INPOP planetary ephemerides

A. Fienga[1,4] A. Verma[2,3] J. Laskar[4] H. Manche[4]
M. Gastineau[4]

[1]Observatoire de la Côte d'Azur, France

[2]Institut UTINAM, France

[3]Centre National d'Etudes Spatiales, France

[4]IMCCE, Observatoire de Paris, France

News: INPOP13a

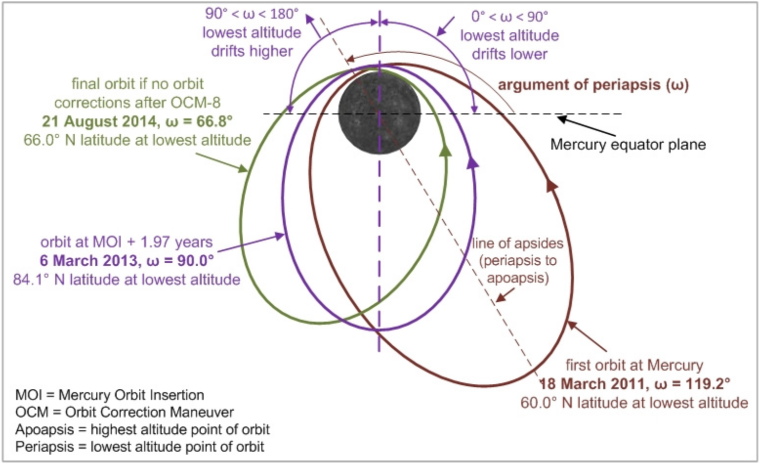
MESSENGER

- 1.5 yr of Doppler + range data (level 2) @ PDS
- Original orbit analysis with GINS software
- with hypothesis on Macro-model, manouvers

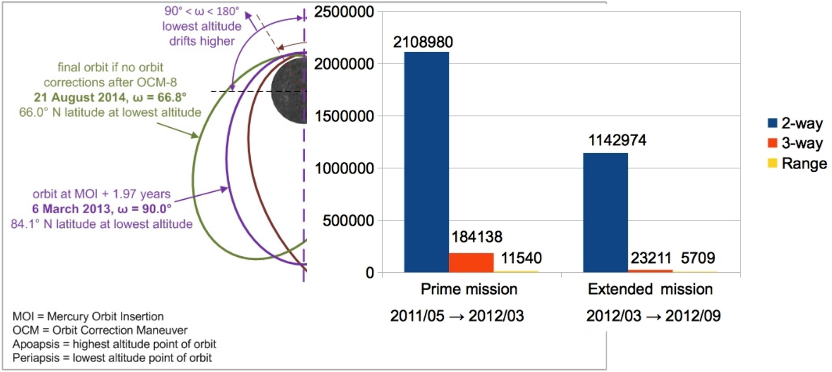
Results

- accurate orbit determination / (Smith et al. 2013)
- Full fit of all planets: INPOP13a
- new constraints over β, γ, $\frac{\dot{G}}{G}$
- Verma et al. 2013, submitted

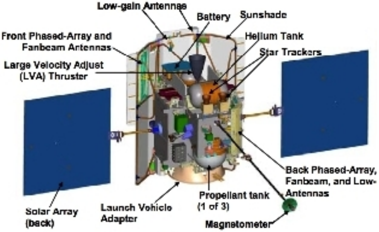
MESSENGER mission: 2 periods



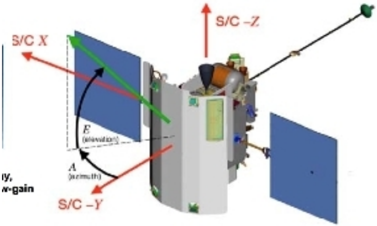
MESSENGER mission: 2 periods



MESSENGER OD with GINS



a. Spacecraft Components



b. Spacecraft coordinate axes

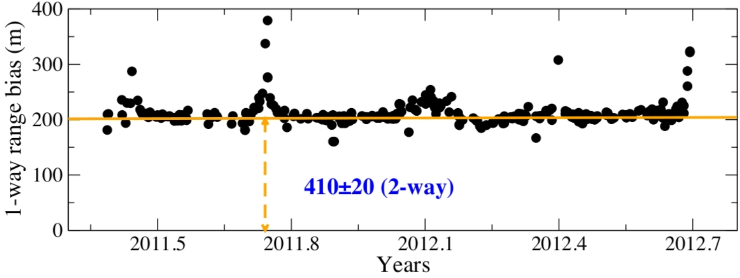
Main characteristics:

1. GINS original multi-arc analysis
2. Rotation (Margot 2009) + gravity (Smith et al.,2012)
3. Macro-modele: Box-and-wings modele (Vaughan et al. 2006)
4. Manouvers: optimization of the data arc length < period of manouvers
5. 3+4 → 1-day data arc for the fit of each arc of orbit

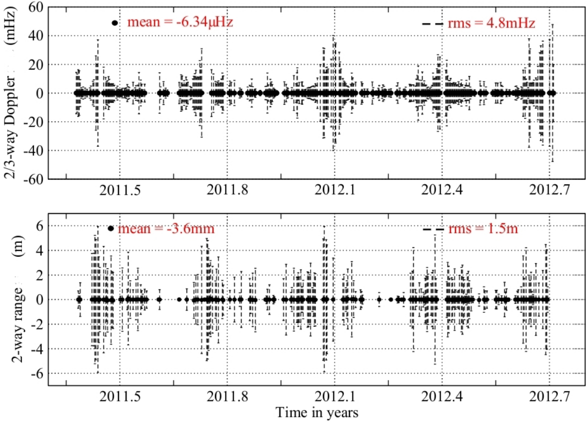
MESSENGER OD results I

Group Delay

- Offset in range measurment due to on-board transponder
- 410±20 m
- Srinivasan et al. 2007: 407-415 m



MESSENGER OD results II



Author	Doppler @ 10s	Range
Verma et al. 2013b	-0.00063±4.8 mHz	-0.003±1.5 m
Genova et al. 2013	-0.00088±3.6 mHz	-0.06±1.87 m
Smith et al. 2012	0.4±2.0 mm/s	-

INPOP13a

Construction

- same structure as INPOP10e (Fienga et al. 2013)
- Messenger range biais deduced from GINS OD
  $\rightarrow$ 314 data points from 2011.4 to 2012.6

INPOP13a

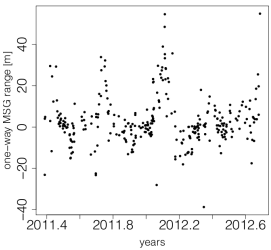
Construction

- same structure as INPOP10e (Fienga et al. 2013)
- Messenger range biais deduced from GINS OD
  → 314 data points from 2011.4 to 2012.6
- Refit over full data sets (INPOP10e + MSG)
  → IC, $GM_{\odot}$, 62 GM_{ast}, $J_2{}^{\odot}$

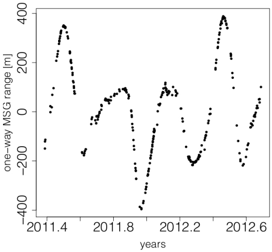
	INPOP13a $\pm 1\sigma$	INPOP10e $\pm 1\sigma$	DE423 $\pm 1\sigma$
$J_2{}^{\odot} \times 10^{-7}$	(2.40 ± 0.20)	(1.80 ± 0.25)	1.80 (2.0 ± 0.20) [P13]
$GM_{\odot}$ - 132712440000 [$km^3 . s^{-2}$]	(48.063 ± 0.4)	(50.16 ± 1.3)	40.944
GM(Ceres) [10^{12} x $M_{\odot}$]	468.430 ± 1.18	467.267 ± 1.85	473.485 ± 1.33
GM(Pallas)	103.843 ± 0.98	102.65 ± 1.60	103.374 ± 6.92
GM(Bamberga)	5.087 ± 0.19	4.769 ± 0.43	5.422 ± 1.00
GM(Metis)	3.637 ± 0.40	4.202 ± 0.67	4.524 ± 0.67

INPOP13a improvement of the Mercury orbit

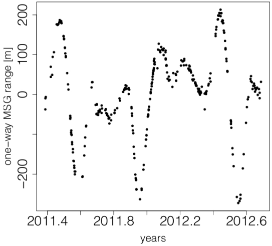
INPOP13a MSG range



INPOP10e MSG range



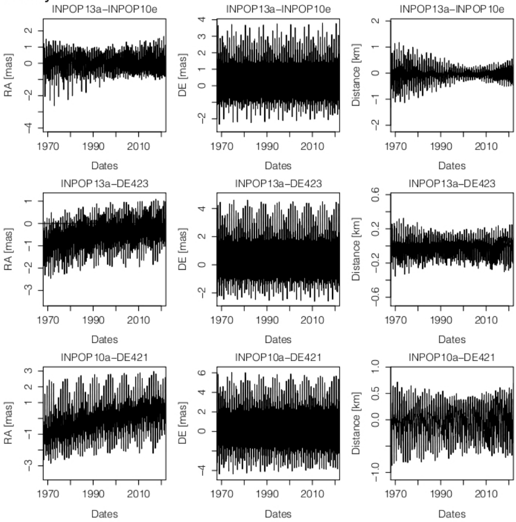
DE423 MSG range



Mercury			INPOP13a	INPOP10e
Direct range [km]	462	1971-1998	-108 ± 866	-45 ± 872
Mariner range [m]	2	1974-1975	124 ± 56	-52 ± 113
MSG flyby ra [mas]	3	2008-2009	0.8 ± 1.3	0.7 ± 1.5
MSG flyby de [mas]	3	2008-2009	2.4 ± 2.4	2.4 ± 2.5
MSG flyby range [m]	3	2008-2009	-1.9 ± 7.7	-5.0 ± 5.8
MSG range [m]	314	2011-2012	-0.4 ± 8.4	6.2± 205

INPOP13a and others: Mercury v EMB

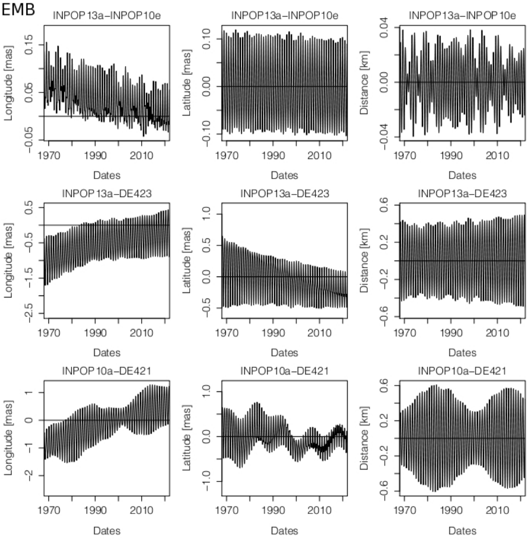
Mercury



Accuracy @ 40 yrs in (RA,DEC,dist):

- Internal: (2 mas, 4 mas, 1 km)
- 13a v DE423 : (2 mas, 4 mas, 250 m)
- 10a v DE421 : (3 mas, 5 mas, 800 m)

INPOP13a and others: EMB v SSB



Accuracy @ 40 yrs in (long,lat,dist):

- Internal: (0.2 mas, 0.1 mas, 40 m)
- 13a v DE423 : (2 mas, 1 mas, 400 m)
- 10a v DE421 : (2 mas, 1 mas, 600 m)

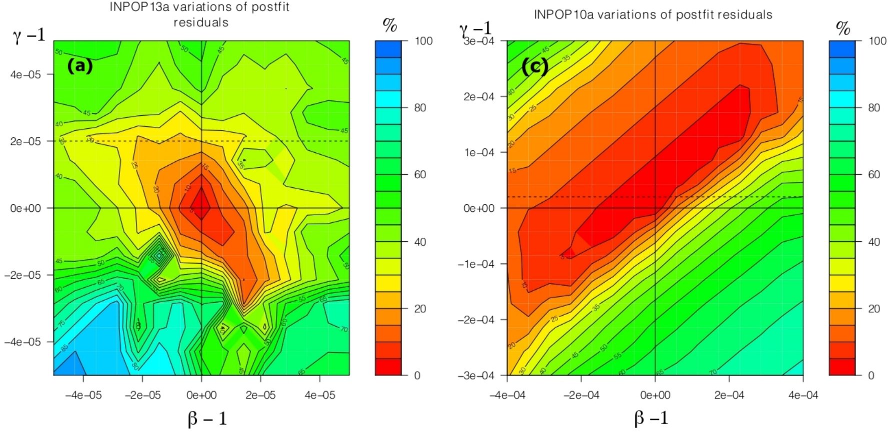
INPOP and tests of GR: the method

Grid of sensitivity for GRP determinations (Fienga et al. 2009), (Fienga et al. 2011)

- GRP: PPN β,γ, $\dot{\varpi}$, $\dot{\Omega}$, a_{supp}
- Construction of different INPOP for different values of GRP
- For each value of GRP , all parameters (IC planets, GM_{Ast}, $GM_{\odot}$) of INPOP are fitted.
- Postfit residuals /INPOP $\rightarrow$ GRP intervals with Δ residuals $< 5\%$

What values of GRP are acceptable at the level of data accuracy ?

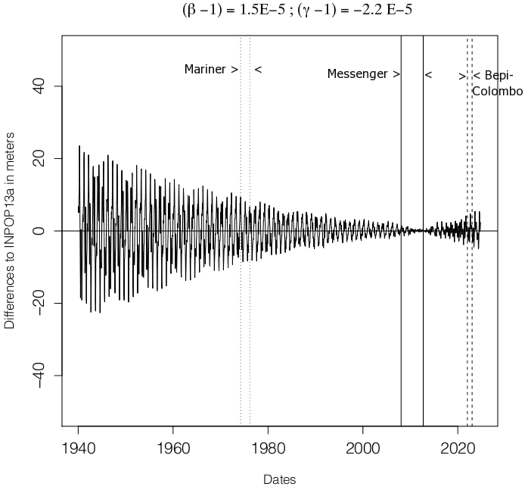
INPOP13a and tests of GR: PPN β and γ



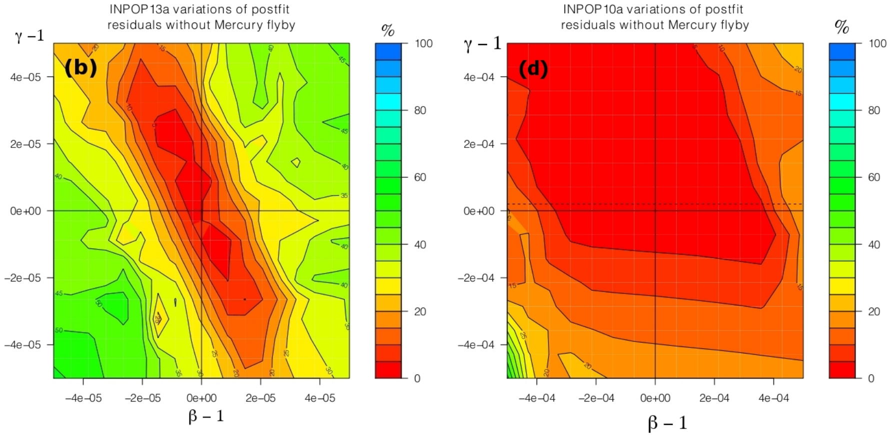
Decorrelation + improvement of a factor 10

INPOP13a and PPN β and γ

- Big constraints obtained during the MSG period (2011-2013)
- Detectable effect by Mariner and the future Bepi-Colombo
- Accuracy/reliability of 2 Mariner flybys @ 20 m (no archive) ?



Results ignoring flyby variations



Improvement of a factor 10

PPN β and γ detectable intervals

	$(\beta-1)\times(\gamma-1)$ $\times\ 10^5$	INPOP13a	Limit [%]	$(\beta-1)\times(\gamma-1)$ $\times\ 10^5$
INPOP10a	$(\beta$-1$)$ = (-6.2 ± 8.1)	All data	25*	$(\beta$-1$)$ = (0.2 ± 2.5)
	$(\gamma$-1$)$ = (4.5 ± 7.5)			$(\gamma$-1$)$ = (-0.3 ± 2.5)
			10	$(\beta$-1$)$ = (-0.15 ± 0.70
K11	$(\beta$-1$)$ = (4± 24)			$(\gamma$-1$)$ = (0.0 ± 1.1)
	$(\gamma$-1$)$ = (18 ± 26)		5	$(\beta$-1$)$ = (0.02 ± 0.12)
M08-LLR-SEP	$(\beta$-1$)$ = (15 ± 18)			$(\gamma$-1$)$ = (0.0 ± 0.18)
W09-LLR-SEP	$(\beta$-1$)$ = (12 ± 11)			
		No flyby	25	$(\beta$-1$)$ = (-0.5 ± 4.5)
B03-CASS	$(\gamma$-1$)$ = (2.1 ± 2.3)			$(\gamma$-1$)$ = (12.5 ± 17.5)
L11-VLB	$(\gamma$-1$)$ = (-8 ± 12)		10	$(\beta$-1$)$ = (0.0 ± 2.0)
				$(\gamma$-1$)$ = (0.5 ± 3.5)
P13	$(\beta$-1$)$ = (-2± 3)		5**	$(\beta$-1$)$ = (-0.25 ± 1.25
	$(\gamma$-1$)$ = (4 ± 6)			$(\gamma$-1$)$ = (-0.1 ± 2.6)

(*) 25 m over Mariner range

(**) 5 cm over MSG range, 15 cm over Mars orbiter range

(Verma et al. 2013b, A&A submitted, arXiv:1306.5569)

Preliminary results about $\dot{\mu}/\mu$ with $\mu = GM_\odot$

Method

- Implementation with $\frac{\dot{\mu}}{\mu} = \frac{\dot{G}}{G} + \frac{\dot{M}_\odot}{M_\odot}$ and

$$
\begin{aligned}
M_\odot(\mathrm{t}) &= M_\odot(t_0) + (t - t_0) \times \dot{M}_\odot \\
\mathrm{G}(\mathrm{t}) &= G(t_0) + (t - t_0) \times \dot{G} \\
\mu(t) &= G(t) \times M_\odot(t)
\end{aligned}
$$

- by fixing $\dot{M}_\odot$ or $\dot{G} \rightarrow \frac{\dot{\mu}}{\mu}$
- At each step, t_i, of the numerical integration of the Eq.of motions of planets, asteroids $\rightarrow M_\odot(\mathrm{t}_i)$ and $\mathrm{G}(\mathrm{t}_i)$ are injected.

Preliminary results about $\dot{\mu}/\mu$ with $\mu = GM_\odot$

Method

- Implementation with $\frac{\dot{\mu}}{\mu} = \frac{\dot{G}}{G} + \frac{\dot{M}_\odot}{M_\odot}$ and

$$
\begin{aligned}
M_\odot(\mathrm{t}) &= M_\odot(t_0) + (t - t_0) \times \dot{M}_\odot \\
\mathrm{G}(\mathrm{t}) &= G(t_0) + (t - t_0) \times \dot{G} \\
\mu(t) &= G(t) \times M_\odot(t)
\end{aligned}
$$

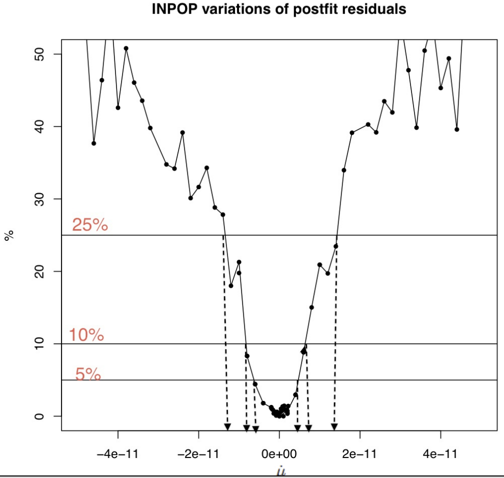
- by fixing $\dot{M}_\odot$ or $\dot{G} \rightarrow \frac{\dot{\mu}}{\mu}$
- At each step, t_i, of the numerical integration of the Eq.of motions of planets, asteroids $\rightarrow M_\odot(\mathrm{t}_i)$ and $\mathrm{G}(\mathrm{t}_i)$ are injected.
- Same method as PPN β,γ $\rightarrow$ grid of $\frac{\dot{\mu}}{\mu}$ + construction of full PE
- What values of $\frac{\dot{\mu}}{\mu}$ are acceptable / data accuracy ?

Preliminary results about $\dot{\mu}/\mu$ with $\mu = GM_\odot$

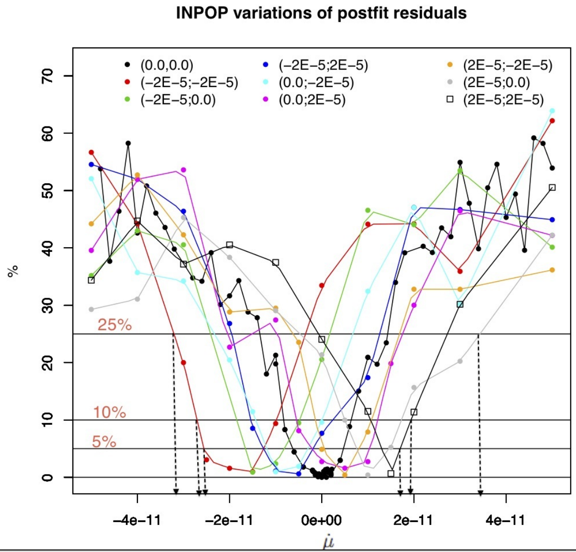
with PPN $\beta,\gamma = 1$

Method	$\dot{G}/G$ $\times\ 10^{13}\ \mathrm{yr}^{-1}$
LLR	(4 ± 9)
Binary pulsar	(40 ± 50)
Helioseismology	(0 ± 16)
Big Bang nucleo.	(0 ± 4)
Planck +WP+BAO	(-1.42± 2.48)
EMP (P12)	$(0.166 \pm 0.724)^{*}$
DE (K11)	$(1.0 \pm 1.6)^{**}$
5%	$(0.62 \pm 0.86)^{*}$ $(0.85 \pm 0.55)^{**}$
10%	$(0.595 \pm 1.035)^{*}$ $(0.825 \pm 0.725)^{**}$
25 %	$(0.72 \pm 1.71)^{*}$ $(0.95 \pm 1.40)^{**}$

* $\dot{M}_\odot/M_\odot = (-0.67 \pm 0.31) \times 10^{13}\ \mathrm{yr}^{-1}$
** $\dot{M}_\odot/M_\odot = -0.9 \times 10^{13}\ \mathrm{yr}^{-1}$



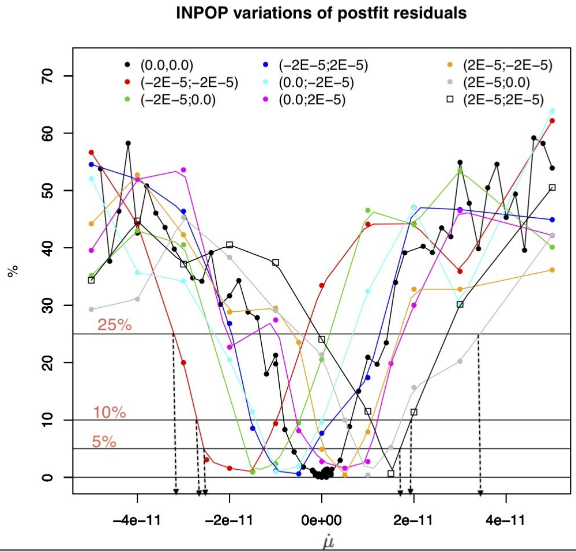
Preliminary results about $\dot{\mu}/\mu$ with $\mu = GM_{\odot}$



with PPN $\beta,\gamma \neq 1$

Shift of the minimum of residual variation with $\dot{\mu}/\mu$ AND β,γ

Preliminary results about $\dot{\mu}/\mu$ with $\mu = GM_\odot$

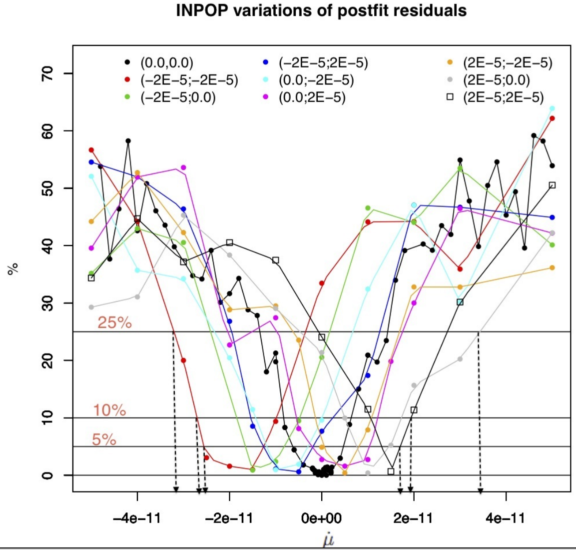


with PPN $\beta,\gamma \neq 1$

Shift of the minimum of residual variation with $\dot{\mu}/\mu$ AND β,γ

$\rightarrow$ 3D grid with $\dot{\mu}/\mu$, β, γ

Preliminary results about $\dot{\mu}/\mu$ with $\mu = GM_\odot$



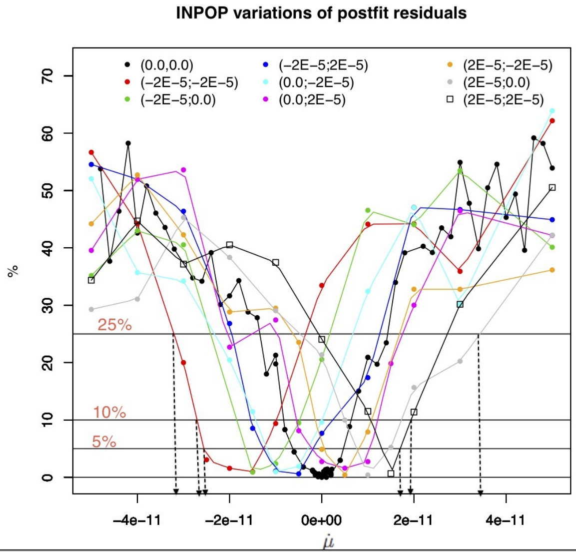
with PPN $\beta,\gamma \neq 1$

Shift of the minimum of residual variation with $\dot{\mu}/\mu$ AND β,γ

→ 3D grid with $\dot{\mu}/\mu$, β, γ

→ 2D grid with $\dot{\mu}/\mu$ and $\eta = 4 \times \beta - \gamma - 3$

Preliminary results about $\dot{\mu}/\mu$ with $\mu = GM_\odot$



with PPN $\beta,\gamma \neq 1$

Shift of the minimum of residual variation with $\dot{\mu}/\mu$ AND β,γ

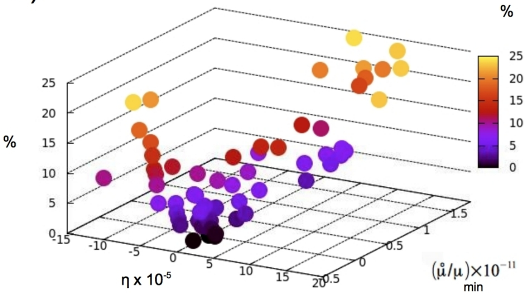
→ 3D grid with $\dot{\mu}/\mu$, β, γ

→ 2D grid with $\dot{\mu}/\mu$ and $\eta = 4 \times \beta - \gamma - 3$

→ BUT, with $\beta = \gamma$ (time of computation)

2D grid with variations of $\dot{\mu}/\mu$ and η

a)



Method	$\dot{G}/G$ $\times\ 10^{13}\ \mathrm{yr}^{-1}$
LLR	(4 ± 9)
Binary pulsar	(40 ± 50)
Helioseismology	(0 ± 16)
Big Bang nucleo.	(0 ± 4)
Planck +WP+BAO	(-1.42$\pm$ 2.48)
EMP (P12)	$(0.166 \pm 0.724)^{*}$
DE (K11)	$(1.0 \pm 1.6)^{**}$

* $\dot{M}_\odot/M_\odot = (-0.67 \pm 0.31) \times 10^{13}\ \mathrm{yr}^{-1}$

** $\dot{M}_\odot/M_\odot = -0.9 \times 10^{13}\ \mathrm{yr}^{-1}$

Method	η $\times\ 10^5$	$\dot{G}/G$ $\times\ 10^{13}\ \mathrm{yr}^{-1}$
5%	(0.2 ± 0.46)	$(1.17 \pm 1.01)^{*}$
10%	(-0.6 ± 3.3)	$(1.32 \pm 1.16)^{*}$
25 %	(1.05 ± 12.55)	$(1.30 \pm 1.46)^{*}$

Conclusions and Perpectives

INPOP13a and β, γ results are presented in
(Verma et al. 2013b, A&A submitted, arXiv:1306.5569)

Conclusions and Perpectives

INPOP13a and β, γ results are presented in
(Verma et al. 2013b, A&A submitted, arXiv:1306.5569)

About $\dot{\mu}/\mu$...

1. Grid of $\dot{\mu}/\mu$ with random $\beta - 1$ and $\gamma - 1$ (running now...)
2. Prolongation of the MSG data set from 2012.6 to 2013.3 (first runs now...)

Conclusions and Perpectives

INPOP13a and β, γ results are presented in
(Verma et al. 2013b, A&A submitted, arXiv:1306.5569)

About $\dot{\mu}/\mu$...

1. Grid of $\dot{\mu}/\mu$ with random $\beta - 1$ and $\gamma - 1$ (running now...)
2. Prolongation of the MSG data set from 2012.6 to 2013.3 (first runs now...)

Future evolution: INPOP13b

1. INPOP13a
2. New Analysis of MRO and Mars Odyssey data (GRGS-ROB)
3. New Pluto occultation