Ring-Lasers and Fundamental Physics

- Gravitomagnetics Effects-GR Tests Costs and Plan
- Application for gravitational waves Research-Direct Search?
- Other Applications
- Conclusions

…a different view of the ring-laser

Sensitivity	Bandwidth	Duty cycle	(accuracy)
✔	✔	✔	Several ideas

Instrument ready for an ‘observatory’ or experiment in which long time observation is necessary

- Metrology
- Known sygnals-cross check of independent measurements
- Active/Passive ring
- Calibration arch

Gyroscopes IN GEneral Relativity
GINGER

- Measure the LenseThirring effect with an Earth based experiment with 1% accuracy

- *Bosi et al*. Measuring gravitomagnetic effects by a multi-ring-laser gyroscope **PHYSICAL REVIEW D 84 12 2011**
- *Di Virgilio et al.* A ring lasers array for fundamental physics

COMPTES RENDUS PHYSIQUE 15 10 866 2014

Published more than 24 papers on: LenseThirring measurement, backscattering subtraction&laser dynamics, scale factor control, signal extraction for the control and results of our prototypes

Original feature of GINGER

- First measurement of the GR features of the gravitational field of the Earth in a terrestrial laboratory (accelerated frame) along an universe line (determined by kinematical and gravitational terms)

$$\Delta\tau = \frac{4\,(\mathbf{\Omega}_{\oplus} + \mathbf{\Omega}') \cdot \mathbf{S}}{c^2}, \quad \leftarrow\rightarrow \quad \Delta f = \frac{4}{\lambda P}\;(\mathbf{\Omega}_{\oplus} + \mathbf{\Omega}') \cdot \mathbf{S},$$

- it measures the kinematical term + GR terms….

- γ measure the effect of curvature
- α_1 measures the effect of preferred frame
- U is the Newtonian potential, $\boldsymbol{J}_\oplus$ is the Angular Momentum
- R and V are position and velocity, W is the velocity of the frame in which the Earth is at rest

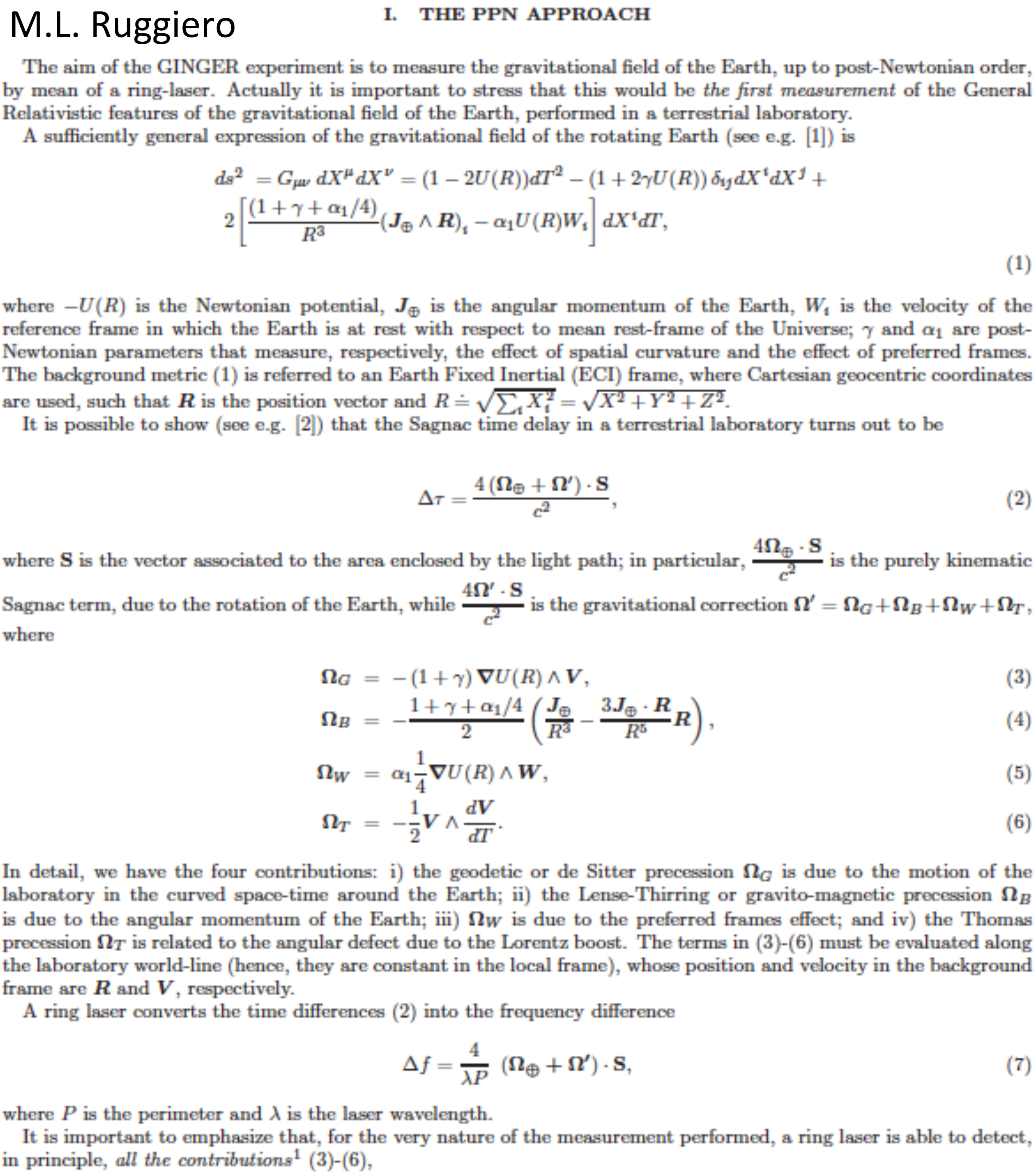
$$
\begin{aligned}
\boldsymbol{\Omega}_G &= -(1+\gamma)\,\boldsymbol{\nabla} U(R) \wedge \boldsymbol{V}, \\
\boldsymbol{\Omega}_B &= -\frac{1+\gamma+\alpha_1/4}{2}\left(\frac{\boldsymbol{J}_\oplus}{R^3} - \frac{3\boldsymbol{J}_\oplus \cdot \boldsymbol{R}}{R^5}\boldsymbol{R}\right), \\
\boldsymbol{\Omega}_W &= \alpha_1 \frac{1}{4} \boldsymbol{\nabla} U(R) \wedge \boldsymbol{W}, \\
\boldsymbol{\Omega}_T &= -\frac{1}{2} \boldsymbol{V} \wedge \frac{d\boldsymbol{V}}{dT}.
\end{aligned}
$$

LARES → only gravitomagnetic term

GINGER/Alternative GR theories

- Horava-Lifshits (e.g. 1408.1247); f(R) (Capozziello: 1410.8316); Chern-Simons (e.g. 1405.7472), Standard Model Extension (e.g. 1005.1435).
- Different angular behaviour→ to do this sort of physics it is necessary to compare several 'GINGER" distributed on the Earth sphere

Short note of M.L. Ruggiero



I. THE PPN APPROACH

The aim of the GINGER experiment is to measure the gravitational field of the Earth, up to post-Newtonian order, by mean of a ring-laser. Actually it is important to stress that this would be *the first measurement* of the General Relativistic features of the gravitational field of the Earth, performed in a terrestrial laboratory.

A sufficiently general expression of the gravitational field of the rotating Earth (see e.g. [1]) is

$$\begin{aligned} ds^2 &= G_{\mu\nu}\, dX^\mu dX^\nu = (1-2U(R))dT^2 - (1+2\gamma U(R))\,\delta_{ij} dX^i dX^j + \\ &2\left[\frac{(1+\gamma+\alpha_1/4)}{R^3}(\boldsymbol{J}_\oplus \wedge \boldsymbol{R})_i - \alpha_1 U(R) W_i\right] dX^i dT, \end{aligned} \tag{1}$$

where $-U(R)$ is the Newtonian potential, $\boldsymbol{J}_\oplus$ is the angular momentum of the Earth, W_i is the velocity of the reference frame in which the Earth is at rest with respect to mean rest-frame of the Universe; γ and α_1 are post-Newtonian parameters that measure, respectively, the effect of spatial curvature and the effect of preferred frames. The background metric (1) is referred to an Earth Fixed Inertial (ECI) frame, where Cartesian geocentric coordinates are used, such that $\boldsymbol{R}$ is the position vector and $R \doteq \sqrt{\sum_i X_i^2} = \sqrt{X^2+Y^2+Z^2}$.

It is possible to show (see e.g. [2]) that the Sagnac time delay in a terrestrial laboratory turns out to be

$$\Delta\tau = \frac{4\,(\mathbf{\Omega}_\oplus + \mathbf{\Omega}')\cdot\mathbf{S}}{c^2}, \tag{2}$$

where $\mathbf{S}$ is the vector associated to the area enclosed by the light path; in particular, $\frac{4\mathbf{\Omega}_\oplus\cdot\mathbf{S}}{c^2}$ is the purely kinematic Sagnac term, due to the rotation of the Earth, while $\frac{4\mathbf{\Omega}'\cdot\mathbf{S}}{c^2}$ is the gravitational correction $\mathbf{\Omega}' = \mathbf{\Omega}_G + \mathbf{\Omega}_B + \mathbf{\Omega}_W + \mathbf{\Omega}_T$, where

$$\begin{aligned} \mathbf{\Omega}_G &= -(1+\gamma)\,\boldsymbol{\nabla} U(R) \wedge \boldsymbol{V}, && (3) \\ \mathbf{\Omega}_B &= -\frac{1+\gamma+\alpha_1/4}{2}\left(\frac{\boldsymbol{J}_\oplus}{R^3} - \frac{3\boldsymbol{J}_\oplus\cdot\boldsymbol{R}}{R^5}\boldsymbol{R}\right), && (4) \\ \mathbf{\Omega}_W &= \alpha_1 \frac{1}{4}\boldsymbol{\nabla} U(R) \wedge \boldsymbol{W}, && (5) \\ \mathbf{\Omega}_T &= -\frac{1}{2}\boldsymbol{V} \wedge \frac{d\boldsymbol{V}}{dT}. && (6) \end{aligned}$$

In detail, we have the four contributions: i) the geodetic or de Sitter precession $\mathbf{\Omega}_G$ is due to the motion of the laboratory in the curved space-time around the Earth; ii) the Lense-Thirring or gravito-magnetic precession $\mathbf{\Omega}_B$ is due to the angular momentum of the Earth; iii) $\mathbf{\Omega}_W$ is due to the preferred frames effect; and iv) the Thomas precession $\mathbf{\Omega}_T$ is related to the angular defect due to the Lorentz boost. The terms in (3)-(6) must be evaluated along the laboratory world-line (hence, they are constant in the local frame), whose position and velocity in the background frame are $\boldsymbol{R}$ and $\boldsymbol{V}$, respectively.

A ring laser converts the time differences (2) into the frequency difference

$$\Delta f = \frac{4}{\lambda P}\;(\mathbf{\Omega}_\oplus + \mathbf{\Omega}')\cdot\mathbf{S}, \tag{7}$$

where P is the perimeter and λ is the laser wavelength.

It is important to emphasize that, for the very nature of the measurement performed, a ring laser is able to detect, in principle, *all the contributions*[1] (3)-(6),

II. BEYOND THE PPN APPROACH

Modified theories of gravity introduce perturbations of the gravitational field of the Earth that, in general, cannot be described within the PPN scheme. So, quite generally, we are led to suppose that the space-time metric (1) could be perturbed in the form

$$G_{00} \to G_{00} + \delta G_{00}, \quad , G_{ij} \to G_{ij} + \delta G_{ij}, \quad G_{0i} \to G_{0i} + \delta G_{0i} \tag{8}$$

where the perturbation terms $\delta G_{\mu\nu}$ are determined by the specific modified gravity model.

Roughly speaking, we may say that the the geodetic term $\mathbf{\Omega}_G$ is sensitive to modifications of both G_{00} and G_{ij}, while the Lense-Thirring term $\mathbf{\Omega}_B$ is sensitive to modification of the G_{0i} term. So, in principle, a measurement performed by a terrestrial ring laser could be used to explore the effects of *all* the modified terms of the metric.

Notice that this is not true, for instance, for the LAGEOS/LARES experiment, which has been designed to measure *only* the gravito-magnetic field of the Earth, that is the G_{0i} term[2] of the metric (1). In other words, the measurements that could be performed by GINGER are *complementary* to those of LAGEOS/LARES.

As an example of modified gravity model, we may consider **Horava-Lifshits gravity** (a four-dimensional theory of gravity which is power-counting renormalizable and, hence, can be considered as a candidate for the ultraviolet completion of GR). In particular, if we denote by θ the colatitude of the laboratory, and by α the angle between the radial direction and the normal vector the interferometer plane, the geodetic term is modified according to (see e.g. [3])

$$-2\frac{GM}{c^2R}\Omega_{\oplus}\sin\theta\sin\alpha \to \left(1 + \frac{G^*}{G}a_1 - \frac{a_2}{a_1}\right)\frac{G^*M}{c^2R}\sin\theta\sin\alpha \tag{9}$$

while the Lense-Thirring one by

$$\frac{GI_{\oplus}}{c^2R^3}\Omega_{\oplus}\left(2\cos\theta\cos\alpha + \sin\theta\sin\alpha\right) \to \frac{G^*I_{\oplus}}{c^2R^3}\Omega_{\oplus}\left(2\cos\theta\cos\alpha + \sin\theta\sin\alpha\right) \tag{10}$$

In the above equations a_1, a_2 are coupling constants of the theory and G^* is the Newtonian constant in the Horava-Lifshits theory, that could, in principle, differ from the GR one. So, we see that the modification of the two terms are different in this modified gravity model: GINGER could, in principle, constrain the constants G^*, a_1, a_2 while the measurements performed by LARES do not depend on a_1, a_2.

A similar situation happens in **extended theories of gravity**: in [4] the authors consider the weak field limit (in order to describe with sufficient accuracy the weak field of the Earth) of a generic scalar-tensor-higher-order model and show that both the geodetic and the Lense-Thirring terms are modified, by somewhat complicated combinations of terms that depend on the effective masses m_R, m_Y, m_ϕ of the model. In particular, $\mathbf{\Omega}_G \to \mathbf{\Omega}_G + \mathbf{\Omega}_G^{EG}$, where

$$\begin{aligned}\mathbf{\Omega}_G^{(EG)} = -\Big[& g(\xi,\eta)(m_R\bar{k}_R r + 1)\,F(m_R\bar{k}_R\mathcal{R})\,e^{-m_R\bar{k}_R r} + \frac{8}{3}(m_Y r + 1)\,F(m_Y\mathcal{R})\,e^{-m_Y r} \\ & + \frac{1}{3} - g(\xi,\eta)](m_R\bar{k}_\phi r + 1)F(m_R\bar{k}_\phi\mathcal{R})\,e^{-m_R\bar{k}_\phi r}\Big]\frac{\mathbf{\Omega}_G}{3}\,.\end{aligned} \tag{11}$$

and $\mathbf{\Omega}_B \to \mathbf{\Omega}_B + \mathbf{\Omega}_B^{EG}$, where

$$\mathbf{\Omega}_B^{(EG)} = -e^{-m_Y r}(1 + m_Y r + {m_Y}^2 r^2)\,\mathbf{\Omega}_B\;,$$

Once again, notice that the modifications of the two terms are different, and that GINGER could be able to test both of them.

Another example of modified gravity model that could be tested, in principle, by GINGER is the **Standard Model Extension**, in which violations of Lorentz symmetry are allowed for both gravity and electromagnetism: actually, these violations could be signals of new physics effects deriving from a still unknown underlying quantum theory of gravity [5]. There are 9 coefficients $\bar{s}^{\mu\nu}$ that parameterize the effects of Lorentz violation in the gravitational sector, under the assumption of spontaneous Lorentz-symmetry breaking. In particular, in [6] it is shown that additional contributions deriving from Lorentz violation are present in the gravitational field of a point-like source of mass M, that to lowest order approximation are

$$\begin{aligned} G_{00} &= 1-2U(R)\left[1+\frac{3}{2}\bar{s}^{00}\right], \qquad (12) \\ G_{0j} &= -U(R)\left[\bar{s}^{0j}\right]. \qquad (13) \end{aligned}$$

We have modifications of the de Sitter contribution, due to (12), and of the gravito-magnetic contribution, due to (13).

Eventually, also **Chern-Simons gravity** [7] introduces peculiar modifications of the ring-laser signal with respect to General Relativty.

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[1] Will, C.M., *Living Rev. Relativity* **9**, 3 (2006), `http://www.livingreviews.org/lrr-2006-3`
[2] M. L. Ruggiero, Galaxies, 2015:84102 (2015)
[3] N. Radicella, G. Lambiase, L. Parisi and G. Vilasi, JCAP **1412** (2014) 12, 014 [arXiv:1408.1247 [gr-qc]].
[4] S. Capozziello, G. Lambiase, M. Sakellariadou and A. Stabile, Phys. Rev. D **91** (2015) 4, 044012 [arXiv:1410.8316 [gr-qc]].
[5] Q. G. Bailey and V. A. Kostelecky, Phys. Rev. D **74** (2006) 045001 [gr-qc/0603030].
[6] Q. G. Bailey, Phys. Rev. D **82** (2010) 065012 [arXiv:1005.1435 [gr-qc]].
[7] D. Kikuchi, N. Omoto, K. Yamada, H. Asada, arXiv:1405.7472 [gr-qc].

Real Implementation of GINGER

- 3 axial system
- Large rings 6-10m side
- At least 4 rings, since redundancy is important

Square or triangular can be discussed, I personally have a preference for a square cavity since has higher sensitivity (higher scale factor)

Scale factor S/P stable 1 part 10^{10}

$$\Delta f = \frac{4}{\lambda P} \; (\mathbf{\Omega}_{\oplus} + \mathbf{\Omega}') \cdot \mathbf{S},$$

- Scale Factor depends on the ratio area S over perimeter P
- Hetero-lithic solution requires to actively fix

the Scale Factor

CONTROL STRATEGY

ERROR SIGNALS AND ACTUATORS

CONTROL STRATEGY

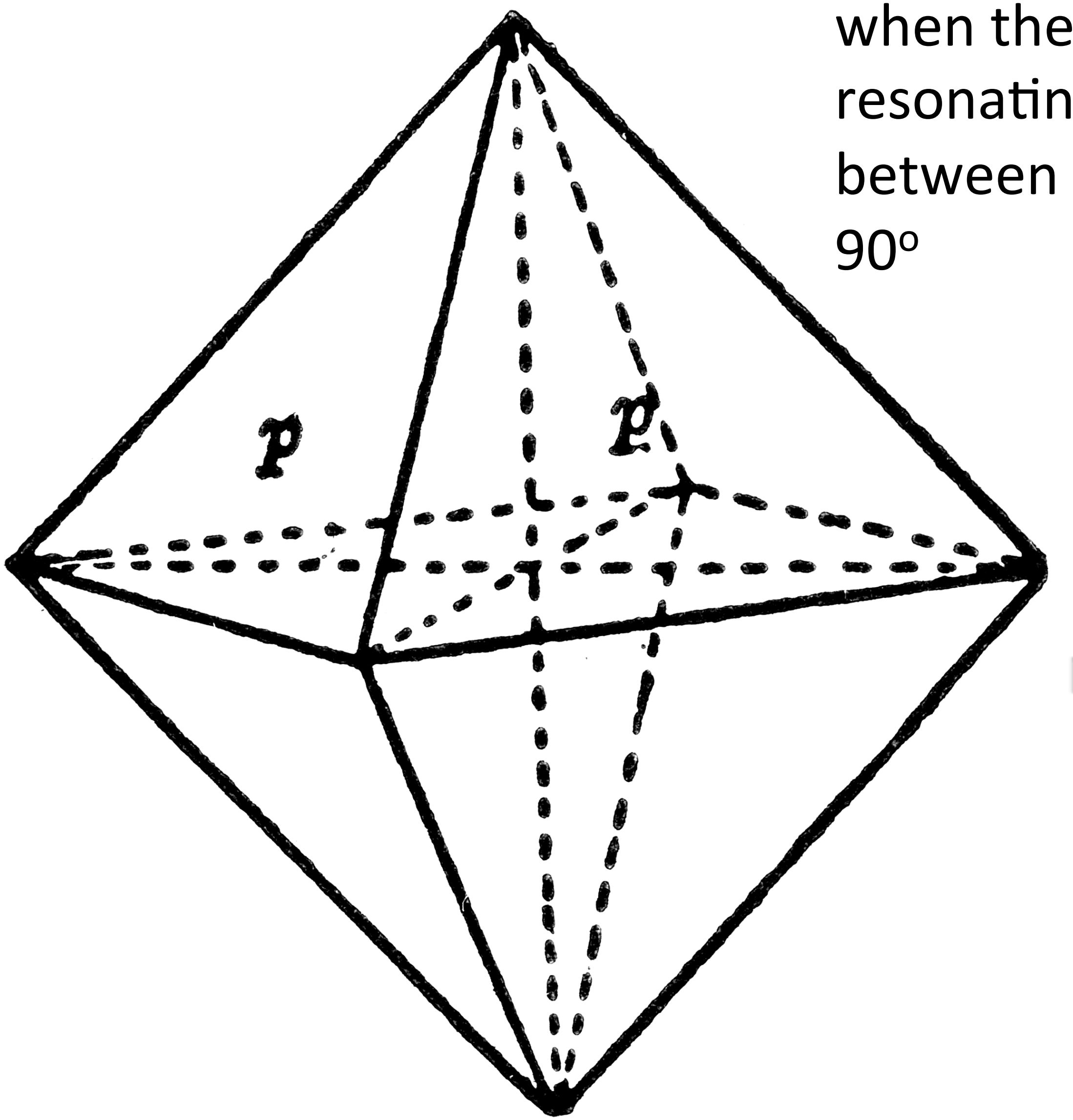
- Ring constructed very close to a regular square ring (~ μm error)
- Error signals: the two diagonals cavities and GEMS
- One reference solution: fix the length of the two diagonals of the square. Other possibilities are under study
- Actuators: mirrors moved by piezoeletric transducer. Large bandwidth is not necessary on the control loop.
- Temperature and pressure controlled environment necessary in order to reduce the overall bandwidth of the control

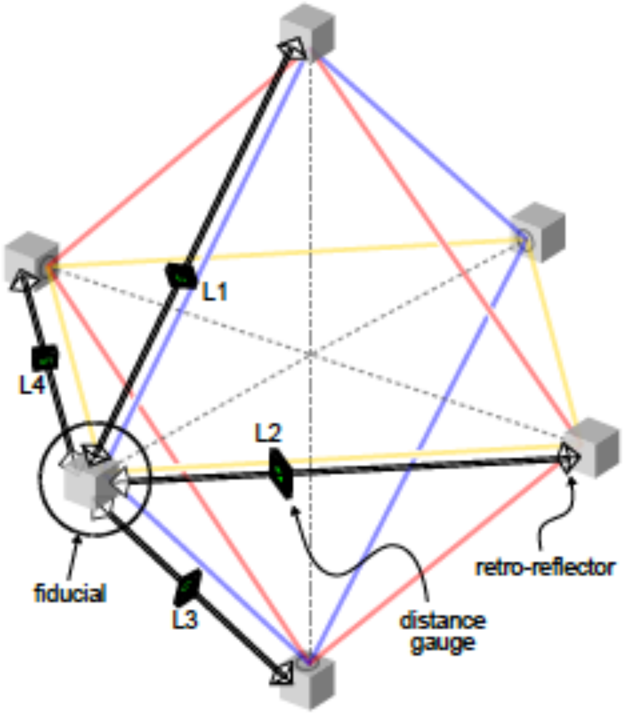
Vector Reconstruction

- Angle with respect to the earth axis larger than 20-30 degrees (avoid Sagnac frequency shutdown)
- Monitor of the relative angle at nrad level

The octahedron is a rigid figure

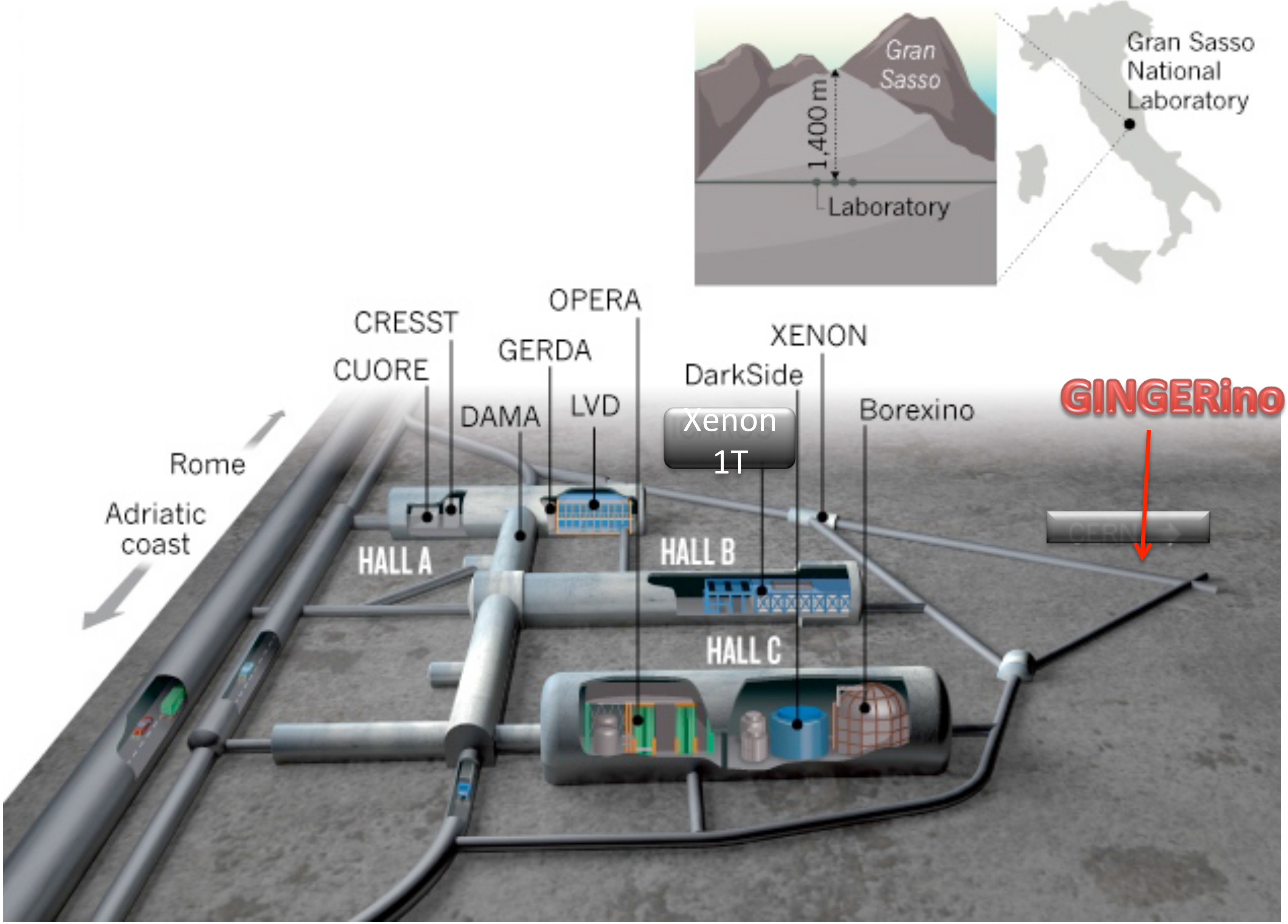
when the 3 ring-laser cavity are resonating, the relative angles between different rings should be 90^o





Possible location inside LNGS

- Node B, if available, could be well isolated from environmental noise, but not larger than 7 (8) m side, with a suitable choice of the geometry
- Hall B, if available, rings up to 10m side could be realized. In this case the north part should be preferable and isolation should be carefully studied


Gran Sasso
1,400 m
Laboratory
Gran Sasso National Laboratory
OPERA
CRESST
XENON
GERDA
CUORE
DarkSide
GINGERino
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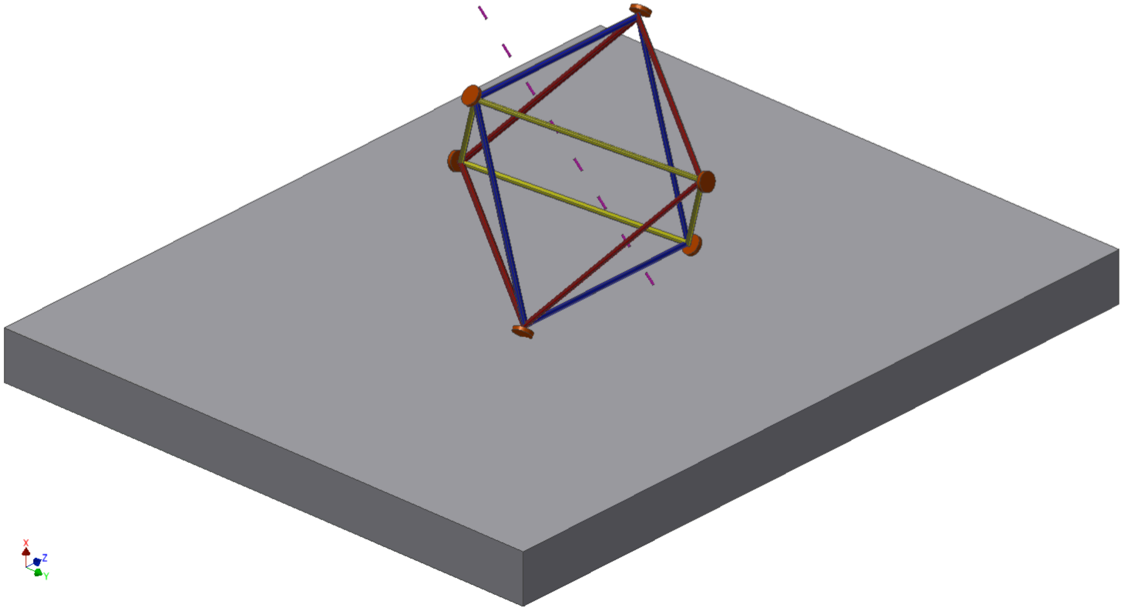
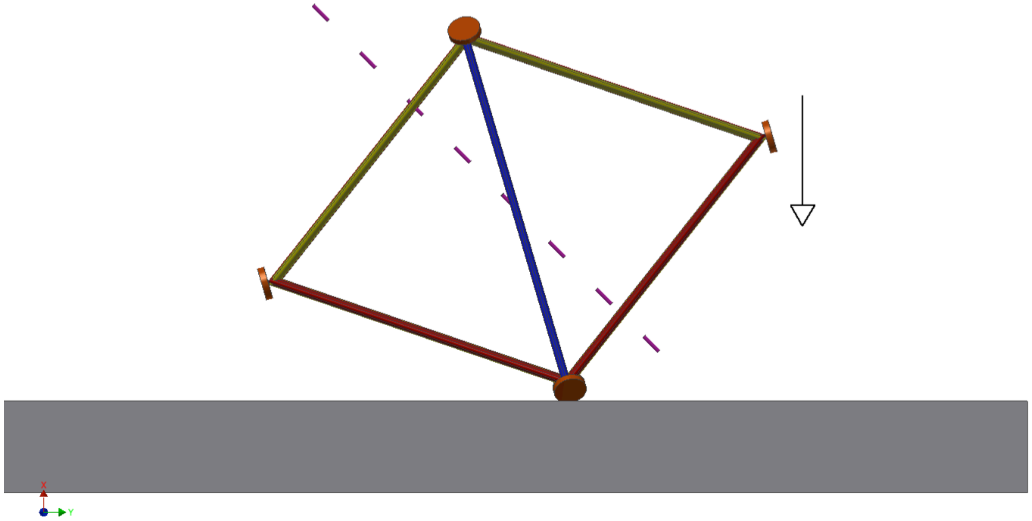
HALL A
HALL B
CERN
HALL C


X
Z
Y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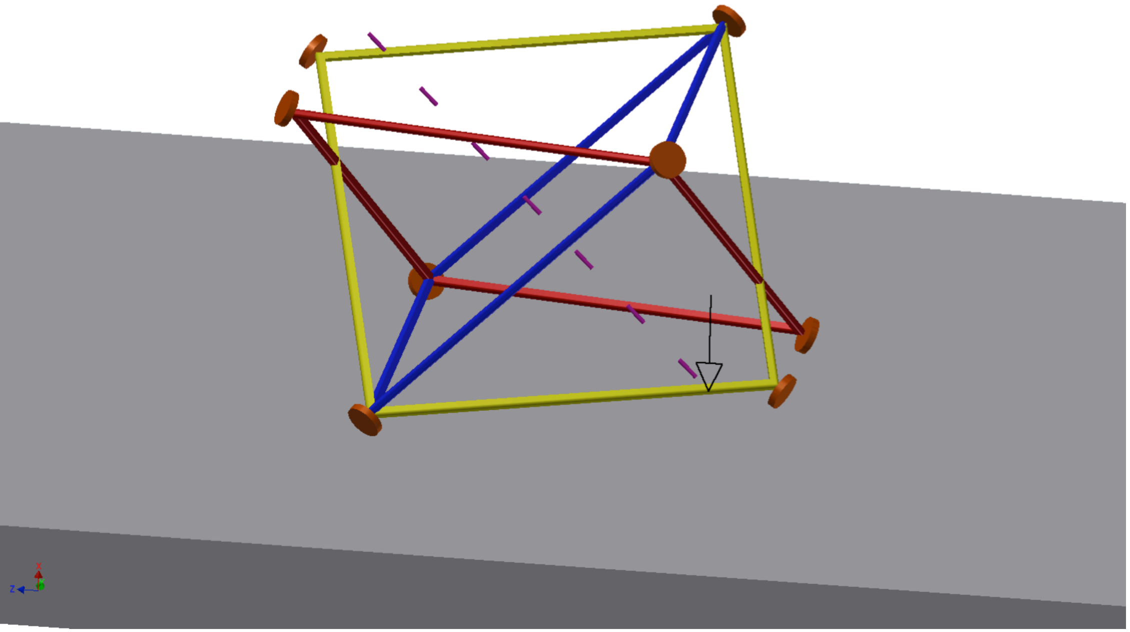
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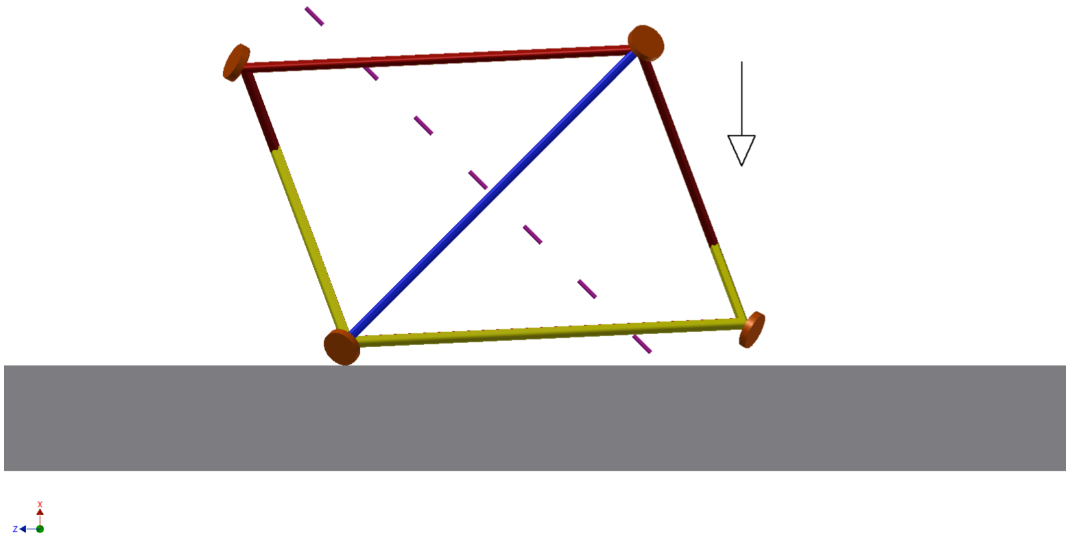

x
z

Costs and Man Power for the apparatus only

- Assuming that the lab. is ready and well controlled in temperature and pressure
- rough estimation 5ME

Let me remark the following

- Physicists/engineers able to run the instrument

should be able to provide the data with quality check, but specific finalized analysis (geophysic-geodesy and GR) need dedicated experts

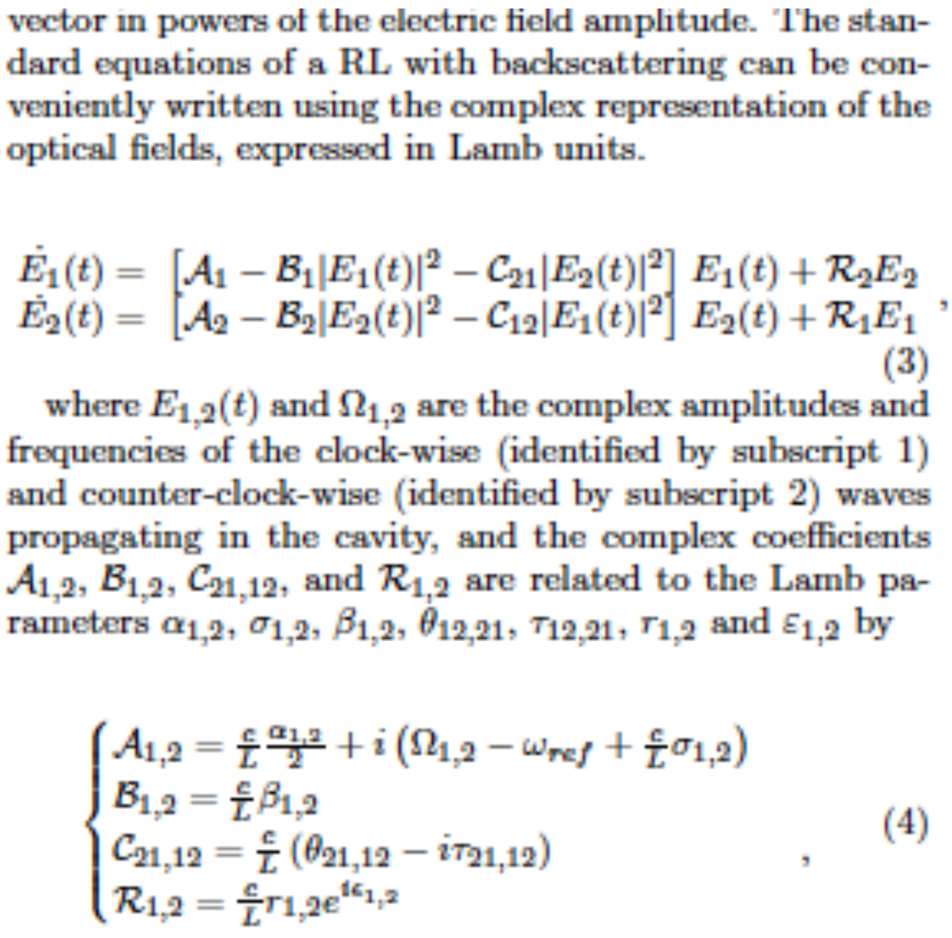
NOTE: it is always very important in high sensitivity apparatus that the researchers dedicated to the instrument are able to analyze the data to a certain extend…they have to be able to listen to the instrument….

Synergy hardwar&software&theory people

Good coordination is more important than the number of people involved

“SENSITIVITY” is the first condition, but “ACCURACY” follows immediately after!

THE EQUATIONS WHICH REGULATES A RING-LASER ARE RATHER COMPLICATED



vector in powers of the electric field amplitude. The standard equations of a RL with backscattering can be conveniently written using the complex representation of the optical fields, expressed in Lamb units.

$$\begin{array}{ll} \dot{E}_1(t) = & \left[\mathcal{A}_1 - \mathcal{B}_1|E_1(t)|^2 - \mathcal{C}_{21}|E_2(t)|^2\right] E_1(t) + \mathcal{R}_2 E_2 \\ \dot{E}_2(t) = & \left[\mathcal{A}_2 - \mathcal{B}_2|E_2(t)|^2 - \mathcal{C}_{12}|E_1(t)|^2\right] E_2(t) + \mathcal{R}_1 E_1 \end{array}, \tag{3}$$

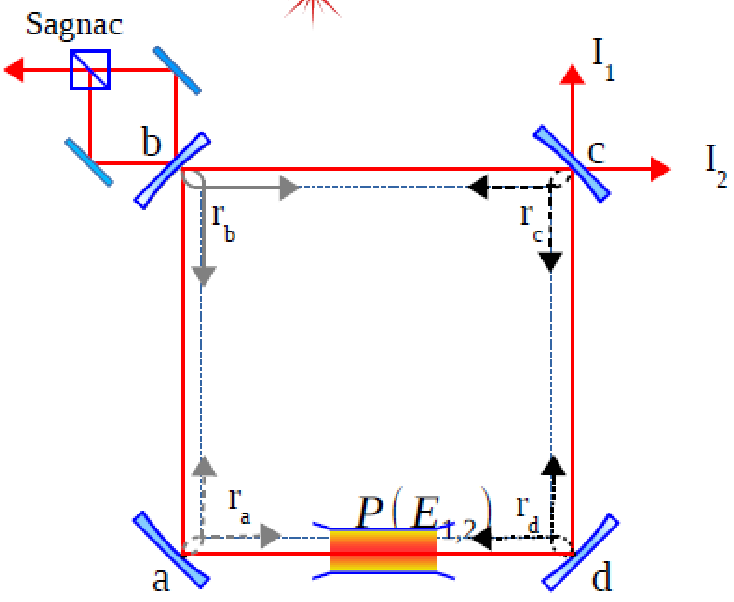
where $E_{1,2}(t)$ and $\Omega_{1,2}$ are the complex amplitudes and frequencies of the clock-wise (identified by subscript 1) and counter-clock-wise (identified by subscript 2) waves propagating in the cavity, and the complex coefficients $\mathcal{A}_{1,2}$, $\mathcal{B}_{1,2}$, $\mathcal{C}_{21,12}$, and $\mathcal{R}_{1,2}$ are related to the Lamb parameters $\alpha_{1,2}$, $\sigma_{1,2}$, $\beta_{1,2}$, $\theta_{12,21}$, $\tau_{12,21}$, $r_{1,2}$ and $\varepsilon_{1,2}$ by

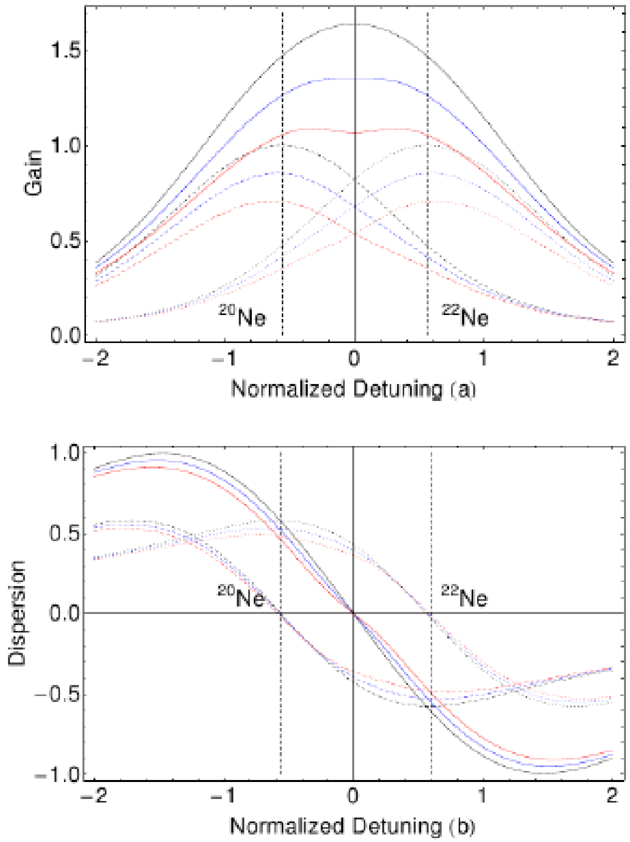
$$\begin{cases} \mathcal{A}_{1,2} = \frac{c}{L}\frac{\alpha_{1,2}}{2} + i\left(\Omega_{1,2} - \omega_{ref} + \frac{c}{L}\sigma_{1,2}\right) \\ \mathcal{B}_{1,2} = \frac{c}{L}\beta_{1,2} \\ \mathcal{C}_{21,12} = \frac{c}{L}\left(\theta_{21,12} - i\tau_{21,12}\right) \\ \mathcal{R}_{1,2} = \frac{c}{L} r_{1,2} e^{i\epsilon_{1,2}} \end{cases}, \tag{4}$$

Ring laser "hacking"

model and study laser sistematics

A. Beghi et al. Applied Optics **51**, 31 (2012)





Active medium He+^{20}Ne+^{22}Ne

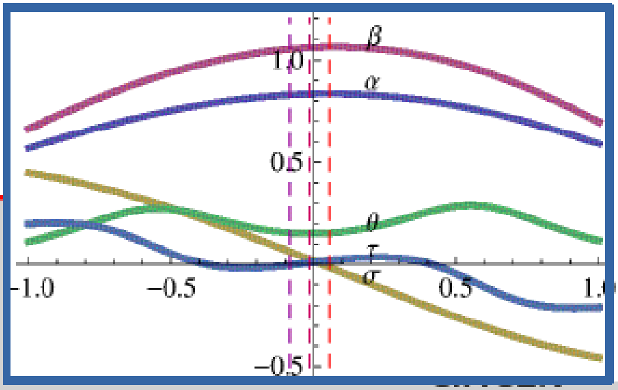
$$P^{(3)}(E_{1,2}) = \frac{-2i\mu_{ab}^{2}}{\gamma_{ab}} \int_{-\infty}^{\infty} \chi_{1,2}(v)\,\rho^{(2)}(v,E_{1,2})\,dv$$

Opposite beams dynamics

$$\dot{I}_1 = \alpha_1 I_1 - \beta I_1^2 - \theta_2 I_2 I_1 + r_2\sqrt{I_1 I_2}\cos(\psi - \epsilon_2)\,,$$

$$\dot{I}_2 = \alpha_2 I_2 - \beta I_2^2 - \theta_1 I_2 I_1 + r_1\sqrt{I_1 I_2}\cos(\psi + \epsilon_2)\,,$$

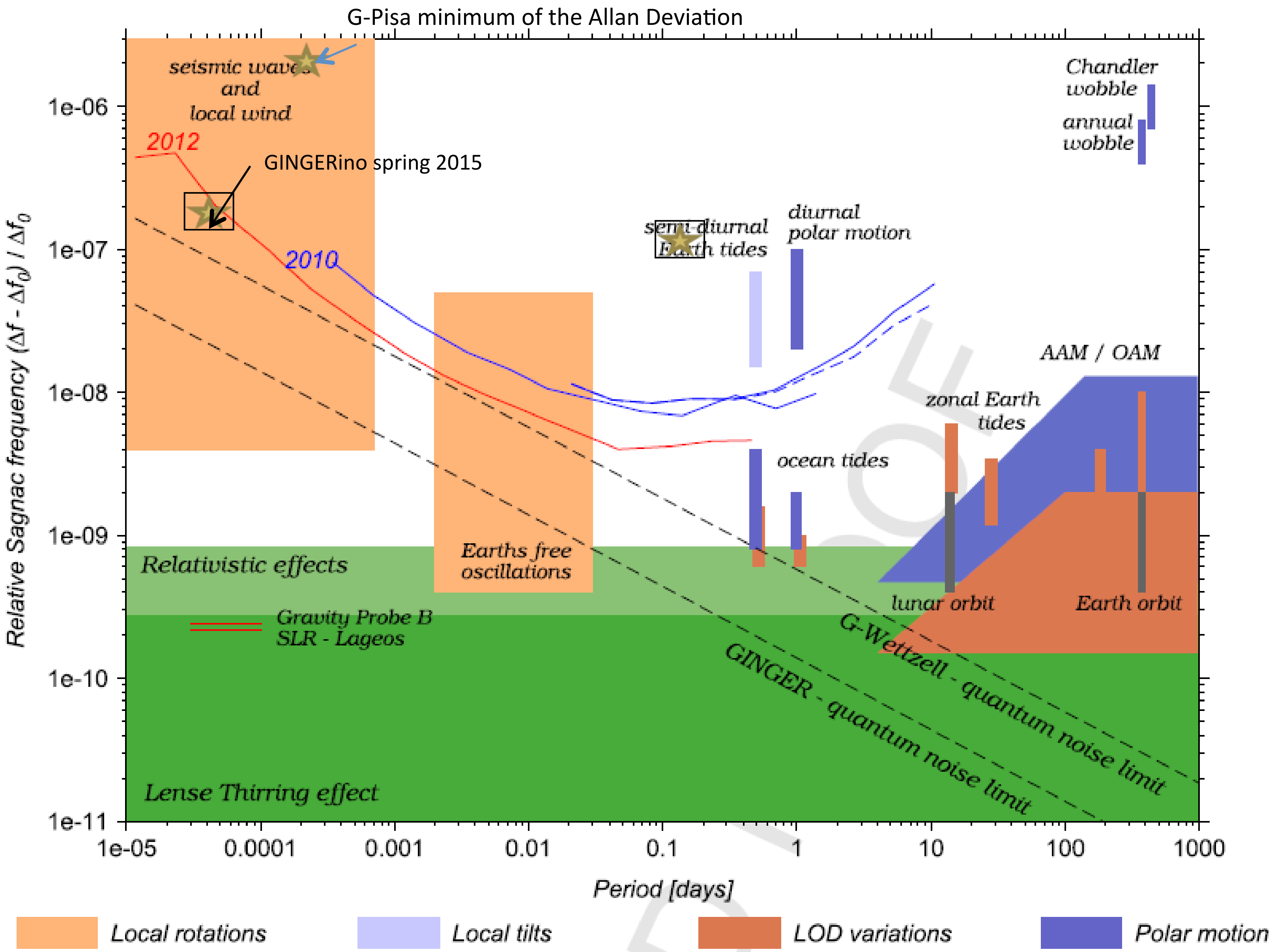
$$\dot{\psi} = \omega_s + \tau_1 I_1 - \tau_2 I_2 - r_2\sqrt{\frac{I_2}{I_1}}\sin(\psi - \epsilon_2) - r_1\sqrt{\frac{I_1}{I_2}}\sin(\psi + \epsilon_1)$$



it is impossible to know each term, especially the gain of the discharge, with 10^{-10} accuracy

‘accuracy….several strategy’

- Redundancy: at least 4 rings, we should not forget that we are measuring vectors
- Confrontation of independent measurements, not only of the Earth angular rotation but as well of the well studied geodetic signals (polar motions etc.)
- Passive-active ring-laser. The same apparatus can be used as an array of passive or active rings
- Calibration lines from thermal noise power spectrum, this is true if we use a solid monument to hold the whole array (very challenging)

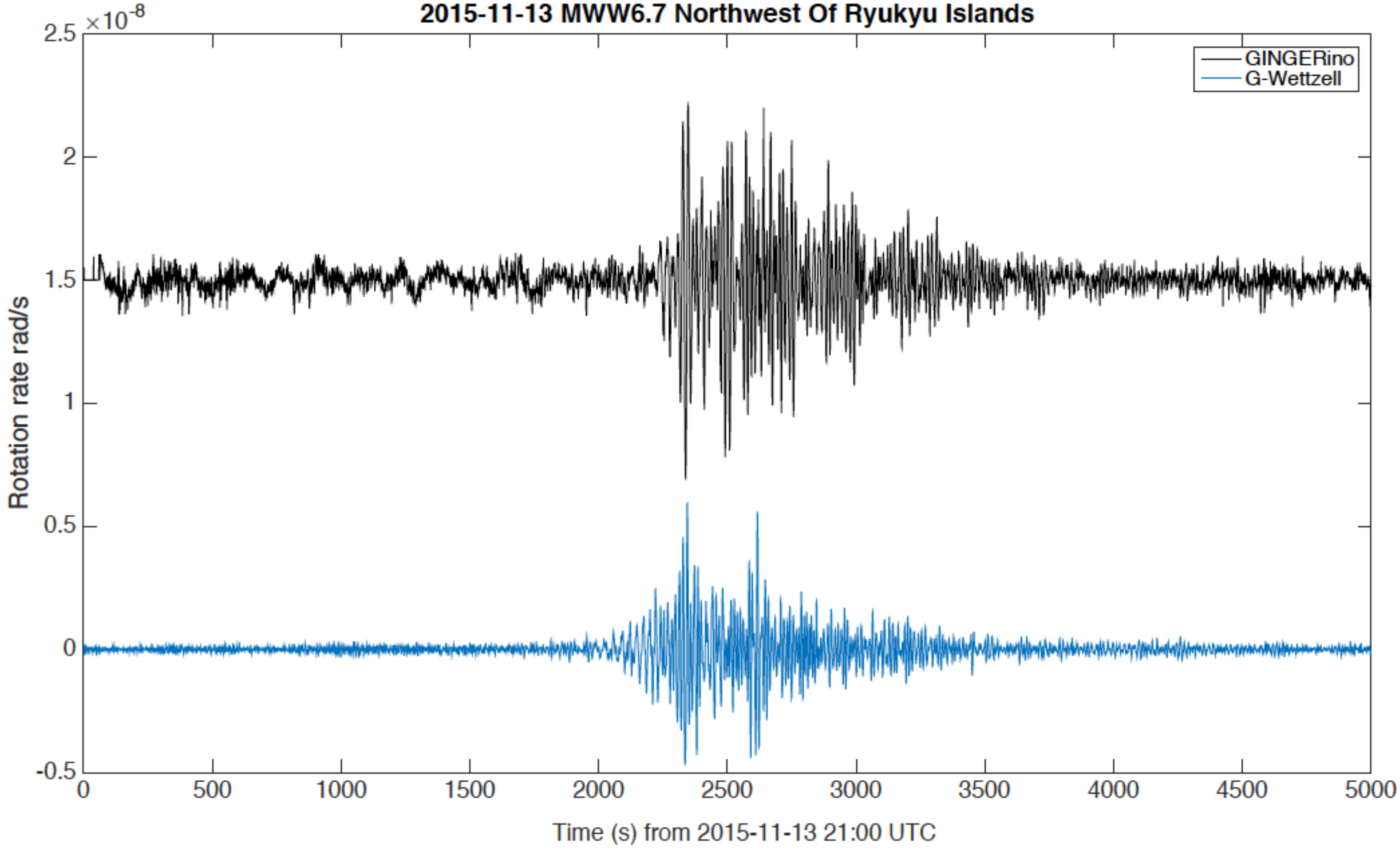


G-Pisa minimum of the Allan Deviation

GINGERino spring 2015

More on ‘accuracy’

- Confrontation of different instruments (ROMY, G, GINGERino and GINGER)
- Redundancy is necessary for large apparatus (at least 4 rings)
- The Hetero-lithic ring-laser could be calibrated with calibrated arches (very challenging)


2015-11-13 MWW6.7 Northwest Of Ryukyu Islands
×10^-8
2.5
2
1.5
1
0.5
0
-0.5
Rotation rate rad/s
GINGERino
G-Wettzell
0
500
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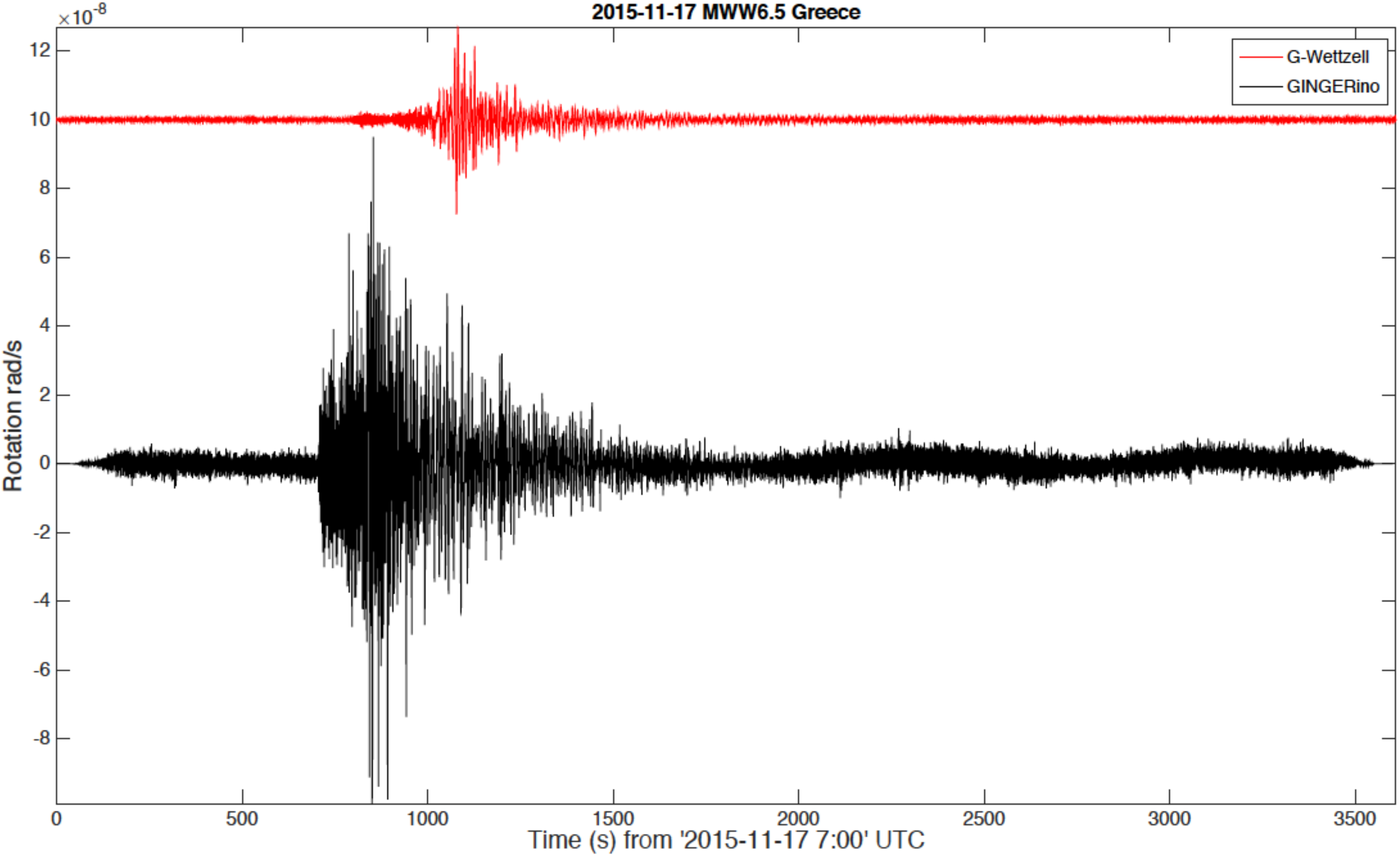
1500
2000
2500
3000
3500
4000
4500
5000
Time (s) from 2015-11-13 21:00 UTC


2015-11-17 MWW6.5 Greece
×10^-8
12
10
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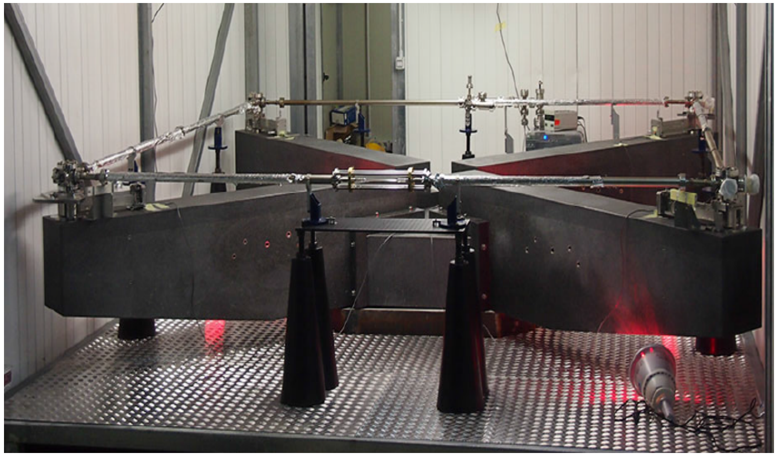
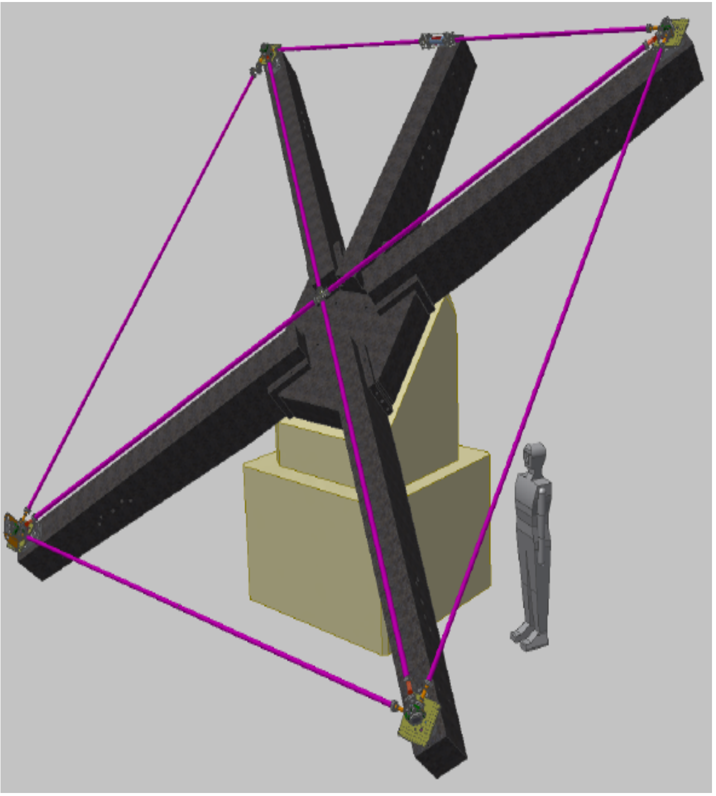
A ring at the maximum signal is less sensitive to local tilts

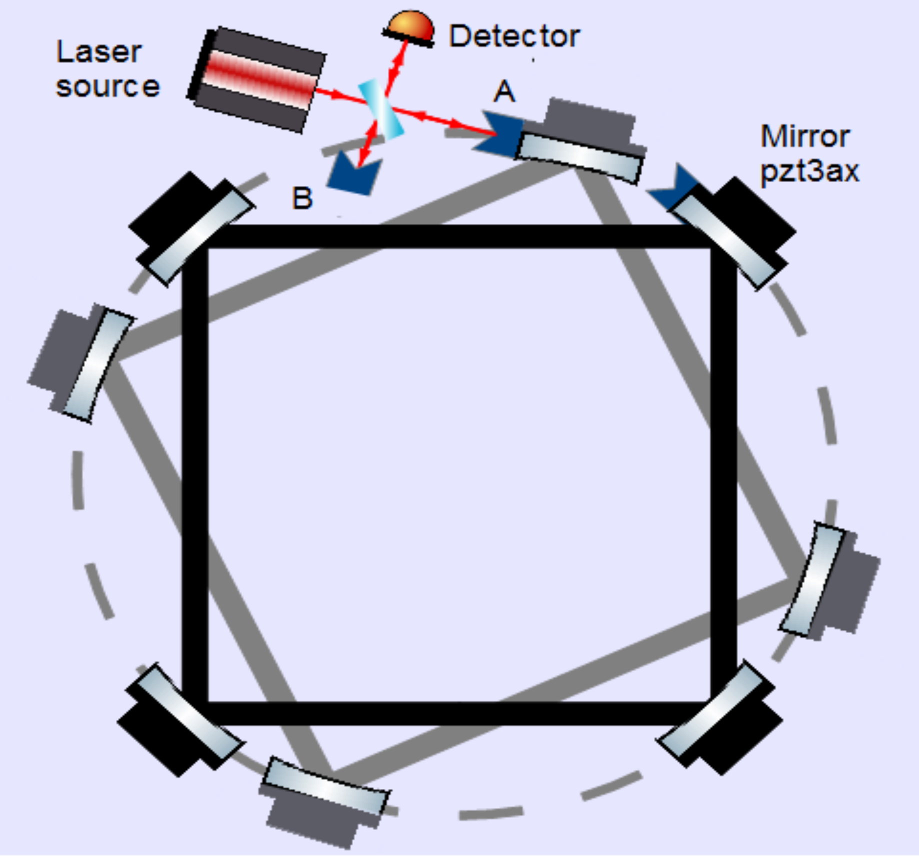




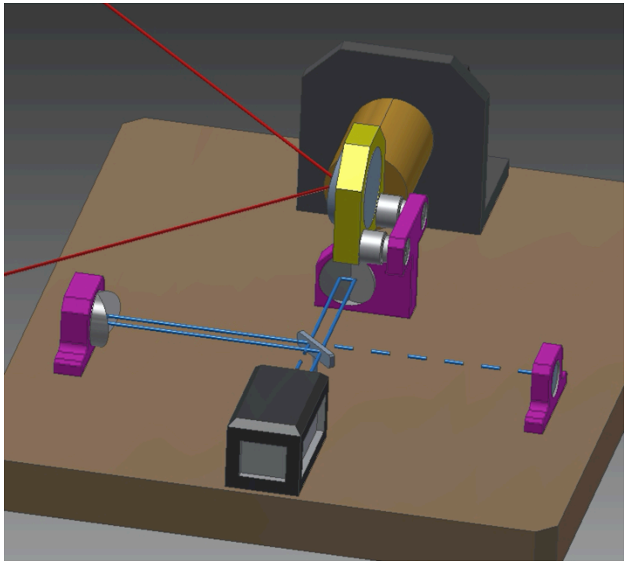
A very special orientation

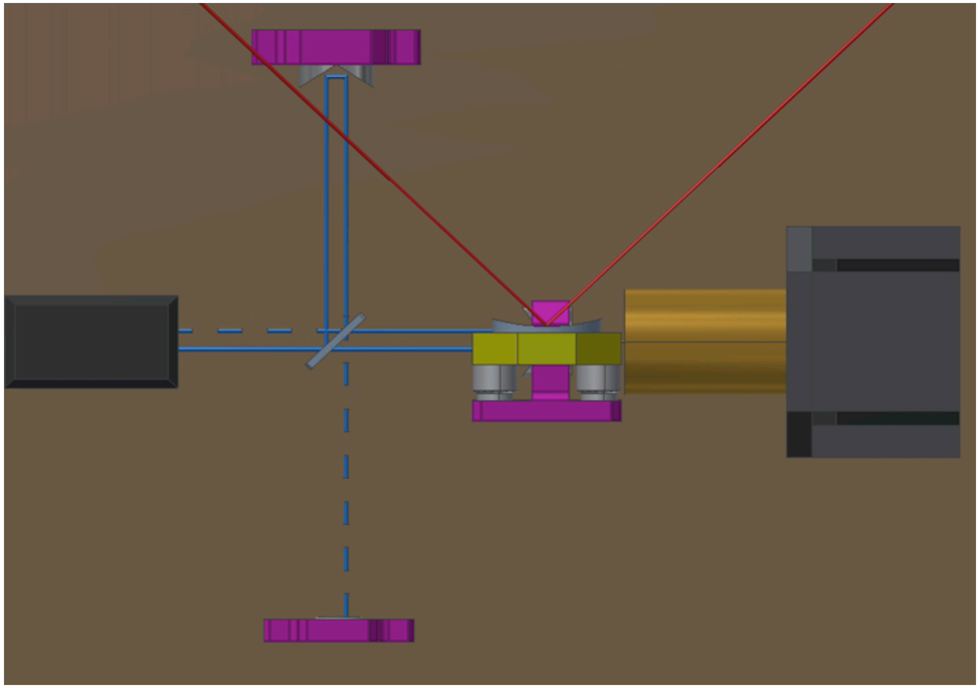
To orientate the ring to the maximum Sagnac signal has several interesting features

Calibration with calibrated arches



- The hetero-lithic design allows the independent motion of each mirrors
- Combining the motion of the 4 mirrors together it is possible to rotate the whole ring





The calibration unit

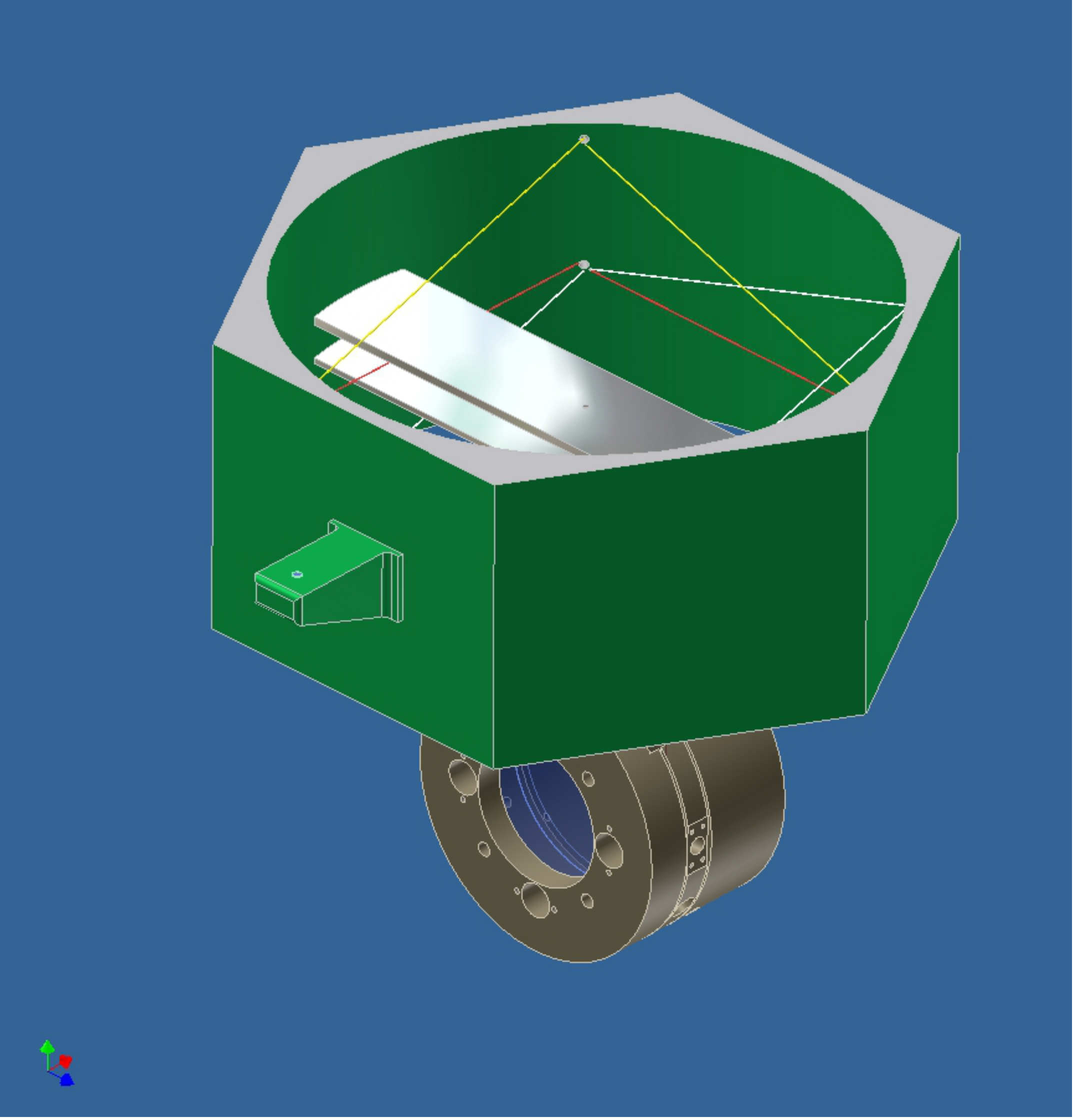
Each mirror describes an equal arch, with a good timing. An independent interferometer measure the arch, giving in this way the absolute calibration

More on Sagnac and Fundamental Physics

SAGNAC and GW-Applications

- Environmental monitor
- to extend to lower frequency the detector bandwidth (subtract Newtonian Wall)
- Reduce the rotational motion of the suspension- a suitable sensor for the active control of the suspension (TOP or LOWER stages)
- It can act at the Lower stage since it is an inertial sensor

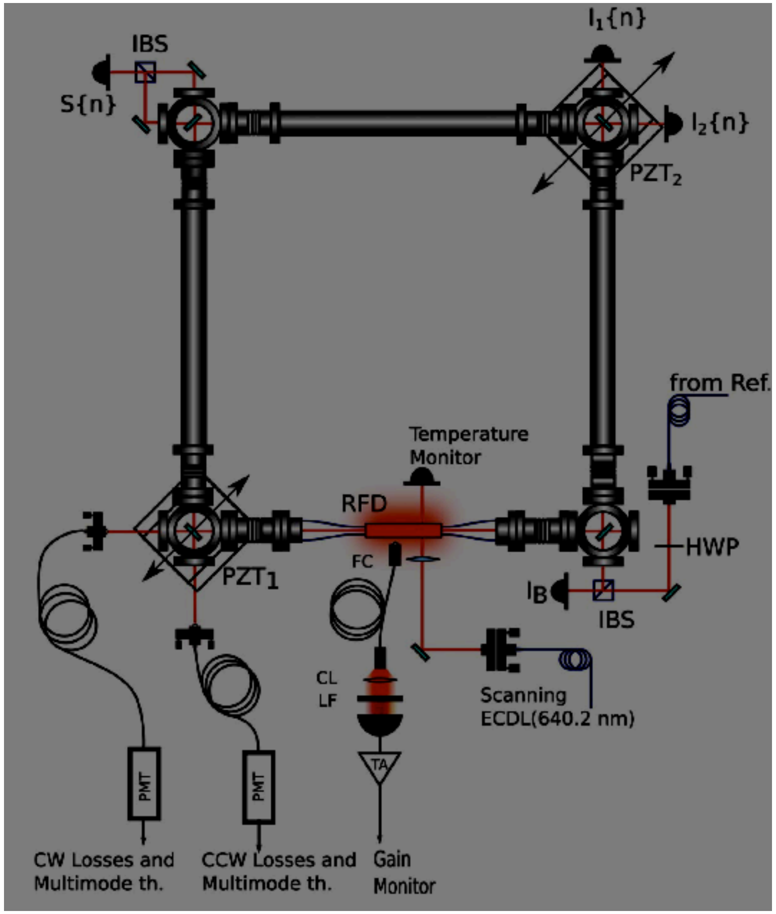
- **It can be directly sensitive to Gravitational Waves!**



- Active control is based on suitable signals. Inertial sensors plays a crucial role
- Ring-Laser are inertial sensors, they could be used to control directly the test mass of the gw antennas
- Reduce the force to control the test mass
- Improve low frequency response
- This could be very important for third generation antennas

A. Di Virgilio et al. About the use of gyro-lasers in gravitational waves interferometric Detectors VIR-019E-07

ACTIVE/PASSIVE SAGNAC



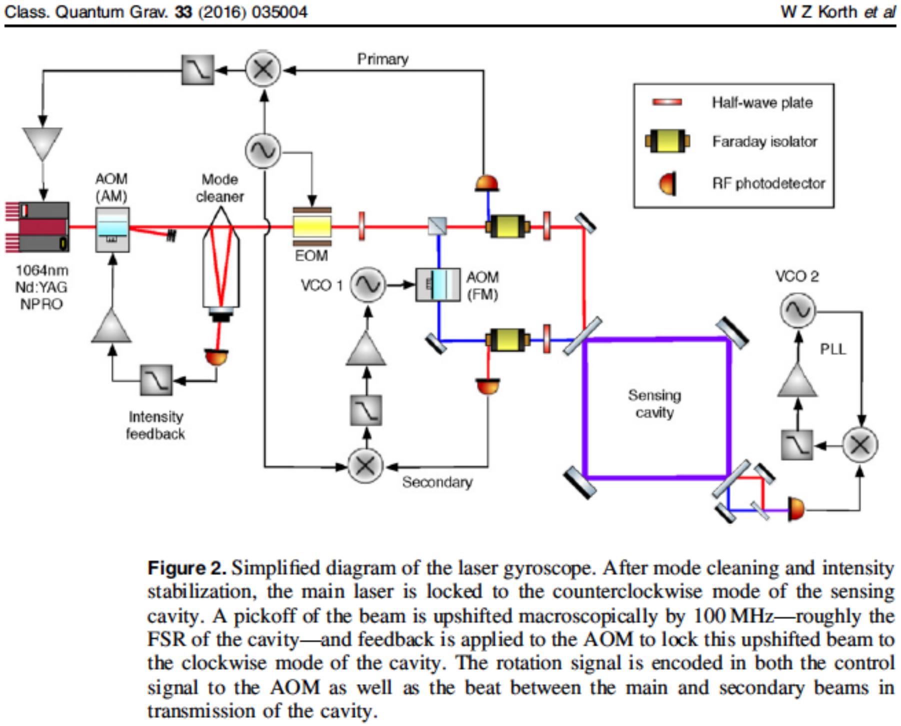

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Figure 2. Simplified diagram of the laser gyroscope. After mode cleaning and intensity stabilization, the main laser is locked to the counterclockwise mode of the sensing cavity. A pickoff of the beam is upshifted macroscopically by 100 MHz—roughly the FSR of the cavity—and feedback is applied to the AOM to lock this upshifted beam to the clockwise mode of the cavity. The rotation signal is encoded in both the control signal to the AOM as well as the beat between the main and secondary beams in transmission of the cavity.

Virgo/Pisa

caltec/Ligo

caltec/Ligo

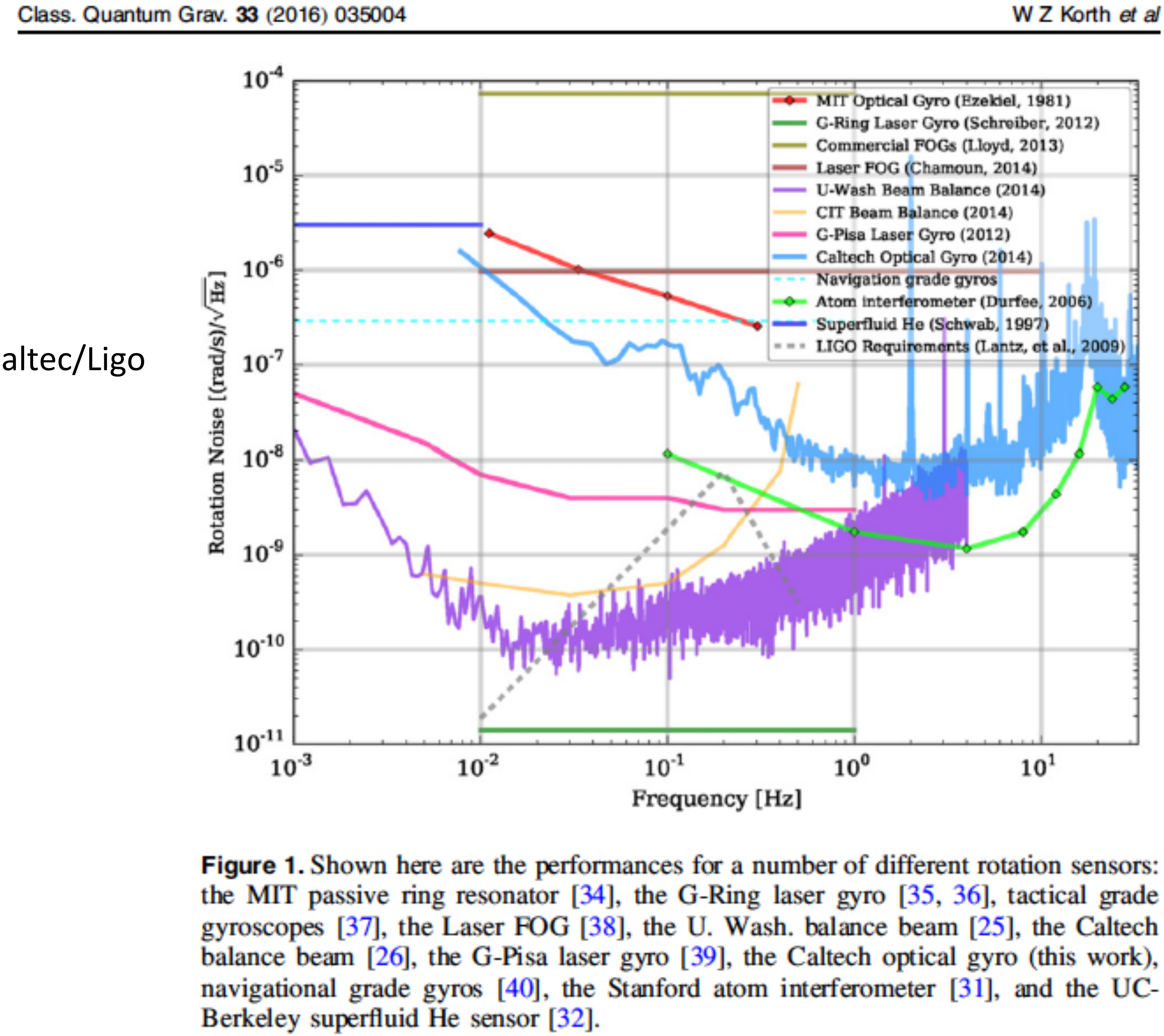

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Figure 1. Shown here are the performances for a number of different rotation sensors: the MIT passive ring resonator [34], the G-Ring laser gyro [35, 36], tactical grade gyroscopes [37], the Laser FOG [38], the U. Wash. balance beam [25], the Caltech balance beam [26], the G-Pisa laser gyro [39], the Caltech optical gyro (this work), navigational grade gyros [40], the Stanford atom interferometer [31], and the UC-Berkeley superfluid He sensor [32].

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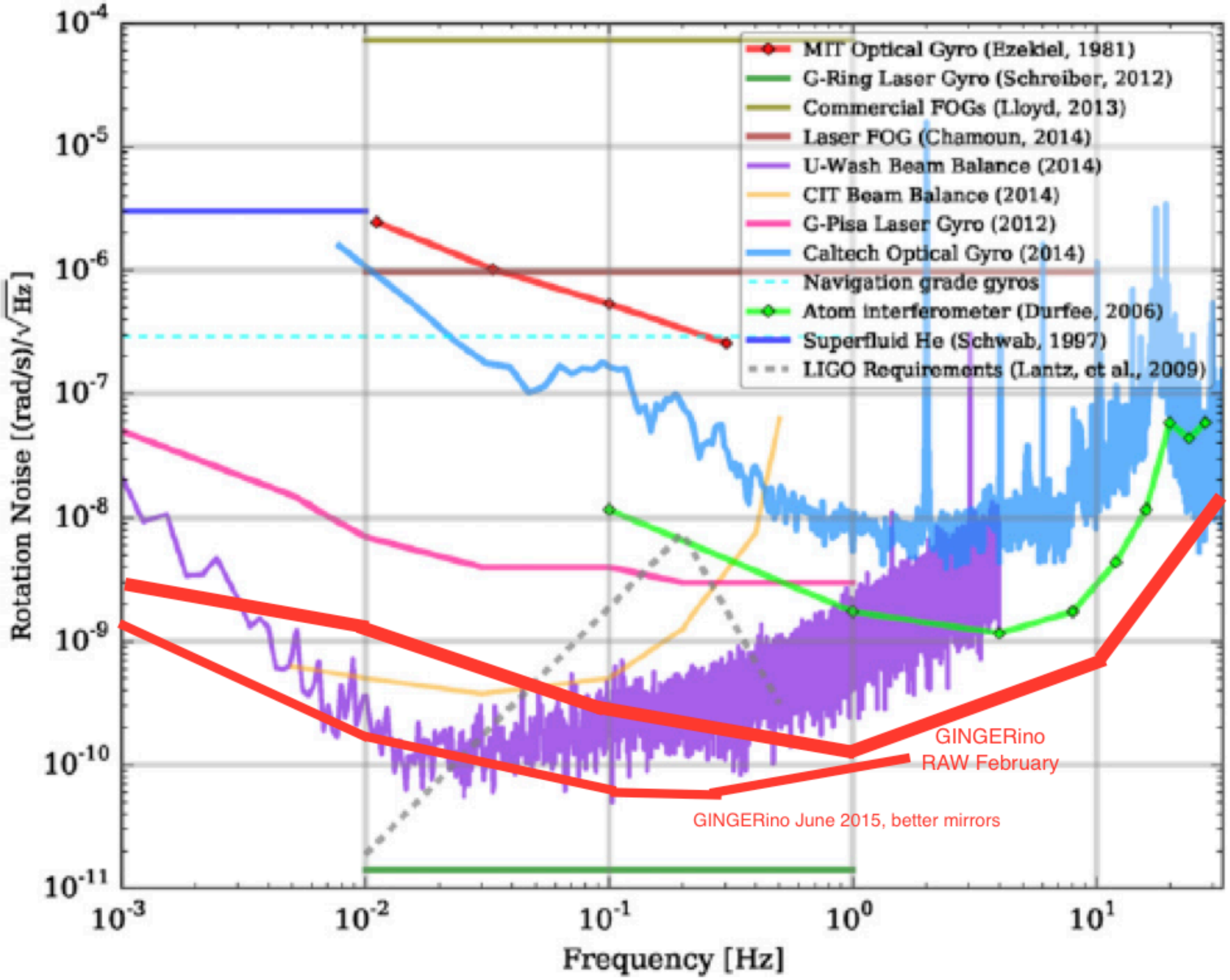
caltec/Ligo



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Is a ring sensitive to GW?
In principle yes

the only advantage is that it could be used to investigate the lower frequency part of the spectrum 0.1-10Hz
$h \sim 10^{-18}\ 10^{-20}$
NECESSARY 10^4 – 10^6 IMPROVEMENT IN SENSITIVITY!

What to do in order to improve the sensitivity

$$\delta\Omega = \frac{cP}{4AQ}\sqrt{\frac{hf}{P_x t}},$$

- Increase size and Q
- Reduce wavelength
- Not easy to increase P_x with active rings

- Squeezing
- N rings
- passive rings could be advantageous, but this device is not yet at the shot-noise limit
- In the high frequency region standard ITF are the best solution

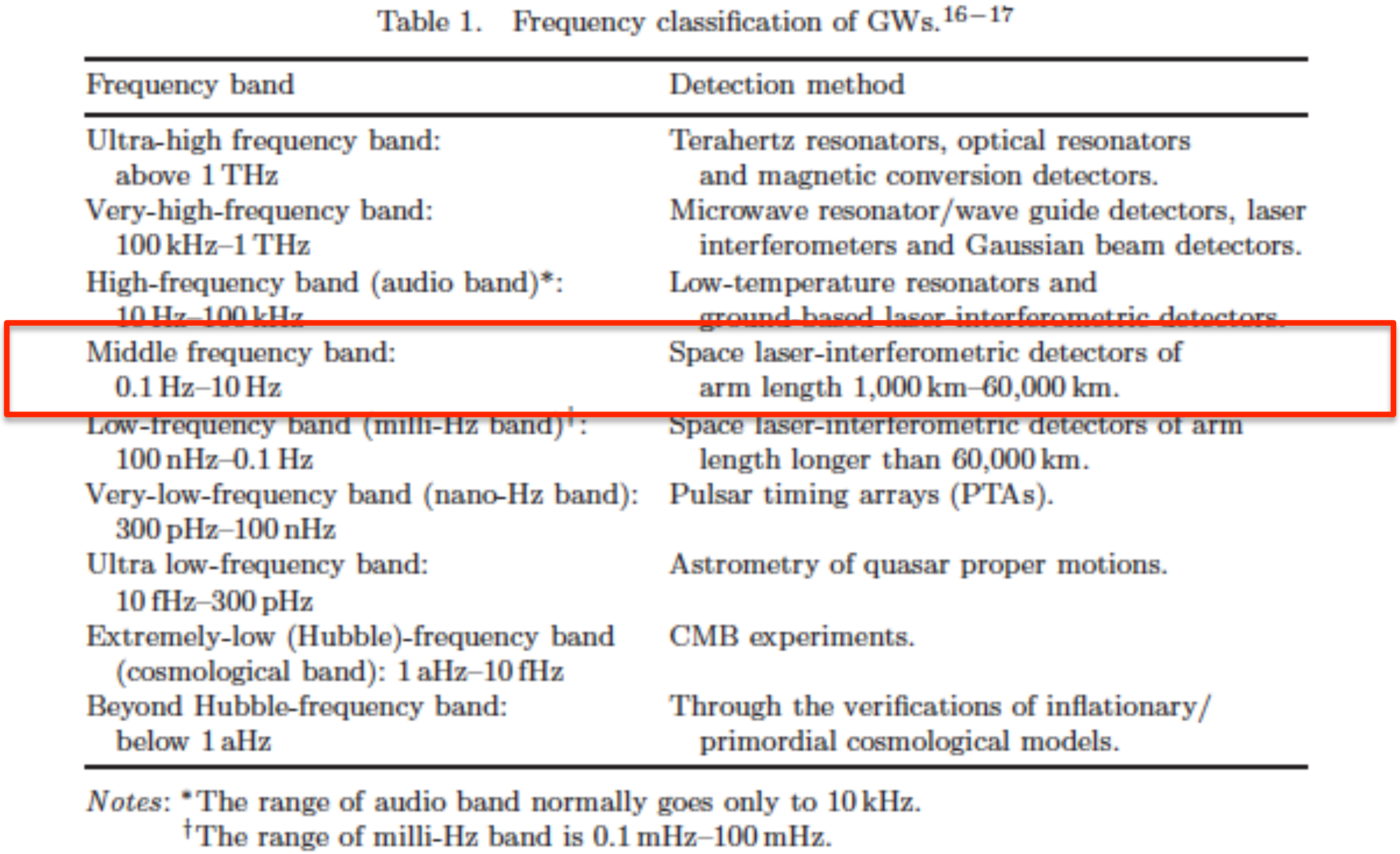

Table 1. Frequency classification of GWs.[16–17]

Frequency band	Detection method
Ultra-high frequency band: above 1 THz	Terahertz resonators, optical resonators and magnetic conversion detectors.
Very-high-frequency band: 100 kHz–1 THz	Microwave resonator/wave guide detectors, laser interferometers and Gaussian beam detectors.
High-frequency band (audio band)*: 10 Hz–100 kHz	Low-temperature resonators and ground-based laser-interferometric detectors.
Middle frequency band: 0.1 Hz–10 Hz	Space laser-interferometric detectors of arm length 1,000 km–60,000 km.
Low-frequency band (milli-Hz band)†: 100 nHz–0.1 Hz	Space laser-interferometric detectors of arm length longer than 60,000 km.
Very-low-frequency band (nano-Hz band): 300 pHz–100 nHz	Pulsar timing arrays (PTAs).
Ultra low-frequency band: 10 fHz–300 pHz	Astrometry of quasar proper motions.
Extremely-low (Hubble)-frequency band (cosmological band): 1 aHz–10 fHz	CMB experiments.
Beyond Hubble-frequency band: below 1 aHz	Through the verifications of inflationary/primordial cosmological models.

Notes: *The range of audio band normally goes only to 10 kHz.
†The range of milli-Hz band is 0.1 mHz–100 mHz.

Why not on Earth! Real Time Detection

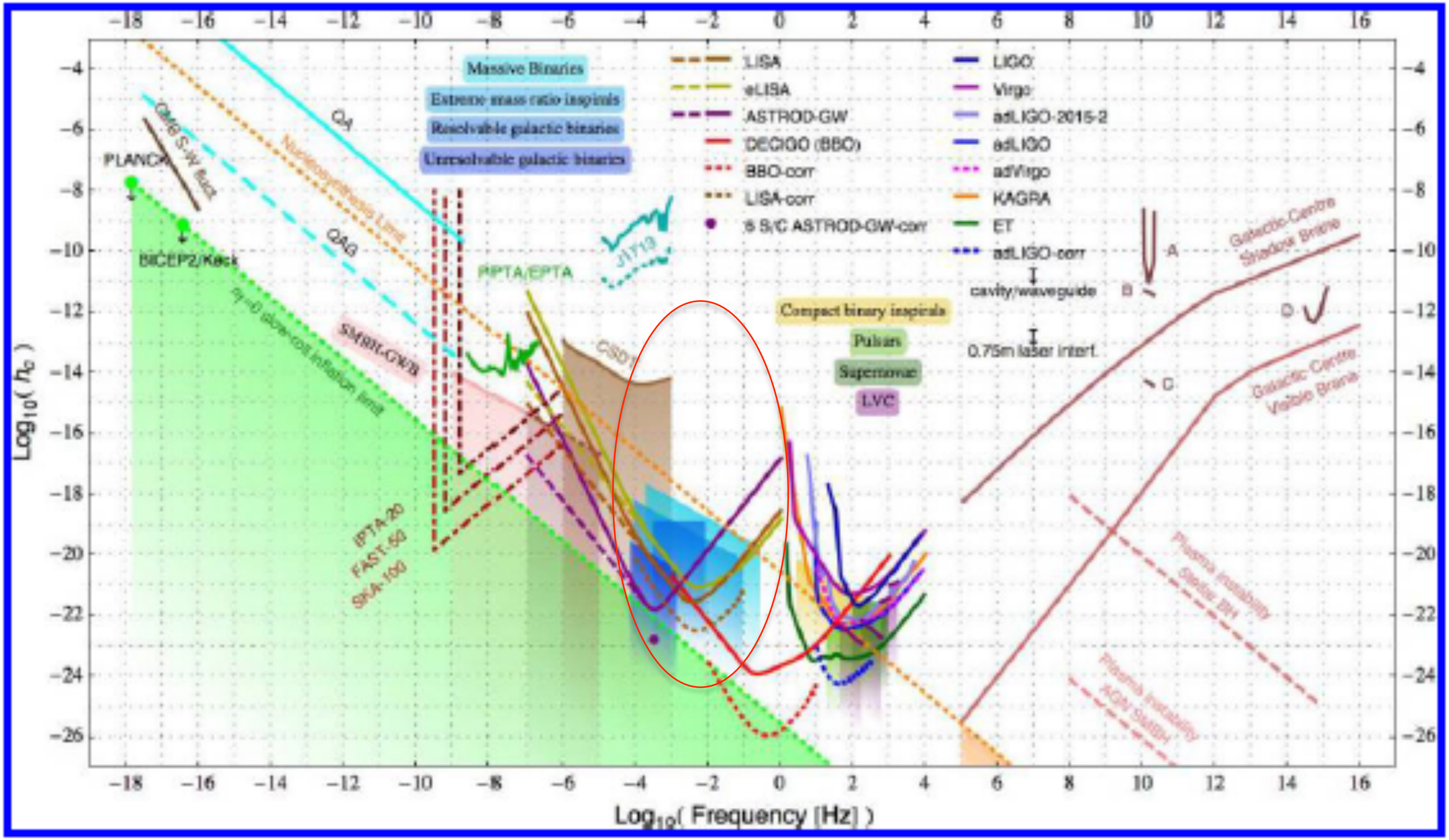

Fig. 2 Characteristic strain h_c versus frequency for various GW detectors and sources. [QA: Quasar Astrometry; QAG: Quasar Astrometry Goal; LVC: LIGO-Virgo Constraints; CSDT: Cassini Spacecraft Doppler Tracking; SMBH-GWB: Supermassive Black Hole-GW Background.]

…a very big experimental work!

- Unaffected by Newtonian Noise, since the probe is the photon
- Using the trigger at high frequency, it could extend the signal at low frequency
- Two apparatus far apart
- Thermal noise reduced since the apparatus is very heavy and could be as well cryogenic
- Squeezing necessary
- It should be investigated if a different active medium could be used, or if it should be passive

….last but not list….

- Future experiment as GLT are going to investigate strong GR observing the halo of the SMBH M87 and Sagittarius: angular resolution necessary 1μrad, a factor 1000 improvement with respect to present

→

- Reference frames plays an important role. This will be as well true for the reconstruction of GW sources

CONCLUSIONS
Let me underline the following

In fundamental physics it is necessary to distinguish between

- FIRST measurement in a certain condition, which can produce Upper Limit, but cannot demonstrate new physics in the case of results different from the majority of the other results
- STATUS of the ART MEASUREMENT which can be compared with independent and different results

Outcome for Fundamental Physics

short medium long term

- Geophysics Geodesy Lense-Thirring 10%-Reference Frames

PPN parameters on Earth frame UL

- GW exp. appar.-(monitoring suspension low frequency enhancement)
- PPN parameters in Earth frame UL-Status of Art
- LT 1%
- PPN parameters in Earth frame Status of Art
- GW low frequency detection? in this calibration is not very important, but sensitivity is an issue

- GINGER
- 3-axial large device-present sensitivity

4 RINGS

- GINGER1& Calibration

sensitivityX10

- Multi-GINGER

SensitivityX100-1000
Full Calibration Squeezing
High power