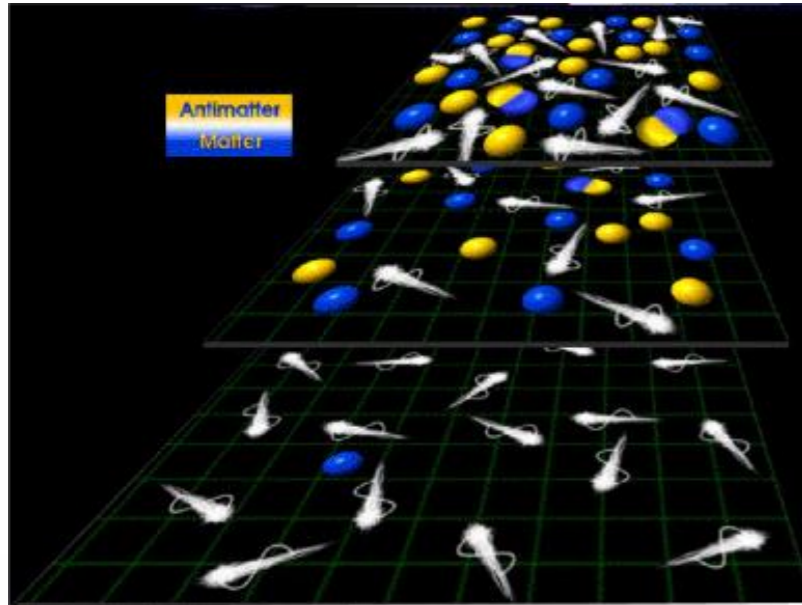
**1 s:** all antimatter has disappeared,

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)

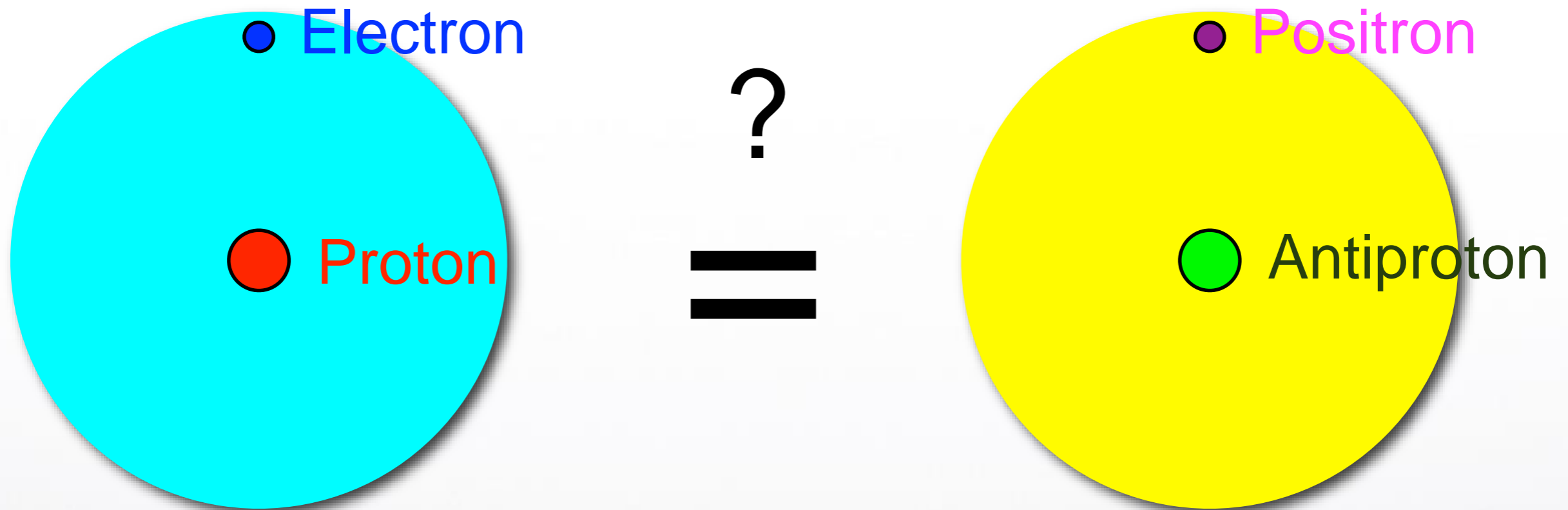
# 4 How to study antimatter ?

The antihydrogen route

...

# 4 How to study antimatter ?

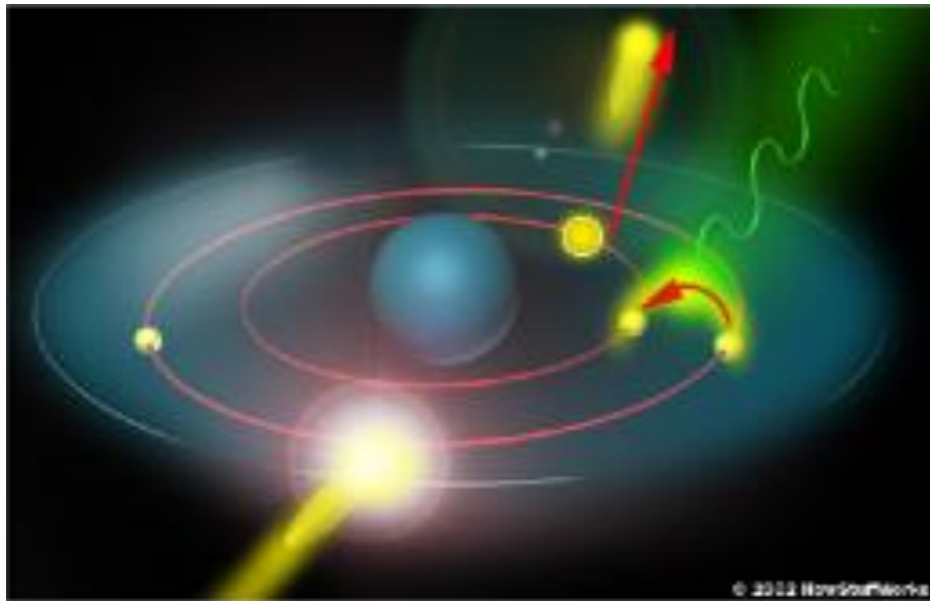
Make antihydrogen + compare with hydrogen atom



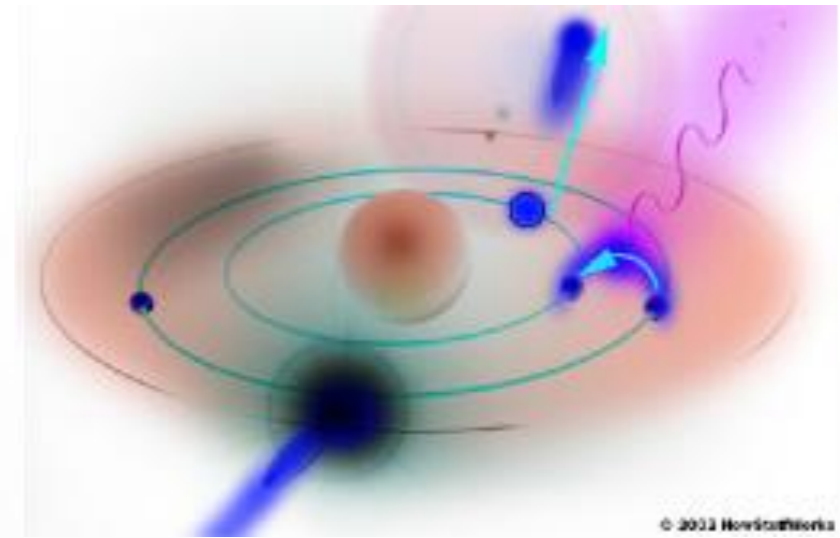
Measure differences to a precision of  
**0.000 000 000 000 001 %**

# 4 How to study antimatter ?

**Same energy levels (1S-2S)?**



Hydrogen



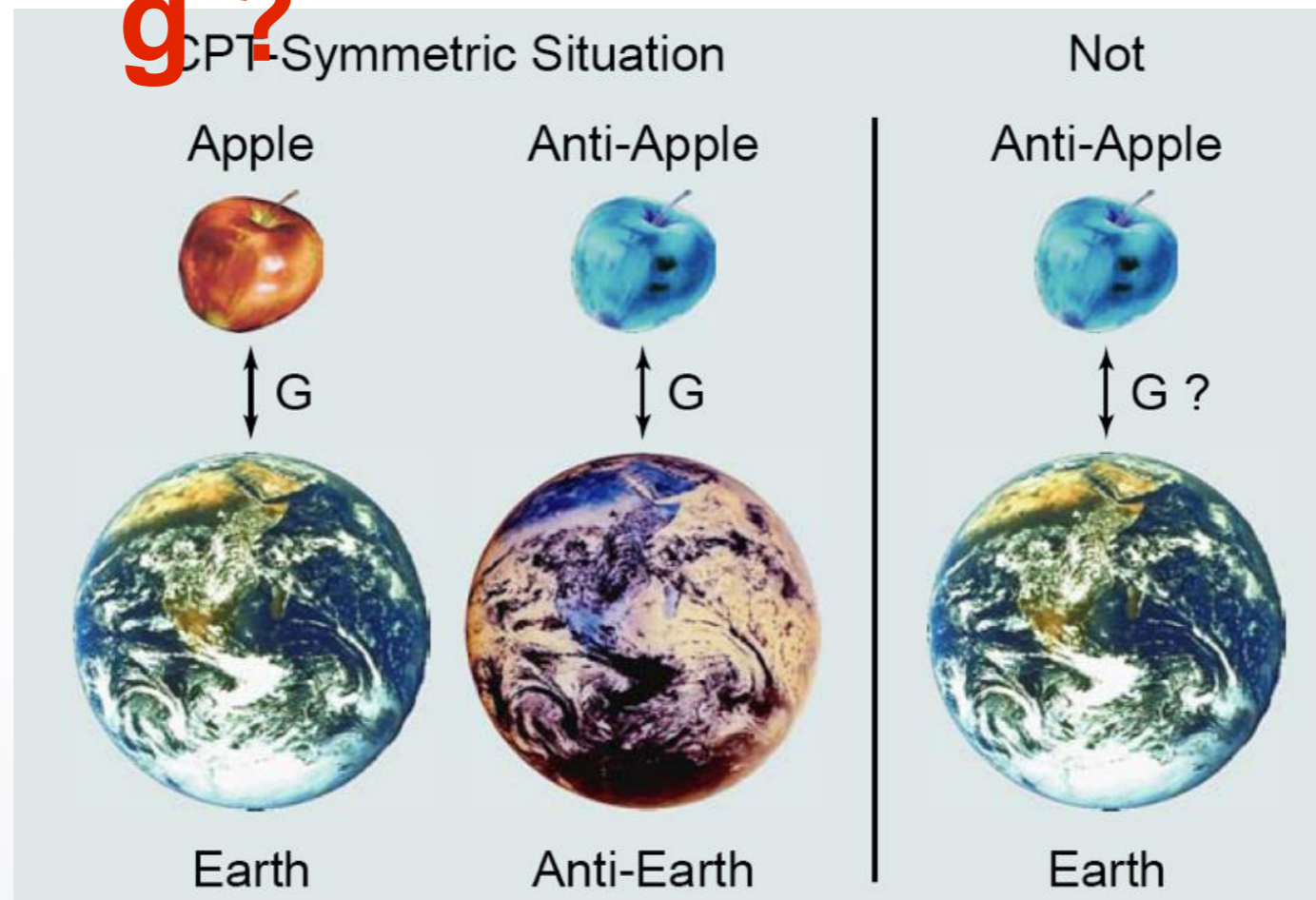
Anti-Hydrogen

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 ?

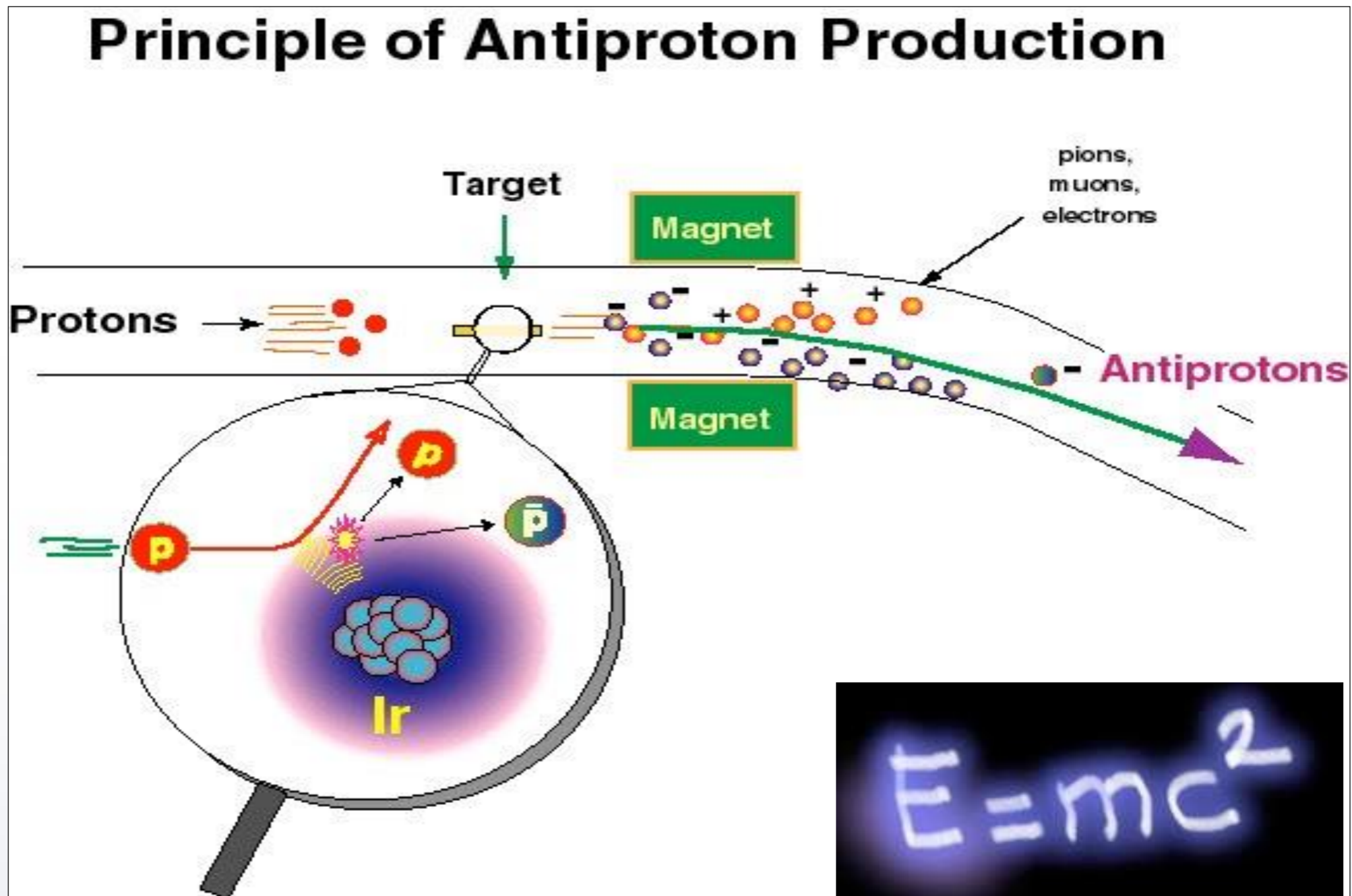


## Antiproton Decelerator

produces 100,000,000  
antiprotons per minute

Slows them down to 10  
% of the speed of light

# 4 How to study antimatter ?

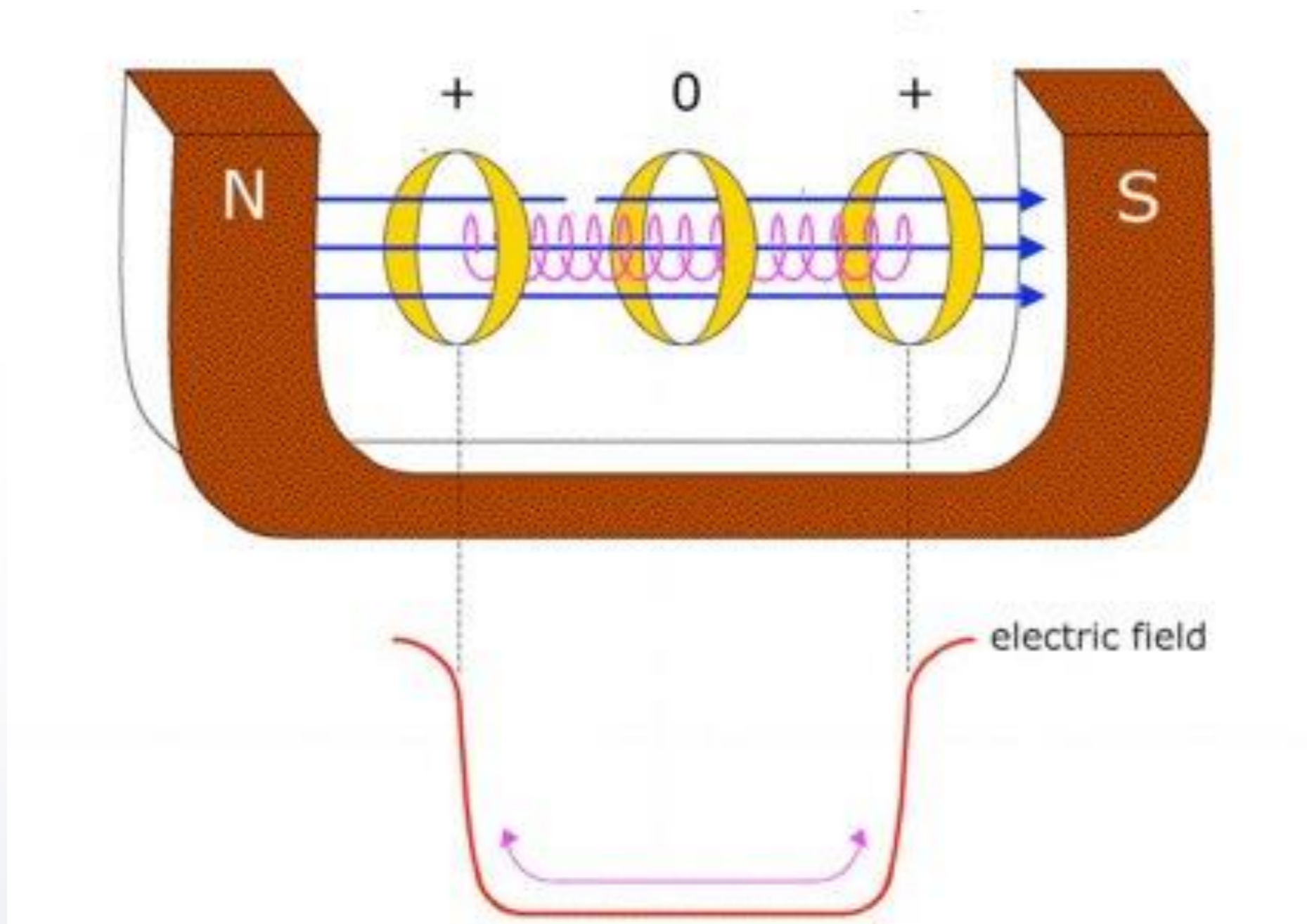


Antiprotons are made in collisions of protons with nuclei

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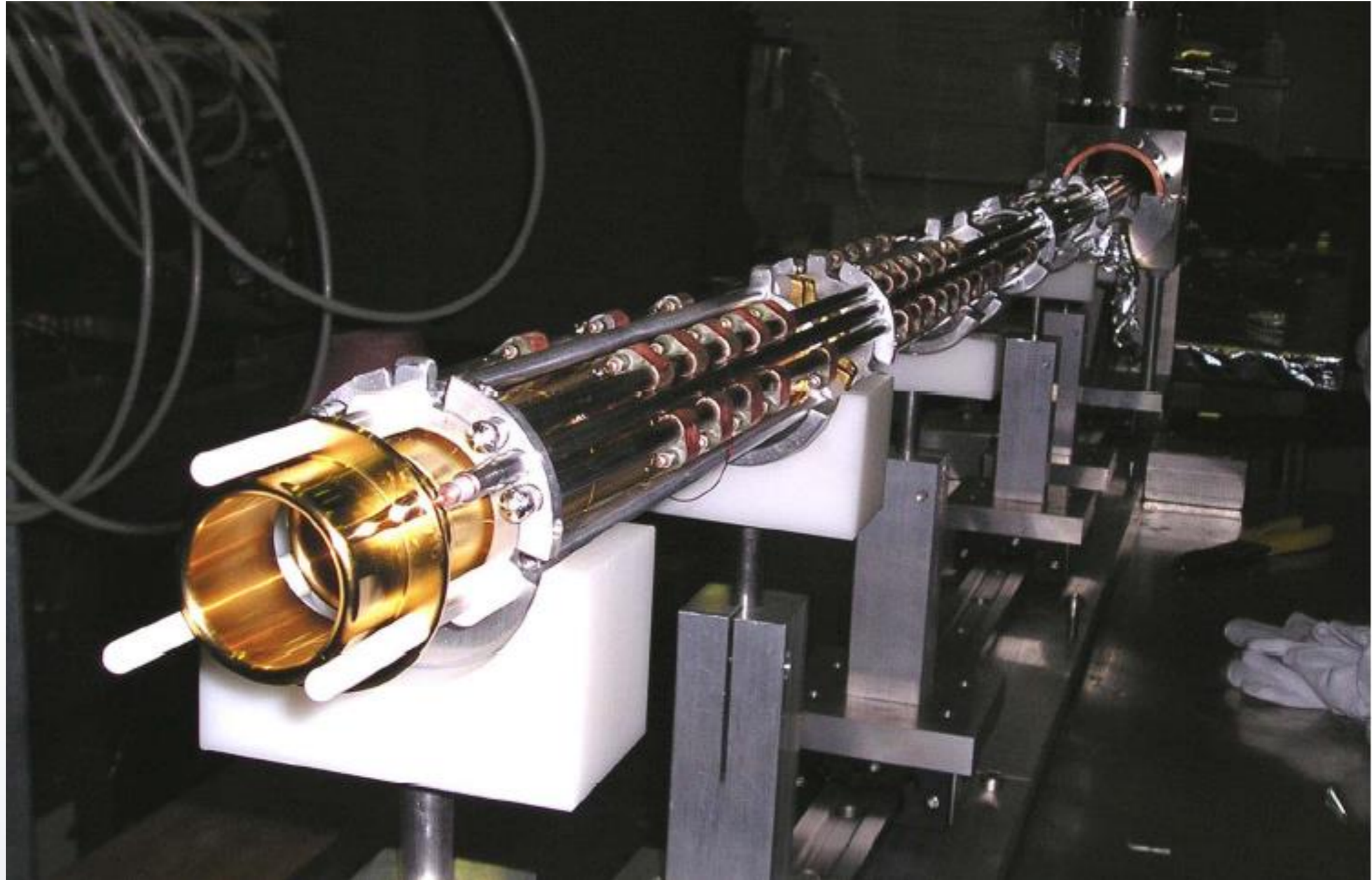
# 4 How to study antimatter ?



## Principle of antiparticle trapping

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## 4 How to study antimatter ?



**A real antimatter trap at CERN**

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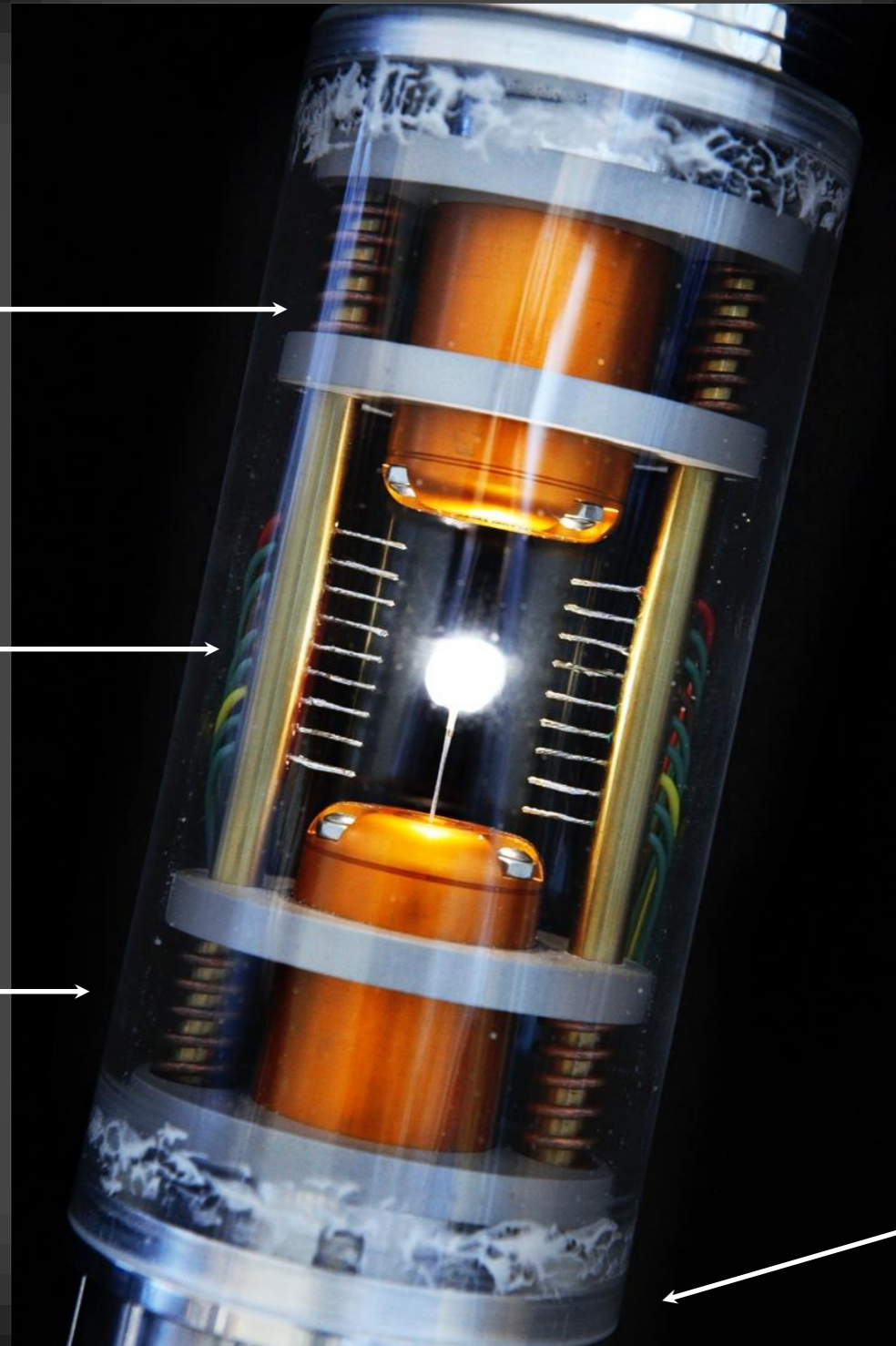
Magnets

Electrodes

Magnets

Ultra-high  
vacuum

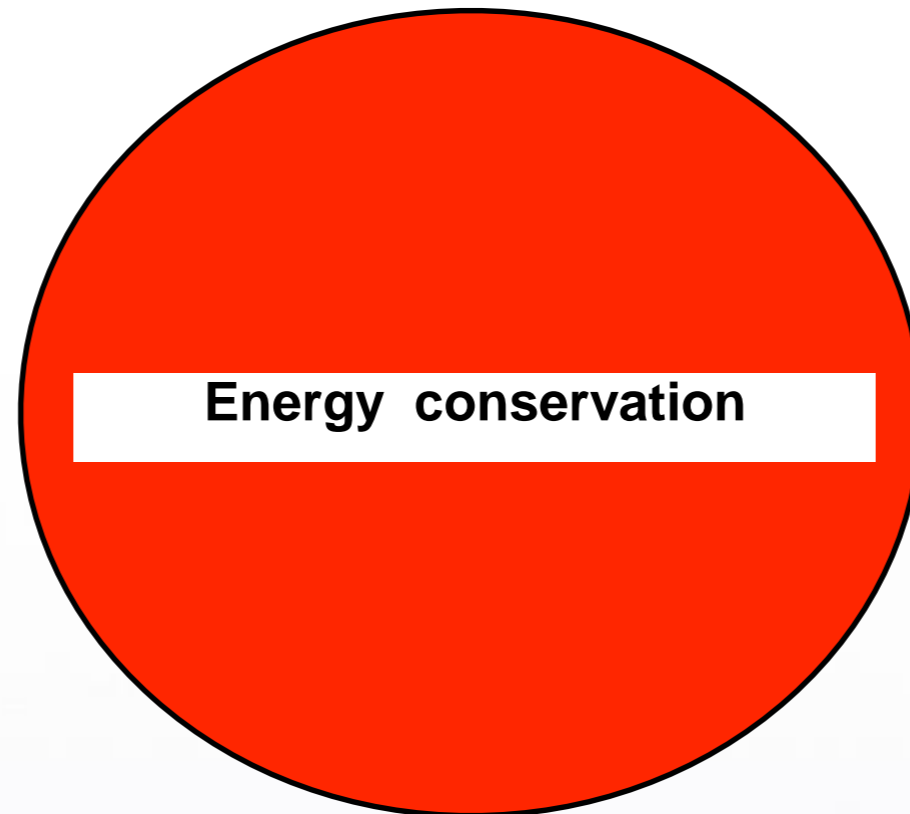
**The “Angels & Demons” version**



# 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**

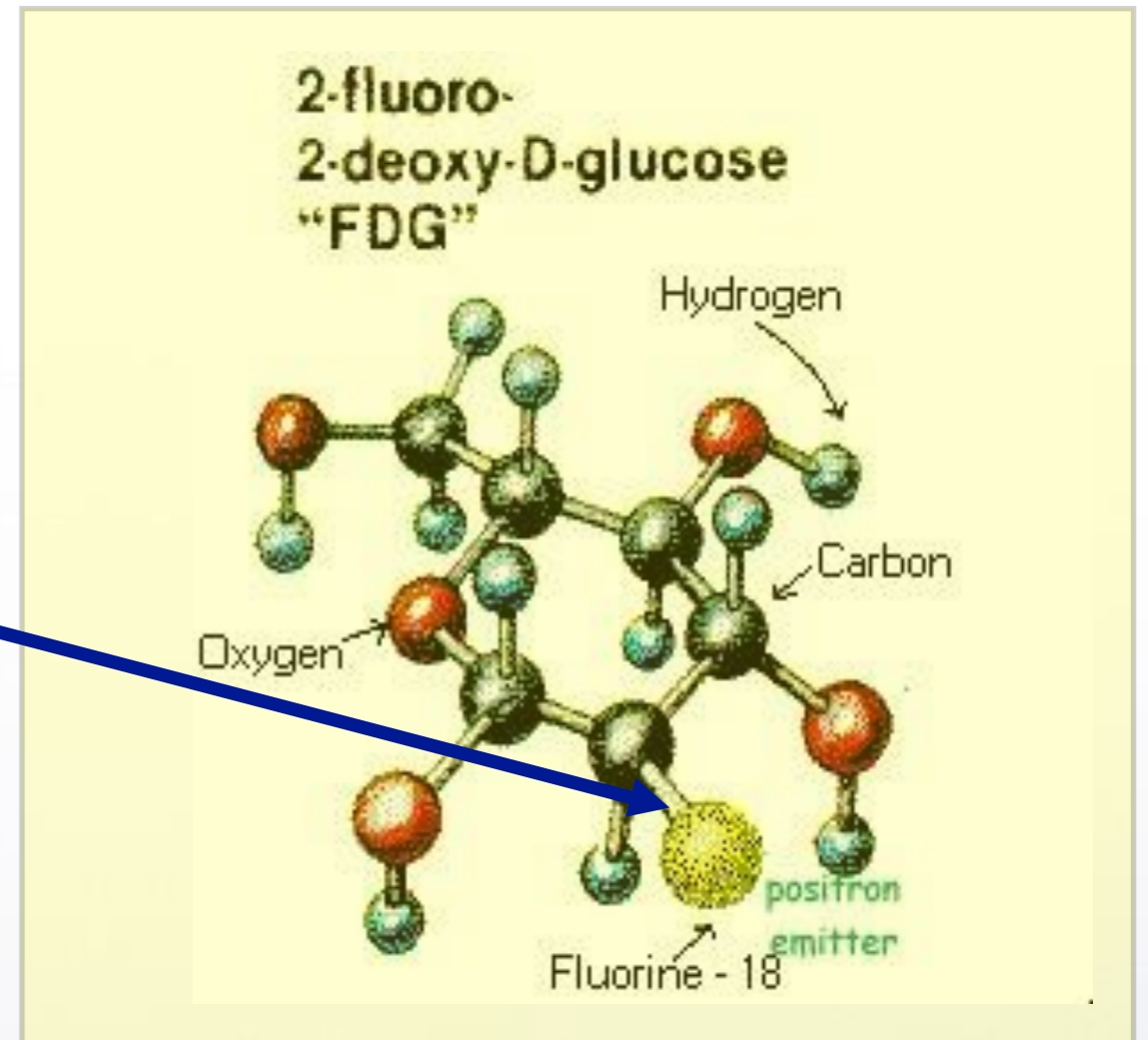
**Glucose supplies energy**

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

Inject into blood stream

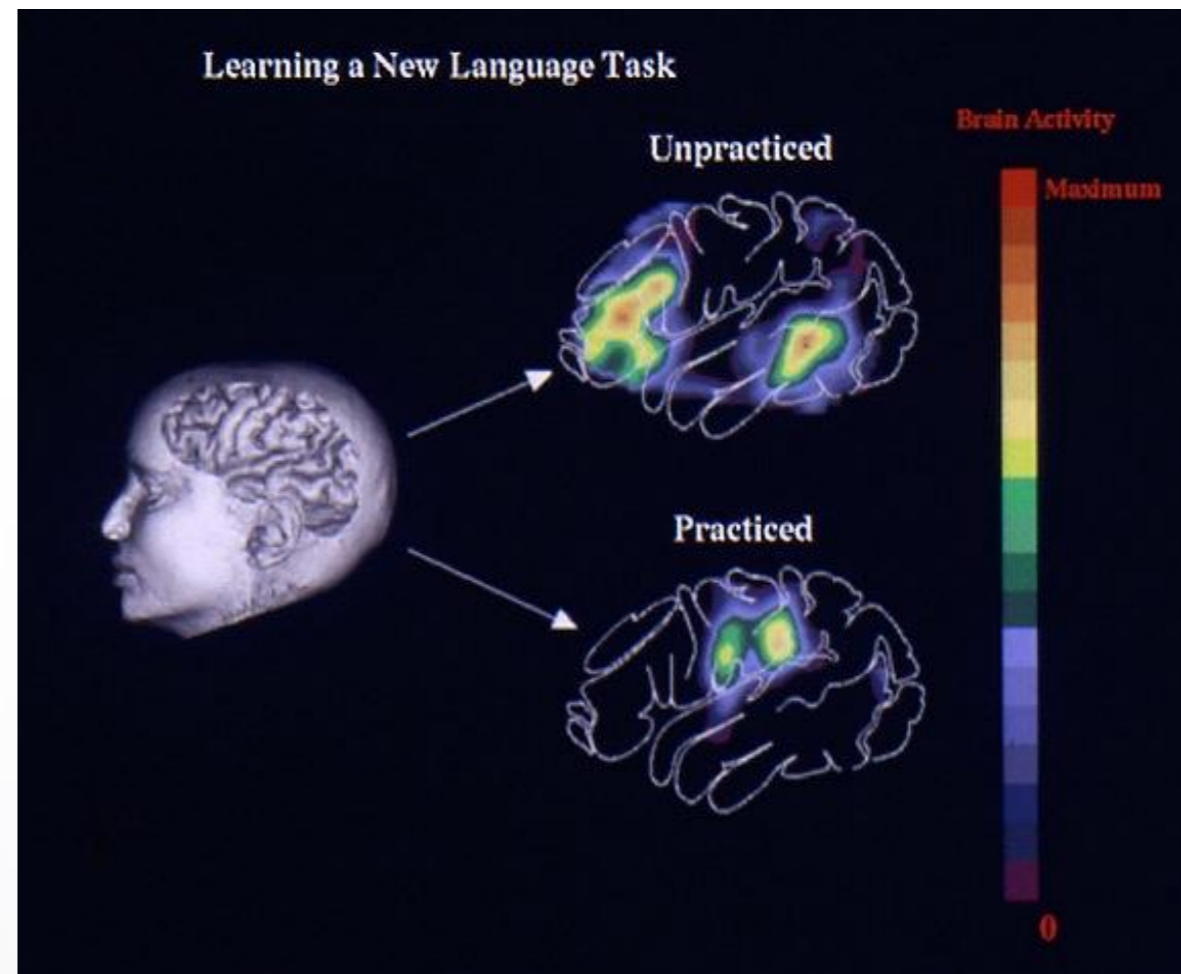
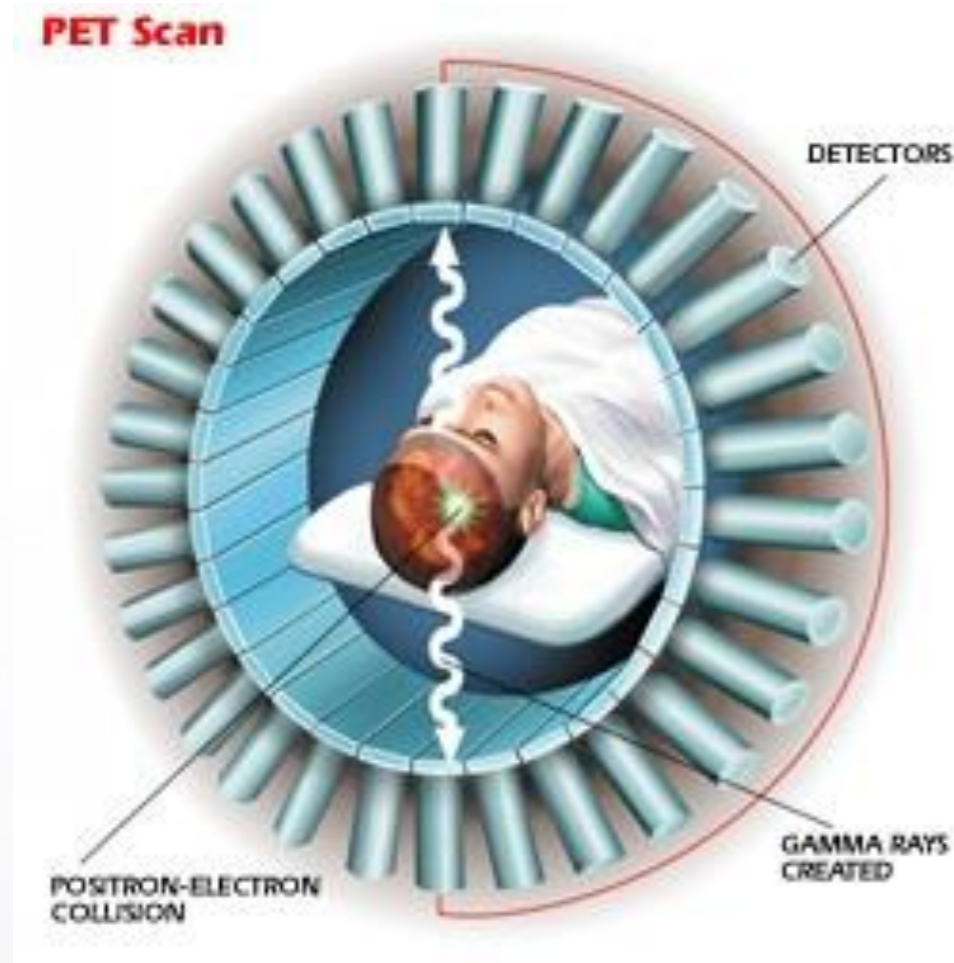
Glucose accumulates where energy is needed

Positron emission and annihilation - detect where the glucose is !



# 5 Antimatter in daily life

## Positron Emission Tomography (“PET Scan”)



**Antimatter helps**

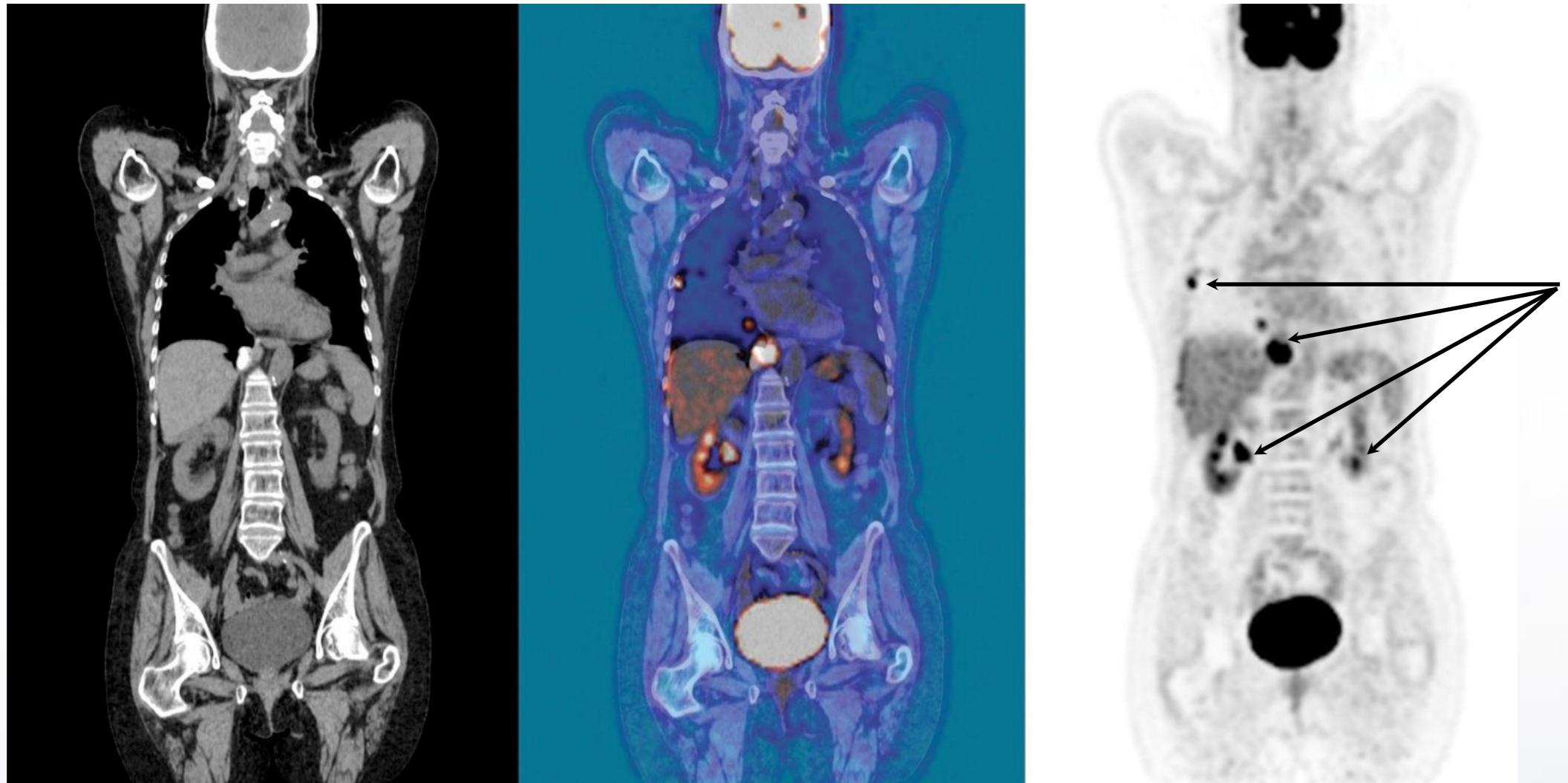
**- to understand how the brain works**

**- 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

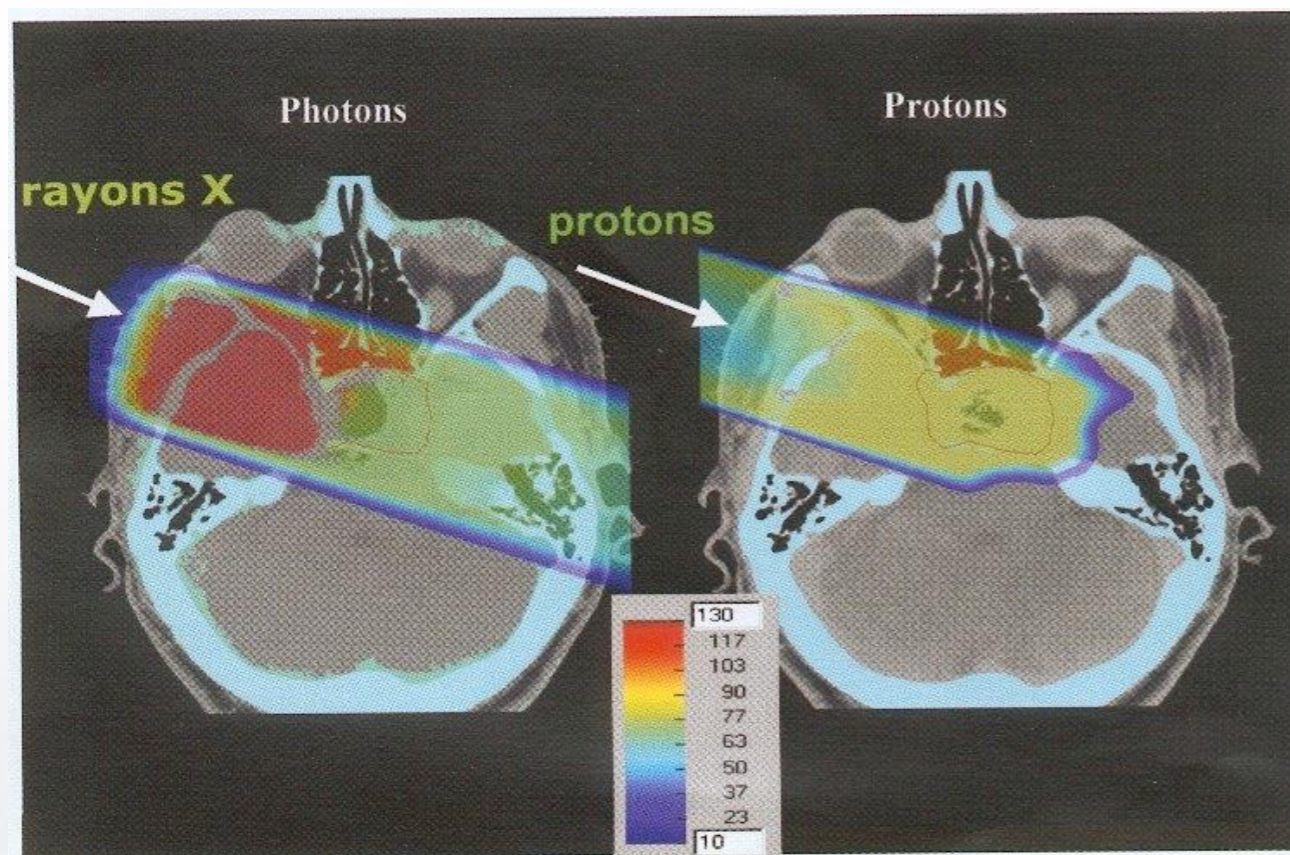
# 5 Antimatter in daily life ?

## Tumour therapy with antiprotons ?

Gamma radiation destroys many healthy cells

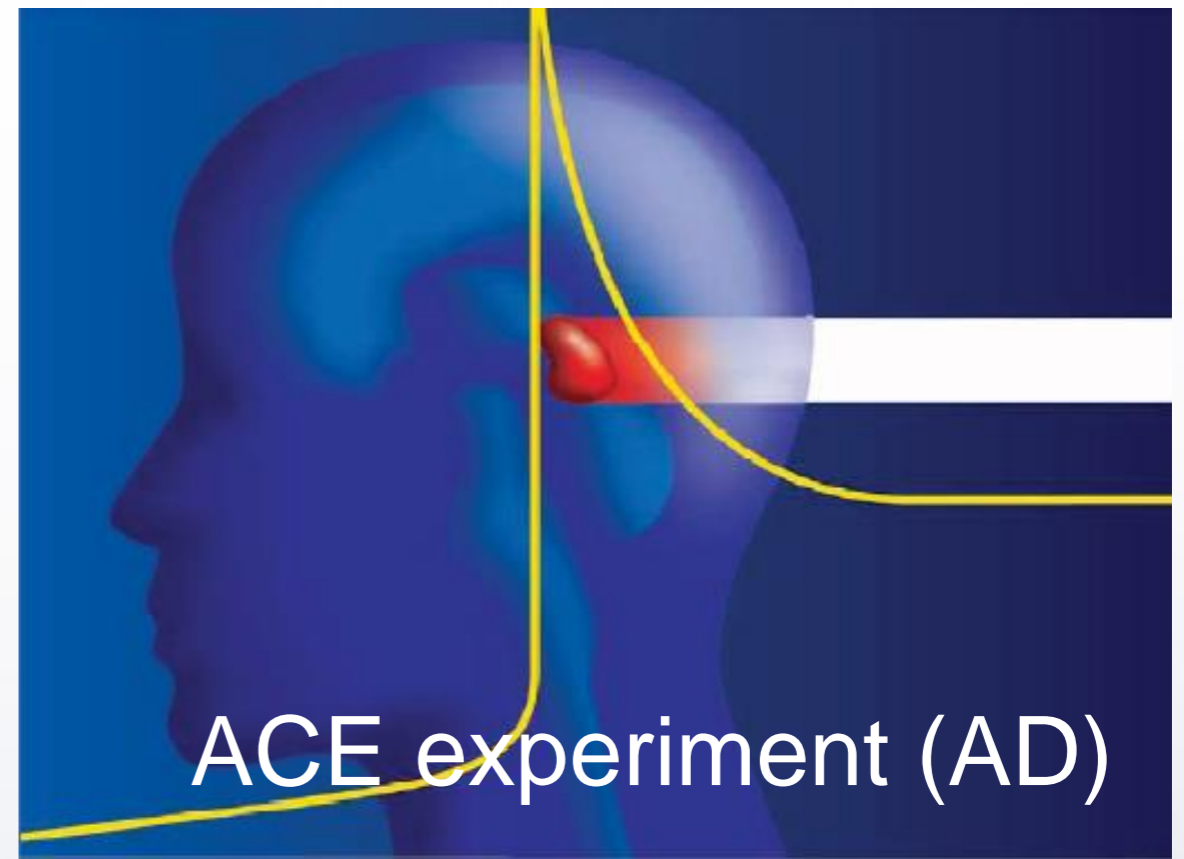
Protons deliver radiation more specifically to tumour cells

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



Gamma radiation

Protons

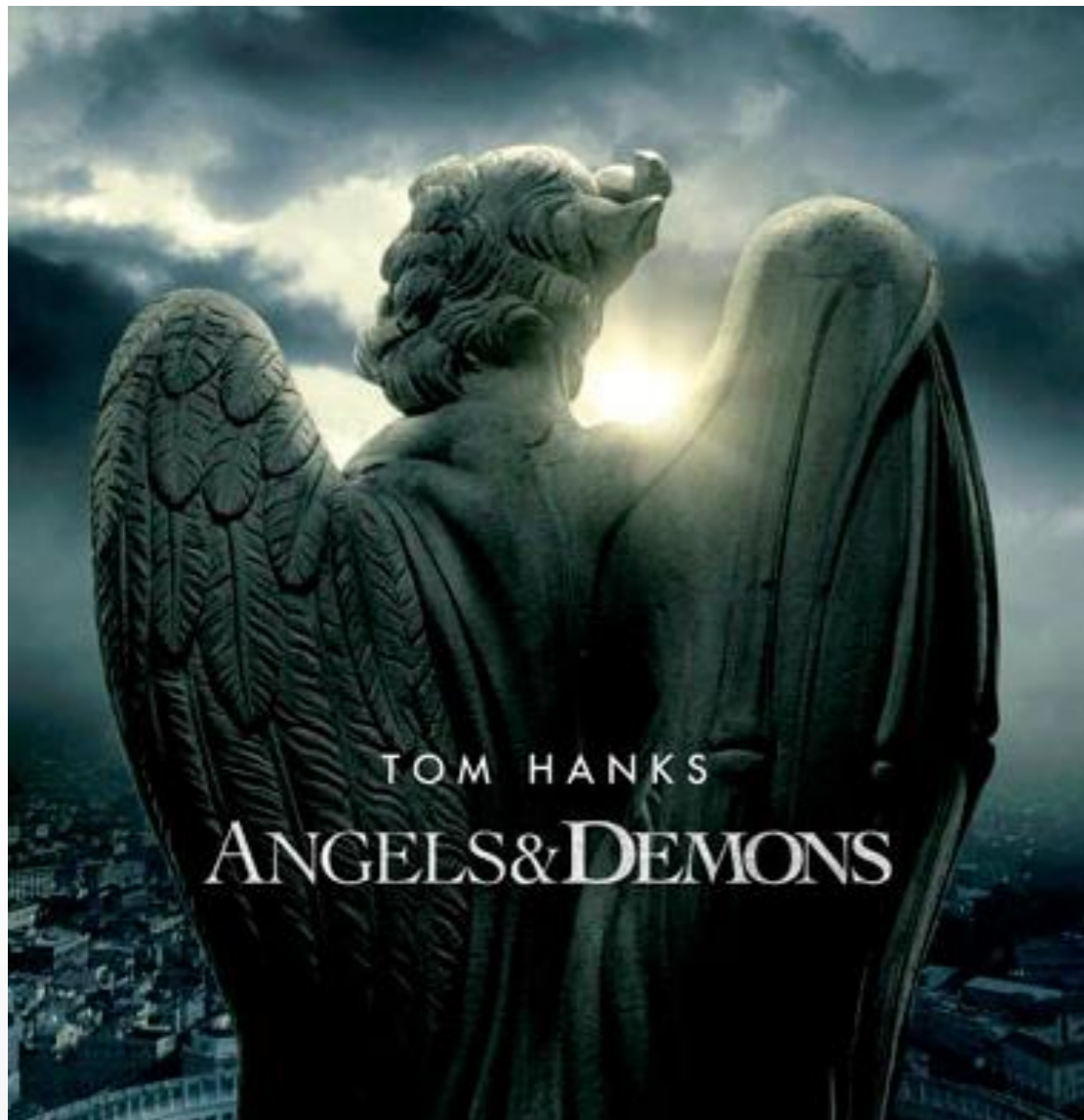


Antiprotons

# What did Ron Howard say ?



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Movie



# 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

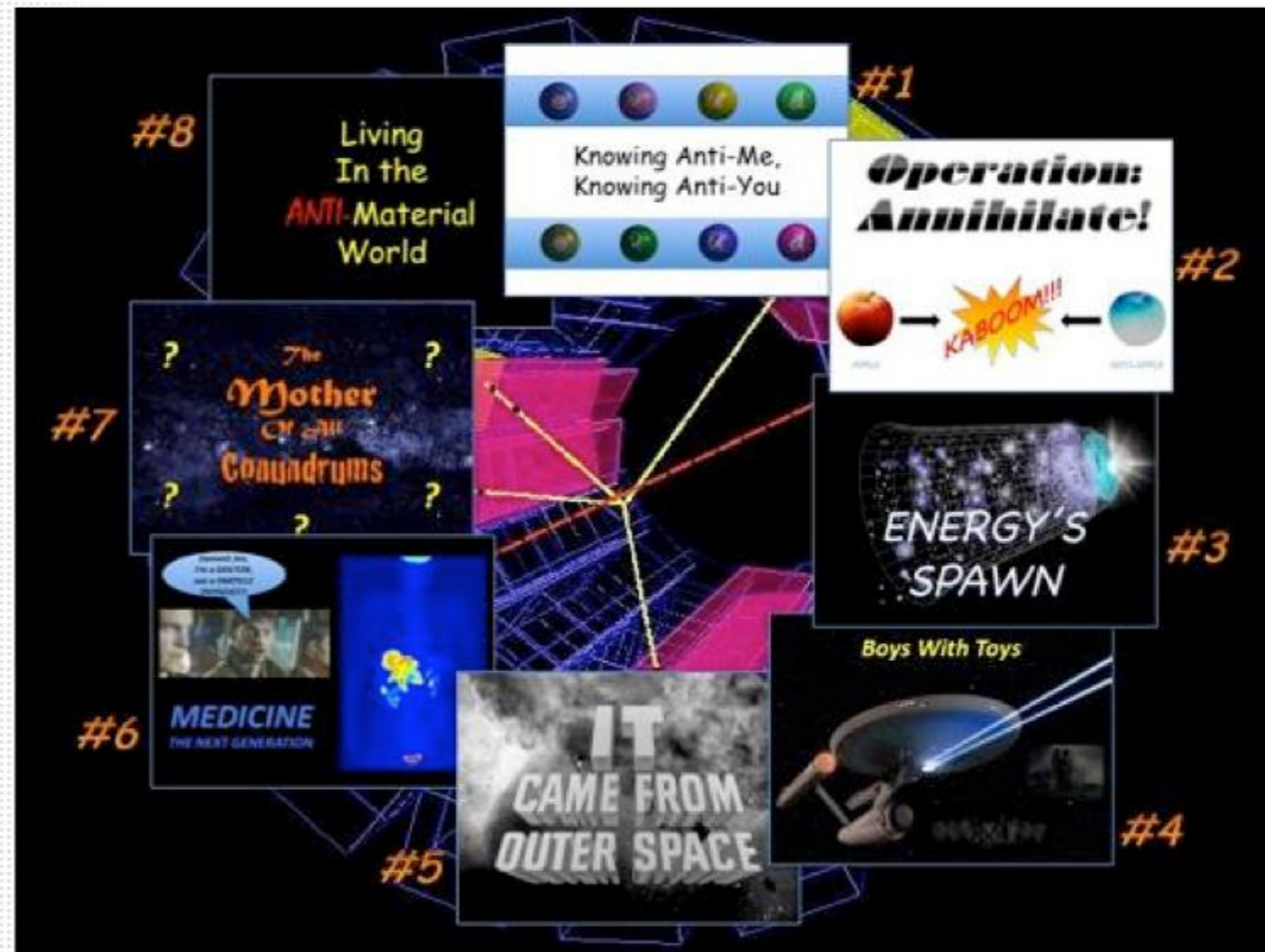
Introduction to Accelerators

Applications of CERN research

Multimedia material

## Teaching Resources - Antimatter Teaching Module

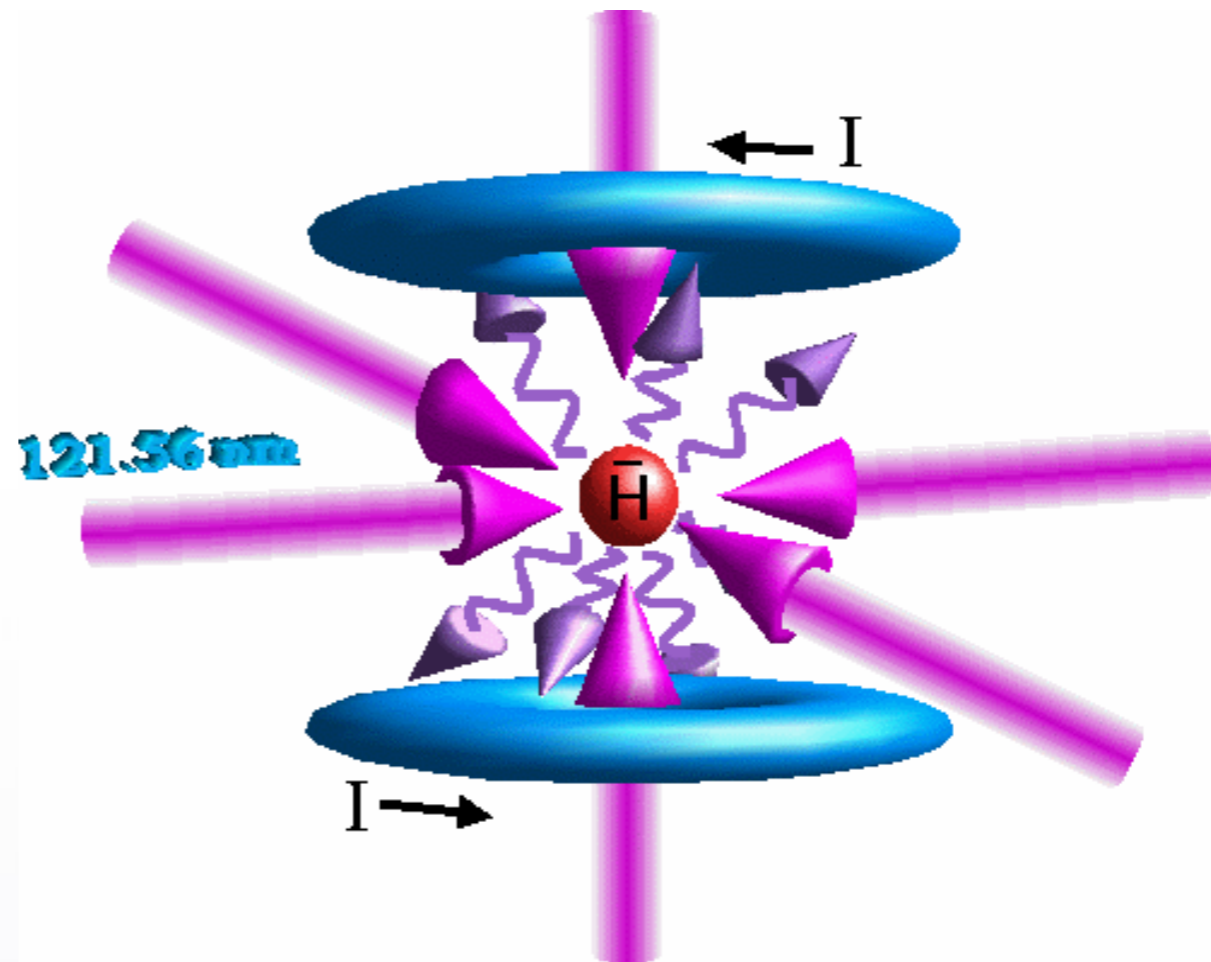
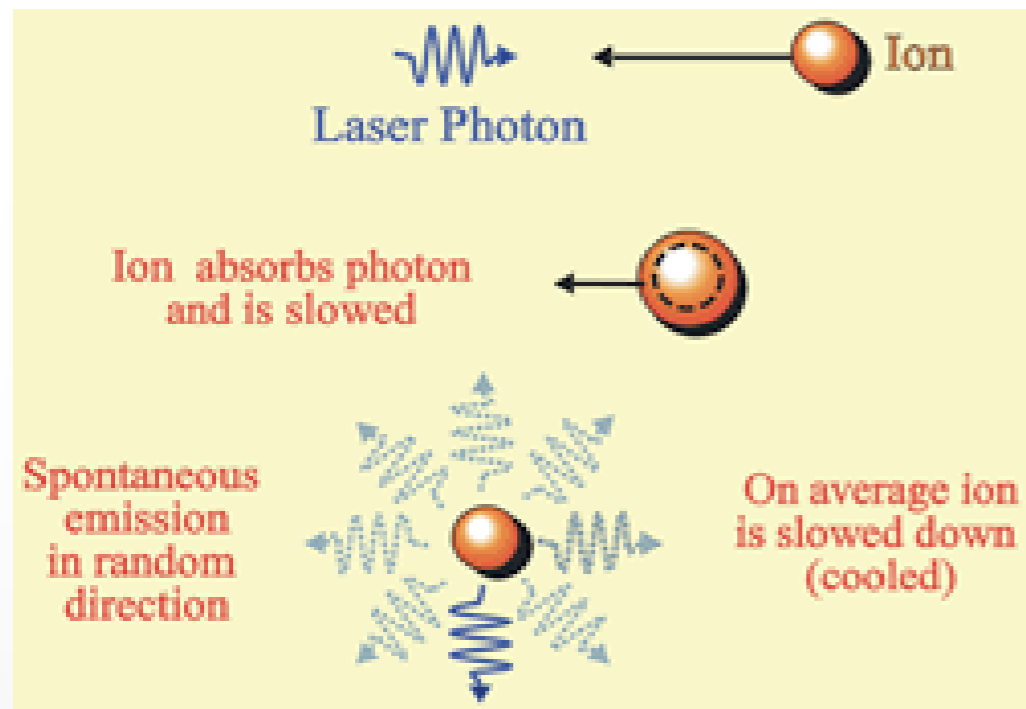
>> Lesson Plans



Back to [Antimatter Teaching Module](#)

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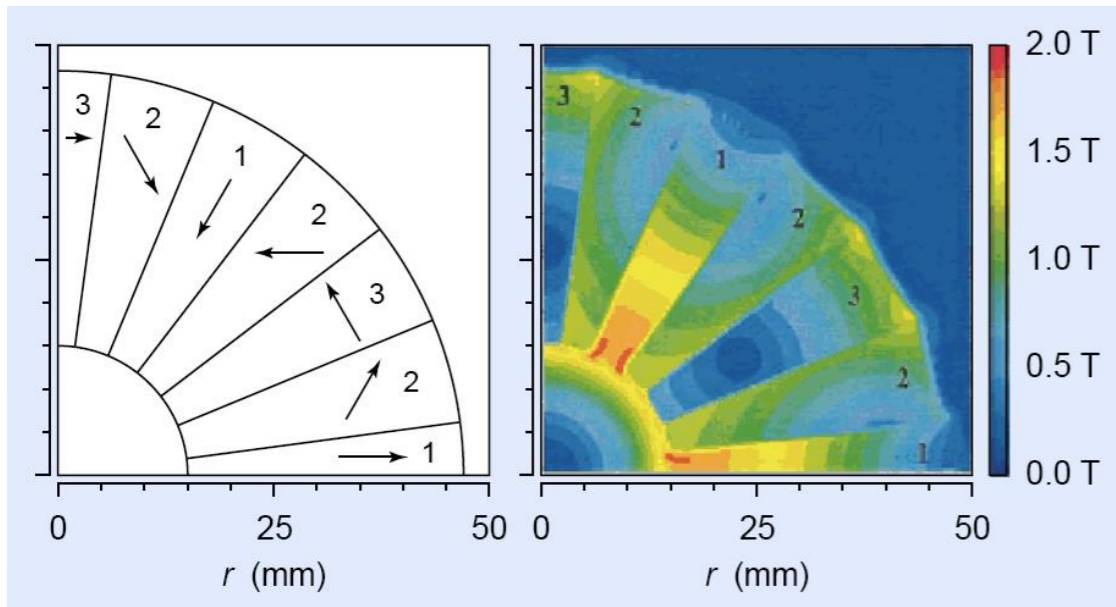
# Laser cooling



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

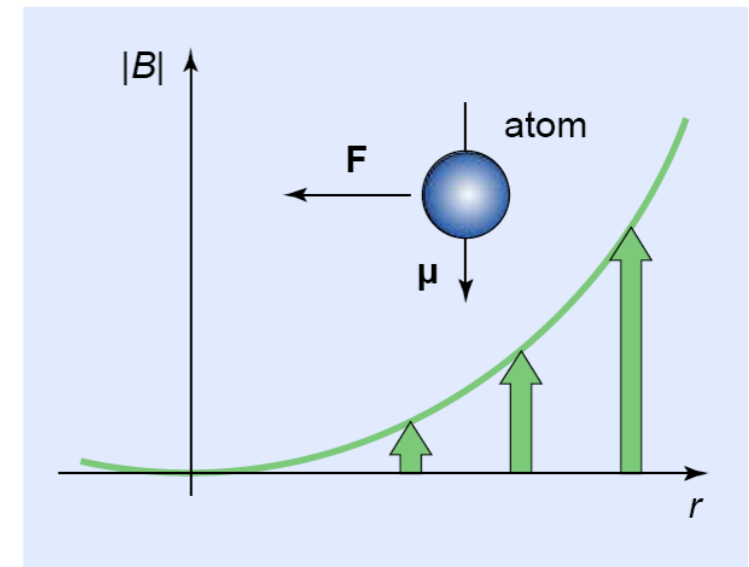


# Magnetic multipole traps ?



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

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



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

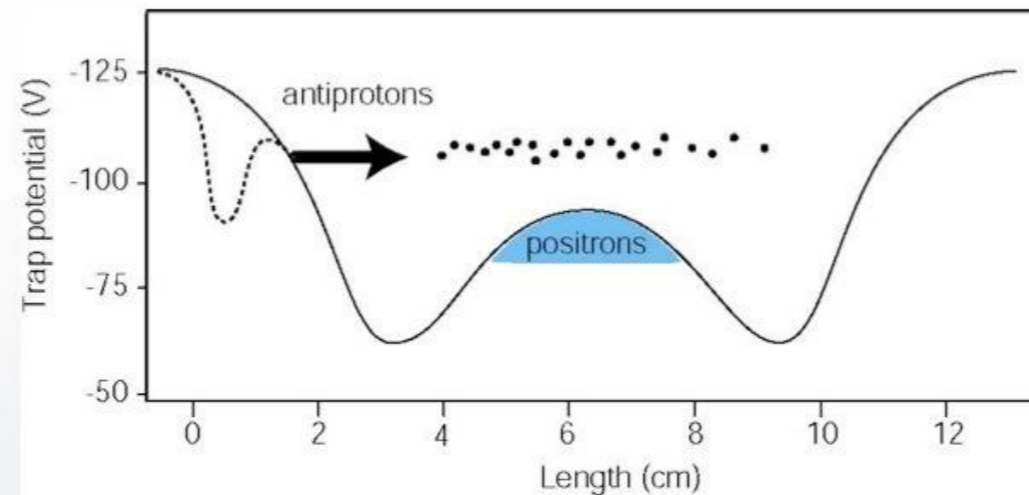
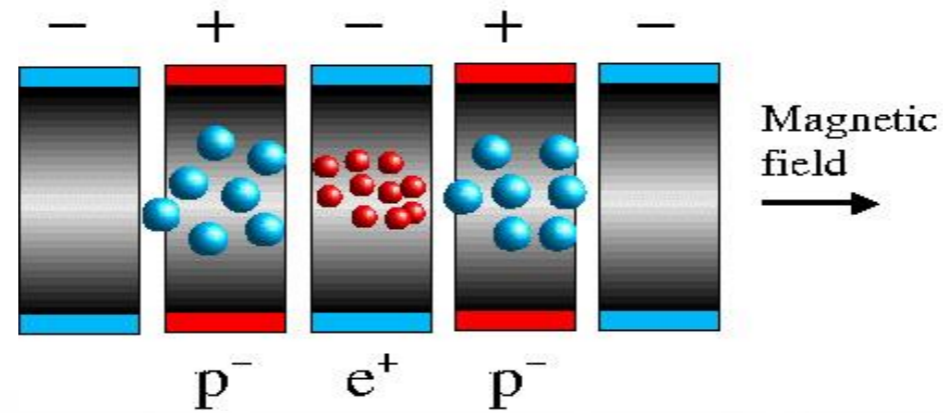
BUT: Very shallow potential ( $\sim 0.07$  meV/T)

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

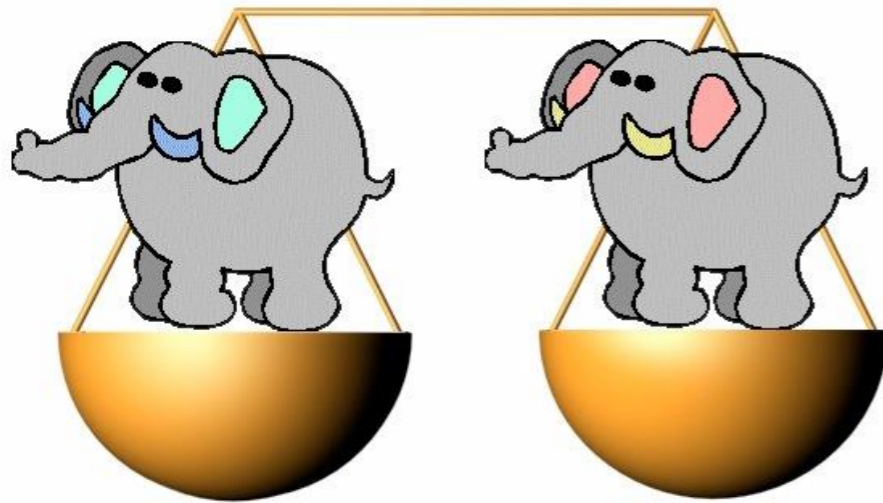
Accumulation (eV)



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



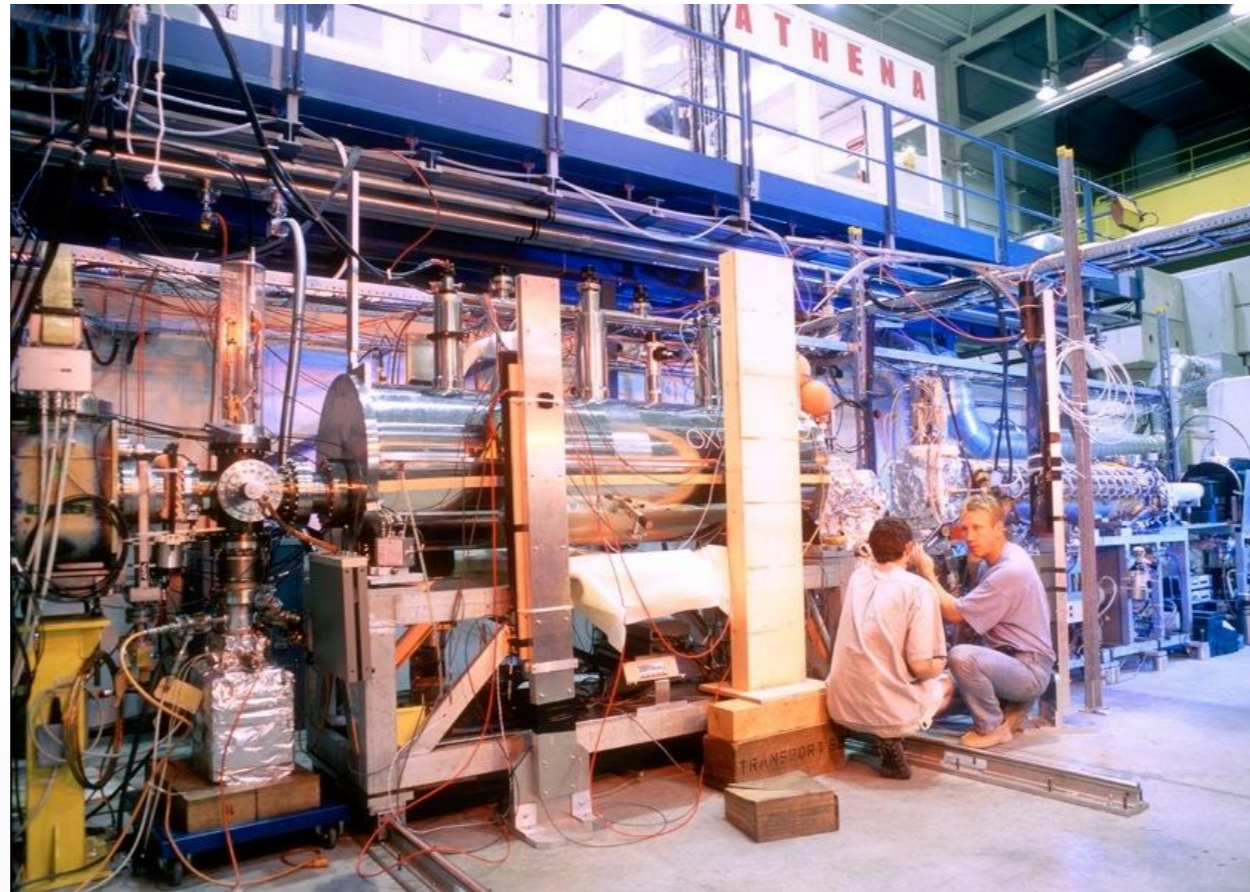
Magnetic moment of electron and positron ?

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

**Present status: excellent agreement !**

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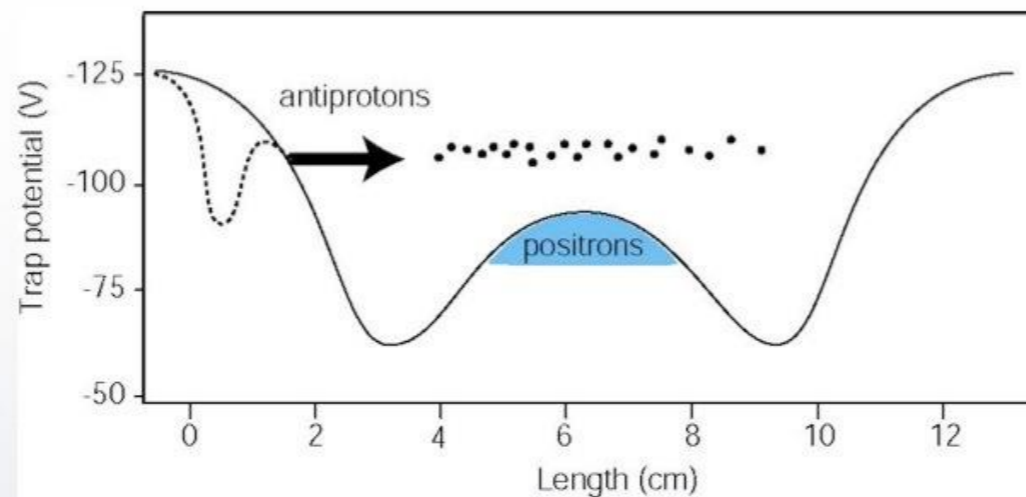
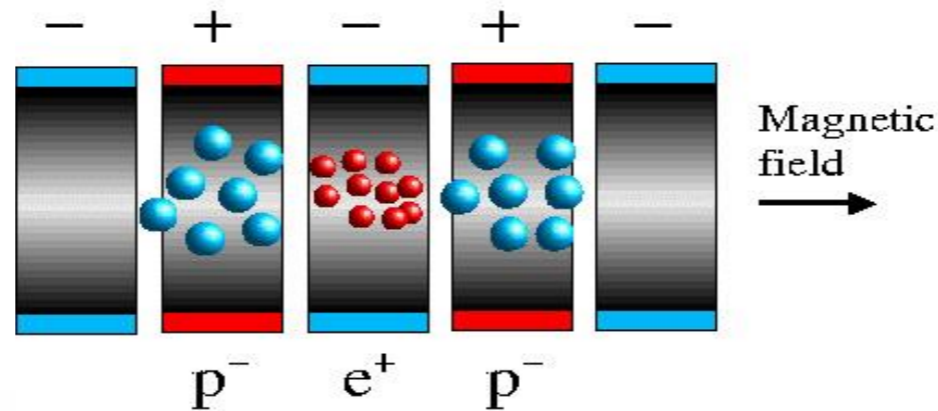
## ATHENA Experiment (2002), at the AD facility



- 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

