Constraining the mass of the graviton with the planetary ephemeris INPOP

Journée Phyfog

Léo Bernus[1],

Agnès Fienga[2], Olivier Minazzoli[3,4], Jacques Laskar[1], Mickaël Gastineau[1], Pierre Deram[2]

[1] IMCCE, CNRS-UMR 8028, Paris
[2] GéoAzur, CNRS-UMR 7329, Valbonne
[3] Centre scientifique de Monaco
[4] Artemis, CNRS-UMR 7250, Nice

May 23, 2019

arXiv:1901.04307

Massive graviton phenomenology

Gravity phenomenology can be derived from particle physics : 2-spin massless *graviton*. Massless or not ?

(Review : C. de Rham, *Massive Gravity*, Living Reviews in Relativity 17, 7 (2014), arXiv:1401.4173)

Different tests of this theory :

- Dispersion relation : $E^2 = p^2c^2 + {m_g}^2c^4 \Rightarrow$ different waveforms (arXiv:1903.04467)
- Galactic scales (Physics Letters B : 778, 325 – 331 (2018) ; 781, 220 – 226 (2018) ; Annals of Physics 399, 85 – 92 (2018).)
- Solar system scales : this work.

Metric tensor in weak field

- In week field and velocity, almost all massive graviton theories are summarized by a Yukawa potential.
- After expansions in $r/\lambda_g \ll 1$ and clever variable changes :

$$\mathrm{d}s^2 = \left(-1 + \frac{2GM}{c^2 r}\left[1 + \frac{1}{2}\frac{r^2}{\lambda_g^2}\right]\right) c^2 \mathrm{d}t^2 + \left(1 + \frac{2GM}{c^2 r}\left[1 + \frac{1}{2}\frac{r^2}{\lambda_g^2}\right]\right) \mathrm{d}\ell^2$$

$$\lambda_g = \frac{h}{m_g c}, \quad r = \sqrt{x^2 + y^2 + z^2},$$

$$\mathrm{d}\ell^2 = \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2.$$

Geometric optics in massive gravity

Modified time travel :

$$\delta(t_r - t_e) \sim \left(\frac{L}{\lambda_g}\right)^2 \times \text{Shapiro delay}$$

- Previous constrains : $\lambda_g > 10^{12}\,\text{km}$.
- Solar system scale $\sim 10^9\,\text{km}$ in the worst case (Neptune).

$\Rightarrow \left(\frac{L}{\lambda_g}\right)^2 < 10^{-6}$ for Neptune. Rather $< 10^{-8}$ for solar system bodies with accurate data.
$\Rightarrow$ term negligible, keep usual GR framework.

Planetary dynamics

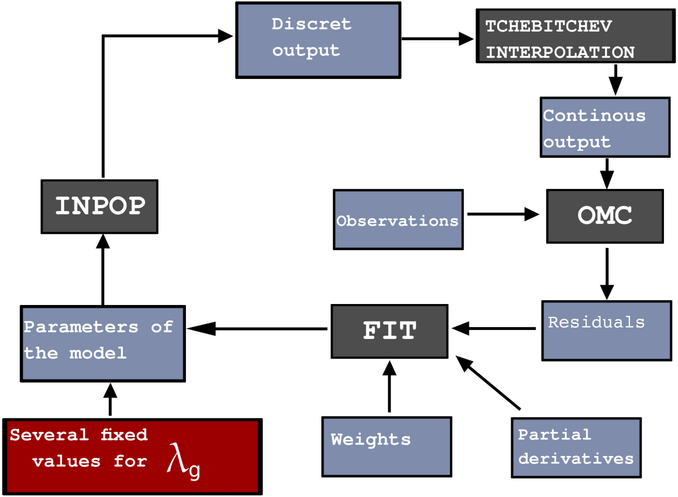
Terms to be added in equations of motion :

$$\delta \frac{\mathrm{d}^2 \boldsymbol{x}_A}{\mathrm{d}t^2} = \frac{1}{2\lambda_g^2} \sum_{B \neq A} G M_B \frac{\boldsymbol{x}_A - \boldsymbol{x}_B}{|\boldsymbol{x}_A - \boldsymbol{x}_B|} + O(\lambda_g^{-3})$$

- Here, A, B = Sun, Mercury, Venus, Earth, Moon, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto.
- Other small bodies : INPOP not changed.
- Clifford Will announced a very good constraint from planetary ephemeris (CQG 35, 17LT01, 2018) : $\lambda_g \geq 2.21 \times 10^{14}$ km. 10 times better than LIGO-VIRGO constraints !

Numerical anlaysis

INPOP and planetary observations



INPOP17b most important observations

Observations	Time Intervals	#	INPOP17b $\sigma(O-C)$ [m]	INPOP17b−DE436 $\sigma(I-D)$ [m]
Messenger	2011 : 2013.2	950	7.2	3.9
Ody, Mex	2002 : 2016.4	52946	5.0	1.4
Cassini	2004 : 2014	175	32.1	11.7

V. Viswanathan, A. Fienga, M. Gastineau, J. Laskar
2017, INPOP17a planetary ephemerides, scientific notes of IMCCE
`https://www.imcce.fr/inpop/`

INPOP17b = INPOP17a + some extended data from Messenger (from Verma et al. 2016 Journal of Geophysical Research (Planets) 121, 1627–1640, or arXiv:1608.01360)

INPOP17b

- Better are observations and physical model, better are tests of alternative theories.

References :

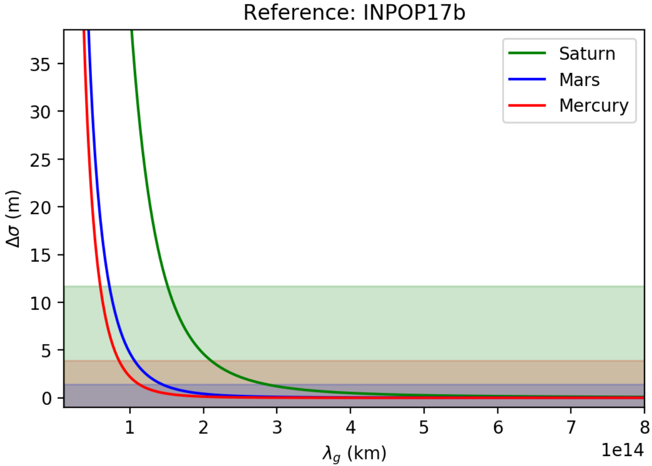
- V. Viswanathan, A. Fienga, O. Minazzoli, L. Bernus, J. Laskar, M. Gastineau
The new lunar ephemeris INPOP17a and its application to fundamental physics
MNRAS 476, 1877-1888 (2018)
- V. Viswanathan, A. Fienga, M. Gastineau, J. Laskar 2017, INPOP17a planetary ephemerides, scientific notes of IMCCE `https://www.imcce.fr/inpop/`

Data analysis

- λ_g fixed, all other parameters are ajusted.
- Same fit for INPOP17b and tested ephemeris (weights, observational data, parameters ajusted).
- After 10 iterations, the fit converges.
- Importance of a global fit : correlations between λ_g and other parameters.

Postfit versus global fit

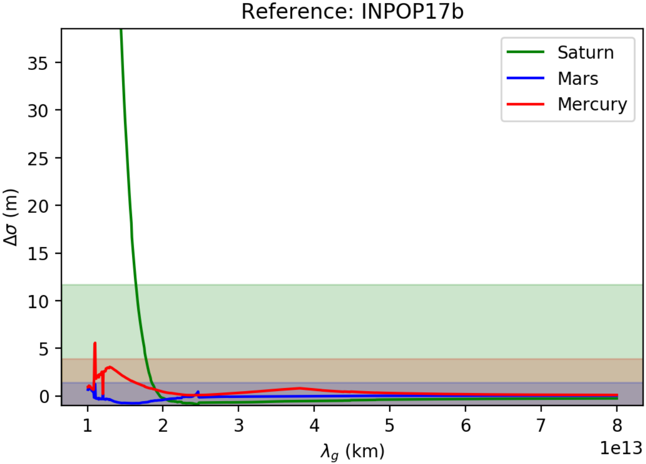
Postfit



Same order of magnitude as Will's constraint, and seems better than GW constraint ! But....

Postfit versus global fit

Global analysis (13 iterations)



10 times smaller !

Pearson test for Cassini data

Tests if residuals distribution come from the same distribution function.
From reference residuals distribution, we compute optimal size of bins for modelling histogram.

- $N_i^I =$ hits in bin i for reference solution (INPOP17b)
- $N_i^G(\lambda_g) =$ hits in bin i for tested solution

$$\chi^2(\lambda_g) = \sum_{i=1}^{n} \frac{(N_i^G(\lambda_g) - N_i^I)^2}{N_i^I}$$

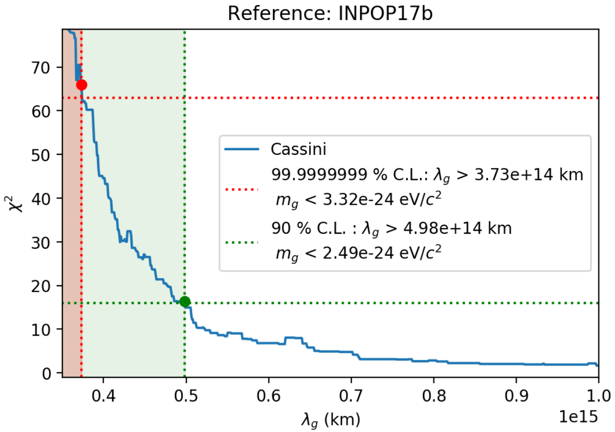
Pearson test for Cassini data

- For Cassini : 175 points $\Rightarrow$ optimal number of bins $= 10$.
- $\chi^2(\lambda)$ follows a 10 degrees of freedom chi square law.
- Exclusion criterion : for a given value of χ^2, residuals come from different distribution with a probability p.

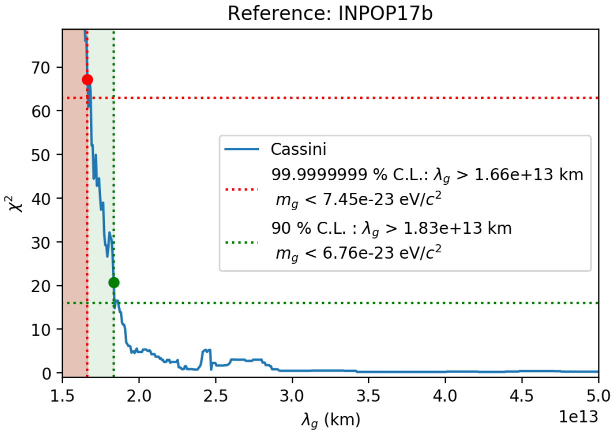
$$p = 90\% \quad \Rightarrow \quad \chi^2 \geq 15.99$$

$$p = 99.9999999\% \quad \Rightarrow \quad \chi^2 \geq 62.94$$

Pearson test with postfit analysis



Pearson test with global analysis



Conclusion

- **For testing a new theory, global fit is crucial !**
- INPOP is a good tool for testing GR in Solar System

Result :

- 90% bound :
  - $\lambda_g > 1.83 \times 10^{13}\,\mathrm{km}$
  - $m_g < 6.76 \times 10^{-23}\,\mathrm{eV}/c^2$
- 99.9999999% bound :
  - $\lambda_g > 1.66 \times 10^{13}\,\mathrm{km}$
  - $m_g < 7.45 \times 10^{-23}\,\mathrm{eV}/c^2$
- Details : arXiv:1901.04307

Future perspectives, work in progress :

- Better constraint criterion based on orbit propagation
- More data and more accurate solution ⇒ better constraint.