Hubble tension, modified gravity and satellite testing General Relativity

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Tension between late and early Universe

Evidence of New Physics

JWST: early massive BHs…

Hubble tension: Riess et al, 2019…

Planck: $H_{global} = 67.4 \pm 0.5$ km s/ Mpc;

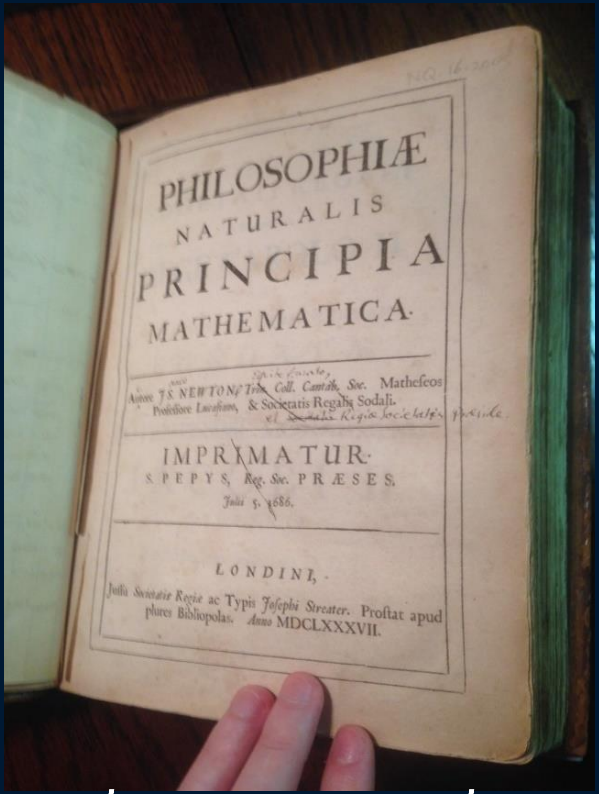
HST : $H_{local} = 74.03 \pm 1.42$ km s/ Mpc.

Modified gravity: two Hubble flows:

Gurzadyan and Stepanian, A&A, 2021;

Gurzadyan, Fimin and Chechetkin, A&A, 2022; 2023a; 2023b

Newton’s shell theorem



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

nunc Equite Aurato,
Autore JS. NEWTON, ~~Trin. Coll. Cantab. Soc.~~ Matheſeos
Profeſſore Lucaſiano, & Societatis ~~Regalis Sodali.~~
et ~~Sodali~~ Regiæ Societatis præside.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

LONDINI,
Juſſu Societatis Regiæ ac Typis Joſephi Streater. Proſtat apud
plures Bibliopolas. Anno MDCLXXXVII.

Universal gravitation (Principia, 1686):

$$F = -G\frac{m_1 m_2}{r^2}$$

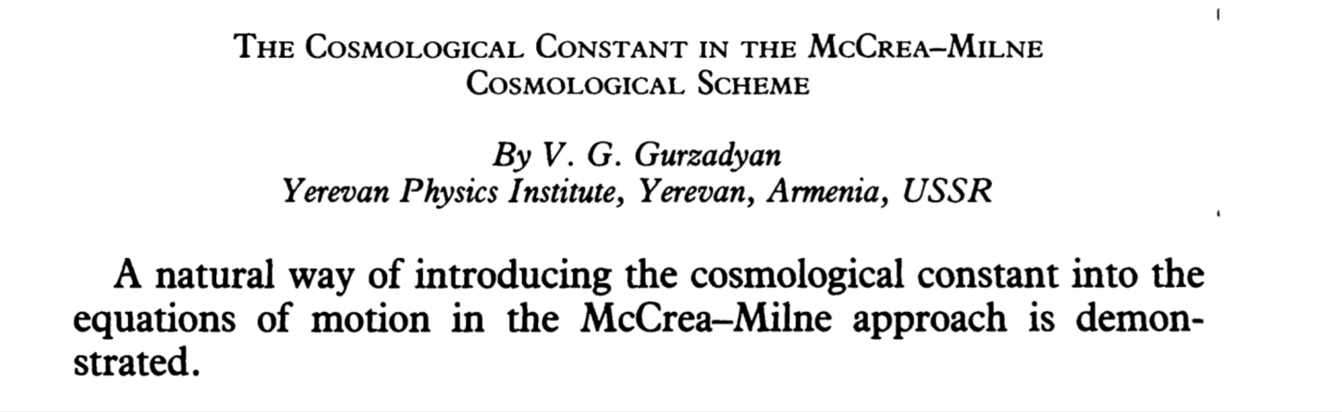
Theorem (shell): The gravitational field of a sphere acting on external objects is equivalent to that of a point mass located at its center; force-free field inside a shell.

According to historians, Newton postponed P’s publication for 20 years to prove this statement.

Lambda as a physical constant;
Two-constant gravity

Theorem: the general function for the “sphere - point” equivalence

$$F = \frac{C_1}{r^2} + C_2 r$$



The Cosmological Constant in the McCrea–Milne
Cosmological Scheme

By V. G. Gurzadyan
Yerevan Physics Institute, Yerevan, Armenia, USSR

A natural way of introducing the cosmological constant into the equations of motion in the McCrea–Milne approach is demonstrated.

Observatory (UK), 105, 42, 1985

Crucial difference from Shell theorem: non-force-free inside a shell.

General Relativity

Einstein: cosmological constant (1917) to get static universe

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Weak field limit of GR (Schwarzschild-de Sitter):

$$g_{00} = 1 + \frac{2\Phi}{c^2} = 1 - \frac{2Gm}{rc^2} - \frac{\Lambda r^2}{3}$$

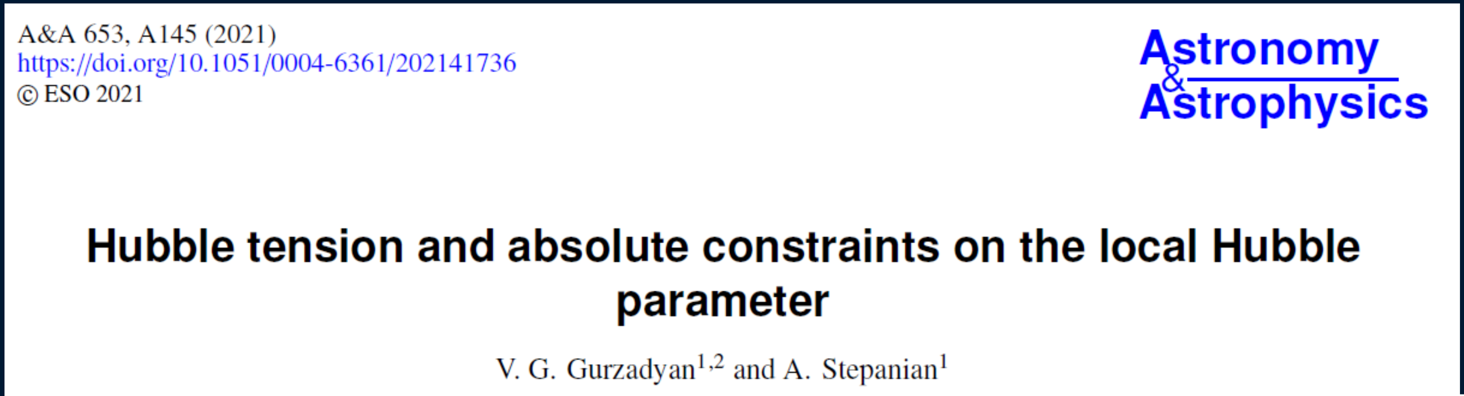
McCrea-Milne cosmology with Lambda

$$\Phi = -\frac{GMm}{r} - \frac{\Lambda c^2 r^2 m}{6}.$$

Local Hubble flow: within non-relativistic limits due to the Lambda-term and not as a result of residuals of the expansion of the Universe.

Zeldovich, 1981:

“paradoxical that the Newtonian theory of expansion was discovered only after the achievement of Friedmann”.



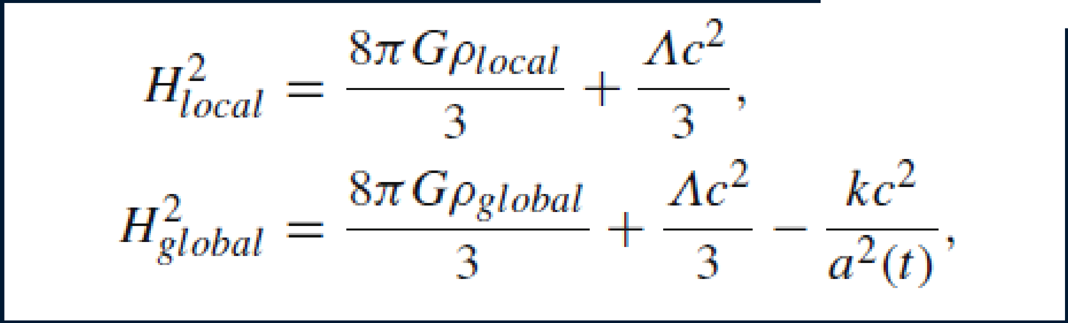
A&A 653, A145 (2021)
https://doi.org/10.1051/0004-6361/202141736

Astronomy & Astrophysics

Hubble tension and absolute constraints on the local Hubble parameter

V. G. Gurzadyan[1,2] and A. Stepanian[1]

Two flows with Λ: local and global

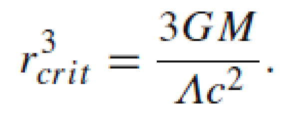


$$H^2_{local} = \frac{8\pi G\rho_{local}}{3} + \frac{\Lambda c^2}{3},$$

$$H^2_{global} = \frac{8\pi G\rho_{global}}{3} + \frac{\Lambda c^2}{3} - \frac{kc^2}{a^2(t)},$$

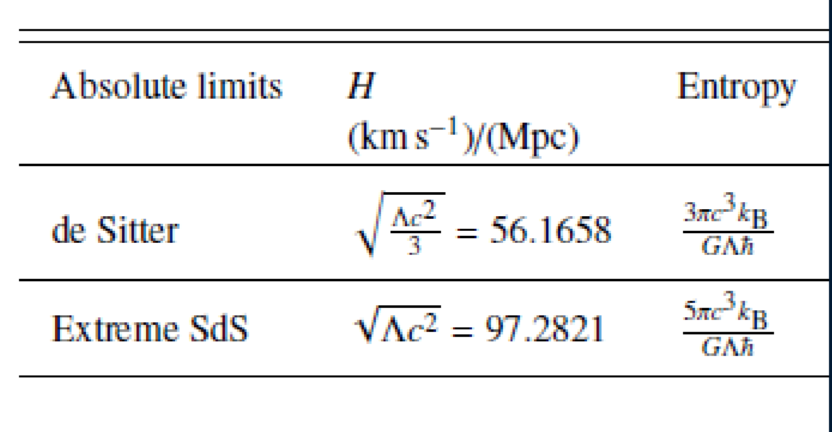
McCrea-Milne + Lambda

Friedmann



$$r^3_{crit} = \frac{3GM}{\Lambda c^2}.$$

when Lambda-term dominates.



Absolute limits	H (km s^{-1})/(Mpc)	Entropy
de Sitter	$\sqrt{\frac{\Lambda c^2}{3}} = 56.1658$	$\frac{3\pi c^3 k_B}{G\Lambda\hbar}$
Extreme SdS	$\sqrt{\Lambda c^2} = 97.2821$	$\frac{5\pi c^3 k_B}{G\Lambda\hbar}$

Absolute constraints for local Hubble parameter.

Dark sector and constants

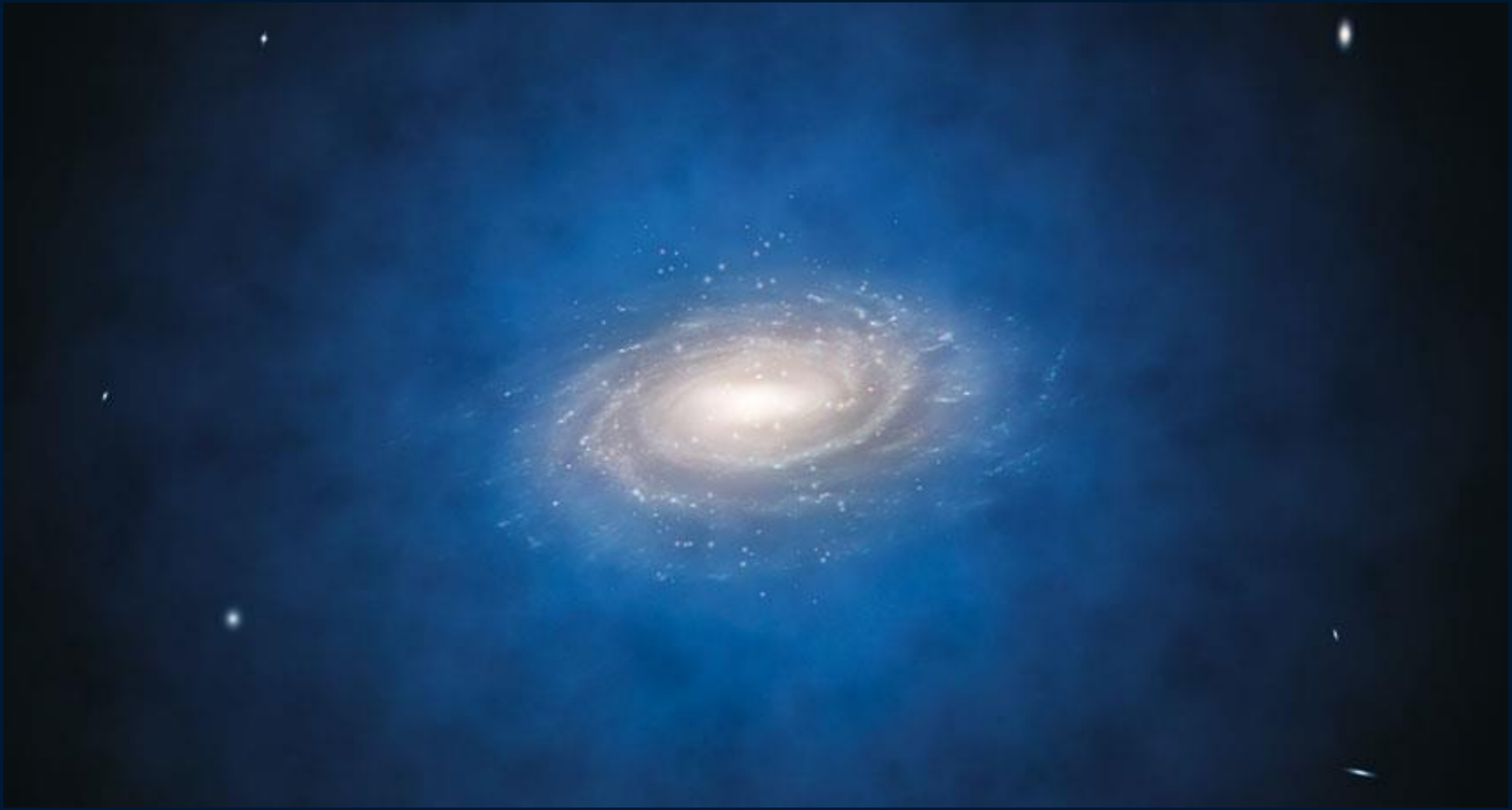
In the GR equations, Λ is considered to describe the accelerated expansion of the Universe.

Planck satellite data

$$\Lambda = 1.11 \times 10^{-52}\, m^{-2}$$

Weak field GR attributed to galactic scales

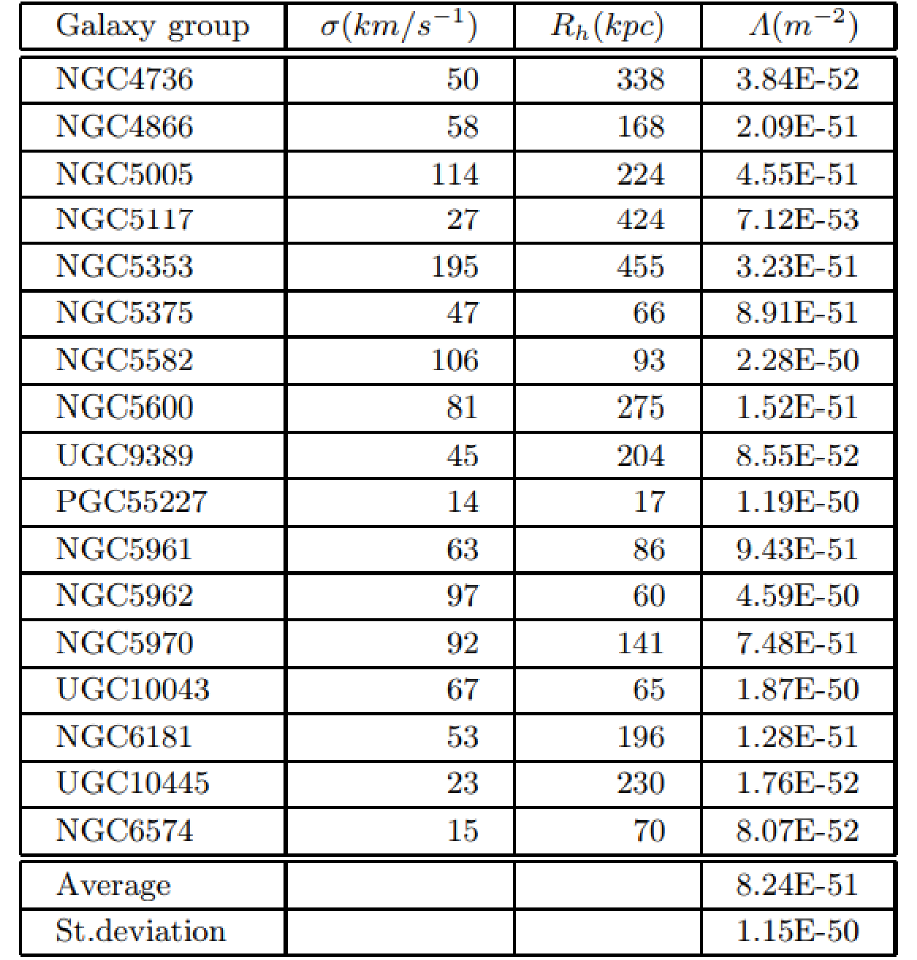
$$\Lambda = \frac{3\sigma^2}{2c^2R^2} \simeq 3 \cdot 10^{-52} \left(\frac{\sigma}{50\,\mathrm{km\,s^{-1}}}\right)^2 \left(\frac{R}{300\,\mathrm{kpc}}\right)^{-2} \mathrm{m}^{-2},$$



Observations: galactic halos determine the disk‘s properties.

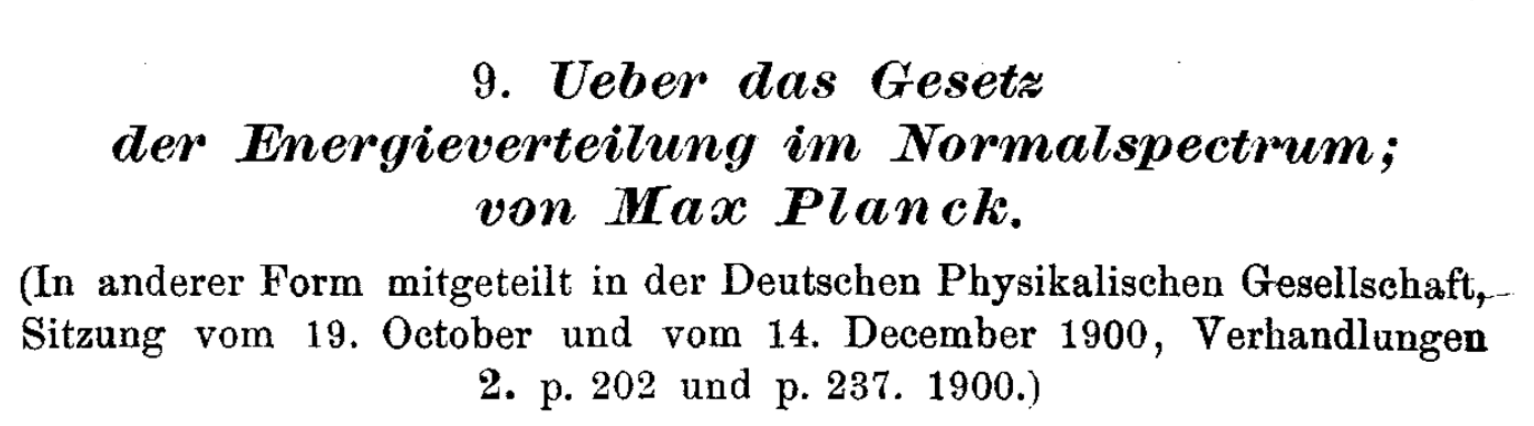
Galaxy groups

For galaxy groups of the Hercules-Bootes region



Galaxy group	$\sigma(km/s^{-1})$	$R_h(kpc)$	$\Lambda(m^{-2})$
NGC4736	50	338	3.84E-52
NGC4866	58	168	2.09E-51
NGC5005	114	224	4.55E-51
NGC5117	27	424	7.12E-53
NGC5353	195	455	3.23E-51
NGC5375	47	66	8.91E-51
NGC5582	106	93	2.28E-50
NGC5600	81	275	1.52E-51
UGC9389	45	204	8.55E-52
PGC55227	14	17	1.19E-50
NGC5961	63	86	9.43E-51
NGC5962	97	60	4.59E-50
NGC5970	92	141	7.48E-51
UGC10043	67	65	1.87E-50
NGC6181	53	196	1.28E-51
UGC10445	23	230	1.76E-52
NGC6574	15	70	8.07E-52
Average			8.24E-51
St.deviation			1.15E-50

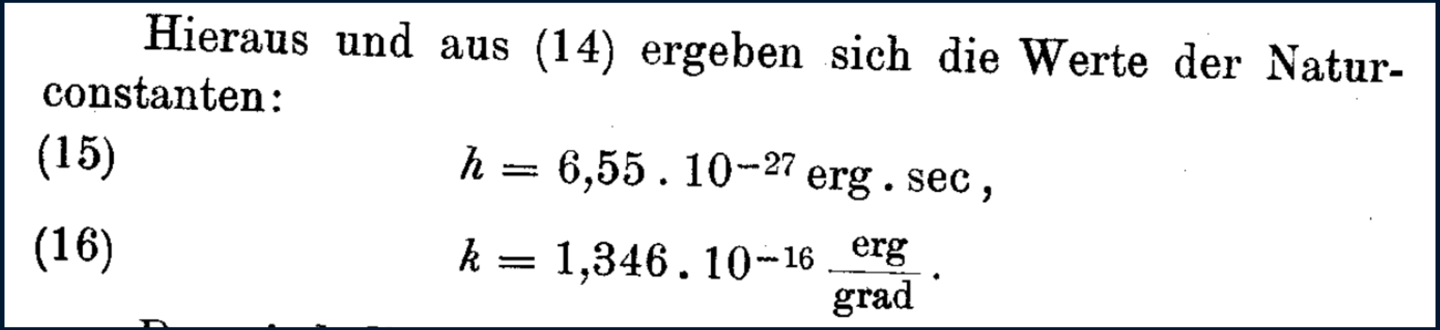
Planck units



9. *Ueber das Gesetz der Energieverteilung im Normalspectrum;*
von Max Planck.

(In anderer Form mitgeteilt in der Deutschen Physikalischen Gesellschaft, Sitzung vom 19. October und vom 14. December 1900, Verhandlungen 2. p. 202 und p. 237. 1900.)

Planck natural units (1900)



Hieraus und aus (14) ergeben sich die Werte der Naturconstanten:

(15) $$h = 6{,}55 \,.\, 10^{-27}\ \mathrm{erg}\,.\,\mathrm{sec}\,,$$

(16) $$k = 1{,}346 \,.\, 10^{-16}\ \frac{\mathrm{erg}}{\mathrm{grad}}\,.$$

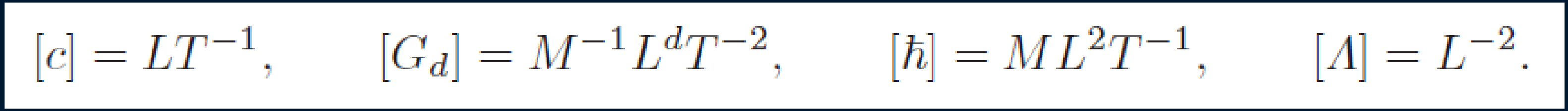
Planck: “retain their meaning for all times and for all cultures, even extraterrestrial and non-human ones”.

l = (h G/ c^3)^1/2 , t = (hG/ c^5)^1/2, m = (hc/G)^1/2

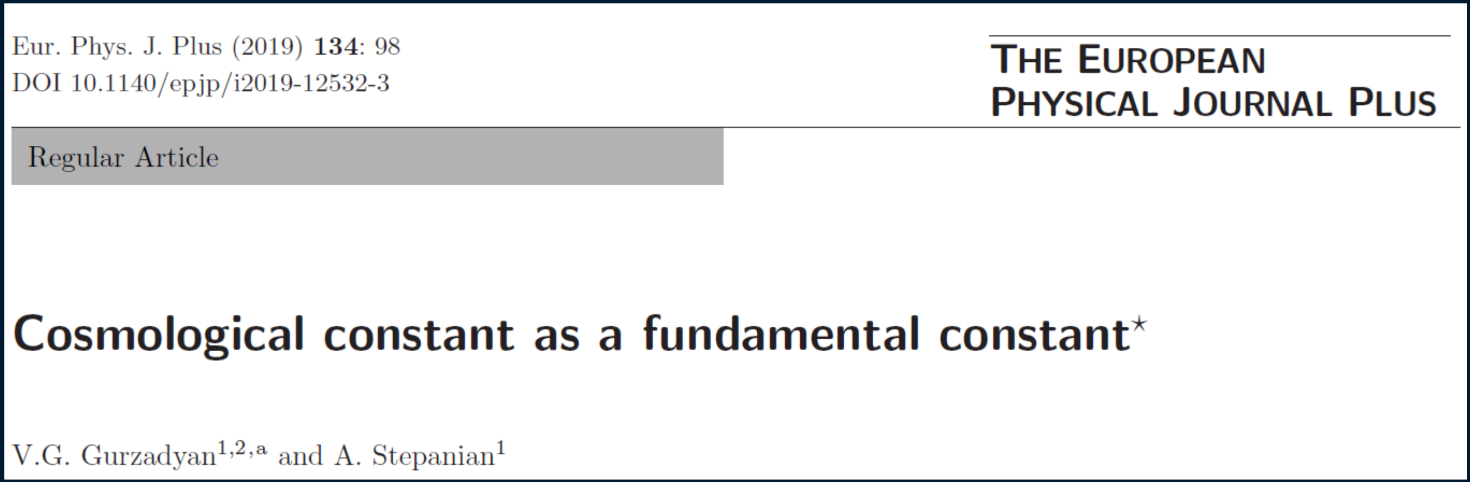
For Planck units no dimensionless combination emerging.

Drastic change when:

Λ is considered as the 4th fundamental constant:



$$[c] = LT^{-1}, \qquad [G_d] = M^{-1}L^{d}T^{-2}, \qquad [\hbar] = ML^2T^{-1}, \qquad [\Lambda] = L^{-2}.$$



Eur. Phys. J. Plus (2019) **134**: 98
DOI 10.1140/epjp/i2019-12532-3

THE EUROPEAN
PHYSICAL JOURNAL PLUS

Regular Article

Cosmological constant as a fundamental constant*

V.G. Gurzadyan[1,2,a] and A. Stepanian[1]

A sequence of dimensionless combinations is produced

$$I = \frac{c^{3a}}{\Lambda^a G^a \hbar^a} ,$$

Bekenstein bound (1981) for de Sitter Universe, a=1, 3π coefficient

$$I_{BB} \leq \frac{2\pi RE}{\hbar c \ln 2} ,$$

$$I_{BB} = \frac{3\pi c^3}{\Lambda G \hbar \ln 2} .$$

information of de Sitter event horizon (Gibbons, Hawking 1977)

$$I_{dS} = 3\pi \frac{c^3}{\Lambda G \hbar} .$$

Generalization to d-dimensions

Gravitational field of a single point at d-dimensional space.

For potential

$$\Delta_{S^{d-1}}\Phi = C_1,$$

$$\frac{1}{r^{d-1}}\left(\frac{d}{dr}r^{d-1}\frac{d}{dr}\Phi\right) = C_1,$$

general form of gravitational potential

$$\Phi(r) = C_1\frac{r^2}{2d} + \frac{C_2}{(d-2)r^{d-2}}, \quad d \neq 2,$$

$$\Phi(r) = C_1\frac{r^2}{4} + C_2\log r, \quad d = 2.$$

d-dimensional Gauss law

$$\Delta\Phi = \frac{2\pi^{\frac{d}{2}}}{\Gamma(\frac{d}{2})} G_d \rho - \Lambda c^2,$$

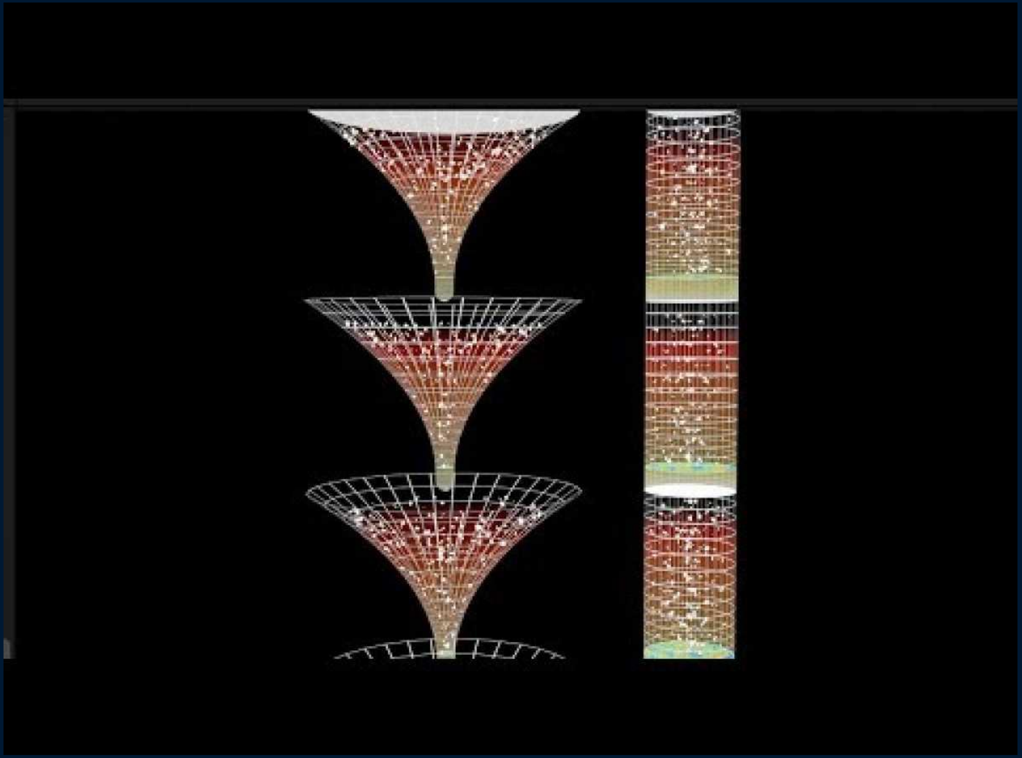
Einstein’s constant

$$\kappa_d = \frac{4\pi^{\frac{d}{2}}}{\Gamma(\frac{d}{2})} \frac{G_d}{c^4}.$$

The Newtonian gravitational constant is dimension-dependent and matter-coupled, while the cosmological constant in neither dimension-dependent nor matter coupled.

Einstein (1917, 1918): Lambda as “universal constant”.

Penrose's Conformal Cyclic Cosmology



The conformal boundary of FLRW universe, sequence of aeons.

Rescale of fundamental constants from one aeon to another

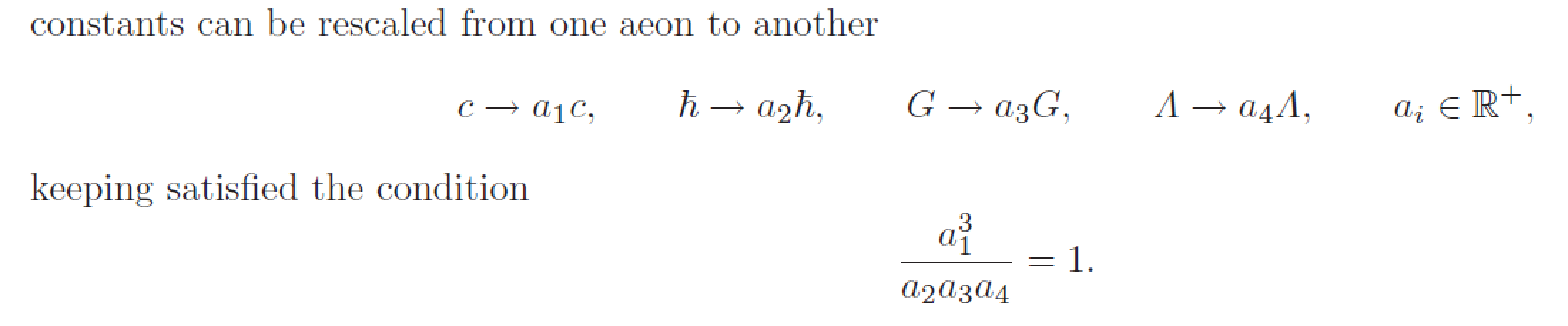
As invariant of conformal transformation

$$\tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}$$

the ratios

$$\frac{Q_{dS}}{Q_p} = m\left(\frac{c^3}{\hbar G \Lambda}\right)^n = mI^n, \quad m, n \in \mathbb{R},$$

For all quantities Q the final (de Sitter) and initial (Planck) eras of an aeon will remain invariant under conformal transformations.



constants can be rescaled from one aeon to another

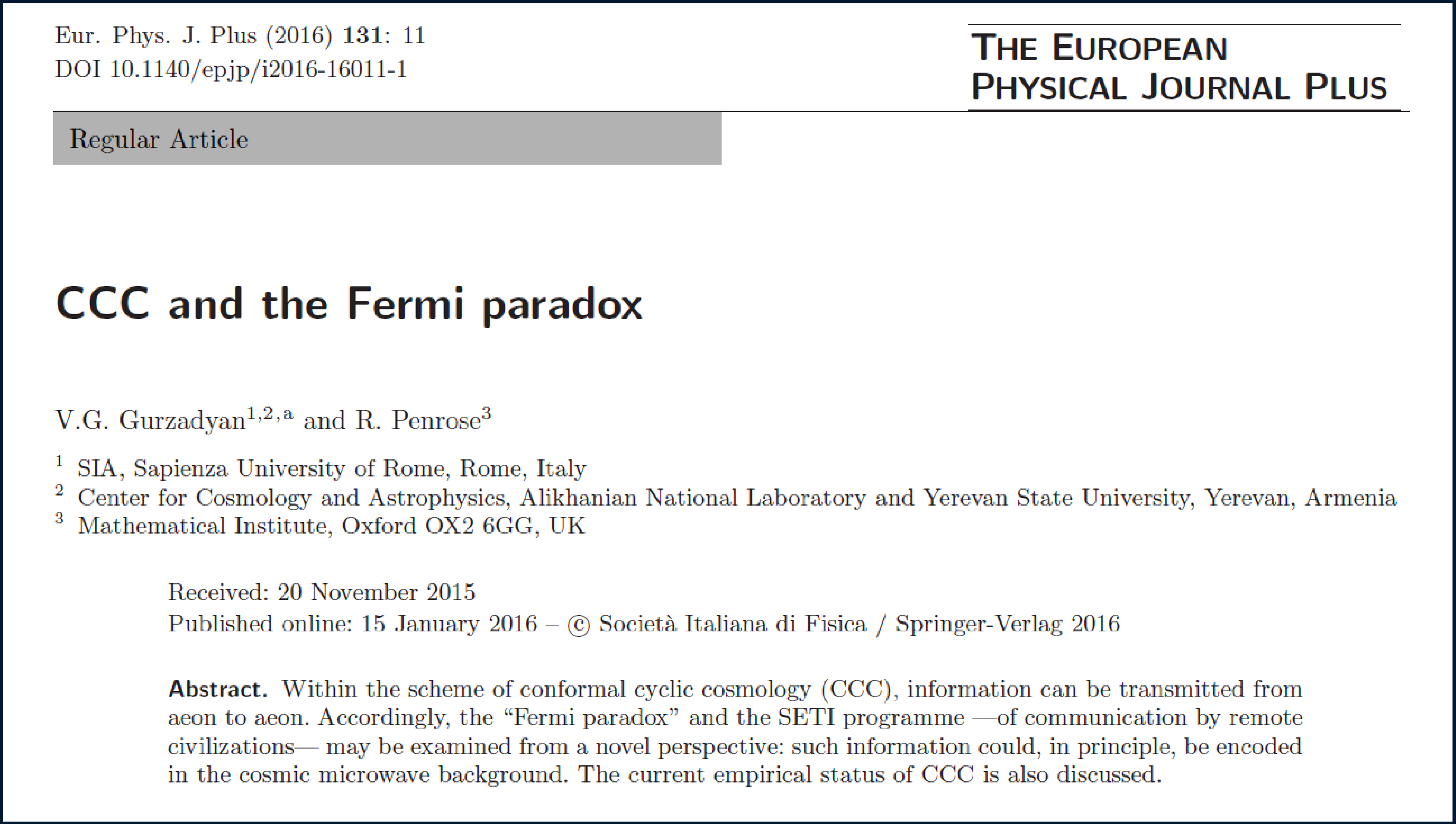
$$c \rightarrow a_1 c, \qquad \hbar \rightarrow a_2 \hbar, \qquad G \rightarrow a_3 G, \qquad \Lambda \rightarrow a_4 \Lambda, \qquad a_i \in \mathbb{R}^+,$$

keeping satisfied the condition

$$\frac{a_1^3}{a_2 a_3 a_4} = 1.$$

Difference between the role of Lambda and of other constants.

Since Lambda is absent at Planck era scales, by fixing Lambda’s value, the values of other constants will be fixed at each aeon.



Eur. Phys. J. Plus (2016) **131**: 11
DOI 10.1140/epjp/i2016-16011-1

THE EUROPEAN
PHYSICAL JOURNAL PLUS

Regular Article

CCC and the Fermi paradox

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[2] Center for Cosmology and Astrophysics, Alikhanian National Laboratory and Yerevan State University, Yerevan, Armenia
[3] Mathematical Institute, Oxford OX2 6GG, UK

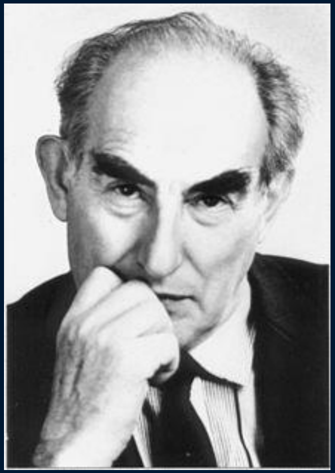
Received: 20 November 2015

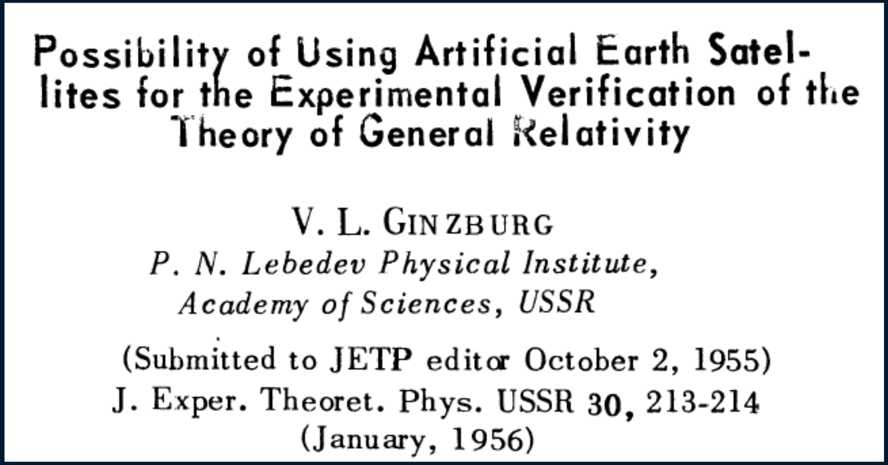
Abstract. Within the scheme of conformal cyclic cosmology (CCC), information can be transmitted from aeon to aeon. Accordingly, the "Fermi paradox" and the SETI programme —of communication by remote civilizations— may be examined from a novel perspective: such information could, in principle, be encoded in the cosmic microwave background. The current empirical status of CCC is also discussed.

Satellites to test General Relativity

Einstein, to Thirring (1918): “*what a pity the earth has no moon just outside its atmosphere*”.

Ginzburg 1956





Possibility of Using Artificial Earth Satellites for the Experimental Verification of the Theory of General Relativity

V. L. GINZBURG
P. N. Lebedev Physical Institute,
Academy of Sciences, USSR

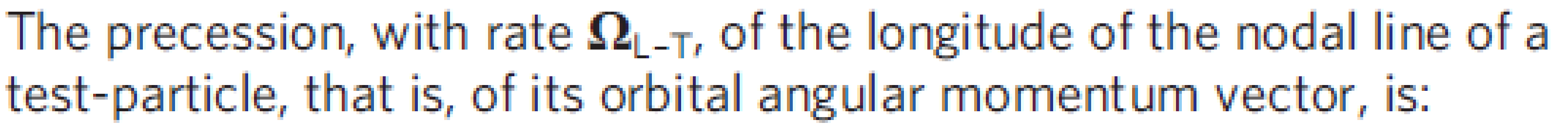
(Submitted to JETP editor October 2, 1955)
J. Exper. Theoret. Phys. USSR **30**, 213-214
(January, 1956)

Ginzburg 1979: “*(L-T) hardly possible in forthcoming future*”.

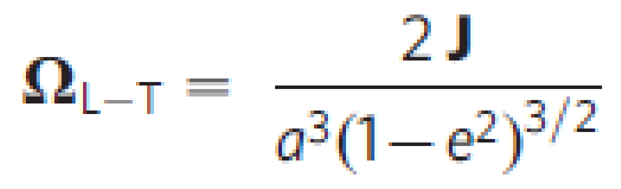
Mach principle, 1872, 1883

Einstein, General Relativity, 1916

Lense-Thirring, weak-field frame dragging, 1918

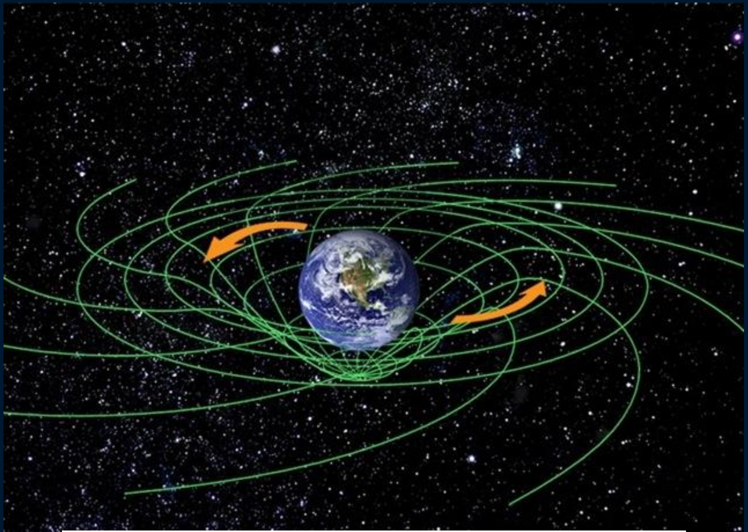


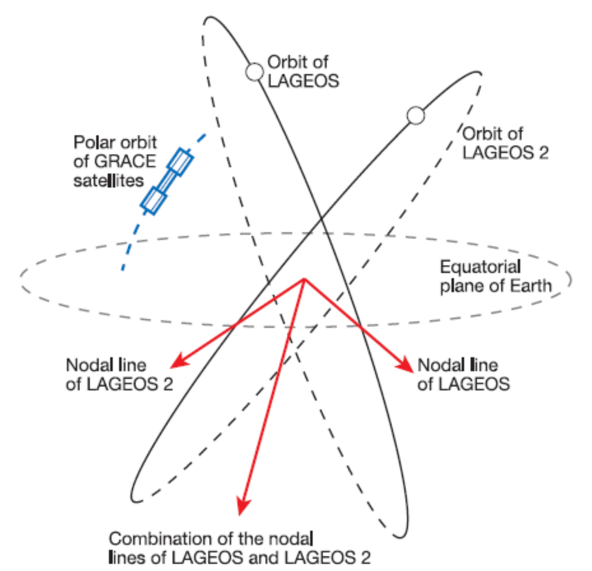
The precession, with rate $\mathbf{\Omega}_{\mathrm{L-T}}$, of the longitude of the nodal line of a test-particle, that is, of its orbital angular momentum vector, is:



$$\mathbf{\Omega}_{\mathrm{L-T}} = \frac{2\,\mathbf{J}}{a^3(1-e^2)^{3/2}}$$

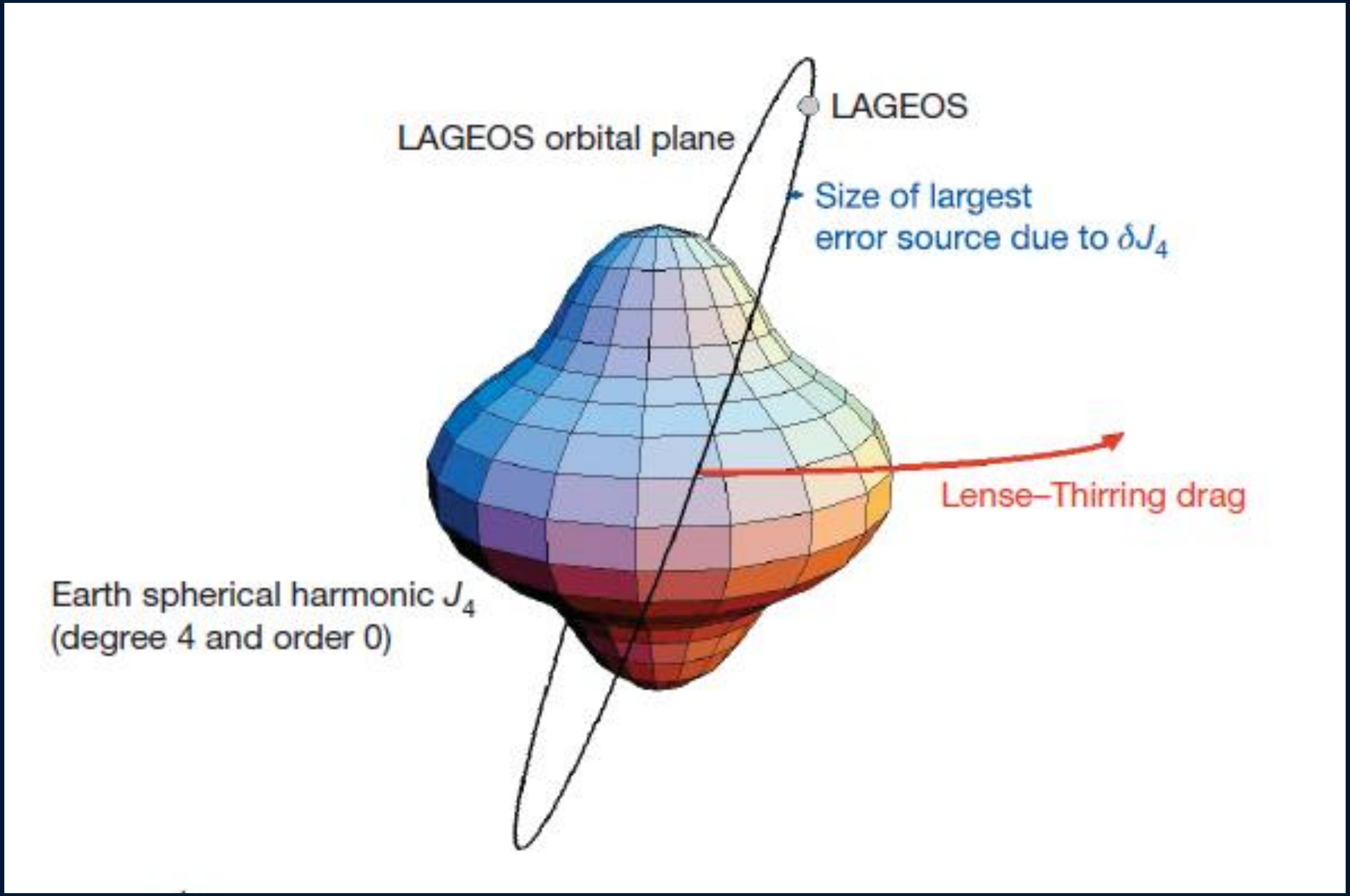
High precision tests of General Relativity in space





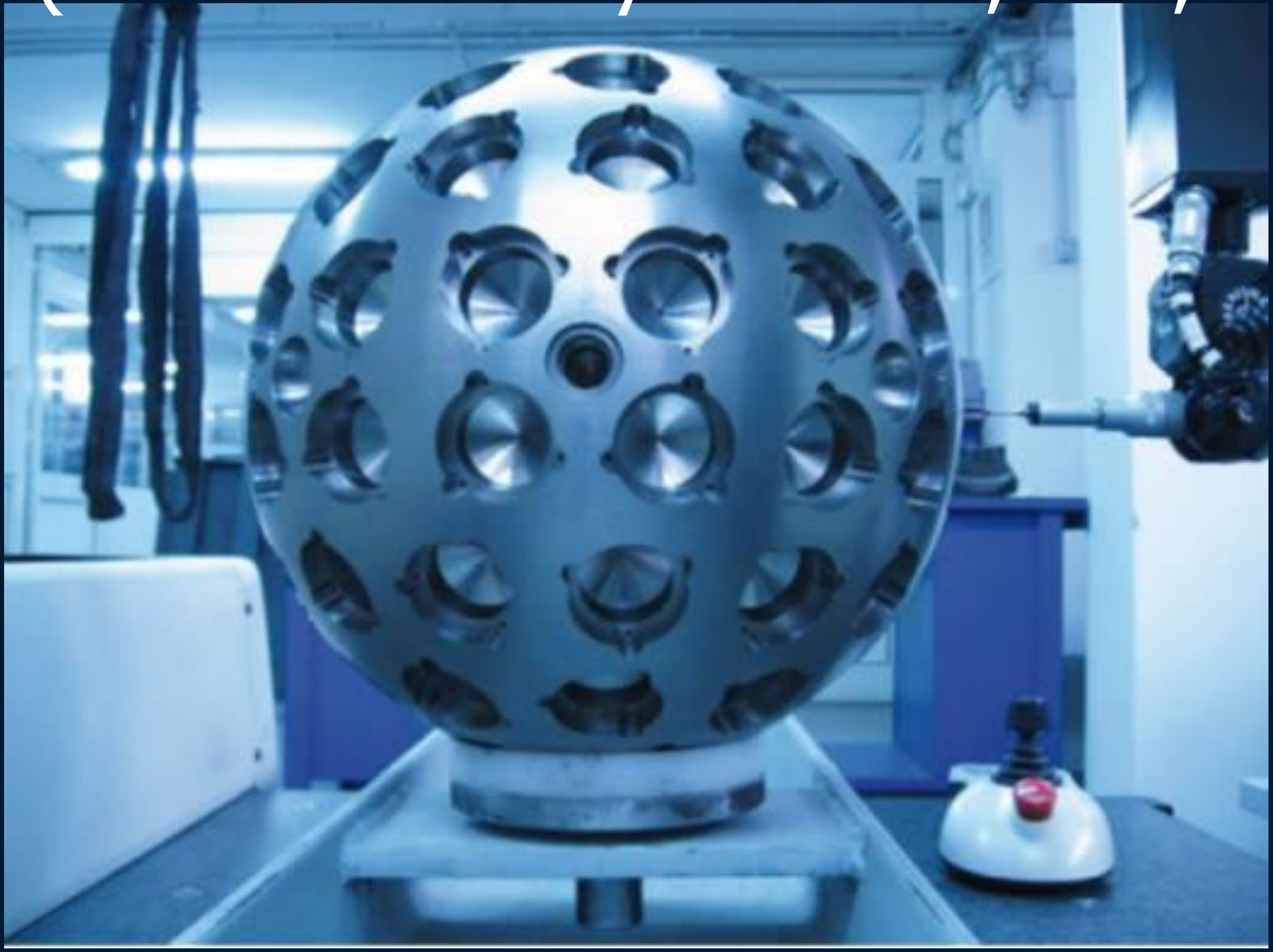
Shift of satellite's orbital plane in the field of rotating massive body (Earth)

LAGEOS, LAGEOS-2, 15%, Ciufolini, Pavlis, 2004



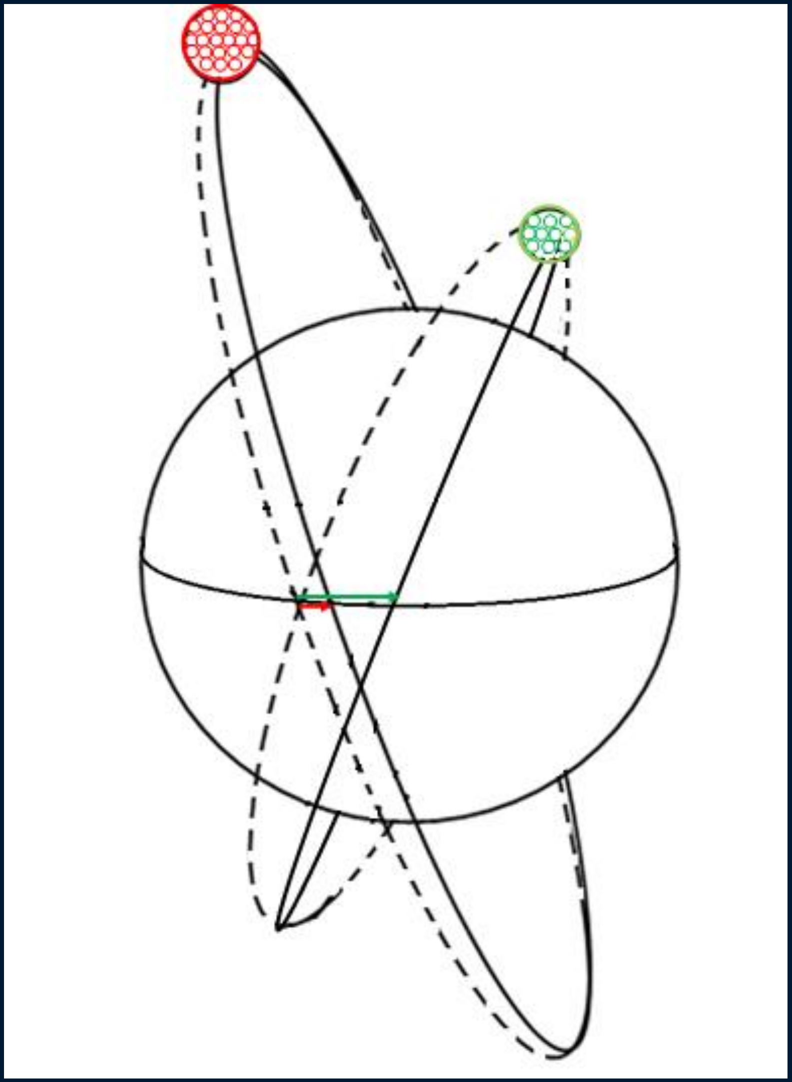
The Lense-Thirring effect and J_4 error box on the orbital plane of LAGEOS satellite.

LARES (LAser Relativity Satellite, ASI, ESA)

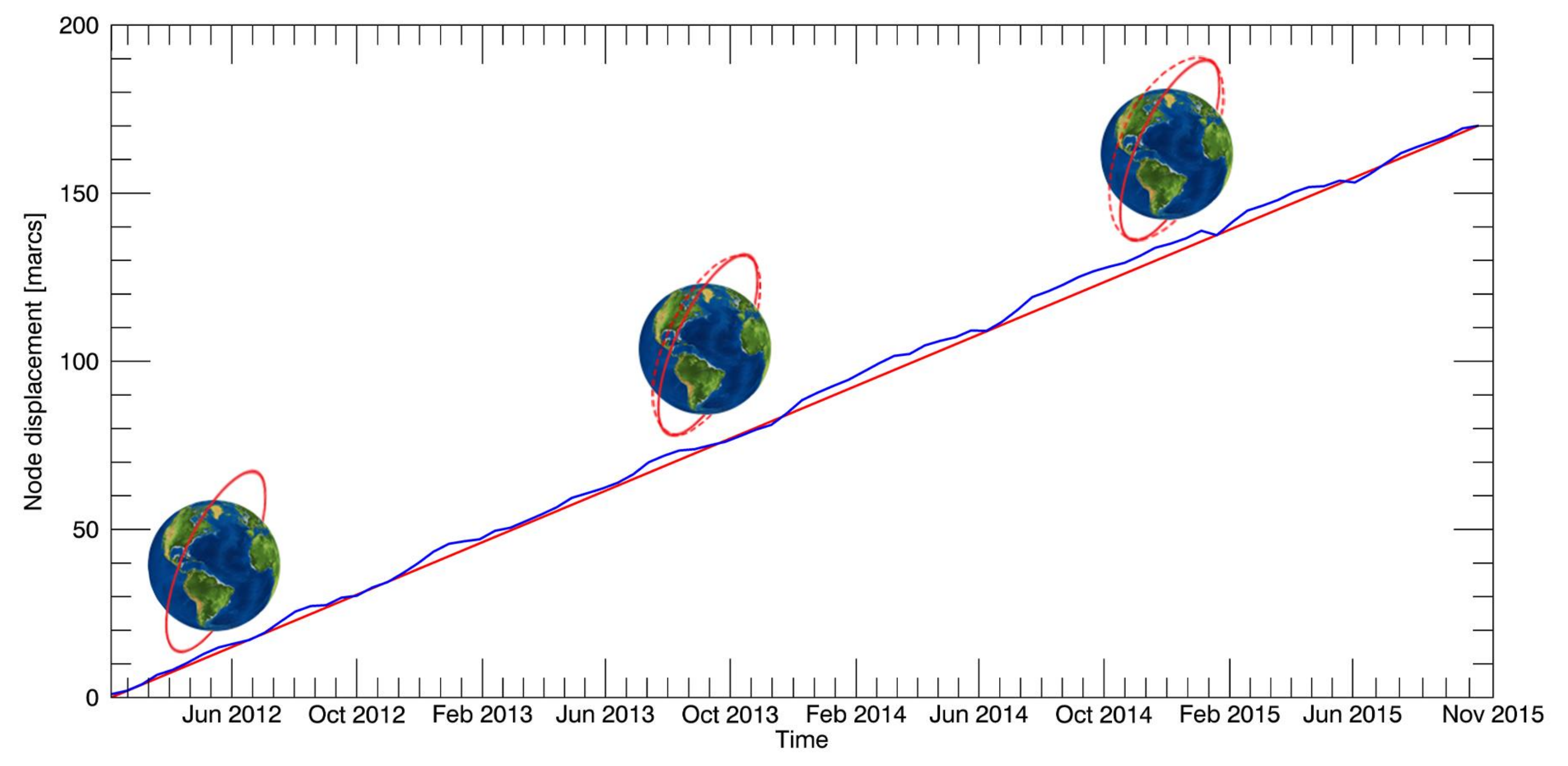


A spherical satellite covered with 92 reflectors, radius 182 mm. Made of tungsten alloy, 387 kg, the highest mean density body in the Solar System.

European Space Agency spaceport, Kourou, French Guiana, 2012



Node shift due to Earth frame-dragging: 118.4 milliarcsec/y on LARES (green, longer arrow) and 30.7 milliarcsec/y on LAGEOS satellites (red, shorter arrow).



Lense-Thirring effect, LARES data.

Earth’s tidal perturbations on the satellites

Perturbative celestial mechanics.

Earth’s gravitational potential

$$U(r) = \frac{GM_\oplus}{r}\left[1+\sum_{l=2}^{\infty}\sum_{m=0}^{l}\left(\frac{R_\oplus}{r}\right)^l P_{lm}(cos(\theta))(C_{lm}cos(m\lambda)+S_{lm}sin(m\lambda)))\right]$$

The perturbations of the Moon and Sun are the dominant ones for the Earth’s tides.

Tidal theory: Laplace, G. Darwin.

Tidal mode classification: Doodson (1921).

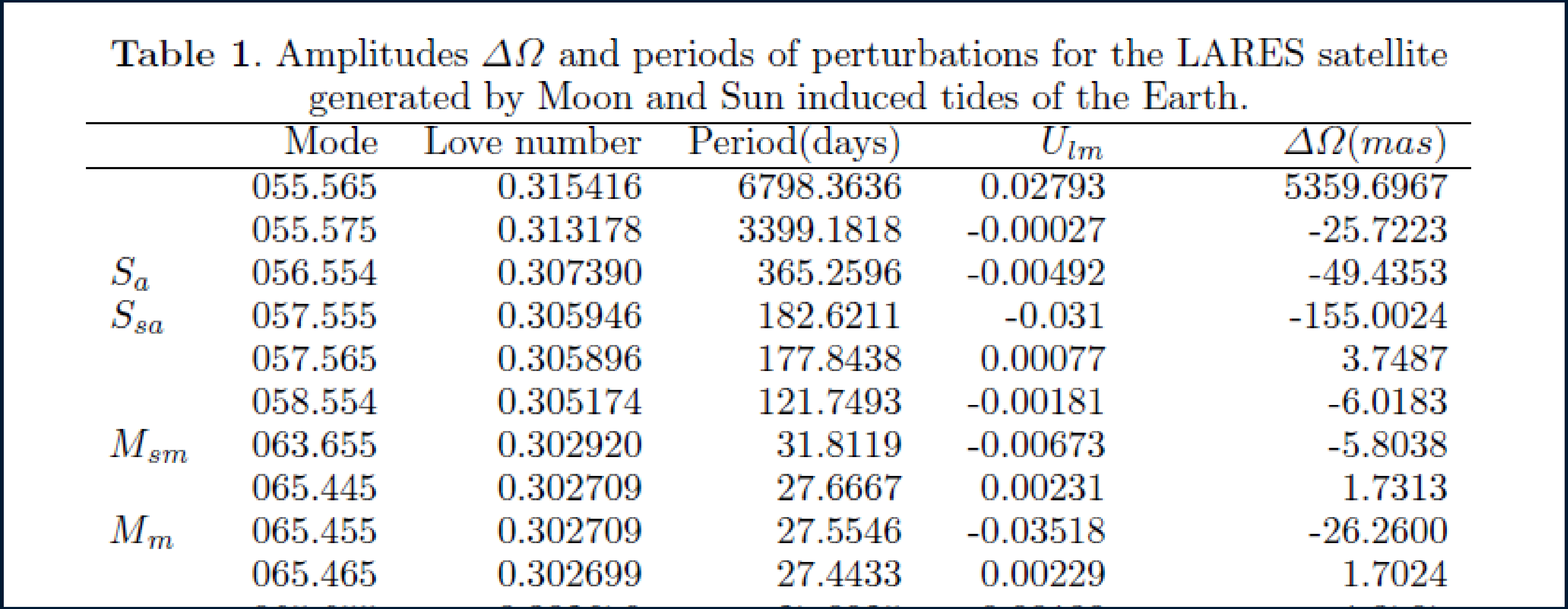


Table 1. Amplitudes $\Delta\Omega$ and periods of perturbations for the LARES satellite generated by Moon and Sun induced tides of the Earth.

	Mode	Love number	Period(days)	U_{lm}	$\Delta\Omega(mas)$
	055.565	0.315416	6798.3636	0.02793	5359.6967
	055.575	0.313178	3399.1818	-0.00027	-25.7223
S_a	056.554	0.307390	365.2596	-0.00492	-49.4353
S_{sa}	057.555	0.305946	182.6211	-0.031	-155.0024
	057.565	0.305896	177.8438	0.00077	3.7487
	058.554	0.305174	121.7493	-0.00181	-6.0183
M_{sm}	063.655	0.302920	31.8119	-0.00673	-5.8038
	065.445	0.302709	27.6667	0.00231	1.7313
M_m	065.455	0.302709	27.5546	-0.03518	-26.2600
	065.465	0.302699	27.4433	0.00229	1.7024

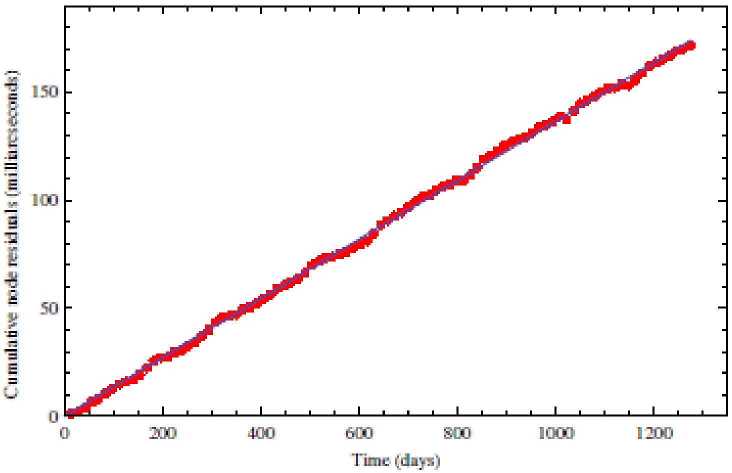
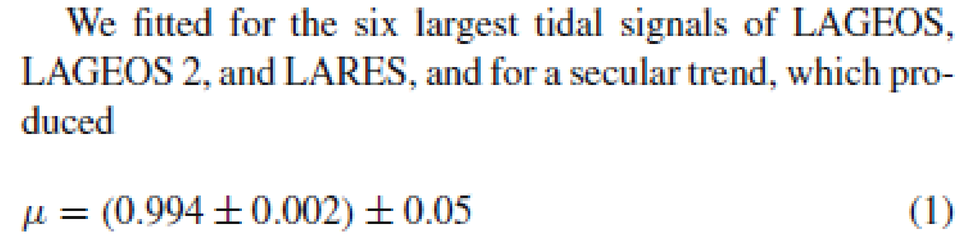
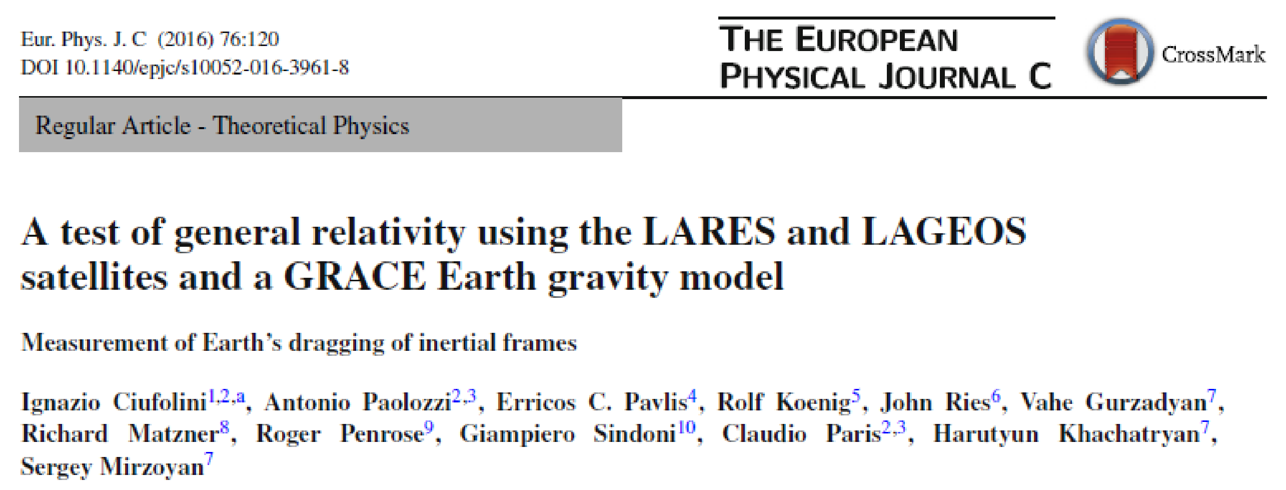


Fig. 4 Fit of the cumulative combined nodal residuals of LARES, LAGEOS, and LAGEOS 2 with a linear regression plus six periodical terms corresponding to six main tidal perturbations observed in the orbital residuals



We fitted for the six largest tidal signals of LAGEOS, LAGEOS 2, and LARES, and for a secular trend, which produced

$$\mu = (0.994 \pm 0.002) \pm 0.05 \qquad (1)$$



Eur. Phys. J. C (2016) 76:120
DOI 10.1140/epjc/s10052-016-3961-8

THE EUROPEAN PHYSICAL JOURNAL C

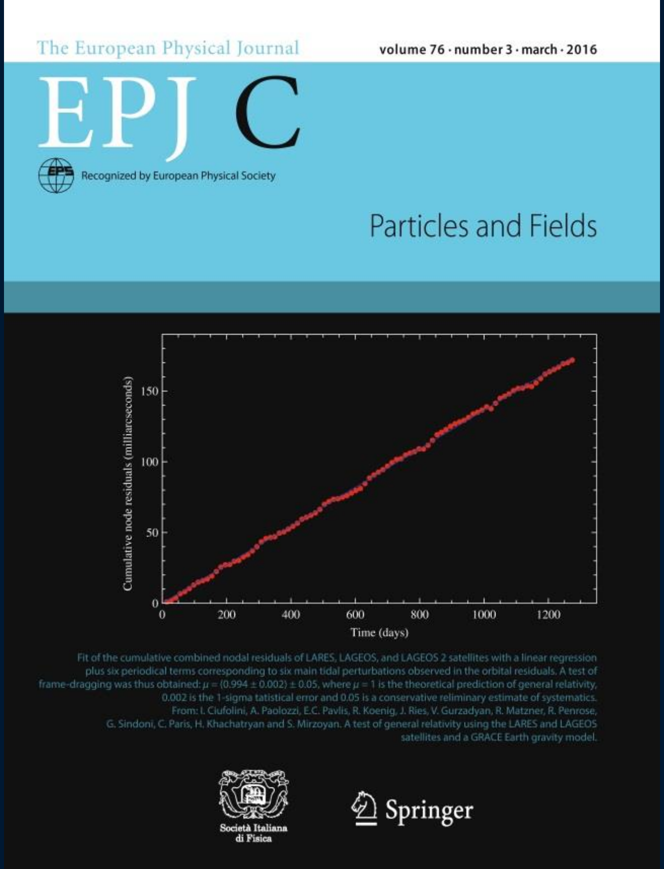
CrossMark

Regular Article - Theoretical Physics

A test of general relativity using the LARES and LAGEOS satellites and a GRACE Earth gravity model

Measurement of Earth's dragging of inertial frames

Ignazio Ciufolini[1,2,a], Antonio Paolozzi[2,3], Erricos C. Pavlis[4], Rolf Koenig[5], John Ries[6], Vahe Gurzadyan[7], Richard Matzner[8], Roger Penrose[9], Giampiero Sindoni[10], Claudio Paris[2,3], Harutyun Khachatryan[7], Sergey Mirzoyan[7]



The European Physical Journal

volume 76 · number 3 · march · 2016

EPJ C

Recognized by European Physical Society

Particles and Fields

Fit of the cumulative combined nodal residuals of LARES, LAGEOS, and LAGEOS 2 satellites with a linear regression plus six periodical terms corresponding to six main tidal perturbations observed in the orbital residuals. A test of frame-dragging was thus obtained: $\mu = (0.994 \pm 0.002) \pm 0.05$, where $\mu = 1$ is the theoretical prediction of general relativity, 0.002 is the 1-sigma tatistical error and 0.05 is a conservative reliminary estimate of systematics.
From: I. Ciufolini, A. Paolozzi, E.C. Pavlis, R. Koenig, J. Ries, V. Gurzadyan, R. Matzner, R. Penrose, G. Sindoni, C. Paris, H. Khachatryan and S. Mirzoyan. A test of general relativity using the LARES and LAGEOS satellites and a GRACE Earth gravity model.

Società Italiana di Fisica

Springer

Il mini-satellite che dà ragione a Einstein

IL VIA NEL 2012
Lares viene preparato per il lancio nella stazione Esa di Kourou, in Guyana

GIOVANNI BIGNAMI

Dopo le onde gravitazionali, arriva dallo spazio un'altra grande scoperta legata alla teoria della relatività di Einstein. Un piccolo satellite tutto italiano, Lares dell'Asi, messo in orbita nel 2012 dall'Esa con il vettore italiano Vega, ha ora misurato l'effetto di trascinamento che la rotazione della Terra genera sulla regione dello spazio intorno a noi. Il risultato è una prima mondiale, anche per la precisione della misura, ed è appena uscito su una prestigiosa rivista scientifica internazionale.

Nel 1918, alla fine della prima guerra mondiale, l'idea fu sviluppata da due fisici austriaci. Seguendo la teoria di Einstein appena pubblicata, studiavano l'effetto di una massa sullo spazio che la circonda, come nel caso della curvatura della luce o delle stesse onde gravitazionali. I due fisici predissero che se una massa, come il pianeta Terra, ruota su se stessa, i punti dello spazio vuoto che le sta intorno non rimangono fermi, ma vengono trascinati dalla massa che gira.

> Le misurazioni fatte grazie ai raggi laser rivelano uno scostamento dall'orbita di 4 metri all'anno

Con un esempio un po' infantile, si può immaginare una biglia di ferro ruotante vorticosamente in un vaso di miele. Il miele intorno alla biglia verrà un po' "trascinato" dal moto di rotazione della piccola massa. Se volessi misurare l'effetto (dovuto in questo caso a banale viscosità) potrei sospendere nel miele vicino alla biglia una particella ben visibile ed osservare il suo trascinamento. La biglia è il nostro pianeta Terra, in rapida rotazione, il miele è lo spazio circostante, e la particella è il satellite dell'Asi.

Lares (*Laser relativity satellite*) è un satellite passivo, che non deve fare niente se non avere una massa ed essere in una posizione ben misurabile. Il primo requisito è facile: una sfera compatta, con la maggior massa nel minimo volume possibile: una semplice palla di meno di 20 centimetri di raggio, fatta di tungsteno, molto denso, e che perciò pesa (sulla Terra) quasi 400 chili. Tra l'altro, dopo averlo messo in orbita, ci siamo resi conto di aver creato l'oggetto più denso di tutto il sistema solare.

Per misurare la posizione di Lares si usa un trucco da discoteca. La palla di tungsteno è coperta di specchietti (pomposamente chiamati retroriflettori) che vengono colpiti da raggi laser sparati da stazioni a terra. Dal tempo di andata-e-ritorno degli impulsi laser si misura con precisione millimetrica la distanza di Lares da vari punti della Terra e quindi la sua posizione lungo l'orbita circolare a 1.450 chilometri di altezza.

Si capisce bene che si tratti di una missione a basso costo ma di altissimo contenuto culturale, cioè il tipo di piccola missione scientifica di interesse per, e alla portata di, Asi. Su proposta un po' pazza di Ignazio Ciufolini, dell'università del Salento, ancor oggi il responsabile scientifico della missione, nel 2008 decidemmo di buttarci a fare Lares, sfruttando le capacità delle Pmi spaziali italiane. Oltre al satellite-palla con specchietti integrati, si trattò di mettere in piedi, un po' artigianalmente, un accrocco piro-meccanico per sganciare Lares in orbita al momento giusto.

Mancava ancora il razzo per arrivare all'orbita richiesta. Decidemmo di prendere un rischio, e usare il lancio di qualifica (gratuito) del nuovissimo vettore Vega, sviluppato dall'Italia per la Esa. Il 13 febbraio 2012, dita di mani e piedi incrociate alla base di lancio Esa di Kourou, nel caldo infernale della Guyana francese, l'ex bagno penale di Papillon. La fortuna arride agli audaci: la matricola Vega si comportò come un veterano, portò l'ultimo stadio con la palla nel posto giusto, l'accrocco a molla funzionò meglio di una trappola per topi e Lares iniziò la sua vita orbitale, pronto farsi prendere a laserate.

> Un esperimento low cost da soli 8 milioni di euro che conferma gli effetti della teoria della relatività

Sommessamente, ma con orgoglio, notiamo che tutta l'operazione costò meno di otto milioni, forse un record nel campo spaziale. Dopo decine di milioni di misure laser, Ciufolini e i suoi sono adesso in grado di confermare che Einstein (guarda caso) aveva ragione. Lares, a 1.450 chilometri di altezza, viene trascinato per ben 4 metri all'anno dallo spazio rotante con la Terra. Per di più, la misura ha una precisione assoluta del 5%, un record mondiale, ma soprattutto è circa quattro volte meglio di quello che hanno fatto in Usa finora, spendendo molto, ma molto, di più.

La missione di Lares

Il satellite

È una palla di **tungsteno**

Massa	386,8 kg
Raggio	18,2 cm
Densità media	15.317 kg/m³
Retro-riflettori	92

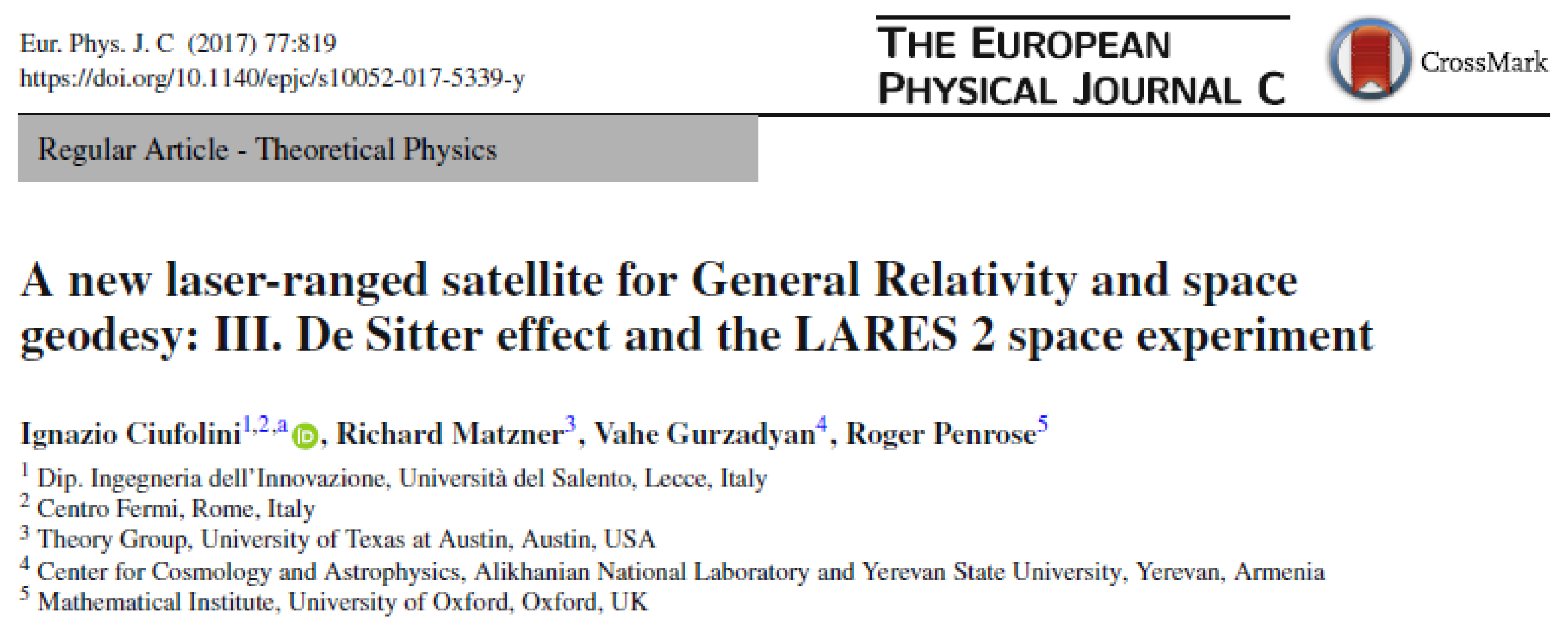
Il viaggio

Il **13 febbraio 2012** è stato lanciato in orbita dall'Agenzia spaziale europea **con il razzo italiano Vega**

1. Circa 50 stazioni a terra colpiscono Lares con impulsi laser
2. Dal tempo di andata-e-ritorno dei raggi si misura con precisione la posizione di Lares lungo l'orbita

La prova

I dati raccolti in 4 anni confermano un effetto della teoria della relatività di Einstein: la rotazione della Terra "trascina" con sé lo spazio circostante, al punto che Lares viene spostato di 4 metri all'anno



Eur. Phys. J. C (2017) 77:819
https://doi.org/10.1140/epjc/s10052-017-5339-y

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

A new laser-ranged satellite for General Relativity and space geodesy: III. De Sitter effect and the LARES 2 space experiment

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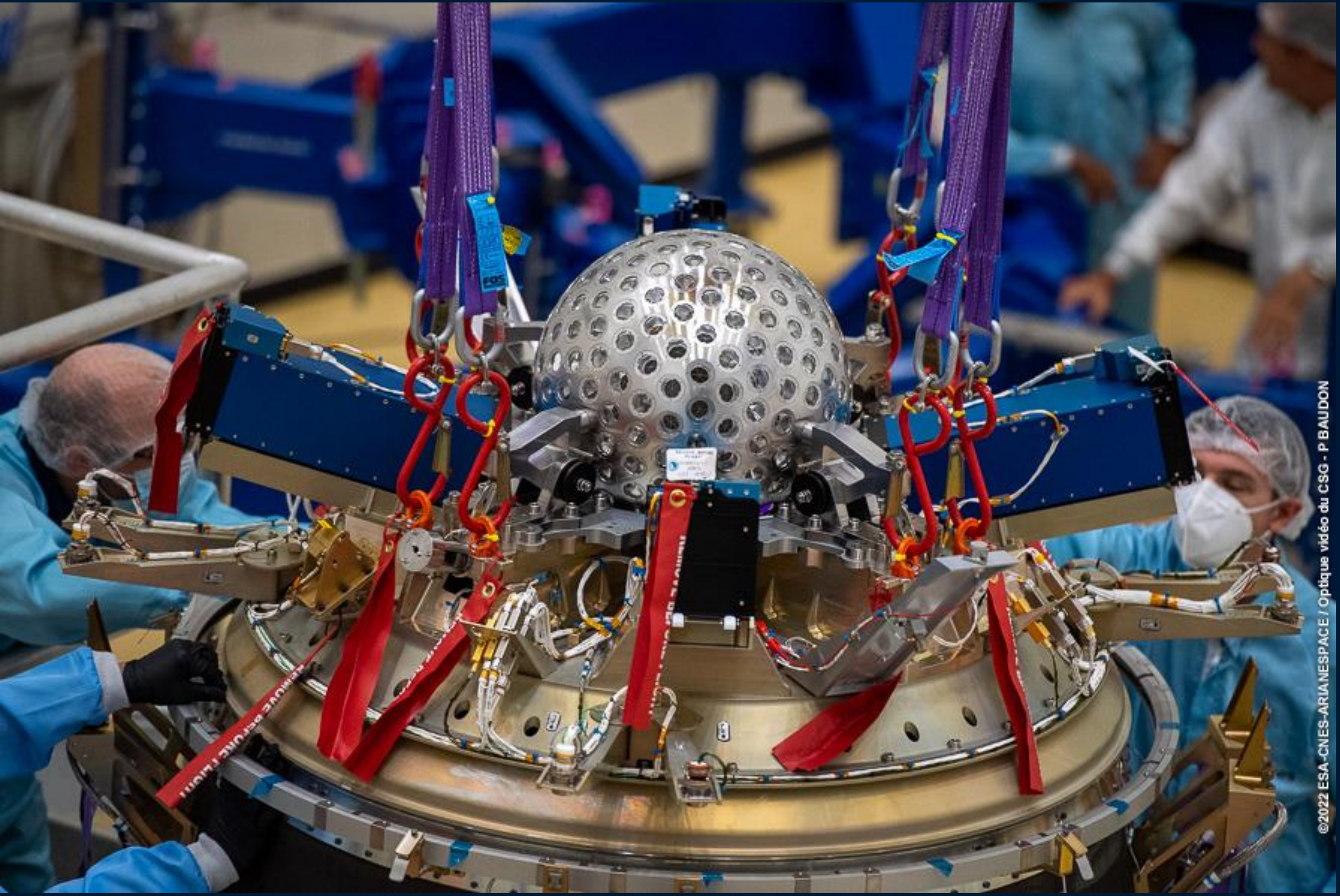

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Arianespace | Vega-C |

LARES-2 (Maiden flight)

July 13, 2022

Lift Off Time *13 July 2022 – 13:13:17 UTC | 10:13:17 GFT*

LAUNCH STATUS Success

LARES

Sir Roger Penrose,
Rome

LARES-2

Kourou

LARES-2 satellite’s separation.

Conclusions

Hubble tension:
Tension between late (local) and early (global) Universe?
Two Hubble flows?

Gravity defined not one but by two constants,
G and Lambda, describe galaxy groups, clusters, Hubble tension.

The cosmological constant is dimension-independent and matter-uncoupled, so even more universal constant than G.

Satellite tests of GR, more coming soon…