Constraints on the **mass of the graviton** from solar system observations and **planetary ephemeris**

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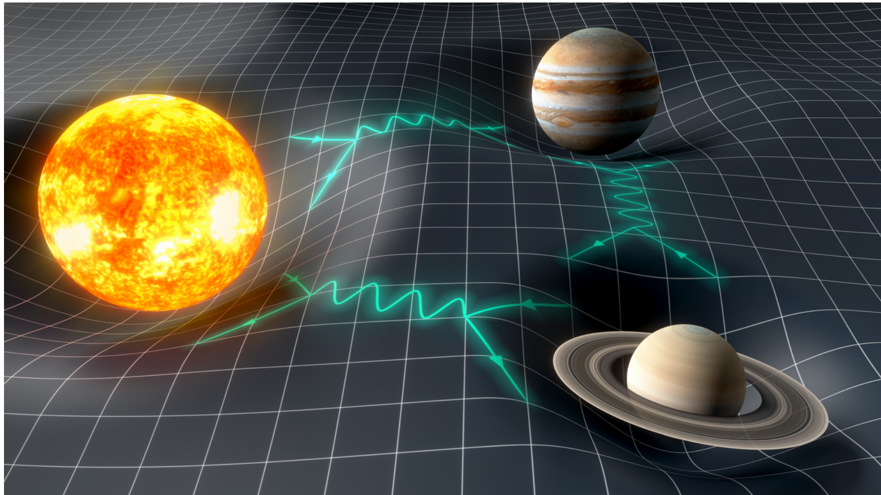
[1]IMCCE, Observatoire de Paris, PSL University
[2]Centre Scientifique de Monaco
[3]Artemis, Observatoire de la Côte d'Azur
[4]Géoazur, Observatoire de la Côte d'Azur



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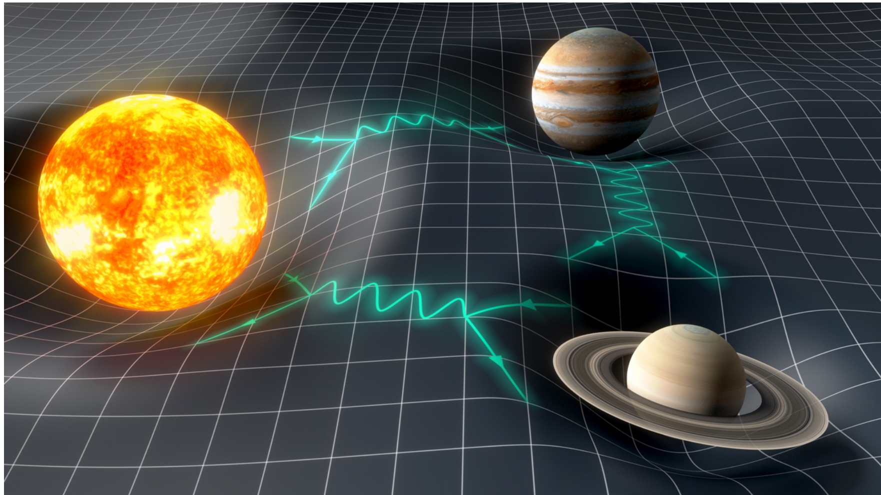
Spoiler alert : it's small !



PHYSICAL REVIEW LETTERS **123,** 161103 (2019)

Editors' Suggestion   Featured in Physics

Constraining the Mass of the Graviton with the Planetary Ephemeris INPOP

L. Bernus,[1] O. Minazzoli,[2,3] A. Fienga,[4,1] M. Gastineau,[1] J. Laskar,[1] and P. Deram[4]

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(Received 14 January 2019; revised manuscript received 15 April 2019; published 18 October 2019)

Physics ABOUT BROWSE PRESS COLLECTIONS

Editors' Suggestio

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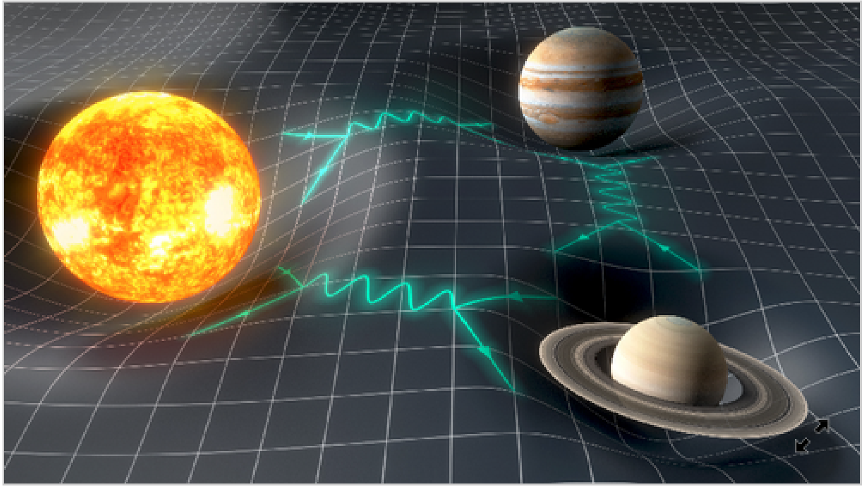
(R r 2019)

Focus: Limits on the Graviton from Planetary Orbits

October 18, 2019 • *Physics* 12, 113

A new analysis improves on estimates of the upper limit on the mass of the graviton particle using Solar System data.



Y. Gominet/Paris Observatory

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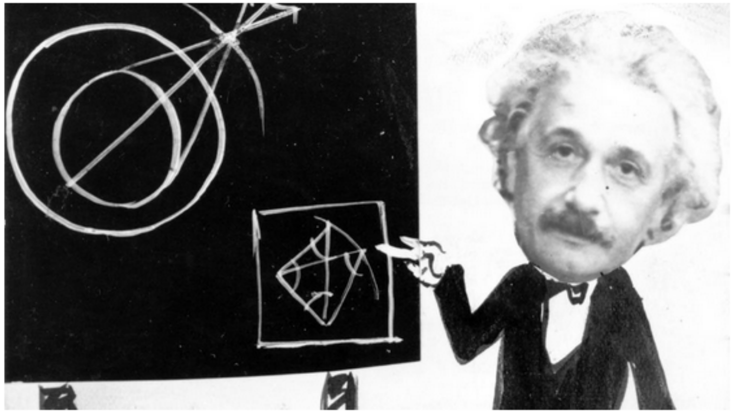
What If Einstein Overlooked Something?

Don Lincoln Contributor
Science
I cover the physics of nothing, everything, and the stuff in between.



Albert Einstein is the architect of our modern understanding of gravity. (Photo by ullstein bild via ... [+] ULLSTEIN BILD VIA GETTY IMAGES

Gravity is the most familiar of the fundamental forces known to modern physics. Babies experiment with it as they drop Cheerios down to a patient puppy. Romantic comedies often begin with a dropped package, falling under gravity's inexorable influence, to land at the feet

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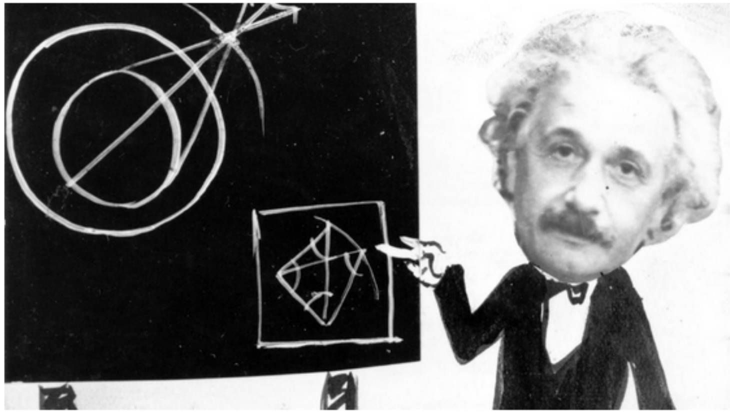

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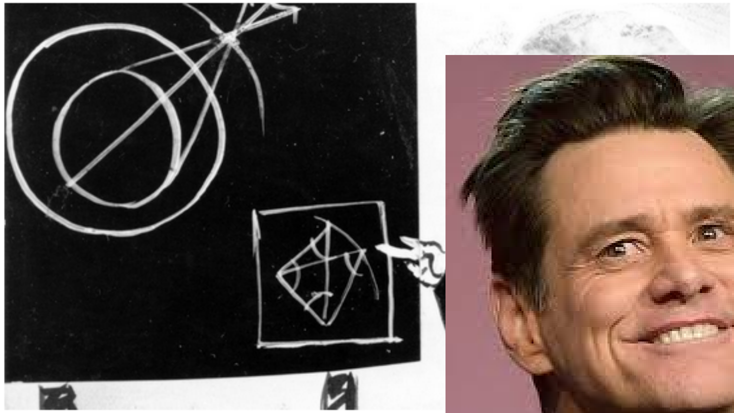

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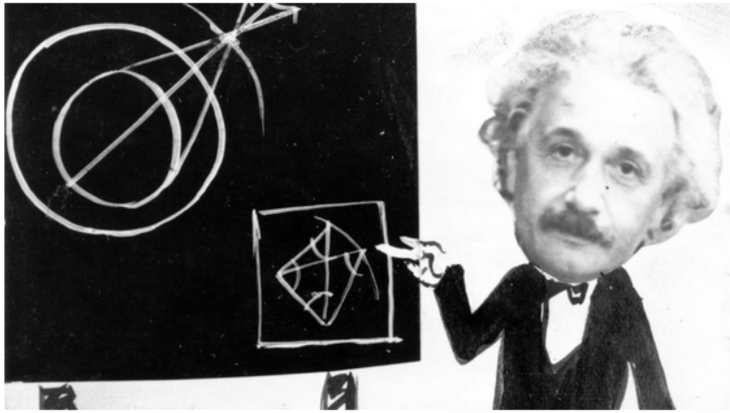

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Gravity is the most familiar of the fundamental forces known to modern physics. Babies experiment with it as they drop Cheerios down to a patient puppy. Romantic comedies often begin with a dropped package, falling under gravity's inexorable influence, to land at the feet

Clearly our motivations !

« The fact that scientists can make measurements with such precision is a real testament to the techniques of modern science. »

Mass of the graviton: what does that mean?

The example of electromagnetism:

$$\Delta A^{\mu} - \frac{1}{c^2}\frac{\partial^2 A^{\nu}}{\partial t^2} = 0$$

Maxwell theory → photons without mass

$$\Delta A^{\mu} - \frac{1}{c^2}\frac{\partial^2 A^{\mu}}{\partial t^2} + \left(\frac{mc}{\hbar}\right)^2 A^{\mu} = 0$$

Procca theory → photons with mass m

$$\frac{mc}{\hbar} = \frac{1}{\lambda_C}$$

Compton wavelength: give a “range” to the interaction

Maxwell: $m \rightarrow 0 \Leftrightarrow \lambda_C \rightarrow \infty$: infinite range

$m_{photon} < 10^{-18}$ eV/c² from experiments (Coulomb interaction) - Particle Data Group

Mass of the graviton: what does that mean?

The example of the Weak nuclear force:

Mass W and Z bosons ~ 85 GeV/c^2 → range ~ 10^{-18} meters

“It vanishes altogether beyond the radius of a single proton” CERN

$$\frac{mc}{\hbar} = \frac{1}{\lambda_C}$$ Compton wavelength: give a “range” to the interaction

Mass of the graviton: what does that mean?

A bit more complicated to define for a space-time

→ there exist several definitions of what a mass could mean for a space-time

From a phenomenological point of view, we considered same definition as Clifford Will:

$$ds^2 = \left(-1 + \frac{2GM}{c^2R} e^{-R/\lambda_g}\right) c^2 dT^2 + \left(1 + \frac{2GM}{c^2R} e^{-R/\lambda_g}\right) dL^2,$$

$\boxed{\text{Nothing quantum!!}}$

The Newtonian potential simply gets an exponential decay (called a “Yukawa suppression”)

As if: $\Delta\Phi + \frac{1}{\lambda_g^2}\Phi = \frac{4\pi G}{c^4}\rho$

Mass of the graviton: what difference?

It modifies the equation of motion according to :

$$\delta\vec{a}=\frac{1}{2}\sum_P \frac{G\,M_P}{\lambda_C^2}\frac{\vec{x}-\vec{x}_P}{r}$$

The difference on the propagation of light is negligible.
(→ same Shapiro delay)

<u>Idea</u>: use solar system observations to see how it can be consistent with the additional acceleration

<u>**THE**</u> most common mistake in the community

<u>Reasoning</u>:

Planetary ephemeris are consistent with observations at the level X (say, residuals are of the order of a few meters)

Any effect of the additional acceleration beyond level X is ruled out by observation

<u>Residuals</u>: difference between best fit of the model to the observations and the observations

THE most common mistake in the community

Reasoning:

Planetary ephemeris are consistent with observations at the level X (say, residuals are of the order of a few meters)

Any effect of the additional acceleration beyond level X is ruled out by observation

Residuals: difference between best fit of the model to the observations and the observations

Wrong: because the best fit is model dependent!!!

i.e. parameters (masses, semimajor axes) take different values when the fit is done assuming another theory

Correlations

Technically, the Compton wavelength is **correlated** to other parameters:

	λ_g	a Mercury	a Mars	a Saturn	a Venus	a EMB	$GM_\odot$
λ_g	1	0.50	0.49	0.04	0.39	0.05	0.66
a Mercury	...	1	0.21	0.001	0.97	0.82	0.96
a Mars	...	...	1	0.03	0.29	0.53	0.06
a Saturn	...	...	...	1	0.003	0.02	0.01
a Venus	...	...	...	...	1	0.86	0.94
a EMB	...	...	...	...	...	1	0.73
$GM_\odot$	...	...	...	...	...	...	1

<u>It means</u>: any observational effect of a graviton mass can in part be obtained by the modification of several other parameters instead

<u>It implies</u>: one overestimates the visible effect of a graviton mass if the model is not adjusted properly → not many have the technology to do that, but we do: **INPOP**

INPOP

Intégrateur Numérique Planétaire de l'Observatoire de Paris

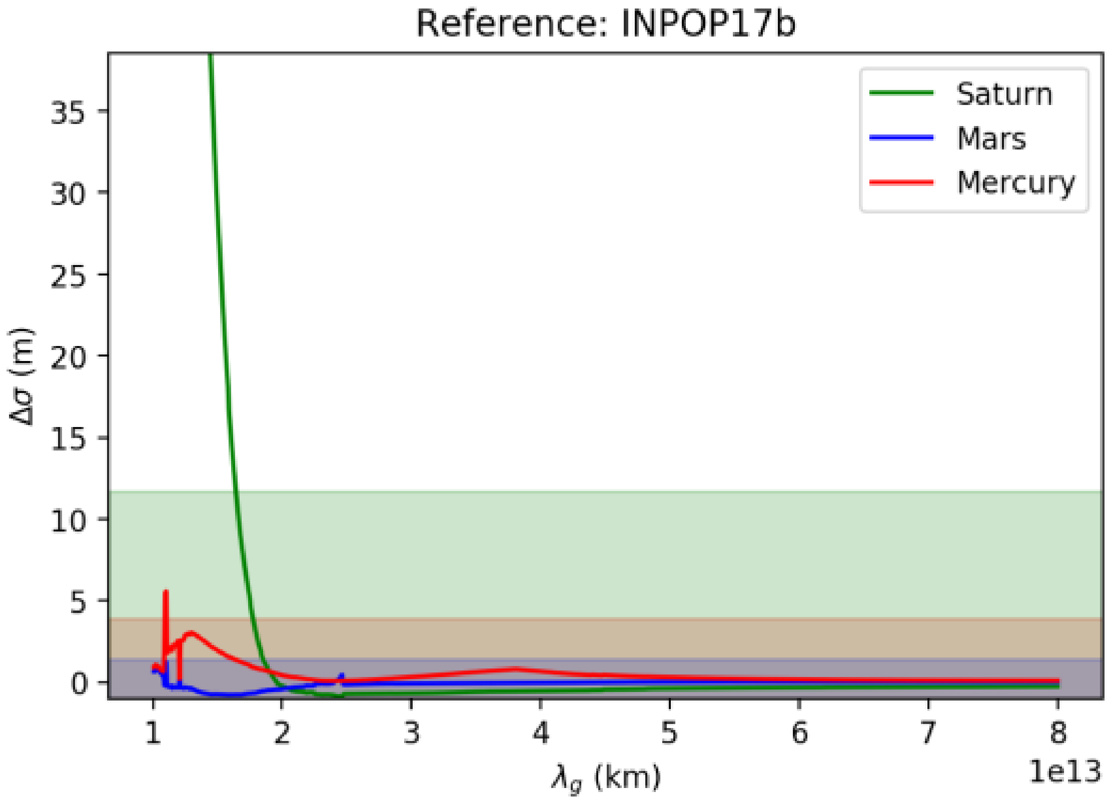
Currently developed at IMCCE (Paris observatory) and GeoAzur (OCA)

Integrate equations of motion and fit to Solar System observations in order to minimize the difference between the integrated equations and the observations (the residuals).

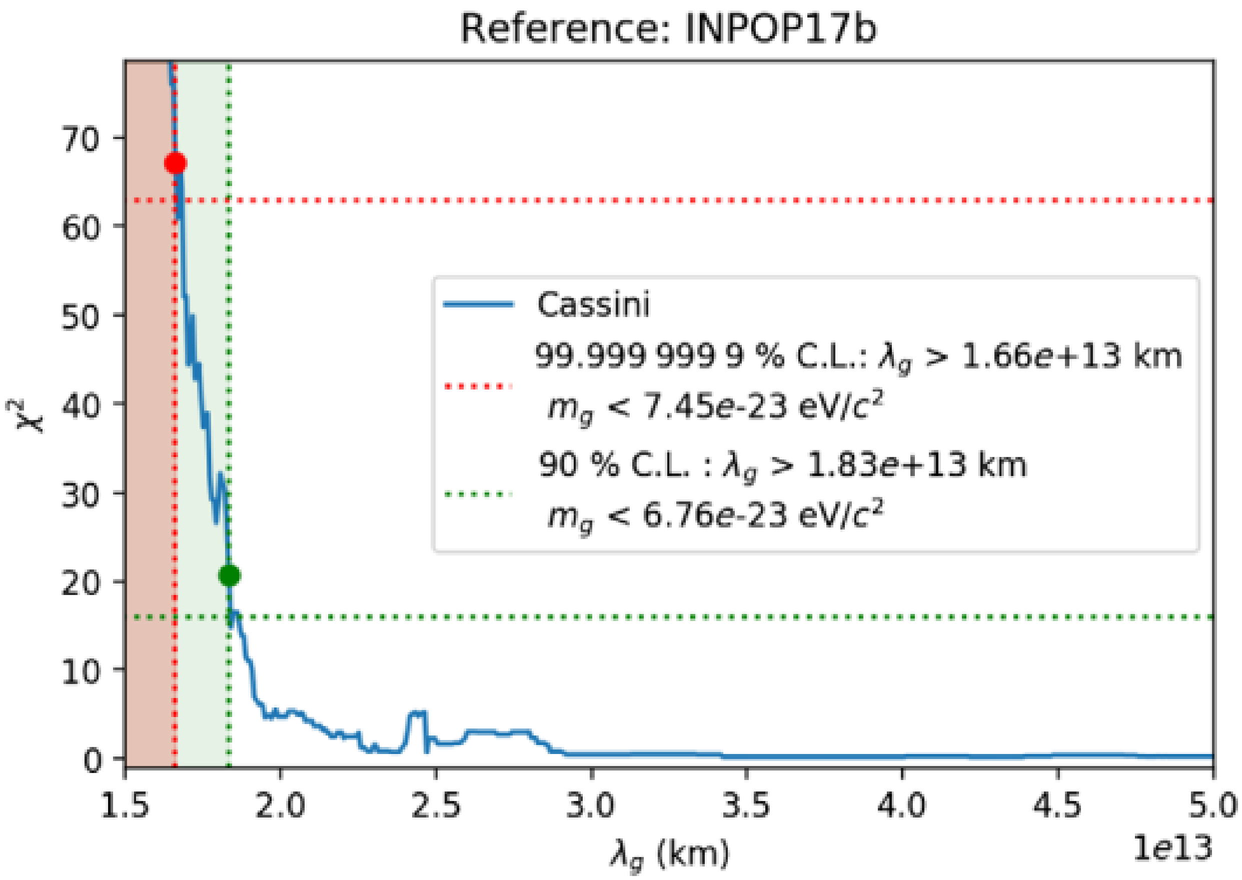
We used INPOP17b:

- Data from 1914 to 2017
- All Solar System bodies up to 168 asteroids
- Better model of the Moon w.r.t. INPOP15a.
- Can include the effect of a Yukawa suppression to the Newtonian potential

Results: standard deviations w.r.t. Compton



Results: chi² w.r.t. Compton



(Confidence levels given according to a Pearson test)

Results at 90% C.L.

$$\lambda_g > 1.83 \times 10^{13}\, km \sim 122 \times 10^{3}\, AU$$

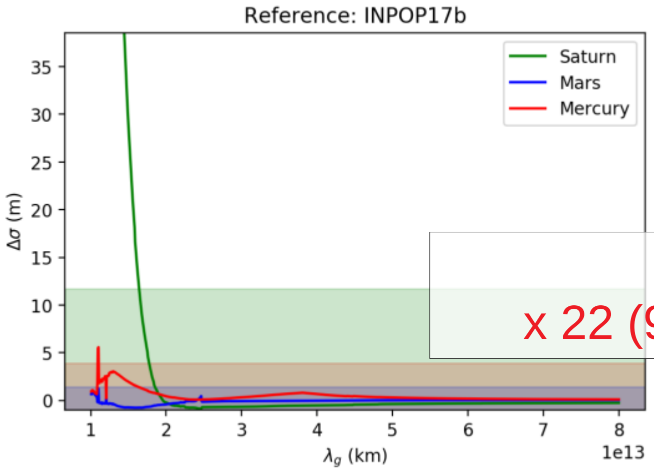
$$m_g < 6.76 \times 10^{-23}\, eV/c^2 \sim 10^{-55}\, g$$

« ...about one ten thousandth of a trillionth of a trillionth of the mass of the electron, which is both the lightest of the familiar subatomic particles and the lightest particle for which a mass has been reliably measured. »

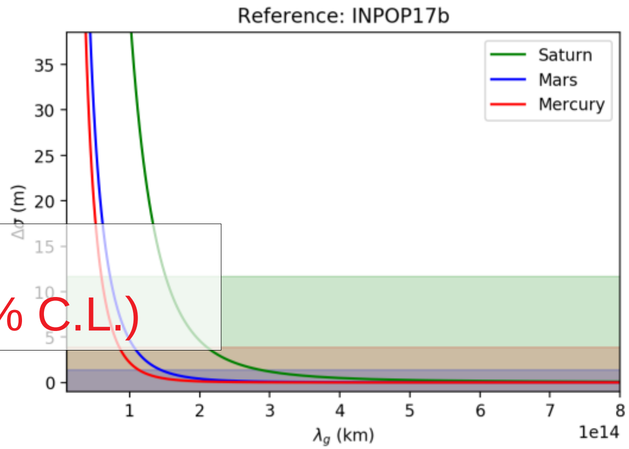
(Don Lincoln in Forbes)

What if we did the usual mistake?

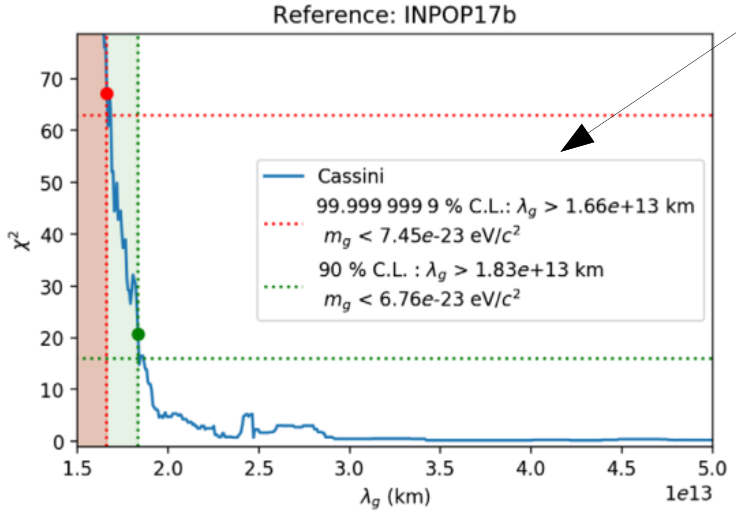
Fit

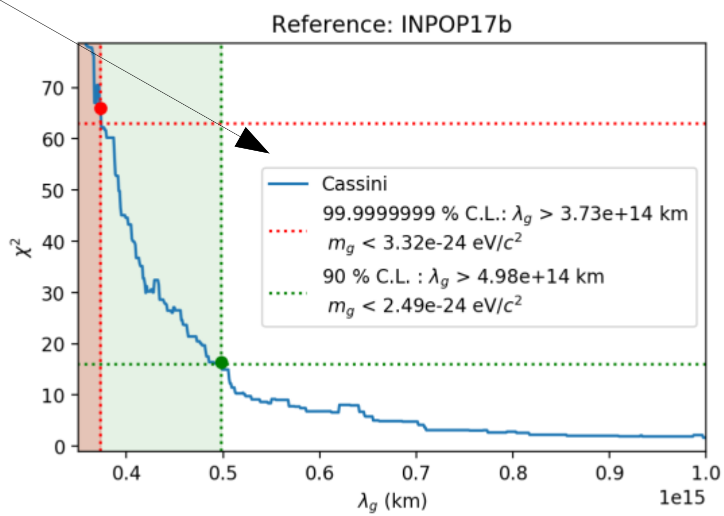


No fit



Spurious better accuracy:
x 22 (90% C.L.) and x 27 (99.999999% C.L.)





Comparison with LIGO-Virgo

PHYSICAL REVIEW D **100,** 104036 (2019)

Tests of general relativity with the binary black hole signals from the LIGO-Virgo catalog GWTC-1

B. P. Abbott *et al.*[*]
(The LIGO Scientific Collaboration and the Virgo Collaboration)

(Received 29 March 2019; published 20 November 2019)

The detection of gravitational waves by Advanced LIGO and Advanced Virgo provides an opportunity to test general relativity in a regime that is inaccessible to traditional astronomical observations and laboratory tests. We present four tests of the consistency of the data with binary black hole gravitational waveforms predicted by general relativity. One test subtracts the best-fit waveform from the data and checks the consistency of the residual with detector noise. The second test checks the consistency of the low- and high-frequency parts of the observed signals. The third test checks that phenomenological deviations introduced in the waveform model (including in the post-Newtonian coefficients) are consistent with 0. The fourth test constrains modifications to the propagation of gravitational waves due to a modified dispersion relation, including that from a massive graviton. We present results both for individual events and also results obtained by combining together particularly strong events from the first and second observing runs of Advanced LIGO and Advanced Virgo, as collected in the catalog GWTC-1. We do not find any inconsistency of the data with the predictions of general relativity and improve our previously presented combined constraints by factors of 1.1 to 2.5. In particular, we bound the mass of the graviton to be $m_g \leq 4.7 \times 10^{-23}$ eV$/c^2$ (90% credible level), an improvement of a factor of 1.6 over our previously presented results. Additionally, we check that the four gravitational-wave events published

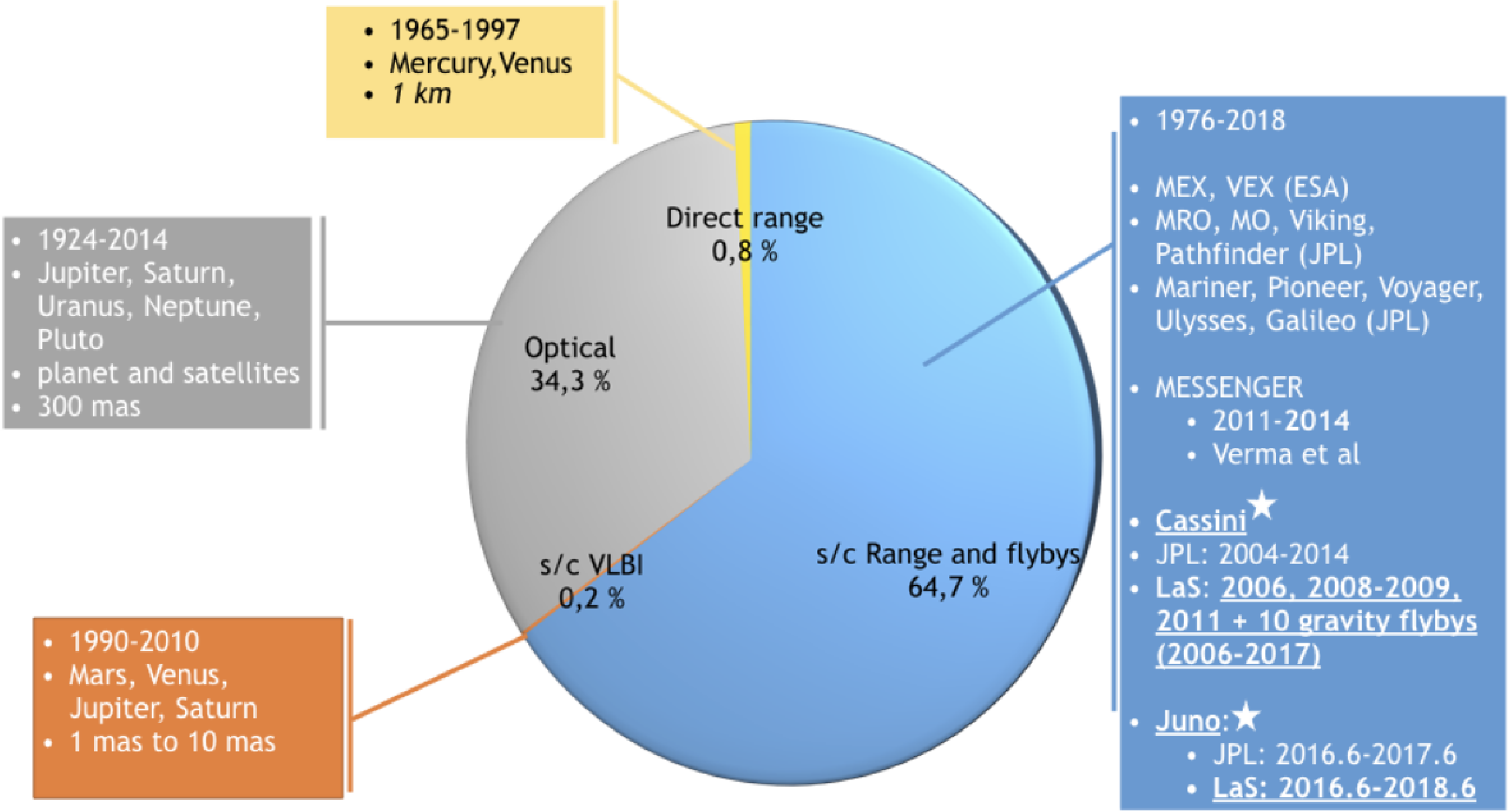
LVC (90% C.L.)

$$m_g \leq 4.7 \times 10^{-23} \, eV/c^2$$

INPOP (90% C.L.)

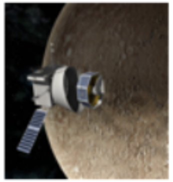
$$m_g < 6.76 \times 10^{-23} \, eV/c^2$$

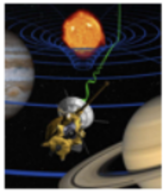
Soon… *INPOP2019a*

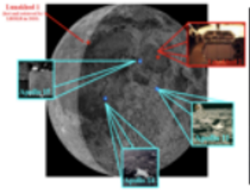


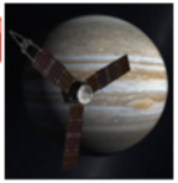
THANK YOU!!

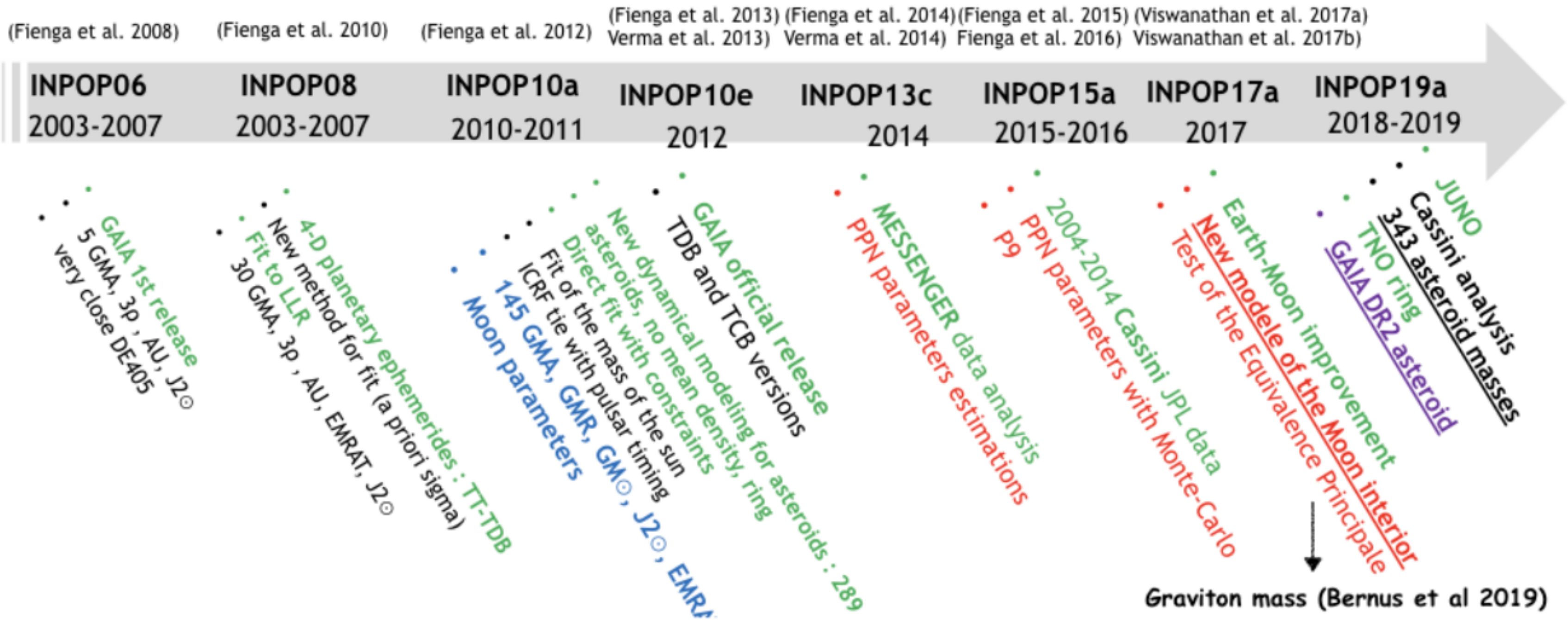
www.imcce.fr/inpop











INPOP

Intégrateur Numérique Planétaire de l'Observatoire de Paris

- Numerical integration of the (Einstein-Imfeld-Hoffmann, c^{-4} PPN approximation) equations of motion.

$$\ddot{x}_{Planet} = \sum_{A \neq B} \mu_B \frac{r_{AB}}{\|r_{AB}\|^3} + \ddot{x}_{GR}(\beta, \gamma, c^{-4}) + \ddot{x}_{AST,300} + \ddot{x}_{J_2^{\odot}}$$

- Adams-Cowell in extended precision
- 8 planets + Pluto + Moon + asteroids (point-mass, ring), GR, $J_2^{\odot}$, Earth rotation (Euler angles, specific INPOP)
- Moon: orbit and librations
- Simultaneous numerical integration TT-TDB, TCG-TCB
- Testing GR and alternative theories, asteroid masses, solar physics
- Fit to observations in ICRF over 1 cy (1914-2014) including LLR
- IERS conventions

INPOP for the earth-moon system

Observational and external constraints:

- GRAIL + 40 years of LLR
- IERS 2010 conventions (Solid tides, atmospheric and ocean loadings)
- External Constraints from GRAIL and GRACE, planetary ephemerides, Rheology, Earth IERS conventions
- External Constraints for Moon and Earth gravity fields, EMRAT, Cf/Ct, Earth time delay

Earth-Moon torques with:

- Orbital and Rotational coupling: Libration Euler angles
- Moon surface deformation, degree 6 point-figure and degree2-degree3 figure-figure interactions
- Moon = mantle (shape described up to degree-6) + fluid core (axisymmetric) in interaction
- Dissipation at CMB with viscous friction (K) such as: $\mathbf{N_c} = K(\omega - \omega_\mathbf{c})$
- Earth tides: orbital and rotation time delays