Ring Laser and fundamental Physics

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- 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

COSMO 2018, Dubrovnik
26/10/18

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?

For example to provide data to test Extended Gravity Theories

Why extending General Relativity?

- ✓ Several issues in modern Astrophysics ask for new paradigms.
- ✓ No final evidence for Dark Energy and Dark Matter at fundamental level (LHC, astroparticle physics, ground based experiments, LUX...).
- ✓ Such problems could be framed extending GR at infrared scales.
- ✓ GR does not work at ultraviolet scales (no Quantum Gravity).
- ✓ ETGs as minimal extension of GR considering Quantum Fields in Curved Spaces
- ✓ Big issue: Is it possible to find out probes and test-beds for ETGs?
- ✓ Further modes of gravitational waves!
- ✓ Constraints at Newtonian and post-Newtonian level could come from:
  - Geodesic motions around compact objects e.g- SgrA*
  - Lense-Thirring effect
  - Exact torsion-balance experiments
  - Microgravity experiments from atomic physics
  - Violation of Equivalence Principle (effective masses related to further gravitational degrees of freedom)

Salvatore Capozziello is already using data from Laser and Gravity Probe B to evaluate parameters and constraints

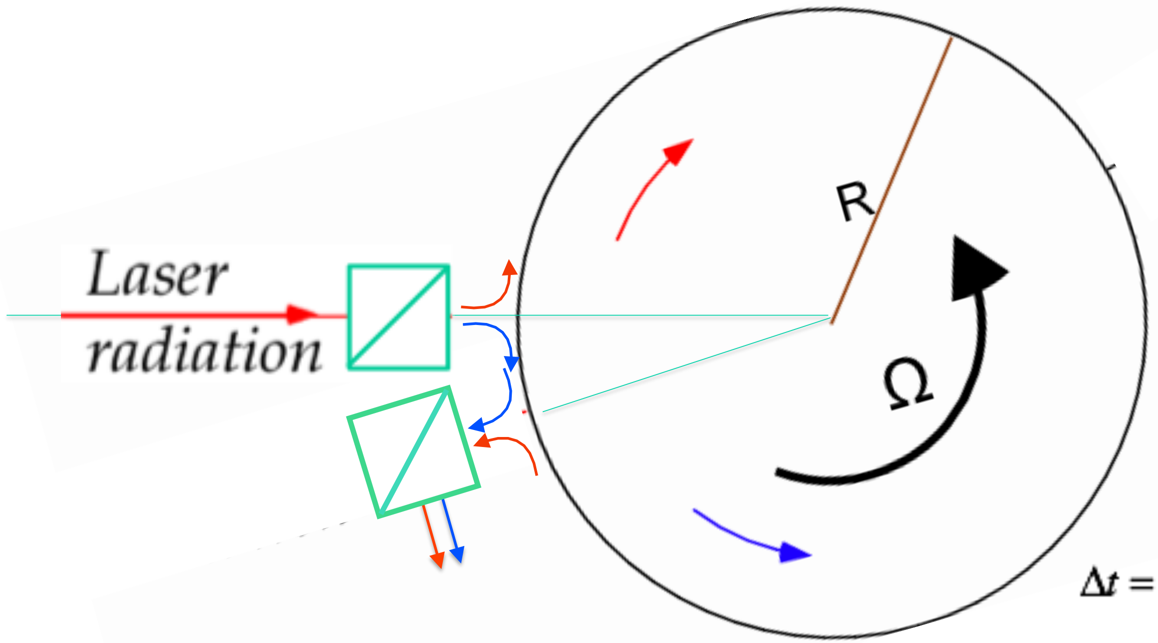
MOREOVER…

- *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*

- M. L. Ruggiero and A. Tartaglia, *Nuovo Cimento* B, **117**, 743-767 (2002)
- 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)

THE SAGNAC EFFECT

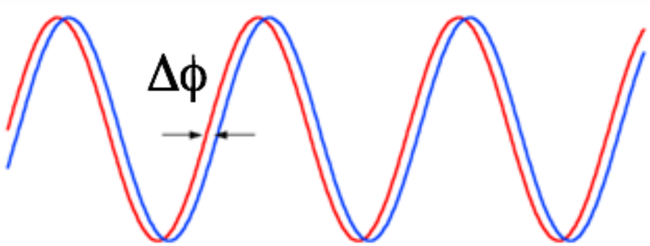
$$\Delta\phi = \frac{8\pi A}{\lambda c}\vec{n}\cdot\vec{\Omega}$$



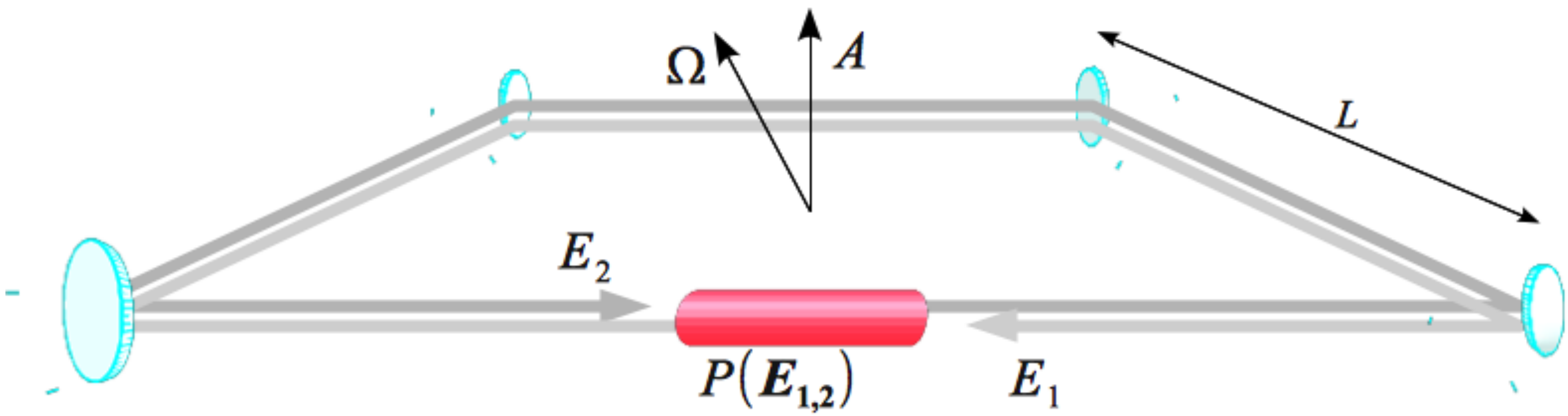
$$t = \frac{2\pi R}{c - \Omega R} \qquad t = \frac{2\pi R}{c + \Omega R}$$

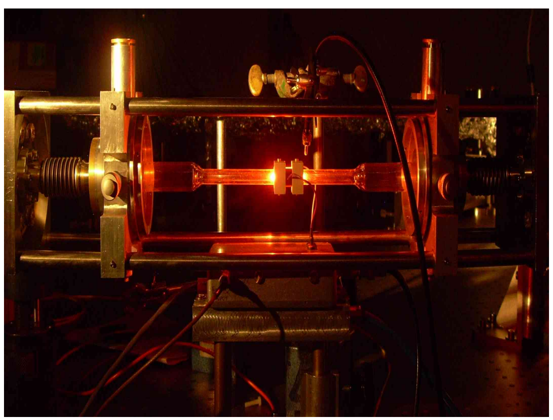
$$\Delta t = \frac{2\pi R}{c - \Omega R} - \frac{2\pi R}{c + \Omega R} \approx \frac{4\pi \Omega R^2}{c^2} = \frac{4\Omega}{c^2}A$$

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



RING LASER GYROSCOPES



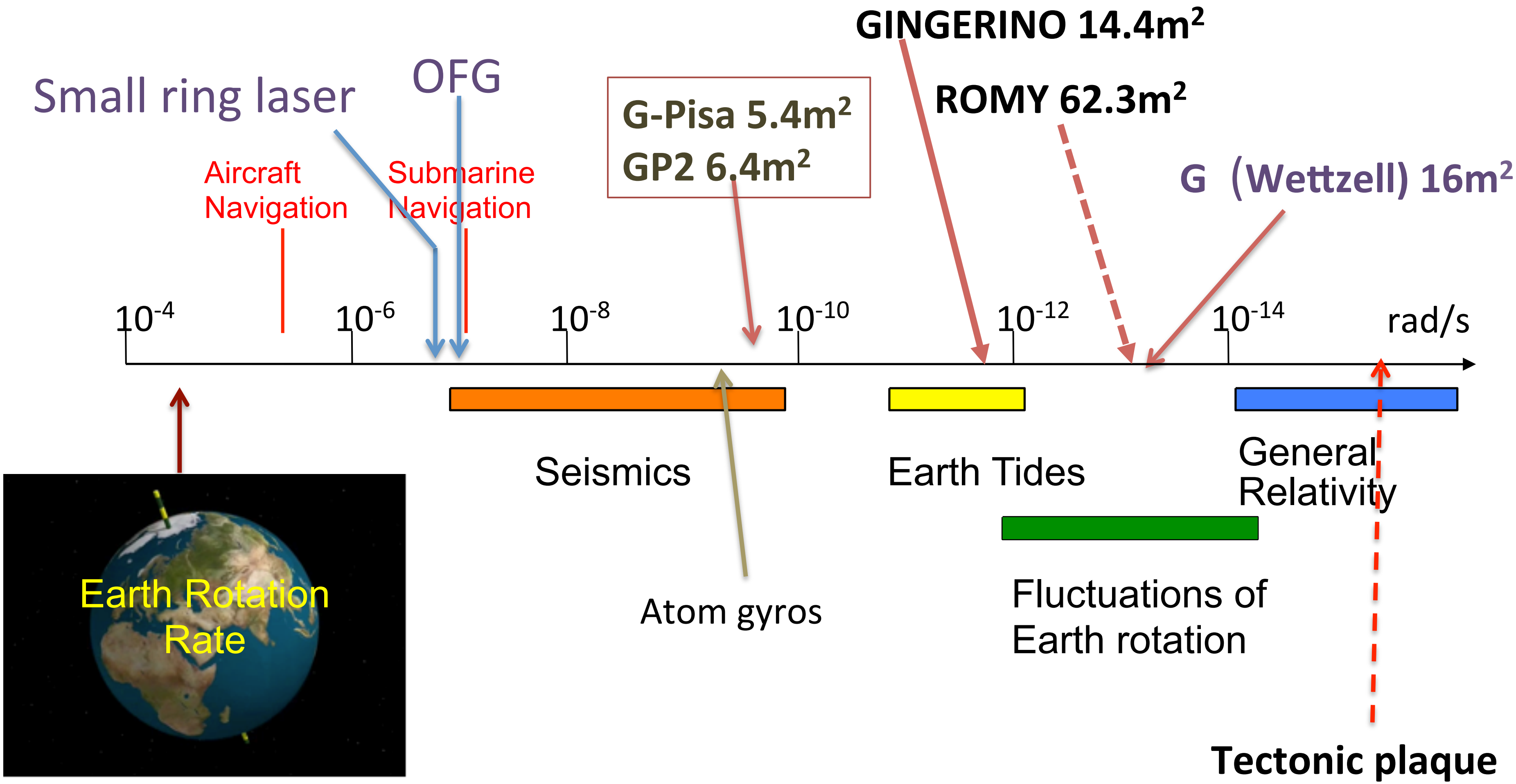


When the ring is rotating, the difference in optical path in the two direction is translated in a frequency difference:

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

GINGER

INERTIAL ANGULAR ROTATION MEASUREMENT



Impossible to distinguish among geophysics and fundamental physics signals

GINGER

THE GR TERMS

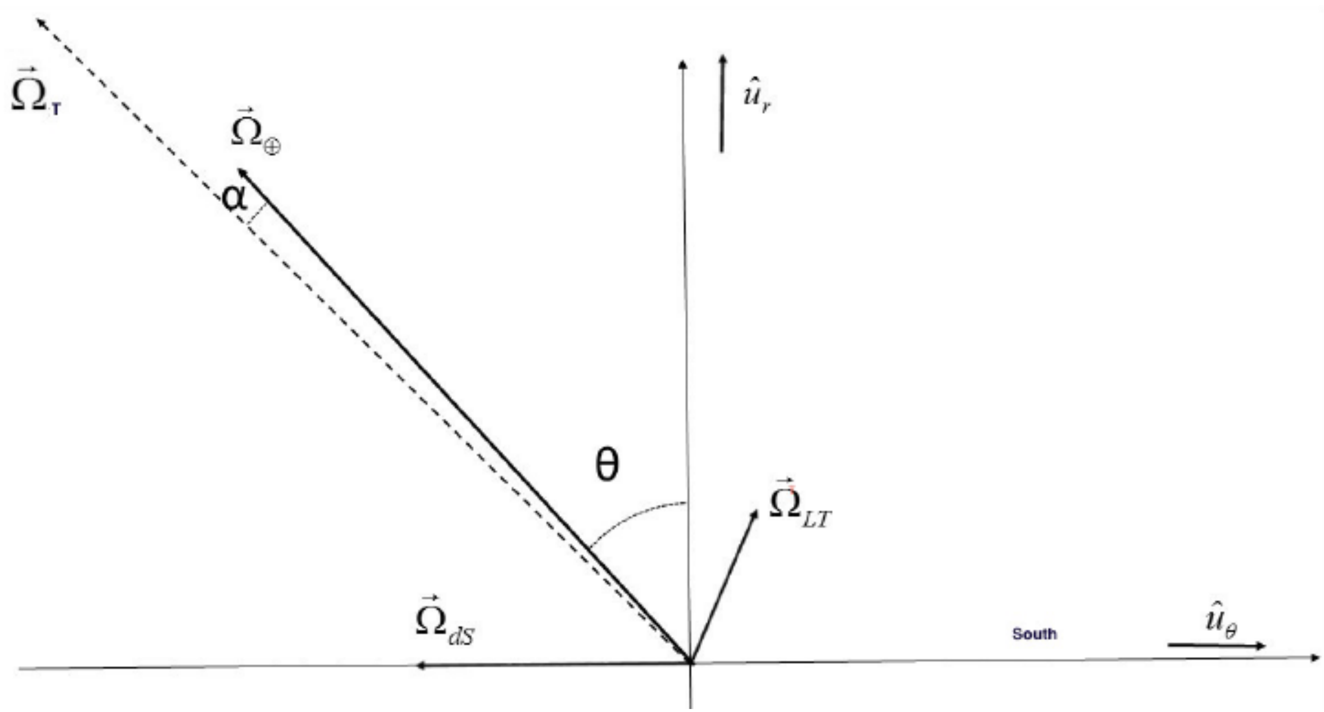
measured by IERS

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.

WHAT IS NECESSARY TO DO

- *PROBLEM: to reconstruct with very high precision a vector in the space using the information of the projectors*

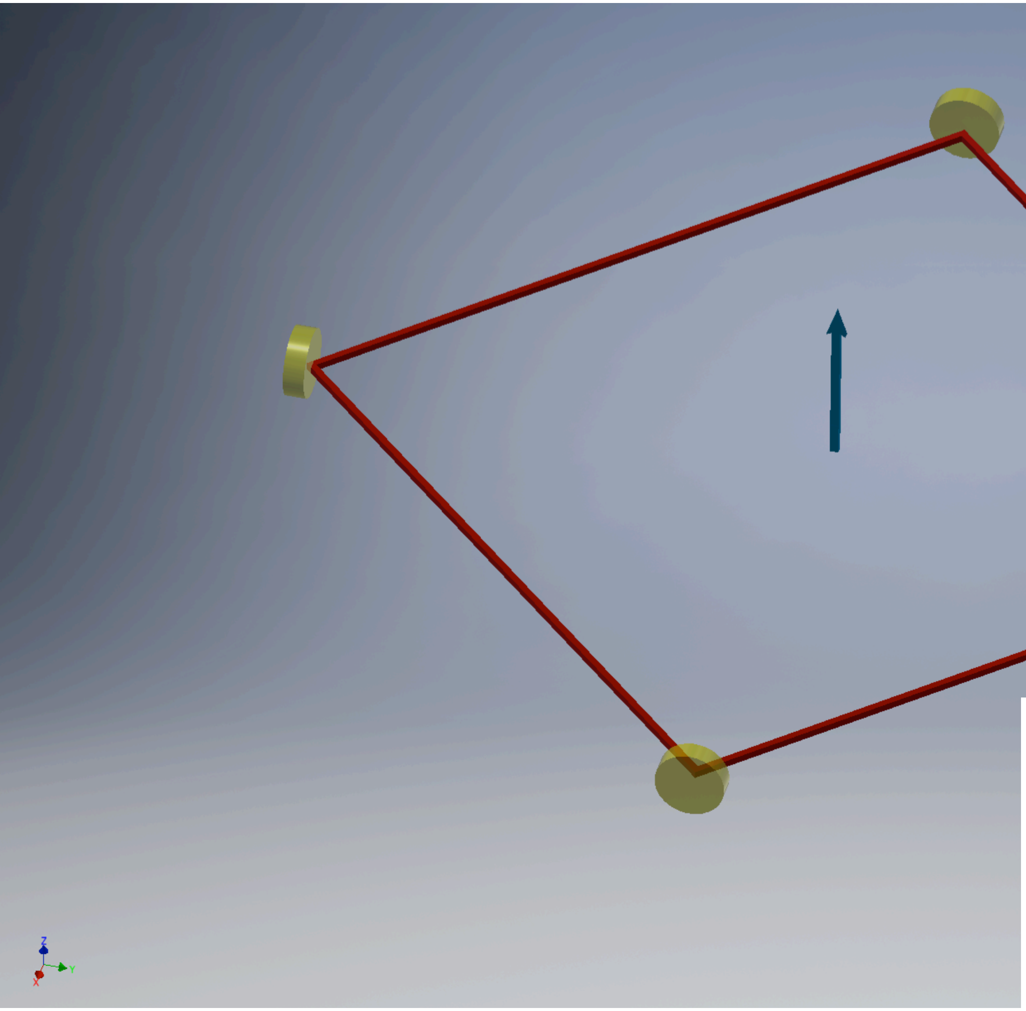
- *In general at least 3, 4 or more would be better (redundancy)*

- *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

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

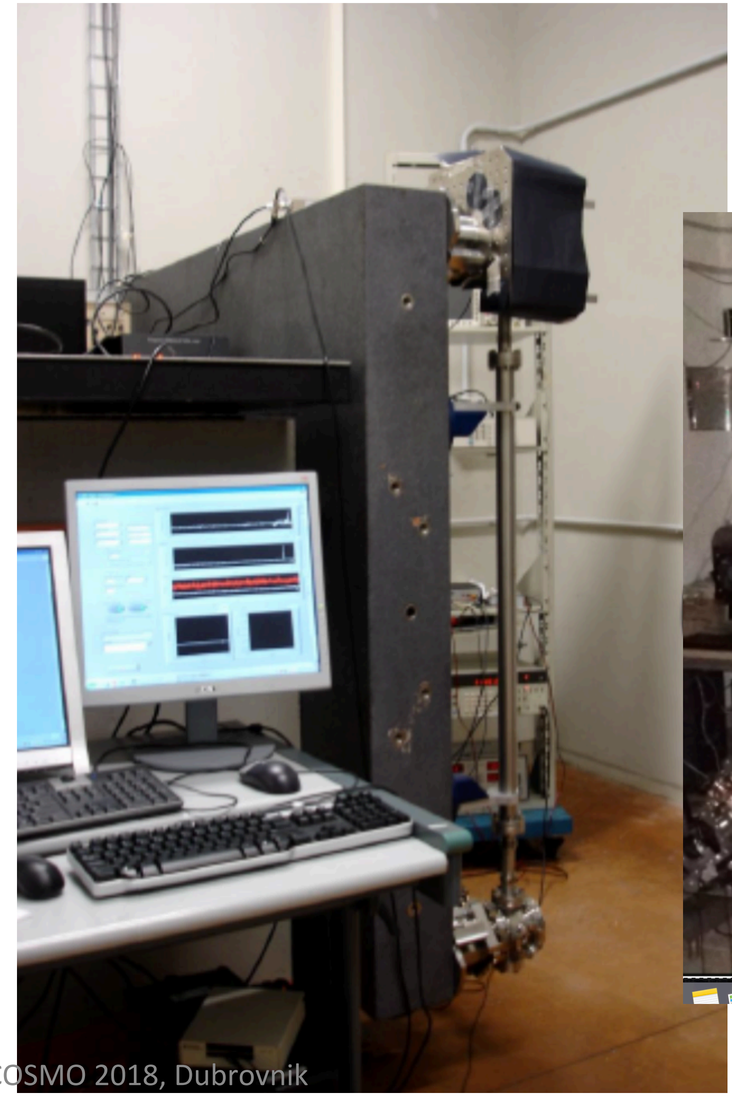
$$f_s = S\ \Omega\ \mathrm{Cos}(\zeta)$$

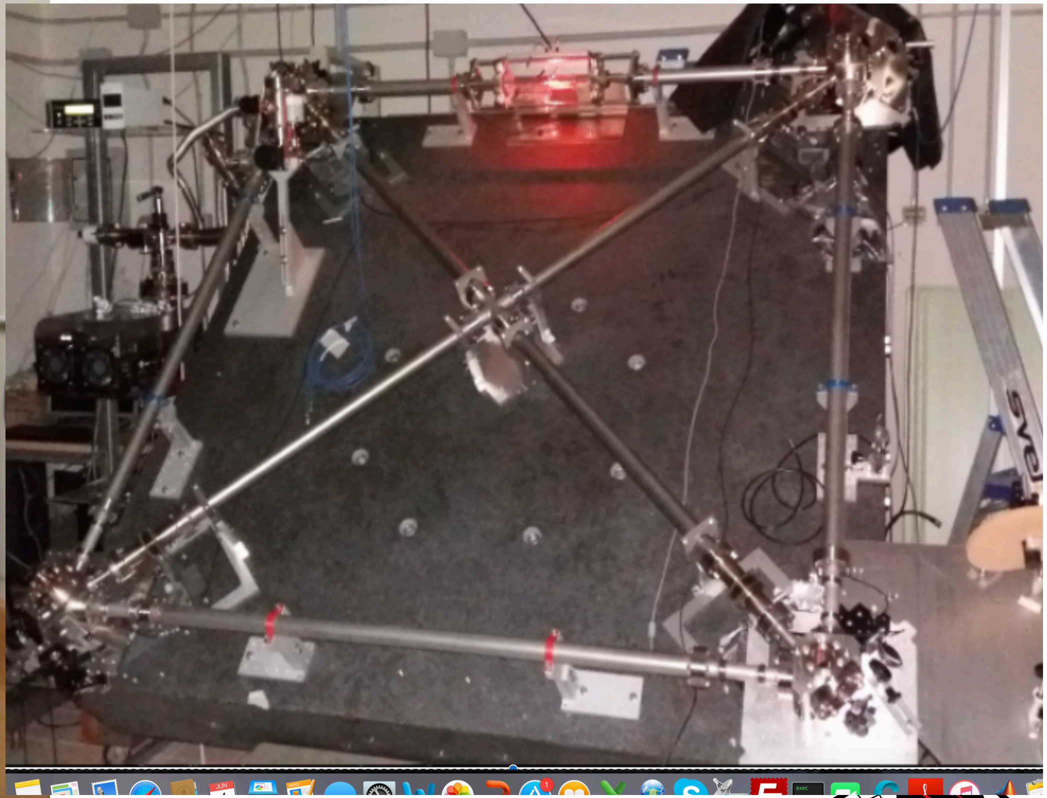
GINGER

IN PRINCIPLE ANY ORIENTATION IS EQUIVALENT, PHOTON HAS ZERO MASS

WE HAVE OPERATED RL HORIZONTAL, VERTICAL AND AT THE MAXIMUM SIGNAL

A SIMPLE APPARATUS





GINGER

2 RLS AT MAXIMUM SIGNAL AT DIFFERENT LATITUDE θ_1 and θ_2

$$a - 3b \simeq 2\frac{f_{\max 2} S_1 - f_{\max 1} S_2}{\Omega_{\oplus} S_1 S_2 (\cos 2\theta_1 - \cos 2\theta_2)}$$

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

WE HAVE STUDIED IN DETAILS THE SYSTEM WITH 2 CO-LOCATED RL FOR THE LENSE-THIRRING 1% TEST

- **GINGER: a feasibility study**, Di Virgilio, A., Belfi, J. et al Eur. Phys. J. Plus (2017) 132: 157

TO DEFINE THE EXPERIMENTAL REQUIREMENTS

THE SIMPLEST APPARATUS

2 RL with area versors n_1 and n_2 inside the meridian plane
It is necessary:
identify and subtract any extra term (tides etc.)

$$\omega = \eta \Omega_\oplus, \ \eta \ll 1$$

$$\eta = \frac{f_1 - S\Omega_\oplus}{S\Omega_\oplus \cos\xi}$$

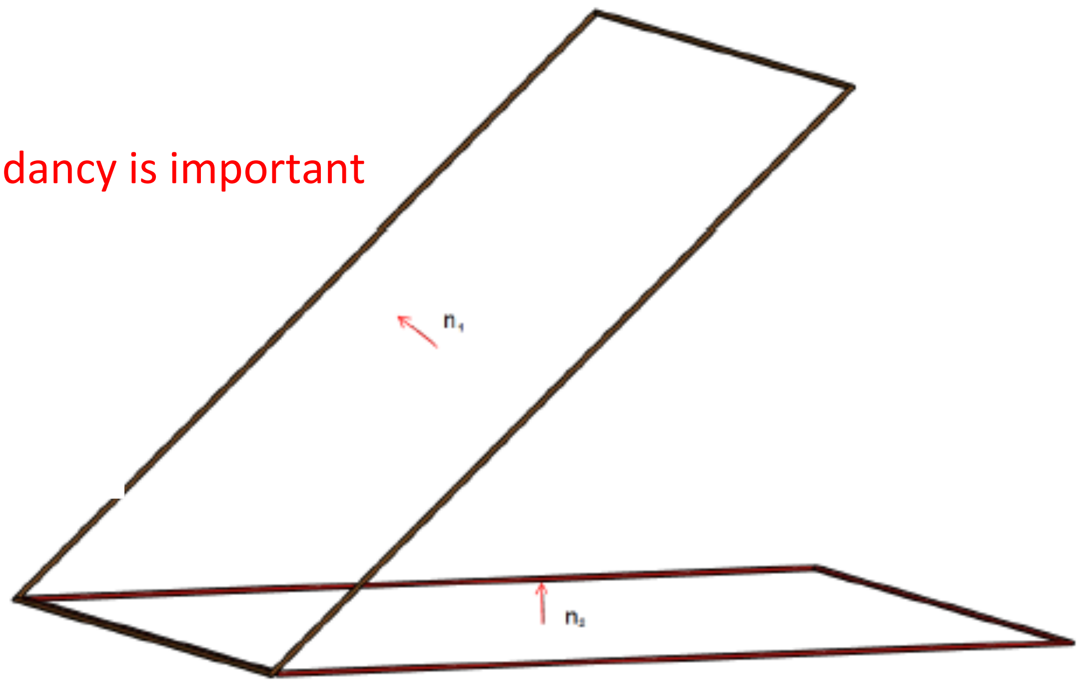
$$\eta = \frac{f_2 - S\Omega_\oplus \cos\zeta}{S\Omega_\oplus \cos\xi \cos\zeta}.$$

$$\alpha = \eta \sin(\xi)$$

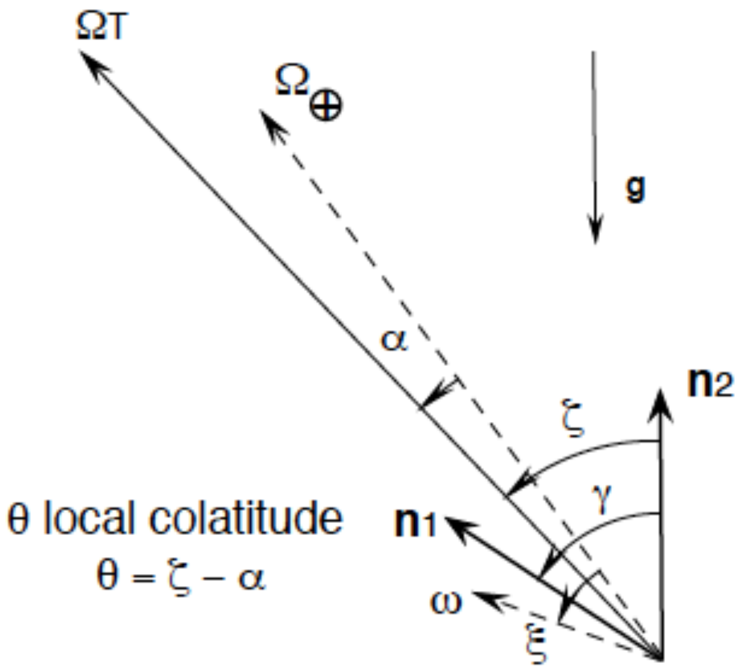
$$\eta_\perp = \eta \sin(\xi)$$

$\eta_\parallel$ and $\eta_\perp$

Redundancy is important



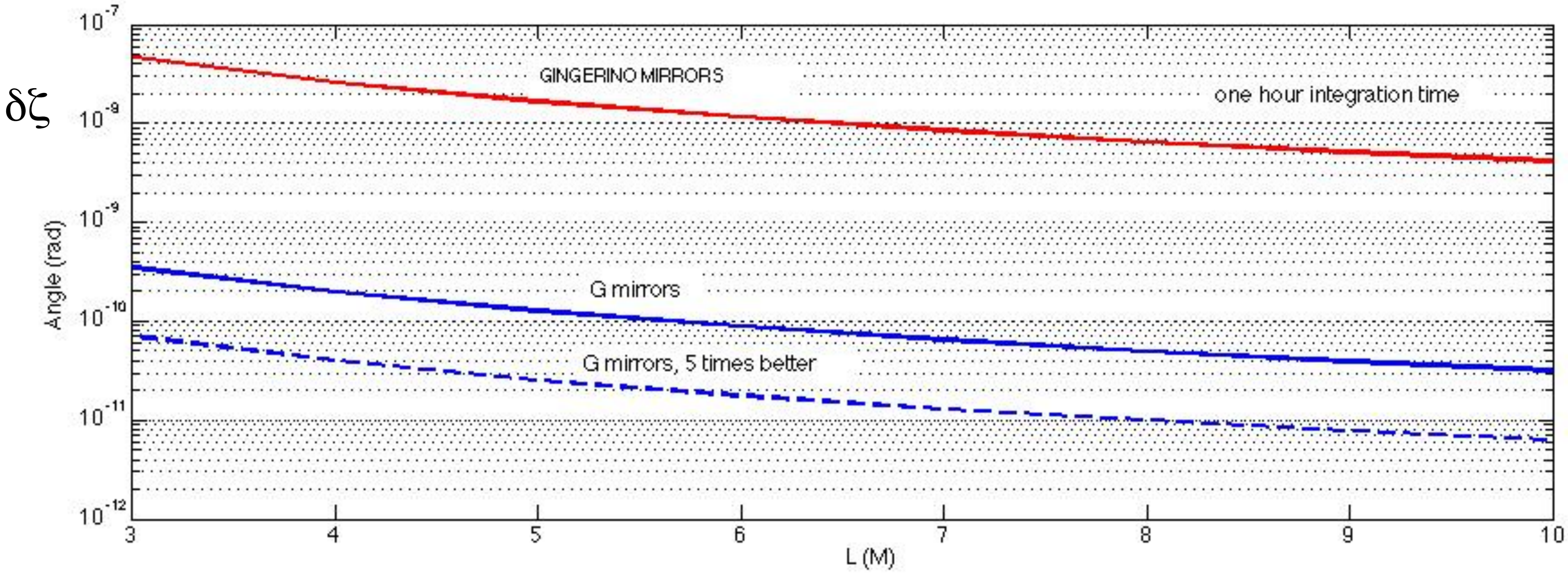
ESSENTIAL POINT OF THE PROBLEM



the angle ζ can be determined by the two Sagnac frequencies

$$\zeta = \tan^{-1}\frac{f_1 - f_2\cos(\gamma)}{f_2\sin(\gamma)}$$

The fast changes of the Earth rotation axis



- 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)

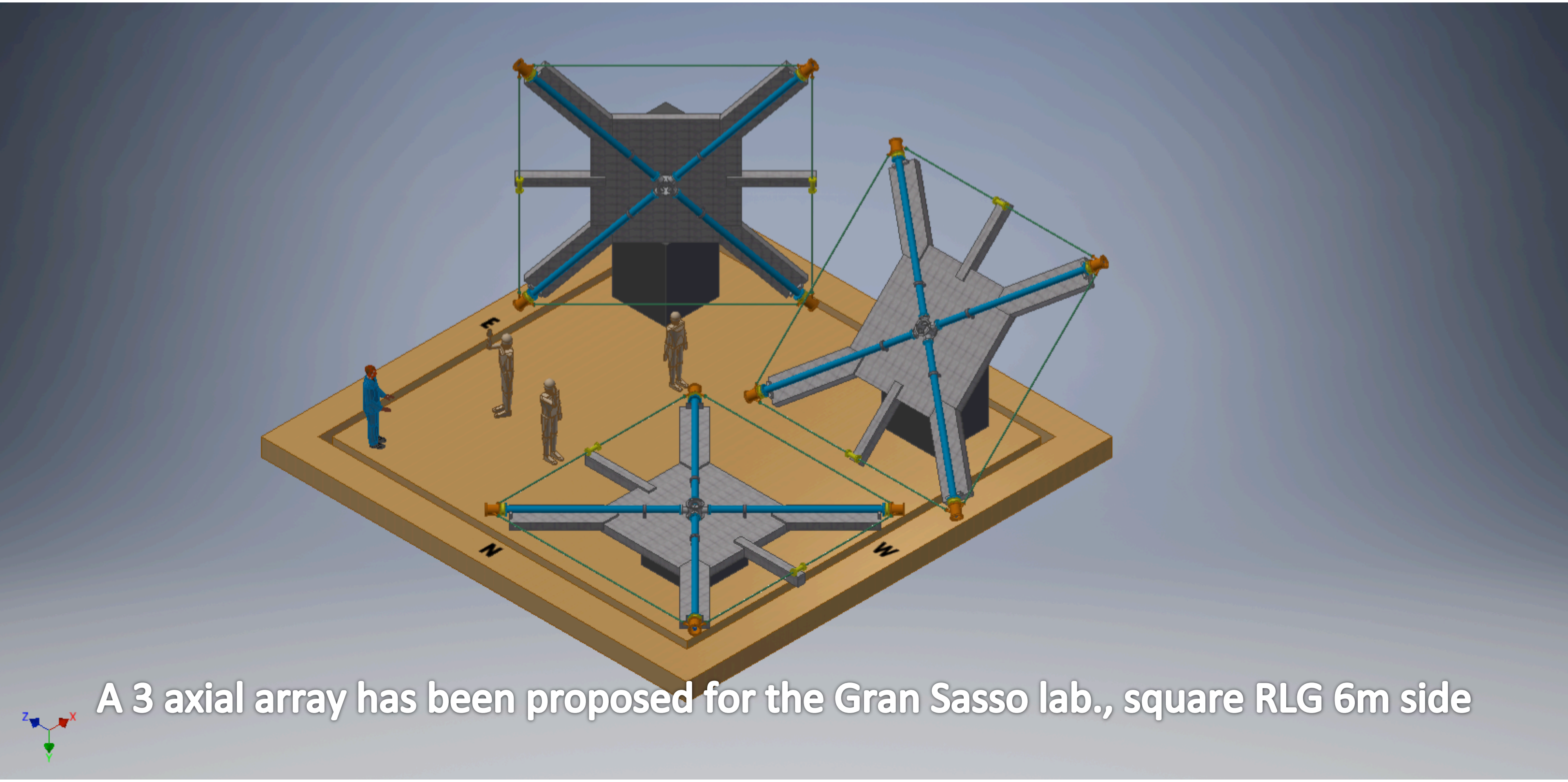
- One RL with area versor outside the meridian plane should be added in a second time. This requires to measure the angles with respect RL_2

COROLLARIO

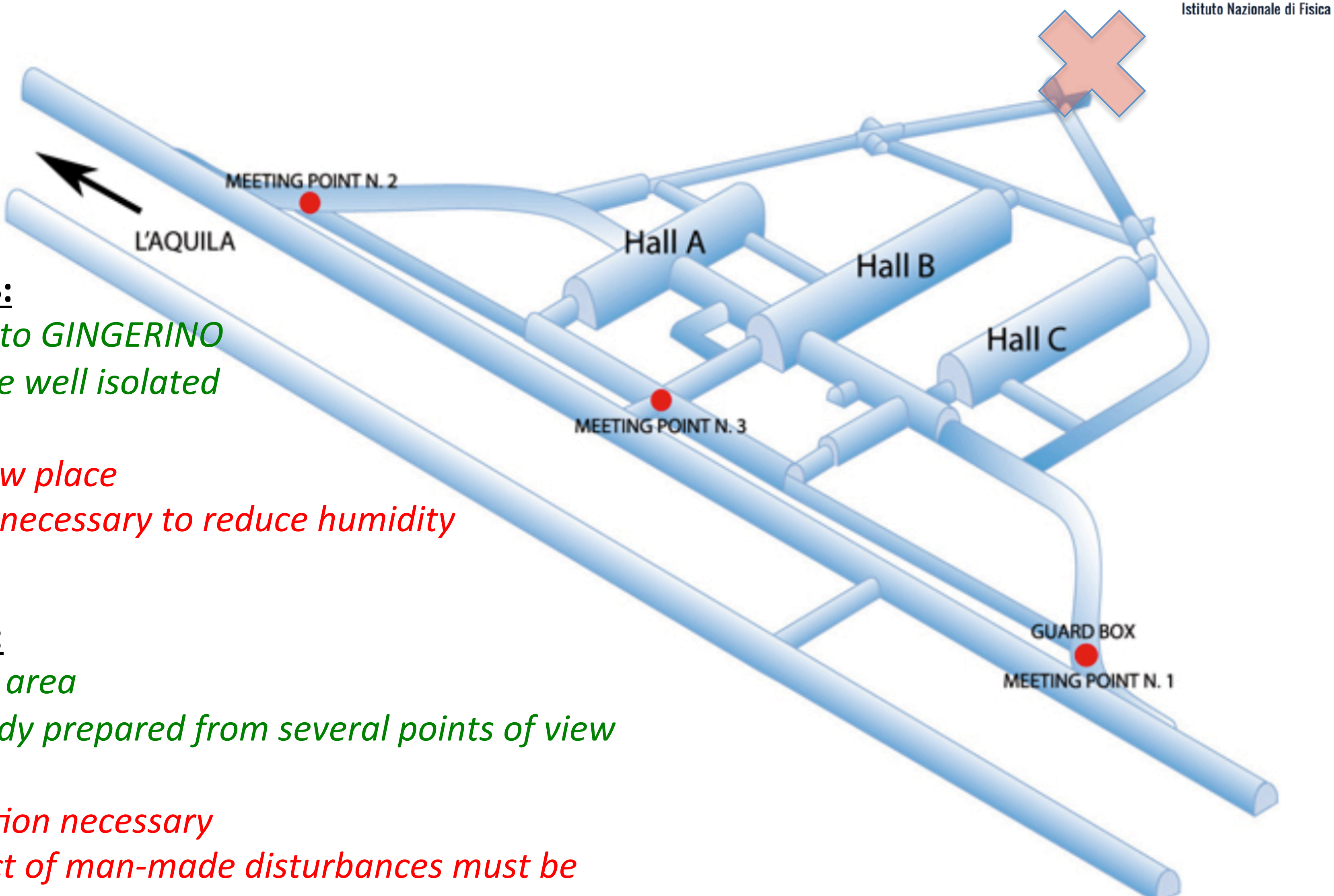
- *In principle at least two separate arrays of RLGs are necessary to test the theory*

- *One array only could do it if the orientation of the horizontal RLG can be compared with some absolute reference. This is in principle feasible since the two light beams are exiting the RL cavity. This is clearly expressed in our papers. At present only the angular rotation is evaluated from the RL data.*

Angular rotation and area versor should be measured, i.e. reconstruct the parallel and perpendicular component of the perturbation



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



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

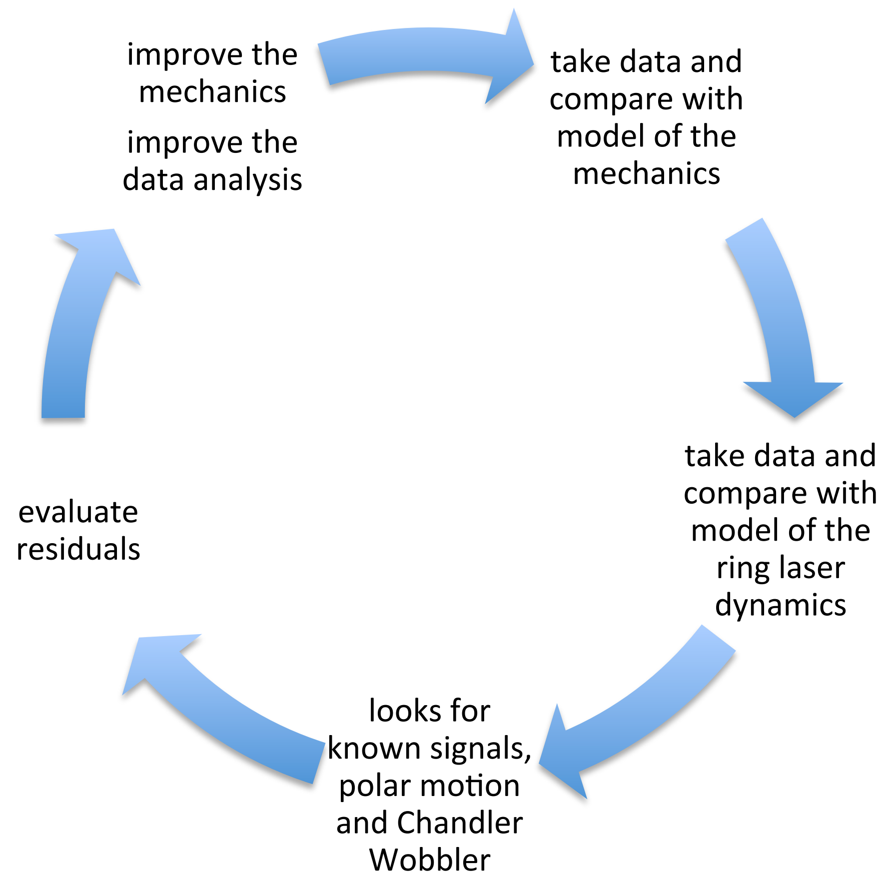
What GINGER delivers

- Variation of the earth rotation rate with relative precision ~ 10^{-9}-10^{-12}
- Lense Thirring 1%

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

GINGER

This is the way in which we proceed



GINGER

A look at the data

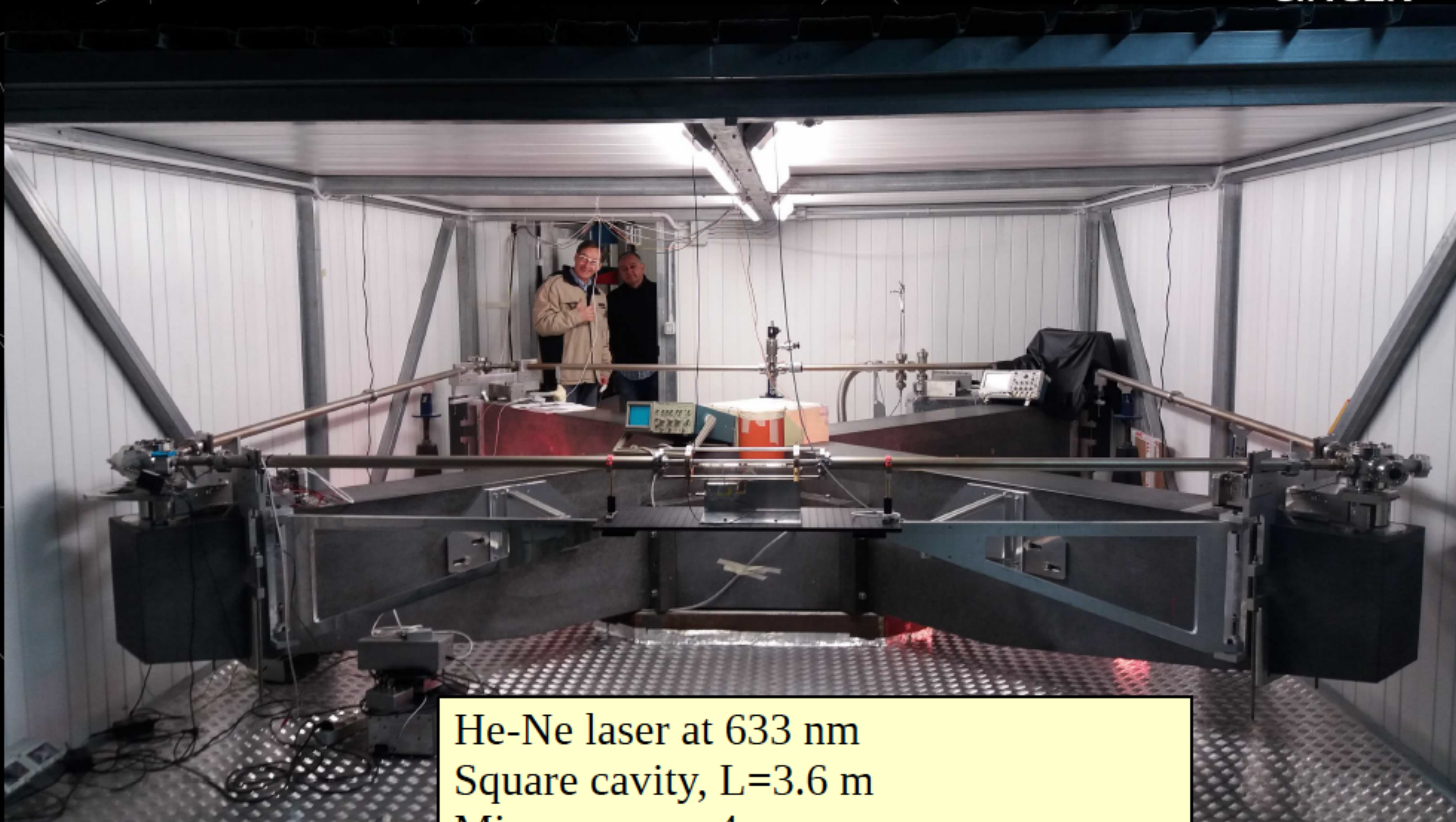
Let us talk about the data of our prototypes:
GINGERINO (horizontal) and GP2 (at maximum signal)

G - Ring the currently best performing gyro

- Perimeter: 16 m
- Area: 16 m^2
- FSR 18.75 MHz
- $\Delta \nu_L \approx 274\ \mu Hz$
- 5 ppm total loss
- $Q = \omega \tau \approx 5 \times 10^{12}$
- 6.5 mB gas pressure in order to avoid multi-moding

GINGERino: deep underground ring laser

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



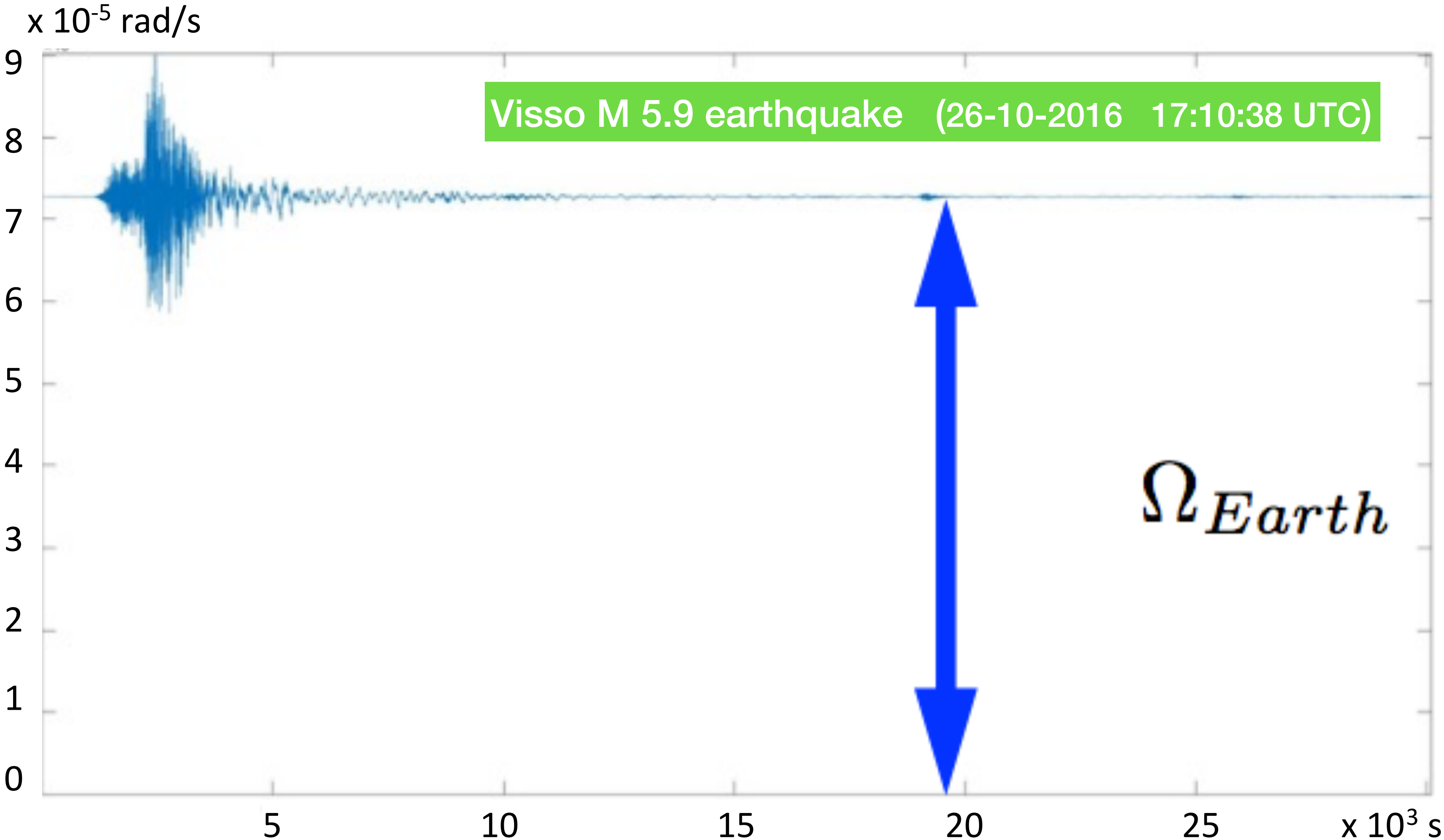
He-Ne laser at 633 nm
Square cavity, L=3.6 m
Mirrors r.o.c= 4 m
Earth rotation Sagnac bias: **fs=280.4 Hz**

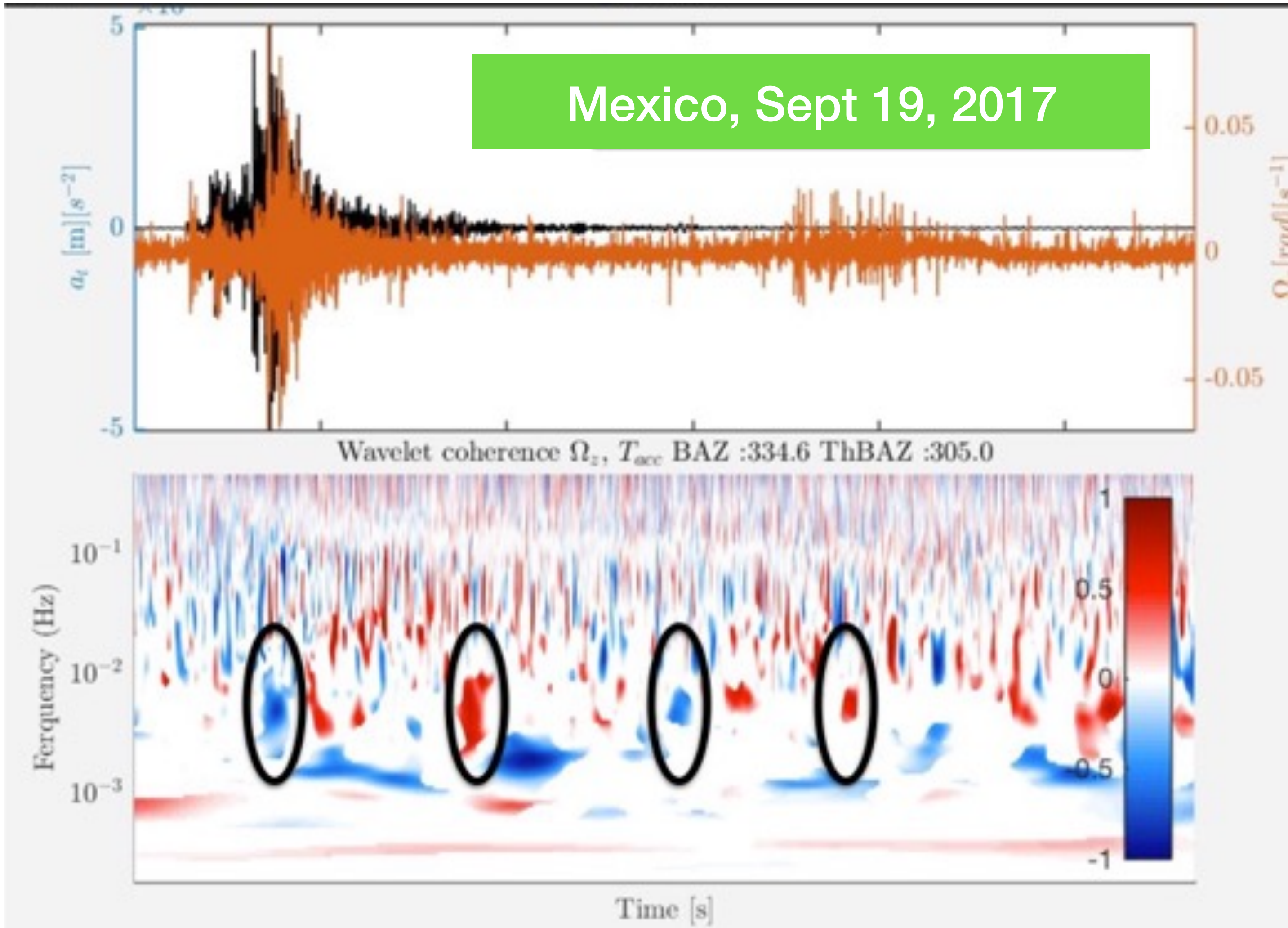
Let us take a look at the data

- 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)

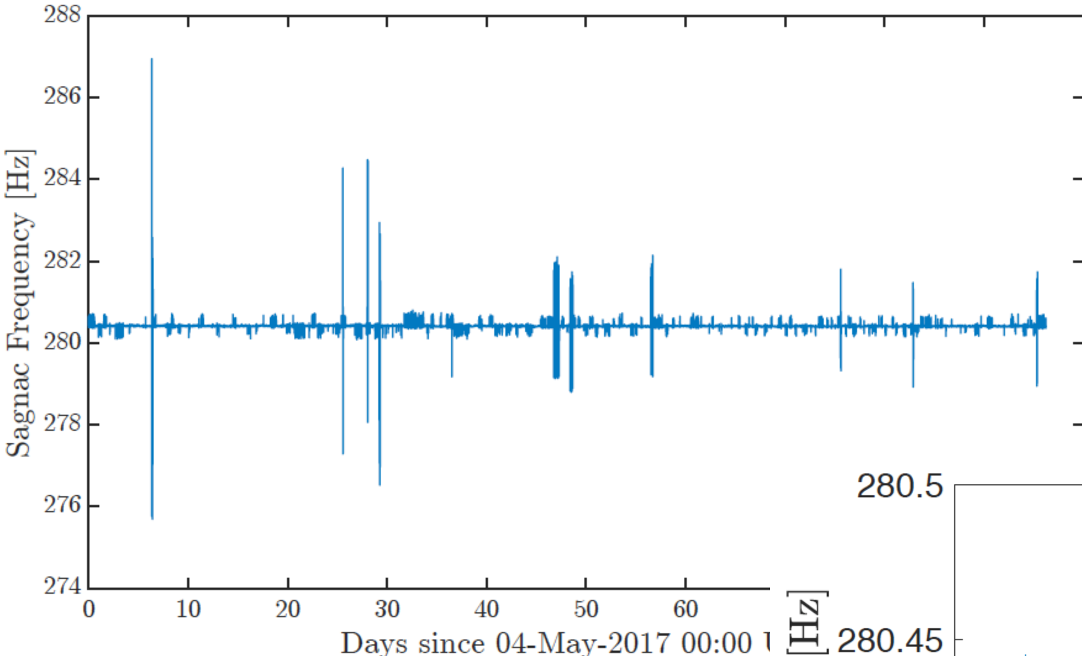
- GINGERINO is not stable enough but we are using the data to develop model and understand the apparatus

Gingerino for seismology

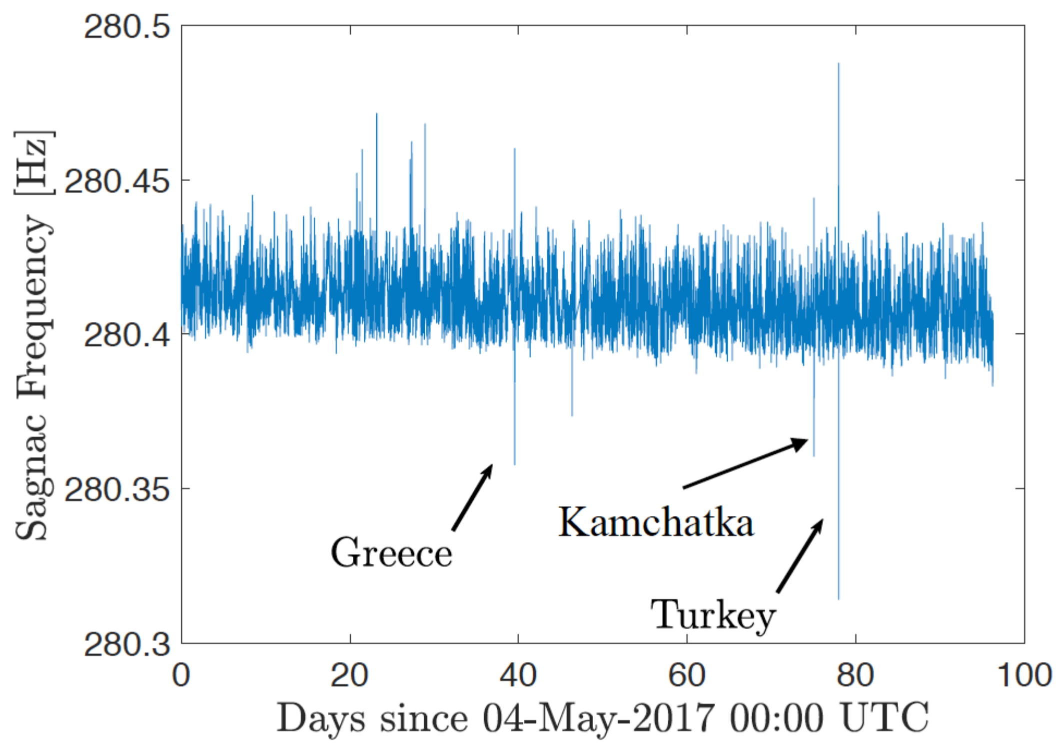



Mexico, Sept 19, 2017
Wavelet coherence Ω_z, T_{acc} BAZ :334.6 ThBAZ :305.0
Ferquency (Hz)
Time [s]

GINGERINO IS THE FIRST HETERO LITHIC RLG WORKING IN ACONTINUOUS BASIS



Raw data

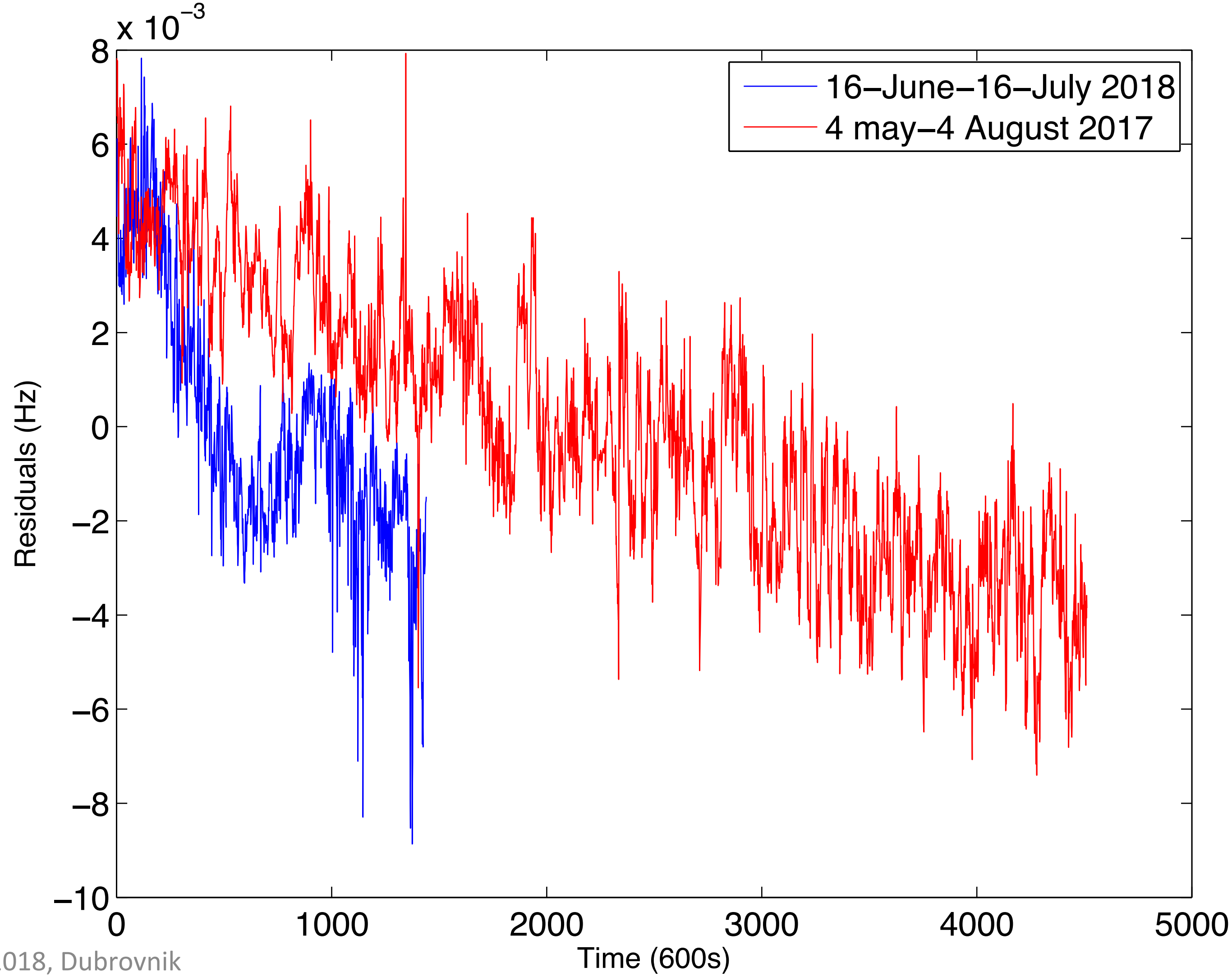


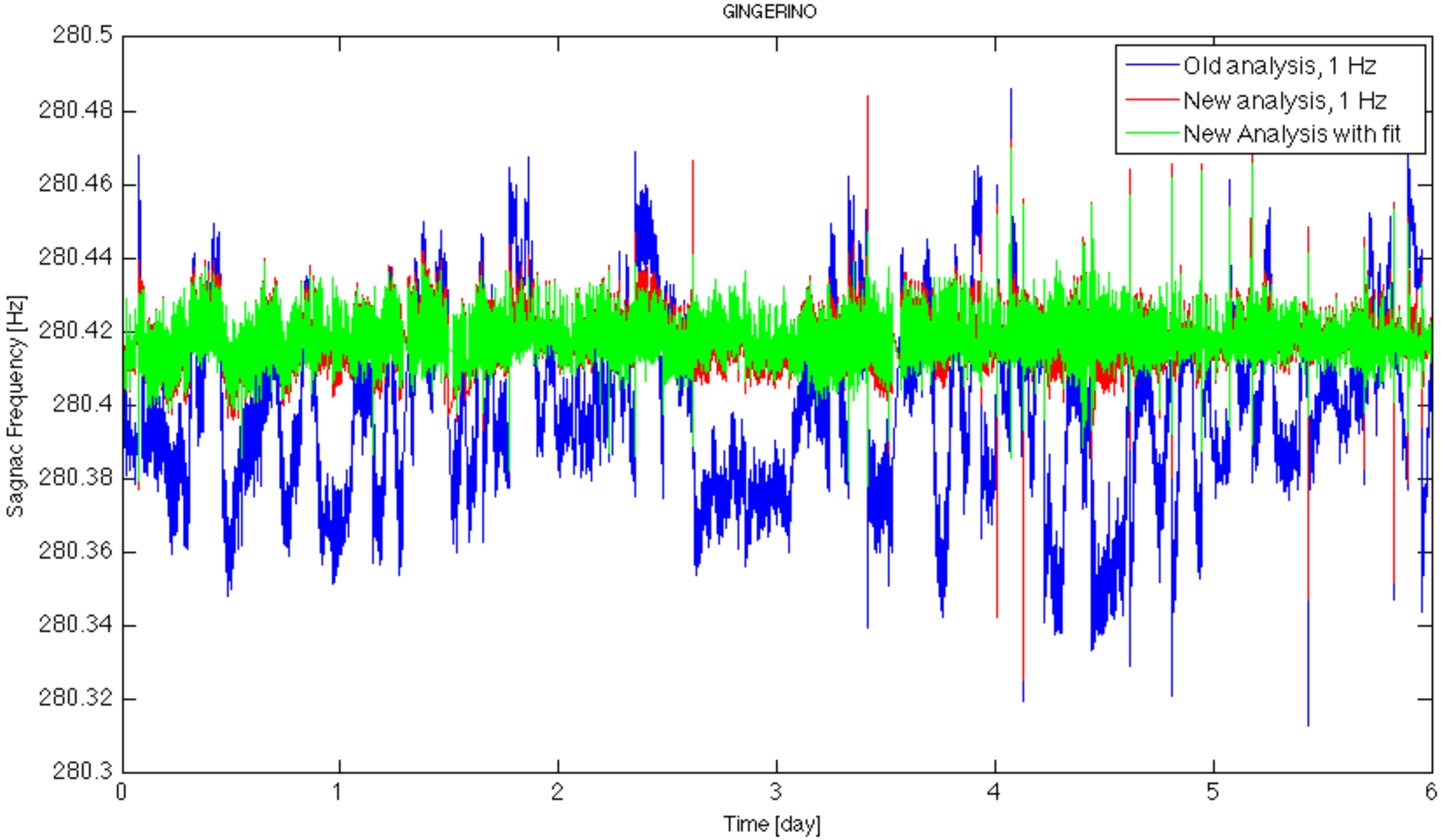
Data cleaned from split mode and mode jumps through FC

Less than 5% of the points were concerned

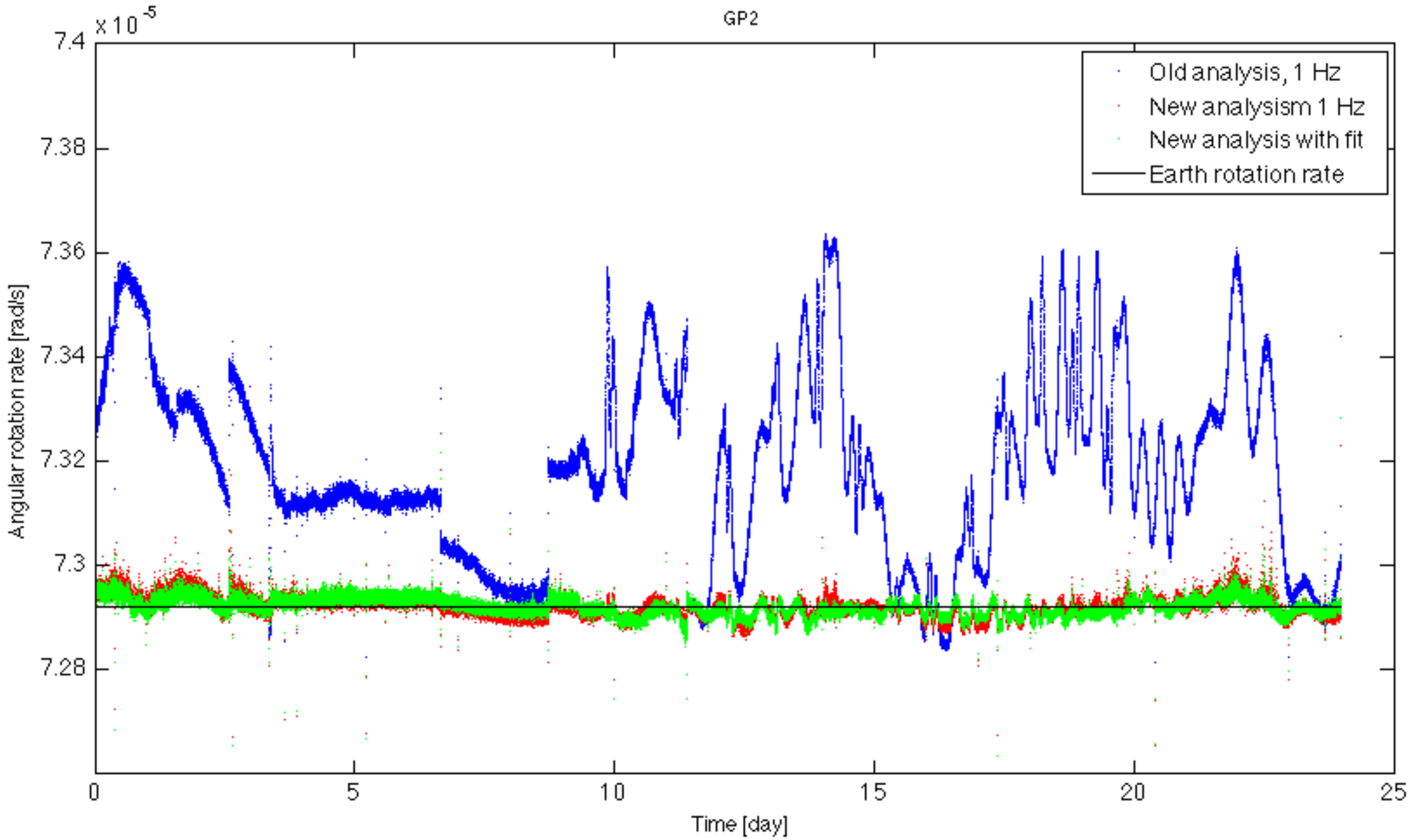
At present we are developing tools to improve the reconstruction of the measured rotation, one of the major problem is the complex dynamic of the laser, in principle not linear and described by more than 10 independent parameters

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


x 10^−3
8
6
4
2
0
−2
−4
−6
−8
−10
Residuals (Hz)
0
1000
2000
3000
4000
5000
Time (600s)
16−June−16−July 2018
4 may−4 August 2017

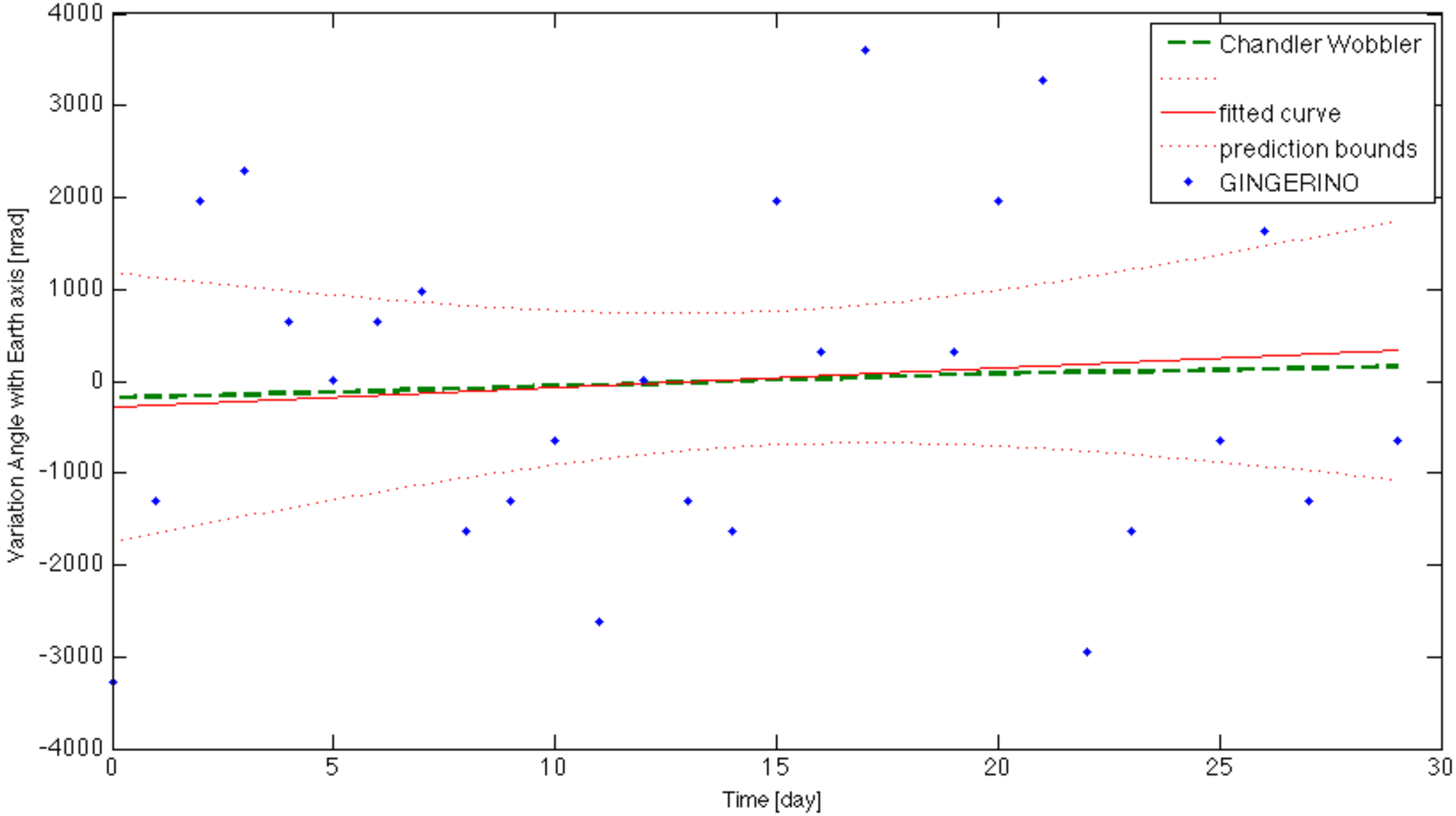

GINGERINO
Old analysis, 1 Hz
New analysis, 1 Hz
New Analysis with fit
Sagnac Frequency [Hz]
Time [day]
280.5
280.48
280.46
280.44
280.42
280.4
280.38
280.36
280.34
280.32
280.3
0
1
2
3
4
5
6

Not only sensitivity but also accuracy!

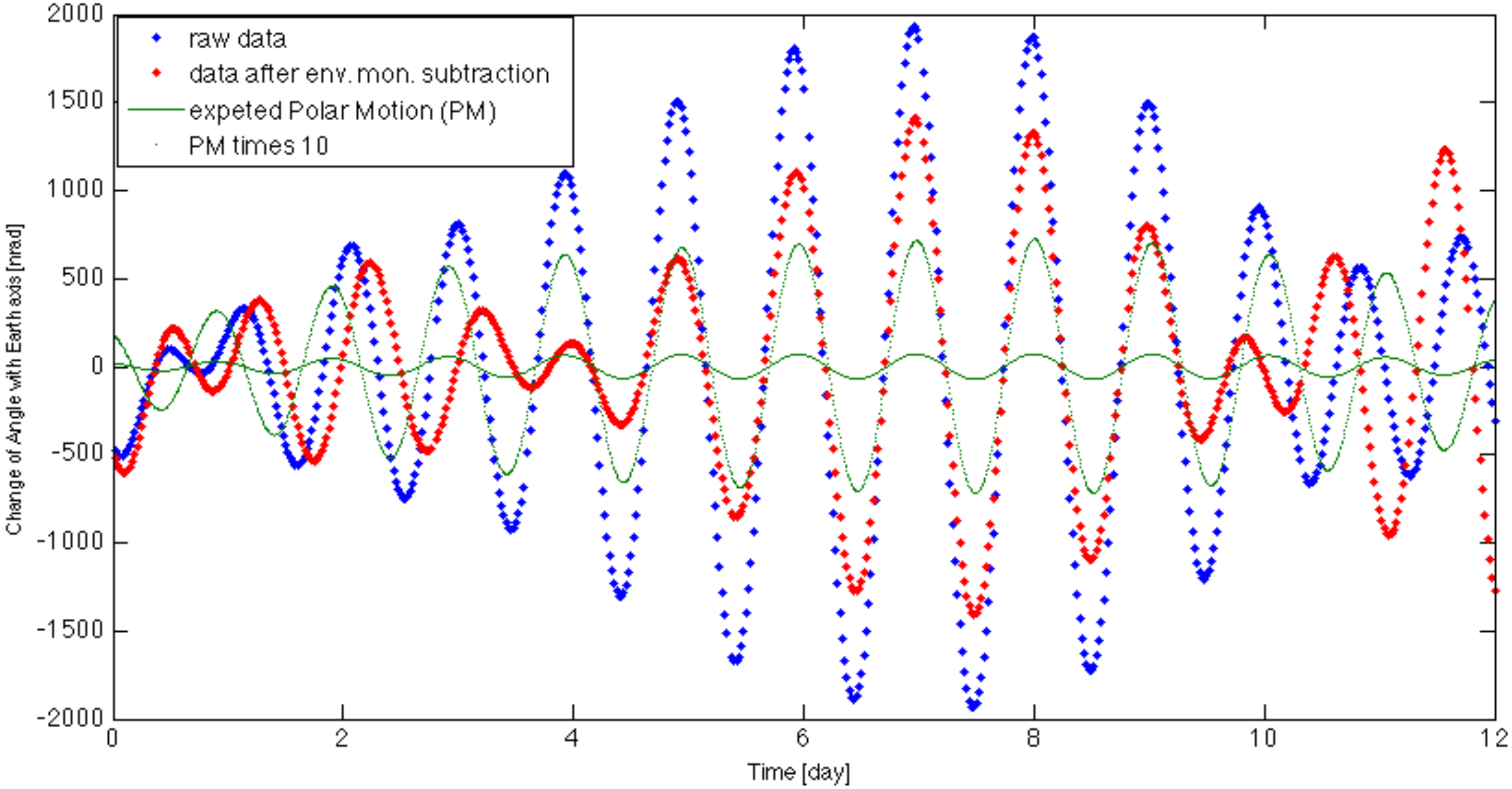


GP2 is meant to study the geometry control,
It is aligned at the maximum signal

Comparison with Chandler Wobbler, preliminary



Comparison with Polar Motion, preliminary



…DO NOT FORGET…

Several very high sensitivity apparatus will be continuously running in the near future, this will give the opportunity to further refine the analysis and the apparatus

2017 3 paper highlighted

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

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

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

INFN Sections: Pisa, LNGS, Legnaro and Napoli