High precision tests of the Weak Equivalence Principle in space coming to reality: Microscope's preliminary results reported. GG shortlisted in the ESA competition for M5 mission.

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WEP experiments: unique composition-dependent tests to probe the foundations of physics

- *Gravity couples in the same way to all forms of mass-energy, in all bodies, regardless of composition: Universality of Free Fall/WEP is the founding pillar of General Relativity*

  - Such universal coupling makes gravity different from all known forces of nature described by the Standard Model of particle physics, and is at the heart of the fact that the two theories have so far resisted all attempts at reconciliation into a single unified picture of the physical world.

  - This is the crossroad physics faces at the present time: 95% of the matter-energy in the Universe is unknown ("dark matter", "dark energy")

- Tests of WEP to very high precision can potentially break this deadlock.
  Experimental evidence of **WEP violation** $\Rightarrow$ **either** GR must be amended **or** a new composition dependent force of nature is at play!
- Tests of WEP can reach very high precision because are **null experiments**, among the most precise in physics *..many orders of magnitude more sensitive than tests based on absolute measurements*
  (No precise target from theories; the more sensitive the test, the deeper the probe, the better the chances to find new physics...)

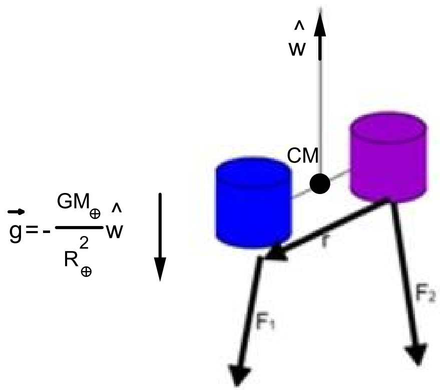
The authors of the first gravitational wave detecttion GW150914 by LIGO interferometer write:

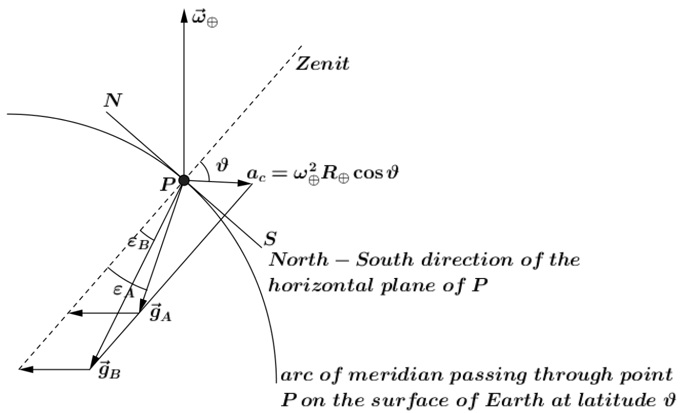
- *"The constraints provided by GW150914 on deviations from GR are unprecedented due to the nature of the source, but they do not reach high precision ... a much higher SNR and longer signals are necessary for more stringent tests."*

- Calibration uncertainties are at the 10 % level and affect directly the reconstructed strain signal.
- The second and third detections GW151226, GW170104 have signal-to-noise ration lower than GW150914

Status of WEP tests: lessons from the experiments

How the torsion balance defeated pendulums & mass dropping experiments





- TB is extremely sensitive (low torsional stiffness, low dissipation) & is intrinsically differential (unlike individual pendulums)
- TB is sensitive only to forces on the test masses **not parallel** to each other (as in case of WEP violation)

$$T_w = \frac{\vec{r} \cdot \vec{F}_1 \times \vec{F}_2}{|\vec{F}_1 + \vec{F}_2|}$$

$\Rightarrow$ can reach relative precisions in the measurement of WEP violating torques much better than its manufacturing tolerances (high rejection of common mode effects)
This property holds on ground, but is lost in space (because of absence of weight)!

- TB test of WEP does not depend on initial conditions and initial condition errors (unlike mass dropping tests in the presence of Earth's gravity gradient)

The milestones (see Table next slide)

- **End of 19th century. First TB tests of WEP in the field of Earth:** Eötvös improves pendulum tests by more than 3 orders of magnitude to 10^{-8} and better... But signal is DC.. checks require manual inversion..

- **1960s - early 1970s. First evidence that up-conversion of signal frequency by rotation is crucial:** Dicke and Braginsky take the Sun as source body and exploit diurnal (passive) Earth rotation to up-convert violation signal from Sun to diurnal frequency reaching 10^{-11} and 10^{-12} in the field of the Sun.

- **End of 20th century - 21st century. First use of rotating TBs to test WEP in the field of Earth and the Sun**. Eöt-Wash improves the old Eötvös results in the field of Earth by almost 5 orders of magnitude (to 10^{-13}) and by almost 1 order of magnitude in the field of the Sun (to a few 10^{-13}).

Lunar Laser Ranging tests of EP for Earth and the Moon in the field of the Sun are at 10^{-13}

Mass dropping tests with bulk masses are more than 3 orders of magnitude behind (at about $7 \cdot 10^{-10}$) despite a driving signal from Earth 600 times stronger than on a torsion balance!

(Mass dropping tests with cold atoms are at 10^{-8})

Tests of UFF/WEP: the milestones

Scientists	Instrument	Source body: Earth	Source body: Sun
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	Rotating torsion balance (with motor and bearings)	10^{-13}	a few 10^{-13}
Williams/Müller Murphy	Lunar laser ranging		$\simeq 10^{-13}$

The next big leaps shall occur in space

The role of space

- *One major plus for experiments with suspended masses: driving signal* $\simeq$ 500 times stronger

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 $\xrightarrow{\textit{factor 1.2 loss}}$	$\simeq 8$	——	——
suspended masses (*regardless of the suspension type : mechanic, electrostatic, superconducting coils...*)	$\simeq 0.016 \longrightarrow$ *factor 500 gain!*	$\simeq 8$ *factor 2.8 loss* $\longrightarrow$	$\simeq 0.0057$	$\simeq 0.0057$

Two key advantages:

- **weightlessness: very weak & low dissipation suspensions can be used, even for large masses**
- **lab (dedicated spacecraft) is an isolated system in space:**
  - no local microseismicity and terrain tilts;
  - rotation can be totally passive (GG - angular momentum conservation): no motor, no bearings; even if rotation is active (Microscope - thrusters): no bearings because there is no stator in space, entire "lab" spins with TMs..

One serious issue to deal with: non gravitational forces on spacecraft outer shell (common mode on TMs)

- **effect of drag many orders of magnitude bigger than signal and competing with it: compensation (by drag free control of spacecraft) & rejection (by TMs: a balance rejects common mode effects) both needed to reach very high precision**

Lessons from ground experiments
&
from space physics

Four key lessons for a high precision test of WEP in low Earth orbit

Lesson 1 Make the test cylinders "nominally" concentric to reduce Earth tidal effects (or gravity gradients: the component proportional to orbital eccentricity competes directly with violation signal)

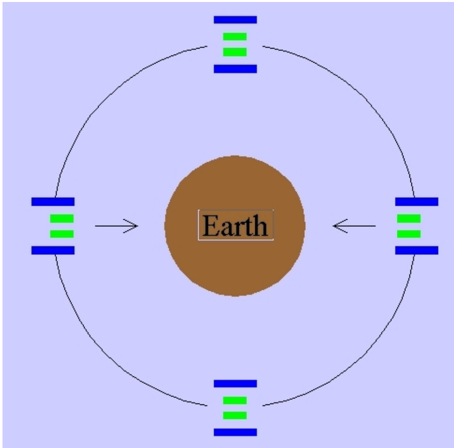
Lesson 2 Spin the spacecraft (the faster, the better) to up-covert the violation signal to higher frequency where noise is lower (also thermal noise..): best of all "passive" rotation (no motor, no bearings: conservation of angular momentum) which also yields spacecraft stabilization..

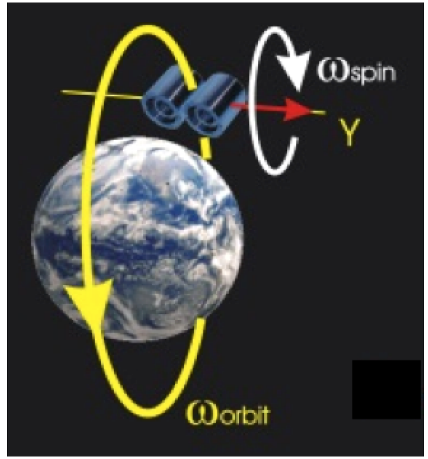
Lesson 3 Arrange the test cylinders as a balance which can work in absence of weight: non gravitational effect of drag partially compensated by drag-free control (propellant & thrusters) & partially rejected by balancing the balance
(Drag free control alone leaves a residual acceleration too large for a test to very high sensitivity)

Lesson 4 Use a readout with very low noise at the signal frequency to avoid it imposing limitations on integration time (experiment duration in space is an issue, integration time grows quadratically with target sensitivity....)

Preliminary results
from Microscope orbiting experiment

Microscope in orbit since April 2016 to test WEP to 10^{-15}





- Two test cylinders concentric by construction; two pairs of test cylinders (one with equal composition)
- Each test cylinder sensitive along symmetry axis:
  rotation must occur around a non-symmetry axis, which is unstable to small perturbations ("active" slow rotation: requires thrusters and propellant, but no bearings)
- Each test cylinder suspended individually (electrostatic suspension):
  no balance; entire drag effect MUST be compensated by drag-free control to make it smaller than target signal
- Capacitive control & readout - ok for current 10^{-15} target

Microscope in orbit: state of the art

- Launched 25 April 2016

- Minor problems
- Equal composition accelerometer reaches sensitivity not too far from target!
- Rotation rate increased because found to be crucial to reach the target
- Thermal stability better than required, possibly thanks to faster rotation (relevant for radiometer effect)
- Orbital eccentricity smaller than target (good for tidal effect at orbital frequency)

The lesson from Microscope

Successful! Not an easy experiment ....

- Despite higher propellant consumption & shorter mission duration, scientists have come to the conclusion that:

“balance is in favour of spinning faster”

Faster rotation rate crucial to reach target
($3.1 \cdot 10^{-3}$ Hz: about 4 times faster than maximum planned)

Non rotating mode (original baseline mode) abandoned

Rotation noise in space lower than than on ground: even if you need thrusters and propellant to control it, there is no stator no bearings

Rotation is a key feature for WEP experiments: the faster the better....

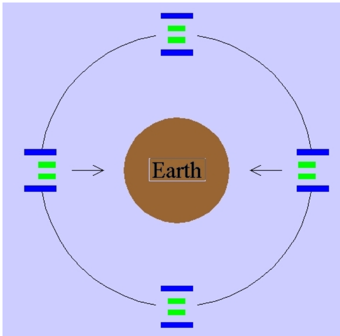
GG test of WEP in space to 10^{-17}: just follow all four lessons

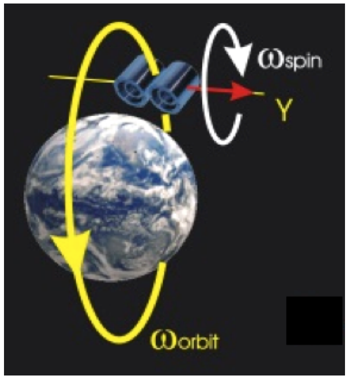
GG currently in the M5 competition of ESA

- **April 2016**: ESA Call for medium size mission M5 opened
- **October 2016**: Closing date of M5 Call
- **June 2017**: Results of technical & programmatic review of submitted proposals officially announced. GG shortlisted for further evaluation
- **November 2017** Scientific evaluation process of shortlisted proposals to be completed

Spin around symmetry axis (Lessons 1 & 2)

Microscope



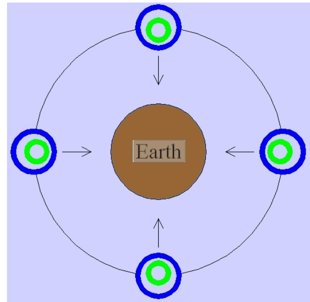


GG

2D sensitivity (in the plane ⊥ to symmetry axis)

Rotation around symmetry axis is stable!

Fast (1 Hz) rotation provides passive s/c stabilization; maintained by **conservation of angular momentum** (after initial setup: no thrusters & no propellant needed)

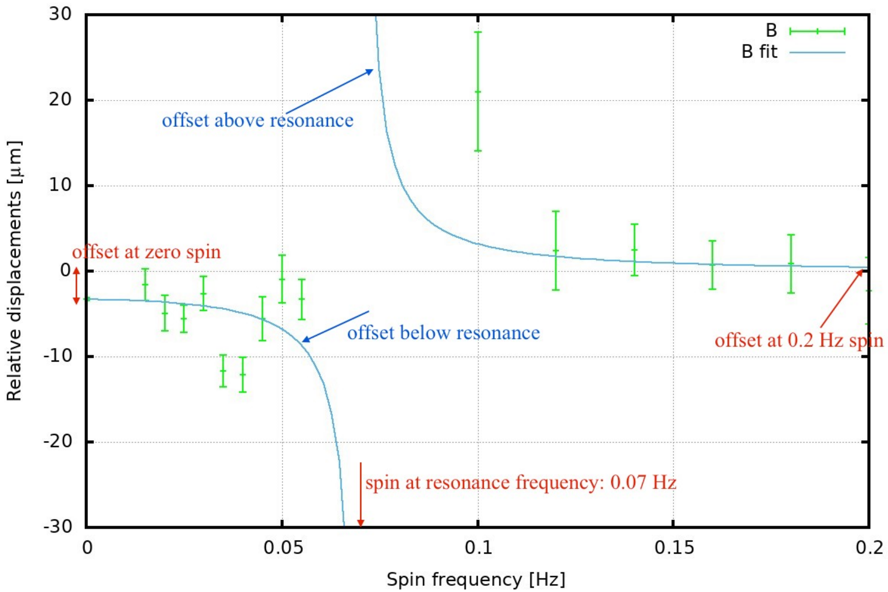


How physics allows rapid rotation in 2D: self-centering

With spin frequency higher than normal mode frequency ($\omega_{spin} > \omega_n$, super-critical rotation) & 2D: the offset error by construction $\vec{\varepsilon}$ is reduced by physics as $\omega_n^2/\omega_{spin}^2$ (self-centering):

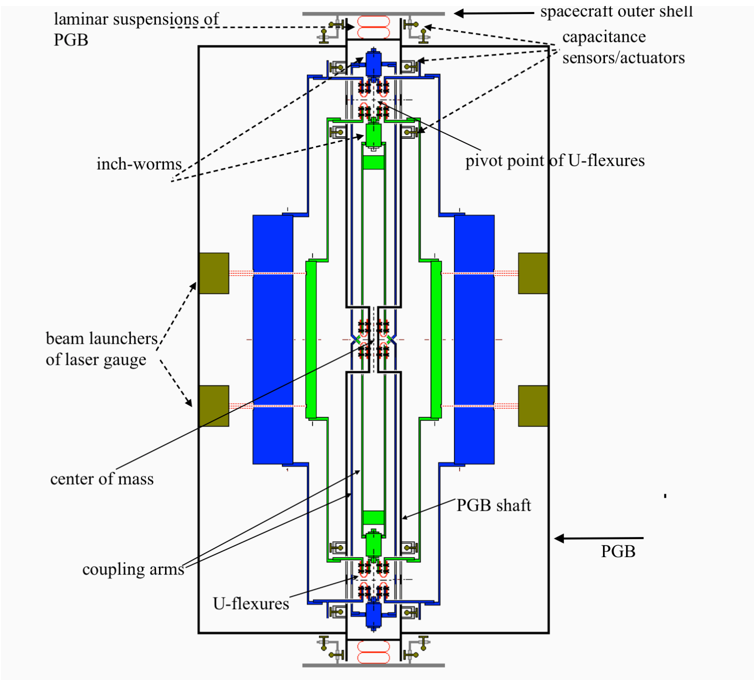
$$\vec{r}(t) \simeq -\varepsilon\left(\frac{\omega_n^2}{\omega_{spin}^2-\omega_n^2}\right)\begin{pmatrix}\cos(\omega_{spin}t+\varphi)\\ \sin(\omega_{spin}t+\varphi)\end{pmatrix} \simeq -\varepsilon\left(\frac{\omega_n^2}{\omega_{spin}^2}\right)\begin{pmatrix}\cos(\omega_{spin}t+\varphi)\\ \sin(\omega_{spin}t+\varphi)\end{pmatrix}$$

Demonstrated by GGG prototype in the lab: test cylinders spinning above the resonance are better centered on one another than they were by construction!

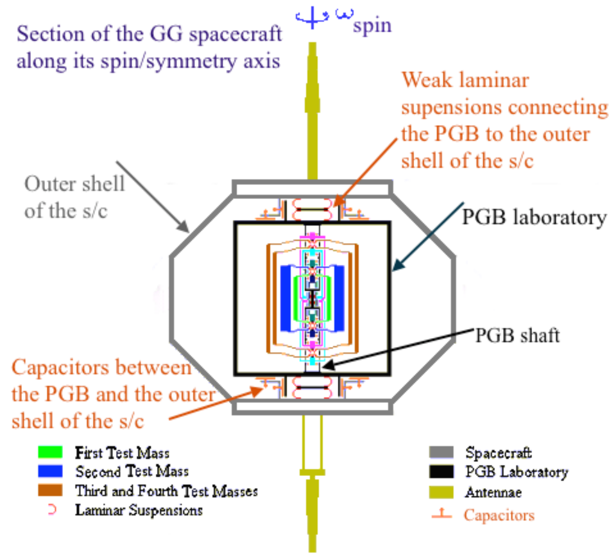


Offset between GGG test cylinders as the spin frequency increases from below the resonance, through the resonance and above the resoance: self-centering above the resonance is apparent. Experimental data agree with theoretical prediction

Fly a balance, not individual cylinders (Lesson 3)

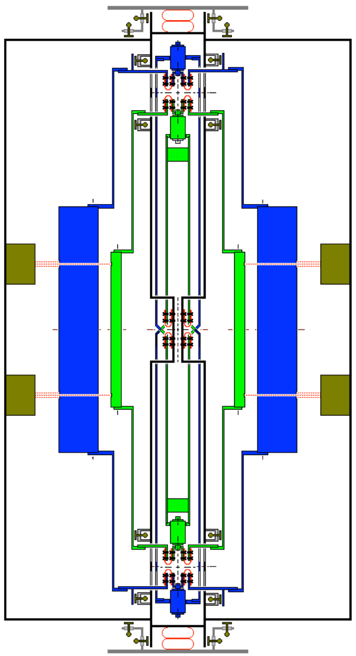


(Click for balance animation online)



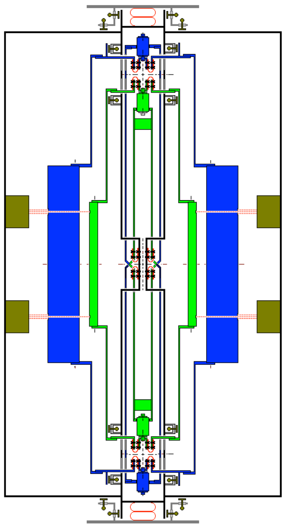
Two pairs of concentric cylinders
External pair with equal composition for checking
Both pairs centered on center of mass!
(gravity gradients issue: s/c has only 1 center of mass!)

Balancing the balance in orbit in order to reject common mode effects (the largest and most dangerous is due to drag/solar radiation pressure)



- Effect of drag many orders of magnitude bigger than target signal but also many orders of magnitude smaller than 1-g: balancing the balance against drag much easier than balancing a balance on ground against 1-g
- PZT actuators (inch-worms) very effective in adjusting the balance arms until the spurious differential effect of drag is minimized
- Precision measurements made possible by balancing (much better than construction tolerances!!!)

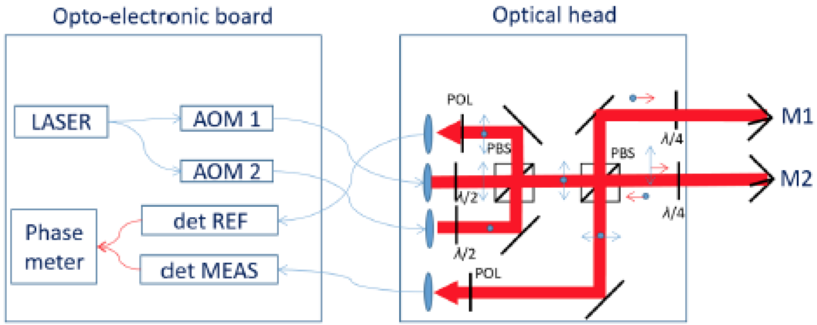
A laser gauge: the ideal readout to replace capacitive sensors (Lesson 4)

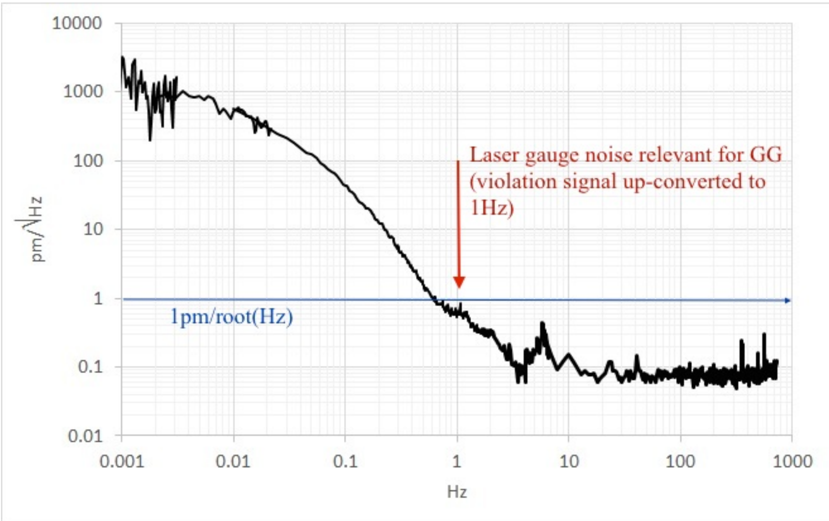


Heterodyne laser interferometer to read relative displacements of test cylinders & recover violation signal

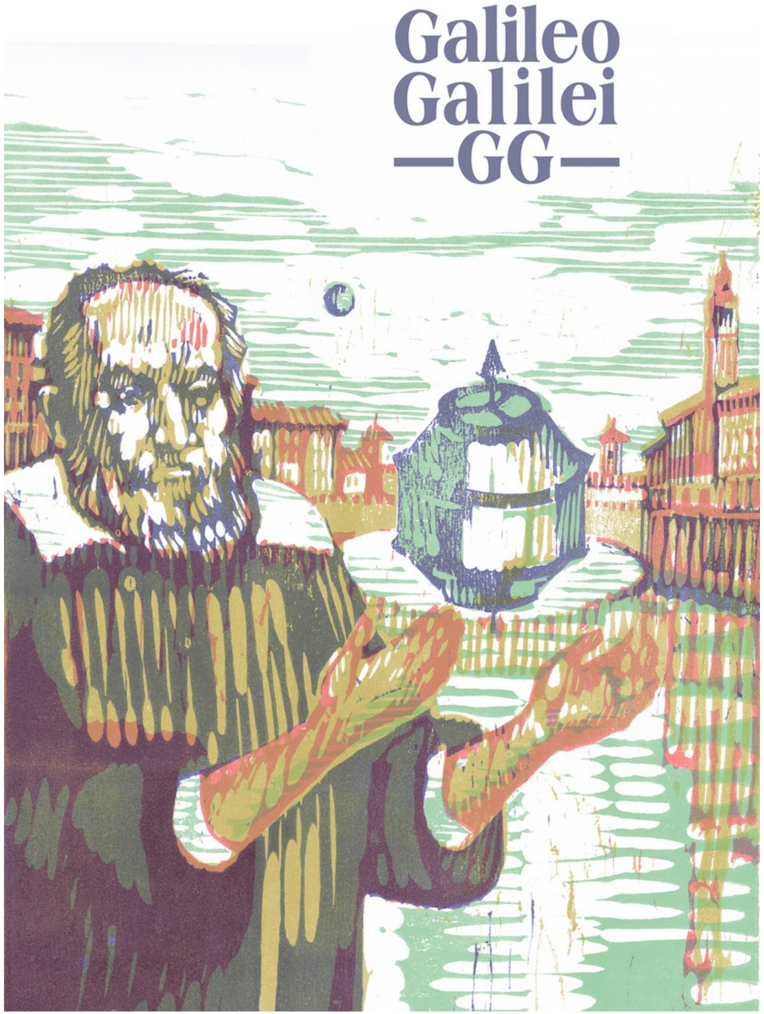
- Inherently differential measurement
- No calibration needed (displacement given in terms of laser wavelength)
- No limitation from size of gap between cylinders
  (gas damping noise relevant if gap is small: $C \propto \frac{1}{d}$)
- Very low noise
- No laser frequency stabilization needed in GG, interferometer far less demanding than the one flown on LISA-PF
- Lesson from LISA-PF: interferometer noise measured in space lower than on ground (further evidence that lab environment in space much more quiet than on ground)

The laser gauge for GG at INRIM: measured displacement noise





- GG: violation signal up-converted to 1 Hz
- Laser gauge displacement noise measured at INRIM: $0.6\,\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ @ 1 Hz
  (low frequency noise due to optical fibers, can be reduced)
- ... noise is 1/3 of target signal after only 10 s of integration time!!!



- If selected as M5 mssion of ESA **GG will test WEP/UFF to 10^{-17} in the field of Earth**
  (4 orders of magnitude improvement over current best tests)
- **Should Microscope detect a violation signal:**
  GG will be able to confirm or rule it out beyond question with one hundred times better precision
- **Should Microscope confirm WEP to** 10^{-15}**:**
  GG will be able to push the test 100 times deeper.
  No precise target from theory: the better the test, the higher the chances to find new physics...

GG webpage: `http://eotvos.dm.unipi.it`