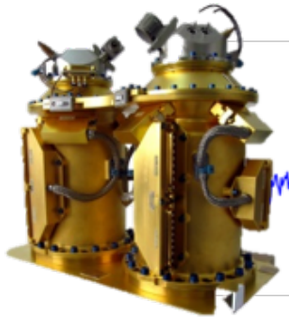
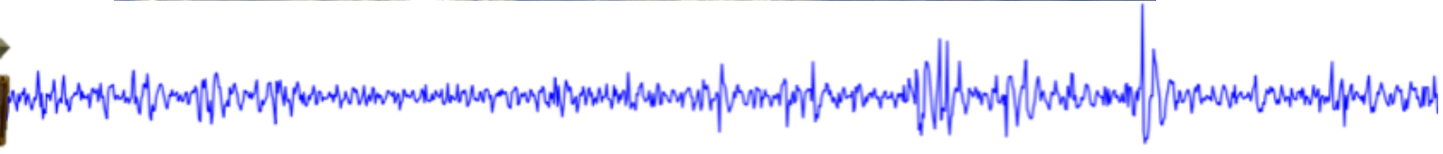
Gravitational interaction of macroscopic particles

Testing the equivalence principle in space

Quentin Baghi, on behalf of the MICROSCOPE collaboration





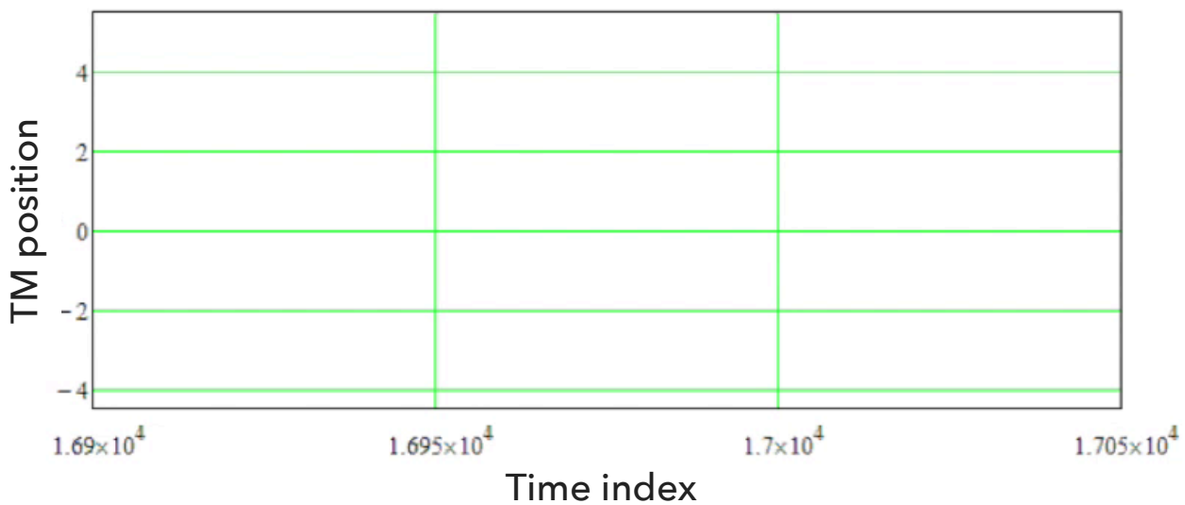
CEA-Saclay - DPhP Seminar - February 6th 2023

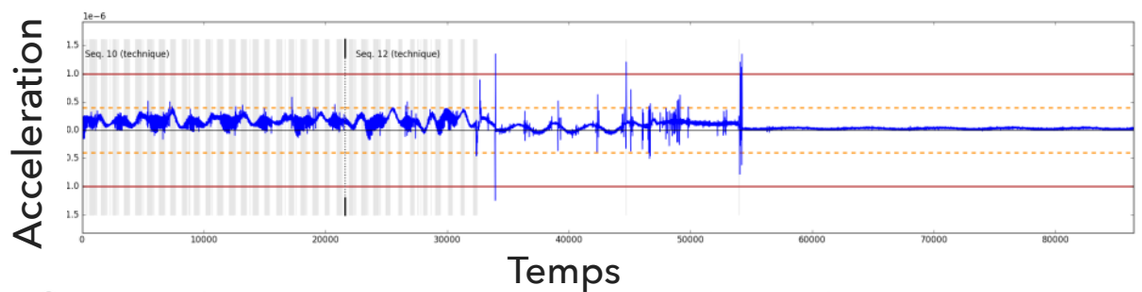
OUTLINE

1. The equivalence principle
2. Mission description and principle of the experiment
3. First WEP test
4. Improved results
5. Conclusion

MISSION MILESTONES

- 25th of April 2016: satellite launch as piggy bag of Sentinel 1B by Soyuz from Kourou
- 2nd of May: test-mass release and activation of the electrostatic control in robust mode
- 11th of May: first test of payload in science mode. But capacitance breakdown! Thankfully without impact





- 7th of June: 1st Attitude control with hybridization of the Star Sensor & the Payload angular accelerometer
- 9th of June: 1st “drag-free” above 6 axes
- December 2016: beginning of scientific measurements.
- October 16th 2018: decommissioning

1. THE EQUIVALENCE PRINCIPLE

THE EQUIVALENCE PRINCIPLE

- The equivalence principle (EP) is an experimental fact whose first observation dates back to the beginning of the 17th century

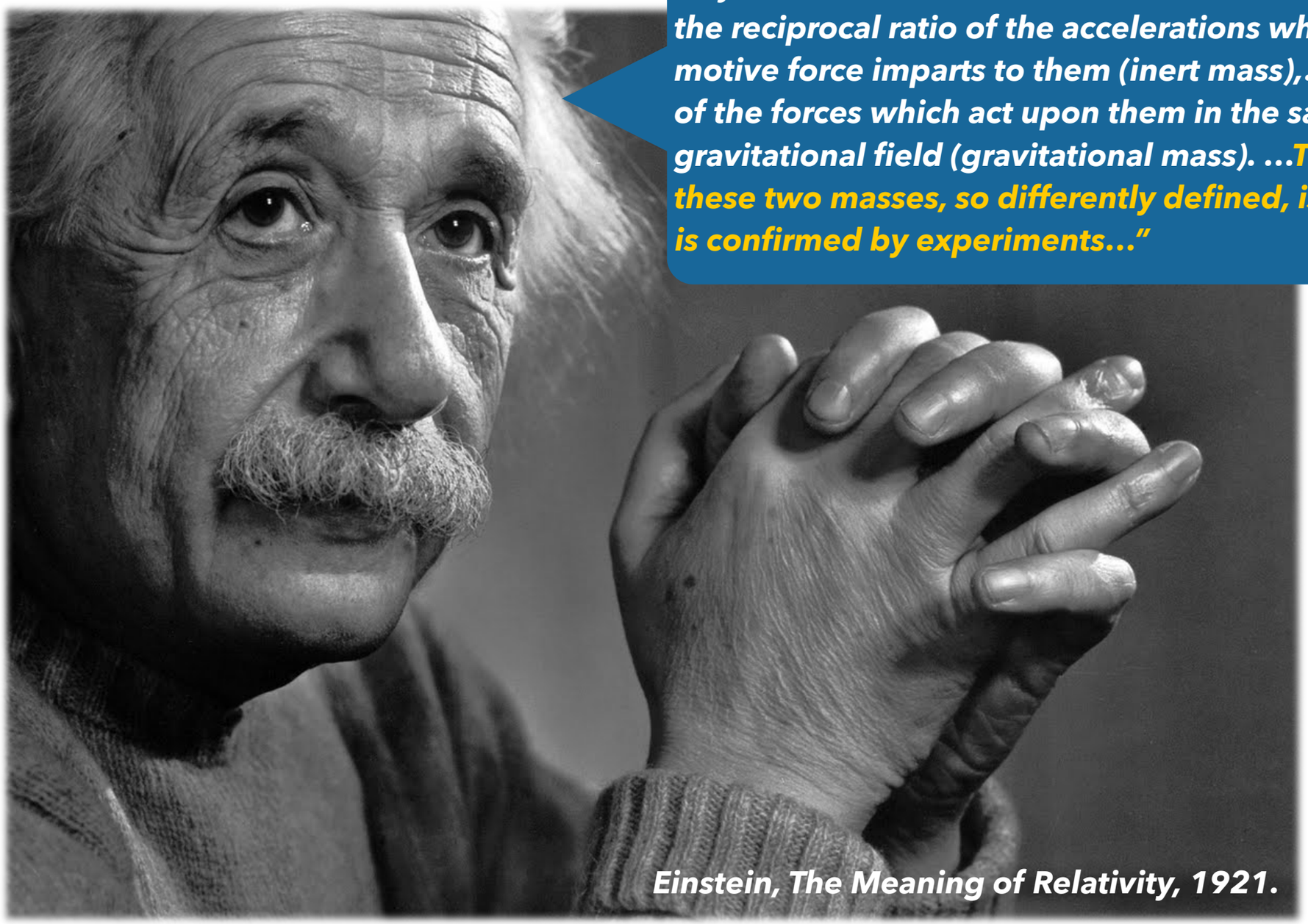
Credits: J.-E. McCONNELL/LOOK AND LEARN/BRIDGEMAN IMAGES

- Galileo noted the simultaneity of the free fall of two different bodies in the same gravitational field, independently of their composition or amount of mass

THE EQUIVALENCE PRINCIPLE

The Equivalence Principle (EP) is at the basis of Einstein's theory of gravitation, general relativity.

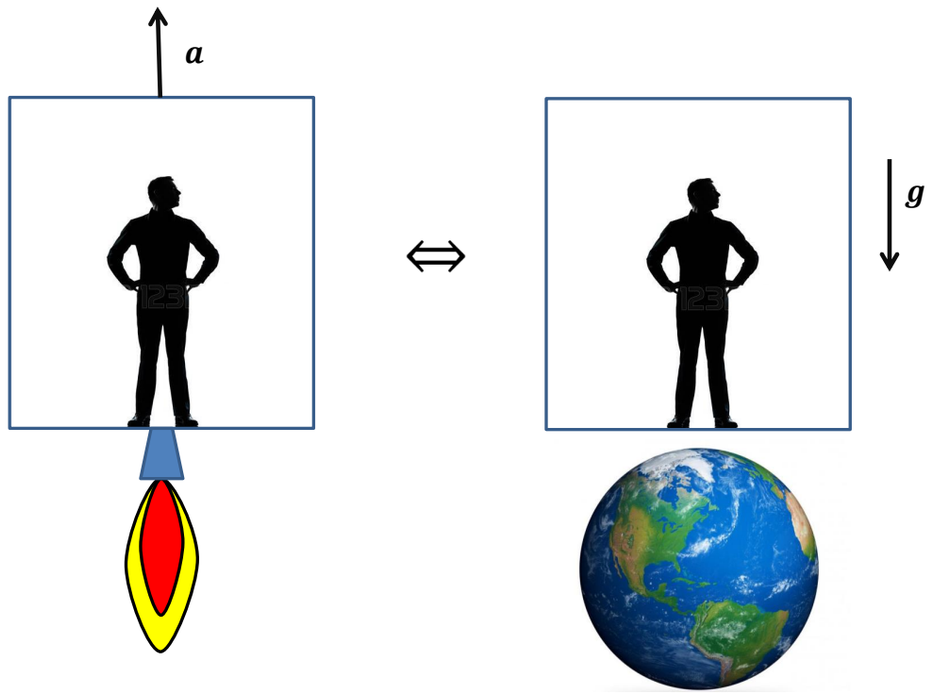
"The ratio of the masses of two bodies is defined in two ways which differ from each other fundamentally,..., as the reciprocal ratio of the accelerations which the same motive force imparts to them (inert mass),..., as the ratio of the forces which act upon them in the same gravitational field (gravitational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



Einstein, The Meaning of Relativity, 1921.

THE EQUIVALENCE PRINCIPLE

- Weak Equivalence Principle: the motions of freely-falling particles are locally the same in a gravitational field and in a uniformly accelerated frame.



- Einstein's Equivalence Principle: the WEP holds, and the outcome of any local non-gravitational experiment in a freely falling laboratory does not depend on its location and velocity

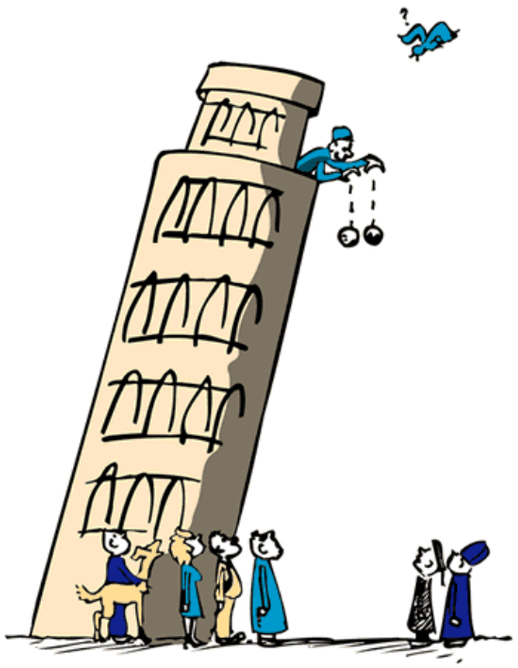
THE EQUIVALENCE PRINCIPLE

- In Newtonian mechanics, the EP stems from two laws:
  - Newton's second law: $\mathbf{F} = m_i \mathbf{a}$
  - Newton's law of gravitation: $\mathbf{F} = -m_g \nabla \Phi$

- The equivalence principle in Newtonian mechanics:

$$\frac{m_g}{m_i} = \text{constant } \forall \text{ bodies}$$

- We define the Eötvös parameter of two test-masses as:



Credit: San Diego State University

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

WHY TESTING THE EP?

- The EP is a well observed experimental fact:

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

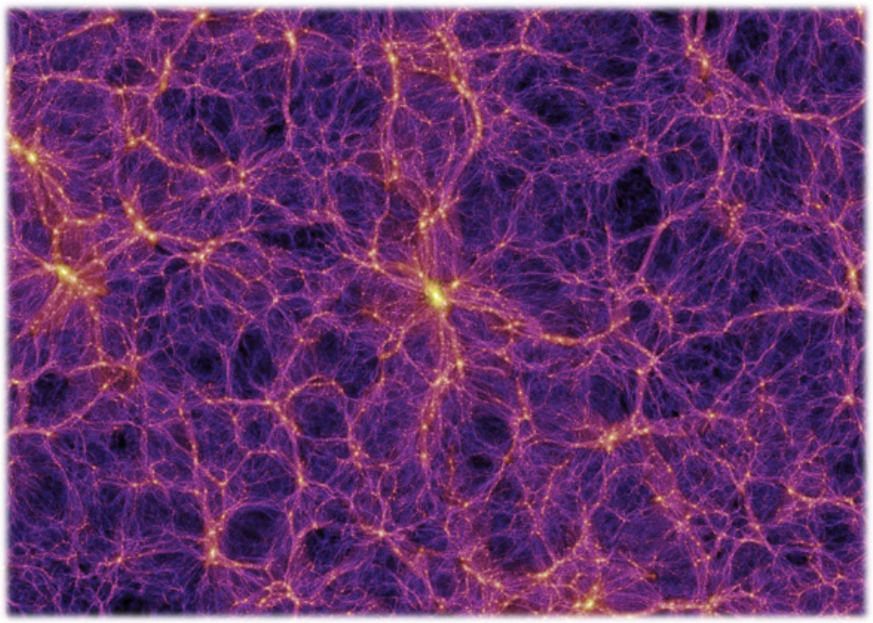
  - Torsion balance: 2 x10^{-13} [Schlamminger et al, 2008]
  - Lunar laser ranging: 7 x 10^{-14} [Viswanathan et al, 2018]

- But key questions remain to be addressed by modern physics:

  - what does the Big Bang mean?
  - what is dark energy?
  - what is the nature of dark matter?
  - unified formalism between gravitation and quantum field theory

➡ Search for a more fundamental collection of degrees of freedom

➡ The EP is called into question by these investigations (emergence of a fifth force)

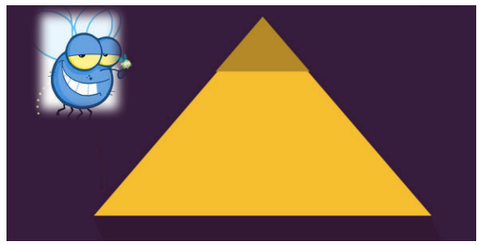


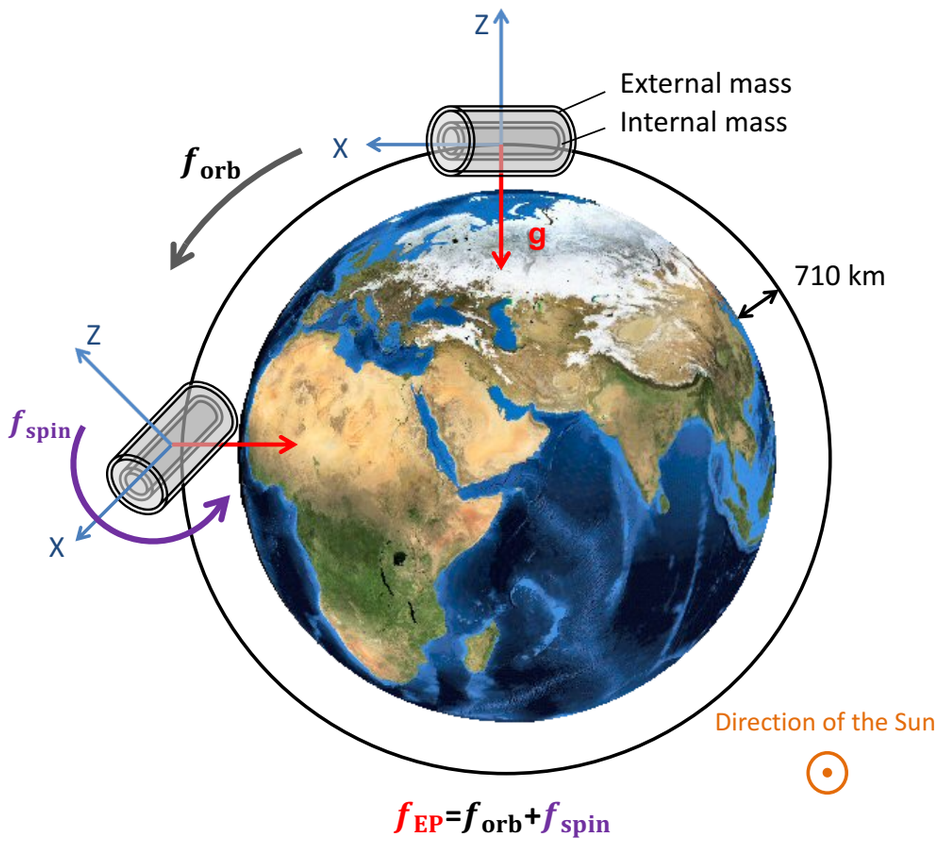
Dark matter simulation. Credit: MIT

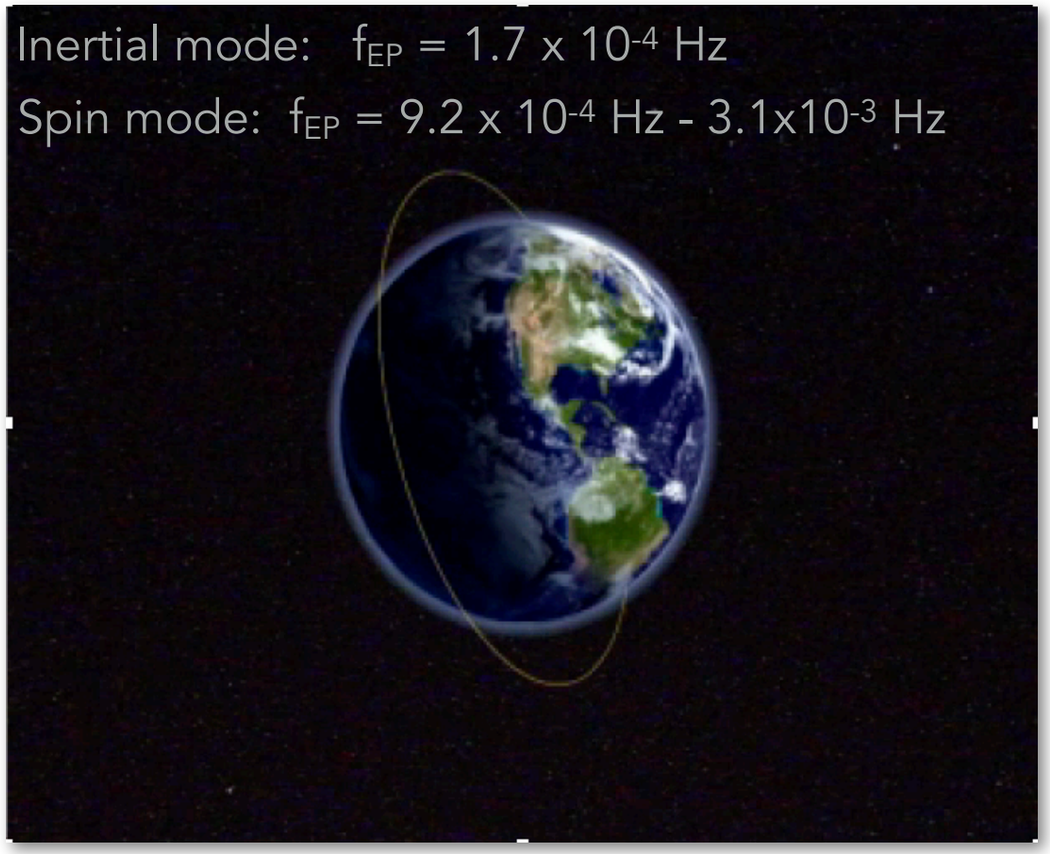
2. MISSION DESCRIPTION AND PRINCIPLE OF THE EXPERIMENT

PRINCIPLE OF THE EXPERIMENT

- Primary mission objective: test the WEP with a precision of **10^{-15} on** η .
- As low as the weight of a fly compared to the Cheops pyramid



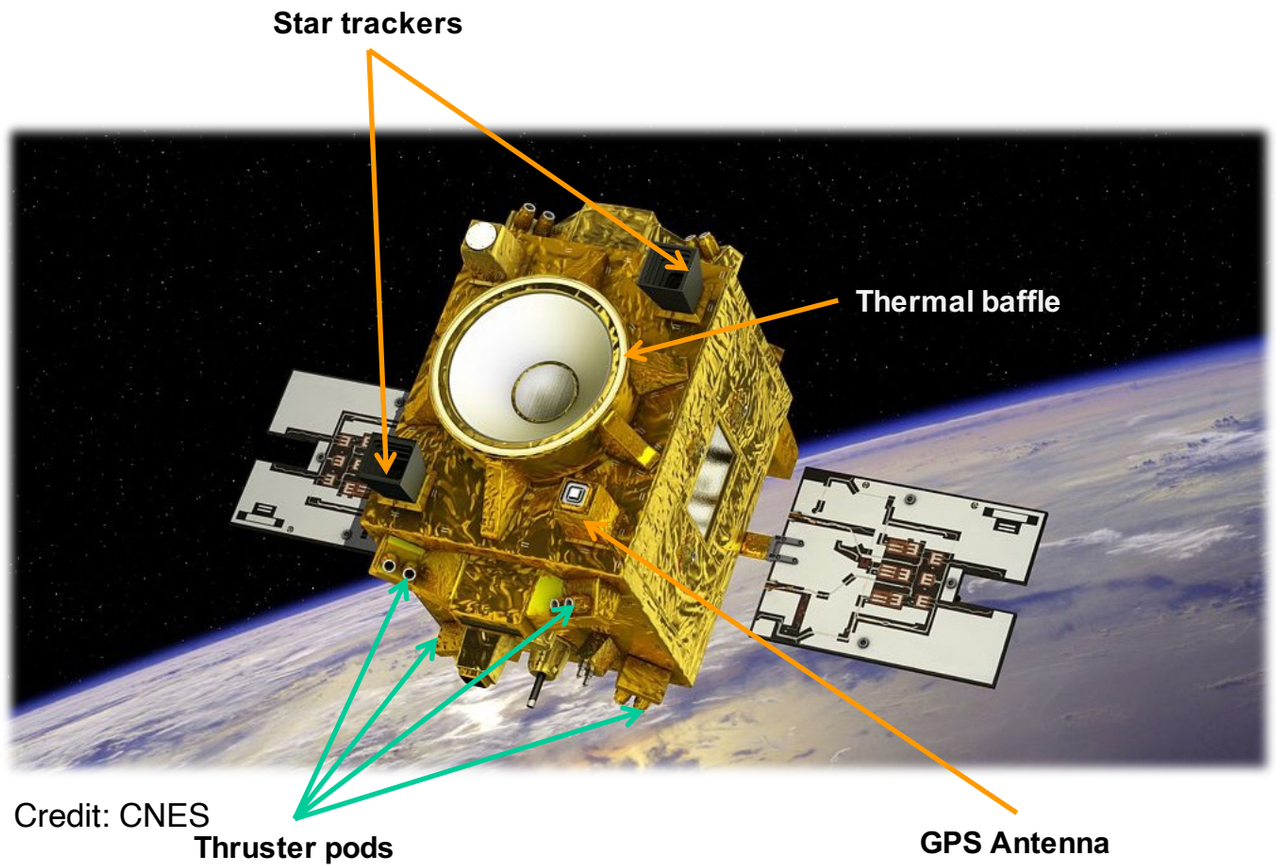




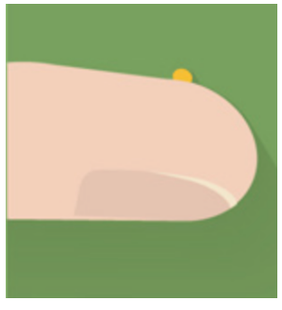
- 2 test-masses (TMs) falling in the gravitational field of Earth
- The difference of the TMs accelerations possibly contains a violation signal $\propto \eta$
- This signal has a particular frequency signature $f_{\mathrm{EP}} = f_{\mathrm{orb}} + f_{\mathrm{spin}}$

DESCRIPTION OF THE SPACE SEGMENT

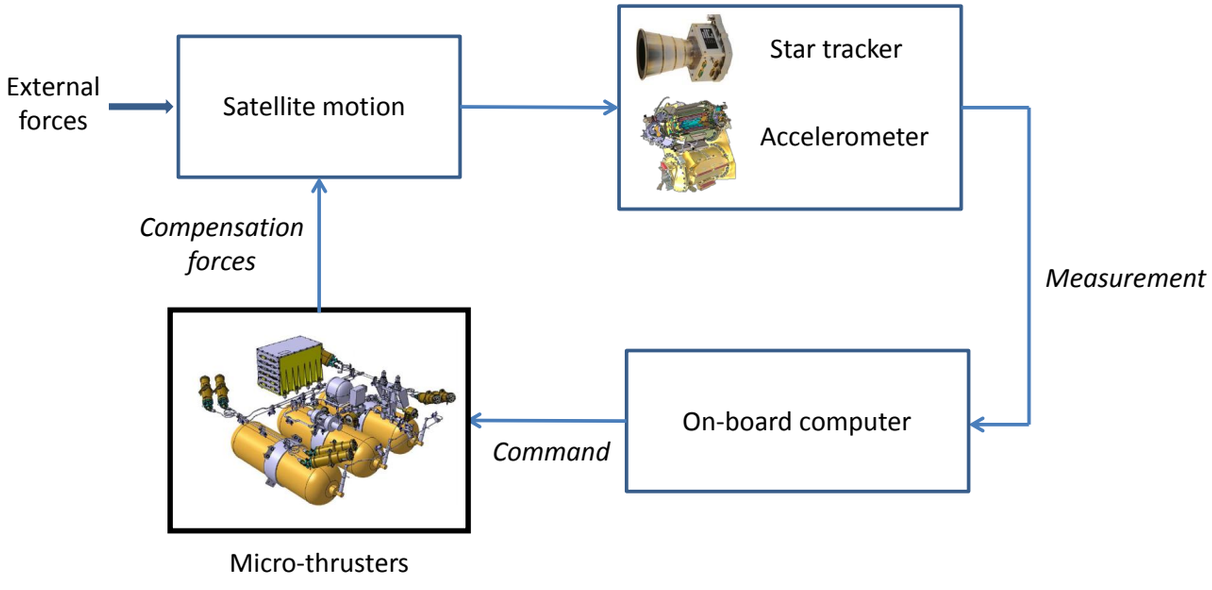
- The experiment is carried on board a CNES microsatellite (Myriades platform)
- Sun-synchronous orbit (constant power supply and thermal stability)
- Quasi-circular (well defined frequency signature of WEP signal)
- Altitude 710 km (trade-off between signal strength/drag)



- Equipped with a drag-free system (compensate for solar radiation and atmospheric drag):

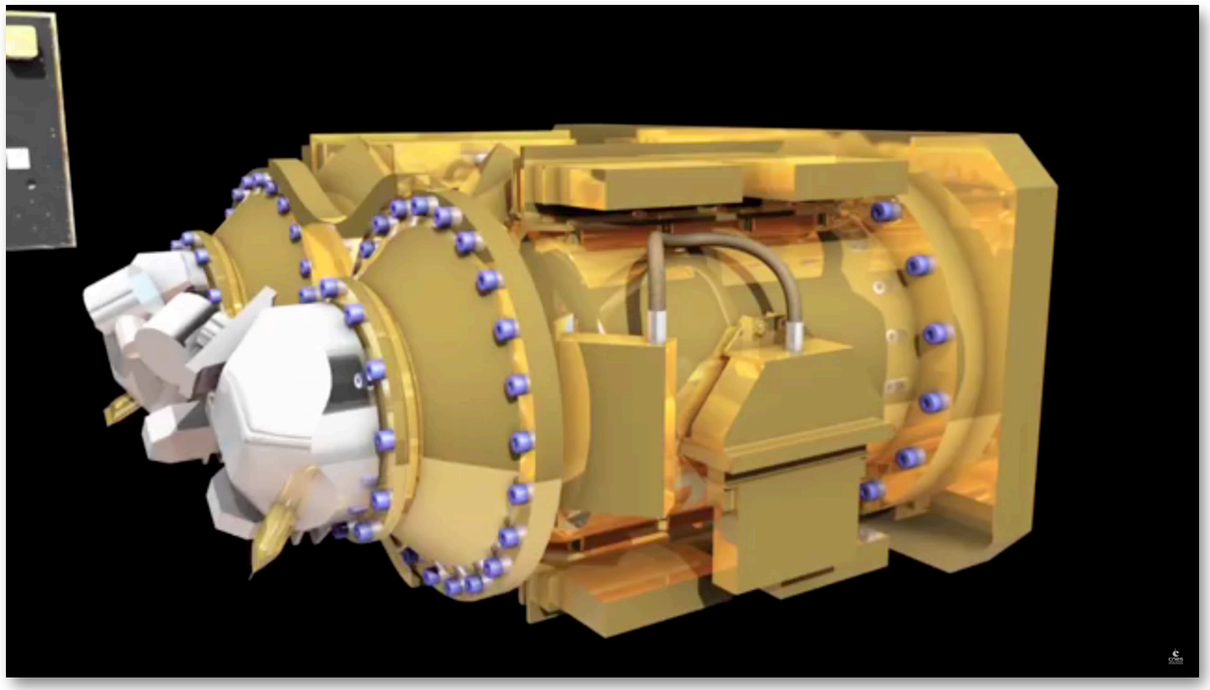


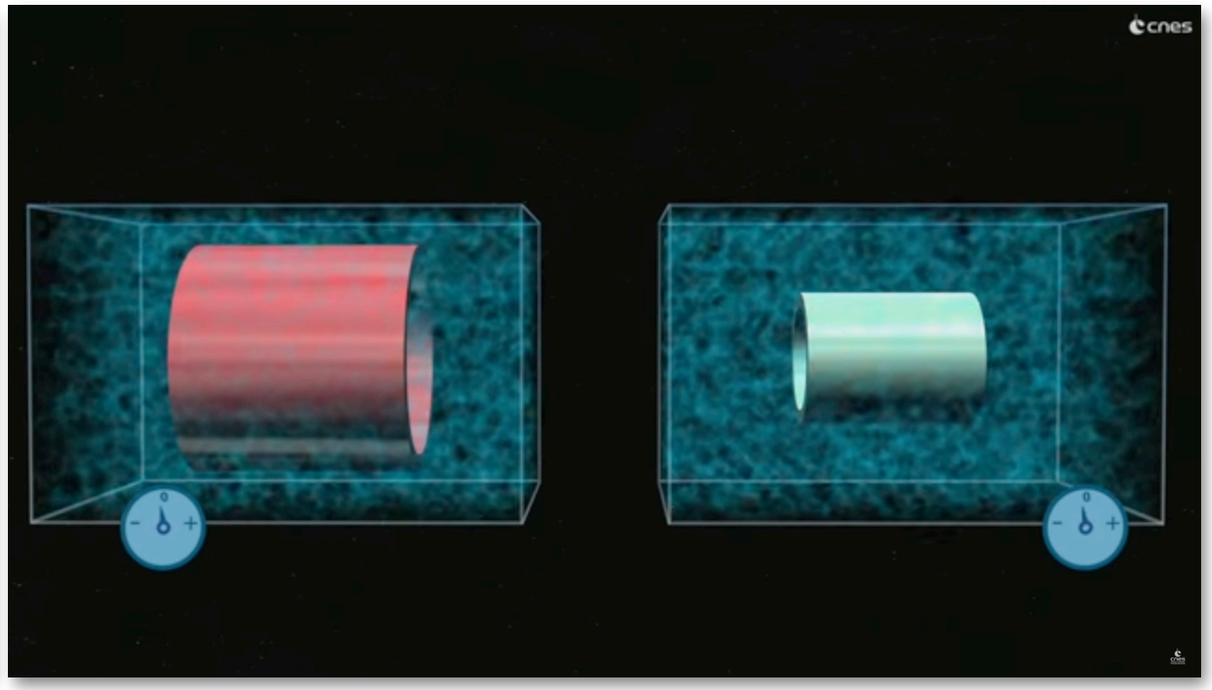
Resolution of 0.1µN
it would compensate for the force necessary to lift a grain of sand on Earth.



DESCRIPTION OF THE INSTRUMENT

- The instrument used for the experiment consists of 2 electrostatic differential accelerometers
- Each accelerometer includes 2 sensors measuring the acceleration of 2 cylindrical and concentric test-masses
  - Reference accelerometer (SUREF): TMs made of the same material Pt-Rh / Pt-Rh
  - EP accelerometer (SUEP): TMs of different composition Ti / Pt-Rh





- We actually measure the electrostatic force applied to each TM to maintain it relatively motionless at the centre of the instrument, with a **10^{-11}m precision in position (< the size of an atom)**

WHAT DO WE MEASURE?

- We define the acceleration modes:

  - Differential acceleration: $$\mathbf{\Gamma}_{\mathrm{App},d} \equiv \frac{1}{2}\left(\mathbf{\Gamma}_{\mathrm{App},1} - \mathbf{\Gamma}_{\mathrm{App},2}\right)$$
  - Common acceleration: $$\mathbf{\Gamma}_{\mathrm{App},c} \equiv \frac{1}{2}\left(\mathbf{\Gamma}_{\mathrm{App},1} + \mathbf{\Gamma}_{\mathrm{App},2}\right)$$

- We look for a difference in the way gravity acts on each test-mass ➔ differential mode:

$$\mathbf{\Gamma}_{\mathrm{App},d} = -\underbrace{1/2 \cdot \eta \cdot \mathbf{g}}_{\text{WEP violation}}$$

- When taking the instrument imperfections into account (scale factors, misalignment, axes coupling and quadratic effects):

$$\mathbf{\Gamma}_{\mathrm{meas},d} = \underbrace{\mathbf{b}_{0d}}_{\text{bias}} + \underbrace{[\mathbf{A}_c]}_{\text{default matrix}}\mathbf{\Gamma}_{\mathrm{App},d} + \underbrace{[\mathbf{A}_d]\mathbf{\Gamma}_{\mathrm{App},c}}_{\text{coupling with common mode}} + \underbrace{\mathbf{Q}_d}_{\text{non-linearity}} + \underbrace{\mathbf{n}_d}_{\text{random noise}}$$

3. FIRST WEP TEST AND LAST RESULTS

PRL 119, 231101 (2017) PHYSICAL REVIEW LETTERS week ending 8 DECEMBER 2017

MICROSCOPE Mission: First Results of a Space Test of the Equivalence Principle

Pierre Touboul,[1,*] Gilles Métris,[2,†] Manuel Rodrigues,[1,‡] Yves André,[3] Quentin Baghi,[2] Joël Bergé,[1] Damien Boulanger,[1] Stefanie Bremer,[4] Patrice Carle,[1] Ratana Chhun,[1] Bruno Christophe,[1] Valerio Cipolla,[3] Thibault Damour,[5] Pascale Danto,[3] Hansjoerg Dittus,[6] Pierre Fayet,[7] Bernard Foulon,[1] Claude Gageant,[1] Pierre-Yves Guidotti,[3] Daniel Hagedorn,[8] Emilie Hardy,[1] Phuong-Anh Huynh,[1] Henri Inchauspe,[1] Patrick Kayser,[1] Stéphanie Lala,[1] Claus Lämmerzahl,[4] Vincent Lebat,[1] Pierre Leseur,[1] Françoise Liorzou,[1] Meike List,[4] Frank Löffler,[8] Isabelle Panet,[9] Benjamin Pouilloux,[3] Pascal Prieur,[3] Alexandre Rebray,[1] Serge Reynaud,[10] Benny Rievers,[4] Alain Robert,[3] Hanns Selig,[4] Laura Serron,[2] Timothy Sumner,[11] Nicolas Tanguy,[1] and Pieter Visser[12]

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[10]*Laboratoire Kastler Brossel, UPMC-Sorbonne Université, CNRS, ENS-PSL Research University, Collège de France, F-75005 Paris, France*
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(Received 12 May 2017; revised manuscript received 20 September 2017; published 4 December 2017)

According to the weak equivalence principle, all bodies should fall at the same rate in a gravitational field. The *MICROSCOPE* satellite, launched in April 2016, aims to test its validity at the 10^{-15} precision level, by measuring the force required to maintain two test masses (of titanium and platinum alloys) exactly in the same orbit. A nonvanishing result would correspond to a violation of the equivalence principle, or to the discovery of a new long-range force. Analysis of the first data gives $\delta(\mathrm{Ti, Pt}) = [-1 \pm 9(\mathrm{stat}) \pm 9(\mathrm{syst})] \times 10^{-15}$ (1σ statistical uncertainty) for the titanium-platinum Eötvös parameter characterizing the relative difference in their free-fall accelerations.

DOI: 10.1103/PhysRevLett.119.231101

FIRST RESULTS

- Press conference at CNES Headquarters, Paris, on December 4th, 2017

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Communiqué de Presse

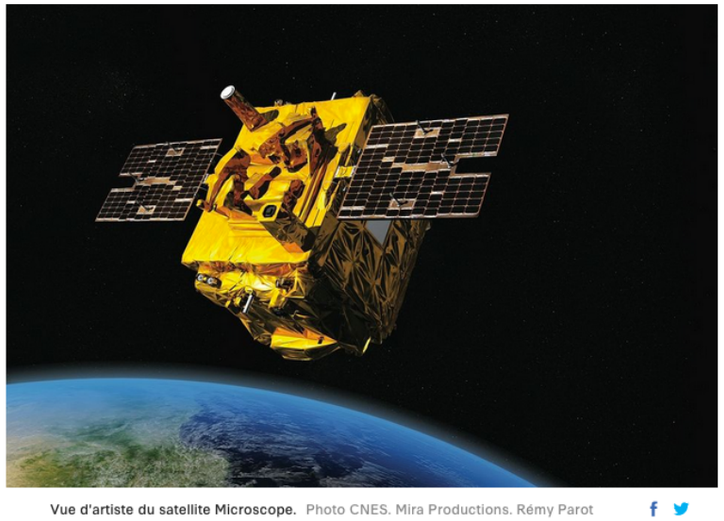
4 Décembre 2017 **CP191-2017**

Les premiers résultats du satellite MICROSCOPE confirment la théorie d'Albert Einstein avec une précision inégalée

SCIENCES

Relativité générale : la théorie d'Einstein validée au «Microscope»

Par Camille Gévaudan — 4 décembre 2017 à 12:00



Vue d'artiste du satellite Microscope. Photo CNES. Mira Productions. Rémy Parot

PARTAGER TWEETER

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M Physique

CIENCES PHYSIQUE Boson de Higgs

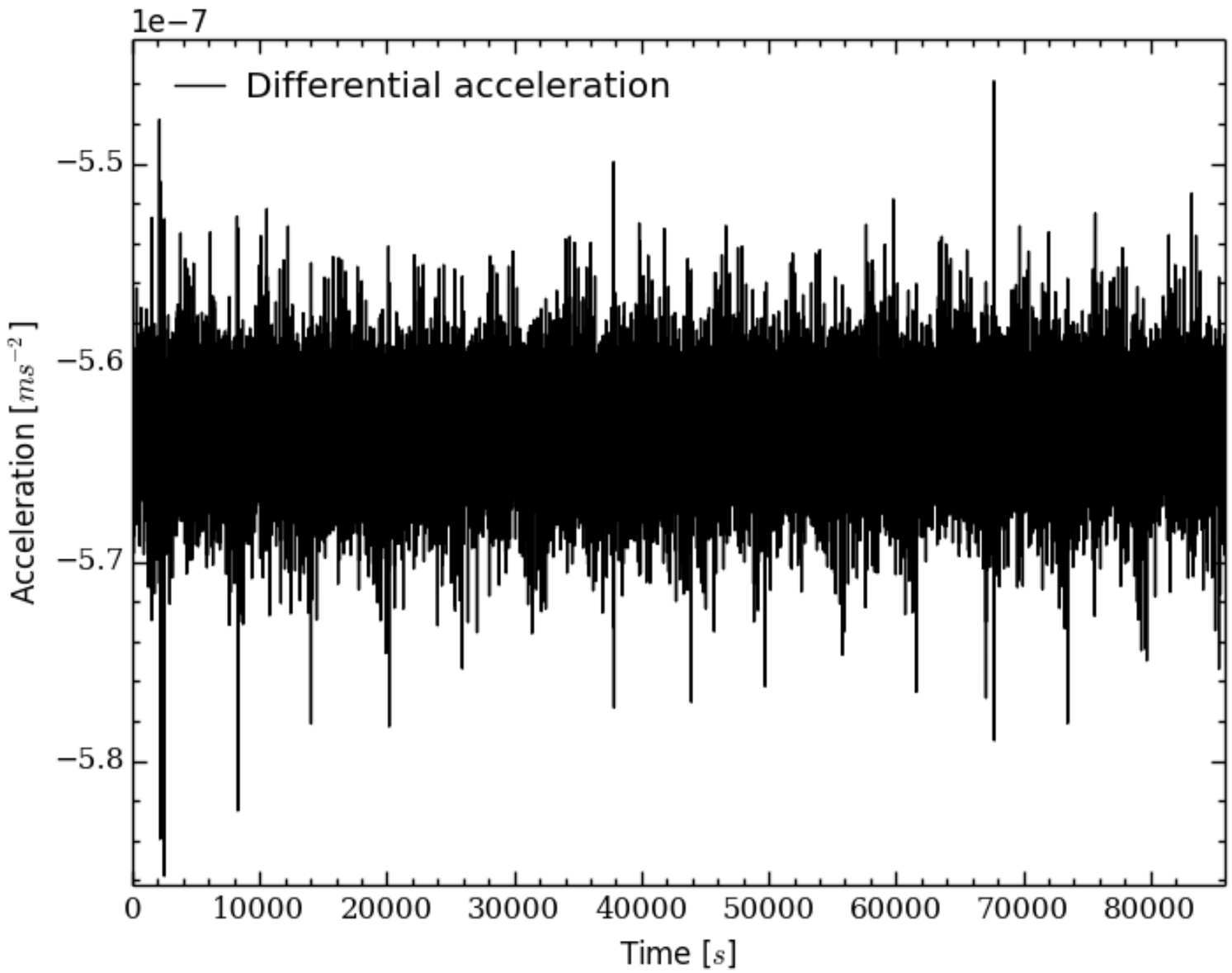
L'universalité de la chute libre confirmée

Physique - Les premiers résultats du satellite Microscope confirment la validité d'un principe fondamental en physique: tous les corps en chute libre tombent dans le vide à la même vitesse, quelle que soit leur masse ou leur composition chimique.

LE MONDE SCIENCE ET TECHNO | 04.12.2017 à 13h03 |

Par **David Larousserie**

MEASUREMENT IN THE TIME DOMAIN…

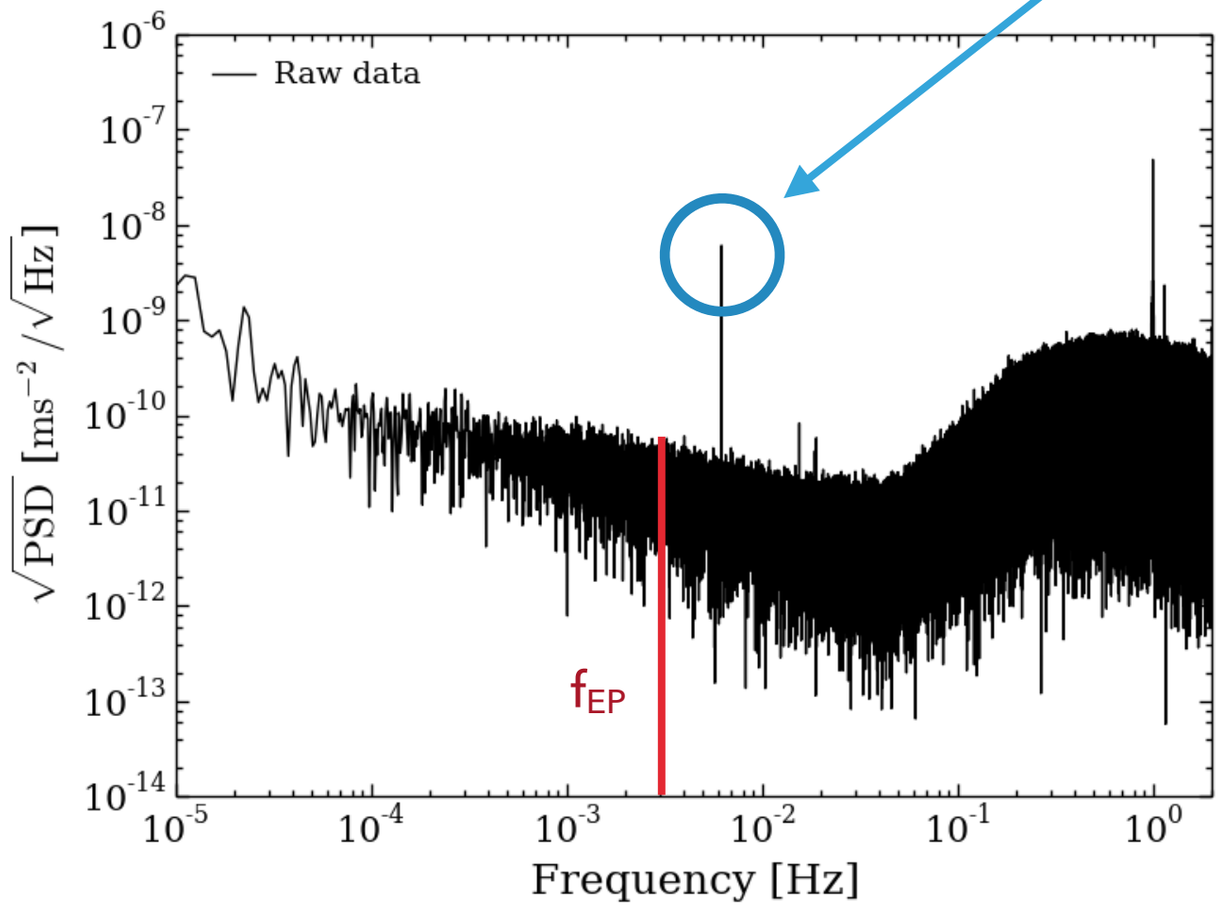


MEASUREMENT IN THE FOURIER DOMAIN…

$f_{\mathrm{orb}} = 1.68 \times 10^{-4}$ Hz

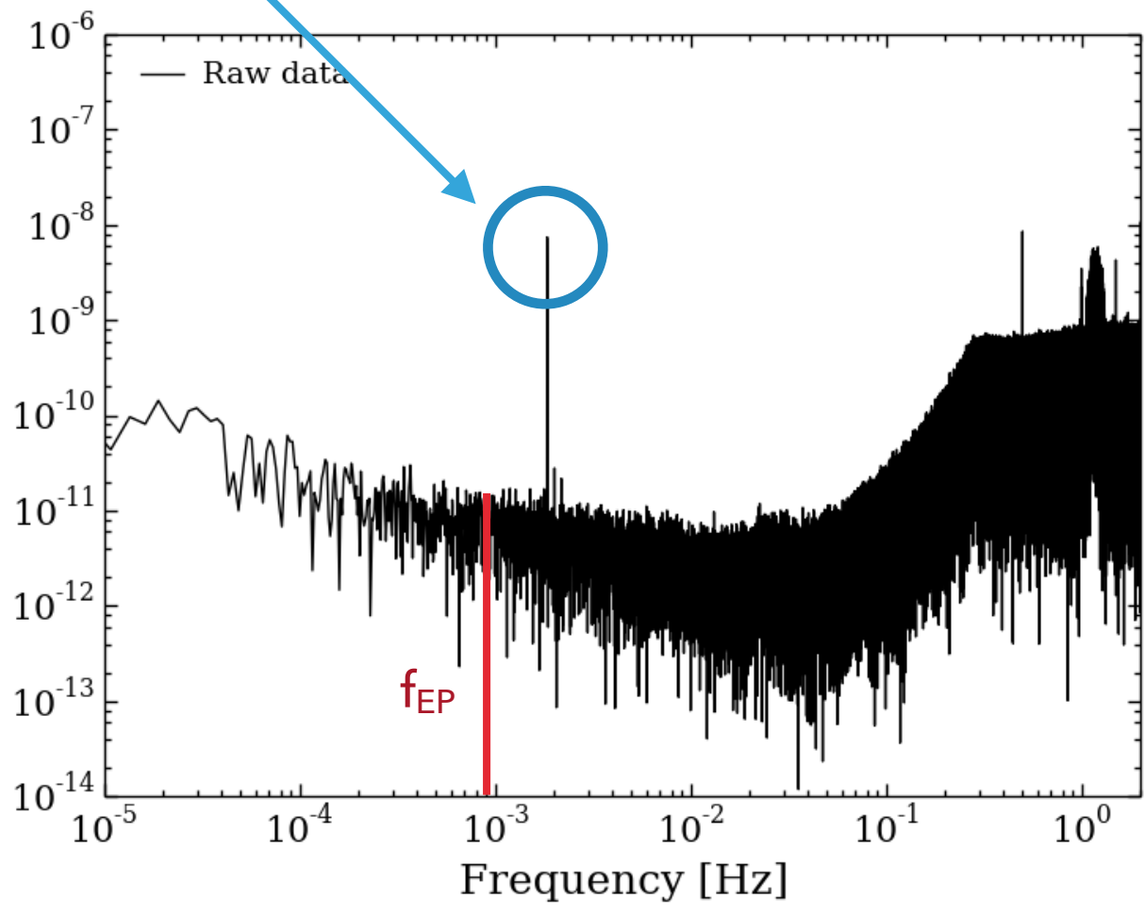
Gravitational gradient effect:
due to an offcentring of the
test-mass as thin as the tenth of a hair!

EP accelerometer



$f_{\mathrm{EP}} = 3.11 \times 10^{-3}$ Hz

REF accelerometer



$f_{\mathrm{EP}} = 0.93 \times 10^{-3}$ Hz

FIRST RESULTS

EP accelerometer

Parameter	Unit	Estimation	Precision	Accuracy
$\delta(\mathrm{Ti},\mathrm{Pt})$	10^{-15}	1.0	9	9
Δ_x	μm	20.1	0.04	0.1
Δ_y	μm	-8.4	0.2	0.2
Δ_z	μm	-5.6	0.04	0.1

Consistent with zero, no apparent violation at this level

REF accelerometer

Parameter	Unit	Estimation	Precision	Accuracy
$\delta(\mathrm{Pt},\mathrm{Pt})$	10^{-15}	+4	4	TBD
Δ_x	μm	-3.5	0.02	0.1
Δ_y	μm	5.9	0.06	0.2
Δ_z	μm	+5.5	0.02	0.1

Pierre Touboul et al.
Phys. Rev. Lett. 119, 231101

4. IMPROVED RESULTS

IMPROVED RESULTS

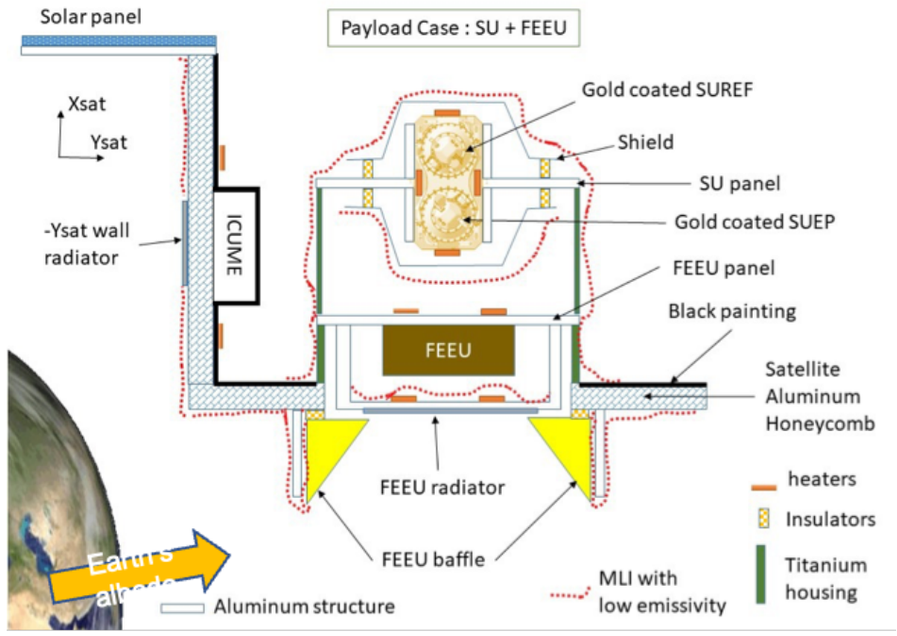
- After this first result we had a long way to go:
  - Reduce the statistical uncertainty by integrating more data (1642 orbits)
  - Better model the systematic errors: 90% came from upper bound limit on T variations

$$\Gamma_{dx,\mathrm{th}} = \frac{\partial \Gamma_{dx}}{\partial T_{\mathrm{SU}}} \delta T_{\mathrm{SU}} + \frac{\partial \Gamma_{dx}}{\partial T_{\mathrm{FEEU}}} \delta T_{\mathrm{FEEU}}$$

Needed to better evaluate the measurement sensitivity to T

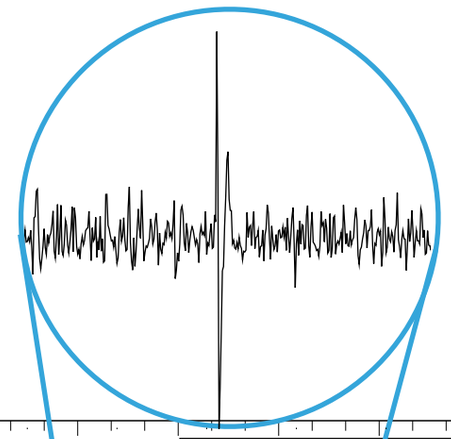
< 15 µK , limited by probe.
Needed to better constrain the SU temperature variations at the EP frequency

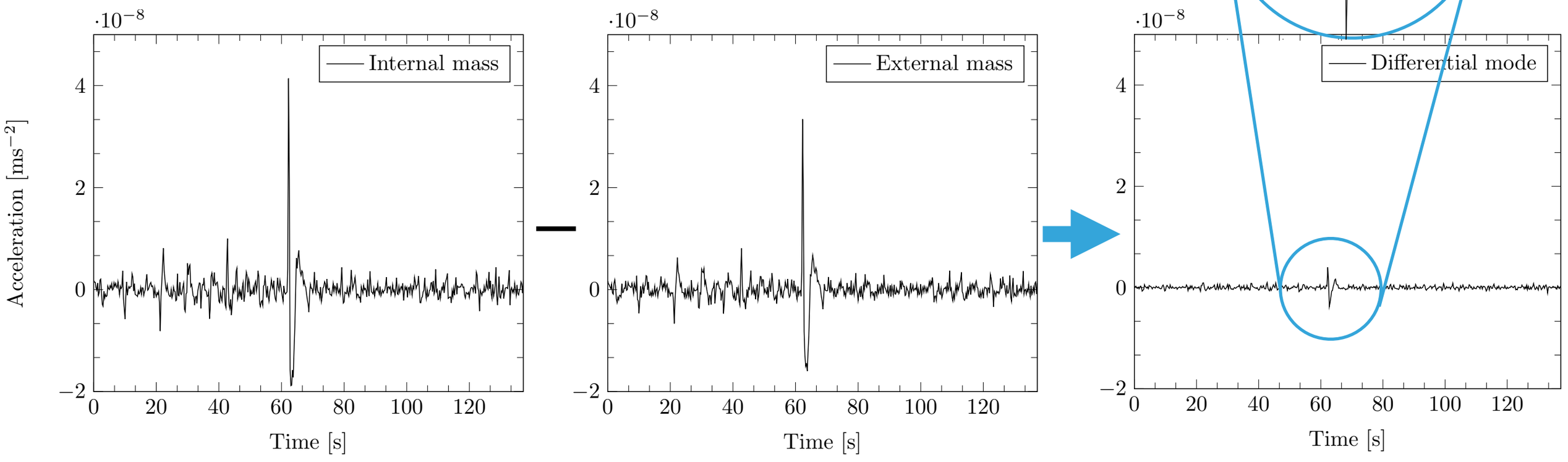
- We designed specific sessions to characterise the thermal sensitivity through a periodic stimulus by on-board heaters
- Showed that temperature variations are driven by the Earth's albedo coming through the FEEU radiator's baffle + they are attenuated between FEEU and SU



DATA ANALYSIS: ADDRESSING THE OUTLIERS ISSUE

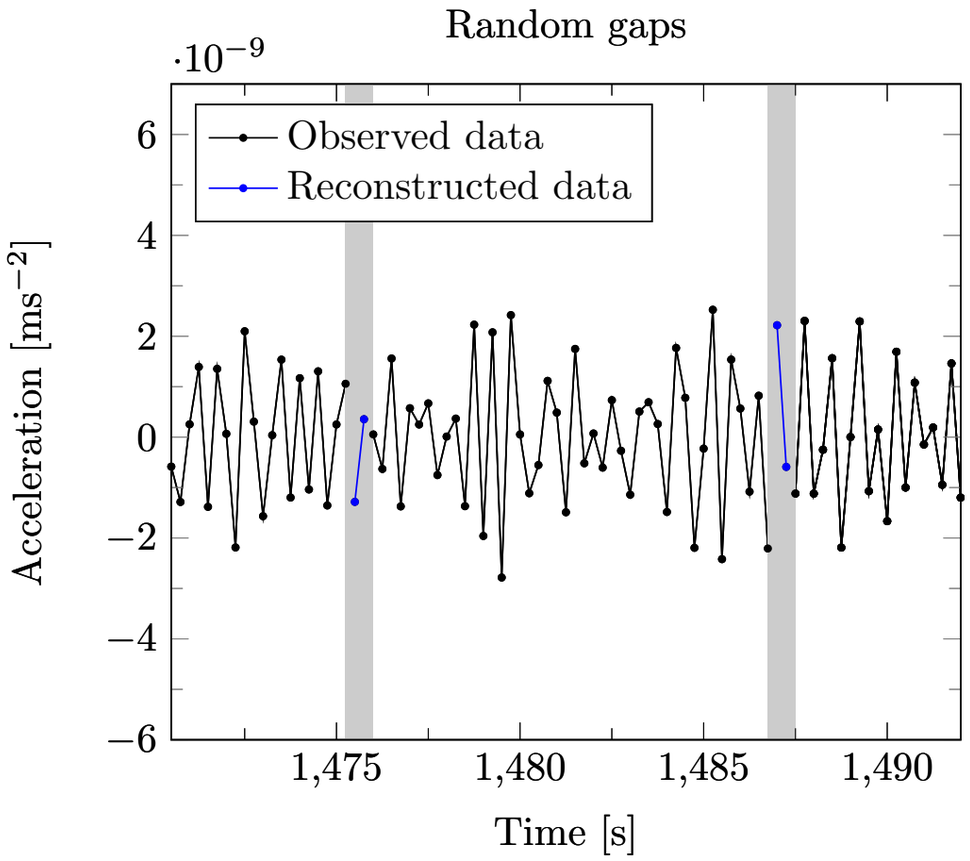
- Many invalid or saturated data spans due to:
  - crackling of the cold gas tanks
  - crackling of the multi layers insulation (MLI)
  - micrometeorites impact

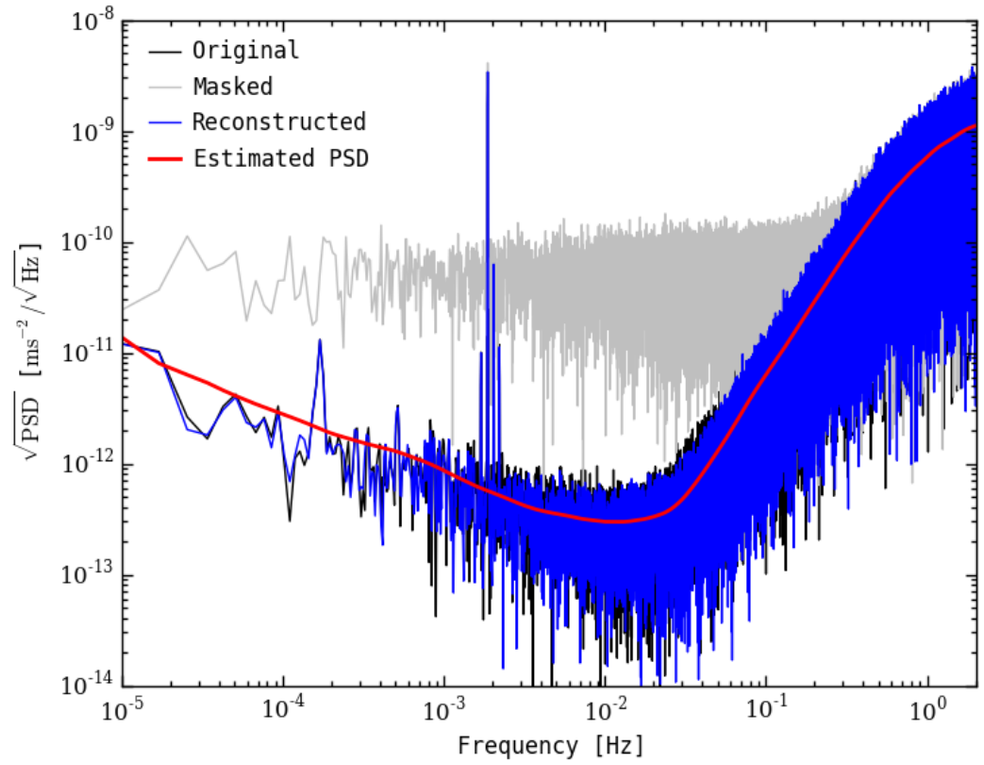




IMPROVED RESULTS

- Example on simulated data: random missing data





	Standard deviation of $\hat{\delta}$ $[10^{-15}]$			
Mask	OLS	KARMA	ECM	CRLB
Periodic gaps	4.12	0.97	1.02	0.97
Random gaps	65.2	1.14	1.15	1.05

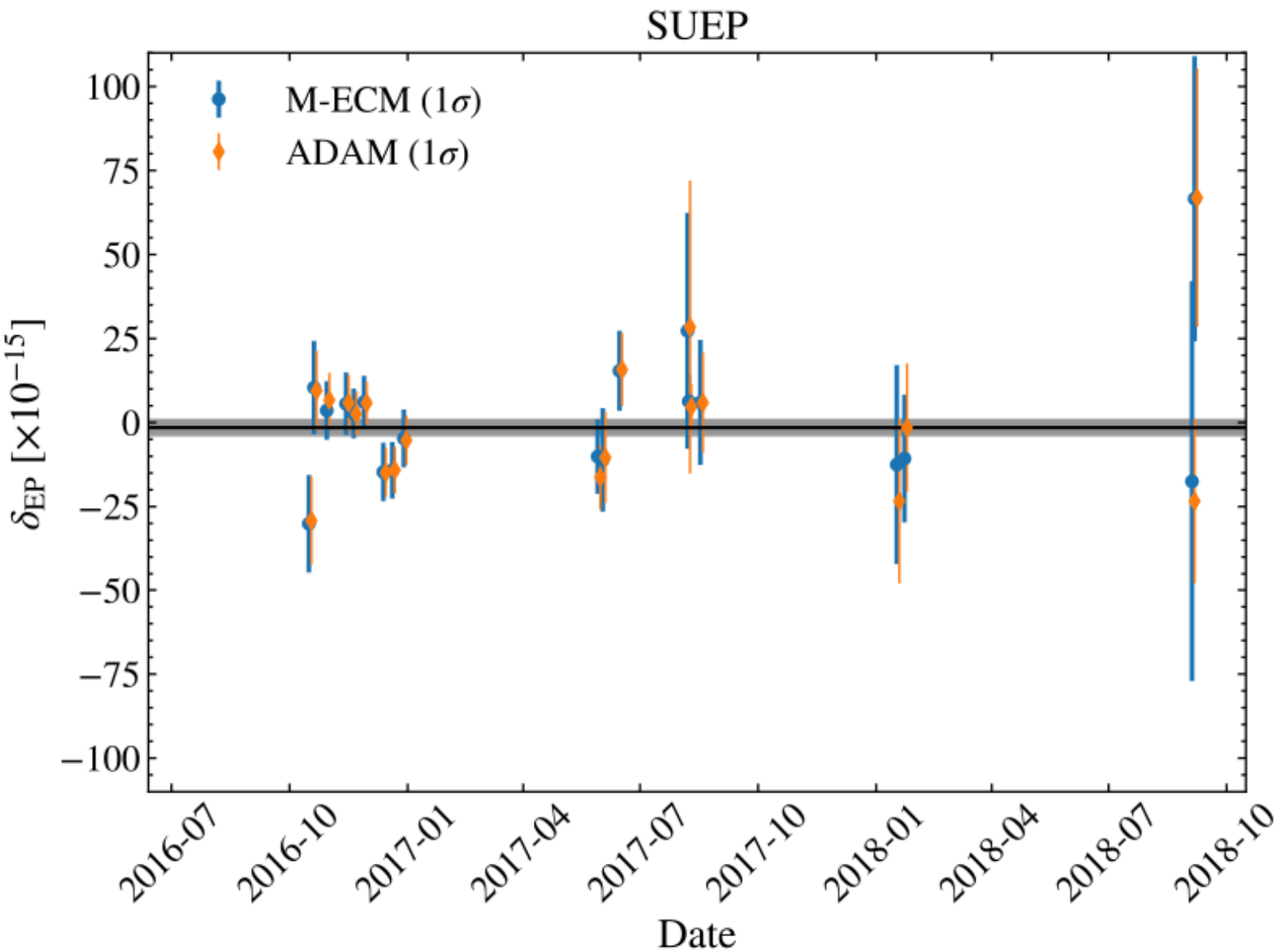
[Baghi et al., Phys. Rev. D 91, 062003, 2015]

[Baghi et al., Phys. Rev. D 93, 122007, 2016]

IMPROVED RESULTS

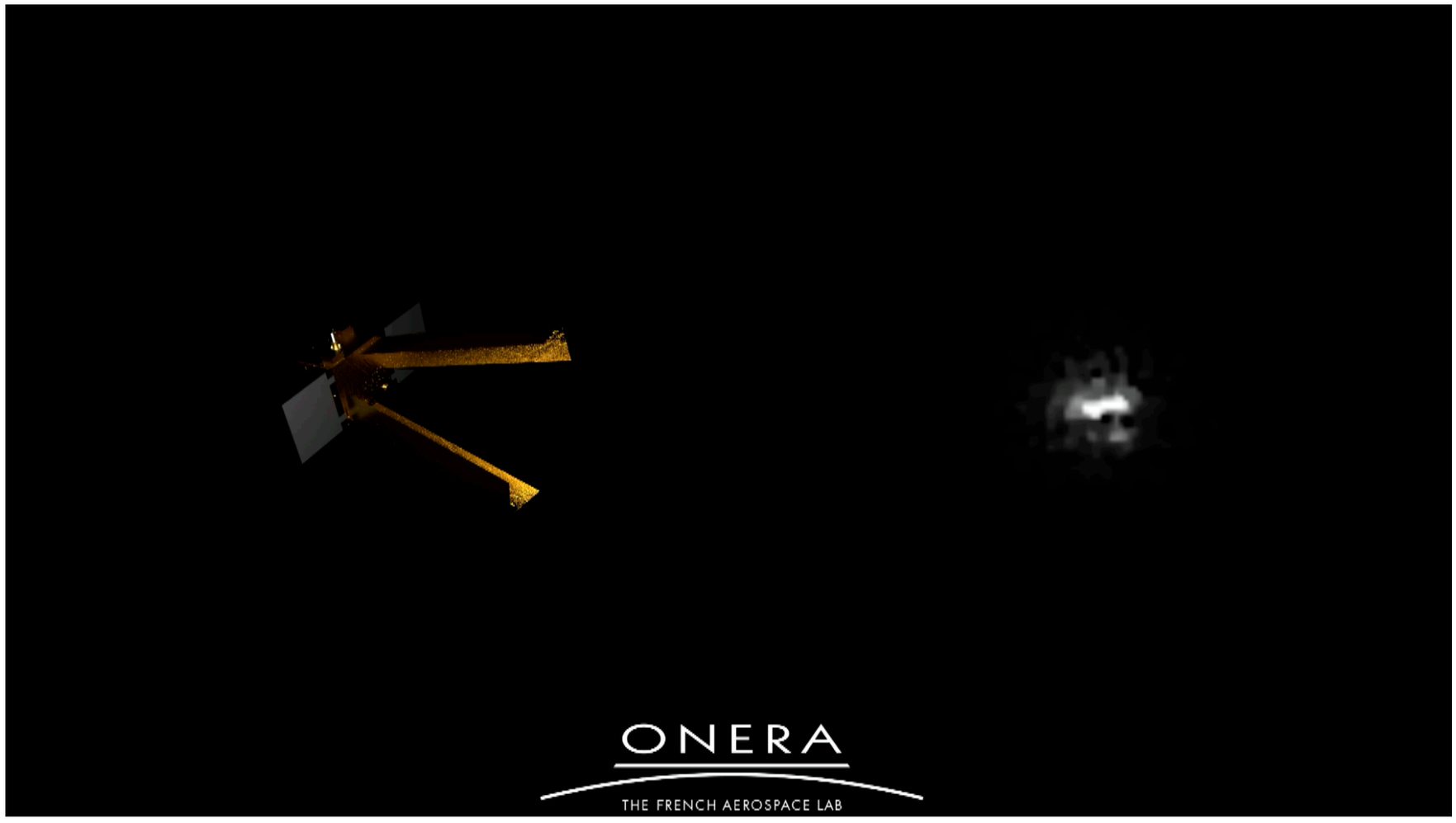
- Ultimately we published the final mission result last September

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



IMPROVED RESULTS

- The satellite was switched off on October 16th 2018
- The de-orbitation system (2 wings) was released

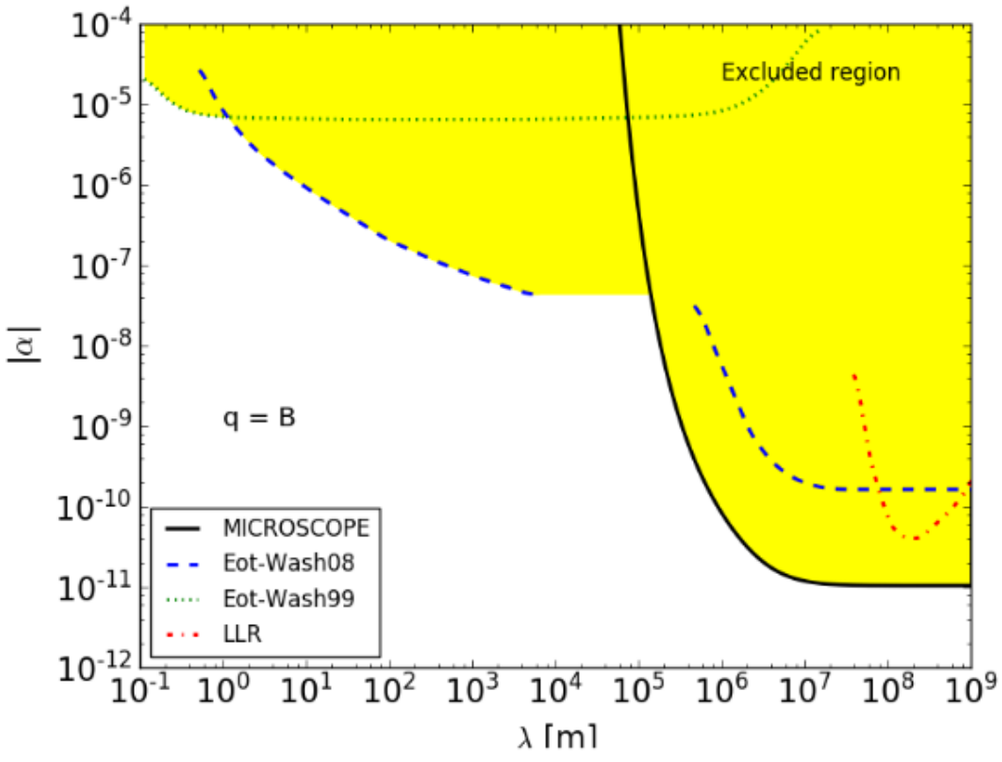


5. CONCLUSION

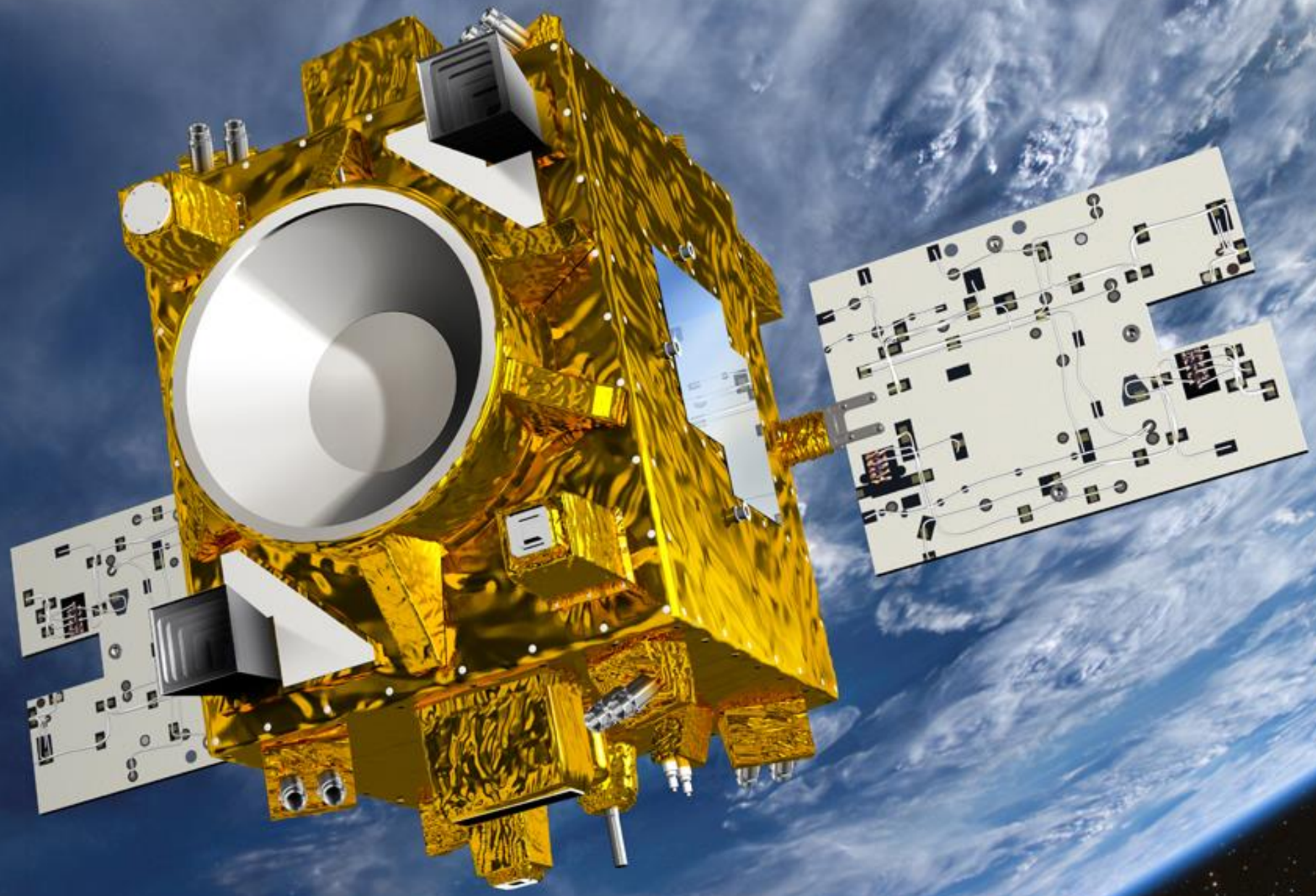
CONCLUSIONS

- Despite the first fears of the commissioning phase, the satellite & all subsystems worked nominally
- The systematic effects estimation was reduced by a better analysis of each source
- The precision of the test was improved by accumulating 1642 orbits
- Set the world reference on the WEP test : 3.8 x 10^{-15}
- Placed constraints on various models including
  - Lorentz invariance
  - Long-range interactions
  - Dark matter searches
- Paves the way for new ambitious experiments to test GR

$$V_{ij}(r) = -\frac{G m_i m_j}{r}\left(1 + \alpha_{ij} e^{-r/\lambda}\right)$$



Constraints on Yukawa deviation from light scalar dilaton [Bergé et al 2018]



"The only source of knowledge is experiment"
A. Einstein

Thank you for your attention.