# GINGER

*AND GINGERINO*

*Angela Di Virgilio, INFN-Pisa*

## *Gyroscopes IN GEneral Relativity*

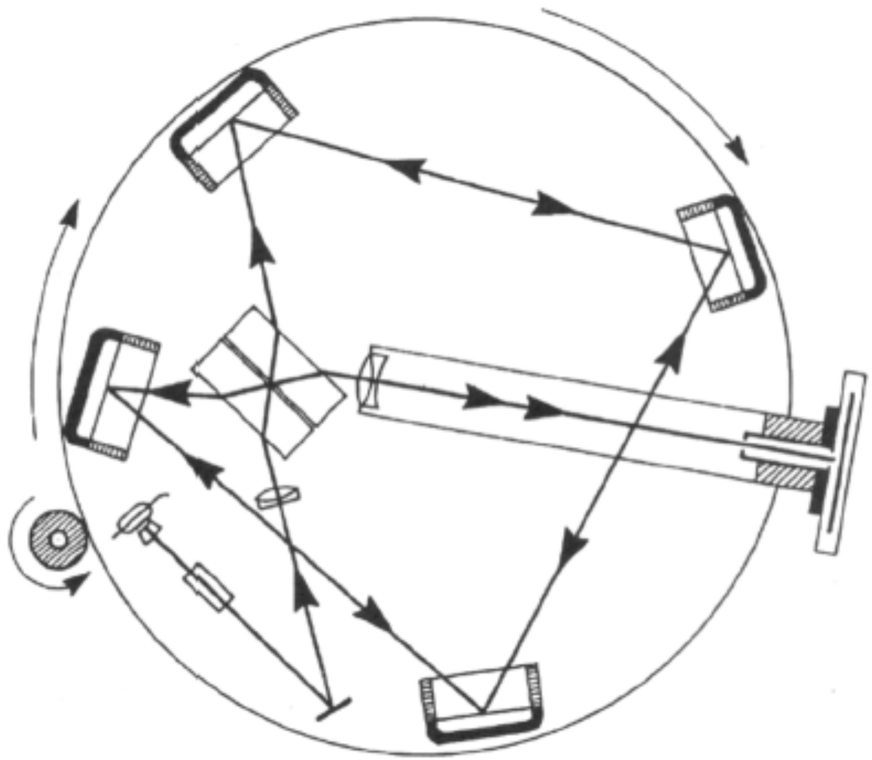
*Lense Thirring effect, on Earth, 1% precision*

*Ring laser measures absolute angular velocity (Sagnac Effect)*

# LAY OUT OF THE TALK

- *A bit of history*
- *The present situation*
- *GINGER: the main problems and the proposed solution*
- *GINGERINO*

# Sagnac Interferometer (1913)



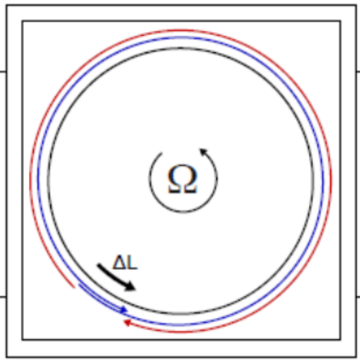
Rotation Rate: 2 rev. per sec.

observed Fringe Shift:

$$\delta\phi = \frac{8\pi A}{\lambda c}\boldsymbol{n}\cdot\boldsymbol{\omega}$$

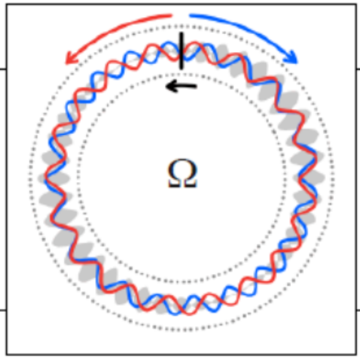
with A = 0.086 m$^2$ this turns out to be 0.07±0.01 fringes

Georges Sagnac was the first to correctly combine theory with experiment. We also acknowledge the experimental skill to build a sufficiently stable apparatus.




**Sagnac effect**

$$\Delta t_{Sagnac} = \frac{4A}{c^2}\vec{\Omega}\circ\vec{n}$$




**Resonant cavity**

$$\Delta f_{Sagnac} = \frac{4A}{P\lambda}\vec{\Omega}\circ\vec{n}$$

## Advantages

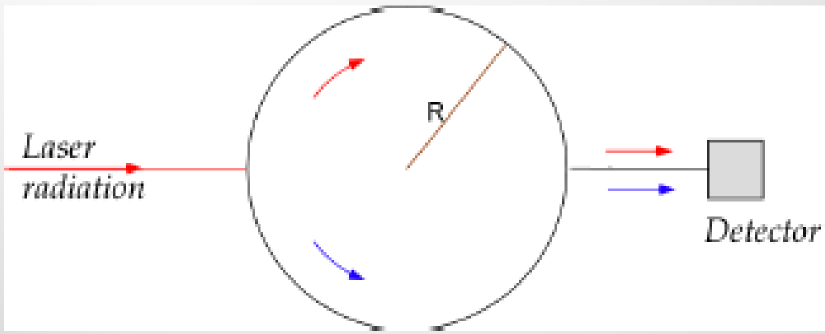
- No moving masses
- No signal for a linearly accelerating reference-frame
- L > 1 m → Earth rotation is the bias

## Quantum limit

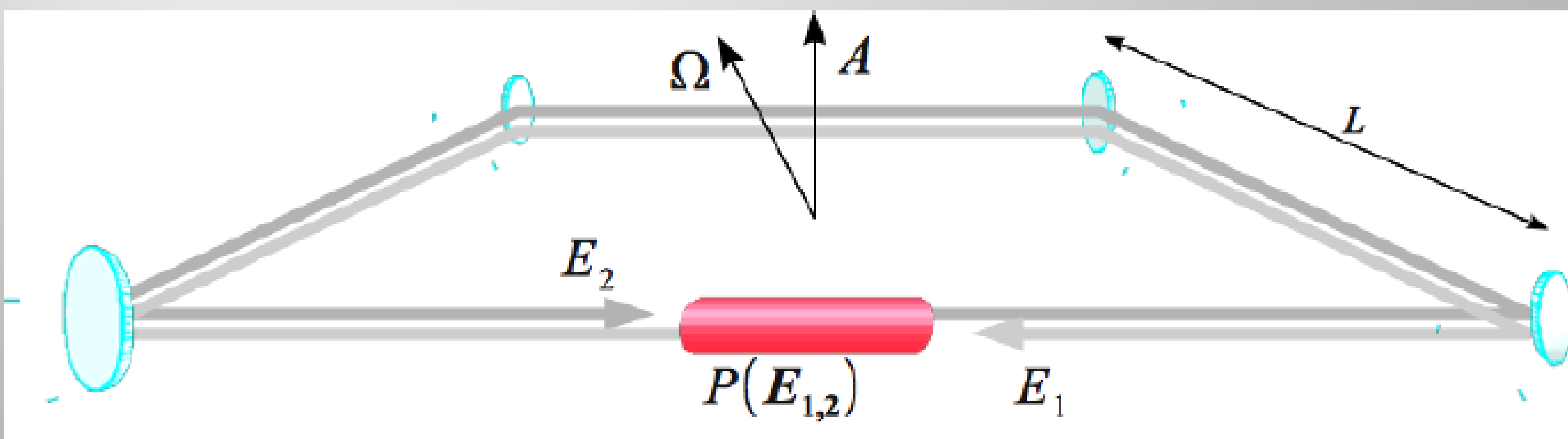
$$\delta\Omega_{shot} = \frac{cP}{4AQ}\left(\frac{h\nu T}{2P_{out}t}\right)^{1/2}$$

- Low cavity losses
- High power
- Large size

# The Sagnac Effect and the ring-laser




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



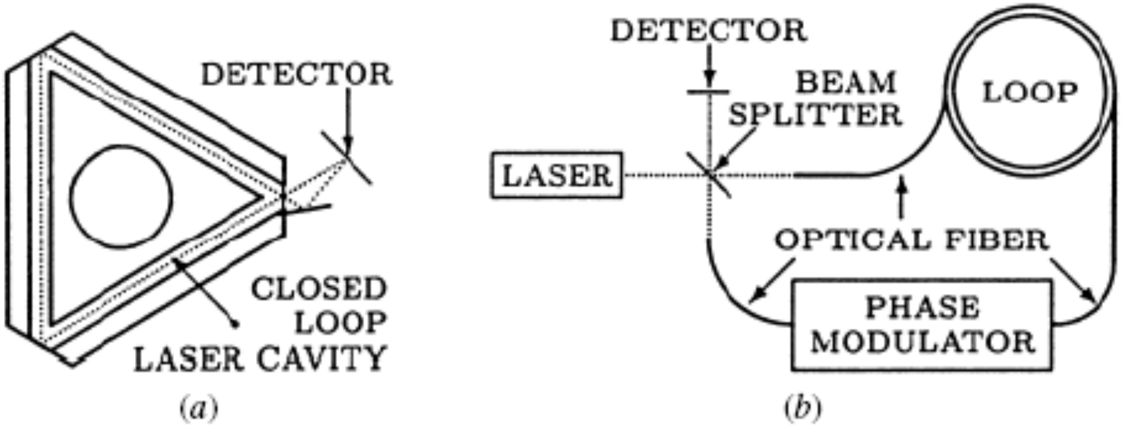



**Fig. 9.10** Laser gyroscopes: (*a*) ring laser gyro (RLG); (*b*) fiberoptic gyro.

**Industry is active in developing RL since more than 50 years, especially for navigation, submarines and drones**

https://www.youtube.com/watch?v=-HzmxW3Jll8

- *Large frame ring lasers are top sensitivity devices to measure absolute angular velocity*
- *Routinely they measure tens of pico-rad/s, present record $10^{-13}$ rad/s in 1 day*

- *Very low frequency measurements are of primary importance for geophysics and geodesy, for this reason 2 installations have been realized in Germany (G and ROMY)*

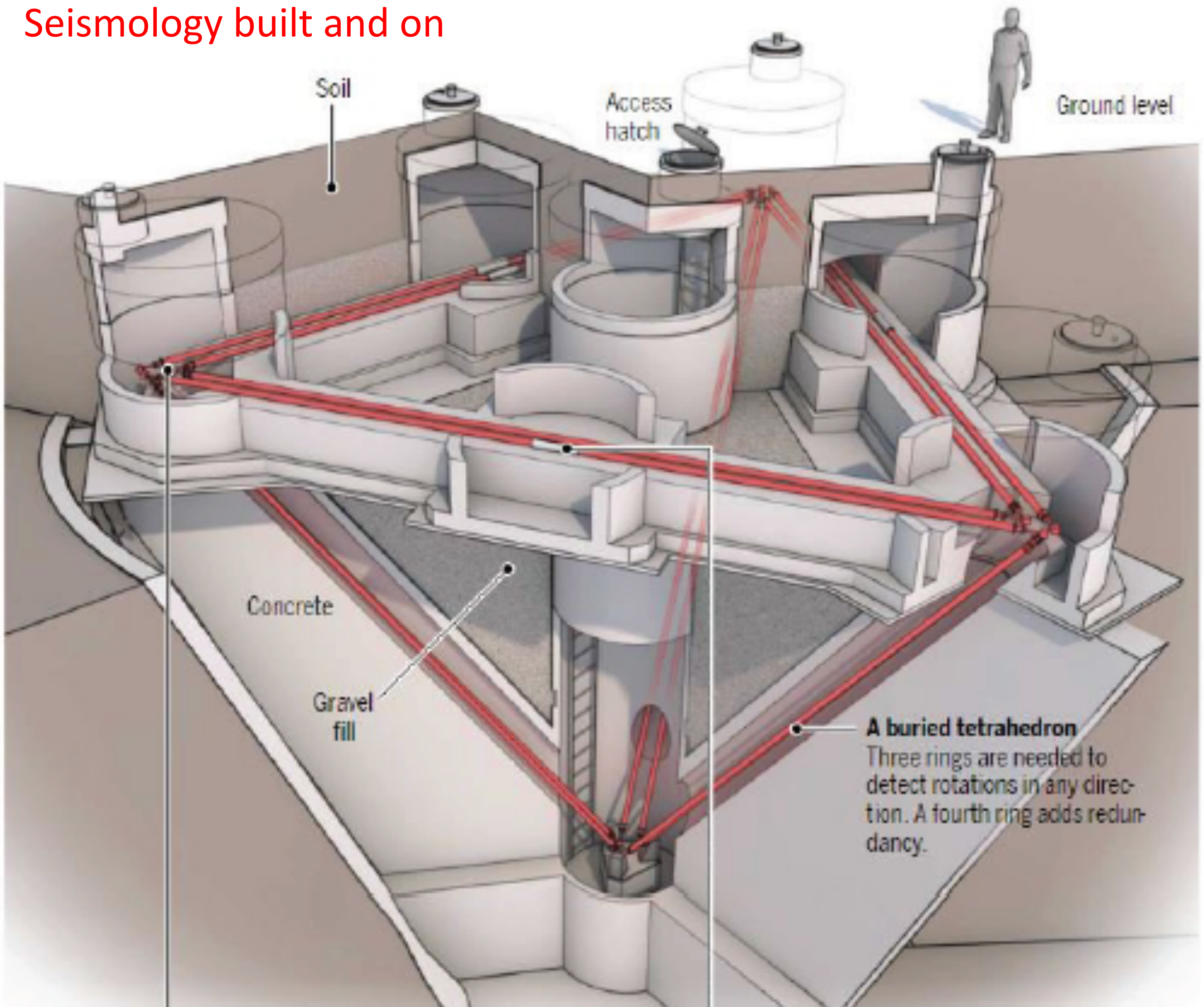
# G - Ring the currently best performing gyro

- Perimeter: 16 m
- Area: 16 $m^2$
- FSR 18.75 MHz
- $\Delta \nu_L \approx 274\ \mu Hz$
- 5 ppm total loss
- $Q = \omega \tau \approx 5x10^{12}$
- 6.5 mB gas pressure in order to avoid multi-moding

## Ring of truth

Buried near Munich, Germany, is Rotational Motions in Seismology (ROMY), a giant ring laser. It will sense the rotation of Earth and tiny wobbles of its spin axis—helping calibrate GPS satellites. It also will detect twisting motions from earthquakes, which researchers have typically ignored.

Seismology built and on



## GINGER → FUNDAMENTAL PHYSICS

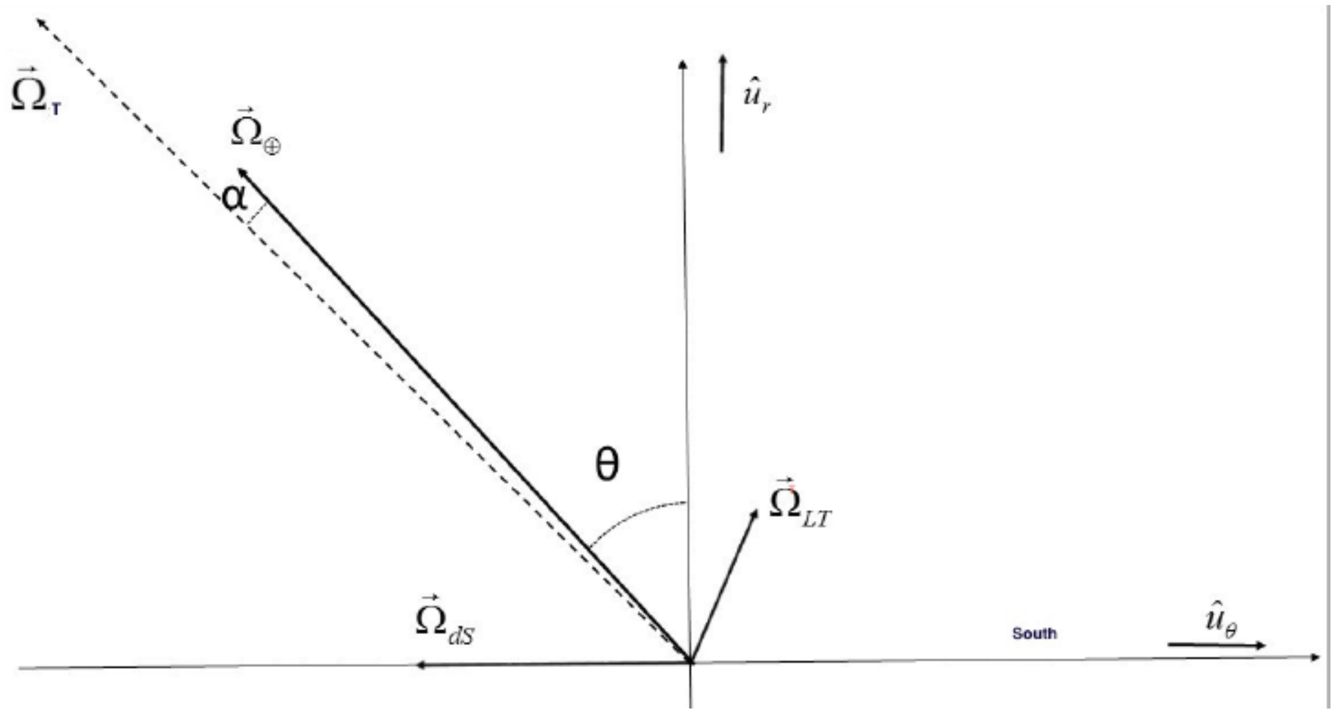
*GINGERINO: SOME DATA WILL BE SHOWN AT THE END OF THIS TALK*

*LET US DISCUSS NOW THE TEST OF GR, THE LENSE-THIRRING EFFECT AT 1%*

# THE GR TERMS

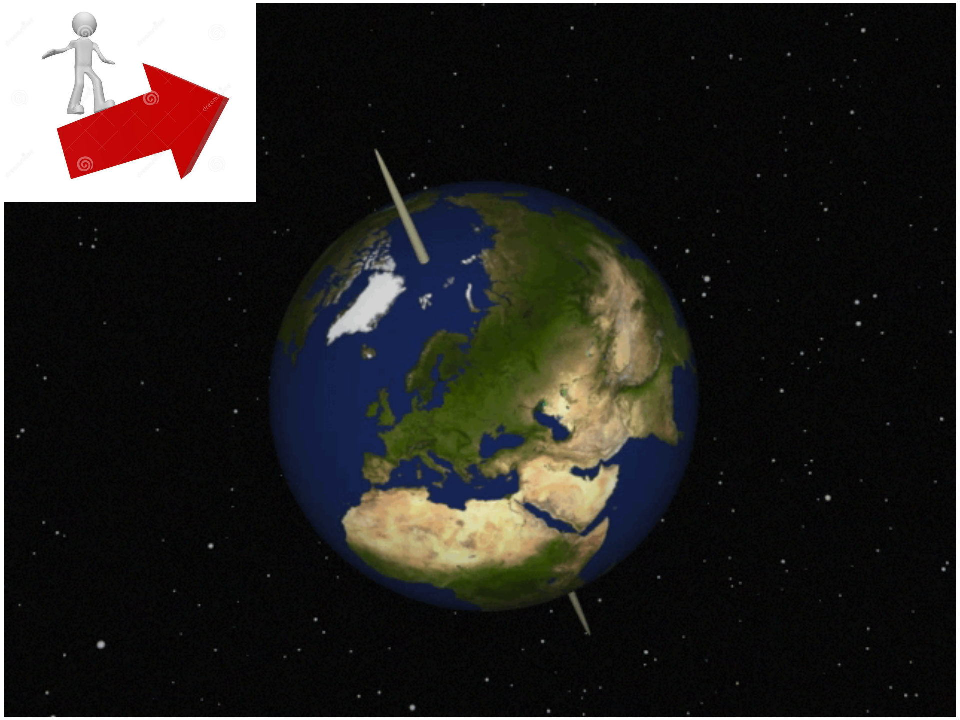
$$f = \frac{4A}{\lambda P}\left[\Omega_{\oplus} - 2\frac{m}{r}\Omega_{\oplus}\sin\theta\hat{u}_{\theta} + G\frac{I\Omega_{\oplus}}{c^2 r^3}\left(2\cos\theta\hat{u}_r + \sin\theta\hat{u}_{\theta}\right)\right]\cdot\hat{u}_n = S\left(\Omega_{\oplus} + \Omega_{dS} + \Omega_{LT}\right)\cdot\hat{u}_n.$$

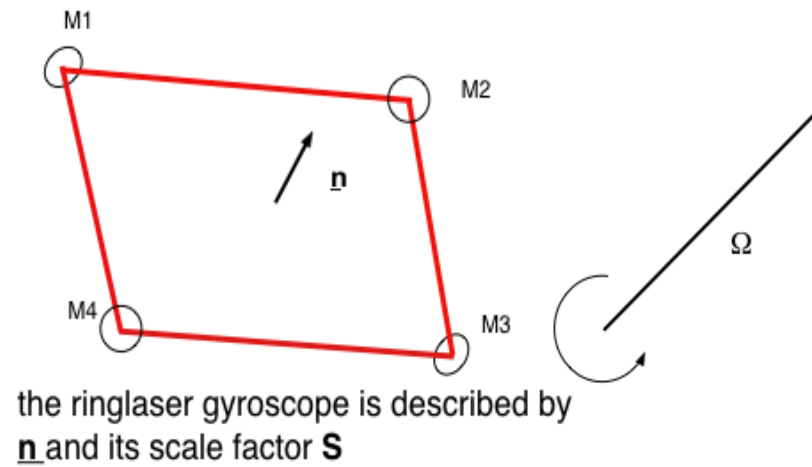
A. Tartaglia, A. Di Virgilio et al. Eur. Phys. J. Plus (2017) 132: 73




The deSitter and LenseThirring terms are equivalent to an extra rotation 9-12 orders of magnitude below the Earth rotation rate

The probe is a vector which can be oriented at will
The quantity to measure is the angular rotation vector
The output is the scalar product between the two vectors





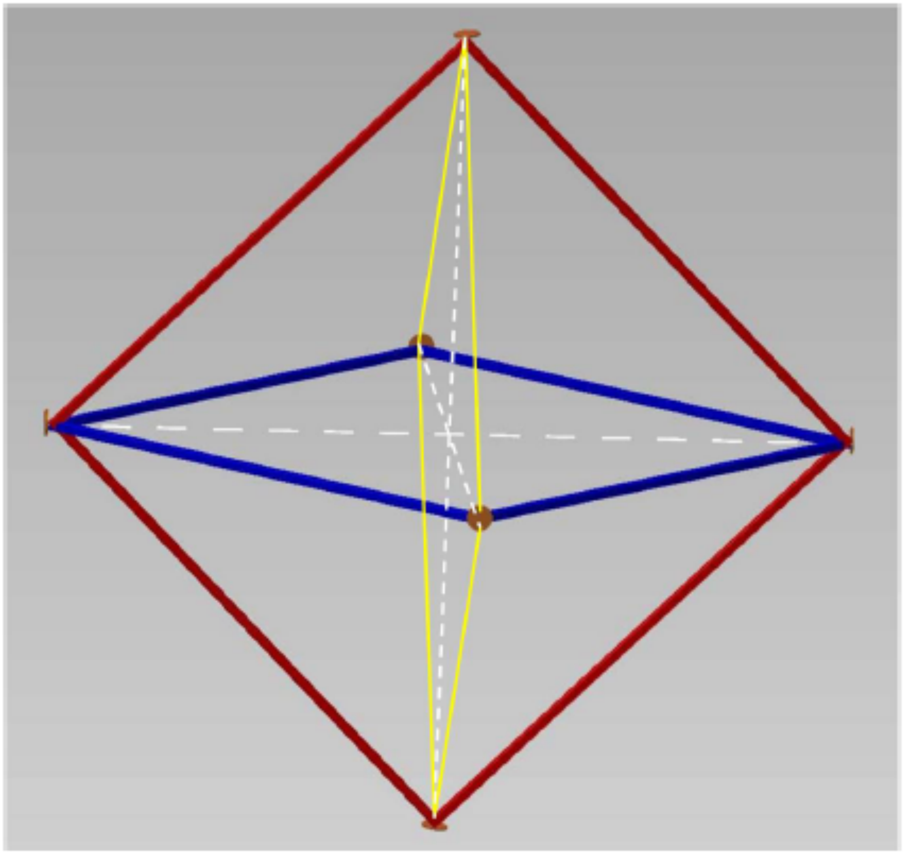

S geometrical scale factor

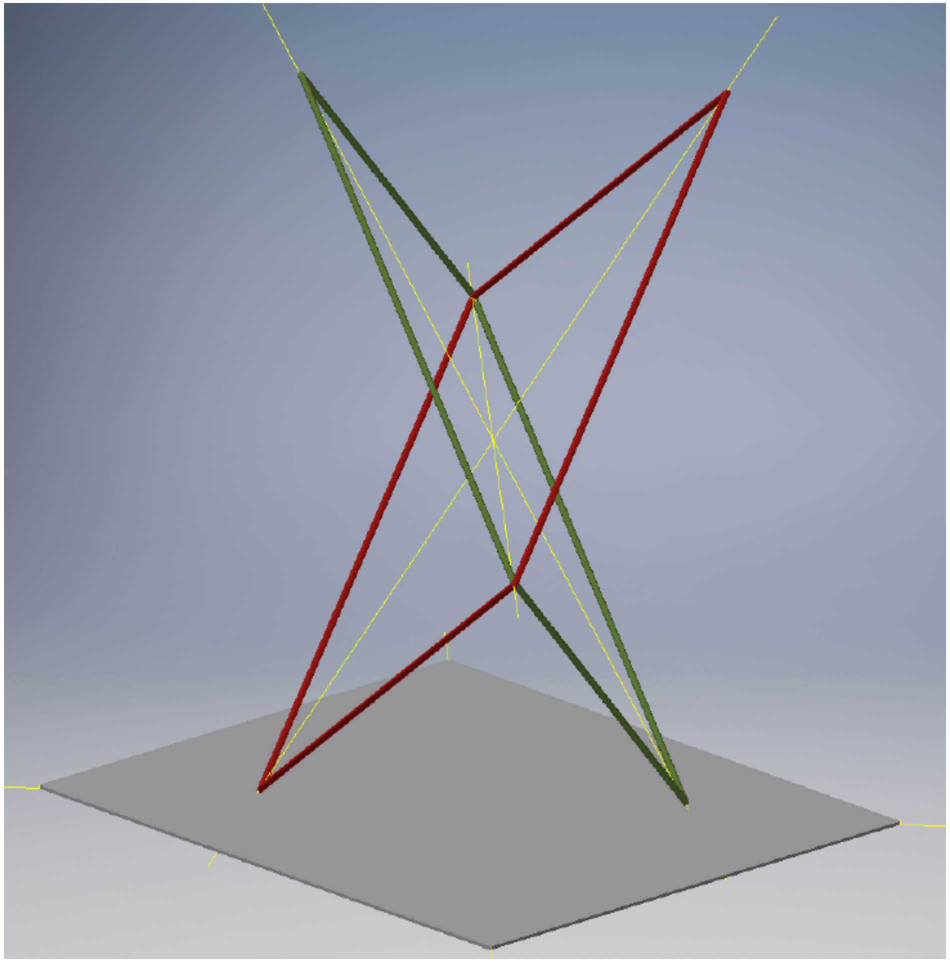
**n** area versor

Beat frequency Scalar product $\mathbf{n} \cdot \boldsymbol{\Omega}$

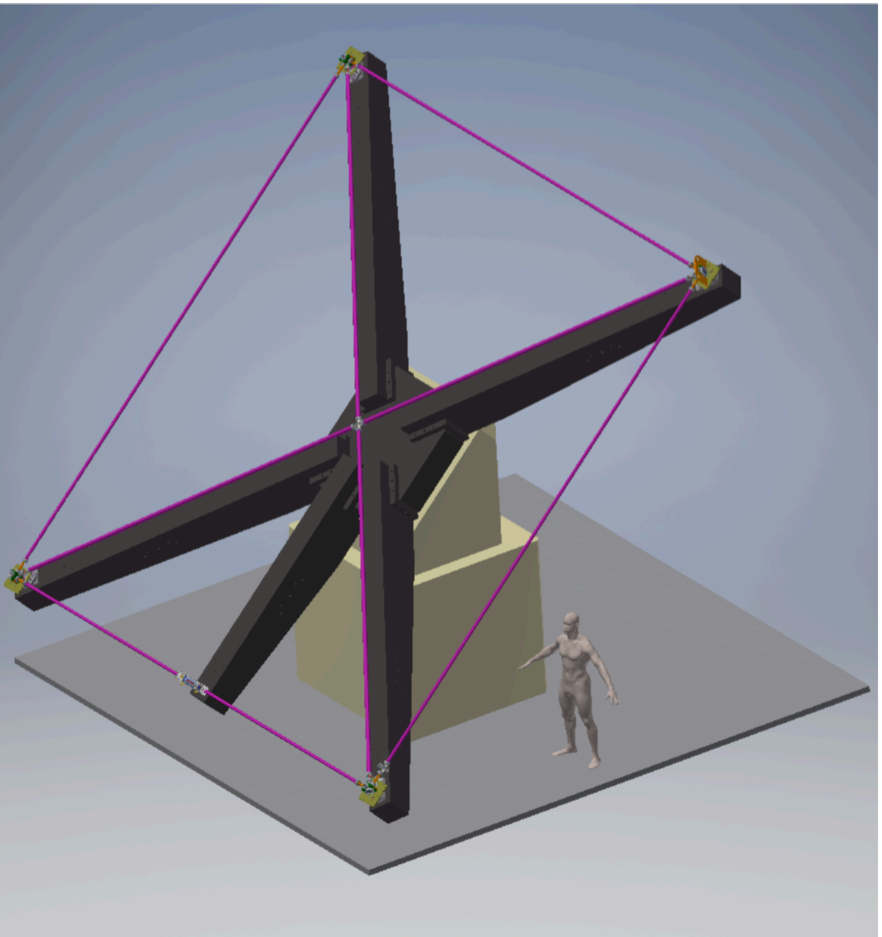
*The measurement of the Lense-Thirring effect implies to measure the modulus of the Earth rotation rate with an accuracy 1 part in $10^{12}$ and subtract the measurement done by IERS, which contains the only kinetic term*

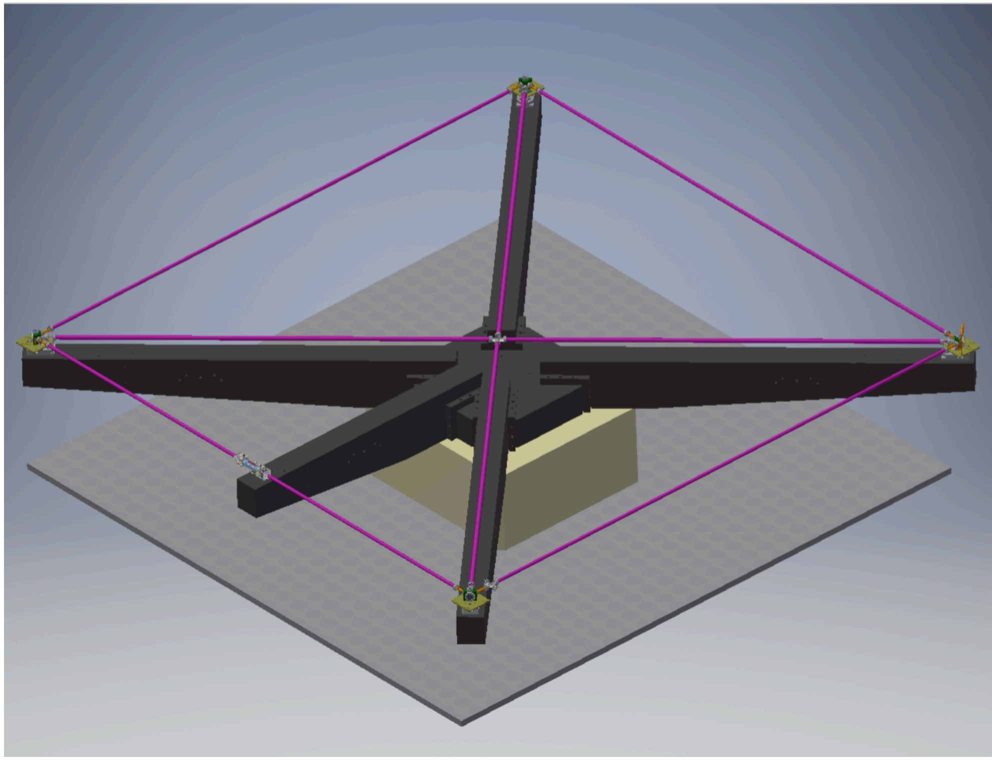
1) *One RL at maximum signal, with an angle with the Earth rotation rate small enough*
2) *An array of RL, but the angles between relative angles must be monitored with prad accuracy*





2D apparatus, 3D adding one more ring





Simplified apparatus, A. Di Virgilio et al: GINGER: a feasibility study

Eur. Phys. J. Plus (2017) **132**: 157
DOI 10.1140/epjp/i2017-11452-6

RELATIVITY

# Proving Einstein right using **the most sensitive Earth rotation sensors ever made**

**A new study use the most precise inertial sensor available to date to measure whether Earth partially drags inertial frames along with its rotation**

▲ Physicists have now found a way to measure Earth's rotation in an extremely accurate way (©Fotolia).

Einstein's theory of gravity, also referred to as General Relativity, predicts that a rotating body such as the Earth partially drags inertial frames along with its rotation. In a study recently published, a group of scientists based in Italy suggests a novel approach to measuring what is referred to as frame dragging

▮ **A. D. V. Di Virgilio, J. Belfi, W.-T. Ni, N. Beverini, G. Carelli, E. Maccioni** and **A. Porzio**, 'GINGER: a feasibility study', *Eur. Phys. J. Plus* **132**, 157 (2017)

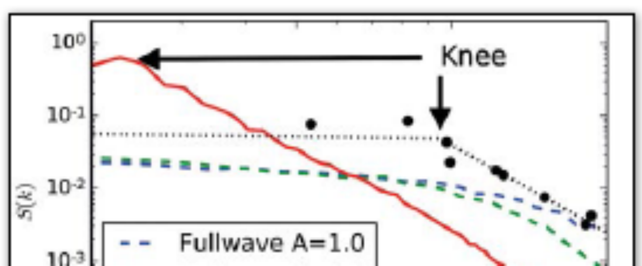
PLASMA PHYSICS

# **X mode Doppler Reflectometry k-spectral** measurements in ASDEX Upgrade: experiments and simulations

Doppler reflectometry is a microwave backscattering diagnostic for measuring flows and density fluctuation spectra in fusion plasmas. One longstanding problem is the discrepancy between the Doppler spectrum and the density fluctuation spectrum from turbulence simulations: The red "GENE" curve has its knee at a different wavenumber compared to the experimental Doppler measurements. The knee position is intrinsic to the turbulent drive mechanism and should be the same in both.

We coupled the sophisticated plasma turbulence code GENE to the fullwave code IPF-FD3D to model the scattering and the power response of the reflectometer in the presence of realistic turbulence. Dashed lines in the figure are the result

▼ Power spectra over perpendicular wavenumber. "GENE" shows density fluctuations, the others are scattered microwave power (a.u.).



- *The combination of 1 RL at maximum signal, 1 horizontal and the other with a different angle outside the meridian plane has several interesting features and it does not require the high sensitivity measurement of the relative angle between the two RL*
- *The RL at maximum measures the modulus*
- *The combination of the two RL provides a very sensitive measurement of the angle between the horizontal RL and the Earth rotation axis (this makes feasible the study of polody)*

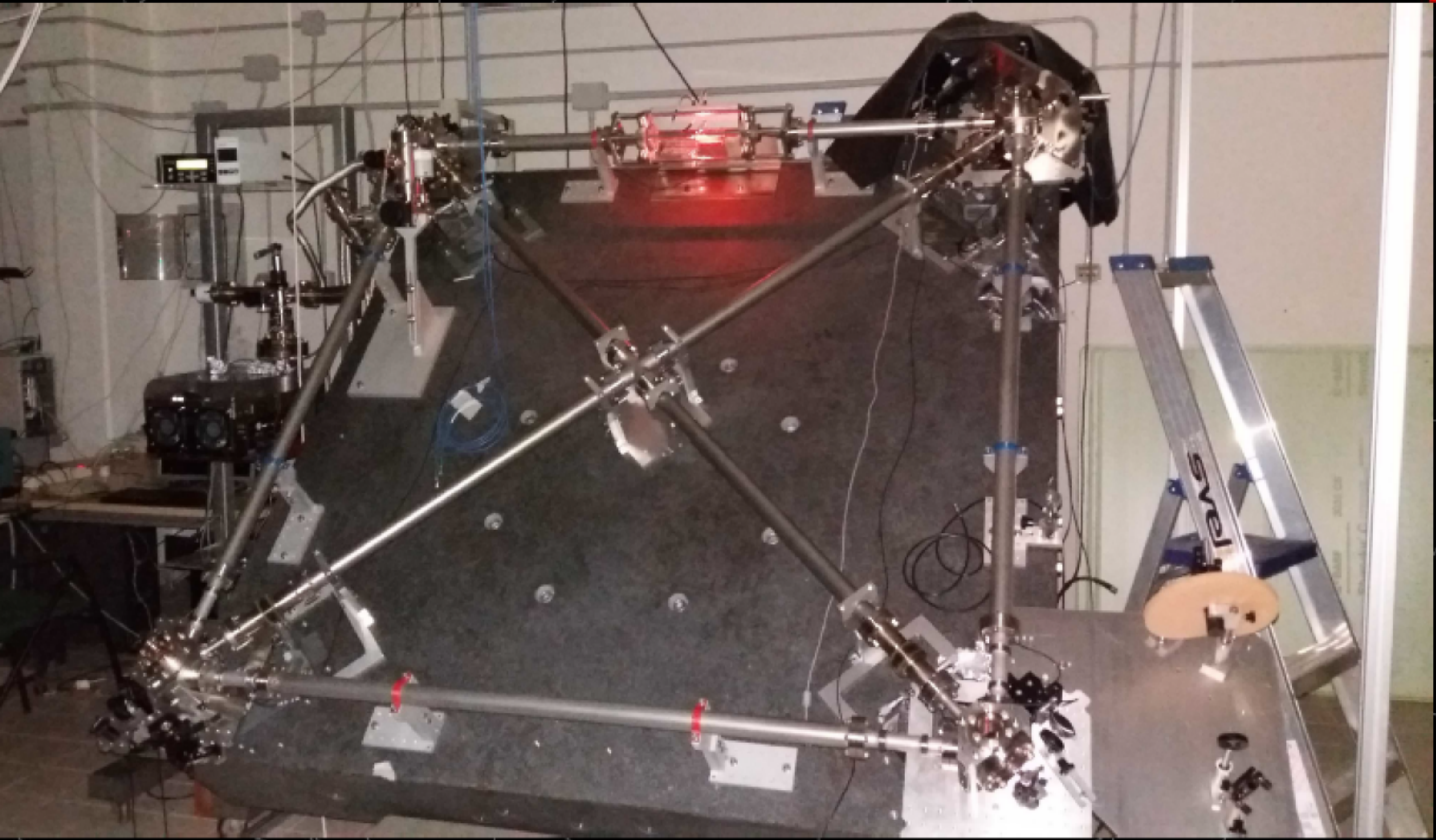
# EXPERIMENTS ON GOING IN ITALY

- *Scale factor control, control of the geometry GP2*
- *Observation of the perturbations affecting the underground laboratory of LNGS*

# G IS MONOLITHIC, OUR PROTOTYPES ARE HETERO-LITHIC

- *Long term stability and control of the geometry of the ring is the key point*
- *We have found a suitable control strategy, which is under test with the prototype GP2 in Pisa*

GINGER



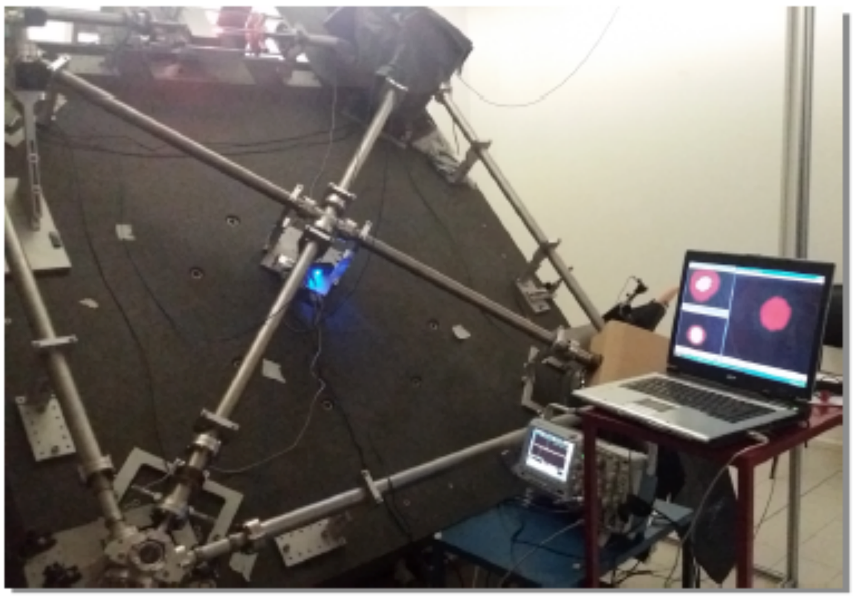

GP2

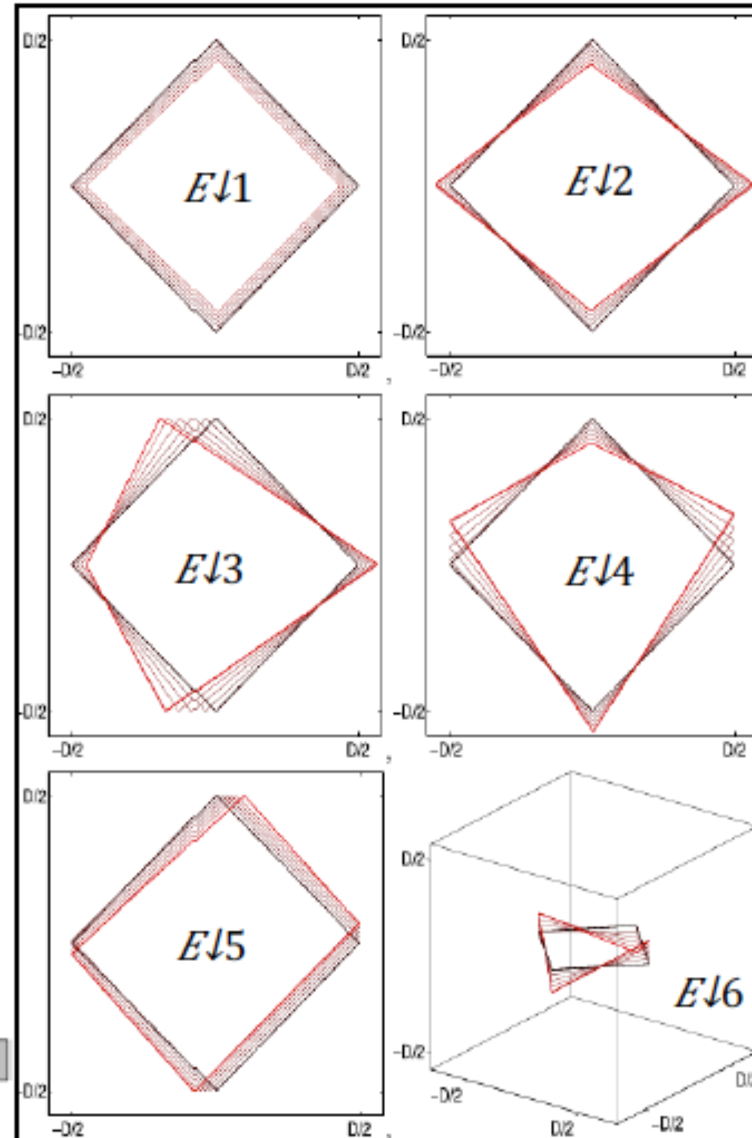
INFN-Pisa

# Multi-resonator stabilization

## Control IDEA

- Lock **opposite mirrors distances** (diagonal Fabry-Pérot ITFs) [(*E1,E5), E2*]
- Optimize the **residual 4 quadratic d.o.f.**
- [*E3(-), E4(-), E5(+), E6(+)*] the looking at
- the **perimeter length**

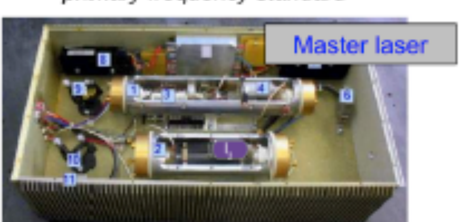





*Deformation quasi-normal modes*

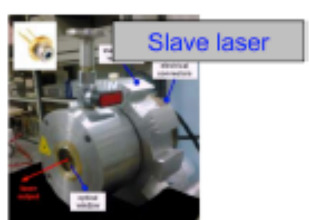
***Reference laser***

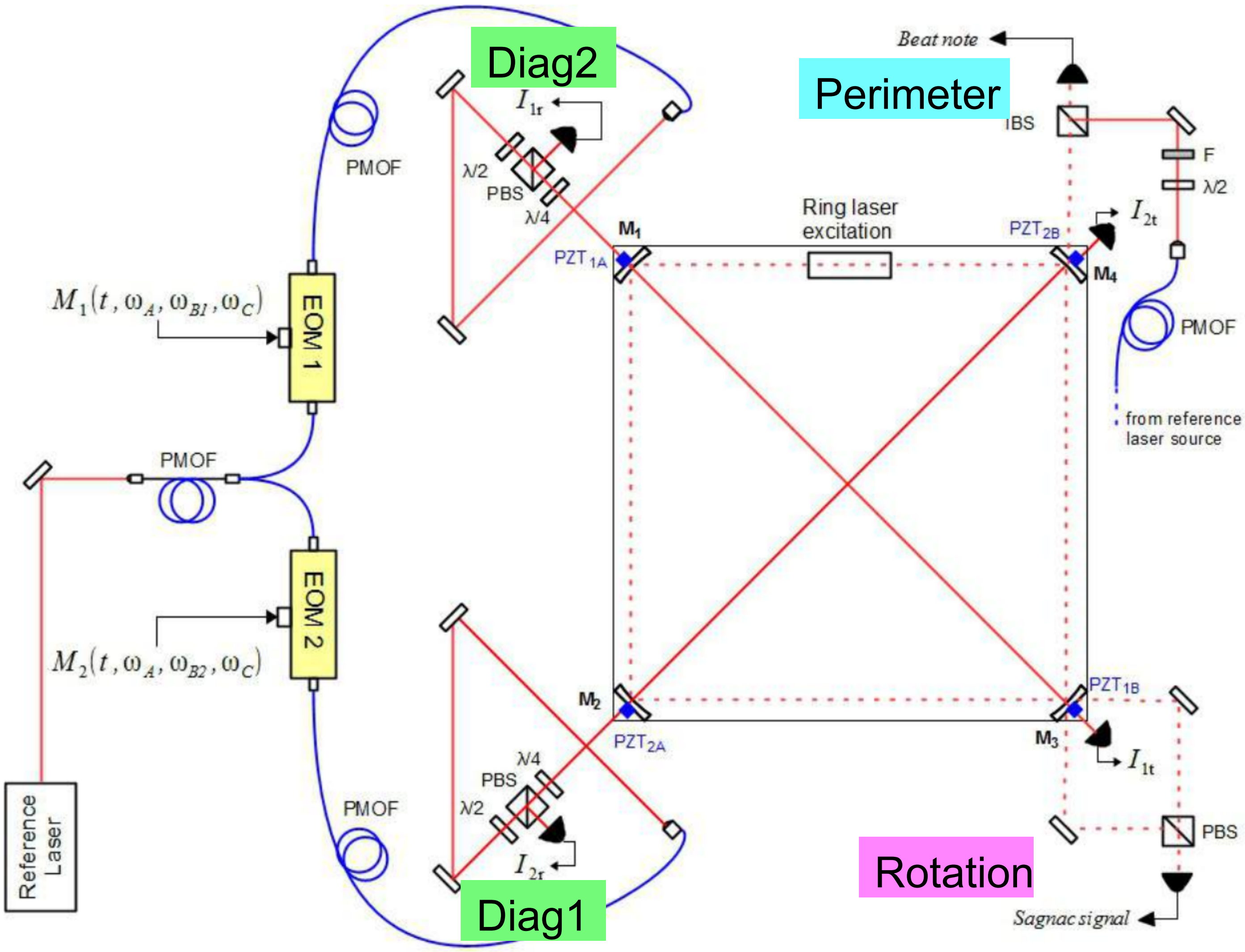
He-Ne/I₂ laser
primary frequency standard



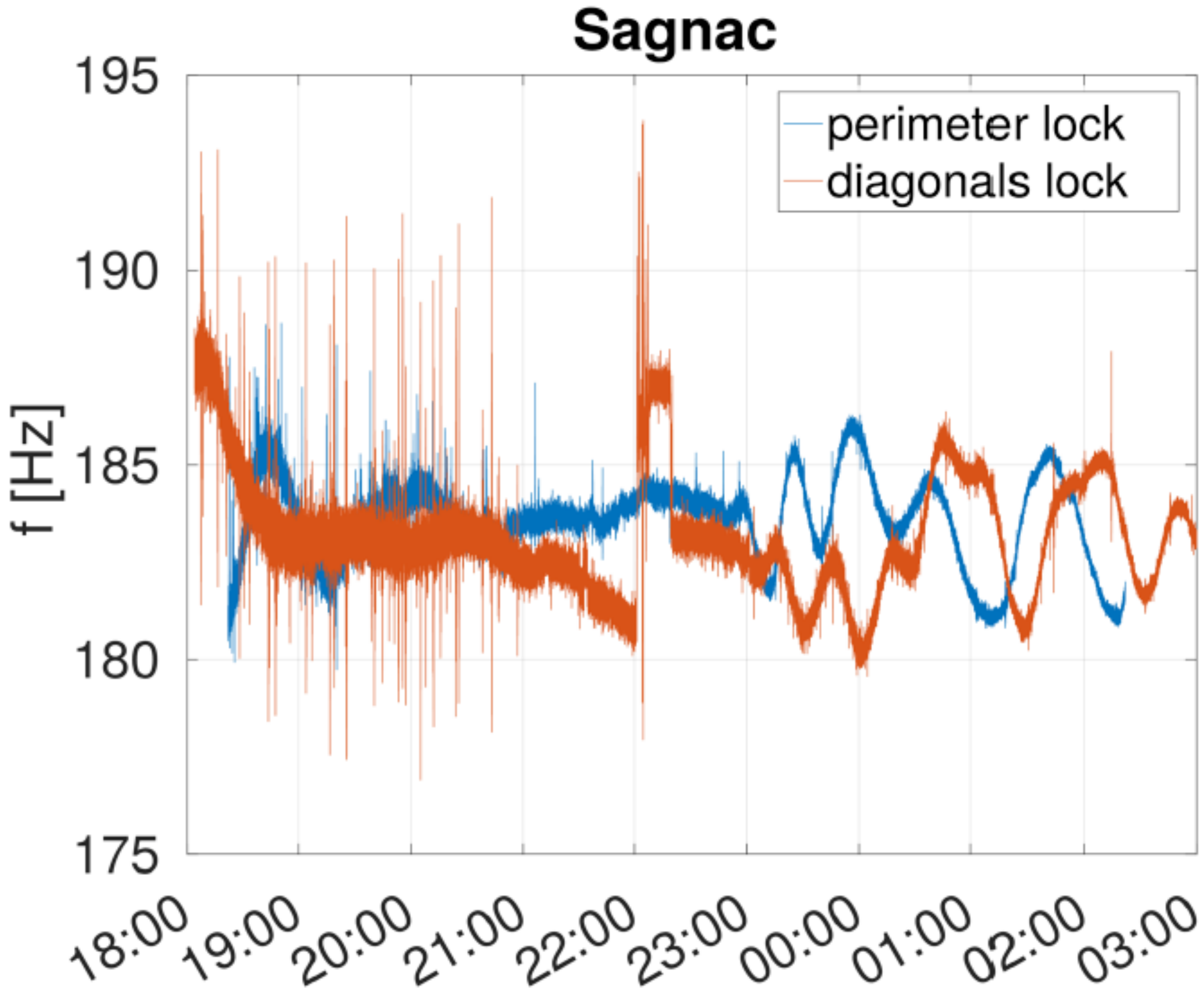

iodine spectral purity

μ-lens coupled cw diode laser
probe laser




Diag2
Beat note
Perimeter
IBS
F
λ/2
PMOF
λ/2
PBS
λ/4
Ring laser
excitation
M1
PZT 1A
PZT 2B
M4
PMOF
from reference
laser source
EOM 1
PMOF
EOM 2
M2
PZT 2A
PZT 1B
M3
λ/4
PBS
λ/2
PMOF
PBS
Reference
Laser
Rotation
Sagnac signal
Diag1

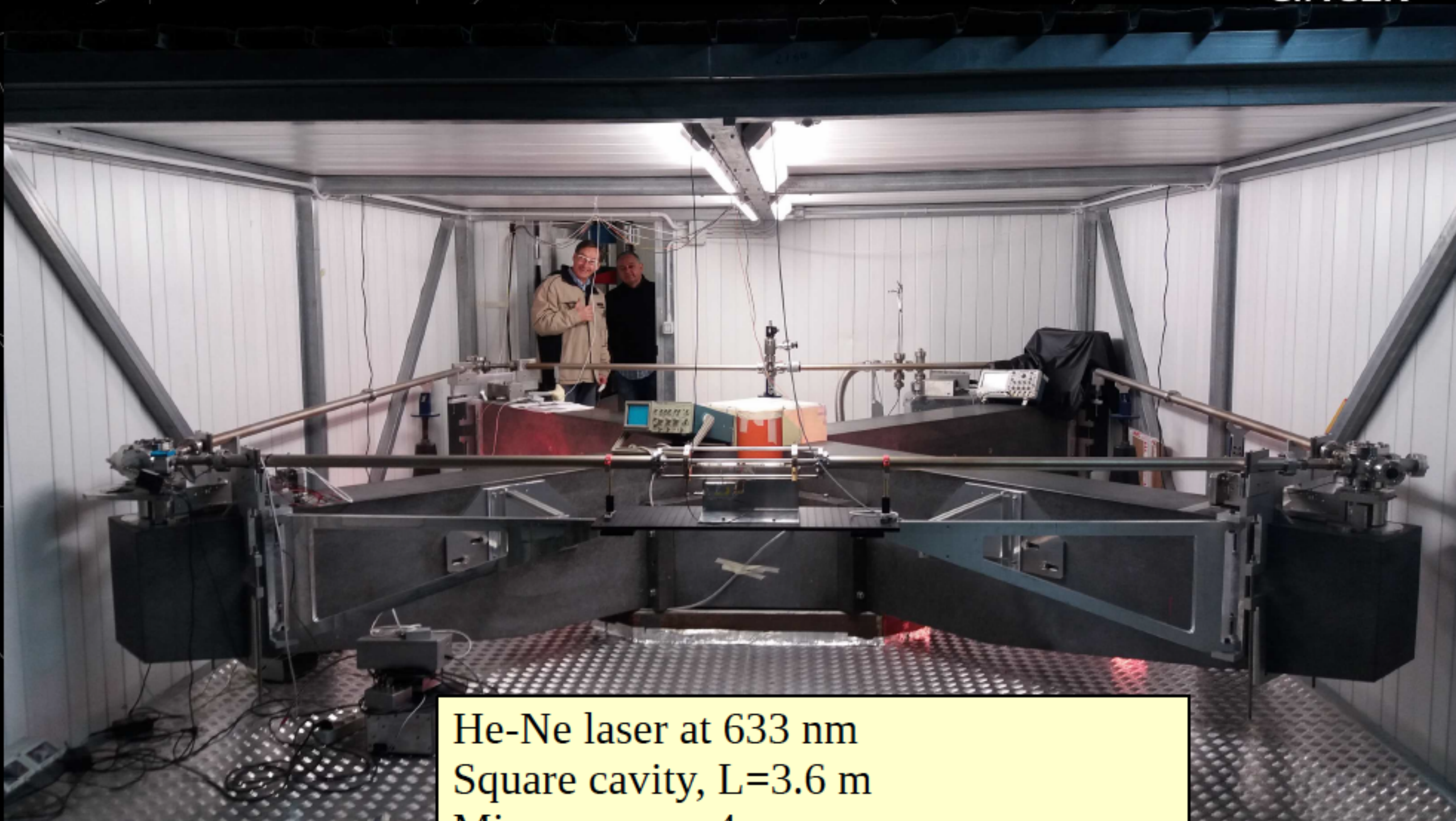
# Coparison Sagnac signals with different lock



# GINGERINO

# 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**

- *GINGERINO has already proved that underground laboratories provides very high thermal stability and quiet environment*

- *It is now working in a continuous basis to provide data to geophysics*

TYPICAL SENSITIVITY

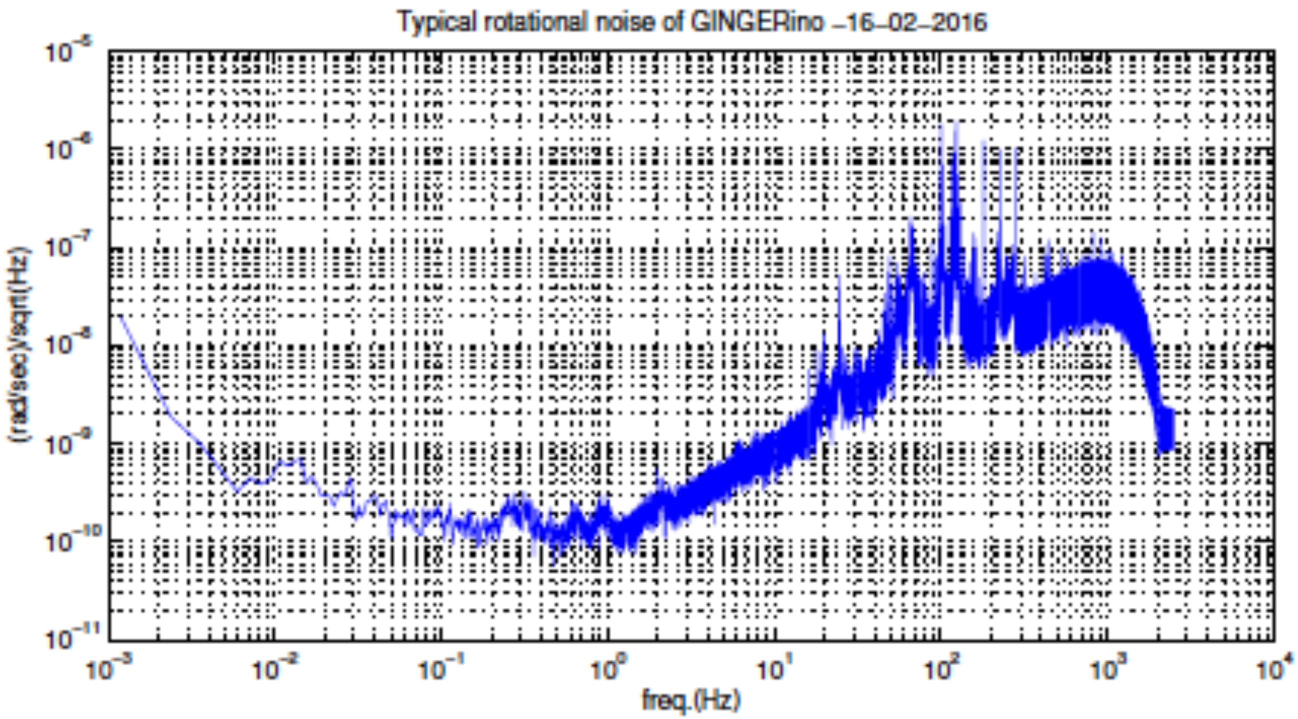
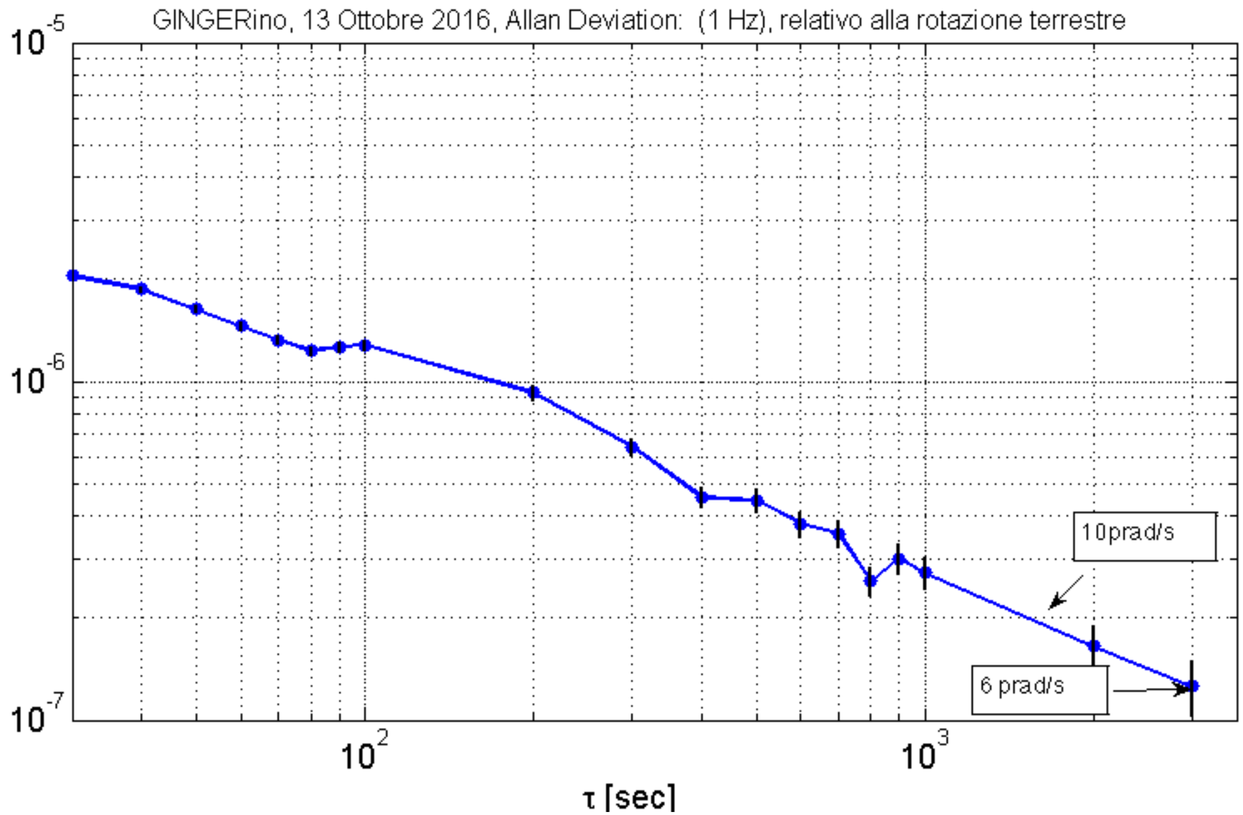


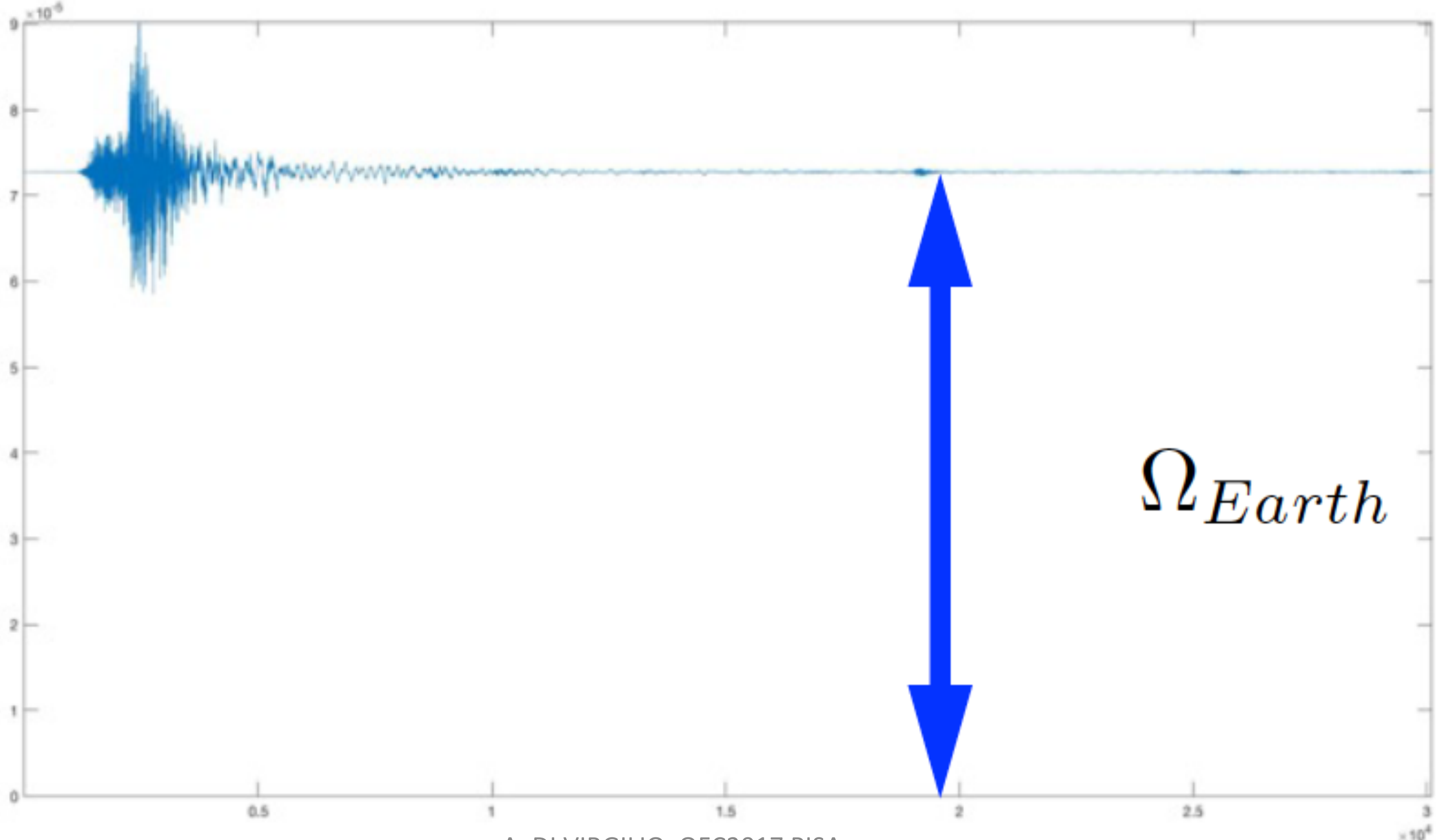

**Figure 3.** Angular velocity linear spectral density of GINGERino during the February 2016 run. Power spectral density is estimated from the raw data interferogram.

# BEST ALLAN, WITH PARTICULAR CARE IN SELECTING THE DATA

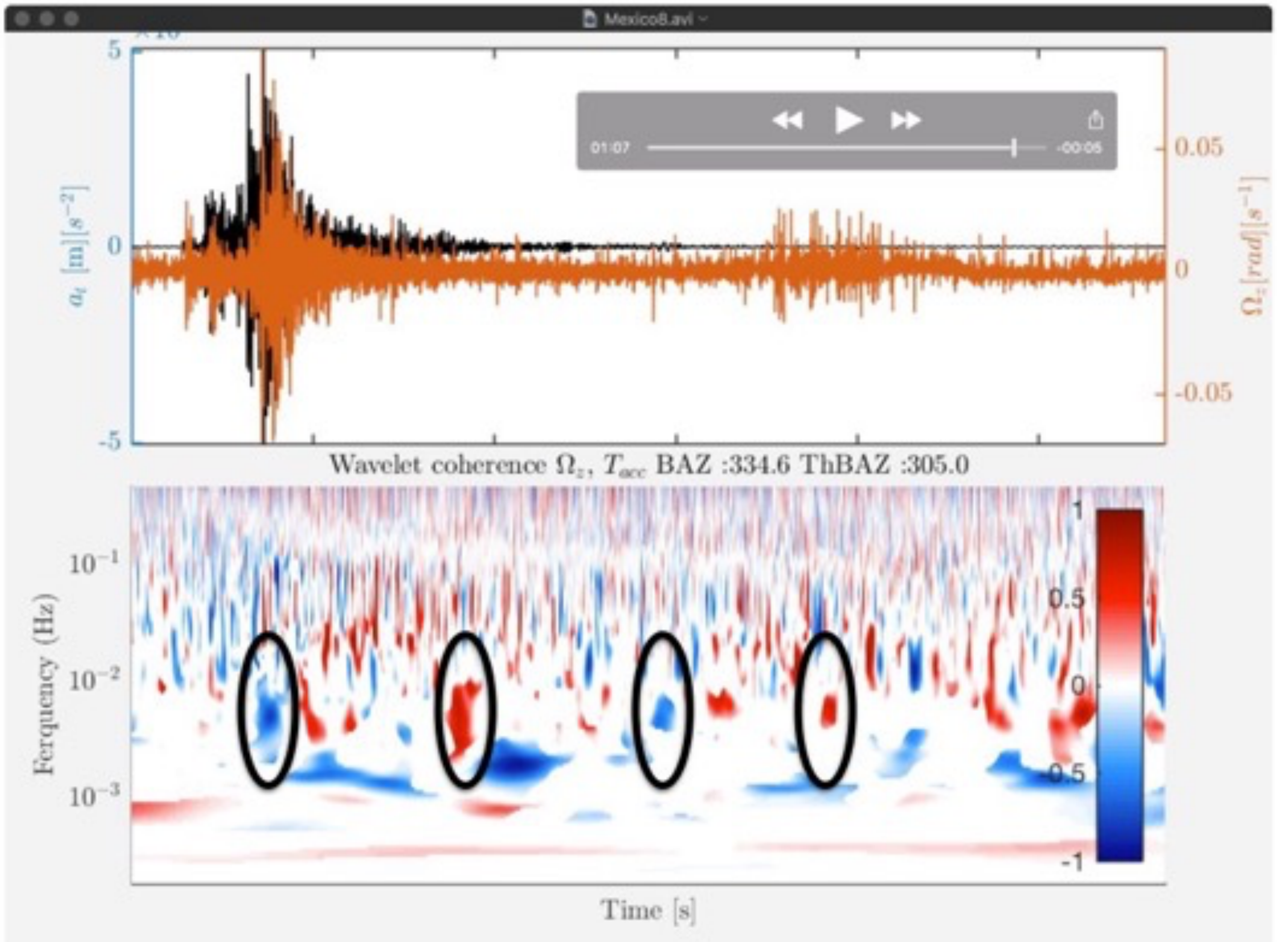


GINGERINO CAN DETECT VERY HIGH ANGULAR ROTATION SIGNALS

The Visso M 5.9 earthquake, probably the largest seismic rotational signal ever recoded

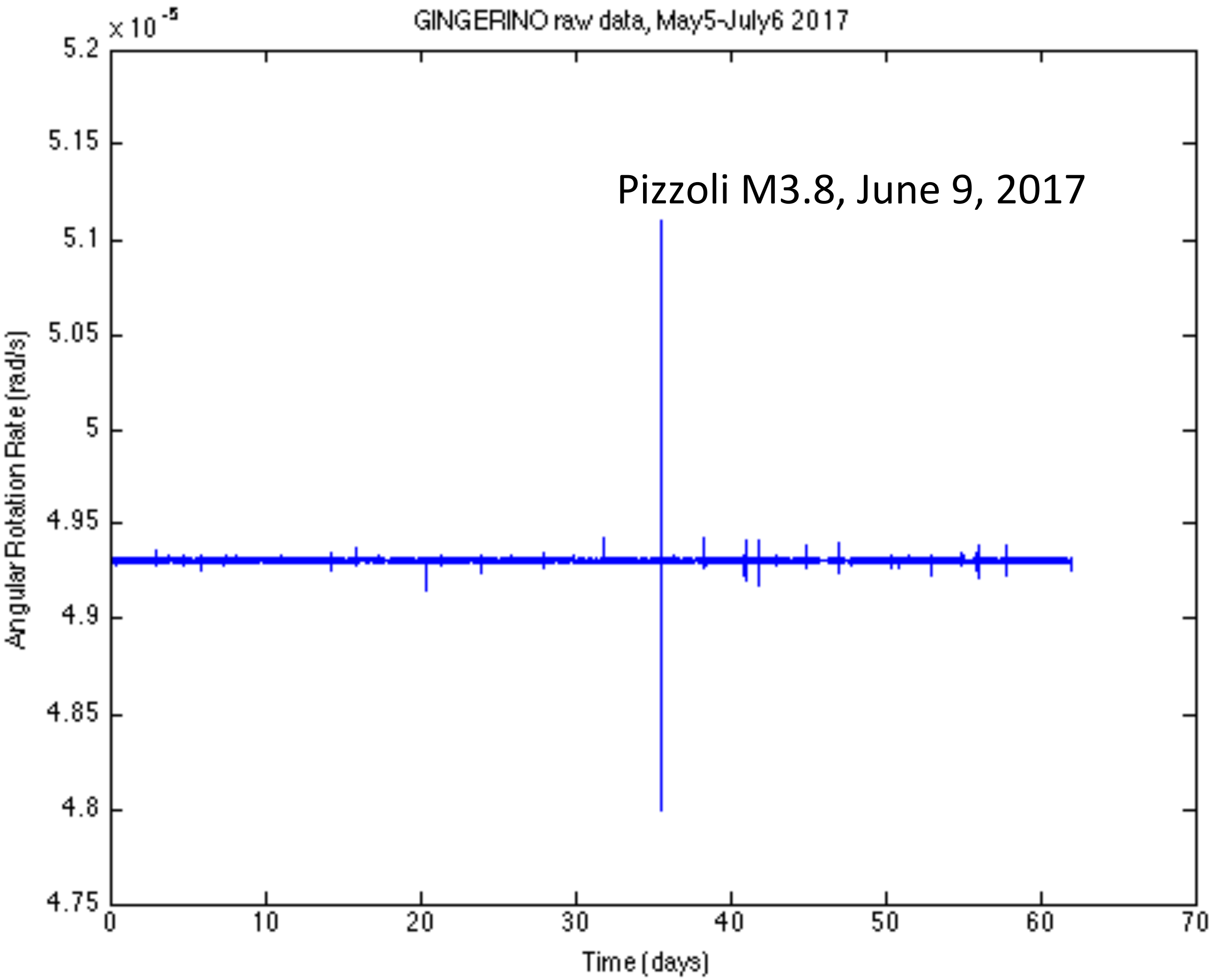


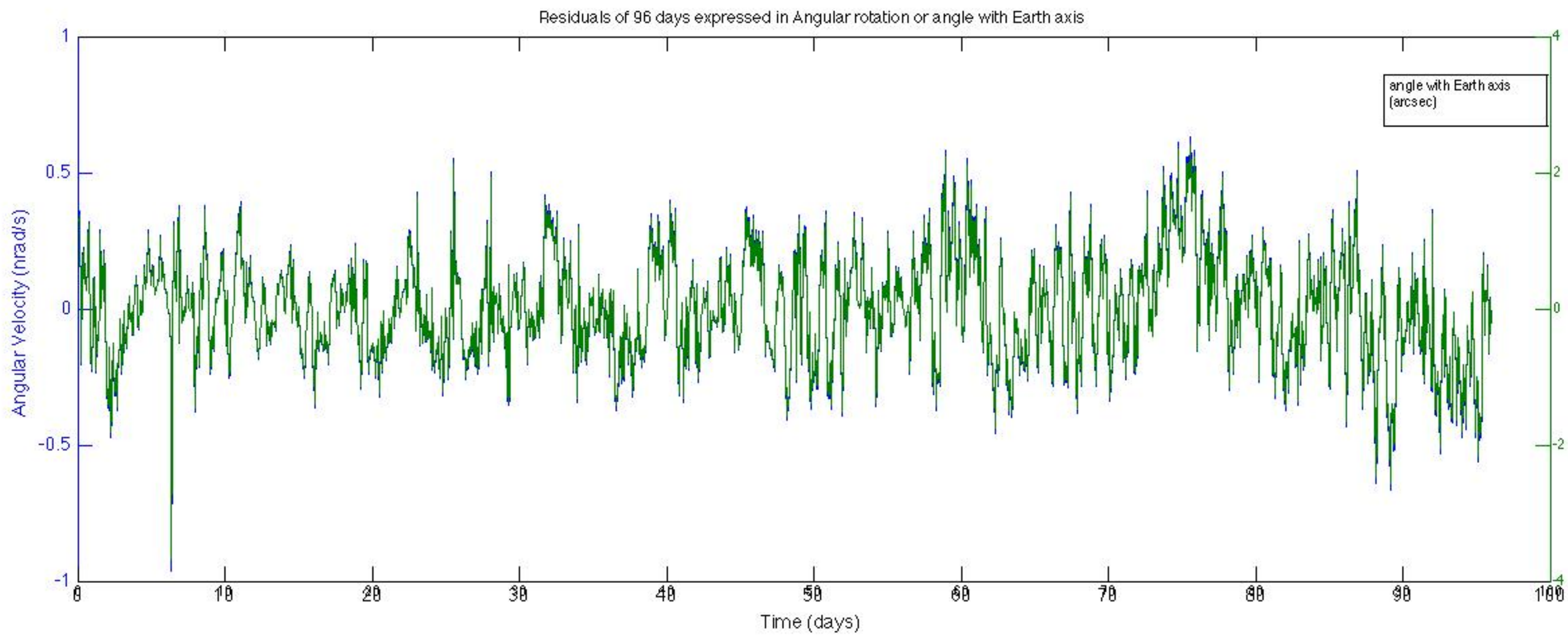
# M8!

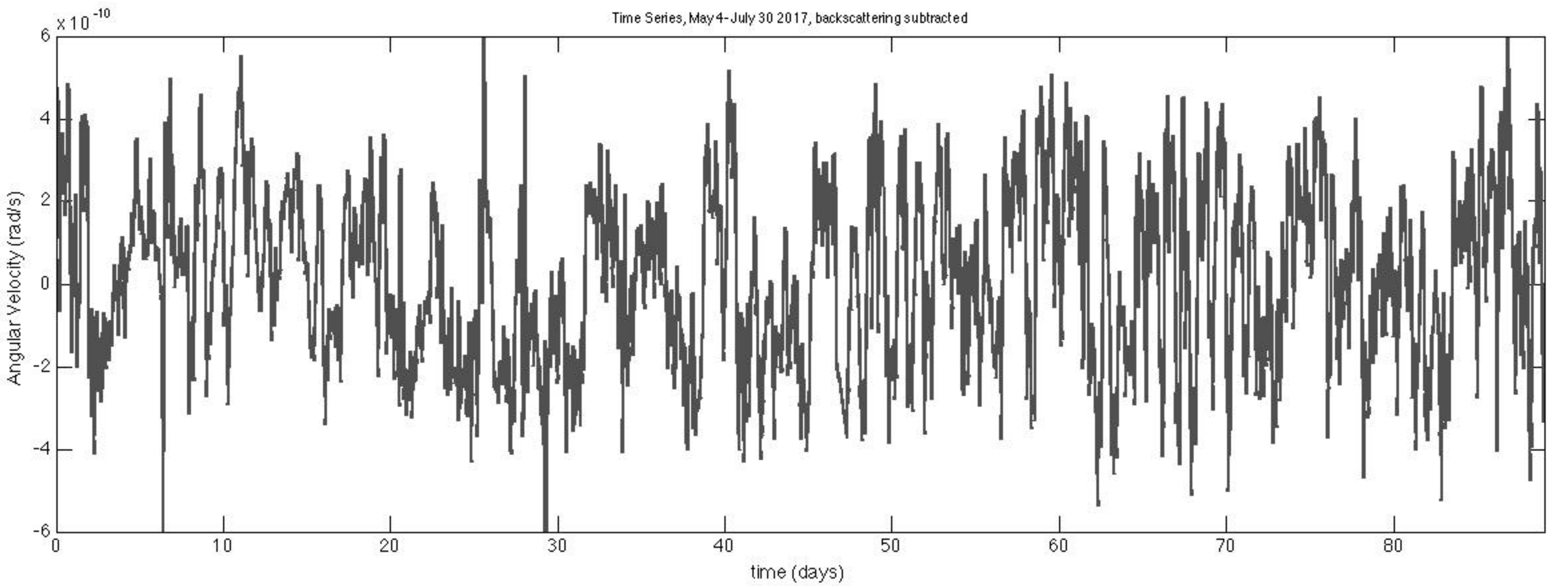


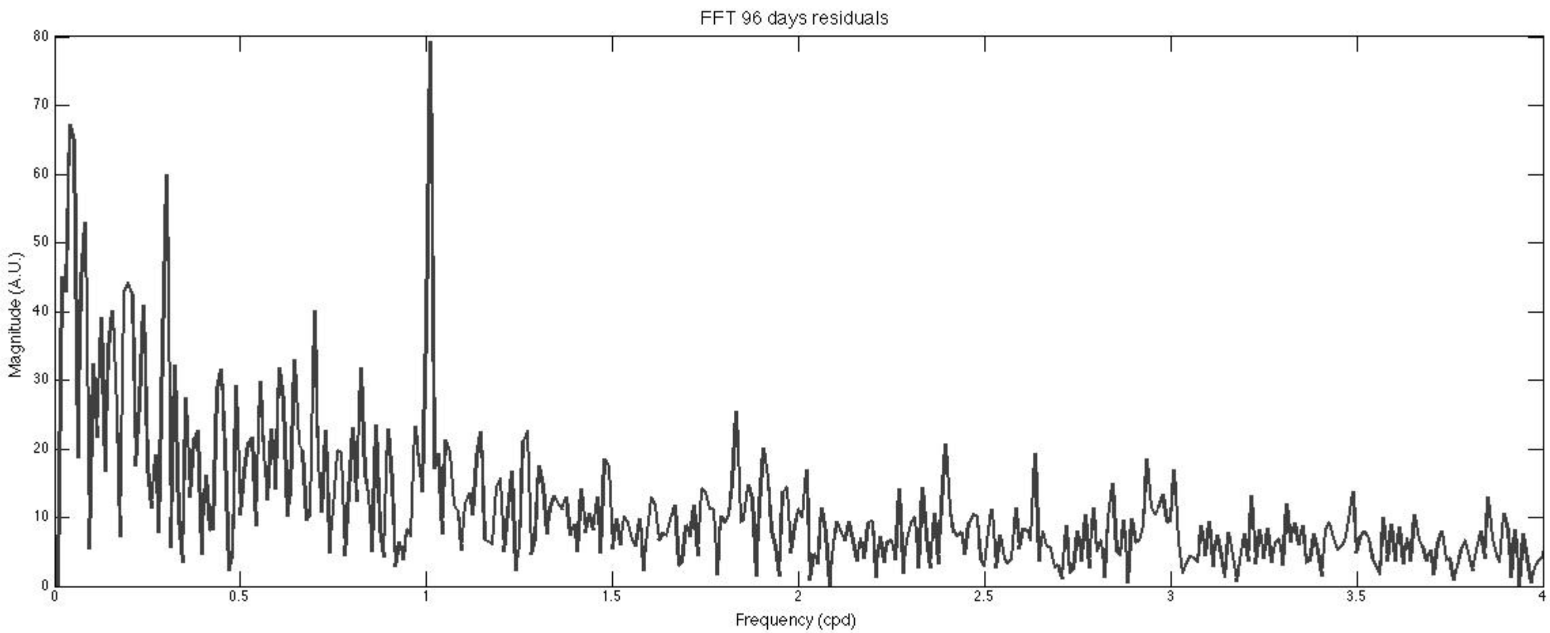
Mexico8.avi
01:07
-00:05
$a_t$ [m][$s^{-2}$]
$\Omega_z$ [$rad$][$s^{-1}$]
0.05
0
-0.05
5
0
-5
Wavelet coherence $\Omega_z$, $T_{acc}$ BAZ :334.6 ThBAZ :305.0
Ferquency (Hz)
$10^{-1}$
$10^{-2}$
$10^{-3}$
1
0.5
0
-0.5
-1
Time [s]

# CONTINUOUS DATA TAKING SINCE MAY 3 2017, DUTY CYCLE > 97%




Residuals of 96 days expressed in Angular rotation or angle with Earth axis
Angular Velocity (nrad/s)
Time (days)
angle with Earth axis (arcsec)
1
0.5
0
-0.5
-1
4
2
0
-2
-4
0
10
20
30
40
50
60
70
80
90
100


Time Series, May 4- July 30 2017, backscattering subtracted
x 10^-10
Angular Velocity (rad/s)
time (days)
6
4
2
0
-2
-4
-6
0
10
20
30
40
50
60
70
80

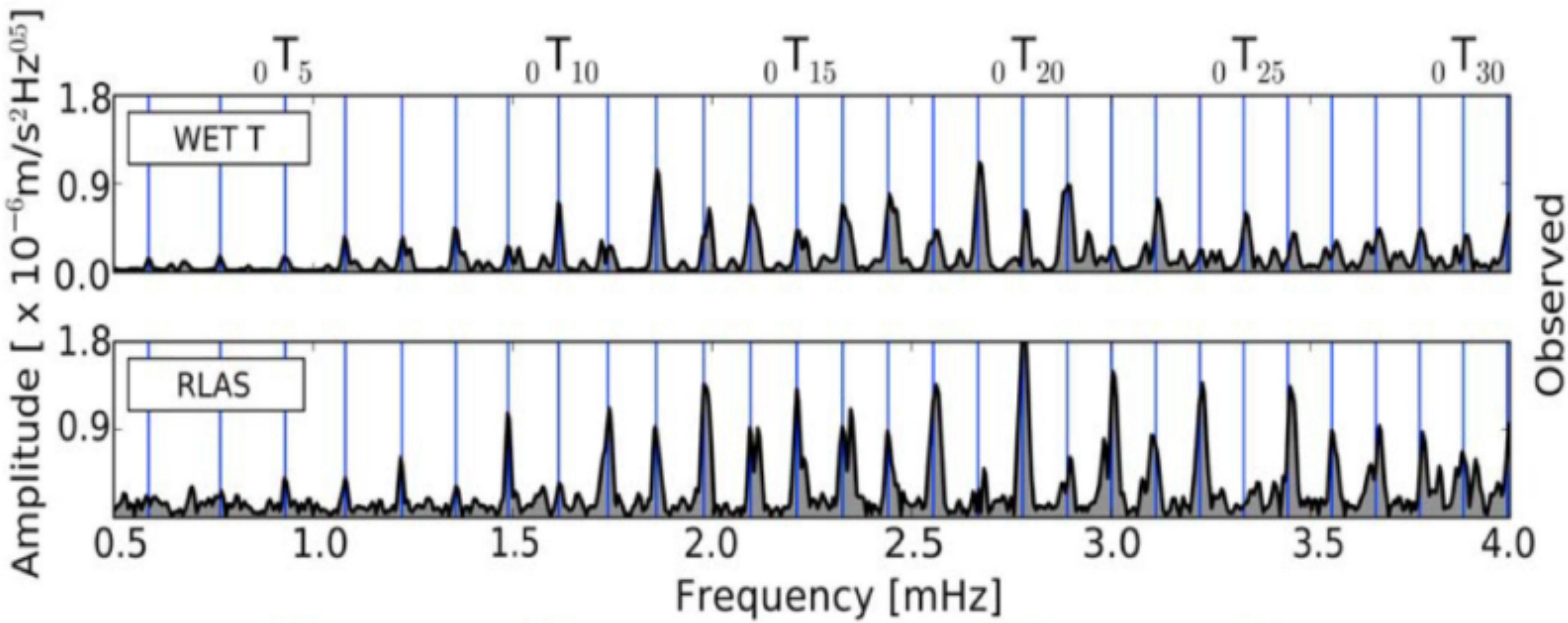

FFT 96 days residuals
Magnitude (A.U.)
Frequency (cpd)
0
10
20
30
40
50
60
70
80
0
0.5
1
1.5
2
2.5
3
3.5
4

# RING LASER AND GEODESY

- *The top sensitivity ring is the Gross Ring G at the geodetic station of Wettzell*
- *The main purposes for geodesy are the daily and subdaily variations of the length of day (LOD) and the earth axis variations, two open questions of the geodesy*

# Ringlaser Measures Eigenmodes of Earth

- Observed eigenmodes of the ringing Earth, stroked by the Tohoku-Oki earthquake




Igel et al. 2011

Gross ring G Wettzell

# CONCLUSIONS

- *Large frame ring lasers are based on a mature technique*
- *high sensitivity and long term stability make RL able to investigate the very low part of the spectrum, providing remarkable measurements for general relativity, geodesy and geophysics*
- *They can measure locally global quantity*

*sensitivity & stability*

*key points to access very low frequency signals*

*Underground-Stability*