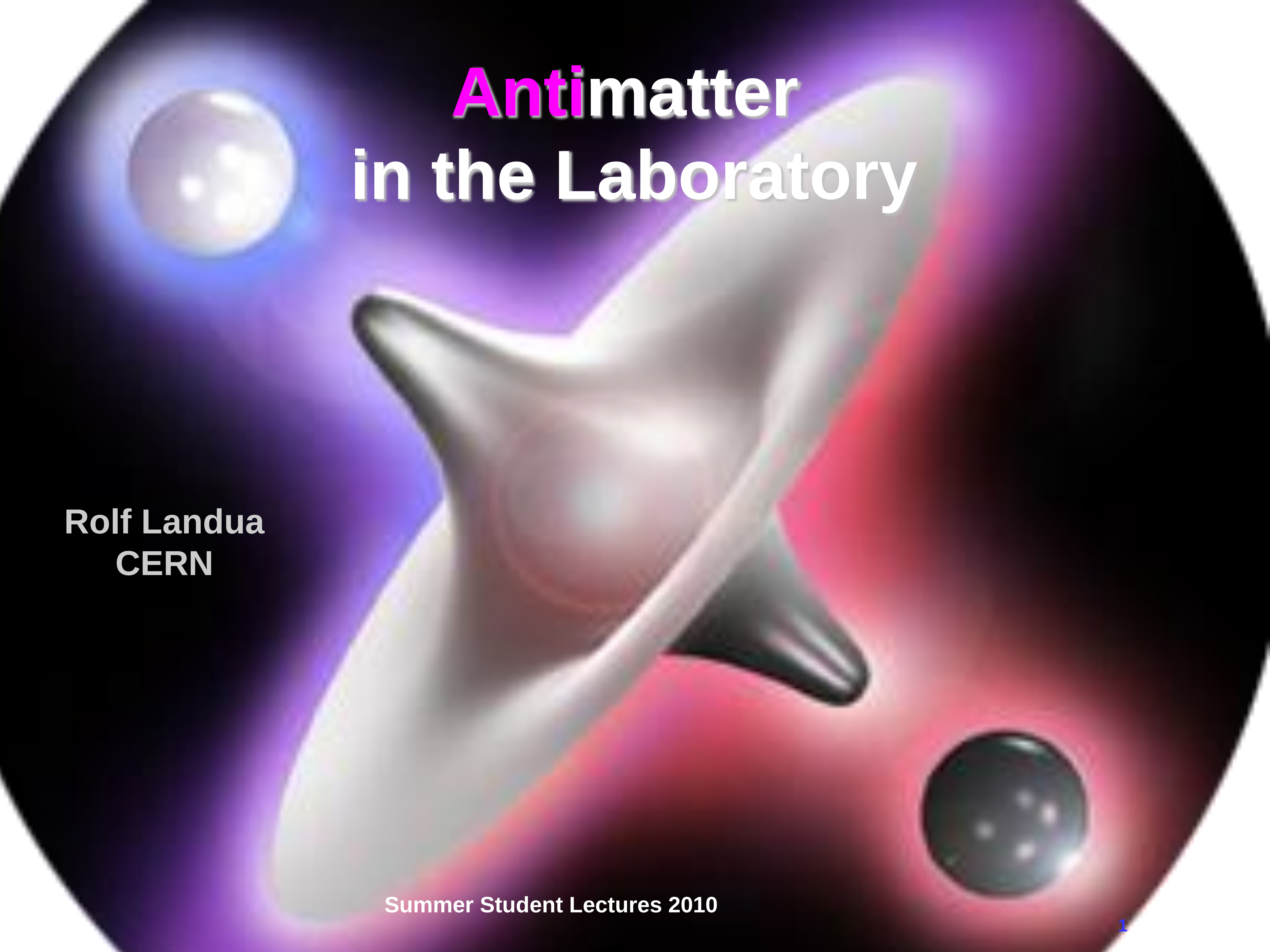
Antimatter in the Laboratory



Rolf Landua
CERN

Summer Student Lectures 2010

Promotional video made for this lecture:

Plan

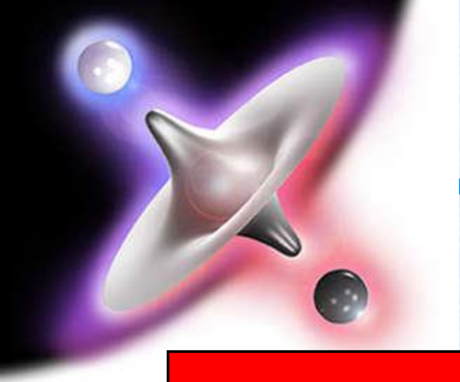
History of Antimatter Einstein, Dirac, Feynman, CPT, ...

Antimatter Mystery The disappearance of antimatter

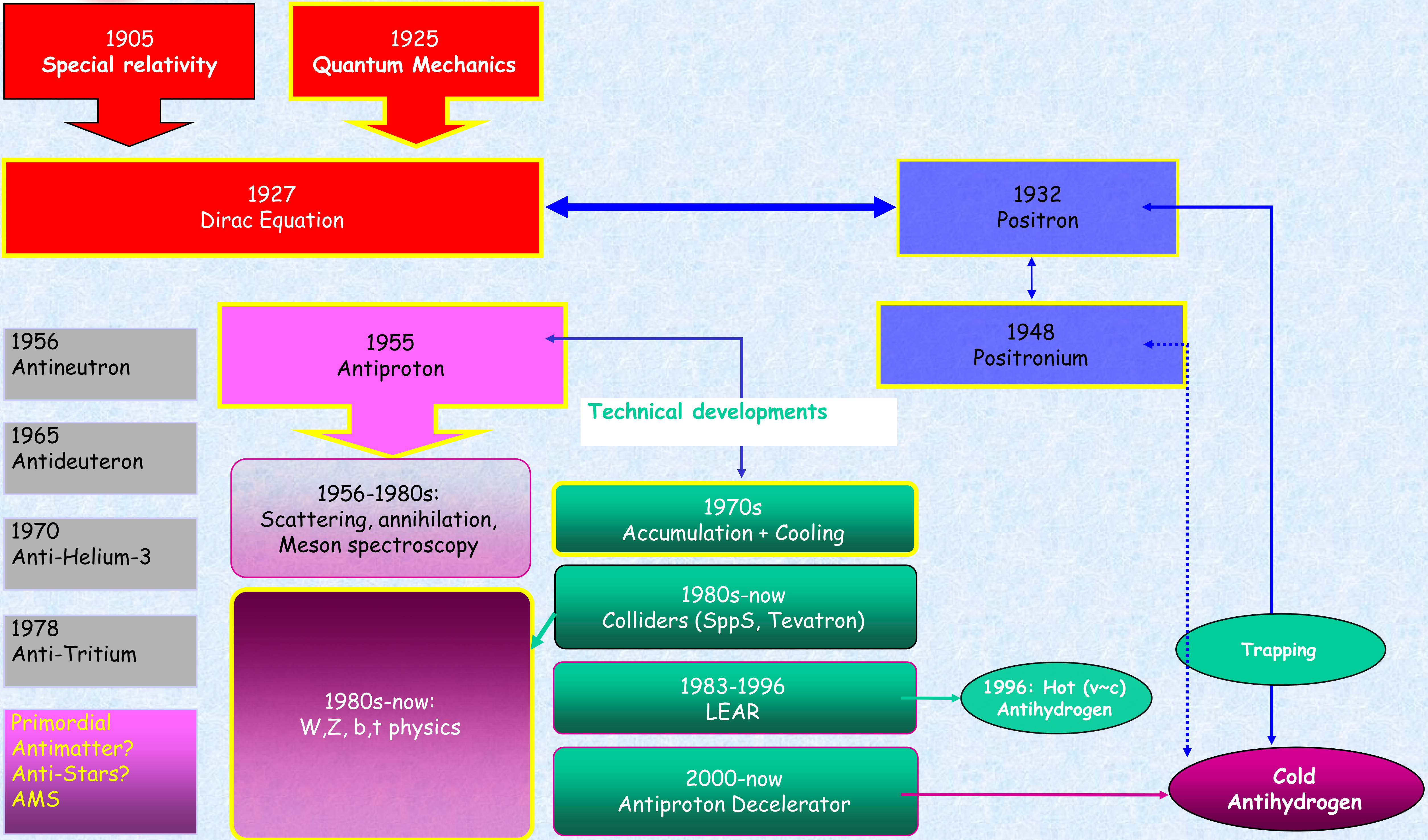
Antimatter 'Factory' How are antiprotons made?

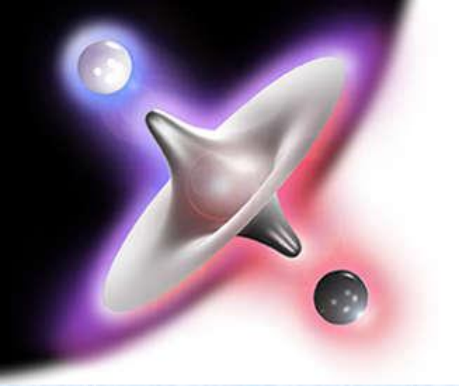
Antihydrogen Short history
How to make antihydrogen
Future developments

Antimatter technology PET
Antiproton therapy?
Rocket propulsion??



1. Overview - History of Antimatter





Early ideas about antimatter

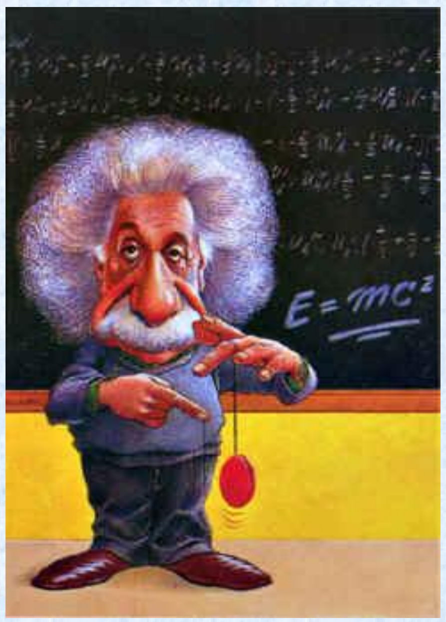
1897: J.J. Thompson discovers the electron

1898: The physicist Arthur Schuster writes to 'Nature' :

If there is negative electricity, why not negative gold, as yellow as our own ?

1905: Relativity

All attempts to find a motion of e.g. the Earth with respect to the "ether" had failed. The speed of light had the same value independent of the relative velocity between source and observer.



Einstein:

1) No preferred inertial system

2) Speed of light always constant

Consequences:

- Lorentz transformations of space-time coordinates

(time dilation, space contraction)

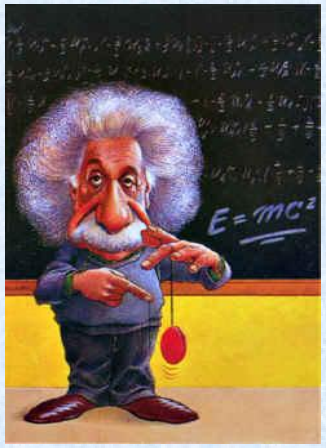
$$t' = \frac{t - \frac{v}{c^2}x}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$x' = \frac{x - vt}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$y' = y$$

$$z' = z$$

1905: Relativity



Equal opportunities for space and time coordinates !

- **Maxwell equations**

$$\begin{aligned} \vec{\nabla} \cdot \vec{D} &= \rho \\ \vec{\nabla} \cdot \vec{B} &= 0 \\ \vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} &= 0 \\ \vec{\nabla} \times \vec{H} - \frac{\partial \vec{D}}{\partial t} &= \vec{J} \end{aligned}$$

o.k.

- **Newton's law**: **not o.k.**; need new definition of energy, momentum

$$E^2 = m^2c^4 + p^2c^4$$

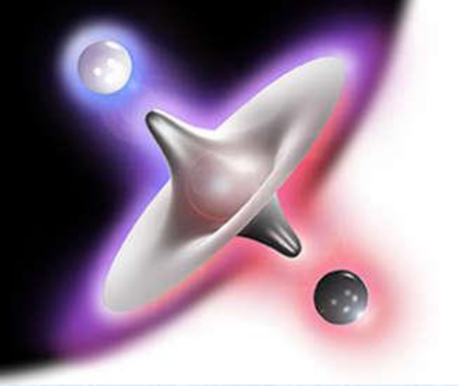
Schrödinger equation (1926)

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

$$E \rightarrow i\hbar \frac{\partial}{\partial t} \qquad \mathbf{p} \rightarrow \frac{\mathrm{h}}{i}\nabla$$

Particle described by **probability amplitude** ψ**(x)**

Observables are described by **operators** acting on ψ**(x)**



What about relativity?

Schrödinger: $E = p^2/2m$ non-relativistic

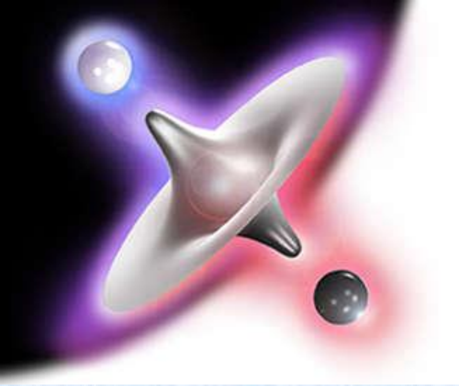
better: $E^2 = p^2 + m^2$ relativistic

Klein-Gordon:

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

number of particles not conserved !?

today we know: describes bosons



Dirac equation

Which equation describes a relativistic electron (v~c)?

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

Linear equation, based on relativistic energy-momentum conservation

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

Solution: 〈, ® are 4x4 matrices (called “©⌈”)

〉 has 4 components (“spinor”)

Τηε ιντερπρετατιον οφ)

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

Electron, spin-up

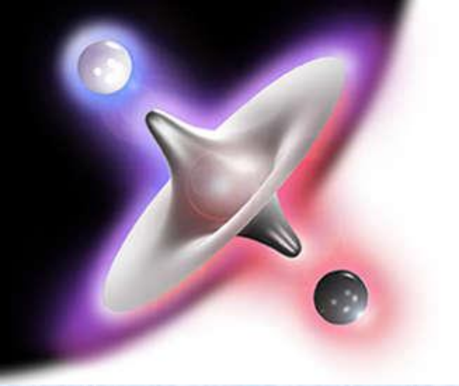
Electron, spin-down

?

?

- 1929: Positive electron = proton ????
- **1930: Positive electron = anti-electron must exist !**

Positron discovery (1932)



Cloud chamber with B=1.5 T.
Two parts separated by a 6-mm lead plate.

Greater curvature of upper track indicates that particle entered the chamber from below. This determines the positive charge of the particle.

From the track curvature and track length, Anderson concluded that the positive charge of the particles is less than twice that of proton and the mass is less than twenty times the proton mass.

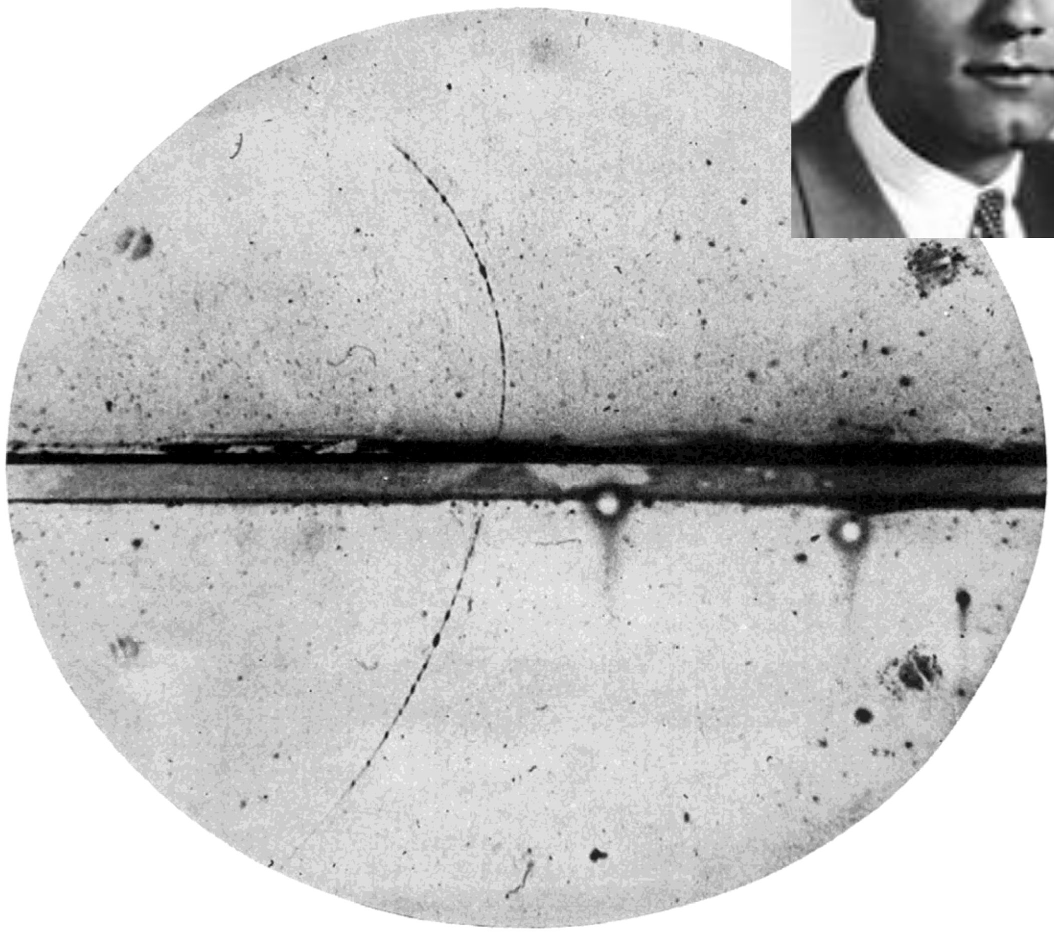


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

C. D. Anderson. "The positive electron", Phys. Rev., **43**, 491 (1933).

Positron discovery- why so late ?

Dirac :

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

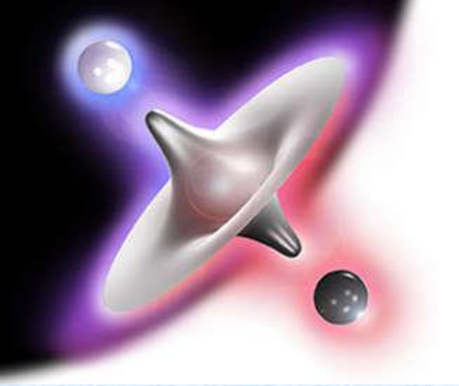
The experimentalists … sometimes saw the opposite curvature, and interpreted the tracks as electrons which happened to be moving into the source, instead of the positively charged particles coming out.

How can we imagine an 'anti-particle'?

Star Wars version

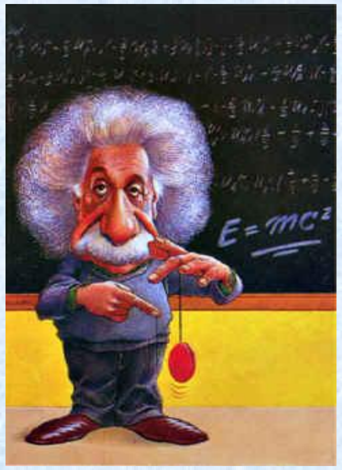
QuickTime™ and a
Animation decompressor
are needed to see this picture.

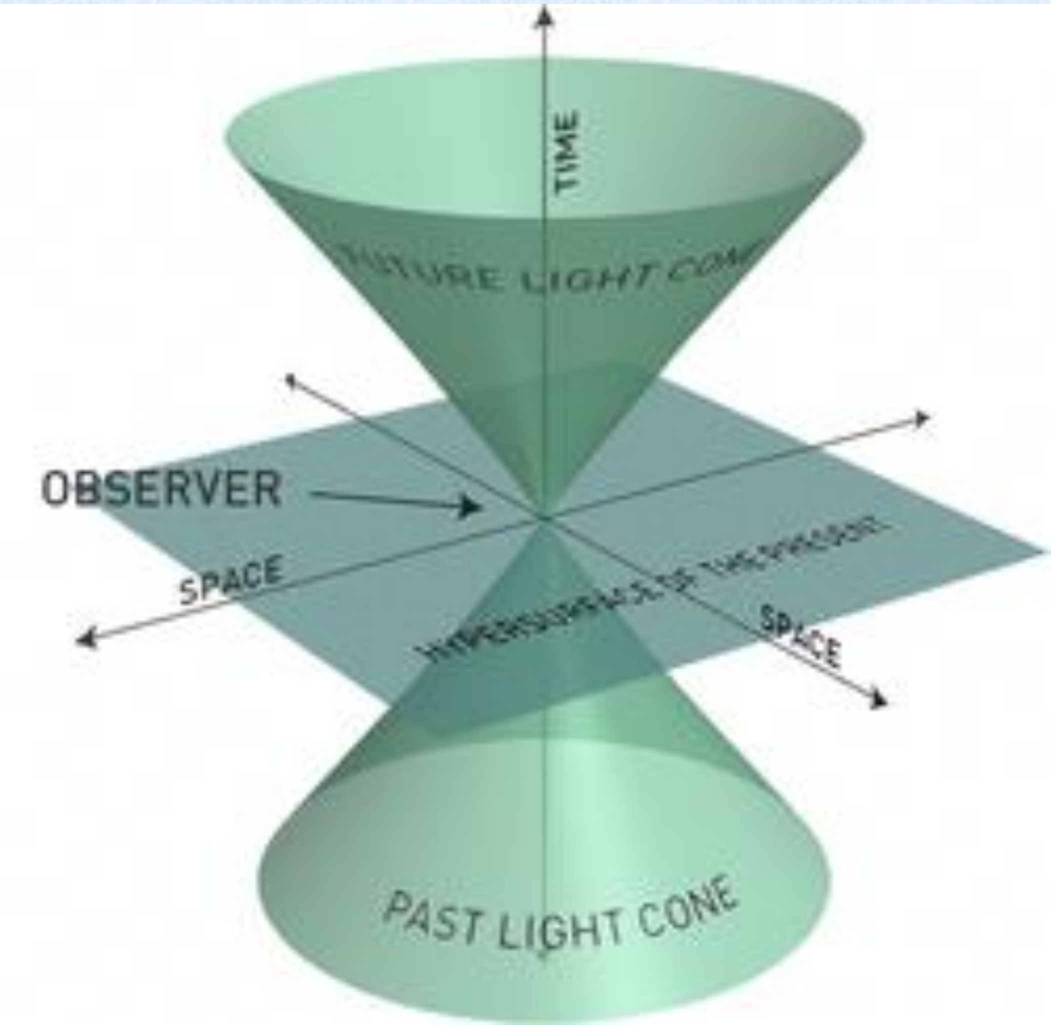
Particles and anti-particles are two manifestations of the same underlying, but yet unknown, physical structure (superstrings??).



Why antimatter must exist (1)

Relativity: Light cone defines possible causal connection between events



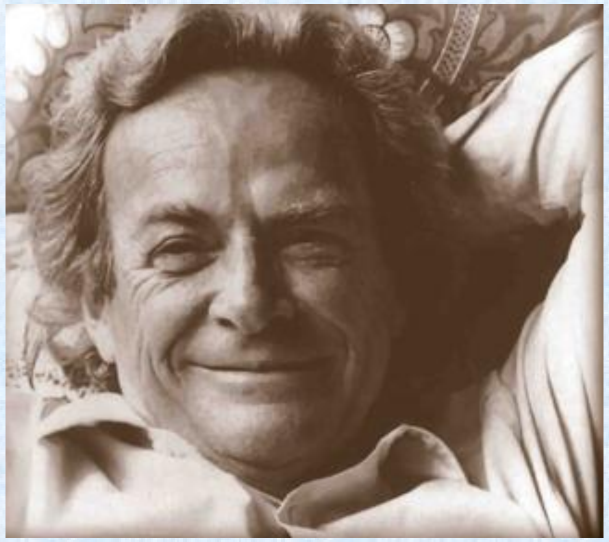


Clear distinction between the

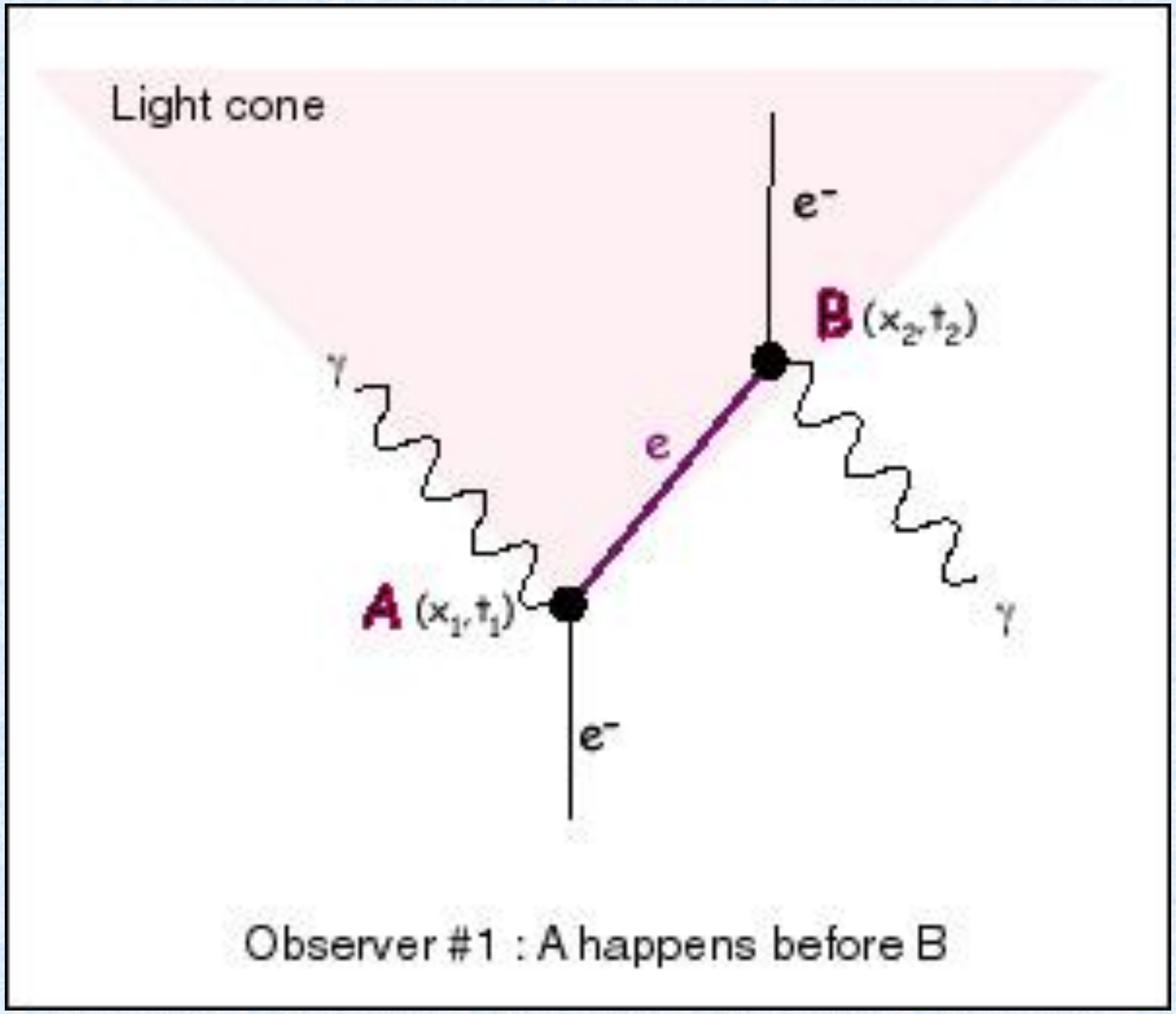
'PAST' and the 'FUTURE'

(for any given observer)

Why antimatter must exist (2): causality



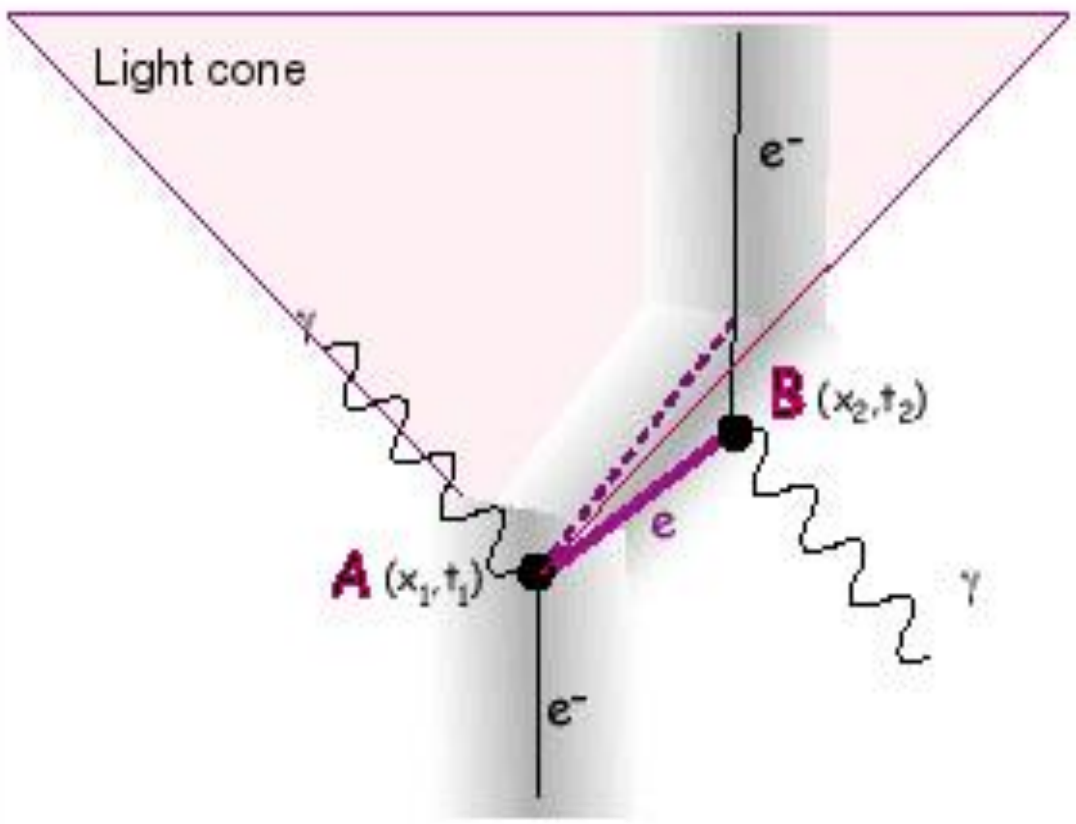
R. P. Feynman



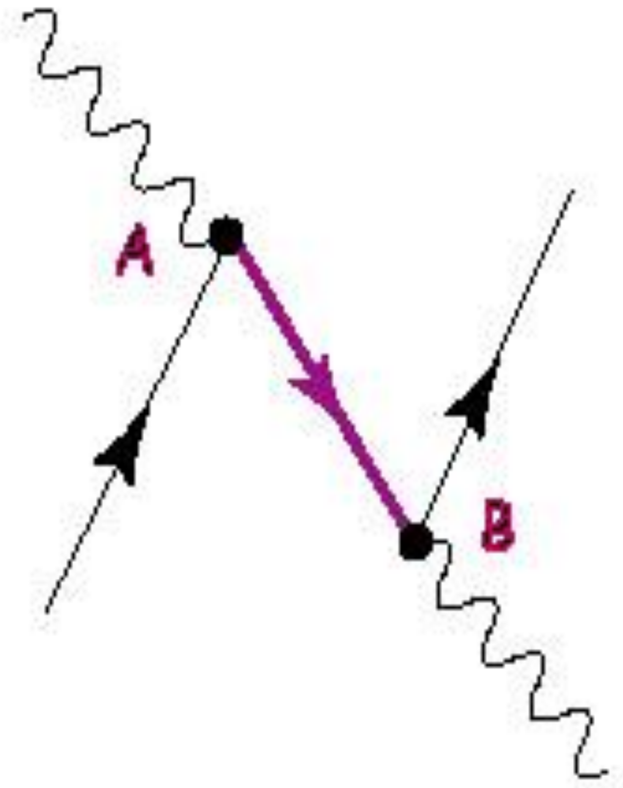
An electron emits a photon at A,
propagates a certain distance,
and then absorbs another photon at B.

Why antimatter must exist (3)

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



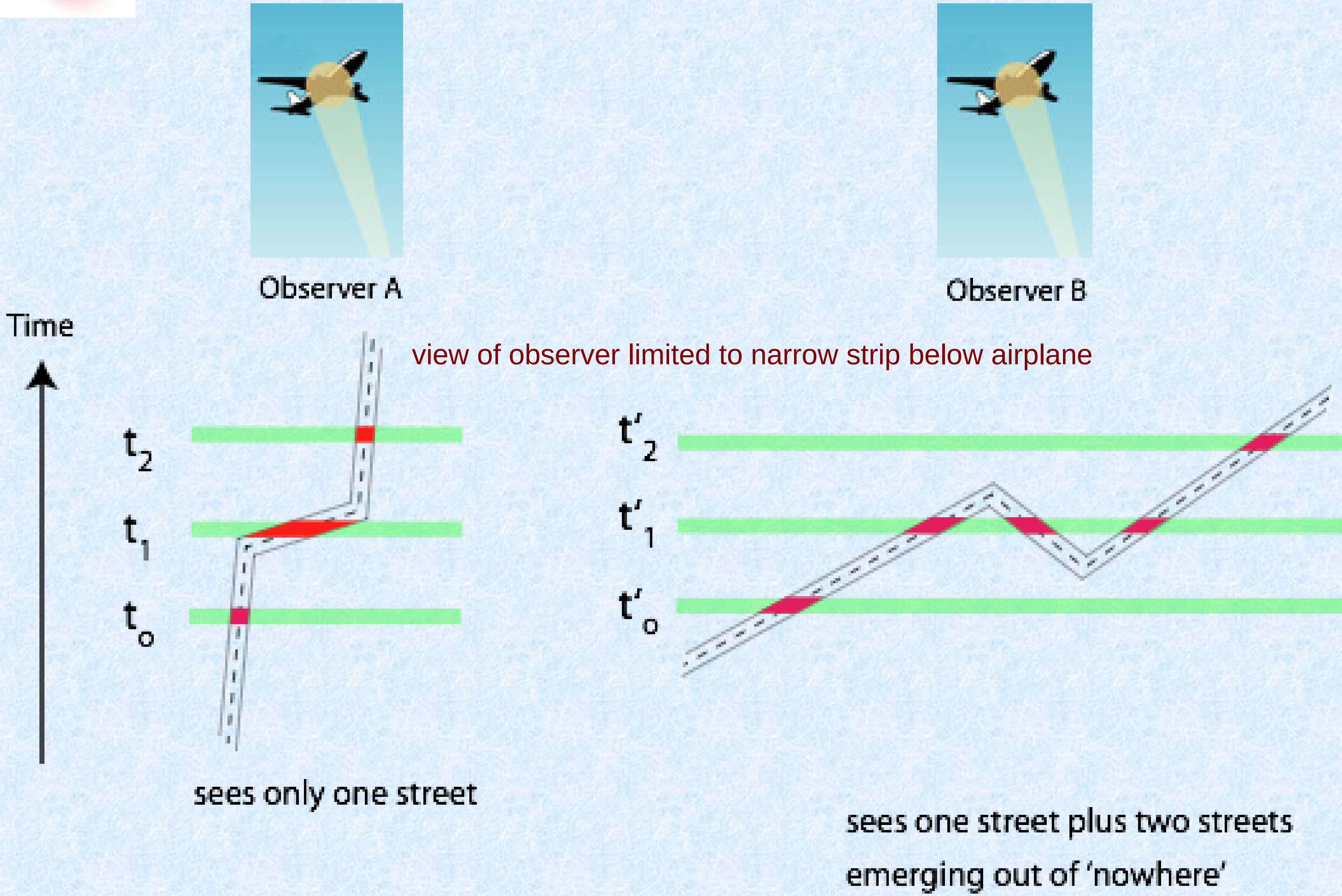
Quantum relativity: electron wave function can be **outside the light cone** (Compton wave length $l = h/m_e c$)

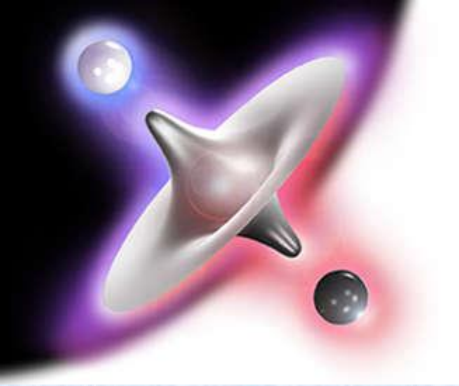


For a moving observer, event B can therefore happen before event A. The process at B is then interpreted as 'pair creation'.

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

Analogy : an airplane flying over a crooked road

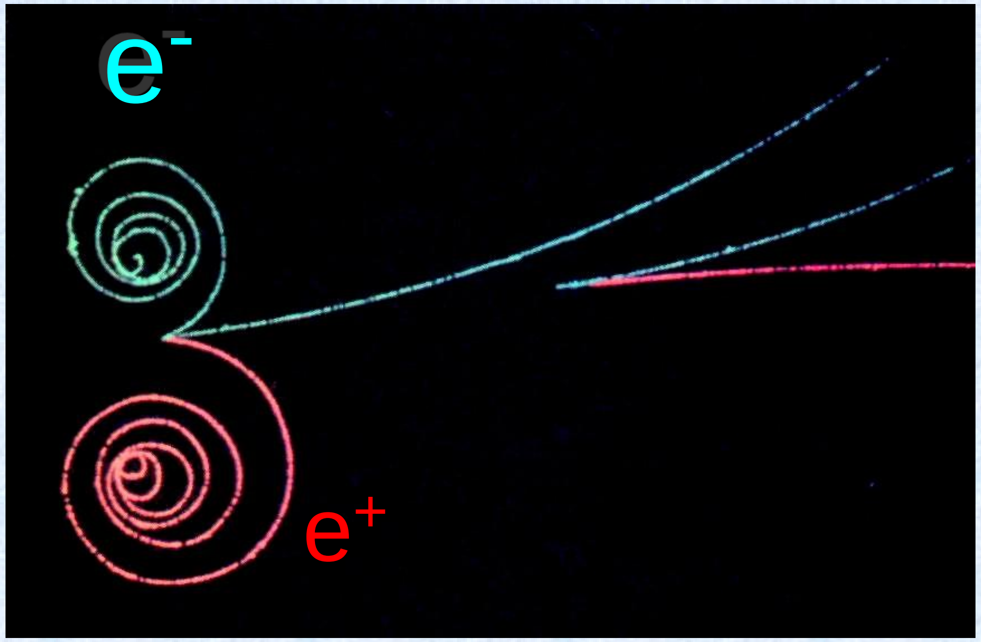




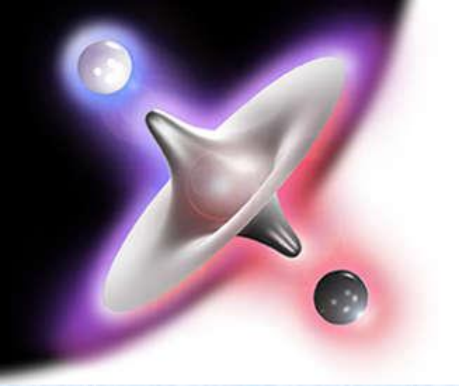
Therefore:

Particles and antiparticles must exist and are created in pairs

Particles		Antiparticles
Electron Neutrino Up-Quark Down-Quark	↔	Positron Anti-Neutrino Anti-Up-Quark Anti-Down-Quark
Muon ...	↔	Anti-Muon ...
Tau ...	↔	Anti-Tau ...



Time reversal: Particles and antiparticles can also destroy each other (annihilation)



1955: The CPT Theorem *

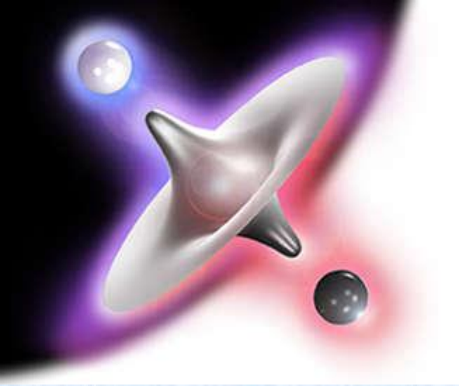
If :

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)

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)



CPT theorem (cont'd)

However, the proof of the CPT theorem is based on further assumptions:

1) Point-like particles

2) Flat 4-D space time

[e.g. G. Barenboim et al., PLB 534 (2002) 106; O.W. Greenberg, PRL 89 (2002) 231602]

These assumptions are not necessarily valid at the Planck (or another fundamental) scale.

Several models **speculate with CPT violation**, induced by e.g.

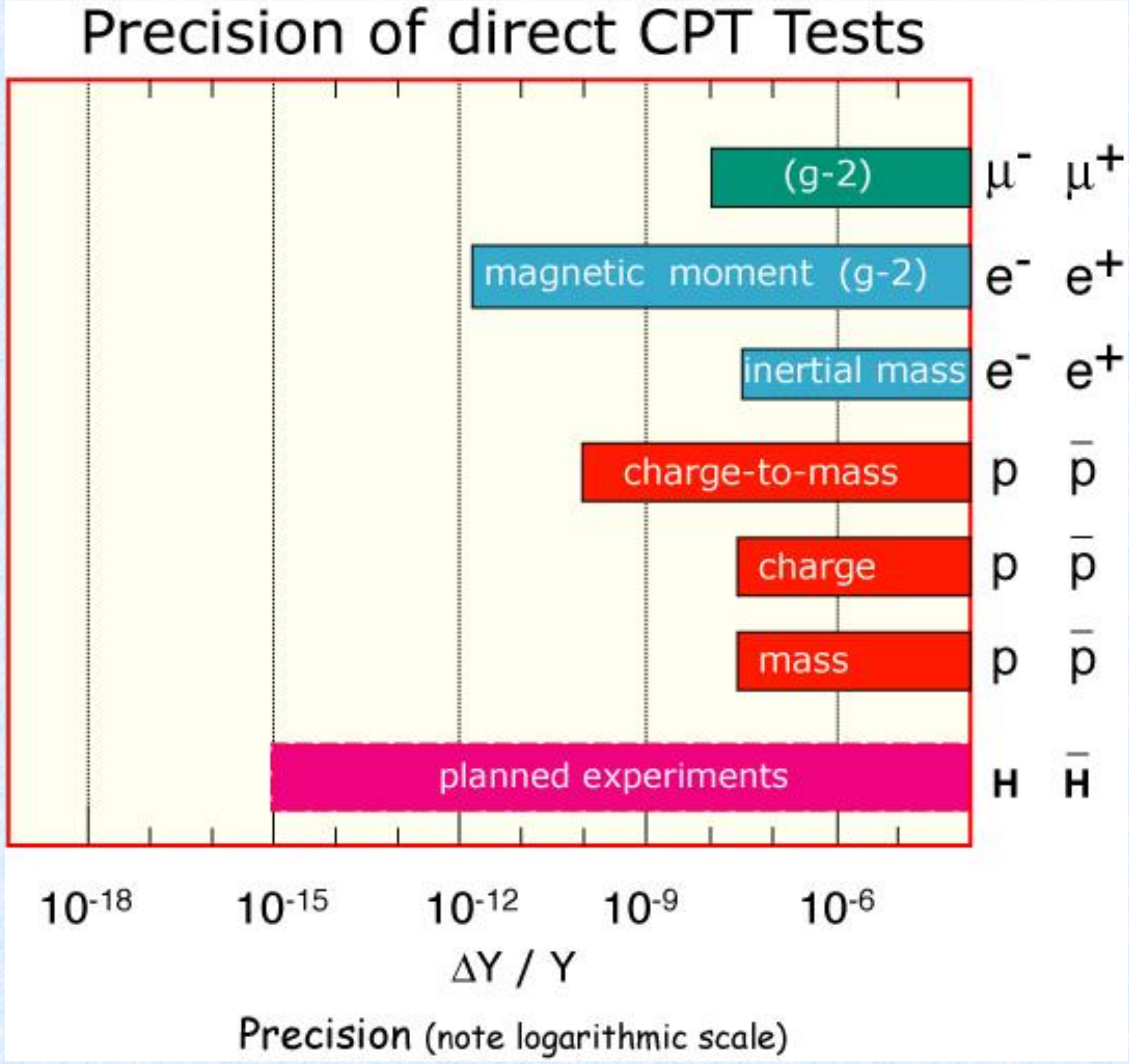
Quantum Gravity (loss of unitarity through space-time foam/black holes)

String theory (spontaneous breaking of Lorentz symmetry)

Overview :   CPT Violation - Theory and Phenomenology

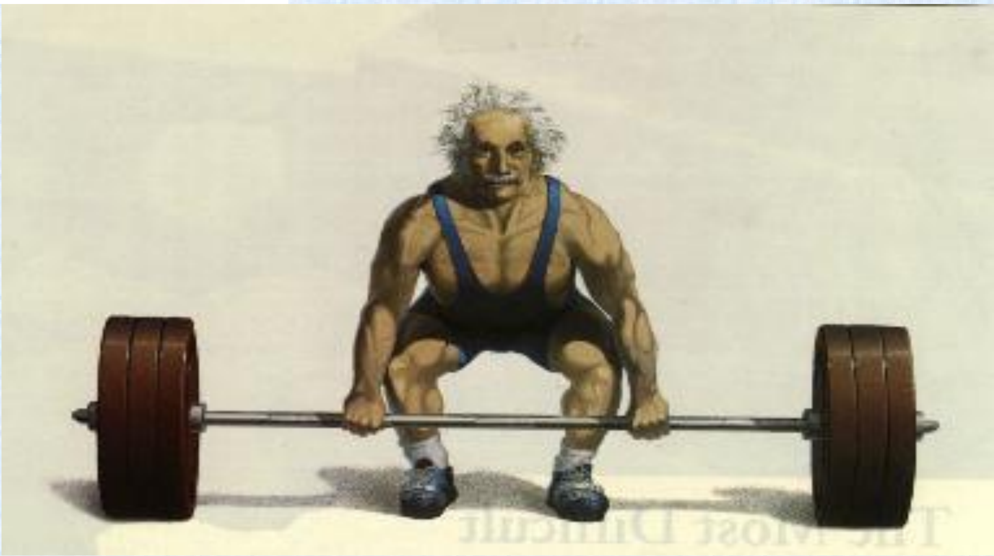
(Nick Mavromatos, arXiv:hep-ph/0504143, 2005)

Direct comparison of stable particles and antiparticles



- DIRECT TESTS CONFIRM CPT ~ 10^{-12} LEVEL
- THERE IS NO "THEORY" OF CPT VIOLATION

Gravitation and Antimatter



Equivalence principle

No way to distinguish locally between gravitational potential and constant acceleration.

WEAK EQUIVALENCE PRINCIPLE

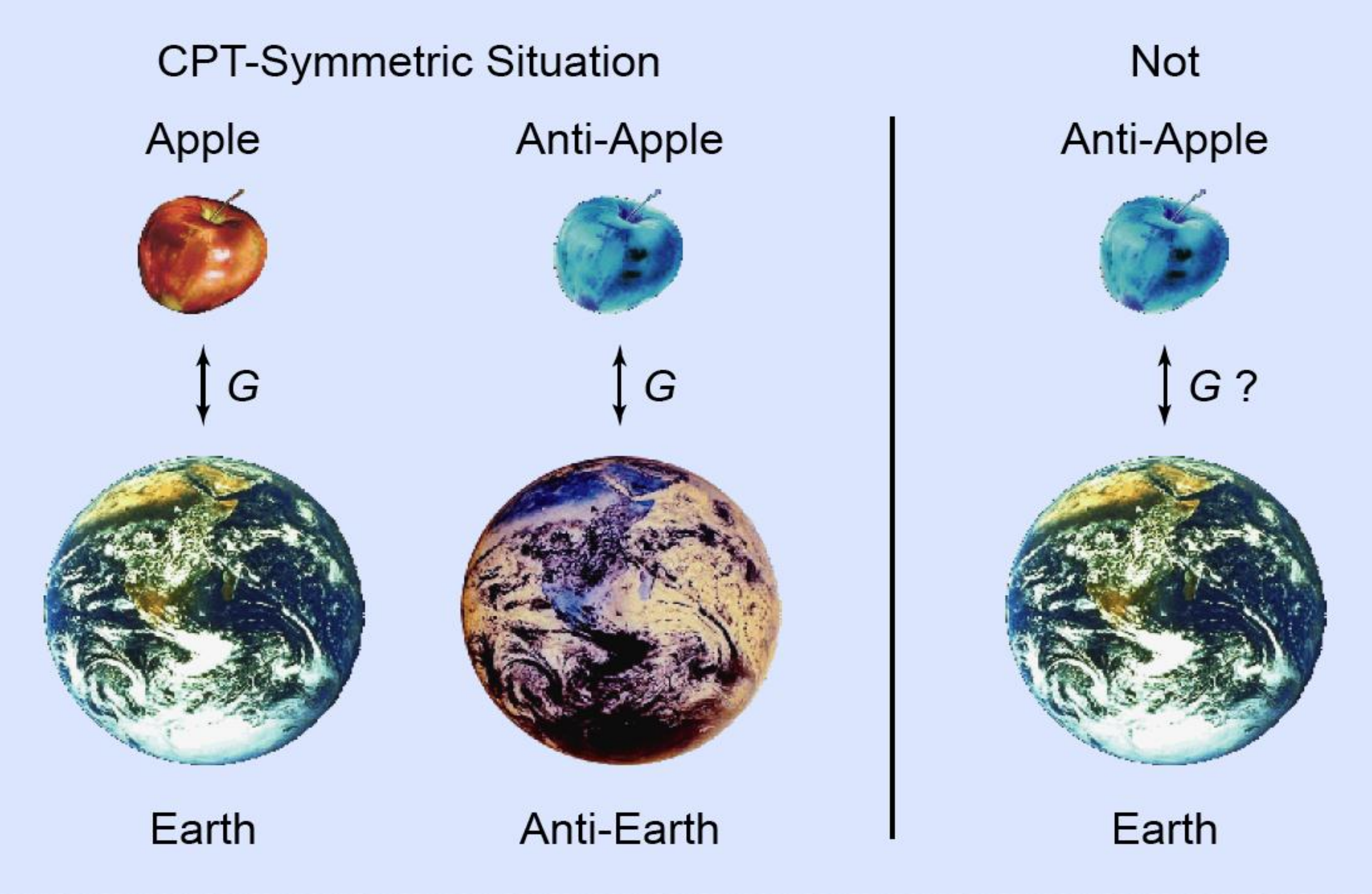
The world line of a freely falling test body is independent of its composition or structure.

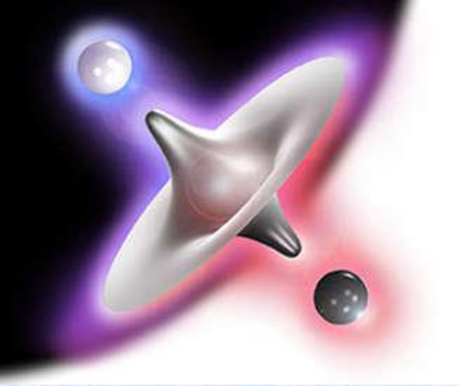
Experimental tests:

Galileo, Huygens, Newton, Bessel, Eotvos, Dicke; Eot-Wash group

$m_i = m_g$ with $\otimes m/m < 10^{-12}$

Gravitation is not constrained by CPT





Gravitation and Antimatter

Argument in favour of weak equivalence principle:

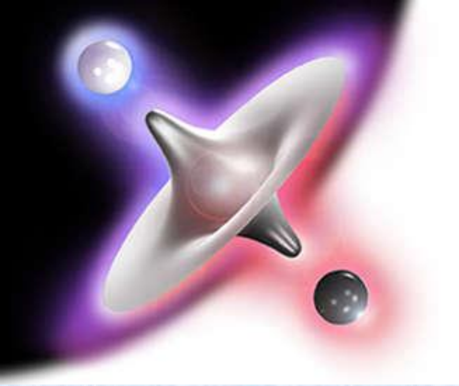
The masses of particles and antiparticles obey $E = mc^2$. Since it is this energy that curves space, antimatter must have the same gravitational interaction as matter

But:

There could be (yet) unknown additional (vector) components of gravity

These may have finite range and change sign for antimatter

What about experiments??



Antiparticle gravitation experiments have been attempted, but …

No measurement of gravitational effects on (charged) antiparticles has yet succeeded ..

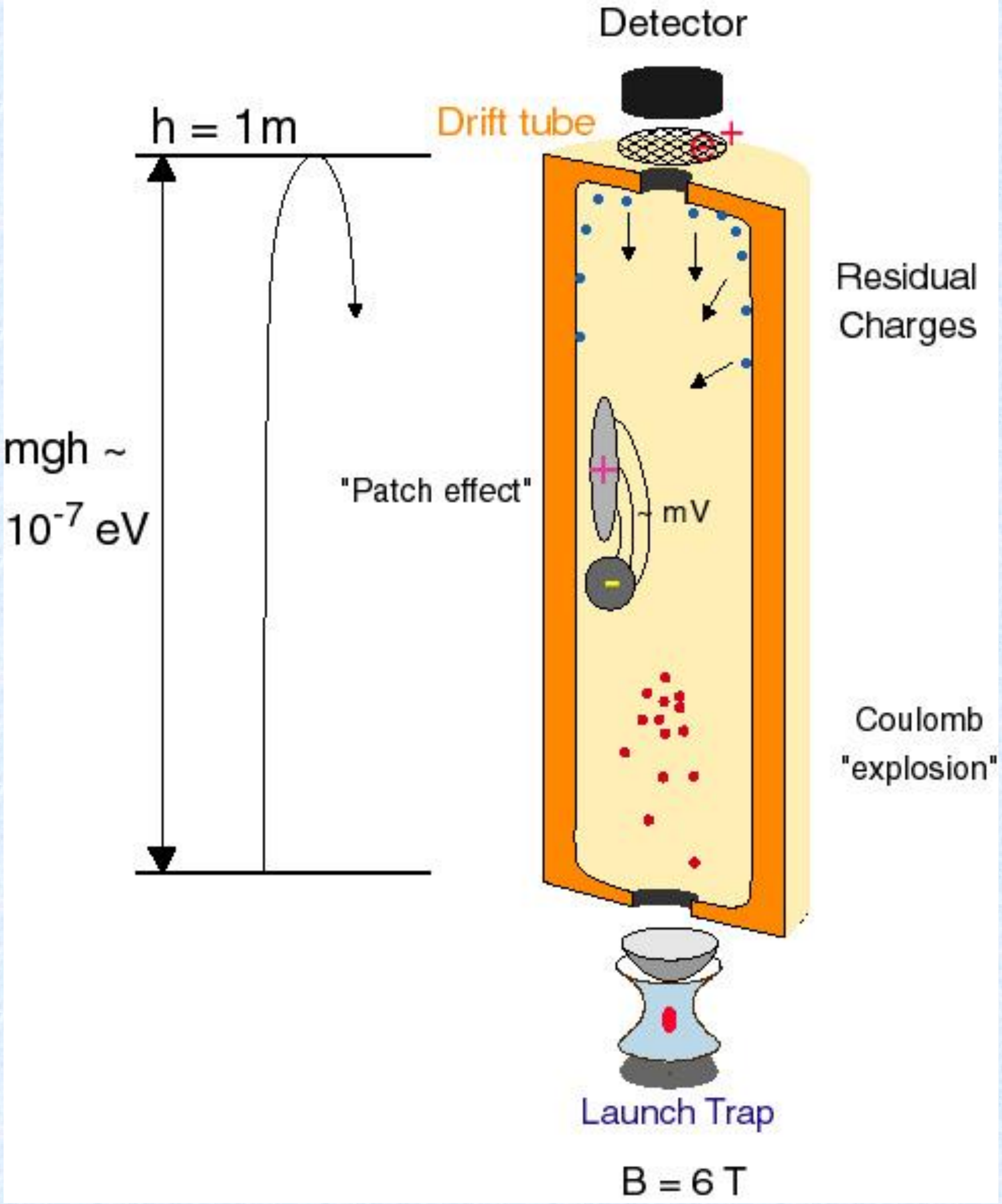
- controversial result for positrons, 1967

- failed attempt with antiprotons at LEAR, 1996

Problems:

- Coulomb explosion
- Patch effect (mV/cm)
- Residual charges

(10^{-7} eV ~ 1 electron at 1 m distance)



Conclusion: Antimatter Gravity

Weak equivalence principle is well tested with ordinary matter*, but not at all with antimatter

*** Overview: B.R. Heckel et al., Adv. Space Res. 25 (2000) 1125**

Tests with single atoms are possible

Measurement of gravitational acceleration by dropping atoms

Achim Peters, Keng Yeow Chung & Steven Chu

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

Nature 400 (1999) 849

Slow moving anti-atoms offer a possibility!

Part 2 - The Antimatter Mystery

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

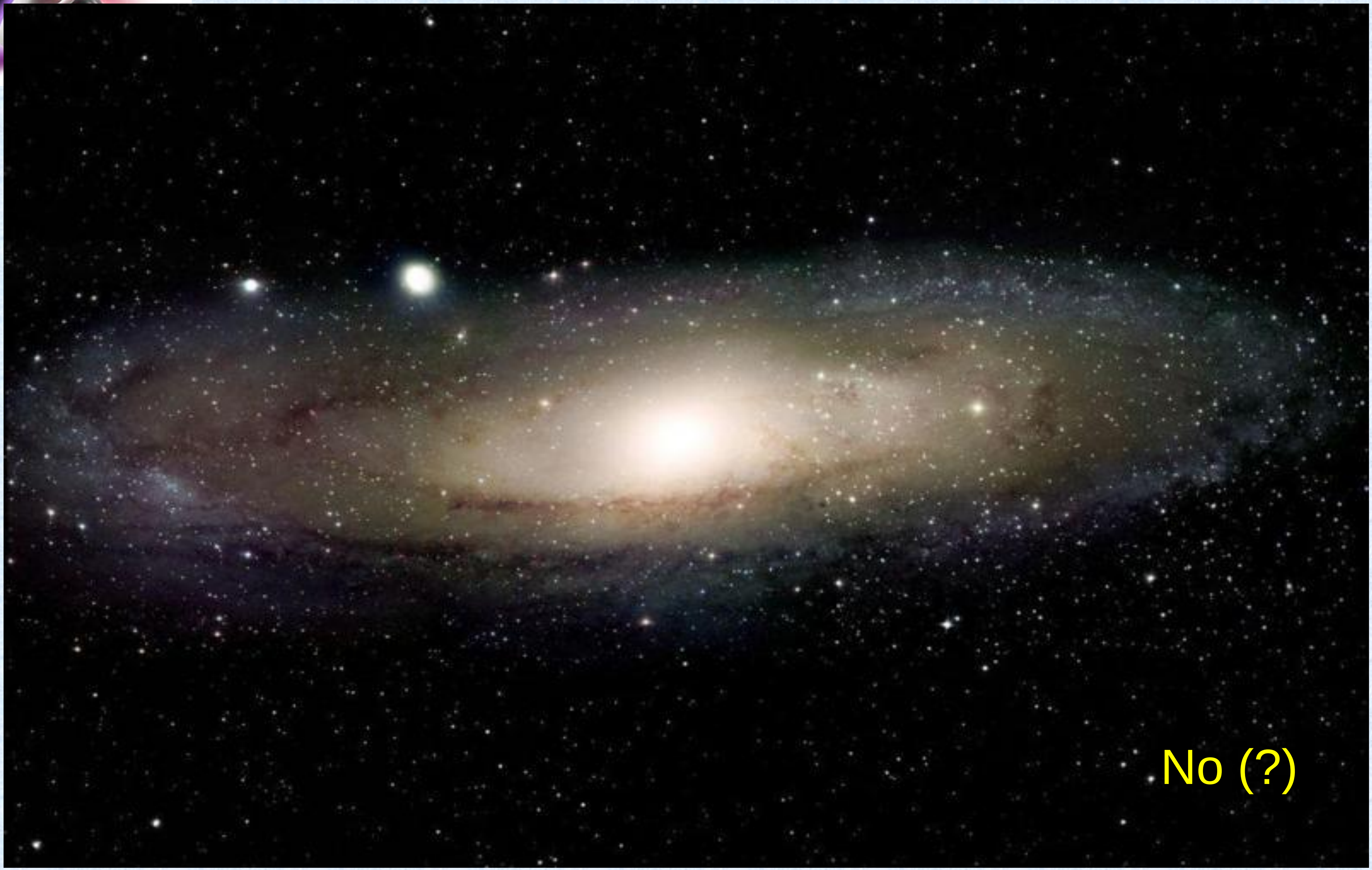
1) There should be matter-antimatter symmetry in the Universe

2) Anti-stars: optical spectrum would be identical

Is there antimatter anywhere in the Universe?

No antinuclei (e.g. anti-helium) seen in cosmic rays (relative limit from BESS: $< 10^{-8}$)

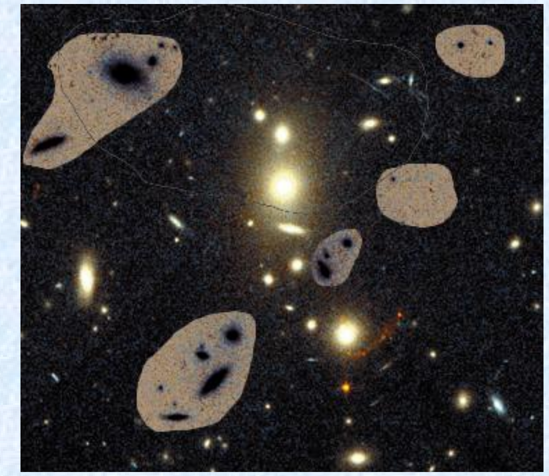
In galaxies far, far away ... ?

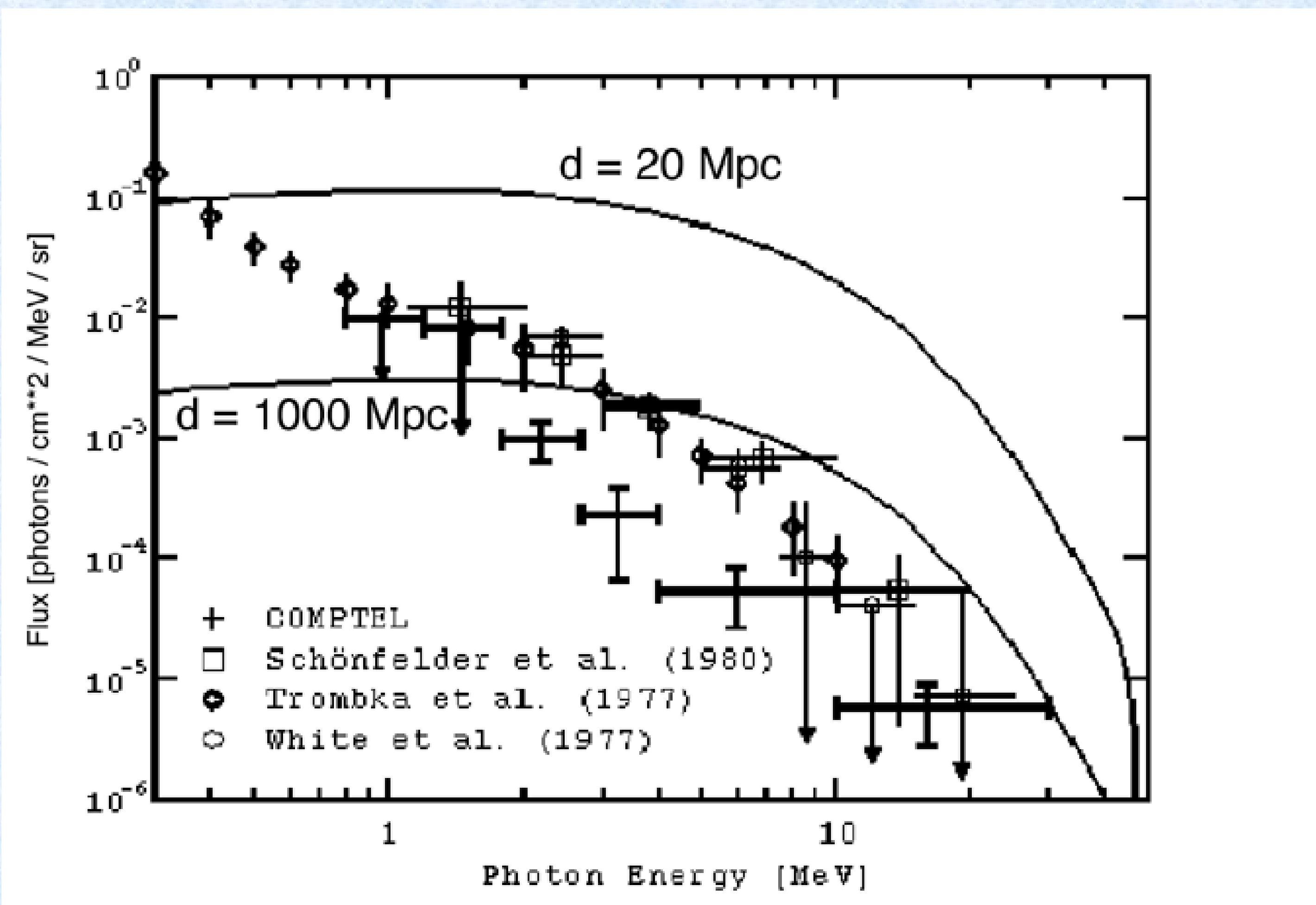


Any sign ?

Could there be 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):



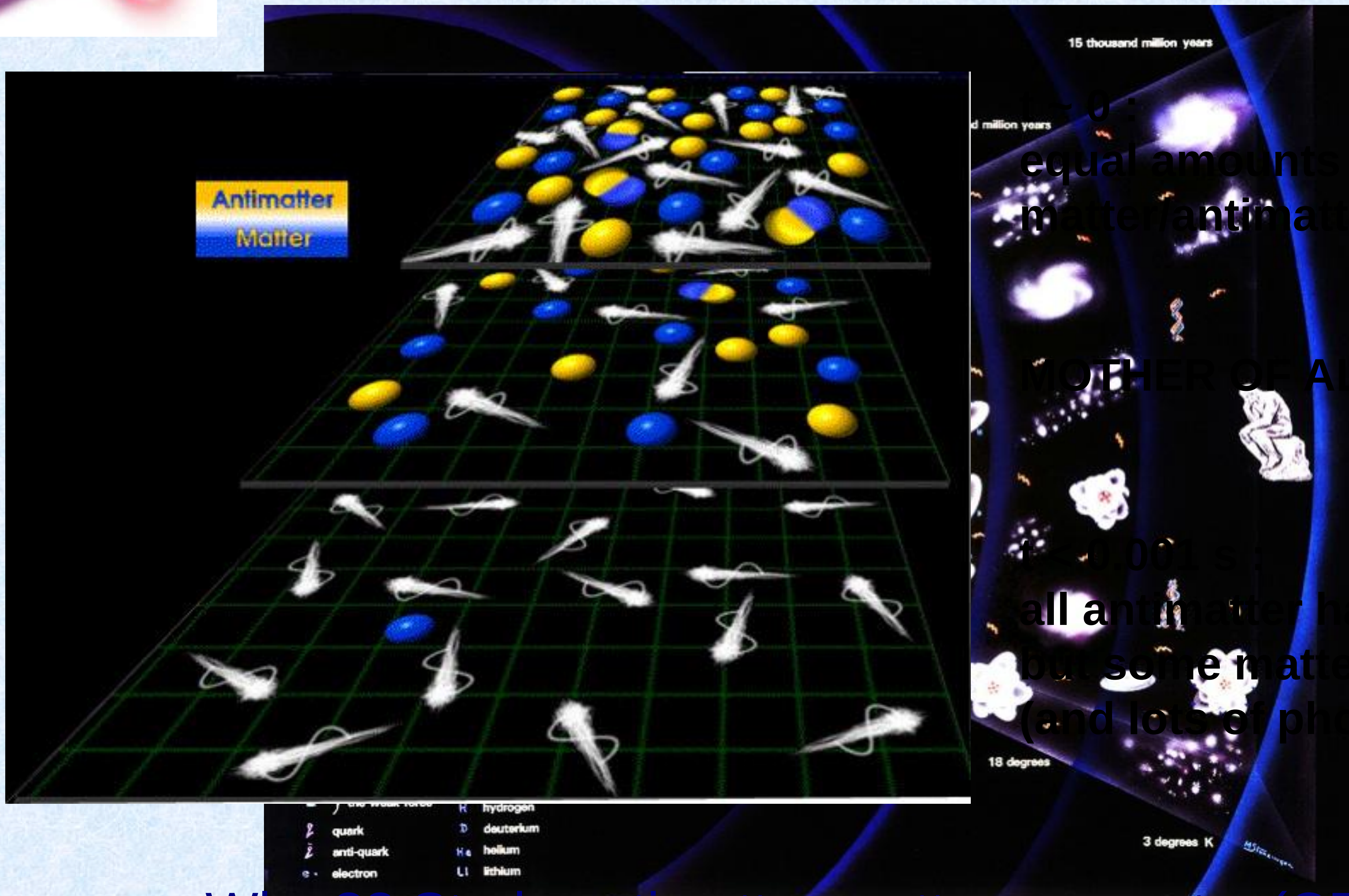


NO !

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

Does the Universe care about CPT symmetry ?

13,700 million years ago

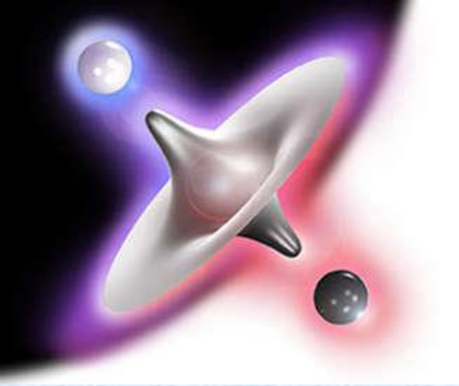


t = 0 :
equal amounts of matter/antimatter

MOTHER OF ALL BATTLES

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

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)

ANY OTHER DIFFERENCE BETWEEN MATTER/ANTIMATTER ?

- 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}