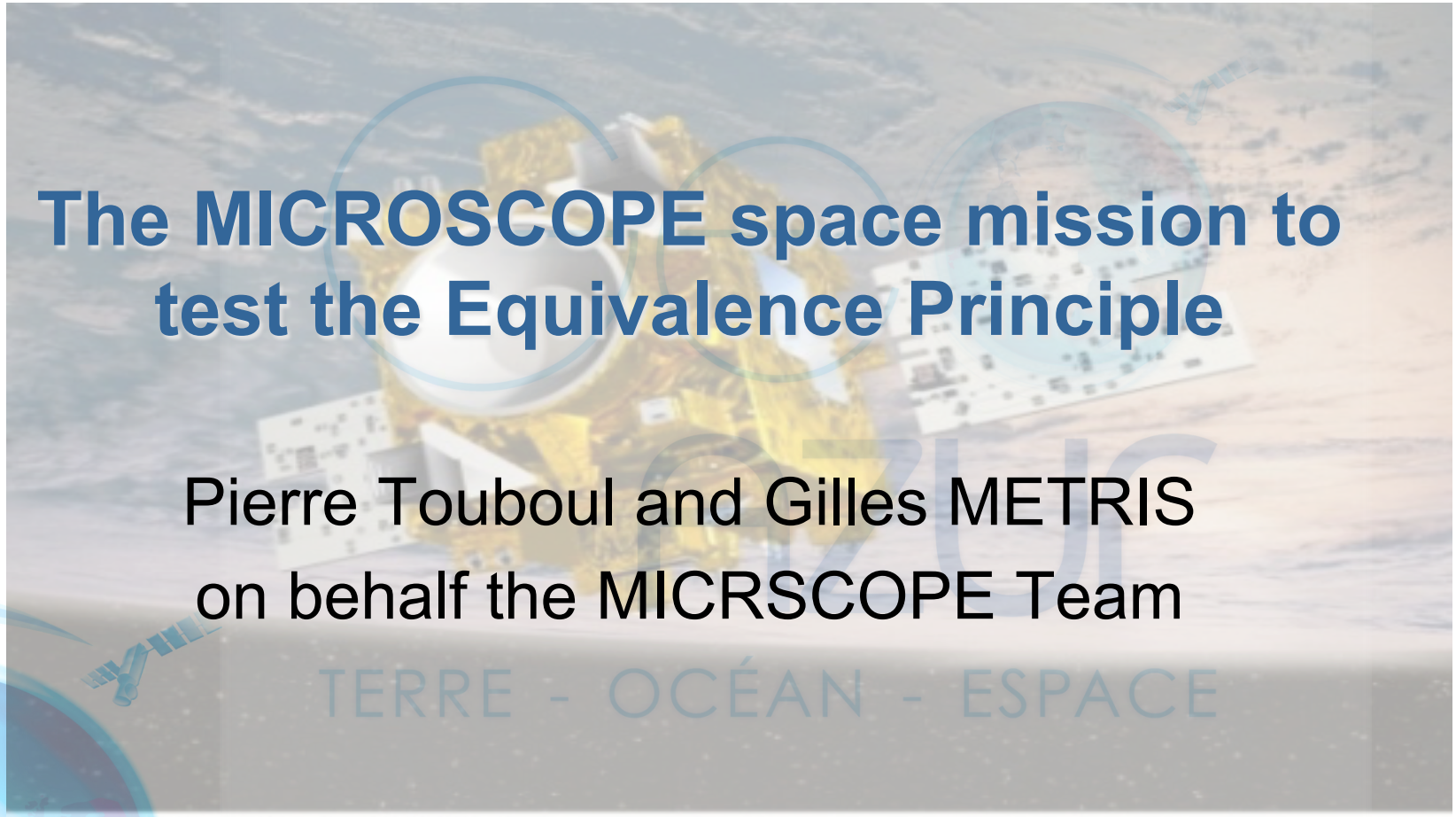
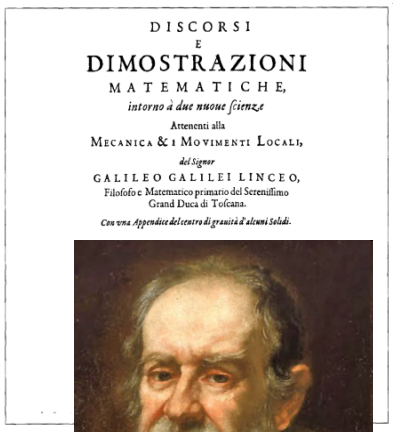
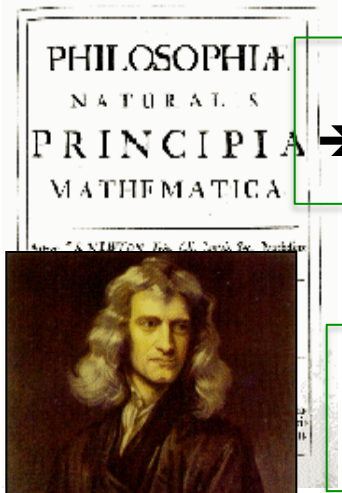
The MICROSCOPE space mission to test the Equivalence Principle

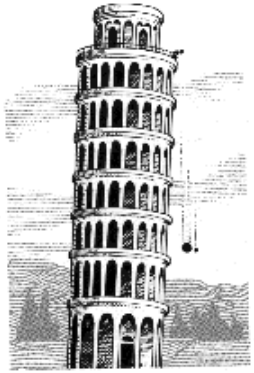
Pierre Touboul and Gilles METRIS
on behalf the MICRSCOPE Team

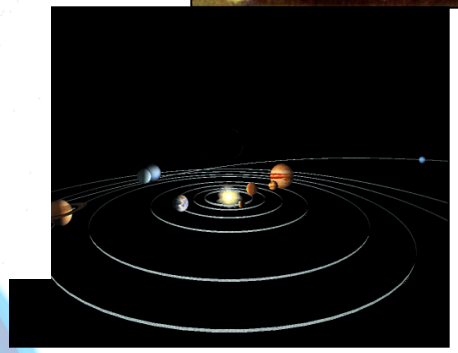


Newton : Gravitational mass and Inertial mass









Gravitational law
➔ Gravitational mass

$$F_G = -\frac{G m_G^1 m_G^2}{r^2}$$

Dynamical law
➔ Inertial mass

$$F = m_I a \quad \Rightarrow \quad m_I = \frac{F}{a}$$

Free fall motion
➔ Ratio of the 2 masses

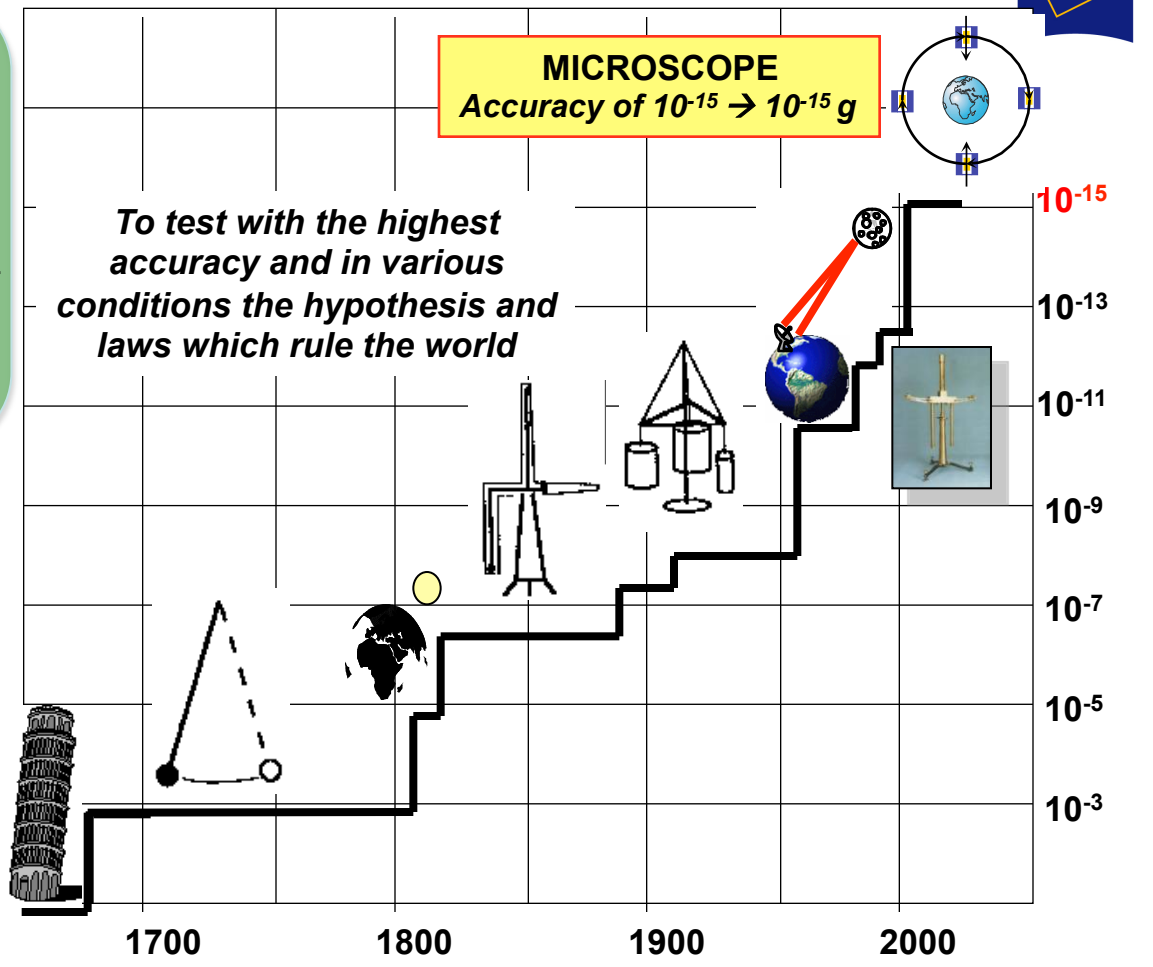
$$\Rightarrow a_G = -\frac{G m_G^2}{r^2}\frac{m_G^1}{m_I^1} = -g\frac{m_G^1}{m_I^1}$$

The Universality of Free Fall

Eotvos parameter:

$$\eta_{12} = 2\frac{\frac{m_{g1}}{m_{i1}} - \frac{m_{g2}}{m_{i2}}}{\frac{m_{g1}}{m_{i1}} + \frac{m_{g2}}{m_{i2}}} \approx \frac{m_{g1}}{m_{i1}} - \frac{m_{g2}}{m_{i2}}$$

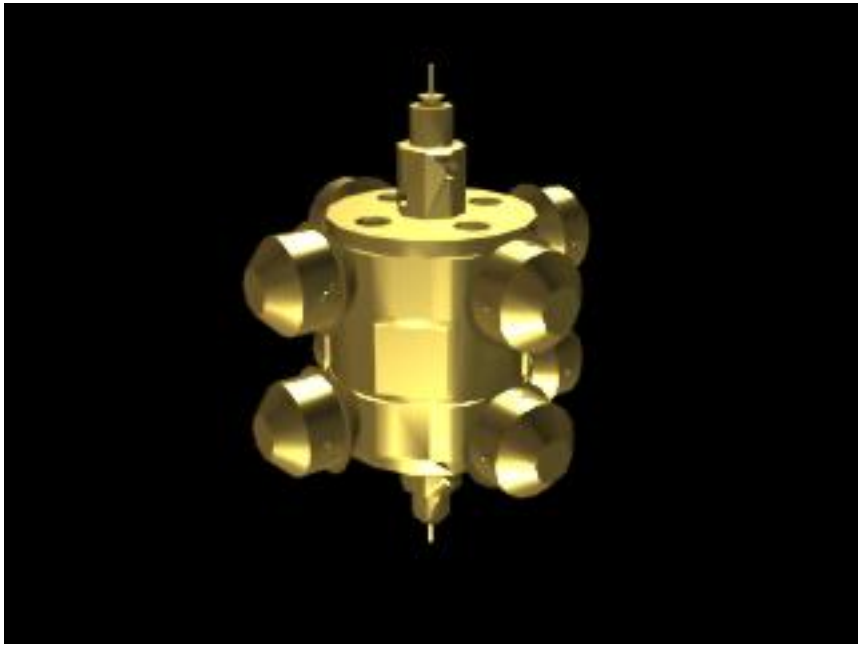
Experiments ➔
$\eta < 10^{-13}$
for various materials



MICROSCOPE space experiment: test of the Equivalence Principle with an accuracy of 10^{-15}

The Eot-Wash experiment

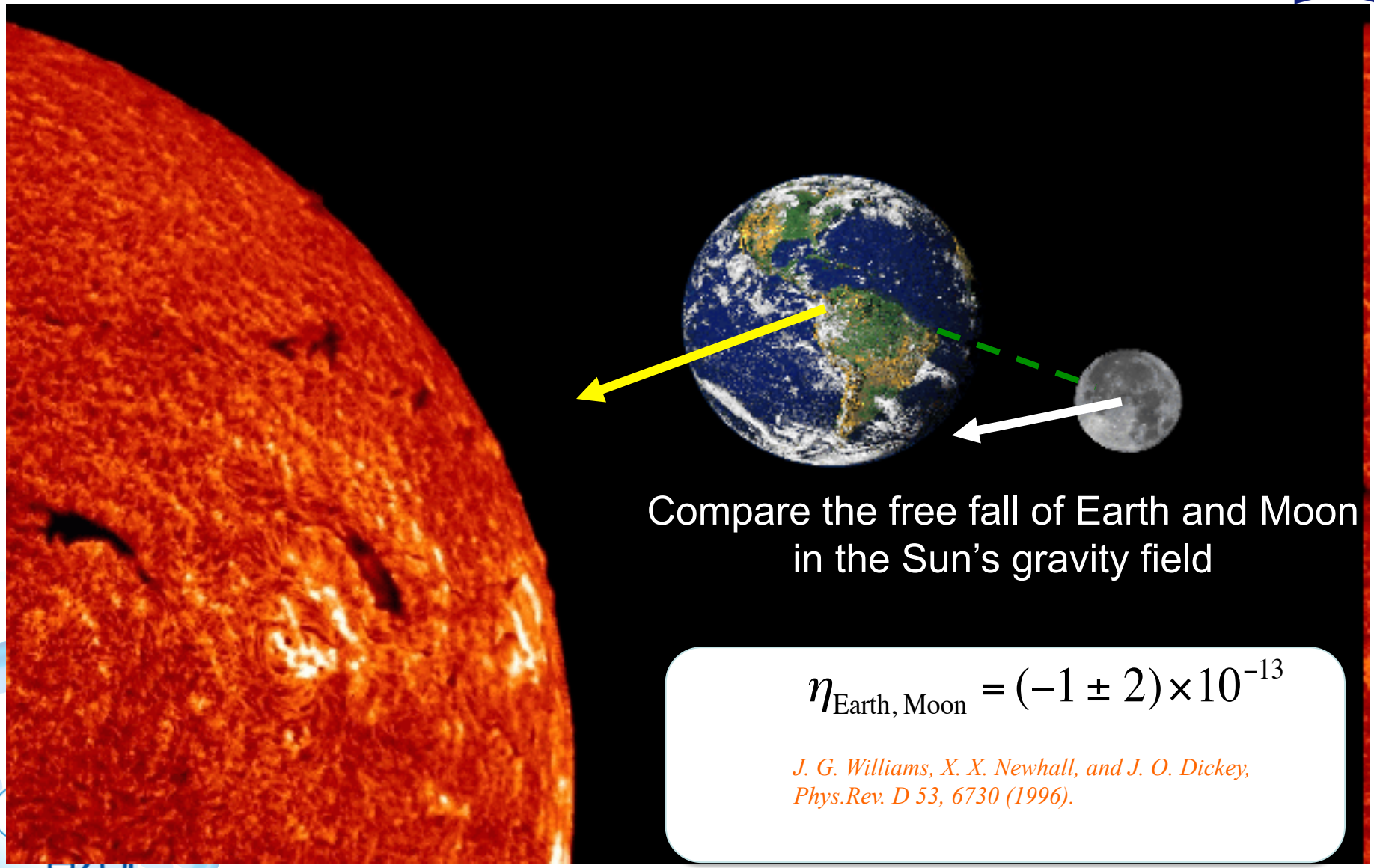
A torsion balance in rotation to compare the UFF of various materials



$$\eta(Earth, Be-Ti) = (0.3 \pm 1.8).10^{-13}$$

Schlamminger, S. et al. Test of the Equivalence Principle Using a Rotating Torsion Balance". Physical Review Letters 100, 4, (2008).

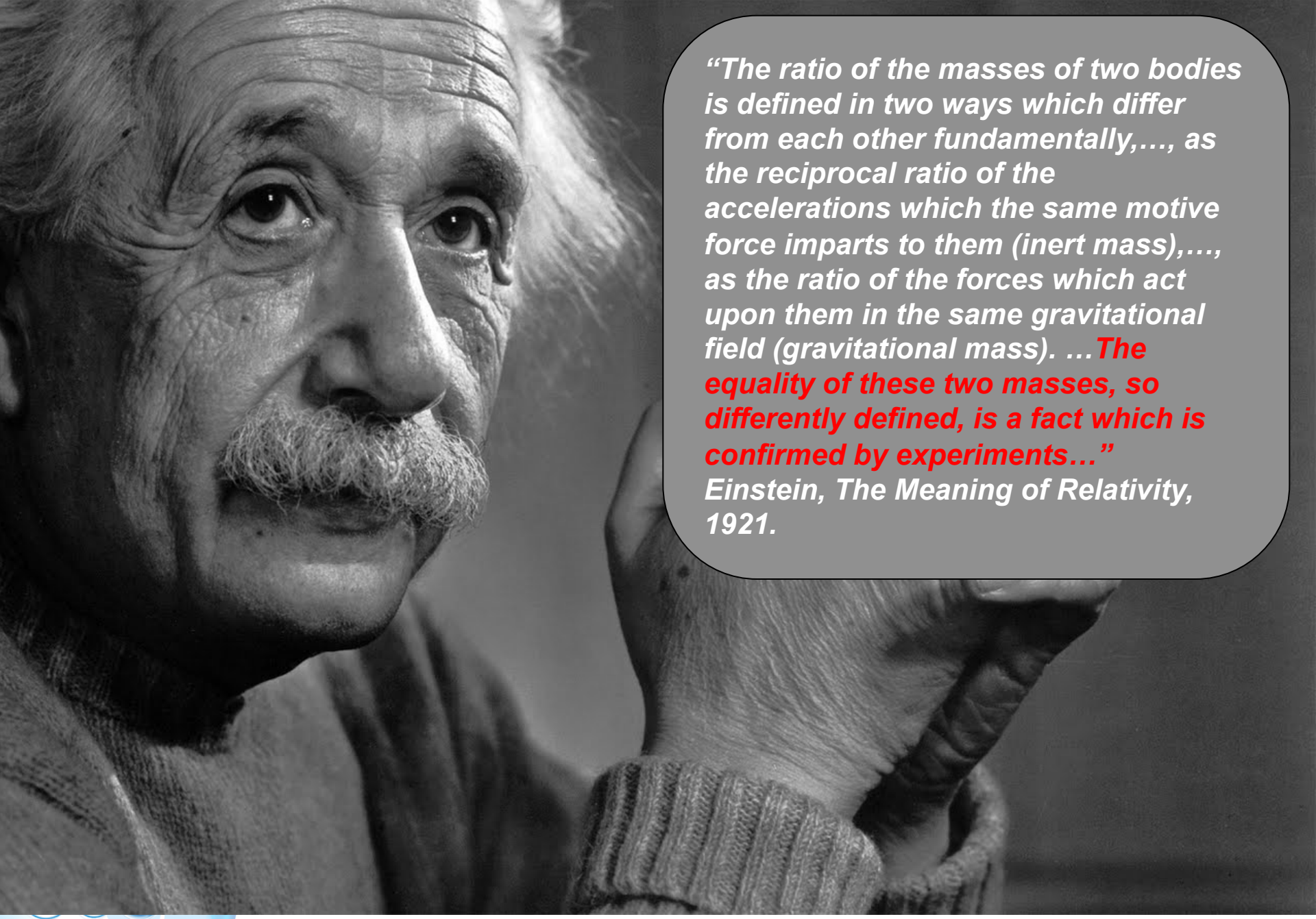
Lunar Laser Ranging



Compare the free fall of Earth and Moon in the Sun's gravity field

$$\eta_{\text{Earth, Moon}} = (-1 \pm 2) \times 10^{-13}$$

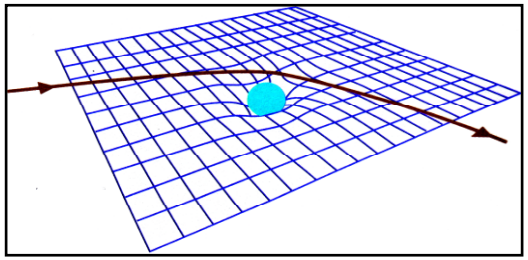
J. G. Williams, X. X. Newhall, and J. O. Dickey, Phys.Rev. D 53, 6730 (1996).

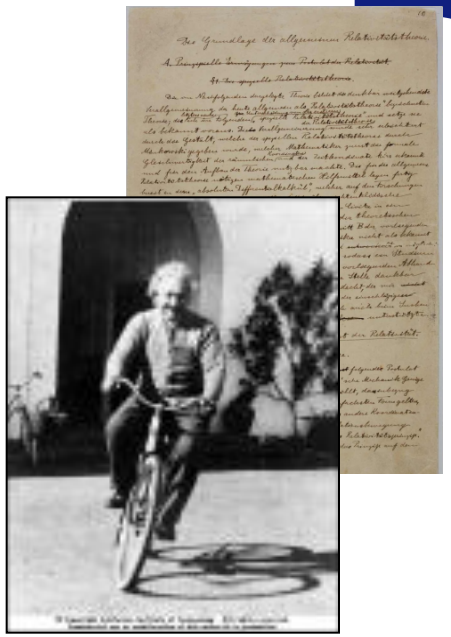


"The ratio of the masses of two bodies is defined in two ways which differ from each other fundamentally,…, as the reciprocal ratio of the accelerations which the same motive force imparts to them (inert mass),…, as the ratio of the forces which act upon them in the same gravitational field (gravitational mass). …The equality of these two masses, so differently defined, is a fact which is confirmed by experiments…"
Einstein, The Meaning of Relativity, 1921.

Einstein : General Relativity

Gravity is the result of the curvature of space-time :





$$T_{\mu\nu} = \frac{8\pi G}{c^4} \cdot G_{\mu\nu}$$

$$T_{\mu\nu} \Rightarrow g_{\mu\nu}$$

General Relativity
Space Time metric
& geodesic free motion
Eddington 1919, Gravitational deflection of light
Mercury perihelion precession
1916.

Standard Model : 3 interactions + 1

Quantum Field Theory

Standard Model, coherent with quantum mechanics, special relativity, but … gravity GR

Elementary particles									
	Matter Fermions								
	1st Generation		2nd Generation		3rd Generation		Electrical charge	Spin	Color
quarks	quark *u*	2.4	quark *c*	1270	quark *t*	171 200	2/3	½	
	quark *d*	4.8	quark *s*	104	quark *b*	4300	-1/3	-½	
leptons	electron	0.511	muon	106	tauon	1780	-1	-½	0
	electron neutrino	0? < 2.2	muon neutrino	0?	tau neutrino	0?	0	½	0
		mass in MeV							

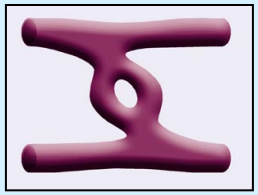
	Interactions & Gauge **Bosons** (Interaction)				
Interaction	Electromagnetic	Weak nuclear	Strong nuclear	**Gravitation**	Scalar
Gauge bosons	photon	bosons W±, Zo	gluons	graviton ?	Higgs
charge	0	+/-1; 0	0		
mass	0	80400/91200	0	0	114 GeV-1TeV ?
spin	1	1	1	2	no
	Electro Weak				
	Quantum Chromodynamic (QCD)				
	?				

quarks + gluons = hardrons

MICROSCOPE RATIONALE

Two formalisms

- **Small scales described by quantum field theory**



- **Large scale described by General Relativity**

  - geometrical theory, not (yet?) a quantum field theory

Under development :

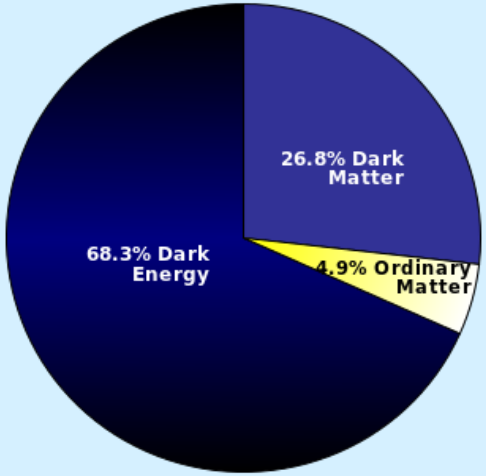
- **String, Brane theories**
- **Loop Quantum Gravity**

ESA roadmap for fundamental physics in space, 2010.

http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=47598

→ **Tests of fundamental laws and principles**

→ **Search for fundamental constituents**



Extract from EP test colloquium (Palaiseau, 19 Sept. 2011) : *Thibault Damour presentation conclusions*

Conclusions (II)

- $\exists$ no firm prediction for level of EP violation, but some phenomenological models show that the violation could naturally be just below the currently tested level.

- In dilaton-like models, the composition-dependence of EP signals is (probably) dominated by two signals, depending on $A^{-1/3}$ and $Z^2\,A^{-4/3}$.

- In such dilaton-like models, there exist correlated modifications of gravity ($\Delta a/a$, $\gamma^{\rm PPN}-1\neq 0$, $\dot{\alpha}_a\neq 0$, $d\alpha_a/dU\neq 0$, ...) but EP tests stand out as our deepest probe of new physics, when compared to, e.g., solar-system ($\gamma^{\rm PPN}$) or clock tests ($\dot{\alpha}_a$ or $d\alpha_a/dU$). Indeed,

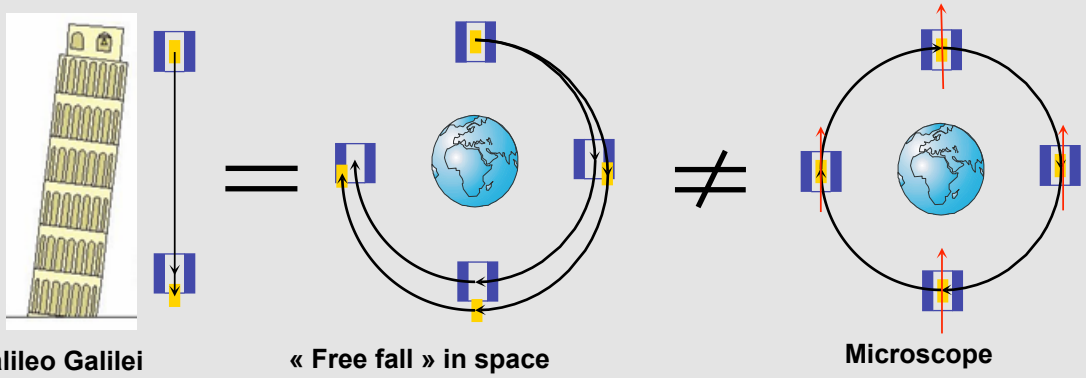
$$\frac{\Delta a}{a}\sim 10^{-2}\,\frac{d_q}{d_g}\,\frac{1-\gamma^{\rm PPN}}{2}$$

where $d_q\equiv\partial\,\ell n(m_q/\Lambda_{\rm QCD})/\partial\varphi$, $d_g\equiv\partial\,\ell n(\Lambda_{\rm QCD}/m_{\rm Planck})/\partial\varphi$ and either $d_q\sim d_g$ or $d_q\sim d_g/40$. In the "worst case" $1-\gamma^{\rm PPN}\sim 10^4\,\Delta a/a$ so that $\Delta a/a\sim 10^{-15}\rightarrow 1-\gamma^{\rm PPN}\sim 10^{-11}$.

Thibault Damour (IHES) | Testing the Equivalence Principle | ONERA | 19/09/2011 | 14 / 14

T Damour et al., PRL vol.89, Nr.8, 2002 : «Our results suggest that the residual dilaton couplings today...corresponding to a violation of the UFF at the $\Delta a/a \sim 10^{-12}$ »

MICROSCOPE : 10 $^{-15}$ EP TEST through UFF



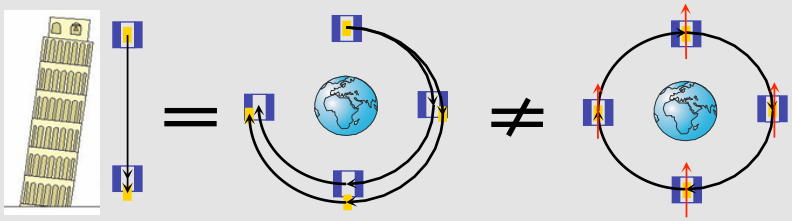
- Gravitational Source : the Earth
- Inertial Acceleration : Orbital Motion
- Control of 2 times 2 masses of different & identical composition

→ Along the same orbit (< 10^{-11}m),

→ With servo-controlled electrostatic pressures.

→ Observation of any dissymmetry along Earth Monopole direction

MICROSCOPE : 10 $^{-15}$ EP TEST through UFF



Galileo Galilei « Free fall » in space Microscope

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- Inertial Acceleration : Orbital Motion
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→ Along the same orbit (< 10^{-11}m),

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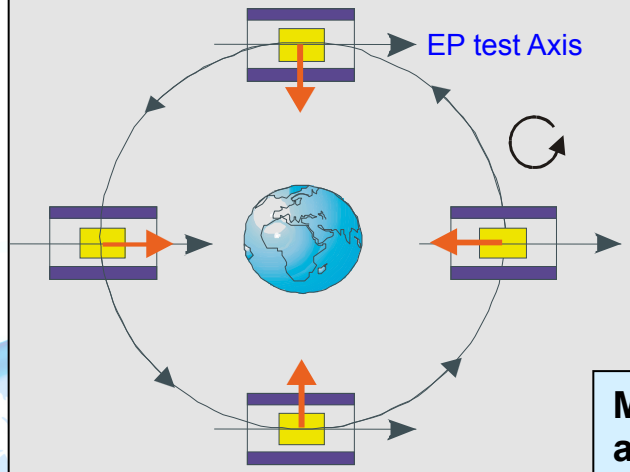
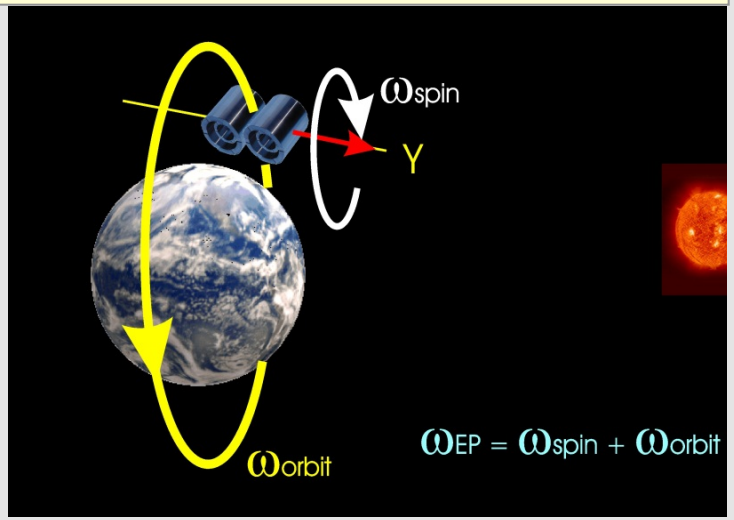
- Dedicated space instrument
- Mission duration : 2 years
- Test duration : series of 20 orbits ~ 1.2×10^5 s
- Signal to be observed at EP test phase & frequency

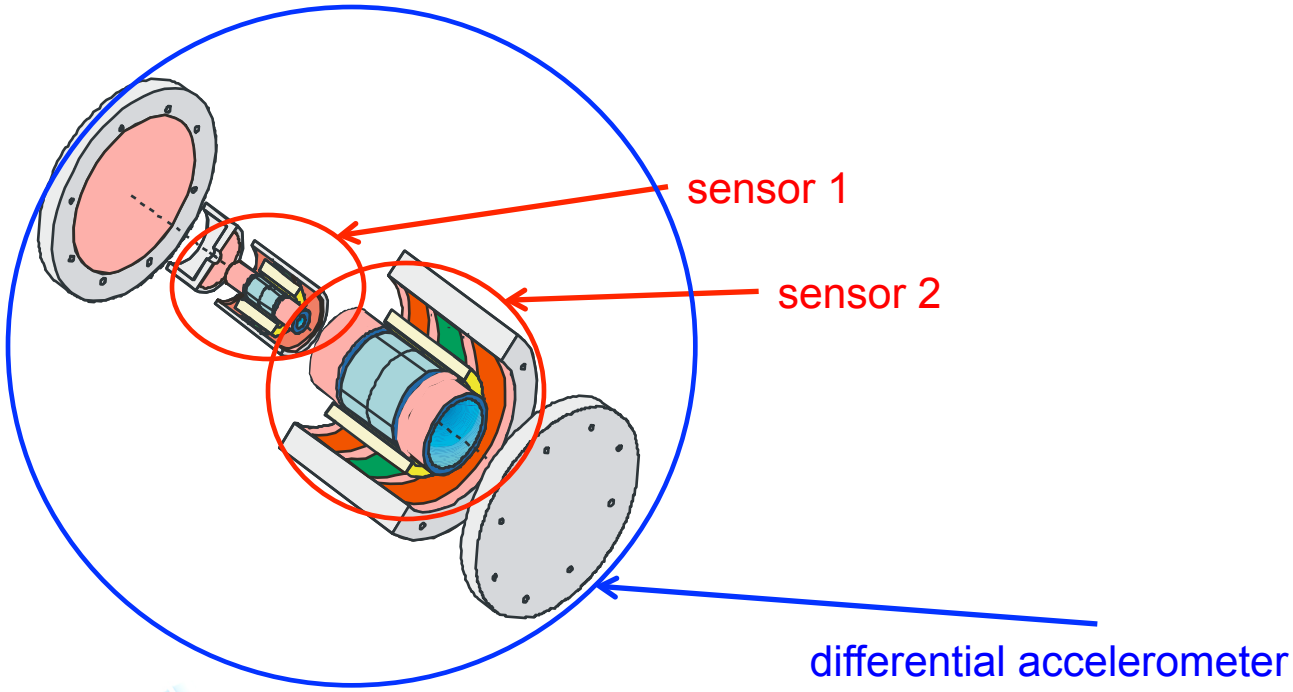
  → rejection of stochastic and tone disturbing signals
- Spatial environment : reduced or controlled disturbances



Mass material : Pt and Ti alloys



Differential accelerometer



Differential acceleration between two test masses

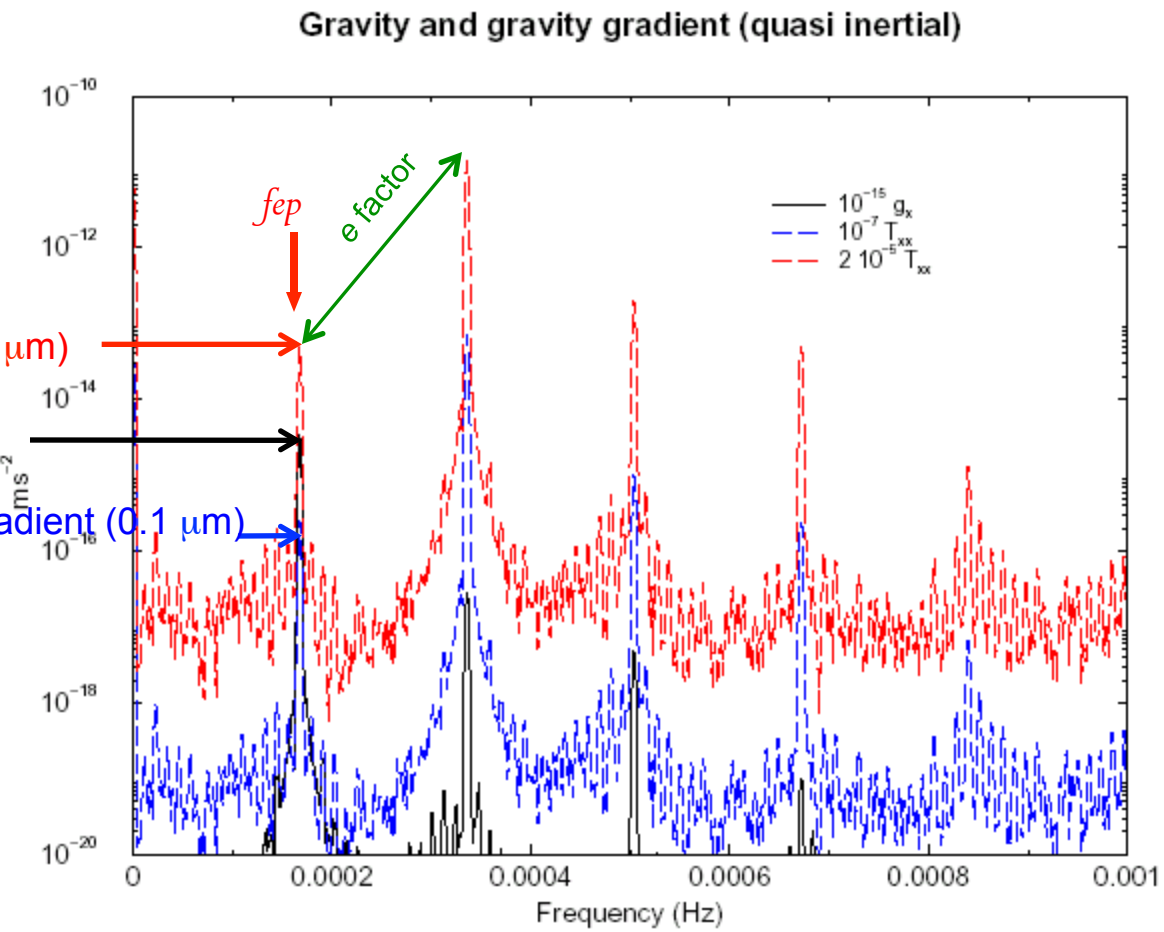
$$
\begin{aligned}
2\overrightarrow{\gamma}^{(d)} = & \left([\mathbf{T}](O_{12}) - [\mathbf{In}] \right) \overrightarrow{O_1O_2} && \textit{gradients: gravity and inertia} \\
& + (\delta_2 - \delta_1)\overrightarrow{g}(O_{12}) && \textit{EP violation} \\
& - 2[\mathbf{\Omega}]\overrightarrow{O_1O_2} - \overrightarrow{O_1O_2} && \textit{relative motion of the test masses} \\
& - 2\overrightarrow{\gamma_p}^{(d)} - 2\overrightarrow{g}_S^{(d)} && \textit{differential perturbations on the masses}
\end{aligned}
$$

The potential EP violation signal is their but:

- We do not measure the difference of acceleration but we compute the difference of two measurements !
- Each of this measurement is affected by the sensor characteristics

e = 0.005

Correction of the gravity gradient effects



Gravity gradient (20 μm)

EP violation @ 10^{-15}

Corrected gravity gradient (0.1 μm)

Non white noise

Spectral band of interest

Specified level for EP detection

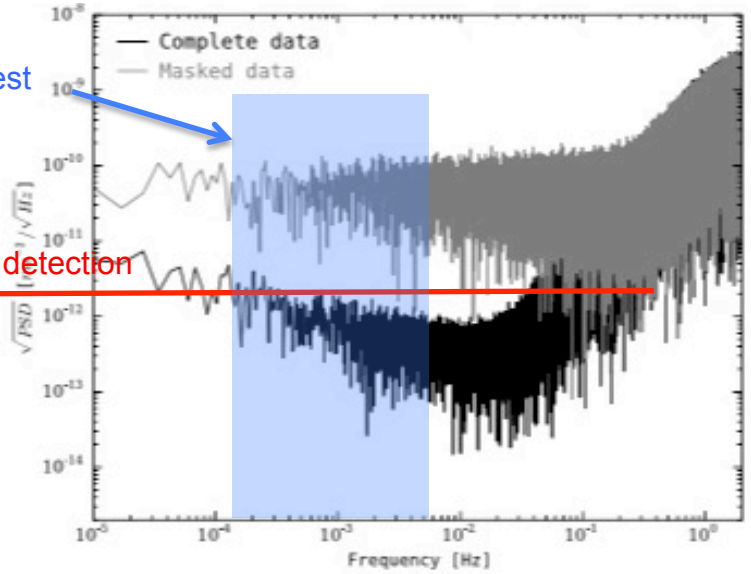
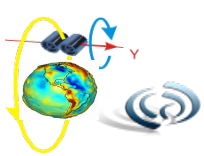


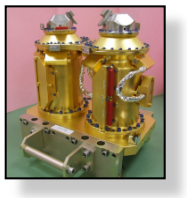
FIG. 1. Periodogram of original (black) and incomplete (grey) time series with 0.5 second data gaps randomly distributed in a 20 orbits session. The simulation is done for 260 random gaps per orbit.

Q. Baghi, G. Metris, J. Bergé, B. Christophe, P. Touboul, and M. Rodrigues. Phys. Rev. D, 91(062003), 2015.

➔ Data analysis

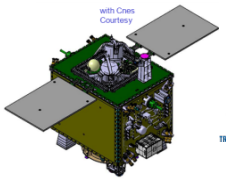
Present Scientific cooperations





Observatoire de la Côte d' Azur

ONERA
THE FRENCH AEROSPACE LAB



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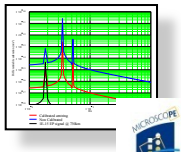
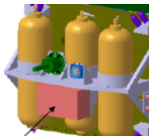


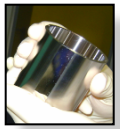
ZARM

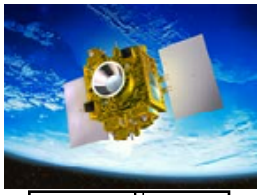
esa

PTB
Physikalisch-
Technische
Bundesanstalt

DLR







Scientific organization : Science Working Group

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Fundamental Interactions	Pierre Fayet
Interdisciplinary Physics	Serge Reynaud
Earth gravity field	Isabelle Planet
Aeronomy	Pieter Visser
European scientist representative of similar space missions	Tim Sumner
CNES Fundamental Physics coordinator	Sylvie Léon-Hirtz
CMS manager	Manuel Rodrigues
CNES project manager	Yves André
Payload manager	Manuel Rodrigues
CECT chairman	Alain Robert

Mission Core Team

Scientific Experts Per domain

Invited Permanent

Invited when needed

Towards a launch in spring 2016

Thank you for your attention