Testing the Equivalence Principle in space after the MICROSCOPE mission

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The WEP & its relevance to fundamental physics and cosmology

"Relevance of the weak equivalence principle and experiments to test it: lessons from the past and improvements expected in space"

Nobili & Anselmi, in the Special Issue in Memory of Vladimir Braginsky, PLA (2018)

The Weak Equivalence Principle (WEP)

In a gravitational field all bodies fall with the same acceleration regardless of their mass and composition.
Also known as the Universality of Free Fall (UFF), or the equivalence of inertial and gravitational mass

- It holds near the surface of Earth, where the gravitational field is almost uniform, and in the Universe at large where the field is not uniform:
  the gravitational motion of celestial bodies does not depend on how massive they are or what they are made of; Celestial Mechanics –paradigm of exact science– is evidence that all bodies fall with the same acceleration

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WEP and General Relativity

- *WEP is the foundation pillar of GR: gravity is a long-range interaction which couples in the same way to all forms of matter-energy*

  Dicke in 1964, after testing WEP for Au and Al analyzed the physical properties of the two atoms in great detail:

  ...“We would conclude that in most physical aspects gold and aluminum atoms differ substantially from each other and that the equality of their accelerations represents a very important condition to be satisfied by any theory of gravitation.”

- **Such universal coupling makes gravity different from all known forces of nature described by the Standard Model of particle physics, and can be tested to very high precision by WEP experiments**

WEP and Dark Matter

- *Basic to our understanding of the cosmos is the assumption that the required non luminous DM interacts with ordinary matter only by the gravitational interaction and there is no new long-range interaction*

  $\Rightarrow$ **this assumption should be tested by the most sensitive possible experiments**

- Candidate DM particles are typically new particles, not included in the Standard Model (SM), which would generate a long-range composition-dependent scalar interaction

  $\Rightarrow$ ***Do test bodies made of ordinary matter fall with the same acceleration toward DM in our galaxy?***

- **WEP experiments set limits which a new long-range interaction MUST obey**

  The best limit is set by torsion balances ($\simeq$ 70 times more sensitive than MICROSCOPE to differential accelerations): they rule out an interaction other than gravity between DM and ordinary matter to a few parts in 10^5

  Eöt-Wash/RTB: Wagner et al., CQG (2012); Stubbs, PRL (1993); Adelberger et al., PRD (1993))

WEP and Dark Energy

- *Evidence that the accelerated expansion of the Universe requires the existence of DE is so strong that ESA is building the* ***Euclid satellite*** *to establish the nature of DE*

- **A major objective of Euclid is to discriminate between DE as cosmological constant and dynamical DE. Most theories envisage dynamical DE as a new long-range scalar field** (in addition to the pure tensor long-range gravitational field)

- Unless the new field couples only to DM (in which case evidence can be found only at large scale) **its coupling to ordinary matter is subject to test by WEP experiments which can place limits or rule out its existence ⇒**

  – **need for time evolution, or screening mechanisms, for the new field to be reconciled with WEP tests**

  – **It has been stated WEP tests in orbit, unlike those on ground, would avoid screening! MICROSCOPE has most likely settled the issue already...**

"Cosmology and Fundamental Physics with the Euclid Satellite", Living Review 2016

WEP and the fine structure constant

- $\alpha = \frac{1}{4\pi\varepsilon_\circ}\frac{e^2}{\hbar c}$

  A time variation of α would imply the existence of a scalar particle which inevitably couples to nucleons, through the α dependence of their masses and therefore mediates a new composition-dependent long-range force

  $\Downarrow$

  WEP violation

- WEP experiments with torsion balances and improvements in space can test this effect at levels of interest (according to large scale observations, e.g. absorption lines in high redshift quasars)

Dvali & Zaldarriaga, PRL (2002)

High precision tests of the WEP can reveal a new, composition dependent, force of nature or disprove many models of new physics.

Rotating torsion balances may still improve
by one order of magnitude,
but big leaps can occur only in space

A WEP experiment in low Earth orbit

Strength of driving signal for WEP experiments
on ground and in Low Earth Orbit (in $m\,s^{-2}$)

	Earth's field		Sun's field	
	Ground	LEO	Ground	LEO
mass dropping (*Galileo – like tests*)	9.8 → (*factor 1.2 loss*)	$\simeq 8$	—	—
suspended masses (*regardless of the suspension type: mechanic, electrostatic, superconducting coils...*)	$\simeq 0.016$ → (*factor 500 gain!*)	$\simeq 8$	$\simeq 0.0057$ (*factor 2.8 loss* from Earth's field, LEO)	$\simeq 0.0057$

For experiments with suspended masses only (does not hold for mass dropping!):

- ***One major plus: driving signal from Earth*** $\simeq 500$ ***times stronger***

Three key advantages:

- **Test masses coupling to s/c: weightlessness makes coupling very weak & with low losses**
- **Local noise: the 'lab' (=dedicated spacecraft) is an isolated system in space:**
  – no 'terrain', no terrain tilts, no local microseismicity
- **Rotation: the whole 'lab' rotates (not possible on ground, motor & bearings needed):**
  – rotation totally 'passive' (by angular momentum conservation - GG): no motor, no bearings
  – controlled rotation (Microscope): thrusters & propellant but no bearings (because there is no stator in space, entire 'lab' spins with TMs..)

Tests of WEP: the milestones (as of Dec 2017)

Scientists	Instrument	Source body: Earth	Source body: Sun	Source body: Dark matter in our galaxy
Galileo	Individual pendulums	$\simeq 10^{-3}$		
Newton	Individual pendulums	$\simeq 10^{-3}$		
Bessel	Individual pendulums	$\simeq 10^{-5}$		
Eötvös	Non-rotating torsion balance	$\simeq 10^{-8}$		
Pisa&CERN	Mass dropping (bulk masses)	$\simeq 7 \cdot 10^{-10}$		
Lin Zhou et al.	Mass dropping (cold atoms)	$\simeq 10^{-8}$		
Dicke	Torsion balance (diurnal rotation relative to the Sun; “passive”, no motor, no bearings)		10^{-11}	
Braginsky	Torsion balance (diurnal rotation relative to the Sun; “passive”, no motor, no bearings)		10^{-12}	
Eöt-Wash	Slowly rotating torsion balance (with motor and bearings). Two composition dipoles	10^{-13}	a few 10^{-13}	a few 10^{-5}
J.G.W. S.G.T./Müller Murphy	Lunar laser ranging		$\simeq 10^{-13}$	
MICROSCOPE First test in low Earth orbit (preliminary results)	Electrostatic suspension and control & thin gold wire connection. Slow rotation (thrusters, but no stator & no bearings). Two sensors, one composition dipole		$\simeq 1.9 \times 10^{-14}$	

MICROSCOPE

First space test of the WEP successful!

MICROSCOPE preliminary result

Pt-Ti composition dipole (SUEP) - 120 orbits (8.26 d) integration time:

- WEP in the field of Earth tested to:

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

Maximum total error:

$$\eta_{\oplus |(-1+9+9)| \times 10^{-15}} = 1.9 \times 10^{-14}$$

– sun-synchronous polar orbit $h = 710\,\mathrm{km}$, $\nu_{orb} = 0.16818\,\mathrm{mHz}$ ($P_{orb} = 5946\,\mathrm{s}$)
– s/c spinning at $\nu_{spin} = 2.9432\,\mathrm{mHz}$ ($P_{spin} = 339.8\,\mathrm{s}$)

Spin rate 3.5 times faster than maximum planned!

$\Downarrow$

– WEP signal at $\nu_{EP} = \nu_{spin} + \nu_{orb} = 3.1113\,\mathrm{mHz}$ ($P_{EP} = 321.4\,\mathrm{s}$).

Touboul et al., PRL (2017)

– *Fourth dedicated fundamental physics science mission since the start of space age (after GP-A, GP-B, LAGEOSII-LARES)*
– *Most relevant scientific objective of all*
– *Successful.. achieved by a small group at comparatively low cost (high science return for money)*

... to be compared with best RTB tests of WEP

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Eöt-Wash Rotating Torsion Balance (RTB): $\nu_{EP-RTB} = \nu_{spin-RTB} = 0.84\,\mathrm{mHz}$

		Be–Ti	Be–Al
Δa_N	$(10^{-15}\ \mathrm{m\,s^{-2}})$	0.6 ± 3.1	-1.2 ± 2.2
Δa_W	$(10^{-15}\ \mathrm{m\,s^{-2}})$	-2.5 ± 3.5	0.2 ± 2.4
$\Delta a_\odot$	$(10^{-15}\ \mathrm{m\,s^{-2}})$	-1.8 ± 2.8	-3.1 ± 2.4
Δa_g	$(10^{-15}\ \mathrm{m\,s^{-2}})$	-2.1 ± 3.1	-1.2 ± 2.6
$\eta_\oplus$	(10^{-13})	0.3 ± 1.8	-0.7 ± 1.3
$\eta_\odot$	(10^{-13})	-3.1 ± 4.7	-5.2 ± 4.0
η_{DM}	(10^{-5})	-4.2 ± 6.2	-2.4 ± 5.2

Wagner et al., CQG (2012)

Sensitivity to differential accelerations at signal frequency:

- $\Delta a_{\oplus\,RTB} \simeq \eta_{\oplus-RTB}(\omega_\oplus^2 \cos\vartheta_{Seattle} \sin\vartheta_{Seattle}) \simeq 10^{-15}\,\mathrm{ms^{-2}}$
- $\Delta a_{\oplus\,Microscope} \simeq \eta_{\oplus-PtTi}\, g(h) \simeq 9 \times 10^{-15} \times 7.9\,\mathrm{ms^{-2}} \simeq 7.1 \times 10^{-14}\,\mathrm{ms^{-2}}$

– Microscope has improved the WEP test in the field of Earth by almost 10 times, despite 70 times worse sensitivity to differential accelerations, thanks to much stronger driving signal from Earth in orbit at low h:

$$\frac{\Delta a_{\oplus\,Microscope}}{\Delta a_{\oplus\,RTB}} \simeq 71$$

More composition dipoles & more attractors needed

To avoid accidental cancellation of violation:

- test more than one composition dipole (Be-Ti, Be-Al)
- test more than one attractor (Earth, Sun, Dark Matter at center of our galaxy)
- test composition dipoles towards DM especially important

Wagner et al., CQG (2012)

		Be–Ti	Be–Al
Δa_N	$(10^{-15}$ m s$^{-2})$	0.6 ± 3.1	-1.2 ± 2.2
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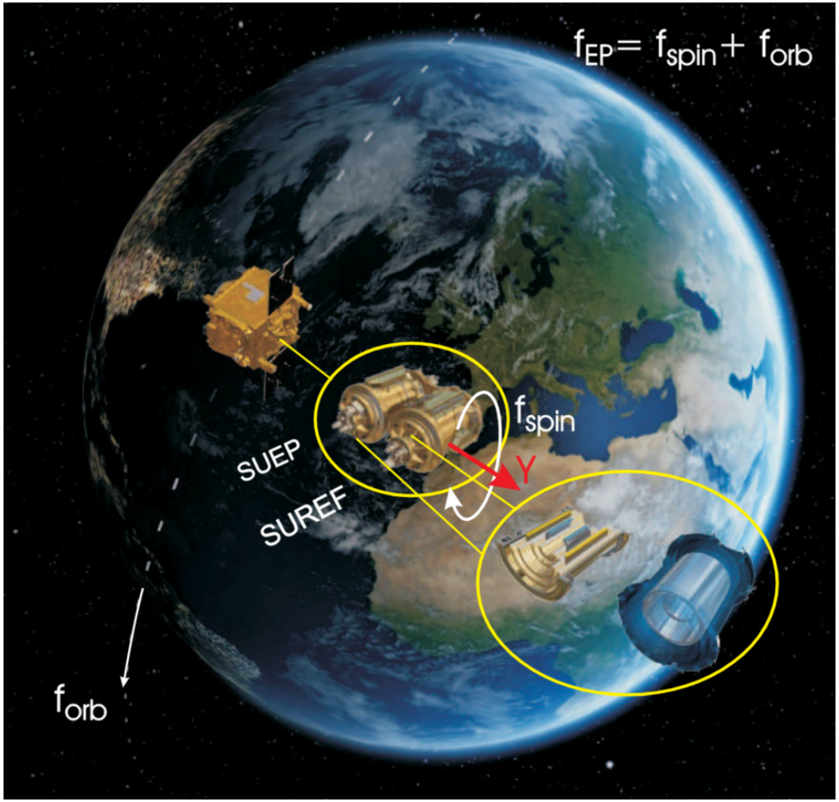
$\eta_\odot$	(10^{-13})	-3.1 ± 4.7	-5.2 ± 4.0
η_{DM}	(10^{-5})	-4.2 ± 6.2	-2.4 ± 5.2

– Only the driving signal from Earth is much stronger in orbit than on TB!!
– To gain in WEP tests towards DM and the Sun a sensitivity to differential accelerations better than torsion balances is needed!!! Microscope cannot improve because 70 times less sensitive than RTB...

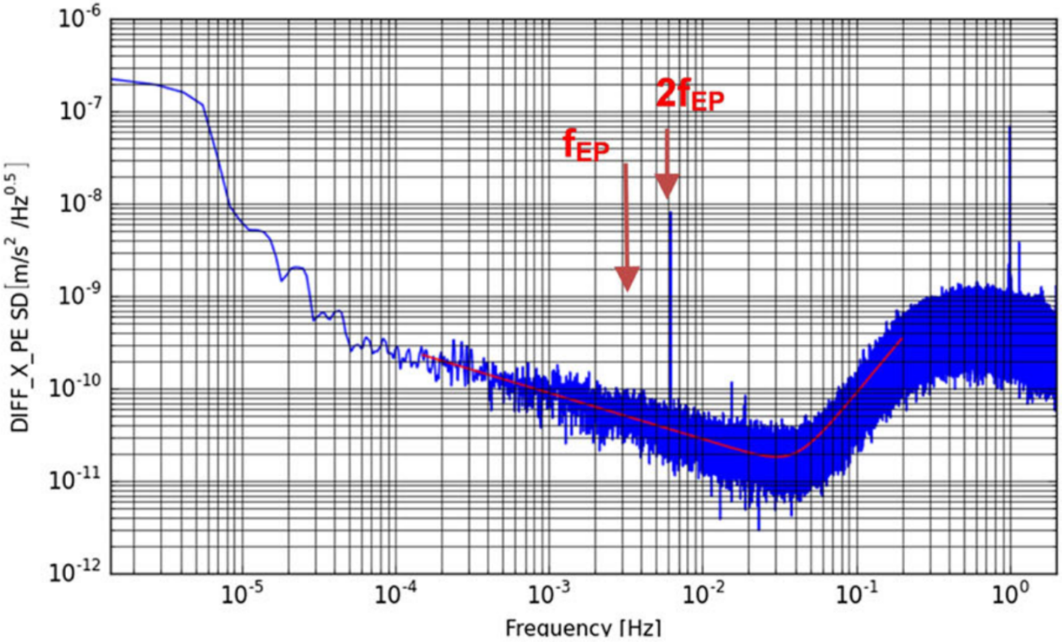
Spacecraft rotation relative to inertial space



– **Rotation up-converts frequency of violation signal (as well as drag) to:** $\nu_{EP} = \nu_{orb} + \nu_{spin}$

Pt-Ti composition dipole: SD

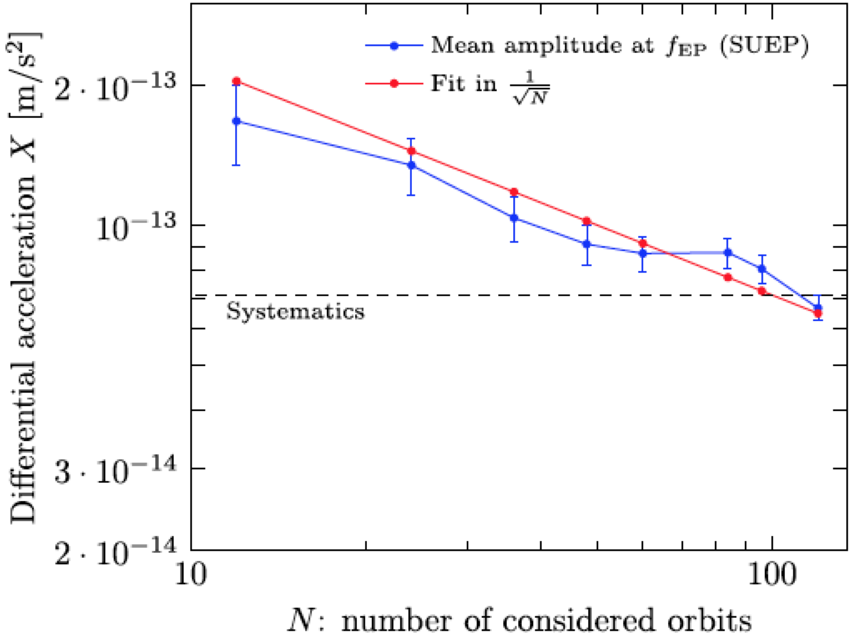
– Integration time: 120 orbits (8.26 d)



$$\hat{\Delta a}_{\nu_{EP}} \simeq 5.6 \times 10^{-11} \frac{\mathrm{ms}^{-2}}{\sqrt{\mathrm{Hz}}}$$

Touboul et al., PRL (2017)

Is residual noise random?



Touboul et al., PRL (2017)

– **YES!**

– 1882 **more science orbits expected** $\Rightarrow \quad \eta_{\oplus final} = \frac{\eta_{\oplus 120 orbits}}{\sqrt{1882/120}} \simeq \frac{1.9 \times 10^{-14}}{3.96} \simeq 4.8 \times 10^{-15}$

–.. **but only** 1 **measurement to this level ... how to check systematics if present?**

What is random noise limited by?

Expectations and real measurements...

The plan before launch:

– "*The adopted trade-off remains on **different sessions of 120 orbital periods. This is long enough to obtain the Eötvös parameter target exactitude of** 10^{-15} **in inertial mode and even better in rotating mode**, by reducing the stochastic error with respect to the systematic evaluated one. This is also short enough to have time for many sessions with different experimental conditions.*"

Touboul et al., CQG (2012)

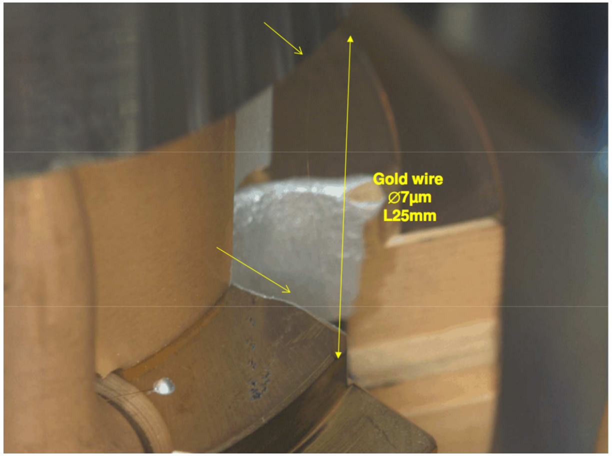
According to the mission PI random noise at the (low) frequency of the signal is dominated by losses in the gold wire connecting each test cylinder to its cage $\Rightarrow \hat{a} \propto 1/\sqrt{Q\nu}$, and the measured Q leads to the choice of measurement sessions lasting 120 orbits

Touboul, Space Sci. Rev. (1999), Willemenot and Touboul, RSI (2000)

But once in orbit ...

– at zero spin ("inertial mode") random noise turned out to be higher than expected, and could be reduced only by increasing the rotation speed to several times more than the maximum value planned before launch!

Thermal noise from internal damping



$$\hat{a}_{thID} = \frac{1}{\mathcal{M}}\sqrt{\frac{4K_BTk_w}{Q_w\omega_{EP}}}$$

– One gold wire for each test cylinder for electric grounding
– Low Q at low rotation/signal frequency, plus fabrication and clamping issues...

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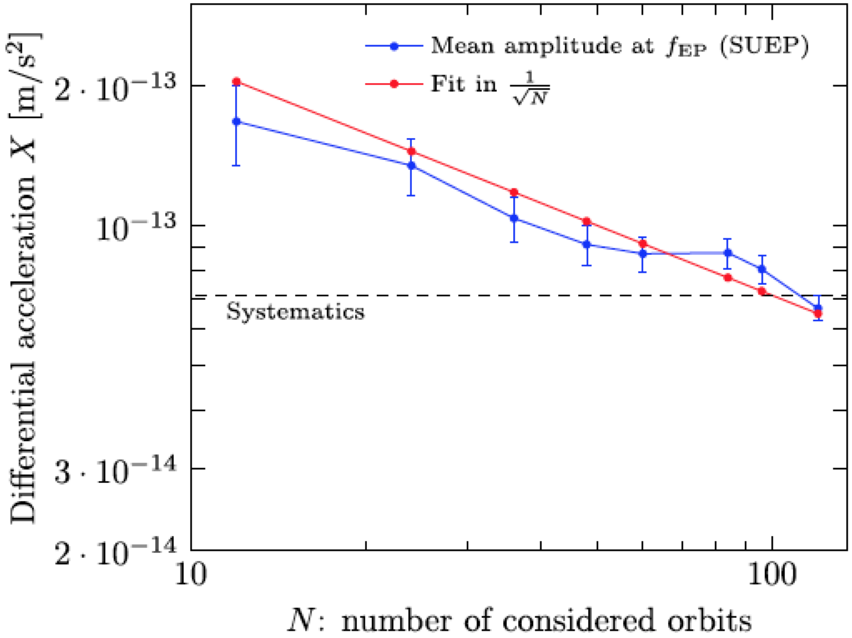
On the spot cure:
increase the frequency of the signal by spinning faster!

– **MICROSCOPE has saved the mission science by increasing the rotation rate to several times more then the maximum planned, thus established rotation as a very effective way of up-converting the signal to higher frequency and achieving low noise!**

– **... and it has worked very well despite the original concerns (since Microscope does not rotate around the symmetry axis of the test cylinders, which is the only stable one)**
WHY?
... because as long as the whole s/c rotates relative to inertial space there are no stator & no bearings (possible only in orbit!) $\rightarrow$ **far less noisy than any rotating experiment on ground!!!**

Systematic errors

Systematic errors in Pt-Ti sensor (SUEP)



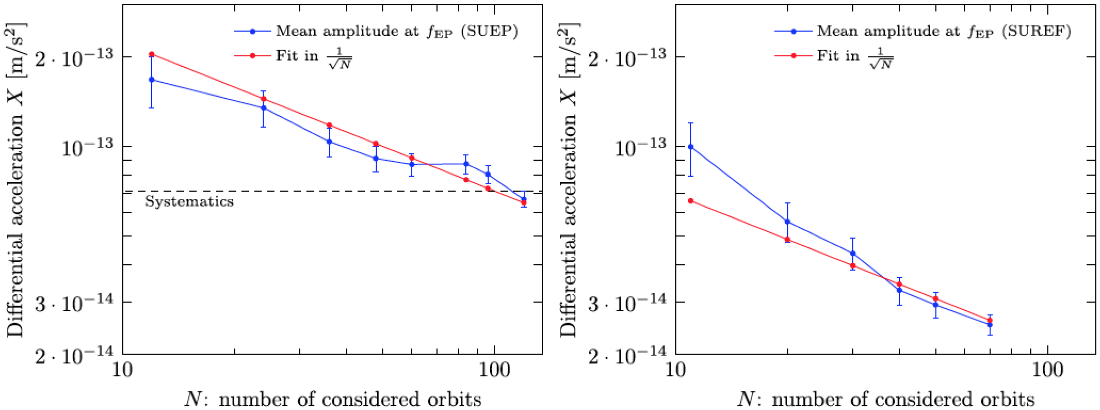
Touboul et al., PRL (2017)

– **Upper limit $\lesssim 7 \times 10^{-14}\,\mathrm{ms}^{-2}$ established experimentally assuming (reasonably..) that they are mostly of thermal origin ...**

– **Includes thermal disturbances (at signal frequency) due to thermal stresses caused by cracks in the mylar blankets (were known to be a concern when GOCE was built, and care was taken in thermal insulation which prevented their occurrence...)**

– **Thermal response and thermal stability of test cylinders not clear...**

Pt-Ti (SUEP) versus Pt-Pt (SUREF) systematic errors



Touboul et al., PRL (2017)

– **Systematics do not disappear or decrease by taking more data!**

– The Pt-Pt (SUREF) sensor is less noisy, enough to detect systematics at the level evaluated for SUEP, **but they do not appear**. WHY???

– **Why is this question very important? Because only a WEP violation signal should be detected in SUEP and not in SUREF...**

Pt-Ti (SUEP) versus Pt-Pt (SUREF) systematic errors
What does physics predict? (I)

– Most non gravitational acceleration disturbances depend on the area-to-mass ratio of the body

Milani, Nobili & Farinella, Adam Hilger Ltd. (1987)

– With MICROSCOPE test cylinders engineering design data:

$$\frac{\Delta a_{ng\mathcal{A}/\mathcal{M}-SUEP}}{\Delta a_{ng\mathcal{A}/\mathcal{M}-SUREF}} = \frac{(\mathcal{A}/\mathcal{M})_{innerSUEP}}{(\mathcal{A}/\mathcal{M})_{innerSUREF}} \cdot \frac{(\mathcal{A}/\mathcal{M})_{outerSUEP}/(\mathcal{A}/\mathcal{M})_{innerSUEP} - 1}{(\mathcal{A}/\mathcal{M})_{outerSUREF}/(\mathcal{A}/\mathcal{M})_{innerSUREF} - 1} \simeq 3.3$$

– The Pt-Pt "reference" ("zero-check") sensor is about 3.3 times less sensitive than the Pt-Ti Equivalence Principle test sensor to a large class of systematic errors $\rightarrow$ should these systematics appear in the EP sensor, it would not be able to rule them out as a source of violation!!!

Nobili & Anselmi, PRD (2018)

Pt-Ti (SUEP) versus Pt-Pt (SUREF) systematic errors What does physics predict? (II)

In addition....

– The Pt-Pt "reference" ("zero-check") SUREF sensor is insensitive to radiometer differential effect (a known "killer" for WEP experiments with 1-axis sensitivity...)

Nobili et al., PRD (2001); New Astronomy (2002)

Confirmed with engineering design data for the test cylinders flown in MICROSCOPE:

$$\frac{a_{rad-outerSUREF}}{a_{rad-innerSUREF}} = \frac{(\mathcal{A}/\mathcal{M})_{outerSUREF} \cdot L_{outer}}{(\mathcal{A}/\mathcal{M})_{innerSUREF} \cdot L_{inner}} = 1.009$$

while SUEP is sensitive to it:

$$\frac{a_{rad-outerSUREF}}{a_{rad-innerSUEP}} = \frac{(\mathcal{A}/\mathcal{M})_{outerSUEP} \cdot L_{outer}}{(\mathcal{A}/\mathcal{M})_{innerSUREF} \cdot L_{inner}} = 4.562$$

Nobili & Anselmi, PRD (2018)

The Pt-Pt second "zero-check" sensor severely questioned

– Should an effect emerge in the Pt-Ti SUEP sensor by the end of the mission with more data, the Pt-Pt "Reference" or "zero-check" will not be able to tell whether it is a systematic error or a violation signal (new physics!!!)

– **A second sensor should rather be a second composition dipole!**

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How to check systematics?

– Torsion balance tests of WEP never use a zero-check equal composition sensor, but rely on checking systematics with more measurements at the same level of sensitivity and in different experimental conditions! $\Rightarrow$ low thermal noise & short integration time needed

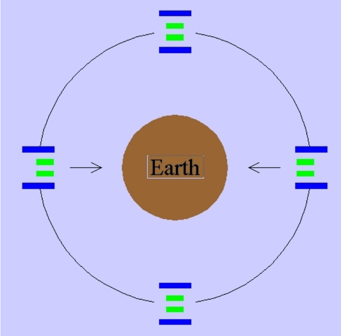
– If MICROSCOPE will use all the remaining integration time to reduce random noise, will have only one measurement: should an effect emerge, how to tell if it is violation or not? ... no time left...

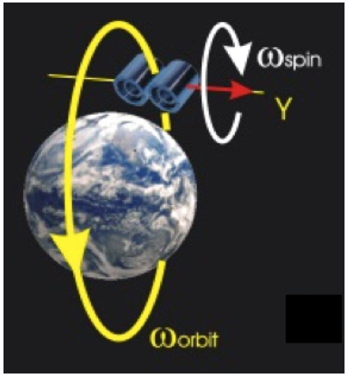
What next?

Lessons to learn from MICROSCOPE

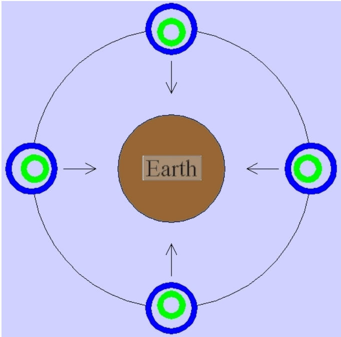
1st: spin around symmetry axis...

Microscope: 10^{-15} ***target***





Galileo Galilei–GG: 10^{-17} ***target***



...and enjoy the advantages of rapid rotation!

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– **Passive stable rotation at $\nu_{spin} = 1\,\mathrm{Hz}$, maintained by angular momentum conservation (no stator, no bearings and also no propellant) up-converts the signal to $\nu_{WEP} \simeq 1\,\mathrm{Hz}$, 3 orders of magnitude higher than torsion balances and MICROSCOPE**

–**At $1\,\mathrm{Hz}$ where thermal noise is much lower and Q much higher $\Rightarrow$ GG can reach a WEP test to 10^{-17} with SNR=2 in about 3 hours and plans 1 full measurement to 10^{-17} per day, with plenty of time left to check systematics**

Pegna et al., PRL (2011);, Nobili et al., PRD (2014)

You gain much more by spinning faster (higher ν, higher Q) than by cooling down (lower T)!

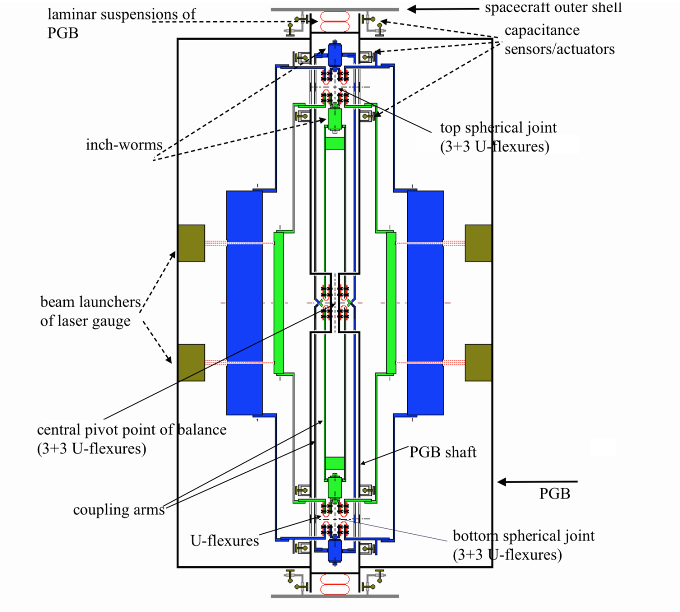
$$\hat{a}_{th} \propto \sqrt{\frac{T}{Q\nu}}$$

.. and it has been shown to work by Microscope itself... while cryogenic torsion balances have been demonstrated not to be competitive

– **With signal at $1\,\mathrm{Hz}$ laser gauge with $\frac{1\,\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ noise well feasible and "easy" can replace capacitance sensors very effectively, as proposed by Mike Shao (JPL) for GG (larger gaps, reduced gas damping noise, reduced electric patch effects...)**.. and it is clear from LPF and Grace-FO that in absence of weight it works even better than on ground..

Pisani, Mana & Nobili (2015); Pisani, Zucco & Nobili, (2016)

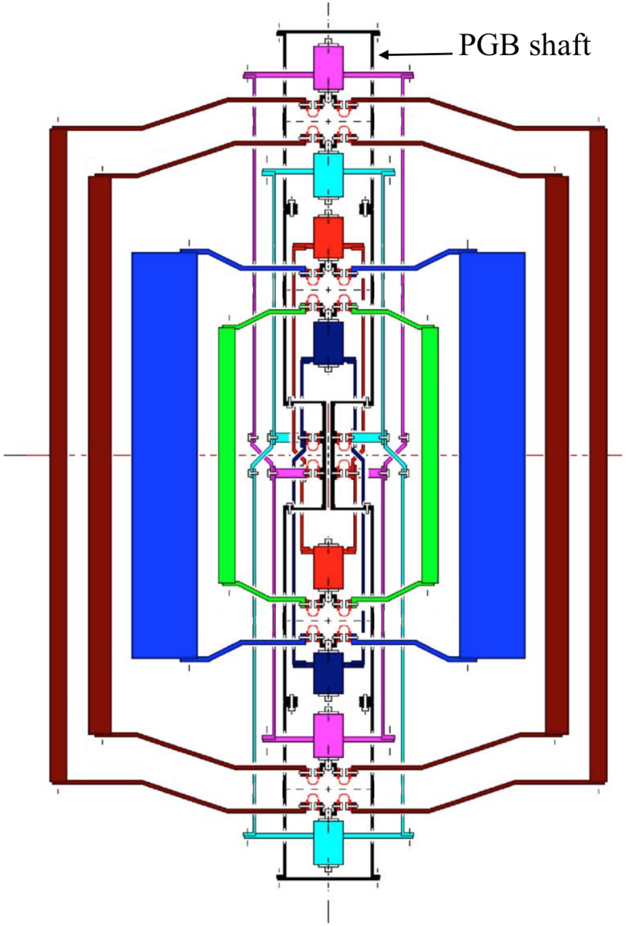
2nd: Mechanical suspensions are the solution, not the problem!



– suspensions can be predicted analytically, and simulated numerically; k and Q can be measured in the lab for the expected conditions of operation.. there is nothing misterious about using them in space (in fact, weightlessness is an advantage!)
– most precise gravitational experiments all use mechanical suspensions (RTB, GW detectors..)
– you don't need to fly a flexure to know how it will work in orbit!!!!

Click to view GG balance animation

3rd: Fly a second concentric composition dipole



MICROSCOPE has demonstrated that a small space experiment with weakly suspended test masses can "easily" test the WEP to very high precision, and has already taught us many important lessons

Whatever step will be taken after MICROSCOPE, it should not ignore these facts of physics...

keep publishing till some space agency will listen...

.. the scientific reward of a possible violation would be enormous

.. a null result will kill many theories and narrow the avenue towards new physics