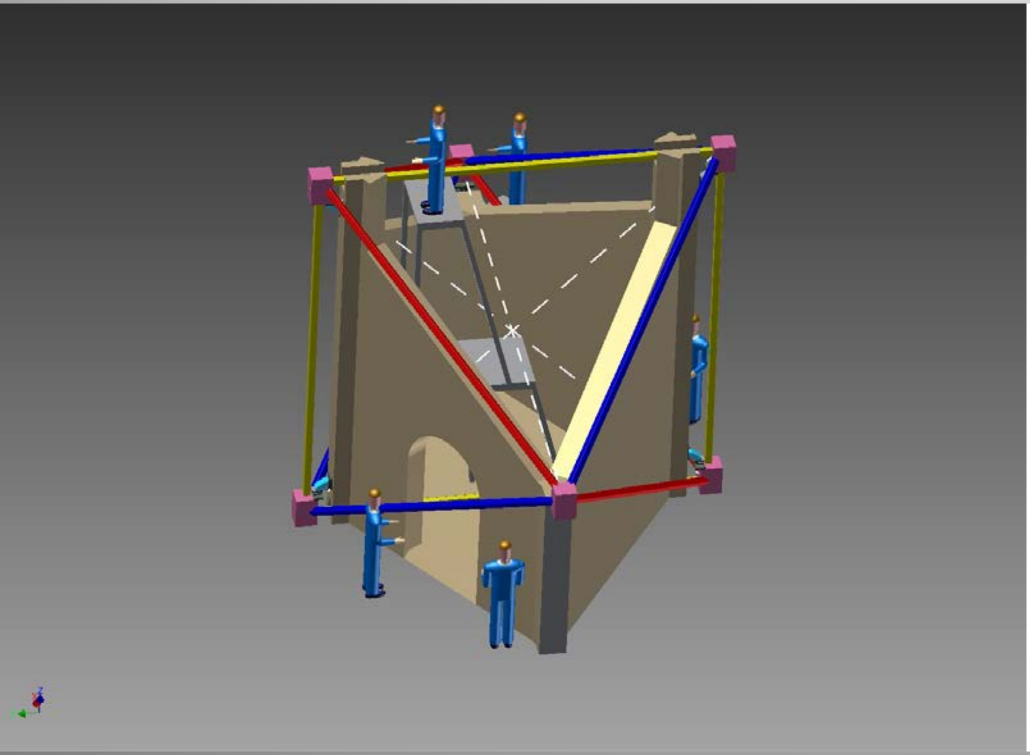
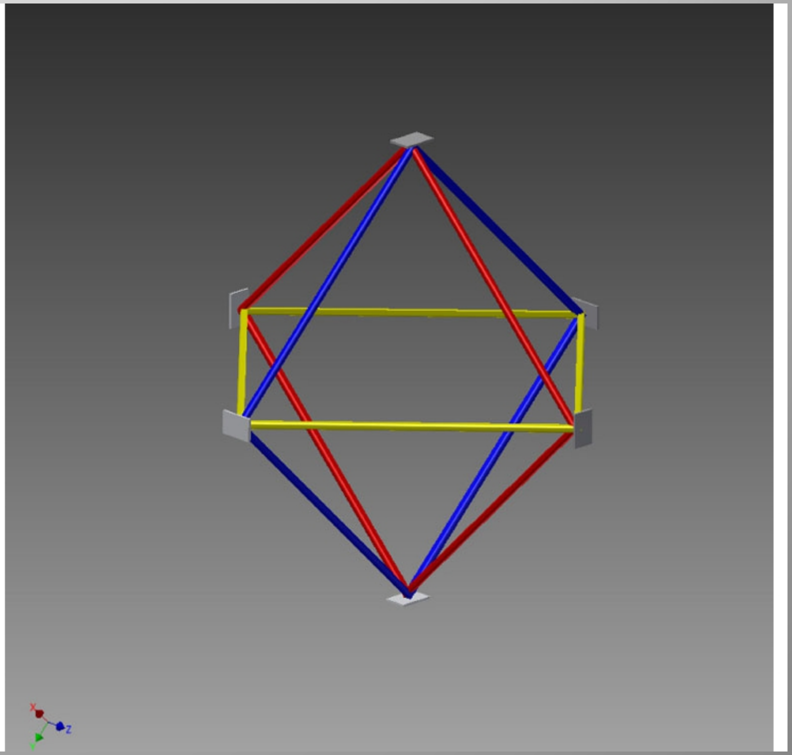
G-GranSasso/GINGER
Gyrolaser IN GEneral Relativity
(INFN CommII)

Introduzione
LNGS
Collaborazione con la NuovaZelanda
GP-2, the test bench for the new prototype

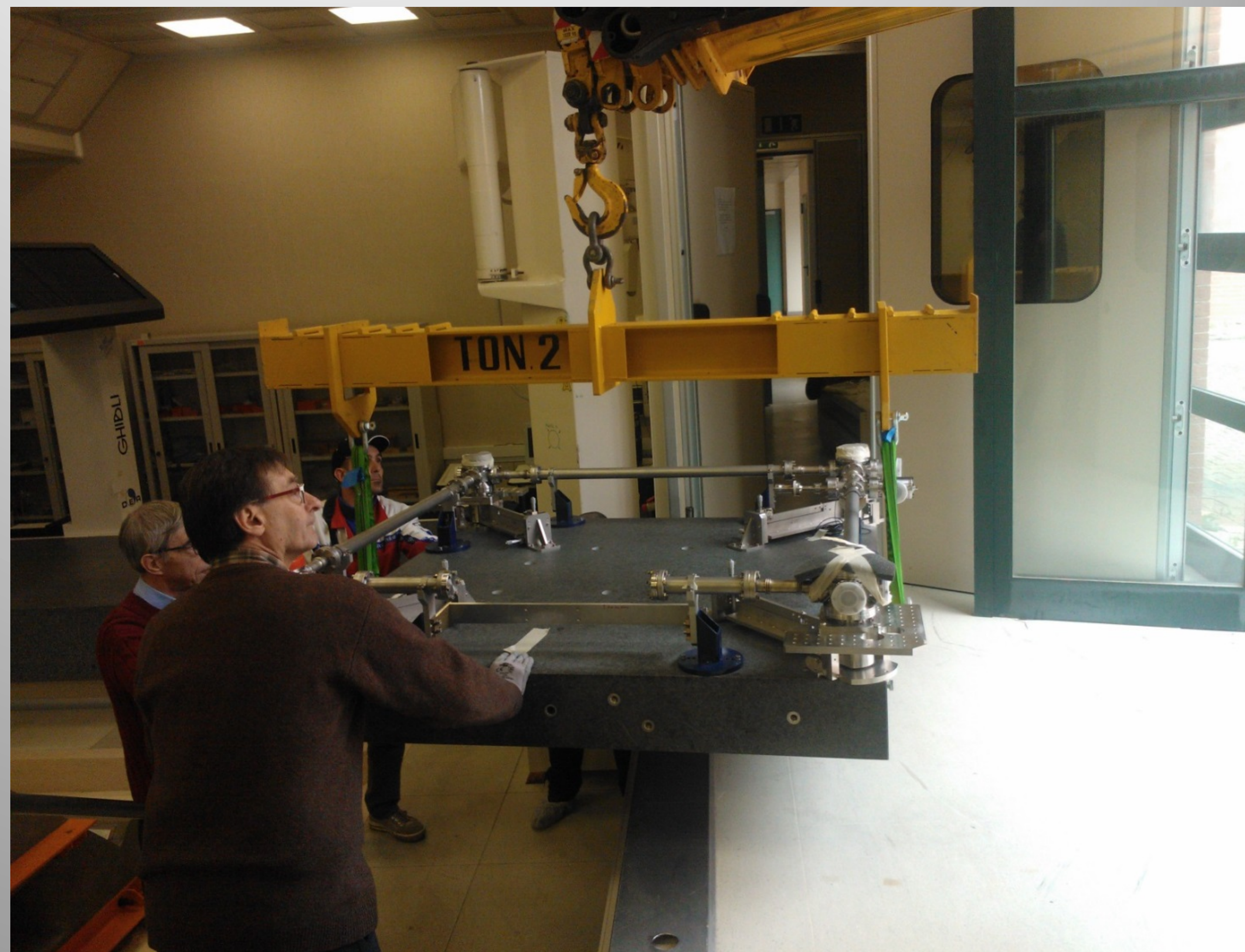
GINGER

Lense-Tirring effect 1% accuracy





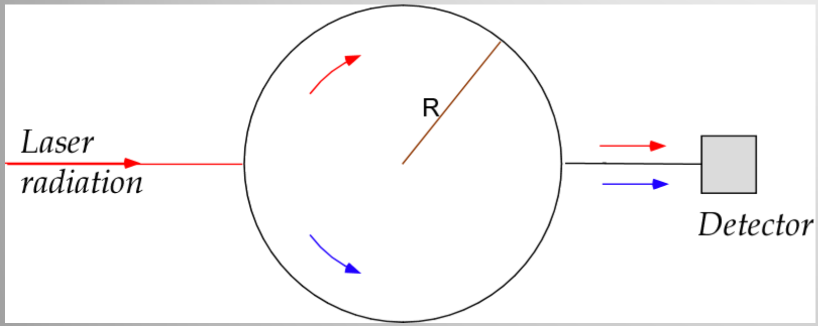
All has started with G-Pisa, financed by GruppoV, a transpoprtable ring laser (Pisa-Virgo-S.Piero-LNGS), which has been oriented in 3 different ways, the first high sensitivity ring which has obtained continuous operation using perimeter control, his sensitivity is about few nrad/s/sqrt(Hz), compatible with the shot noise.



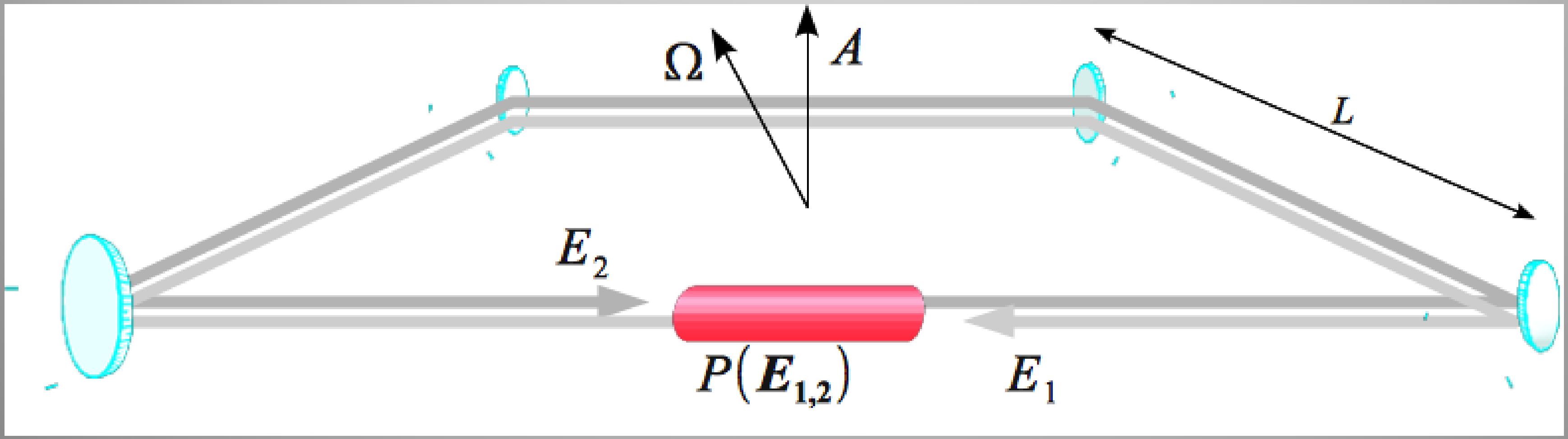
GINGER/G-GranSasso_RD

- I ring laser sono misuratori assoluti di velocità angolare basati sull'effetto Sagnac
- G-GranSasso è un esperimento R&D della CommII, che si propone di realizzare un array di ring laser di altissime prestazioni, per fare un misura di Relatività Generale: la misura a terra dell'effetto LenseThirring al 1%
- Stretti legami con la Geodesia (misura veloce del LoD, Length of the Day) e con la geofisica

The Sagnac Effect and the ring-laser



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



General relativity effects on a laser gyroscope

$$\nu \cong 4\frac{S}{\lambda p}\Omega_{\oplus}\left[\cos(\vartheta+\psi)-2\frac{GM_{\oplus}}{c^2R_{\oplus}}\sin\vartheta\sin\psi + \frac{GI_{\oplus}}{c^2R_{\oplus}^3}(2\cos\vartheta\cos\psi+\sin\vartheta\sin\psi)\right]$$

Sagnac

De Sitter (gravito-electric)

Lense-Thirring (gravito-magnetic)

$\vartheta = \angle(\hat{u}_r, \hat{u}_{\oplus})$ *local co-latitude*

$\psi = \angle(\hat{u}_r, \hat{u}_S)$

$$\Omega_{\oplus} = \frac{2\pi}{\text{LOD}}\ \text{rad/s} \approx 7.29\times10^{-5}\ \text{rad/s}$$

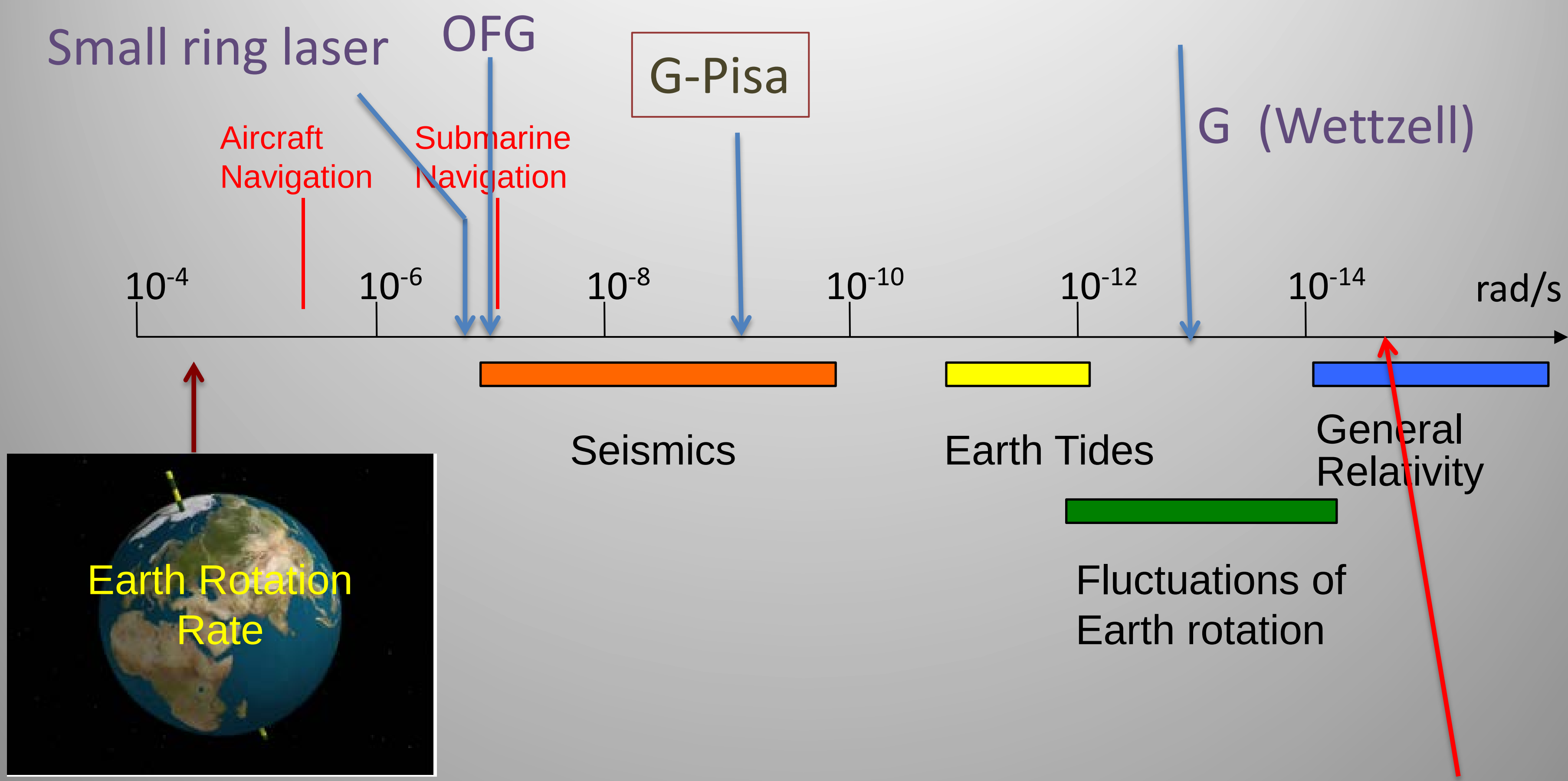
$$\text{LOD} = 86164.09053\ \text{s}$$

$\hat{u}_S$ gyro axial direction,

$\hat{u}_r$ radial direction (*zenith*),

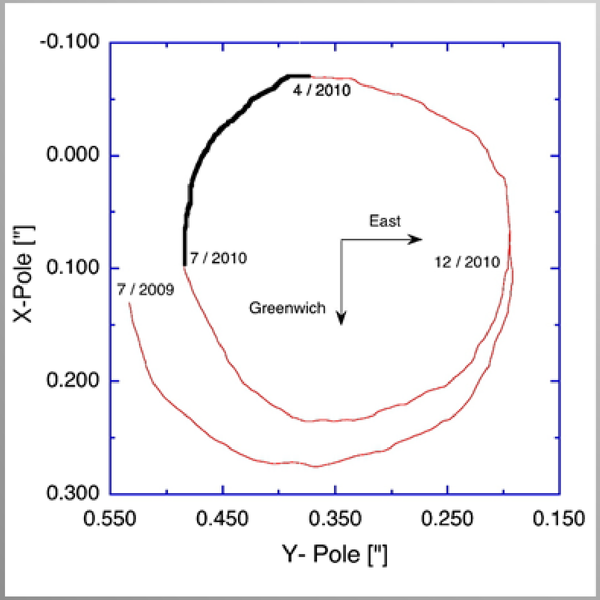
$\hat{u}_{\oplus}$ Earth axial direction

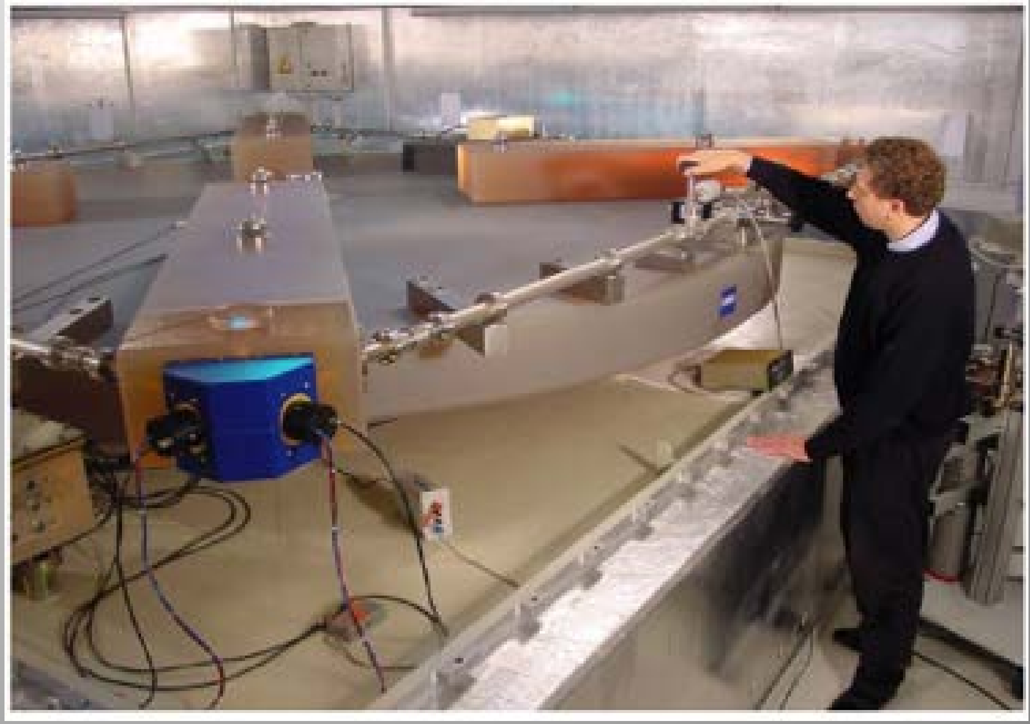
Measuring rotations



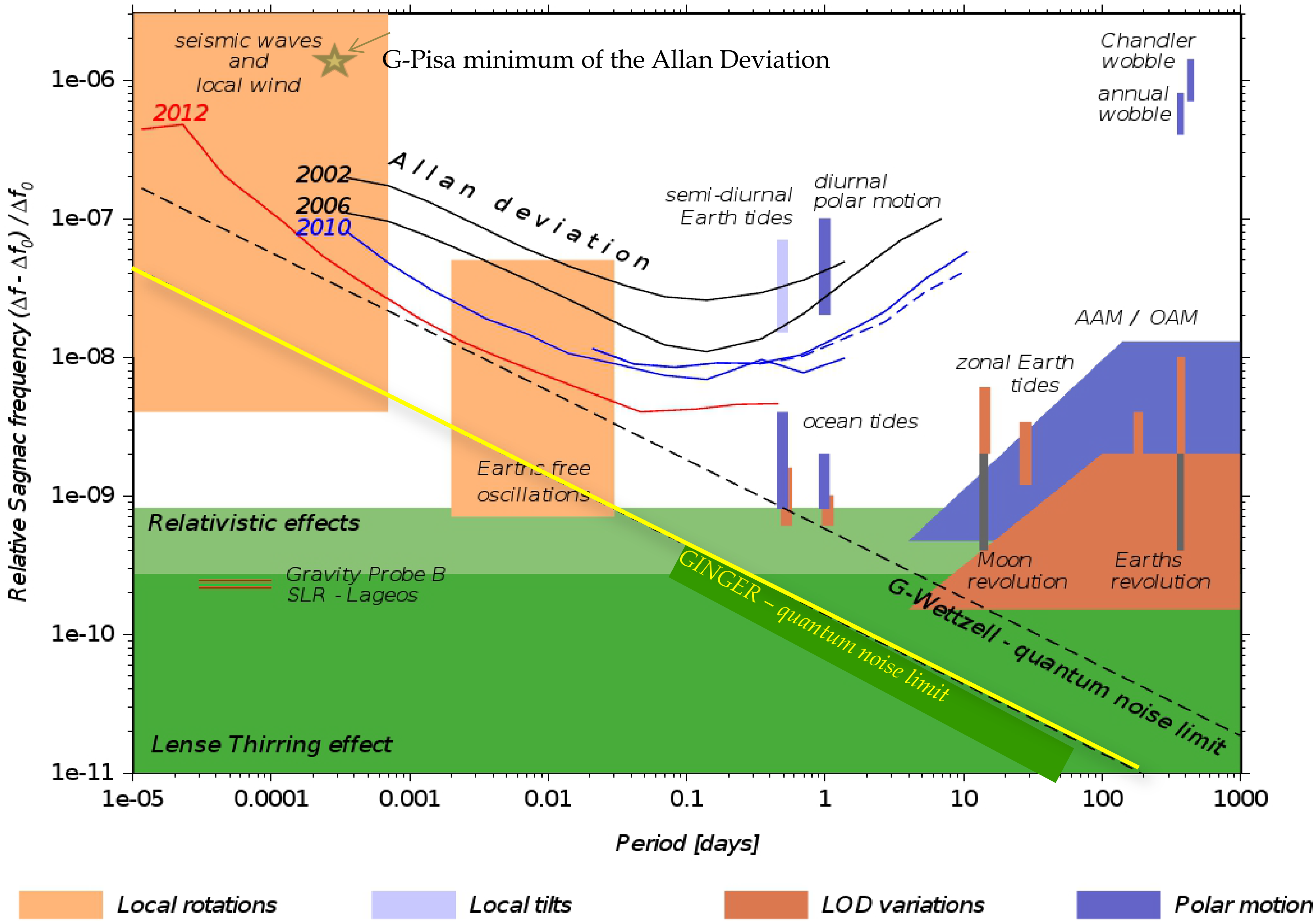
Present gyrolasers sensitivity

- *At present, the gyrolaser with the lowest noise level, very near to the shot-noise limit, is "G", located in Wettzell, Bavaria.*
- *It achieves a fractional stability of 4×10^{-9} in 1 hour (about 10^{-13} rad/s), a factor 5 from the target (but accuracy is necessary)*





Blue star the minimum of the Allan for G-Pisa in S.Piero, applying Kalman filters to subctract backscatter noise. It should be better at LNGS since we expect to integrate longer



Satellite measurements

- *Gravity-Probe B (GP-B)* *(proposed in 1970)*
  - *a satellite, with four superconducting gyroscopes and a telescope on board, in polar orbit around the Earth. Mission started in 2004 and lasted one year and a half.*
  - *data analysis takes many years*
  - *final data analysis (2012) reports an accuracy of 0.28% on the geodetic (de Sitter) precession, but only 19% on LT. Large problems arise in controlling systematic effects.*
- *LAGEOS and LASER laser ranging.*
  - *Ciufolini and Pavlis analysed data, based on laser ranging with the LAGEOS and LAGEOS II satellites (measurement of the precession of the orbital nodes, induced by the gravito-magnetic field).*
  - *Evidence of the LT effect within 10% accuracy,*
  - *Planning to reach 1-2% by exploiting LARES satellite mission, dedicated to the precision measurement of the LT effect (started on February 13^{th} 2012) .*
- *Suggestion for a mission around Jupiter…*

ALL THESE EVALUATIONS REQUIRE A VERY ACCURATE KNOWLEDGE OF THE GRAVITATIONAL FIELD ALONG THE ORBITS

GINGER
Gyrolaser in General Relativity

Ground vs Space Experiments

- *In space the observer is in geodetic motion (free fall),*
- *In a terrestrial laboratory the observer is in a non inertial (accelerated) motion.*
- *The LT is measured locally, while the space one gives an averaged value.*

- *The apparatus is more accessible in a terrestrial laboratory Cost of an Earth-based experiment is much lower than a space-based one*
- *Times needed to prepare the experimental setup are shorter on the Earth.*
- *Absolutely different experiment interpretation, accurate model of the gravitational field not necessary*

GINGER
Gyrolaser in General Relativity

INFN - Pisa
- *Angela Di Virgilio*
- Filippo Bosi
- Bachir Bouadef

Università di Pisa
- Jacopo Belfi
- Massimo Calamai
- Giorgio Carelli
- Enrico Maccioni
- Rosa Santagata
- Maria Allegrini

Politecnico di Torino
- Angelo Tartaglia

Lab. INFN di Legnaro
- Antonello Ortolan

INGV –Pisa
- Gilberto Saccorotti

Università di Padova (DEI)
- Alessandro Beghi DEI PD
- Davide Cuccato

INFN - Napoli
- Alberto Porzio
- Salvatore Solimeno

Technische Universität München
- *Ulrich Schreiber*
- André Gebauer

University of Cantenbury (NZ)
- Jon-Paul Wells
- Bob Hurst

GINGER

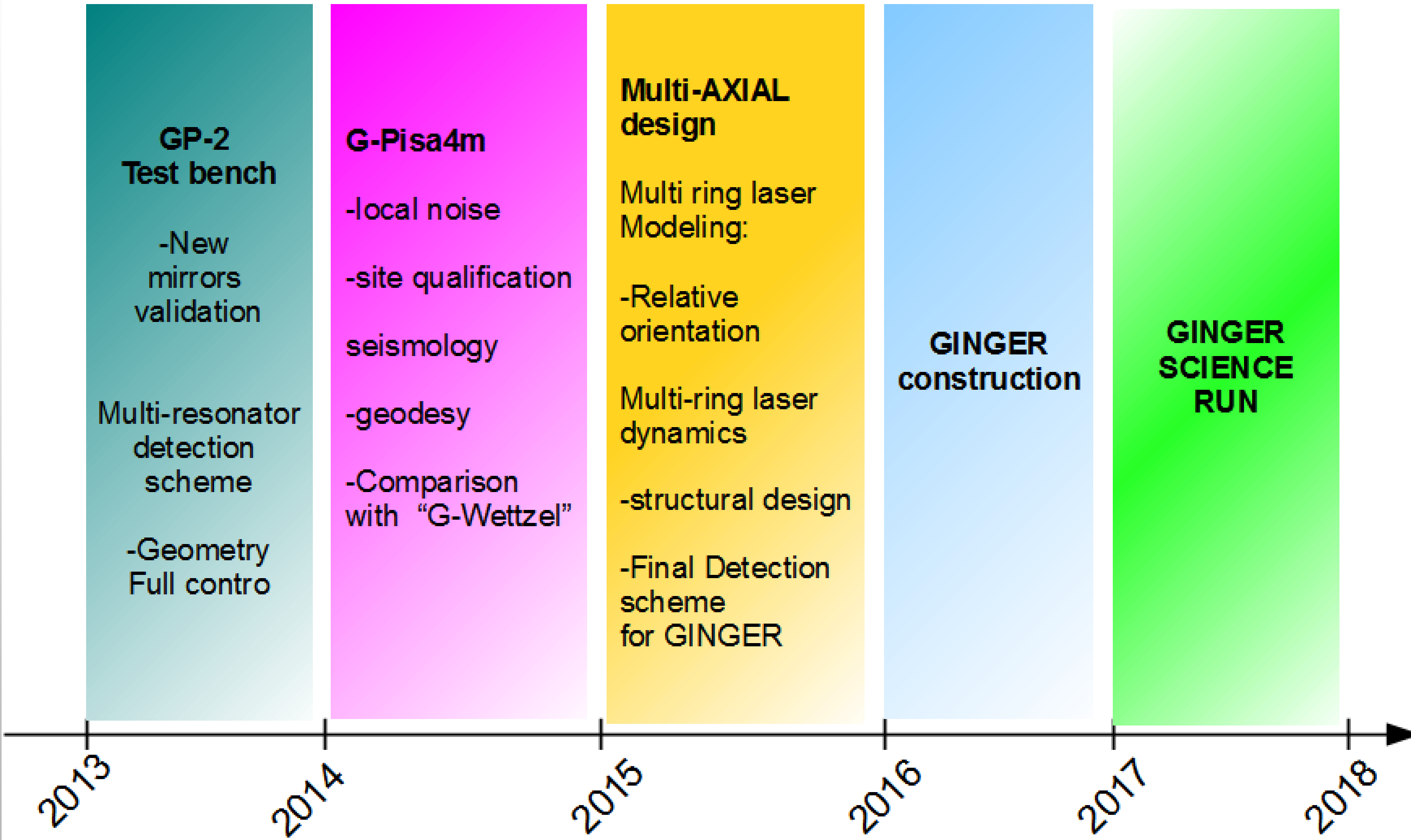
Key points:

- Larger ring (6 - 8 m) to improve the shot-noise by a factor 3 - 4 with respect to G in Wettzell (4 m of side),
- Increasing the long-term stability and the accuracy to be better than 10^{-10} over 1 day.
- Underground laboratory
- Correction of all the known geophysical perturbation.
- Stabilization of the area, of the perimeter, and of the wavelength better than 10^{-10}
- 3 axial system, relative alignment at nrad level

sensitivity $$\Delta f = \frac{4}{\lambda} \frac{A}{p} \vec{n} \cdot \vec{\Omega}$$

$$\Omega_{sn} = \frac{c}{2\,Q} \frac{p}{A} \sqrt{\frac{h\nu_L}{P_{out}\,T}}$$ shot-noise

GINGER roadmap



LNGS
SITE CARACTERIZATION

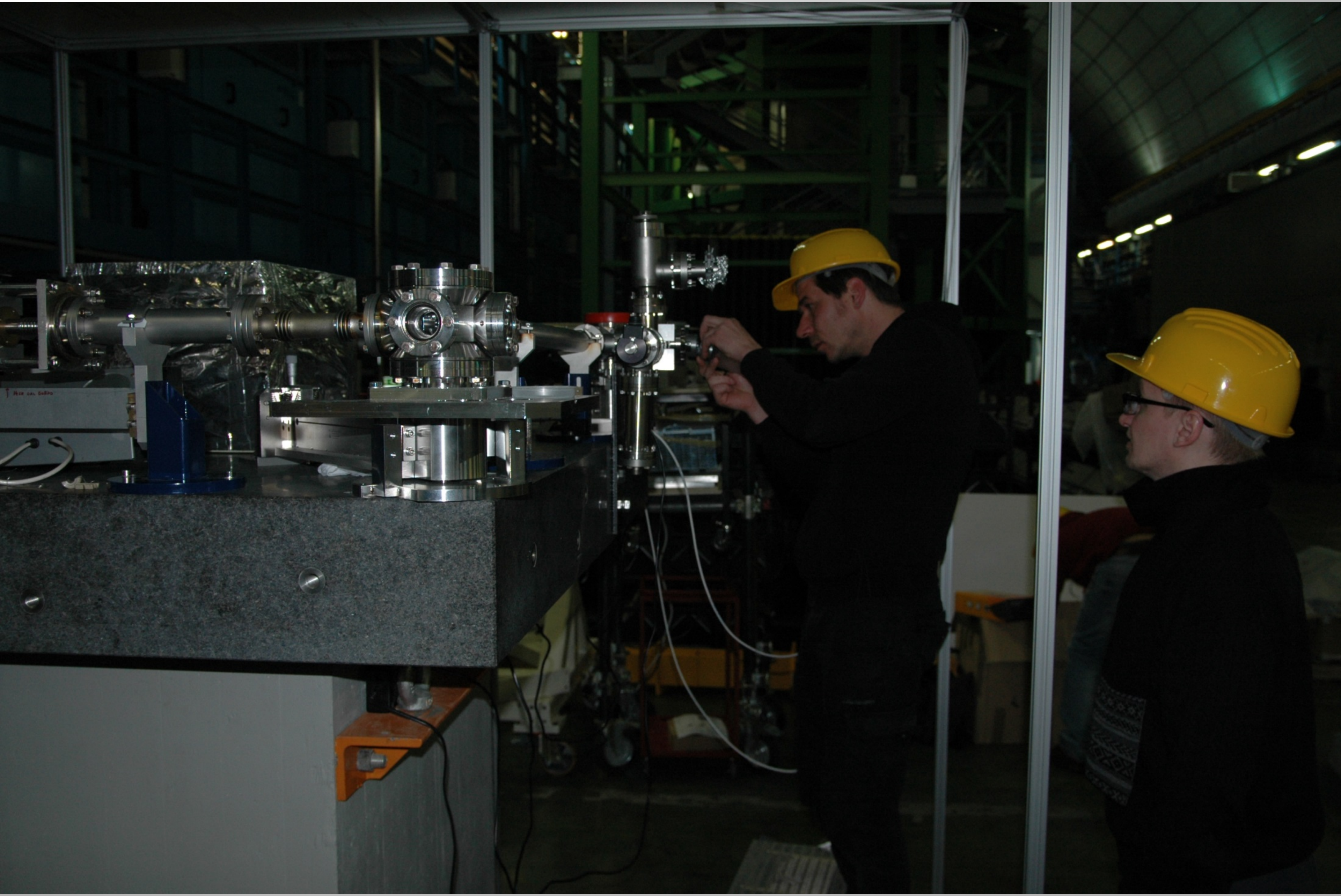
First set of measurements taken april/may 2013

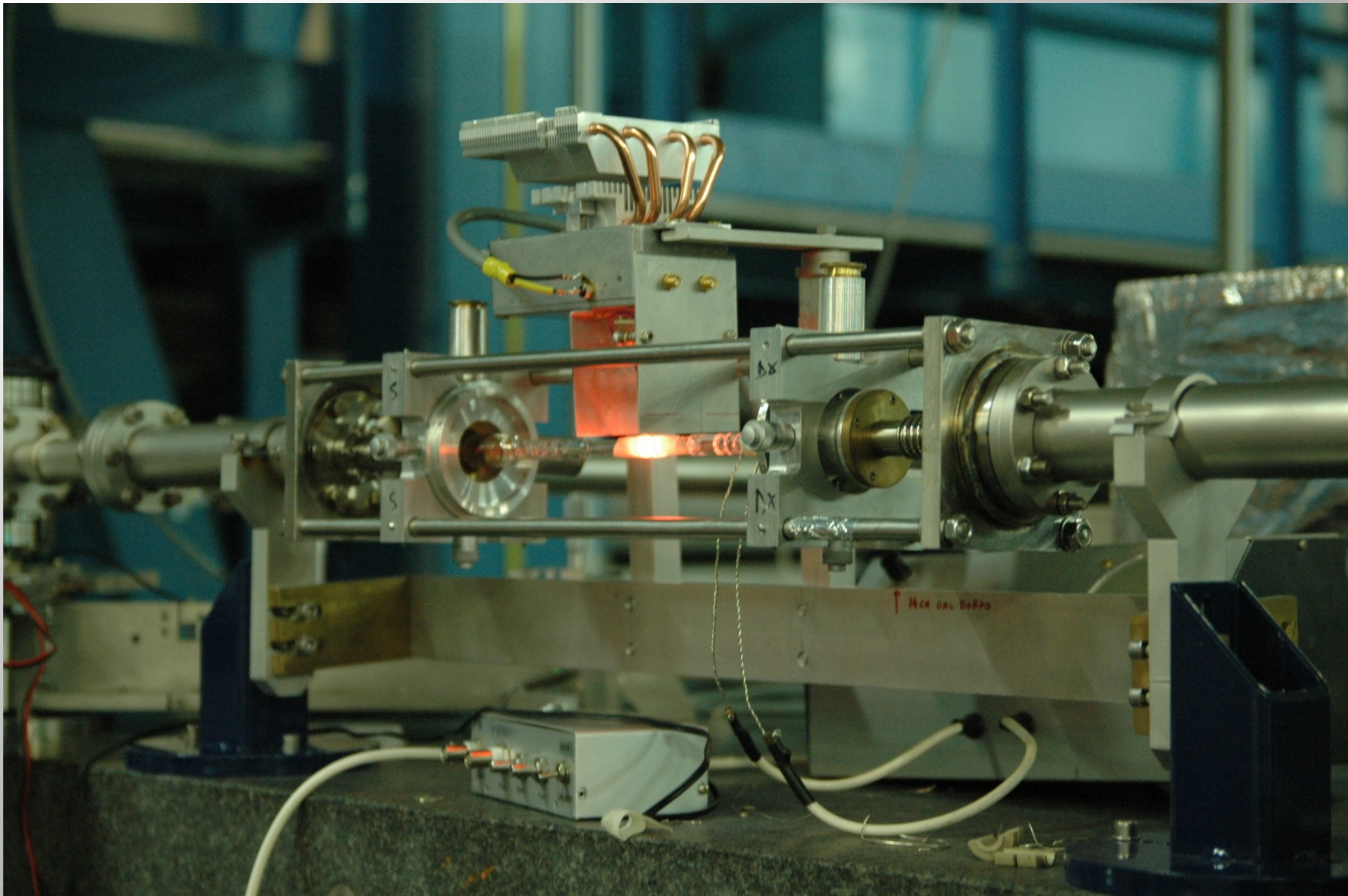
Good indication to go further

Presented July 23 in Comm2, meeting in Rome

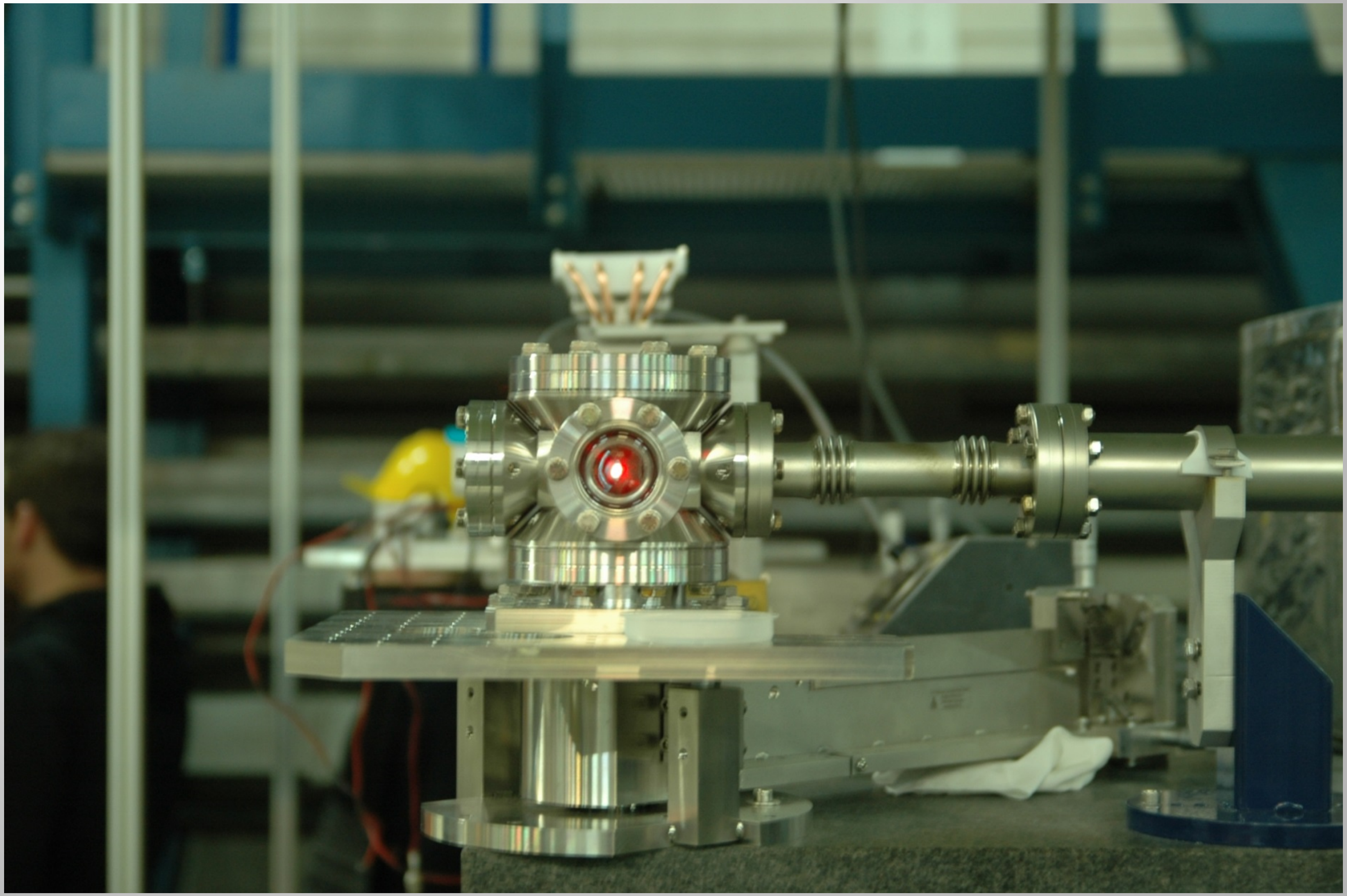
And in a seminar to LNGS last spring

GINGERino





The discharge of the laser, less than 1 cm long. The capillary is in quartz

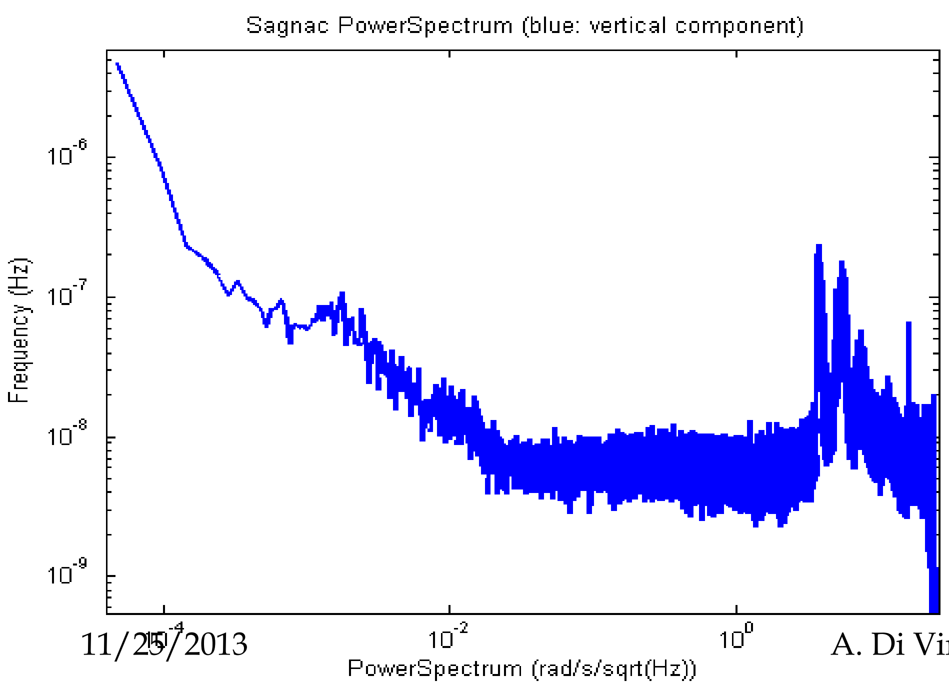


The transfer of the instrument has been very succesfull, and after 1 day (necesary to evacuate the vacuum tank) the cavity has been filled with He-Neon, and aligned with a green light; when the plasma has been turned on, G-Pisa has started immediately lasing! This picture shows the red light of the laser coming out of the mirror

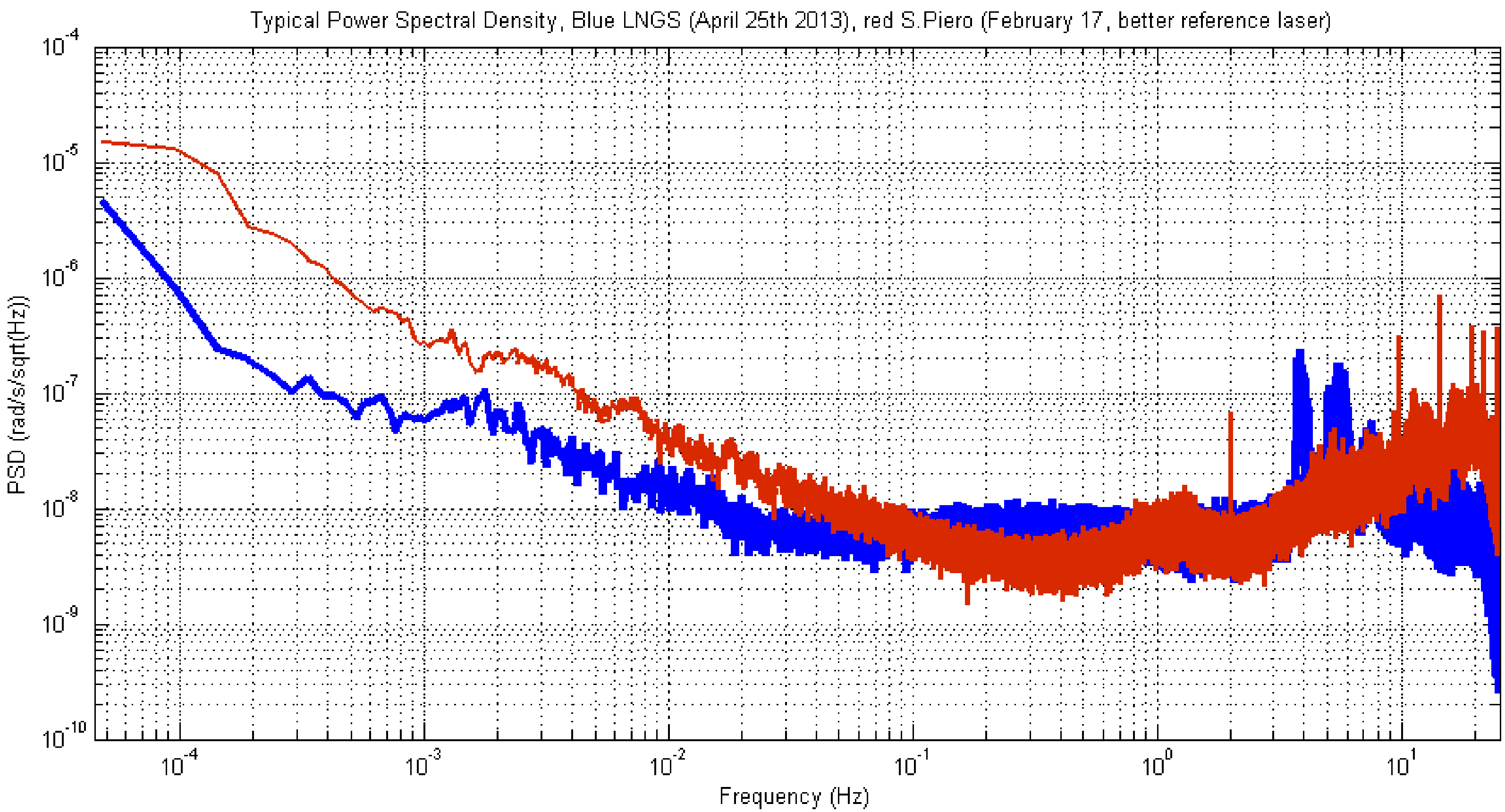
The ring-laser is protected by a box done with ‘stiferite’, which should as well acustical
isolate the ring. Th electronics and computers is outside the box

Main Characteristics

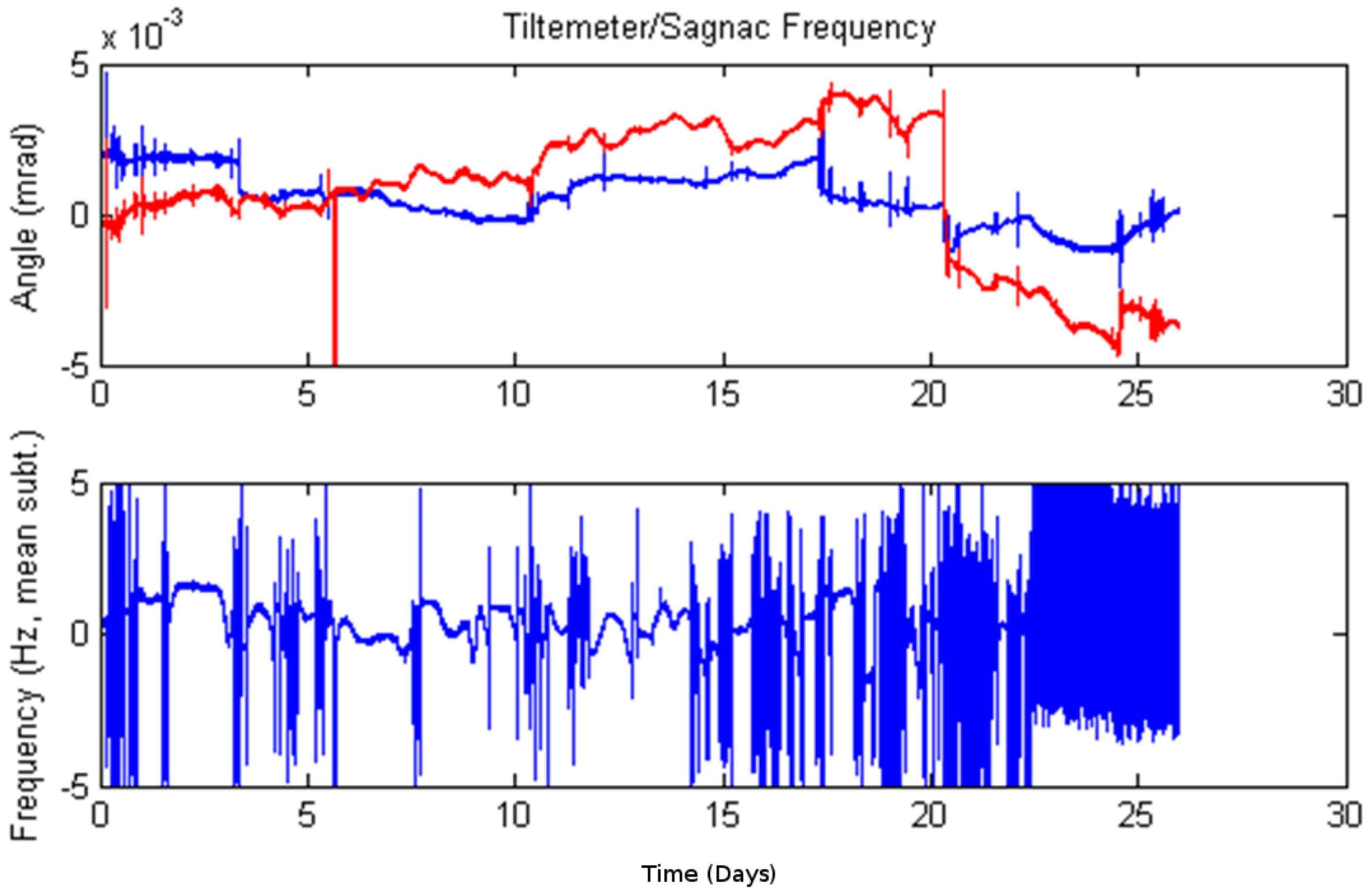
- Q of the cavity around 10^{11} (this depends on the mirrors, could be higher)
- PSD(noise floor) 4-5 nrad/s/sqrt(Hz) (sometimes better…)
- Two seismometers are co-located (3 axis each, one owned by TUM and the other by ingv-Pisa)
- One nano-tiltmeter (2 axis)
- Few environmental monitors: temperature, pressure and humidity
- Below 10mHz the instrument is backscattering dominated



Analysis of the Sagnac is in progress
In order to reduce the large backscattering
Noise below 0.01 Hz


Typical Power Spectral Density, Blue LNGS (April 25th 2013), red S.Piero (February 17, better reference laser)
PSD (rad/s/sqrt(Hz))
Frequency (Hz)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

The two TiltMeter channels and the Sagnac Signal (mean subtracted)

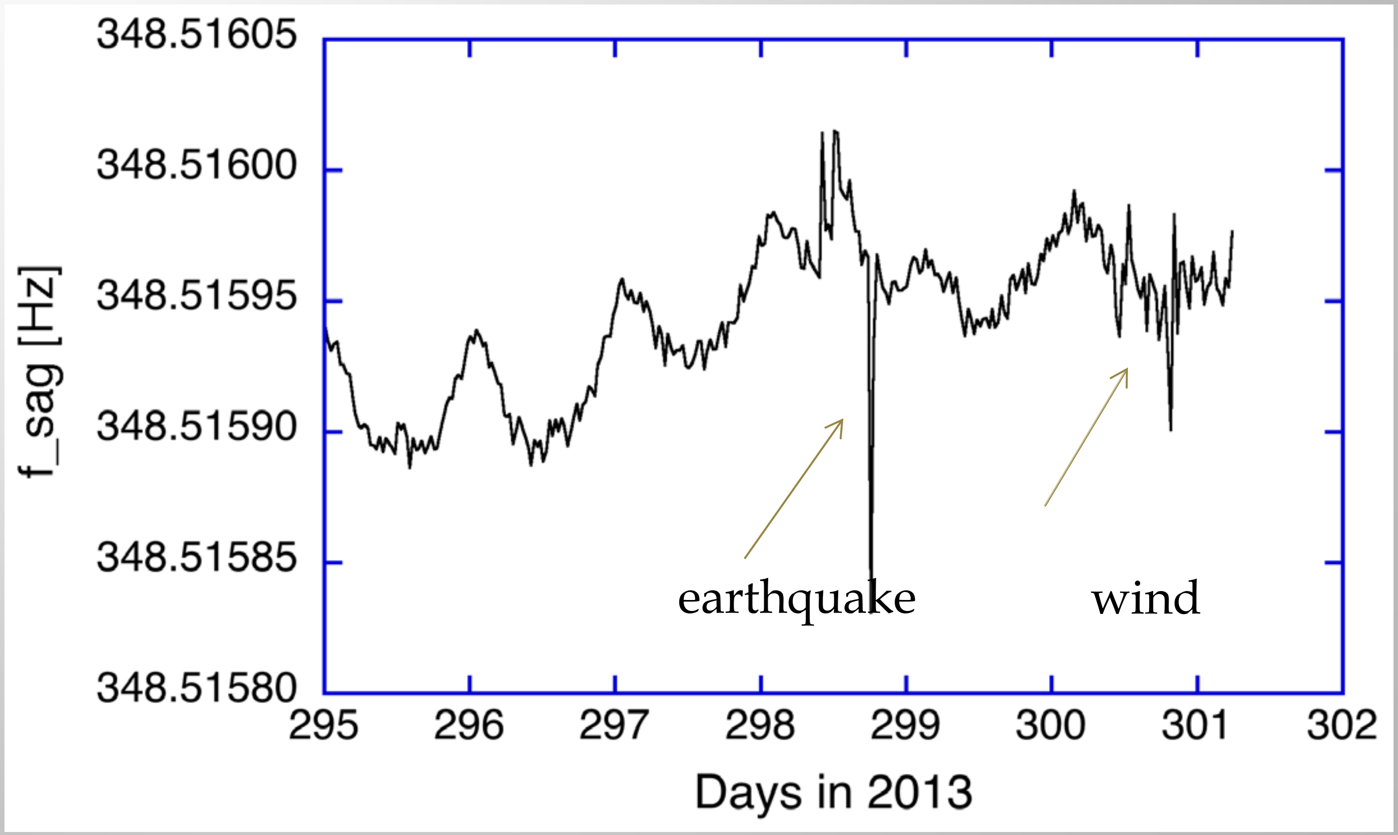


After 15 days the gas mixture has started to be contaminated, for a problem of the capillary of the plasma discharge

a summary of the analysis

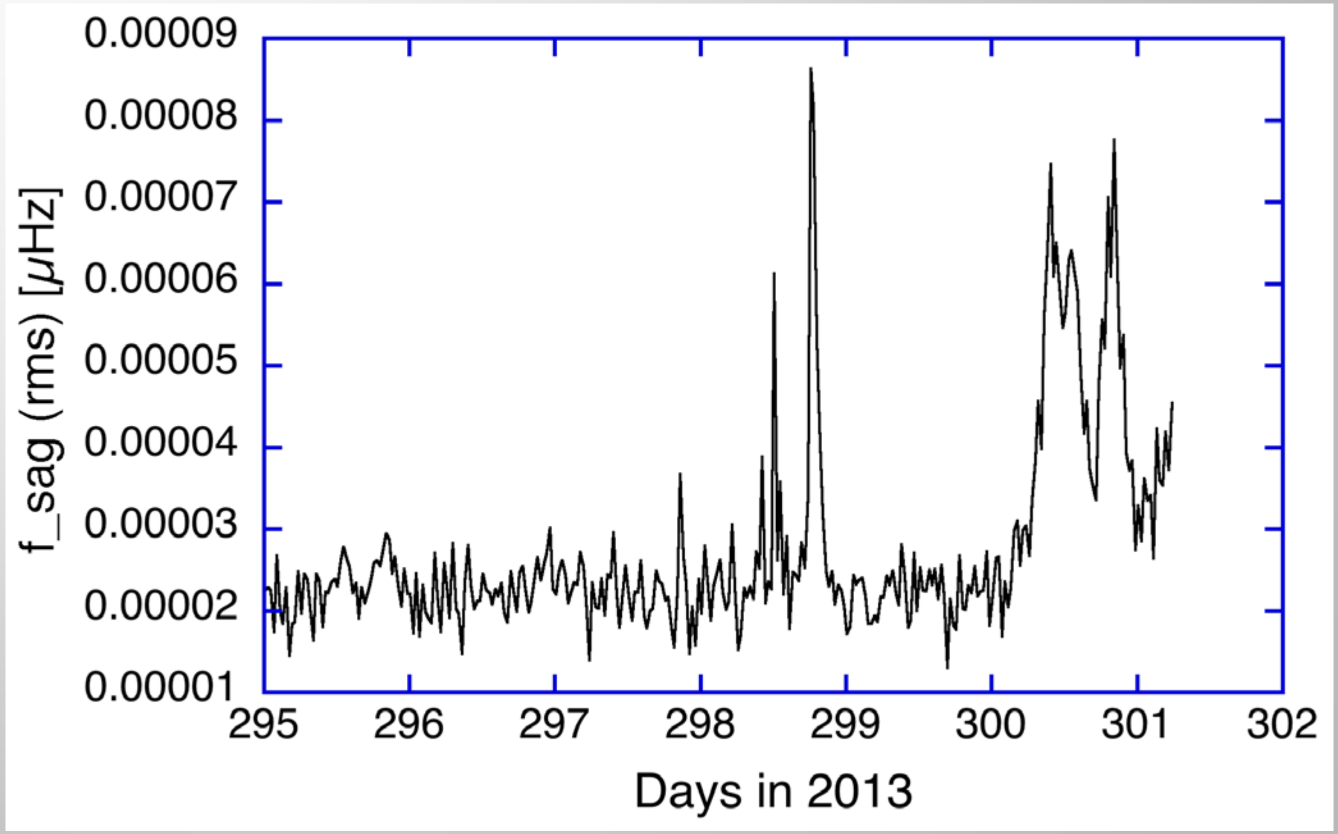
- G-Pisa has been moved to LNGS with its equipment
- A first set of data (approx. 1 month) has been recorded
- The first set of data shows that LNGS is close to the typical LNM, this gives us a good motivation to further and improve the apparatus.
- **Necessary to increase the sensitivity i.e. increases the size of G-Pisa up to about 4m side (3.6m side, inside the octagon)**

Good motivation for deep underground installation



Data recorded in Wettzell; note the noisy signal during excessive wind

A big signal from the San GIUDA tunderstorm



...underground the wind effect should not be present

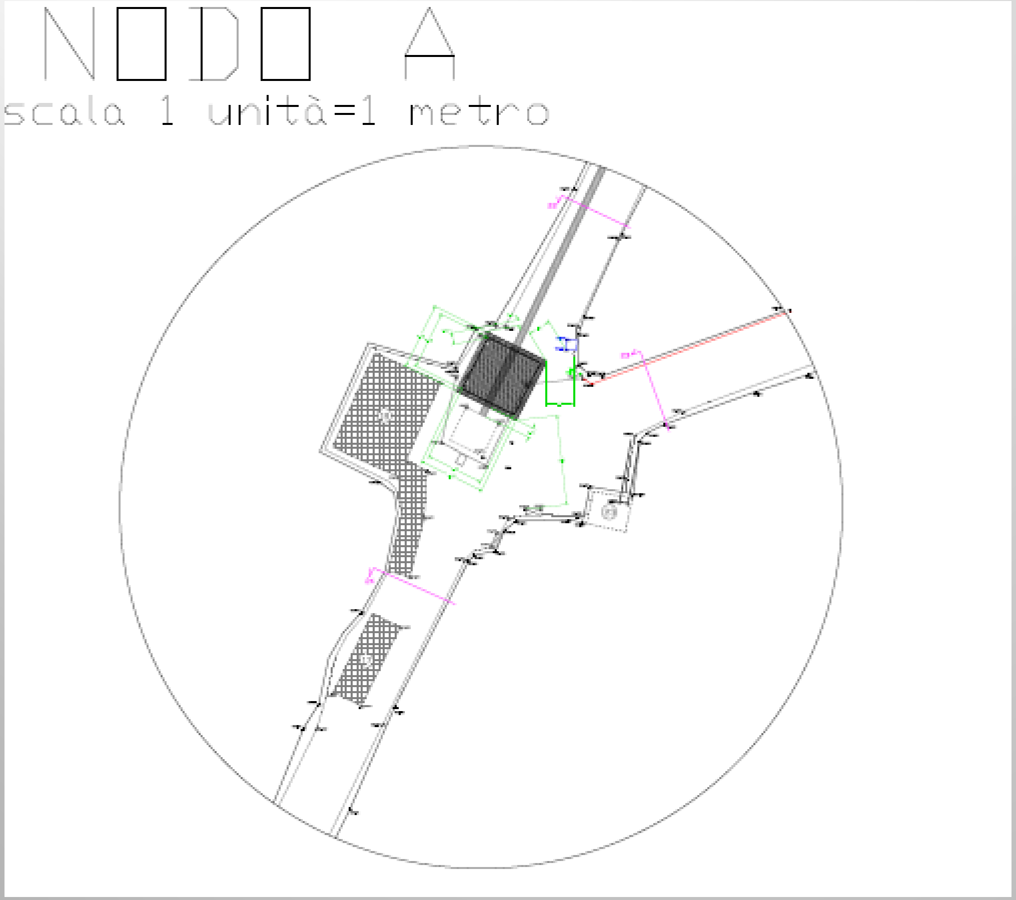
Essential of GINGERino

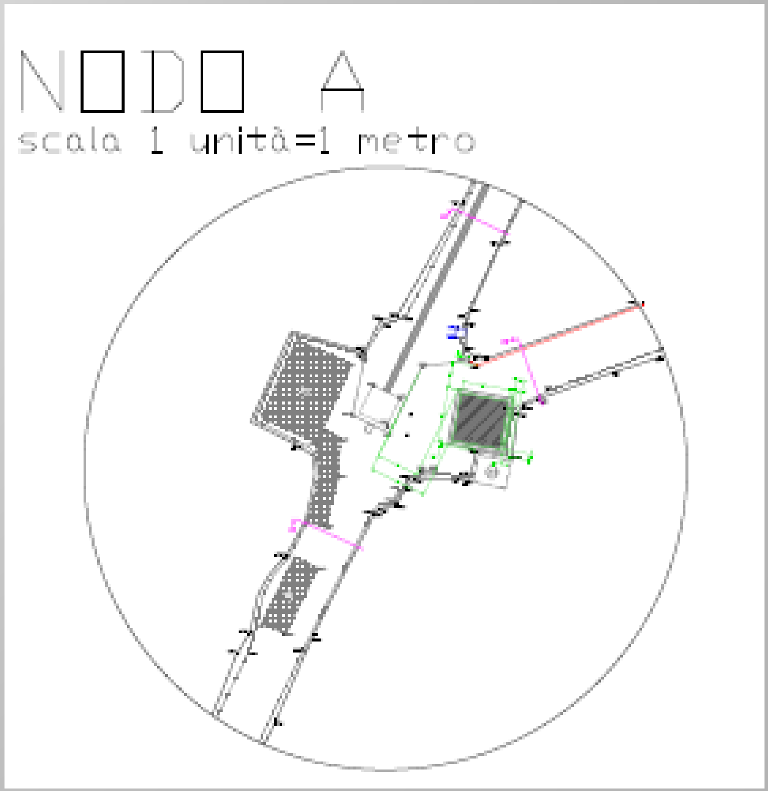
- The ring, 3-4 m side (depending on the available space), will be covered by a good acoustic/thermal shielding (Napoli is in charge of that)
- DAQ and all related electronics will be contained in a separated box, outside the acoustic shielding
- GPS clock necessary

Collaboration with Schreiber shoudl become more effective

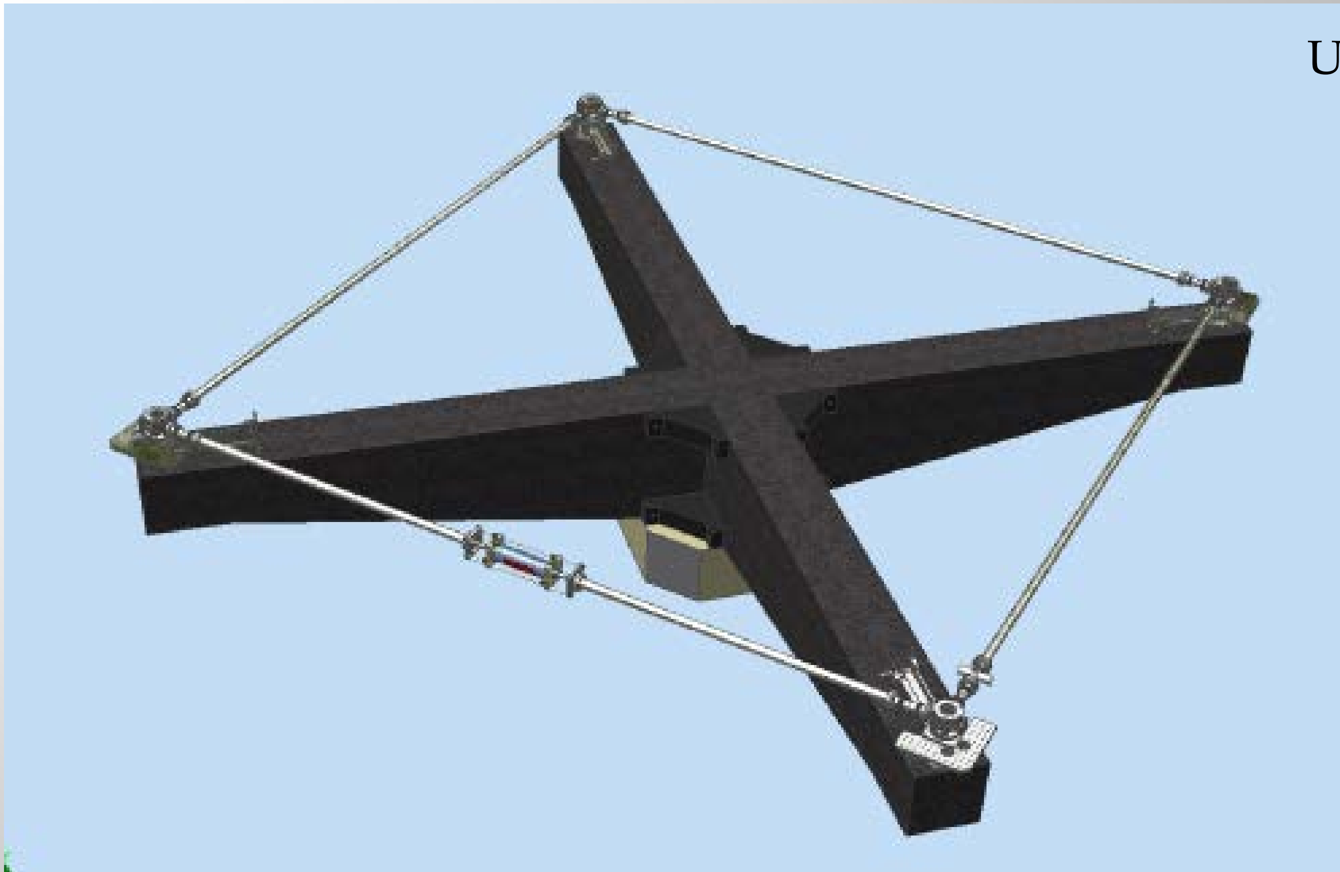
- Contribution in-kind from Germany: the iodine stabilized reference laser, it should be located very close to the 4m ring, but outside the acoustic/thermal shielding

LNGS-Node A, a 4m side ring laser GINGERino Phase I, diurnal and semidiurnal polar motion should be observed



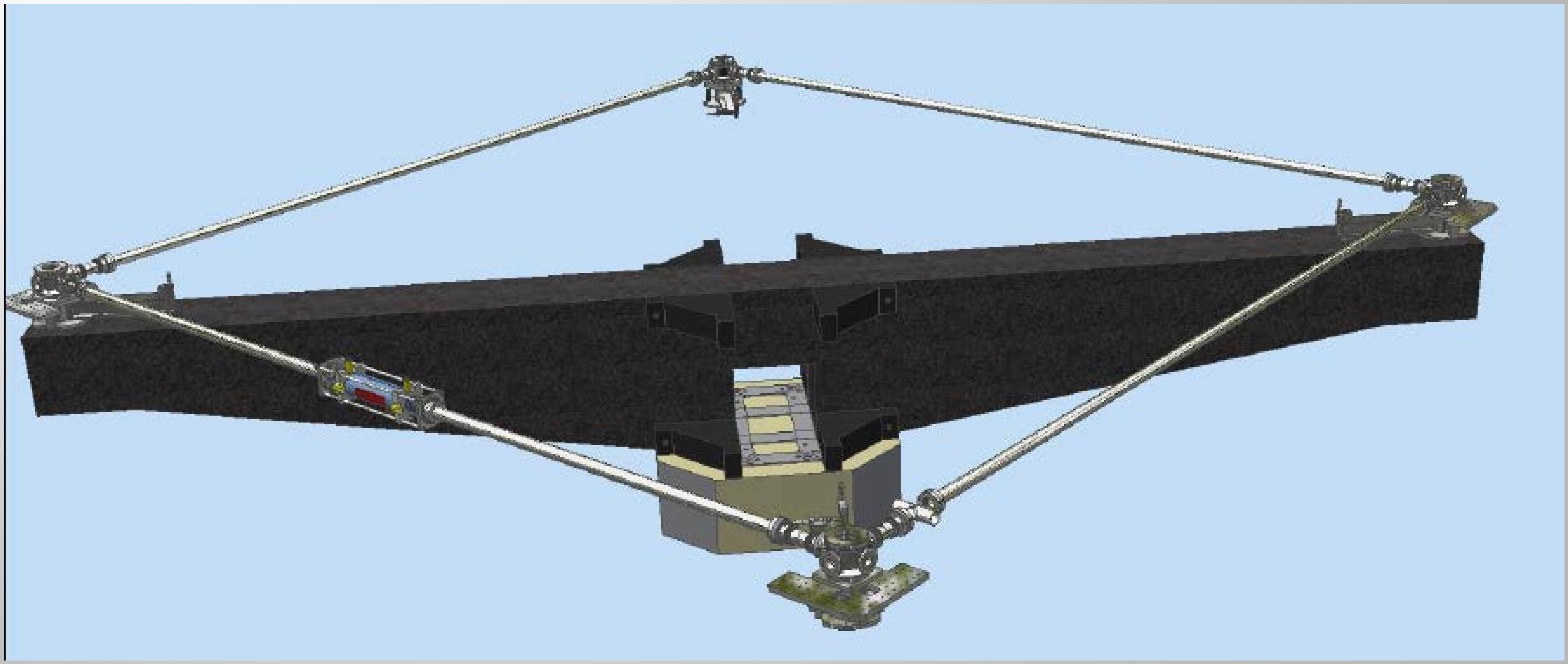


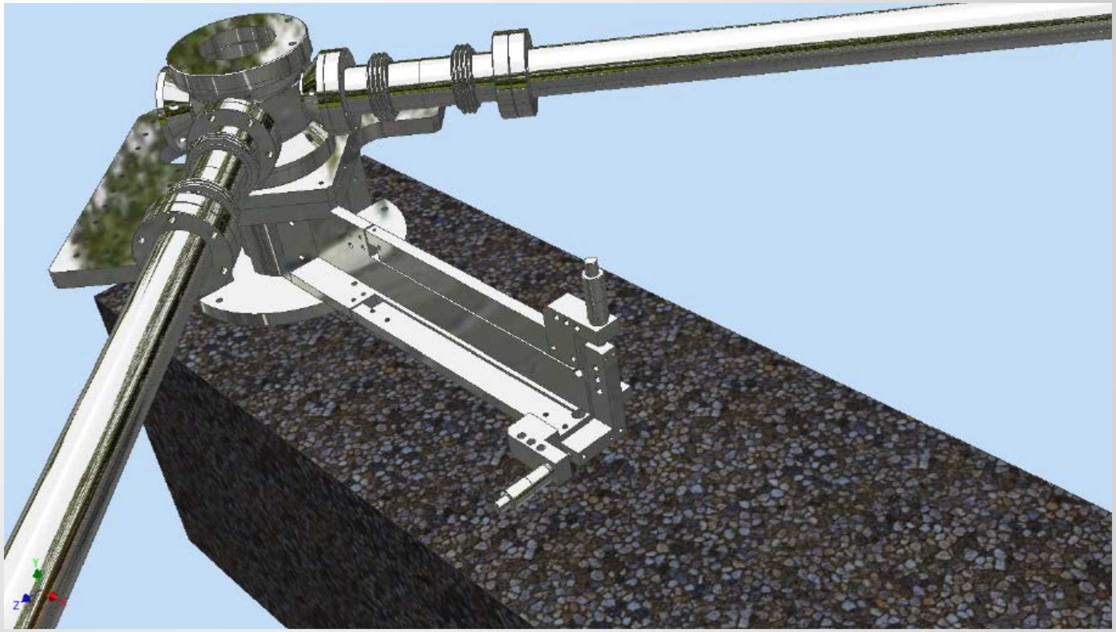
Under discussion

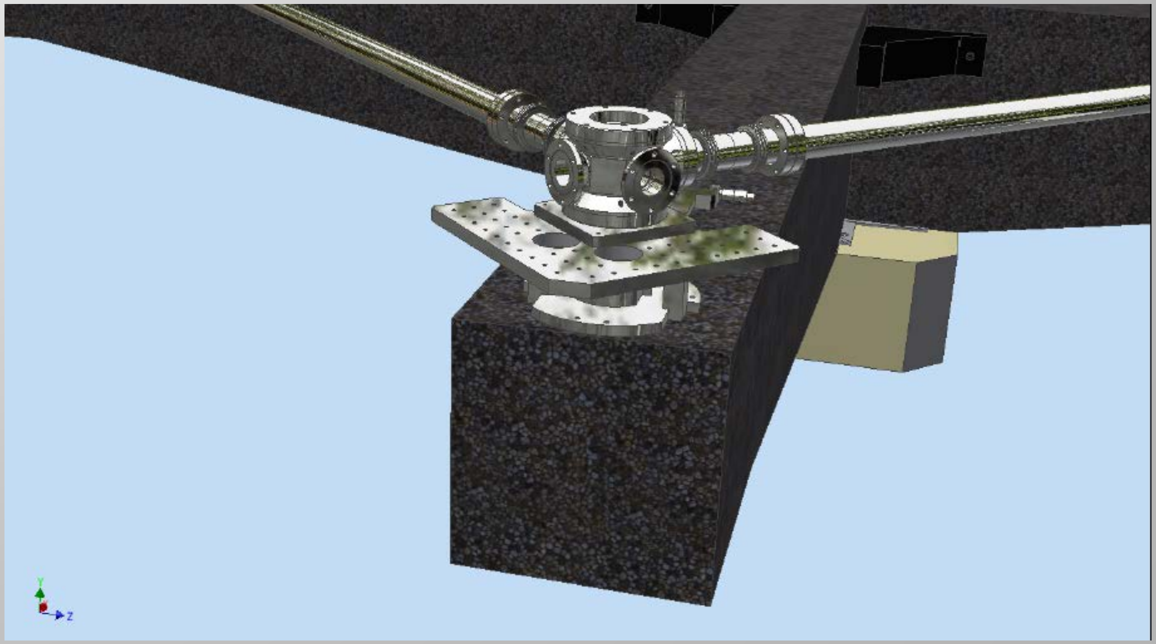


How to hold the ring laser is at the moment under discussion, in particular if we have to attach the four mirrors independently to the ground, or if we have to use a common frame. The advantage of this last choice is that has a reduced impact with the cavern, the mirrors can be installed with a better relative alignment, it is easy to install, it is a facility which can be moved to an other place (if necessary)

...not monolithic, but tight







My letter to Commissione-Spazi

- Gentilissima Commissione-Spazi,

  l'installazione di GINGERino, che avverrà dentro la 'gabbia verde' della sala B, necessita di alcune precisazioni.

  I ring-lasers verranno installati dentro la struttura, e saranno isolati acusticamente e termicamente da un sistema di pannelli che è in fase di progettazione e che verrà appoggiato alla gabbia. Per ottimizzare tale isolamente chiediamo un'area di rispetto di circa 2m all'intorno della gabbia stessa, libera da installazioni permaneti e operazioni sistematiche, il passaggio standard delle persone è ovviamente concesso. E' importante evitare fonti di calore, e di vibrazioni nel sui intorno, in particolare soffi di aria diretti verso la gabbia stessa. Sarebbe inoltre molto spiacevole se qualcuno usasse il tetto della gabbia stessa per stoccare materiale.

  Inoltre la nostra elettronica, i computers e il DAQ dovrebbe essere installati nella prossimità della gabbia, e lo spazio che chiediamo è dell'ordine di 10-15m2.
  Per questo scopo non ci sarebbero problemi ad adoperare parte, se non tutta, l'ex camera grigia di warp.

  La scala è attaccata alla gabbia verde, quando i ring saranno in presa dati sarà necessario proibire l'accesso alla scala stessa.
  Per la nostra installazione questa scala non è necessaria.

  Inoltre, prevedendo e sperando di venire più spesso a LNGS ci farebbe molto piacere avere un ufficio in superficie per la nostra collaborazione con due o tre tavoli

  rimango a disposizione per ogni chiarimenti e vi saluti cordialmente

  Angela Di Virgilio

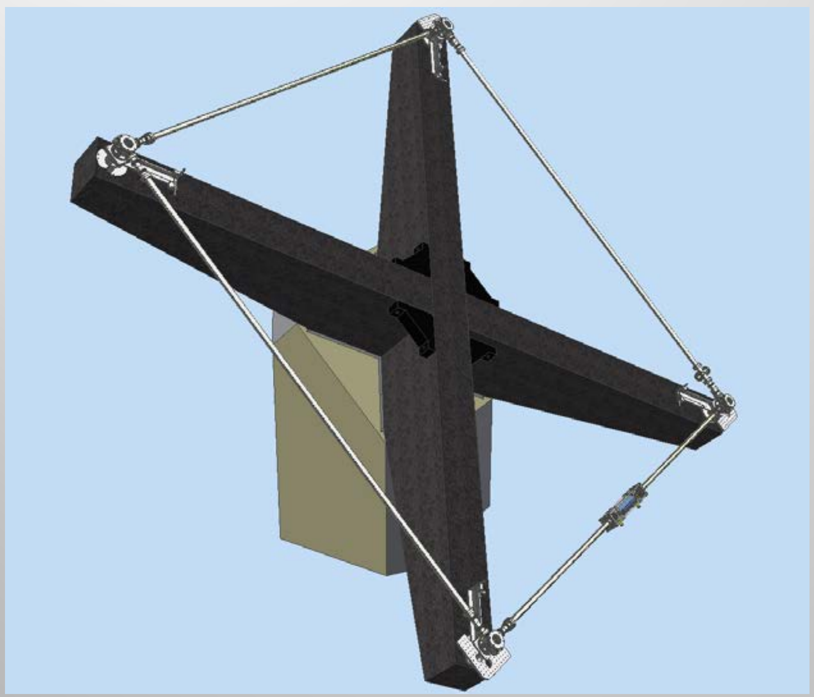
In summary: we need a 2m respect area around our apparatus and chillers, sources of heat or drafts should not be positioned near by

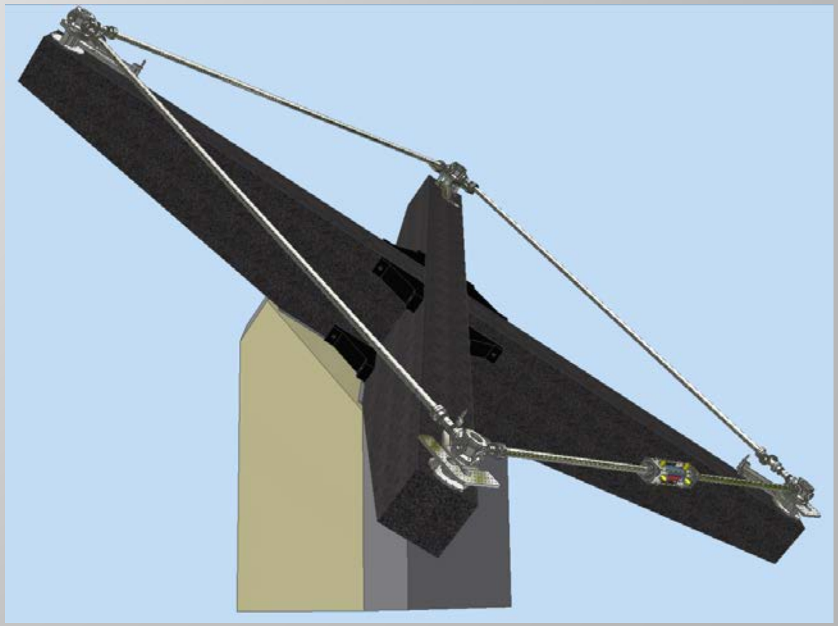
At this moment is….

- **The GINGERino installation inside Noda A has been discussed last week, this should be (I hope) the final step for the 'green light'**
- **Necessary to enter in the details of the construction**

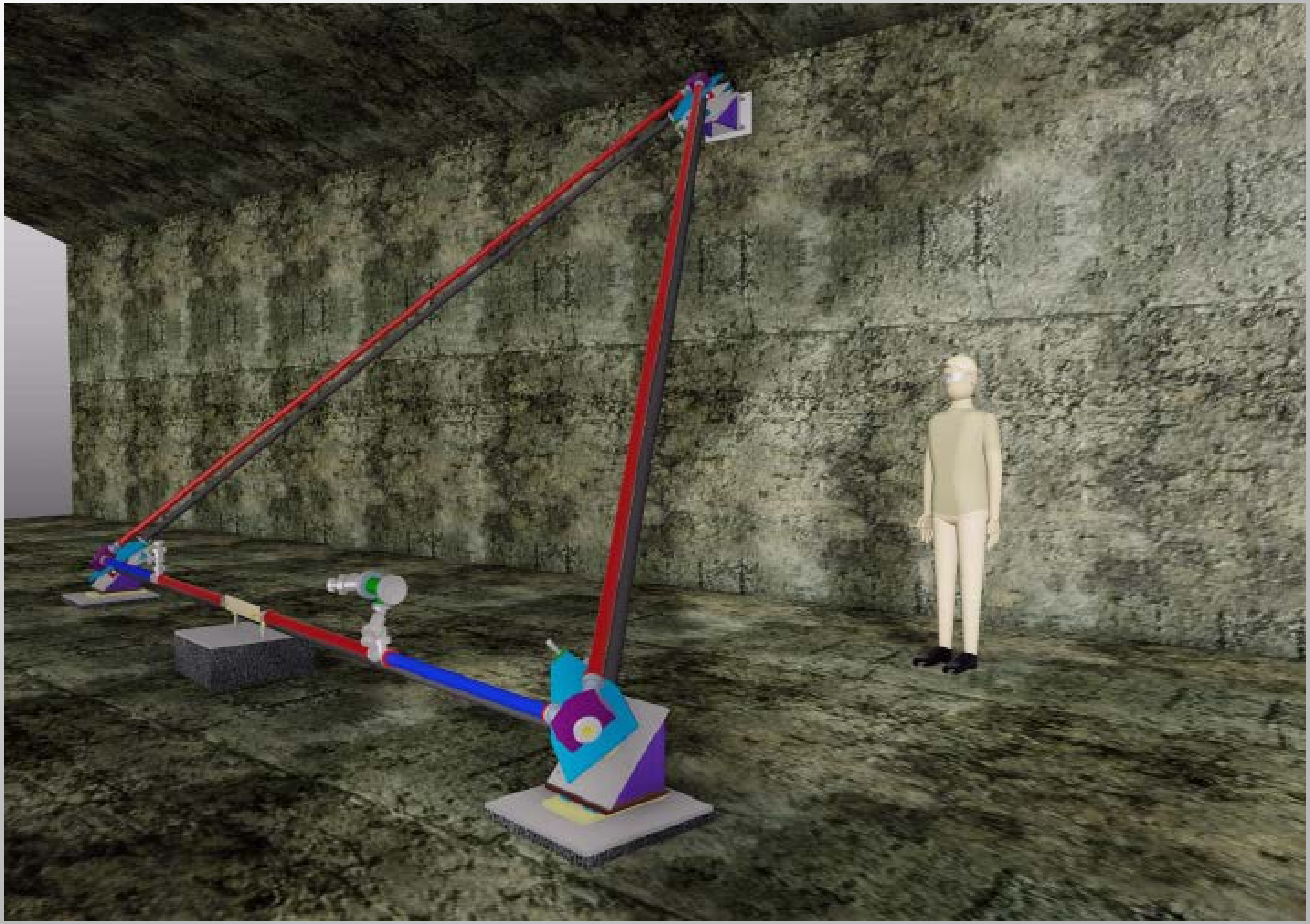
GINGERino Phase II?

- Ring laser at maximum Sagnac signal, important for geodesy, LoD measurement feasible, Filippo Bosi will tell more about the granite frame.



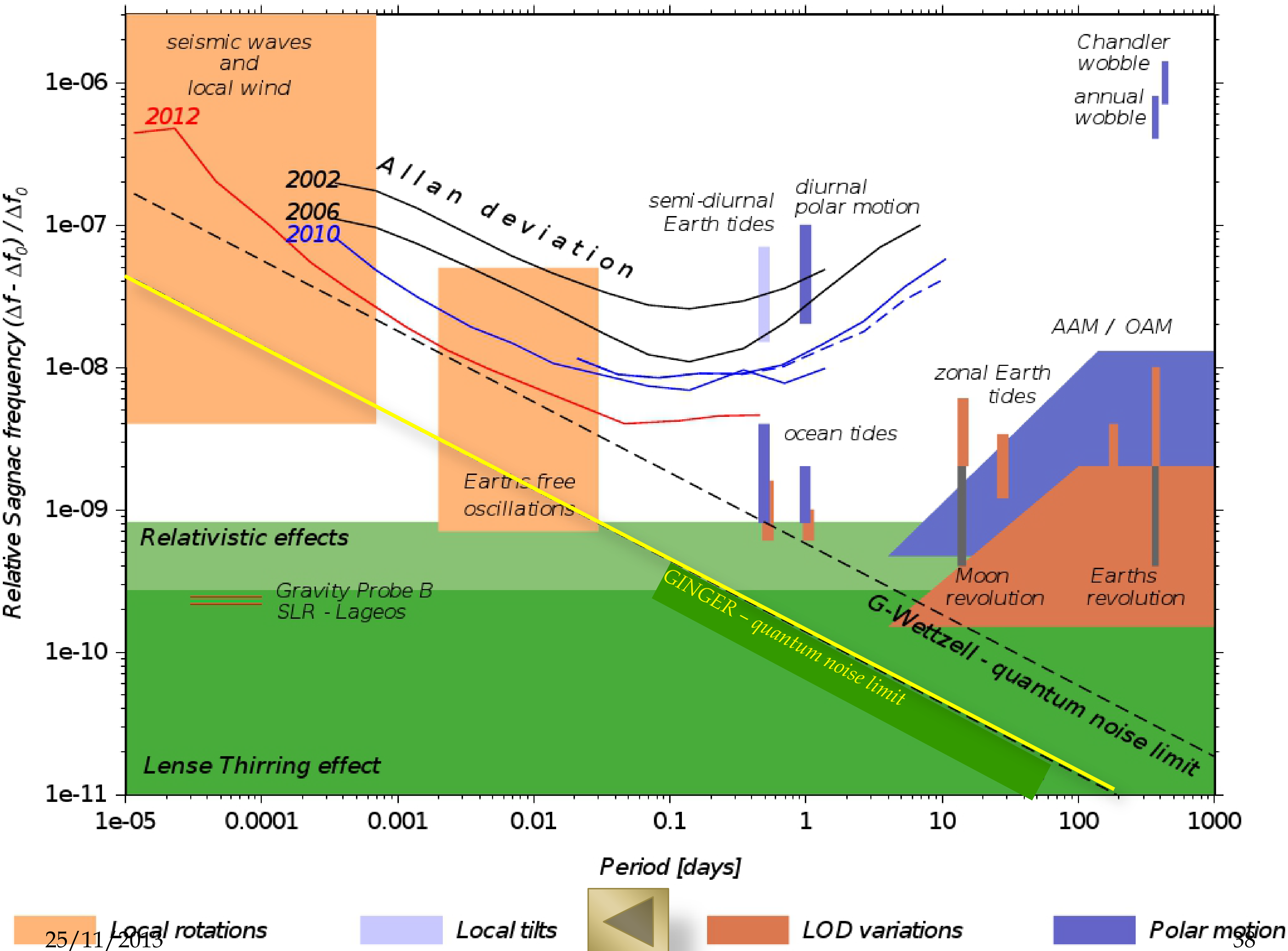


A bit of history? (the triangular ring under construction in NewZealand, currently homeless because of the Christchurch earthquake (2011))



Phase II – in Collaboration with NZ?

- In Phase II the ringlaser should be aligned with the maximum Sagnac signal (parallel to the pole in order to measure the modulus of the Earth angular rotation, measurement of the LoD feasible (length of the Day))
- An MOU is in preparation, we should discuss it in December with J-P Wells, which is the PI of the NZ project, U. Schreiber is the Co-PI


seismic waves
and
local wind
2012
2002
2006
2010
Allan deviation
semi-diurnal
Earth tides
diurnal
polar motion
Chandler
wobble
annual
wobble
AAM / OAM
zonal Earth
tides
ocean tides
Earths free
oscillations
Relativistic effects
Gravity Probe B
SLR - Lageos
GINGER – quantum noise limit
G-Wettzell - quantum noise limit
Moon
revolution
Earths
revolution
Lense Thirring effect
Relative Sagnac frequency (Δf - Δf0) / Δf0
Period [days]
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-05
0.0001
0.001
0.01
0.1
1
10
100
1000
Local rotations
Local tilts
LOD variations
Polar motion

Real vs. Ideal

$$\Delta f = k_s\left(1 + k_A\right)\Omega + \Delta f_0 + \Delta f_{bs}$$

k_s Geometrical scale factor
k_A Atomic scale factor
Δf_0 Null shift
Δf_{BS} Back-scattering

All these terms must be controlled at least at 10^{-10}

Geometrical factor

$$\Delta f = k_s(1+k_A)\Omega + \Delta f_0 + \Delta f_{bs}$$

- The geometrical factor A/p must be actively controlled better than 10^{-10}.

➪ Mirror relative position and orientation should be accurate better than 1 nm and 1 nrad!

Very hard task

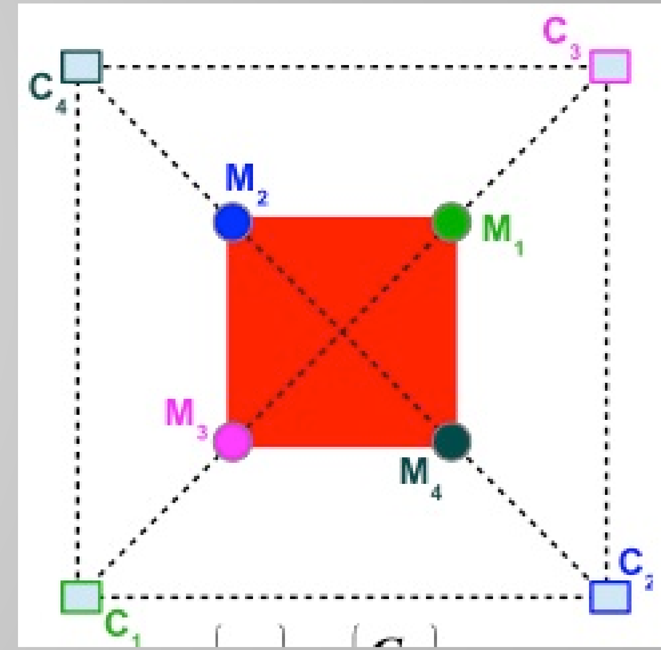
But,

let us consider a perfect square geometry!

Geometry

The geometry of a 4-mirror cavity is fully defined by the coordinates of the centre of curvature of the mirrors.

➪ 12 independent degrees of freedoms (3 linear actuators on each mirrors)



A set of orthogonal linear combinations of these movements can be chosen that produces:

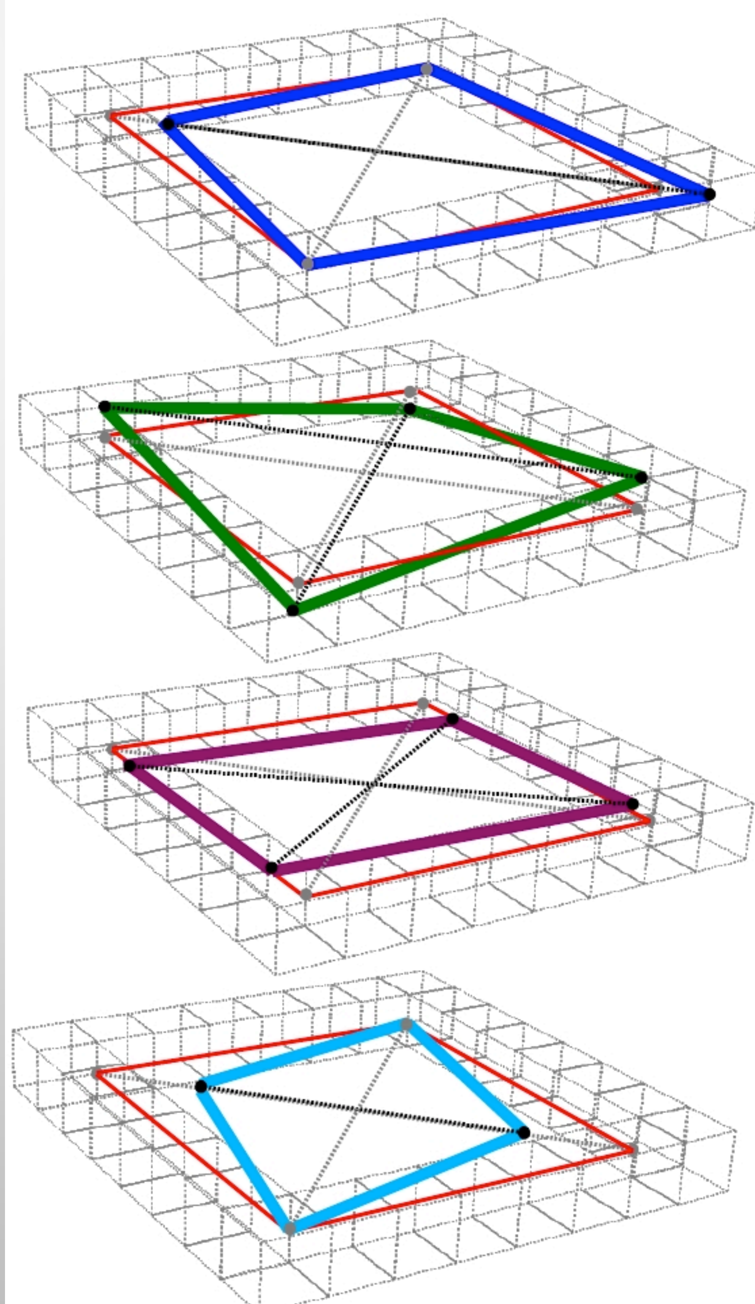
- Rigid body movements 6 d.o.f
- Relative motions of the two diagonals, keeping fixed their lengths (no rotation) 2_d.o.f. horizontal + 1 d.o.f. vertical
- Relative rotation of the diagonals keeping fixed their lengths 1 d.o.f.
- Stretching of the square diagonals 2 d.o.f.

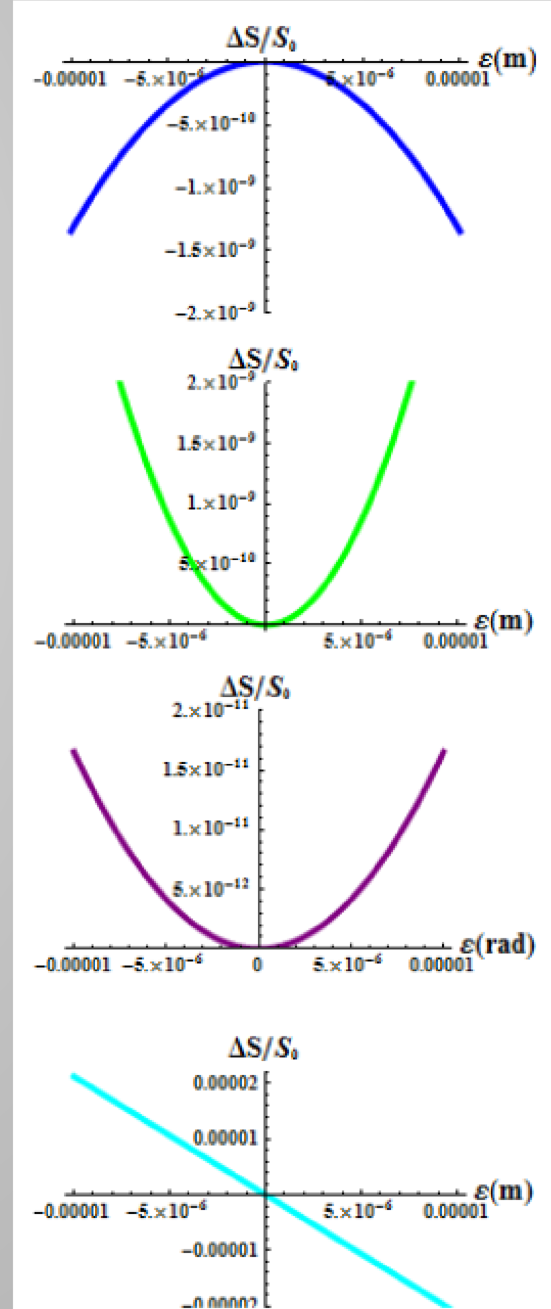
Relative motions of the two diagonals 2_d.o.f. horizontal

+ 1 d.o.f. vertical

Relative rotation of the diagonals 1 d.o.f.

Stretching of the diagonals 2 d.o.f.

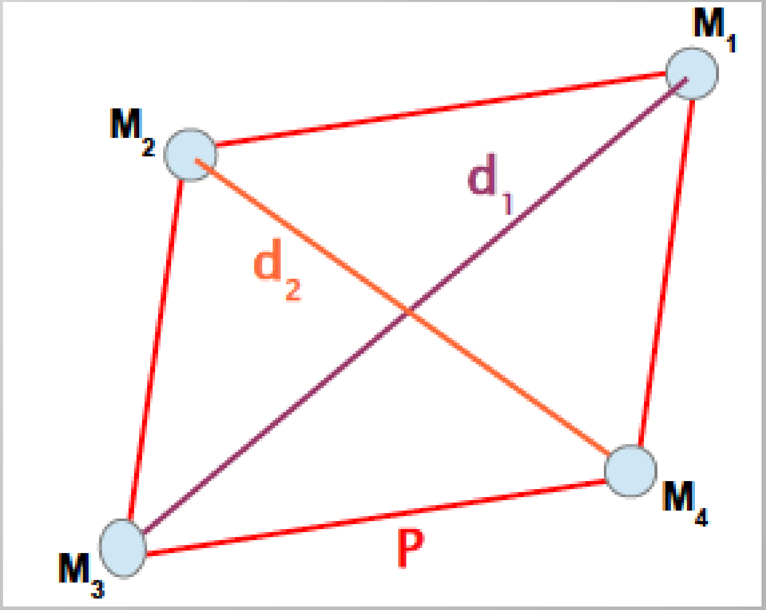




Geometry

How to arrive to ***perfect square*** *configuration?*

- The ring cavity perimeter can be known with very high accuracy (> 10^{11}), by the beat note of the laser emission and a reference laser.
- In a near-square 4-mirror cavity, the opposite mirrors define two Fabry-Pérot resonators whose length can be locked to the reference laser.
- ➪ Keeping the diagonal lengths locked, the other d.o.f. can be optimized one by one.

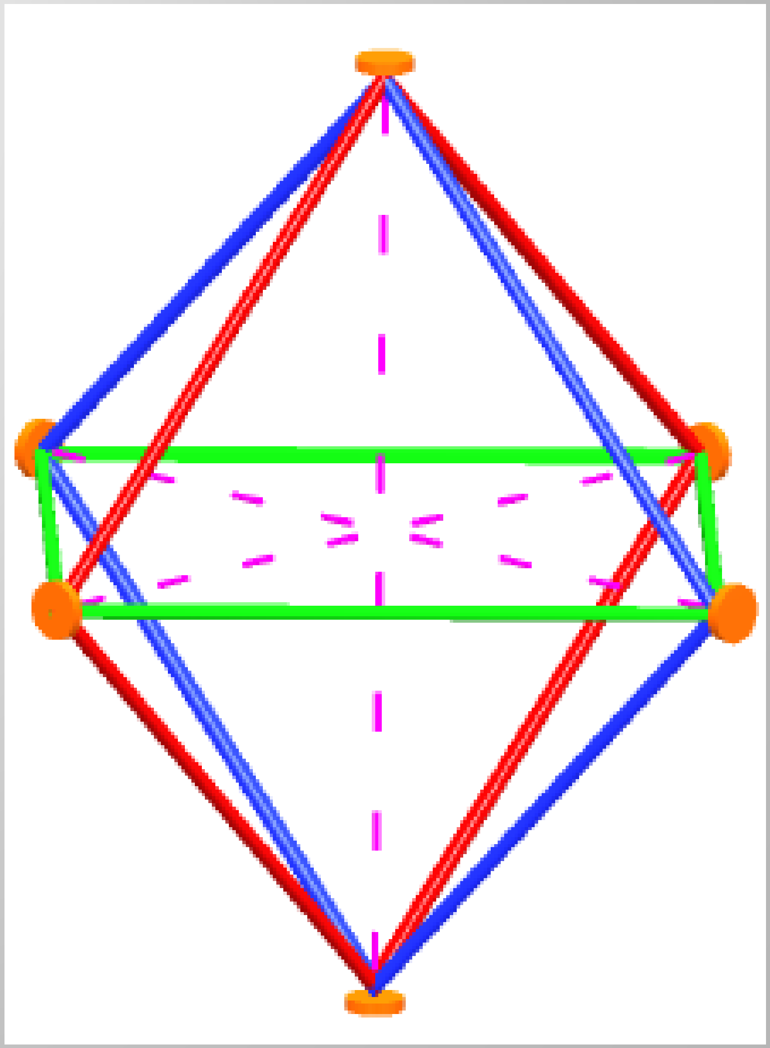


➪ A *perfect square* geometry can be achieved with the scale factor *A/p* stabilised at 10^{-11} level.

Octrahedral structure
solve the relative alignment problem (1nrad)

- 3 mutually orthogonal nested ring cavities in octahedral structure.
- Each mirror is shared by 2 rings.
- Diagonals gives signals for the relative alignment control

- **Diagonals play an important role for the ring stabilization**



Atomic factor

$$\Delta f = k_s\left(1 + k_A\right)\Omega + \Delta f_0 + \Delta f_{bs}$$

- The laser action is sensitive to changes of the discharge properties that can produce variation in the laser gain and in the plasma dispersion function.
  - Evolution of the discharge gas composition
  - Stability of the discharge power

➪ Control of the lab temperature, pressure, humidity

➪ Good stabilization of the discharge power and of the laser wavelength

➪ Control of wall outgassing through getter pumps

➪ *Diagnostics of the sensitive parameters of the discharge*

Null-shift

$$\Delta f = k_s(1 + k_A)\Omega + \Delta f_0 + \Delta f_{bs}$$

Non-reciprocity in the optical cavity

- For an ideal ring laser the two counter-propagating laser beams would be identical both in size and in intensity.
- In practice, there have been found differences in the intensities of more than 10% for small gyros (1 – 2 m of side)
- G shows a beam power difference around 1%.
- Probably due to coatings exhibit some minute anisotropy or birefringence in the super mirror

➪ *This null-shift effect can be modelled, together with the atomic factor, and the back-scattering, accounting for laser dynamics, dispersive frequency detuning and hole burning.*

➪ *Diagnostic: relative intensity of the two beams*

Back-scattering

$$\Delta f = k_s(1+k_A)\Omega + \Delta f_0 + \Delta f_{bs}$$

Mirror's backscattering couples together the two counter-propagating laser beams through a coupling parameter r :

$$r = \sum_i r_i \exp(2ikz_n)$$

sum of the contributions the back-scattering by the four mirrors

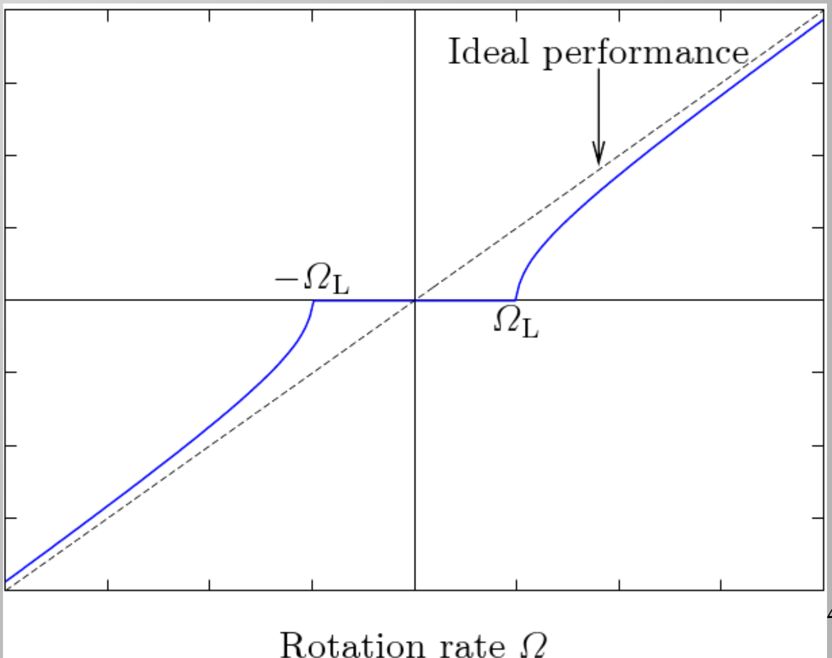
This produce a frequency difference that is actually given by:

$$p = \sqrt{f^2 - l^2} \quad \text{for} \quad f > l$$

$l = r/\pi$ lock-in threshold frequency.

If $f \le l$, the two oscillators are locked one to the other

➪ no Sagnac signal



Back-scattering

$$r = \sum_i r_i \exp(2ikz_n)$$

r_i is the mirror relative amplitude backscattering rate in the cavity mode of the counter-propagating beam.

r value can vary between $-\sum_i |r_i|$ and $\sum_i |r_i|$ for small perturbations in the ring geometry of the order of λ

By geometry $|r_i| \propto \frac{1}{L}$

Moreover, its effectiveness is related to the ratio between cavity line-width ($\propto 1/L$) and the beams frequency difference ($\propto L$) .

Back-scattering effect is strongly reduced by increasing ring dimension

Approaching GINGER

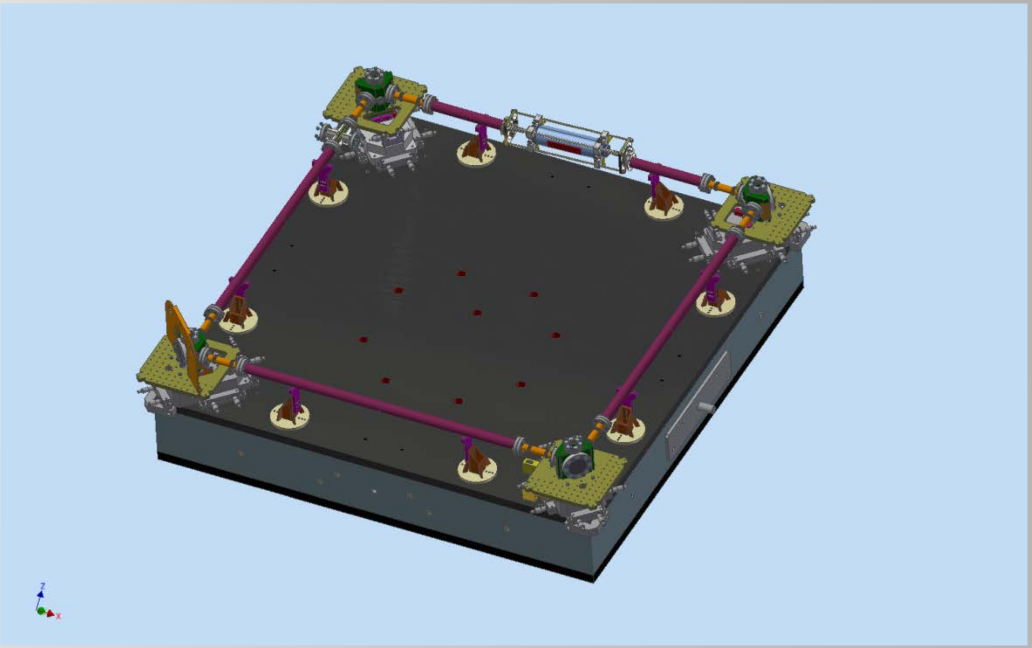
- Test on the geometry control (GP-2)
- Diagnostic of the laser kinematics and Kalman filtering
- Mirror optimization
- Site analysis in Gran Sasso (upgrading of G-Pisa to 4-m)

Real Work

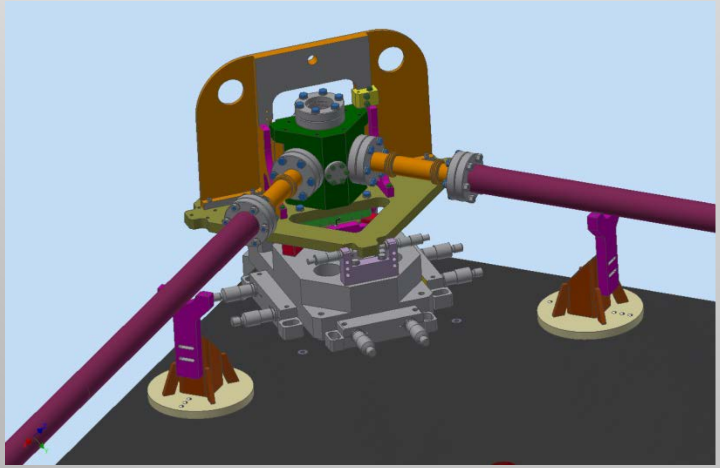
- Geometry Study (PhD Rosa Santagata)
- Laser Dynamics and Kalman (PhD Davide Cuccato with A. Ortolan at LNL)
- Plasma/Laser study and experimental work Jacopo Belfi

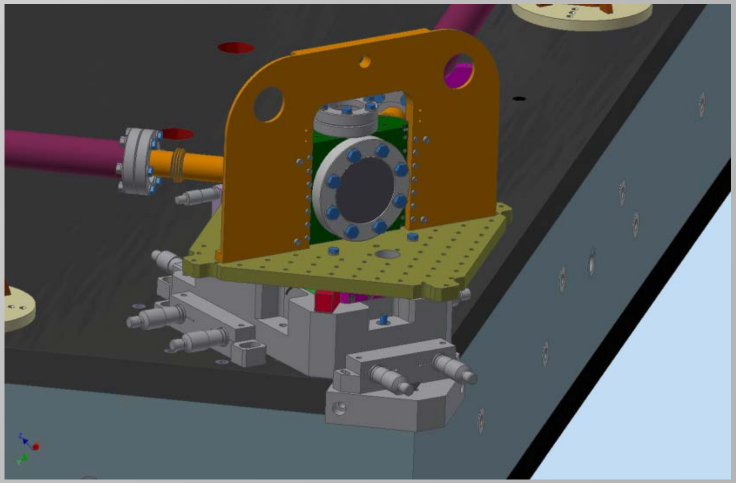
GP-2:

- Easy alignment and mirror change
- 6 degrees of freedom translation (80μm range)
- Table in 'light' granite, machined with few microns precision
- Manual rough alignment
- Optical quality windows

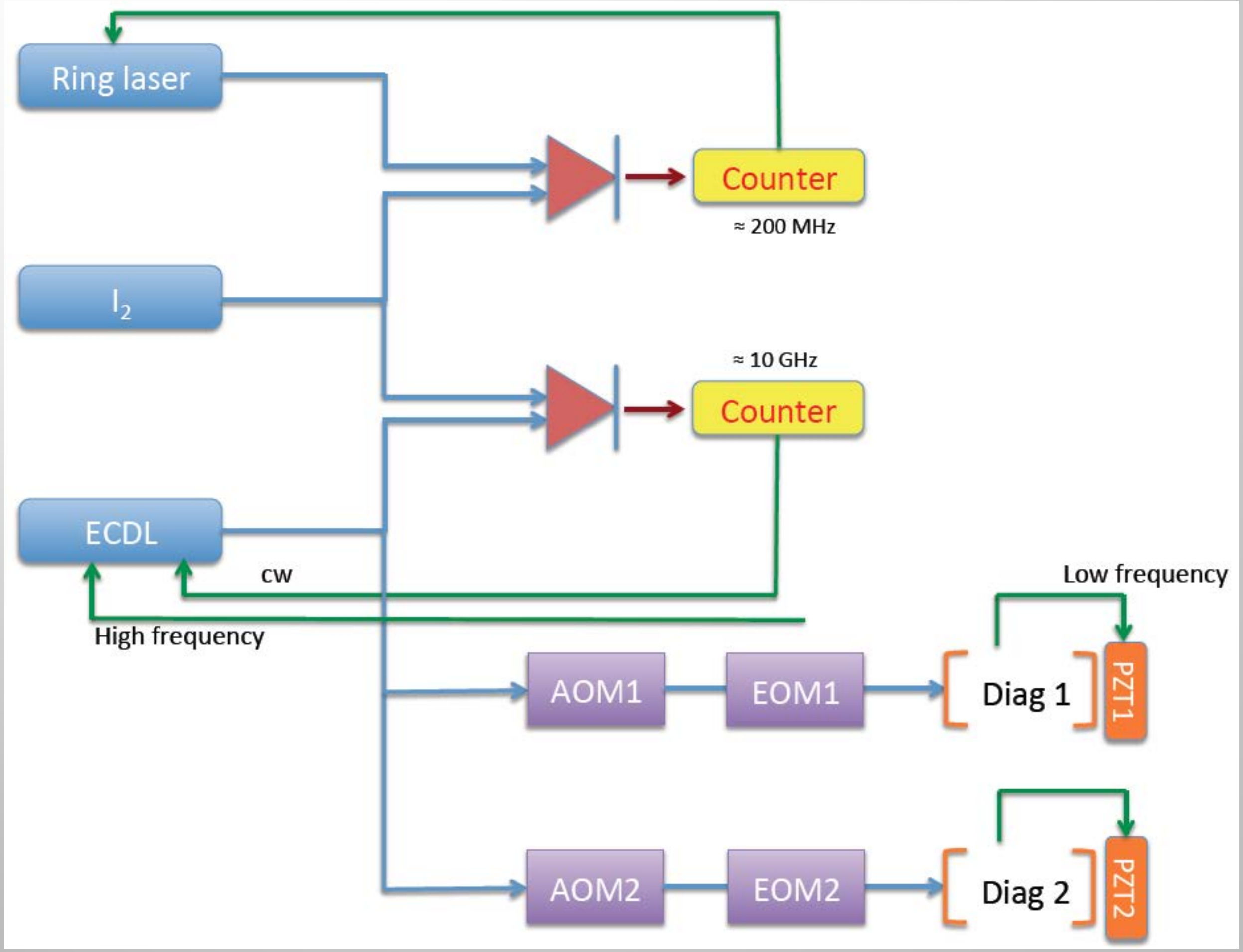


Under-Construction in Pisa

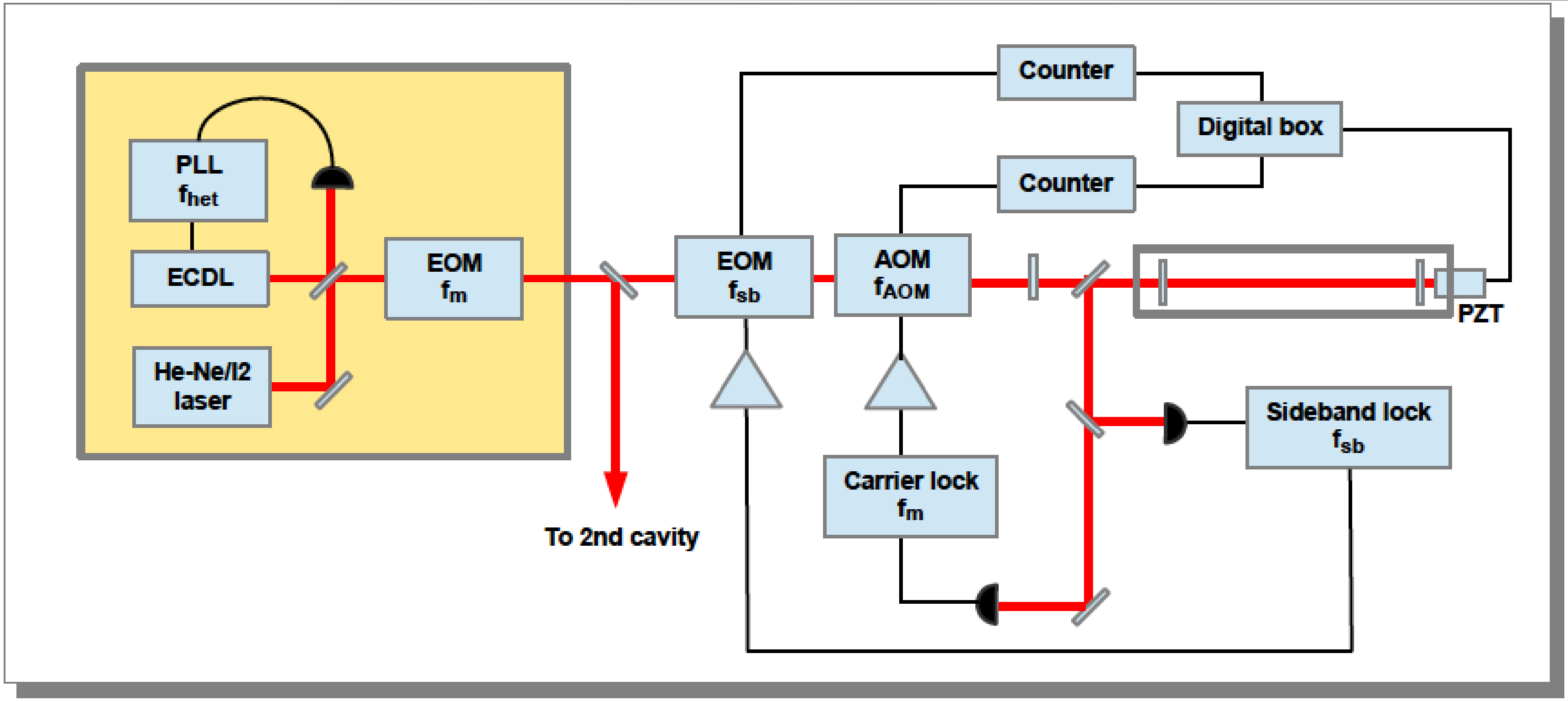




GP2 : diagonal control



The two diagonal must set to an identical absolute value.



The two diagonal must be set to an identical absolute value.

Resonance condition: $\nu_n = \frac{c}{2L}(n+\varepsilon)$ with $\varepsilon = \frac{1}{\pi}\arccos(1-L/R)$

To fix at 10^{-11} the lengths is necessary to measure at 10^{-10} the resonance frequency by a frequency stabilized laser, and to know the order of interference *n* (that is measure the FSR with an accuracy better than *n*) .

For a diagonal length of ~10 m, n ≈ 3·10^{7}.

Laser model

Diagnostic of the laser kinematics and Kalman filtering

- Laser action has been modelled under Lamb/Aronowitz formalism at the 3rd order in atomic polarization.

$$P^{(3)}(E_{1,2}) = -\frac{2i m \mu_{ab}^2}{\gamma_{ab}} \int_{-\infty}^{\infty} \chi_{1,2}(v)\, \rho^{(2)}(v, E_{1,2})\, dv$$

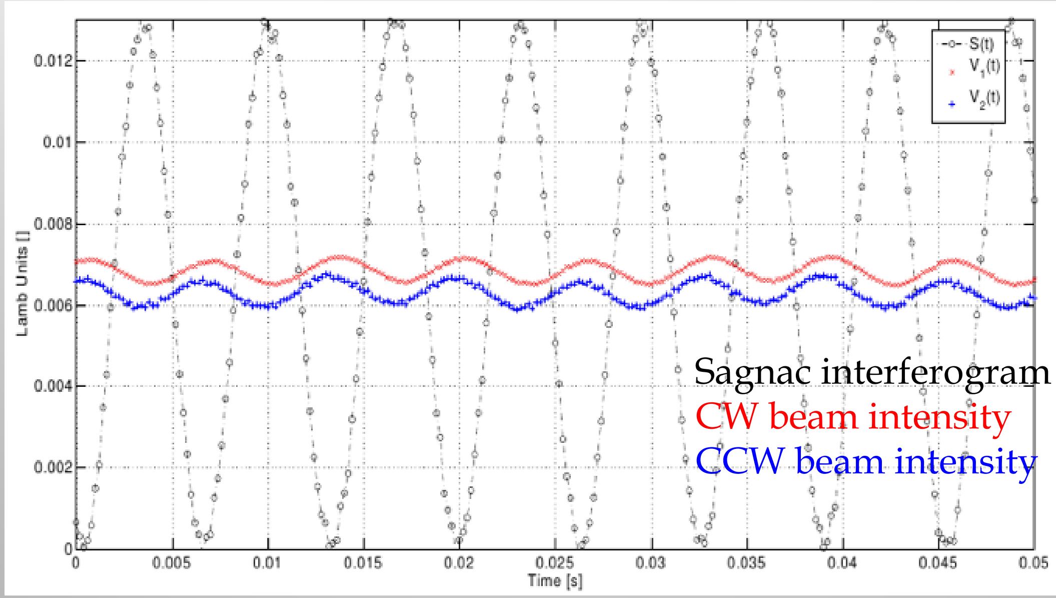
$$\dot{I}_1 = \alpha_1 I_1 - \beta I_1^2 - \theta_2 I_2 I_1 + r_2 \sqrt{I_1 I_2} \cos(\psi - \varepsilon_1)$$

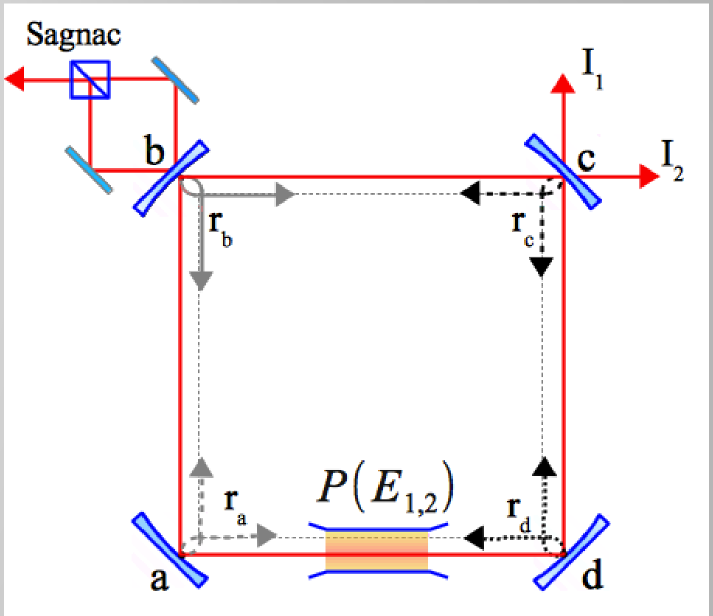
$$\dot{I}_2 = \alpha_2 I_2 - \beta I_2^2 - \theta_1 I_2 I_1 + r_1 \sqrt{I_1 I_2} \cos(\psi + \varepsilon_2)$$

$$\dot{\psi} = \omega_s + \tau_1 I_1 - \tau_2 I_2 - r_2 \sqrt{\frac{I_1}{I_2}} \sin(\psi - \varepsilon_2) - r_2 \sqrt{\frac{I_1}{I_2}} \sin(\psi + \varepsilon_1)$$

Kalman filter

The model parameters are obtained by continuous monitoring of the interpherogram and the single beam intensities



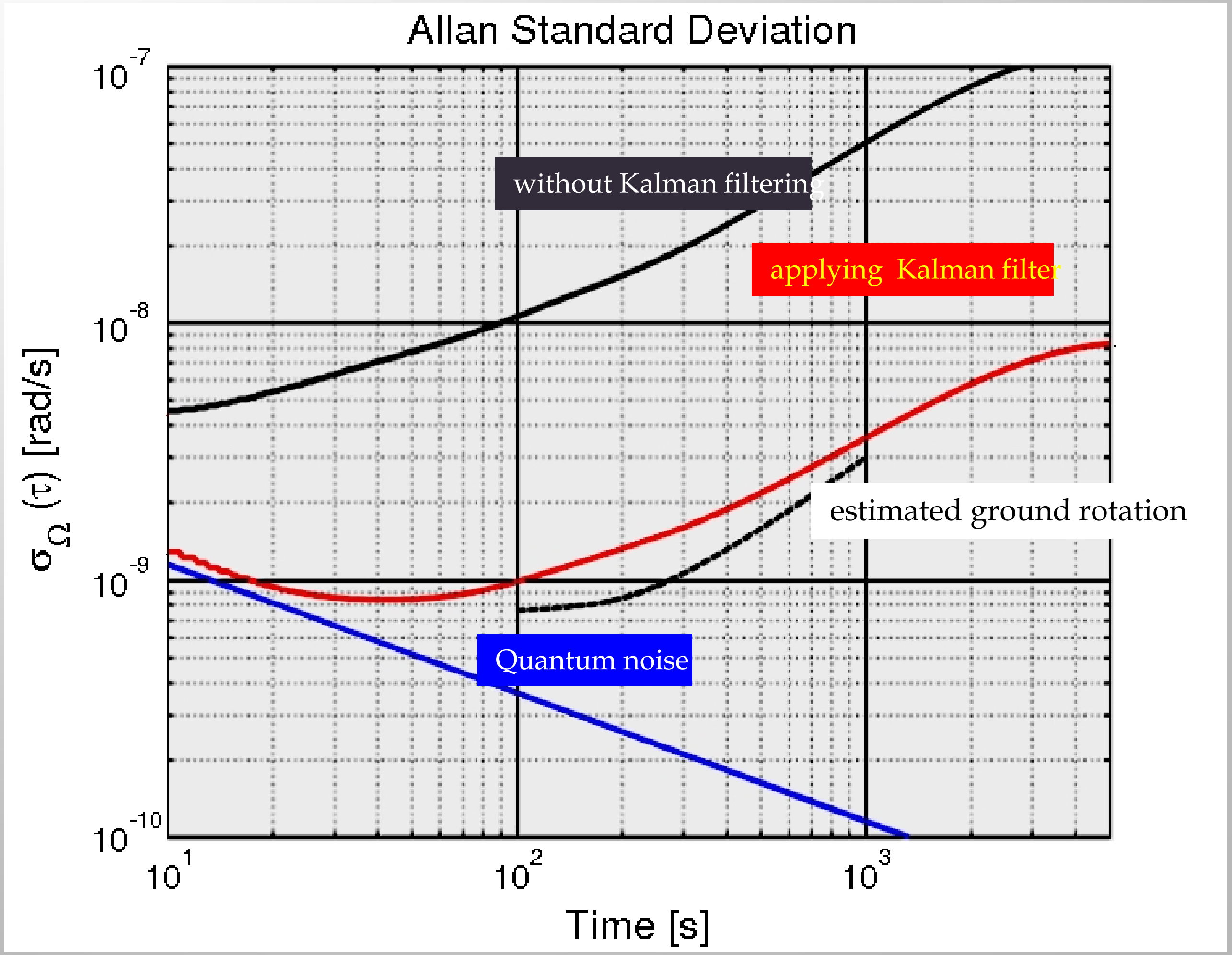


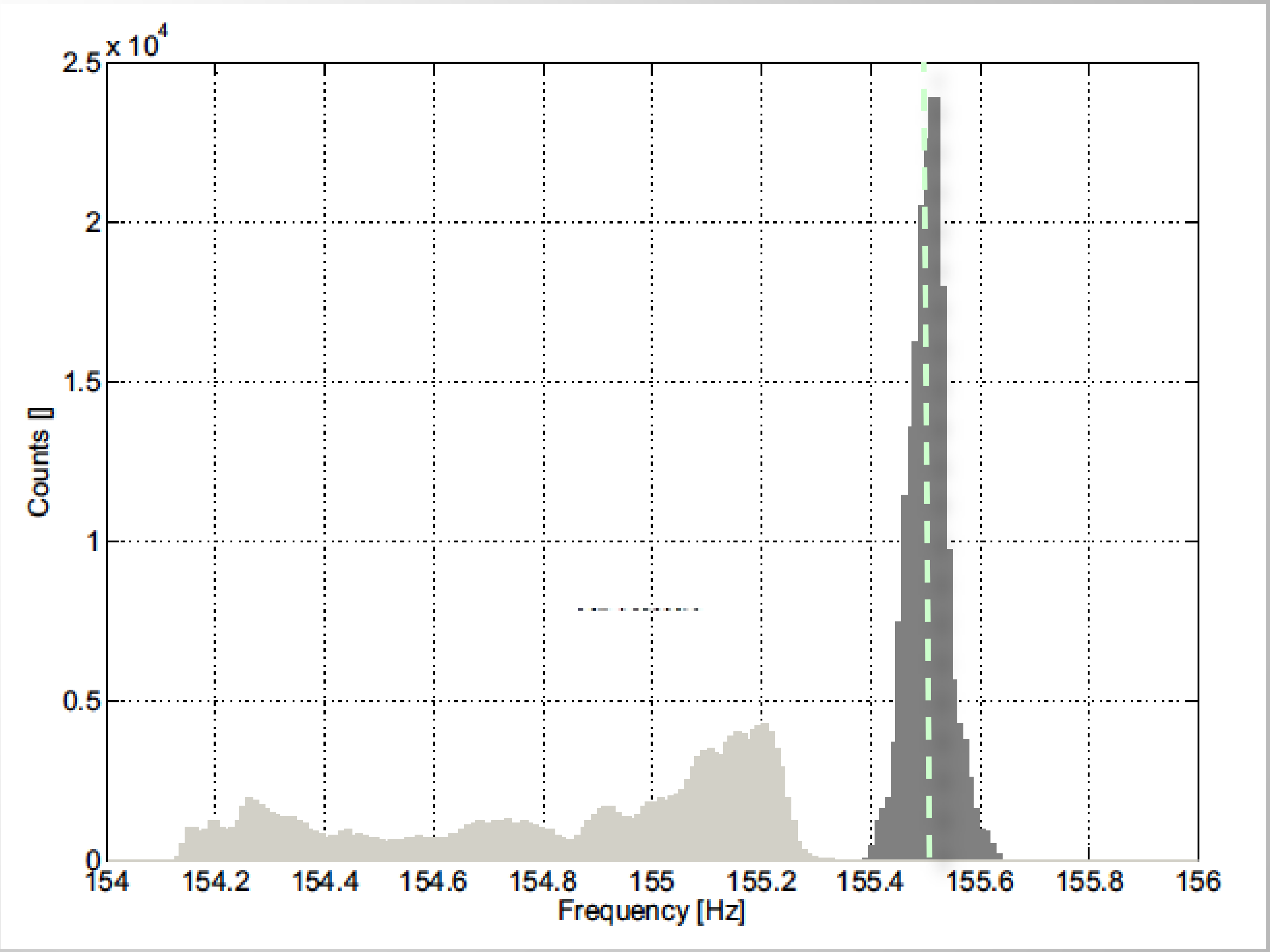
By these experimental data and by estimating the laser parameters like atomic temperature, cavity losses, unsaturated gain, a Kalman filter has been build to reduce long-term noise

A. Beghi, J. Belfi, N. Beverini, B. Bouhadef, D. Cuccato, A. Di Virgilio, A. Ortolan: **Appl. Opt. 51, 7518-7528** (2012)

Improved Kalman, with calibration and monitoring of the gas gain and identification of all lamb coefficients

arXiv:1309.4694



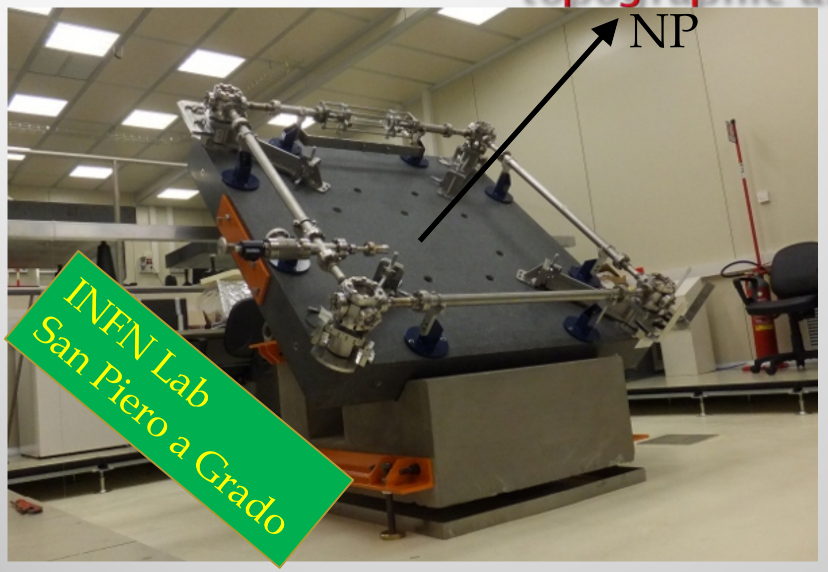


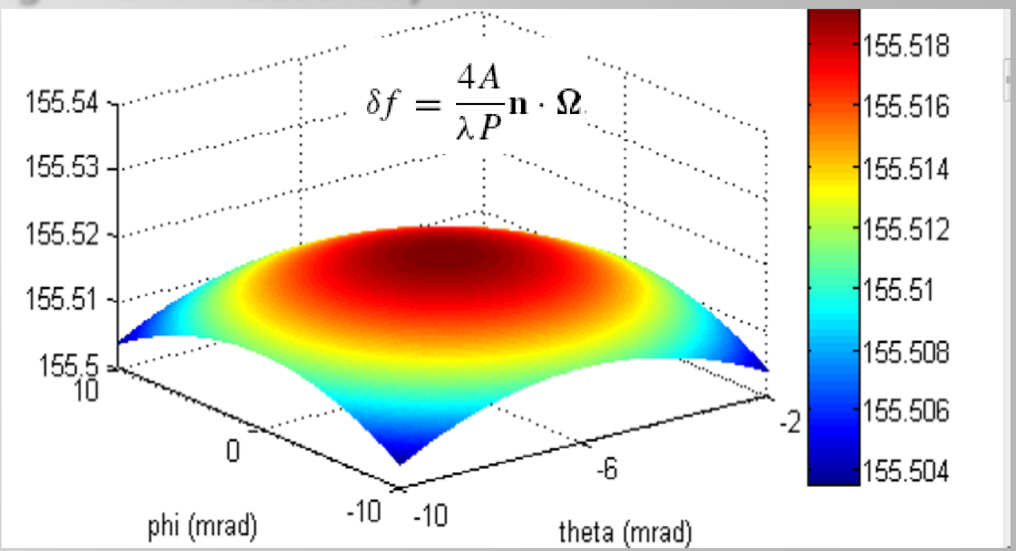
Histograms of the estimates of Sagnac frequency during 2 days of G-PISA data
(1 point each second) .
Note : - null shift contribution is removed (increasing accuracy),
- the standard deviation is ~ 10 times lower (increasing long tem stability)

Controlling the nonlinear intracavity dynamics of large He-Ne laser gyroscopes

[A. Beghiet al., Arxiv]

Data taken with G-PISA oriented at the maximum Sagnac (Earth rotation rate), the best orientation to measure the modulus of the Earth angular rotation; topographic alignment→ accuracy~1°



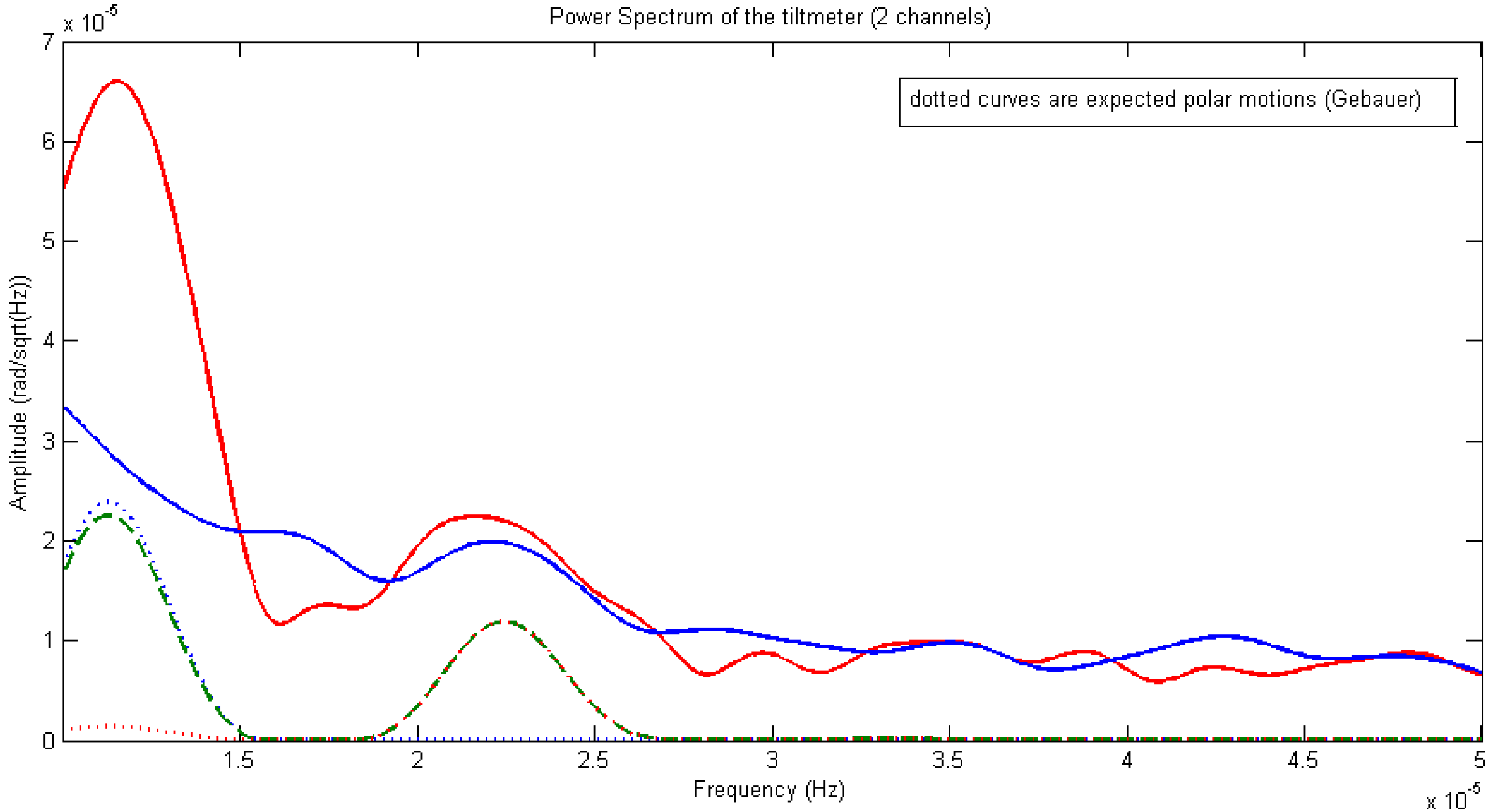


Last July, Jacopo Belfi and Davide Cuccato have been to Wettzell to insert in the DAQ the signals necessary to efficiently apply the Kalman Filter. Work is in progress for the analysis

Note

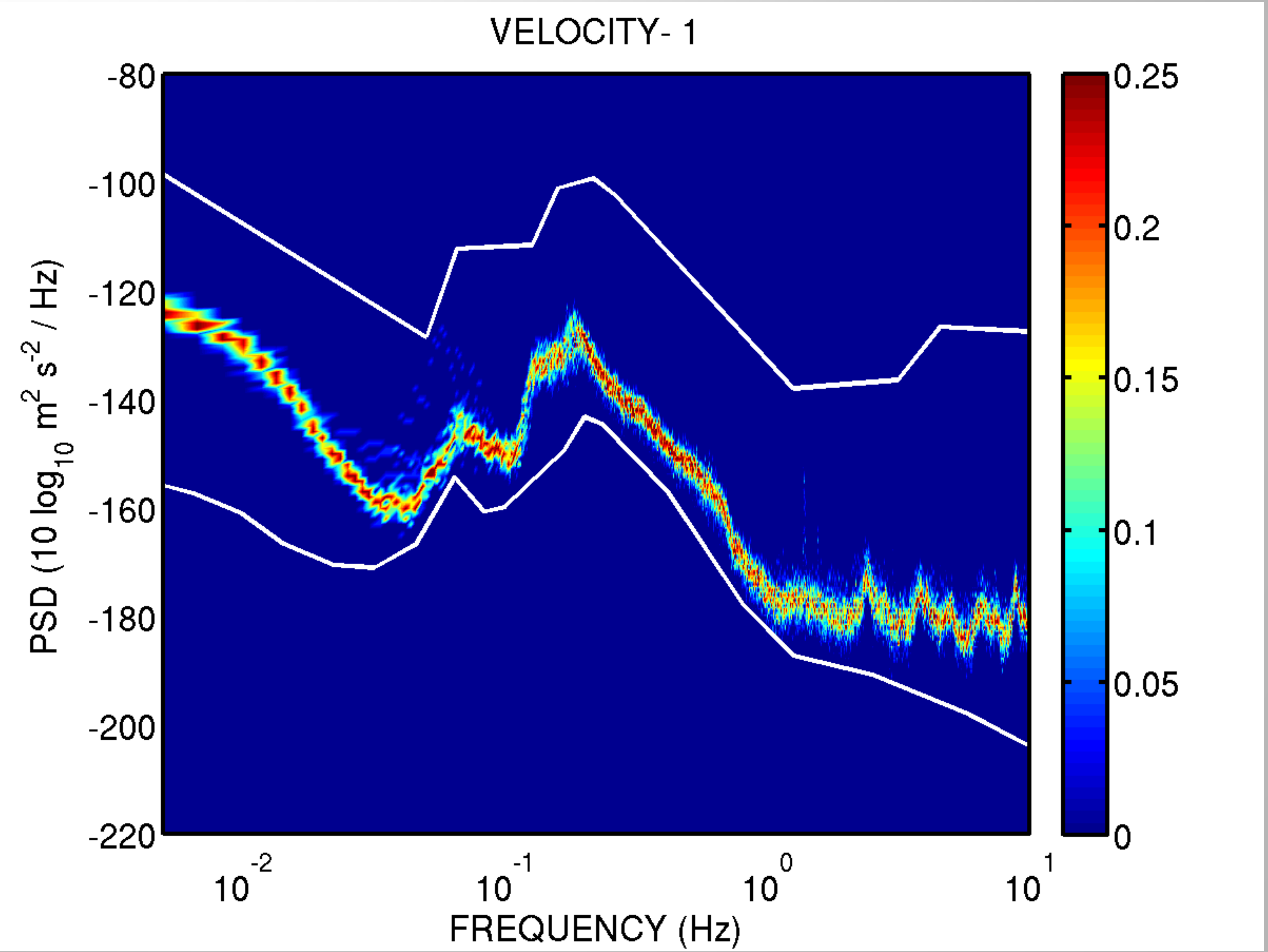
- Siamo in un premiale INRIM che ‘apparentemente’ ha vinto
- Costruzione di un ring-laser di 1m di lato da essere posizionato su di una tavola rotante, risoluzione 50nrad.
- Importante per check di calibrazione assoluta
- Heiner Igel (LMU) ha vinto un ERC (ROMY) per la sismologia rotazionale basata su sistemi triassiali di ringlaser, noi siamo considerati parte del team

...despite the tilt-meter signals are noisy, the Fourier Analysis clearly shows the two Diurnal and semidiurnal tides, induced by the Moon

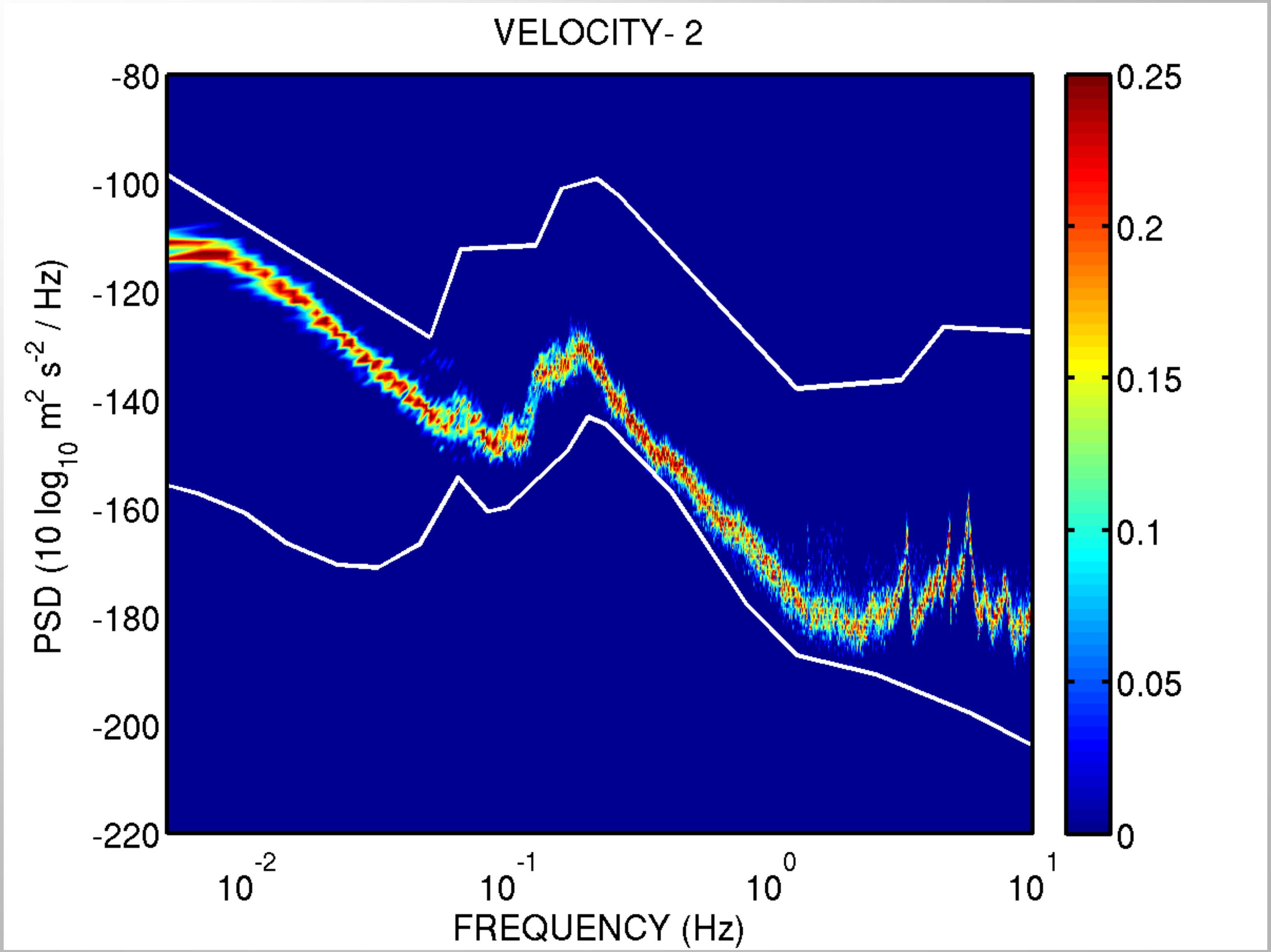


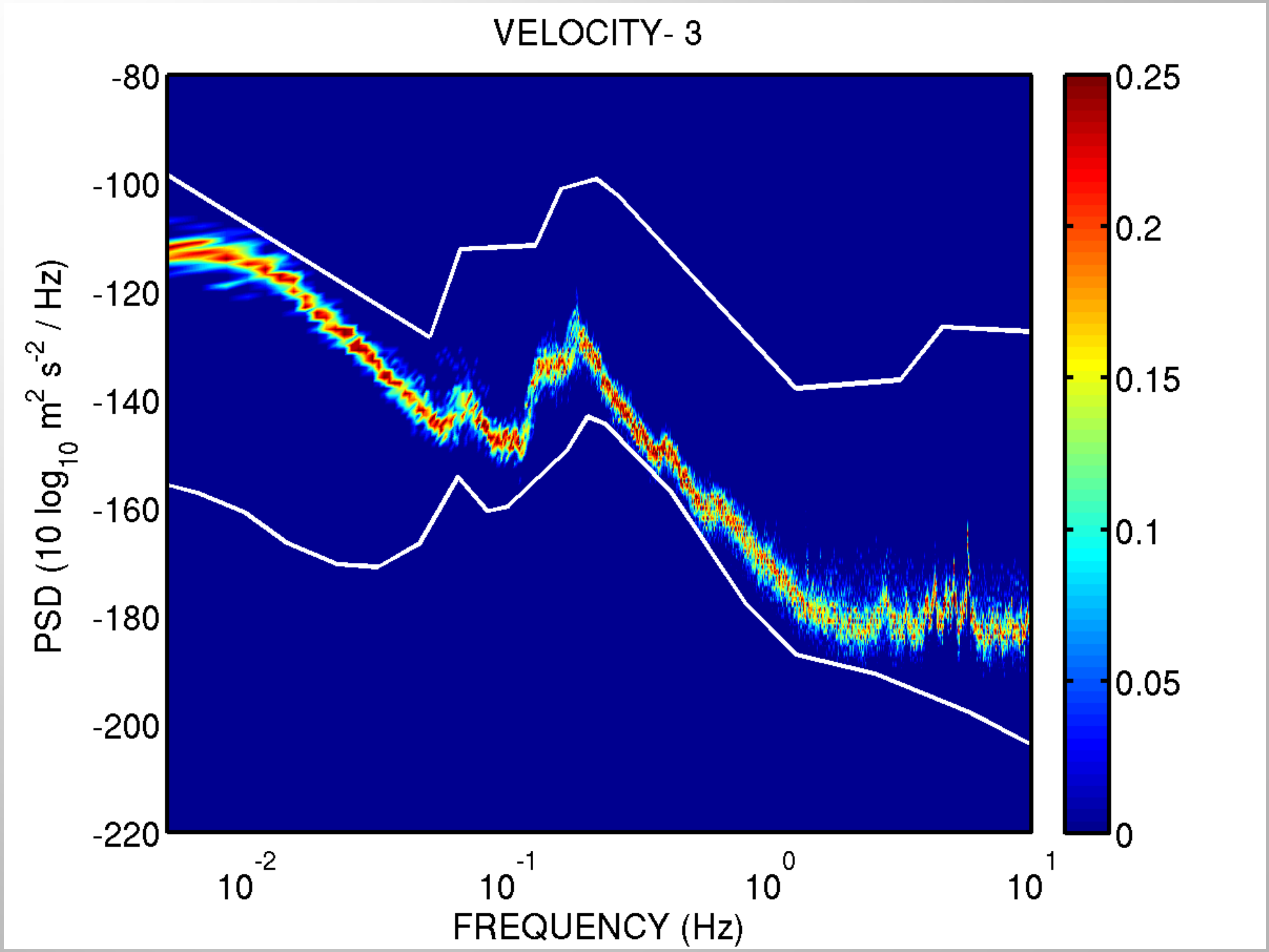
Seismometer STS-2 Streckeisen (ingv-Saccorotti)

- ST-2 co-located with G-Pisa, on top of the granite table
- Confrontation with the USGS New Low Noise Model



VELOCITY- 1
-80
-100
-120
-140
-160
-180
-200
-220
PSD (10 log$_{10}$ m^2 s^{-2} / Hz)
10^{-2}
10^{-1}
10^{0}
10^{1}
FREQUENCY (Hz)
0.25
0.2
0.15
0.1
0.05
0


VELOCITY- 2
-80
-100
-120
-140
-160
-180
-200
-220
PSD (10 log10 m2 s-2 / Hz)
10-2
10-1
100
101
FREQUENCY (Hz)
0.25
0.2
0.15
0.1
0.05
0


VELOCITY- 3
PSD (10 log$_{10}$ m^2 s^{-2} / Hz)
-80
-100
-120
-140
-160
-180
-200
-220
10^{-2}
10^{-1}
10^{0}
10^{1}
FREQUENCY (Hz)
0.25
0.2
0.15
0.1
0.05
0

Typical PSD on the top surface (VIRGO)