"GINGER" - Gyroscope in General Relativity
Observing general relativity effects by rotation sensing

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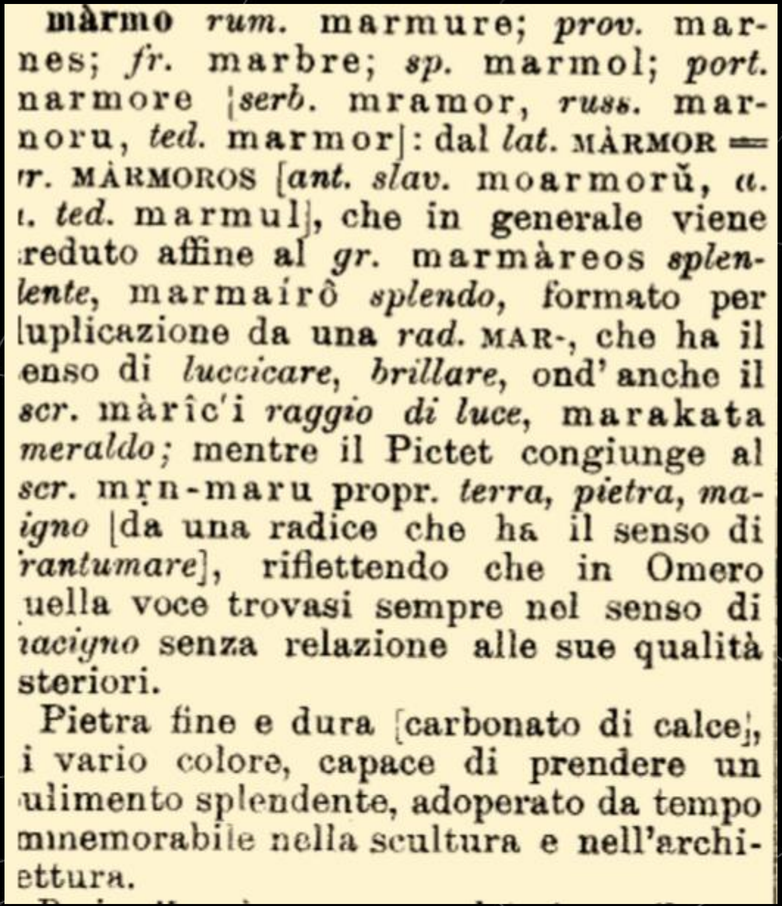
Outline

- Premise
- Sagnac effect and rotation sensing
- The gyrolaser
- GINGER and General Relativity
- GINGER design
  - Some technical issues (and requirements)
- GINGERino and the LNGS campaign
- GP2 and the diagonal issue
- (Inconclusive) Conclusions

GINGERino seats on a “MARMO” basement



màrmo *rum.* marmure; *prov.* marnes; *fr.* marbre; *sp.* marmol; *port.* narmore [*serb.* mramor, *russ.* marnoru, *ted.* marmor]: dal *lat.* MÀRMOR = ɪr. MÀRMOROS [*ant. slav.* moarmorŭ, *a.* ɪ. *ted.* marmul], che in generale viene :reduto affine al *gr.* marmàreos *splenlente*, marmairô *splendo*, formato per luplicazione da una *rad.* MAR-, che ha il enso di *luccicare*, *brillare*, ond' anche il *scr.* màrîc'i *raggio di luce*, marakata *meraldo*; mentre il Pictet congiunge al *scr.* mṛn-maru propr. *terra*, *pietra*, *maigno* [da una radice che ha il senso di *rantumare*], riflettendo che in Omero uella voce trovasi sempre nel senso di *iacigno* senza relazione alle sue qualità steriori.

Pietra fine e dura [carbonato di calce], i vario colore, capace di prendere un ulimento splendente, adoperato da tempo mmemorabile nella scultura e nell'archiettura.

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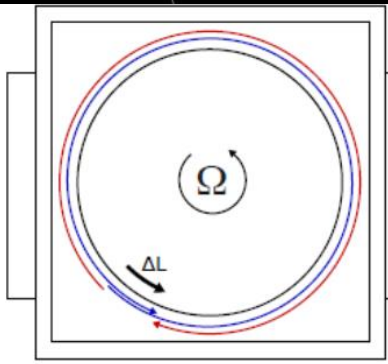
Premise

- GINGER is an INFN leaded proposal for exploiting extremely high sensitivity rotation sensing to measure General Relativity Effects such as Lense-Thirring in an underground laboratory;
- The peculiarity of this approach seats on measuring LT effect induced by the Earth rotation while rotating together with the effect source itself: the Earth;
- So far the general physics aspect of the proposal have been clearly identificated while the experiment is the *proof of principle* phase.

The Sagnac effect from scratch



Sagnac effect

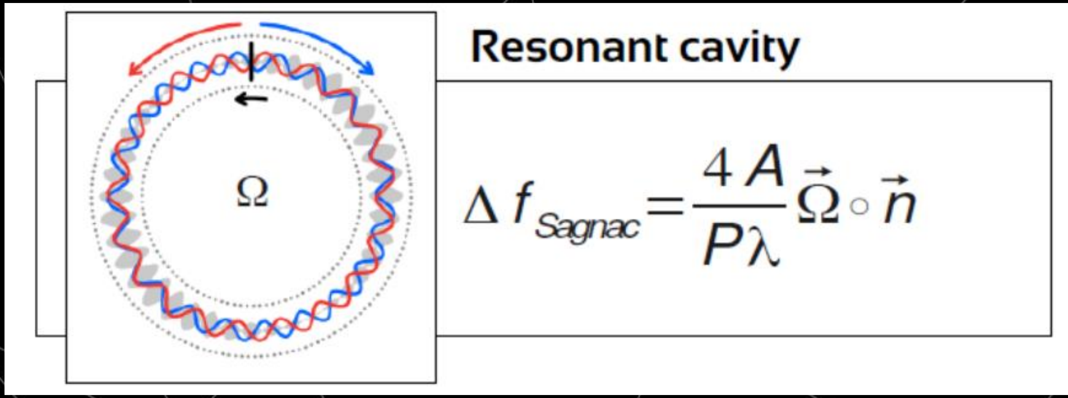
$$\Delta t_{Sagnac} = \frac{4A}{c^2} \vec{\Omega} \circ \vec{n}$$

- light travelling along a closed path will experience a different transit time if the path is rotating
- the time difference depends on the area enclosed by the path, and on the projection of the angular speed along the surface versor

Advantages

- no moving masses (the ring rotates as the Earth rotates)
- insensible to linear acceleration and translation of the reference frame

Sagnac effect in an empty cavity

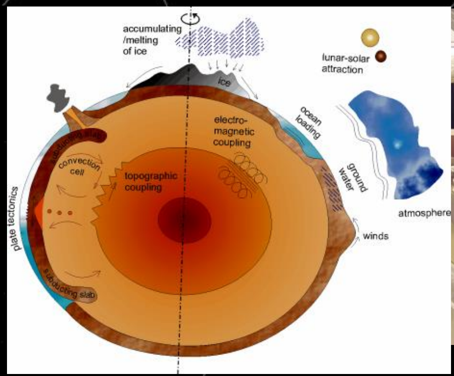


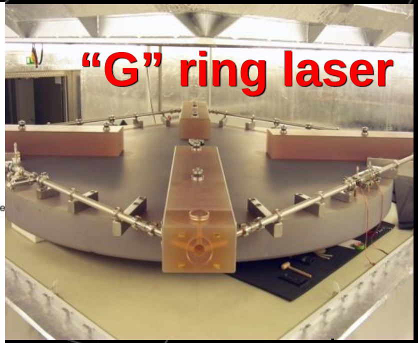
- *from an e.m.* point of view in a rotating ring cavity resonances are shifted by a quantity that depends on the the area (A), the path length (P), the wavelength (λ), and the projection of the angular speed onto the path versor

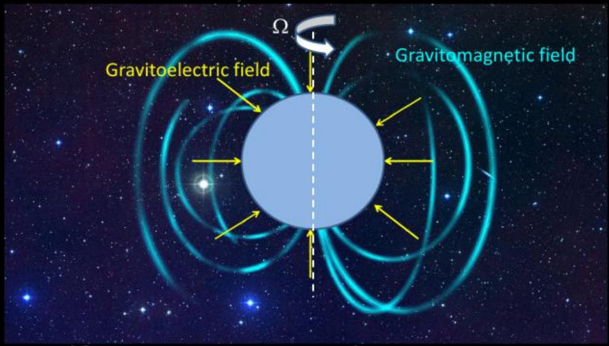
to *precisely* measure angular speed one has to know with the required precision all the geometrical factors entering into the formula:

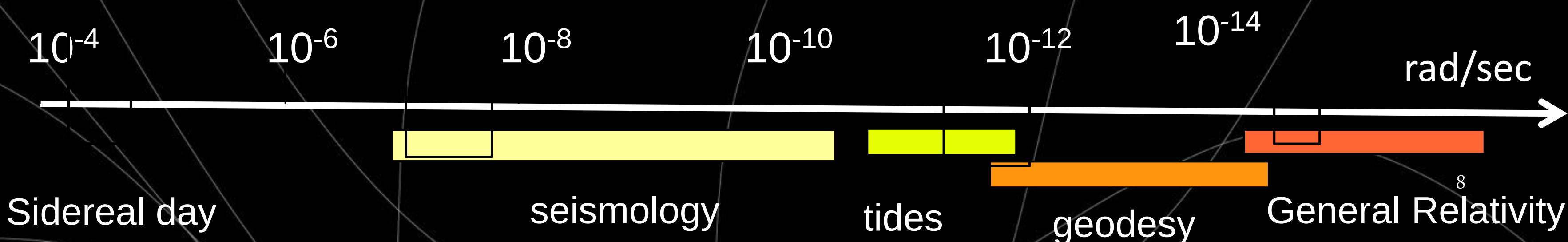
- the *scale* factor of the Sagnac ring
- the orientation with respect to Ω

Sagnac based rotation sensing









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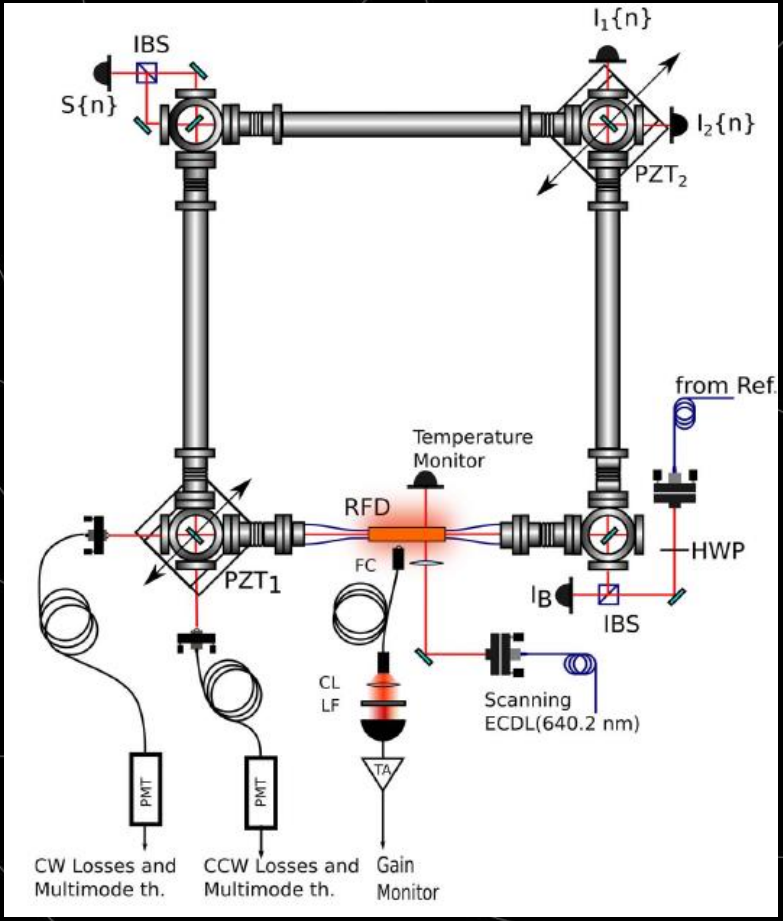
The GYROS (gyro-lasers)

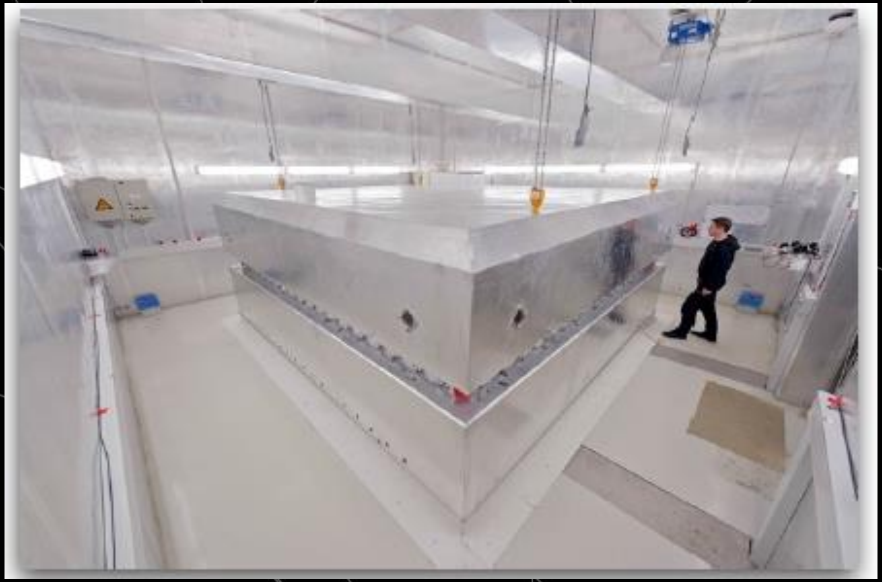


- Sagnac interferometers are turned into active ring laser by adding the laser gain medium inside the ring itself
- in this case the two counter-propagating laser beams will feel a different cavity and the two emission will be frequency split

Gyros and their applications

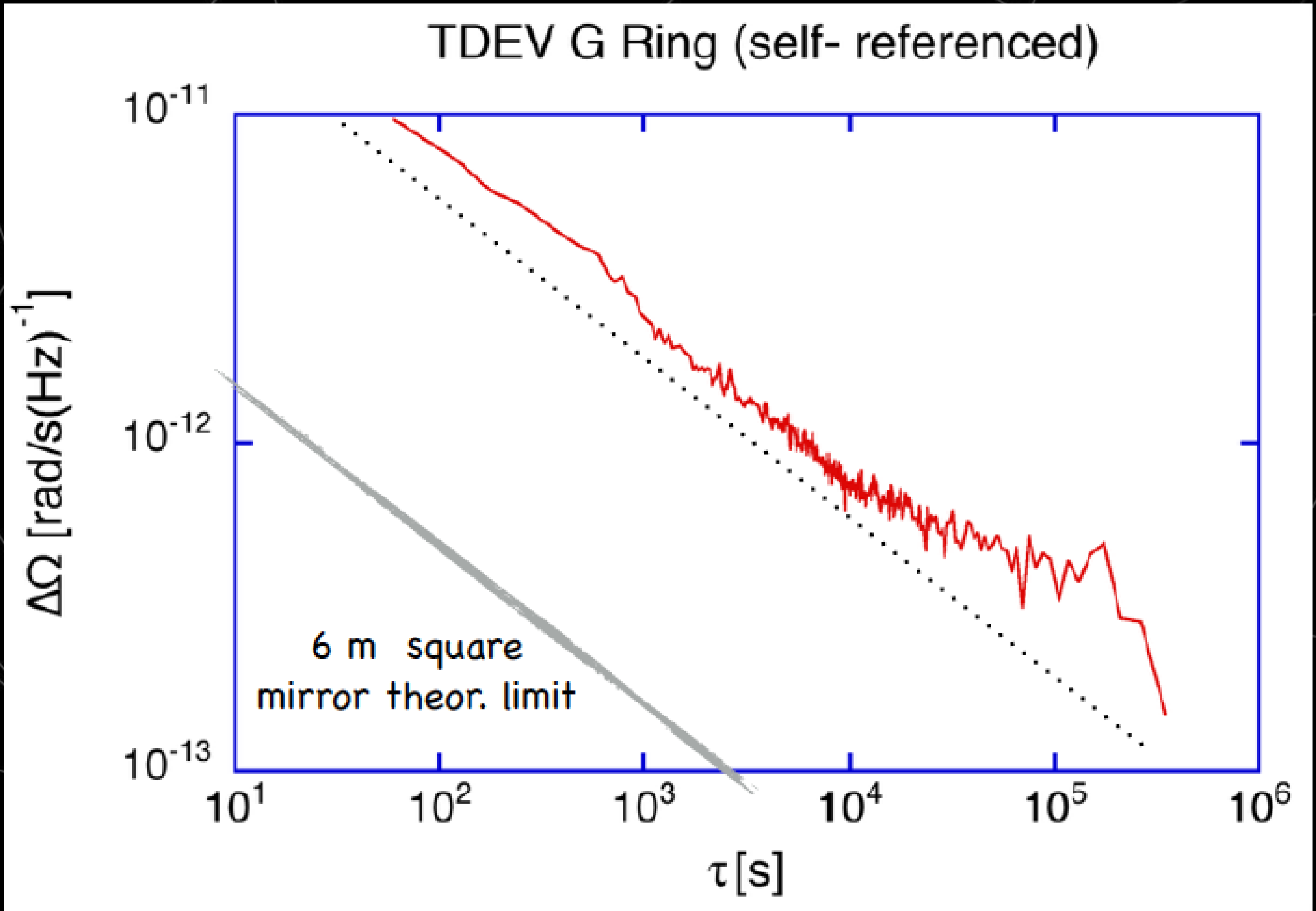
- Ring lasers have large application in navigation (aircraft and ships all have small gyros on board)
- Few large frame rings have been developed for geodetic and geophysical application

The G-RING in Wettzell



- monolithic design in zerodur (very expensive and not flexible, relies on mechanical precision)
- 16 m^2 in size
- actually the best performing ringlaser in the world
- it allowed to measure the slow motion of the earth axes
- is able to access the LOD and is considered into the VLBI standard

Sensitivity of G



Gyroscopes In GEneral Relativity - GINGER

- Measure the LenseThirring effect with an Earth based experiment with 1% accuracy
- *Bosi et al.*

PHYSICAL REVIEW D 84, 122002 (2011)

Measuring gravitomagnetic effects by a multi-ring-laser gyroscope

GINGER – Measurement principle

$$\delta f = \frac{4A}{\lambda P} \mathbf{u}_n \cdot \mathbf{\Omega}, \longrightarrow \mathbf{\Omega} = \mathbf{\Omega}_{\oplus} + \mathbf{\Omega}'$$

Along with the pure kinematic Sagnac term it comes a relativistic contribution

It amounts to about $10^{-9} \times$ the Earth rotation rate (10^{-14} rad/sec)

- The total relativistic contribution to the rotation signal is

$$\Omega' = \Omega_G + \Omega_B + \Omega_W + \Omega_T$$

- In particular, the total precession rate is made of four contributions:
- (i) the geodetic or de Sitter precession Ω_G due to the motion of the laboratory in the curved space-time around the Earth;
- (ii) the Lense-Thirring precession Ω_B due to the angular momentum of the Earth;
- (iii) Ω_W due to the preferred frames effect;
- (iv) the Thomas precession Ω_T related to the angular defect due to the Lorentz boost.

The last two terms are orders of magnitude smaller than the first two so they can be neglected in our system.

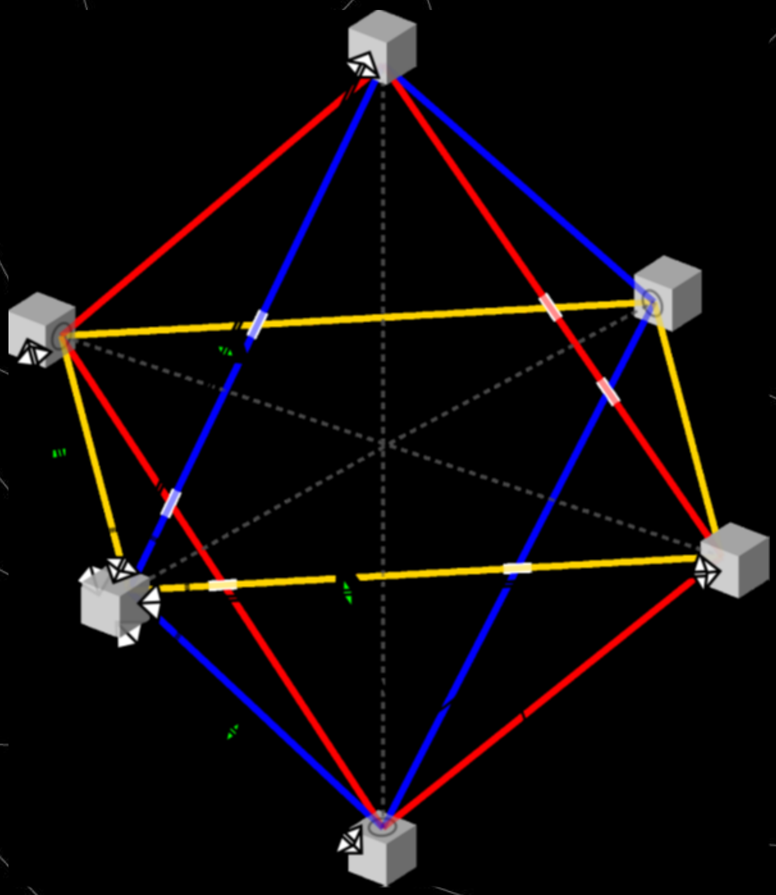
Requirements for LT measurements

- 3D reconstruction of the angular rotation vector
- scale factor stable to 1 part over 10^{10}
- Perfect orientation of the ring (nrad) is not necessary. Only the relative orientation is required at nrad level
- A clear view on the limit sensitivity

Redundancy and 3D

- In order to reconstruct the whole angular rotation vector at least 3 gyros are necessary
  - the angle between the 3 gyros has to be known with the required precision
- With 4 rings the systematics of the laser can be studied
  - The measure is affected by many *technical* noise sources
    - *backscattering, laser/plasma dynamics, geometrical factors, local vibrations etc. etc.*
- Allows the study of the systematics of the array (reconstruct the angular velocity vector with different combination of rings)

A 3D ring – the octahedron

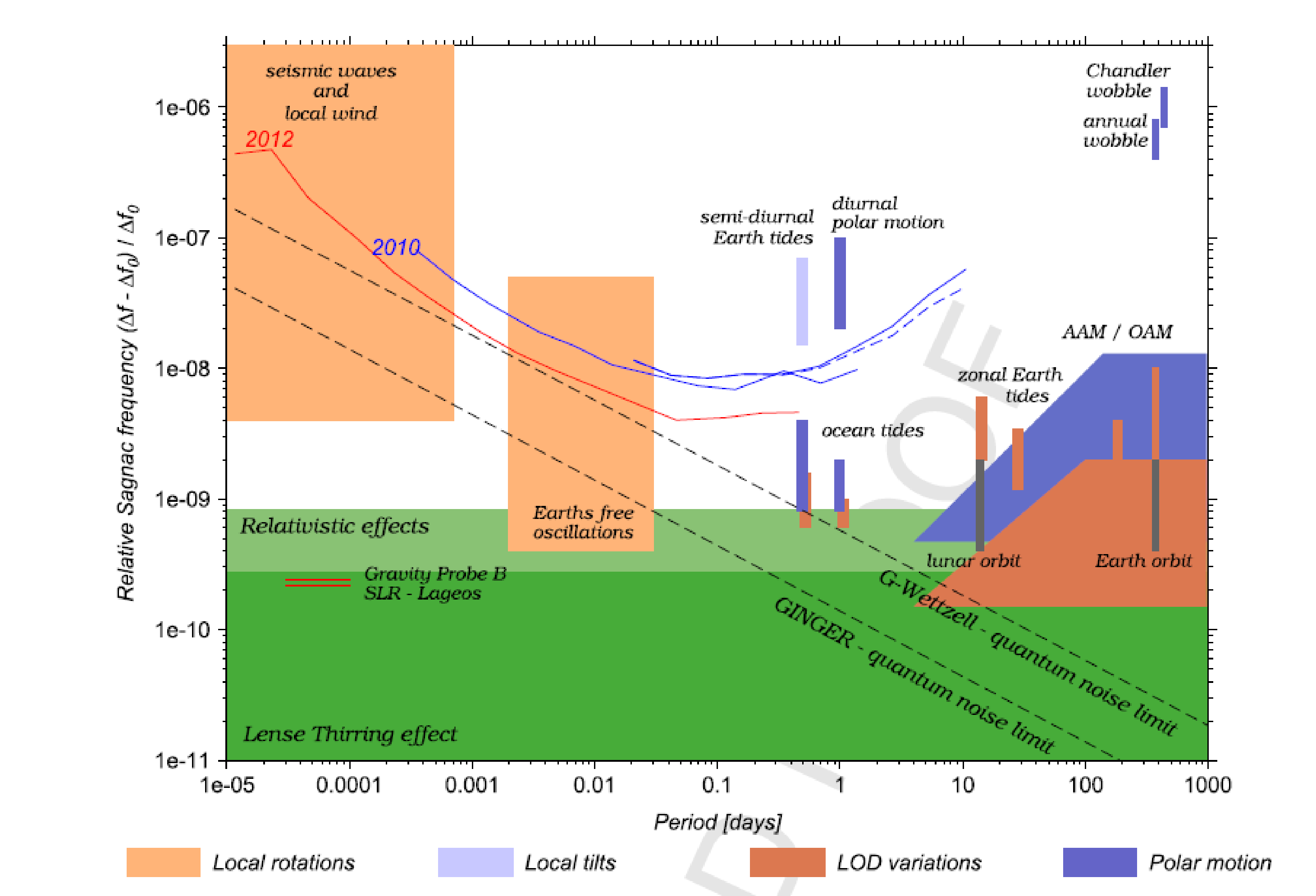


- three large square rings (6-10 meters) can be allocated along the octahedron edges
- each mirror will sustain two cavities (6 mirrors form three cavities)
- when the 3 ring-laser cavities are *ON*, the relative angles between different rings should be 90°

Subtracting the kinematic term

- Subtract the measurement from IEARS (International Earth Rotation System)
- IEARS gives daily the Earth rotation rate with the respect to fixed stars (by VLBI)
- With 2 array located at different latitude it is possible to avoid the use of the IERS data
- Partnership with Germany is crucial
  - ROMY, 4 rings are in construction in Baviera. It is an ERC project, its first stage is focused on seismology; but a second improved array is planned
  - G is already reliable as a IERS data station

The path to GINGER – State of art



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What to do to improve sensitivity

GINGER

$$\delta\Omega = \frac{cP}{4AQ}\sqrt{\frac{hf}{P_x t}},$$

To come after suitable investigation

- N rings
- Passive rings? vs gyrolaser

- Increase size and Q (cavity quality factor)
- Increase P_x (circulating power)
- Increase duty cycle (t measurement time)

Limiting sensitivity estimation

SHOT NOISE CONTRIBUTIONS (SNL)

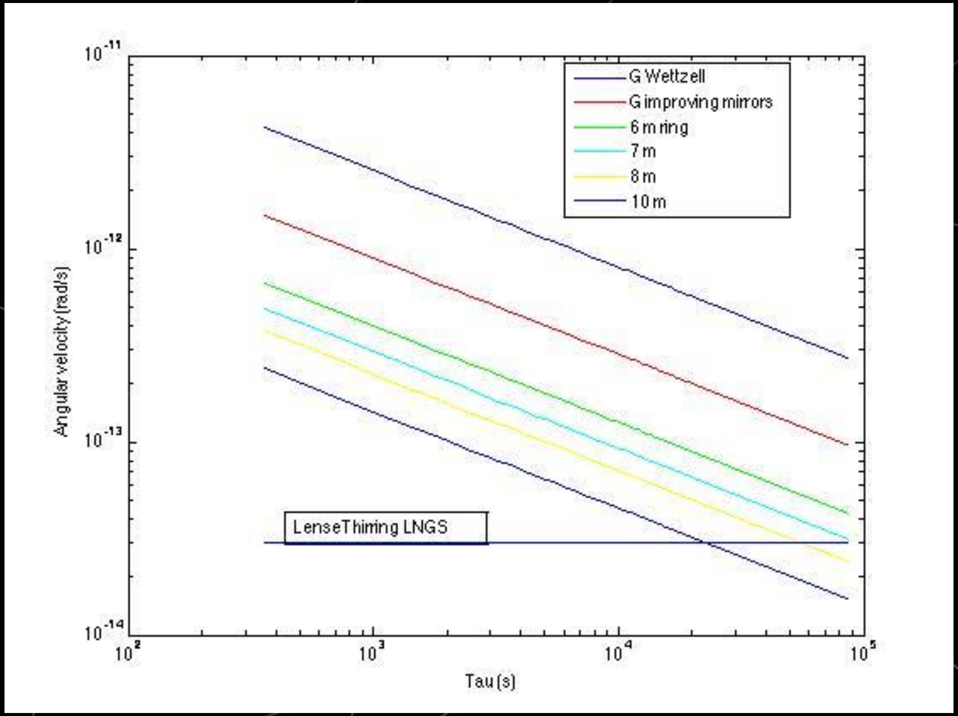
28.3 prad/s/sqrt(Hz) for 4m

12.6 ....6m

9.2..7 m

7.0..8 m

4.5..10 m



Increasing measurement averaging times

One Day residual

14.2 prad/s/sqrt(Hz) for 4m

6.3 ....6m

4.6..7 m

4.5..8 m

4.3..10 m

NOTE: it would be necessary to subtract all the known signals, and avoid tele-seismic events

More average

- 1 year divide by   19
- 2 years......................27
- 5 years......................43

Will GINGER measure LT

$3\ 10^{-14}$rad/sqrt(Hz)/s (7m in side rings, ~ 3 times the SNL)

✓ each day 50%

✓ one year 2.6%

✓ five years 1.1%

- *8m array would do 1.1% in 3 years*
- 4-ring 10m side in one day would measures LT with 8%!

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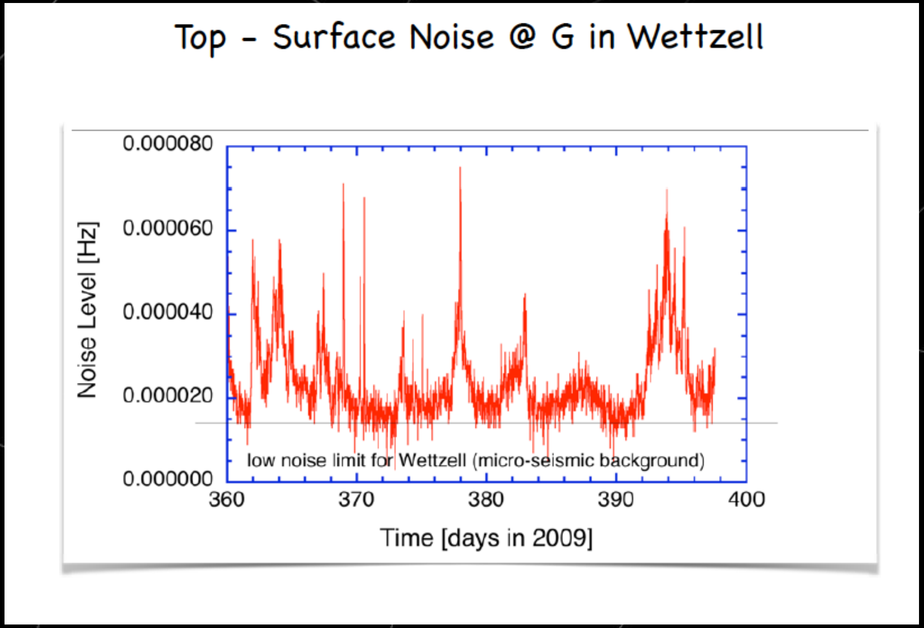
Tech requirements

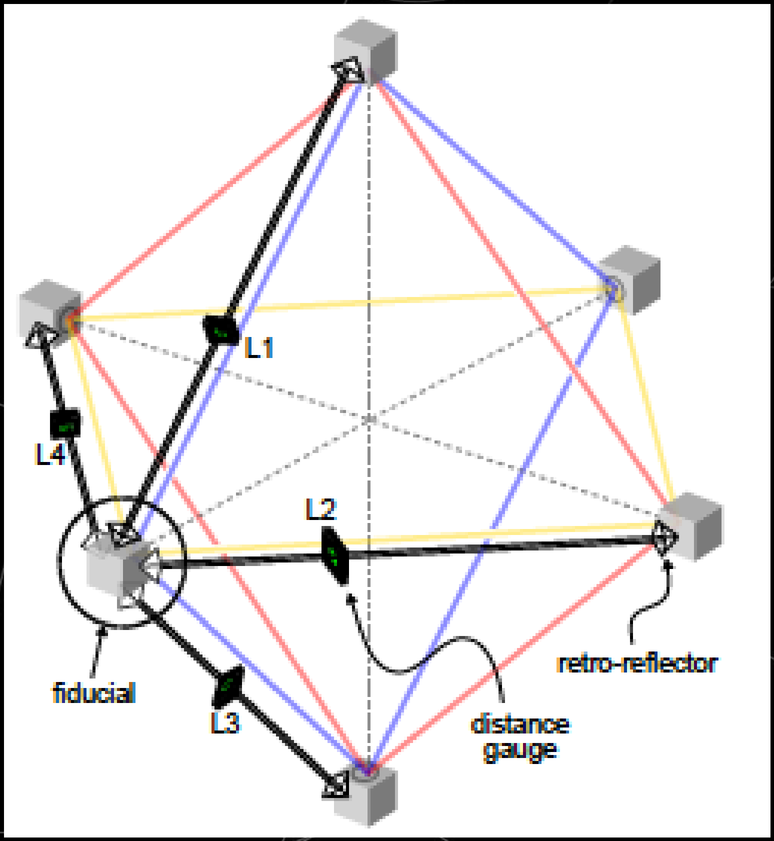
- Scale factor ha to be known within 1 part over 10^{-10}
- The same holds true for the different rings relative orientation (known at the nrad level)
- An underground location would reduce the surface noise



- wind load
- tides
- top soil motion

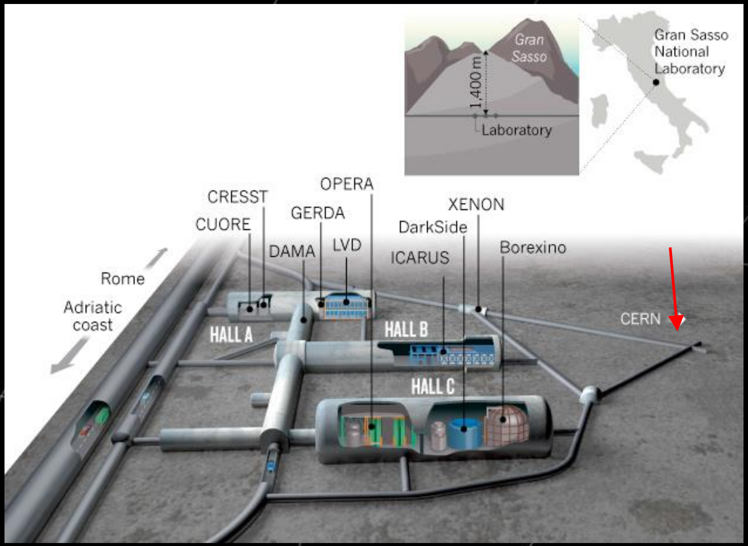
The scale factor

- Scale Factor depends on the ratio area A over perimeter P
- An hetero-lithic solution, like GINGER requires the active control of the Scale Factor
- Distances between mirrors can be measured by external metrology (*on going*)
- If the two ring diagonals are *equal* the geometrical errors scale quadratically instead of linearly in the mirror position and tilting



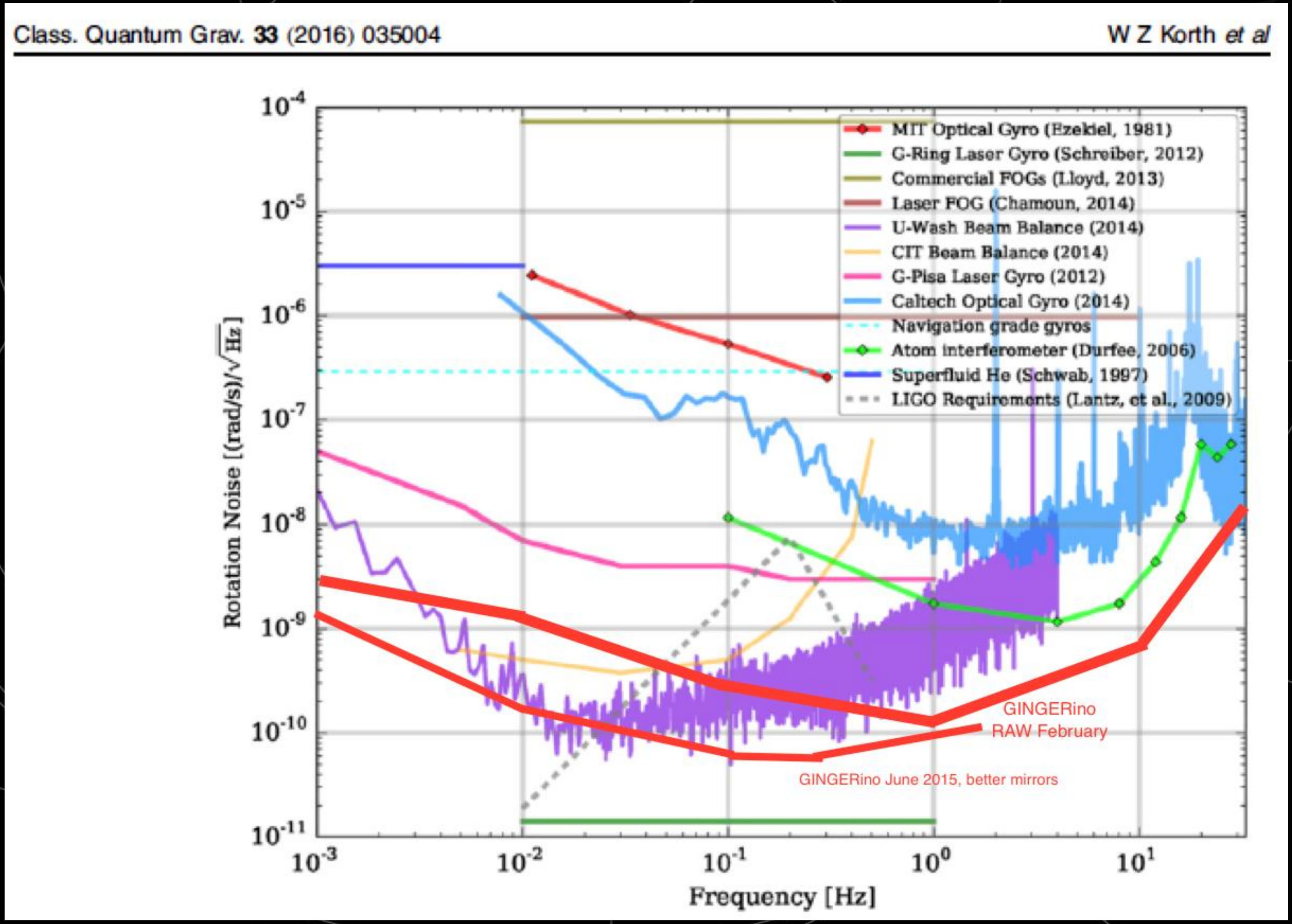
On the route to GINGER - GINGERino

- A 3.6m ring cavity inside LNGS



- A high sensitivity for Earth rotation measurement
- Rotational noise of a deep underground site
- Site validation for GINGER

GINGERino sensitivity



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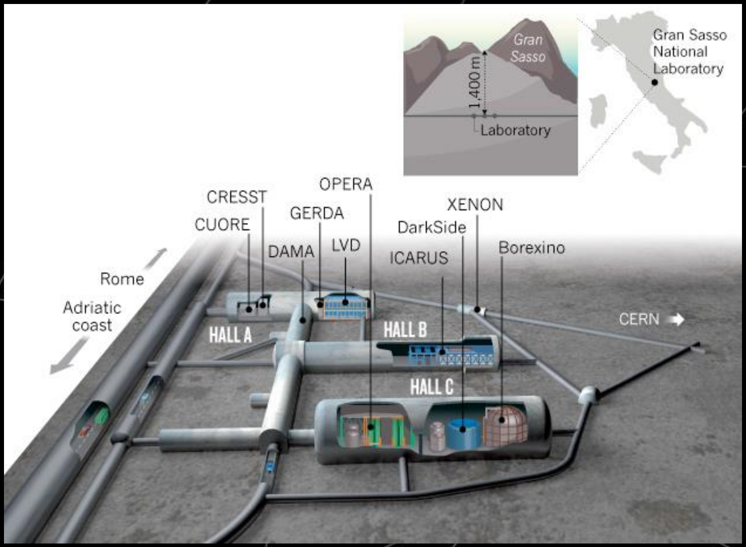
GINGER inside LNGS?

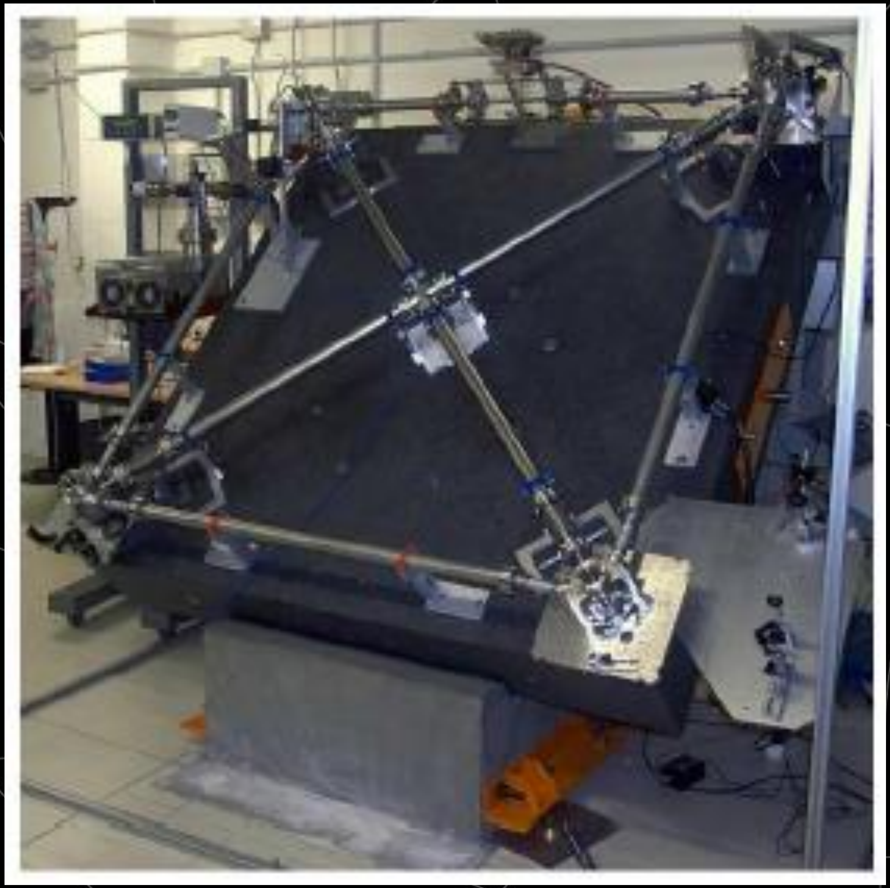
- Node B, if available, could be well isolated from environmental noise, but not larger than 7 (8) m side, with a suitable choice of the geometry
- Hall B, if available, rings up to 10m side could be realized. In this case the north part should be preferable and isolation should be carefully studied



Tech strategies

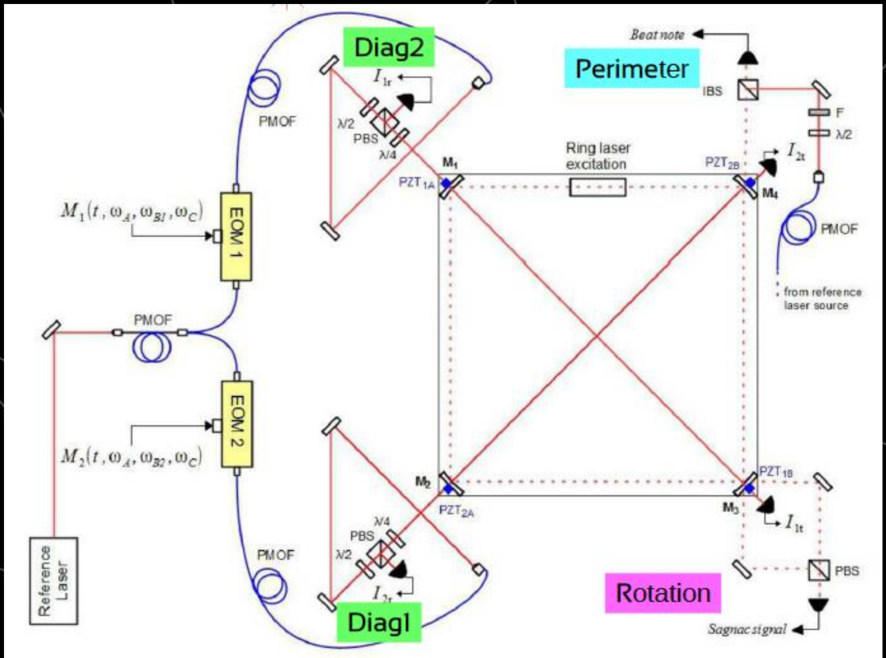
- Ring constructed very close to a regular square ring (~ μm error)
- Error signals
  - the two diagonals cavities and external metrology
- Single reference solution
  - fix the length of the two diagonals of the square. Other possibilities are under study
- Actuators
  - mirrors moved by PZT transducer
- Temperature and pressure controlled environment necessary in order to reduce the required control bandwidth.

The GP2 prototype



- A 1.6m square ring oriented along the Erath rotation axes (max of Sagnac signal)
- A test bench for control and operating (laser dynamics) strategies
- Accessible linear diagonal cavities for diagnostics and controls

Geometry control strategy



- the two diagonals forms linear optical cavity
- the length of these two cavities are a *good* observable for controlling the geometry of the ring
- if the diagonal are equal (it is feasible at the *sub* nm level!!!) all the noise contributions to the total noise from the mirror position and orientation become quadratic

(Inconclusive) Conclusions

- The road to GINGER has been designed but it has to travelled...
- A clear plan will be ready by late 2016 early 2017
- Technical issues have been mostly identified (hopefully!)
  - suitable strategies to follow...
  - two prototypes are currently operated for preliminary studies

Happy Brithday BEPPE