Bayesian test with Planetary Ephemerides: mass of the Graviton and Strong Equivalence Principle

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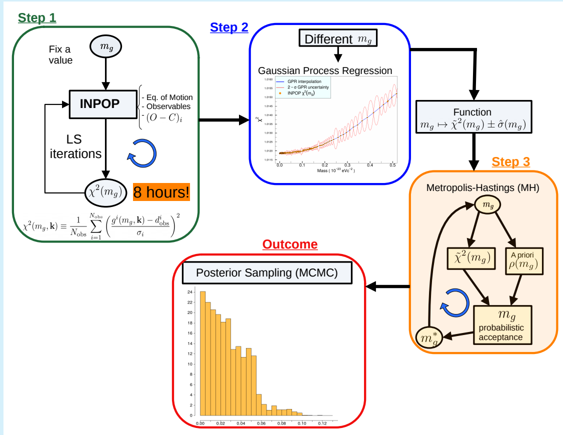
Introduction: INPOP Planetary Ephemerides

- The **INPOP** (Integrateur Numerique Planetaire de l'Observatoire de Paris) planetary ephemerides has started to be built in 2003 (Fienga et al. 2008).
- Numerical integration of the Einstein-Infeld-Hoffmann (c^{-4} PPN approximation) equations of motion
- Simultaneous numerical integration TT-TDB, TCG-TCB (relativistic time scales)
- 8 planets + Pluto + Moon + asteroids, J_2
- $\approx 180,000$ observations fitted, 65% from radio-science experiments (CassiniHuygens, MEX, VEX, Juno, etc.)
- meters-level observational accuracy for inner planets
- tens of meters observational accuracy for outer planets (Jupiter and Saturn)
- Testing GR and alternative theories of gravity with INPOP: observations fitted within the **whole framework** of the **alternative theory**
- Version : **INPOP21a** (see Fienga et al. 2021)

Methodology: GPR + Markov Chain Monte Carlo (MCMC)



Massive Graviton (G) (PhysRevD.108.024047)

(G-1) Phenomenology: Massive graviton

- Yukawa suppression of the Newtonian potential as function of the **Compton wavelenght** λ_g (Bernus et al. 2019,2020)

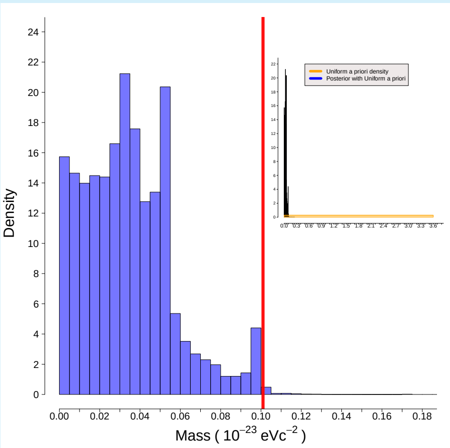
$$\lambda_g = \frac{\hbar}{c m_g}$$

- Terms added to the EIHDL equations ($N-$body system)

$$\delta a^i = \frac{1}{2}\sum_P \frac{c^2 G M_P m_g^2}{\hbar^2}\frac{x^i - x_P^i}{r} + \mathcal{O}(m_g^3).$$

- Results: posterior distribution for m_g

(G-2) Posterior for the mass of the graviton



Uniform a priori distribution on m_g between 0 and $3.62 \times 10^{-23} eVc^{-2}$.

The 99.7%-quantile of such posterior is $\mathbf{m_g \leq 1.01 \times 10^{-24} eVc^{-2}}$.

1. 99.7% confidence level on posterior $\Rightarrow$ **upper bound** on m_g
2. **non** positive **detection** $\Leftrightarrow$ no preference for one m_g

(G-3) Comparison with previous work

Comparison with Bernus et al. 2020: **same methodology**, Upper bound 99.7% confidence level

- INPOP19a : $m_g \leq 3.62 \times 10^{-23} eVc^{-2}$,
- INPOP21a : $\mathbf{m_g \leq 1.18 \times 10^{-23} eVc^{-2}}$.

Model + observations in INPOP21a

$\Downarrow$

factor 3 improvement relative to INPOP19a

New bound of $m_g \leq 1.01 \times 10^{-24} eVc^{-2}$: mainly due to GPR + MCMC

(G-4) Possible Improvement from BepiColombo

- Analysis on the Mercury-Earth distance perturbation induce by massive graviton m_g using BepiColombo MORE radio science experiment simulated observations.
- The smallest m_g that might produce a significant perturbation is roughly $m_g = 0.087 \times 10^{-23} eVc^{-2}$.
- Because of correlations between parameters, we consider such a limit as a minimum threshold below which the mass of the graviton will not be detectable by the BepiColombo radio science experiment.

(G-5) Conclusions

- New method applied $\Longrightarrow$ improvement **1 order of magnitude**
- Minor improvement: due to **INPOP21a** (against previous INPOP19a)
- Major improvement: due to Gaussian Process + MH algorithm

GRT is sufficient to explain the data at the current accuracy level

Brans-Dicke theory (BD) *(in preparation)*

(BD-1) Phenomenology: Brans-Dicke theory

- Special one-parameter case of a generic formalism allowing SEP violation (Einstein-dilaton theories).
- Introduction in INPOP of **EIHDL** and Shapiro **modified equations** (Bernus et al. 2022)
- PPN parameter γ depends only on a universal coupling constant α_0 such that

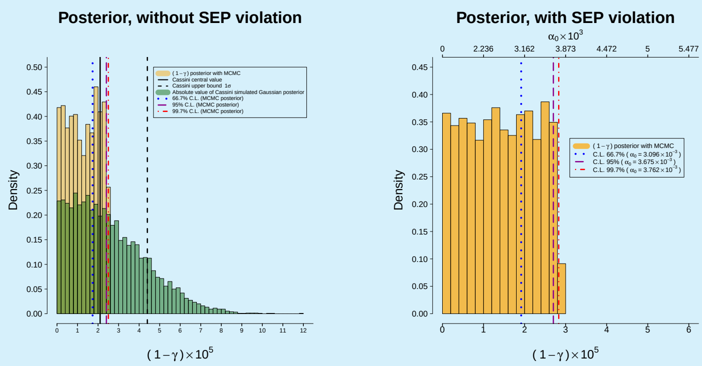
$$\gamma = \frac{(1-\alpha_0^2)}{(1+\alpha_0^2)}$$

- Results: posterior distribution for $(1-\gamma)$

(BD-2) Posterior for $(1-\gamma)$: with or without SEP violation

99.7% C.L. without SEP: $(1-\gamma) \lesssim 2.50 \times 10^{-5}$

99.7% C.L. with SEP: $(1-\gamma) \lesssim 2.83 \times 10^{-5}$



(BD-3) Shift in the confidence level!

- Testing the Brans-Dicke (BD) class of scalar tensor theories with INPOP
- Obtaining a constrain on γ
- We extrapolate information on the SEP parameter

Confidence level 99.7%: 2.50×10^{-5} (wo SEP) $\Rightarrow 2.83 \times 10^{-5}$ (SEP)

(BD-4) Conclusions

- The effect of the SEP starts to be relevant with present planetary ephemerides accuracy.
- The constraint on γ is becoming as good as the one obtained with Cassini (even though a true comparison is difficult due to different methodologies)

References

[1] A. Fienga et al. "Tests of General relativity with planetary orbits and Monte Carlo simulations". In: (Sept. 2014).
[2] A. Fienga et al. "Numerical estimation of the sensitivity of INPOP planetary ephemerides to general relativity parameters,". In: *Celestial Mechanics and Dynamical Astronomy* 123.3 (2015), pp. 325–349.
[3] A. Fienga et al. *INPOP19a planetary ephemerides*. Research Report. IMCCE, 2019.
[4] L. Bernus et al. "Constraining the mass of the graviton with the planetary ephemeris INPOP". In: *Phys.Rev.Lett.* 123.16 (2019), p. 161103.
[5] V. Mariani et al. "Testing the mass of the graviton with Bayesian planetary numerical ephemerides B-INPOP". In: (2023).
[6] C. E. Rasmussen and C. K. I. Williams. *Gaussian processes for machine learning.*. MIT Press, 2006.
[7] S. Brooks et al. *Handbook of Markov Chain Monte Carlo.* CRC press, 2011.
[8] V. Mariani et al. "Bayesian test of the mass of the graviton with planetary ephemerides". In: *Phys. Rev. D* 108 (2 2023), p. 024047.
[9] L. Bernus et al. "Constraining massless dilaton theory at Solar system scales with the planetary ephemeris INPOP". In: *Phys. Rev. D* 105 (4 2022), p. 044057.

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