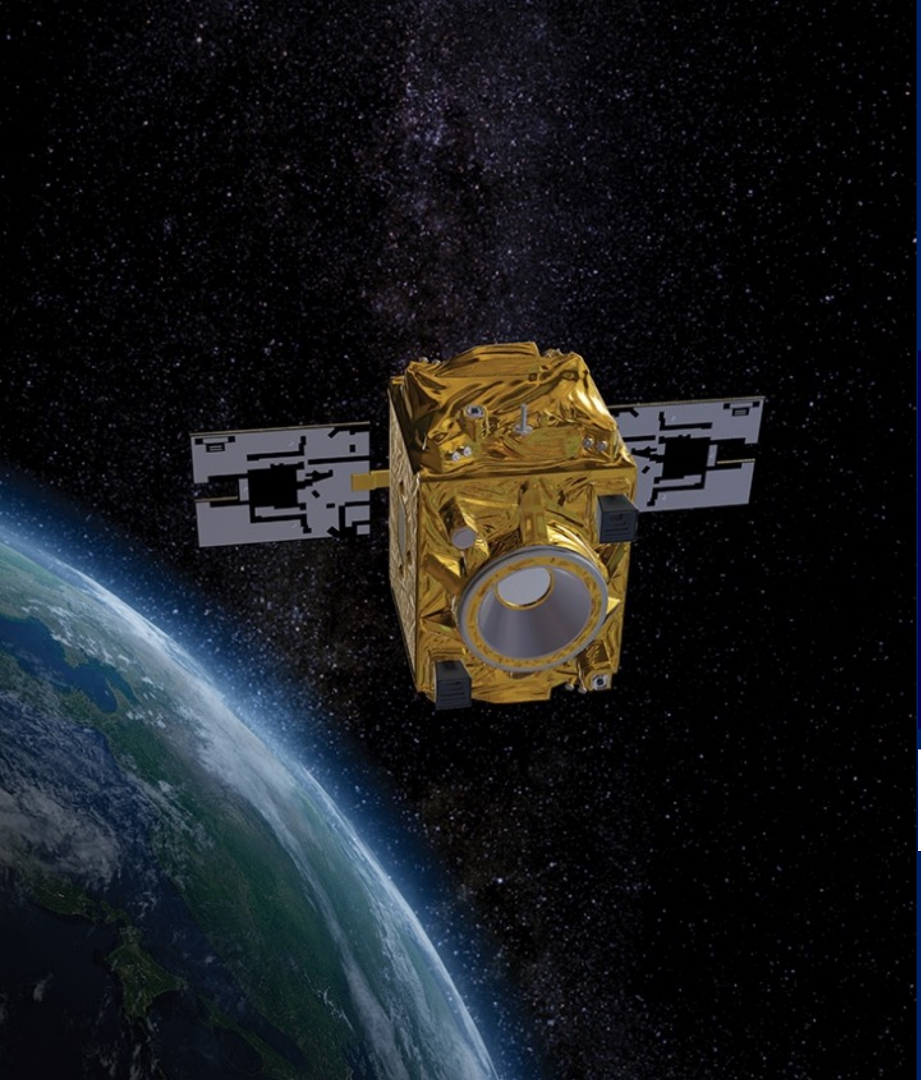


Dark energy direct detection in space with MICROSCOPE and beyond

Joel Bergé

On behalf of the MICROSCOPE consortium

and with P. Brax, M. Pernot-Borràs, J.P. Uzan

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.

Newton's laws: $F = m_i\, a$, $F_g = m_g\, g$
$F = F_g \Rightarrow m_i = m_g$

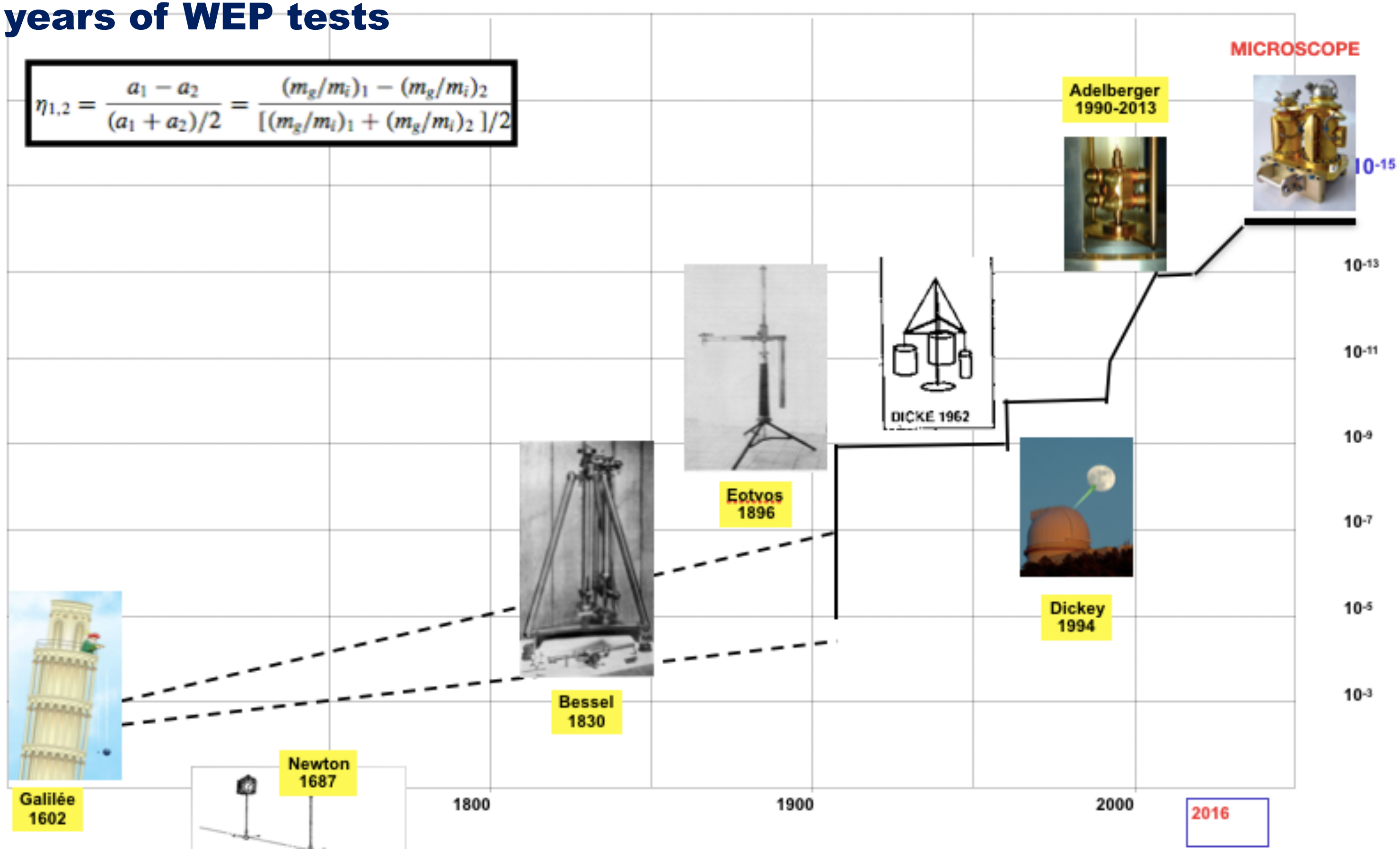
m_i = inertial mass: "opposes" changes in motion (universal)
m_g = gravitational mass: feels gravity (specific to the gravitational force)

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

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

400 years of WEP tests

$$\eta_{1,2} = \frac{a_1 - a_2}{(a_1 + a_2)/2} = \frac{(m_g/m_i)_1 - (m_g/m_i)_2}{[(m_g/m_i)_1 + (m_g/m_i)_2]/2}$$



MICROSCOPE's goal: test the Weak Equivalence Principle (WEP) down to 10^{-15}

Test universality of free-fall

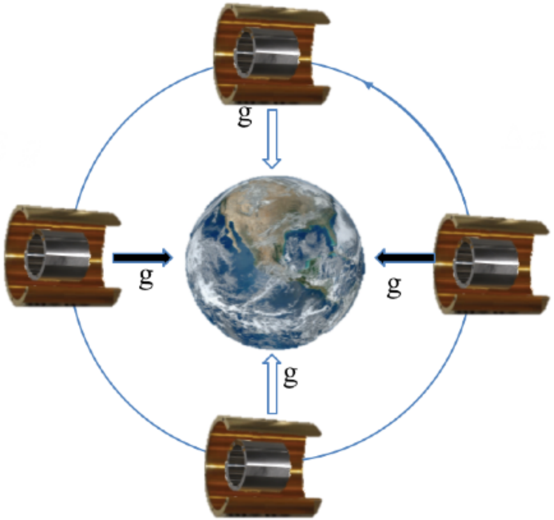
m_g = gravitational mass  m_i = inertial mass 

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

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

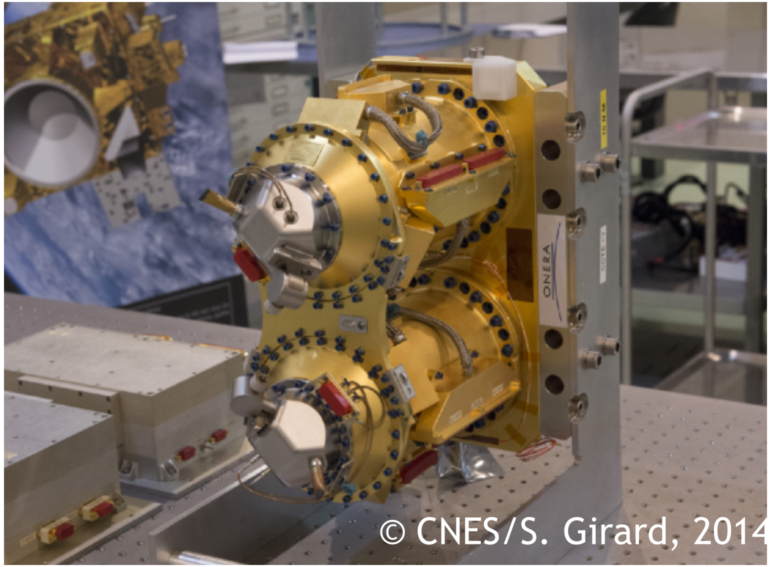
If $\eta_{12} = 0 : \ \Delta a = 0$

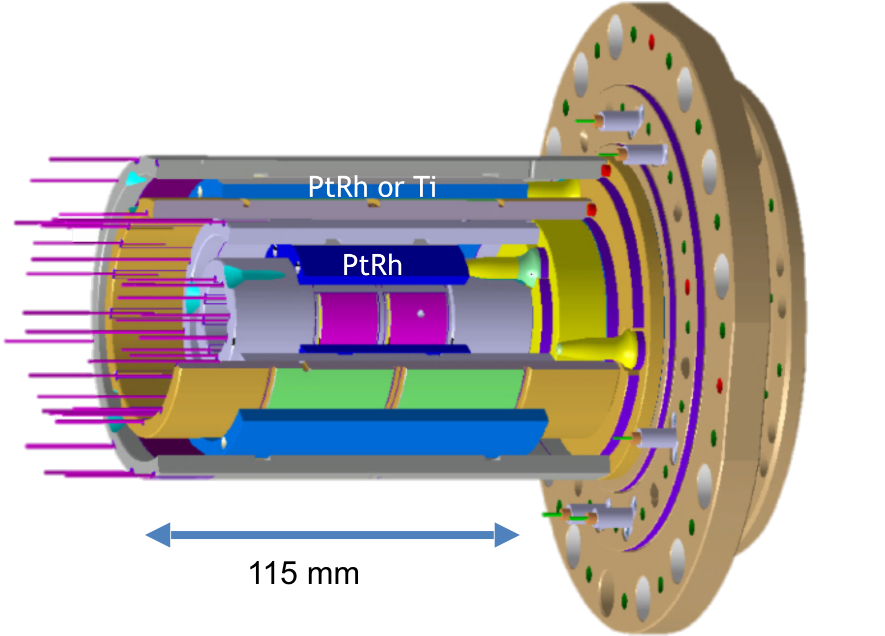
If $\eta_{12} \neq 0 : \ \Delta a \neq 0$ detection of a signal collinear to g (same phase, same frequency)



2 double accelerometers for the test

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

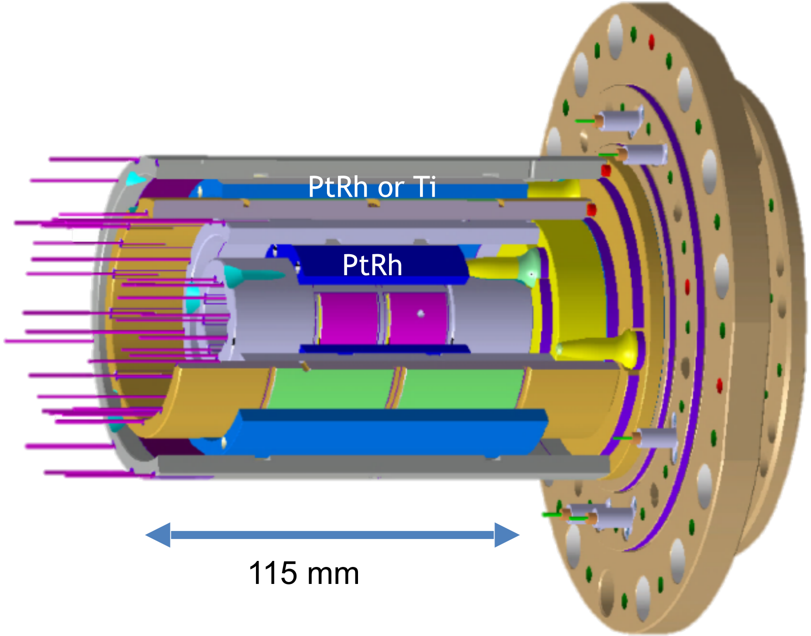




2 double accelerometers for the test

2 similar instruments on board which comprise each 2 concentric test-masses
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



The MICROSCOPE satellite

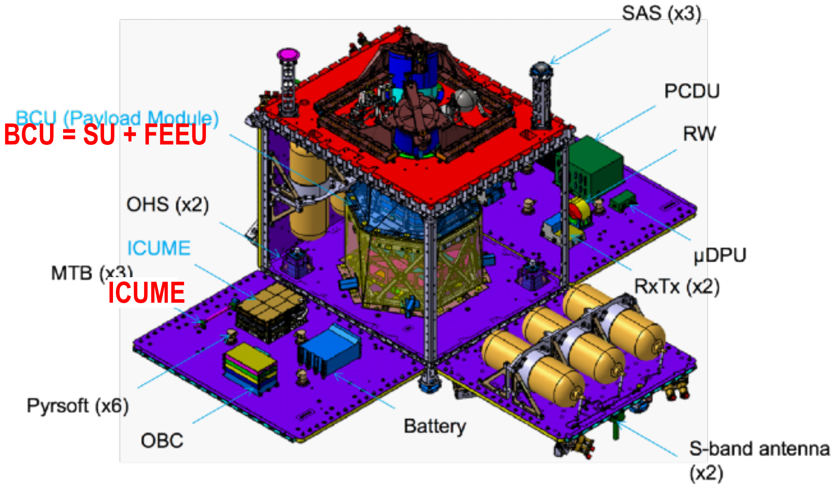
Cold Gaz propulsion / Drag-free, Attitude control

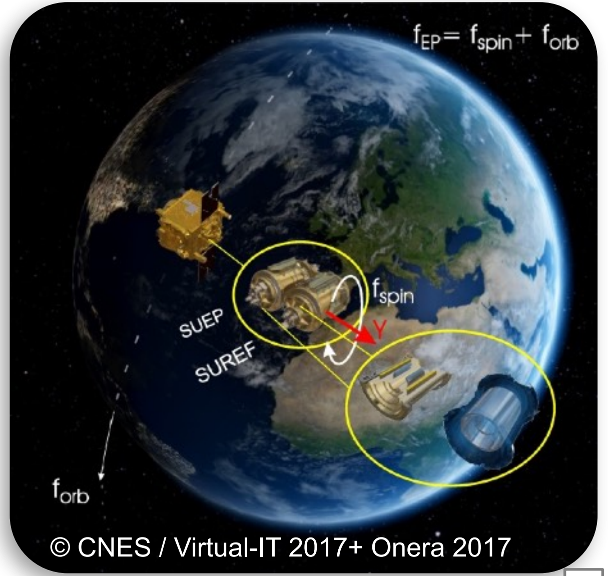
A space laboratory of 300kg

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

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

- **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



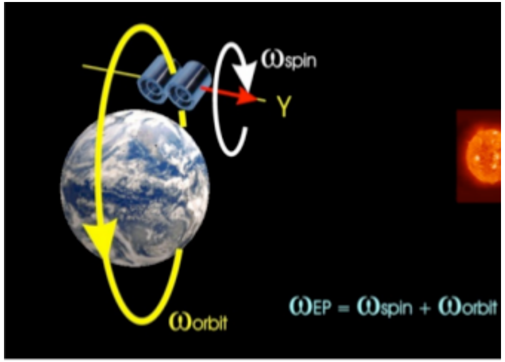


The signal we're looking for

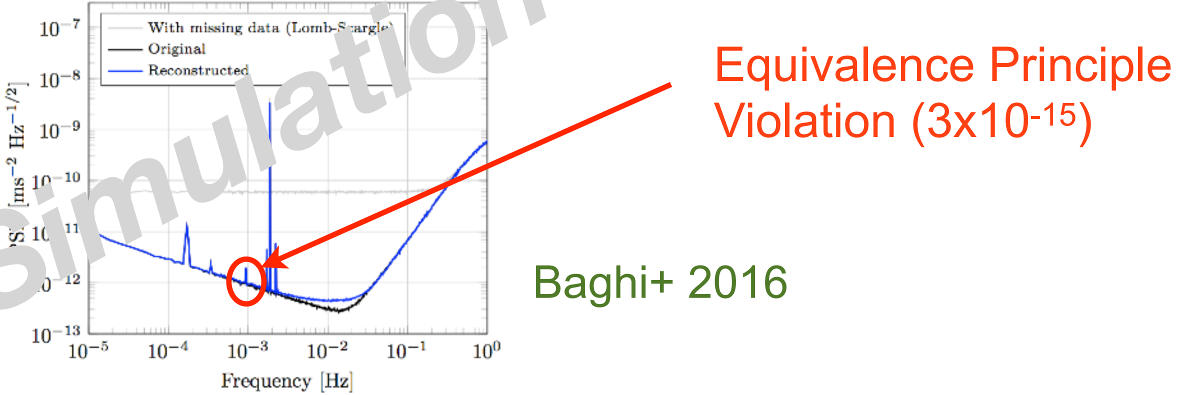
Earth gravity field modulated by satellite's motion around the Earth => sine of known frequency f_{EP}

f_{EP} can be varied by either:

- Keeping the satellite in inertial motion
- Or spinning it



How to extract the signal? Easy! We must look for a noise-dominated sine in measured time series.



Accelerometer measurement

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

Contains the Eötvös parameter

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

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

Biais

Scale factors
+ axis coupling
(symmetric matrix)

Test mass rotation

Quadratic terms

Angular to linear
acceleration coupling

Noise
(not white!)

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

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

+ 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

The new upper bound on the WEP

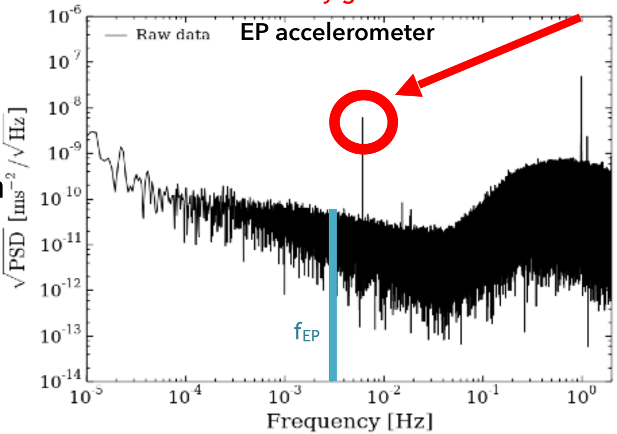
Touboul+ 2017, PRL 119 231101

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

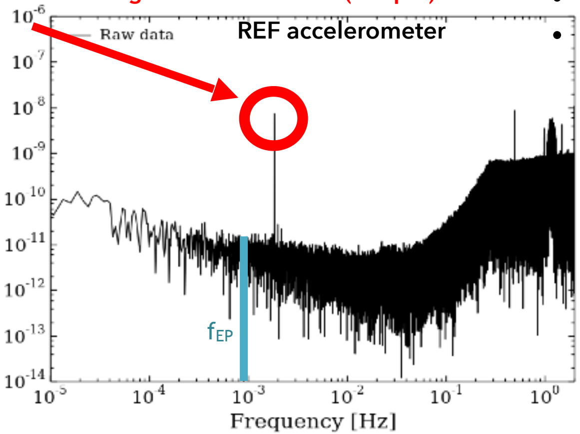
Over 120 orbits

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

Gravity gradient effect: due to an offcentring of the test-mass (<30µm)



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



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

Over 62 orbits

- Statistical noise integrated
- Systematics evaluated after publication

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

$$\eta_{Pt,Pt} = [+4 \pm 4(\text{stat}) \pm 8(\text{syst})] \times 10^{-15}$$

Touboul+ 2019, CQG 36 225006

MICROSCOPE and Modified gravity

JB, P. Brax, G. Métris, M. Pernot-Borràs, P. Touboul, J.-P. Uzan, 2018, PRL 120 141101
M. Pernot-Borràs, JB, P. Brax, J.-P. Uzan, 2019, PRD 100 084006
M. Pernot-Borràs, JB, P. Brax, J.-P. Uzan, 2020, PRD 101 124056
M. Pernot-Borràs, JB, P. Brax, J.-P. Uzan, G. Métris, M. Rodrigues, P. Touboul, 2021, PRD 103 064070

MICROSCOPE and modified gravity: generic 5th force model

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

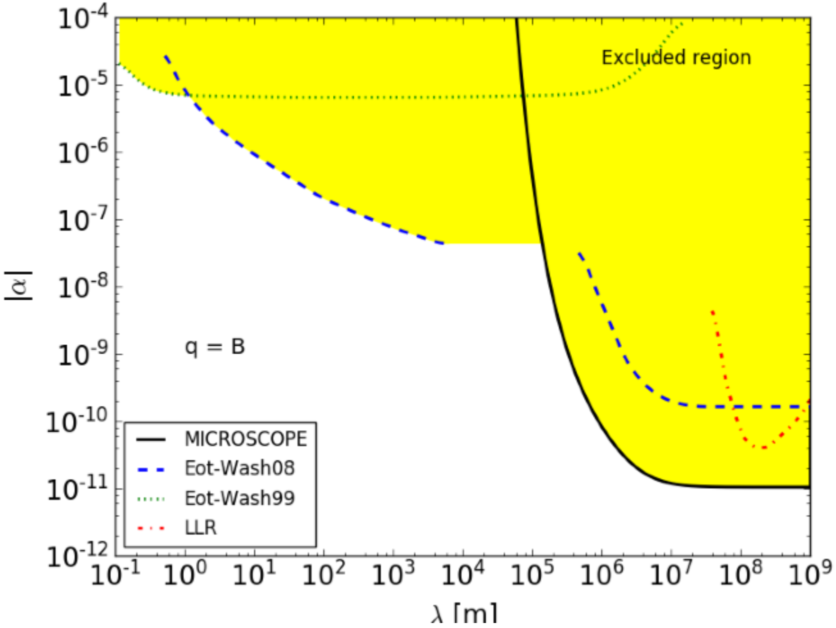
Yukawa potential

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

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

WEP violation

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



Light dilaton

Damour & Donoghue 2010

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

EM quarks electrons gluons

Coupling to matter

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

WEP violation

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

Dilaton charges (must be computed for given atoms)

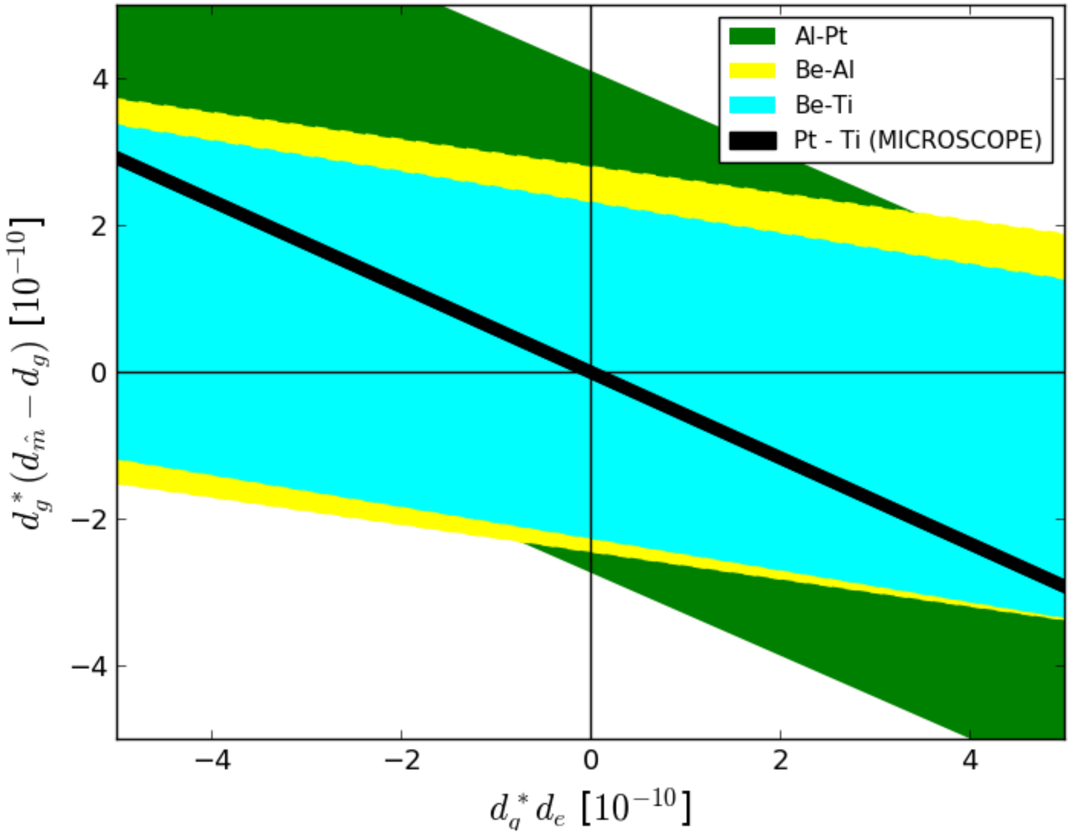
$$Q'_e = -1.4 \times 10^{-4} + 7.7 \times 10^{-4} \frac{Z(Z-1)}{A^{4/3}} \qquad Q'_{\tilde{m}} = 0.093 - \frac{0.036}{A^{1/3}} - 1.4 \times 10^{-4} \frac{Z(Z-1)}{A^{4/3}}$$

<u>Parameters to constrain</u>

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

Light dilaton vs MICROSCOPE

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

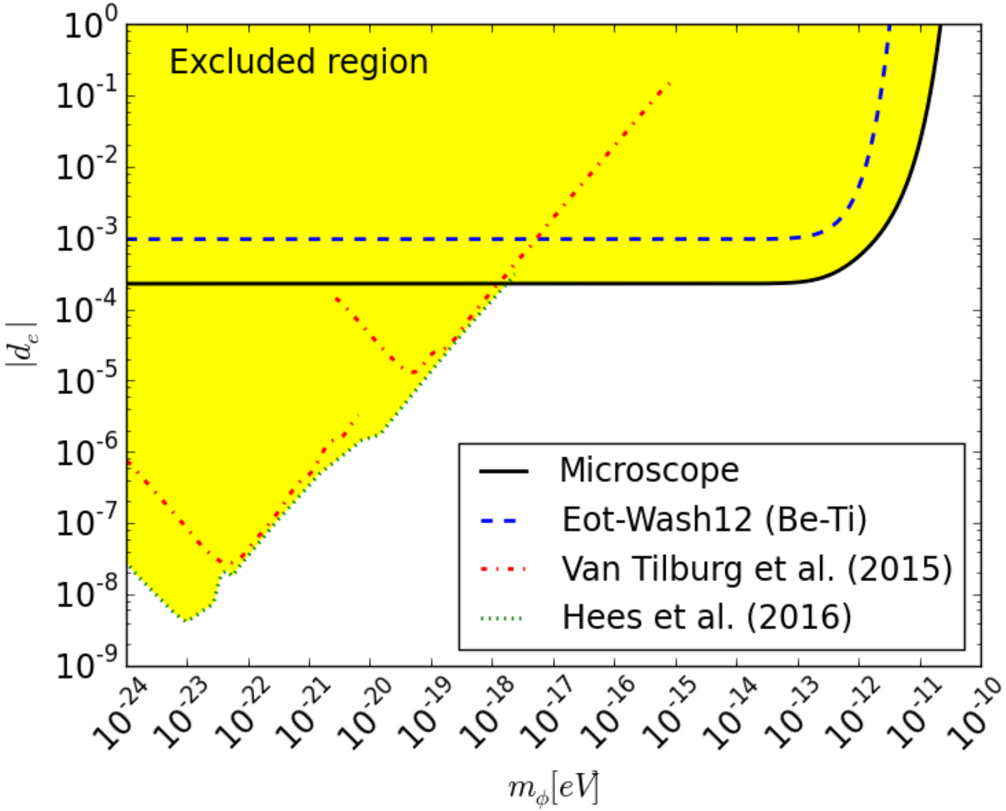


Massive dilaton coupled to EM only

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

$$d_g = d_{m_i} = 0$$

$$D_e \propto (d_e)^2$$



Van Tilburg, Hees: oscillations of the fine structure constant in a spectroscopic analysis of two isotopes of dysprosium

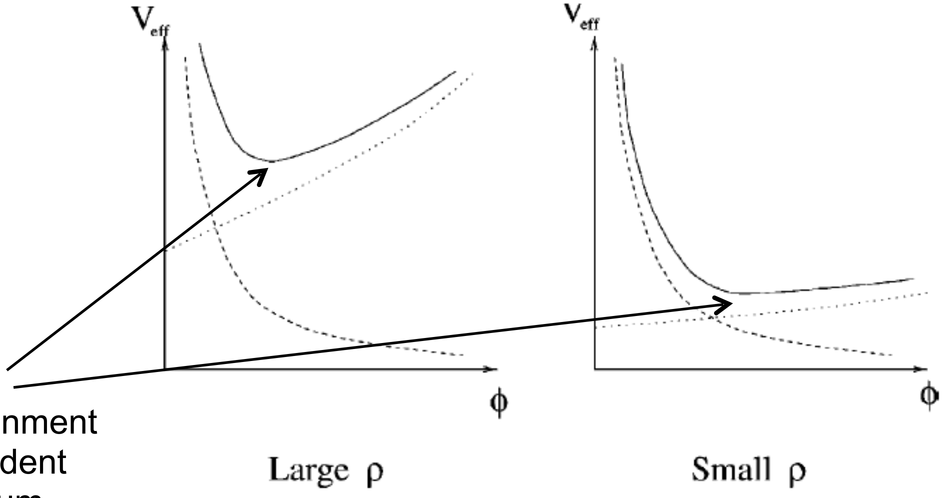
Chameleon gravity and screening

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

$$V_{eff}(\phi) \equiv V(\phi) + \sum_i \rho_i e^{\beta_i \phi / M_{Pl}}$$



Environment dependent minimum

Environment-dependent mass

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!).

ONERA
THE FRENCH AEROSPACE LAB

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

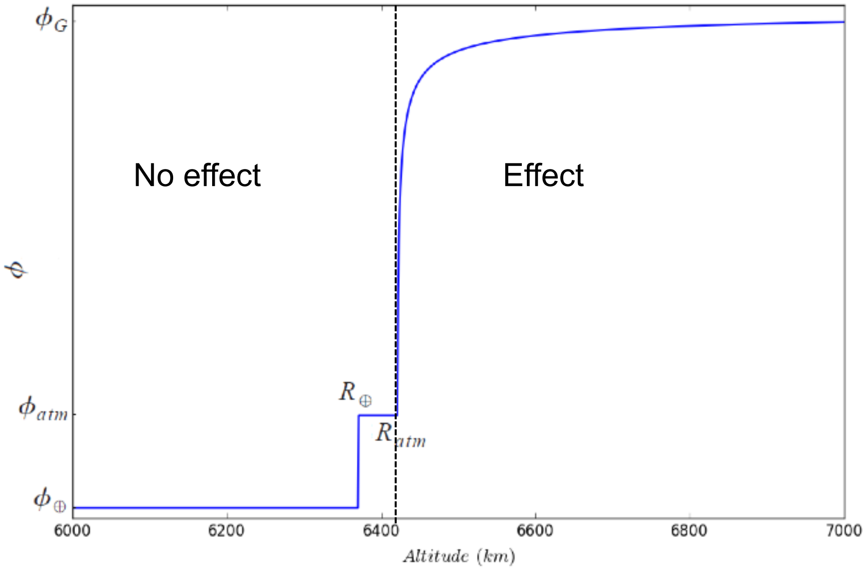
$$\beta^2 \times 10^{-19} < \eta < \beta^2 \times 10^{-11}$$

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

Khoury & Weltman, PRD 2004

...

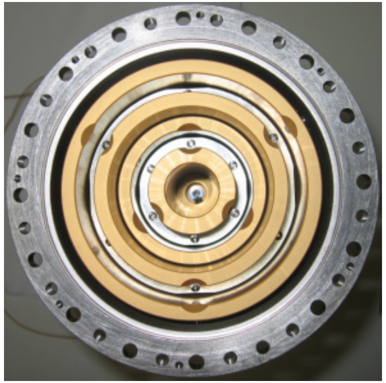
$$\phi(r) \approx \begin{cases} \phi_\oplus & \text{for} \quad 0 < r \lesssim R_\oplus , \\ \phi_{atm} & \text{for} \quad R_\oplus \lesssim r \lesssim R_{atm} , \\ -\left(\frac{\beta}{4\pi M_{Pl}}\right)\left(\frac{3\Delta R_\oplus}{R_\oplus}\right)\frac{M_\oplus e^{-m_G(r-R_{atm})}}{r} + \phi_G & \text{for}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



Chameleon force :

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

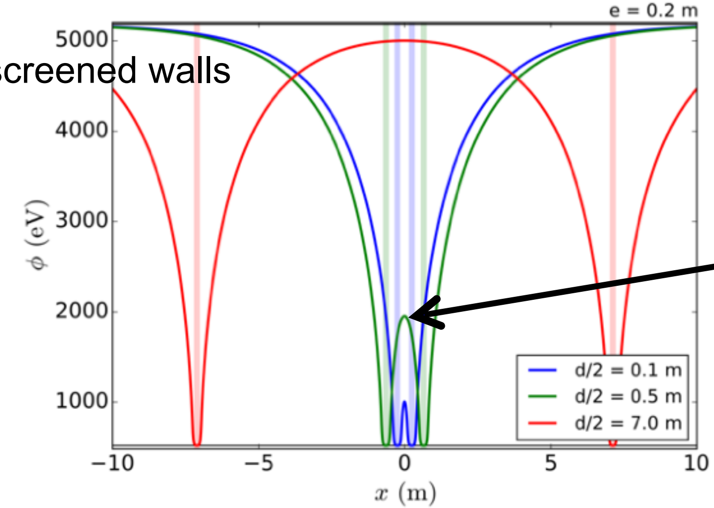
...but real life is tougher than theory (I)

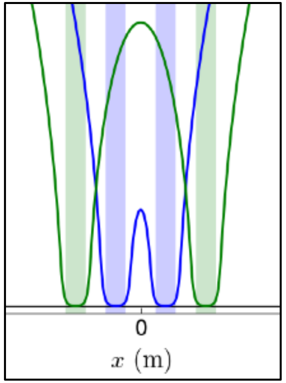


- Still some atmosphere @700km
- Test-masses are not in vacuum… but surrounded by a satellite and an experimental apparatus
- Need to know how the chameleon field propagates through the cylinders

  - Its dynamics follows $$\nabla^2\phi = V_{\mathrm{eff},\phi} = V_{,\phi} + \frac{\beta}{M_{\mathrm{Pl}}}\rho_{\mathrm{mat}}$$

If screened walls

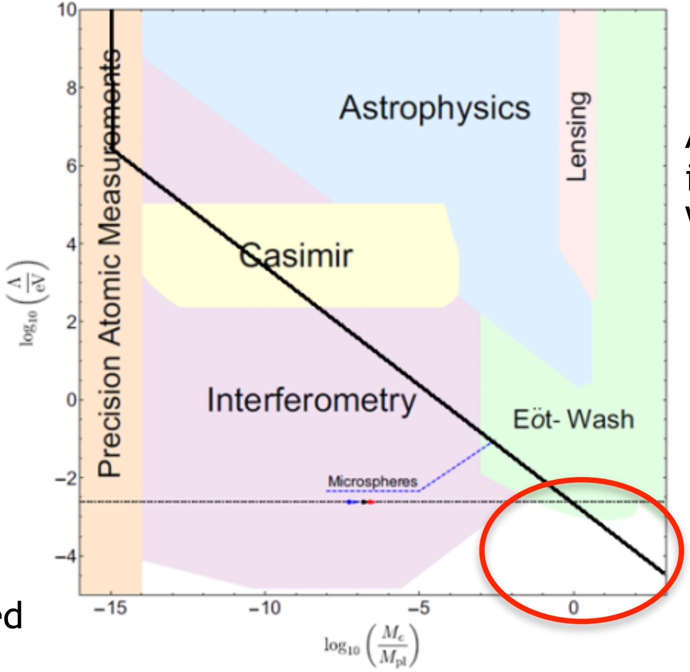




Pernot-Borras+ 2019, 2020, 2021

...but real life is tougher than theory (II)

Burrage & Sakstein 2018, LRR 21:1
Pernot-Borras+ 2019, 2020



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

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

Beyond MICROSCOPE

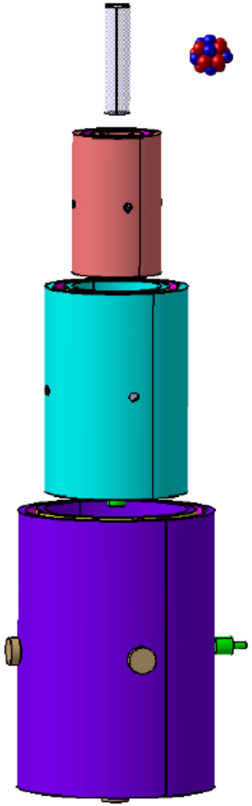
JB, L. Baudis, P. Brax, S.w. Chiow et al, 2021, Experimental Astronomy (Voyage 2050)
B. Battelier, JB, A. Bertoldi, L. Blanchet et al, 2021, Experimental Astronomy (Voyage 2050)

ESA and NASA long term planning

- Voyage 2050 (ESA)
  - call for white papers in 2019
    - 100ish white papers
    - Dark energy direct detection related
      - Measure gravity outside the Solar System (clock + tracking)
      - Test Equivalence Principle (STE-Quest, MICROSCOPE 2)
  - ESA recommendations spring 2021
    - Themes for L-missions: Moons of the Solar System, Exoplanets, Early Universe
    - Possibilities for fundamental physics with M-mission calls
    - Interest in cold atoms technology
      - Draft of roadmap by cold atoms community
      - Do we want and need a Pathfinder?
- NASA Biological and Physical Sciences (BPS) decadal survey
  - current call for white papers, deadline October 31st

MICROSCOPE 2: WEP at 10^{-17}

- **Number of test-masses: 3 concentric accelerometers**
  - 2 different materials: A B A => A-B ; B-A & A-A at the same time
    - A-B & B-A give a gain of √2 in noise
    - 2[A-B]-[A-A]-[B-A] could partially cancel systematics on the test of A and B
    - Only 2 materials tested => 1 EP test
  - 3 different materials: A B C => A-B; B-C & A-C at the same time
    - [A-B] + [B-C] – [A-C] should be null => test of performance
    - 3 materials => 3 EP tests
  - To be led by theoretical motivations



- **TM Charge management**

- **Cold atom as a 4th test-mass ?**

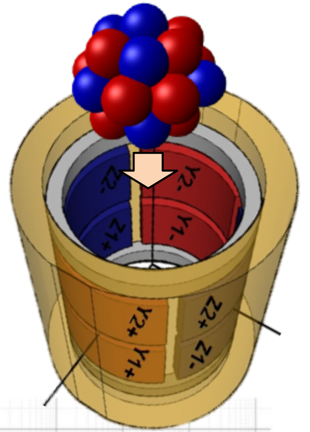
Cold atoms

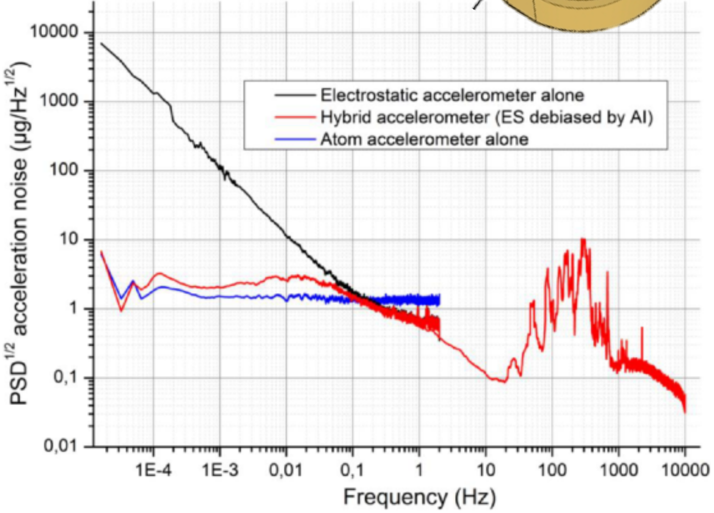
- **(-) The maturity and the complexity BUT**
- **(++) Allows to extend science & performance**
  - Calibration of bias
  - Calibration of absolute scale factor
  - Improve rejection of common modes
  - If 3D Cold atom ACC: even better
  - BEC conf ?
  - G measurable by combining electrostatic & atoms
  - Motion of 1 or more TM by electrostatic loops:

    -Gravitational signal on atoms (with 1 TM)

    -Gradient of Gravity tuning : could the cold atoms drop in a gravity potential?

    -Gradient of Gravity variations (1 or 2 TM): ~10^{-6} s^{-2}

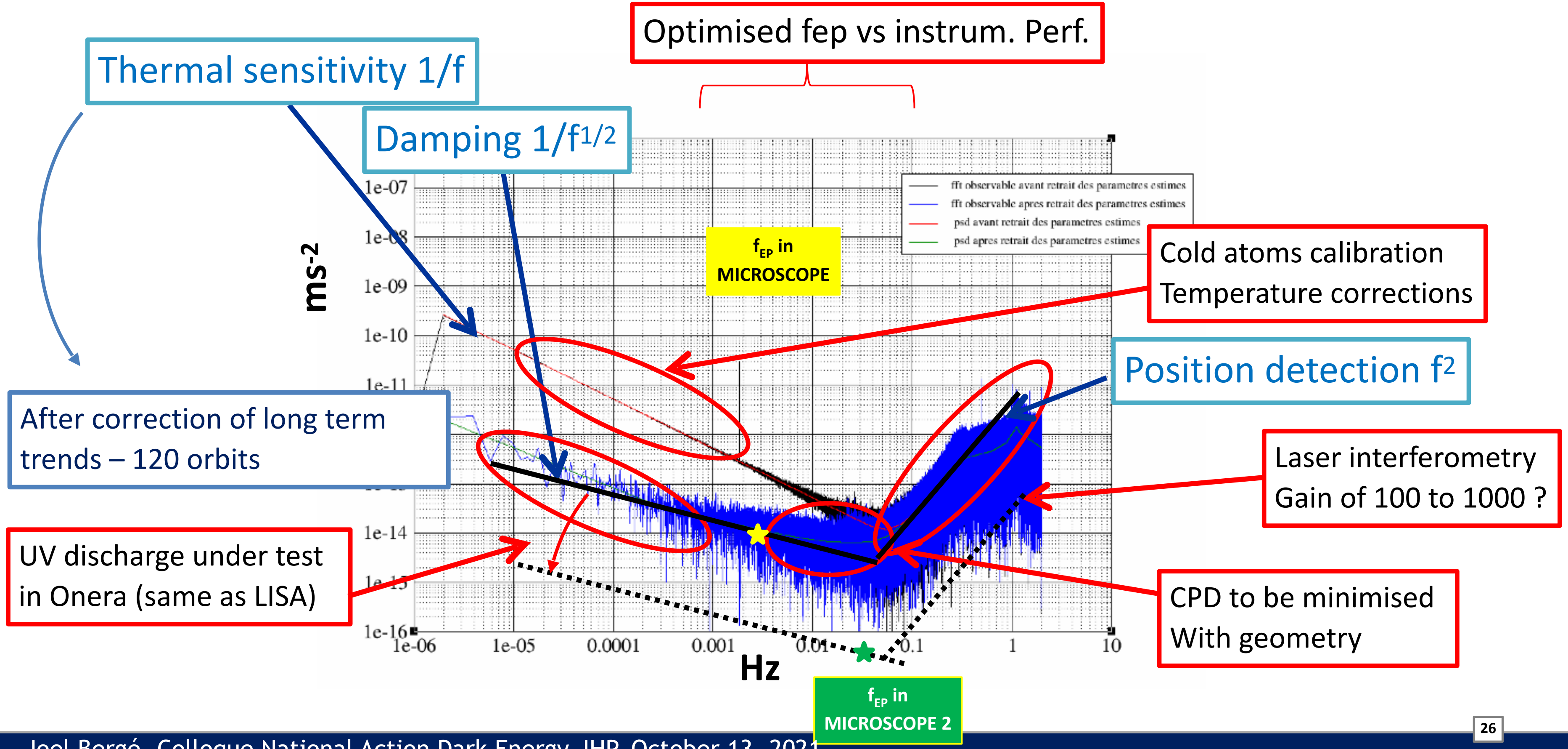




Hybridization of Macroscopic & atomic mass

- Test of EP between macroscopic mass and atomic mass
- Test of screening from TM with different sizes of the cold atom ball
- Improve TM position measurement & reduce the f^2 noise in the accelerometer loop : by using the laser source for interferometry (TBC)
- Absolute accelerometer [DC-0.1Hz]
- Take advantage of the most mature technologies in both areas (Electrostatic accelerometers & cold atoms) : MICROSCOPE, MAIUS, QUANTUS, LISA Pathfinder, GRACE

The noise from MICROSCOPE to MICROSCOPE 2



Conclusion

MICROSCOPE

- First results (2017): no WEP violation > 2×10^{-14}
- Constraints on long-range 5th force and modified gravity: Yukawa, dilaton, chameleon
- Constraints on short-range 5th force: Yukawa, chameleon (not competitive)
- Constraints on SME (Standard Model Extension) parameters: Lorentz invariance
- 10 times as much data now, a lot of work done to better constrain systematics
- Final results end of 2021 or early 2022

The future

- Mission concepts to test gravity in space (STE-Quest, FOCOS, GODDESS…)
- MICROSCOPE 2
  - WEP at 10^{-17}
  - Modified gravity: orbit around the Moon (no atmosphere, good for chameleon)?
  - Proven MICROSCOPE technology + cold atoms?
    - => cold atoms pathfinder (make ESA happy) + science returns