Physics Beyond the Standard Model (2nd Part)

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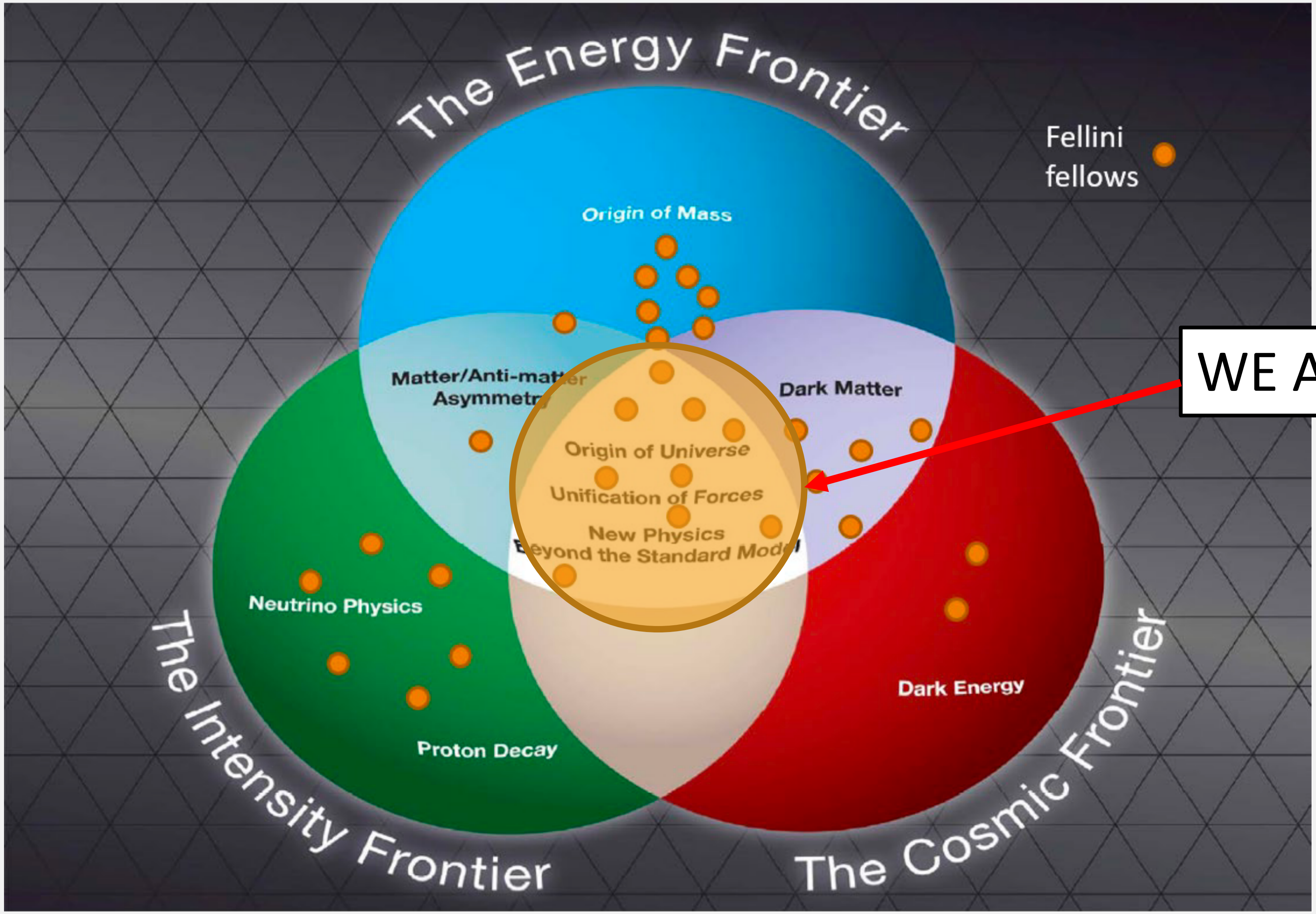
FELLINI "LANDSCAPE”



WE ARE HERE!

[taken from: A. Masiero, Mid Term Review (2020)]

LEPTON FLAVOUR UNIVERSALITY

The Higgs particle has provided the ultimate experimental verification of the Standard Model. However, theoretical arguments and experimental observations point towards the existence of physics beyond the SM.

Recent hint of NP came from a possible lepton flavour universality violation observed by the LHCb experiment in the decays $B^+ \rightarrow K^+ l^+ l^-$ and $B^0 \rightarrow K^{*0} l^+ l^-$ decays with a significance of 2.1 – 2.5 standard deviations.

These decays involving $b \rightarrow s l^+ l^-$ transitions, mediated by flavor-changing neutral currents, are suppressed in the SM, as they proceed only through amplitudes that involve electroweak loop diagrams.

The electroweak couplings of all three charged leptons are identical in the SM decay properties are expected to be the same up to corrections related to the lepton mass, regardless of the lepton flavour.

These processes are sensitive to virtual contributions from new particles (for example z' boson or leptoquark), which could be inaccessible with direct searches for resonances in LHC.

PROBE LFU WITH KAONS

The same NP mediators explaining the observed flavour anomalies in B mesons can induce effects of lepton flavour universality violation in rare kaon decays as of $K^+ \rightarrow \pi^+\mu^+\mu^-$ and $K \rightarrow \pi^+e^+e^-$.

The weak form factor of these K decays can be parametrized at Next–to–Leading–Order (NLO) in Chiral Perturbation Theory (ChPT) as

$$V_+(z) = a_+ + b_+ z + V_+^{\pi\pi}(z)$$

Where a_+ and b_+ are phenomenological constants, $V_+^{\pi\pi}(z)$ is a pion loop term and z is the transferred momentum.

If Lepton Flavour Universality (LFU) is not violated, the parameters a_+ and b_+ must be identical for both the decays $K^+ \rightarrow \pi^+\mu^+\mu^-$ and $K \rightarrow \pi^+e^+e^-$.

Galileo/Newton's (Weak) Equivalence Principle

The free-fall is independent of free-falling body masses

$$\begin{cases} \mathbf{F} = m_i \mathbf{a} \\ \mathbf{F_g} = m_g \mathbf{g} \end{cases} \longrightarrow m_i = m_g$$

Einstein's Equivalence Principle

The result of any local non-gravitational experiment is independent from the velocity of an observer in free-fall and his position and time in the universe

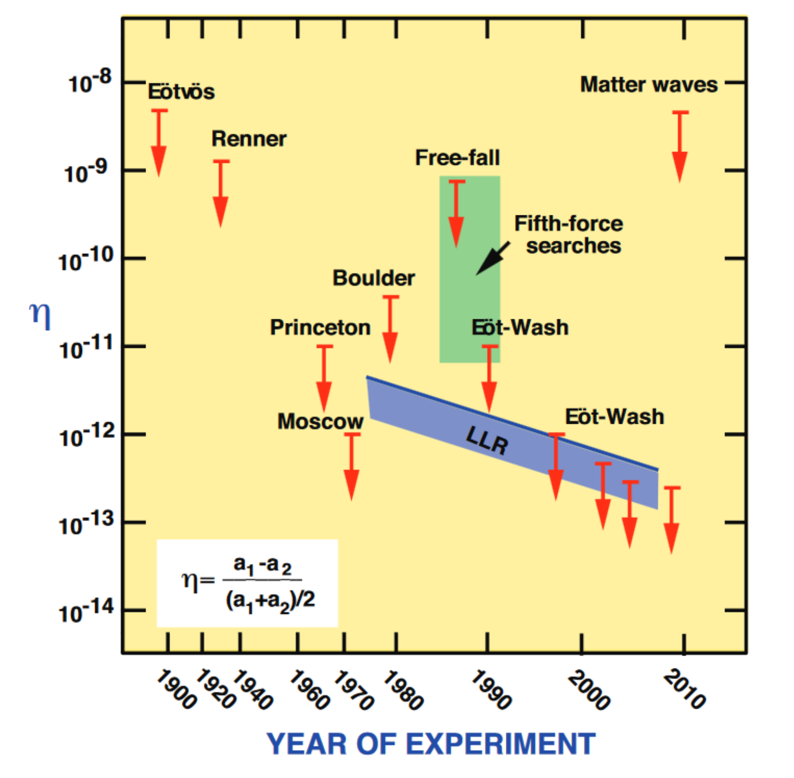
~ the Equivalence Principle is at the heart of any metric theory of gravity ~

~ testing it means probing our paradigm in understanding gravitation ~

Clifford M. Will, *Theory and experiment in gravitational physics* (1993)

Extremely accurate with normal matter

- MICROSCOPE satellite reached 2 part in 10^{14}
- Eötvös torsion balances reached 2 part per 10^{13}
- Lunar laser ranging reached 3 part per 10^{12}
- Cold atoms interferometry reached 3 part per 10^{8}



With antimatter?

- Failed attempts with charged positrons ~ 1967
- Failed attempts with charged antiprotons ~ 1985
- Some questioned indirect limits 1987 - 2000
- Very rough limit set the ALPHA collaboration with antihydrogen in 2014

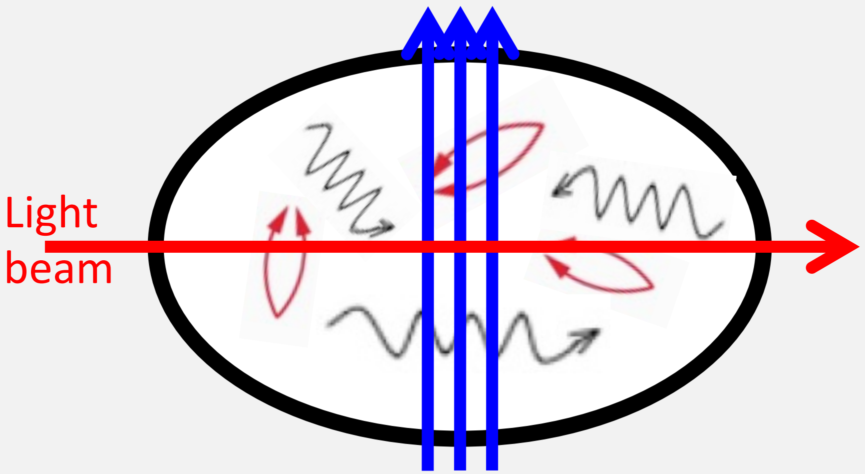
WEP tests with antimatter are a young active line of research

Any deviation from the expected perfect equality would be an indication of new physics

Will C. M., Living Rev. Rel. 9 (2006) 3

The vacuum is structured and has properties that can be studied.

Light propagation in an external field



The complex index of refraction of vacuum is modified by an external magnetic field:

$$\tilde{n} = 1 + (n_B + i\,\kappa_B)$$

The induced changes depend also on the direction of the applied field:

$$\Delta\tilde{n} = \underbrace{\Delta n_B}_{\text{BIREFRINGENCE}} + \underbrace{i\,\Delta\kappa_B}_{\text{DICHROISM}}$$

Experimental method:

- Perturb the quantum vacuum with an external B field
- Probe with a (polarised) light beam
- Detect changes in the polarisation state

VACUUM MAGNETIC BIREFRINGENCE

Lagrangian of the electromagnetic field by **Heisenberg, Euler and Weisskopf (1936)**
Maxwell's equations are still valid but they are no longer linear.

At lowest order, for fields much smaller than the critical field ($B \ll 4.4\cdot10^{9}$ T; $E \ll 1.3\cdot10^{18}$ V/m):

$$L = L_{em} + L_{EH} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{E}}{c}\cdot\vec{B}\right)^2\right]$$

$$A_e = \frac{2}{45\mu_0}\left(\frac{\alpha^2 \lambda_e^3}{m_e c^2}\right) = 1.32\cdot10^{-24}\ \mathrm{T}^{-2}$$

[W Heisenberg and H Euler, *Z. Phys.* **98**, 714 (1936)]
[H Euler, *Ann. Phys.* **26**, 398 (1936)]

This Lagrangian was later validated in **the framework of QED** [J. Schwinger, Phys. Rev., 82, 664 (1951)]

$$\Delta n_B = 3A_e B^2$$

VACUUM MAGNETIC BIREFRINGENCE

$$\Delta\kappa_B \simeq 0$$

NO DICHROISM