Searching for a Fifth Force with Atomic and Nuclear Clocks

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Introduction

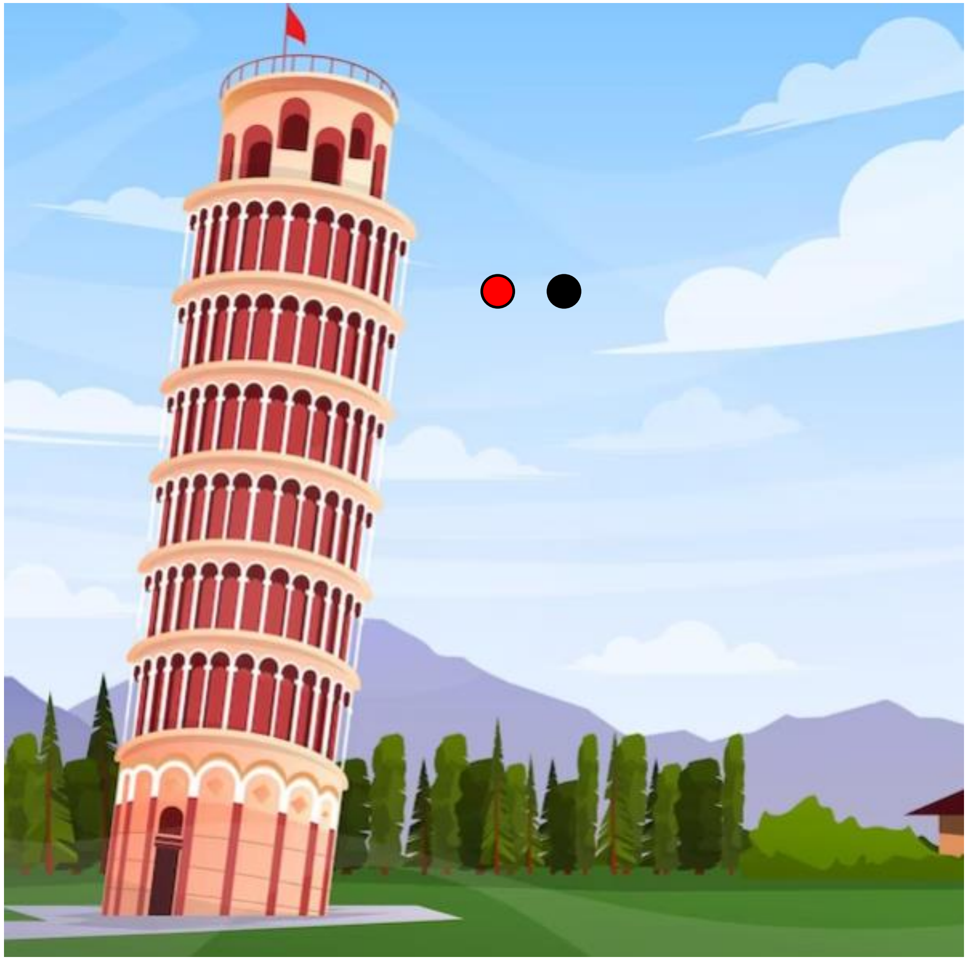
The existence of a long-range fifth force is one of the most exciting possibilities for physics beyond the Standard Model.

In general, we expect such a force to violate the equivalence principle (EP).

There have been numerous experimental searches for EP-violating fifth forces. Most of these have been direct searches, based on comparing the motions of two bodies of different compositions in the gravitational field of a third.

In this talk, I will discuss an alternative approach to detecting such forces, based on the rapidly-improving sensitivity of atomic and nuclear clocks.

Direct searches have been performed using free-falling masses. These are more sophisticated versions of Galileo's famous experiment.



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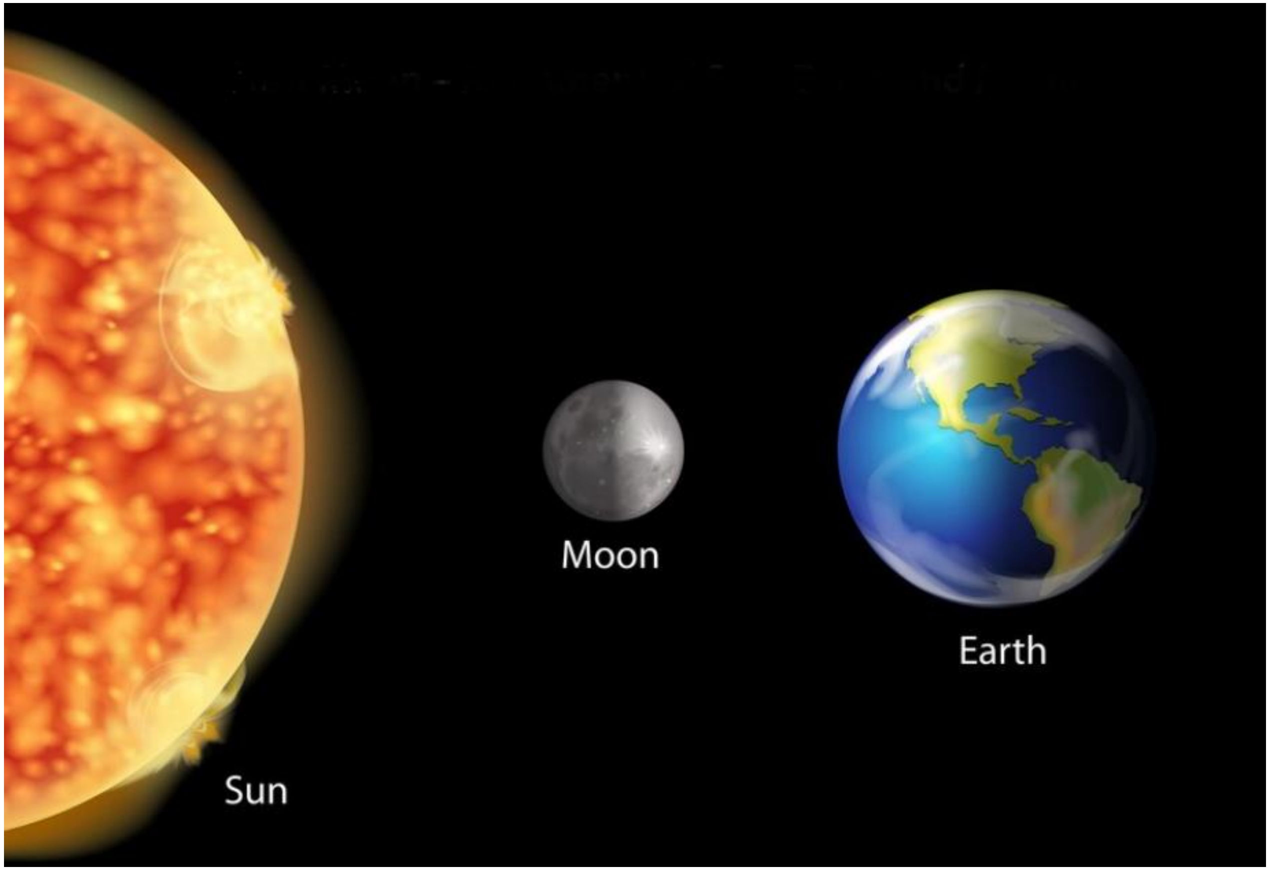
This includes observations of the rates at which the earth and moon fall towards the sun.



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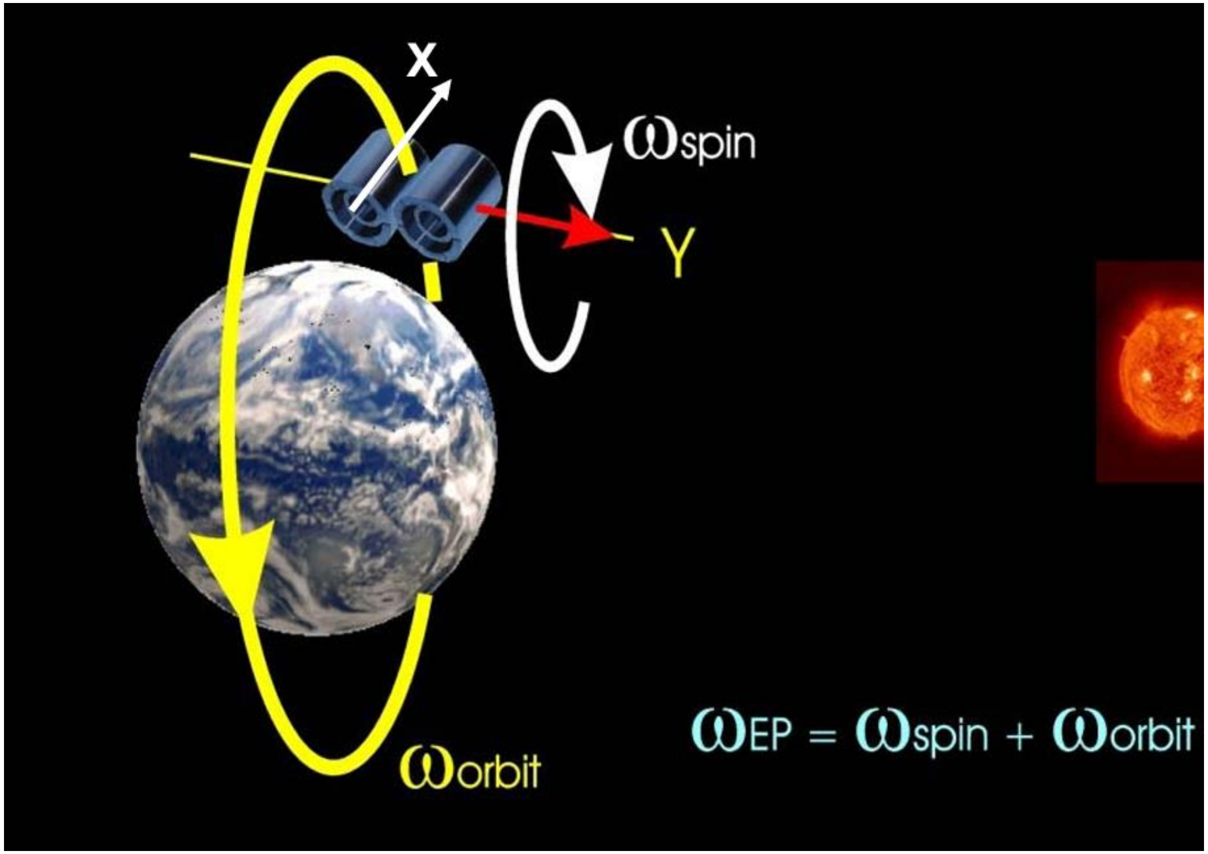
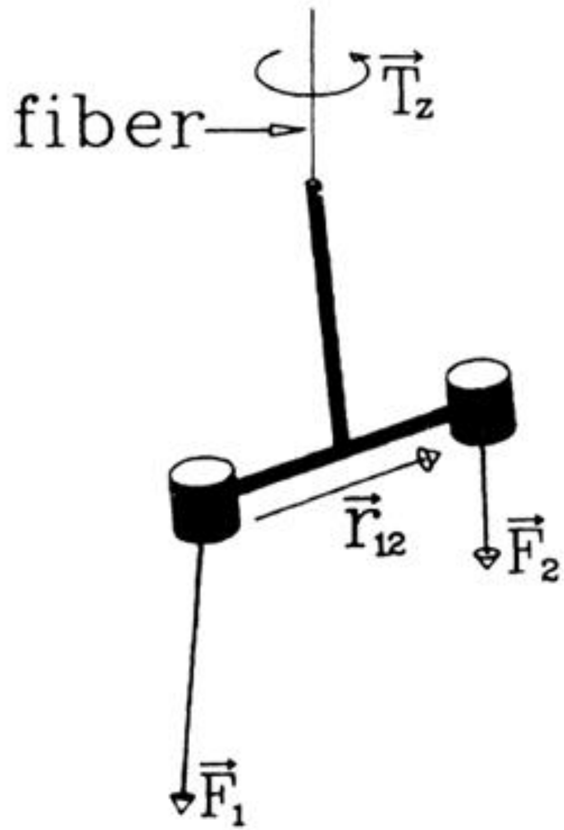
At present, the strongest limits on EP violation are from the MICROSCOPE space mission, which observed the motion of test masses of different materials in the gravitational field of the earth.



Direct searches have also been performed using suspended masses in the laboratory. At present, the limits are weaker than from direct searches.

Wagner, Schlamminger, Gundlach and Adelberger



Atomic clocks offer an alternative approach to detecting long-range fifth forces that are mediated by scalar fields.

Flambaum & Shuryak
Shaw

Consider, for example, a light scalar that couples to the photon field strength.

$$\mathcal{L} \supset \kappa\phi\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu}\right] \qquad\qquad \kappa = \sqrt{4\pi G}$$

It is possible to construct models in which the lightness of such a scalar is technically natural.

Brzemisnki, Chacko, Dev & Hook

Then the effective value of α at any location depends on the value of ϕ at that location.

$$\alpha(x) = \bar{\alpha}[1 + d_e\kappa\phi(x)]$$

Consider the electromagnetic contribution to the mass of the nucleon.

Through its dependence on α, the nucleon mass now has ϕ dependence.

$$m_N = m_N(\alpha(\phi))$$

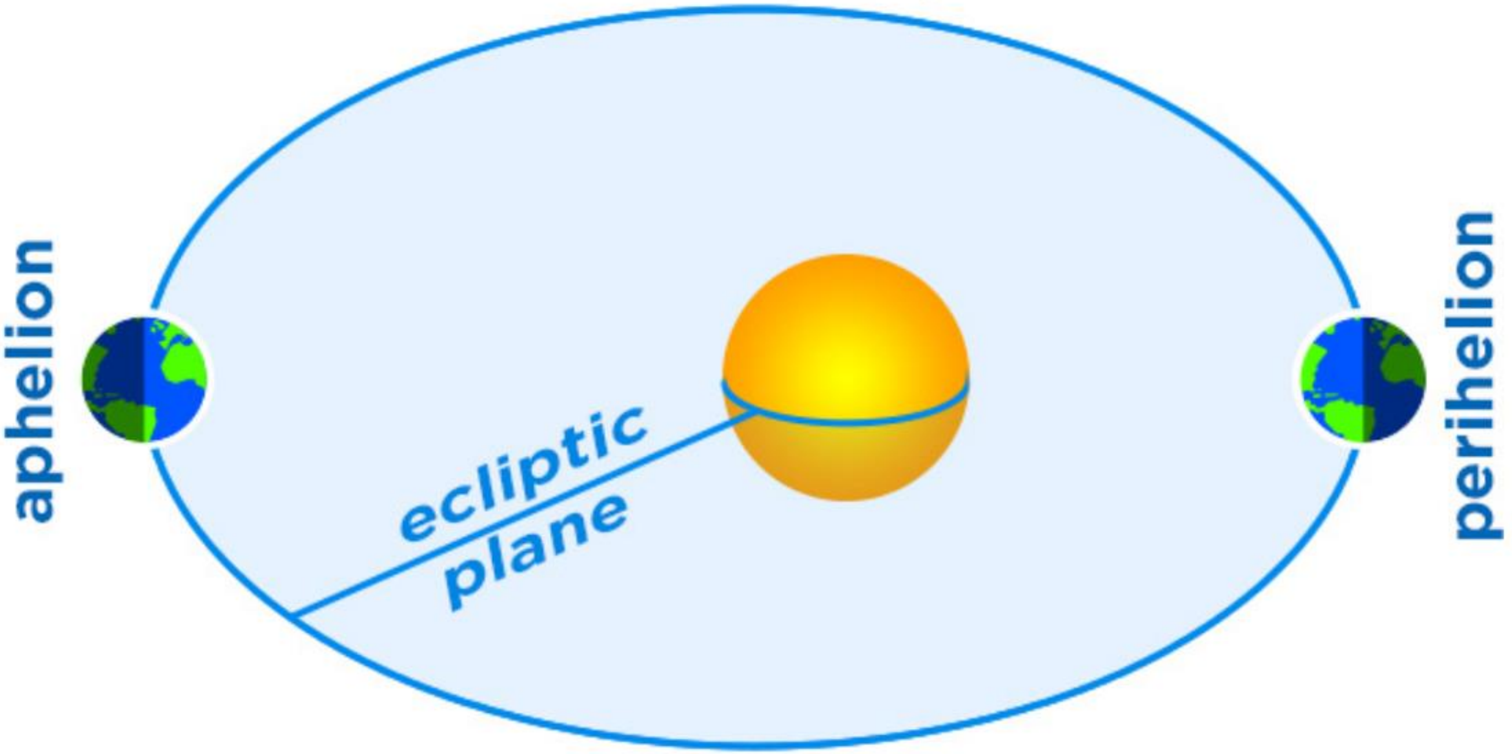
This translates into a Yukawa coupling between the nucleon and ϕ.

$$\mathcal{L} \supset m_N(\phi)\bar{N}N \to \left.\frac{\partial m_N}{\partial \phi}\right| \phi\bar{N}N$$

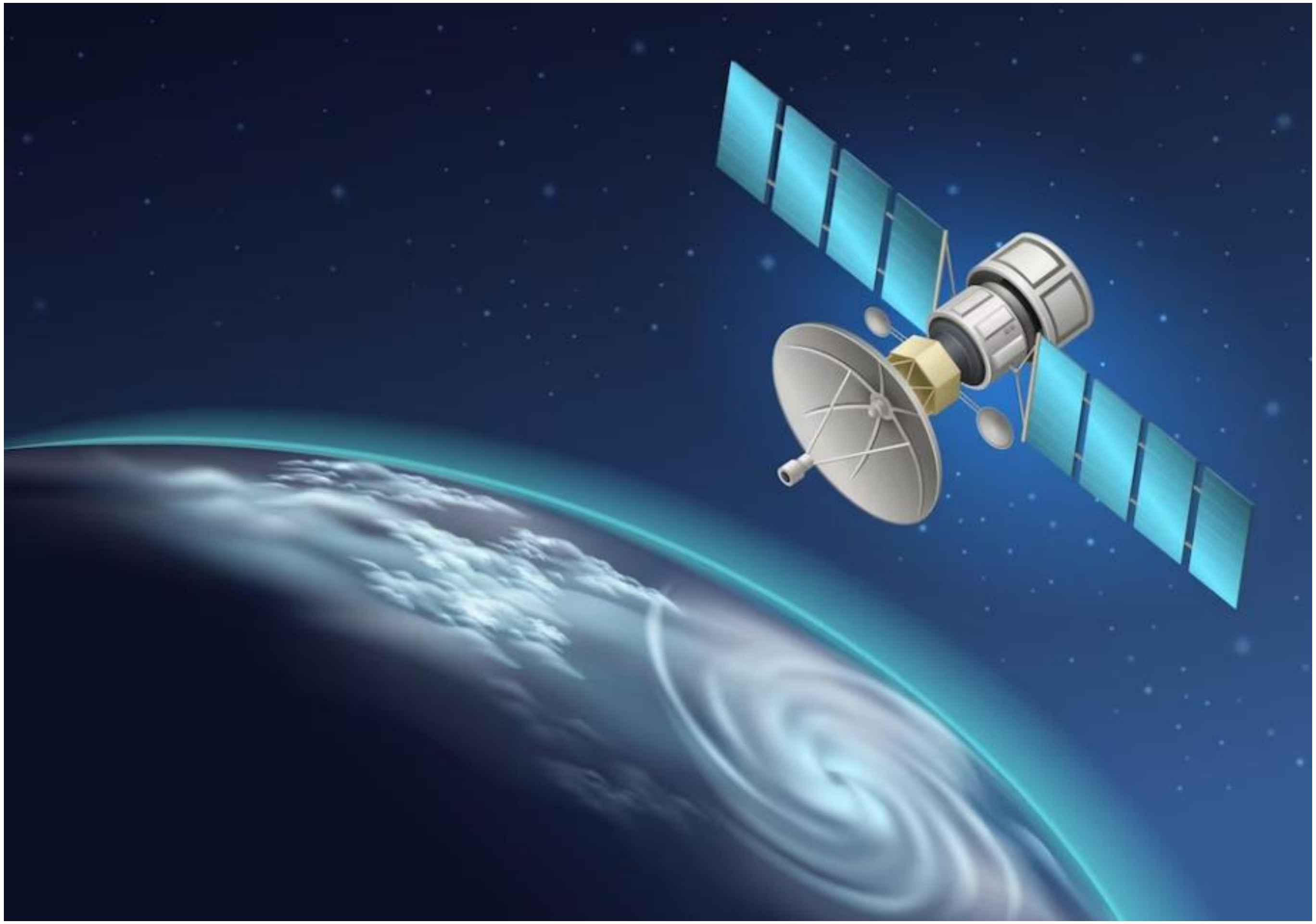
Then massive objects such as the earth and sun act as sources for ϕ.

The local value of ϕ, and therefore of α, depends on the distance from these sources!

The earth's orbit around the sun is an ellipse. Annual modulation in the value of α!



The value of α is different in space from what it is on earth!



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Atomic clocks can be used to detect changes in α. Very sensitive!

These clocks are based on the frequencies of spectral lines.

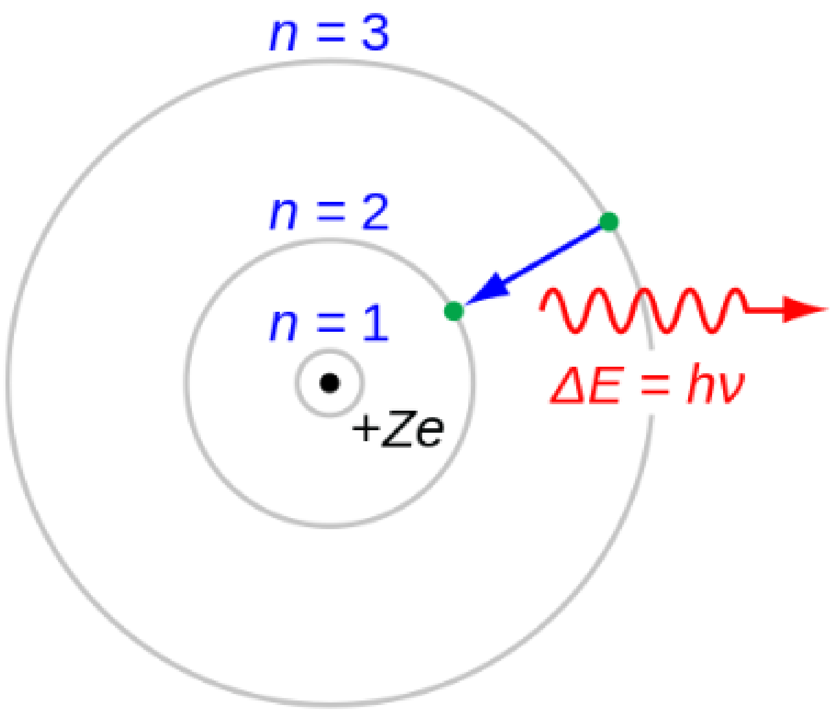
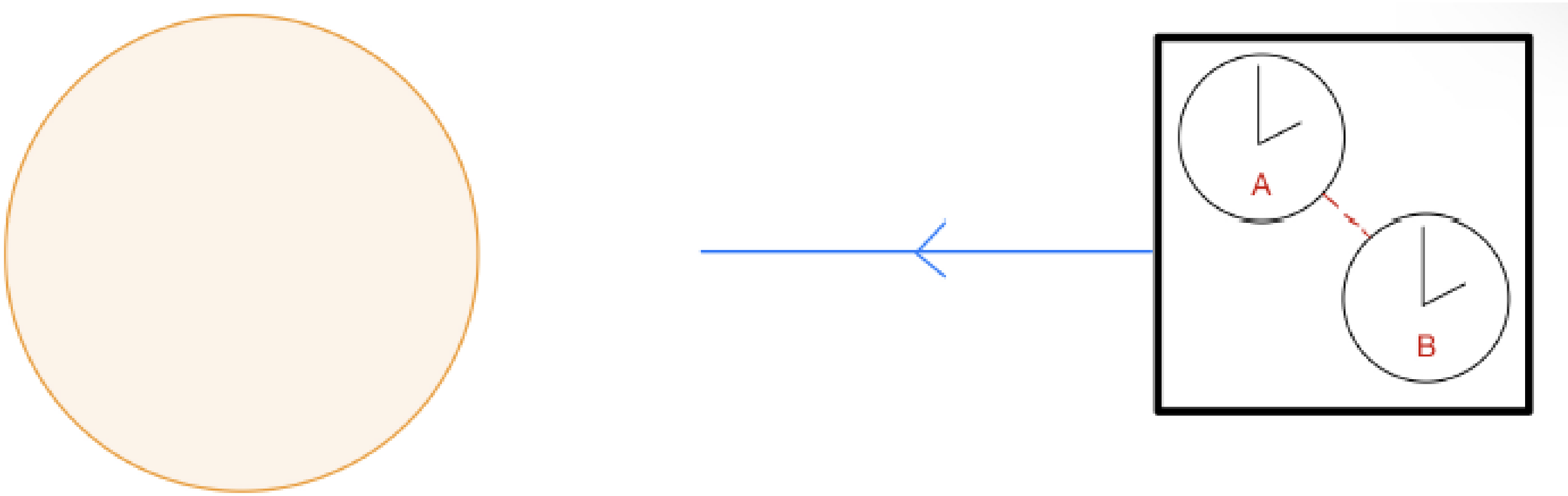


Image by JabberWok.

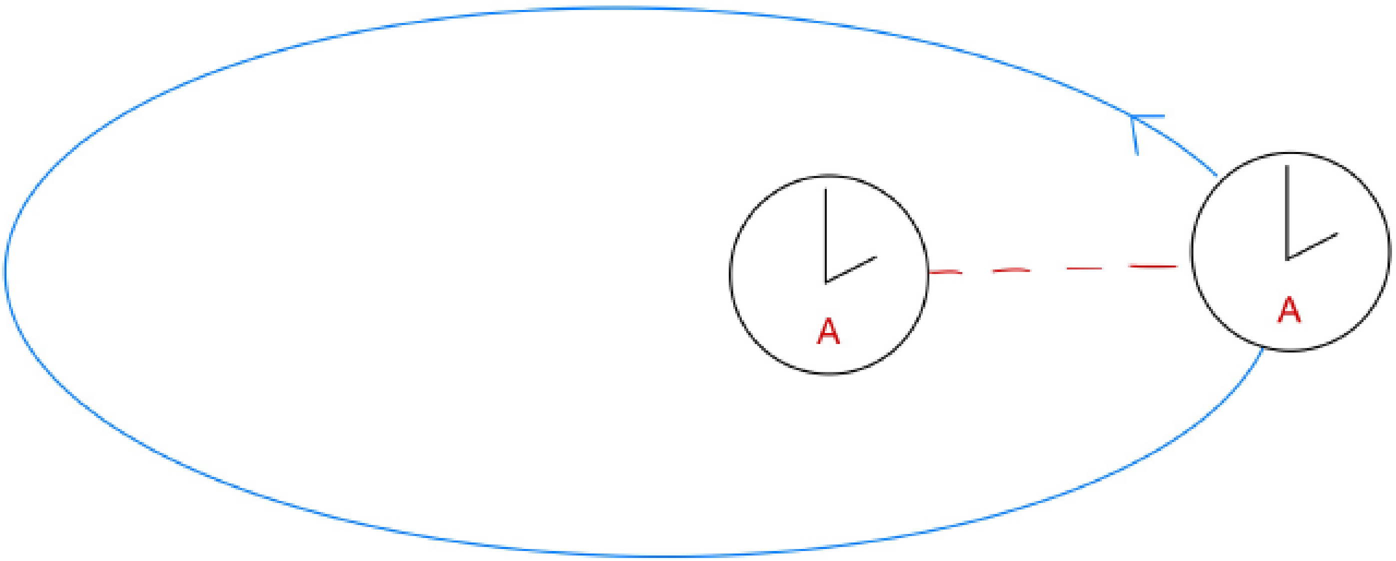
Changes in α will result in changes in the frequencies of these lines.

An experiment can be done with two different atomic clocks that at the same location on earth.



As the earth goes round the sun, the relative frequencies of the two clocks will change depending on the distance from the sun!

Alternatively, an experiment can be done with two identical atomic clocks at different locations, one on earth and the other in space.



The dependence of the frequencies of the two clocks on the difference in the gravitational potential can be used to probe EP violation.

Ultralight Scalars and EP Violation

The interactions of a light scalar field ϕ with the stable matter fields and light force carriers of the Standard Model can be parametrized as below.

Damour & Donoghue (2010)

$$\mathcal{L} \supset \kappa\phi\Big[\overbrace{\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu}}^{\text{coupling to photons}} - \overbrace{\frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu}}^{\text{coupling to gluons}} - \overbrace{d_{m_e}m_e\bar{\psi}_e\psi_e}^{\text{coupling to electrons}}$$

$$- \underbrace{\sum_{i=u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\Big]}_{\text{coupling to up and down quarks}} .$$

$$\kappa = \sqrt{4\pi G}$$

The limit $d_e = 0$, with all the other d equal corresponds to the EP-preserving limit of a Brans-Dicke scalar.

The scalar ϕ gives a correction to the force between two macroscopic bodies.

$$V = -G\frac{m_{\mathbf{A}} m_{\mathbf{B}}}{r_{\mathbf{AB}}}\left(1 + \alpha_{\mathbf{A}}\alpha_{\mathbf{B}} e^{-\frac{r_{\mathbf{AB}}}{\lambda}}\right)$$

Here $\lambda \equiv 1/m_\phi$ and the parameters α_{A} and α_{B} are functions of the couplings d but also depend on the compositions of the bodies A and B.

$$\alpha_{\mathbf{X}} \simeq d_g^* + \left[(d_{\hat{m}} - d_g)Q_{\hat{m}} + (d_{\delta m} - d_g)Q_{\delta m} + (d_{m_e} - d_g)Q_{m_e} + d_e Q_e\right]_{\mathbf{X}} ,$$

The composition-independent (EP-preserving) part has been separated out,

$$d_g^* \equiv d_g + 0.093(d_{\hat{m}} - d_g) + 10^{-4}\left[2.7 d_e + 2.75(d_{m_e} - d_g)\right].$$

$$\alpha_{\mathbf{X}} \simeq d_g^* + \left[(d_{\hat{m}} - d_g)Q_{\hat{m}} + (d_{\delta m} - d_g)Q_{\delta m} + (d_{m_e} - d_g)Q_{m_e} + d_e Q_e\right]_{\mathbf{X}} ,$$

The composition dependence is contained in the parameters Q.

$$Q_{\hat{m}} \equiv -\frac{0.036}{A^{1/3}} - 1.4 \times 10^{-4}\frac{Z(Z-1)}{A^{4/3}} - 0.02\frac{(A-2Z)^2}{A^2},$$

$$Q_{\delta m} \equiv 1.7 \times 10^{-3}\frac{A-2Z}{A},$$

$$Q_e \equiv 7.7 \times 10^{-4}\frac{Z(Z-1)}{A^{4/3}} + 8.2 \times 10^{-4}\left(\frac{Z}{A} - \frac{1}{2}\right),$$

$$Q_{m_e} \equiv 5.5 \times 10^{-4}\left(\frac{Z}{A} - \frac{1}{2}\right).$$

Here Z and A are the atomic and mass numbers of the nuclei of which the material is composed.

At present, the most precise tests of EP violation are based on how two test bodies A and B composed of different materials accelerate toward a third body C, which is usually the earth or sun.

The experimental limits are expressed in terms of the Eotvos parameter,

$$\eta \equiv 2\frac{|\vec{a}_{\mathbf{A}} - \vec{a}_{\mathbf{B}}|}{|\vec{a}_{\mathbf{A}} + \vec{a}_{\mathbf{B}}|}$$

where $\boldsymbol{a}_{\mathrm{A}}$ and $\boldsymbol{a}_{\mathrm{B}}$ are the accelerations of A and B. In our parametrization,

$$\eta \approx (\alpha_{\mathbf{A}} - \alpha_{\mathbf{B}})\alpha_{\mathbf{C}}$$

Assuming the composition-independent part of α dominates (as is the case in most simple models), then we can approximate

$$\begin{aligned}\eta &\approx \left[\Delta Q_{\hat{m}}(d_{\hat{m}} - d_g) + \Delta Q_e d_e + \Delta Q_{m_e}(d_{m_e} - d_g)\right] d_g^* \\ &\approx \Delta Q_{\hat{m}} D_{\hat{m}} + \Delta Q_e D_e + \Delta Q_{m_e} D_{m_e} \ .\end{aligned}$$

Here $D_e \equiv d_g^* d_e$, $D_{\hat{m}} \equiv d_g^*(d_{\hat{m}} - d_g)$ and $D_{m_e} \equiv d_g^*(d_{m_e} - d_g)$

The experimental limits on EP violation become limits on the parameters D.

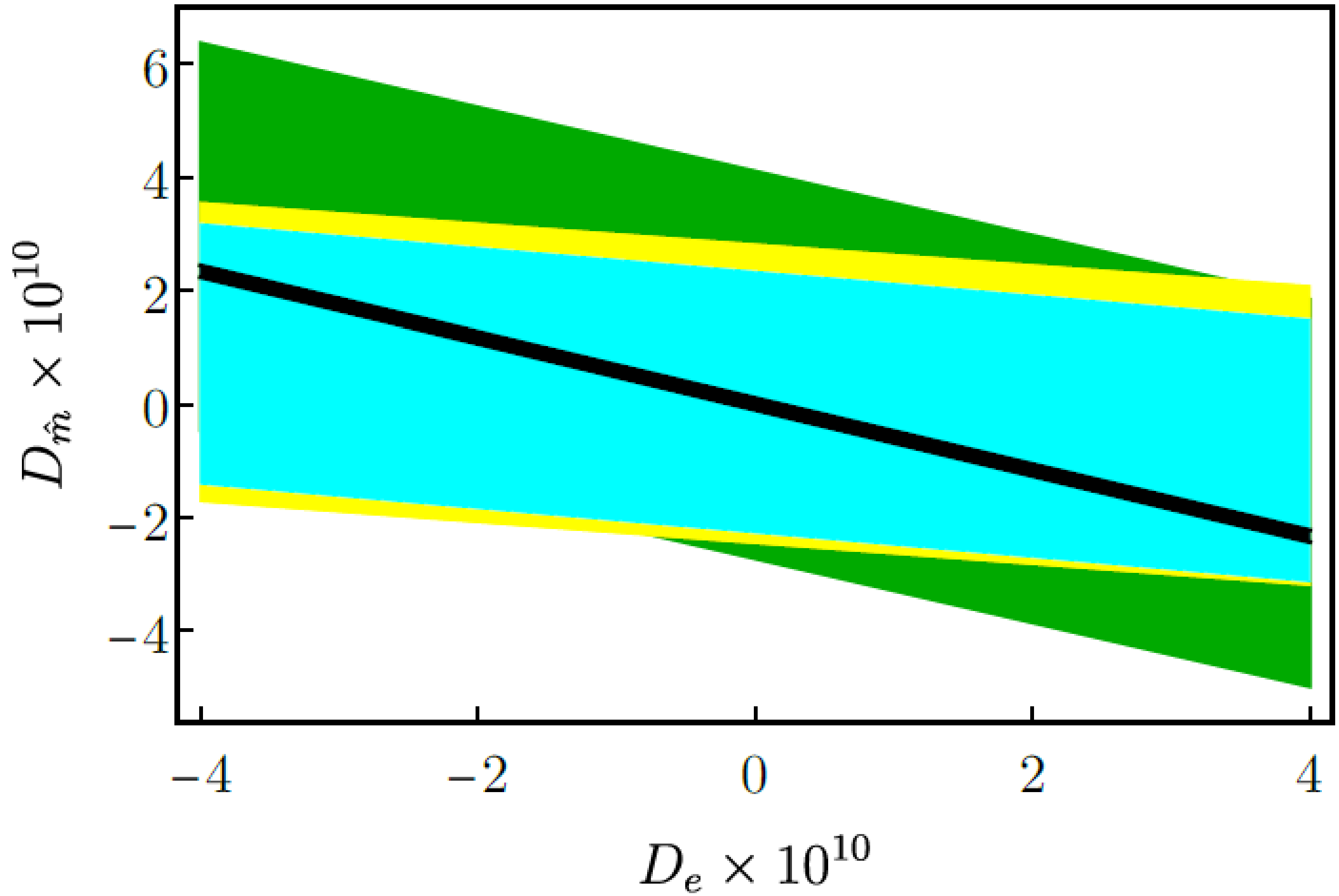


FIG. 1: Current bounds on D_e vs. $D_{\hat{m}}$ set by fifth force experiments [27, 30, 31, 67]. The black band represents the bound set by MICROSCOPE [31, 67], the blue and yellow bands are the constraints set by the EotWash group with Be-Ti and Be-Al masses [30], and the green band is the Moscow group's result obtained with Al-Pt masses [27].

We now turn our attention to clock searches for EP violation.

The principle of Local Position Invariance (LPI) states that the frequency f_A of any given clock A in its local frame is independent of its position in space.

$$f_A^{local}(x) = f_A^{local}(\infty)$$

The class of theories we are considering violate LPI since the values of fundamental constants are not the same at different points in space.

LPI violation is parametrized in terms of the anomalous redshift parameter β_A .

$$\frac{f_A^{local}(x) - f_A^{local}(\infty)}{f_A^{local}(\infty)} = \beta_A U(x)$$

In general, the value of β_A depends on the clock A.

The dependence of a clock transition on fundamental parameters is conventionally parametrized as

$$f_A \propto R\,\alpha^{K_\alpha^A}\mu^{K_\mu^A}X_q^{K_q^A} \propto m_e\,\alpha^{K_\alpha^A+2}\mu^{K_\mu^A}X_q^{K_q^A}$$

Here, *R* is the Rydbergh constant. $\mu \equiv m_p/m_e \quad X_q \equiv m_q/\Lambda_{QCD}$

The coefficients *K* characterize the sensitivity of a given transition to changes in the corresponding parameters. K_α and K_q must be calculated for each transition. K_μ= -1 for hyperfine, 0 for optical and +1 for nuclear transitions.

From this, we can obtain an expression for the anomalous redshift parameter,

$$\begin{aligned}\beta_A &= \left[(K_\alpha^A+2)d_e - K_\mu^A(d_{m_e}-d_g) + K_q^A(d_{\hat{m}}-d_g) + d_{m_e}\right]\alpha_{\mathbf{X}} \\ &\approx (K_\alpha^A+2)D_e + (1-K_\mu^A)D_{m_e} + K_q^A D_{\hat{m}} + D_g\ .\end{aligned}$$

Once again, limits on EP violation become limits on the parameters *D*.

At present, the bounds on β from annual modulation experiments are at the level of 10^{-7}. This leads to the limits below.

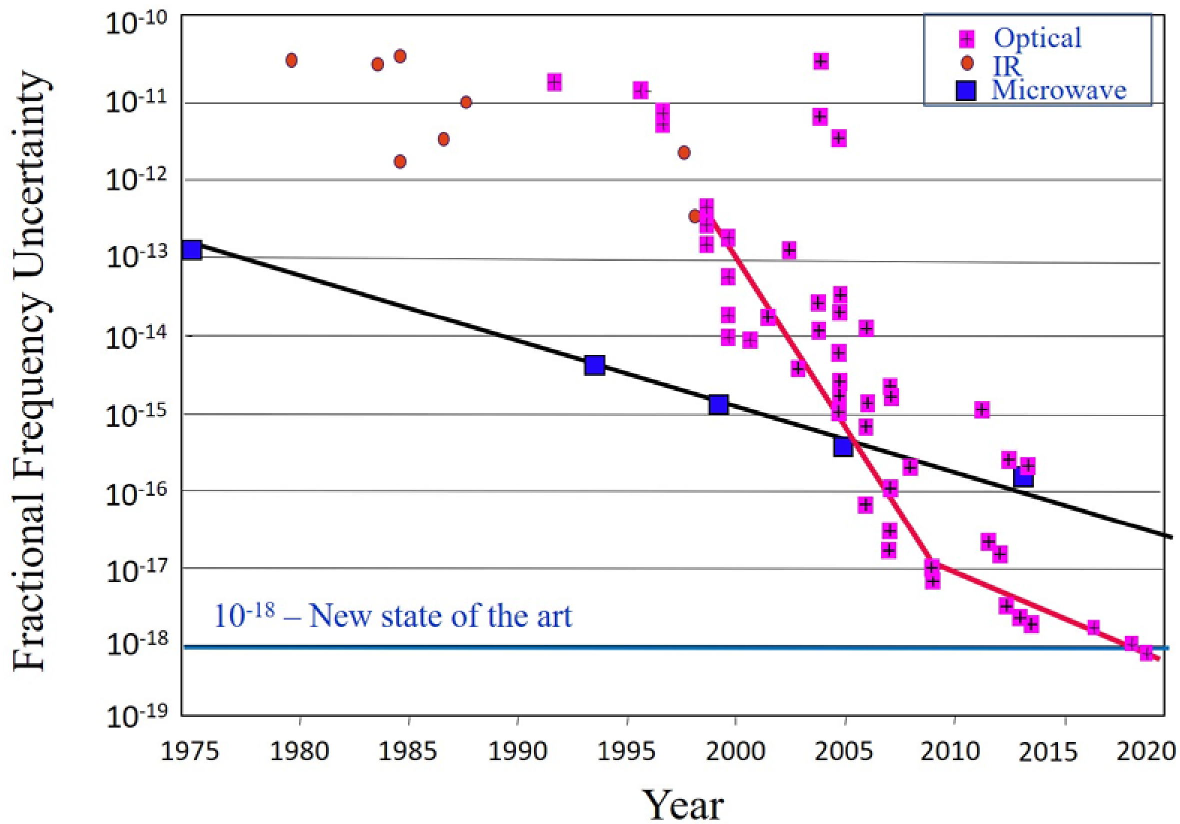
$$D_e \lesssim 10^{-8}, \quad D_{m_e} \lesssim 10^{-6}, \quad D_{\hat{m}} \lesssim 10^{-6}$$

About three orders of magnitude weaker than limits from direct searches.

The bounds on β from satellite experiments are at the level of 10^{-5}. Much weaker than limits from direct searches.

Future Prospects

The precision of atomic clocks has been improving rapidly, by an order of magnitude every 7 years or so. Derevianko et al. (2021)



Based on current projections, atomic clock searches for annual modulation will be competitive with direct searches within the next two decades.

Nuclear clocks are a potential game changer!

The thorium 229 nucleus has an excited state that lies a few eV above the ground state.

The excited states of nuclei are typically separated by energies of order an MeV. The fact that this splitting is so small indicates a very delicate cancellation between nuclear and electromagnetic effects.

This makes the splitting exquisitely sensitive to changes in fundamental parameters. A 1% change in α would change the splitting between the ground state and excited state by two orders of magnitude!

A nuclear clock of the same precision as current atomic clocks would already be able to improve on the existing limits on EP violation by an order of magnitude or more!

New space-based experiments have been proposed.

The SpaceQ proposal is two send two different atomic clocks on a spaceship towards the sun, first to Merury's orbit ($r = 0.39$ AU) and then to $r = 0.1$ AU.

Since the gravitational field, and hence the scalar field value, are much larger close to the sun, the sensitivity could exceed the current limits on EP violation even with current clock technology.

The FOCOS experiment proposes to place a satellite carrying an optical clock in an elliptical orbit around the earth. It would communicate with an identical clock on earth.

Even with existing clock technology, this would be competitive with the current limits on EP violation for scalar fields that couple primarily to electrons! For more general couplings, nuclear clocks would be needed to improve on the current sensitivity.

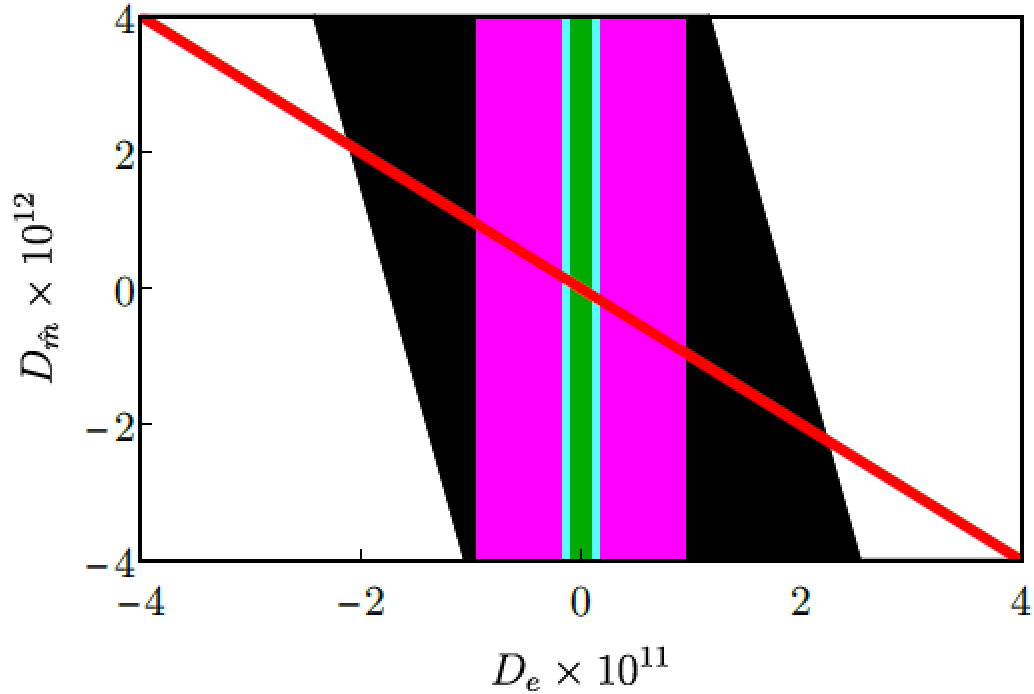


FIG. 4: In the $D_{\hat{m}}$ vs. D_e plane, we show how the projected limits from future earth and space based differential redshift experiments compare against the current bounds from direct fifth force searches. The black region represents the current bound set by MICROSCOPE [31, 67]. The magenta and light cyan lines show the projected sensitivity of the SpaceQ experiment [63] while traveling towards the $r = 0.39$ AU and $r = 0.1$ AU orbits respectively, assuming that the satellite is equipped with two optical clocks with $\Delta K_\alpha = 7$ and $\Delta\tilde{f}/\tilde{f} = 10^{-18}$. The green band shows the projected sensitivity of an earth based experiment based on two optical clocks with $\Delta K_\alpha = 7$, $\Delta K_q = 0$ and $\Delta\tilde{f}/\tilde{f} = 10^{-21}$. The red line shows the bound that could be set by an earth based nuclear clock - optical clock system, with $\Delta K_\alpha = 10^4$, $\Delta K_q = 10^5$ and $\Delta\tilde{f}/\tilde{f} = 10^{-18}$.

Conclusions

Atomic and nuclear clocks offer an alternative approach to testing EP violation mediated by ultralight scalar fields.

At present, these methods are not competitive with direct searches.

However, given the rapid improvements in clock technology and the proposals to place clocks in space, in the future these methods may offer the most sensitive probe of this class of theories.