Constraints on SME coefficients with Lunar Laser Ranging, VLBI, and planetary motions

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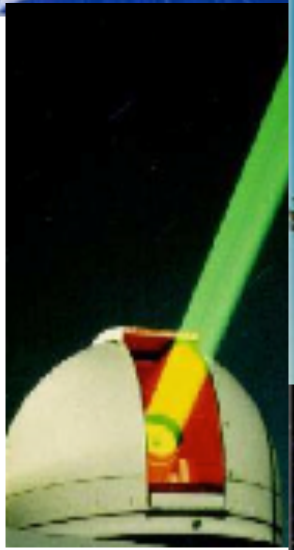
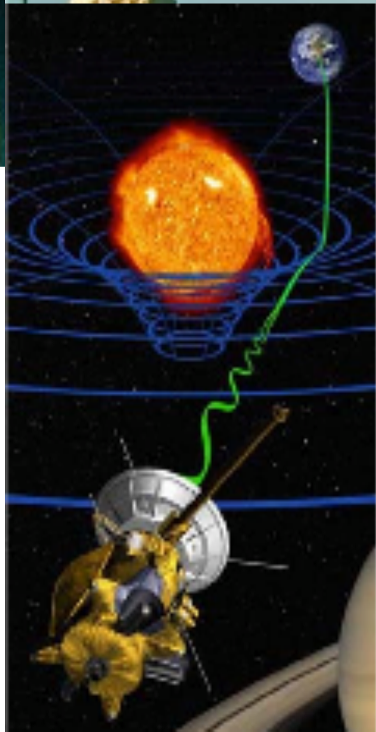
(A. Hees, A. Bourgoin, S. Lambert, S. Bouquillon, D. Hestroffer, G. Francou, F. Meynadier, M.-C. Angonin, P. Wolf)

More and more precision !







Ground & space geodesy accuracy is increasing:

LLR & SLR → From cm to mm
GALILEO

Gravity Probe A to ACES/Pharao → factor 80 on Grav. Redshift

Ground & space astrometry:

Gaia, Gravity → from milli to micro-arcsecond

Navigation of interplanetary probes :

Cassini Experiment, use of Ka Band
MORE Experiment on BepiColombo → factor 10 on Doppler
JUNO Experiment 2016, JUICE towards 2030


Need to describe light propagation/dynamic more precisely in relativistic framework :go to 2PN theory !
(see Kopeikin, Klioner, Soffel, CLPL, Teyssandier & Hees works)

- One can *catch* more relativistic effects
- But we can also study alternative theory => SME !

Lorentz symmetry violation : SME

- SME: consider violations of the Lorentz symmetry (coming from more fundamental theory) in all sectors of physics
- metric parametrizing a violation of Lorentz symmetry in the gravitational sector depends on $\bar{s}^{\mu\nu}$: does not enter PPN of fifth force formalisms
- currently a few analysis (Gravity probe B, binary pulsars, LLR postfit analysis)
- matter sector leads to violations of the EEP (in terms of the so-called $\bar{a}^{\mu}$ coefficients). Go to gravity-matter coupling ?

Can Solar System observations constrain Lorentz symmetry violation ?

see Q. Bailey, V.A. Kostelecky, PRD, 2006
V.A. Kostelecky, J. Tasson, PRD, 2011

SME Post-fit analysis of experiments

Several papers on Lunar Laser Ranging, Gravity Probe B and binary pulsars :

$$|\bar{s}^{TT}| < 1.6 \times 10^{-5} \quad (95\% \text{ C.L.}),$$

Shao PRD 2014

But can we speak about *Constraints* ?

Not really, we are speaking about post-fit analysis. Exception : Battat *et al.* 2007, but the dynamical modeling is far from reality and finally is not adequat. We are missing several key points : data time span analysis, correlation with others parameters, modeling & fit in GR and then another fit in the residuals…

Over-estimation of SME coefficients !

Up to now :

- **NO constraint** on gravitational sector of SME
- but **ONLY Upper Limit**

TABLE III. The predicted sensitivity to each $\bar{s}_{\rm LLR}$ parameter (from [6]) and the values derived in this work including the realistic (scaled) uncertainties ($F\sigma$) with $F = 20$. In this analysis, the PPN parameters were fixed at their GR values. The SME parameters are all within 1.5 standard deviations of zero. We see no evidence for Lorentz violation under the SME framework.

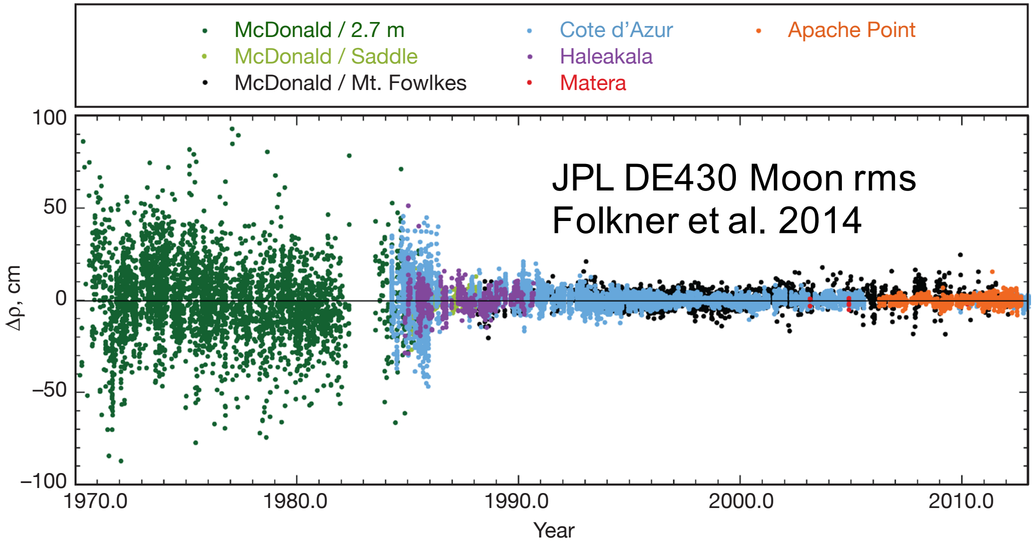
Parameter	Predicted sensitivity	This work
$\bar{s}^{11}-\bar{s}^{22}$	10^{-10}	$(1.3 \pm 0.9) \times 10^{-10}$
$\bar{s}^{12}$	10^{-11}	$(6.9 \pm 4.5) \times 10^{-11}$
$\bar{s}^{02}$	10^{-7}	$(-5.2 \pm 4.8) \times 10^{-7}$
$\bar{s}^{01}$	10^{-7}	$(-0.8 \pm 1.1) \times 10^{-6}$
$\bar{s}_{\Omega_\oplus c}$	10^{-7}	$(0.2 \pm 3.9) \times 10^{-7}$
$\bar{s}_{\Omega_\oplus s}$	10^{-7}	$(-1.3 \pm 4.1) \times 10^{-7}$

Battat et al. PRL 2007

TABLE I. Pulsar constraints on the coefficients of the pure-gravity sector of mSME [13]. The K factor reflects the improvement over the combined limits from lunar laser ranging and atom interferometry [24]. Notice the probabilistic assumption made in the text.

SME coefficients	68% confidence level	K factor
$\bar{s}^{TX}$	$(-5.2, 5.3) \times 10^{-9}$	118
$\bar{s}^{TY}$	$(-7.5, 8.5) \times 10^{-9}$	163
$\bar{s}^{TZ}$	$(-5.9, 5.8) \times 10^{-9}$	650
$\bar{s}^{XY}$	$(-3.5, 3.6) \times 10^{-11}$	42
$\bar{s}^{XZ}$	$(-2.0, 2.0) \times 10^{-11}$	70
$\bar{s}^{YZ}$	$(-3.3, 3.3) \times 10^{-11}$	42
$\bar{s}^{XX} - \bar{s}^{YY}$	$(-9.7, 10.1) \times 10^{-11}$	16
$\bar{s}^{XX} + \bar{s}^{YY} - 2\bar{s}^{ZZ}$	$(-12.3, 12.2) \times 10^{-11}$	310

Shao PRL 2014



Pre-Process data, dynamical modeling & fit in a complete SME framework

In 3 words : Our Ultimate Goal !

Today Menu

Appetizers

Post-fit analysis with planetary ephemerides
&
Simulations for Solar System Objects with Gaia data

Main dishes

Constraint with Very Long Baseline Interferometry

Desserts

Constraint with Lunar Laser Ranging

Planetary ephemerides and Lorentz symmetry

- Use of observations to fit orbital dynamics: optical, radar, VLBI, spacecraft tracking (~ 800 000 observations)

- influence of SME on orbital dynamics studied in Q. Bailey, V.A. Kostelecky, PRD, 2006

$$\left\langle \frac{d\Omega}{dt} \right\rangle = \frac{n}{\sin i (1-e^2)^{1/2}} \left[\frac{\varepsilon}{e^2} \bar{s}_{kP} \sin\omega + \frac{(e^2-\varepsilon)}{e^2} \bar{s}_{kQ} \cos\omega - \frac{2na\varepsilon}{ec} \bar{S}^k_{\odot} \cos\omega \right]$$

$$\left\langle \frac{d\omega}{dt} \right\rangle = -\cos i \left\langle \frac{d\Omega}{dt} \right\rangle - n \left[\frac{(e^2-2\varepsilon)}{2e^4} (\bar{s}_{PP} - \bar{s}_{QQ}) + \frac{2na(e^2-\varepsilon)}{ce^3(1-e^2)^{1/2}} \bar{S}^Q_{\odot} \right]$$

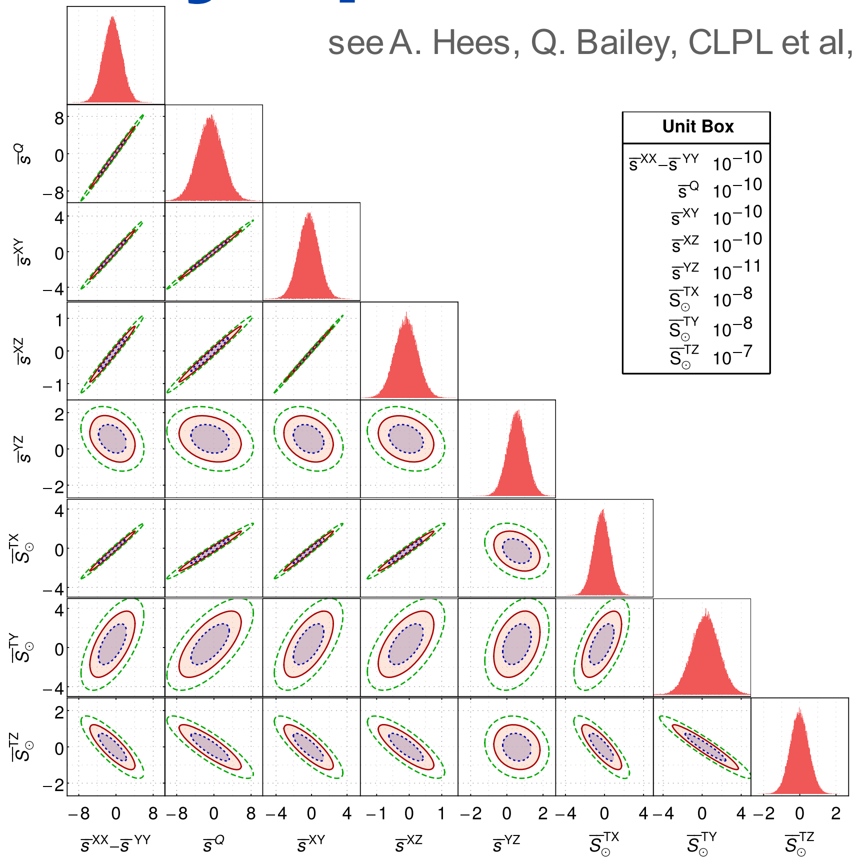
- Post-fit Bayesian analysis with INPOP10a (room for improvement by integrating directly the eq. of motion) INPOP10a: A. Fienga, et al, Cel. Mec. Dyn. Astr, 2011

- difficulty: strong correlations. Reason: similar orbital plane and eccentricity

SME Upper limits from planetary ephemerides

see A. Hees, Q. Bailey, CLPL et al, PRD, 2015

SME coefficients	Estimation
$\bar{s}^{XX} - \bar{s}^{YY}$	$(-0.8 \pm 2.0) \times 10^{-10}$
$\bar{s}^{Q} = \bar{s}^{XX} + \bar{s}^{YY} - 2\bar{s}^{ZZ}$	$(-0.8 \pm 2.7) \times 10^{-10}$
$\bar{s}^{XY}$	$(-0.3 \pm 1.1) \times 10^{-10}$
$\bar{s}^{XZ}$	$(-1.0 \pm 3.5) \times 10^{-11}$
$\bar{s}^{YZ}$	$(5.5 \pm 5.2) \times 10^{-12}$
$\bar{S}^{TX}_{\odot}$	$(-2.9 \pm 8.3) \times 10^{-9}$
$\bar{S}^{TY}_{\odot}$	$(0.3 \pm 1.4) \times 10^{-8}$
$\bar{S}^{TZ}_{\odot}$	$(-0.2 \pm 5.0) \times 10^{-8}$



- best Upper Limits on some linear combinations (difficult to decorrelate)

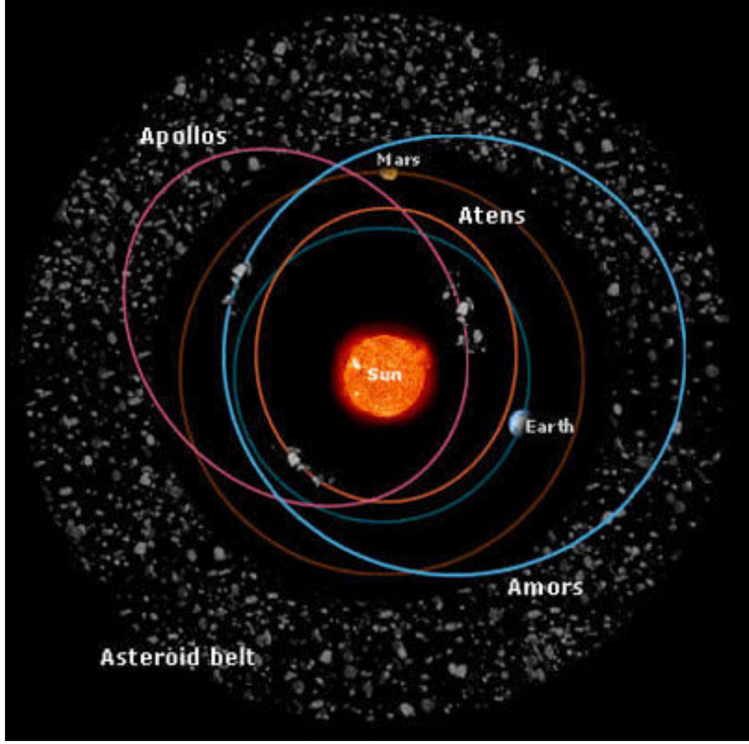
SME coefficients	Estimation
$\bar{s}^{XX} - \bar{s}^{YY}$	$(9.6 \pm 5.6) \times 10^{-11}$
$\bar{s}^{Q} = \bar{s}^{XX} + \bar{s}^{YY} - 2\bar{s}^{ZZ}$	$(1.6 \pm 0.78) \times 10^{-10}$
$\bar{s}^{XY}$	$(6.5 \pm 3.2) \times 10^{-11}$
$\bar{s}^{XZ}$	$(2.0 \pm 1.0) \times 10^{-11}$
$\bar{s}^{YZ}$	$(4.1 \pm 5.0) \times 10^{-12}$
$\bar{s}^{TX}$	$(-7.4 \pm 8.7) \times 10^{-6}$
$\bar{s}^{TY}$	$(-0.8 \pm 2.5) \times 10^{-5}$
$\bar{s}^{TZ}$	$(0.8 \pm 5.8) \times 10^{-5}$
$\alpha(\bar{a}^{e}_{\rm eff})^X + \alpha(\bar{a}^{p}_{\rm eff})^X$	$(-7.6 \pm 9.0) \times 10^{-6}$ GeV/c^2
$\alpha(\bar{a}^{e}_{\rm eff})^Y + \alpha(\bar{a}^{p}_{\rm eff})^Y$	$(-6.2 \pm 9.5) \times 10^{-5}$ GeV/c^2
$\alpha(\bar{a}^{e}_{\rm eff})^Z + \alpha(\bar{a}^{p}_{\rm eff})^Z$	$(1.3 \pm 2.2) \times 10^{-4}$ GeV/c^2
$\alpha(\bar{a}^{n}_{\rm eff})^X$	$(-5.4 \pm 6.3) \times 10^{-6}$ GeV/c^2
$\alpha(\bar{a}^{n}_{\rm eff})^Y$	$(4.8 \pm 8.2) \times 10^{-4}$ GeV/c^2
$\alpha(\bar{a}^{n}_{\rm eff})^Z$	$(-1.1 \pm 1.9) \times 10^{-3}$ GeV/c^2

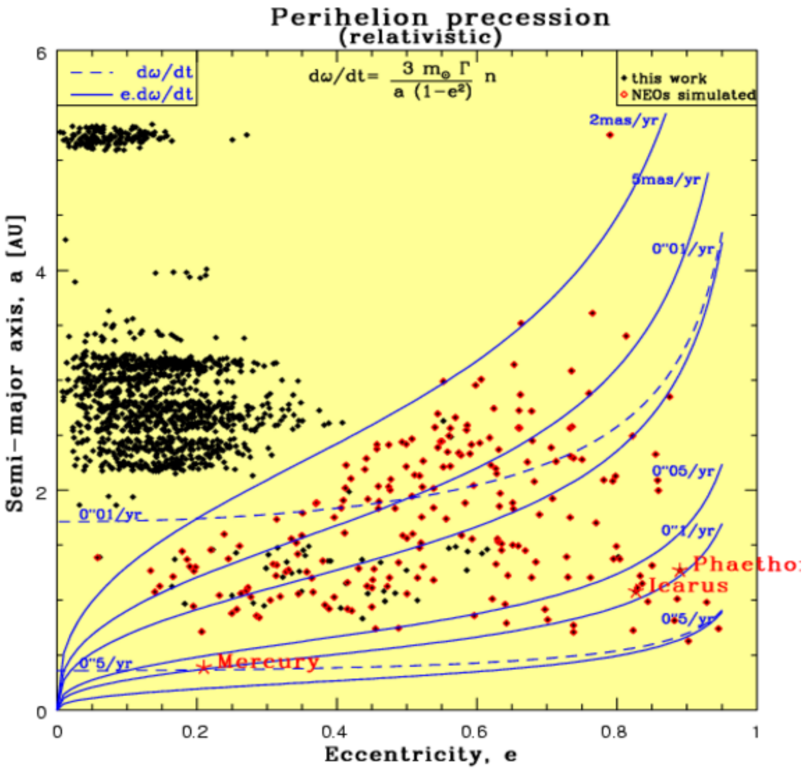
- combined analysis:
  - atom interferometry see H Muller, et al, PRL, 08
  - LLR see J. battat, et al, PRL 07

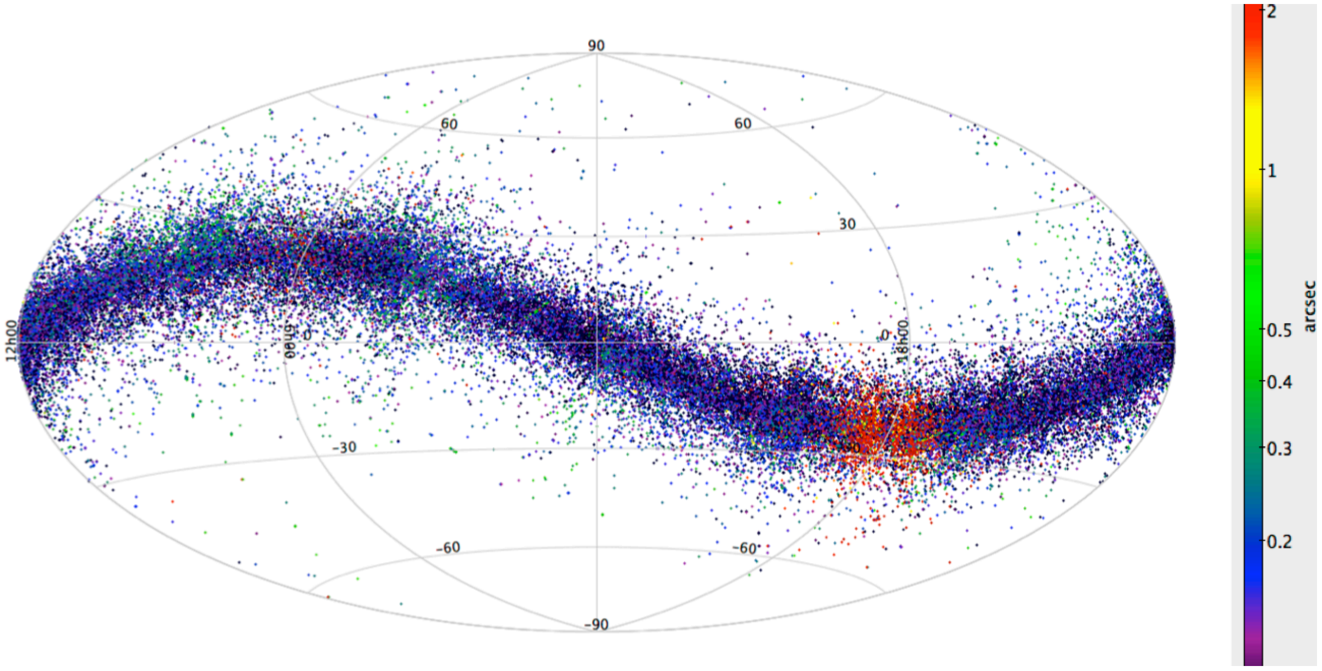
=> possible to decorrelate all gravity AND matter/gravity coefficients

Gaia and SSO (asteroids)

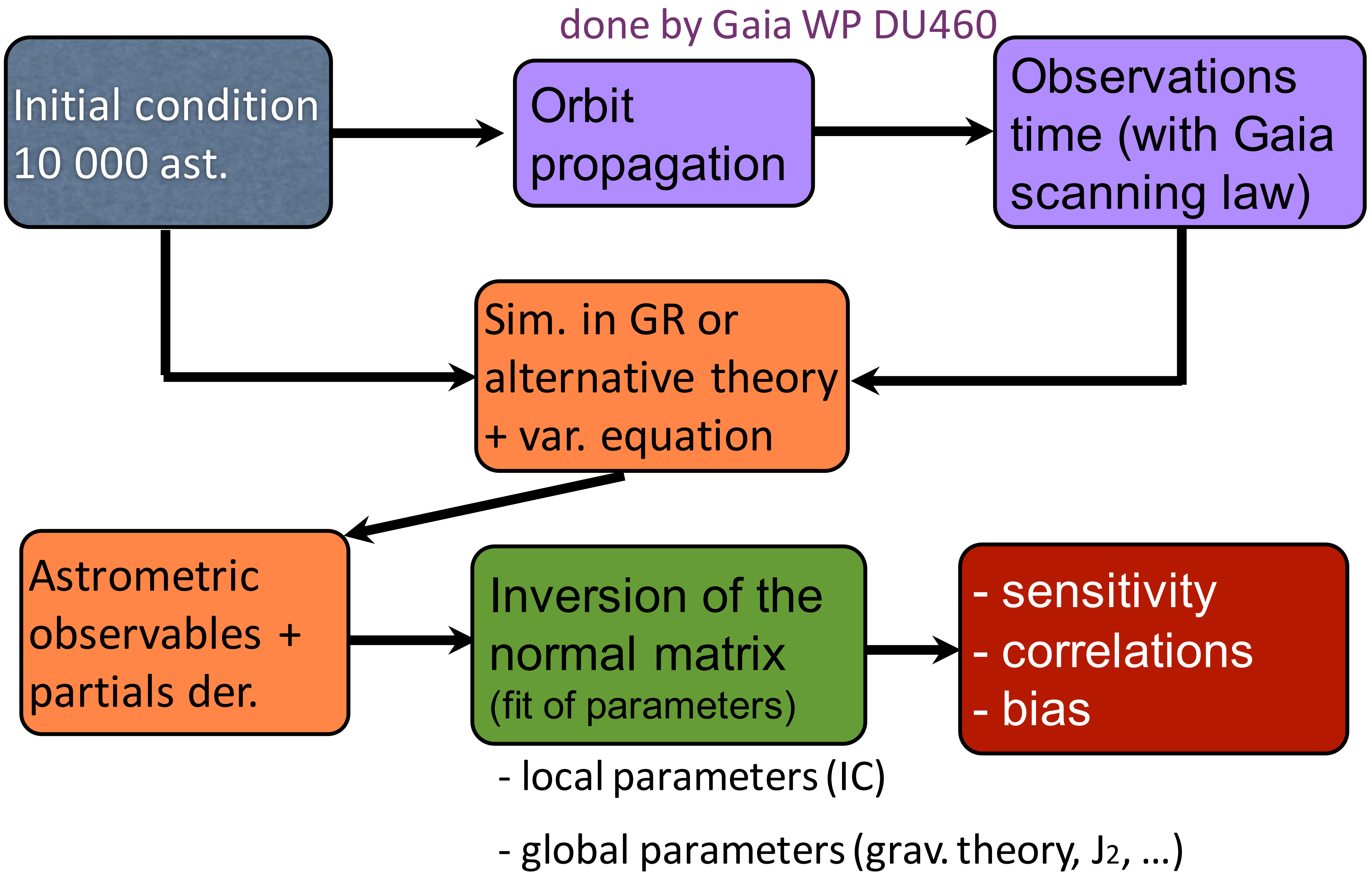
- Use GAIA asteroid observations = advantage of a large sample of different orbital parameters (300 000 objects)
  - decorrelation of SME parameters
  - complementary to planetary ephemerides (different bodies, different type of observations, different method to analyze the data)
- accuracy ~ 0.2-0.5 mas







How simulate Gaia SSO observations ?



Parameters considered

- local parameters: 6 initial conditions / asteroids (60 000 par.)
- global parameters:
  - Solar Quadrupole moment J_2.
  - Post-Newtonian Parameter β
  - Sun Lense-Thirring effect: depends on the Sun spin S
  - Violation of the Strong Equivalence Principle (Nordtvedt effect): η
  - Fifth Force formalism: (λ, α)
  - Time variation of G: constant $\dot{G}/G$
  - Periodic variation of G
  - Standard Model Extension formalism: $\bar{s}^{\mu\nu}$
- 10 000 asteroids with astrometric accuracy of 0.2 mas

What to expect with 5 years mission

SME Parameter	sensitivity (σ)
$\bar{s}^{XX} - \bar{s}^{YY}$	9×10^{-12}
$\bar{s}^{XX} + \bar{s}^{YY} - \bar{s}^{ZZ}$	2×10^{-11}
$\bar{s}^{XY}$	4×10^{-12}
$\bar{s}^{XZ}$	2×10^{-12}
$\bar{s}^{YZ}$	4×10^{-12}
$\bar{s}^{TX}$	1×10^{-8}
$\bar{s}^{TY}$	2×10^{-8}
$\bar{s}^{TZ}$	4×10^{-8}

1+ order of magnitude improvement wrt current *upper limits* for several SME coefficients

Main advantage: decorrelation of the SME parameters

	$\bar{s}^{XX} - \bar{s}^{YY}$	$\bar{s}^{XX} + \bar{s}^{YY} - \bar{s}^{ZZ}$	$\bar{s}^{XY}$	$\bar{s}^{XZ}$	$\bar{s}^{YZ}$	$\bar{s}^{TX}$	$\bar{s}^{TY}$	$\bar{s}^{TZ}$
$\bar{s}^{XX} - \bar{s}^{YY}$	1							
$\bar{s}^{XX} + \bar{s}^{YY} - \bar{s}^{ZZ}$	0.28	1						
$\bar{s}^{XY}$	-0.06	-0.01	1					
$\bar{s}^{XZ}$	-0.17	-0.06	0.46	1				
$\bar{s}^{YZ}$	-0.16	0.71	0.01	0.01	1			
$\bar{s}^{TX}$	10^{-3}	-0.01	-0.01	10^{-3}	-0.01	1		
$\bar{s}^{TY}$	0.03	0.09	0.01	-0.01	0.02	-0.16	1	
$\bar{s}^{TZ}$	-0.02	-0.1	-0.01	0.01	-0.02	0.13	-0.67	1

Preliminary results with 10000 Gaia SSO

- First possibility to decorrelate all SME parameters

- Analysis done including the Sun J_2: similar results ; J_2 decorrelates as well

- Improvement by ~ 1 order of magnitude wrt current upper limits, but based on 10000 SSO simulation, not 300 000 as expected with Gaia ☺

- Results obtained on 5 years time-span and pessimistic astrometric accuracy

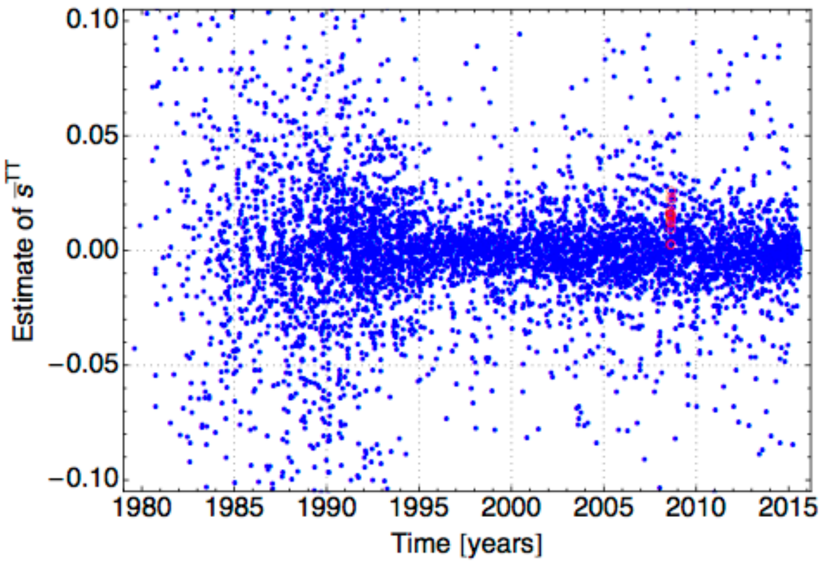
- We plan to extend the study to include gravity-matter coupling, but we have to consider also Gaia photometric observations ➡ Need of light curve !

- Possible extension to 10 years mission. Simulations ongoing.

details in Hees, Hestroffer, CLPL & David, SF2A proceedings 2015, **arXiv:1509.06868**
Hees, CLPL *et al.* in preparation for PRD

Modeling SME-VLBI delay & fit

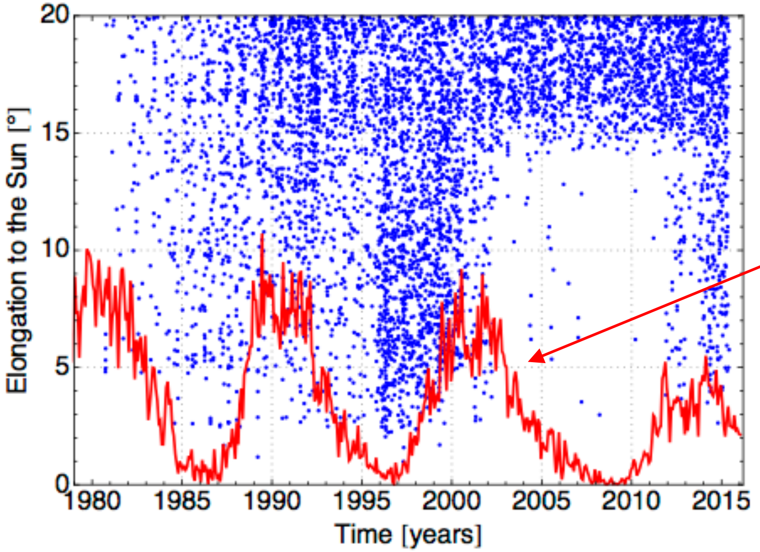
Lambert & CLPL, 2009 and 2011 : determination of PPN Gamma at the level of 10^{-4},
1 order of mag below Cassini **but strong statistics & robustess**



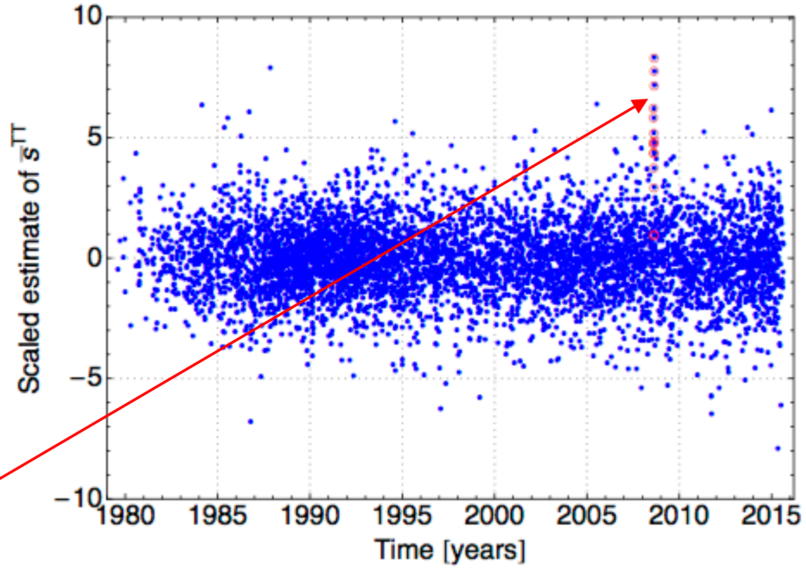
First, we derive the VLBI delay in SME from Bailey (2009) :

$$\Delta\tau_{(\mathrm{grav})} = 2\frac{\widetilde{GM}}{c^3}\left(1-\frac{2}{3}\bar{s}^{TT}\right)\ln\frac{r_1+\boldsymbol{k}.\boldsymbol{x}_1}{r_2+\boldsymbol{k}.\boldsymbol{x}_2} + \frac{2}{3}\frac{\widetilde{GM}}{c^3}\bar{s}^{TT}\left(\boldsymbol{n}_2.\boldsymbol{k}-\boldsymbol{n}_1.\boldsymbol{k}\right) .$$

with $\boldsymbol{x}_{1/2}$ positions of stations and $r_{1/2} = |\boldsymbol{x}_{1/2}|$ $\quad \boldsymbol{n}_{1/2} = \frac{\boldsymbol{x}_{1/2}}{r_{1/2}}$
and $\boldsymbol{k}$ is the direction of the source.



- Modification of CALC with module USERPART. Test with post-fit analysis : $\bar{s}^{TT} = (-0.6 \pm 2.1)\times 10^{-8}$
- 2 & 8 Ghz for solar activity
- 8 Ghz for SME analysis
- Systematics on CONT08 data but we kept them.



$\bar{s}^{TT} = (-5 \pm 8)\times 10^{-5}$

CLPL, Hees & Lambert, submitted PRL
arXiv:1604.01663

LLR and SME

State of the art

PRL **99,** 241103 (2007) PHYSICAL REVIEW LETTERS week ending 14 DECEMBER 2007

Testing for Lorentz Violation: Constraints on Standard-Model-Extension Parameters via Lunar Laser Ranging

James B.R. Battat, John F. Chandler, and Christopher W. Stubbs
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA
(Received 6 September 2007; published 13 December 2007)

We present constraints on violations of Lorentz invariance based on archival lunar laser-ranging (LLR) data. LLR measures the Earth-Moon separation by timing the round-trip travel of light between the two bodies and is currently accurate to the equivalent of a few centimeters (parts in 10^{11} of the total distance). By analyzing this LLR data under the standard-model extension (SME) framework, we derived six observational constraints on dimensionless SME parameters that describe potential Lorentz violation. We found no evidence for Lorentz violation at the 10^{-6} to 10^{-11} level in these parameters. This work constitutes the first LLR constraints on SME parameters.

DOI: 10.1103/PhysRevLett.99.241103 PACS numbers: 04.80.−y, 06.30.Gv, 11.30.Cp

14401 normal points spanning over 09/1969 to 12/2003.

Post-fit LLR analysis:

- Looked for analytical signals derived in Bailey *et. al.*, 2006.
- Planetary Ephemeris Program (PEP) developed at MIT to re-iterate => cross-correlation possible

Provide 6 *SME coefficient estimates* combinations at the level 10^{-6} and 10^{-11}. *Realistic* error $\sigma_r = F\sigma$ with $F = 20$, from PPN analysis.

$\alpha = cste$ and $\beta = cste$. From observation $T = 2\pi/\dot{\alpha} = 2\pi/\dot{\beta} = 18,6\ y$.
Analytic solution only accounting for short periodic terms. Only available for few years time-span.

Least-square fit, estimating only SME coefficients. No correlations taken into account with others global parameters, only cross-correlation.

SME oscillating signatures at the same frequencies than natural frequencies :

$$\delta r_{SME}(t) = A_{SME}\cos(2\omega t + 2\theta) + B_{SME}\sin(2\omega t + 2\theta)$$

Lunar potential 2d degree !

$$\delta r_{2\omega,2\theta}(t) = [A_{20} + A_{22}]\cos(2\omega t + 2\theta) + B_{22}\sin(2\omega t + 2\theta)$$

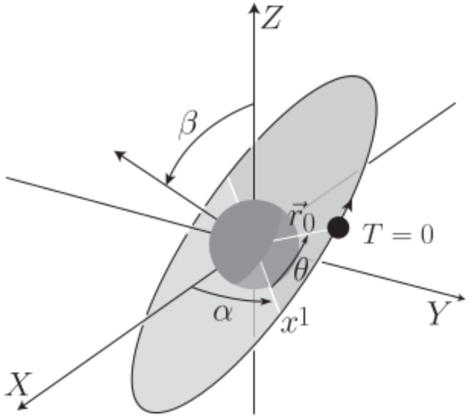
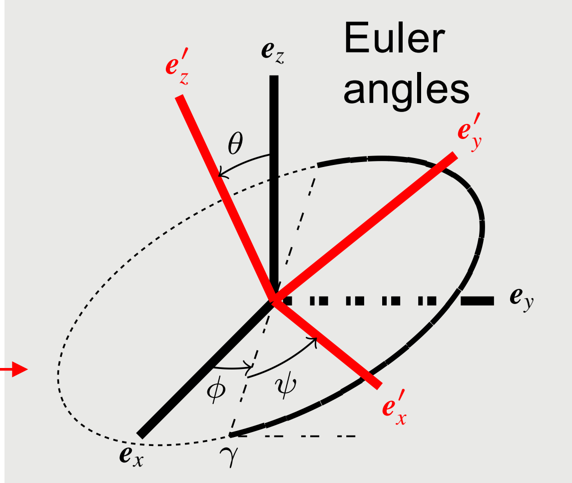


FIG. 2. Lunar orbital parameters: here the Earth is shown translated to the center of the Sun-centered coordinate system. The lunar orbit is described by r_0, the mean distance between the Earth and Moon, e (not labeled) the eccentricity of the lunar orbit, α, the longitude of the ascending node, β, the angle between the normal to the lunar orbital plane and the normal to the Earth's equatorial plane, and θ, the angle, along the Lunar orbit, subtended by the ascending node line and the position of the Moon at $t = 0$. Reprinted figure with permission from [6].

ELPN, SME lunar ephemeride



Dynamical modeling from scratch :

- Integrate the motion of Solar System bodies
  - Newtonian point-mass interactions.
  - Figure potential of bodies :
    - Orientation of bodies,
    - J_2 of the Sun,
    - J_2, J_3, J_4 and J_5 of the Earth,
    - Degree 2, 3, 4 and 5 of the Moon.
  - Tidal and spin effects :
    - Dissipation inside anelastic bodies,
    - Time-lag of degree 2 with RK4.
  - Relativistic point-mass interactions :
    - Solar system barycentre,
    - Integrate the time scale correction (in pure GR).
    - SME correction for Earth-Moon system only
  - Lunar librations :
    - Momentums due to punctual (5^{th} degree) and extended (2^{th} degree) bodies,
    - Geodetic precession effect,
    - Fluid lunar core,
    - Friction between solid mantle and fluid core.
- Integrate partials at the same time than forces and momentums.

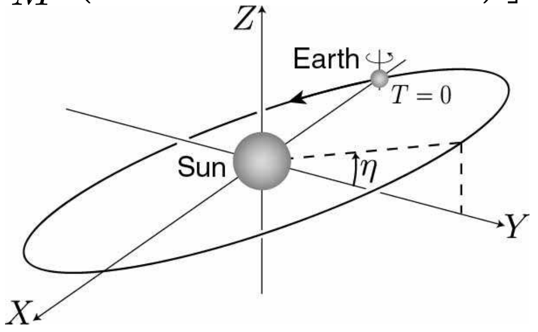
ODE system of 6000 equations

ODEX, Everheart
quadruple precision = 10^{-34}
6 CPU days for a solution !

Pre-processing of LLR normal points :
Update of the CAROLL software

- Tchebychev polynomials of the solution and partials.
- LLR analysis in SME framework by chi-square fitting

$$a^J_{\mathrm{LV}} = \frac{\bar{G}M}{r^3}\Big[\bar{s}^{JK}_t r^K - \frac{3}{2}\bar{s}^{KL}_t \hat{r}^K \hat{r}^L r^J + 3\bar{s}^{TK}\hat{V}^K r^J - \bar{s}^{TJ}\hat{V}^K r^K - \bar{s}^{TK}\hat{V}^J r^K + 3\bar{s}^{TL}\hat{V}^K \hat{r}^K \hat{r}^L r^J + 2\frac{\delta m}{M}\left(\bar{s}^{TK}\hat{v}^K r^J - \bar{s}^{TJ}\hat{v}^K r^K\right)\Big],$$

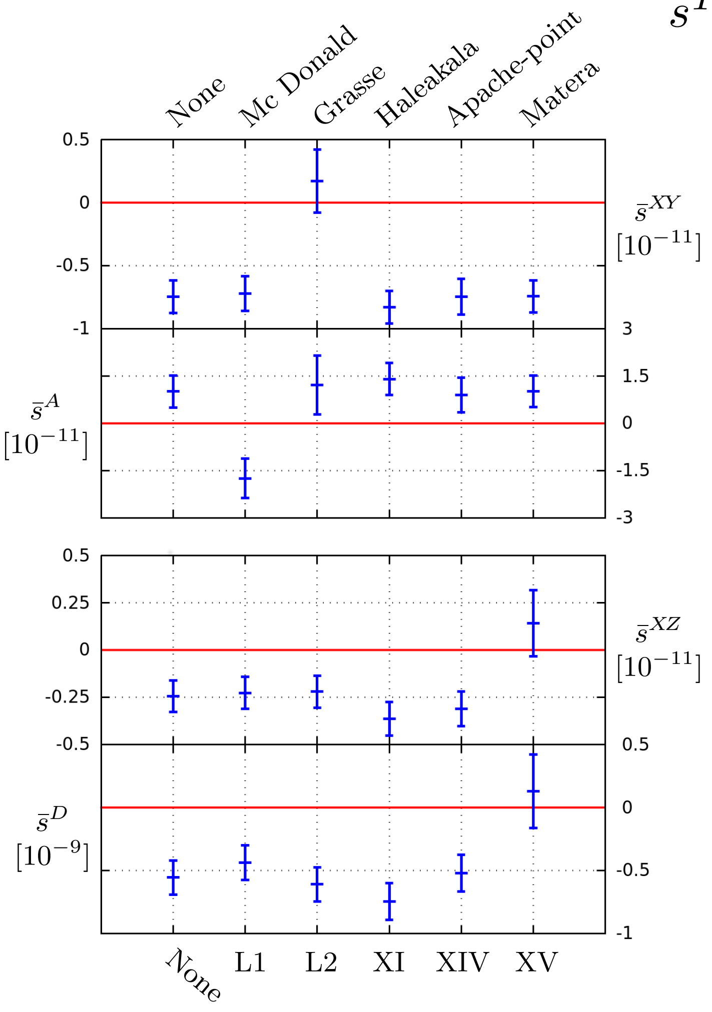


Our SME analysis

Bourgoin, Hees, Bouquillon, CLPL *et al.*, submitted PRL, **arXiv:1607.00294**

SME parameters considered : $\bar{s}^A = \bar{s}^{XX} - \bar{s}^{YY}$ $\bar{s}^B = \bar{s}^{XX} + \bar{s}^{YY} - 2\ \bar{s}^{ZZ}$
$\bar{s}^C = \bar{s}^{TY} + 0.43\ \bar{s}^{TZ}$ $\bar{s}^D = \bar{s}^B - 0.045 \bar{s}^{YZ}$.
$\bar{s}^{TX}, \bar{s}^{XY}, \bar{s}^{XZ}$.

$\bar{s}^A$ and $\bar{s}^B$
Enforce the traceless condition



Study of systematics, *i.e.* split data set !

Variation of SME sigma with data-set → Sigma over-estimated. Need to find a realistic scale factor F (not from PPN !)

Jackknife resampling method allows to estimate systematics uncertainties :

SME	Other works	This work
$\bar{s}^{TX}$	$(+5.2 \pm 5.3) \times 10^{-9}$	$(-0.9 \pm 1.0) \times 10^{-8}$
$\bar{s}^{XY}$	$(-3.5 \pm 3.6) \times 10^{-11}$	$(-5.7 \pm 7.7) \times 10^{-12}$
$\bar{s}^{XZ}$	$(-2.0 \pm 2.0) \times 10^{-11}$	$(-2.2 \pm 5.9) \times 10^{-12}$
$\bar{s}^{A}$	$(-1.0 \pm 1.0) \times 10^{-10}$	$(+0.6 \pm 4.2) \times 10^{-11}$
$\bar{s}^{C}$	$(-1.0 \pm 0.9) \times 10^{-8}$	$(+6.2 \pm 7.9) \times 10^{-9}$
$\bar{s}^{D}$	$(-1.2 \pm 1.2) \times 10^{-10}$	$(+2.3 \pm 4.5) \times 10^{-11}$

We improve :

- by a factor 30 to 800 results from Battat *et al.* 2007 (different combinaison)
- by a factor 5 post-fit analysis of 1 coefficient from binary pulsars

Conclusions

Build a framework of systematic SME tests with Solar System usual experiments :

- VLBI and LLR complete
- New modeling of observation analysis developped
- New dynamical modeling developped
- New fitting procedures developped,
- Versatile tools. Modifications are *under control* → Possible to add new features on request. PLEASE FEEL FREE TO CONTACT US !

We do not work with post-fit residuals to find SME signal :

- Complete process from the data analysis in SME
- Assess correlation between local & global parameters
- We derive realistic constraints not *upper limit* !

Soon, SLR and navigation experiments will be available…

Construction of ephemerides directly in SME (planetary and natural satellites) :

- Ongoing work on Martian Moon (Phobos and Deymos) as *a test case*

Gravity-matter coupling to be done soon.