Universality of free fall versus ephemeris (INPOP)

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INPOP

Intégrateur Numérique Planétaire de l’Observatoire de Paris

Planetary numerical integrator of the Paris Observatory

though, also developed a the Observatoire de la Côte d’Azur with A. Fienga

[Fienga et al., A&A 2008]
[Fienga et al., Celest. Mech. & Dyn. Astron. 2011]
[Fienga et al., Celest. Mech. & Dyn. Astron. 2015]
...

Theory: massless dilaton

$$S=\int d^4x\sqrt{-g}\left[\frac{1}{2\kappa}\left(R-2\left(\partial\varphi\right)^2\right)+L_m\left(g_{\mu\nu},\varphi;\Psi_i\right)\right]$$

Theory: massless dilaton

$$S=\int d^4x\sqrt{-g}\left[\frac{1}{2\kappa}\left(R-2(\partial\varphi)^2\right)+L_m(g_{\mu\nu},\varphi;\Psi_i)\right]$$

$$S_{point\ particles}=\sum_A\int m_A(\varphi)\,d\tau$$

Implies a violation of the **universality of free fall** (UFF)

Roughly: $\delta\vec{a}_A=-\frac{d\ln m_A}{d\varphi}\vec{\nabla}\varphi$ depends on composition of A

Linear coupling model:

[Damour & Donoghue, Phys. Rev. D 2010]

$$L_{\text{int}} = \varphi \left(\frac{d_e}{4e^2} F^2 - \sum_i d_{m_i} m_i \bar{\psi}_i \psi_i - d_g T_g^{anom} \right)$$

Coefficients parameterizing the coupling to different sectors

$$T_g^{anom} = \frac{\beta_3}{2 g_3} G^2 + \sum_i \gamma_{m_i} m_i \bar{\psi}_i \psi_i$$

An anomaly is said to occur when a symmetry of the classical action is not a true symmetry of the full quantum theory

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[Damour & Donoghue, Phys. Rev. D 2010]

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$$\delta \vec{a}_A = -\frac{d \ln m_A}{d\varphi} \vec{\nabla} \varphi$$

$$\frac{d \ln m_A}{d\varphi} = d_g^* + \bar{\alpha}_A$$

Dilatonic charges computed from atomic physics
(depends on atomic numbers A and Z)

$$\bar{\alpha}_A = \left[(d_{\hat{m}} - d_g) Q'_{\hat{m}} + (d_{\delta m} - d_g) Q'_{\delta m} + (d_{m_e} - d_g) Q'_{m_e} + d_e Q'_e \right]_A$$

Linear coupling model:

[Damour & Donoghue, Phys. Rev. D 2010]

At the end of the day:

$$\vec{a}_T = \vec{\nabla} \sum_A \frac{GM_A}{r_{AT}} (1+\delta_T)$$

$$\frac{m_A^G}{m_A^I} = 1 + \delta_A$$

$$\delta_T \sim d_g^* \bar{\alpha}_T$$

Parametrizes UFF violation

$$\bar{\alpha}_T = \left[(d_{\hat{m}} - d_g) Q'_{\hat{m}} + (d_{\delta m} - d_g) Q'_{\delta m} + (d_{m_e} - d_g) Q'_{m_e} + d_e Q'_e \right]_T$$

Non-linear generalization:

[Minazzoli & Hees, Phys. Rev. D 2016]

$$L_{\text{int}} = \left(\frac{D_e(\varphi)}{4e^2} F^2 - \sum_i D_{m_i}(\varphi) m_i \bar{\psi}_i \psi_i - D_g(\varphi) T_g^{anom} \right)$$

As well as generalization of gravity sector

$$S_G = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa} \left(f(\varphi) R - \frac{\omega(\varphi)}{\varphi} (\partial \varphi)^2 \right) \right]$$

In general:

[Minazzoli & Hees, Phys. Rev. D 2016]

At the end of the day:

$$\vec{a}_T = \vec{\nabla} \sum_A \frac{GM_A}{r_{AT}} \left(1 + \delta_T\right)$$

$$\delta_T \sim d_g^* \bar{\alpha}_T$$

New!

$$\vec{a}_T = \vec{\nabla} \sum_A \frac{GM_A}{r_{AT}} \left(1 + \delta_T + \delta_{AT}\right)$$

$$\delta_T \propto \left[d_g^* - \frac{f'}{2f} \right] \bar{\alpha}_T$$

$$\delta_{AT} \propto \bar{\alpha}_A \bar{\alpha}_T$$

$$\vec{a}_T = \vec{\nabla} \sum_A \frac{GM_A}{r_{AT}} \left(1 + \delta_T + \delta_{AT} \right)$$

Most of the time: $\delta_T \gg \delta_{AT}$

$$\delta_T \propto \left[d_g^* - \frac{f'}{2f} \right] \bar{\alpha}_T$$

$$\delta_{AT} \propto \bar{\alpha}_A \bar{\alpha}_T$$

But sometimes: $\delta_T <\sim \delta_{AT}$

In particular, for a universal coupling of the following form:

$$L_{\text{int}} = \sqrt{f(\varphi)} \left(\frac{1}{4e^2} F^2 - \sum_i m_i \bar{\psi}_i \psi_i - T_g^{anom} \right)$$

In general:

[Minazzoli & Hees, Phys. Rev. D 2016]

One truly has to consider:

$$\vec{a}_T = \vec{\nabla} \sum_A \frac{GM_A}{r_{AT}} \left(1 + \delta_T + \delta_{AT}\right)$$

1/ Because it can happen from a theoretical point of view

2/ Most importantly: when it happens, the theory is closer to satisfying UFF constraints

Or in other words

When it happens, the theory describes something closer to what we observe

What equation of motion goes in

INPOP?

What goes in INPOP

$$\boldsymbol{a}_T = -\sum_{A\neq T} \frac{\tilde{G}\tilde{m}_A}{r_{AT}^3}\boldsymbol{r}_{AT}\left(1+\delta_T+\delta_{AT}\right) - \boldsymbol{Q}_T$$
$$-\sum_{A\neq T} \frac{\tilde{G}\tilde{m}_A}{r_{AT}^3 c^2}\boldsymbol{r}_{AT}\Bigg\{\tilde{\gamma}v_T^2 + (\tilde{\gamma}+1)v_A^2 - 2(1+\tilde{\gamma})\boldsymbol{v}_A.\boldsymbol{v}_T - \frac{3}{2}\left(\frac{\boldsymbol{r}_{AT}.\boldsymbol{v}_A}{r_{AT}}\right) - \frac{1}{2}\boldsymbol{r}_{AT}.\boldsymbol{a}_A$$
$$-2(\tilde{\gamma}+\tilde{\beta}+\mathrm{d}\tilde{\beta}^T)\sum_{B\neq T}\frac{\tilde{G}\tilde{m}_B}{r_{TB}} - (2\tilde{\beta}+2\mathrm{d}\tilde{\beta}^A-1)\sum_{B\neq A}\frac{\tilde{G}\tilde{m}_B}{r_{AB}}\Bigg\} \quad (1)$$

Post-Newtonian EIH equation of motion

$$\delta_T \sim \alpha_0\left(d_{\hat{m}}Q'_{\hat{m}}|_T + d_{\delta m}Q'_{\delta m}|_T + d_{m_e}Q'_{m_e}|_T + d_e Q'_e|_T\right) - \eta\frac{|\Omega_A|}{m_A c^2}, \quad (2)$$

← Nordtvedt effect

where Ω_A is the gravitational binding energy while $m_A c^2$ is the rest mass energy. We also have

$$\delta_{AT} \sim \left(d_{\hat{m}}Q'_{\hat{m}}|_A + d_{\delta m}Q'_{\delta m}|_A + d_{m_e}Q'_{m_e}|_A + d_e Q'_e|_A\right) \times \left(d_{\hat{m}}Q'_{\hat{m}}|_T + d_{\delta m}Q'_{\delta m}|_T + d_{m_e}Q'_{m_e}|_T + d_e Q'_e|_T\right), \quad (3)$$

Usual PN param.

$$\tilde{\gamma} \propto 1-\alpha_0^2 \qquad \tilde{\beta} \propto 1+\beta_0\alpha_0^2 \qquad \eta \approx \alpha_0^2(1+4\beta_0)$$

In total, 6 parameters to be determined: $\alpha_0, \beta_0, d_{\hat{m}}, d_{\delta m}, d_{m_e}, d_e$

What about clocks?

$$\delta\left(\ln\frac{\nu_I}{\nu_J}\right)=\left(\hat{\delta}_I-\hat{\delta}_J+\hat{\delta}_{IA}-\hat{\delta}_{JA}\right)\frac{\delta W_A}{c^2}$$

Atomic spectroscopy

Coefficients given in [Minazzoli & Hees, Phys. Rev. D, 2016]

Gravitational redshift
e.g. ACES

$$\left.\frac{\Delta\nu}{\nu}\right|_{grav}=\frac{G\,m_E}{r_g}\left(1+\hat{\delta}_g+\hat{\delta}_{g\,E}\right)-\frac{G\,m_E}{r_s}\left(1+\hat{\delta}_s+\hat{\delta}_{s\,E}\right)$$

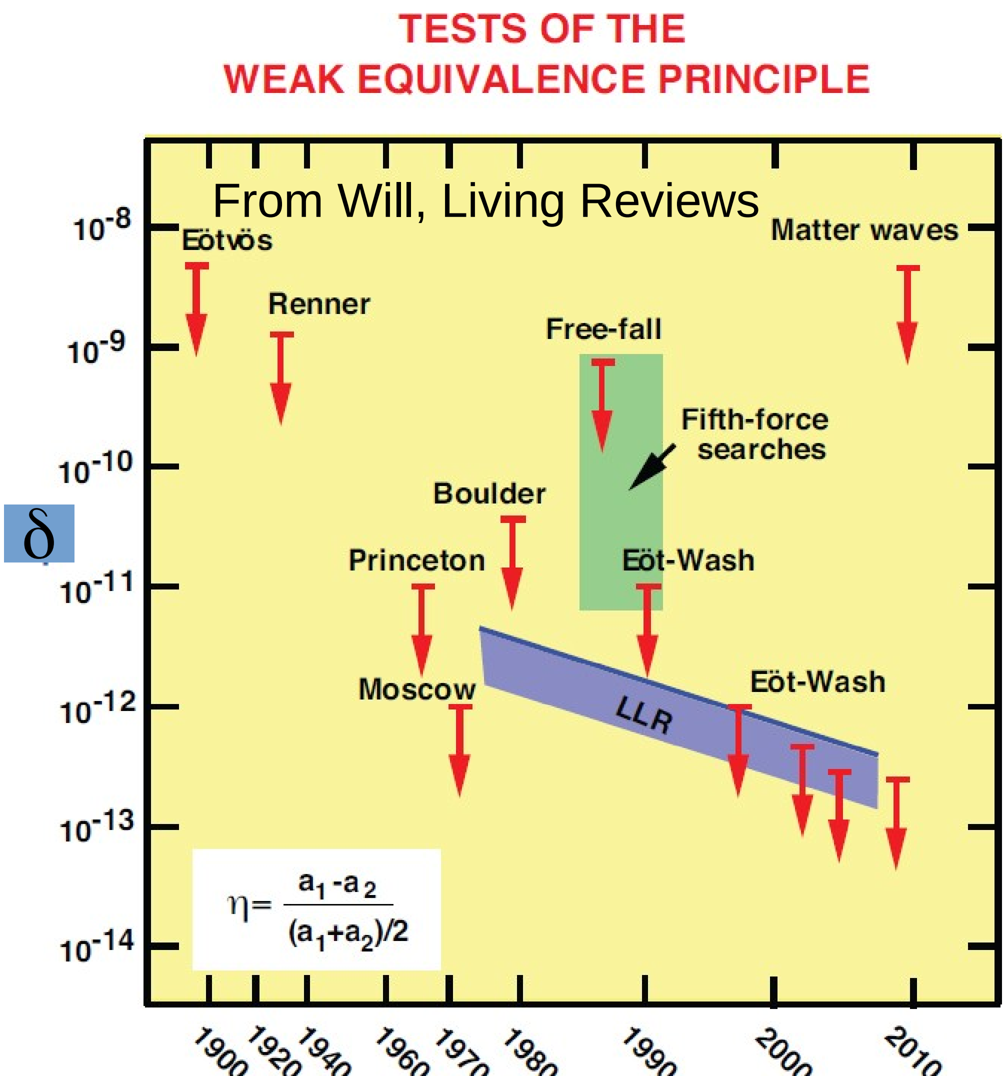
g stands for “*ground*”, and s for “*satellite*”

All the theory is given in

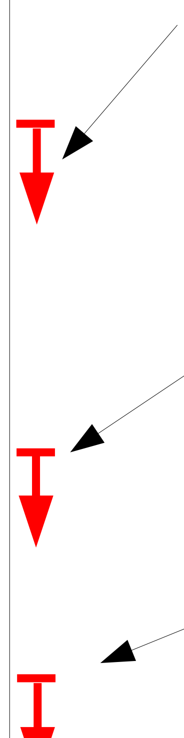
[Hees & Minazzoli, arXiv:1512.05233]

Currently being re-written, new version should appear soon

Results with INPOP are on their way



Expectations:



INPOP (planets)
Fienga et al.

INPOP (Moon)
Viswanathan, Fienga et al.

MICROSCOPE
(launched 2016)
Co-PI G. Metris

supplements

Linear coupling model:

[Damour & Donoghue, Phys. Rev. D 2010]

Remark:

$$\delta \vec{a}_A = -\frac{d \ln m_A}{d\varphi} \vec{\nabla} \varphi$$

$$\frac{d \ln m_A}{d\varphi} = d_g^* + \bar{\alpha}_A$$

$$\bar{\alpha}_A = \left[\left(d_{\hat{m}} - d_g\right) Q'_{\hat{m}} + \left(d_{\delta m} - d_g\right) Q'_{\delta m} + \left(d_{m_e} - d_g\right) Q'_{m_e} + d_e Q'_e \right]_A$$

$$d_g = d_{m_u} = d_{m_d} = d_{m_e}, \quad d_e = 0$$

→ UFF → ✔

$$L_{\text{int}} = -d_g \varphi \left(\sum_i m_i \bar{\psi}_i \psi_i + T_g^{anom} \right)$$

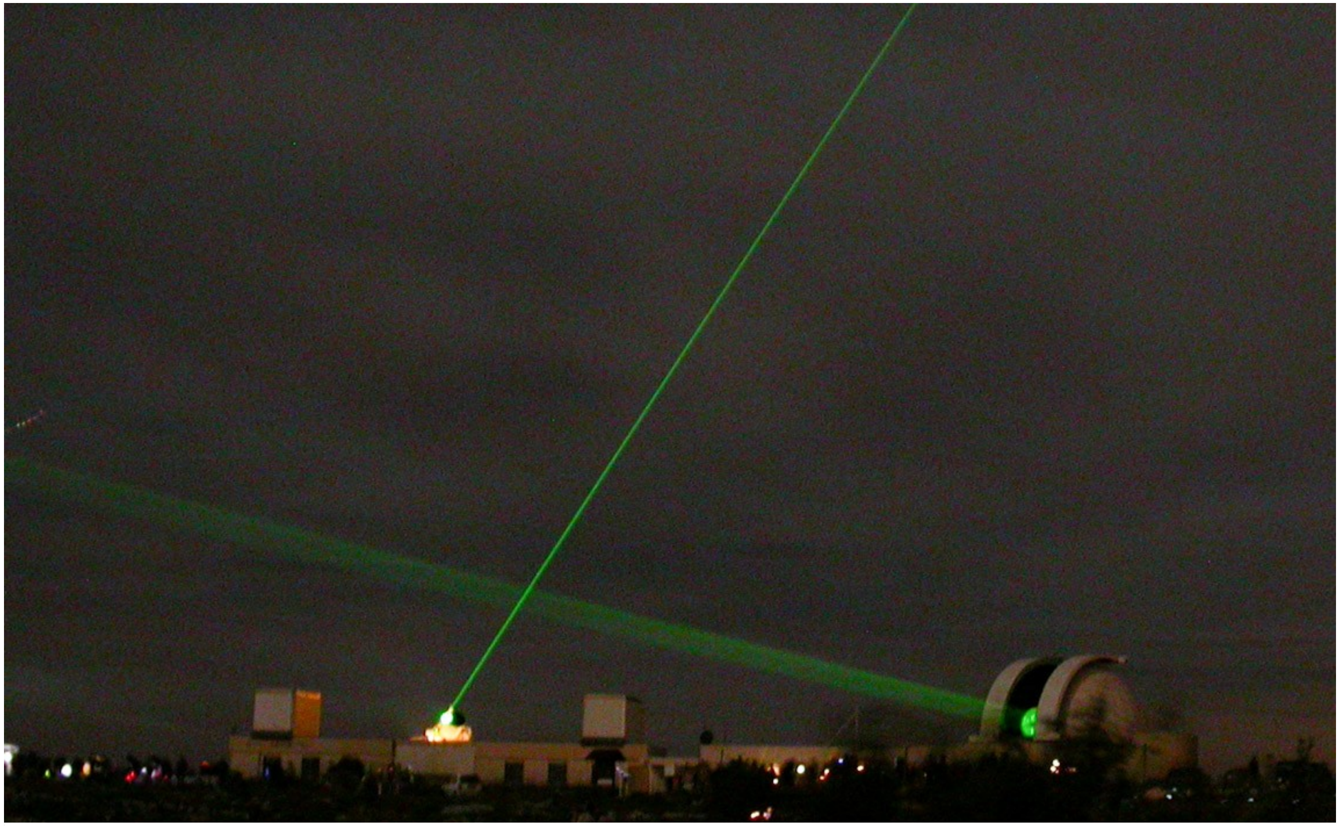
The Earth-Moon system

At the newtonian level, the relative acceleration between the Earth and the Moon reads

$$\boldsymbol{a}_M - \boldsymbol{a}_E = -\frac{\tilde{G}\tilde{\mu}}{r_{EM}^3}\boldsymbol{r}_{EM} + \tilde{G}\tilde{m}_S\left[\frac{\boldsymbol{r}_{SE}}{r_{SE}^3}(1+\delta_E+\delta_{SE}) - \frac{\boldsymbol{r}_{SM}}{r_{SM}^3}(1+\delta_M+\delta_{SM})\right], \qquad (9)$$

with

$$\tilde{\mu} \equiv \tilde{m}_M + \tilde{m}_E + (\delta_E + \delta_{EM})\tilde{m}_M + (\delta_M + \delta_{EM})\tilde{m}_E. \qquad (10)$$



Calern station

Observatoire de la Côte d'Azur

Lunar and satellite laser ranging

~50% of LLR data!!