Fisica Fondamentale nello Spazio

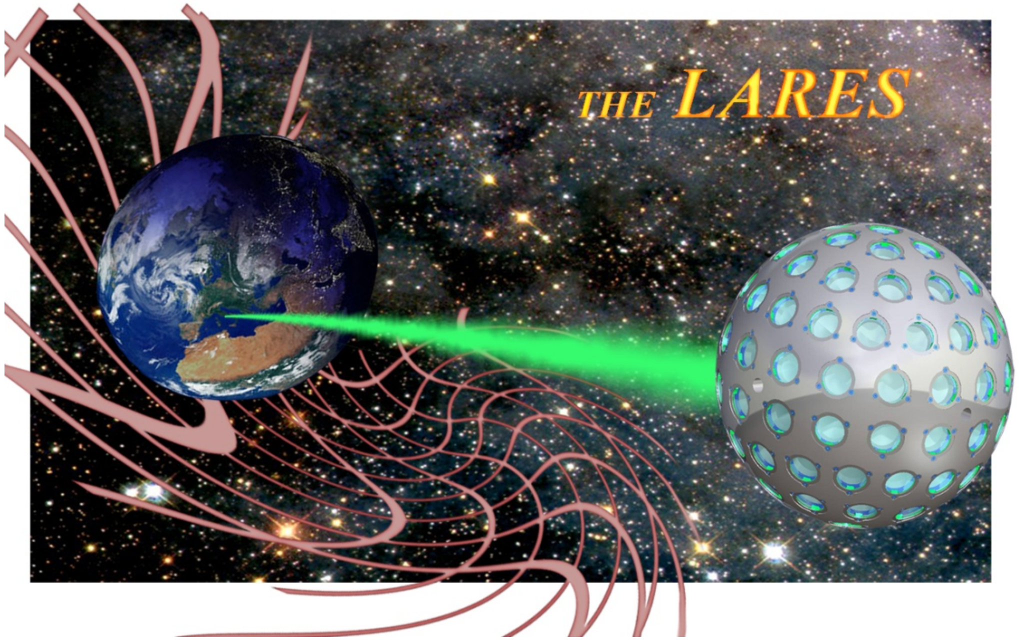
Project Coordinator: Prof. Ignazio Ciufolini

Italian Institutions & Collaborations:
Dipartimento di Ingegneria dell'Innovazione, Università del Salento.
Scuola di Ingegneria Aerospaziale – Sapienza Università di Roma.
Centro Fermi, Roma

Projects:
LARES satellite
A new satellite: LARES 2 (LAGEOS 3)
Nanosatellite: small particle detector

Centro Fermi: 2 March 2017

Ignazio Ciufolini
University of Salento, Lecce and Centro Fermi, Roma



A. Paolozzi*, E. Pavlis*,
R. Koenig*, J. Ries*,
R. Matzner*, V. Gurzadyan*,
R. Penrose*, G. Sindoni*,
C. Paris*

*Sapienza Un. Rome,
*Maryland Un.,
*Helmholtz Cent.-GFZ, Potsdam
*Un. Texas Austin
*Alikhanian Nat. Lab., Yerevan
*Oxford Un.

Fisica Relativistica nello Spazio

Research Group:

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Dr. Claudio Paris, **assegnista di ricerca Centro Fermi.**

Dr. Giampiero Sindoni, assegnista di ricerca, Scuola di Ingegneria Aerospaziale – Sapienza Università di Roma.

Foreign Research Group:

Erricos C. Pavlis (Univ. Maryland and NASA Goddard, USA),
Rolf Koenig (GFZ, Germany),
J. Ries (Univ of Texas at Austin, USA),
Vahe Gurzadyan (Center for Cosmology and Astrophysics, Armenia),
Richard Matzner (Univ of Texas at Austin, USA),
Roger Penrose (Univ. of Oxford, UK).

DRAGGING OF INERTIAL FRAMES

(*FRAME-DRAGGING* as Einstein named it in 1913)

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

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

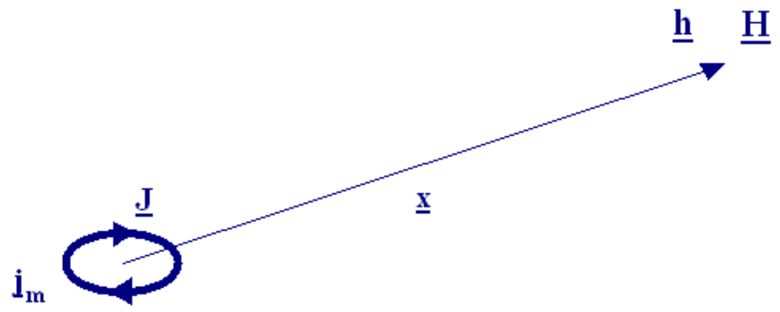
$$= \chi\, [(\varepsilon + p)\, u^{\alpha} u^{\beta} + p\, g^{\alpha\beta}]$$

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

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

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:

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

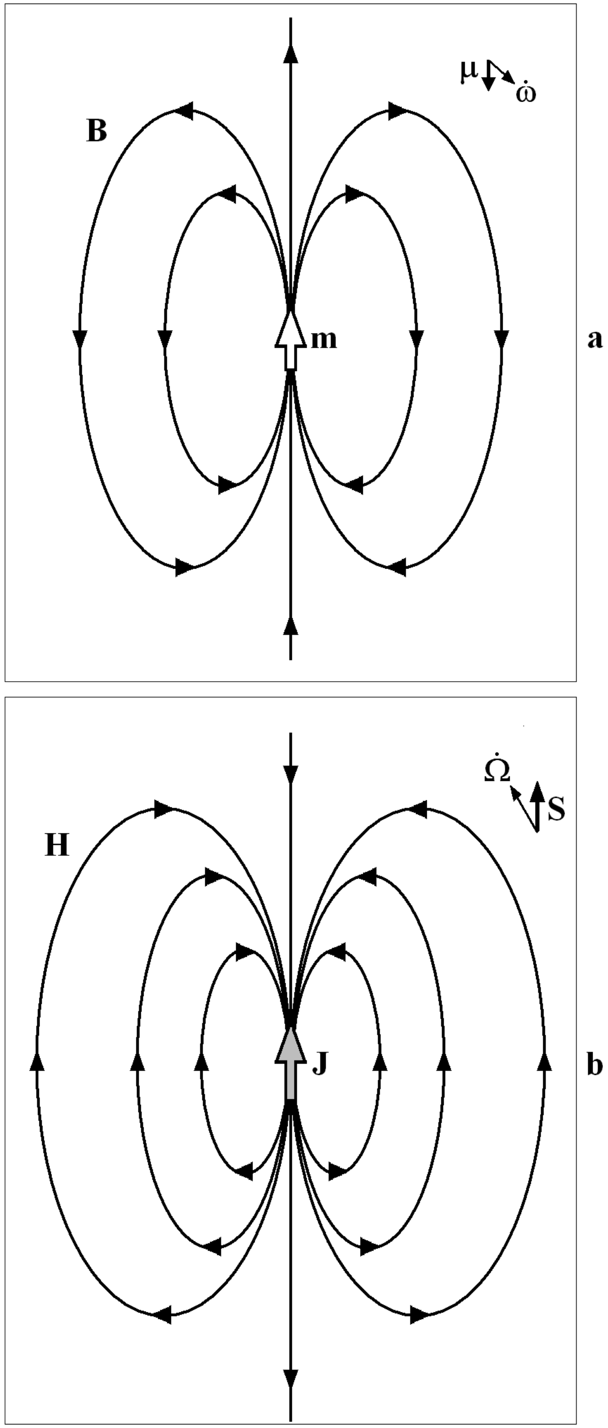
$$\mathbf{B} = \nabla\times\mathbf{A} \cong \frac{3\,\hat{\mathbf{x}}\,(\hat{\mathbf{x}}\cdot\mathbf{m}) - \mathbf{m}}{|\mathbf{x}|^3}$$

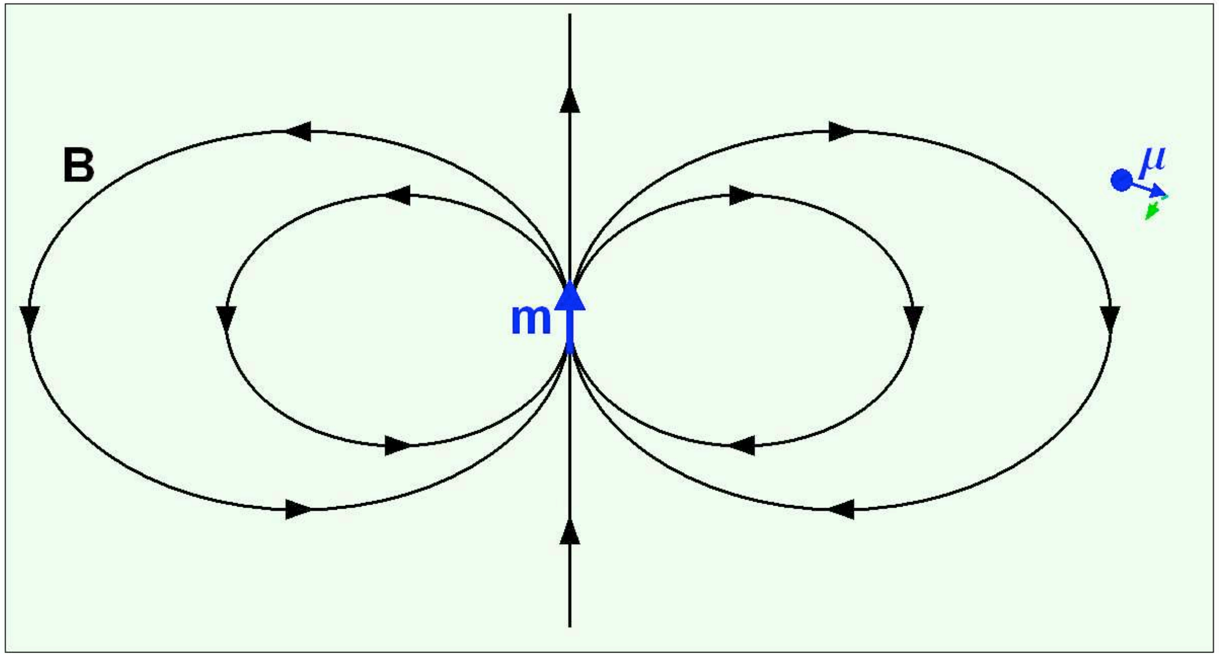
From weak field and slow motion limit of D u=0:

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

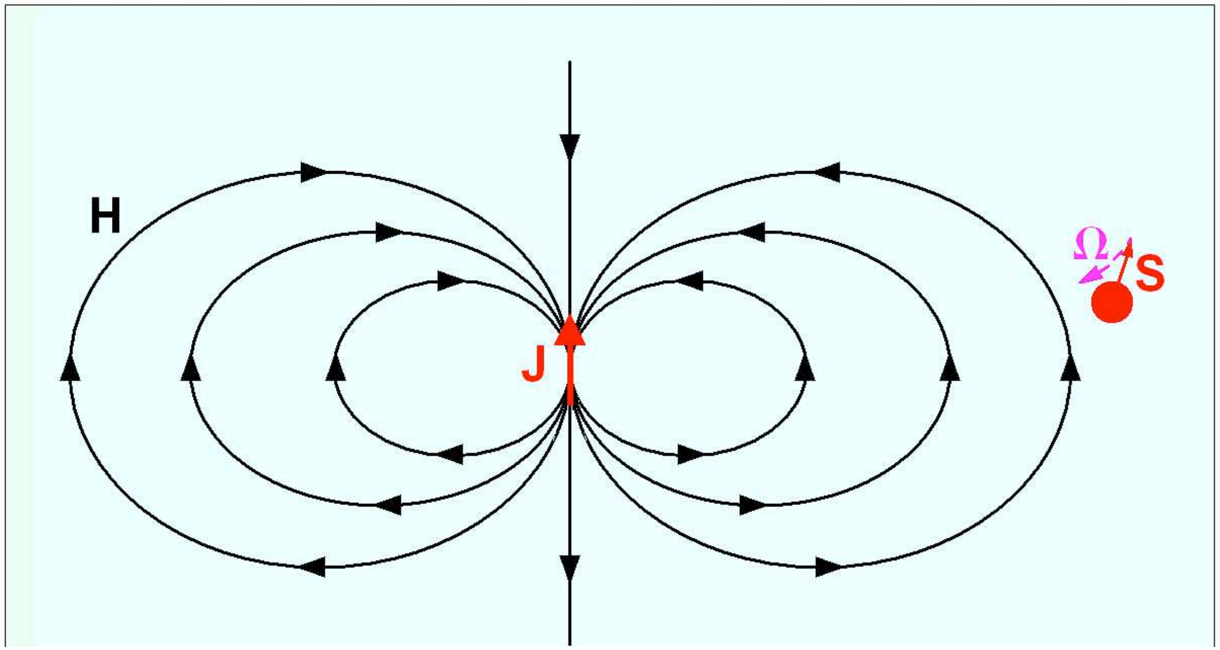
$$m\,\frac{d^2\mathbf{x}}{dt^2} = q\,(\mathbf{E} + \frac{d\mathbf{x}}{dt}\times\mathbf{B})$$

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

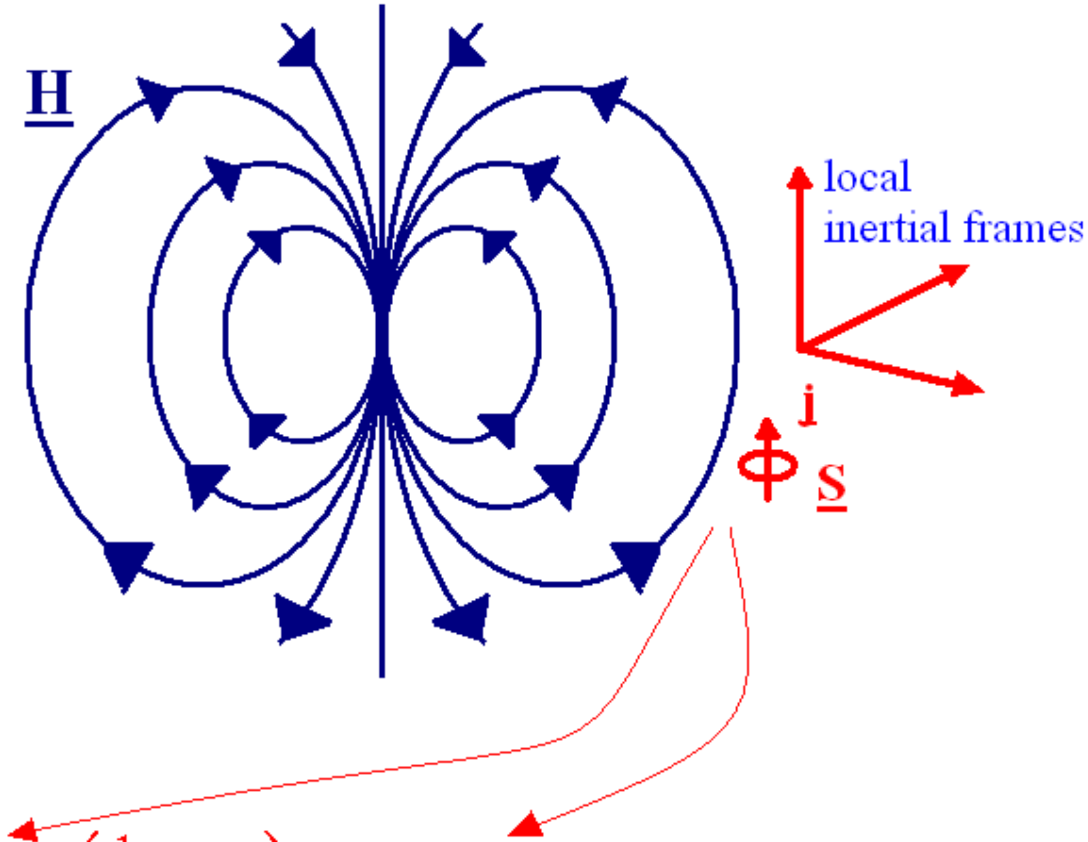




a



b



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

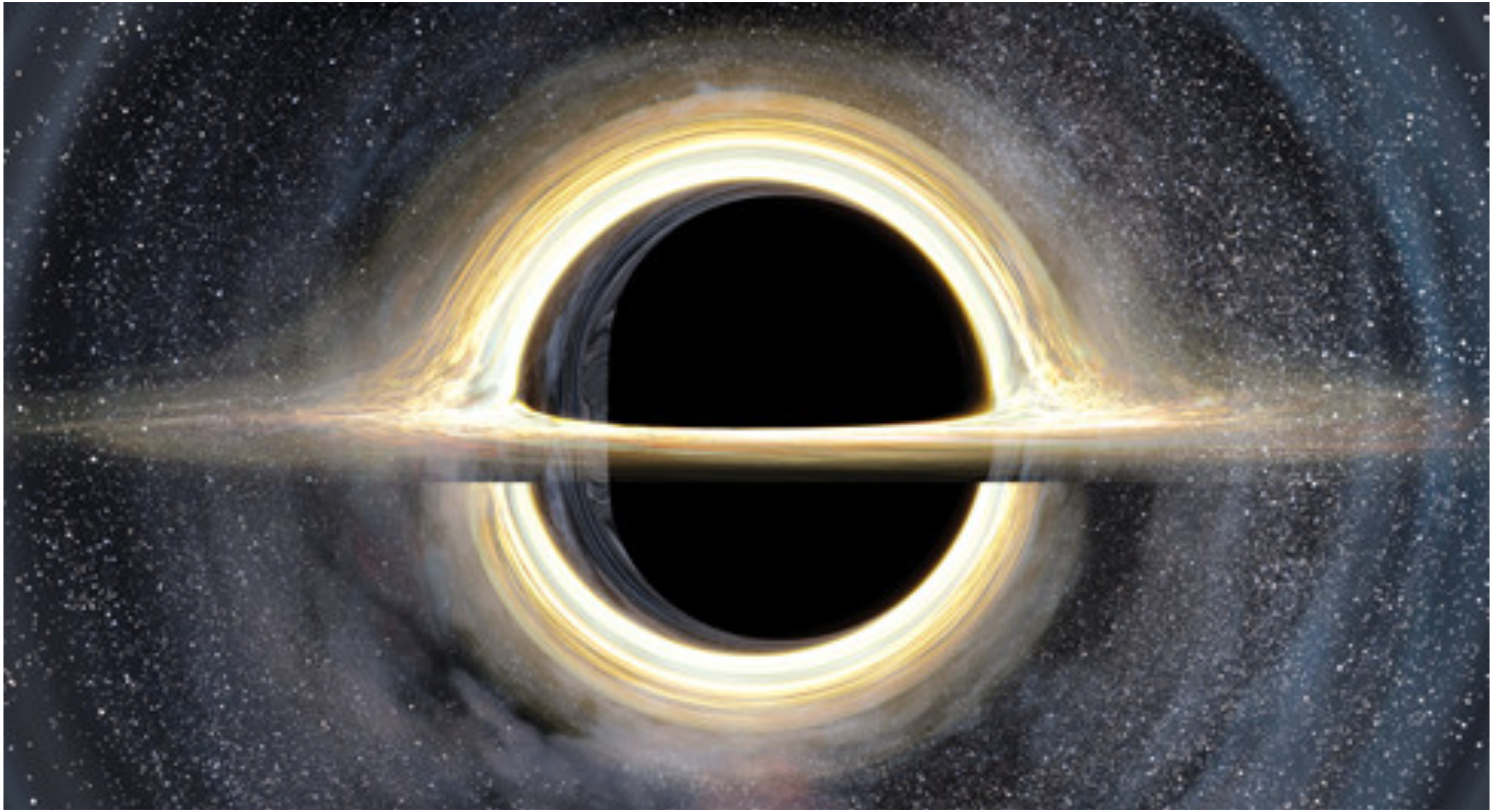
$$\dot{\mathbf{\Omega}} = -\tfrac{1}{2}\mathbf{H} = \frac{-\mathbf{J} + 3(\mathbf{J}\cdot\hat{\mathbf{x}})\hat{\mathbf{x}}}{|\mathbf{x}|^3}$$

Dragging of inertial frames:

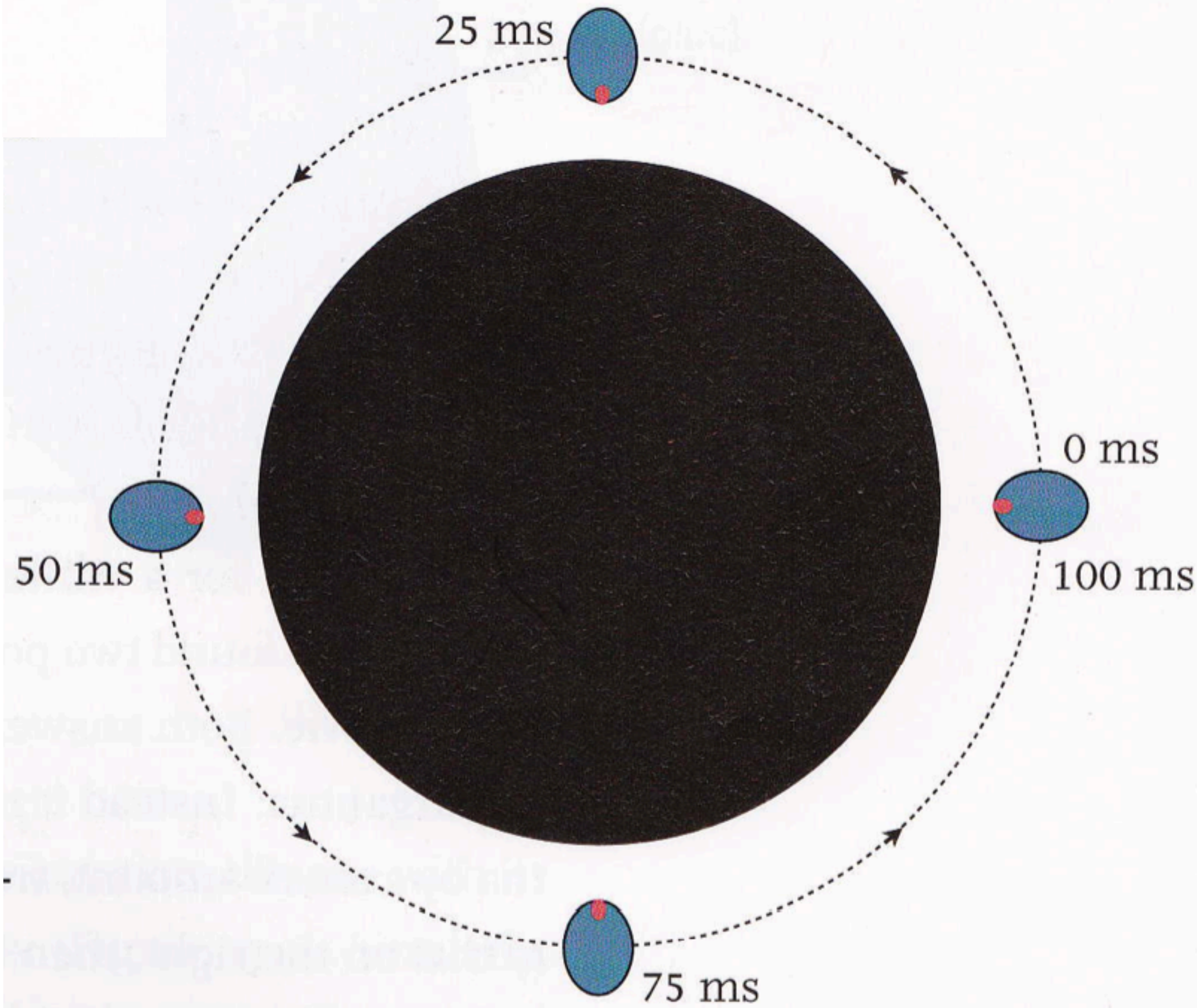
Mach principle in general relativity

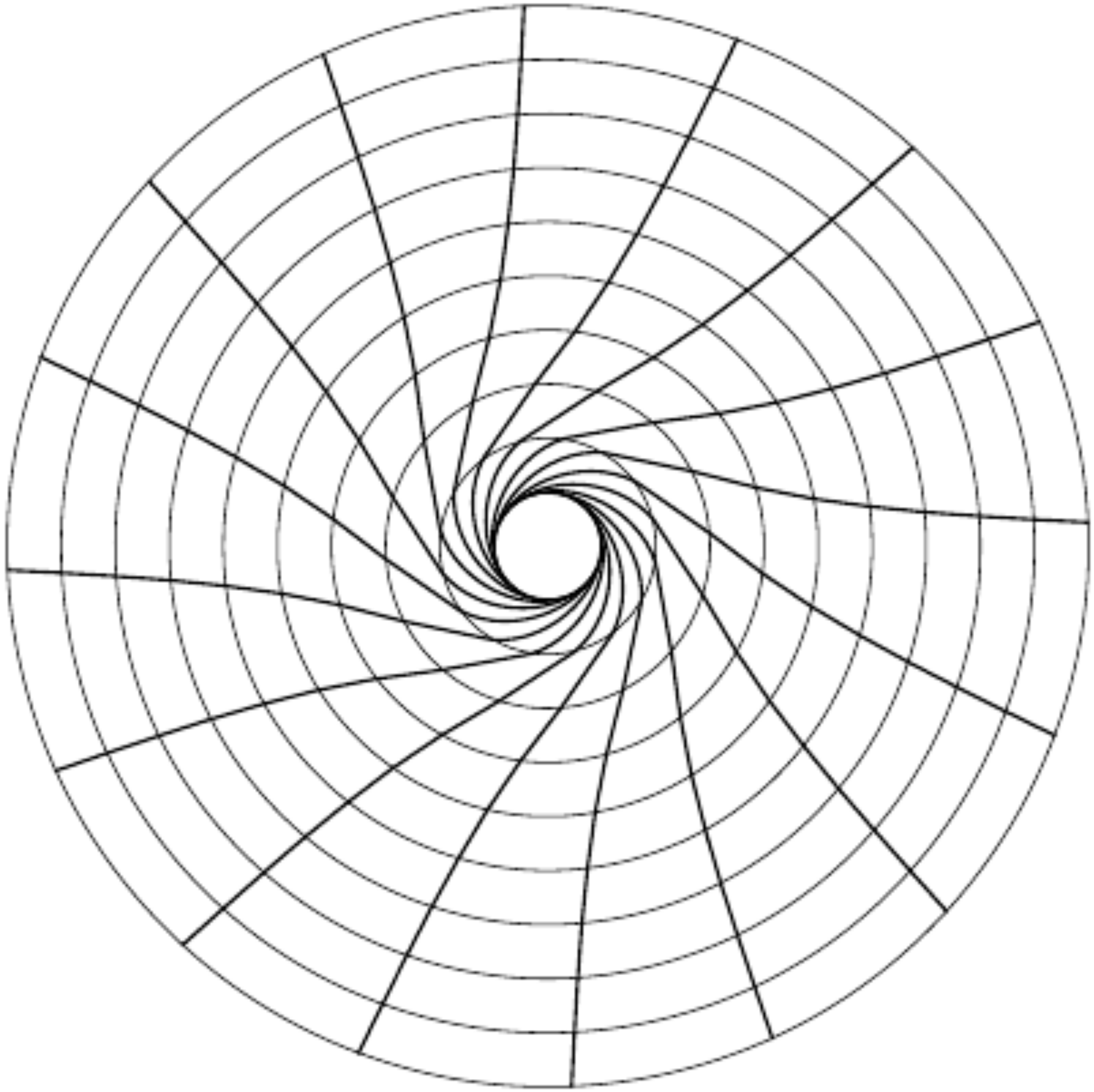
GRAVITATION AND INERTIA

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



GARGANTUA: a supermassive rotating black hole: frame-dragging plays a key role

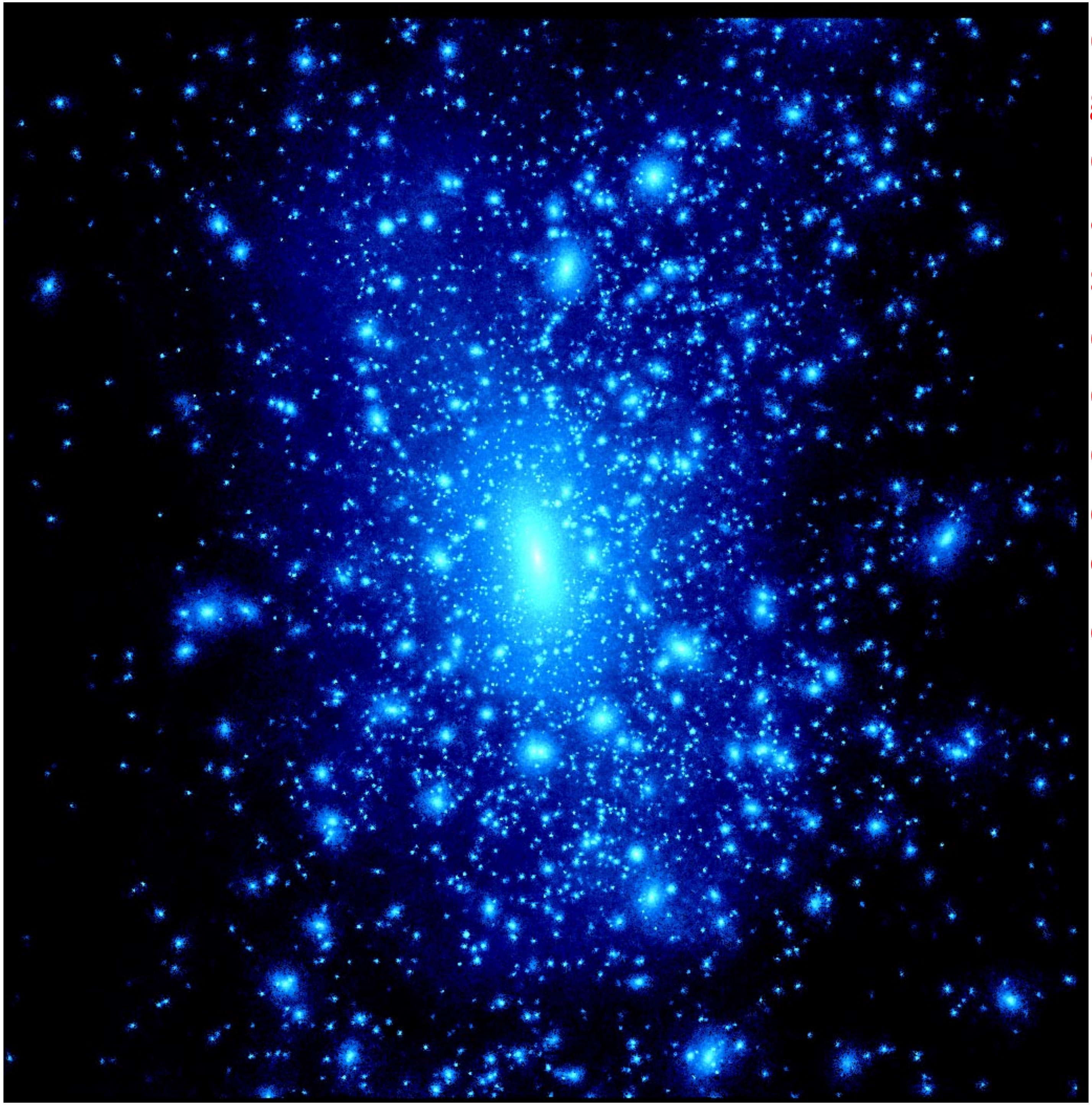

25 ms
0 ms
100 ms
50 ms
75 ms



https://www.youtube.com/watch?v=aEPIwEJmZyE

6:38, 8:55 31:24, **35:00** by Kip Thorne and Harald Pfeiffer

GW and frame-dragging



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:

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

$^*R \cdot R = ½\, \varepsilon_{\alpha\beta\sigma\rho}\, R^{\sigma\rho}{}_{\mu\nu}\, R^{\alpha\beta\mu\nu}$ is the Pontryagin pseudoscalar, θ 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 θ is:

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

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 ρ, of radius R, rotating with angular velocity ω, outside the sphere we have:

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

Where the General Relativity contribution is:

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

And the Chern-Simons contribution is:

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

where:

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

$$D_2(r) = m_{cs}R j_2(m_{cs}R) y_1(m_{cs}r) \,,$$

$$D_3(r) = m_{cs}R j_2(m_{cs}R) y_2(m_{cs}r) \,,$$

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.
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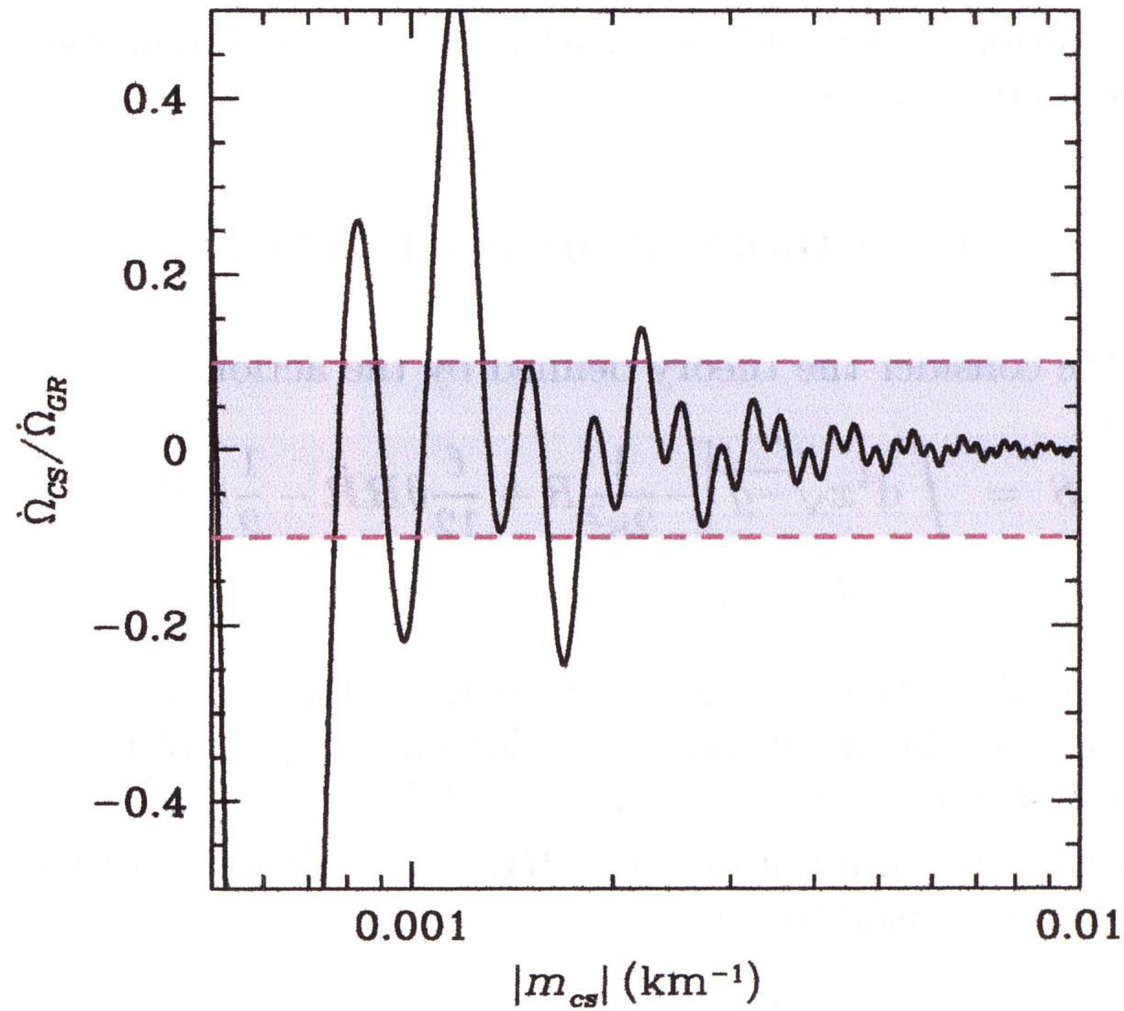


$m_{cs} \geq 2 \times 10^{-22}$ GeV

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.

A brief history of the main tests of frame-dragging (see also, e.g., Clifford Will papers on reviews of tests of General Relativity)

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. Cost of GRAVITY PROBE B almost 1 billion of dollars.

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 …). Lettere di supporto al LAGEOS 3 sono state scritte alla NASA e all'ASI da alcuni dei più noti fisici: JOHN ARCHIBALD WHEELER, KIP THORNE, TULLIO REGGE, NICOLA CABIBBO, ..

LAGEOS and LAGEOS 2: The LAGEOS satellite was launched in 1976 by NASA and LAGEOS 2 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.

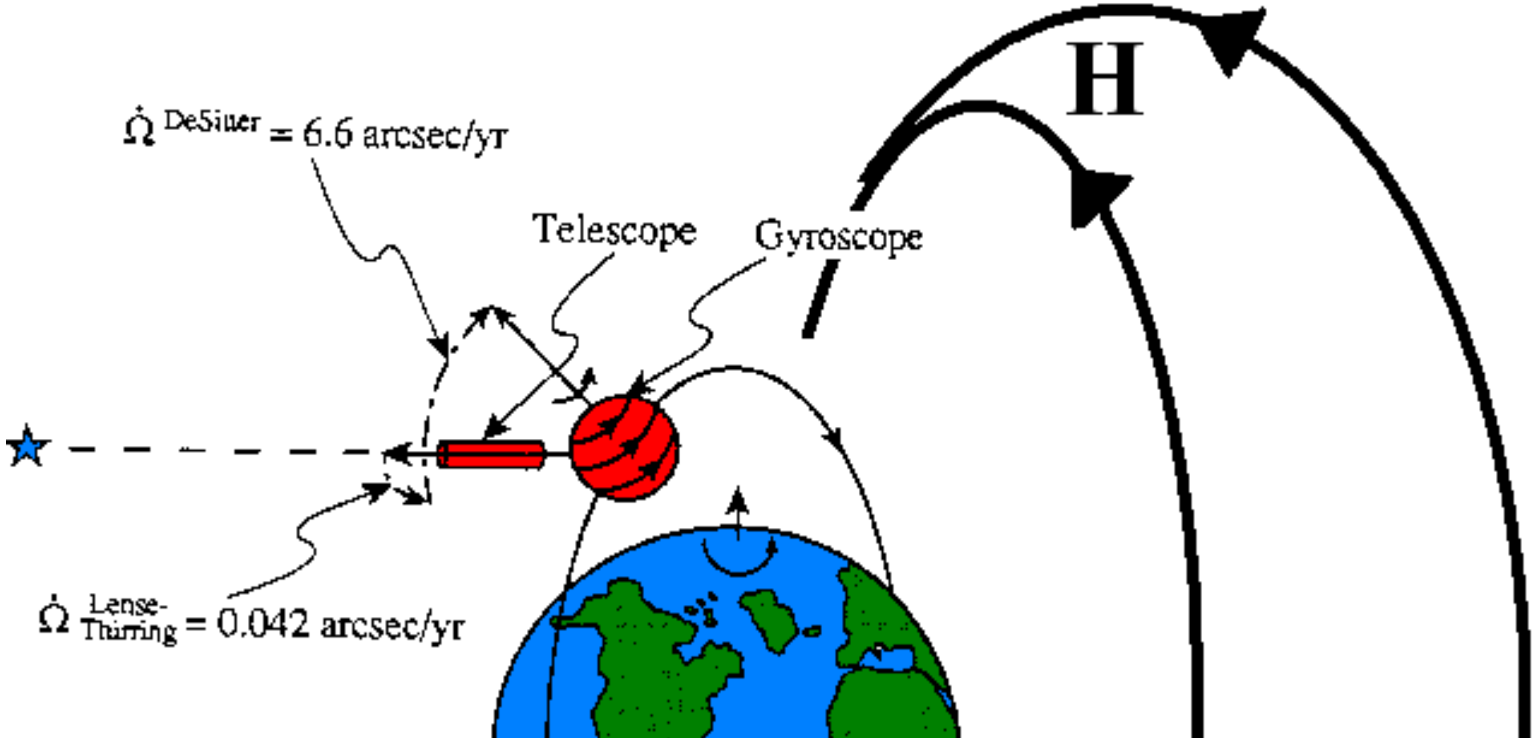
LAGEOS and LAGEOS 2: 2004-2010: it was published the first measurement (with accuracy of approximately 10%) of frame-dragging (*Nature 2004, General Relativity book 2010, etc.*) using GEODYN. Independently confirmed by the Univ. of Texas at Austin (2008/2009, with UTOPIA) and GFZ-DLR (2010, with EPOSOC).

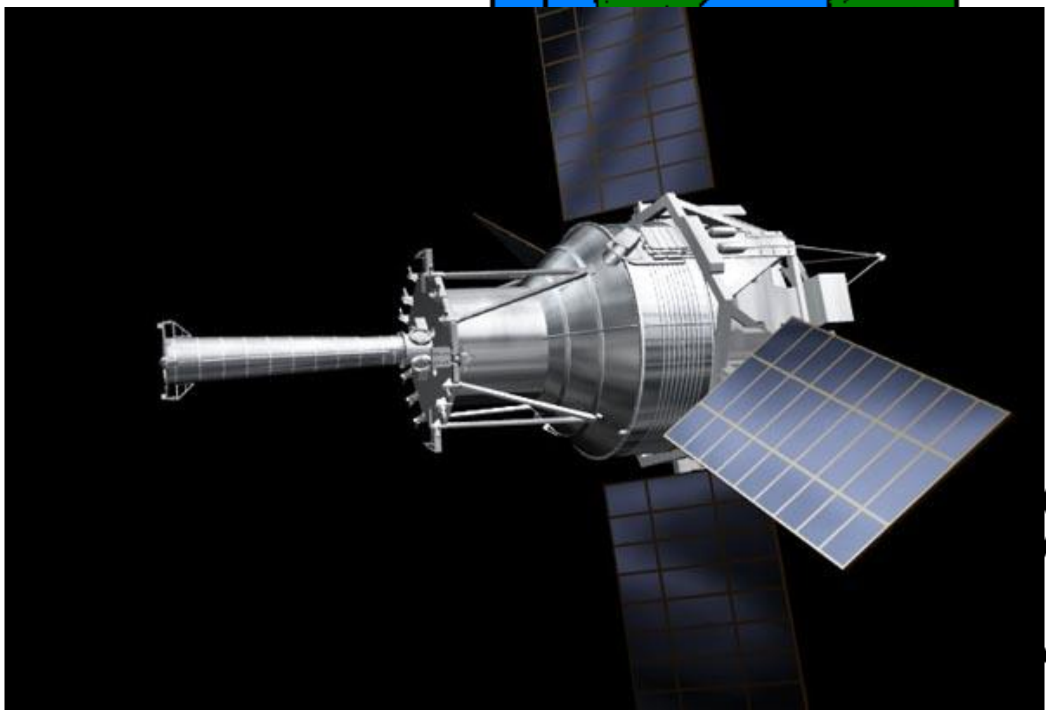
Gravity Probe result, 2011-2015: it was published a measurement of frame-dragging with approximately 20% accuracy (*Phys. Rev. Lett. 2011 and CQG 2015*).

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

LARES forthcoming results will reach about 2% accuracy

LARES 2: 0.2% accuracy



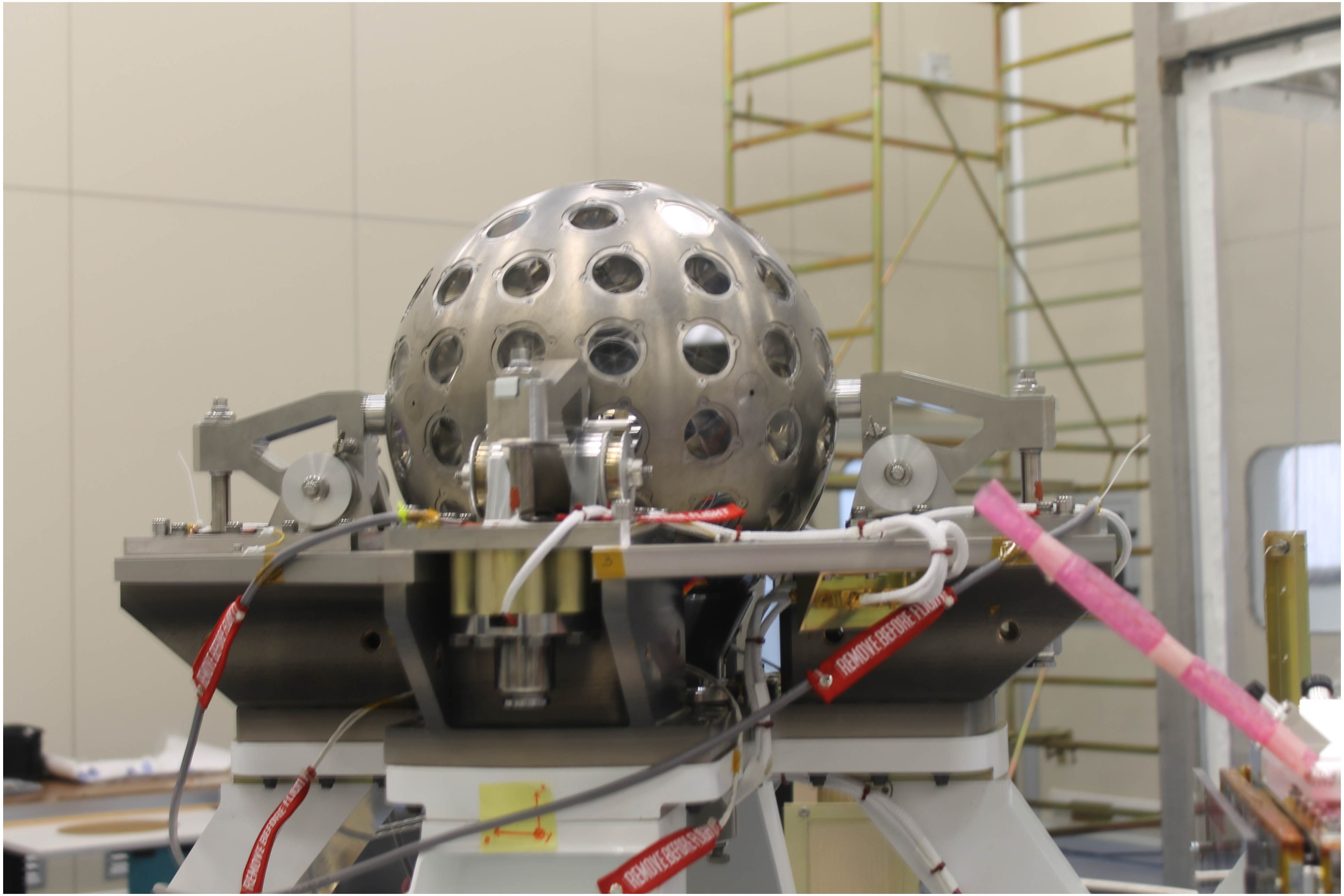


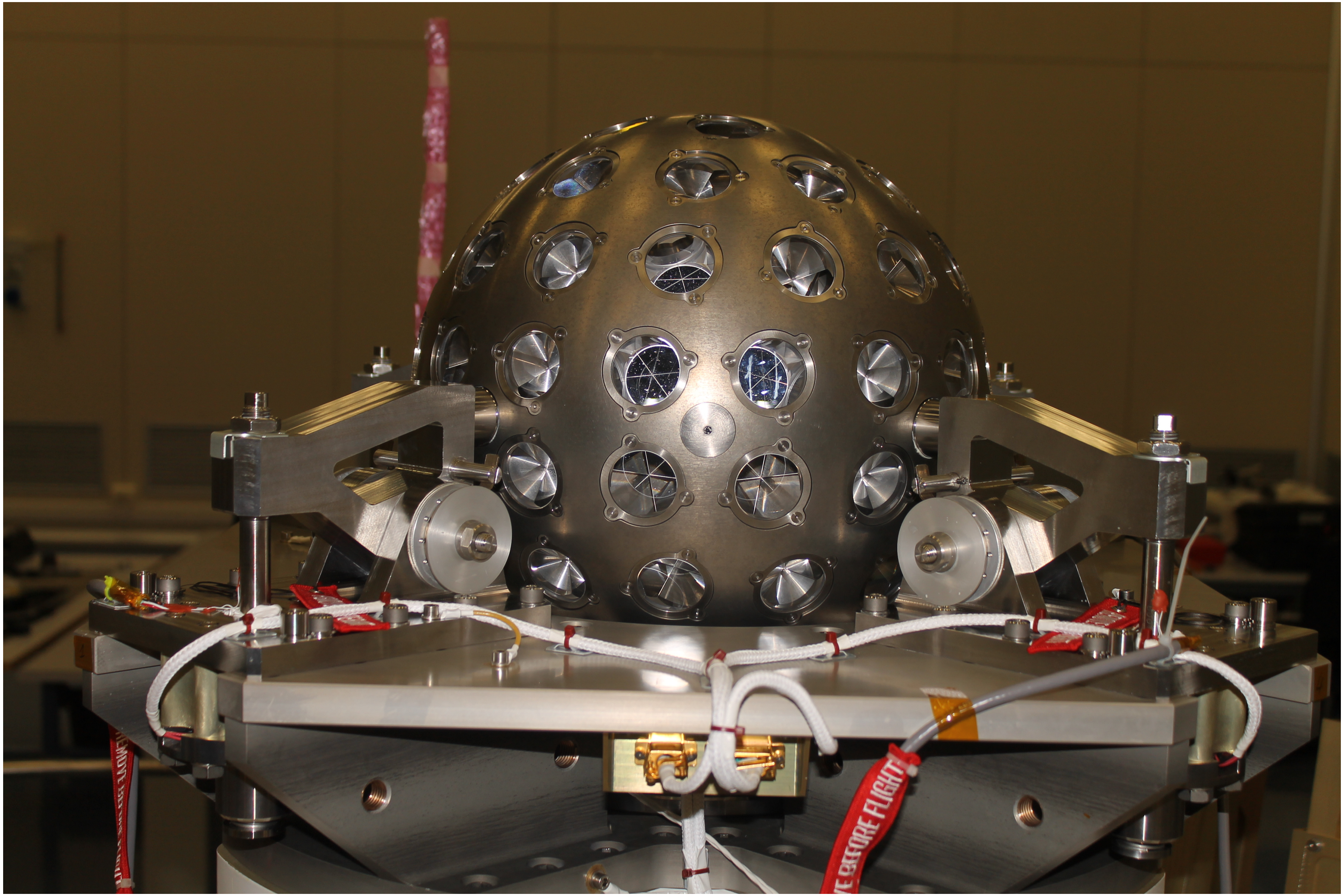
GRAVITY PROBE B, 1960-2015

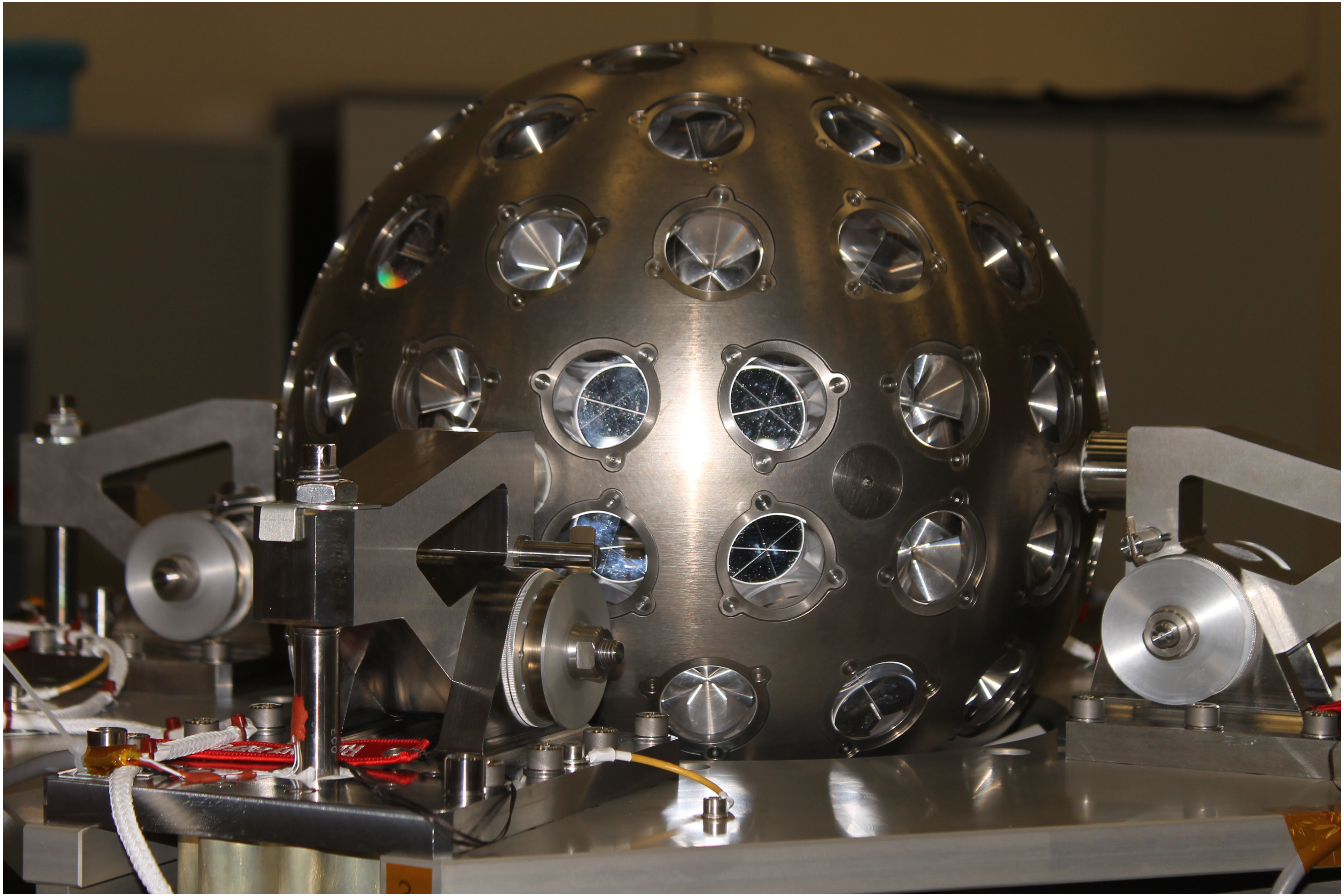
GRAVITY PROBE B

LARES
(LAser RElativity Satellite)

LARES was successfully launched and very accurately injected in the nominal orbit on the 13th of February 2012 with the new launching vehicle of ESA/ASI built by AVIO/ASI/ELV.


REMOVE BEFORE FLIGHT

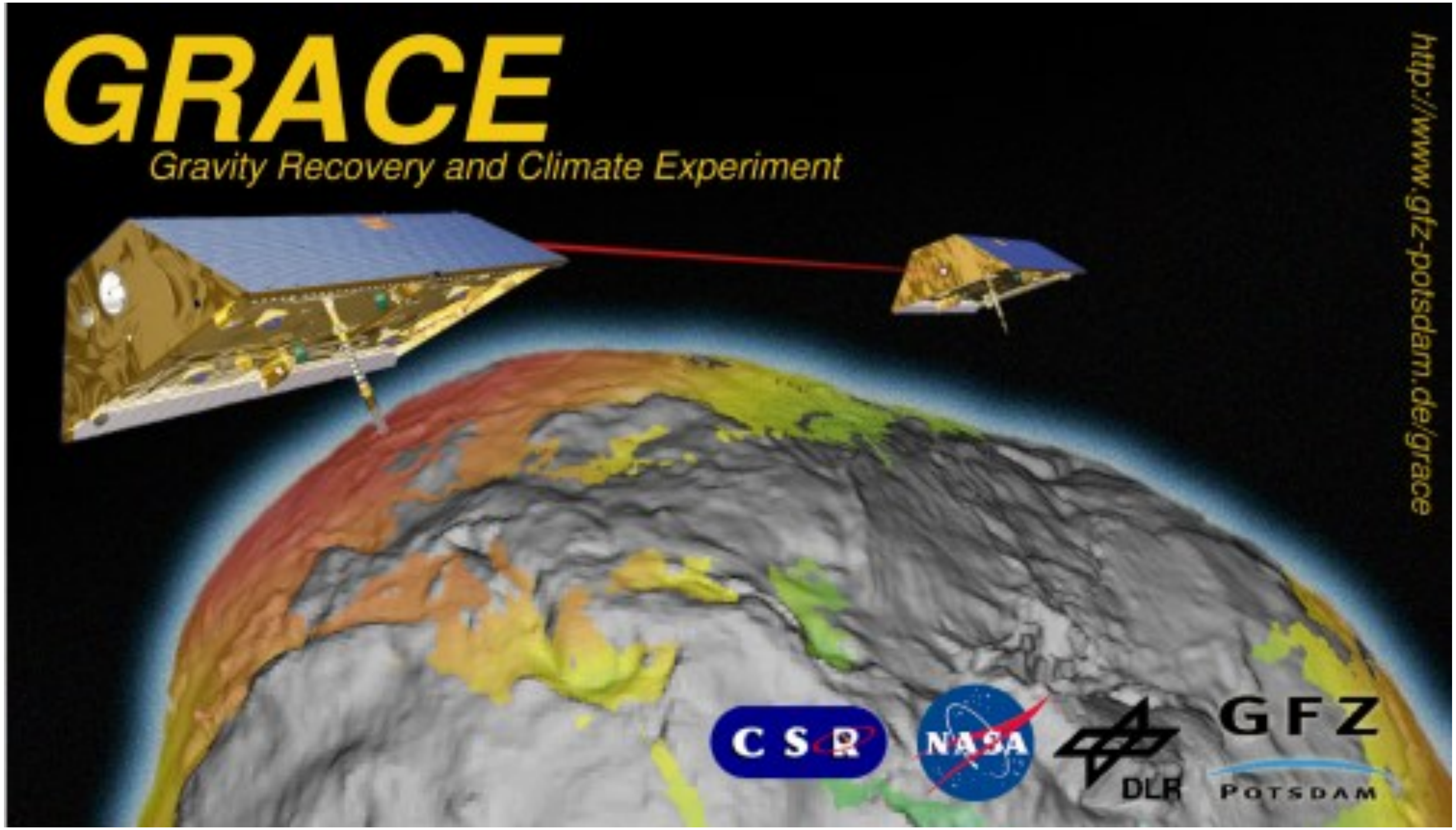




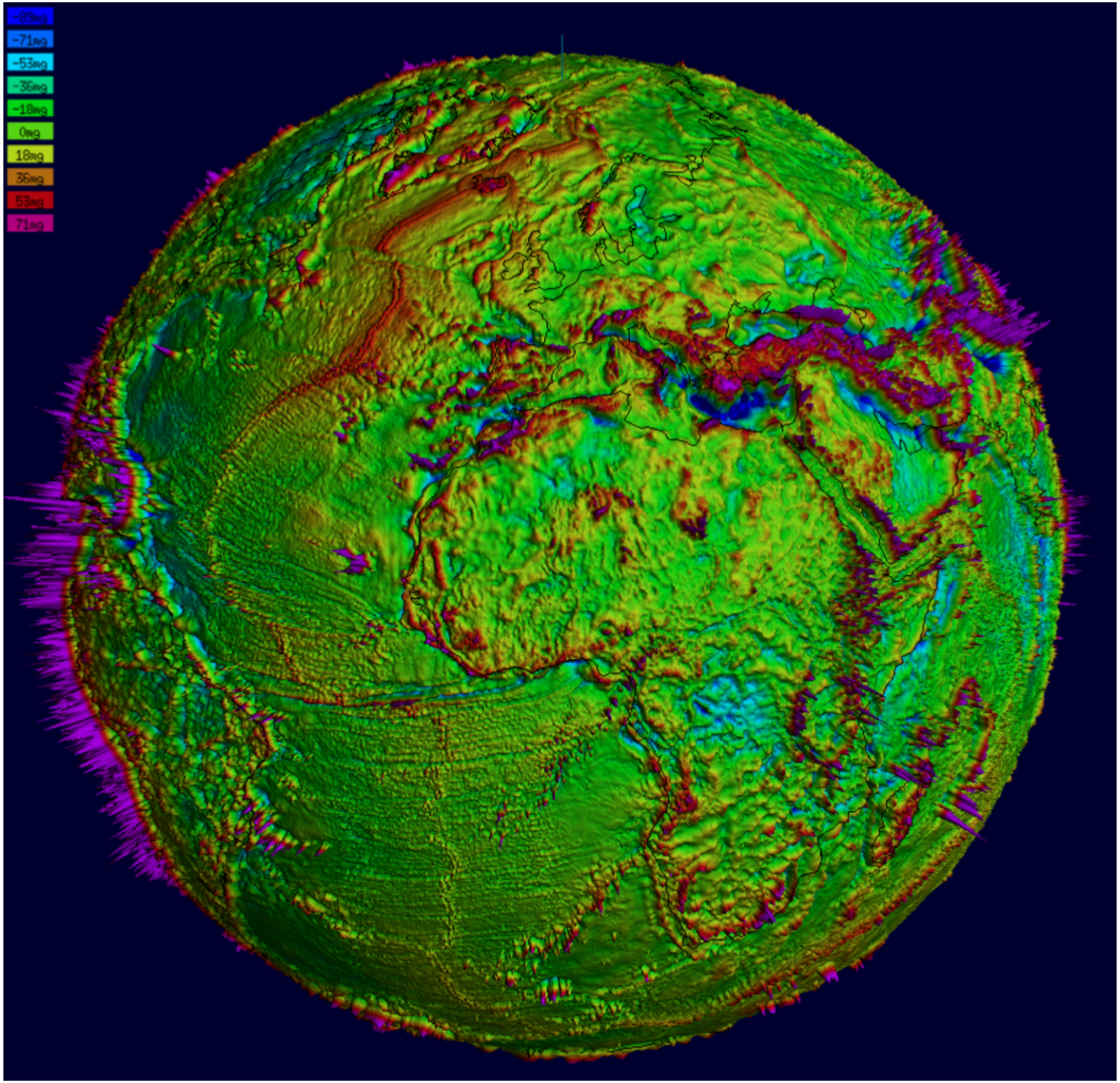
LARES
(LAser RElativity Satellite)
Italian Space Agency

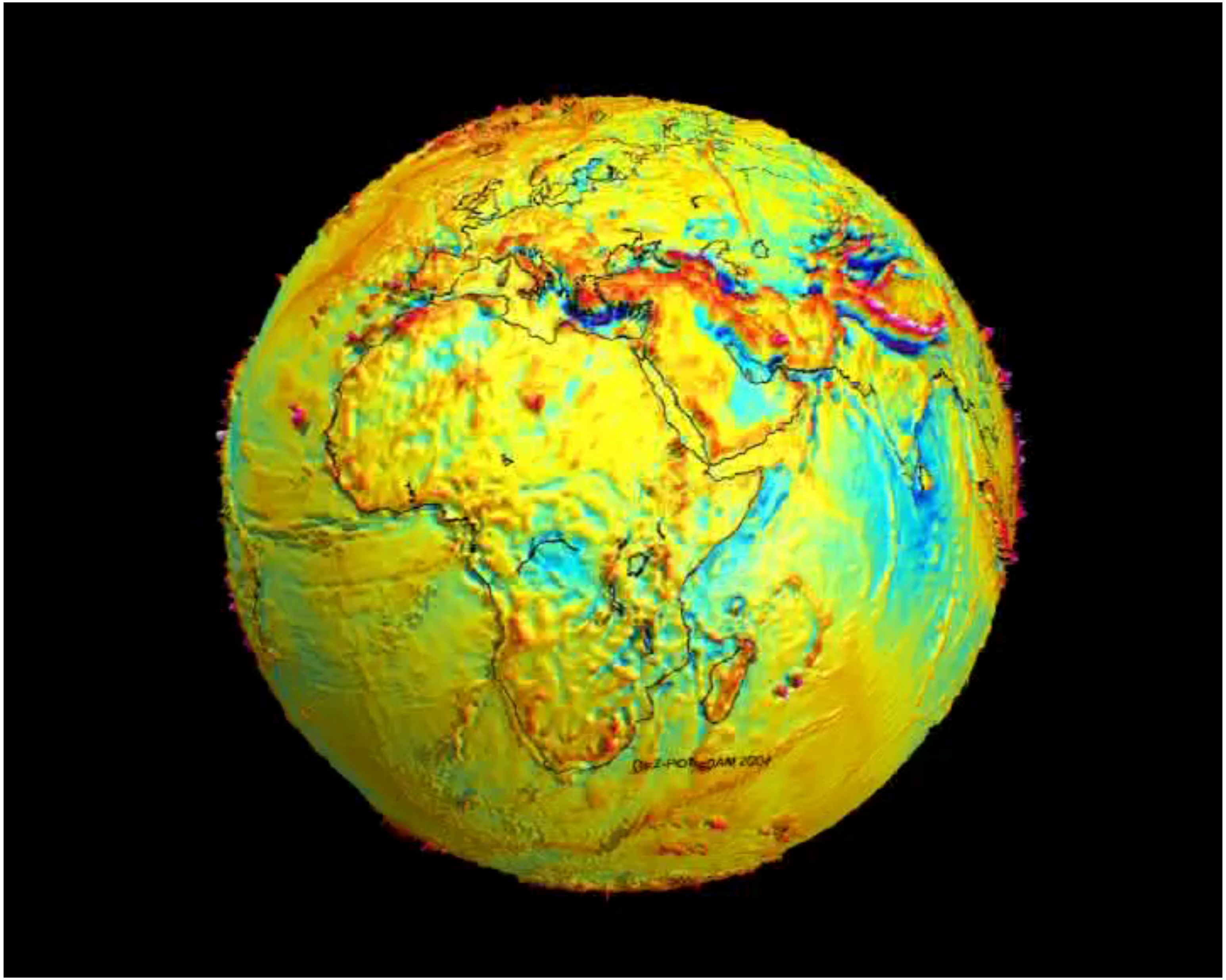
- **Combined with the LAGEOS and LAGEOS 2 orbital data and using the GRACE Earth gravity field determinations, LARES would provide a confirmation of Einstein General Relativity, the measurement of frame-dragging, with accuracy of about 1%.**

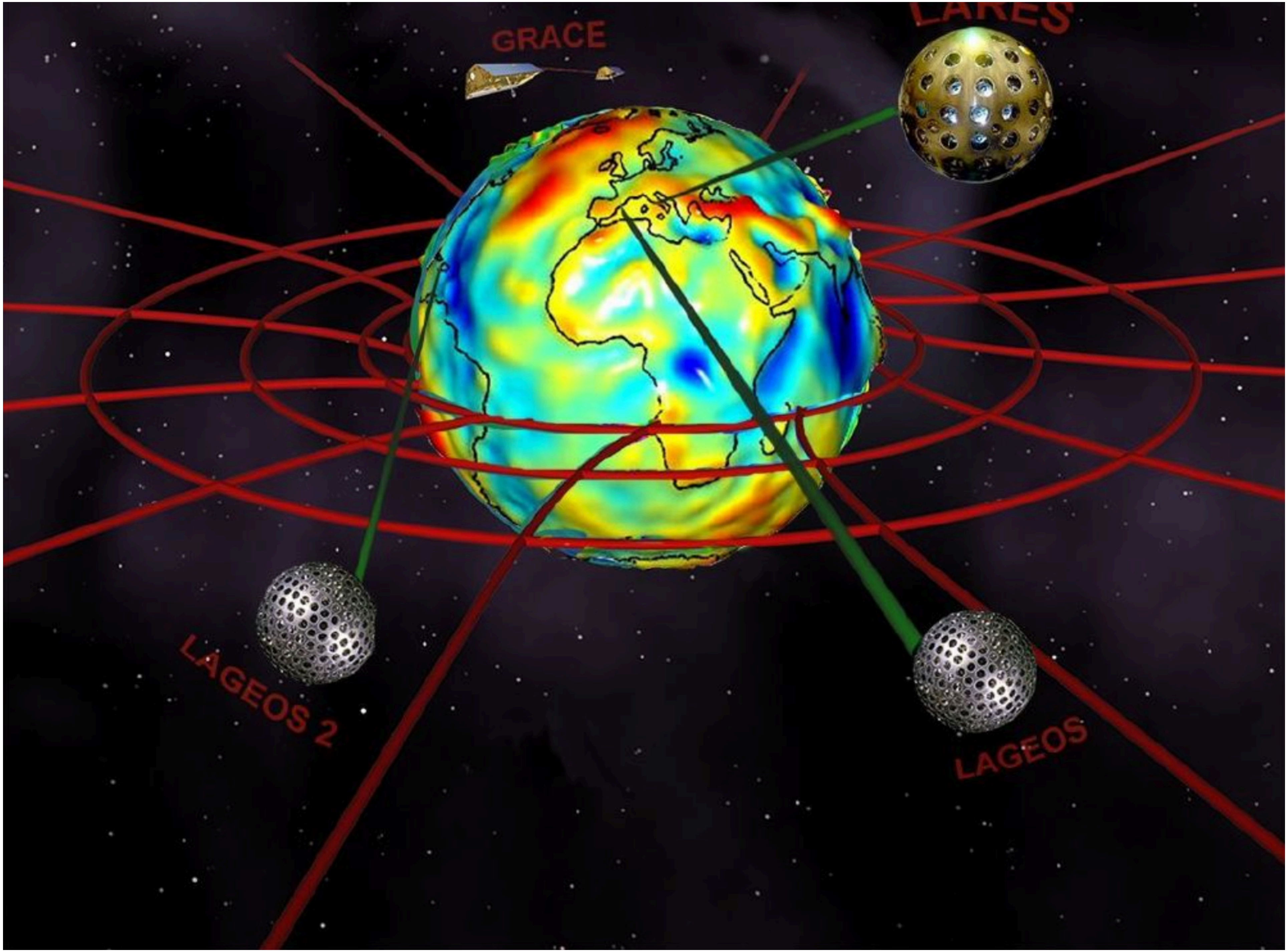
2002



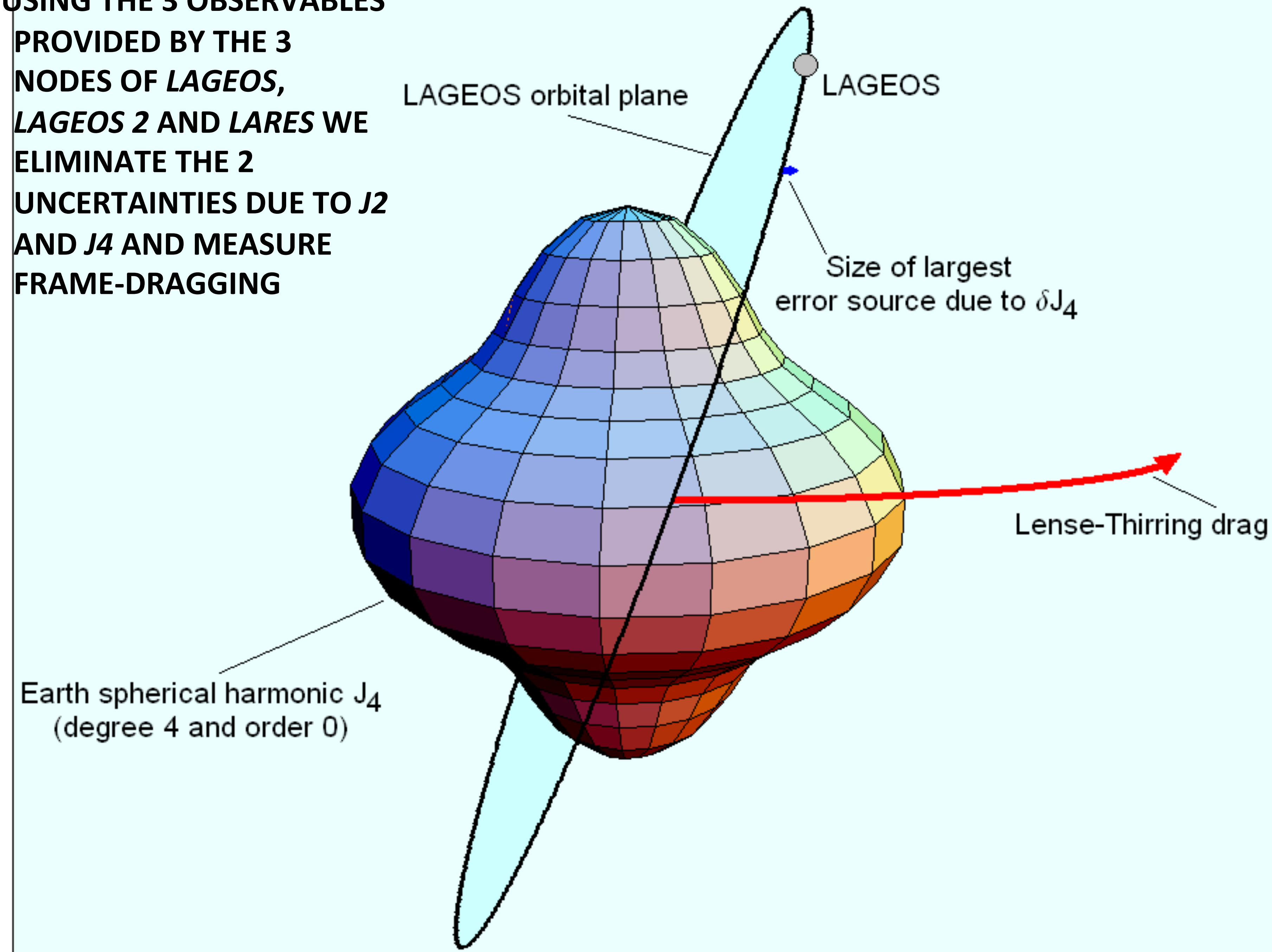
Use of GRACE to test Lense-Thirring at a few percent level:
J. Ries et al. 2003 (1999),E. Pavlis 2002 (2000)


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



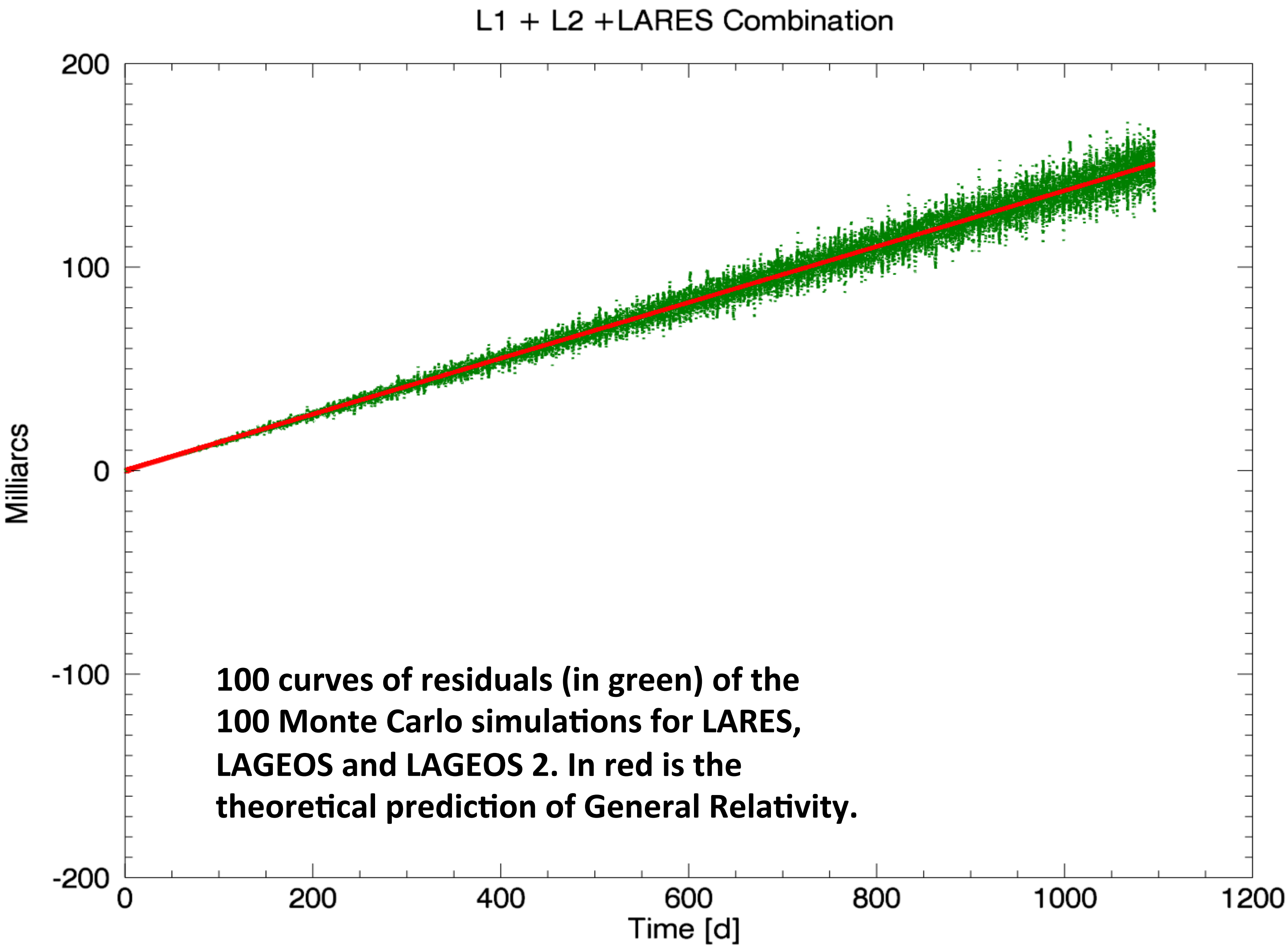

GRACE
LARES
LAGEOS 2
LAGEOS

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



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.

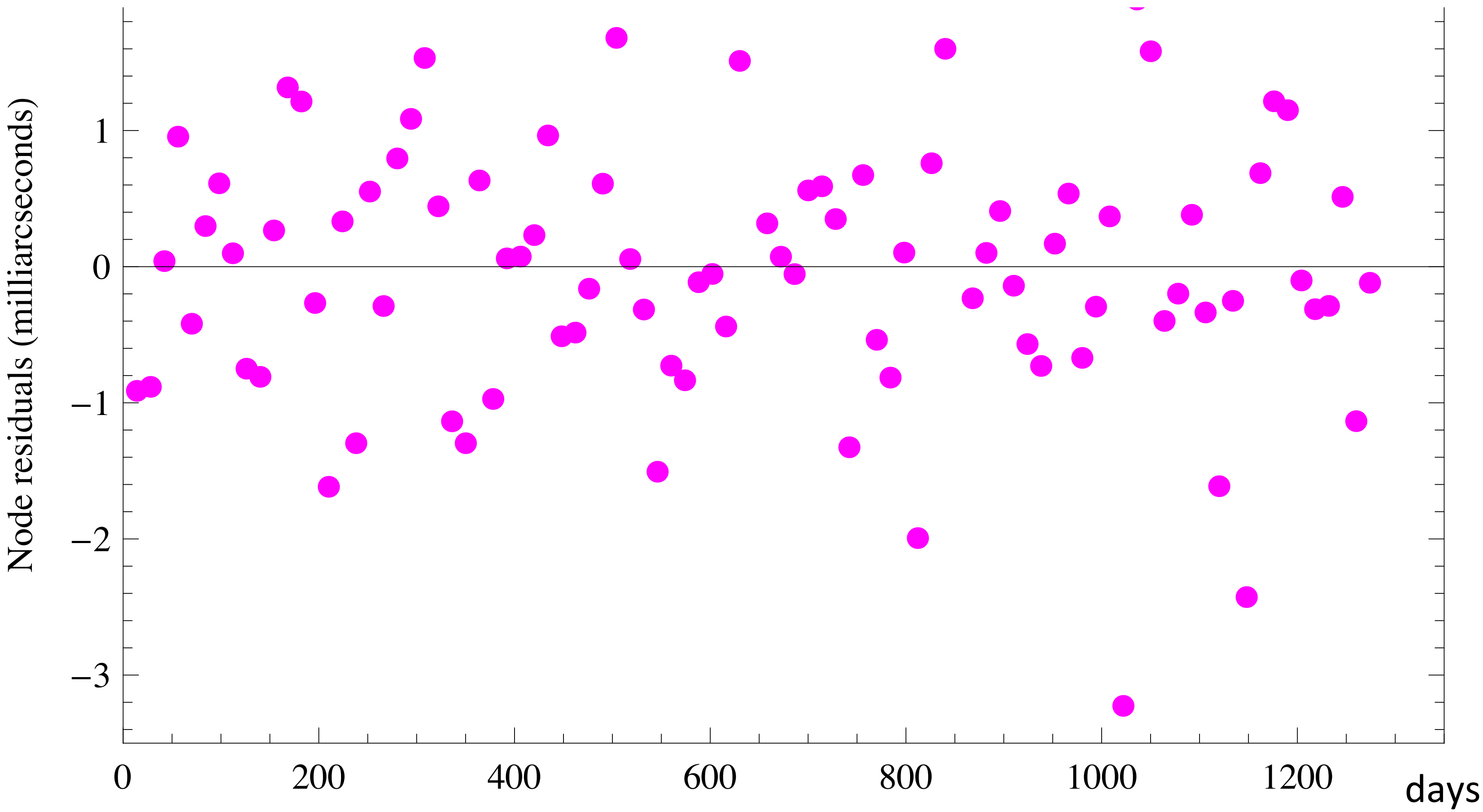
Results of the Monte Carlo simulation for the LARES experiment

Mean value of the frame-dragging effect

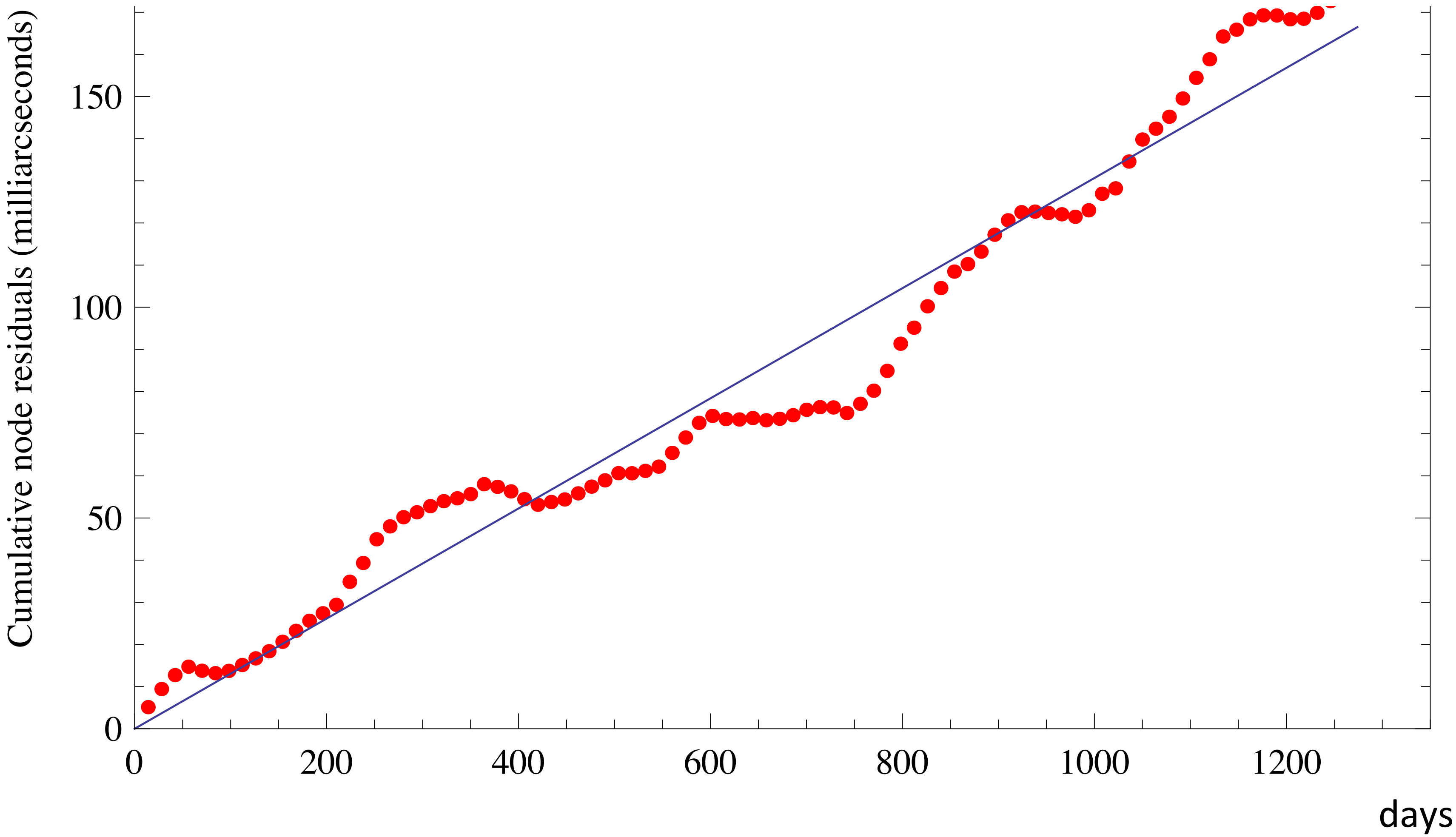
= 100.25 % of the frame-dragging effect predicted by General Relativity

Standard deviation:

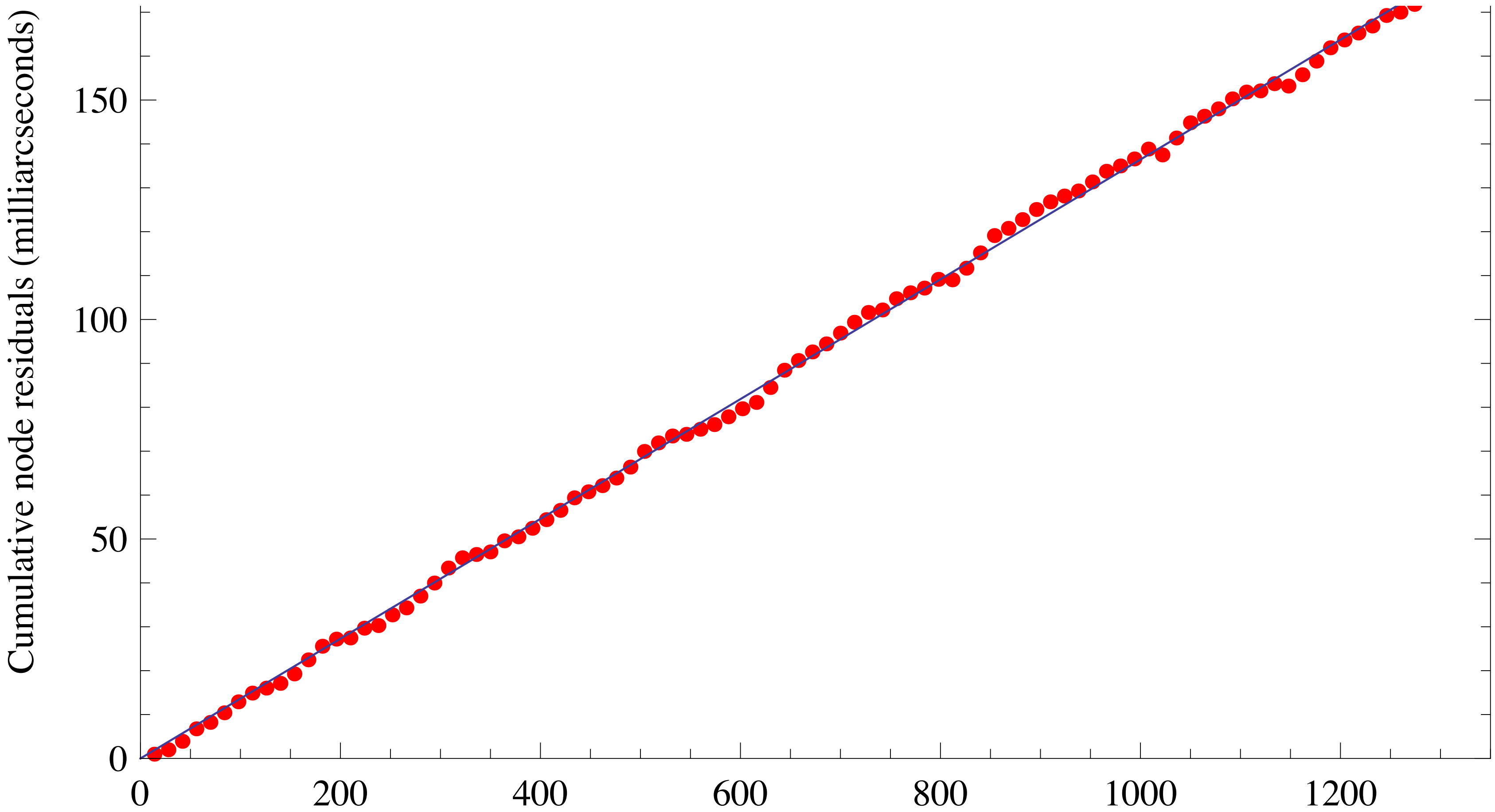
= 1.55 %



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

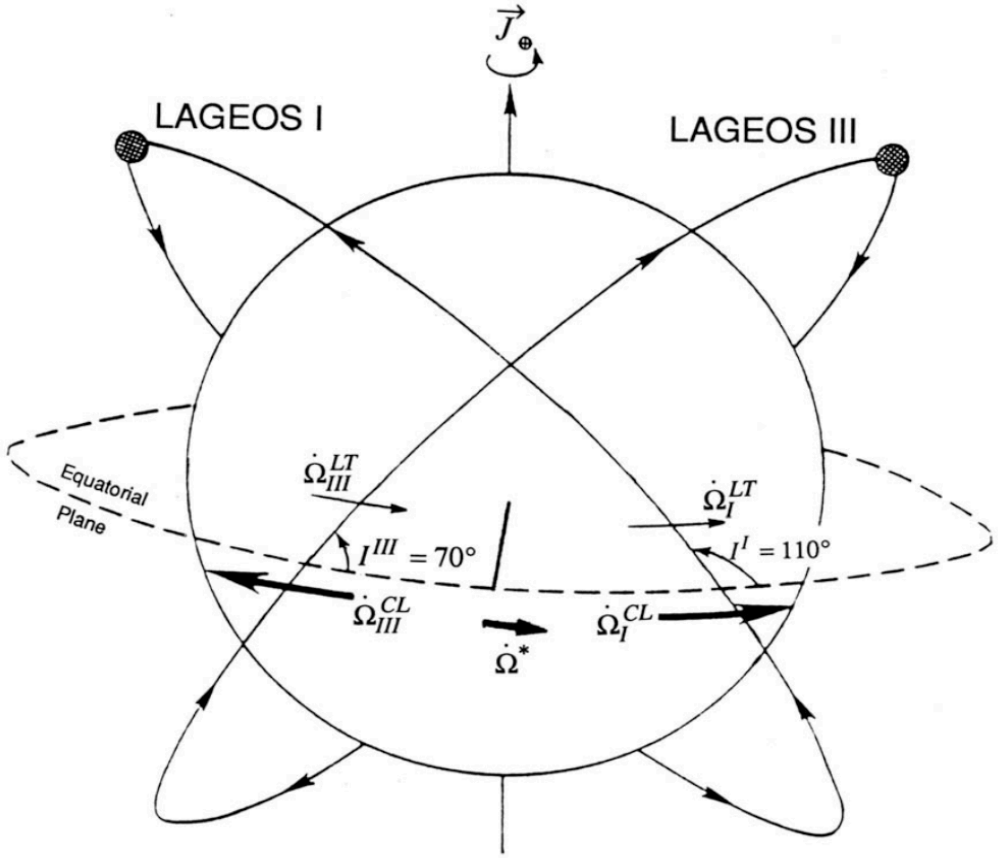
0.05 is our preliminary estimate of systematic error mainly due to the uncertainties in the Earth gravity model GGM05S

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

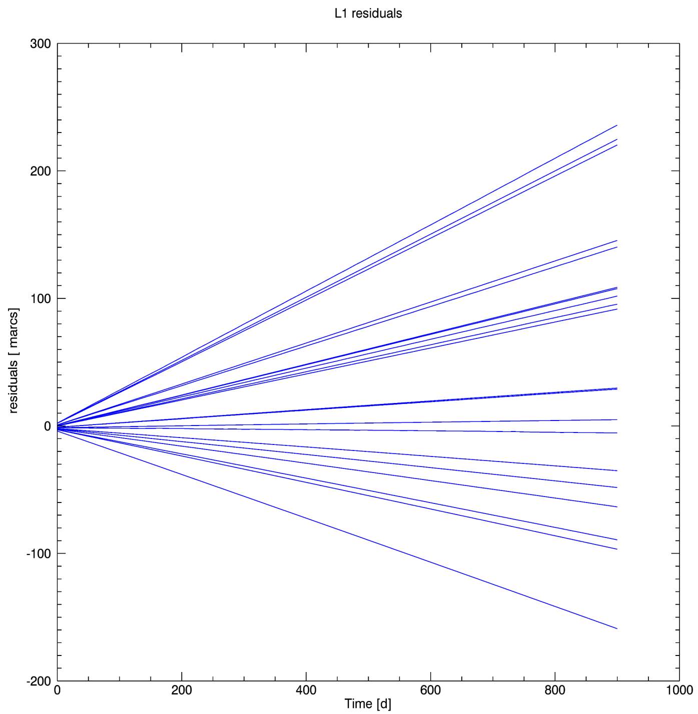
The LARES 2 (LAGEOS 3) satellite for test of frame-dragging with accuracy at the 0.2% level and other tests of General Relativity and Fundamental Physics (and space geodesy and geodynamics).

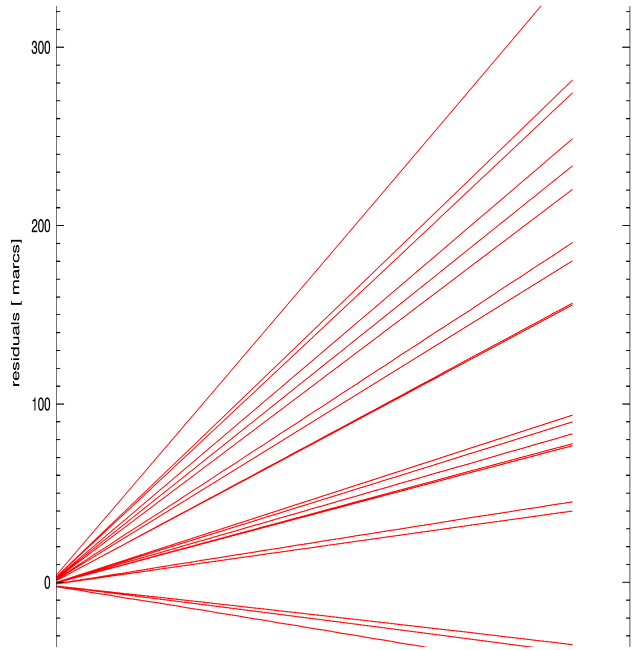


Object of measurement:

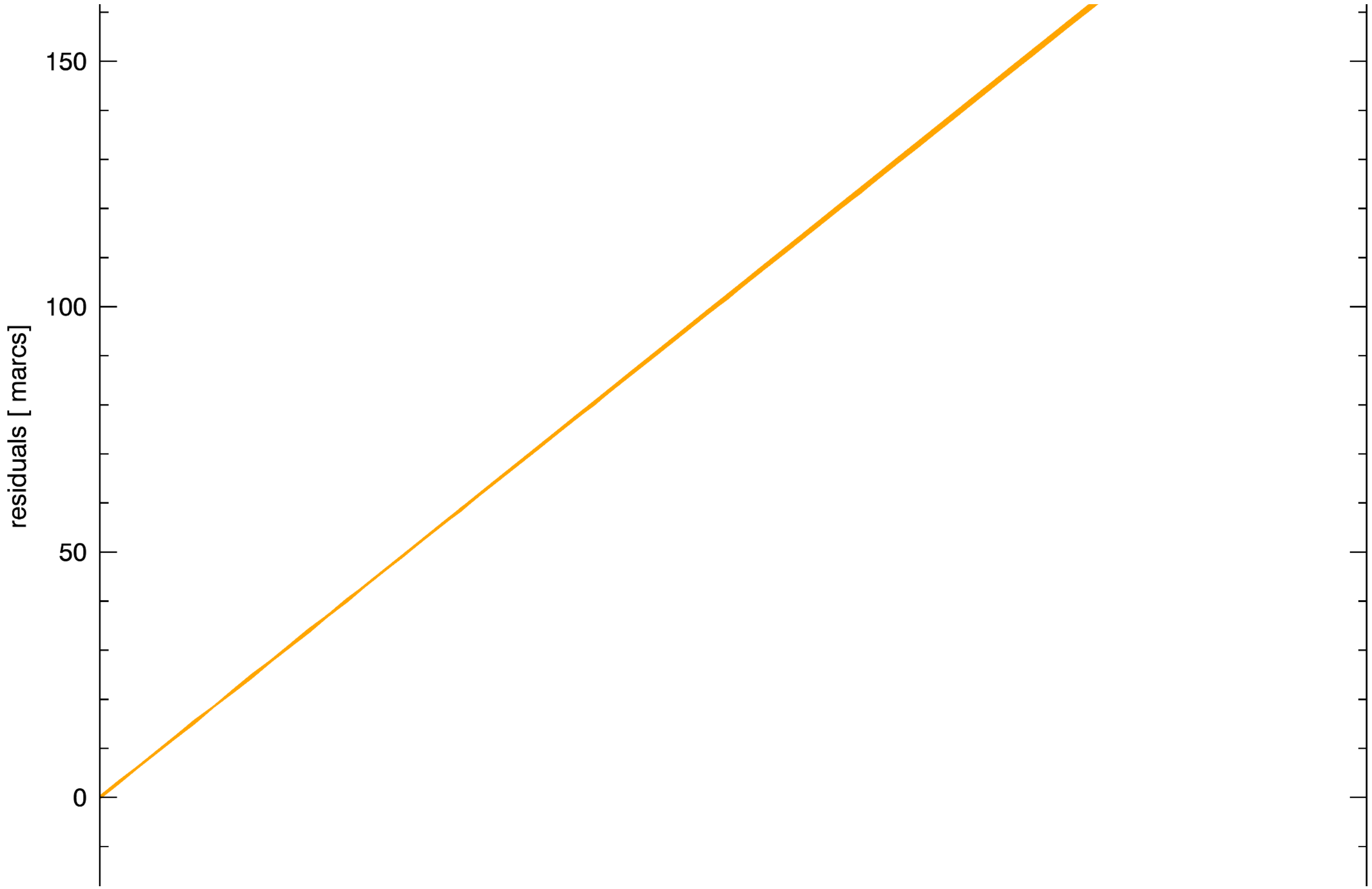
$$\dot{\Omega}^* = ½ (\dot{\Omega}^I + \dot{\Omega}^{III})$$

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).





Monte Carlo simulations of the LARES 2 experiemnt



Result: the spread is at the level of about 0.15%

Elenco pubblicazioni february 2017-2015 (about 60 papers)

2017 – in stampa

- **V. Gagliarducci, A. Gerardi, C. Paris, Contribution of radar meteor scatter technology to NEO and ozone layer monitoring, 17th IEEE International Conference on Environment and Electrical Engineering - EEEIC, Milan, Italy, June 2017.**
- **A. Paolozzi, C. Paris, C. Vendittozzi, F. Felli, M. Mongelli, A. Colucci, H. Asanuma, Test of FBG sensors for monitoring high pressure pipes, SPIE Smart Structures & NDE, Portland, Oregon, United States, 25 - 29 March 2017**

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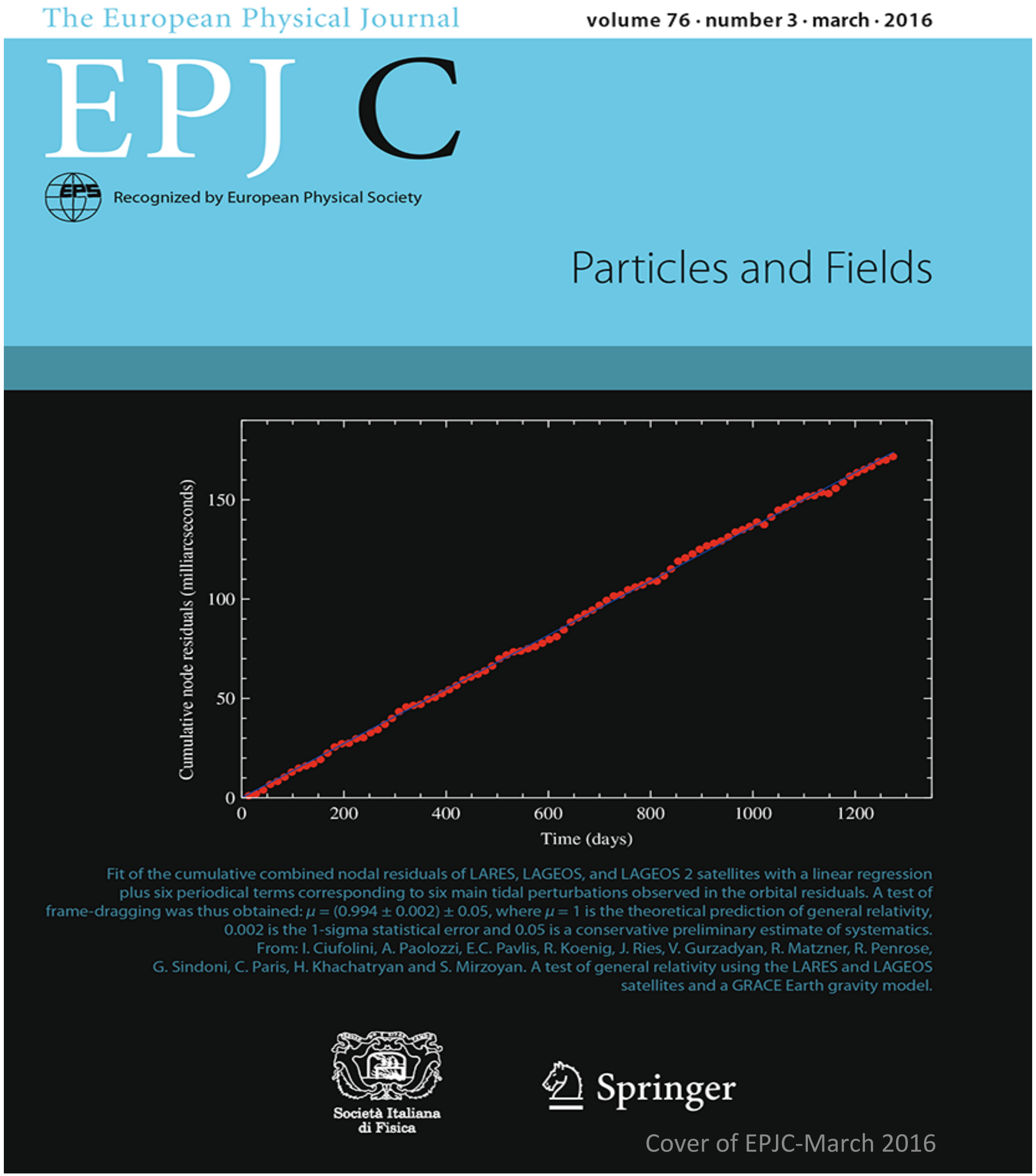

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March cover of EPJC dedicated to our research

Fisica Fondamentale nello Spazio

Expected funding in the 3-year period:

- **Request of funding by Centro Fermi for LARES**
  - 2017/19. Post-doctoral grant or similar: 130 k€
  - Travel (missioni e soggiorni all'estero): 25 k€
  - Visiting professors (travel and local expenses): 10 k€
  - 4th International LARES Science Workshop: 10k€
  - Contracts (prestazioni occasionali di ricerca): 10k€
  - Computers for data analysis and related equipments, portable computers, compilers and software: 20k€
  - Laboratory equipments and consumables: 10k€

- **Co-funding (**2017-2019**)**

Agenzia Spaziale Italiana:

- LARES: 650 k€