GINGERINO *sensitivity and quantum noise*

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(and GINGER collaboration)

Outline

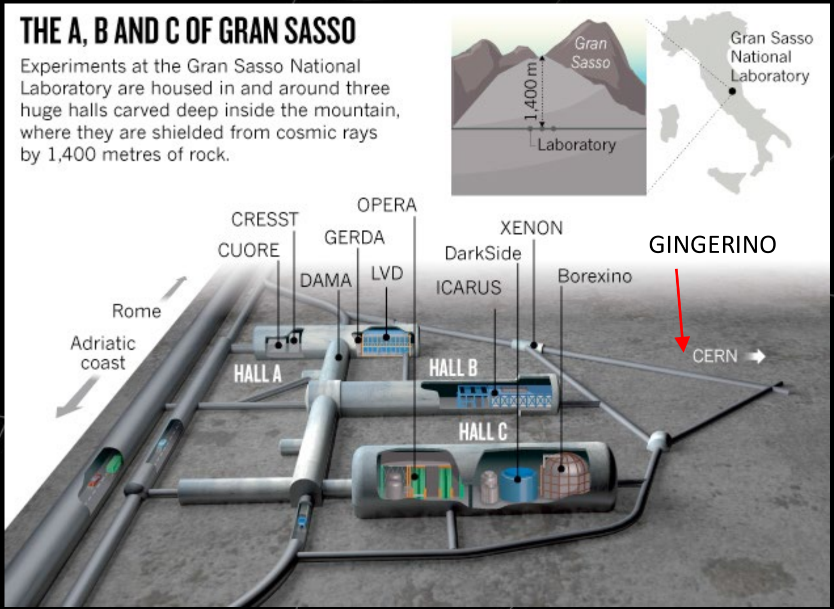
- Premise
- Measuring sensitivity in a RLG
- GINGERINO sensitivity – measurements - data analysis stategy
- GINGERINO sensitivity – the shot-noise issue
- The sub shot-noise feature
- The noise model
    - Quantum noise model
- (Inconclusive) Conclusions

Premise

- GINGERINO is the GINGER prototype a RLG running at LNGS since 2015
- Intended from the beginning as a bench test for gaining inside the sensitivity of large frame RLG and to test the reliability of LNGS as a candidate site for GINGER
- It has proven that LNGS is suited for GINGER and revealed an unexpected level of noise upper bound
- Reaching the level of sensitivity we reached, one must cope with intrinsic noise: the *quantum noise*

GINGERINO – the GINGER prototype @ LNGS

- A 3.6m ring cavity inside LNGS



- No active controls
- Runs completely unattended – remote ignition
- Off-line data analysis in Pisa

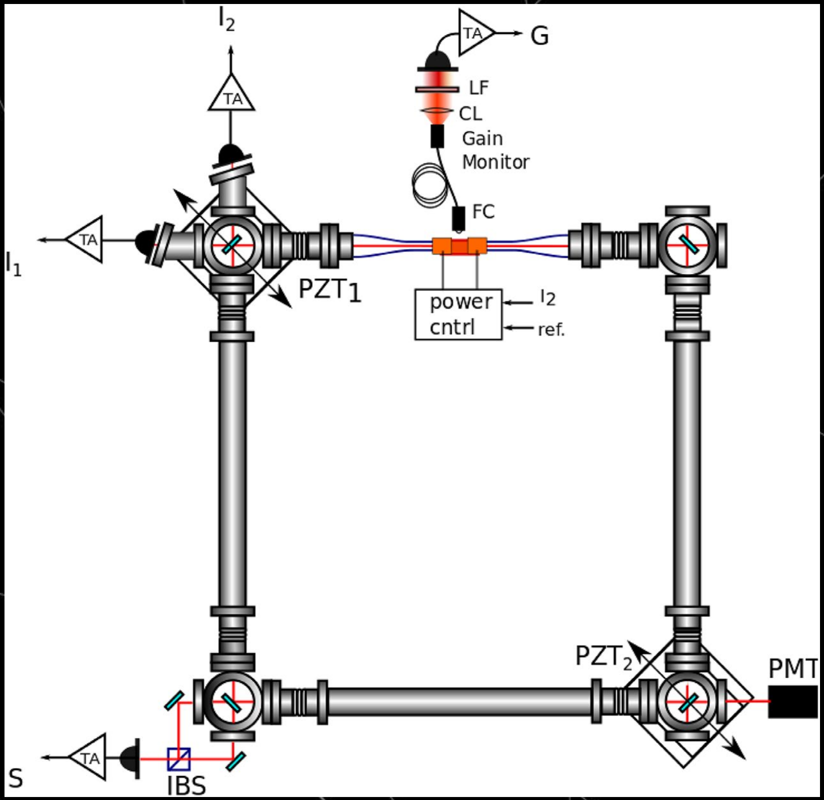
Measuring RLG sensitivity

- One goal of GINGERINO has been the evaluation of the sensitivity in such a particular environment
- Evaluating the noise floor of the instrument is a difficult task and implies identifying all the possible rotational signals
- By principle, the intrinsic noise is limited by the shot-noise level
- Retrieving the Sagnac frequency from the acquired time dependent optical interferogram relies on the (discrete) Hilbert transform

Main Noise sources in RLG

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

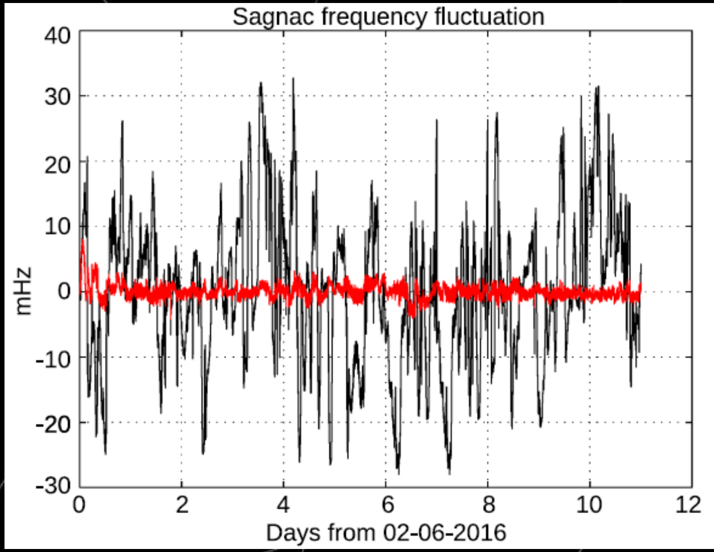
GINGERINO *sensitivity (A)*



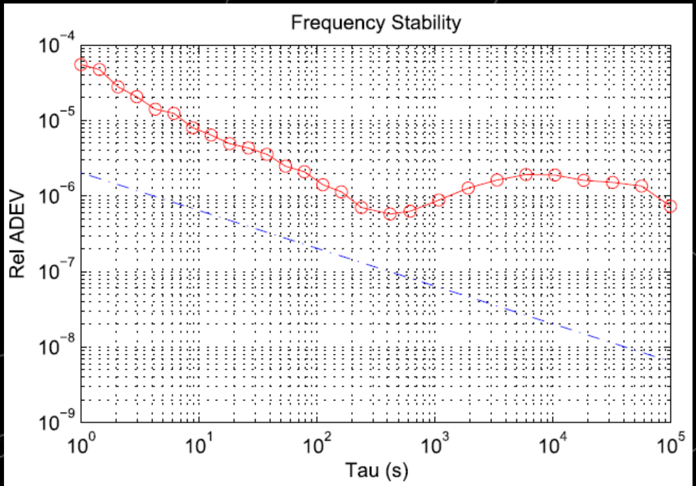
- GINGERINO is an heterolytic RLG
- Acquired signals include
  - Sagnac interferogram (@ S)
  - Monobeams (@ I_1 and I_2)
- The instrument sensitivity is given by the minimal (unknown) signal that the instrument is able to detect
- Two main experimental figures give sensitivity estimation
  - Angular velocity spectral density
  - Allan deviation

GINGERINO sensitivity (A1)

- Typical raw data (black) and bocksattering corrected one (red) from GINGERINO in 2016
- Data filtering procedures (in use in different large RLGs) is evident



- 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

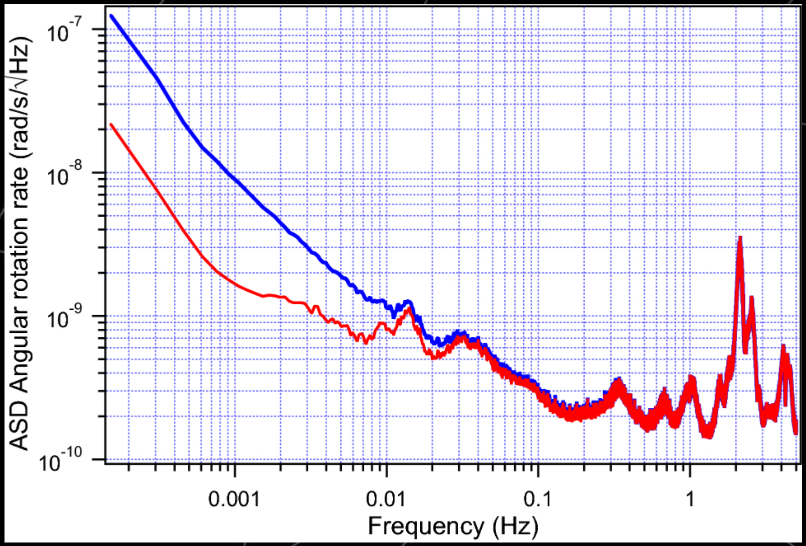
- Since the first configuration several improvements have been applied to GINGERINO
- Novel acquisition boards, higher quality mirrors, new gain tube …
- All these improvements lead to a “different” instruments with increased performances as far as bandwidth, long term operation and sensitivity are concerned
- A novel analysis method has been casted requiring the increased data size a simpler approach to reduce the time to obtain reliable rotational measurements
- Later on the cancellation of known signal, by linear regression, was used to evaluate the instrument sensitivity limit

Eur. Phys. J. C 79, 573 (2019) and Eur. Phys. J. C 80, 163 (2020)

GINGERINO analysis (2019-2020) (1)

Standard analysis

- $\omega_s = \omega_m$ is assumed with ω_m reconstructed from the interferogram by means of the Hilbert transform
- only back scatter noise is subtracted



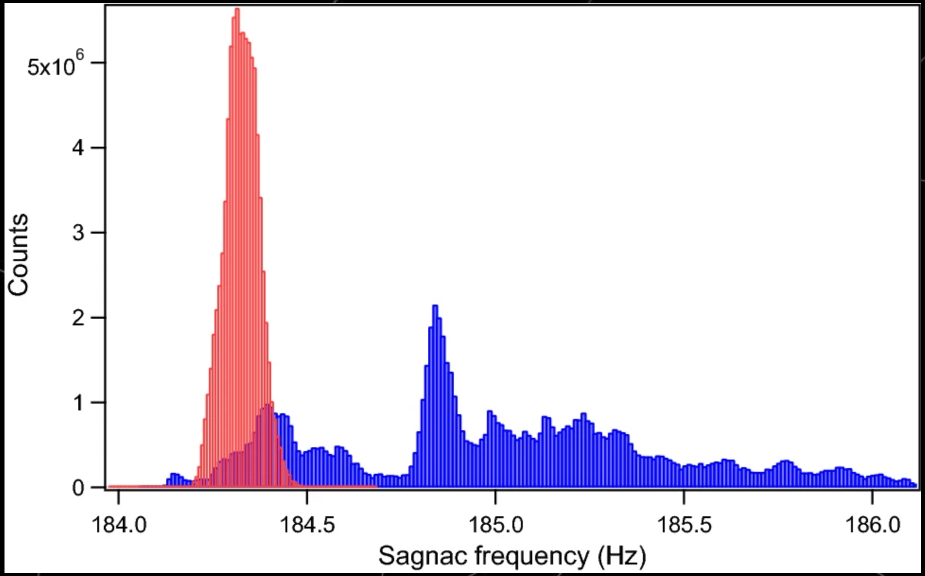
Laser dynamics is non-linear and can be modeled by Lamb theory

- the number of involved parameters is high (> 10)
- working close to the laser threshold and making some reasonable assumption leads to (approximate) analytical solutions

GINGERINO analysis (2019-2020) (1)

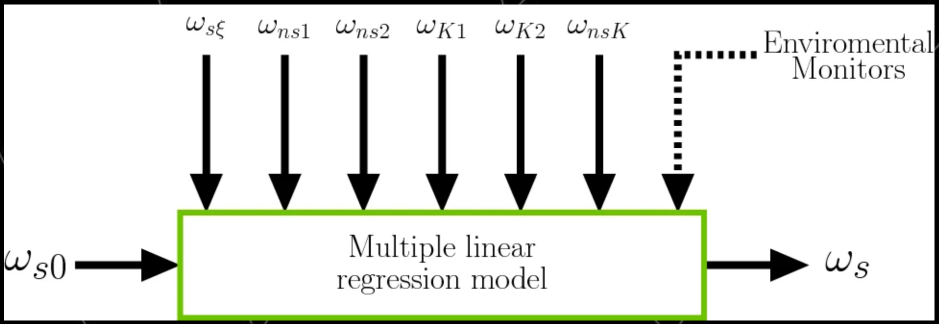
Novel approach can be done by power expanding in the laser parameters

- ω_s is the sum of 6 different terms of different weight that can be independently evaluated, and analyzed
- The predominant term is indicated as ω_{so} and depends only on ω_m the result of the Hilbert transform) and backscattering (easily subtracted)

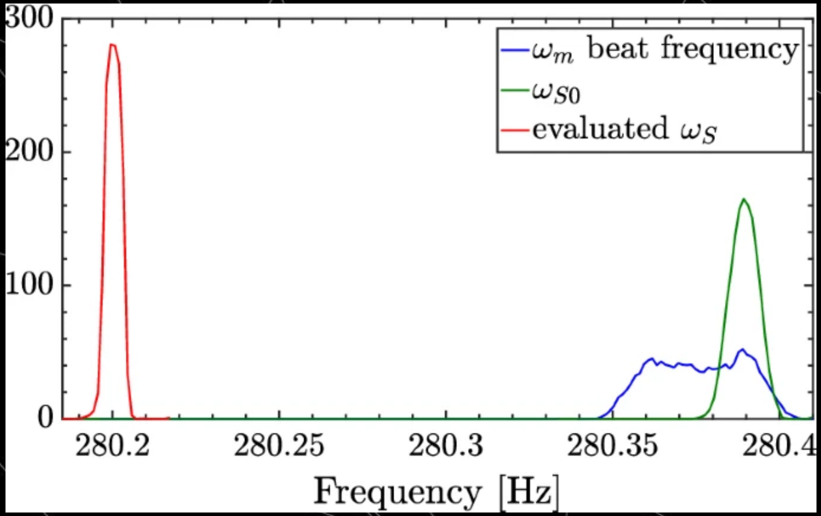


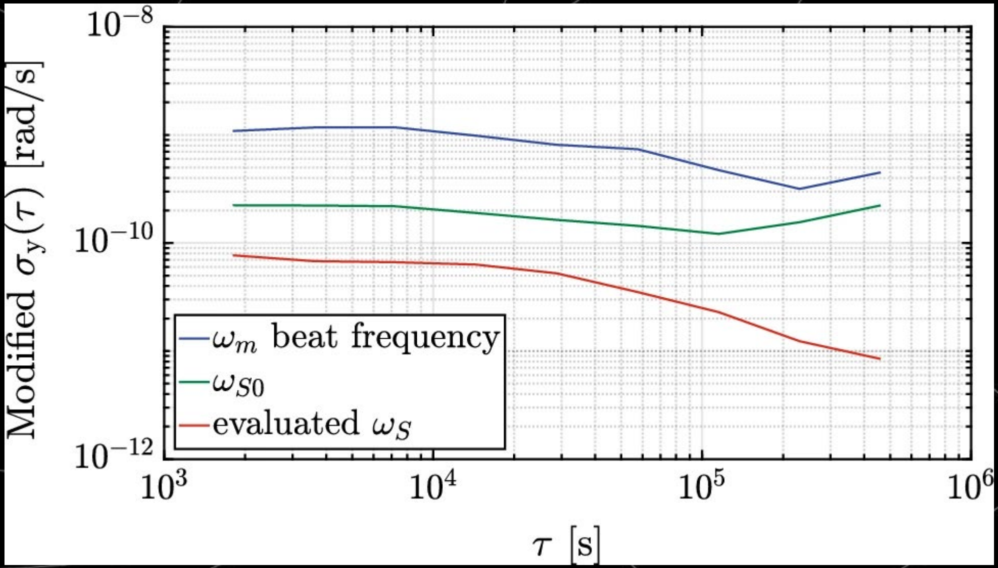
Eur. Phys. J. C 79, 573 (2019) and Eur. Phys. J. C 80, 163 (2020)

GINGERINO analysis (2019-2020) (2)



The method relies on multiple linear regressions to identify all the 6 contributions so that a sharper and more precise estimation of the Sagnac frequency is possible

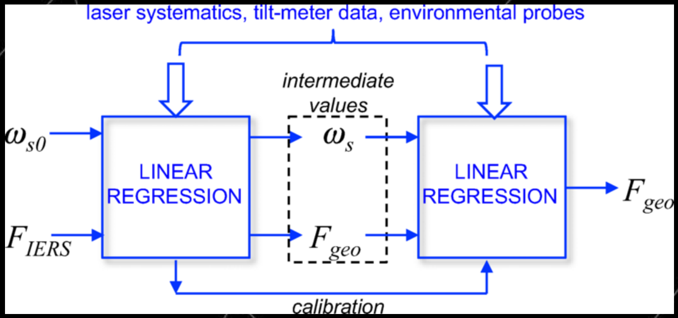


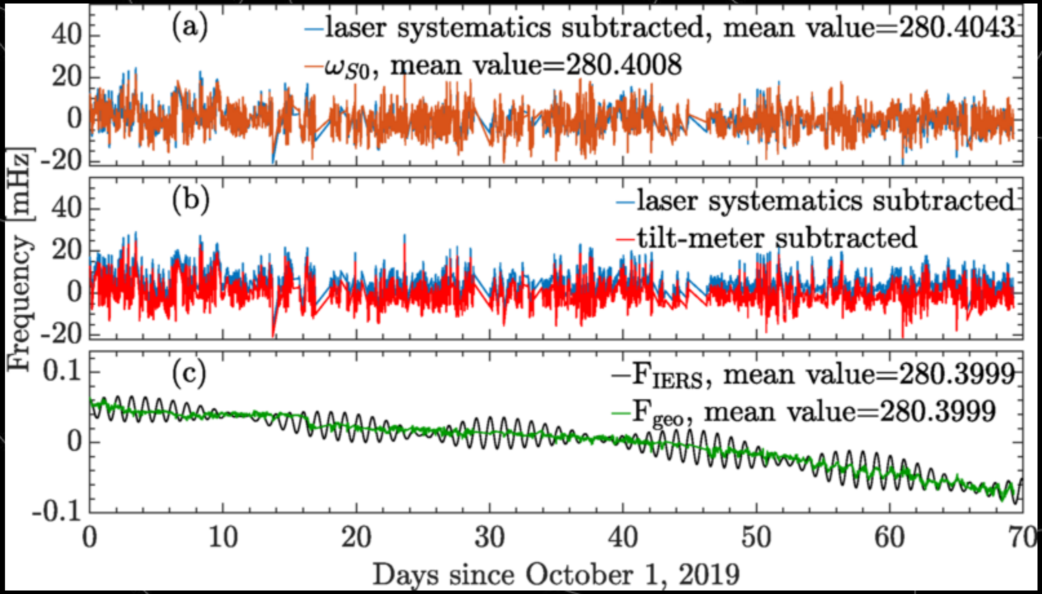


PHYSICAL REVIEW RESEARCH 2, 032069(R) (2020)

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

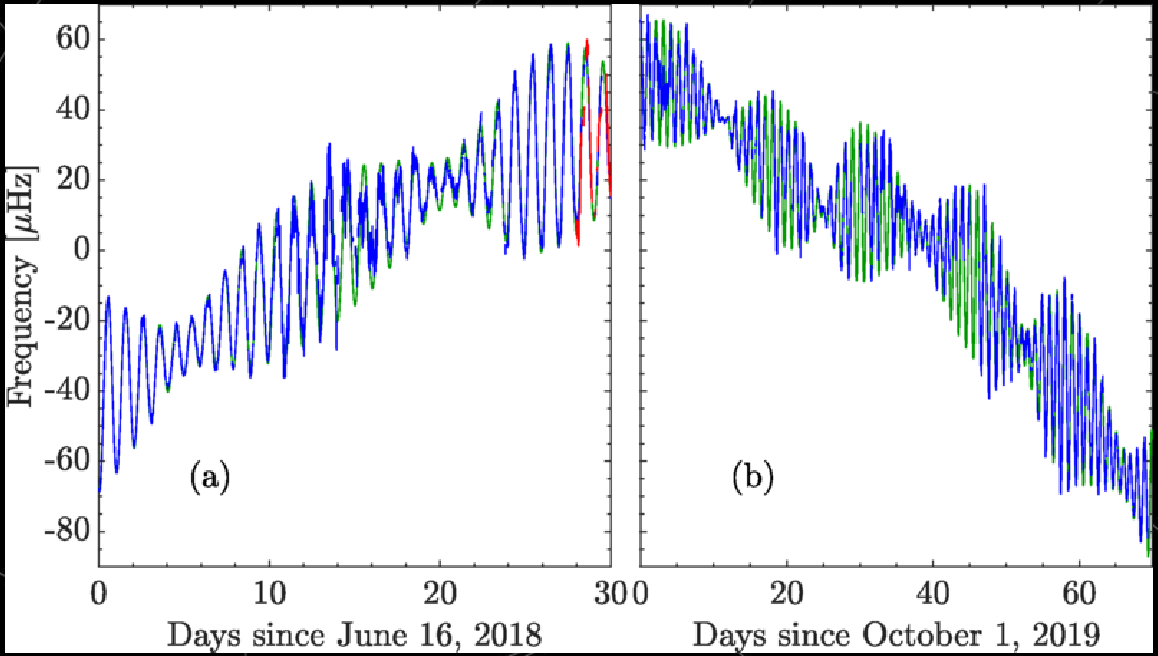
Detecting geodetic signals, some of them measured independently by other groups and systems make it possible to calibrate the instrument response and further investigate the statistical residuals thus evaluating the actual noise level of the instrument

PHYSICAL REVIEW RESEARCH 2, 032069(R) (2020)

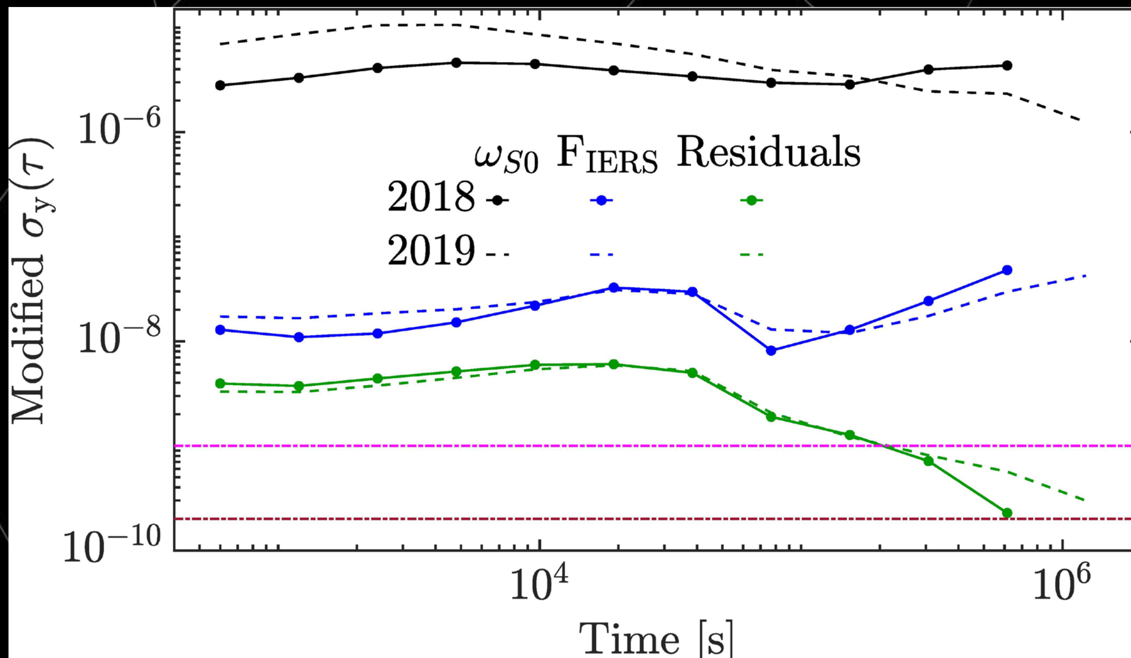
GINGERINO accuracy

GINGERINO measured Earth rotation compared with data coming from IERS (International Earth Rotation and Reference System Service) has been our first check on GINGERINO accuracy

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.



GINGERINO noise in 2019

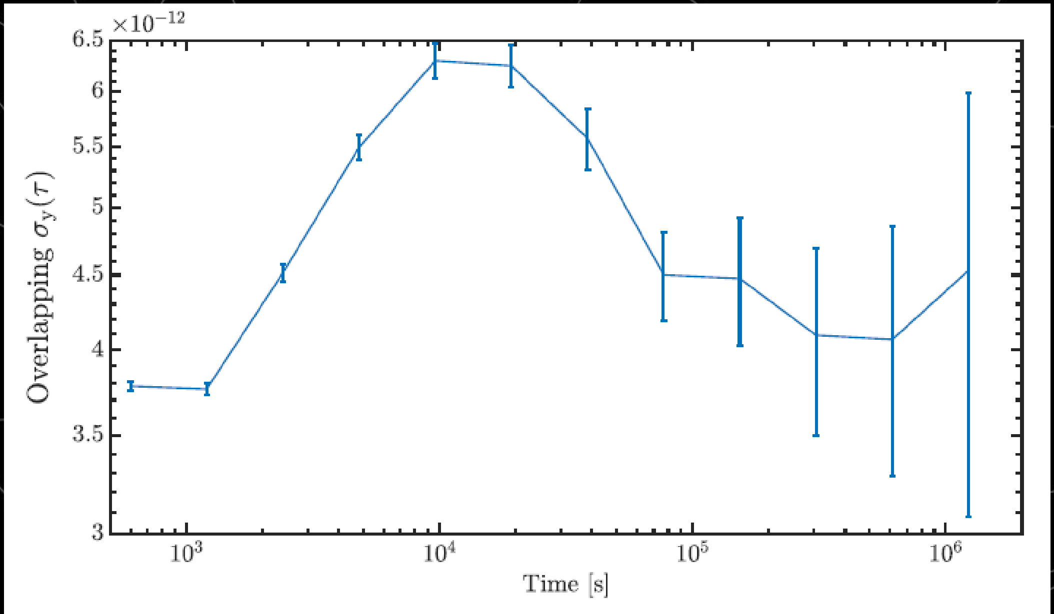


For the first time we had evidence that the reached sensitivity was in the range that would allow, for a multi-axial gyroscope, the detection of GR terms

Eur. Phys. J. C (2021) 81:400

GINGERINO sensitivity 2020-2021

- The 2020 result urged us to reconsider the analysis on the limiting noise of the apparatus.
- focus on "residuals" *i.e.* everything left out from known sources by improving signal analysis via cross-check with IERS and subtraction of local disturbances (temperature, local tilts, pressure variations) as independently measured

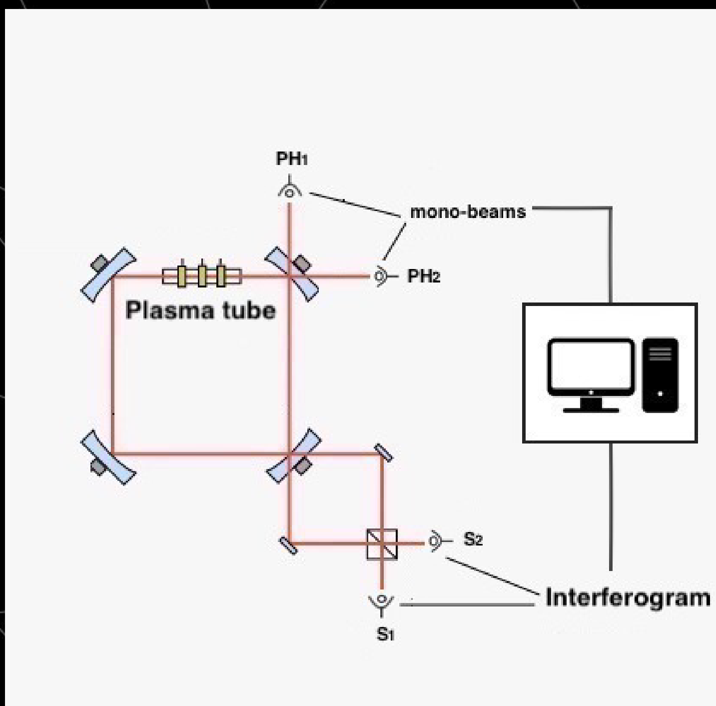


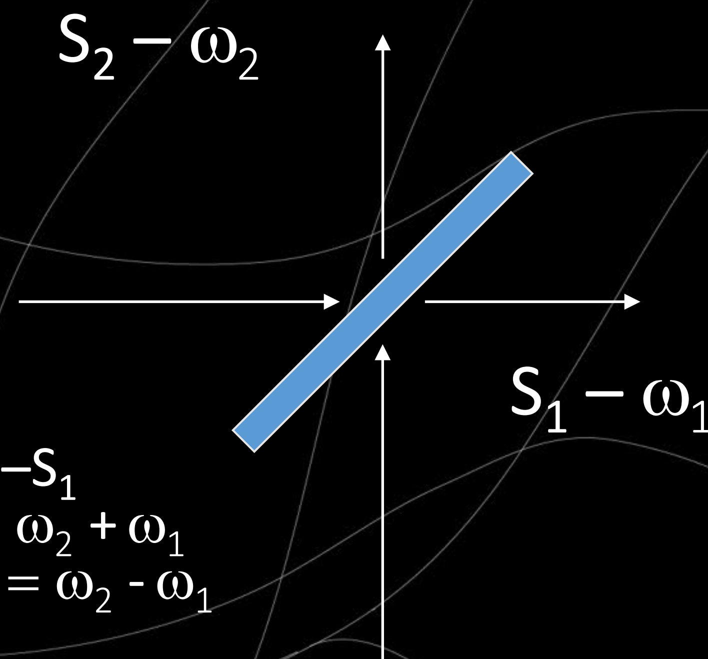
WARNING
Soon the Analysis of residuals has shown some inconsistency with the expected shot-noise limit in a limited range of frequency

arXiv:2301.01386 (submitted)

Noise by differential measurement

GINGERINO noise was analysed considering two Sagnac signal (opposite in phase) obtained by looking at the two ports of the recombination beam-splitter.





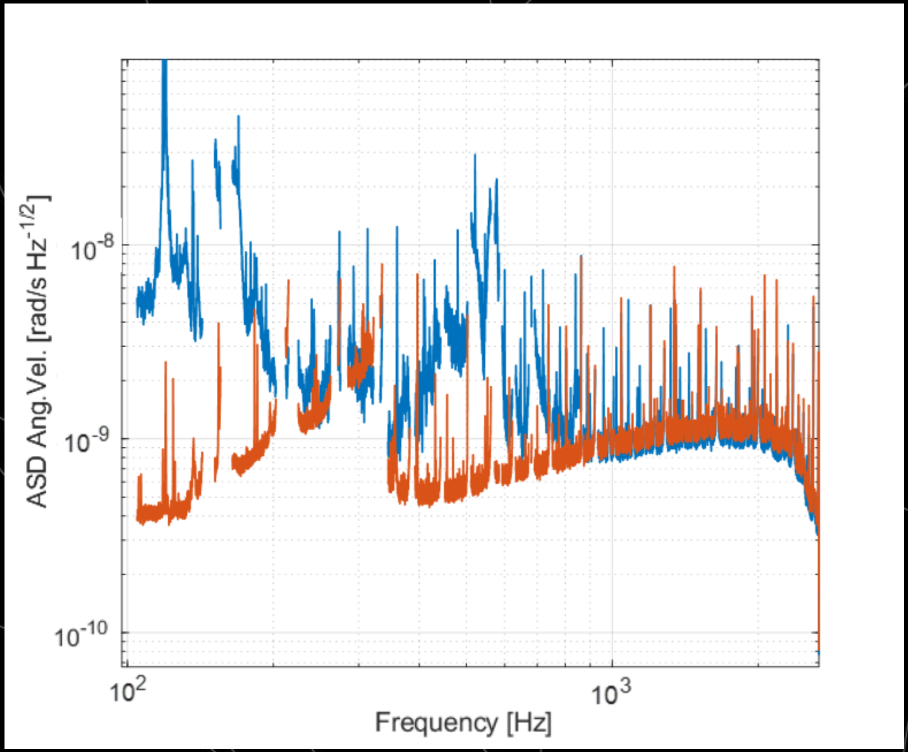
$S = S_2 - S_1$

$\omega_d = \omega_2 + \omega_1$

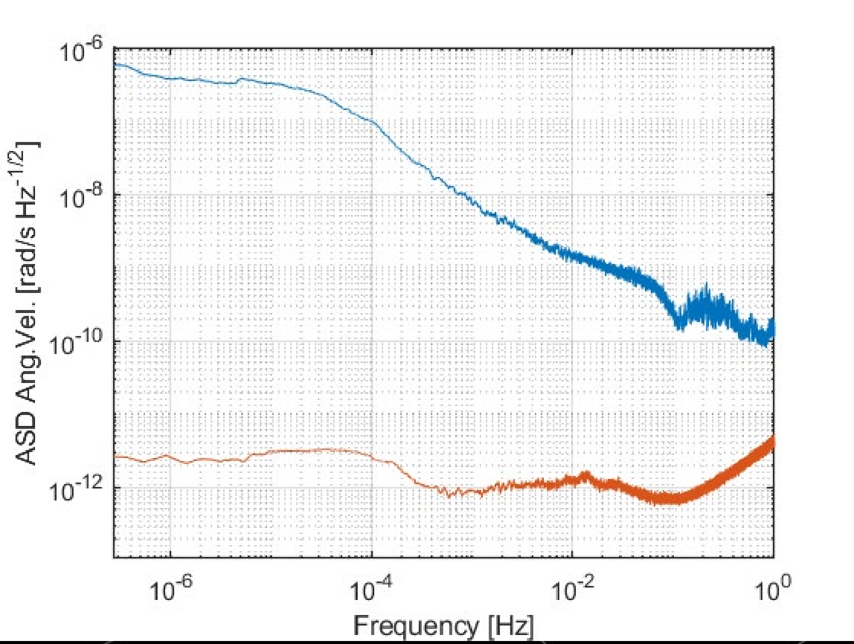
$\omega_{n12} = \omega_2 - \omega_1$

HINT: Hilbert transform is the only “manipulation” performed on differential data

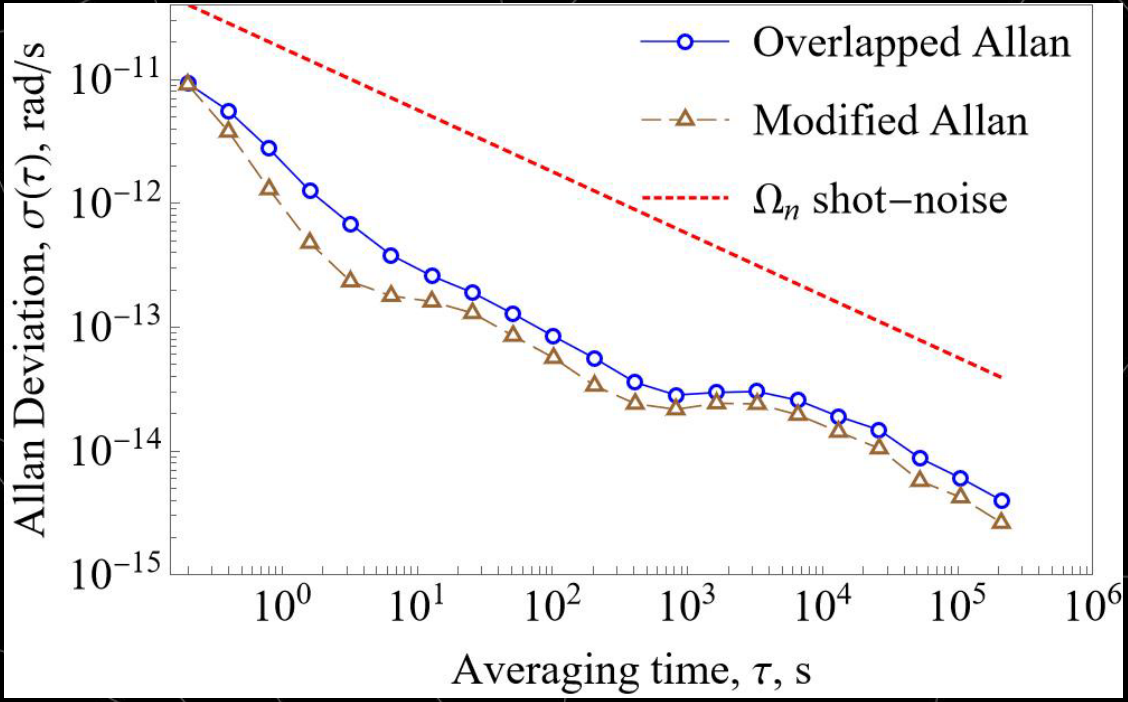
Measured ASD (amplitude spectral densities)



So doing we trace-out all possible rotational signals or technical (common mode) noise providing an upper limit for the resulting background noise, including all possible sources of quantum nature



GINGERINO Allan deviation for differential detection

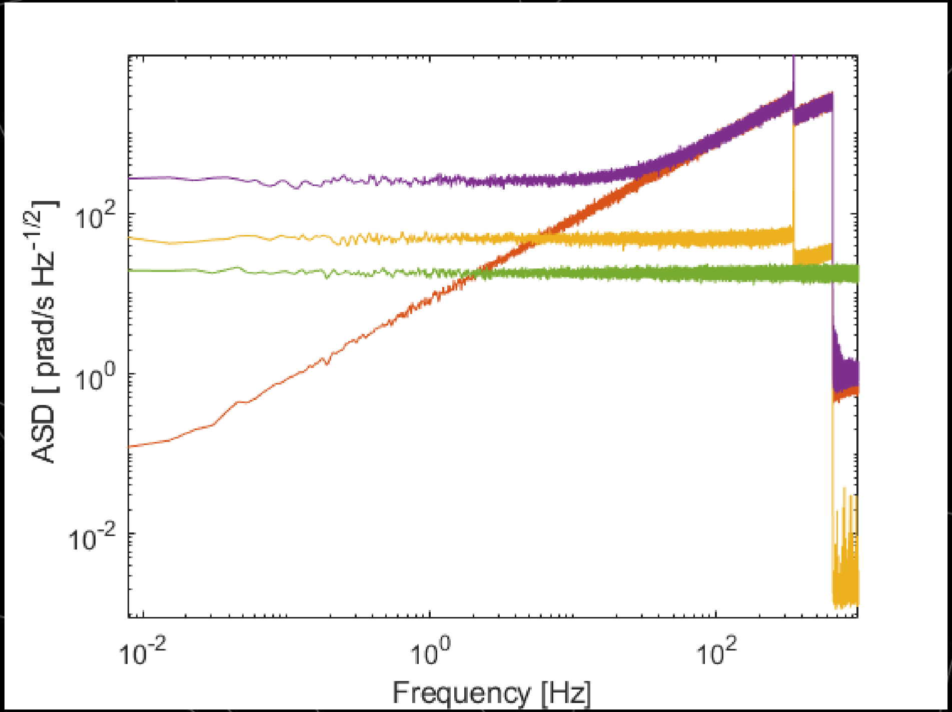


The Allan deviation give the experimentally conclusive proof of the sub-shot-noise character of GINGERINO

Open questions

- To what extent is this a true *quantum* effect?
- Are there *quantum* correlation in the systems?
- is the calculated shot-noise correct?
- is the independent beams model (usually adopted for RLG) suited for such highly sensitive device?

Types of noises in a RLG



green ω_n – injected white frequency noise

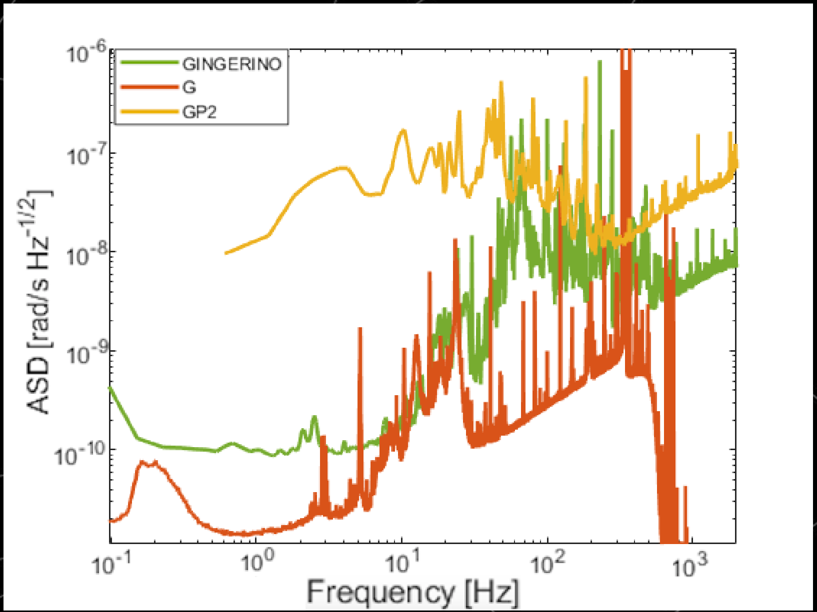
purple – reconstructed frequency noise

red – reconstructed from $\omega_n x \tau$ (phase noise)

yellow – Wiener process noise

ASD of three large RLGs

All show a behavior compatible with a dominant phase noise (especially going up in frequency)



The model (what we have so far)

- Shot noise formula assumes the beating of two coherent beams (it coincides with the so-called Standard Quantum Limit SQL)
- Relies on the assumption that the two beams are totally independent *i.e.* their dynamics is completely uncoupled

BUT

- Classical equations for the counter propagating beams are not uncoupled there is at least one mechanism that couples the two beams (backscattering)
- Coupling, in this context, means exchange of phase information being the dynamical variable the phase difference and may happen at a more fundamental level

$$\Omega_N = \frac{cP}{4AQ}\sqrt{\frac{hf_0}{P_o T}}.$$

G E Stedman 1997 Rep. Prog. Phys. 60 615

- Q -> cavity quality factor
- Po -> rate of power loss (total loss!)
- T -> observation time

J.R. Wilkinson Prog. Quant. Electr. 1987. Vol. 11, pp. 1-103

$$\omega_n^2 E_{+n}(t) + \frac{d^2E_{+n}}{dt^2} + 2ik_{+n}a_0\frac{dE_{+n}}{dt} + 2ik_{-n}a_{+2n}\frac{dE_{-n}}{dt} = -\chi_0^+\frac{d^2E_{+n}}{dt^2} - \chi_{+2n}^-\frac{d^2E_{-n}}{dt^2} \quad (4.24)$$

$$\omega_n^2 E_{-n}(t) + \frac{d^2E_{-n}}{dt^2} + 2ik_{-n}a_0\frac{dE_{-n}}{dt} + 2ik_{+n}a_{-2n}\frac{dE_{+n}}{dt} = -\chi_0^-\frac{d^2E_{-n}}{dt^2} - \chi_{-2n}^+\frac{d^2E_{+n}}{dt^2} \quad (4.25)$$

What more...

- The role of the laser medium in cross-talking among the two beams cannot be excluded as far as the two beams emerge from the same laser medium volume
- The optical field may create standing phase grating inside the gain medium that may cause unaccounted correlations (Antonio Mecozzi, "Frequency noise of laser gyros", Optica Open. Preprint n. 22679749.v1 (2023))
- A full quantum model, starting from scratch and possibly neglecting as many as possible coupling terms by phenomenological as well as experimental consideration may help in identifying the issue and possibly give a reasonable answer to the actual inconsistency of our conclusive experimental result with the shot-noise as far as the actual model is granted for true

There is only one possible conclusion…