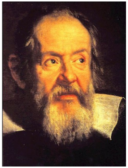
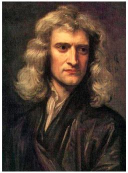
1500 years of universality of free fall


[Philiponus V$^{\text{th}}$ century, Galileo 1610, Newton 1687, Laplace 1780, Bessel 1850, Eötvös 1898]

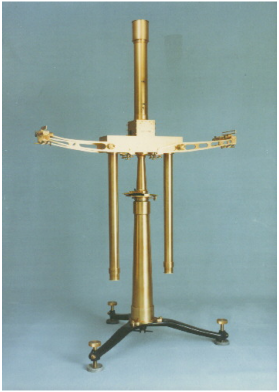
All test bodies follow the same universal trajectory in a gravitational field, independently of their mass and detailed internal structure and composition

$$m_i = m_g$$

$$\mathbf{F} = m_i \, \boldsymbol{a} \qquad (m_i = \text{inertial mass})$$

$$\mathbf{F}_g = m_g \, \boldsymbol{g} \qquad (m_g = \text{passive gravitational mass})$$

1898 Eötvös experiment



$$\eta_{\text{Eötvos}} = \left| \left(\frac{m_g}{m_i} \right)_A - \left(\frac{m_g}{m_i} \right)_B \right|$$

1911 Einstein's equivalence principle

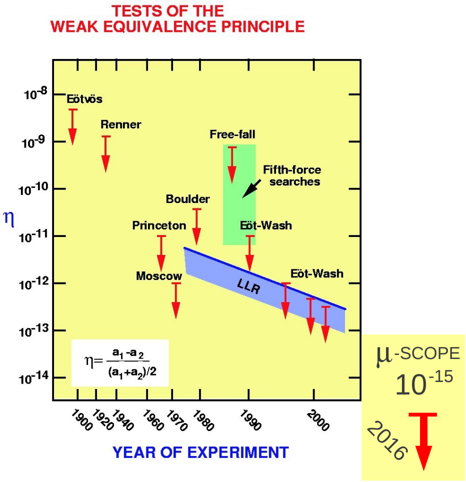
1. Weak equivalence principle. Implies the existence of preferred frames in free fall with all test bodies
2. Local Lorentz invariance. The result of any non gravitational experiment performed in a freely falling frame is independent of the velocity of the frame
3. Local position invariance. The result of any non gravitational experiment in a freely falling frame is independent of the position in space and time

EEP is equivalent to a universal coupling of matter to the metric [Will 1993]

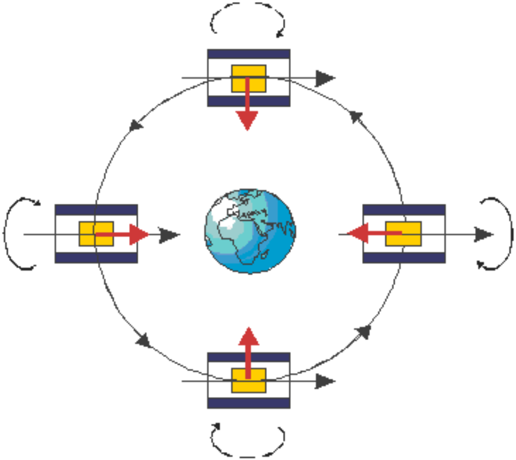
$$g_{\mu\nu}$$

which reduces to the Minkowski metric in freely falling frames

100 years of tests of the weak equivalence principle



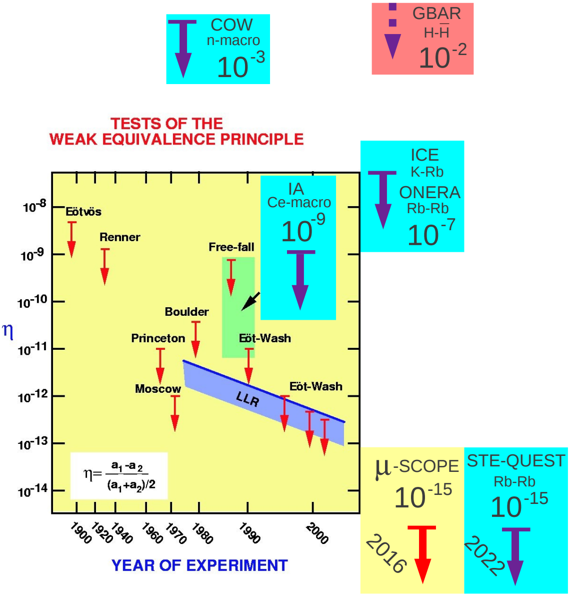
2016 The μ-SCOPE experiment [Touboul *et al.* 2010]



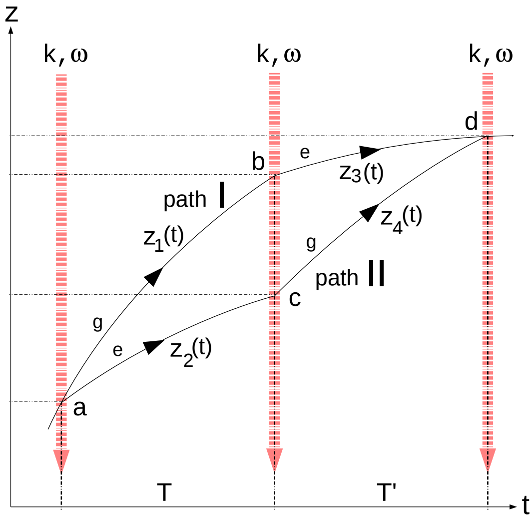
Expected accuracy 10^{-15}

Two accelerometers
Pt−Pt and Pt−Ti

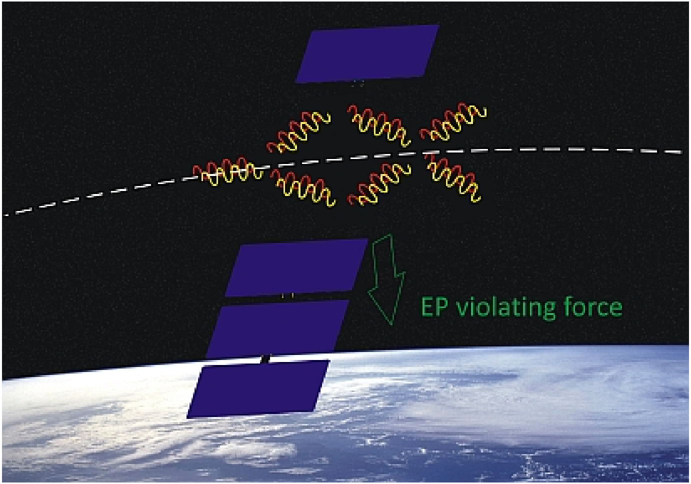
1975-2025 Quantum tests of the equivalence principle



1998 Atom interferometry

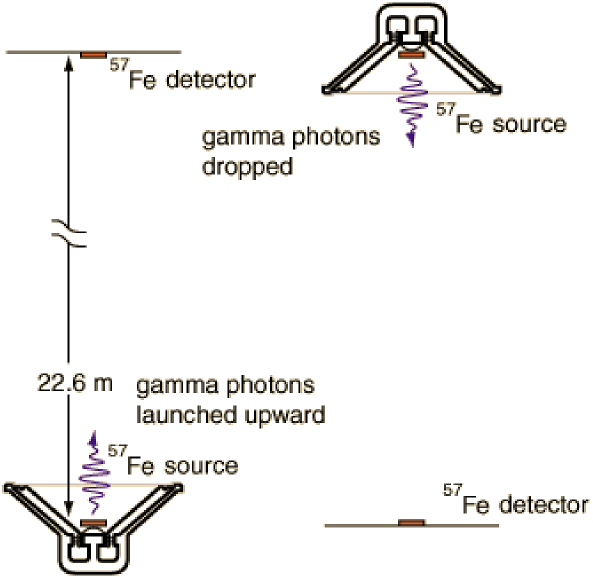


2025 STE-QUEST experiment [Bouyer, Rasel, Wolf *et al.* 2014]

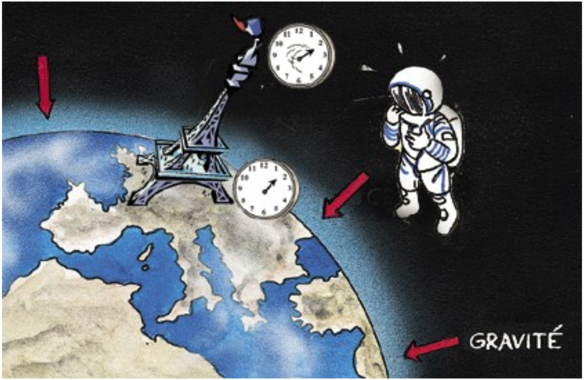


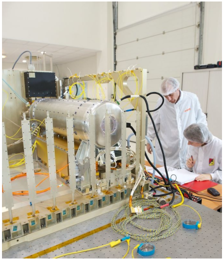
Expected accuracy 10^{-15}

1960 Pound-Rebka experiment



2017 Atomic Clock Ensemble in Space [Cacciapuoti & Salomon 2009]

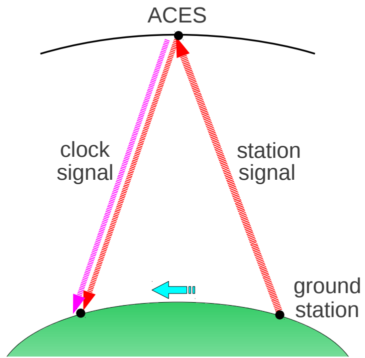




Expected accuracy 10^{-6}

PHARAO atomic clock

2017 Testing the gravitational redshift with Pharao/ACES

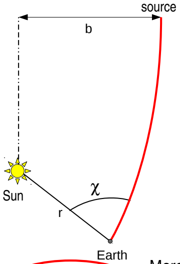


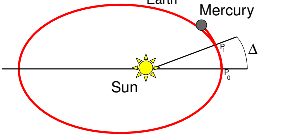
Prediction from GR in a two-way transfer

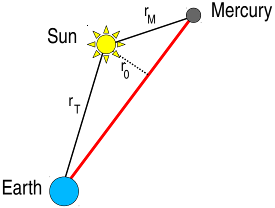
$$\boxed{\frac{\Delta\nu}{\nu} = \frac{1}{c^2}\left[\Delta U - \frac{1}{2}\mathbf{v}^2 - \mathbf{R}\cdot\mathbf{a}\right]\left(1 + \frac{1}{c}\mathbf{N}\cdot\mathbf{v}\right) + \mathcal{O}\left(\frac{1}{c^4}\right)}$$

This will permit to test the redshift with an accuracy of 2×10^{-6}

1915-1964 Classical tests in the Solar System







Light deflection [Einstein 1915; Eddington 1919]

$$\delta\chi = \frac{2G\,M}{c^2 r \tan\frac{\chi}{2}}\left(\frac{1+\gamma}{2}\right)$$

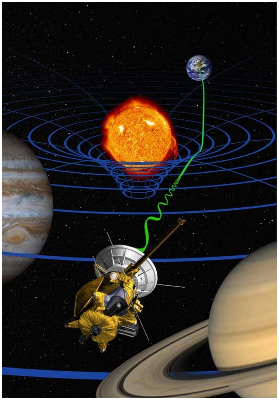
Perihelion precession [Le Verrier 1859; Einstein 1915]

$$\Delta = \frac{6\pi G\,M}{c^2\,p}\left(\frac{2+2\gamma-\beta}{3}\right) + 3\pi J_2\left(\frac{R}{p}\right)^2$$

Gravitational time delay [Shapiro 1964]

$$\delta T = \frac{4GM_\odot}{c^3}\left(\frac{1+\gamma}{2}\right)\left[\ln\left(\frac{4r_T\,r_M}{R_\odot^2}\right)+2\right]$$

1990-2020 Precision measurement of PPN parameters



- The best measurement of γ has been achieved using the navigation data of the CASSINI satellite [Bertotti *et al.* 2008]
- The best measurement of β is obtained by lunar laser ranging (LLR) and by high precision planetary ephemerides [Fienga, Laskar *et al.* 2013]
- GAIA will measure γ with precision 10^{-7}