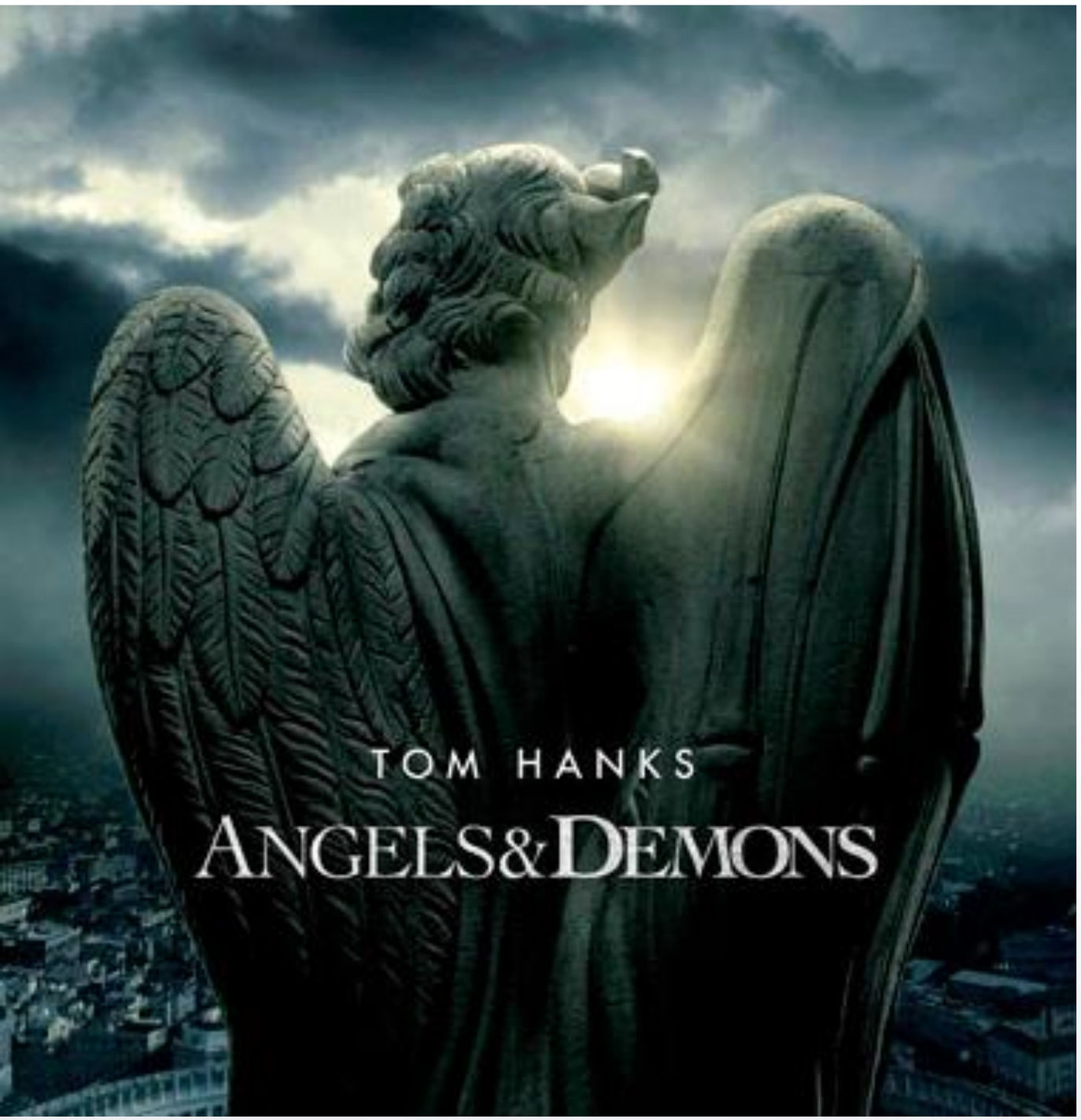


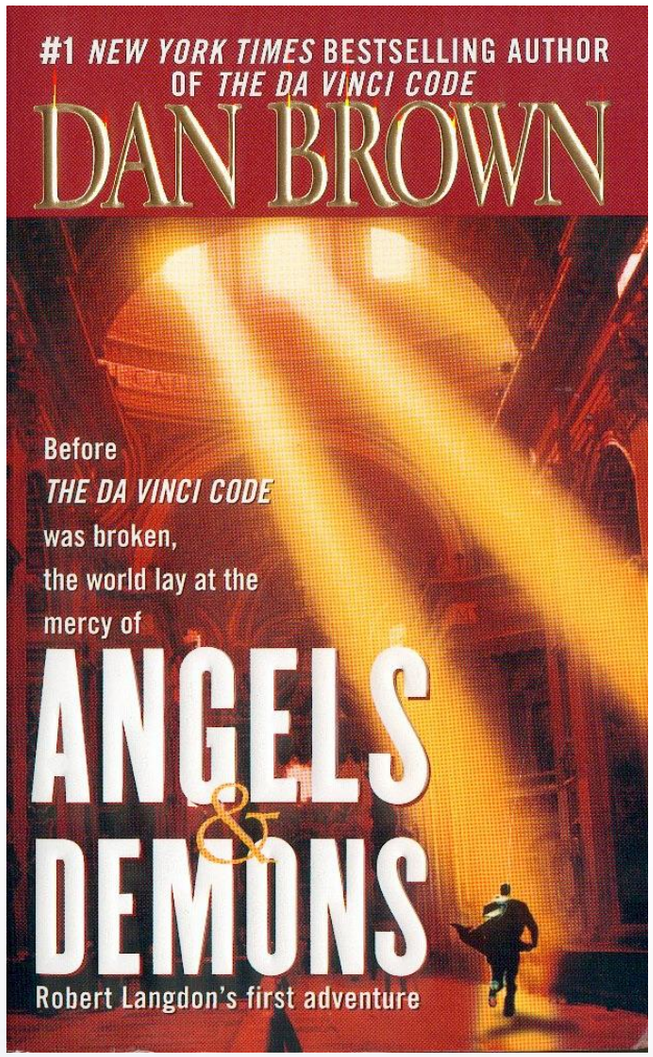
Angels&Demons

The Physics Behind the Movi

Rolf Landua

CERN

Dan Brown's "Angels + Demons"



Illuminati

CERN

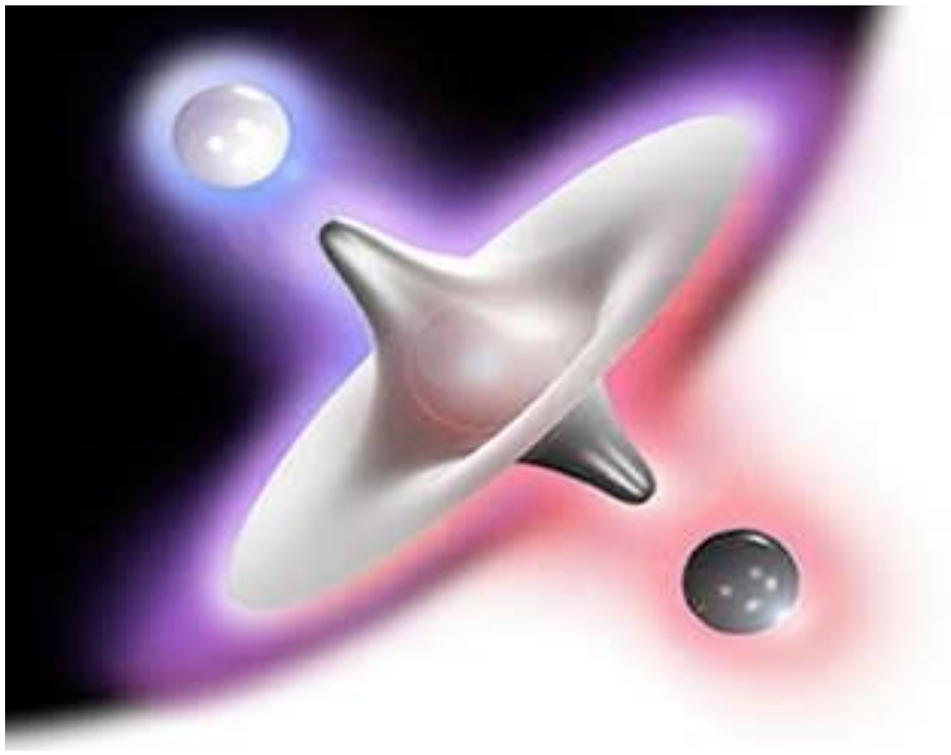
... steal 1 g of antimatter from a physicist at the 'LHC' in a place called "CERN" ...

... 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 Physics behind the Movie

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 ....

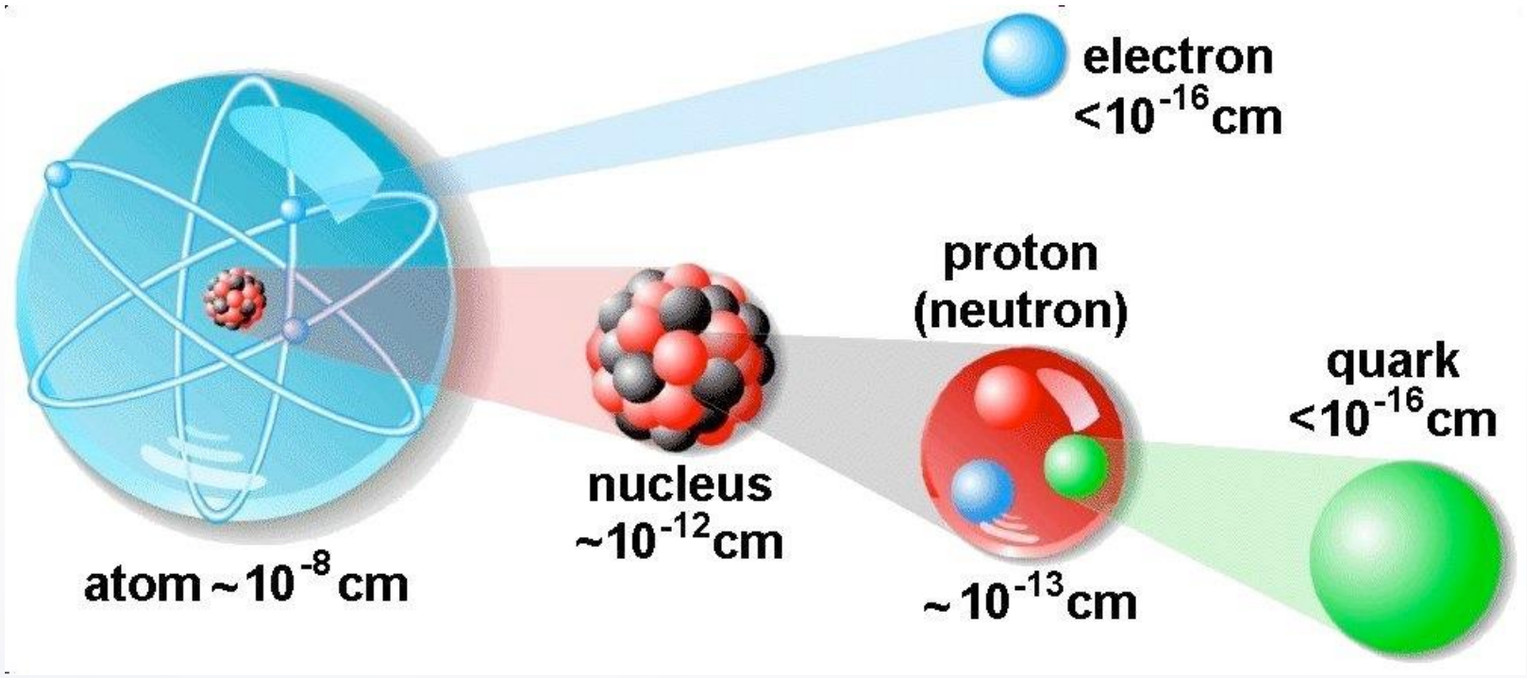
Who wants to be a millionaire ?

1 What is antimatter ?

1 What is antimatter ?

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

Hierarchy of matter



Electrons
Protons
Neutrons
} Quarks

Matter is made of **particles**

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

Angels & Demons - The Physics behind the Movie

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

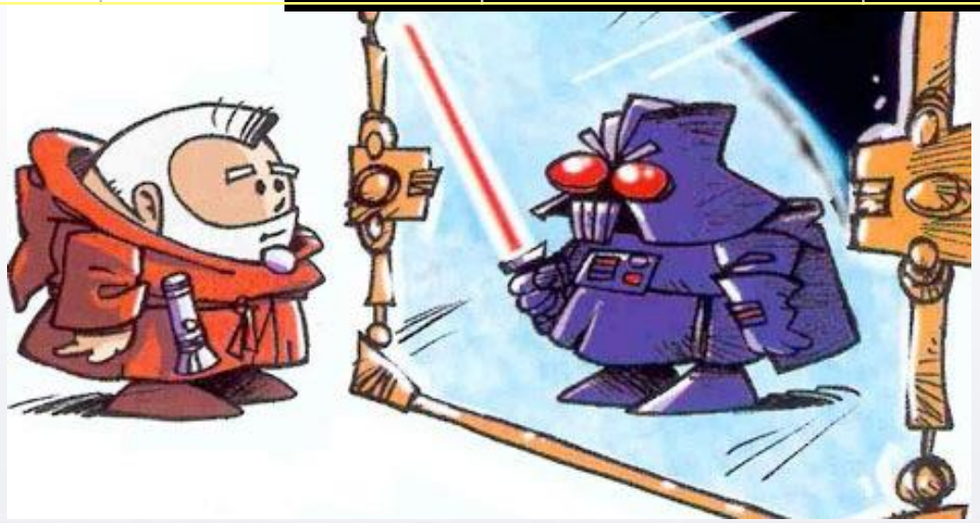
*GeV = Giga-Electron Volt = 1,000,000,000 Electron-Volt = $1.8 \cdot 10^{-27}$ kg

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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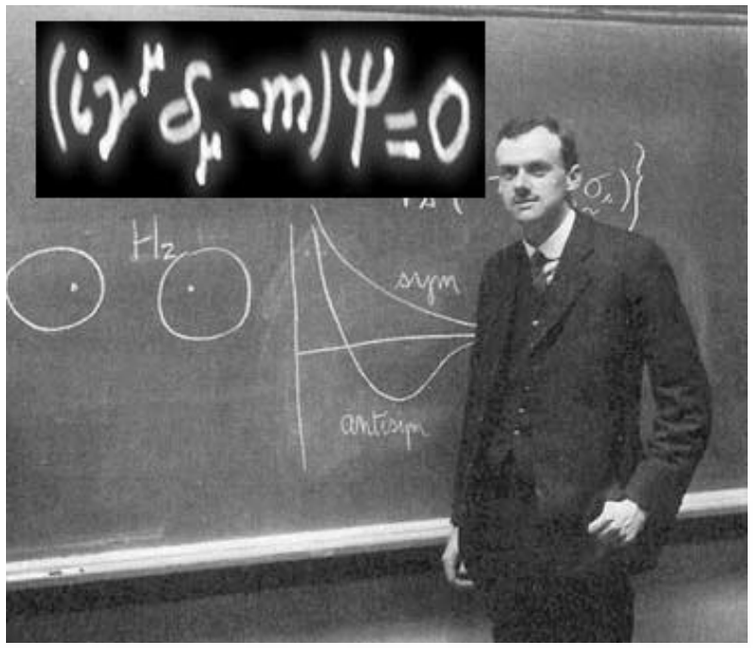
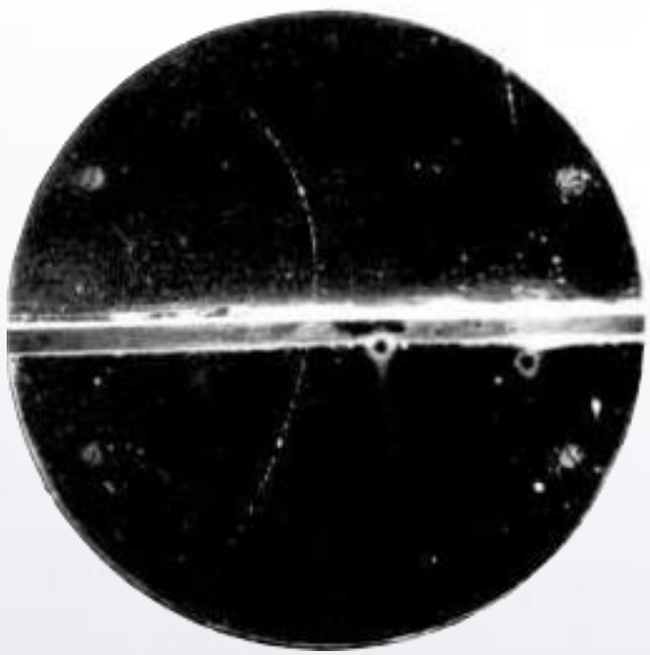
1 What is antimatter ?

Predicted by
Paul Dirac (1928) ...





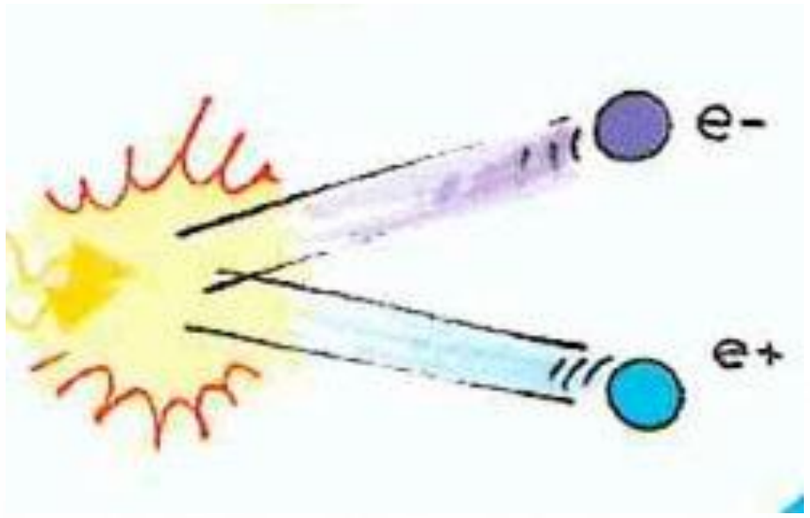
... first antiparticle (positron)
found by Carl Anderson (1932)

Angels & Demons - The Physics behind the Movie

1 What is antimatter ?

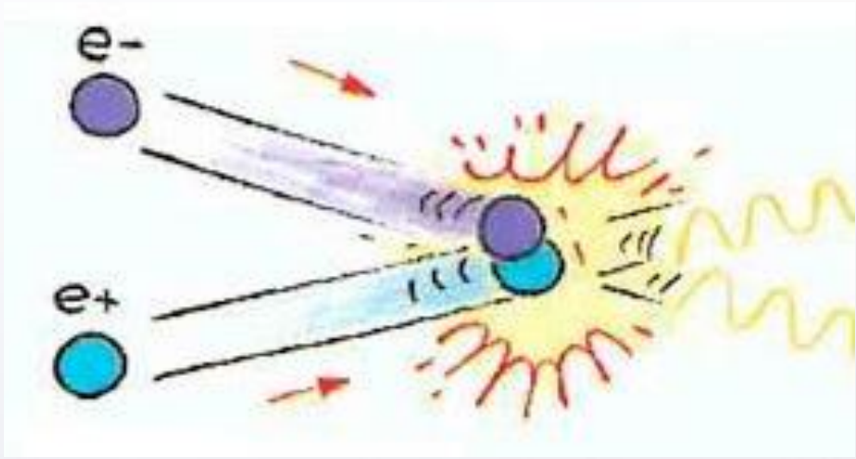
Particles and anti-particles are always **created in pairs** ...

Energy to mass:



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

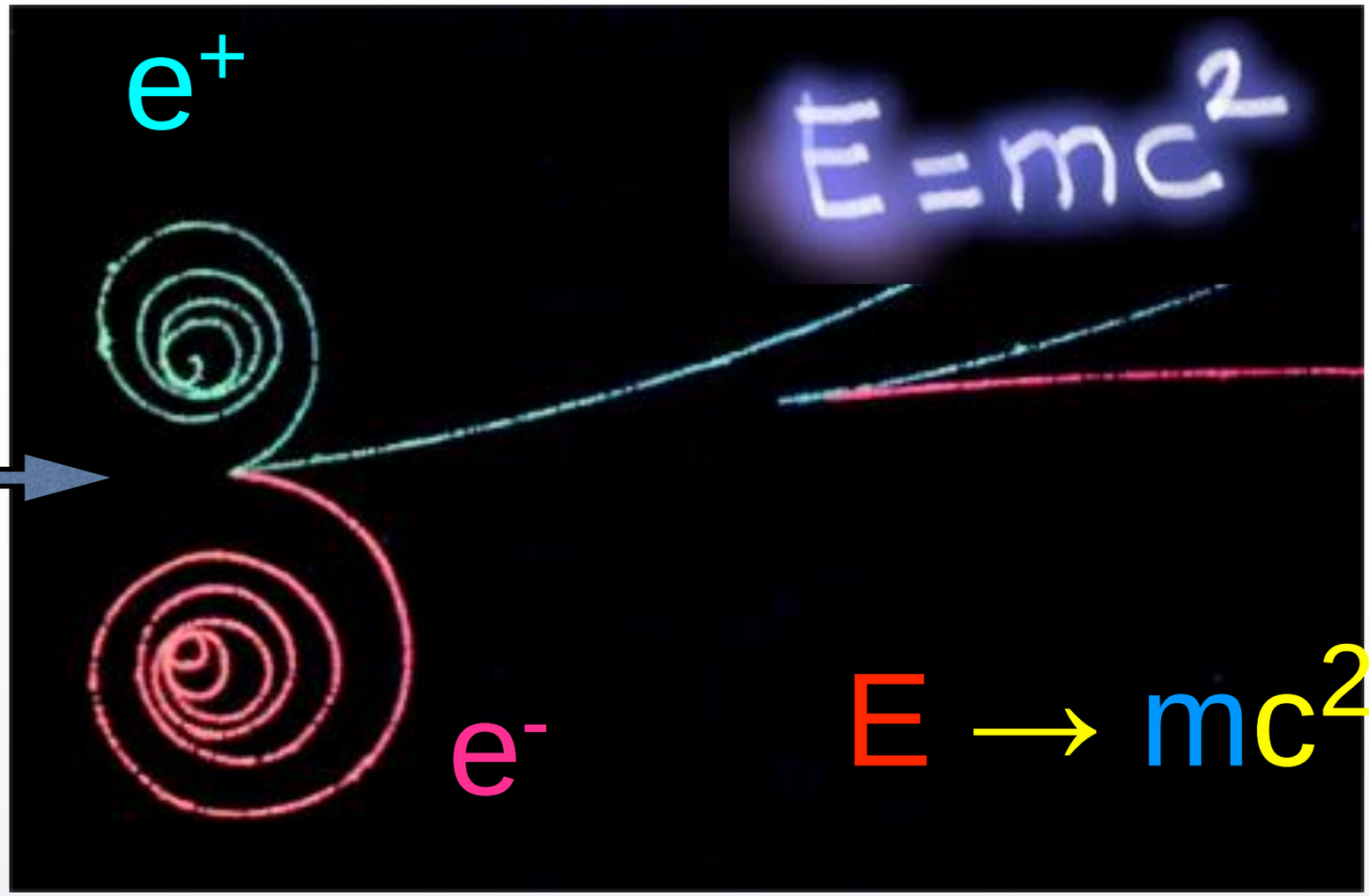
Mass to energy:



1 What is antimatter ?

When Energy is converted to mass

an equal amount of matter and antimatter particles are created



Key: high energy **density**

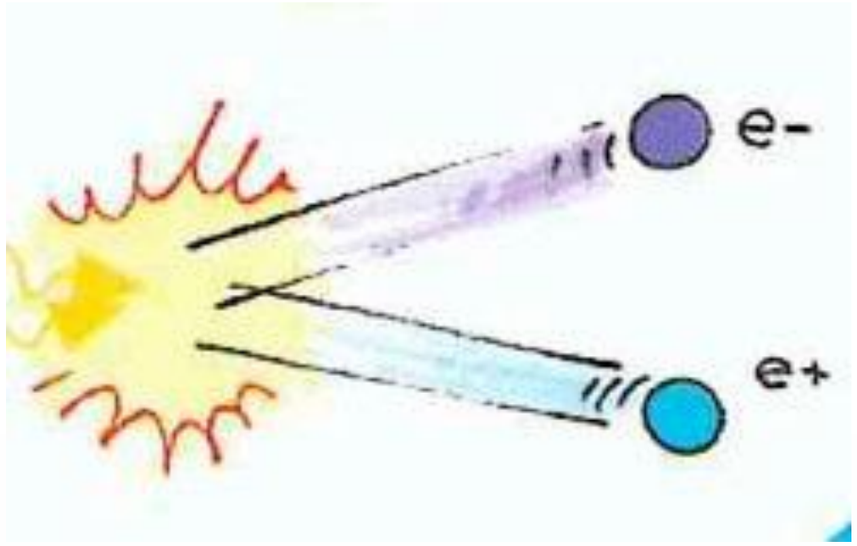
Angels & Demons - The Physics behind the Movie

1 What is antimatter ?

Metaphors for the relation between particles and anti-particles

Angels & Demons - The Physics behind the Movie

1 What is antimatter ?



Press here

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

Matter becomes antimatter

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

Angels & Demons - The Physics behind the Movie

1 What is antimatter ?

Careful with “antimatter E.T.” !

2 Antimatter in the LHC ?

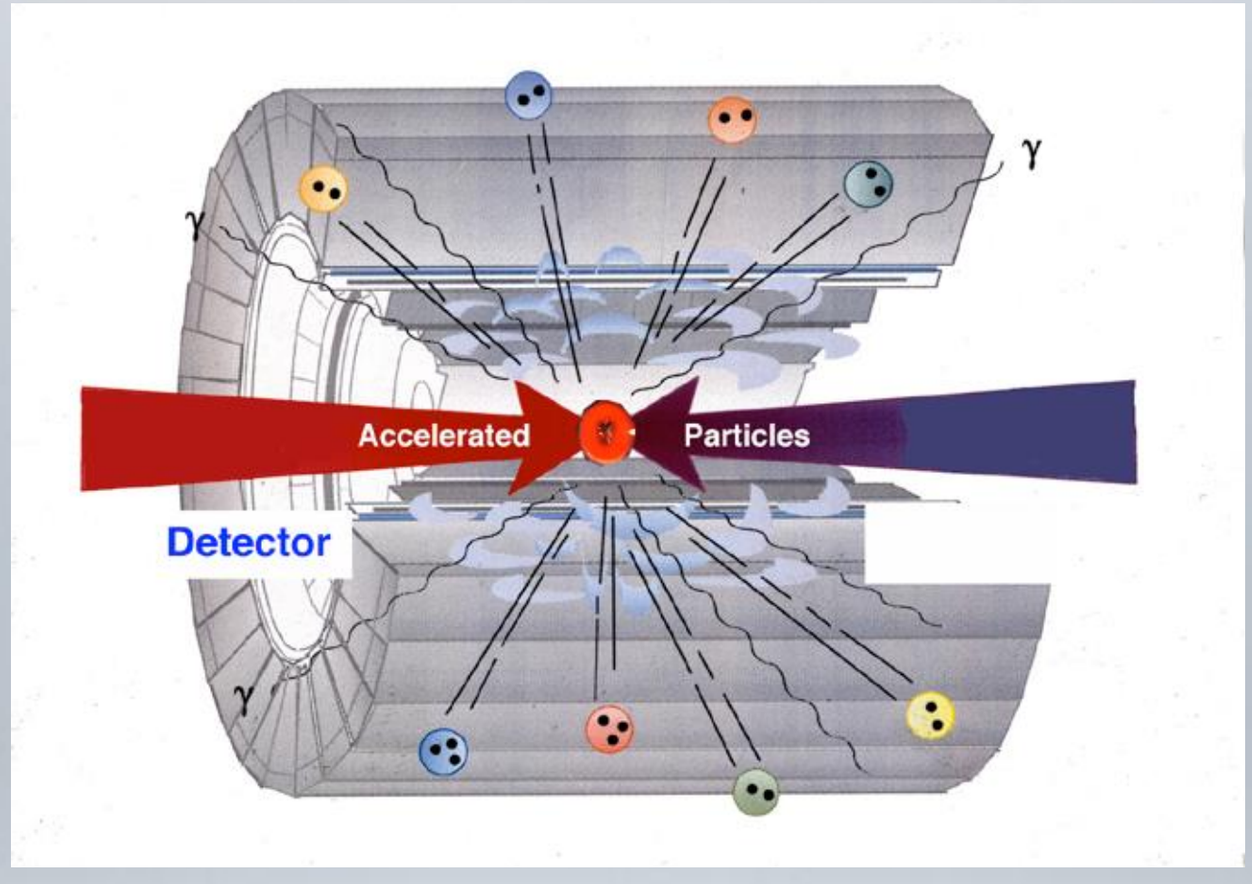
2 Antimatter in the LHC ?

Angels & Demons - The Physics behind the Movie

2 Antimatter in the LHC ?

Angels & Demons - The Physics behind the Movie

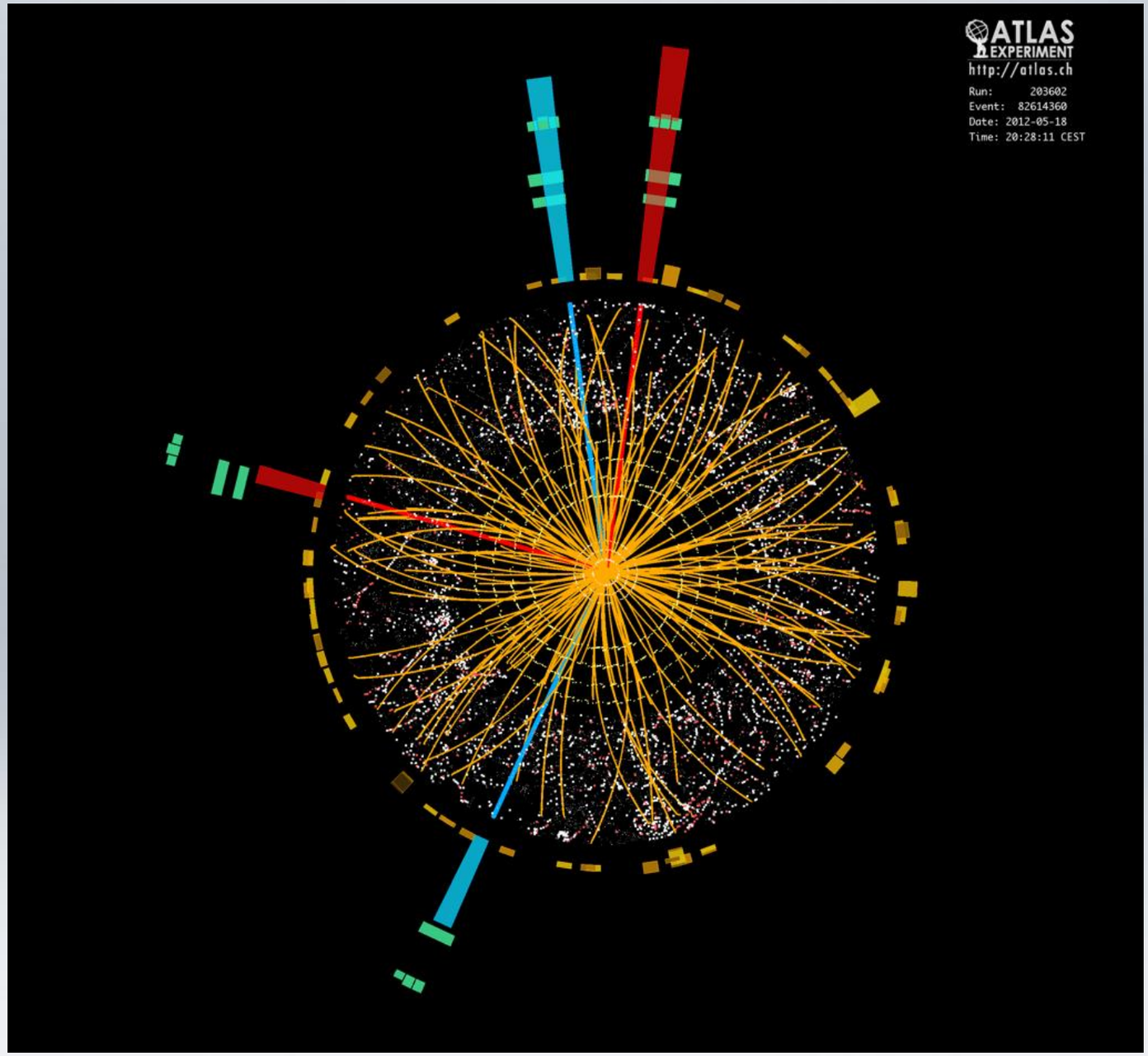
2 Antimatter in the LHC ?



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

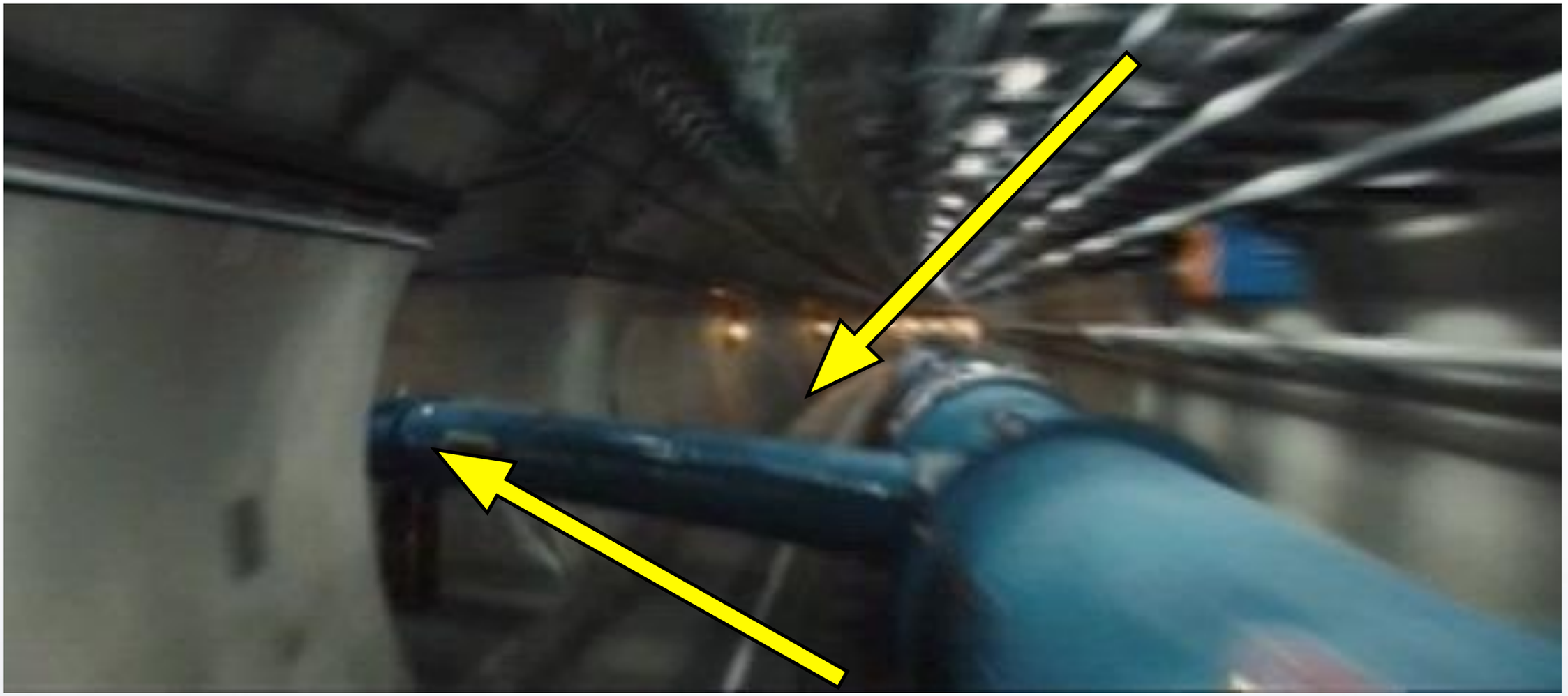
The real ATLAS covern - 100 m underground

The noisy Hollywood version of antimatter production

2 Antimatter in the LHC ?

Bend 20 GeV antiprotons around 5 m radius?

B = E [GeV] /0.3 / R[m] = 20/0.3/5 ~ **13 T** (?)



Decelerate 20 GeV antiprotons within 100 m?

Gradient = 20000 MeV/100 m = **200 MeV/m**

3 The mystery of

atter

2009:
Pre-premiere of Angels+Demons at CERN

Angels & Demons - The Physics behind the Movie

3 The mystery of antimatter

N

Tom Hanks explains the research at CERN

Angels & Demons - The Physics behind the Movie

Antimatter and ...

God particle ?? No.

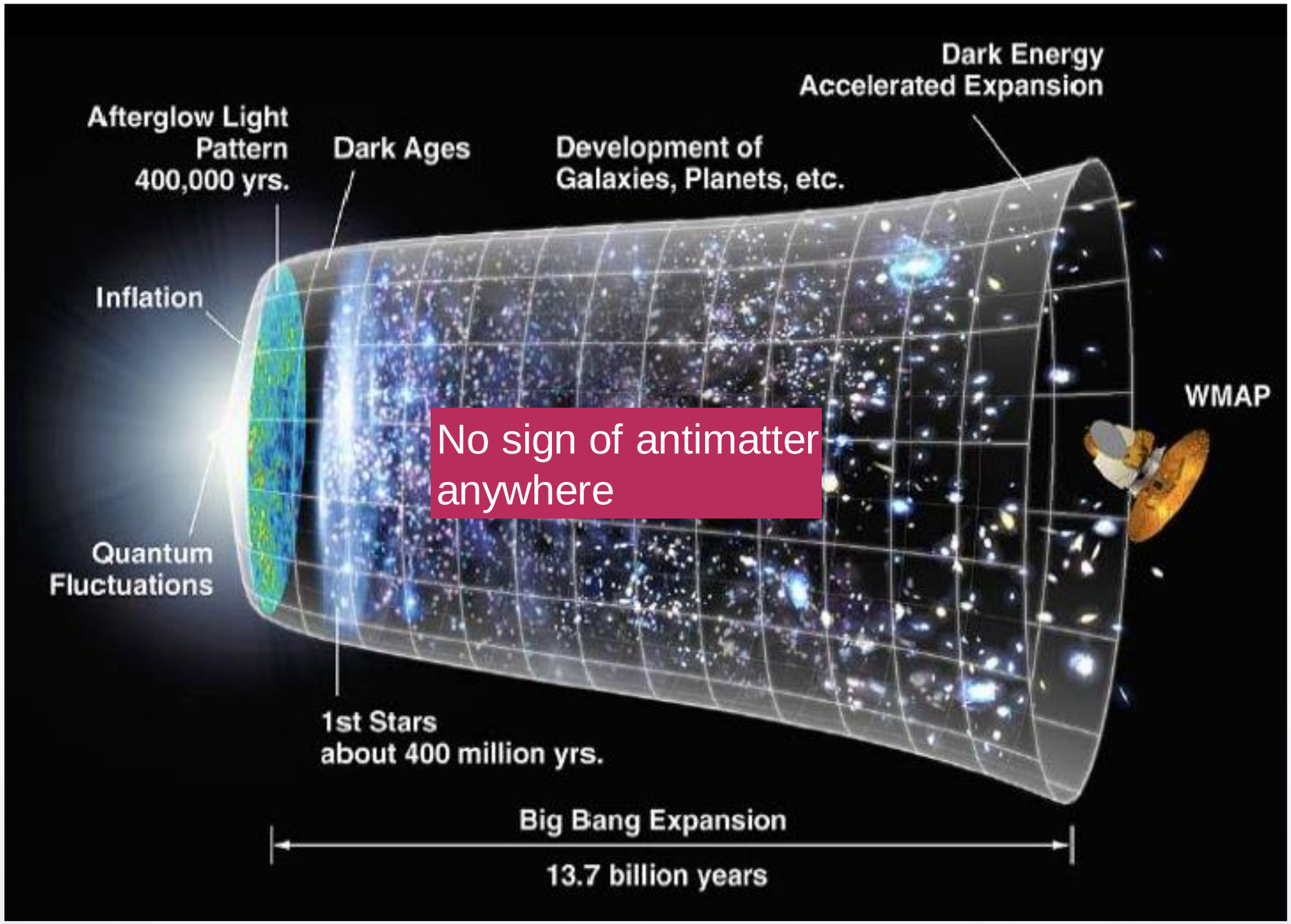
Implications for energy research ? Hmmm.

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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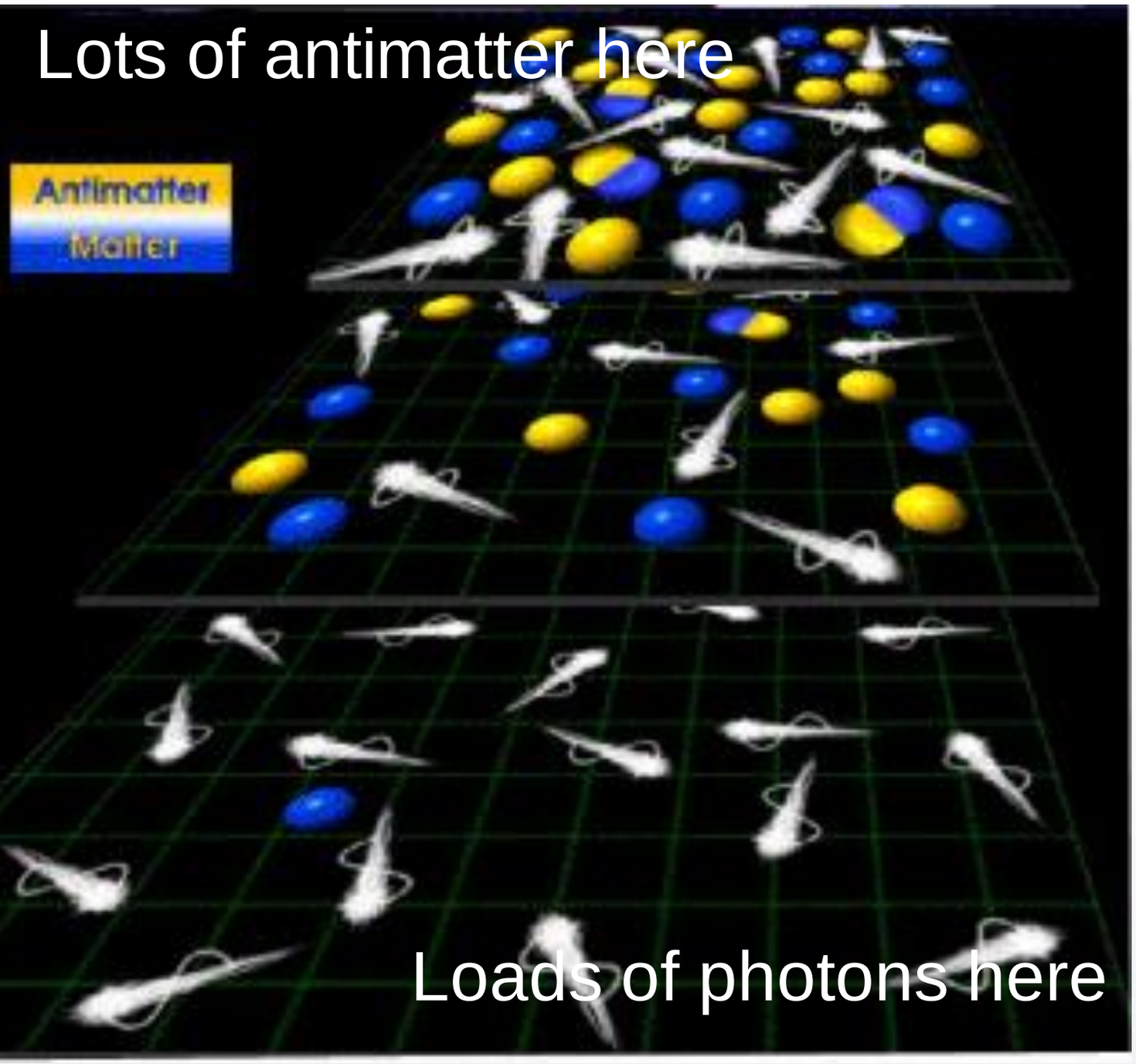
3 The mystery of antimatter

3 The mystery of antimatter

No antimatter in the Universe ?

Why not ???

3 The mystery of antimatter



Cosmic CSI

Big Bang:
Energy transforms to mass

< 1 µs: **matter = antimatter**

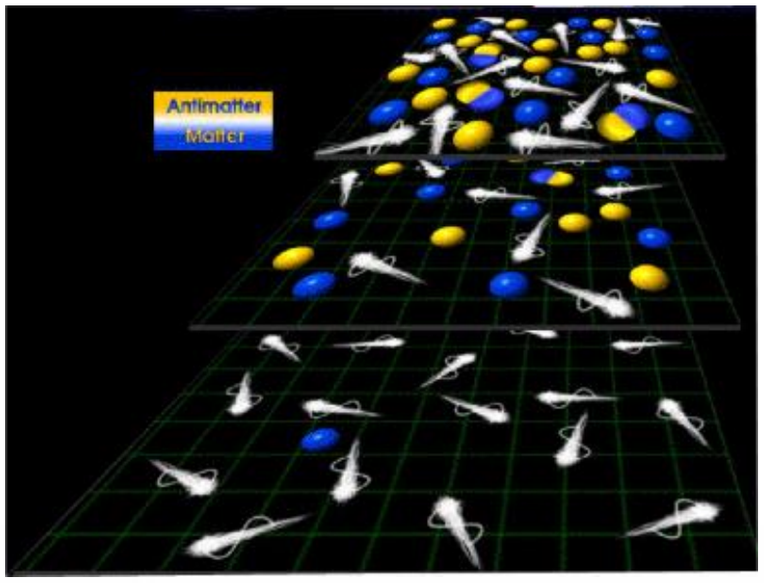
Annihilation battle

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)

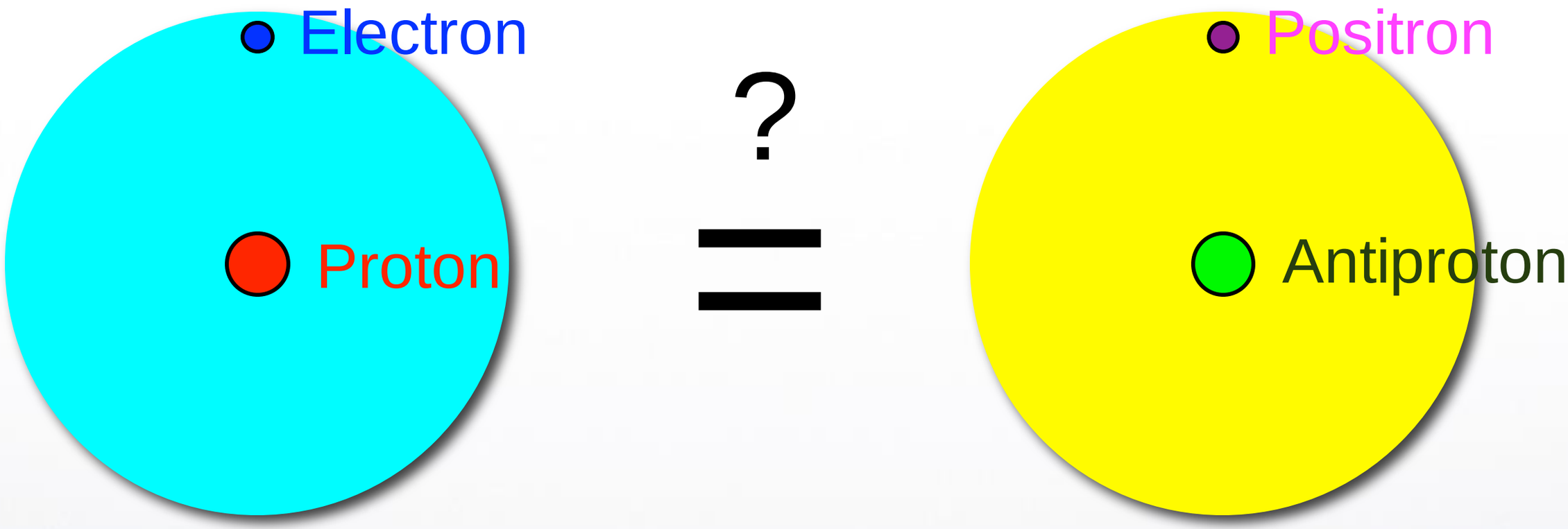
4 How to study antimatter ?

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 %

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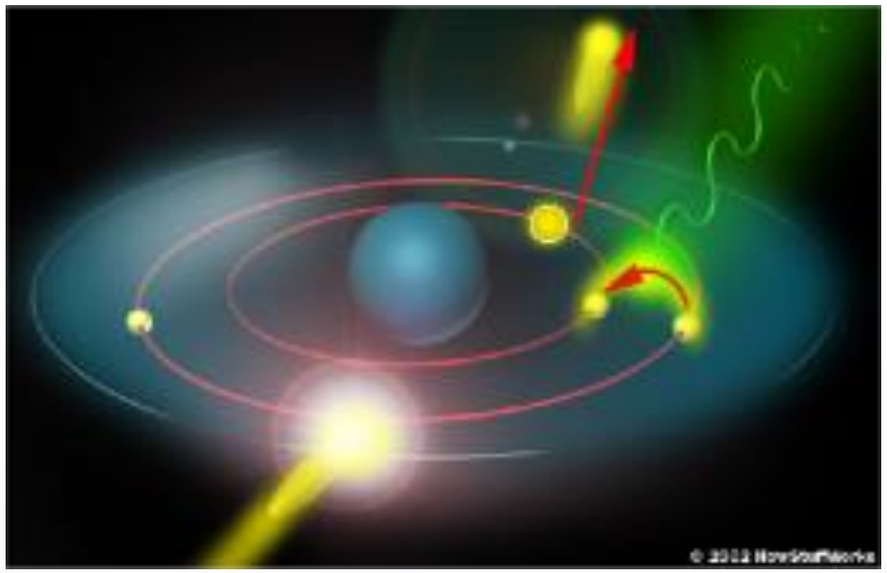
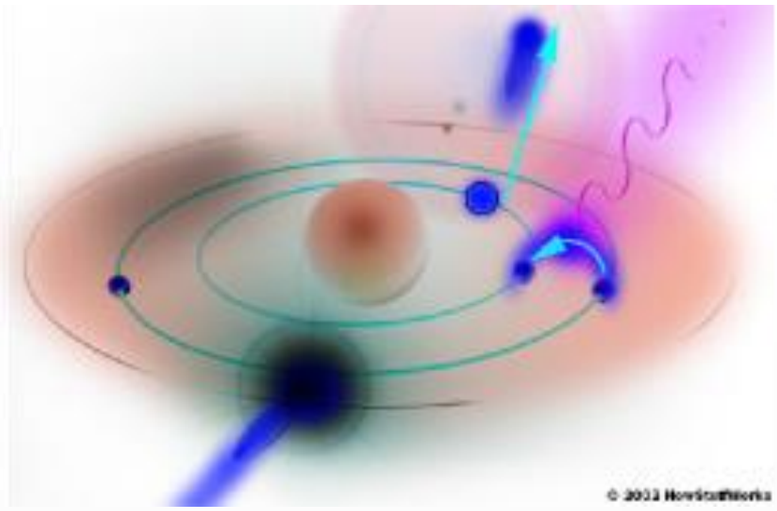
4 How to study antimatter ?

Same energy levels (1S-2S)?



Hydrogen

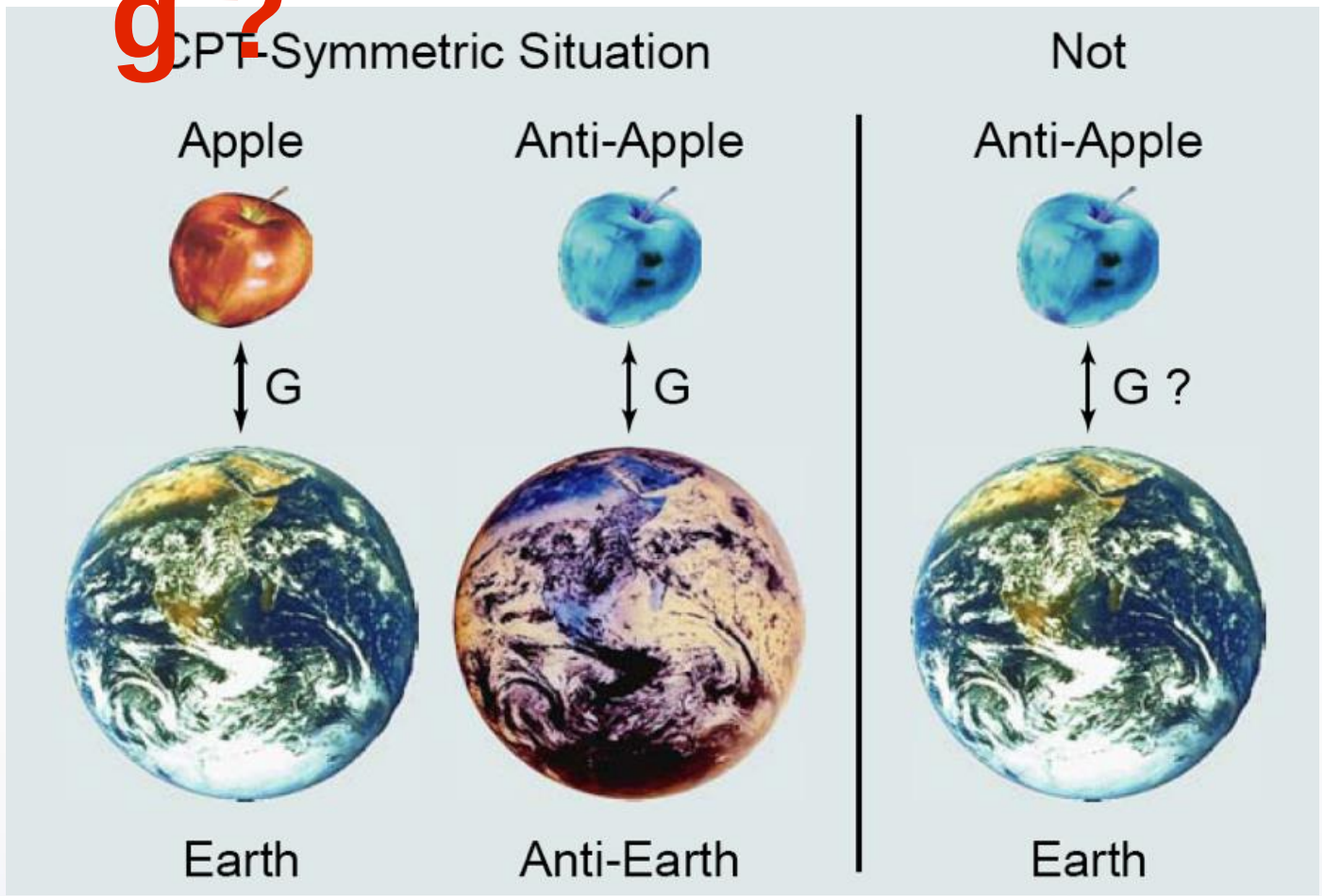


Anti-Hydrogen

AD experiments: ALPHA, ATRAP, ASACUSA

4 How to study antimatter ?

Same gravity: g ≡ g ?



AD experiments: Aegis, Gbar

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Antiproton Decelerator at CERN

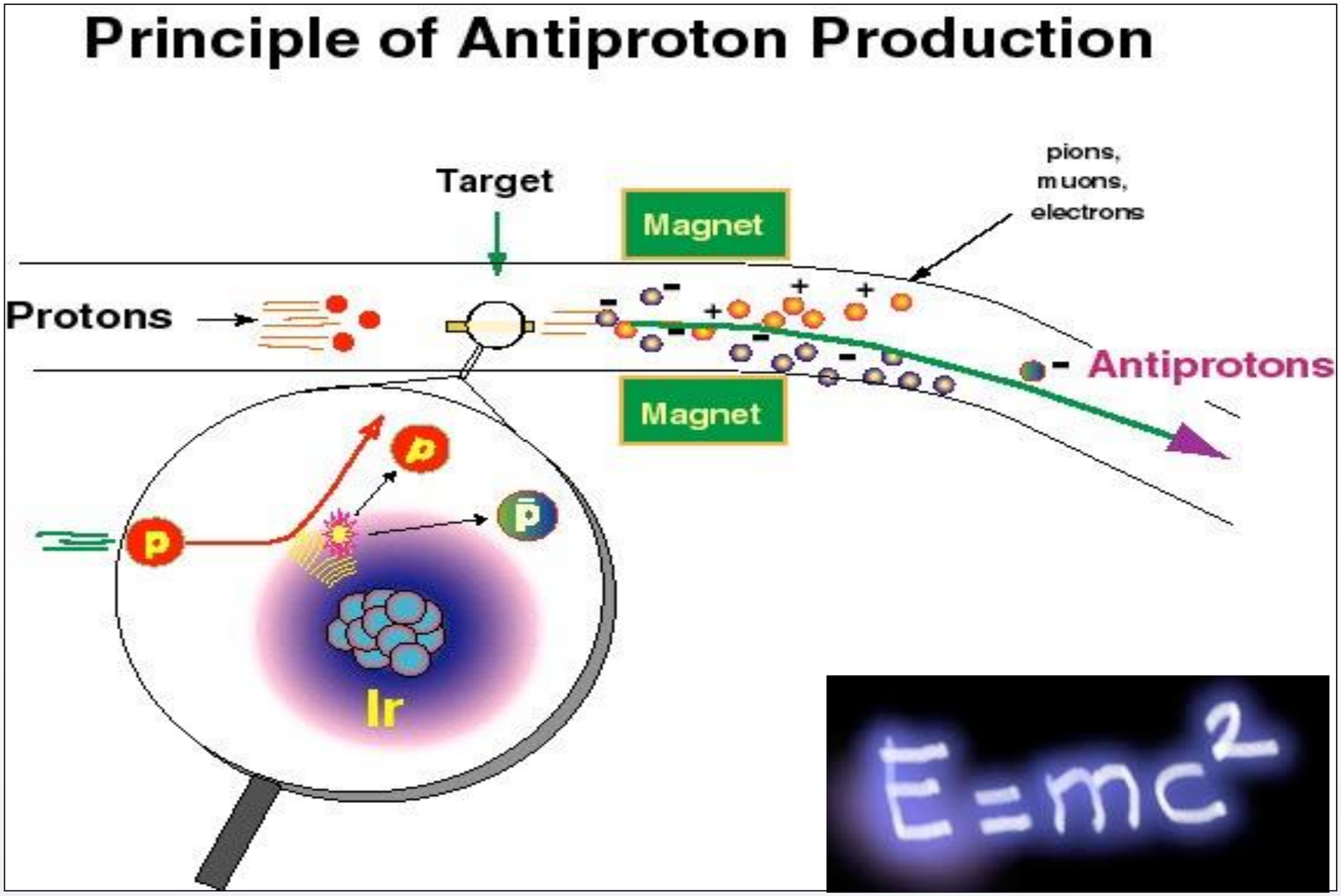
4 How to study antimatter ?

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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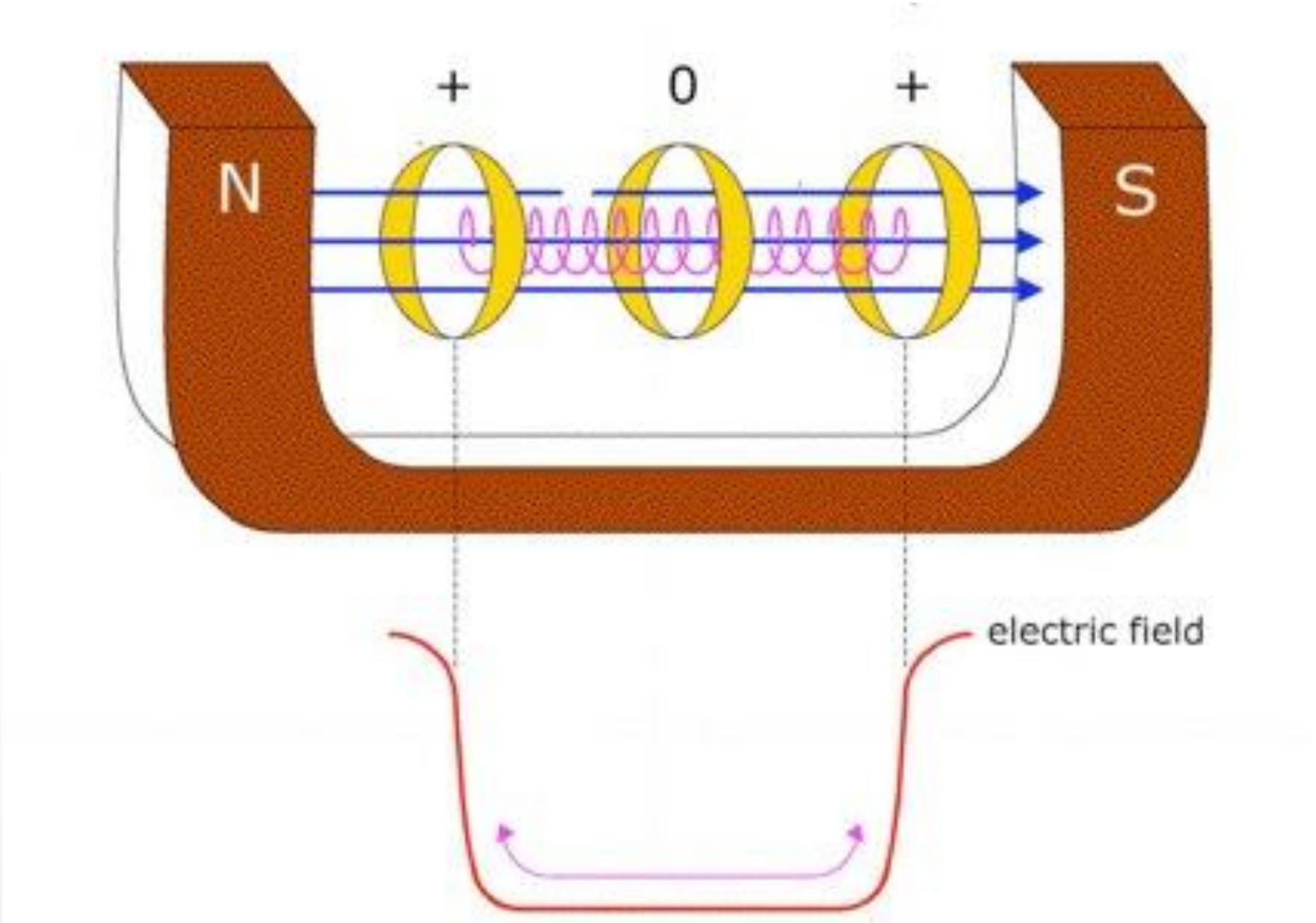
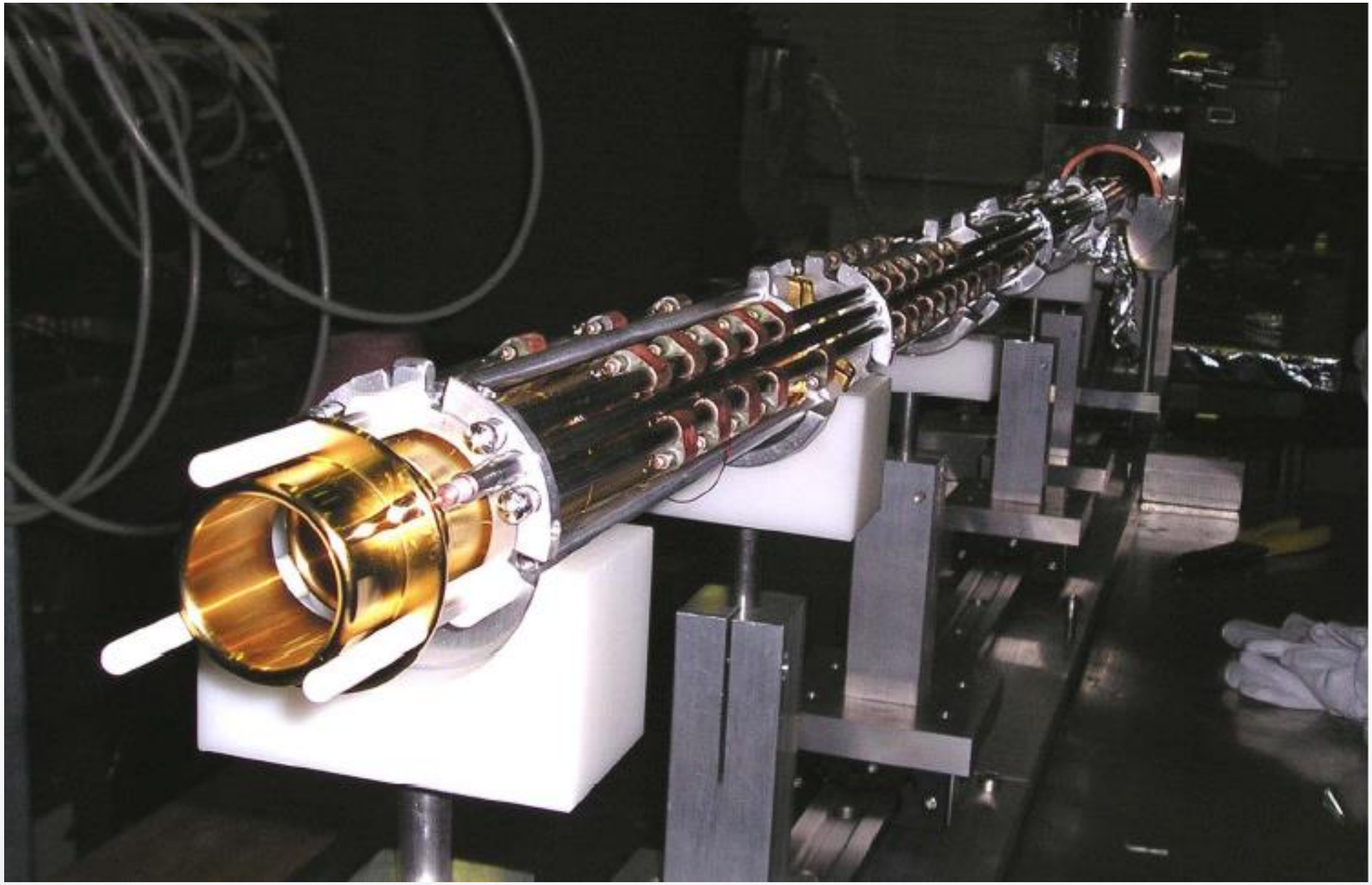
4 How to study antimatter ?



Principle of antiparticle trapping

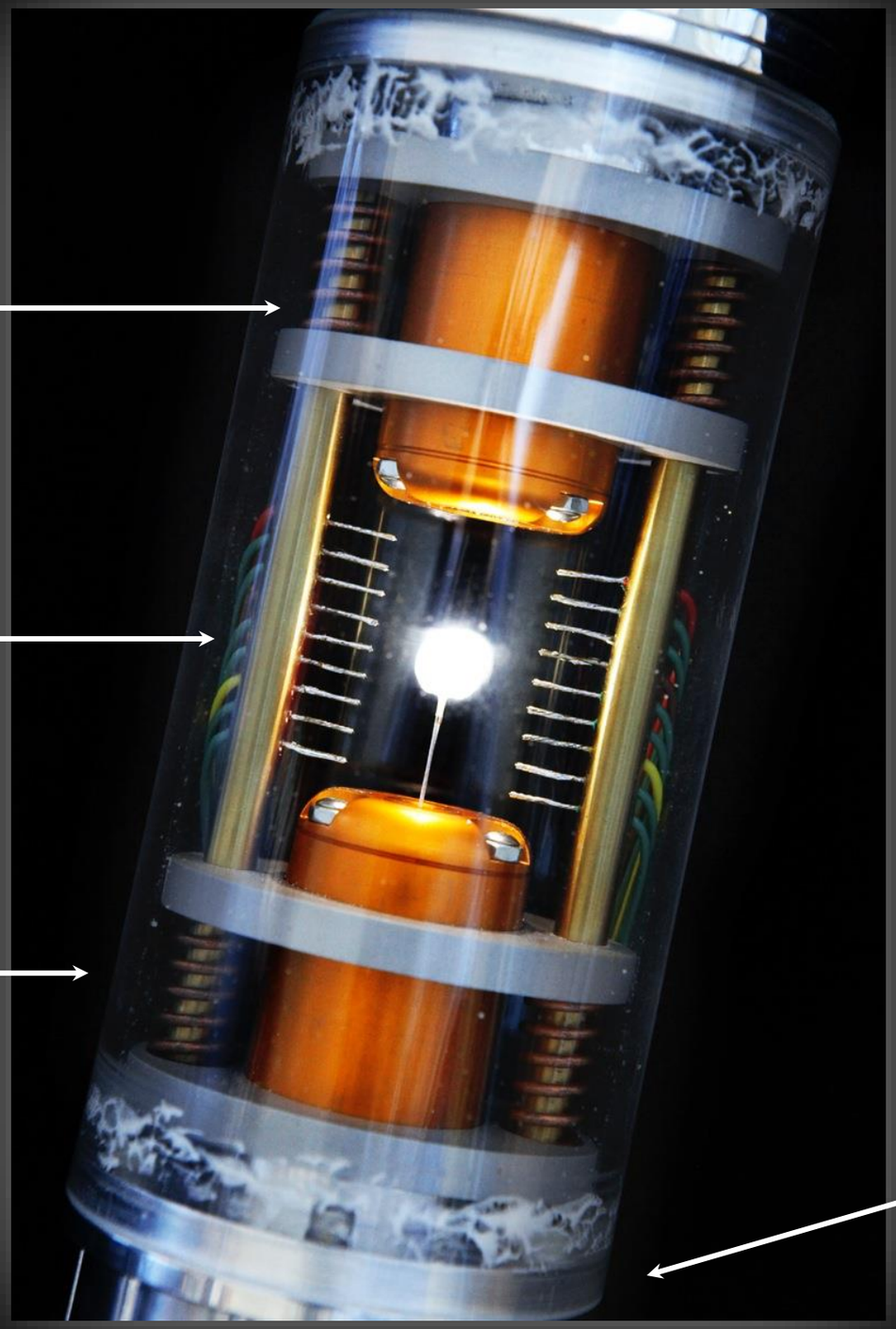
4 How to study antimatter ?



A real antimatter trap at CERN

Magnets

Electrodes



Magnets

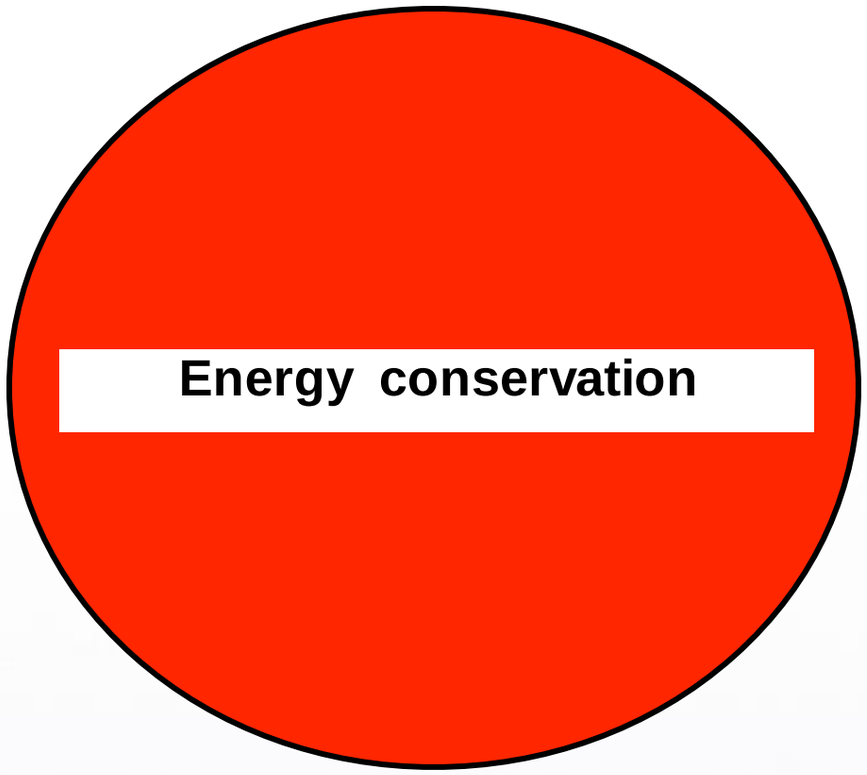
Ultra-high vacuum

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

Angels & Demons - The Physics behind the Movie

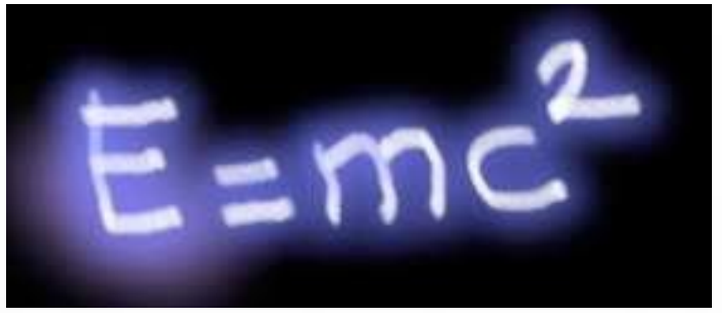
Antimatter explosion in “Angels & Demons”

5 An energy source? A bomb?

Hiroshima - 20 kt TNT equivalent

Dan Brown:

"0.5 g antimatter makes a powerful bomb"



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

So this is correct, but ....

Angels & Demons - The Physics behind the Movie

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**

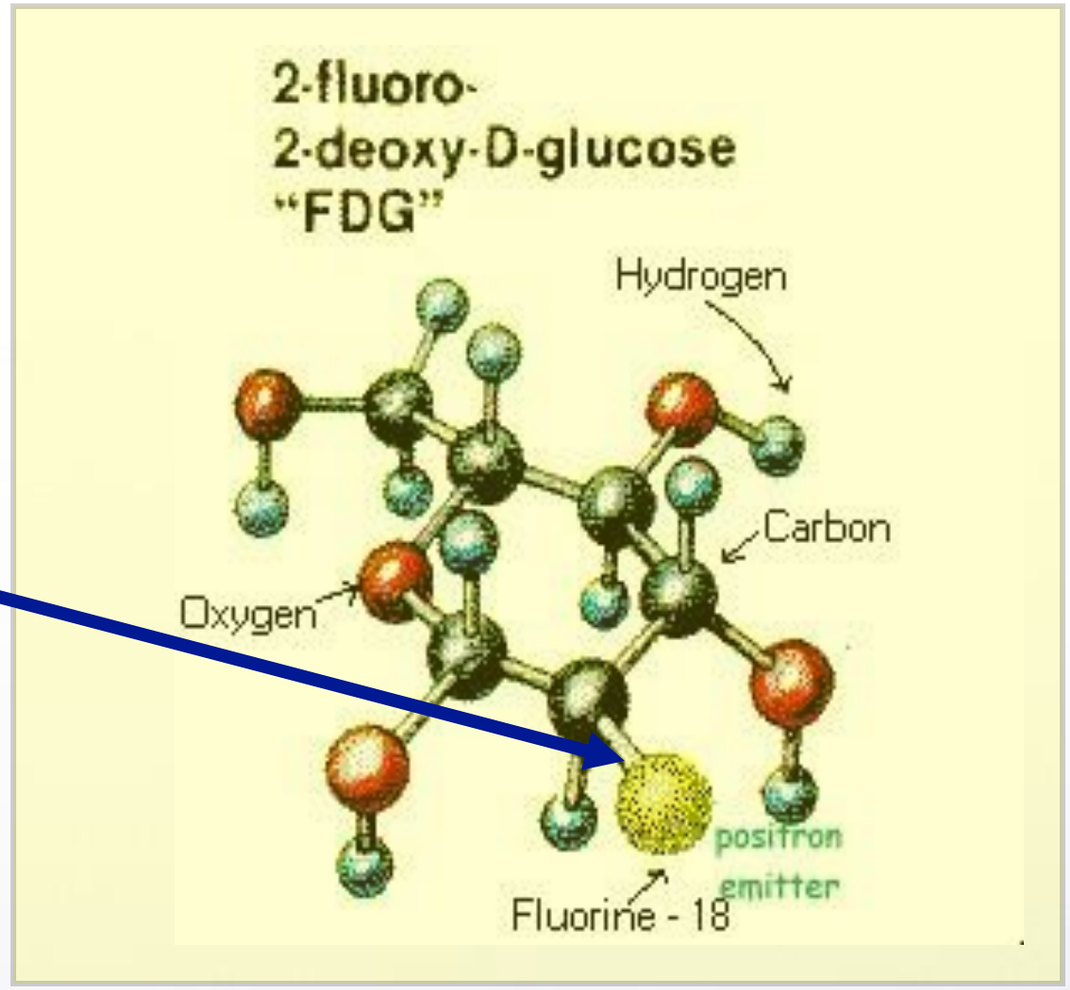
Anything useful ??

Yes - the PET scanner can save lifes!

Positron Emission Tomography

Glucose supplies energy

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



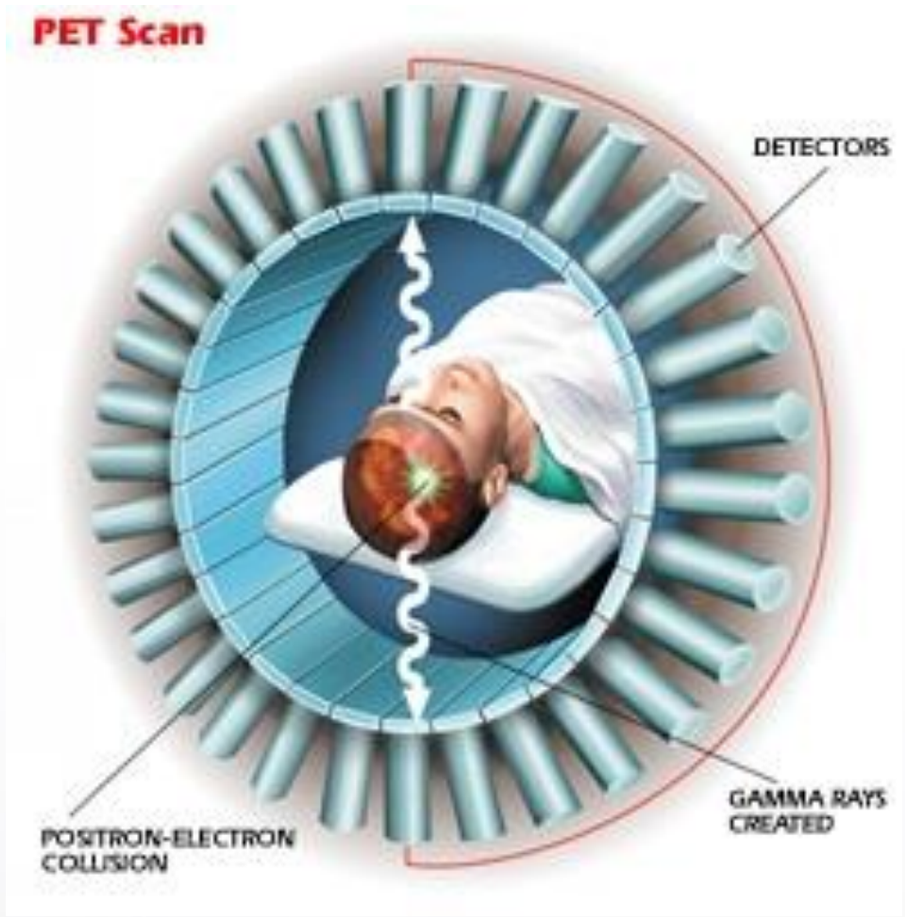
Inject into blood stream

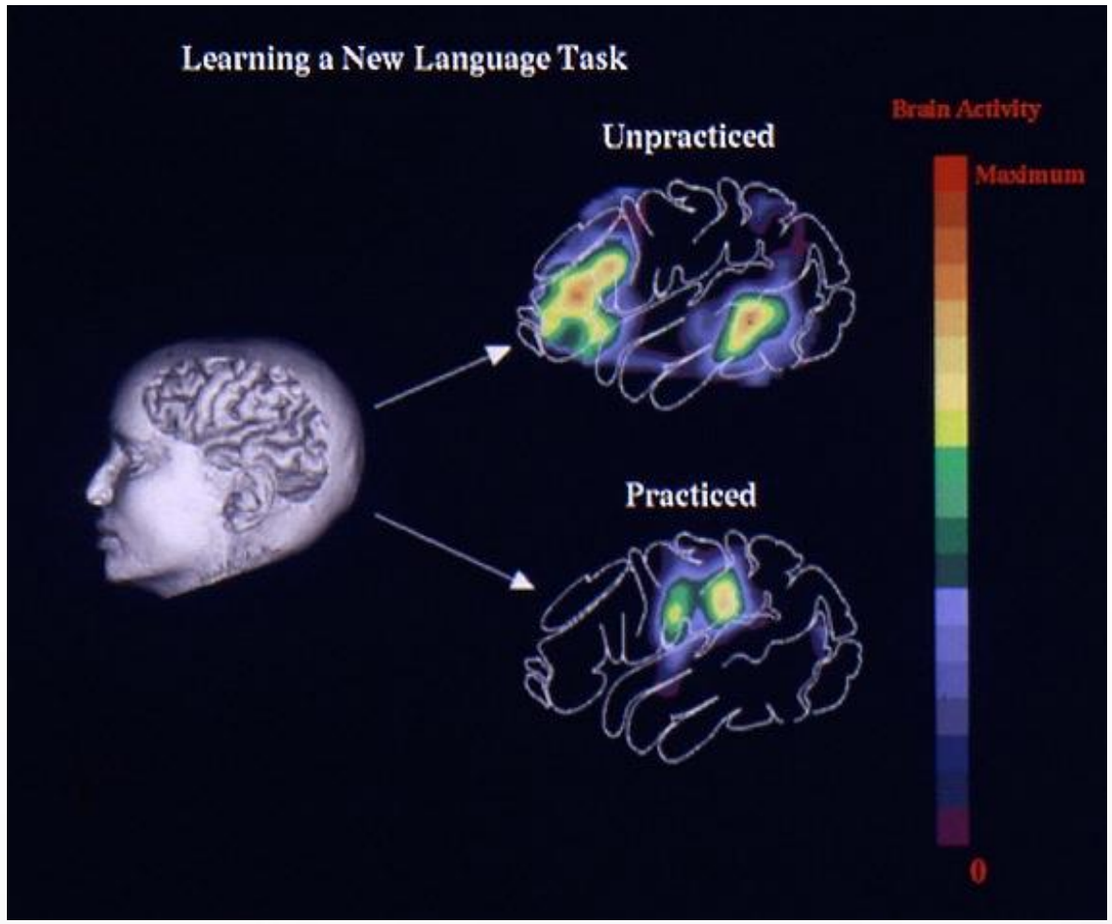
Glucose accumulates where energy is needed

Positron emission and annihilation - detect where the glucose is !

5 Antimatter in daily life

Positron Emission Tomography ("PET Scan")



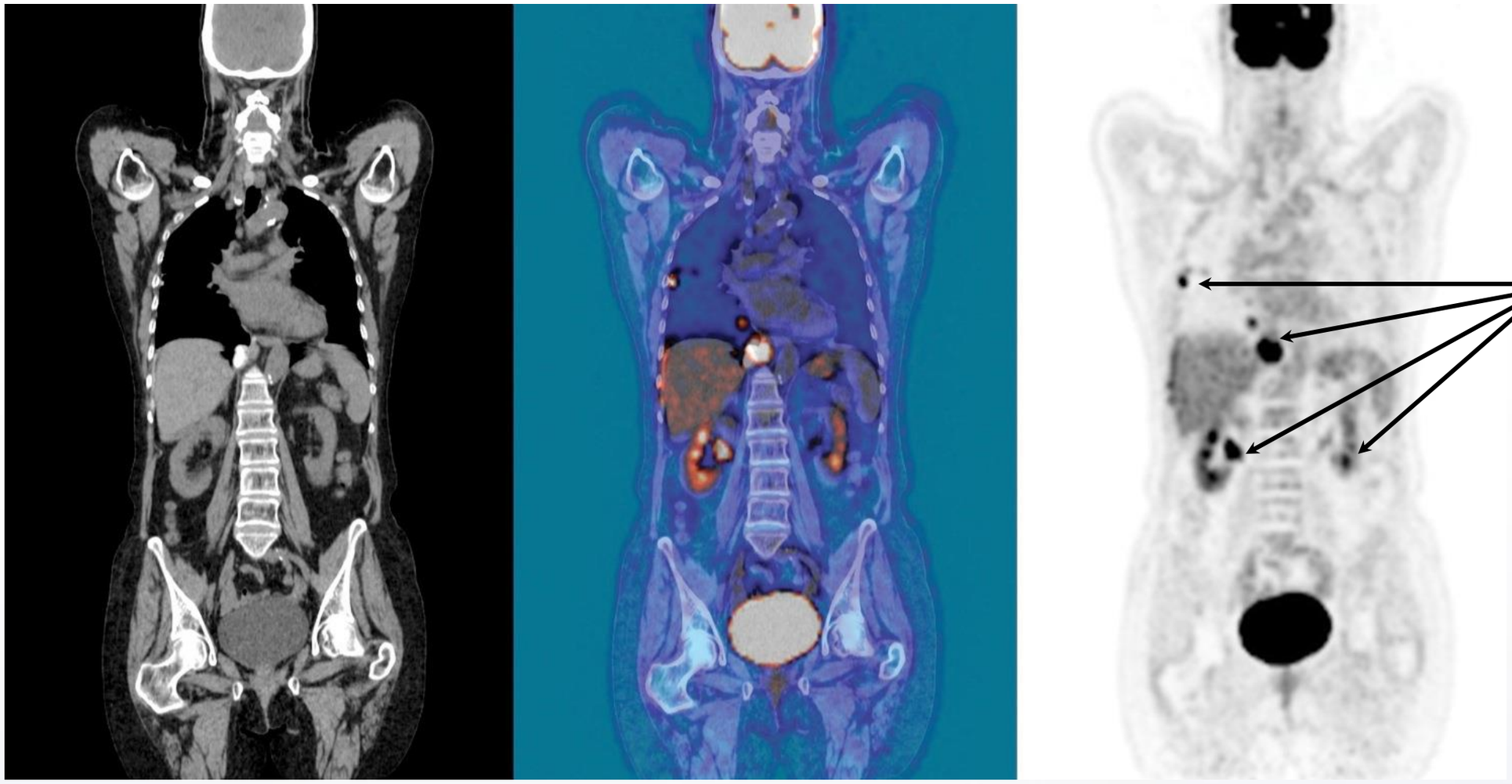


Antimatter helps
- to understand how the brain works
- to find tumours

Angels & Demons - The Physics behind the Movie

5 Antimatter in daily life ?

Positron Emission Tomography (“PET Scan”)



CT Scan only Combination PET scan only

Antimatter helps to find tumours

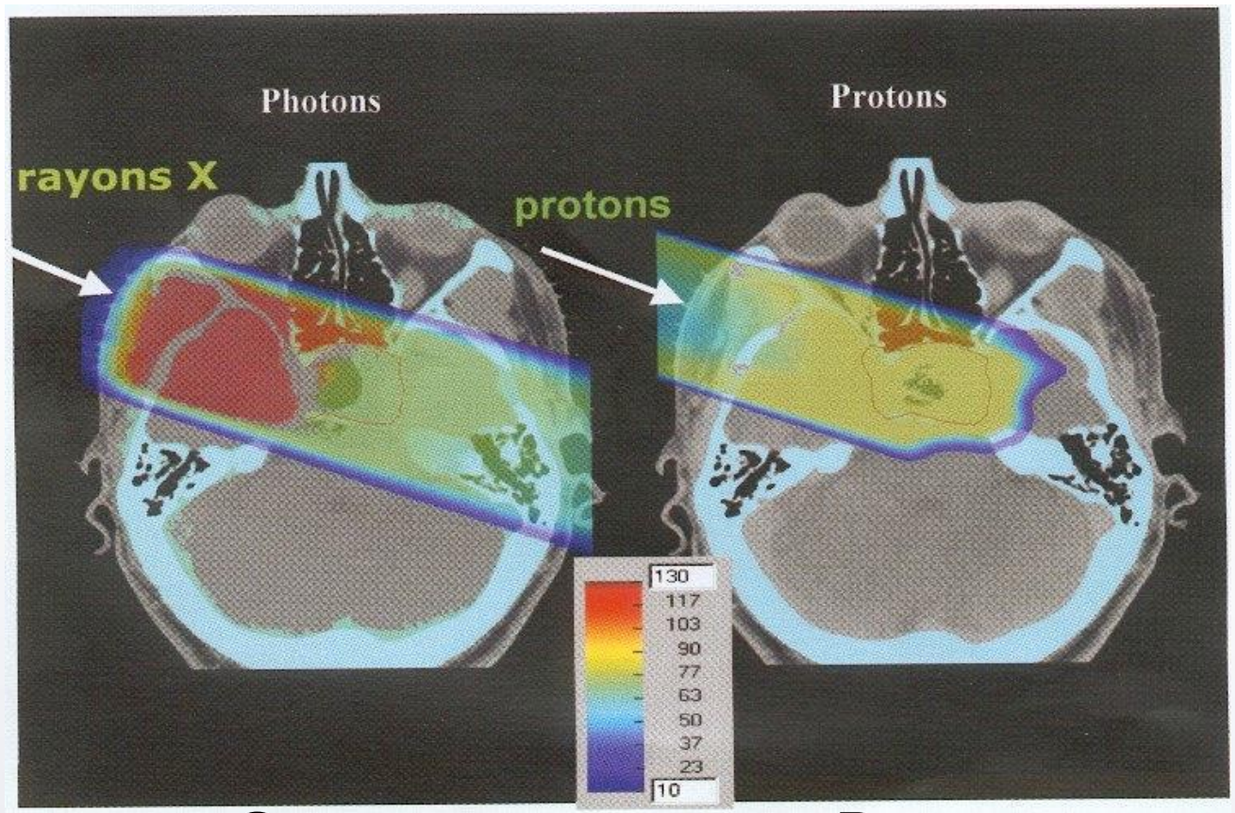
Angels & Demons - The Physics behind the Movie

5 Antimatter in daily life ?

Tumour therapy with antiprotons ?

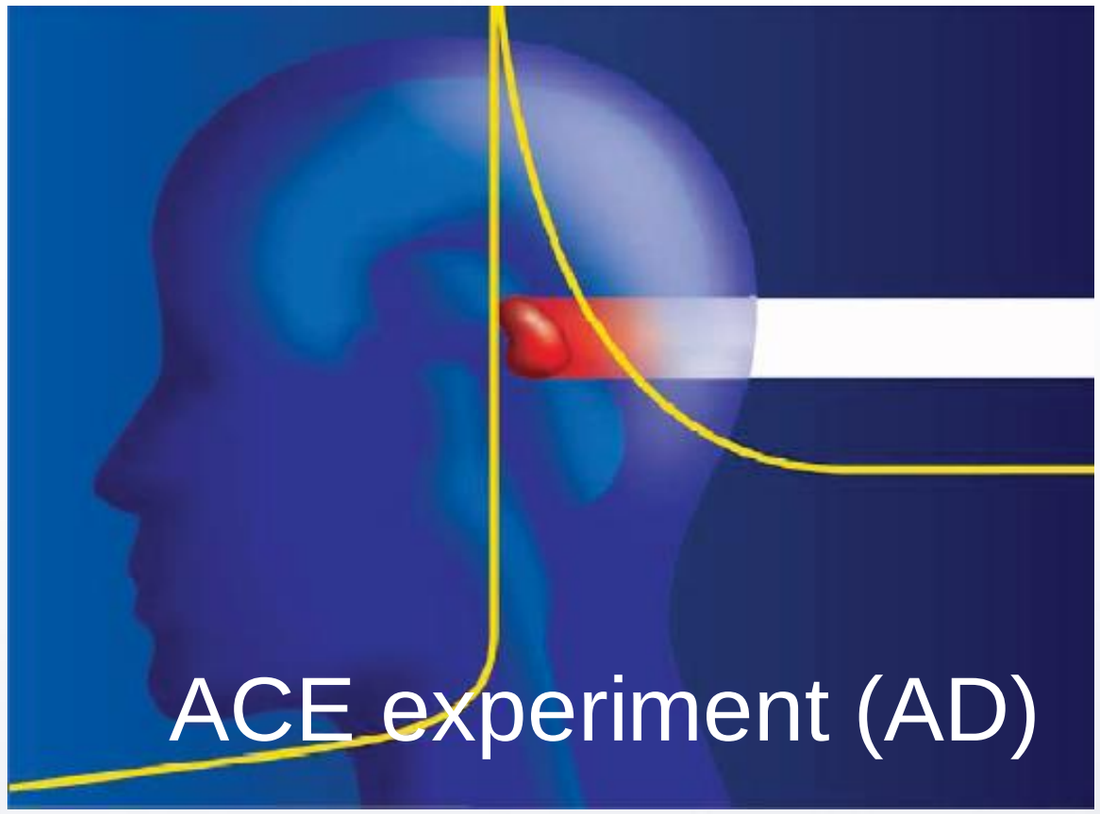
Gamma radiation destroys many healthy cells
Protons deliver radiation more specifically to tumour cells

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



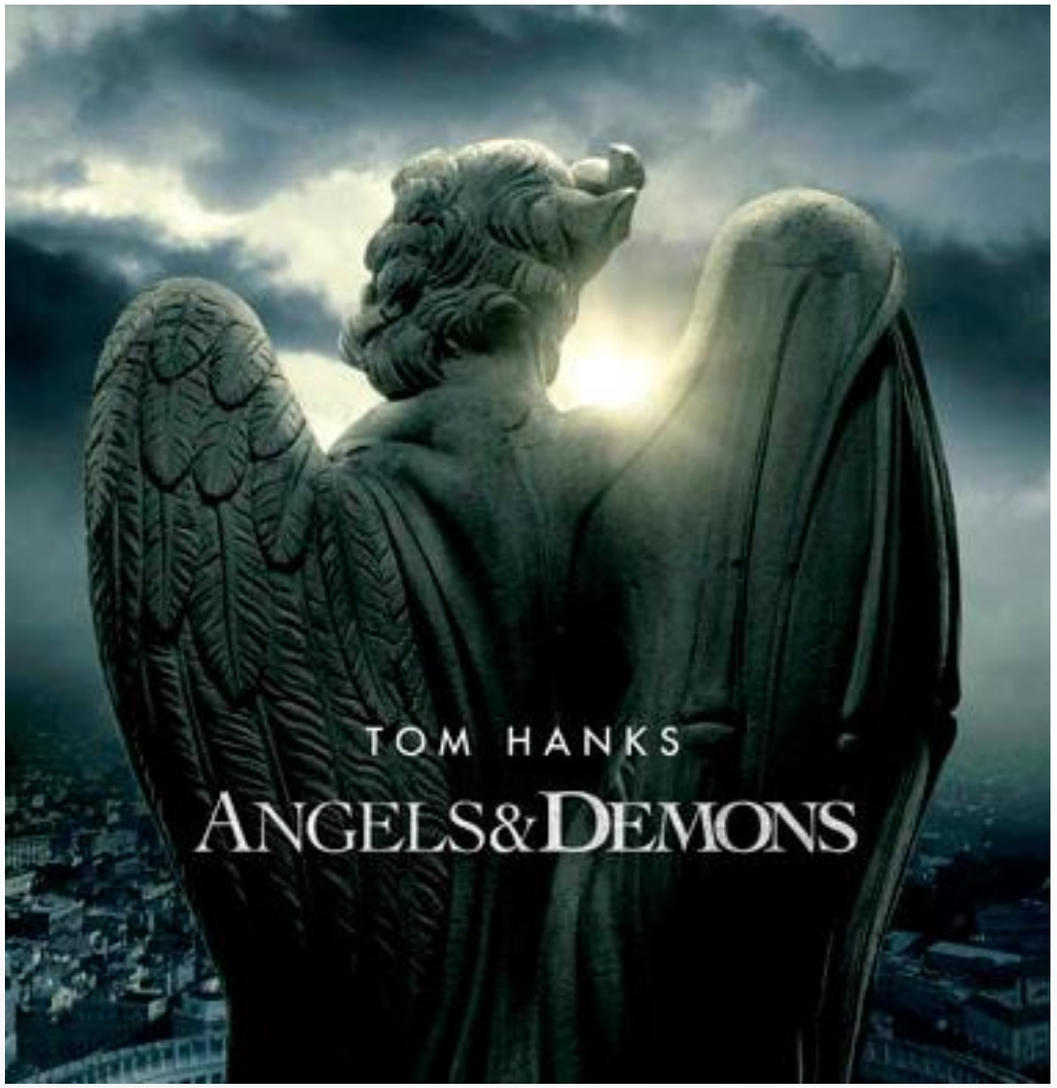
Gamma radiation

Protons



Antiprotons

What did Ron Howard say ?



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.

Angels & Demons - The Physics behind the Movie

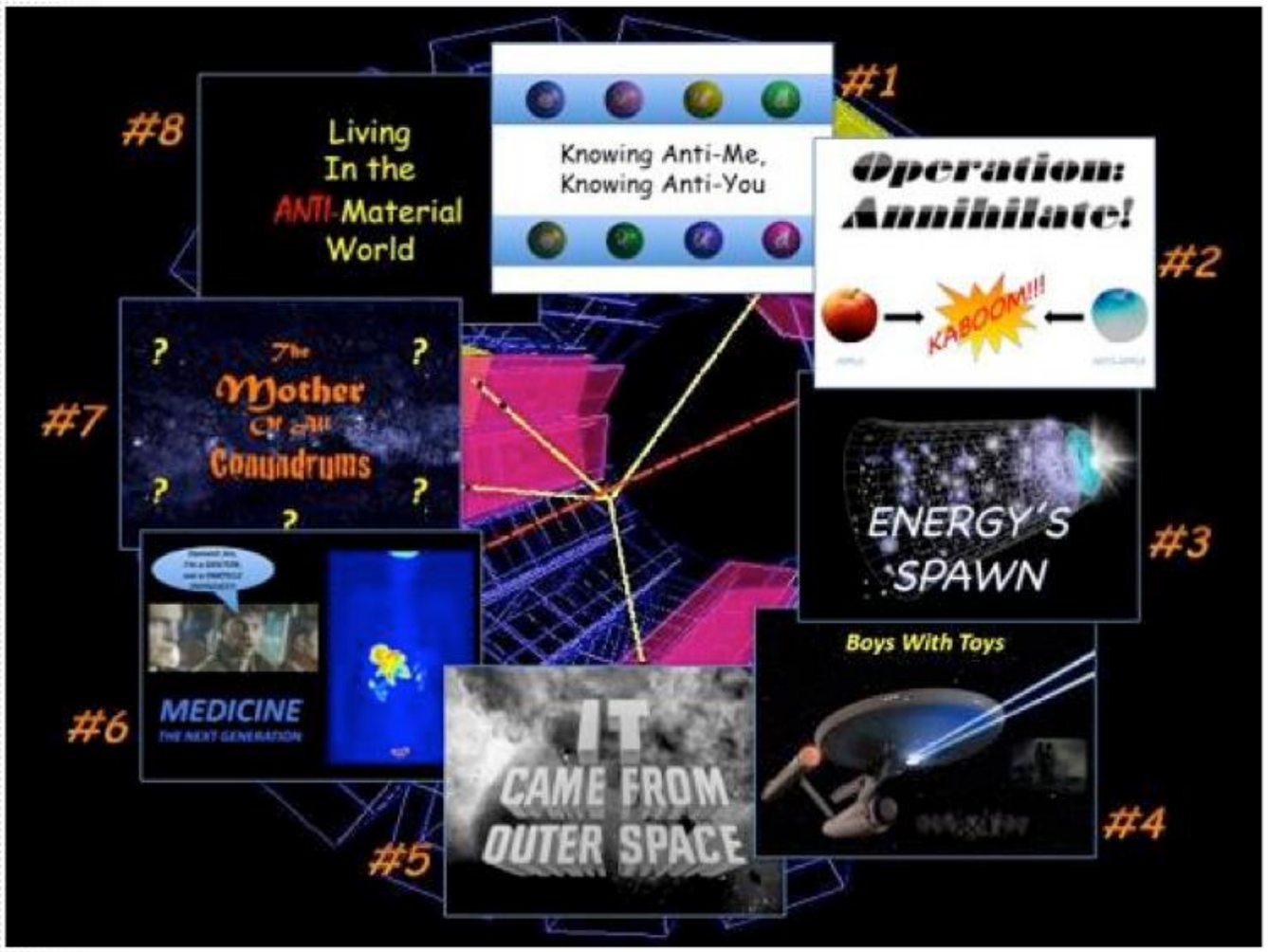
Antimatter @ School

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

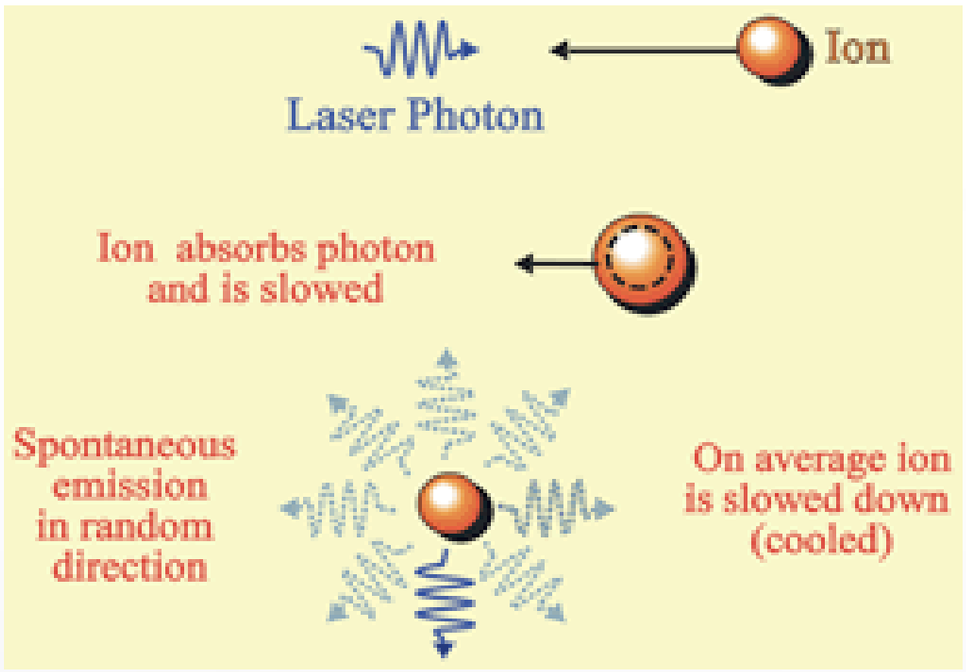
>> Lesson Plans

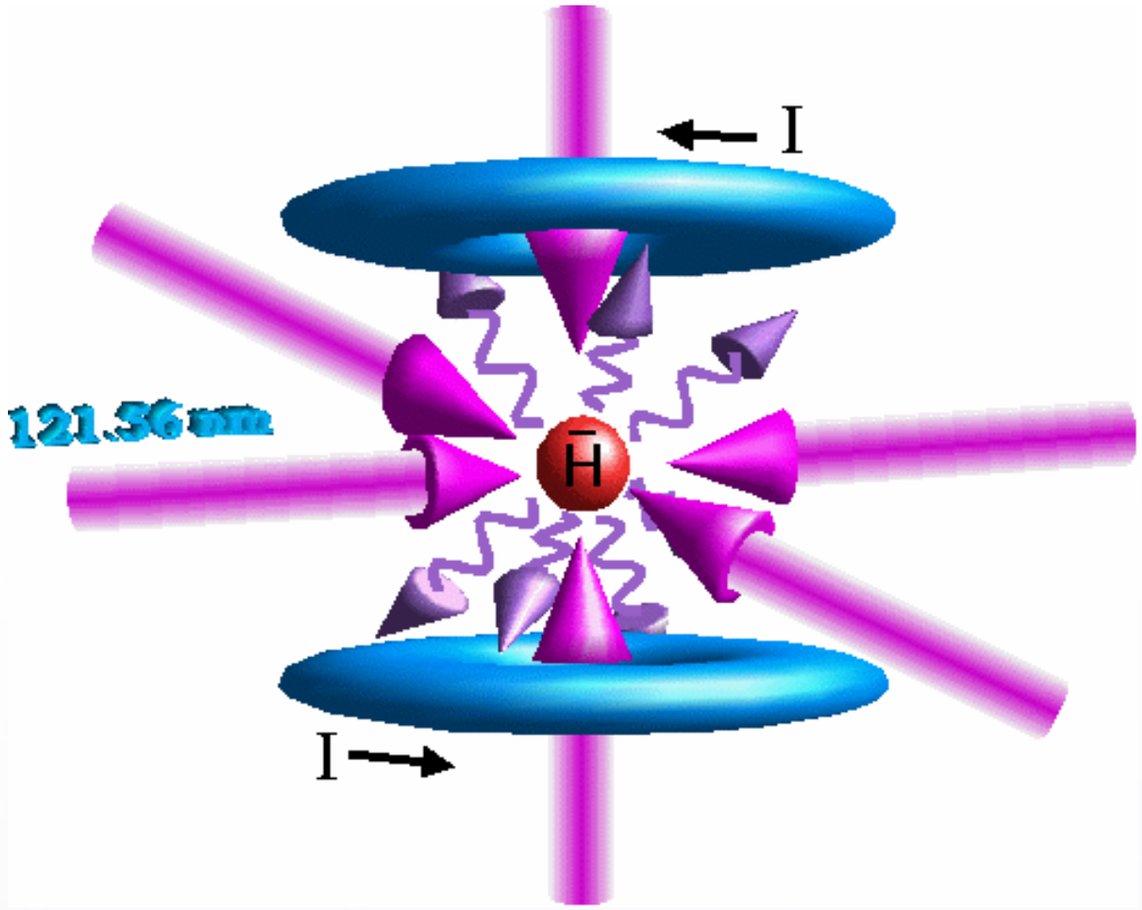


Back to Antimatter Teaching Module

Angels & Demons - The Physics behind the Movie

Laser cooling



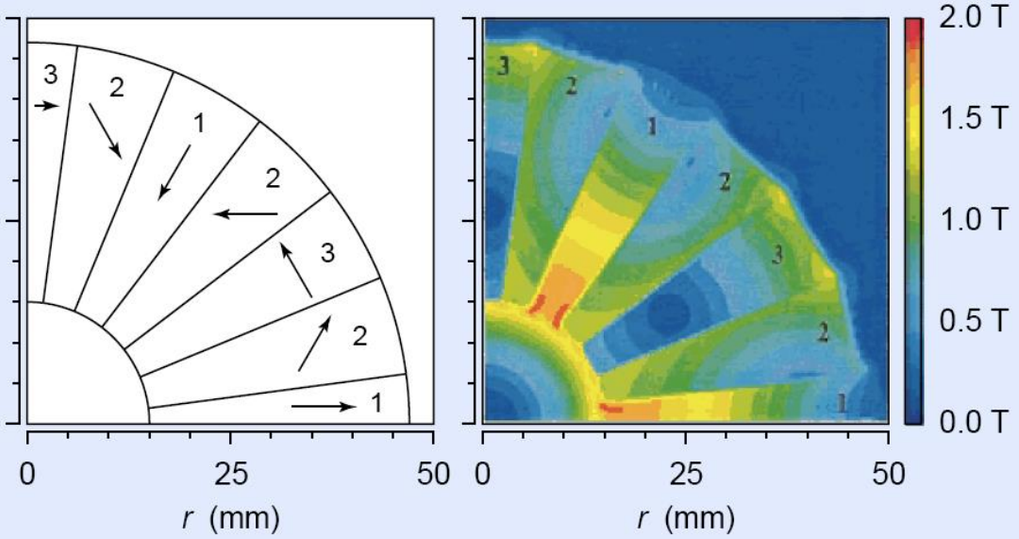


121 nm laser needed

Prototype at MPI Munich

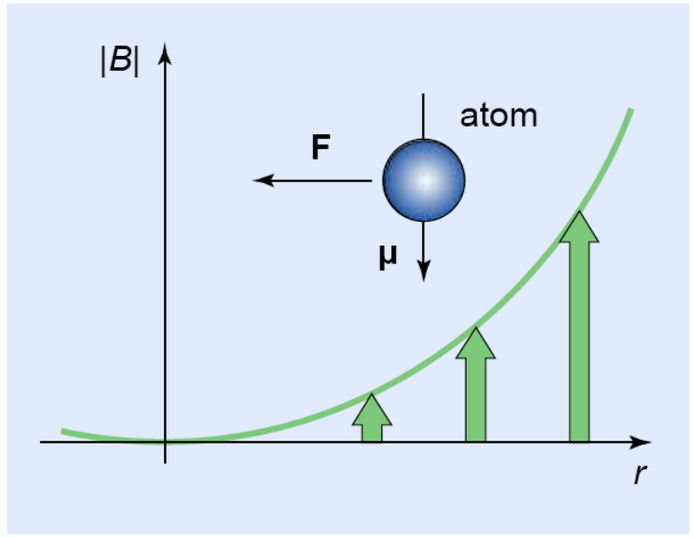
… only 50 nW

Magnetic multipole traps ?



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

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



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

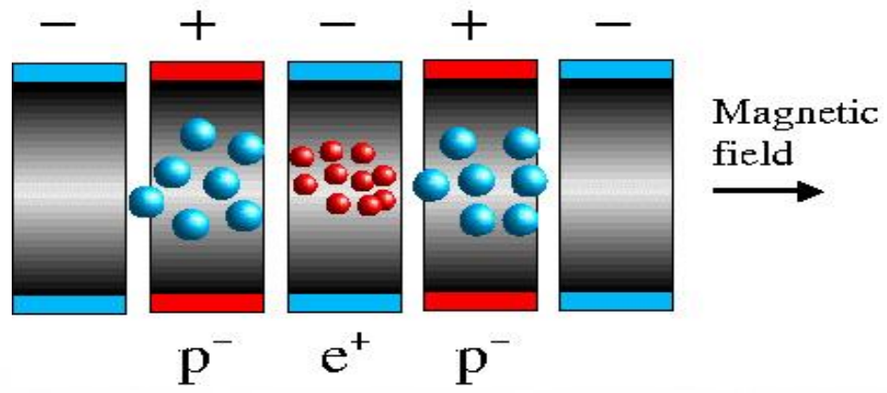
BUT: Very shallow potential (~ 0.07 meV/T)

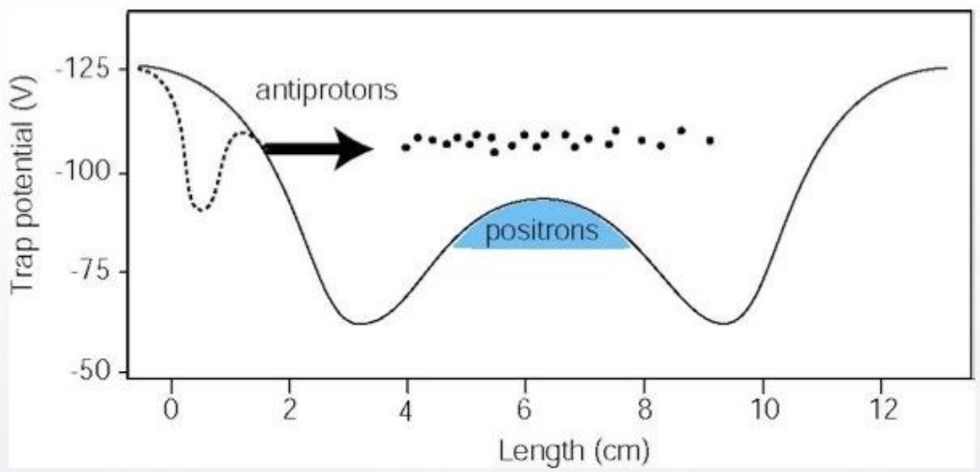
Realistic ΔB ~ 0.2-0.3 T ⇨ **E < 0.02 meV**

(reminder: produced antihydrogen has E_{kin} ~ 1-200 meV)

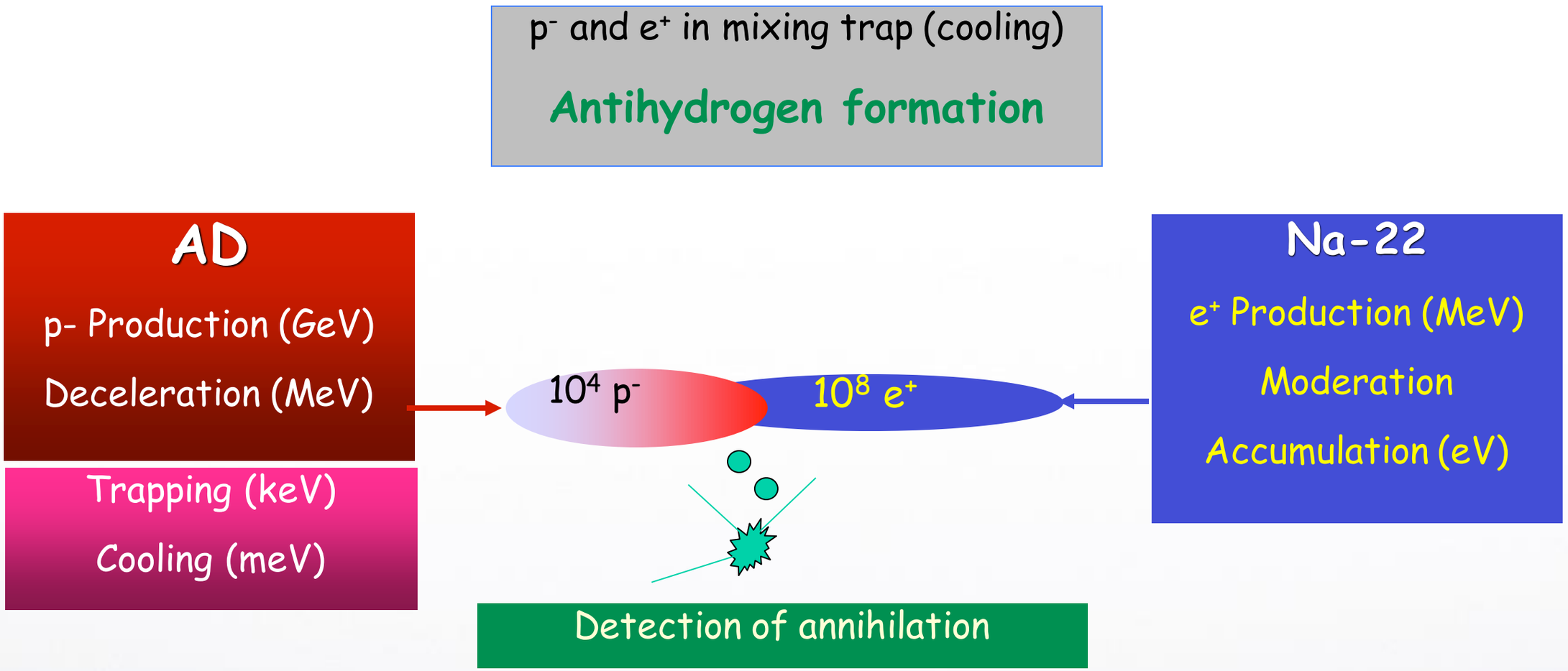
Trap antihydrogen from low energy 'Boltzmann tail' ?

Example: Sextupole magnet





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



Antihydrogen milestones

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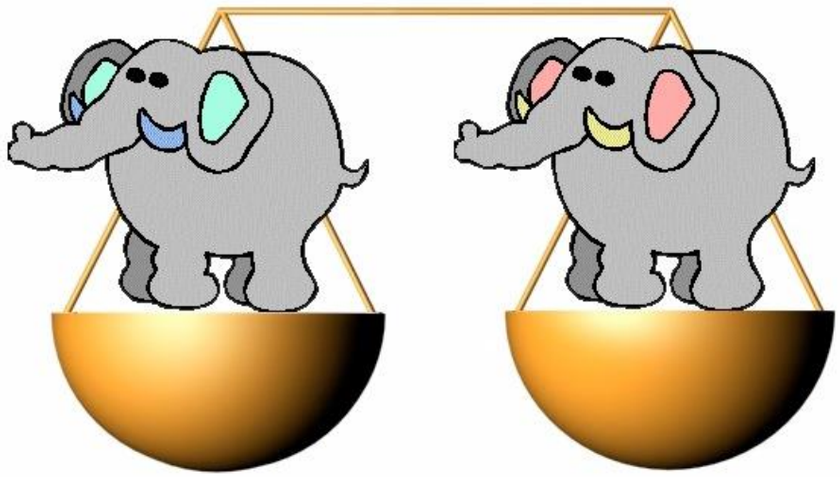
Is that true? Make very precise comparisons!



Mass of proton and antiproton ?

Present result: $\Delta M/M < 0.\ 000\ 000\ 000\ 1$

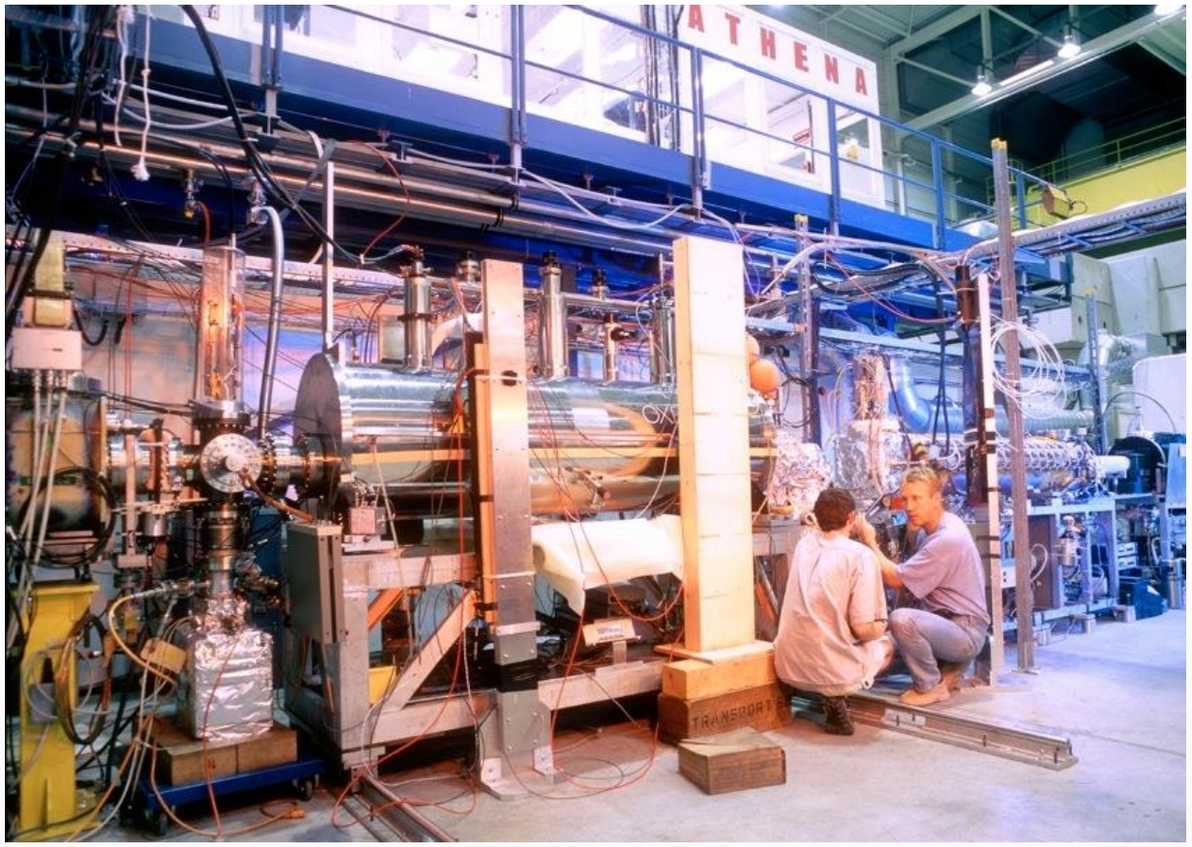
difference less than one dust grain

Magnetic moment of electron and positron ?

Present result: $\Delta\mu/\mu < 0.\ 000\ 000\ 000\ 001$

Present status: excellent agreement !

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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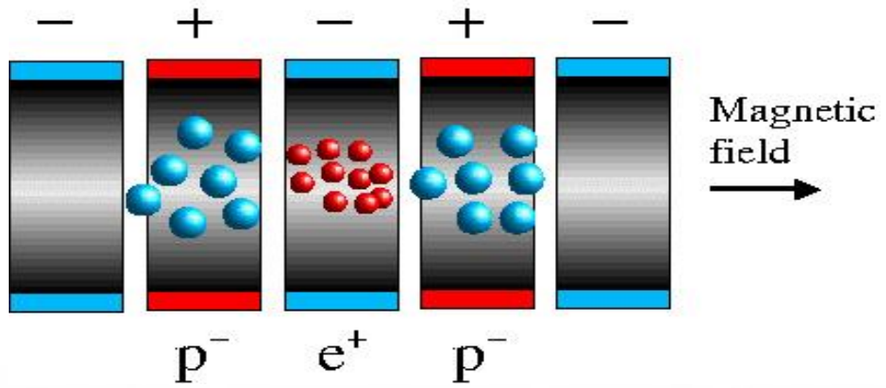
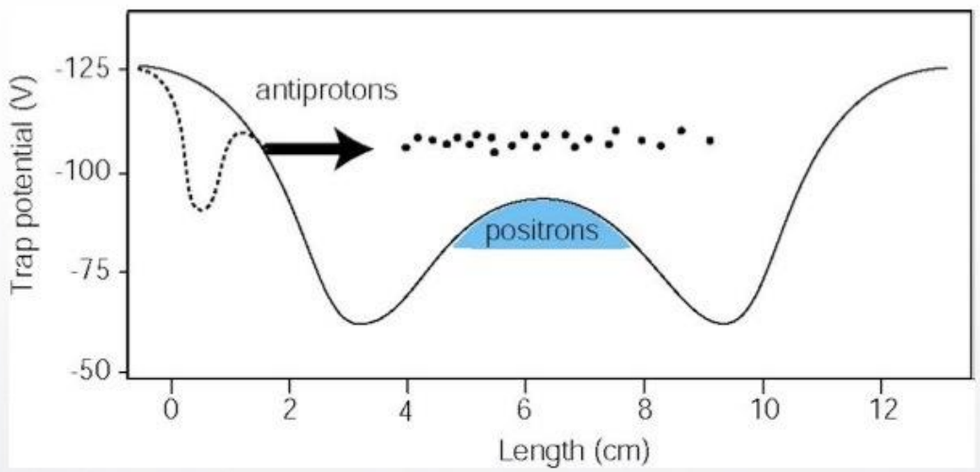
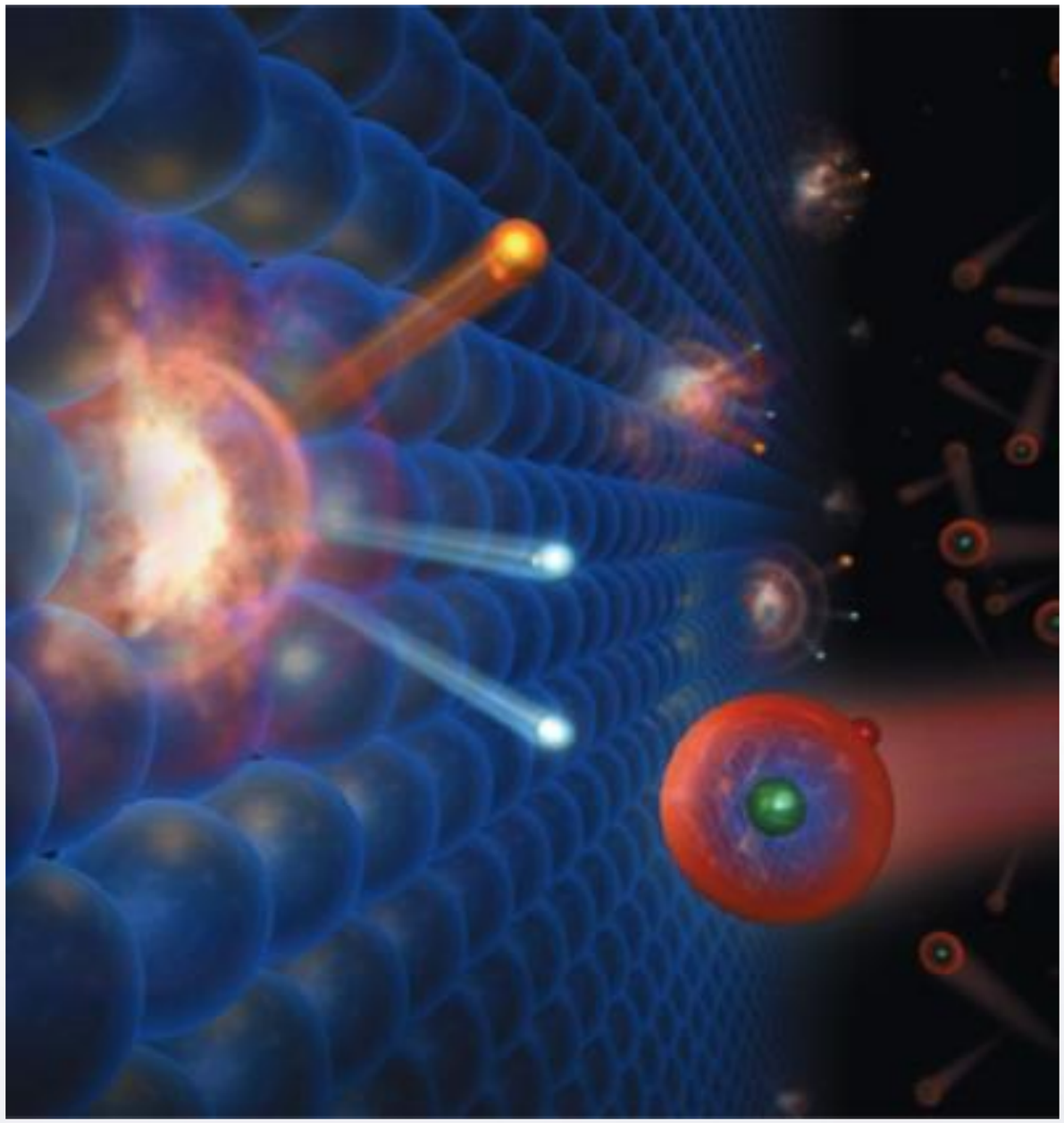
Recombination





- 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