MICROSCOPE, the Equivalence Principle and the search for a fifth force

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On behalf of the MICROSCOPE consortium

Weak Equivalence Principle (WEP)

Postulate central to General Relativity

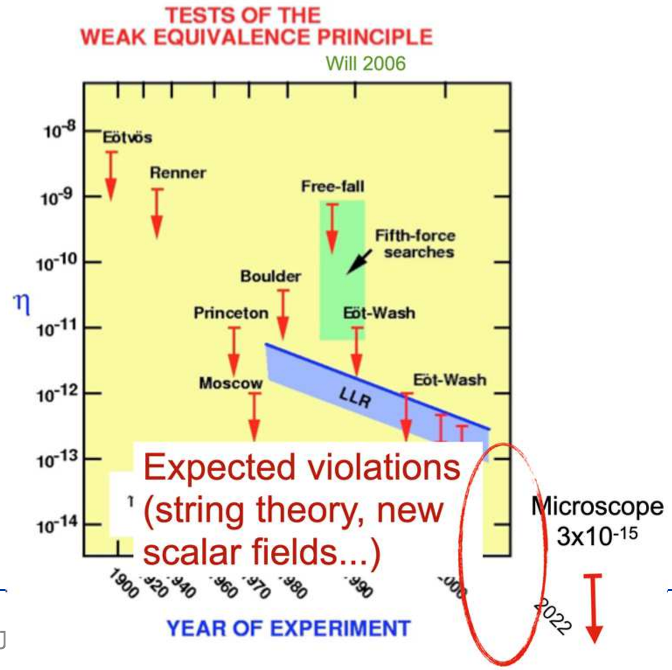
All test bodies follow the same universal trajectory in a gravitational field, independently of their mass, detailed internal structure and composition.

Eötvös parameter

$$\eta_{12} = \frac{a_1 - a_2}{(a_1 + a_2)/2} = \frac{\frac{m_{g1}}{m_{i1}} - \frac{m_{g2}}{m_{i2}}}{\frac{1}{2}\left(\frac{m_{g1}}{m_{i1}} + \frac{m_{g2}}{m_{i2}}\right)}$$

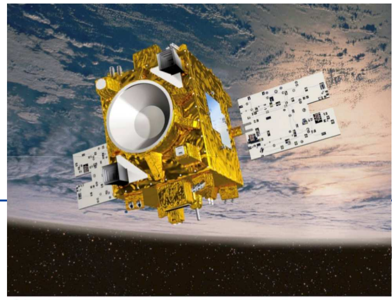
m_i: inertial mass (opposes motion -- universal)
m_g: gravitational mass (feels gravity – specific to gravity)

For all test bodies, the inertial and gravitational masses are equal, $m_i = m_g$



MICROSCOPE

- *Micro-satellite à traînée compensée pour l'Observation du Principe d'Equivalence /* Drag-free microsatellite for the observation of the Equivalence Principle
- CNES satellite to test the Equivalence principle with 10^{-15} precision
- PI: ONERA, co-PI: Observatoire de la Côte d'Azur



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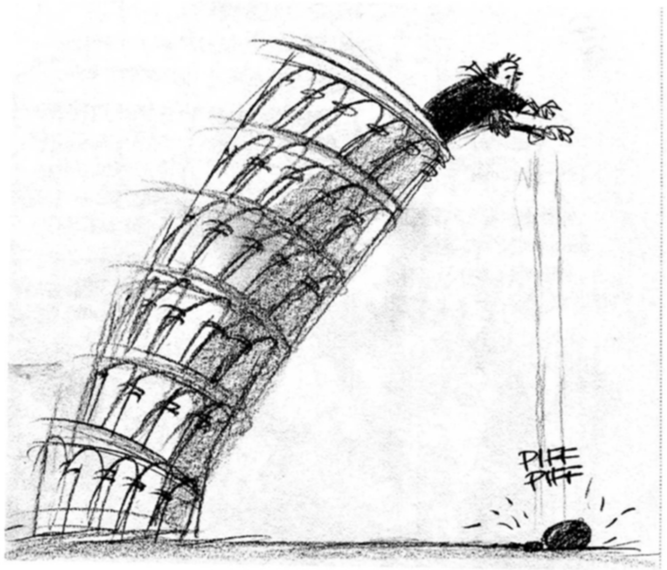
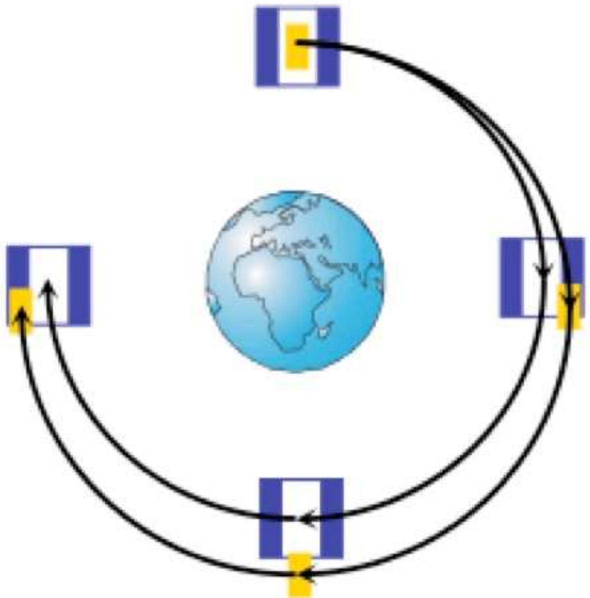
MICROSCOPE's principle – Test of the Universality of Free Fall



https://johnmanders.wordpress.com/2020/04/12/galileo/



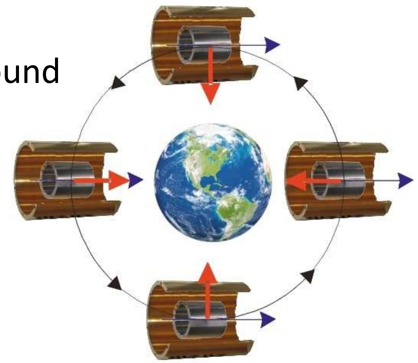
NB: just for the intuition… This is not how MICROSCOPE works…

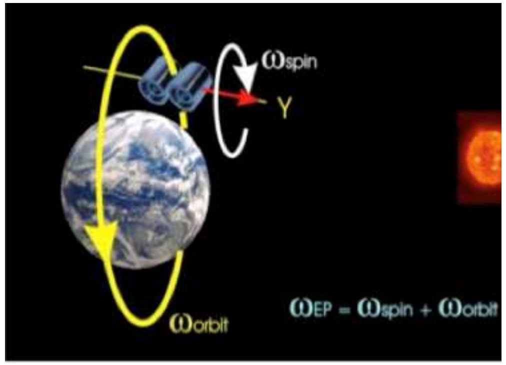
Experimental concept

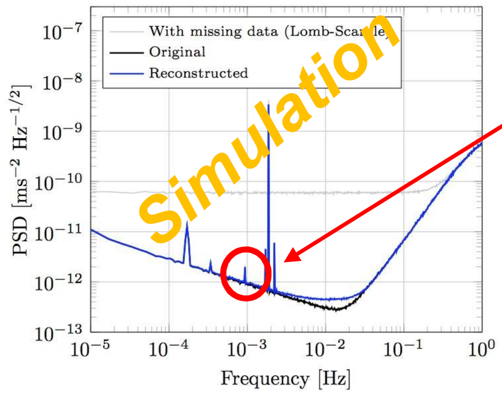
Earth gravity field modulated by satellite's motion around the Earth => sine of known frequency $f_{EP} = f_{orb}+f_{spin}$

f_{EP} can be varied by either:

- Keeping the satellite in inertial motion
- Or spinning it



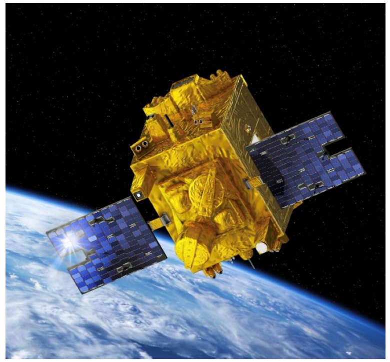




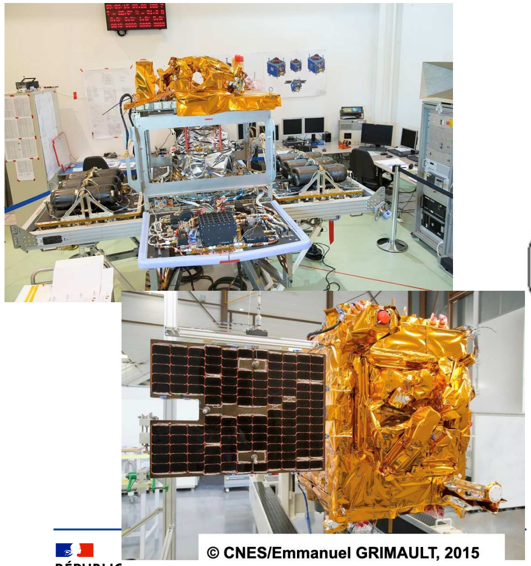
Simulated Equivalence Principle Violation ($3x10^{-15}$)

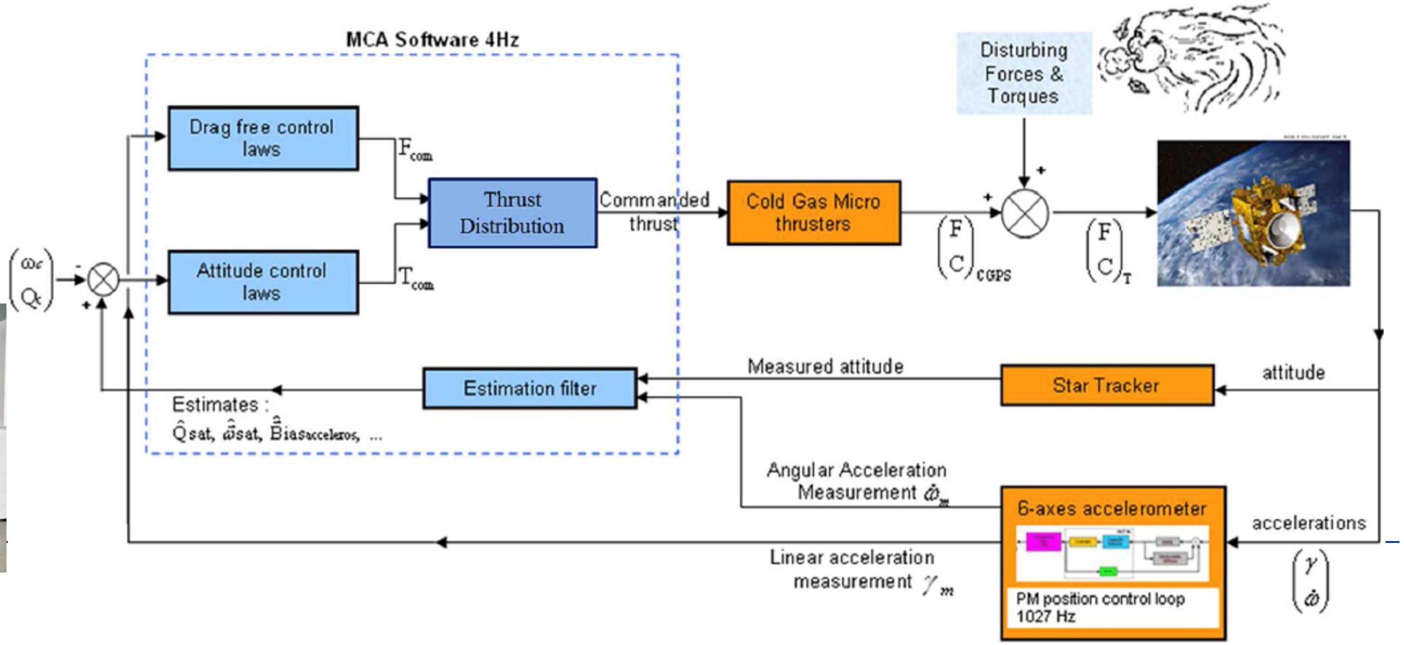
Baghi+ 2016

Drag-free satellite



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
- Cold Gaz propulsion / Drag-free, Attitude control — Star tracker Hybridized with scientific instruments

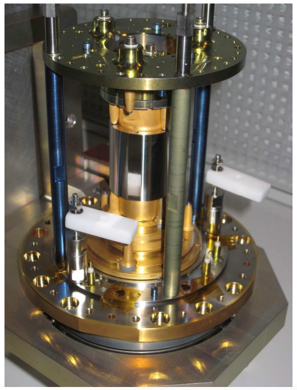


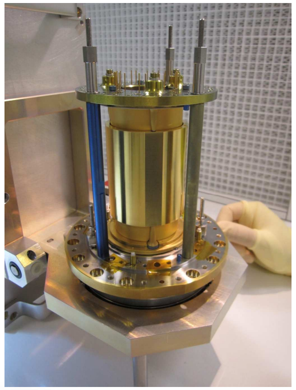


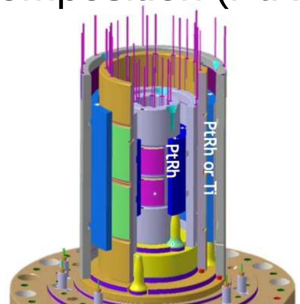
Science payload

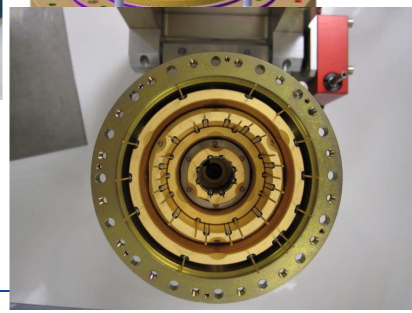
Two twin differential accelerometers (SU – Sensor Units)

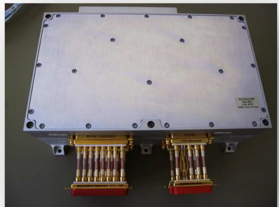
- SUEP (Equivalence Principle test): two test masses of different compositions (Ti vs PtRh)
- SUREF (reference): two test masses of the same composition (PtRh)











Differential acceleration along x-axis

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

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

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

ad_{11}: Scale factor matching

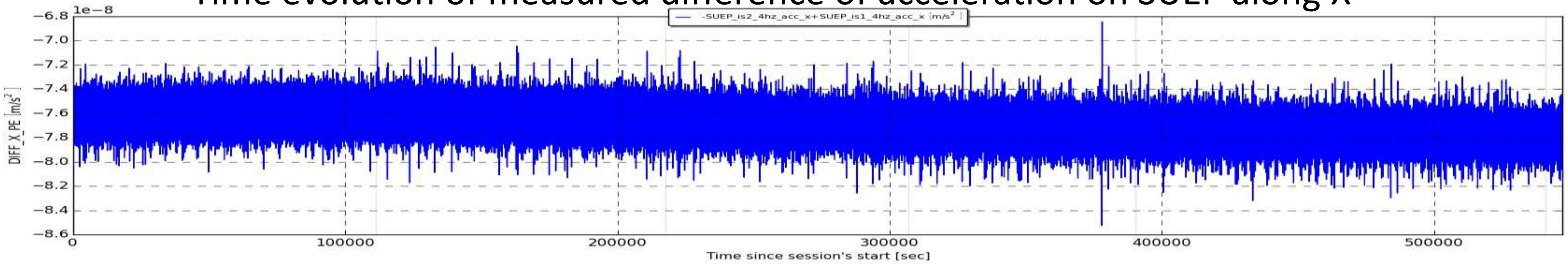
ad_{12} , ad_{13}: Misalignment of 2 test-masses

Eötvös parameter

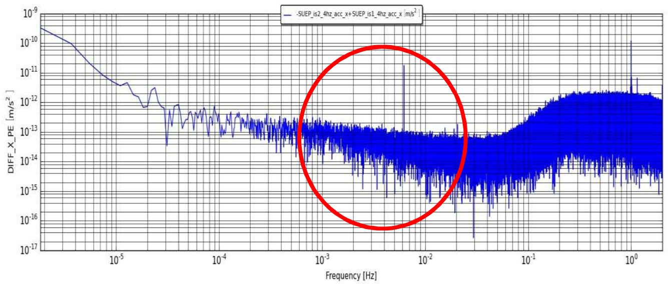
estimated by calibration
observed or/and computed
negligible at Fep

Measured time series / In-flight calibration

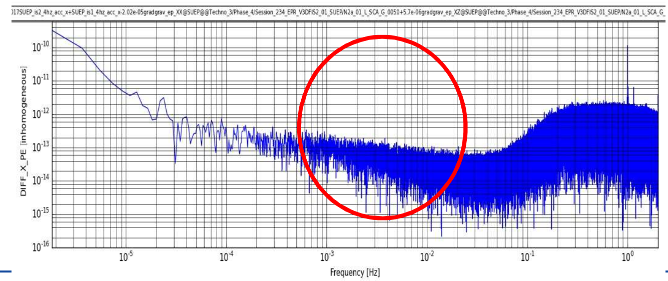
Time evolution of measured difference of acceleration on SUEP along X



Scale factor matching through a dedicated session before the EP session
Test-mass off-centering estimated through the Earth's gravity effect at $2f_{EP}$
=> Correction of off-centering effects at all frequencies (f_{EP} and $2f_{EP}$ included)



Kdx = 0.0085 +/- $6x10^{-5}$
Δx = (20.2 +/- 0.03) µm
Δz=(-5.7 +/- 0.03) µm

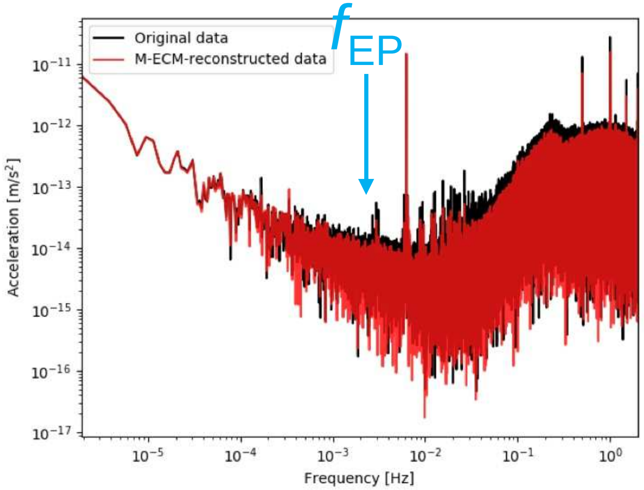


Glitches and their impact on the test of the WEP

Short-lived events

- observed in previous missions (GRACE)
- expected to originate from random crackles of the satellite's coating and gas tanks
- expected to cancel in differential acceleration (seen by both accelerometers), at least below the noise

Impact very difficult to quantify a priori. Requires a very fine understanding of all parts of the instrument and measurement.

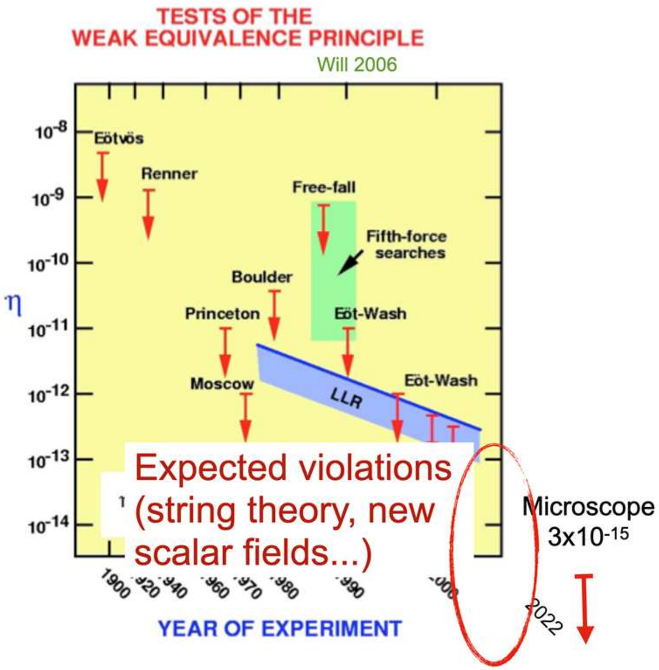


- Detection of an unexpectedly high S/N violation on SUREF on 2 sessions.
- Mask glitches, fill in gaps: the signal disappears.

==> glitches impact the test of the WEP!!! Data analysis process: mask glitches and deal with gaps.

The new upper bound on the WEP

Touboul+ 2022 PRL 129 121102
Touboul+ 2022 CQG 39 204009



From 1600 orbits (SUEP) and 800 orbits (SUREF)

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

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

Long-range composition-dependent Yukawa interaction

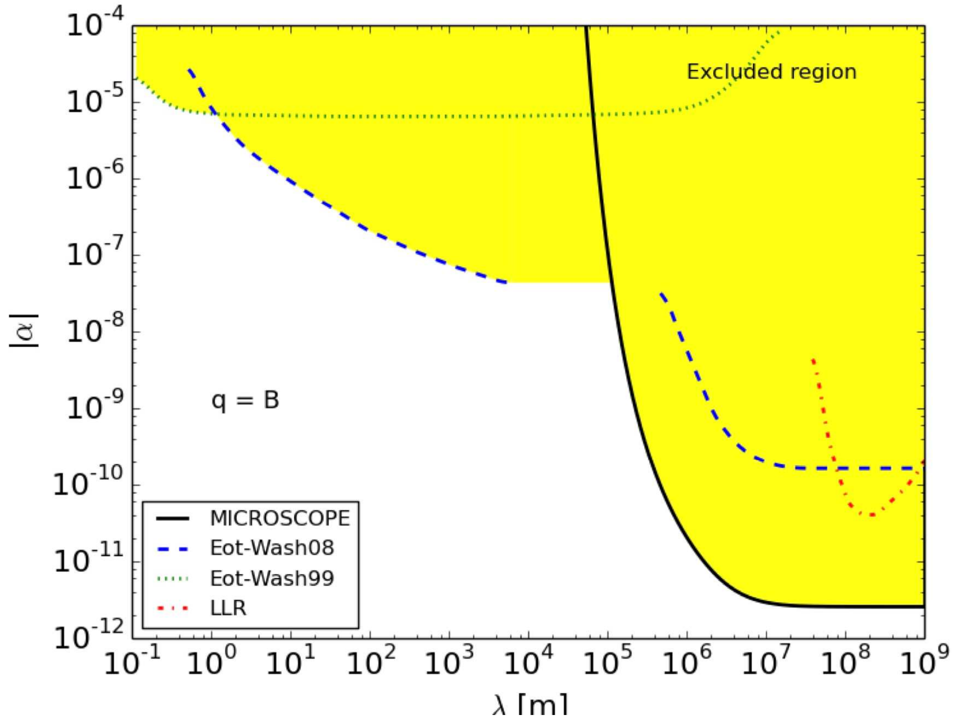
Bergé+ 2018 PRL 120 141101
Bergé 2023

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

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

WEP violation

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



Short-range Yukawa interaction

Bergé+ 2022

- Technical sessions to characterise the instrument
- (Electrostatic) stiffness estimation

$$\vec{F}_{\mathrm{el},i} \approx -m\left\{G_{\mathrm{act}}V_e + \omega_p^2\left[1+\left(\frac{V_e}{V_p}\right)^2\right]\delta\right\}$$

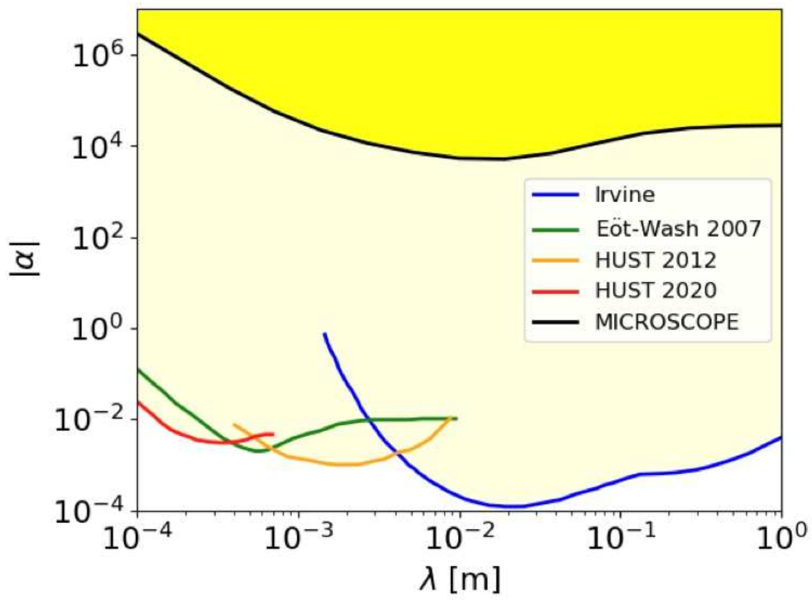
Stiffness

Test-mass displacement wrt equilibrium position

- Gravitational interaction between cylinders:
  at first order, acts as a stiffness

$$\mathscr{F}_x(x_0,\delta) \approx -16\pi^2 G\rho\rho'\alpha \sum_i K_i(x_0)\delta^i$$

δ: test-mass displacement wrt equilibrium position
K_i: functions of the geometry



Light dilaton / Ultra light dark matter

Damour & Donoghue 2010

EM quarks electrons gluons

Scalar field couples non-universally to matter: coupling constants $(d_e, d_{m_u}, d_{m_d}, d_{m_e}, d_g)$

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

Dilaton charges (to be computed for given atoms)

$$Q'_e = -1.4 \times 10^{-4} + 7.7 \times 10^{-4} \frac{Z(Z-1)}{A^{4/3}} \qquad Q'_{\tilde{m}} = 0.093 - \frac{0.036}{A^{1/3}} - 1.4 \times 10^{-4} \frac{Z(Z-1)}{A^{4/3}}$$

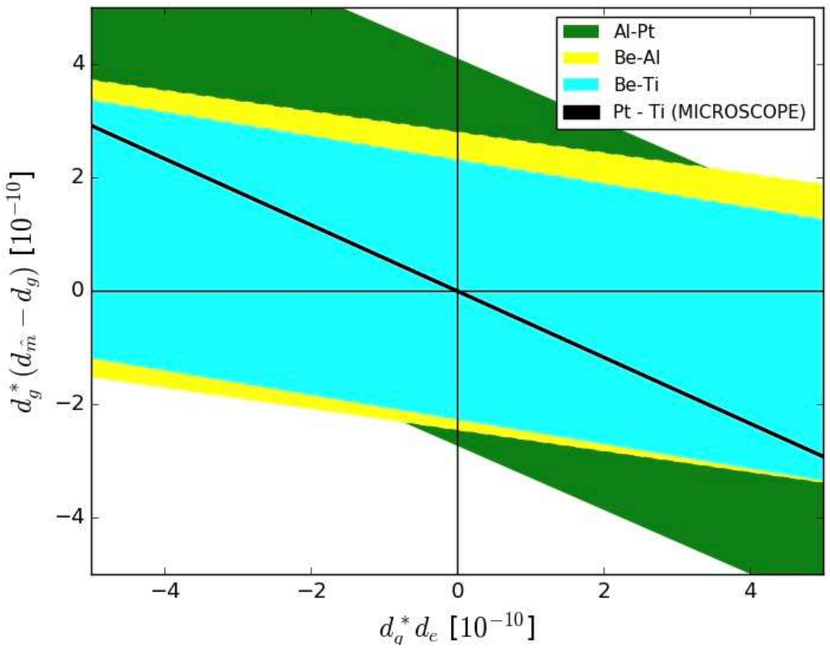
WEP violation $\boxed{\eta = D_{\tilde{m}} \left([Q'_{\tilde{m}}]_{\mathrm{Pt}} - [Q'_{\tilde{m}}]_{\mathrm{Ti}}\right) + D_e \left([Q'_e]_{\mathrm{Pt}} - [Q'_e]_{\mathrm{Ti}}\right)}$

Parameters to constrain

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

Light dilaton vs MICROSCOPE

Bergé+ 2018 PRL 120 141101
Bergé 2023



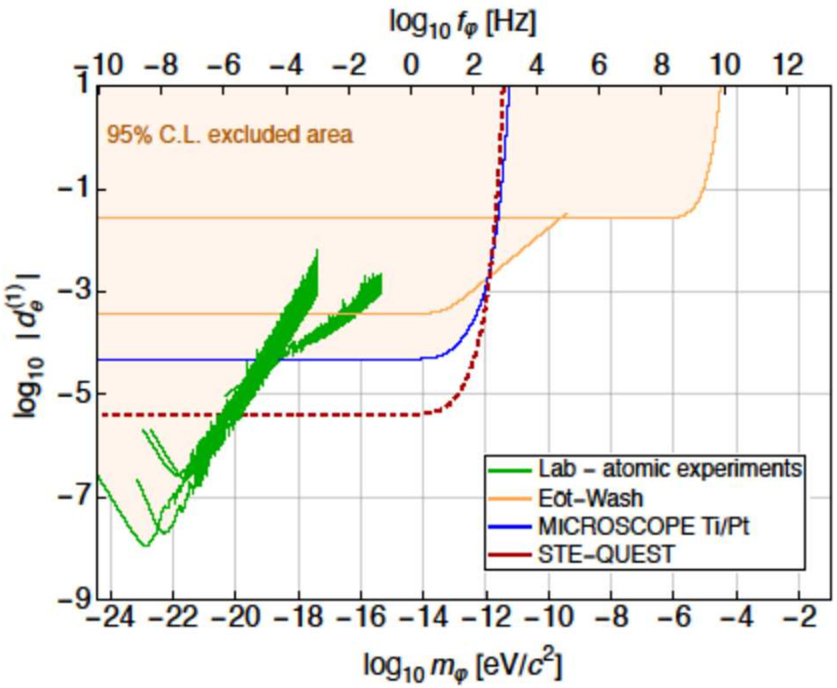


Figure courtesy A. Hees

MICROSCOPE and chameleon: high expectations…

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.

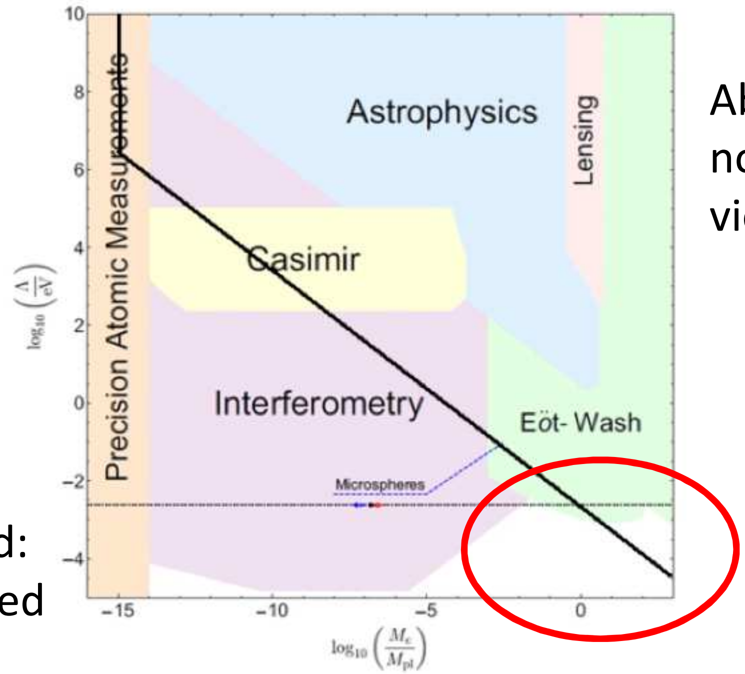
DOI: 10.1103/PhysRevLett.93.171104 PACS numbers: 04.50.+h, 04.80.Cc, 98.80.–k

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

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

…but life's tougher than theory!

Burrage & Sakstein 2018
Pernot-Borràs+ 2019



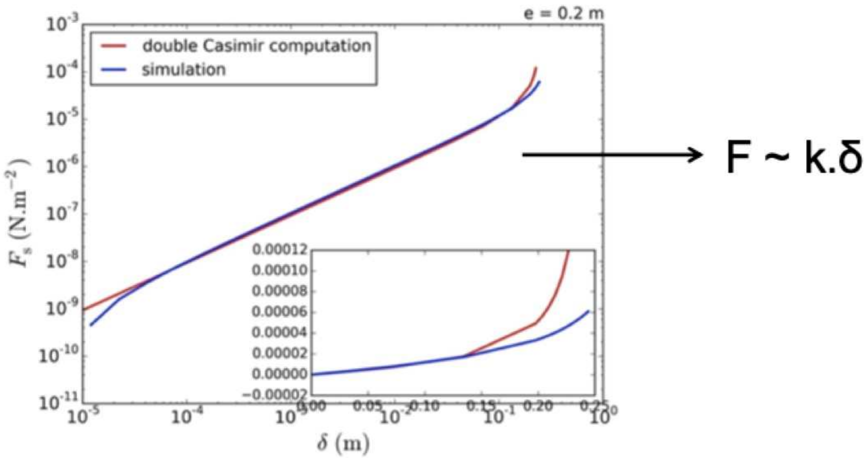
Above the line, MICROSCOPE is not screened: possible WEP violation

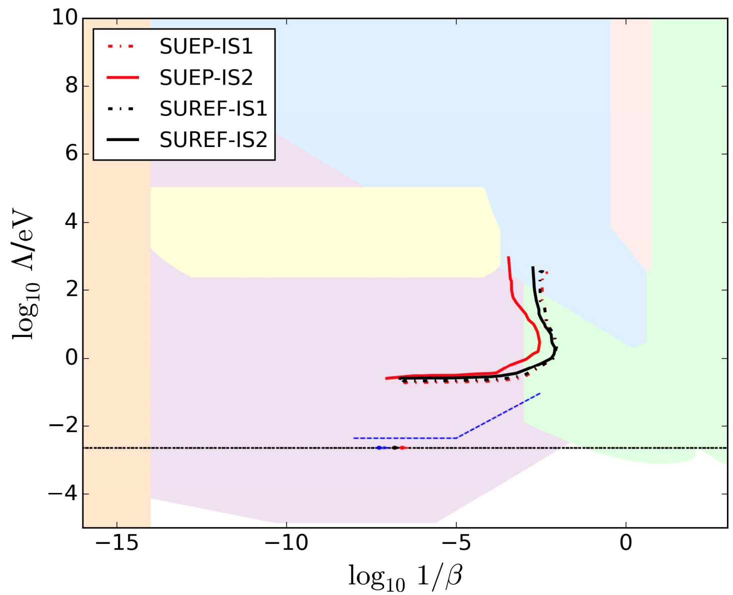
Below the line, MICROSCOPE is screened: no WEP violation expected

Region of interest

Constraints on chameleon:

Bergé+ 2022
Pernot-Borràs+ 2019, 2020, 2021





Chameleon acts as a stiffness between cylinders: we can constrain it with MICROSCOPE!

Conclusion

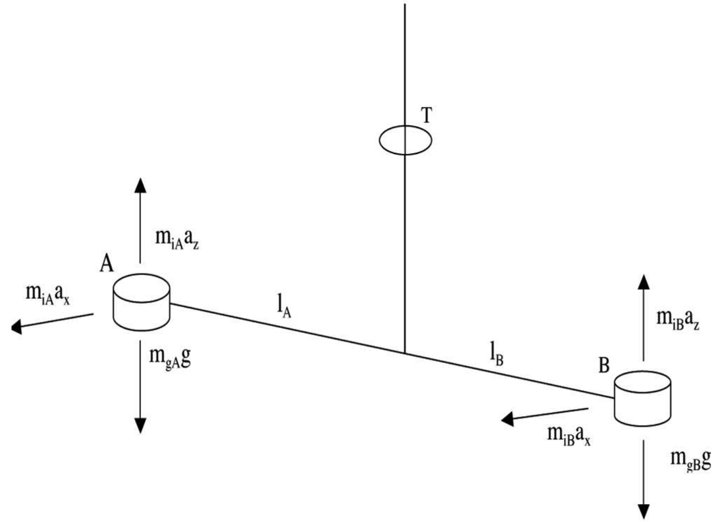
- Final MICROSCOPE results: no WEP violation

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

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

- New constraints on modified gravity
  - generic Yukawa fifth force
    - long-range: state-of-the-art
    - short-range: not competitive
  - light dilaton: competitive
  - chameleon: not competitive, but experimental tests of WEP in space are not as clean and groundbreaking as expected
- New constraints on Lorentz invariance: state-of-the-art

Torsion pendulum (Eötvös)



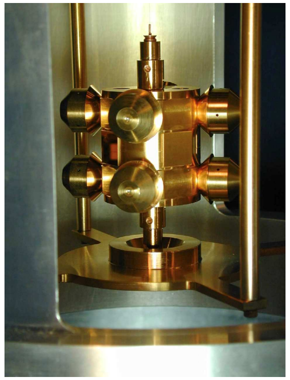
Competition between gravitational and inertial masses of test masses of different composition in the Earth gravity field (Eötvös: wood vs platinum)

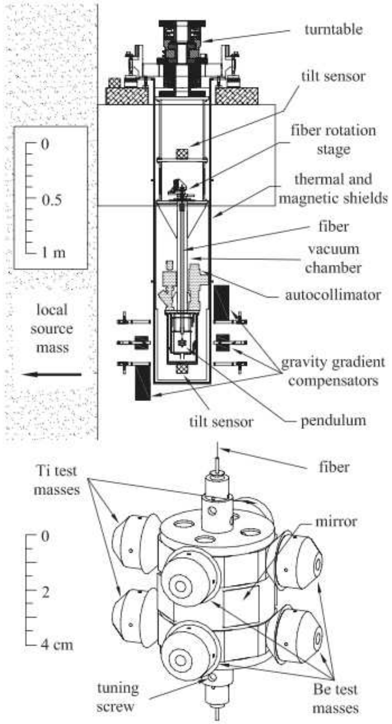
- *gravitational*: weight
- *inertial*: centrifugal force (Earth rotation)

$$\mathcal{C} = l_A m_{gA} \omega^2 R_\oplus \sin\varphi \left(\frac{m_{iA}}{m_{gA}} - \frac{m_{iB}}{m_{gB}} \right)$$

If the m_i/m_g ratio is not universal, measurable non-zero couple.

Torsion pendulum (Eöt-Wash)

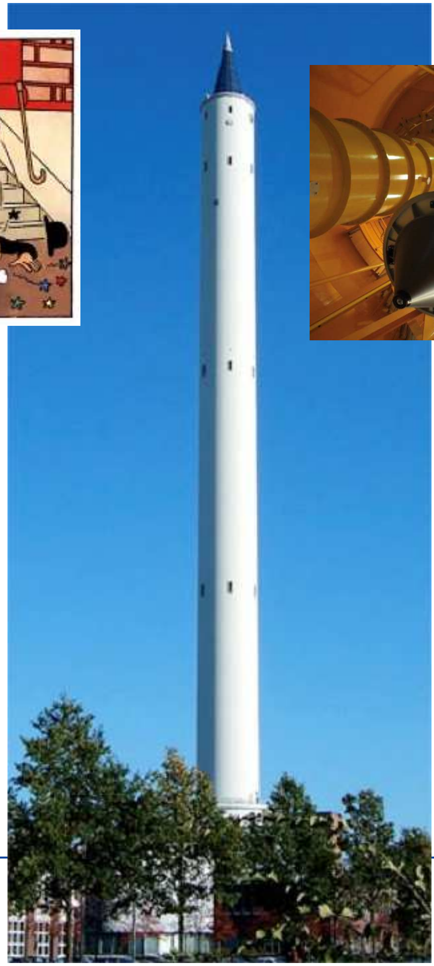


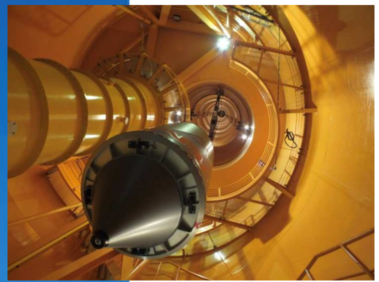


Schlamminger+ 2008

- Pendulum: 70.3 g, wire 1.07m, 20 μm
- 4 beryllium masses and 4 titanium masses: 4.84 g
- Vacuum 10^{-5} Pa
- Deviation measured with corotating autocollimator
- Thermal et magnetic shield in mu-metal
- 888 kg of lead et 8.8 kg of aluminium to cancel local gravity gradients

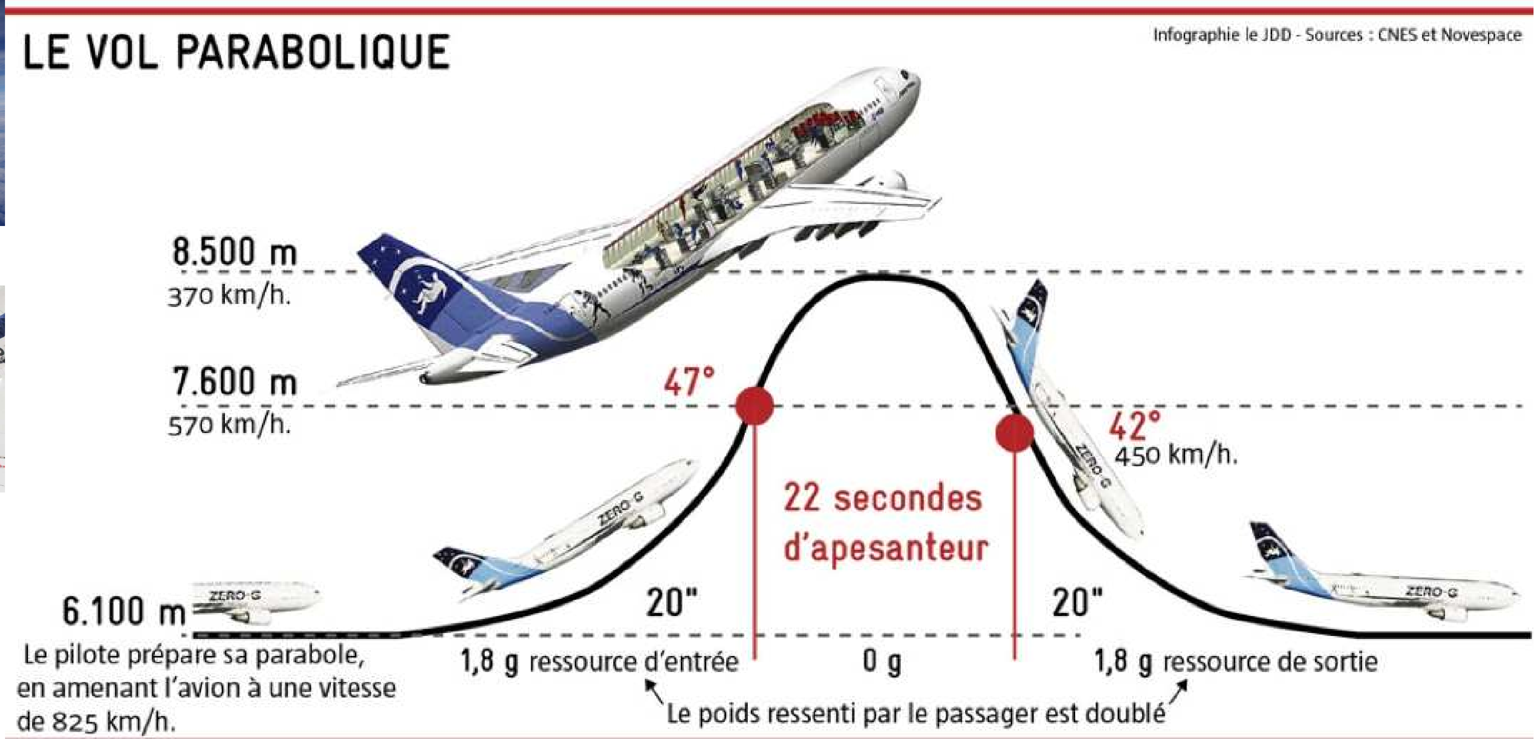
Free fall on Earth



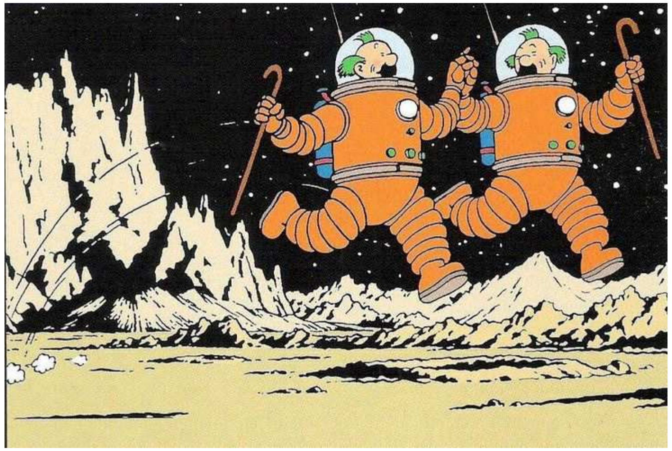


Free fall tower at ZARM (Bremen, Germany)
100 meters, 4-8 seconds of free fall

Zero-g flight



Free fall on the Moon

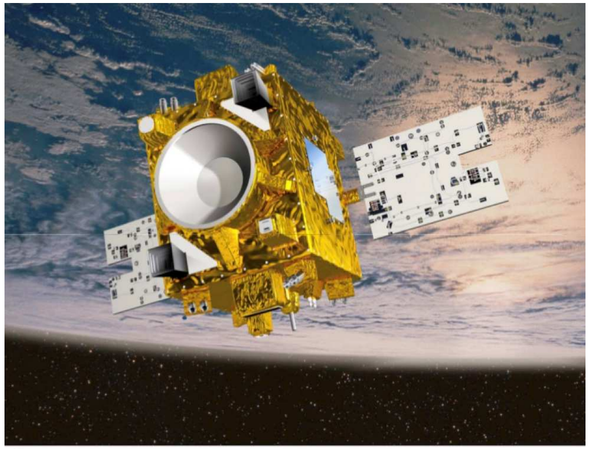


- no atmosphere
- gravity weaker than on Earth

David Scott, Apollo 15, august 1971
Hammer (1.32 kg) vs feather (30 g)

Ideal case: free fall in space

As long as possible…



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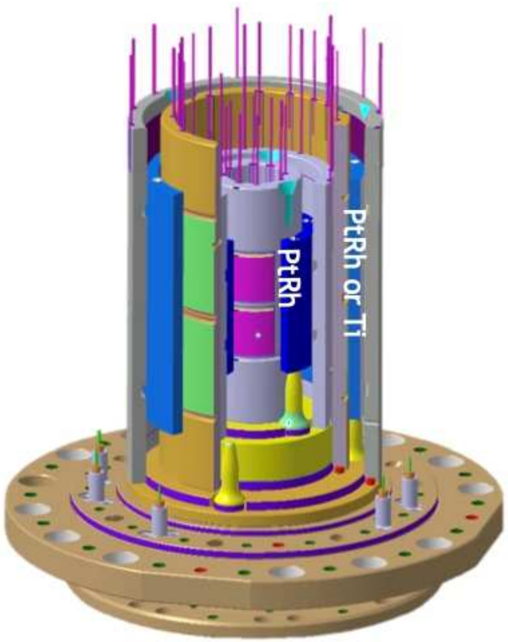
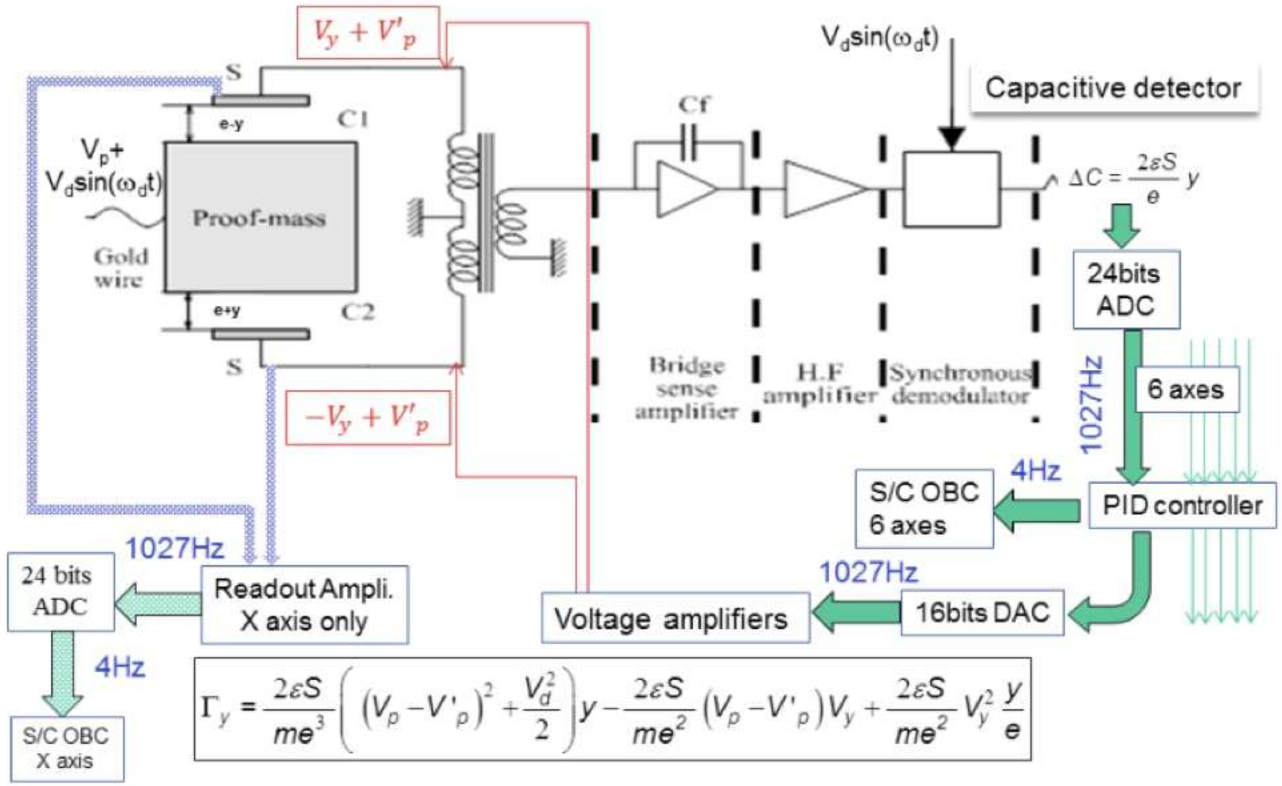
Capacitive sensing



$$F_{force} = F_1 - F_2 = \frac{1}{2}\left[\frac{\partial C_1}{\partial y}\left(V_y + V'_p - V_p - V_d \sin(\omega_d t)\right)^2\right] - \frac{1}{2}\left[\frac{\partial C_2}{\partial y}\left(-V_y + V'_p - V_p - V_d \sin(\omega_d t)\right)^2\right]$$



$$\Gamma_y = \frac{2\varepsilon S}{me^3}\left(\left(V_p - V'_p\right)^2 + \frac{V_d^2}{2}\right)y - \frac{2\varepsilon S}{me^2}\left(V_p - V'_p\right)V_y + \frac{2\varepsilon S}{me^2}V_y^2\frac{y}{e}$$

Accelerometer measurement

Up to electrostatic parasitic forces, the electrostatic force corresponds to a “control” acceleration responding to the contribution of the various contributors to the dynamics of the test mass

Earth gravity acceleration (satellite - test mass)

Internal/ local forces

Parasitic forces

External forces

Thrusters forces

$$\vec{\Gamma}_{\mathrm{cont}} = \frac{\vec{F}_{\mathrm{el}}}{m} = \overrightarrow{\Delta\Gamma}_{\oplus} + \vec{\Gamma}_{\mathrm{kin}} - \frac{\vec{F}_{\mathrm{loc}}}{m} - \frac{\vec{F}_{\mathrm{pa}}}{m} + \frac{\vec{F}_{\mathrm{ext}}}{M} + \frac{\vec{F}_{\mathrm{th}}}{M}$$

Satellite’s mass

Test-mass’ mass

Kinematics acceleration (satellite’s inertia and test-mass motion) $\vec{\Gamma}_{\mathrm{kin}} = [\mathrm{In}]\vec{P} + 2[\Omega]\dot{\vec{P}} + \ddot{\vec{P}}$

Satellite’s angular velocity

$[\mathrm{In}] \equiv [\dot{\Omega}] + [\Omega][\Omega]$

Test-mass position wrt satellite’s center

(Simplified) measured acceleration $\vec{\Gamma}_{\mathrm{meas|instr}} = \vec{B}_0 + \overrightarrow{\Delta\Gamma}_{\oplus|\mathrm{sat}} + \vec{\Gamma}_{\mathrm{kin|sat}} - \frac{\vec{F}_{\mathrm{loc|instr}}}{m} + \vec{n}$

Accelerometer measurement

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

Contains the Eötvös parameter

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

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

Biais

Scale factors
+ axis coupling
(symmetric matrix)

Test mass rotation

Quadratic terms

Angular to linear
acceleration coupling

Noise
(not white!)

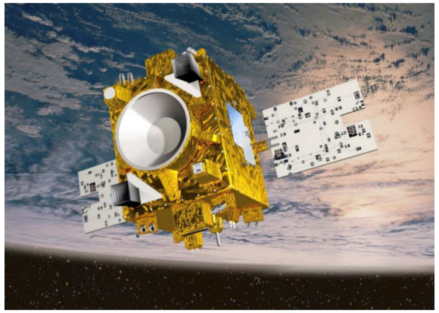
Systematic errors

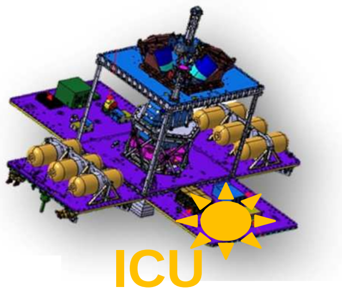
Touboul+ 2019, CQG 36 225006

Table 11. Evaluation of systematic errors in the differential acceleration measurement for SUEP @f_{EP}=3.1113×10^{-3} Hz.

Term in the Eq. (1) projected on $\overrightarrow{x}$ in phase with g_x at f_{EP}	Amplitude or upper bound	Method of estimation
Gravity gradient effect $[T]\overrightarrow{\Delta}$ **in** $m\,s^{-2}$		
$(T_{xx}\Delta x;\ T_{xy}\Delta y;\ T_{xz}\Delta z)$	$< (10^{-18};10^{-19};10^{-17})$	Earth's gravity model.
Gradient of inertia matrix $[In]$ **effect along** X **in** $m\,s^{-2}$		
$\dot{\Omega}_y\Delta z - \dot{\Omega}_z\Delta y$	5×10^{-17}	DFACS performances and calibration.
$\Omega_x\Omega_y\Delta y - \Omega_x\Omega_z\Delta z - (\Omega_y^2 + \Omega_z^2)\,\Delta x$	1.3×10^{-17}	DFACS performances and calibration.
Drag-free control in $m\,s^{-2}$		
$([M_d]\,\overrightarrow{\Gamma}_c^{app}).\overrightarrow{x}$	1.7×10^{-15}	DFACS performances and calibration.
Instrument systematics and defects in $m\,s^{-2}$		
$(\overrightarrow{\Gamma}_d^{quad}).\overrightarrow{x}$	5×10^{-17}	DFACS performances and calibration.
$([Coupl_d]\overrightarrow{\Omega}).\overrightarrow{x}$	$< 2 \times 10^{-15}$	Couplings observed during commissioning phase.
Thermal systematics	$< 67 \times 10^{-15}$	Thermal sensitivity in-orbit evaluation.
Magnetic systematics	$< 2.5 \times 10^{-16}$	Finite elements calculation.
Total of systematics in Γ_{dx}^{meas}	$< 71 \times 10^{-15}\ m\,s^{-2}$	
Total of systematics in δ	$< 9 \times 10^{-15}$	

Tackling thermal systematics

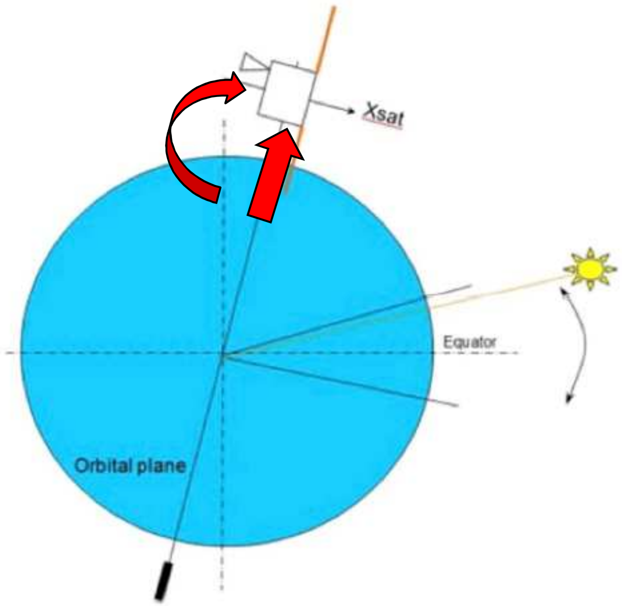


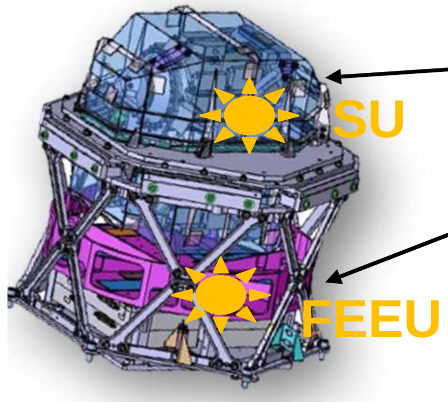


The thermal flux can enter into the satellite through the walls or from the bottom baffle, at the f_{EP} frequency, and create an acceleration:

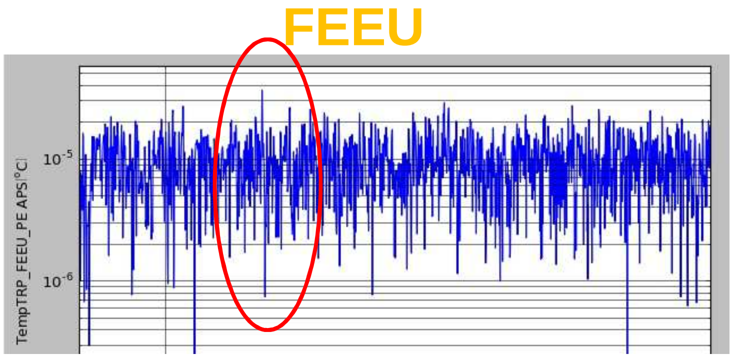
$$B^d_{0x} = \Gamma^d_{xth} + \cdots$$

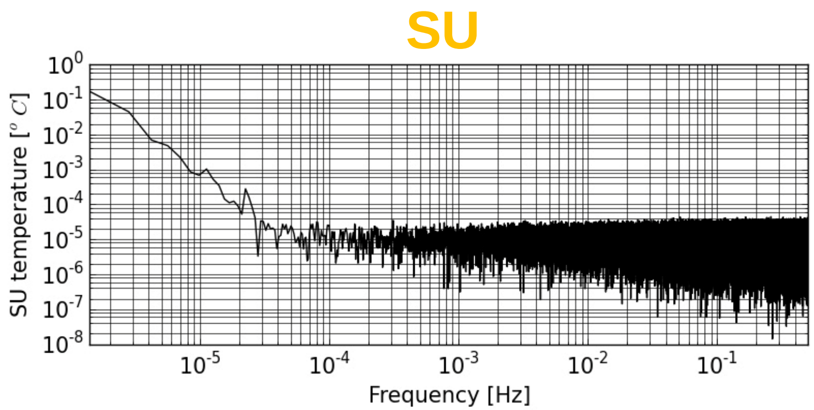
$$\Gamma^d_{xth} = \frac{\partial \Gamma^d_x}{\partial T_{SU}} \delta T_{SU}(f_{EP}) + \frac{\partial \Gamma^d_x}{\partial T_{FEEU}} \delta T_{FEEU}(f_{EP})$$





Measured thermal variations



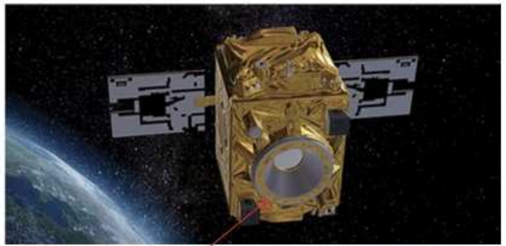


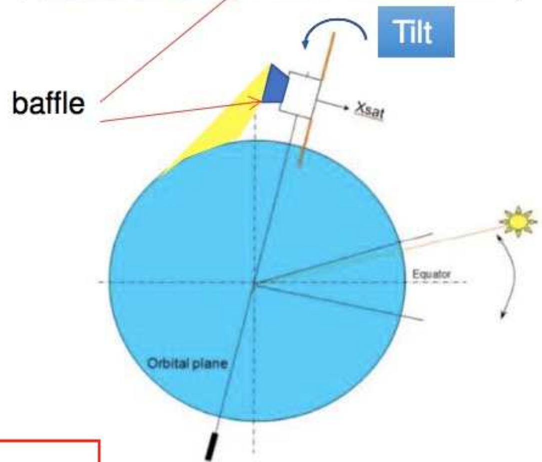
Cumulating sessions 234 to 238 (332 orbits with SUEP @ Spin V3):
signal detected (?) on ΔTFEEU =72μK@fep
No signal on ΔTSU<15μK (1σ noise)@fep

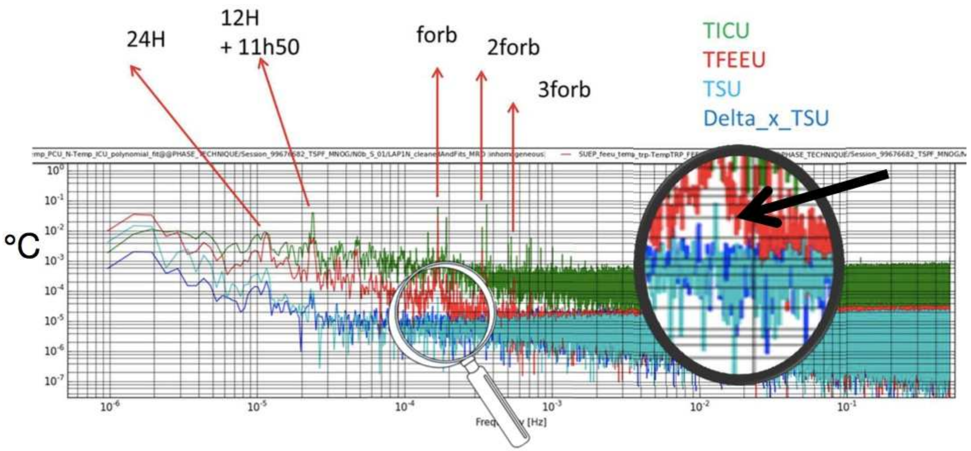
Not conclusive => additional measurements to better estimate thermal filtering up to the SU

Refined thermal filtering characterization

- Objective: measure a thermal signal at FEEU and SU interface and estimate the temperature filtering between radiator to FEEU and then to SU
- Pointing: tilt of 30° of s/c spin axis
- FEEU radiator pointed to the Earth at the north pole and to the space at the south pole
- Temperature variations amplified at forb







$$\left(\frac{\Delta T_{\mathrm{FEEU}}}{\Delta T_{\mathrm{SU}}}\right)_{f>1.7\times10^{-4}\mathrm{Hz}} = 500 \text{ worst case}$$

Thermal sensitivity: $< 9.3 \times 10^{-15}\mathrm{ms}^{-2}$

Glitches and missing data

Glitches: short-lived events

- observed in previous missions (GRACE)
- expected to originate from random crackles of the satellite's coating and gas tanks
- expected to cancel in differential acceleration (seen by both accelerometers), at least below the noise

Missing data

- telemetry losses
- flagged data (e.g. saturation in electronics)

Development/adaptation of data analysis tools to deal with gaps in the data (inpainting, M-ECM)

Baghi+ 2015, 2016
Bergé+ 2015, Pires 2016

Short-range Yukawa interaction

- Technical sessions to characterise the instrument
- (Electrostatic) stiffness estimation

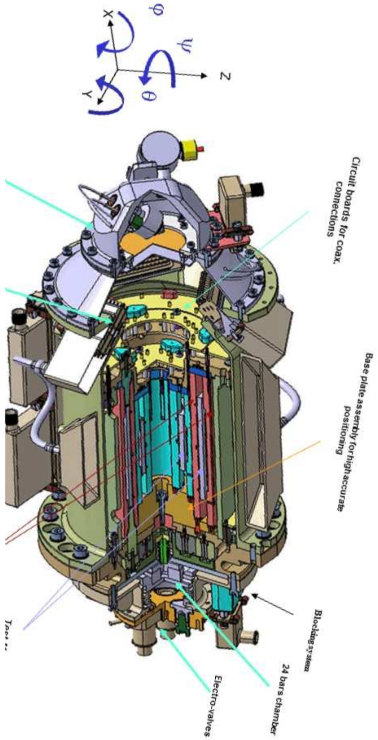
$$\vec{F}_{\mathrm{el},i} \approx -m\left\{G_{\mathrm{act}}V_e + \omega_p^2\left[1+\left(\frac{V_e}{V_p}\right)^2\right]\delta\right\}$$

Stiffness

Test-mass displacement wrt equilibrium position

Measured acceleration

$$\vec{\Gamma}_{\mathrm{meas|instr}} = \vec{B}_0 + \overrightarrow{\Delta\Gamma}_{\oplus|\mathrm{sat}} + \vec{\Gamma}_{\mathrm{kin|sat}} - \frac{\vec{F}_{\mathrm{loc|instr}}}{m} + \vec{n}$$



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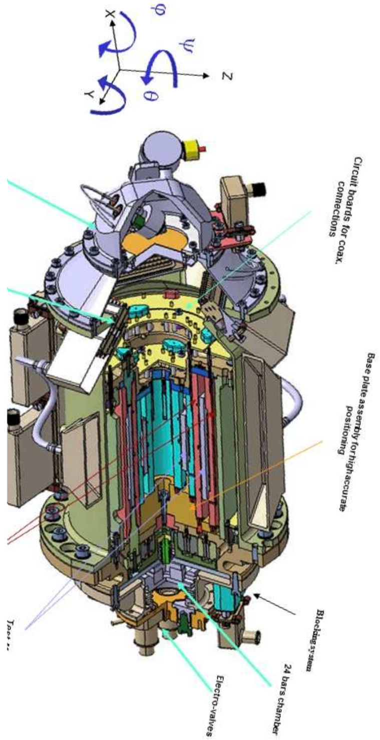
Stiffness

Test-mass displacement wrt equilibrium position



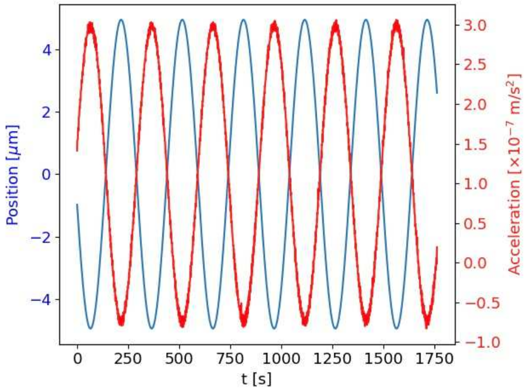
- Gravitational interaction between cylinders:
  at first order, acts as a stiffness

$$\mathscr{F}_x(x_0,\delta) \approx -16\pi^2 G\rho\rho'\alpha \sum_i K_i(x_0)\delta^i$$

δ: test-mass displacement wrt equilibrium position

K_i: functions of the geometry

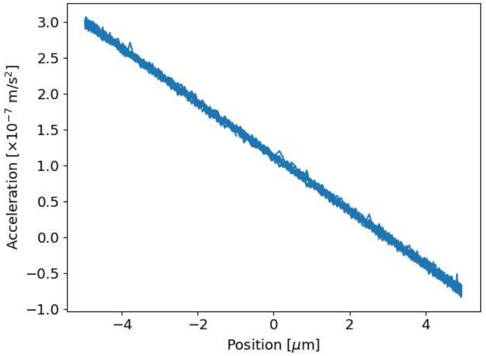
Short-range Yukawa interaction



Total stiffness along one axis (for one sensor) $k_{0,j} = m\omega^2 + k_{\epsilon,j} + k_N + k_Y$

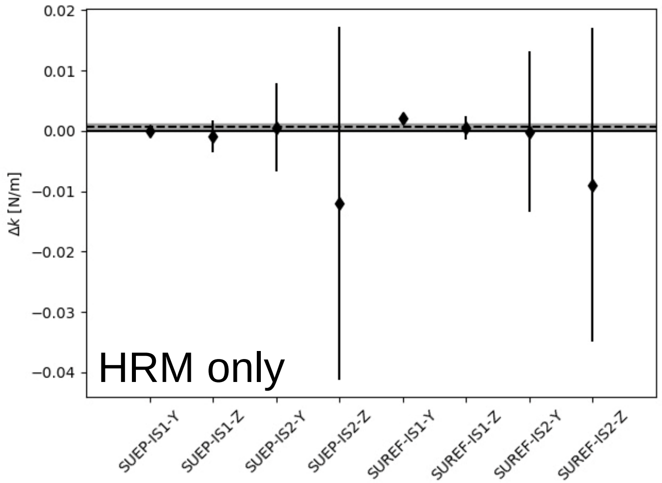
Difference between theoretical electrostatic stiffness and measured total in-phase stiffnesses corrected for the excitation and Newtonian gravity stiffnesses

$$\Delta k = \hat{k}_0 - k_N - m\omega^2 - k_{\epsilon,\mathrm{th}}$$



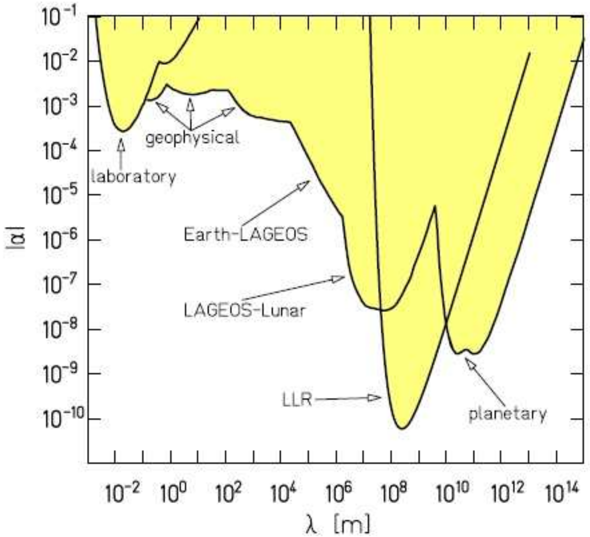
Mean and 1σ error

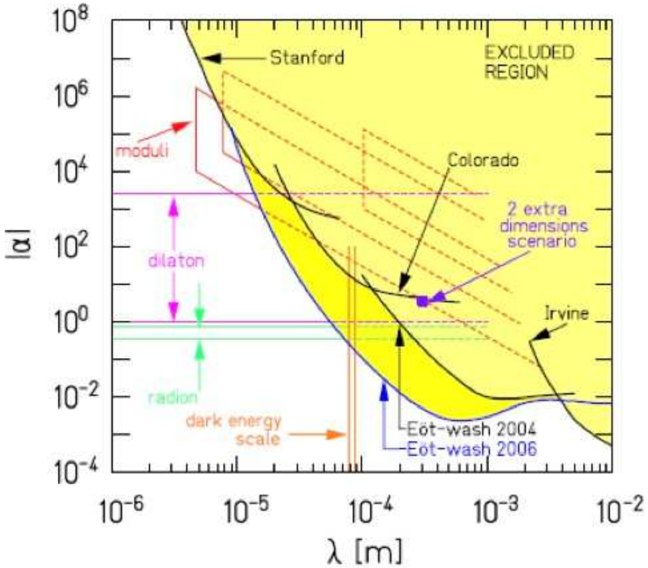
$$\langle \Delta k \rangle = (7.1 \pm 6.0) \times 10^{-4}\ \mathrm{N/m}$$



The problem with massless scalar fields

Long range => should be easily seen in Solar System / Earth experiments of 1/r2 law and EP tests. But we don't see them.





Do they hide? Or are they really absent?

Modified gravity: theories that can violate the WEP

Example: scalar-tensor theories with non-universal coupling

Idea: add an extra scalar degree of freedom to GR

$$\tilde{I} = (16\pi G)^{-1} \int \left[\tilde{R} - 2\tilde{g}^{\mu\nu}\partial_\mu\varphi\,\partial_\nu\varphi - V(\varphi)\right](-\tilde{g})^{1/2}\,d^4x + I_{\rm m}\left(\psi_{\rm m}, A^2(\varphi)\tilde{g}_{\mu\nu}\right)$$

- well motivated theories (string theory…), easy to deal with
- Effects:
  - fundamental constants are spacetime-dependent
  - can be tested in many systems (CMB, BBN, QSO, clocks)
  - masses are spacetime-dependent
  - violation of the WEP
- Phenomenologically, we need to determine the charge of each body

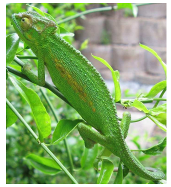
However… scalar-tensor theories difficult to reconcile with Solar System tests

The way to pass Solar System tests: screening

Under some conditions, a scalar field which couples to matter can become hidden to our measurements and evade the constraints
⇒The field has no detectable signature in these conditions, but behaves differently in other conditions. E.g., long-range in low-density regions (cosmological scales) but small-range in high-density regions (Earth, Solar System).

Zoology of screening mechanisms:
- Coupling with matter depends on local density: *Damour-Polyakov mechanism; symmetron, dilaton*
- Mass depends on local density: *chameleon*
- Mass / coupling depends on local gravitational acceleration: *MOND*-type theories
- Coupling depends on local curvature: *Vainshtein* mechanism

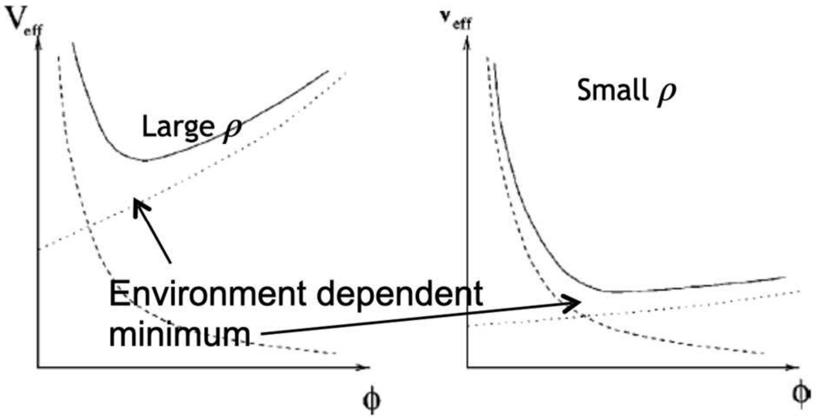
Chameleon gravity



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

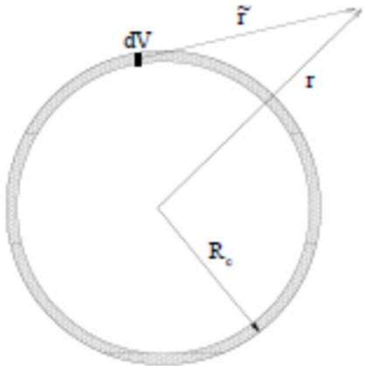
Environment dependent mass

When coupled to matter, scalar field has a matter dependent effective potential $V_{eff}(\phi) \equiv V(\phi) + \sum_i \rho_i e^{\beta_i \phi / M_{Pl}}$



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!).

Thin-shell screening



$$\frac{\Delta R_c}{R_c} = \frac{\phi_\infty - \phi_c}{6\beta M_{Pl}\Phi_c}$$

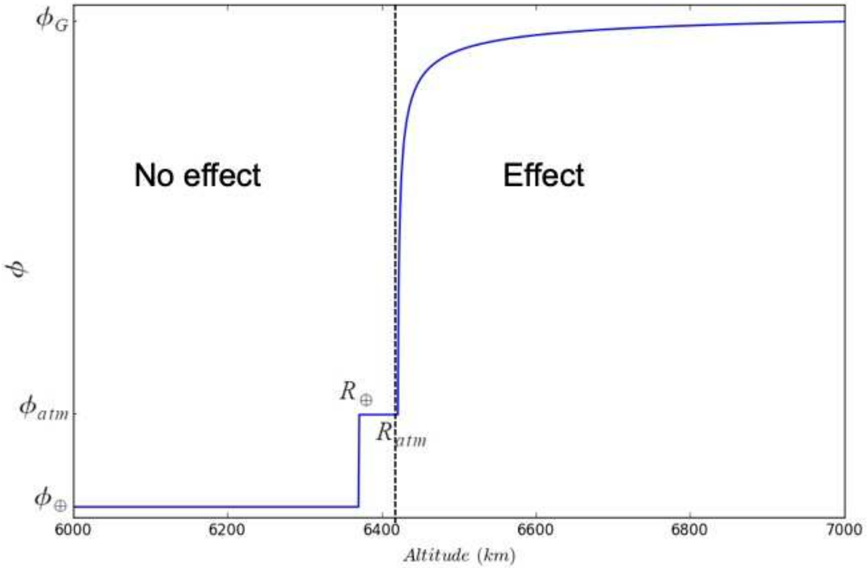
$$\phi(r) \approx -\left(\frac{\beta}{4\pi M_{Pl}}\right)\left(\frac{3\Delta R_c}{R_c}\right)\frac{M_c e^{-m_\infty r}}{r} + \phi_\infty$$

The field generated from deep inside is Yukawa suppressed. Only a thin shell radiates outside the body. Hence suppressed scalar contribution to the fifth force.

Chameleon around the Earth

Khoury & Weltman 2004

$$\phi(r) \approx \begin{cases} \phi_\oplus & \text{for} \quad 0 < r \lesssim R_\oplus\,, \\ \phi_{atm} & \text{for} \quad R_\oplus \lesssim r \lesssim R_{atm}\,, \\ -\left(\frac{\beta}{4\pi M_{Pl}}\right)\left(\frac{3\Delta R_\oplus}{R_\oplus}\right)\frac{M_\oplus e^{-m_G(r-R_{atm})}}{r} + \phi_G & \text{for} \quad r \gtrsim R_{atm}\,, \end{cases}$$

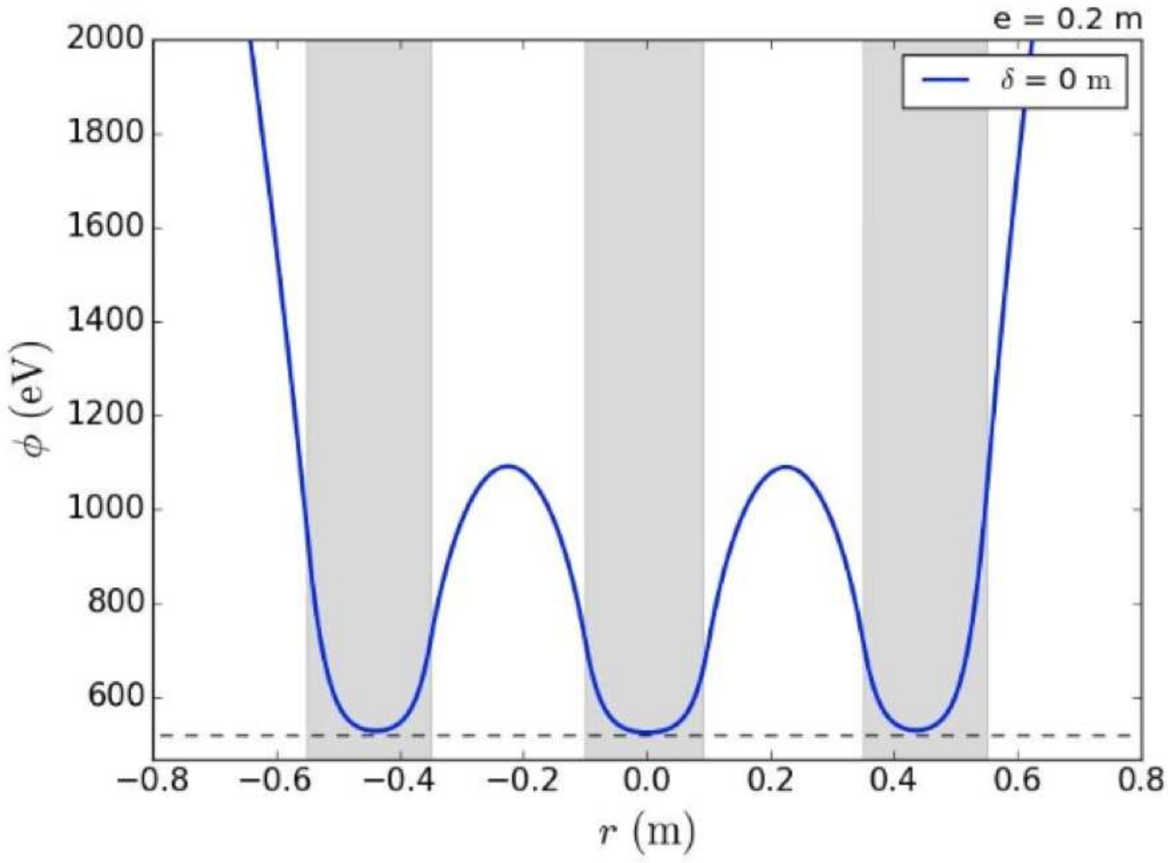


Chameleon force

$$\vec{F} = -\frac{\beta}{M_{Pl}} M_{test} \vec{\nabla}\phi$$

Wall moving in a cavity

Pernot-Borràs+ 2019, 2020



Wall moving in a cavity

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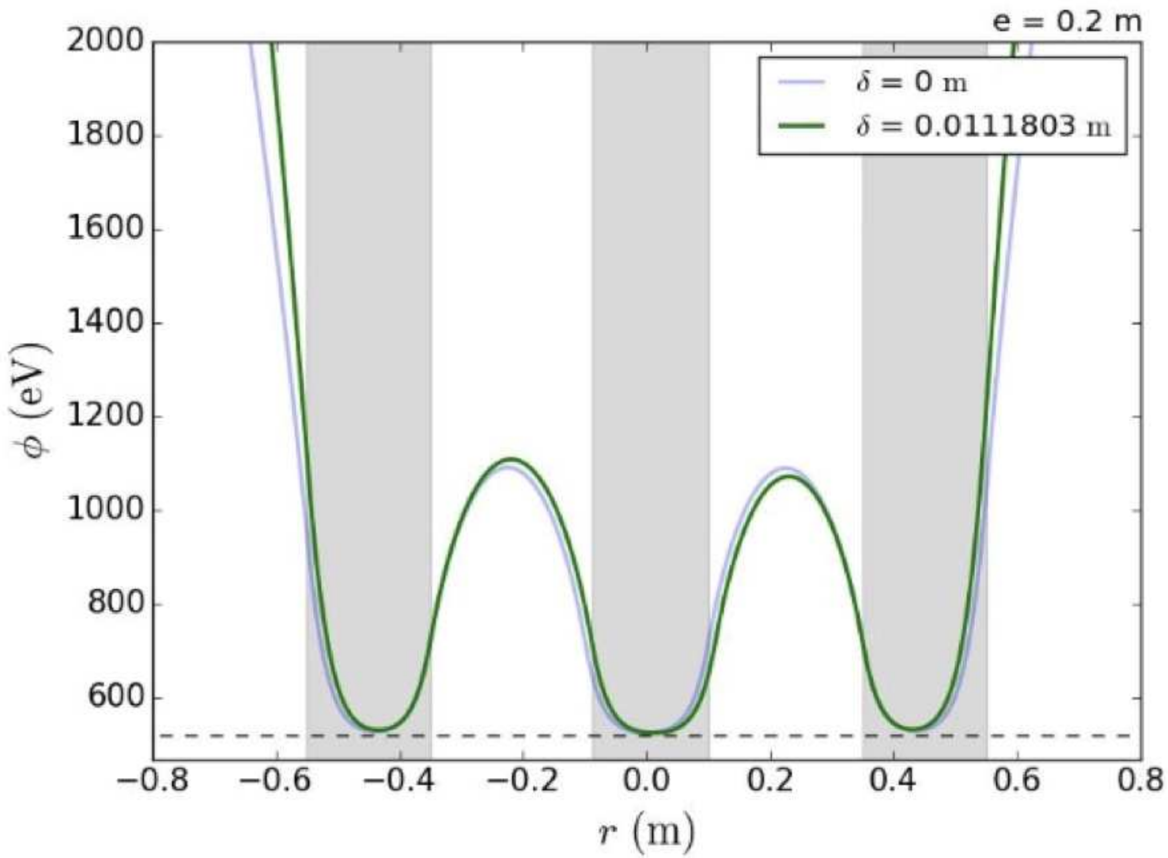
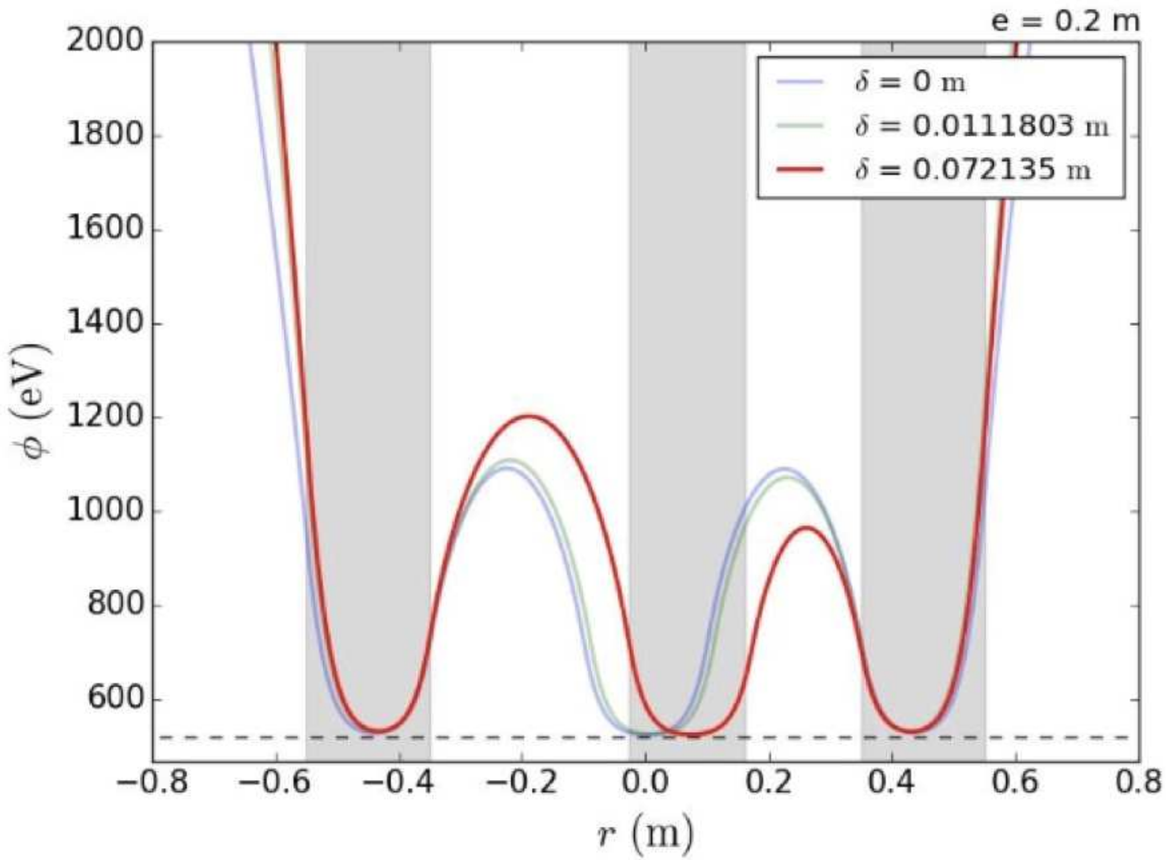


Wall moving in a cavity

Pernot-Borràs+ 2019, 2020



Wall moving in a cavity

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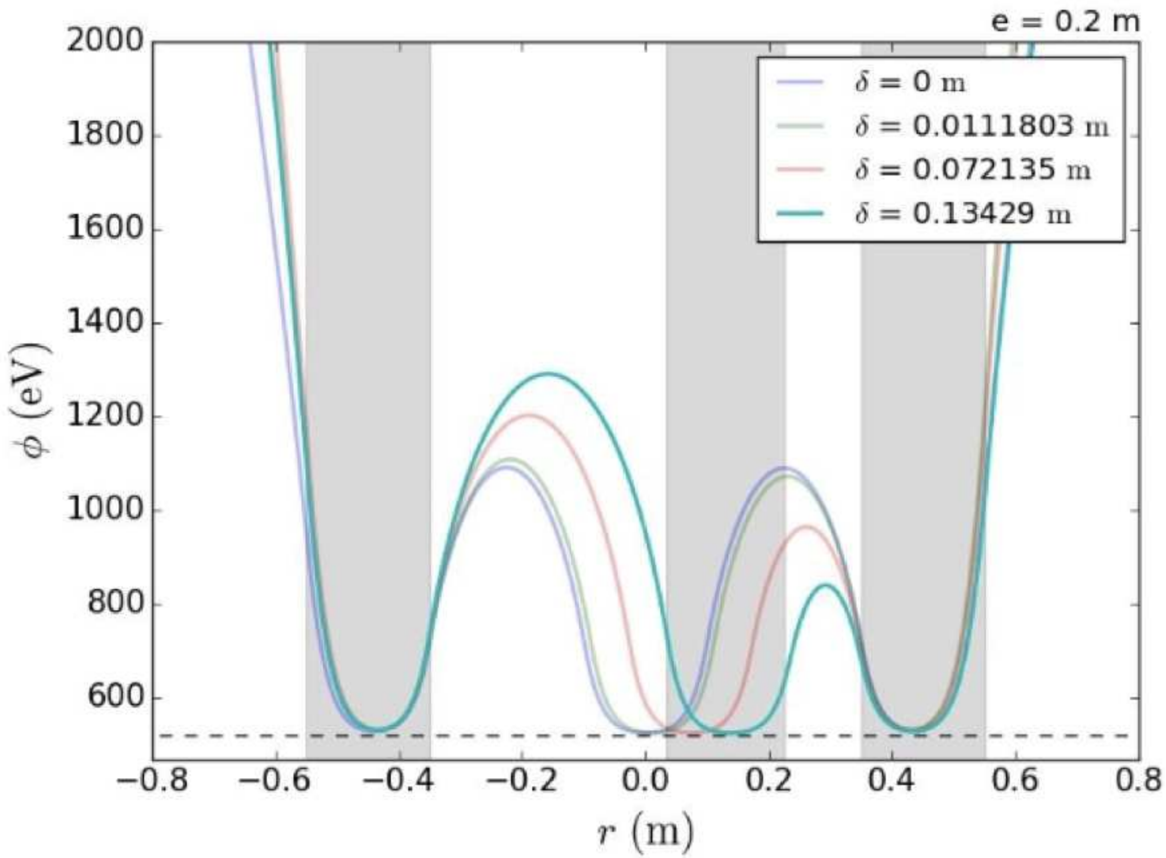

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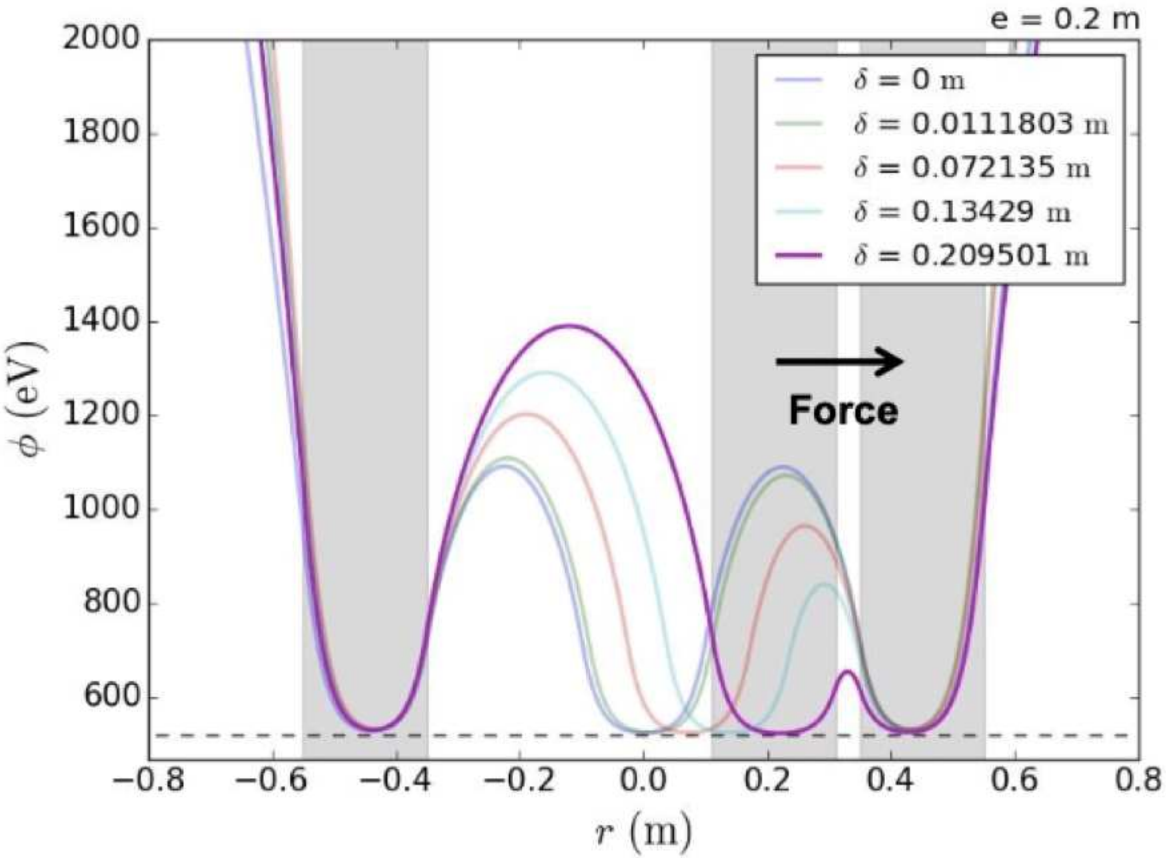
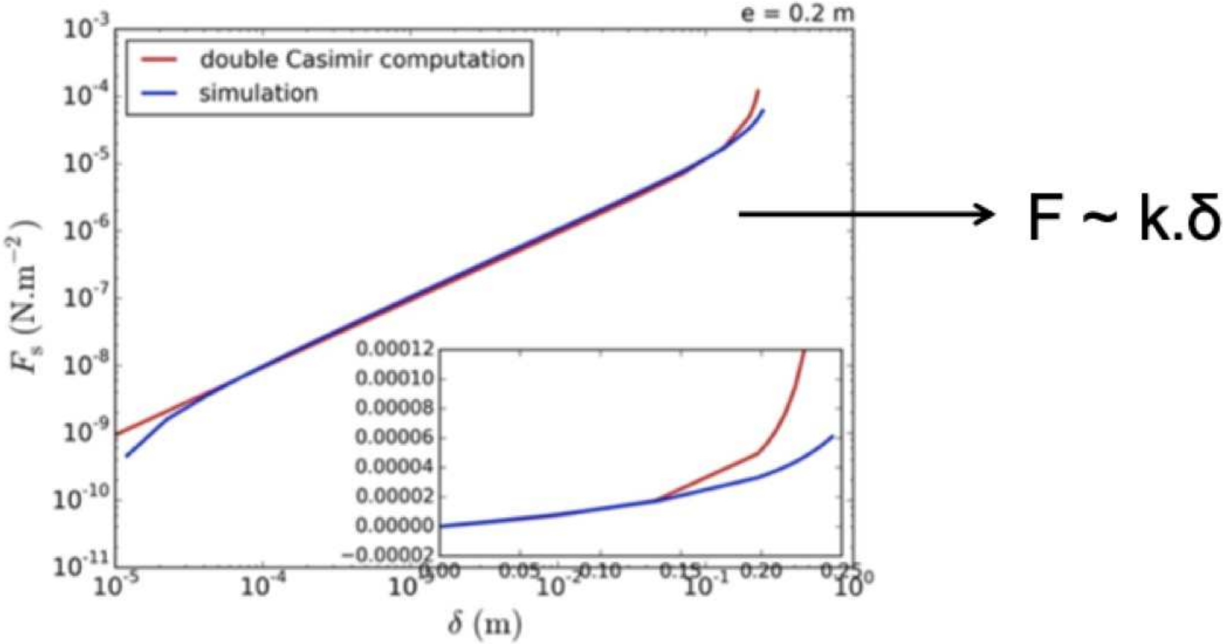
Pernot-Borràs+ 2019, 2020



Chameleon force between cylinders

Pernot-Borràs+ 2019, 2020



Chameleon acts as a stiffness: we can constrain it with MICROSCOPE!

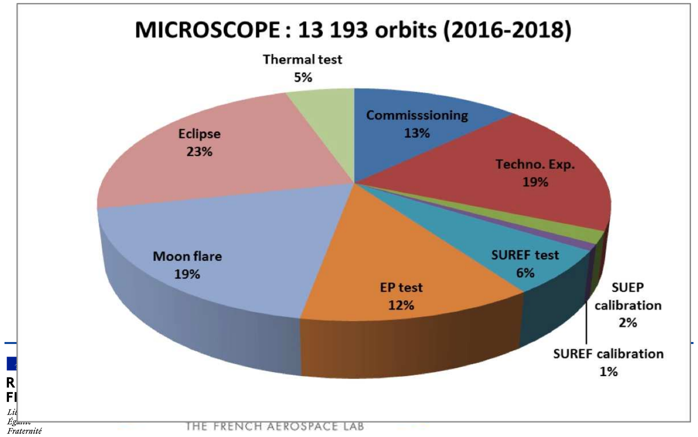
The new upper bound on the WEP

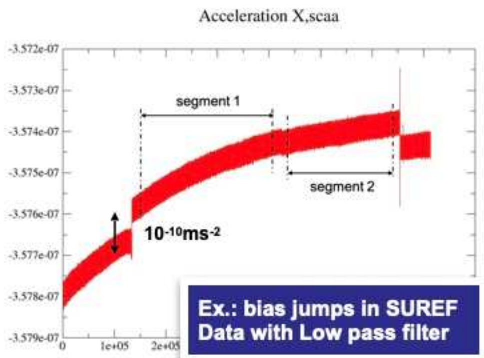
Touboul+ 2022 PRL 129 121102
Touboul+ 2022 CQG 39 204009

From 1600 orbits (SUEP) and 800 orbits (SUREF)

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

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





Segment number	Duration (orbits)	Position in the session (orbits)	Percentage of data eliminated (glitches)
120-1	22	23 to 44	4
120-2	64	57 to 120	15
174	86	34 to 119	25
176	62	1 to 62	40
294	76	18 to 93	17
376-1	36	8 to 43	14
376-2	28	52 to 79	11
380-1	46	24 to 69	7
380-2	34	75 to 108	5
452	32	1 to 32	20
454	56	1 to 56	22
778-1	38	1 to 38	0
778-2	18	41 to 58	6

Segment number	Duration (orbits)	Position in the session (orbits)	Percentage of data eliminated (glitches)
210	50	1 to 50	18
212	60	1 to 60	17
218	120	1 to 120	15
234	92	1 to 92	18
236	120	1 to 120	21
238	120	1 to 120	24
252	106	1 to 106	26
254	120	1 to 120	27
256	120	1 to 120	28
326-1	66	2 to 67	12
326-2	34	69 to 102	7
358	92	1 to 92	14
402	18	3 to 20	35
404	120	1 to 120	23
406	20	1 to 20	23
438	32	1 to 32	21
442	40	1 to 40	21
748	24	1 to 24	25
750	8	1 to 8	19