



# Angels&Demons

The Physics Behind the Movie

Rolf Landua

CERN

# The story line of Angels & Demons

**Illuminati**

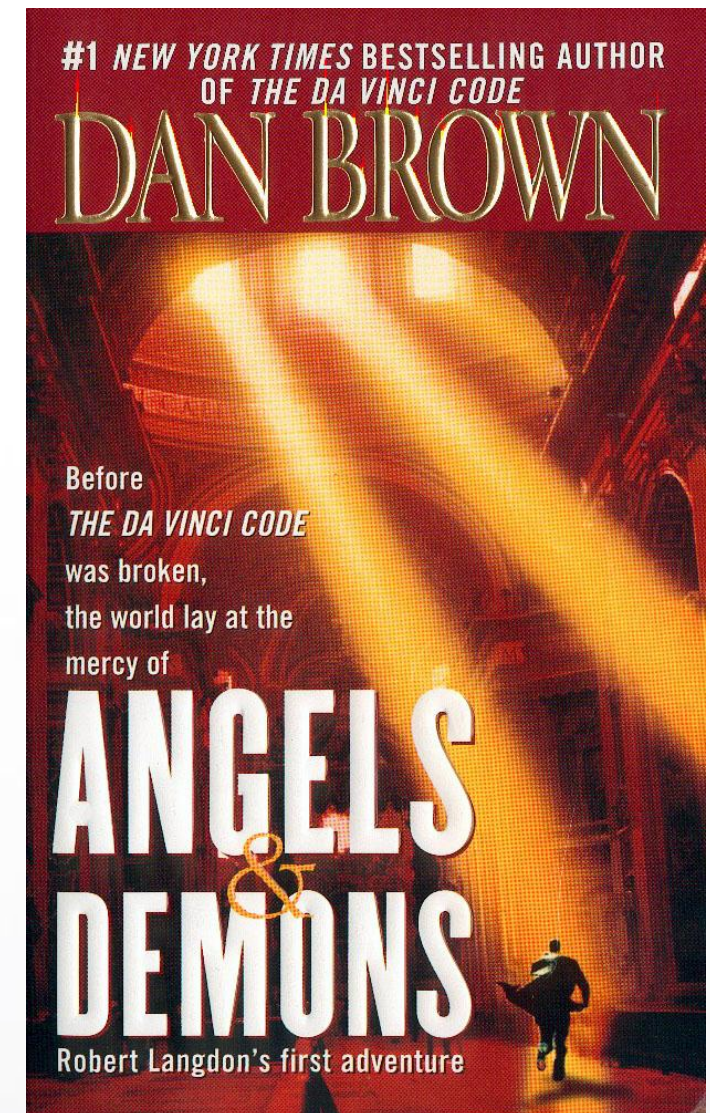
Detective story about a secret society which ...



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



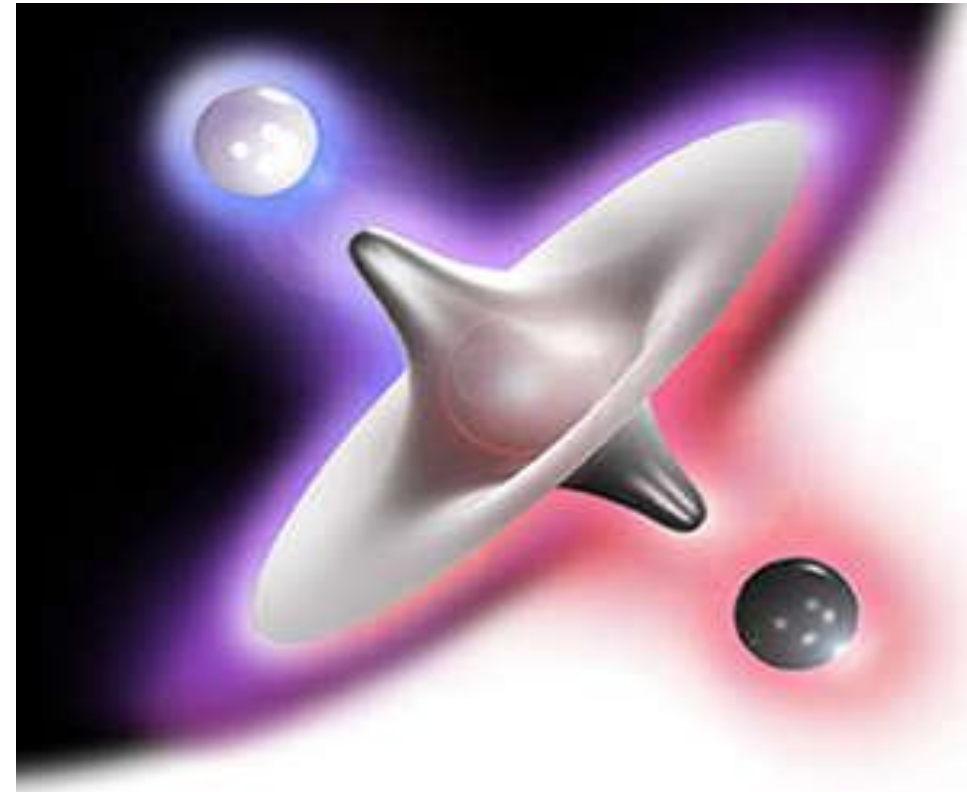
... to blow up the Vatican, an old "enemy of science and CERN".



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

Angels & Demons - The Physics behind the Movie

# Antimatter Questions



Seven questions

What is antimatter ?

Where is antimatter made ?

How is antimatter made ?

The mystery of antimatter ?

How to study antimatter ?

Energy source? A bomb ?

Antimatter in daily life ?

# 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?



That's how small I feel after seeing the huge machines ...

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

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

This is what Dan Brown understands about antimatter ....

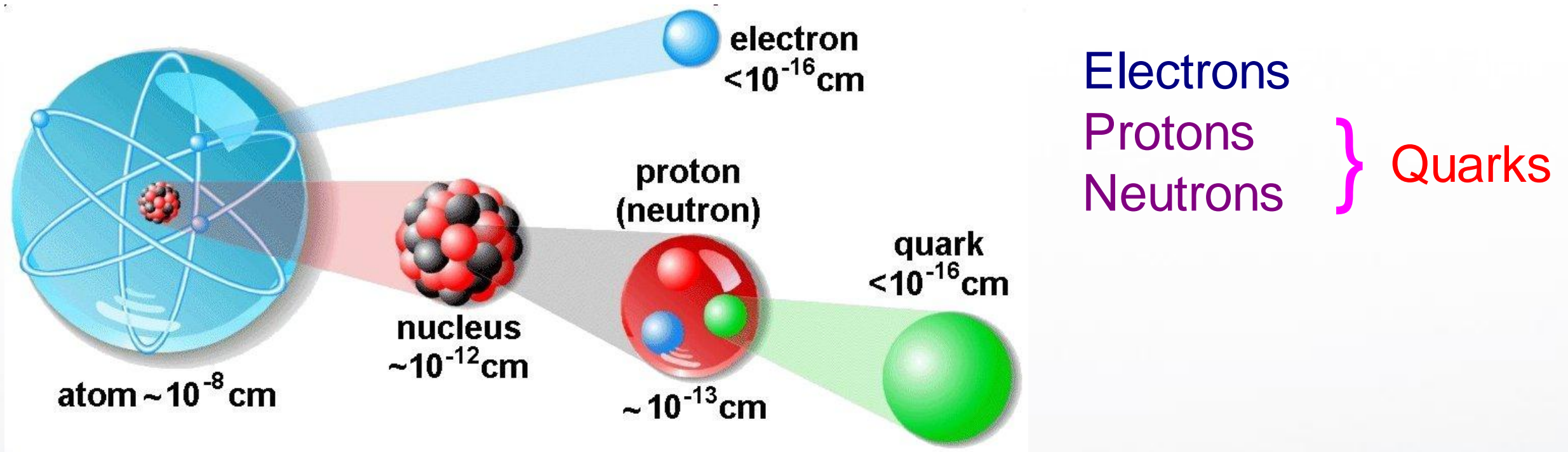
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# 1 What is antimatter ?

# 1 What is antimatter ?

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

## Hierarchy of matter structures



**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

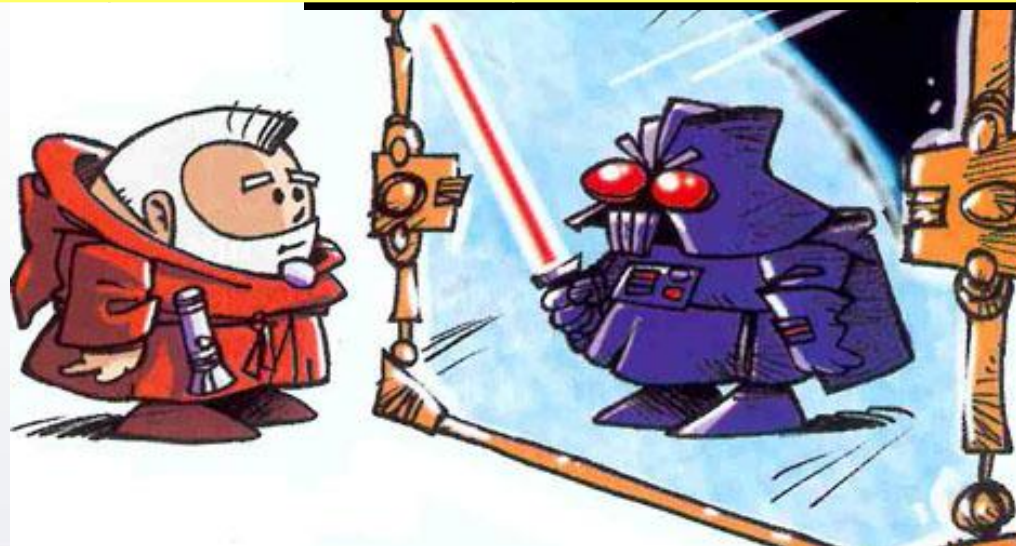
# 1 What is antimatter ?

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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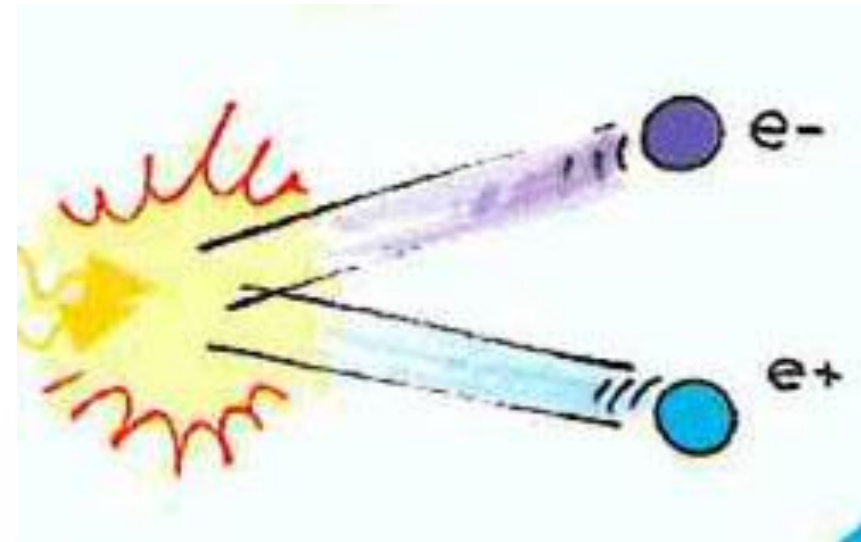


# 1 What is antimatter ?

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

$$E=mc^2$$

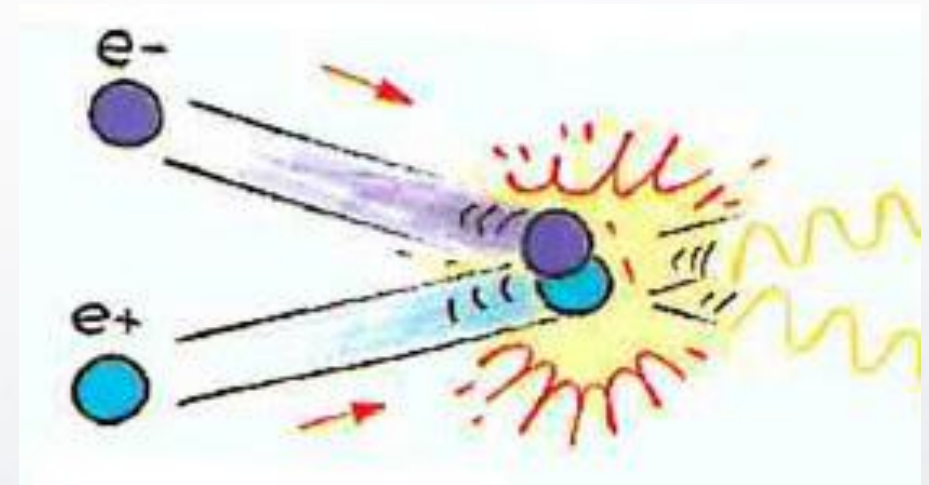
Energy to  
mass:



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

$$E=mc^2$$

Mass to energy:

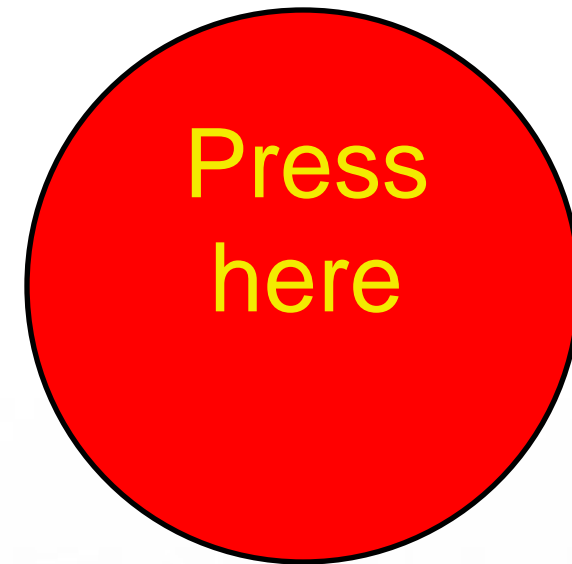
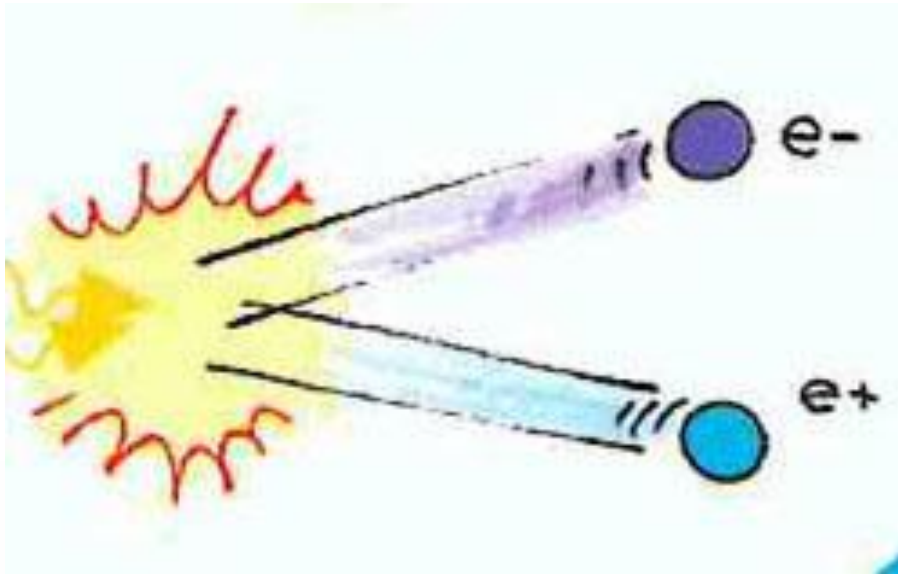


# 1 What is antimatter ?

## 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 ?

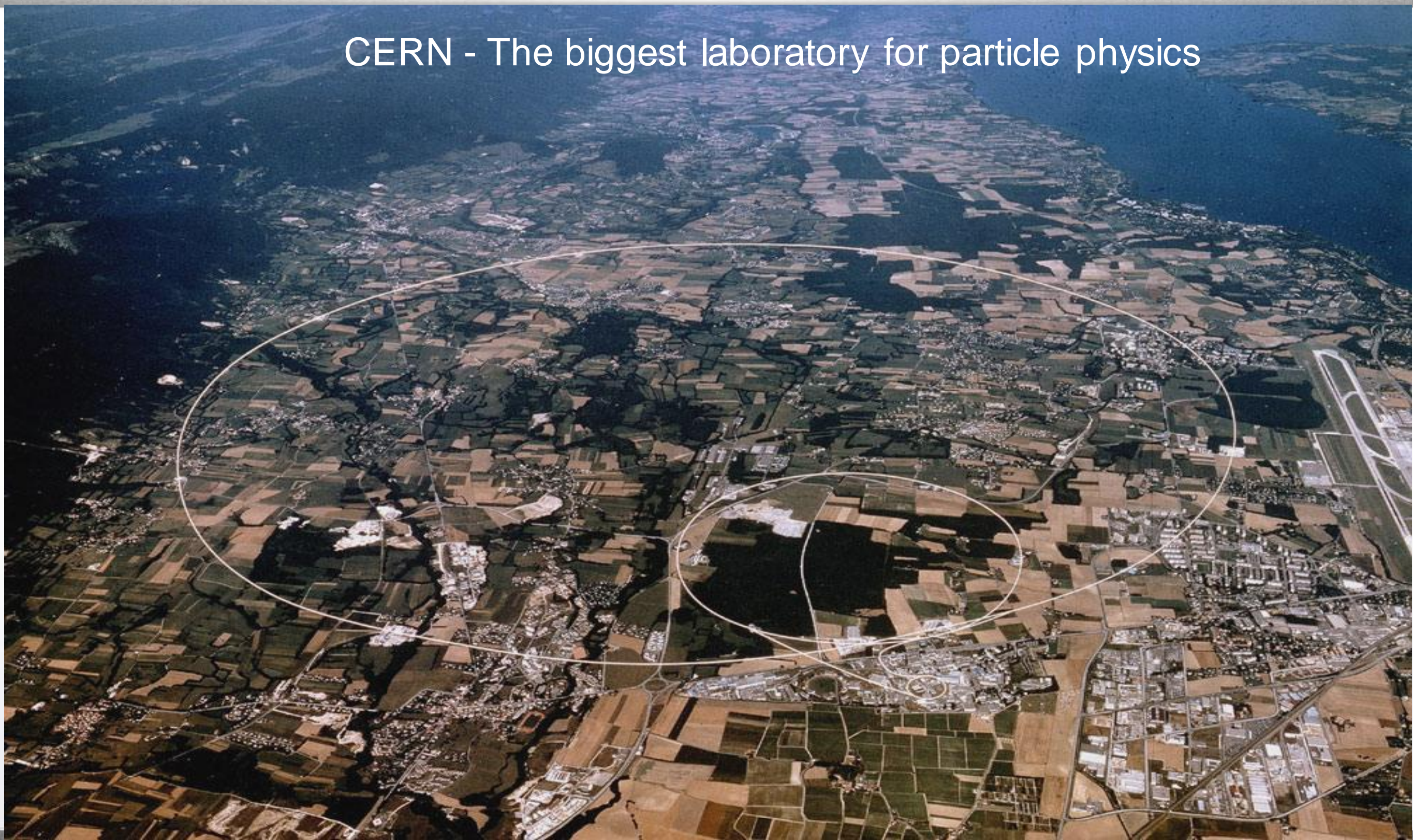
Careful with “antimatter E.T.” !



## 2 Where is antimatter made ?

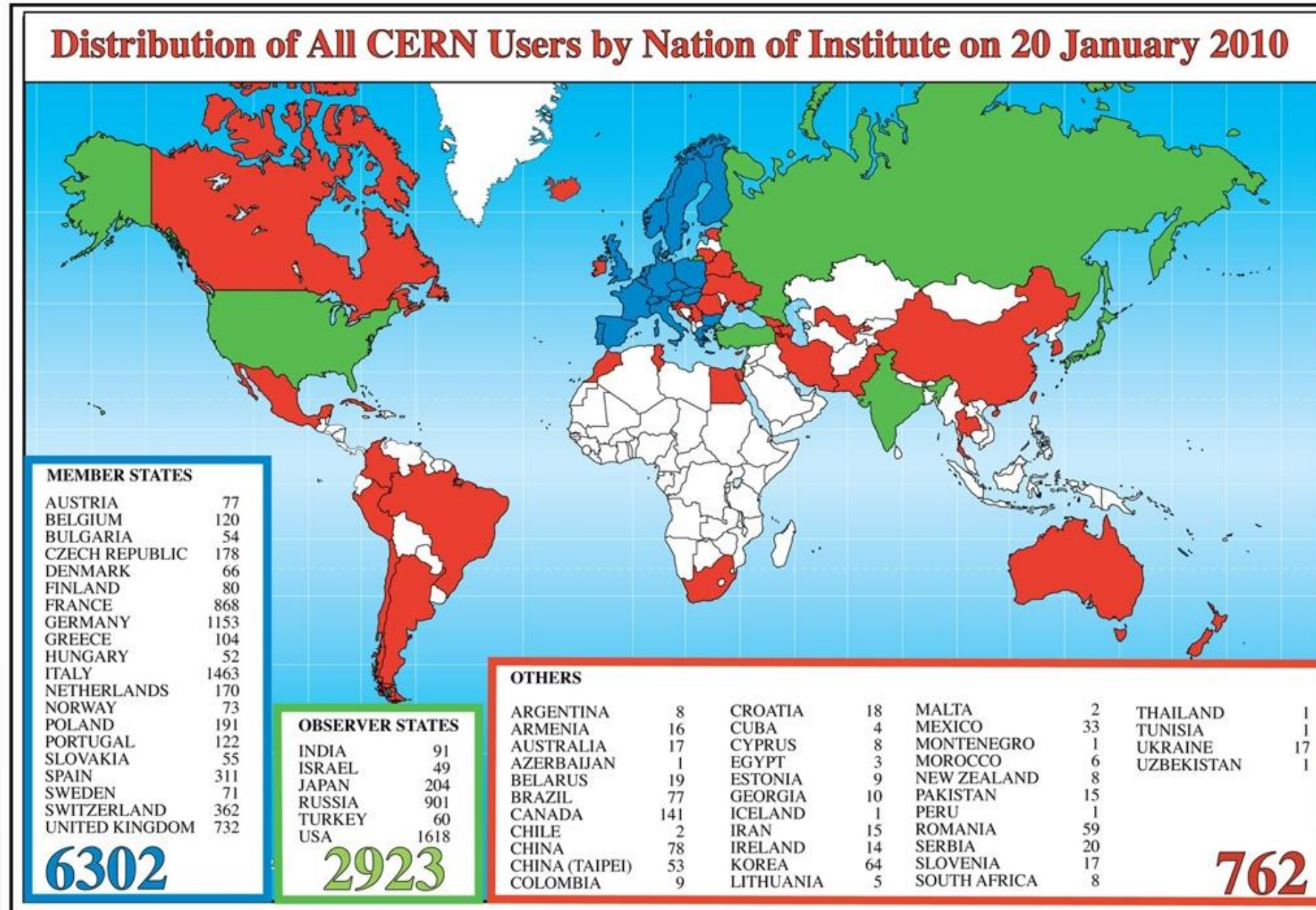
## 2 Where is antimatter made ?

CERN - The biggest laboratory for particle physics



Angels & Demons - The Physics behind the Movie

## 2 Where is antimatter made ?



10,000+ scientists from 104 countries work at CERN

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## 2 Where is antimatter made ?



Large  
Hadron  
Collider

27 km long  
100 m underground

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Movie



LHC experiments are in caverns 100 m underground



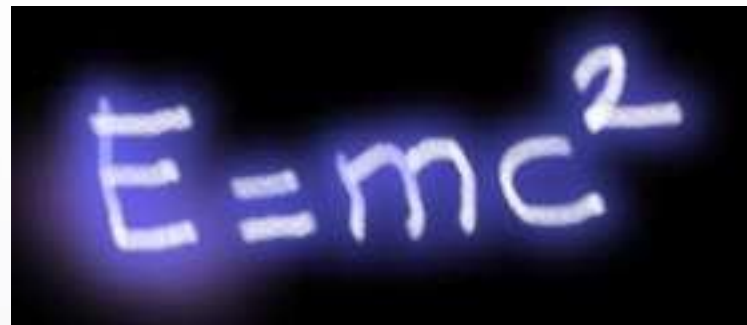
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# The Hollywood version of antimatter production



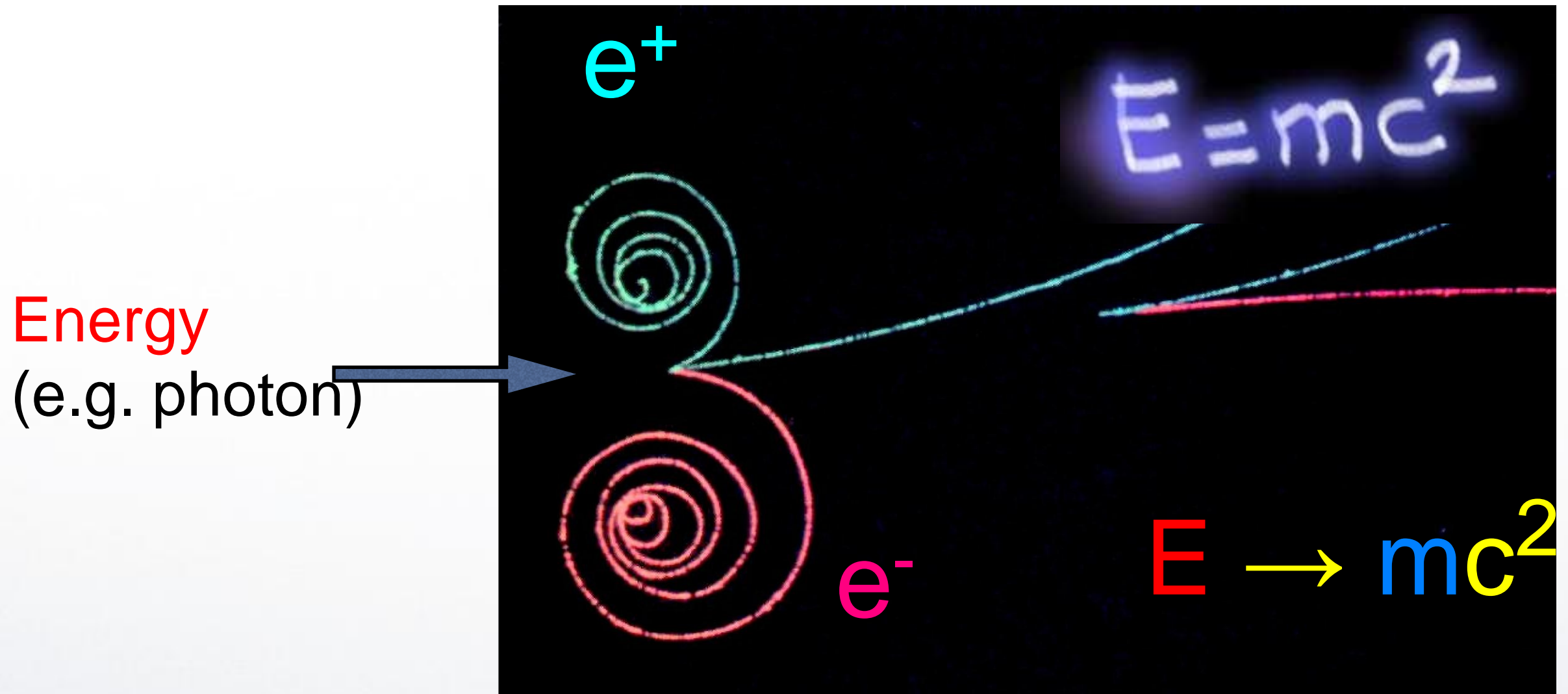
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# 3 How is antimatter made ?

A rectangular image showing the equation  $E=mc^2$  written in white chalk on a dark, textured blackboard. The equation is centered within the image.

### 3 How is antimatter made ?

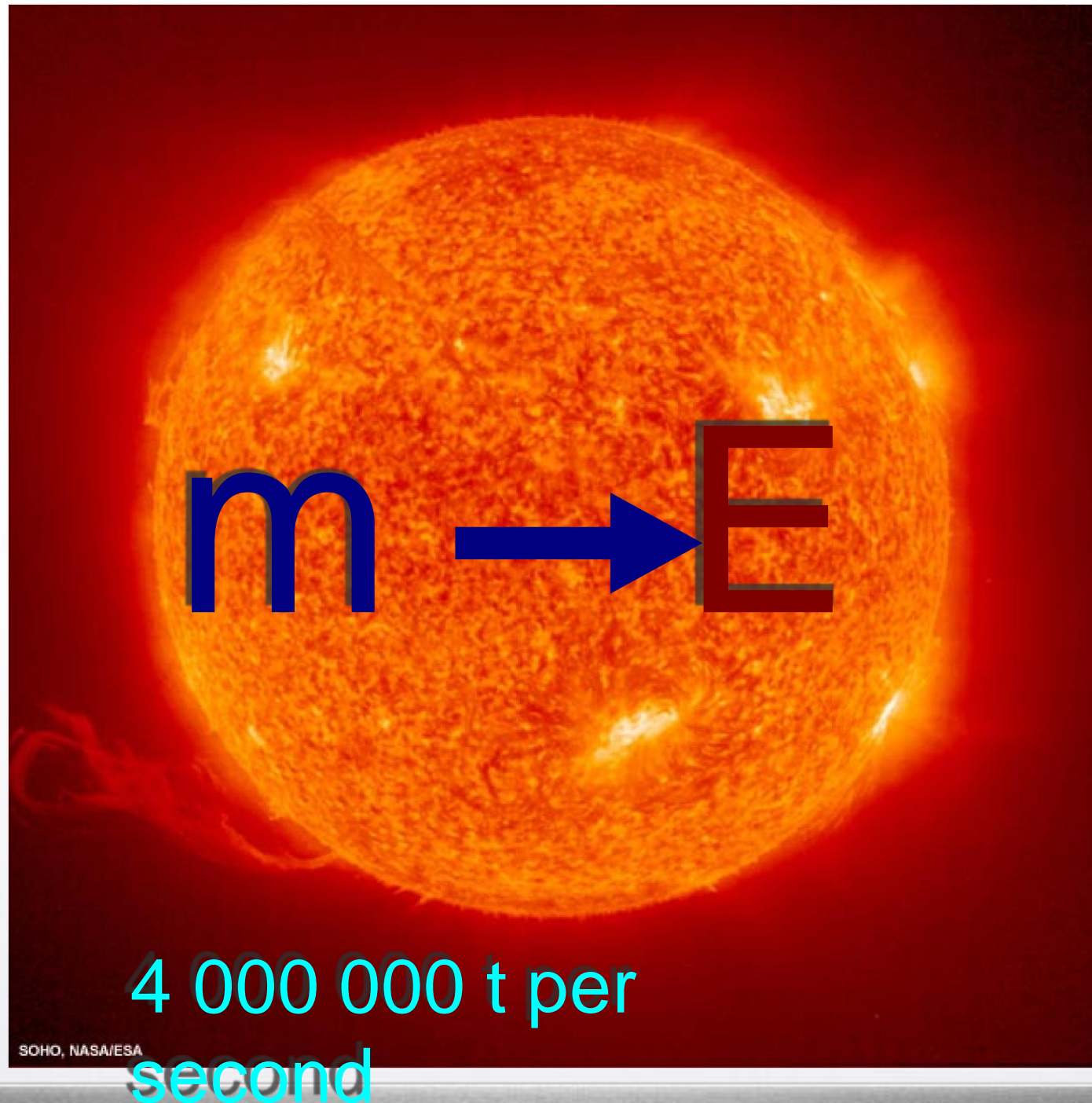
**Energy** is converted to **mass**



**Mass** of electron and positron

### 3 How is antimatter made ?

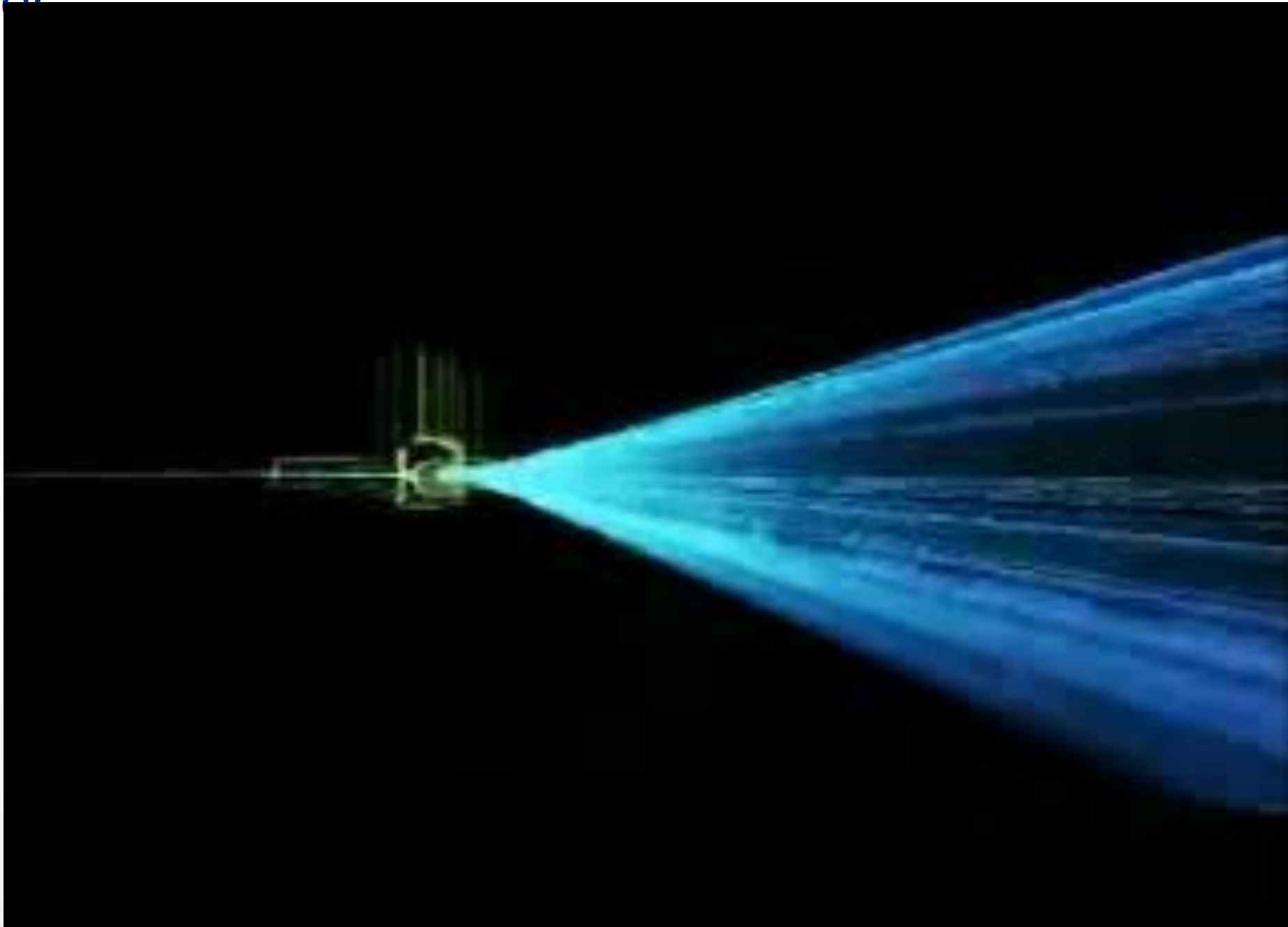
In the centre of the Sun, mass is converted to energy



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# 3 How is antimatter made ?

In particle collisions, **energy** is transformed into **matter and antimatter**



# 3 How is antimatter made ?

**New particles and antiparticles are produced in collisions**



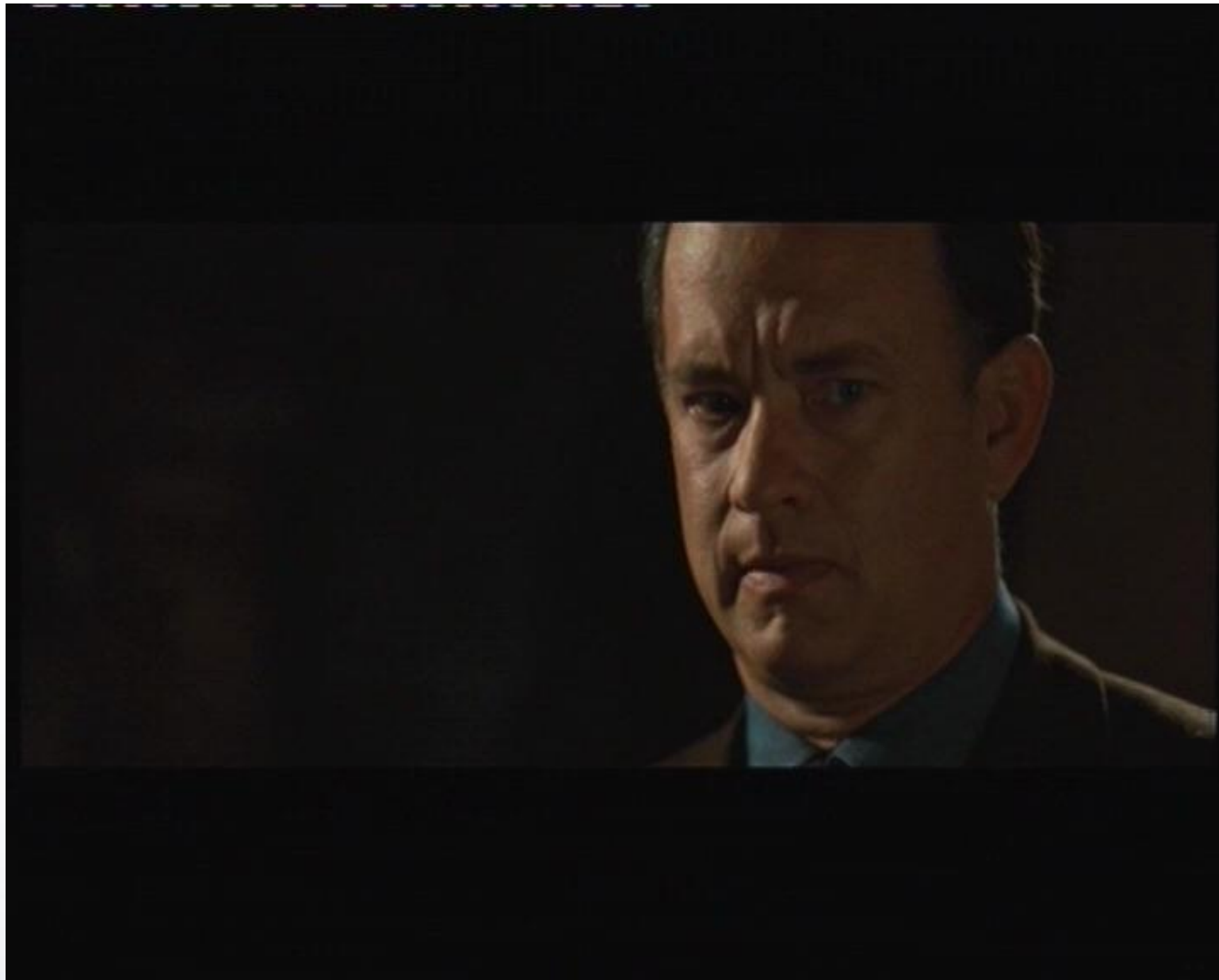
# 4 The mystery of antimatter



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## 4 The mystery of antimatter



**Tom Hanks explains the research at CERN**

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# 4 The mystery of antimatter

## Antimatter and ...

God particle ?? No.

Implications for energy research ? Hmmm.

Combustible substance ? May be.

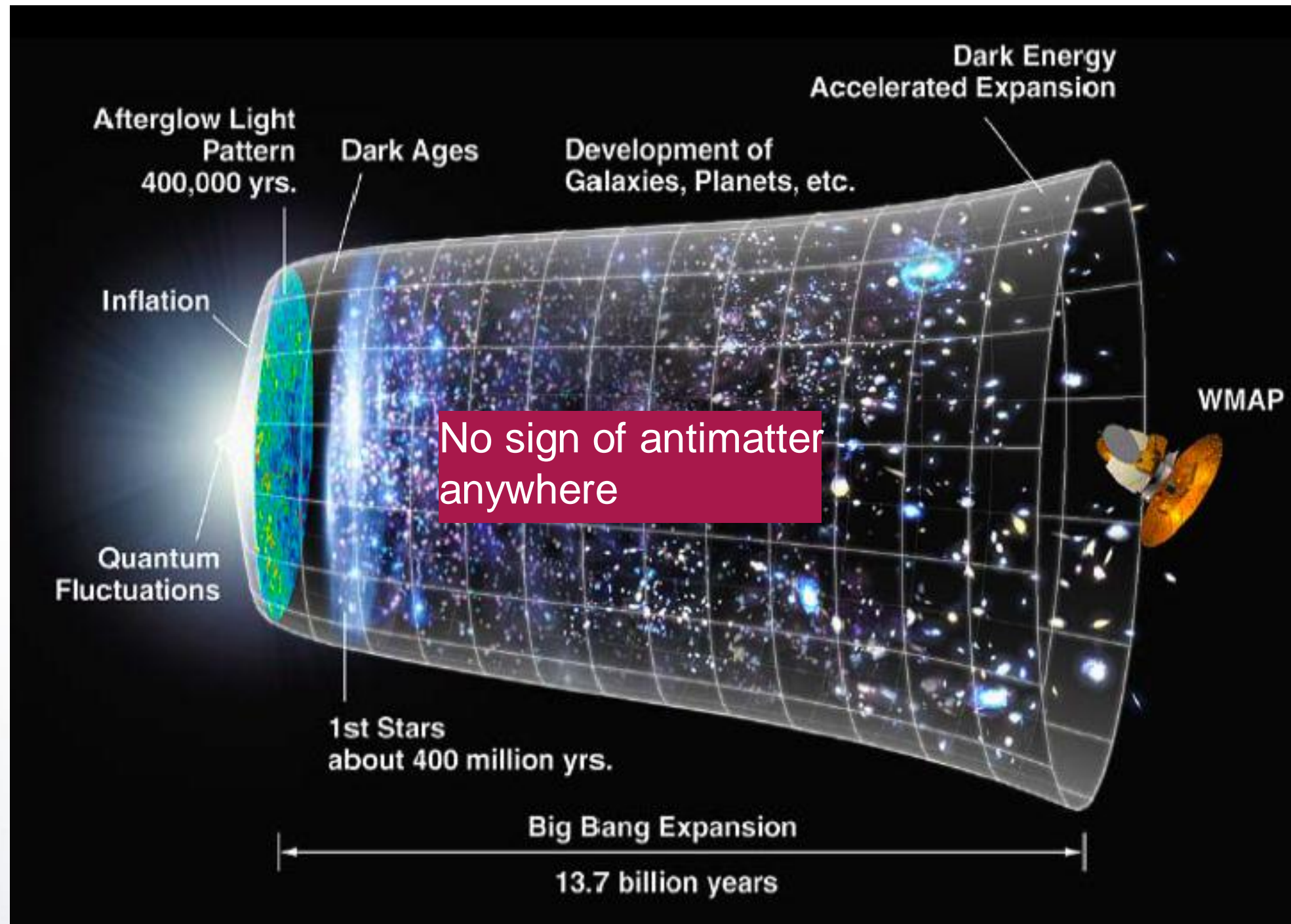
**An airtight nanocomposite container with magnets ....**

**The moment of creation ...**

# From the Big Bang to Today



# 4 The mystery of antimatter



## Big Bang model: the evolution of the Universe

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## 4 The mystery of antimatter

Where has the antimatter gone  
?

Solar System ? No !

## 4 The mystery of antimatter

Where has the antimatter gone

?

In galaxies far, far away ? No.

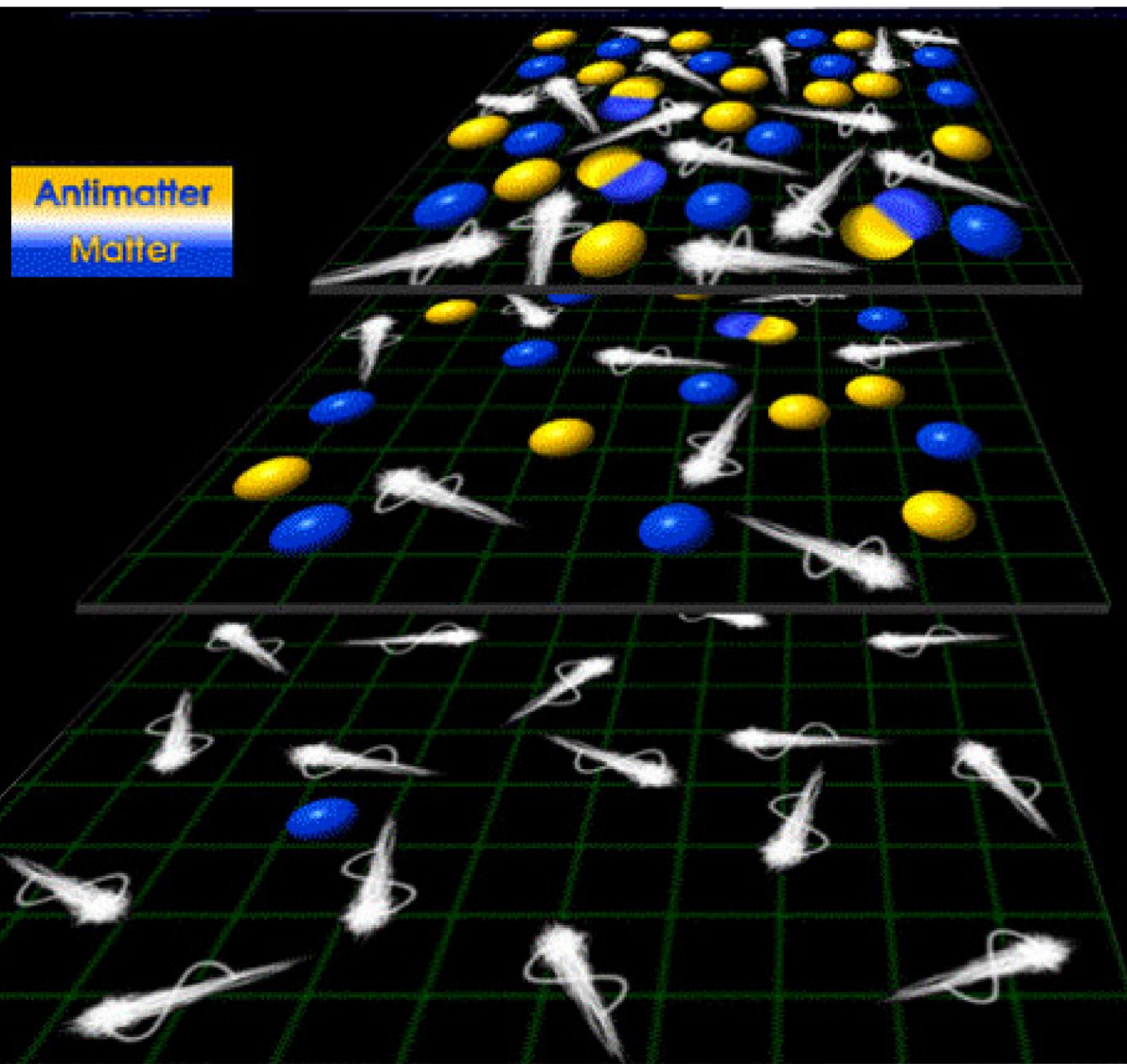
There seems to be no antimatter in the Universe  
!

## 4 The mystery of antimatter

**No antimatter in the Universe ?**

**Why not ???**

# 4 The mystery of antimatter



## Cosmic CSI

### Big Bang:

Energy transforms to mass

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

### Annihilation battle

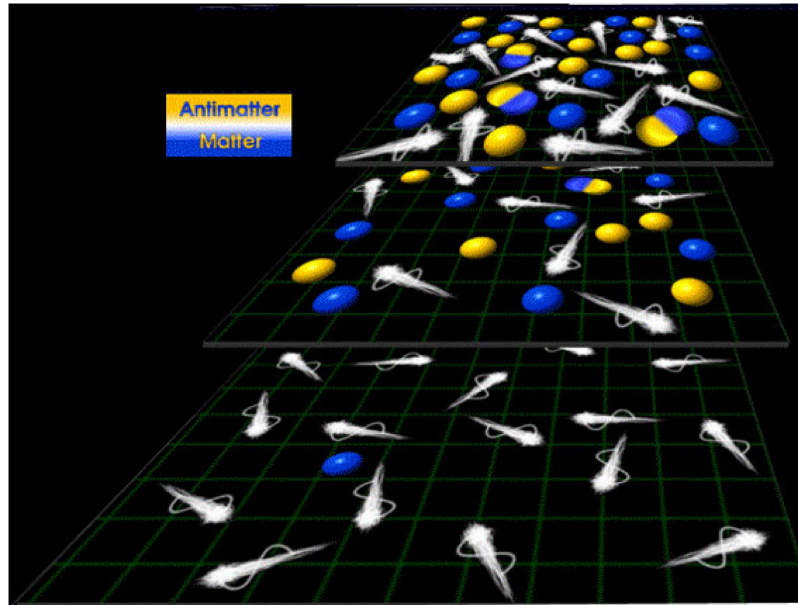
1 s: all antimatter has disappeared,

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

**Universe filled with light  
(cosmic microwave  
backg.)**



# 4 The mystery of antimatter



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

**Matter and antimatter: (slightly) different properties?**

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

CP violation (CERN: LHCb experiment)

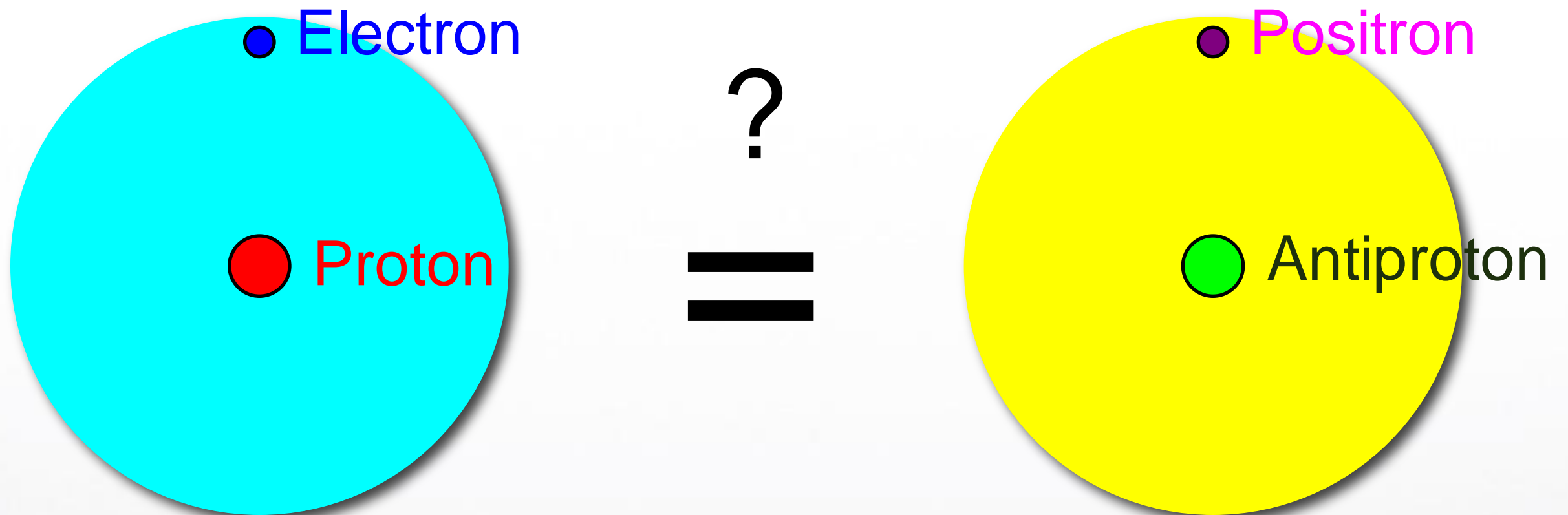
# 5 How to study antimatter ?

The antihydrogen route

...

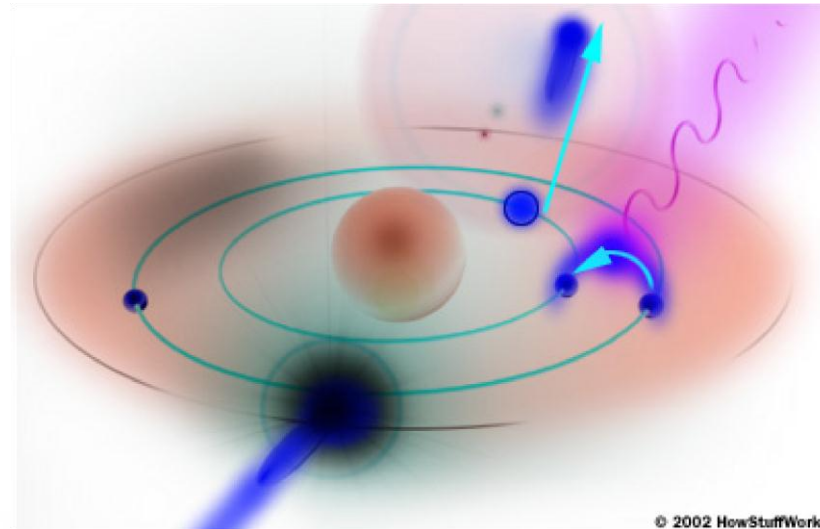
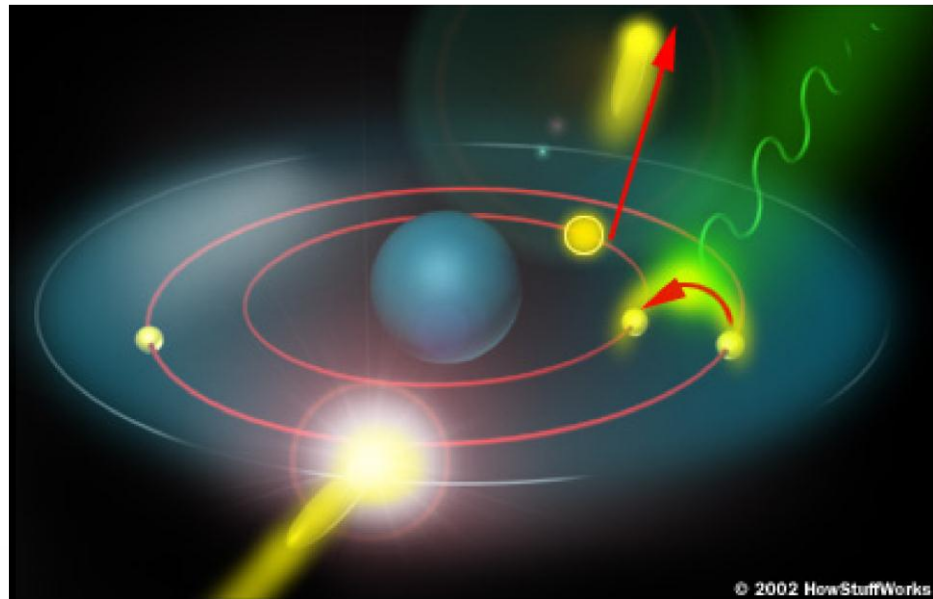
# 5 How to study antimatter ?

Compare hydrogen with **antihydrogen** atom

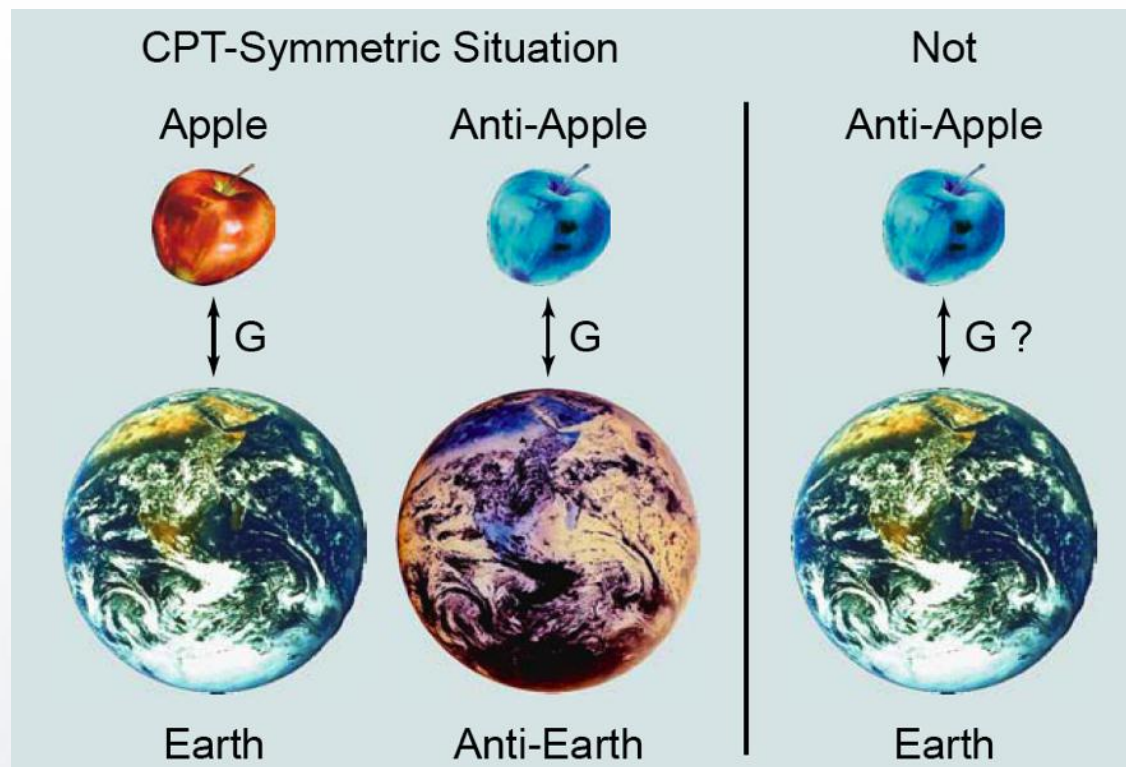


Measure differences to a precision of  
**0.000 000 000 000 001 %**

# 5 How to study antimatter ?



**Same energy levels ?**



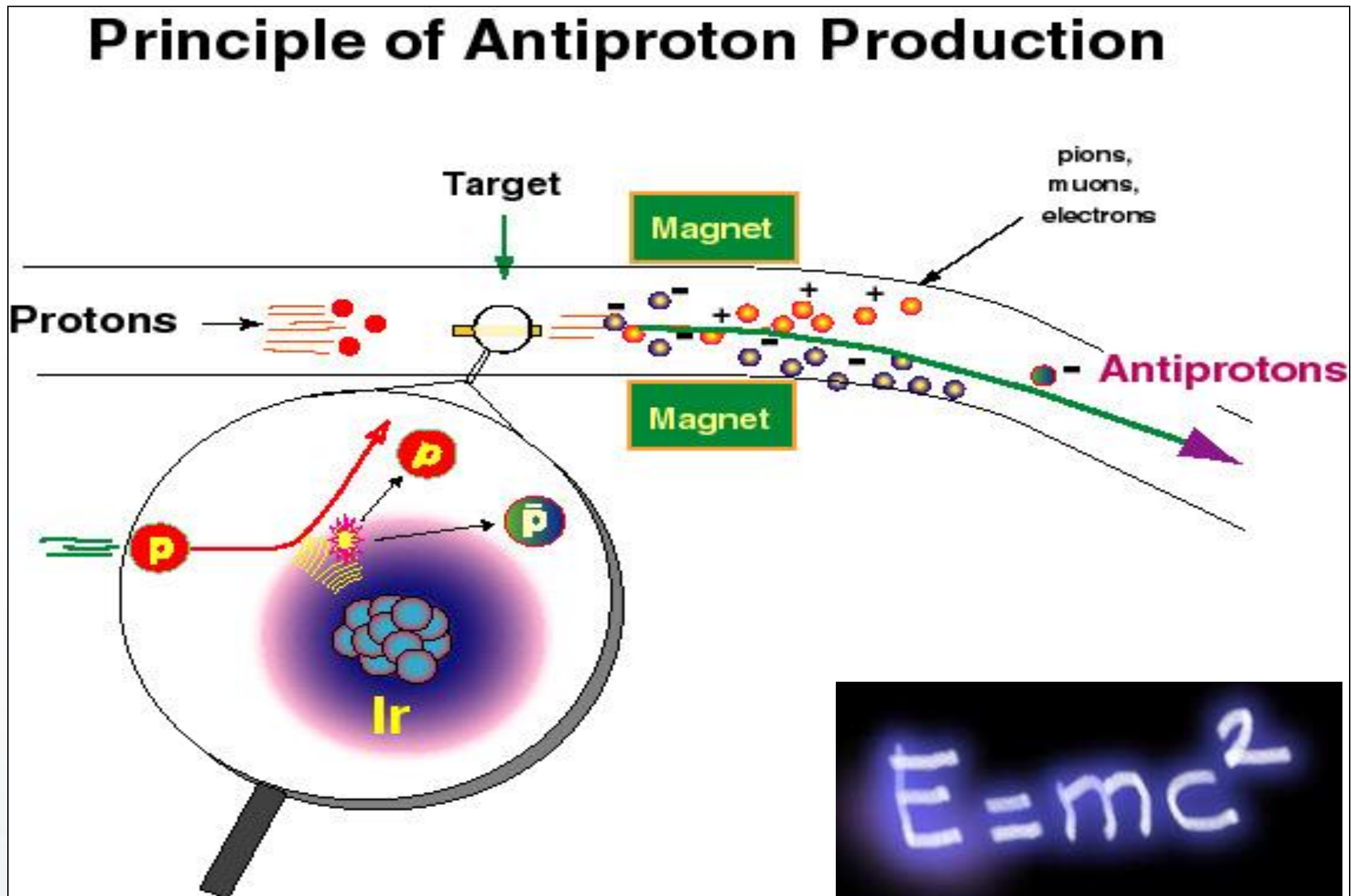
**Same gravity ?**

# 5 How to study antimatter ?

## **How to make millions of antihydrogen atoms (ATHENA, 2002)**

- 1 - Produce, decelerate, and trap antiprotons
- 2 - Produce and trap positrons
- 3 - Merge antiproton and positron plasmas
- 4 - Produce antihydrogen atoms (recently: trap antihydrogen)

# 5 How to study antimatter ?



Antiprotons are made in collisions of protons with nuclei

# 5 How to study antimatter ?



## Antiproton Decelerator

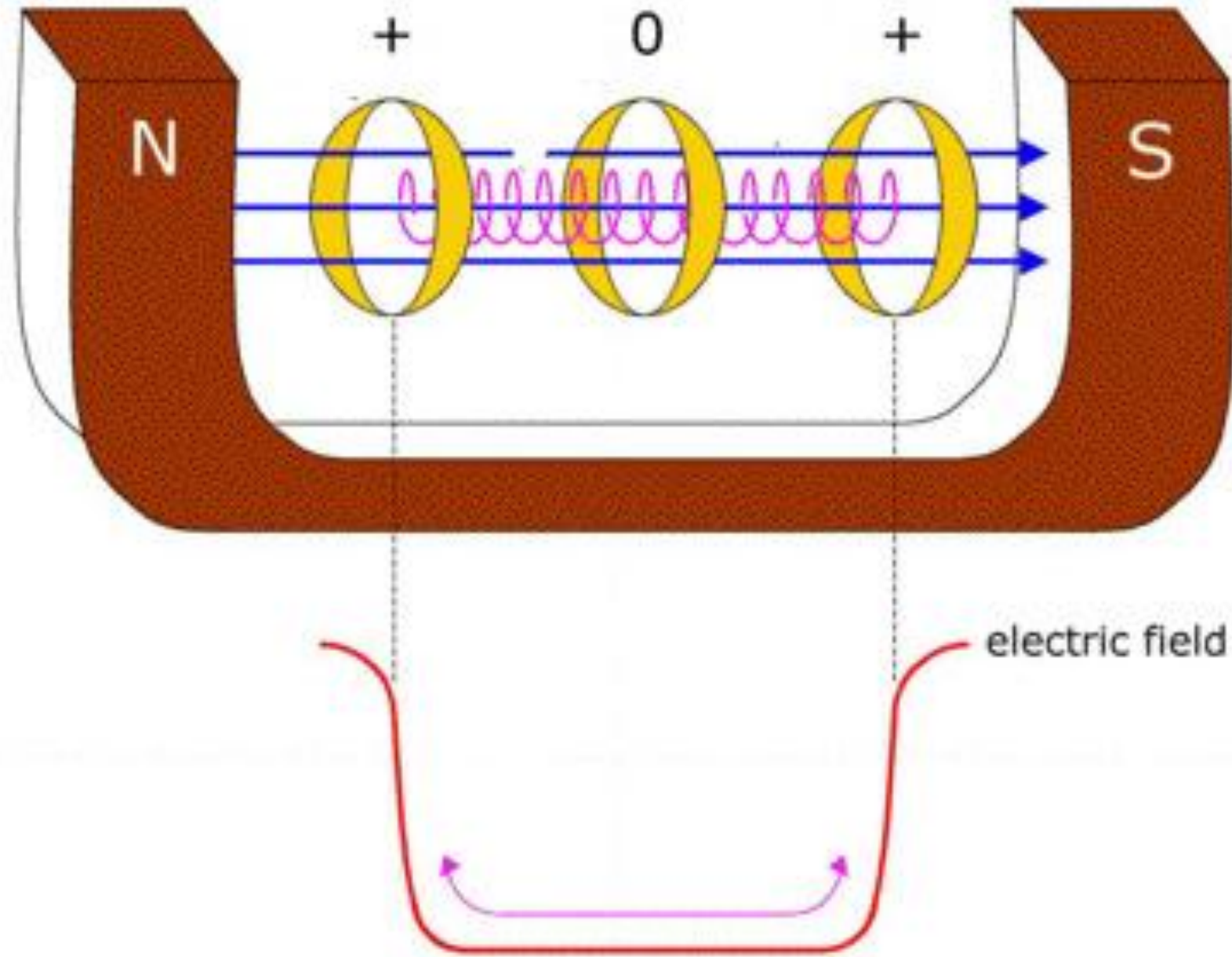
produces 100,000,000  
antiprotons per minute

Slows them down to 10  
% of the speed of light

# Antiproton Decelerator at CERN

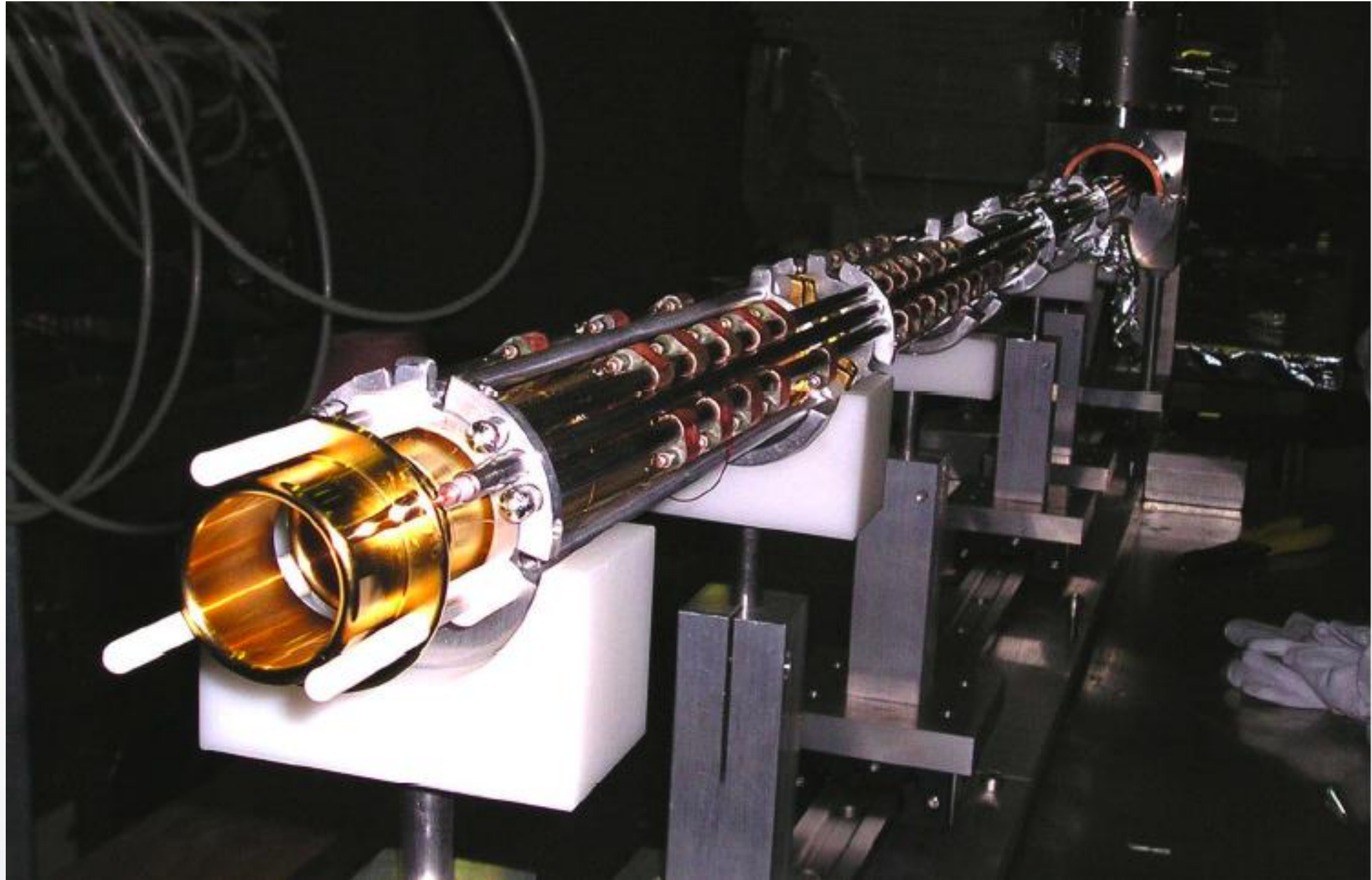


# 5 How to study antimatter ?



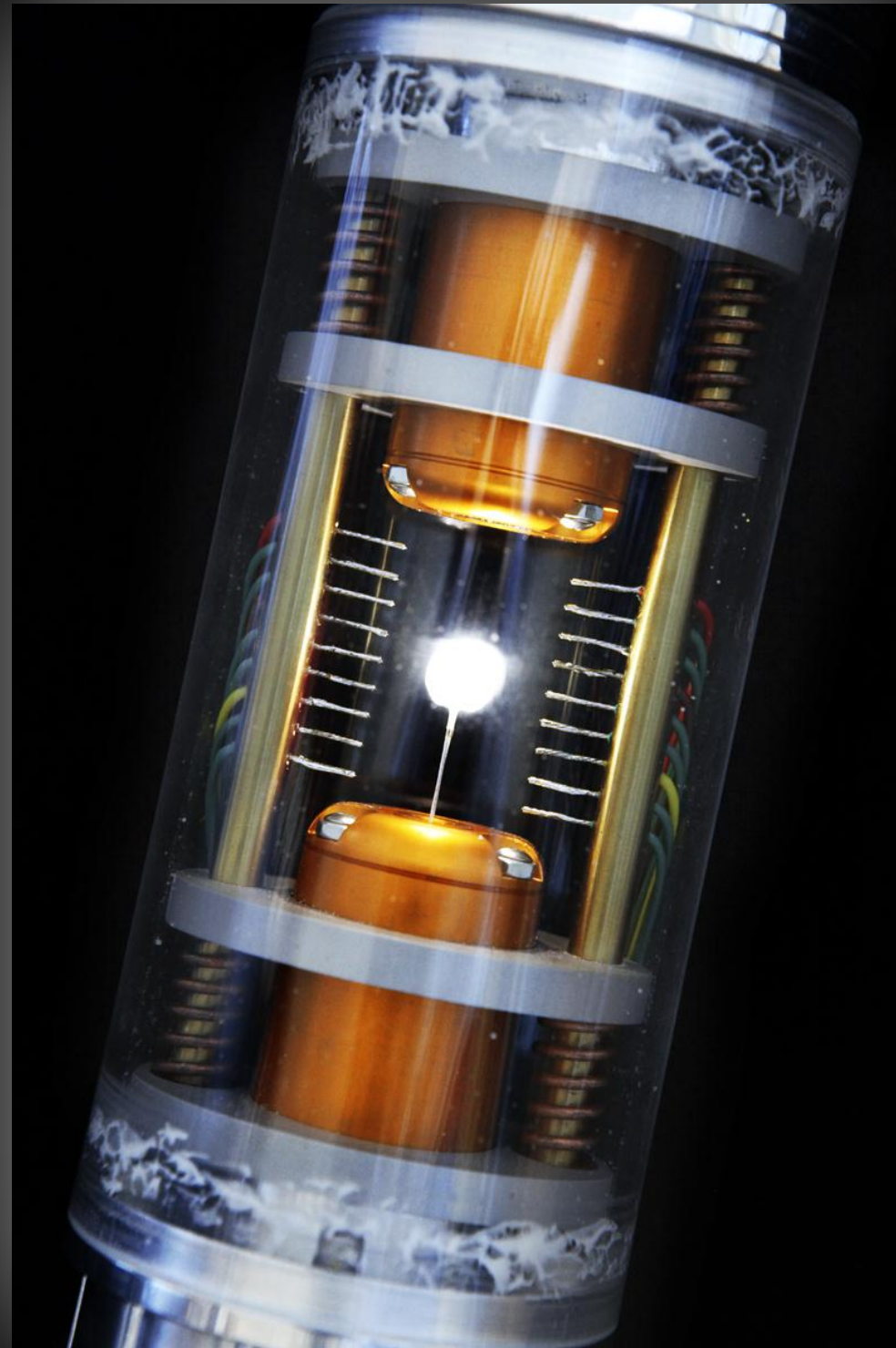
## Principle of antiparticle trapping

## 5 How to study antimatter ?



**The real antimatter trap at CERN**

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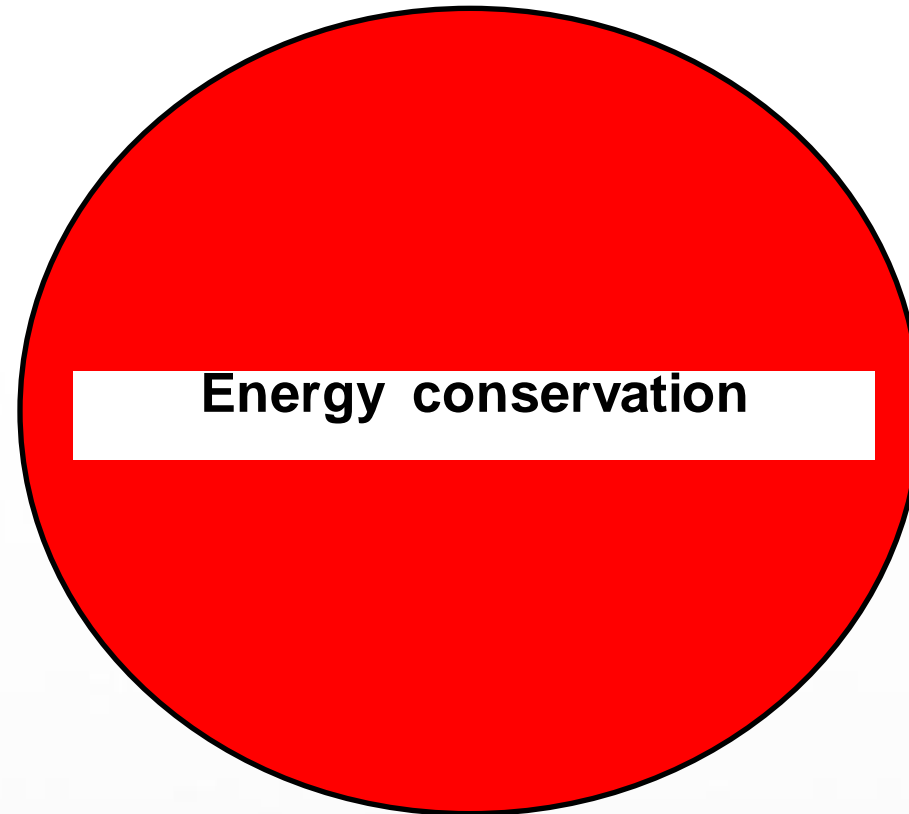


**The “Angels & Demons” version**

# 6 An energy source? A bomb?

# 6 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”**

# 6 An energy source? A bomb?



Hiroshima - 20 kt TNT equivalent

Dan Brown:

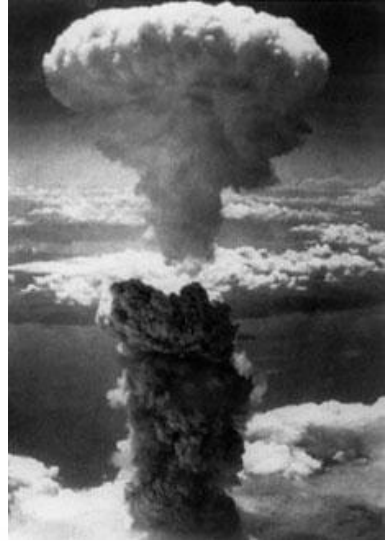
**“0.5 g antimatter makes a powerful bomb”**

$$E=mc^2$$

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

**So this is correct, but ....**

# 6 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**



# 7 Antimatter in daily life ?

# 7 Antimatter in daily life ?

## Antimatter in your body !

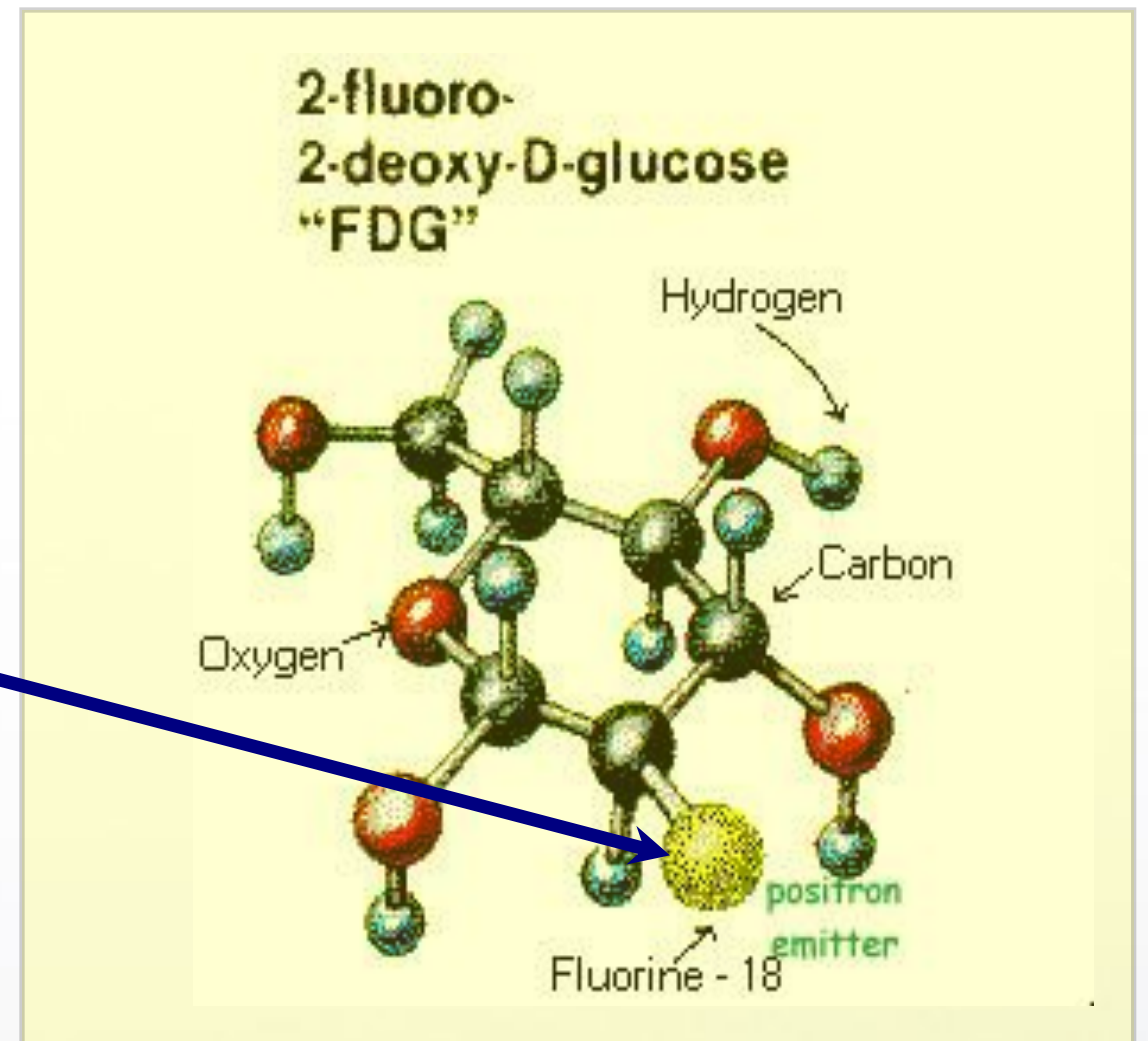
Glucose supplies energy

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

Inject into blood stream

Glucose accumulates where energy is needed

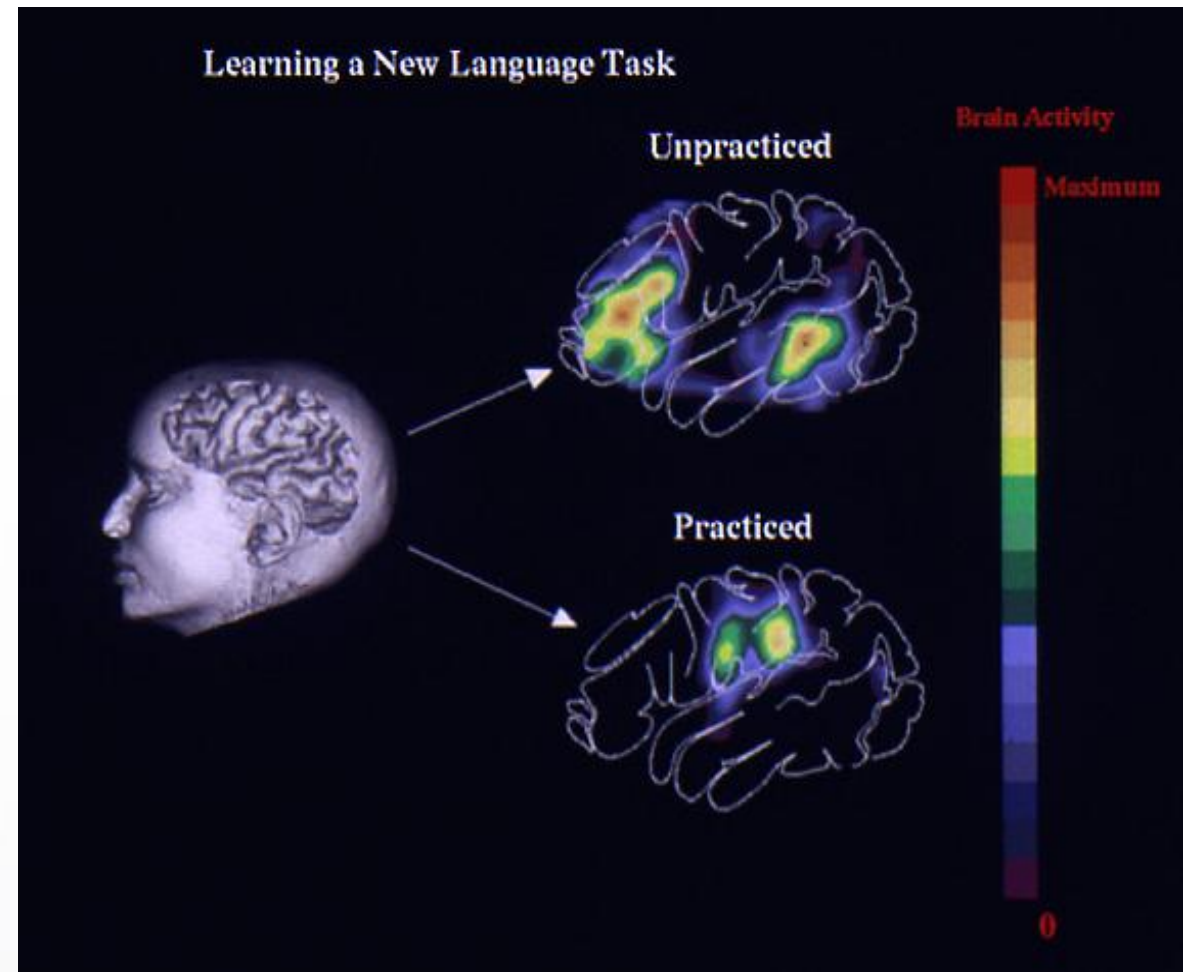
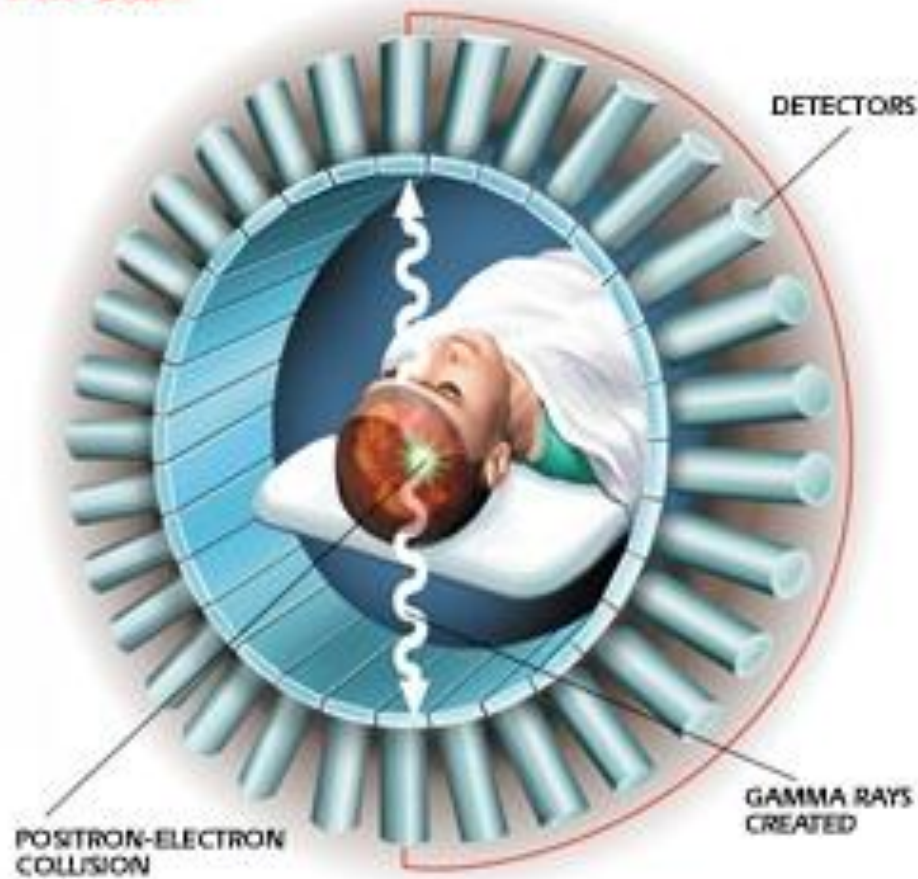
Positron emission and annihilation - detect where glucose is !



# 7 Antimatter in daily life ?

## Positron Emission Tomography (“PET Scan”)

PET Scan



**Antimatter helps**

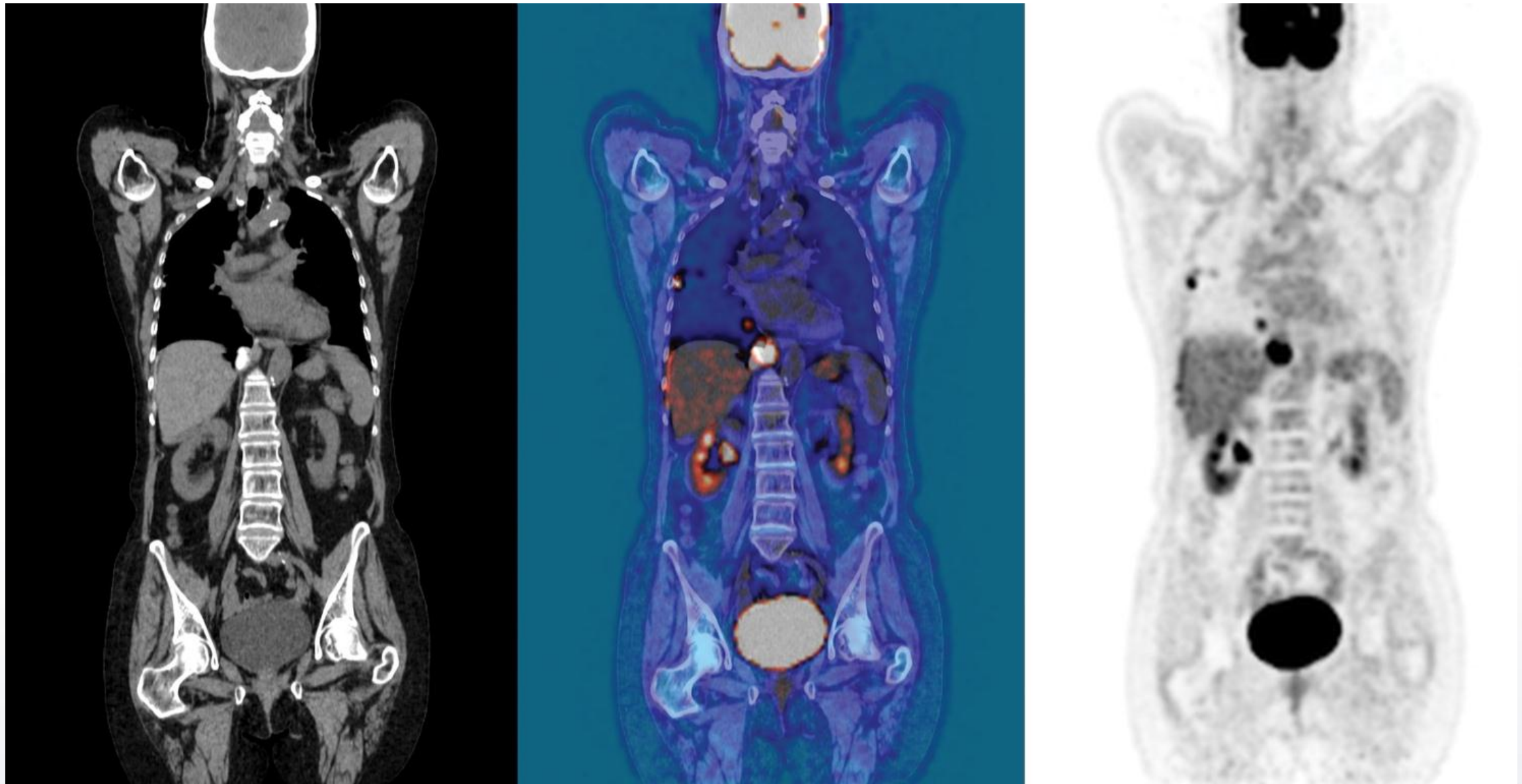
**- to understand how the brain works**

**- to find tumours**

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# 7 Antimatter in daily life ?

## Positron Emission Tomography (“PET Scan”)



**Antimatter helps to find  
tumours**

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Movie

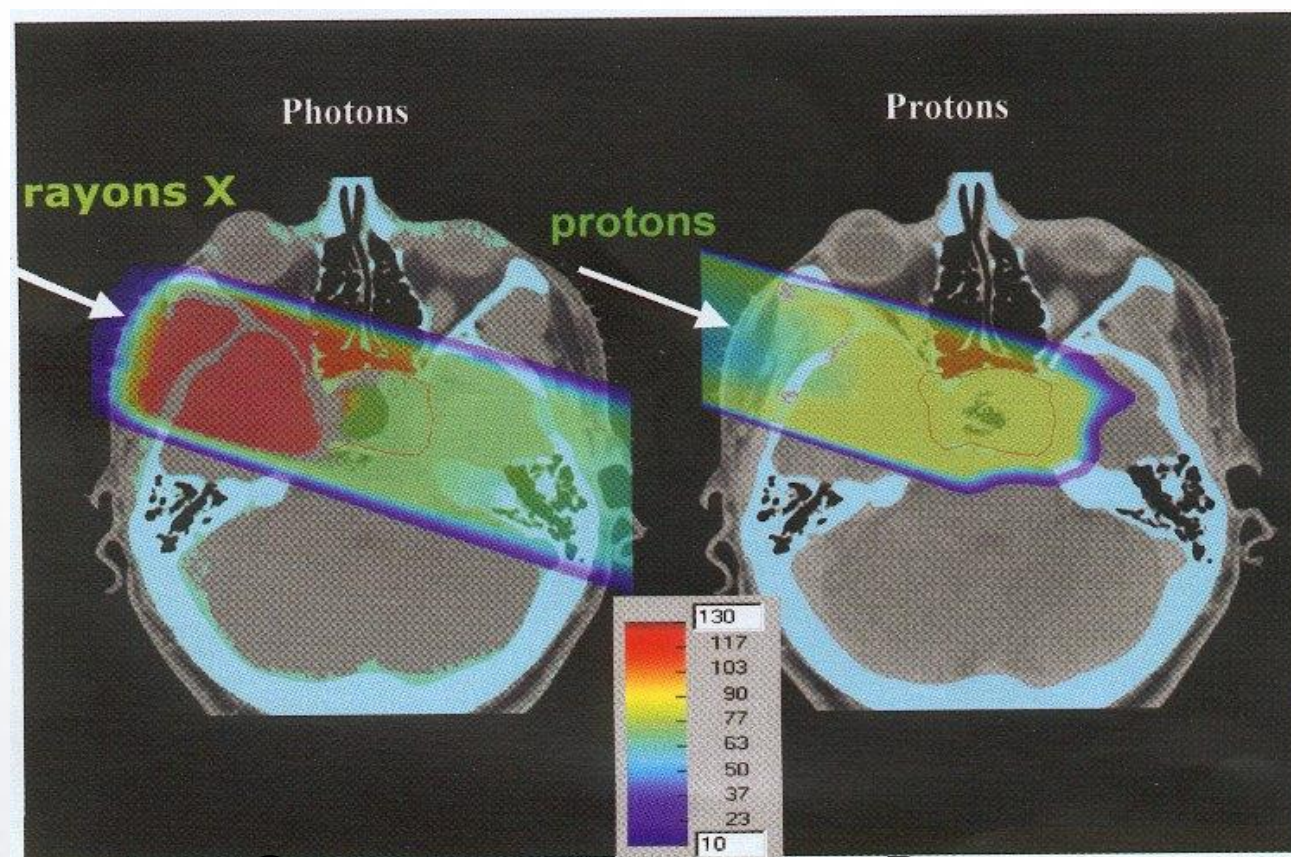
# 7 Antimatter in daily life ?

## Tumour therapy with antiprotons ?

Gamma radiation destroys many healthy cells

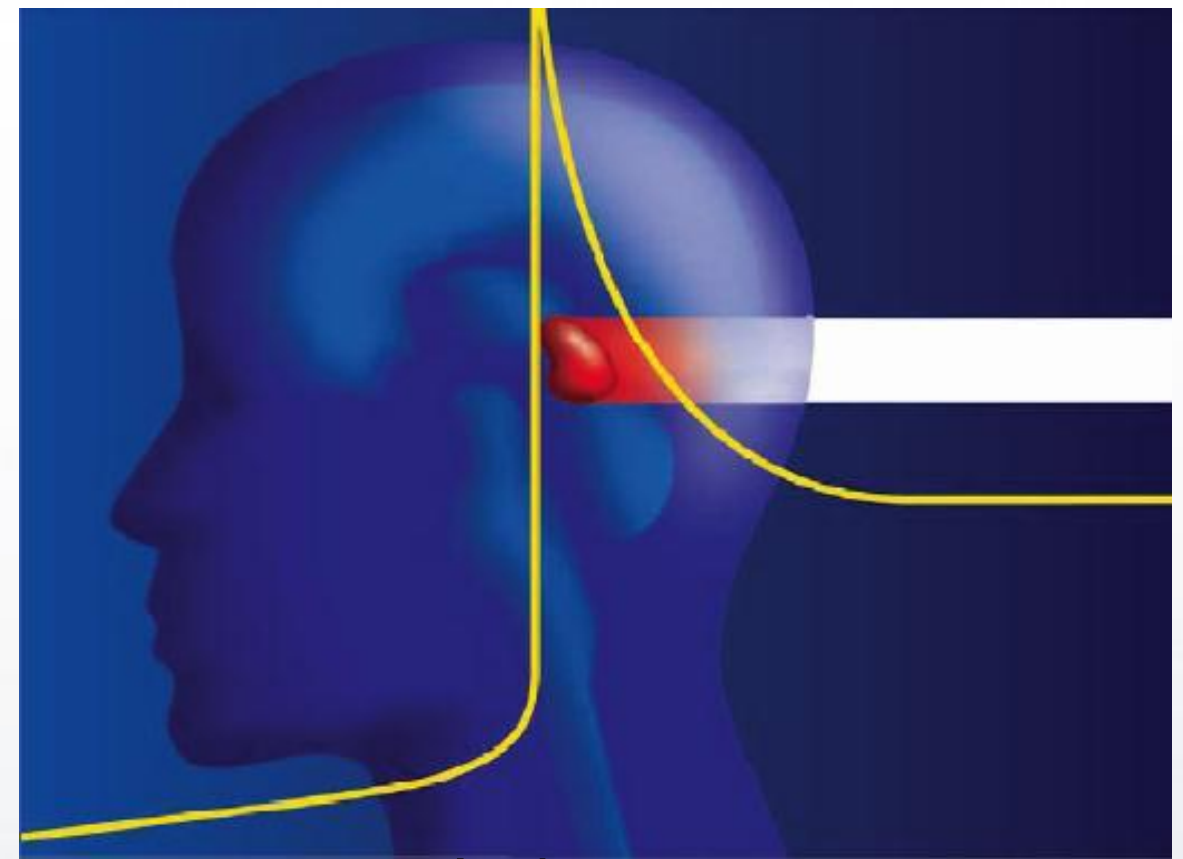
Protons deliver radiation more specifically to tumour cells

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



Gamma radiation

Protons

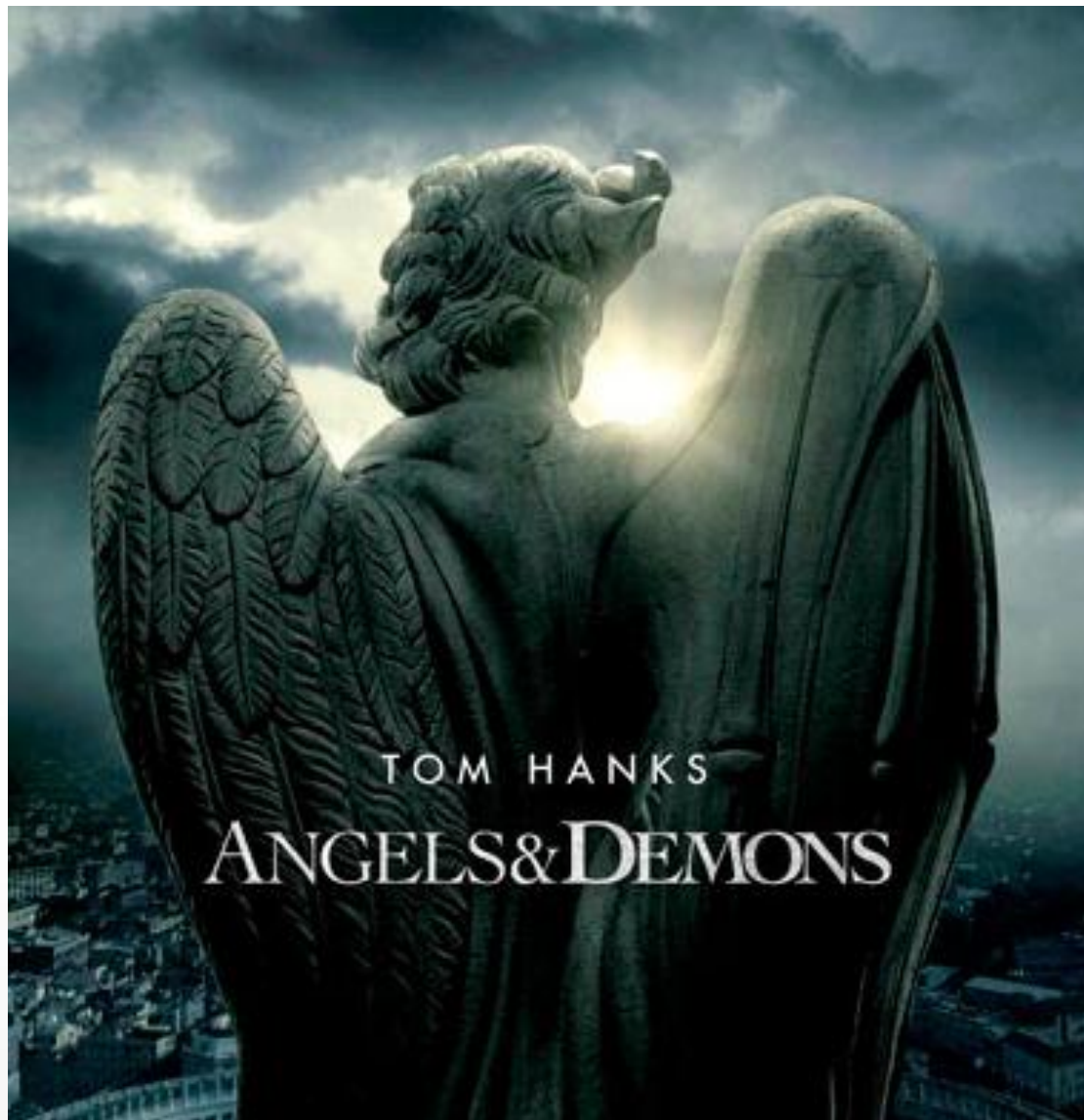


Antiprotons

# What did Ron Howard say ?



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Movie



# Angels&Demons

The Physics Behind the  
Movie

Rolf Landua

CERN

**Thank you for your attention.**

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Movie

# Antimatter @ School

## For Teaching

Antimatter Teaching Module

NEW

CERN

Particle Physics

Cosmology

Principles of Experimental Physics

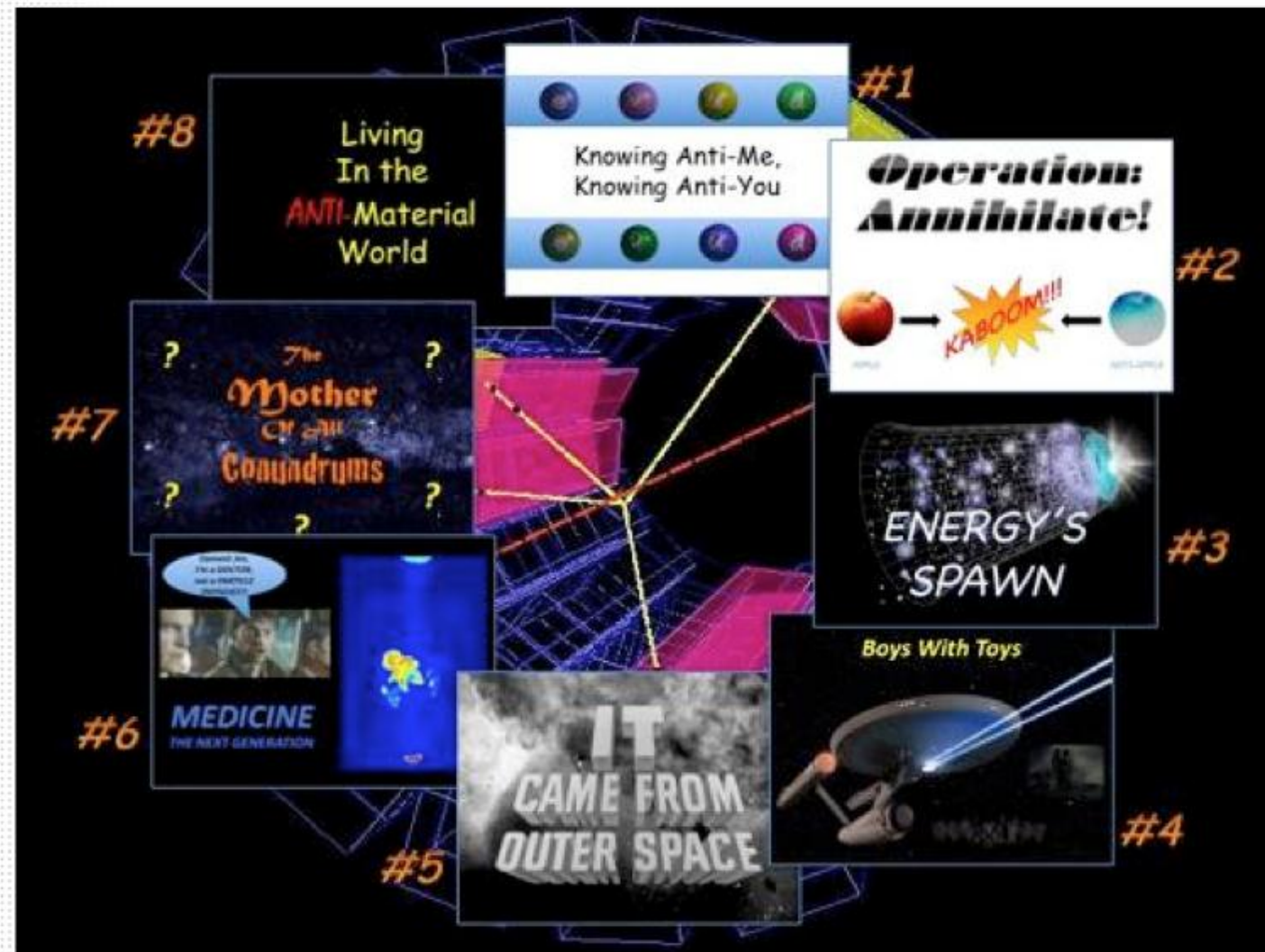
Introduction to Accelerators

Applications of CERN research

Multimedia material

## Teaching Resources - Antimatter Teaching Module

>> Lesson Plans

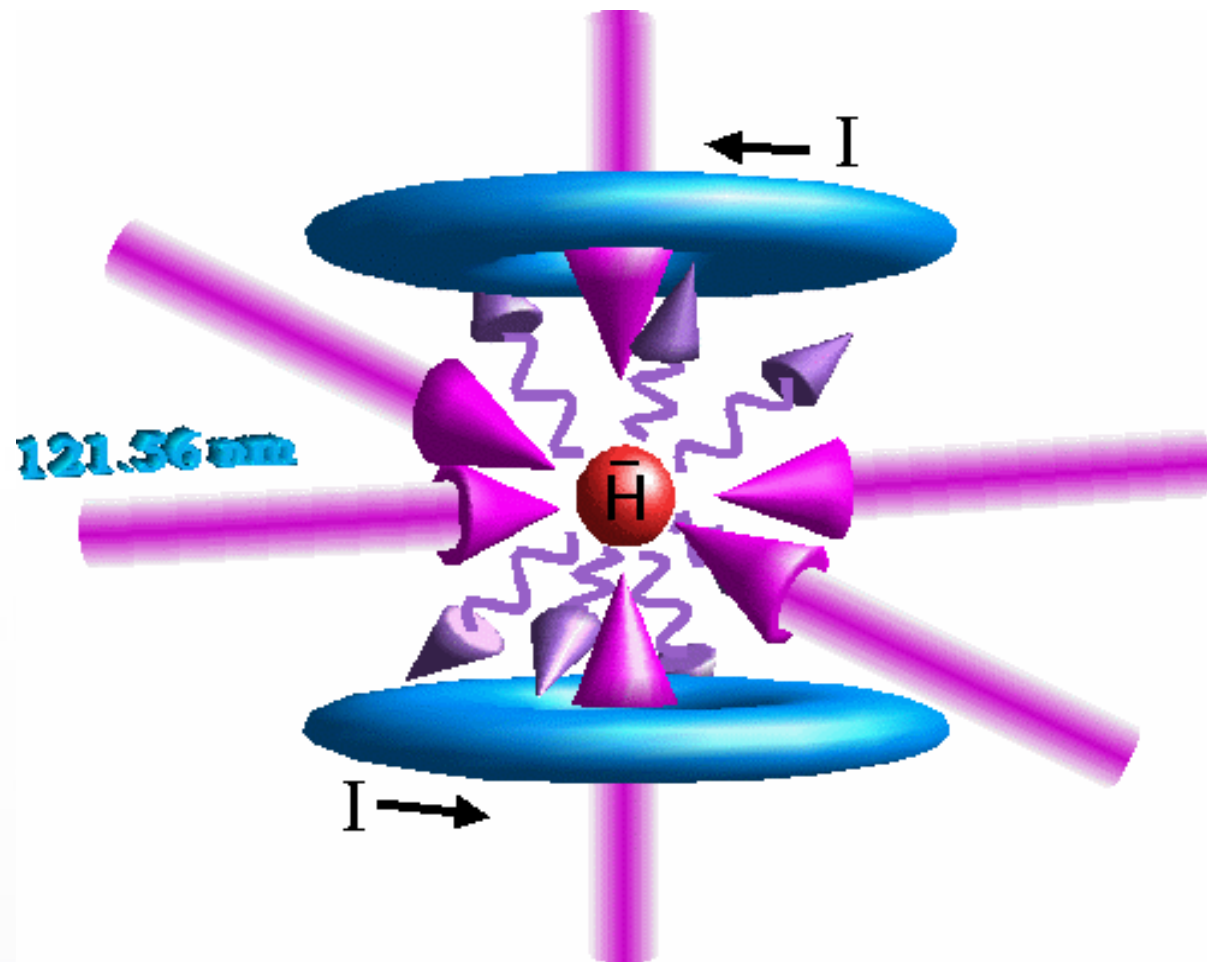
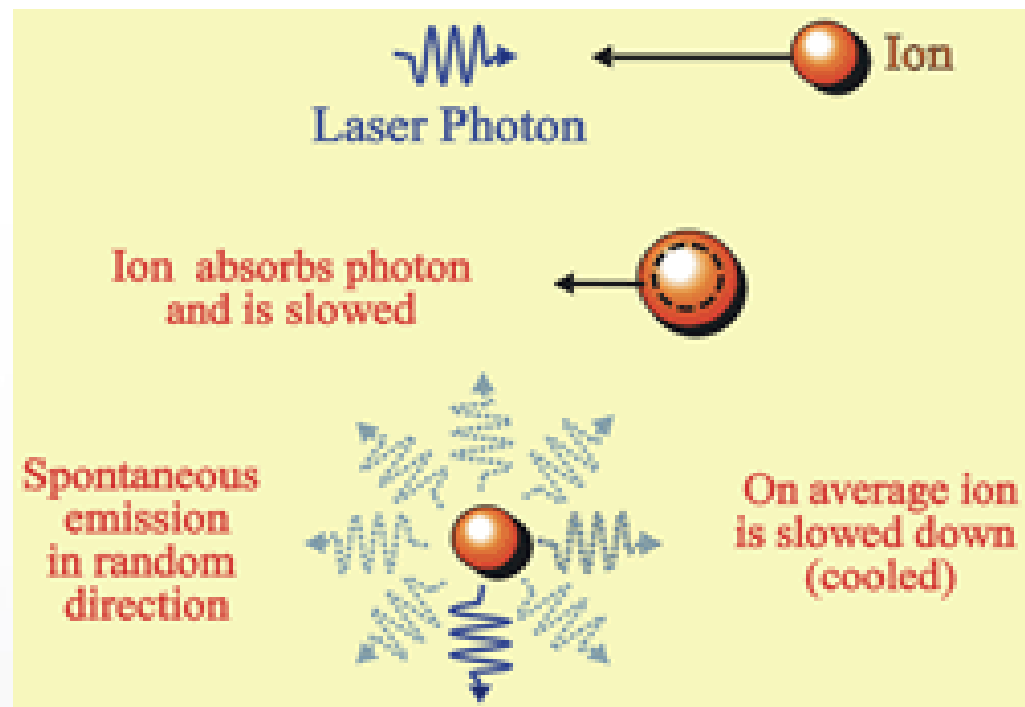


Back to [Antimatter Teaching Module](#)

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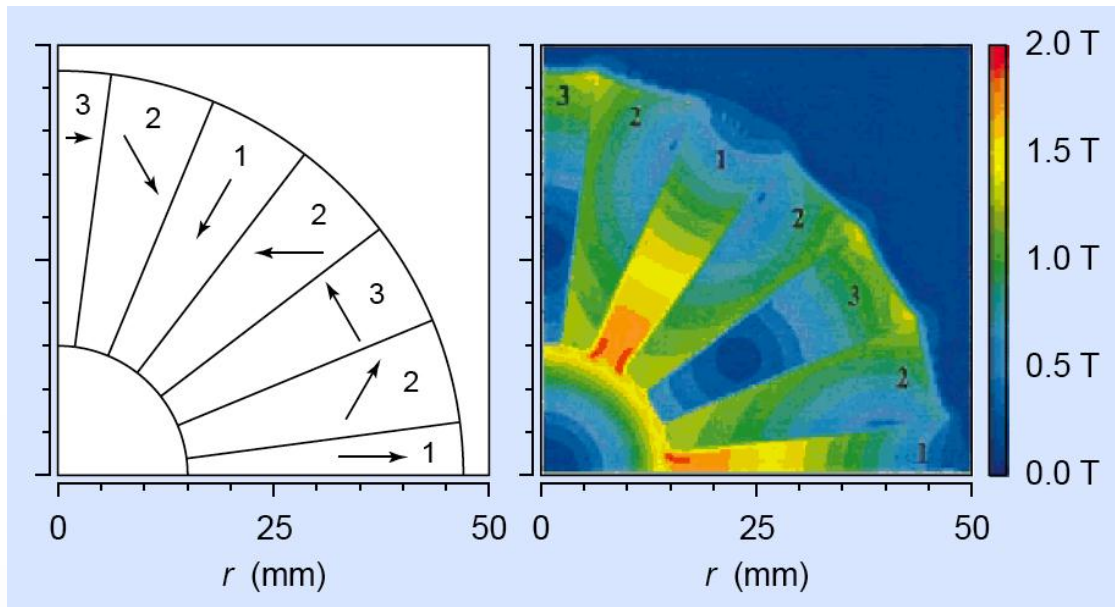


# Laser cooling



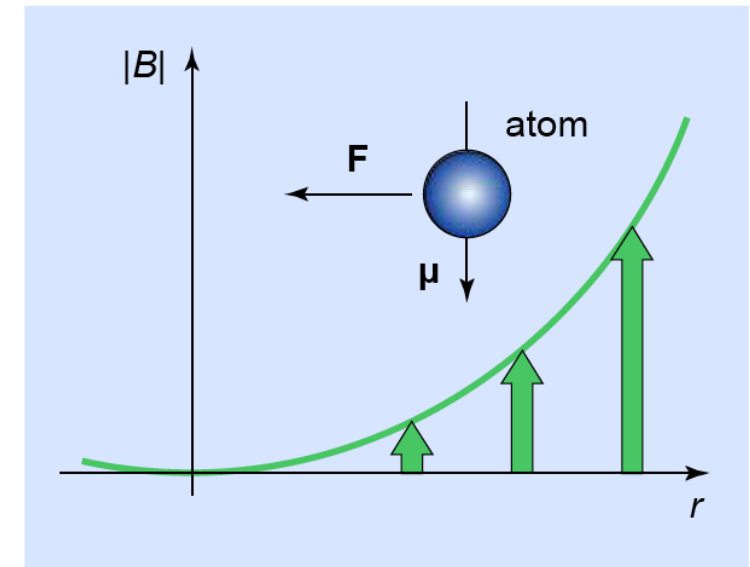
121 nm laser needed  
Prototype at MPI Munich  
... only 50 nW

# Magnetic multipole traps ?



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

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



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

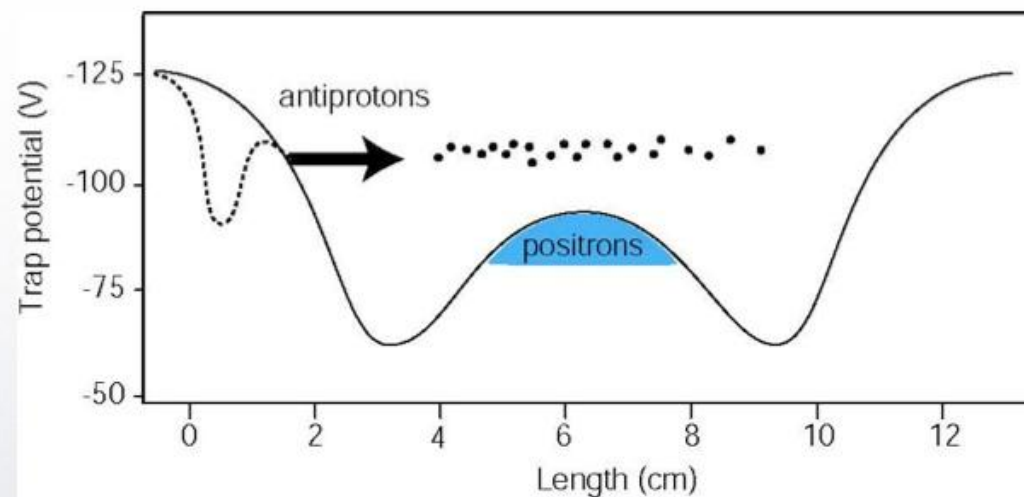
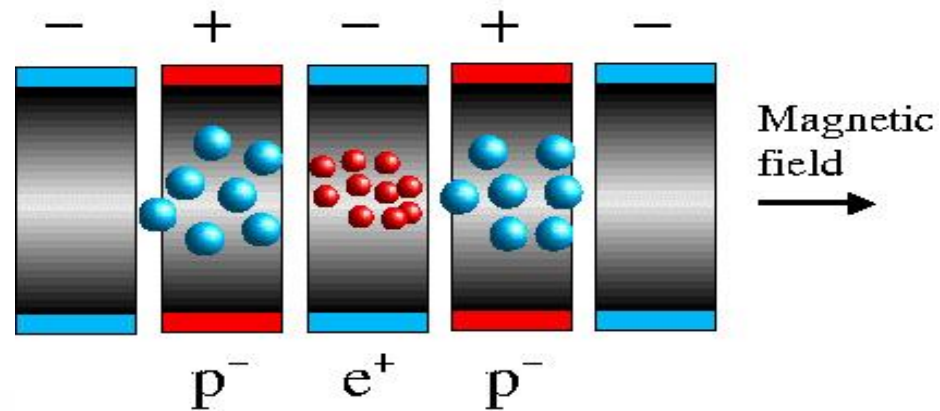
BUT: Very shallow potential ( $\sim 0.07$  meV/T)

Realistic  $\Delta B \sim 0.2-0.3$  T  $\star$   **$E < 0.02$  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)

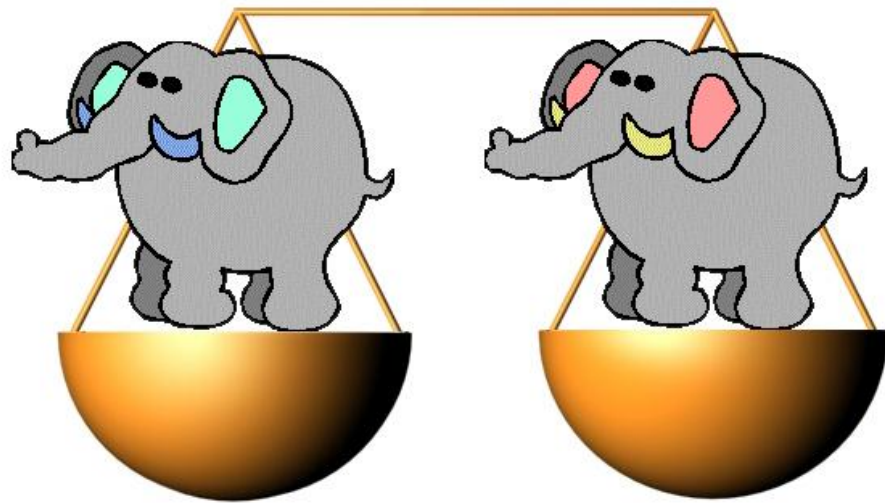
Moderation

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



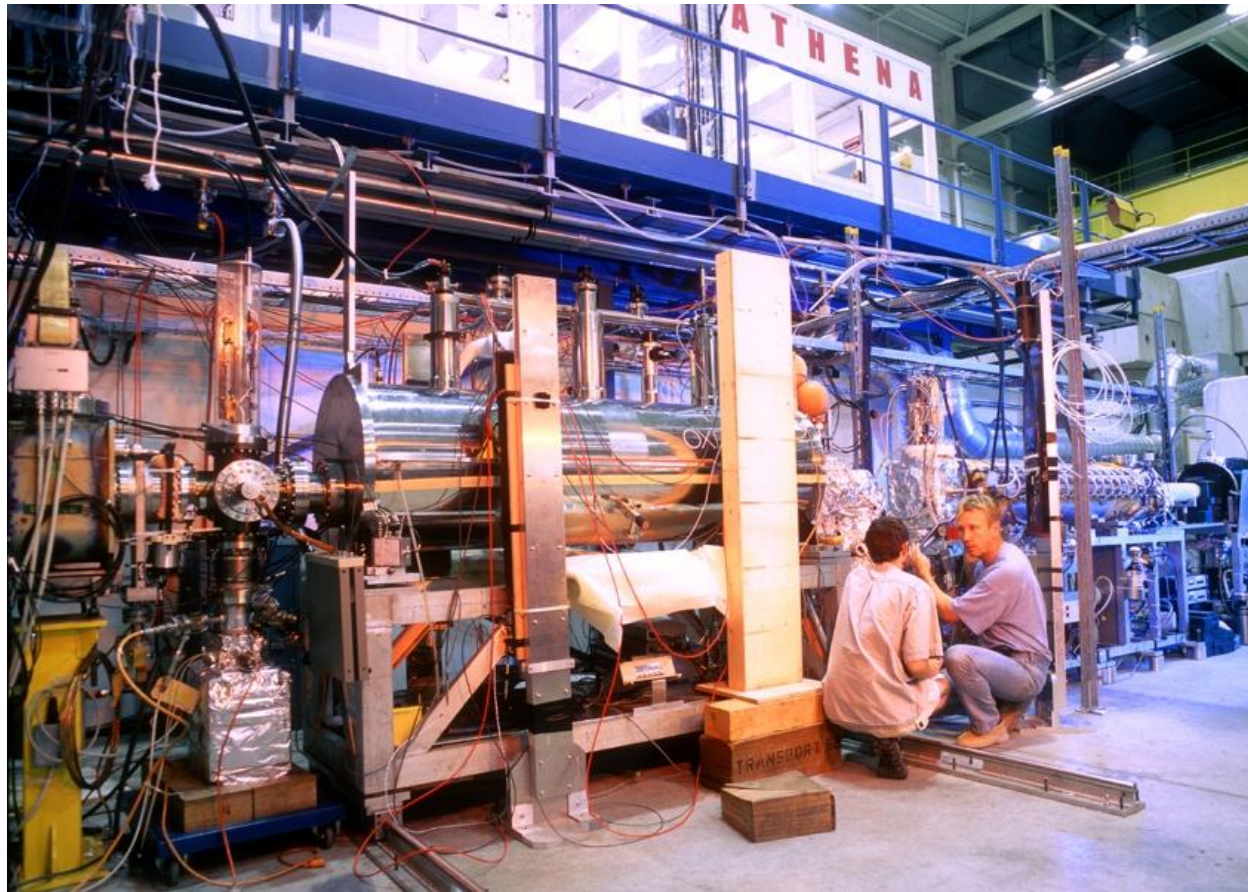
Magnetic moment of electron and positron ?

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

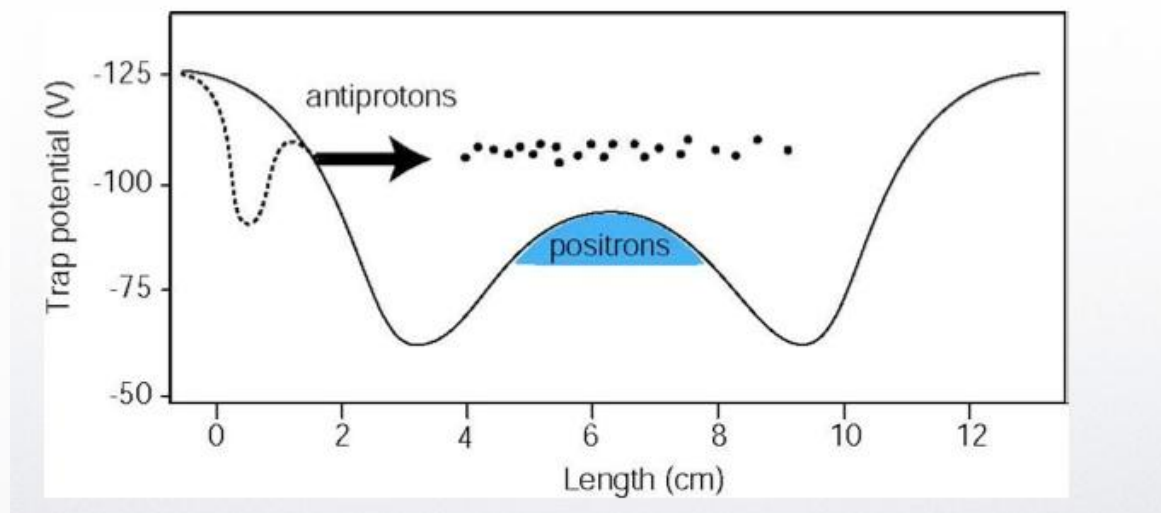
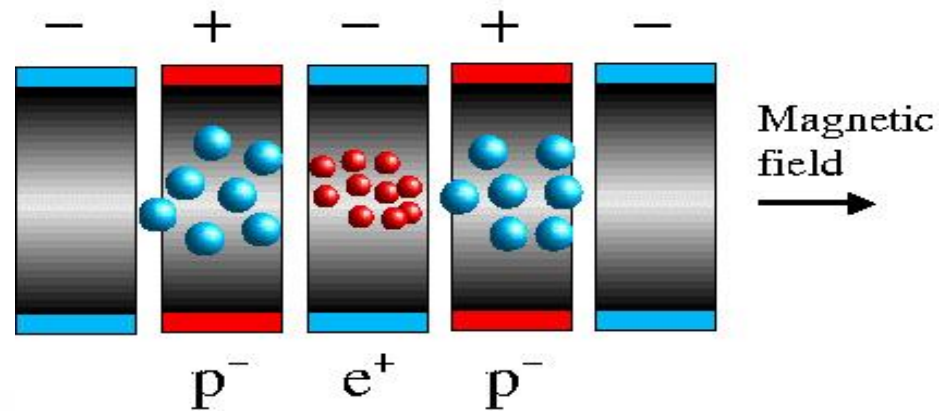


- More than 1 million antihydrogen atoms produced
- Small kinetic energy ( $< 0.01$  eV)
- Next step (in progress): trap antihydrogen atoms

**2002: 'Cold' antihydrogen production by AD experiments\***

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# 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

