Gravitational signals other than Gravitational Waves

Giovanni Maria Piacentino

What is meant by signal?

- The word "***signal***" has different meanings in different branches of science, in particular in the Sciences of the Cosmos it has a semantic load tending to an observational interpretation.
- On the contrary in High Energy Physics it has a sharper experimental character.

The Universe, the Kingdom of Gravity

- In this conversation I will try to conjecture a possible experimental fremework to investigate the secrets of Gravity that, as is well known, dominates among Fundamental Interactions at Cosmological level

Problems in Astrophysics and Cosmology still Open

i. In the observed Universe the matter prevails on antimatter even if both are always created together
ii. CMB is not anisotropic nor inhomogeneous enough to be compatible with the Big Bang model without the introduction of a still unknown interaction driving the inflation
iii. Given the gravity we expect a negative acceleration of the expansion. On the contrary that seems to accelerate
iv. The gravitational field of Galaxies, clusters and even of the Solar system seems much stronger the the one due to the visible matter.

Possible Solutions

i. The Sakarov suggested mechanism for matter/antimatter asymmetry is connected to CPV but experimentally this phenomenon is far too weak
ii. Models have been proposed to justify inflation by supersymmetric vacuum energy and SSB but at present no evidence for supersymmetry has been found yet
iii. Dark Energy has been introduced by hand in order to give a motivation to the accelerated expansion of the universe
iv. Dark Matter has been introduced in order to give a motivation to the observed discrepancies between theory and measurements of the orbital speed of the stars of the external part of the galaxies

SO MANY DIFFERENT MOTIVATIONS?

From the point of view of the elegance the situation is far from being satisfactory:

i. As many hypothesis as problems
ii. Most of them just put by hand into the theory
iii. Dark Matter and Dark Energy hypotheses are similar in nature to that of the Luminiferous aether hypothesis for the transmission of the electromagnetic signals.

Ockham's razor,

- This "lex parsimoniae" Is due to the English Franciscan Scholar William of Ockahm (1287-1347), who inspired the character of William of Baskerville in the Umberto Eco's novel "The name of the Rose$_1$". It can be presented as:
- If there are several competing Hypotheses in order to explain a phenomenon or create a theory , The one that needs the fewest assumptions and parameters should be selected

- *1) Le cose e i loro nomi,*Toraldo Di Francia [Laterza, 1986]

Matter Antimatter symmetry

- Matter is always produced with the corresponding antimatter
- Matter seems to dominate the landscape of the Universe
- No stable Antimatter seems to populate our Galaxy nor the Universe in general

Scales

- At the scale of 10^6 m even the electromagnetic interaction is mostly screened and the only residual interaction is the gravity
- At this scale no significant presence of antimatter can be find
- Is there any connection between absence of antimatter and presence of gravitation?

Repulsion?

- Antimatter particles correspond to negative energy solution.
- Could this correspond to a negative gravitational mass and to a consequent gravitational repulsion between matter and antimatter?

What is antimatter?

(Feynman~Stueckelberg) Definition:

Matter ⇦ (Time reversal x Charges coniugation) ⇨ Antimatter

What kind of time reversal is the one to be used in GR?

How antimatter affects Gravitation?

Let's try to figure a classical antimatter

- Feynman-Stueckelberg interpretation of antimatter:
- Positive energy objects travel into the future
- Negative energy objects travel into the past

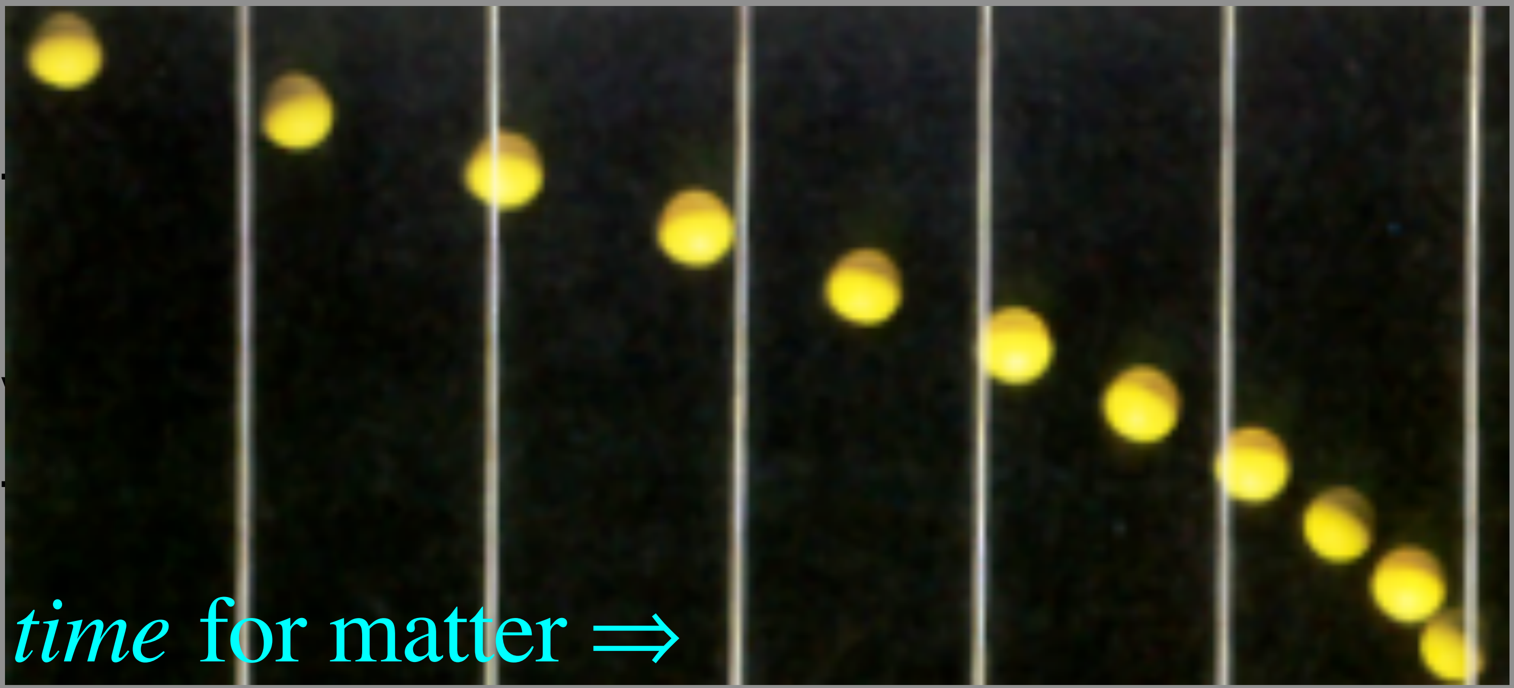
- Classical antimatter:
- Extended special relativity allows both Superluminal transformations and superluminal particles, confined to superluminal speed and with negative energy

Classical antimatter:

- Reinterpretation principle:
- the trajectory of a tachyon is seen inverted in time from the point of view of an infraluminal observer so the time simmetry should be violated by gravitational interaction

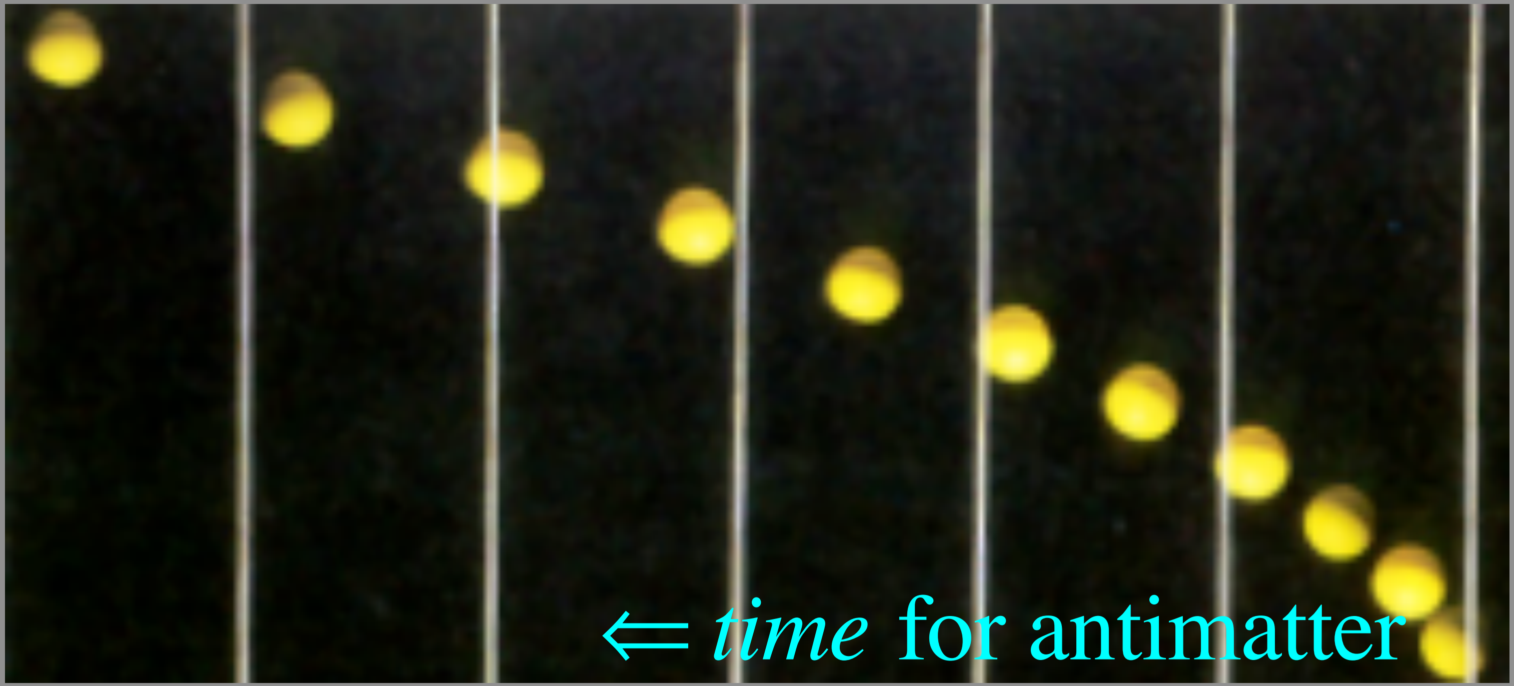
curiosity

- Classical antimatter:



curiosity

- Classical antimatter:
-
-



antimatter and antigravity are connected classical concepts

- Several opposition based on three points:
- 1) energy conservation violation
- 2) equivalence principle violation
- 3) Induction of CPV
- Most of them not valid (Nieto et al.)

The Good argument

- Myron Good observed that if the gravitational potential is explicitly assumed to have absolute meaning the difference of energy between neutral kaons ,

$$\Delta E_{K^0 \bar{K}^0} = 2 m_K \Phi_G$$

The Good argument

Would induce a time evolution of the components $K^0 \bar{K}^0$ in K_L

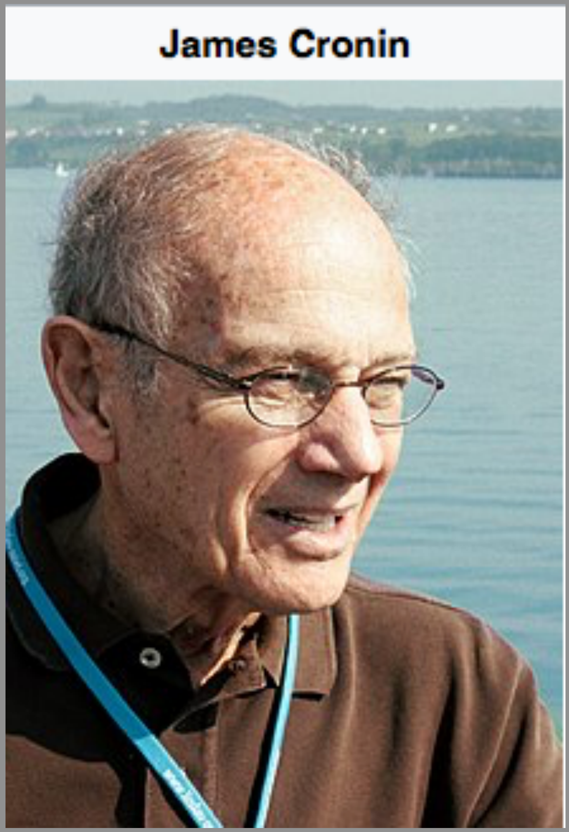
- Of the kind:

$$e^{i\frac{2m_K\Phi_G}{\hbar}t}$$

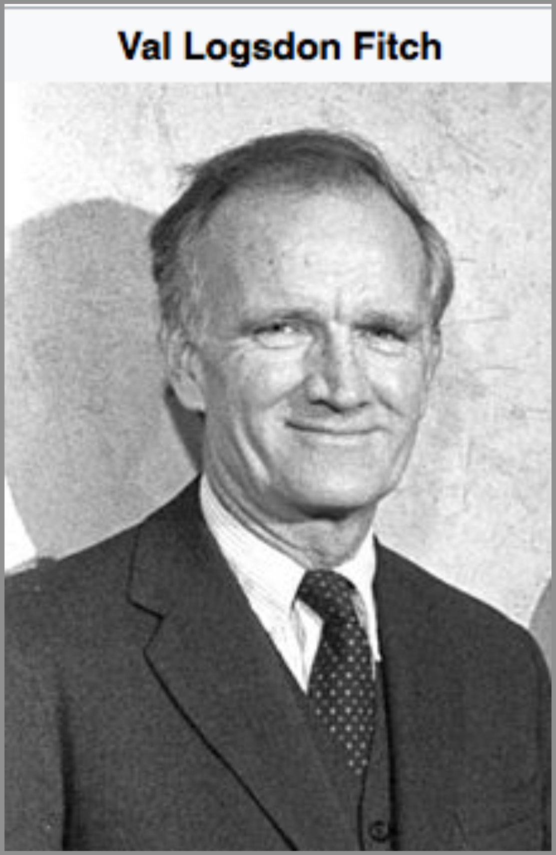
- So to induce a K_s regeneration

The Good argument

At the time of the Good argument, CP violation was still unknown, but in the 1964



Discovered the phenomenon in the K_L decay



The Good argument

- Similar arguments are possible also for non absolute potentials.
- Even if we now know that direct CPV is connected to KMC Matrix we will take advantage from the Good argument in the following

What is antimatter?

(Feynman~Stueckelberg) Definition:

Matter ⇦ (Time reversal x Charges coniugation) ⇨ Antimatter

What kind of time reversal is the one to be used in GR?

How antimatter affects Gravitation?

Taxonomy of matter in GR:

In GR. Matter can evolve, symmetrically, in the positive or negative time direction

So we can classificate respect to a system of reference that is not
In motion respect to the matter. If we define positive the proton with
Positive charge, we have in principle four different type of matter:

q^+	τ^-
q^+	τ^+
q^-	τ^+
q^-	τ^-

Where τ is the proper time

Taxonomy of matter in GR:

τ is the proper time so we have:

$$d\tau = \sqrt{dx^{\mu}dx_{\mu}} = \frac{dt}{\gamma}$$

Both signs are allowed to τ since

$$\gamma = \frac{1}{\sqrt{1-\beta^{2}}}$$

A change in the sign of γ affects also:

$$m = m_0 \gamma;$$
$$u^{\mu} = \gamma(1, u)$$
$$p^{\mu} = m_0 \gamma(1, u)$$

So the mass is odd under proper time inversion

This is true also for the energy stress tensor in fact:

$$E = p^{\mu} u_{\mu};$$

$$p^{\mu} = T^{\mu\nu} u_{\nu};$$

$$E = T^{\mu\nu} u_{\mu} u_{\nu};$$

So we can introduce the time reversal in order to understand how antimatter behaves from the point of view of a matter made observer:

	$\tau \to -\tau$	$q \to -q$	$t \to -t$	
m	$-$	$+$	$+$	$-$
q	$+$	$-$	$+$	$-$
τ	$-$	$+$	$+$	$-$
x^{μ}	$+$	$+$	$-$	$-$
u^{μ}	$-$	$+$	$-$	$+$
p^{μ}	$-$	$+$	$-$	$+$
$\frac{du^{\mu}}{d\tau}$	$+$	$+$	$-$	$-$
$T^{\mu\nu}$	$-$	$+$	$+$	$-$

So in principle antimatter could antigravitate

The Neutral Kaon Experiments

- Performed by Cronin & Fitch in 1964
- Discovered that the combined symmetry CP is violated in the Kaon system
- This had major implications for cosmology, although not realised by Cronin & Fitch
  - They had discovered the mechanism for producing dynamic asymmetry
- They were awarded the Nobel Prize for their discovery in 1980

The Neutral Kaon Experiments

- Kaons contain a strange and first family quark
- Kaons decay via the weak interaction
- The weak interaction does <u>not</u> see the kaon as the strong force does:

$$|K^0\rangle \equiv d\bar{s}$$

$$|\bar{K}^0\rangle \equiv \bar{d}s$$

The Neutral Kaon Experiments

- Instead, the weak interaction sees the *mass* eigenstates, not the flavour eigenstates
- Mass eigenstates appear as a linear superposition of K^0 and anti-K^0
- These eigenstates are called K_1^0 & K_2^0, and also happen to be pure CP eigenstates:

The Neutral Kaon Experiments

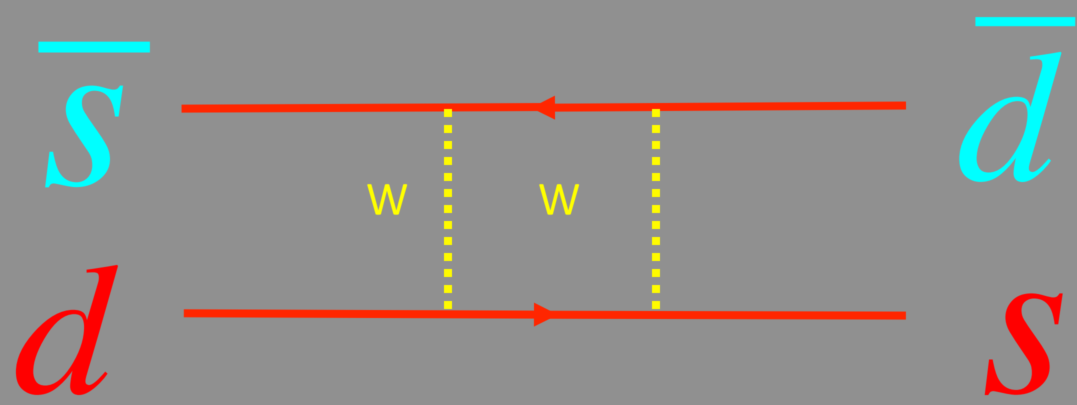
- Mass eigenstates:

$$\left|K_1^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\bar{K}^0\right\rangle\right)$$ **CP = +1**

$$\left|K_2^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\bar{K}^0\right\rangle\right)$$ **CP = -1**

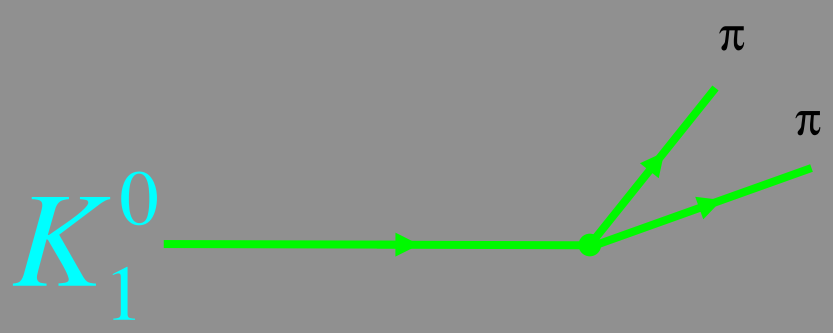
The Neutral Kaon Experiments

- The reason that the weak force sees the kaon as a linear superposition of *K* and anti-*K* is that they 'mix'
- At the quark level, this is done via a second-order weak interaction:



The Neutral Kaon Experiments

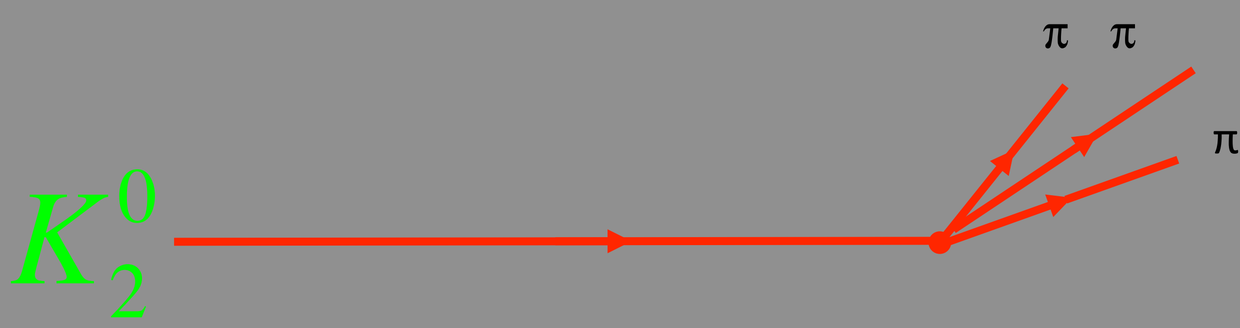
- K_1^0 & K_2^0 are easily distinguished by their different decay modes and lifetimes
- K_1^0 normally decays to $\pi^-\pi^+$ very quickly
  - Decays in 9 x 10^{-11} seconds
  - This conserves CP since $\pi^-\pi^+$ have **CP = +1**



CP = +1　　　CP = +1　　Conserved

The Neutral Kaon Experiments

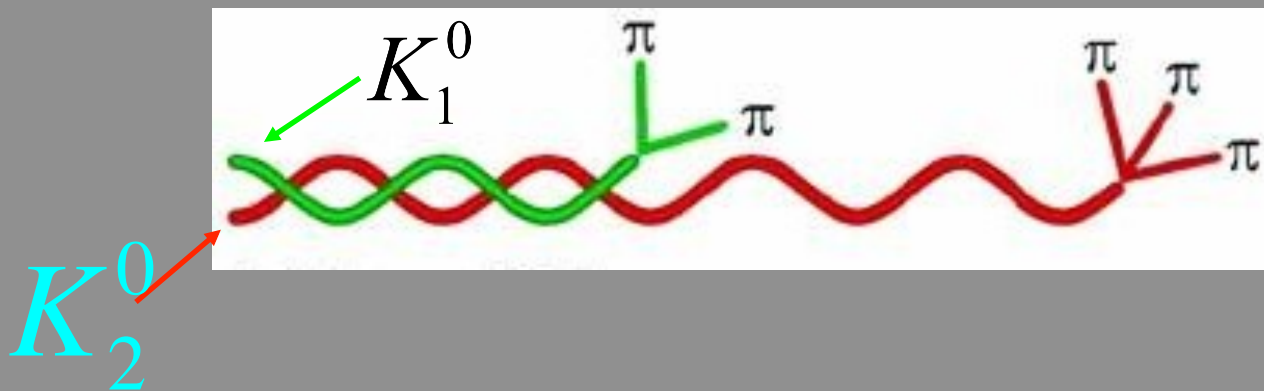
- K_2^0 normally decays to $\pi^-\pi^+\pi^0$ slowly
  - Slower decay because of reduced phase space
  - Decays in 5 x 10^{-8} seconds
  - This also conserves CP since $\pi^-\pi^+\pi^0$ have **CP = -1**



CP = -1 CP = -1 Conserved

The Neutral Kaon Experiments

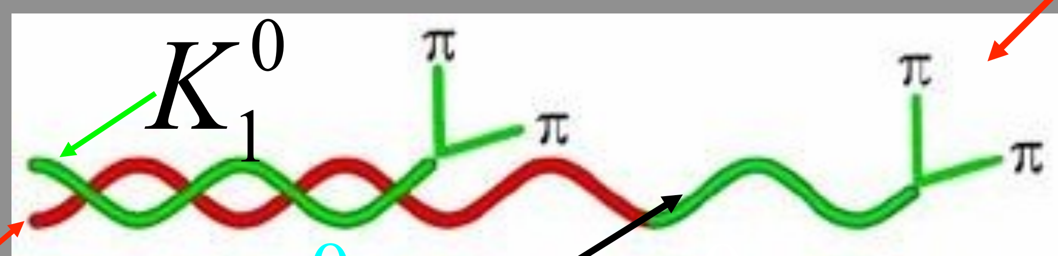
- This is what should happen:



CP conserved

- But occasionally (1 in 500 times), this happens:

(CP = +1)



K_2^0 (CP = -1)

K_2^0 turns into K_1^0 & **CP is violated!**

The Neutral Kaon Experiments

- The weak interaction can (indirectly) violate the CP symmetry
- How does this happen?
  - Clearly the definition of K_1^0 & K_2^0 is incorrect
  - The weak interaction must 'see' something that is not a pure CP eigenstate for this to happen
  - The kaons that the weak interaction can see were redefined as *K*-short and *K*-long
  - These are a mixture of the original K_1^0 & K_2^0

The Neutral Kaon Experiments

- The **new** weakly interacting Kaons:

$$\left|K_s^0\right\rangle = \alpha\left|K_1^0\right\rangle_{CP=+1} + \beta\left|K_2^0\right\rangle_{CP=-1}$$

Where α>>β

$$\left|K_L^0\right\rangle = \gamma\left|K_2^0\right\rangle_{CP=-1} + \delta\left|K_1^0\right\rangle_{CP=+1}$$

Where γ >>δ

- These are no longer pure CP eigenstates

The Neutral Kaon Experiments

- Two theories were generated to explain this kaon mixing
- The first was Wolfenstein's 'superweak' force (1964)
  - This elegantly and simply explained observations
  - However, it brought a new unknown force into play

The Neutral Kaon Experiments

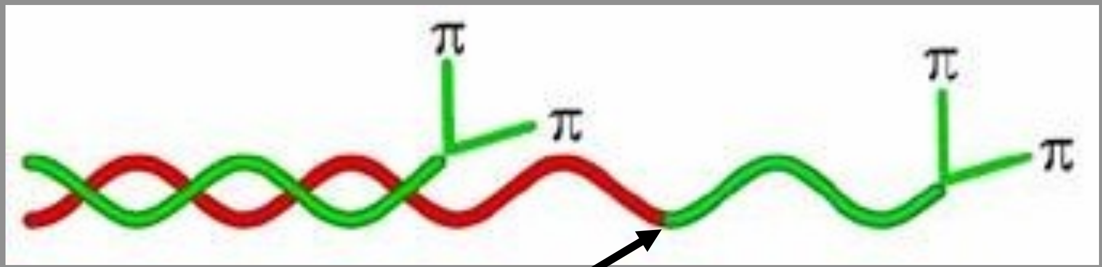
- The second proposition was from Kobayashi & Maskawa in 1973
  - Observed that CP could be violated in weak quark interactions if there were three families of quarks
    - Only two families were known at the time
  - This led to the CKM matrix, that uses a complex phase parameter to explain CP violation
  - A more complex theory than Wolfenstein's, but in terms of known forces

Superweak vs. CKM Matrix?

- Which theory was correct?
- The superweak theory could only explain ‘indirect’ CP
  - CP violation could only occur via the mixing of one particle into the other
- Kobayashi and Maskawa’s theory suggested that CP violation could occur directly at the decay stage

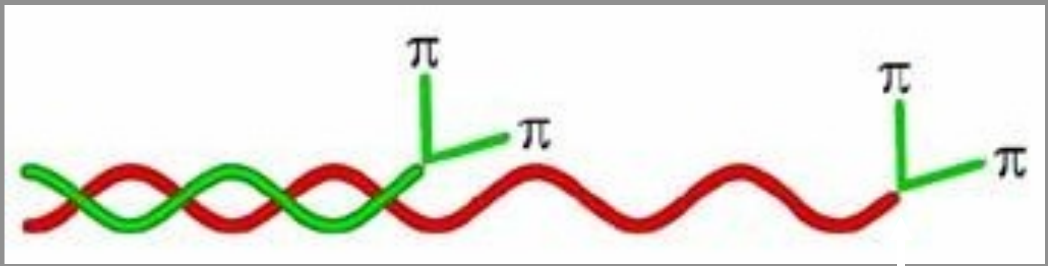
Superweak vs. CKM Matrix

- **Indirect CP:**



K_L ‘mixes’ to K_S before decay **INDIRECT**

- **Direct CP:**



K_L decays directly to a CP violating state **DIRECT**

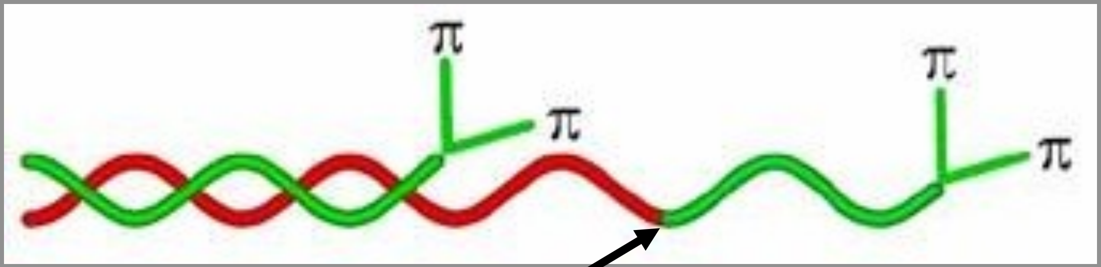
Let's go back to the Good's argument

- Indirect CP Violation could be due to Gravity and we could take advantage from that in order to understand if Gravity is even or odd for matter and Antimatter

Let us restrict to CPV in the K_s-K_l system

Consider an indirect CPV:

- **Indirect CP:**



K_L 'mixes' to K_S before decay **INDIRECT**

The gravitational field is described by the acceleration g so the components of antimatter and matter of a meson are divided by a distance growing with the time that can be written as:

$$\Delta\zeta = gt^2$$

The time useful for the phenomenon is a fraction $\Omega^{-1/2}$ of the mixing time $\Delta\tau$ where:

$$\Delta\tau = \frac{\pi\hbar}{\Delta m c^2} \approx 5.9x10^{-10}\,s \approx 6\tau_s$$

Where τ_s is the life time of K_s

The dimension of a K meson is about 0.5 fm or:

$$\Delta L_k = \frac{\hbar}{m_k c}$$

The ratio: $$\frac{\Delta\zeta}{\Delta L_k}$$ Is the adimensional constant that characterizes the phenomenon

So we have:

$$\Omega \frac{g \dfrac{\pi^2 \hbar^2}{\Delta m^2 c^4}}{\dfrac{\hbar}{m_k c}} = \Omega \frac{\pi^2 \hbar \; g m_k}{\Delta m^2 c^3} = \Omega x 0.88 x 10^{-3}$$

And obtain the CPV parameter as:

$$\varepsilon = \Omega \frac{g \dfrac{\pi^2 \hbar^2}{\Delta m^2 c^4}}{\dfrac{\hbar}{m_k c}} = \Omega \frac{\pi^2 \hbar \; g m_k}{\Delta m^2 c^3} = \Omega x 0.88 x 10^{-3}$$

This means that gravity could be responsible for most of the CPV in the neutral K seen on the Earth

This is very good in fact:

An equal mix of matter and antimatter will give a net repulsive force, this could generate inflaction;

Antigravity generated CPV could explain "missing" antimatter;

Antigravity could also explain dark energy.

Where Could the Mass of Potential Energy Be Localized?

This question was put forward as soon as in the panphlet "Relativity Reexamined" by Leon Brillouin (AP 1970). The question is equivalent to ask about the nature of the gravitational vacuum. In Quantum Mechanics Vacuum, the space is populated of particle-antiparticle virtual pairs. If the gravity is repulsive on antiparticles, each pair represents a gravitational dipole so that the vacuum can be polarized and have a non zero gravitational dipole charge per volume unit.

Gravitational dipoles

If we consider that the distance between particle and antiparticle in a dipole should be of the order of the Compton wavelength, we obtain that the dipolar charge of each pair is indipendent of the mass of the particle:

$$\vec{p}_g = m\vec{d};$$

$$\left|\vec{d}\right| \approx \lambda\!\!\!^{-} = \frac{\hbar}{mc};$$

$$\left|\vec{p}\right| \approx m\lambda\!\!\!^{-} = \frac{\hbar}{c}$$

Energy of the dipoles

- If the vacuum is permeated by an external gravitational Field, interaction energy is given by:

Field of intensity $\vec{g}_0$

$$\eta = -\vec{p} \cdot \vec{g}_0;$$

$$\eta = -\frac{\not{h}}{c} \vec{g}_0; \text{ or in the case of a field of a spherical mass } M_0$$

$$\eta = -\frac{\not{h}}{c} \frac{GM_0}{r^2}$$

Energy of the dipoles

- The polarization is the result of the competing action of the external Field and of the thermal agitation and as usual is described by a Langevin like equation:
- $$P = Np\left[\coth\theta - \frac{1}{\theta}\right];$$
- Where N is the number of Dipoles/ volume

Energy of the dipoles

- So the polarization can be written as:

$$\vec{P} = -N\frac{\hbar}{c}\left[\coth\left(\frac{M_b}{\rho_{dip} r}\right) - \frac{\rho_{dip} r}{M_b}\right]\hat{r}$$

- Where $\hat{r}$ is the radial versor

Energy of the dipoles

- In order to estimate N, we can consider that the dipoles can be at low energy a pure pion gas si that the density can be written:

$$N = \frac{1}{\lambda_\pi^3} = \left[\frac{m_\pi c}{2\pi\hbar}\right]^3$$

Energy of the dipoles

- So we have for the density from polarization:

$$\rho_P = -\nabla \cdot \vec{P} = \frac{1}{3} N \frac{\not{h}}{c} \frac{M_B}{\rho_{dip} r^2}$$

Mass due to Polarization

- So we have the mass due to polarization:

$$M_P(r) = \frac{4\pi}{3} N \frac{\hbar}{c} \frac{M_B}{\rho_{dip}} (r - R_B)$$

- That is the same behavior of the Dark Matter

Dark Energy

- As it is well known the accelerated expansion of the universe can be accomplished introducing a positive cosmological constant:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

Dark Energy

- Now in our model energy and mass density of gravitational dipoles of the vacuum can accomplish for the positive cosmological constant:

$$\Lambda = \frac{8\pi G}{c^4}\rho_{\mathrm{E}dipol} \qquad \Lambda = \frac{8\pi G}{c^2}\rho_{Mdipol}$$

The International Space Station

Or the Moon after 50 years are waiting for an experiment

AKNOWLEDGMENTS

- I WOULD LIKE TO THANK:
- Gabriel Chardin CEA Saclay France
- Erasmo Recami University of Milan Italy
- Giovanni Fabrizio Bignami INAF
- Thomas j. Phillips- Duke University NC USA
- Anthony Palladino Boston University
- Luca Latronico INAF Torino Italy
- Patrizia Caraveo INAF Milano Italy
- Graziano Venanzoni INFN Italy
- Dragan Slavkov Hajdukovic CERN
- Dan Kaplan Illinois Institute of Technology

Thanks