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THE FRENCH AEROSPACE LAB

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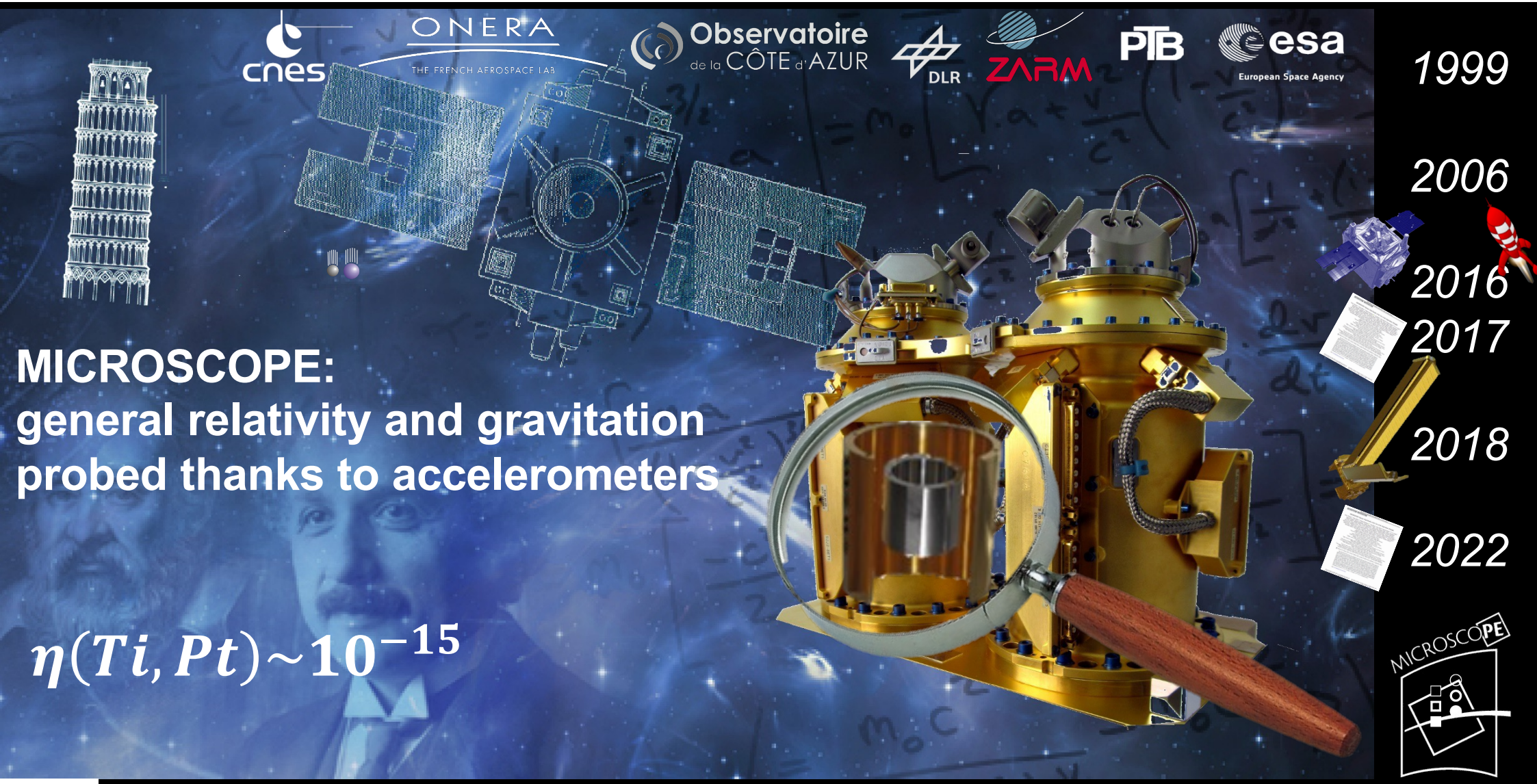

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Manuel RODRIGUES – MICROSCOPE Co-I & Head of Research Unit

Summary

- Gravitation and general relativity
- MICROSCOPE : A Physics Lab in space for the test of Equivalence Principle
- MICROSCOPE results
- And now what’s beyond ?

Gravitation before Einstein – XVII Century

- Galileo:

Gravitation = force that leads all bodies to fall to the Earth

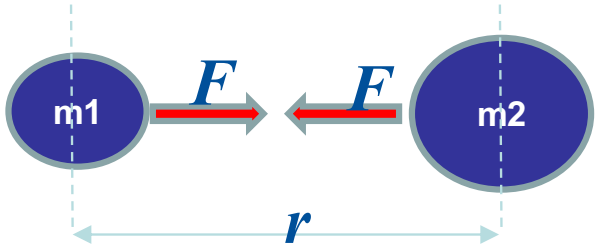
$$h(t) = -\frac{g\,t^2}{2} + h0$$

- Newton:

Gravitation is the same force that rules the free-fall and the motion of planets around the Sun

⇒ Universal Gravitation :

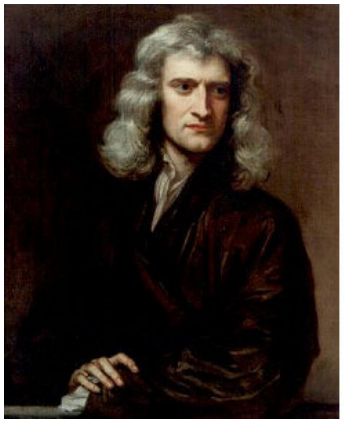
$$F = G\frac{m_1 m_2}{r^2}$$

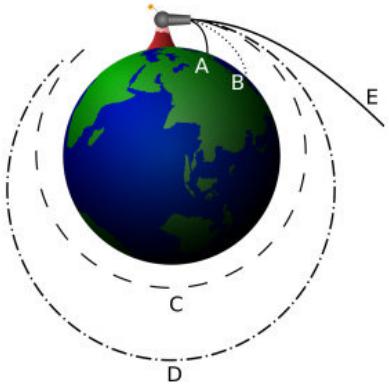


All seems to be solved

Solar system better understood.

New planets discovered.





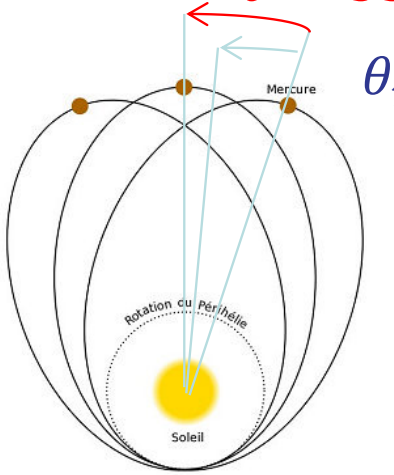
BUT Mercury does not fit the model

- **Perihelia of Mercury is in advance by 43 arc-sec per century**
- **Einstein General Relativity explained it all :**

Sun Mass modifies space and time nearby and affects Mercury

$\theta = 5599{,}7 \pm 0.04$ **arcsec**

$\theta_{newton} = \theta - 43$ **arcsec**

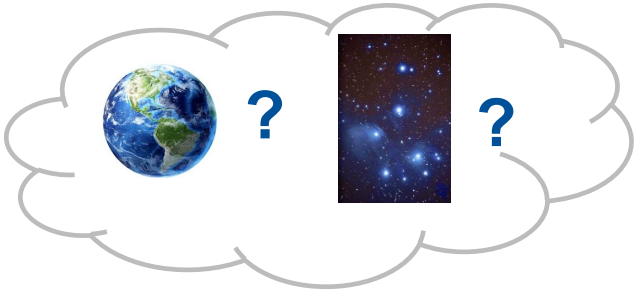


5599 **arcsec = 1,5553 degré**

The Einstein's Eureka : the fall of bodies

Force of inertia

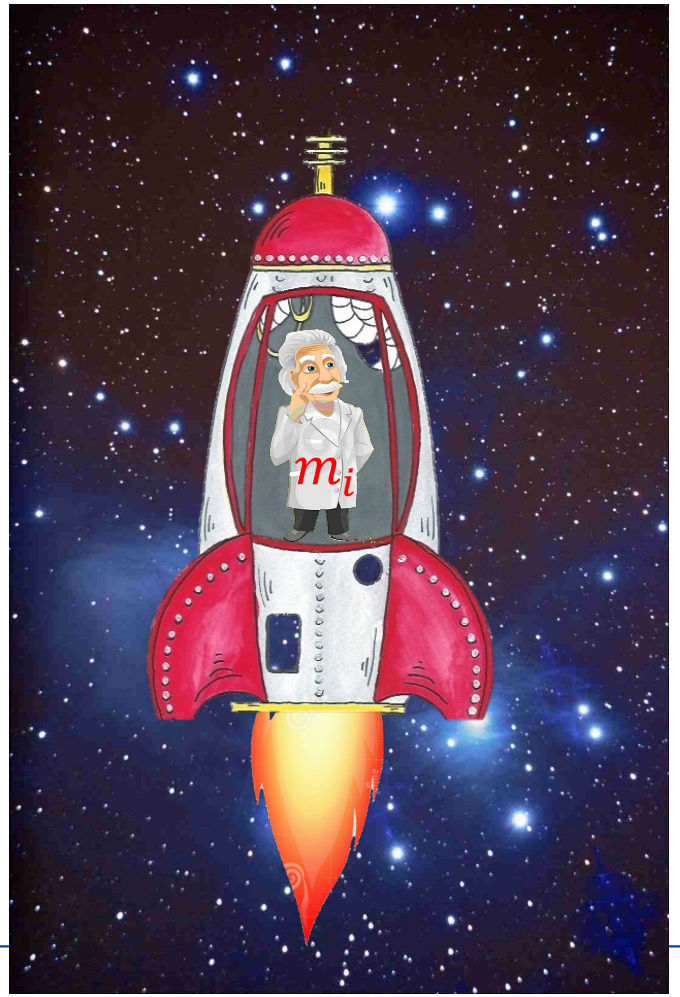
$$F = m_i a$$



$$a \equiv g$$

Force of gravity

$$F_g = \frac{GM_T}{r^2} m_g = m_g\, g$$

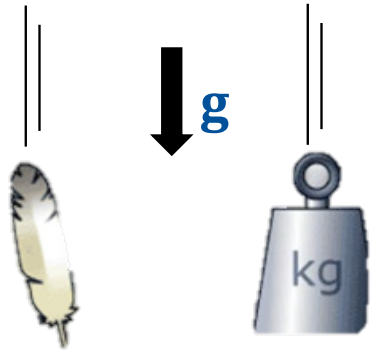


EQUIVALENCE PRINCIPLE= FONDATION PRINCIPLE

- Force of gravitation : $F_g = m_g g$
- 2nd law of Newton for free-falling bodies : $m_i a = F_g = m_g g$

$\boldsymbol{m_g}$ = mass grave

$\boldsymbol{m_i}$ = mass inert



General relativity : $a \equiv g$ => $\frac{m_i}{m_g} = 1$

Universality of free-fall

$$\eta = \frac{\frac{mg1}{mi1} - \frac{mg2}{mi2}}{\frac{1}{2}\left(\frac{mg1}{mi1} + \frac{mg2}{mi2}\right)}$$

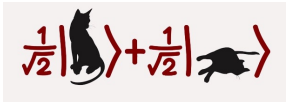
Eötvös Parameter

Why to test EP

- 1900: 2 Theories made Physics jumping in a new era !

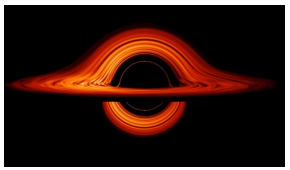
atomic scale

galaxy scale



Quantum Physics

General relativy



- Both theories have led to outstanding predictions
- Both theories seem nevertheless incompatibles
- The Graal of Physicist : the theory of everything (quantum gravity, string theory, …) => could violate the EP at 10^{-14} (Damour 2002)

MICROSCOPE – test of Weak Equivalence Principle

Objective : to test η with 10^{-15} accuracy

To measure an acceleration of : $10^{-15}\mathbf{g} = 7.9\times10^{-15} m/s^2$

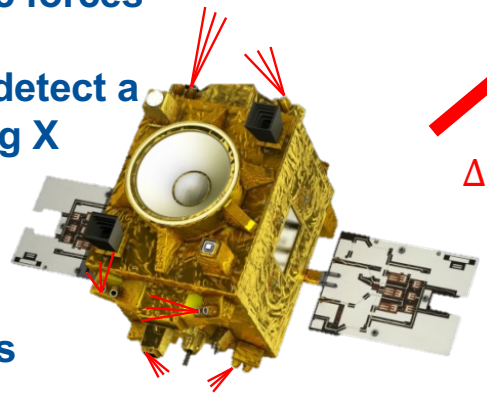
2 materials : PtRh10 vs Ti (TA6V)

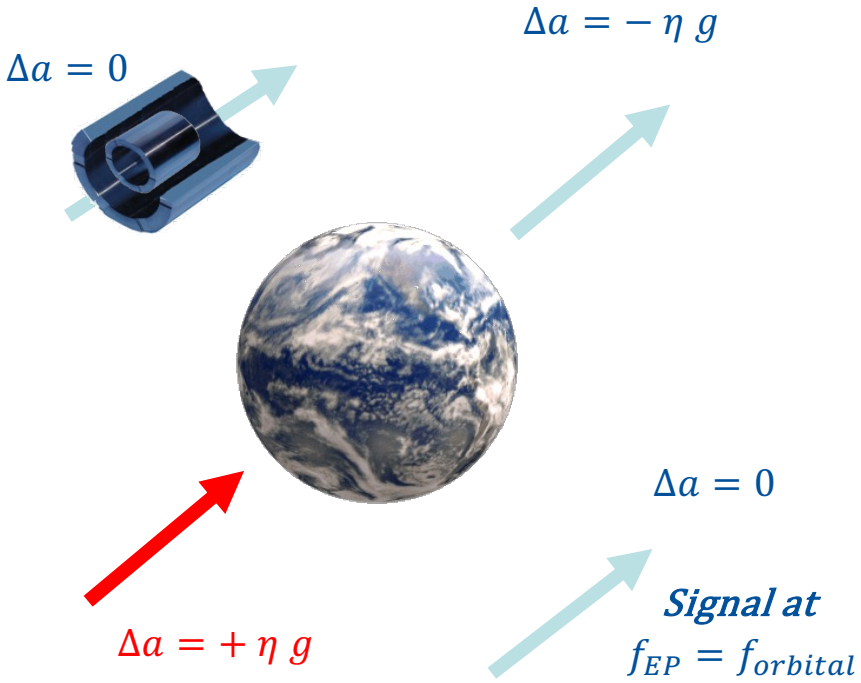
Cylindrical test-masses controlled by electrostatic forces

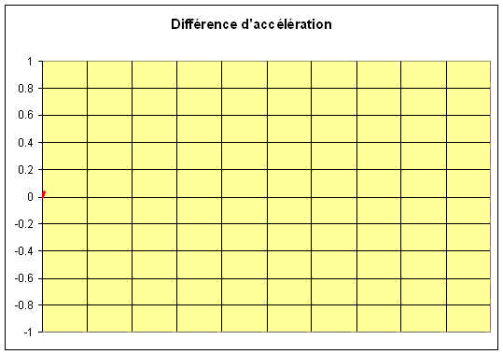
To measure the difference of acceleration and to detect a potential signal at "g" frequency modulation along X

Micro-satellite:

Launch at 710 km, circular orbit, sun synchronous
320 kg - 1,4 m x 1 m x 1,5 m
Cold gas propulsion for a drag-free and attitude control







Eötvös Parameter $\eta = \frac{a1-a2}{\frac{1}{2}(a1+a2)} = \frac{\frac{mg1}{mi1}-\frac{mg2}{mi2}}{\frac{1}{2}\left(\frac{mg1}{mi1}+\frac{mg2}{mi2}\right)}$

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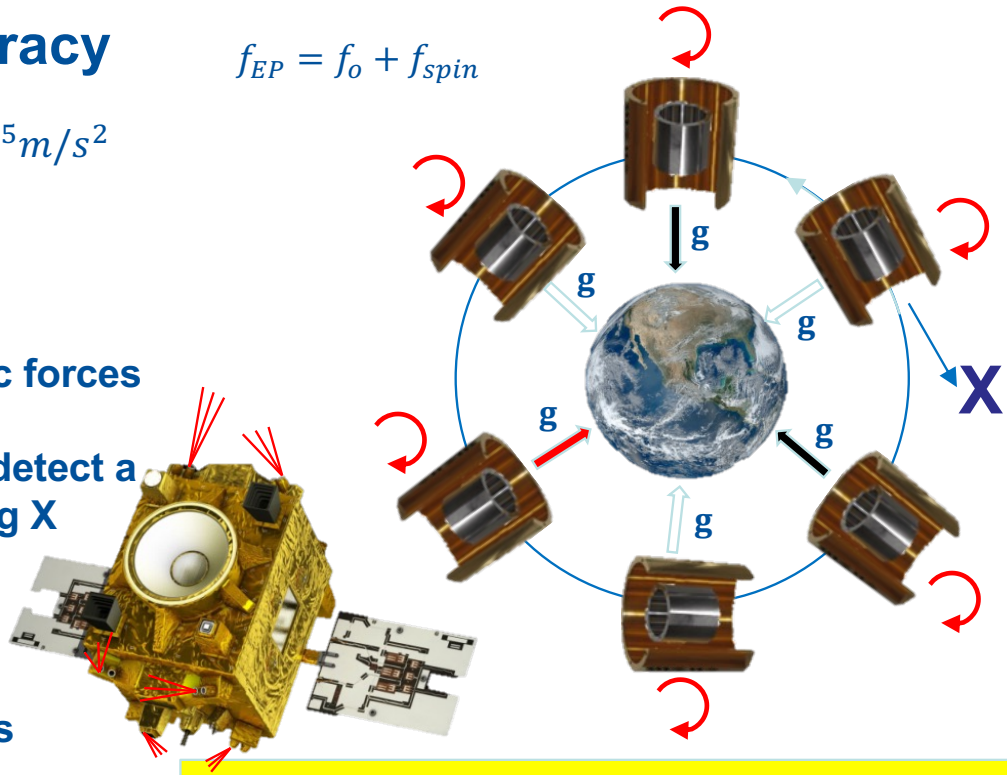
$$f_{EP} = f_o + f_{spin}$$



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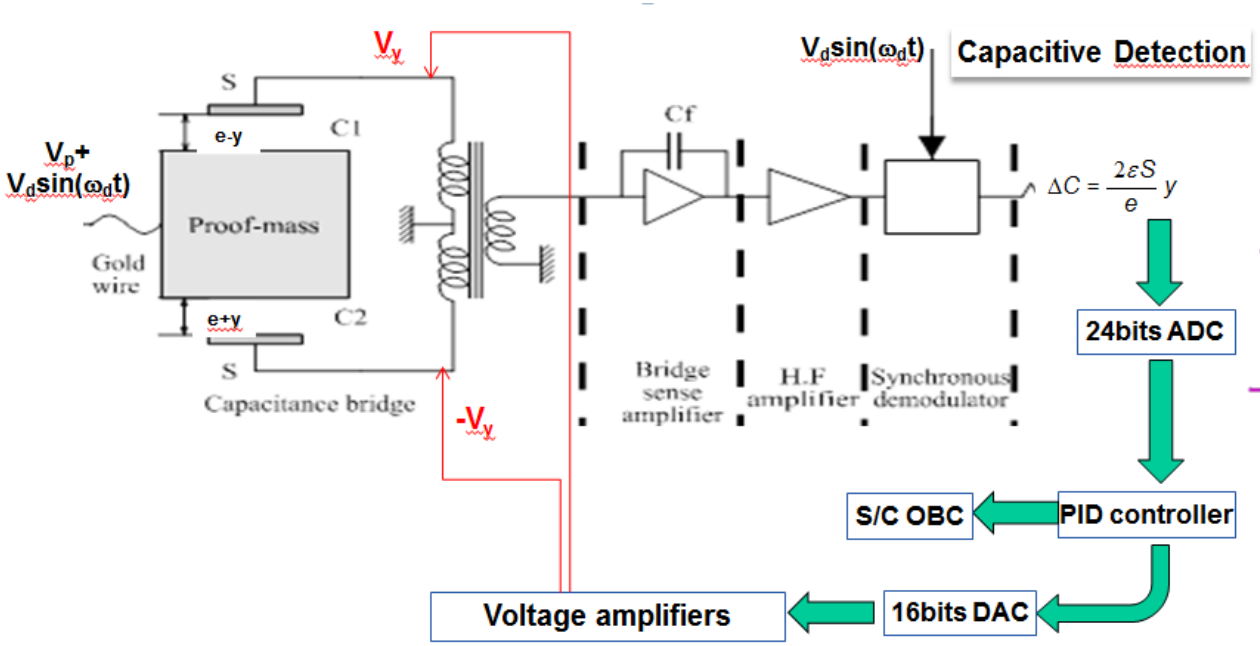
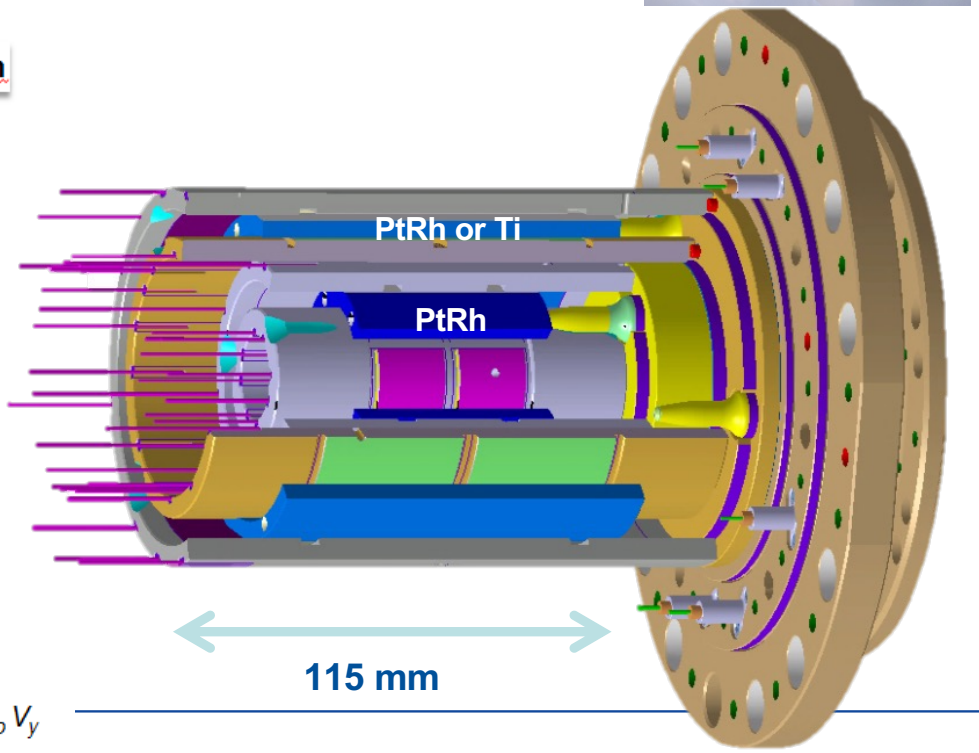
Instrument : 2 double accelerometers for the test

2 Sensor Units on board which comprise each 2 concentric test-masses
SUEP : Sensor Unit with Ti / PtRh
SUREF : Sensor Unit with PtRh / PtRh, helps to get confidence on the overall performance and data process



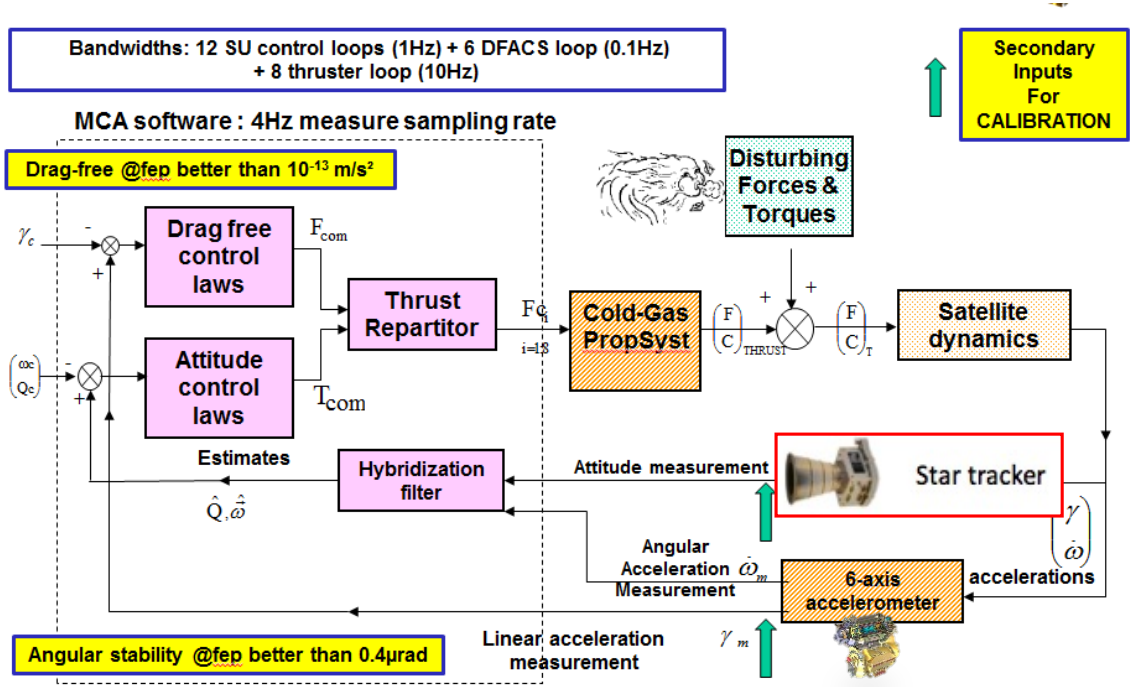


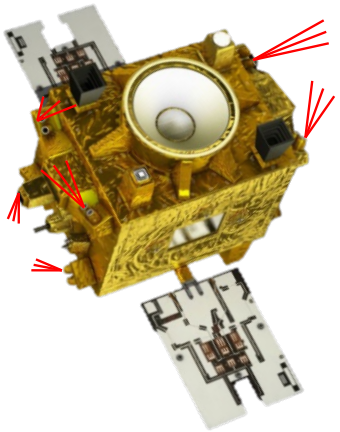
$$F = F_1 - F_2 = \frac{1}{2}\left[\frac{\partial C_2}{\partial y}\left(V_y - V_p - V_d\sin(\omega_d t)\right)^2\right] - \frac{1}{2}\left[\frac{\partial C_1}{\partial y}\left(V_y + V_p + V_d\sin(\omega_d t)\right)^2\right] \quad \Rightarrow \quad a_y \sim -\frac{2\varepsilon S_y}{me^2} V_p V_y$$

DRAG-FREE SATELLITE LABORATORY OF PHYSICS

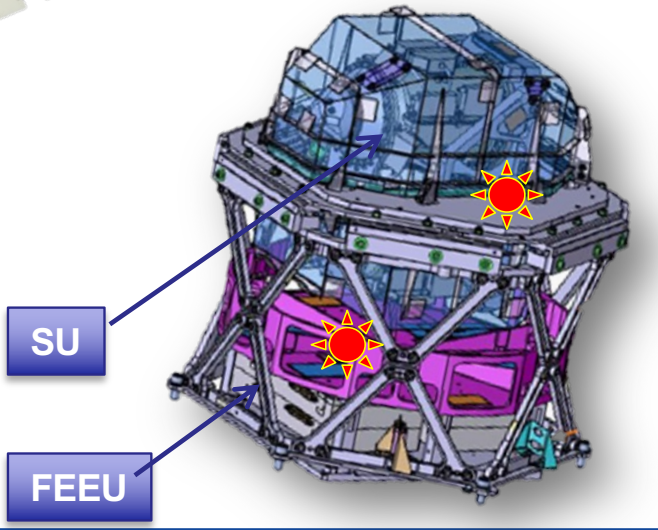
With capabilities of stimuli production:

- linear or angular sine accelerations,
- Test-masses displacements,
- controlled thermal heaters (Off in science mode).





- Performance of drag-free
- $\Gamma(f_{EP}) < 3 \times 10^{-13}$ m/s²
- $\dot{\Omega}(f_{EP}) < 4 \times 10^{-12}$ rad/s²
- $\Omega(f_{EP}) < 3 \times 10^{-10}$ rad/s
- $\int \Omega < 1\mu rad$



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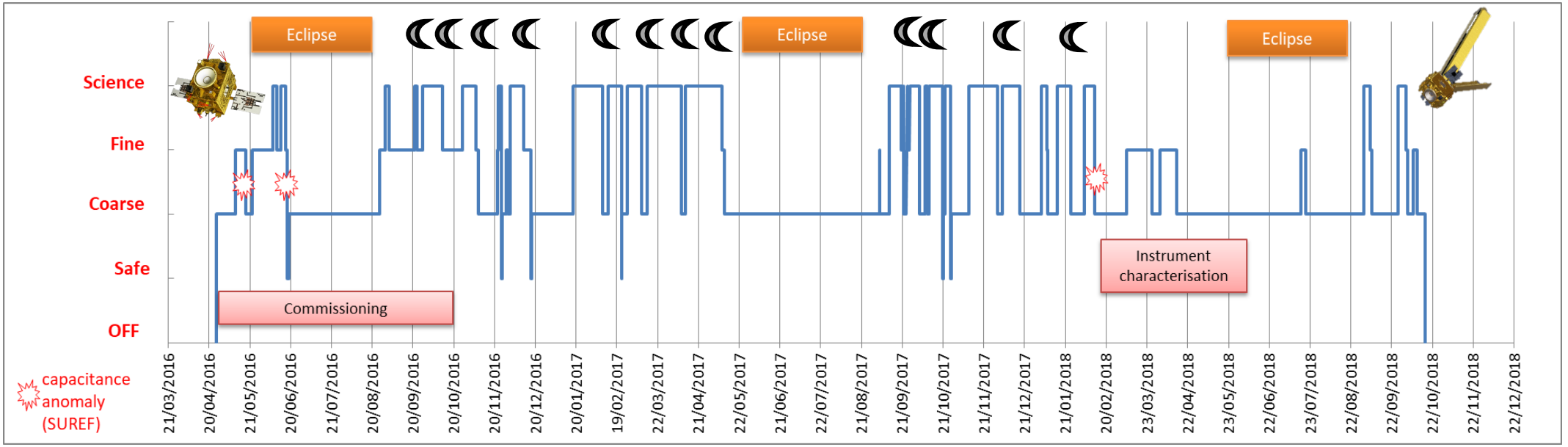
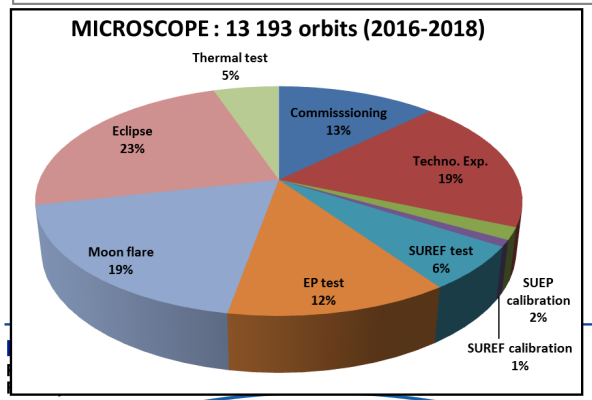
Déroulé de la mission : 25 avril 2016 ➔ 16 octobre 2018





Distance parcourue
560 milliards de km
~ aller retour Terre – Mars

Science : 110 Mds km
240 aller retour Terre-Lune

Session Test EP	Drag Free	SUREF	SUEP
Spin V3	IS2	214	1266.08
	IS1	0	23.16
	IS1+IS2	0	112.78
Spin V2	IS2	561.19	101.70
	IS1	2.25	138.15
	IS1+IS2	0.00	0.00
Spin V1	IS2	0.00	0.00
	IS1	20.00	0.00
	IS1+IS2	0.00	0.00
EPI	IS1	7.55	0.00
	IS1+IS2	16.50	0.00
Total		821	1642

Systematic error analysis

Temperature variations :
Higher sensitivity of the instrument than expected : the major limitation

Non linearity:
The common quadratic parameter is not calibrated and thus established to worse case values

Error in the final result: $\sqrt{\sum_k (\Gamma_k^{(d)})^2}$

Actual budget in the final result (same result for Systematics)

$$\frac{1}{\sum_l \frac{1}{\sigma_l^2}} \sum_l \frac{1}{\sigma_l^2} \left(\sum_k \left(\Gamma_{k,l}^{(d)} \right)^2 \right)^{\frac{1}{2}}$$

$$\Gamma_k^{(d)} = \frac{1}{\sum_l \frac{1}{\sigma_l^2}} \sum_l \frac{1}{\sigma_l^2} \Gamma_{k,l}^{(d)}$$

k = error source
l = session number

Table 15: Budget of systematic error analysis compared to specification analysis [5].

	Systematic error sources	SUEP $\mathrm{m\,s^{-2}}$	SUREF $\mathrm{m\,s^{-2}}$	Specification $\mathrm{m\,s^{-2}}$
$\Gamma_1^{(d)}$	Earth gravity gradients	0.0×10^{-15}	0.0×10^{-15}	0.0×10^{-15}
$\Gamma_2^{(d)}$	Instrument gravity	0.0×10^{-15}	0.0×10^{-15}	0.2×10^{-15}
$\Gamma_3^{(d)}$	Satellite gravity gradients	0.1×10^{-15}	0.1×10^{-15}	0.3×10^{-15}
$\Gamma_4^{(d)}$	Angular motions	0.1×10^{-15}	0.1×10^{-15}	1.1×10^{-15}
$\Gamma_5^{(d)}$	Instrument parameters	0.2×10^{-15}	0.1×10^{-15}	0.8×10^{-15}
$\Gamma_6^{(d)}$	Temperature variations	9.3×10^{-15}	17.9×10^{-15}	0.9×10^{-15}
$\Gamma_7^{(d)}$	Drag-Free residuals	0.0×10^{-15}	0.0×10^{-15}	0.5×10^{-15}
$\Gamma_8^{(d)}$	Magnetic sensitivity	0.0×10^{-15}	0.0×10^{-15}	0.4×10^{-15}
$\Gamma_9^{(d)}$	Non linearity	6.0×10^{-15}	3.1×10^{-15}	0.8×10^{-15}
Total quadratic sum ($\mathrm{m\,s^{-2}}$)		11.5×10^{-15}	18.3×10^{-15}	
Total systematic errors for the Eötvös δ estimation with $g = 7.9\,\mathrm{m/s^2}$				
	Quadratic sum of errors	1.5×10^{-15}	2.3×10^{-15}	

Einstein's GR theory has resisted to the more accurate experiment ever realised

!!! No violation @ 10^{-15} level !!!

- **SUEP :**

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

- **SUREF :**

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

Physical Review Letters (American Physics Society):

Phys. Rev. Lett. 129, 121102

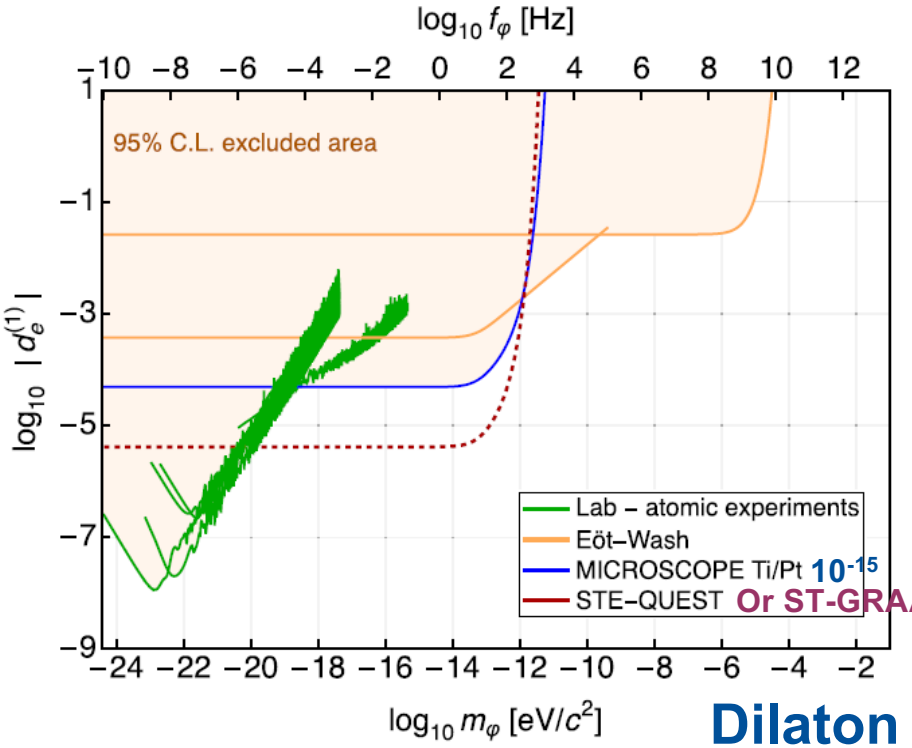
Classical Quantum Gravity (IOP Publishing): A special edition of 11 papers (in open access)

CQG Vol 39, N.20, 2022

Ultra-Light Dark Matter a particular case of massive Dilaton

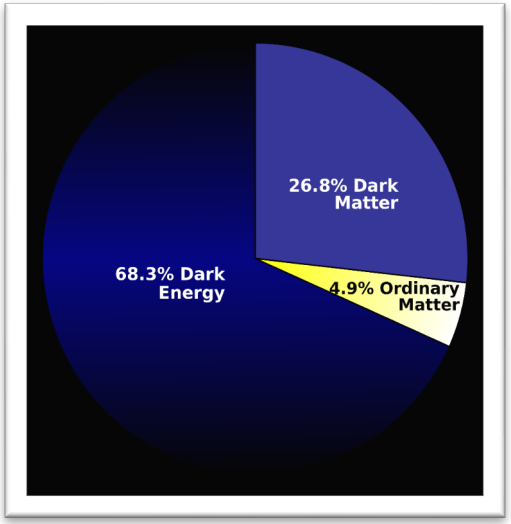
$$\eta = \eta_0 \Phi \left(\frac{R_E}{\lambda_\phi} \right) \left(1 + \frac{r}{\lambda_\phi} \right) e^{-r/\lambda_\phi}.$$

Joel Bergé 2023 Rep. Prog. Phys. 86 066901



10^{-15}

Or ST-GRAAL : 10^{-17}

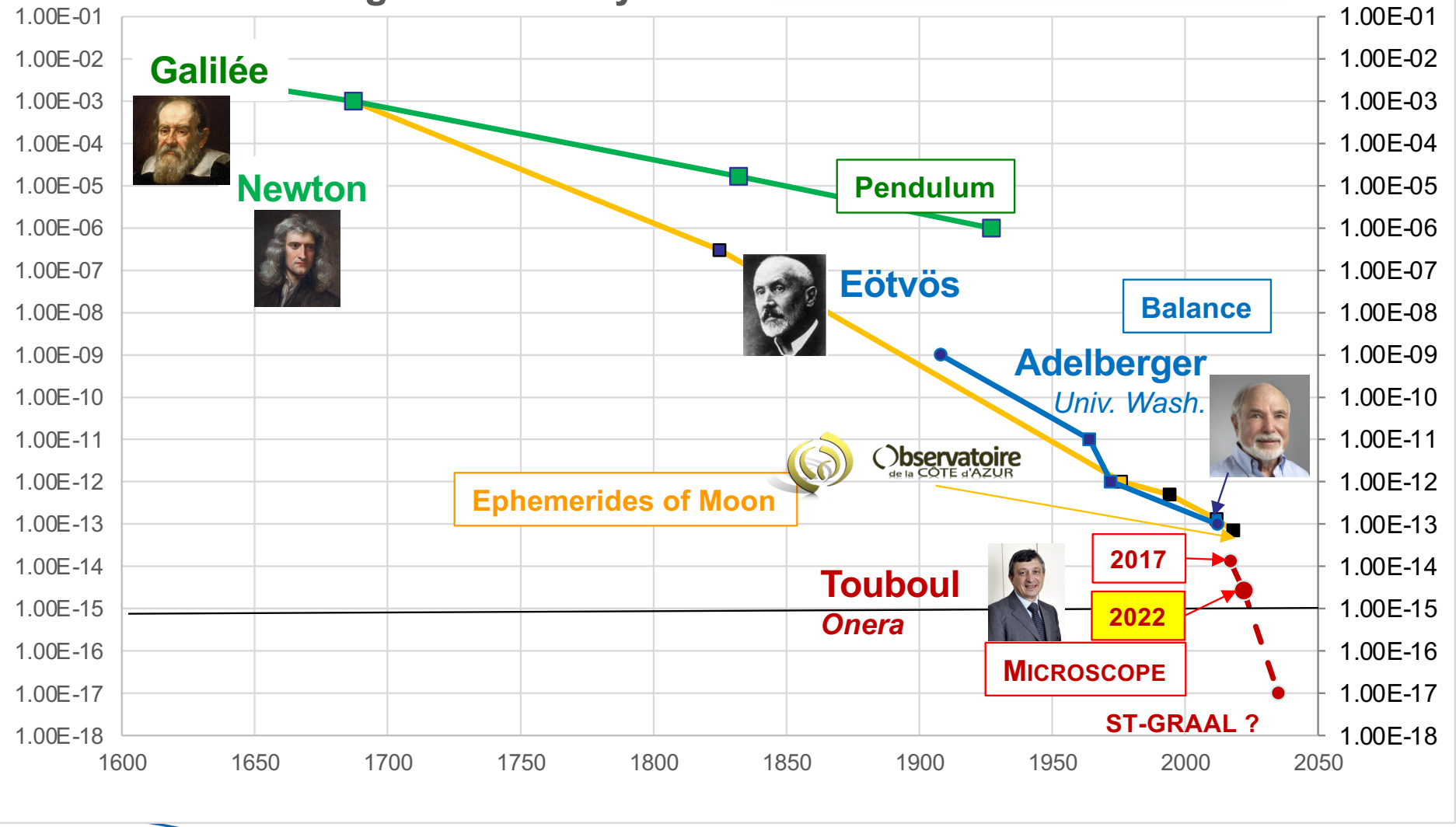


Dilaton mass modifies the range of Yukawa potential

Philoponus (~500)

DATA available on : https://cmsm-ds.onera.fr

A breakthrough in accuracy……..



CONCLUSION

- MICROSCOPE :
  - EINSTEIN is still right at 10^{-15}
  - 1st fundamental physics experiment in space in Europe
  - 1st satellite with control of the 6 degrees of freedom in Earth's orbit
  - 1st test in space of the EP
  - The best test of GR ever and very hard to compete in the coming decade

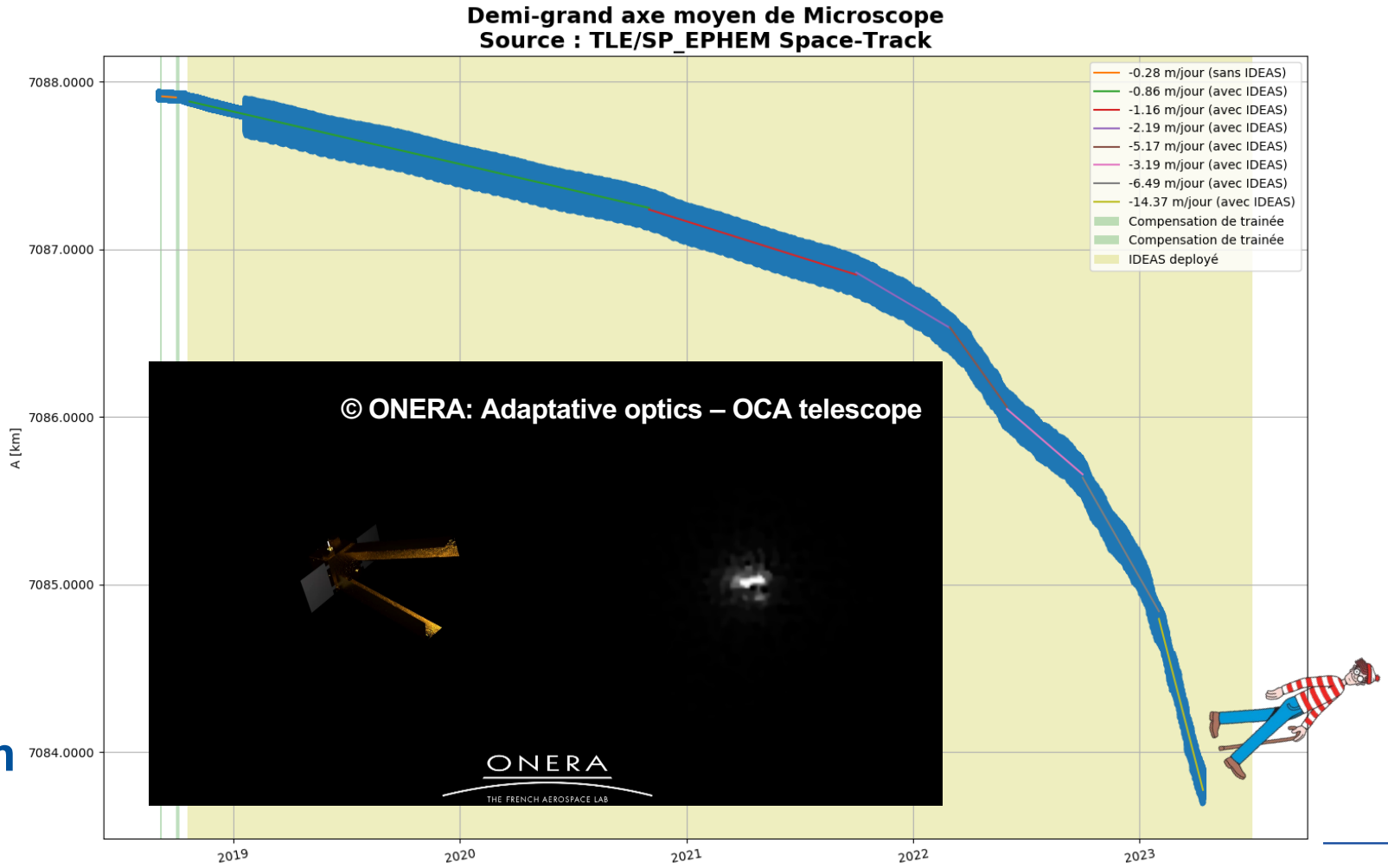
- FUTURE :
  - Space can be used for very accurate experiment in Physics
  - YES we have to continue the tests on EP as most of Physicist are convinced that GR is not completed and that EP has no reason to be maintained in this frame
  - The quest of the GRAAL goes on …with the follow-on mission Space Test of General Relativity and ALternative theories" (ST-GRAAL)

Where is MICROSCOPE ???

Altitude de 717 km

en
5 ans

Altitude de 713 km



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