Planetary and Lunar Ephemerides : from tests of SEP and graviton to ITLN

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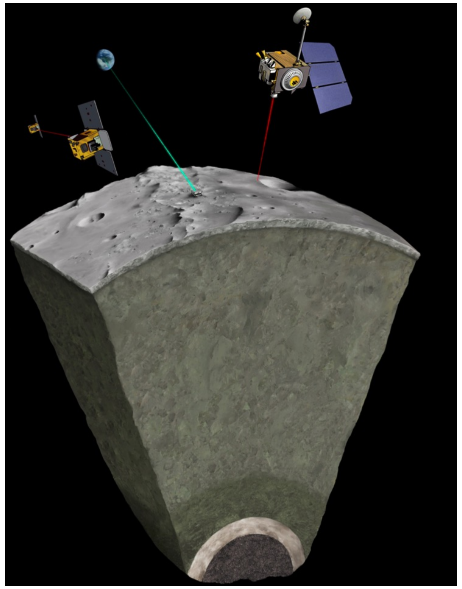
1) INPOP update in 2023
2) New results for graviton and SEP
3) ITLN



1) INPOP update in 2023
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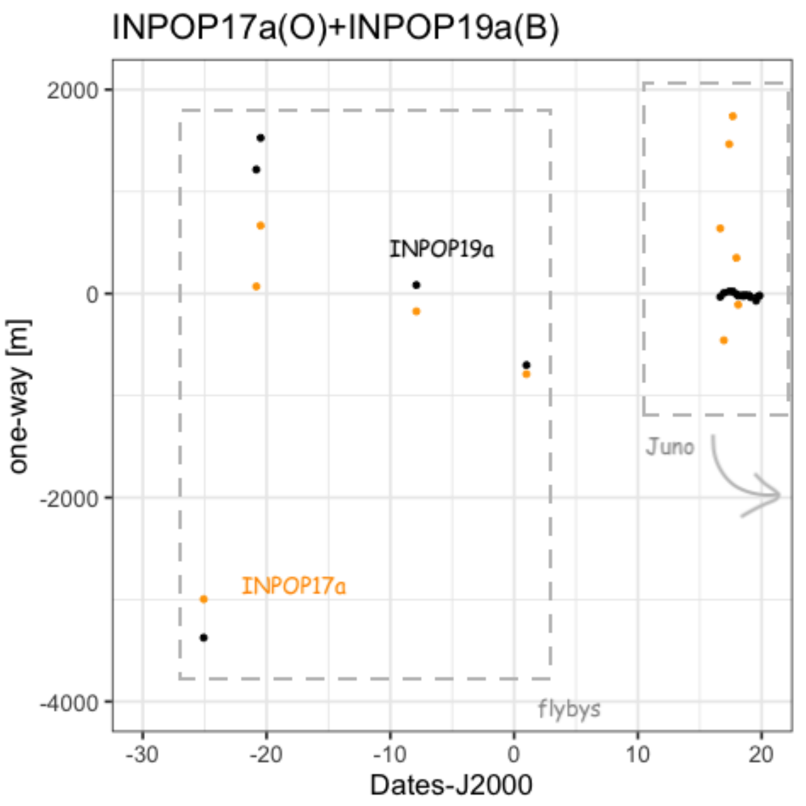
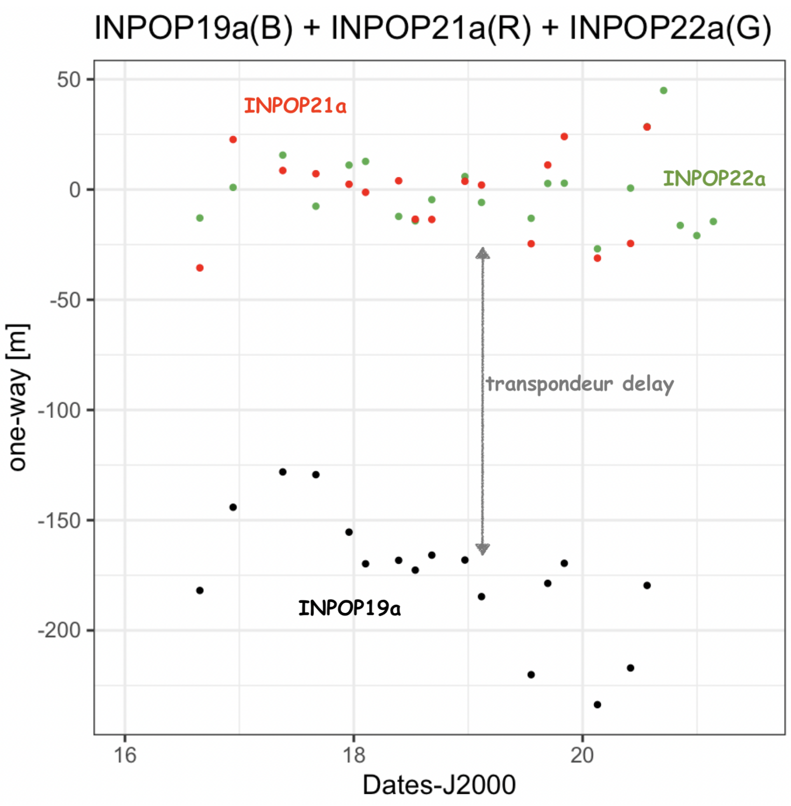
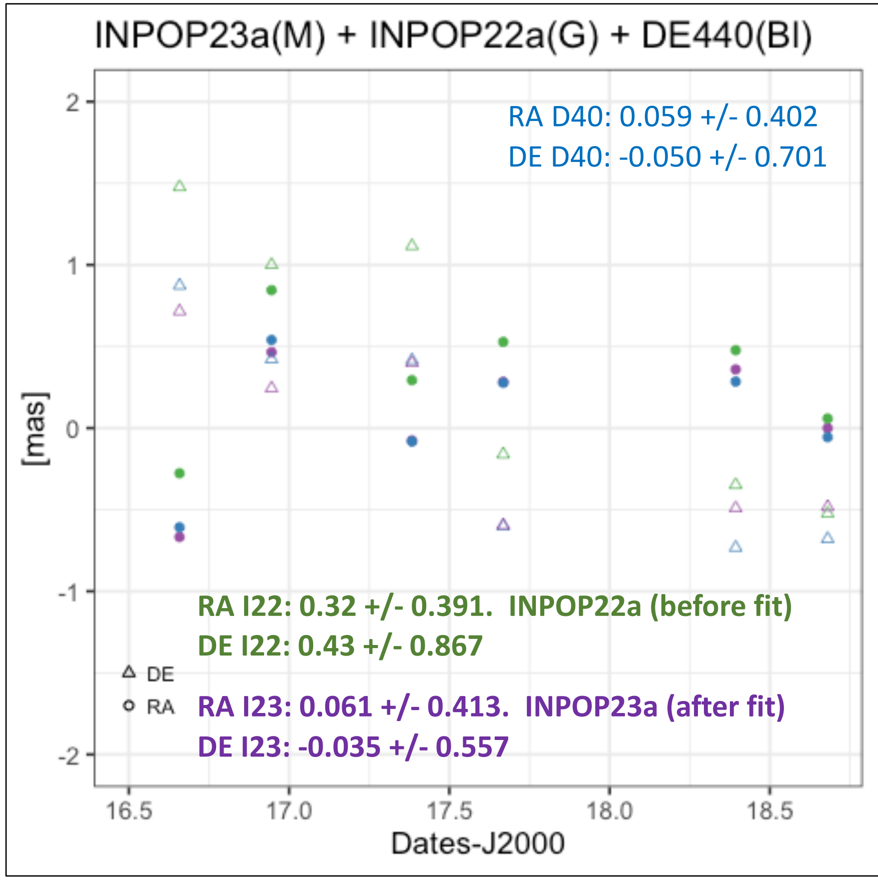
INPOP update in 2023

- **Juno CRAS range analysis from 2016 to 2021.5**
- **INPOP23a : Juno VLBA**
- Gain on Jupiter orbit accuracy : from 2 km (17a) to 20 m.
- MEX additional set

	INPOP17a 2018	INPOP19a 2019	INPOP20a/21a/22a 2020/2021
Dynamics			
MBA	343 + 1 ring	343	343
TNO	none	3 rings + 9 ind	509 ind
Lense-Thirring	N	N	Y
Fit			
Parameters	210	402	402
GM_A	152	343	343
Method	BVLS	BVLS + MC	BVLS + MC
Dataset	1913:2014	1924:2019.5	1924:2020/2020.5/2021.5
Jupiter	2 km	20 m	20 m
Saturn	2004-2014	2004-2017	2004-2017
SSB shift / INPOP10e	0	94 km	94 km







Comparisons with DE

Convergency of the models

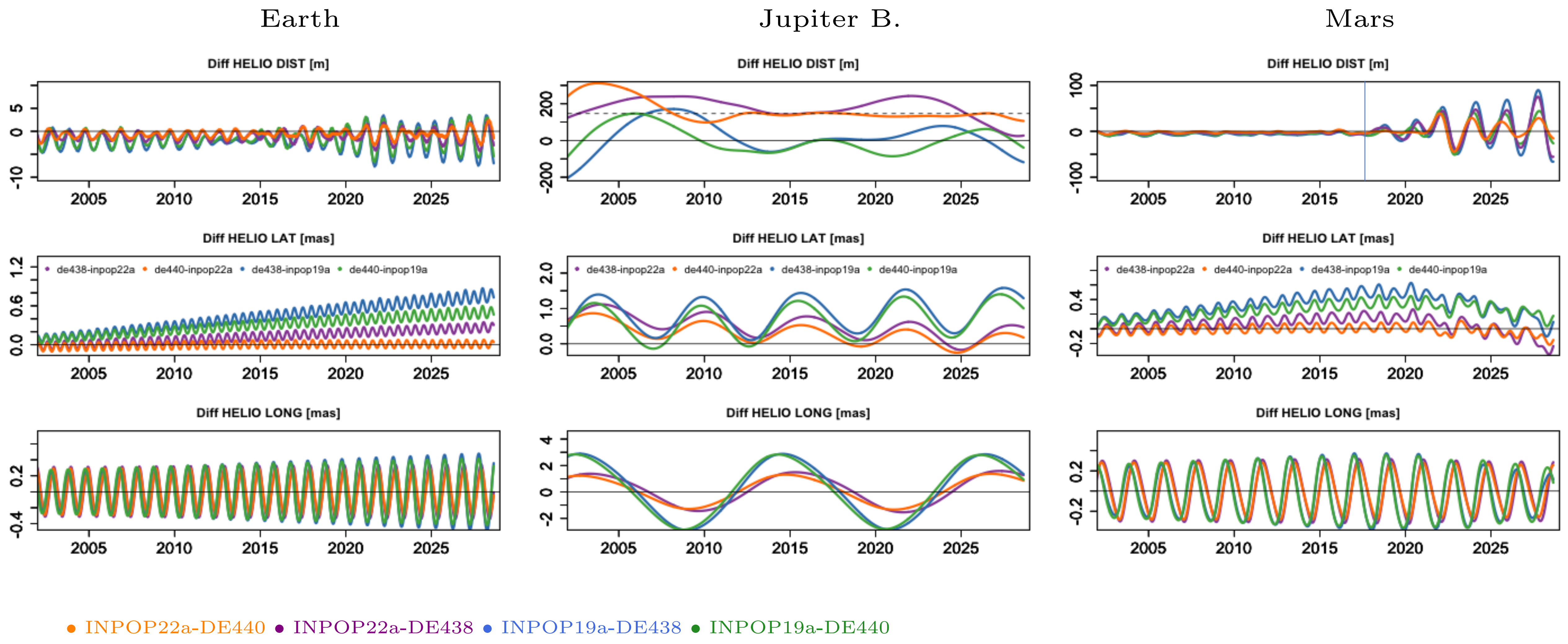
I22a-D440 < I19a-D440 < I19a-D438

	INPOP17a 2018	INPOP19a 2020	DE438 2018	DE440 2021
Dynamics				
MBA	343 i.m. + 1 ring	343 i.m.	343 i.m.	343 i.m.
TNO	none	3 rings + 9 ind I21a: 509 ind	none	1 ring + 36 ind
General Relativity	EIH	EIH + LT	EIH	EIH + LT
Fit				
GM_A	153 BVLS + 1 ring	343 MC	343 LS	343 LS
TNO	none	1 ring mass I21a: 1 mass @ 509 ind.	none	1 ring mass
Dataset	1913:2014	1924:2019.5 I21a: 1924:2020.5 I22a: 1924:2021.5	1924:2013+	1924:2020
SSB shift	0	94 km	0	$\approx$ 100 km

Comparisons with DE

Convergency of the models

I22a-D440 < I19a-D440 < I19a-D438



1) INPOP update in 2023
2) New results for graviton and SEP
3) ITLN

New results for graviton (Will 2018, Bernus et al. 2019, 2020)

- What about if metric field has a mass, m_g ? or Yukawa suppression of massive interactions at the Compton length, λ_g such as:

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

(Will, 2018) :

$$w = w_{\rm Newton} \exp(-r/\lambda_g),$$

$$\longrightarrow \quad w = w_{\rm Newton}\left(1 + \frac{1}{2}\frac{r^2}{\lambda_g^2}\right) + \mathcal{O}(\lambda_g^{-3}),$$

(Bernus et al. 2019)

- What about if the metric doesn't have a mass but an additional gravitational field does ? (Fifth force)

$$w = w_{\rm Newton}(1 + \alpha \exp(-r/\lambda))$$

with

- α , the strenght of the force relative to gravity
- λ, the range of the force

B19 + 5thF :

If $\alpha < 1$ and $\lambda_g \gg r$, then $\lambda_g \approx \frac{\lambda}{\sqrt{|\alpha|}}$

Massive graviton / Yukawa suppression

(Mariani et al., Phys.Rev. D, 108:024047, Jul 2023)

$$w = w_{\text{Newton}} \left(1 + \frac{1}{2}\frac{r^2}{\lambda_g^2}\right) + \mathcal{O}(\lambda_g^{-3}),$$

(Bernus et al., 2019, 2021) — Random exploration (RW) + cost function

(Mariani et al., 2023) — MCMC

	GWTC-1	GWTC-3	INPOP17a	INPOP19a	INPOP21a RW	INPOP21a MCMC
CL	0.90	0.90	0.90	0.90	0.9	0.9
Graviton mass						
$\lambda_g \times 10^{-13}$ [km]	2.6	9.77	1.83	3.93	12.01	209.67
$m_g \times 10^{23}$ [eV/c^2]	4.7	1.27	6.76	3.16	1.03	0.059
Fifth Force						
$\frac{\lambda}{\sqrt{\lvert\alpha\rvert}} \times 10^{-13}$[km], $\alpha > 0$			1.83	3.93		
$\frac{\lambda}{\sqrt{\lvert\alpha\rvert}} \times 10^{-13}$[km], $\alpha < 0$				3.77		

(Mariani et al., 2023)

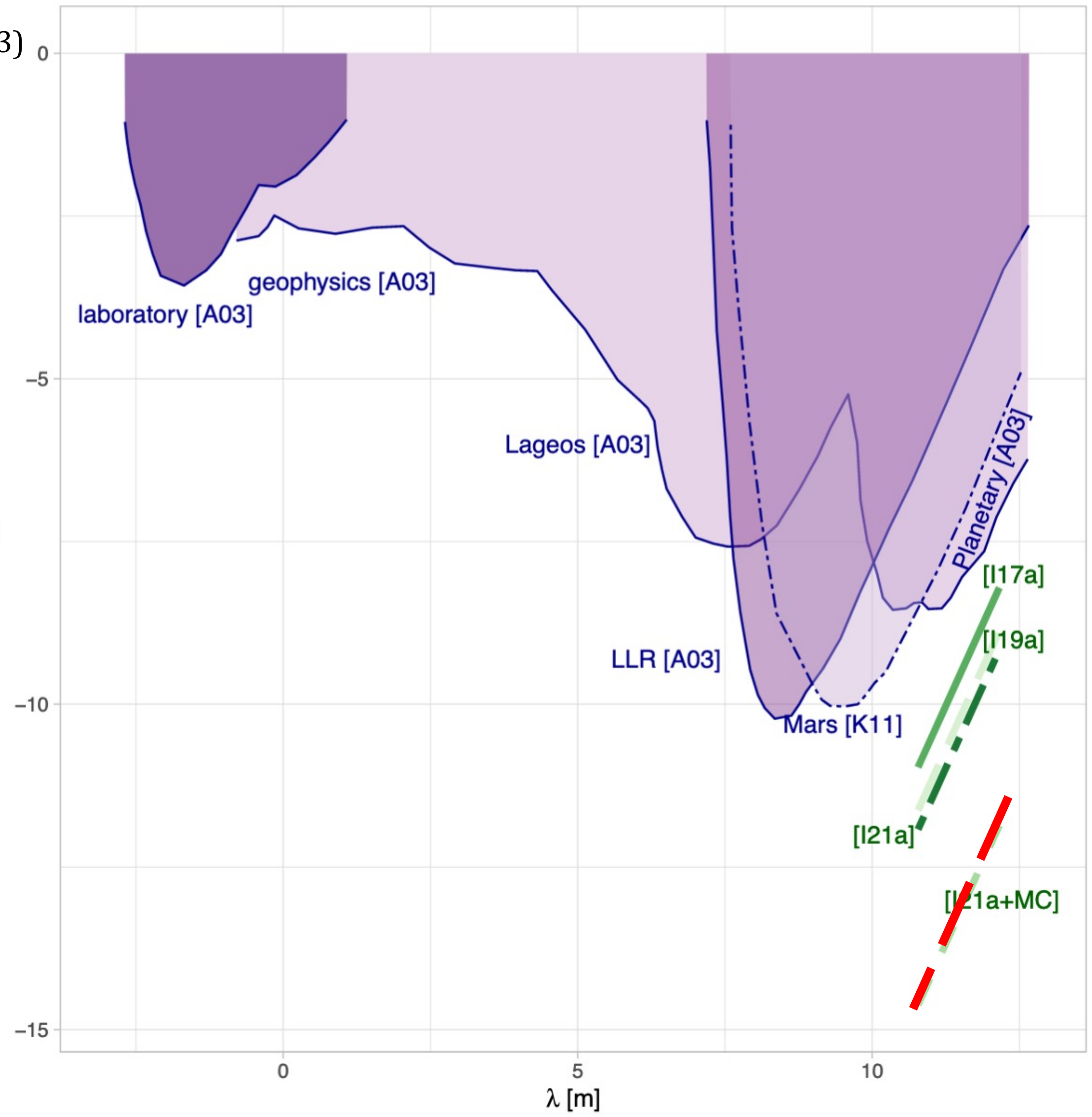
$m_g < 0.10 \times 10^{-23}$ eV/c^2. C.L. 99.7 %

$\lambda_g > 122.48 \times 10^{13}$ km C.L. 99.7 %

(Will 2018): postfit analysis

$m_g < 0.40 - 0.8 \times 10^{23}$ eV/c^2

$\lambda_g > 14 - 27 \times 10^{-13}$ km



Einstein massless dilaton : INPOP test (Bernus et al. 2022)

$$g_{\mu\nu} = \frac{f_0}{f(\varphi)} g^*_{\mu\nu} \quad m^*_A(\phi) = \sqrt{\frac{f_0}{f(\varphi)}} m_A(\varphi).$$

$$\delta_A = \frac{\alpha_0 \tilde{\alpha}_A}{1+\alpha_0^2}, \quad \delta_{AB} = \frac{\tilde{\alpha}_A \tilde{\alpha}_B}{1+\alpha_0^2};$$

$$\mu_A = \frac{G}{f_0}(1+\alpha_0^2)(1+\delta_A) m_A(\varphi_0);$$

(Z)

$$\gamma = \frac{1-\alpha_0^2}{1+\alpha_0^2}, \quad \beta = 1 + \frac{\beta_0}{2}\frac{\alpha_0^2}{(1+\alpha_0^2)^2};$$

(Minazzoli and Hees, 2016)

- Generic formalism allowing both WEP, GWEP and SEP violation
- Non-universal coupling between scalar field and matter (linear or non-linear)
- Parameters of the metric $(\tilde{\alpha}, \beta_0)$ depend on dilatonic charges (proton, nucleon)

(Bernus et al. 2022)

- Introduction in INPOP of previous EIHDL and Shapiro modified equations
- Linear coupling ($d\beta_X = 0, \ \beta = 1$)
- Random exploration for α_G , α_T and α_0 starting with flat large priors
- Cost functions

	INPOP19a (Bernus et al. 22)	
Confidence:	90%	99.5%
$\alpha_0(\times 10^5)$	-0.94 ± 5.35	1.01 ± 23.7
$\alpha_T(\times 10^6)$	0.24 ± 1.62	0.00 ± 24.5
$\alpha_G(\times 10^5)$	0.01 ± 4.38	-1.46 ± 12.0
$(\gamma - 1) \times 10^8$	0.2 ± 6	0.2 ± 11.2

(Bernus et al. 2022)

$$\begin{aligned}\boldsymbol{a}_T = &-\sum_{A\neq T}\frac{\mu_A}{r_{AT}^3}\boldsymbol{r}_{AT}\left(1+\delta_T+\delta_{AT}\right)\\ &-\sum_{A\neq T}\frac{\mu_A}{r_{AT}^3 c^2}\boldsymbol{r}_{AT}\Bigg\{\gamma v_T^2+(\gamma+1)v_A^2-2(1+\gamma)\boldsymbol{v}_A.\boldsymbol{v}_T-\frac{3}{2}\left(\frac{\boldsymbol{r}_{AT}.\boldsymbol{v}_A}{r_{AT}}\right)^2-\frac{1}{2}\boldsymbol{r}_{AT}.\boldsymbol{a}_A\\ &\qquad -2(\gamma+\beta+\mathrm{d}\beta_T)\sum_{B\neq T}\frac{\mu_B}{r_{TB}}-(2\beta+2\mathrm{d}\beta_A-1)\sum_{B\neq A}\frac{\mu_B}{r_{AB}}\Bigg\}\\ &+\sum_{A\neq T}\frac{\mu_A}{c^2 r_{AT}^3}\left[2(1+\gamma)\boldsymbol{r}_{AT}.\boldsymbol{v}_T-(1+2\gamma)\boldsymbol{r}_{AT}.\boldsymbol{v}_A\right](\boldsymbol{v}_T-\boldsymbol{v}_A)+\frac{3+4\gamma}{2}\sum_{A\neq T}\frac{\mu_A}{c^2 r_{AT}}\boldsymbol{a}_A\end{aligned}$$

$$c(t_r - t_e) = \frac{R}{c} + \sum_A (\gamma + 1 - \delta_A)\frac{\mu_A}{c^2}\ln\frac{\boldsymbol{n}\cdot\boldsymbol{r}_{rA}+r_{rA}}{\boldsymbol{n}\cdot\boldsymbol{r}_{eA}+r_{eA}}$$

Revised test with (Mariani et al, 2023b, arXiv:2310.00719)

(Minazzoli and Hees, 2016)

- Generic formalism allowing both WEP, GWEP and SEP violation
- Non-universal coupling between scalar field and matter (linear or non-linear)
- Parameters of the metric ($\tilde{\alpha}, \beta_0$) depend on dilatonic charges (proton, nucleon)

$$(1+\gamma-\delta_A)\mu_A = (1+\gamma)\mu_A^I$$

$$\gamma = \frac{1-\alpha_0^2}{1+\alpha_0^2}, \quad \beta = 1 + \frac{\beta_0}{2}\frac{\alpha_0^2}{(1+\alpha_0^2)^2},$$

From these equations, the Nordtvedt parameter η is now fonction of α_0

$$c(t_r - t_e) = \frac{R}{c} + \sum_A (\gamma + 1 - \delta_A)\frac{\mu_A}{c^2} \ln \frac{\boldsymbol{n}\cdot\boldsymbol{r}_{rA} + r_{rA}}{\boldsymbol{n}\cdot\boldsymbol{r}_{eA} + r_{eA}}$$

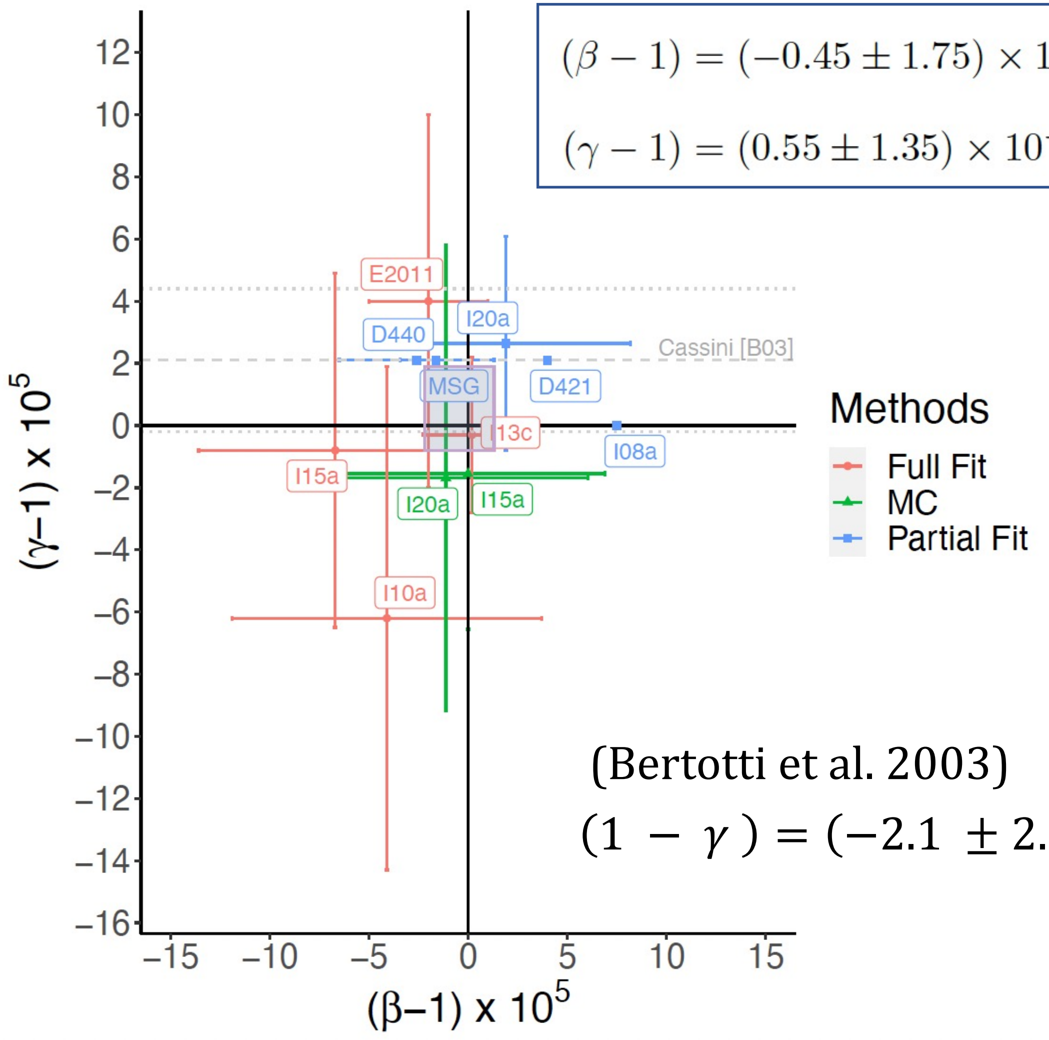
(Marini et al, 2023b, arXiv:2310.00719)

- INPOP21a
- MCMC on γ (Test A) : $\delta_A = 0$
- MCMC on γ with only the universal coupling of dilaton → Brans-Dicke theory-like framework (Test B) → η
- New SEP limit
- Limitation : $(1-\gamma) > 0$; $\eta < 0$

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

Revised test with (Mariani et al, 2023b, arXiv:2310.00719)

(Fienga and Minazzoli, 2023)



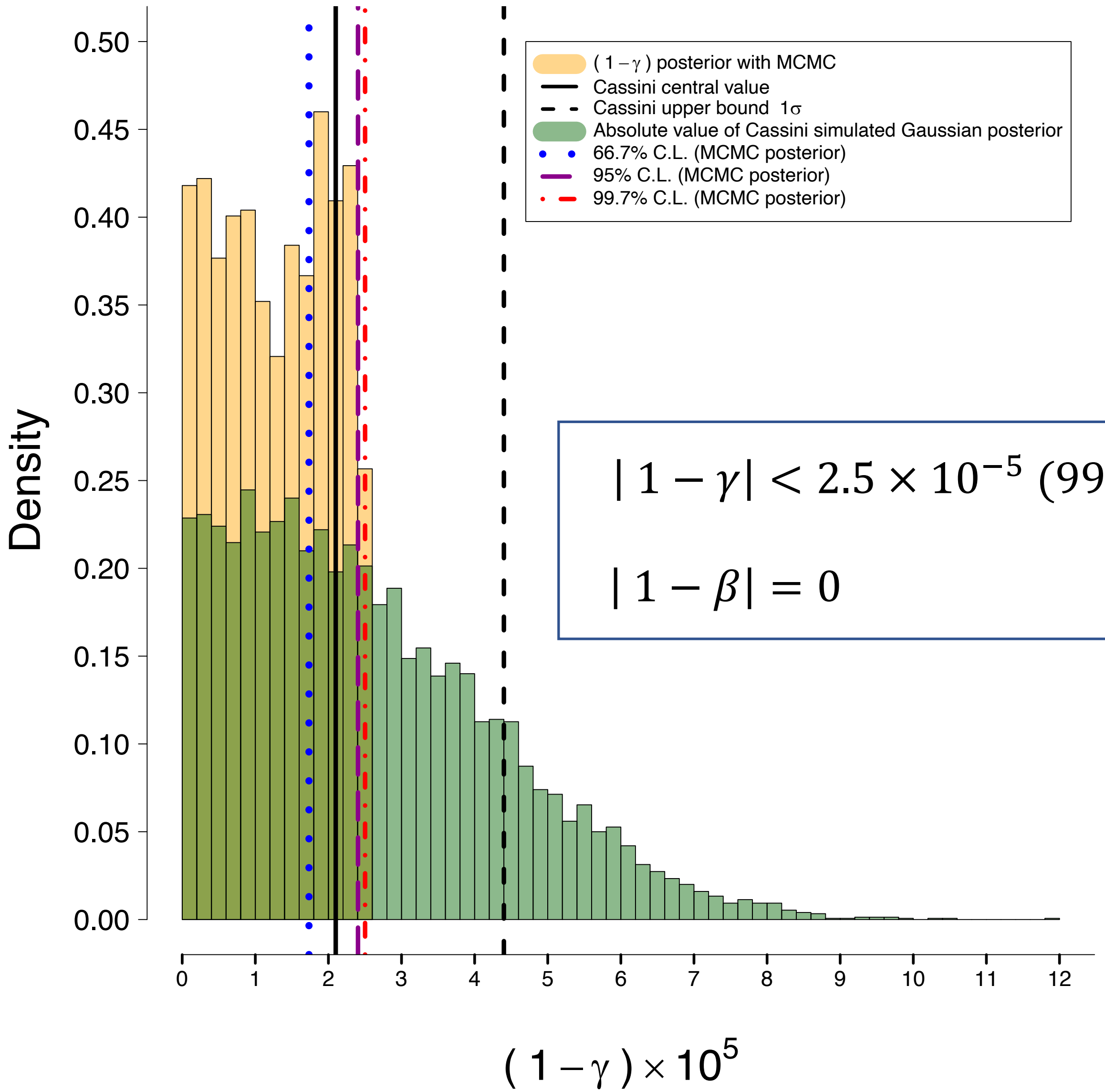
$$(\beta - 1) = (-0.45 \pm 1.75) \times 10^{-5}$$

$$(\gamma - 1) = (0.55 \pm 1.35) \times 10^{-5}$$

(Bertotti et al. 2003)

$$(1 - \gamma) = (-2.1 \pm 2.3) \times 10^{-5}$$

Test A: MCMC on γ in PPN (without SEP, $\delta_A = 0$)



$$|1 - \gamma| < 2.5 \times 10^{-5} \ (99.7\%)$$

$$|1 - \beta| = 0$$

Revised test with (Mariani et al, 2023b, arXiv:2310.00719)

Test B : MCMC on γ with only the universal coupling of dilaton

- Brans-Dicke theory-like framework
- SEP

without SEP

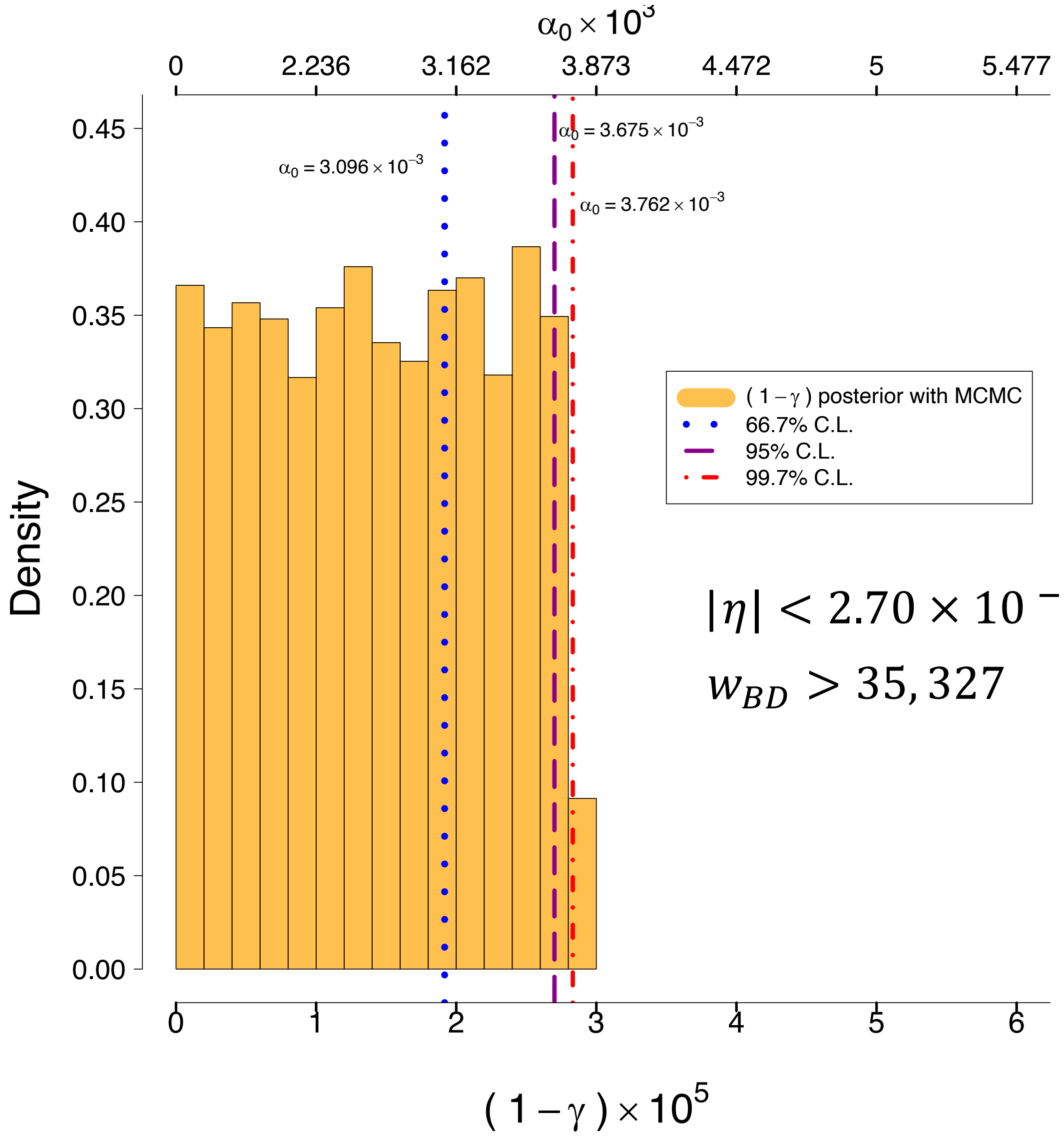
$|\eta| < 2.5 \times 10^{-5}$ (99.7%)

with SEP

$|\eta| < 2.8 \times 10^{-5}$ (99.7%)

↓

Detectability of SEP with planetary orbits



$|\eta| < 2.70 \times 10^{-5}$ (95%)

$w_{BD} > 35,327$

Messenger

(Genova et al. 2018)

$\eta = (-5.48 \pm 7.3) \times 10^{-5}$

LLR

(Viswanathan et al. 2018)

$|\eta| < 30 \times 10^{-5}$

Binary pulsar

(Voisin et al. 2020)

$|\eta| < 0.76 \times 10^{-5}$ (95%)

$w_{BD} > 140,000$

1) INPOP update in 2023

2) New results for graviton and SEP

3) ITLN: **Interplanetary Laser Tri-lateration Network**

Interplanetary Trilateration Workshop
Martin Johnson House
Scripps Institute of Oceanography, University of San Diego, CA
Feb 28 - Mar 1, 2023

Interplanetary Laser Tri-lateration Network

PERGAMON

Journal of Geodynamics 34 (2002) 551–594

JOURNAL OF GEODYNAMICS

www.elsevier.com/locate/jgeodyn

Asynchronous laser transponders for precise interplanetary ranging and time transfer

John J. Degnan

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Planetary and Space Science

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Sensitivity and antenna pattern for an interplanetary laser trilateration network

Bruce G. Bills, Krzysztof M. Gorski

- Centimetric measurements of interplanetary distances
- (First) concept : Smith et al. 2018
- Recent sensitivity and feasibility studies: (Bills et al. 2022)
- Earth, Venus, Mars

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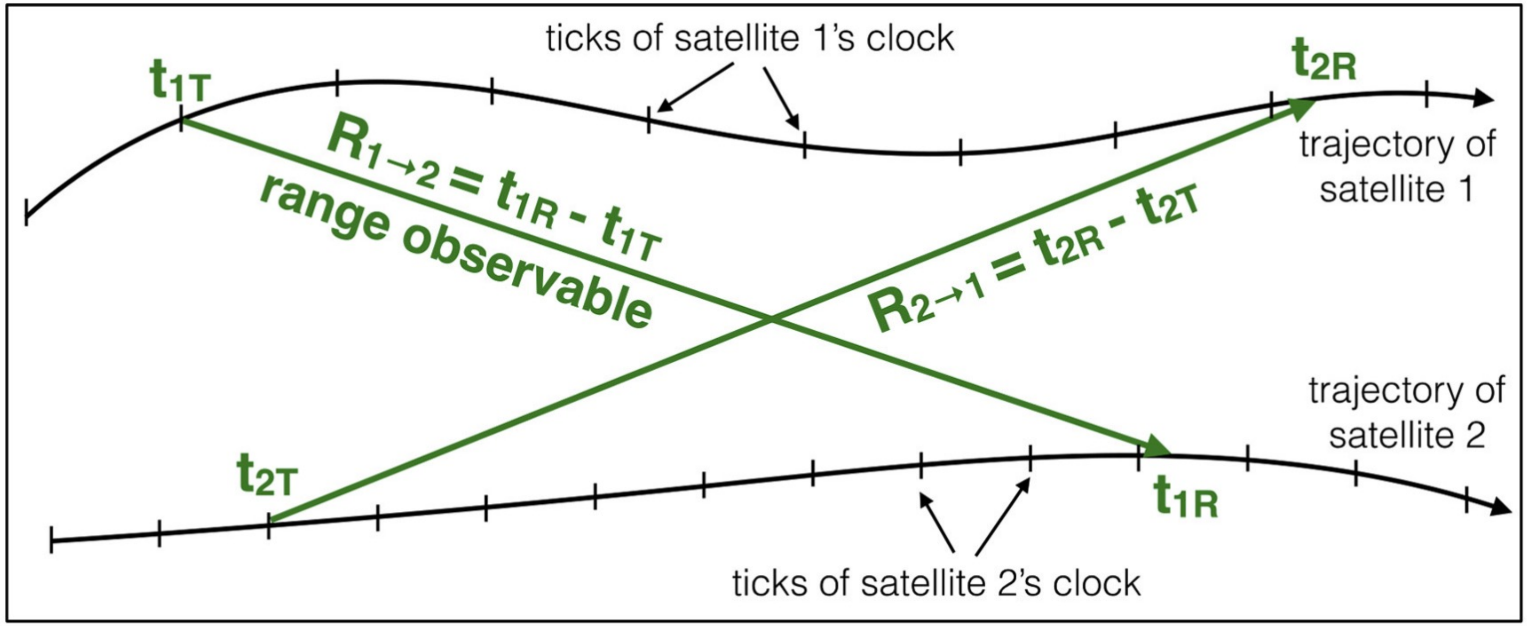
Trilogy, a planetary geodesy mission concept for measuring the expansion of the solar system

Check for updates

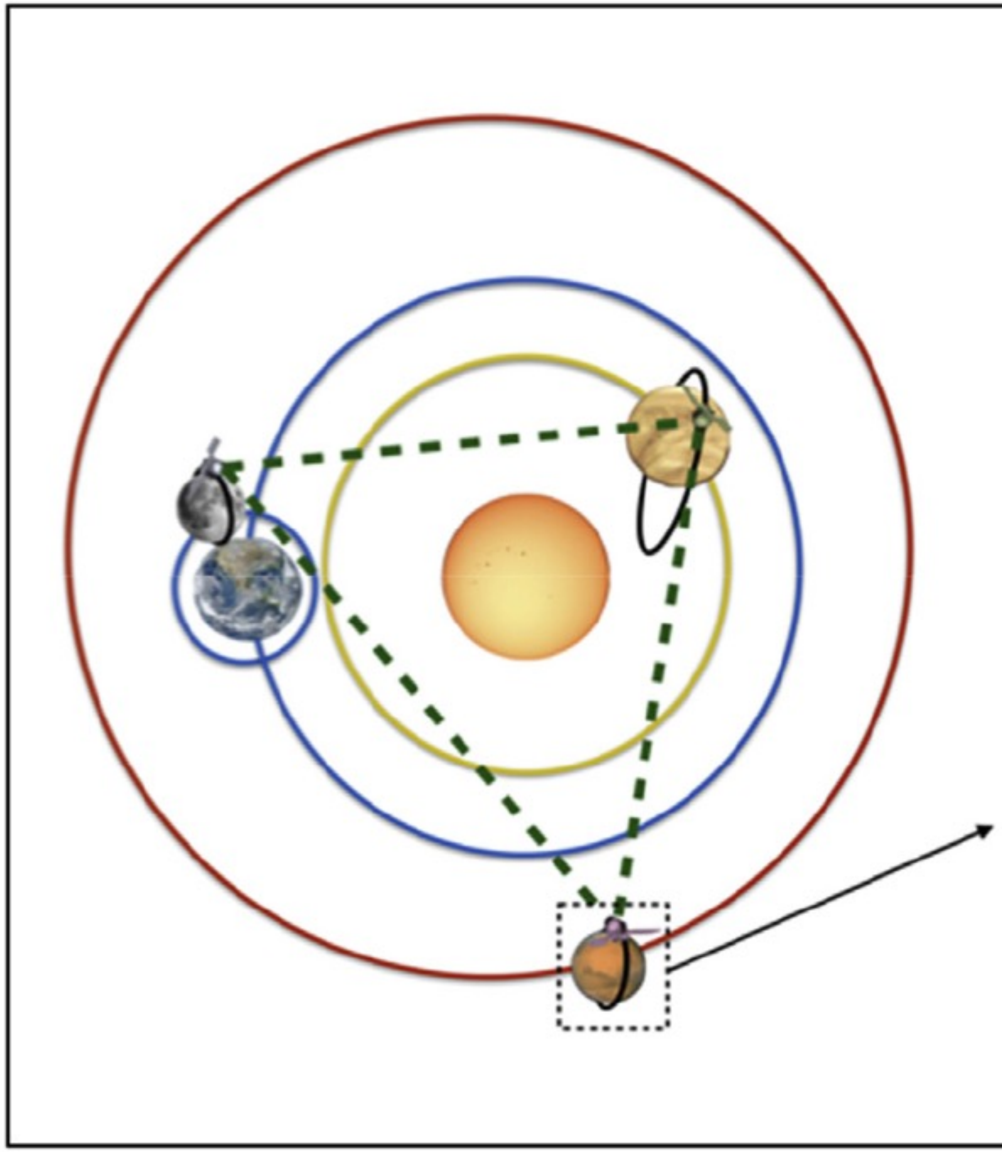
David E. Smith [a,*], Maria T. Zuber [a], Erwan Mazarico [b], Antonio Genova [a], Gregory A. Neumann [b], Xiaoli Sun [b], Mark H. Torrence [c], Dan-dan Mao [d]

Interplanetary Laser Tri-lateration Network

- Laser transponders based on LISA technology
- Asynchronous ranging



(Mazarico 2023)



(Smith et al. 2018)

Interplanetary Laser Tri-lateration Network

(Smith et al. 2018) : GM-dot of 10^{-14} over 5 years

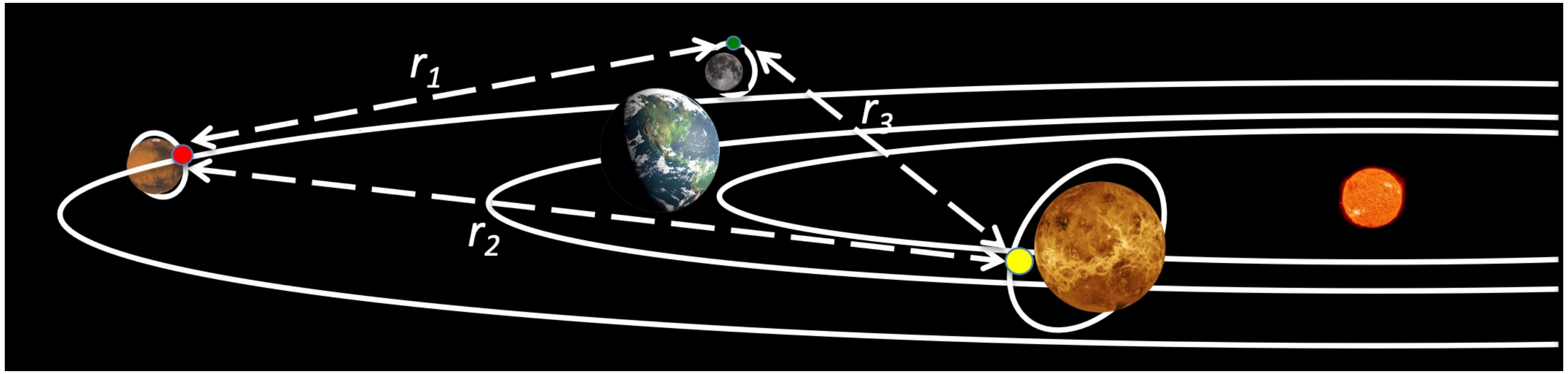
Scientific Rational

Loss of solar mass by internal nuclear reactions
Change in the gravitational constant, *G-dot/G*
Test of equivalence principle
Expansion of the solar system
Lense-Thirring precession of reference frame
Relativistic parameters, β & γ
Gravitational flattening of the sun, J_2
Precession, nutation & rotation of host planets
Obliquity, tides, moment of inertia of host planets
Low-degree gravity, seasonal change on host planets
Inferences on interior structure
Orbits of host planets

Interplanetary Laser Tri-lateration Network

(Smith et al. 2018) : GM-dot of 10^{-14} over 5 years

ILTN



- 3 spacecraft, orbiting 3 planets, ~200 millions km apart connected by ranging measurements.
- Accuracy ~1 cm for one single measurement
- at a cadence of 1 measurement per second
- continued for 1 day (86400 s) → diurnal normal point

Sensitivity analysis

(Bills 2023)

If we use parameter values

$\varepsilon = 1\ cm$
$N = 86400$ (seconds/day)

the resulting diurnal RMS error values are

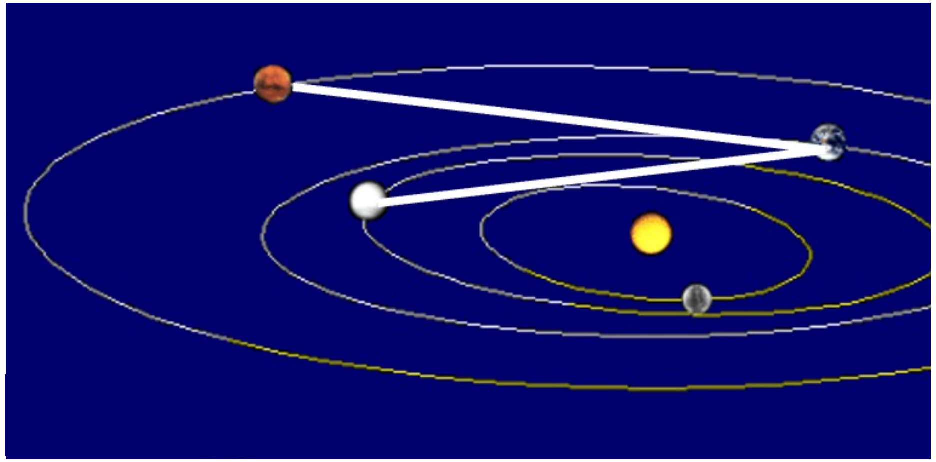
$\sigma[a] \sim \varepsilon\sqrt{\frac{9}{N}} = 1.04\,10^{-6}\ m$

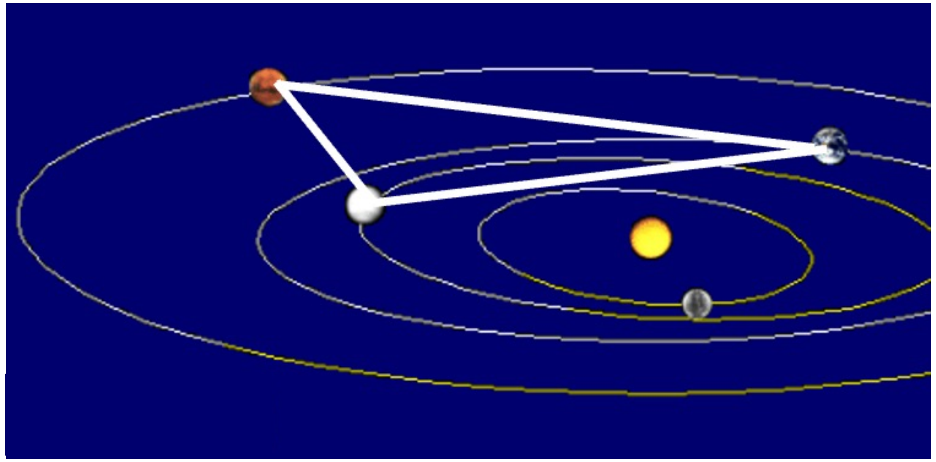
$\sigma[b] \sim \varepsilon\sqrt{\frac{192}{N^3}} = 2.57\,10^{-10}\ m/s$

$\sigma[c] \sim \varepsilon\sqrt{\frac{180}{N^5}} = 2.79\,10^{-15}\ m/s^2$

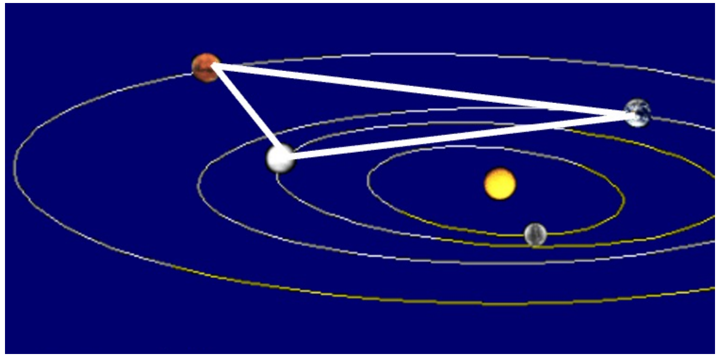
Simulations with ITLN : several possible configurations

(Fienga, arXiv:2301.06394)





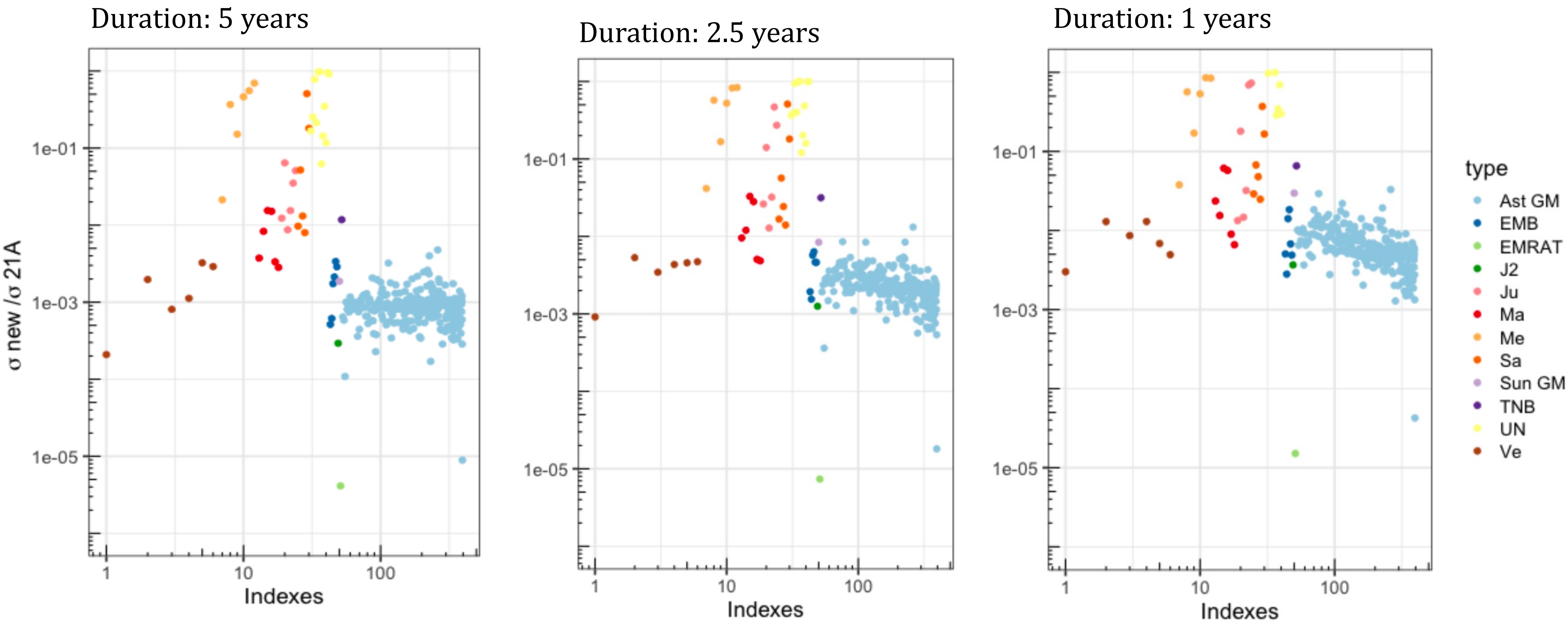
- With and without Venus-Mars link
- Durations: 1 year, 2.5 years and 5 years
- 1 normal point per day with 0.1 mm accuracy



(Fienga, arXiv:2301.06394)

Impact of the mission duration for 0.1 mm with Venus-Mars link

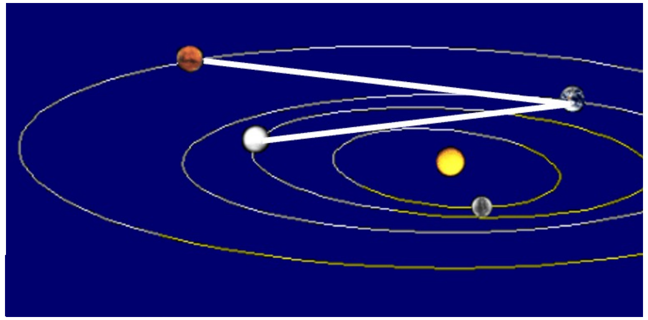
Conclusion A: 1 order improvement from 1 to 5 yrs mission

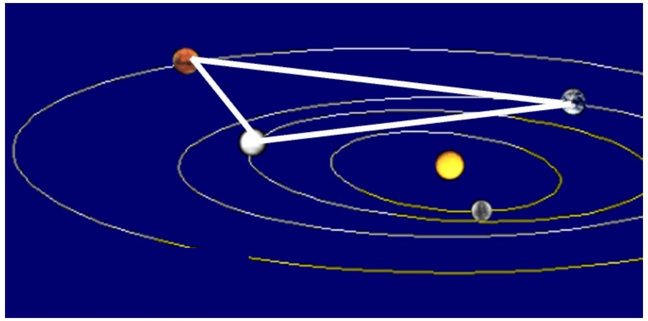


(Fienga, arXiv:2301.06394)

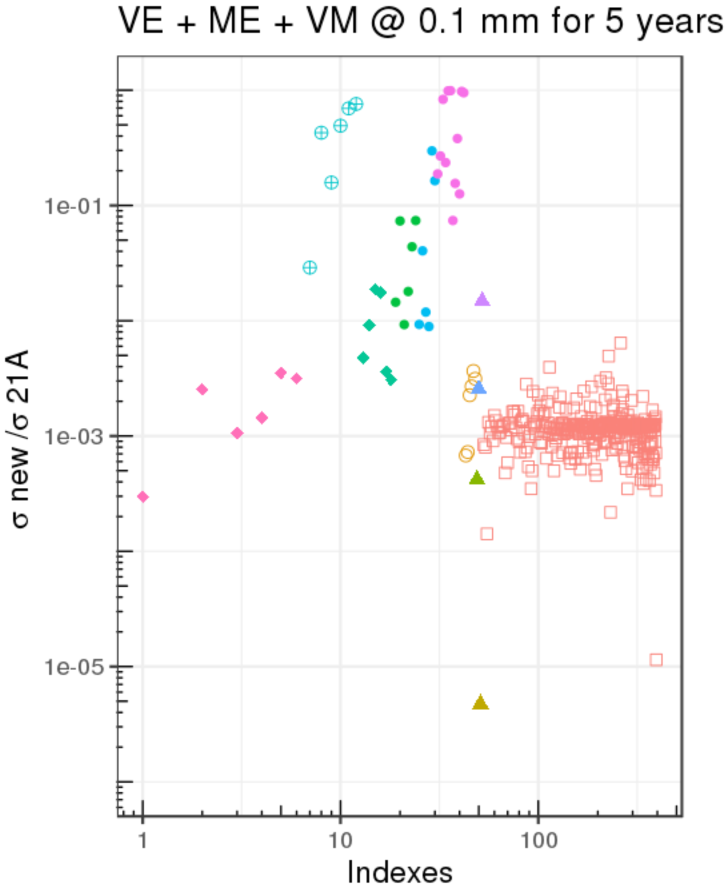
Impact of the Venus-Mars link for 0.1 mm

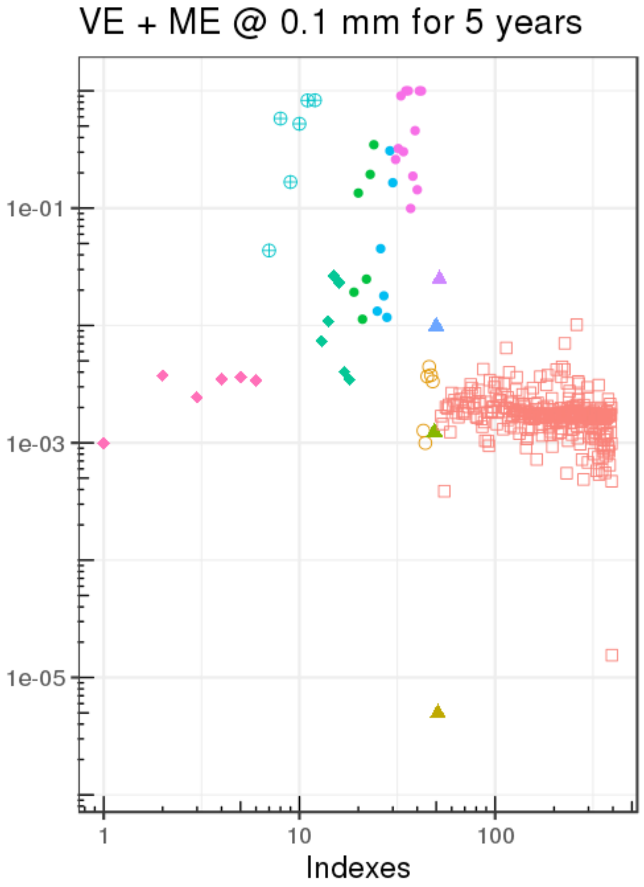
Duration: 5 years

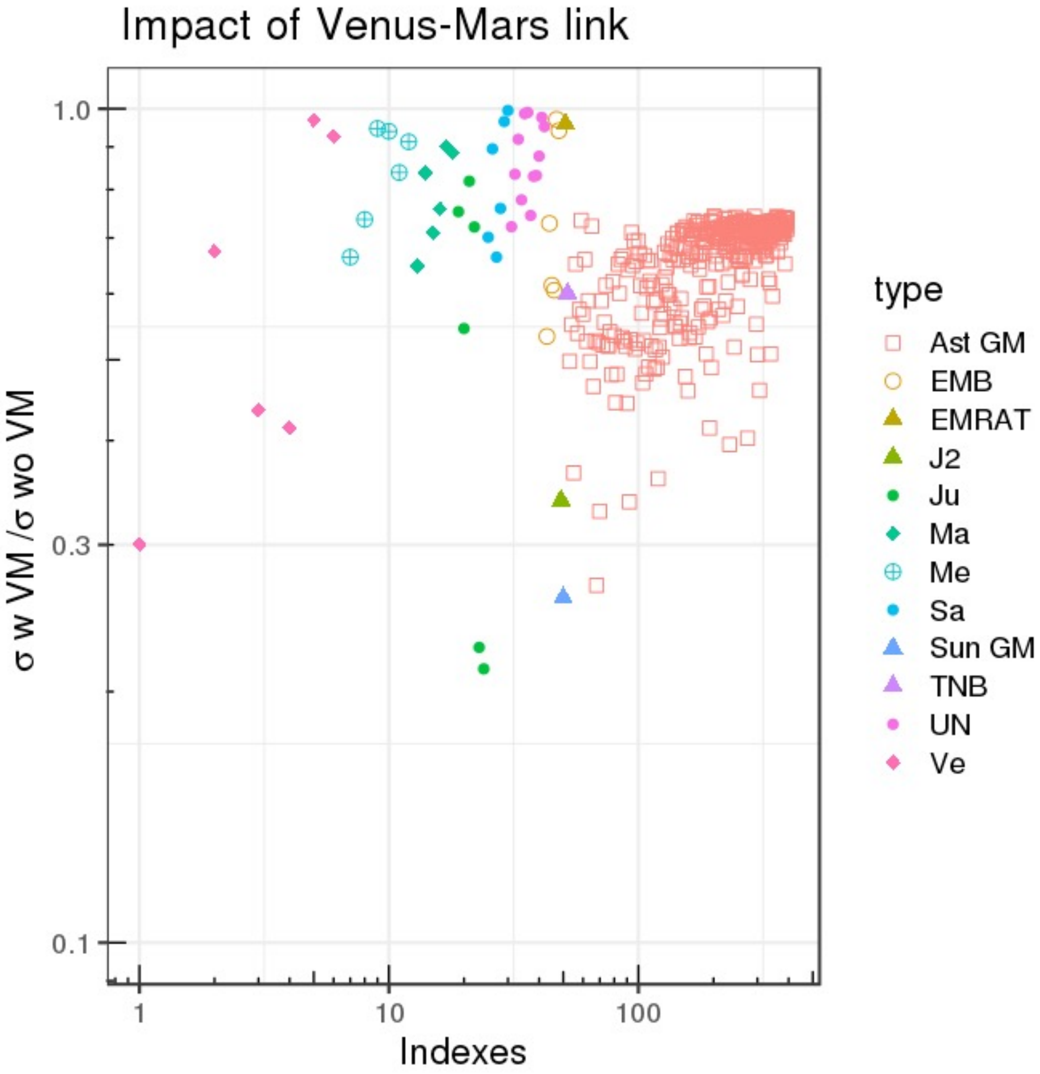




Conclusion B: Factor 2 improvement with Venus-Mars link



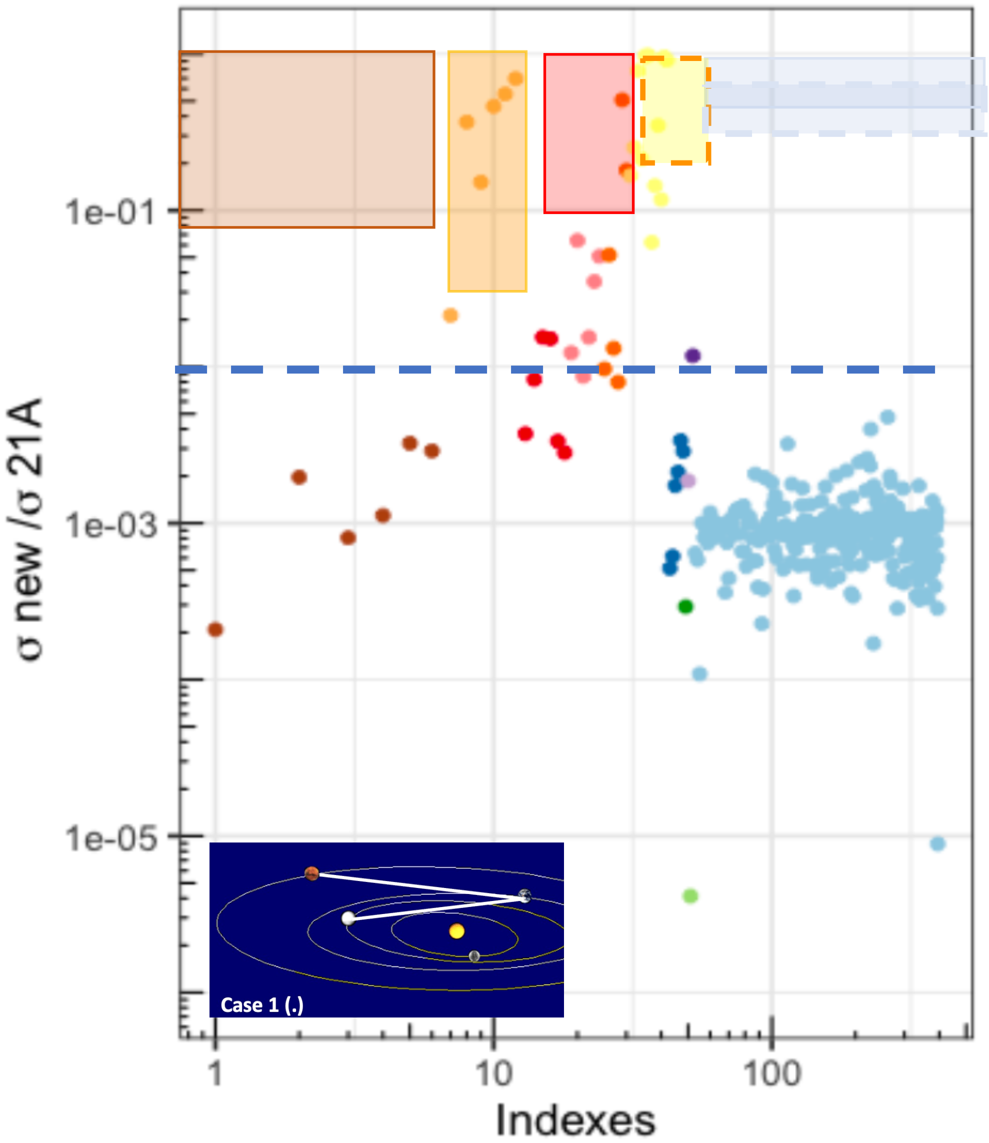




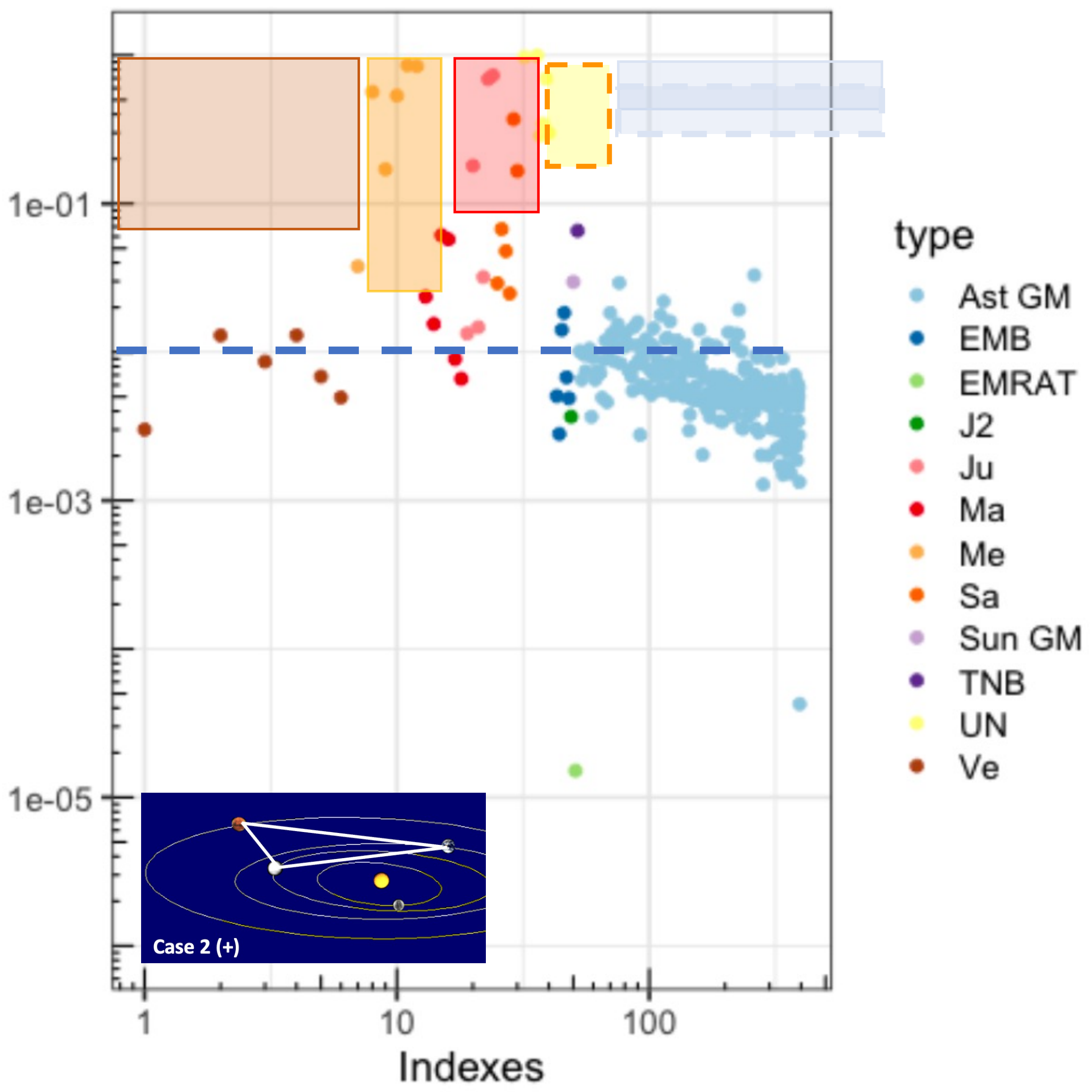
Comparison with BC/JUICE

Conclusion C: Interesting in particular for MB asteroids

- Duration: 5 years
- Accuracy : 0.1 mm
- Without Venus-Mars link



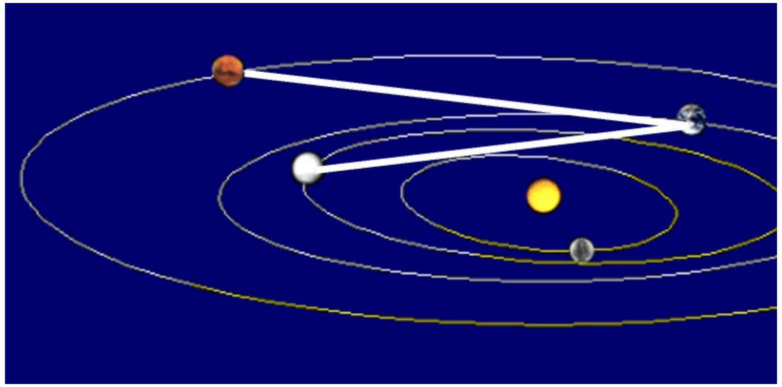
- Duration: 1 years
- Accuracy : 0.1 mm
- With Venus-Mars link

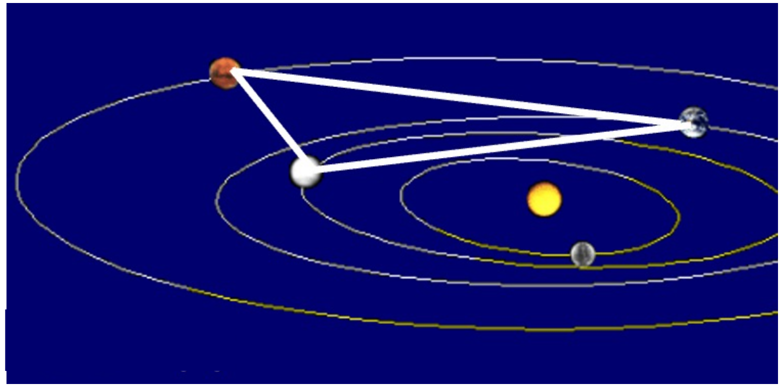


Simulations with ITLN for $\dot{\mu}/\mu$

(Fienga, arXiv:2301.06394)

Ratio of covariances for $\dot{\mu}/\mu$ estimated together with other planetary ephemeris parameters





	VE+ME+VM 0.1 mm	VE+ME 0.1 mm		VE+ME+VM 1 cm
5 yrs	0.001	0.0018	0.55	0.05
2.5 yrs	0.003	0.0045	0.66	0.10
1 yrs	0.009	0.012	0.75	0.20

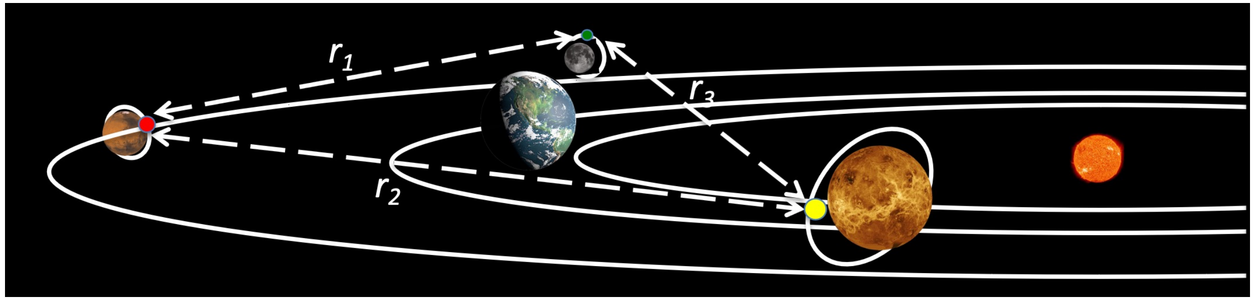
Present measurement (INPOP21a) = 6 x 10^{-13} yr $^{-1}$

Ratio with Bepi-Colombo (2yrs @ 1 cm) = 0.17

Conclusion D: Significant improvement for $\dot{\mu}/\mu$

No BC nor EC/JUICE data included

Interplanetary Laser Tri-lateration Network : conclusions

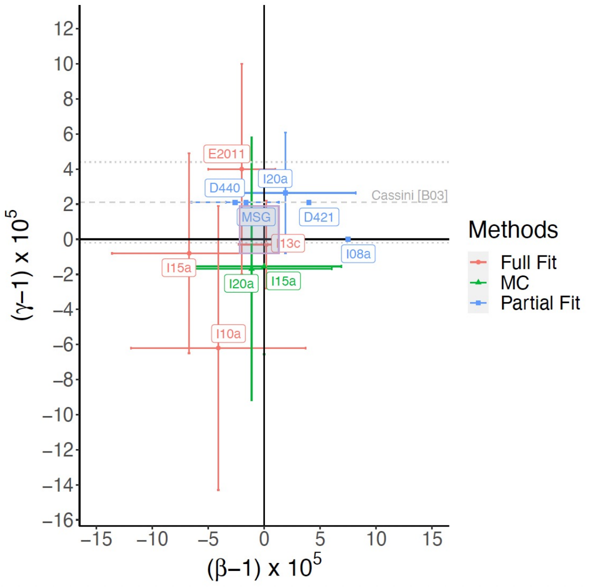


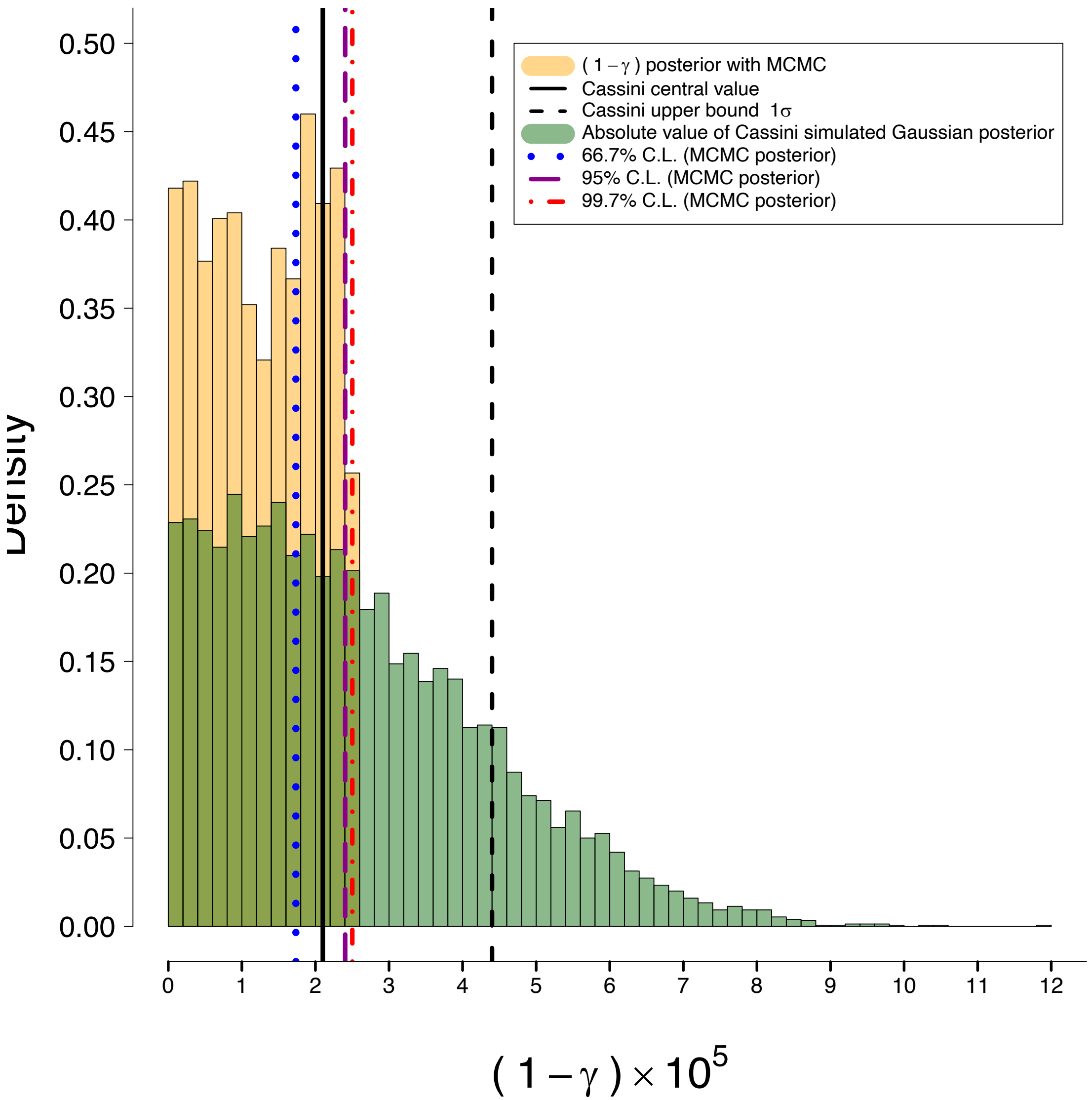
- Another meeting is planned for first semester 2024
- Technological challenges seem significant (LISA heritage)

fin

Revised test with (Marini et al, 2023b, arXiv:2310.00719)

Test A: MCMC on γ in PPN (without SEP, $\delta_A = 0$)





$|1-\gamma| < 2.5 \times 10^{-5}$ (99.7%)

(Bertotti et al. 2003)

$(1 - \gamma) = (-2.1 \pm 2.3) \times 10^{-5}$

$(\beta - 1) = (-0.45 \pm 1.75) \times 10^{-5}$

$(\gamma - 1) = (0.55 \pm 1.35) \times 10^{-5}$