GINGER

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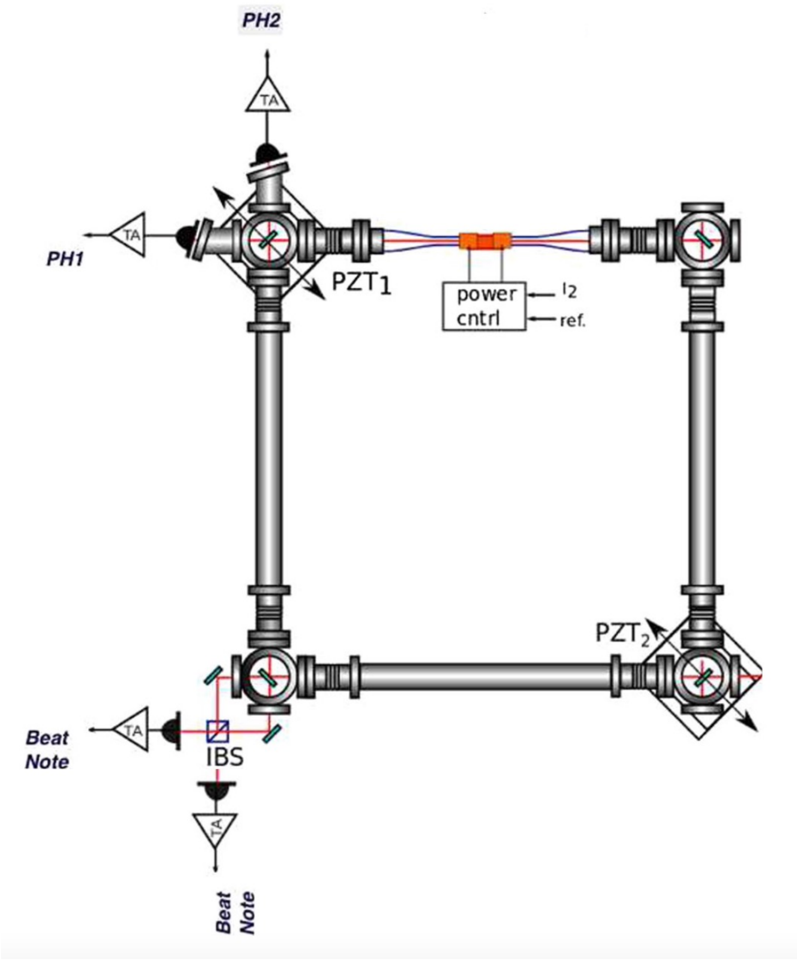
- ✓ GINGER, t_0 February 2023
- ✓ A bit of history
- ✓ Fundamental physics
- ✓ Near future plan
- ✓ Conclusions

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.

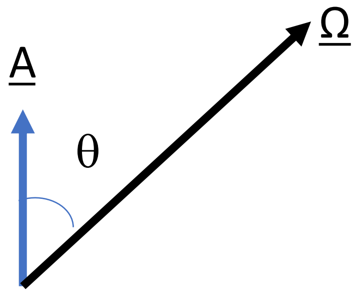
GINGER is highly interdisciplinary and able to provide data not only for fundamental physics but also for geophysics and geodesy. The validity of GINGER for fundamental physics investigation requires long time measurements and very high sensitivity, the relevant target being ***to reach and go behind the sensitivity of 1 part in 10^9 of the Earth rotation rate***, target that has been already demonstrated.

RLG



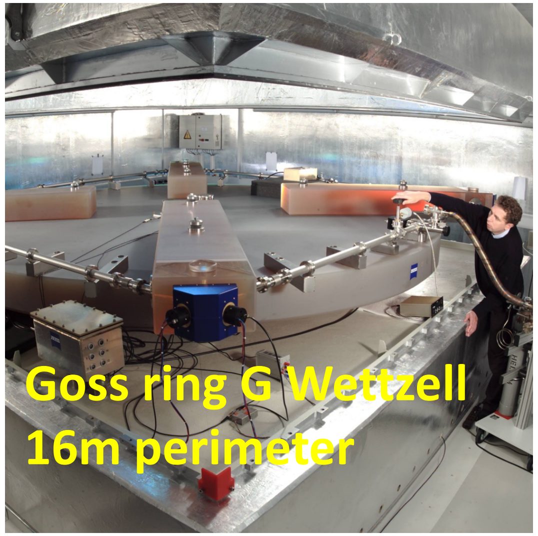
- *a physical system composed of an active medium inside a polygonal optical cavity, such to generate two counterpropagating beams (traveling waves)*
- *Differences between the two directions of propagation, non reciprocity, generate small differences between the two beams, that interferometry can detect*
- *The Sagnac effect is due to the non reciprocity between the two waves when the cavity and the active medium rigidly rotate*
- ***scalar product between the vector Ω and the area vector A***

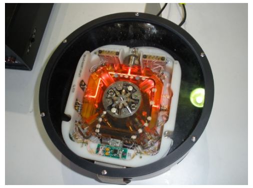
$$f_s = 4\frac{A}{\lambda L}\Omega\cos\theta$$

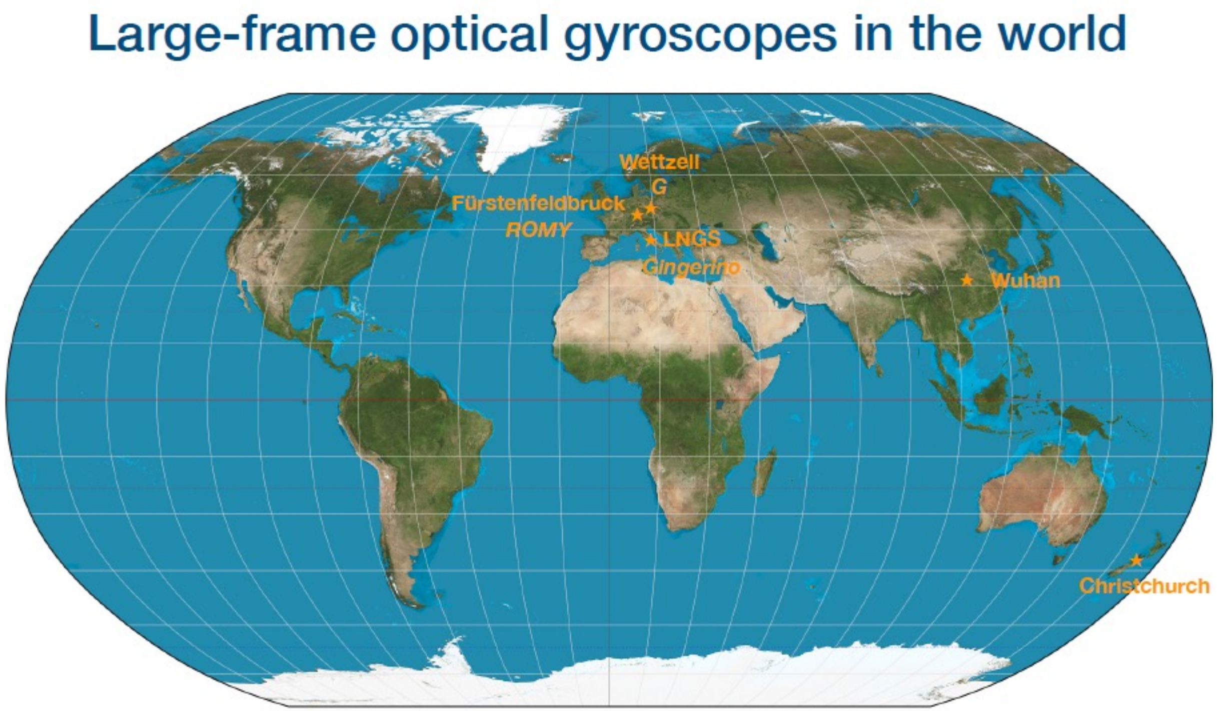


Large frame RLGs

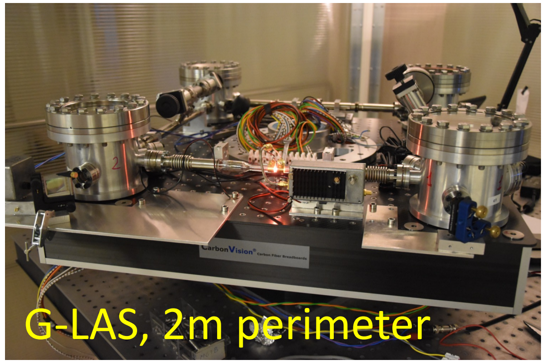
MONOLITHIC



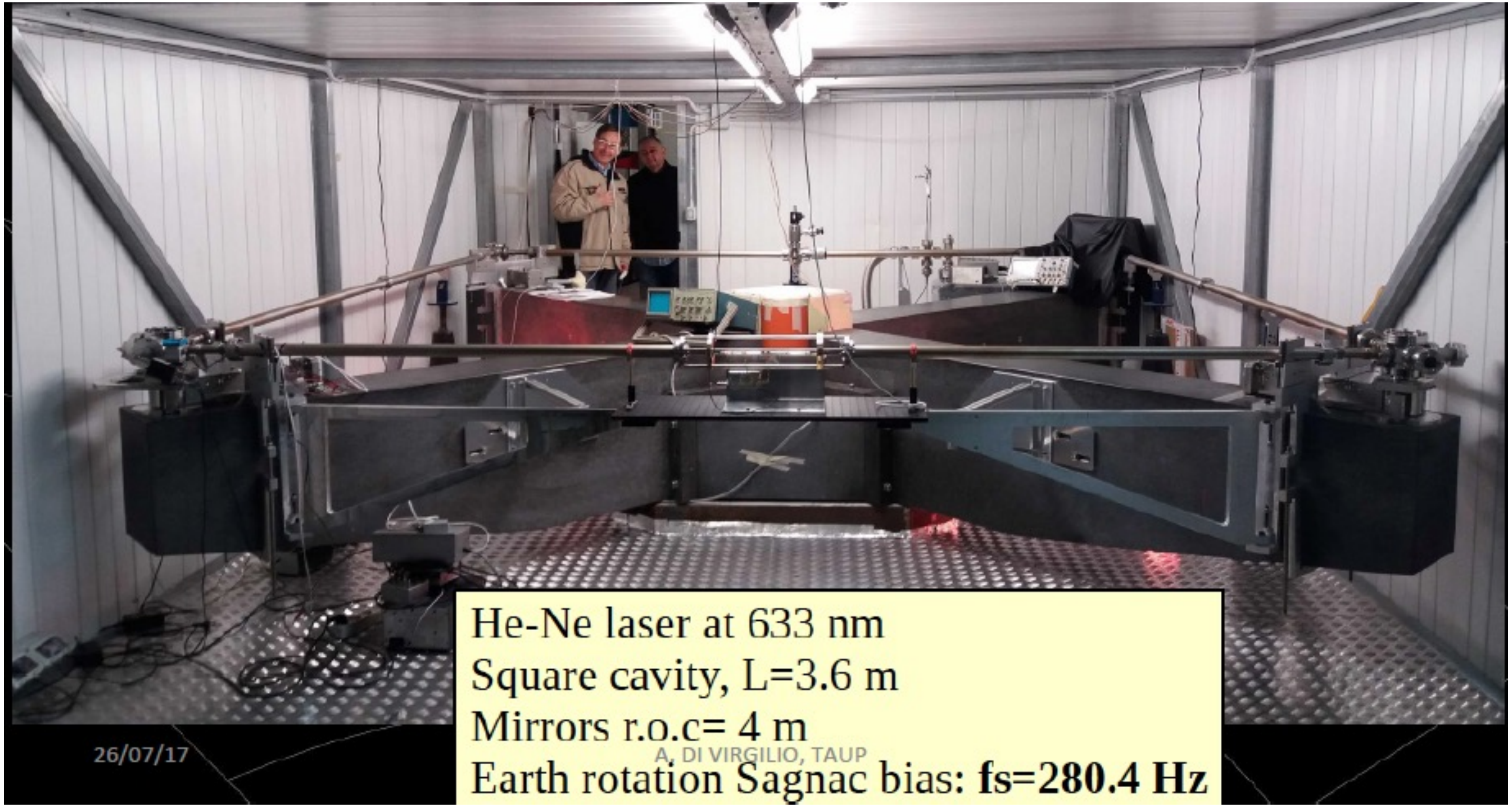




HETEROLITHIC

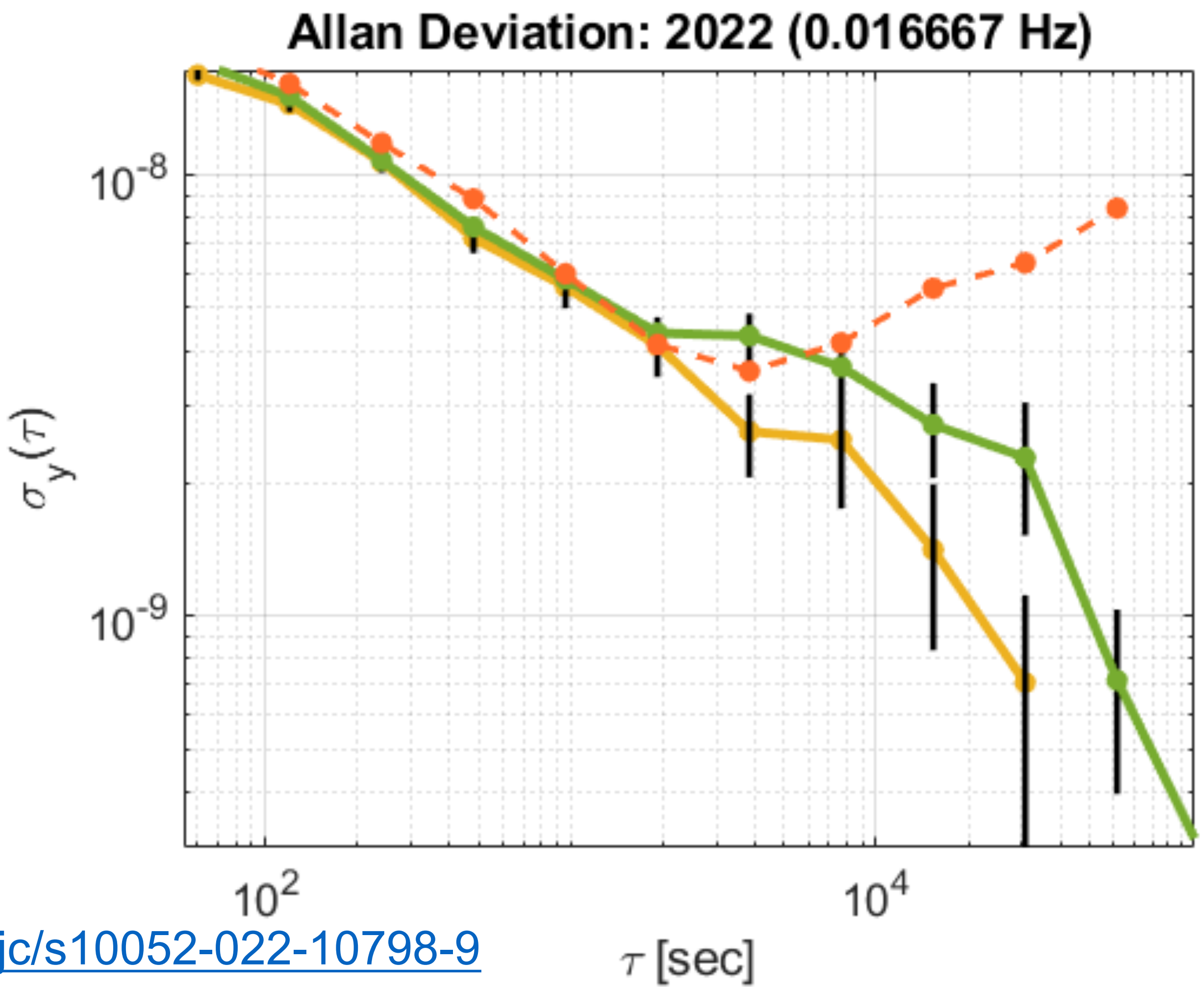


GINGERINO



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**

G crosses 1 part 10^9 boundary



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

Impact on fundamental physics

- Large discussion can be found in GINGER https://arxiv.org/pdf/2209.09328.pdf, which will soon appear in MEMOCS
- I will show few slides from last IV GRM workshop, 14 June 2023, Salvatore Capozziello talk: https://agenda.infn.it/event/33962/contributions/197082/attachments/107230/151344/Capozziello_GRM4.pdf

Horava-Lifshitz vs General Relativity

General Relativity

$$\Omega_S = \frac{4A}{P\lambda}\Omega_E \quad \left[\cos(\theta+\alpha) - \frac{G_N M}{c^2 R}\sin\alpha\sin\theta - \frac{G I_E}{c^2 R^3}\left(2\cos\theta\cos\alpha + \sin\theta\sin\alpha\right)\right]$$

$G = G_N$

$G = G_N$

$G = G_N$

Horava-Lifshitz Gravity

$$\Omega_S = \frac{4A}{P\lambda}\Omega_E \quad \left[\cos(\theta+\alpha) - \left(1 + \frac{G}{G_N}a_1 - \frac{a_2}{a_1}\right)\frac{GM}{c^2 R}\sin\alpha\sin\theta - \frac{G I_E}{c^2 R^3}\left(2\cos\theta\cos\alpha + \sin\theta\sin\alpha\right)\right]$$

Advantages of using GINGER

Salvatore Capozziello

- The precision of GINGERINO is 1/1000 in the geodesic term, 1/100 in the LT term
- GINGER experiment should overcome such uncertainty providing a precision of 1/1000 in the LT term
- The presence of two rings yields a dynamical measurement of the angle **α**

$$\Omega_S = \frac{4A}{P\lambda}\Omega_E \left[\cos(\theta+\alpha) - \underbrace{\left(1+\frac{G}{G_N}a_1 - \frac{a_2}{a_1}\right)\frac{GM}{c^2R}\sin\alpha\sin\theta}_{\text{Geodesic Term}} - \underbrace{\frac{GI_E}{c^2R^3}\left(2\cos\theta\cos\alpha + \sin\theta\sin\alpha\right)}_{\text{LT Term}}\right]$$

- *Measurement of LT term constrains the value of G, measurement of geodesic term constrains a_1 and a_2*
- *The precision of GINGERINO close to 10^{-15} rad/s corresponds to a precision of 1.4 $\cdot\, 10^{-9}$ with respect to the dominant term.*

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Perspectives

Salvatore Capozziello

In $f(R, R^{\mu\nu}R_{\mu\nu}, \varphi)$ gravity, GP-B and LARES satellites provide

$$m_Y \geq 7.3 \times 10^{-7} m^{-1} \qquad\qquad m_Y > 1.2 \times 10^{-6} \mathrm{m}^{-1}$$

constraint on m_y by GINGER

constraints on a_1, a_2 by GINGER

In Horava-Lifshitz gravity, the weak-field limit provide

$$\begin{aligned} c\,\delta\tau &= \frac{4A\Omega_E}{c}\left[\cos(\theta+\alpha) - \left(1 + \frac{G}{G_N}\,a_1 - \frac{a_2}{a_1}\right)\frac{GM}{c^2R}\sin\theta\sin\alpha \right. \\ &\left. - \frac{GI_E}{c^2R^3}\left(2\cos\theta\cos\alpha + \sin\theta\sin\alpha\right)\right] \end{aligned}$$

Salvatore Capozziello

Perspectives

$$\Omega_S = \frac{4A}{P\lambda}\,\Omega_E\left[\cos(\theta+\alpha) - \left(1+\frac{G}{G_N}\,a_1 - \frac{a_2}{a_1}\right)\frac{GM}{c^2R}\sin\alpha\sin\theta - \frac{GI_E}{c^2R^3}\left(2\cos\theta\cos\alpha + \sin\theta\sin\alpha\right)\right]$$

- Fixing a_1 and a_2 by GINGER allows to retain or reject viable theories
- GINGER could select effective models for Quantum Gravity in the weak field limit
- With respect to satellite experiments, results can be tuned and reproduced.

S. Capozziello, C. Altucci, F. Bajardi, A.Di Virgilio et al... Euro. Phys. J. Plus 136 (2021) 5

A.Di Virgilio, U. Giacomelli, A. Simonelli et al... Euro. Phys. J. C 81 (2021) 457

A. Porzio, C. Altucci, S. Capozziello, R. Velotta, et al... PoS Corfù 2017 (2018) 181

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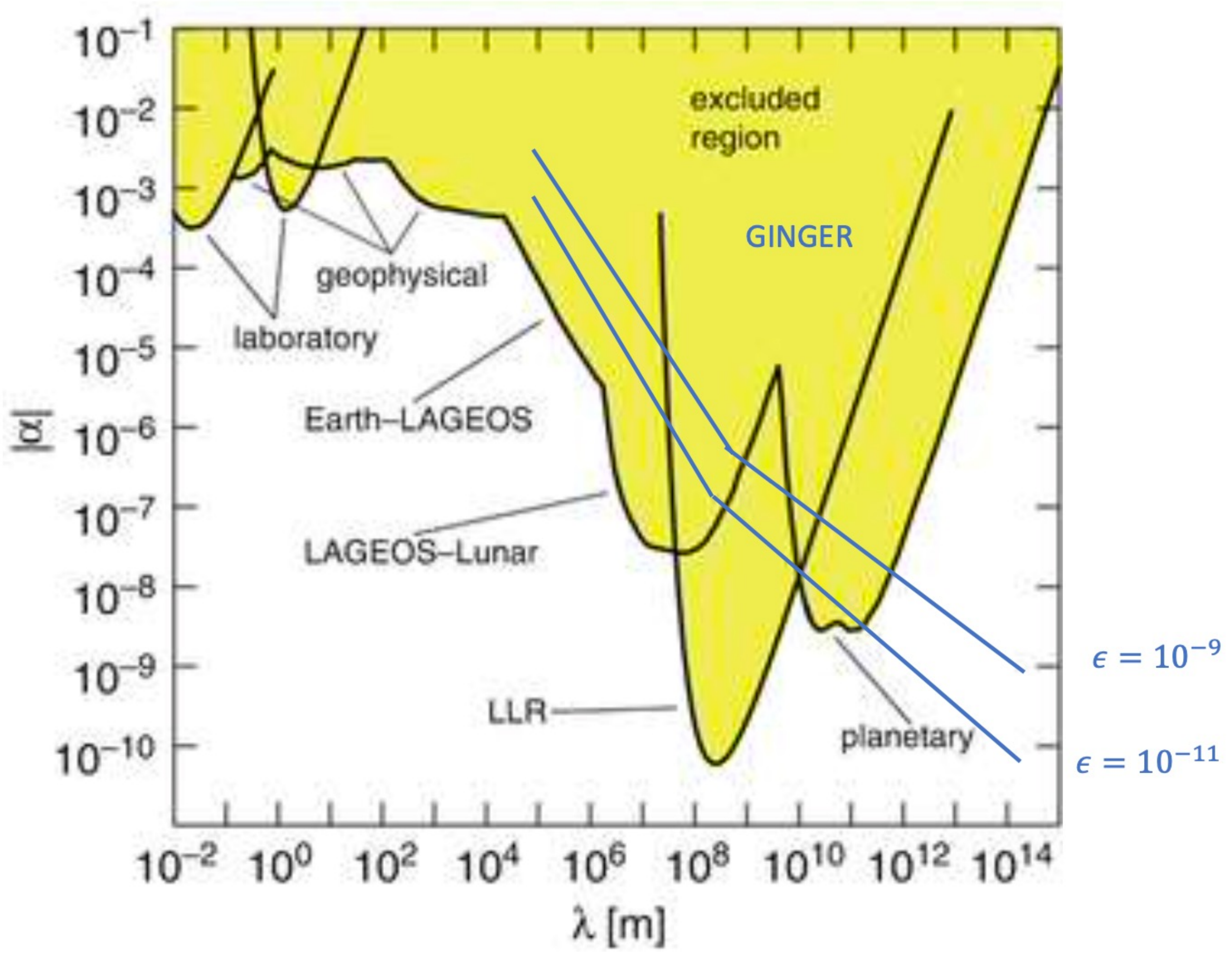
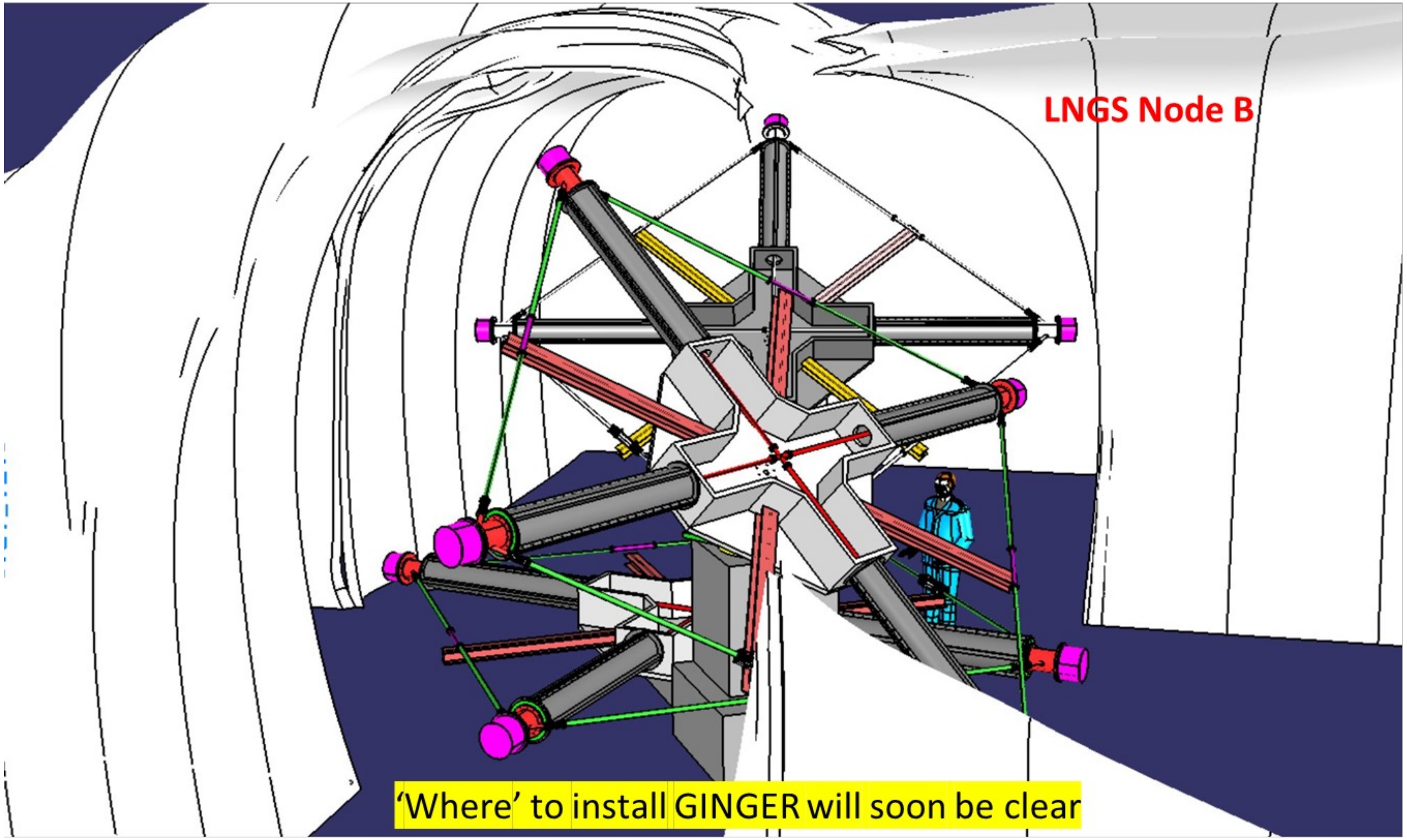
Yukawa-like corrections (GINGER)
GINGER α λ exclusion plot

fixing the compatibility ranges of Yukawa-like parameters can be a fundamental tool to discriminate among viable gravitational models.





Array of 3 ring laser gyroscopes (RLG), 5m sides, the drawing is related to Node B of LNGS
This area is large enough to separate most of the electronics in a separate room.

RLX oriented at maximum Sagnac Signal, to measure the absolute value of the angular rotation

RLH with vertical area vector

RLO with area vector outside the meridian plane

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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Alberto Porzio *(CNR-SPIN)*
Raffaele Velotta
Università di Salerno
Gaetano Lambiase

GINGER is part of UGGS

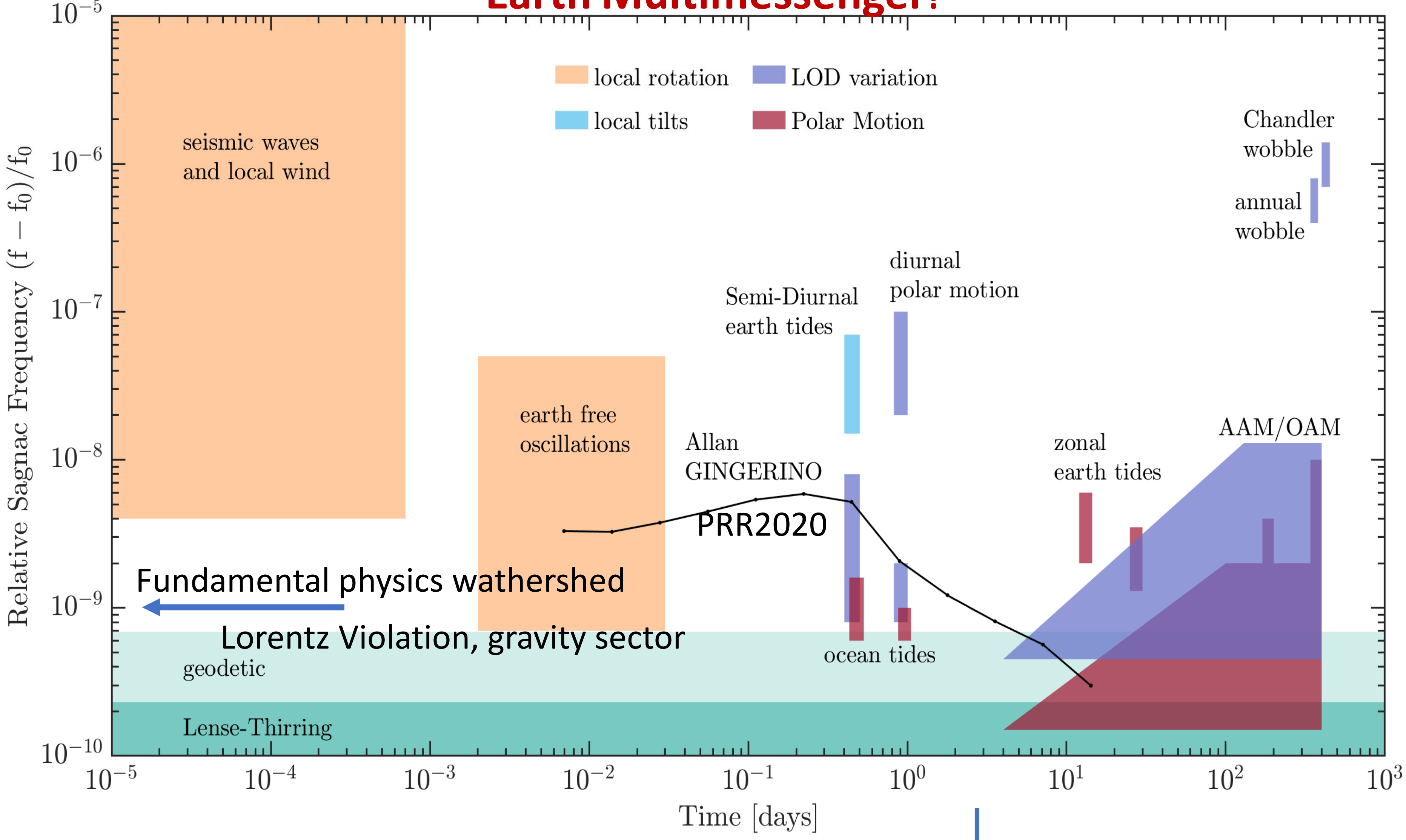
(Underground Geophysics at Gran Sasso)
see Gaetano De Luca talk this afternoon

Authors	Article Title	Source Title
Maccioni, E; Beverini, N; Carelli, G; Di Somma, G; Di Virgilio, A; Marsili, P	High sensitivity tool for geophysical applications: a geometrically locked ring laser gyroscope	APPLIED OPTICS
Di Virgilio, ADV; Terreni, G; Basti, A; Beverini, N; Carelli, G; Ciampini, D; Fuso, F; Maccioni, E; Marsili, P; Kodet, J; Schreiber, KU	Overcoming 1 part in 10(9) of earth angular rotation rate measurement with the G Wettzell data	EUROPEAN PHYSICAL JOURNAL C
Giacomelli, U; Beverini, N; Di Virgilio, A; Maccioni, E; Marsili, P	Radial distribution gain at 633 nm in a He-Ne RF-excited small bore discharge	APPLIED OPTICS
Capozziello, S; Altucci, C; Bajardi, F; Basti, A; Beverini, N; Carelli, G; Ciampini, D; Di Virgilio, ADV; Fuso, F; Giacomelli, U; Maccioni, E; Marsili, P; Ortolan, A; Porzio, A; Simonelli, A; Terreni, G; Velotta, R	Constraining theories of gravity by GINGER experiment (vol 136, 394, 2021)	EUROPEAN PHYSICAL JOURNAL PLUS
Basti, A; Beverini, N; Bosi, F; Carelli, G; Ciampini, D; Di Virgilio, ADV; Fuso, F; Giacomelli, U; Maccioni, E; Marsili, P; Passeggio, G; Porzio, A; Simonelli, A; Terreni, G	Effects of temperature variations in high-sensitivity Sagnac gyroscope	EUROPEAN PHYSICAL JOURNAL PLUS
Di Virgilio, AD; Altucci, C; Bajardi, F; Basti, A; Beverini, N; Capozziello, S; Carelli, G; Ciampini, D; Fuso, F; Giacomelli, U; Maccioni, E; Marsili, P; Ortolan, A; Porzio, A; Simonelli, A; Terreni, G; Velotta, R	Sensitivity limit investigation of a Sagnac gyroscope through linear regression analysis Sagnac gyroscope sensitivity limit	EUROPEAN PHYSICAL JOURNAL C
Di Virgilio, AD; Altucci, C; Bajardi, F; Basti, A; Beverini, N; Capozziello, S; Carelli, G; Ciampini, D; Fuso, F; Giacomelli, U; Maccioni, E; Marsili, P; Ortolan, A; Porzio, A; Simonelli, A; Terreni, G; Velotta, R	Sensitivity limit investigation of a Sagnac gyroscope through linear regression analysis (vol 81, 400, 2021)	EUROPEAN PHYSICAL JOURNAL C
Capozziello, S; Altucci, C; Bajardi, F; Basti, A; Beverini, N; Carelli, G; Ciampini, D; Di Virgilio, ADV; Fuso, F; Giacomelli, U; Maccioni, E; Marsili, P; Ortolan, A; Porzio, A; Simonelli, A; Terreni, G; Velotta, R	Constraining theories of gravity by GINGER experiment	EUROPEAN PHYSICAL JOURNAL PLUS
Di Virgilio, ADV; Basti, A; Beverini, N; Bosi, F; Carelli, G; Ciampini, D; Fuso, F; Giacomelli, U; Maccioni, E; Marsili, P; Ortolan, A; Porzio, A; Simonelli, A; Terreni, G	Underground Sagnac gyroscope with sub-prad/s rotation rate sensitivity: Toward general relativity tests on Earth	PHYSICAL REVIEW RESEARCH
Beverini, N; Carelli, G; Di Virgilio, A; Giacomelli, U; Maccioni, E; Stefani, F; Belfi, J	Length measurement and stabilization of the diagonals of a square area laser gyroscope	CLASSICAL AND QUANTUM GRAVITY
Di Virgilio, ADV; Beverini, N; Carelli, G; Ciampini, D; Fuso, F; Giacomelli, U; Maccioni, E; Ortolan, A	Identification and correction of Sagnac frequency variations: an implementation for the GINGERINO data analysis	EUROPEAN PHYSICAL JOURNAL C
Bosi, F; Di Virgilio, ADV; Giacomelli, U; Simonelli, A; Terreni, G; Basti, A; Beverini, N; Carelli, G; Ciampini, D; Fuso, F; Maccioni, E; Marsili, P; Stefani, F	Small scale ring laser gyroscopes as environmental monitors	16TH INTERNATIONAL CONFERENCE ON TOPICS IN ASTROPARTICLE AND UNDERGROUND PHYSICS (TAUP 2019)
Bosi, F; Di Virgilio, ADV; Giacomelli, U; Simonelli, A; Terreni, G; Basti, A; Beverini, N; Carelli, G; Ciampini, D; Fuso, F; Maccioni, E; Marsili, P; Stefani, F; Ortolan, A; Porzio, A; Altucci, C; Bajardi, F; Capozziello,	Sagnac gyroscopes, GINGERINO, and GINGER	16TH INTERNATIONAL CONFERENCE ON TOPICS IN ASTROPARTICLE AND UNDERGROUND PHYSICS (TAUP 2019)
Di Virgilio, ADV; Beverini, N; Carelli, G; Ciampini, D; Fuso, F; Maccioni, E	Analysis of ring laser gyroscopes including laser dynamics	EUROPEAN PHYSICAL JOURNAL C
Beverini, N; Basti, A; Bosi, F; Carelli, G; Ciampini, D; Di Virgilio, A; Ferrante, I; Fuso, F; Giacomelli, U; Maccioni, E; Simonelli, A; Stefani, F; Terreni, G; Altucci, C; Porzio, A; Velotta, R	Ring laser gyroscopes in the underground Gran Sasso Laboratories	QUANTUM ELECTRONICS
Belfi, J; Beverini, N; Carelli, G; Virgilio, A; Giacomelli, U; Maccioni, E; Simonelli, A; Stefani, F; Terreni, G	Analysis of 90 day operation of the GINGERINO gyroscope: publisher's note (vol 57, pg 5844, 2018)	APPLIED OPTICS
Belfi, J; Beverini, N; Carelli, G; Di Virgilio, A; Giacomelli, U; Maccioni, E; Simonelli, A; Stefani, F; Terreni, G	Analysis of 90 day operation of the GINGERINO gyroscope	APPLIED OPTICS
Simonelli, A; Igel, H; Wassermann, J; Belfi, J; Di Virgilio, A; Beverini, N; De Luca, G; Saccorotti, G	Rotational motions from the 2016, Central Italy seismic sequence, as observed by an underground ring laser gyroscope	GEOPHYSICAL JOURNAL INTERNATIONAL
Stefani, F; Beverini, N; Carelli, G; Ciampini, D; Di Virgilio, A; Fuso, F; Giacomelli, U; Maccioni, E	Long term stabilization of large frame laser gyroscopes	2018 EUROPEAN FREQUENCY AND TIME FORUM (EFTF)
Di Virgilio, A; Belfi, J; Bosi, F; Morsani, F; Terreni, G; Beverini, N; Carelli, G; Giacomelli, U; Maccioni, E; Ortolan, A; Porzio, A; Altucci, C; Velotta, R; Donazzan, A; Naletto, G; Cuccato, D; Beghi, A; Pelizzo, MG;	The GINGER Project	NUCLEAR AND PARTICLE PHYSICS PROCEEDINGS
Di Virgilio, ADV; Belfi, J; Ni, WT; Beverini, N; Carelli, G; Maccioni, E; Porzio, A	GINGER: A feasibility study	EUROPEAN PHYSICAL JOURNAL PLUS
Belfi, J; Beverini, N; Bosi, F; Carelli, G; Cuccato, D; De Luca, G; Di Virgilio, A; Gebauer, A; Maccioni, E; Ortolan, A; Porzio, A; Saccorotti, G; Simonelli, A; Terreni, G	Deep underground rotation measurements: GINGERino ring laser gyroscope in Gran Sasso	REVIEW OF SCIENTIFIC INSTRUMENTS
Tartaglia, A; Di Virgilio, A; Belfi, J; Beverini, N; Ruggiero, ML	Testing general relativity by means of ring lasers	EUROPEAN PHYSICAL JOURNAL PLUS
Belfi, J; Beverini, N; Carelli, G; Di Virgilio, A; Giacomelli, U; Maccioni, E; Astrua, M; Pisani, M; Santiano, M	G-LAS A Ring Laser Goniometer for Angular Metrology	2017 JOINT CONFERENCE OF THE EUROPEAN FREQUENCY AND TIME FORUM AND IEEE INTERNATIONAL FREQUENCY CONTROL SYMPOSIUM (EFTF/IFC)
Belfi, J; Bosi, F; Di Virgilio, A; Beverini, N; Carelli, G; Giacomelli, U; Maccioni, E; Simonelli, A; Beghi, A; Cuccato, D; Donazzan, A; Naletto, G; Ortolan, A; Pelizzo, MG; Porzio, A; Altucci, C; Velotta, R; Tartaglia,	Very High Sensitivity Laser Gyroscopes for General Relativity Tests in a Ground Laboratory	2016 EUROPEAN FREQUENCY AND TIME FORUM (EFTF)
Belfi, J; Beverini, N; Di Virgilio, A; Maccioni, E; Astrua, M; Pisani, M; Santiano, M	Planar Angle Metrology: G-LAS, the INRIM - INFN Ring Laser Goniometer	2016 EUROPEAN FREQUENCY AND TIME FORUM (EFTF)
Beverini, N; Di Virgilio, A; Belfi, J; Ortolan, A; Schreiber, KU; Gebauer, A; Klugel, T	High-Accuracy Ring Laser Gyroscopes: Earth Rotation Rate and Relativistic Effects	8TH SYMPOSIUM ON FREQUENCY STANDARDS AND METROLOGY 2015
Donazzan, A; Naletto, G; Pelizzo, MG; Cuccato, D; Beghi, A; Ortolan, A; Belfi, J; Bosi, F; Di Virgilio, A; Beverini, N; Carelli, G; Maccioni, E; Santagata, R; Simonelli, A; Porzio, A; Tartaglia, A	External Metrology System for the Stabilization of Large Ring-Lasers	2016 IEEE METROLOGY FOR AEROSPACE (METROAEROSPACE)
Donazzan, A; Naletto, G; Pelizzo, MG; Cuccato, D; Beghi, A; Ortolan, A; Belfi, J; Bosi, F; Simonelli, A; Beverini, N; Carelli, G; Maccioni, E; Santagata, R; Porzio, A; Tartaglia, A; Di Virgilio, A	A network of heterodyne laser interferometers for monitoring and control of large ring-lasers	INTERFEROMETRY XVIII
Ortolan, A; Belfi, J; Bosi, F; Di Virgilio, A; Beverini, N; Carelli, G; Maccioni, E; Santagata, R; Simonelli, A; Beghi, A; Cuccato, D; Donazzan, A; Naletto, G	The GINGER project and status of the GINGERino prototype at LNGS	XIV INTERNATIONAL CONFERENCE ON TOPICS IN ASTROPARTICLE AND UNDERGROUND PHYSICS (TAUP 2015), PTS 1-7
Simonelli, A; Belfi, J; Beverini, N; Carelli, G; Di Virgilio, A; Maccioni, E; De Luca, G; Saccorotti, G	First deep underground observation of rotational signals from an earthquake at teleseismic distance using a large ring laser gyroscope	ANNALS OF GEOPHYSICS
Simonelli, A; Belfi, J; Beverini, N; Carelli, G; Di Virgilio, A; Maccioni, E; De Luca, G; Saccorotti, G	First deep underground observation of rotational signals from an earthquake at teleseismic distance using a large ring laser gyroscope	ANNALS OF GEOPHYSICS
Santagata, R; Beghi, A; Belfi, J; Beverini, N; Cuccato, D; Di Virgilio, A; Ortolan, A; Porzio, A; Solimeno, S	Optimization of the geometrical stability in square ring laser gyroscopes	CLASSICAL AND QUANTUM GRAVITY
Belfi, J; Di Virgilio, A; Beverini, N; Carelli, G; Maccioni, E; Simonelli, A; Santagata, R	Geometrical scale-factor stabilization of square cavity ring laser gyroscopes	2015 JOINT CONFERENCE OF THE IEEE INTERNATIONAL FREQUENCY CONTROL SYMPOSIUM & THE EUROPEAN FREQUENCY AND TIME FORUM (FCS)
Di Virgilio, A; Allegrini, M; Beghi, A; Belfi, J; Beverini, N; Bosi, F; Bouhadef, B; Calamai, M; Carelli, G; Cuccato, D; Maccioni, E; Ortolan, A; Passeggio, G; Porzio, A; Ruggiero, ML; Santagata, R; Tartaglia, A	A ring lasers array for fundamental physics	COMPTES RENDUS PHYSIQUE
Belfi, J; Beverini, N; Cuccato, D; Di Virgilio, A; Maccioni, E; Ortolan, A; Santagata, R	Interferometric length metrology for the dimensional control of ultra-stable ring laser gyroscopes	CLASSICAL AND QUANTUM GRAVITY
Beverini, N; Allegrini, M; Beghi, A; Belfi, J; Bouhadef, B; Calamai, M; Carelli, G; Cuccato, D; Di Virgilio, A; Maccioni, E; Ortolan, A; Porzio, A; Santagata, R; Solimeno, S; Tartaglia, A	Measuring general relativity effects in a terrestrial lab by means of laser gyroscopes	LASER PHYSICS
Cuccato, D; Beghi, A; Belfi, J; Beverini, N; Ortolan, A; Di Virgilio, A	Controlling the non-linear intracavity dynamics of large He-Ne laser gyroscopes	METROLOGIA
Belfi, J; Bosi, F; Di Virgilio, A; Santagata, R; Ortolan, A; Beverini, N; Carelli, G; Maccioni, E; Cuccato, D	Experimental activity toward GINGER (Gyroscopes IN GEneral Relativity)	2014 INTERNATIONAL CONFERENCE LASER OPTICS
Beverini, N; Carelli, G; Maccioni, E; Solimeno, S; Passeggio, G; Cuccato, D; Porzio, A; Ortolan, A; Belfi, J; Bosi, F; Di Virgilio, A; Santagata, R	Toward the Perfect square Ring Laser Gyroscope	2014 FOTONICA AEIT ITALIAN CONFERENCE ON PHOTONICS TECHNOLOGIES
Beverini, N; Carelli, G; Maccioni, E; Belfi, J; Di Virgilio, A; Pisani, M; Ortolan, A	Ring Laser Gyroscope for accurate angle metrology	2014 INTERNATIONAL CONFERENCE LASER OPTICS
Tartaglia, A; Belfi, J; Beverini, N; Di Virgilio, A; Ortolan, A; Porzio, A; Ruggiero, ML	Light and/or atomic beams to detect ultraweak gravitational effects	ISEG5 - FIFTH INTERNATIONAL SYMPOSIUM ON EXPERIMENTAL GRAVITATION
Belfi, J; Beverini, N; Calamai, M; Carelli, G; Maccioni, E; Cuccato, D; Di Virgilio, A; Ortolan, A; Santagata, R; Solimeno, S; Porzio, A	Absolute Control of the Scale Factor in GP2 Laser Gyroscope: Toward a Ground Based Detector of the Lense-Thirring Effect	2013 JOINT EUROPEAN FREQUENCY AND TIME FORUM & INTERNATIONAL FREQUENCY CONTROL SYMPOSIUM (EFTF/IFC)
Cuccato, D; Ortolan, A; Belfi, J; Beverini, N; Calamai, M; Di Virgilio, A	Laser Dynamics Effects on the Systematics of Large Size Laser Gyroscopes	2013 JOINT EUROPEAN FREQUENCY AND TIME FORUM & INTERNATIONAL FREQUENCY CONTROL SYMPOSIUM (EFTF/IFC)
Beghi, A; Belfi, J; Beverini, N; Bouhadef, B; Cuccato, D; Di Virgilio, A; Ortolan, A	Compensation of the laser parameter fluctuations in large ring-laser gyros: a Kalman filter approach	APPLIED OPTICS
Belfi, J; Beverini, N; Bosi, F; Carelli, G; Di Virgilio, A; Kolker, D; Maccioni, E; Ortolan, A; Passaquieti, R; Stefani, F	Performance of G-Pisa ring laser gyro at the Virgo site	JOURNAL OF SEISMOLOGY
Belfi, J; Beverini, N; Carelli, G; Di Virgilio, A; Maccioni, E; Saccorotti, G; Stefani, F; Velikoseltsev, A	Horizontal rotation signals detected by G-Pisa ring laser for the M-w=9.0, March 2011, Japan earthquake	JOURNAL OF SEISMOLOGY
Belfi, J; Beverini, N; Bosi, F; Carelli, G; Di Virgilio, A; Maccioni, E; Ortolan, A; Stefani, F	A 1.82 m(2) ring laser gyroscope for nano-rotational motion sensing	APPLIED PHYSICS B-LASERS AND OPTICS
Allegrini, M; Belfi, J; Beverini, N; Bosi, F; Bouhadef, B; Carelli, G; Cella, G; Cerdonio, M; Di Virgilio, AD; Gebauer, A; Maccioni, E; Ortolan, A; Porzio, A; Ruggiero, ML; Schreiber, UK; Solimeno, S; Stefani, F; Tarta	A laser gyroscope system to detect the gravito-magnetic effect on Earth	12TH INTERNATIONAL CONFERENCE ON TOPICS IN ASTROPARTICLE AND UNDERGROUND PHYSICS (TAUP 2011), PTS 1-6
Belfi, J; Beverini, N; Bouhadef, B; Carelli, G; Cuccato, D; Di Virgilio, A; Licciardi, A; Maccioni, E; Ortolan, A; Saccorotti, G; Stefani, F	Laser gyroscopes for very high sensitive applications	2012 EUROPEAN FREQUENCY AND TIME FORUM (EFTF)
Bosi, F; Cella, G; Di Virgilio, A; Ortolan, A; Porzio, A; Solimeno, S; Cerdonio, M; Zendri, JP; Allegrini, M; Belfi, J; Beverini, N; Bouhadef, B; Carelli, G; Ferrante, I; Maccioni, E; Passaquieti, R; Stefani, F; Ruggiero,	Measuring gravitomagnetic effects by a multi-ring-laser gyroscope	PHYSICAL REVIEW D
Belfi, J; Beverini, N; Bosi, F; Carelli, G; Di Virgilio, A; Maccioni, E; Passaquieti, R; Stefani, F	High Sensitivity Rotation Measurements with a mid-size Laser Gyroscope	ICONO 2010: INTERNATIONAL CONFERENCE ON COHERENT AND NONLINEAR OPTICS
Di Virgilio, A; Schreiber, KU; Gebauer, A; Wells, JPR; Tartaglia, A; Belfi, J; Beverini, N; Ortolan, A	A LASER GYROSCOPE SYSTEM TO DETECT THE GRAVITO-MAGNETIC EFFECT ON EARTH	INTERNATIONAL JOURNAL OF MODERN PHYSICS D
Belfi, J; Beverini, N; Bosi, F; Carelli, G; Di Virgilio, A; Maccioni, E; Pizzocaro, M; Sorrentino, F; Stefani, F	Active control and sensitivity of the G-Pisa gyrolaser	NUOVO CIMENTO DELLA SOCIETA ITALIANA DI FISICA B-BASIC TOPICS IN PHYSICS
Di Virgilio, A; Allegrini, M; Belfi, J; Beverini, N; Bosi, F; Carelli, G; Maccioni, E; Pizzocaro, M; Porzio, A; Schreiber, U; Solimeno, S; Sorrentino, F	Performances of 'G-Pisa': a middle size gyrolaser	CLASSICAL AND QUANTUM GRAVITY
Belfi, J; Beverini, N; Bosi, F; Carelli, G; Di Virgilio, A; Maccioni, E; Pizzocaro, M	Rotational Sensitivity of the G-Pisa Gyrolaser	IEEE TRANSACTIONS ON ULTRASONICS FERROELECTRICS AND FREQUENCY CONTROL
Belfi, J; Beverini, N; Bosi, F; Carelli, G; Di Virgilio, A; Graham, R; Maccioni, E; Pizzocaro, M; Porzio, A; Schreiber, U; Solimeno, S; Sorrentino, F; Velikoseltsev, A	G-Pisa gyrolaser	2009 JOINT MEETING OF THE EUROPEAN FREQUENCY AND TIME FORUM AND THE IEEE INTERNATIONAL FREQUENCY CONTROL SYMPOSIUM, VOLS 1 AND 2

In 10 years we have published more than 60 papers, spanning from theory, completely new RLG data analysis and experimental set up, noise investigation and geophysics, turning the RLG from a not acceptable instrument because laser non linearity to fundamental tool for angular rotation investigation.

GINGER is attached to the Earth, which provides a natural 'test-beam': highly interdisciplinary

Earth Multimessenger!



Fundamental Physics
Geophysics
Geodesy --> FUNDAMENTAL SCIENCE

..a natural playground to test the apparatus

inertial platforms, next generation GW detector space missions

Most recent measurements indicates feasible to reach 1 part 10^{11}

- To observe the environment in which we are immerse brings the advantage to compare our data with independent apparatus, very important to validate the analysis procedure

- Comparison GINGERINO and GNSS data: https://arxiv.org/abs/2308.01277

GINGER is based on a single device, different from most experiments

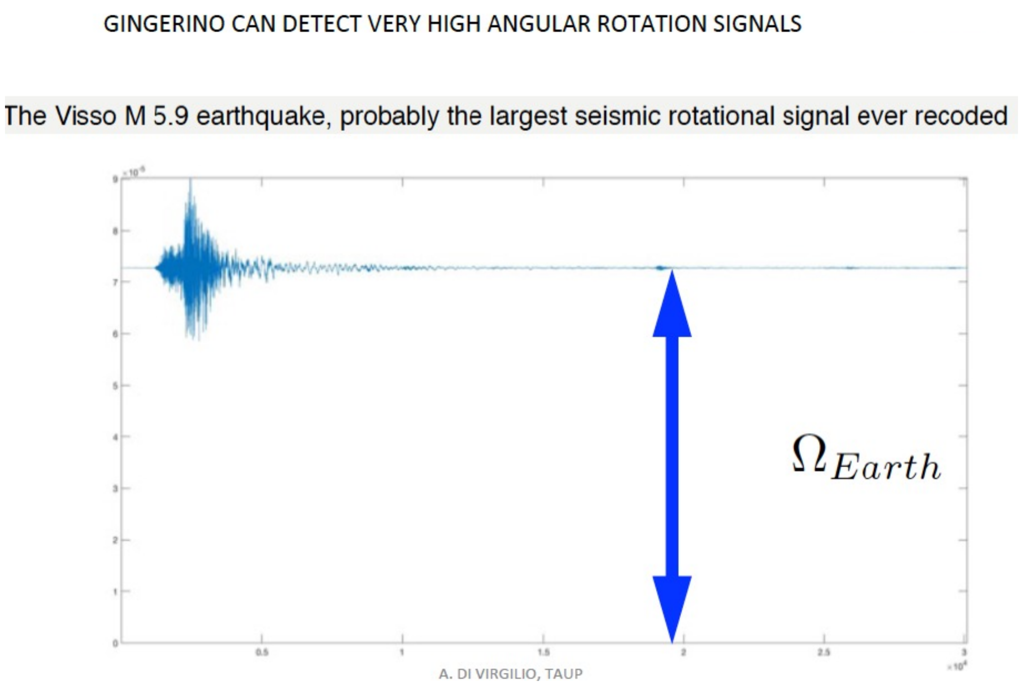
- Focus on lower frequency, as a consequence it needs: sensitivity, accuracy and <u>stability</u>
- based on highly symmetric interferometer: it can operate free running
- It is based on frequency reconstruction–> not affected by electronic 1/f noise and has huge dynamic range

- The laser cavity plays a crucial role, it is rigid; effective limitations are deformations, that can cause ‘rotation’ of the optical cavity→ difficult to study with fine elements analysis, avoid thermal gradients and use uniform materials; structural analysis of the mechanical system for second generation retrofitting

RLG a special kind of interferometer

goal → rotational degree of freedom for fundamental physics

- Electromagnetic radiation at the equilibrium with atomic gass in a high Q optical cavity
- The two counterpropagating modes are 'almost' equal -> the typical noise sources disappear as common mode
- It is based on frequency measurements -> very robust method and huge dynamic range



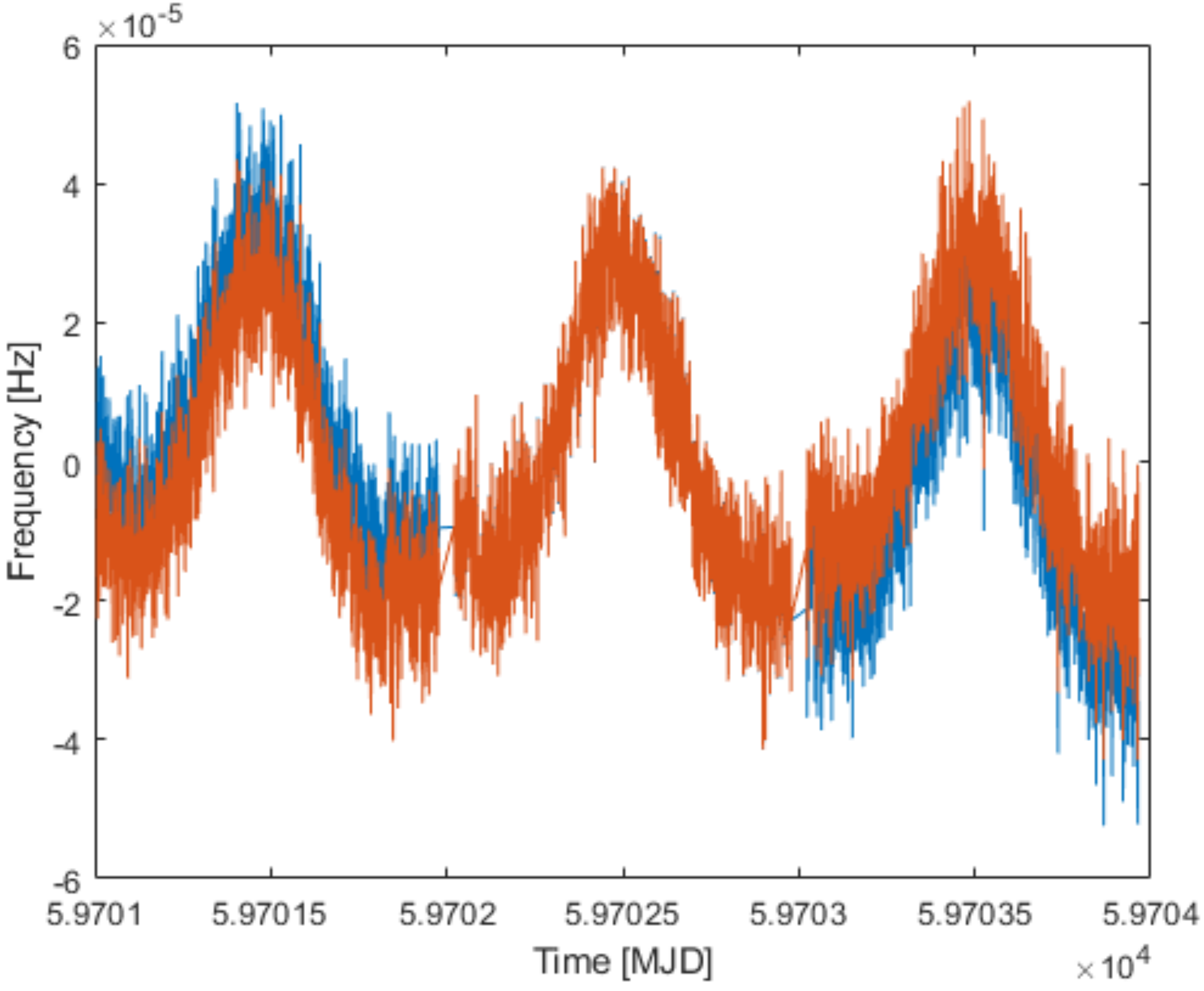
RLG: ideal instruments for low frequency investication (0-1Hz)

…angular rotation are ideal for low frequency investigation…

Semidiurnal tides are usually dominating the low frequency signals, but the diurnal polar motion dominates the RLG signal

This is the signal of G Wettzell, based on a perfectly rigid cavity.

We have to obtain the same with hetero lithic RLG structure.



Overcoming 1 part in 10^9 of earth angular rotation rate measurement with the G Wettzell data

A. D. V. Di Virgilio[1a], G. Terreni[1], A. Basti[1,2], N. Beverini[2], G. Carelli[2], D. Ciampini[2], F. Fuso[2], E. Maccioni[1,2], P. Marsili[2], J. Kodet[3] and K. U. Schreiber[3]

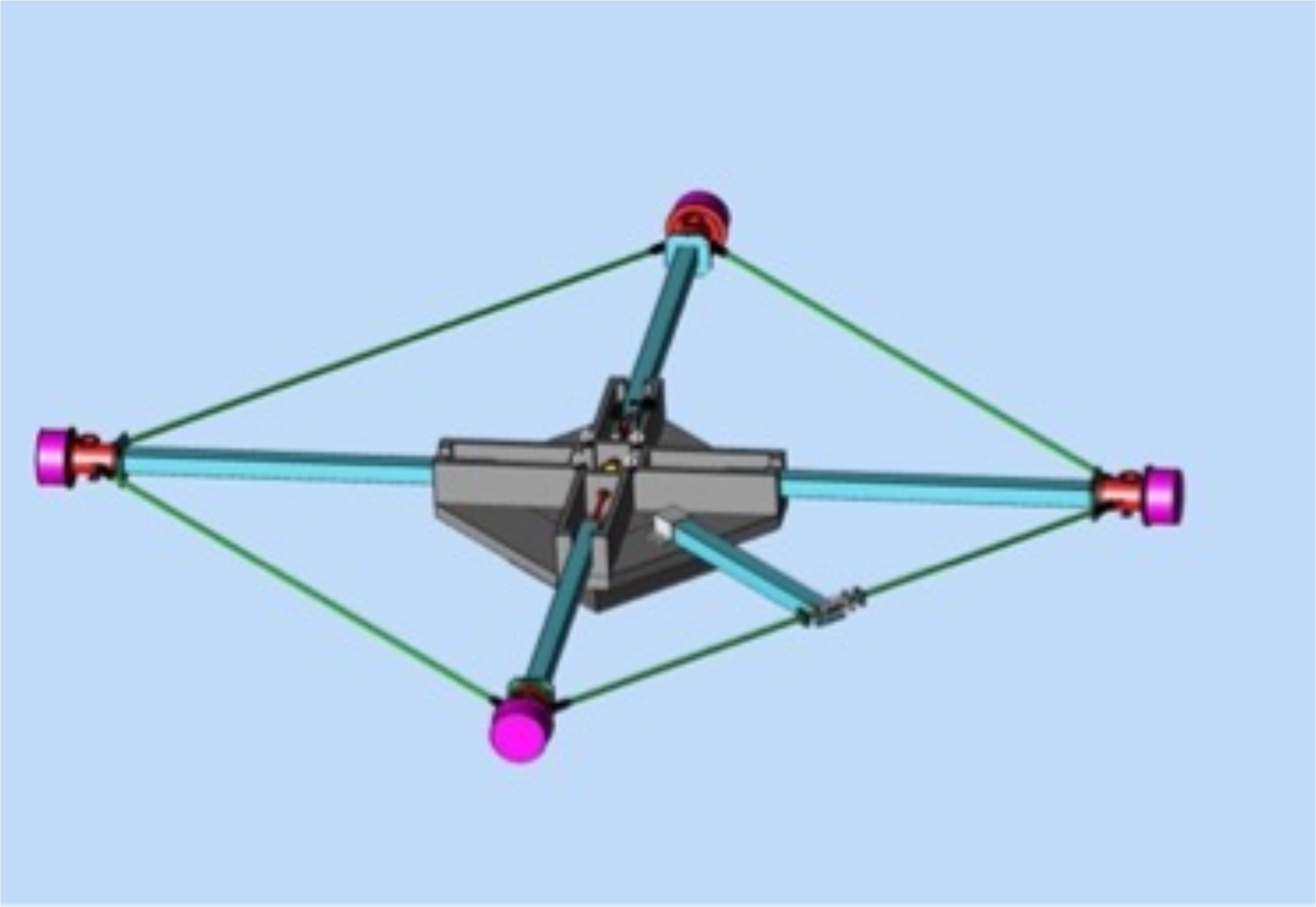
HL RLG our general rules

- Whole apparatus contained in a thermal bath
- Natural termal stability of the cave around fractions of degrees for long time basis. If necessary actively improve thermal stability
- Attached to the floor with a single rigid monument in granite. Granite is a reasonably homogeneous material which can be well machined.
- Isolate the mirrors from external disturbances and reduce couplings among cavity mirrors
- Components machined with high precision in order to have the center of the mirrors on the vertex of a regular square with fractions of mm accuracy.

RLG side 4m

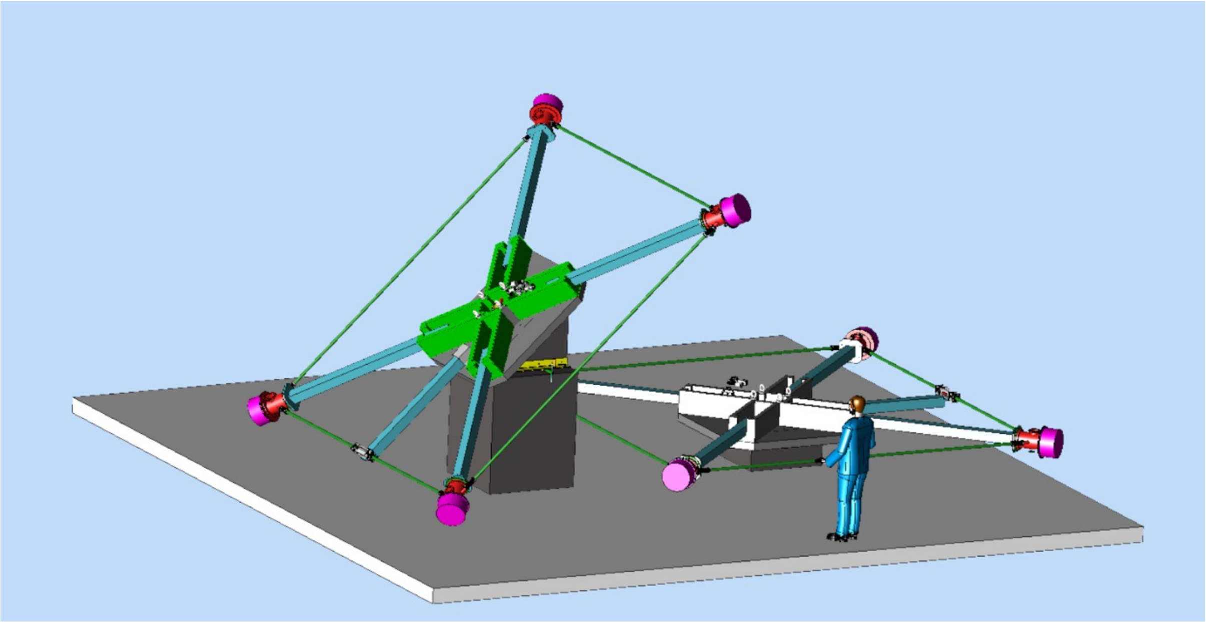
GP3 is the model of the HL RLG developed for GINGER. Mechanical parts in titanium to reduce weight in the perimetral part

The structure looks rather slim, but we have verified that it is rigid enough thanks to the SiC properties. Static arrows are at the level of tens of microns



GINGER: RLX & RLH

- **Installation at LNGS 4 m side**
- It would provid the orientation angle reconstruction and the test of the mechanics, to be compared with GINGERINO and GP2 data
- Lack of redundancy, very relevant for accuracy, important for fundamental physics



Key point: Earth Rotation rate subtraction

$$f = \frac{4\,A}{p\,\lambda}\Omega\cos\vartheta \;\rightarrow \frac{f - f_0}{f_0} < 10^{-9}\,(10^{-11})$$

- $\frac{4\,A}{p\,\lambda}$ $geometrical\ scale\ factor\ \rightarrow parameter$ **X0**
- *in* $\theta(t) = \theta_0 + \delta\theta(t)$*….error* $\delta\theta < 2\ 10^{-9}$ *rad (2* 10^{-12}*rad !)-> parameter* **θ0**

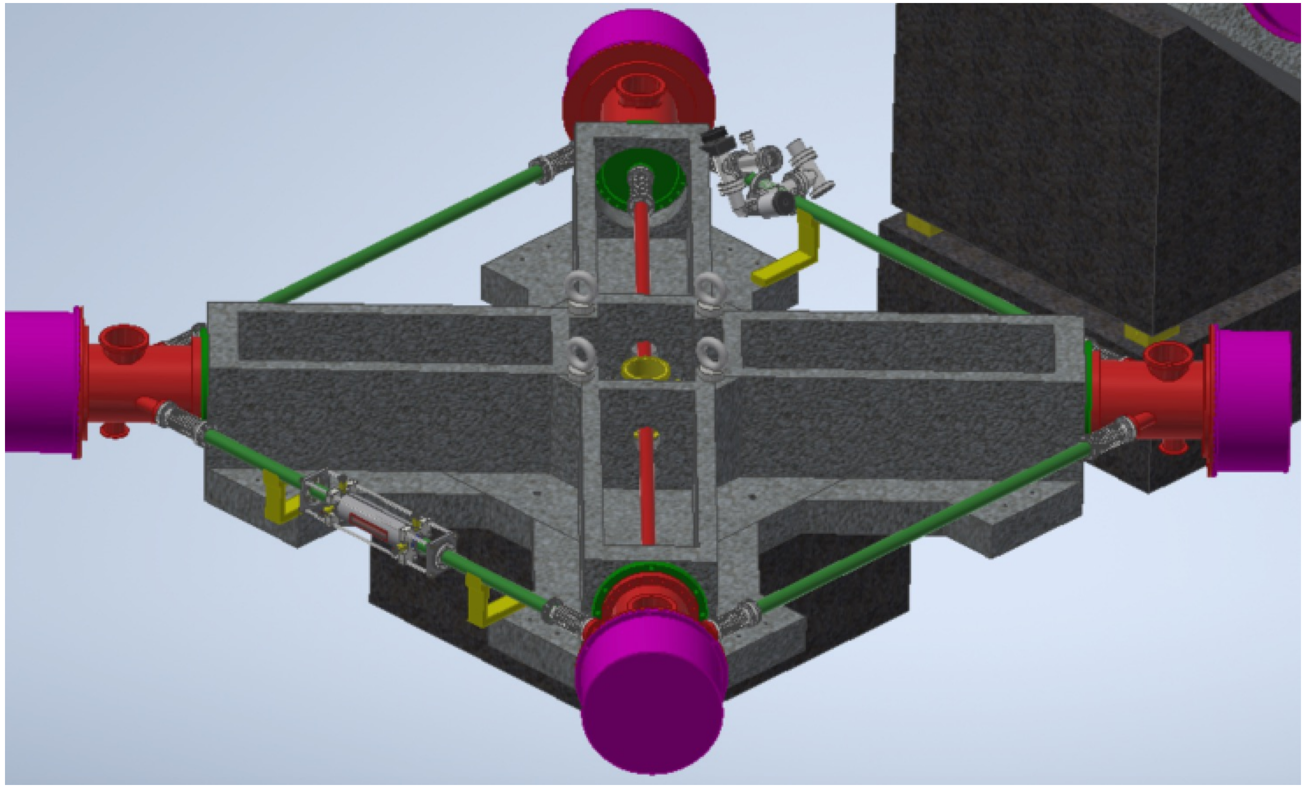
GINGER design is such that X0 and θ0 acts at second order

- **Di Virgilio, A.D.V., Belfi, J., Ni, WT. *et al.* GINGER: A feasibility study. *Eur. Phys. J. Plus* 132, 157 (2017). https://doi.org/10.1140/epjp/i2017-11452-6**

TRIO (Transportable Ring Laser Observatory, GP3 model)

TRIO is a 1.5 m side RLG wich uses the mechanical scheme of GINGER. It is under construction, expected to be completed in fall.

It will provide a suitable test of the GP3 mechanics for GINGER.



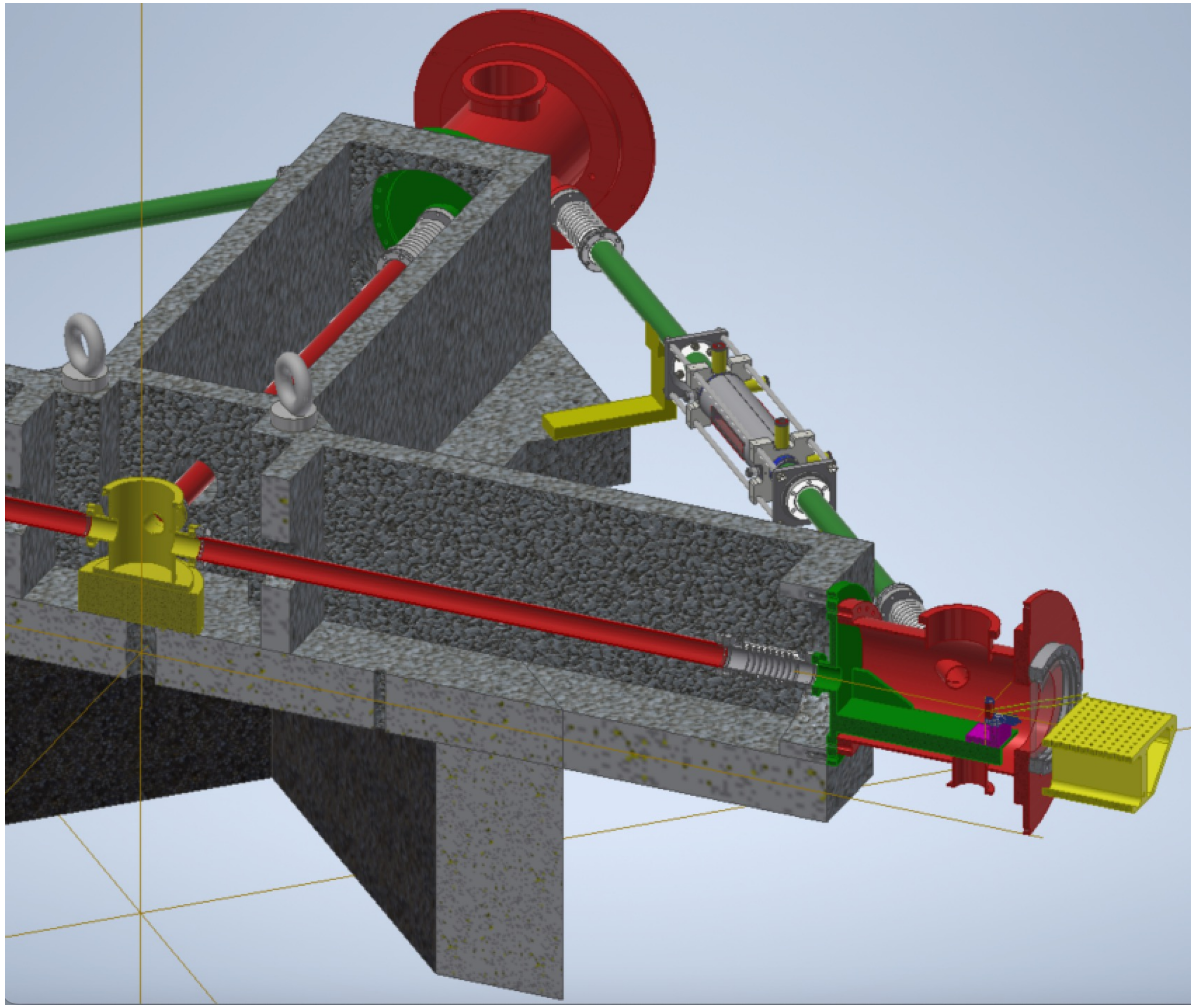
GP3

The same scheme will be used for GINGER, adding spacers in SiC in order to extenbd up to 4m the size of the square

commercially available components as:

High stability mirror holders equipped with actuators, UHV

Decouple the mirrors from the perimeter pipes using bellows as dumpers



TRIO -> test of GP3

TRIO will provide a suitable test of the GP3 concept.

TRIO will be tested in Pisa and we will compare the results with GP2 typical behaviour

Installation and commissioning

- Attach the monument to the floor, alignment of RLX at 100μrad level
- Install mechanical parts, high vacuum required to avoid gas contamination
- **Install mirrors and fill the tank with special gas mixture**
- **Align the cavity**
- **Start the laser**
- **Install read out for the beat note and for the monobeams**
- **Install photodiode to monitor the plasma**
- Take and store data
- Analyse the data

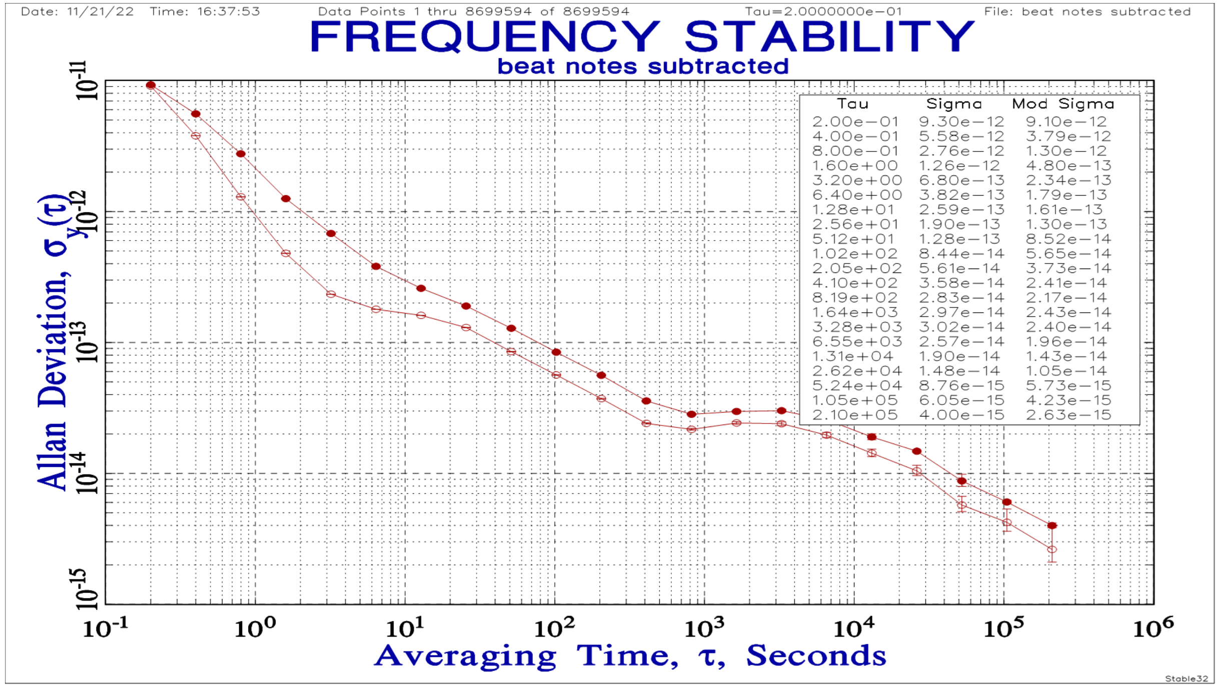
RED: optics experts activity

Spreading out competences during installation

- Care is required for mirrors handling, installation and cavity alignment
- Online tools to control the apparatus have been developed and tested with GP2 and GINGERINO

WE ARE LOOKING FOR YOUNG RESEARCHERS WILLING TO BECOME RLG EXPERTS

- This result confirms the validity of 1 part in 10^{11} of the Earth rotation rate
- It is important to remark that the 1 part in 10^{9} of the Earth rotation would be in any case new and important for fundamental science



conclusions

- The GINGER Project has started at the beginning of 2023, in collaboration with INGV
- Shortly we will discuss with LNGS the location and the installation details
- Details of the drawings will be reviewed
- Main orders will be placed asap
- The plan is to built it in 2024 and start taking data in 2025