GINGER

GYROSCOPES IN GENERAL RELATIVITY

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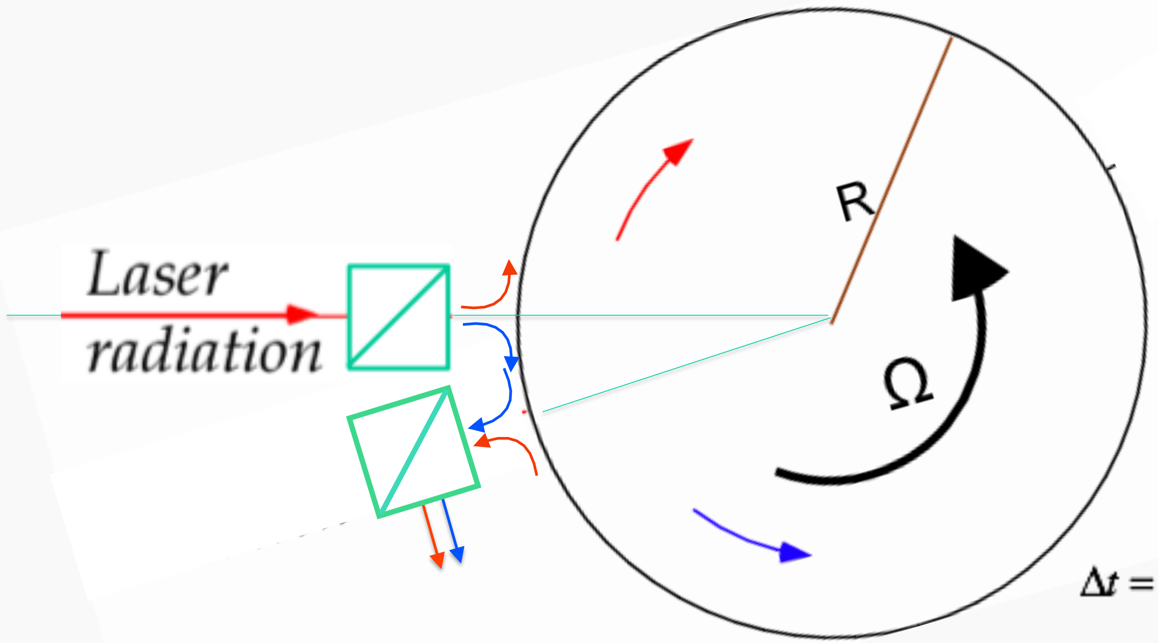
- *SAGNAC Gyroscopes (Ring laser), the Lense-Thirring measurement on Earth and the Lorentz violation test*
- *Proposed experiment and its sensitivity*
- *multidisciplinarity and conclusions*

THE SAGNAC EFFECT

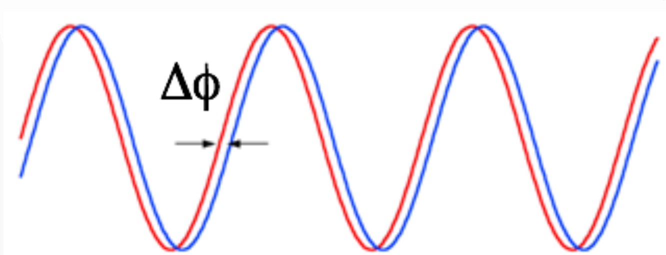
$$\Delta\phi = \frac{8\pi A}{\lambda c}\vec{n}\cdot\vec{\Omega}$$



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

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

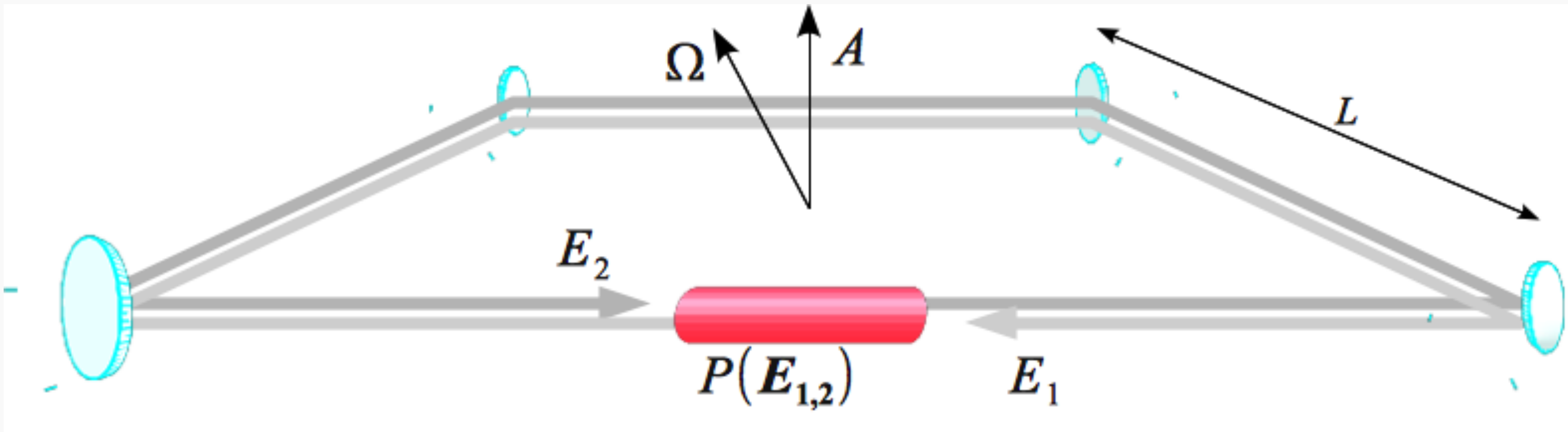
$$\Delta\phi = 2\pi\frac{c\Delta t}{\lambda} = \frac{8\pi\Omega A}{\lambda c}$$

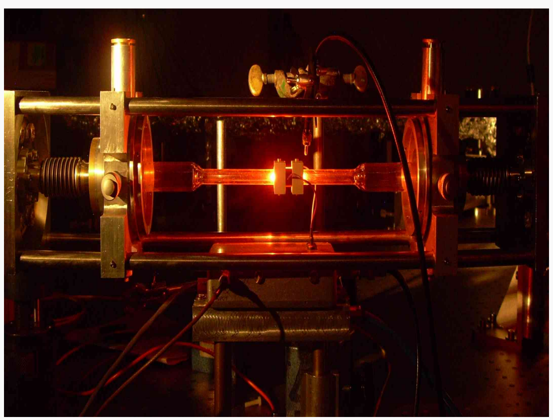


GINGER

SAGNAC GYROS ACTIVE/PASSIVE

ACTIVE…*THE LASER DOES THE WORK FOR YOU….*





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

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

GINGER

SAGNAC GYROS

PROJECTORS TO MEASURE INERTIAL ANGULAR ROTATION RATES

photons, atoms and Helium superfluid and Josephson junction (not active anymore)

100 years of the the Sagnac effect, Compte rendu 2014.

	Active ring cavity	Passive ring cavity	Fiber FOG	Atom
Bandwidth	High	High	High	<20Hz
ASD nrad/s 1 s meas.	Typ. <1 Rec ~$7 \cdot 10^{-3}$	Approaching 1	Commercial 10	~250
Minim. Allan nrad/s	~ 10^{-4} 1 day GINGERINO best ~$5 \cdot 10^{-3}$ 10 days		10	0.3 (10^4 s) SIRTE 2019
perimeter	>4-16m (also ~100 m)	~1 m	>3-4km	~1-10cm, 11 cm^2

GINGER a factor less than 10 improvements, 1 part in 10^9

INFN/FUNDAMENTAL PHYSICS

GINGER: Gyroscopes IN GEneral Relativity
Lense Thirring effect, on Earth, 1% precision

'measurement depending on latitude'
Not averaged
Gravitational map not required

Confrontation space/earth based apparatus?

INFN Sections: Pisa, LNGS, Legnaro, Napoli Department of Physics of Pisa (condensed matter and applied physics)

GINGER

THE GR TERMS

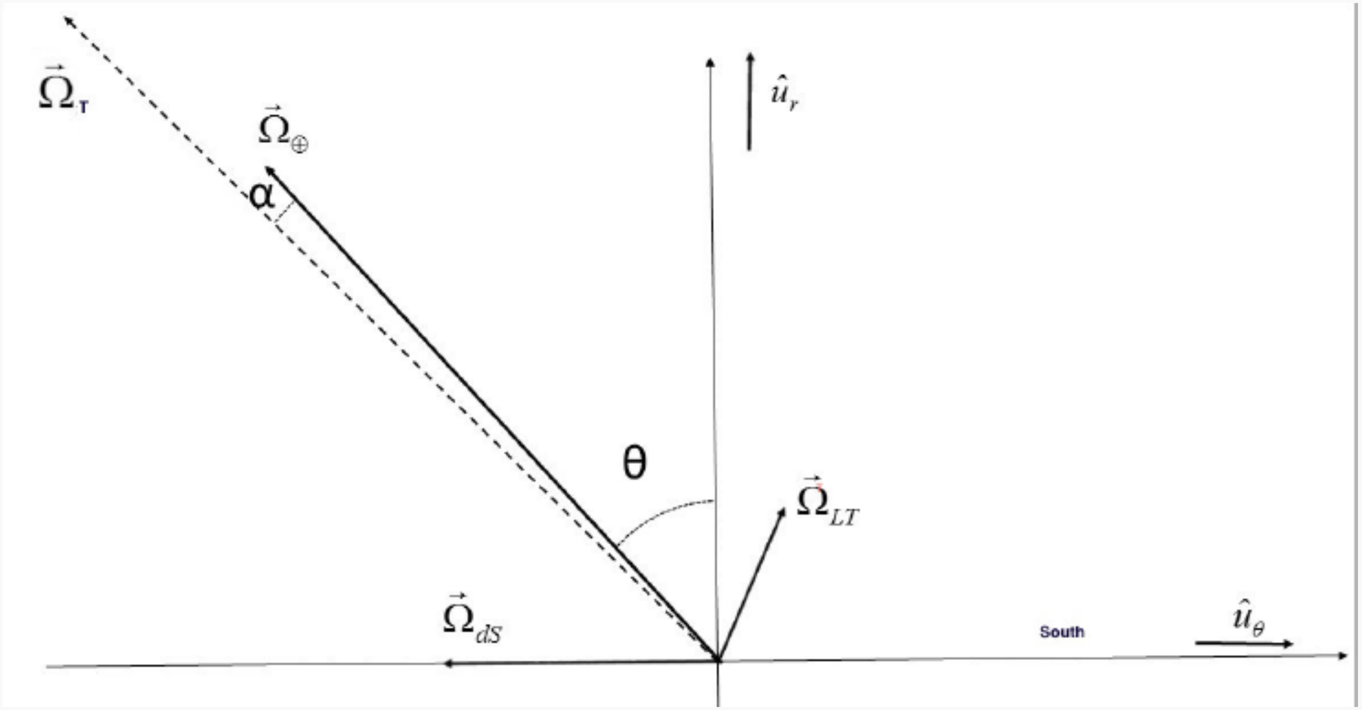
measured by IERS

deSitter

Lense Thirring

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

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 orders of magnitude below the Earth rotation rate.

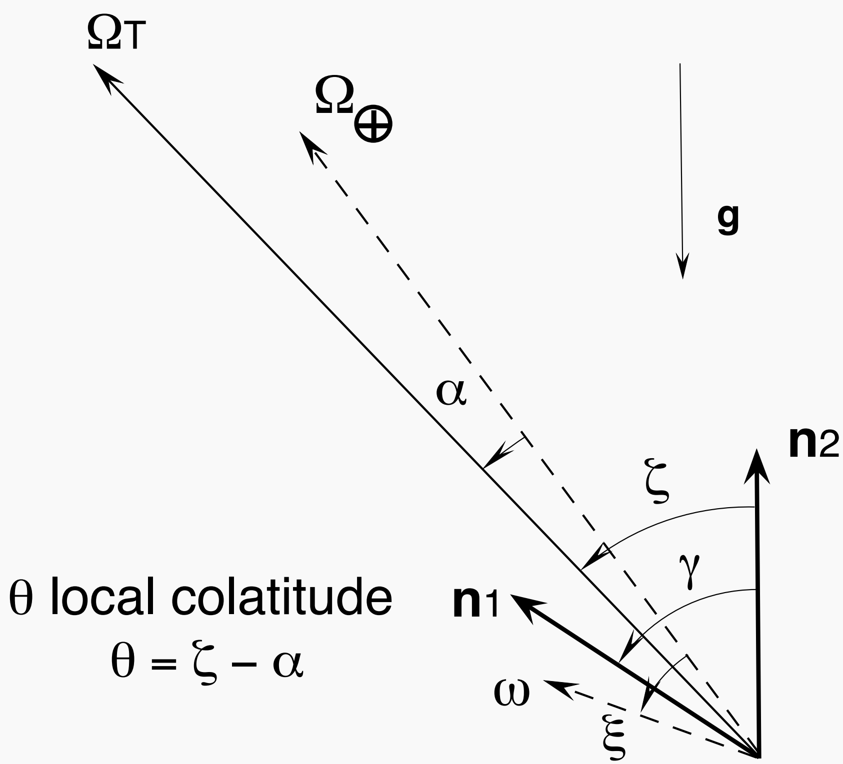
LORENZ VIOLATION AND SAGNAC GYROSCOPES

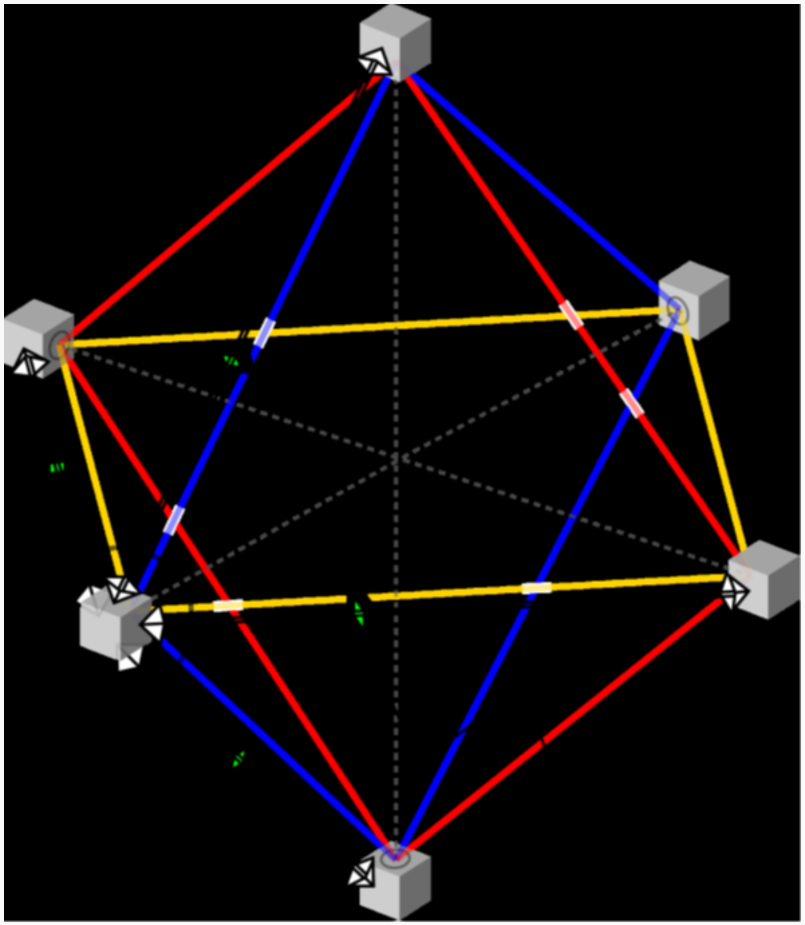
Moseley, Scaramuzza, J. Tasson and M. Trostel, Lorentz,
Phys. Rev. D, 100, 6, pg-064031, 2019,

GINGER could provide valuable test of Lorenz Invariance in the SME framework: in summary 1 part in 10^9 would provide the measurement of the parameter $sbar^{TJ}$, with sensitivity competitive with other laboratory experiments, while for dimension 5 coefficients, these sensitivities are competitive with the best existing measurements from binary pulsars.

GINGER

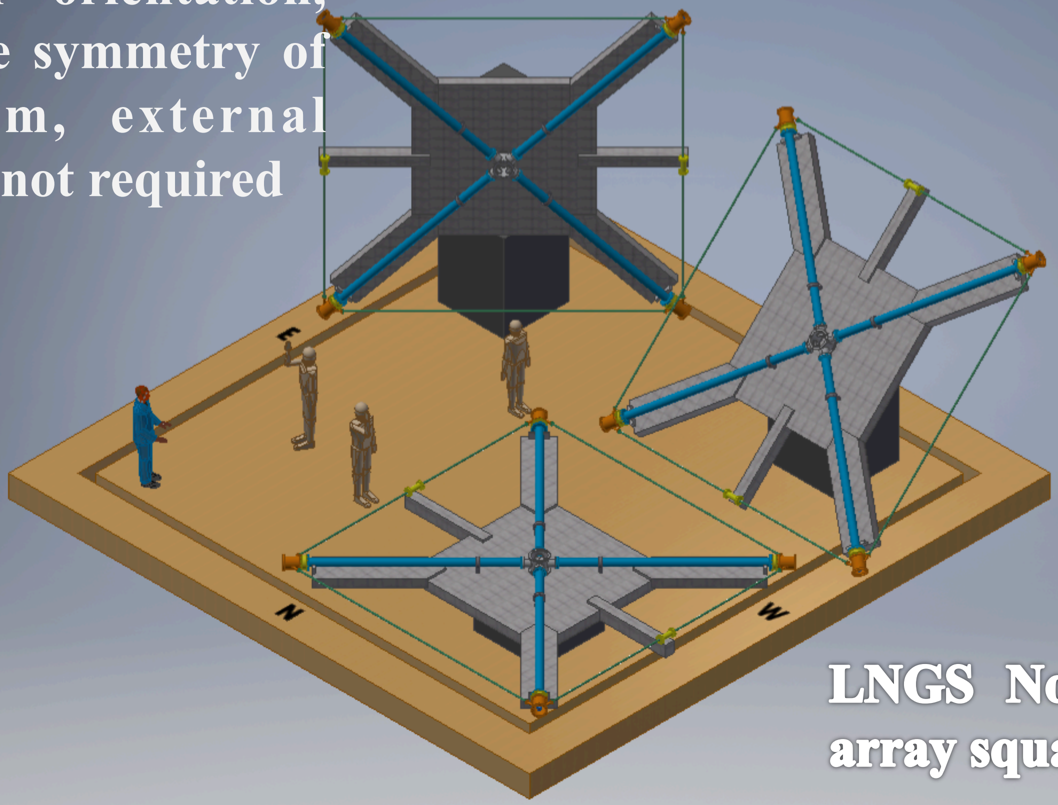
The general problem is to reconstruct the local angular rotation vector and compare it with the independent measurement done by IERS
For Lorenz violation observe the signal at the sideral day frequency





The first proposal was based on 3 RLG arranged to have mirrors on the vertex of an octahedron.

External metrology to evaluate the relative angle between different RLG with sub-nrad accuracy I required with proper orientation, following the symmetry of the problem, external metrology is not required



LNGS Node B allows 3 axial array square RLG 5-6m in side

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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.

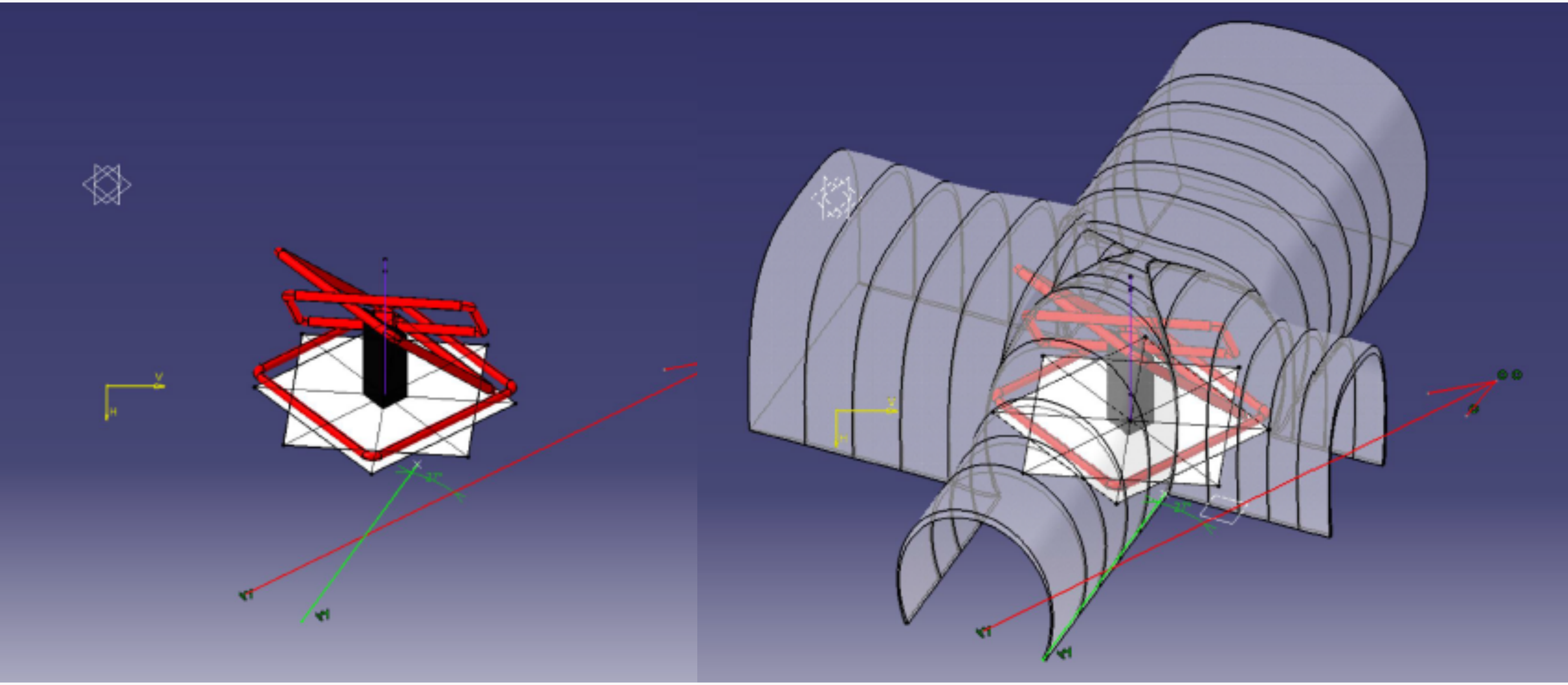
Highlighted as ‘Change the World’

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



Node B is a possible location, but other locations can be taken under consideration

EACH RING CAN BE OPERATED AS ACTIVE OR PASSIVE

SHOT NOISE LIMIT (SQUARE RLG)

h_P and c are Plank constant and speed of light

P_{Losses} and P_{in} are lost power and internal power

Losses indicates the losses of each mirror

l is the square side

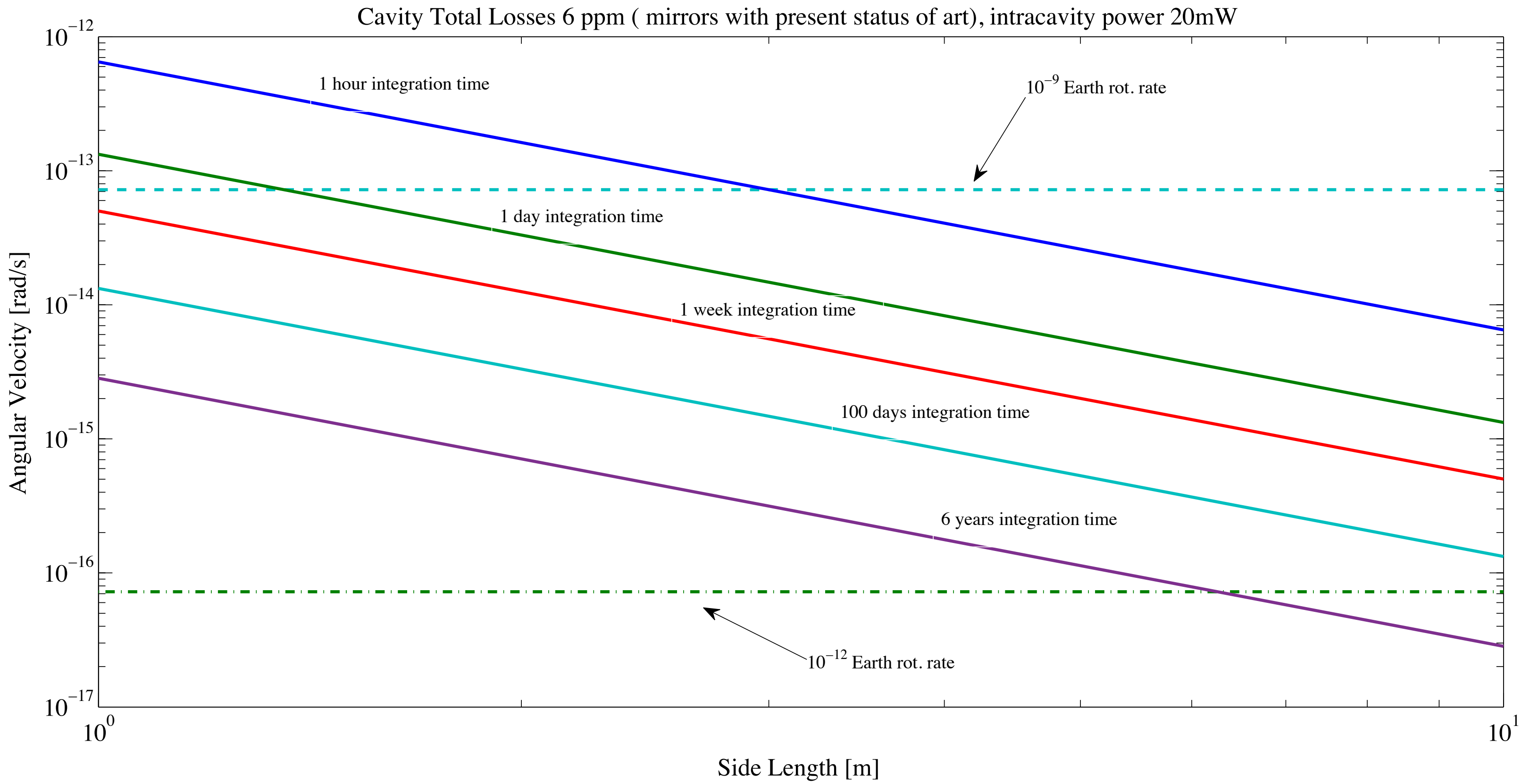
Q_q is the quality factor of the optical cavity

the shot noise depends on the size, the losses, the wavelength and the integration time

$$\omega_{sn} = \frac{c}{l\, Q_q}\sqrt{\frac{h_P\, \nu_0}{P_{Losses}\, T}}$$

$$\omega_{sn} = \frac{c^2}{4\, l^2\, \pi}\sqrt{\frac{h_P\, Losses}{P_{in}\, \nu_0\, T}}$$

SENSITIVITY & STABILITY



WHAT GINGER DELIVERS

- *Lense Thirring 1% IERS (10^{-9}-10^{-12} Earth rotation rate)*
- *Amplitude at the sidereal day modulation (Lorenz Invariance), meaningful from 10^{-9} Earth rotation rate*

- *Variation (fast) of the earth rotation rate with relative precision ~ 10^{-9} (~ 0.1prad/s in 1 h or better)*
- *Variation of the rotation axis (local), 1 nrad in 1 h, corresponding to 1 cm at the pole*
- *High sensitivity measurements of the local rotational motion (seismology)*

Highly Multi-disciplinar

SO FAR ..

- *Scale Factor control: square device, built close to regular square (microns level) and control the diagonals of the square*
- *Developed all necessary tools to measure the square geometry with the required accuracy (μm)*

- *developing and testing a new mechanical scheme to reduce coupling between mirrors, in order to avoid rotations induced by external forces*

- ***New analysis to take into account laser dynamics***

We are ready for GINGER

The dynamic of the laser is in principle a nightmare!

$$\dot{I}_1 = \frac{c}{L}(\alpha_1 I_1 - \beta_1 I_1^2 - \theta_{12} I_1 I_2 + 2r_2\sqrt{I_1 I_2}\cos(\psi + \epsilon))$$
$$\dot{I}_2 = \frac{c}{L}(\alpha_2 I_2 - \beta_2 I_2^2 - \theta_{21} I_1 I_2 + 2r_1\sqrt{I_1 I_2}\cos(\psi - \epsilon))$$
$$\dot{\psi} = \omega_s - \sigma_1 + \sigma_2 - \tau_{12} I_2 + \tau_{21} I_1 + - \frac{c}{L}(r_1\sqrt{\frac{I_1}{I_2}}\sin(\psi - \epsilon) + r_2\sqrt{\frac{I_2}{I_1}}\sin(\psi + \epsilon))$$

IN GENERAL ANALYTICAL SOLUTION DOES NOT EXIST, BUT STATIONARY SOLUTION DOES

STARTING FROM THE STATIONARY SOLUTION WE HAVE FOUND THE WAY TO TAKE INTO ACCOUNT THE LASER DYNAMIC

$$I_1(t) \simeq \frac{\alpha_1}{\beta} + \frac{2\sqrt{\alpha_1\alpha_2} r_2 (\frac{L\omega_s \sin(t\omega_s+\epsilon)}{c} + \alpha_1 \cos(t\omega_s+\epsilon))}{\beta(\alpha_1^2 + \frac{L^2\omega_s^2}{c^2})} + \\ - \frac{2cr_1r_2\sin(2\epsilon)}{\beta L\omega_s}$$

$$I_2(t) \simeq \frac{\alpha_2}{\beta} + \frac{2\sqrt{\alpha_1\alpha_2} r_1 (\alpha_2 \cos(\epsilon - t\omega_s) - \frac{L\omega_s \sin(\epsilon - t\omega_s)}{c})}{\beta(\alpha_1^2 + \frac{L^2\omega_s^2}{c^2})} + \\ + \frac{2cr_2r_1\sin(2\epsilon)}{\beta L\omega_s}$$

$$\psi_0(t) \simeq \frac{c(\sqrt{\frac{\alpha_1}{\alpha_2}} r_1 \cos(\epsilon - t\omega_s) + \sqrt{\frac{\alpha_2}{\alpha_1}} r_2 \cos(t\omega_s+\epsilon))}{L\omega_s} + \\ + t(\omega_s - \frac{2r_1r_2(\frac{c}{L})^2\cos(2\epsilon)}{\omega_s})$$

$$\omega_s \simeq \omega_{s0} + \omega_{ns1} + \omega_{ns2} + \omega_{K1} + \omega_{K2} + \omega_{nsK} \quad (9)$$

$$\omega_{s0} = (\frac{1}{2}\sqrt{\frac{8c^2 r_1 r_2 \cos(2\epsilon)}{L^2} + \omega_m^2} + \frac{\omega_m}{2}) \quad (10)$$

$$\omega_{ns1} = -\delta_{ns} \times (\frac{\omega_m}{2\sqrt{\frac{8c^2 r_1 r_2 \cos(2\epsilon)}{L^2} + \omega_m^2}} + \frac{1}{2})$$

$$\omega_{ns2} = \delta_{ns}^2 \times \frac{2c^2 r_1 r_2 \cos(2\epsilon)}{(8c^2 r_1 r_2 \cos(2\epsilon) + L^2\omega^2)\sqrt{\frac{8c^2 r_1 r_2 \cos(2\epsilon)}{L^2} + \omega_m^2}}$$

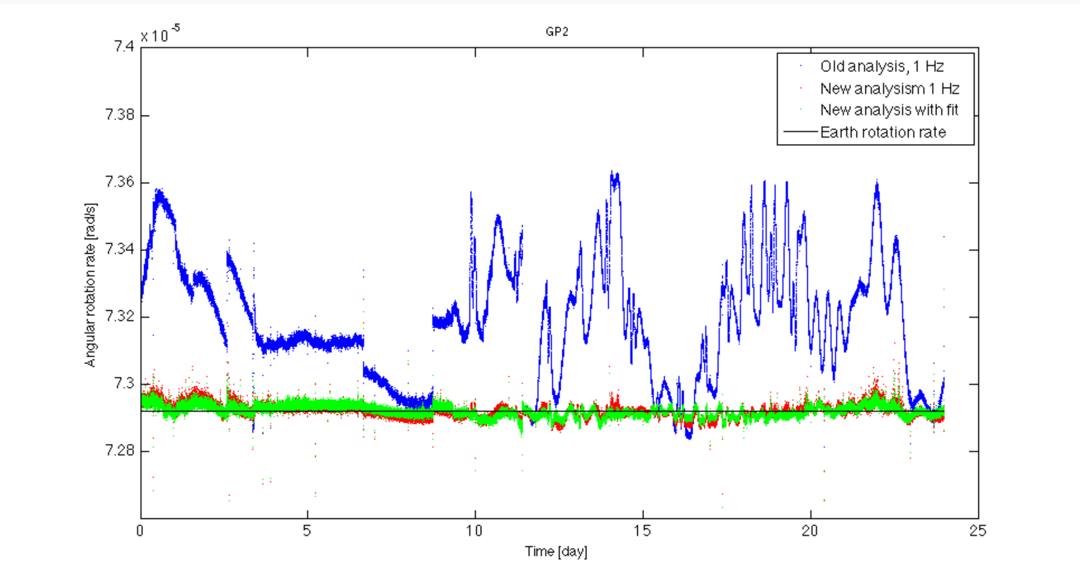
$$\omega_{K1} = K \times (-\frac{\omega_m}{2L\sqrt{\frac{8c^2 r_1 r_2 \cos(2\epsilon)}{L^2} + \omega_m^2}} - \frac{1}{2L})$$

$$\omega_{K2} = K^2 \times \frac{2c^2 r_1 r_2 \cos(2\epsilon)\sqrt{\frac{8c^2 r_1 r_2 \cos(2\epsilon)}{L^2} + \omega_m^2}}{(8c^2 r_1 r_2 \cos(2\epsilon) + L^2\omega_m^2)^2}$$

$$\omega_{nsK} = \frac{\delta_{ns} K}{2\sqrt{8c^2 r_1 r_2 \cos 2\epsilon + L^2 {\omega_m}^2}}$$

Di Virgilio, A.D.V., Beverini, N., Carelli, G. et al. Eur. Phys. J. C (2019) 79: 573. https://doi.org/10.1140/epjc/s10052-019-7089-5

GP2, MIDDLE SIZE RLG, HAS REACHED 2NRAD/S SENSITIVITY (MIRROR LOSSES MORE THAN 50 PPM EACH)



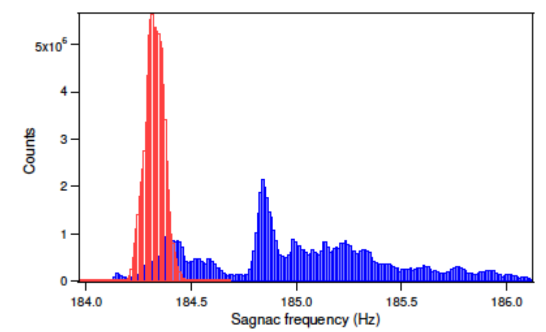
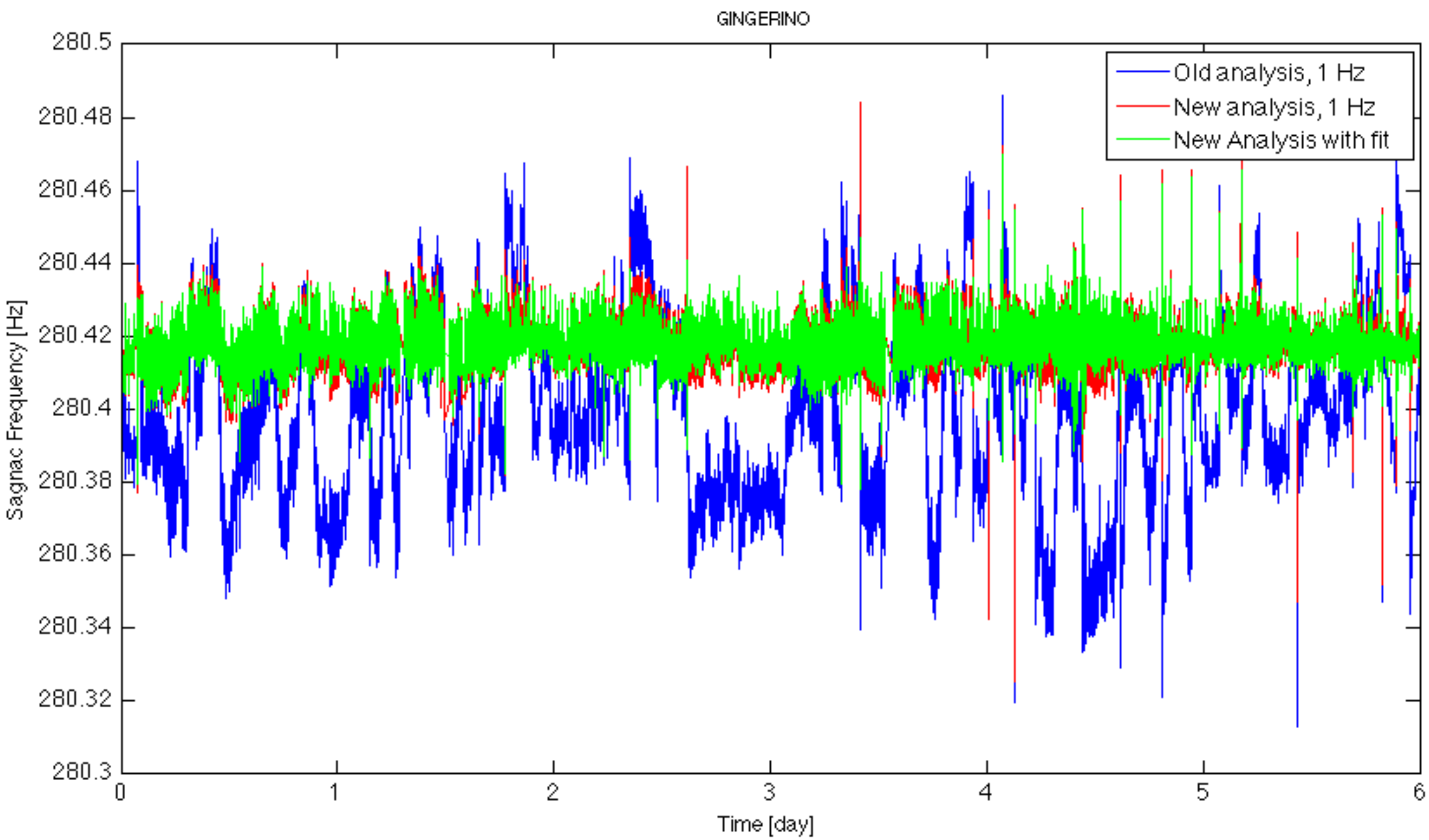
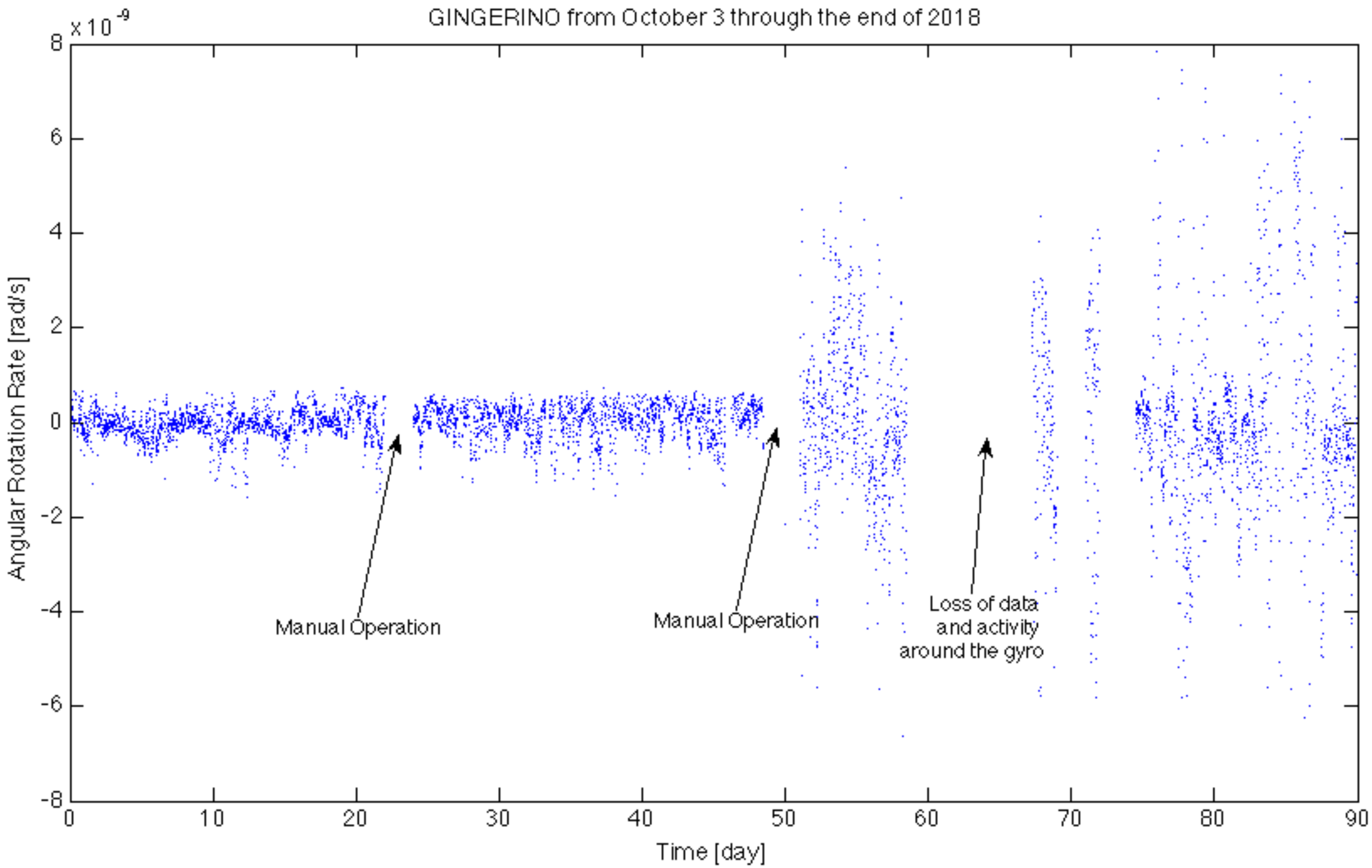
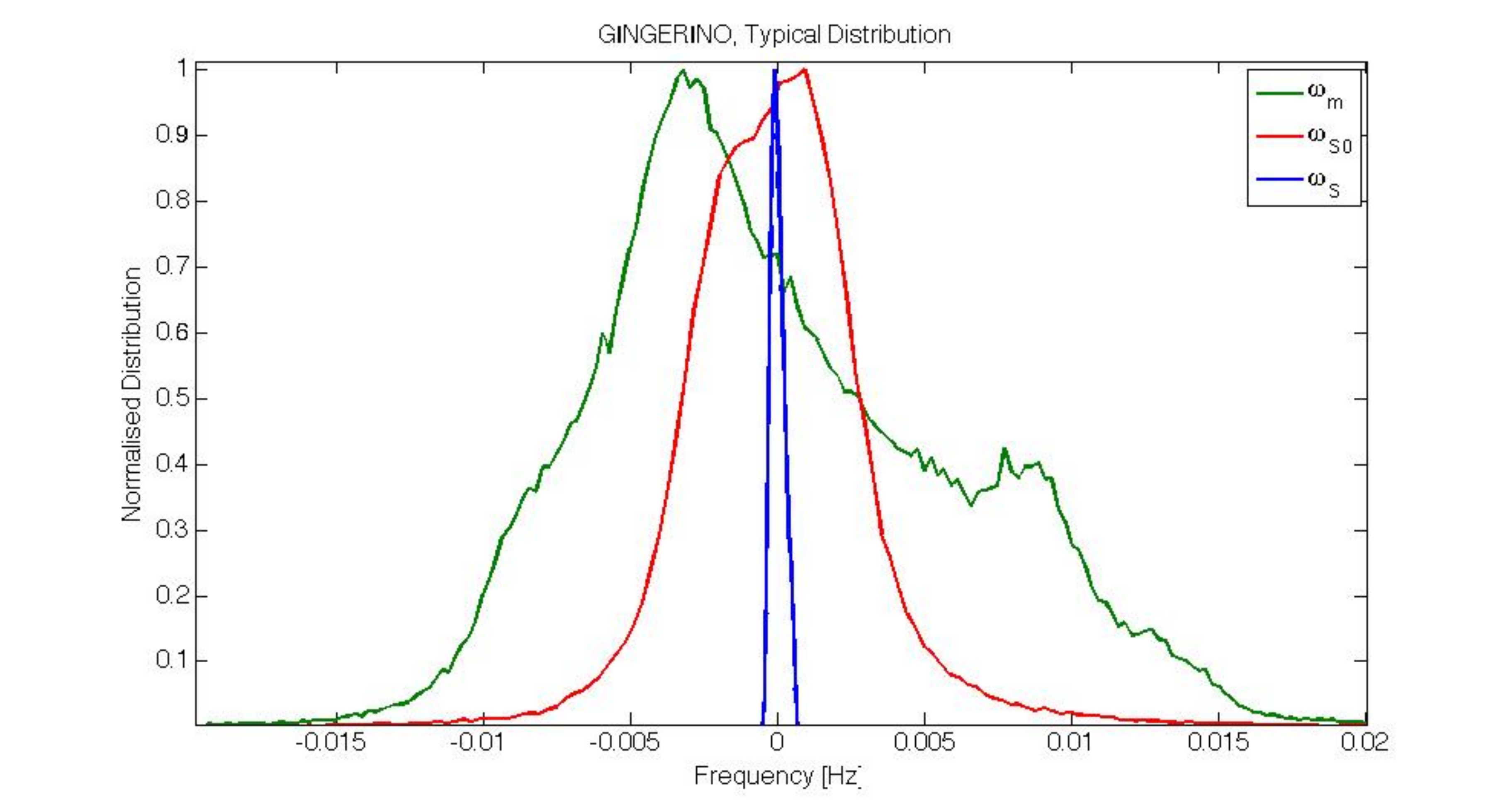


Fig. 4 Comparison of the histograms of the Sagnac frequency estimated with the standard method (blue) and by the new one (red). Clearly the new method leads to a narrower and more Gaussian-like distribution, with mean value 184.29 Hz.


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

GINGERINO RUNS UNATTENDED WITH HIGH DUTY CYCLE AND SENSITIVITY





GINGERINO, Typical Distribution
Normalised Distribution
Frequency [Hz]
ω_m
ω_{S0}
ω_S
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-0.015
-0.01
-0.005
0
0.005
0.01
0.015
0.02

The second paper about the analysis procedure is in the revision process

Several papers are in preparation with the analysis of GINGERINO

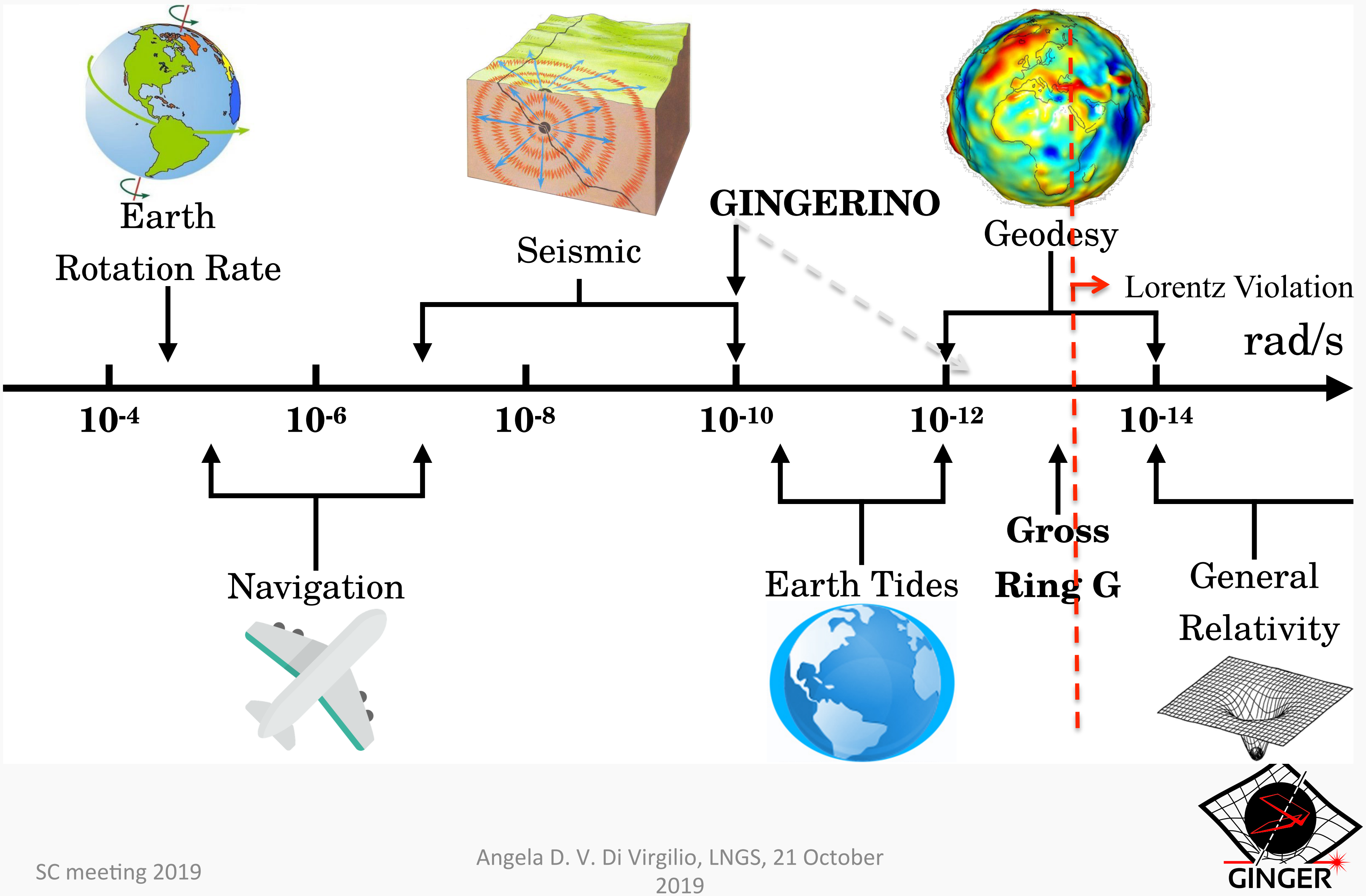
FISR 2019

- *In 2018 a project to build an array of RLG at LNGS was submitted to MIUR by INGV and INFN*

- *This operation has been repeated in October 2019*

PRESS (PRECURSORI SISMICI E GIROSCOPI SAGNAC: SUPERARE LE ATTUALI FRONTIERE DELLA SISMOLOGIA)

- *This project considers RLG with 5m side, since it is the maximum size to utilize 1" mirrors*

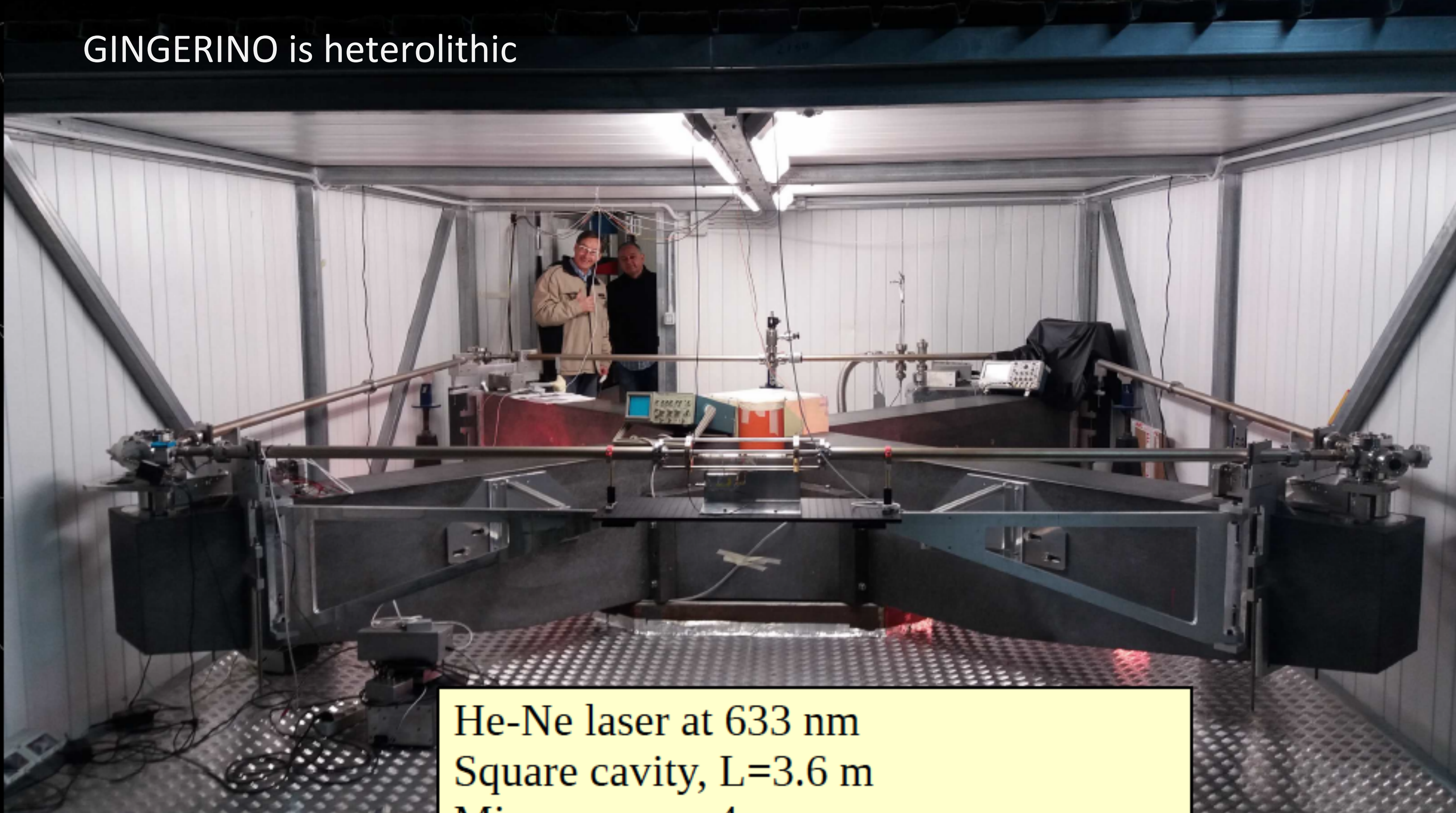

Earth
Rotation Rate
Seismic
GINGERINO
Geodesy
Lorentz Violation
rad/s
10-4
10-6
10-8
10-10
10-12
10-14
Navigation
Earth Tides
Gross
Ring G
General
Relativity
GINGER

GINGERino: deep underground ring laser

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

GINGER

GINGERINO is heterolithic

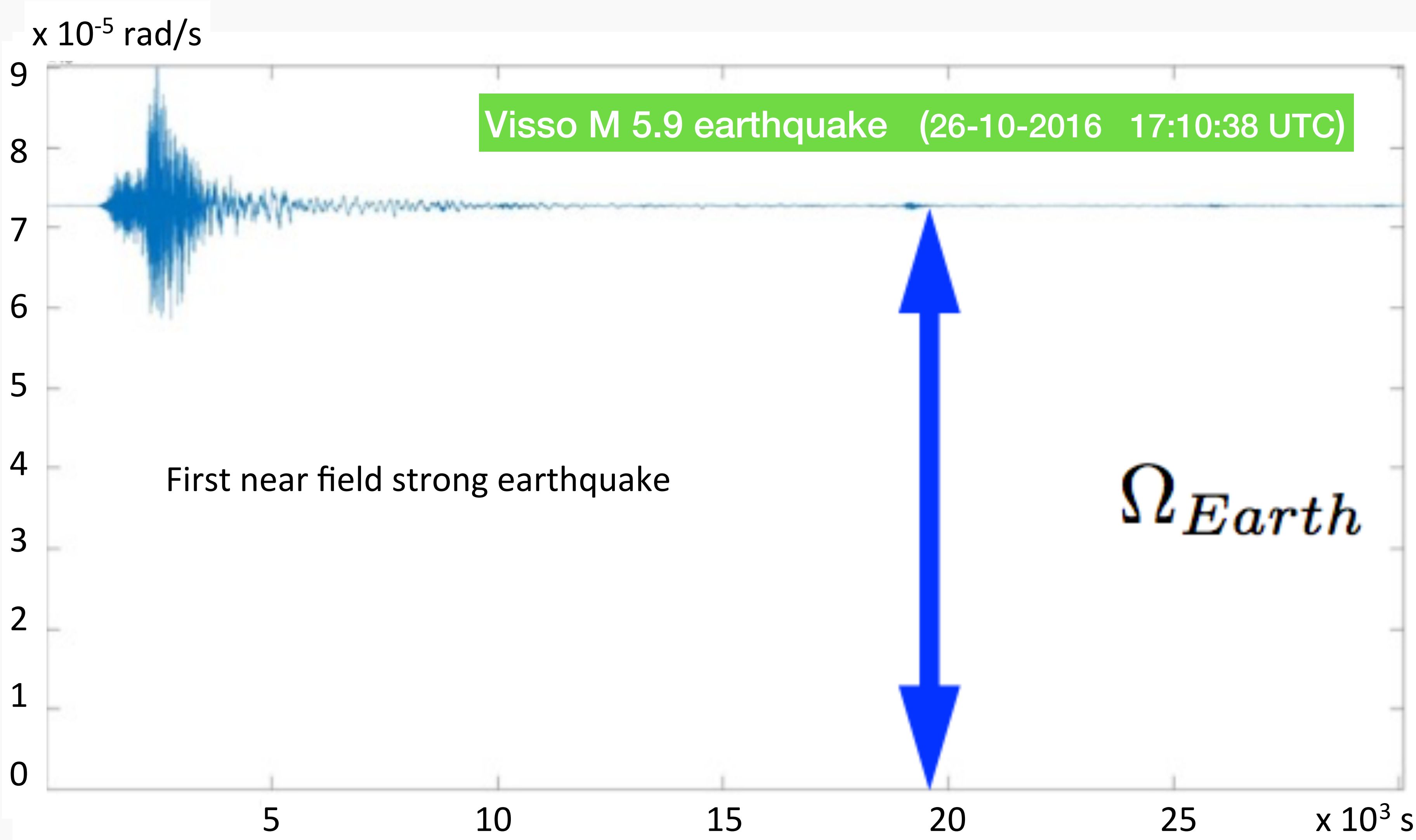


He-Ne laser at 633 nm
Square cavity, L=3.6 m
Mirrors r.o.c= 4 m
Earth rotation Sagnac bias: **fs=280.4 Hz**

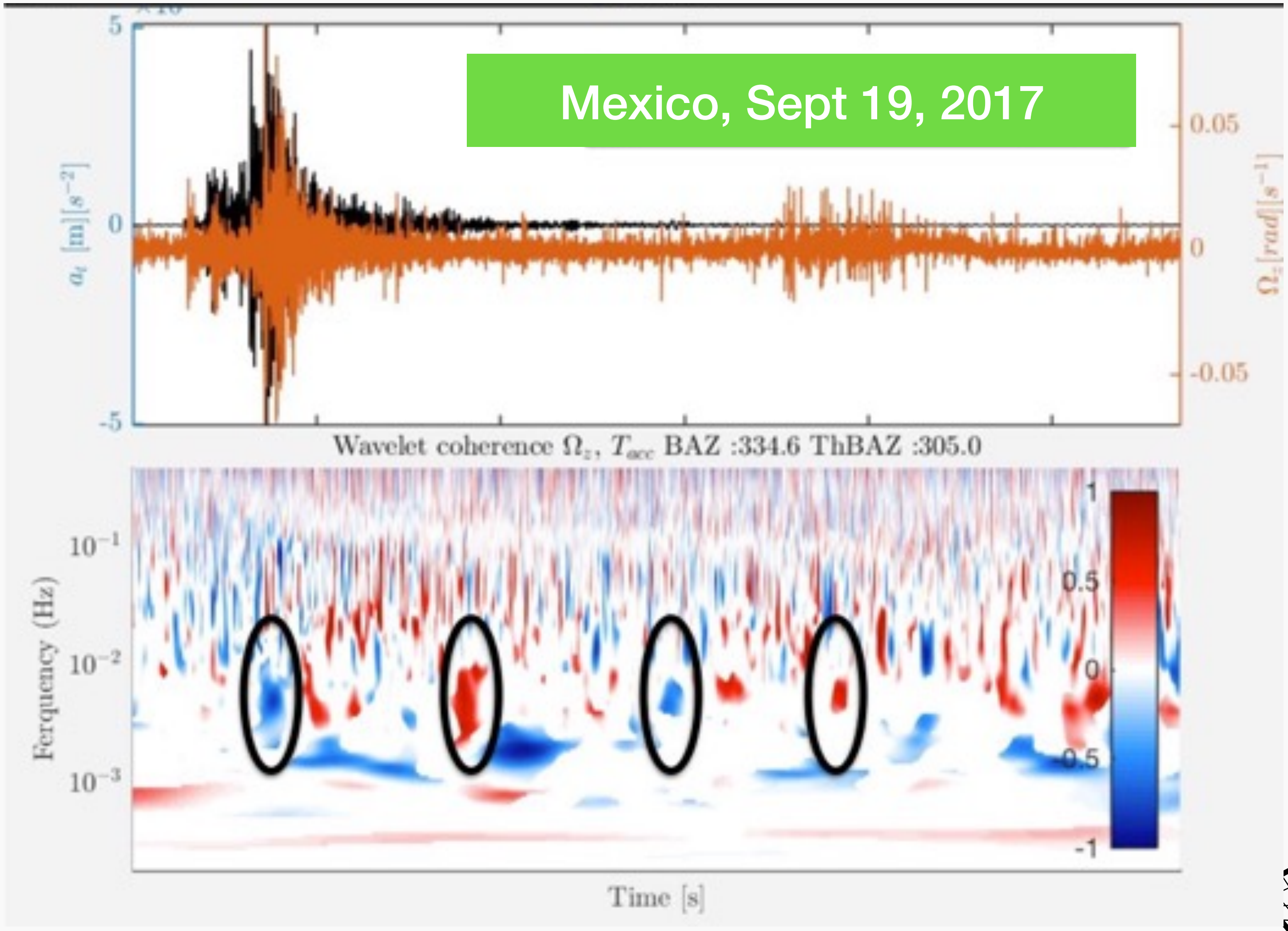
SEISMOLOGY

GINGERINO is the only high sensitivity RLG operative in a seismically active area

GINGERINO IS THE ONLY RLG LOCATED IN A SEISMICALLY ACTIVE AREA



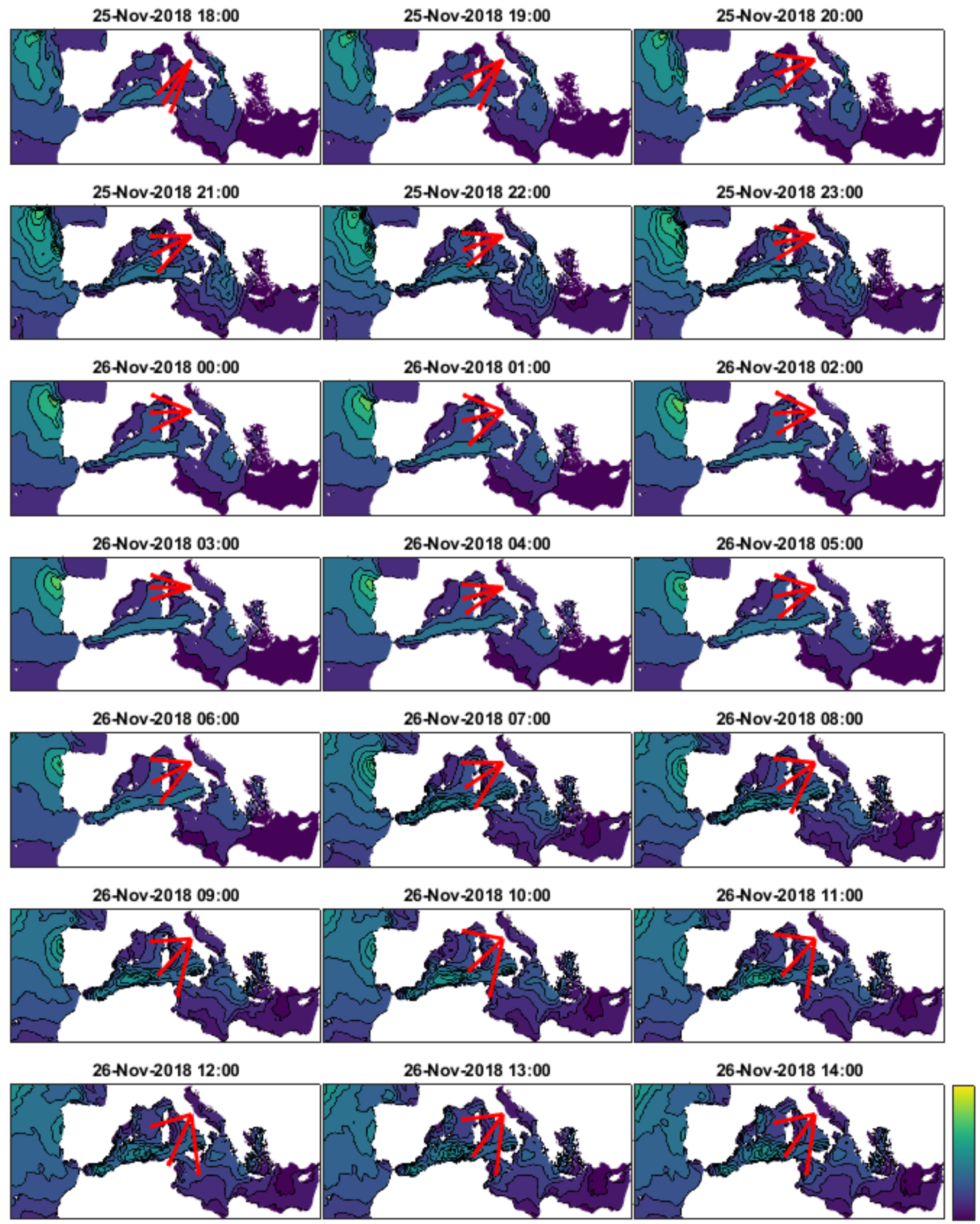
A single station with seismometer and RLG is able to recover amplitude and direction of the wave, 4D STATION



GINGER

FIRST OBSERVATION OF THE LOVE COMPONENT OF THE MICROSEISM IN OUR REGION

LNGS
4D observatory



http://arxiv.org/abs/1906.11338

Data taken 16 June 15 July, during the heavy work for the installation of LUNA

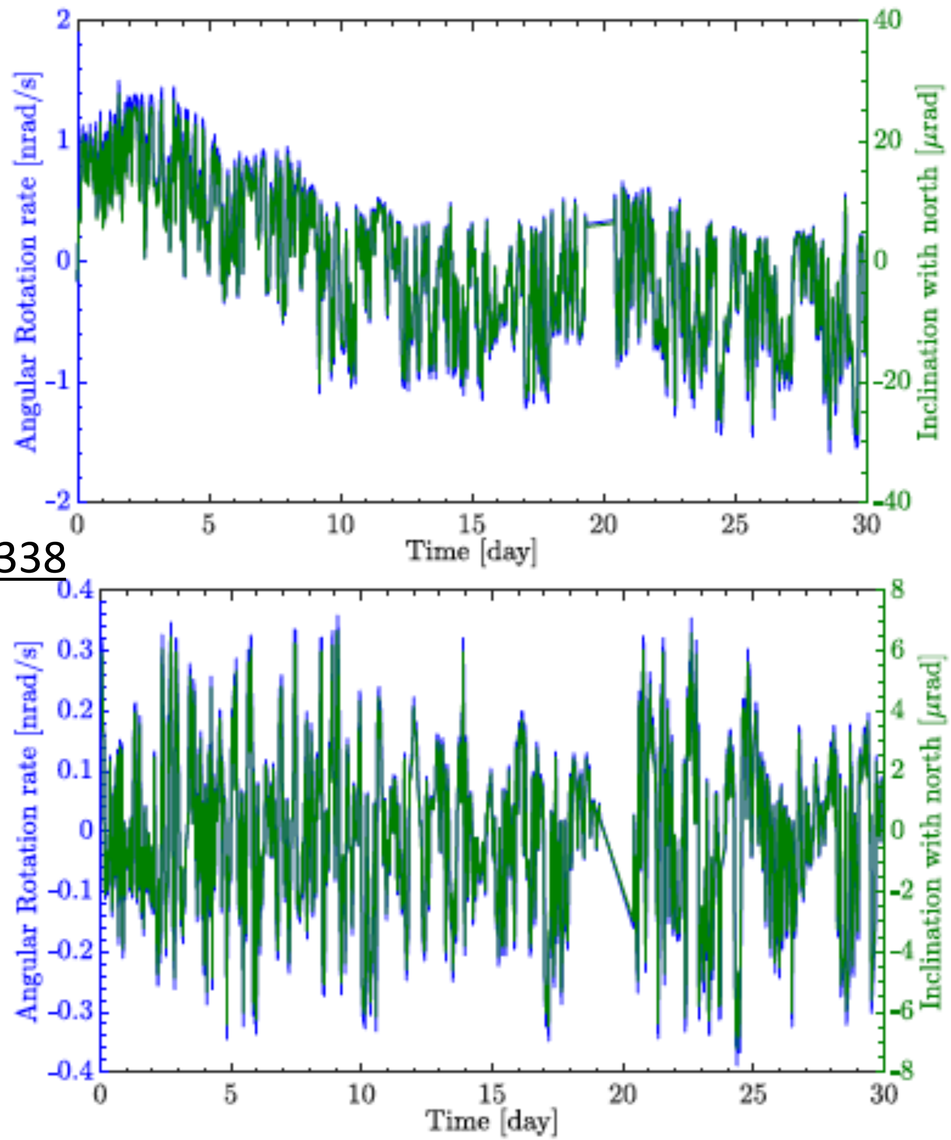


Fig. 1 Top: Time variations expressed as Ω and θ, see Eq. 2, of the analysed data [utilising ω_{S0} with the mean value subtracted; the mean value is $2\pi \times (280.208 \pm 0.001\text{Hz})$, compatible with a RLG with area versor vertical with a few mrad error]. Bottom: as above, but using ω_S evaluated with the linear regression model.

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

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.)

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

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

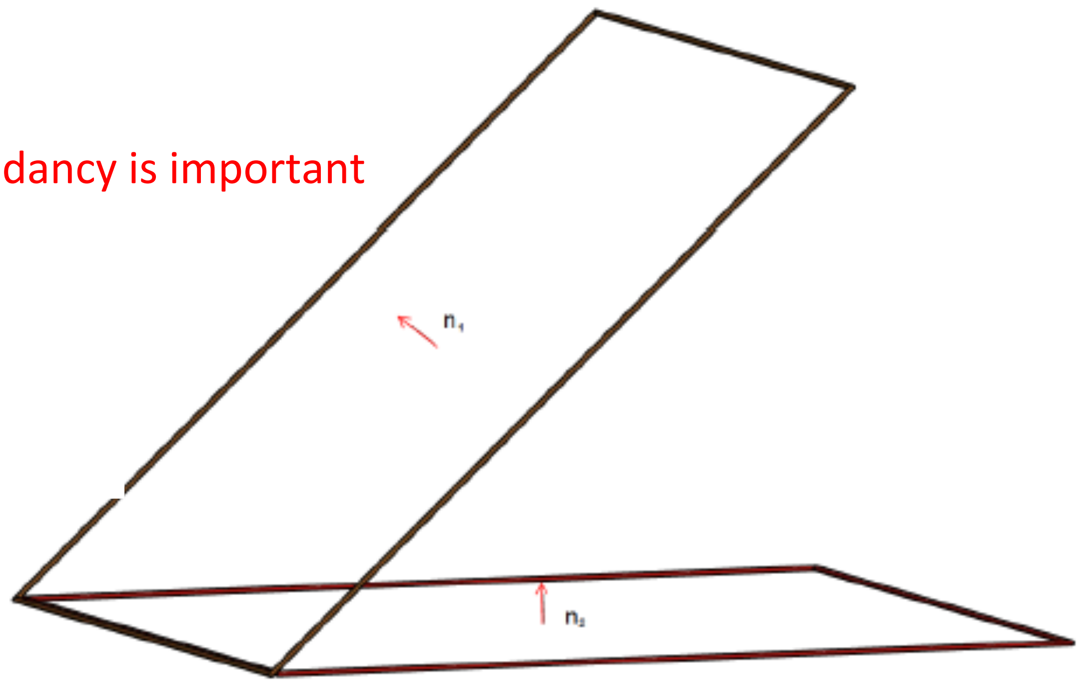
$$\eta = \frac{f_2 - S\Omega_{\oplus} \cos\zeta}{S\Omega_{\oplus} \cos\xi \cos\zeta}.$$

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

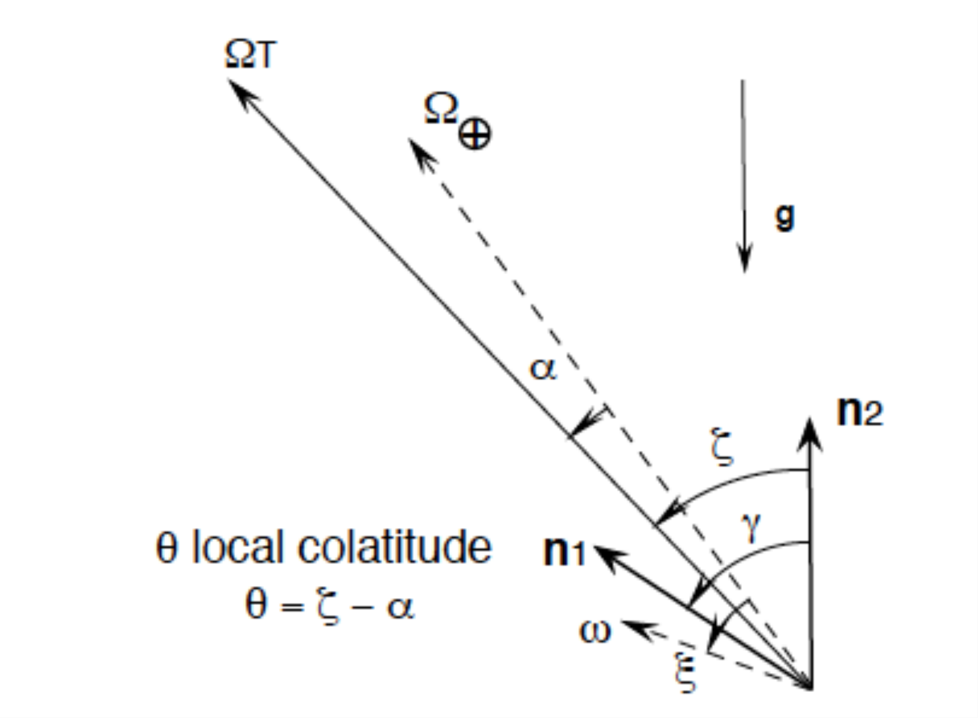
$$\eta_{\perp} = \eta \sin(\xi).$$

$\eta_{\|}$ and $\eta_{\perp}$

Redundancy is important



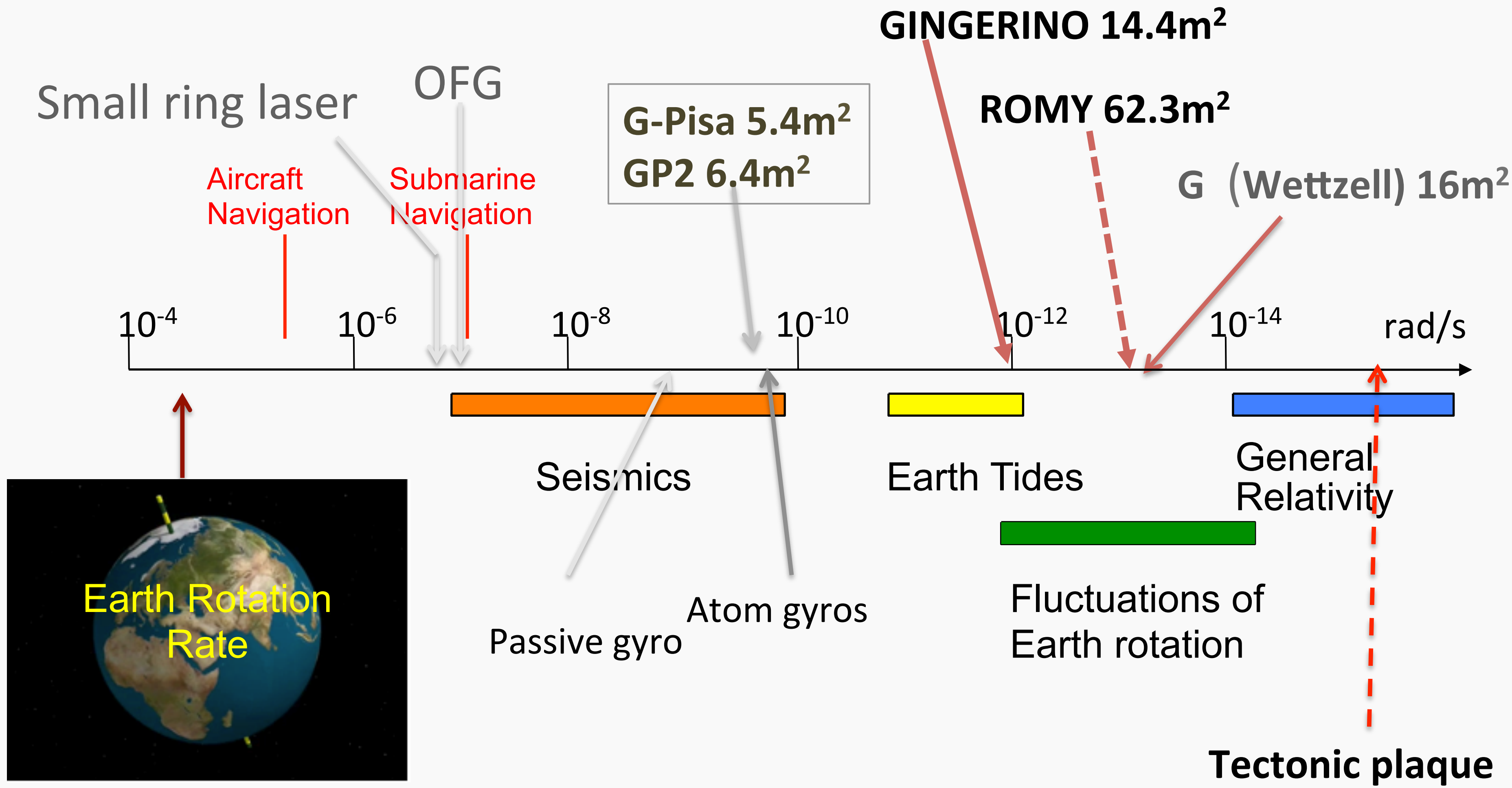
ESSENTIAL POINT OF THE PROBLEM



the angle ζ can be determined by the two Sagnac frequencies

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

INERTIAL ANGULAR ROTATION MEASUREMENT



Impossible to distinguish among geophysics and fundamental physics signals

GINGER