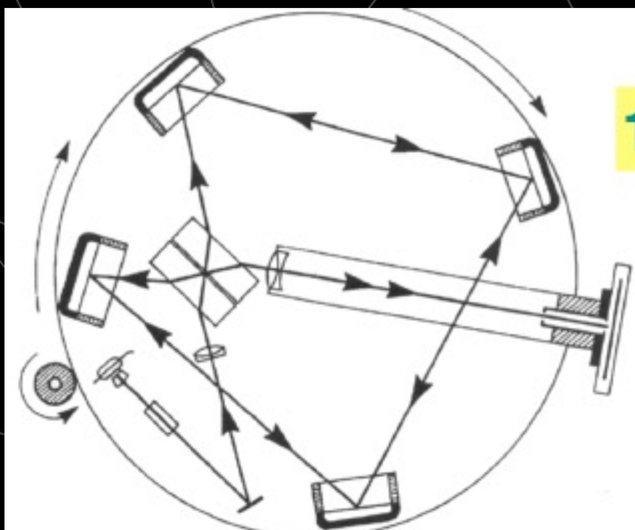
GINGER

A very unique device:

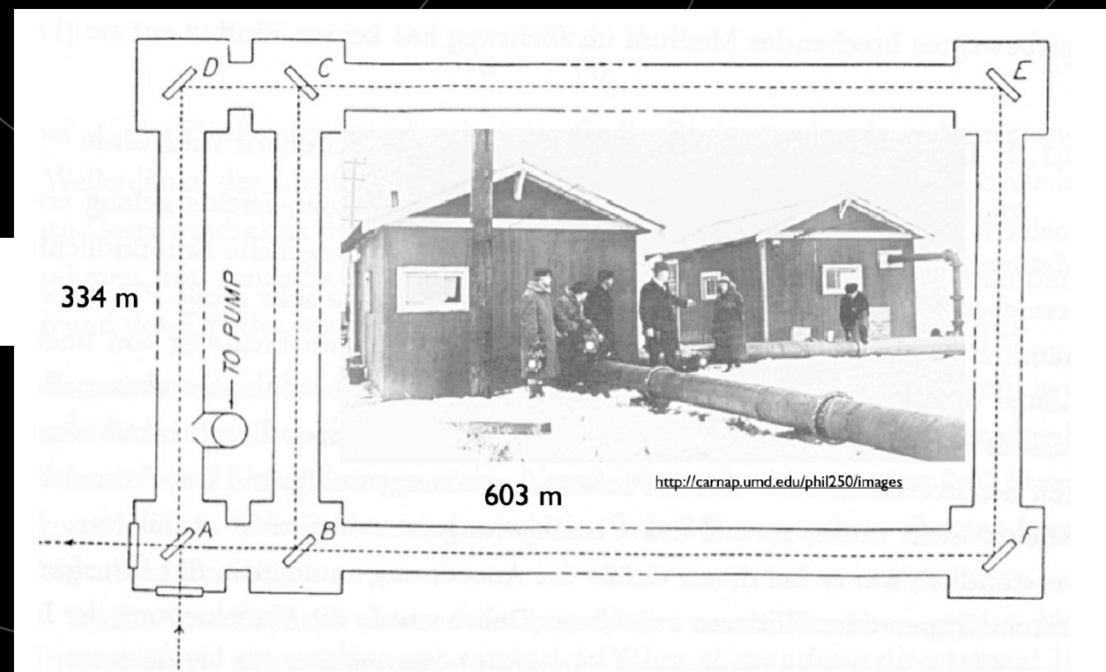
Optical Cavity +
Active Medium +
Equal arms interferometer +
2 independent beat notes +
the solid crust of our Earth

Interferometry and Sagnac effect are 100 years hold

- Georges Sagnac (1913) realized the first gyroscope to disprove Einstein relativity



Fringe pattern solely caused by Earth rotation



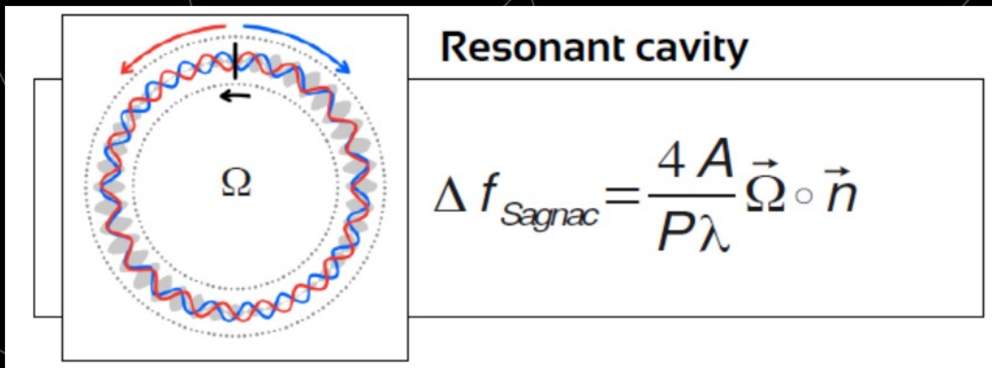
Michelson - Gale Interferometer in Clearing, Illinois (1925)

We aim at exploiting Sagnac effect to prove General Relativity by measuring the Earth rotation rate

Outline

- A ring laser gyroscope (RLG) at a glance
- GINGERINO the Great and GP2
- The GINGER experiment
- Future plan and Conclusion

Sagnac effect in an empty cavity

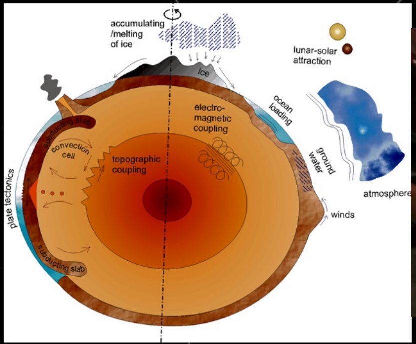


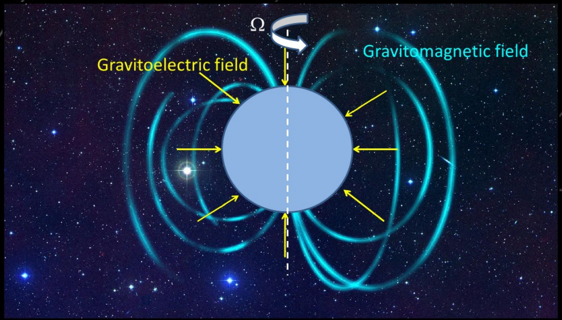
- from an *e.m.* point of view in a rotating ring cavity the time difference become a shift for the cavity resonances
- the shift depends on the area (A), the path length (P), the wavelength (λ), and the projection of the angular speed onto the path versor

The Ω measure is affected by:

- the scale factor of the cavity ring
- the orientation with respect to the rotation axis

Angular rotation/ sensitivity

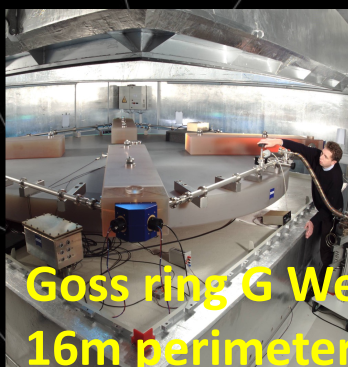




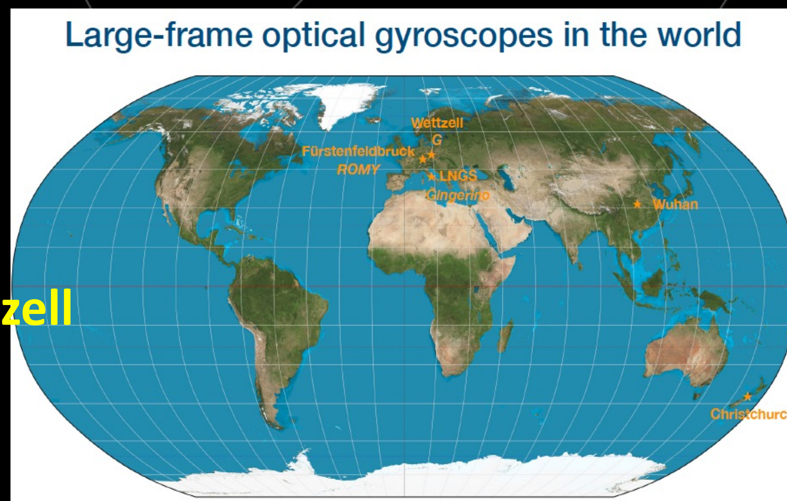
10^{-4} 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14} rad/sec

Sidereal day | seismology | tides | geodesy | General Relativity

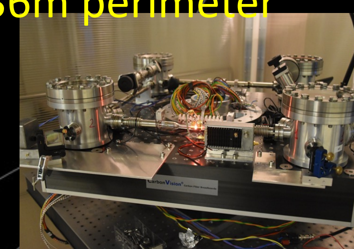
RLG in the worls



Goss ring G Wettzell
16m perimeter



ROMY 4 RLGs, ERC
36m perimeter

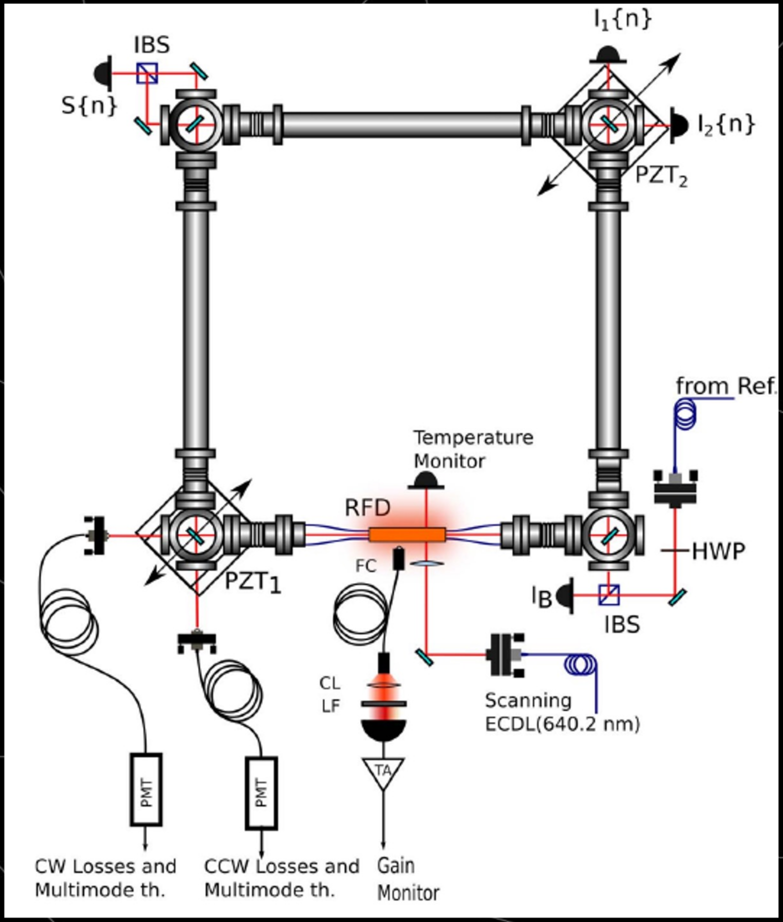


so fare large frame RLG have top sensitivity for Earth rotation

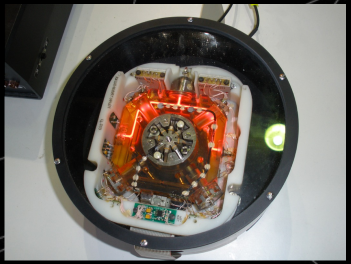
Main Noise sources in RLG

- Backscattering
  - Scattered photons at the mirrors may couple to the reverse resonating mode of the cavity so adding theirselves to the counter-propagating beam
  - It results in a perturbation of the single (mono) beam amplitude and phase
  - Monitoring the two beams allows to cancel this contribution
- Laser dynamics (null shift)
  - The laser dynamics is a rather complex non-linear process. Methods exist to evaluate its weight through the estimation of Lamb parameters in a semiclassical approach.

The ring laser gyro

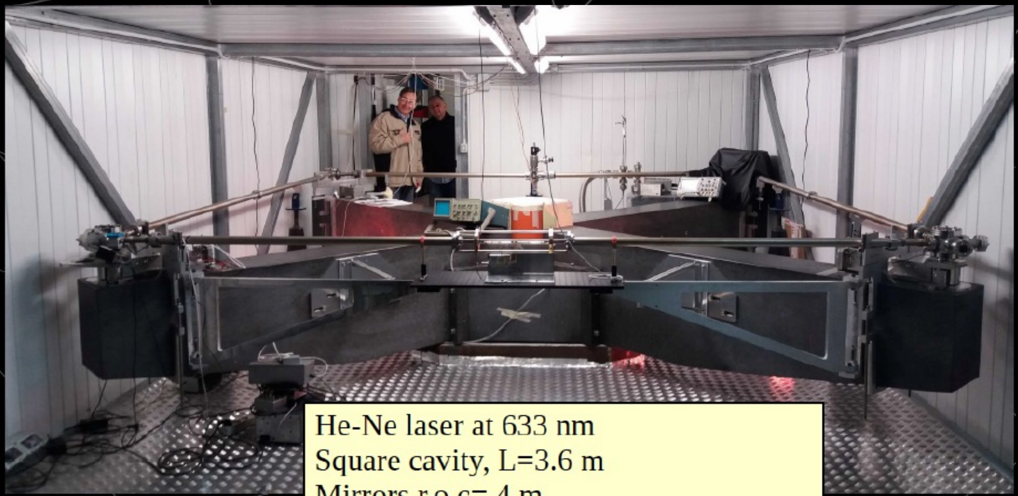


- He-Neon laser gain medium is inside the cavity
- the two laser beams will feel different cavities and the two emission will be frequency split
- This concept has been demonstrated on monolithic structure, we develop hetero-lithic structures

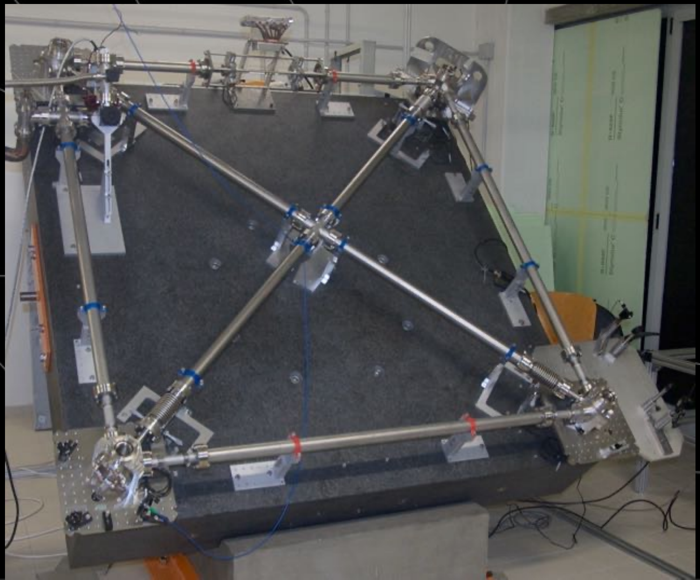


GINGERINO *prototype @* LNGS, GP2 *prototype* @basement of INFN Pisa

GINGER



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**



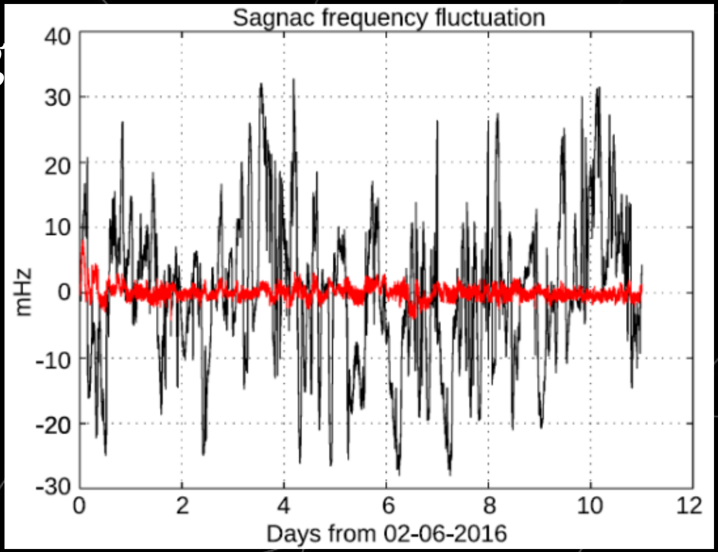
- A 3.6m ring cavity inside LNGS, operative since 2015
- No active controls
- Runs completely unattended – remote ignition
- Off-line data analysis for very low frequency study
- Online data transferred to EIDA data base for seismology study (0.01-100Hz)

- GP2, 1.6m side, oriented at the maximum signal, used to develop geometry control and measurement and remote control of apparatus

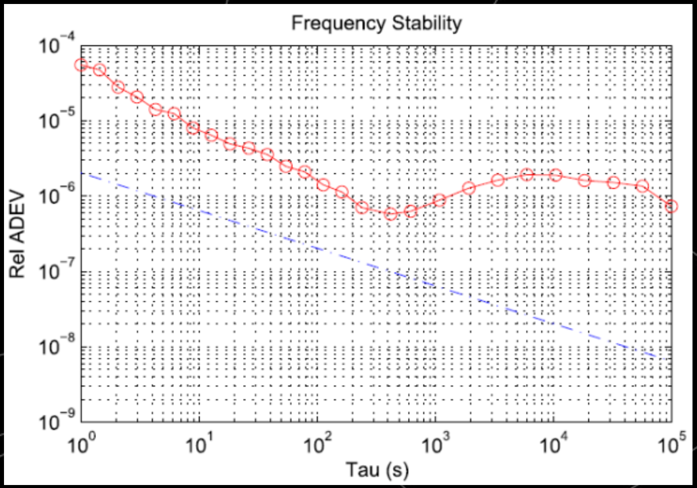
Data from REVIEW OF SCIENTIFIC INSTRUMENTS **88**, 034502 (2017)

GINGERINO sensitivity (2016-17)

- Typical raw data (black) and backscattering corrected one (red) from GINGERINO in 2016



- Frequency stability of the interferogram is evaluated by the Allan deviation (red)
- Blue-dashed is the expected level of shot noise
- In 2016 sensitivity was a factor 2 - 3 below 10^{-10} rad/sec more than one order of magnitude above its SNL



GINGERINO after 2016

- Since the first configuration several improvements have been applied to GINGERINO
- Novel acquisition boards, higher quality mirrors, new gain tube ...
- A novel analysis method has been casted to eliminate laser dynamic contamination
- Later on, the cancellation of known signal, by linear regression, was used to evaluate the instrument sensitivity limit

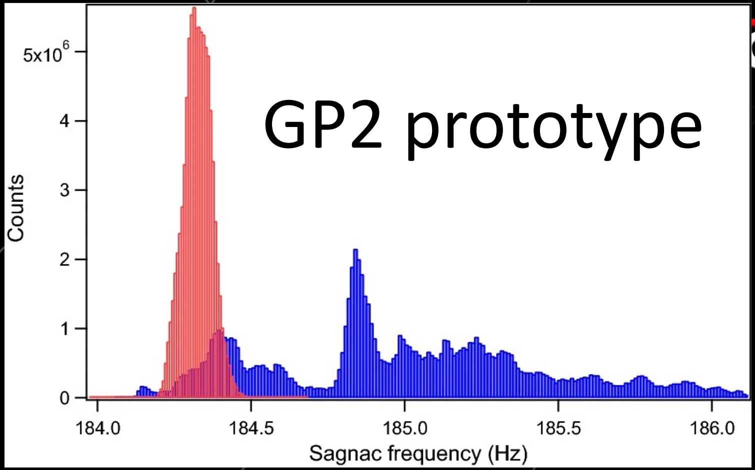
GINGERINO In short.....

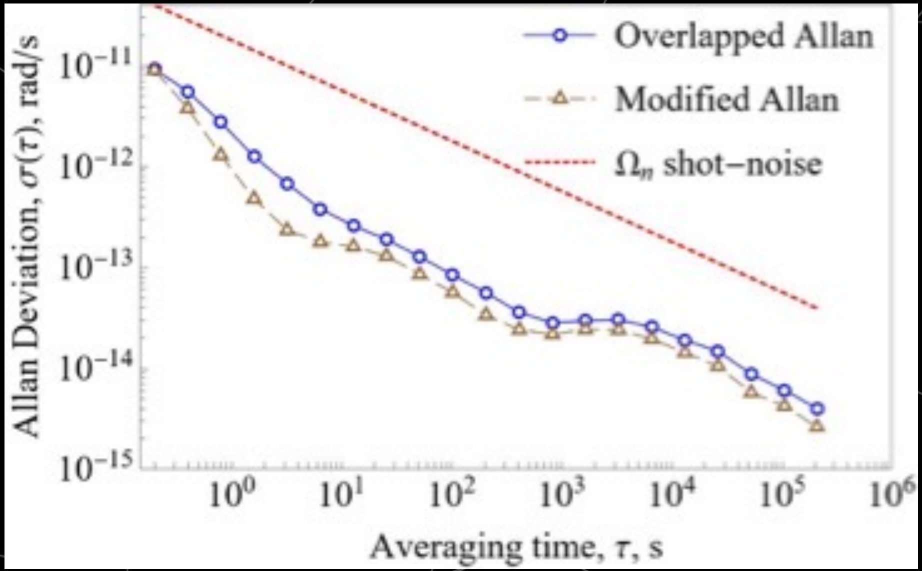
The first H-L RLG able to run unattended for months and to provide suitable data for earthquakes studies

it has shown the importance to be underground located and the validity of LNGS for GINGER

With its data we have been able to test novel analysis strategies to pick up from the data the true Sagnac frequency. We have completely changed the RLG analysis paradigm, demonstrating that the 'backscatter' problem can be completely solved analytically and developing algorithms to subtract the null-shift, which is the real problem for very low frequency investigation, completely ignored in previous analysis.

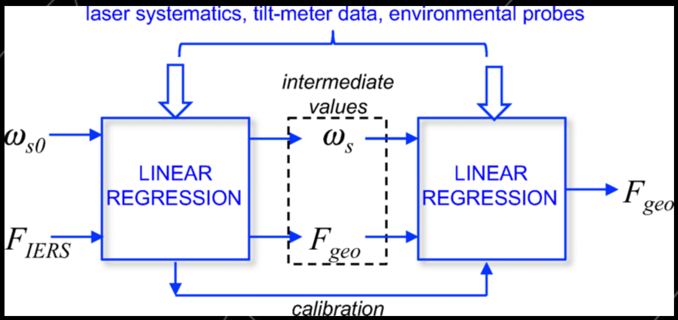
It has given the opportunity to directly verify the limiting noise of RLG at low frequency, showing that the 'standard noise estimation' is not correct, and the low frequency fundamental limit is much lower than expected

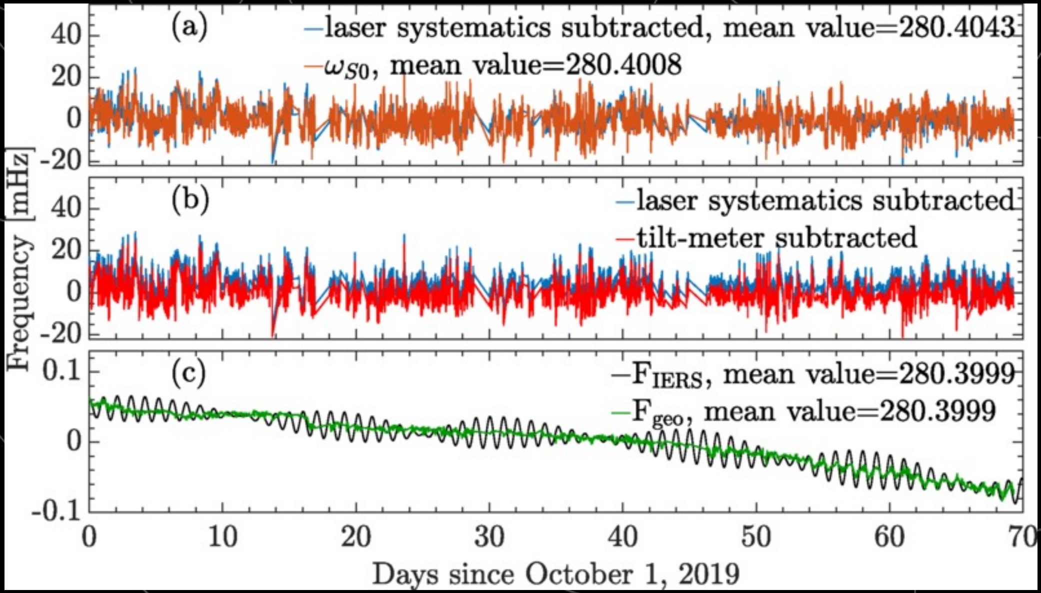




GINGERINO and geodesy

At the end of 2019 GINGERINO run for more than 2 months continuously





This allowed to perform a more complete analysis to identify, using the linear regression method, known geodetical signals

Detecting geodetic signals, some of them measured independently by other groups and systems make it possible to calibrate the instrument response and further investigate the statistical residuals thus evaluating the actual noise level of the instrument

F_{geo} measured by GINGERINO reproduces all main geodetic features, such as annual and Chandler wobbles, daily polar motion, and the very low-frequency contribution due to LOD and zonal tides.

GINGER

Gyroscopes In GEneral Relativity

- Thought for measuring the LenseThirring effect with an Earth based experiment (at fixed latitude, not averaged and gravity map not needed) with <1% accuracy -> to set different bounds on the validity of alternative theory of gravity
- We are completing the details of the project to send the orders asap, planning to start construction by the end of 2024 and operation in 2025

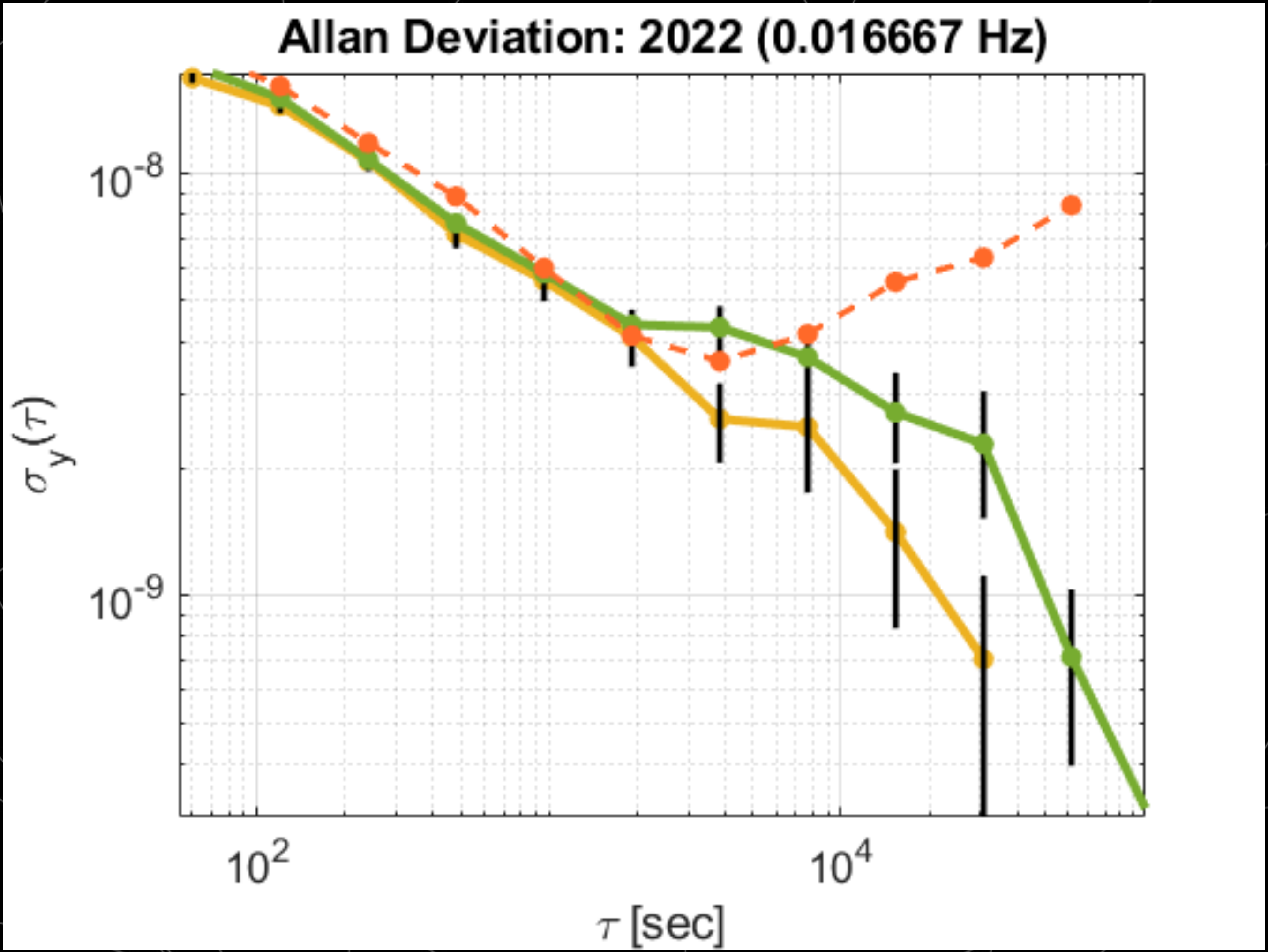
- *Bosi et al.* PRD 84:122002 (2011) "Measuring gravitomagnetic effects by a multi-ring-laser gyroscope"
- *Di Virgilio et al.* **EPJ *Plus*** 132:157 (2017) "GINGER – a Feasibility study"
- *Capozziello et al.* **EPJ *Plus*** 136:394 (2021) "Constraining theories of gravity by GINGER experiment"

GINGER

GINGER is an array of high sensitivity laser gyroscopes (Ring Laser Gyroscopes, RLG). RLG are based on a square active cavity where two counter-propagating modes circulate. The two modes are in general highly symmetric, but non reciprocity is present and the RLG signal gathers information on non reciprocity on the light propagation in different directions. Very small variations are expected in General relativity, the larger being due to the de Sitter and Lense Thirring effect on the Earth surface, Lorentz violation tests on the gravity sector in the Standard Model extended formalism, and on the non classical electromagnetism. The larger effect is certainly the Sagnac effect, which links the RLG response with the absolute rotation rate of the optical cavity. This is a large effect on the Earth surface, and at present RLG has top sensitivity to measure Earth absolute angular rotation rate in order to investigate any tiny deviations.

GINGER is highly interdisciplinary and able to provide data not only for fundamental physics but also for geophysics and geodesy.

Relevant target: ***to reach and go behind the sensitivity of 1 part in 10^9 of the Earth rotation rate****, target that has been already demonstrated.*



https://doi.org/10.1140/epjc/s10052-022-10798-9

Data analysis of GINGERINO applied to the G Wettzell ring laser

GINGER – Measurement principle

$$\delta f = \frac{4A}{\lambda P}\mathbf{u}_n \cdot \boldsymbol{\Omega},$$

→

$$\boldsymbol{\Omega} = \boldsymbol{\Omega}_{\oplus} + \boldsymbol{\Omega}'$$

Along with the pure kinematic Sagnac term it comes a relativistic contribution

It includes 4 terms and amounts to about 10^{-9} x the Earth rotation rate (10^{-14} rad/sec)

$$\boldsymbol{\Omega}' = \boldsymbol{\Omega}_G + \boldsymbol{\Omega}_B + \boldsymbol{\Omega}_W + \boldsymbol{\Omega}_T$$

- (i) the geodetic or de Sitter precession Ω_G;
- (ii) the Lense-Thirring precession Ω_B;
- (iii) Ω_W the preferred frames effect;
- (iv) the Thomas precession W_T

The last two terms are orders of magnitude smaller than the others so they are neglected

GINGER hints

- Lense-Thirring (and de Sitter) act on the RLG as angular rotation vector summed to the Earth rotation rate. These are the most important effects of GR on our planet
- First direct measurement of Post Newtonian effects on the Earth surface with sensitivity better than 1 part 10^9 of the Earth rotation rate
- DIRECT MESUREMENT: controllable, repeatable, replicable, here (on the Earth) and now (real time data analysis)
- Discriminate among different theories implies to find small differences in the measurements.
- The measurement precision will indicate a limit to alternative theories of gravity like Horava–Lifshitz

GINGER collaboration

- Pisa University: RLG laser and optics, responsible of the RLG realization and maintenance;
- INFN Pisa and LNL: coordination of the Sagnac frequency reconstruction;
- Naples: optics simulation and quantum noise;
- LNL, Naples, Salerno and Turin: interface with fundamental physics;
- INGV: DAQ and remote control of the apparatus;
- INGV: interface with geophysics analysis;
- UNIVAQ: mechanics simulation and test.

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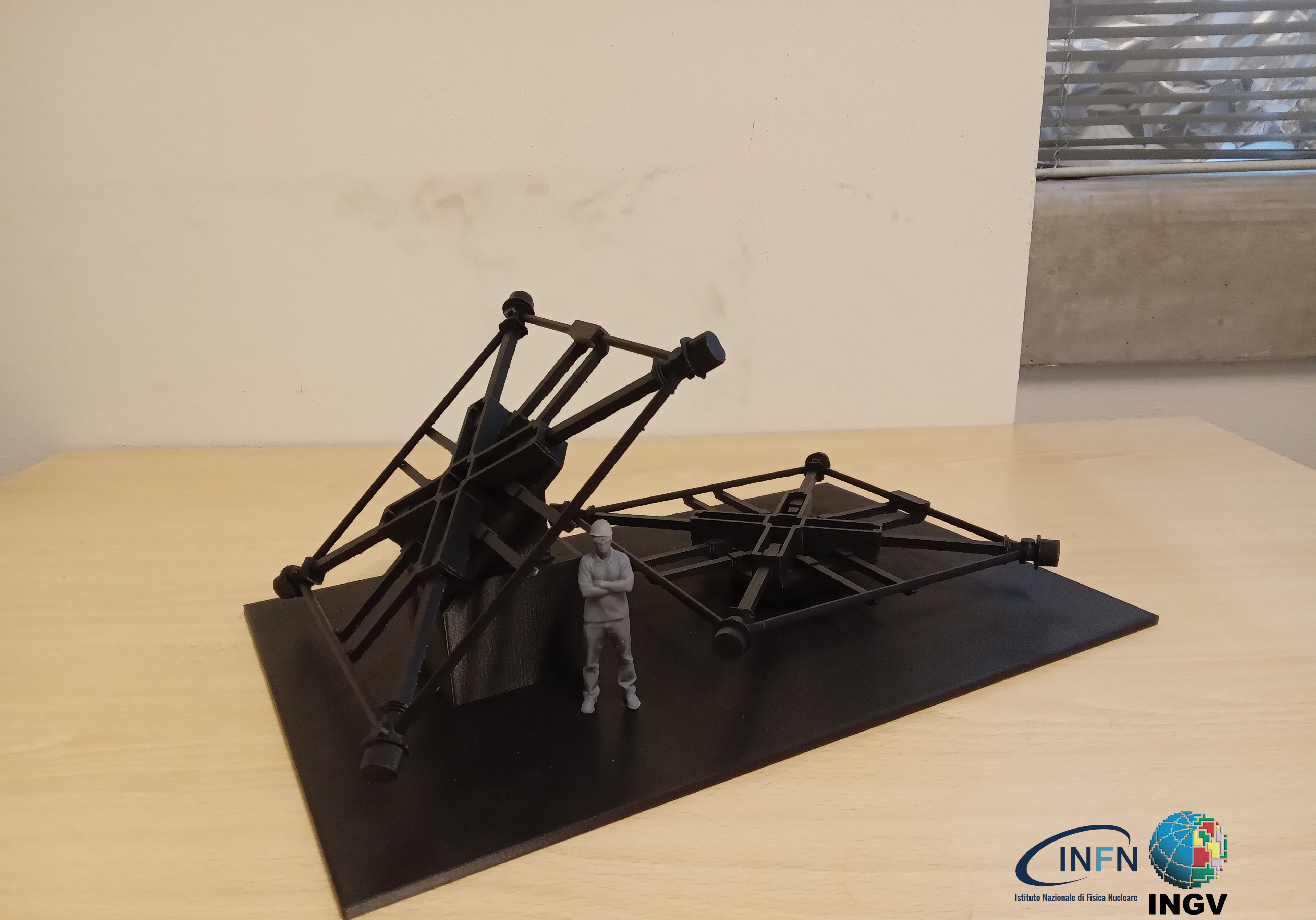


Istituto Nazionale di Fisica Nucleare

INGV

Main requiremens

<u>to keep GINGERINO sensitivity</u>

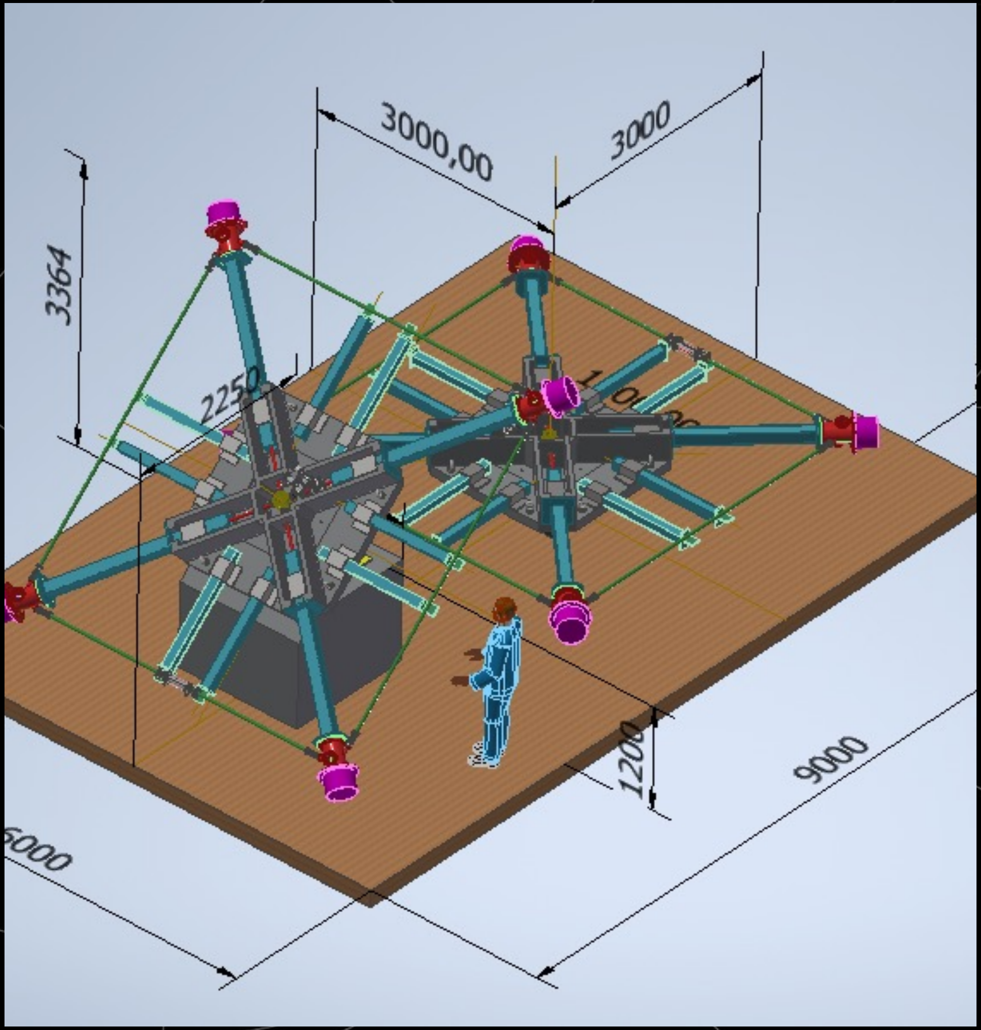
Perimeter between 14.4-16m

Beat-note >= 280Hz (GINGERINO)

<u>homogeneous materials</u>

GRANITE GNU, spacers in silicon carbide, mechanical parts in titanium, avoid mechanical couplings between mirrors

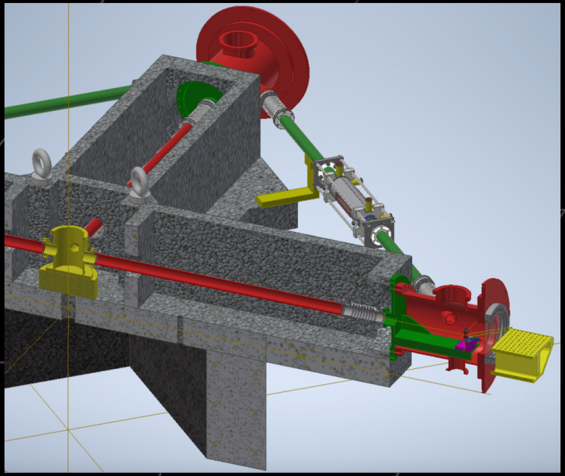
All machined with high mechanical precision

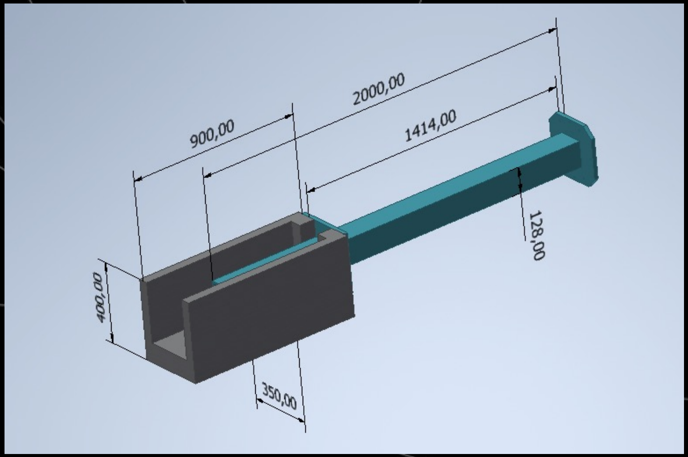


GINGER tests on going

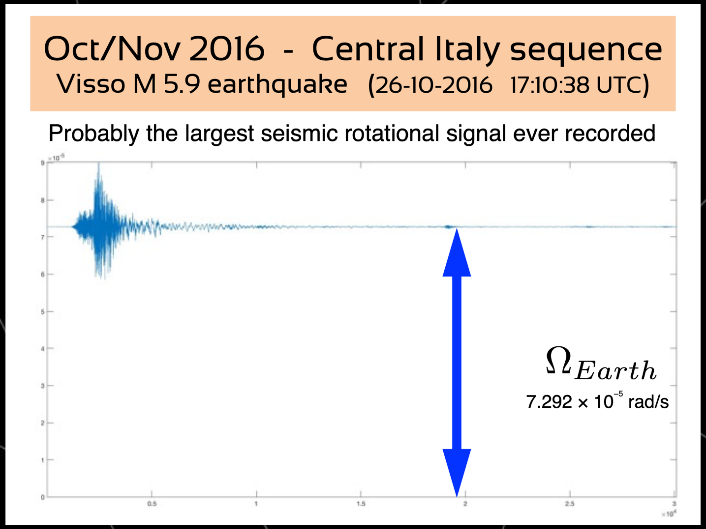
- TRIO (STRIC+ project) first test of the improved cavity mechanics
- spacers, mainly to test the joints,

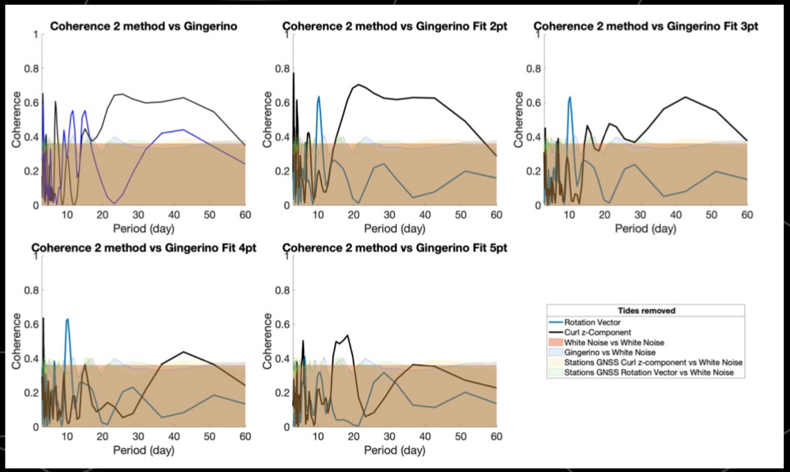
the piece will be used in GINGER

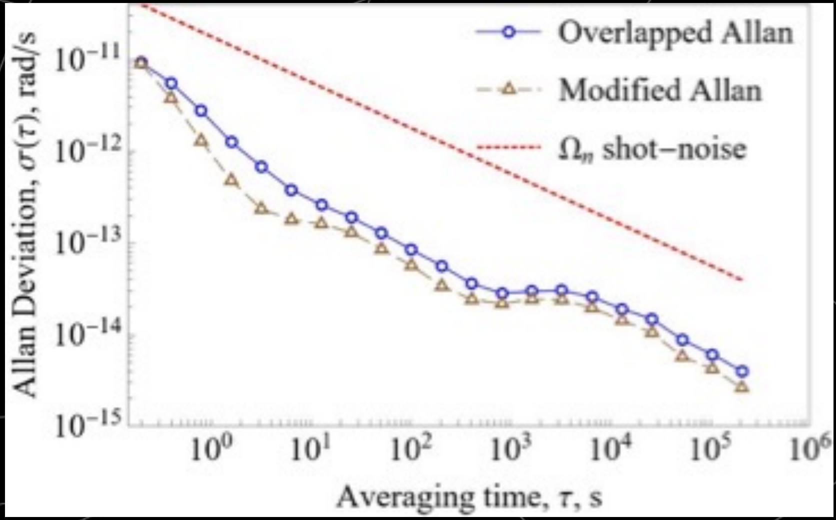




Interdisciplinarity/test of the apparatus







GINGER status report
Featured Paper of
AVS Quantum Science


BS

Conclusions…so far

- RLGs are suitable for fundamental physic tests, tyhe key point is the sensitivity, it should be at least 1 part 10^9 of the earth rotation rate
- GINGER is now under construction, expected to be ready in 2 years. First target 1 part 10^9 of the earth rotation rate, final target 1 part 10^{12}
- GINGER is affected by many signals of geophysical origin, which are important by their own, providing a natural 'test beam' for GINGER
- GINGER uses an improved mechanical design based on the experience gained with our 2 protypes. Similar apparata can be easily build on earth.