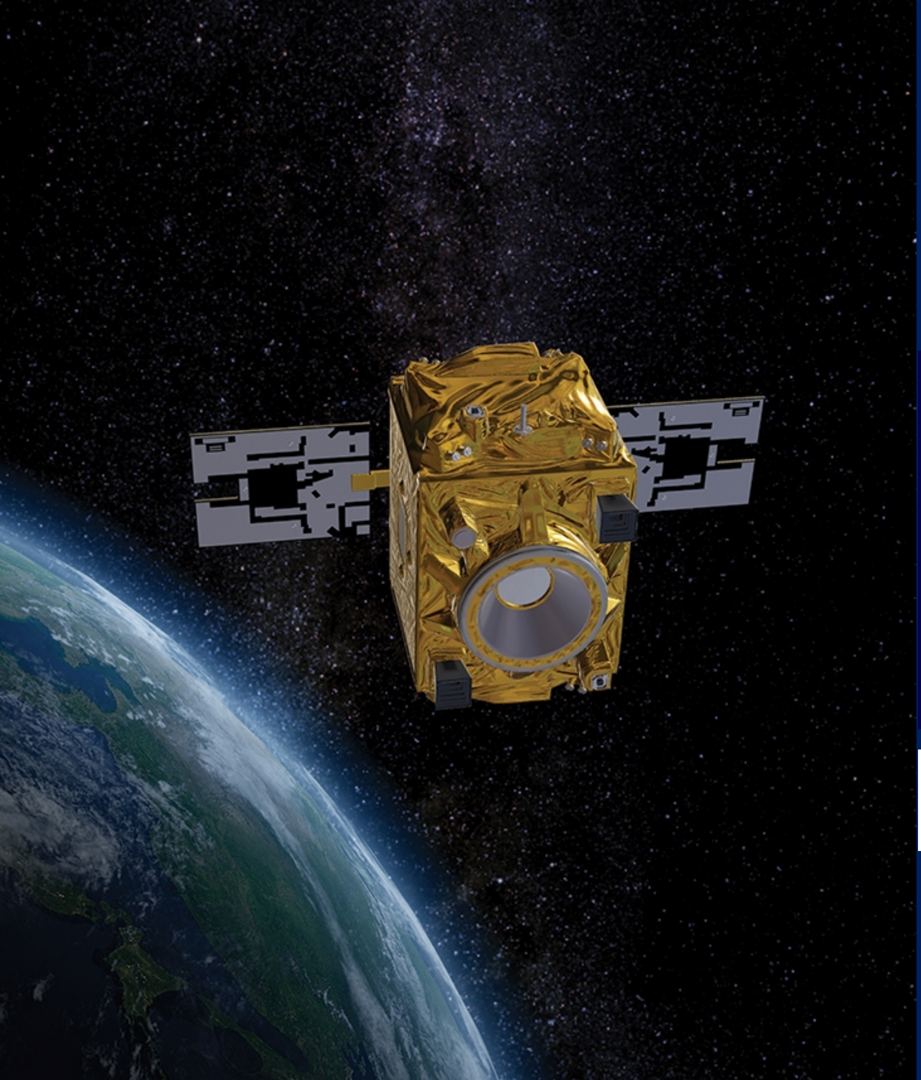


MICROSCOPE: the first results

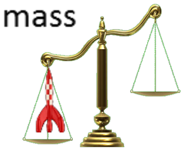
Joel Bergé

On behalf of the MICROSCOPE consortium

And with P. Brax, M. Pernot-Borràs & J.-P. Uzan

The « free-fall » test in space with MICROSCOPE resolution objective on δ : 10^{-15}

m_g= gravitational mass



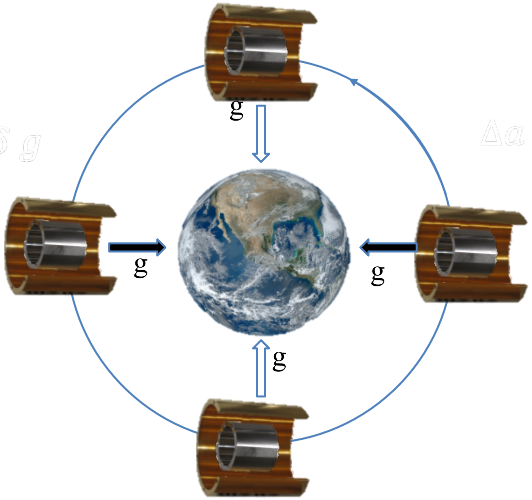
m_i= inertial mass

Comparison of the 2 body free-fall ⇔ comparison of their acceleration:

$$\boxed{\boldsymbol{\delta} = \frac{\boldsymbol{a1} - \boldsymbol{a2}}{\frac{1}{2}(a1 + a2)} = \frac{\frac{mg1}{mi1} - \frac{mg2}{mi2}}{\frac{1}{2}\left(\frac{mg1}{mi1} + \frac{mg2}{mi2}\right)}}$$

If $\boldsymbol{\delta} = \mathbf{0}$: $\Delta \boldsymbol{a} = \mathbf{0}$

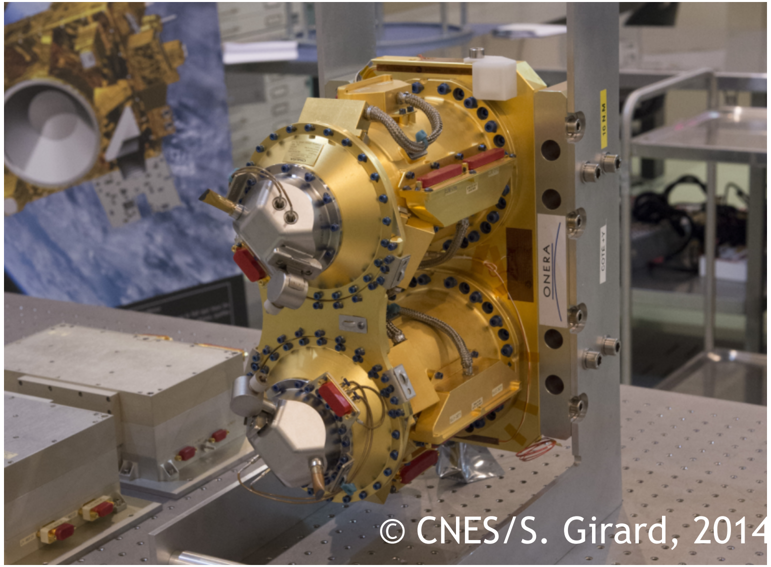
If $\boldsymbol{\delta} \neq \mathbf{0}$: $\Delta a \neq 0$ detection of a signal collinear to g (same phase, same frequency)

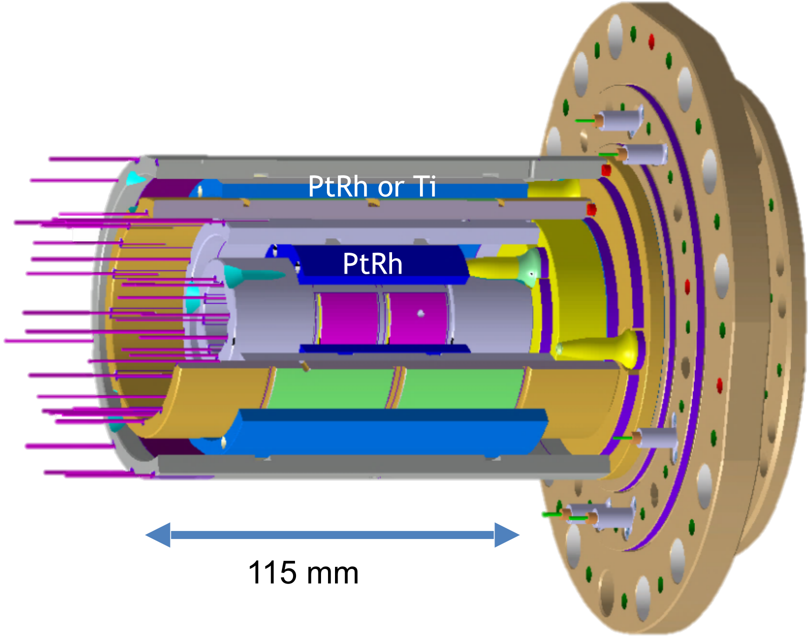


$$g(@710km) = 7.9m/s^2$$

2 double accelerometers for the test

<u>2 similar instruments on board which comprise each 2 concentric test-masses</u>
SUEP :   Sensor Unit with Ti / PtRh
SUREF : Sensor Unit with PtRh / PtRh

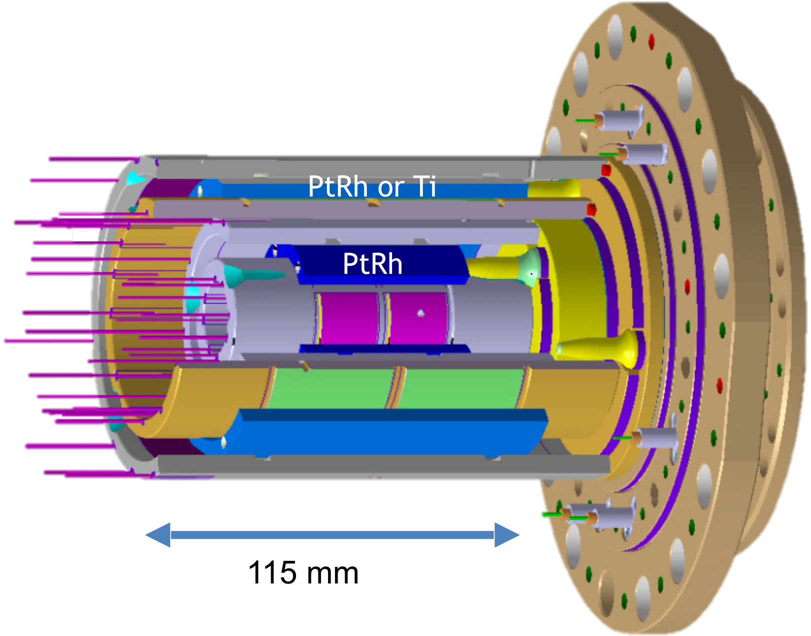




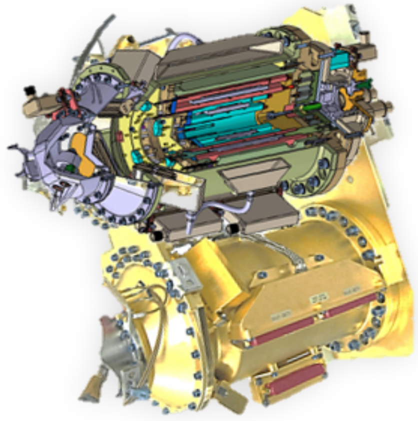
2 double accelerometers for the test

<u>2 similar instruments on board which comprise each 2 concentric test-masses</u>
SUEP :   Sensor Unit with Ti / PtRh
SUREF : Sensor Unit with PtRh / PtRh

Silica part realized by ultrasonic machining (ONERA patent). Accuracy is 2 to 5µm



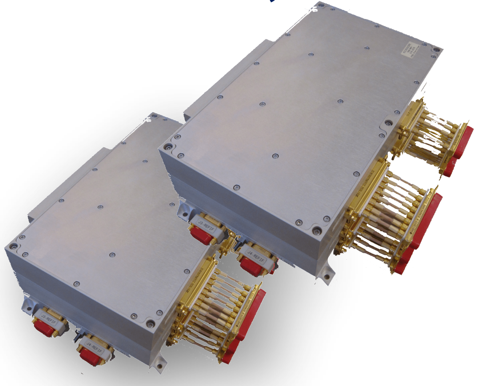
T-SAGE (Twin Space Accelerometer for Gravitation Experiment) – micrometer & microvolt accuracy inherited from GOCE, GRACE ONERA know how



Sensors: **SU PE + SU REF**

2 double-accelerometers

Each SU gives a TM difference of acceleration to femto-g level



Analog Front End Electronics :
1 FEEU for each SU

Low Noise voltage references
0.2μV $Hz^{-1/2}$

Low noise measurement pick-up <1μV $Hz^{-1/2}$

Digital Interface Electronics:
2 stacked **ICU**

DSP + FPGA
Control loop handling
2x 24 x 40bits signals @ 1kHz

Science TM = 24bits @ 4Hz

The MICROSCOPE satellite

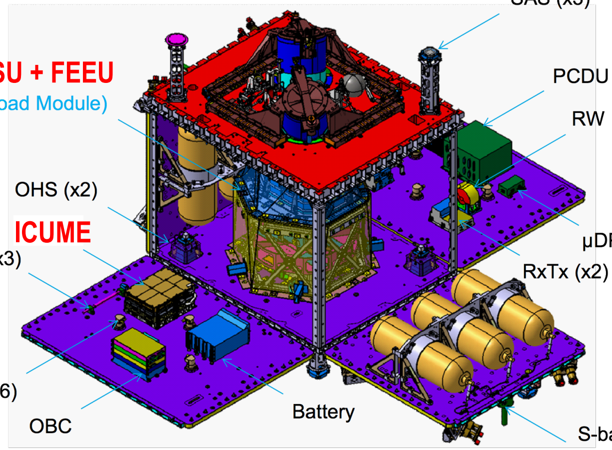
- **Sun-synchronous polar orbit @ 710 km**
- **Several modes :**
  - Inertial f_{EP} = orbital frequency = 1.7×10^{-4} Hz
  - 2 rotation rates of S/C
    $f_{EP} = 0.9\times10^{-3}$Hz & $f_{EP} = 3.1\times10^{-3}$Hz

Cold Gaz propulsion

A space laboratory of 300kg

1,4 m x 1 m x 1,5 m

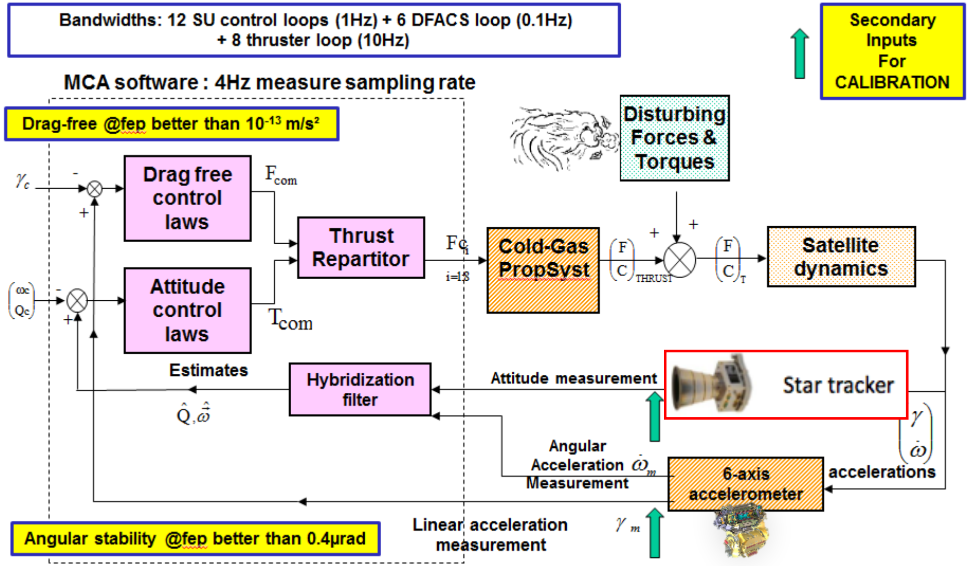
Instrument in the BCU (Payload Thermal Cocoon Case) at the center of the satellite

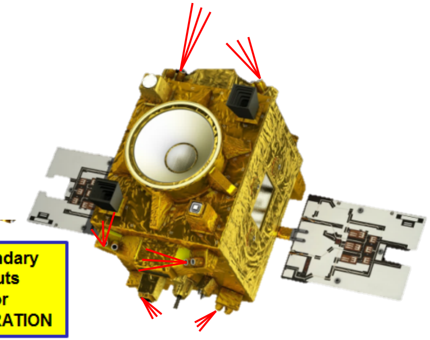


DRAG-FREE SATELLITE LABORATORY OF PHYSICS

With capabilities of stimuli production:

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





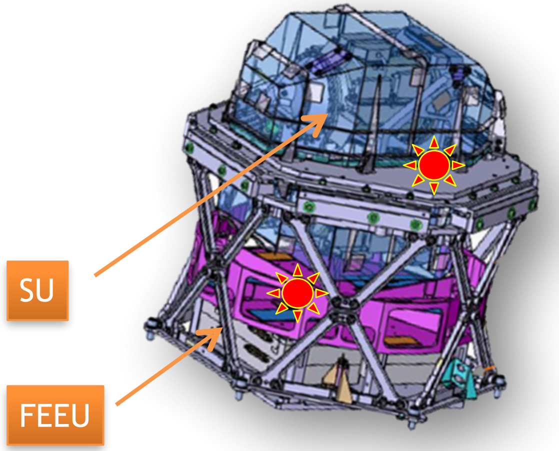
Performance of drag-free

$\Gamma(f_{EP}) < 3\times10^{-13}$ m/s²

$(f_{EP}) < 4\times10^{-12}$ rd/s²

$(f_{EP}) < 3\times10^{-10}$ rd/s

< 1µrd



ACCELEROMETER MEASUREMENT

- sensor (test mass) k
- theoretical acceleration (input): $\vec{\gamma}^{(k)}$

Contains the Eötvös parameter

- measured acceleration (output): $\vec{\Gamma}^{(k)}$

$$\vec{\Gamma}^{(k)} = \vec{B}^{(k)} + [\mathbf{M}]^{(k)} [\boldsymbol{\Theta}]^{(k)} \vec{\gamma}^{(k)} + \vec{Q}^{(k)} + \left[\mathbf{N}^{(\mathbf{k})}\right] \dot{\vec{\Omega}}^{(k)} + \vec{\Gamma}_n^{(k)}$$

Noise
(not white!)

Biais

Scale factors
+ axis coupling
(symmetric matrix)

Test mass rotation

Angular to linear
acceleration coupling

Quadratic terms

The measure along the cylinder axis (X) = the main measure

$$
\begin{aligned}
2\Gamma_x^{(d)} = {} & 2B_x^{(d)} \\
& + \delta_x g_x \\
& + \boxed{\Delta_x S_{xx} + \Delta_y S_{xy} + \Delta_z S_{xz} + (ac_{13}\Delta_y + ac_{12}\Delta_z)S_{yz} + ac_{12}\Delta_y S_{yy} + ac_{13}\Delta_z S_{zz}} \\
& + (-ac_{13}\Delta_y + ac_{12}\Delta_z + 2nd_{11})\dot{\Omega}_x - (\Delta_z - 2ac_{13}\Delta_x + 2nd_{12})\dot{\Omega}_y + (\Delta_y - 2ac_{12}\Delta_x + 2nd_{13})\dot{\Omega}_z \\
& + 2\left(-ac_{13}\dot{\Delta}_y + ac_{12}\dot{\Delta}_z\right)\Omega_x - 2\left(\dot{\Delta}_z - 2ac_{13}\dot{\Delta}_x\right)\Omega_y + 2\left(\dot{\Delta}_y - 2ac_{12}\dot{\Delta}_x\right)\Omega_z \\
& - mc_{11}\ddot{\Delta}_{x,inst} - mc_{12}\ddot{\Delta}_{y,inst} - mc_{13}\ddot{\Delta}_{z,inst} \\
& + 2\left(ad_{11}\Gamma_x^{(c)} + ad_{12}\Gamma_y^{(c)} + ad_{13}\Gamma_z^{(c)}\right) \\
& + K_{2xx}^{(1)}\left(\frac{\Gamma_x^{(1)} - {b_{0x}}^{(1)}}{{K_{1x}}^{(1)}}\right)^2 - K_{2xx}^{(2)}\left(\frac{\Gamma_x^{(2)} - {b_{0x}}^{(2)}}{{K_{1x}}^{(2)}}\right)^2
\end{aligned}
$$

+ noise

g = 7,9 ms^{-2}

Eötvös parameter

Earth's gravity gradients with test-mass off-centering Δ

ad_{11} : Scale factor matching

$Ad_{12 \text{ or } 13}$: Misalignment of 2 test-masses

are negligible in the bandwidth of the test-mass servo loops

estimated by calibration
observed or/and computed
negligible at *Fep*

FIRST RESULTS PUBLISHED IN PRL BASED ON 2 SESSIONS

SUEP

	dateDebut	nomFiche	Num Orb	contrainte Environnement	crit.	duree	etat	conso GazZp	conso GazZm	capacite GazZp	capacite GazZm	
	02-13T13:59:55.846867		4321	NO_ECLIPSE_NO_LUNE	2	1.01295	E	0.7	1.1	6587	6622.4	
206	2017-02-13T15:40:18.833216	CAL_K1dxDFIS1_01_SUEP	4322	NO_ECLIPSE_NO_LUNE	2	5.07000	E	4	3.7	6582.9	6618.5	
207	2017-02-14T00:02:44.983178		4327	NO_ECLIPSE_NO_LUNE	2	1.01295	E	0.5	0.6	6582.5	6617.9	
208	2017-02-14T01:43:07.970959	CAL_K1dxDFIS2_01_SUEP	4328	NO_ECLIPSE_NO_LUNE	2	5.07000	E	2.9	3.3	6579.4	6614.3	
209	2017-02-14T10:05:34.128091		4333	NO_ECLIPSE_NO_LUNE	2	3.07939	E	10	9.3	6569.1	6604.9	
210	2017-02-14T15:10:44.141758	EPR_V3DFIS2_01_SUEP	4337	NO_ECLIPSE_NO_LUNE	2	50.00000	E	176	151.3	6392.6	6453.3	
211	2017-02-18T01:45:43.539435		4387	NO_ECLIPSE_NO_LUNE	2	1.51531	EI	5.4	4.2	6386.9	6448.7	
212	2017-02-18T04:15:53.554441	EPR_V3DFIS2_01_SUEP	4388	NO_ECLIPSE_NO_LUNE	2	76.07591	EI	263.5	235.1	6123.1	6213.3	
213	2017-02-23T09:55:00.000000		4464	NO_ECLIPSE_NO_LUNE	0	0.00000	E	0	0	6123.1	6213.3	
214	2017-02-23T09:55:00.000000	TSNA	4464	NO_ECLIPSE_NO_LUNE	0	61.80639	E	0	3.3	6122.9	6209.7	Rep
215	2017-02-27T16:00:00.028541		4526	NO_ECLIPSE_NO_LUNE	2	1.01295	E	1.3	1.1	6121.7	6207.8	
216	2017-02-27T17:40:23.014532	CAL_K1dxDFIS2_01_SUEP	4527	NO_ECLIPSE_NO_LUNE	2	5.07000	E	4.9	8.3	6116.9	6199.3	
	2017-02-28T02:02:49.160909		4532	NO_ECLIPSE_NO_LUNE	2	3.07939	E	10.4	11	6106.4	6187.8	
218	2017-02-28T07:07:59.169132	EPR_V3DFIS2_01_SUEP	4535	NO_ECLIPSE_NO_LUNE	2	120.00000	E	384.8	405.8	5721	5781.7	
	2017-03-08T13:19:57.511429		4655	NO_ECLIPSE_NO_LUNE	2	2.57703	E	3.7	4.9	5716.8	5776.4	
220	2017-03-08T17:35:20.494387	CAL_tetadZDFIS2_01_SUEP	4658	NO_ECLIPSE_NO_LUNE	2	5.07000	E	3.9	7.9	5712.9	5768.3	
221	2017-03-09T01:57:46.642557		4663	NO_ECLIPSE_NO_LUNE	2	1.01295	E	0.8	1.4	5712.1	5766.8	
222	2017-03-09T03:38:09.628548	CAL_tetadYDFIS2_01_SUEP	4664	NO_ECLIPSE_NO_LUNE	2	5.07000	E	3.6	8.3	5708.3	5758.3	
223	2017-03-09T12:00:35.776718		4669	NO_ECLIPSE_NO_LUNE	2	1.18063	E	2.9	4	5705	5754	
224	2017-03-09T13:5											
225	2017-03-09T22:2											
226	2017-03-10T00:1											

Phys. Rev. Letts. 119 231101 (2017) : No evidence of violation > $1,9\times10^{-14}$

Over 120 orbits

- Statistical noise integrated over 120 orbits
- Systematics evaluated with a majoring of SU temperature variations (15µK @ f_{EP})

SUREF

	1-18T14:22:59.978006		3944	NO_ECLIPSE_NO_LUNE	1	1.01295	E	0.9	0.9	6808.7	6826.2
	1-18T16:03:22.968294	CAL_K1dxDFIS2_01_SUREF	3945	NO_ECLIPSE_NO_LUNE	1	5.07000	E	4.7	5.6	6804	6820.6
173	2017-01-19T00:25:49.137973		3950	NO_ECLIPSE_NO_LUNE	1	3.07939	E	2.5	2.5	6801.2	6818
174	2017-01-19T05:30:59.159261	EPR_V2DFIS2_01_SUREF	3953	NO_ECLIPSE_NO_LUNE	1	120.00000	E	81.1	67.5	6720	6750.3
	2017-01-27T11:42:57.925815		4073	NO_ECLIPSE_NO_LUNE	1	1.51531	E	1	0.6	6719	6749.6
176	2017-01-27T14:13:07.942964	EPR_V2DFIS2_01_SUREF	4074	NO_ECLIPSE_NO_LUNE	1	82.00000	E	56	48.4	6662.9	6701
	2017-02-02T05:39:19.100109		4156	NO_ECLIPSE_NO_LUNE	1	2.57703	E	1.8	2	6661	6699
178	2017-02-02T09:54:42.094912	CAL_tetadZDFIS2_01_SUREF	4159	NO_ECLIPSE_NO_LUNE	1	5.07000	E	3.1	2.8	6657.8	6696.2
179	2017-02-02T18:17:08.262799		4164	NO_ECLIPSE_NO_LUNE	1	1.01295	E	0.6	0.7	6657.2	6695.5
180	2017-02-02T19:57:31.253445	CAL_tetadYDFIS2_01_SUREF	4165	NO_ECLIPSE_NO_LUNE	1	5.07000	E	2.6	3.1	6654.6	6692.4
181	2017-02-03T04:19:57.421332		4170	NO_ECLIPSE_NO_LUNE	1	1.18063	E	3.9	3.6	6650.5	6688.3
182	2017-02-03T06:16:57.435594	CAL_deltaYDFIS2_01_SUREF	4171	NO_ECLIPSE_NO_LUNE	1	5.07000	E	13.2	13.5	6637.1	6674.5
183	2017-02-03T14:39:23.605273		4176	NO_ECLIPSE_NO_LUNE	1	1.18365	E	0.4	0.6	6636.6	6673.8
184	2017-02-03T16:36:41.576425	CAL_K21xx_02_SUREF	4178	NO_ECLIPSE_NO_LUNE	1	10.00000	E	5.1	5.3	6631.4	6668.5

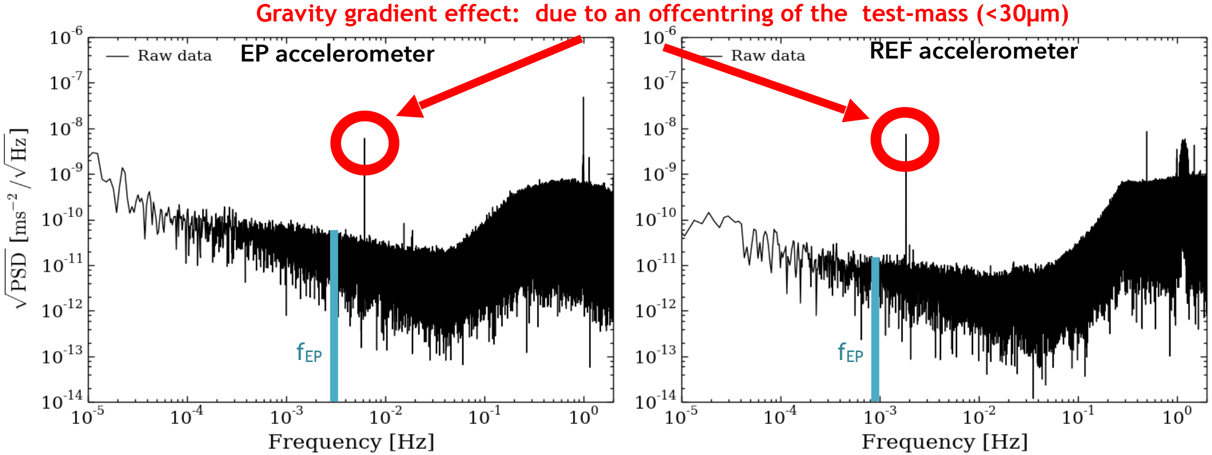
Over 62 orbits

- Statistical noise integrated
- Systematics evaluated after PRL (TBC) with a majoring of SU temperature variations (30µK @ f_{EP})

The new upper bound on the WEP

Touboul+ 2017, PRL 119 231101

From 2 sessions representing 7% of available data for the EP test :
We detect the Earth's gravity gradient effect but no WEP violation…



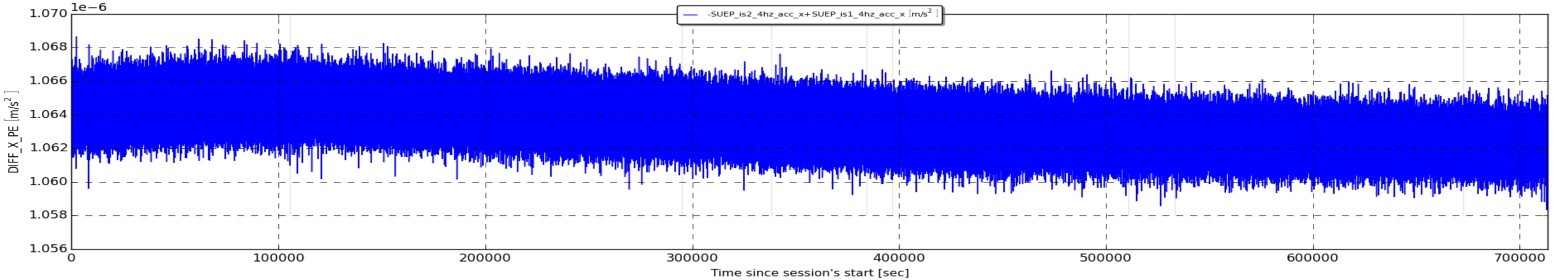
$f_{\mathrm{EP}} = 3.11 \times 10^{-3}$ Hz

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

$$\boxed{\delta(\mathrm{Ti}, \mathrm{Pt}) = [-1 \pm 9(\mathrm{stat}) \pm 9(\mathrm{syst})] \times 10^{-15}}$$

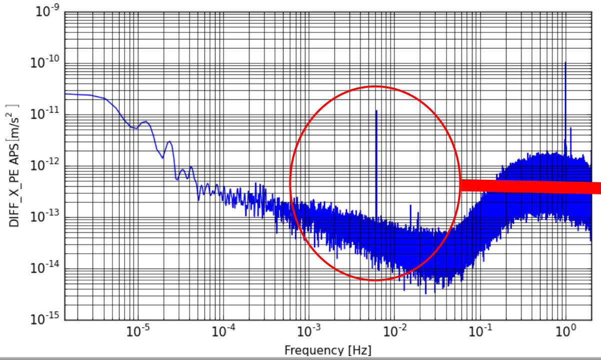
Effect of in-flight calibration on session 218 (SUEP)

- Time evolution of measured difference of acceleration on SUEP along X



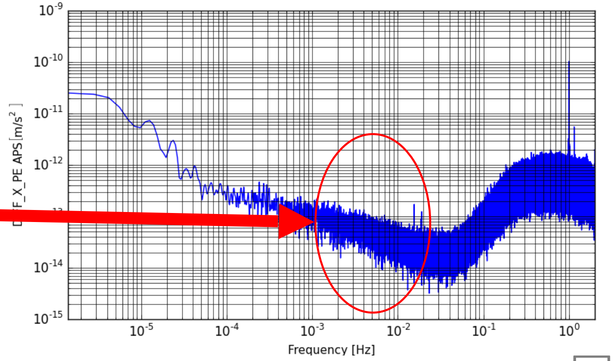
- Test-mass off-centering estimated through the Earth's gravity effect at $2f_{EP}$

=> Correction of off-centering effects at f_{EP} and $2f_{EP}$



Δx = (20.15 +/- 0.03) µm
Δz=(-5.69 +/- 0.03) µm

Level of acceleration to be corrected @f_{EP} < 3×10^{-17} m/s²
NEGLIGIBLE for a rotating satellite



MICROSCOPE and modified gravity: generic 5th force model

JB, P. Brax, G. Metris, M. Pernot-Borras, P. Touboul, J.-P. Uzan, 2018, PRL 120 141101

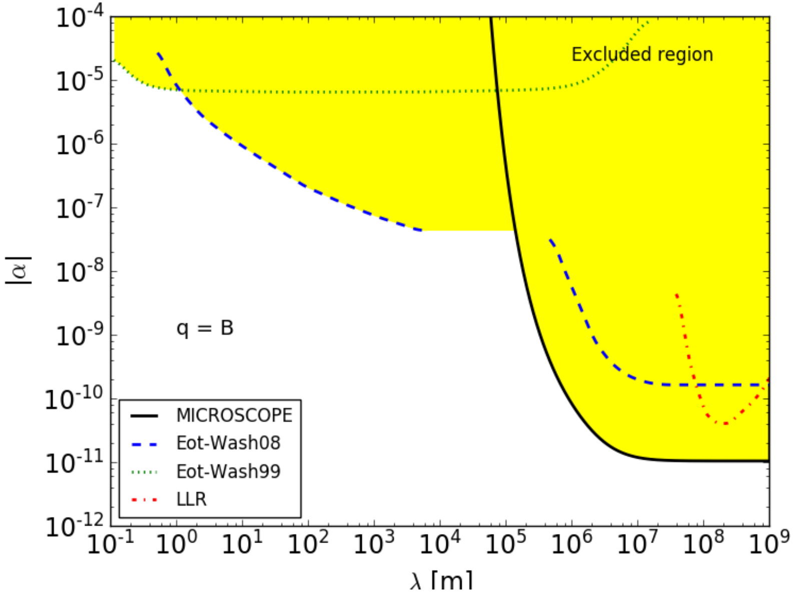
Yukawa potential

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

$$\alpha_{ij} = \alpha \left(\frac{q}{\mu}\right)_i \left(\frac{q}{\mu}\right)_j$$

WEP violation

$$\eta = \alpha \left[\left(\frac{q}{\mu}\right)_{\mathrm{Pt}} - \left(\frac{q}{\mu}\right)_{\mathrm{Ti}}\right]\left(\frac{q}{\mu}\right)_E \left(1 + \frac{r}{\lambda}\right) \mathrm{e}^{-\frac{r}{\lambda}}$$



MICROSCOPE and modified gravity: high expectations (chameleon)...

VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

Chameleon Fields: Awaiting Surprises for Tests of Gravity in Space

Justin Khoury and Amanda Weltman

ISCAP, Columbia University, New York, New York 10027, USA

(Received 10 September 2003; published 22 October 2004)

We present a novel scenario where a scalar field acquires a mass which depends on the local matter density: the field is massive on Earth, where the density is high, but is essentially free in the solar system, where the density is low. All existing tests of gravity are satisfied. We predict that near-future satellite experiments could measure an effective Newton's constant in space different from that on Earth, as well as violations of the equivalence principle stronger than currently allowed by laboratory experiments.

DOI: 10.1103/PhysRevLett.93.171104 PACS numbers: 04.50.+h, 04.80.Cc, 98.80.–k

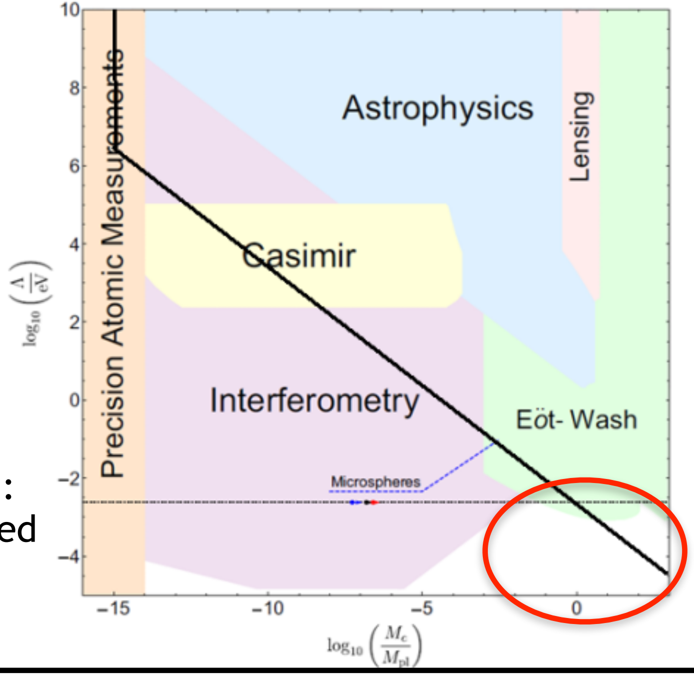
$$\boxed{\beta^2 \times 10^{-19} < \eta < \beta^2 \times 10^{-11}}$$

MICROSCOPE can see a significant chameleon-induced WEP violation if it is not itself screened

...but real life is tougher than theory

- Test-masses are not in vacuum... but surrounded by a satellite
- Still some atmosphere @700km

Burrage & Sakstein 2018, LRR 21:1
Pernot-Borras+ in prep



Above the line, MICROSCOPE is not screened: possible WEP violation

Below the line, MICROSCOPE is screened: no WEP violation expected

Region of interest

Don’t take theorists’ ballpark numbers for granted, real life is much more complicated

MICROSCOPE status: in 2018 less science and more sensitivity tests & technological tests

- 750 orbits dedicated to sensor thermic behavior and systematic check have been successfully performed => very promising

- March to August 2018: SUEP continuously measuring without switch off (for technological experiment purposes)
- In 2018: more than 5 months of experiment dedicated to aeronomy (Drag Free Off)

- EP test data available from the beginning : 1882 orbits for SUEP and 932 orbits for SUREF (including different temperature conditions & test-mass displacements) ; 300 orbits for calibration.

Conclusion

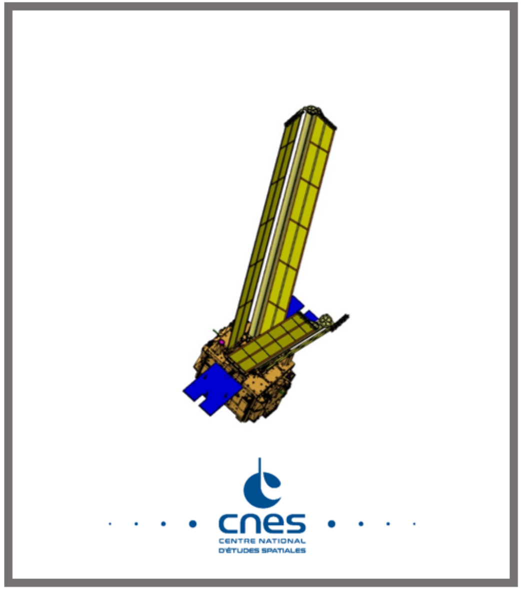
- No WEP violation seen at $>2\times10^{-14}$
- A lot of work done to better understand systematics… Expect improvements!
- New constraints on 5th force and modified gravity
- Final results end of 2019… Stay tuned

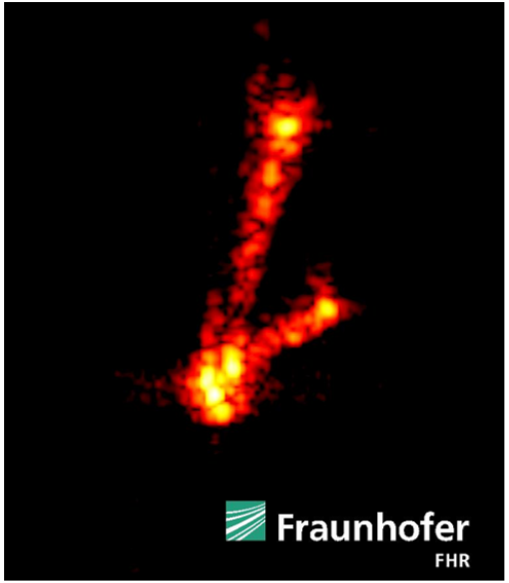
ONERA
THE FRENCH AEROSPACE LAB

Conclusion

- No WEP violation seen at $>2\times10^{-14}$
- A lot of work done to better understand systematics… Expect improvements!
- New constraints on 5th force and modified gravity
- Final results end of 2019… Stay tuned

- MICROSCOPE was successfully passivated October 16, 2018. Back to Earth in 25 years





Satellite MICROSCOPE du CNES avec ses 2 ailes de désorbitation déployées (17/10/2018)
Modèle CAO (à gauche) et image radar capturée par le système TIRA du Fraunhofer Institute (à droite)

TSAGE PAYLOAD TEAM - ONERA

S/C OPERATION – CNES ONERA

MICROSCOPE MISSION SCIENCE CENTER (CMSM) – ONERA+OCA

Pierre Touboul (ONERA)
Prime Investigator

Gilles Metris (CNRS-UCA-OCA-Géoazur
Co PI - Data analysis

Manuel Rodrigues (ONERA)
Co-I - Instrument + CMSM

Pierre-Yves Guidotti (CNES)
MICROSCOPE Proj. Manager

Alain Robert (CNES)
Perf. Group

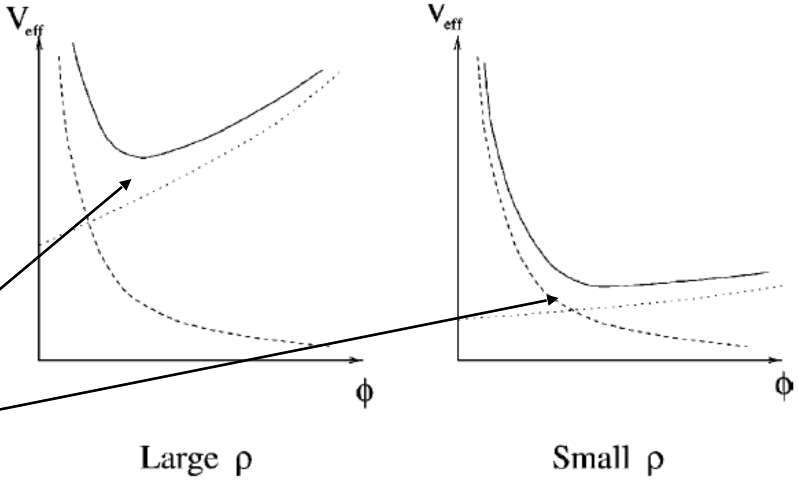
MICROSCOPE and modified gravity: chameleon

Khoury & Weltmann 2004 + a lot!!!

$$\mathcal{L} = \sqrt{-g}\left\{-\frac{M_{\rm Pl}^2 \mathcal{R}}{2} + \frac{(\partial\phi)^2}{2} + V(\phi)\right\} + \mathcal{L}_m(\psi^{(i)}, g_{\mu\nu}^{(i)})$$

When coupled to matter, scalar field has a matter dependent effective potential

$$\boxed{\nabla^2\phi = V_{eff,\phi} = V_{,\phi} + \frac{\beta}{M_{Pl}}\rho_{mat}}$$



Environment
dependent minimum

Larger ρ correspond to smaller ϕ_{min} and larger mass => field can be massive enough on Earth to evade constraints but light enough in space to affect the gravitational dynamics (with no fine-tuning of β!).