# Testing gravity on accelerators

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|---|---|
| **1506.08063 (PLB)** | Gravitational mass of relativistic matter and antimatter |
| **1506.01963 (PLB)** | Testing general relativity on accelerators |
| **1604.04486 (PRL)** | Comment on “Testing Planck-Scale Gravity with Accelerators” |
| **1508.04377 (Sci.Rep.)** | Gravitational mass of positron from LEP synchrotron losses |

Disclaimer: This work was done as a private venture and not in the author's capacity as an employee of the Jet Propulsion Laboratory, California Institute of Technology.

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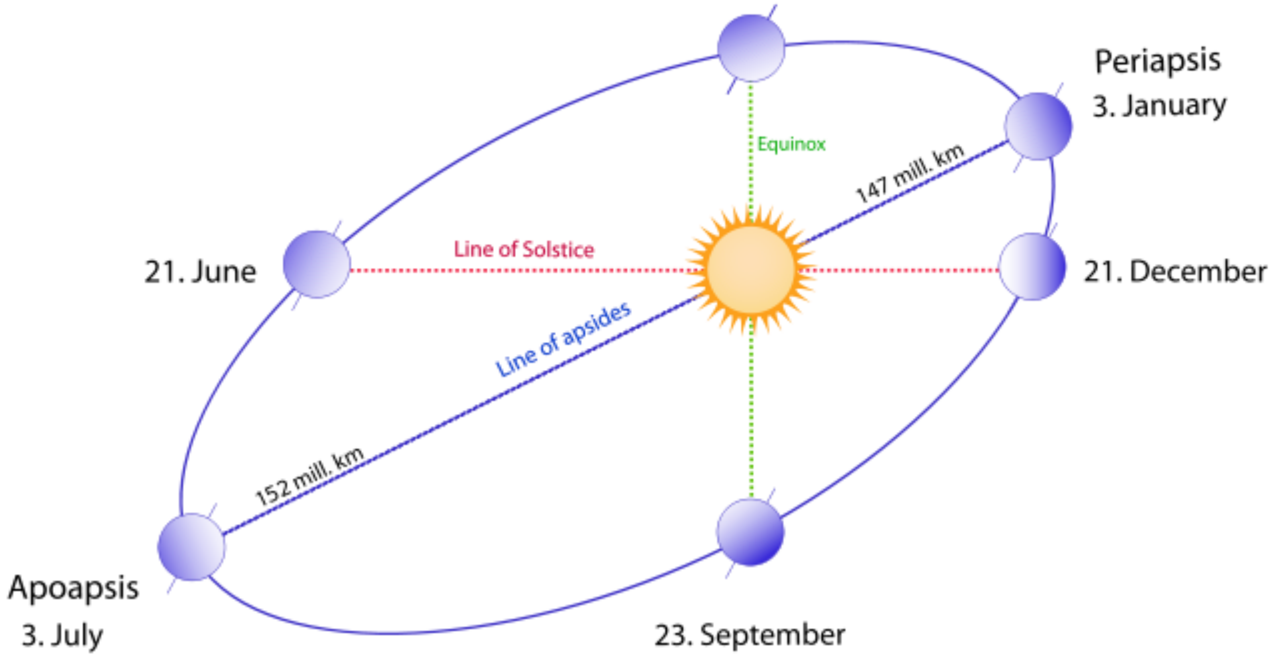
# Motivation

## Tests of gravity at high energies

## Antimatter gravity $\left(-65 < m_g^{\bar{H}}/m^{\bar{H}} < 110\right)$

**How?**

**Perform tests on the isotropic Lorentz violation on two different days of the year.**




C. Amole et al. [ALPHA Collaboration], Nature Commun. 4, 1785 (2013).

# Theory in brief

**Gravitational field around the accelerator:**

$$ds^2 = \mathcal{H}^2 dt^2 - \mathcal{H}^{-2}(dx^2 + dy^2 + dz^2)$$ **where** $$\mathcal{H}^2 = 1 + 2\Phi$$

**For a massive particle (in our case ultrarelativistic electron or positron)**

$$\Phi_m = \Phi \, \frac{m_{e,g}}{m_e} \, , \qquad \mathcal{H}_m^2 \equiv 1 + 2\Phi_m$$

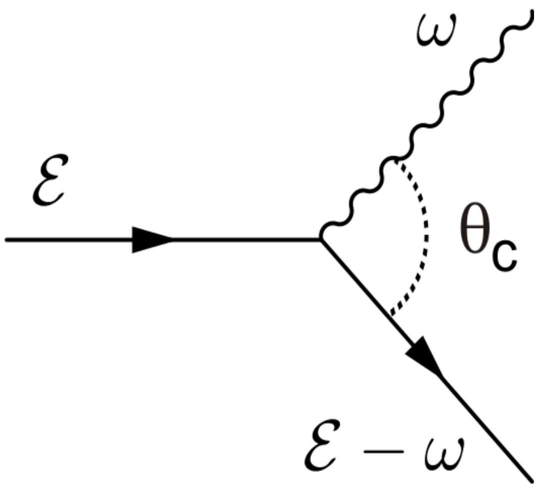
**which will modify the dispersion relation of the particle and the relation between energy and mass (we assume the speed of light to be universal)**

$$\mathbf{p}^2 = (1 + 2\kappa)\left(\mathcal{E}^2 - m_e^2\right), \qquad \mathcal{E} = \frac{m_e \mathcal{H}^{-1}\mathcal{H}_m}{\sqrt{1 - \mathcal{H}^4 \mathcal{H}_m^{-4} \mathbf{v}^2}},$$

**where** $\kappa = 2\Phi\Delta m_e/m_e, \quad \Delta m_e = m_{e,g} - m_e.$

**Imagine that** $|\kappa| < \kappa_{1,2}$ **for two experiments, then** $\left|\frac{\Delta m_e}{m_e}\right| < \frac{\kappa_1 + \kappa_2}{2\Delta\Phi}$

# 1. Vacuum Cherenkov radiation



**Threshold energy:** $$\mathcal{E}_{\rm th} = \frac{m_e}{\sqrt{-2\kappa}}$$

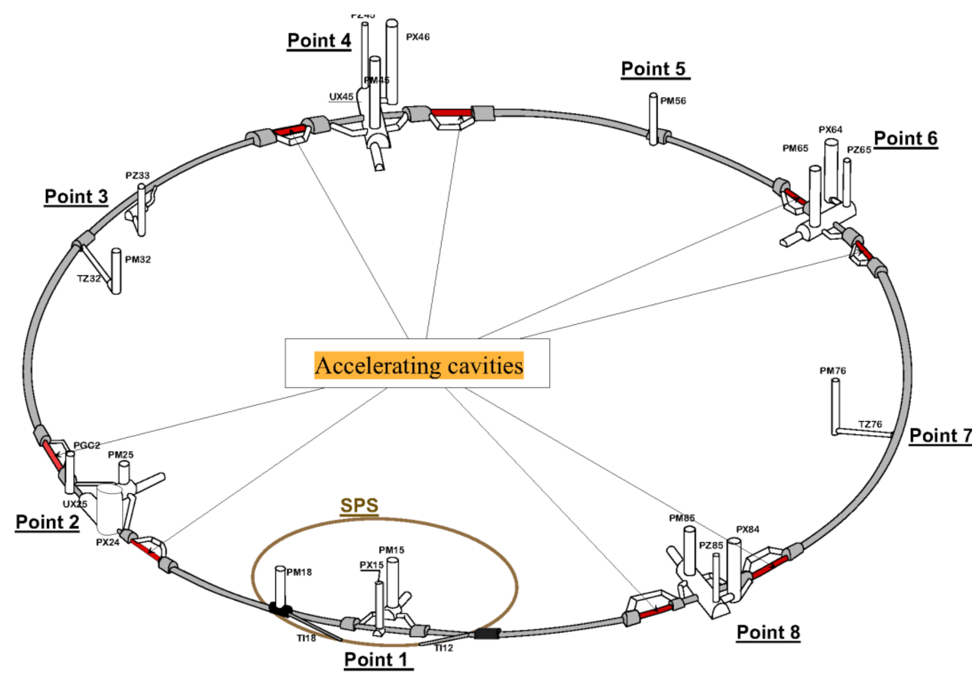
**Emission rate:** $$\Gamma_C = \alpha\, m_e^2\, \frac{(\mathcal{E} - \mathcal{E}_{\rm th})^2}{2\mathcal{E}^3}$$

**Let us take E = 104.5 GeV electrons and positrons at LEP.**

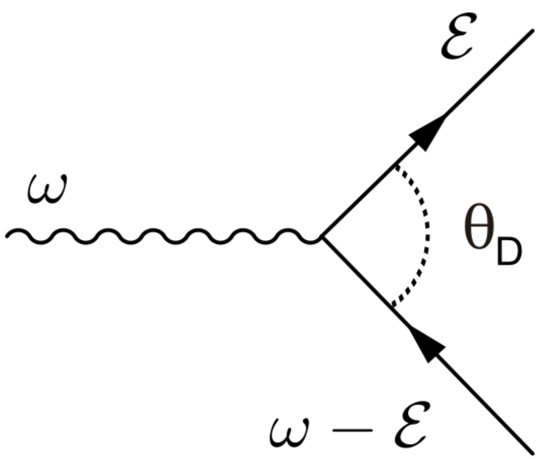
$$\mathcal{E}_{\rm th} = 100\,\mathrm{GeV}$$

**Compare: 1.2cm (decceleration distance) vs 6 km (approximate distance between accelerating RF systems).**

$$\kappa > -1.3 \times 10^{-11}$$



# 2. Photon decay




**Threshold energy:**

$$\omega_{\rm th} = \sqrt{\frac{2}{\kappa}}\, m_e$$

**Decay rate:**

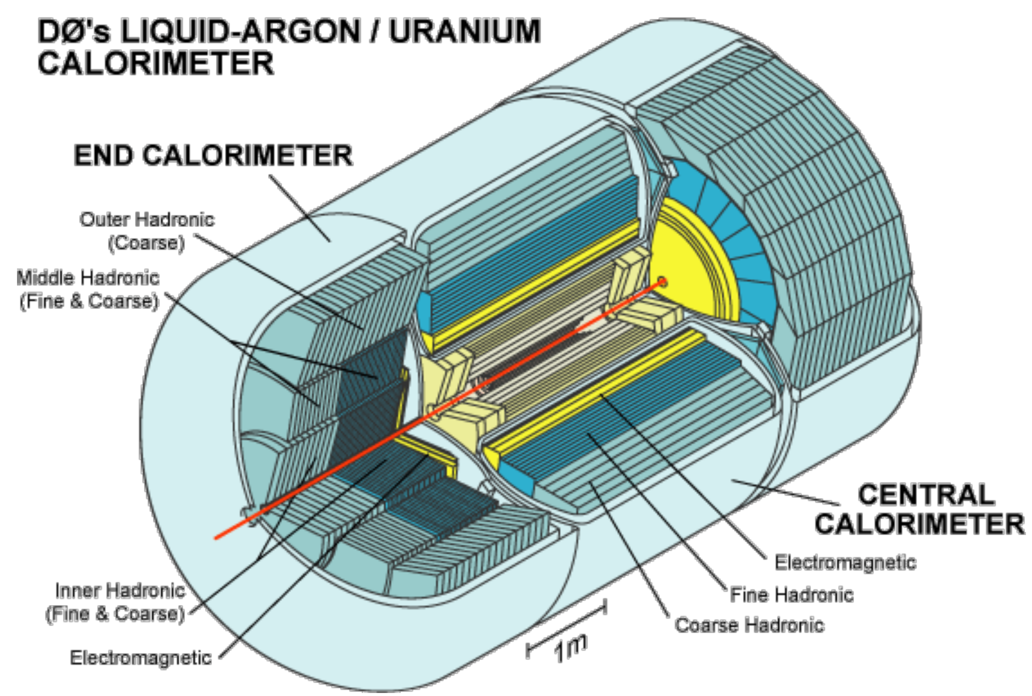
$$\Gamma_D = \frac{2}{3}\alpha\,\omega\,\frac{m_e^2}{\omega_{\rm th}^2}\left(2 + \frac{\omega_{\rm th}^2}{\omega^2}\right)\sqrt{1 - \frac{\omega_{\rm th}^2}{\omega^2}}$$

**Let us take E = 340.5 GeV photons at Fermilab's Tevatron.**

$$\omega_{\rm th} = 300\,{\rm GeV}$$

**Compare: 0.1 mm (decay distance) vs 78 cm (minimal path from interaction point to the central calorimeter of D0 detector).**

$$\kappa < 5.8 \times 10^{-12}$$



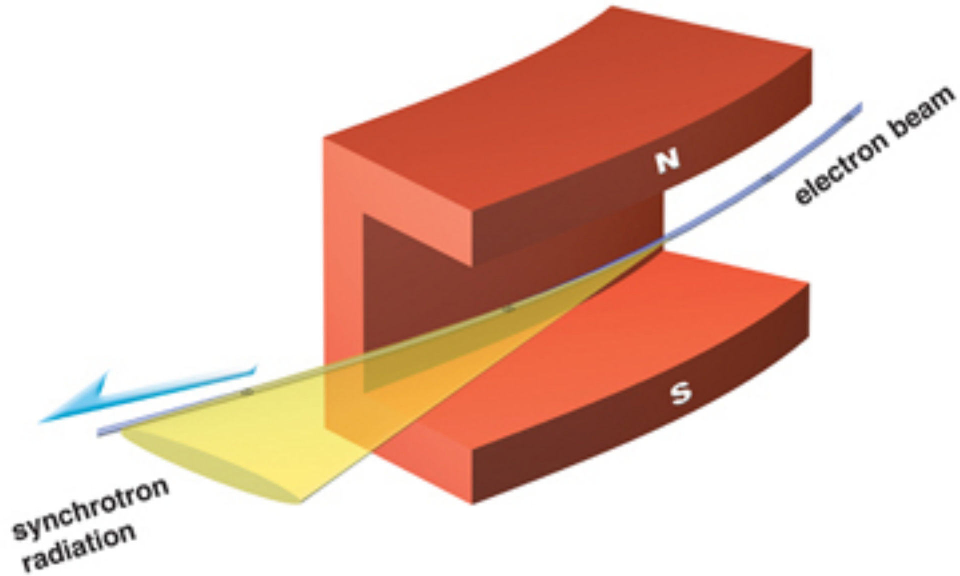
# 3. Synchrotron radiation

**Radiation power without gravity**

$$P = \frac{2}{3}\frac{e^2\dot{\mathbf{v}}^2}{c^3}\left(\frac{\mathcal{E}}{m_e}\right)^4$$

**Modification of the gamma-factor leads to**

$$\Delta P/P = 4\kappa\gamma^2$$




**LEP E = 80 GeV electrons and positrons.**
**Energy was estimated by 3 methods: NMR and flux-loop magnetic field measurement; spectrometry; synchrotron tune vs RF voltage fit.**

$$Q_s^4 = \left(\frac{\alpha_c h}{2\pi}\right)^2 \left\{\frac{g^2 e^2 V_{RF}^2}{E^2} + M g^4 V_{RF}^4 - \frac{U^2}{E^2}\right\}$$

**One can reinterpret it as a fit to *U* and possible uncertainty in the synchrotron losses**

$|\kappa| < 9 \times 10^{-15}$ **for two experiments (13 Aug & 15 Sep 1999)**

Taking the two-sided bound $\kappa^- < \kappa < \kappa^+$ for two potentials, $\Phi$ and $\Phi + \Delta\Phi$ (e.g., both the vacuum Cherenkov radiation and photon decay were absent during the experiment), one can easily derive

$$\kappa^- - \kappa^+ < -2\Phi_\odot \frac{\Delta d_{SE}}{d_{SE}} \frac{\Delta m_e}{m_e} < \kappa^+ - \kappa^- ,$$

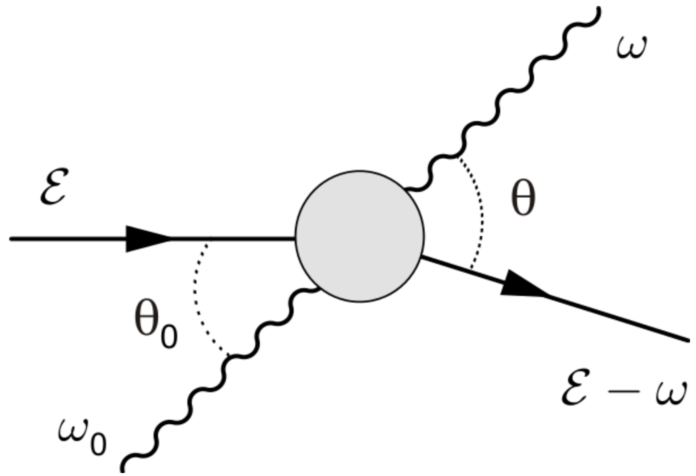
where $\Delta d_{SE}$ is the variation of the distance between Sun and Earth, $d_{SE}$, due to the eccentricity of the Earth's orbit, and obtain $|\Delta m_e/m_e| < 0.0389$, i.e., a 4% limit on the possible deviation.

One can also relate the fractional deviation in the masses and the fractional uncertainty in the measured synchrotron radiation power in two experiments,

$$\left|\frac{\Delta m_e}{m_e}\right| < \frac{|\Delta P/P|_1 + |\Delta P/P|_2}{8\gamma^2|\Phi_\odot \Delta d_{SE}[\mathrm{AU}]|} .$$

Following [Altschul, 2009], we consider the beam energy measurements of the LEP Energy Working Group for the LEP 2 programme in the last few years of LEP operation. Analysis of their data on the synchrotron losses collected at different moments of time leads to the limit $|\Delta m_e/m_e| < 0.0013$, i.e., 0.1%, for both electrons and positrons.

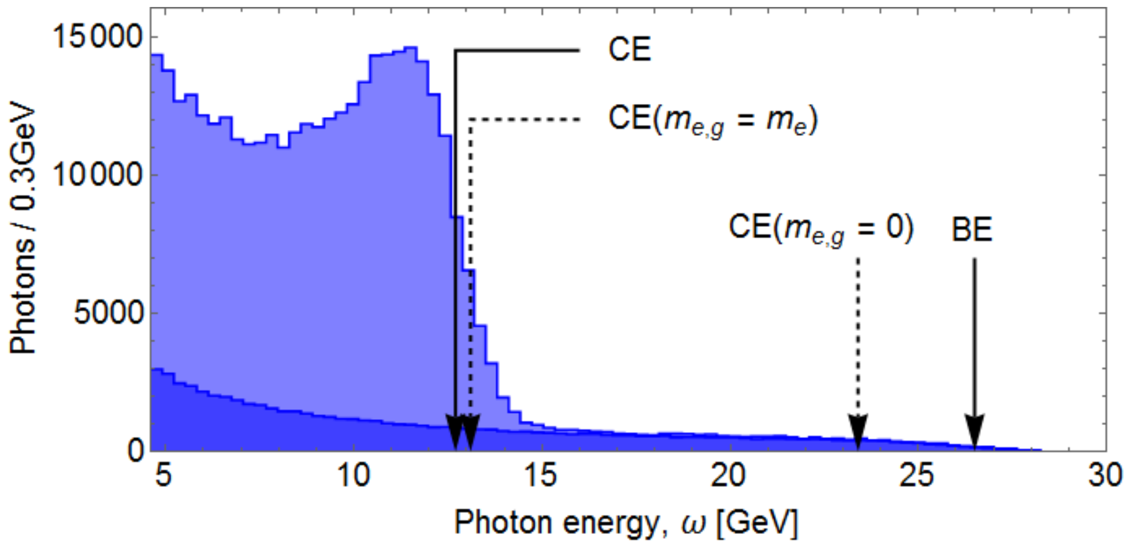
# 4. Compton scattering

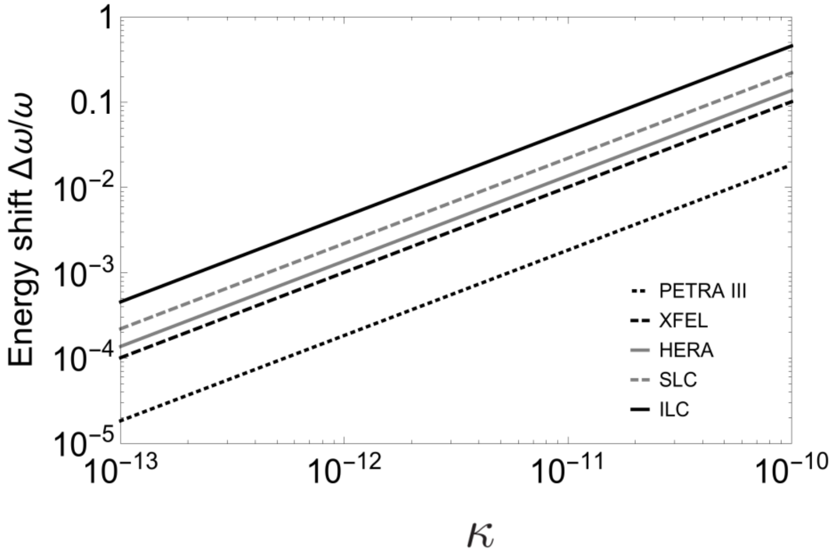



**Shifts in the Compton edge give**

$$\left|\frac{\Delta m_e}{m_e}\right| < \frac{\Delta\omega_1 + \Delta\omega_2}{\omega_{max}} \cdot \frac{m^2(1+x)^2}{4\mathcal{E}^2|\Delta\Phi|}$$

**where** $x \equiv 4\mathcal{E}\omega_0 \sin^2(\theta_0/2)/m_e^2$



# Results

- **Absence of vacuum Cherenkov radiation at LEP and photon stability at Tevatron give 4% limit on the difference between the gravitational and inertial masses of the electron/positron at GeV energies.**
- **Synchrotron losses at LEP reduce this figure to 0.13%**
- **Compton scattering can provide a similar or better precision if performed at ILC/CLIC twice: when Earth is at the aphelion and perihelion of its orbit. One can also study day to day variations.**

**With development of accelerator technologies, we are finally able to rule out antigravity and confirm weak equivalence principle for the high-energy matter and antimatter.**