Hot topics in Modern Cosmology
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Dedicated experiments on gravitational effects on antimatter in space

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Presented by G.M. Piacentino

Moon Village Scientific Environment

- At the future „Moon village" planned by the European Space Agency, it would be possible, for the first time in the human history, *to perform the same experiment in laboratories with significantly different gravitational background*.
- This presentation refers to a proposed experiment on the interference of gravitation on CPV that is completely model indipendent.
- Nevertheless we will for euristic pourpose first describe one of the possible models of the phenomenon

Open problems in Astrophysics and Cosmology

- The Standard Cosmological Model, even if concordant on with the experiment on several Phenomena*, features an extremely strange structure, with the “Magic“ Contribute of Dark Matter and Dark Energy that reaches 96% of the total.

*i.e. baryon acoustic oscillations (BAO), type-1a supernovae (SN1a) luminosity distance, primordial nucleosynt(hesis and cosmic microwave background (CMB))

A closer glance to the open problems in Astrophysics and Cosmology

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 that the one due to the visible matter.

Present state of Possible solutions

i. The mechanism suggested by Sakarov 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 speeds of the stars of the external part of the galaxies.

WHY 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 artificial.

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]

Can we master all the problems with a single Hypothesis?

- Let’s start from Matter Antimatter symmetry:

i. Matter is always produced with the corresponding antimatter;

ii. Matter seems to dominate the landscape of the Universe;

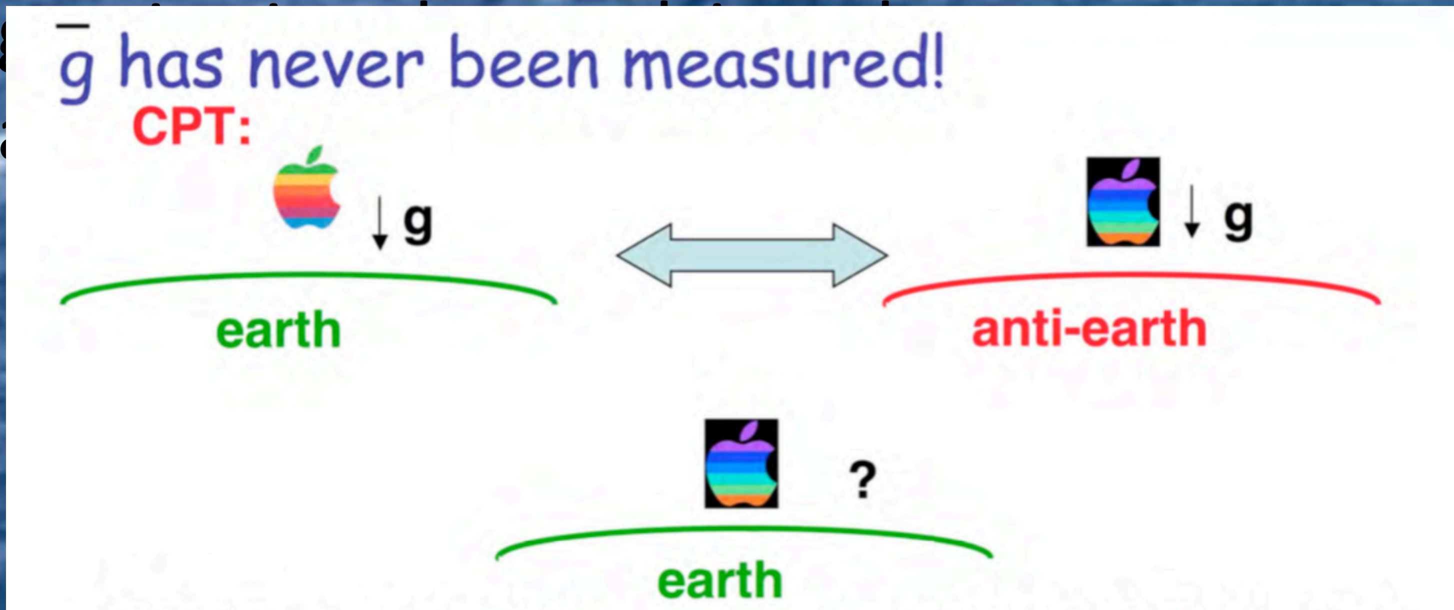
iii. No stable Antimatter seems to populate our Galaxy nor the Universe in general.

Strong, Weak and electromagnetic Interactions are limited in range

- 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



Suppose that gravitational interaction between matter and antimatter is repulsive

- This could explain matter antimatter asymmetry;
- This could be the nature of Dark Energy;
- Repulsion could have powered the Inflaction;
  - An equal mix of matter and antimatter would give a net repulsive force
  - This could even be the nature of the Dark Matter

The working hypothesis

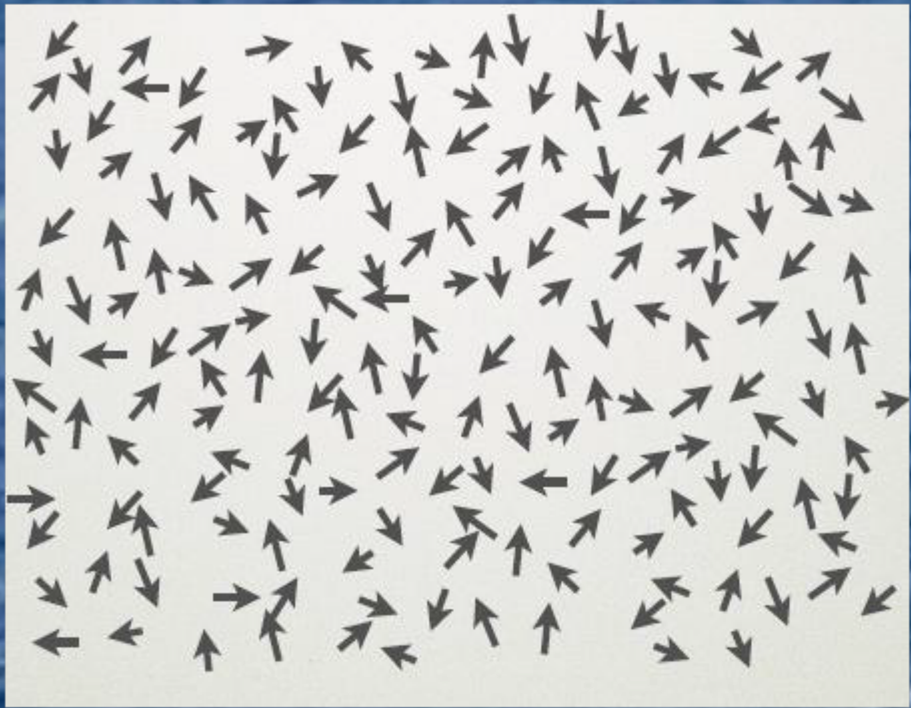
- Even if the experiment we are proposing is completely model independent, we are fascinated by the working hypothesis that,

by their nature, *quantum vacuum fluctuations are virtual gravitational dipoles*

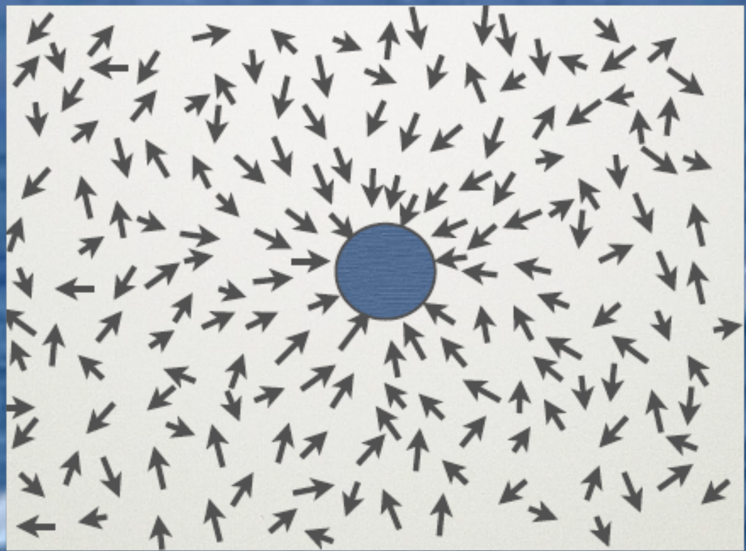
- This hypothesis permits to consider the well established Standard Model matter (i.e. matter made from quarks and leptons interacting through the exchange of gauge bosons) as **the only** matter –energy content of the Universe; of course a content immersed in quantum vacuum.
- Apparently there is no need to invoke dark matter, dark energy, inflation field …

From the gravitational point of view quantum vacuum is a continuum of virtual gravitational dipoles

The random orientation of the gravitational dipoles makes the total gravitational charge density of the vacuum equal to zero



Around a galaxy or a massive body a gravitational polarization is in action:



An halo of the polarized quantum vacuum acts as an effective gravitational charge on the on the boundary between the saturated zone and the non-polarized area where a mass density arises from

$$\rho_{qv} = -\nabla \cdot \vec{P}_g$$

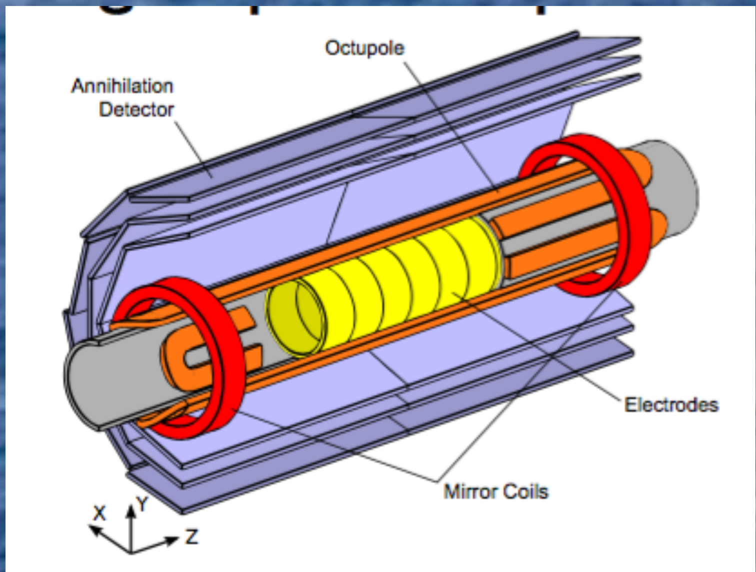
So that gravitational polarization of the quantum vacuum might be the true nature of what we call Dark Matter and the negative pressure of the polarized vacuum fluid could be the nature of Dark Energy. (the complete theory has been presented elsewhere by Dragan Hajdukovic)

Antimatter gravitational experiments

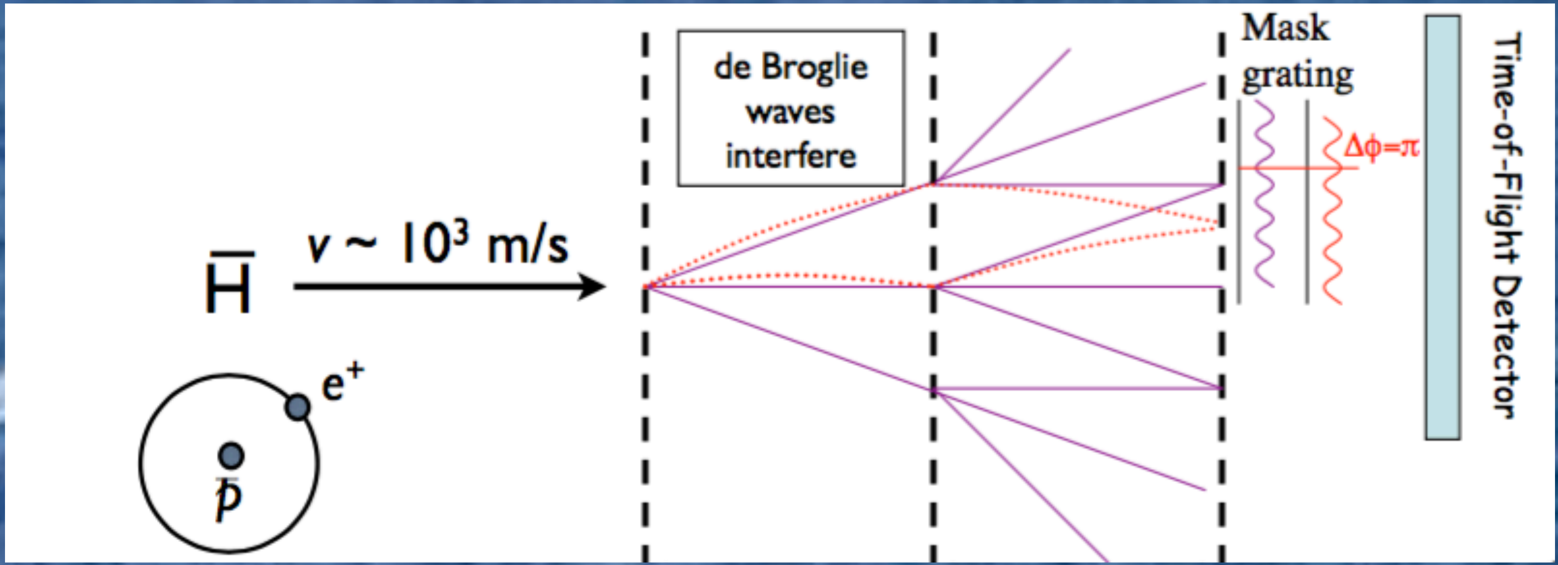
- Whitteborn & Fairbanks attempt to measure gravitational force on positrons
- Los Alamos-led team proposed (1986) to measure gravitational force on antiprotons at the CERN Low Energy Antiproton Ring (LEAR)
- Projects ended inconclusively
- too various to describe here...
- Many $\bar{H}$ efforts in progress at CERN AD (ALPHA, ATRAP, ASACUSA, AEgIS, GBAR)

World leader: ALPHA* at CERN Antiproton Decelerator

- They make antihydrogen from p^- and e^+ in an octupolar trap then shut the magnet and & see whether antihydrogen annihilate on the top or at the bottom.



Interference, at CERN (AEgIS) and proposed at Fermilab (Phillips)



Testing Gravity with Muonium

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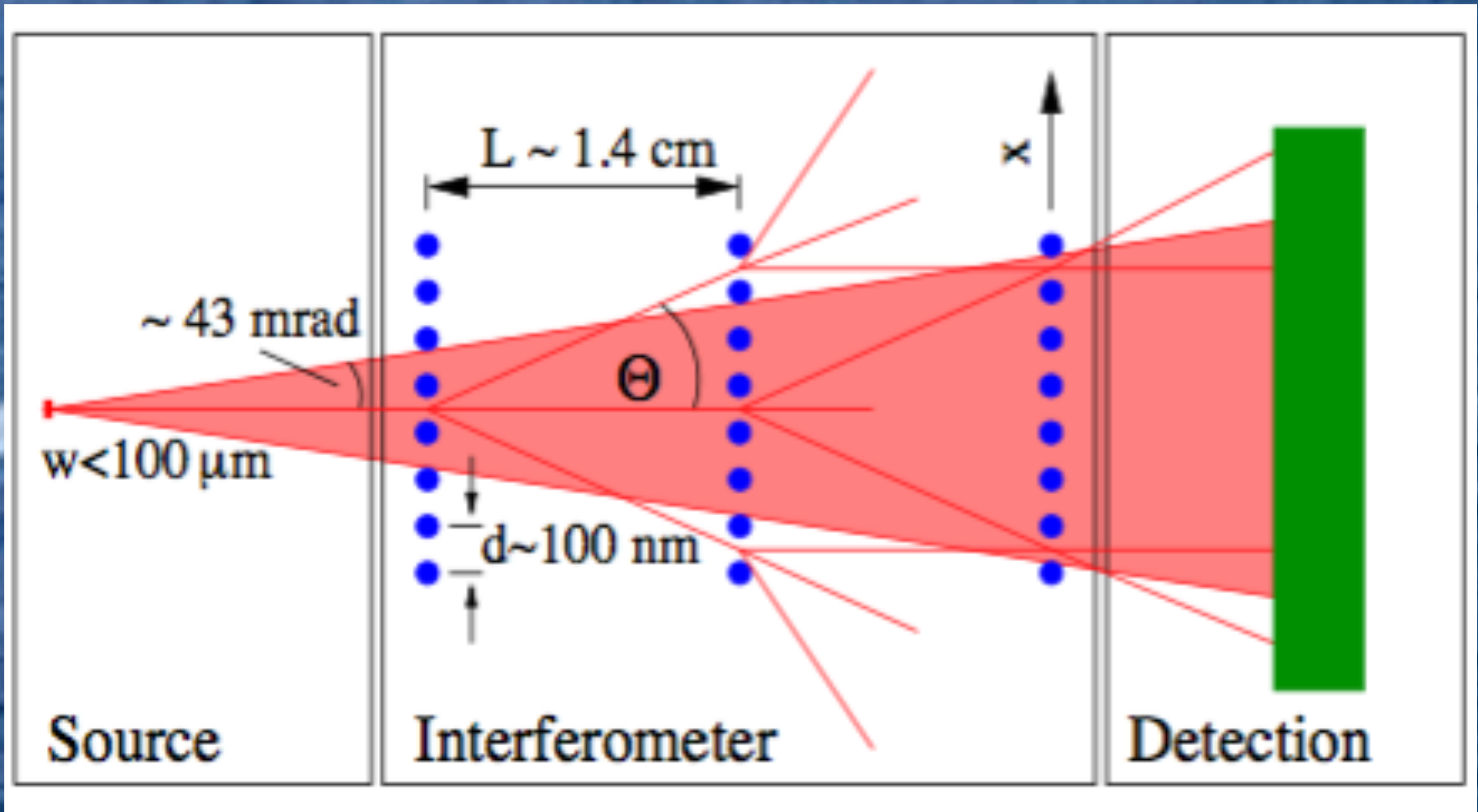


Antigravity and CPV from P. d. G.

- “Despite the phenomenological success of the KMC mechanism, it fails (by several orders of magnitude) to accommodate the observed asymmetry [21].This discrepancy strongly suggests that Nature provides additional sources of CP violation beyond the KM mechanism.”

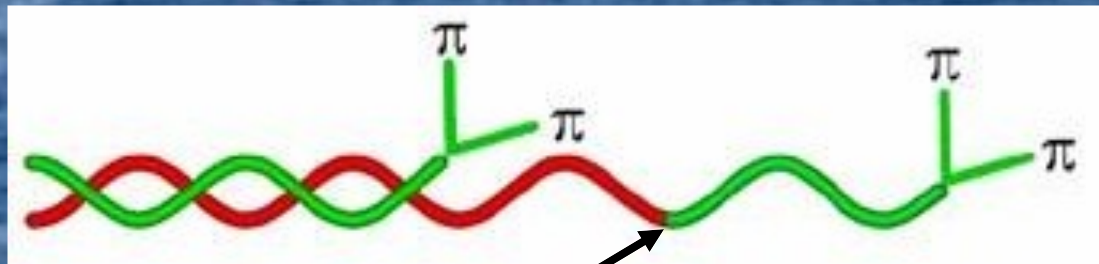
CPV and Gravity

- In the 1958, eight years before the discovery of CPV, Philip Morrison published on the American Journal of Physics a paper showing that a strong difference in the gravitational interaction for matter and antimatter could generate a CPV in neutral Kaons system.
- The CPV in neutral Kaons has been discovered 8 years later !!

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 $\Omega^{-½}$ of the mixing time $\Delta\tau$ where:

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

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 some of the CPV in the neutral K seen on the Earth

CPV and Gravity

in 1992 Gabriel Chardin showed that gravity on Earth has the right intensity to generate CPV in the mixing of the neutral K and B mesons;

He also demonstrated that the phenomenon of antigravity for antimatter could be compatible with the General Relativity and that it could be the motivation of an instability of quantum vacuum in the presence of strong gravitational fields, mimic of the Hawking radiation.

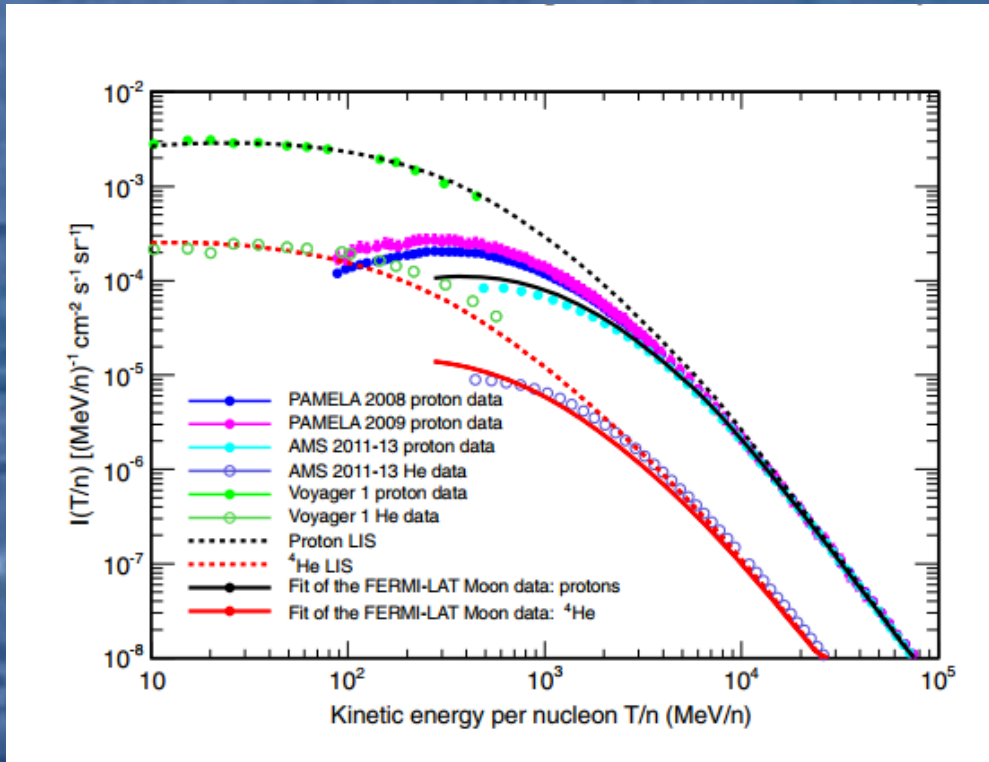
CPV and Gravity on The Moon

i. The gravitational acceleration on the surface of the Moon (1, 62m/s^2) is about six time smaller than that one on the surface of the Earth. Hence, it would be possible to perform historical experiments in a significantly different gravitational field;

ii. In the past in all the particle experiment gravitationa interaction has not been considered i.e it is a general systematic never measured nor extimate;

iii. We argue that it is feasible to repeat on the Moon the famous Nobel Prize winning experiment that revealed the CP violation in a neutral kaon system.

Particle beam on the Moon



CR proton and helium spectra obtained from the best fit of the Fermi LAT Moon gamma-ray data. The fit was performed using the MP lunar surface model. The results of the fit (continuous black and red lines) are compared with the proton measurements taken by PAMELA [39] in 2008 (blue points) and 2009 (purple points) and with the AMS-02 proton [5] (cyan points) and helium data [6] (violet points).

PHYSICAL REVIEW D 93, 082001 (2016) (Fermi LAT Collaboration)

AMS

Primary proton spectrum. Data collected during the three perio
with different zenith pointing criteria are combined. Kinetic e
ergy is in GeV, flux in $(m^2\,sr\,s\,MeV)^{-1}$, ε_{stat} stands for t
statistical error and $\varepsilon_{sys1,2,3}$ for the systematic errors

Kinetic energy	Flux $\pm\,\varepsilon_{stat} \pm \varepsilon_{sys1} \pm \varepsilon_{sys2} \pm \varepsilon_{sys3}$
0.22 – 0.31	$(154.\pm 1.6 \pm 5.9 \pm 4.0 \pm 1.9)\times 10^{-2}$
0.31 – 0.44	$(156.\pm .99 \pm 6.0 \pm 3.8 \pm 1.3)\times 10^{-2}$
0.44 – 0.62	$(143.\pm .59 \pm 6.0 \pm 3.6 \pm 1.0)\times 10^{-2}$
0.62 – 0.85	$(120.\pm .39 \pm 4.6 \pm 3.1 \pm .82)\times 10^{-2}$
0.85 – 1.15	$(966.\pm 2.6 \pm 37.\pm 24.\pm 6.7)\times 10^{-3}$
1.15 – 1.54	$(738.\pm 1.8 \pm 28.\pm 18.\pm 5.1)\times 10^{-3}$
1.54 – 2.02	$(533.\pm 1.2 \pm 20.\pm 13.\pm 3.4)\times 10^{-3}$
2.02 – 2.62	$(372.\pm .80 \pm 14.\pm 8.9 \pm 2.7)\times 10^{-3}$
2.62 – 3.38	$(247.\pm .53 \pm 9.5 \pm 5.8 \pm 1.8)\times 10^{-3}$
3.38 – 4.31	$(161.\pm .33 \pm 6.2 \pm 3.7 \pm 1.3)\times 10^{-3}$
4.31 – 5.45	$(101.\pm .20 \pm 3.9 \pm 2.3 \pm .74)\times 10^{-3}$
5.45 – 6.86	$(630.\pm 1.3 \pm 24.\pm 14.\pm 5.2)\times 10^{-4}$
6.86 – 8.60	$(378.\pm .84 \pm 14.\pm 8.6 \pm 3.3)\times 10^{-4}$
8.60 – 10.7	$(226.\pm .54 \pm 8.7 \pm 5.2 \pm 2.0)\times 10^{-4}$
10.7 – 13.3	$(135.\pm .36 \pm 5.2 \pm 3.1 \pm 1.5)\times 10^{-4}$
13.3 – 16.5	$(786.\pm 2.3 \pm 30.\pm 18.\pm 10.)\times 10^{-5}$
16.5 – 20.5	$(449.\pm 1.5 \pm 17.\pm 11.\pm 6.6)\times 10^{-5}$
20.5 – 25.3	$(266.\pm .98 \pm 10.\pm 6.4 \pm 4.3)\times 10^{-5}$
25.3 – 31.2	$(148.\pm .61 \pm 5.7 \pm 3.7 \pm 2.7)\times 10^{-5}$
31.2 – 38.4	$(856.\pm 4.0 \pm 33.\pm 22.\pm 16.)\times 10^{-6}$
38.4 – 47.3	$(496.\pm 2.7 \pm 19.\pm 13.\pm 9.2)\times 10^{-6}$
47.3 – 58.2	$(284.\pm 1.8 \pm 11.\pm 7.9 \pm 5.7)\times 10^{-6}$
58.2 – 71.5	$(154.\pm 1.2 \pm 5.9 \pm 4.4 \pm 3.0)\times 10^{-6}$
71.5 – 87.8	$(86.2 \pm .80 \pm 3.3 \pm 2.4 \pm 1.7)\times 10^{-6}$
87.8 – 108.	$(49.4 \pm .55 \pm 1.9 \pm 1.3 \pm .94)\times 10^{-6}$
108. – 132.	$(29.0 \pm .40 \pm 1.1 \pm .78 \pm 1.1)\times 10^{-6}$
132. – 162.	$(16.4 \pm .27 \pm .63 \pm .44 \pm .80)\times 10^{-6}$
162. – 199.	$(9.39 \pm .18 \pm .36 \pm .25 \pm 1.0)\times 10^{-6}$

CPV and Gravity

- On a square target of 70 cm of side, about 1.4x 10^4 protons per second will impact, The energy of the cosmic protons ranges from a few MeV to ~200 GeV with the maximum flux around 1 GeV and several smaller local maxima at 5, 13, and 31 GeV. This spectrum can produce the neutral Kaons. The total number of K mesons decays over a space mission lifetime (> 2 years) will yield the required physical measurement.

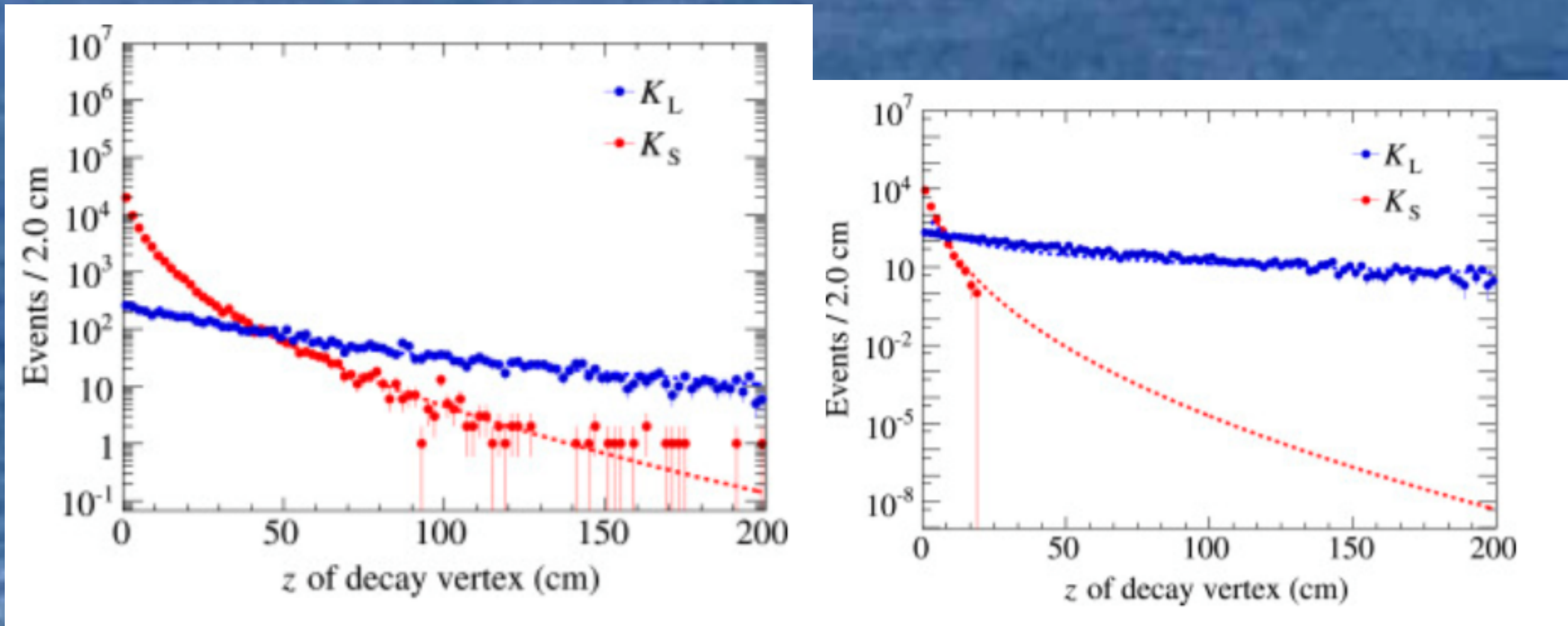
A dedicated detector on the Moon

- We suggest the use of a dedicated detectro to be installed on the Moon surface as part of the Moon Village program;
- The apparatus should have an active target, a magnetic spectrometer, tracker and calorimeter
- Active Target: We simulated the production of the K_l “long” (long decay neutral mesons) and K_s (“short”) mesons by the cosmic protons on an appropriate target


Active Target
Tracker Layers
Permanent
Magnet
ECAL

The Target system

- We performed Geant4 simulations using the angular and energy spectrum of the incident cosmic protons as measured by AMS-02 spectrometer. We simulated incident protons with $\theta_{max} = 45^\circ$ over a target surface corresponding to a π=4 solid-angle acceptance.
- We considered an active target consisting of alternating layers of Tungsten and scintillating crystals (Stolzite, PbWO4) for a total depth of 18 cm), to be read with photodiodes



- G. M. Piacentino, A. Palladino and G. Venanzoni, ``Measuring
- gravitational effects on antimatter in space,''
- Phys. Dark Univ. {\bf 13} (2016) 162

Kaons that decay in the detector volume

Volume Kinematics	R < 50 cm	R < 50cm $P_z < 0{,}5$ GeV/c	R < 100cm $P_z < 0{,}5$ GeV/c
$\frac{N(K_L decays)}{year}$	$3{,}54 \times 10^{6}$	$1{,}50 \times 10^{6}$	$3{,}36 \times 10^{6}$
$\frac{N(K_S decays)}{K_L decays}$	$3{,}03 \times 10^{-1}$	$4{,}15 \times 10^{-5}$	

Number of K_L that decay within various tracking region volumes 50 cm downstream of the target (50 < z < 150 cm, r < 50 cm or r < 100 cm), with and without a kinematical cut on the axial momentum at the $K_{S;L}$ decay vertex.

Critical parameters

	Requirements 3σ	Requirements 5σ	Simulation result 3σ	Simulation result 5σ
$N(K_L decays)$	>2,5 x 10^4	> 7 x 10^4	6 days	17 days
$\frac{N(K_S decays)}{K_L decays}$	<1 x 10^{-4}	< 5,7 x 10^{-5}	4,15 x 10^{-5}	
$\frac{\delta N(K_L \rightarrow \pi\mu\nu)}{(K_L \rightarrow \pi\pi)}$	< 4 x 10^{-2}	< 2 x 10^{-2}	Kinematical cuts	

Critical parameters necessary for 3σ and 5σ measurements of a gravitational modulation in the level of CP violation (85% change in R) along with the values obtained from our Monte Carlo simulation. The results take into account a basic geometrical event selection of KS;L decay vertices within a 1 m × 1 m cylindrical tracking volume 50 cm downstream of the target (50 < z < 150 cm, r < 50 cm), and axial momentum at the $K_{S;L}$ decay vertex of pz < 0:5 GeV/c. These values assume a 100% detection efficiency, 2% (4%) statistical and 2% (4%) systematic fractional uncertainties for 5σ (3σ).

conclusions

- We have proposed a possible test of the gravitational behavior of antimatter by measuring the rate of the CP violating decay in the gravitational environment of the Moon surface. We estimate that:
- 5σ measurement of a possible change in the CP violation parameter ε could be obtained within a years, depending on the detection efficiency, few days with a 100% efficiency.
- Any difference between the amount of CP violation on the Moon with respect to the level of CP violation on the Earth's surface would be an indication of the nature of the gravitational interaction between matter and antimatter.
- A positive result may offer an explanation for the cosmic baryon asymmetry and may offer a contribution to the observed effects thought to come from dark matter and dark energy