

Frascati, 3 October 2014



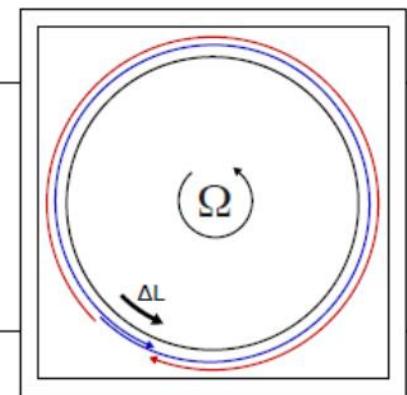
# Applied and fundamental physics with ring-lasers

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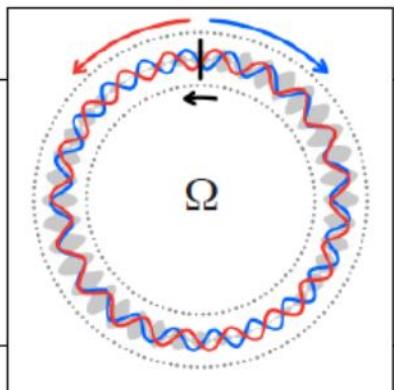
- Sagnac Effect
- Applications and Ring-Lasers
- Ring-Laser and General Relativity (Lense-Thirring)
- Ring-Lasers, G Wettzell, Geodesy and Geophysics
- GINGER and its roadmap
- CONCLUSIONS

# Sagnac Effect and basic of ring laser



## Sagnac effect

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



## Resonant cavity

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

## Advantages

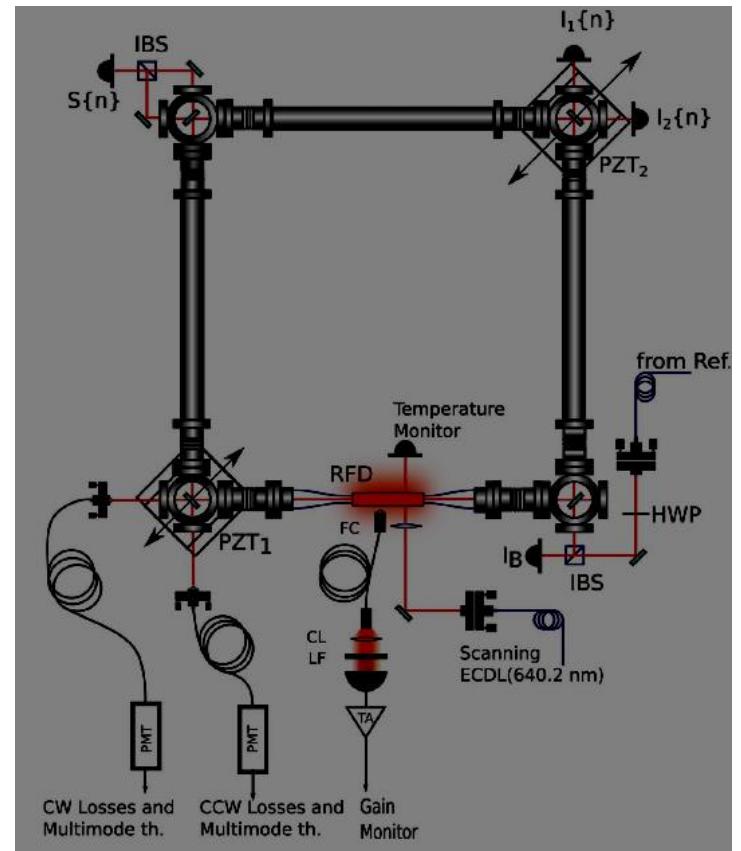
- No moving masses
- No signal for a linearly accelerating reference-frame
- $L > 1 \text{ m} \rightarrow$  Earth rotation is the bias

## Quantum limit

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

- Low cavity losses
- High power
- Large size

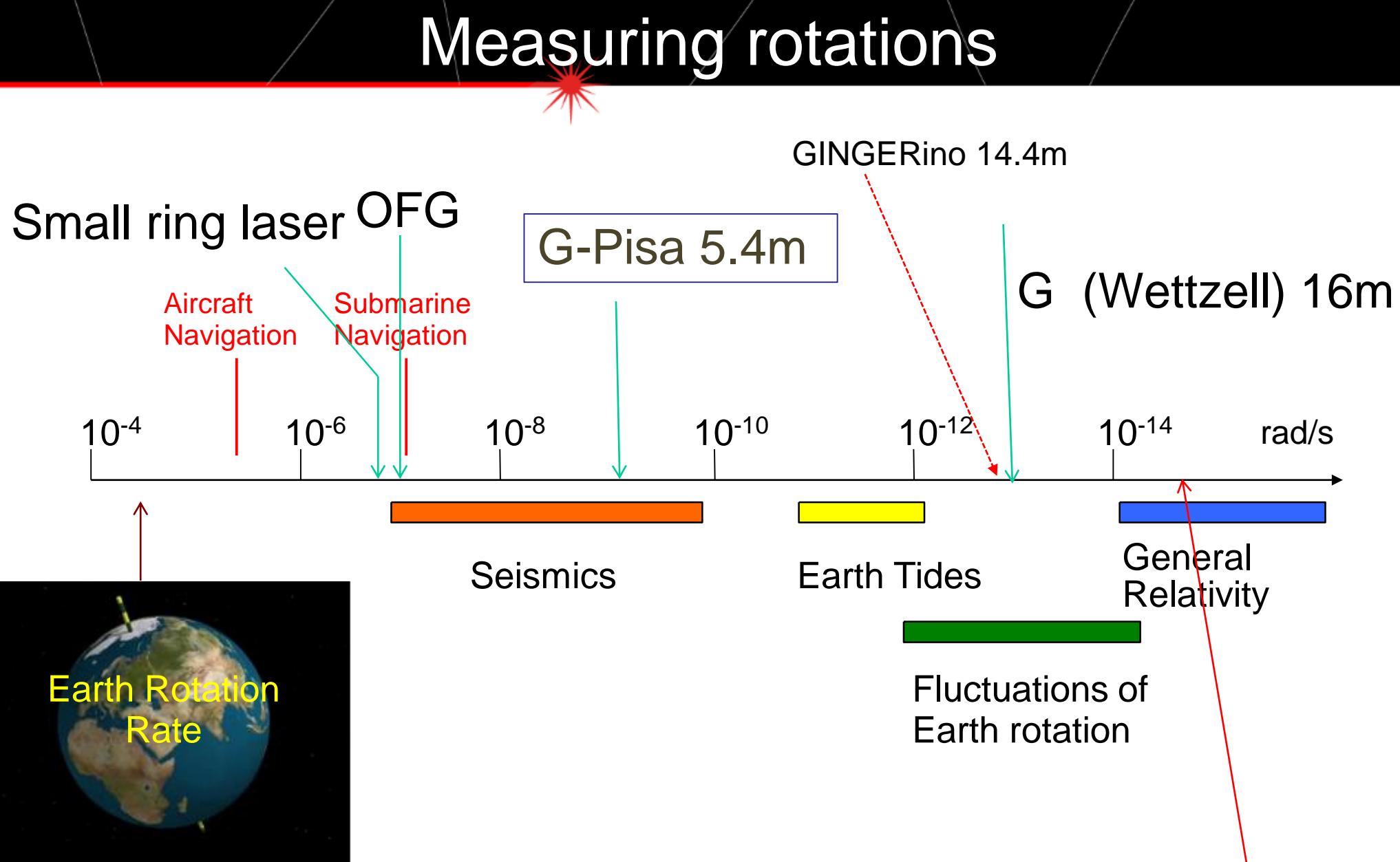
Several devices developed for inertial navigation and other applications using fibers , laser and atoms



From fraction of micro-rad/s to fraction of prad/s

**Sensitivity depends on the size of the ring,  
stability depends on the construction and environment**

# Measuring rotations





## CONFRONTO Sagnac RingLaser e Atomi Freddi (Guvstanson, Kasevich et al.)

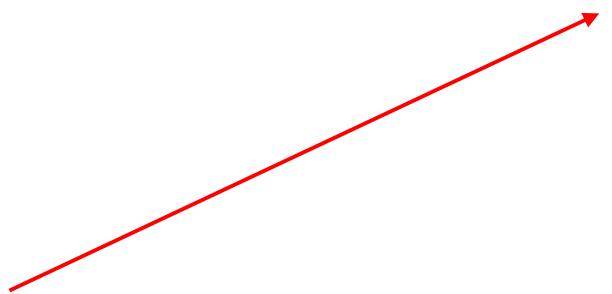
Sensibilità		
1997, Gustavson et al. PRL	$2 \times 10^{-9}$ rad/s/sqrt(Hz) a 1Hz	Sagnac con atomi
2000 Gustavson et al CQG	$6 \times 10^{-10}$ rad/s/sqrt(Hz) a 1 Hz	
G-Pisa (typical)	$3 \times 10^{-9}$ rad/s/sqrt(Hz) a 1 Hz	ringlaser
G-Wettzell (typical)	<b>&lt; <math>10^{-12}</math> rad/s/sqrt(Hz) a 1 Hz</b>	

Stabilità	
Kasevich et al- (2005), stabilità 1 ora	$96 \mu\text{deg}/\text{h}$ (circa 800 nrad in una ora)
FILATOV, ringlaser per metrologia	Accuratezza 100nrad circa
G-Pisa, integrabile pochi minuti	$8 \times 10^{-10}$ rad/s (sottratto backscattering )
G-Wettzell, integrato 4 ore	$6-7 \times 10^{-14}$ rad/s

**Stato dell'arte della metrologia angolare: decine di nrad**

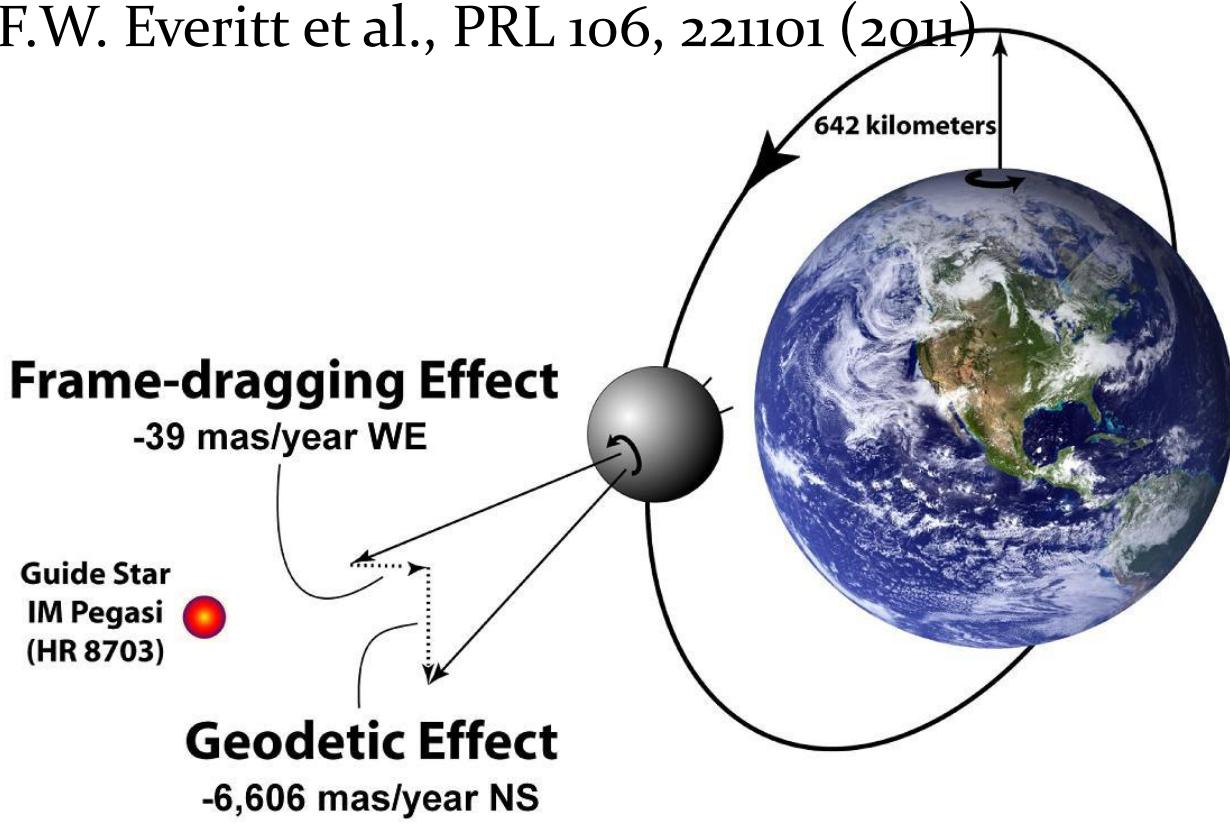


- (Cosmology)
- Celestial mechanics
- Lensing
- Gravitational waves
- Equivalence principle
- Rotation effects (gravitomagnetism)



# Experiments: Gravity Probe-B

C.F.W. Everitt et al., PRL 106, 221101 (2011)



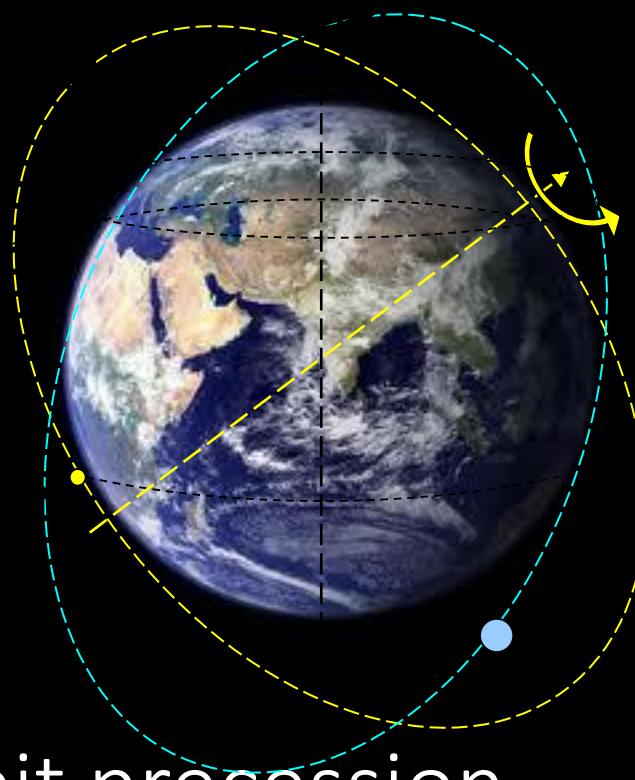
GR geodetic (de Sitter) precession confirmed within  $\pm 0.28\%$  (previous best result  $\pm 0.7\%$  from lunar laser ranging)

GR frame dragging confirmed within  $\pm 19\%$  (previous best result  $\pm 10\%$  from the laser ranging of the LAGEOS satellites)

Final accuracy limited by an unexpected patch effect

Systematic analysis of the reconstructed orbits  
Good model of the gravitoelectric field of the Earth needed  
First results (1998): Lense-Thirring verified within 30%  
2004-2010 results, using a model of the gravity of the Earth based on the results of the GRACE experiment: LT verified within 10%

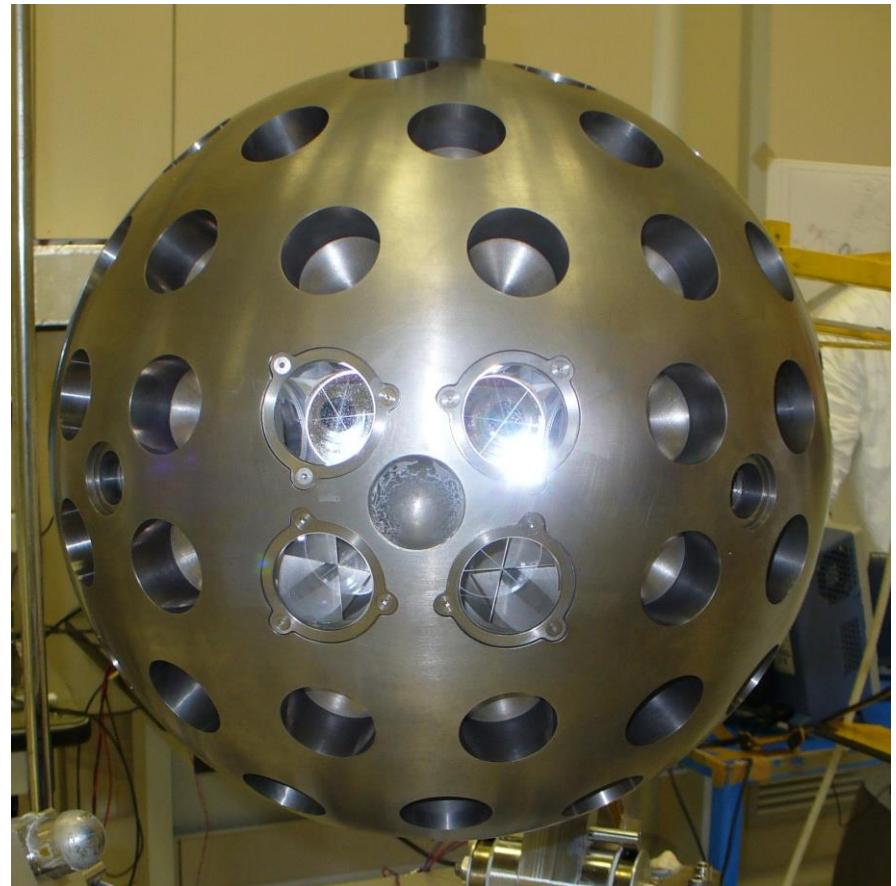
I. Ciufolini et al., *Testing Gravitational Physics with Satellite Laser Ranging*, to appear on *Eur. Phys. J. Plus* (2011)



LAGEOS orbit precession

# The LARES mission

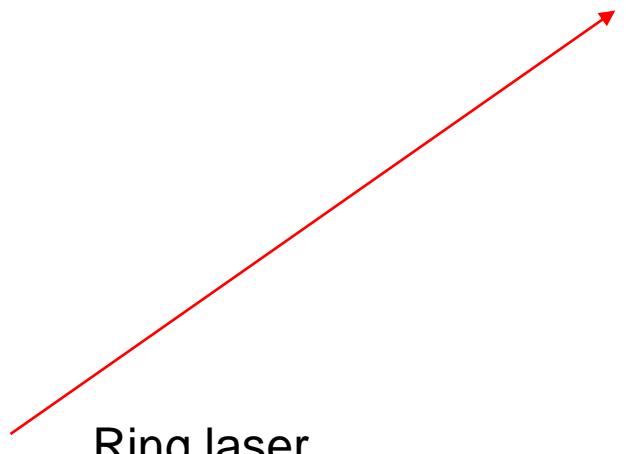
- A compact sphere (36.4 cm diameter) made of a tungsten alloy; 96 retroreflectors.
- Almost spherical orbit at a height of 1450 km.
- Purpose: to allow for an LT effect measurement within a few %.
- Flying since February 2012



## Expected detectable effect



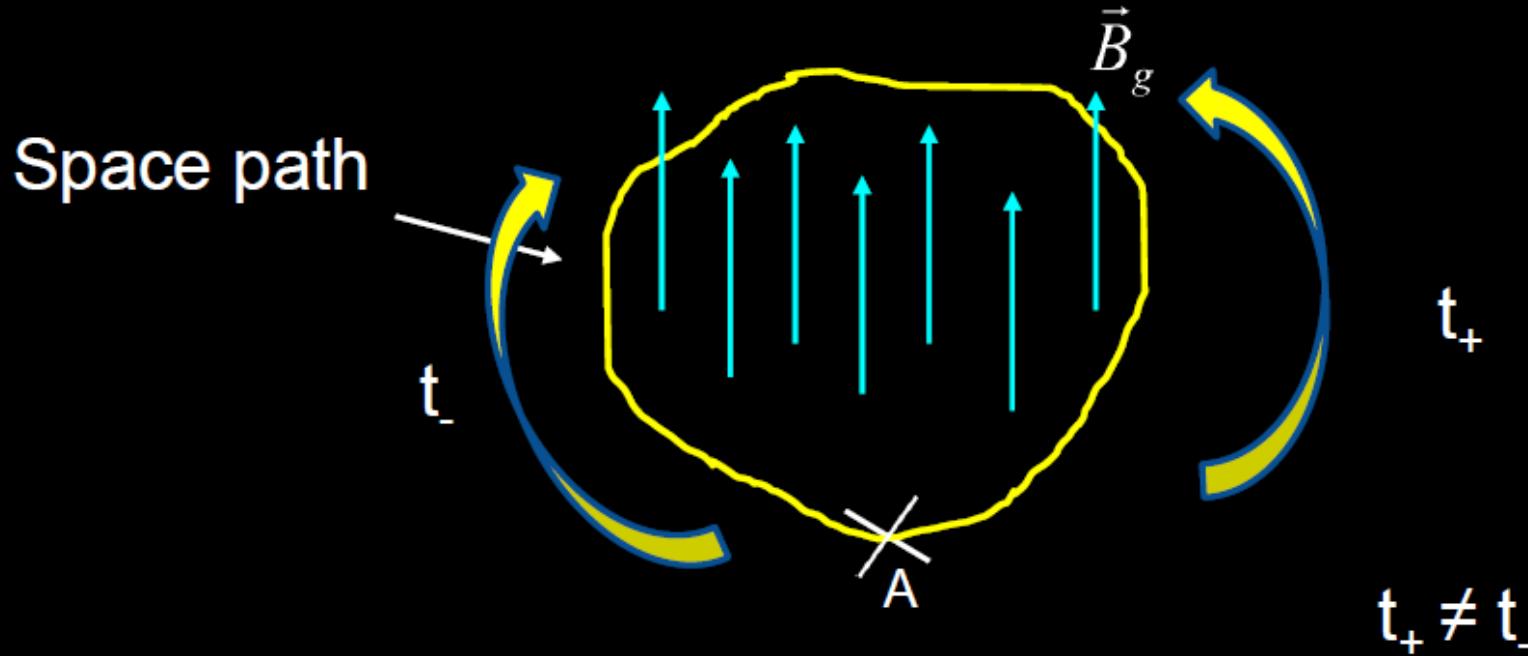
- Torque on massive gyroscopes
- Asymmetric propagation along closed paths (in space)



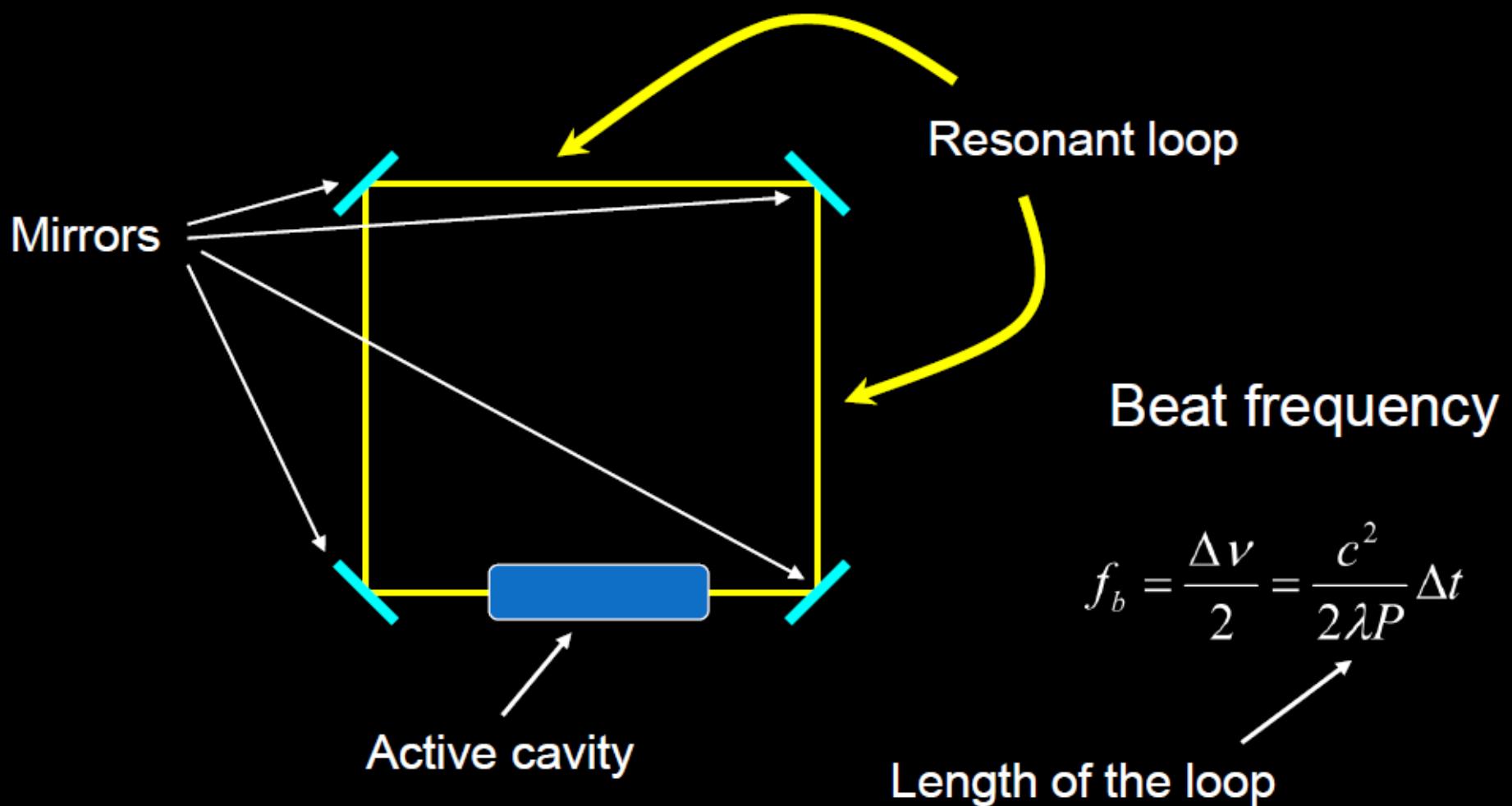


# Asymmetric propagation

$$ds^2 = g_{00}c^2dt^2 + g_{ij}dx^i dx^j + 2g_{0i}cdtdx^i$$



## A Ring Laser





# Time of flight difference

$$\Delta t = t_+ - t_- = -\frac{2}{c} \oint_{+} \frac{g_{0i}}{g_{00}} dx^i \quad \text{Global coordinated time}$$

$$\Delta \tau = \tau_+ - \tau_- = -\frac{2}{c} \sqrt{g_{00}} \oint_{+} \frac{g_{0i}}{g_{00}} dx^i \quad \text{Proper laboratory time}$$

# Earth-bound laboratory (lowest approximation order)

$$g_{0\phi} \approx \left( 2 \frac{j}{r} - r^2 \frac{\omega}{c} - 2\mu r \frac{\Omega}{c} \right) \sin^2 \vartheta$$

$$g_{00} \approx 1 - 2 \frac{\mu}{r} - \frac{\omega^2 r^2}{c^2} \sin^2 \vartheta$$

$$\mu = G \frac{M_\oplus}{c^2} \approx 4.4 \times 10^{-3} \text{ m}$$

$$j = G \frac{J_\oplus}{c^3} \approx 1.75 \times 10^{-2} \text{ m}^2$$

$\Omega$  = angular velocity of the Earth

$\omega$  = angular velocity of the instrument

$\theta$  = colatitude of the laboratory

# Expected signal

$$\omega = \Omega$$

$$\Delta v = 4 \frac{A}{\lambda P} \Omega \left[ \cos(\theta + \alpha) - 2 \frac{\mu}{R} \sin \theta \sin \alpha + \frac{GI_{\oplus}}{c^2 R^3} (2 \cos \theta \cos \alpha + \sin \theta \sin \alpha) \right]$$

Scale factor

Area of the loop

Sagnac

$\vec{\Omega}_G$

$\vec{\Omega}_B$

$\downarrow$

$$\delta v = 4 \frac{A}{\lambda P} \left[ \vec{\Omega} - 2 \frac{\mu}{R} \Omega \sin \theta \hat{u}_{\theta} + \frac{GJ_{\oplus}}{c^2 R^3} (2 \cos \theta \hat{u}_r + \sin \theta \hat{u}_{\theta}) \right] \cdot \hat{u}_n$$

# Orders of magnitude



$$\Omega = 7.2 \times 10^{-5} \text{ s}^{-1}$$

$$\Omega_G \approx \Omega_B \approx 10^{-9} \Omega$$

Necessary to measure the Earth angular rotation 1 part  $10^9$

# Ring-laser and Geodesy

Earth: “The living Planet”

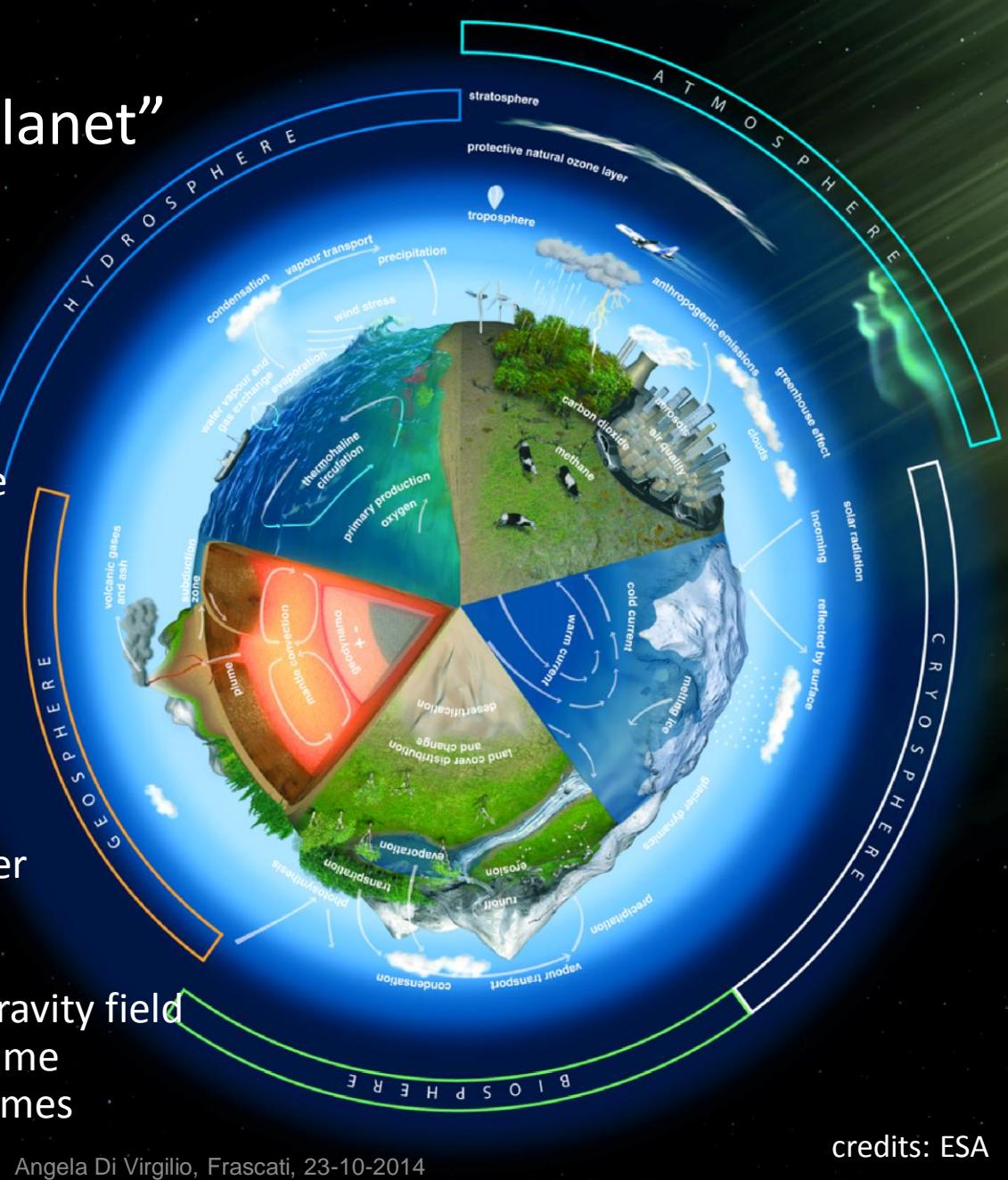
complex interaction  
of coupled subsystems

large numbers of dynamic  
processes over a wide range  
of time scales

Resources of the Earth are  
limited

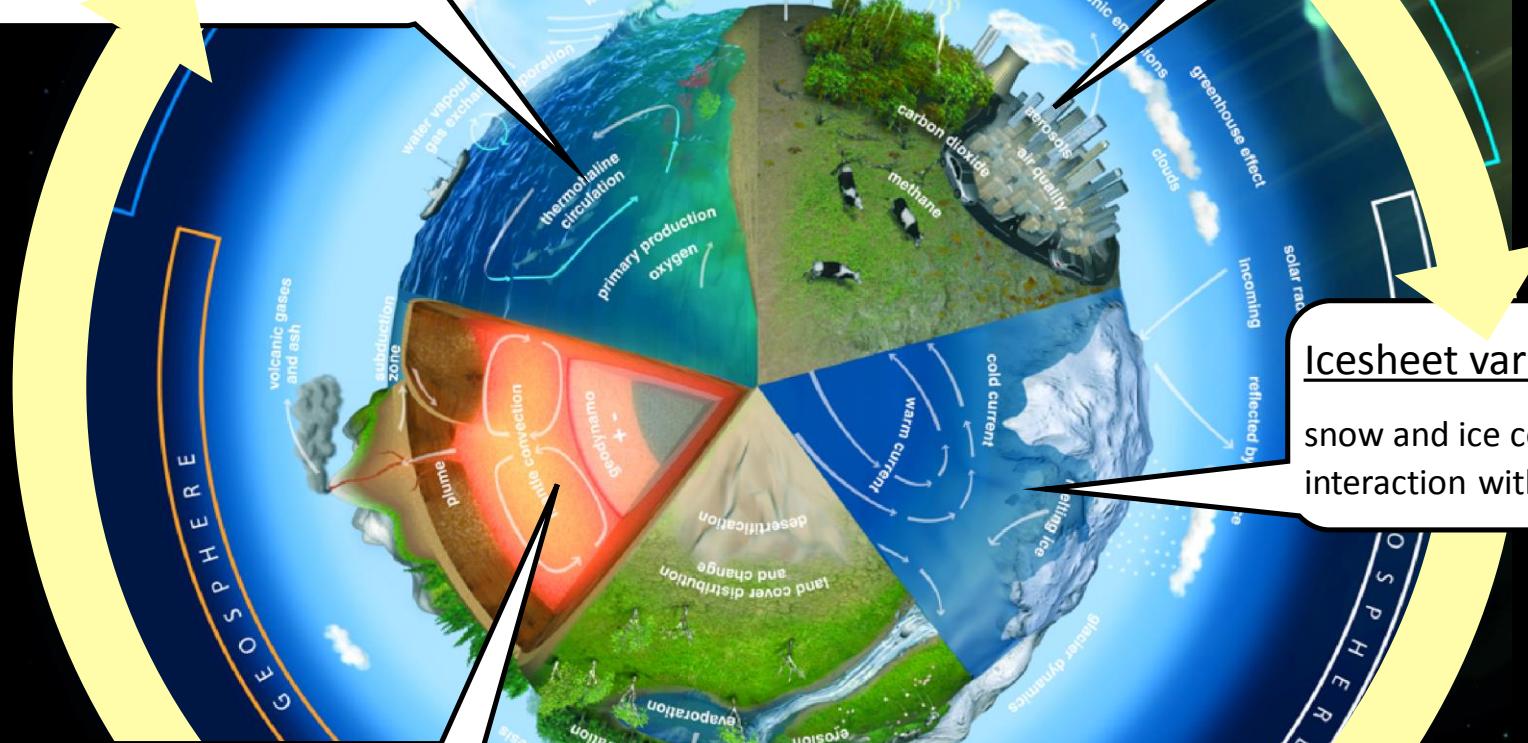
Geodesy contributes to better  
understanding by:

- mapping the figure and gravity field
- observing changes over time
- establishing reference frames



## Ocean. Mass Transport

ocean circulation  
mass and heat transport  
sea level height variation  
Change of mass & volume



## climate change

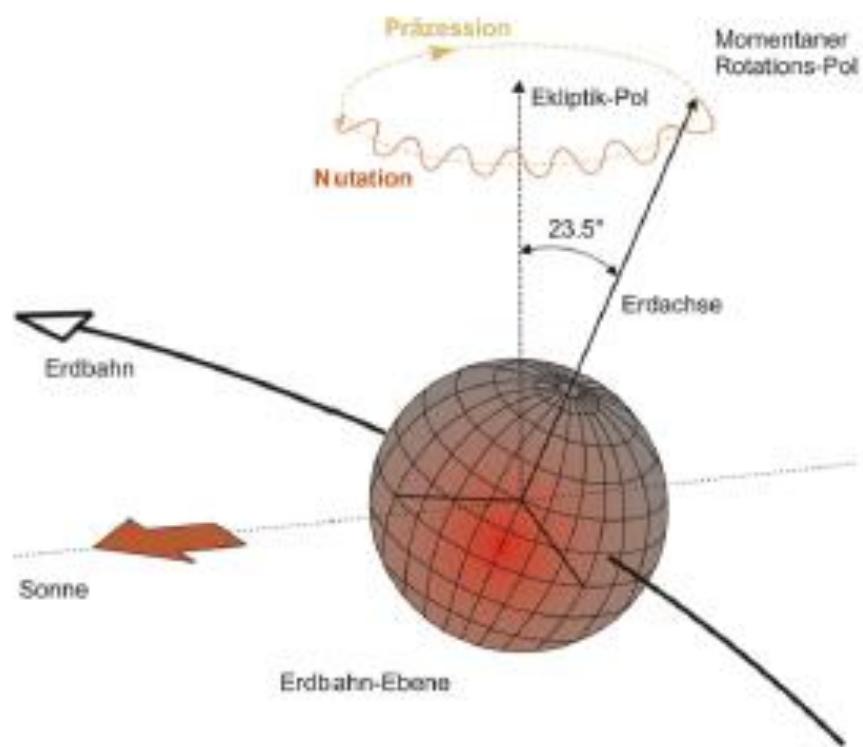
interaction of atmosphere & ocean  
anthropogenic interaction

## Dynamic of the interior

mantle convection, plumes  
plate tectonics  
isostasy and variation of geoid

## Hydrological Cycle

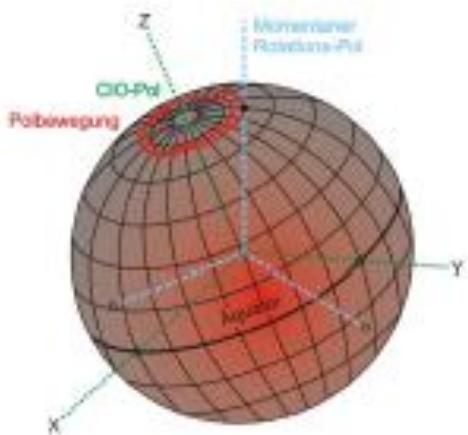
## Earth rotation as the link between ICRF and ITRF



a) the rotation rate of the Earth is not constant. Deceleration by dissipation and variation by momentum exchange. Free oscillations excited by ocean, atmosphere

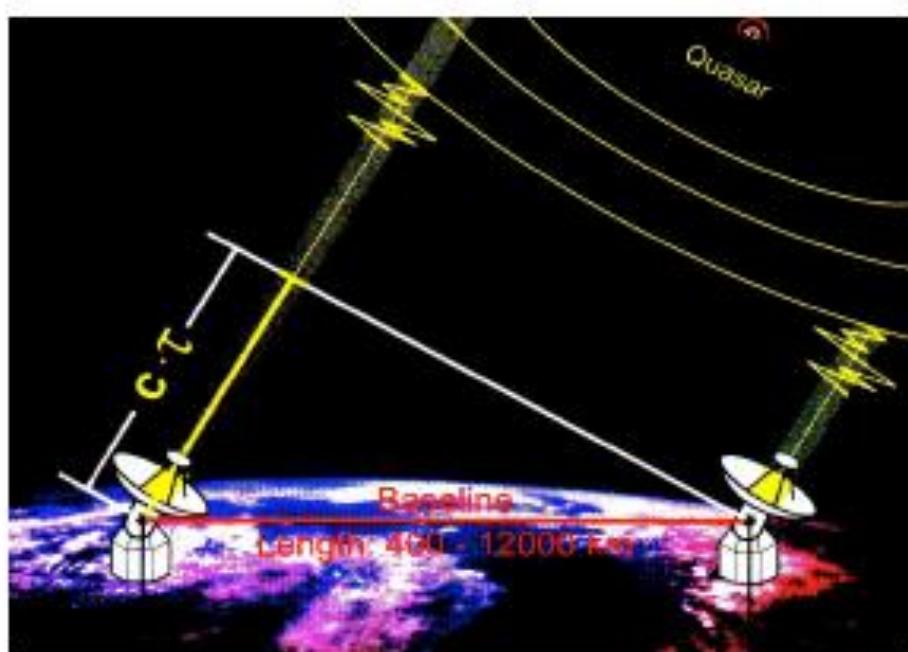
b) gravitational attraction of sun and moon on a near spherical object give rise to precession and nutation

c) mass redistribution on Earth and the fact that the figure axis and the axis of Inertia are not coinciding, give rise to polar motion

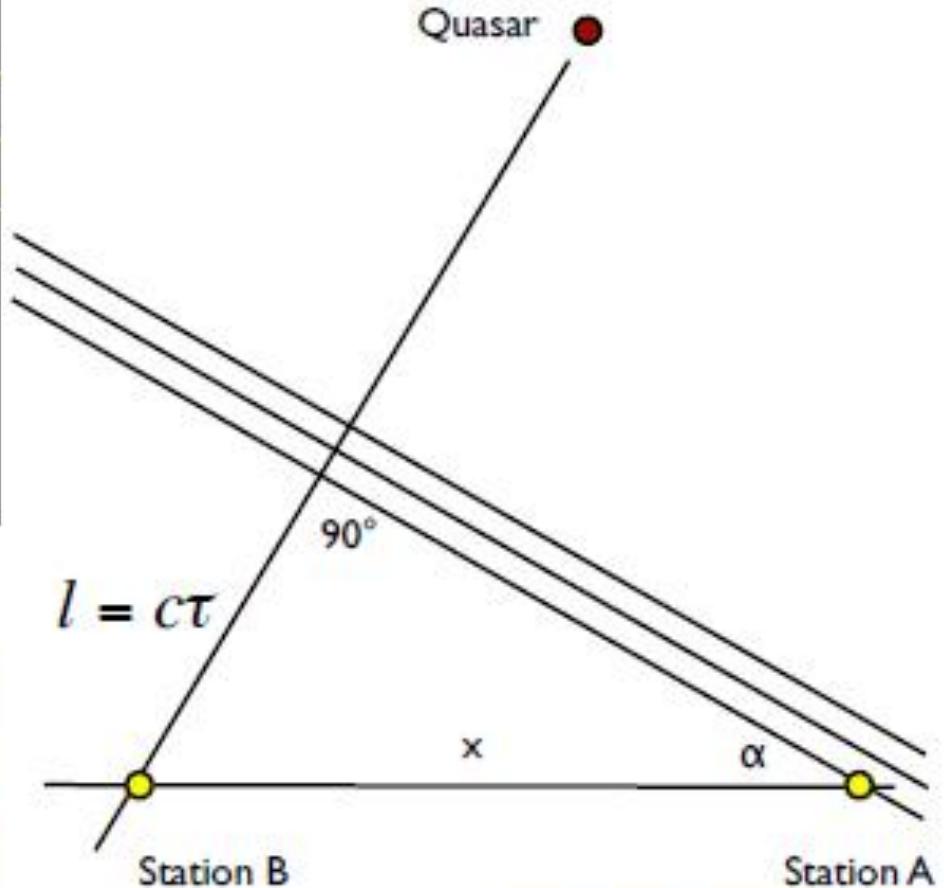
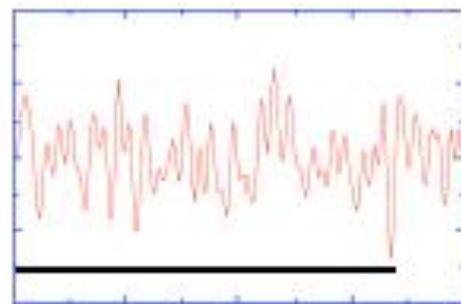


Earth rotation measured 1 part  $10^{10}$

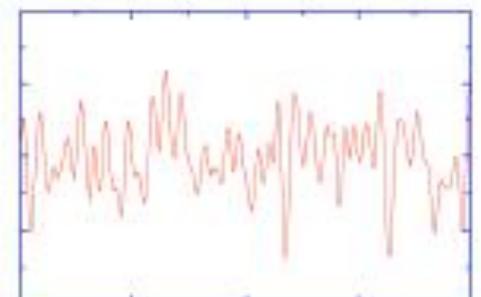
But few measurements for weeks



Very Long Baseline Interferometry



$$\sin \alpha = \frac{l}{x}$$



## G - Ring the currently best performing gyro

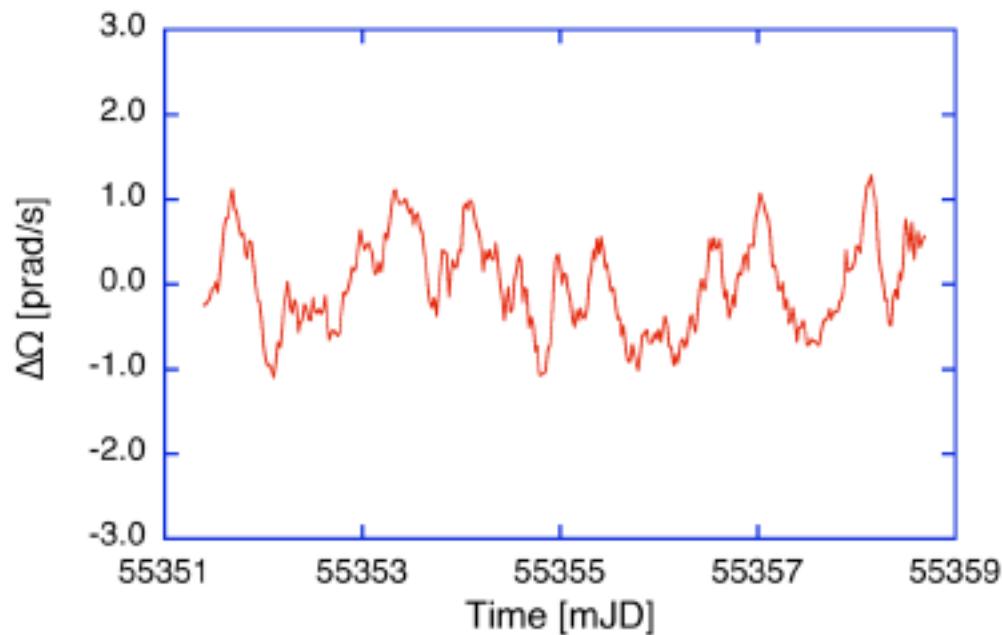
- Perimeter: 16 m
- Area: 16 m<sup>2</sup>
- FSR 18.75 MHz
- $\Delta \nu_L \approx 274 \mu\text{Hz}$
- 5 ppm total loss
- $Q = \omega \tau \approx 5 \times 10^{12}$
- 6.5 mB gas pressure in order to avoid multi-moding



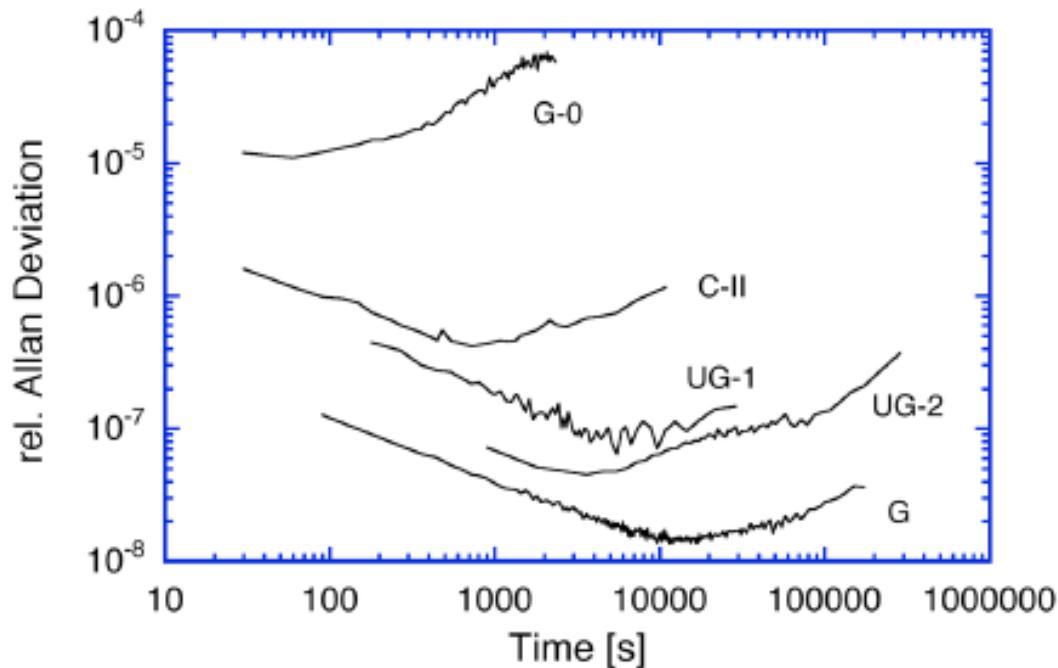
Geodetic Observatory of Wettzell

Angela Di Virgilio, Frascati, 23-10-2014

A typical timeseries of G ring laser measurements...

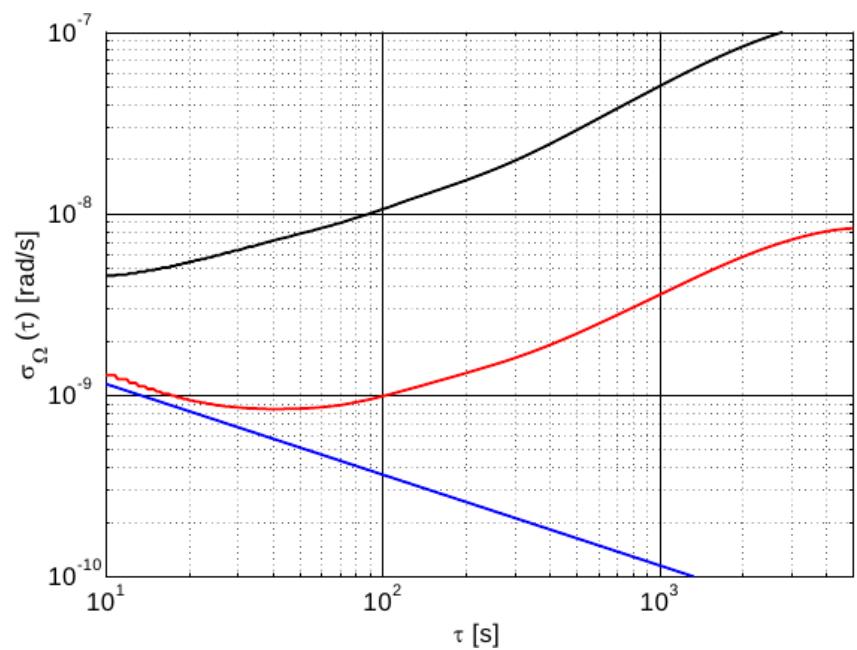


... containing not modeled external signals and sensor noise (most prominently backscatter contributions)



Allan Deviation, relative to the Earth  
Rotation rate,  
Left: large rings in Germany and  
New Zealand

Right: typical performance of our  
prototypes G-Pisa and GP2  
(backscattering sub.)  
Not designed to have large stability



# GEOPHYSICS: rotational seismology is a new branch of geophysic



Plane transversely polarized wave propagating in x-direction with phase velocity c

$$u_y(x,t) = f(kx - \omega t) \quad c = \omega / k$$

Acceleration  $a_y(x,t) = \ddot{u}_y(x,t) = \omega^2 f''(kx - \omega t)$

Rotation rate  $\dot{\Omega}(x,t) = \frac{1}{2} \nabla \times [0, \dot{u}_y, 0] = \left[ 0, 0, -\frac{1}{2} k \omega f''(kx - \omega t) \right]$

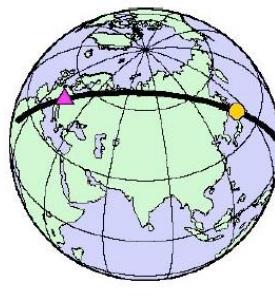
→  $a(x,t) / \dot{\Omega}(x,t) = -2c$

Rotation rate and acceleration should be **in phase** and the amplitudes scaled by two times the horizontal phase velocity

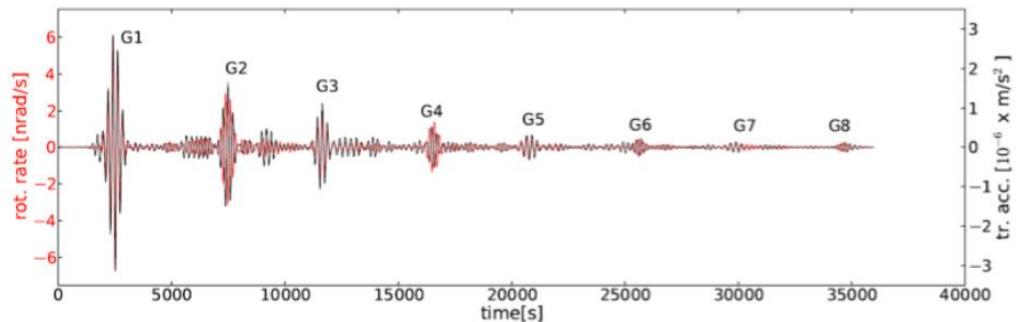
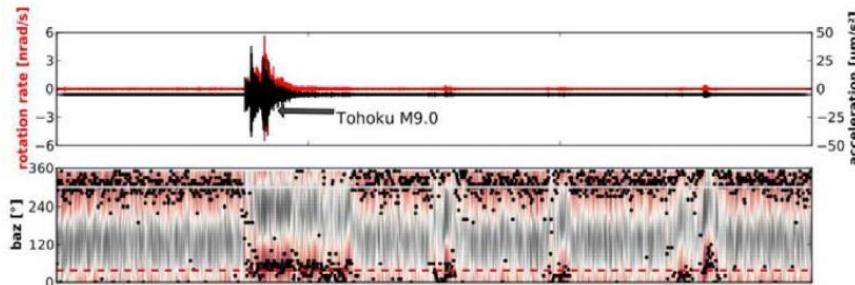
# Combining seismometer and ringlaser data the direction of wave prop. is reconstructed



In order to get the transversal acceleration, one has to rotate the signal of the two horizontal seismometer components to the correct back-azimuth.



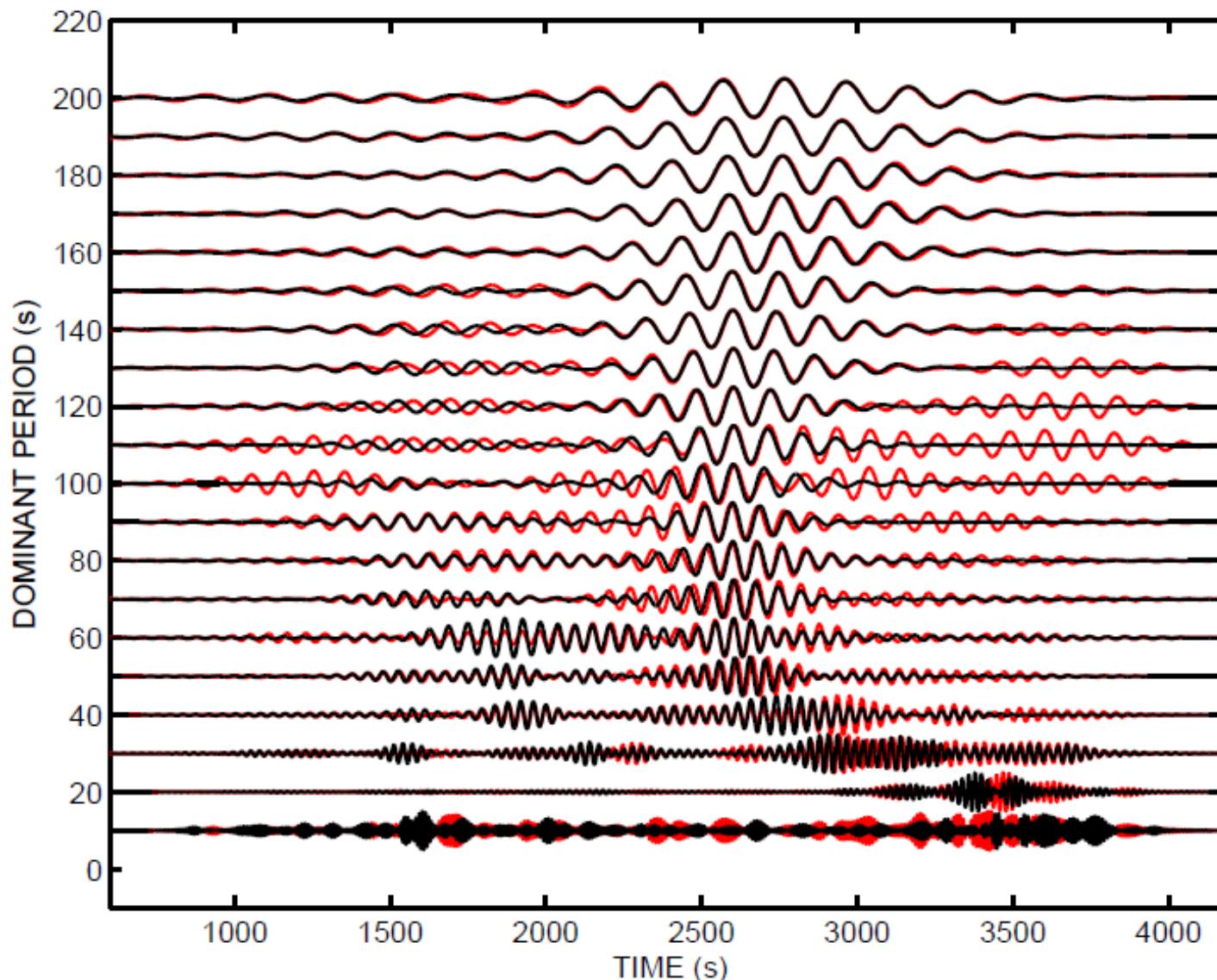
$$\varepsilon = a_x \cos \varphi + a_y \sin \varphi$$



RLG (red) and Seismometer (black)

G1, G3, G5, G7: Signal directly coming from Japan to Wettzell (going west)  
G2, G4, G6, G8: Waves going via North America to Wettzell (going east)

# Rayleigh wave, Japan 2011, recorded by our prototype G-Pisa



**Fig. 5** Superposition of vertical acceleration (black) and rotation rate (red) as a function of dominant period after narrow-band filtering. Each trace has been individually normalised. Signals start 1800s before the expected Rayleigh wave arrival; the time scale is referred to the event's origin time.

## G in Wettzell is a very expensive monolithic device



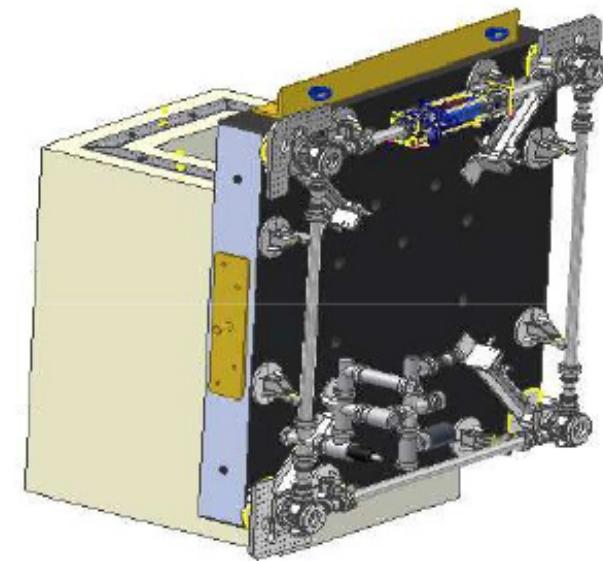
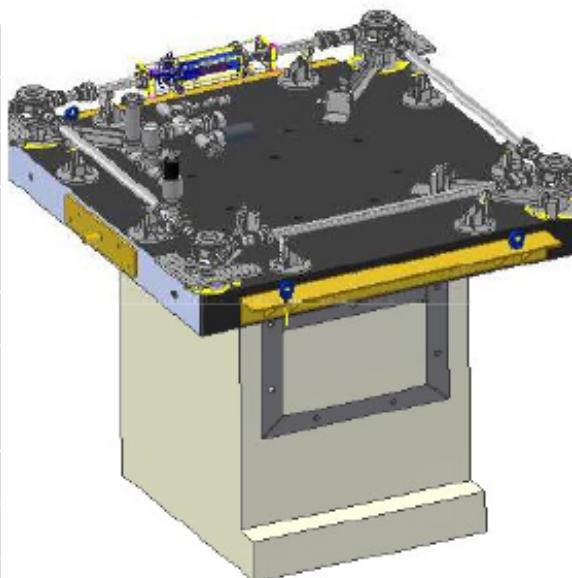
Impossible to develop a 3D device and monitor the relative angle with nrad accuracy

# G-Pisa Ring Laser

Very cheap design, but transportable

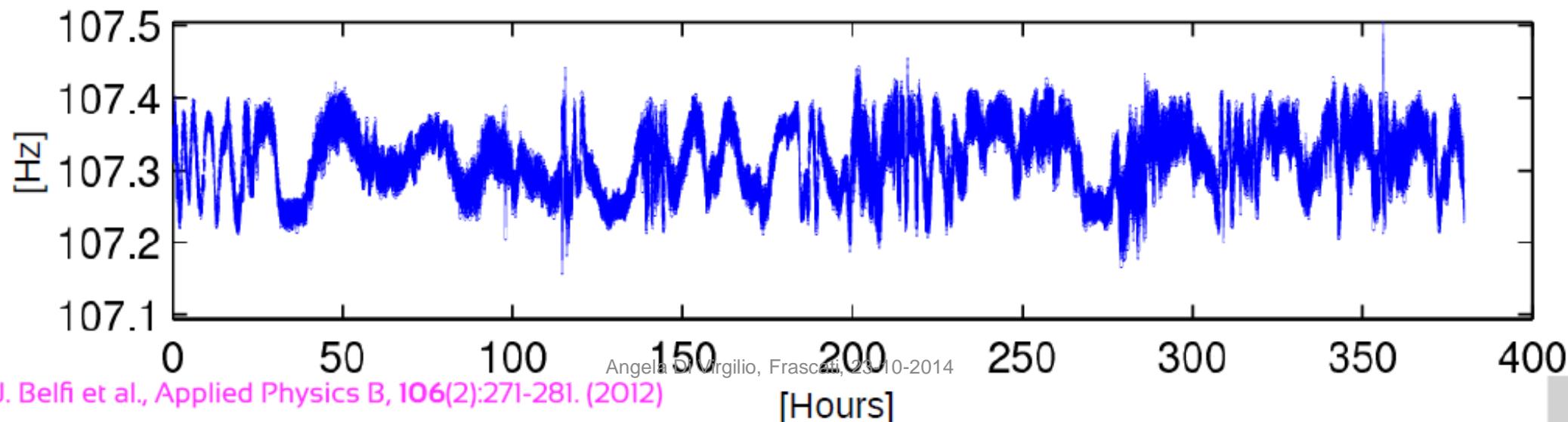


G-Pisa	
Geometry	
Cavity	square
Side length	1.350 m
Cavity mirrors	
Radius of curvature	4 m
Total losses	3.7 ppm
Transmission	0.25 ppm
Scatter+absorption	3.5 ppm
Optical properties	
Wavelength	632.8 nm
Output power	1.6 nW (single mode)
Spatial mode	TEM <sub>00</sub>
Beam waist (s,h)	(1.97 mm, 2.43 mm)

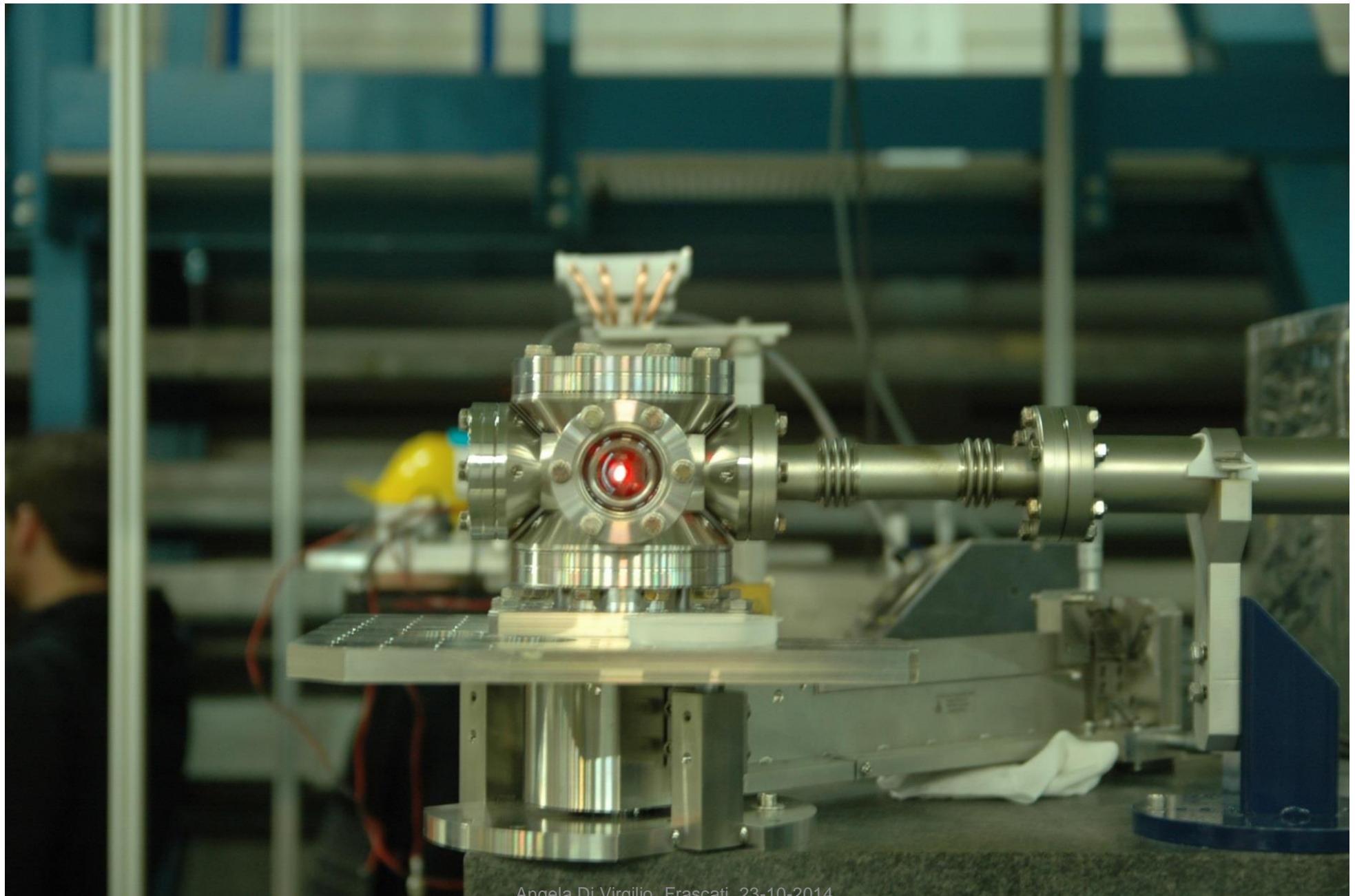


$$\Delta f_s = K_R (1 + K_A) \Omega + \Delta f_0 + \Delta f_{bs}$$

A. Velikoseltsev, PhD thesis (2005)



# G-Pisa



Angela Di Virgilio, Frascati, 23-10-2014

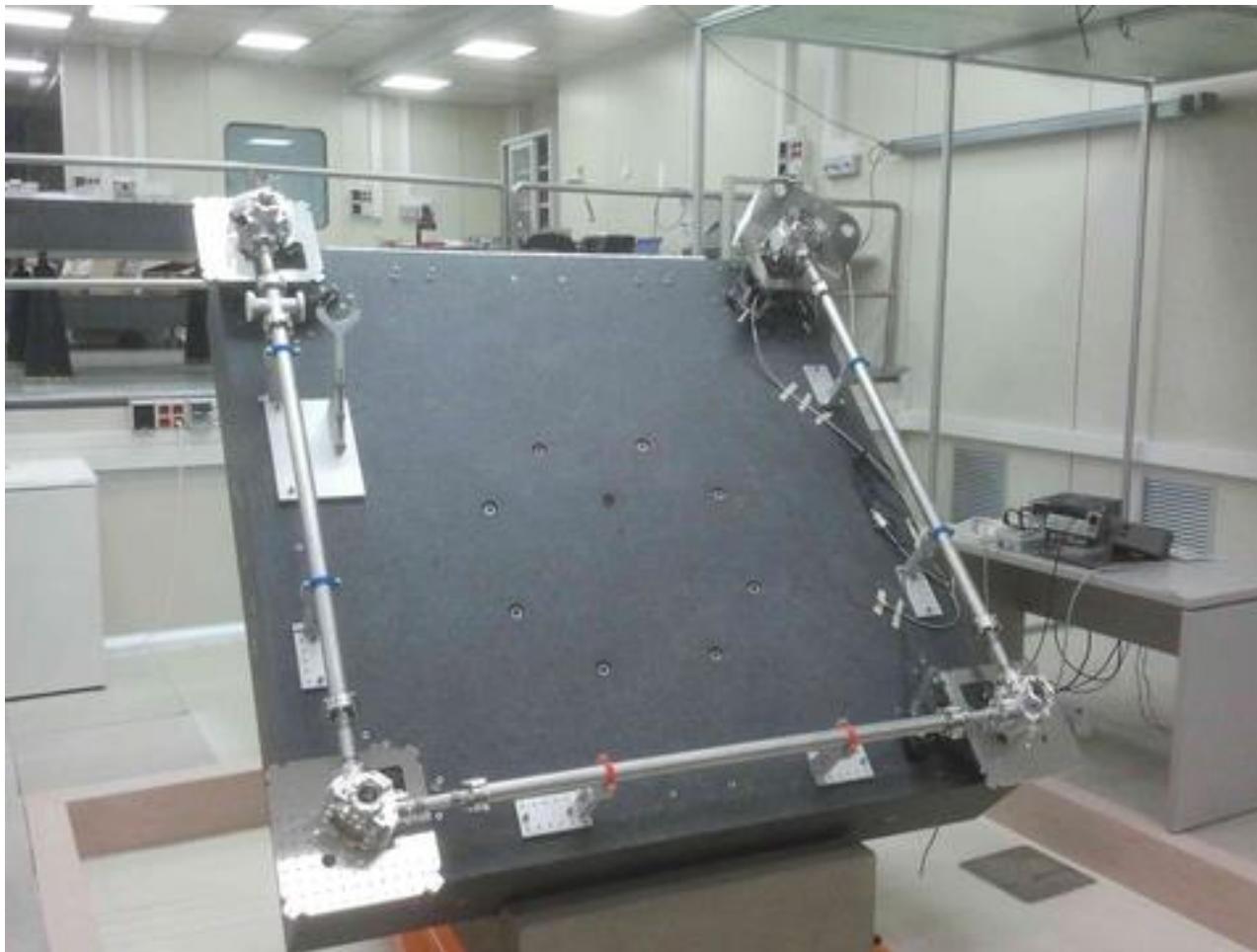


Monolithic devices are expensive and not suitable  
to be extended to 3D

The basic idea is to develop a strategy to  
enhance the stability of a simple etherolithic  
design by using control loops

improve the stability

# GP-2, geometry control prototype



Angela Di Virgilio, Frascati, 23-10-2014

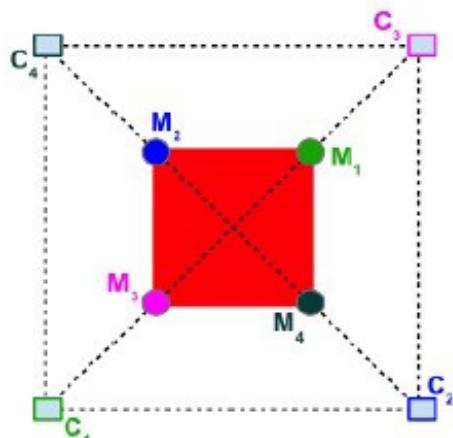
# Single ring geometry “controllability”

Scope: Adjust the beam path to the regular square shape

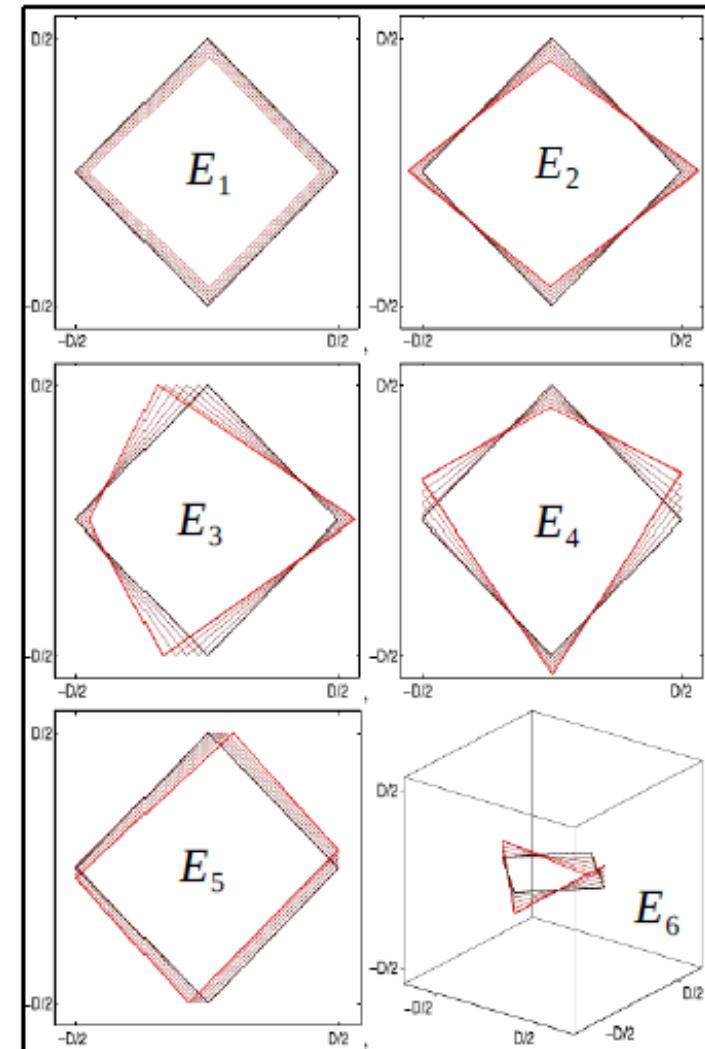
## 12 degrees of freedom

-6 d.of. (Rigid body)

= 6 d.of. (Cavity deformation)



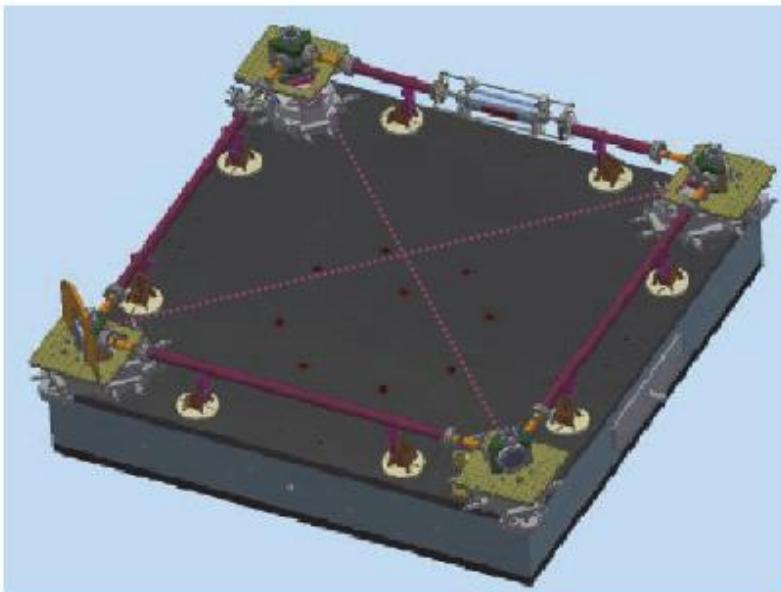
The only linear contribution to the perimeter length comes from  $E_1$



## Strategy

- Block the diagonal cavity lengths to the same value (FP intrf.)  $[(E1, E5), E2]$
- Optimize the residual 4 quadratic d.o.f.  $[E3(-), E4(-), E5(+), E6(+)]$  at the “saddle point” for the perimeter

# “Blocking” the diagonals length



## Basic Idea

Inject the 2 Fabry Perot cavities with an external laser

-Measure the 2 absolute lengths

-Set them equal by controlling mirrors positions



$$f_n = \left( \frac{v}{2L} \right) \left[ n + \frac{1}{2\pi} (\Psi_R + \Phi_n) \right]$$

$$\Psi_R = 2 \cos^{-1} \left[ 1 - \frac{L}{R} \right]$$

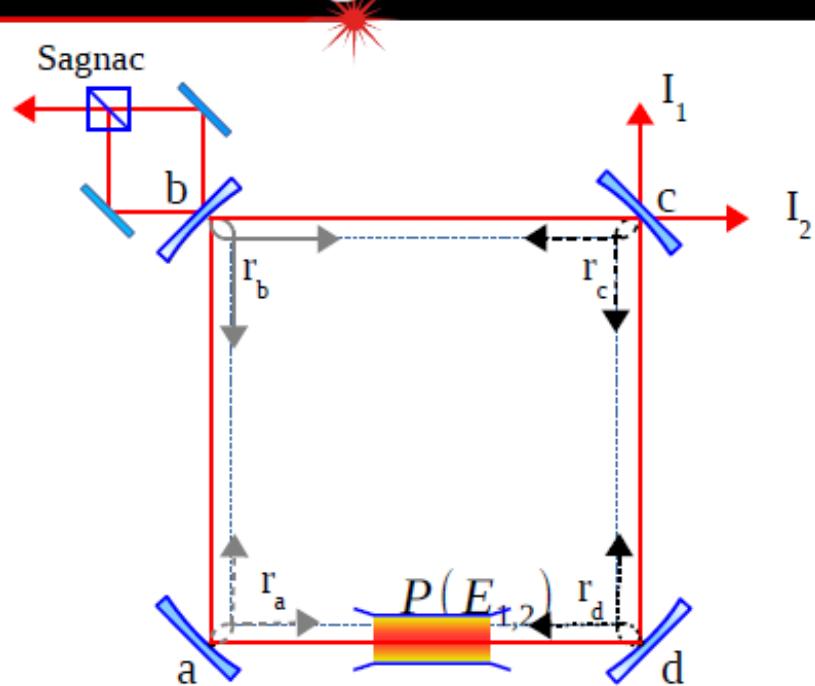
$\Phi_n$  = dielectric phase shift

Use a single laser for both the two cavities

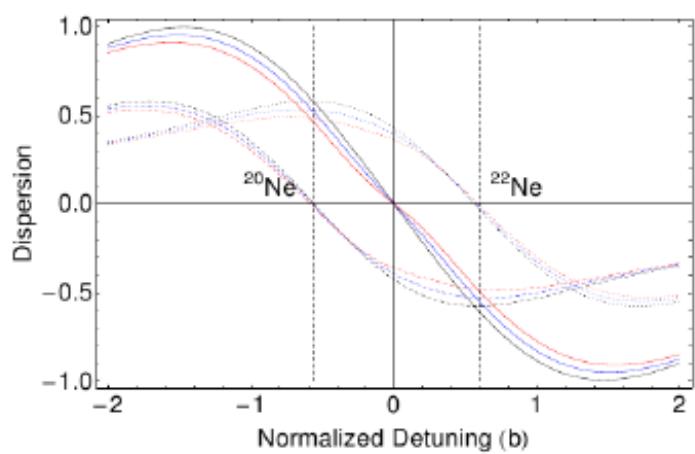
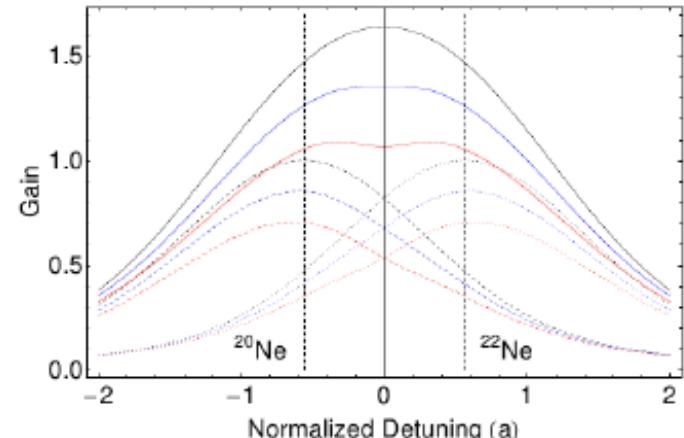
- 1) Lock the cavities to the laser (Pound-Drever-Hall) (set optical resonance frequency)
- 2) Measure the FSR by observing the “cavity dynamic resonance”  
(tuning FM sidebands to a multiple  $m$  of FSR)

# Ring laser “hacking”

model and study laser sistematics



A. Beghi et al. Applied Optics 51, 31 (2012)



Active medium  $\text{He} + ^{20}\text{Ne} + ^{22}\text{Ne}$

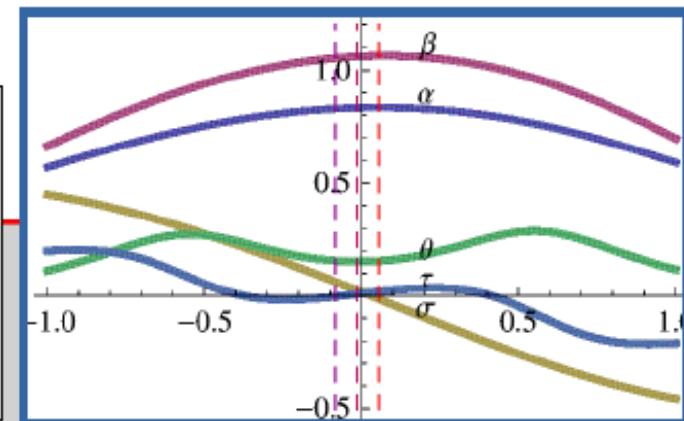
$$P^{(3)}(E_{1,2}) = \frac{-2i\mu_{ab}^2}{\gamma_{ab}} \int_{-\infty}^{\infty} \chi_{1,2}(v) \rho^{(2)}(v, E_{1,2}) dv$$

Opposite beams dynamics

$$\dot{I}_1 = \alpha_1 I_1 - \beta I_1^2 - \theta_2 I_2 I_1 + r_2 \sqrt{I_1 I_2} \cos(\psi - \epsilon_2),$$

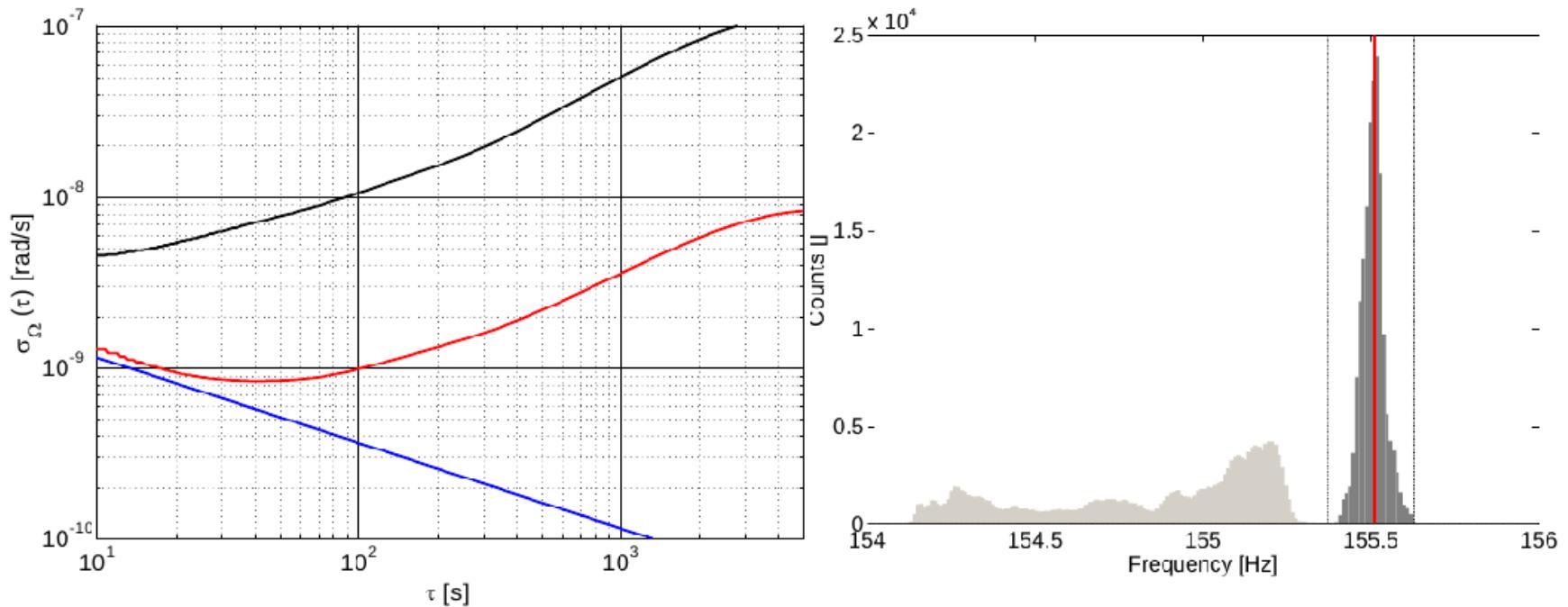
$$\dot{I}_2 = \alpha_2 I_2 - \beta I_2^2 - \theta_1 I_2 I_1 + r_1 \sqrt{I_1 I_2} \cos(\psi + \epsilon_2),$$

$$\dot{\psi} = \omega_s + \tau_1 I_1 - \tau_2 I_2 - r_2 \sqrt{\frac{I_2}{I_1}} \sin(\psi - \epsilon_2) - r_1 \sqrt{\frac{I_1}{I_2}} \sin(\psi + \epsilon_1)$$



Kalman Filter to reduce back-scatter noise  
 Best experimental set-up-----align with the Earth Axis

## Filtering results



**Allan variances** of AR2 (upper curve) and EKF (lower curve) rotational frequency estimates. The straight line represents the shot noise level of G-PISA

Histograms of the estimates of AR2 (pale gray) and EKF (dark gray) during 2 days of G-PISA data.

**Red line:** is the expected Sagnac frequency due to Earth rotation,  
**Dotted lines** represent its residual uncertainty bounds due to geometric and orientation tolerances.

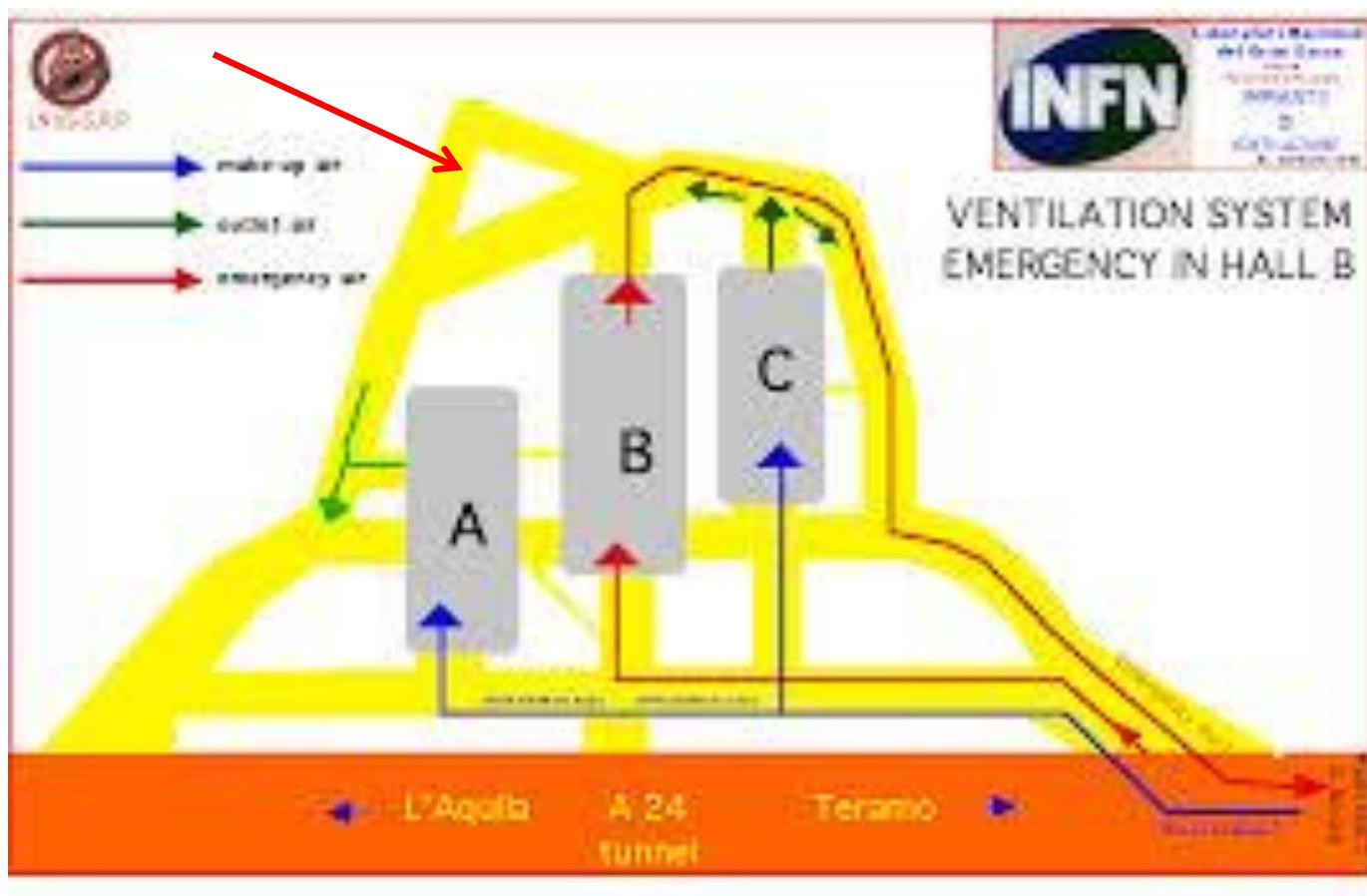
# Essential of GINGERino, under construction at LNGS

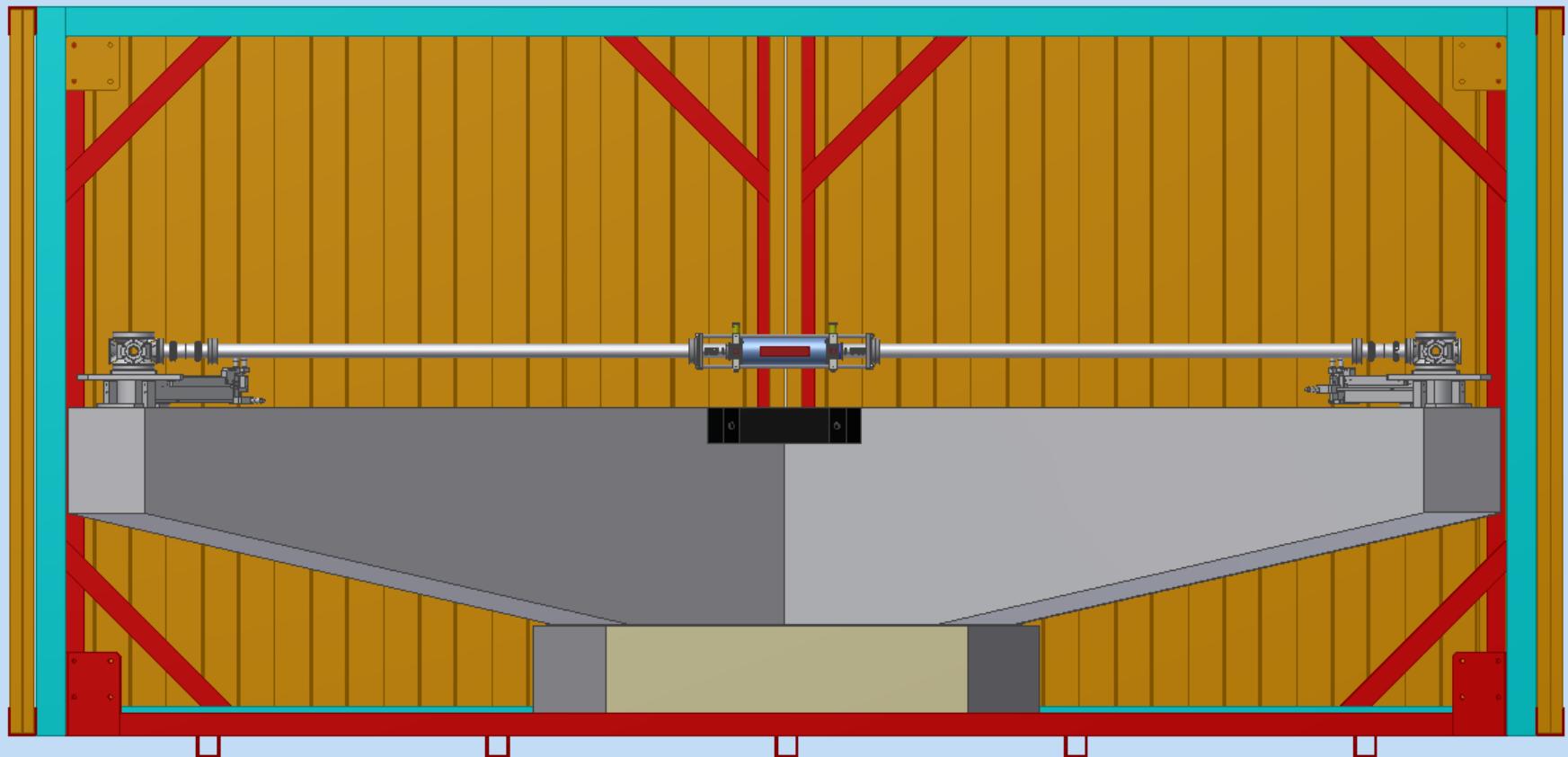
- The ring, 3.6 m side, covered by a good acoustic/thermal shielding
- DAQ and all related electronics will be contained in a separated box, outside the acoustic shielding
- GPS clock necessary

**Underground location external disturbances should be small**

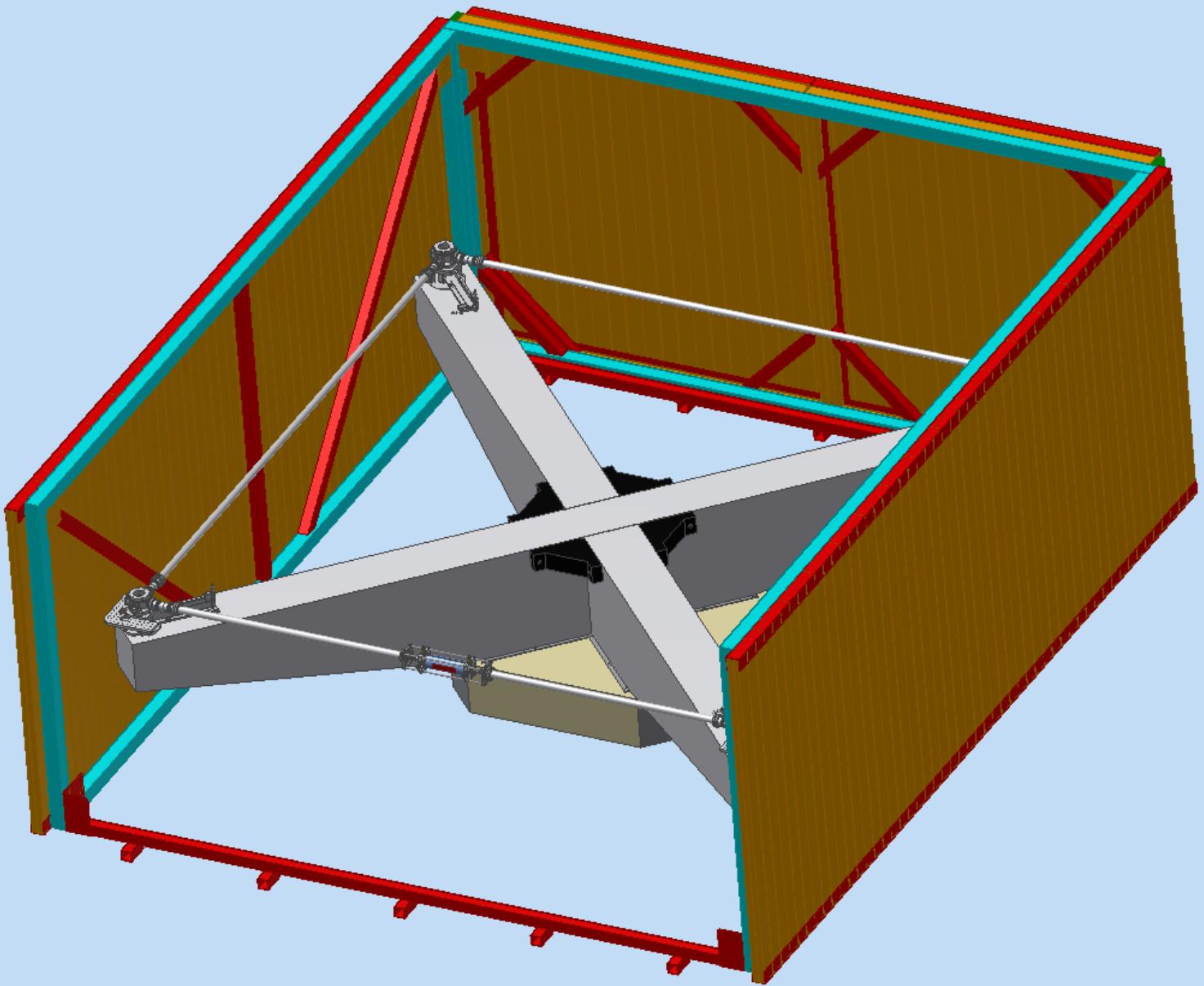
LNGS-Node  
polar motions should be observed

A,

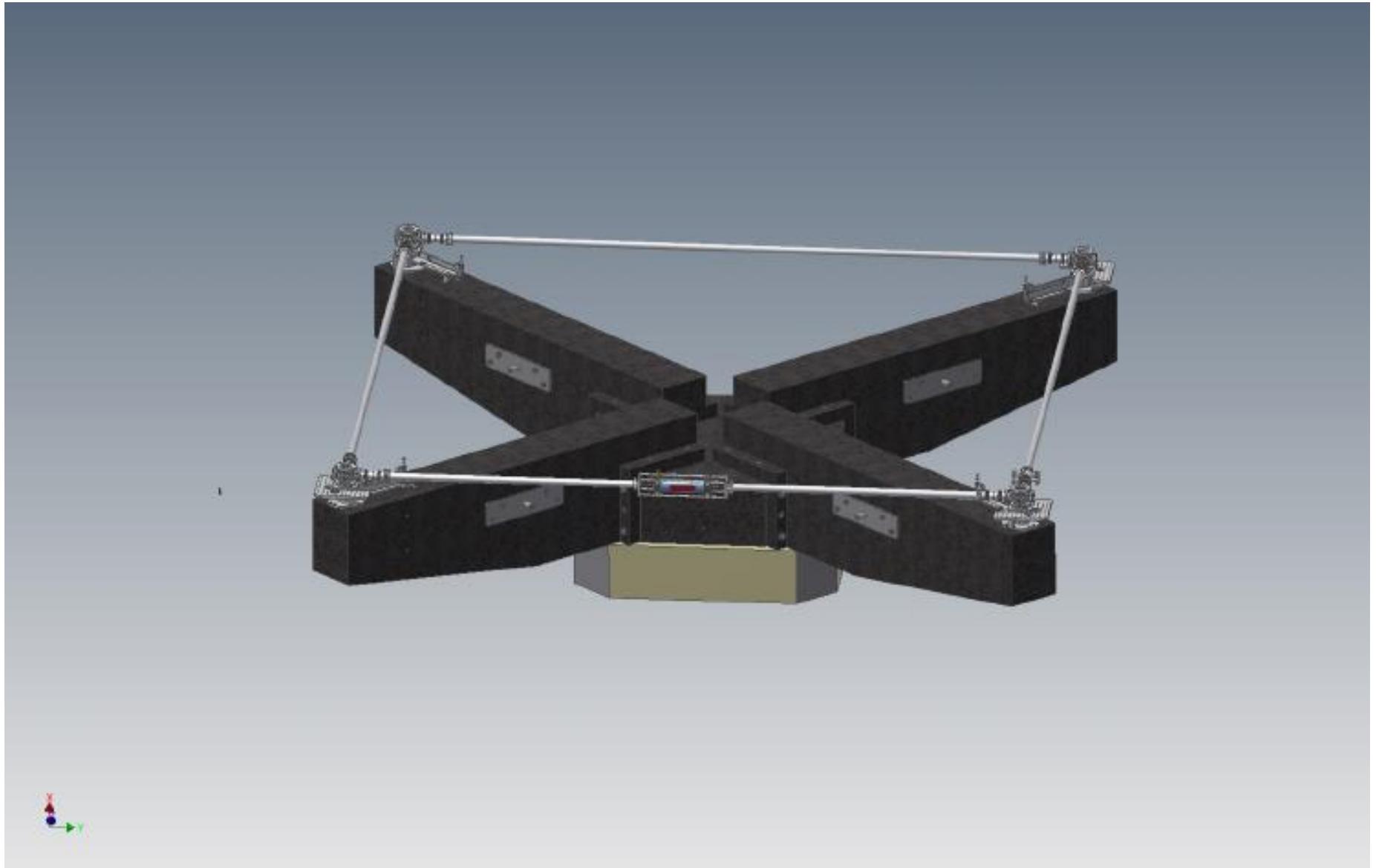




Angela Di Virgilio, Frascati, 23-10-2014



Angela Di Virgilio, Frascati, 23-10-2014



Angela Di Virgilio, Frascati, 23-10-2014

# First step....



# GINGERino, third step



First signals in December? We hope so, but  
we cannot guarantee

22-10-2014



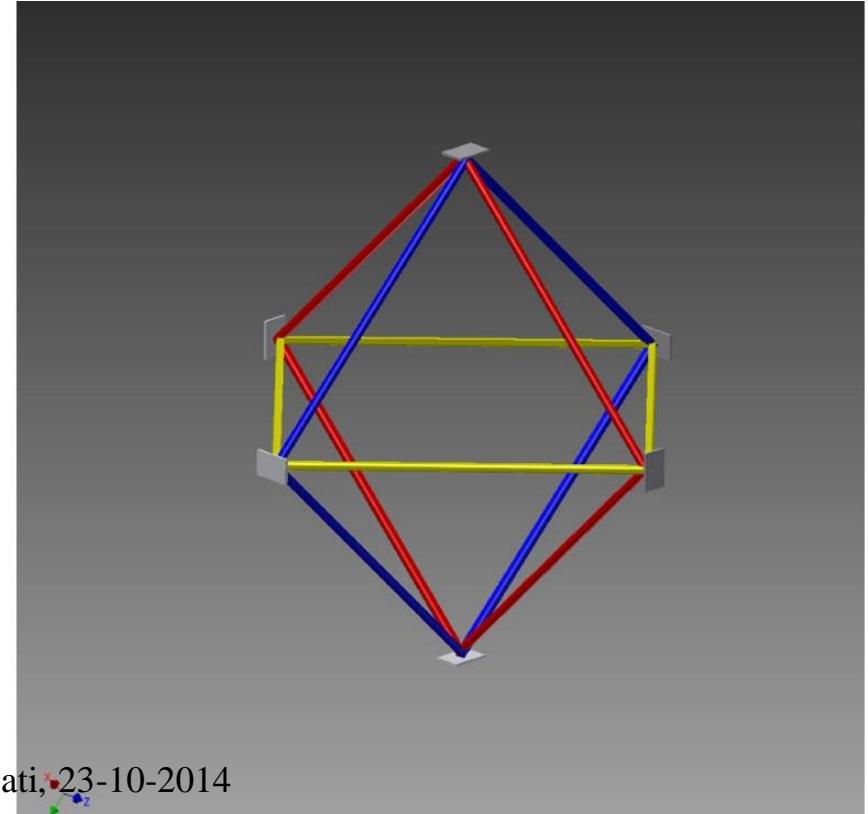
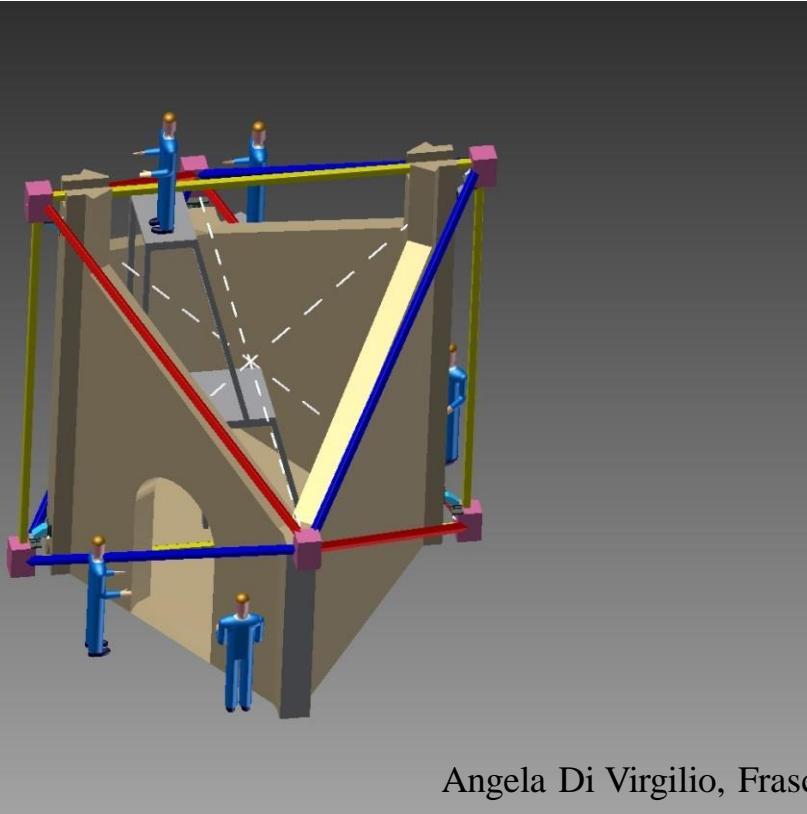




# GINGER (Gyrosopes IN GEneral Relativity)

*Lense-Tirring effect 1% accuracy*

Measuring Gravito-magnetic Effects by Multi Ring-Laser Gyroscope - Bosi, F. et al. Phys.Rev. D84 (2011) 122002





Pisa, Napoli, LNL and DEI, Napoli, Torino Politecnico, INGV, in  
collab. with U. Scieber (TUM), H. Igel (LMU) and J.P. Wells  
(Christchurch NZ)

Di Virgilio, Allegrini, Belfi, Beverini, Bosi, Carelli, Cella, Maccioni,  
Simonelli and Santagata (PhD Siena), Terreni

Ortolan, Cuccato

Beghi, Naletto, Pelizzo, Donazzan

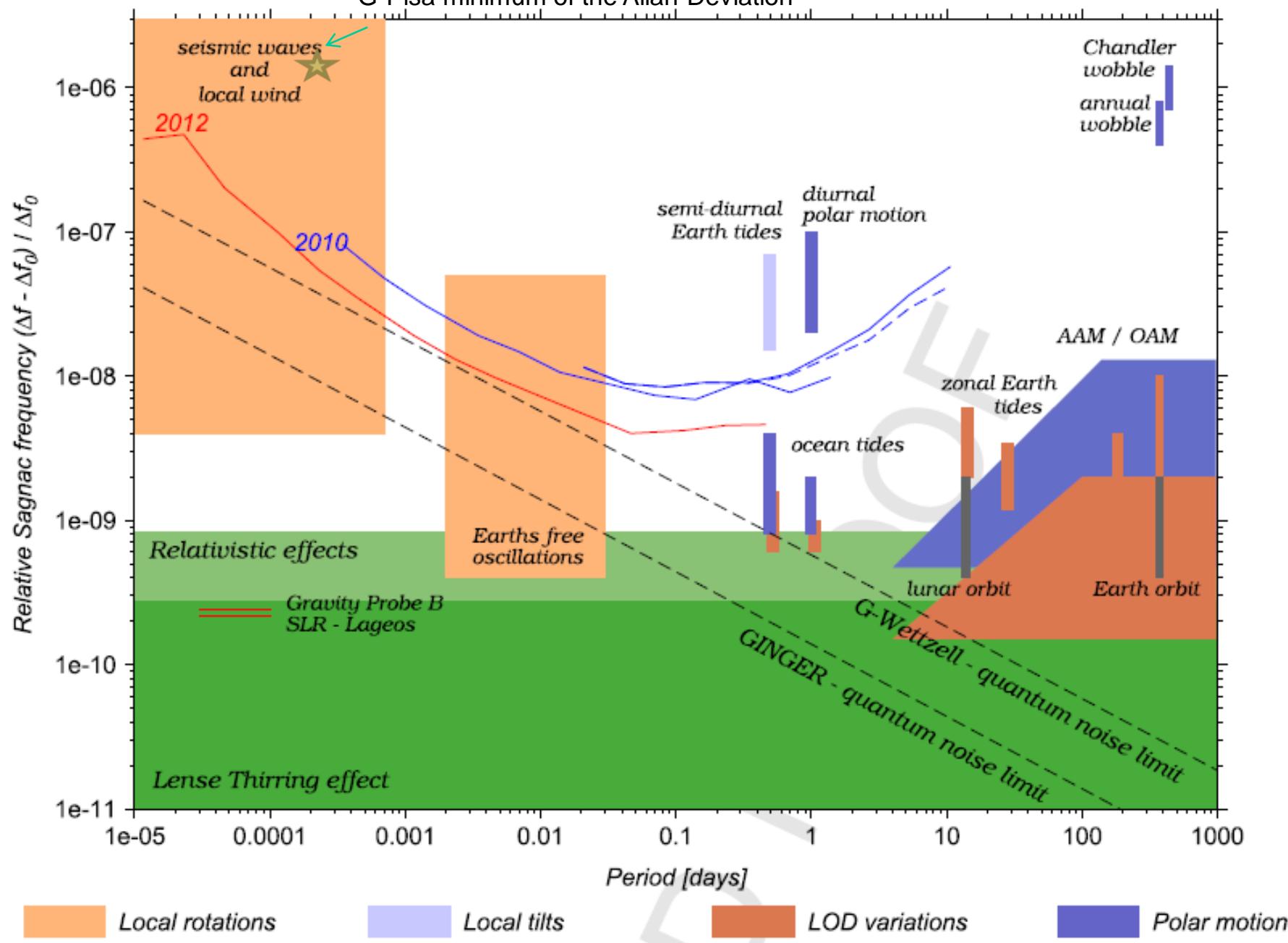
Porzio, Altucci e Velotta

Ortolan

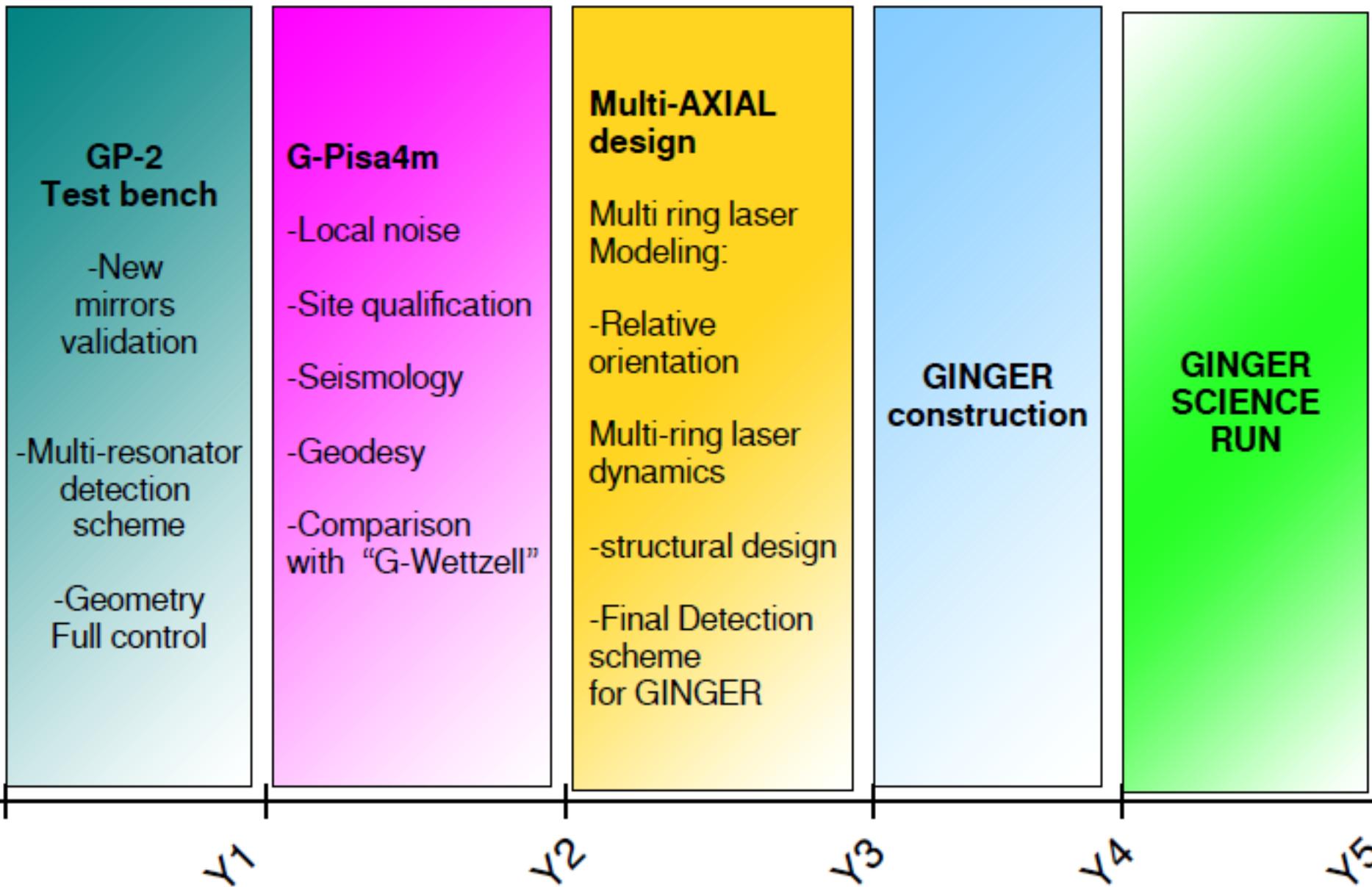
Tartaglia, Ruggiero



### G-Pisa minimum of the Allan Deviation



# ***GINGER roadmap***



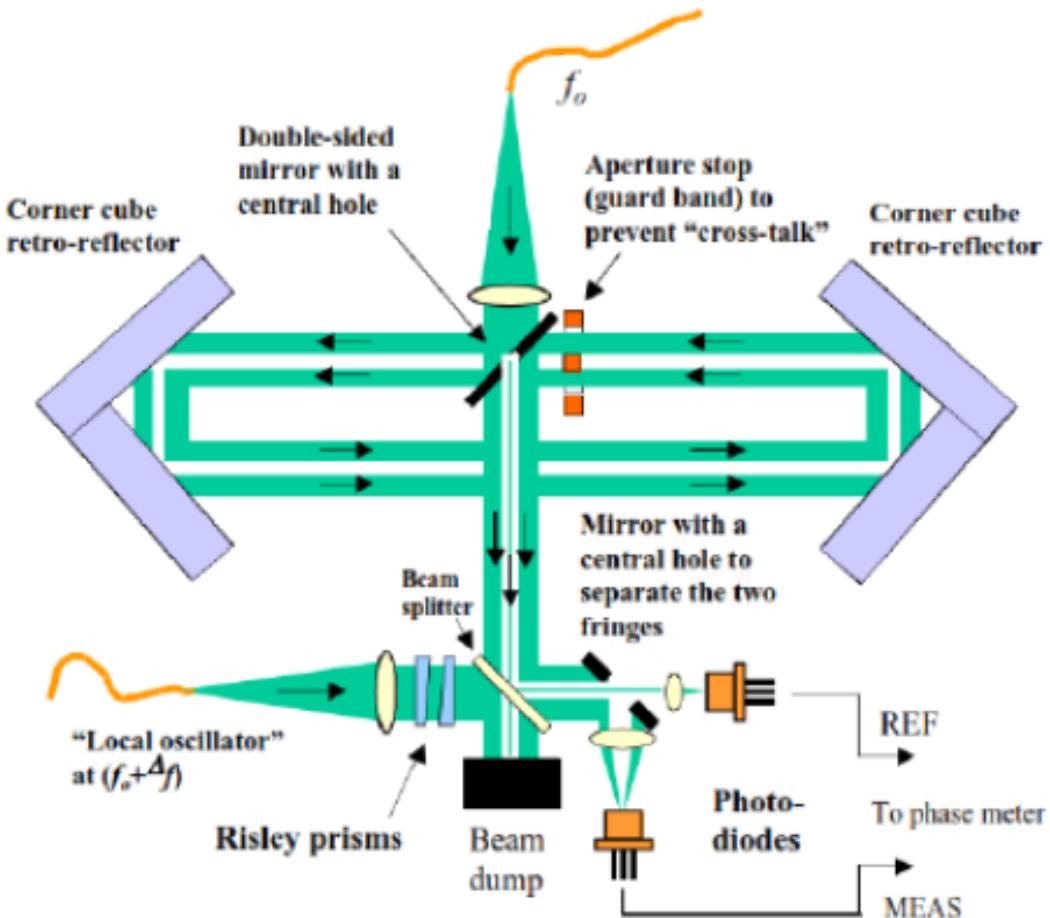
G. Naletto, M. Pelizzo, DEI Padova

# DESIGN

## Heterodyne interferometer

Two spatially isolated beams:

- Reference beam
- Measurement beam ("racetrack" loop)



# Conclusions



Large size ringlaser are very simple object, which can provide useful information for geodesy and geophysics

An array of ringlaser could measure locally the lense-thirring effect (GINGER project)

We (G-GranSasso, CommII) are working in order to realize such a beauty, the three main points are:

- is LNGS a suitable location? GINGERino
- can a control system ensure the necessary stability? GP-2
- Relative alignment of the ringlaser monitored with nrad accuracy

**SENSITIVITY, STABILITY and ACCURACY**