GINGER AND GINGERINO

EXPERIMENTAL COMMUNITY

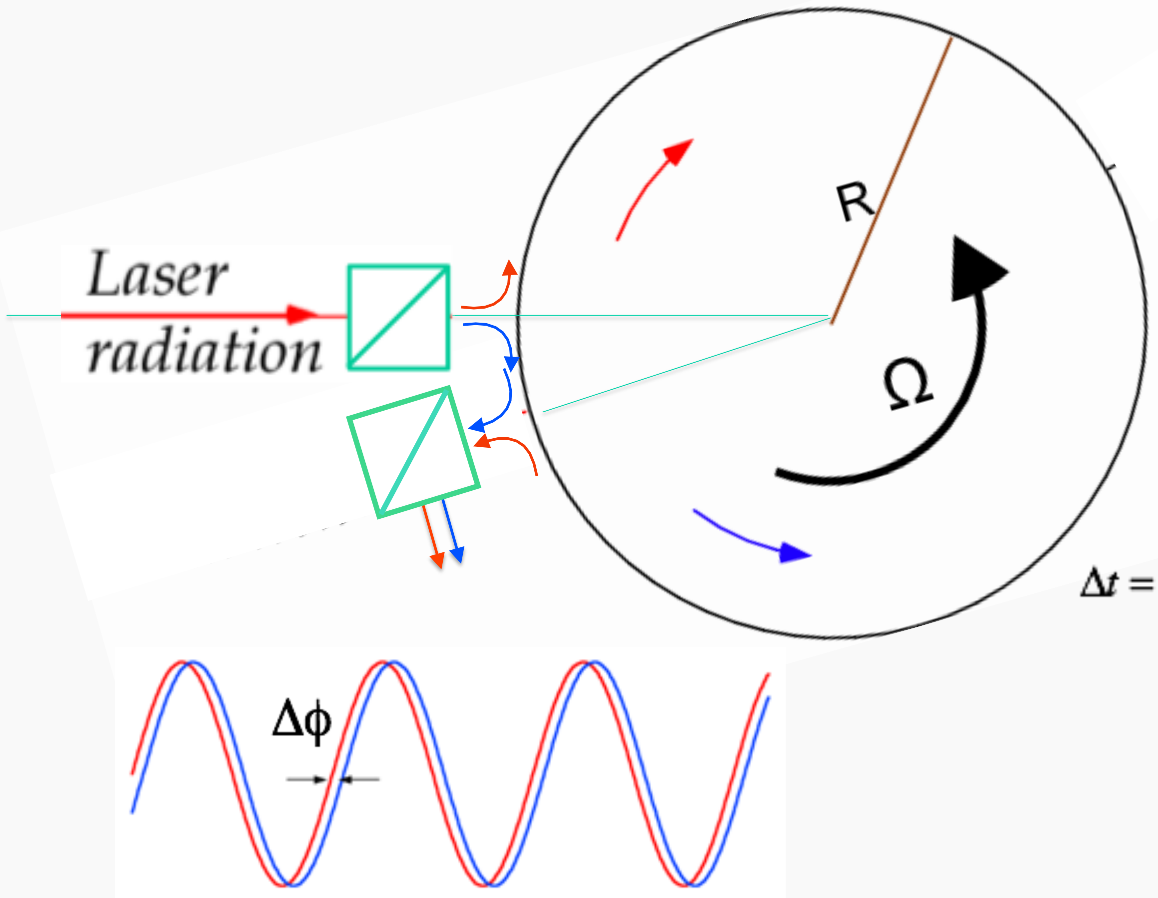
GENERAL RELATIVITY EXPERIMENTS

Angela Di Virgilio, INFN sez. Di Pisa, Italy

- **Ring laser and the experimental problem of the Lense-Thirring measurement on Earth(GINGER)**
- **The measurements we can provide: a multi purpose apparatus**
- **Final remarks**

THE SAGNAC EFFECT

$$\Delta\phi = \frac{8\pi A}{\lambda c}\vec{n}\cdot\vec{\Omega}$$



$$t = \frac{2\pi R}{c-\Omega R} \qquad t = \frac{2\pi R}{c+\Omega R}$$

$$\Delta t = \frac{2\pi R}{c-\Omega R} - \frac{2\pi R}{c+\Omega R} \approx \frac{4\pi\Omega R^2}{c^2} = \frac{4\Omega}{c^2}A$$

$$\Delta\phi = 2\pi\frac{c\Delta t}{\lambda} = \frac{8\pi\Omega A}{\lambda c}$$

GINGER

Sagnac effect is largely used for inertial navigation:

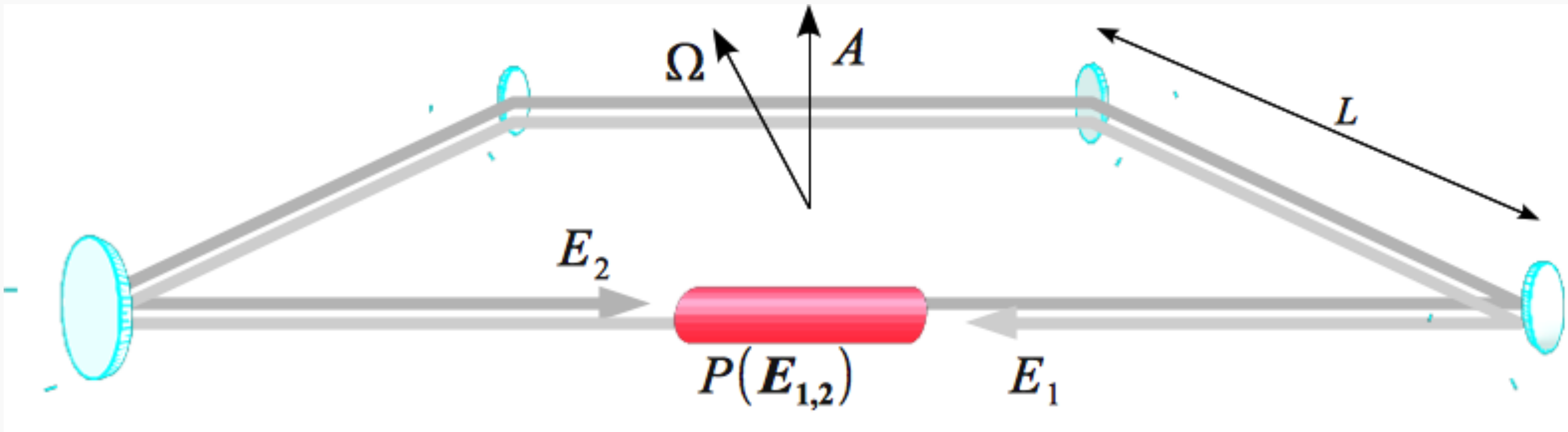
No mechanical parts

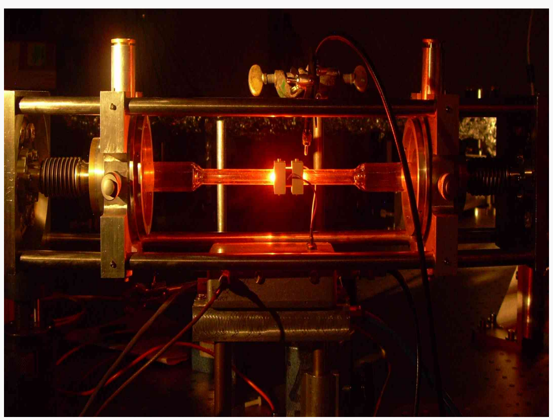
Light: constant and high speed and not coupled with environmental disturbances

RLG and FOG

GINGER

RING LASER GYROSCOPES





When the ring is rotating, the difference in optical path in the two direction is translated in a frequency difference:

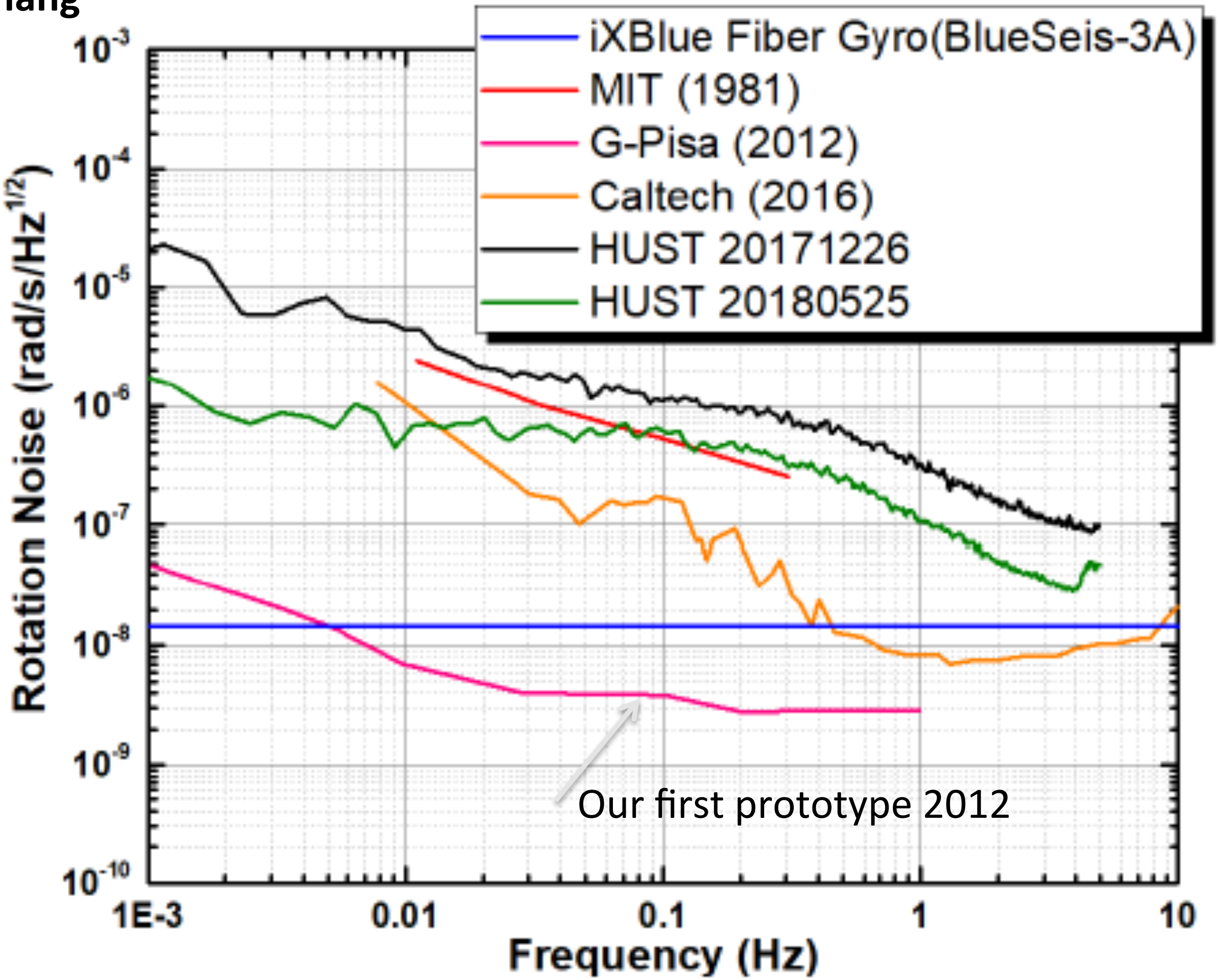
$$f_{Sagnac} = \left| f_{CW} - f_{CCW} \right| = \frac{4\vec{A} \cdot \vec{\Omega}}{\lambda p}$$

LET ME POINT OUT:

- *the cavity+laser system transforms the signal in frequency, this has the advantage to have a very large dynamical range*
- *Fast response → high bandwidth (at least kHz)*
- *To inject light from outside is feasible, but difficult task*

1 m×1 m prototype result

Courtesy Jie Zhang
Hurst



INFN/FUNDAMENTAL PHYSICS

GINGER: Gyroscopes IN GEneral Relativity

Lense Thirring effect, on Earth, 1% precision

General aim is to provide measurements able to pose constraints on the parameters of the theories

Confrontation space/earth based apparatus?

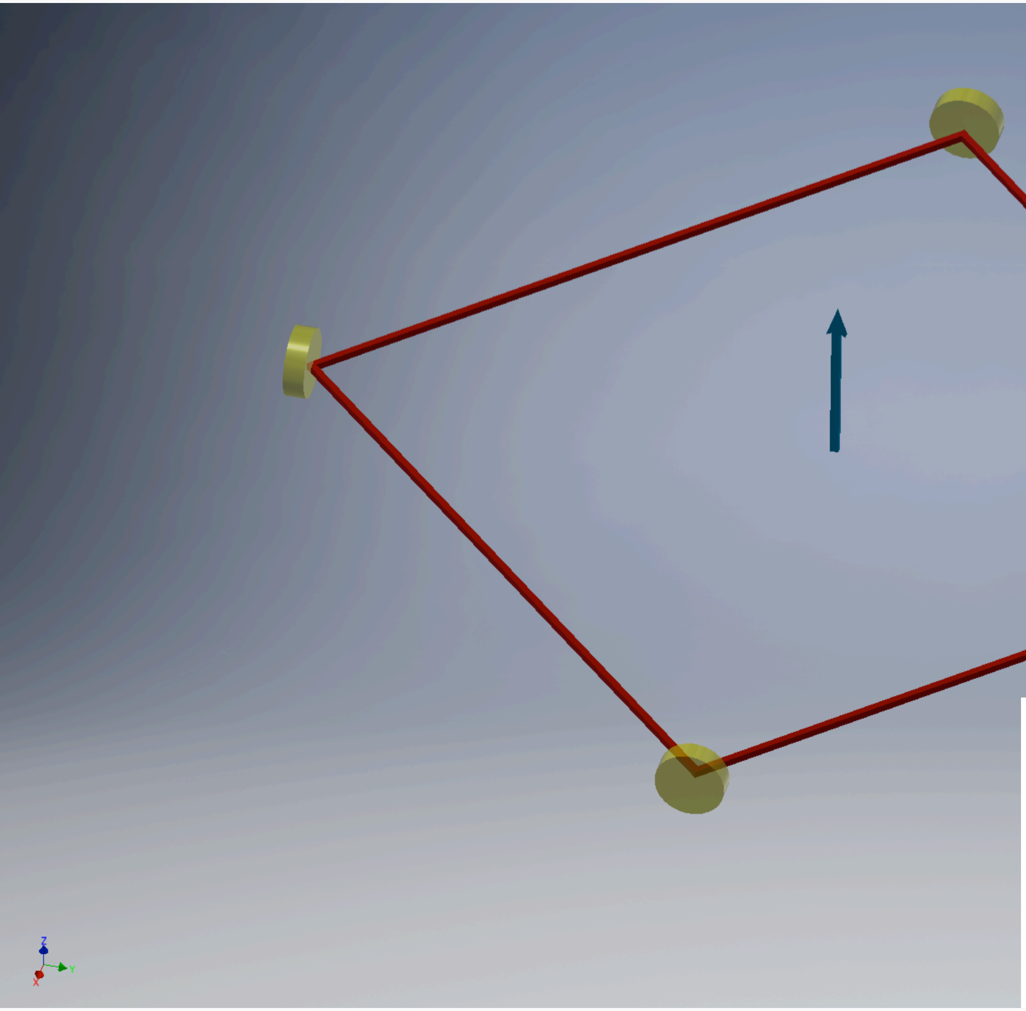
Department of Physics of Pisa (condensed matter and applied physics)

INFN Sections: Pisa, LNGS, Legnaro and Napoli

MOREOVER…

- *LenseThirring measurements are used to constrain parameters of the EGT.* ***Capozziello, Lambiase et al. , Phys. Rev. D 91, 044012 (2015)***
- *Angelo Tartaglia has shown the link between the gravitomagnetic measurement (closely related to the angular moment) and the Dark Matter which should be visible through the presence of its angular moment, its rotation should modulate the LenseThirring.* **A. Tartaglia, in *General Relativity and Gravitational Physics*, AIP Conference Proceedings, 751 , 136-145, (2004) A. Tartaglia et al., *Gen Rel. Grav.*, 50-9, 1-22 (2018)**

Each RLG is a projector,
4 mirrors: a very simple apparatus, photons do not interact with the outside world



S geometrical scale factor

n area versor, ζ angle between n and Ω

RLG output is

$$f_s = S\ \Omega\ Cos(\zeta)$$

GINGER

KEEP IN MIND: SENSITIVITY IS AN ISSUE
SHOT NOISE LIMIT

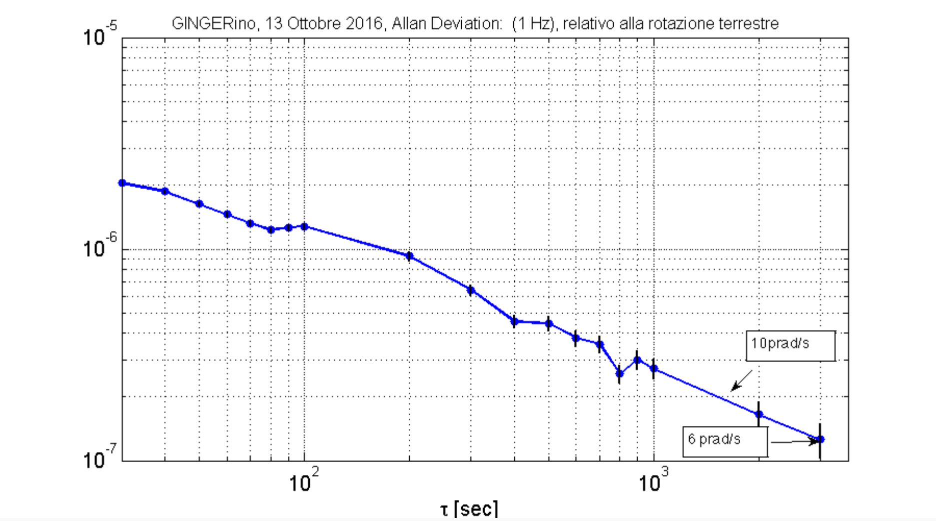
- *RLG are shot noise limited*
- *The shot noise depends on the size L and the mirror losses*

$$\delta f_{sn} \propto \frac{\text{Losses}}{L^2}$$

L side of the ring cavity
Losses: mirror losses

Present limit for L ~ 4m (G&GINGERINO)

$$10^{-10} - 0.6\ 10^{-12}\ \frac{\text{rad}}{\sqrt{\text{Hz}}\ \text{s}}$$



VARIATIONS: $\delta\Omega_T$ δS and $\delta\zeta$

For a single RLG with angle ζ with the rotation axis

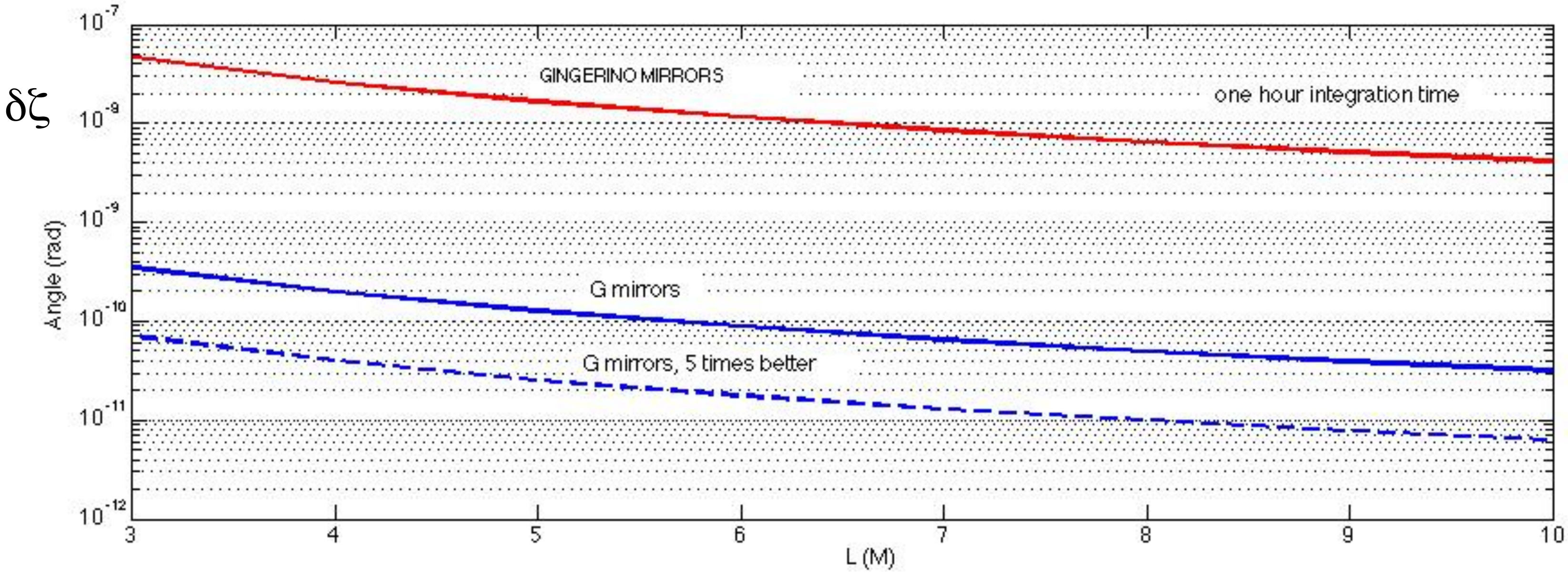
$$f_S = S\,(\Omega_T)\cos(\zeta),\ \text{assuming}\ \Omega_T \sim \Omega_\oplus$$

$$\delta f_S = S\,\Omega_T \sin(\zeta)\,\delta\zeta + \delta S\,(\Omega_T)\cos(\zeta) + S\,(\delta\Omega_T)\cos(\zeta)$$

The control eliminates the changes δS
$\delta\Omega_T$ and $\delta\zeta$ two cannot be distinguished

The scale factor can be controlled electronically

THE FAST CHANGES OF THE ROTATION AXIS



THE GR TERMS

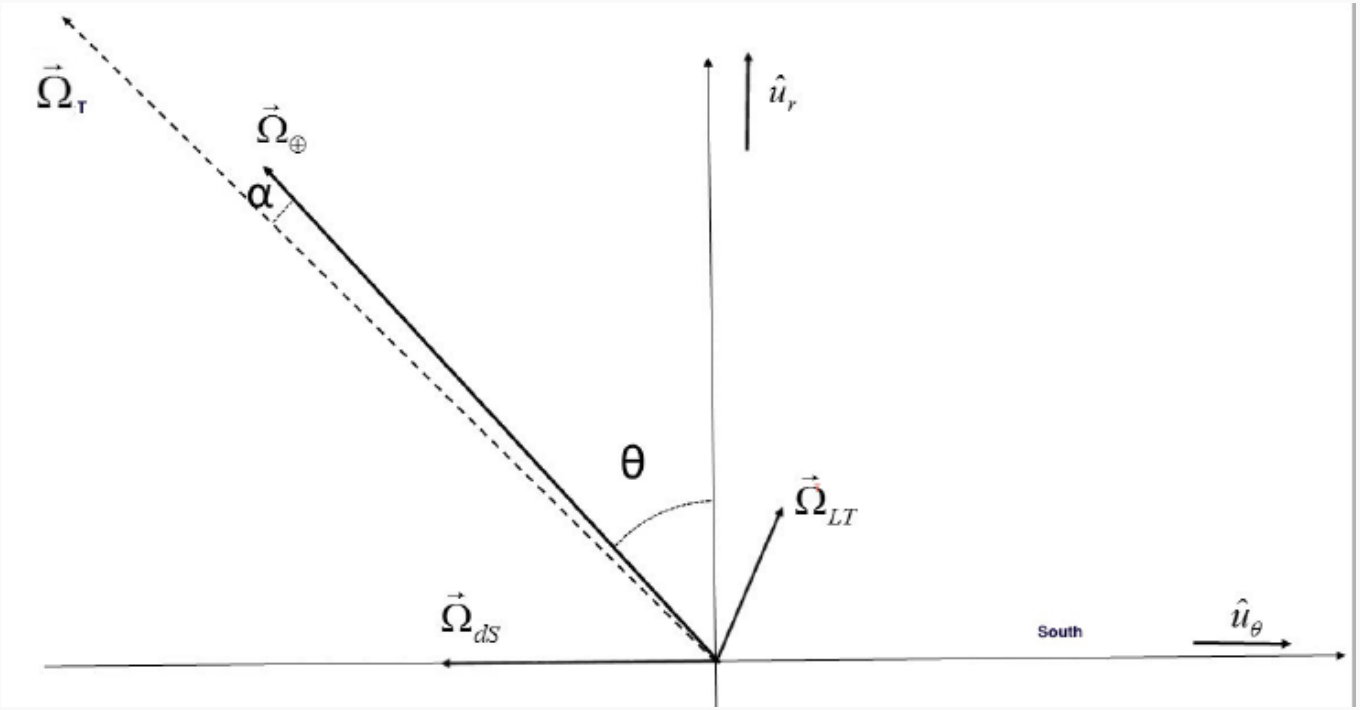
measured by IERS

deSitter

Lense Thirring

$$f = \frac{4A}{\lambda P}\left[\Omega_\oplus - 2\frac{m}{r}\Omega_\oplus \sin\theta \hat{u}_\theta + G\frac{I\Omega_\oplus}{c^2 r^3}\left(2\cos\theta \hat{u}_r + \sin\theta \hat{u}_\theta\right)\right]\cdot \hat{u}_n = S\left(\Omega_\oplus + \Omega_{dS} + \Omega_{LT}\right)\cdot \hat{u}_n.$$

A. Tartaglia, A. Di Virgilio et al. Eur. Phys. J. Plus (2017) 132: 73



The deSitter and LenseThirring terms are equivalent to an extra rotation 9-12 orders of magnitude below the Earth rotation rate.

GINGER

WHAT IS NECESSARY TO DO

- *PROBLEM: to reconstruct with very high precision a vector in the space using the information of the projectors*
- *In general at least 3, 4 or more would be better (redundancy)*
- *Necessary to study the noise related to any kind of variations of the apparatus, in particular all geophysical signals*

Strong relationship with geophysics

Main difficulty: DC signal and 9-10 order of magnitude smaller than the dominant signal, the Earth rotation rate

2017 PAPERS DEFINES THE REQUIREMENTS FOR GINGER

Highlighted by springer and eurekalert

Angela D. V. Di Virgilio et al. "GINGER: A feasibility study". In: *The European Physical Journal Plus* 132.4 (2017), p. 157. ISSN: 2190-5444. DOI: 10.1140/epjp/i2017-11452-6. URL: https://doi.org/10.1140/epjp/i2017-11452-6.

Highlighted as 'Change the World'

Angelo Tartaglia et al. "Testing general relativity by means of ring lasers". In: *The European Physical Journal Plus* 132.2 (2017), p. 73. ISSN: 2190-5444. DOI: 10.1140/epjp/i2017-11372-5. URL: https://doi.org/10.1140/epjp/i2017-11372-5.

The most prestigious Repubblica e Nature

For example:
General relativity Going underground
Luke Fleet *Nature Physics* **volume 13**, page 321 (2017)

Europhysics news

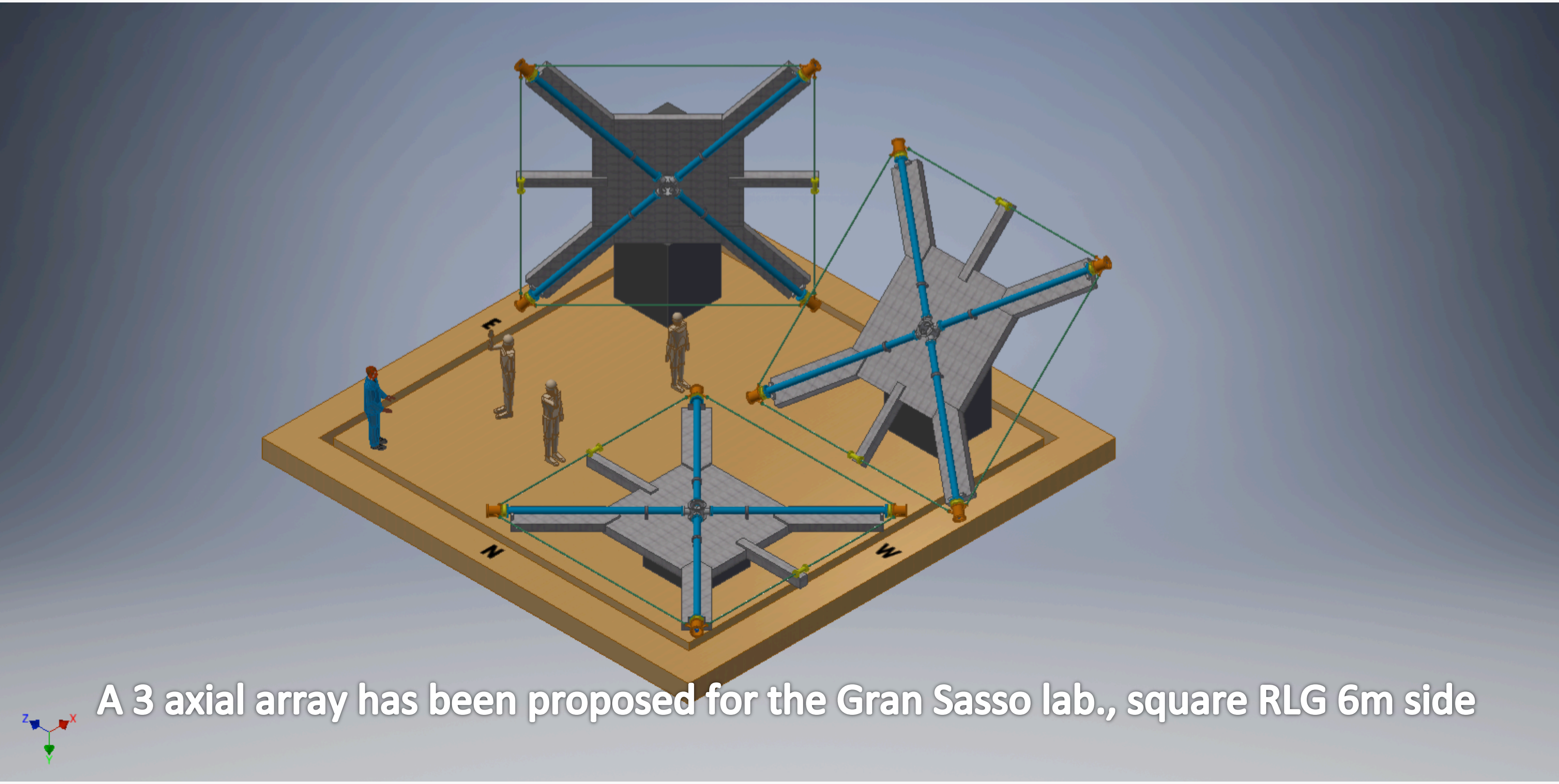
- The RL_1 at maximum signal is the best solution to measure the amplitude of Ω_T (η parallel)

- RL_2 provides redundancy and the link between the angle Ω_T and the local vertical or horizontal plane. It could be vertical or horizontal

- Linking RL_2 with the local common reference (vertical/ horizontal) the angle α can be measured (η perpendicular)

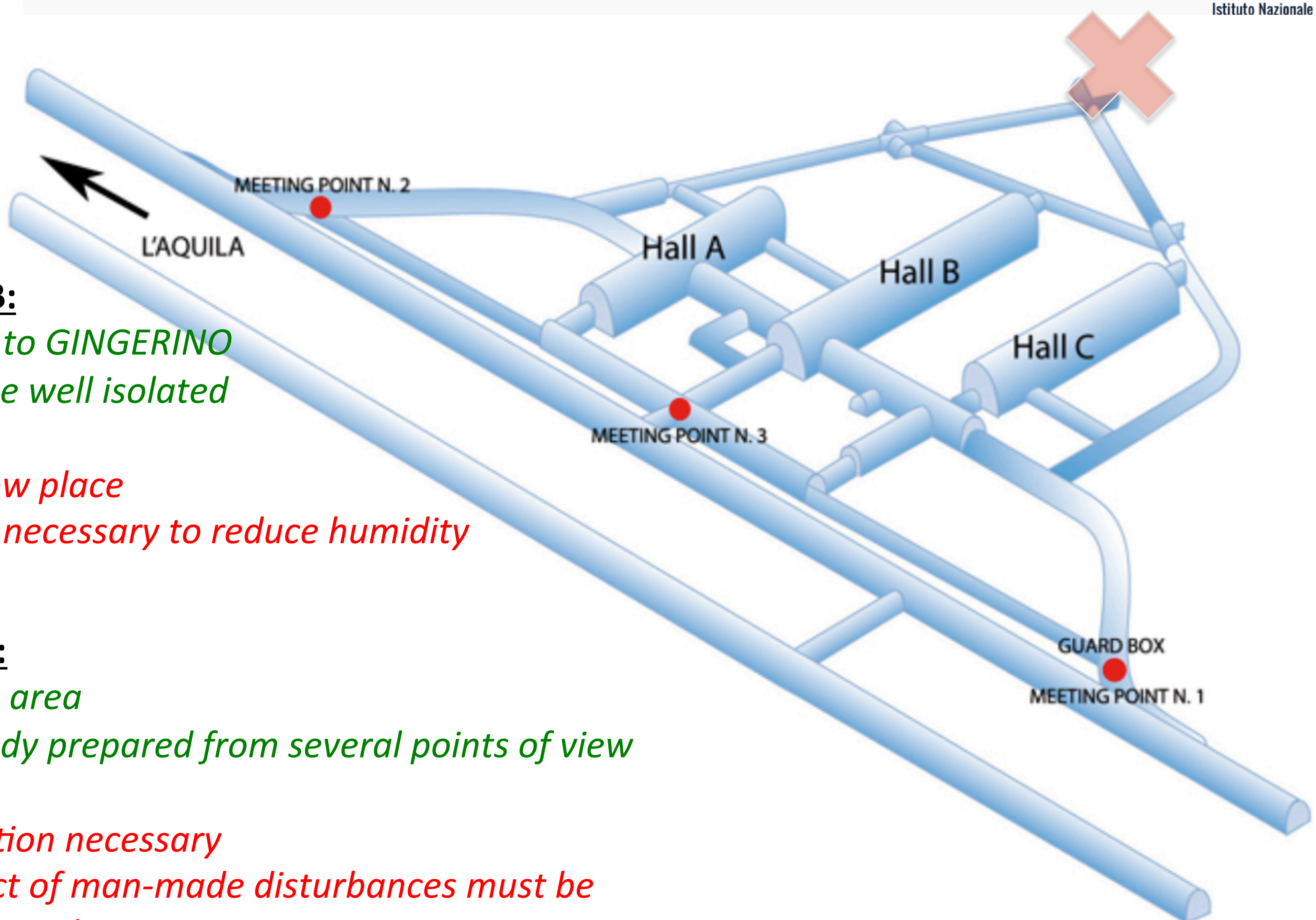
- One RL with area versor outside the meridian plane should be added in a second time. This requires to measure the angles with respect RL_2

INFN
Istituto Nazionale di Fisica Nucleare



A 3 axial array has been proposed for the Gran Sasso lab., square RLG 6m side

GINGER



NODE B:

close to GINGERINO

can be well isolated

narrow place

work necessary to reduce humidity

HALL B:

large area

already prepared from several points of view

Isolation necessary

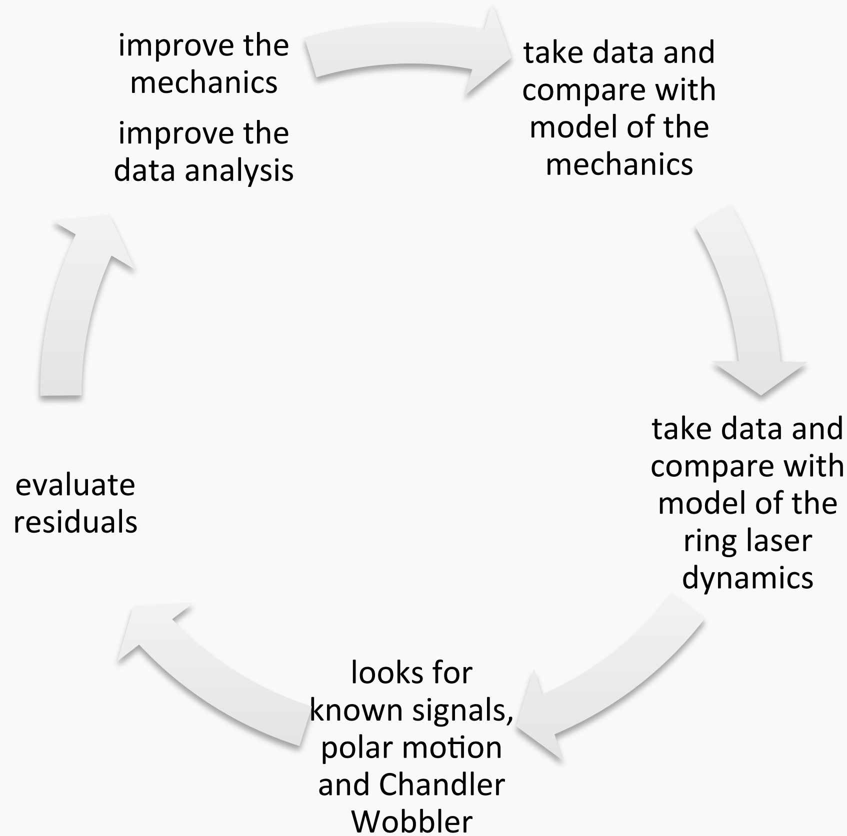
impact of man-made disturbances must be investigated

WHAT GINGER DELIVERS

- *Variation of the earth rotation rate with relative precision ~ 10^{-9}-10^{-12}*
- *Variation of the rotation axis (local)*
- *Lense Thirring 1% comparing with IERS data*

- *Other measurements connected to the sidereal day modulation are feasible (for example Lorenz Invariance)*

PROTOTYPES ARE VERY USEFUL TO IMPROVE THE DESIGN AND THE COMPREHENSION OF THE INSTRUMENT

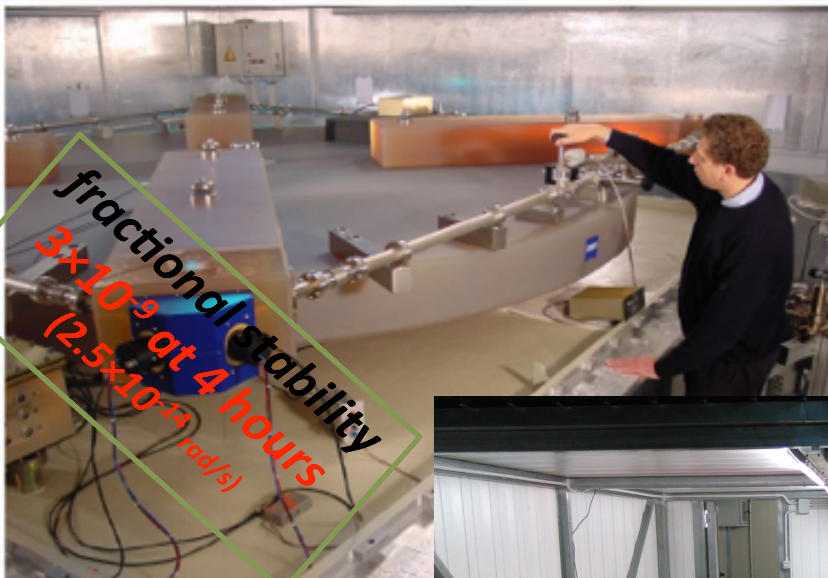


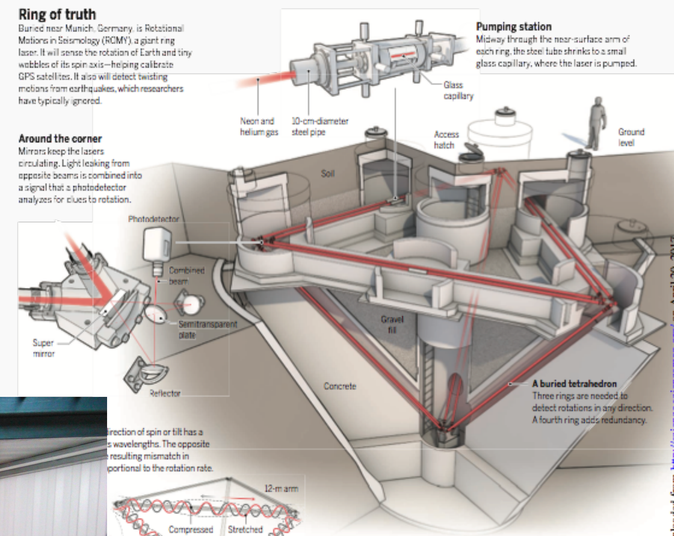
The Groß Ring *G (Monolithic)*

ROMY & GINGERINO (Heterolithic)

➢ *At present, the gyrolaser with the lwest noise level, very near to the shot-noise limit, is the "Gross RING* ***G****", located in Wettzell, Bavaria.*

Monolithic ring laser of 16-m^2 constructed on a Zerodur monolithic frame.





nloaded from http://science.sciencemag.org/ on April 20, 2017

HIGH SENSITIVITY PROTOTYPES

- *G of the geodetic observatory of Wettzell has reached the relative precision of 3 10^{-9} (a factor 3 far from the first goal of GINGER)*
- *ROMY is a 3 axial RLG system, each 36m perimeter. Very high sensitivity, in short term more sensitive than G. It is still under commissioning. Its main purpose is seismology.*
- *GINGERINO is free running, and takes advantage of the underground location. It is not stable enough but we are using the data to develop model and understand the apparatus*

A LOOK AT THE DATA

Let us talk about the data of our prototypes: GINGERINO (horizontal) and GP2 (at maximum signal)

GINGERINO HAS HIGH SENSITIVITY

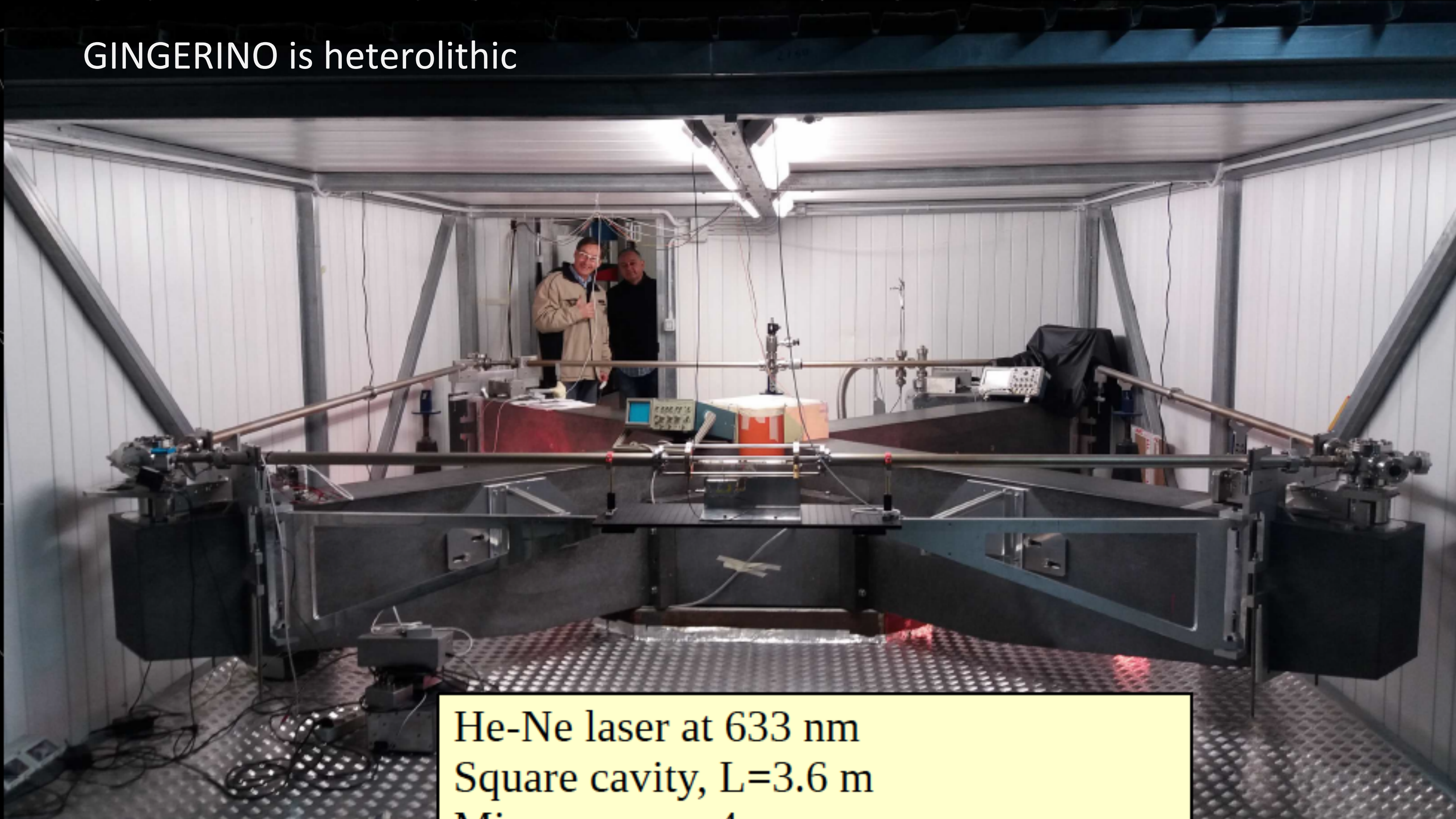
GP2 IS DEDICATED TO TESTS AND GEOMETRY CONTROL

GINGERino: deep underground ring laser

GINGER-ino (INFN-LNGS)+ Seismometers (INGV)

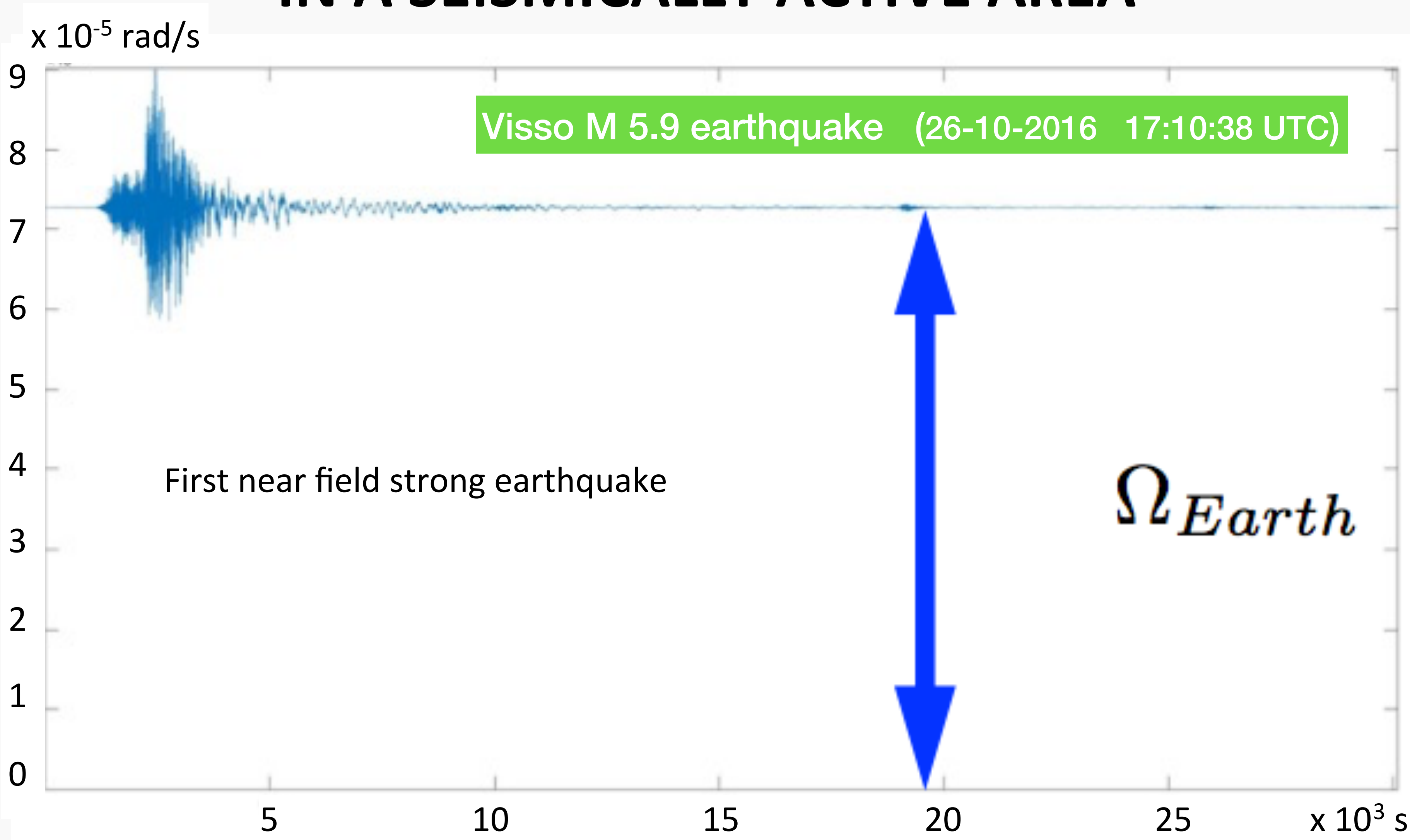
GINGER

GINGERINO is heterolithic



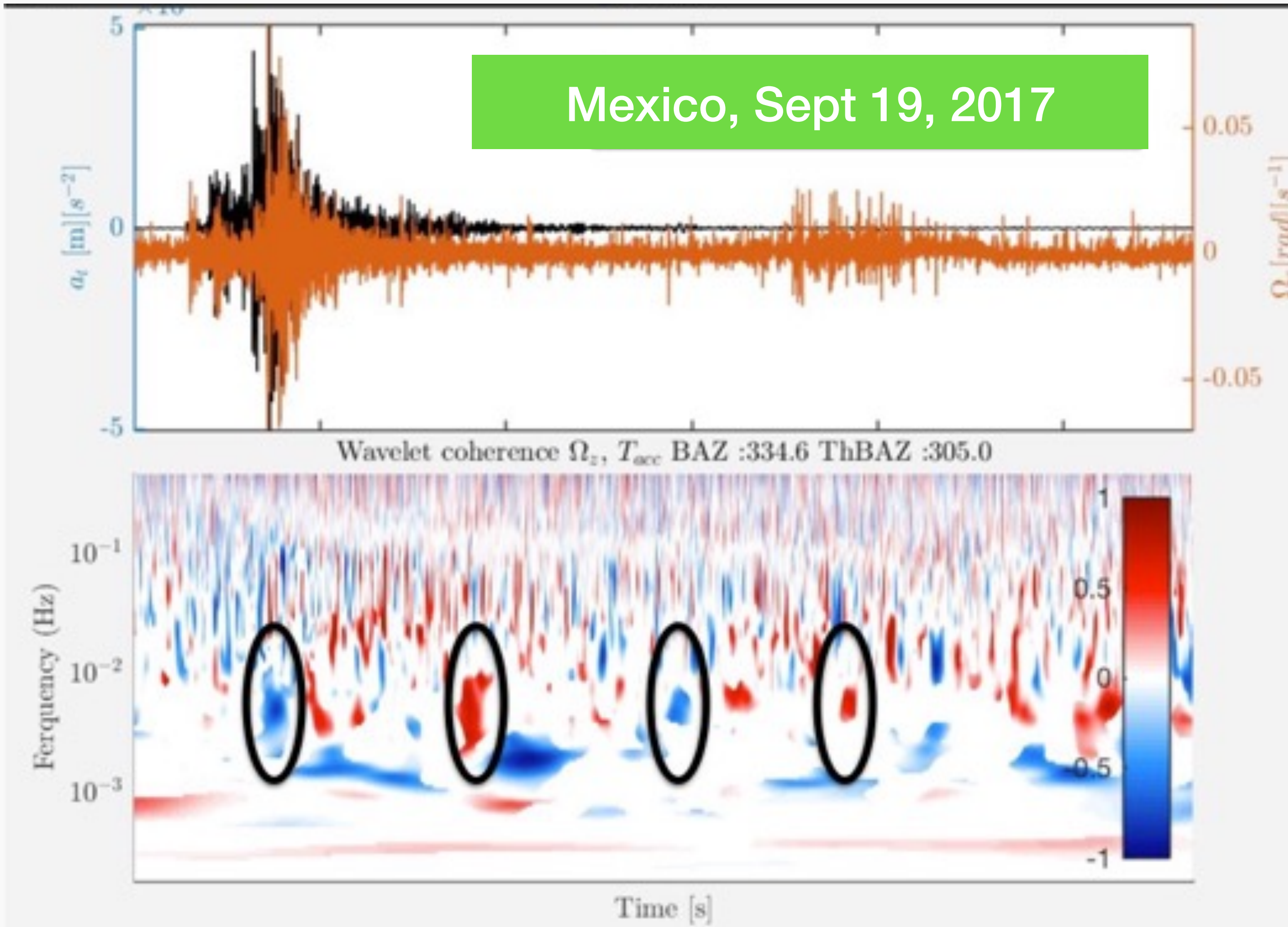
He-Ne laser at 633 nm
Square cavity, L=3.6 m
Mirrors r.o.c= 4 m
Earth rotation Sagnac bias: **fs=280.4 Hz**

GINGERINO IS THE ONLY RLG LOCATED IN A SEISMICALLY ACTIVE AREA

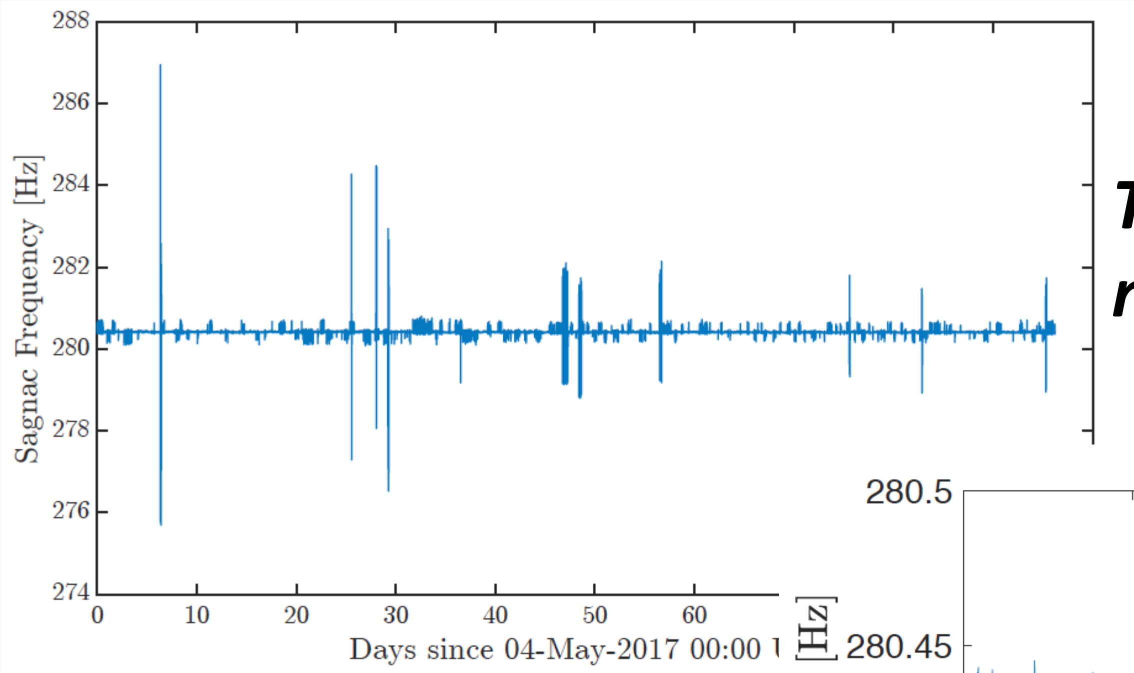


GINGER

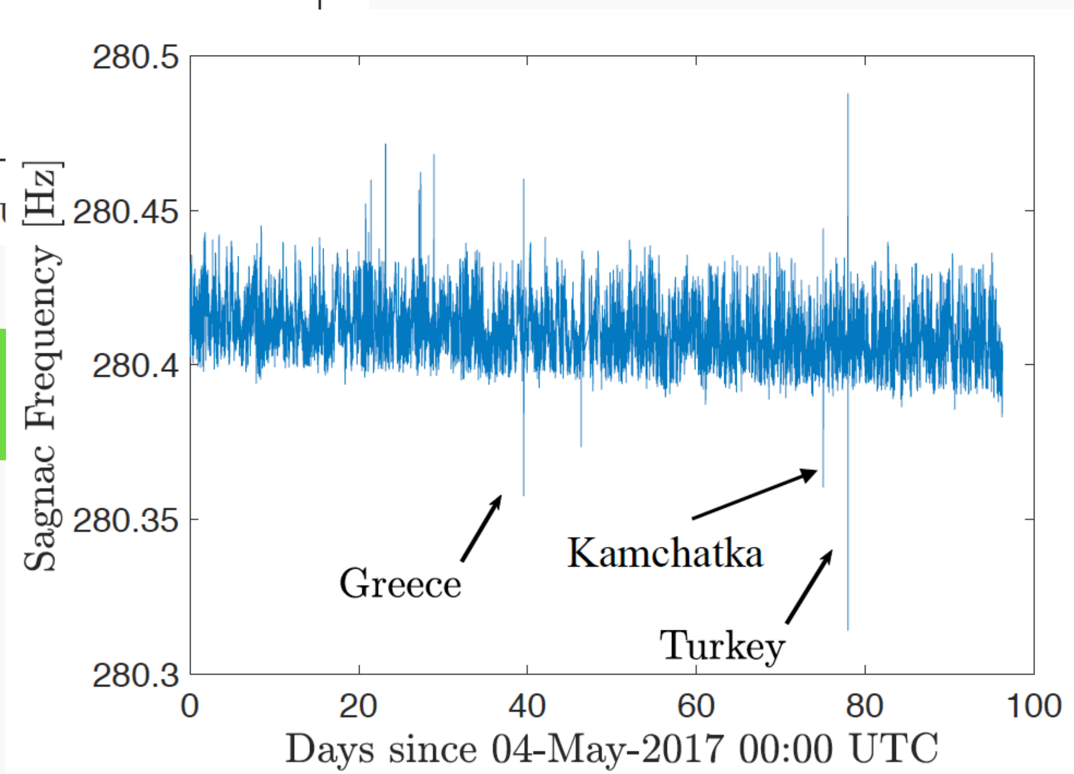
A single station with seismometer and RLG is able to recover amplitude And direction of the wave, 6D STATION



GINGERINO IS THE FIRST HETERO LITHIC RLG WORKING IN A CONTINUOUS BASIS



Typical sensitivity ~ 0.1 nrad/s in one second

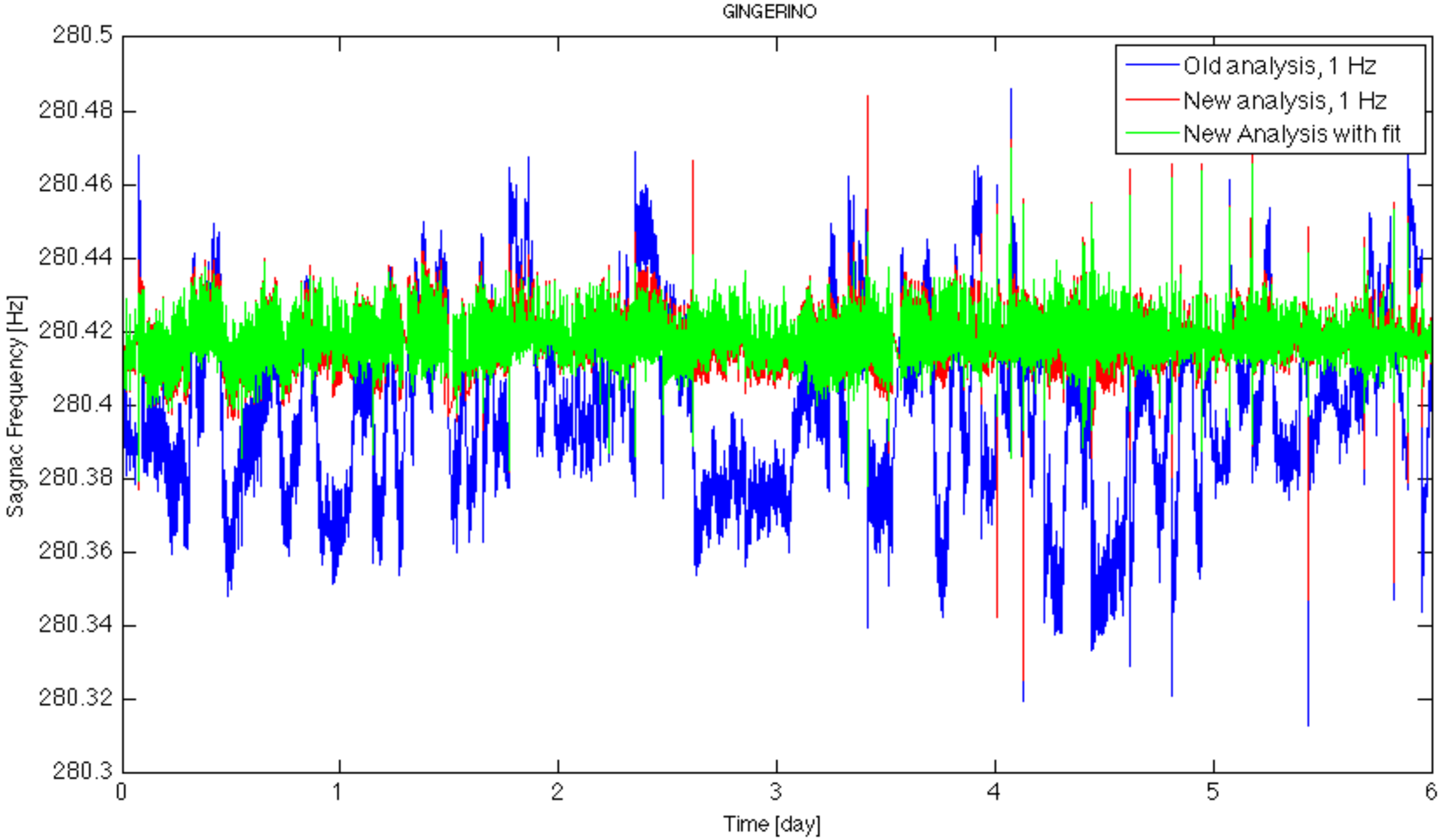


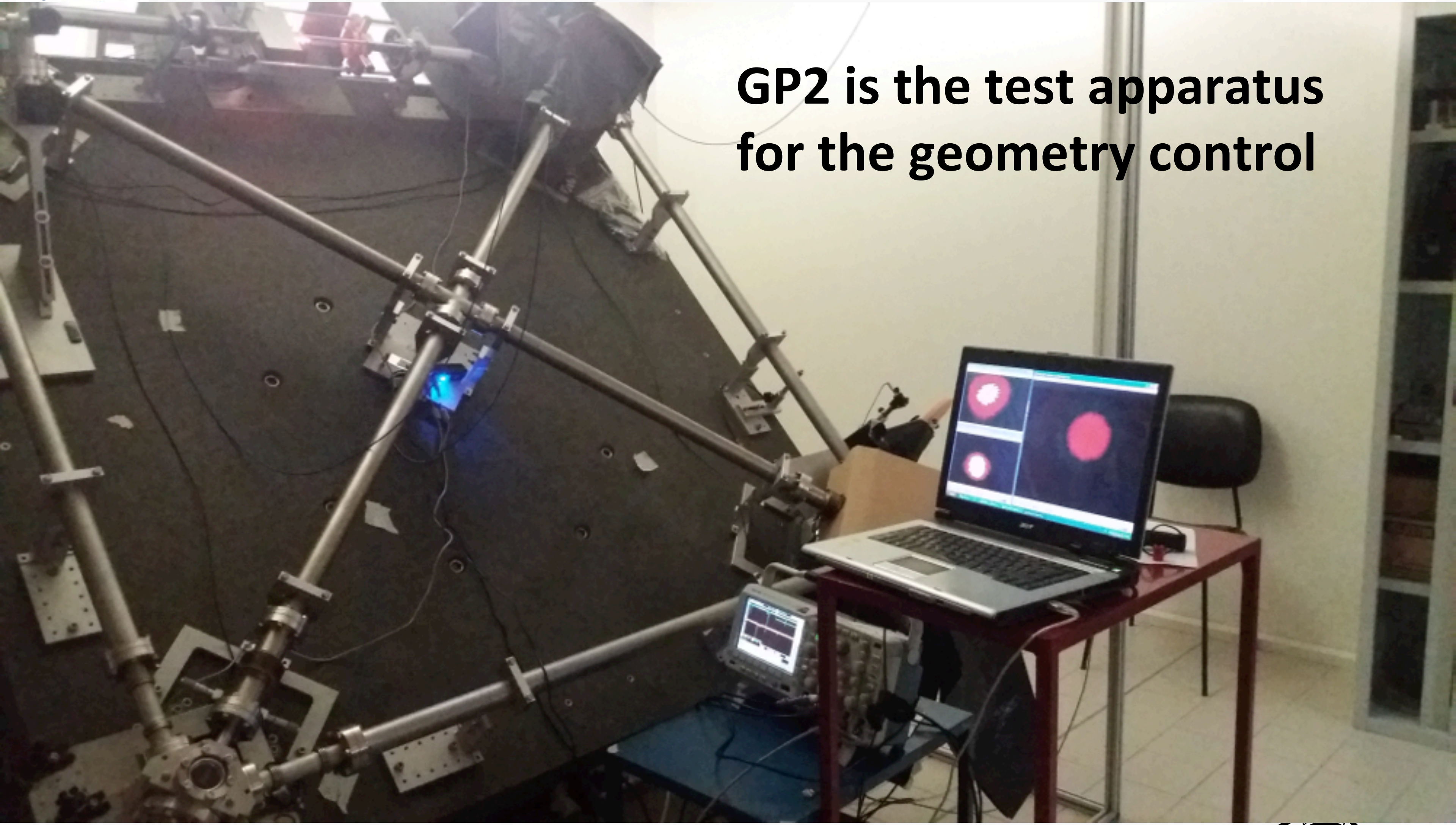
Data cleaned from split mode and mode jumps through FC

Less than 5% of the points were cancelled

At present we are developing tools to improve the reconstruction of the measured rotation, one of the major problem is the complex dynamic of the laser, in principle not linear and described by more than 10 independent parameters

$$
\begin{aligned}
\dot{I}_1 &= \frac{c}{L}\left[\alpha_1 I_1 - \beta_1 I_1^2 - \theta_{12} I_1 I_2 + 2r_2\sqrt{I_1 I_2}\cos(\psi+\varepsilon)\right] \\
\dot{I}_2 &= \frac{c}{L}\left[\alpha_2 I_2 - \beta_2 I_2^2 - \theta_{21} I_1 I_2 + 2r_1\sqrt{I_1 I_2}\cos(\psi-\varepsilon)\right] \\
\dot{\psi} &= \omega_s + \sigma_2 - \sigma_1 + \tau_{21} I_1 - \tau_{12} I_2 - \\
&\quad - \frac{c}{L}\left[r_1\sqrt{\frac{I_1}{I_2}}\sin(\psi-\varepsilon) + r_2\sqrt{\frac{I_2}{I_1}}\sin(\psi+\varepsilon)\right] ,
\end{aligned}
$$

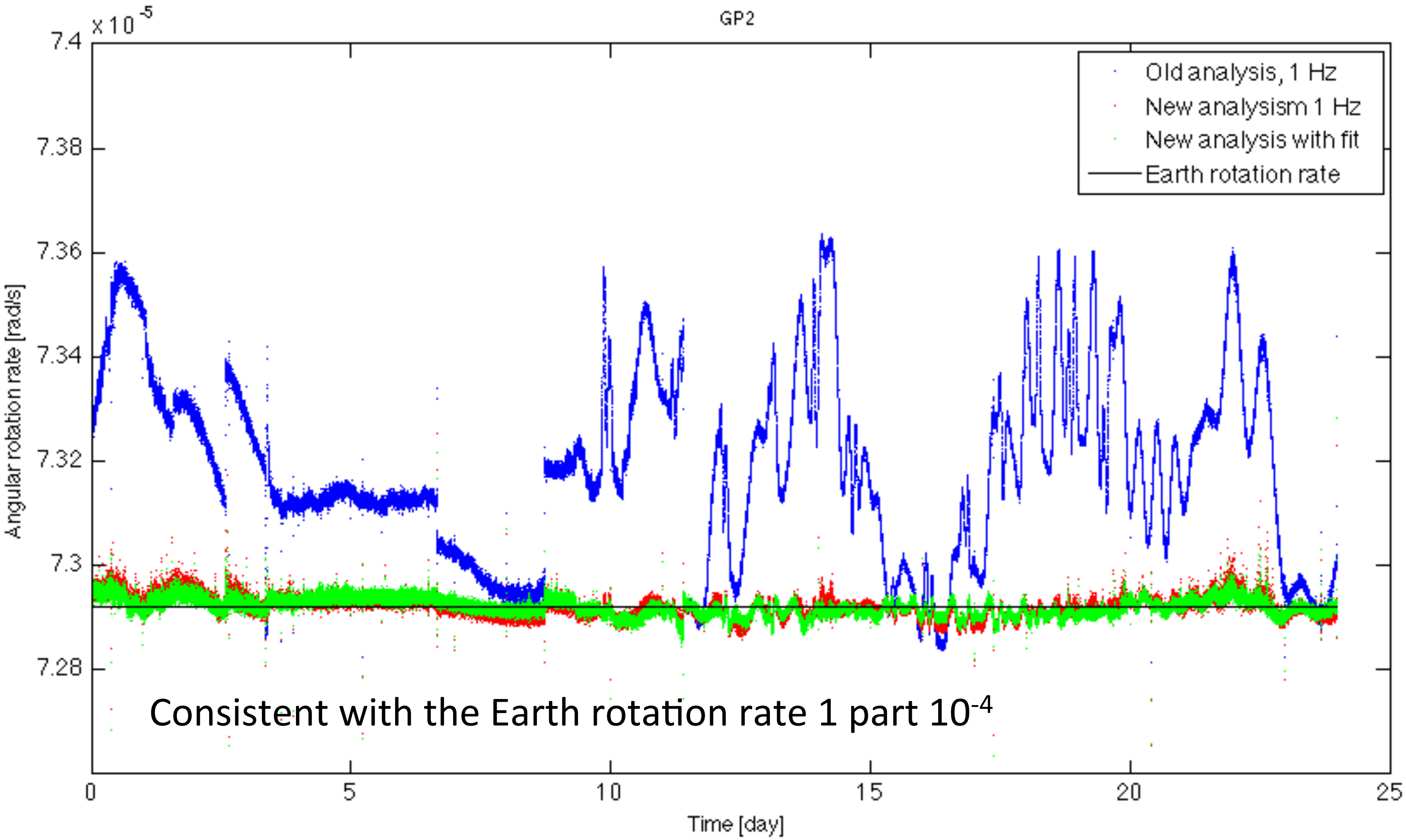

GINGERINO
Old analysis, 1 Hz
New analysis, 1 Hz
New Analysis with fit
Sagnac Frequency [Hz]
Time [day]
280.5
280.48
280.46
280.44
280.42
280.4
280.38
280.36
280.34
280.32
280.3
0
1
2
3
4
5
6



GP2 is the test apparatus for the geometry control

GP2

NOT ONLY SENSITIVITY BUT ALSO ACCURACY!



Consistent with the Earth rotation rate 1 part 10^{-4}

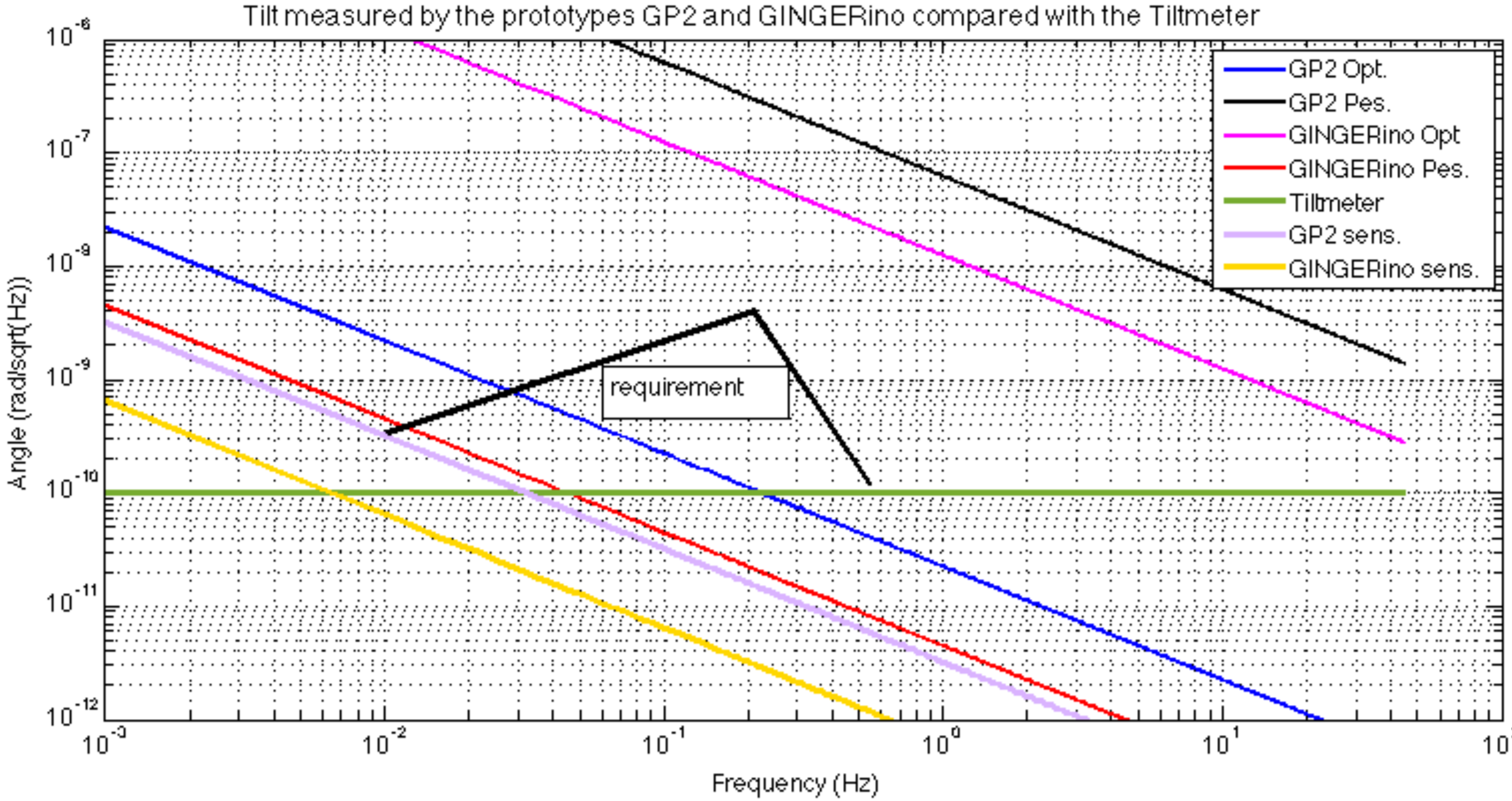
GP2 is meant to study the geometry control. It is aligned at the maximum signal, it is a very simple apparatus, mirrors are not top quality

I HAVE NOT DISCUSSED, BUT IT IS OBVIOUS THAT RLG COULD SERVE FOR.....

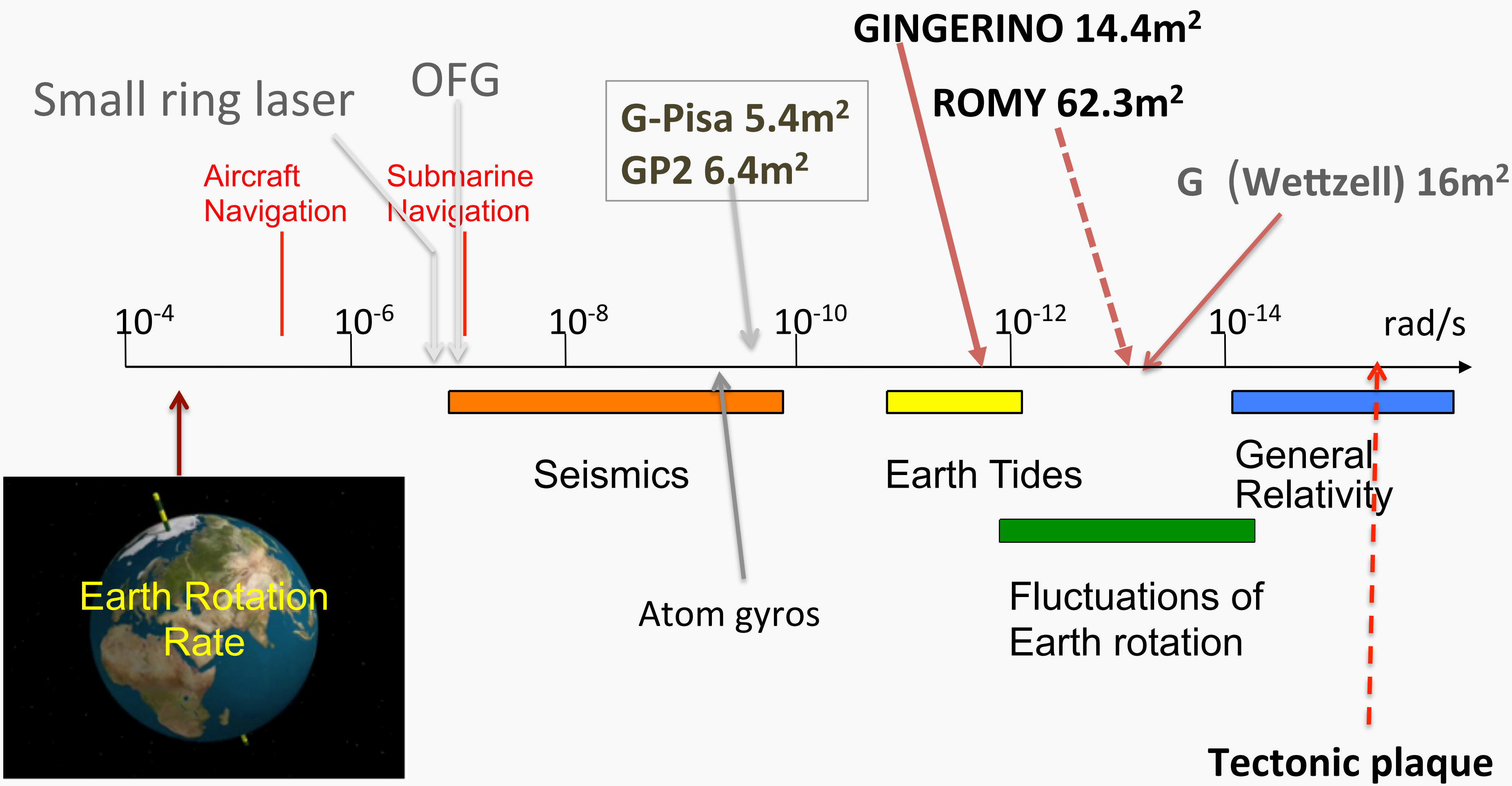
- *Development of inertial platform*
- *Environmental monitor for third generation Gravitational Waves detection*
- *In 2011-2012 our first prototype G-Pisa was installed in the central area of Virgo and has measured the influence of the strong wind on the apparatus*

COMPARISON with the LIGO TILTMETER

characteristics of our prototypes GP2 and GINGERINO have been utilized (June, 2016)



INERTIAL ANGULAR ROTATION MEASUREMENT



Impossible to distinguish among geophysics and fundamental physics signals

CONCLUDING REMARKS

- *Ring lasers are very sensitive but also useful instruments, they provide unique data for geophysics and rotational seismology*
- *The experimental requirements for GINGER have been found, now we are working along different lines:*

a) *mechanics & precise alignment of the mirrors*

b) *Scale Factor control and reduction of laser systematics (i.e. better mirrors and systematics subtraction/elimination*

c) *data analysis and diagnostics tools development (for laser dynamics and to debug the apparatus)*

d) *provide data for seismology with GINGERINO*

e) *We are investigating whether GINGERINO is already fruitful for geodecy*

We are working to built an array inside LNGS for geophysics: the effort is in improving the long term response and the comprehension of the laser dynamics