Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

# Fundamental physics with the space missions LARES and LARES 2

**Ignazio Ciufolini and the LARES team**

LARES

Ignazio Ciufolini
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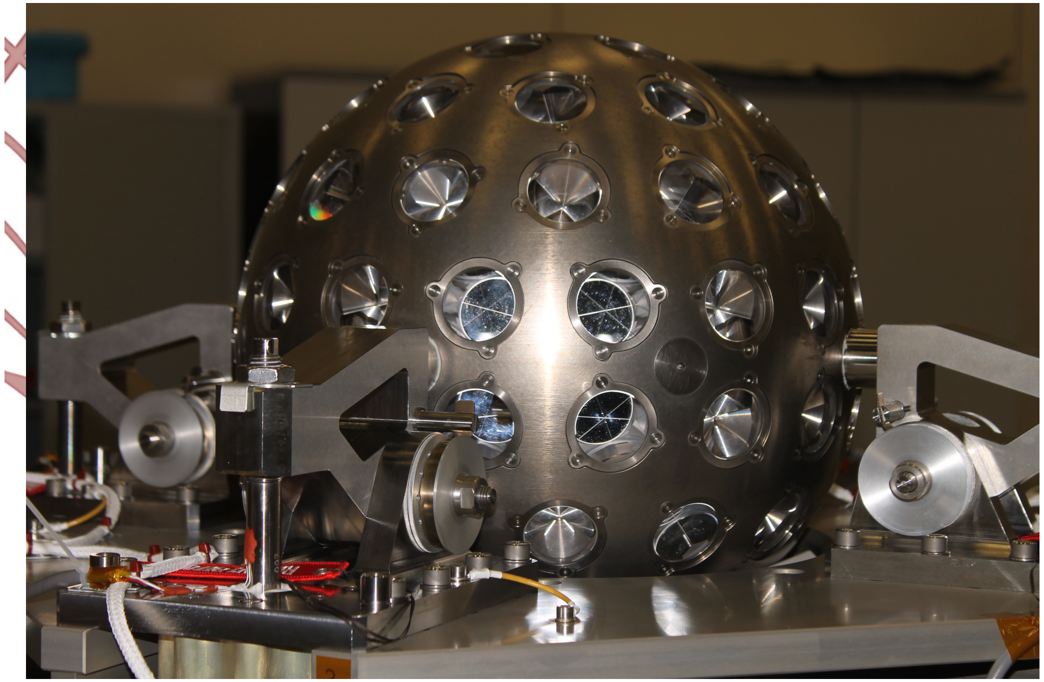

A. Paolozzi*,
E. Pavlis*,
R. Koenig*,
J. Ries*,
R. Matzner*,
V. Gurzadyan*,
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## CONTENT OF THIS TALK

- A brief introduction to frame-dragging and General Relativity and some history of tests of frame-dragging
- The LARES satellite and its present and future results
- The LARES 2 satellite and its objectives

# DRAGGING OF INERTIAL FRAMES
## (*FRAME-DRAGGING* as Einstein named it in 1913)

- **Spacetime curvature is generated by mass-energy currents: $\varepsilon\, u^{\alpha}$**

$$G^{\alpha\beta} = \chi\, T^{\alpha\beta} =$$

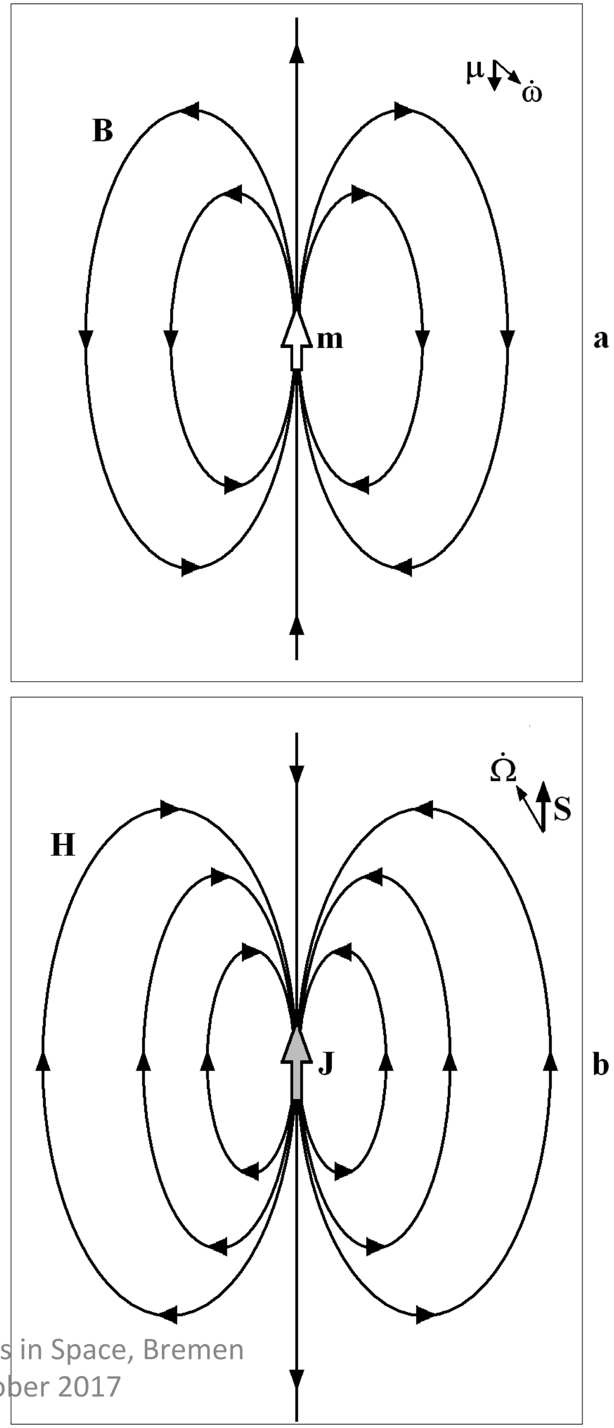
$$= \chi\, [(\varepsilon + p)\, u^{\alpha} u^{\beta} + p\, g^{\alpha\beta}]$$

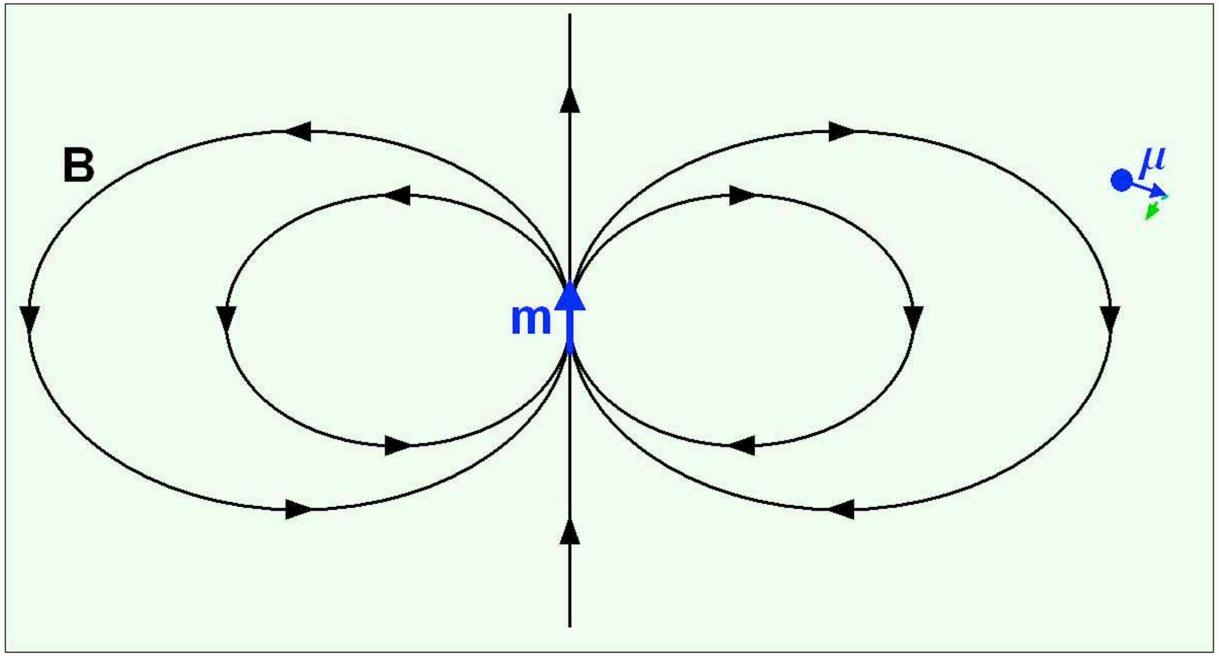
- **It plays a key role in high energy astrophysics (Kerr metric)**

**Thirring 1918**
Braginsky, Caves and Thorne 1977
Thorne 1986
I.C. 1994-2001

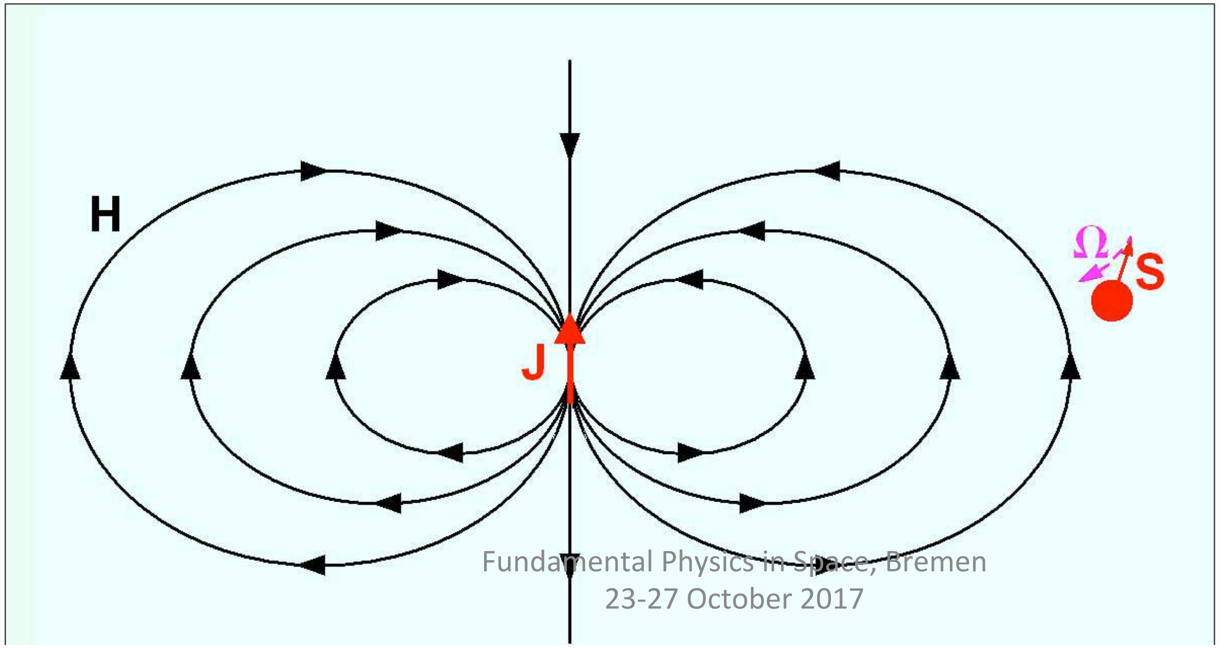
**There is a interesting analogy of weak-field and slow-motion General Relativity with electromagnetism**

Magnetic field **B**, gravitomagnetic field **H** and the precession of a magnetic dipole $\mu$ and of a gyroscope **S**

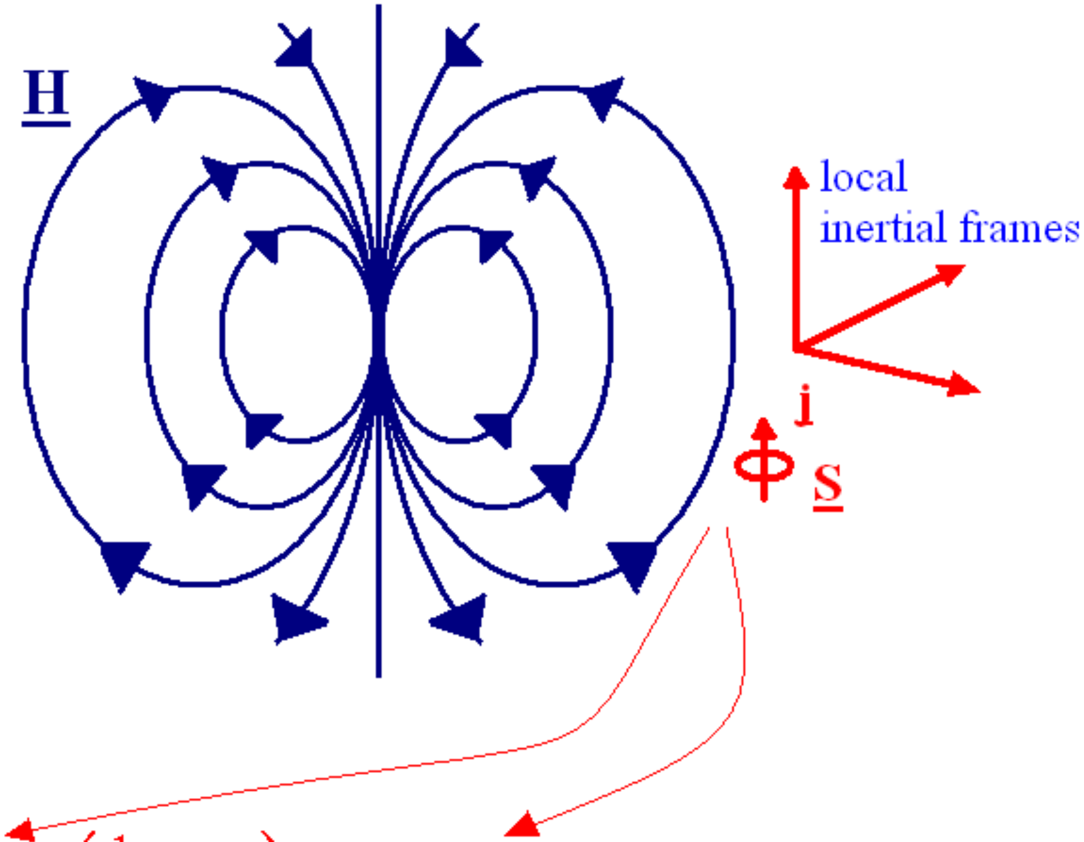





a




b




$$\mathbf{F} = \left(\frac{1}{2}\mathbf{S}\cdot\nabla\right)\mathbf{H} \qquad \tau \cong \tfrac{1}{2}\mathbf{S}\times\mathbf{H} = \frac{d\mathbf{S}}{dt} \equiv \dot{\mathbf{\Omega}}\times\mathbf{S}$$

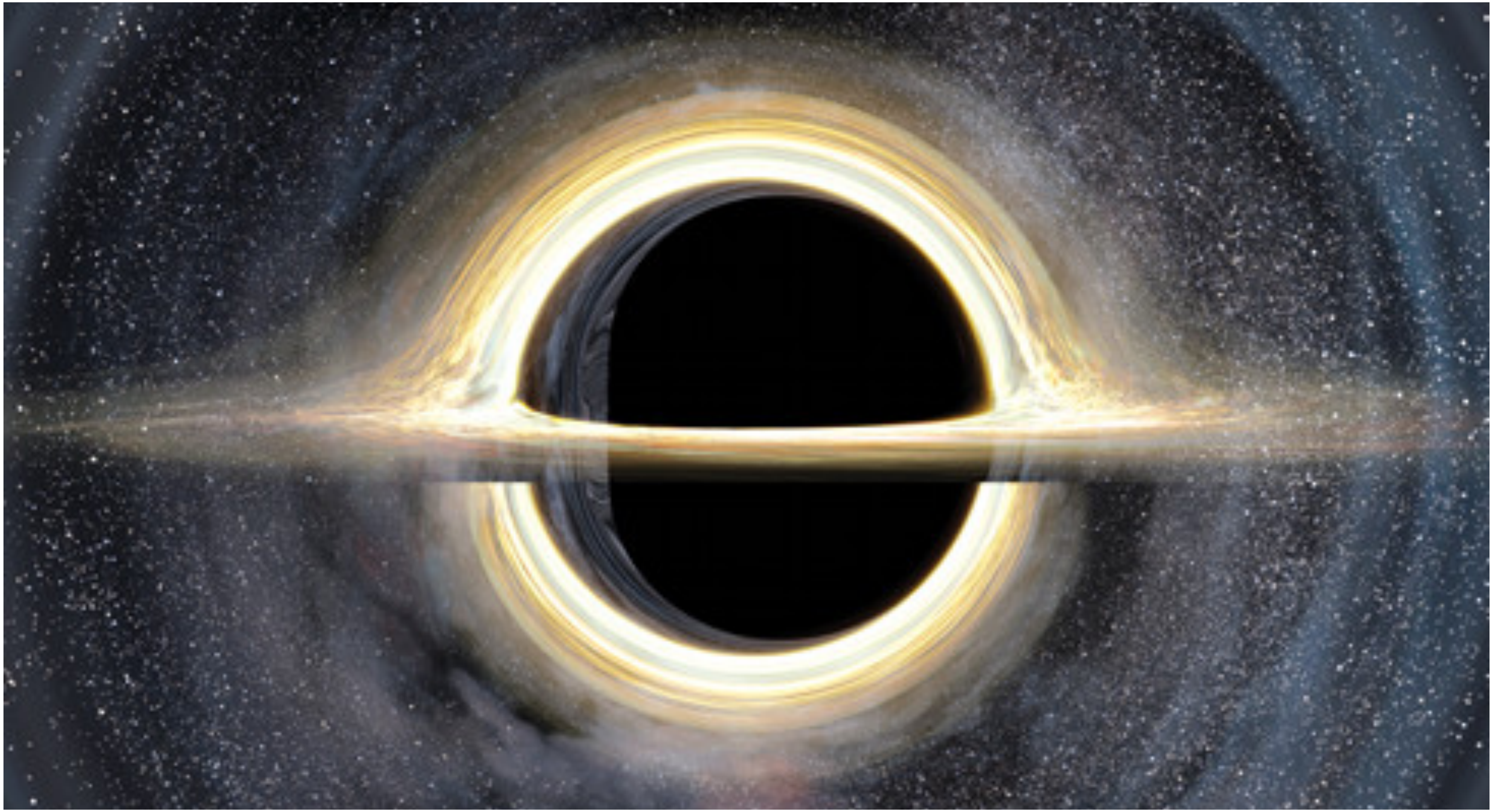
$$\dot{\mathbf{\Omega}} = -\tfrac{1}{2}\mathbf{H} = \frac{-\mathbf{J} + 3(\mathbf{J}\cdot\hat{\mathbf{x}})\hat{\mathbf{x}}}{|\mathbf{x}|^3}$$

*Dragging of inertial frames:*

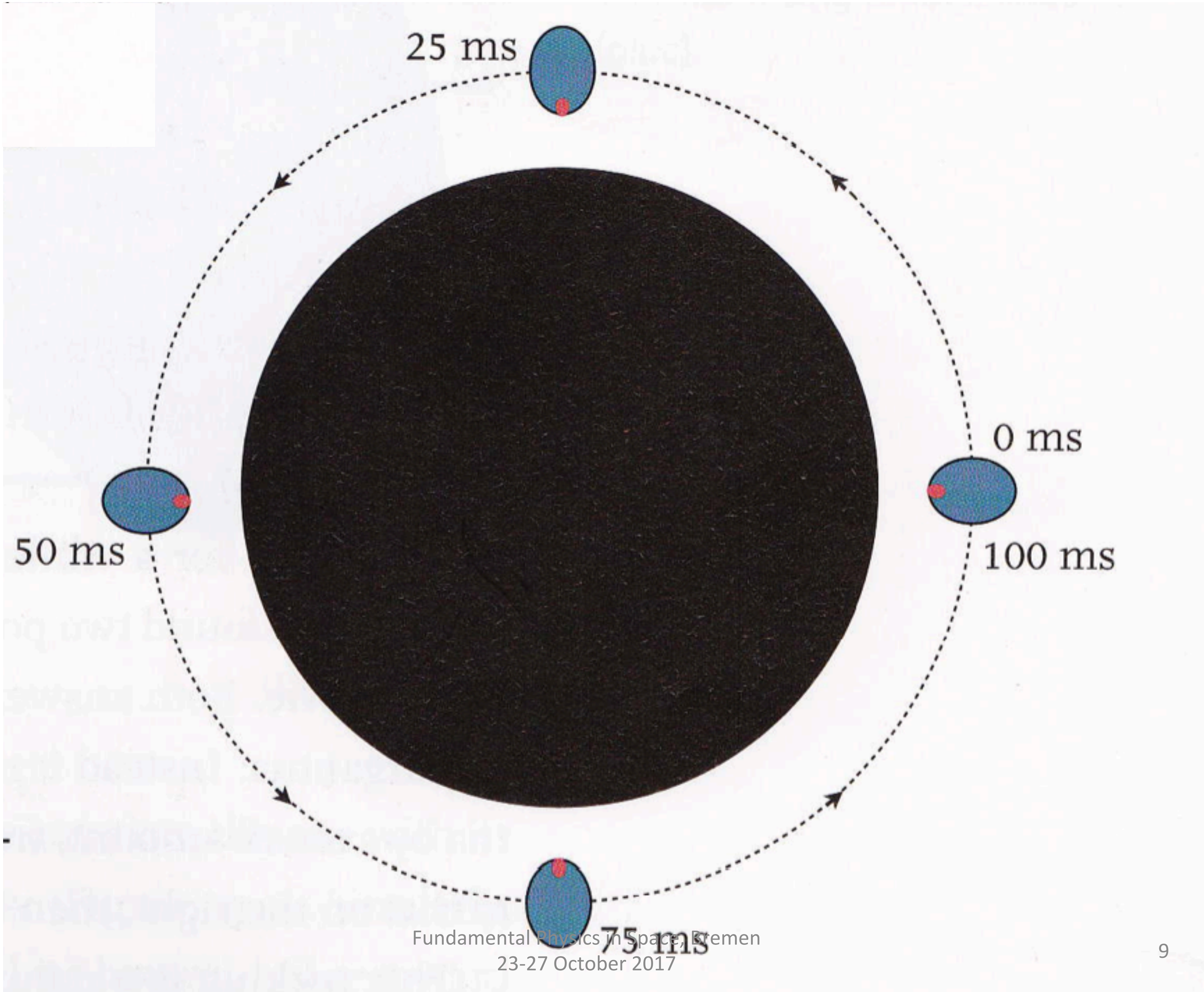
**Mach principle in general relativity**

**GRAVITATION AND INERTIA**

**I.C. and J.A. Wheleer -1995**



*GARGANTUA: a supermassive rotating black hole: frame-dragging plays a key role*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100 ms
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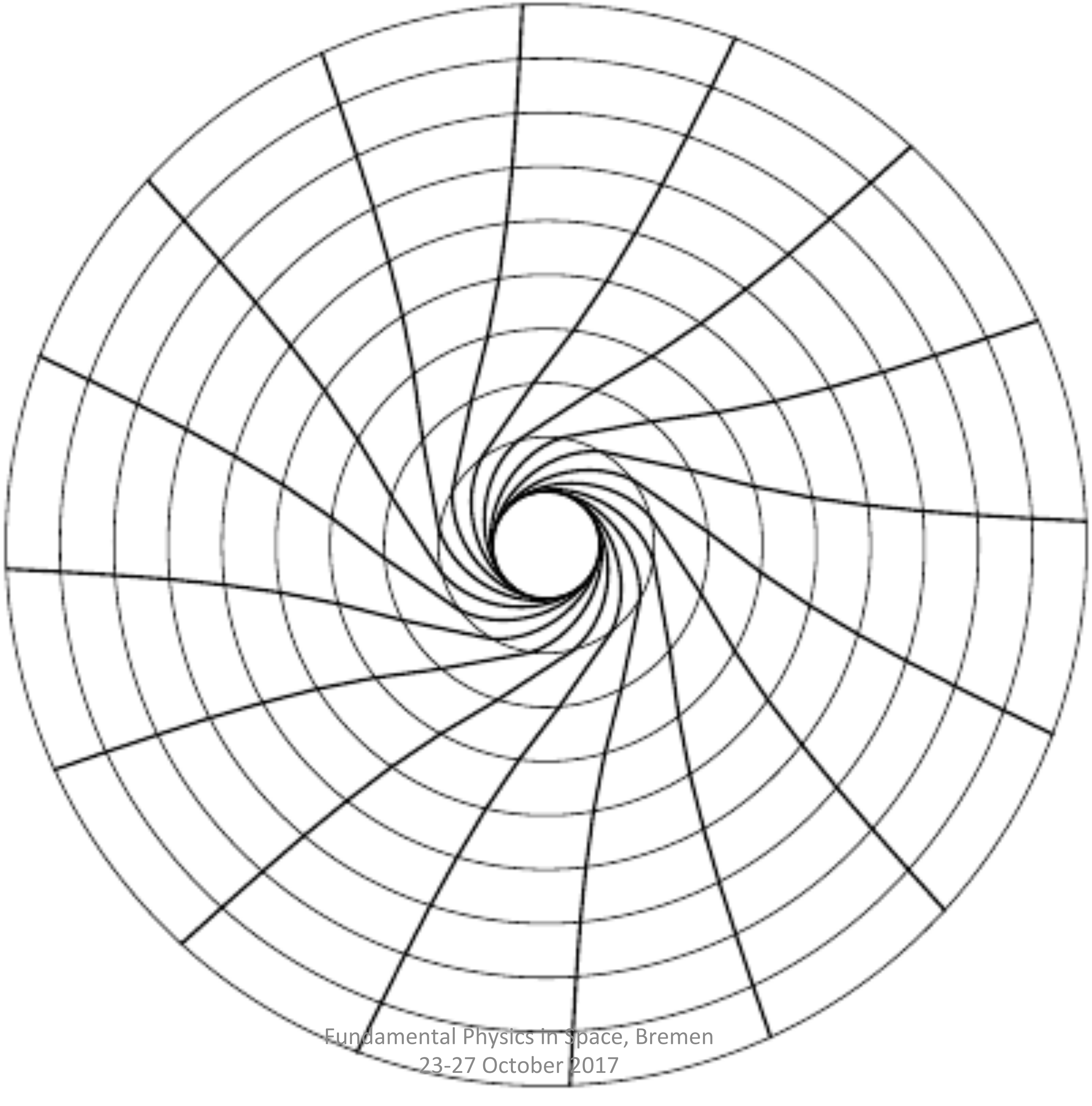
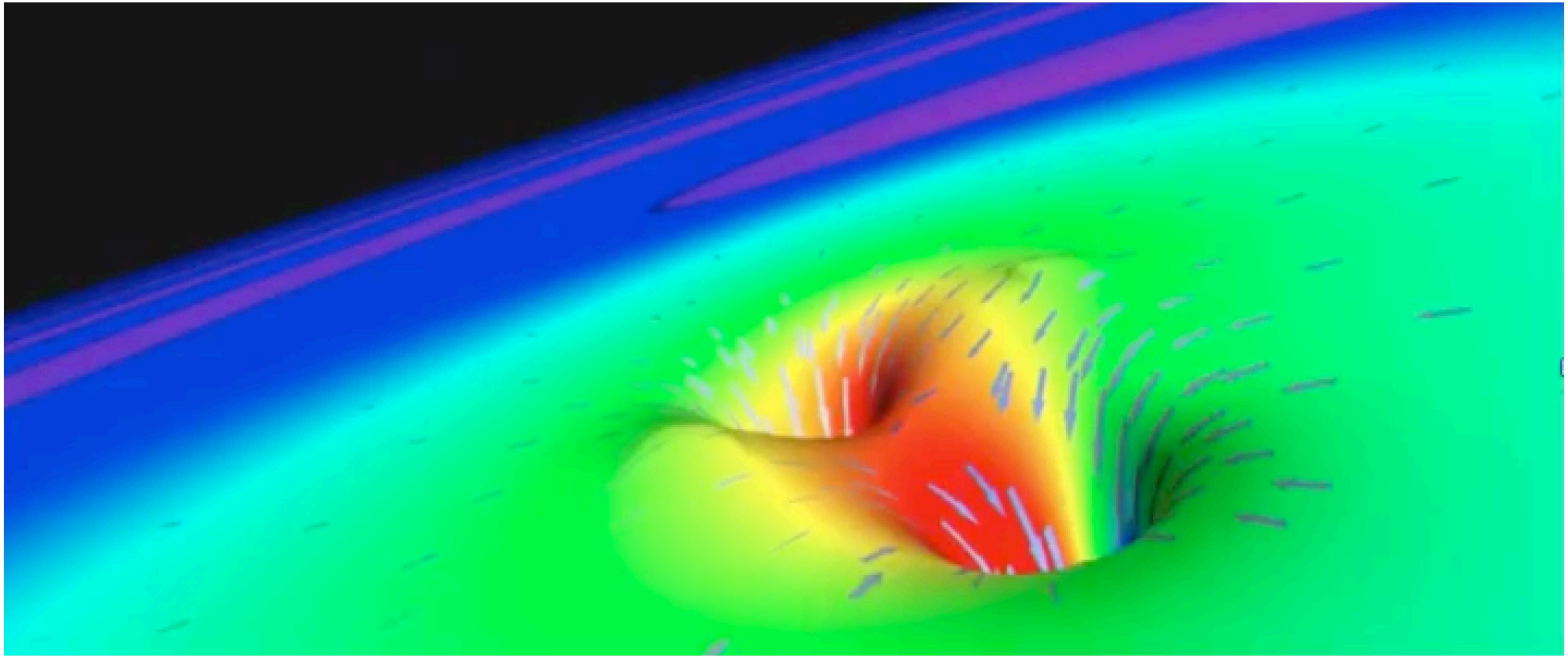
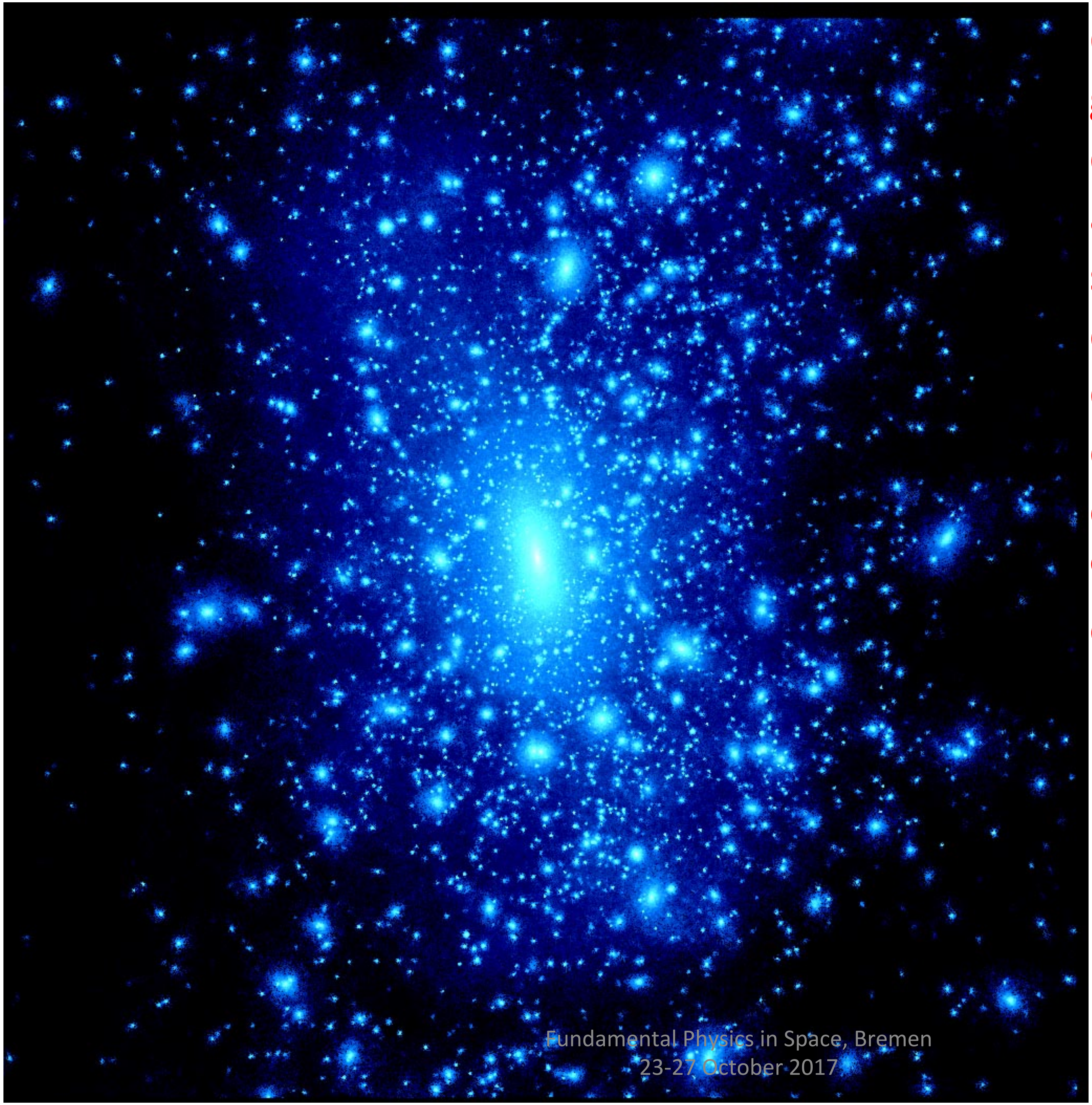
75 ms



**Frame-dragging and Kerr metric can play a key role in the computer analysis of the detection of gravitational waves by LIGO due to the coalescence of two spinning black holes to form a Kerr spinning black hole**



**Computer simulation of the collision of two black holes detected by LIGO in 2015 by their emission of gravitational waves, the silver arrows represent frame-dragging.**
**Kip Thorne NSF 2016 presentation**



**One of the greatest "recent" discoveries: accelerating supernovae: dark energy or quintessence + dark matter may constitute about 95 % of the universe**

# Chern-Simons Gravity

The modified action of Chern–Simons theory is then:

$$S_{CS} = \int d^4x\sqrt{-g}\left[\frac{1}{16\pi}R - \frac{l}{12}\theta^*\mathbf{R}\cdot\mathbf{R} - \frac{1}{2}(\partial\theta)^2 - V(\theta) + L_{mat}\right]$$

**$^*\mathbf{R}\cdot\mathbf{R} = \frac{1}{2}\,\varepsilon_{\alpha\beta\sigma\rho}\,\mathbf{R}^{\sigma\rho}{}_{\mu\nu}\,\mathbf{R}^{\alpha\beta\mu\nu}$** is the Pontryagin pseudoscalar, $\theta$ is a Scalar field, *g* the determinant of the metric, *R* the Ricci scalar, *l* is a new length parameter, $L_{mat}$ the matter Lagrangian density.

The dynamical equation for the scalar field $\theta$ is:

$$\Box\theta = \frac{dV}{d\theta} + \frac{1}{12}l^*\mathbf{R}\cdot\mathbf{R}\,.$$

# The Chern-Simons field equation is then

$$G_{\alpha\beta} - \frac{16\pi}{3} l C_{\alpha\beta} = 8\pi T_{\alpha\beta} ,$$

Where $C_{\alpha\beta}$ is the Cotton-York tensor:

$$C^{\alpha\beta} = \frac{1}{2}\left[(\partial_\sigma\theta)\left(\epsilon^{\sigma\alpha\mu\nu}\nabla_\mu R^\beta_\nu + \epsilon^{\sigma\beta\mu\nu}\nabla_\mu R^\alpha_\nu\right) + \nabla_\rho(\partial_\sigma\theta)\left({}^*R^{\rho\alpha\sigma\beta} + {}^*R^{\rho\beta\sigma\alpha}\right)\right]$$

In the weak field and slow motion approximation we then get:

$$\Delta h_{0i} + \frac{1}{m_{cs}} \Box H_i \cong 16\pi\rho v^i$$

where:

$$\mathbf{H} = \nabla \times \mathbf{h}$$

For a homogeneous sphere with mass density $\rho$, of radius R, rotating with angular velocity $\omega$, outside the sphere we have:

$$\mathbf{H} = \mathbf{H}_{GR} + \mathbf{H}_{CS}$$

Where the General Relativity contribution is:

$$\mathbf{H_{GR}} = \frac{-16\pi G\rho R^5}{15r^3}[2\omega + 3\hat{\mathbf{r}} \times (\hat{\mathbf{r}} \times \omega)]$$

And the Chern-Simons contribution is:

$$\mathbf{H_{CS}} = -16\pi G\rho R^2\{D_1(r)\omega + D_2(r)\hat{\mathbf{r}} \times \omega$$
$$+ D_3(r)\hat{\mathbf{r}} \times (\hat{\mathbf{r}} \times \omega)\}$$

where:

$$D_1(r) = \frac{2R}{r} j_2(m_{cs}R)y_1(m_{cs}r) \,,$$
$$D_2(r) = m_{cs}Rj_2(m_{cs}R)y_1(m_{cs}r) \,,$$
$$D_3(r) = m_{cs}Rj_2(m_{cs}R)y_2(m_{cs}r) \,,$$

Finally by integrating the Lorentz force equation for a test particle:

$$m\frac{d^2\mathbf{x}}{dt^2} \cong m\left(\mathbf{G} + \frac{d\mathbf{x}}{dt} \times \mathbf{H}\right)$$

We find the ratio of the nodal drag of Chern-Simons gravity and General Relativity:

$$\frac{\dot{\Omega}_{\rm CS}}{\dot{\Omega}_{\rm GR}} = 15\frac{a^2}{R^2} j_2(m_{\rm CS}R) y_1(m_{\rm CS}a),$$

Where $j_2$ and $y_l$ are spherical Bessel functions and $m_{cs}$ is the Chern-Simons mass:

$$m_{\rm cs} \equiv -3/(\ell\kappa^2\dot{\theta}).$$

where $k^2 = 8\,\pi$

$\dot{\theta}$ may be related to quintessence

- **Chern-Simons gravity is equivalent to a type of String Theory (**Smith, Erickcek, Caldwell and Kamionkowski Phys. Rev. D 2008). In Smith et al. is shown that the 4-D string action for a type of string theory may reduce to the Chern-Simons gravity action. See also: Yagi K., Yunes N. and Tanaka T., Phys. Rev. D., 86 (2012) 044037 and references therein.
- **Then, on the basis of our 2004-2010 measurements of frame-dragging, using the LAGEOS satellites, in 2008, Smith, Erickcek, Caldwell and Kamionkowski (Phys. Rev. D 77, 024015, 2008) have placed limits on some possible low-energy consequences of string theory that may be related to dark energy and quintessence.**
- **See also: Radicella, Lambiase, Parisi, and Vilasi, Constraints on Covariant Horava-Lifshitz gravity from frame-dragging experiment, JCAP (2014)**


- S. Alexander and N. Yunes "Chern-Simon Modified General Relativity", Physics Reports, Volume 480, 2009, p. 1-55.
- T. Clifton, P.Ferreira, A. Padilla and C. Skordis, "Modified Gravity and Cosmology".
- K. Yagi, N. Yunes and T. Tanaka, Phys. Rev. D., 86 (2012) 044037.

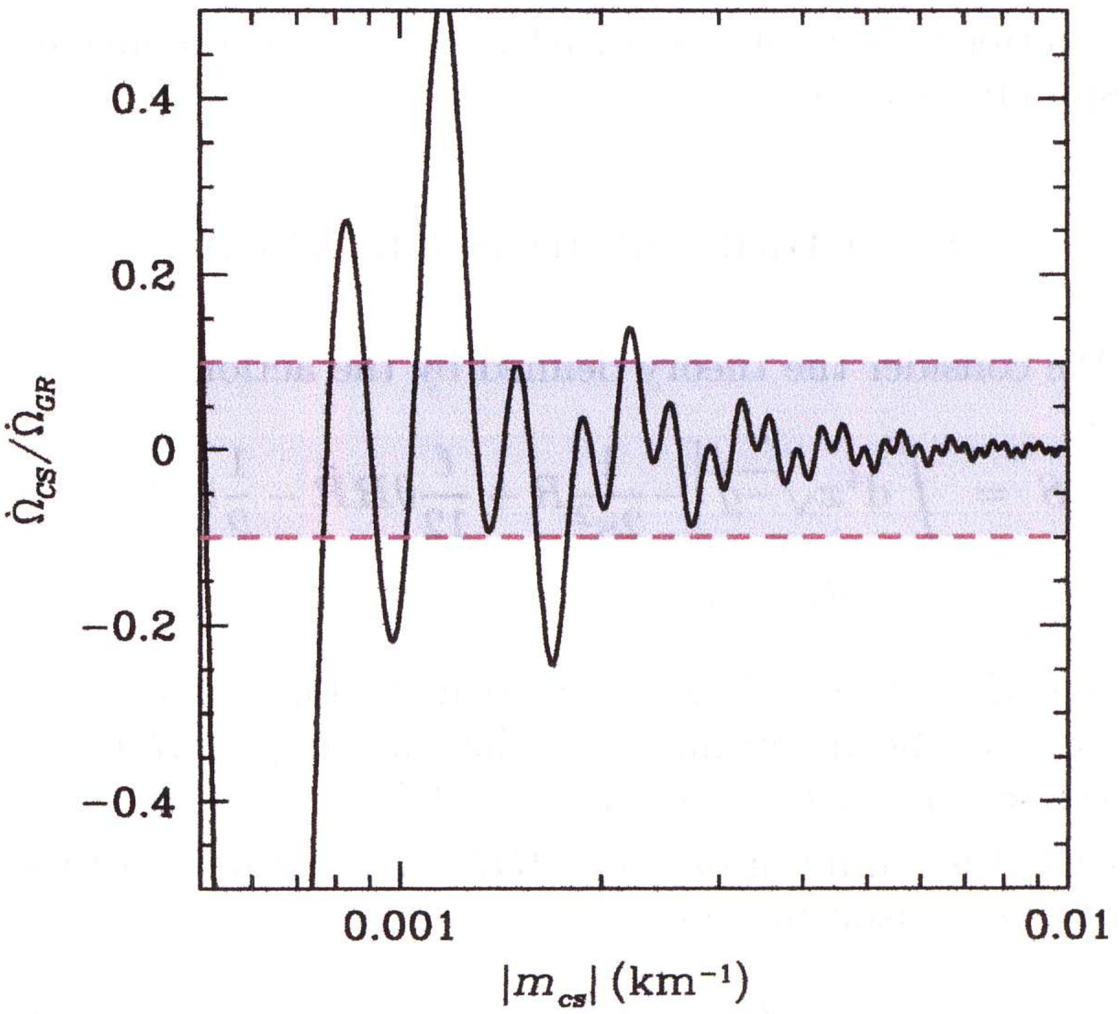



FIG. 1: The ratio $\dot{\Omega}_{\rm CS}/\dot{\Omega}_{\rm GR}$ for the LAGEOS satellites orbiting with a semimajor axis of $a \approx 12,000$ km. A 10% verification of general relativity [16] (the shaded region) leads to a lower limit on the Chern-Simons mass of $|m_{\rm cs}| \gtrsim 0.001$ km$^{-1}$. A 1% verification of the Lense-Thirring drag will improve this bound on $m_{\rm cs}$ by a factor of roughly five.

**$m_{cs} \geq 2 \times 10^{-22}$ GeV**

## A brief history of the main tests of frame-dragging

**GRAVITY PROBE B**: since 1960 the GRAVITY PROBE B space mission was under development in USA with the goal of a 0.1% test of frame-dragging. Gravity Probe B was finally launched in 2004 after almost half a century.

LAGEOS (LAser GEOdynamics Satellite) was launched in 1976 by NASA for space geodetic measurements.

Two active counter-orbiting, drag-free satellites in polar orbit with satellite-to-satellite Doppler ranging in 1976.

**LAGEOS 3**: In 1984-1989 a new laser-ranged satellite called "LAGEOS 3", identical to the LAGEOS satellite (launched in 1976 by NASA) was proposed with orbital parameters identical to those of LAGEOS but a *supplementary inclination*, that is with *inclination I = 70.16 °* and *semimajor axis = 12270 km*. A number of ASI and NASA studies confirmed its feasibility to measure frame-dragging (I.C. 1984/1986/1989, B.Tapley, I.C et al. NASA/ASI study 1989/1990, J. Ries 1989 …). Support letters for LAGEOS 3 were written to NASA and ASI (Italian Space Agency) by: JOHN ARCHIBALD WHEELER, KIP THORNE, TULLIO REGGE, NICOLA CABIBBO, ..

**LAGEOS 2**: The LAGEOS 2 satellite in 1992 by ASI and NASA for space geodetic measurements.

**LAGEOS and LAGEOS 2, 1997/1998**: it was obtained the first rough observation of frame-dragging using the data of LAGEOS and LAGEOS 2 (*CQG 1997, Science 1998*).

**GRACE, 2002:** it was launched the DLR (GFZ) and NASA (CSR) space mission to accurately measure the Earth's gravity field.

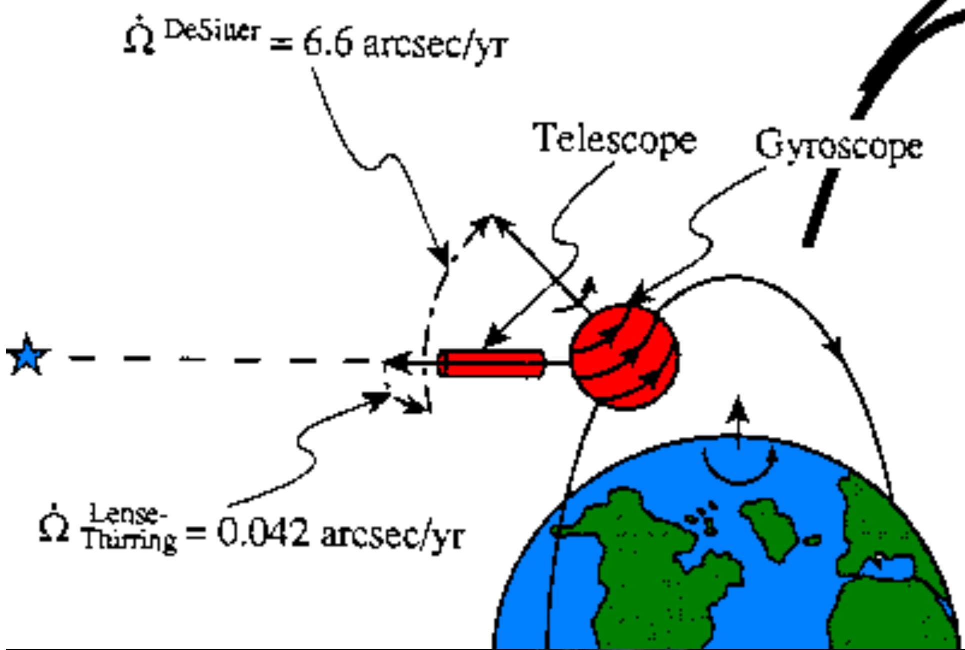
**LAGEOS and LAGEOS 2: 2004-2010**: it was published the first measurement (with accuracy of approximately 10%) of frame-dragging (*Nature 2004, General Relativity book 2010, etc.*) using GEODYN. Independently confirmed by the Univ. of Texas at Austin (2008/2009, with UTOPIA) and GFZ-DLR (2010, with EPOSOC).

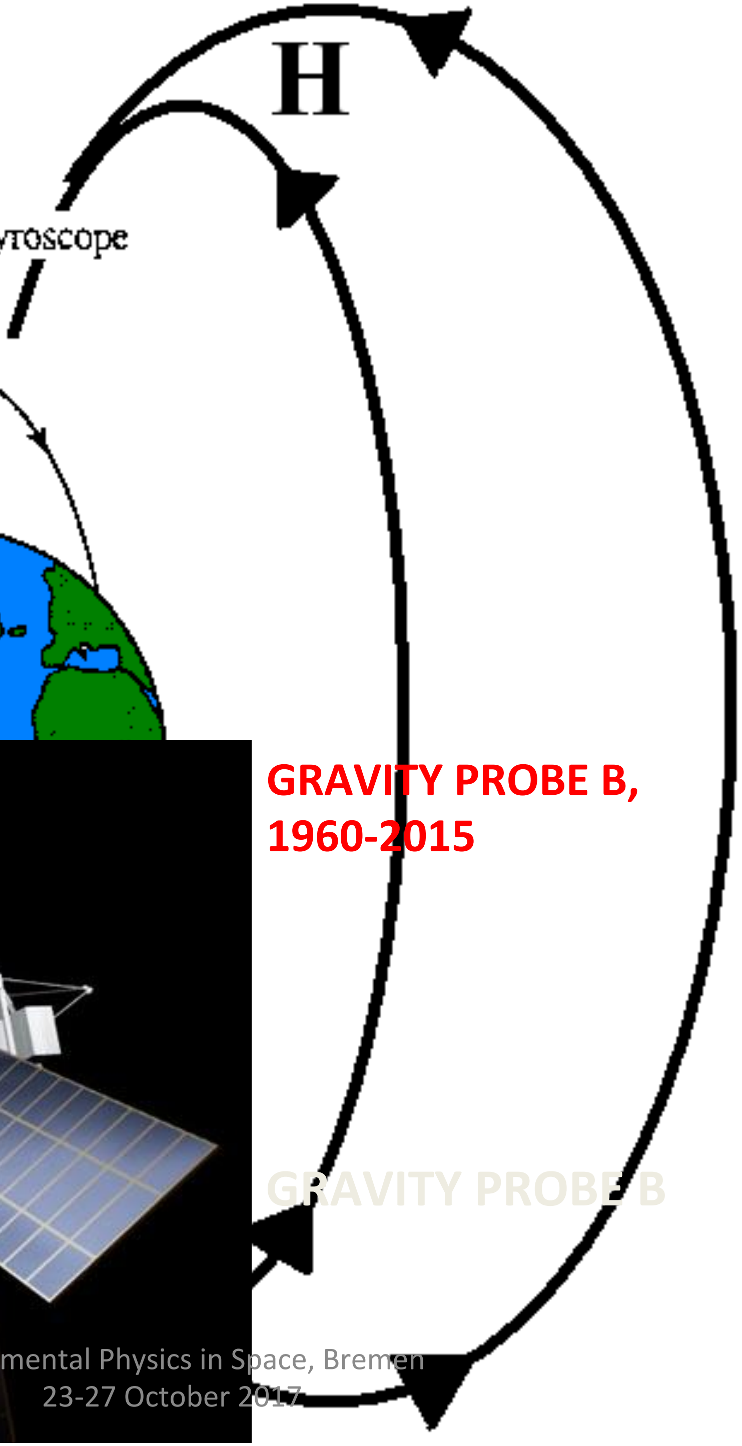
**Gravity Probe result, 2011-2015:** it was published a measurement of frame-dragging with approximately 19% accuracy (*Phys. Rev. Lett. 2011 and CQG 2015*).

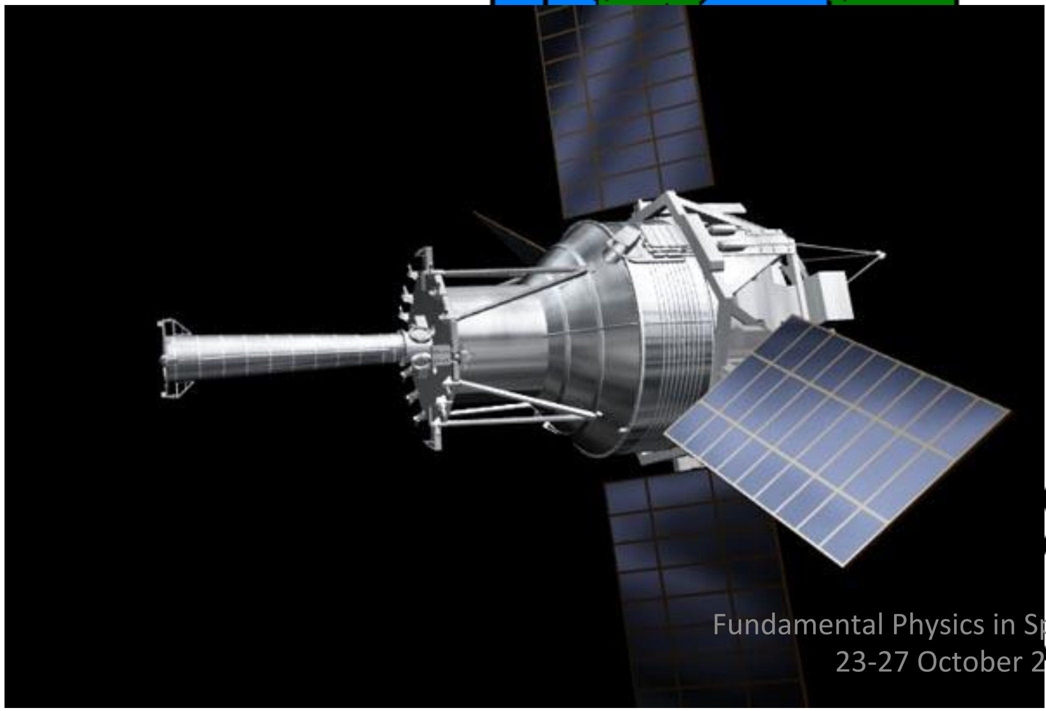
**LARES first results, with LAGEOS and LAGEOS 2, 2016:** it was published a measurement of frame-dragging with approximately 5% accuracy (*Eur. Phys. J. C, 2016*).

**LARES forthcoming results, with LAGEOS and LAGEOS 2:** should reach about 2% accuracy

**LARES 2, to be launched in 2019, should reach 0.2% accuracy**

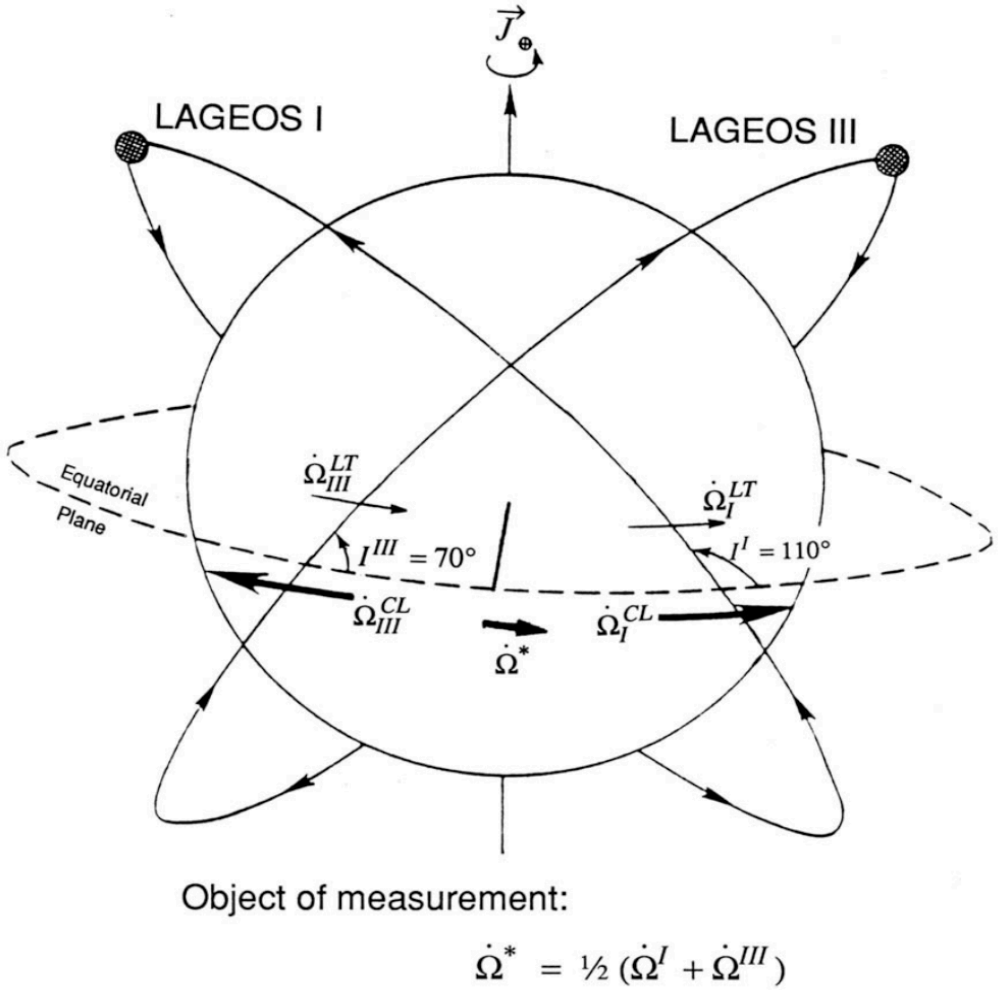


**GRAVITY PROBE B, 1960-2015**

GRAVITY PROBE B




**The idea of the LARES 2/LAGEOS 3 experiment**: I.C. Phys. Rev. Lett. 1986, I.C. Ph.D. dissertation 1984, I.C. IJMPA 1989, B. Tapley, I.C. et al, NASA and ASI studies 1989, J. Ries 1989).

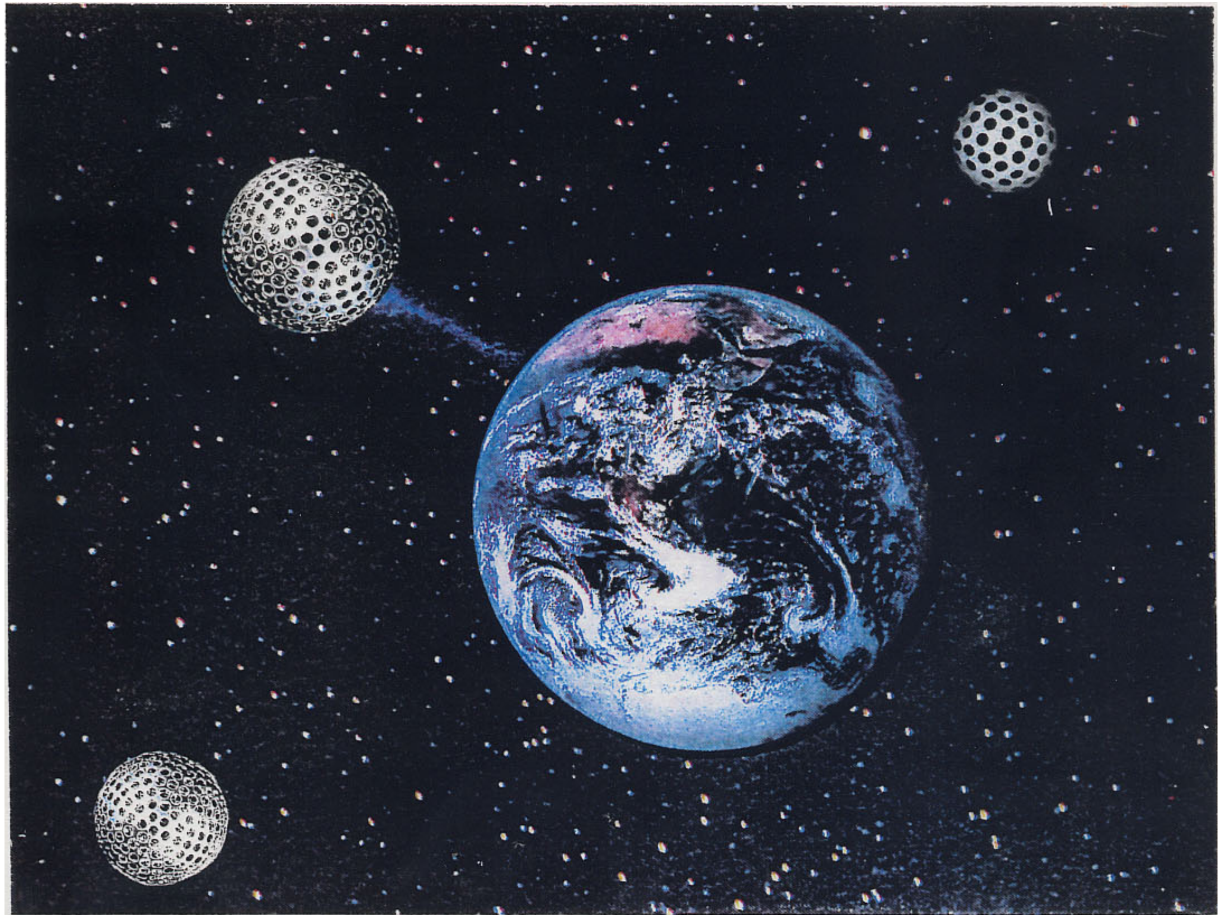
The classical rate of change of the node of a satellite as a function of its orbital parameters, *a*, *I*, *e*, and Earth's parameters: mass, radius and even zonal harmonics $J_2$, $J_4$, …

$$\dot{\Omega}_{Class} = -\frac{3}{2}\, n\, \frac{\cos I}{(1-e^2)^2} \left\{ J_2 \left(\frac{R_\oplus}{a}\right)^2 + J_4 \left(\frac{R_\oplus}{a}\right)^4 \left[\frac{5}{8}\,(7\,\sin^2 I - 4)\, \frac{(1+\frac{3}{2}e^2)}{(1+e^2)^2}\right]\right\}$$

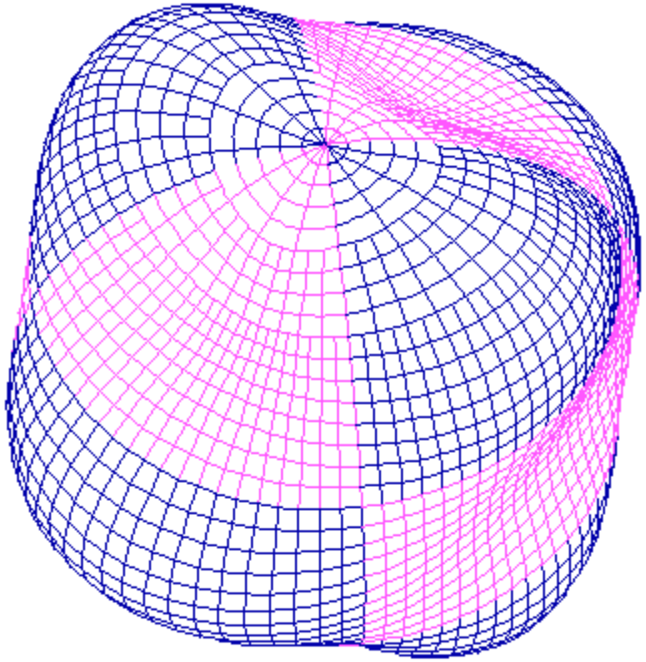
Whereas frame-dragging does **not** depend on the inclination *I* of a satellite

$$\dot{\Omega}^{\text{Lense–Thirring}} = \frac{2\mathbf{J}}{a^3(1-e^2)^{3/2}}$$

# Satellite Laser Ranging
# (and Lunar Laser Ranging)

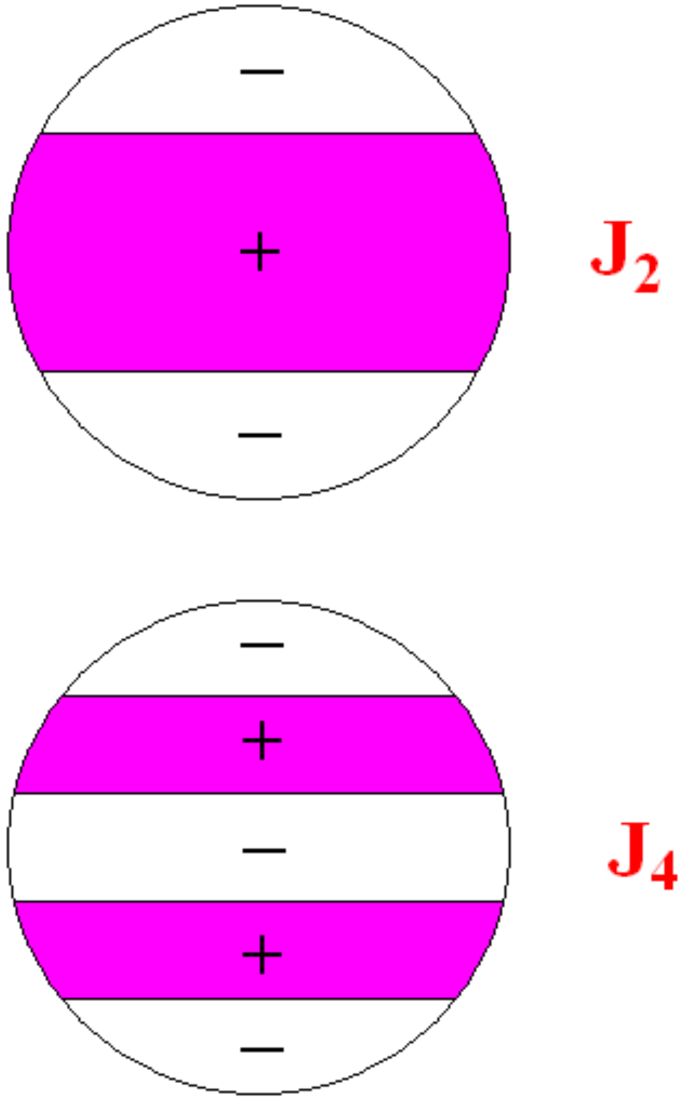


l=3, m=1



**Using two satellites with supplementary inclinations, we can eliminate the uncertainty due to all the even zonal harmonics $J_{2n}$**

## EVEN ZONAL HARMONICS



# Measurement of the Lense-Thirring Drag on High-Altitude, Laser-Ranged Artificial Satellites

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(Received 16 October 1984; revised manuscript received 19 April 1985)

We describe a new method of measuring the Lense-Thirring relativistic nodal drag using LAGEOS together with another similar high-altitude, laser-ranged satellite with appropriately chosen orbital parameters. We propose, for this purpose, that a future satellite such as LAGEOS II have an inclination supplementary to that of LAGEOS. The experiment proposed here would provide a method for experimental verification of the general relativistic formulation of Mach's principle and measurement of the gravitomagnetic field.

PACS numbers: 04.80.+z

In special and general relativity there are several precession phenomena associated with the angular momentum vector of a body. If a test particle is orbiting a rotating central body, the plane of the orbit of the particle is dragged by the intrinsic angular momentum $J$ of the central body, in agreement with the general relativistic formulation of Mach's principle.[1]

In the weak-field and slow-motion limit the nodal lines are dragged in the sense of rotation, at a rate given by[2]

$$\dot{\Omega} = [2/a^3(1-e^2)^{3/2}]J, \tag{1}$$

where $a$ is the semimajor axis of the orbit, $e$ is the eccentricity of the orbit, and geometrized units are used, i.e., $G=c=1$. This phenomenon is the Lense-Thirring effect, from the names of its discoverers in 1918.[2]

In addition to this there are other precession phenomena associated with the intrinsic angular momentum or spin $\mathbf{S}$ of an orbiting particle. In the weak-field and slow-motion limit the vector $\mathbf{S}$ precesses at a rate given by[1] $d\mathbf{S}/d\tau = \dot{\boldsymbol{\Omega}} \times \mathbf{S}$ where

$$\dot{\boldsymbol{\Omega}} \equiv -\tfrac{1}{2}\mathbf{v}\times\mathbf{a} + \tfrac{3}{2}\mathbf{v}\times\nabla U + \frac{1}{r^3}\left[-\mathbf{J} + \frac{3(\mathbf{J}\cdot\mathbf{r})\mathbf{r}}{r^2}\right], \tag{2}$$

where $\mathbf{v}$ is the particle velocity, $\mathbf{a} \equiv d\mathbf{v}/d\tau - \nabla U$ is its nongravitational acceleration, $\mathbf{r}$ is its position vector, $\tau$ is its proper time, and $U$ is the Newtonian potential.

The first term of this equation is the Thomas precession.[3] It is a special relativistic effect due to the noncommutativity of nonaligned Lorentz transformations. It may also be viewed as a coupling between the particle velocity $\mathbf{v}$ and the nongravitational forces acting on it.

The second (de Sitter[4]–Fokker[5]) term is general relativistic, arising even for a nonrotating source, from the parallel transport of a direction defined by $\mathbf{S}$; it may be viewed as spin precession due to the coupling between the particle velocity $\mathbf{v}$ and the static —$g_{\alpha\beta,0}=0$ and $g_{i0}=0$—part of the space-time geometry.

The third (Schiff[6]) term gives the general relativistic precession of the particle spin $\mathbf{S}$ caused by the intrinsic angular momentum $\mathbf{J}$ of the central body—$g_{i0}\neq 0$.

We also mention the precession of the periapsis of an orbiting test particle due to the angular momentum of the central body. This tiny shift of the perihelion of Mercury due to the rotation of the Sun was calculated by de Sitter in 1916.[7]

All these effects are quite small for an artificial satellite orbiting the Earth.

We propose here to measure the Lense-Thirring dragging by measuring the nodal precession of laser-ranged Earth satellites. We shall show that two satellites would be required; we propose that LAGEOS[8–10] together with a second satellite LAGEOS $X$ with opposite inclination (i.e., with $I^X = 180° - I$, where $I \simeq 109.94°$ is the orbital inclination of LAGEOS) would provide the needed accuracy.

The major part of the nodal precession of an Earth satellite is a classical effect due to deviations from spherical symmetry of the Earth's gravity field —quadrupole and higher mass moments.[11] These deviations from sphericity are measured by the expansion of the potential $U(r)$ in spherical harmonics. From this expansion of $U(r)$ follows[11] the formula for the classical precession of the nodal lines of an Earth satellite:

$$\dot{\Omega}_{\rm class} \simeq -\frac{3}{2}n\left(\frac{R_\oplus}{a}\right)^2 \frac{\cos I}{(1-e^2)^2}\left\{J_2 + J_4\left[\frac{5}{8}\left(\frac{R_\oplus}{a}\right)^2 (7\sin^2 I - 4)\frac{1+\frac{3}{2}e^2}{(1-e^2)^2}\right] + \dots\right\}, \tag{3}$$



IC, PRL 1986: Use of the nodes of two laser-ranged satellites to measure the Lense-Thirring effect

International Journal of Modern Physics A, Vol. 4, No. 13 (1989) 3083–3145


# A COMPREHENSIVE INTRODUCTION TO THE LAGEOS GRAVITOMAGNETIC EXPERIMENT: FROM THE IMPORTANCE OF THE GRAVITOMAGNETIC FIELD IN PHYSICS TO PRELIMINARY ERROR ANALYSIS AND ERROR BUDGET

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Received 3 May 1988
Revised 7 October 1988

The existence of the gravitomagnetic field, generated by mass currents according to Einstein geometrodynamics, has never been proved. The author of this paper, after a discussion of the importance of the gravitomagnetic field in physics, describes the experiment that he proposed in 1984 to measure this field using LAGEOS (Laser geodynamics satellite) together with another non-polar, laser-ranged satellite with the same orbital parameters as LAGEOS but a supplementary inclination.

The author then studies the main perturbations and measurement uncertainties that may affect the measurement of the Lense-Thirring drag. He concludes that, over the period of the node of ~ 3 years, the maximum error, using two nonpolar laser ranged satellites with supplementary inclinations, should not be larger than ~ 10% of the gravitomagnetic effect to be measured.

**Table of Contents**



IC IJMPA 1989: Analysis of the orbital perturbations affecting the nodes of LAGEOS-type satellites

(1) Use two LAGEOS satellites with supplementary inclinations to eliminate the effect of all the $J_{2n}$

OR:

Use n satellites of LAGEOS-type to measure the first n-1 even zonal harmonics: $J_2$, $J_4$, … and the frame-dragging effect (IC IJMPA 1989)



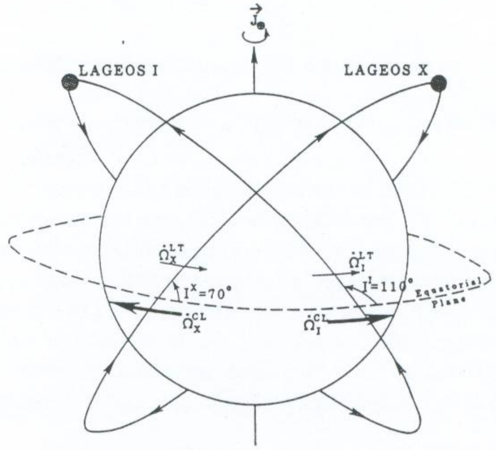


Fig. 5. The LAGEOS and LAGEOS $X$ orbits and their classical and gravitomagnetic nodal precessions. A new[17] configuration to measure the Lense-Thirring effect.

For $J_2$, this corresponds, from formula (3.2), to an uncertainty in the nodal precession of 450 milliarcsec/year, and similarly for higher $J_{2n}$ coefficients. Therefore, the uncertainty in $\dot{\Omega}^{\text{Class}}_{\text{Lageos}}$ is more than ten times larger than the Lense-Thirring precession.

A solution would be to orbit several high-altitude, laser-ranged satellites, similar to LAGEOS, to measure $J_2$, $J_4$, $J_6$, etc., and one satellite to measure $\dot{\Omega}^{\text{Lense-Thirring}}$.

Another solution would be to orbit polar satellites; in fact, from formula (3.2), for polar satellites, since $I = 90°$, $\dot{\Omega}^{\text{Class}}$ is equal to zero. As mentioned before, Yilmaz proposed the use of polar satellites in 1959.[40,41] In 1976, Van Patten and Everitt[46,47] proposed an experiment with two drag-free, guided, counter-rotating, polar satellites to avoid inclination measurement errors.

A new solution[15,16,17,21,22,23] would be to orbit a second satellite, of LAGEOS type, with the same semimajor axis, the same eccentricity, but the inclination supplementary to that of LAGEOS (see Fig. 5). Therefore, "LAGEOS X" should have the following orbital parameters:

$$I^X \cong \pi - I^I \cong 70°\,, \qquad a^X \cong a^I\,, \qquad e^X \cong e^I\,. \tag{3.3}$$

With this choice, since the classical precession $\dot{\Omega}^{\text{Class}}$ is linearly proportional to $\cos I$, $\dot{\Omega}^{\text{Class}}$ would be equal and opposite for the two satellites:

$$\dot{\Omega}^{\text{Class}}_X = -\dot{\Omega}^{\text{Class}}_I\,. \tag{3.4}$$

By contrast, since the Lense-Thirring precession $\dot{\Omega}^{\text{Lense-Thirring}}$ is independent of the inclination (Eq. (3.1)), $\dot{\Omega}^{\text{Lense-Thirring}}$ will be the same in magnitude and sign for both satellites:

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## On a new method to measure the gravitomagnetic field using two orbiting satellites

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(ricevuto il 20 Settembre 1996; approvato il 15 Novembre 1996)

**Summary.** — We describe a new method to obtain the first direct measurement of the Lense-Thirring effect, or dragging of inertial frames, and the first direct detection of the gravitomagnetic field. This method is based on the observations of the orbits of the laser-ranged satellites LAGEOS and LAGEOS II. By this new approach one achieves a measurement of the gravitomagnetic field with accuracy of about 25%, or less, of the Lense-Thirring effect in general relativity.

PACS 11.90 – Other topics in general field and particle theory.
PACS 04.80.Cc – Experimental test of gravitational theories.

### 1. – The gravitomagnetic field, its invariant characterization and past attempts to measure it

Einstein's theory of general relativity [1, 2] predicts the occurrence of a «new» field generated by mass-energy currents, not present in classical Galilei-Newton mechanics. This field is called the gravitomagnetic field for its analogies with the magnetic field in electrodynamics.

In general relativity, for a stationary mass-energy current distribution $\varrho_m \boldsymbol{v}$, in the weak-field and slow-motion limit, one can write [2] the Einstein equation in the Lorentz gauge: $\Delta \boldsymbol{h} \cong 16\pi\varrho_m \boldsymbol{v}$, where $\boldsymbol{h} \equiv (h_{01}, h_{02}, h_{03})$ are the $(0i)$-components of the metric tensor; $\boldsymbol{h}$ is called the gravitomagnetic potential. For a localized, stationary mass-energy distribution, in the weak-field and slow-motion limit, we can then write: $\boldsymbol{h} \cong -2((\boldsymbol{J} \times \boldsymbol{x})/r^3)$, where $\boldsymbol{J}$ is the angular momentum of the central body. In general relativity, one can also define [2] a gravitomagnetic field $\boldsymbol{H}$ given by $\boldsymbol{H} = \nabla \times \boldsymbol{h}$.

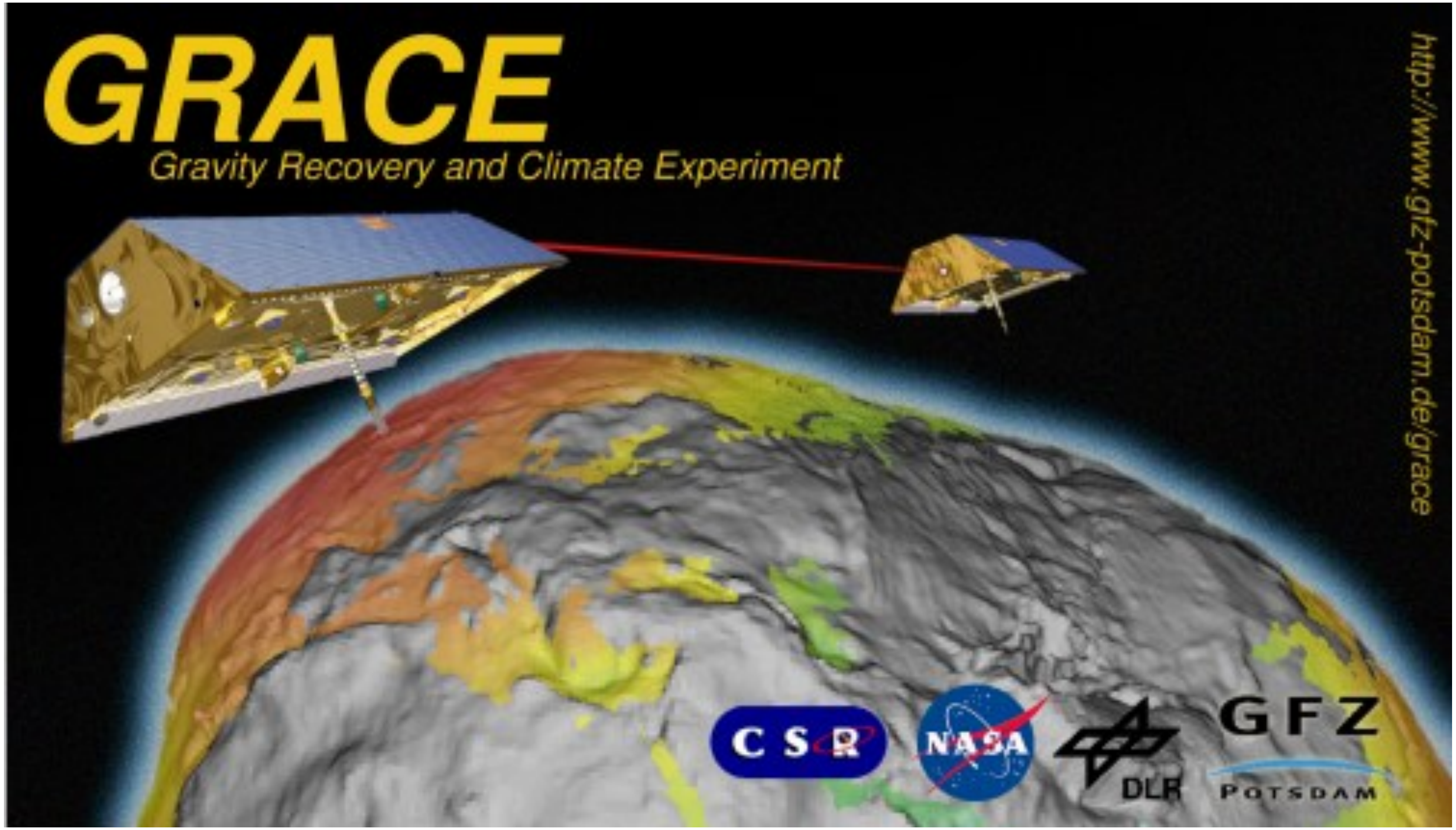
The Lense-Thirring effect is a consequence of the gravitomagnetic field and consists of a tiny perturbation of the orbital elements of a test particle due to the angular momentum of the central body. To characterize the gravitomagnetic field generated by the angular momentum of a body, and the Lense-Thirring effect, and distinguish it from other relativistic phenomena, such as the de Sitter effect, due to the



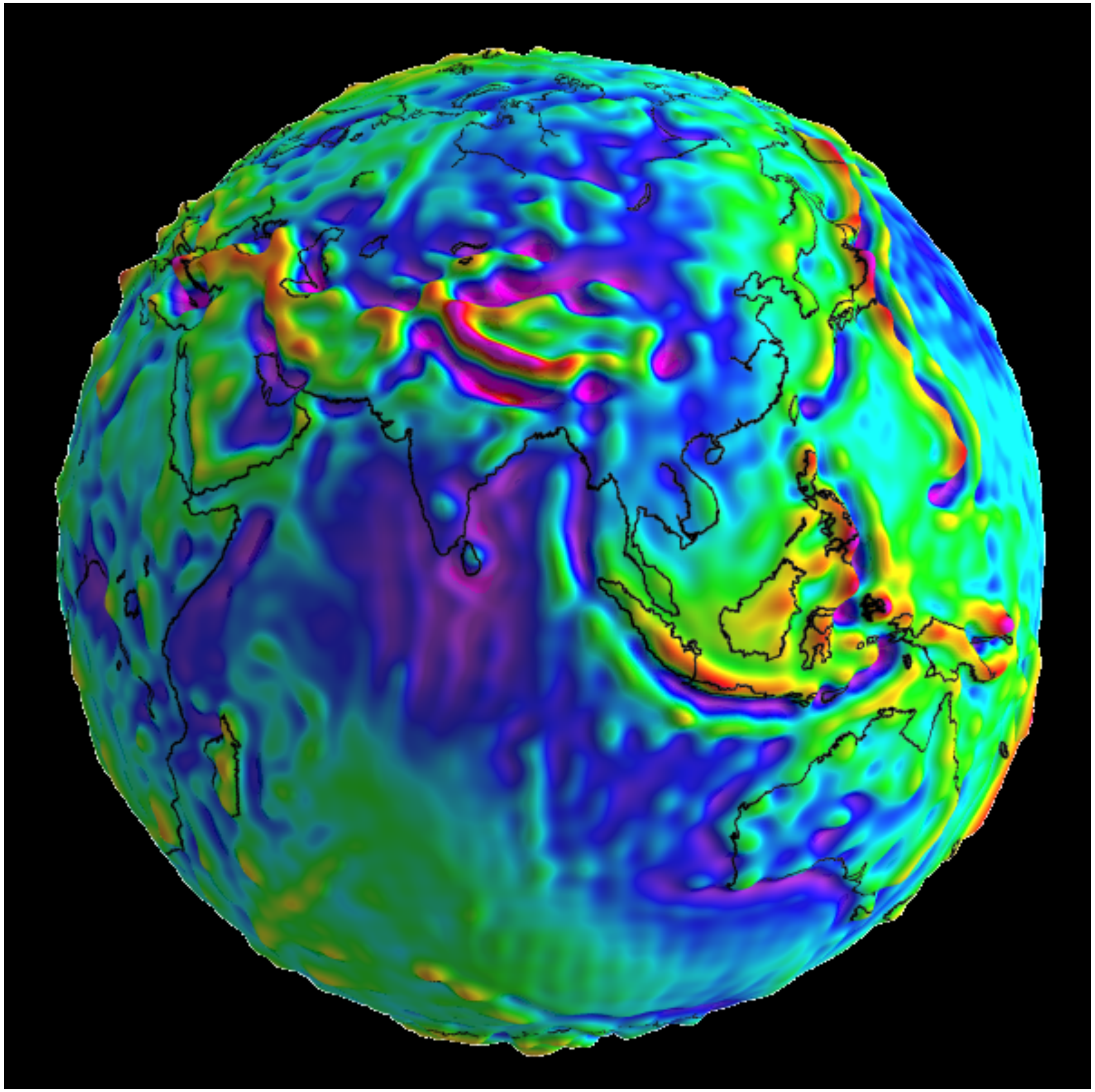
IC NCA 1996:
use the node of LAGEOS and the node of LAGEOS II to measure the Lense-Thirring effect

However, in 1996 the two nodes were not enough to measure the Lense-Thirring effect

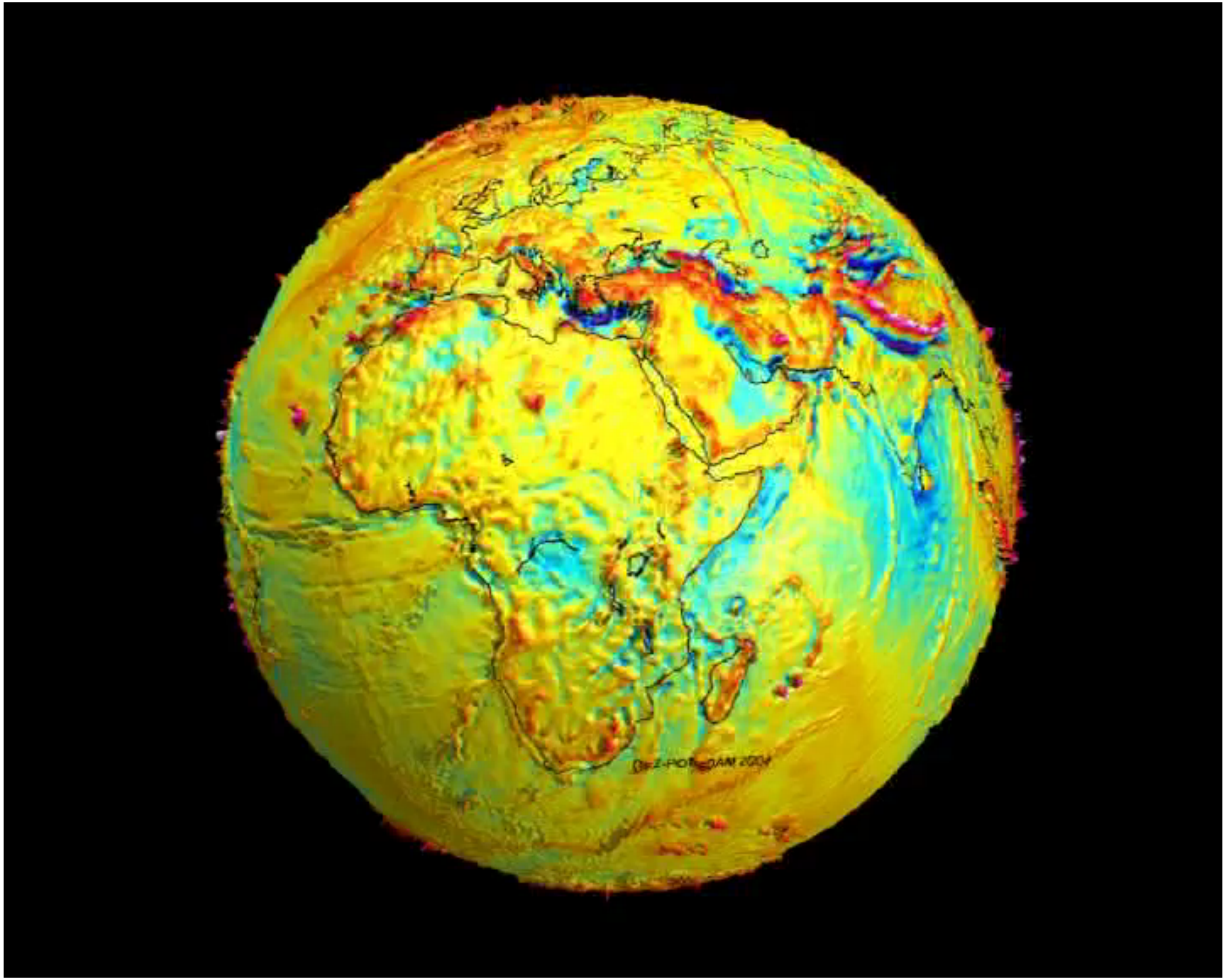
The LAGEOS 3 satellite was never funded but in 2002 the GRACE space mission was launched.




Use of GRACE to test Lense-Thirring at a few percent level:
J. Ries et al. 2003 (1999),E. Pavlis 2002 (2000)

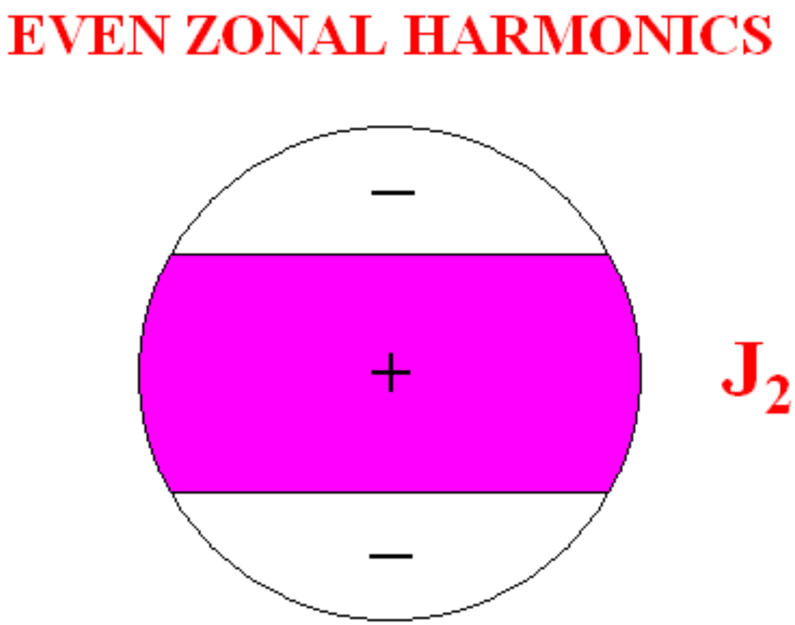


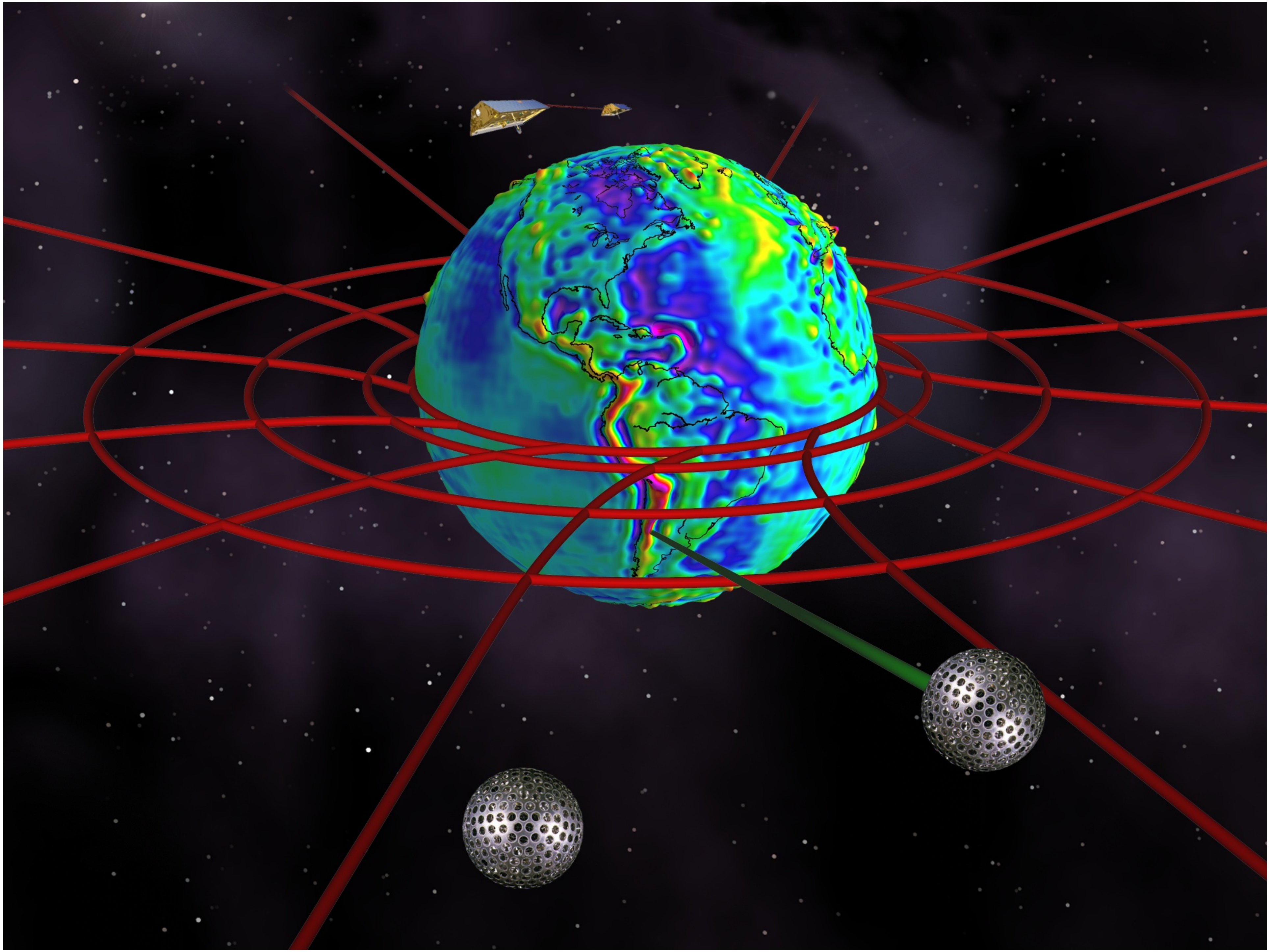
EIGEN-GRACE-S (GFZ 2004)



**Using LAGEOS +LAGEOS 2 and the GRACE determinations of the Earth gravitational field we were able to measure the frame-dragging effect and eliminate the uncertainties in J2.**

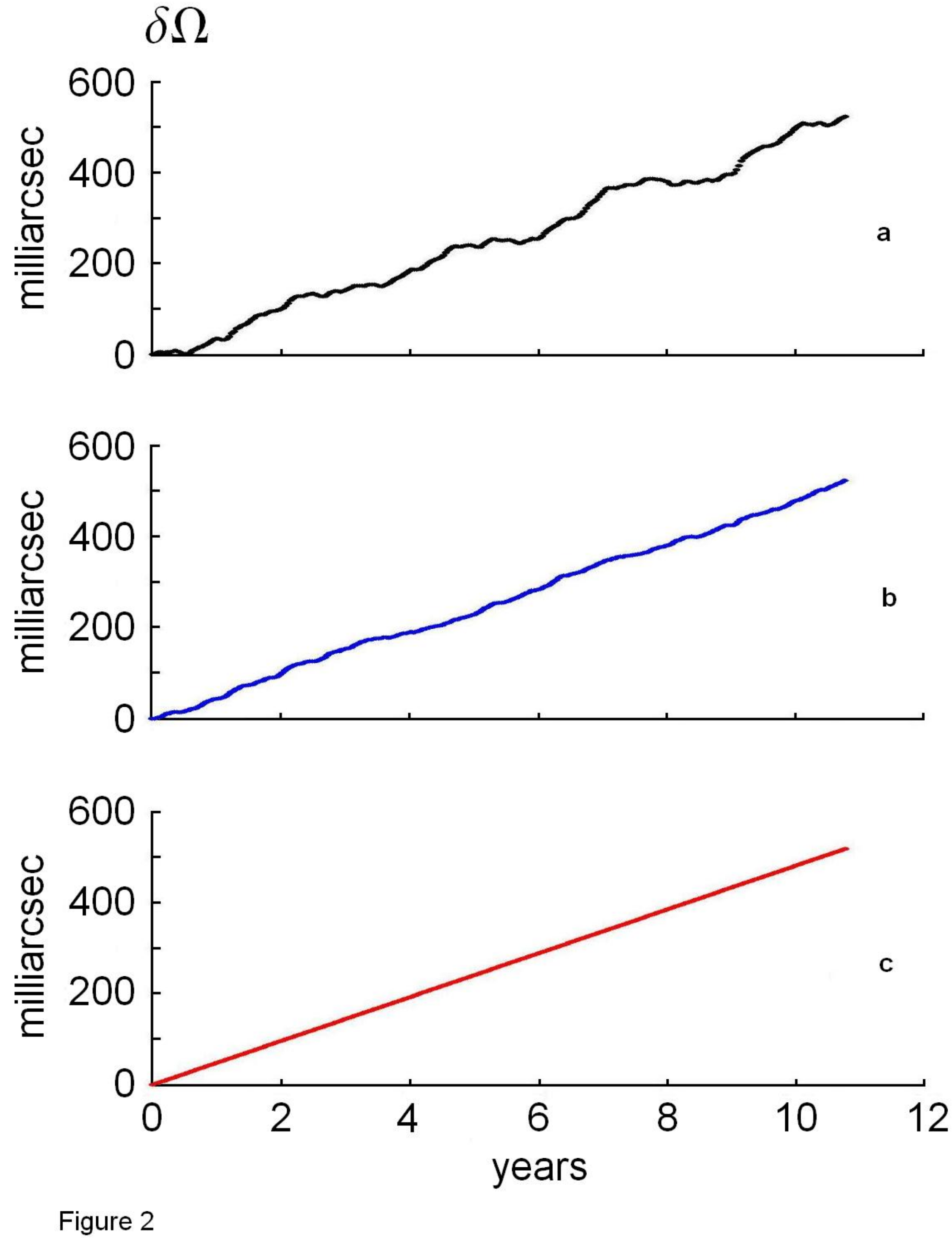
**Even zonal harmonics, of degree even and zero order, are the axially symmetric deviations of the Earth potential (of even degree) from spherical symmetry also symmetric with respect to the Earth's equatorial plane.**





# EIGEN-GRACE02S Model and Uncertainties

| Even zonals lm | Value · $10^{-6}$ | Uncertainty | Uncertainty on node I | Uncertainty on node II | Uncertainty on perigee II |
|---|---|---|---|---|---|
| 20 | −484.16519788 | $0.53 \bullet 10^{-10}$ | $1.59\ \Omega_{LT}$ | $2.86\ \Omega_{LT}$ | $1.17\ \omega_{LT}$ |
| 40 | 0.53999294 | $0.39 \bullet 10^{-11}$ | $0.058\ \Omega_{LT}$ | $0.02\ \Omega_{LT}$ | $0.082\ \omega_{LT}$ |
| 60 | −.14993038 | $0.20 \bullet 10^{-11}$ | $0.0076\ \Omega_{LT}$ | $0.012\ \Omega_{LT}$ | $0.0041\ \omega_{LT}$ |
| 80 | 0.04948789 | $0.15 \bullet 10^{-11}$ | $0.00045\ \Omega_{LT}$ | $0.0021\ \Omega_{LT}$ | $0.0051\ \omega_{LT}$ |
| 10,0 | 0.05332122 | $0.21 \bullet 10^{-11}$ | $0.00042\ \Omega_{LT}$ | $0.00074\ \Omega_{LT}$ | $0.0023\ \omega_{LT}$ |

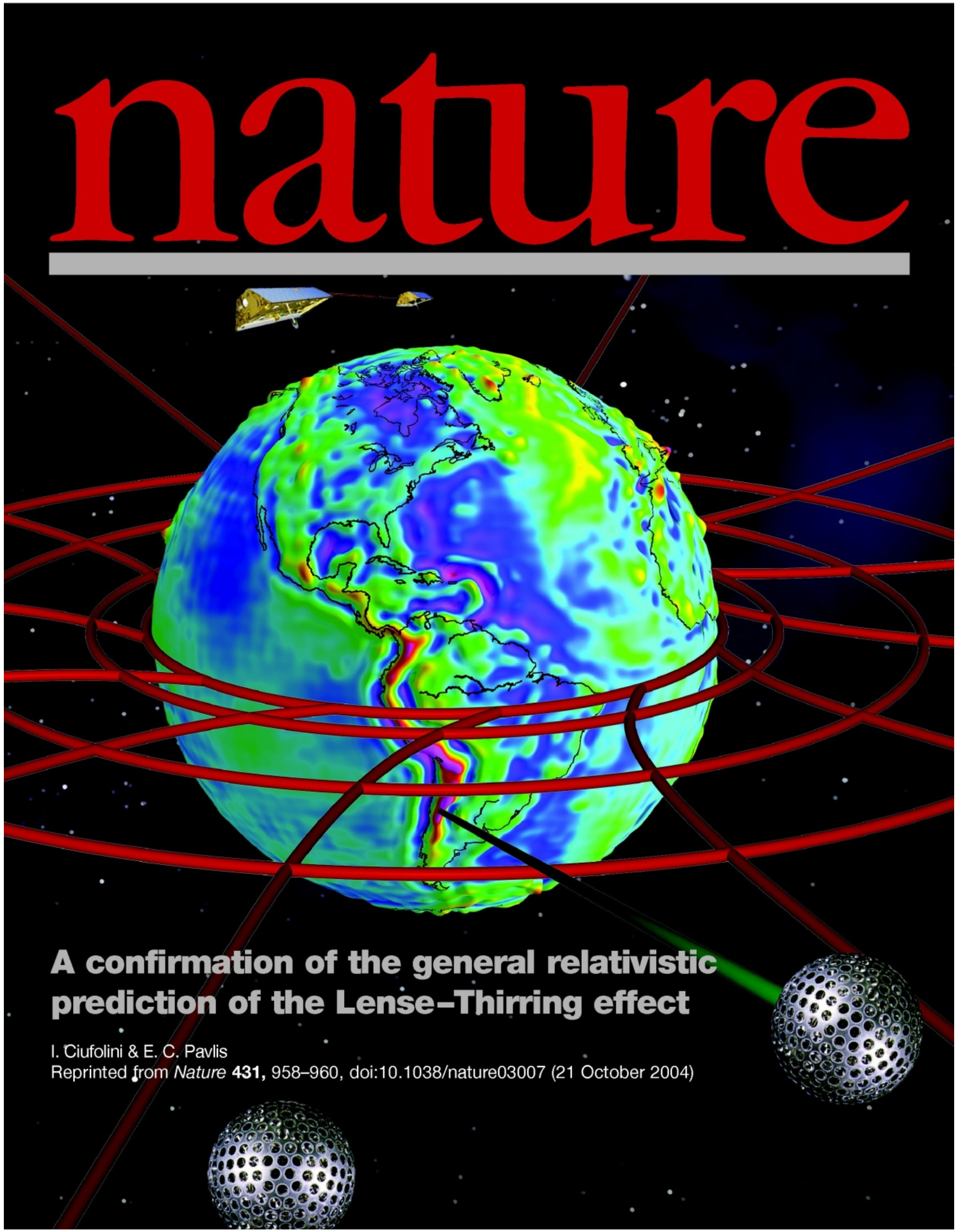



**Observed value of Lense-Thirring effect using The combination of the LAGEOS nodes.**

**Observed value of Lense-Thirring effect = 99% of the general relativistic prediction. Fit of linear trend plus 6 known frequencies**

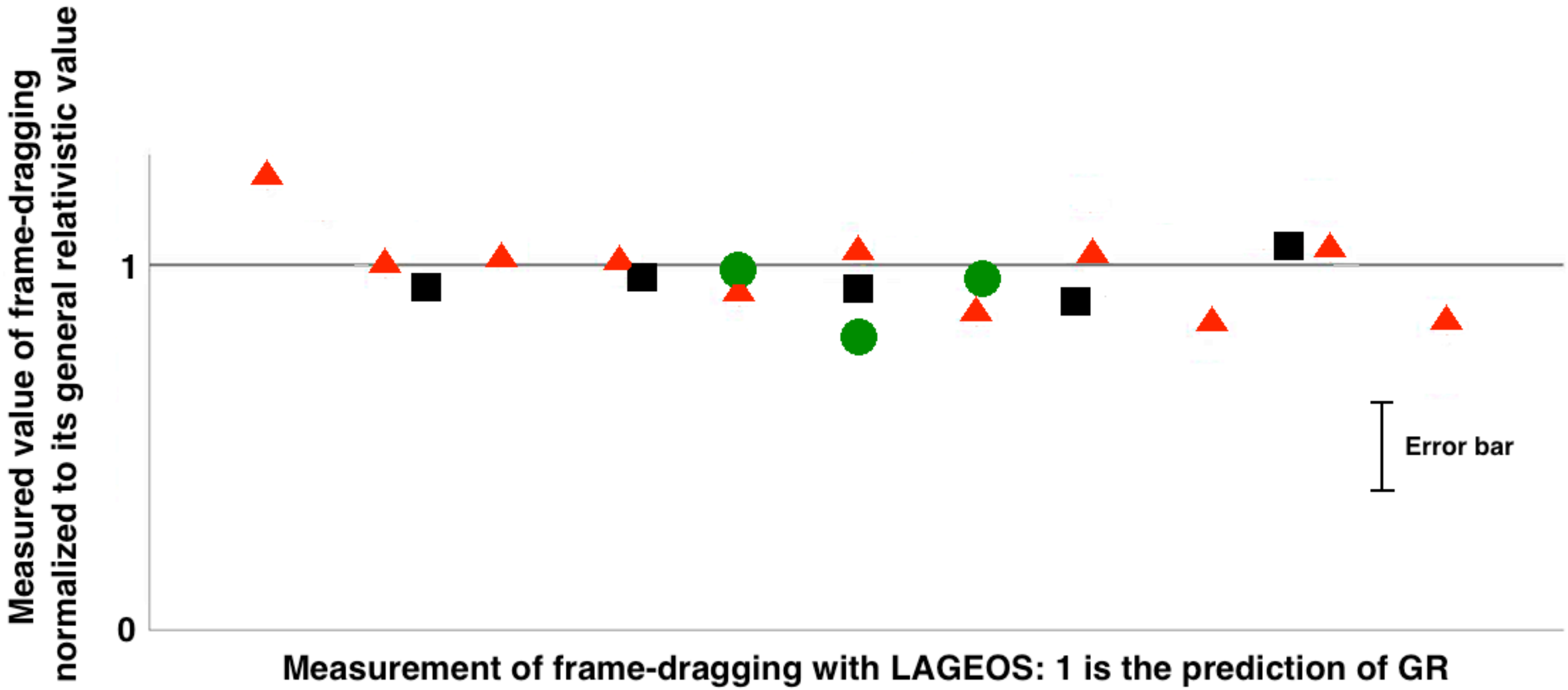
**General relativistic Prediction = 48.2 mas/yr**

**I.C. & E.Pavlis, Letters to NATURE, 431, 958, 2004.**




**The result was published in Nature Letters in 2004**

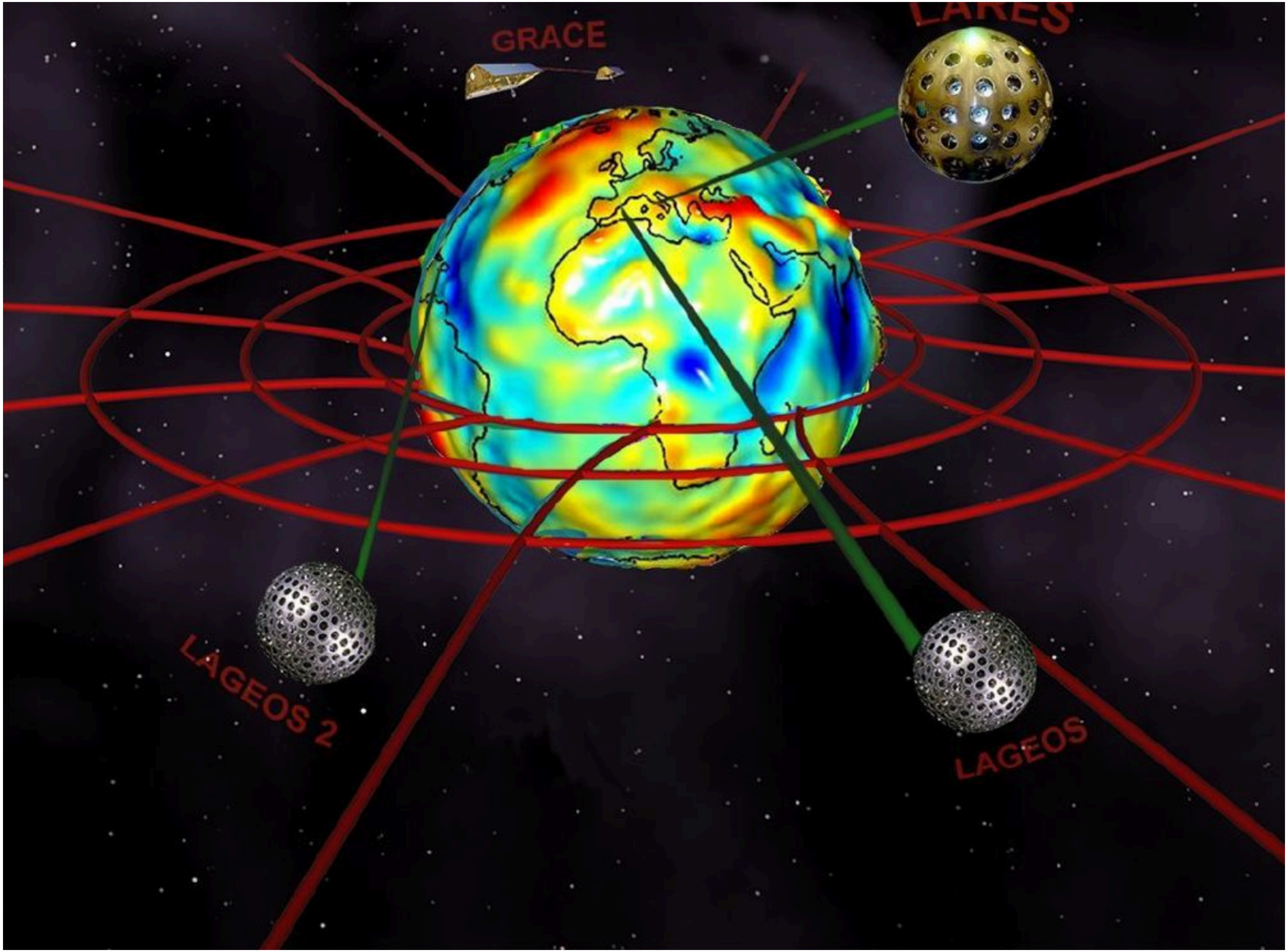

6 September 2007 | www.nature.com/nature | £10
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
nature
THE K/T IMPACT
Baptistina asteroids in the frame
BIOMETRICS
The questions you meant to ask
TSUNAMIS
Tracking risk off the Myanmar coast
THE RIDDLE OF INERTIA
How Earth's rotation reshapes space and time
NATUREJOBS
Hydrogen technology
36>
9 770028 083095




Triangles: **CSR UT-Austin**: with orbital estimator **UTOPIA**

**Squares**: **GFZ-Helmholtz Inst.**-Germany: with orbital estimator **EPOSOC**

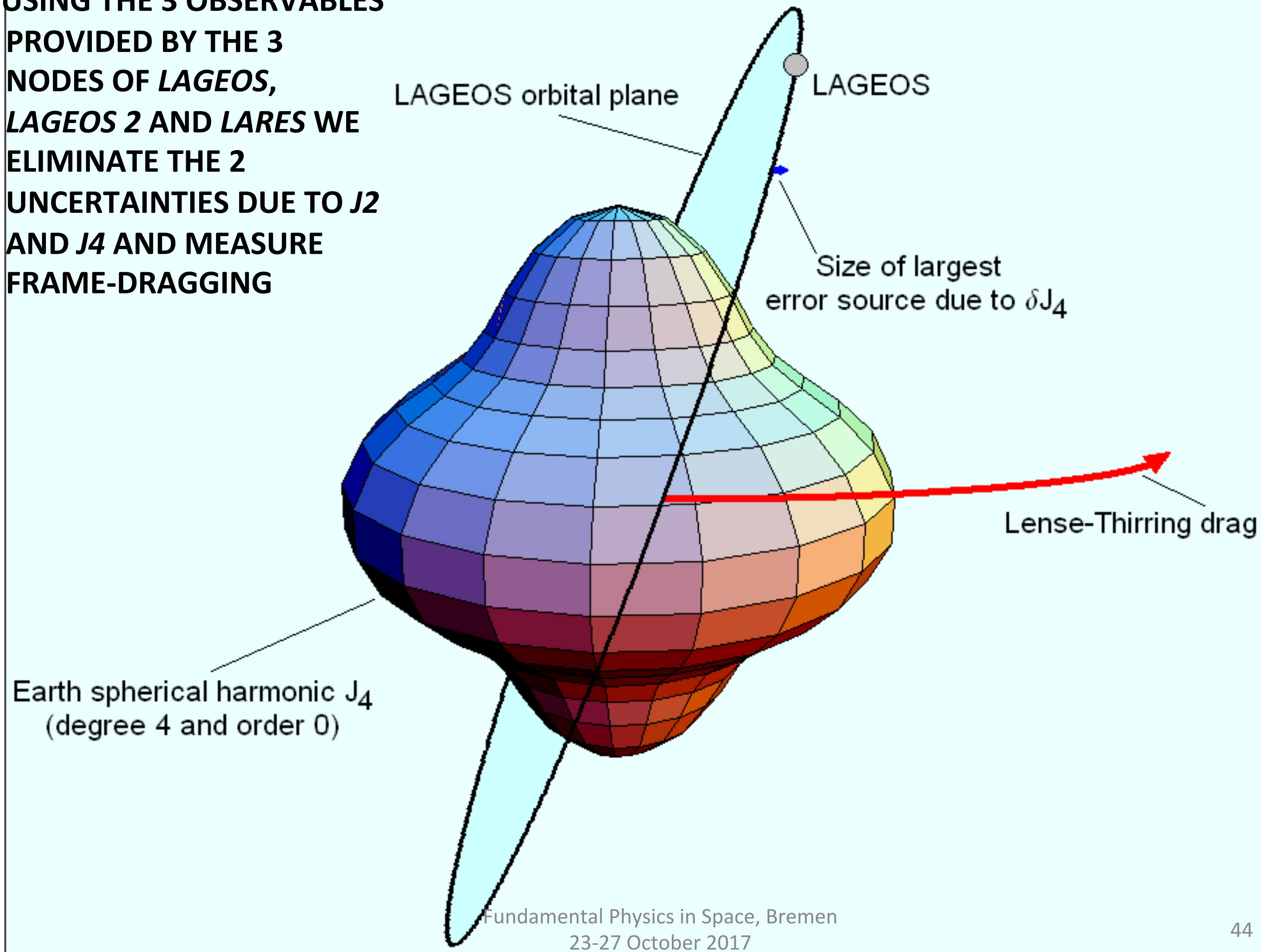
Circles: **Univ. Salento-Rome-Maryland (NASA Goddard)**: with orbital estimator **GEODYN**


GRACE
LARES
LAGEOS 2
LAGEOS

# LARES
## (LAser RElativity Satellite)

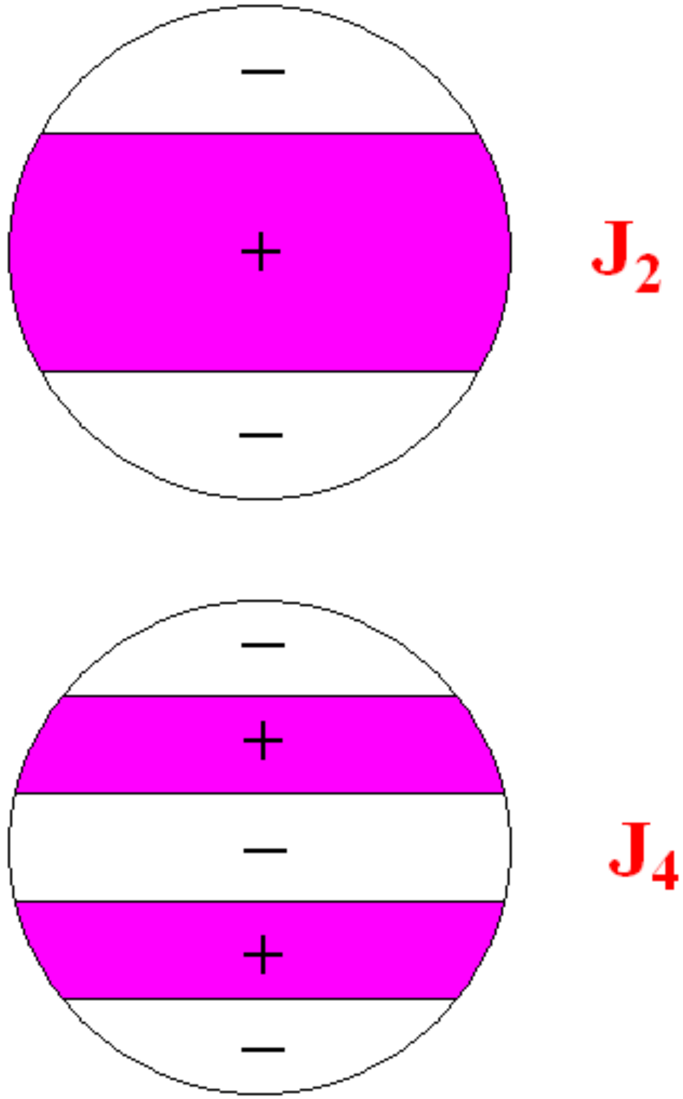
**LARES was successfully launched and very accurately injected in the nominal orbit on the 13th of February 2012 with the VEGA launching vehicle.**

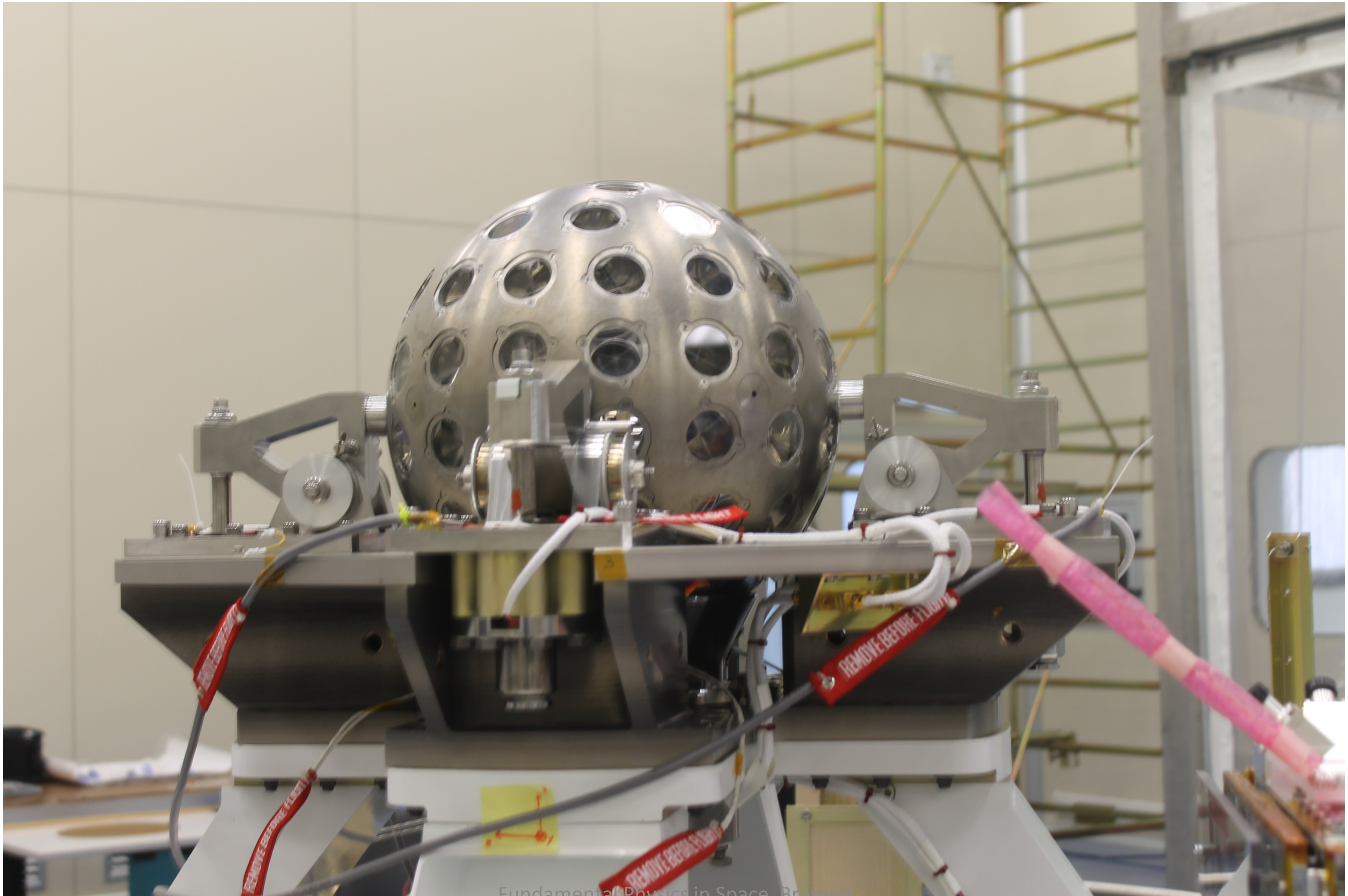
**USING THE 3 OBSERVABLES PROVIDED BY THE 3 NODES OF *LAGEOS*, *LAGEOS 2* AND *LARES* WE ELIMINATE THE 2 UNCERTAINTIES DUE TO *J2* AND *J4* AND MEASURE FRAME-DRAGGING**

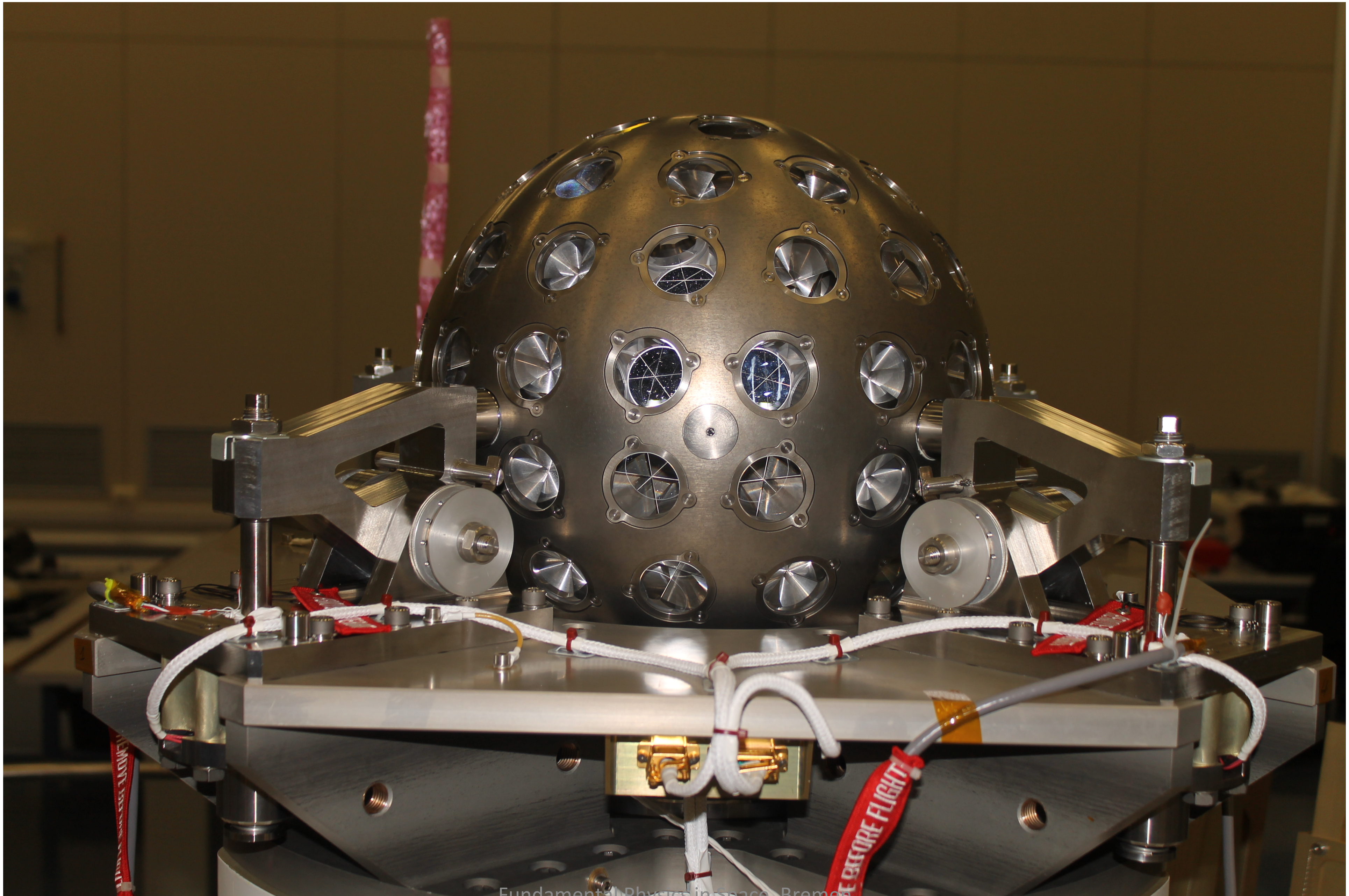


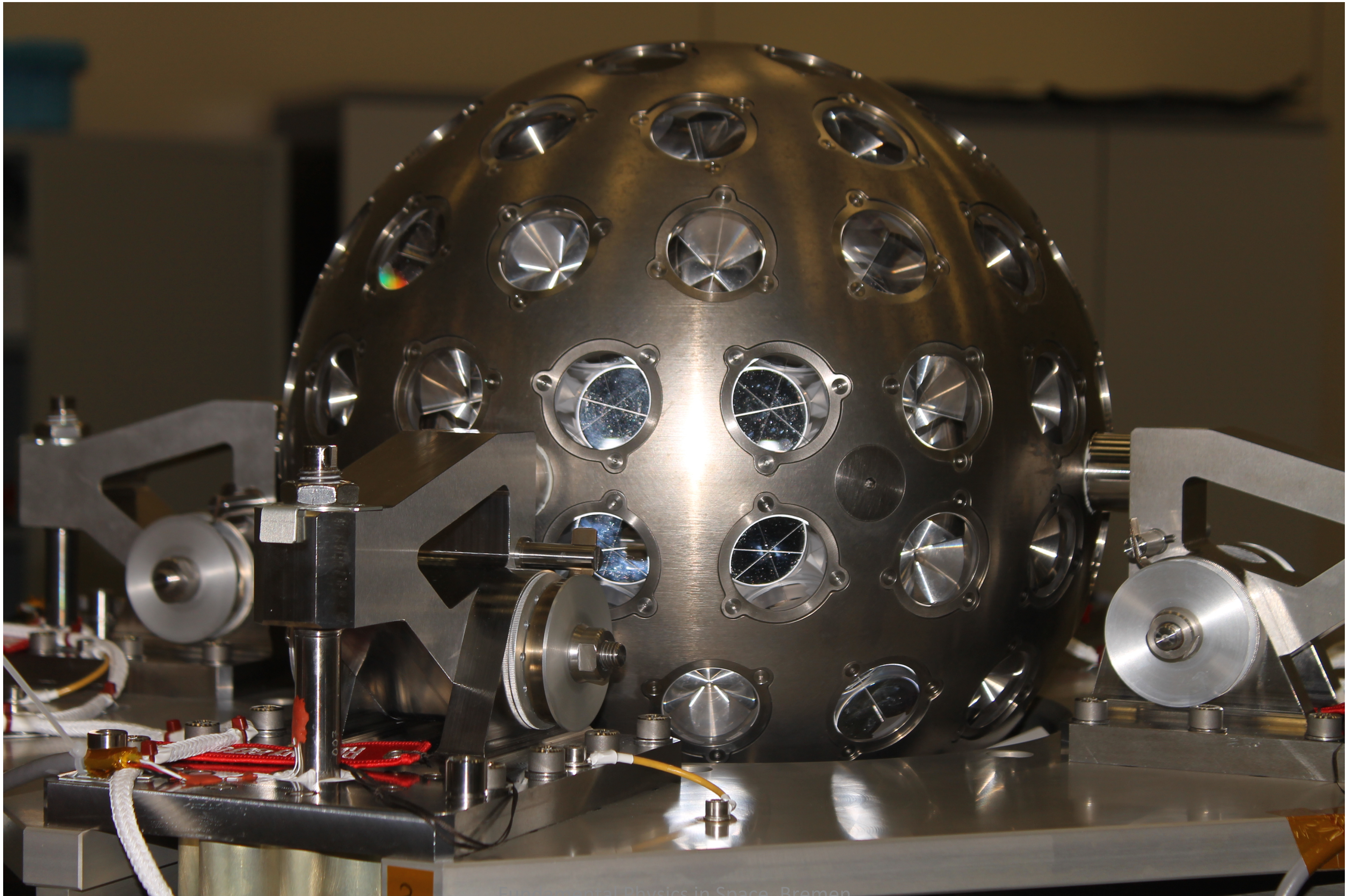
# EVEN ZONAL HARMONICS

**Using LARES+LAGEOS +LAGEOS 2 and the GRACE determinations of the Earth gravitational field we were able to measure the frame-dragging effect and eliminate the uncertainties in J2 and J4.**



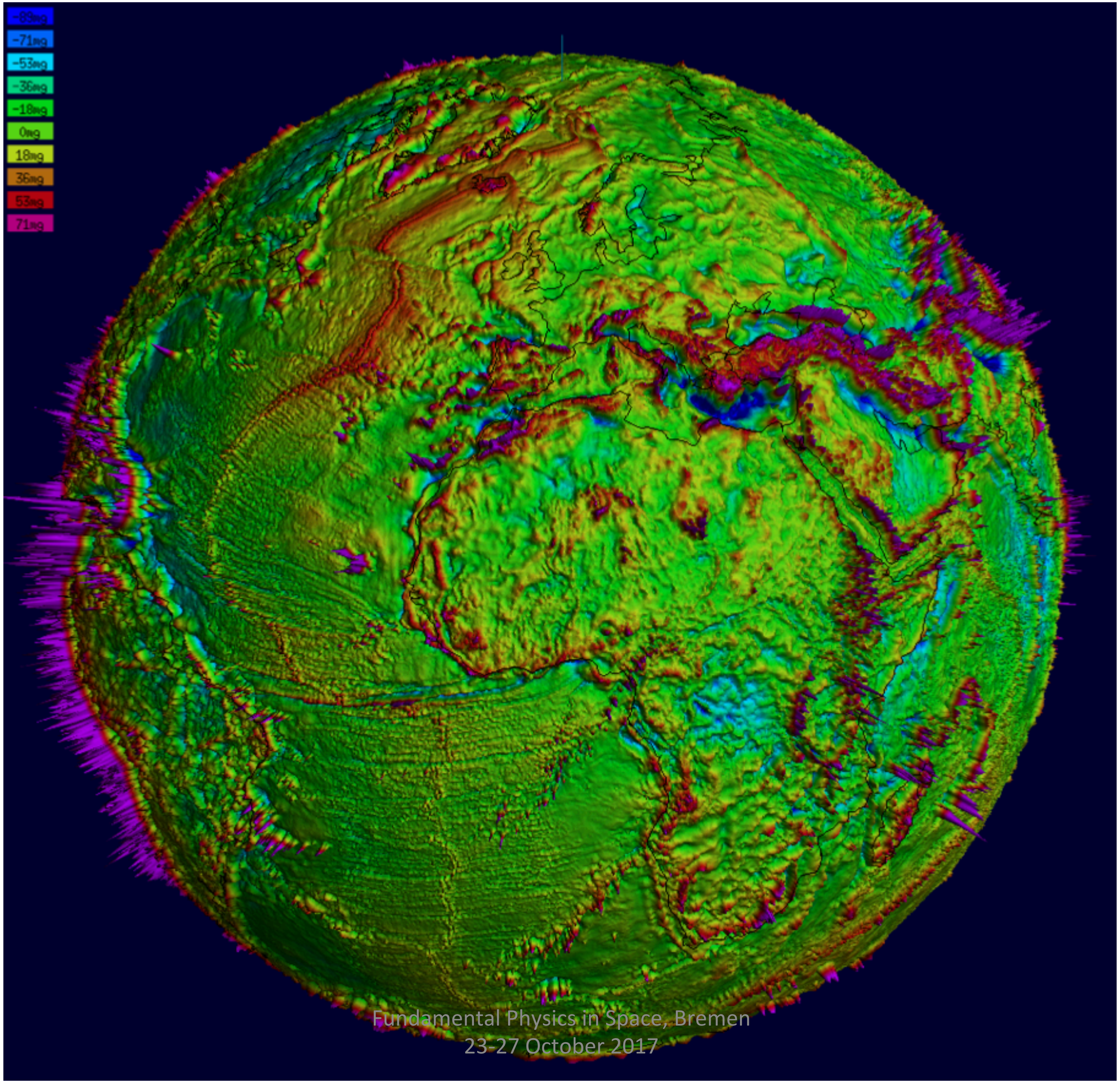

REMOVE BEFORE FLIGHT
REMOVE BEFORE FLIGHT





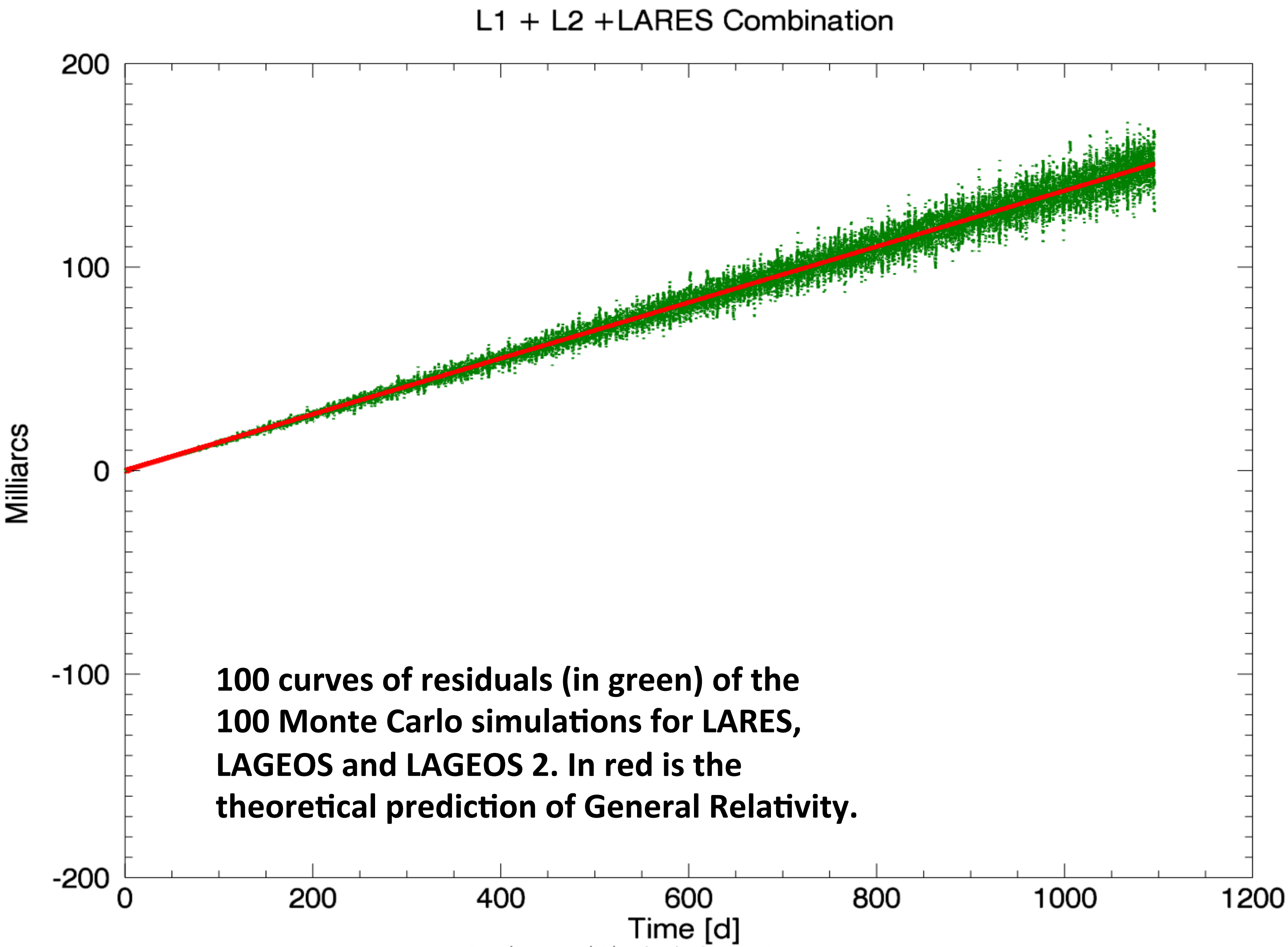
# LARES
## (LAser RElativity Satellite)
*Italian Space Agency*

- **Combined with the LAGEOS and LAGEOS 2 orbital data and using the GRACE Earth gravity field determinations, LARES provides a confirmation of Einstein General Relativity, the measurement of frame-dragging, with accuracy of about a few percent.**


-89mg
-71mg
-53mg
-36mg
-18mg
0mg
18mg
36mg
53mg
71mg

| Parameter | Nominal value | 1-Sigma |
|---|---|---|
| **GM** | 0.3986004415E+15 | 8E+05 |
| **C20** | -.484165112E-03 | 2.5E-10 |
| **C40** | 0.539968941E-06 | 0.12280000E-11 |
| **C60** | -.149966457E-06 | 0.73030000E-12 |
| **C80** | 0.494741644E-07 | 0.53590000E-12 |
| **C10 0** | 0.533339873E-07 | 0.43780000E-12 |
| **C20-dot** | 0.116275500E-10 | 0.01790000E-11 |
| **C40-dot** | 0.470000000E-11 | 0.33000000E-11 |
| **Cr LAGEOS 1** | 1.13 | 0.00565 |
| **Cr LAGEOS 2** | 1.12 | 0.0056 |
| **Cr LARES** | $Cr_L$ | 0.0054 |

**Main parameters of the Monte Carlo simulations (100 simulations) GFZ**
**I. C. et al., Class. and Quantum Grav., 2013**


L1 + L2 +LARES Combination
200
100
0
-100
-200
Milliarcs
0
200
400
600
800
1000
1200
Time [d]
100 curves of residuals (in green) of the
100 Monte Carlo simulations for LARES,
LAGEOS and LAGEOS 2. In red is the
theoretical prediction of General Relativity.

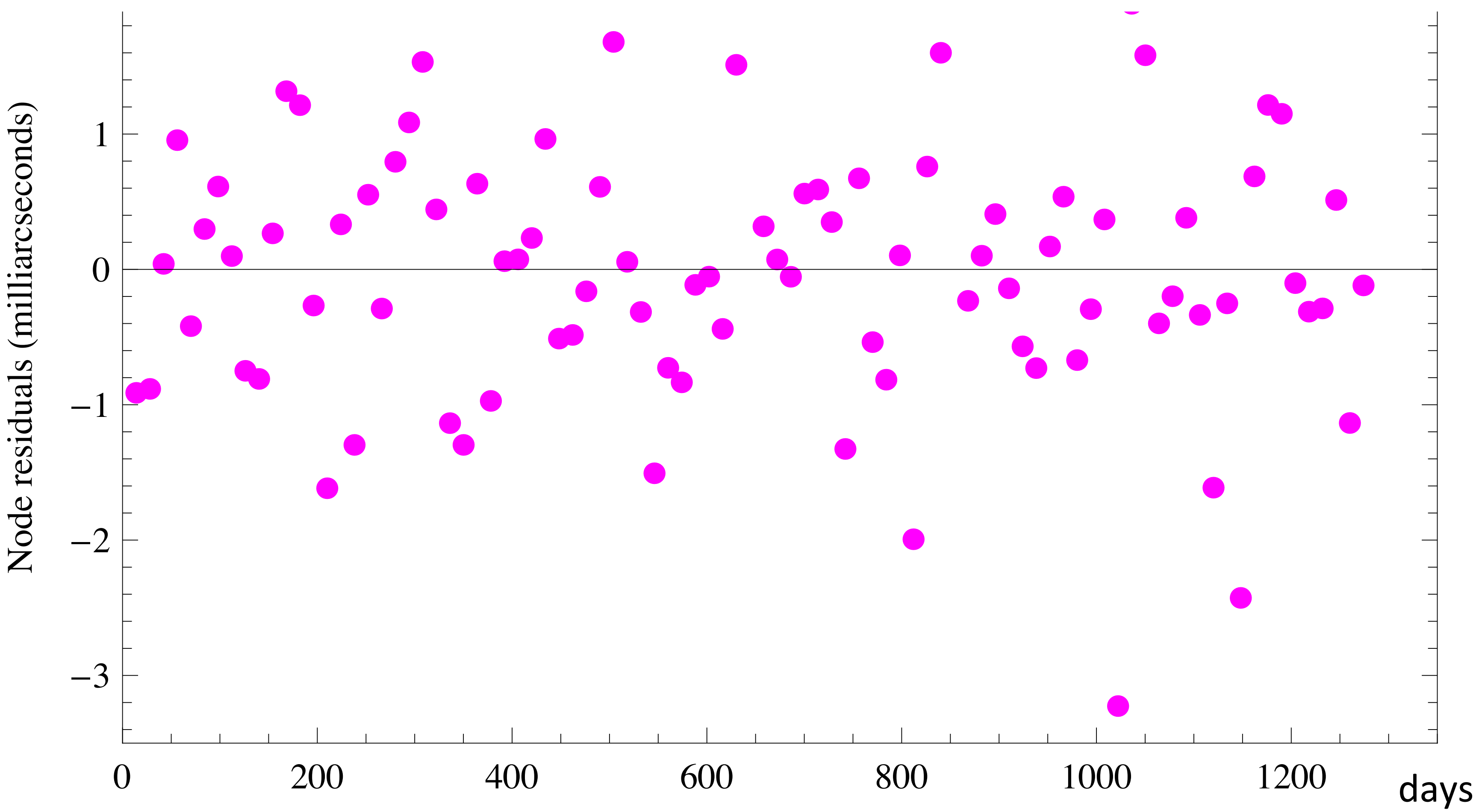
**Results of the Monte Carlo simulation for the LARES experiment**

**Mean value of the frame-dragging effect**

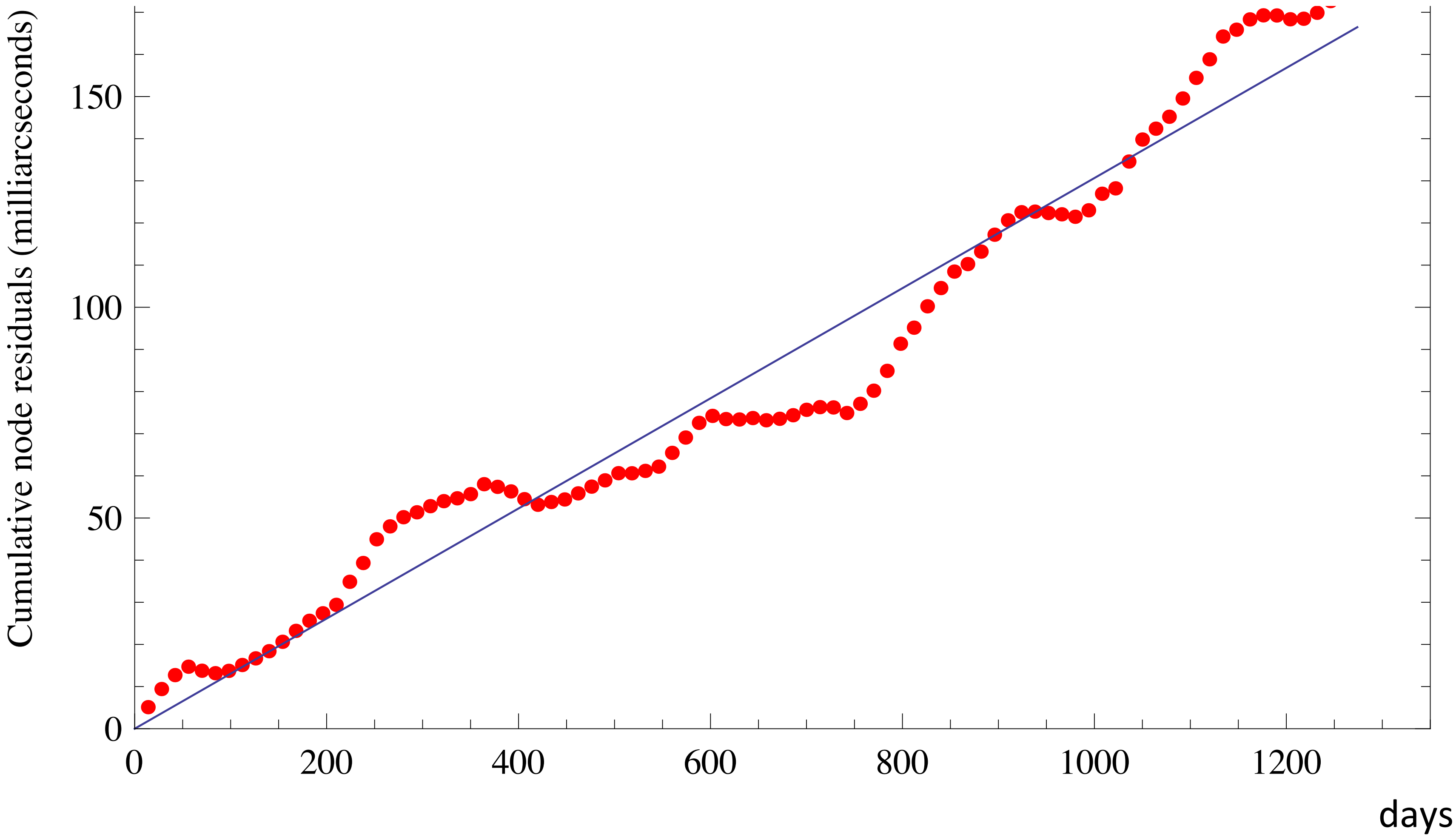
**= 100.25 % of the frame-dragging effect predicted by General Relativity**

**Standard deviation:**

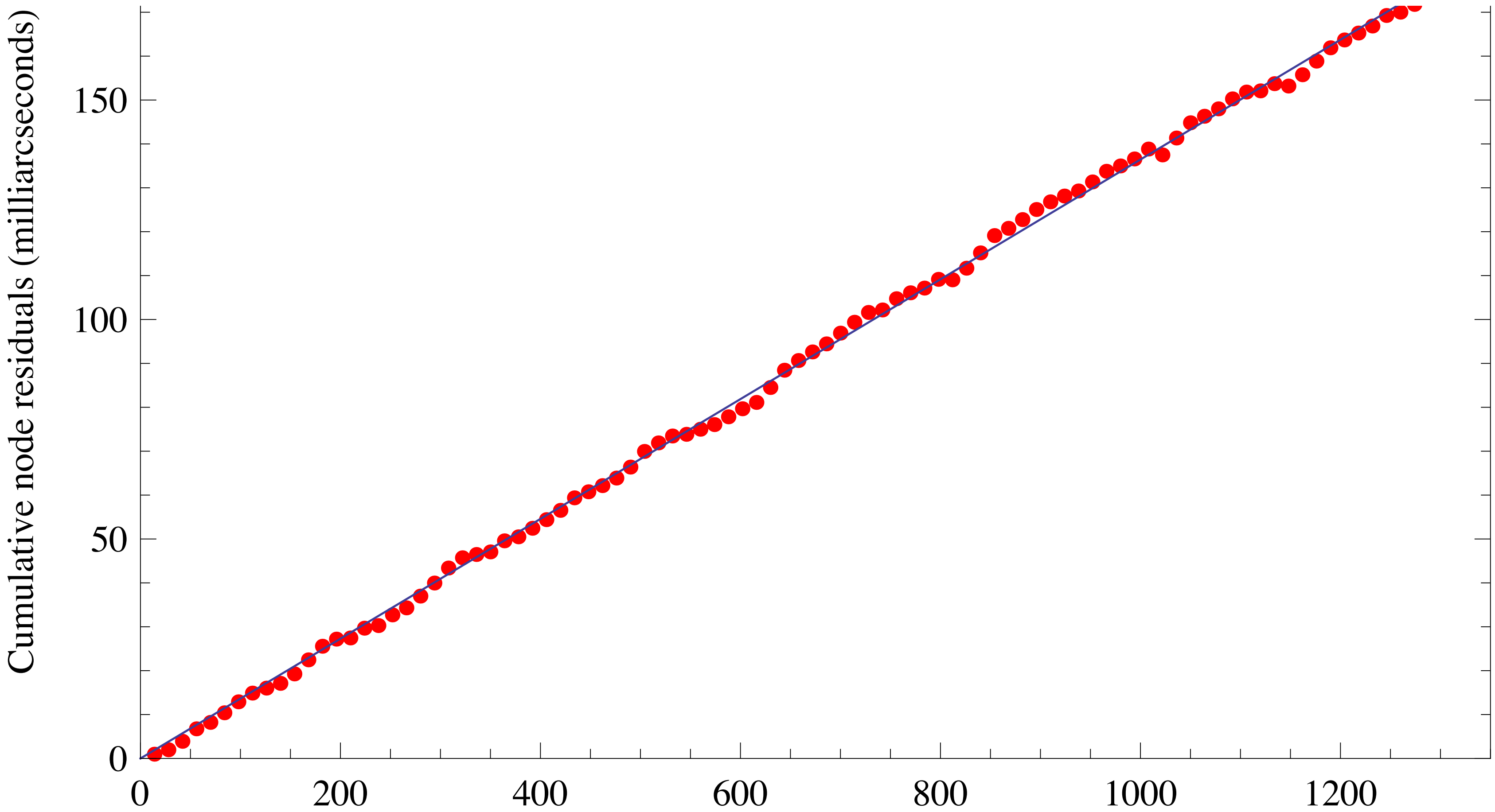
**= 1.55 %**




**Combined residuals of LARES, LAGEOS, and LAGEOS 2, over about 3.5 years of orbital observations, after the removal of six tidal signals and a constant trend**




**Fit of the cumulative combined nodal residuals of LARES, LAGEOS, and LAGEOS 2 with a linear regression only**




**Fit of the cumulative combined nodal residuals of LARES, LAGEOS, and LAGEOS 2 with a linear regression plus six periodical terms corresponding to six main tidal perturbations observed in the orbital residuals: published in EPJC 2016 (Ciufolini et al.)**

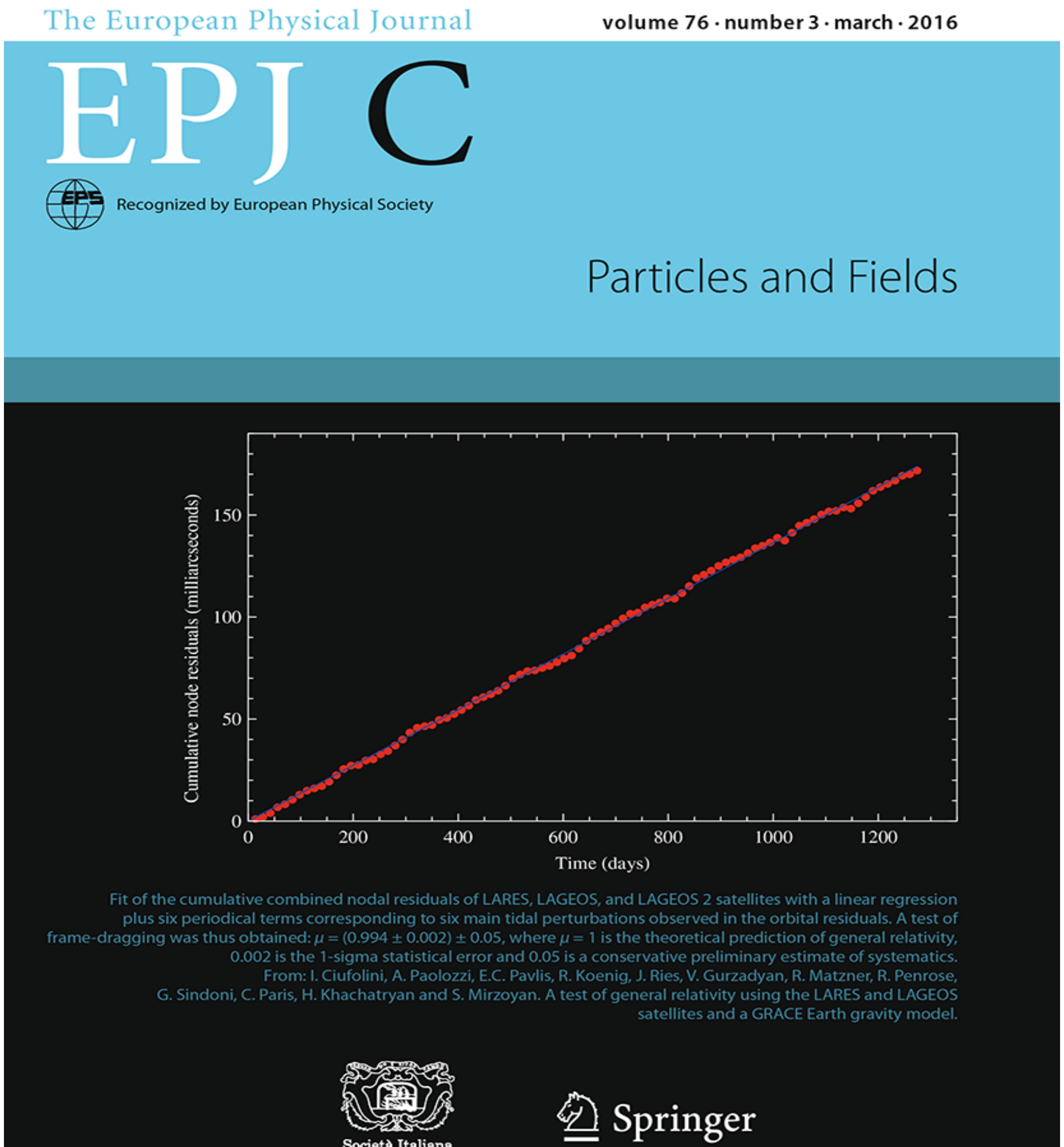
# RESULT:

## (0.994 +/- 0.002) +/- 0.05

**1 is the Earth's dragging of inertial frames normalized to its general relativity value,**

**0.002 is the 1-sigma statistical error**

**0.05 is our preliminary estimate of systematic error mainly due to the uncertainties in the Earth gravity model GGM05S**




**March cover of EPJC dedicated to our research**

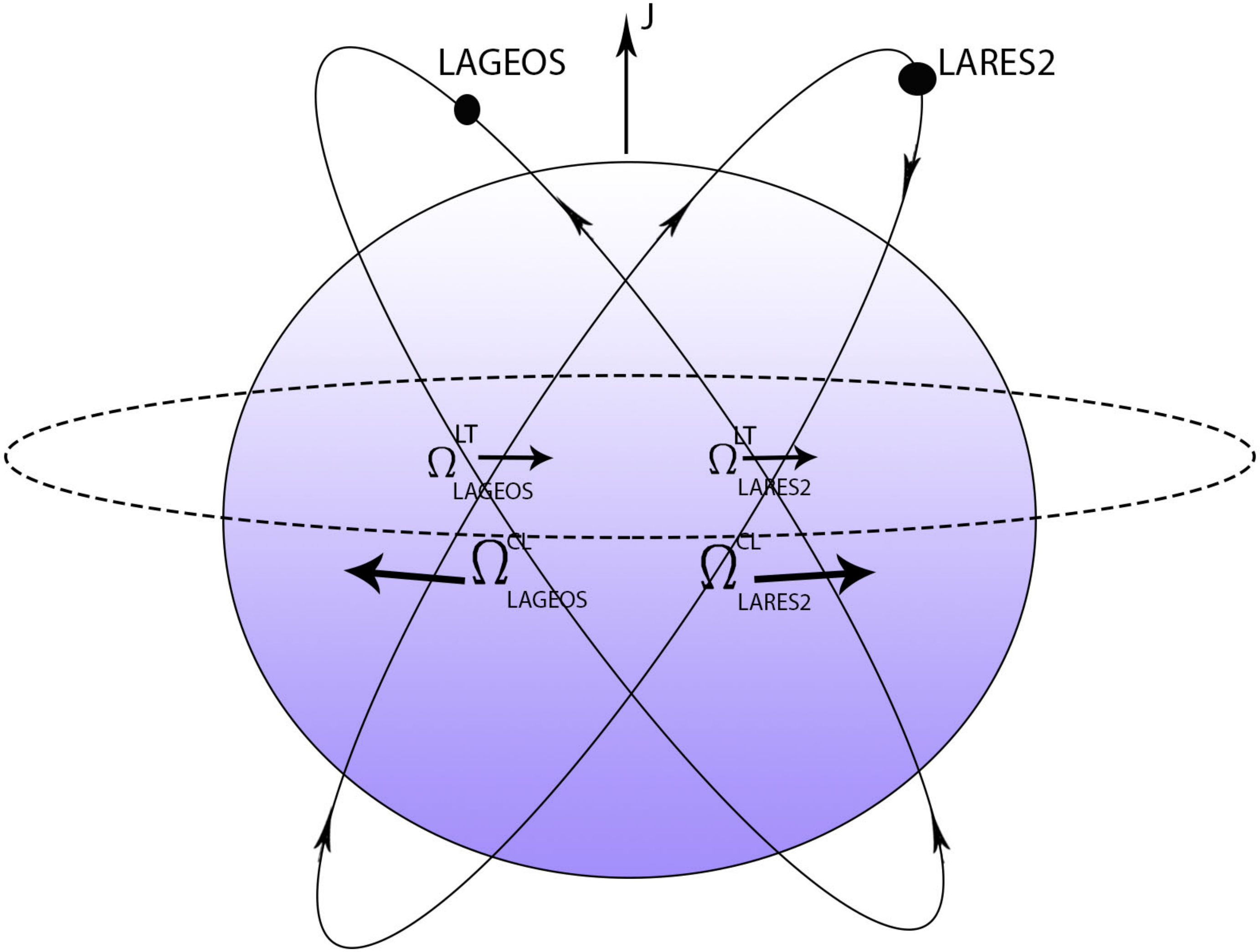
**LARES already shows an outstanding behaviour for testing General Relativity and gravitational physics. LARES-type satellites could well test other fundamental physics effects and much improve the existing limits on C-S mass.**

**After a few years of laser-ranging data of the LARES satellite, together with LAGEOS and LAGEOS 2 and with the future improved Earth's gravity models, we would be able to measure the frame-dragging effect with accuracy of about 2%, with other implicational for fundamental physics such as improving the limits on C-S mass and placing further limits on String Theories equivalent to Chern-Simon gravity.**

# LARES 2/LAGEOS 3

**The LARES 2 (LAGEOS 3) satellite for test of frame-dragging with accuracy at the 0.2% level and other tests of General Relativity and Fundamental Physics (and space geodesy and geodynamics).**

# LARES 2/LAGEOS 3

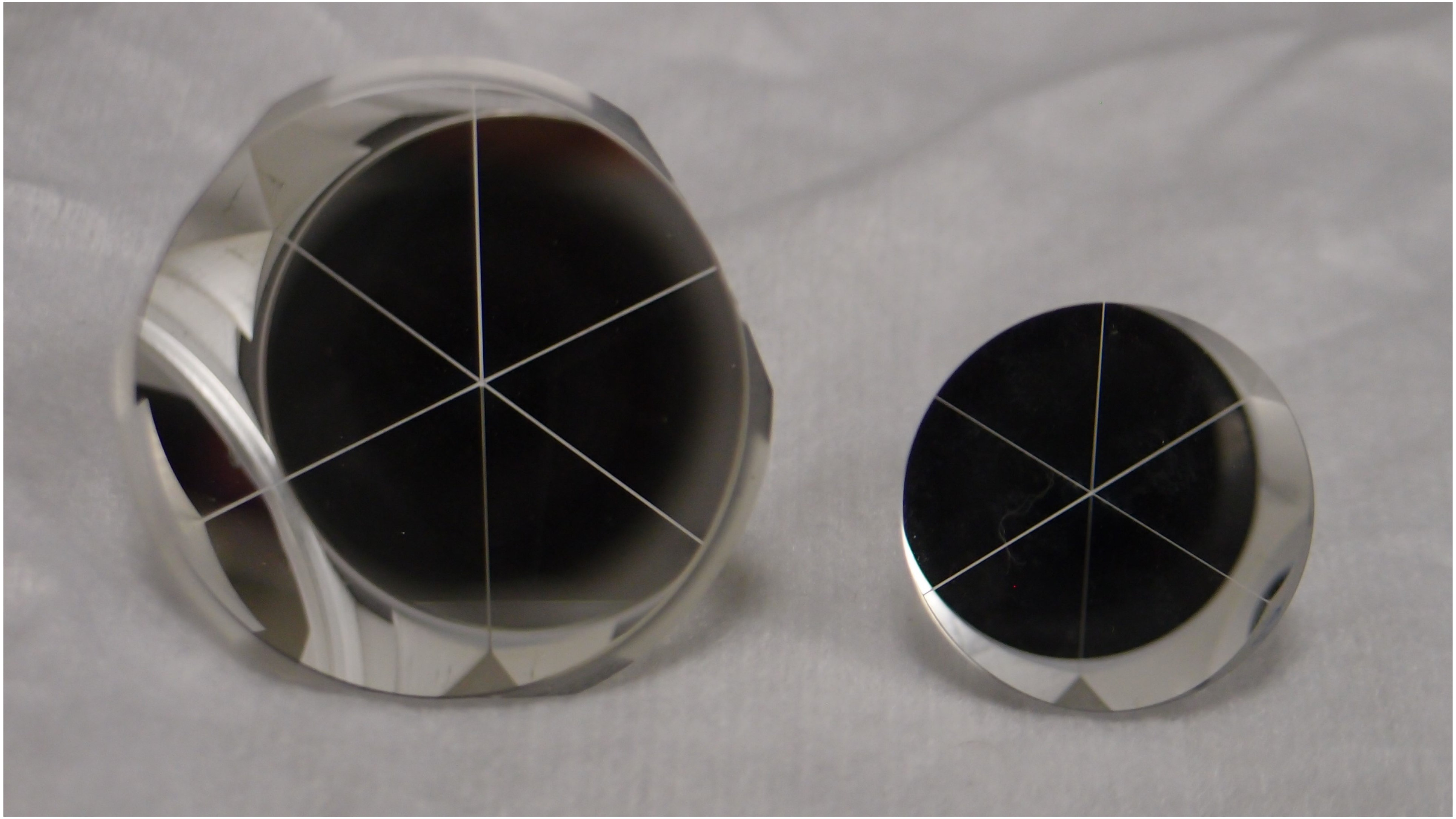


# LARES 2: what is new with respect to LAGEOS 3?

1) The Earth gravity field and the even zonal harmonics are today extremely improved thanks to the **GRACE** space mission (and the forthcoming **GRACE Follow On** space mission.)
The Earth quadrupole moment, J2, is and will be improved by a factor of more than 100 with respect to the Earth gravity field determinations in 1984!
The satellite can be injected into the orbit supplementary to LAGEOS with better accuracy than in 1984.

2) The knowledge of other orbital perturbations, such as the Earth's tidal perturbations, is quite improved with respect to 1984.

3) The satellite structure is quite improved with respect to all the other laser-ranged satellites. Using new retroreflectors we can today reach less than 1 mm accuracy in ranging!



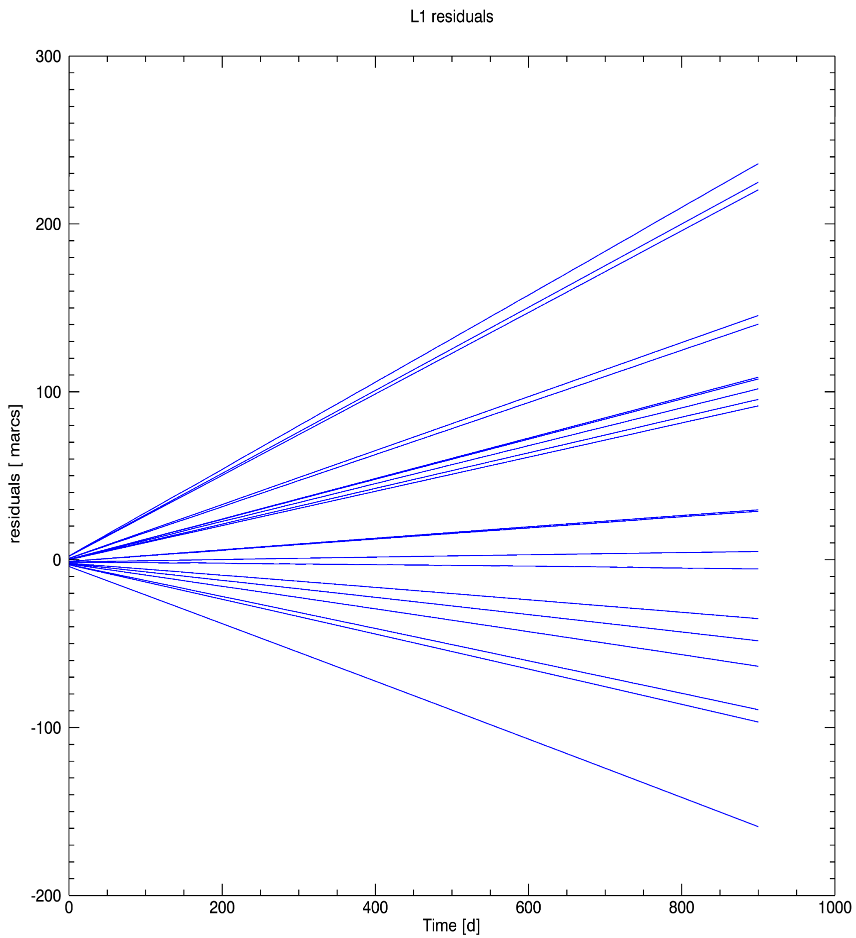
**1.5 inches CCR (LAGEOS, LAGEOS 2 and LARES) and 1 inch CCR**

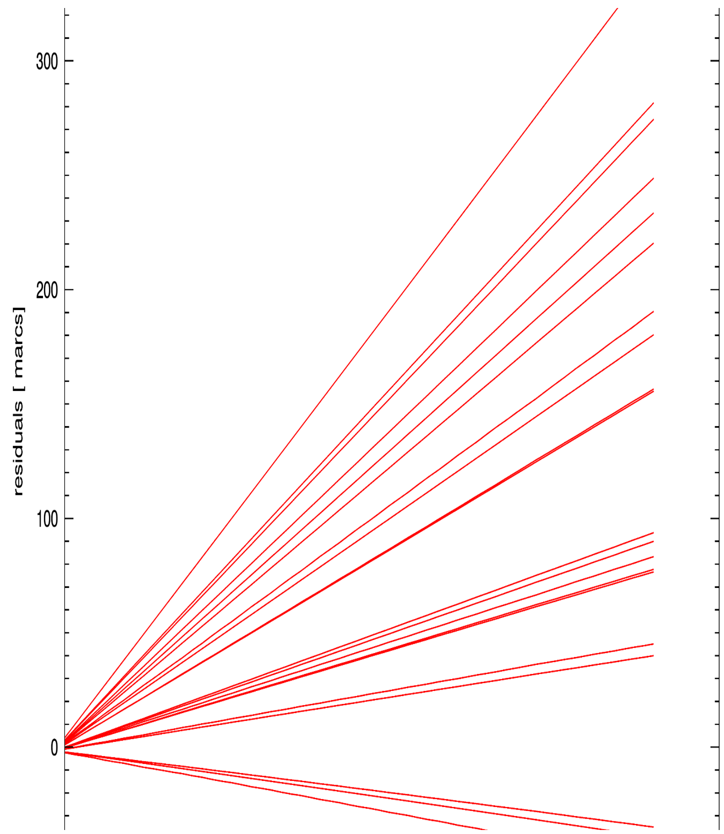
| Source of Error | Estimated error |
|---|---|
| Injection Error and Even Zonal Harmonics | ≅ 0.1\% of frame-dragging |
| Non-zonal harmonics and tides | ≅ 0.1\% of frame-dragging |
| Albedo | ≅ 0.1\% of frame-dragging |
| Thermal Drag and Satellites Eclipses | ≅ 0.1\% of frame-dragging |
| Measurement Error of the LAGEOS and LARES 2 Orbital Parameters | ≅ 0.1\% of frame-dragging |
| | |
| Total RSS Error | ≅ 0.2\% of frame-dragging |

## Error Budget of frame-dragging test with LARES 2 and LAGEOS

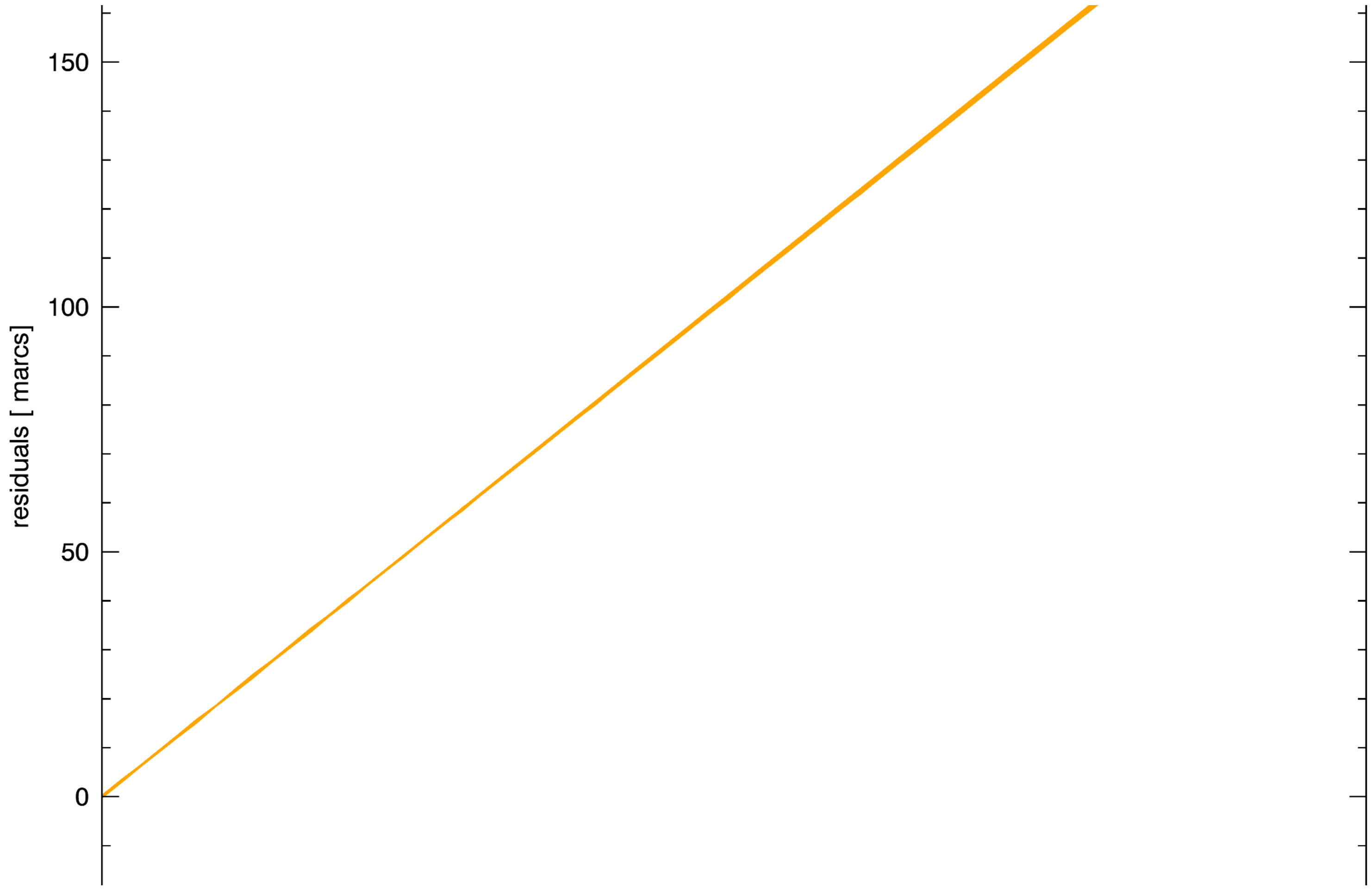
| Parameter | Nominal Value | 1-Sigma |
|---|---|---|
| GM | $0.3986004415 \cdot 10^{15}$ | $8 \cdot 10^{5}\ m^{3}/s^{2}$ |
| $C_{2,0}$ | $-0.4841652170620 \cdot 10^{-3}$ | $0.5 \cdot 10^{-11}$ |
| $C_{4,0}$ | $0.539998760 7610 \cdot 10^{-6}$ | $0.0614 \cdot 10^{-11}$ |
| $C_{6,0}$ | $-0.1499755784130 \cdot 10^{-6}$ | $0.36515 \cdot 10^{-12}$ |
| $C_{8,0}$ | $0.4947711611930 \cdot 10^{-7}$ | $0.26795 \cdot 10^{-12}$ |
| $C_{10,0}$ | $0.5334231244770 \cdot 10^{-7}$ | $0.2189 \cdot 10^{-12}$ |
| $\dot{C}_{2,0}$ | $1.207500000000 \cdot 10^{-11}$ | $0.00895 \cdot 10^{-11}$ |
| $\dot{C}_{4,0}$ | $0.470000000000 \cdot 10^{-11}$ | $0.165 \cdot 10^{-12}$ |
| $C_{30,0}$ | $9.571735690410 \cdot 10^{-7}$ | $0.6531 \cdot 10^{-11}$ |
| $C_{50,0}$ | $6.864653382320 \cdot 10^{-8}$ | $1.61115 \cdot 10^{-12}$ |
| $C_r$ LAGEOS | 1.13 | $0.3 \cdot 10^{-2}$ |
| $C_r$ LARES 2 | 1.10 | $0.3 \cdot 10^{-2}$ |

**Parameters considered in the Monte Carlo simulations with their sigmas (gravity field GOCO05S: 2015)**

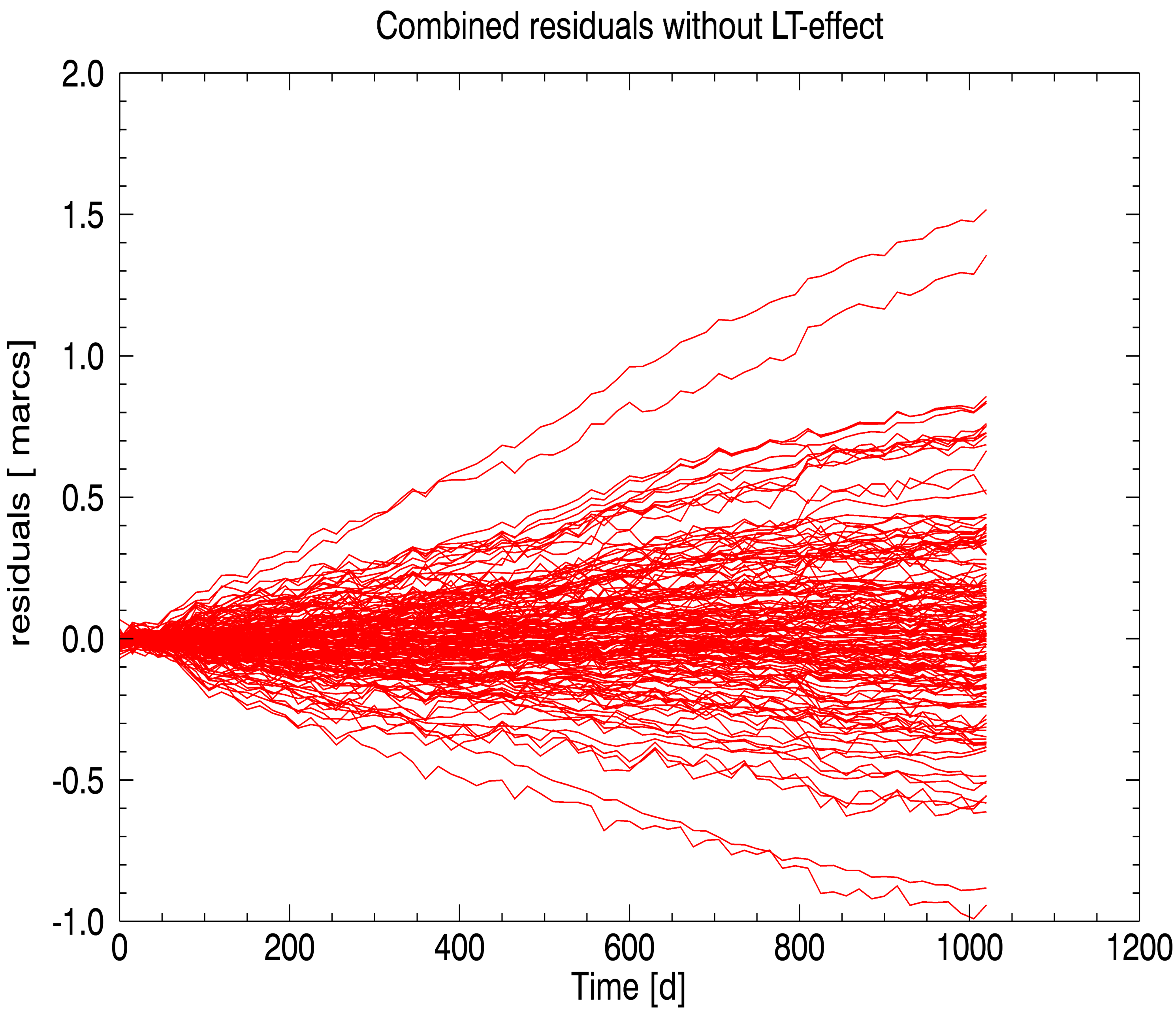



**Monte Carlo simulations of the LARES 2 experiment**

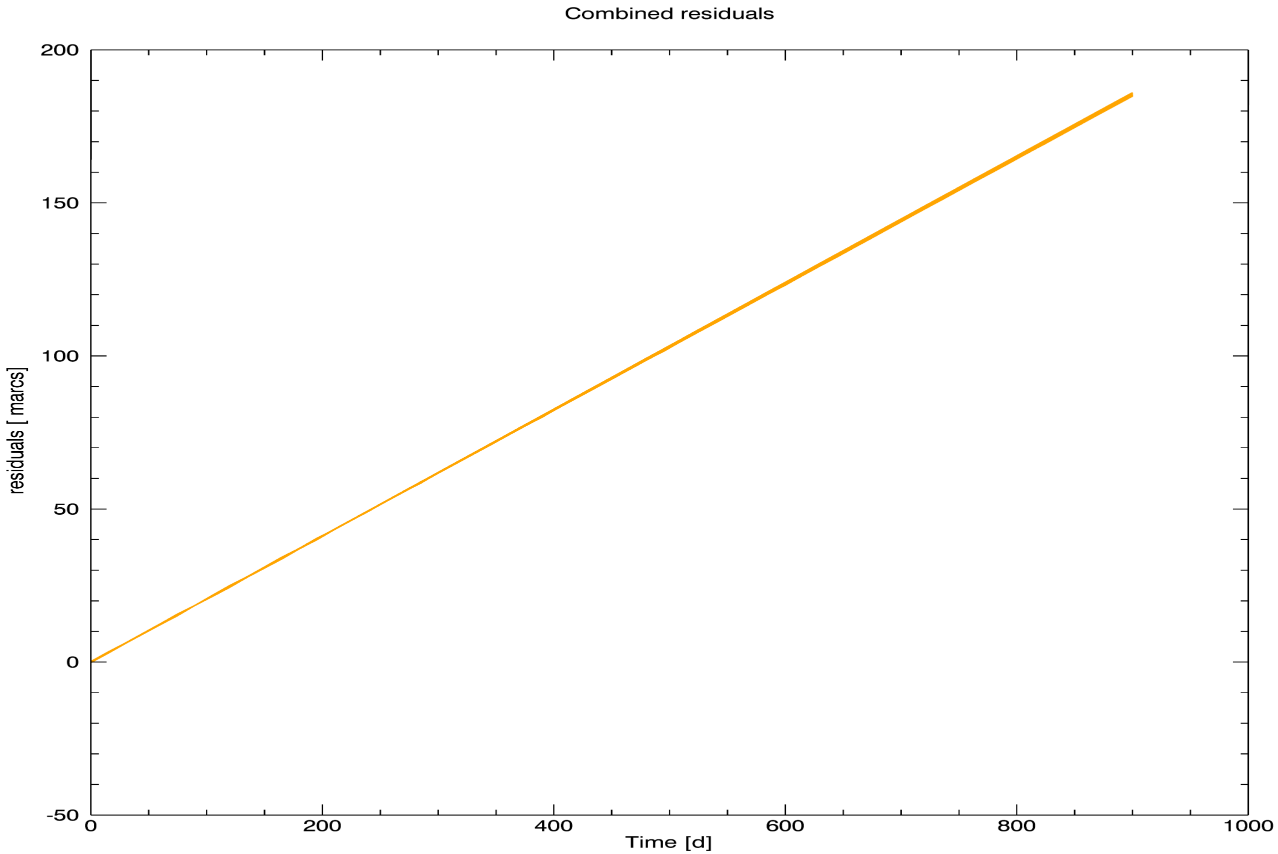



**Result: when the LAGEOS and LARES 2 orbits are combined the spread is at the level of about 0.15% of frame-dragging.**


Combined residuals without LT-effect
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
residuals [ marcs]
0
200
400
600
800
1000
1200
Time [d]

Similarly with a covariance analysis of the LARES 2-LAGEOS experiment we found:

$$\mu = 1.0007 \pm 0.0019$$



# Conclusions

Frame-dragging was measured in 2016 with about 5% accuracy using **LARES** + LAGEOS + LAGEOS 2.

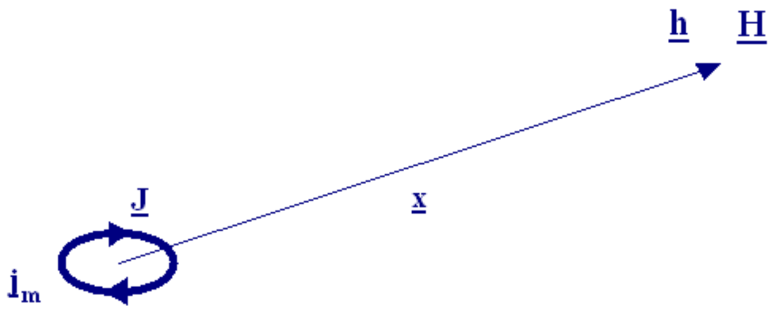
Frame-dragging will be measured (we have now almost 6 years of data) with about 2% accuracy using **LARES** + LAGEOS + LAGEOS 2.

**LARES 2** will be launched in 2019 and after about

3 years of data we may rech an accuracy of about 0.2% in testing frame-dragging, plus other tests of fundamental physics (under study).

# THE WEAK-FIELD AND SLOW MOTION ANALOGY WITH ELECTRODYNAMICS

## Gravitomagnetic Field in General Relativity




From weak field and slow motion limit of G= χ T:

$$\Delta\, h_{0i} \cong 16\,\pi\,\rho\, v^i$$

Lorentz gauge

**Electromagnetism**

$$\Delta\,\mathbf{A} = -\frac{4\pi}{c}\,\mathbf{j}$$

where $\mathbf{h} \equiv (h_{01},\ h_{02}\ , h_{03})$ is the gravitomagnetic potential

$$h_{0i}\,(\mathbf{x}) \cong -\,4\int \frac{\rho(\mathbf{x}')v^i(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}\,d^3x'$$

$$\mathbf{A}\,(\mathbf{x}) = \frac{1}{c}\int \frac{\mathbf{j}(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}\,d^3x'$$

$$\mathbf{h}\,(\mathbf{x}) \cong -\,2\,\frac{\mathbf{J}\times\mathbf{x}}{|\mathbf{x}|^3}$$

$$\mathbf{A}\,(\mathbf{x}) \cong \frac{\mathbf{m}\times\mathbf{x}}{|\mathbf{x}|^3}$$

The gravitomagnetic field is:

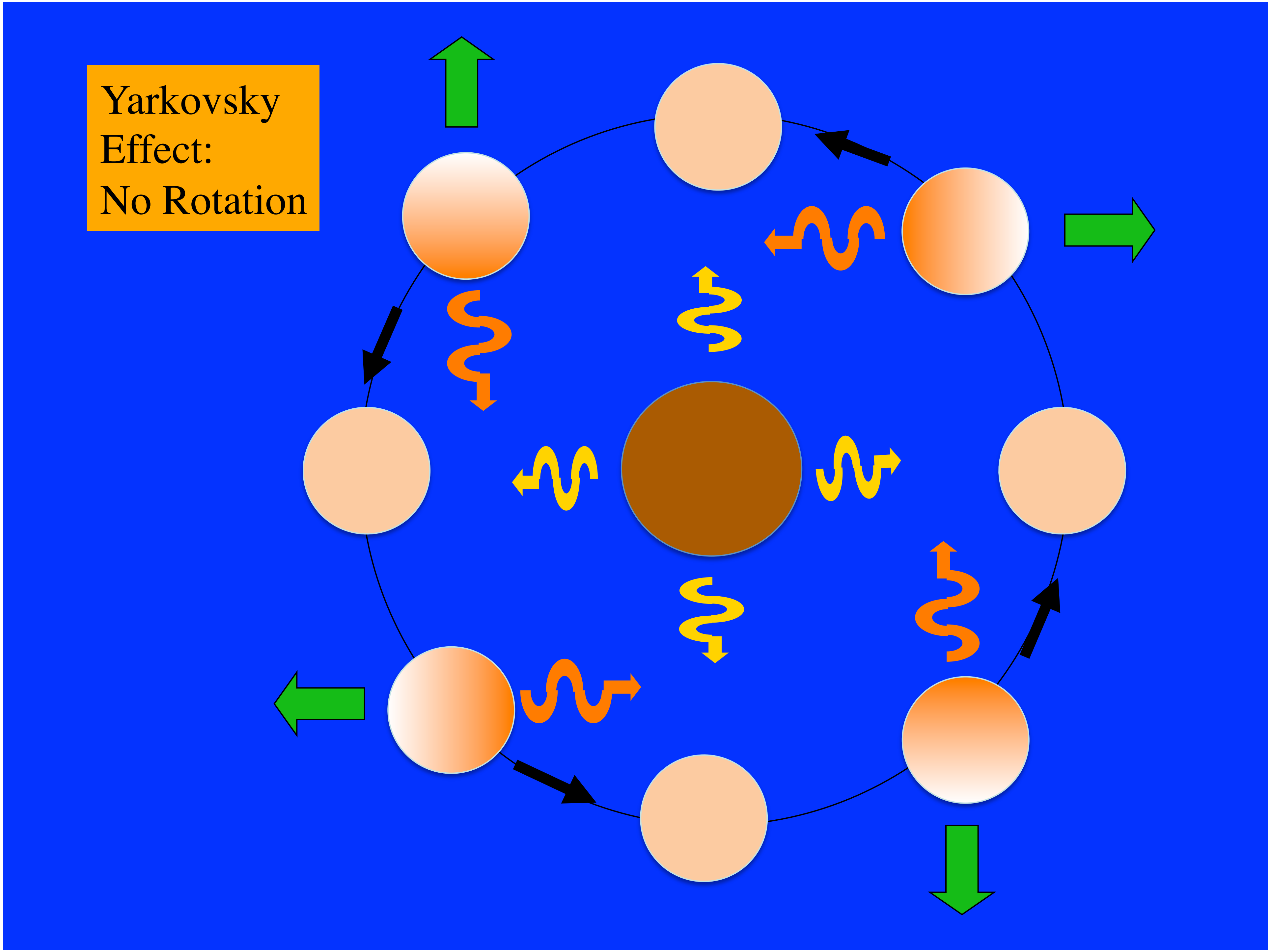
$$\mathbf{H} = \nabla\times\mathbf{h} \cong 2\left[\frac{\mathbf{J}-3(\mathbf{J}\cdot\hat{\mathbf{x}})\,\hat{\mathbf{x}}}{|\mathbf{x}|^3}\right]$$

$$\mathbf{B} = \nabla\times\mathbf{A} \cong \cong \frac{3\,\hat{\mathbf{x}}\,(\hat{\mathbf{x}}\cdot\mathbf{m})-\mathbf{m}}{|\mathbf{x}|^3}$$

From weak field and slow motion limit of D u=0:

$$m\,\frac{d^2\mathbf{x}}{dt^2} \cong m\,(\mathbf{G}+\frac{d\mathbf{x}}{dt}\times\mathbf{H})$$

$$m\,\frac{d^2\mathbf{x}}{dt^2} = q\,(\mathbf{E}+\frac{d\mathbf{x}}{dt}\times\mathbf{B})$$


Yarkovsky
Effect:
No Rotation