"Гироскоп Саньяка" как детектор слабых грави-инерциальных возмущений

(проект “Кольцо Саньяка")

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in consulting with

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Outline

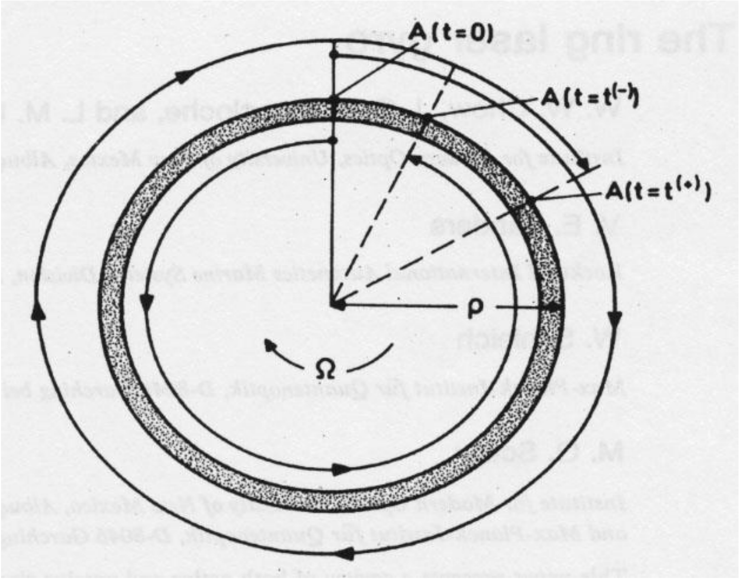
1. Principle of the instrument
2. Required $\Delta\Omega$ resolution
3. Local and celestial compasses
4. Relativistic gravity effects
5. Axion search for
6. Seismic monitoring

Sagnac Effect

- First experiments concerning light propagation in rotating media were carried out by F. Harress in 1911.
- George Sagnac published his results in 1913 and is credited with the effect since Harress made numerous errors in interpretation of his experiment
- A thought experiment:

$$ct_+=2\pi R+R\Omega t_+ \quad t_+=2\pi R(c-\Omega R)$$

$$ct_-=2\pi R-R\Omega t_- \quad t_-=2\pi R/(c+\Omega R)$$

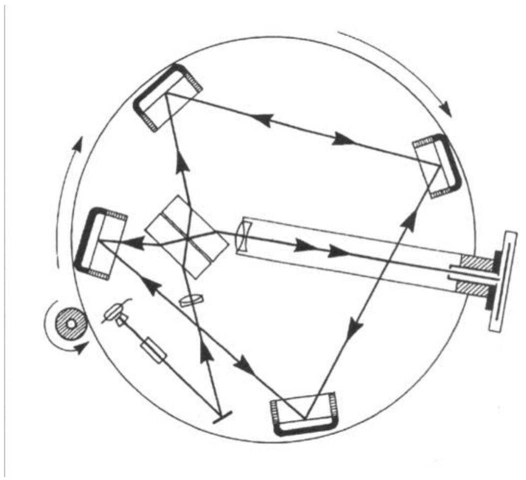


$$\delta t = 4\,\mathbf{\Omega A}/c^2$$

$$\delta\varphi = 8\pi\,\mathbf{\Omega A}/\lambda\mathbf{c}$$

Ω - angular velocity , **A** – ring square

Sagnac Interferometer (1913)



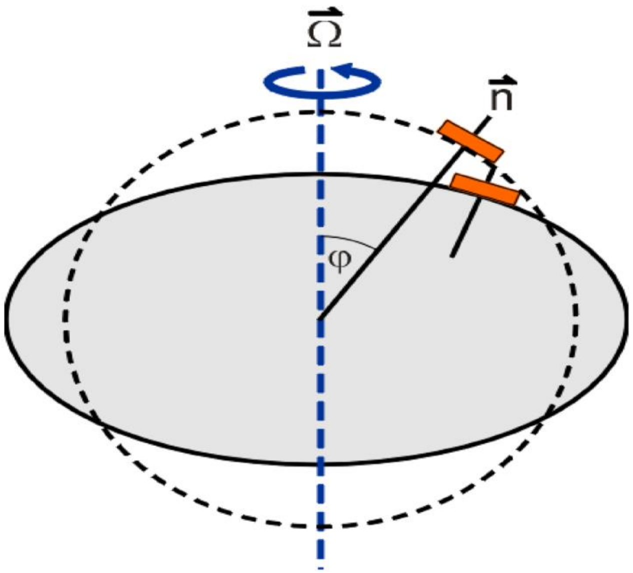
Georges Sagnac was the first to correctly combine theory with experiment.
We also acknowledge the experimental skill to build a sufficiently stable apparatus.

Rotation Rate: 2 rev. per sec.

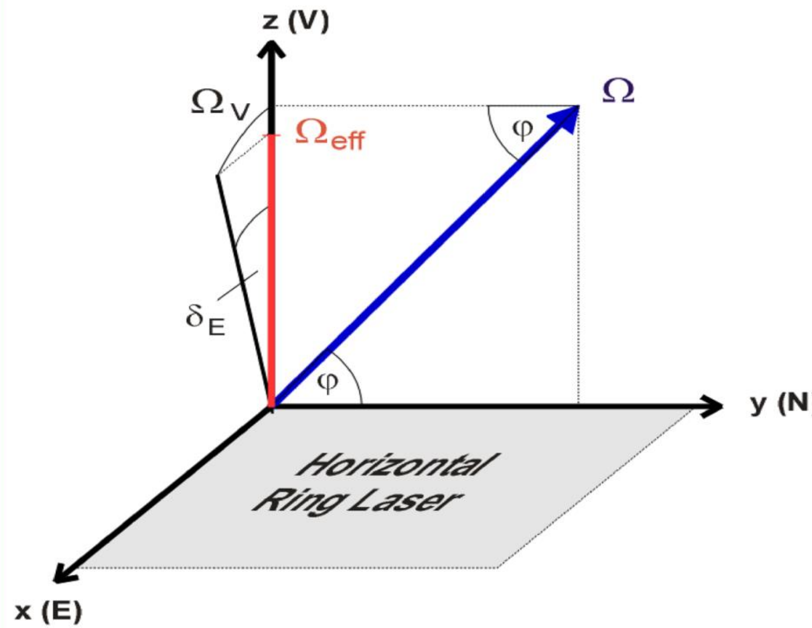
observed Fringe Shift: $\delta\varphi = 8\pi \, \boldsymbol{\omega} \mathbf{A} / \lambda c$

with A = 0.086 m2 this turns out to be 0.07±0.01 fringes

Large Ring Lasers are directly linked to the rotational Axis of the Earth



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



$$\Omega_{eff} = \Omega \, \sin(\varphi + \delta_N) \, \cos(\delta_E)$$

Ω Rotation vector
δ_N Tilt angle towards N
δ_E Tilt angle towards E
φ Latitude

оценки

частотный сдвиг (расщепление) мод $\delta f_{sagn} = |f_- - f_+|$

$$\delta f_{sagn} = \frac{4(\mathbf{A\Omega})}{P\lambda}$$

предел Пуассоновского шума

$$\Delta f_q = < \Delta f^2 >^{1/2} = \frac{\nu}{Q}\sqrt{\frac{h\nu}{W}\frac{1}{\nu_m}}$$

условие регистрации

$$\Delta f_{sagn} \geq \Delta f_q \qquad \Omega \geq \frac{c}{2RQ}\sqrt{\frac{h\nu}{W}\frac{1}{\nu_m}} \qquad R \geq \frac{c}{2\Omega Q}\sqrt{\frac{h\nu}{W}\frac{1}{\nu_m}}$$

Типичные параметры: $W \approx 1mW$, $\nu \approx 3\ 10^{14}$ Hz, $Q \approx 10^{10}$ позволяют детектировать угловую скорость вращения земли $\Omega = 7.3\ 10^{-5}$ rad/sec.

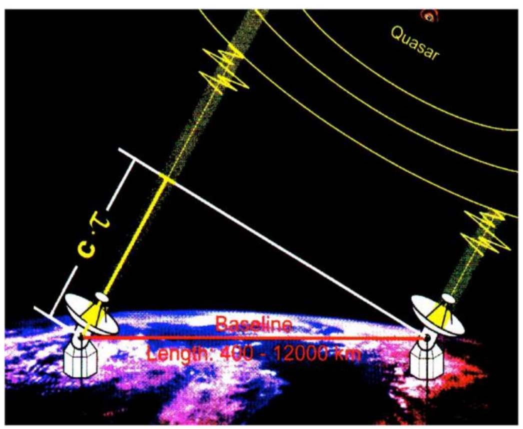
Для регистрации вариаций $(10^{-8} - 10^{-10})\ \Omega$

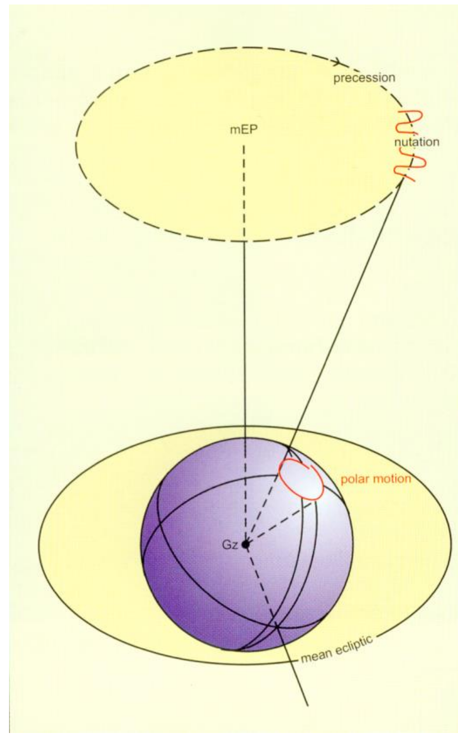
$$R \geq \frac{3 \cdot (10^4 \div 10^6)}{\sqrt{\tau_m}} cm$$

Даже при $\tau_m = 10^5$ sec, требуется $R \geq 1\text{-}100$ m!

Linking Celestial and Terrestrial Reference Frames

Star Compass

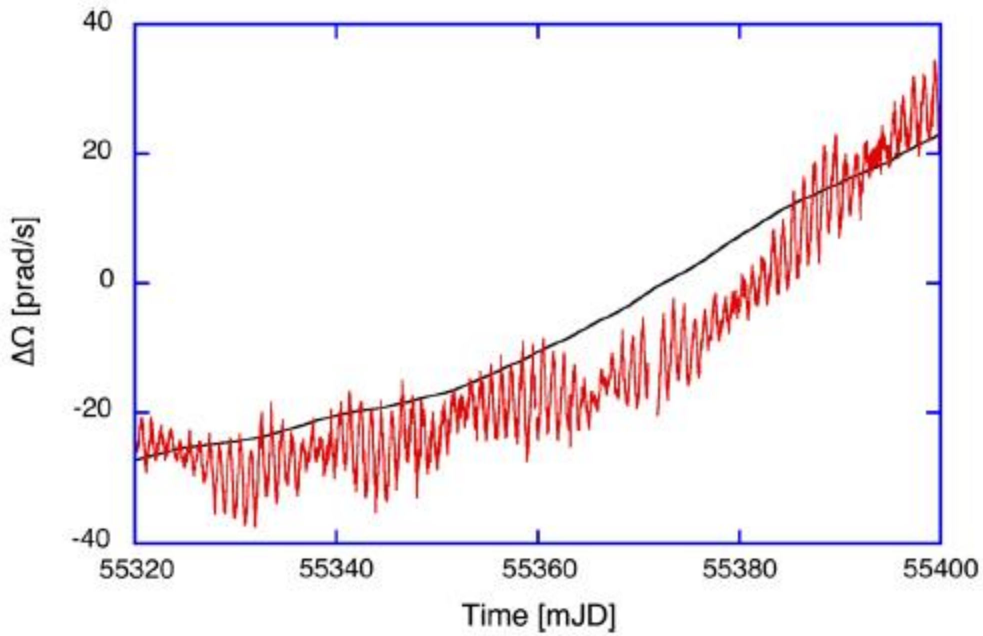




Earth Rotation

Orientation

Inertial Compass



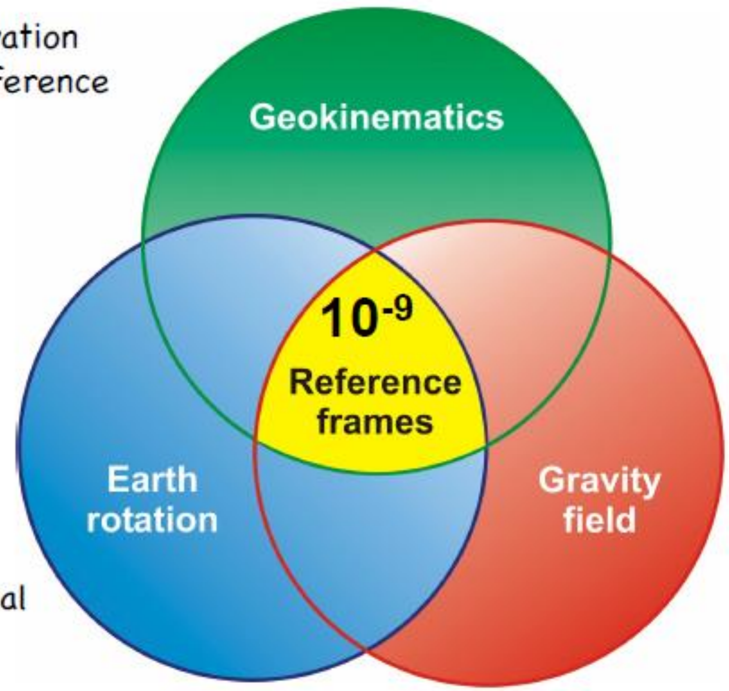
Time series of rotations derived from the large-ring laser G at the Geodetic Observatory Wettzell. Solid Earth tides, diurnal polar motion and the long-period Chandler and the Annual wobble are clearly visible in the data. VLBI measurements carried out twice per week are shown for comparison.

- „Internal" Goal

Evolution of GGOS and the geodetic observation technologies to establish an Earth fixed reference frame with a relative accuracy of at least

10^{-9} = 1 ppb

with high spatial and temporal resolution.



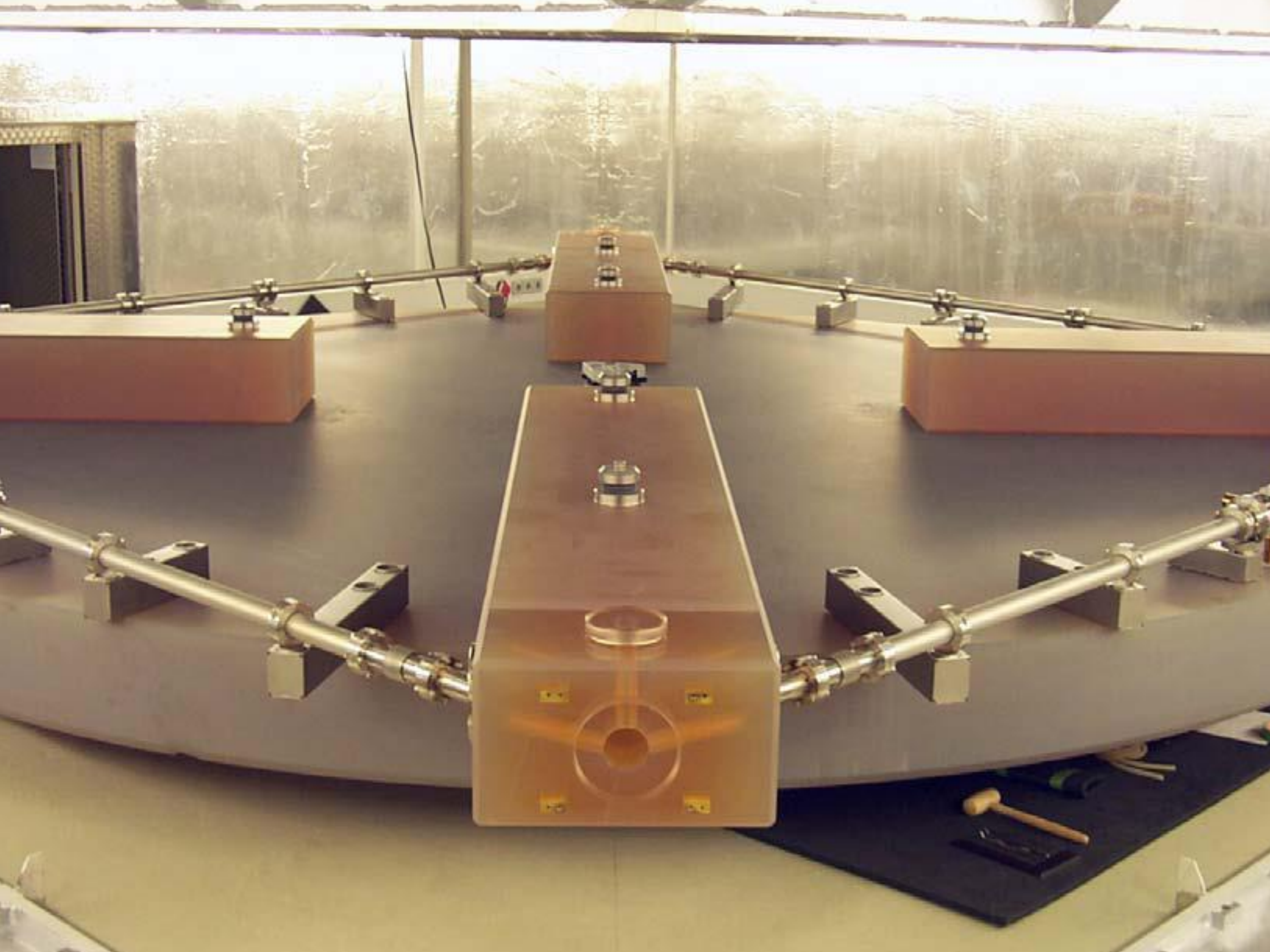
- „External" Goal

Integration of GGOS as an important contributor into **Earth System Research** (Modeling of physical, chemical and biological processes).

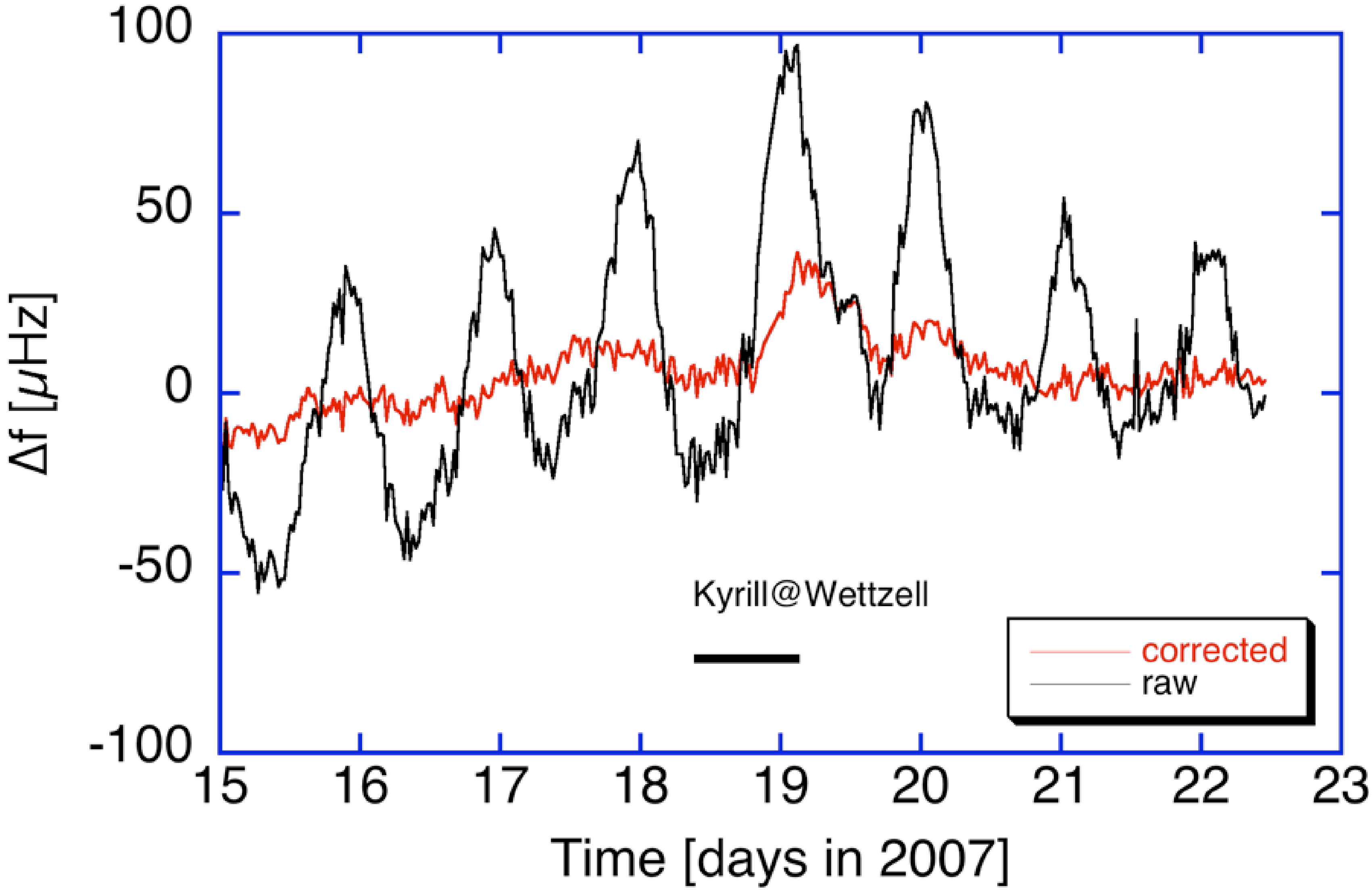
Contributions: Mass transport, dynamics, surface deformations

Geodetic Observatory Wettzell


SALLER

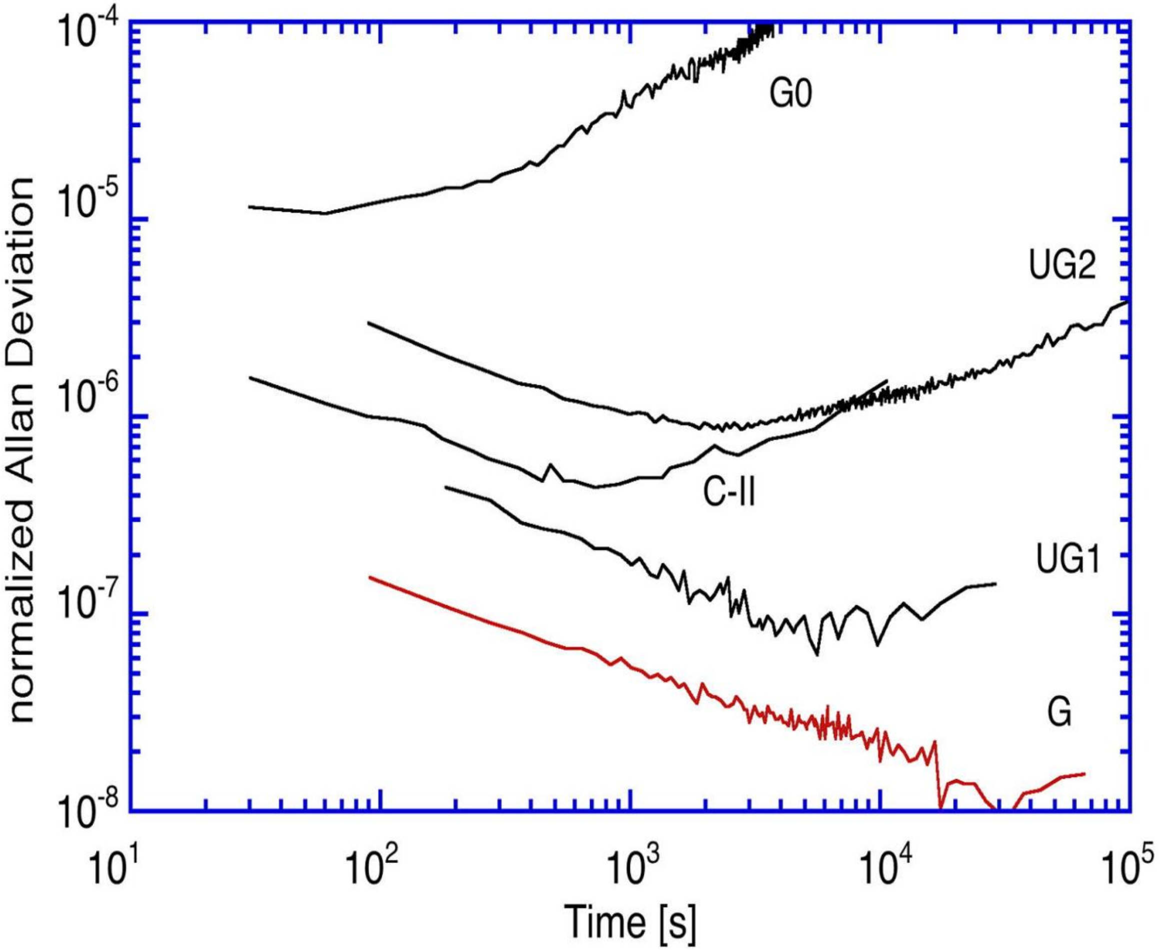


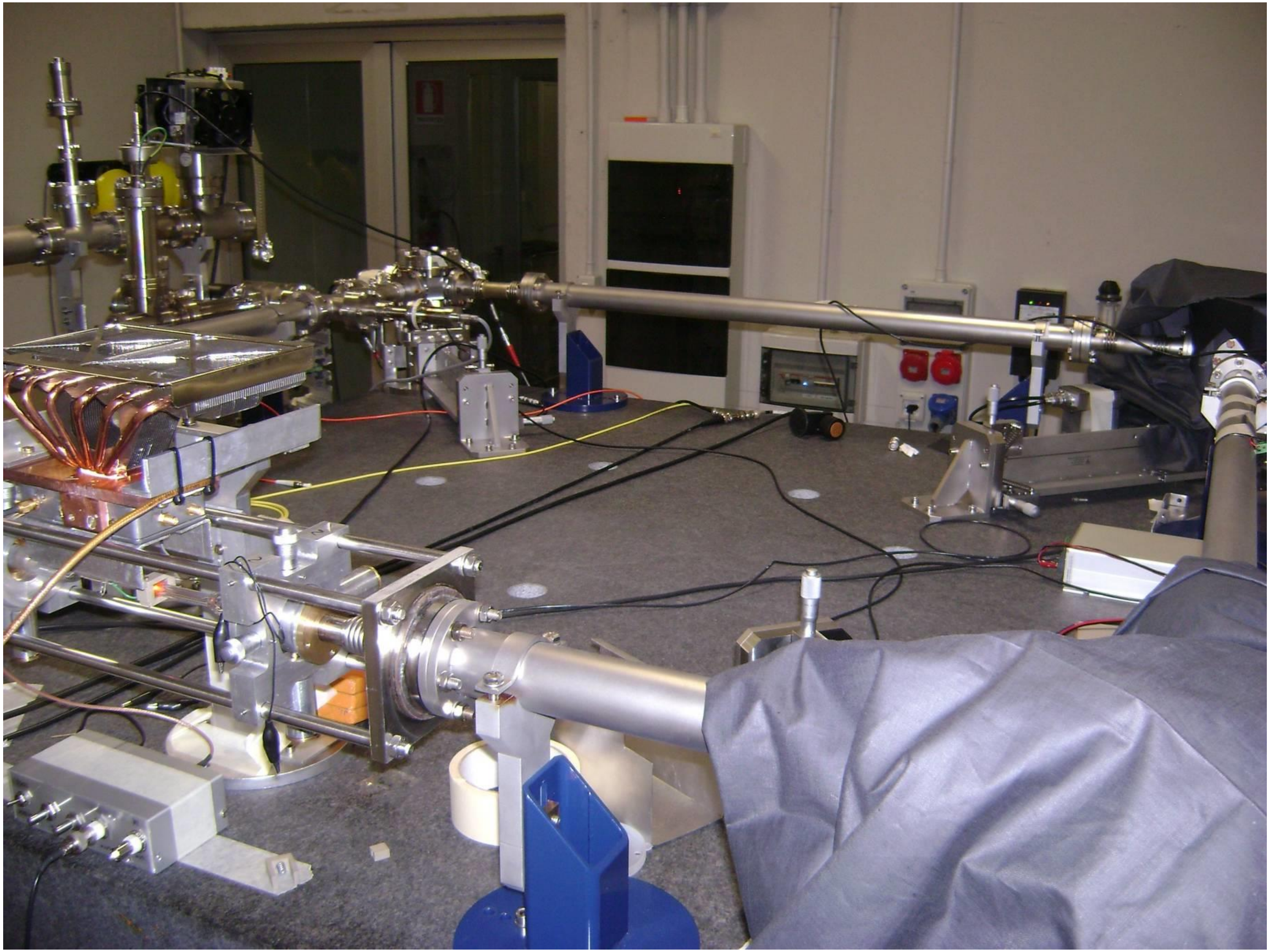
Tidal Effects on Ring Laser Measurements ΔΩ/Ω 10^{– 8}



Ring Lasers Performance

- Resolution 10^{-10} rad
- Angle of a hair viewed from 2000 km
- PSD ~ 10^{-11} rad/s/rtHz





Sagnyac VIRGO

Phys.Dept. Univ. of Pisa

PHYSICAL REVIEW D 84, 122002 (2011)

- F. Bosi,a G. Cella,b and A. Di Virgilioc, M. Allegrini,i J. Belfi,j N. Beverini,k B. Bouhadef,l G. Carelli,m I. Ferrante,n E. Maccioni,o R. Passaquieti,p and F. Stefaniq
  INFN Sezione di Pisa, Pisa, Italy University of Pisa and CNISM, Pisa, Italy
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Technische Universitaet Muenchen, Forschungs einrichtung Satellitengeodaesie, **Wettzell, 93444 Bad Ko¨tzting, German**

We propose an **underground experiment to detect the general relativistic effects** due to the curvature of **space-time around the Earth (de Sitter effect)** and to the rotation of the planet **(dragging of the inertial frames or Lense-Thirring effect).** It is based on the comparison between the IERS value of the Earth rotation vector and corresponding measurements obtained by a triaxial laser detector of rotation. The proposed detector consists of six large ring lasers arranged along three orthogonal axes. In about two years
of data taking, the 1% sensitivity required for the measurement of the Lense-Thirring drag can be reached with square rings of 6 m side, assuming a shot noise limited sensitivity **(20 prad/s/Hz^{-1/2})**

The beat frequency with relativistic correction

$$f_b \simeq 2\frac{A}{\lambda P}\Omega(\hat{u}_a \cdot \hat{u}_n) +$$

$$\frac{cA}{\lambda PR}\left(2\left(\frac{\Omega\mu}{c}\sin\theta - \frac{j}{R^2}\cos\theta\right)(\hat{u}_r \cdot \hat{u}_n) - \frac{j}{R^2}(\hat{u}_\theta \cdot \hat{u}_n)\sin\theta\right)$$

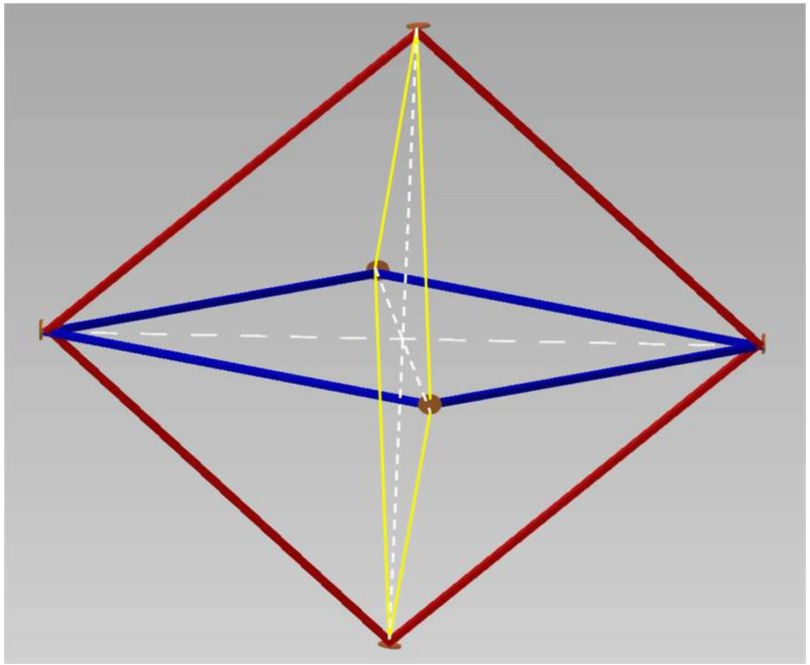
$$\frac{\Omega R}{c} \sim 10^{-6}$$

$$G\frac{M}{c^2 R} = \frac{\mu}{R} \sim 10^{-9}$$

$$G\frac{J}{c^3 R^2} = \frac{j}{R^2} \sim 10^{-15}$$

The recent performance of G, expressed in terms of measured equivalent angular velocity, is below **1prad/s (pico radian/second) at 1000-s integration time**
.
This sensitivity is above the requirement for the measurement of the GR effects, but various improvements in technologies, global design and signal cleaning should fill the remaining gap.

the first term is the classical Sagnac term, whereas the second one contains both the Lense–Thirring drag, depending on the angular momentum ***J*** (whose norm appears in the equation in its geometrized form ***j***), and the de Sitter or geodetic term expressing the interaction of the local Newtonian force with the angular velocity of the Earth.

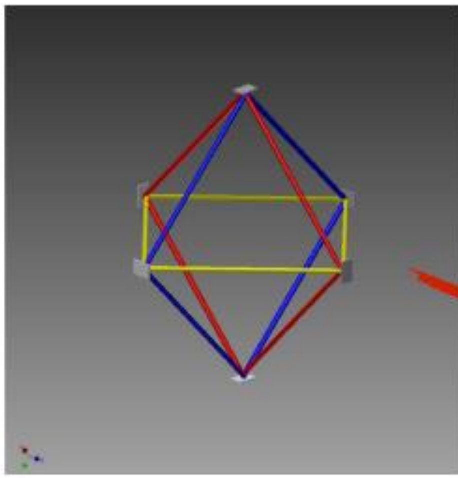


Octahedral configuration of GINGER. Six mirrors give rise to three mutually perpendicular square rings. The active control of the geometry may be achieved by laser cavities along the three diagonals connecting the mirrors.

The main difficulty of the Lense–Thirring measurement is that it corresponds to a constant signal and the calibration is quite demanding. This is the reason why we are investigating as deeply as possible the systematics of the laser, and different techniques to extract the signal: the result could be validated repeating the measurement with different techniques and operating the laser at a different working point. The Sagnac effect works as well for a passive cavity, i.e. the measurement could be repeated with the same apparatus, but using an external laser source to interrogate the array of cavities. The technique of the passive cavity Sagnac, however, is not as mature as the active one. In summary: any measurement of constant effects is in principle difficult, but a ring-laser system allows one to repeat the measurement with two different methods, which have different systematic

GINGER

- 3D- Sensor
- Larger Scale Factor
- Active Stabilization
- Deep Underground Installation

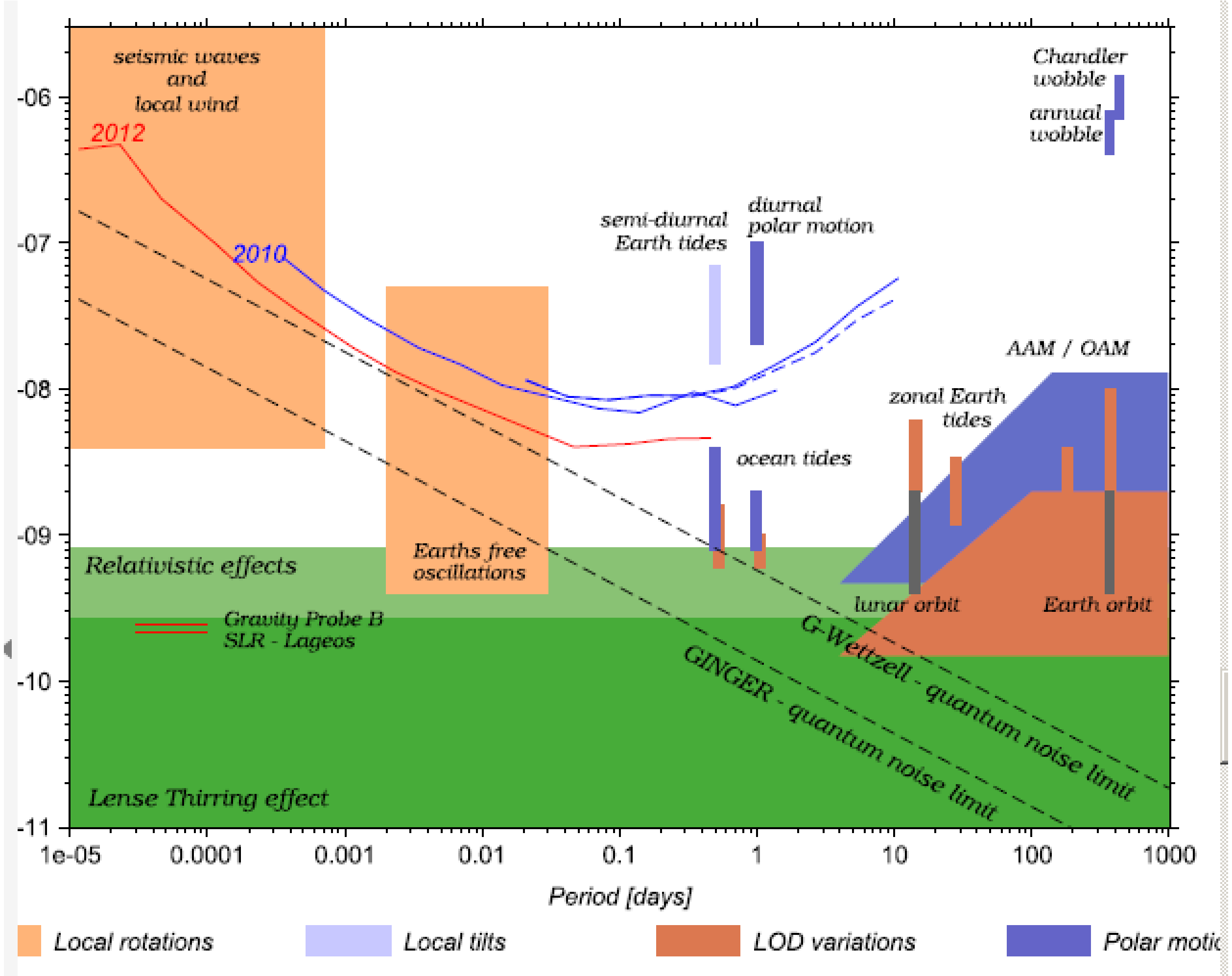


Shared Cavities with control of diagonals...

... however we are after a DC quantity!!!!

Relative Sagnac frequency ($\delta f/\Delta f_0$)

1E -05



The picture compares the Allan deviation of G in Wettzell (years 2012 and 2010, courtesy of K.U. Schreiber) with the most relevant geodetic signals. The green parts show the region of interest for the geodetic precession and the Lense–Thirring effect; on the left of the picture it is possible to see the present level of test obtained by Gravity Probe B and Lageos. The two dotted lines show the shot noise of the G (16-m perimeter), and of a ring with perimeter 24m.

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Ring-laser tests of fundamental physics

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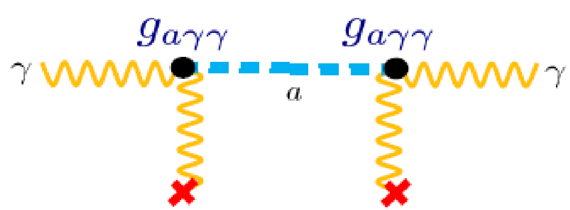
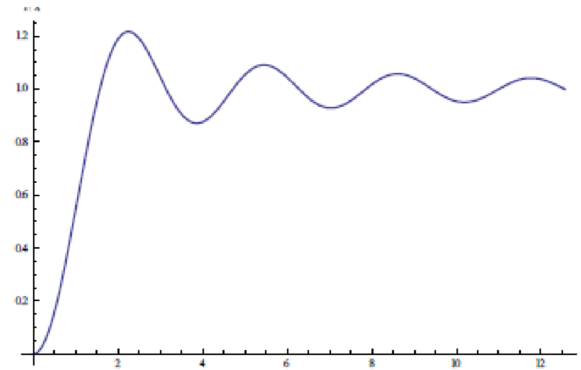
Received 29 January 1997

Abstract

HeNe ring-laser gyros are standard sensors in inertial guidance; mirror reflectances now reach **99.9999%.** Present research instruments have an area of **1 m^2**, a passive quality factor of **> 10^{11}**, and a **resolution of the frequency difference of counter-rotating optical beams approaching microhertz**. In the Sagnac effect this difference is proportional to the angular velocity. Present resolution is limited by thermal drifts in frequency pulling, itself reflecting mirror backscatter. The capability of ring lasers for measurements of **geodesic interest**, including seismometry, **nonreciprocal refractive indices, including axions and CP violation**, are discussed. In standard polarization geometries the observable is necessarily time-reversal odd. Scaling rules for dimensions, finesse etc summarizing past progress and suggesting future potential are given.

Modified Gyrolaser[*]

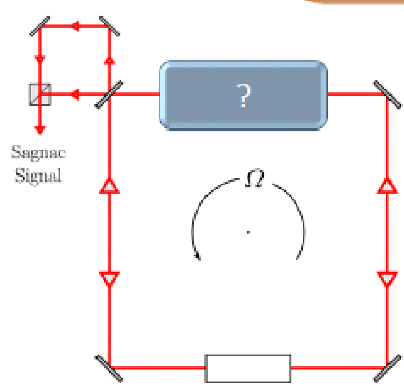




1. Refraction index correction
2. Attenuation

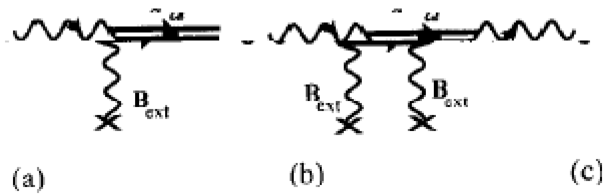
$$\Delta n = \frac{\alpha^2}{4\pi^2}\left(\frac{g_{a\gamma\gamma}}{f_a}\right)^2 \frac{B_{ext}^2}{2m_a^2} F\left(\frac{Lm_a^2}{2\omega}\right)$$

$$\delta = 2\left(\frac{\omega B_{ext} g_{a\gamma\gamma}}{m_a^2}\right)^2 \sin^2\left(\frac{m_a^2 \ell}{4\omega}\right)$$



- Only the $\vec{E}_\perp$ is affected
- Phase modulation
- Amplitude modulation

[*] L. Cooper, GE. Stedman/ Physics Letters B 357 (1995) 464-468



(a) Photons propagating in a transverse magnetic field producing axions through the Primakoff effect. (b) Virtual axion production leading to vacuum birefringence. (c) **QED** vacuum birefringence via y-y scattering.

Лагранжиан для системы аксионов и фотонов имеет вид

$$\mathcal{L} = -\frac{1}{4}F_{\alpha\beta}F^{\alpha\beta} + \frac{1}{2}\left(\partial_\alpha \partial^\alpha a - m_a^2 a^2\right) - \frac{1}{4} g a F_{\alpha\beta}\tilde{F}^{\alpha\beta}. \quad (1)$$

Член, отвечающий за аксион-фотонное взаимодействие может быть выражен через векторы напряженностей электрического и магнитного поля:

$$\mathcal{L}_{\text{int}} = g a \boldsymbol{E}\boldsymbol{H}. \quad (2)$$

Константа связи $g = g_\gamma \alpha / \pi f_a$ обратно пропорциональна константе распада аксиона f_a. Здесь α — постоянная тонкой структуры, а g_γ — модельно зависимая величина порядка 1. Кроме того, механизм Печчеи–Куин подразумевает, что константа распада и масса аксиона связаны соотношением $m_a f_a \approx \frac{1}{2} m_\pi f_\pi \approx 6 \cdot 10^{15}$ eV^2.

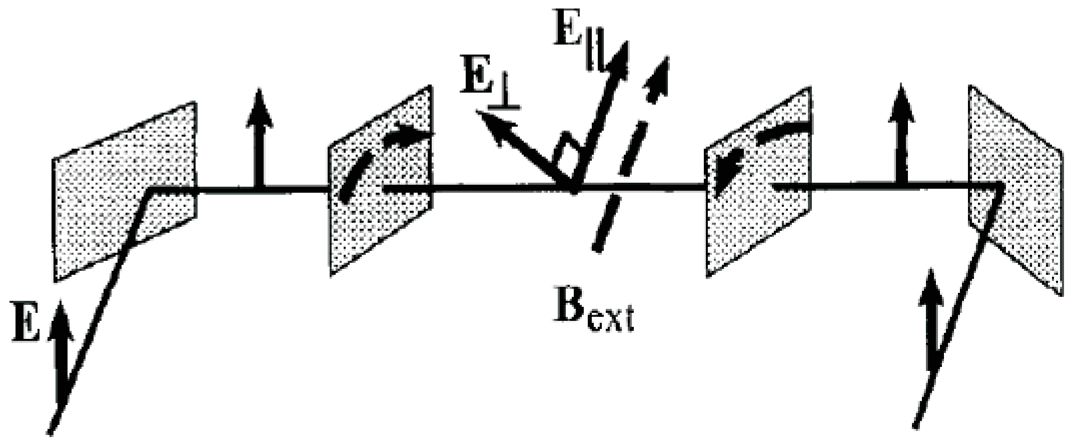


Рис. 1: Схема эксперимента по вакуумному двулучепреломлению. Рисунок

разность фаз. В работе [1] вычислена аксионно-индуцированная разность фаз и отношение амплитуд фотонов, поляризованных параллельно и перпендикулярно магнитному полю:

$$\Delta\phi = \left(\frac{g\omega B_{\text{ext}}}{m_a^2}\right)^2 \left(\frac{m_a^2 l}{2\omega} - \sin\frac{m_a^2 l}{2\omega}\right), \tag{3}$$

$$\frac{E_{||}}{E_{\perp}} = 2\left(\frac{g\omega B_{\text{ext}}}{m_a^2}\right)^2 \sin^2\left(\frac{m_a^2 l}{4\omega}\right), \tag{4}$$

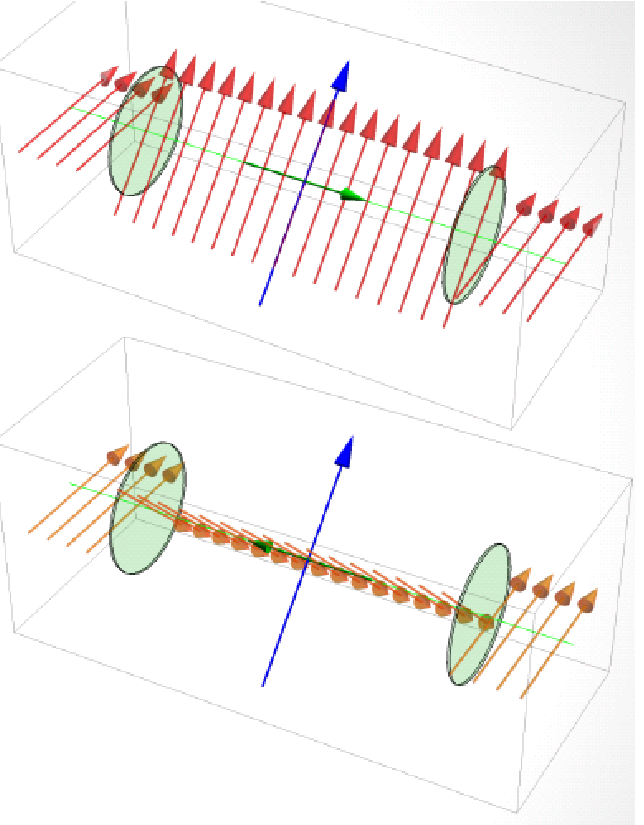
где l — длина пути, который проходит луч в магнитном поле. В работе [1] выполнены оценки сдвига фаз для луча, претерпевающего многократные отражения, так что область с магнитным полем длиной 4 метра проходится 500 раз. Магнитное поле $B_{\text{ext}} \sim 10$ Тл $= 10^5$ Гс, энергия фотона $\omega \sim 2.4$ эВ. Наиболее оптимистическая оценка $\Delta\phi \sim 10^{-12}$.

Modified Gyrolaser

- Simplest scheme (sensitivity below QN)
- Losses introduced by Faraday rotators

$$\frac{\Delta f}{f} = \frac{\ell}{L}\Delta n$$

- Improvements:
  - Better rotators
  - Multipass geometry
  - Modulation spectroscopy
  - Magnetic field modulation



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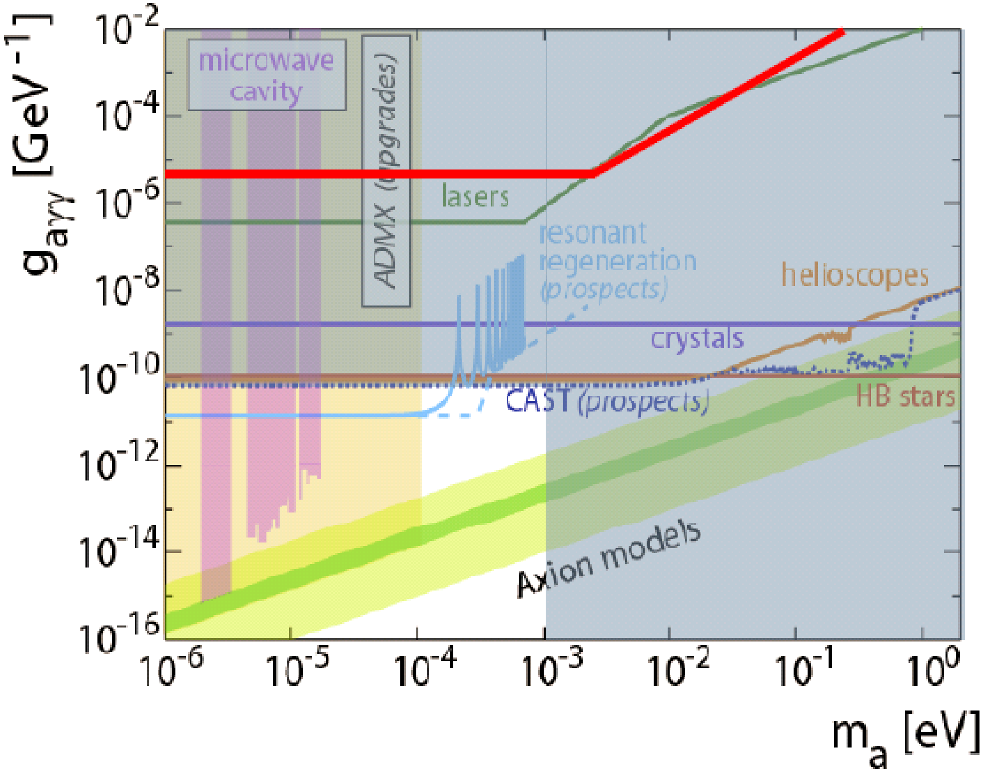
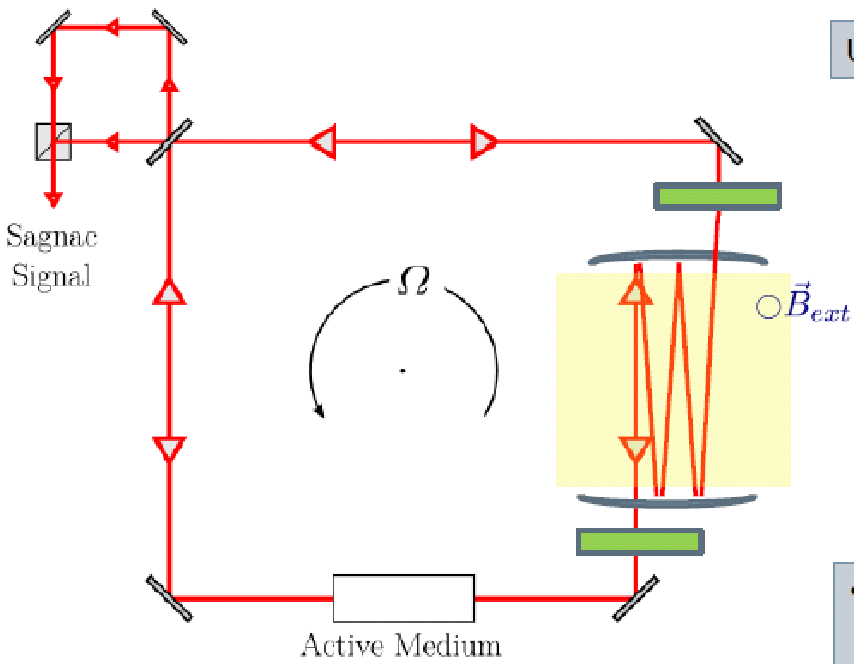
Modified Gyrolaser



Multipass Gyrolaser



Use a delay line

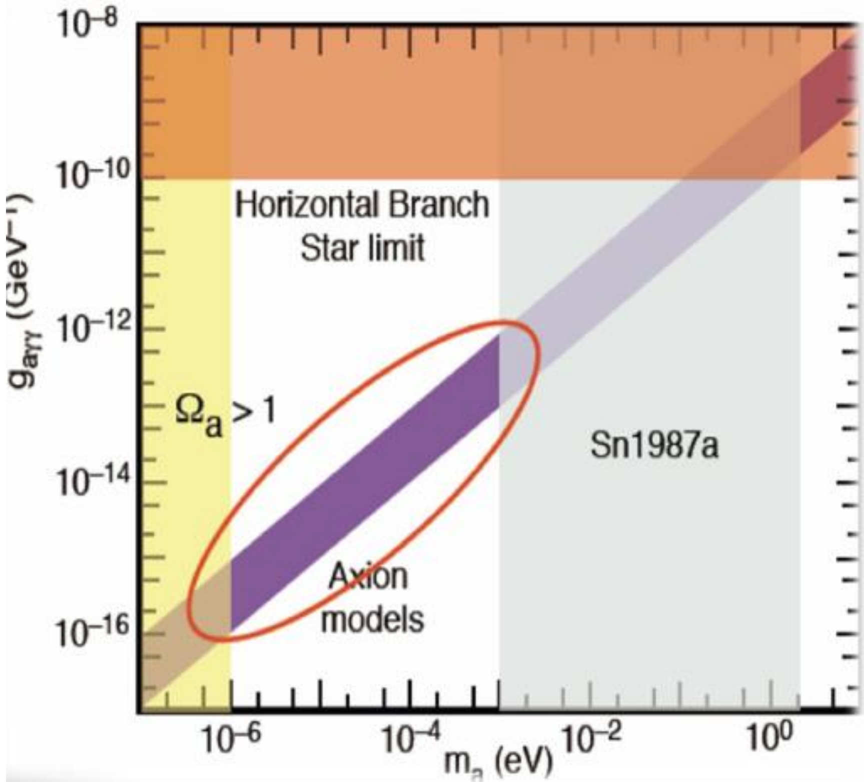
$$\frac{\Delta f}{f} = \frac{\ell}{L}\Delta n$$

- Not a big improvement
- Losses are not reduced

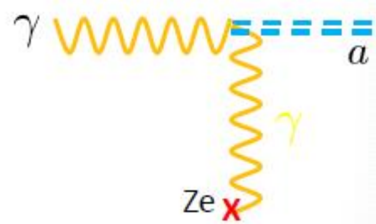
Astrophysical bounds

- SN1987A

Efficient axion production ⇒ too short ν burst if $m_a > 10^{-3}$ eV



- Study of overall energy loss rate

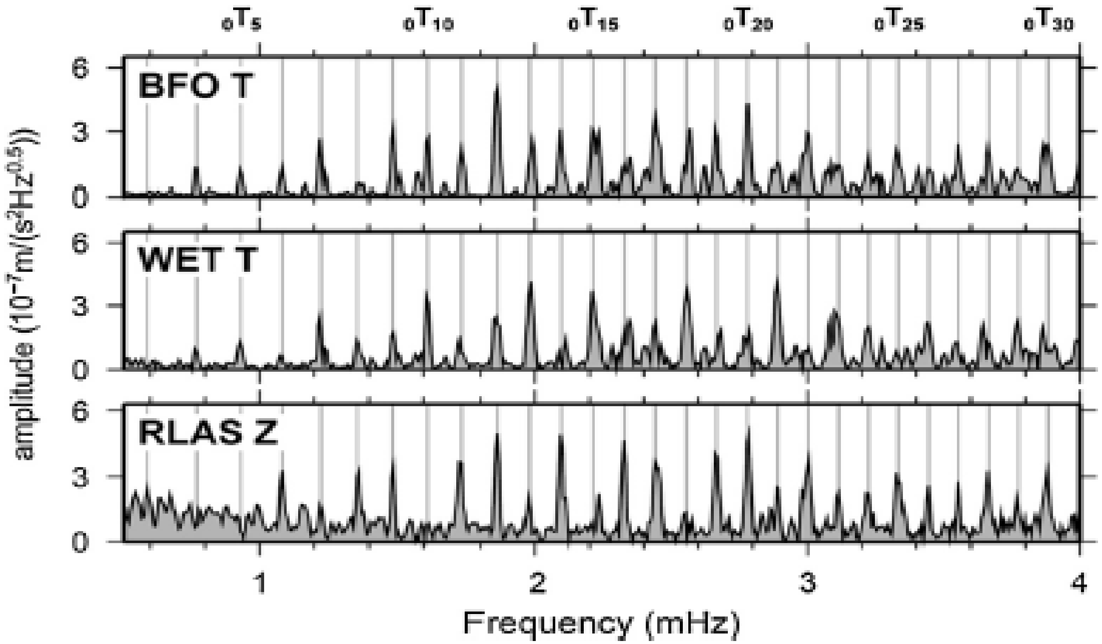


$$L_a \propto g_{a\gamma\gamma}^2 L_\gamma$$

$$L_a < 10^{-1} L_\gamma$$

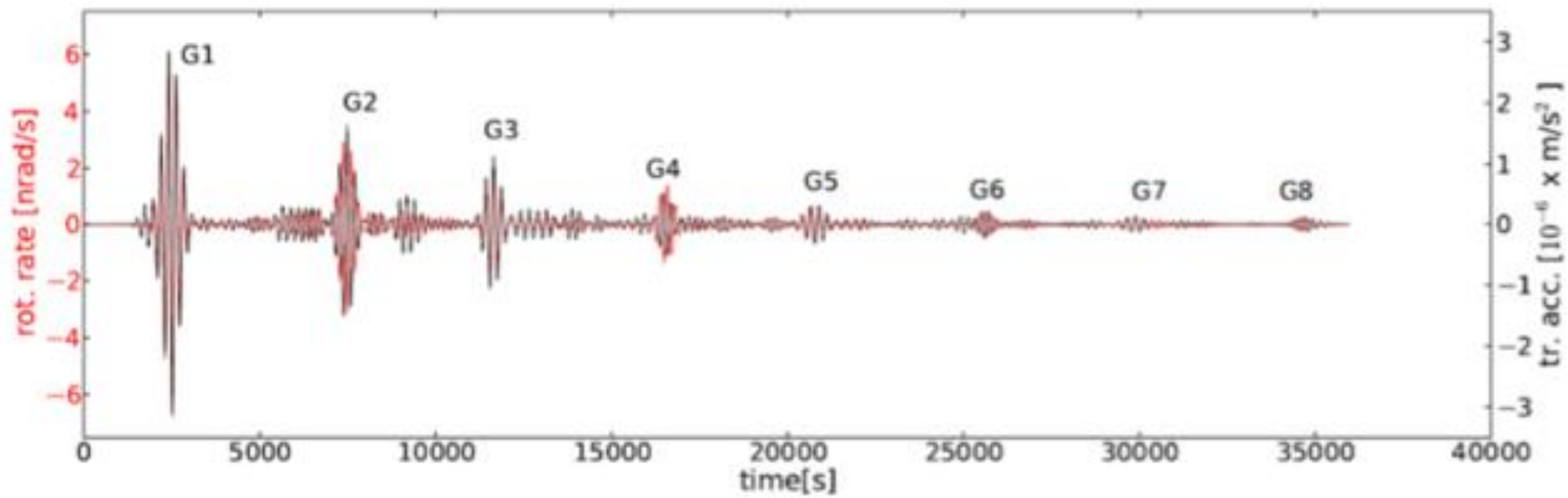
$$g_{a\gamma\gamma} < 7 \times 10^{-10}\ \mathrm{GeV}$$

Seismology Global Survey



Amplitude spectra of ground motion observations following the M8.8 Maule earthquake in Chile 27 February 2010. The spectra are based on 36 hr seismograms. The vertical gray lines are theoretical predictions of toroidal ***nTm*** free oscillations based upon a spherically symmetric Earth model. The spectral lines indicate the excitation of individual modes (overtones of the fundamental modes). Top: For comparison the transverse component of ground motion at the Black Forest Observatory, Germany (BFO). Middle: Transverse component of ground motion at Wettzell, collocated with the ring laser. Bottom: Vertical component of rotational motions (ring laser observations).

Love Surface Waves cycling around the Earth 4 times (first observation!)



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)

Resume

Большой кольцевой лазерный интерферометр как детектор слабых грави-инерциальных возмущений

«Гироскоп Саньяка»

Прецизионный инструмент для исследования и мониторинга слабых инерциальных и гравитационных эффектов…

в том числе для исследования природы темной материи

прагматическая цель:- **инициировать новый фундаментальный долгосрочный проект по экспериментальной гравитации с применением передовых лазерных оптических технологий,** имеющий **междисциплинарный характер и международную значимость**

Thanks for attention !