LAG
(Liquid Actuated Gravity)

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Talk summary

- Introduction
- Scientific motivation
- Background and available facility
- Principle of operation
- Goal of the R&D
- Possible future upgrades
- Group composition

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 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 one or more FMs with respect to the TM.
- In the proposed technique, we can modulate the gravitational force without moving parts close to the apparatus

Scientific motivation

Laboratory tests of gravitation have two main target, the first is a better determination of the Gravitation constant that appears in Newton interaction, presently known with a relative precision of about 5 x 10^{-5}

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

The second target is to investigate possible deviation from inverse square law (ISL) dependence on distance. Several theories predict deviation form ISL that manifest their effect below a characteristic scale λ. This can be parametrized introducing a Yukawa-like potential:

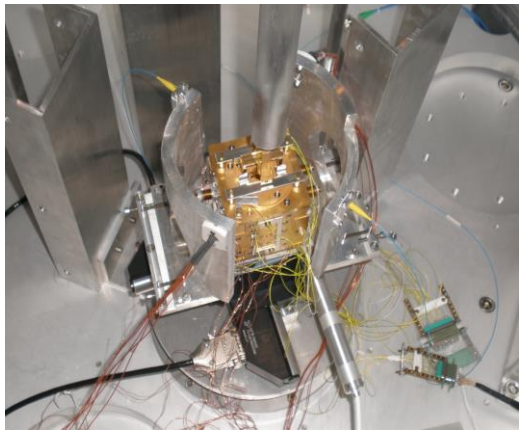
$$V_{\text{Yukawa}}(r) = -G_\infty \frac{Mm}{r}\left(1 + \alpha e^{-r/\lambda}\right).$$

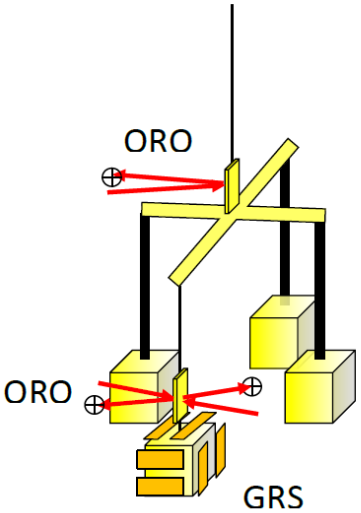
For this reason, several experimental efforts have been devoted to the measurement of a deviation of ISL for gravitation at any range λ so far, only upper limits to the strength a have been put for specific values.

Background

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

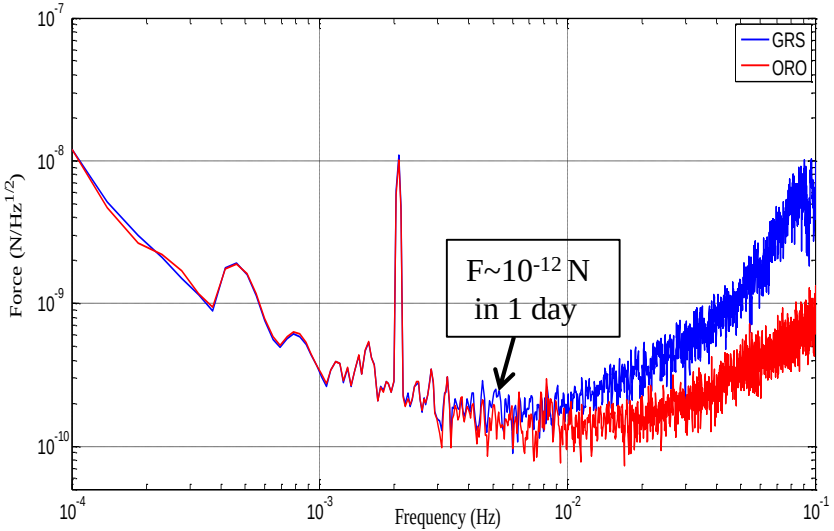
- it was developed for ground testing of the LISA-Pathfinder Inertial Sensor
- it is a unique apparatus that allows simultaneous measurement of both **force and torque acting on the TM**
- It is an ideal instrument for gravity (and other small forces) experiments



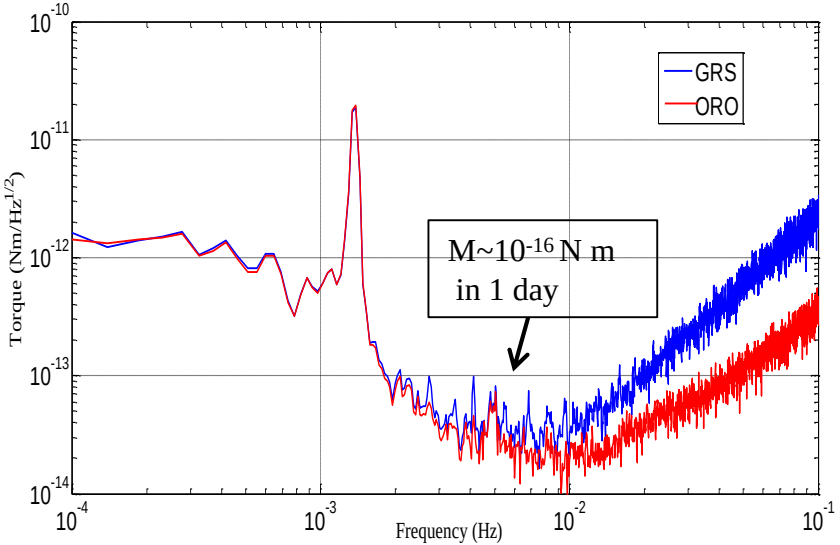


Force and Torque measurement

Force



Torque



The cross-talk Force-Torque was experimentally tested to be lower than 0.1 % when the TM is centered.

for more details

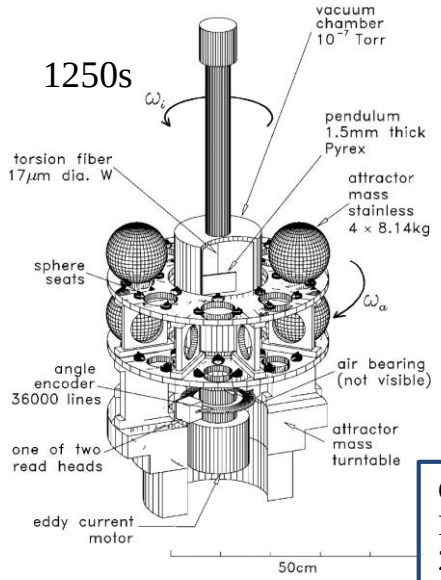
1. F.De Marchi, G.Pucacco, M.Bassan, R.De Rosa, L.Di Fiore, F.Garufi, A.Grado, L.Marconi, R.Stanga, F. Stolzi and M. Visco, "*Quasi-complete mechanical model for a double torsion pendulum*"; **Phys. Rev. D 87** (2013)122006.

1. M.Bassan, A.Cavalleri, M.De Laurentis, F.De Marchi, R.De Rosa, L.Di Fiore, R.Dolesi, N.Finetti, F.Garufi, A.Grado, M. Hueller, L.Marconi, L.Milano, G.Pucacco, R.Stanga, M.Visco, S.Vitale, and W.J.Weber, "*Approaching Free Fall on Two Degrees of Freedom: Simultaneous Measurement of Residual Force and Torque on a Double Torsion Pendulum*"; **Phys. Rev. Lett. 116** (2016)051104

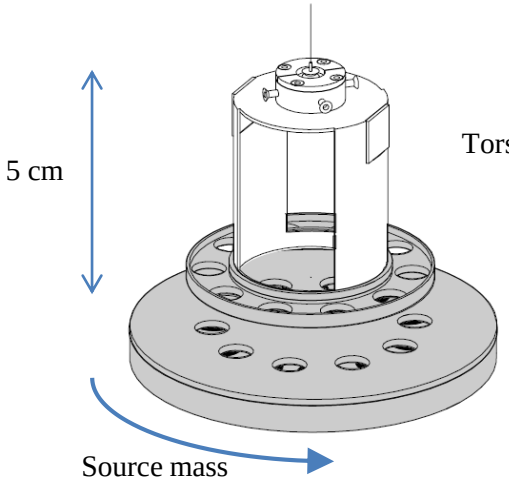
2. M. Bassan, A. Cavalleri, M. De Laurentis, F. De Marchi, R. De Rosa, L. Di Fiore,, R. Dolesi, N. Finetti, F. Garufi, A. Grado, M. Hueller, L. Marconi, L. Milano, Y. Minenkov, G. Pucacco, R. Stanga, D.Vetrugno, M. Visco, S. Vitale, W. J. Weber, "*Actuation cross-talks in free-falling systems: torsion pendulum results for the LISA-Pathfinder gravitational reference sensor*", **Astroparticle Phys. 97** (2018)19–26

Field Masses

- Modulation of the Gravitational force is essential to improve S/N ratio in laboratory experiments
- This is generally obtained by periodically moving one or more Field Masses (FM) acting on a TM suspended to a torsion pendulum



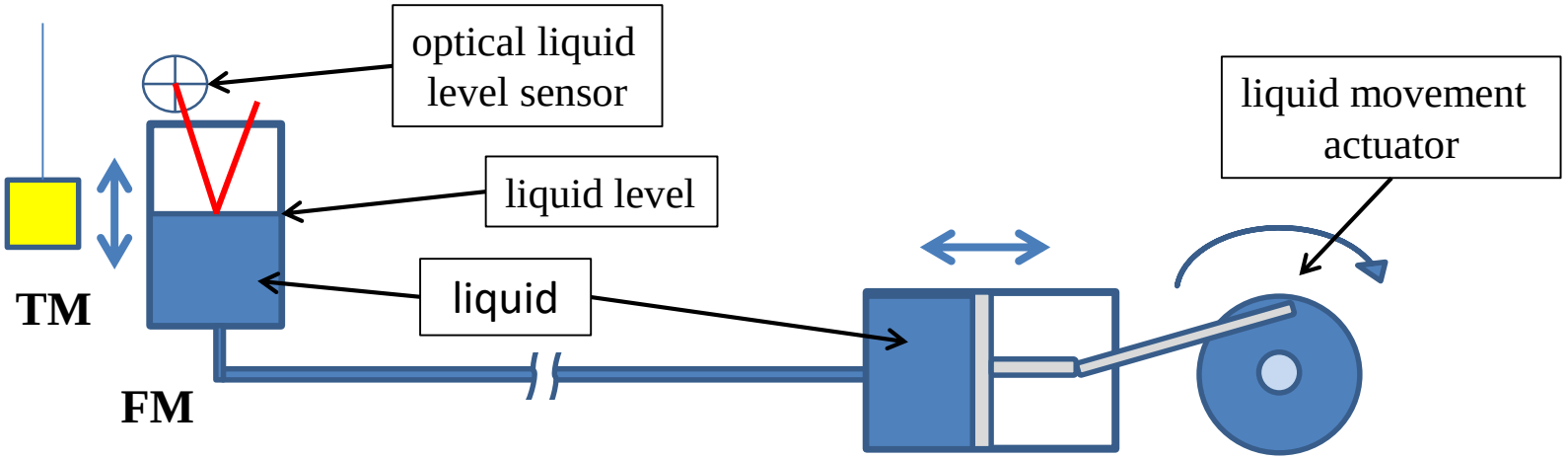
Gundlach, Merkowitz, Phys. Rev. Lett.,**85**, 2869, 2000



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

Principle of operation

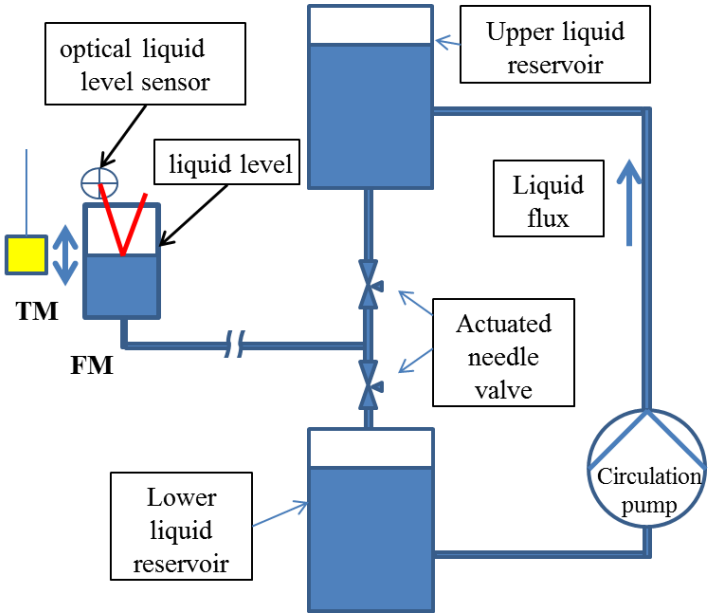
We want to test a new modulation technique where there are no mechanical parts moving close to the apparatus, but the level of a liquid is changed in a controlled way in a container close to the TM



- 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 at low frequency (5-10 mHz) and measurement is averaged for long time (order of 1day)
- TM- FM relative position can be changed and measurement repeated

Alternative technical solutions

We will develop a configuration based on a piston driven by a stepping motor, but we have considered also alternative schemes for the apparatus.



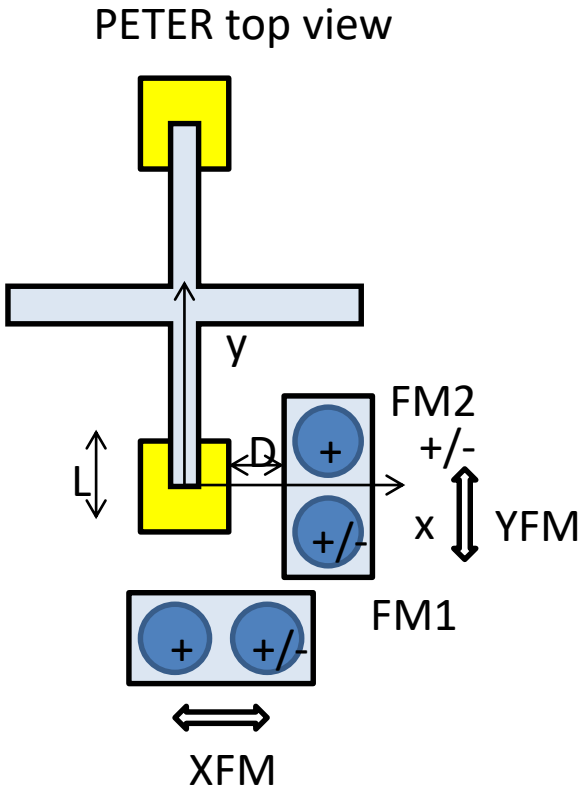
In a possible alternative scheme the FM is filled from an upper reservoir.

The inflow is controlled by an electrically actuated needle valve.

The outflow is controlled by a second needle valve towards a lower liquid reservoir

The liquid is transferred from lower and upper reservoirs by a pump.

Some practical considerations

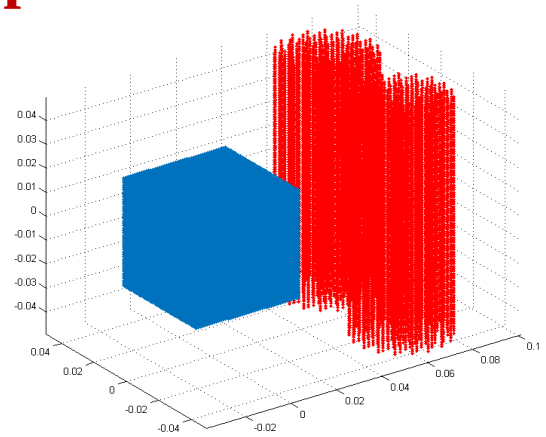


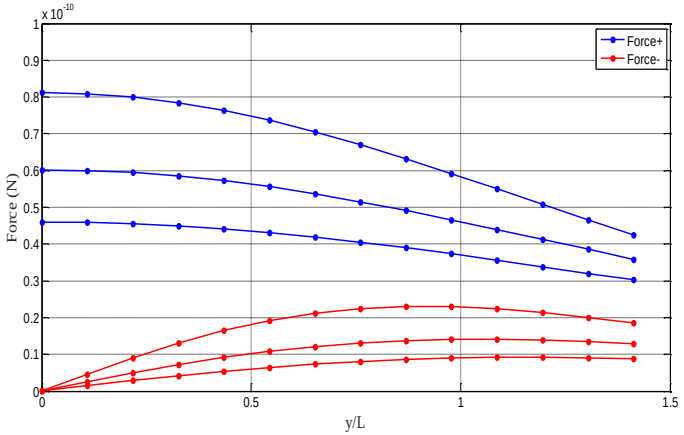
- It is convenient to have two FMs that we can fill in phase (+/+) or anti-phase (+/-) to disentangle system asymmetries
- we can repeat force and torque measurement at various relative position in x or y
- Force and torque depend on TM e FM density, but their ratio doesn't
- Force and torque scale differently with relative position: the measurement of their ratio gives information on deviations from $1/r^2$ and on the metrology
- both TM and FMs are not point-like masses: we need a detailed mechanical model to compute the expected values to compare to experimental results

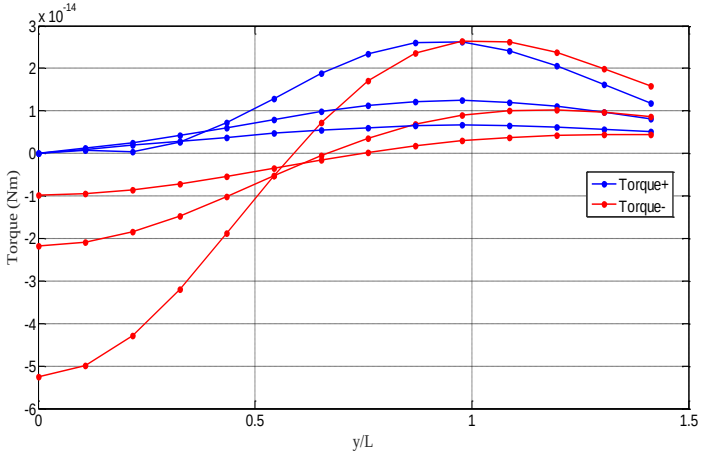
we have many different possible configurations

One example of Force and Torque computation

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.

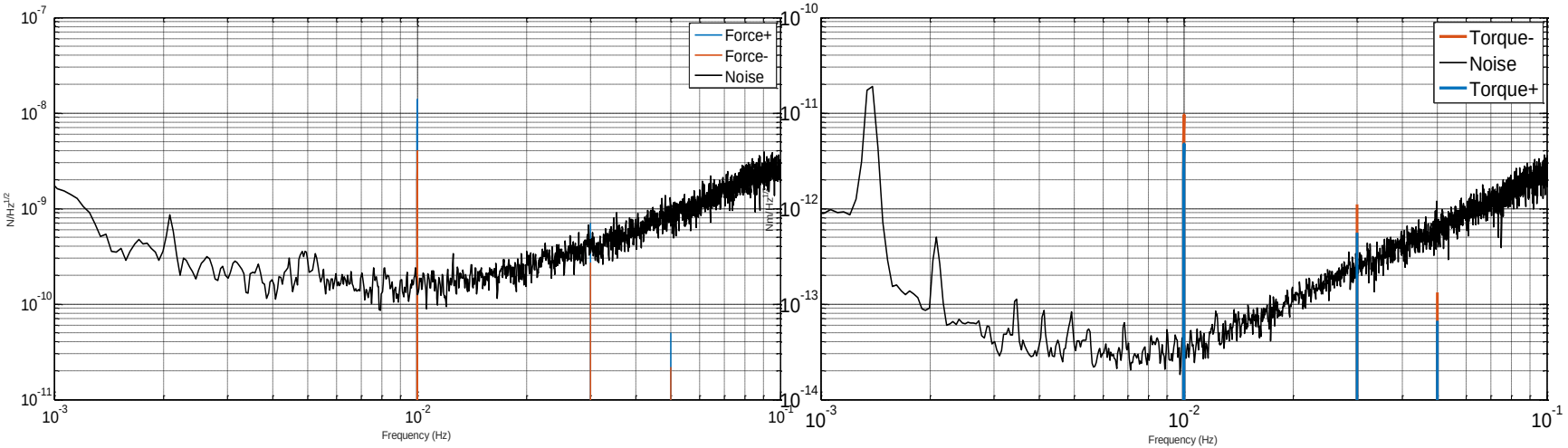






Comparison of expected signals with PETER sensitivity

Liquid level variation 10 cm p-p; liquid H_2O mod. freq. 10 mHz, measurement time 80000 s



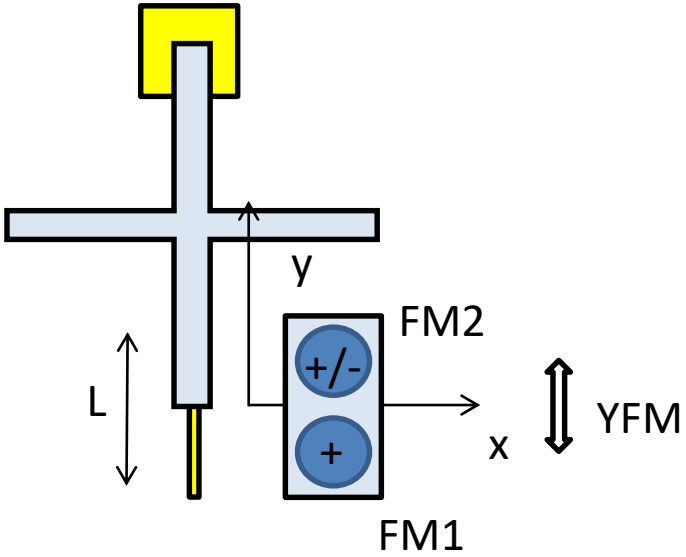
- We can measure both force and torque with S/N of order of 100
- this is more than enough for the purpose of our R&D
- but (as expected) it is non enough to improve α–λ limits or to increase G measure.

Goal of the LAG R&D

- design and build a prototype liquid gravity actuator for vacuum operation
- integrate it in the PETER facility and test reliability and performance
- develop a complete model of the apparatus (actuator + pendulum sensor), including Yukawa corrections, to be compared with experimental results
- define and test the procedure to extract α–λ parameters and to measure G, using different configurations.

Possible upgrades for a future experiment (in CSN2)

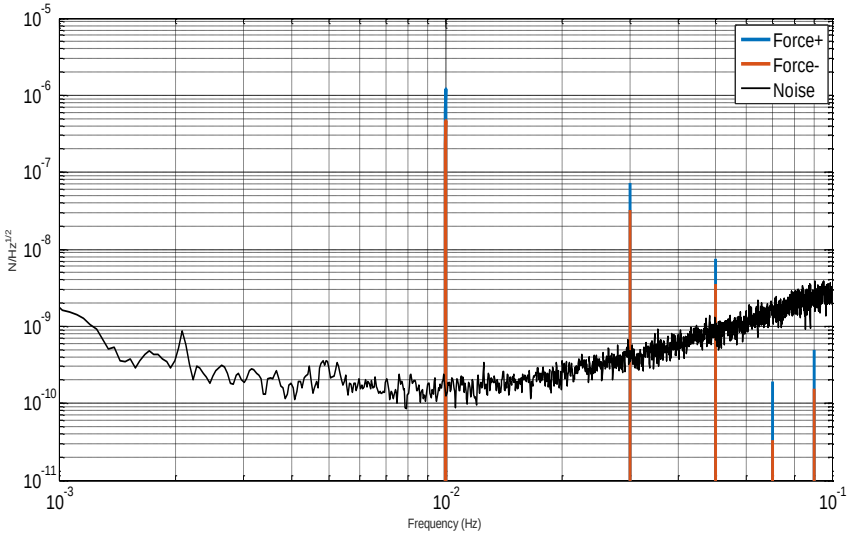
PETER top view

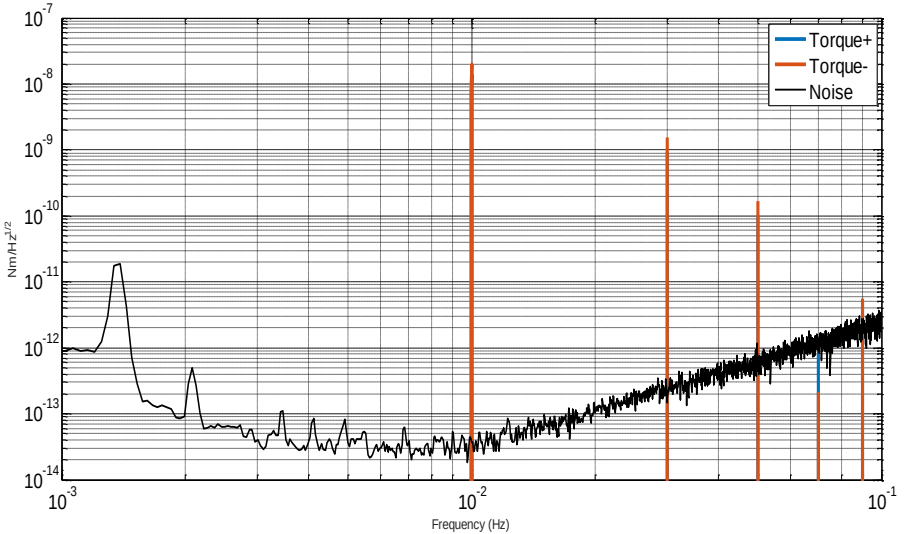


we need to increase S/N ratio, this implies:

- reduce TM-FM distance ➔ plate TM
- increase TM density ➔ Mo (10000 kg/m^3)
- increase FM density ➔ Hg (13000 kg/m^3)
- improve Peter sensitivity ➔ we are not at a fundamental limit

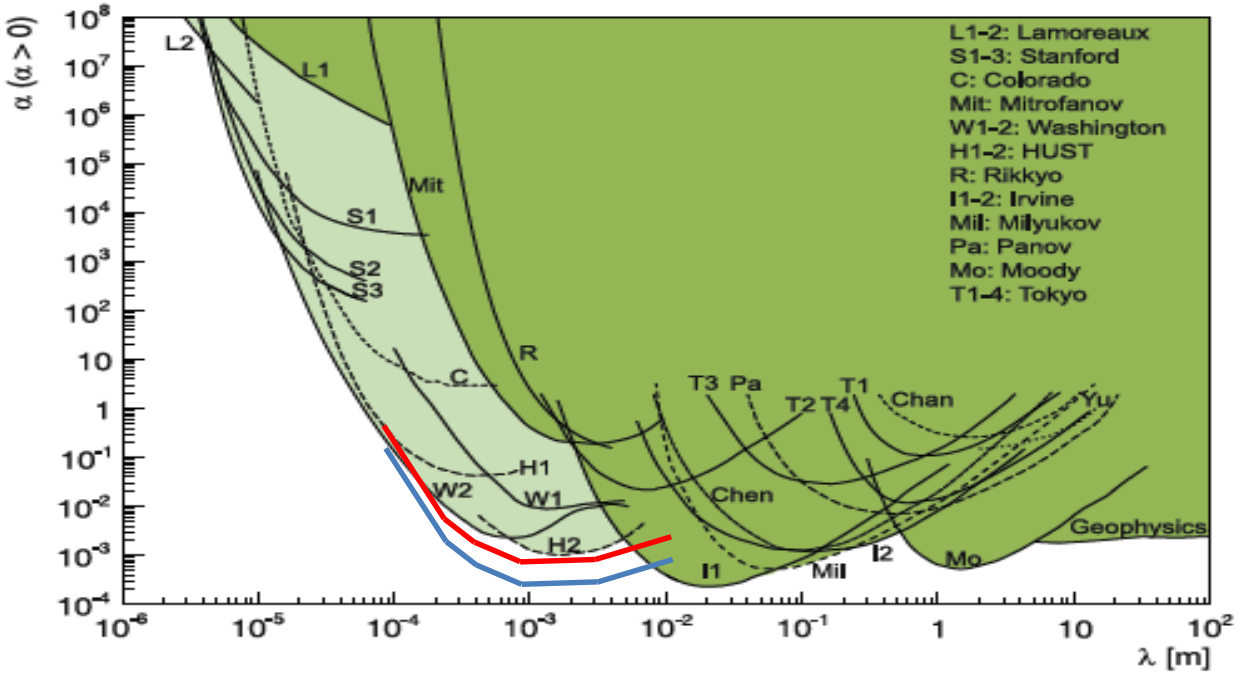
Expected S/N ratio





- in this configuration we have S/N ratio larger that 10^4 (with PETER present sensitivity)
- this should allow to improve α-λ exclusion (provided the geometry is under control and well modeled)
- this configuration is not optimized and can still be improved

first estimate (simplified model) of α-λ limits
(red = PETER sensitivity, blue = improved by a factor 5)



Research group composition

Napoli

Luciano Di Fiore	50%
Aniello Grado	50%
Rosario De Rosa	10%
Fabio Garufi	10%
	1.20 FTE

tasks:

- Experiment definition
- Hardware design and implementation
- Modeling
- Data analysis

Roma Tor Vergata

Massimo Visco	30 %
Giuseppe Pucacco	20 %
Massimo Bassan	10 %
	0.6 FTE

tasks:

- Experiment definition
- Coordination of modeling activity
- Finite elements modeling
- Data analysis

Richieste economiche

La Sezione di Tor Vergata si occuperà principalmente di **coordinare l'attività di sviluppo dei modelli** utili a definire con precisione il progetto della FM a liquido e le sue interazioni con la TM di PETER. La sezione contribuirà anche alla progettazione e la costruzione dell'apparato, che avverrà presso la sezione di Napoli.
La richiesta di finanziamento per questo primo anno è limitato alle trasferte presso il laboratorio di Napoli, alla fine di questo periodo saremo anche in grado di definire se sia necessario acquistare software o hardware, oltre quello già a disposizione per la modellazione.

Richieste finanziarie 2018 (Tor Vergata): ~ 2.5 k€

- 3 missioni per 3 persone a Napoli per due giorni