Experimental determination of gravitomagnetic effects by means of ring lasers

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The field of a rotating mass

$$ds^2 = g_{00}dt^2 + g_{rr}dr^2 + g_{\theta\theta}d\theta^2 + g_{\varphi\varphi}d\varphi^2 + 2g_{0\varphi}dtd\varphi$$

Source of the gravito-magnetic effects

$$h_i = g_{0i} \quad \rightarrow \quad \vec{B}_G = \vec{\nabla} \wedge \vec{h}$$

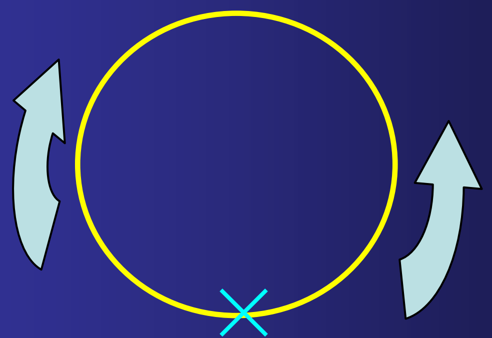
Gravitomagnetic field

Lense Thirring drag

- Precessing gyroscopes:
  - GPB: confirmed within ±19% (C.F.W. Everitt et al., PRL 106, 221101 (2011))
  - LAGEOS nodes precession: confirmed within ±10% (I. Ciufolini et al., *Eur. Phys. J. Plus*, ***126***, *72*, (2011))
  - LARES nodes precession: flying, aiming to a few % accuracy.

Light as a probe for gravito-magnetism

Closed loop

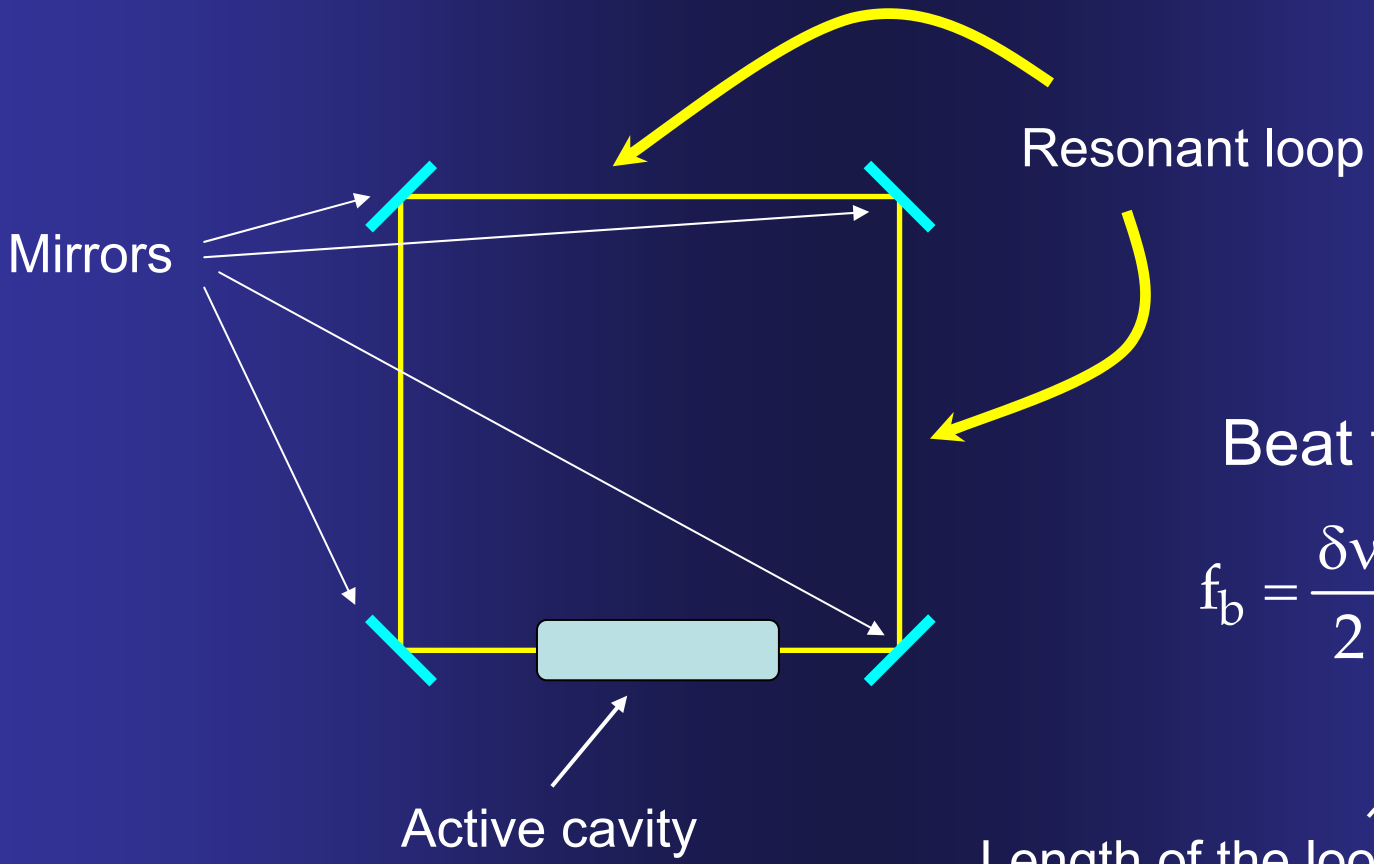


Counterrotating light beams

Time of flight difference

$$\delta T = T_{+} - T_{-} = -2\oint \frac{g_{0\phi}}{g_{00}} d\phi \neq 0$$

A gyrolaser



Beat frequency

$$f_b = \frac{\delta\nu}{2} = \frac{c^2}{\lambda P}\delta T$$

Length of the loop

Earth-bound laboratory (lowest approximation order)

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

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

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

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

$$\delta T = -2\sqrt{g_{00}}\oint\frac{g_{0\phi}}{g_{00}}d\phi$$

Expected signal

Normal in the meridian plane $\omega = \Omega_\oplus$

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

Scale factor

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

Area of the loop

Sagnac

$\vec{\Omega}_G$

$\vec{\Omega}_B$

Orders of magnitude

$$\Omega_{\oplus} = 7.2 \times 10^{-5}\, \mathrm{s}^{-1}$$

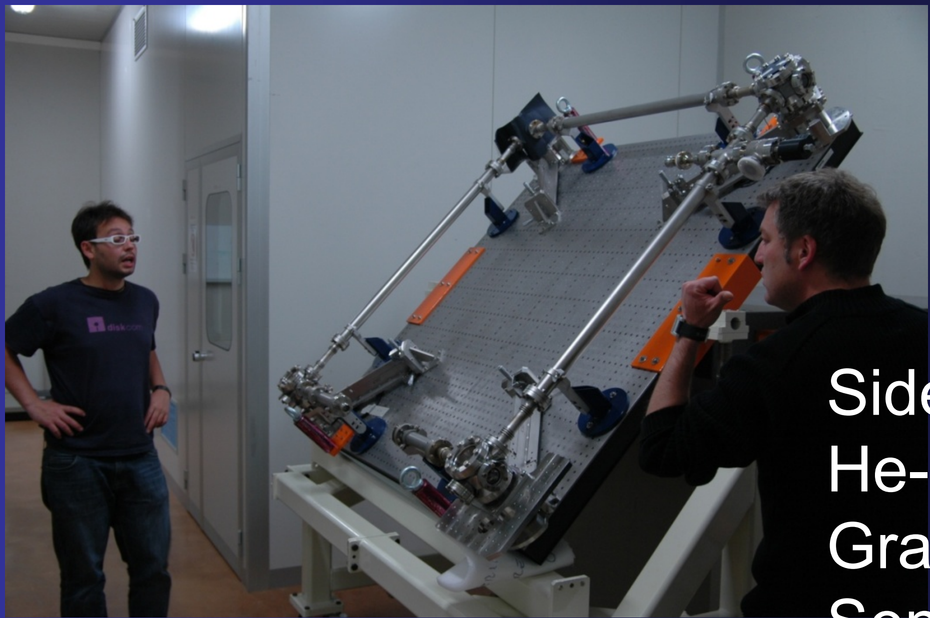
$$\Omega_{\mathrm{G}} \approx \Omega_{\mathrm{B}} \approx 10^{-9}\, \Omega_{\oplus}$$

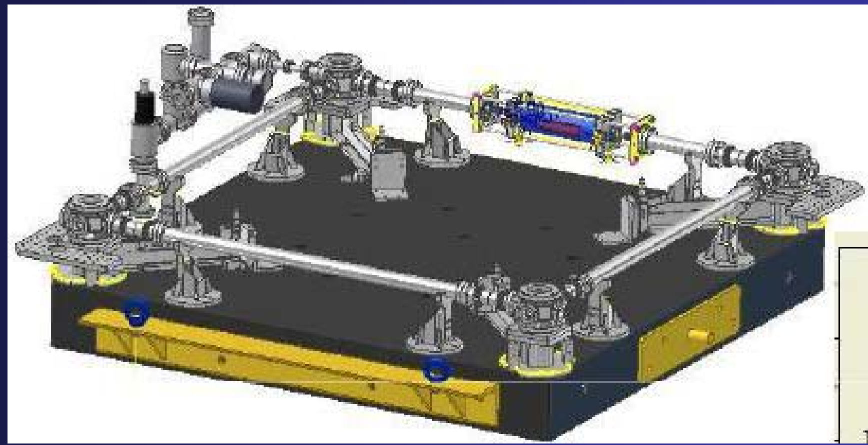
Actual gyrolasers

Commercial fiber optics gyroscope

Sensitivity: ~ 10^{-7} rad/s/√Herz

Research gyrolasers: G-Pisa





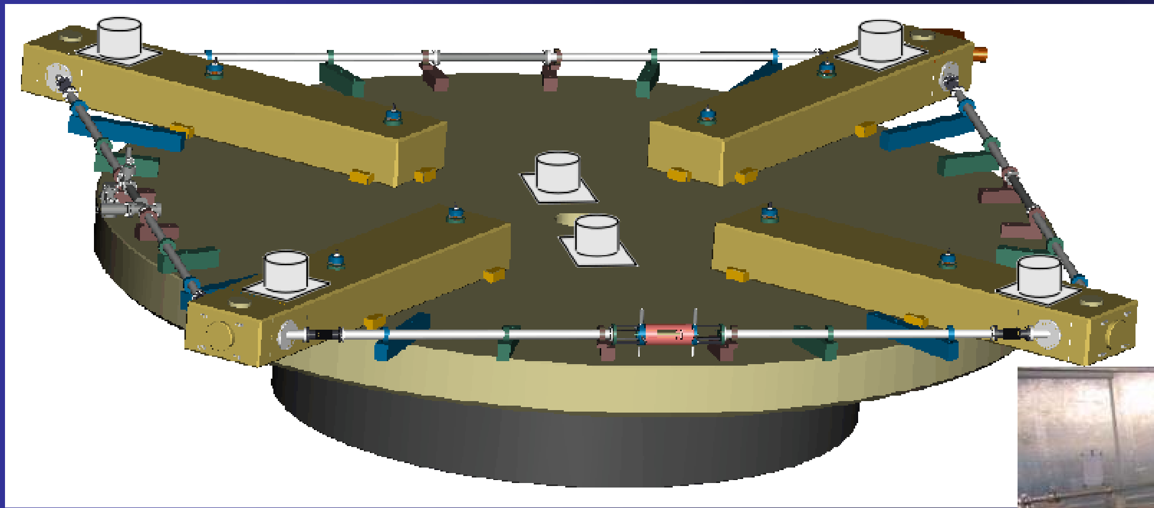
Side: 1.35 m
He-Ne laser
Granite support
Sensitivity: $10^{-10} \sim 10^{-9}$ rad/s/√Herz

The Cashmere Cavern near Christchurch (NZ)

Various configurations, side up to 20 m

A triangular loop, 5 m side will be built

G instrument at the Geodätisches Observatorium Wettzell

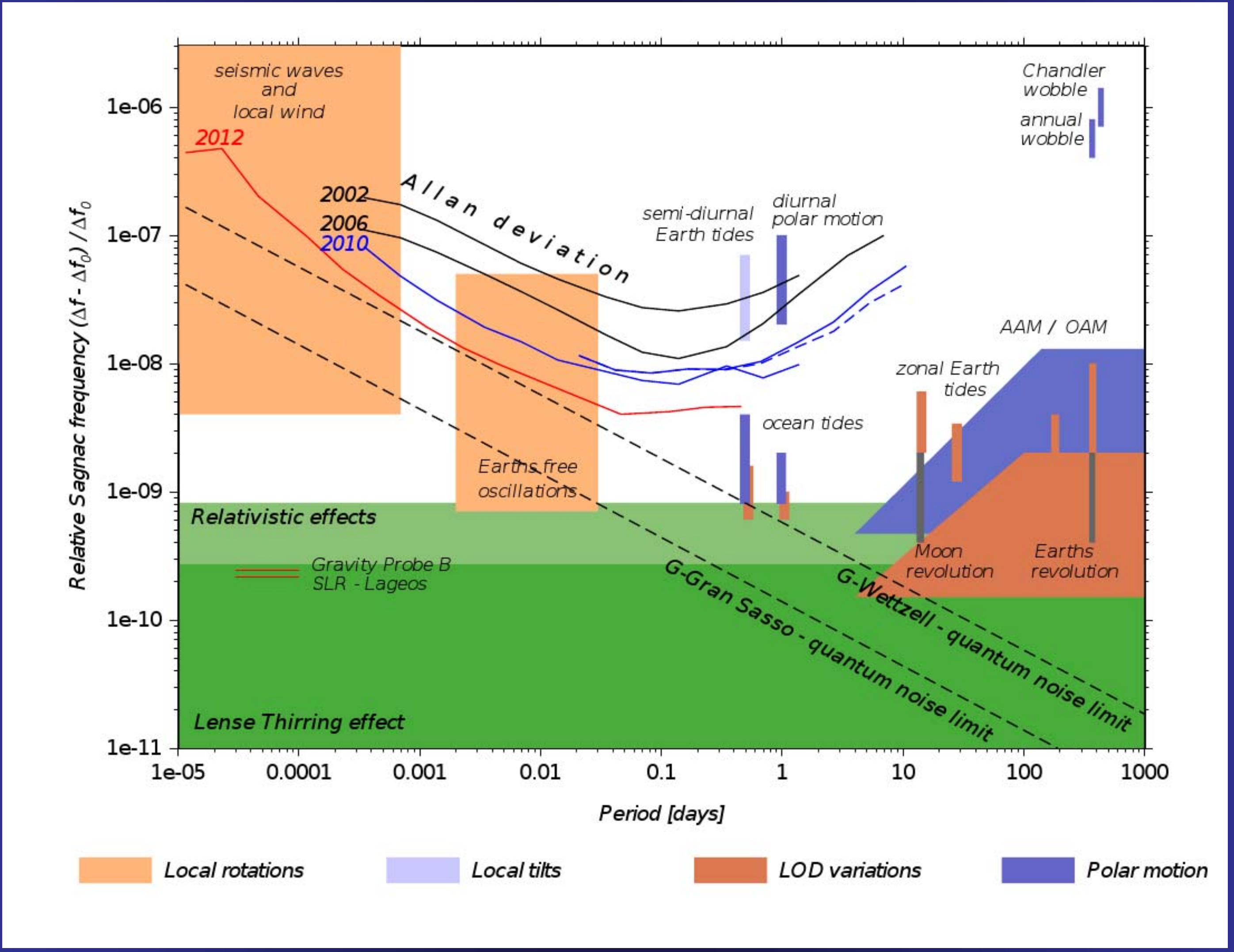


Absolute sensitivity:

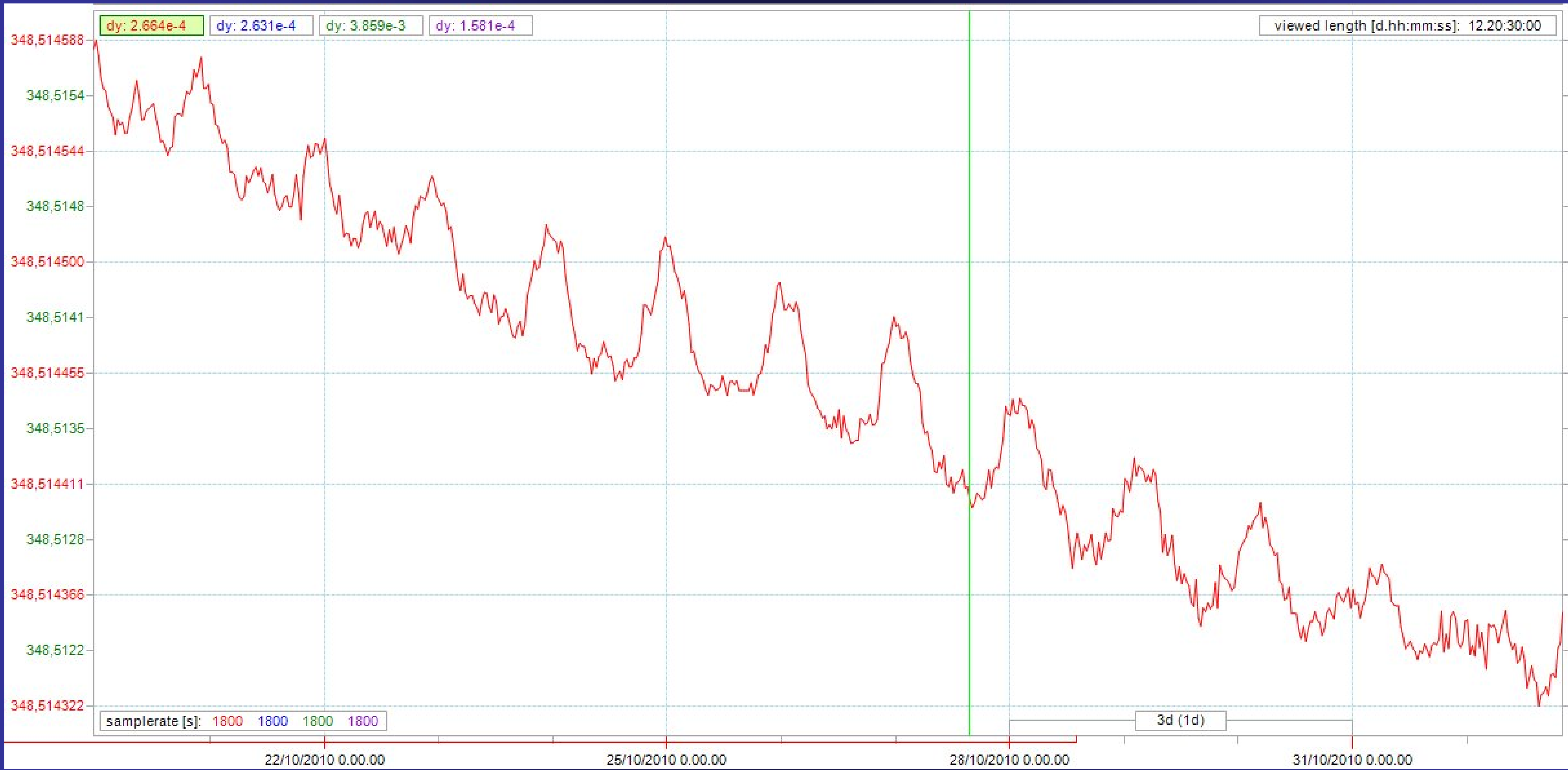
4.5×10^{-12} rad/s/$\sqrt{\text{Hz}}$

Side: 4 m
Power: 20nW
Zerodur support

Relative resolution and stability of G



Wettzell data



PPN constraints

$$\vec{\Omega}_G = -(1+\gamma)\Omega_{\otimes}\frac{GM}{c^2 r}\sin\theta\,\hat{u}_\theta$$

$$\vec{\Omega}_B = -\frac{1+\gamma+\alpha_1/4}{2}\frac{G}{c^2 r^3}\left(\vec{J}_{\otimes} - 3\left(\vec{J}_{\otimes}\cdot\hat{u}_r\right)\hat{u}_r\right)$$

$$\vec{\Omega}_W = -\frac{\alpha_1}{4}\frac{GM}{c^2 r^2}\hat{u}_r \wedge \vec{W}$$

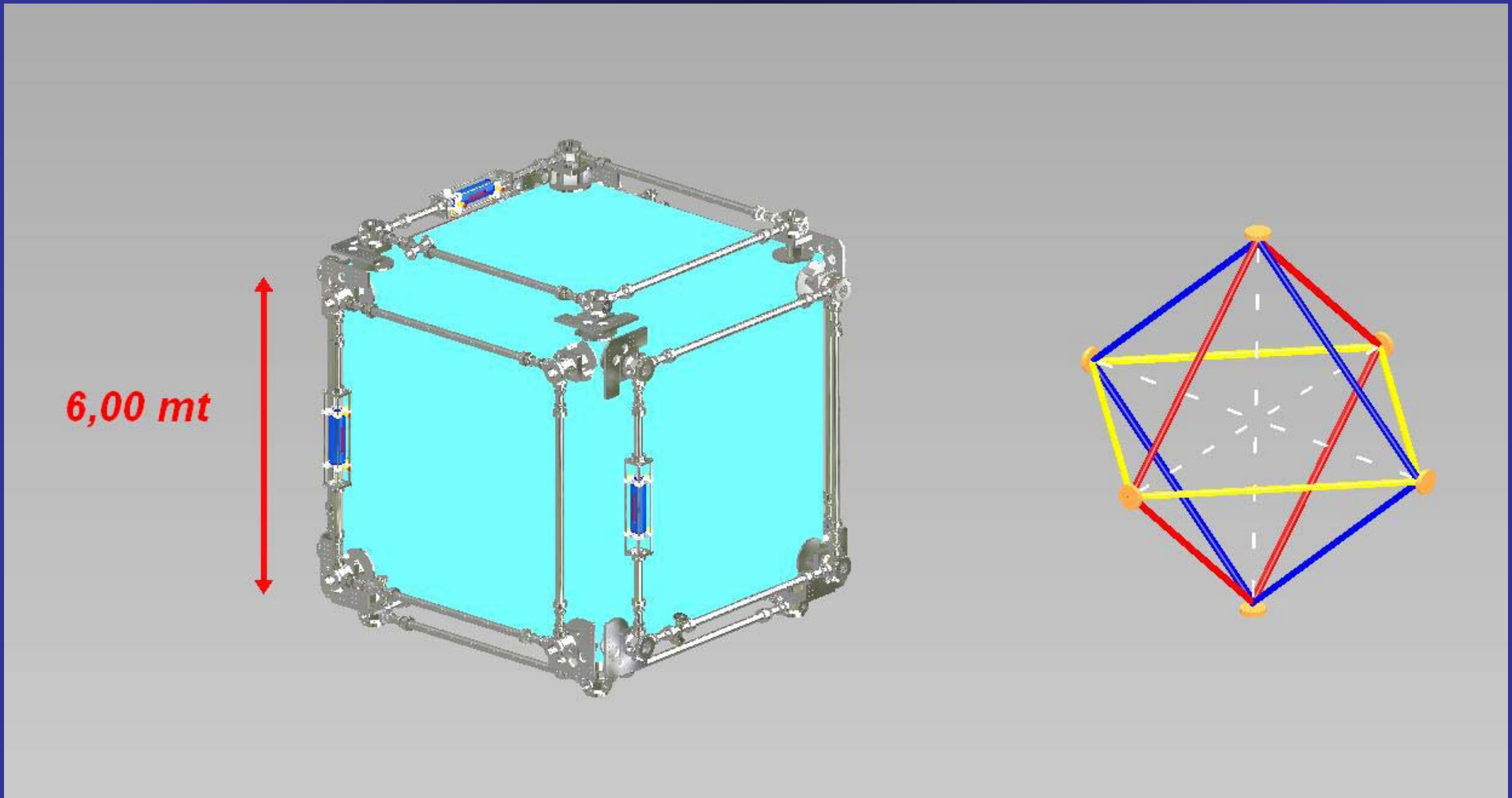
Upper bounds analysis of the values of the parameters

GINGER: proposed and under R&D stage

- Ring lasers array (three to six or more)
- Laser power: 200 nW
- Quality factor of the cavity: $Q = 3 \times 10^{12}$
- Square loop, 6 m in side
- Each loop differently oriented
- Underground location
- Purpose: to measure the LT effect with a 1% accuracy (one year integration time)

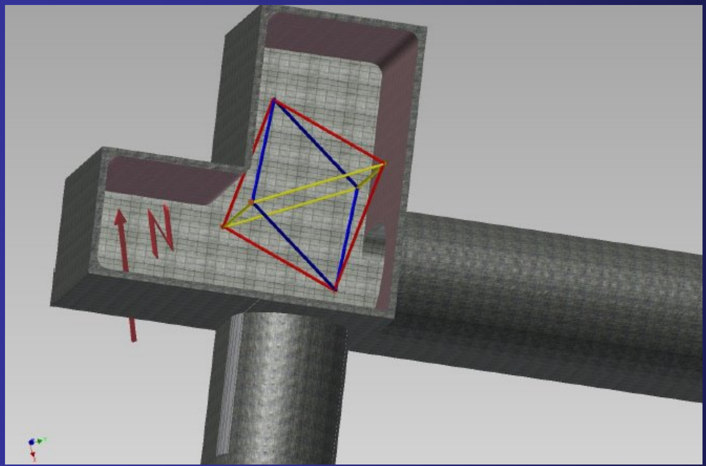
F. Bosi et al., Phys. Rev. **D**, **84**, 122002-1-122002-23. (2011)

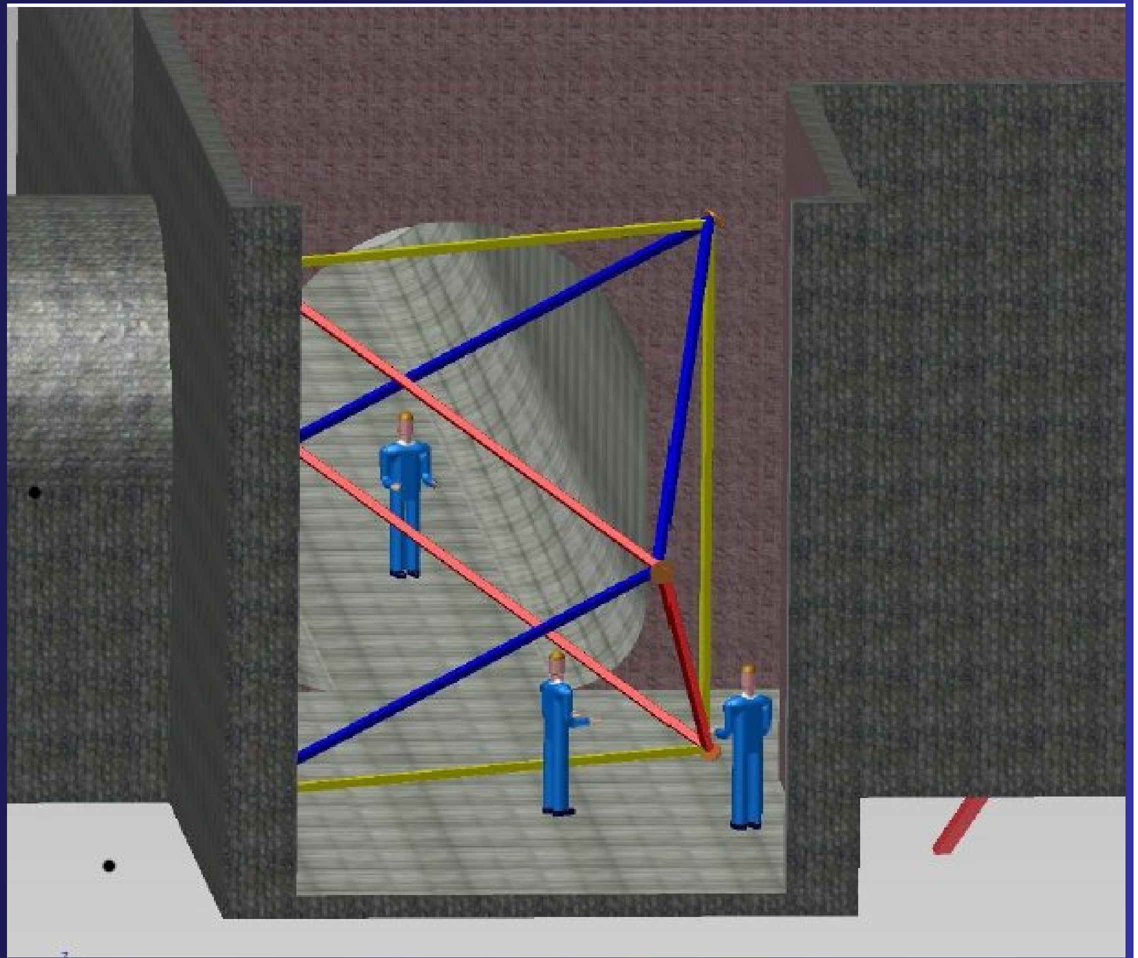
Configurations



Location at the LNGS

Artist's view of the rings in situ





The collaboration

- *F. Bosi, G. Cella, A. Di Virgilio* **INFN-Pisa**
- *M. Allegrini, J. Belfi, N. Beverini, G. Carelli, I. Ferrante, A. Fioretti, E. Maccioni, F. Stefani* **Univ. of Pisa and CNISM**
- *F. Sorrentino* **Univ. of Florence**
- *A. Porzio and S. Solimeno* **Univ. of Naples and CNISM**
- *M. Cerdonio, A. Ortolan and J.P Zendri,* **University of Padova and INFN-LNL**
- *M.L. Ruggiero and A.Tartaglia* **Politecnico di Torino**
- *Ulrich Schreiber and Team*, **Technische Universität München-Fundamentalstation Wettzell and Forschungseinrichtung Satellitengeodäsie , Germany**
- *Jon-Paul Wells and Team*, **University of Canterbury, New Zealand**

– G-Gran Sasso is being selected for further development and small scale tests by the Italian INFN

– Seismic control of the intended location at the LNGS has been made by our German colleagues at the beginning of 2011

– Preliminary studies of the behaviour of the mirrors, stability and control of the geometry etc. are under way using G-Pisa

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