ADW2016

GINGER

Ring-Lasers

seismic rotational sensing

Angela Di Virgilio-INFN-Pisa

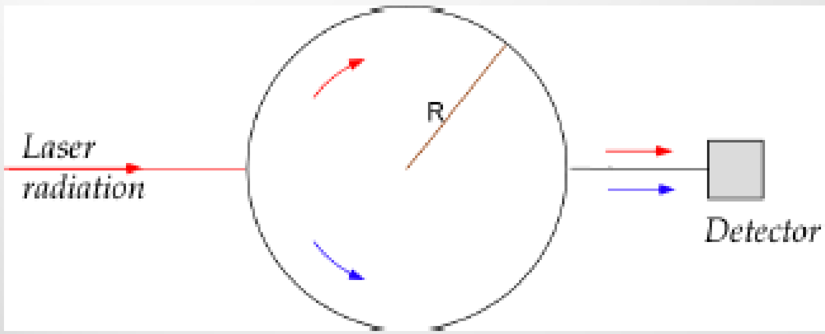
The Sagnac effect

G-Pisa sensitivity and some data taken at VIRGO in 2010-2011

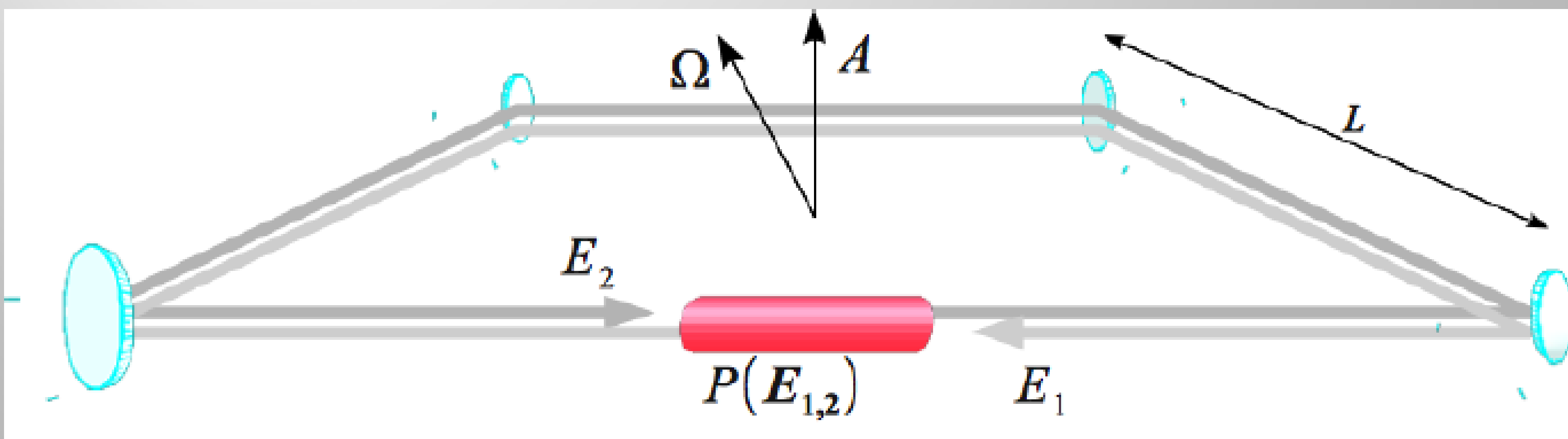
GP2 GINGERino G-Las

Sagnac Effect
and basic of ring laser

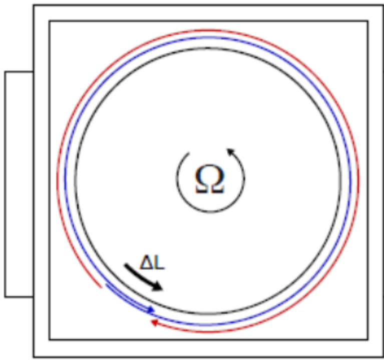
The Sagnac Effect and the ring-laser



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

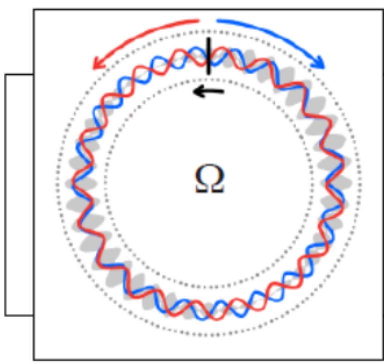


Angular Rotation Inertial Sensor- No moving parts



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

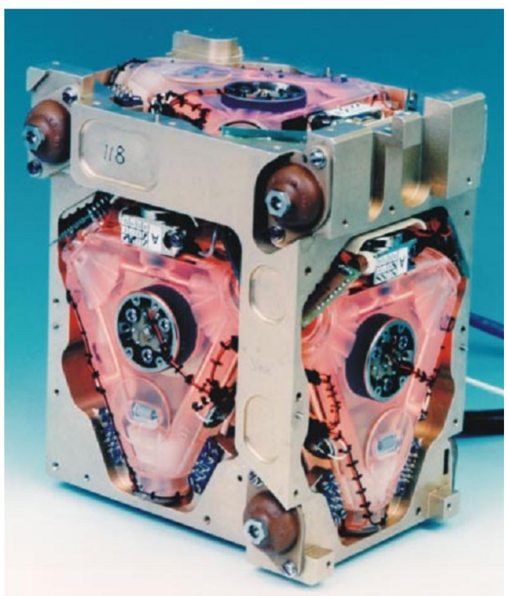
$$\delta\Omega_{shot} = \frac{cP}{4AQ}\left(\frac{h\nu T}{2P_{out}t}\right)^{1/2}$$

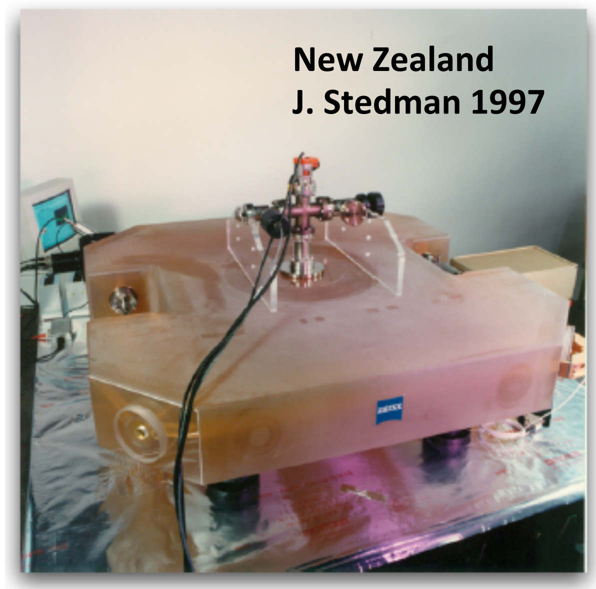
- Low cavity losses
- High power
- Large size

Mechanical, fiber optic, and ring laser gyroscopes

Status of the Art of ring-laser

- Ring laser have a large application in navigation
- Few large frame rings have been developed for geodetic and geophysical application





- Prototype: C-II (1997)
- Perimeter 4 m
- He-Ne (632.8 nm)
- Cavity in Neutral Plane
- UHV-Compatibility
- RF-Excitation
- $\Delta\Omega/\Omega < 10^{-6}$ @ 1000 s

<u>Feasibility of Concept shown</u>

OUR INFN PROTOTYPES

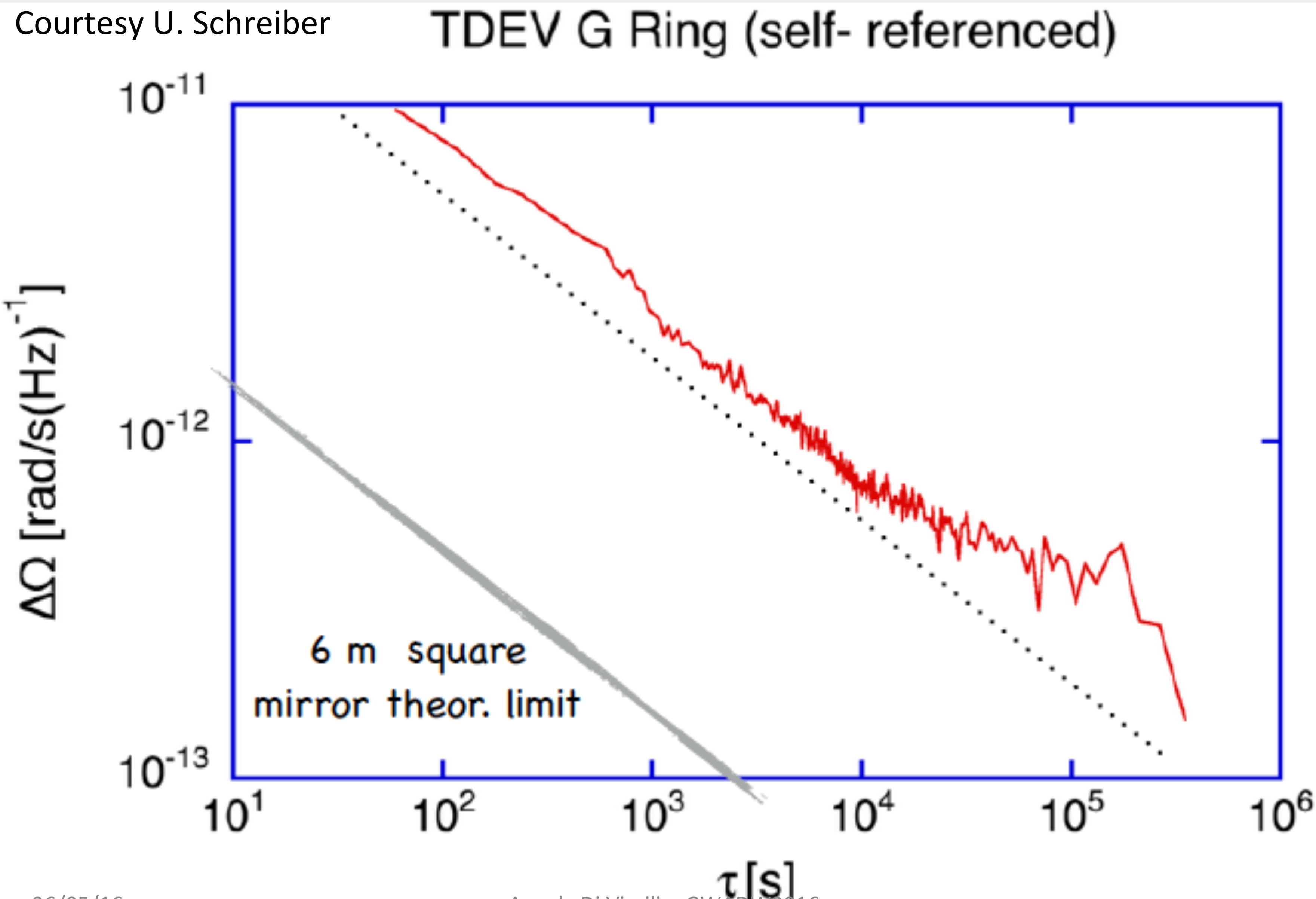
- Hetero-lithic mechanical design
- Stable by control

LONG TERM STABILITY IS OUR MAIN CONCERN

Since 2008, in collaboration with U. Schreiber of the GrossRing G of the Geodetic observatory of Wettzell

What 'long term' stability means for us:

Courtesy U. Schreiber



Ringlaser/Seismology

- Colocate one ring-laser+seismometer
- The simultaneous measurement of ground translation and rotation
- dispersion curve of Love waves over a broad frequency range, from which a local shear-wave velocity profile can be inferred with resolutions on the order of 100 m and penetration depths up to several tens of kilometers.

Several INFN experiments, from 2008
G-Pisa/ G-GranSasso-DS/ G-GranSasso-RD

At present G-GranSasso-RD (CommII):

Pisa: J. Belfi, N. Beverini, G. Carelli, A. Di Virgilio, U. Giacomelli, E. Maccioni, A. Simonelli

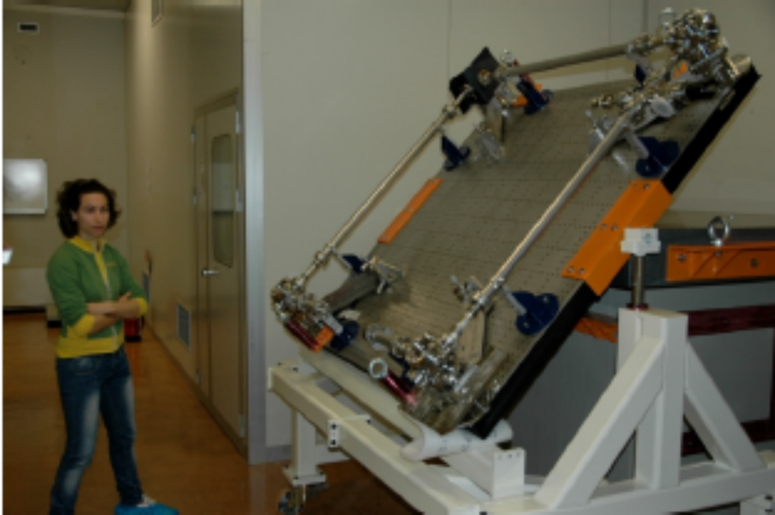
LNL: A. Ortolan

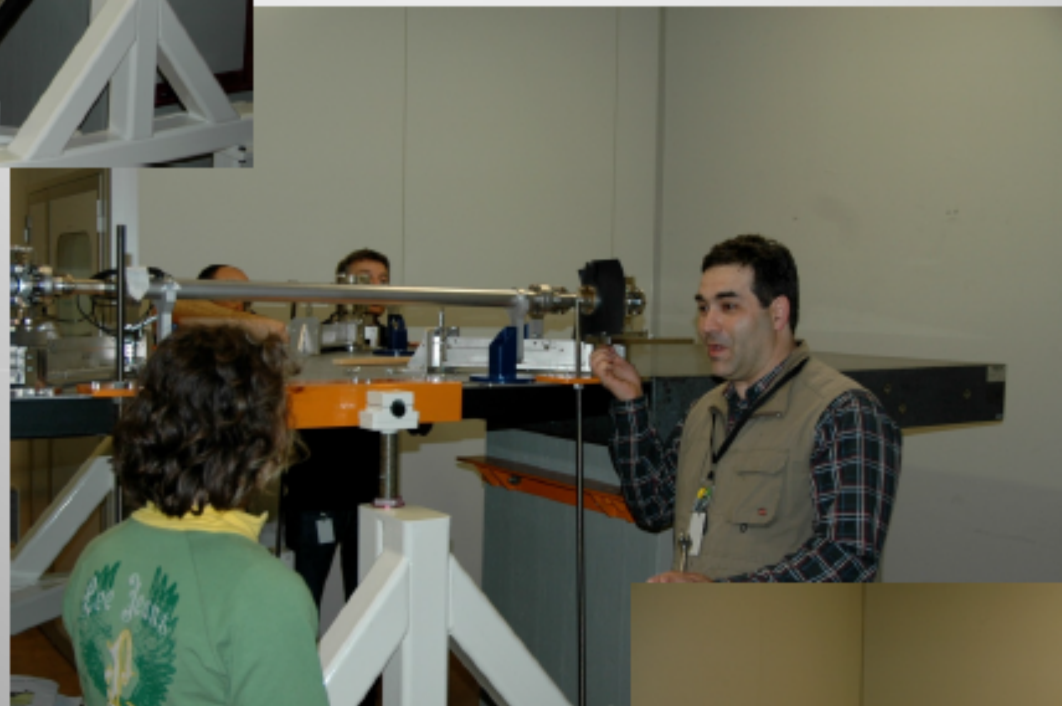
Padova-DEI: A. Beghi, D. Cuccato, A. Donazzan, G. Naletto, M. Pelizzo

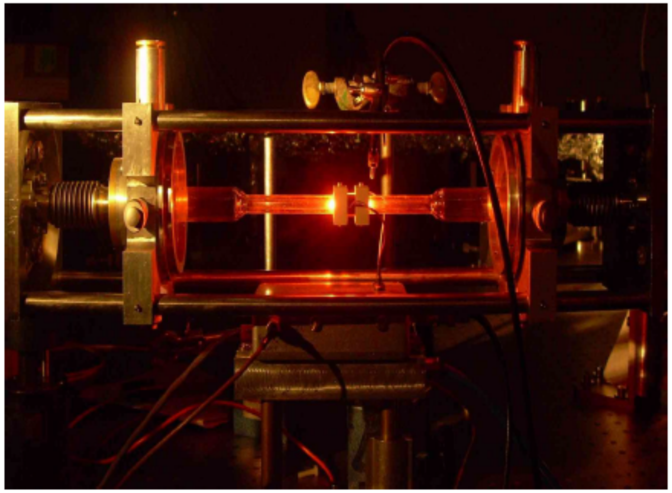
Napoli: C. Altucci, A. Porzio, R. Velotta

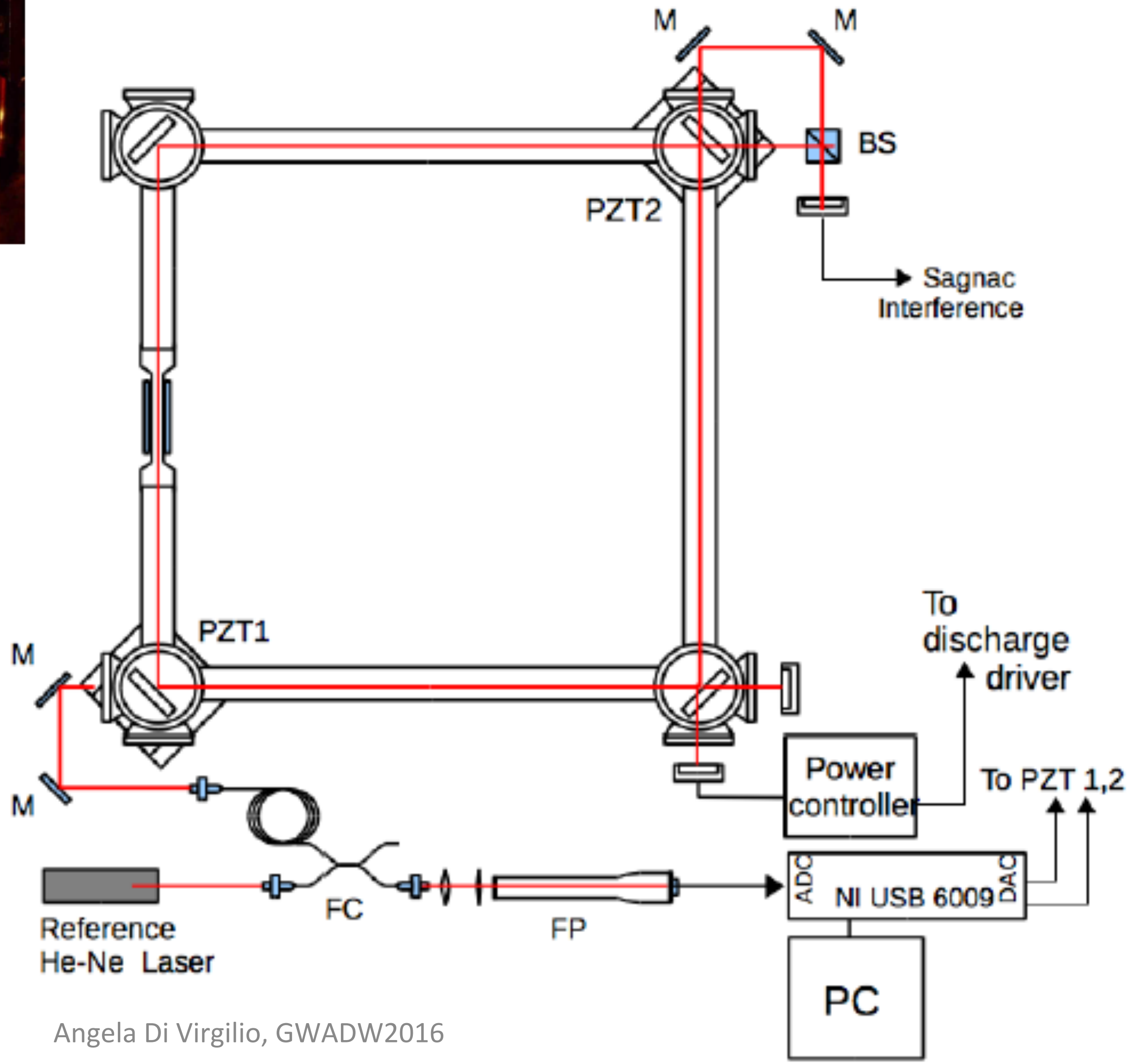
Torino: ML Ruggiero, A. Tartaglia *General Relativity theory*

G-Pisa during the installation in Virgo









Getters pumps avoid the aging of the gas

Ring Lasers are Shot-Noise Limited

- sensitivity inproves quadratically with L (Q & p/A)
- P_{out} , tipically 10-20 nW, but should be possible go up to 500mW-1mW
- Typical wavelength 633nm, but infrared and green are feasible
- Squeezing in principle feasible, but no experience so far

Quantum limit $$\Omega_{SN} = \frac{c\,p}{2\,Q\,A}\sqrt{h\frac{\nu_L}{P_{out}\,t}}$$

Sensitivity depends on several parameters

- Wavelength, losses and transmission of the mirrors, side length, output power

Example: 4.5 total losses, 633nm (other wavelength feasible-infrared and green)

Side/power	1. m, PSD rad/s 1 s	2m
10 nW	**$3.8\ 10^{-10}$**	**$1.9\ 10^{-10}$**
50 nW	**$1.7\ 10^{-10}$**	**$8.5\ 10^{-10}$**
500 nW	**$5\ 10^{-11}$**	**$2.7\ 10^{-11}$**

Bandwidth depends on the ringdown time of the cavity

- Size of the ring and quality of the mirrors
- Typical value in our prototypes (meter size): from 80μs up to 660μs

~1kHz bandwidth

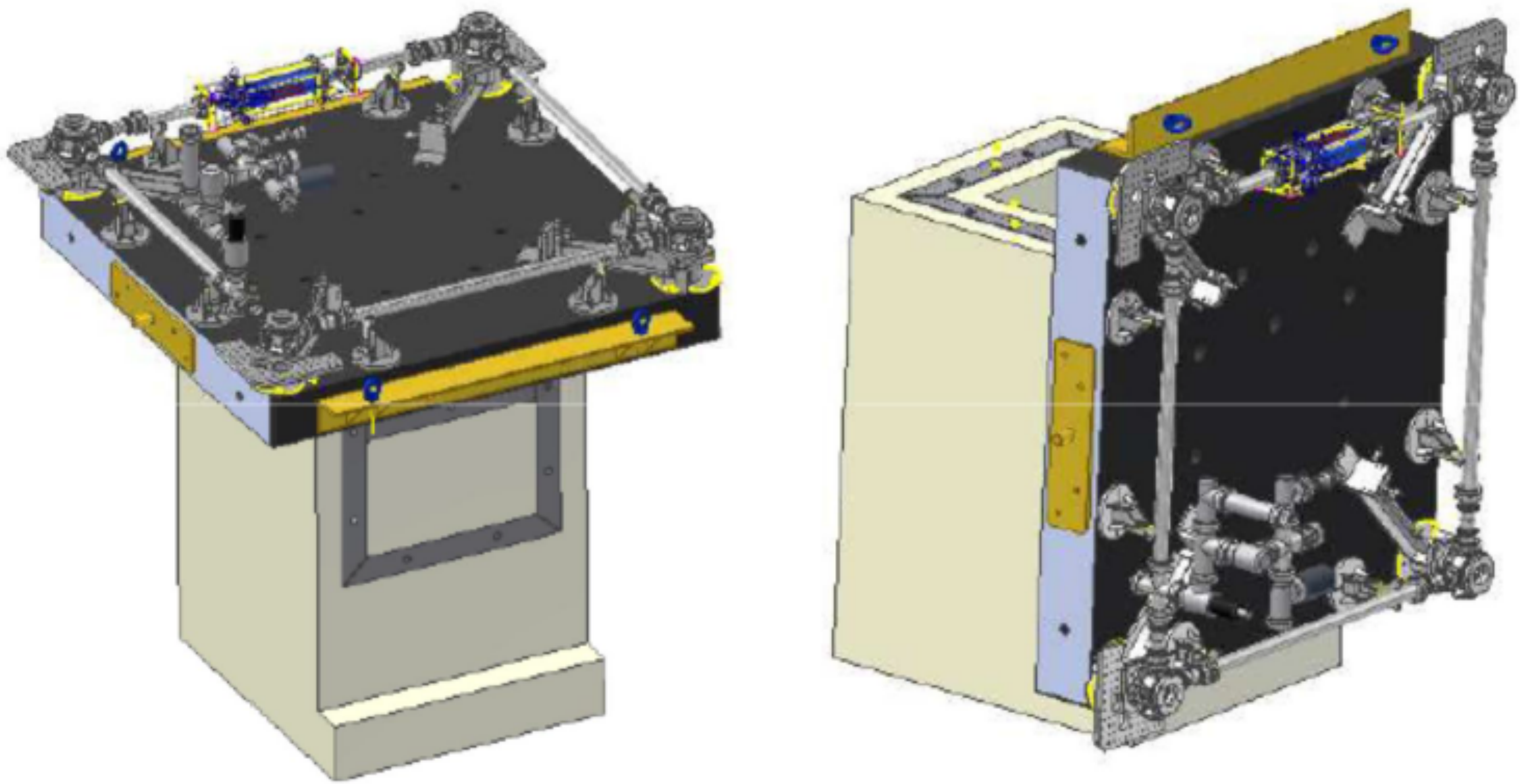
They can run continuously un-attended

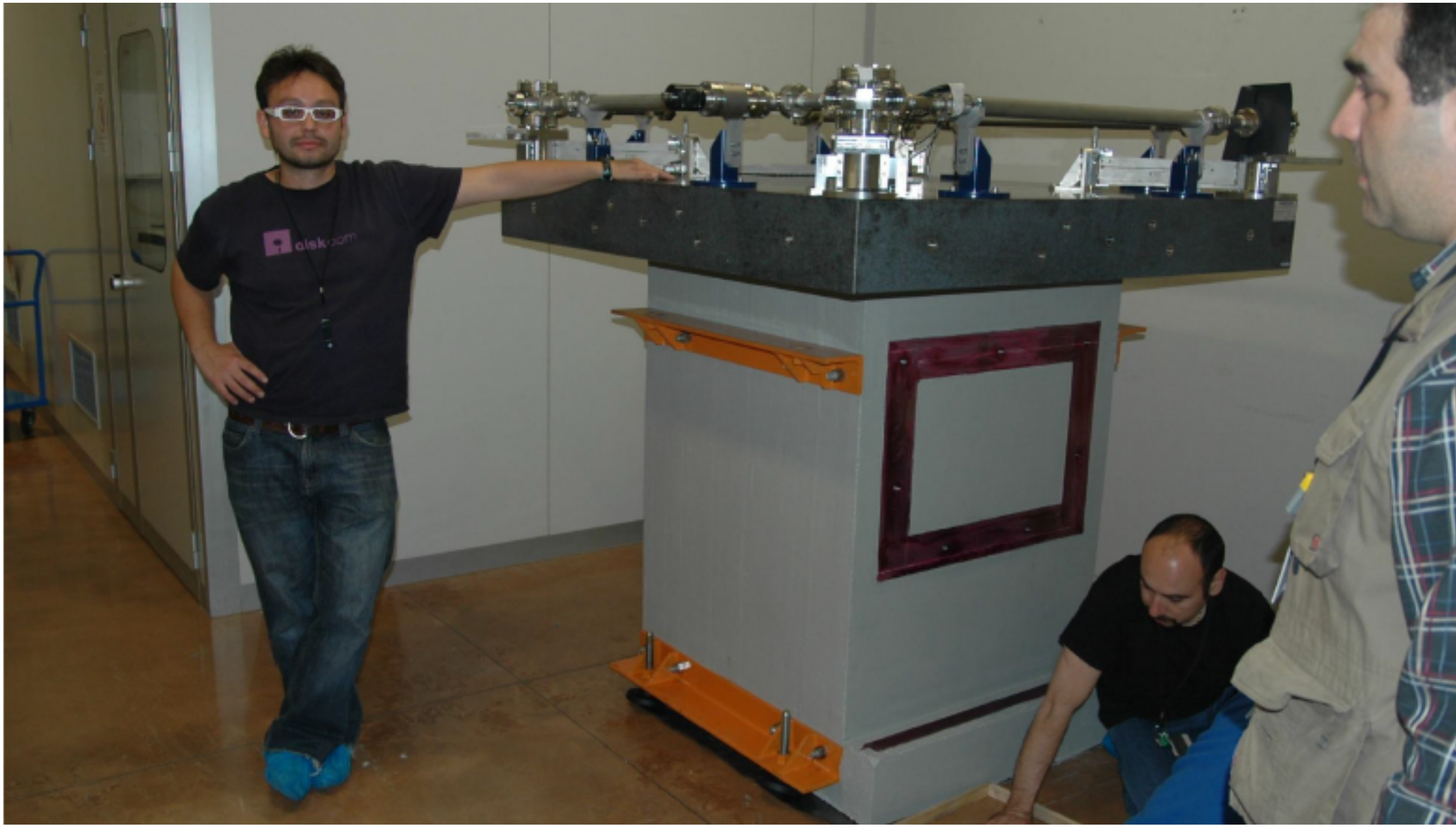
Transportable

Our first prototype G-Pisa:

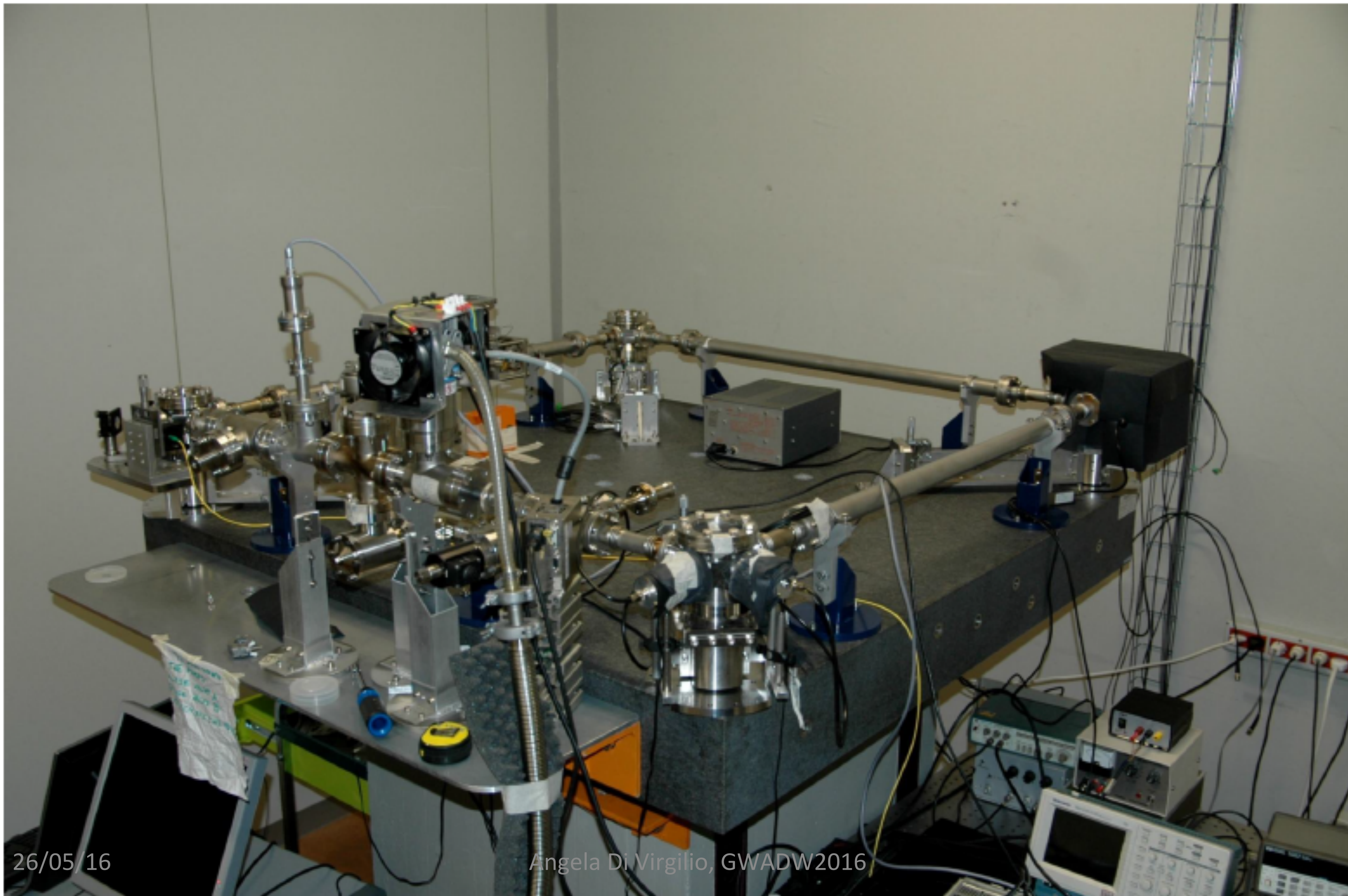
- assembled in Pisa, and has taken data in Pisa
- moved to the VIRGO central area
- has taken data for several months during last Virgo run (data stored in the raw data)
- Has been moved to S.Piero, and has taken data there
- Has been moved to the GranSasso national lab. And has taken data there
- In 2015 it has been disassembled and the mechanical parts are now user for the new prototype GINGERino

Horizontal and vertical gyrolaser operation

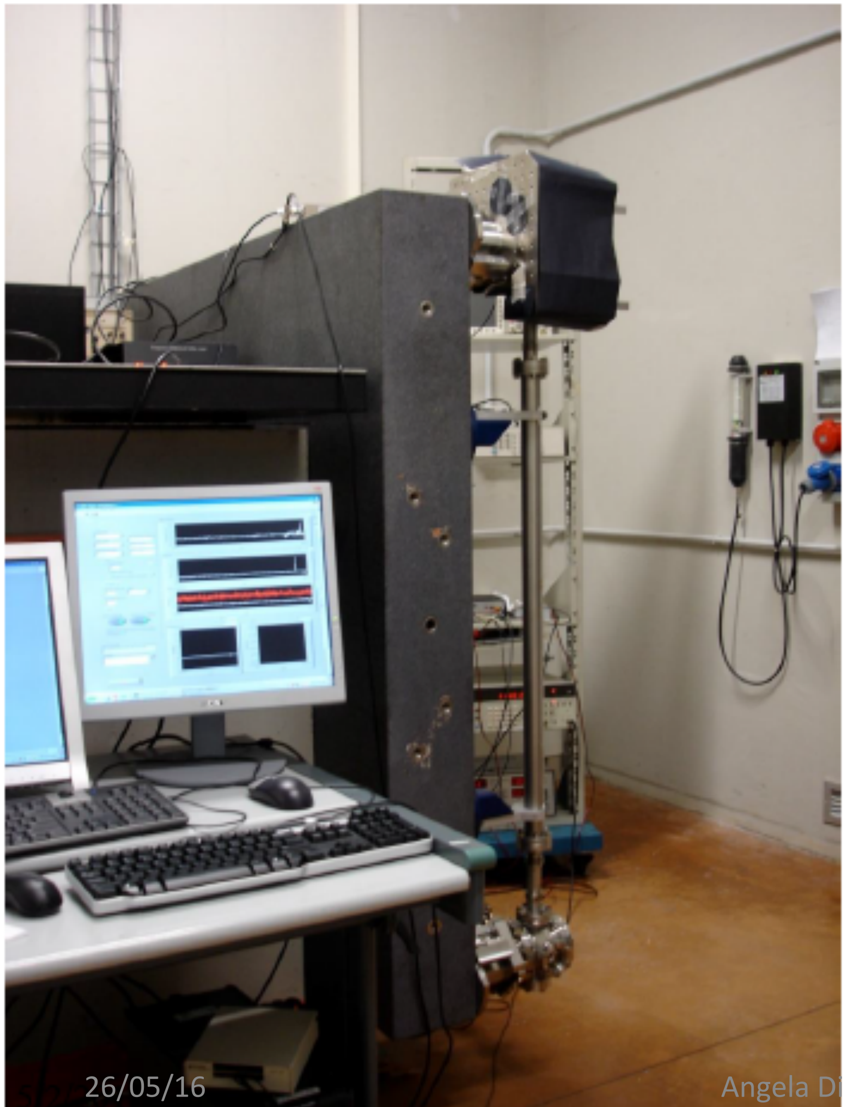


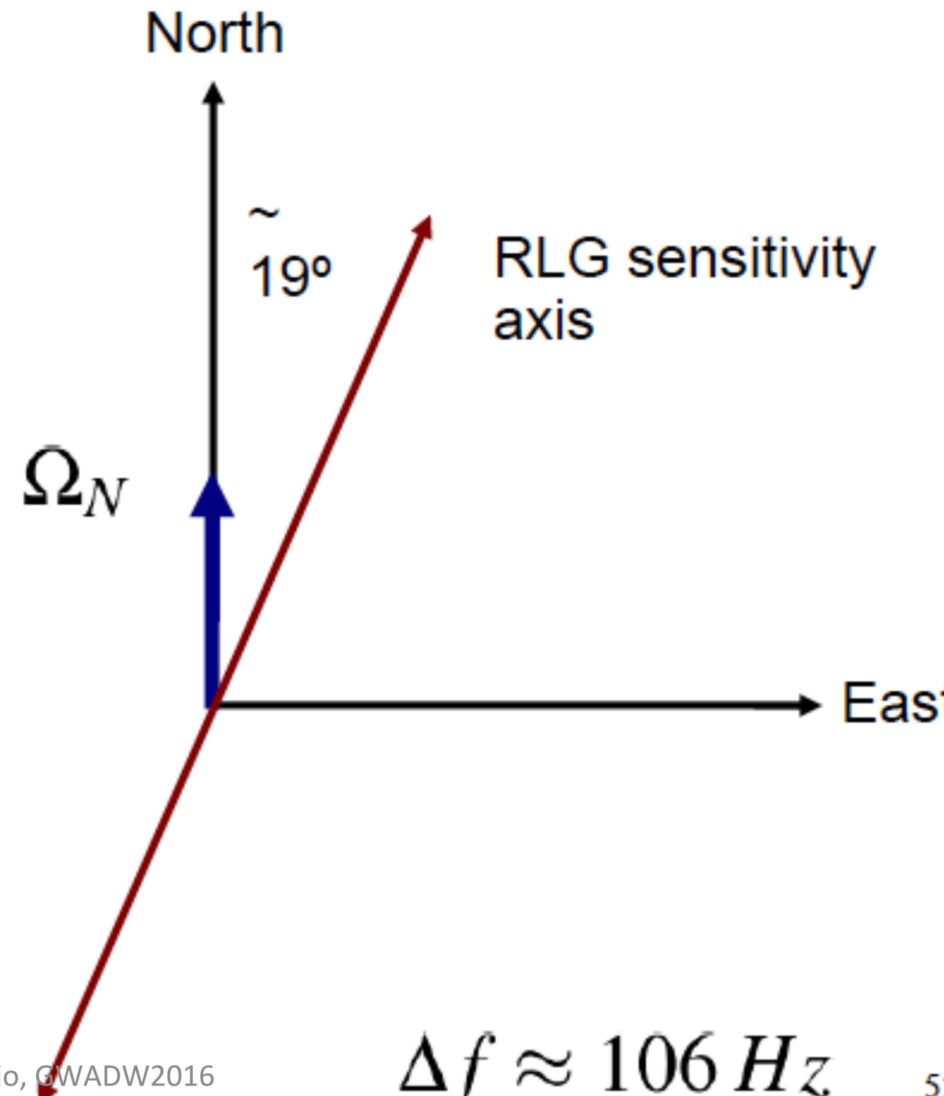


G-Pisa in the Virgo Central Area



G-Pisa RLG





$$\Delta f \approx 106\, Hz$$

Low frequency sensitivity limited by backscattering
This noise can be canceled

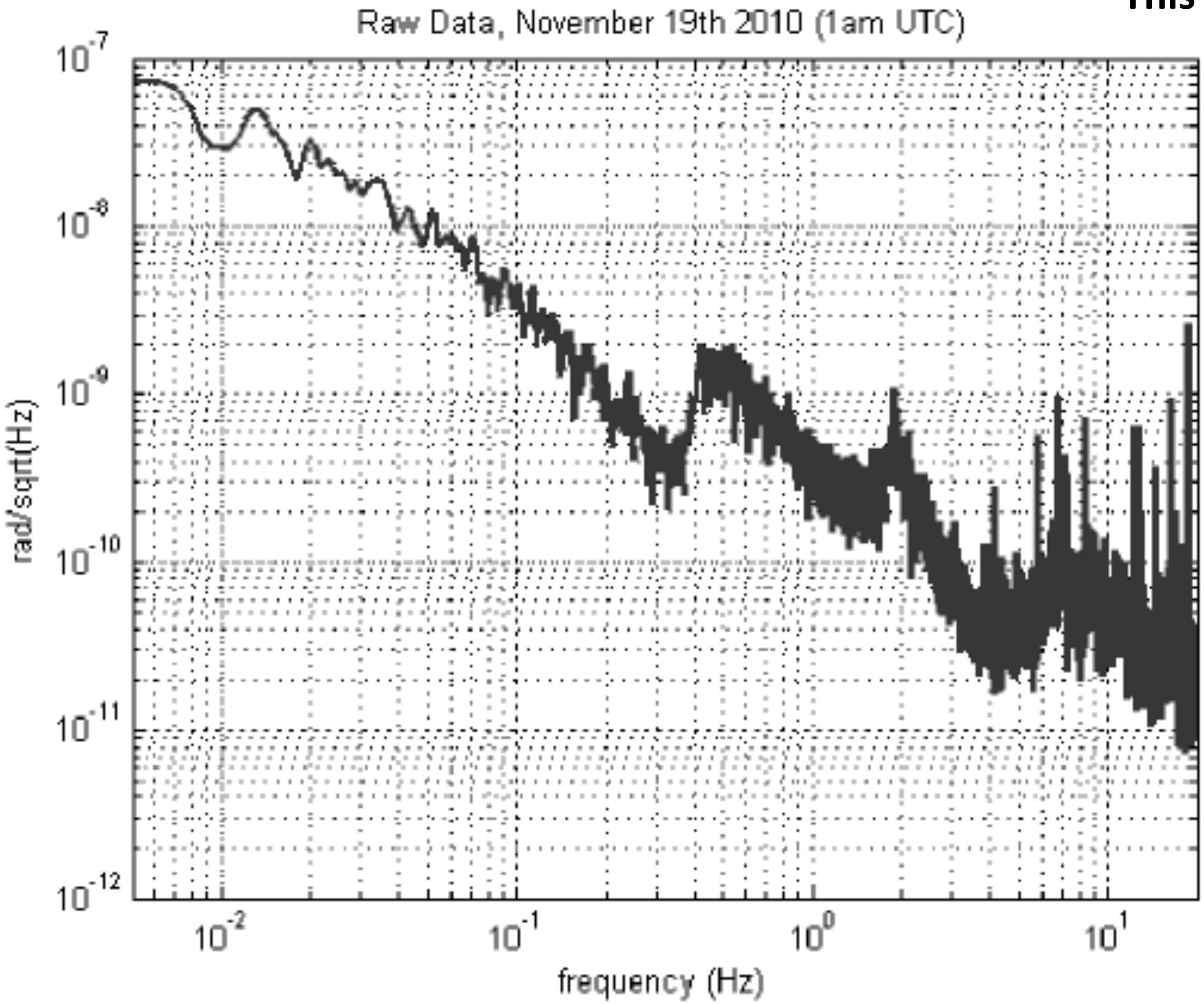
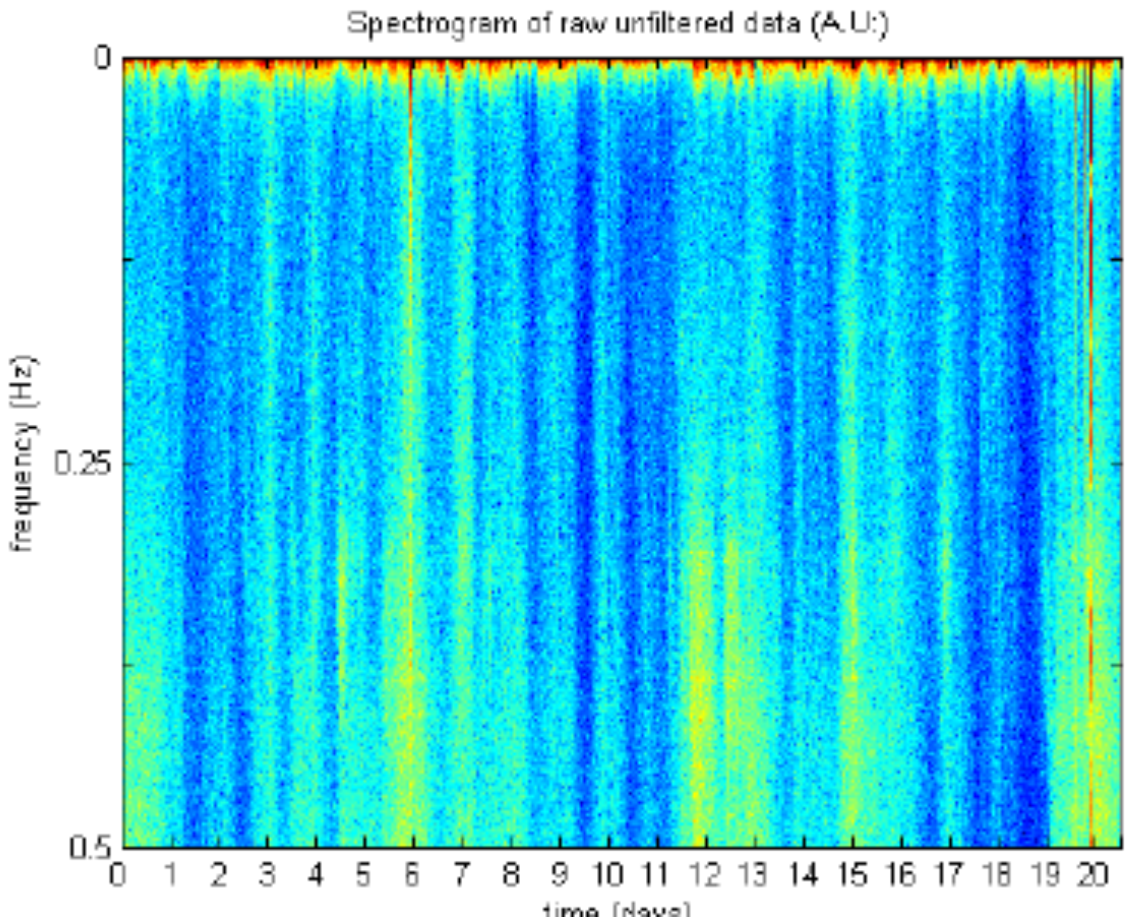
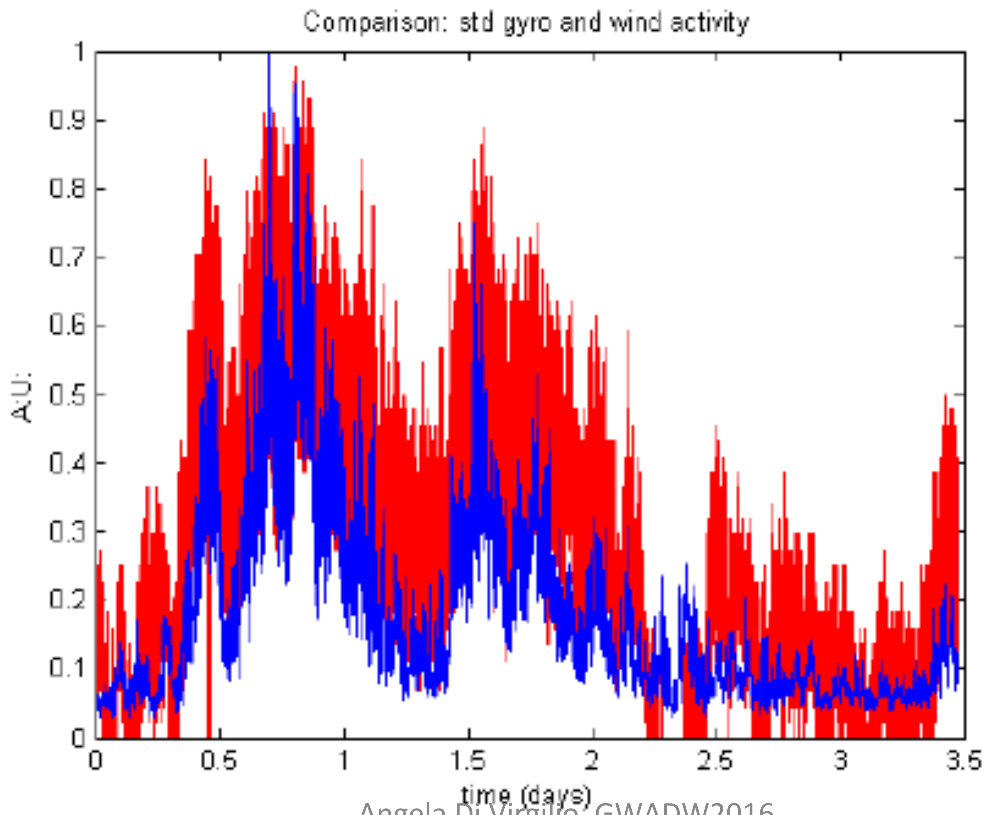


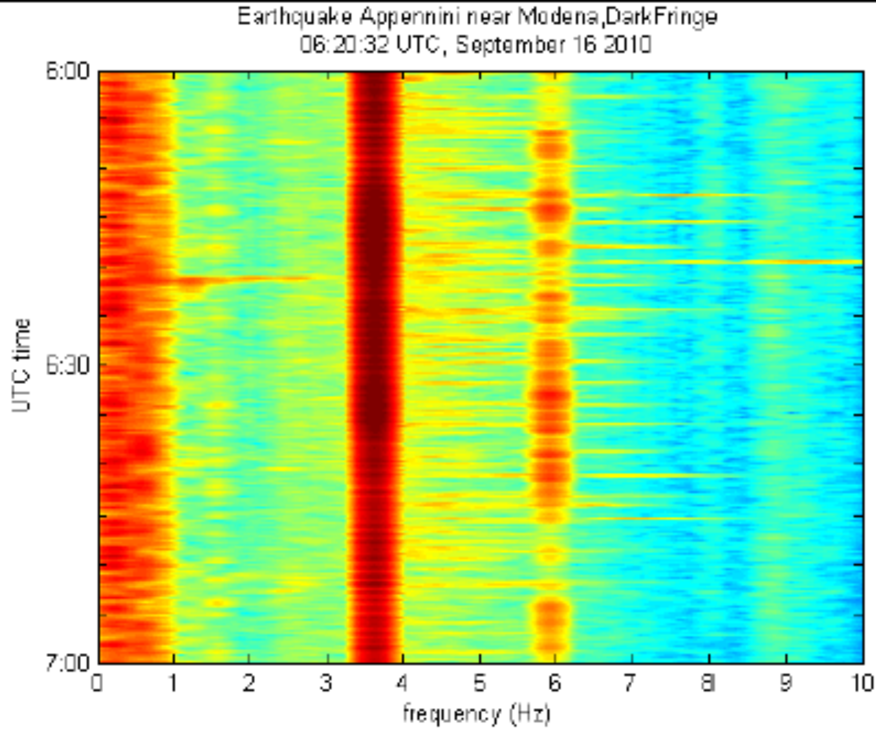
Fig. 10 Tilt sensitivity in a very quiet period, the requirements of AdVirgo are 10^{-8} rad/$\sqrt{\text{Hz}}$ in the range 5 − 500 mHz.

On month of continuous Data Taking with perimeter locked



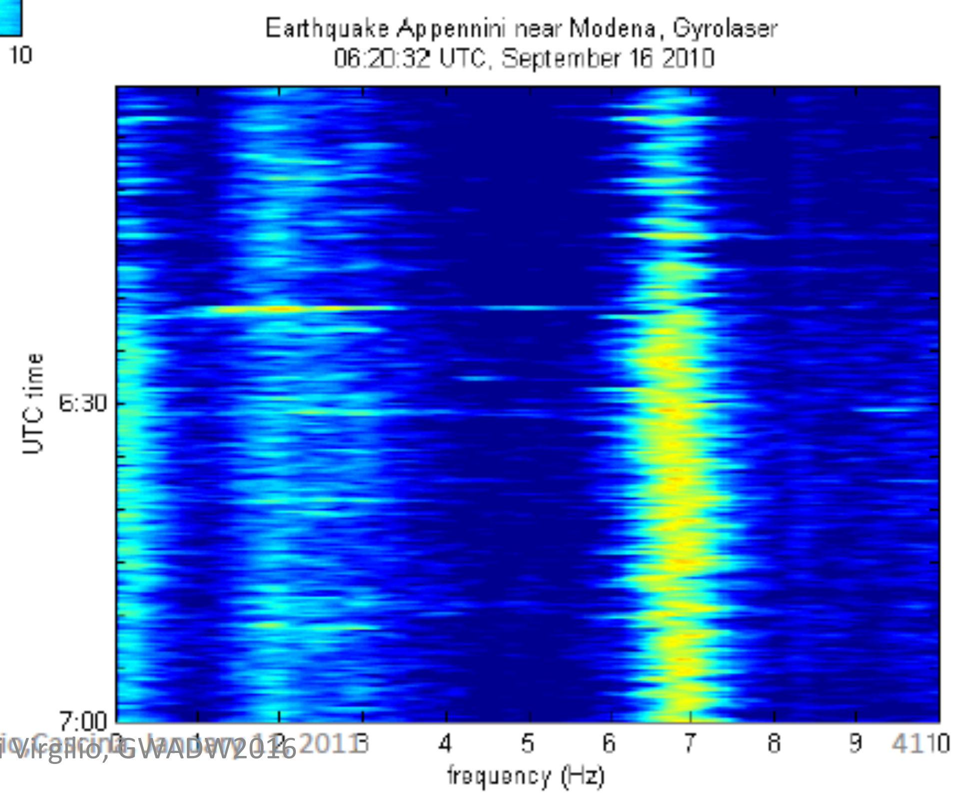
Comparison with the Wind Monitor



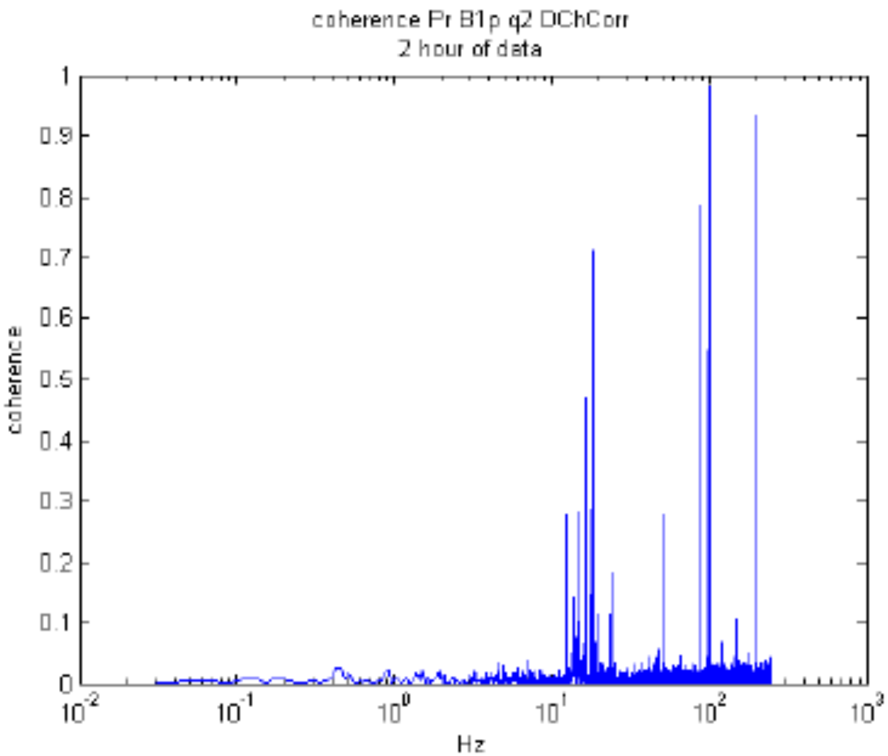


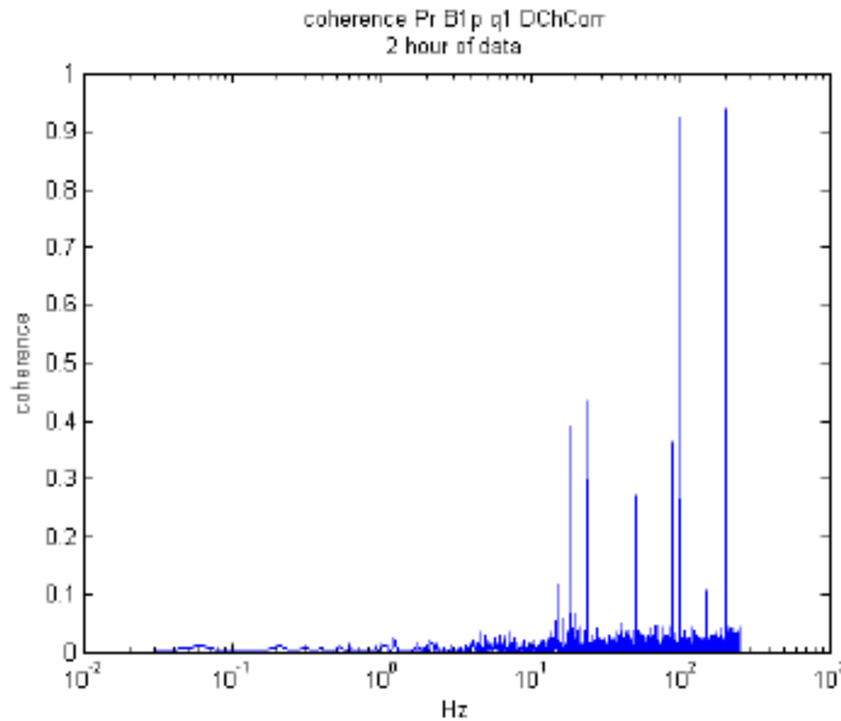
-Virgo was not affected by this
-Shock, no evidence of jitter of the output beam or in the accelerometers
-But the DarkFring has seen it

More on G-Pisa@VIRGO, 2011



Coherence with Dark Fringe

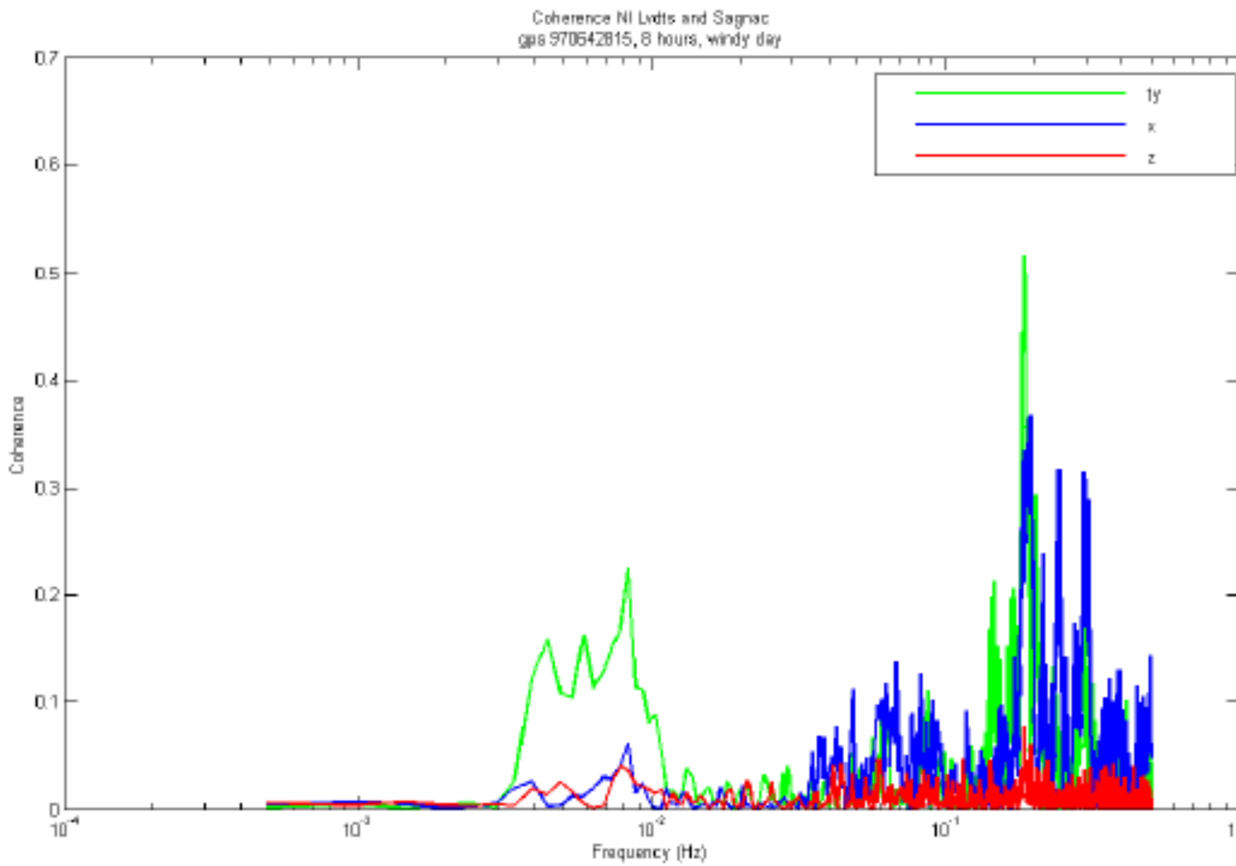




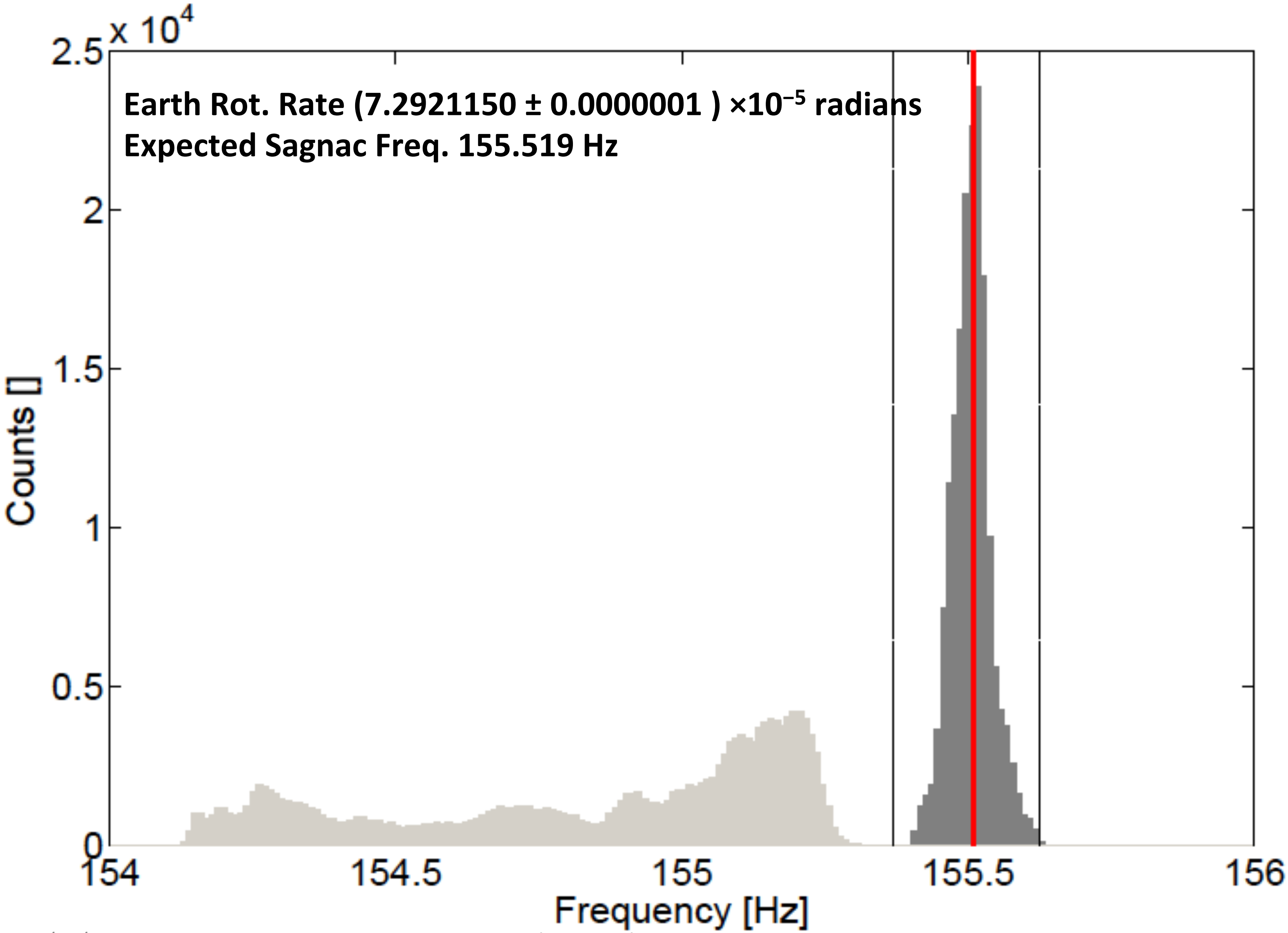
Coherence between our signal and the DarkFringe has not been done extensively, but there is evidence of coherence

G-Pisa bandwidth at the moment is 1kHz

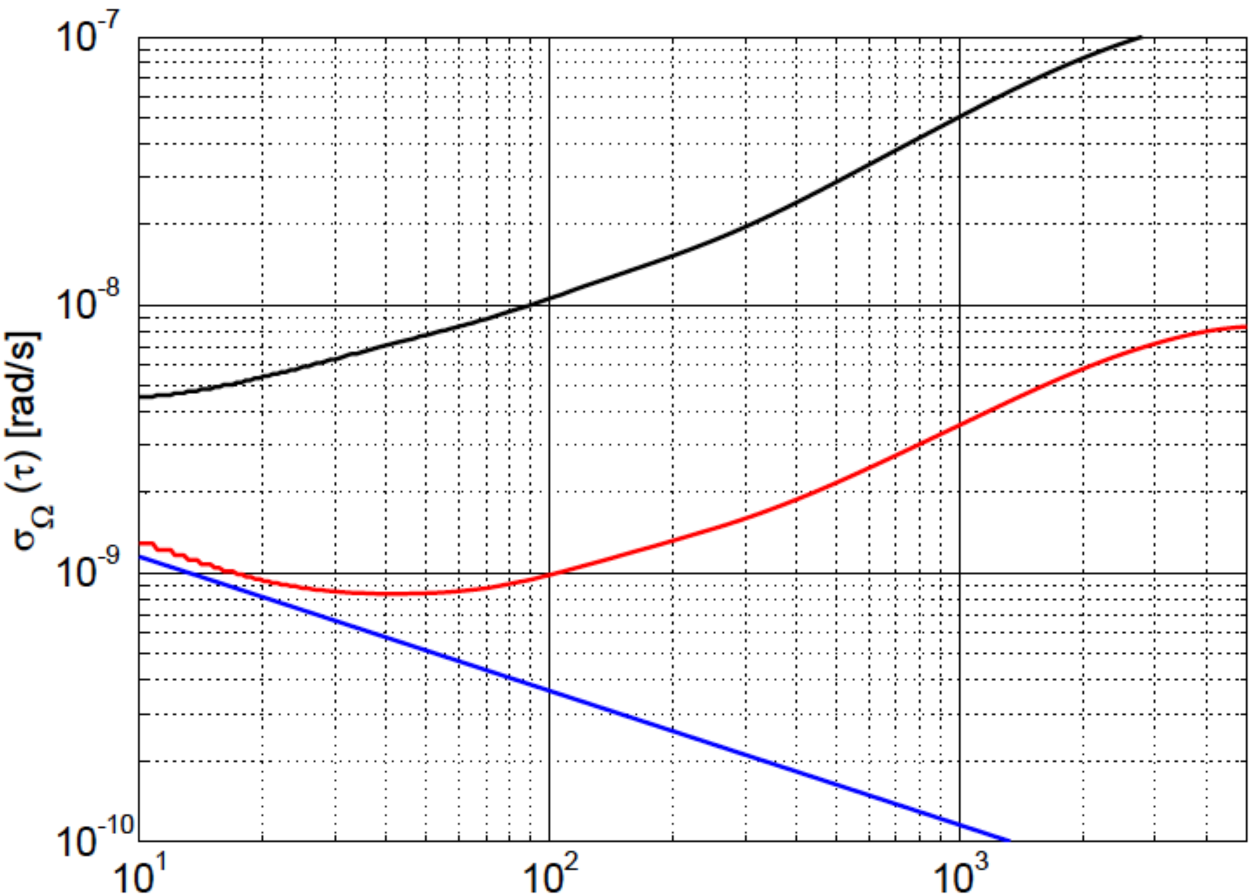
There is coherence at low frequency between the gyrolaser and LVDT signals



Backscatter noise dominates below 0.1 Hz, it can be subtracted



Allan Deviation, G-Pisa in a 'standard laboratory' 2014 implementable on-line

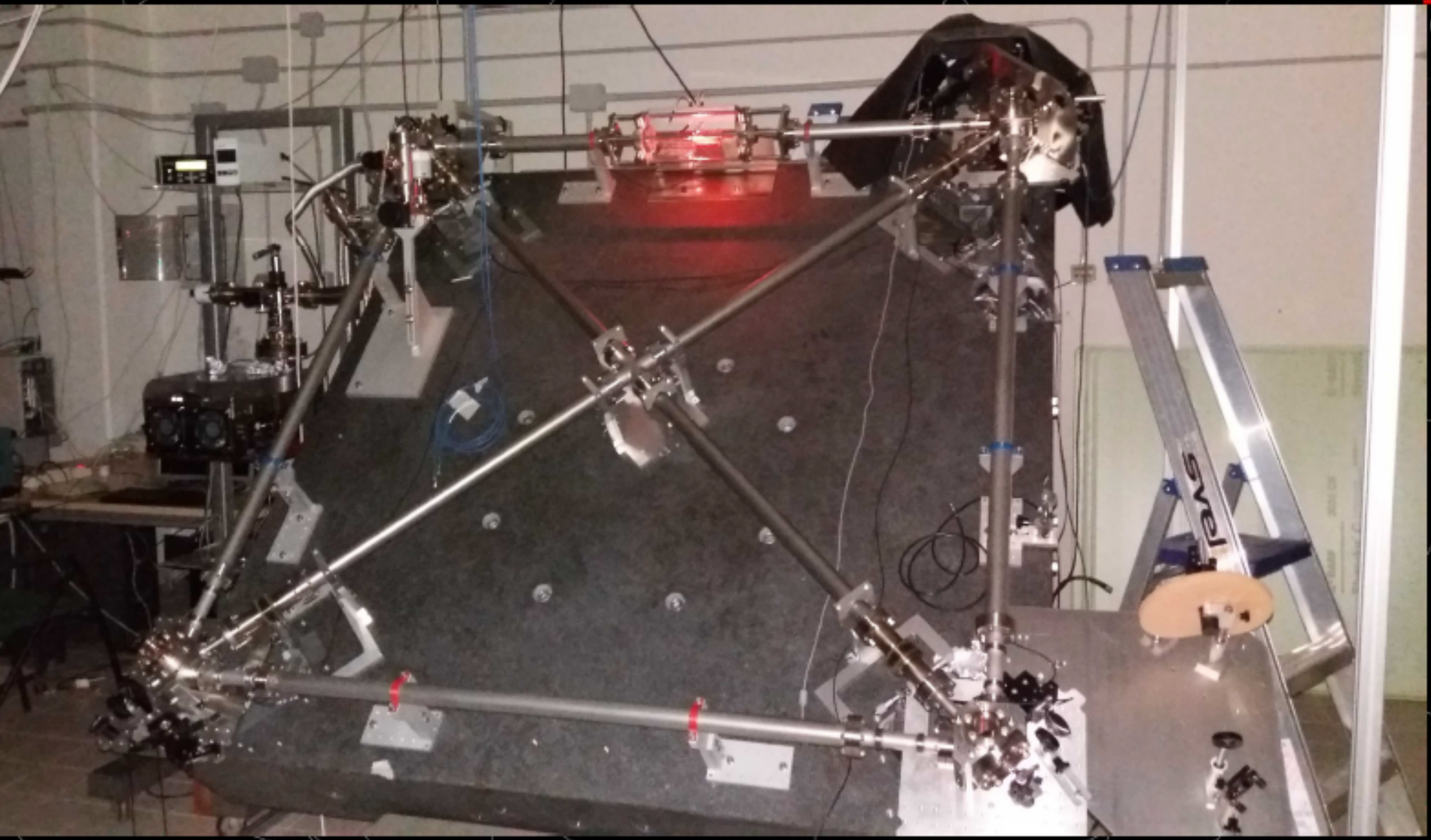


Published METROLOGIA

Figure 19: *Allan* deviations of *AR(2)* (upper curve) and *EKF* (lower curve) rotational frequency estimates. The straight line represents the shot noise level of *G-PISA* for a cavity quality factor of 5.4×10^{11} and an output power of 4 nW.

GP2- 1.6m in side GEOMETRY CONTROL STUDY necessary for the long term stability

GINGER



GP2

INFN-Pisa

GP2: Geometry control via interferometry

Problem

The magnitude of the *relativistic frame dragging* term is of 1 part in 10^9 of the Earth rotation

⇒ scale factor k_S stabilization better than 10^{-10}

- accuracy on mirror position better than 1 nm

Approach used in the past

Observable: RL optical frequency (cavity perimeter control)

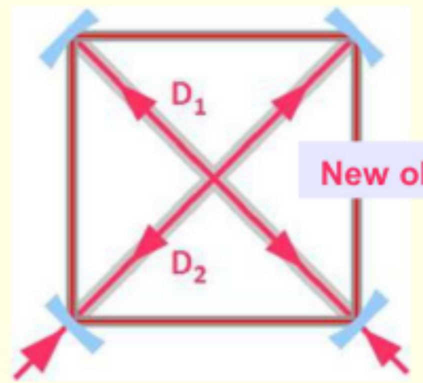
Stabilization methods: comparison with reference laser; by tuning the environmental pressure; by locking to a frequency comb

Limitation: variations of mirror inter-distances remain uncontrolled

Our original approach

Observables: distance between opposite mirrors (& perimeter)

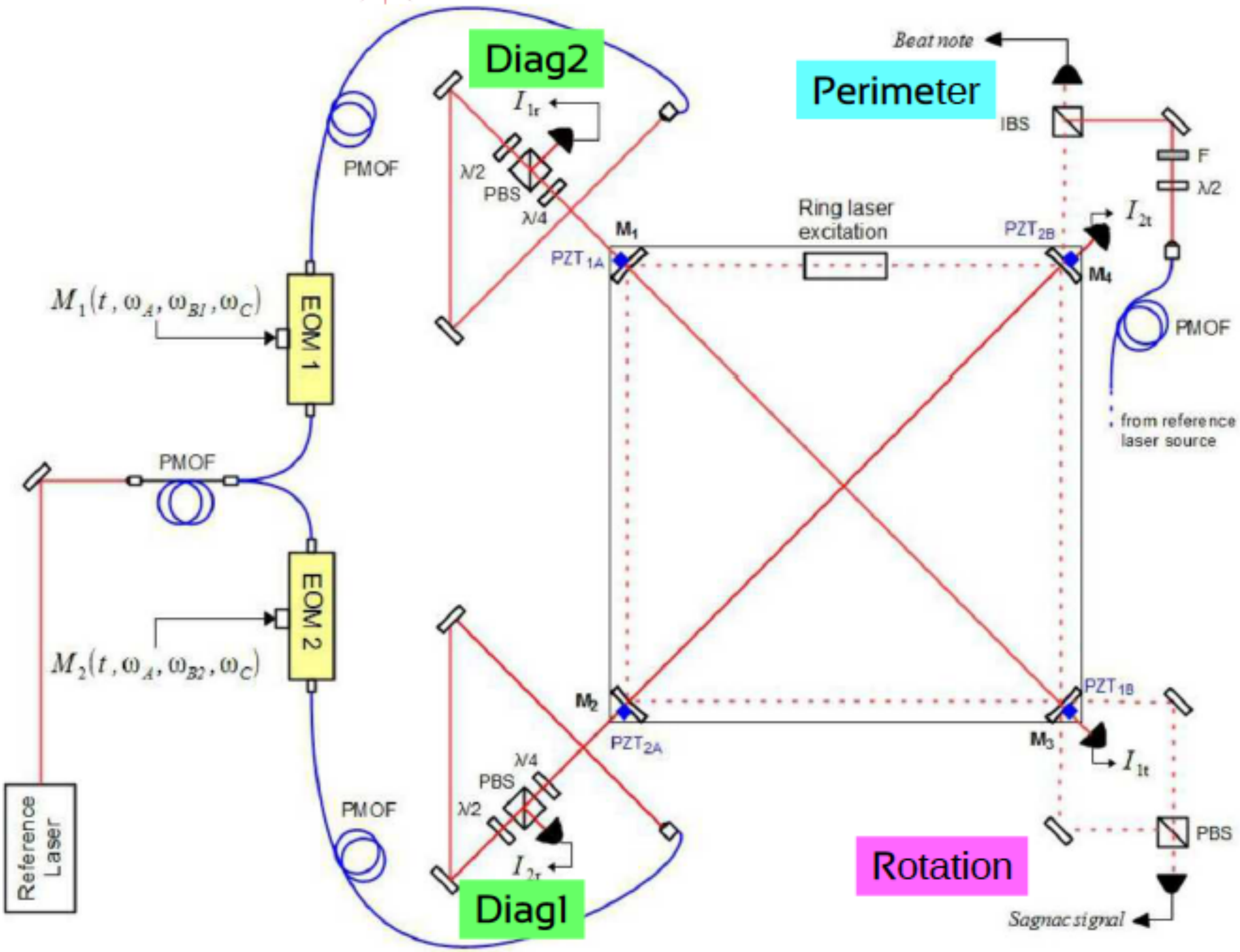
Stabilization methods: lock of diagonal cavities respect to a frequency standard



Interferometric length metrology for the dimensional control of ultra-stable ring laser gyroscopes, Class. Quantum Grav. 31 (22), 225003, (2014)

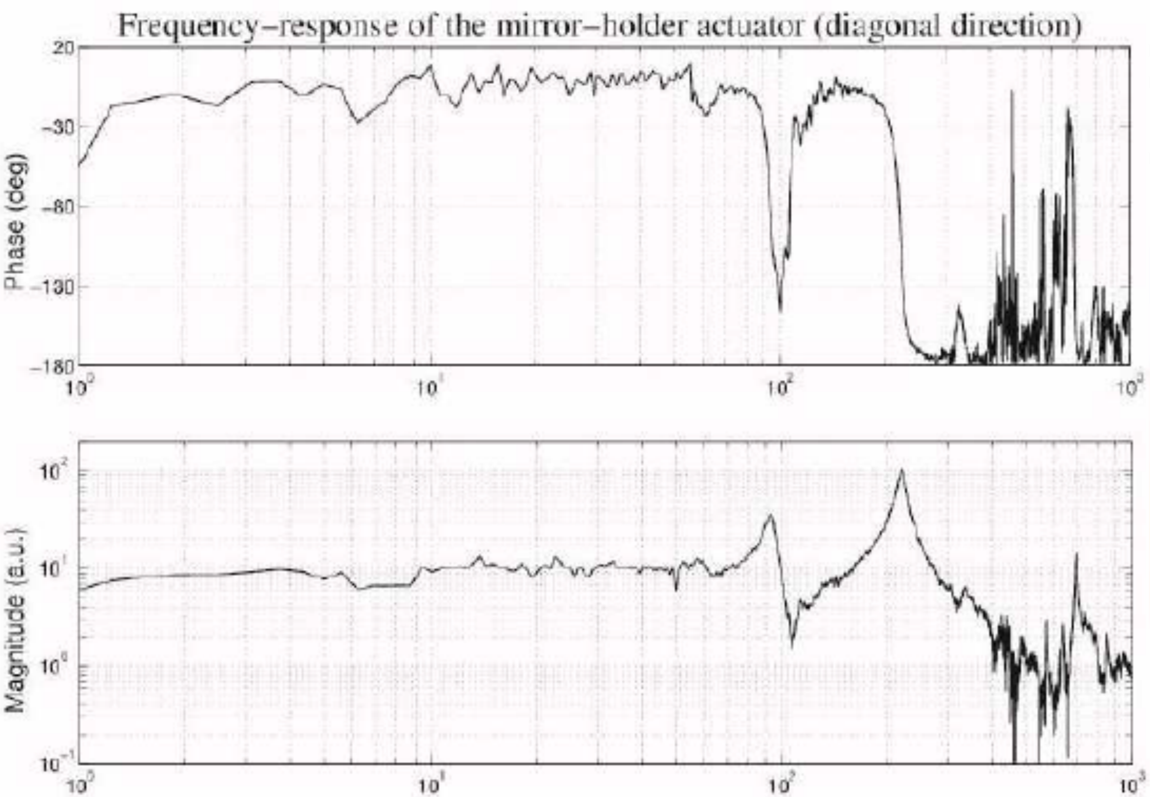
GINGER

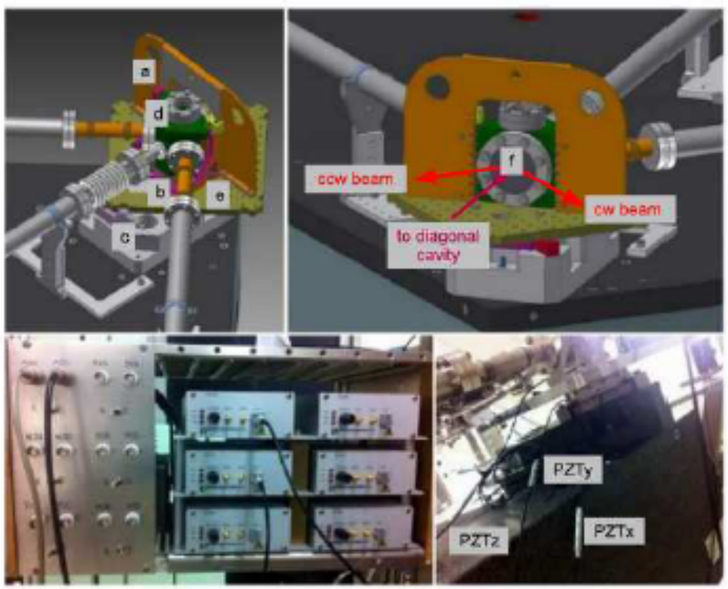
GP2: Optical setup



Mirrors position actuators

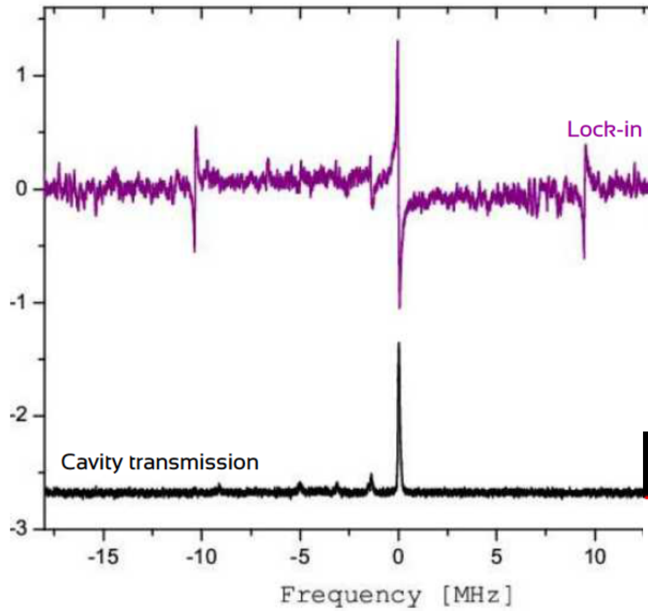
- #3 1-axial PZT; #1 3-axial PZT
- dynamic range (measured): 80 μm
- control bandwidth (measured): few tens of Hz





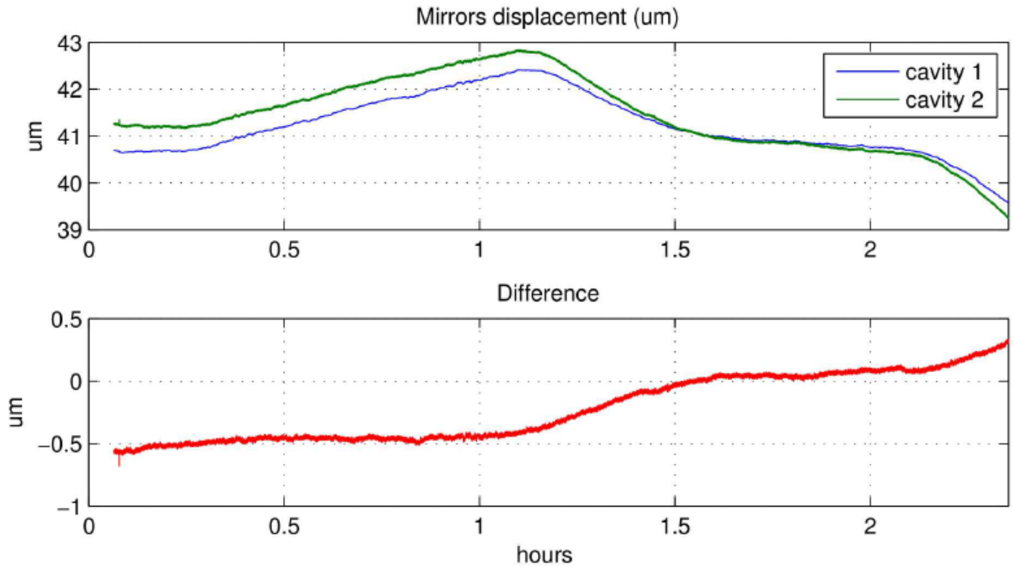
Carrier error signal on GP2

Digital lock-in amplifier



2 diagonals stabilization

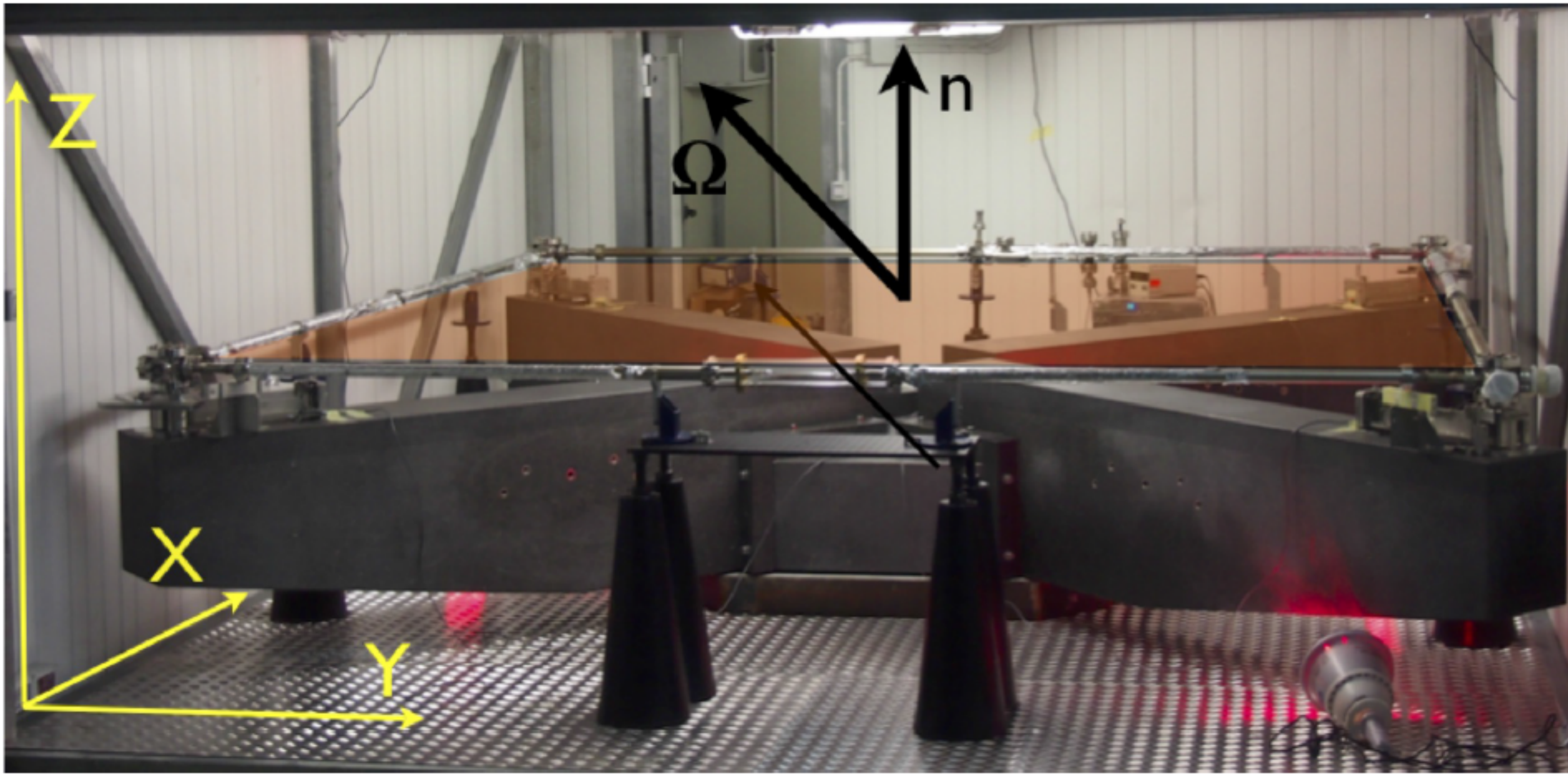
Closed-loop correction to the opposite mirrors (digital PI controller)

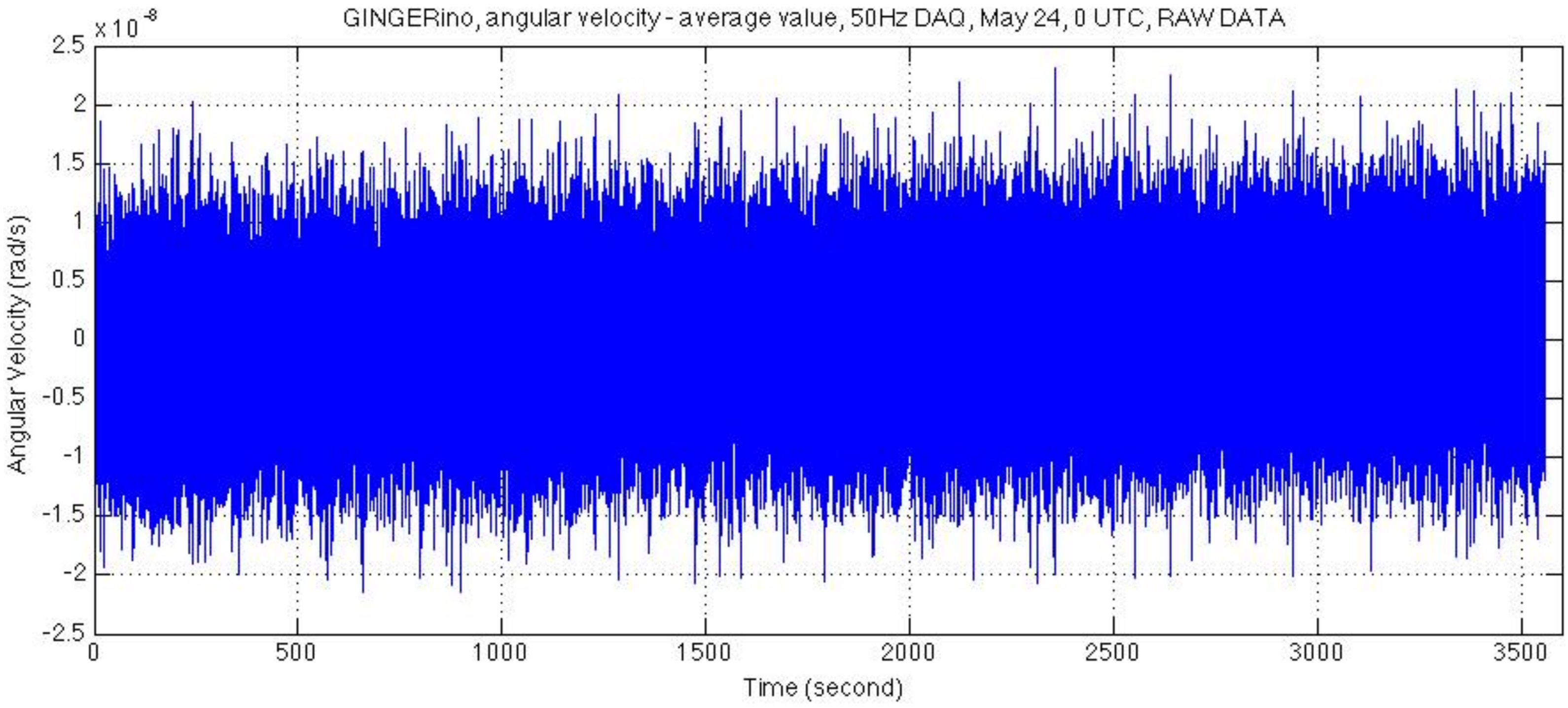


Sub-nanometer length metrology for ultra-stable ring laser gyroscopes, R. Santagata's PhD thesis, Siena 2015.

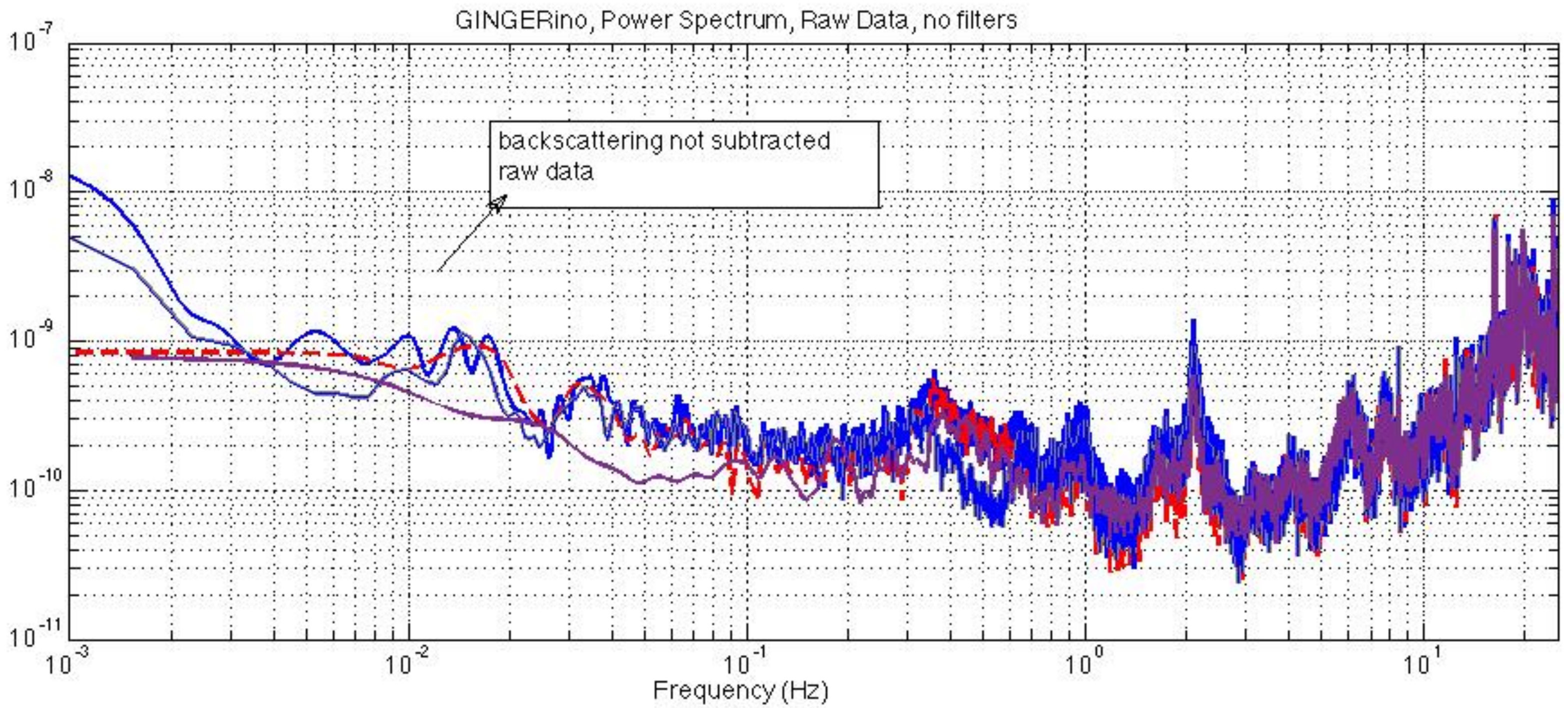
GINGER

GINGERino, the ring laser inside LNGS, 3.6m in side





GINGERino, angular velocity - average value, 50Hz DAQ, May 24, 0 UTC, RAW DATA
x 10^-8
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Angular Velocity (rad/s)
0
500
1000
1500
2000
2500
3000
3500
Time (second)


GINGERino, Power Spectrum, Raw Data, no filters
backscattering not subtracted
raw data
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency (Hz)

G-LAS, Gyro-Laser Angle Standard under assembling, 0.5 m in side

Fig. 1. Picture of the carbon fibre board mounted on the turntable. Three corner tower and two sides of the ring vacuum chamber has been already fixed on the board .

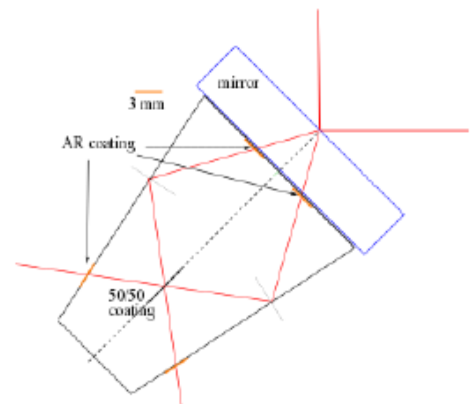


Fig. 3. The combining prism (Koester prism). It consists in two symmetric quartz prism glued together. On the contact region of the two prisms a semitransparent 50/50 coating allows beams combining

Transportable Goniometer for metrology INRIM/INFN

Accuracy 5 10^{-9} rad

Two papers with the analysis of tele-seismic events:
both Love and Rayleigh waves

References

[1] J. Belfi et al. "First Results of GINGERino, a deep underground ringlaser". In: (2016). arXiv: 1601.02874.

[2] A. Simonelli et al. "First deep underground observation of rotational signals from an earthquake at teleseismic distance using a large ring laser gyroscope". In: *Annales of Geophysics* 59 (2016), Fast Track 4. DOI: 10.4401/ag-6970.

[3] R. Santagata et al. "Optimization of the geometrical stability in square ring laser gyroscopes". In: *Classical and Quantum Gravity* 32.5 (2015). DOI: 10.1088/0264-9381/32/5/055013.

[4] J. Belfi et al. "Interferometric length metrology for the dimensional control of ultra-stable ring laser gyroscopes". In: *Classical and Quantum Gravity* 31.22 (2014). DOI: 10.1088/0264-9381/31/22/225003.

[5] D. Cuccato et al. "Controlling the nonlinear intracavity dynamics of large He-Ne laser gyroscopes". In: *Metrologia* 51.1 (2014), pp. 97–107. DOI: 10.1088/0026-1394/51/1/97.

[6] Angela Di Virgilio et al. "A ring lasers array for fundamental physics". In: *Comptes Rendus Physique* 15.10 (2014), pp. 866–874. DOI: 10.1016/j.crhy.2014.10.005.

[7] Alessandro Beghi et al. "Compensation of the laser parameter fluctuations in large ring-laser gyros: a Kalman filter approach". In: *Applied Optics* 51.31 (2012), pp. 7518–7528. DOI: 10.1364/ao.51.007518.

[8] J. Belfi et al. "A 1.82 m(2) ring laser gyroscope for nano-rotational motion sensing". In: *Applied Physics B-Lasers and Optics* 106.2 (2012), pp. 271–281. DOI: 10.1007/s00340-011-4721-y.

[9] Jacopo Belfi et al. "Horizontal rotation signals detected by "G-Pisa" ring laser for the M-w=9.0, March 2011, Japan earthquake". In: *Journal of Seismology* 16.4 (2012), pp. 767–776. DOI: 10.1007/s10950-012-9276-9.

[10] Jacopo Belfi et al. "Performance of "G-Pisa" ring laser gyro at the Virgo site". In: *Journal of Seismology* 16.4 (2012), pp. 757–766. DOI: 10.1007/s10950-012-9277-8.

[11] F. Bosi et al. "Measuring gravitomagnetic effects by a multi-ring-laser gyroscope". In: *Physical Review D* 84.12 (2011). DOI: 10.1103/PhysRevD.84.122002.

[12] J. Belfi et al. "Active control and sensitivity of the "G-Pisa" gyrolaser". In: *Nuovo Cimento Della Societa Italiana Di Fisica B-Basic Topics in Physics* 125.5-6 (2010), pp. 557–567. DOI: 10.1393/ncb/i2010-10859-5.

[13] A. Di Virgilio et al. "A LASER GYROSCOPE SYSTEM TO DETECT THE GRAVITO-MAGNETIC EFFECT ON EARTH". In: *International Journal of Modern Physics D* 19.14 (2010), pp. 2331–2343. DOI: 10.1142/s0218271810018360.

[14] Angela Di Virgilio et al. "Performances of 'G-Pisa': a middle size gyrolaser". In: *Classical and Quantum Gravity* 27.8 (2010). DOI: 10.1088/0264-9381/27/8/084033.

1

Summary

- Ringlaser with ~ 1m in side are robust, bandwidth ~ 1kHz
- Triangular rings feasible
- the independent components of the angular rotation vector can be measured changing the orientation of the ring (ROMY 4 rings array in construction in Baviera, ERC Heiner Igel)
- They are suitable for 'observatory', they run un-attended
- Sensitivity depends on mirror and size, easily better than 10^{-9} rad/s/sqrt(Hz)