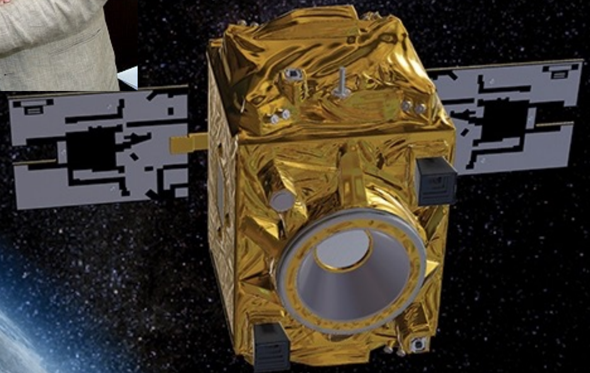


A la mémoire de
Pierre Touboul
(PI de MICROSCOPE)
1958-2021

La mission MICROSCOPE pour le test du principe d'équivalence

Gilles METRIS

pour l'équipe MICROSCOPE

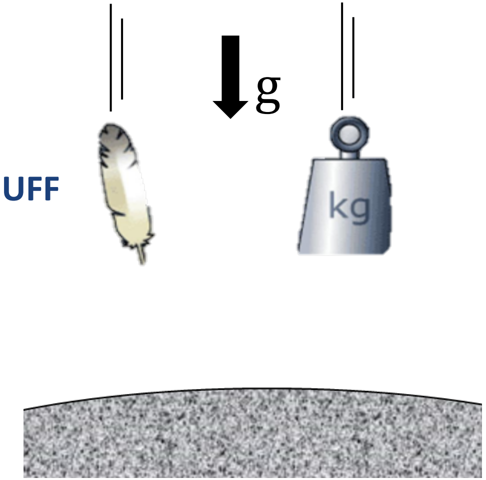
The Weak Equivalence Principle (WEP)

- The WEP states the identity between gravitational mass (the charge to which gravity couples) and inertial mass (how fast an object accelerates, given the same force)

gravitational mass

inertial mass

UFF

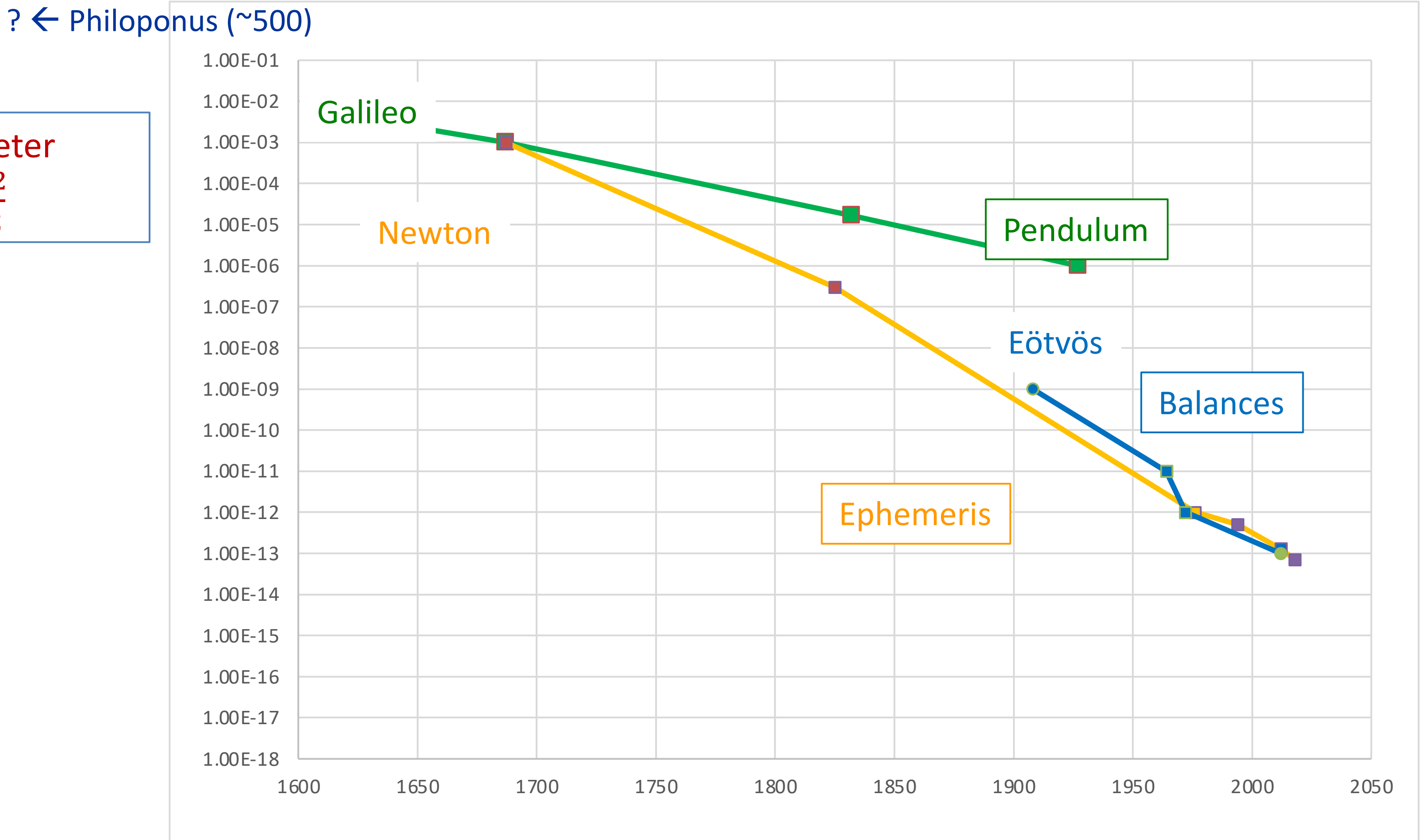


- Related to the Universality of Free Fall (UFF)
- Generalized by Einstein Equivalence Principle (not essential here)
- EP is fundamental for General Relativity (GR)

The WEP: an experimental result

Eötvös parameter

$$\eta \simeq \frac{mg1}{mi1} - \frac{mg2}{mi2}$$



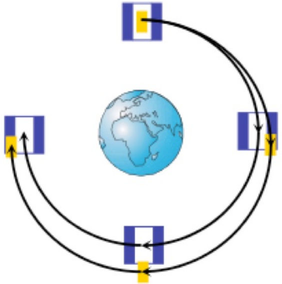
Why continue to test?

- **Everything looks in order…**
  - WEP is very well tested ($\simeq 10^{-13}$ before MICROSCOPE)
  - All predictions of GR have been verified

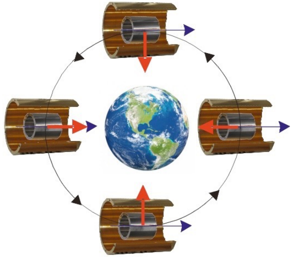
- **…but not completely**
  - Despite its name, EP is not a fundamental law of physics
  - Problem to unify GR and particle physics
  - Unification models suggest violation of the EP at a very low level:
    - 10^{-12}-10^{-22} [Dilaton, Damour & Polyakov 1994].
    - 10^{-12}-10^{-16} [U boson, Fayet 2018].

MICROSCOPE: a test of the EP in space @10^{-15}

Free fall on the earth's surface



Free fall in orbit

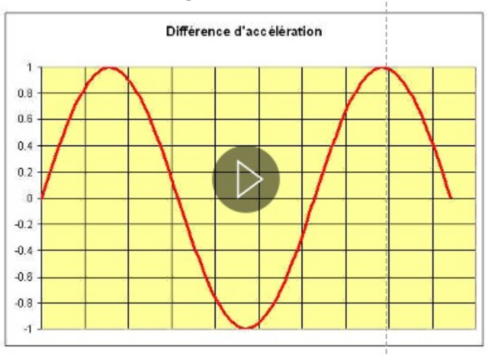


"Controlled" free fall in orbit

Objective:
compare the free fall of 2 test masses
of different compositions
with a gain of 2 orders of magnitude
➔ 10^{-15} accuracy for the Eötvös parameter
➔ Compare the accelerations @10^{-15} $g \simeq 8\ 10^{-15}$ ms^{-2}

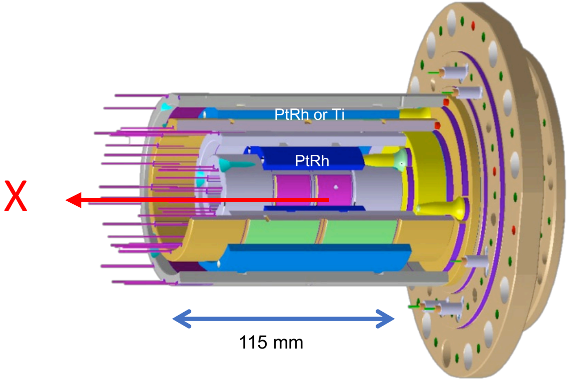
$$10^{-15} = \frac{M_{Drosophila}}{M_{SuperTanker}}$$

=



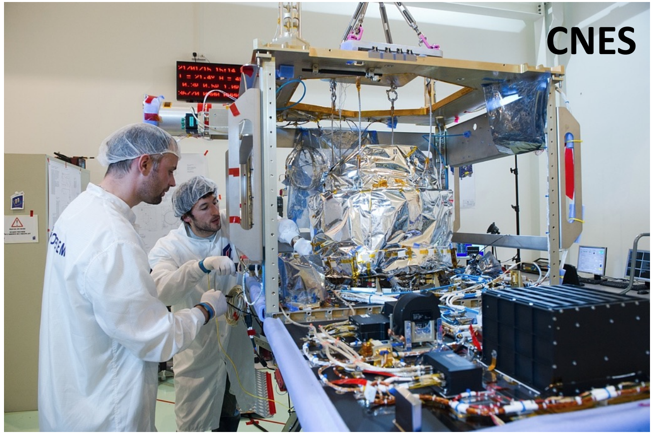
The payload: differential accelerometers (ONERA)

- **2 cylindrical, concentric, test masses surrounded by internal and external electrodes**
- **Servo loop:**
  - Capacitive detection of the displacement
  - Action: electrostatic force
  - Control law: motionless test-masses
- **The (measured) electrostatic force equilibrates all other forces**
- **2 differential accelerometers:**
  - SUEP = 1 mass in PtRh10 and 1 mass in Ti
  - SUREF = 2 masses in Pt



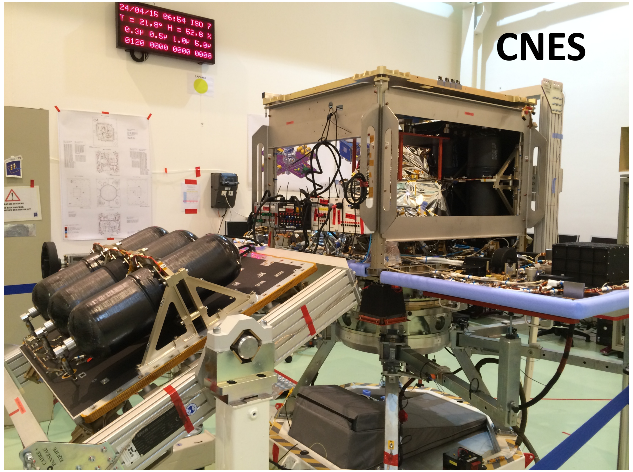
The satellite (CNES)

- **1.4m x 1m (2.8 with solar panels deployed) x 1.3m ; ≃ 300 kg**
- **Payload at the center of the satellite in a thermal and magnetic cocoon**
- **No moving masses**
- **Cold gas thrusters micro propulsion to ensure attitude and acceleration control**



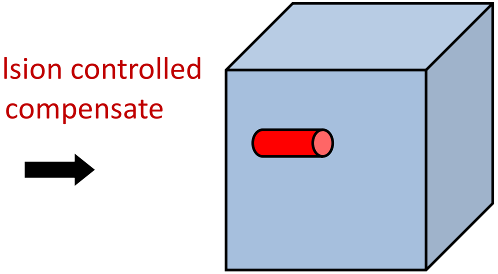
- **Sun synchronous orbit @ 710 km (T = 6000 s)**
- **Several modes :**
  - (quasi) inertial pointing $f_{EP} = f_{orb} = 1.7\times10^{-4}$ Hz
  - 2 spin rates: $f_{EP} = f_{orb} + f_{spin}$

    ➔ $f_{EP} = 0.9\times10^{-3}$Hz & $f_{EP} = 3.1\times10^{-3}$Hz

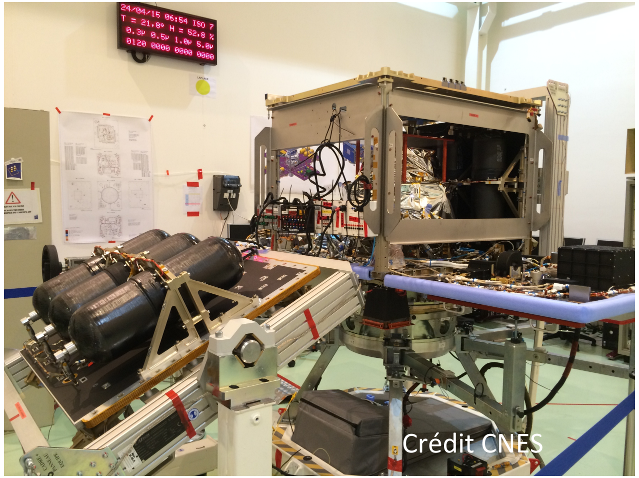


Attitude and Acceleration Control System (SCAA)

Propulsion controlled to compensate



"Natural" non gravitational forces and torques



Cold gas thrusters (similar to GAIA or LPF)
- 8 thrusters, 6 tanks, 16.5 kg of gas @ 300 bars

Residual acceleration < 3×10^{-13} ms^{-2}
Angular stability < 10^{-6} rad

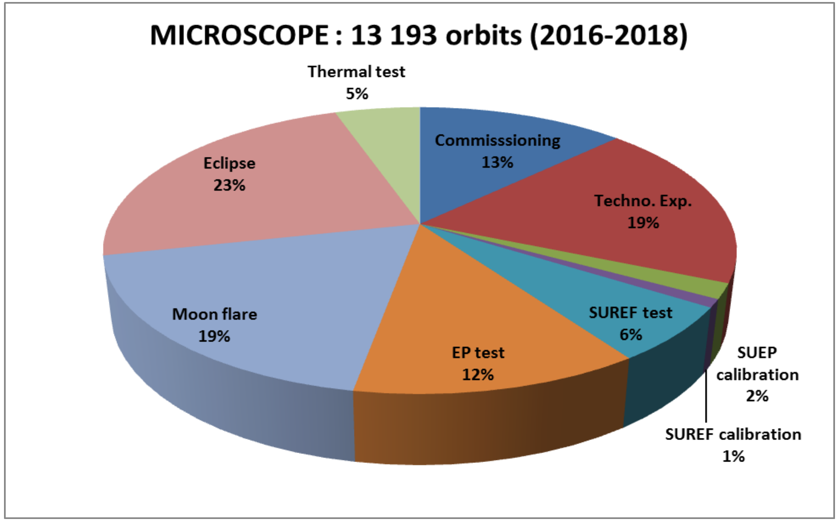
} @ test frequency

The mission (CNES – ONERA – OCA – ESA)

- Launched on the 25th of April 2016
- Switched off on the 16th of October 2018
- 20% of the 2.5 years (2768 orbits) dedicated to science

Configuration	Number of cumulated orbits SUREF	SUEP
EPR_{V2}	563	240
EPR_{V3}	214	1402
	53 days	113 days

Orbital period: T = 5946 s = 1.65 h



The measurement model

Dynamics

$$\overrightarrow{\gamma}^{(i)} = -[\mathbf{T}]\,\overrightarrow{GO}_i$$ *Gravity gradient*

$$+(\delta_S - \delta_i)\overrightarrow{g}$$ *EP violation*

Inertia $$+[\mathbf{In}]\,\overrightarrow{GO}_i + 2\,[\mathbf{\Omega}]\,\overset{\circ}{\overrightarrow{GO}_i} + \overset{\circ\circ}{\overrightarrow{GO}_i}$$

$$+\frac{\overrightarrow{F}}{M}$$ *Satellite NG accel.*

$$-\sum_j \frac{\overrightarrow{fe_j}}{M}$$ *Sat. react. To other masses*

$$-\frac{\overrightarrow{fp_i}}{m_i}$$ *masse NG accel.*

$$-\overrightarrow{g}_S(m_i)$$ *Self gravity*

Instrument model

$$\overrightarrow{\Gamma}^{(i)} = \overrightarrow{b_0}^{(i)} + \left[\mathbf{A^{(i)}}\right]\overrightarrow{\gamma}^{(i)} + \overrightarrow{Q}^{(i)} + \left[\mathbf{C^{(i)}}\right]\dot{\overrightarrow{\Omega}}^{(i)} + \overrightarrow{n}^{(i)}$$

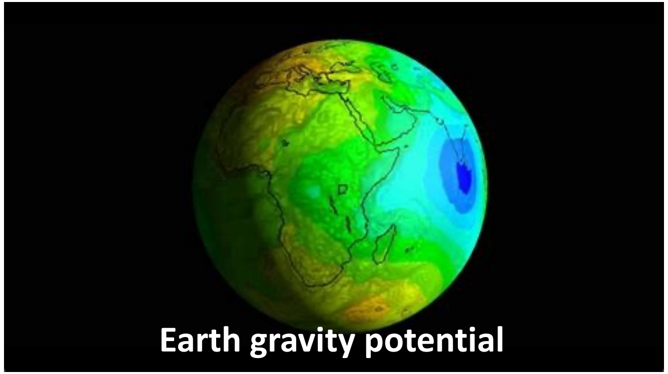
Difference

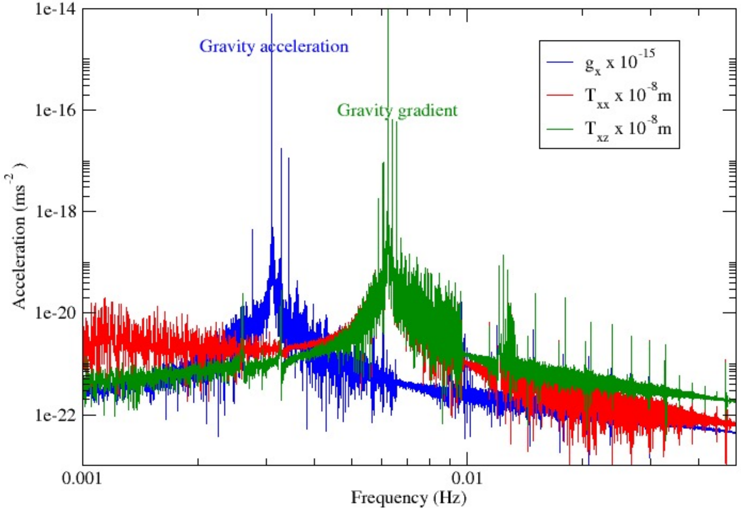
$$\vec{\Gamma}^{(d)} = \vec{\Gamma}^{(1)} - \vec{\Gamma}^{(2)}$$

X component

The gravity gradient

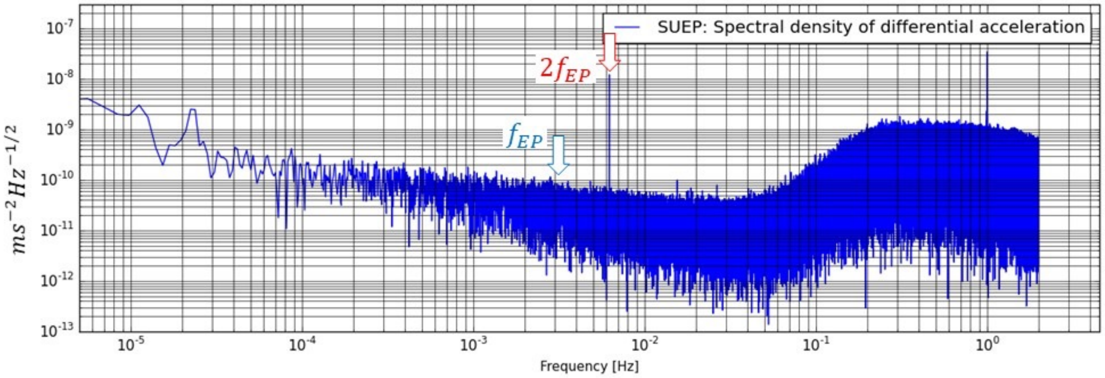
- Test masses are not perfectly concentric
- ➔ The measured differential acceleration is dominated by the gravity gradient:
  $a = [T]\,\Delta \simeq 10^{-6}\ s^{-2} \times 10^{-5}\ m = 10^{-11}\ ms^{-2}$
- Dominant w.r.t the expected limit of detection of a WEP signal ($8\ 10^{-15}\ ms^{-2}$), but
  - WEP @ $f_{ep}=f_{orb}+f_{spin}$ and GG @ 2 f_{ep}
  - [T(U,**r**)] accurately computed and **Δ** estimated
  - ➔ corrected


Earth gravity potential

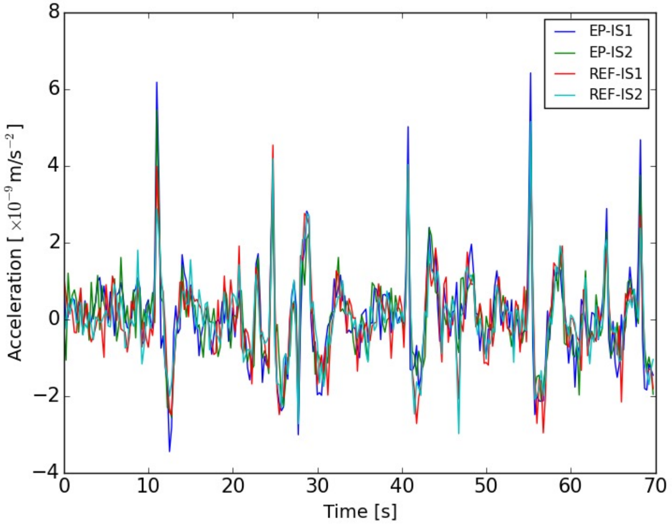


Available data

- EP tests are conducted in a very stable configuration during up to 120 orbital periods (8.26 days)
- 2 spin frequency used:
  $f_{\mathrm{spin}_2} = 7.57 \times 10^{-4}\mathrm{Hz}$ and $f_{\mathrm{spin}_3} = 2.94 \times 10^{-3}\mathrm{Hz}$
  ➔ $f_{\mathrm{EP}_2} = 9.25 \times 10^{-4}\mathrm{Hz}$ and $f_{\mathrm{EP}_3} = 3.11 \times 10^{-3}\mathrm{Hz}$
- 18 sessions with SUEP and 9 sessions with SUREF

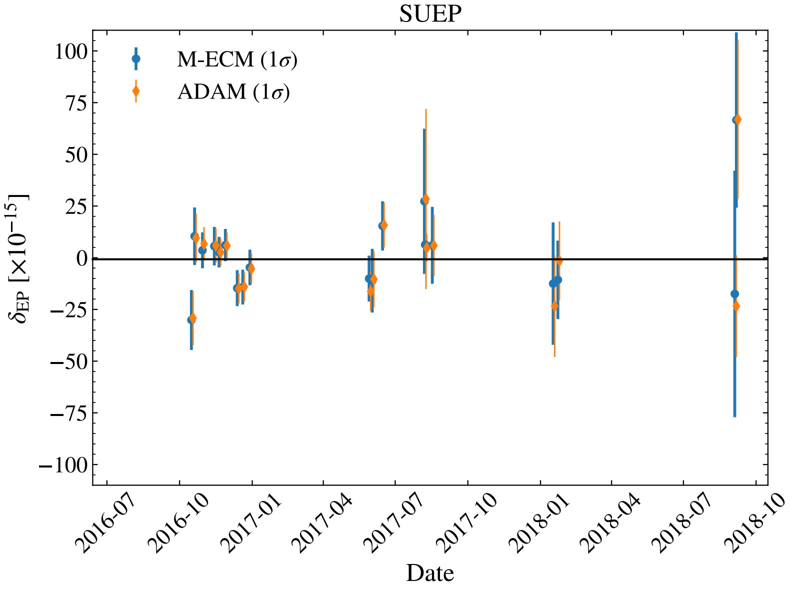


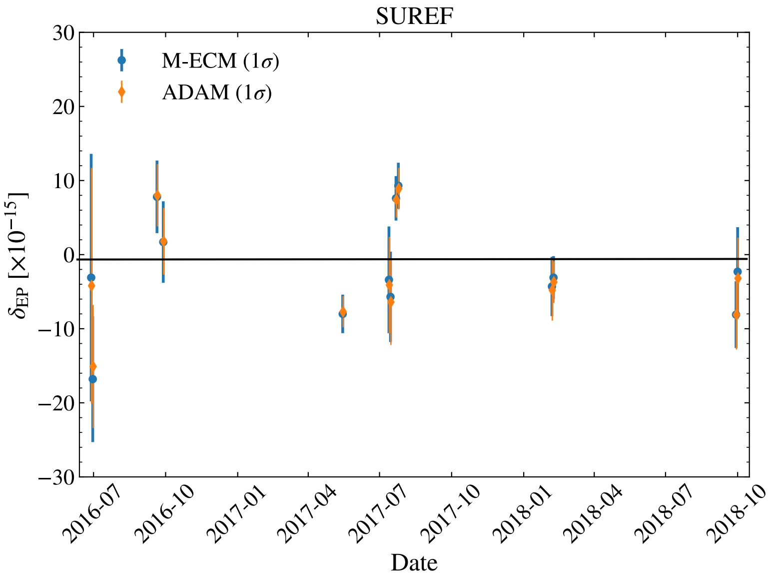
Glitches



- **Short and rather large accelerations detected simultaneously on all test masses**
- **➔ common origin, the satellite**
  - crackles of the MLI
  - Insulation from Sun and Earth modulated by the rotation
  - Contributions @ Fspin and Fep
- **Detection and elimination in the time domain**

Estimation of the Eötvös parameter for each segment

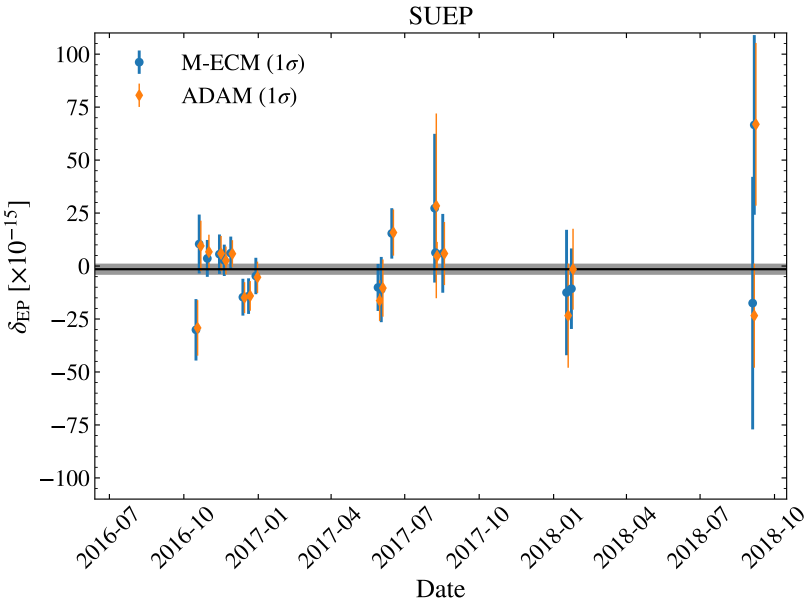


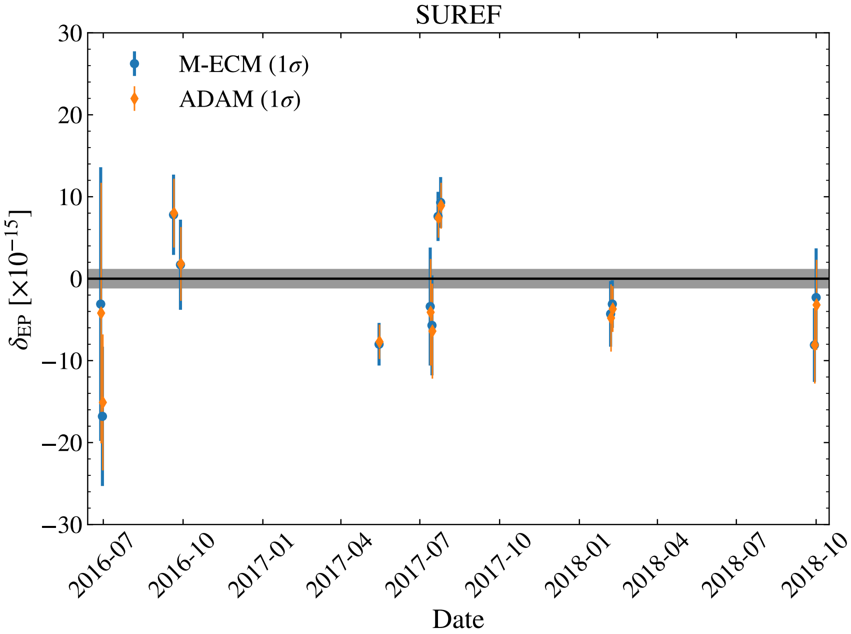


- All segments compatible with 0 @2σ except the first (2.2 σ)

All segments compatible with 0 @2σ
except the 3 segments @$\boldsymbol{f}_{\mathbf{spin_3}}$ which are between 3 and 3.5 σ

Global result

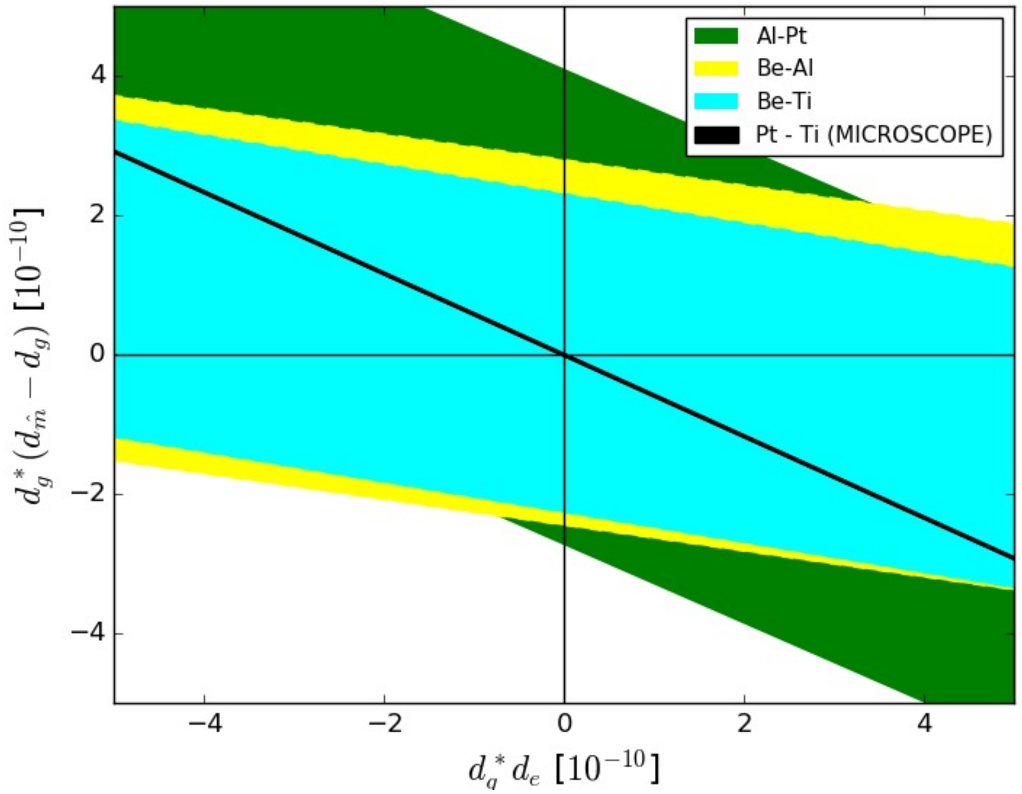




$\eta(\mathrm{Ti, Pt}) = [-1.5 \pm 2.3(\mathrm{stat}) \pm 1.5(\mathrm{syst})] \times 10^{-15}$

$\eta(\mathrm{Pt, Pt}) = [0.0 \pm 1.1(\mathrm{stat}) \pm 2.3(\mathrm{syst})] \times 10^{-15}$

Constraint on light dilaton with MICROSCOPE (published in 2017 and updated in 2022)



$$D_e = d_g^* d_e$$

Damour & Donoghue 2010

Scalar field couples non-universally to matter: coupling constants

$$(d_e, d_{m_u}, d_{m_d}, d_{m_e}, d_g)$$

EM quarks electrons gluons

Coupling to matter

$$\alpha_i \approx d_g^* + [(d_{\tilde{m}} - d_g)\, Q'_{\tilde{m}} + d_e Q'_e]_i$$

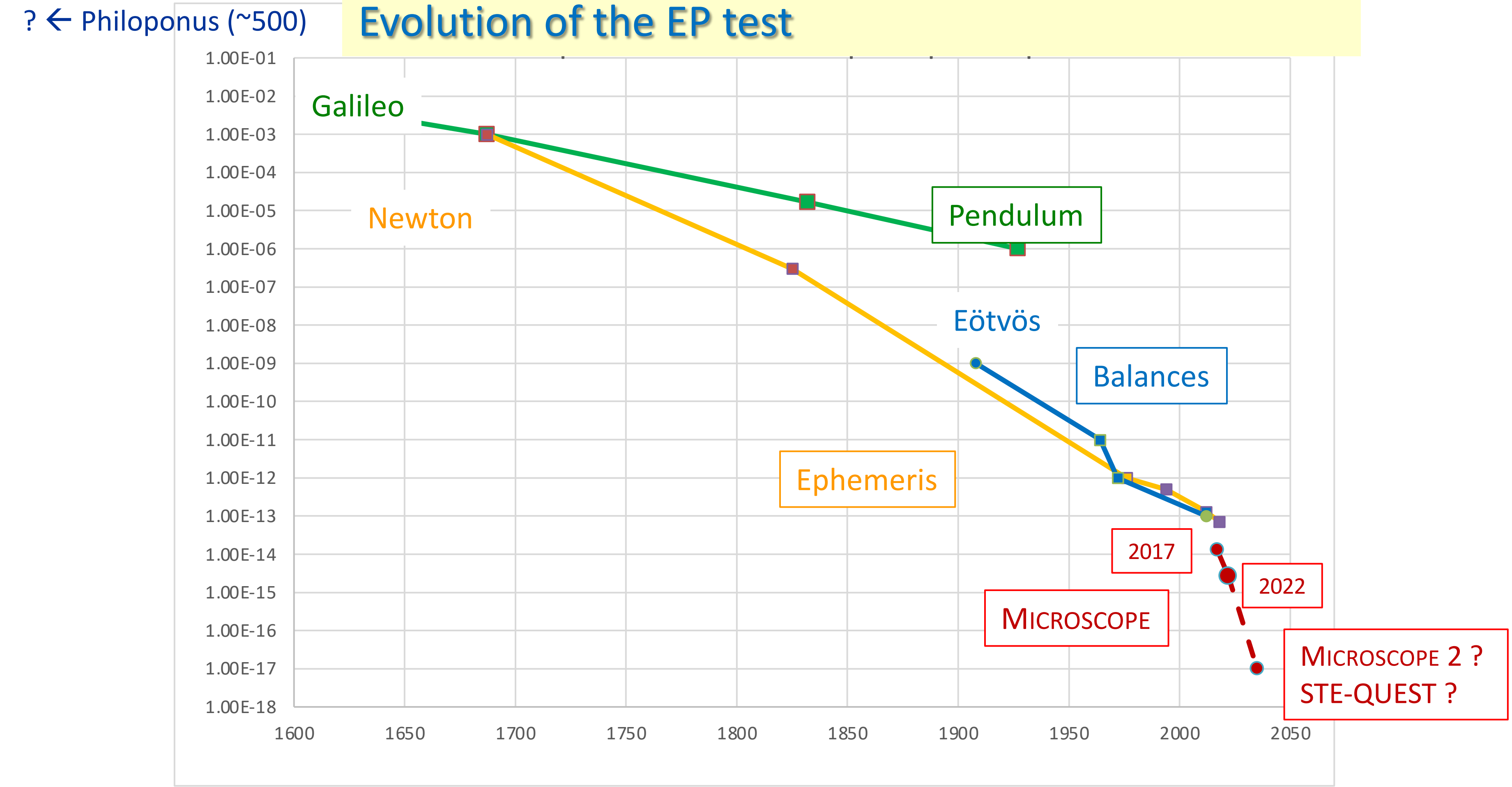
WEP violation

$$\eta = D_{\tilde{m}} \left([Q'_{\tilde{m}}]_{\rm Pt} - [Q'_{\tilde{m}}]_{\rm Ti} \right) + D_e \left([Q'_e]_{\rm Pt} - [Q'_e]_{\rm Ti} \right)$$

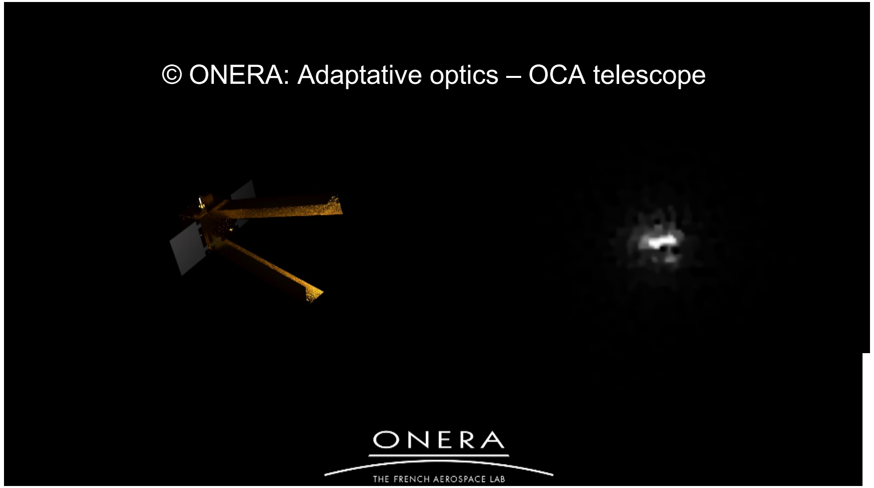
J.Bergé, P. Brax, G. Métris, M. Pernot-Borràs, P. Touboul, J.-P. Uzan, 2018, PRL 120 141101

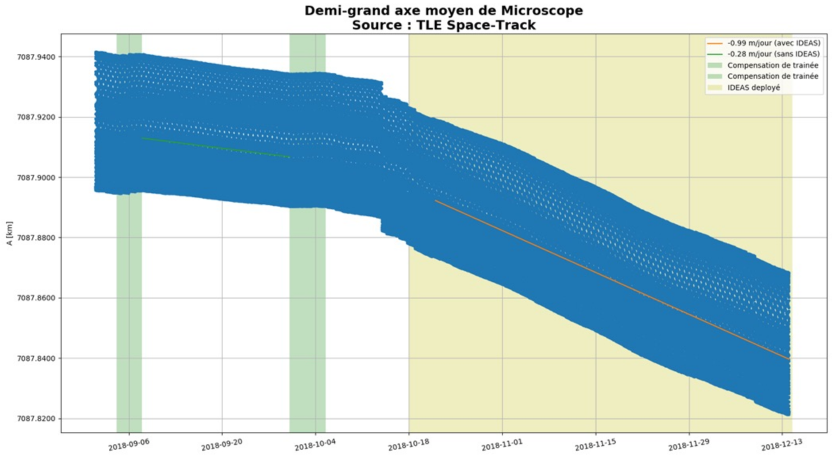
$$d_g^* = d_g + 0.093(d_{\tilde{m}} - d_g) + 0.00027 d_e$$

Evolution of the EP test



Deorbitation





Conclusion

- Accumulation of 1362 orbits (94 days) of free fall for a couple of platinum and titanium test-masses.
- No EP violation detected at the level of 2.7×10^{-15} (quadradic summation of stat. and syst. Error)
- 41 days of free fall for the couple platinum-platinum reveal no obvious bias in the experiment
- More information in *Touboul et al. Phys. Rev. Lett., 129:121102, Sep 2022* and in *CQG, Volume 39, Number 20, 20 October 2022* (10 articles).
- Data and documentation are available here: https://cmsm-ds.onera.fr/

MICROSCOPE TEAM (A LARGE PART)

CNES – 6 octobre 2018 : passivation du satellite MICROSCOPE

MERCI !