LAG
(Liquid Actuated Gravity)

Luciano Di Fiore

INFN - Sezione di Napoli

Massimo Bassan[1,2], Martina De Laurentis[3,4], Rosario De Rosa[3,4], Luciano Errico[3,4], Fabio Garufi[3,4], Aniello Grado[4,5,] Yury Minenkov[1], Giuseppe Pucacco[1,2], Massimo Visco[2,6]

1 Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
2 INFN - Sezione Roma Tor Vergata, Roma, Italy
3 Dipartimento di Fisica, Università di Napoli “Federico II”, Napoli, Italy
4 INFN - Sezione di Napoli, I-80126, Napoli, Italy
5 INAF - Osservatorio Astronomico di Capodimonte, Napoli, Italy
6 INAF - Istituto di Astrofisica e Planetologia Spaziali, Roma, Italy

this work is supported by INFN commission V

Talk summary

- Introduction
- Scientific motivation
- Principle of operation
- Background and available facility
- Application to ISL test
- Conclusions and next steps

Introduction

- This R&D activity is devoted to the development of a new actuation technique for gravity experiments

- The basic idea is to use as an attractor field mass (FM) a container where the level of a liquid can be changed in a controlled and repeatable way in order to modulate the gravitational force acting on a test mass (TM), that is suspended to a torsion pendulum

- Modulation of the gravitational force is essential in gravity experiments to improve S/N ratio by coherent detection. This is generally achieved by changing the position of a FM with respect to the TM

- In the proposed technique, we can modulate the gravitational force without moving parts close to the apparatus

Scientific motivation

Newton interaction between point-like masses follows inverse square law (ISL) dependence on distance

$$F_N(r) = -G_\infty \frac{Mm}{r^2}$$

Several theories predict deviation form ISL that manifest their effect below a characteristic scale λ (that can be related to the mass of the boson mediating the interaction or to the characteristic size of extra dimensions). This can be regarded as a distance depending gravity constant:

$$F(r) = -G(r)\frac{Mm}{r^2} = -G_\infty \frac{Mm}{r^2}(1 + a(r))$$

This can be parametrized introducing a Yukawa potential:

$$V_{Yukawa}(r) = -G_\infty \frac{Mm}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

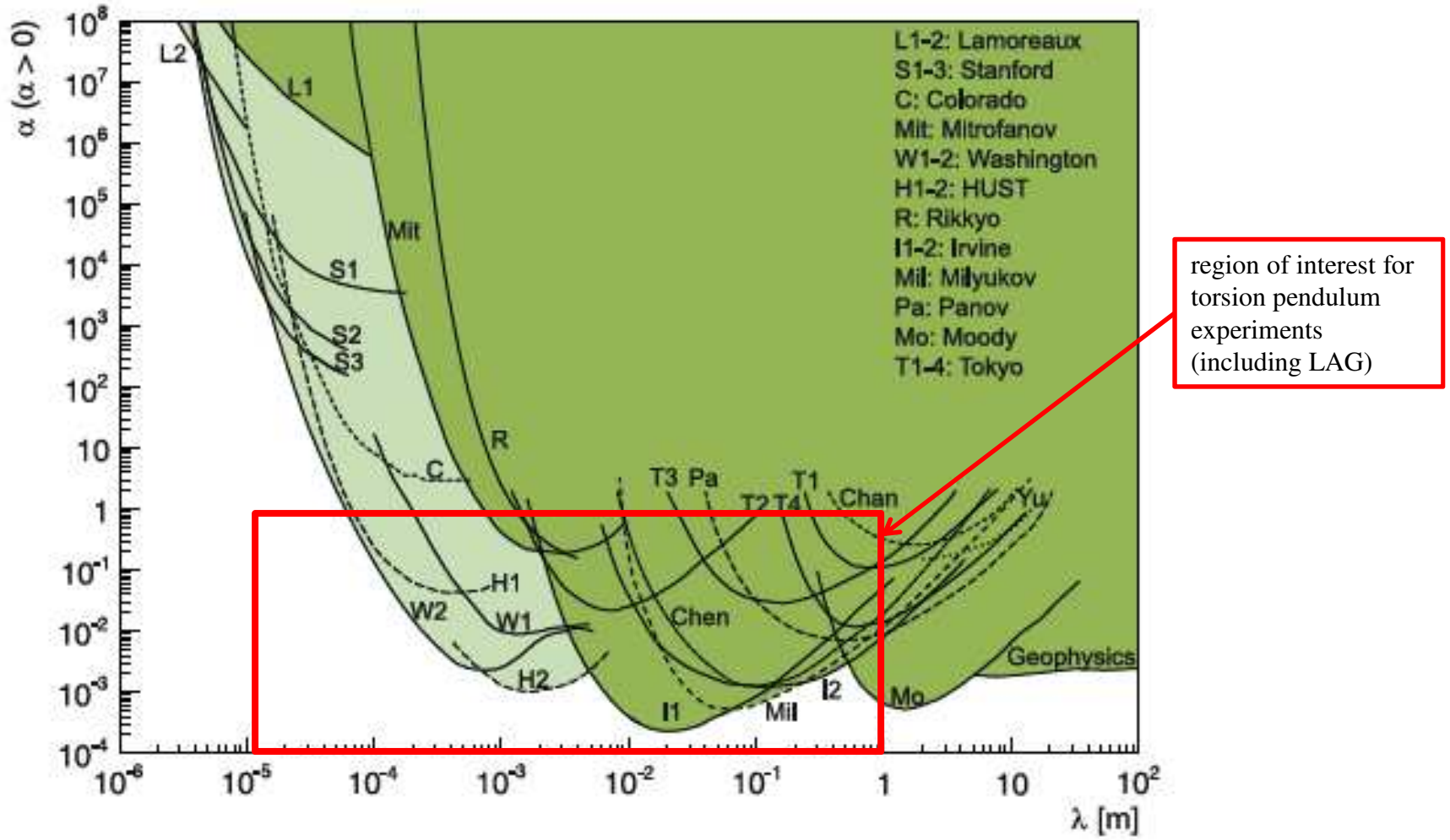
In ISL test experiments, gravity force (or torque) is generally measured at two (or more) FM-TM distances. We define the quantity γ asv(if the same, point-like masses are used at the two positions):

$$\gamma = \frac{F_N}{F_F} \cdot \left(\frac{r_N}{r_F}\right)^2$$

with: r_N and r_F the near and far position
F_N and F_F the corresponding forces acting on the TM.

Where $\gamma = 1$ if Newtonian gravity holds; deviations is represented introducing $\delta = 1 - \gamma$

So far, only upper limits to the strength α have been set for specific values of λ



plot form: Murata J and Tanaka S 2015 *Class. Quantum Grav.* **32** 033001

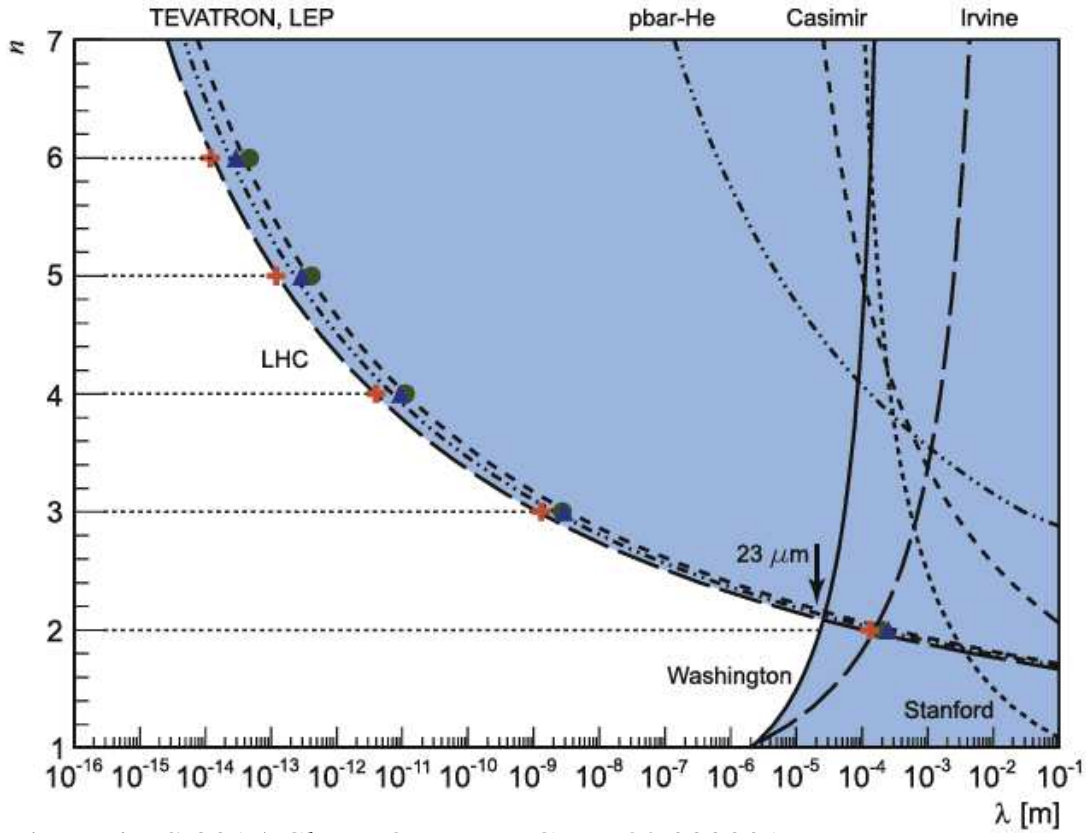
Power law parametrization

Another possible representation of deviation from ISL is the power law parametrization.

in 1998 Arkani-Hamed, Dimopoulos, and Dvali (ADD) introduced a model with *n* large extra dimensions ($n \geq 2$) to explain the so called hierarchy problem of the weakness of gravity with respect to other forces.

It can be represented by a potential of the form:

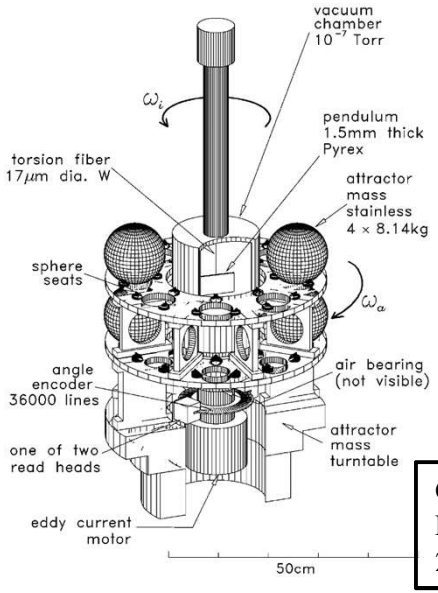
$$V_{power}(r) = -G_\infty \frac{Mm}{r}\left(1 + \left(\frac{\lambda}{r}\right)^n\right)$$



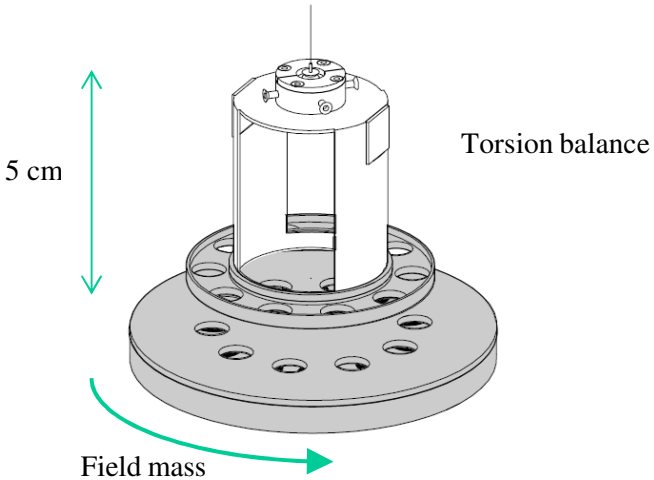
plot form: Murata J and Tanaka S 2015 *Class. Quantum Grav.* **32** 033001

Modulation of the Gravitational force is essential to improve S/N ratio in laboratory experiments

This is generally obtained by moving periodically one or more Field Masses (FM) acting on a TM suspended to a torsion pendulum



Gundlach, Merkowitz, Phys. Rev. Lett.,**85**, 2869, 2000

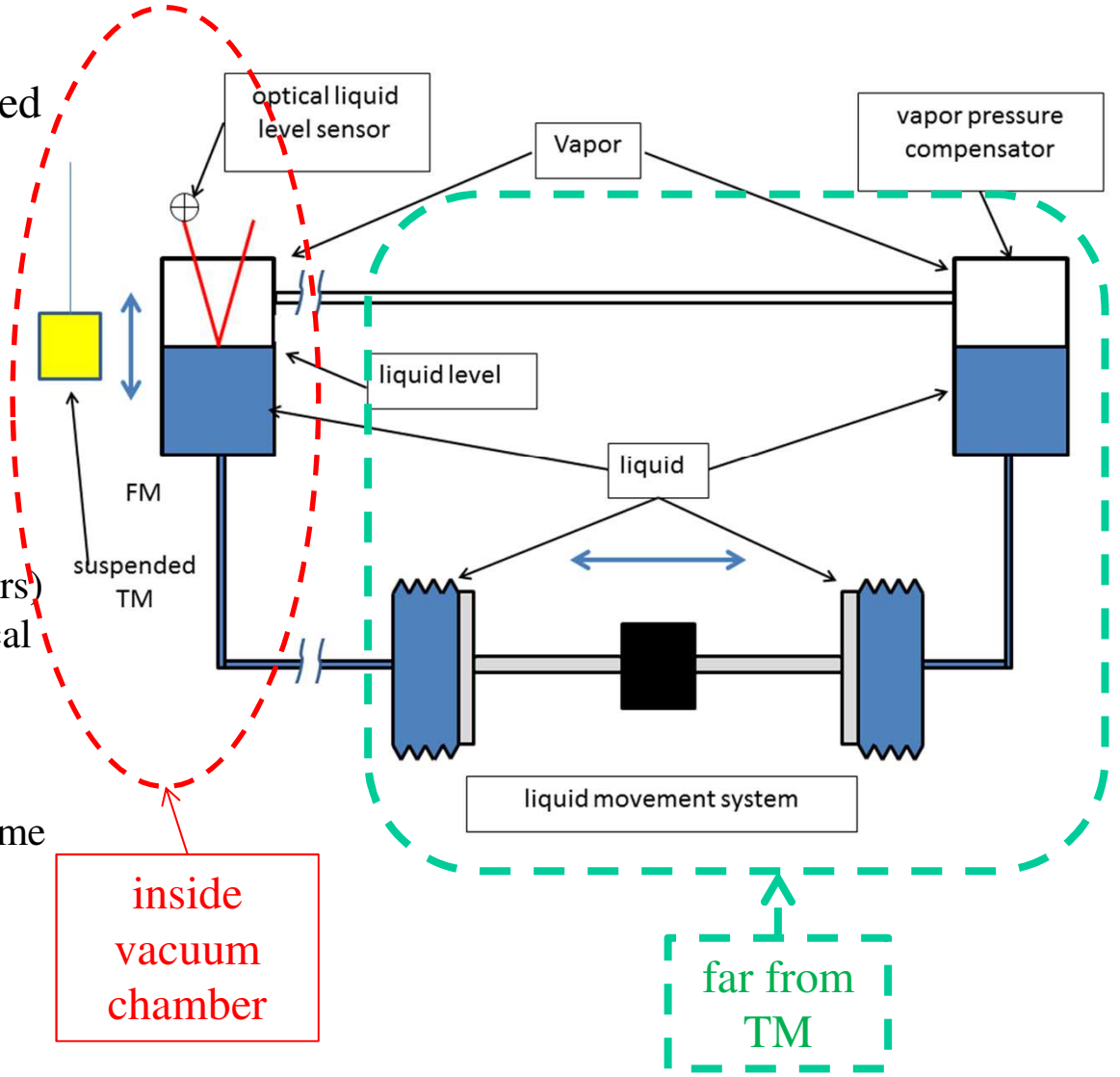


D.J.Kapner et al., Phys. Rev. Lett., **98,** 021101, 2007

LAG: Principle of operation

We propose a new modulation technique where there are no based on a liquid Field Mass (FM)

- gravity force is modulated by the varying liquid level
- all moving parts are far away (meters)
- liquid level is monitored by an optical sensor
- force/torque are modulated in low frequency (5-10 mHz) and measurement is averaged for long time (order of 80000 s)
- TM- FM relative position can be changed and measurement repeated

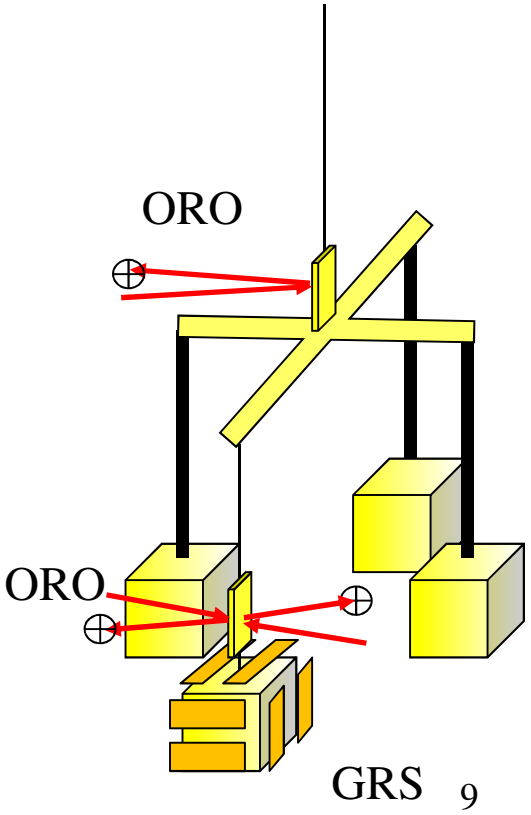


Background

PETER (PEndolo Traslazionale e Rotazionale): a two-fold torsion pendulum facility

- it was developed for ground testing of the LISA-Pathfinder Inertial Sensor
- it is a unique apparatus that allows simultaneous measurement of both force and torque acting on the TM
- It is an ideal instrument for gravity (and other small forces) experiments

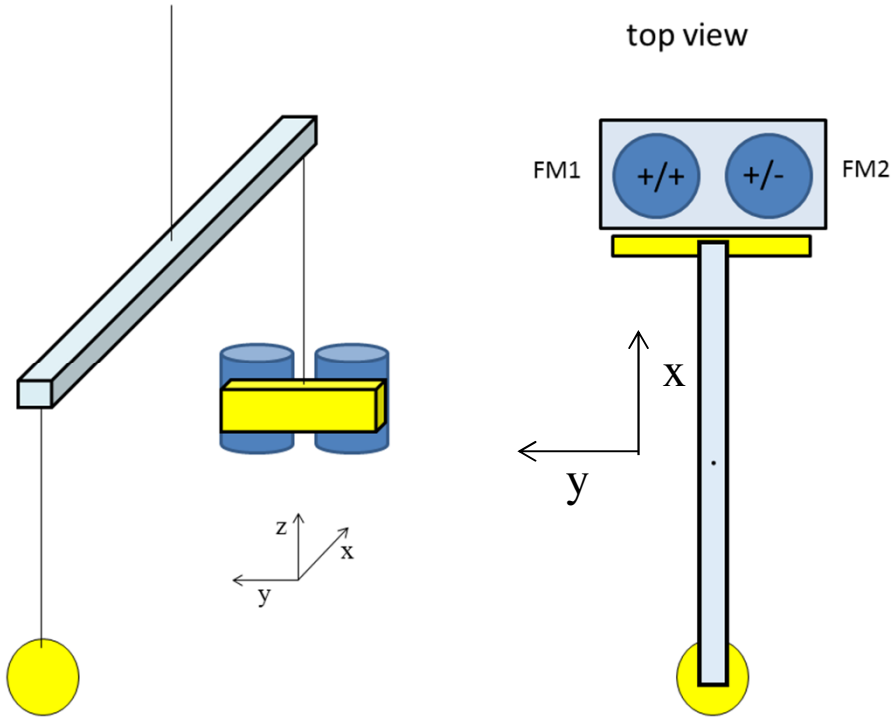
PETER in the Gravitational Physics Laboratory in Napoli. (left). The GRS inside the PETER facility (right).



for more details:

- F.De Marchi et al. **Phys. Rev. D 87** (2013)122006.
- M.Bassan et al. **Phys. Rev. Lett. 116** (2016)051104
- M. Bassana et al. **Astroparticle Phys. 97** (2018)19

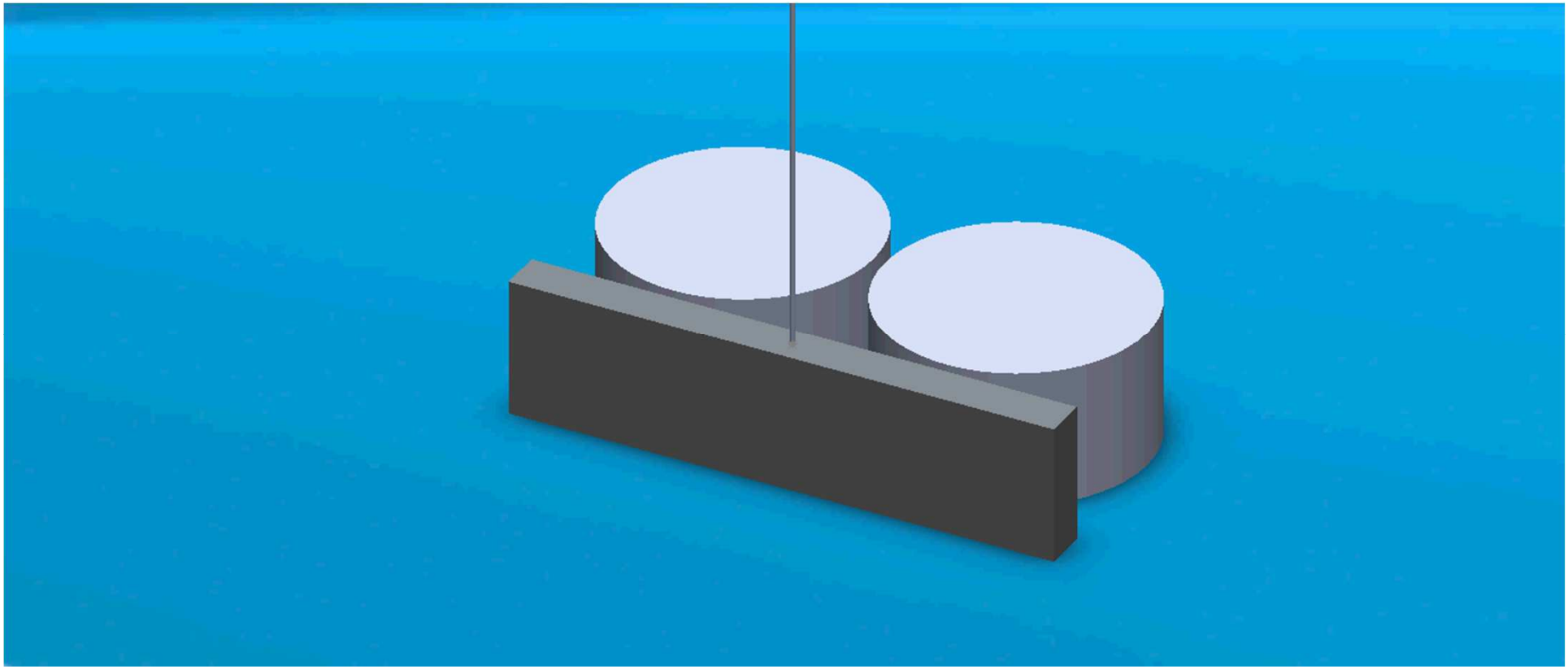
The proposed set-up for ISL test



- two FMs that we can fill in phase (+/+) or anti-phase (+/-) to disentangle system asymmetries
- force and torque measurement at various TM FMs relative position in the x-y plane
- pure Liquids are more uniform in density than solids
- both TM and FMs are not point-like masses: need for an accurate mechanical model to compute the expected values to compare to experimental results
- force and torque depend on density, but their ratio only depend on geometry

- TM (Mo) L= 0.1 m h_{TM}=0.025 m t=0.008 m M= 0.2 kg
- 2 FMs (Hg) R=0.024 m, h_{fFM} =0.1 m centers distance = L/2 , M_{tot}=1.3 kg

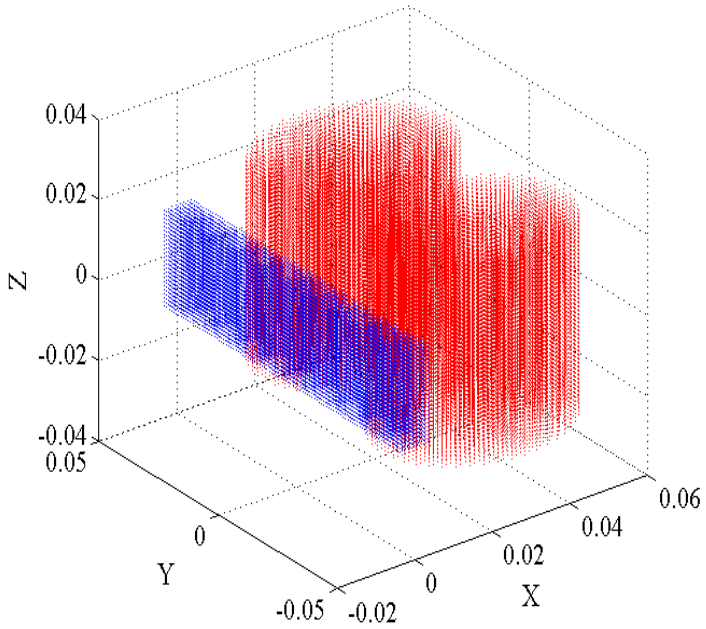
Example of the +/- actuation mode

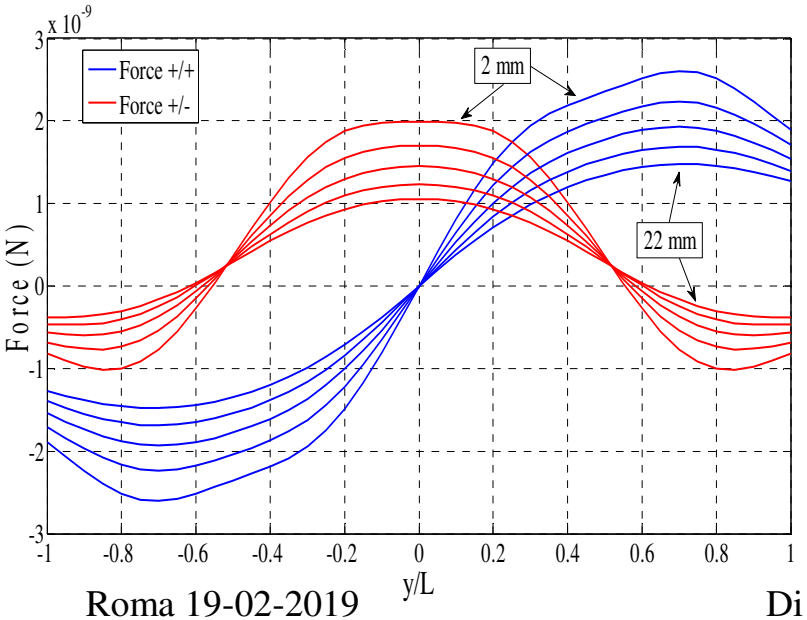


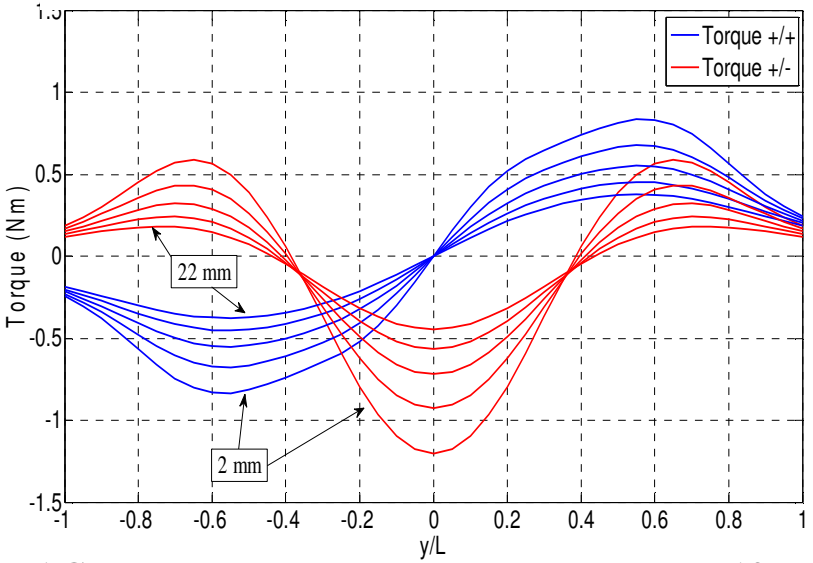
one example of Force and Torque comp

we divide TM and FM in small elements and compute the sum of forces and torques on all the TM elements due to all the FM elements (for each liquid level) at various TM-FM relative positions

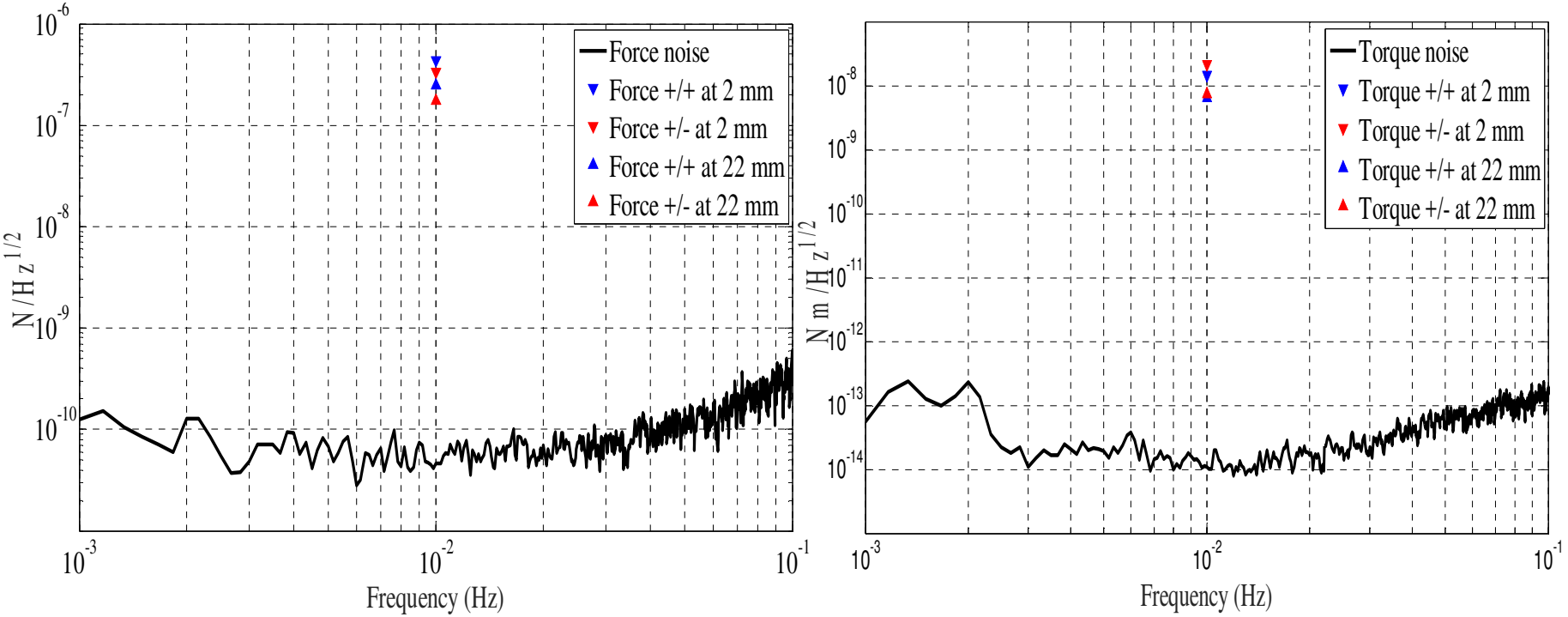
liquid level modulation h = ± 25 mm
frequency 10 mHz
lateral FM displacement -L ≤ y ≤ L
5 x position from 2 to 22 mm with steps of 5 m





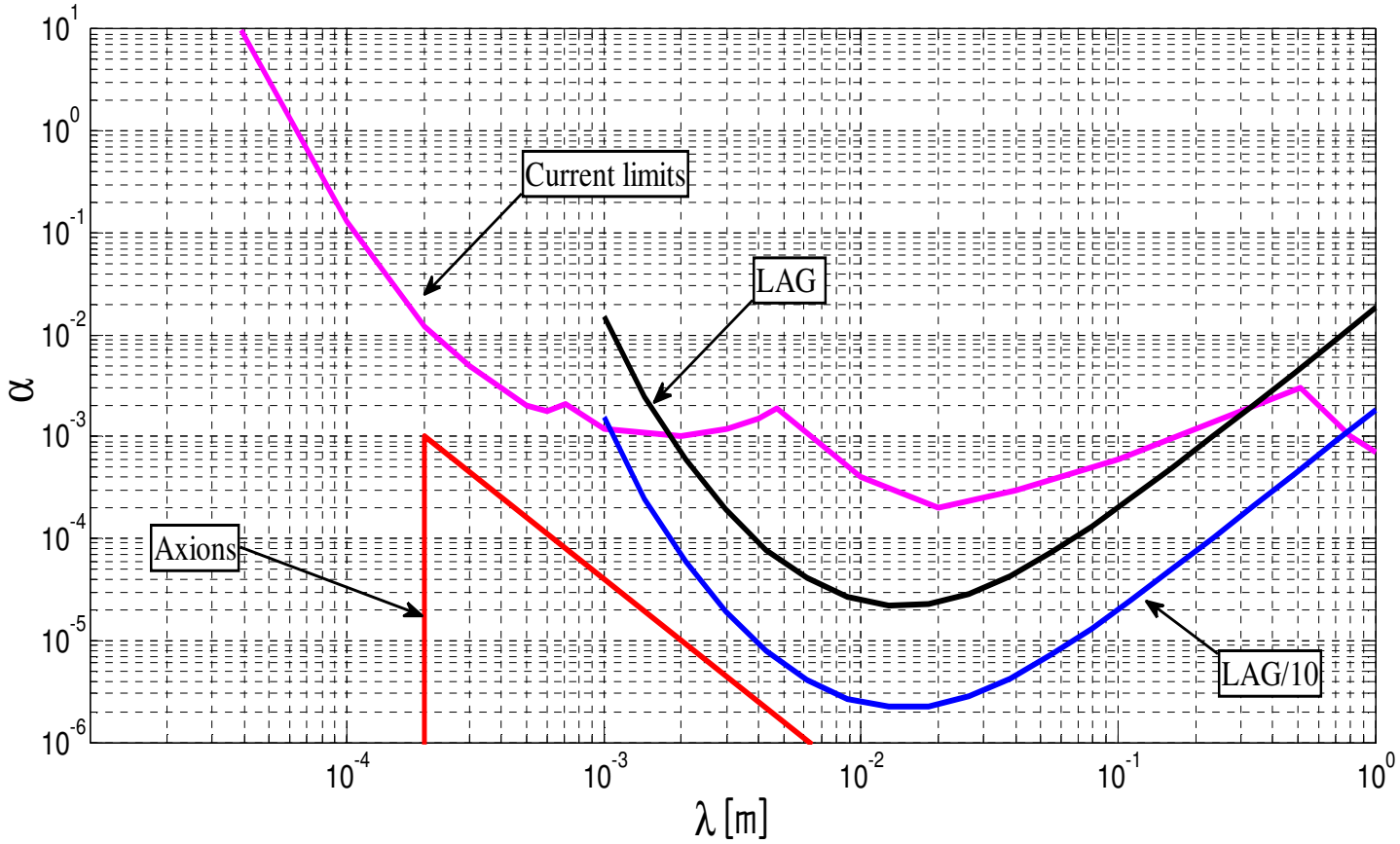


Expected S/N ratio



- f_m = 10 mHz h_m =.024 m, measurement time = 80000 s
- noise: assumed present PETER sensitivity
- S/M ratio larger that 10^4 for force and 10^5 for torque
- Assuming uncertainty on δ of 10^{-5} limited by torque sensitivity (provided geometry and model incertitude is lower) we can compute α–λ exclusion from a set of measurement in +/- mode from 2 to 22 mm

Estimated α–λ upper limits with present PETER sensitivity (black)



- We can improve by more than one order of magnitude the exclusion for 1 mm < λ < 1 m approaching the region of interest for probing axion's mass
- For the ADD model, we could limit λ ≤ 15 μm (with present sensitivity)

Conclusion and future steps

- We have presented a new liquid actuation technique (LAG) for gravity experiments,
- We propose as first application to test violation of ISL with perspective to improve current limits in the mm to cm λ region, where interesting physics is existence of axions and range of extra dimensions (ADD model)
- A two years R&D program funded by INFN (commission V) is starting in 2019 to test principle of operation and reliability of the LAG actuator
- We are now designing a LAG prototype that will be integrated in the existing two fold torsion pendulum facility (PETER) operational in Napoli
- If the test is successful, the full experiment for testing ISL will be performed
- The principle of the LAG actuator can be adapted to other gravity experiments (for example measurement of gravity constant G).

Thank you for your attention