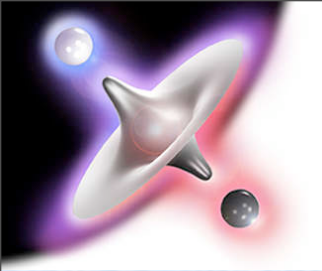


Antimatter in the Laboratory

An abstract 3D rendering of a particle interaction. A large, white, teardrop-shaped object with a central hole is the central focus. It is surrounded by a purple and blue glow. To the right, a red and pink glow surrounds a smaller, dark, spherical object with a central hole. In the upper left, a bright, glowing sphere is visible. The background is a gradient of purple and blue.

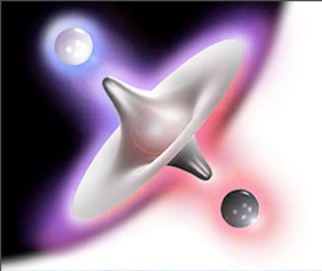
Rolf Landua
CERN



Plan

Overview

Einstein, Dirac, Feynman, CPT, ...



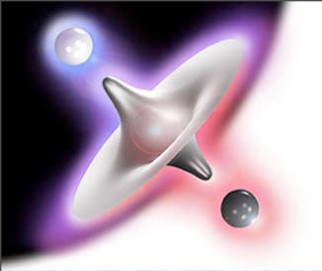
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Antimatter 'Factory'

How are antiprotons made?



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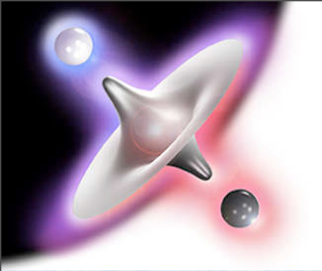
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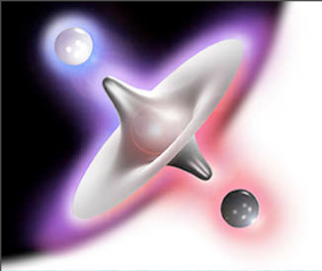
Future developments

Antimatter technology

PET

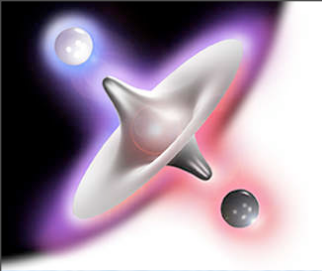
Antiproton therapy?

Rocket propulsion??



How CERN **really** became famous

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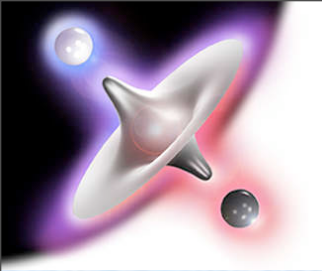


1996

Nine antihydrogen atoms (LEAR)

$v \sim c$

How CERN **really** became famous

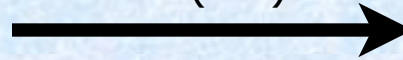


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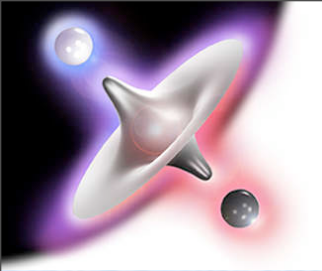
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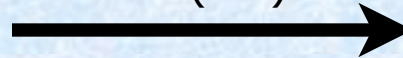


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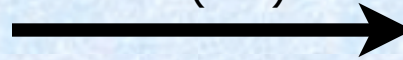
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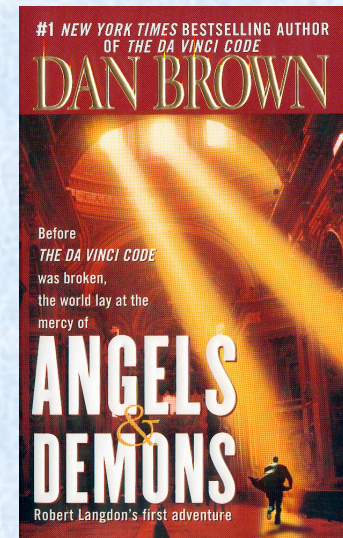
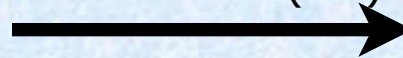


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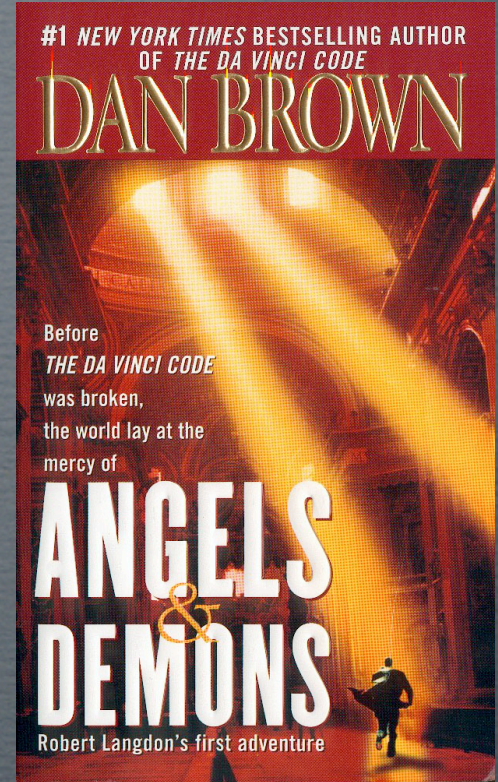
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Dan Brown (US)



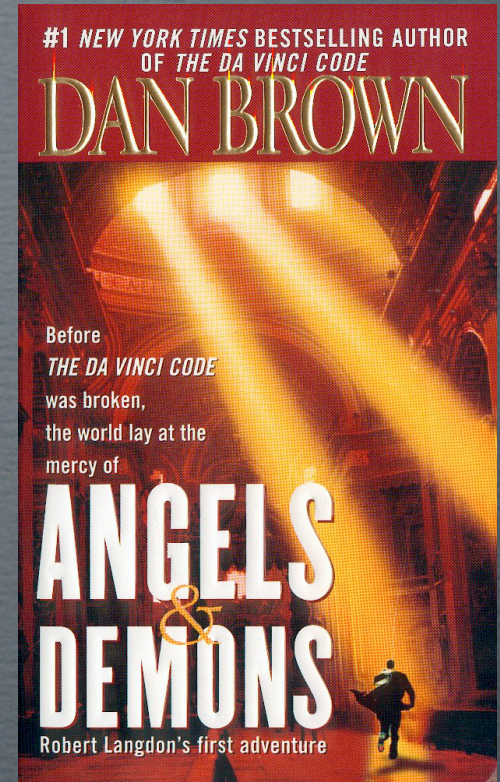
ANGELS AND DEMONS



ANGELS AND DEMONS

Illuminati

Detective story about a
secret society which ...



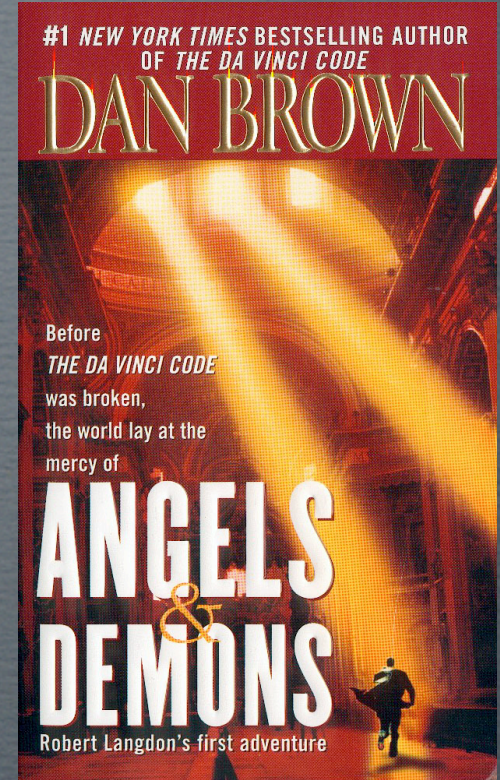
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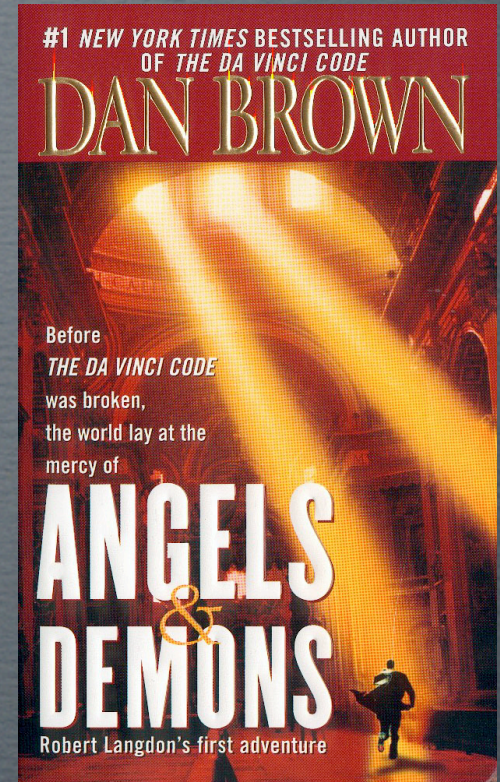
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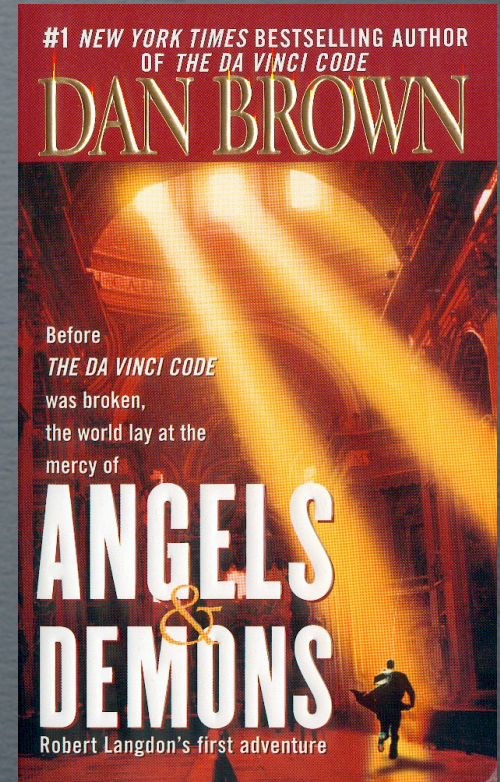
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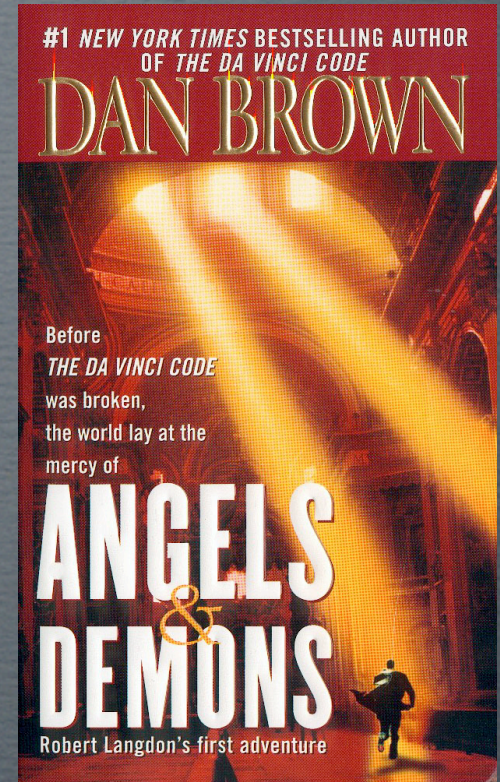
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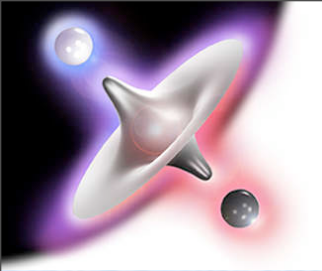


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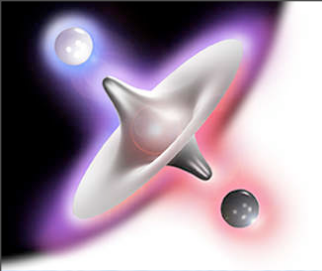
A mix of fact and fiction. What is true? What is false?

“Angels and Demons” - The Movie



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

“Angels and Demons” - The Movie

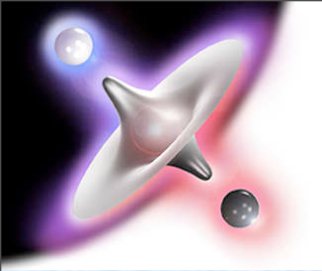


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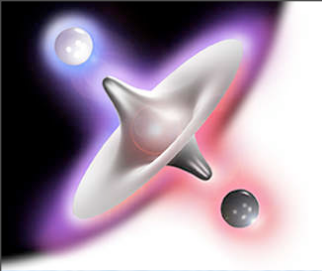
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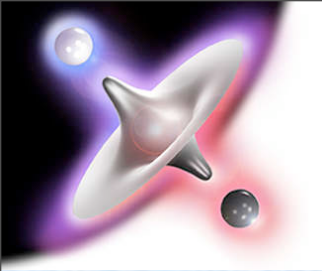


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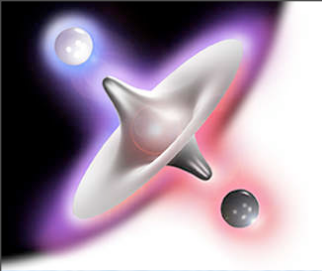
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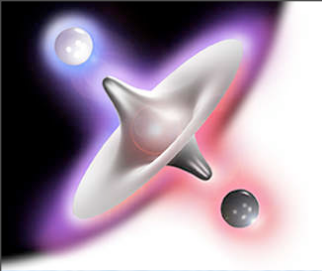
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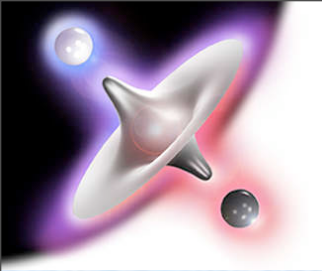
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The correct answer at the end of this lecture....



1. Overview - History of Antimatter

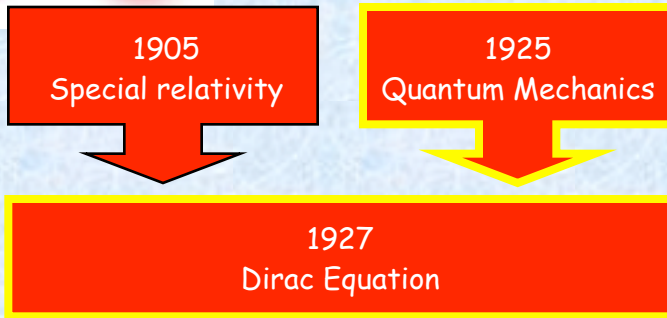
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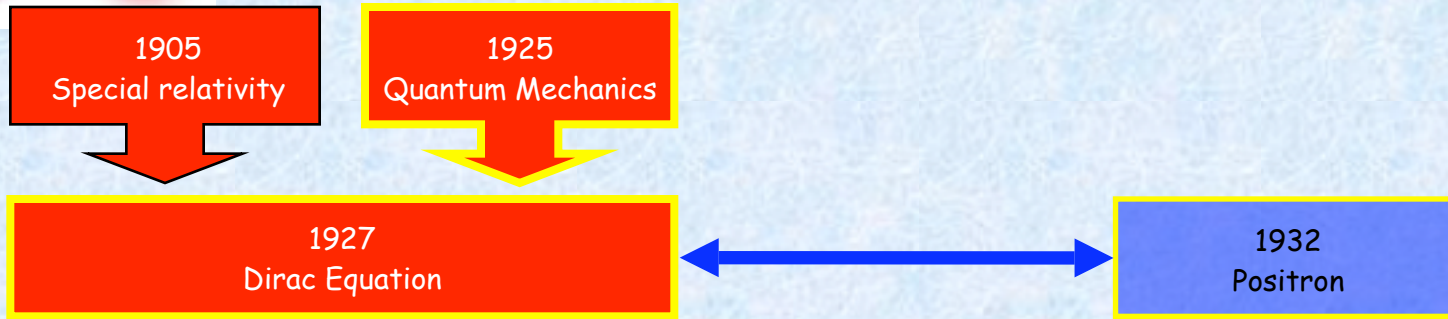
1905
Special relativity

1925
Quantum Mechanics

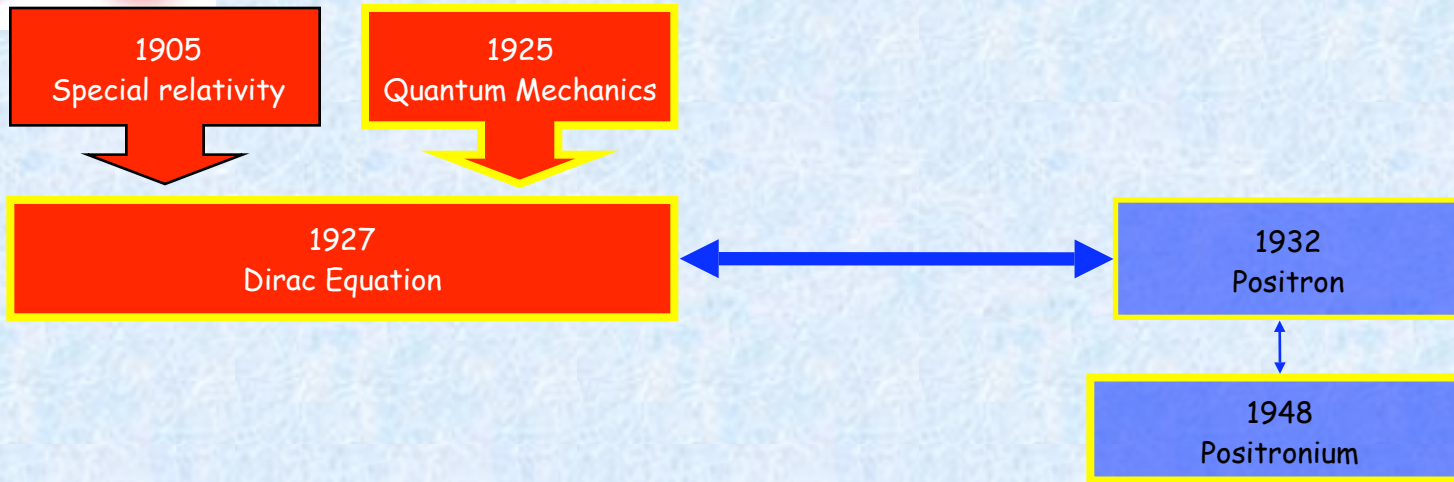
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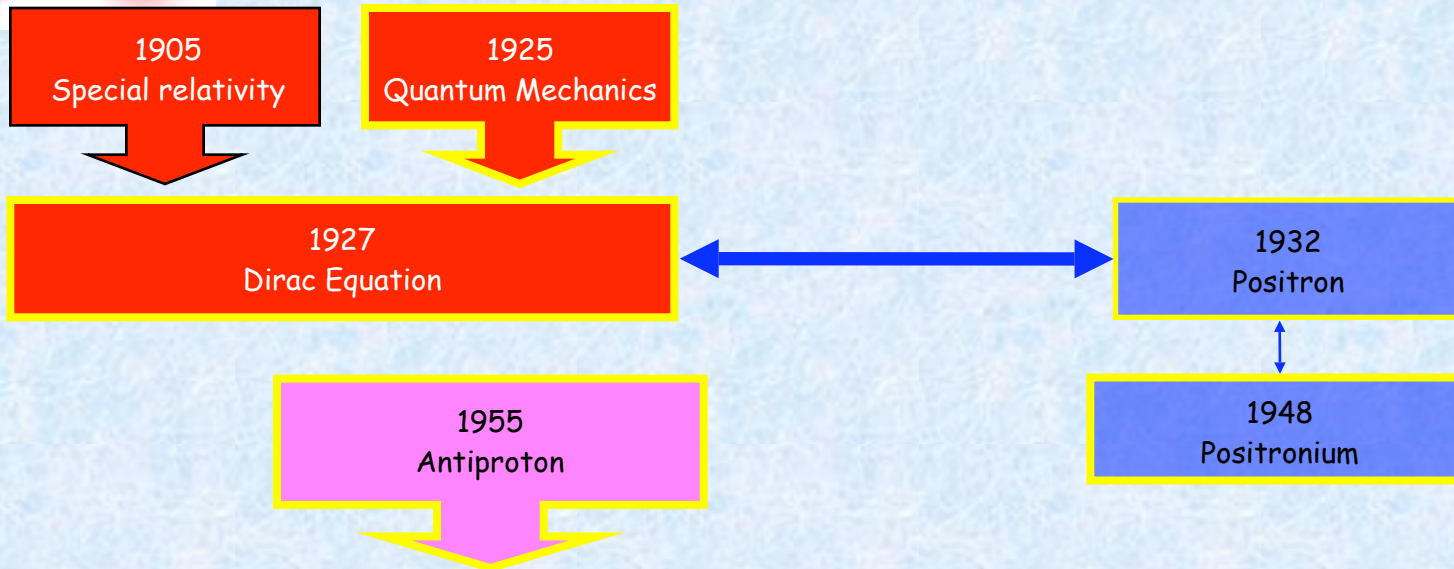
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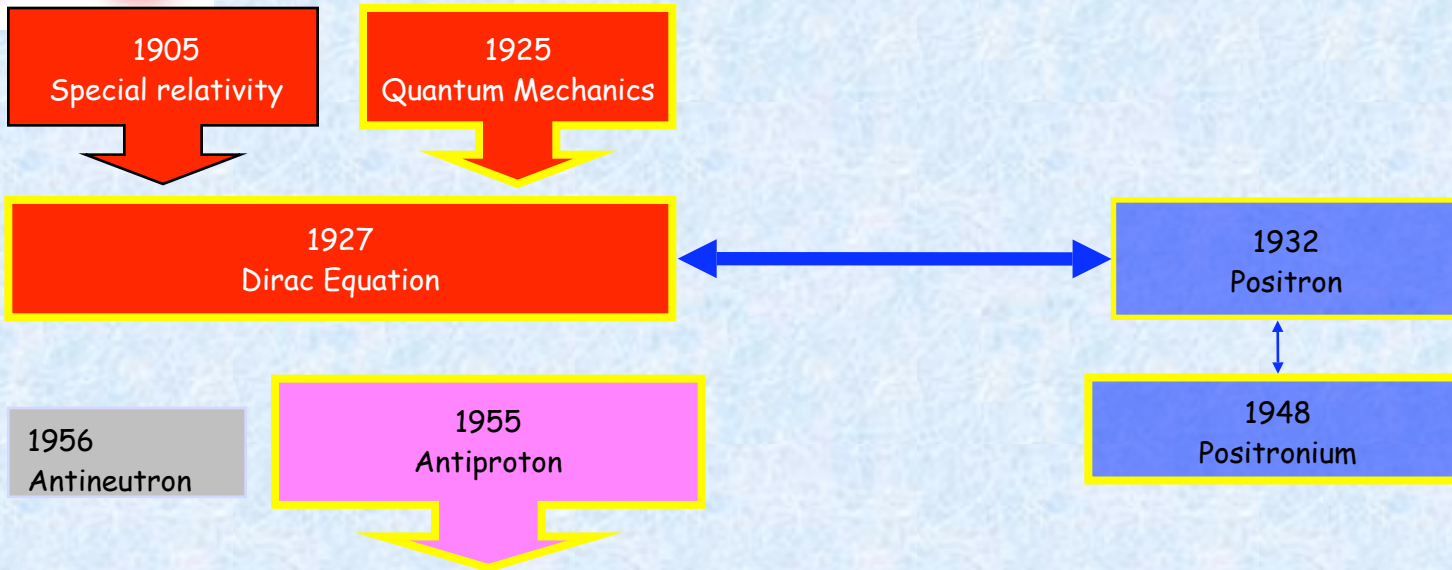
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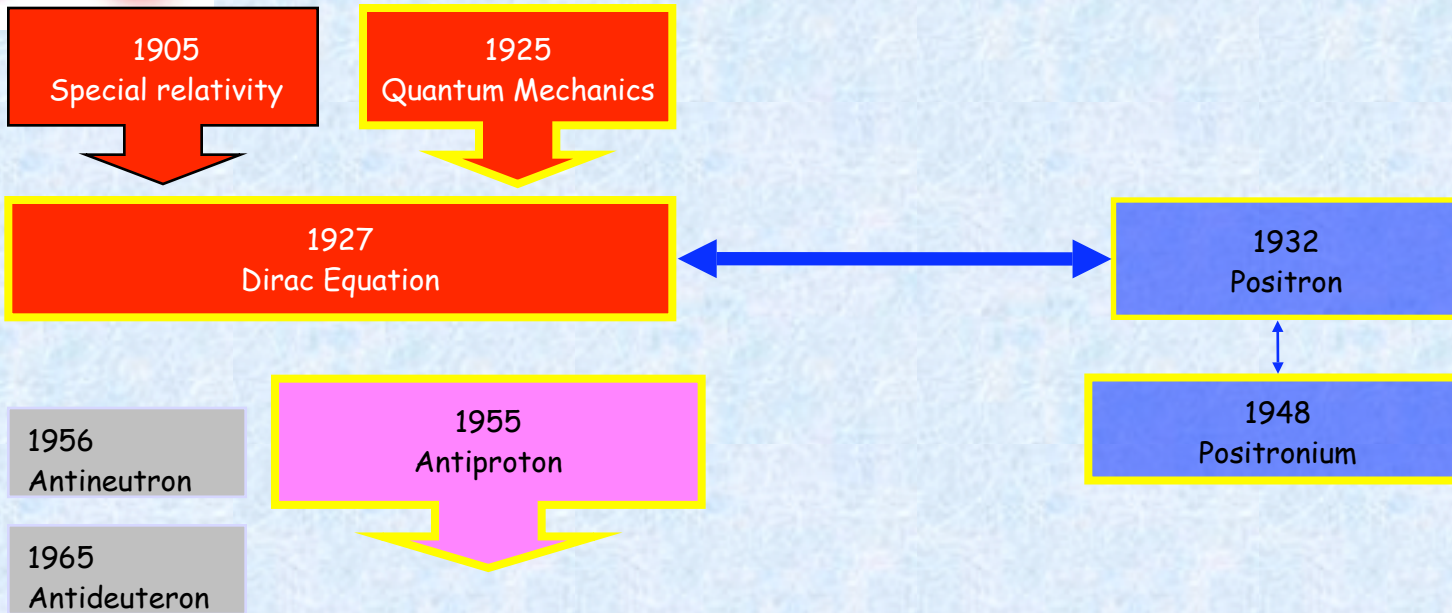
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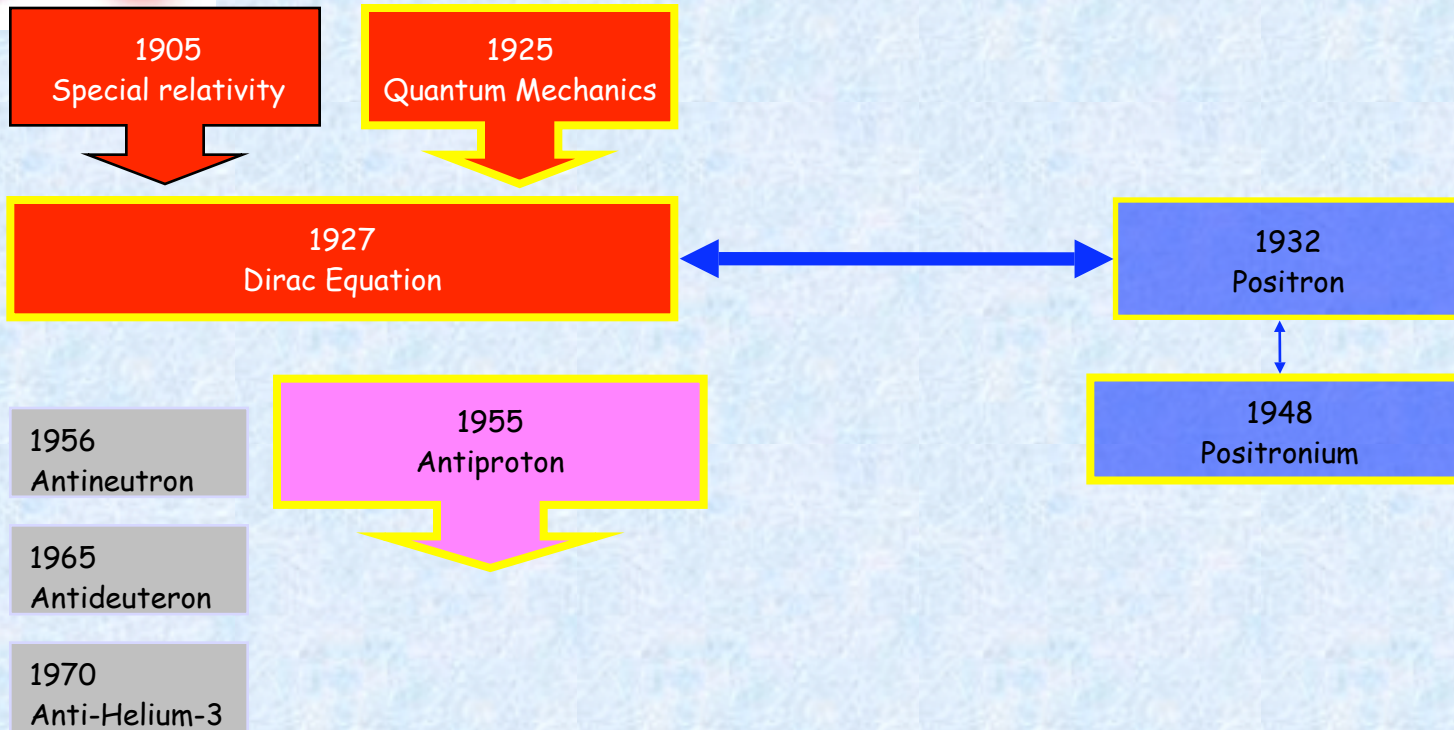
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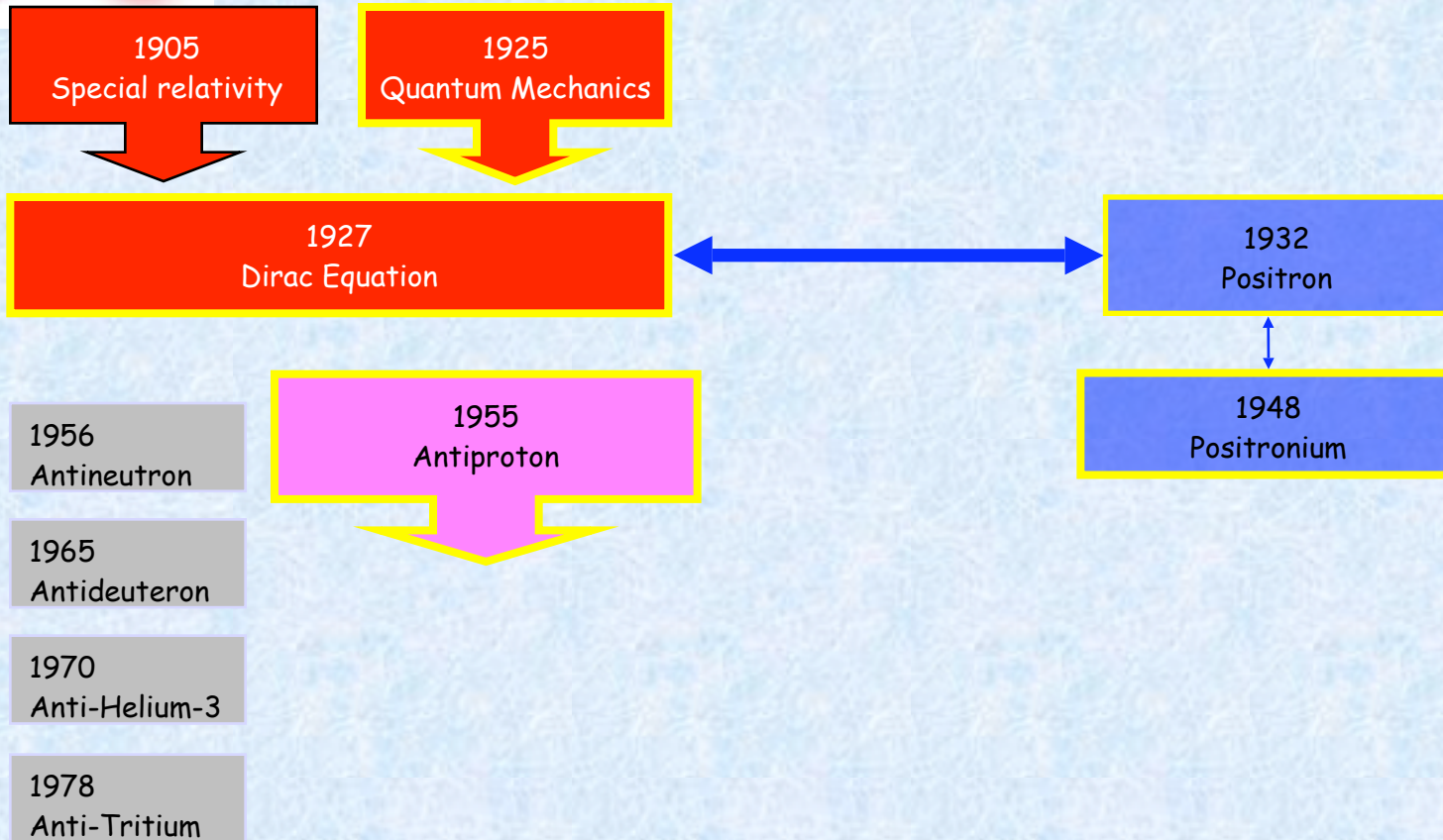
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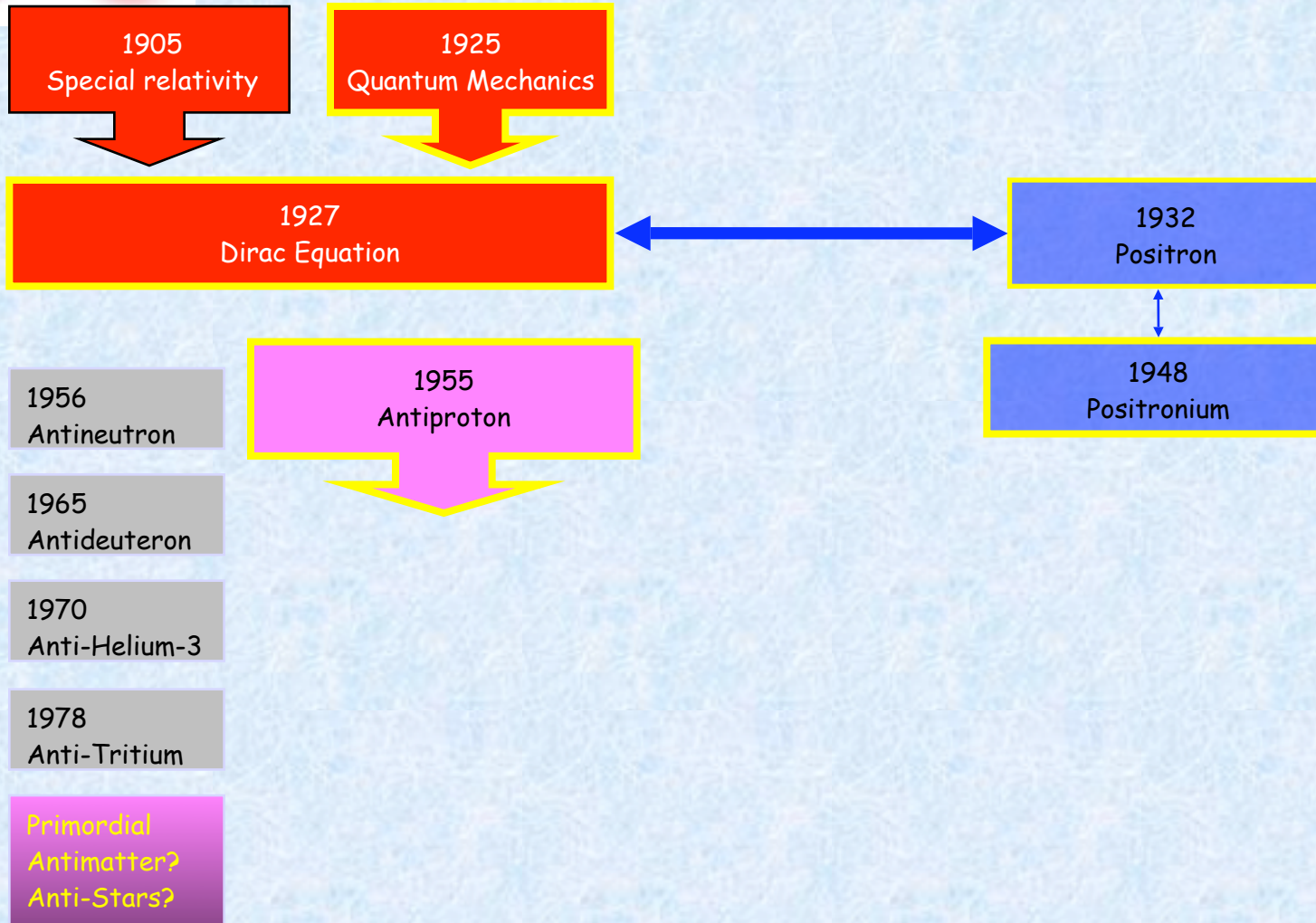
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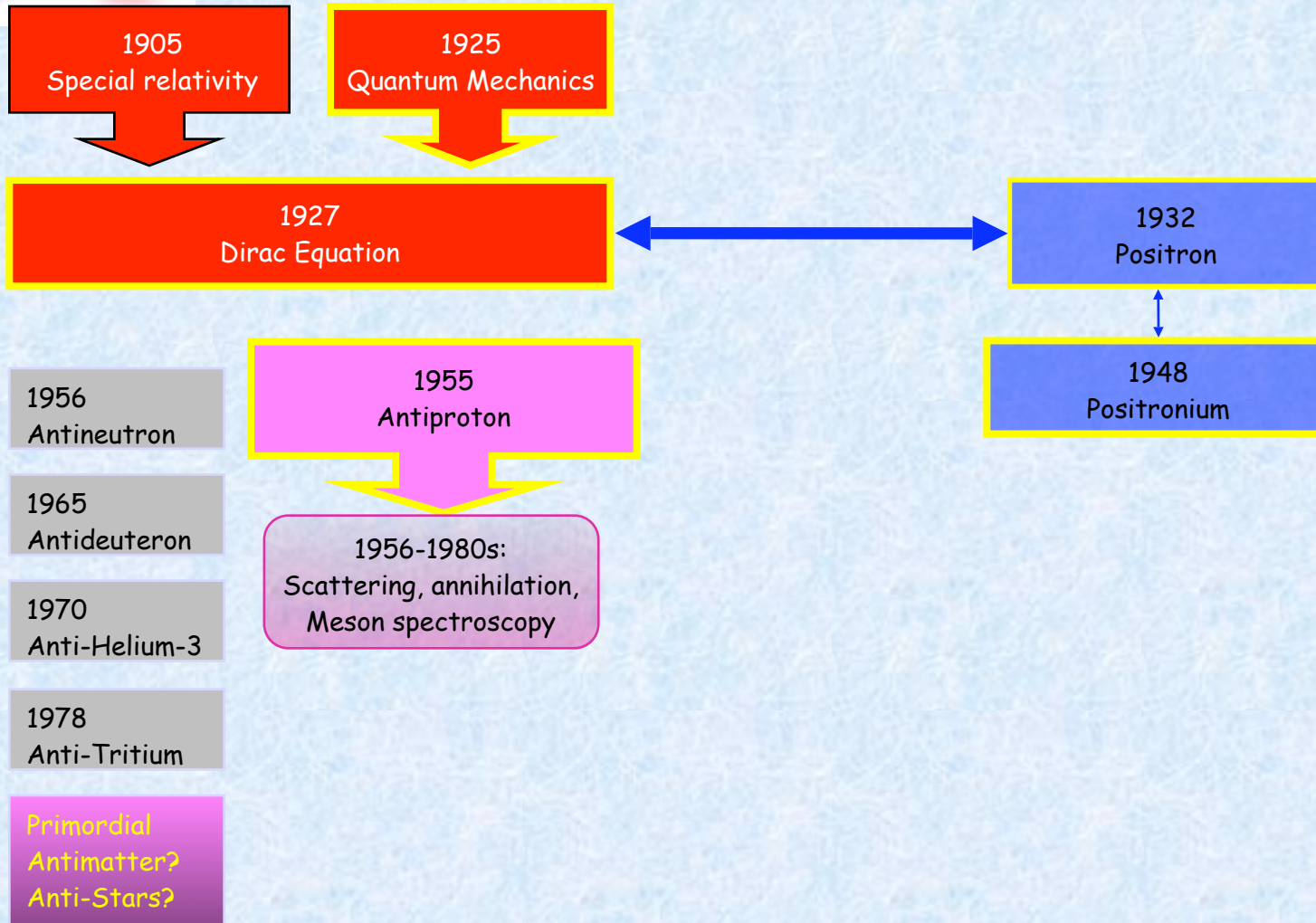
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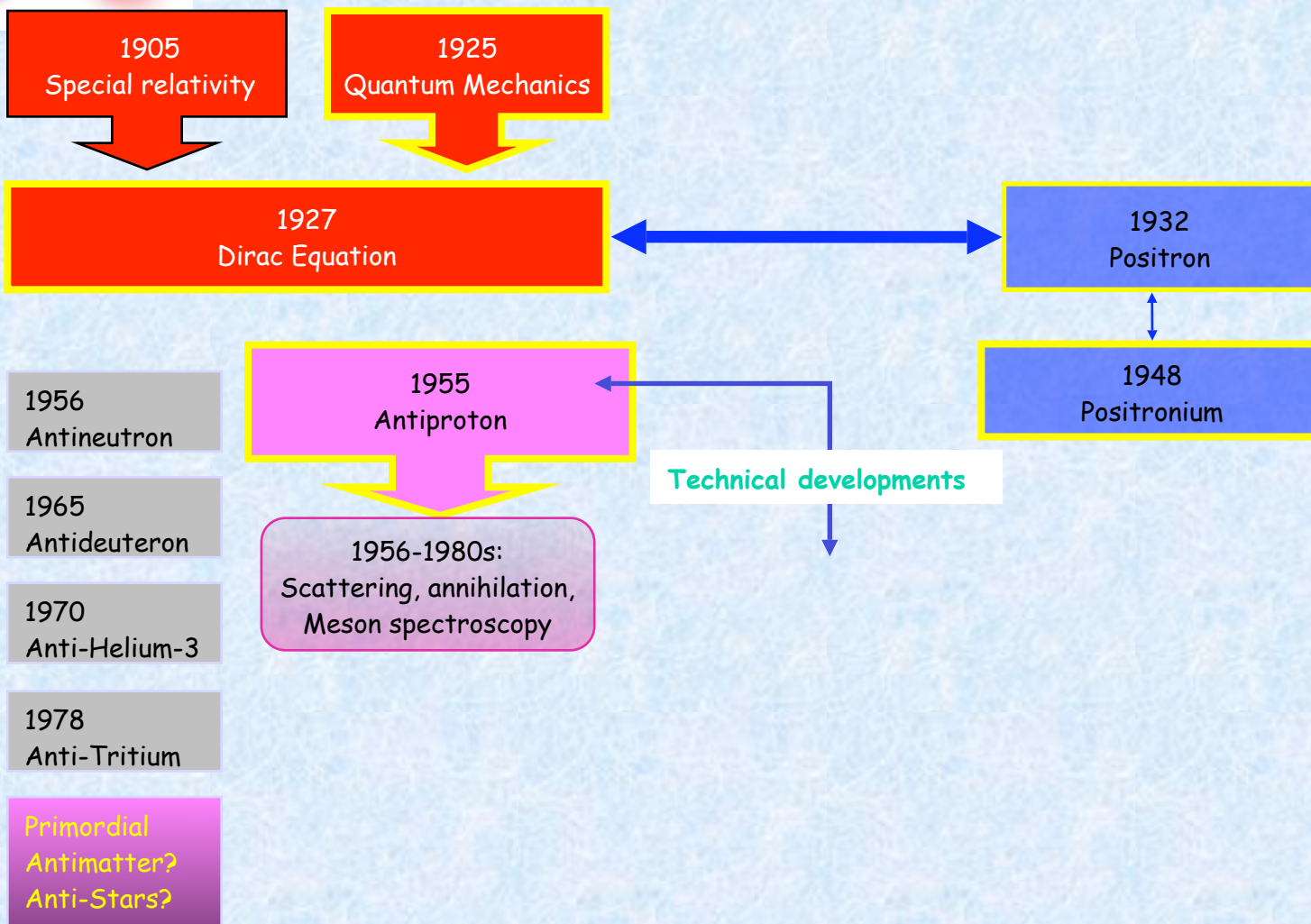
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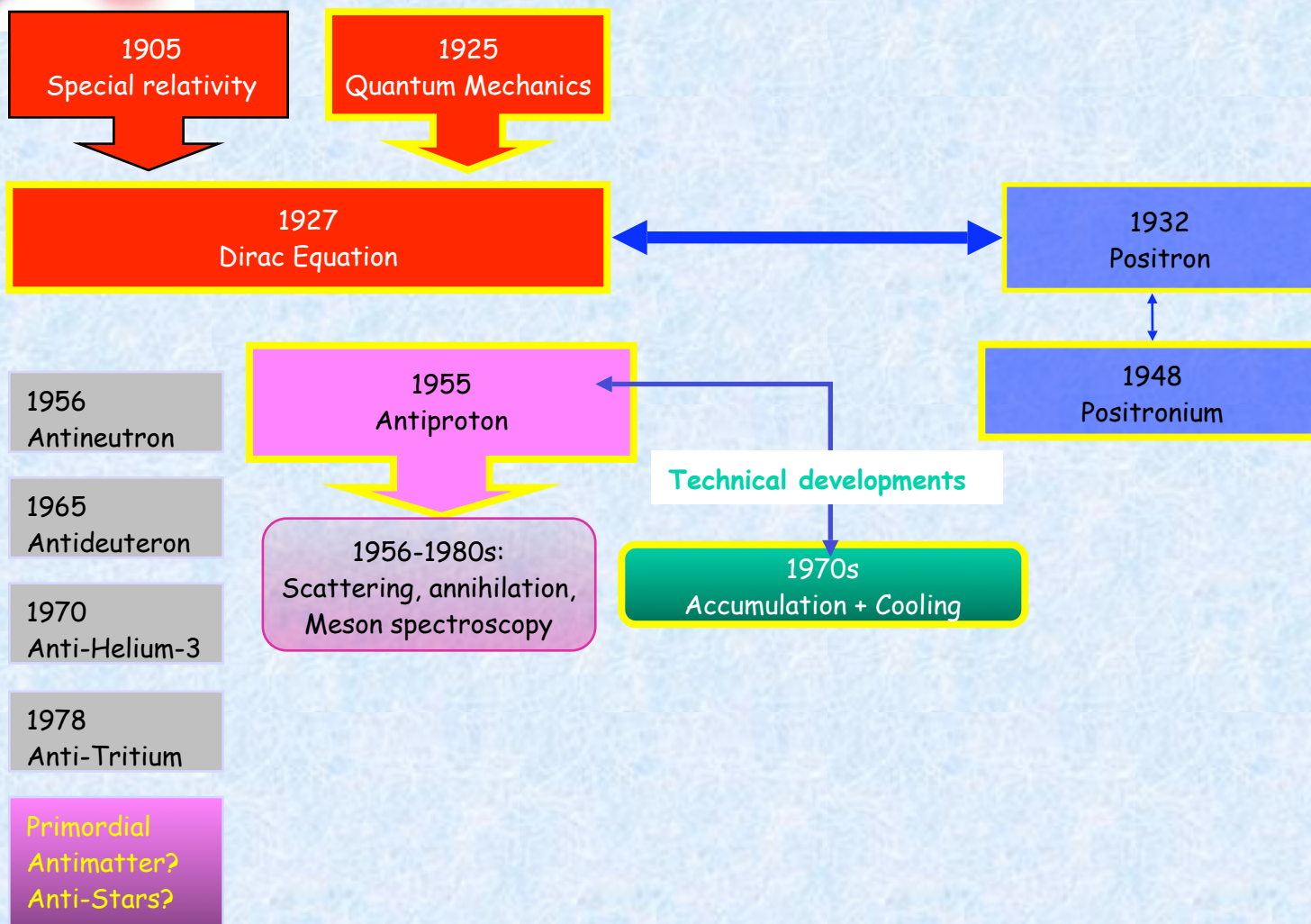
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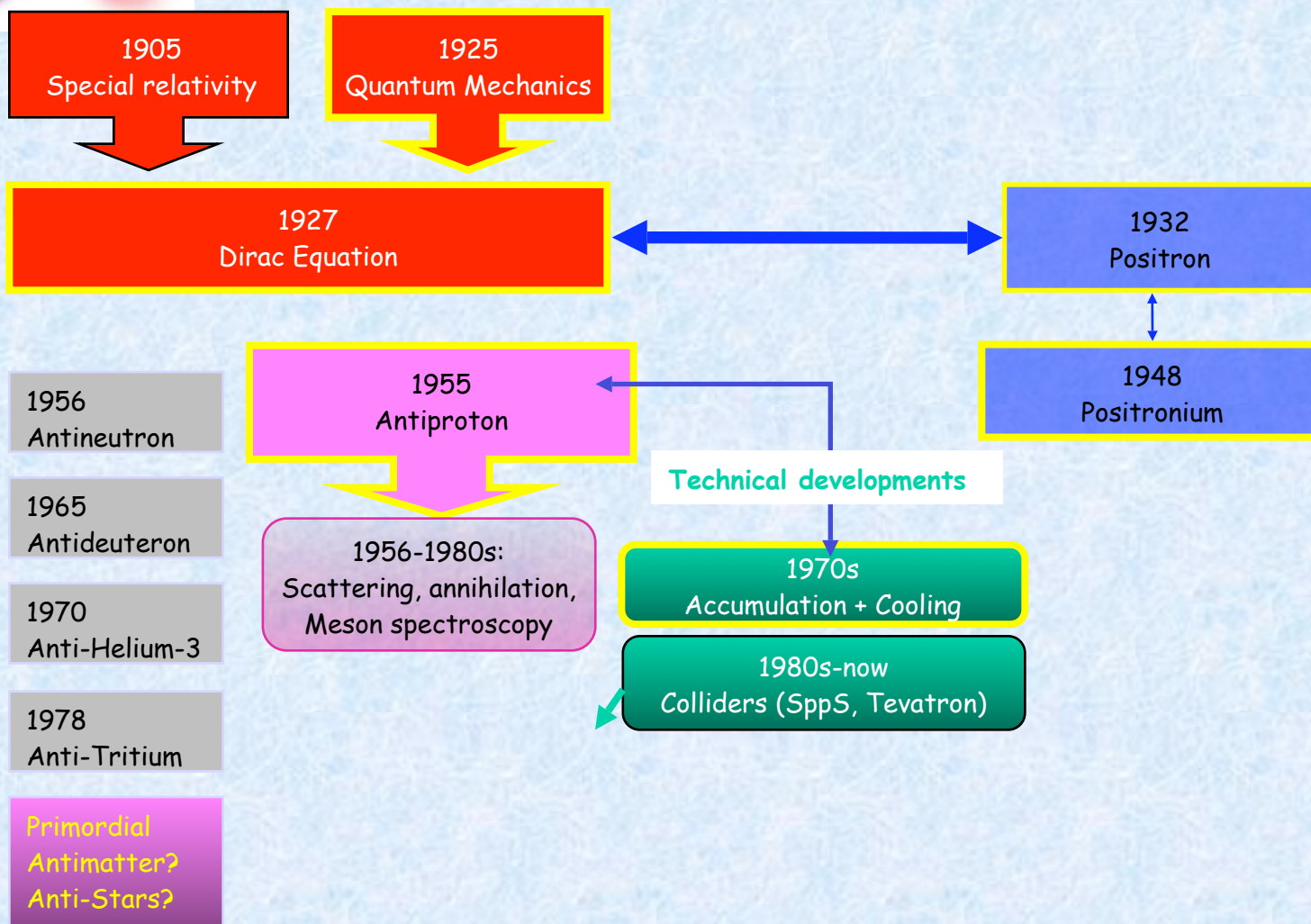
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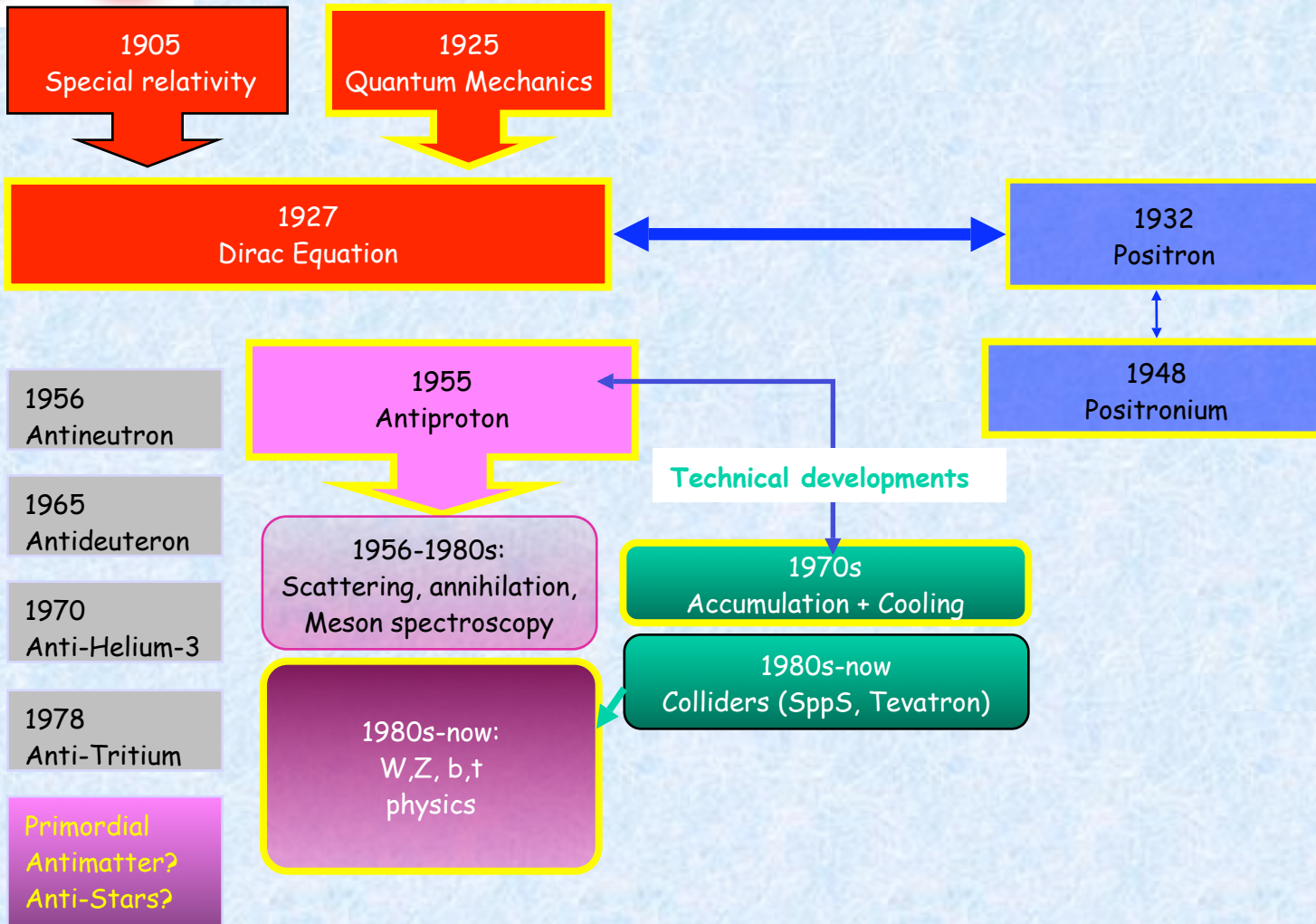
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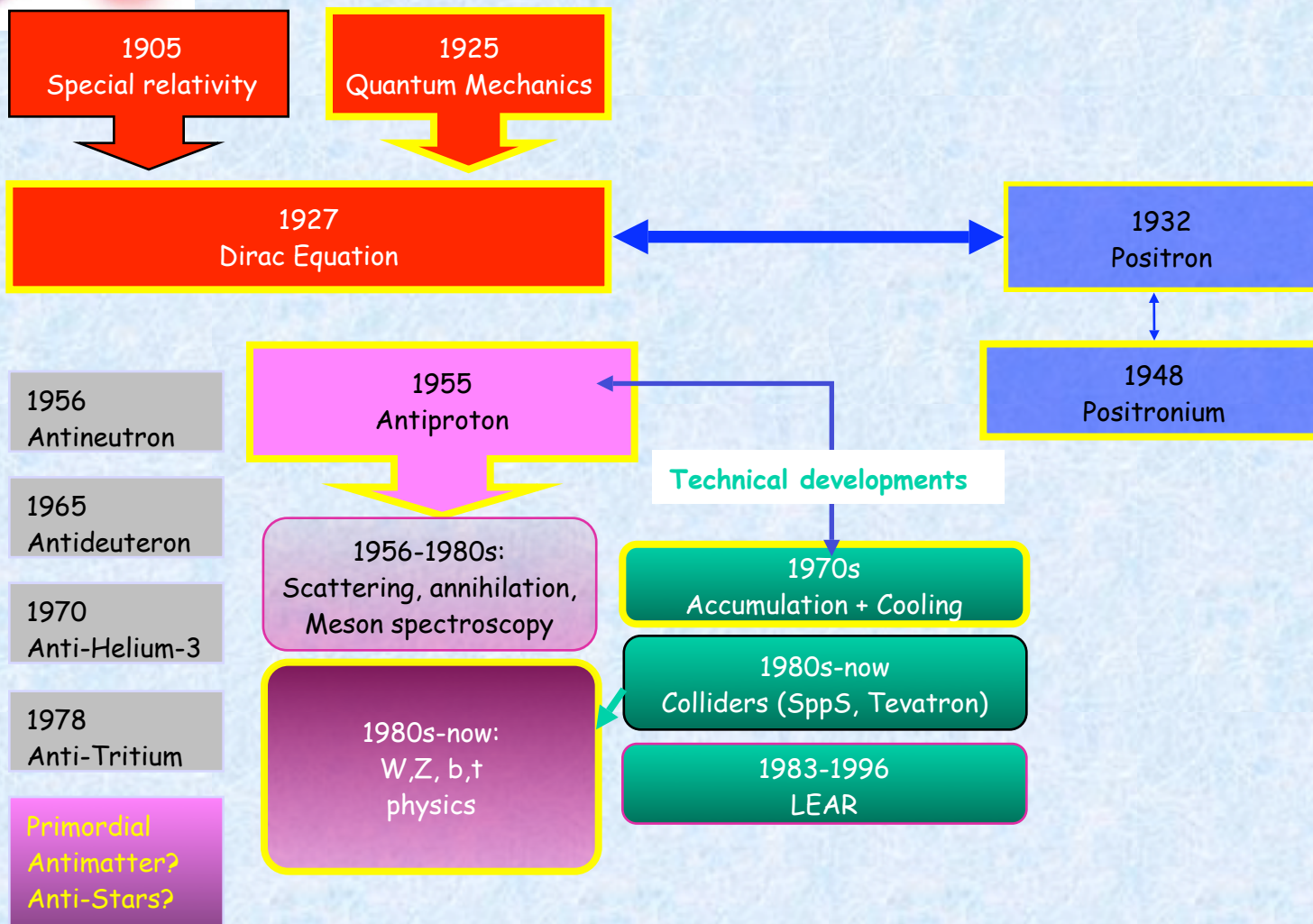
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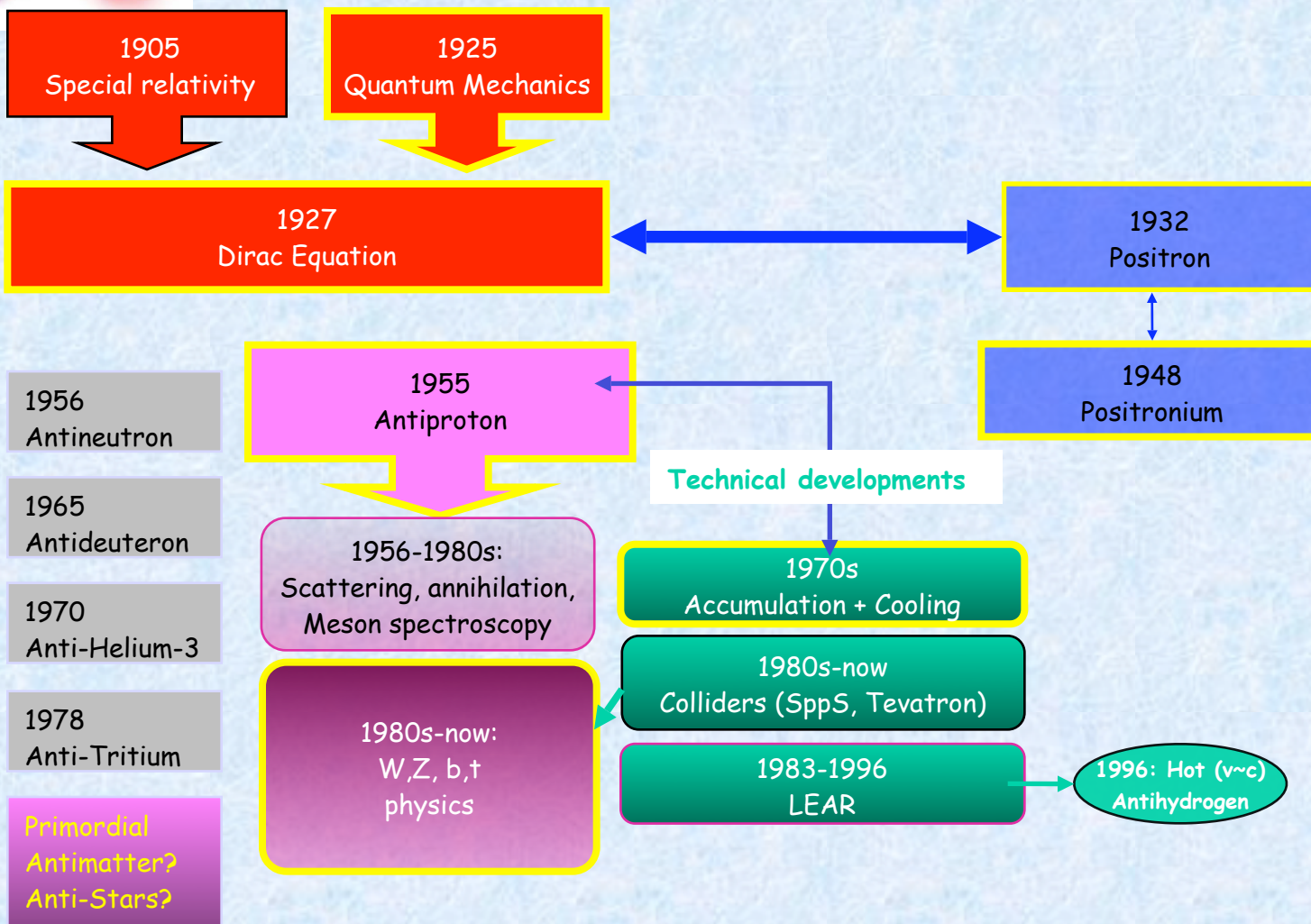
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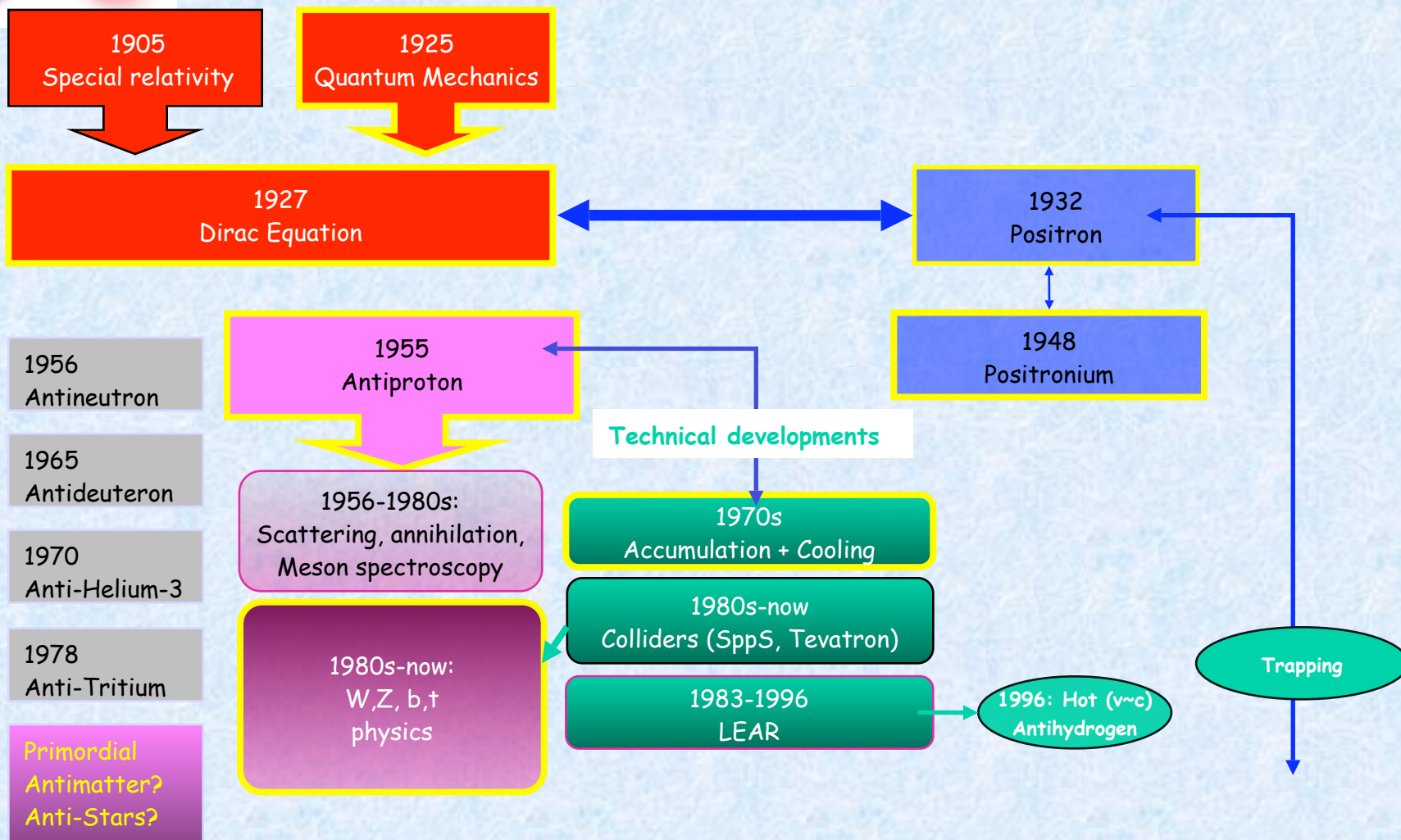
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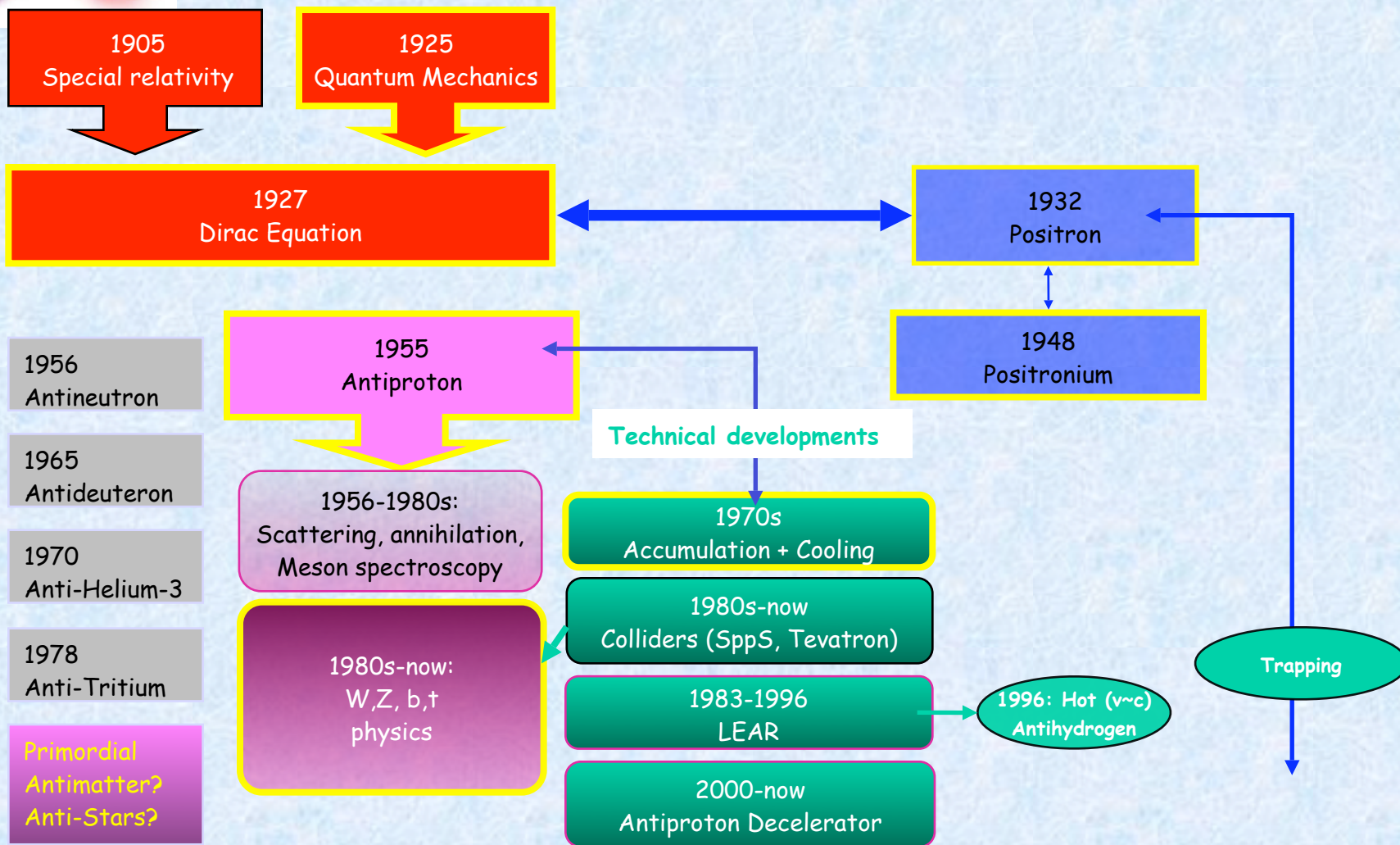
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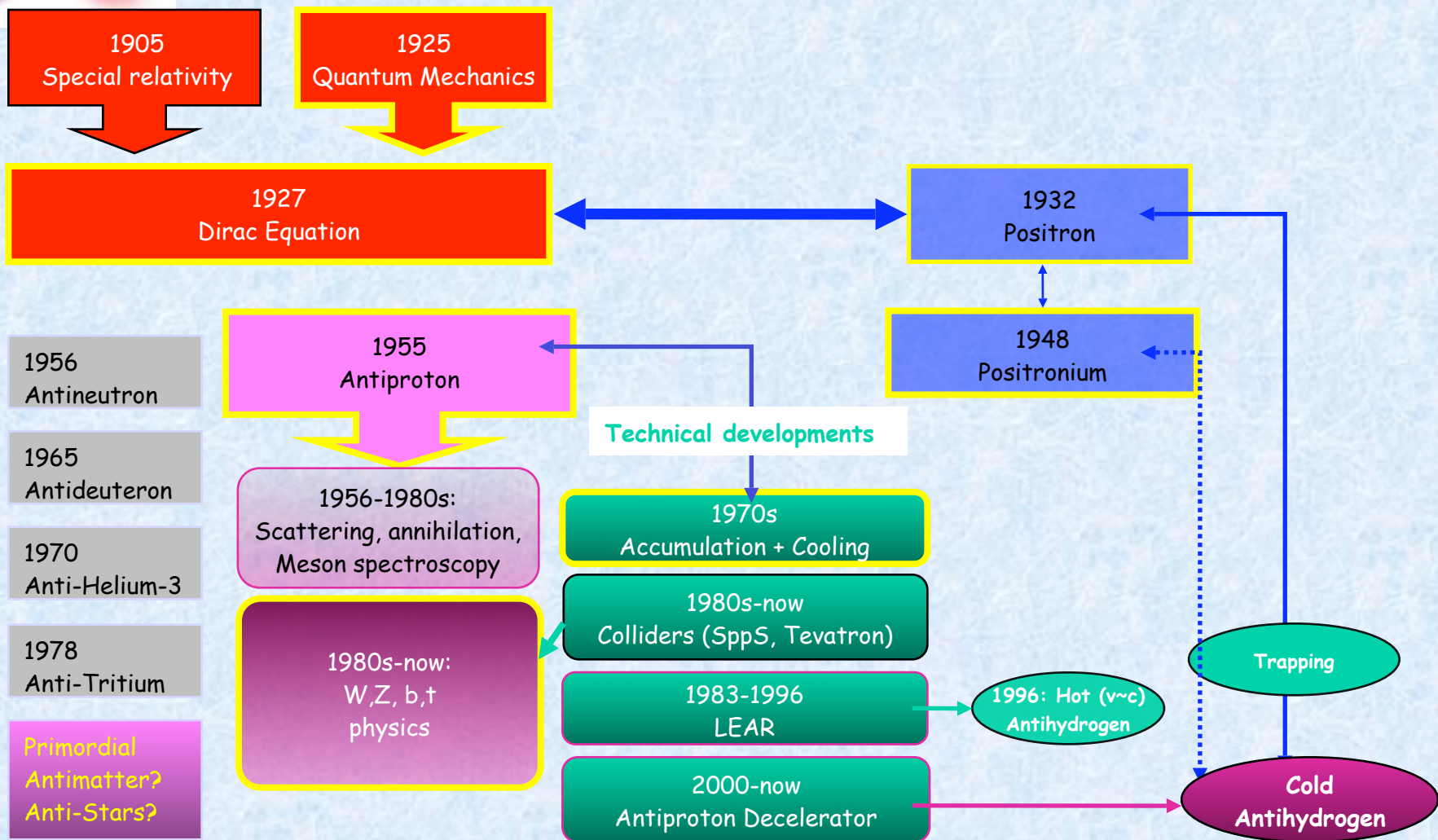
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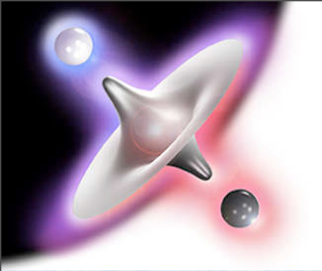


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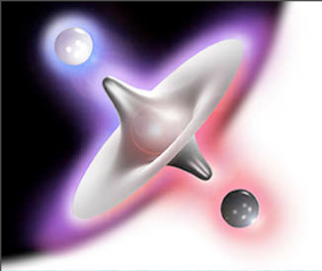


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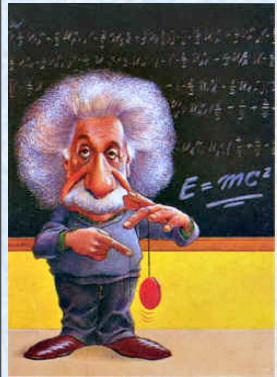




Special relativity + Quantum Mechanics = Antimatter



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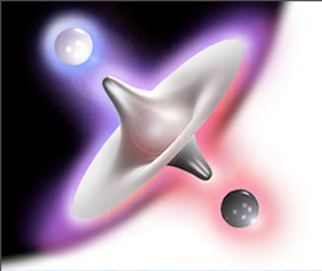
$$E=mc^2$$

A. Einstein (1905)

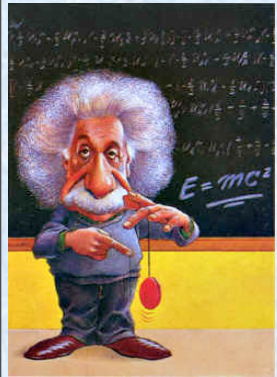
Mass is condensed energy

(c^2 = exchange rate!)

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

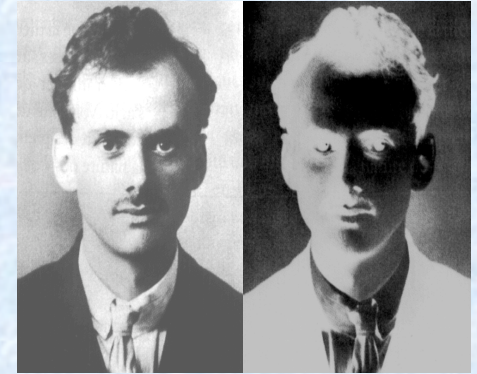


Special relativity + Quantum Mechanics = Antimatter



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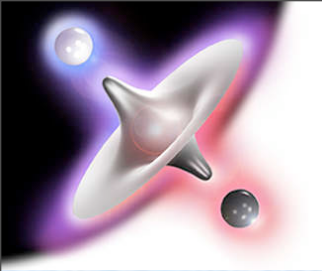
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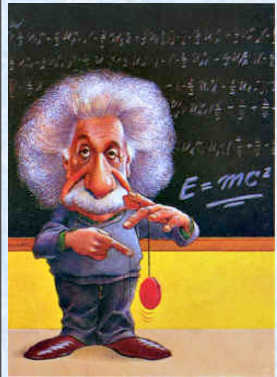
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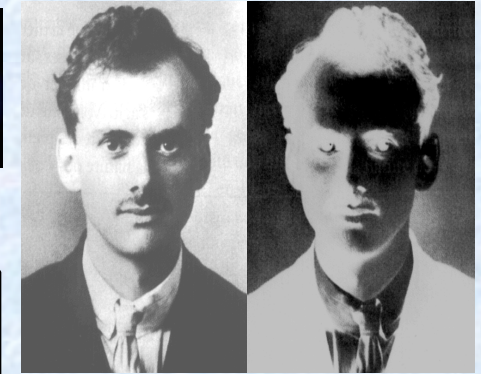
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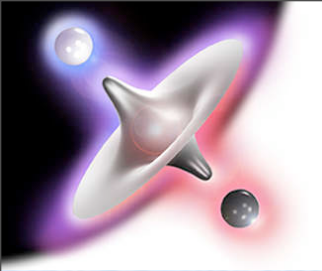
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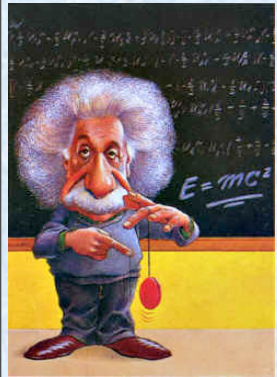
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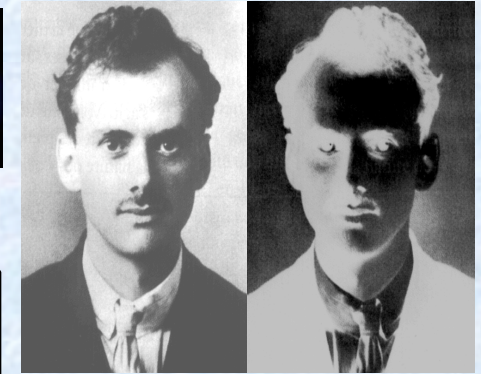
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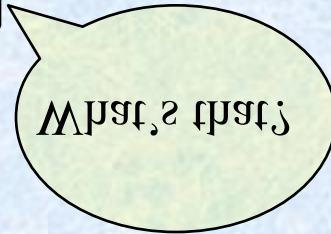
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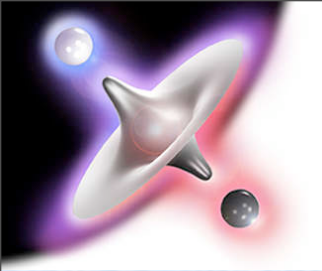
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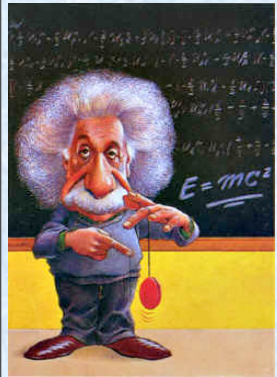


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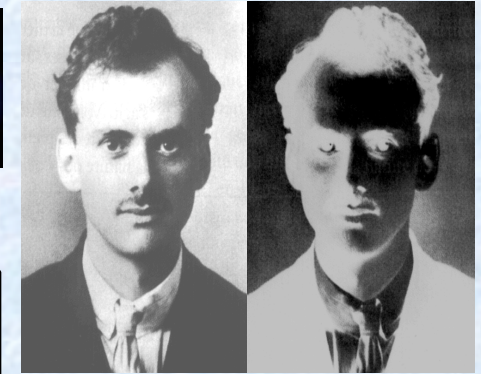
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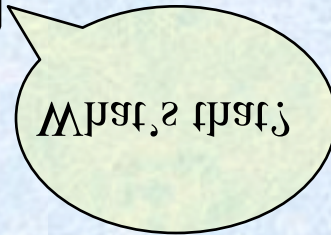
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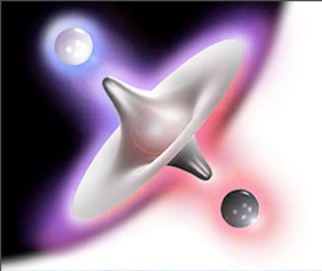
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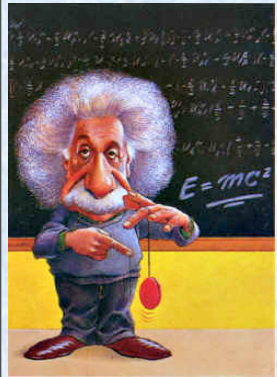
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- 1929: Positive electron = proton ????



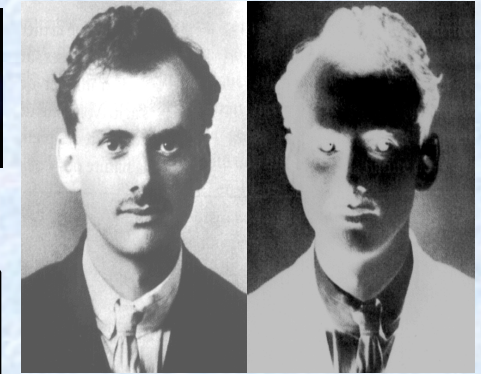
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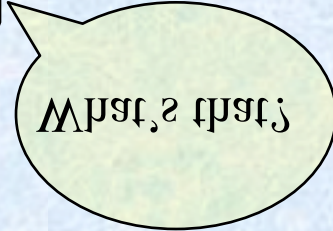
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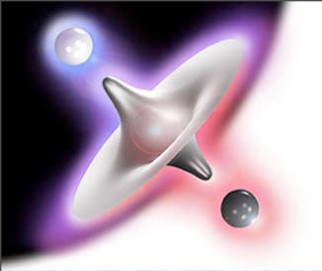
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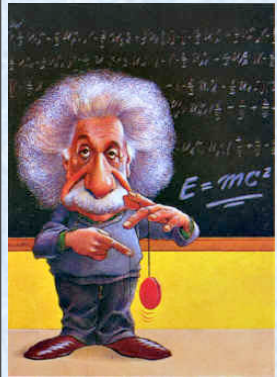
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$$1 \text{ kg} = 9 \cdot 10^{16} \text{ J} = 2.85 \text{ GW} \cdot \text{year}$$

- 1929: Positive electron = proton ????
- 1930: Positive electron = anti-electron !

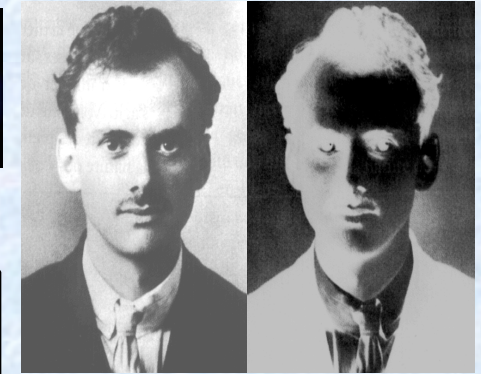


Special relativity + Quantum Mechanics = Antimatter



$$E=mc^2$$

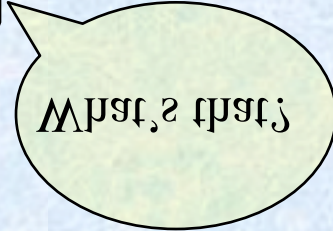
$$(i\gamma^\mu \partial_\mu - m)\Psi = 0$$



A. Einstein (1905)

$$\Psi = \begin{pmatrix} e^- \uparrow \\ e^- \downarrow \\ e^+ \uparrow \\ e^+ \downarrow \end{pmatrix}$$

Paul A.M. Dirac (1928)

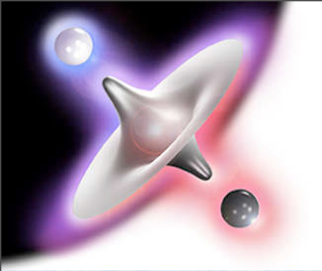


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- 1929: Positive electron = proton ????
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Dirac: Anti-Electron must exist !



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

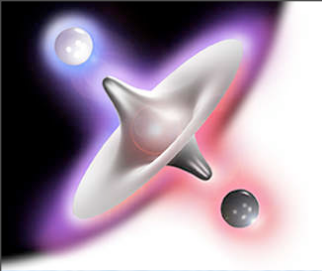
Interlude: playing with equations (best guesses ...)

Schrödinger:

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

non-relativistic

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



Schrödinger:

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non-relativistic

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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Dirac:

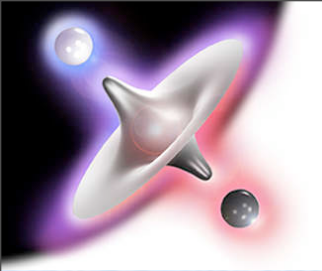
$$E^2 = p^2 + m^2 \rightarrow$$
$$E = \pm(\alpha \cdot p) + \beta m$$

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

relativistic, spin 1/2

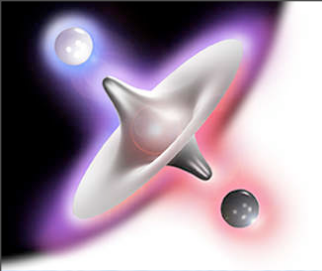
(number of particles conserved)

Positron discovery- why so late ?



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

Positron discovery- why so late ?



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

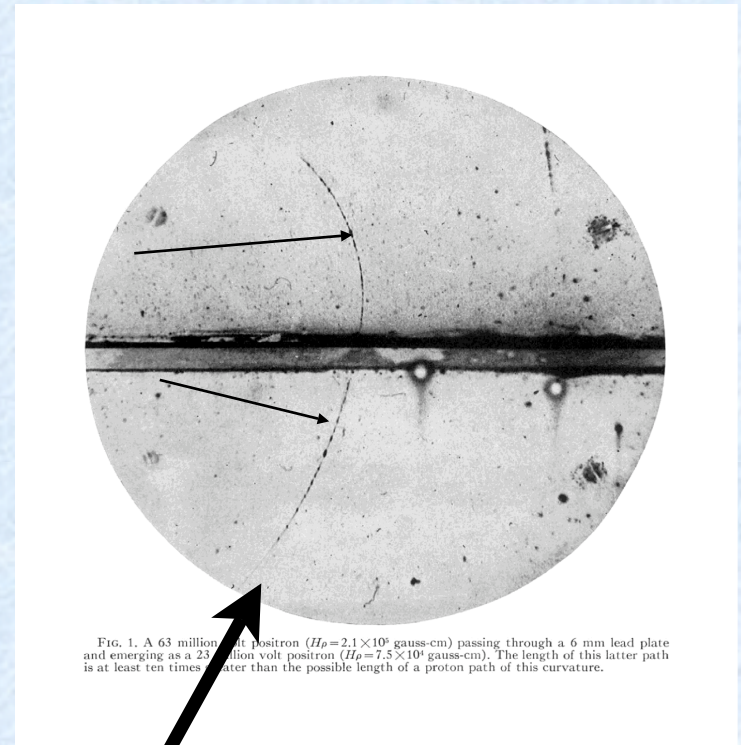
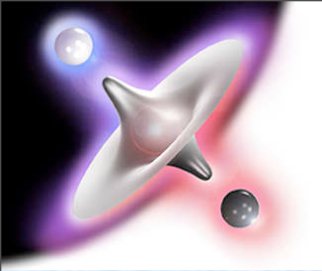


FIG. 1. A 63 million volt positron ($H_p = 2.1 \times 10^6$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H_p = 7.5 \times 10^5$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Positron from below

Positron discovery- why so late ?

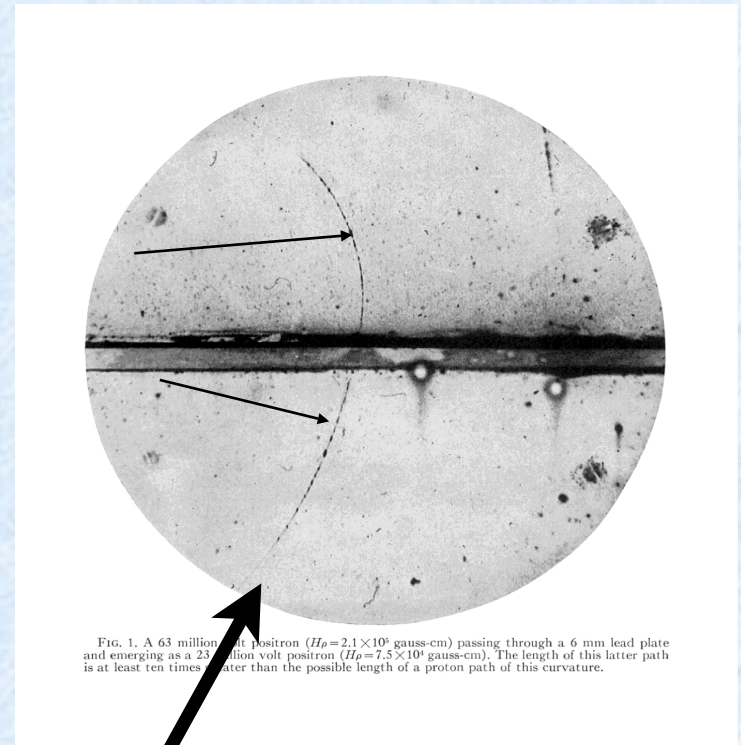


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Phys. Rev., **43**, 491 (1933)

Dirac :

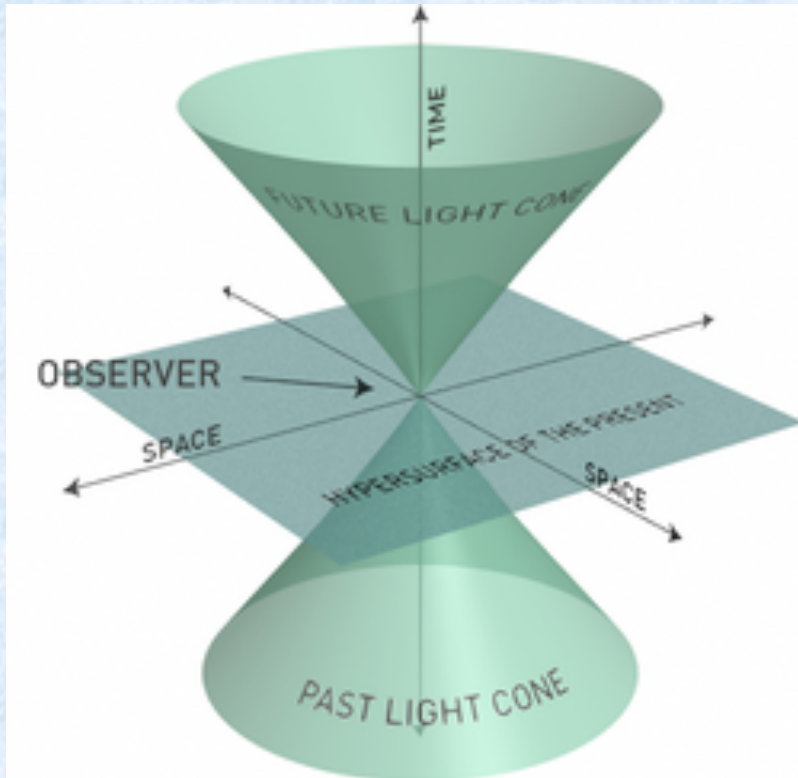
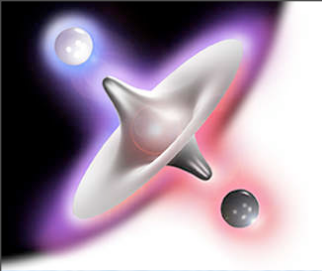
"Why did the experimentalists not see them?
Because they were prejudiced against them.

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.



Positron from below

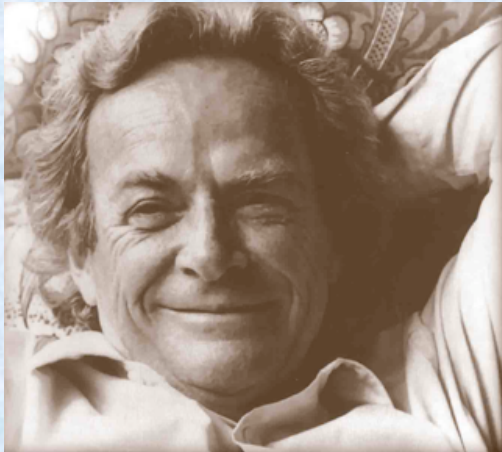
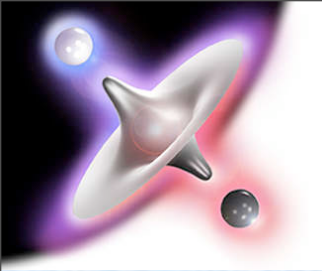
Relativity and Causality



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

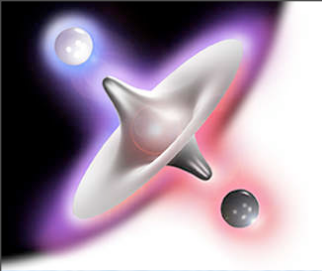
Clear distinction between the PAST and the FUTURE (for a given observer)

Antimatter in Quantum Field Theory

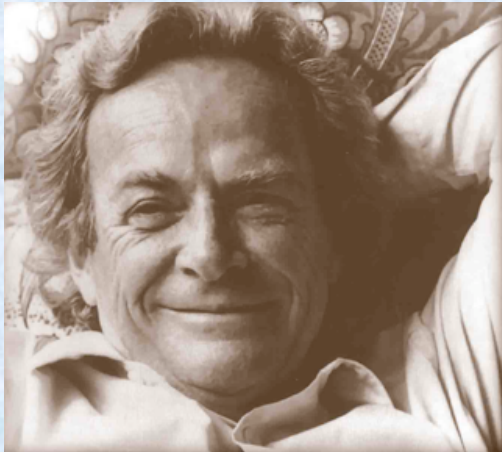


R. P. Feynman

Antimatter in Quantum Field Theory



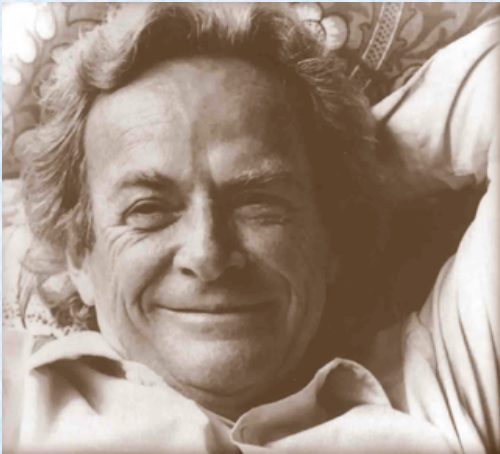
The electron (field) is no longer described by a wave function but an operator that creates and destroys particles. All energies are positive.



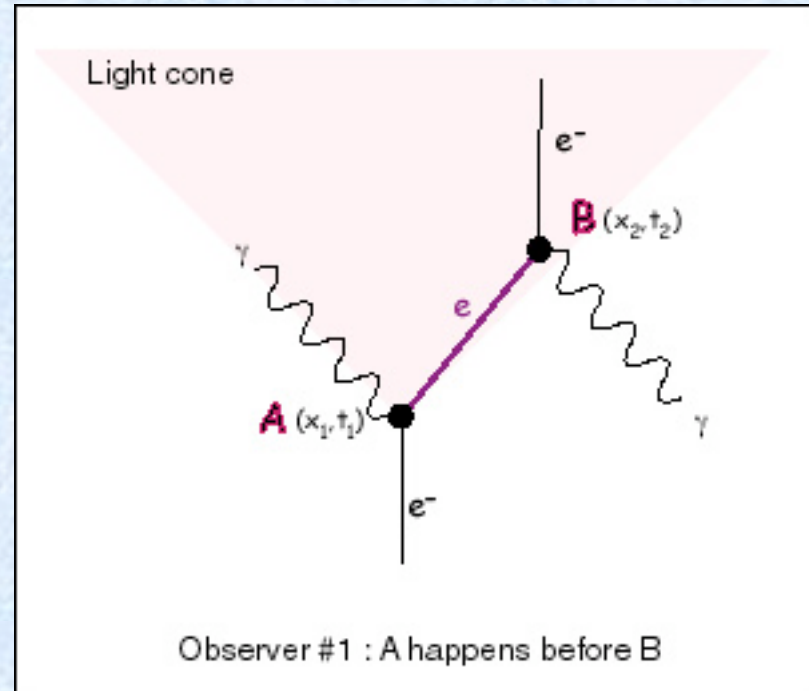
R. P. Feynman

Antimatter in Quantum Field Theory

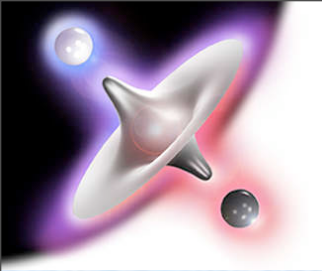
The electron (field) is no longer described by a wave function but an operator that creates and destroys particles. All energies are positive.



R. P. Feynman



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

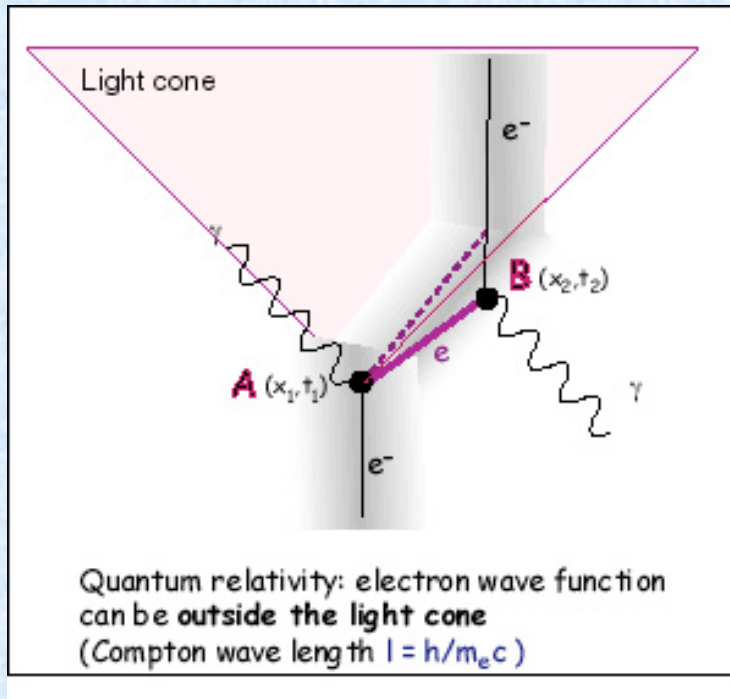


Causality requires antiparticles to exist

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

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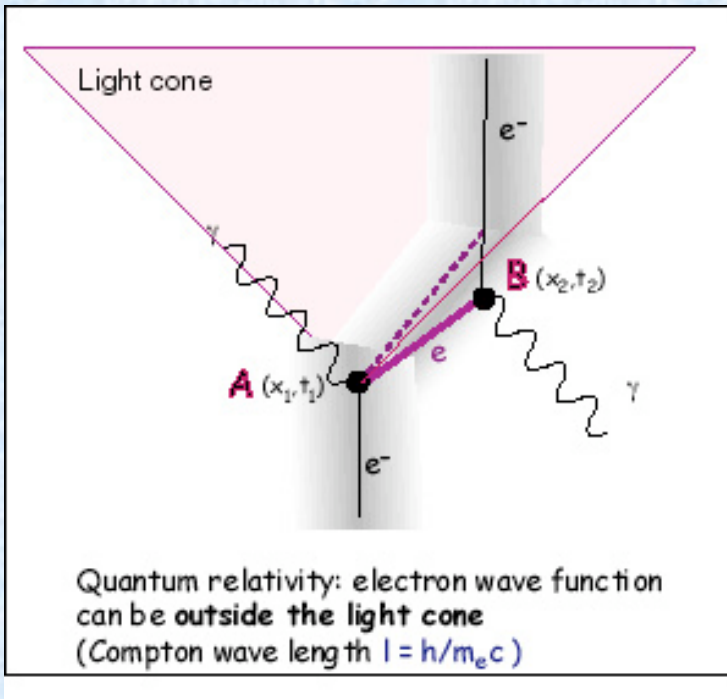


†

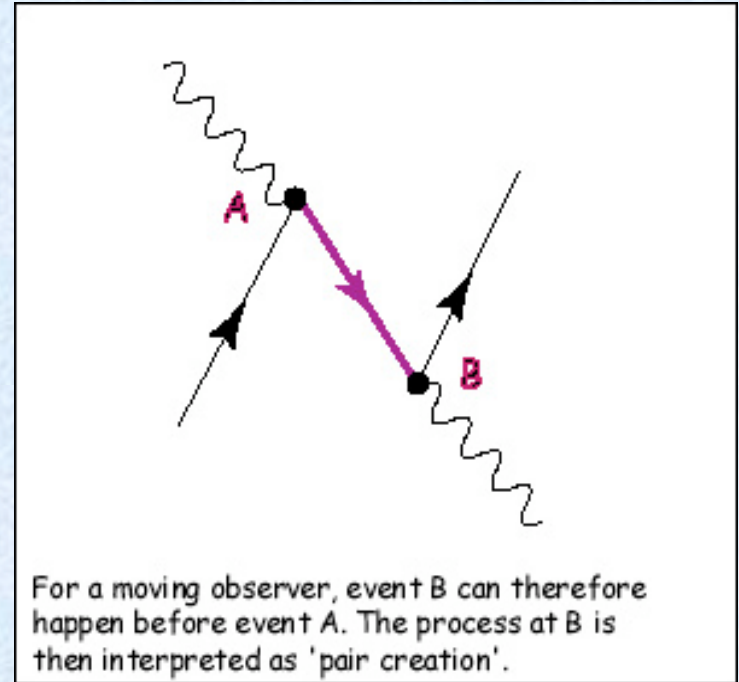
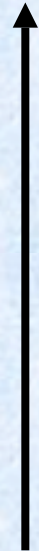


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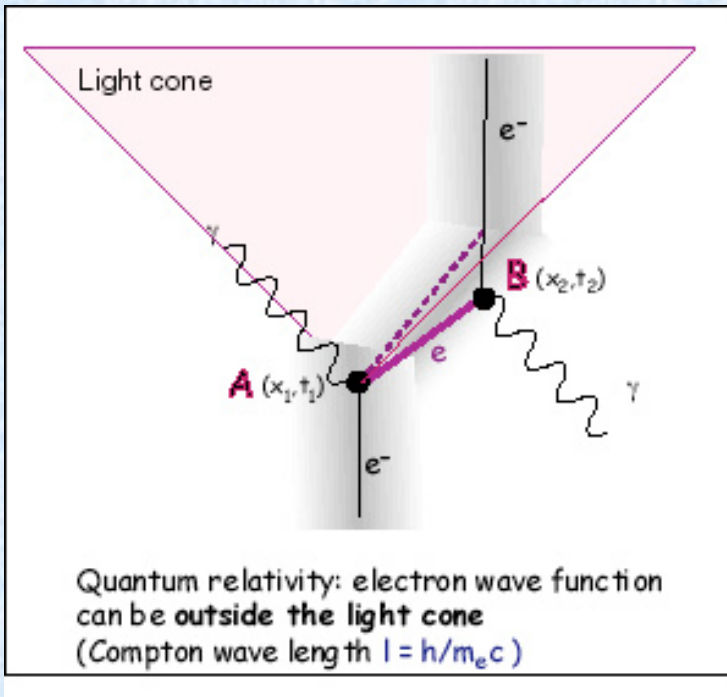


†

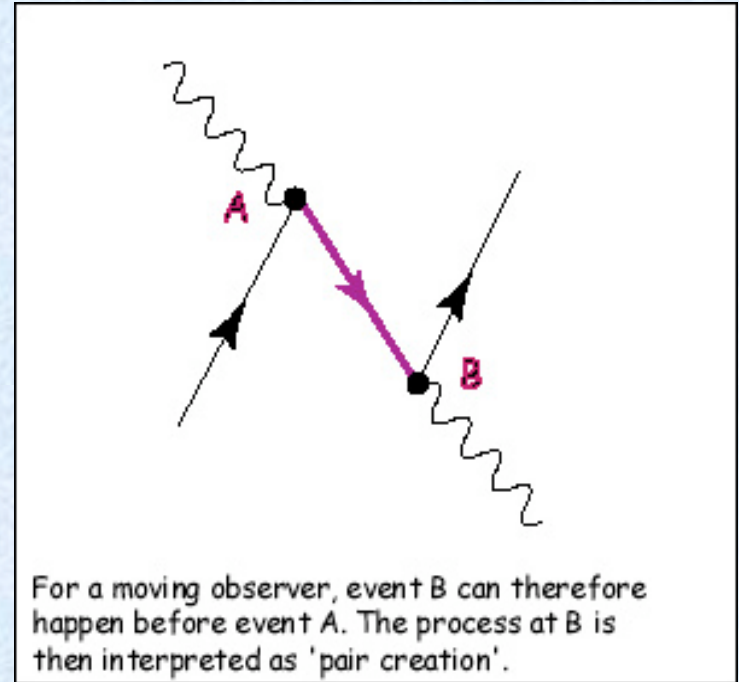


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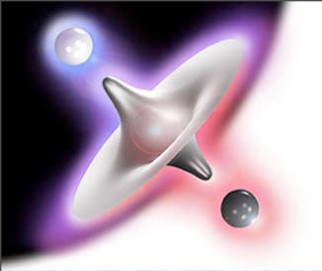
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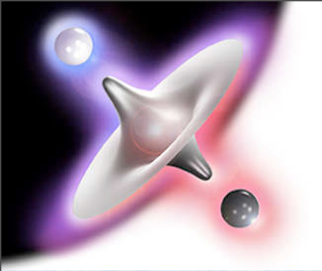
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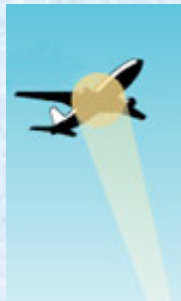
“One observer's electron is the other observer's positron”



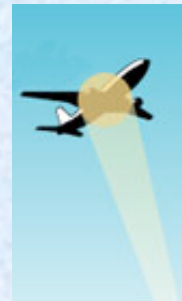
Analogy : an airplane flying over a crooked road



Analogy : an airplane flying over a crooked road

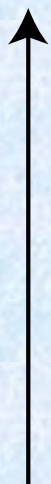


Observer A



Observer B

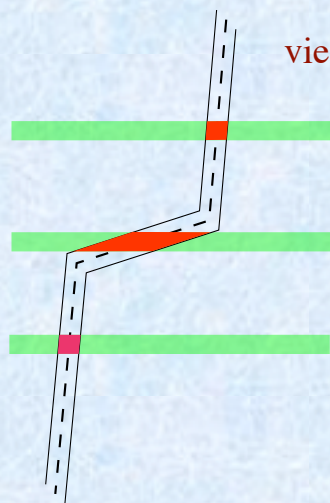
Time



t_2

t_1

t_0



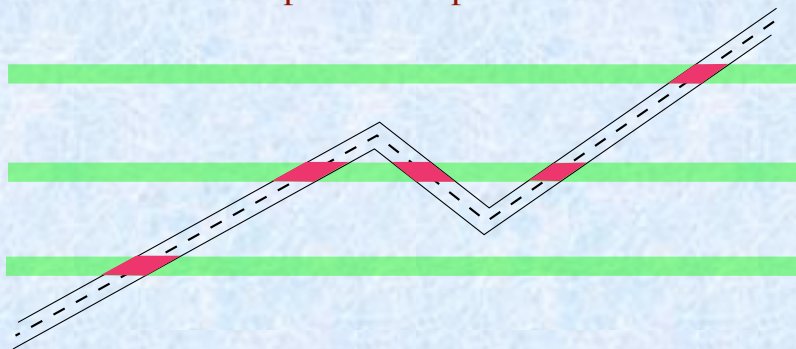
sees only one street

view of observer limited to narrow strip below airplane

t'_2

t'_1

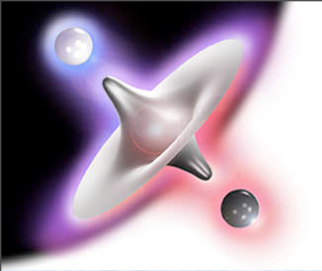
t'_0



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

Particles and antiparticles

How can we imagine an 'anti-particle'?



Particles and antiparticles

How can we imagine an 'anti-particle'?



Star Wars

Particles and antiparticles

How can we imagine an 'anti-particle'?



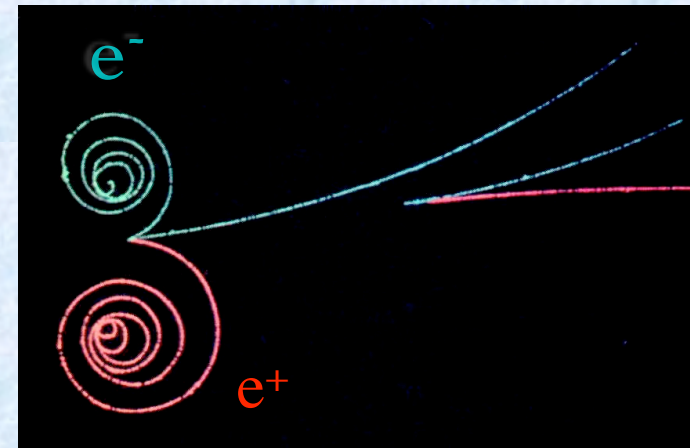
Particles and antiparticles

How can we imagine an 'anti-particle'?

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)

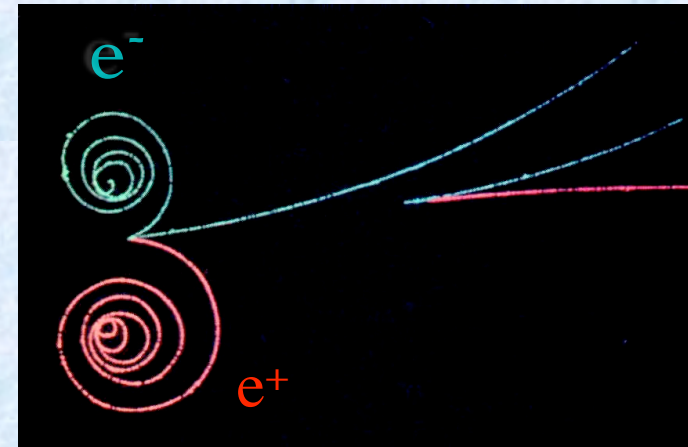
Therefore:

Particles and antiparticles are created in pairs

Electron
Neutrino
Up-Quark
Down-Quark



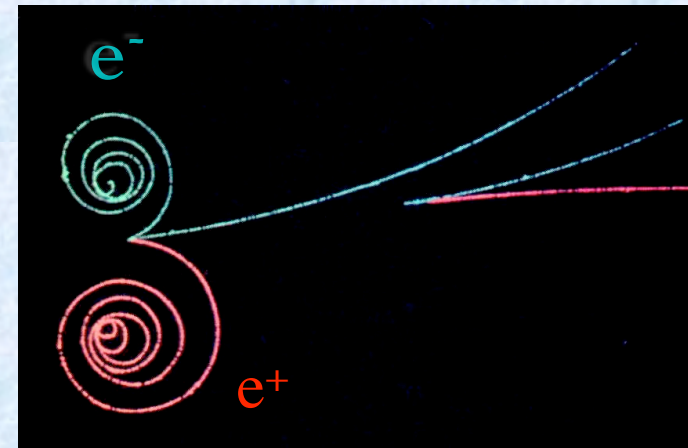
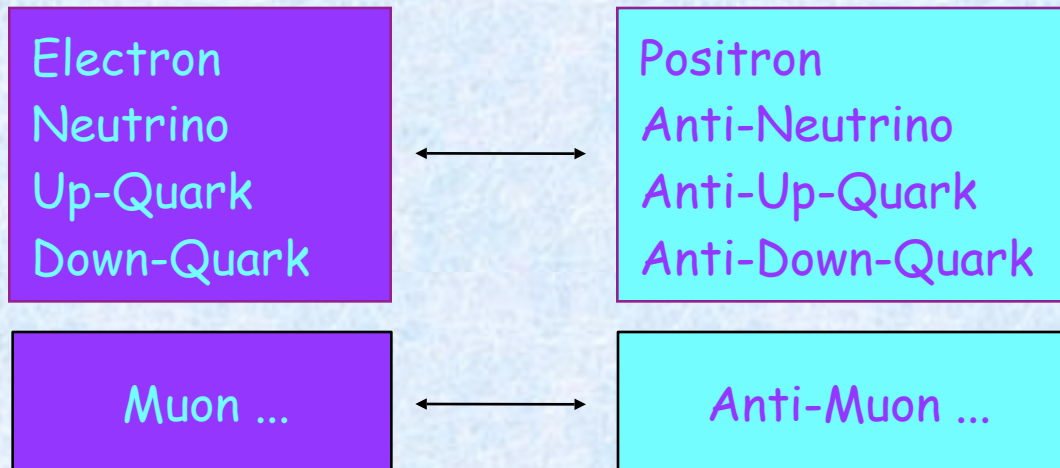
Positron
Anti-Neutrino
Anti-Up-Quark
Anti-Down-Quark



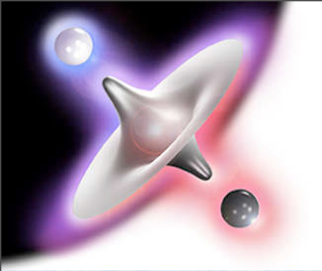
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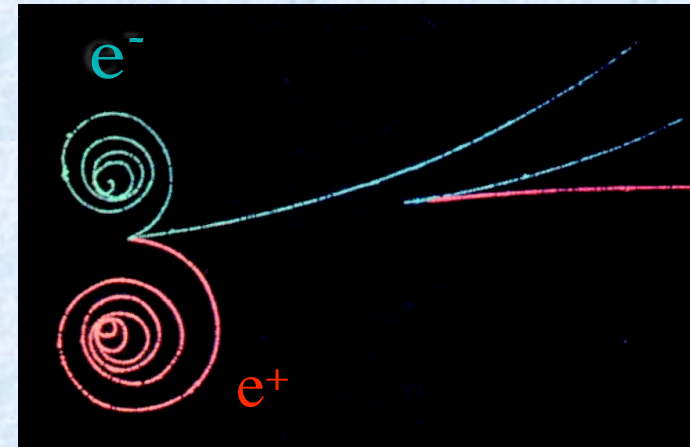
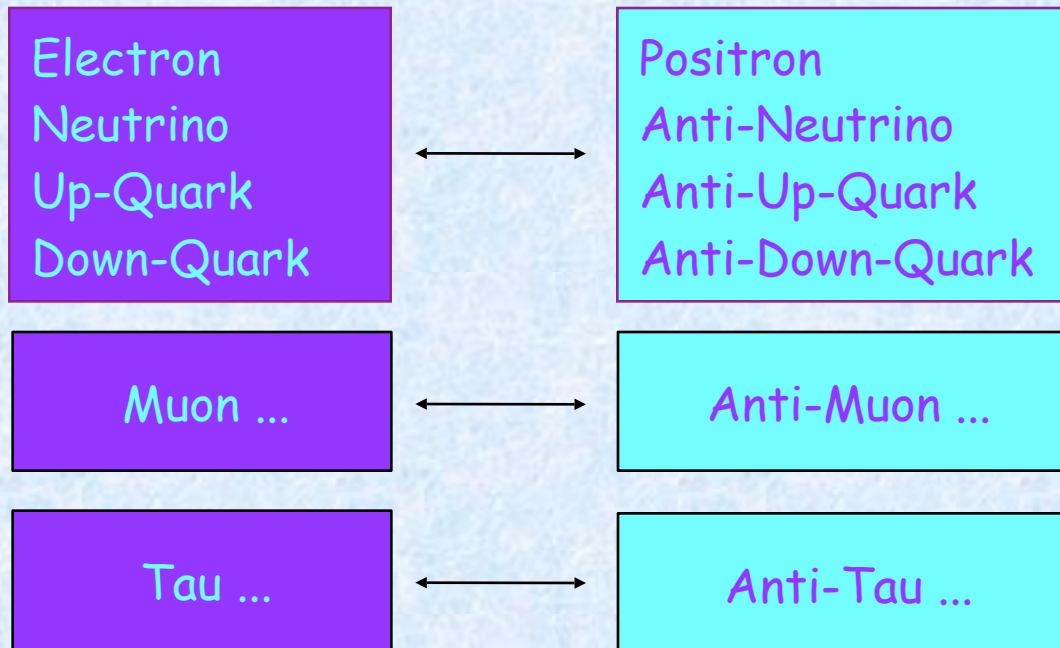


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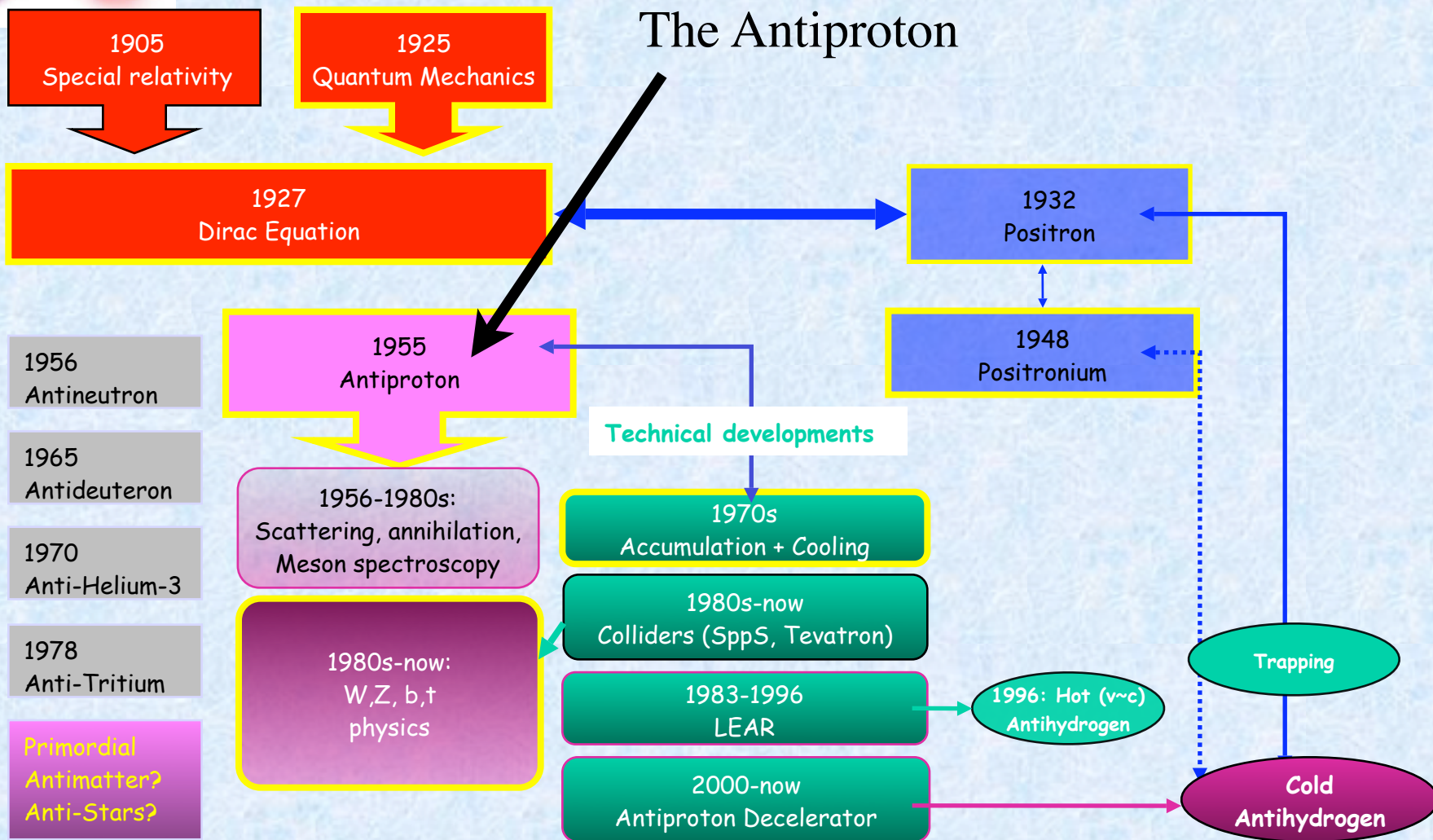


Particles and antiparticles can also destroy each other (annihilation)

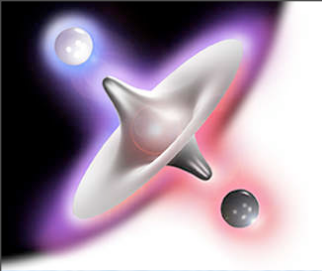
Enter the antiproton



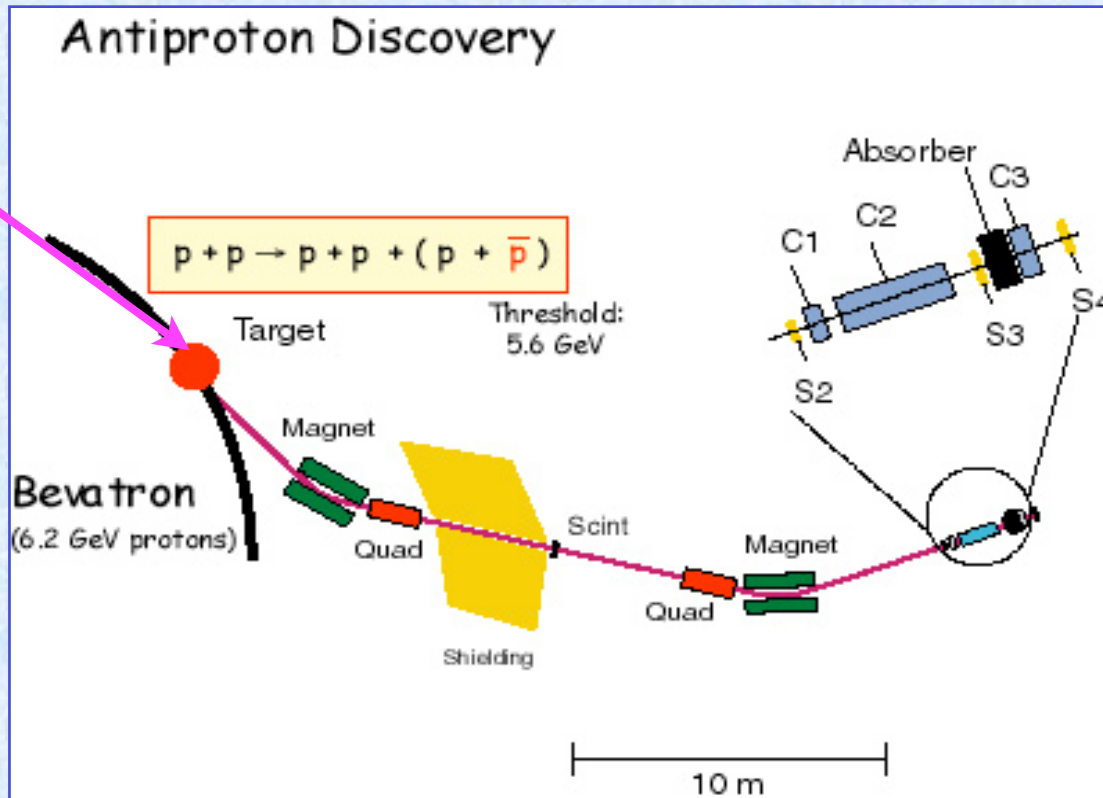
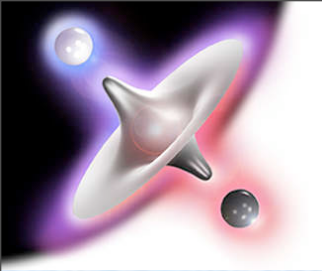
The Antiproton



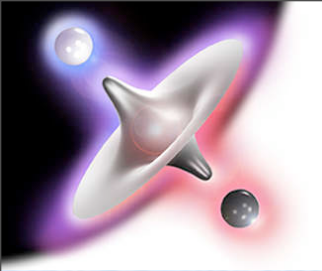
Antiproton Discovery (1955)



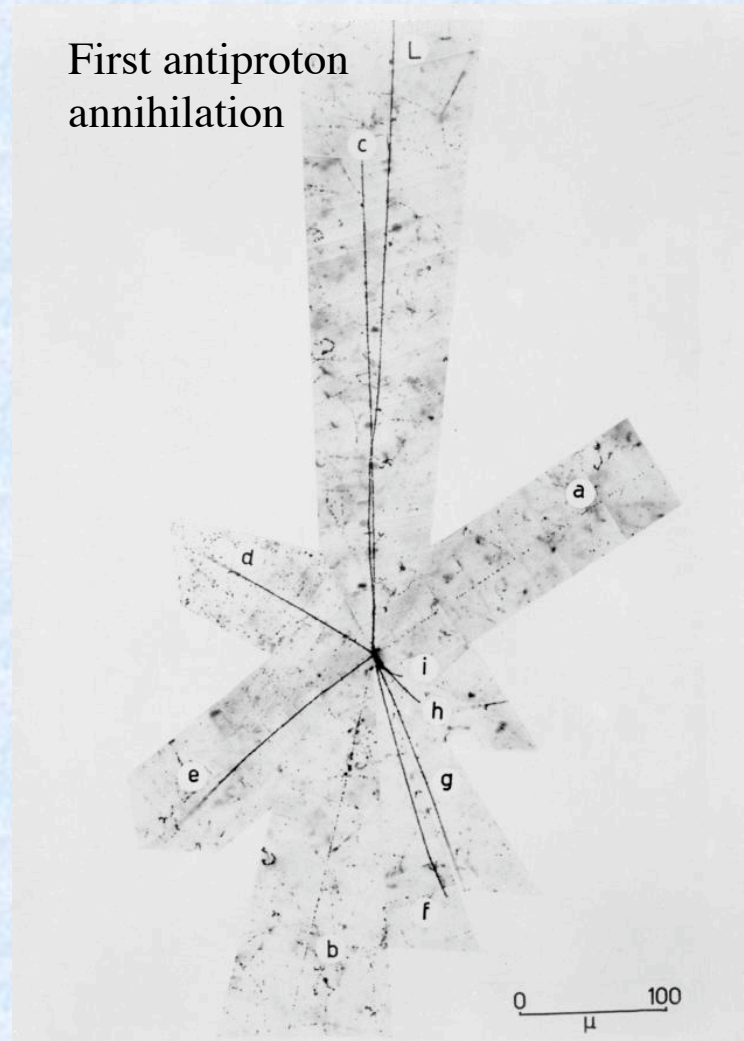
Antiproton Discovery (1955)



Antiproton Discovery (1955)



First antiproton
annihilation



Antiproton Discovery (1955)

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 100, No. 3

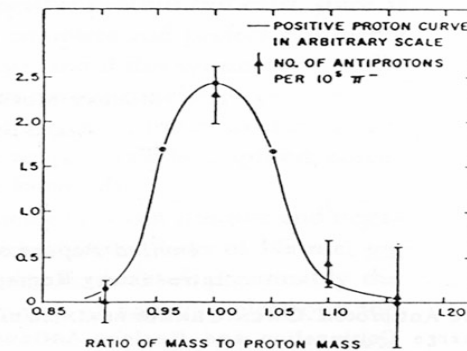
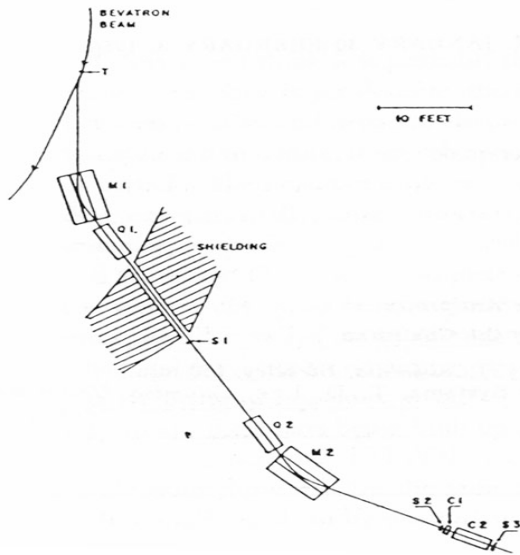
NOVEMBER 1, 1955

Observation of Antiprotons*

OWEN CHAMBERLAIN, EMILIO SEGRÈ, CLYDE WIEGAND,
AND THOMAS YPSILANTIS

*Radiation Laboratory, Department of Physics, University of
California, Berkeley, California*

(Received October 24, 1955)



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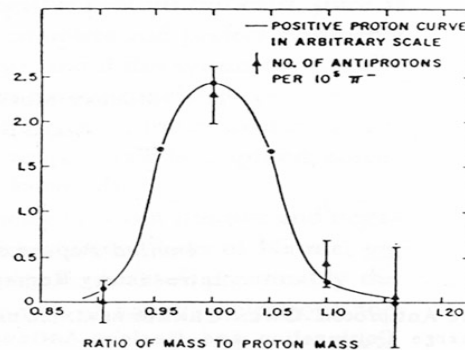
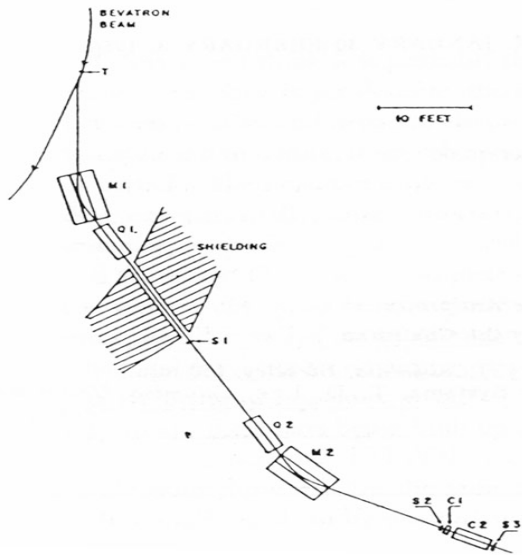
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for 50% of the collaboration**



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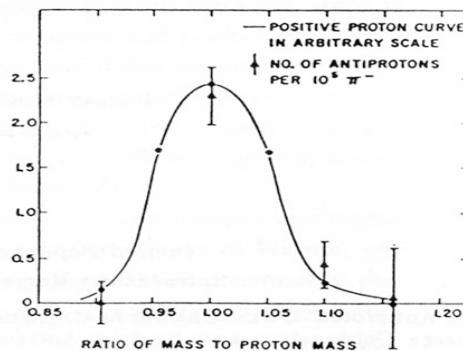
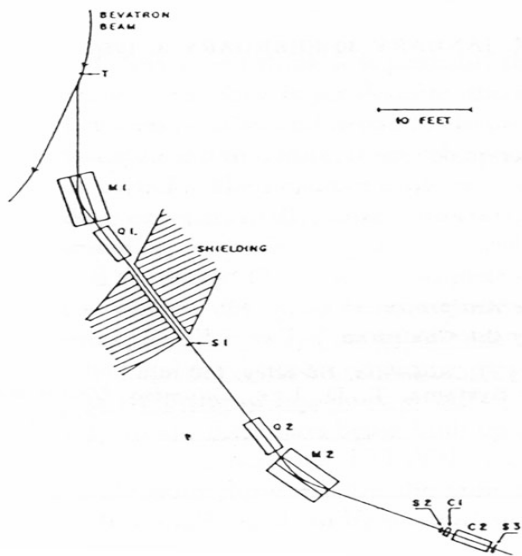
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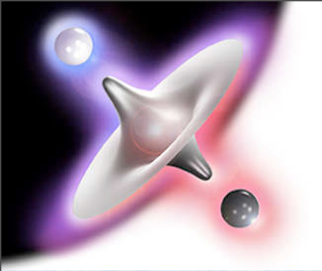
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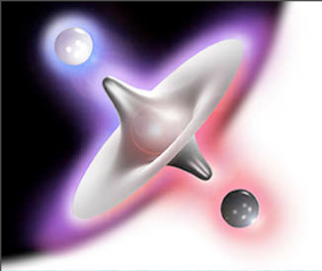


Tedious analysis



Also in 1955: The CPT Theorem *

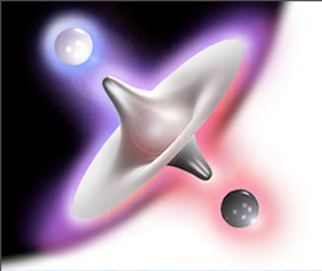
*1955 - Proof of CPT theorem by Pauli (following work by Schwinger and Lüders)



Also in 1955: The CPT Theorem *

If :

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

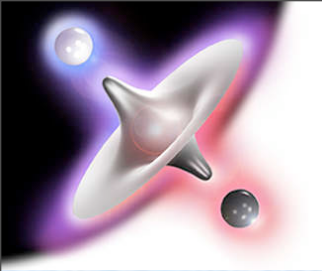


Also in 1955: The CPT Theorem *

If :

- 1) Locality (no action at a distance)
- 2) Lorentz invariance (all inertial frames are equivalent)
- 3) Causality (no interaction between two space-time points outside each other's light cone)
- 4) Vacuum = lowest energy (spin-statistics connection)
- 5) Flat space-time (no black holes anywhere near)
- 6) Point-like particles

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



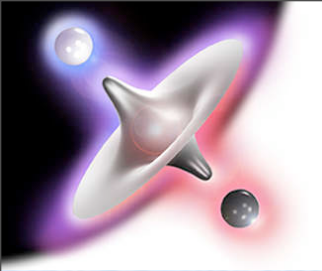
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|---------------------------|--|
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Then :

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Also in 1955: The CPT Theorem *

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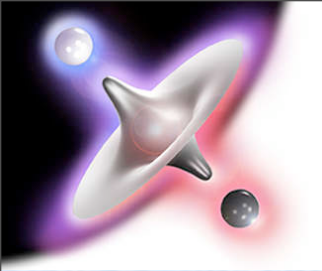
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- 5) Flat space-time (no black holes anywhere near)
- 6) Point-like particles

Then :

Particles and antiparticles must have **exactly equal**

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

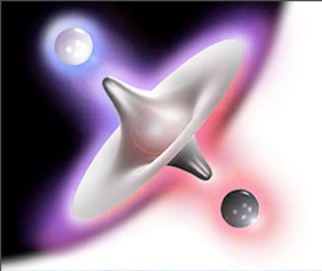
*1955 - Proof of CPT theorem by Pauli (following work by Schwinger and Lüders)



Does the Universe care about CPT symmetry ?

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

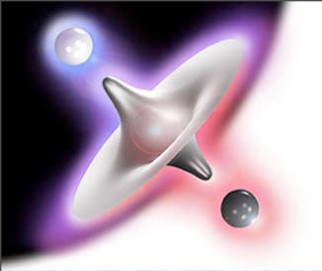
- 1) There may be matter-antimatter symmetry in the Universe
- 2) Anti-stars: optical spectrum would be identical



Does the Universe care about CPT symmetry ?

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):

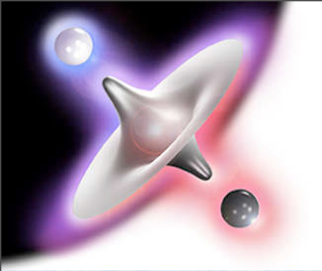


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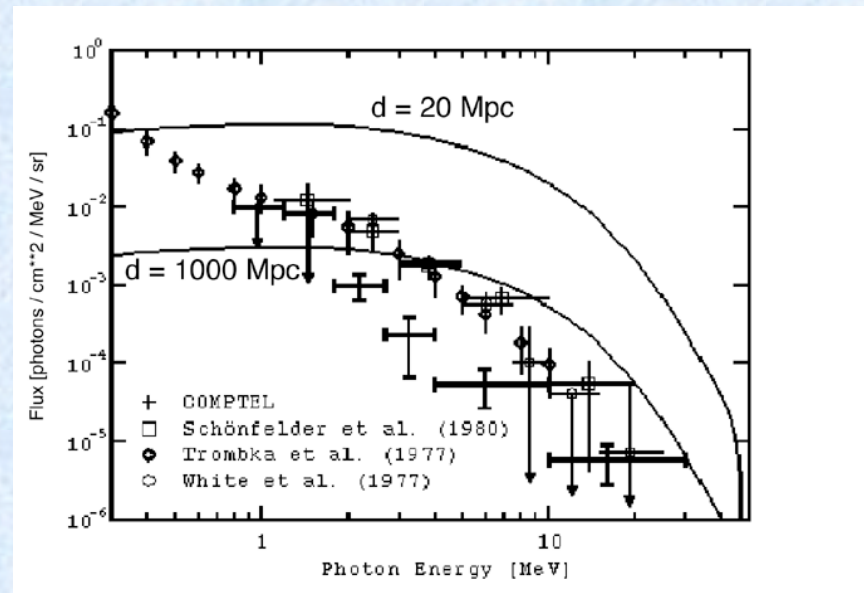




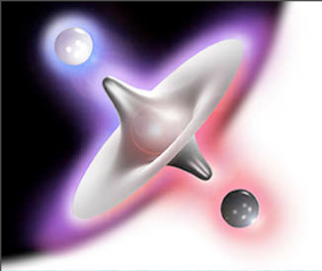
Does the Universe care about CPT symmetry ?

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):



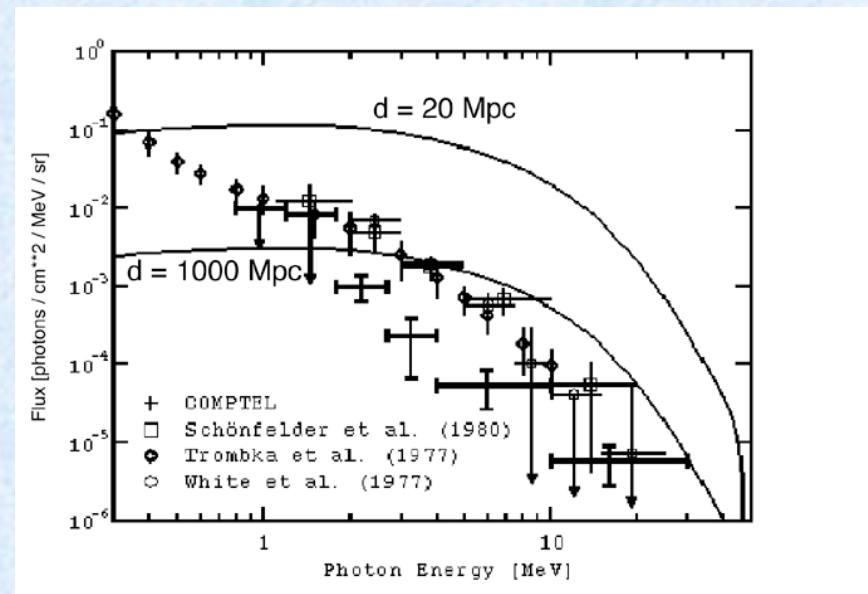
*A.G. Cohen, A. De Rujula, S. Glashow, *Astrophys. J.* 495 (1998) 539



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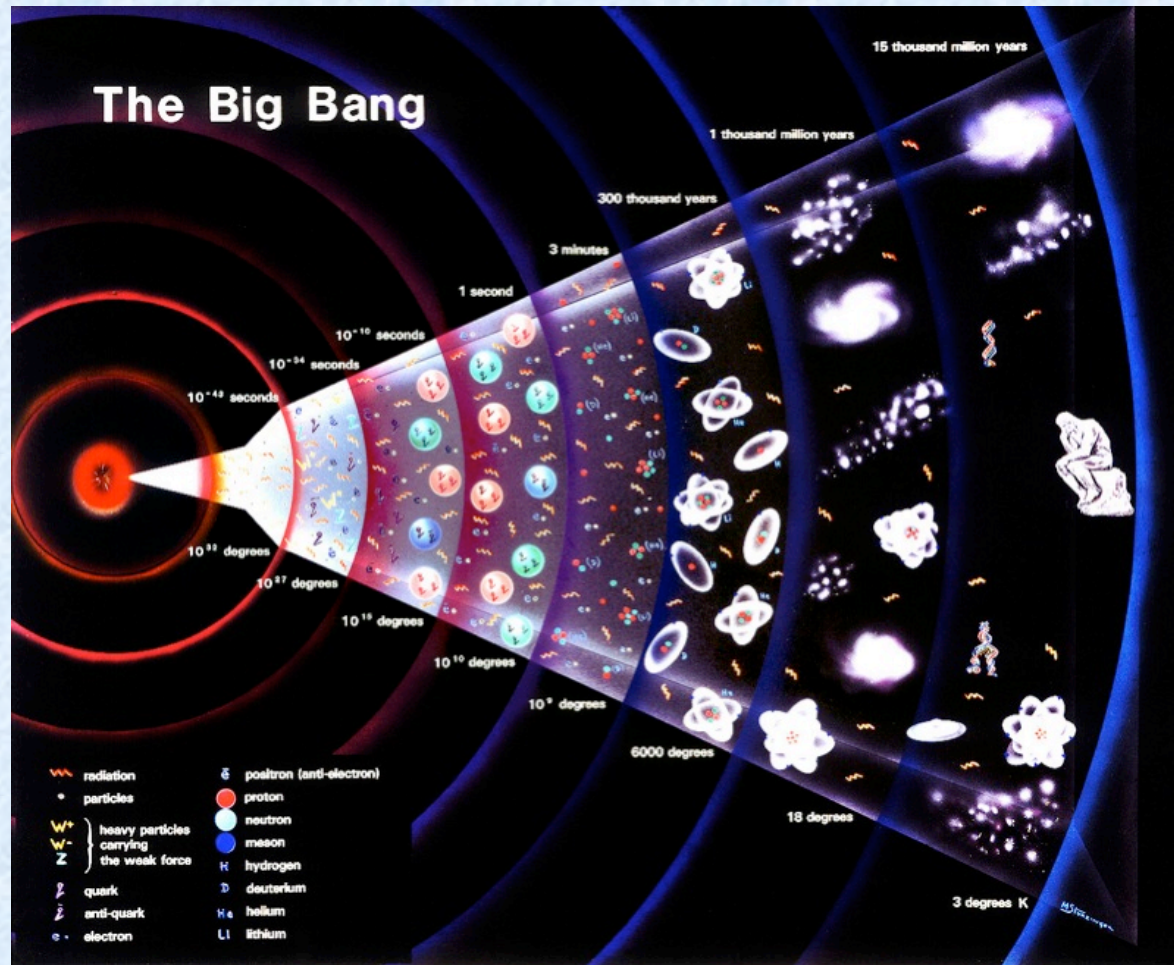


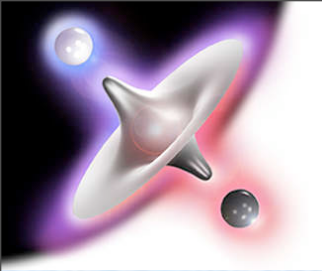
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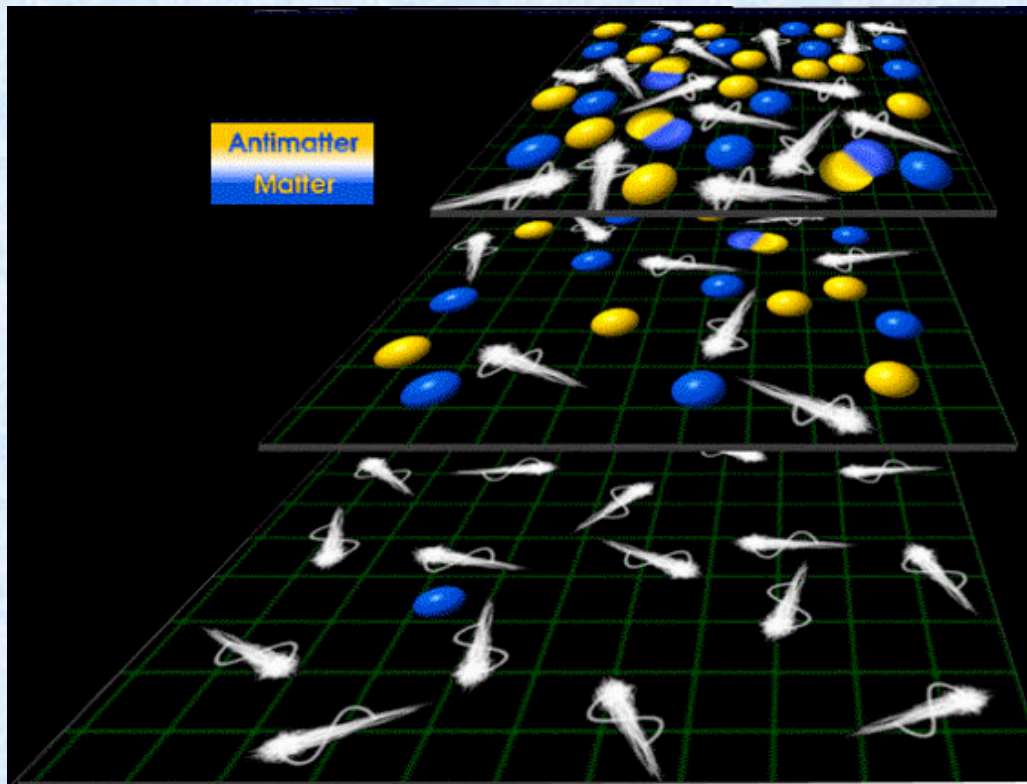
13,700 million years ago

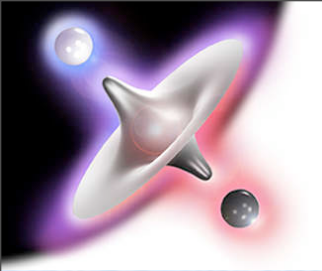




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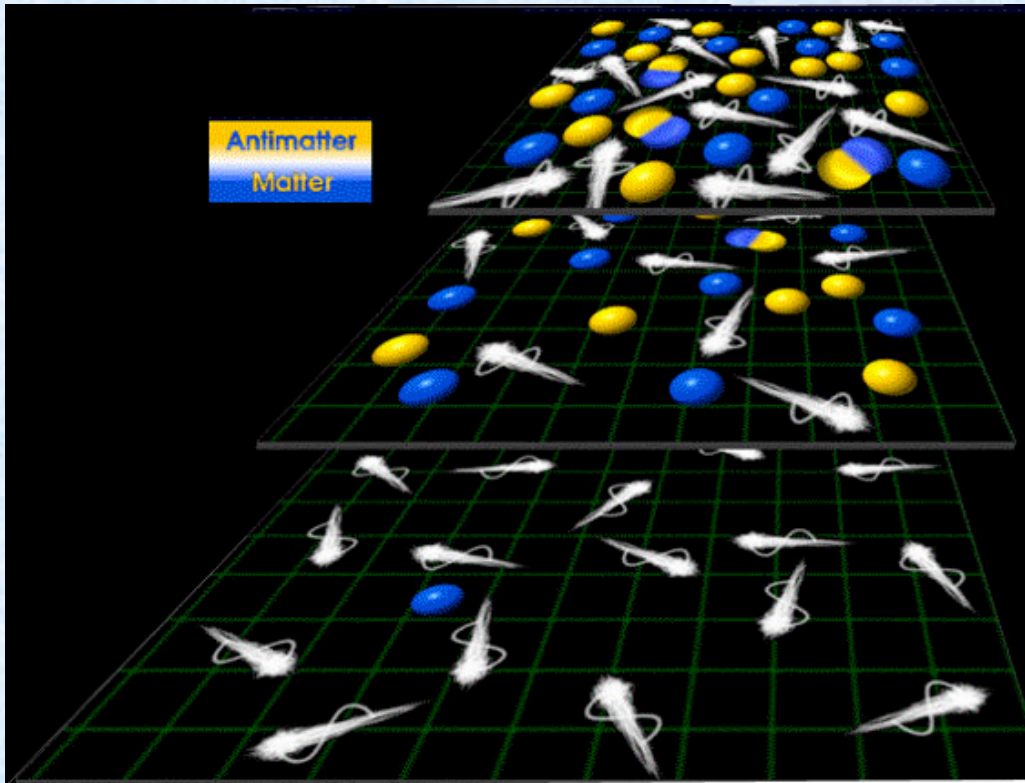
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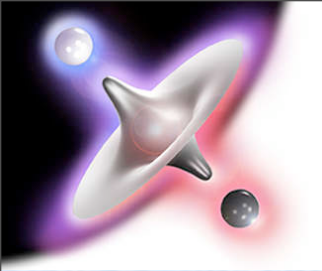


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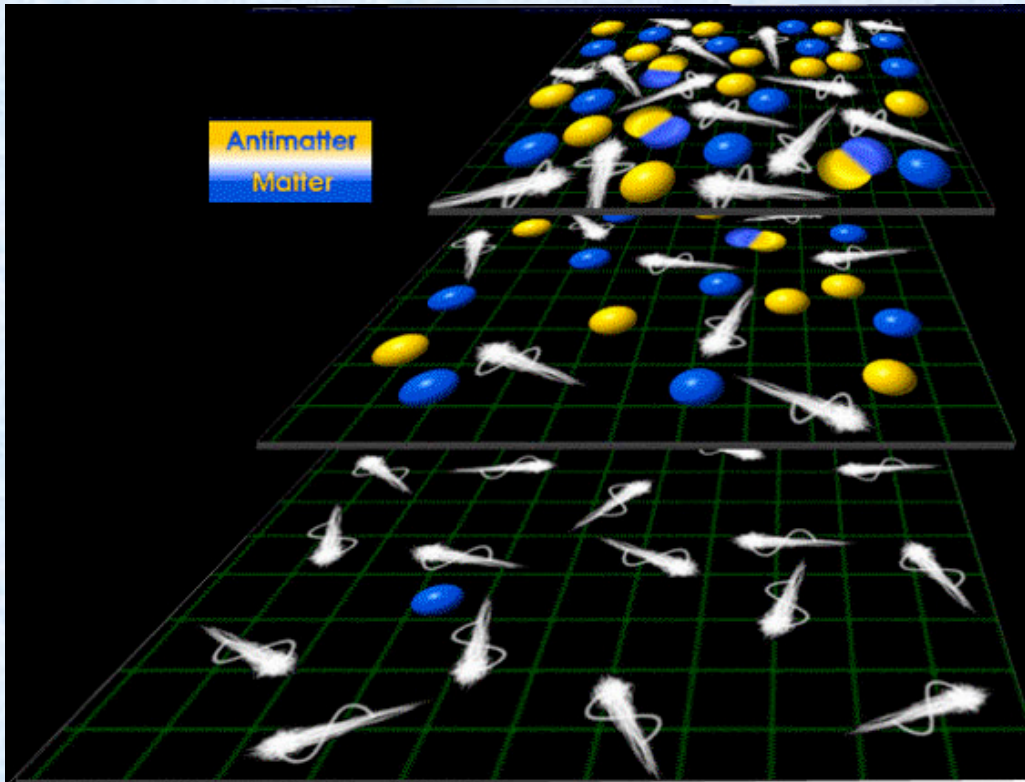


$t \sim 0$:
equal amounts of
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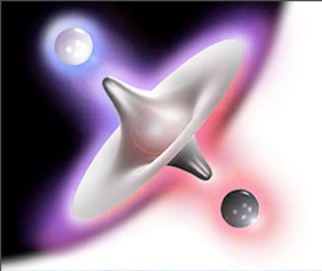
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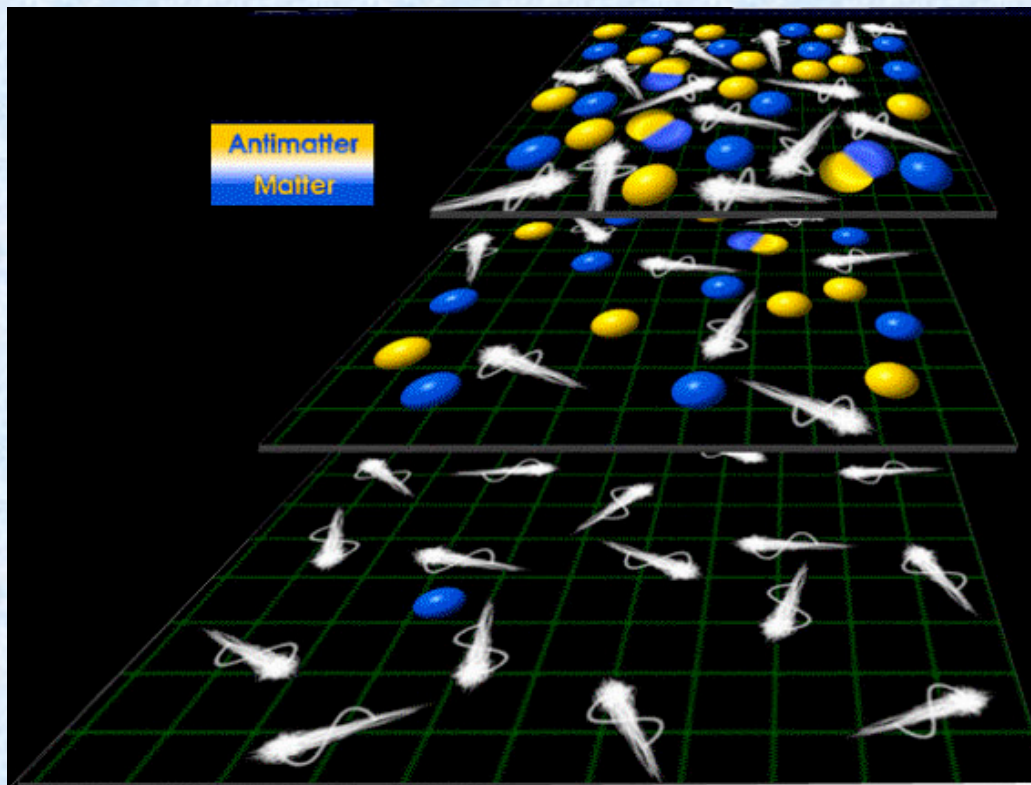
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MOTHER OF ALL BATTLES



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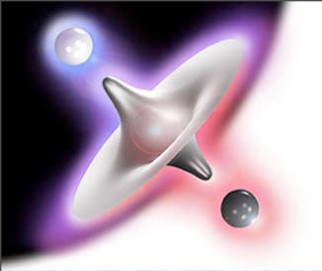
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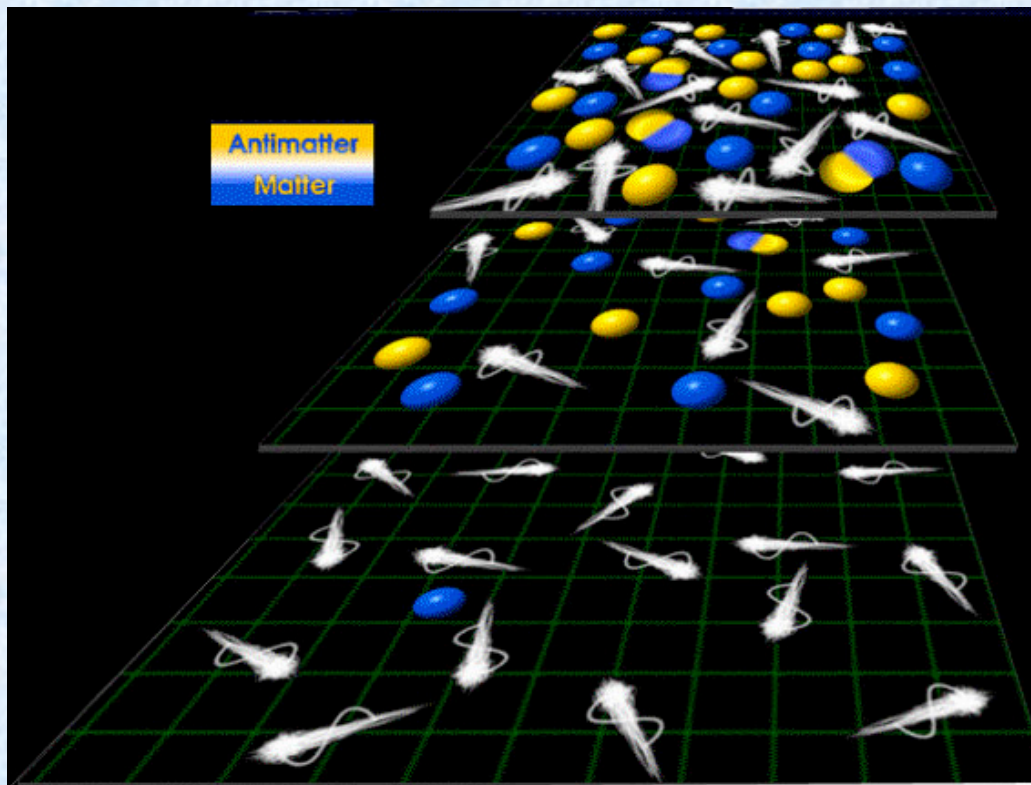
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$t < 0.001$ s :
all antimatter has disappeared,
but some matter (us!) left
(and lots of photons)



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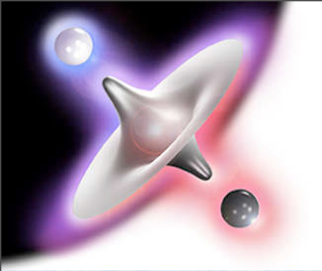


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Why ?? Study antimatter-matter symmetry (CP and CPT)



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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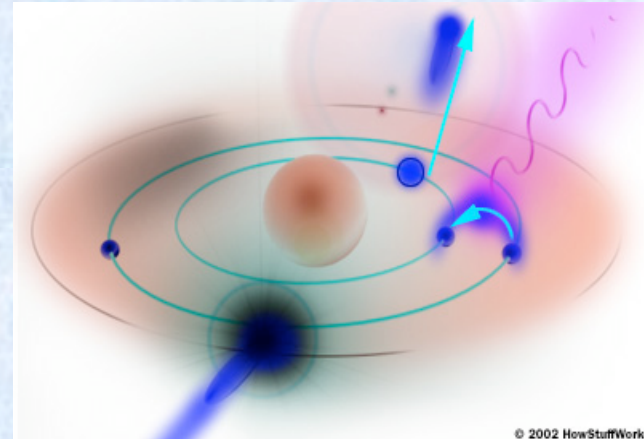
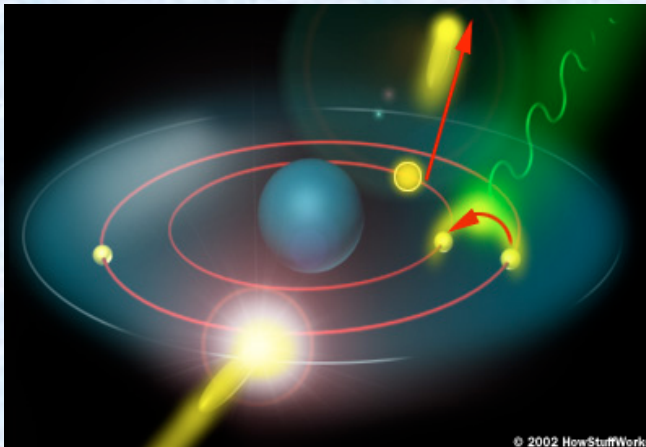
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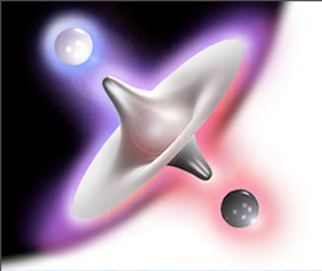
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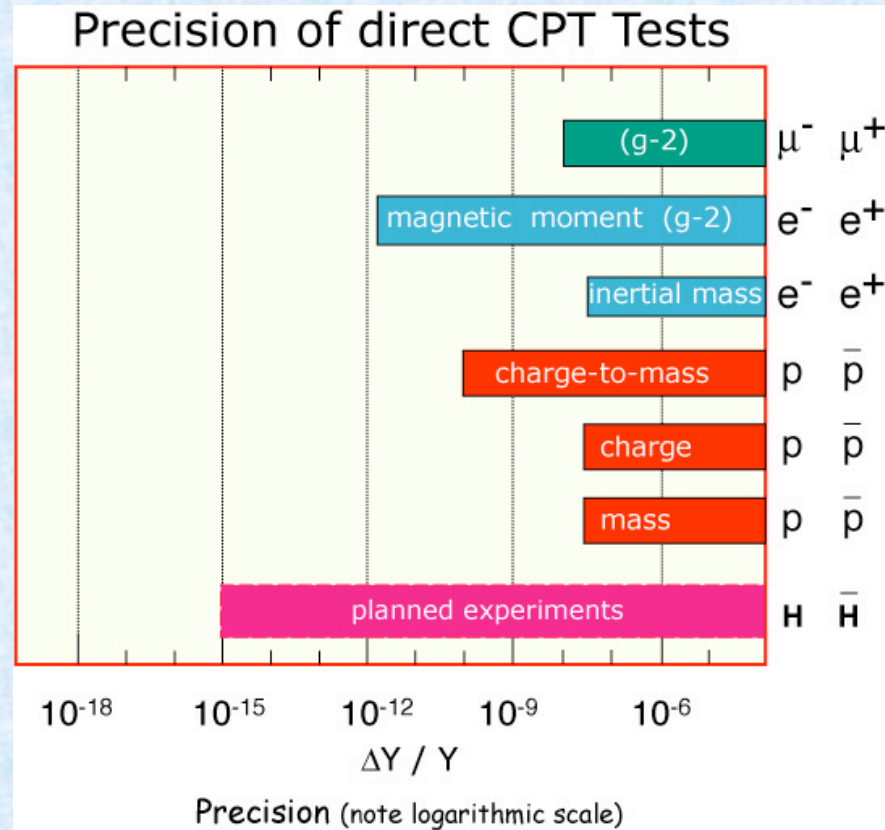
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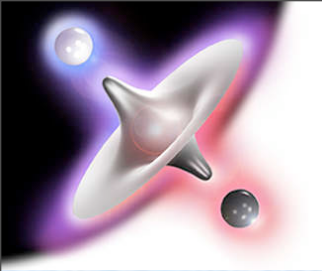
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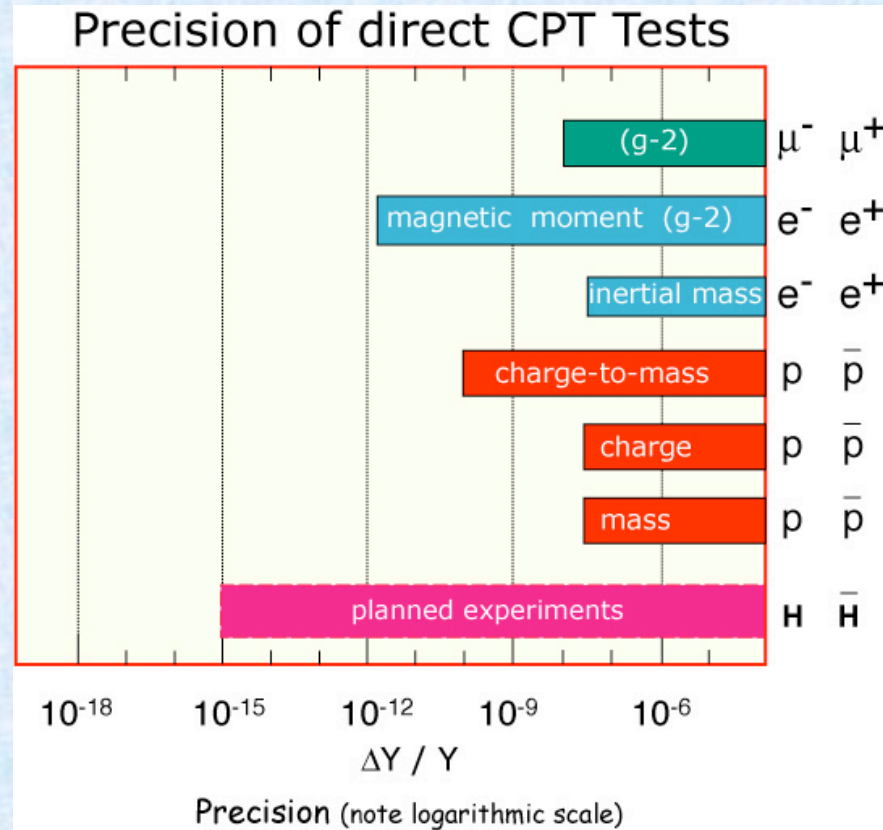


CPT symmetry works very well in the laboratory

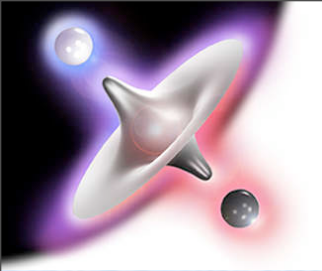




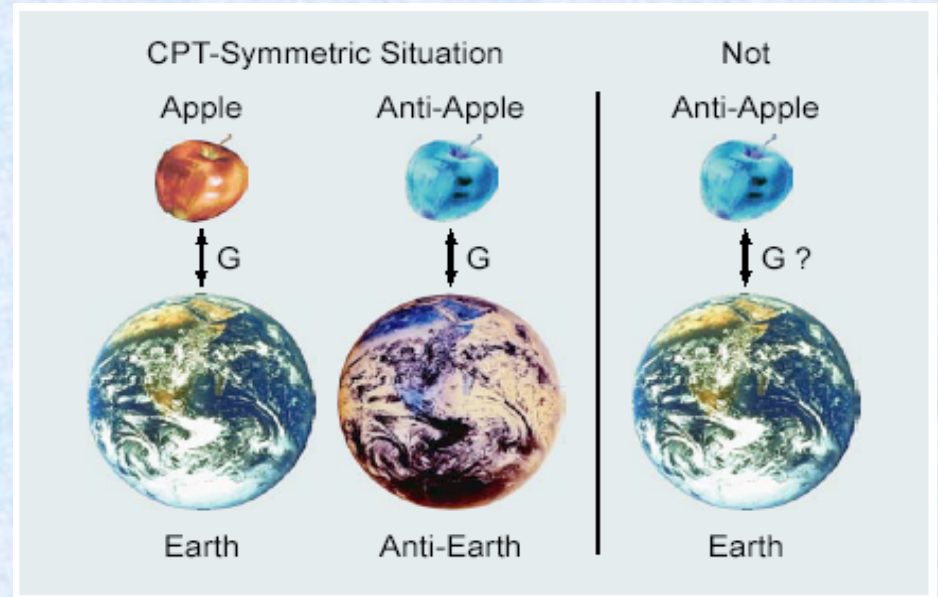
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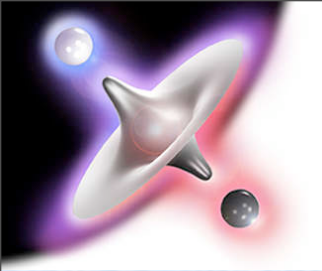


- DIRECT TESTS CONFIRM CPT $\sim 10^{-12}$ LEVEL
- HYDROGEN - ANTIHYDROGEN COMPARISON PROMISING ($< 10^{-15}$)
- THERE IS NO "THEORY" OF CPT VIOLATION



Antimatter gravitation is not constrained by CPT

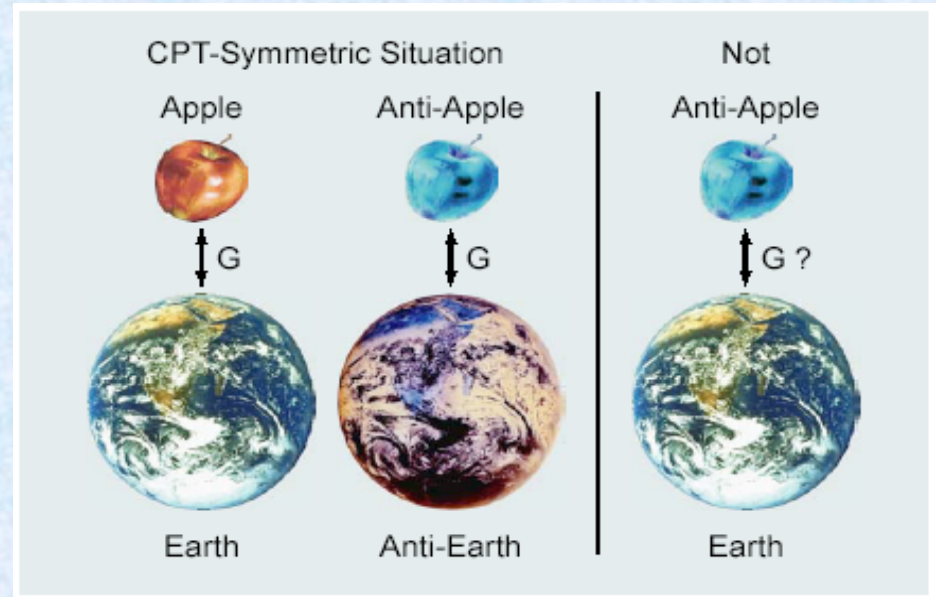


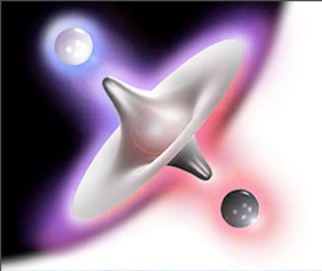


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Theoretical expectation:
Gravitational = Inertial mass

Antimatter falls like matter

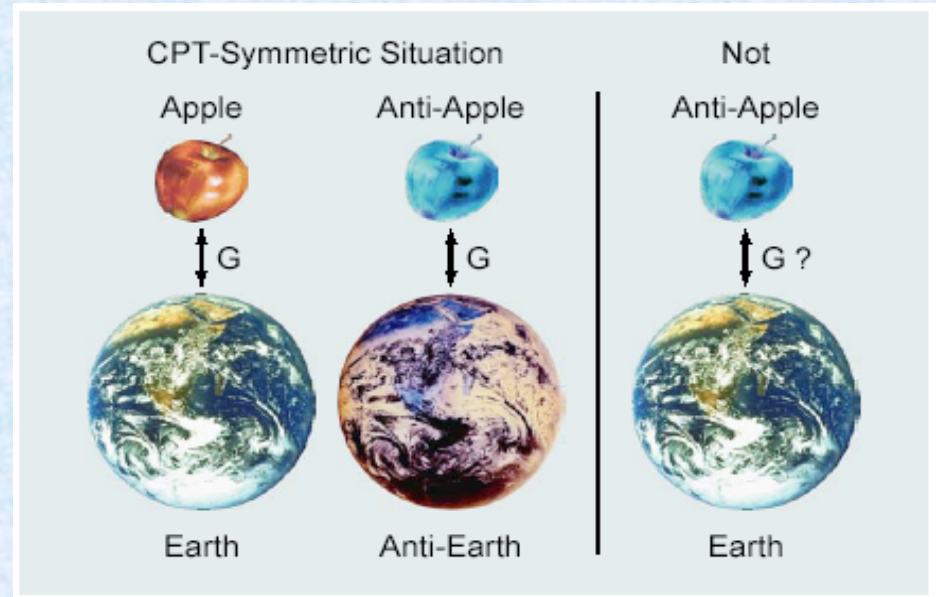




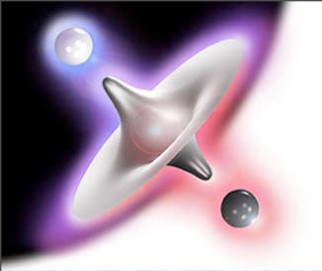
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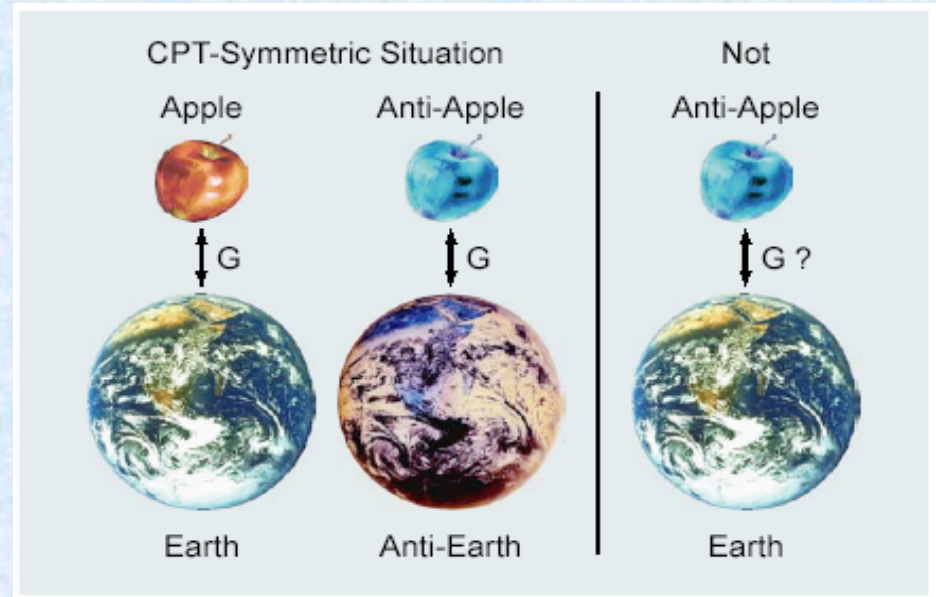
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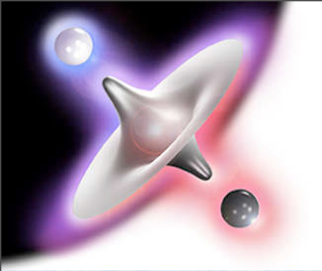
**Measurement of
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Achim Peters, Keng Yeow Chung & Steven Chu

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

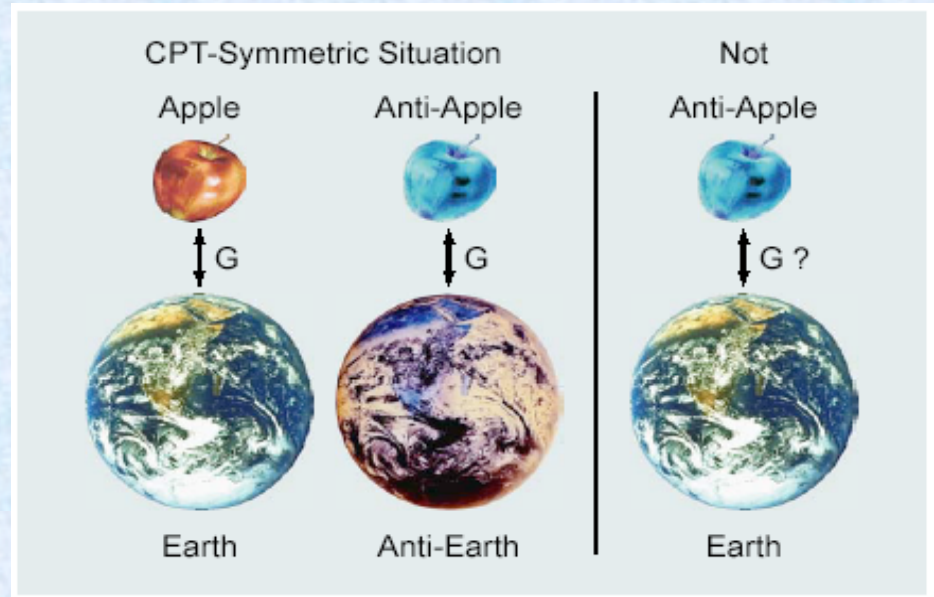
(anti-)



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**Slow moving anti-atoms offer
a possibility:**

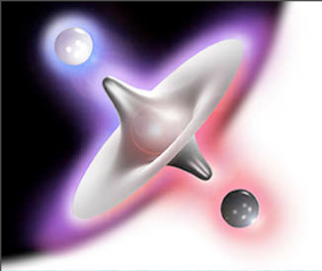
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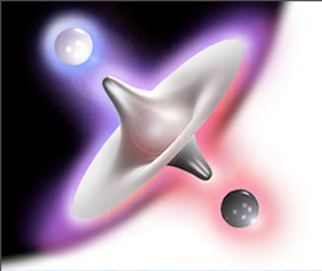
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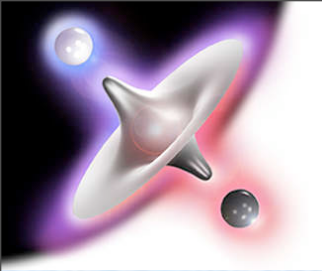


AD



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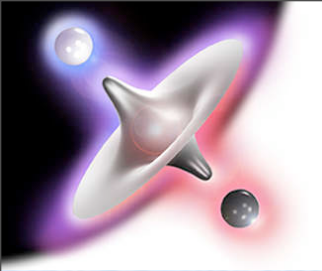
II. ANTIMATTER 'FACTORY'



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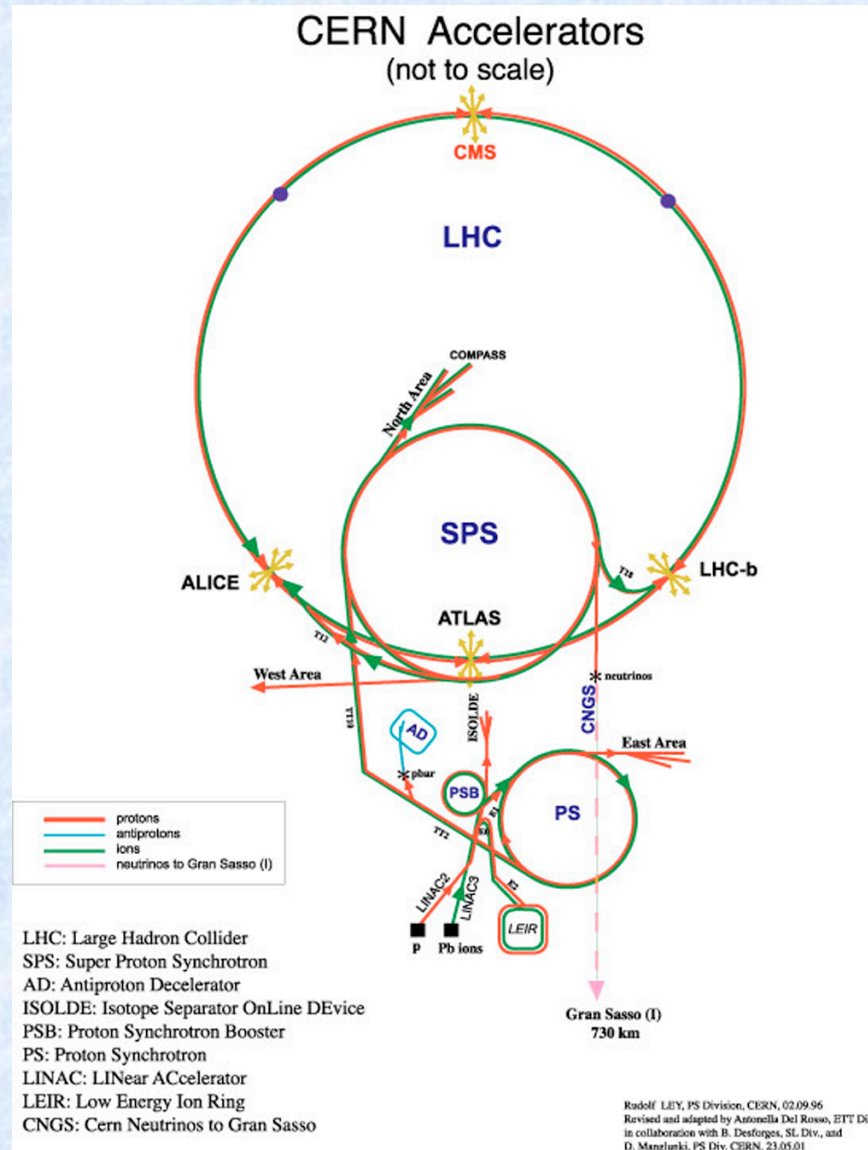
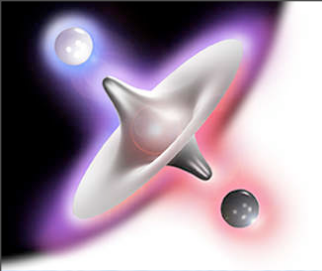
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(also-known-as: “Antiproton **D**ecelerator”)

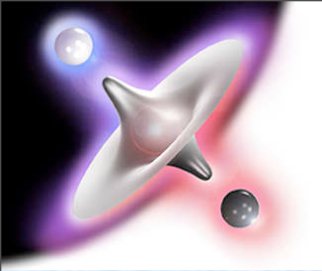


CERN - The Lord of the Rings

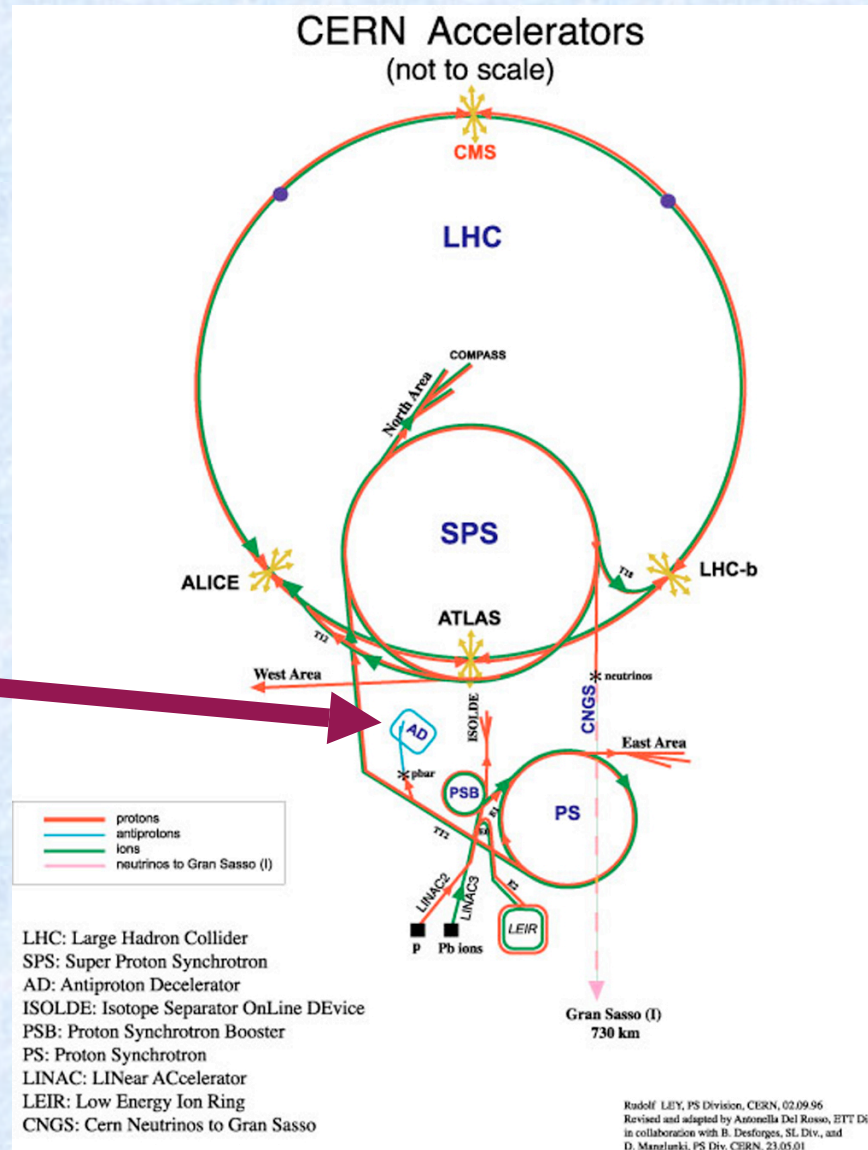
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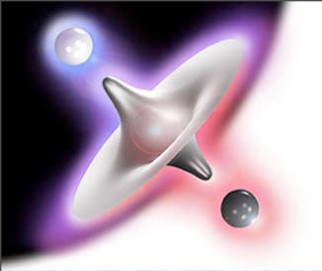


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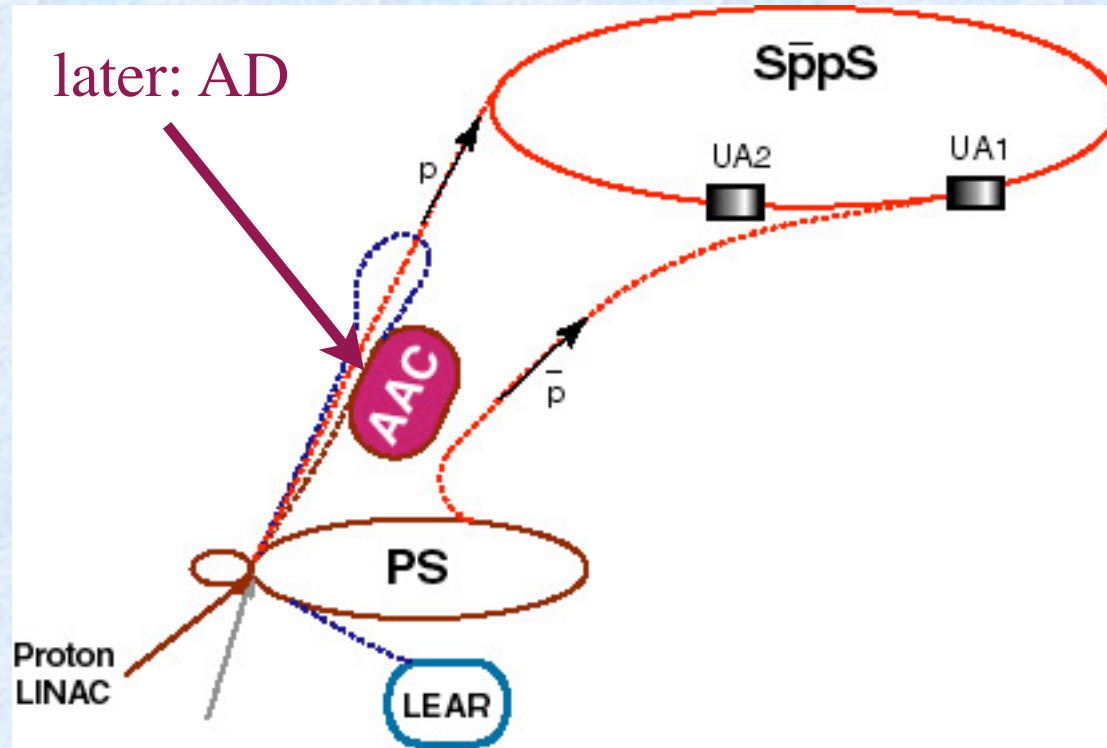


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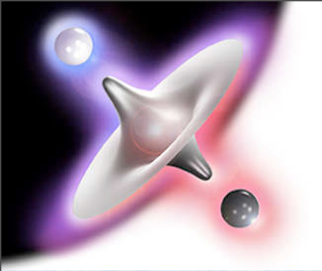




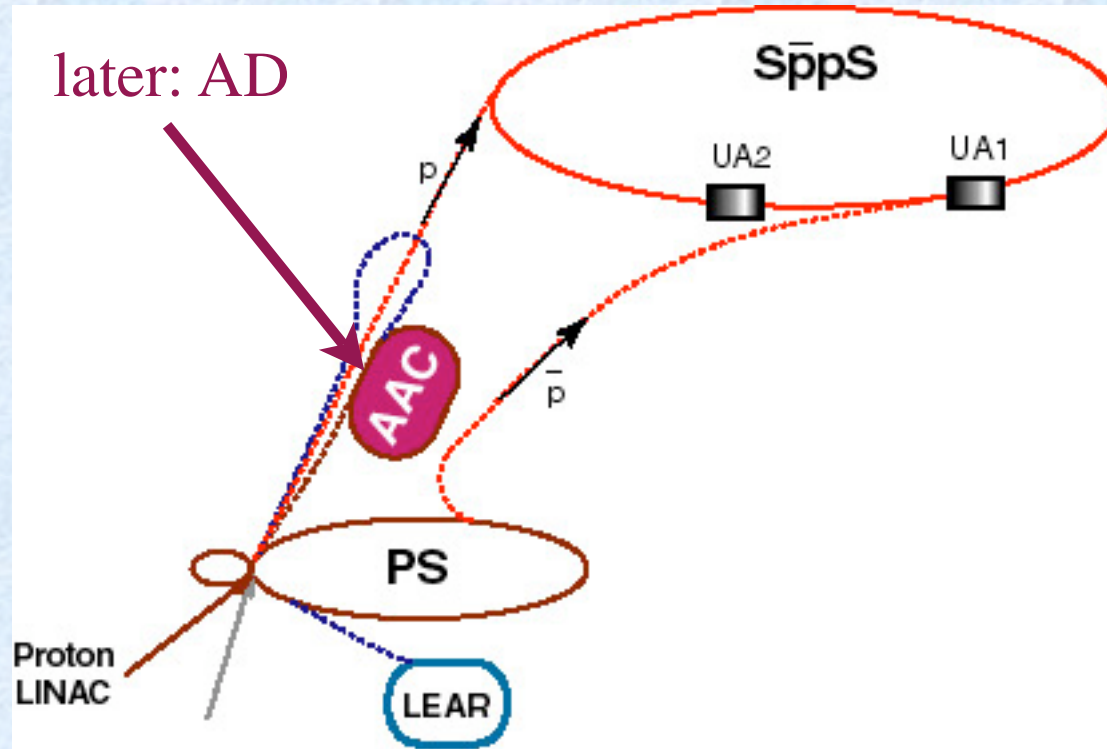
The reason for antiproton beams at CERN (1980)



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

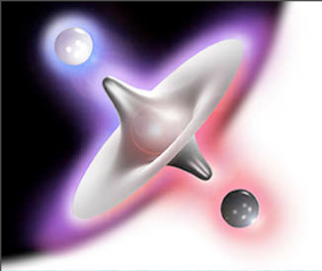


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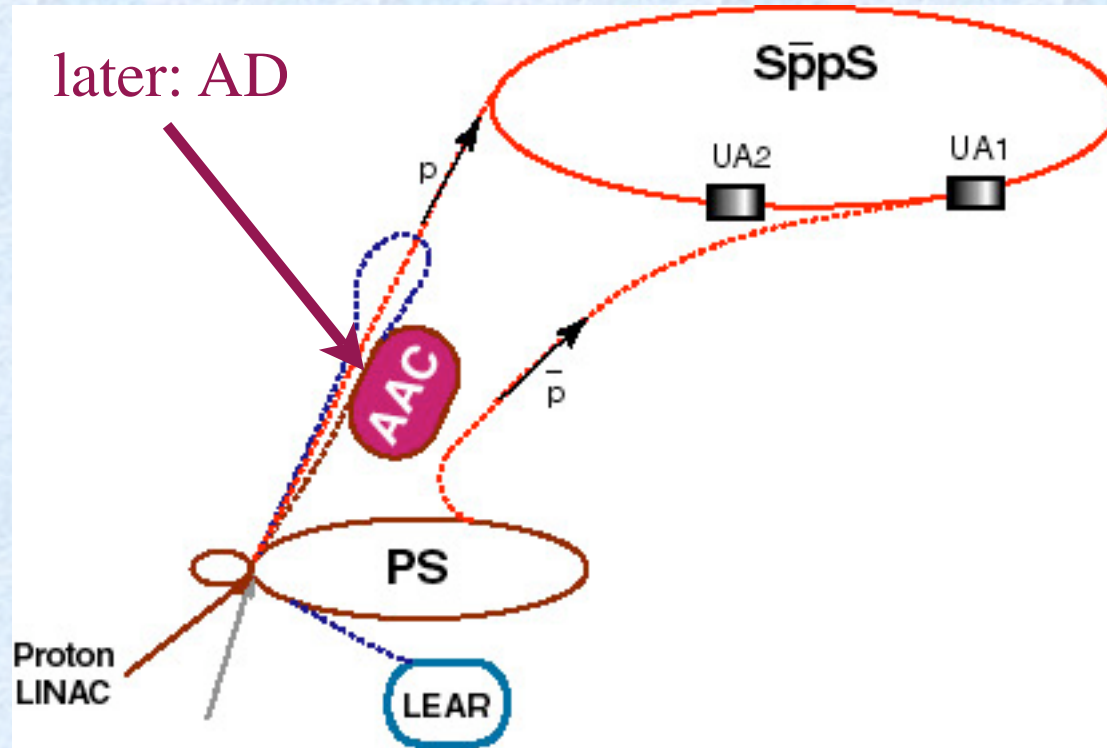


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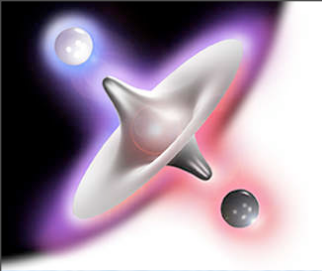


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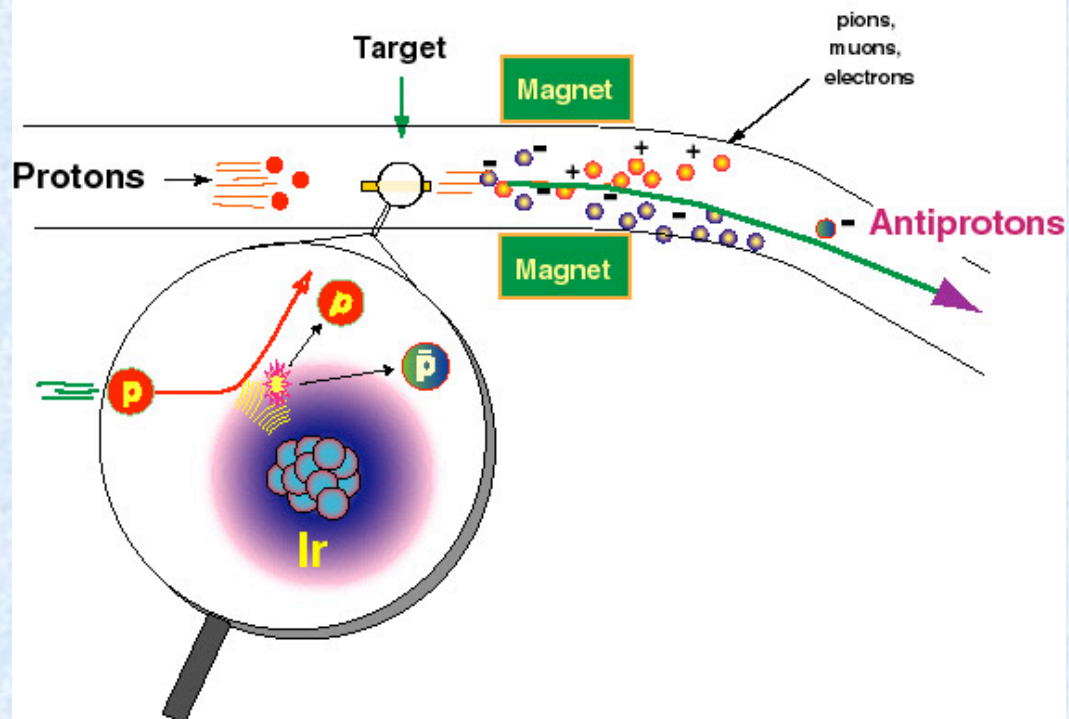
Discovery of W, Z bosons

Search for SUSY, Top, Higgs

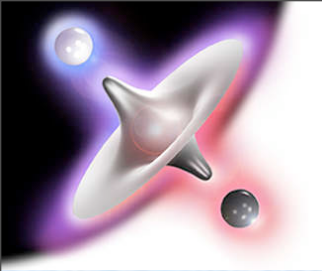
An accelerator 'condenses' energy in collisions



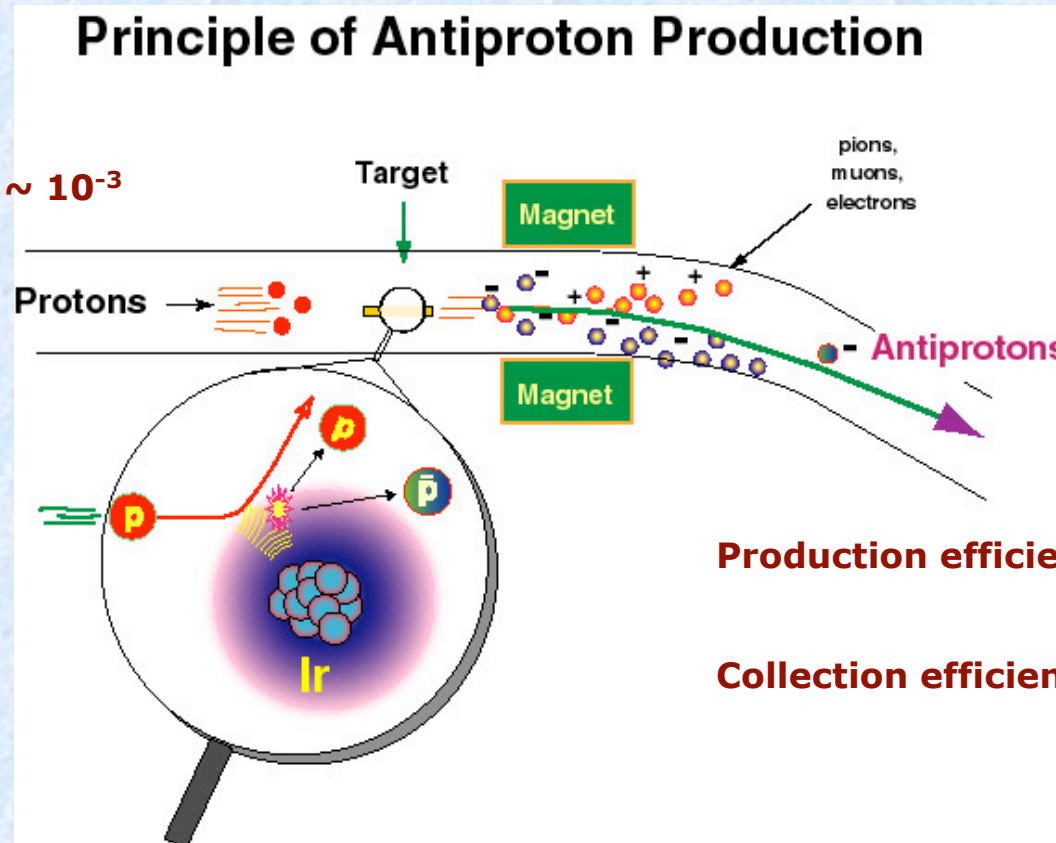
Principle of Antiproton Production



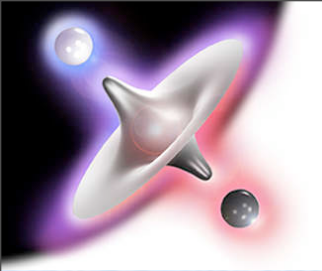
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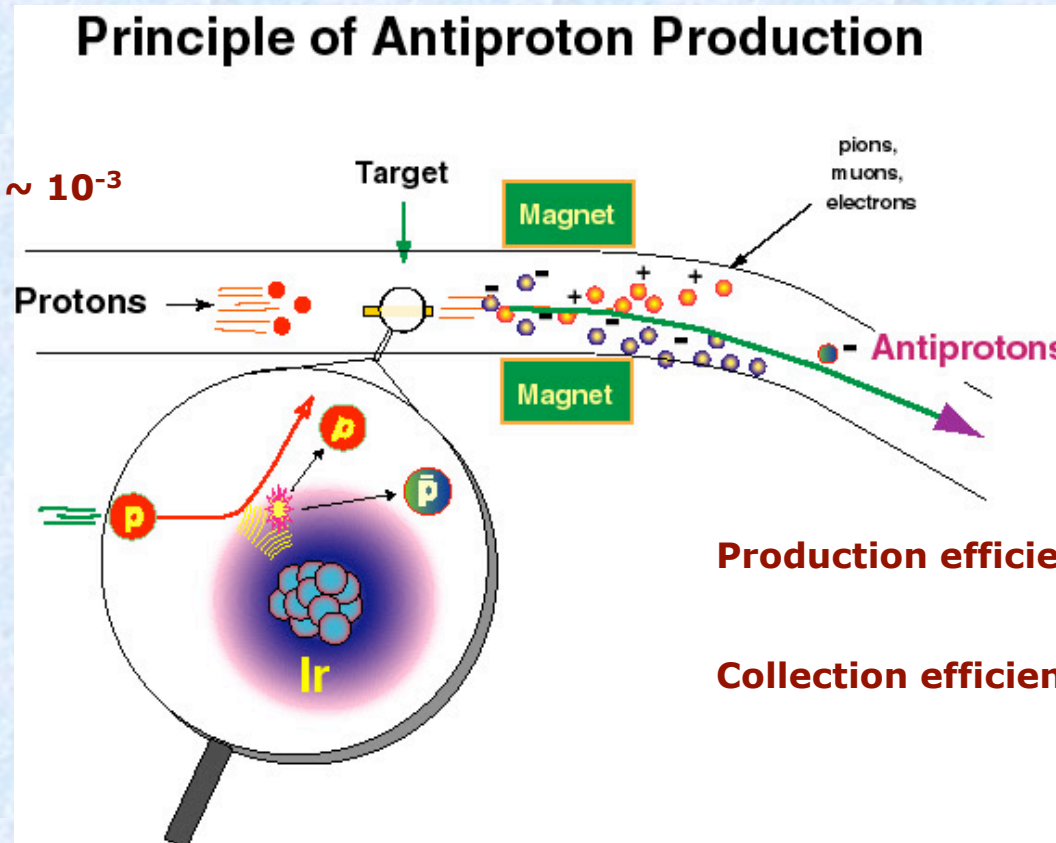
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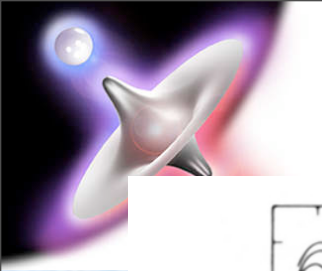


Production efficiency $\sim 10^{-4}$

Collection efficiency (AD) $\sim 10^{-2}$

Peak production at CERN $\sim 200,000,000,000,000$ antiprotons/year

(only 0.3 nano-gram, overall efficiency $\sim 10^{-9}$)



Efficiency of antiproton production

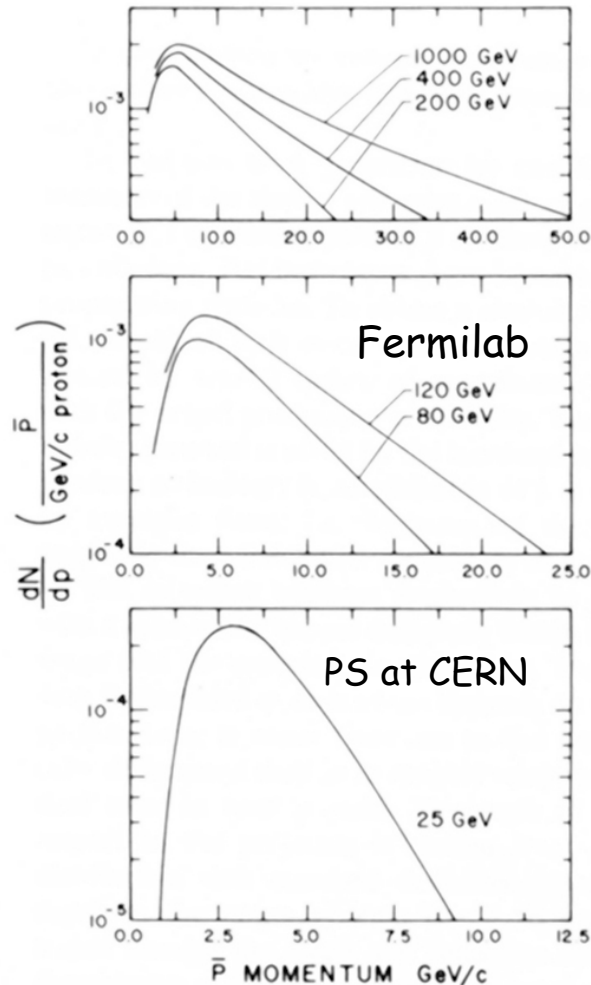


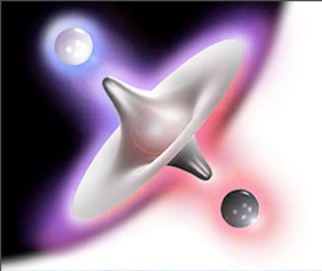
Fig. 7. Total laboratory \bar{p} production on tungsten below 0.30 GeV/c from eq. (1) (per interacting proton).

Energy dependent

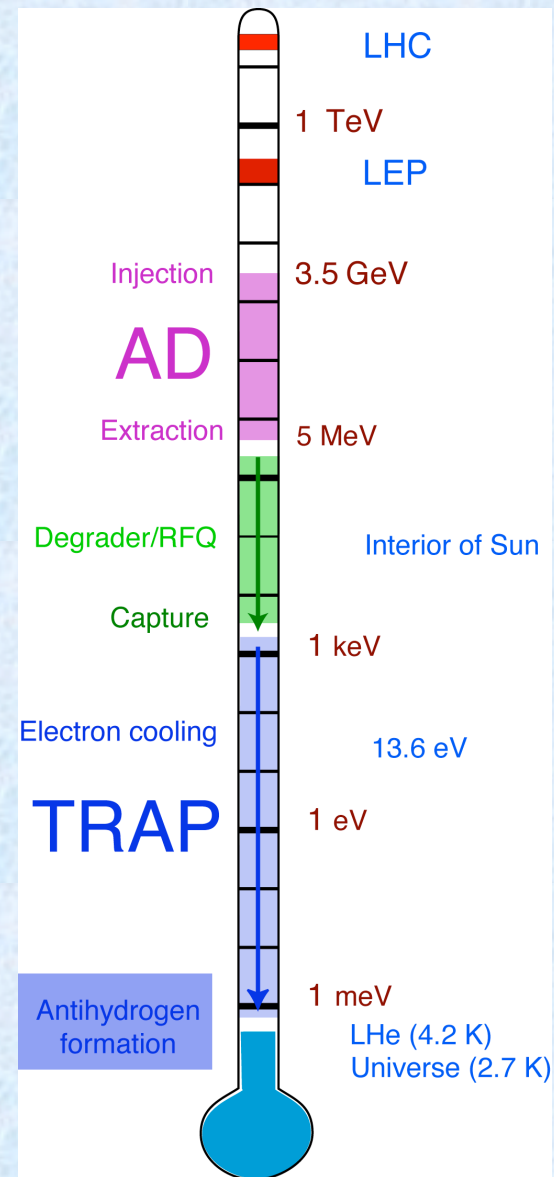
Few 10^{-4} (CERN, 26 GeV/c)

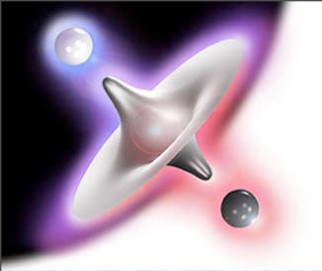
Few 10^{-3} (Fermilab, 120 GeV)

➤ 99 % of interacting protons do NOT produce antiprotons



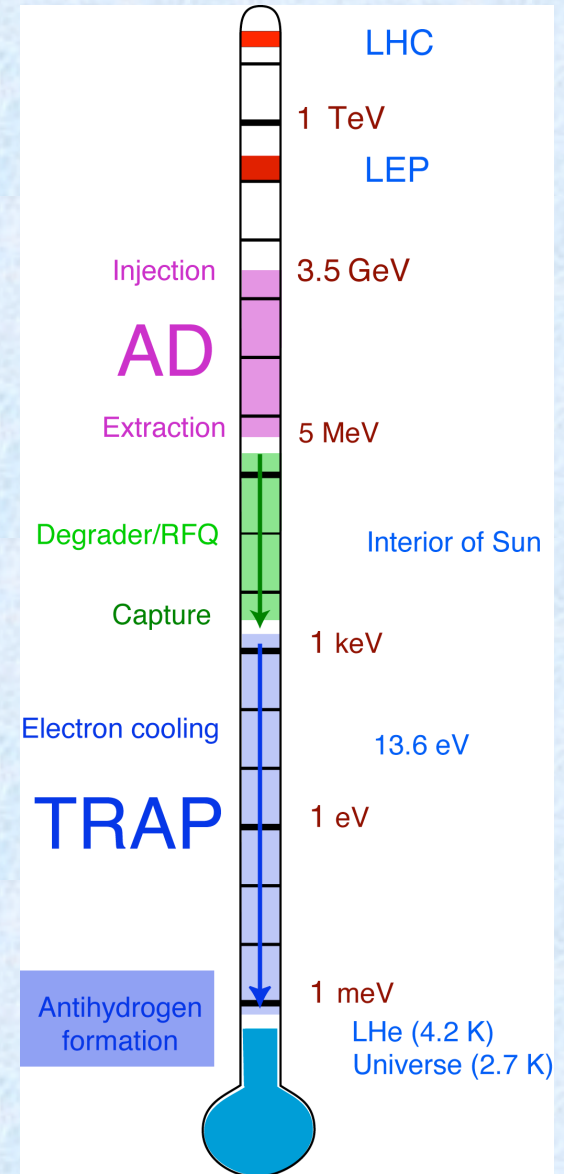
Challenge of antihydrogen production

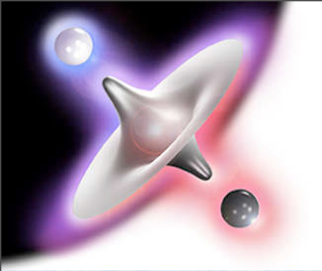




Challenge of antihydrogen production

Antiprotons and positrons (when young) are hot



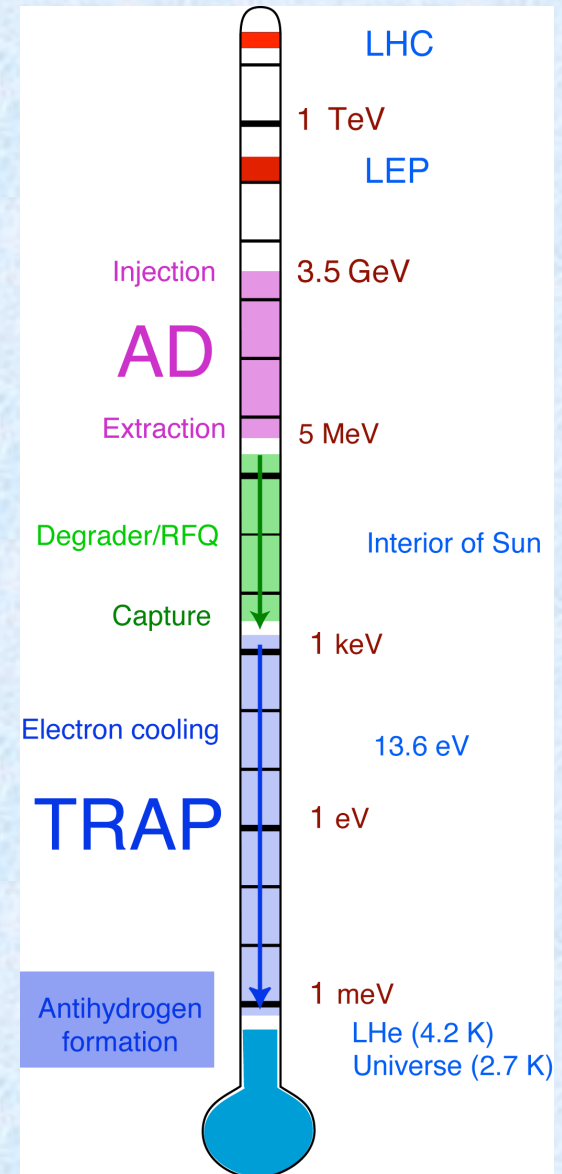


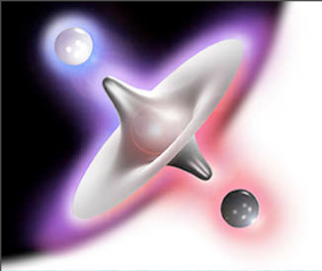
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Hydrogen atom is a weakly bound system:

$$E(1s) = -0.000\,000\,013\,6 \text{ GeV}$$





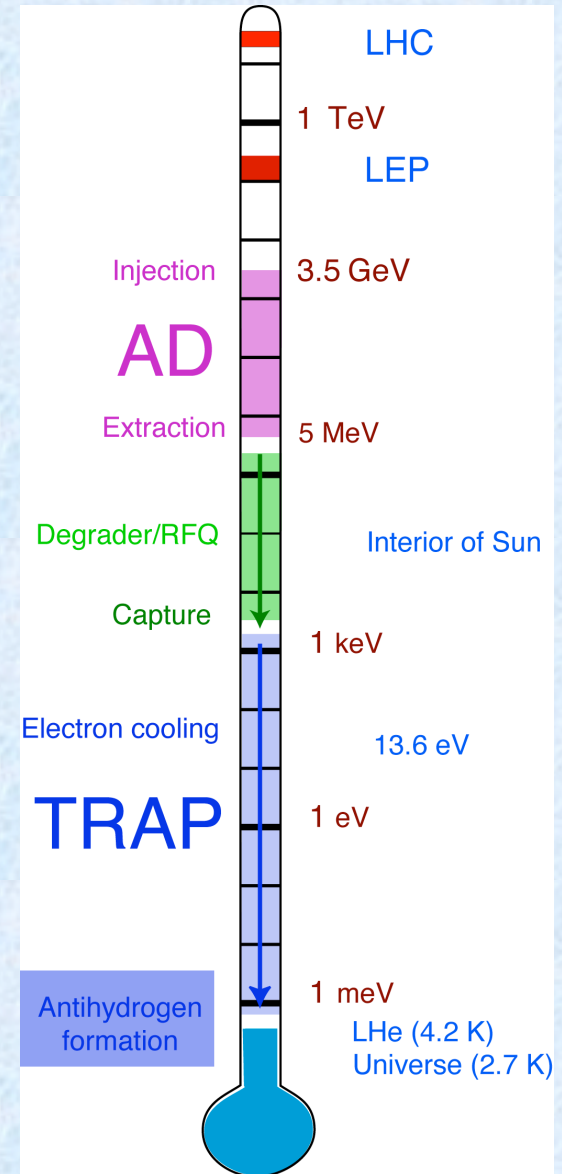
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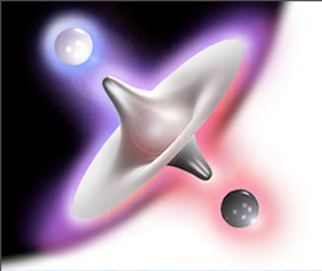
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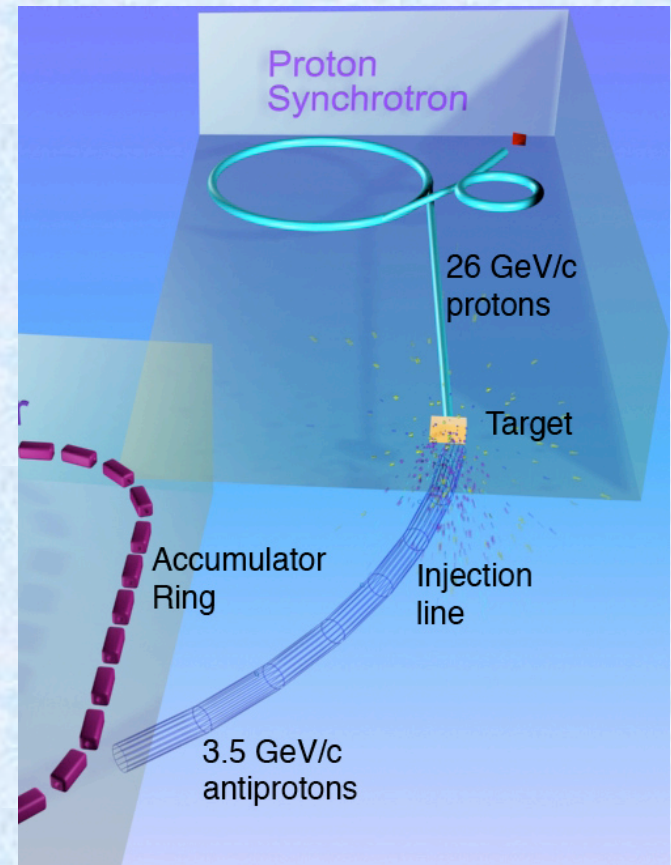
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Constituents need to chill before getting married

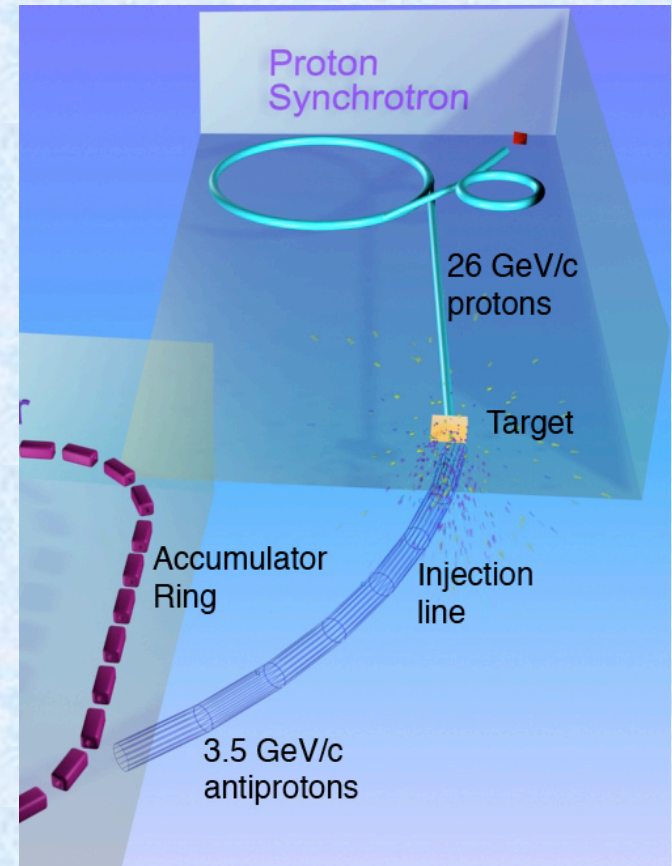
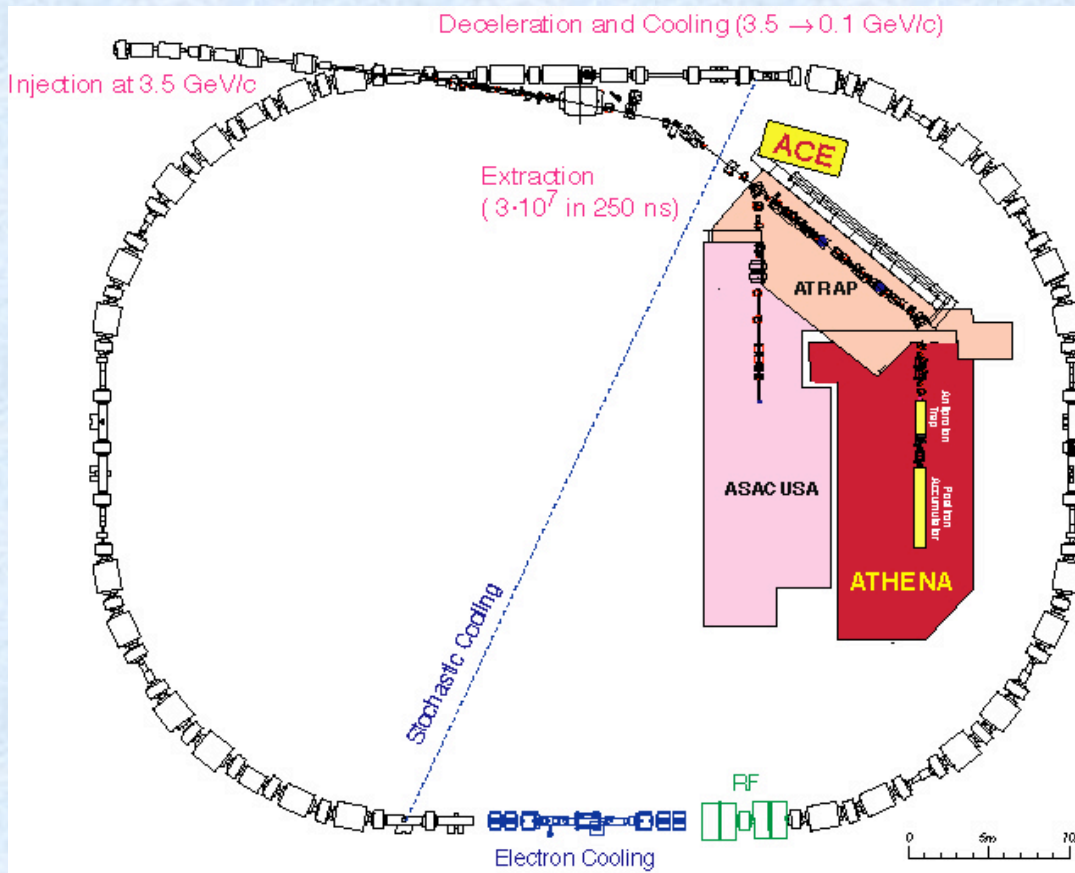


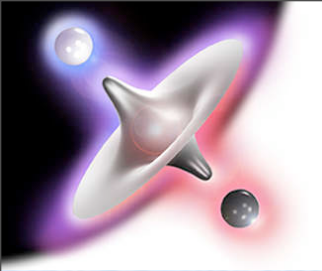


Antiproton Decelerator (AD)

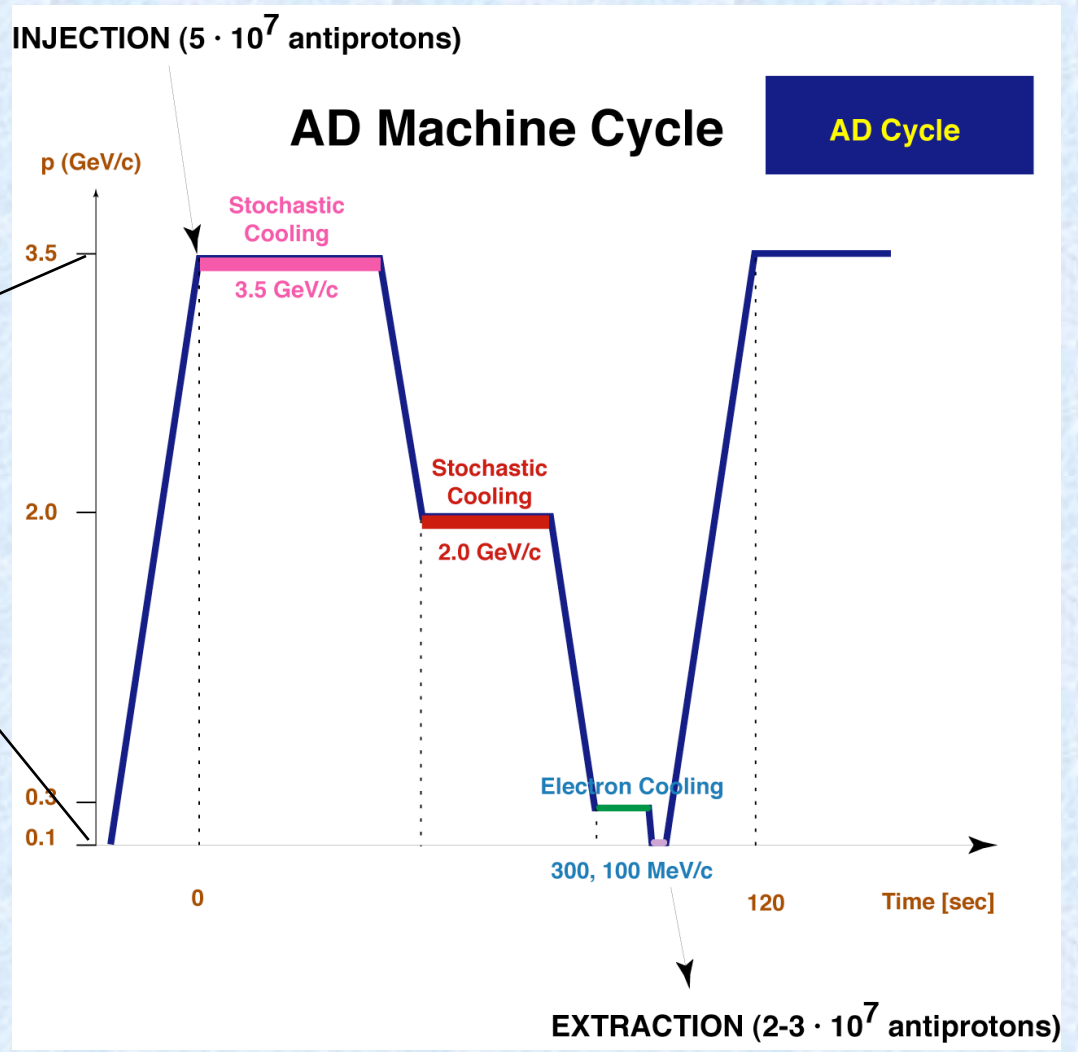
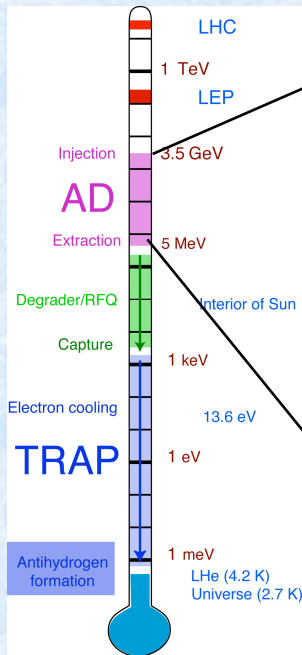


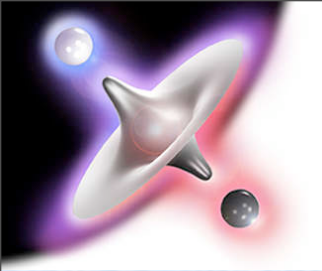
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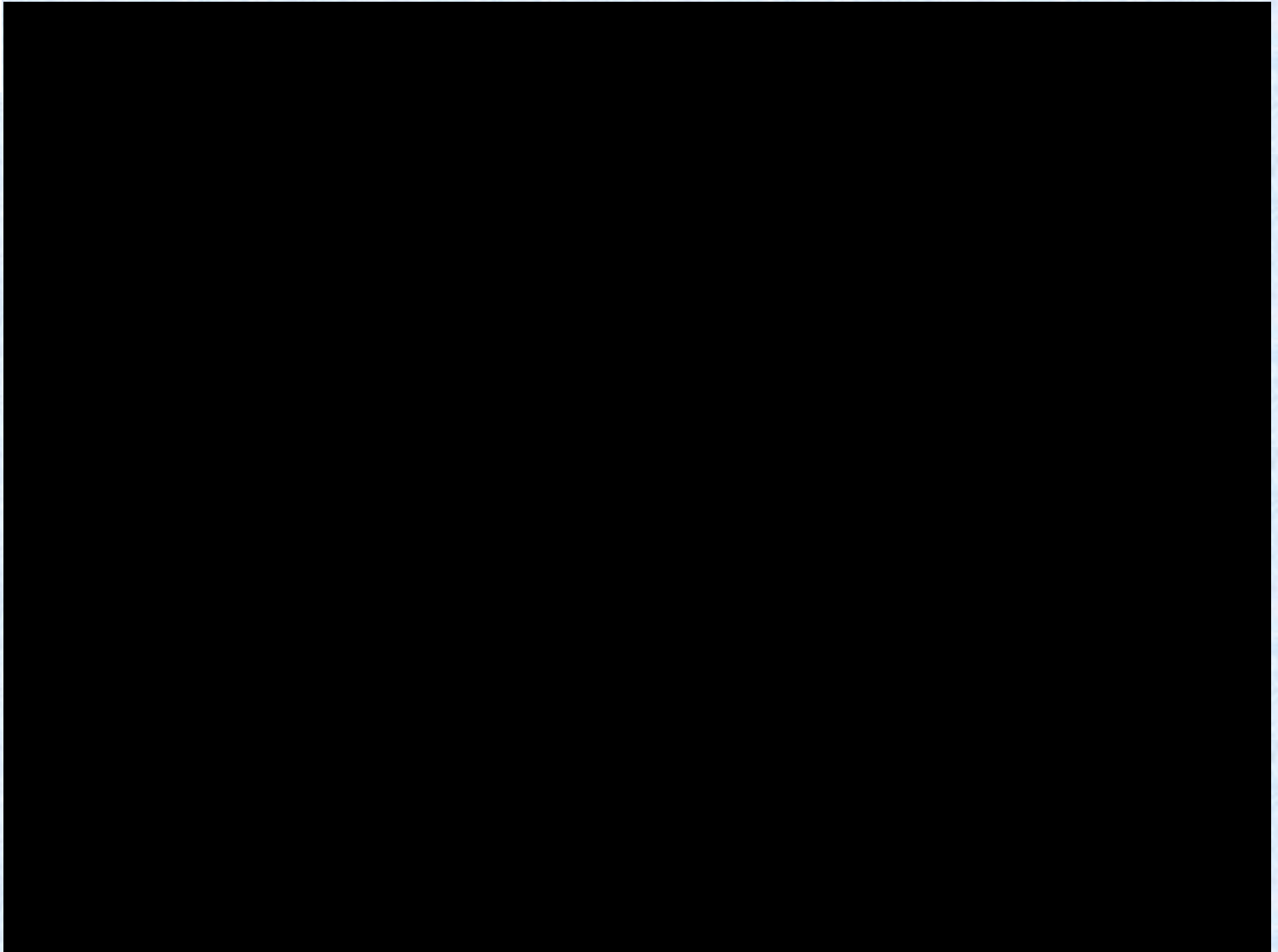


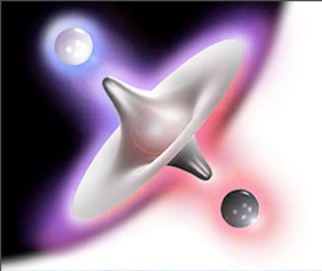
The Antiproton Decelerator (AD)



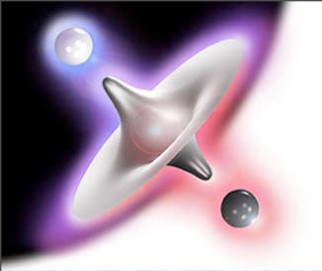


The AD Movie

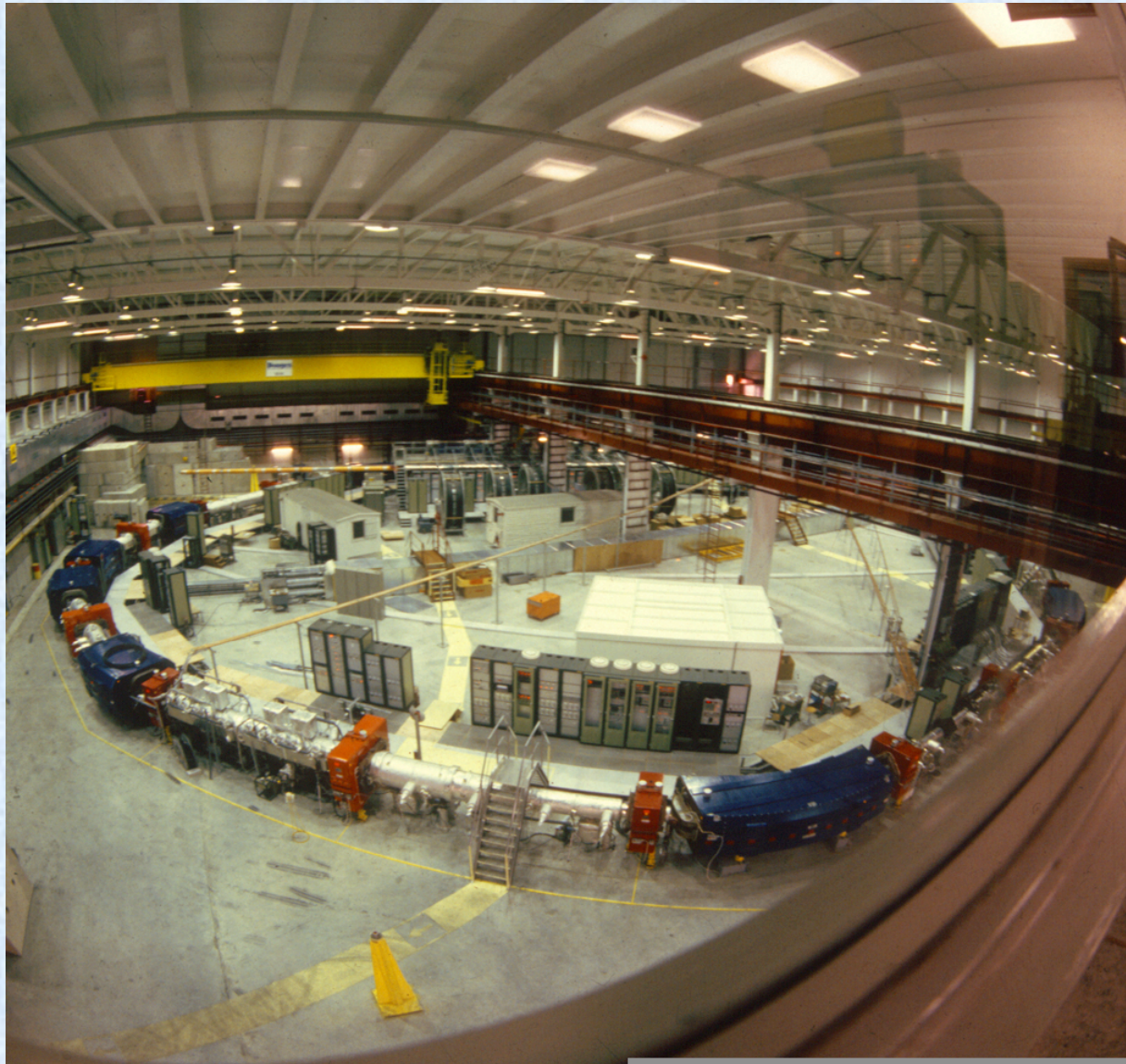


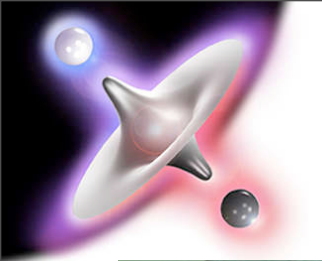


The AD - a machine and its team

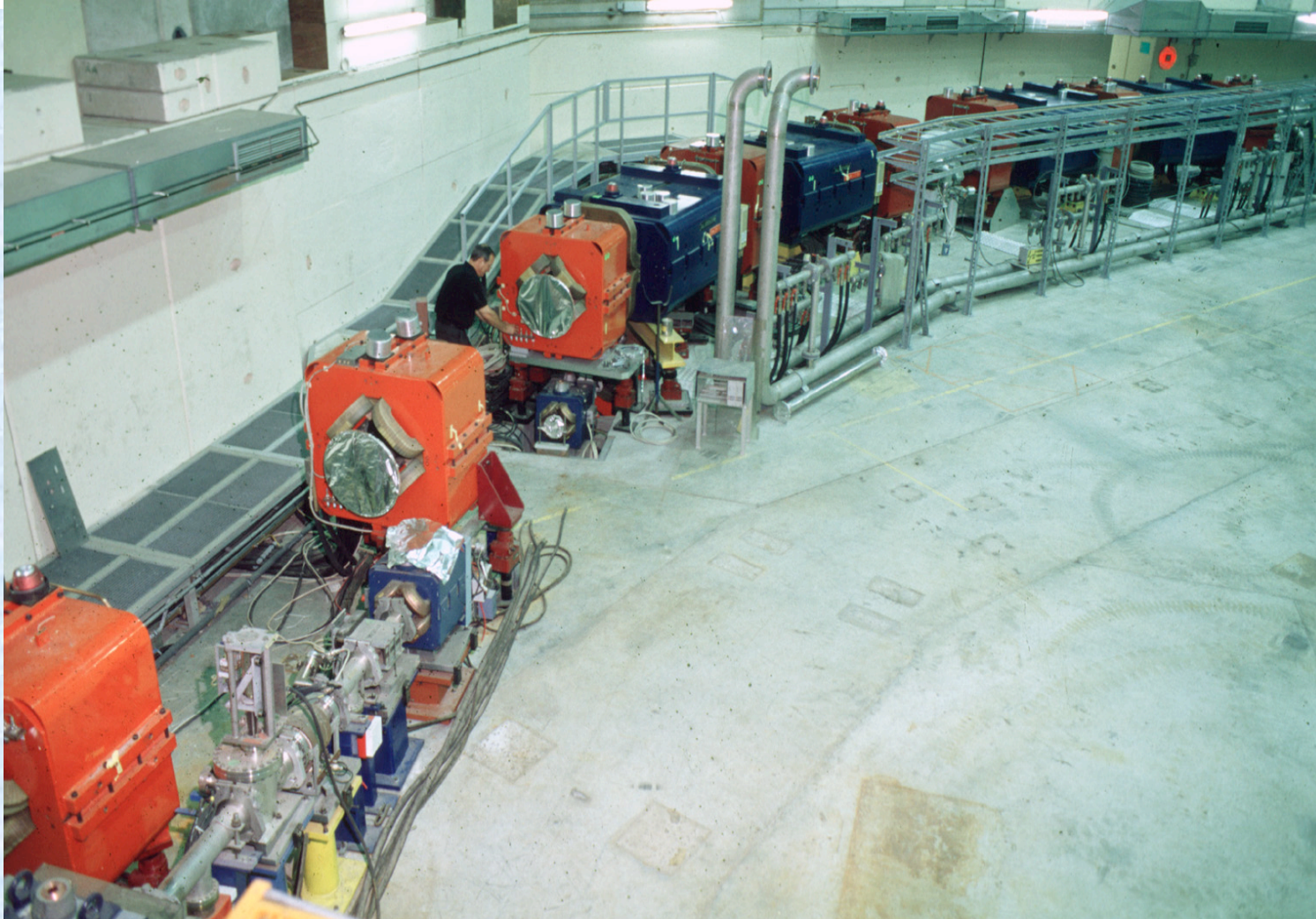


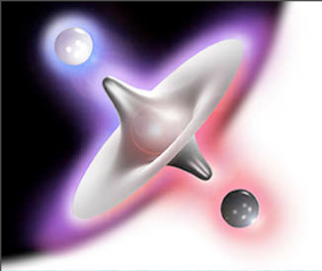
The AD - a machine and its team



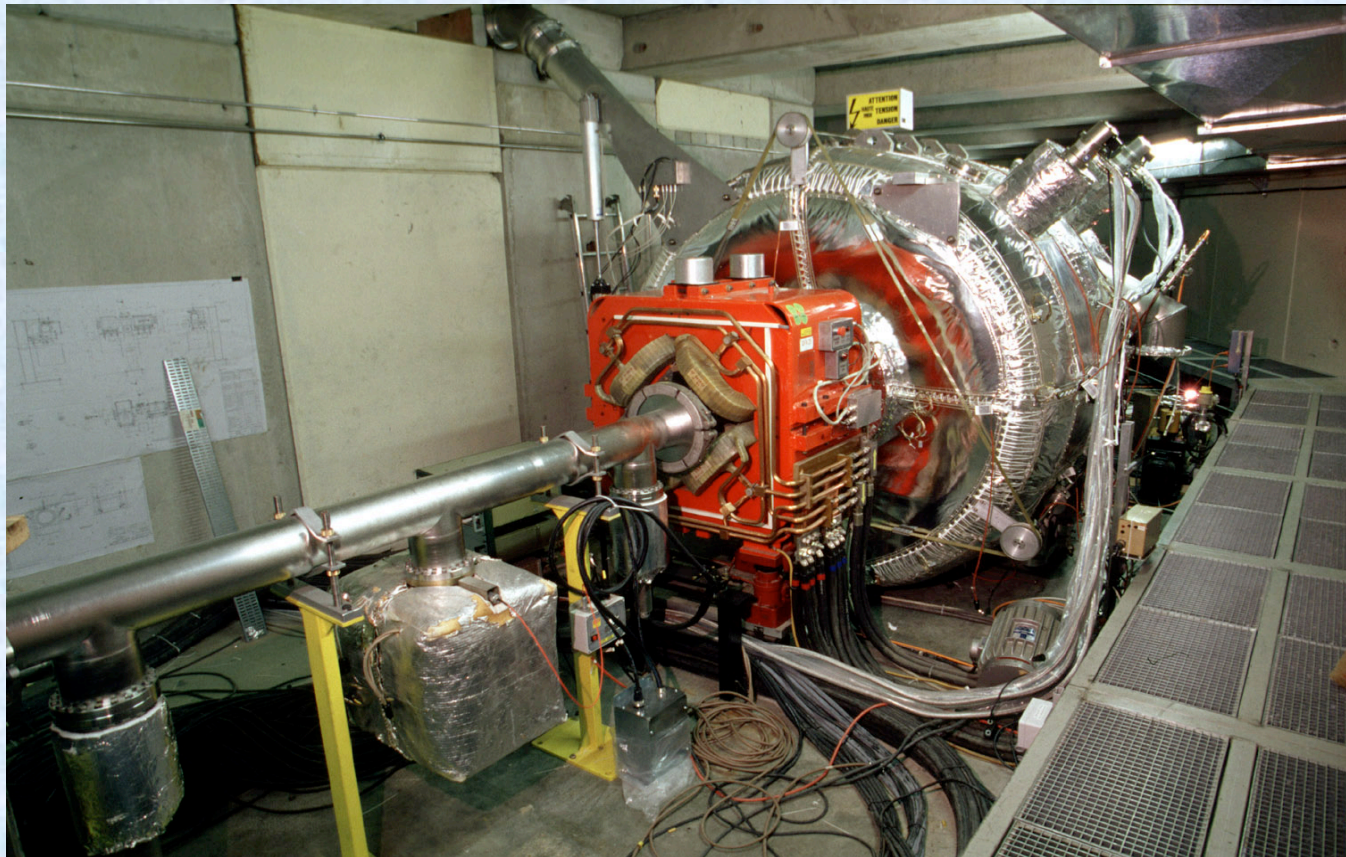


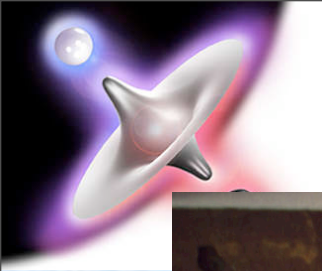
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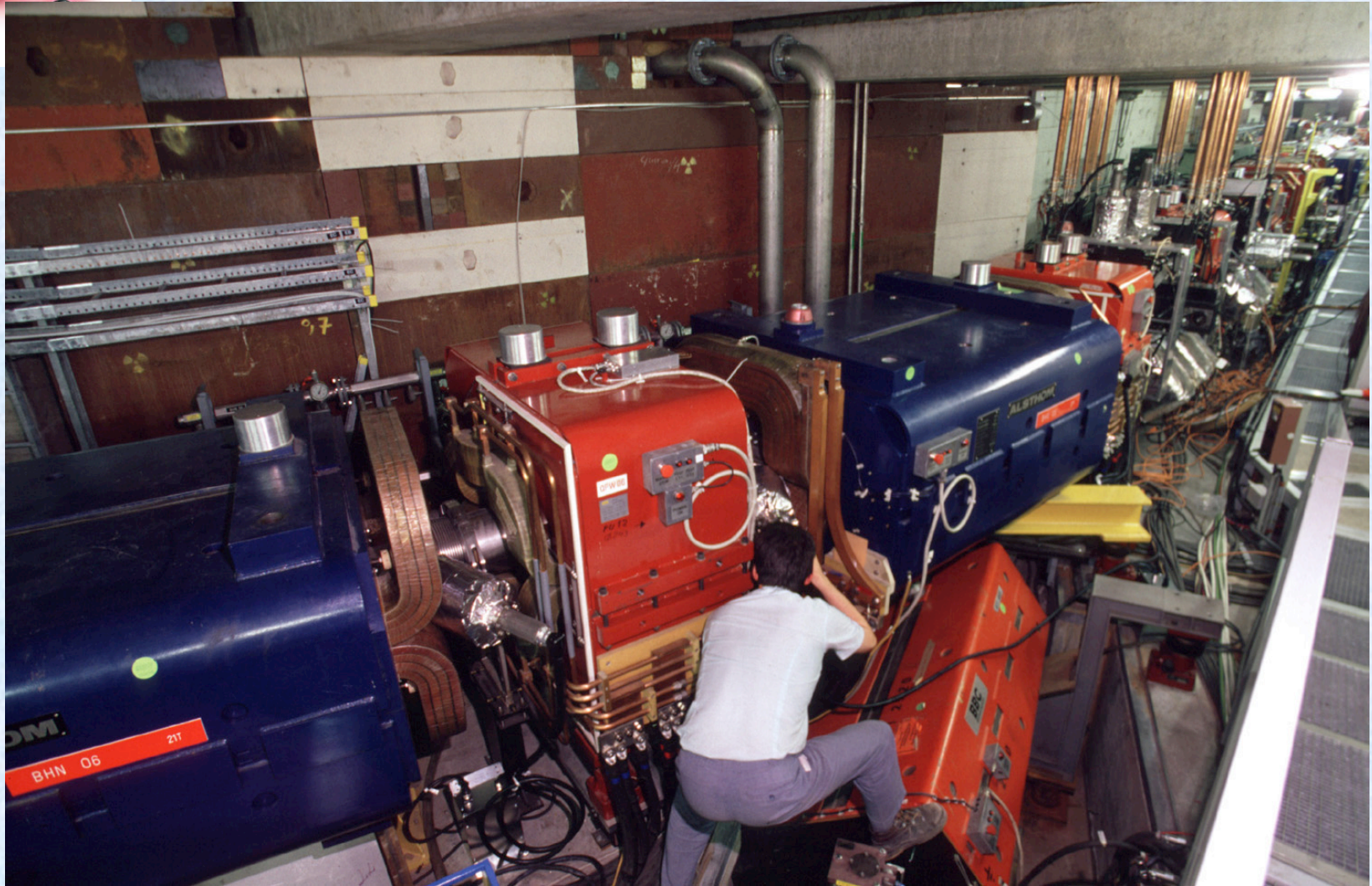


The AD - a machine and its team





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The AD - a machine and its team



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

What did
Ron Howard
say after a
visit to CERN?

