The GINGER Project

A. Di Virgilio- INFN-Pisa

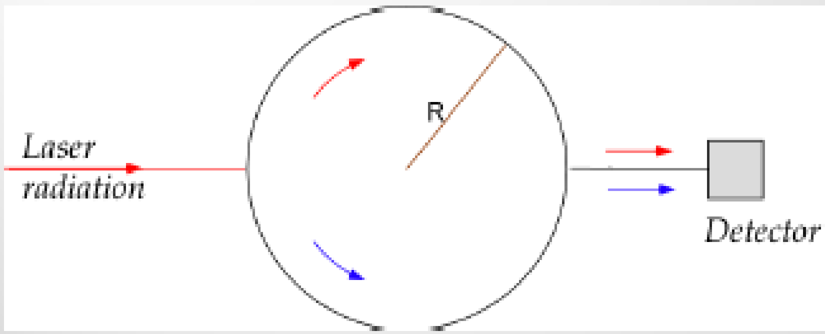
G-GranSasso is and R&D experiment aiming at the use of an array of ring-laser for fundamental physics experiment

Gyroscopes IN GEneral Relativity

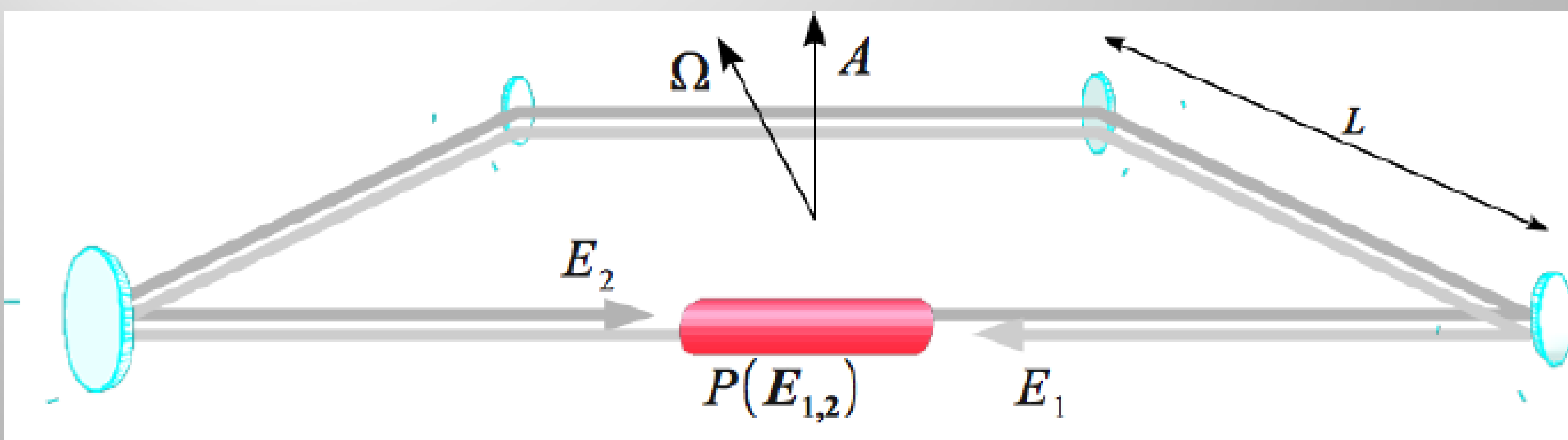
outline

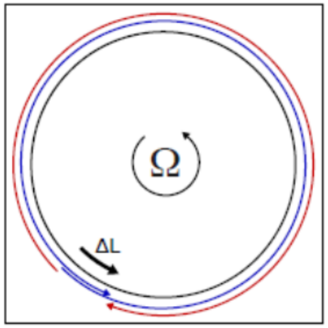
- Generals of the measurement
- **Ring-Laser** Status of the art and importance of the measurement (inter-disciplinarity)
- Status of a single rings
- The proposal / work in progress
- Inter-disciplinarity
- Our prototypes: GINGERino and GP2
- Conclusions

The Sagnac Effect and the ring-laser



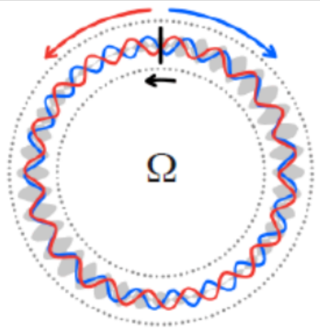
$$f_{Sagnac} = \left| f_{CW} - f_{CCW} \right| = \frac{4\vec{A}\cdot\vec{\Omega}}{\lambda p}$$





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

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

- Low cavity losses
- High power
- Large size

Mechanical, fiber optic, and ring laser gyroscopes

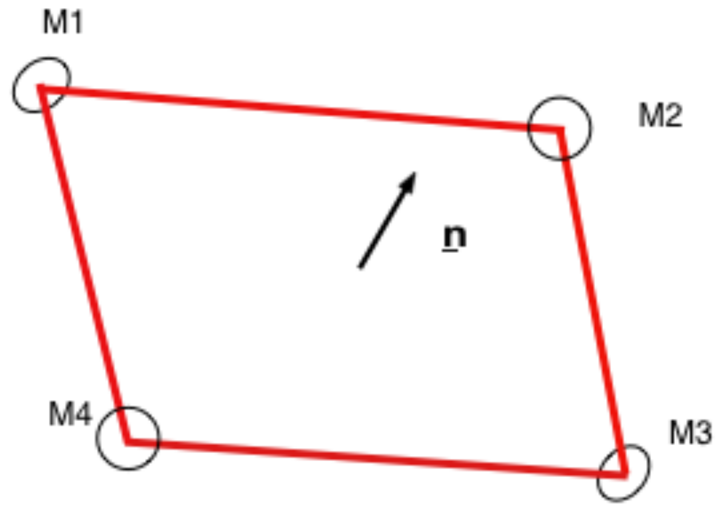
We have focused our attention to the applications of RingLasers to GR test
INFN-Fundamental Physics Research

- (Cosmology)
- Celestial mechanics
- Lensing
- Gravitational waves
- Equivalence principle
- Rotation effects (gravitomagnetism)

First point: increase the sensitivity

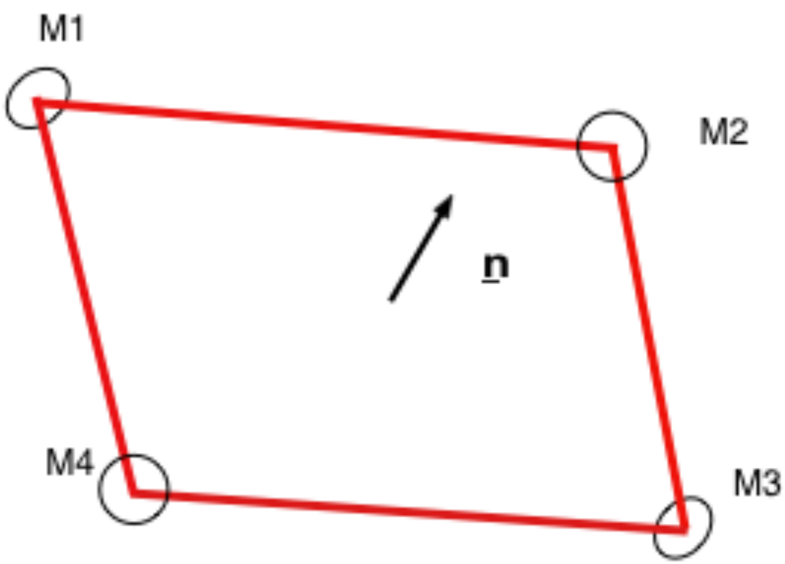
GINGER- General Relativity test on a Earth based laboratory

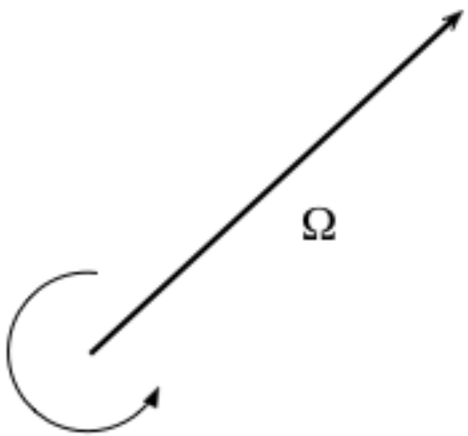
(Improvement at low frequency of the GW interferometric antennas?)



the ringlaser gyroscope is described by **n** and its scale factor **S**

Basic of the ring-laser

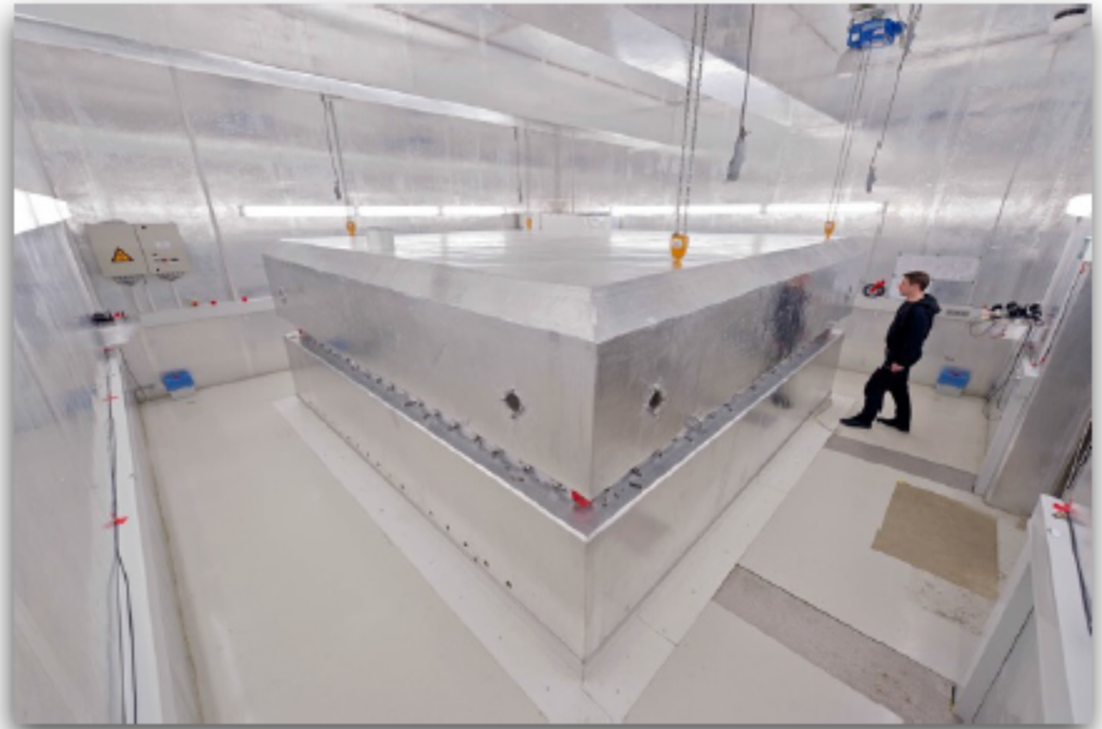




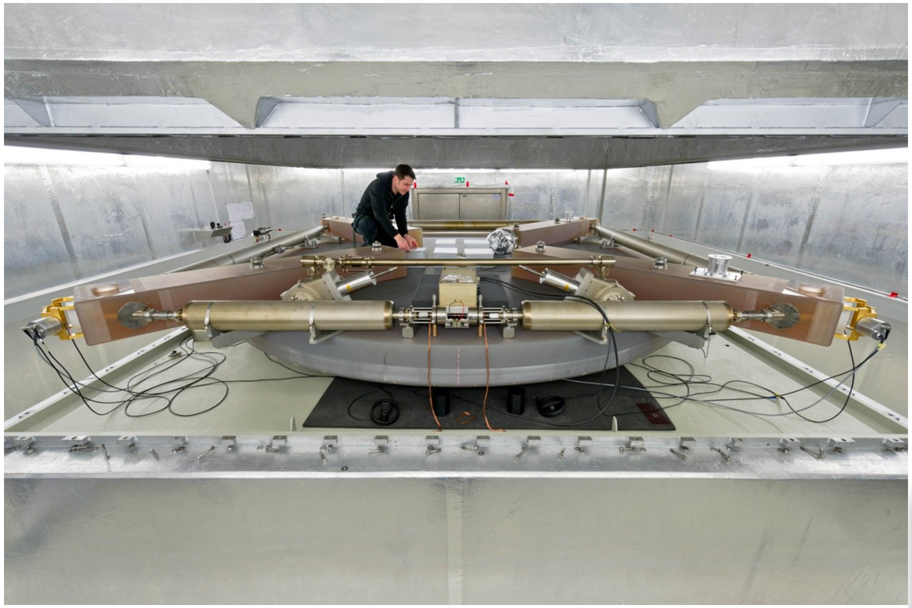
the ringlaser gyroscope is described by **n** and its scale factor **S**

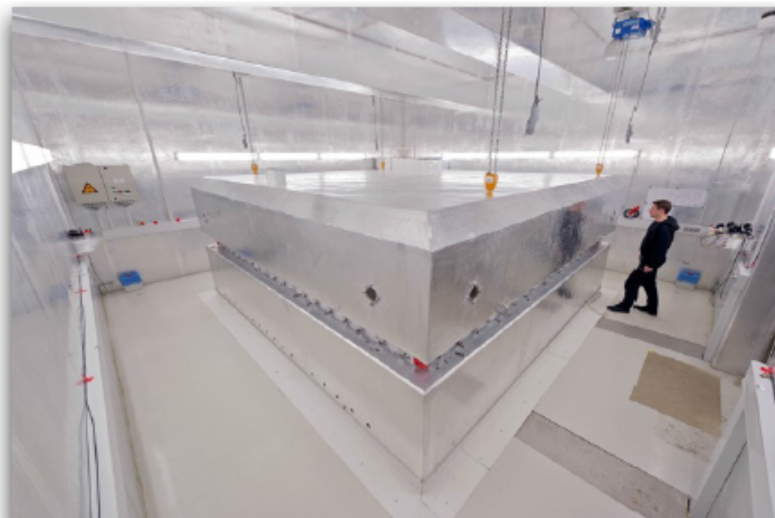
The Gross Ring G of the geodetic observatory of Wettzell

Operations can be stabilized by controlling the perimeter via piezo actuators and pressure stab. vessel



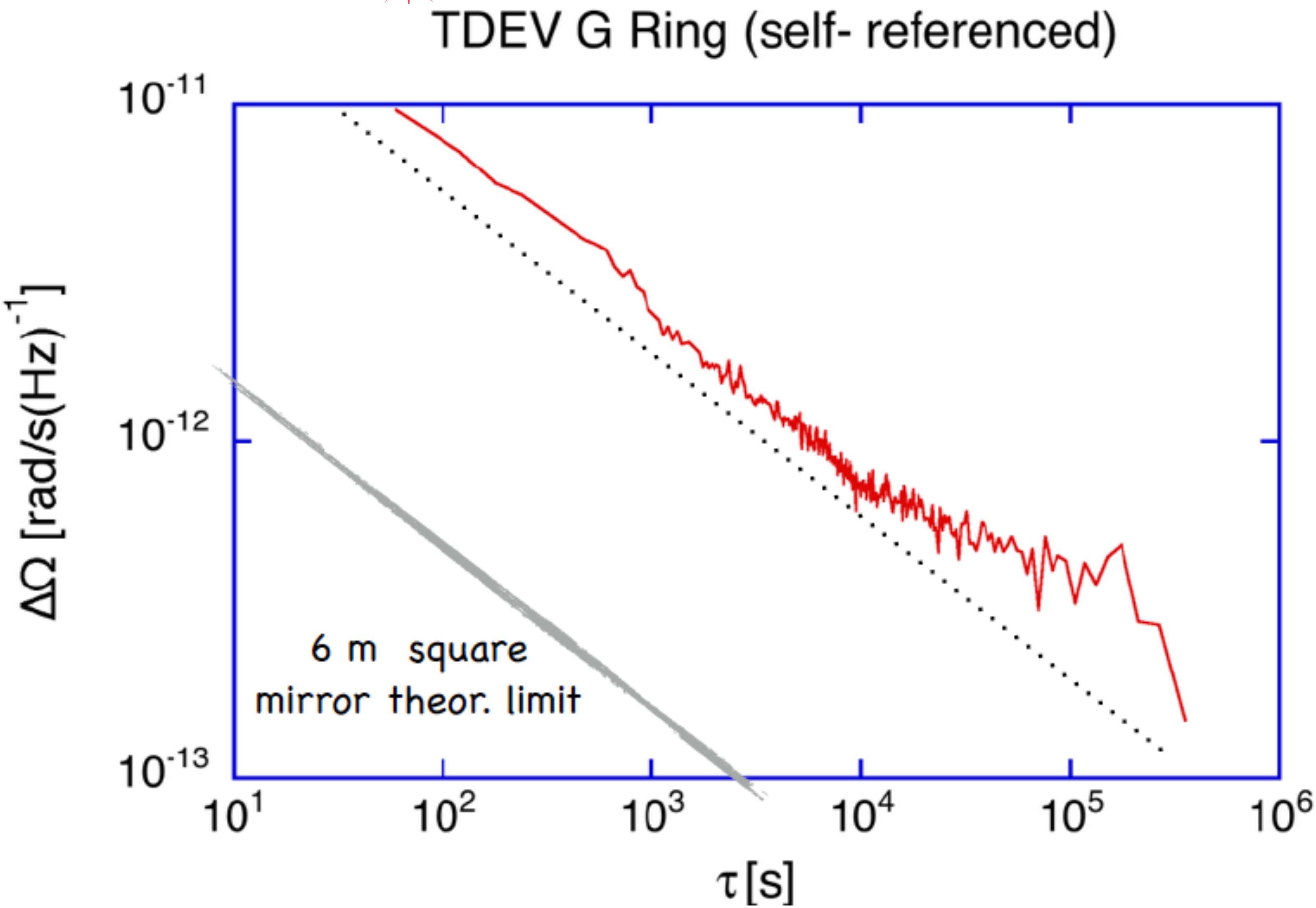
G





Impossible to develop a 3D device and monitor the relative angle with nrad accurac

Status of the Art (G Wettzell) target → 10^{-14} rad/s



U. Schreiber courtesy

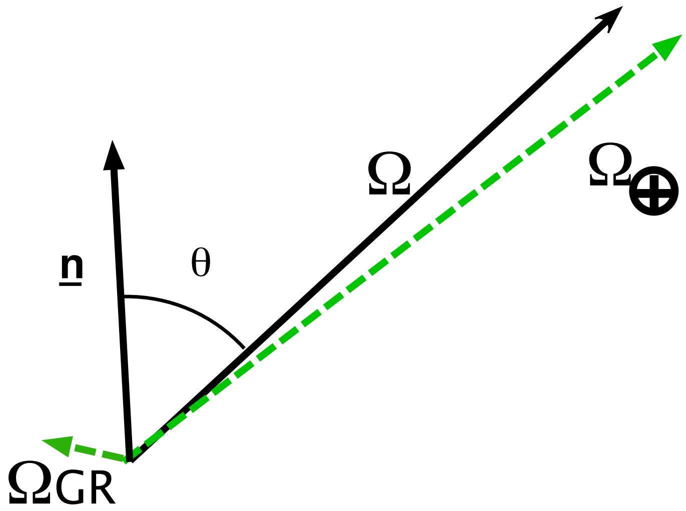
the ring-laser signal in more detail….

The ring laser frequency is proportional to the kinematical term $\Omega_\oplus$ and other relativistic terms, the two main terms are:

$$\mathbf{\Omega}_G = -(1+\gamma)\frac{GM}{c^2R}\sin\vartheta\,\Omega_\oplus \boldsymbol{u}_\vartheta,$$

$$\mathbf{\Omega}_B = -\frac{1+\gamma+\frac{\alpha_1}{4}}{2}\frac{GI_\oplus}{c^2R^3}[\mathbf{\Omega}_\oplus - 3(\mathbf{\Omega}_\oplus\cdot\boldsymbol{u}_r)\boldsymbol{u}_r],$$

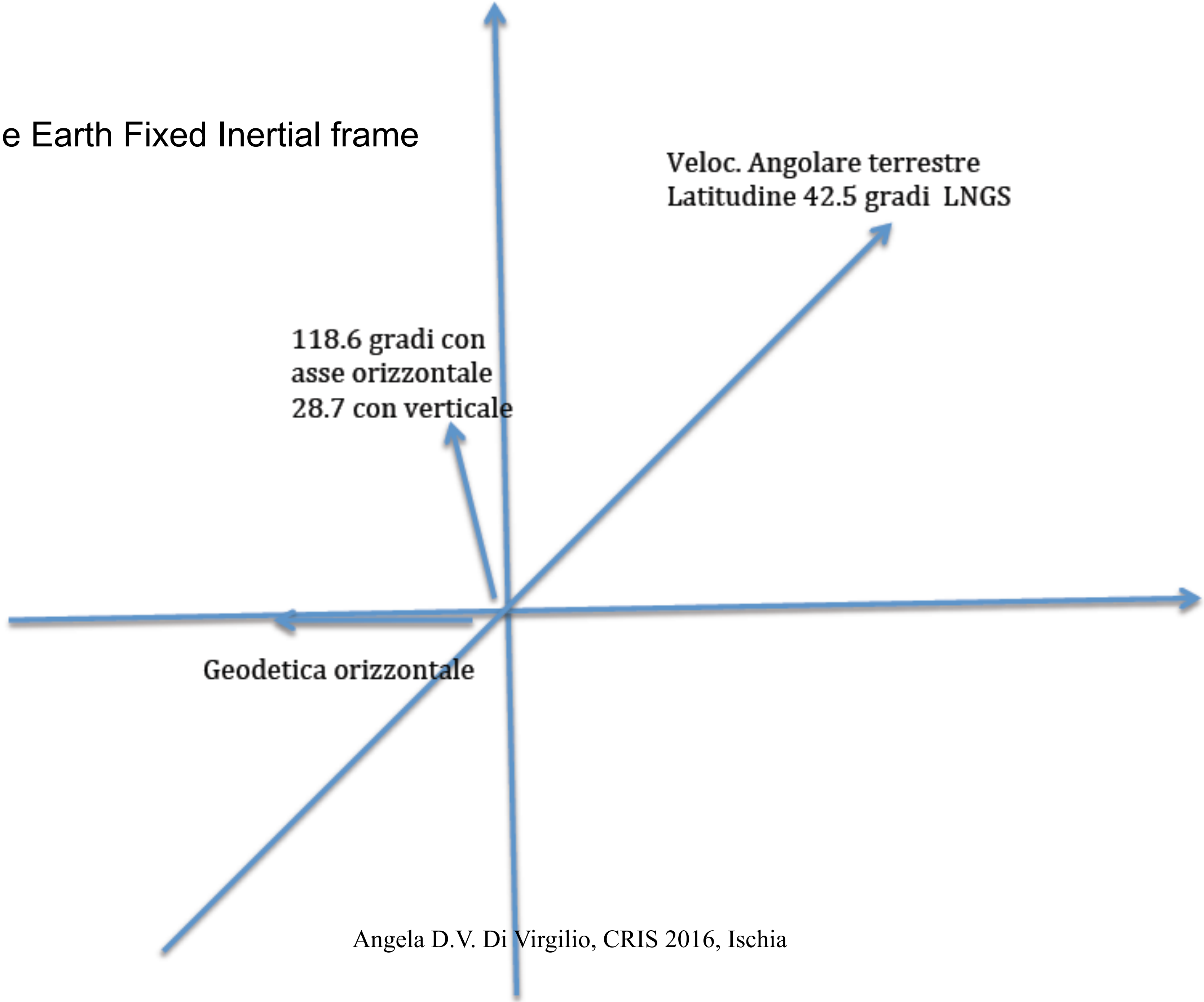
The equations are very complicated but in practice



- We measure Ω
- We know $\Omega_{\oplus}$
- We want to know Ω_{GR}
- **<u>$\langle \Omega \rangle$ is sum of this two terms</u>**

- **Increase the sensitivity**
- **Necessary to know the orientation**
- **Necessary to link Ω and <u>n</u> with high precision (θ)**

In the Earth Fixed Inertial frame



Ring Laser/ Shot Noise Limit

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

- improves quadratically with L (Q & A/p)
- P_{out} room for improvements **20 nW→ 500nW** in principle feasible?
- shorter wavelength poses several problems (mirrors, diffusion etc)
- Squeezing feasible, but so far never it has been applied

GINGER

Increase Sensitivity

Increase the size L

Mirror: low loss and at the same time high transmission

High transmitted power

Shorter λ

$$3\times10^{-13}\left(\frac{Losses}{\frac{2ppm}{m}}\right)\left(\frac{7\times7}{L^2}\right)\left(\frac{\lambda}{633nm}\right)\sqrt{\frac{500nW}{Pout}\times\frac{1}{t}\frac{rad}{s}}\sqrt{Hz}$$

mirror transmission 1ppm, it is part of the Losses

Short Discussion on Mirrors

Status of the art:

substrates + coating+ care in handling

Total losses **~ 1-2 ppm**

Transmission should be of the same order at least for one of the mirrors

Characterization of each mirror should help (select the best…)

We know how to obtain such mirrors, and substantial improvements on mirror quality does not seems feasible in the near future

Test area under development in the Pisa Clean Rooms

In practice

High sensitivity ring lasers are feasible

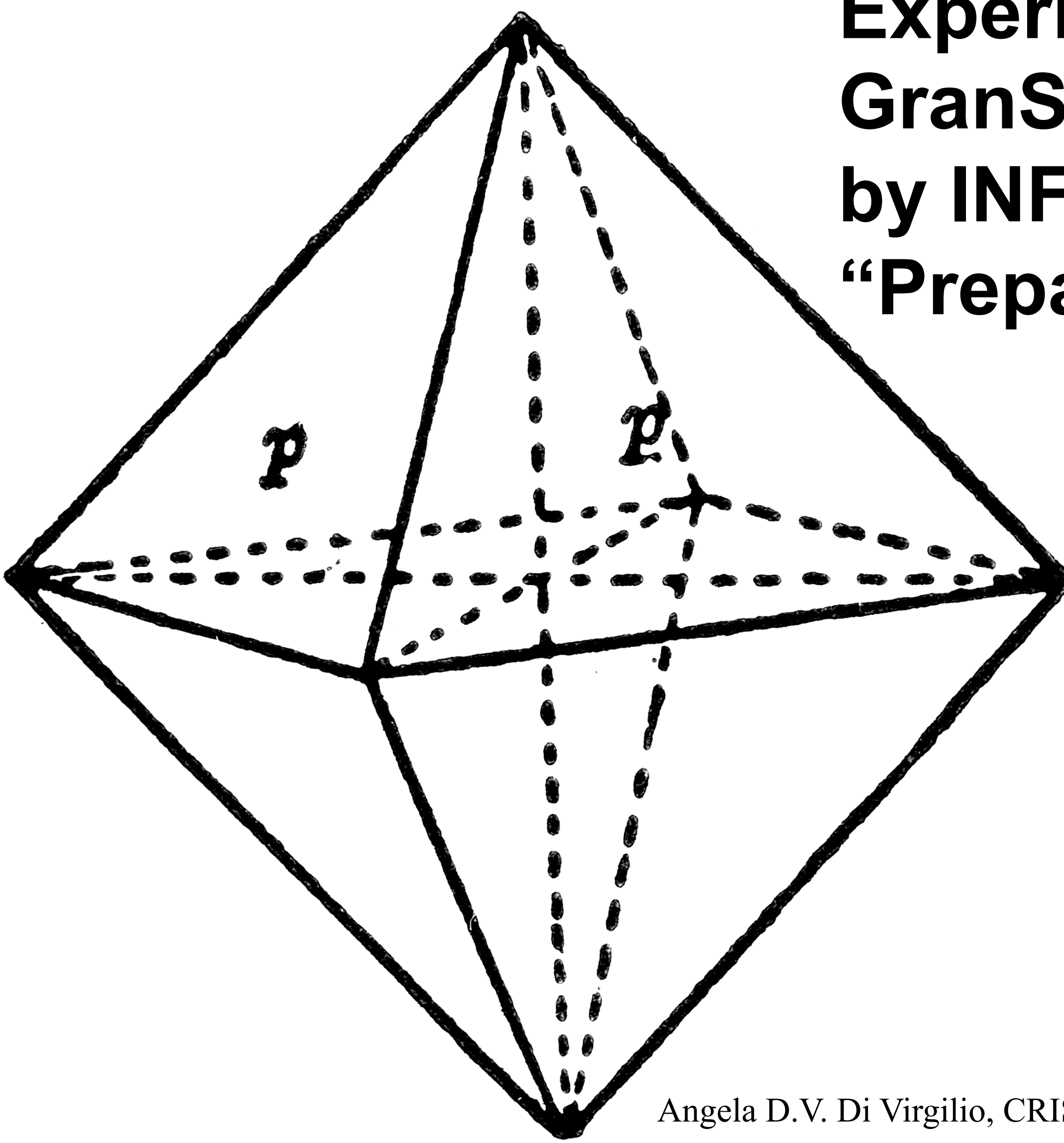
Next step→ build arrays and ROMY ERC project is the first array (Baviera-Geophysics)

Alignment of the rings

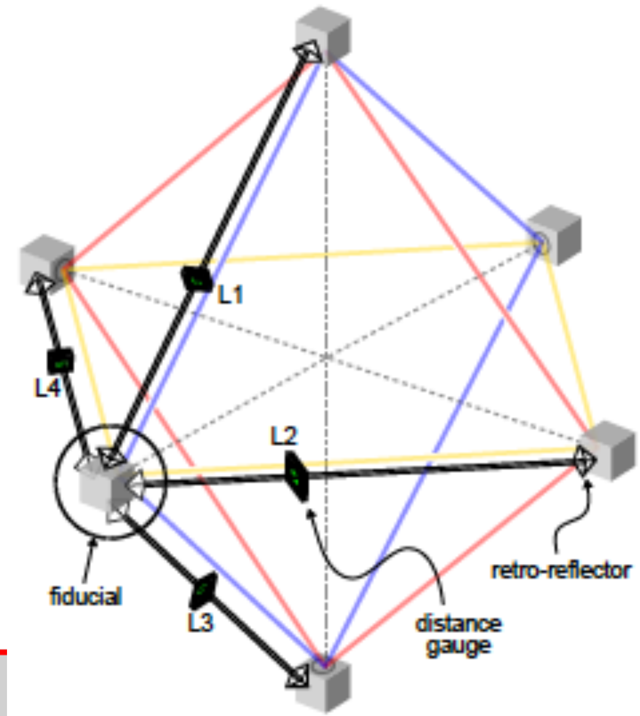
The sensitivity is not an issue, the absolute and relative alignment of the rings is the present limitation for the reconstruction of the signals, especially for General Relativity tests and Geodesy

In the first GINGER set up relative alignment of rings determined at nrad precision

GINGER The octahedron is a 3D rigid figure

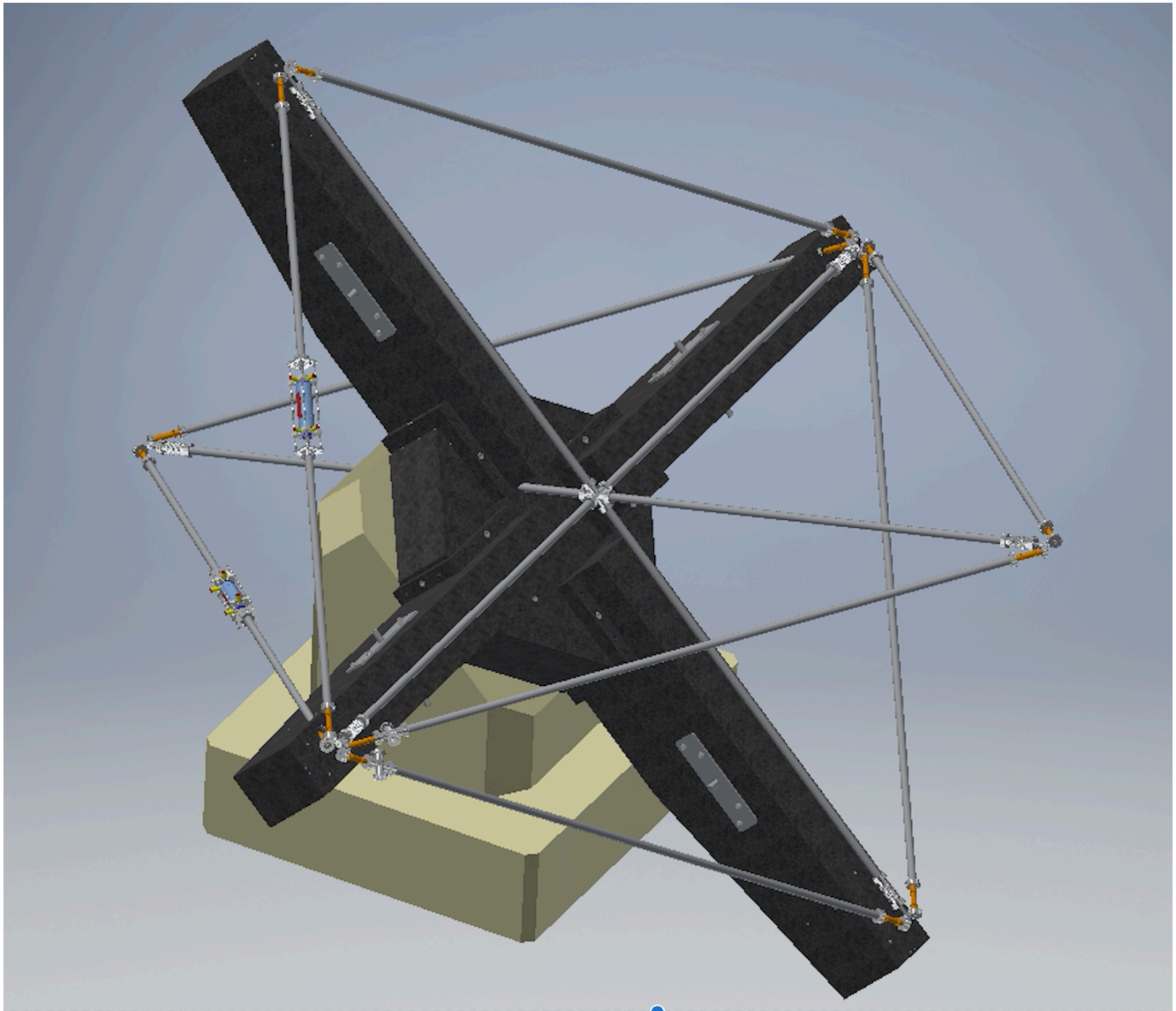


Experiment G-GranSasso-R&D financed by INFN Group II→ "Preparing GINGER"



GINGER

Preparing a proposal for LNGS: investigating 2 (or 3) rings in the meridian plane as a first step toward the octahedron



We hope to complete the proposal before the end of the year

People involved:

Pisa: J. Belfi, N. Beverini, G. Carelli, A. Di Virgilio, E. Maccioni,F. Morsani, A. Simonelli, G. Terreni

LNL: A. Ortolan

Napoli: C. Altucci, A. Porzio(CNR) and L. Velotta

Padova-DEI: A. Beghi, D. Cuccato, A. Donazzan, G. Naletto, M. Pellizzo (CNR)

Torino-Pol.: M.L. Ruggiero and A. Tartaglia

TUM: U. Hugentobler and U. Schieiber

LMU: I. Higel and J. Wassermann

Canterbury-NZ: JP Wells

Interdisciplinarity

Rotational Sismology

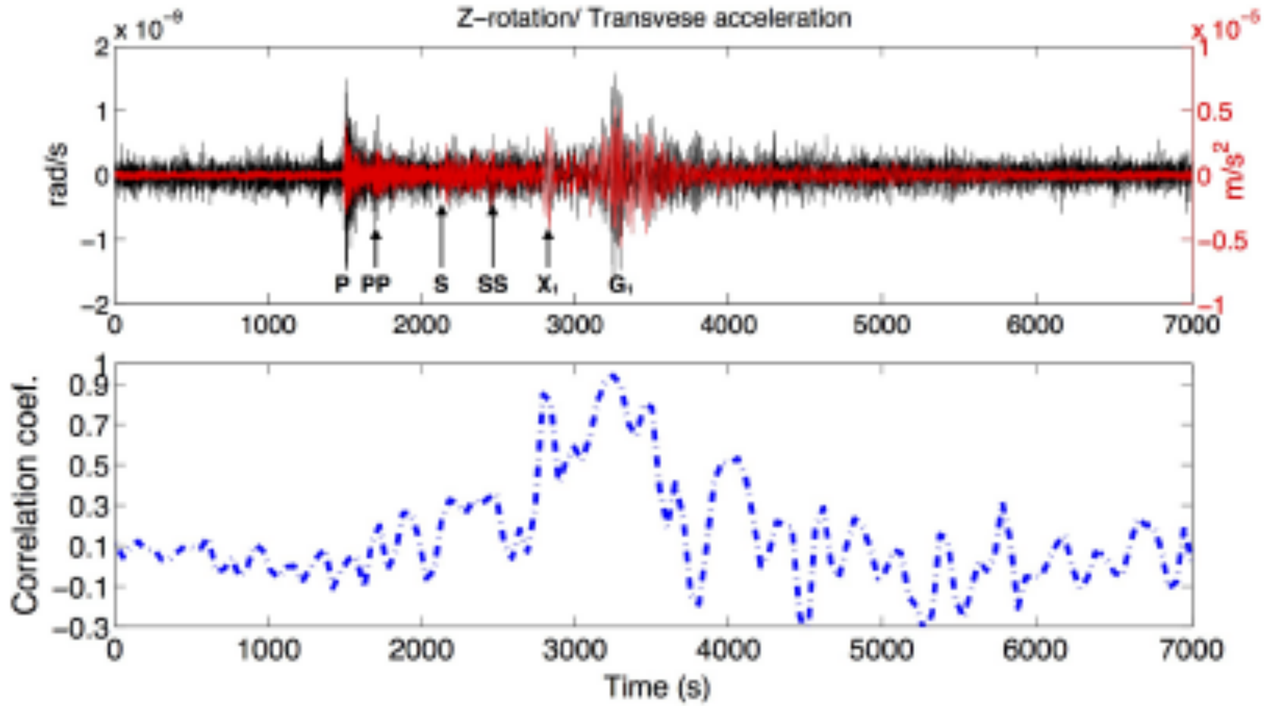


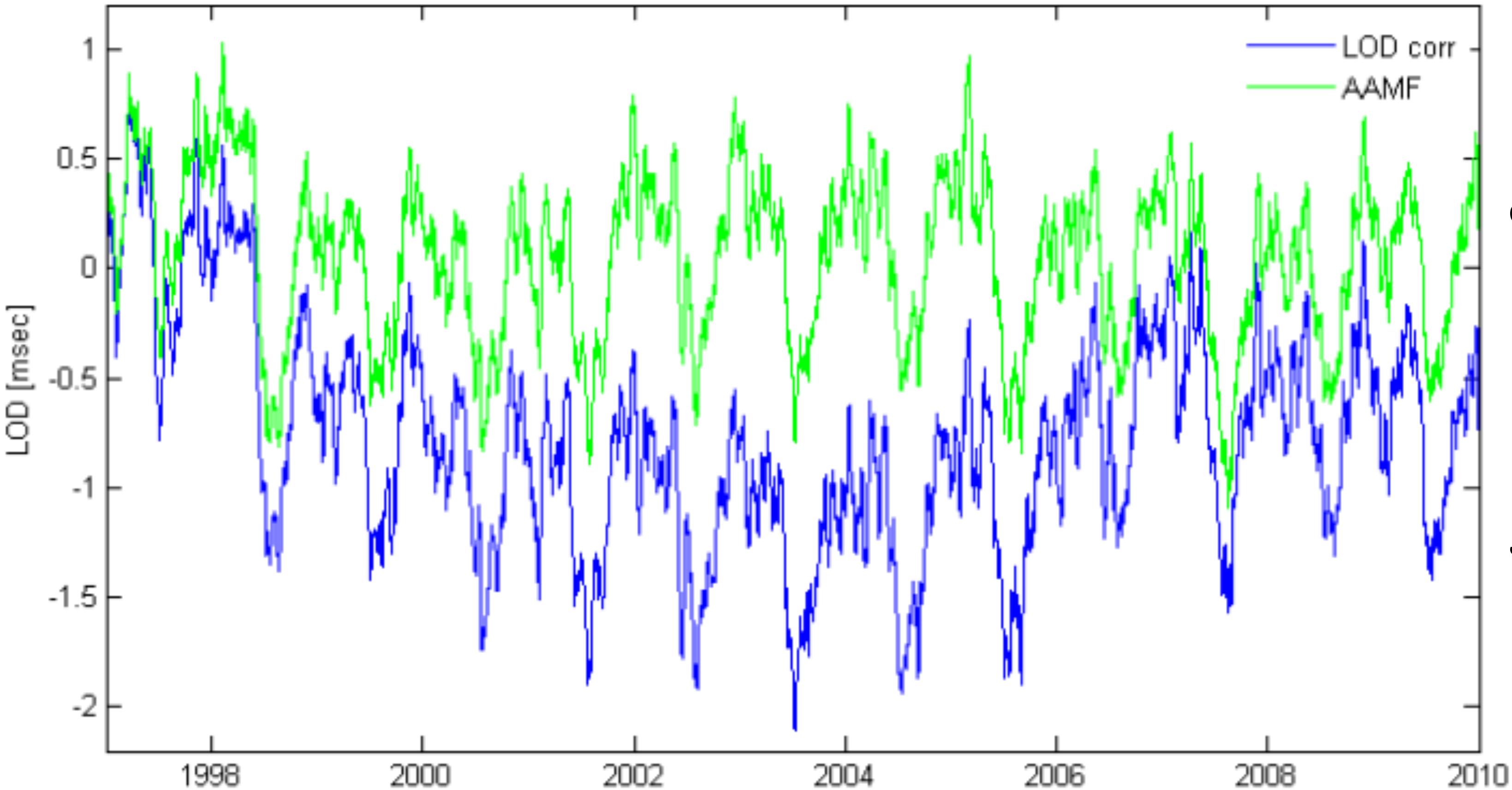
Figure 4: *(top) Ground rotation and transverse acceleration time histories (black and blue lines, respectively), time zero is at 12:40:00 UTC. (bottom) ZLCC between the above traces.*

GINGERino: collaboration with INGV

Earth Rotation

GEODESIA

- Measured LOD and Atmospheric Angular Momentum from Weather Model



U. Hugentobler courtesy

Our prototypes

GINGERino/ underground laboratory of GranSasso

GP2, prototype in Pisa

+ G-LAS progetto premiale INRIM-INFN

G-LAS, Gyro-Laser Angle Standard under construction

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 .

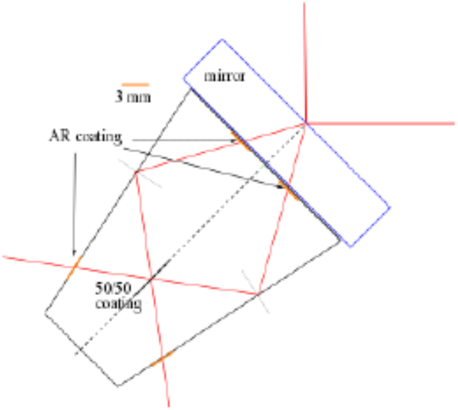


Fig. 3. The combining prism (Koester prism). It consists in two symmetric quartz prism glued together. On the contact region of the two prisms a semitransparent 50/50 coating allows beams combining

Hetero-lithic ring laser and its geometry control

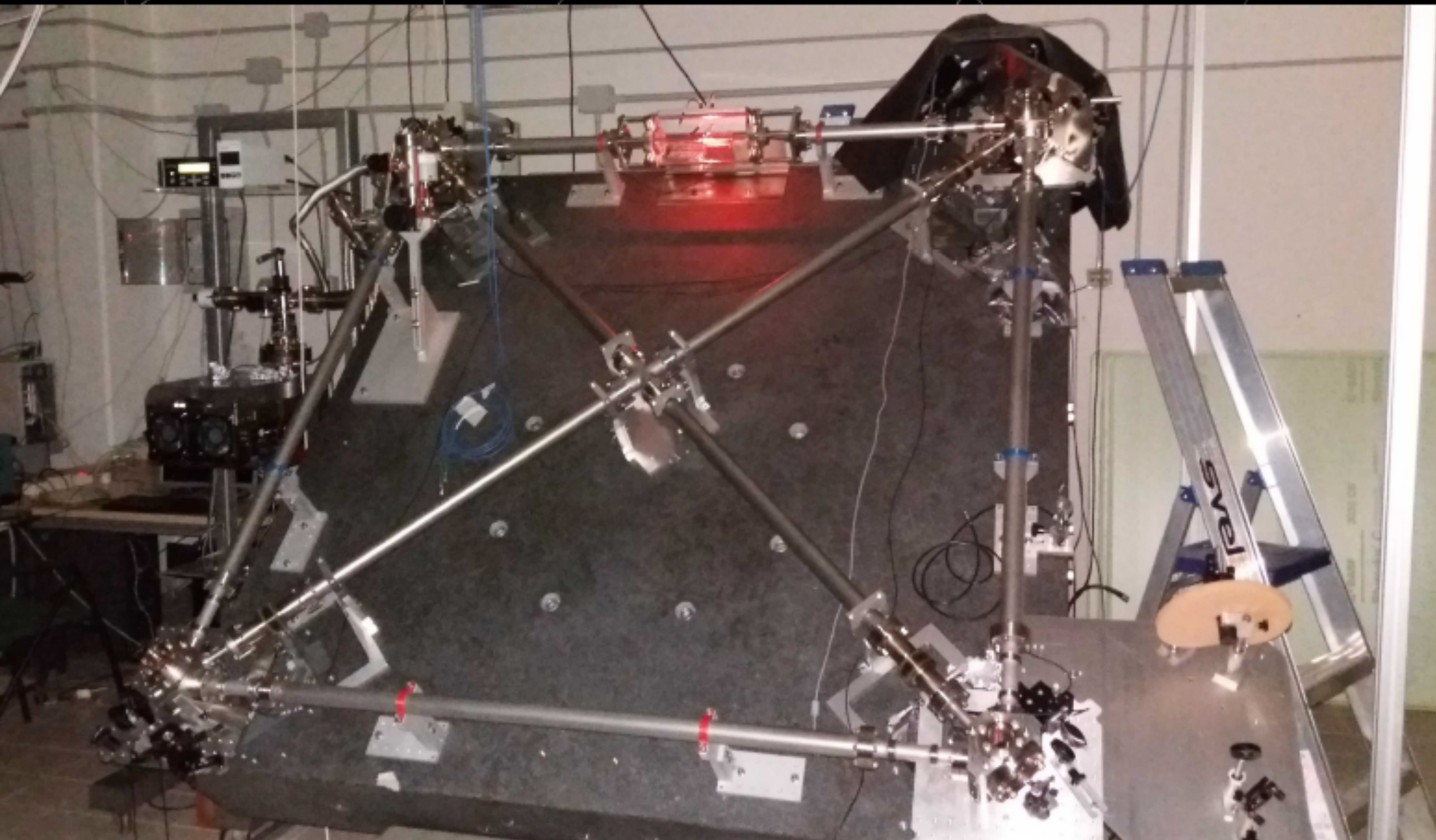
Basic element of the array

the control of each ring →

bring the ring close to the ideal square and

keep constant the length of the diagonals

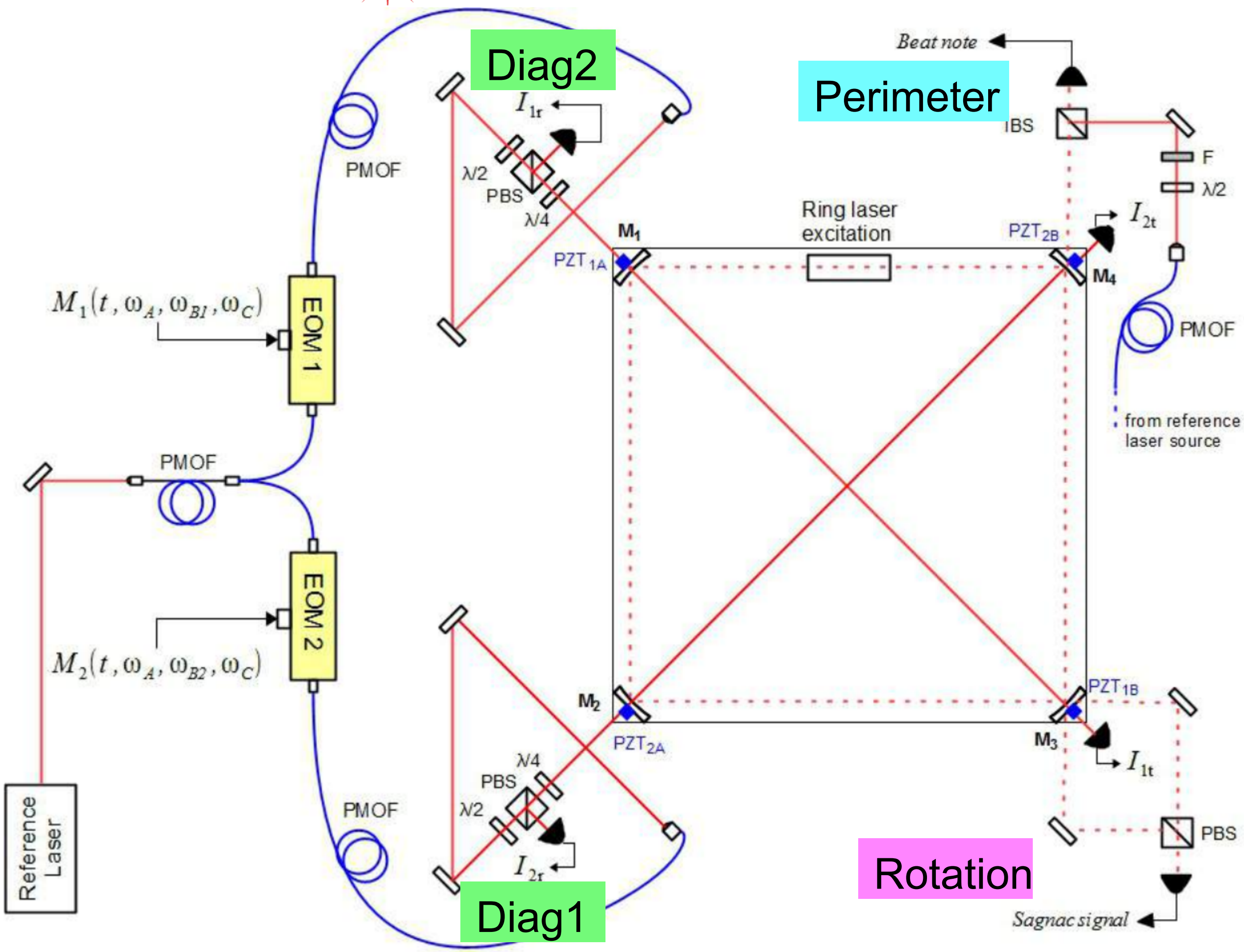
keep fixed the perimeter



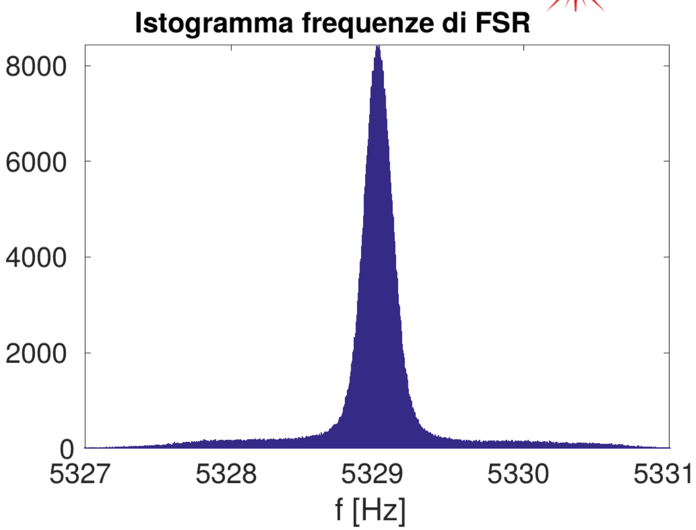
GP2

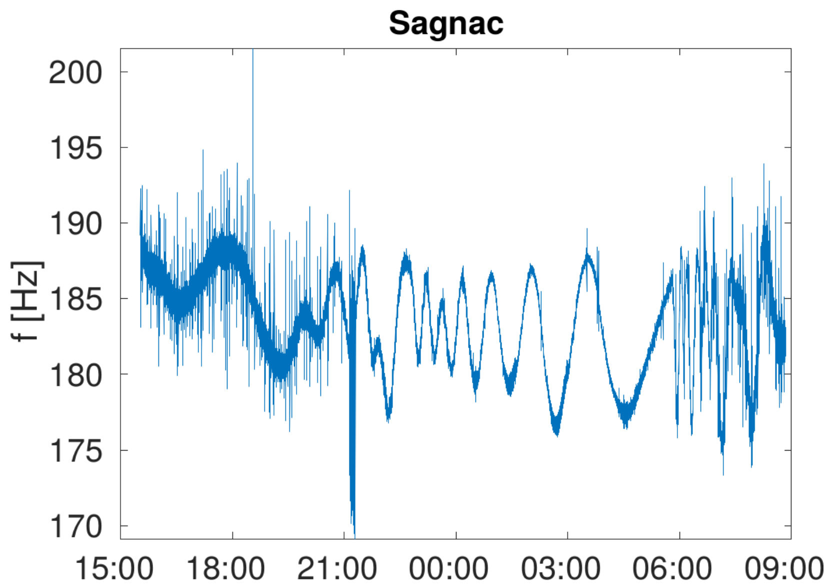
INFN-Pisa

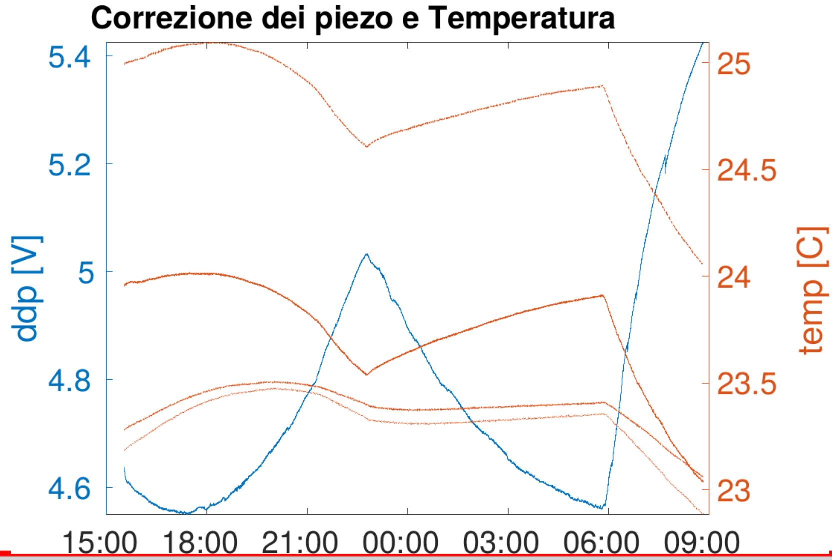
GP2: Optical setup



GP2: perimeter locked using the FSR methode

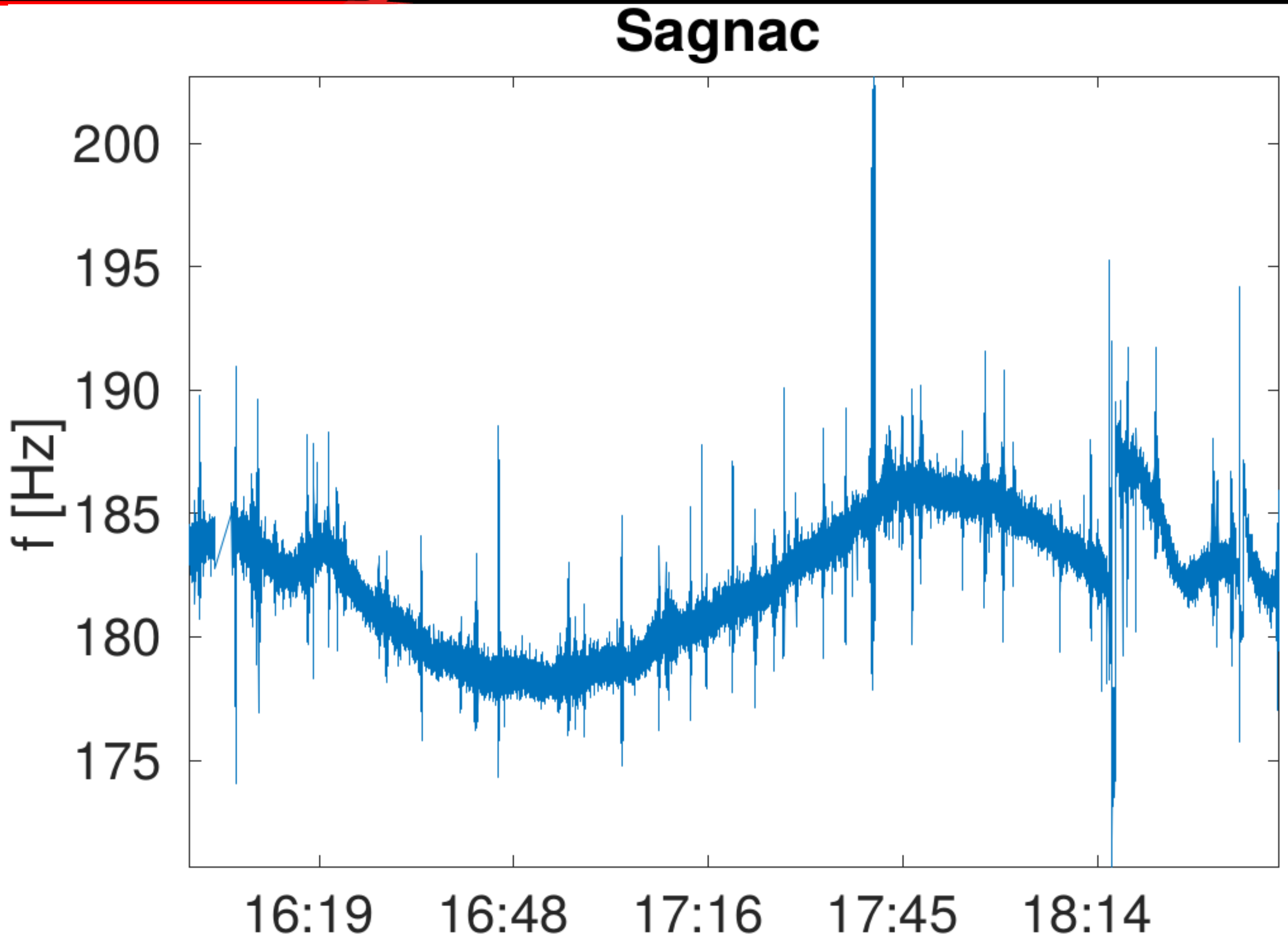






Correction compensate the temperature effect on the geometry

GP2: diagonals locked



Status of GP2

Ring laser on and the two diagonals resonating (mirrors are suitable for 45^o and 90^o incidence)

GP2 has been working continuously for few days controlling the diagonals

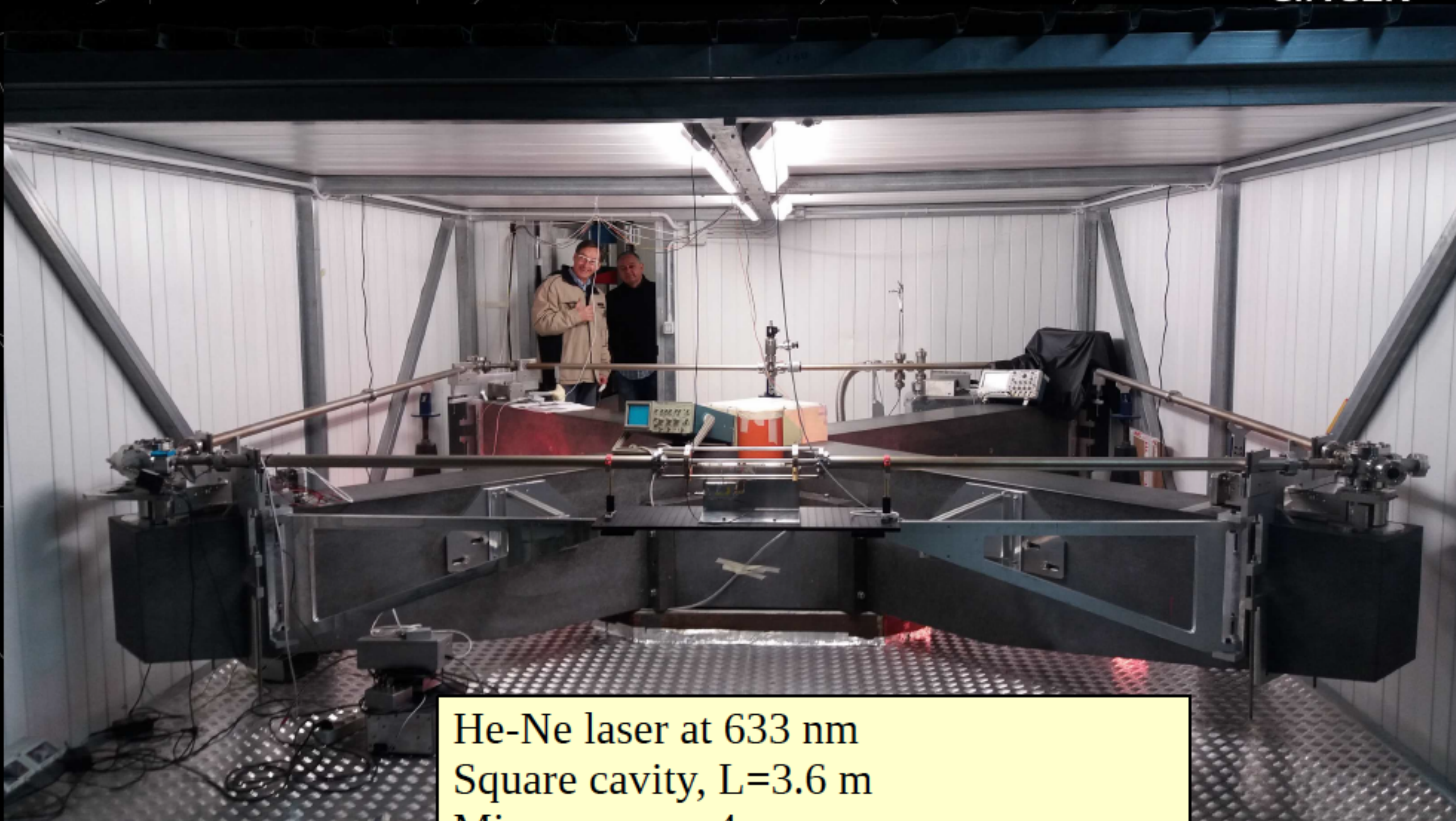
We hope to complete the test in one year

GINGER

GINGERino: deep underground ring laser

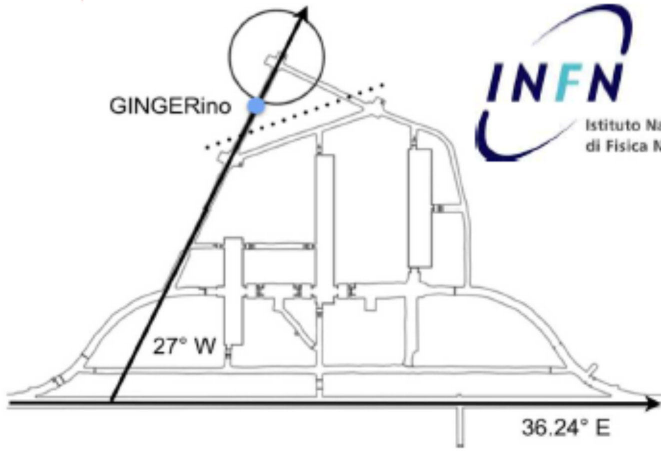
GINGER-ino (INFN-LNGS)+ Seismometers (INGV)

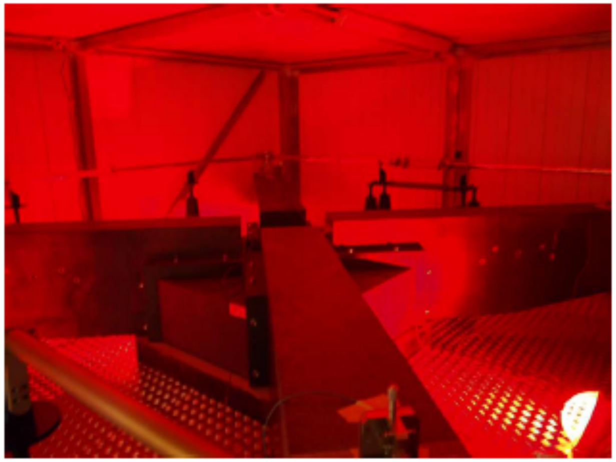
GINGER



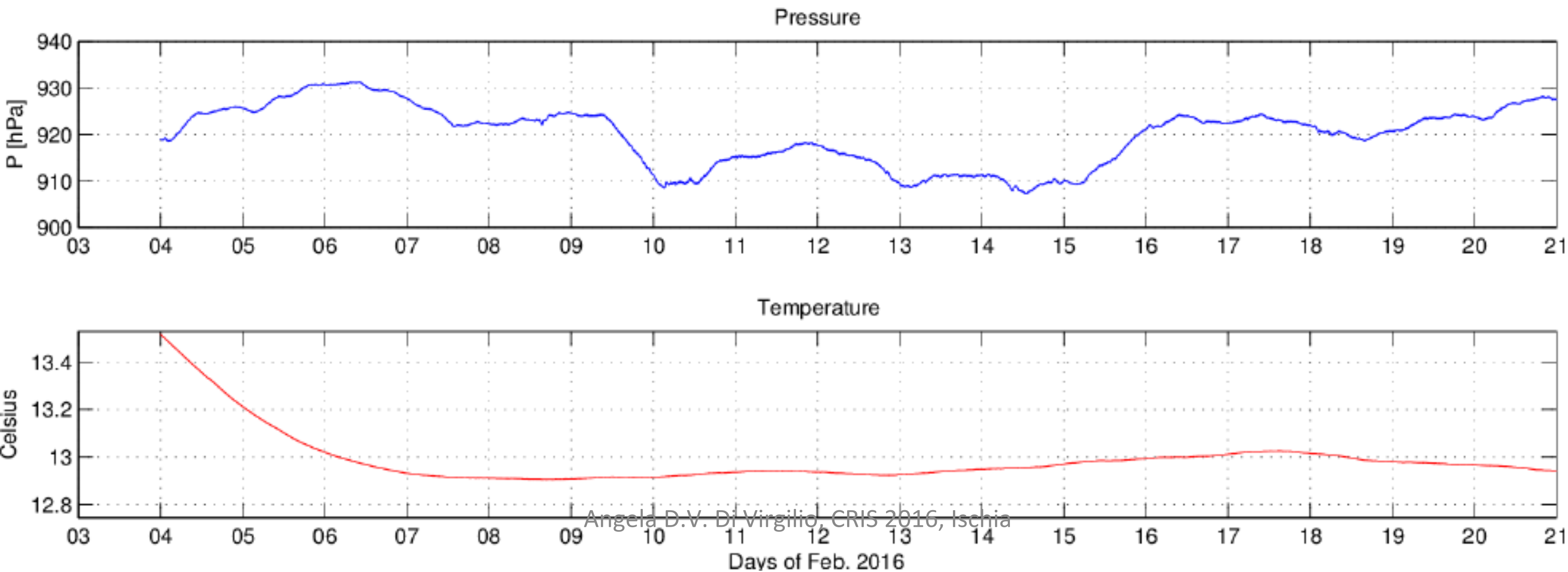
He-Ne laser at 633 nm
Square cavity, L=3.6 m
Mirrors r.o.c= 4 m
Earth rotation Sagnac bias: **fs=280.4 Hz**

Installation site

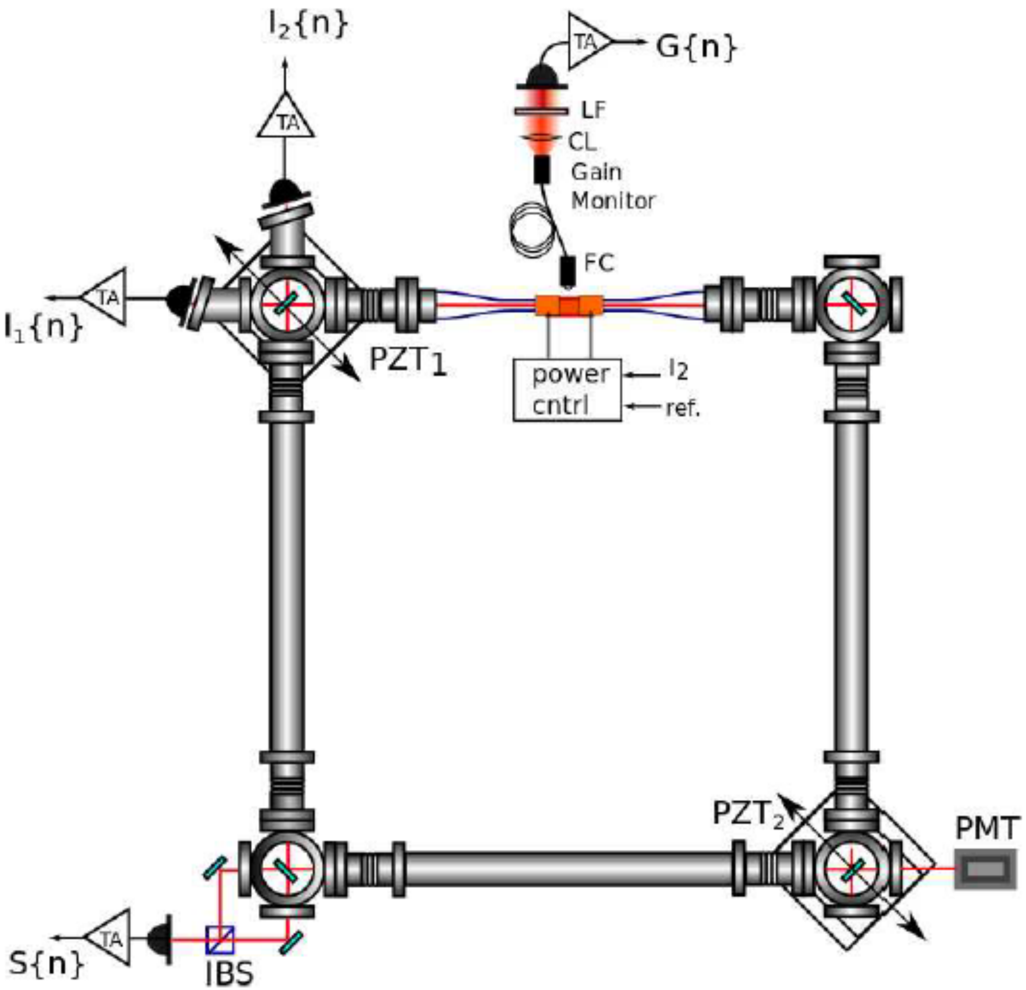




Internal temperature is controlled by IR-lamps T: 8°C--> 13°C, relative humidity--> 60%



Optical setup



Acquired optical signals (5 kS/s)

S(n)	=	Sagnac interferogram
I1(n)	=	CCW monobeam
I2(n)	=	CW monobeam
G(n)	=	Excitation level

Power Control

Analog PI circuit stabilizing the I2 drifts (t >1 s)

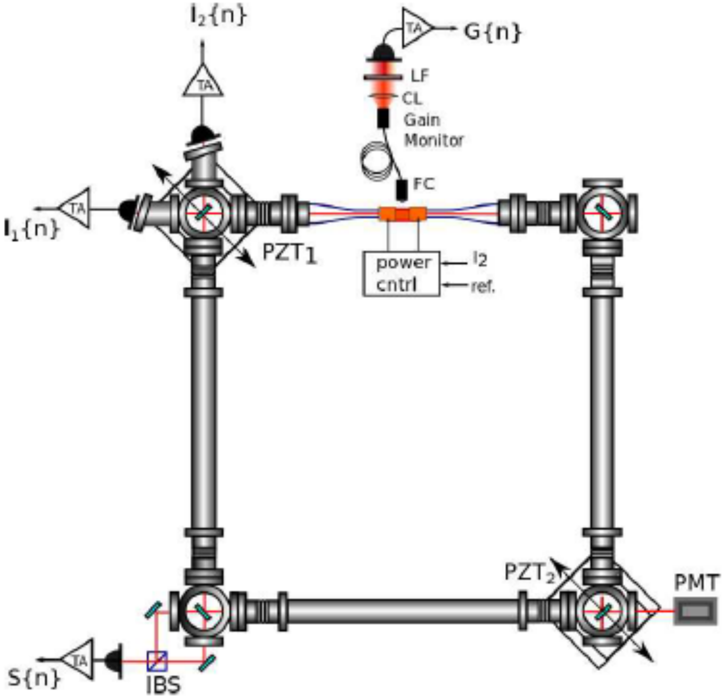
Fast detector (BW >300 MHz) for:

Ring-down-time measurement
Multimode beat detection

Backscattering subtraction

Perturbative solutions of semiclassical ring laser equations

D. Cuccato et al. Metrologia **51**, 97, (2014)
A. Beghi et al. Applied Optics **51**, 31 (2012)



Identified parameters

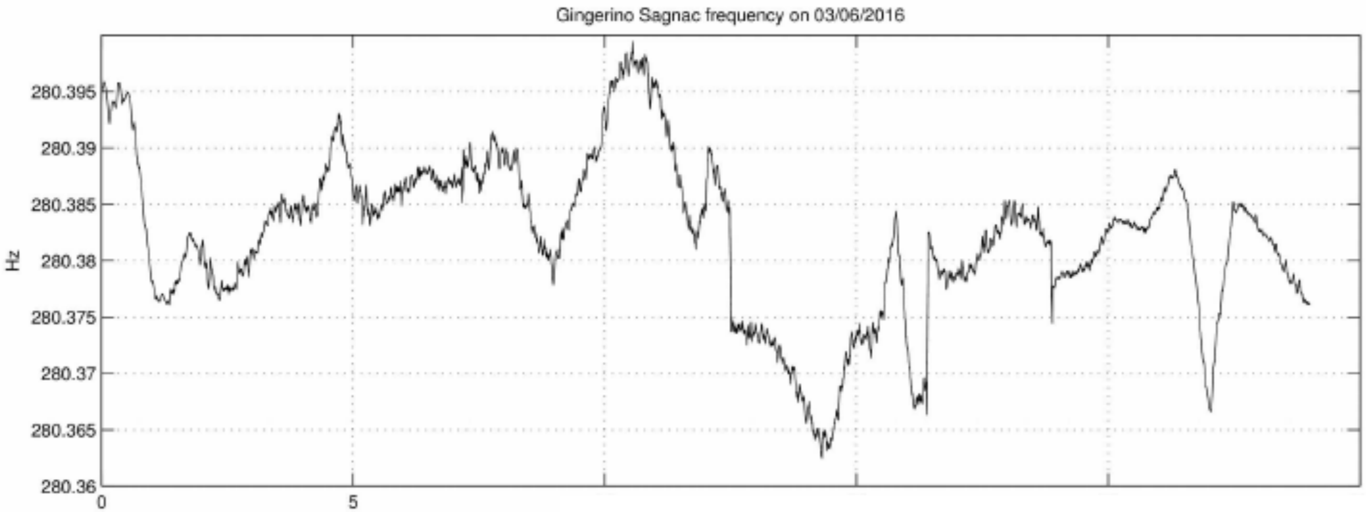
$$\widehat{\varepsilon} = \frac{\phi_1 - \phi_2}{2}$$

$$\widehat{r_1} = \frac{i_2 \omega}{2(c/L)\sqrt{I_1 I_2}}$$

$$\widehat{r_2} = \frac{i_1 \omega}{2(c/L)\sqrt{I_1 I_2}}$$

$$\begin{cases} \mathcal{I}_1(t) \simeq \dfrac{\alpha_1}{\beta} + 2 r_2 \sqrt{\alpha_1 \alpha_2}\dfrac{\alpha_1 \cos(\varepsilon + \omega_s t) + (\frac{\omega_s}{c/L}) \sin(\varepsilon + \omega_s t)}{\beta \left(\alpha_1^2 + (\frac{\omega_s}{c/L})^2\right)} - 2\dfrac{r_1 r_2 (c/L)}{\beta \omega_s} \sin(2\varepsilon) \\ \mathcal{I}_2(t) \simeq \dfrac{\alpha_2}{\beta} + 2 r_1 \sqrt{\alpha_1 \alpha_2}\dfrac{\alpha_2 \cos(\varepsilon - \omega_s t) - (\frac{\omega_s}{c/L}) \sin(\varepsilon - \omega_s t)}{\beta \left(\alpha_1^2 + (\frac{\omega_s}{c/L})^2\right)} + 2\dfrac{r_1 r_2 (c/L)}{\beta \omega_s} \sin(2\varepsilon) \\ \Psi(t) \simeq (\omega_s - \dfrac{2 r_1 r_2 (c/L)^2 \cos(2\varepsilon)}{\omega_s}) t + (c/L)\dfrac{r_1 \sqrt{\frac{\alpha_1}{\alpha_2}} \cos(\varepsilon - \omega_s t) + r_2 \sqrt{\frac{\alpha_2}{\alpha_1}} \cos(\varepsilon + \omega_s t)}{\omega_s} \end{cases}$$

Example: 24 h backscattering correction



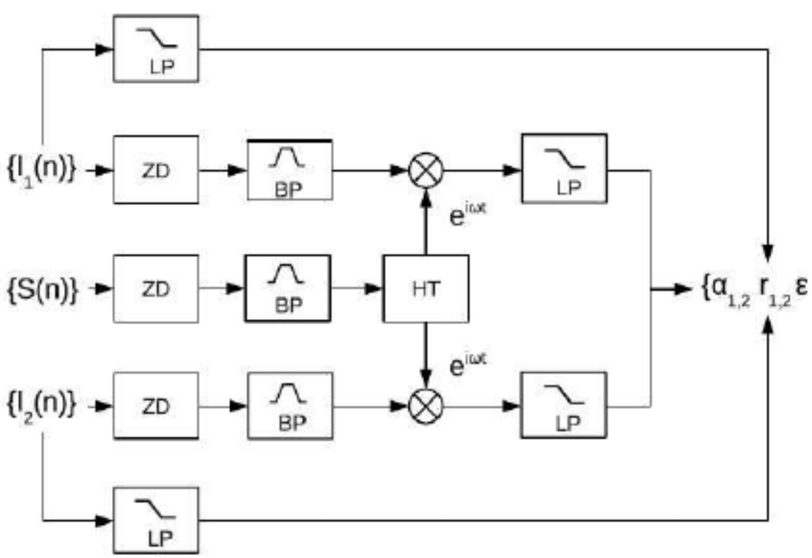
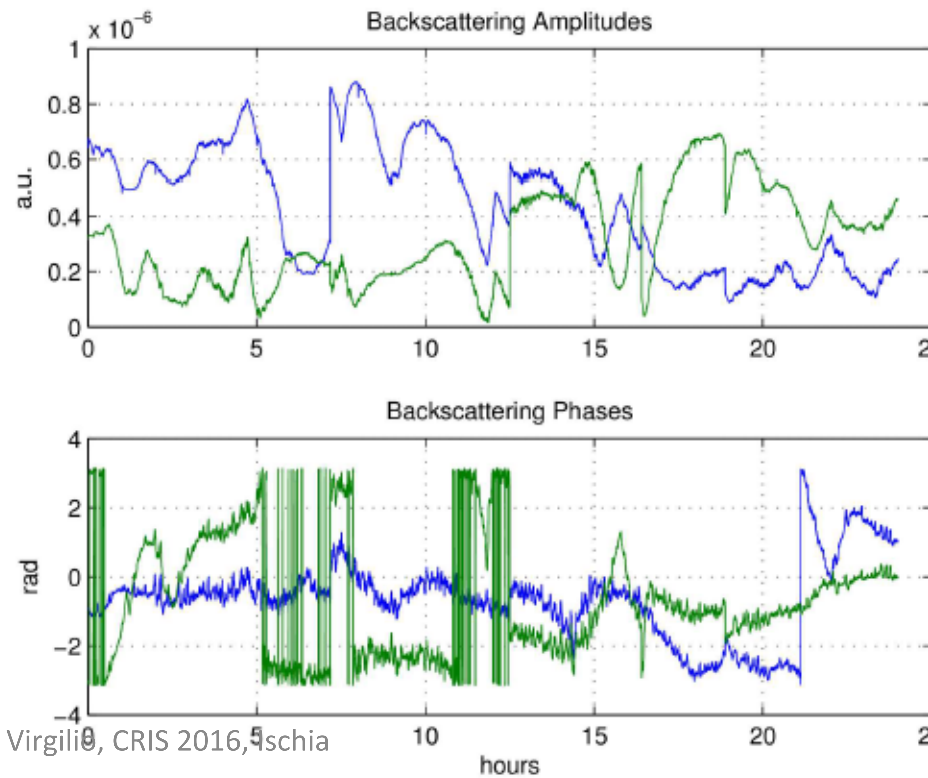
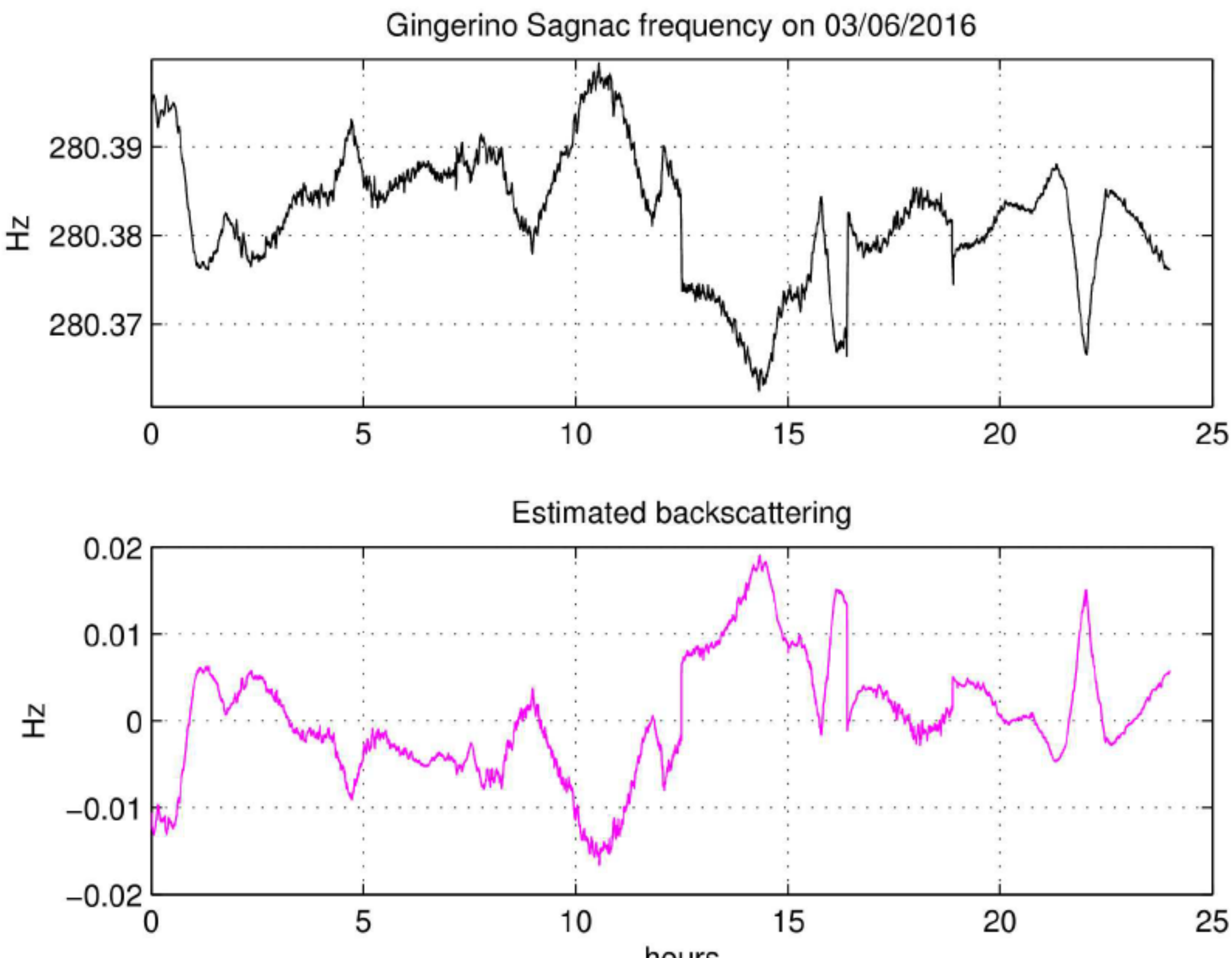


Fig. 3. Schematic of the parameter estimation procedure. I lowpass Butterworth filter; BP, bandpass Butterworth filter; Z zoom and decimation routine; HT, Hilbert transform (see text)

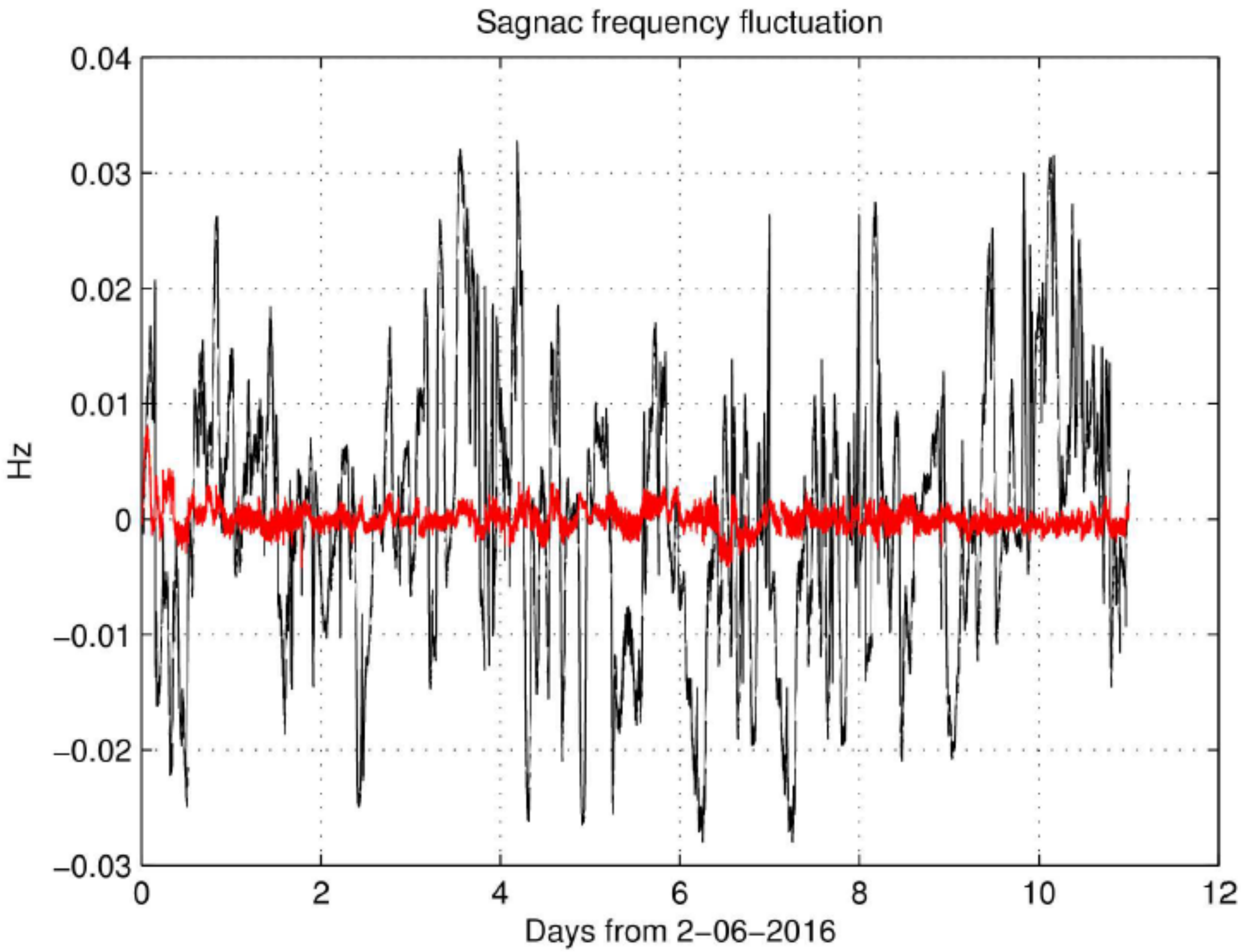


Example: 24 h backscattering correction

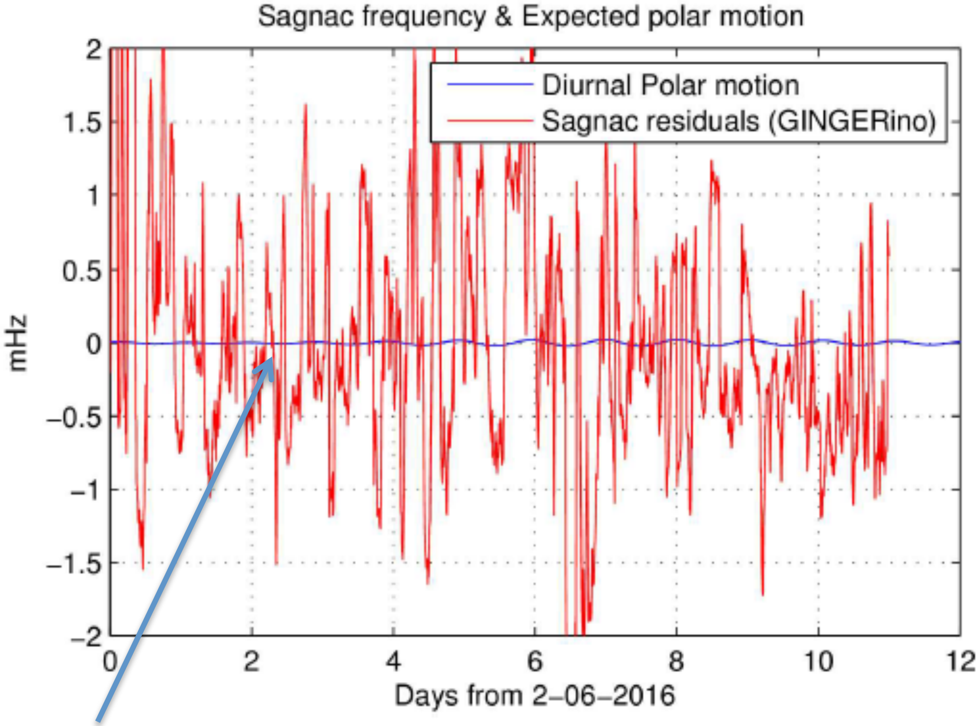


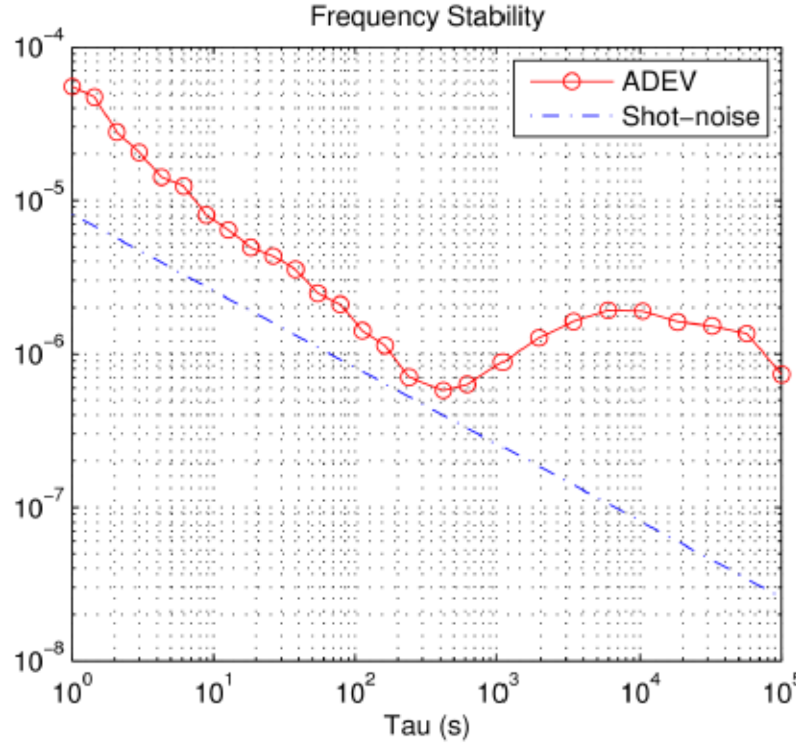
Example: 24 h backscattering correction

Long period observations 2-13 june 2016



Long period observations 2-13 june 2016





Maximum resolution: 0.6 ppm at 500 s of integration time
→ **30 p rad/s**

Noise limits:

-Laser optical frequency fluctuations

-Residual fluctuation in the ambient temperature and pressure

-Local Tilts (to be investigated)

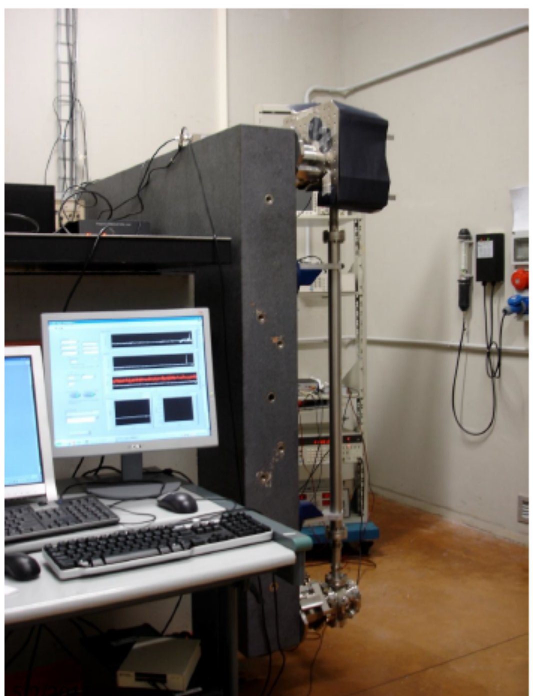
Intersection with GW interferometers

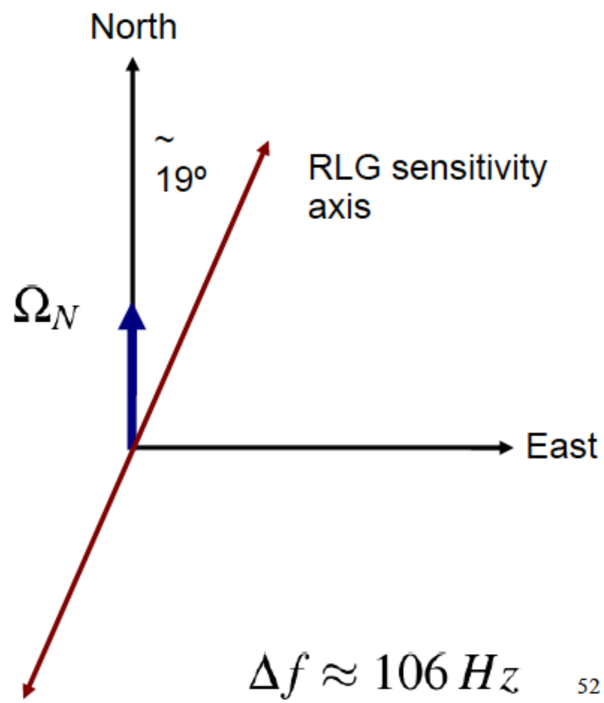
Ring-Lasers can be arranged in order to be sensitive to local tilts

Newtonian noise subtraction for next generation gw antennas

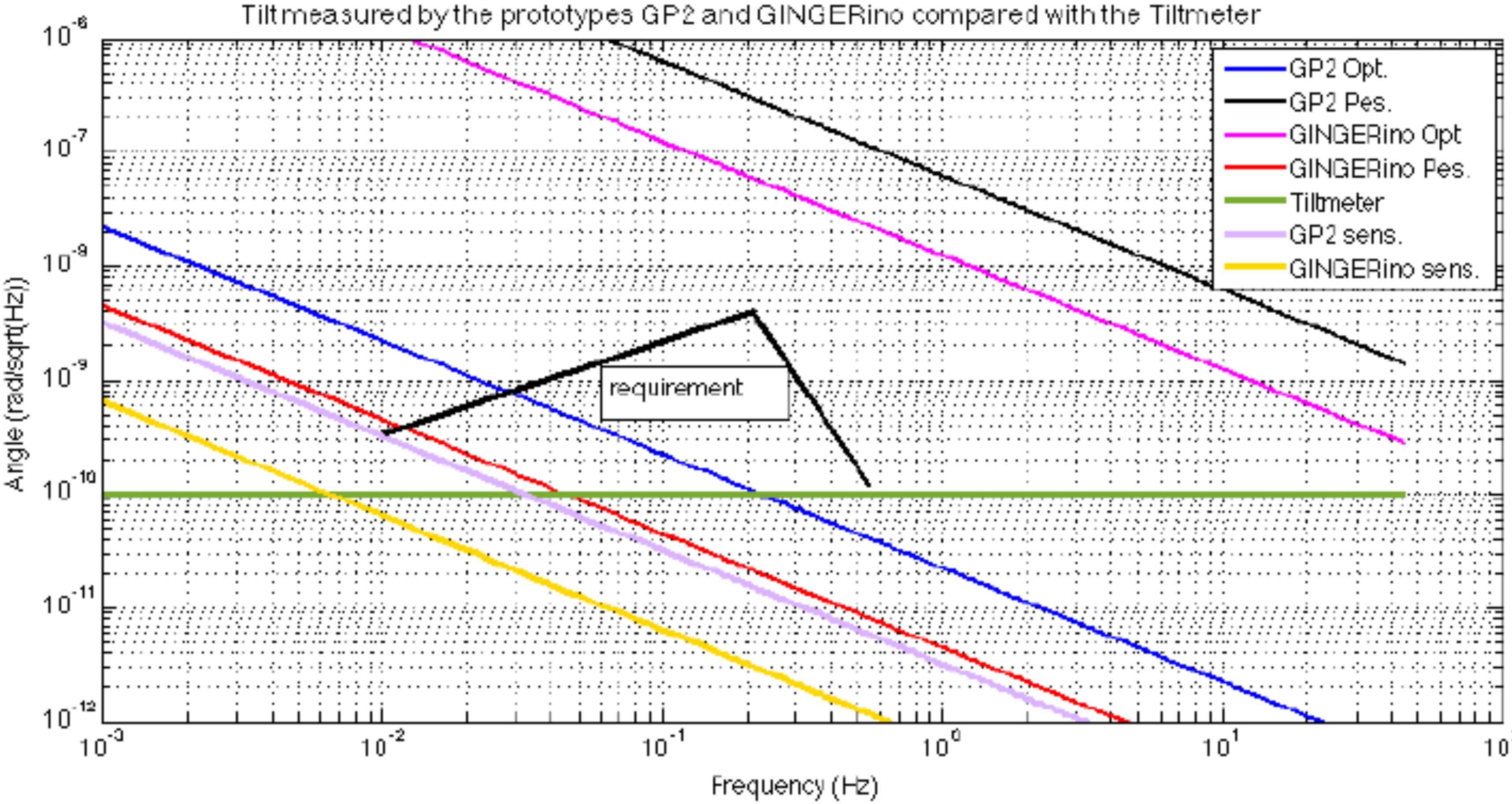
Tiltmeters have been developed for this purpose, ringlaser could do the same

G-Pisa RLG **Virgo 2011**





Comparision of RL sensitivity with the Ligo-Washington tiltmeter



GINGER

Conclusions

Ring Lasers measure absolute rotations

Sensitivity of 10^{-13} rad/s already demonstrated

We hope to present a proposal for an array suitable for high energy physics

GINGERino is delivering very interesting data for sesmology, we hope to observe geodetic signals in the near future

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 non-linear 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