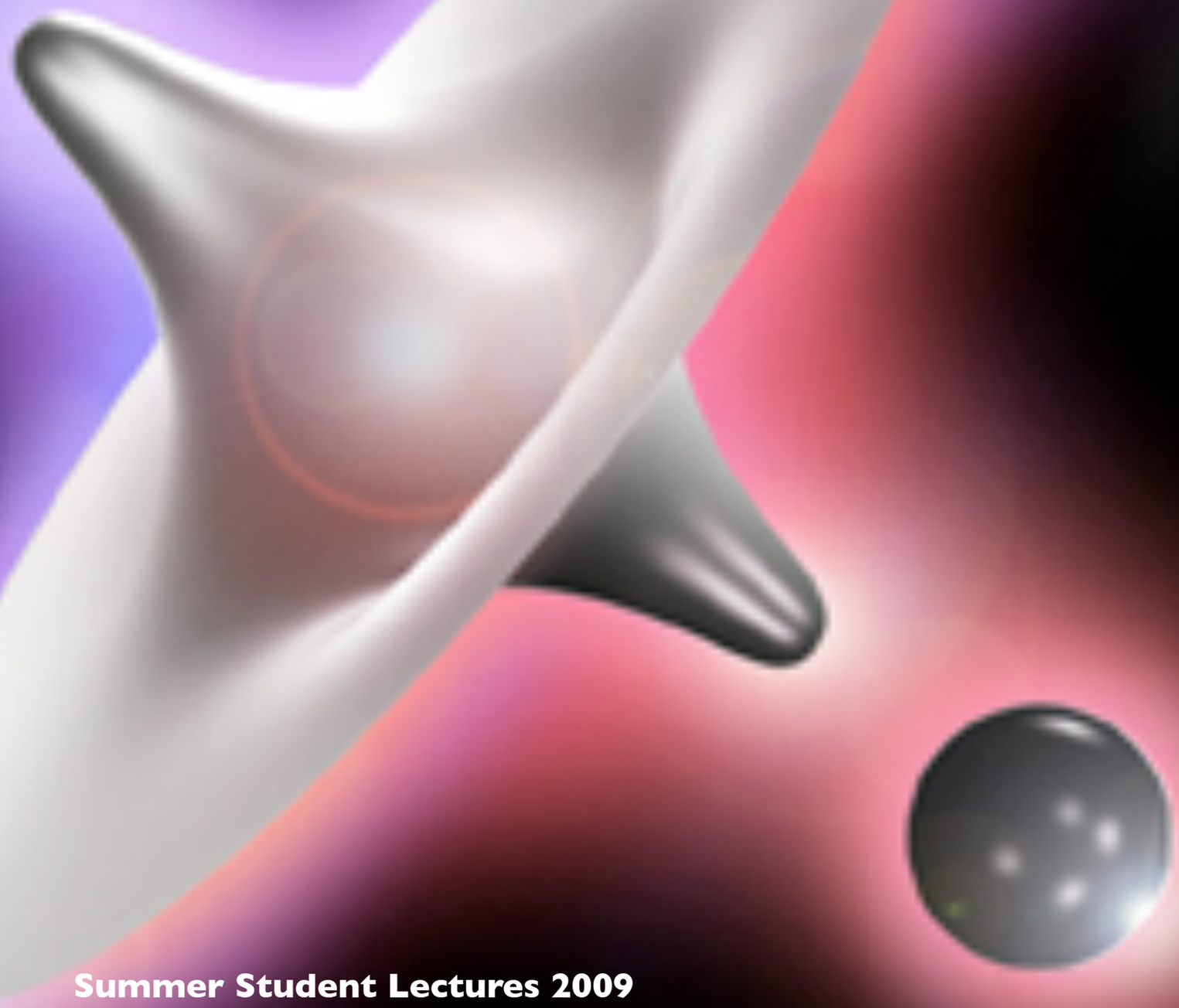
Antimatter in the Laboratory

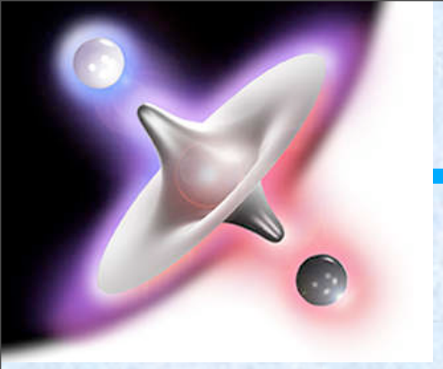
Rolf Landua
CERN



Summer Student Lectures 2009

Promotional video made for this lecture:

‘Angels+Demons’ crew looks at your lecture theatre



How CERN **really** became famous

1996

Nine antihydrogen atoms (LEAR)

v ~ c

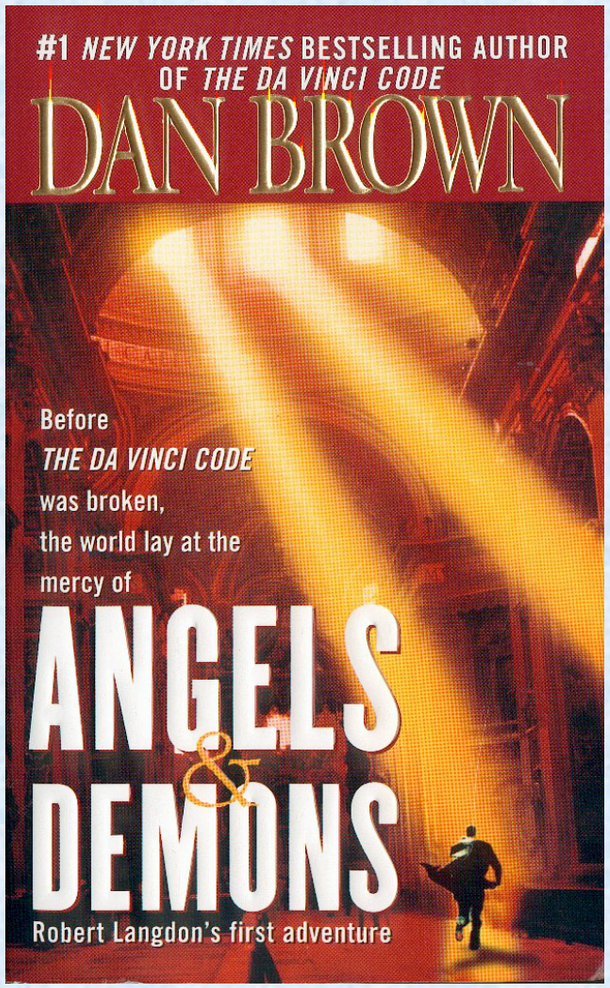
2 BLICK • Samstag, 6. Januar 1996 AKTUELL

E.T., wir kommen!

In Genf wurde Wunder-Energie entdeckt

VON WERNER BUCHER ment: Einen klitzekleinen und sind Forscher auf der mentell ist der Nachweis stoss ins Universum (lie-

"Blick" (CH)

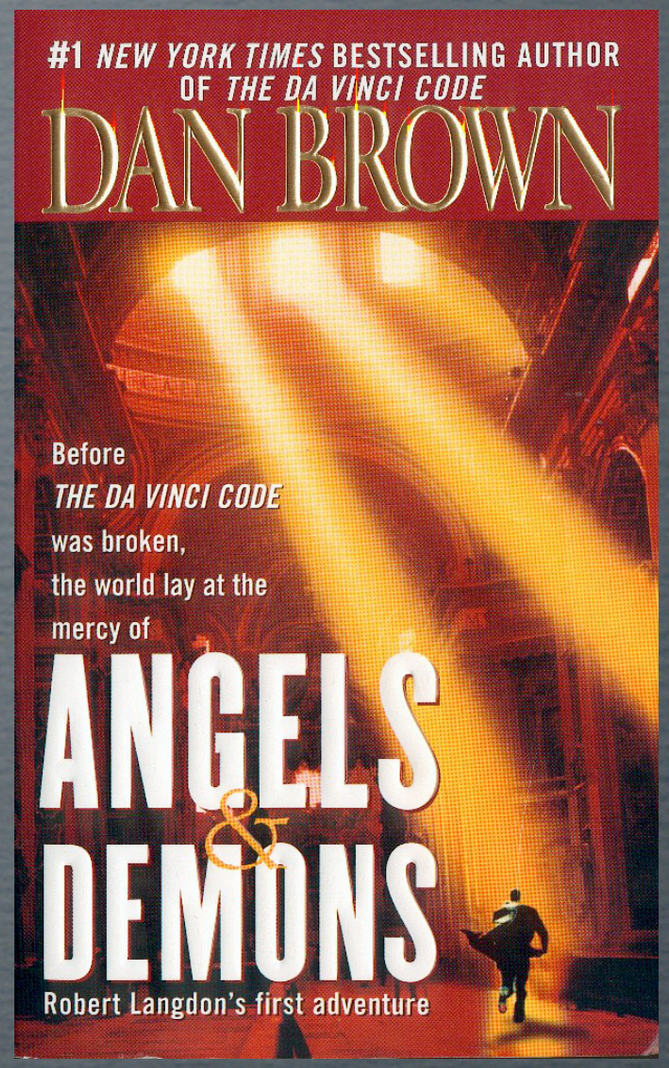


2000

Start of CERNs 'Antimatter Factory' (AD)

Production and capture (?) of 'slow' antihydrogen

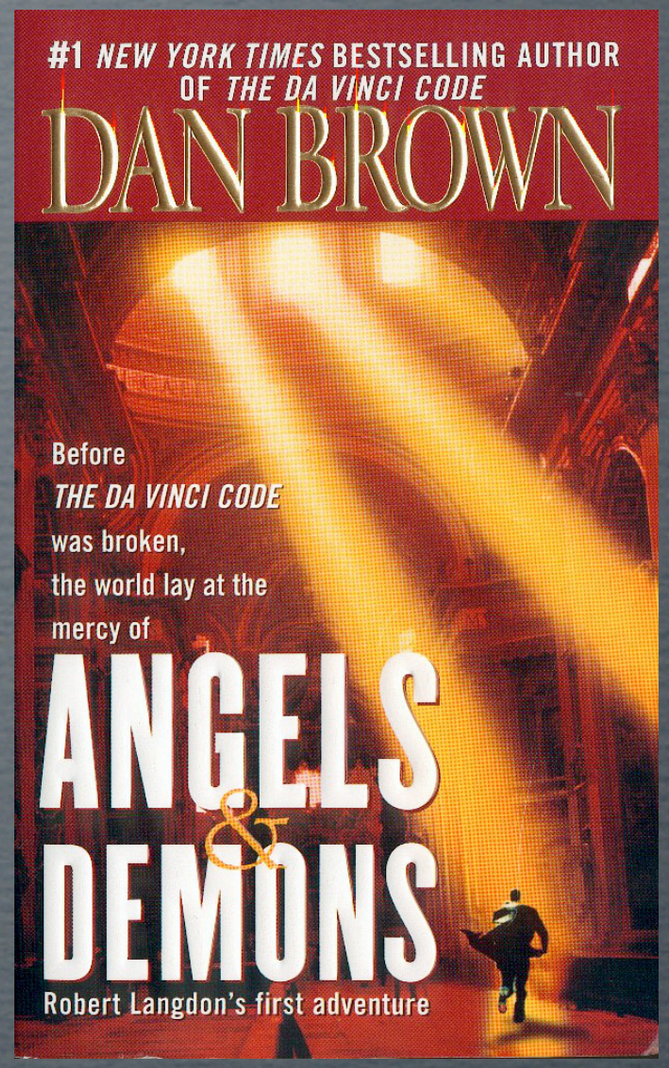
ANGELS AND DEMONS



ANGELS AND DEMONS

Illuminati

Detective story about a secret society which ...



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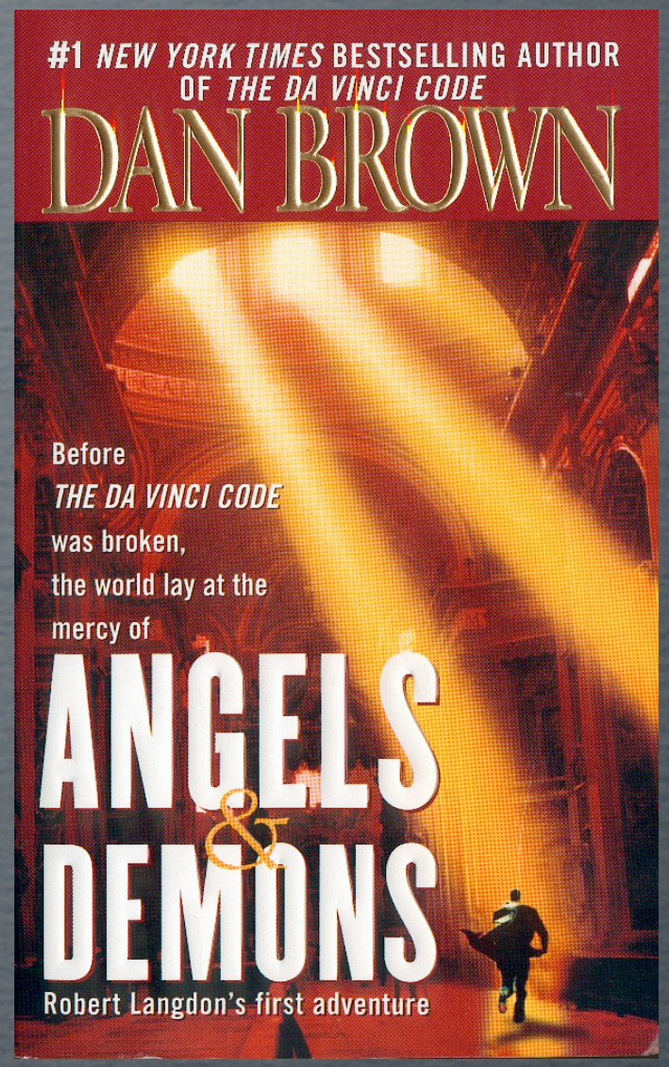

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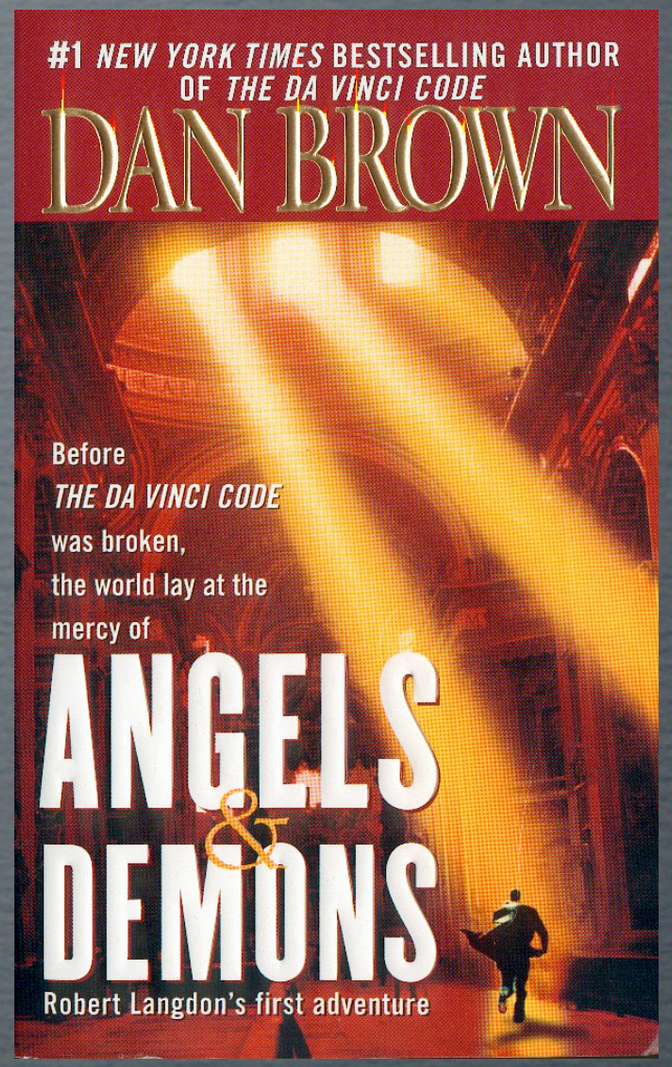

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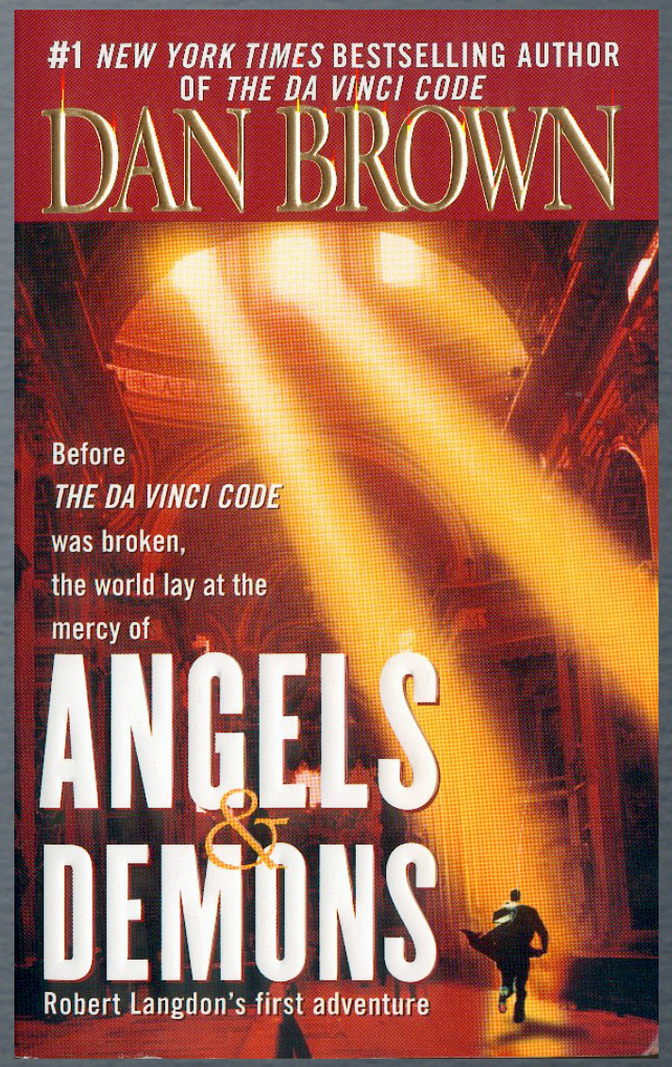
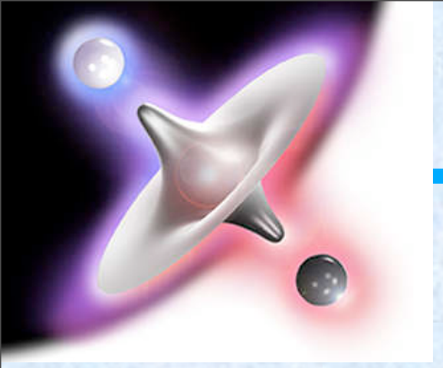
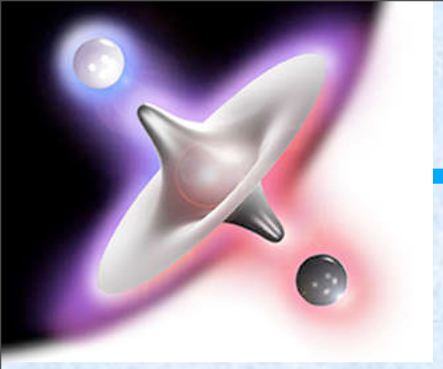


A mix of fact and fiction. What is true? What is false?



“Angels and Demons” - The Movie

***Da Vinci Code, Apollo 13, Beautiful mind, …**



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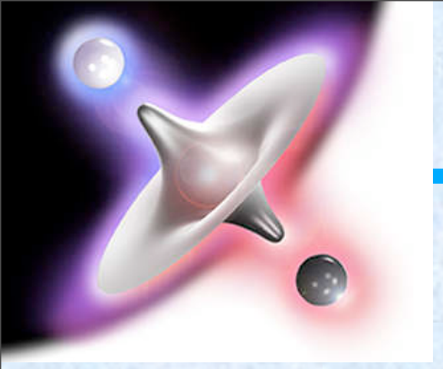

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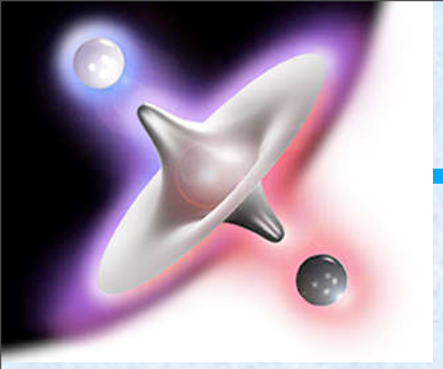

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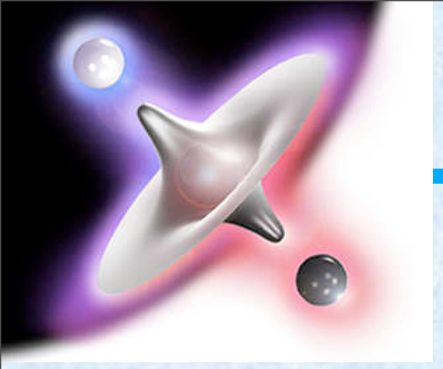

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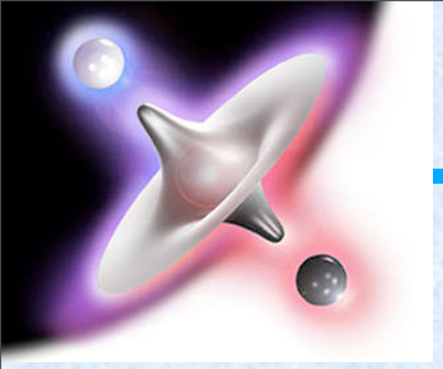

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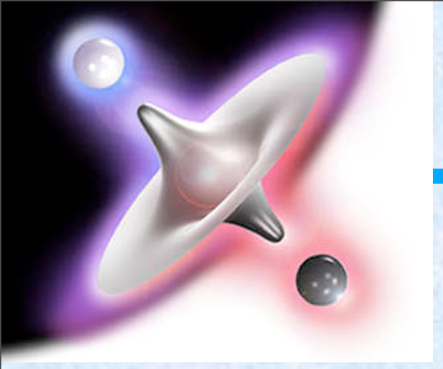

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The correct answer at the end of this lecture....

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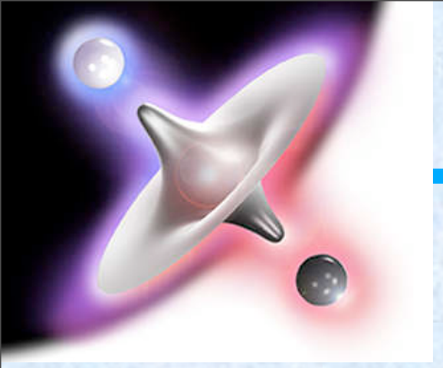
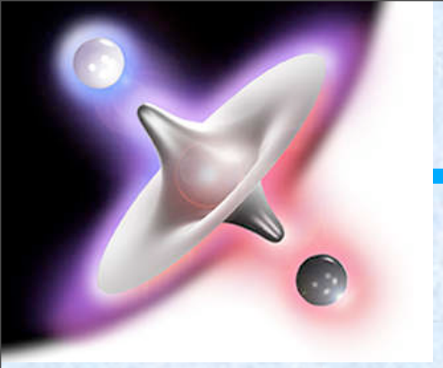


Plan

Overview Einstein, Dirac, Feynman, CPT, ...



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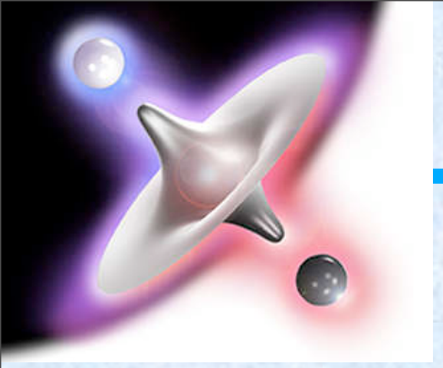
Antimatter 'Factory' — How are antiprotons made?



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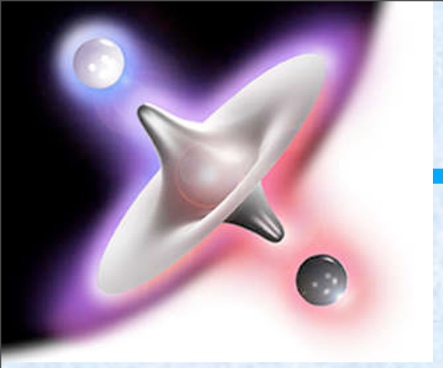
Antihydrogen

- Short history
- How to make antihydrogen
- Future developments



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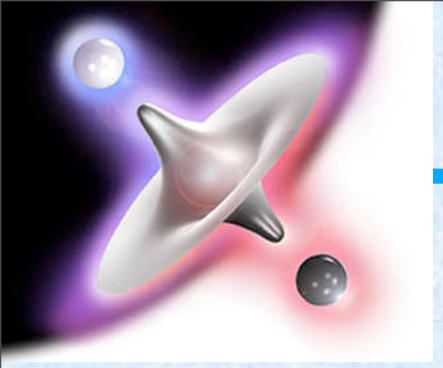
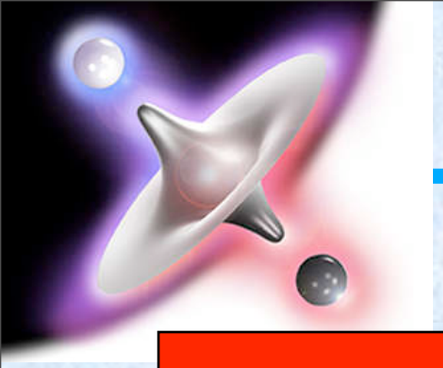
Antimatter technology
- PET
- Antiproton therapy?
- Rocket propulsion??



1. Overview - History of Antimatter



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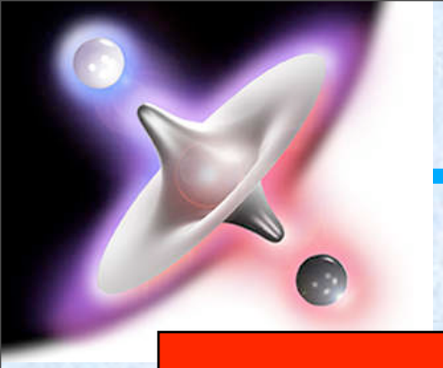
1905
Special relativity

1925
Quantum Mechanics



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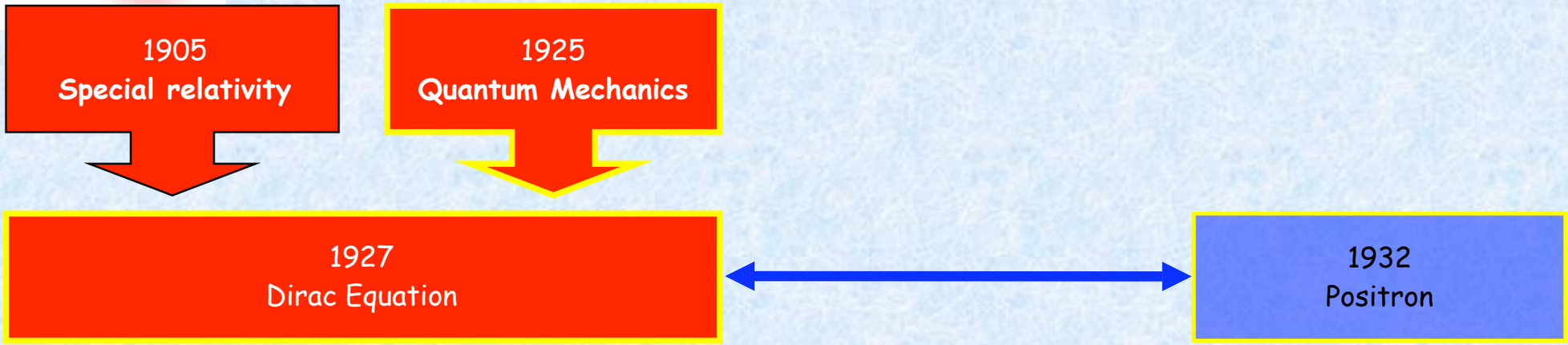

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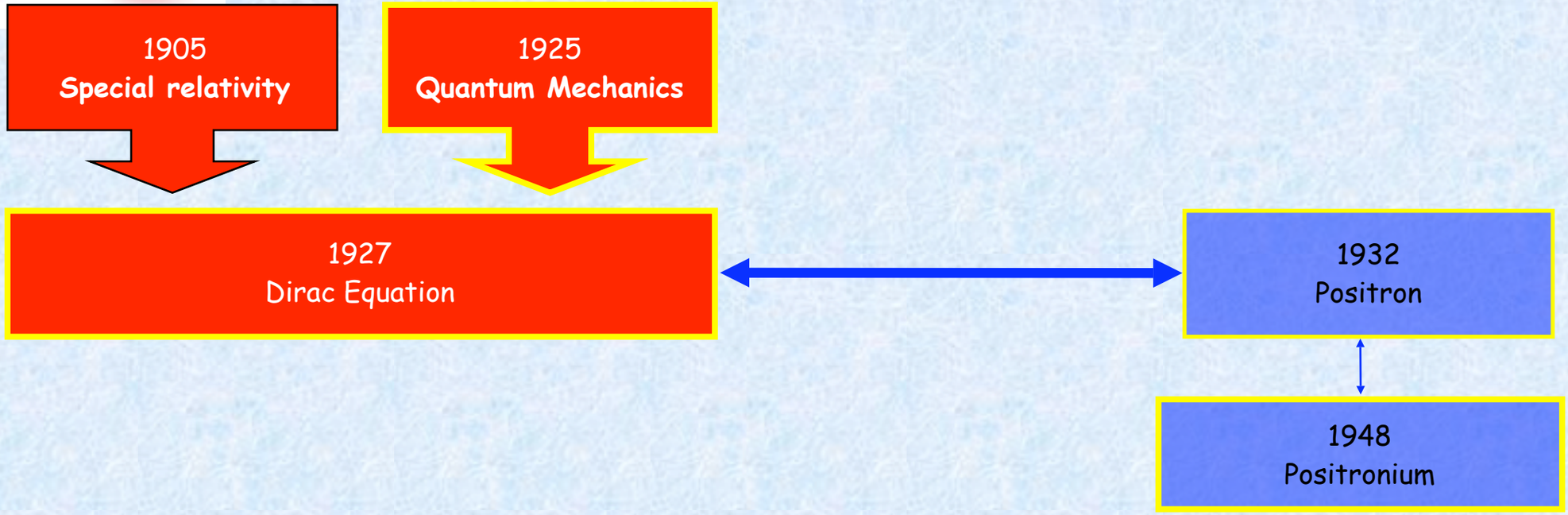

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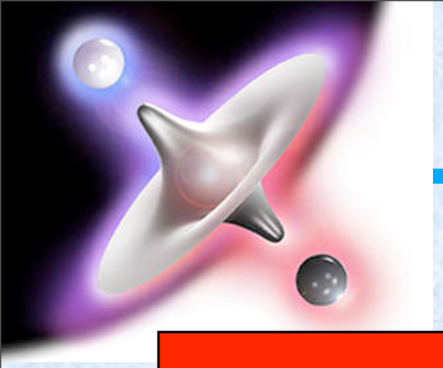

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1996: Hot (v~c) Antihydrogen

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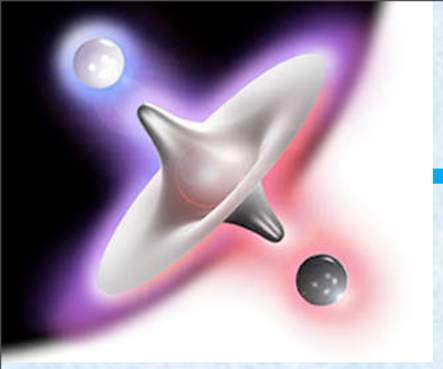
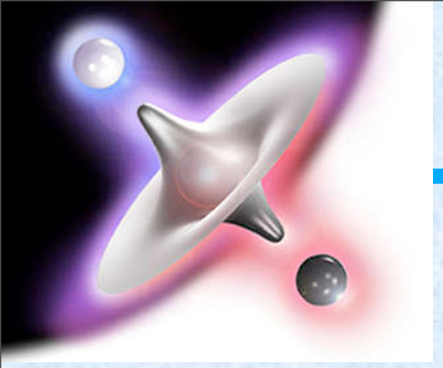
Cold Antihydrogen



Special relativity + Quantum Mechanics = Antimatter



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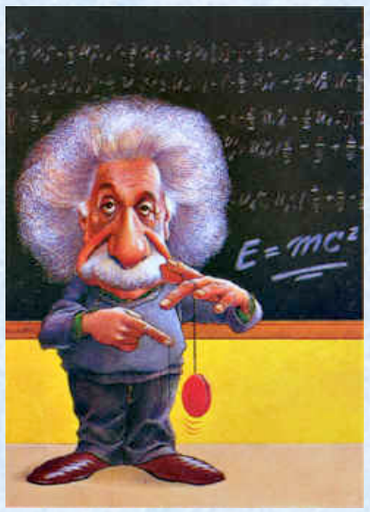
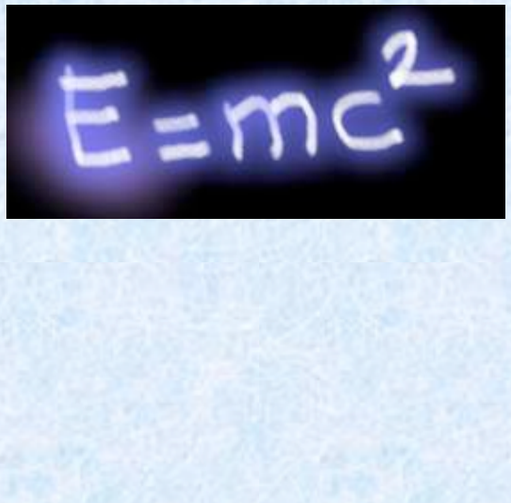


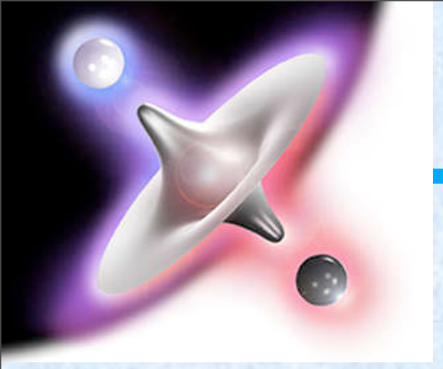


A. Einstein (1905)

Mass is condensed energy

(c^2 = exchange rate!)

1 kg = $9 \cdot 10^{16}$ J = 2.85 GW · year



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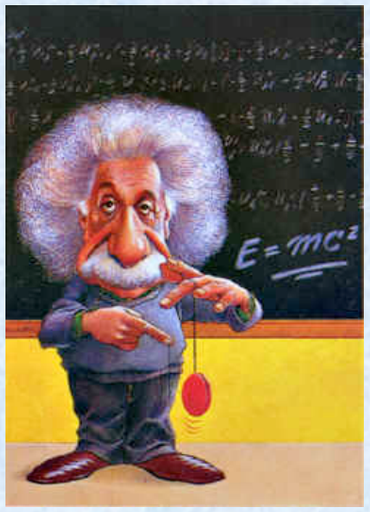
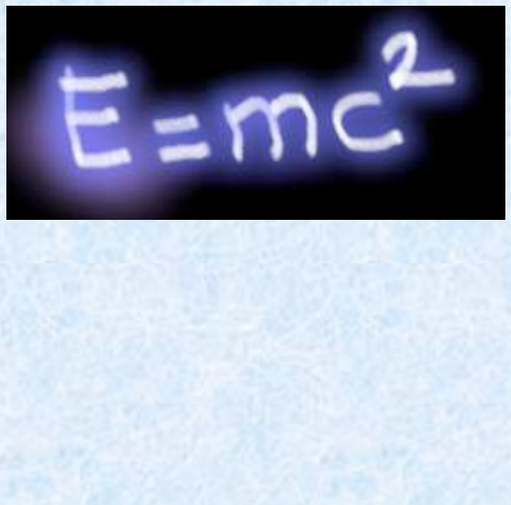
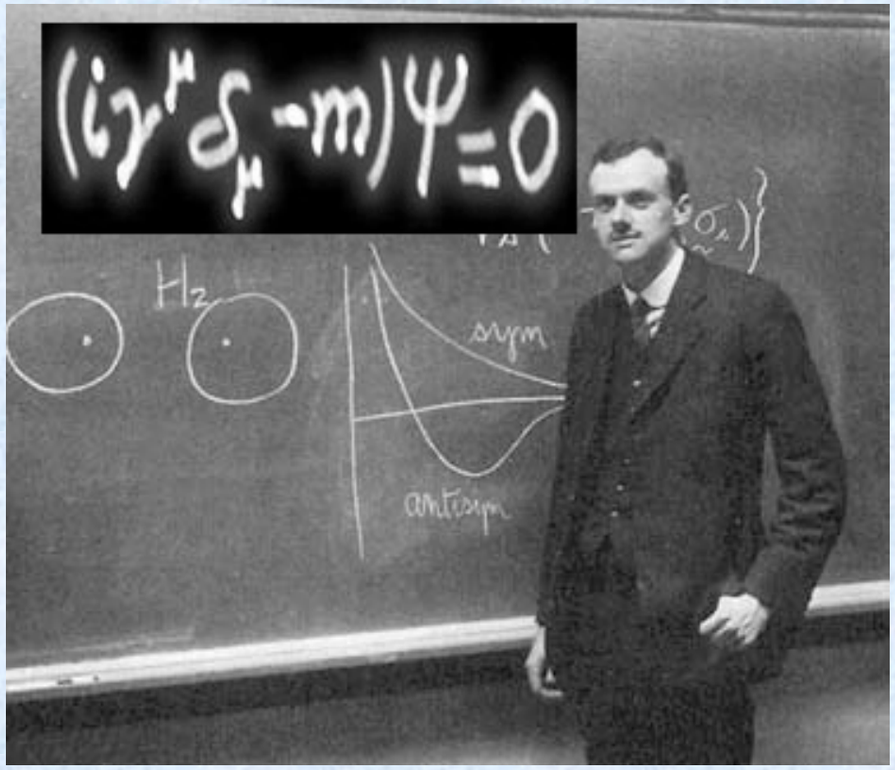


A. Einstein (1905)





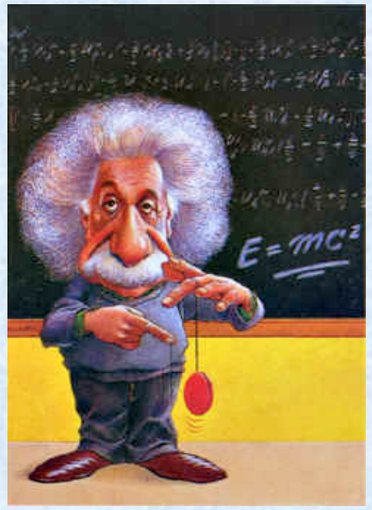
Paul A.M. Dirac (1928)

Mass is condensed energy

(c^2 = exchange rate!)

1 kg = $9 \cdot 10^{16}$ J = 2.85 GW · year

Special relativity + Quantum Mechanics = Antimatter



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$E = mc^2$

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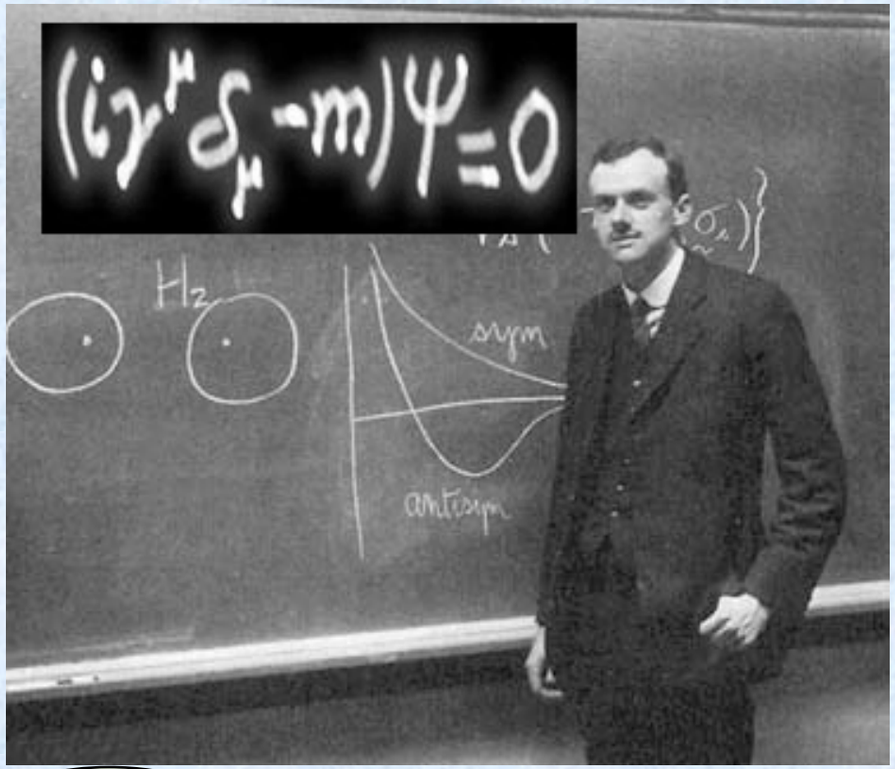

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What's that?

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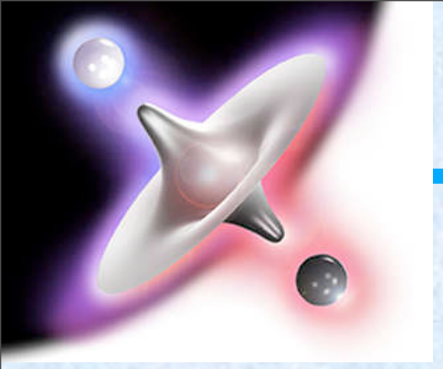

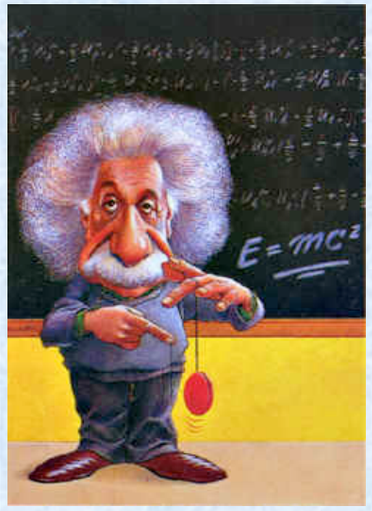

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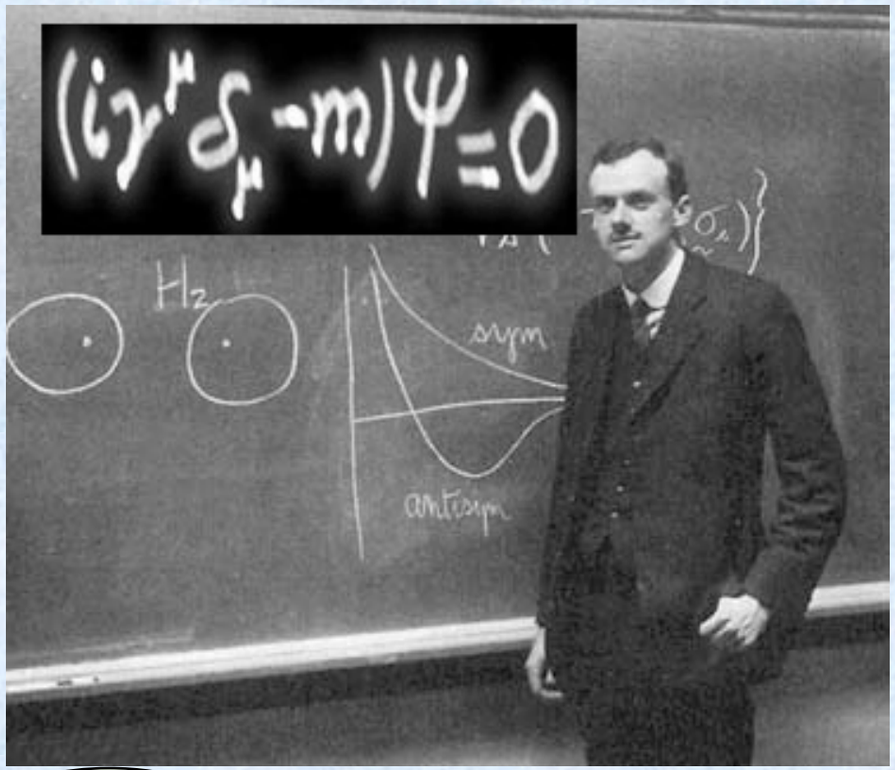

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- 1929: Positive electron = proton ????

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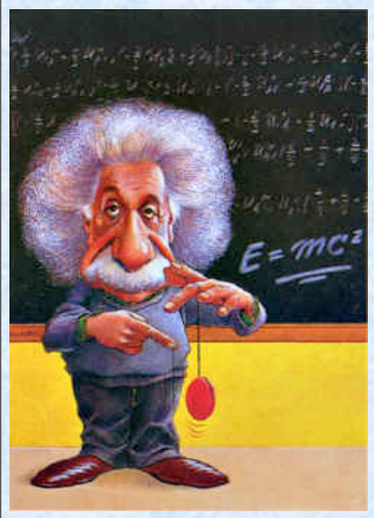

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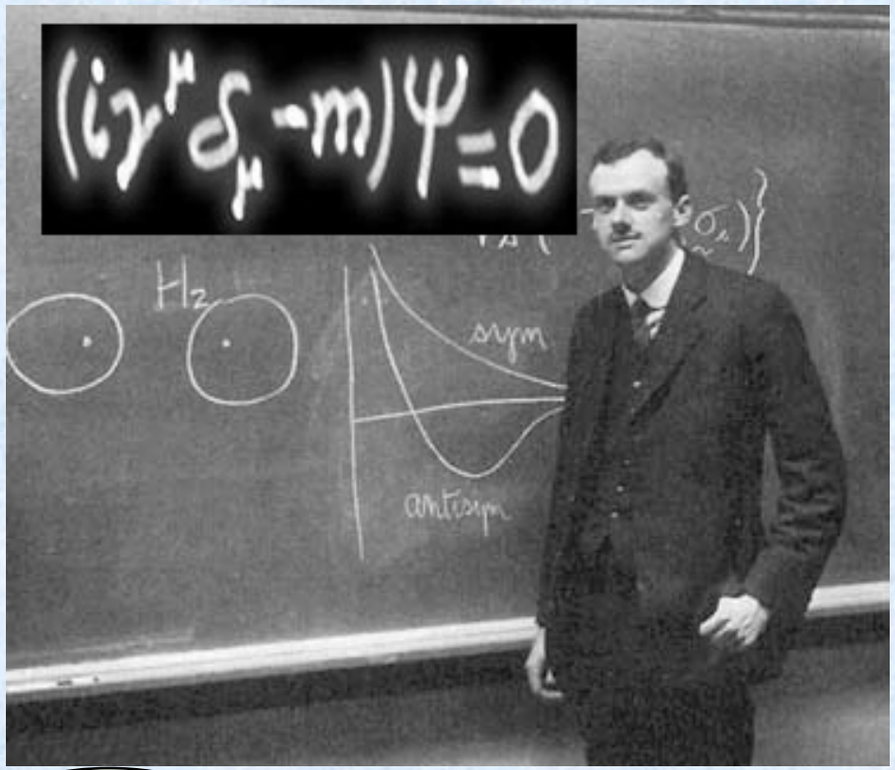

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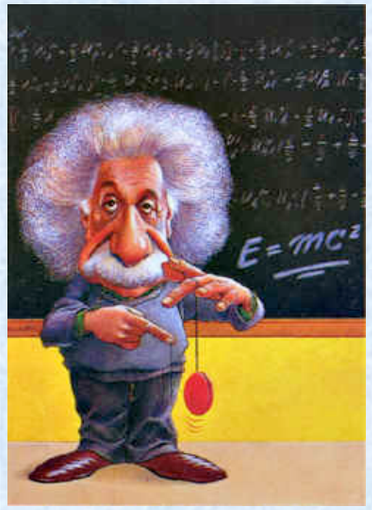

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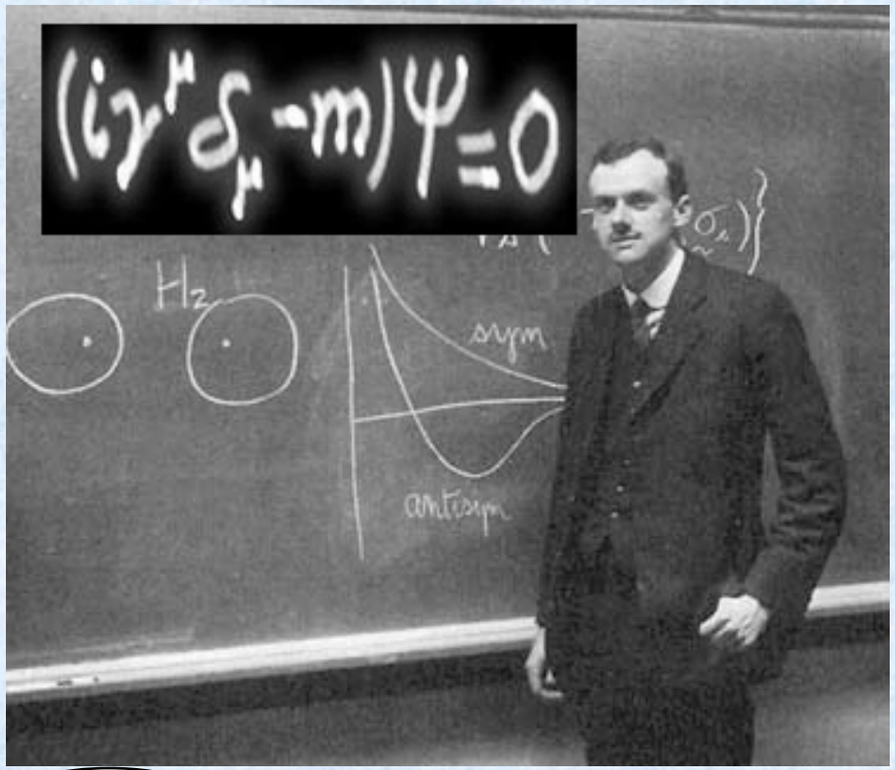

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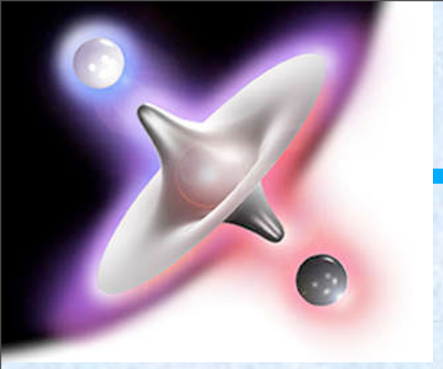
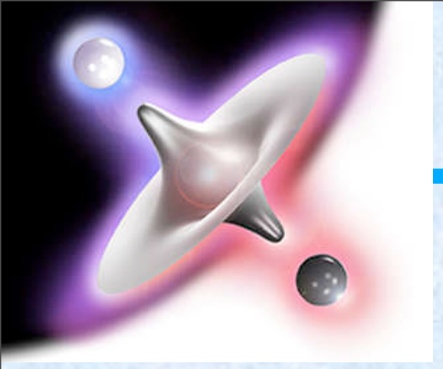
Dirac: Anti-Electron must exist !



Interlude: playing with equations (best guesses ...)



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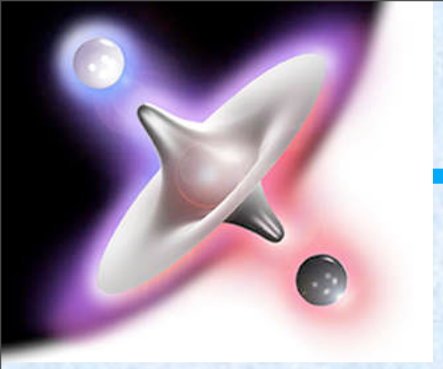
$$E = \frac{p^2}{2m} \rightarrow i\hbar\frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\nabla^2\psi$$

non-relativistic



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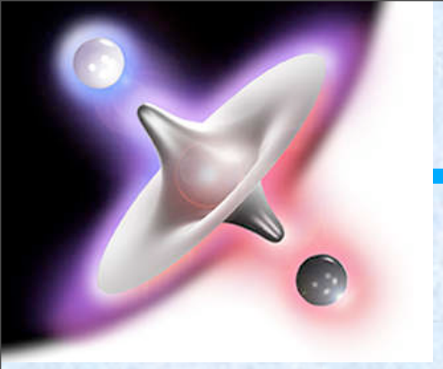
Klein-Gordon:

$$E^2 = p^2 + m^2 \rightarrow -\hbar^2\frac{\partial^2}{\partial t^2}\psi = -\hbar^2\nabla^2\psi + m^2\psi$$

relativistic, spin 0
(number of particles not conserved)



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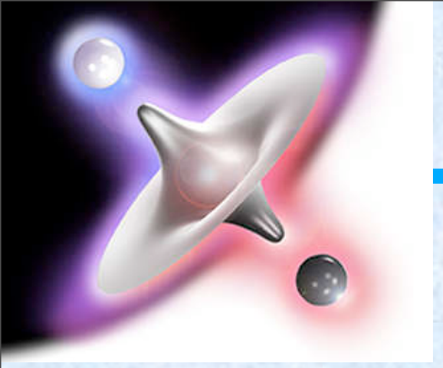
relativistic, spin 0
(number of particles not conserved)

Dirac:

$$E^2 = p^2 + m^2 \rightarrow$$
$$E = \pm(\alpha\cdot p) + \beta m$$

$$i\frac{\partial}{\partial t}\psi = -i\,(\alpha_x\frac{\partial}{\partial x}\psi + ...) + \beta\, m\, \psi$$

relativistic, spin 1/2
(number of particles conserved)



Positron discovery- why so late ?

C. D. Anderson.
Phys. Rev., **43**, 491 (1933)

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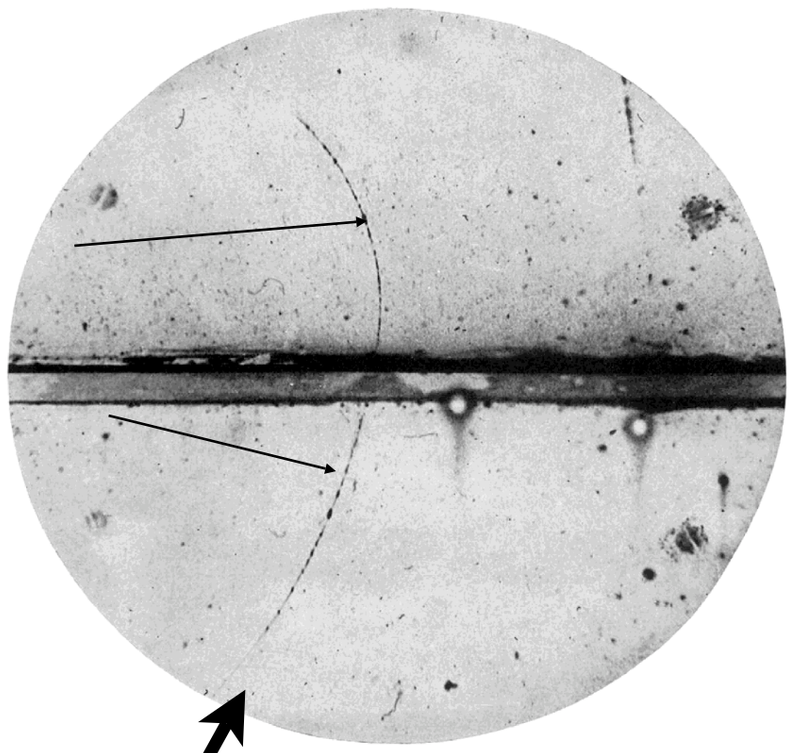


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Positron from below

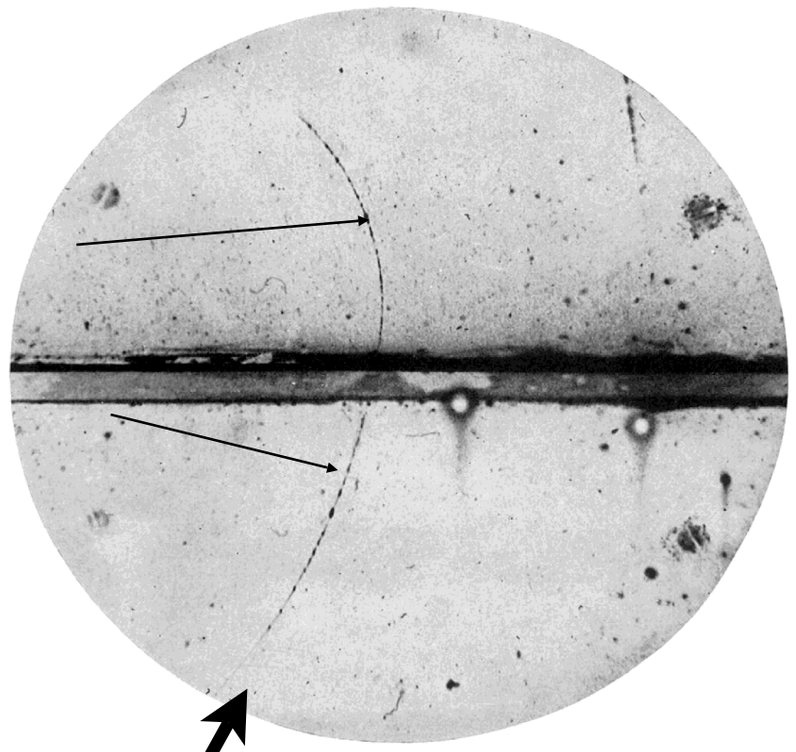
Positron discovery- why so late ?

C. D. Anderson.
Phys. Rev., **43**, 491 (1933)

Dirac :

"Why did the experimentalists not see them? Because they were prejudiced against them.

The experimentalists … sometimes saw the opposite curvature, and interpreted the tracks as electrons which happened to be moving into the source, instead of the positively charged particles coming out.



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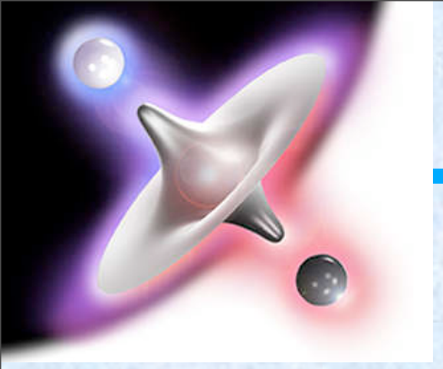
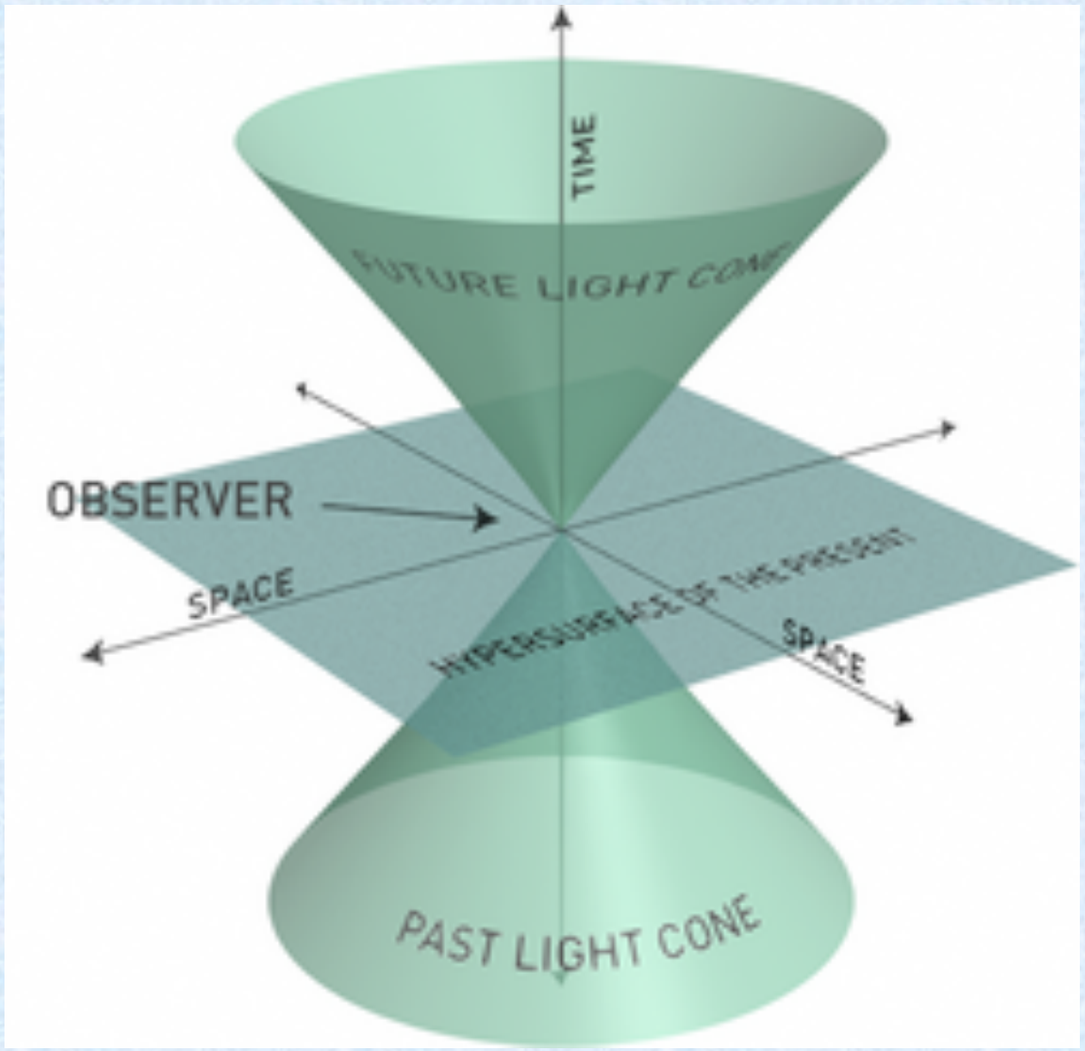


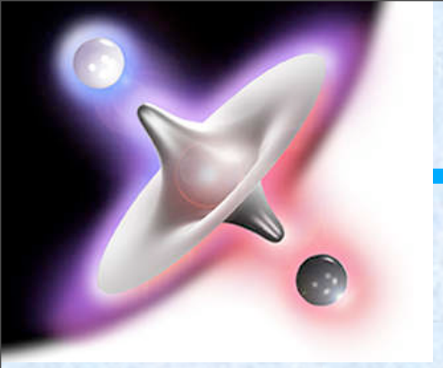
WHY ANTIPARTICLES MUST EXIST

Relativity and Causality

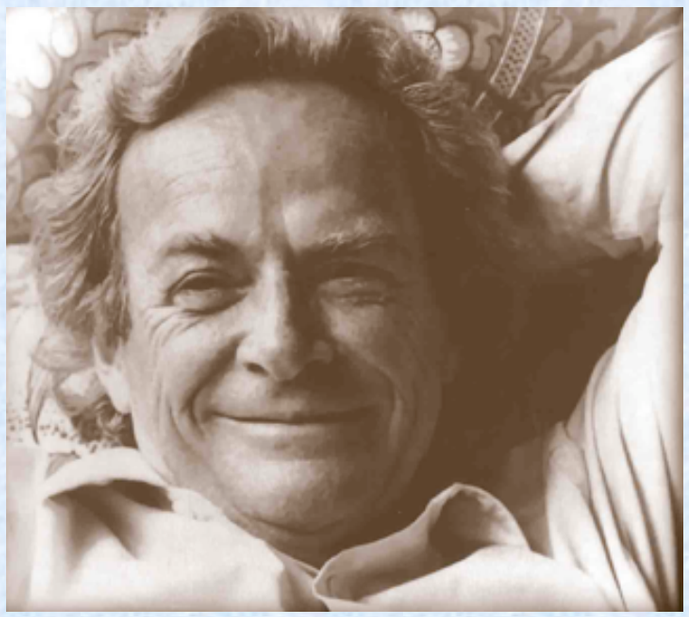


Causal connection between two events can only exist within "light cone"

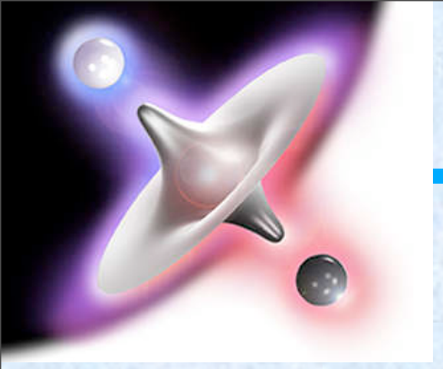
Clear distinction between the PAST and the FUTURE (for a given observer)



Antimatter in Quantum Field Theory

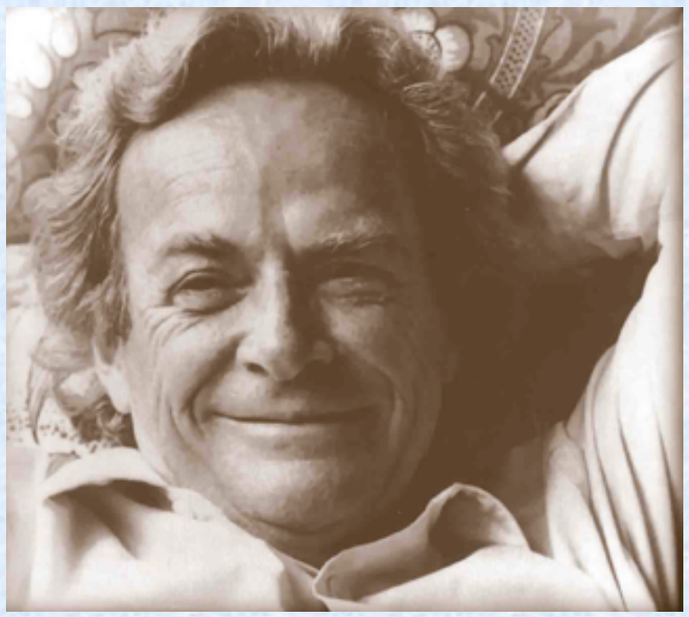


R. P. Feynman



Antimatter in Quantum Field Theory

The electron (field) is no longer described by a wave function but an operator that creates and destroys particles. All energies are positive.



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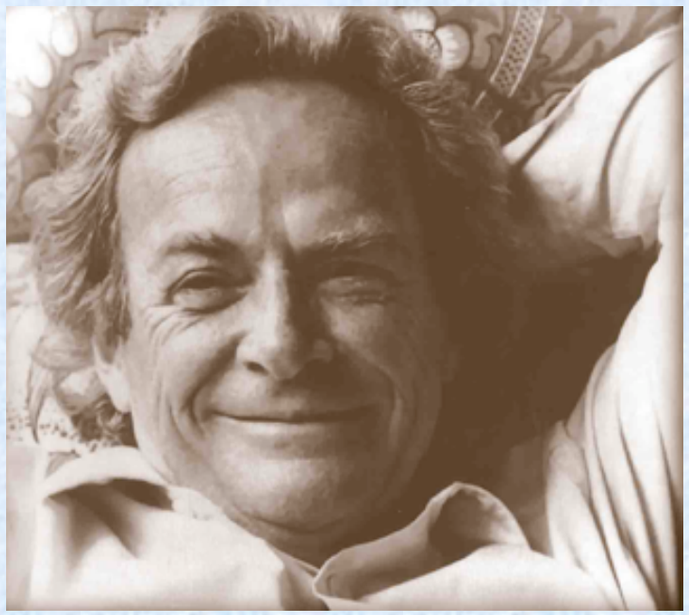

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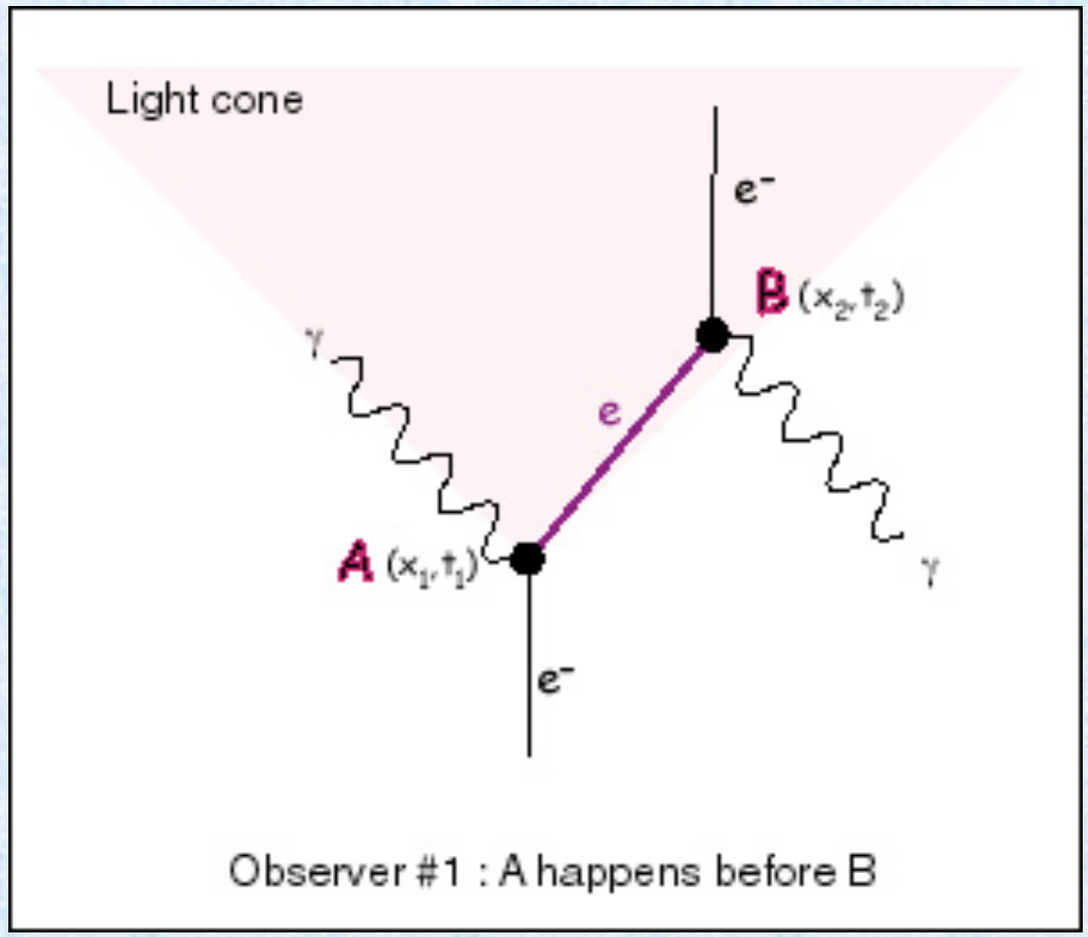
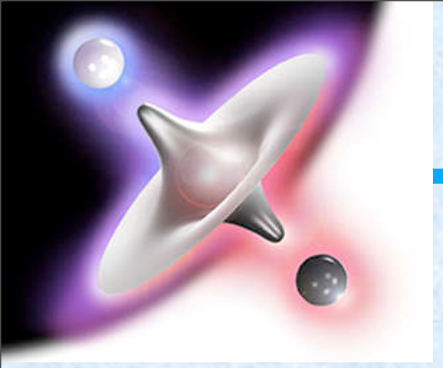
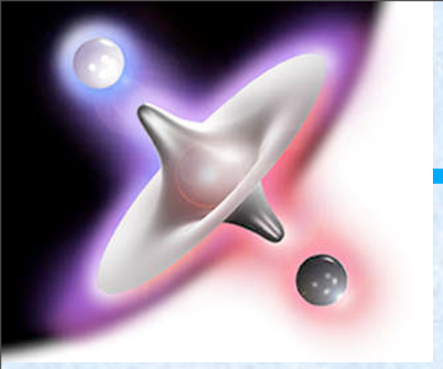


An electron can emit a photon at A, propagate a certain distance, and then absorb another photon at B.



Causality requires antiparticles to exist

Wave function only localized within Compton wave length ($\lambda \sim 1/m$).



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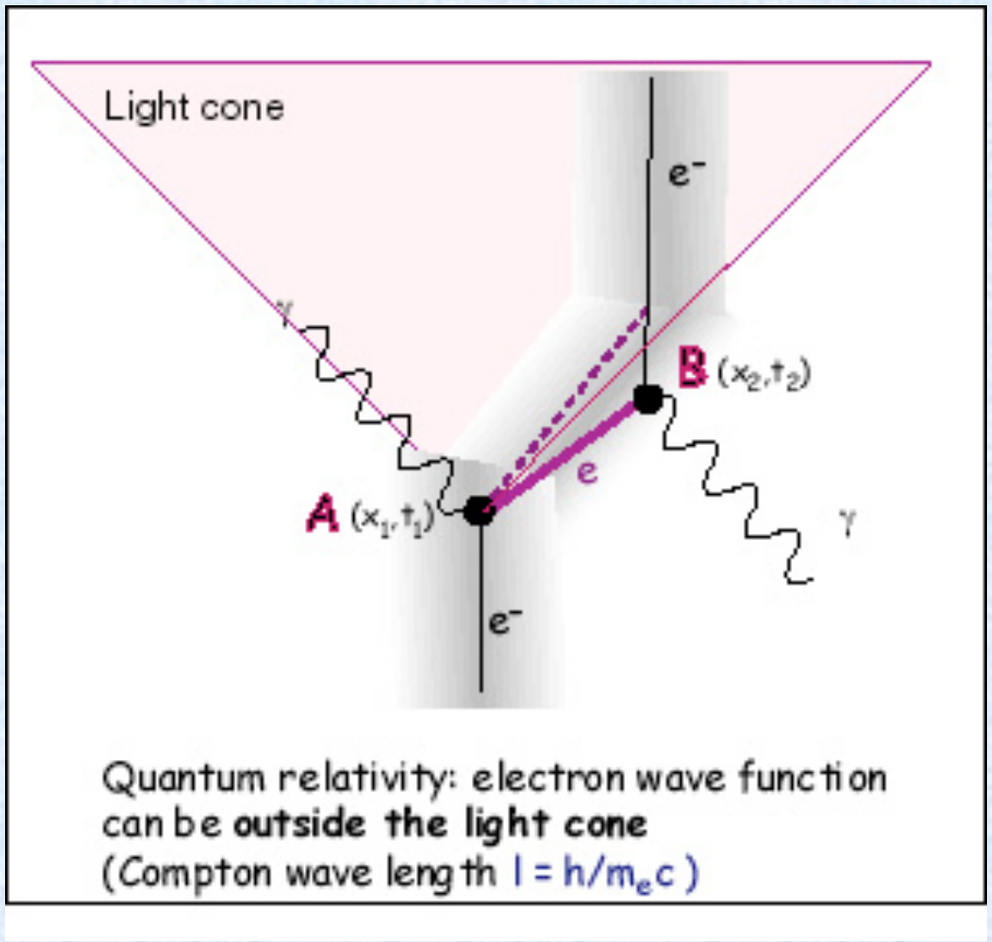

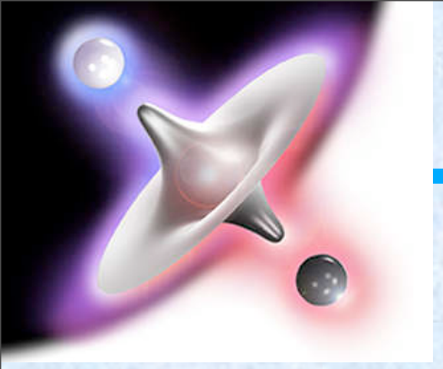

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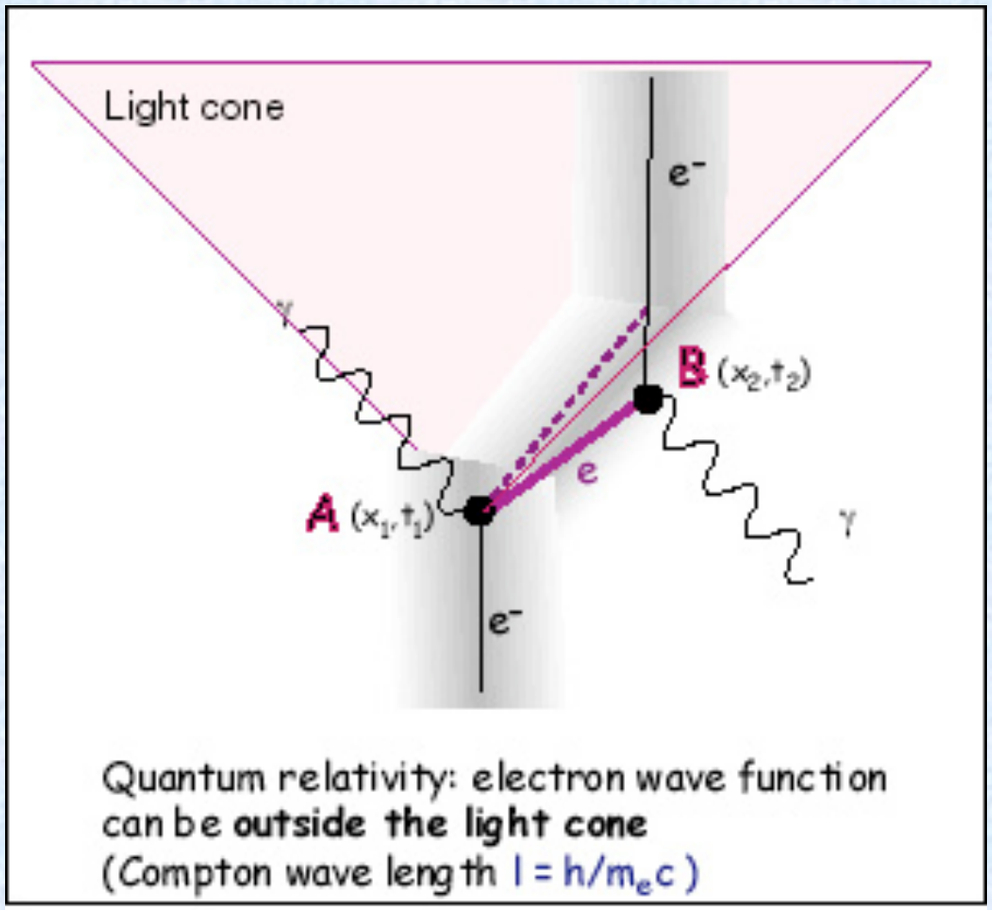
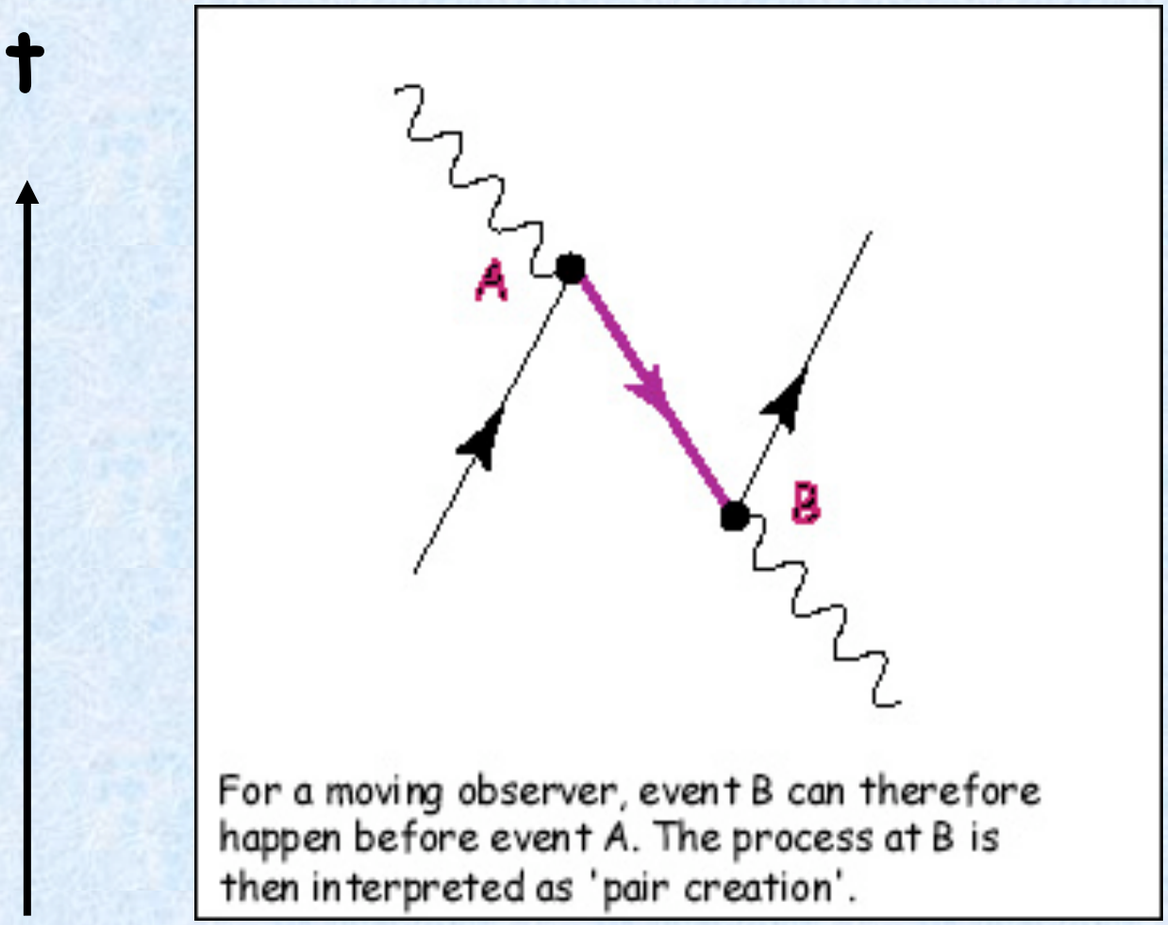
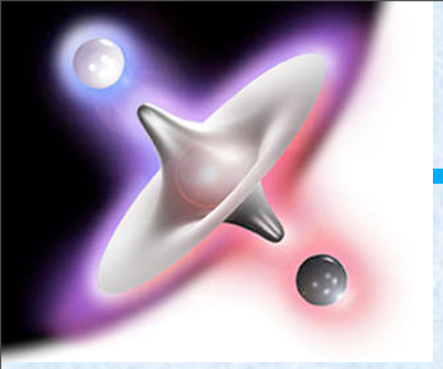


Quantum relativity: electron wave function can be **outside the light cone** (Compton wave length $l = h/m_e c$)



For a moving observer, event B can therefore happen before event A. The process at B is then interpreted as 'pair creation'.



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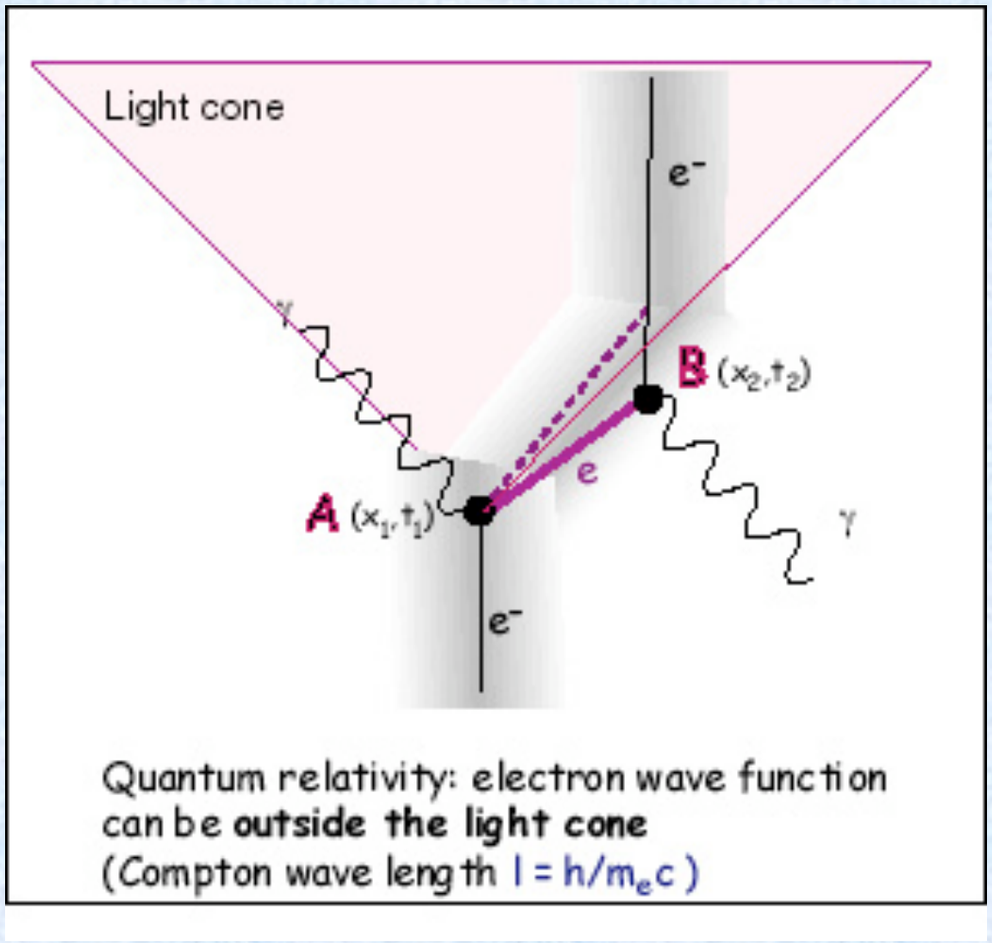

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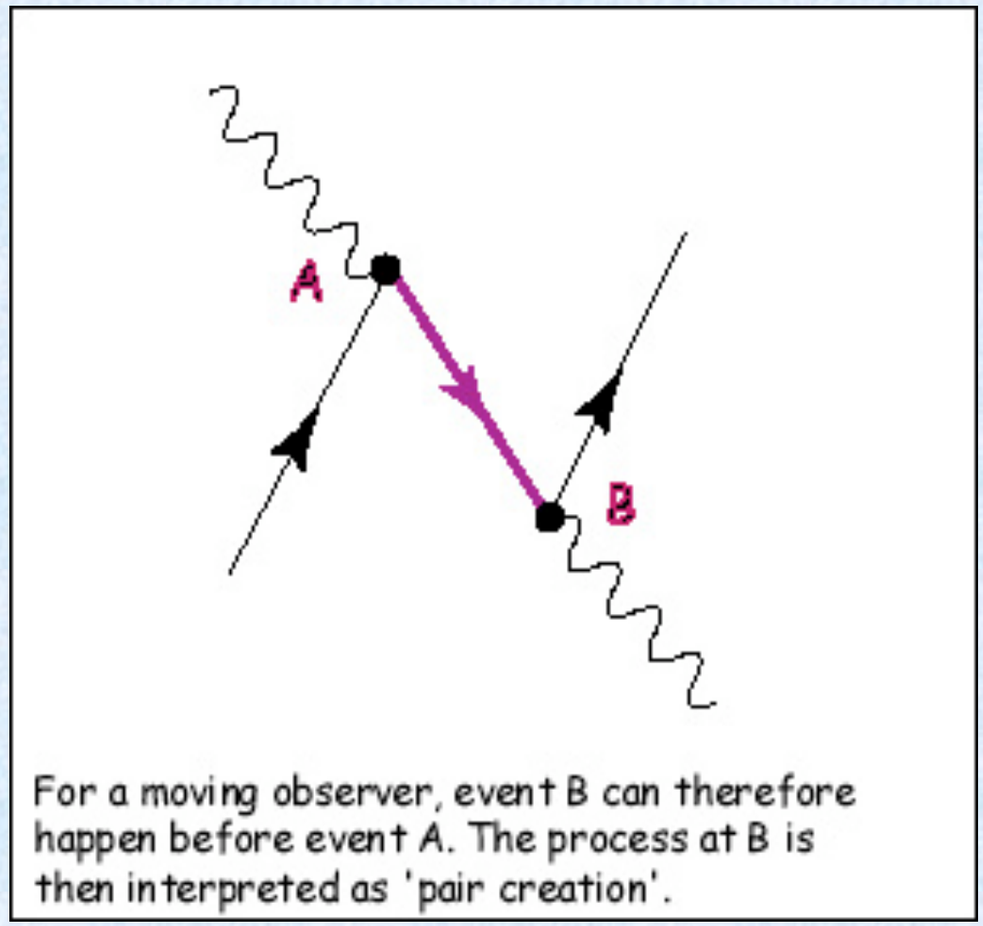

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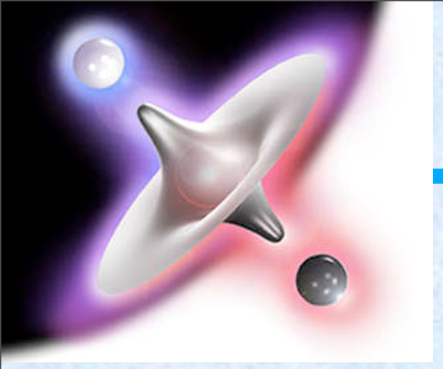
"One observer's electron is the other observer's positron"



Analogy : an airplane flying over a crooked road

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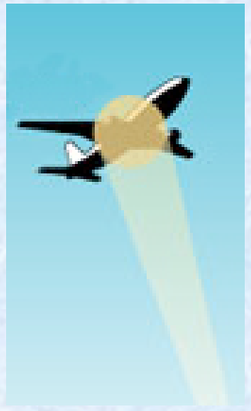
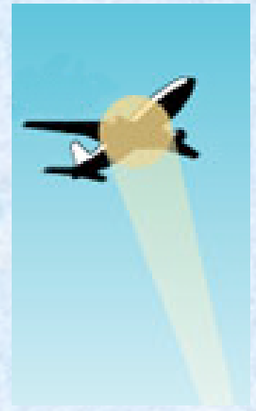
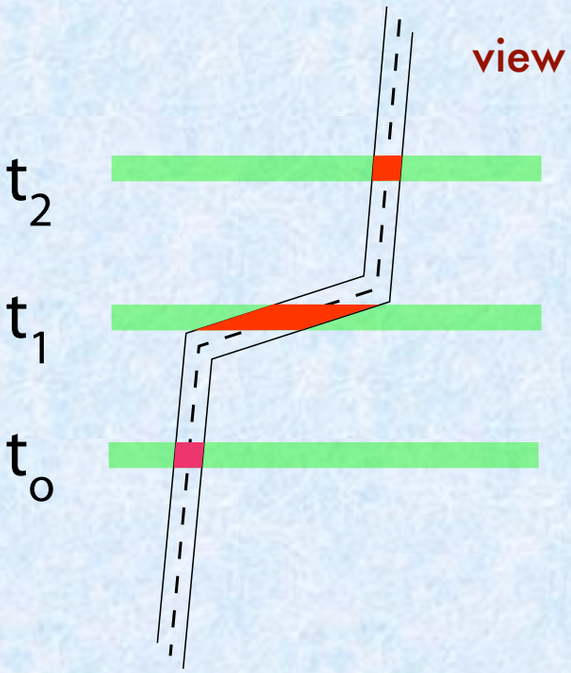


Observer A



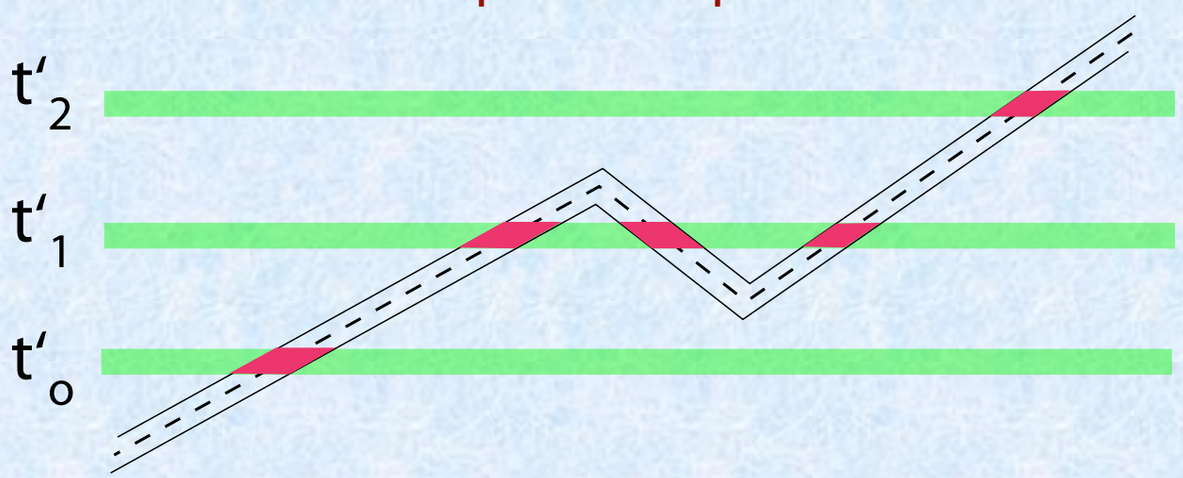
Observer B

Time

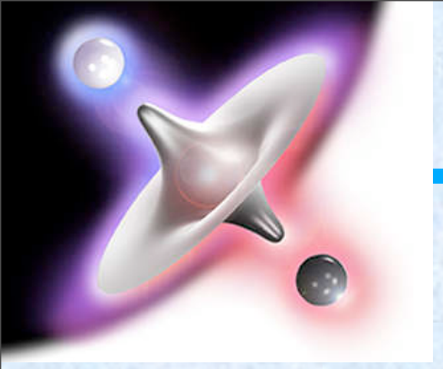


sees only one street

view of observer limited to narrow strip below airplane

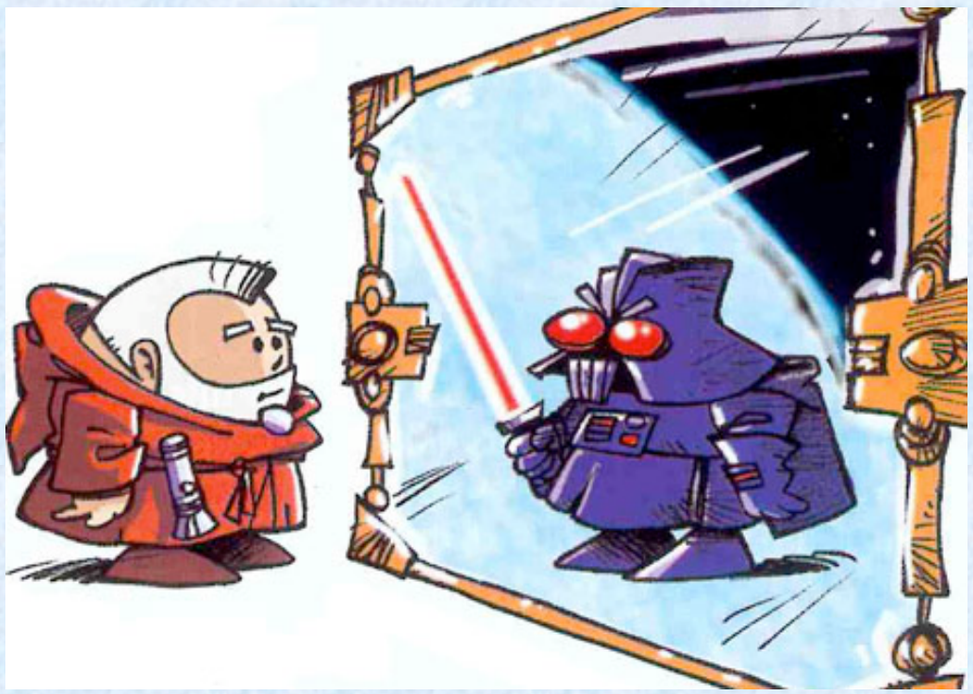


sees one street plus two streets emerging out of 'nowhere'

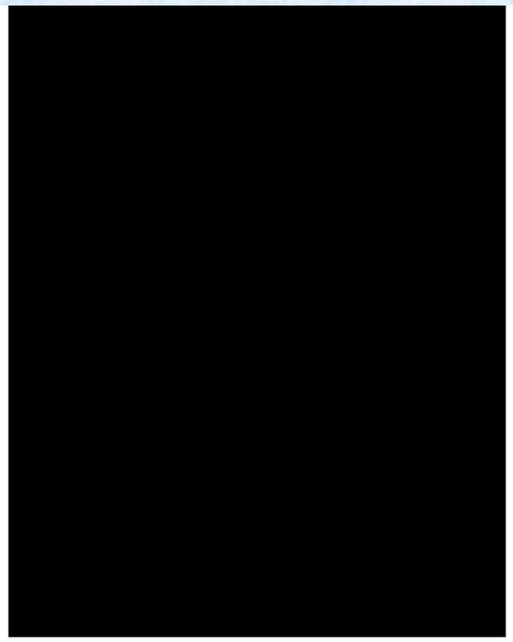


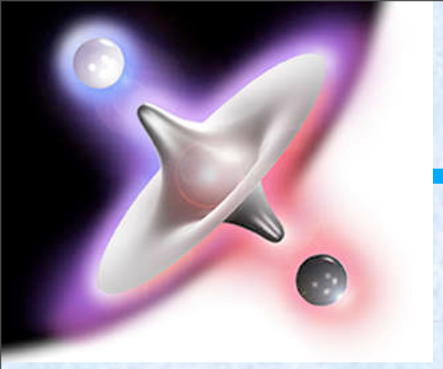
Particles and antiparticles

How can we imagine an 'anti-particle'?



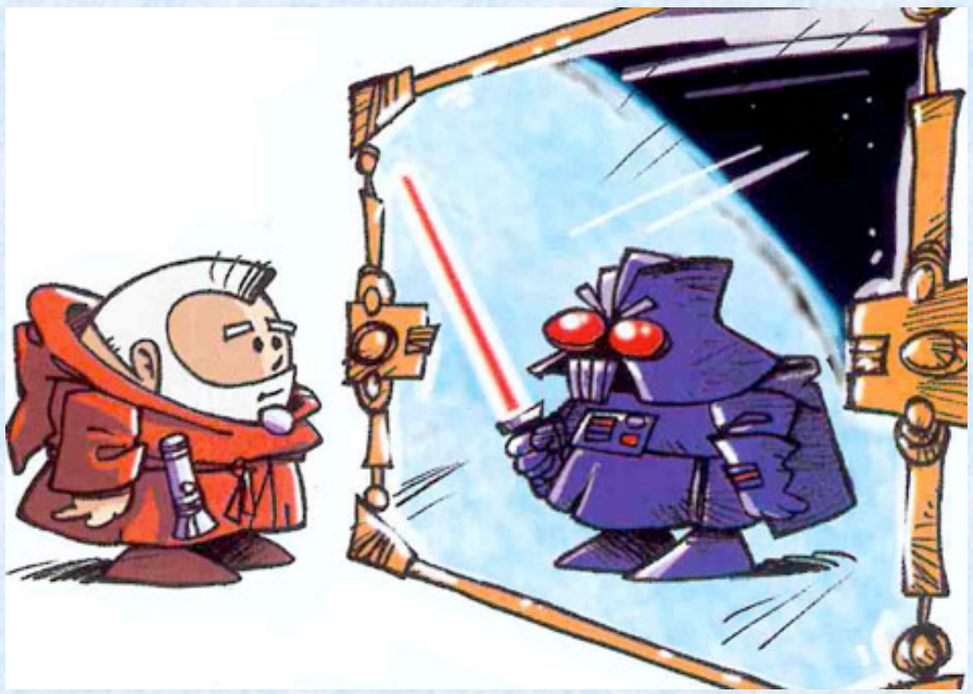
Star Wars version

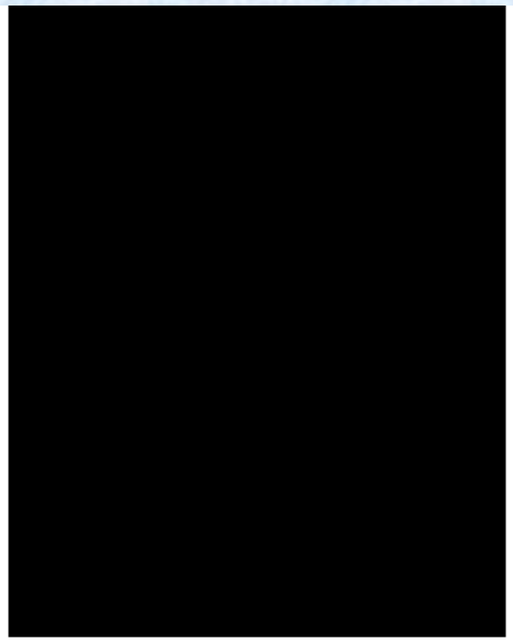




Particles and antiparticles

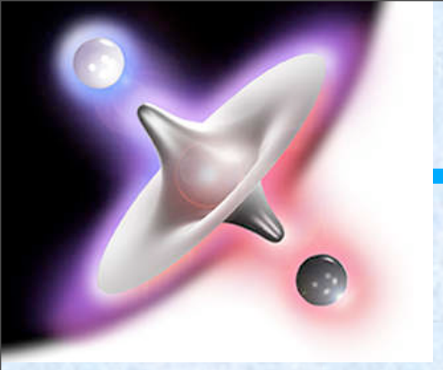
How can we imagine an 'anti-particle'?





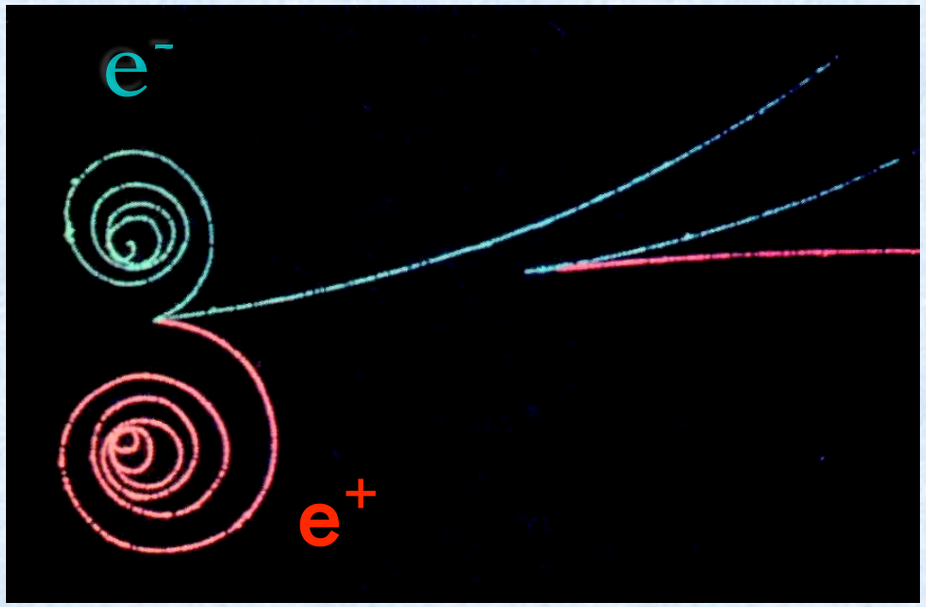
Star Wars version

Particles and anti-particles are two manifestations of the same underlying, but yet unknown, physical structure (superstrings??).

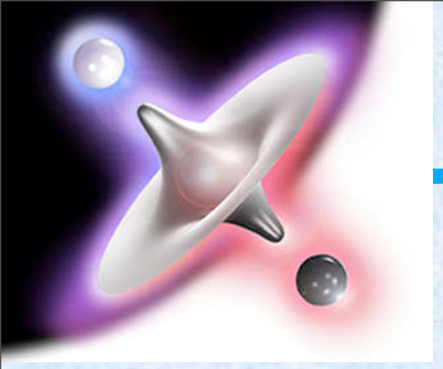


Therefore:

Particles and antiparticles are created in pairs



Particles and antiparticles can also destroy each other (annihilation)



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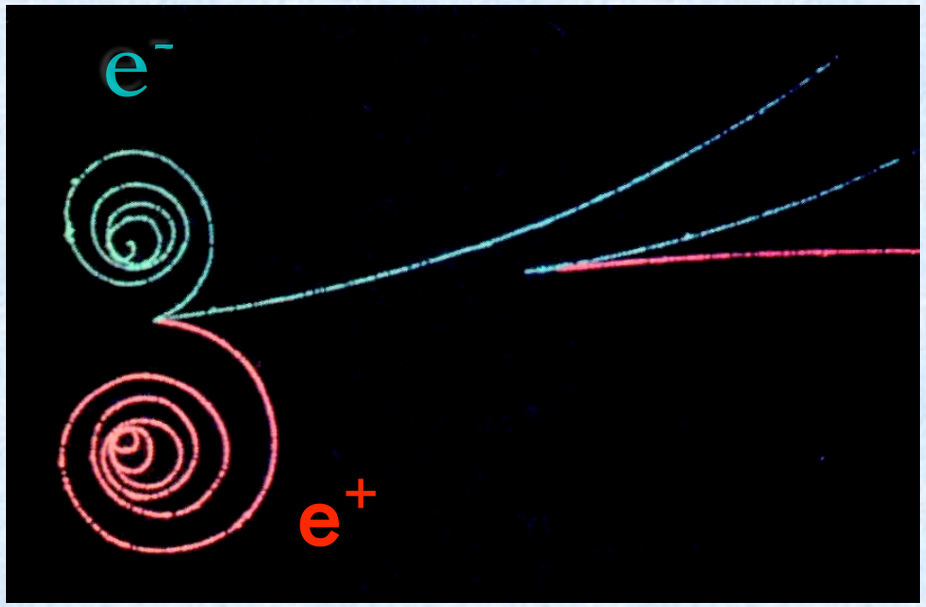
Electron	⟷	Positron
Neutrino		Anti-Neutrino
Up-Quark		Anti-Up-Quark
Down-Quark		Anti-Down-Quark



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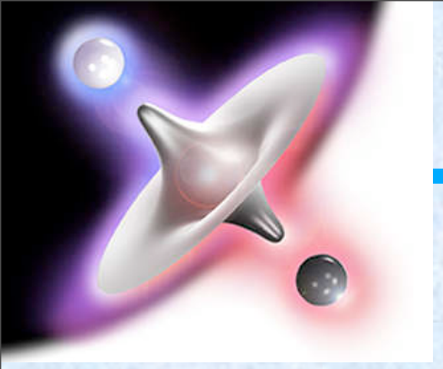

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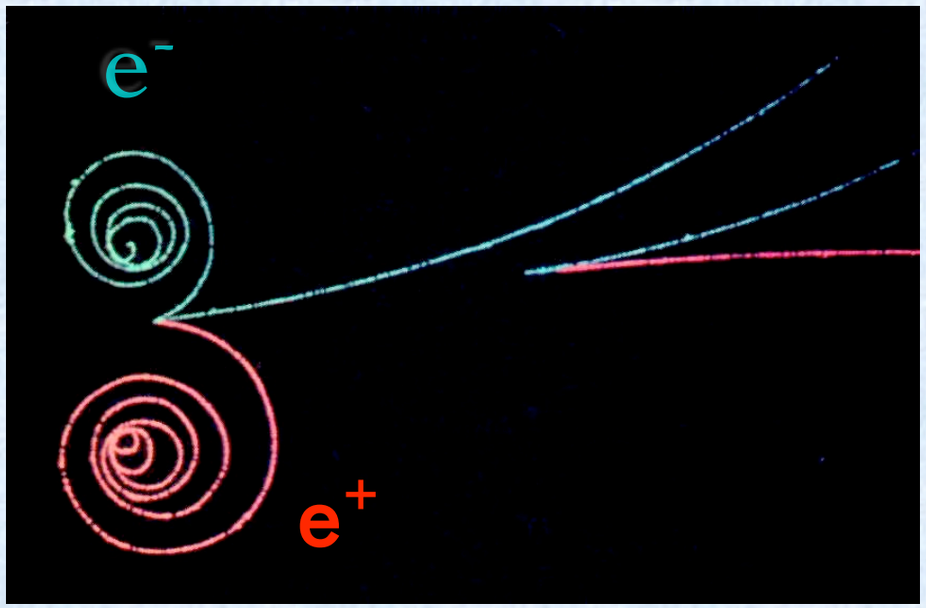
Down-Quark	⟷	Anti-Down-Quark
Muon …	⟷	Anti-Muon …



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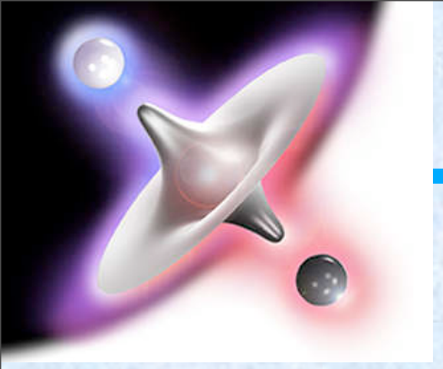

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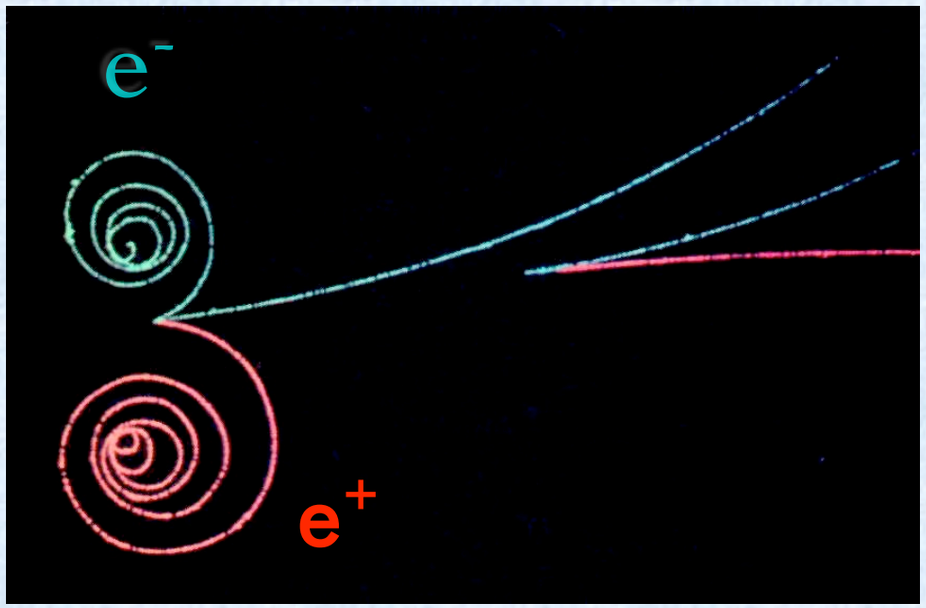
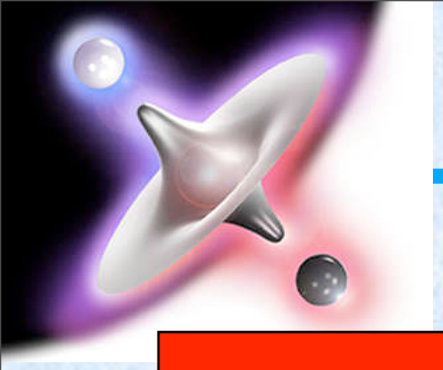
Muon ...	⟷	Anti-Muon ...
Tau ...	⟷	Anti-Tau ...



Particles and antiparticles can also destroy each other (annihilation)

Enter the antiproton



The Antiproton

1905
Special relativity

1925
Quantum Mechanics

1927
Dirac Equation

1932
Positron

1948
Positronium

1955
Antiproton

1956
Antineutron

1965
Antideuteron

1970
Anti-Helium-3

1978
Anti-Tritium

Primordial Antimatter?
Anti-Stars?

1956-1980s:
Scattering, annihilation, Meson spectroscopy

1980s-now:
W,Z, b,t physics

Technical developments

1970s
Accumulation + Cooling

1980s-now
Colliders (SppS, Tevatron)

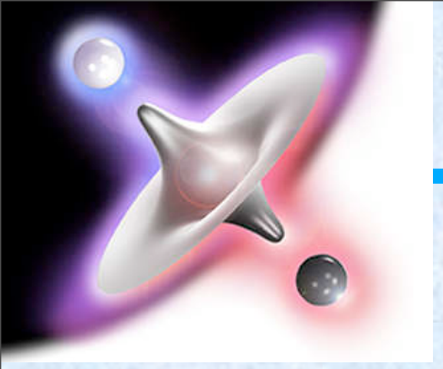
1983-1996
LEAR

1996: Hot (v~c) Antihydrogen

2000-now
Antiproton Decelerator

Trapping

Cold Antihydrogen



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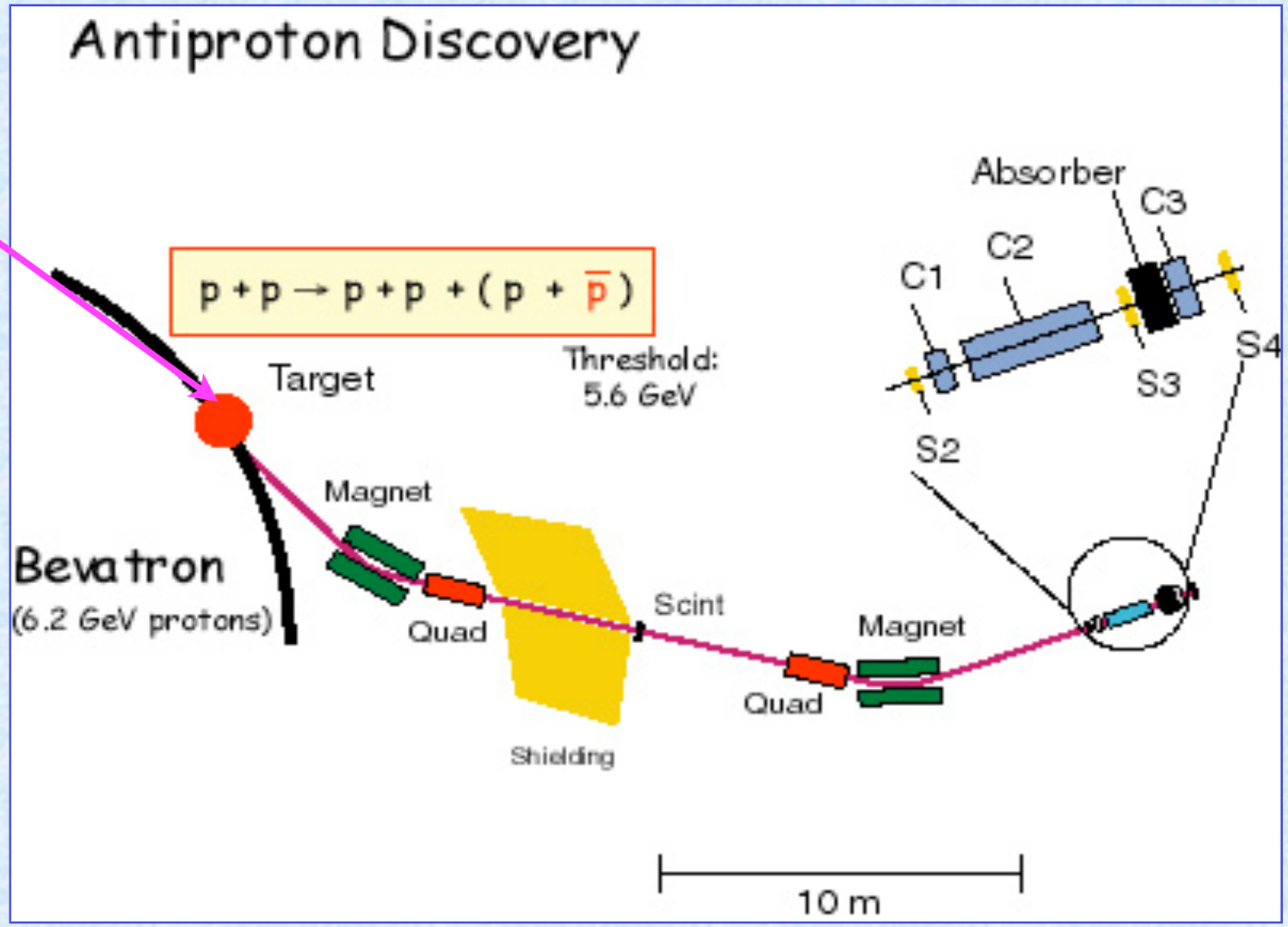
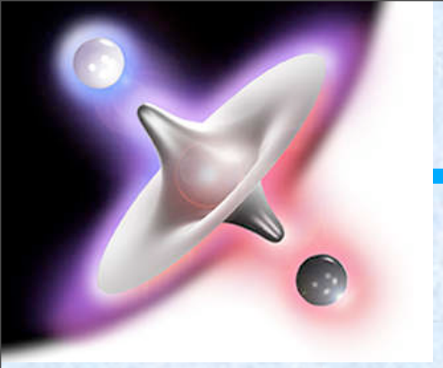
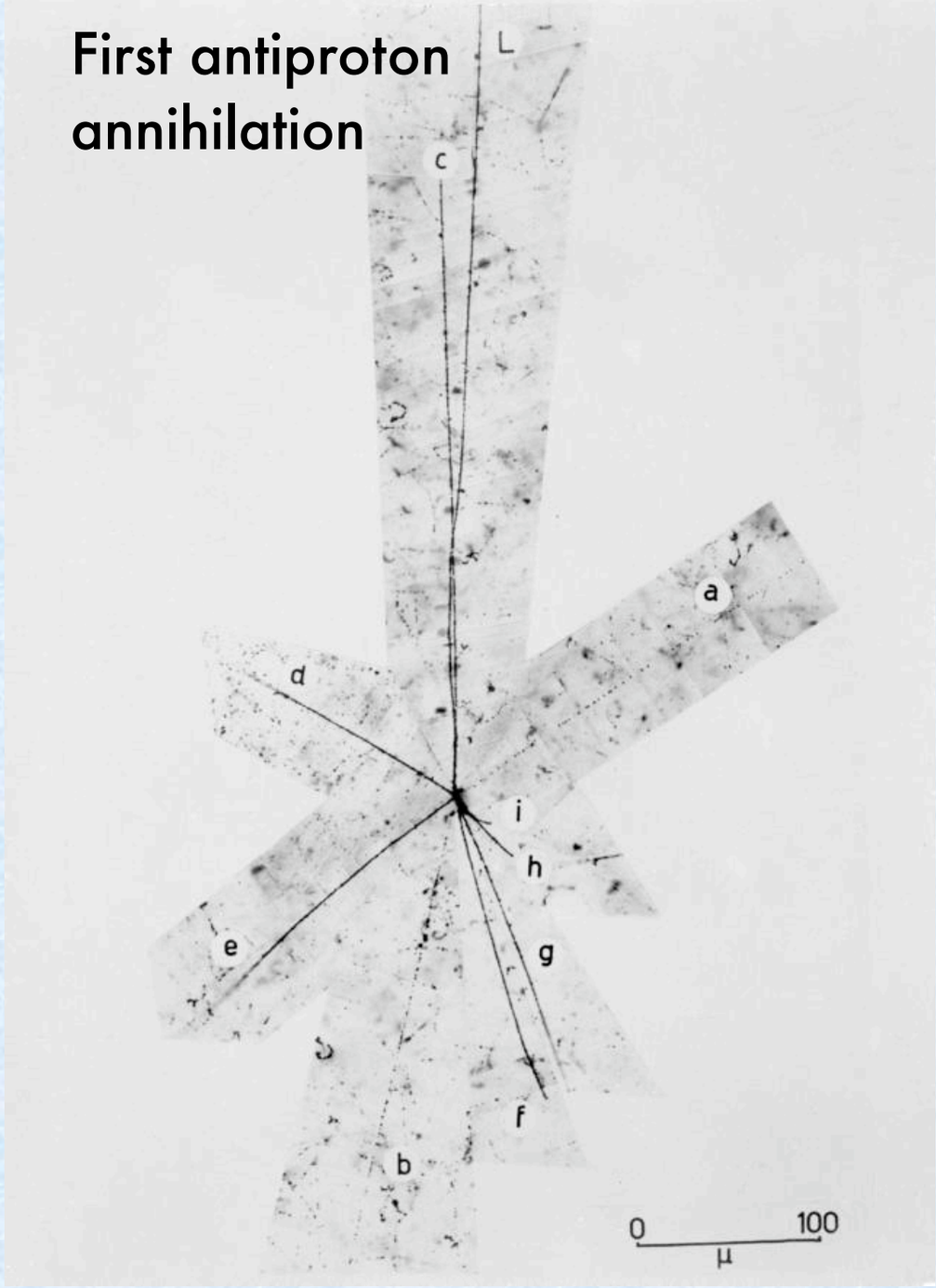




Antiproton Discovery (1955)

First antiproton annihilation



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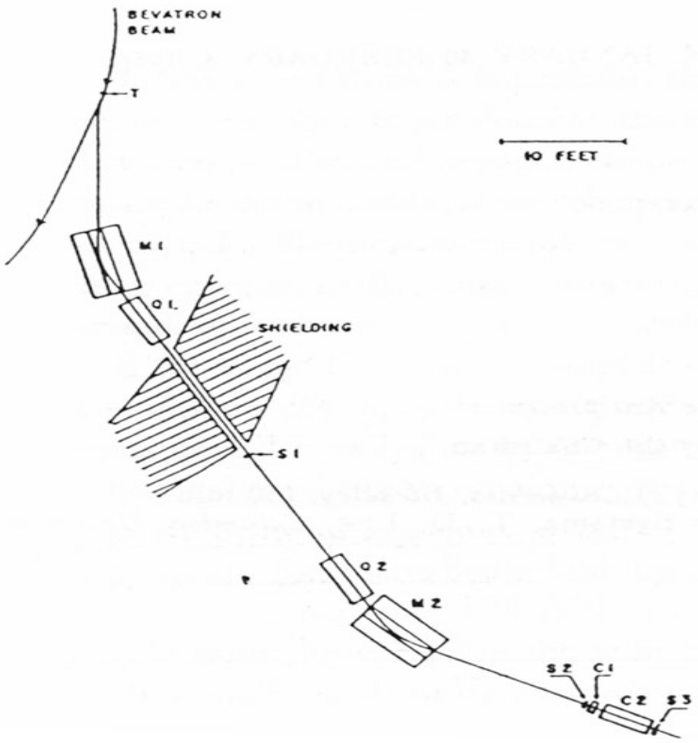

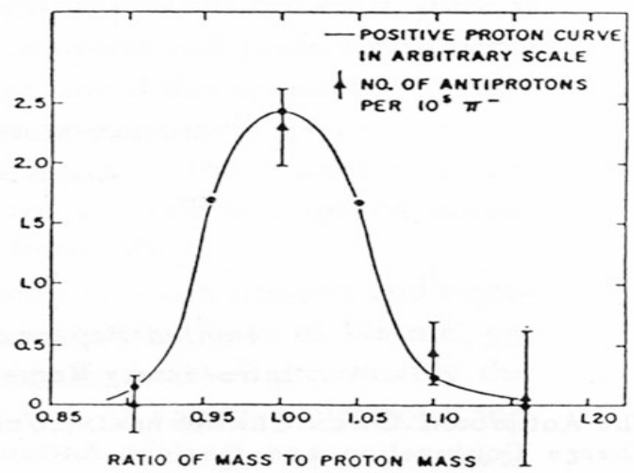

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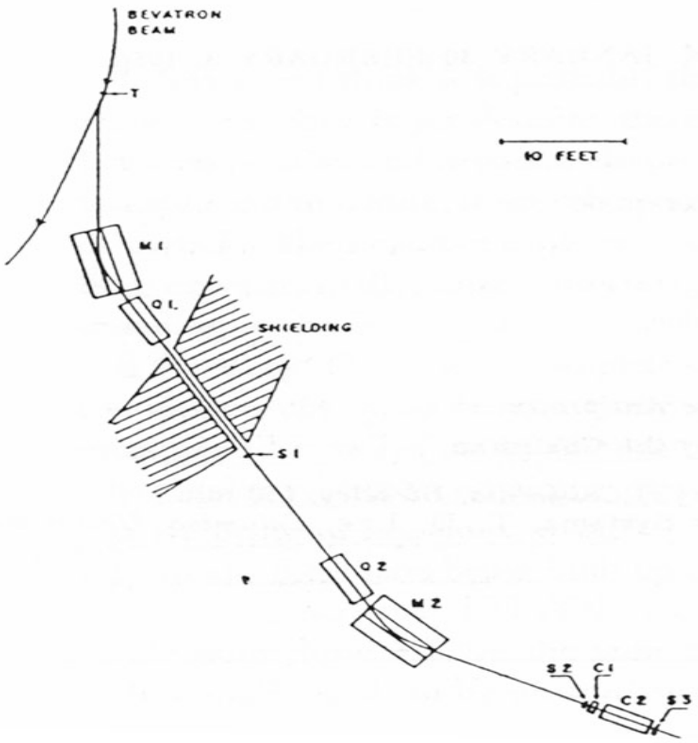

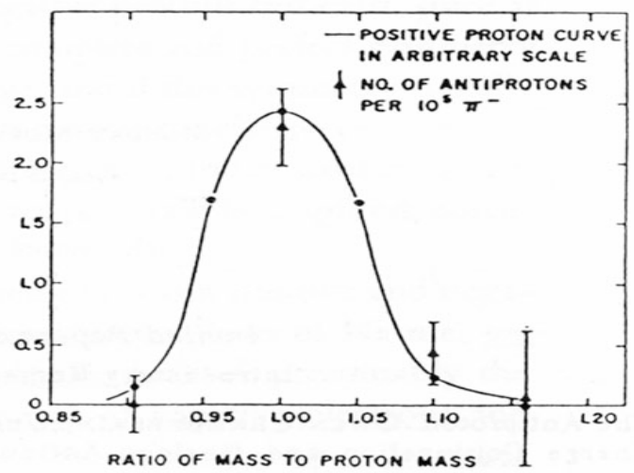

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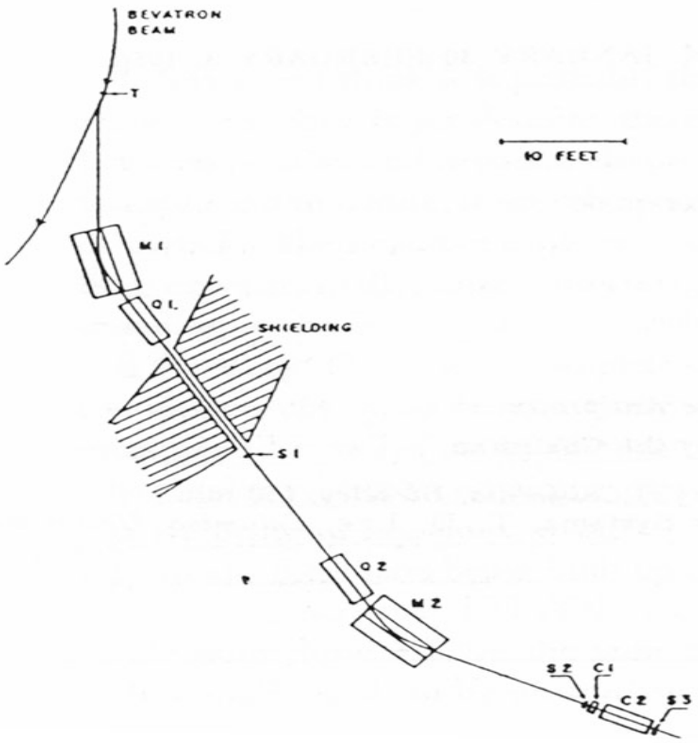
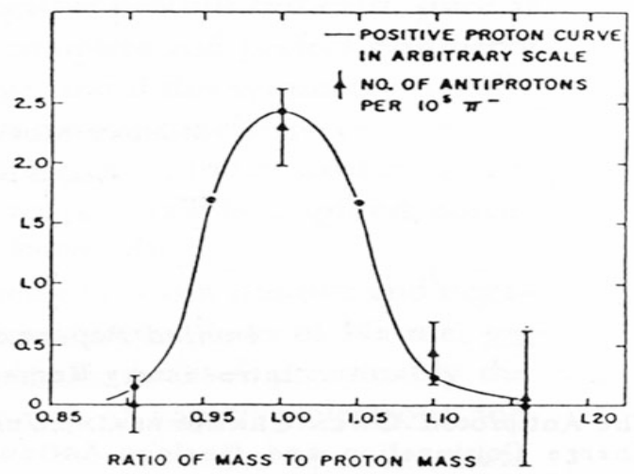
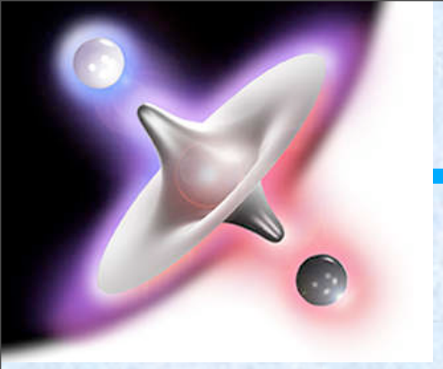




Tedious analysis ….



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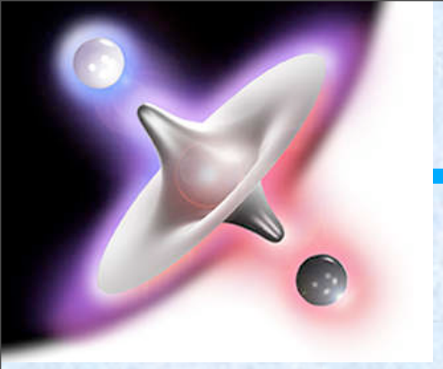
*1955 - Proof of CPT theorem by Pauli (following work by Schwinger and Lüders)



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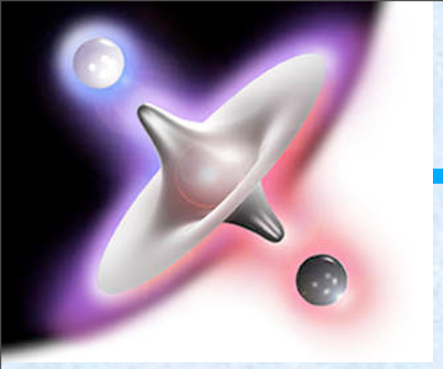

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If :

1) Locality (no action at a distance)
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5) Flat space-time (no black holes anywhere near)
6) Point-like particles

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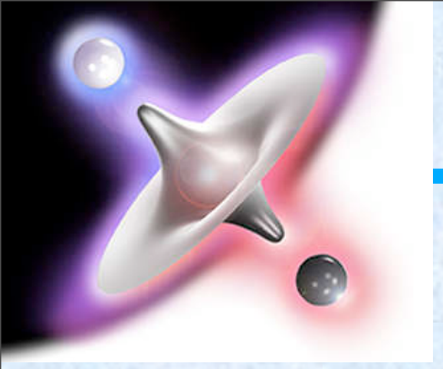

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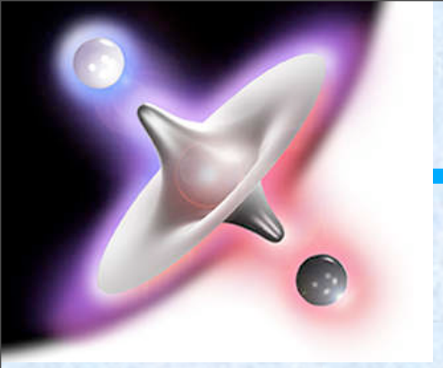

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Then :

Particles and antiparticles must have **exactly equal**

- mass
- lifetime
- charge (magnitude)
- energy levels of bound states

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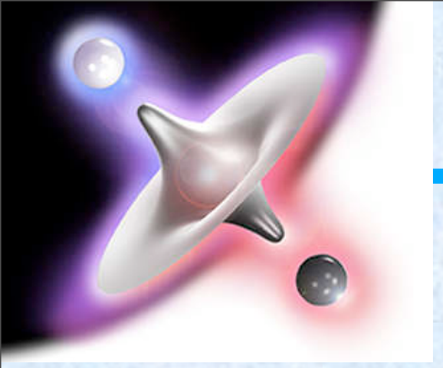
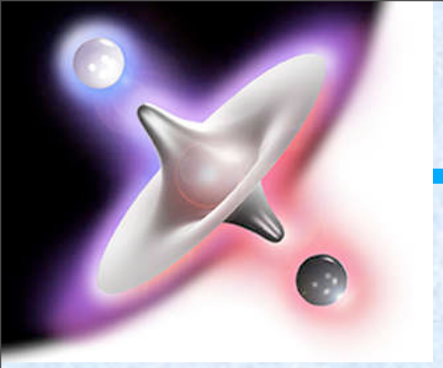


Does the Universe care about CPT symmetry ?

Dirac's Vision (from his Nobel lecture, 1933)

1) There may be matter-antimatter symmetry in the Universe

2) Anti-stars: optical spectrum would be identical



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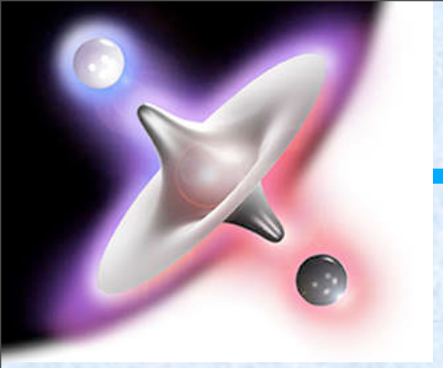
Is the Universe divided into matter and antimatter domains?

Annihilations at boundaries would lead to a relic diffuse gamma-ray flux* shows that exceeds the observed Cosmic Diffuse Gamma (CDG) spectrum (0.1 - 10 MeV region):



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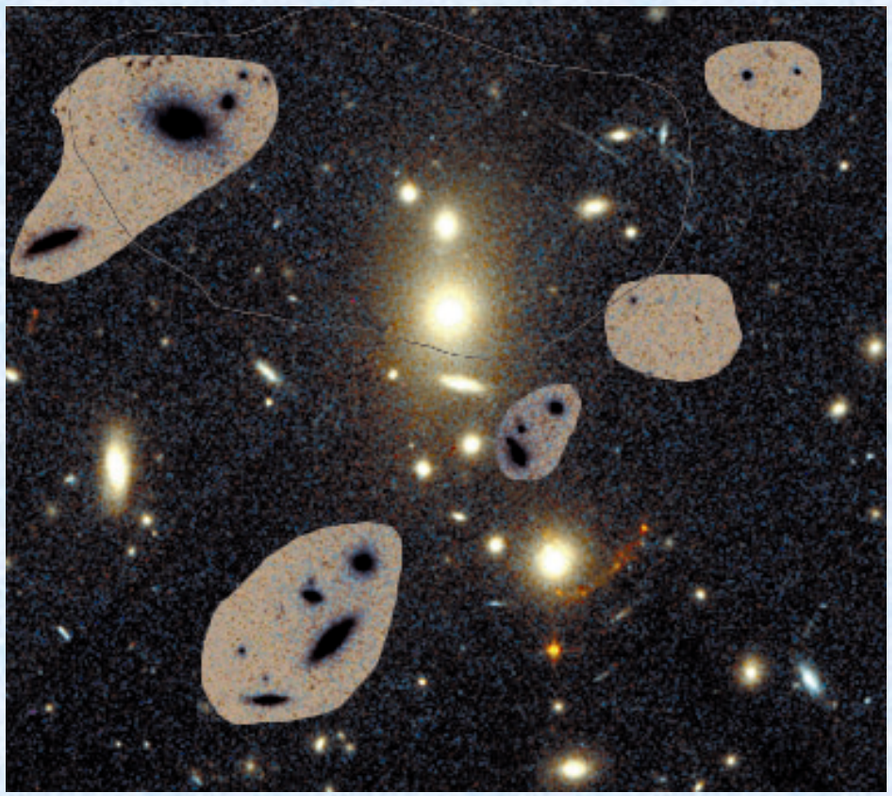

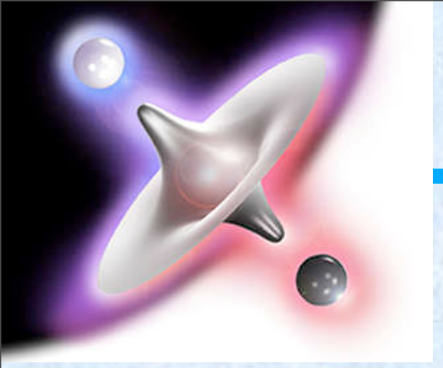

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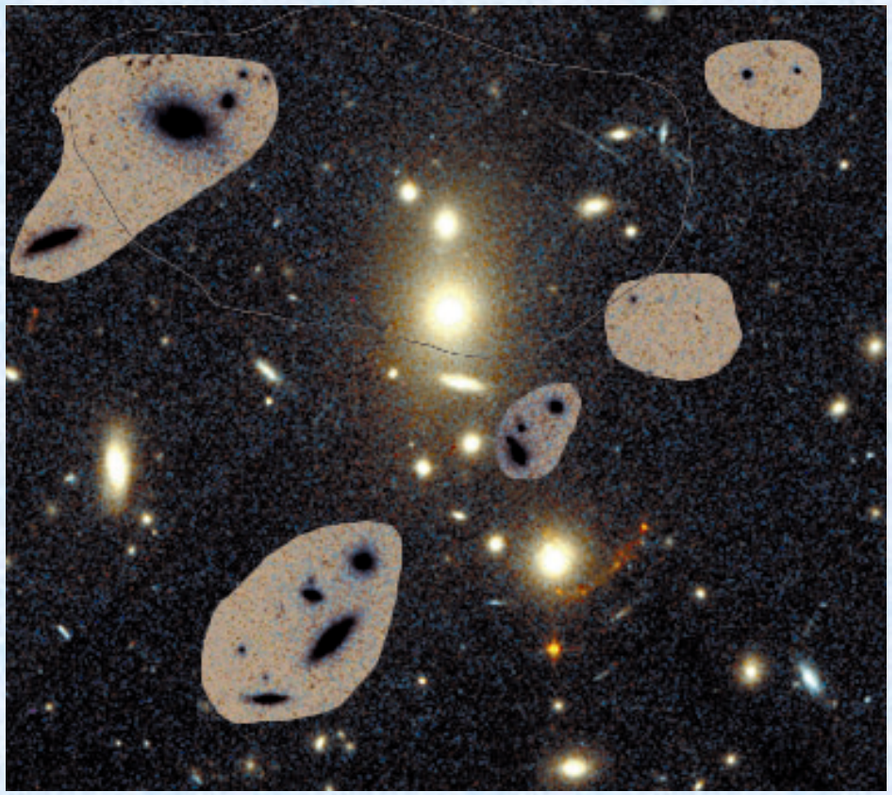
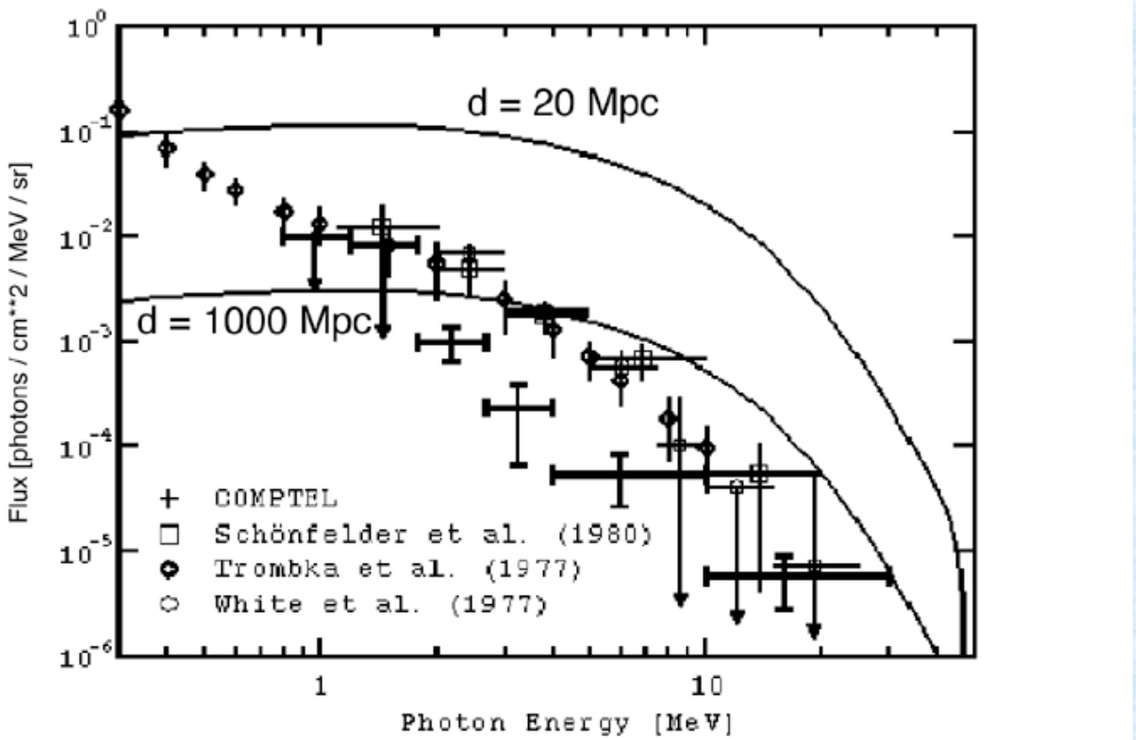
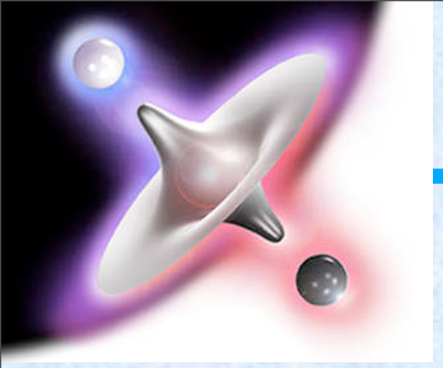




*A.G. Cohen, A. De Rujula, S. Glashow, Astrophys. J. 495 (1998) 539



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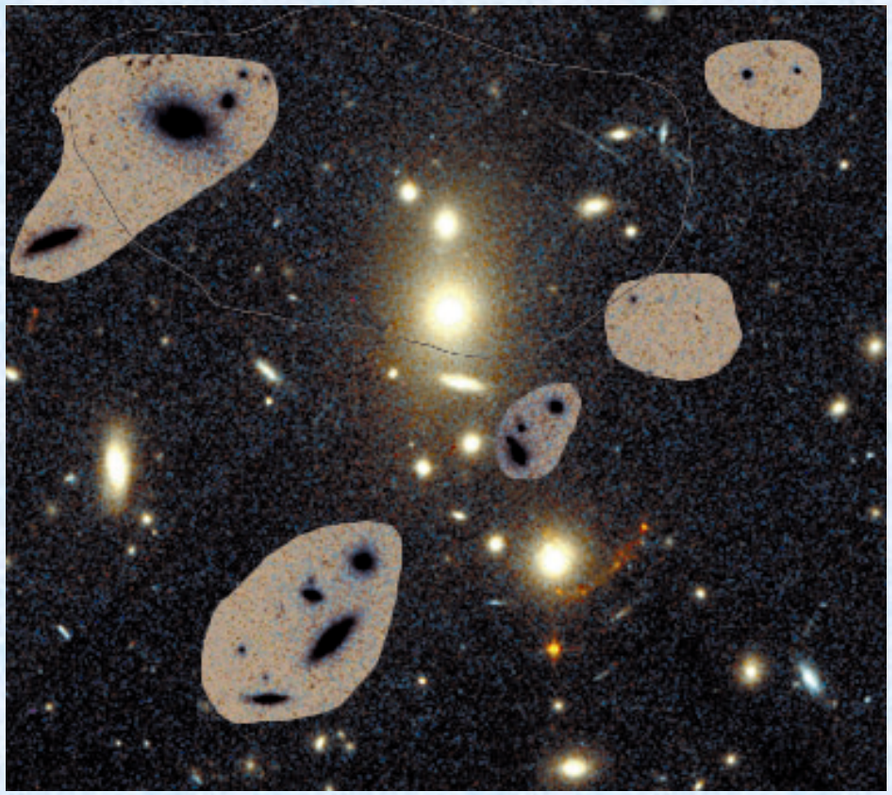

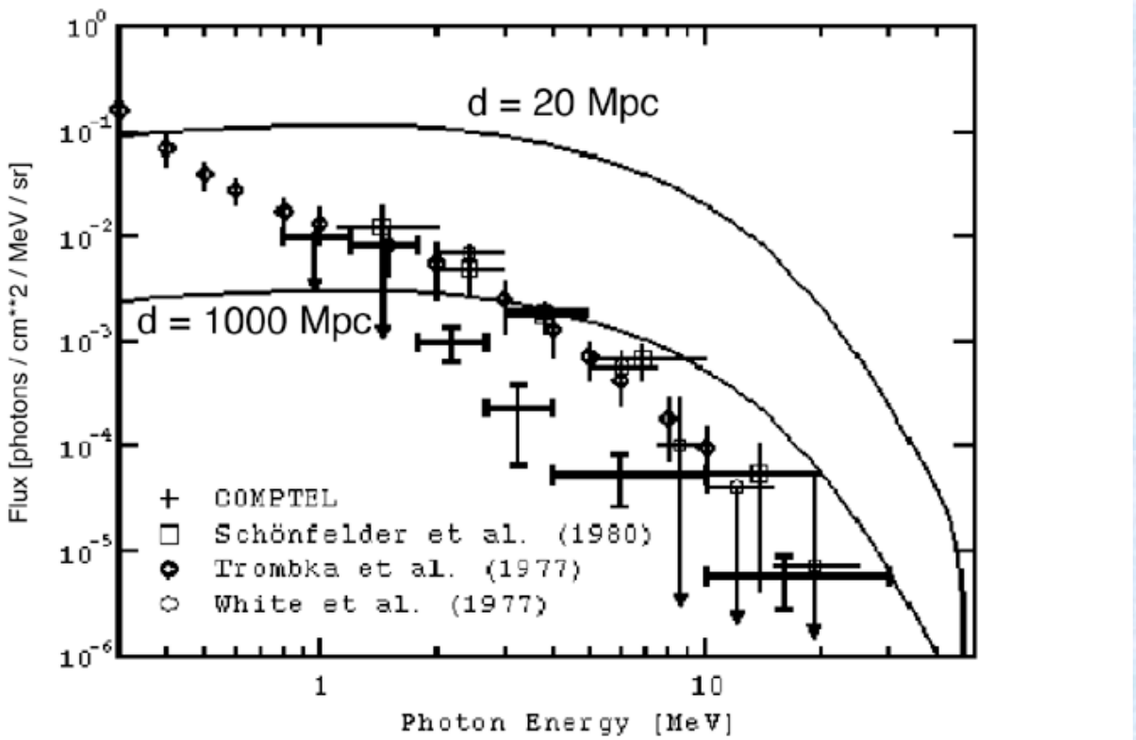

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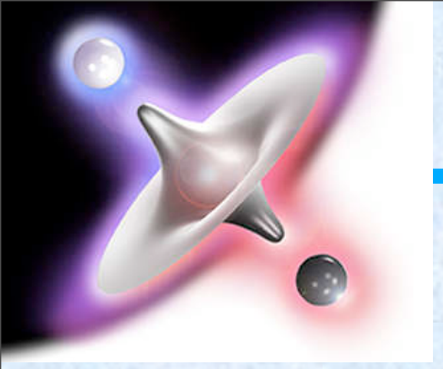
NO !



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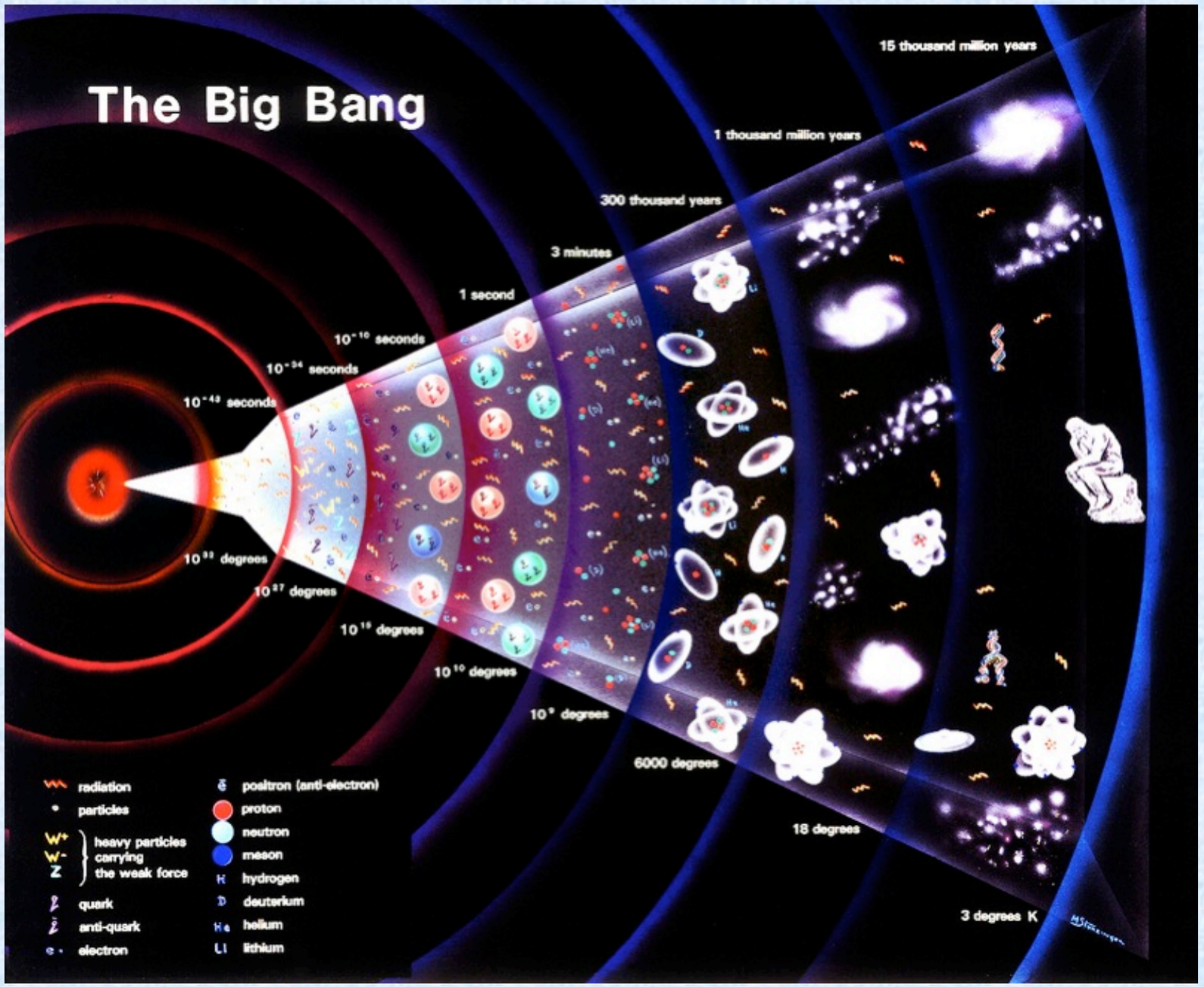
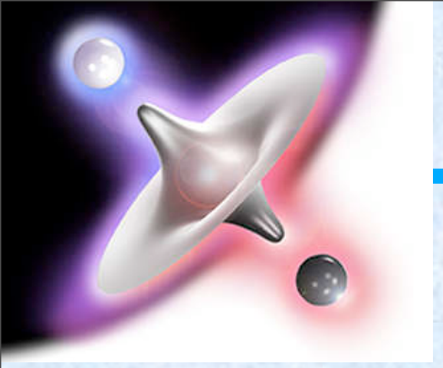
13,700 million years ago





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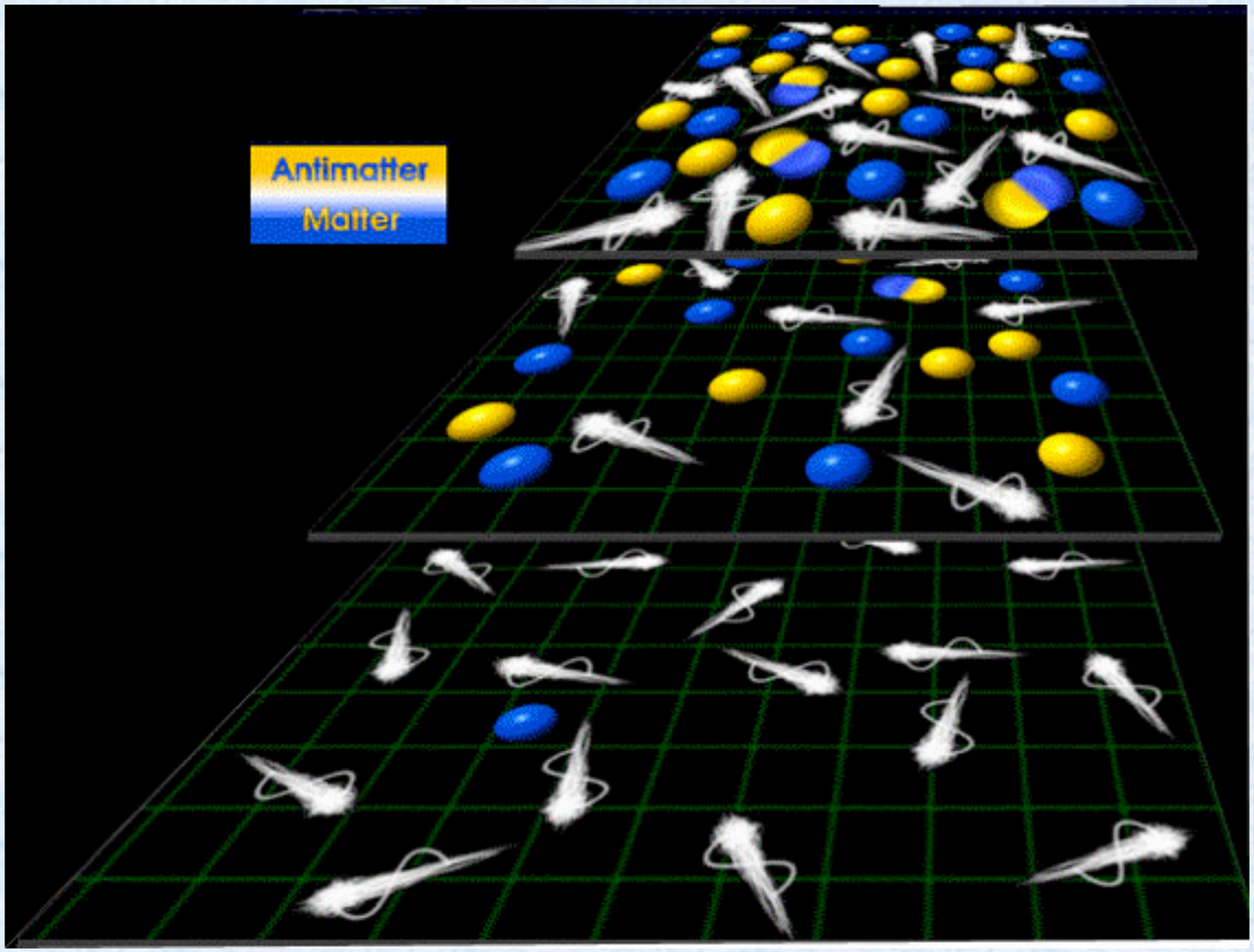

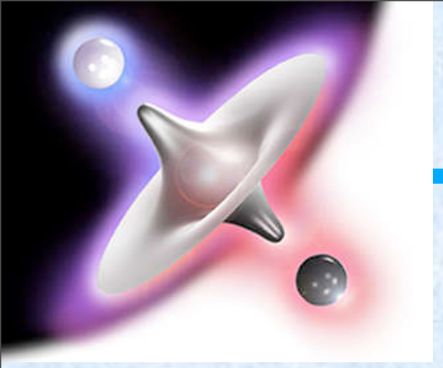

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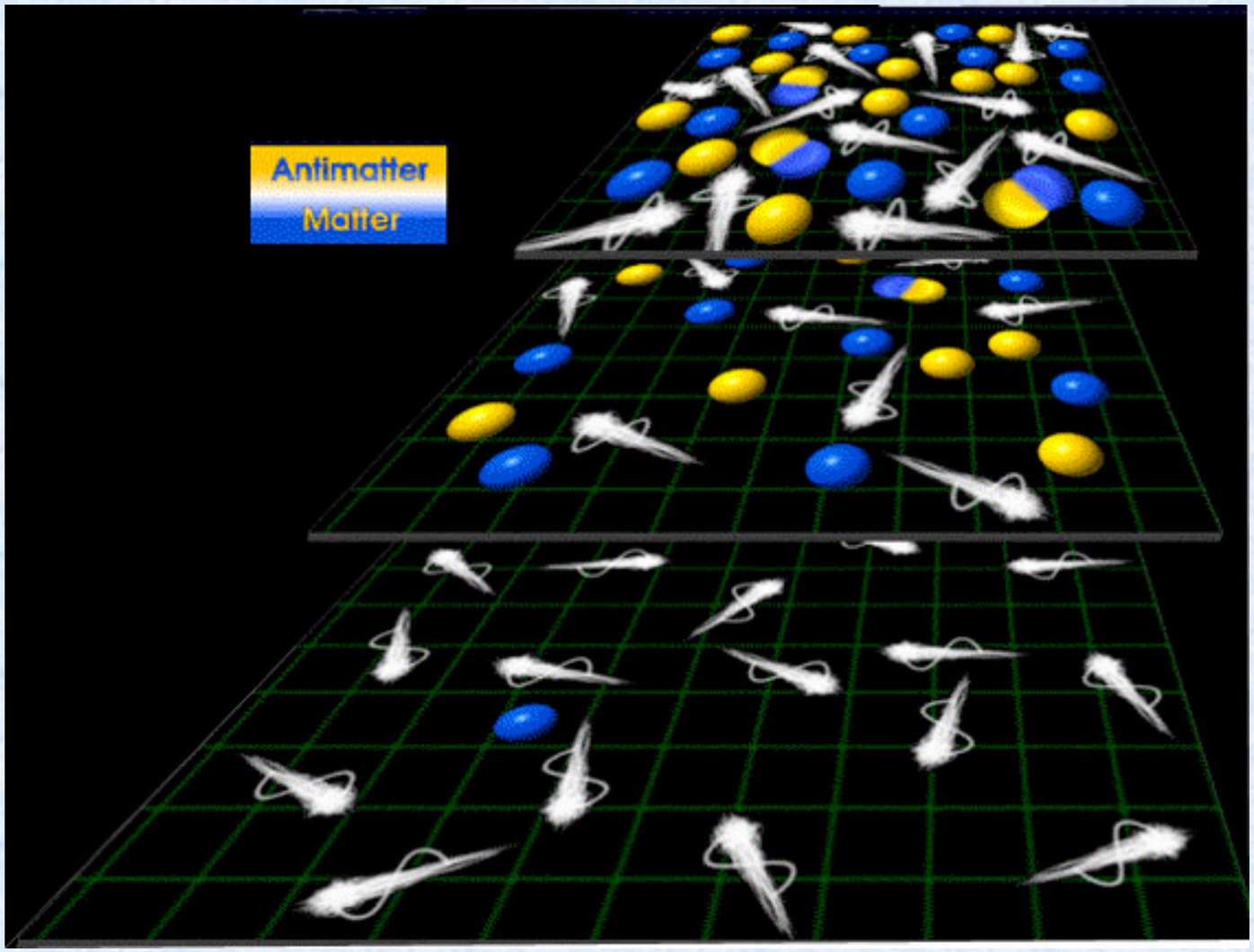

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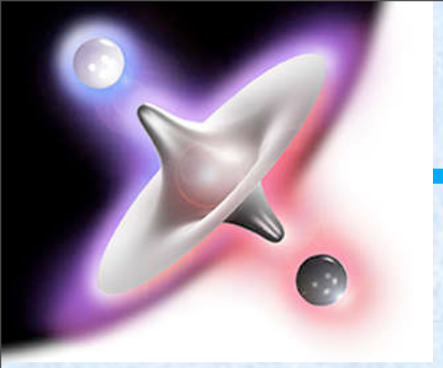
equal amounts of matter/antimatter



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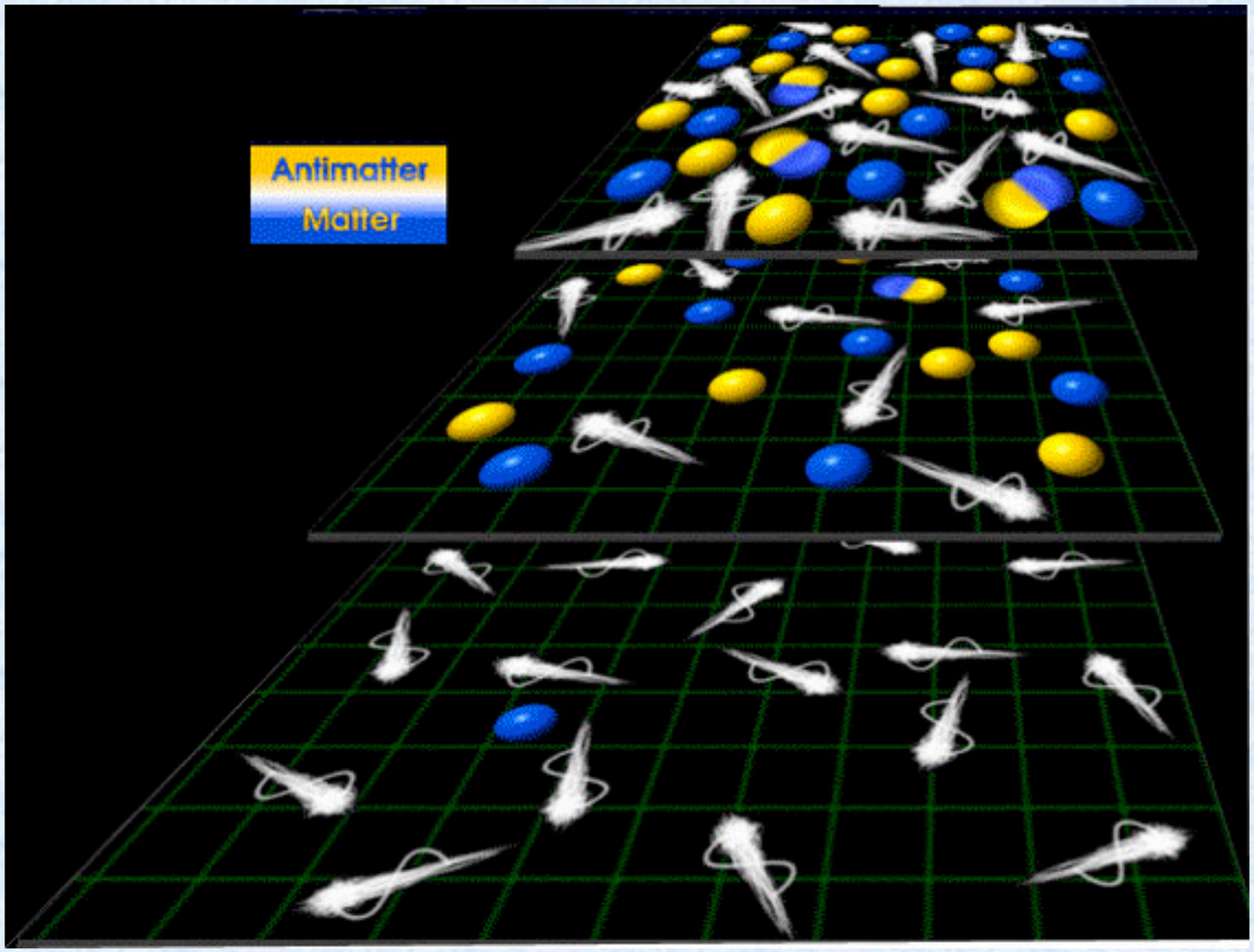

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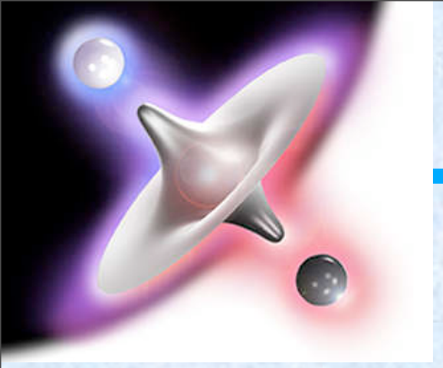

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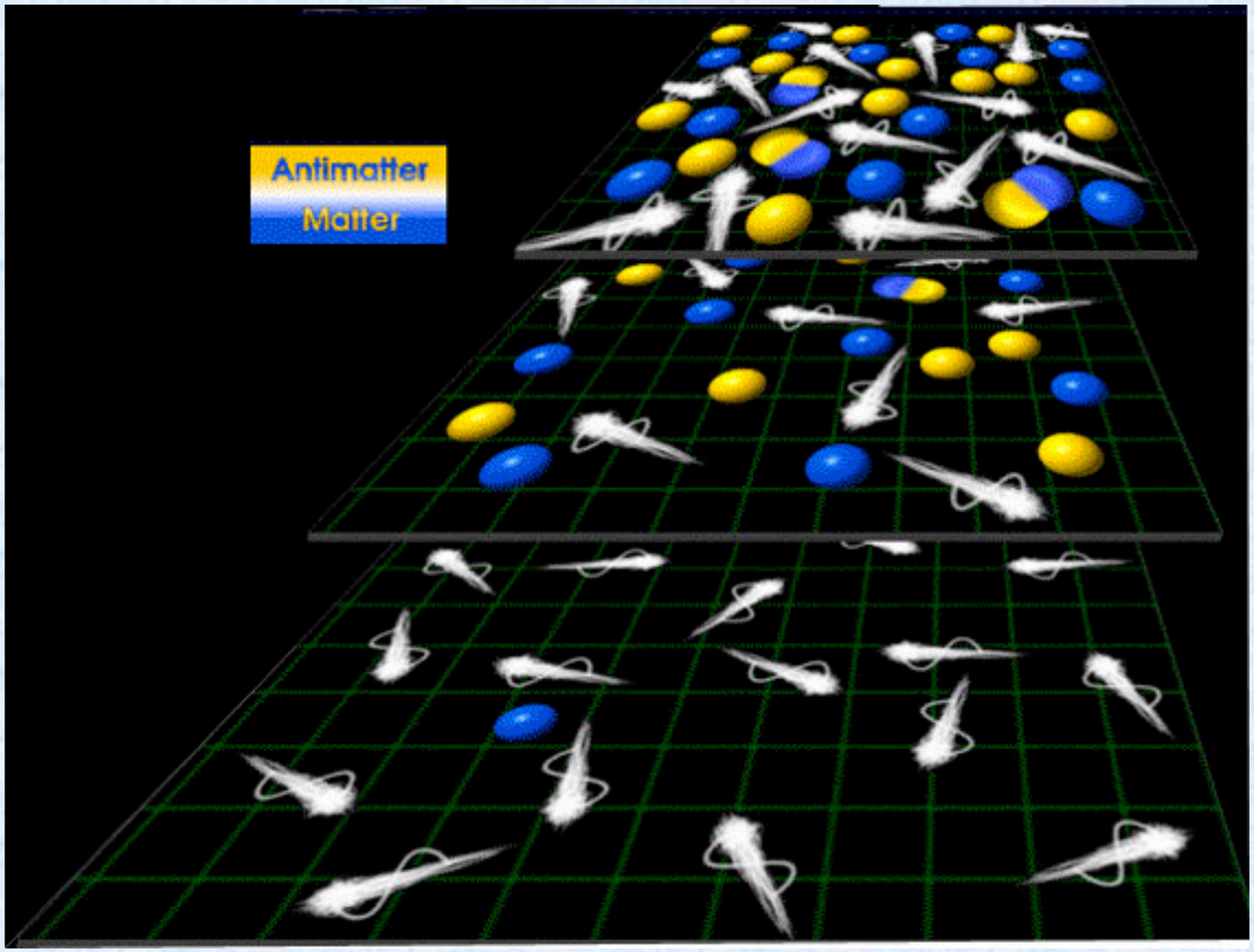

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all antimatter has disappeared,
but some matter (us!) left
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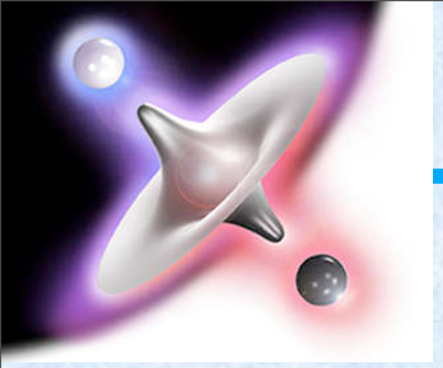

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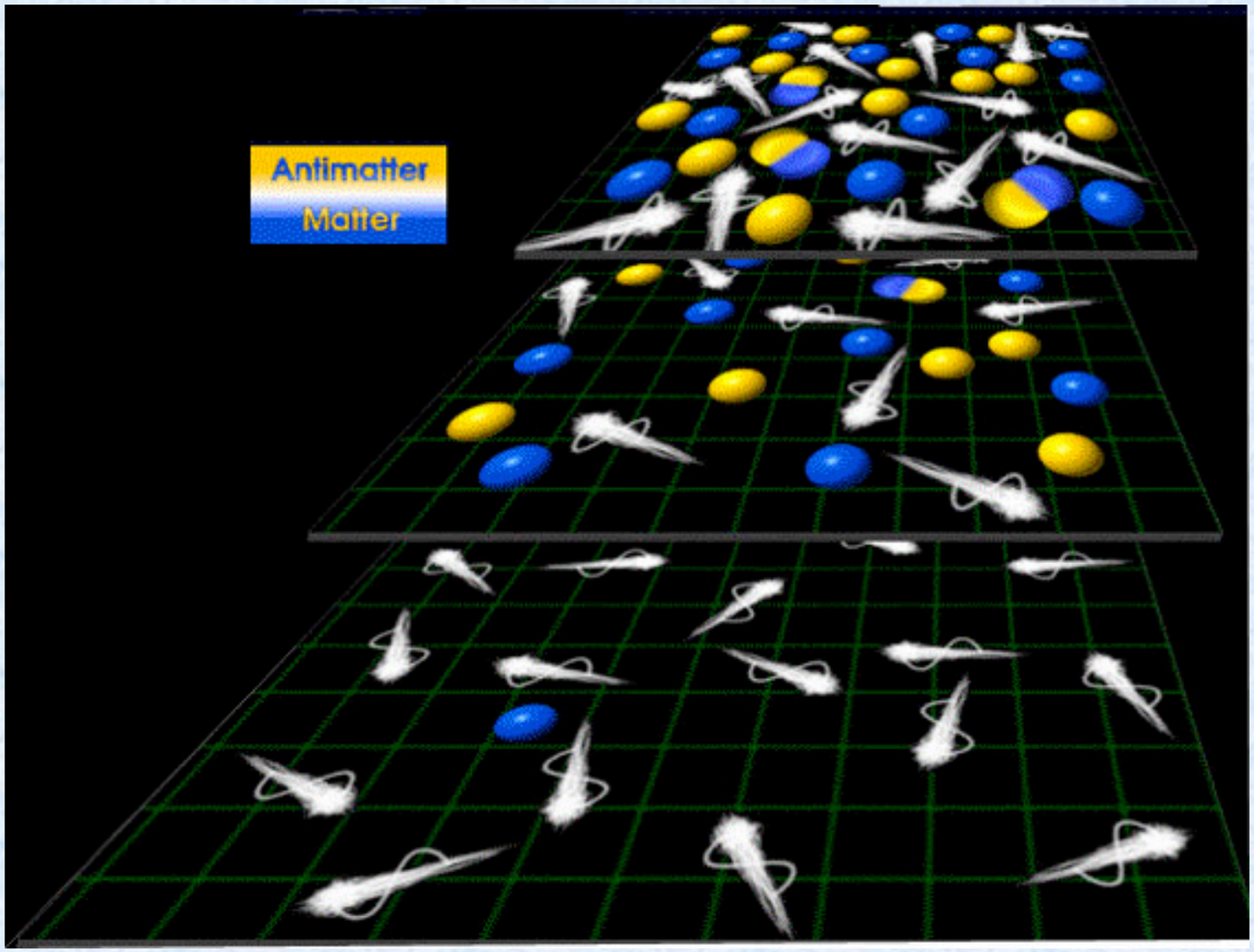

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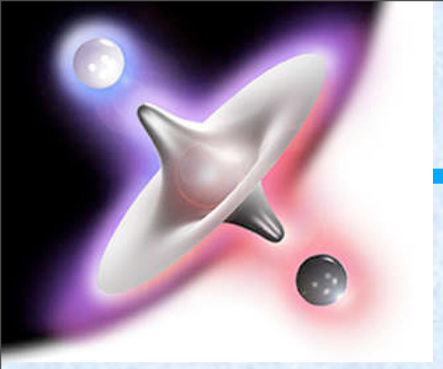
Why ?? Study antimatter-matter symmetry (CP and CPT)



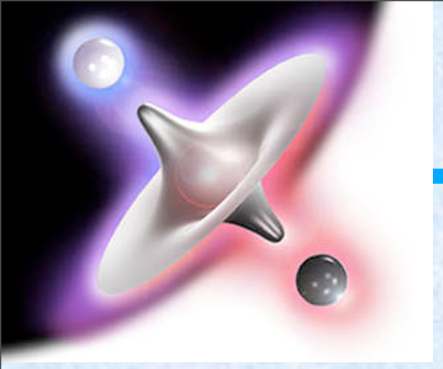
Origin of the antimatter disappearance ?

CP VIOLATION !

- Look at decay of s- or b-quark (at CERN: LHCb)

CPT VIOLATION ?

- Theorists don’t like this idea, but experimentalists are less picky.
- Look for ANY difference between matter/antimatter
- BUT: experiments have to be VERY precise



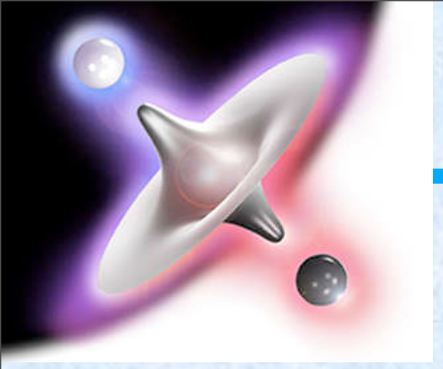
Precision Experiments with Antimatter

Precision measurements: high statistics or long observation times

For charged (anti)particles: trap and observe (e, p: see next lecture)

(Anti-)Hydrogen:

neutral (anti-)atom
simple structure
energy levels known to 10^{-14}



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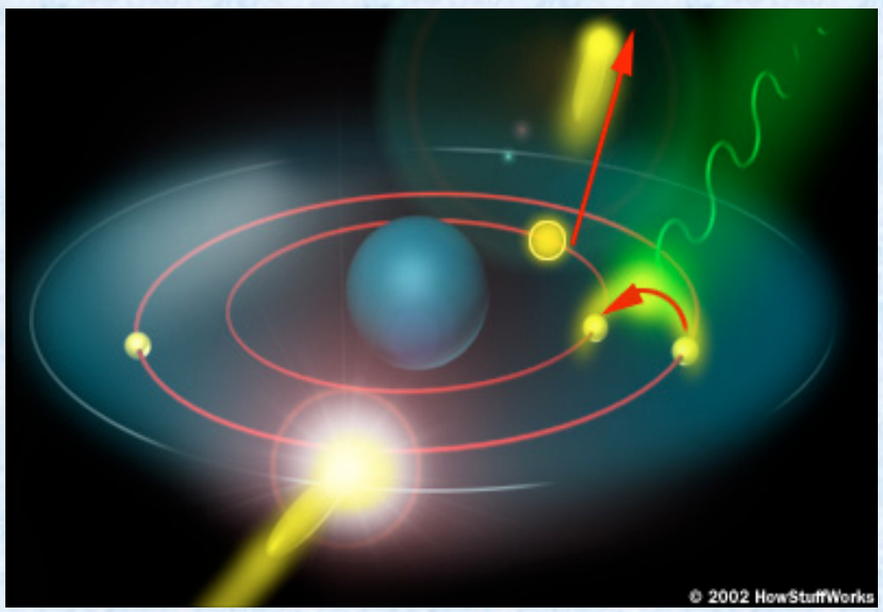
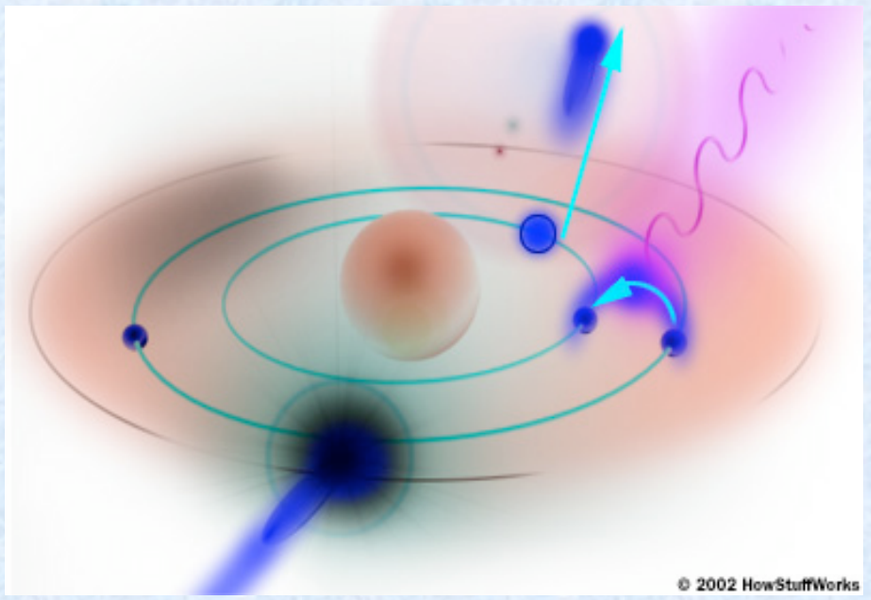
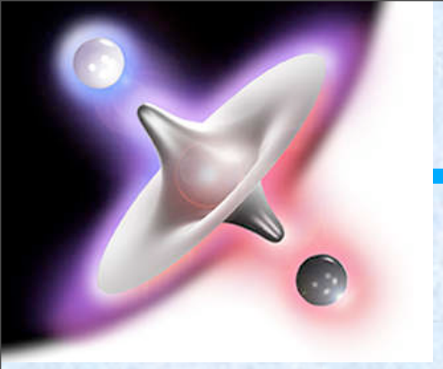
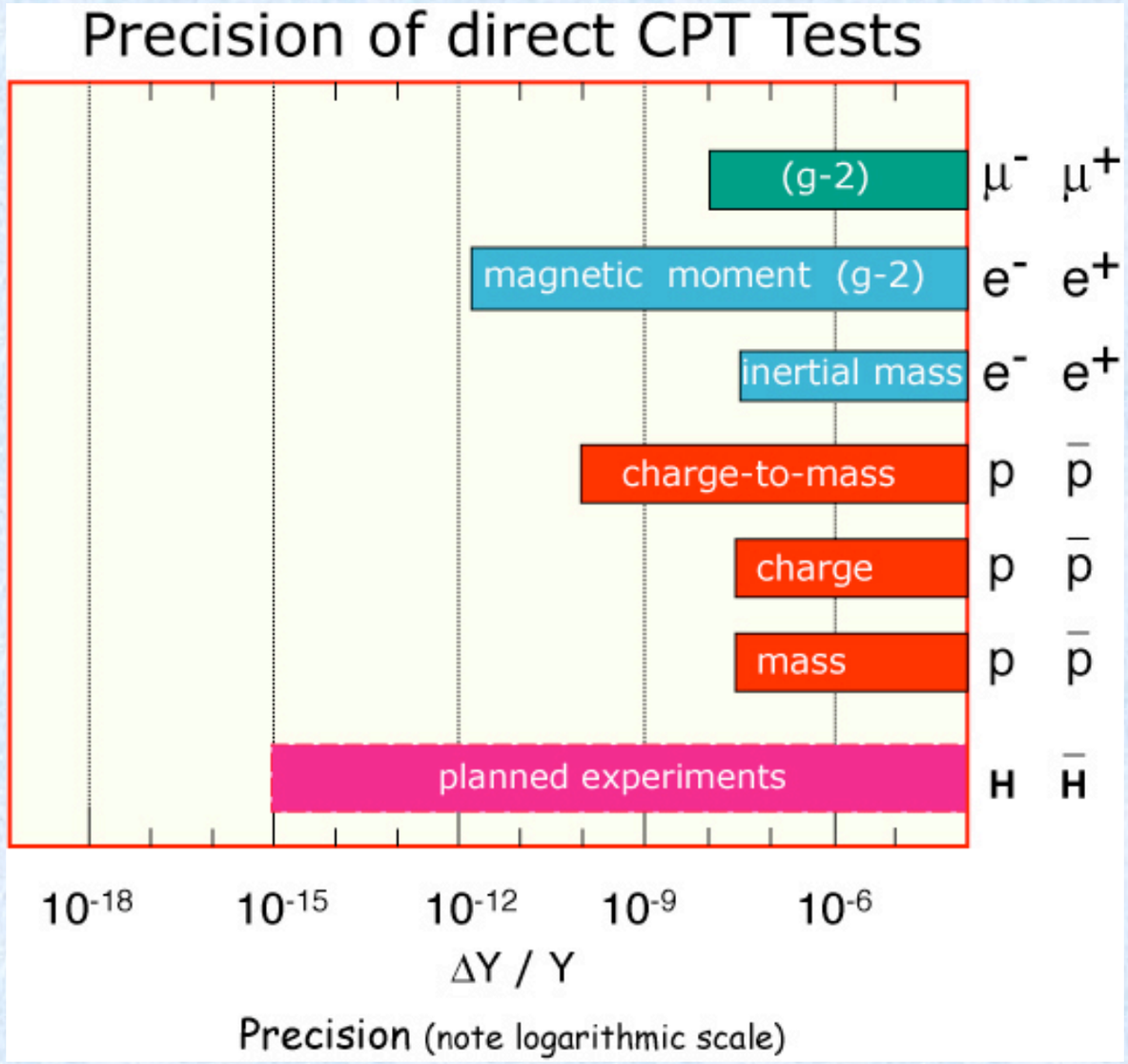
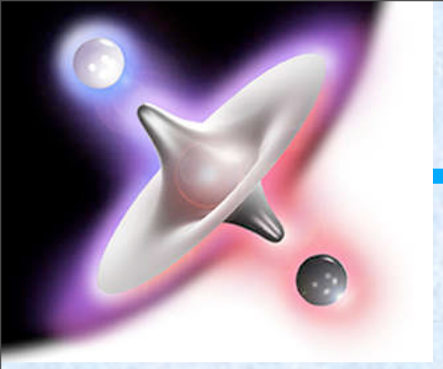






CPT symmetry works very well in the laboratory





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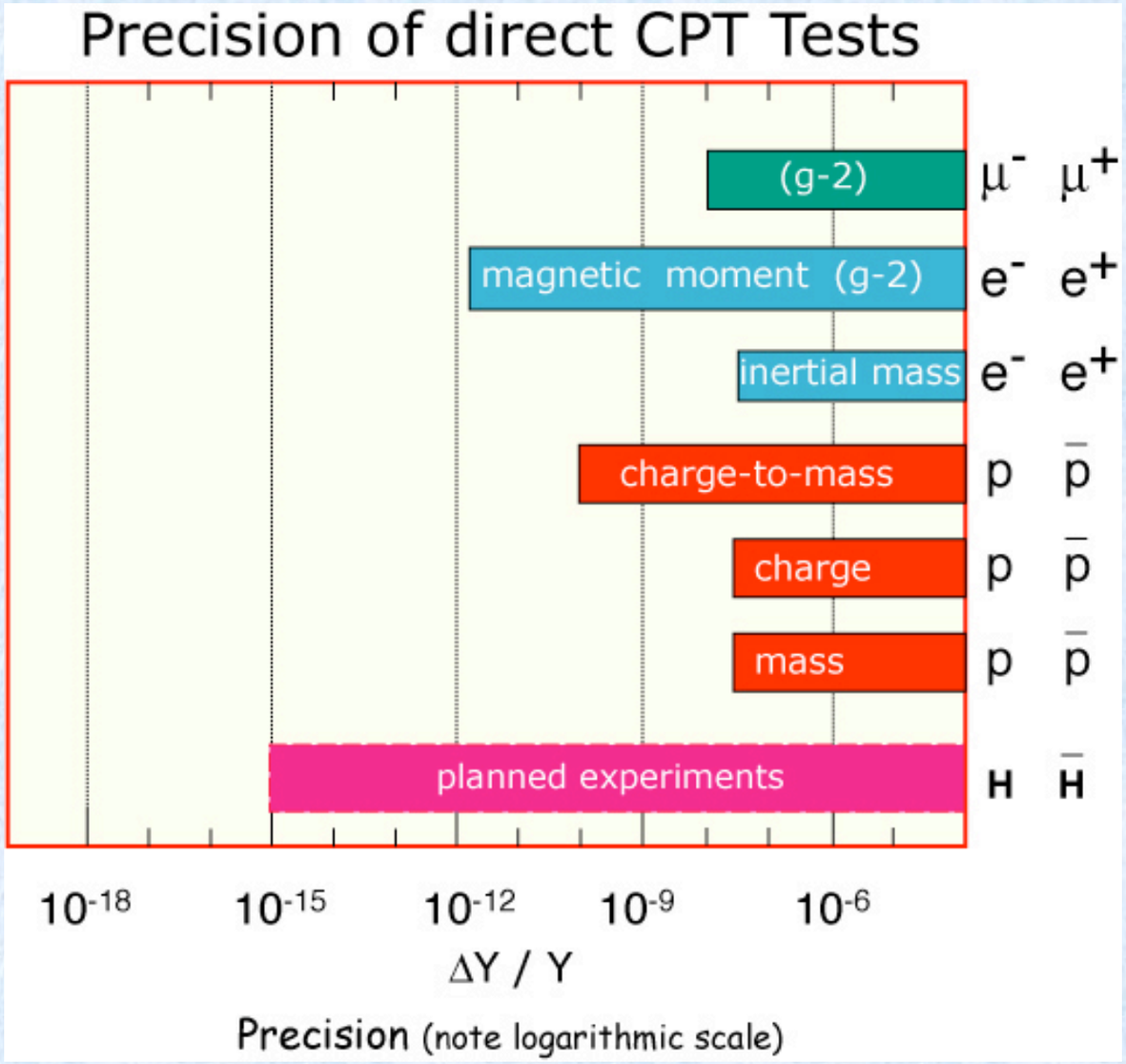
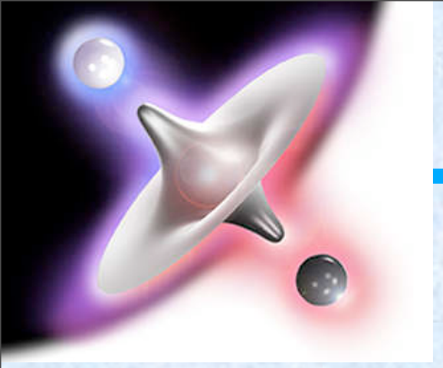
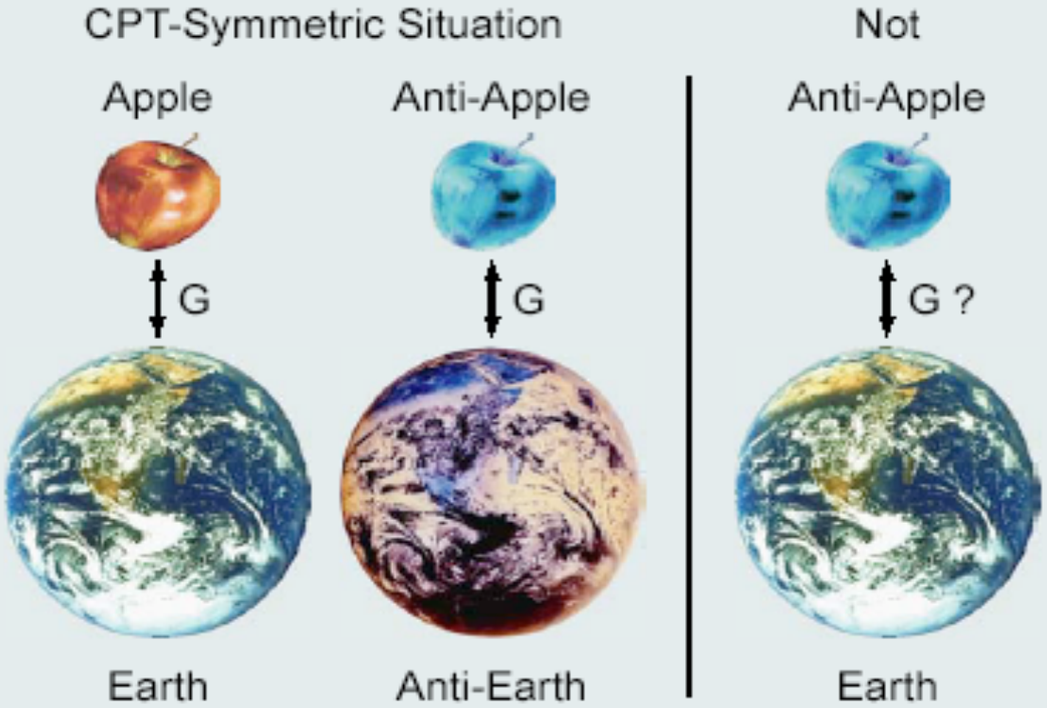
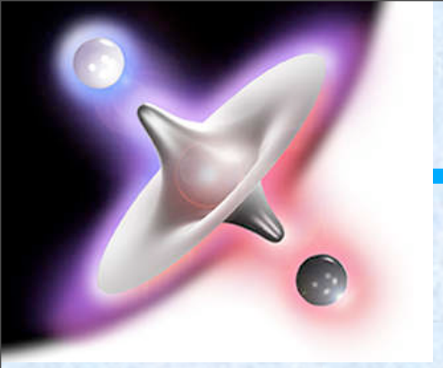


- DIRECT TESTS CONFIRM CPT ~ 10^{-12} LEVEL
- HYDROGEN - ANTIHYDROGEN COMPARISON PROMISING (< 10^{-15})
- THERE IS NO "THEORY" OF CPT VIOLATION



Antimatter gravitation is not constrained by CPT





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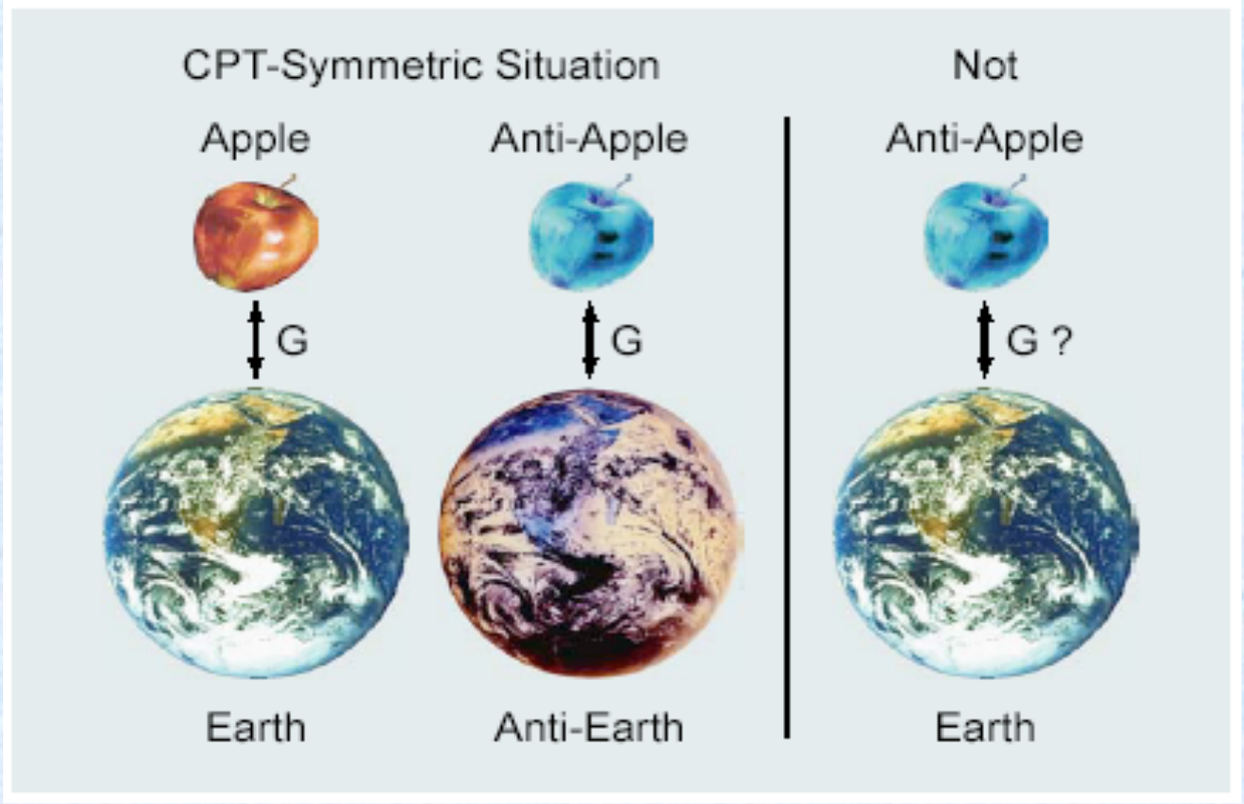
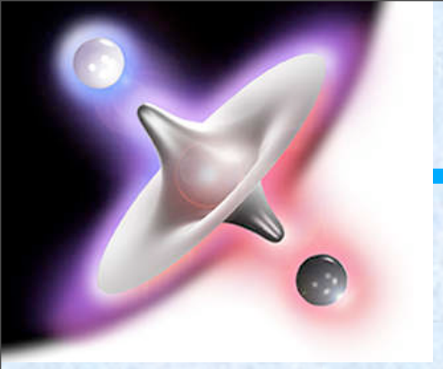
Theoretical expectation:
Gravitational = Inertial mass

Antimatter falls like matter





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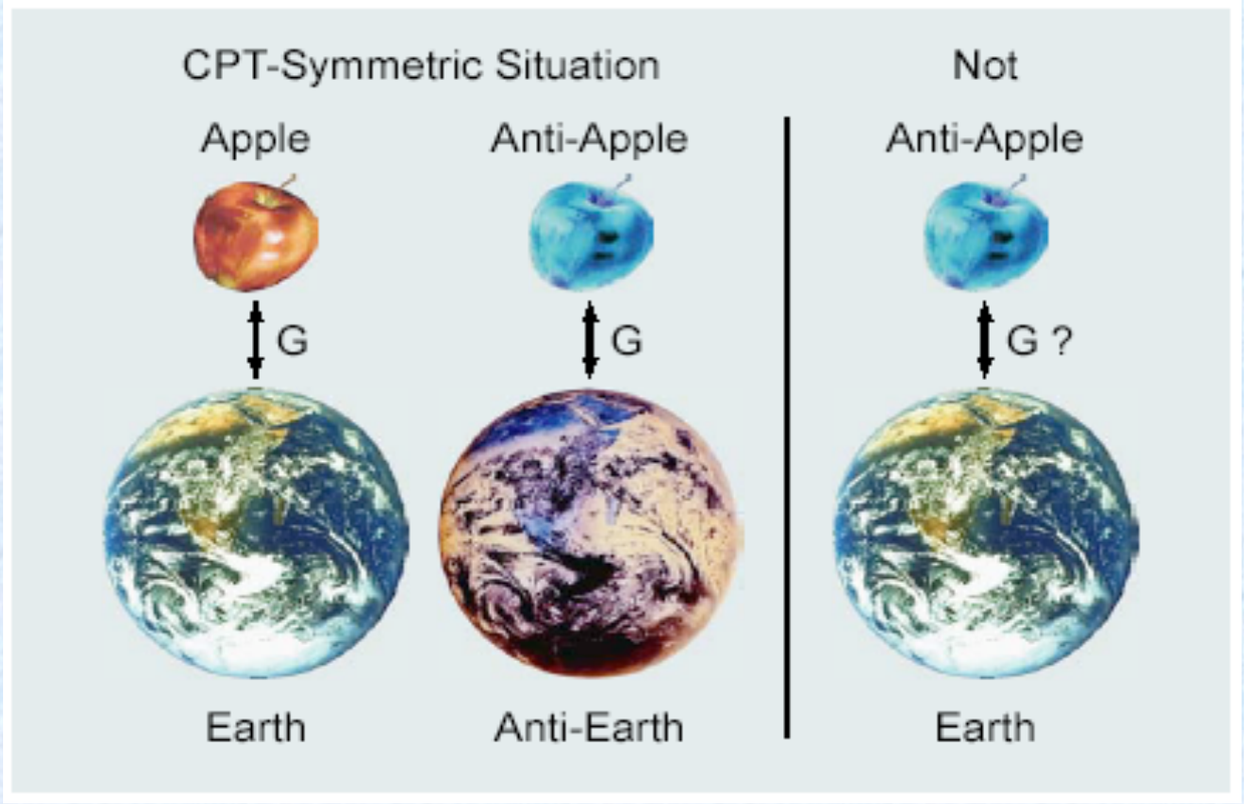

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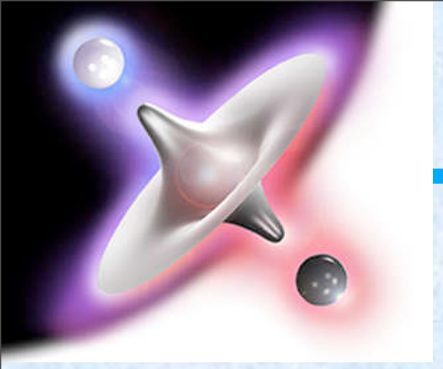

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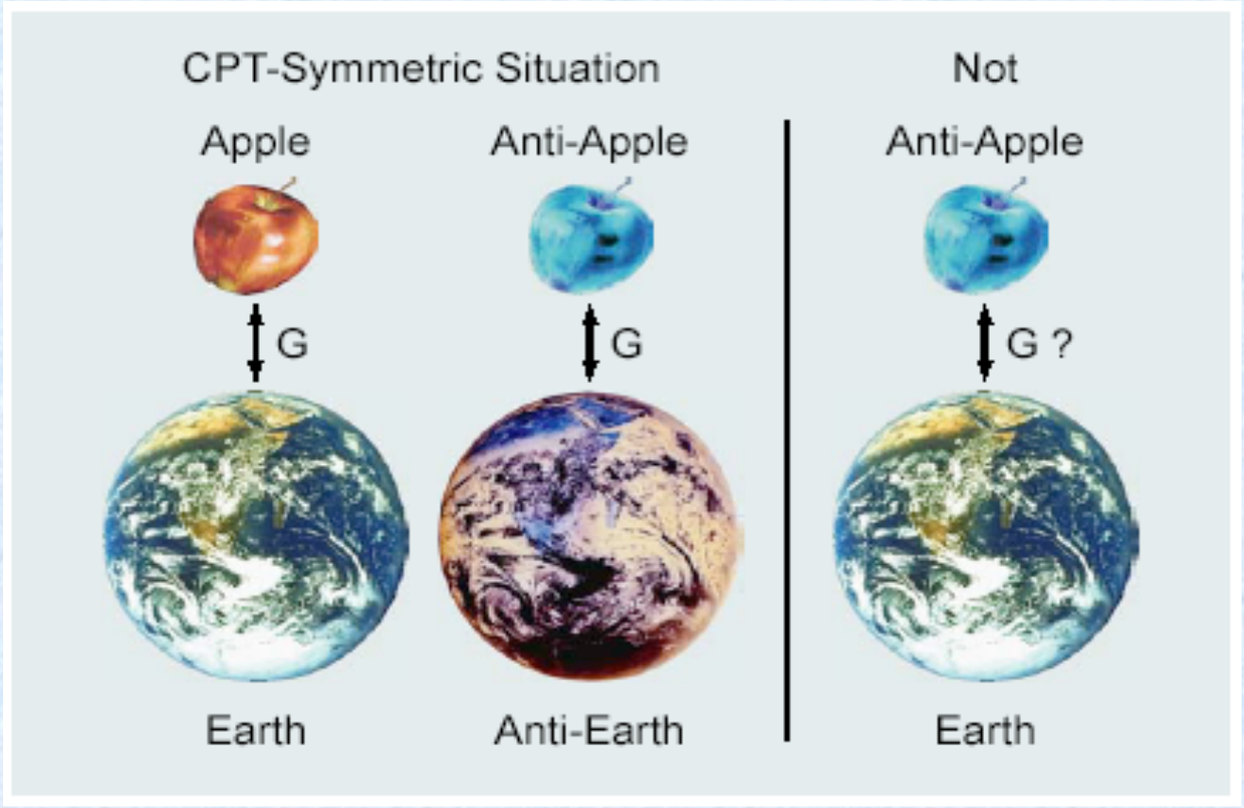

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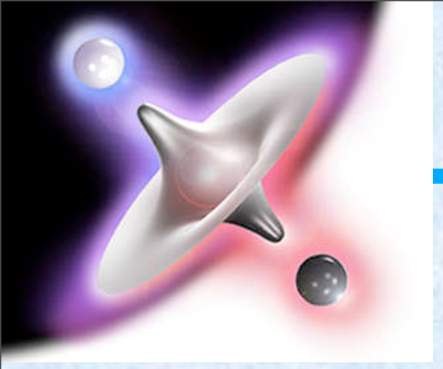
(anti-)

Measurement of gravitational acceleration by dropping atoms Nature 400 (1999) 849

Achim Peters, Keng Yeow Chung & Steven Chu

Physics Department, Stanford University, Stanford, California 94305-4060, USA



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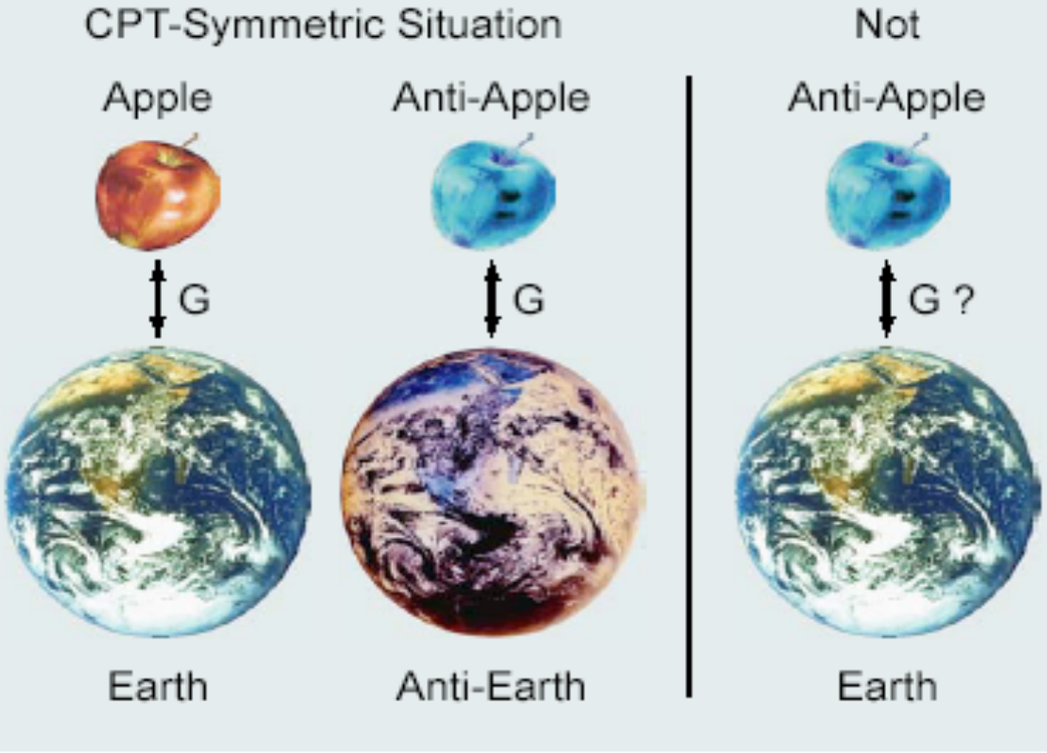

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Slow moving anti-atoms offer a possibility:

(anti-)

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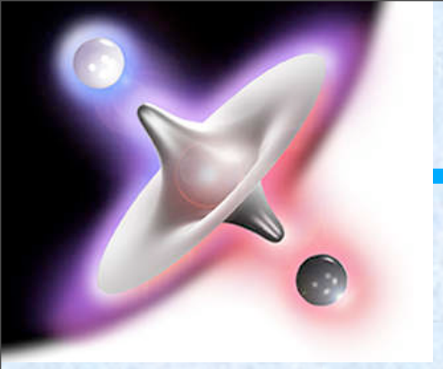
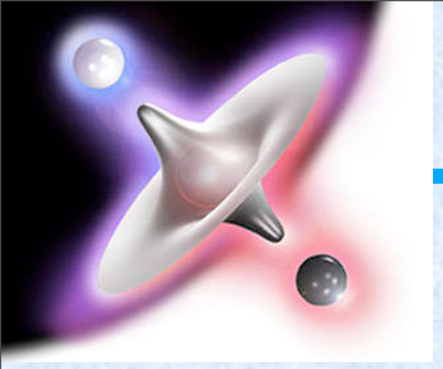


AD



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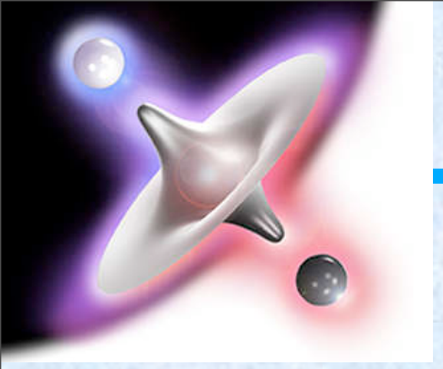
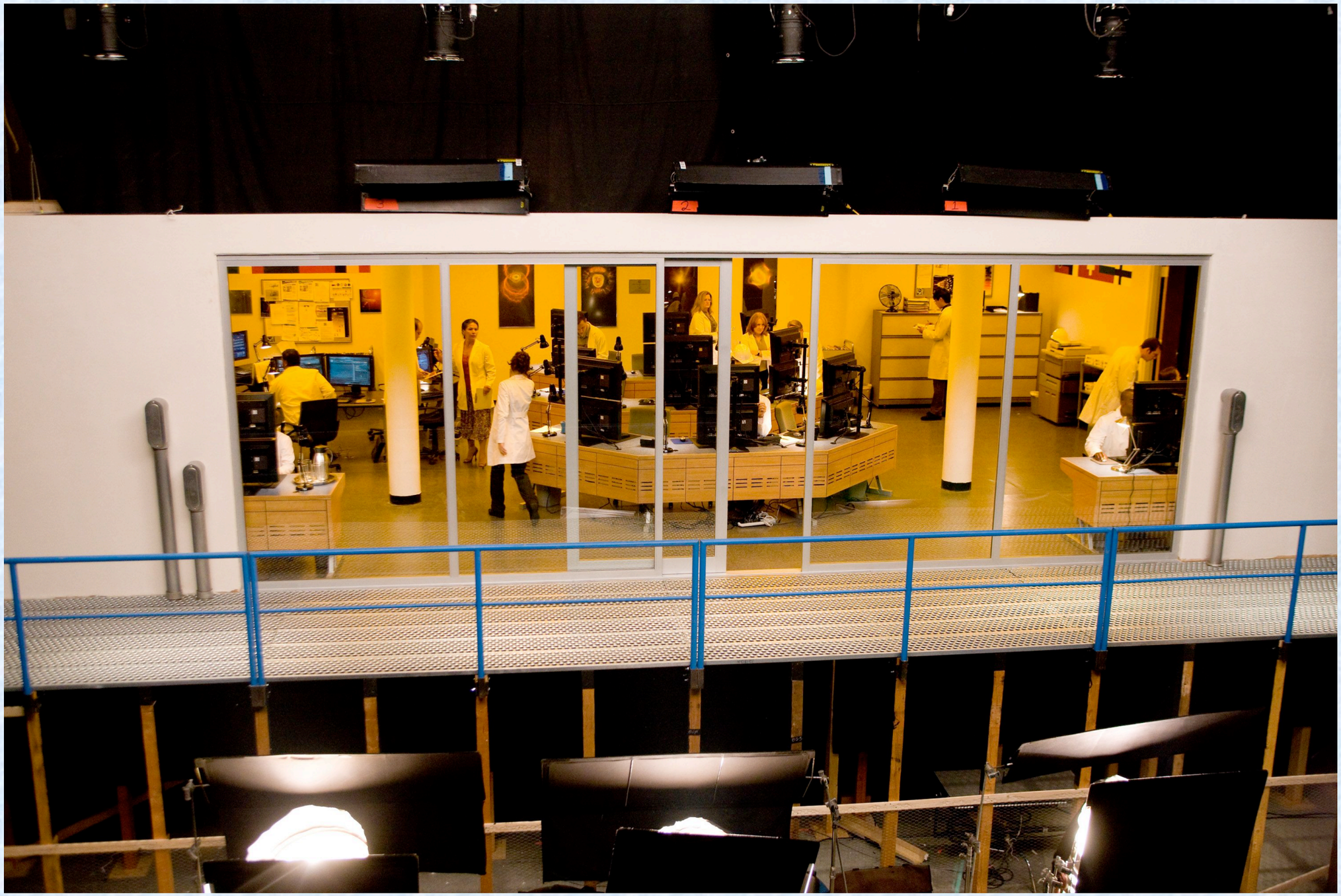
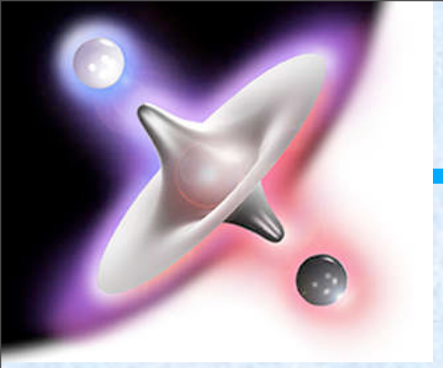


II. ANTIMATTER ‘FACTORY’

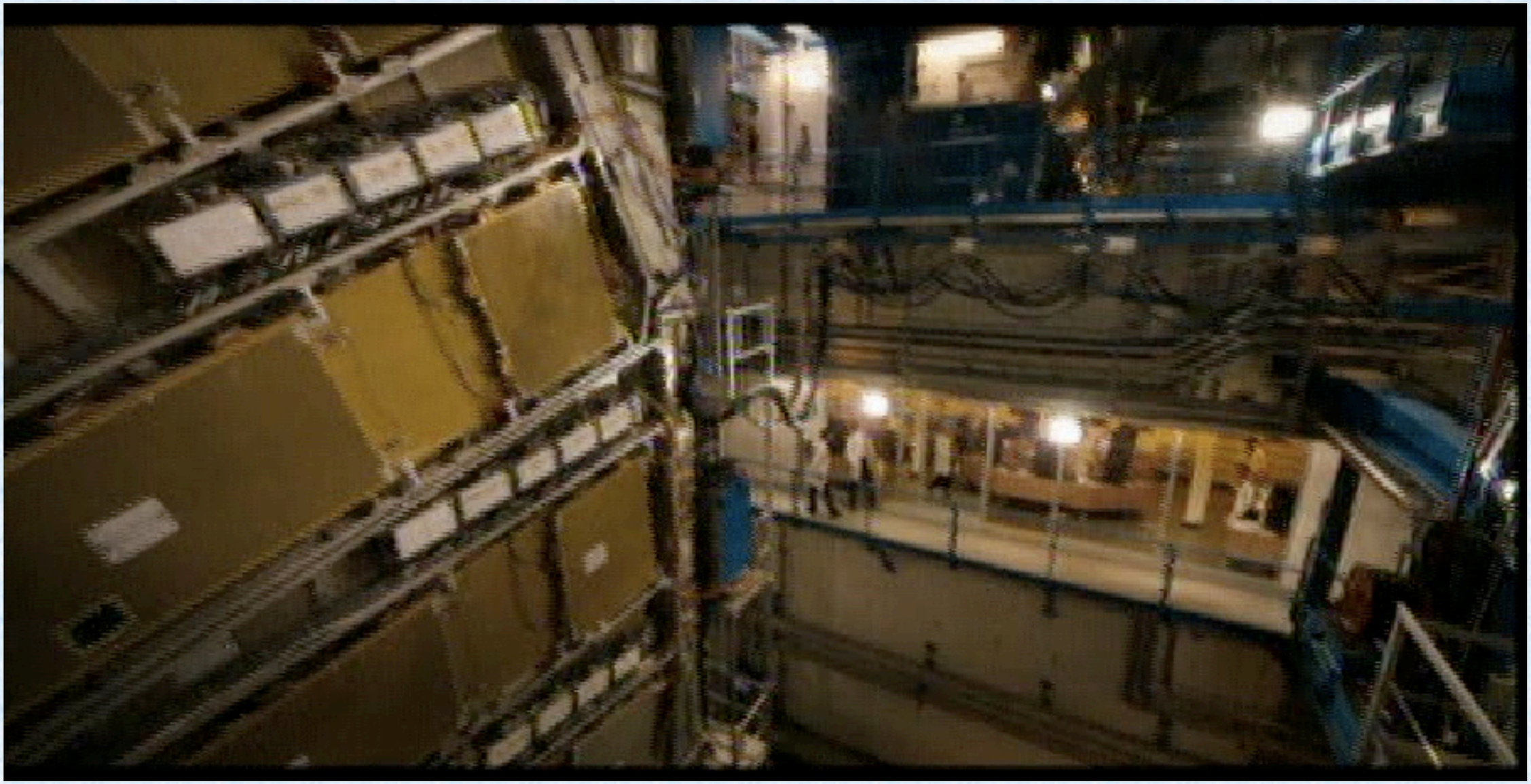
(also-known-as: “Antiproton Decelerator”)

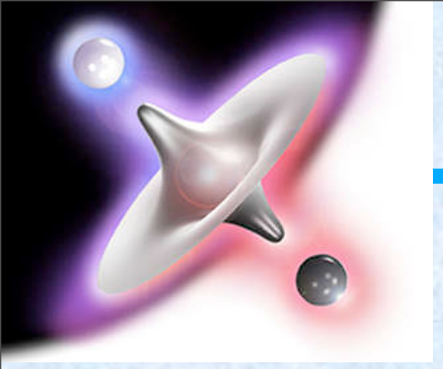
Antimatter factory in Hollywood studios





...seemlessly merged into the ATLAS cavern ....





... and the naked truth at CERN.

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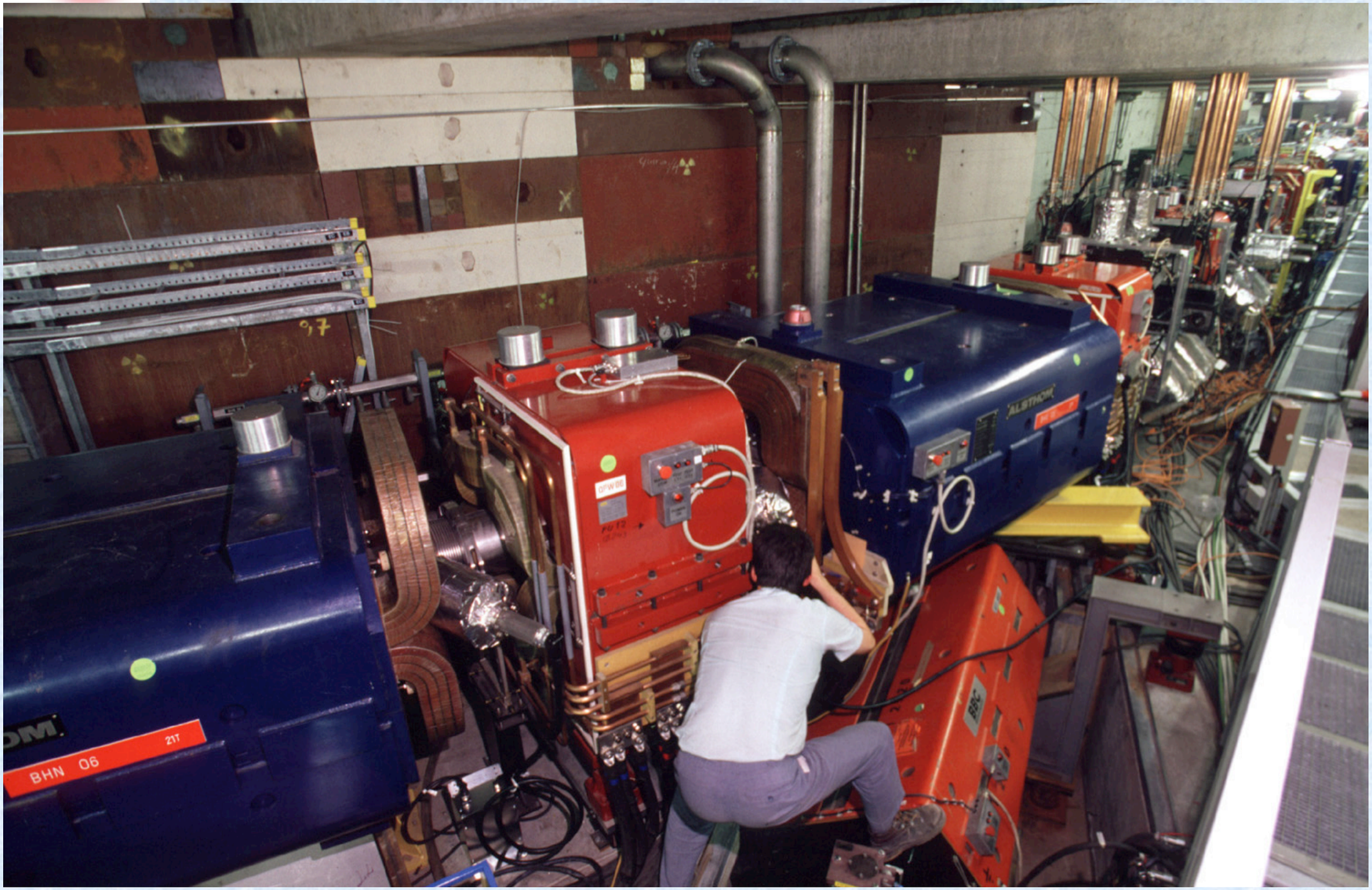
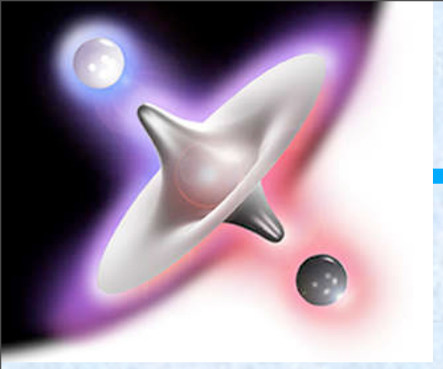
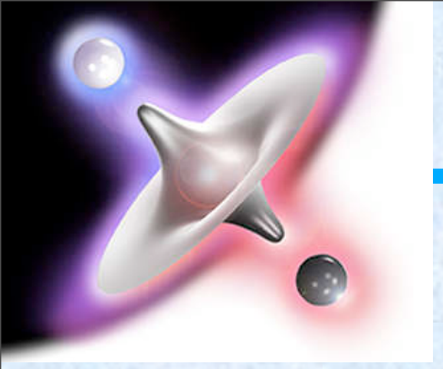




CERN - The Lord of the Rings



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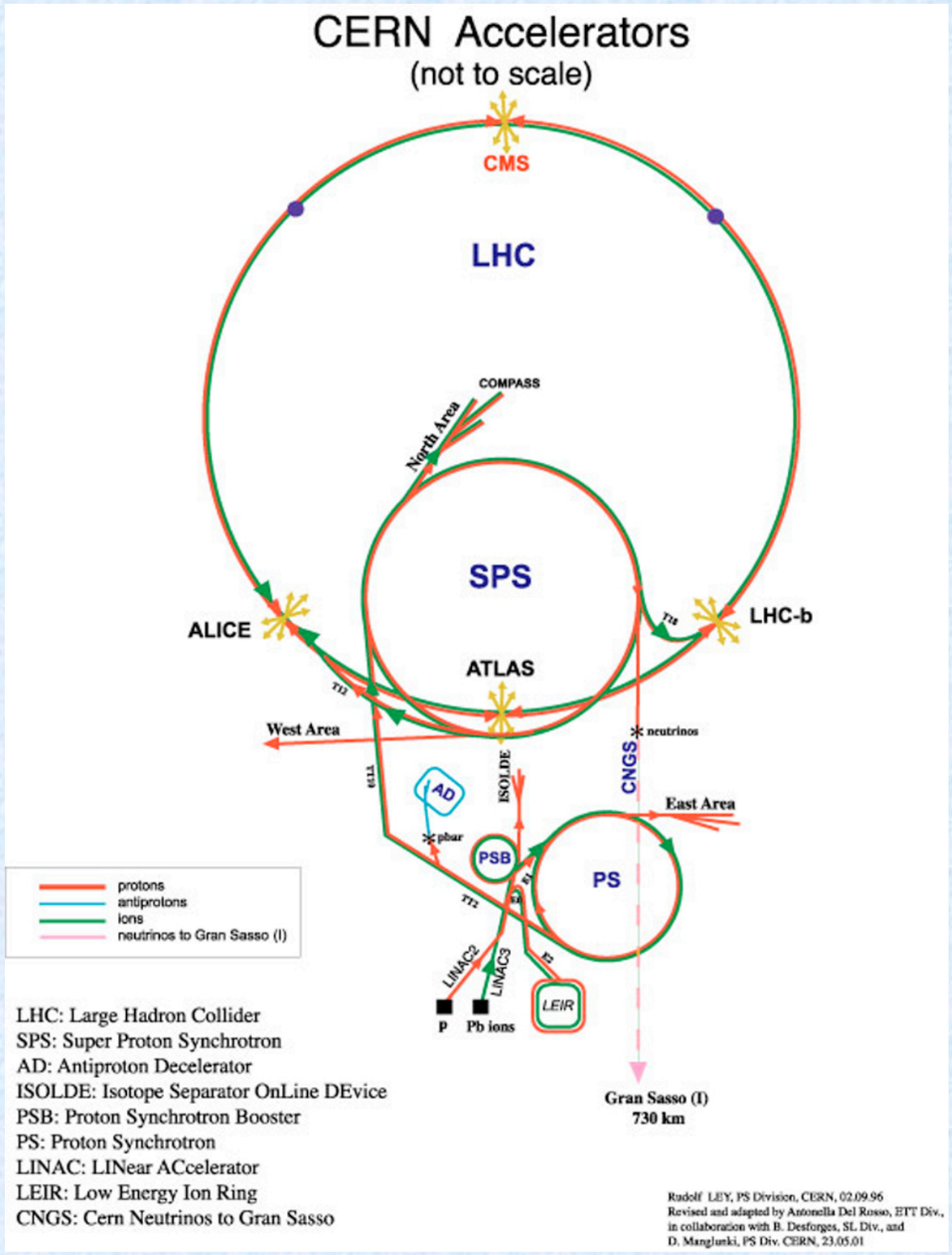

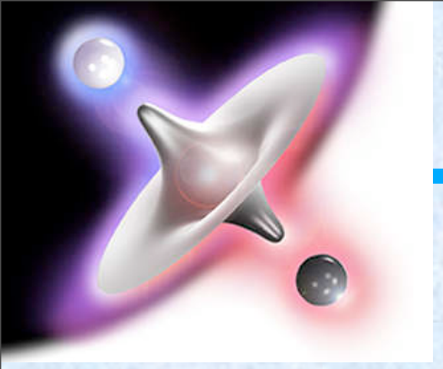

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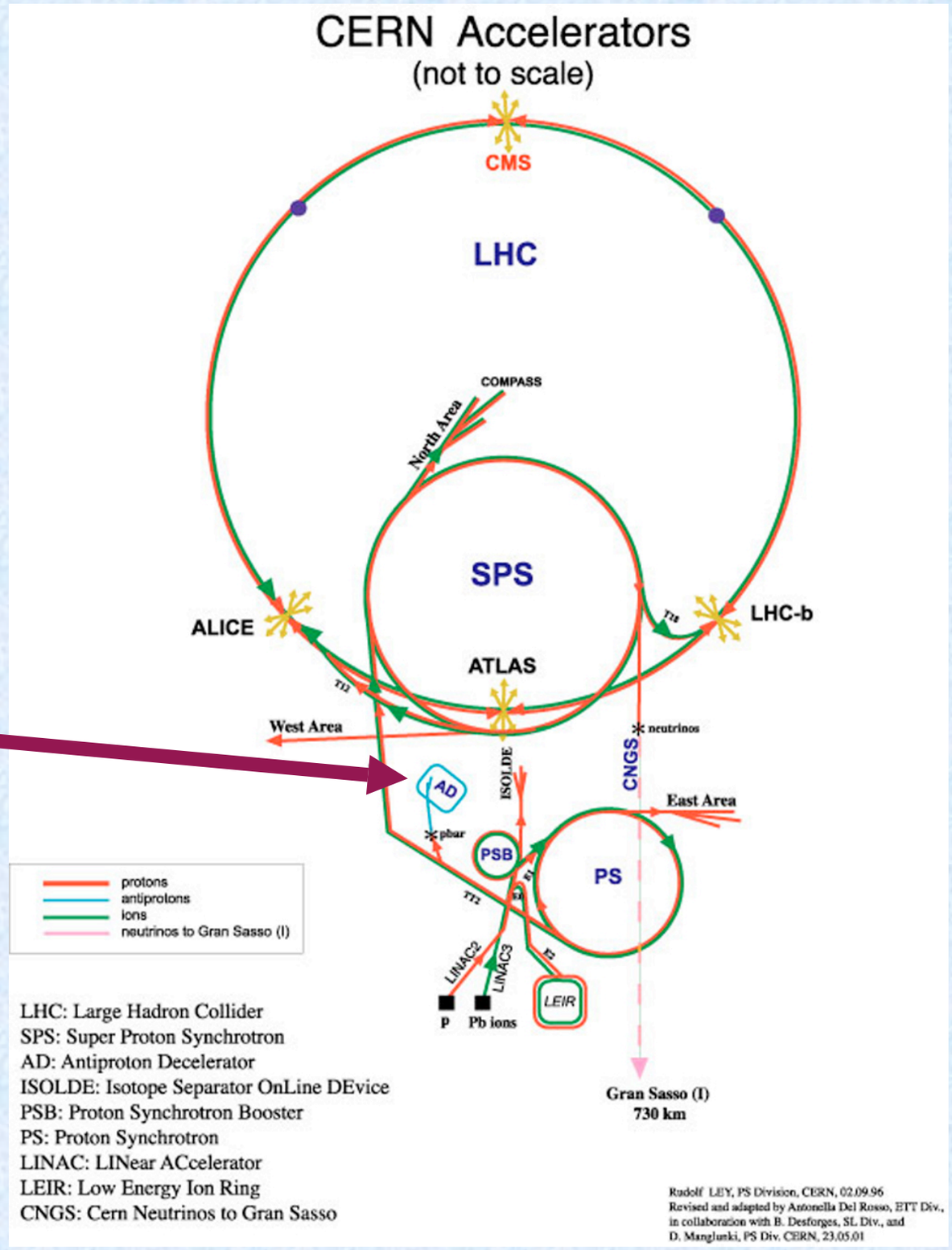
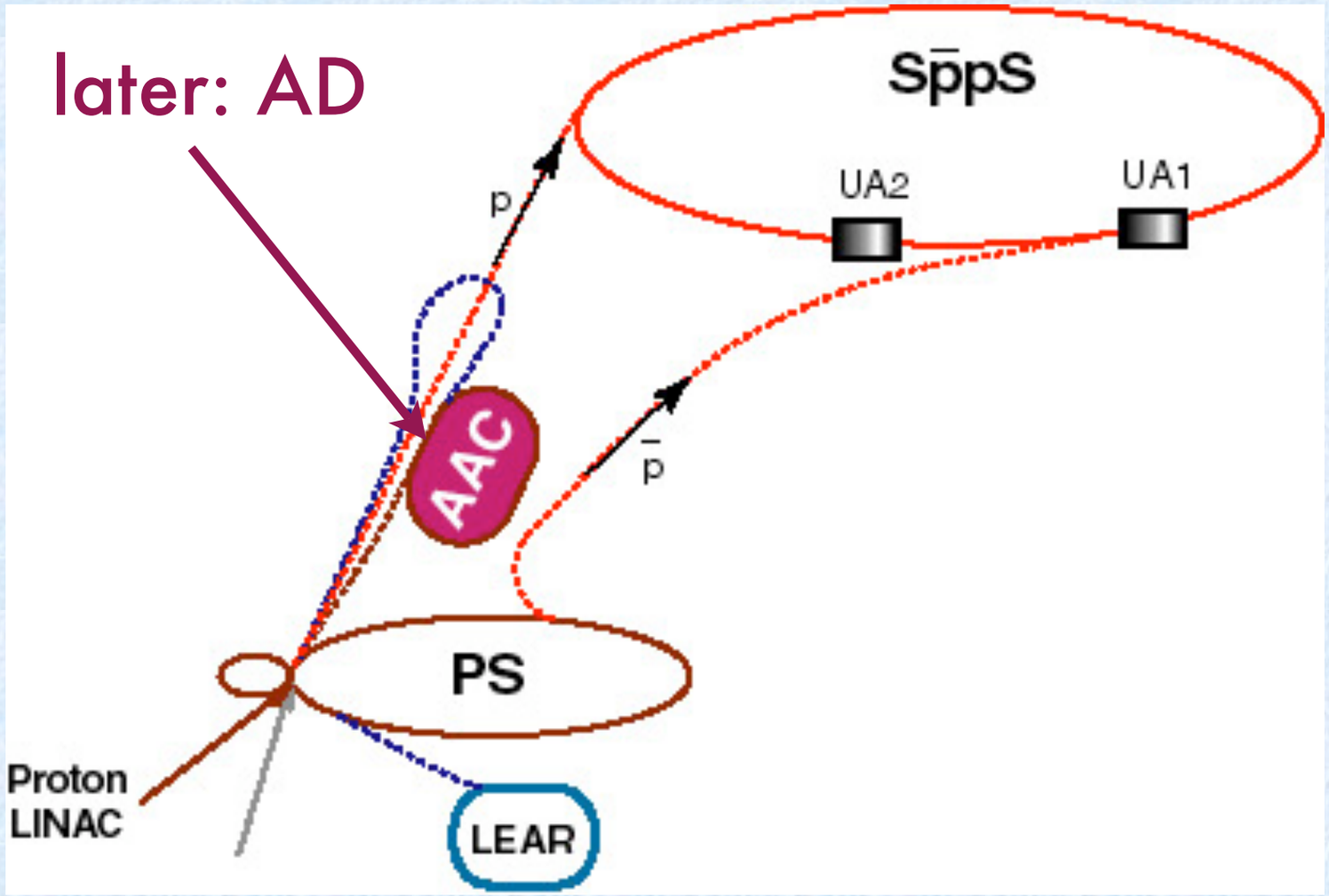


AD

The reason for antiproton beams at CERN (1980)



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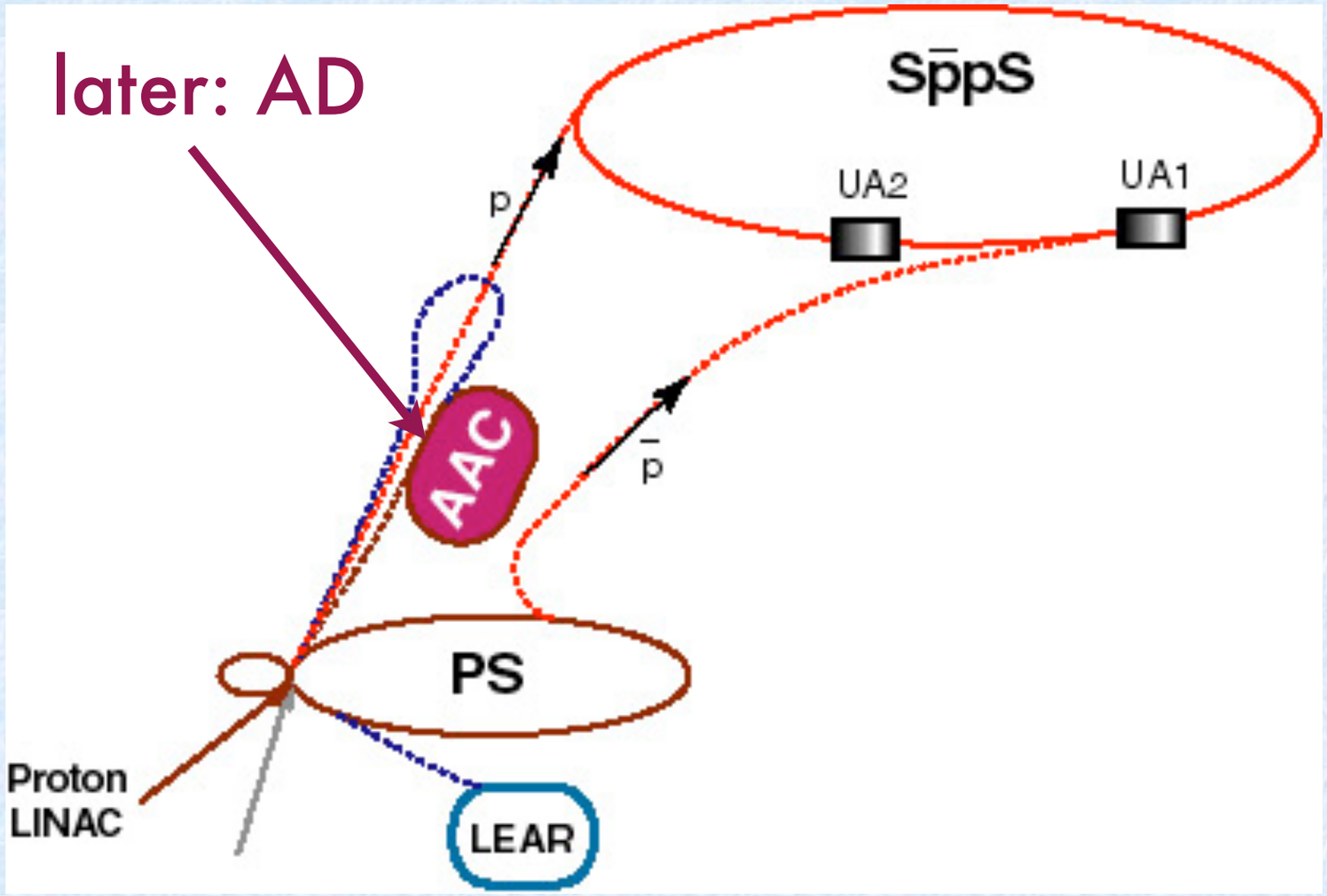

Antiprotons were needed for the SpS collider (270+270 GeV)

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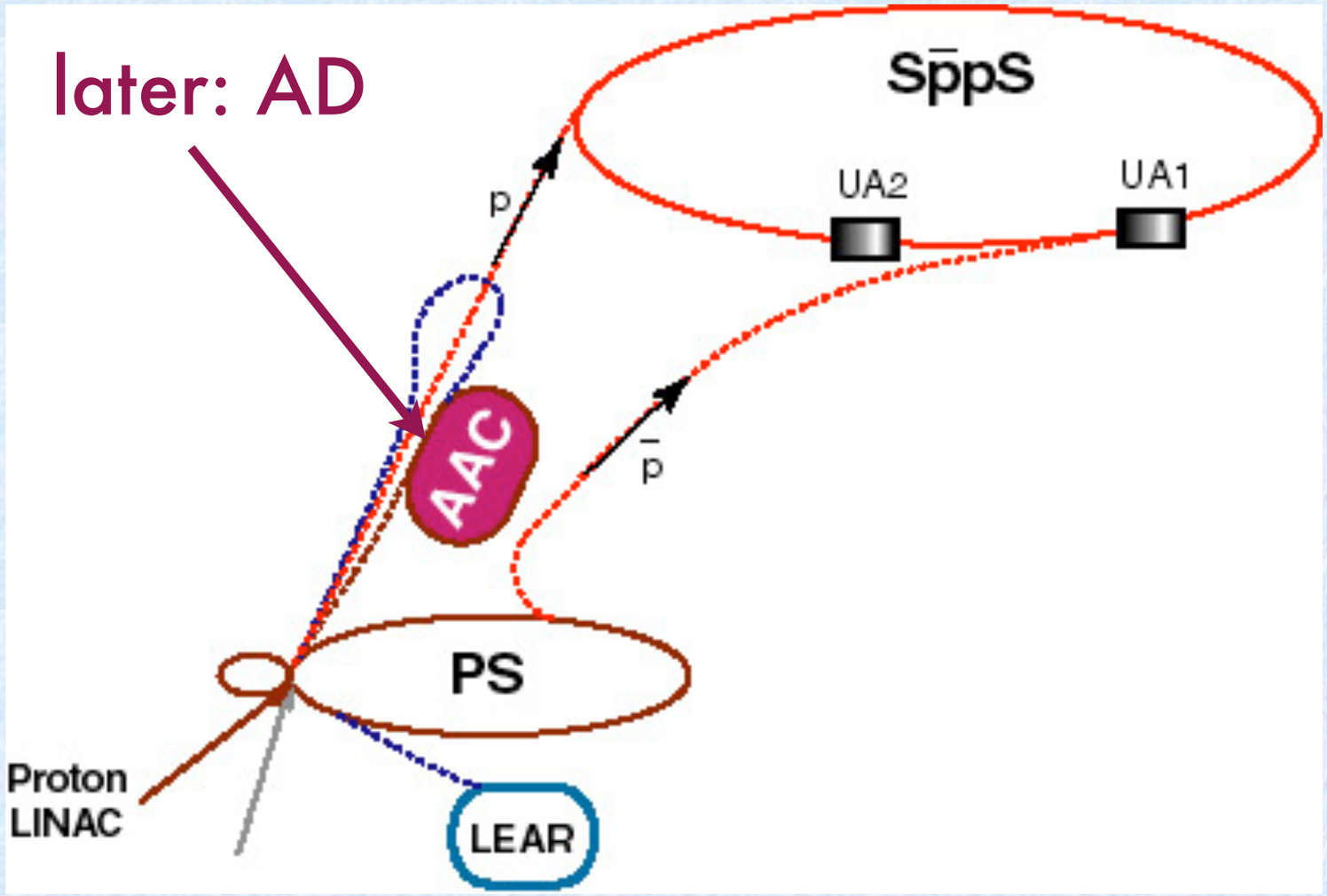

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Discovery of W, Z bosons

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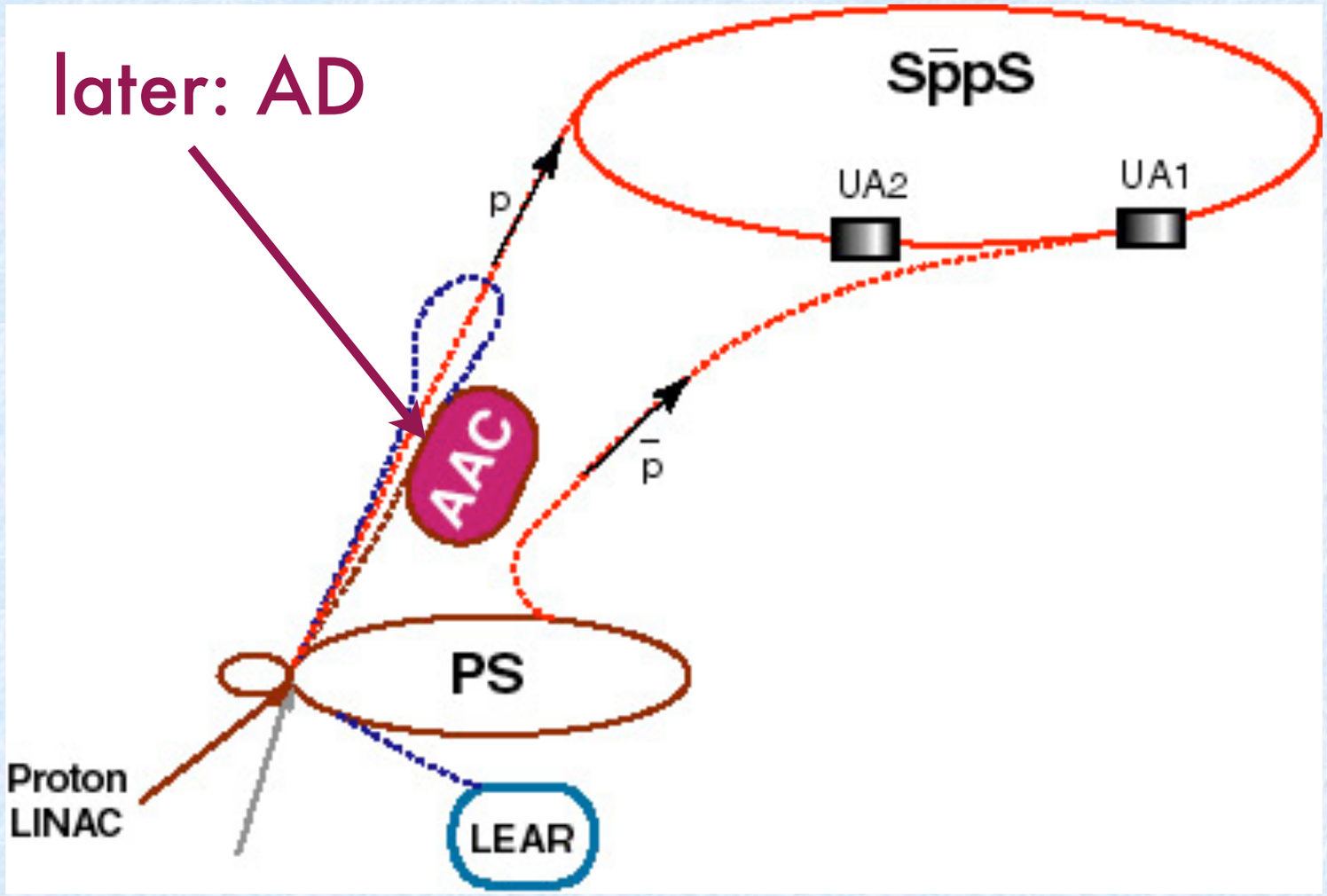
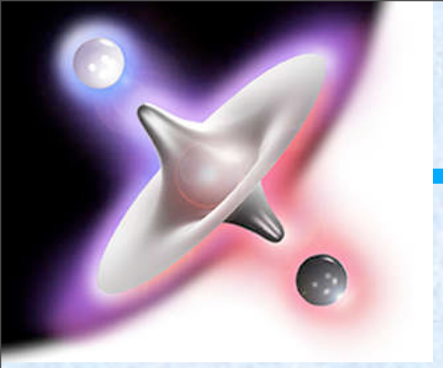


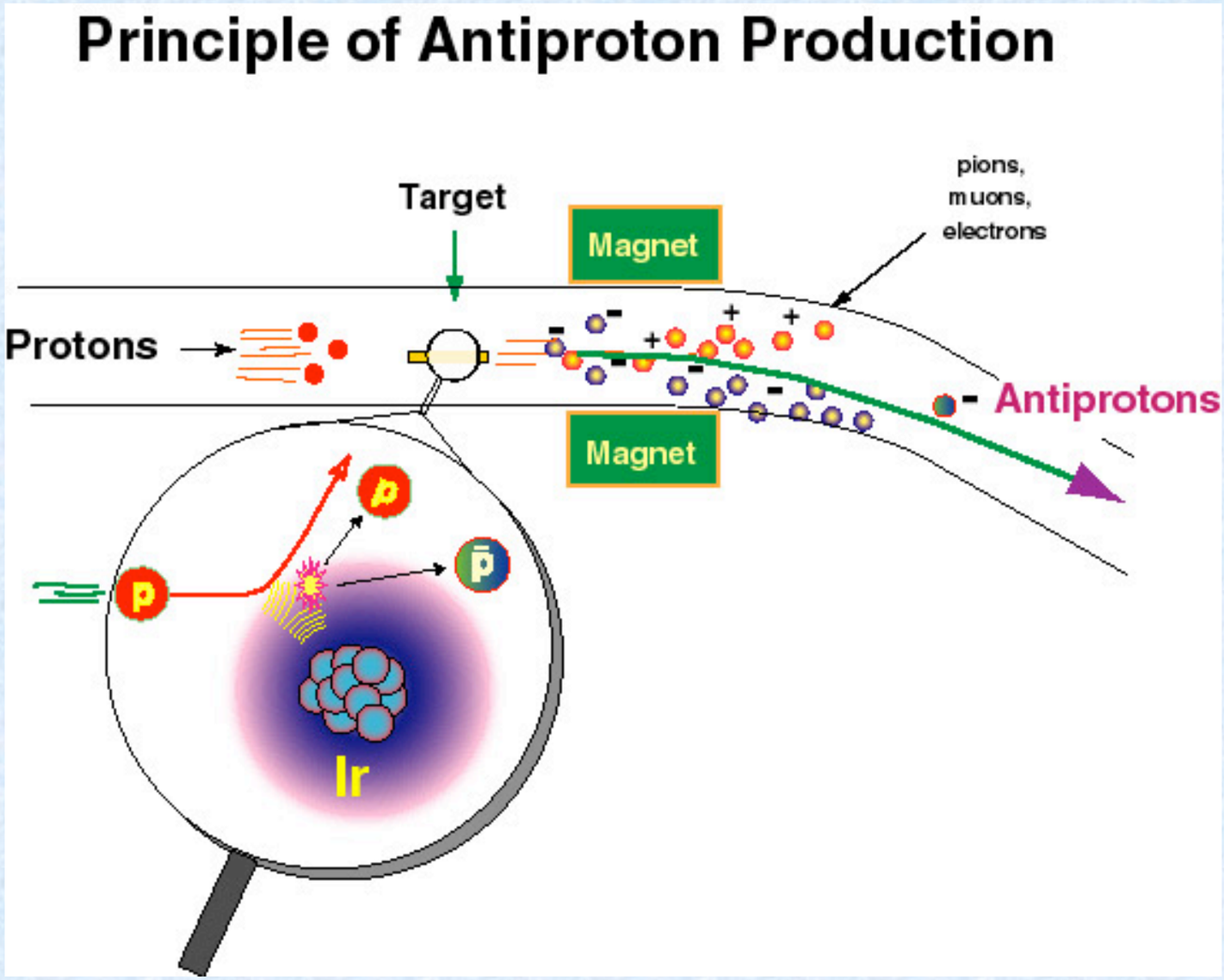
Antiprotons were needed for the SpS collider (270+270 GeV)

Discovery of W, Z bosons

Search for SUSY, Top, Higgs

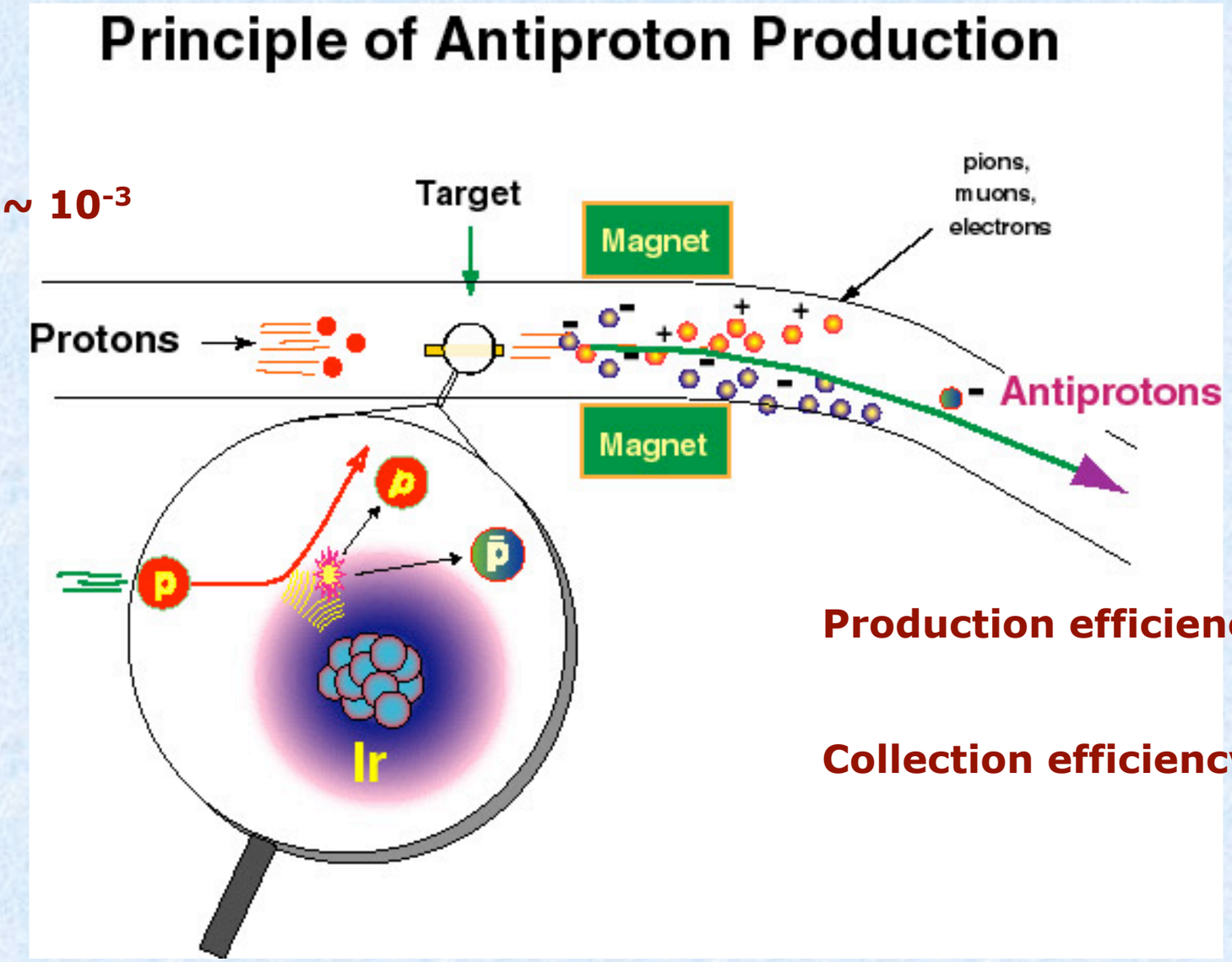


An accelerator 'condenses' energy in collisions



An accelerator 'condenses' energy in collisions

Acceleration efficiency ~ 10^{-3}



Production efficiency ~ 10^{-4}

Collection efficiency (AD) ~ 10^{-2}

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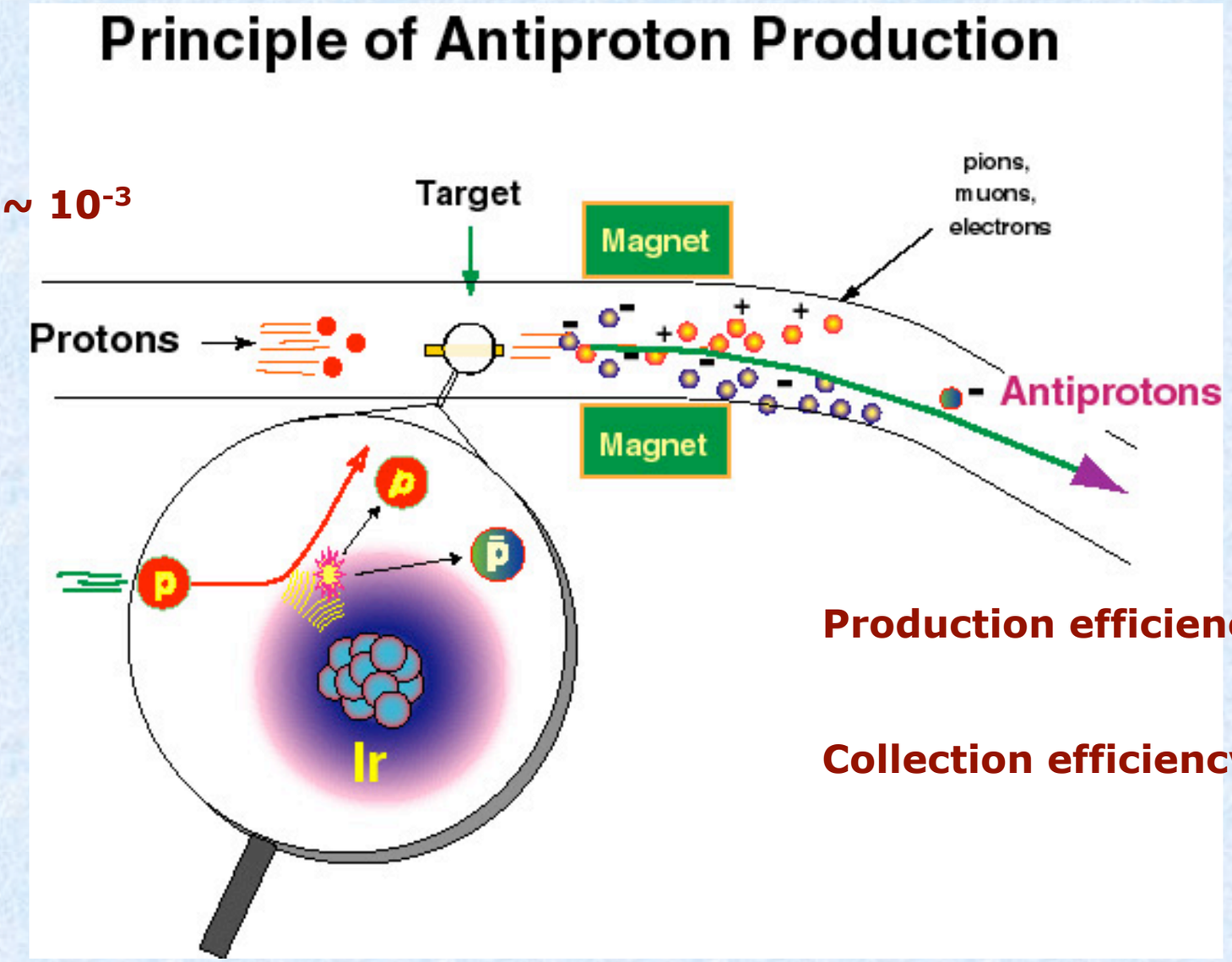


Production efficiency ~ 10^{-4}

Collection efficiency (AD) ~ 10^{-2}

Peak production at CERN ~ 200,000,000,000,000 antiprotons/year

(only 0.3 nano-gram, overall efficiency ~ 10^{-9})

Efficiency of antiproton production

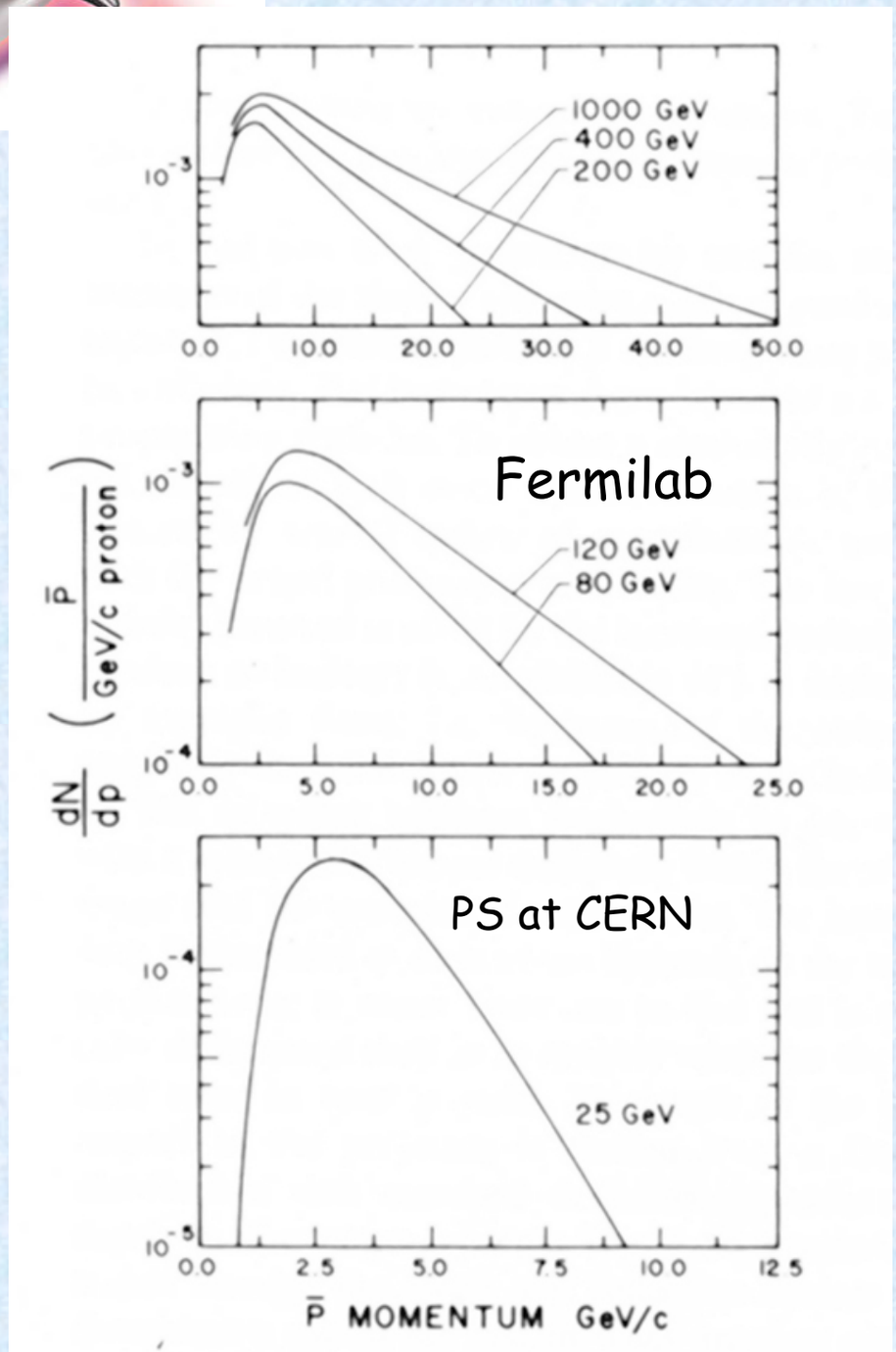


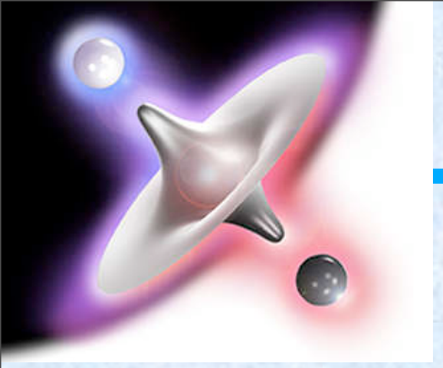
Fig. 7. Total laboratory $\bar{p}$ production on tungsten below 0.30 GeV/c from eq. (1) (per interacting proton).

Energy dependent

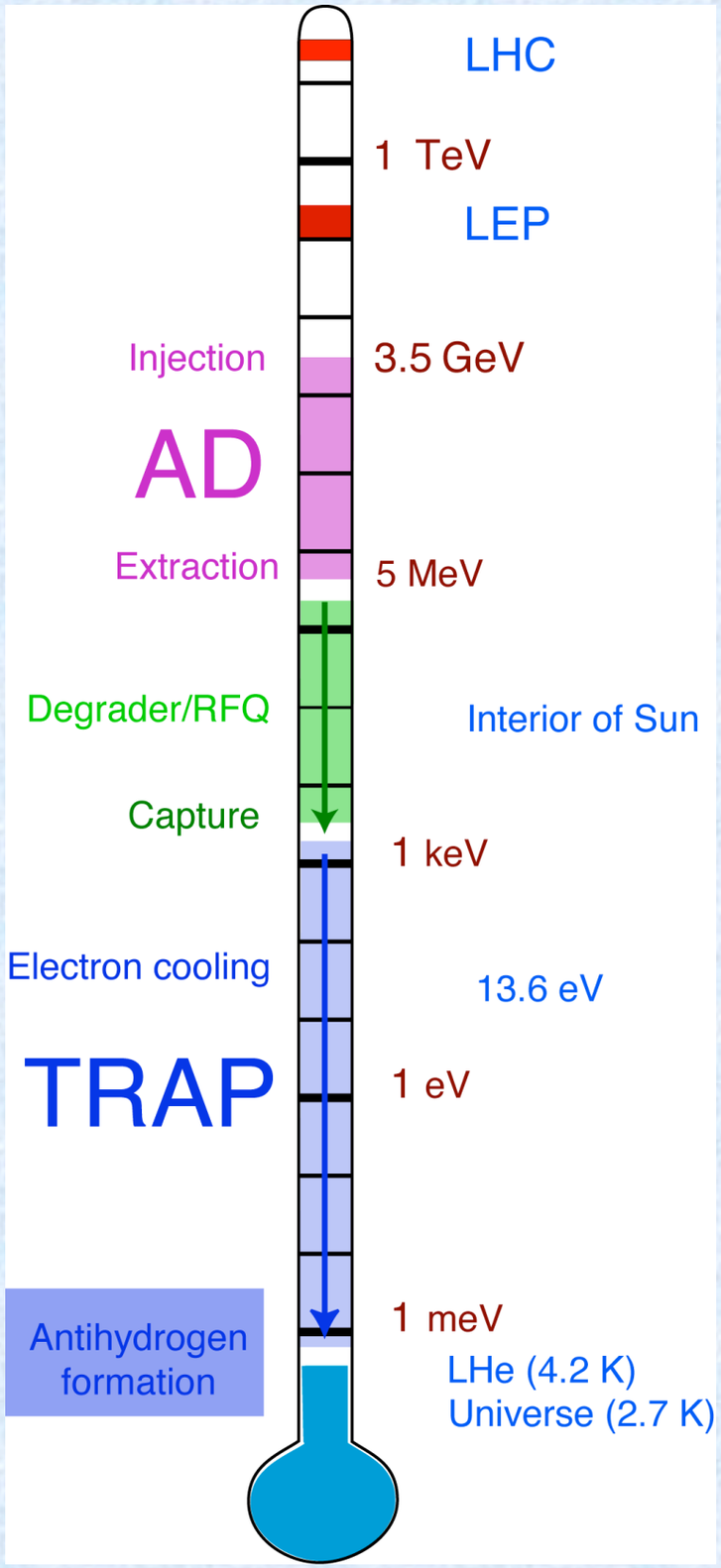
Few 10^{-4} (CERN, 26 GeV/c)

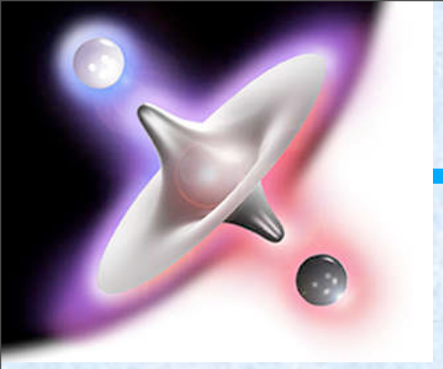
Few 10^{-3} (Fermilab, 120 GeV)

➢99 % of interacting protons
do NOT produce antiprotons



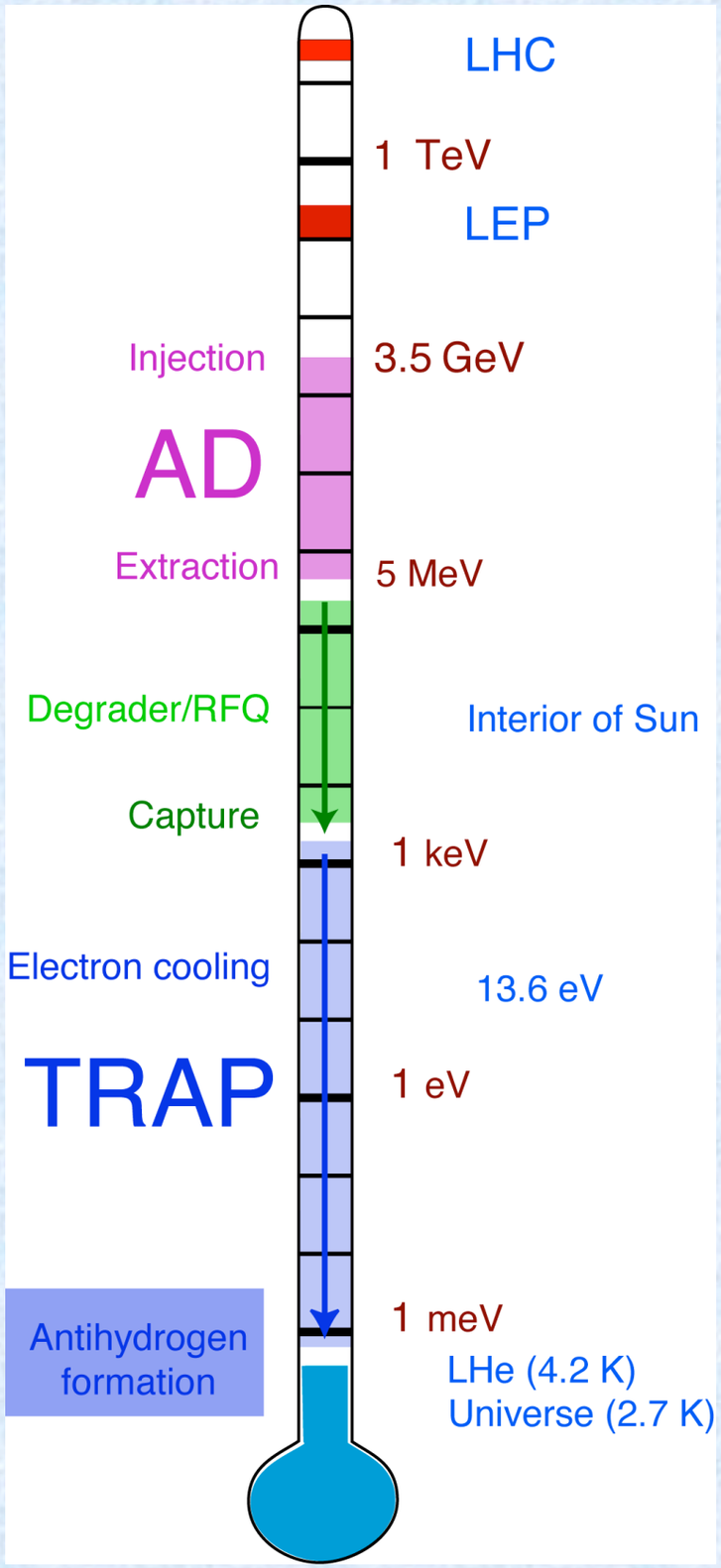
Challenge of antihydrogen production

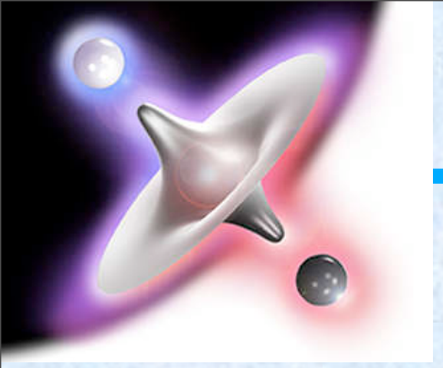




Challenge of antihydrogen production

Antiprotons and positrons (when young) are hot



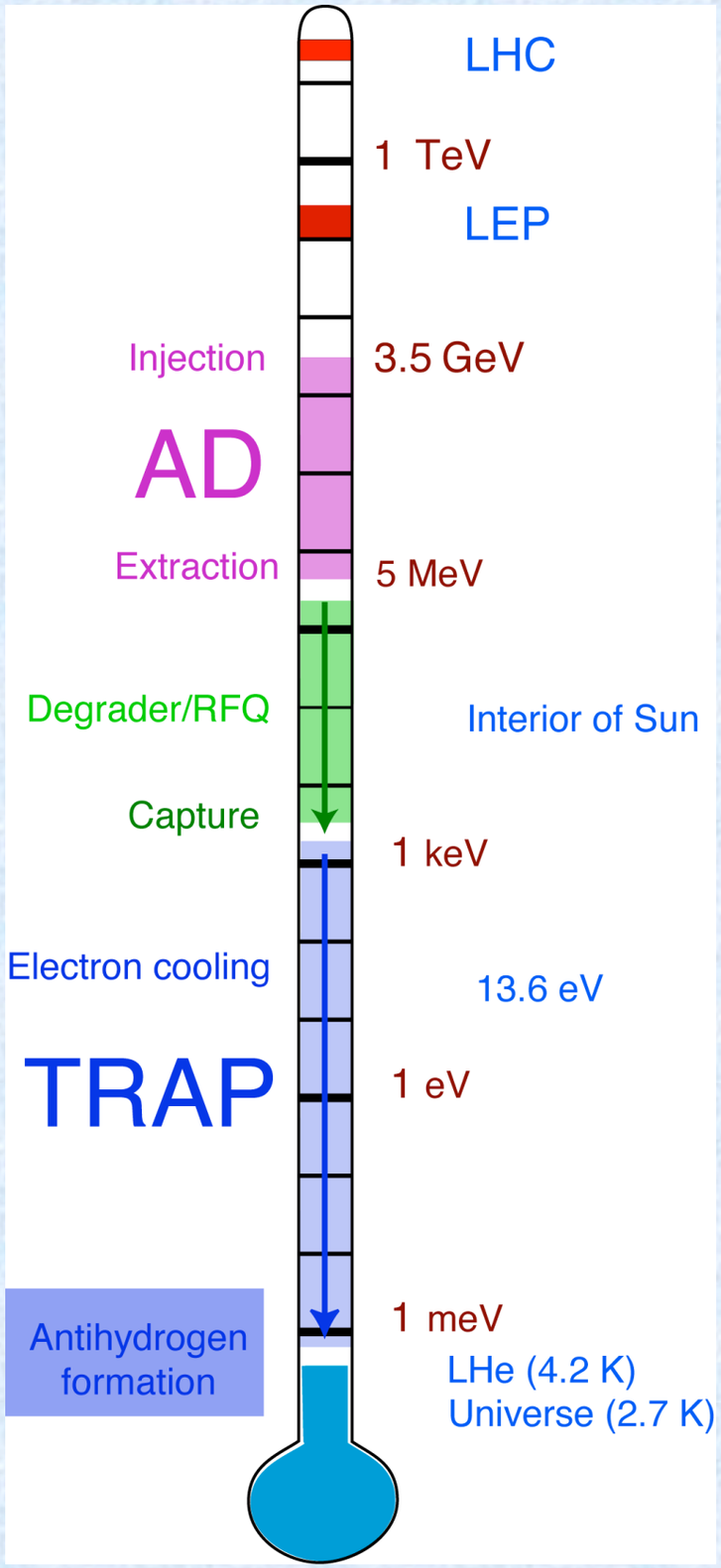


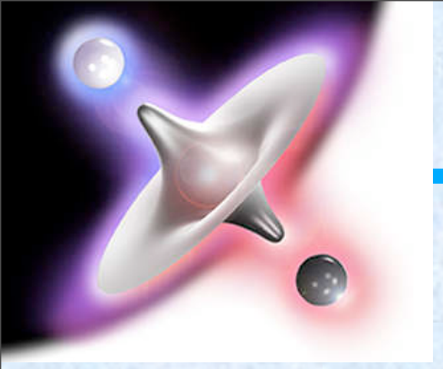
Challenge of antihydrogen production

Antiprotons and positrons (when young) are hot

Hydrogen atom is a weakly bound system:

E (1s) = - 0.000 000 013 6 GeV





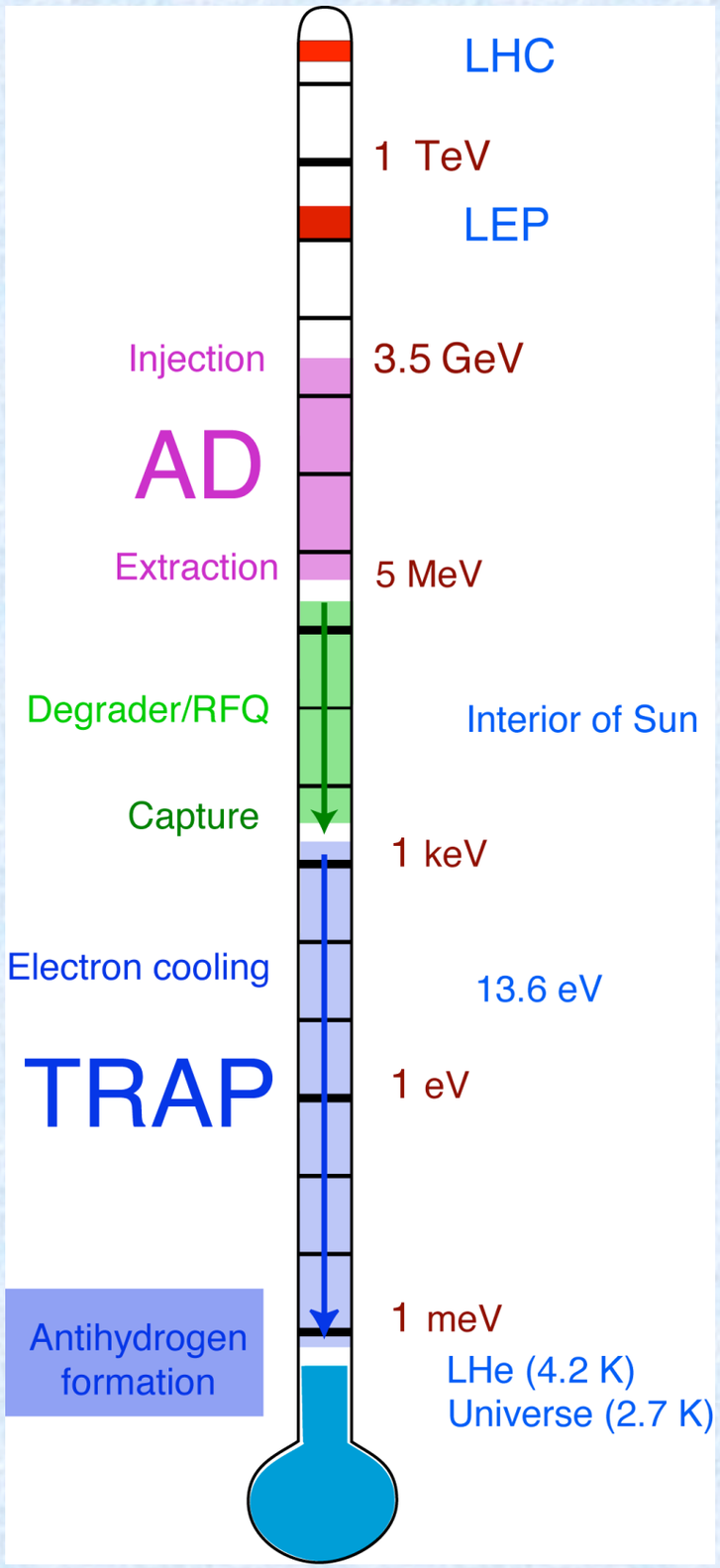
Challenge of antihydrogen production

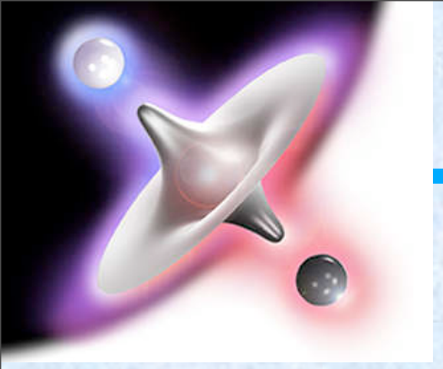
Antiprotons and positrons (when young) are hot

Hydrogen atom is a weakly bound system:

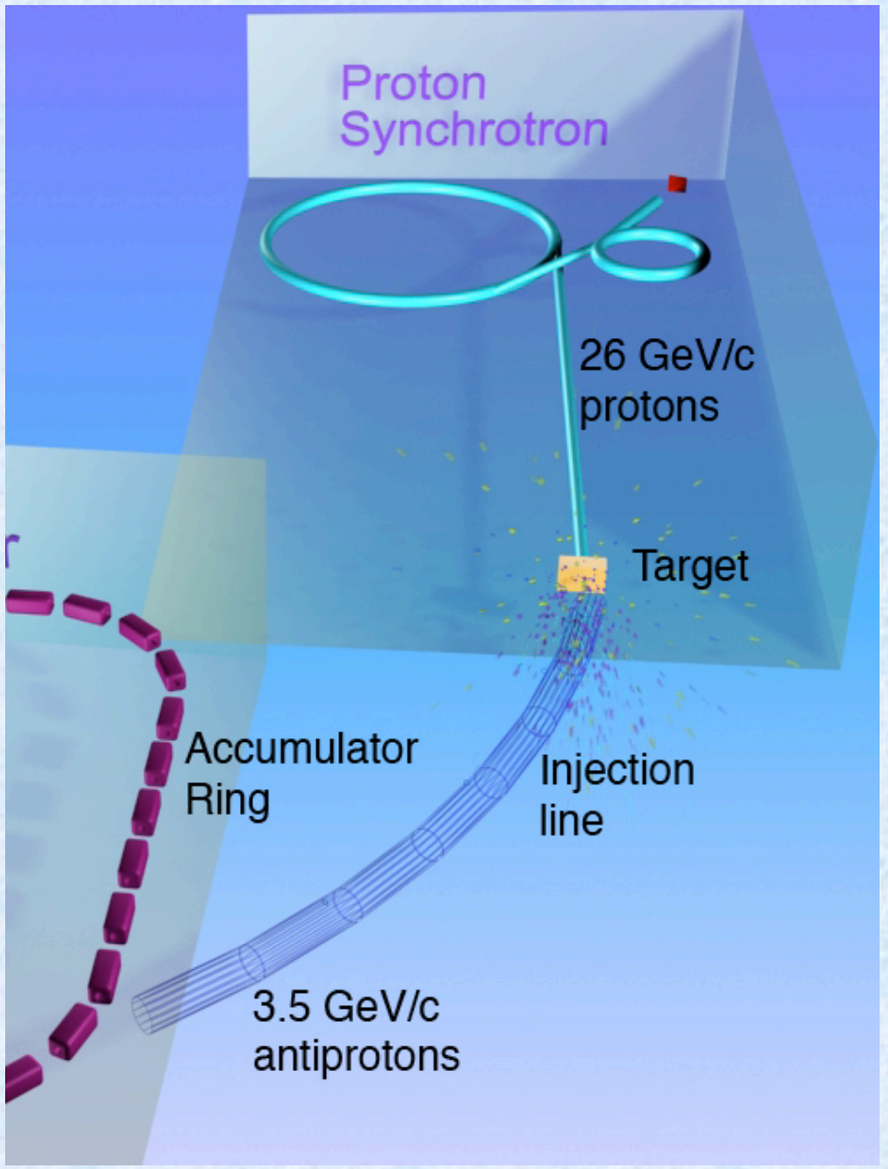
E (1s) = - 0.000 000 013 6 GeV

Constituents need to chill before getting married





Antiproton Decelerator (AD)



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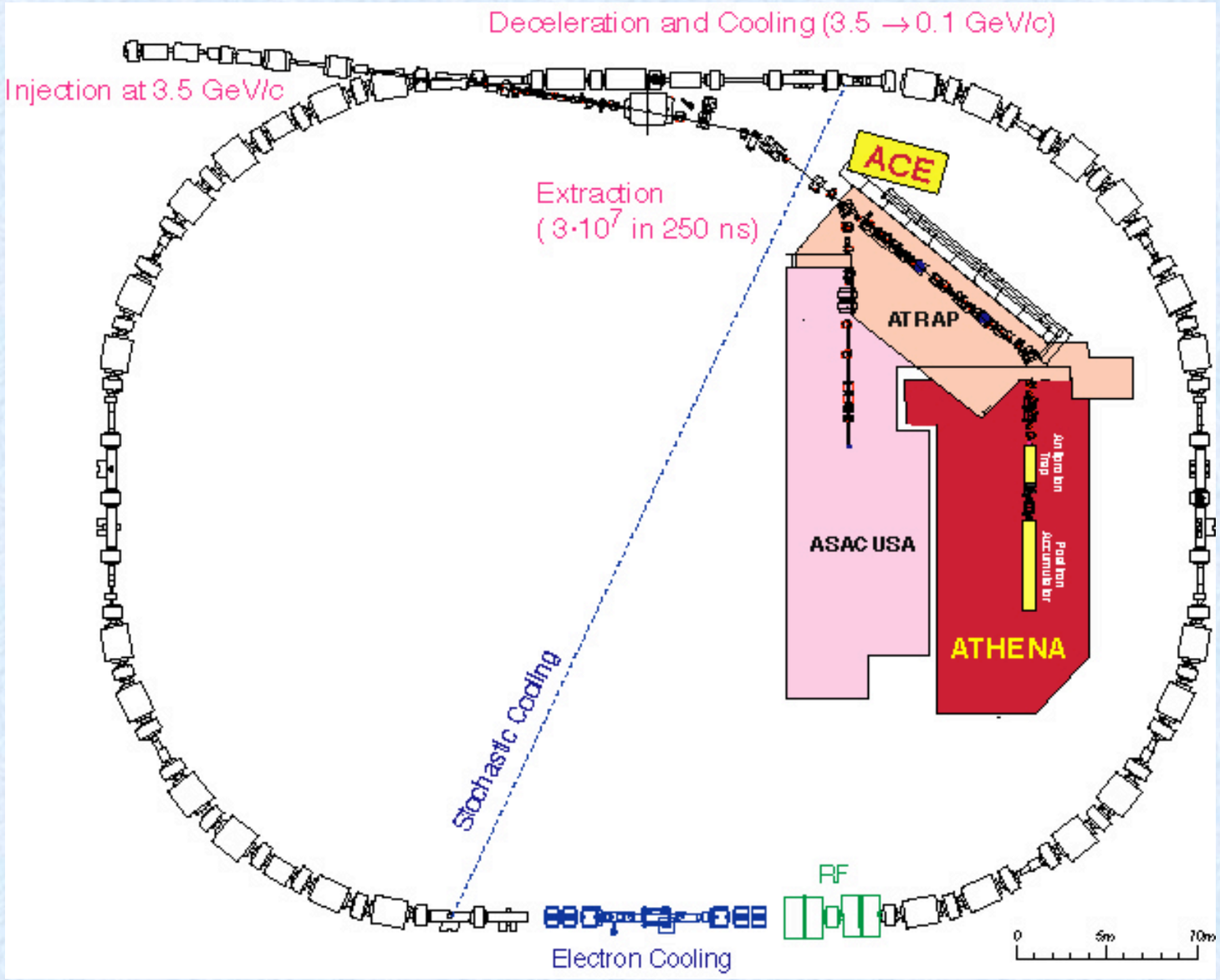
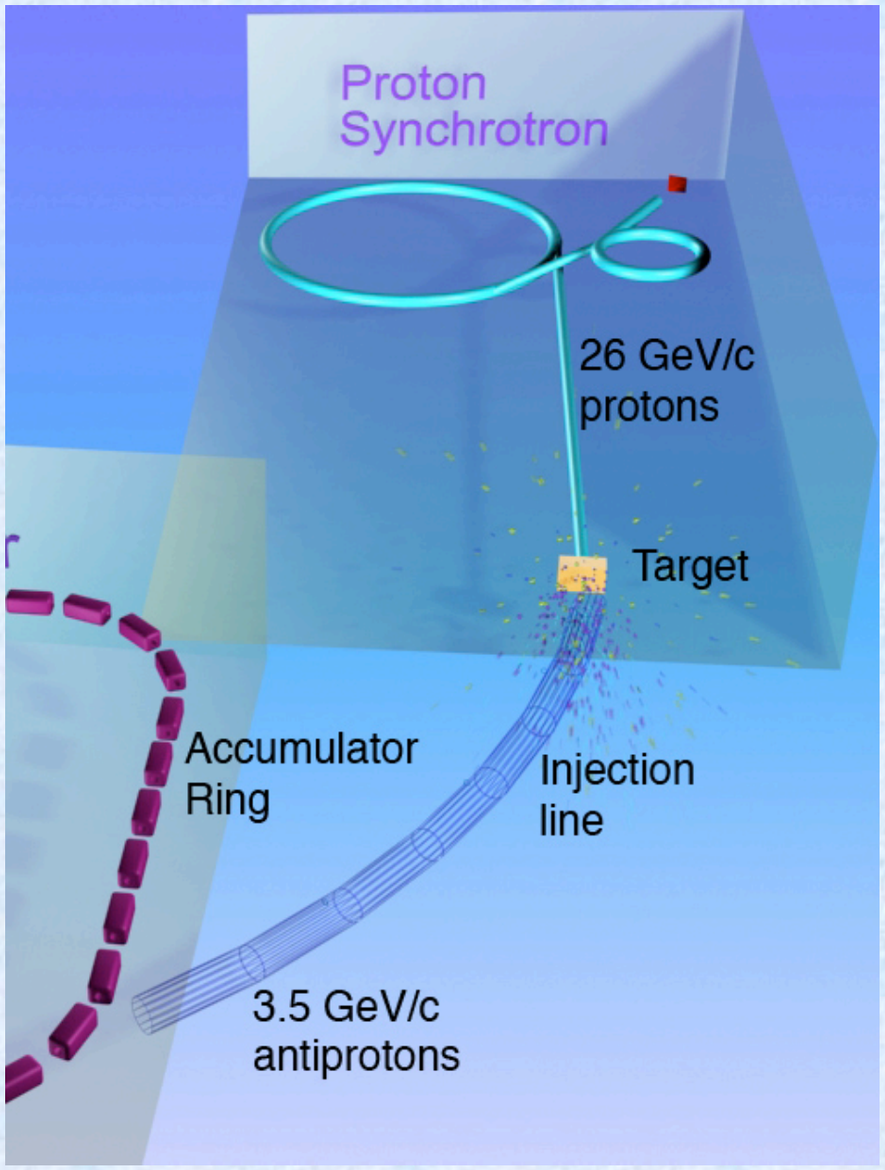
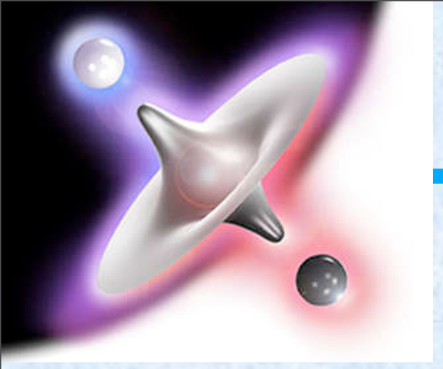
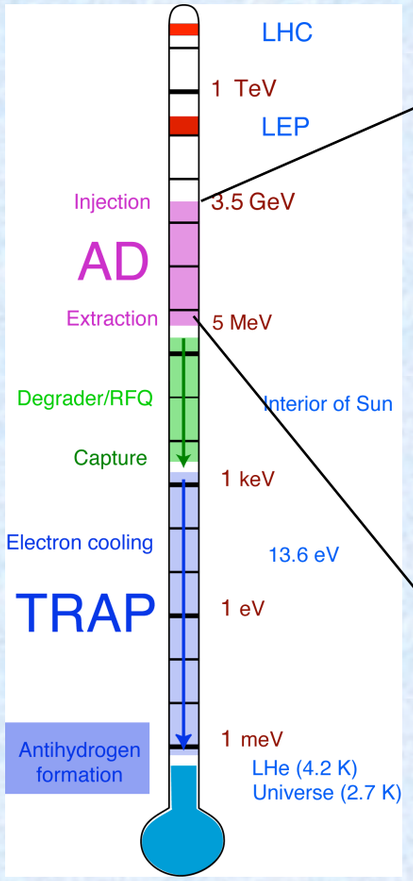
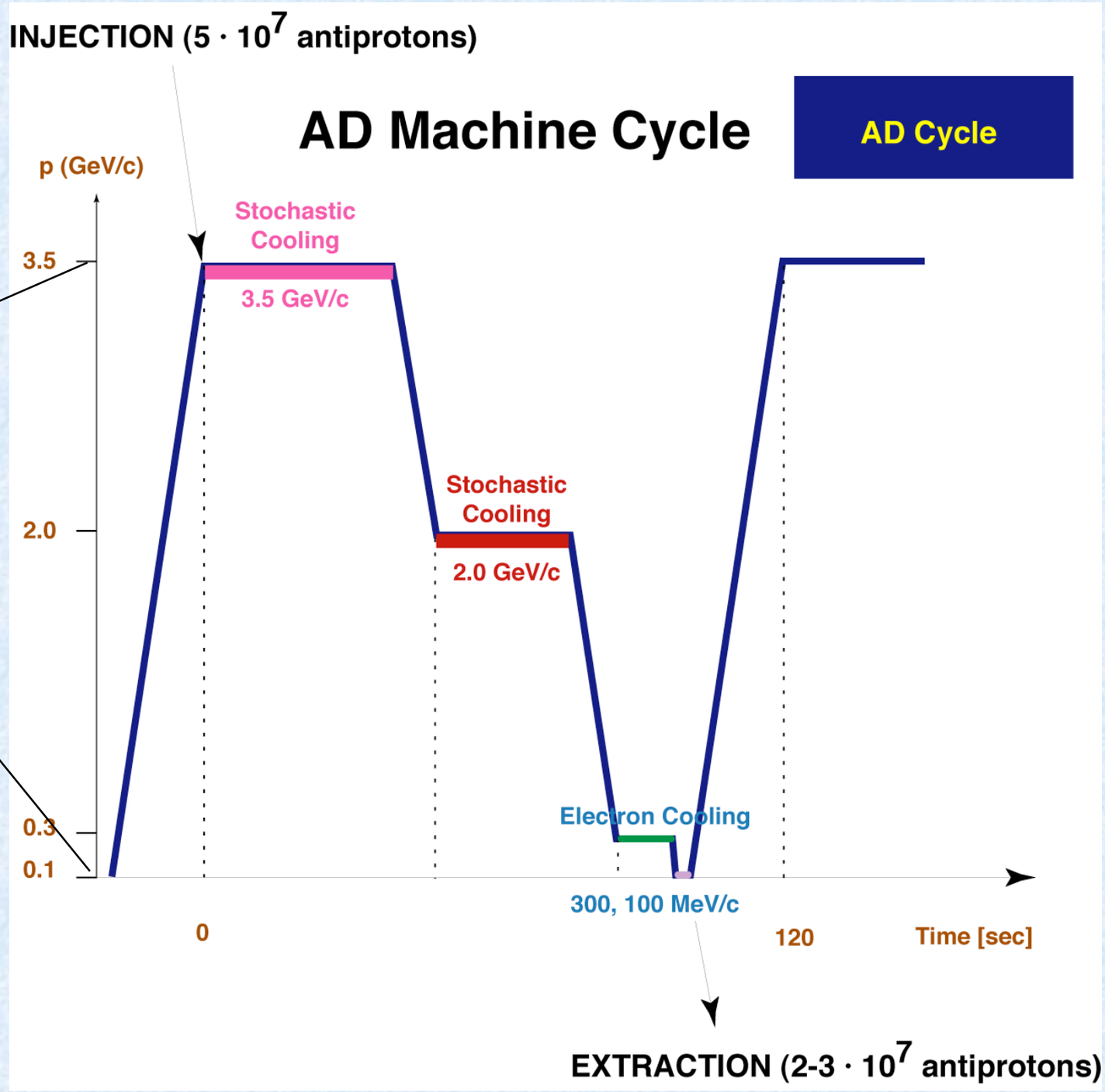


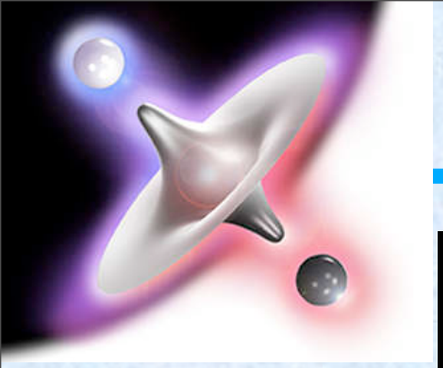




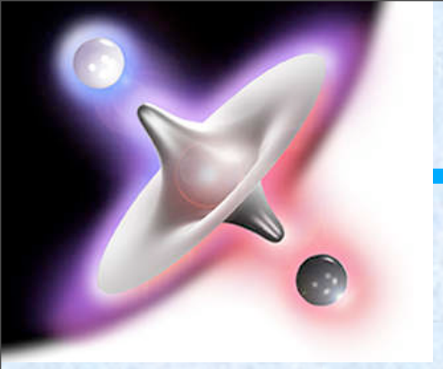
The Antiproton Decelerator (AD)







The AD Movie



The AD - a machine and its team

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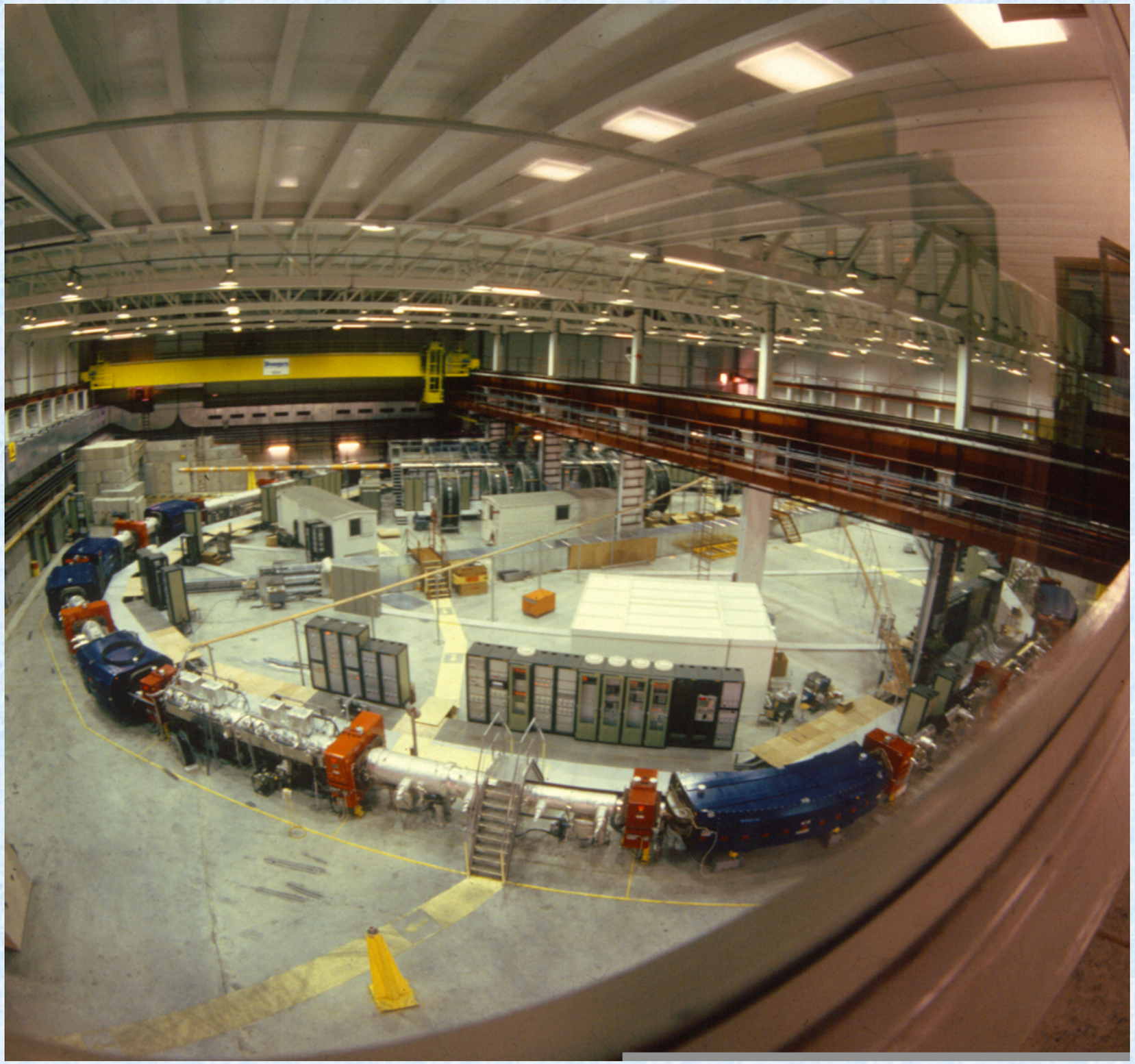
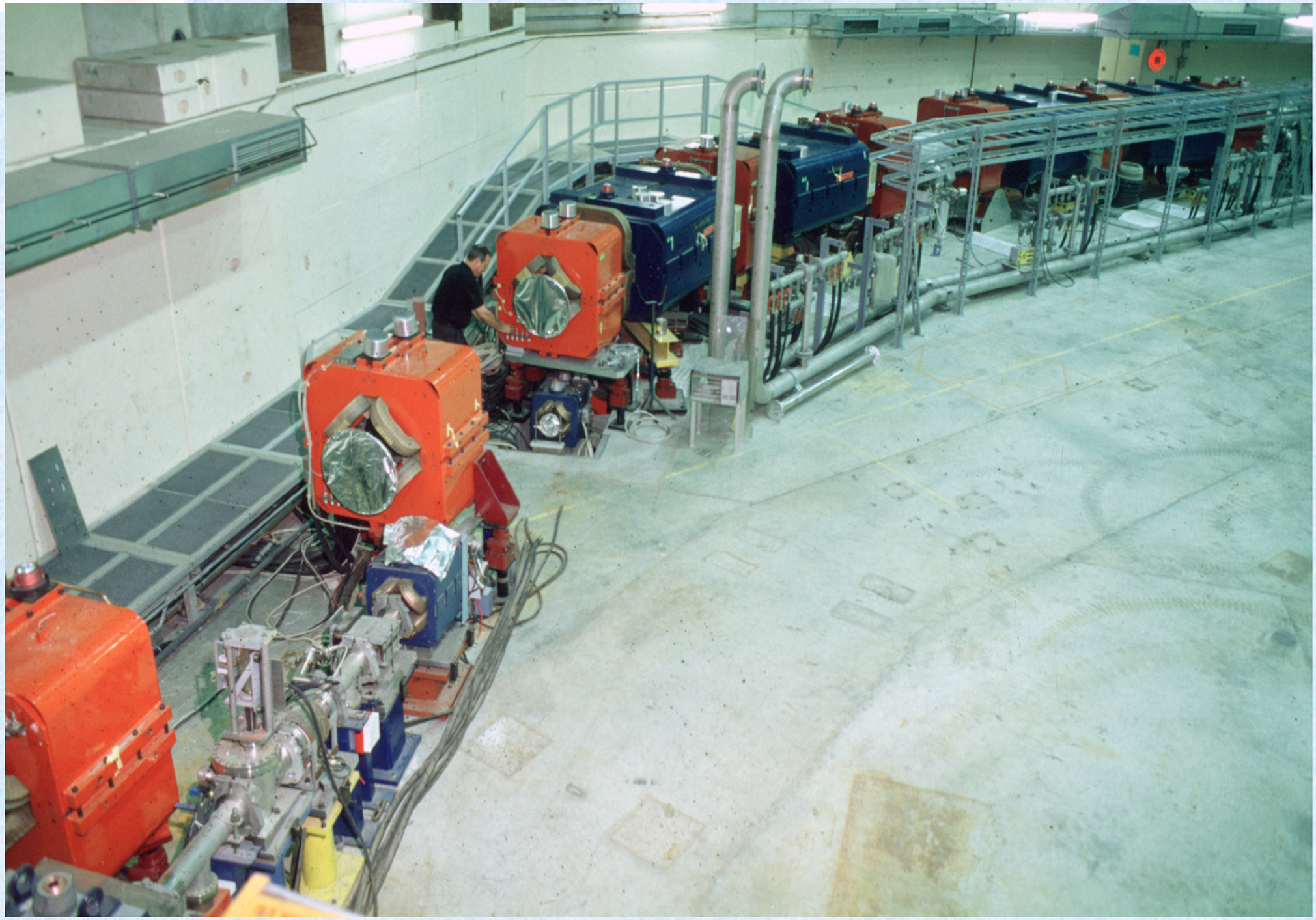
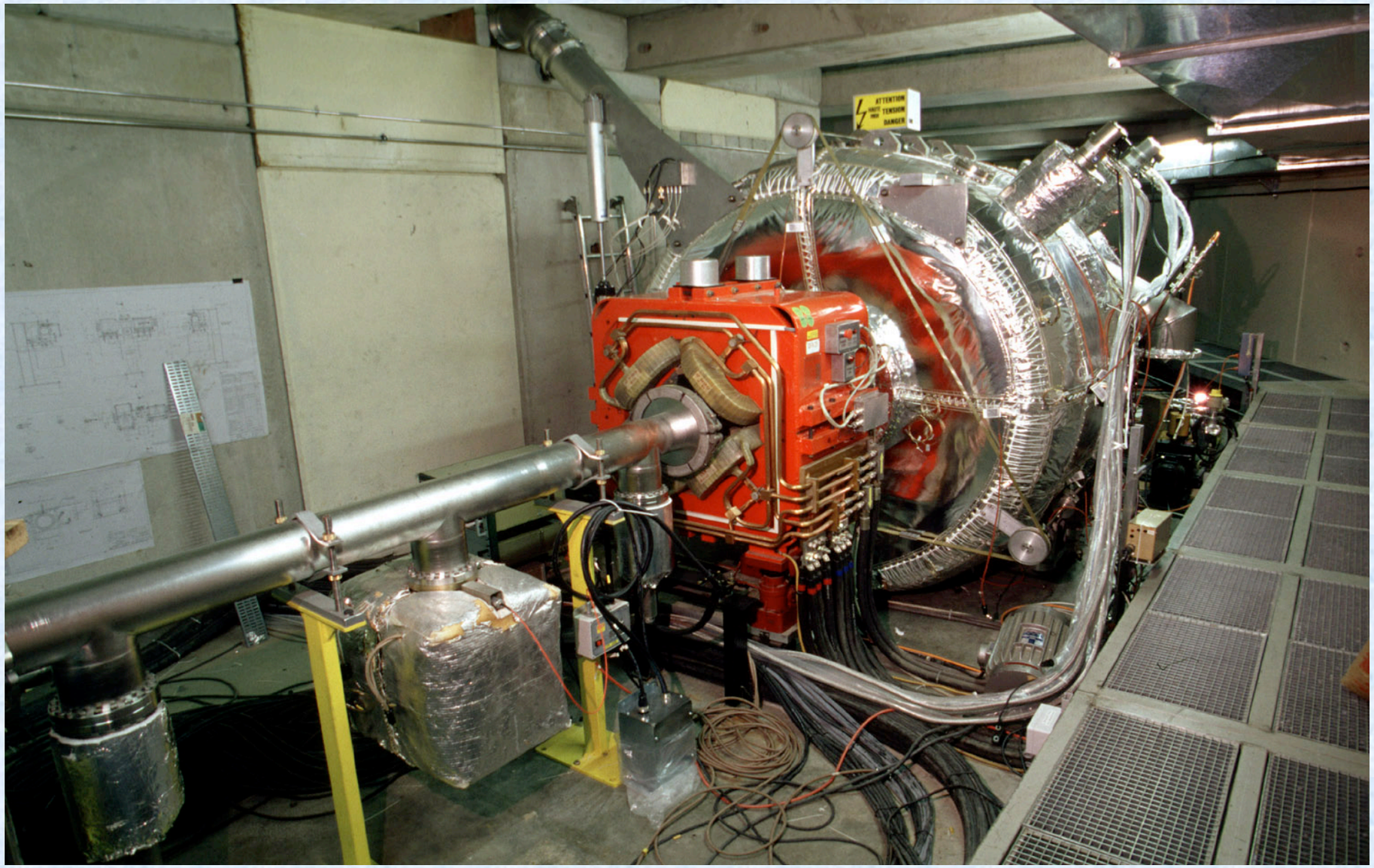


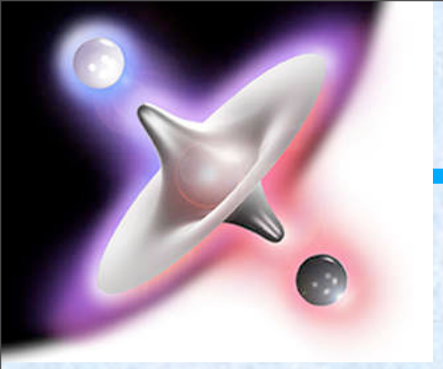
The AD - a machine and its team



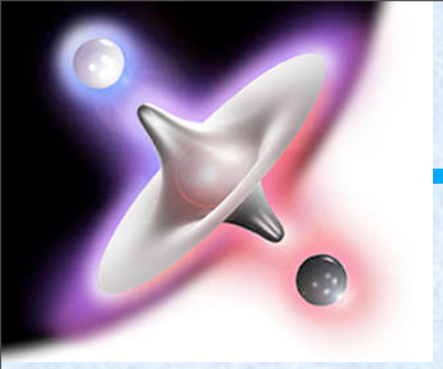
The AD - a machine and its team



The AD - a machine and its team

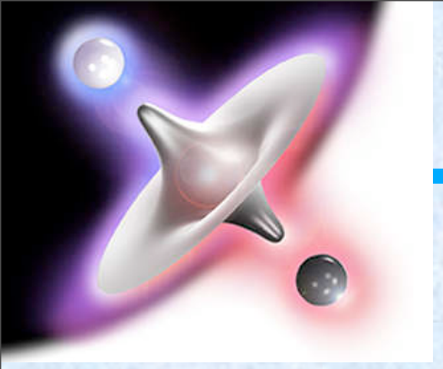


Tomorrow (trailer!)



Tomorrow (trailer!)

Where is the secret antimatter lab ?



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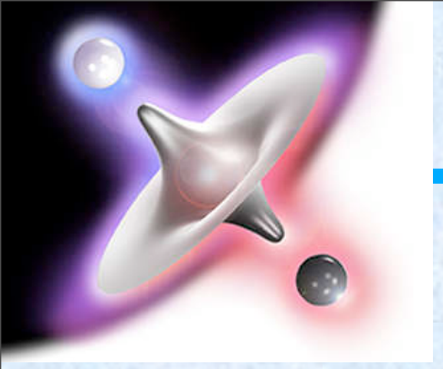
Where is the secret antimatter lab ?

Am I a priest ?

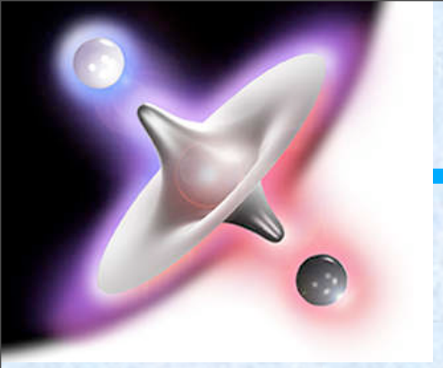


Tomorrow (trailer!)

Where is the secret antimatter lab ?

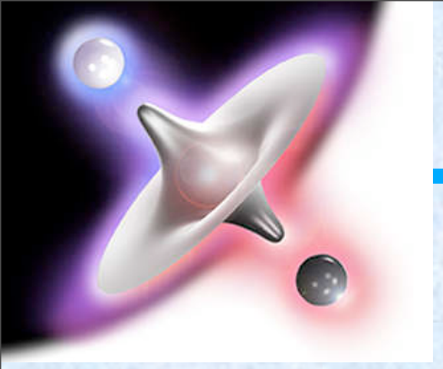
Am I a priest ?

Do we have 1 gram of antimatter ?



The real 'AD' (**A**ngels + **D**emons) Movie

What did Ron Howard say after a visit to CERN?



Thank you for your attention