Tests of gravitation at Solar System scale beyond PPN formalism

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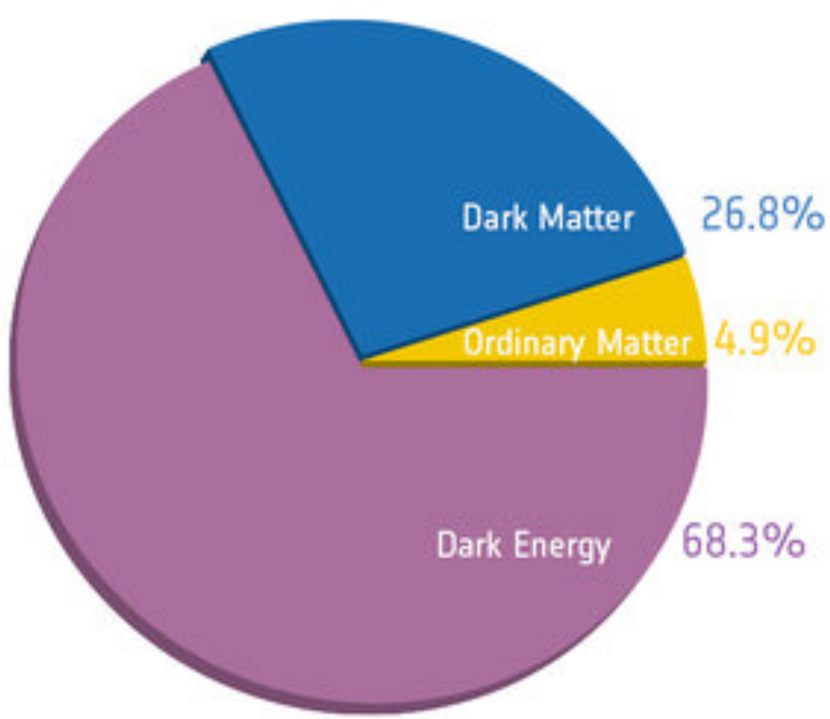
JSR13, Paris
September 18 2013

Systèmes de Référence Temps-Espace

Motivations to test GR

- Search for a quantum theory of gravity: loop quantum gravity, supergravity, ...
- Unification of all fundamental interactions: string theories, branes, ...
- Cosmological and galactic observations not explained by GR and standard model of particles
  - introduction of Dark Matter and Dark Energy
  - no direct detection so far ⇒ hints of a deviation from GR ?



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GR in the Solar System

I) Einstein Equivalence Principle:

- very well tested (up to 10^{-13})[1] and improvements planned MICROSCOPE, Galileo Galilei, STE-QUEST, ACES, ...
- Gravitation ⇔ space-time curvature (described by a metric $g_{\mu\nu}$)

II) Einstein Field Equations:

- determination of the metric:
  space-time curvature (metric) ⇔ matter-energy content
- up to now, 2 formalisms mainly used to test the form of the metric:

  a) PPN formalism[1]: metric parametrized by 10 coefficients: very good constraints (γ and β constrained at 10^{-5} - see A. Fienga's talk)

  b) fifth force formalism[2]: Search for a deviation of the Newton potential of the form of a Yukawa potential: very good constraints except at very small and large distances[3]

[1] C. Will, LRR, 9, 2006 [2] E.G. Adelberger, Prog. in Part. and Nucl. Phys., 2009 [3]A.Konopliv et al, Icarus, 2011

Is it necessary to go beyond ?

Post Einsteinian Grav.

- phenomenology
- non local field equation: quantization ?

$$G_{\mu\nu}[k] = \chi_{\mu\nu}{}^{\alpha\beta}[k] T_{\alpha\beta}[k]$$

- metric: parametrized by 2 arbitrary functions

M.T. Jaekel, S. Reynaud, CQG, 2005

SME

- phenomenology
- violation of Lorentz symmetry coming from a fundamental level
- action parametrized by a tensor $\bar{s}^{\mu\nu}$

Q. Bailey, A. Kostelecky, PRD, 2006

Fab Four

- General 2nd order tensor-scalar theory
- developed in cosmology: Dark Energy
- weak-field metric: parametrized by 4 parameters

J.P. Bruneton et al, Adv. in Astr., 2012

MOND

- phenomenology
- developed for galactic observations: Dark Matter (galactic rotation curves)
- main effect in the Solar System: External Field Effect

$$U = \frac{GM}{r} + \frac{Q_2}{2} x^i x^j \left(e_i e_j - \frac{1}{3}\delta_{ij} \right)$$

L. Blanchet, J. Novak, MNRAS, 2011

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~~PPN formalism : γ, β, ...~~

~~5th force formalism: α, λ~~

Is it necessary to go beyond ?

Post Einsteinian Grav.	SME	Fab Four

Currently: lack of constraints from Solar System for these theories !

Interesting to consider them and to constrain them using Solar System observations

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- main effect in the Solar System: External Field Effect $U = \frac{GM}{r} + \frac{Q_2}{2} x^i x^j \left(e_i e_j - \frac{1}{3}\delta_{ij} \right)$

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~~PPN formalism : γ, β, ...~~

~~5^{th} force formalism: α, λ~~

MOND in the Solar System

- main effect: External Field Effect - the gravitational field is dependent of the external galactic gravitational field[1]

$$U = \frac{GM}{r} + \frac{Q_2}{2} x^i x^j \left(e_i e_j - \frac{1}{3}\delta_{ij} \right)$$

- Q_2 depends on the MOND interpolating function and can be computed theoretically[1]

$$2.1 \times 10^{-27} s^{-2} \leq Q_2 \leq 4.1 \times 10^{-26} s^{-2}$$

- increase with the distance: Cassini data around Saturn are sensitive to this effect

- effect on light propagation negligible[2]: less than 10^{-8} m

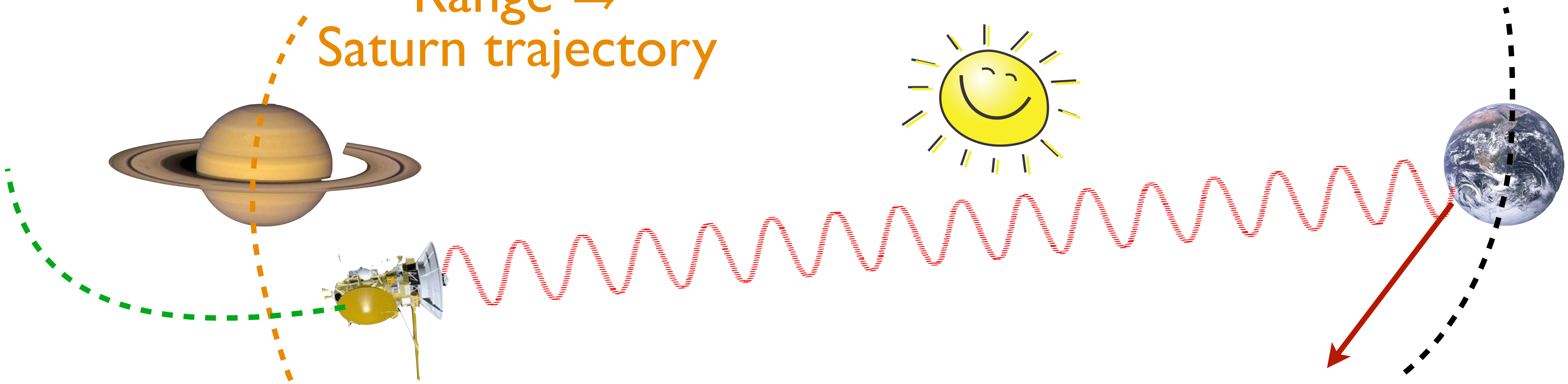
[1] L. Blanchet, J. Novak, MNRAS, 2011

[2] A. Hees, W. Folkner, et al, submitted to A&A, 2013

Cassini data

- 9 years of range and Doppler data

Range ⇒ Saturn trajectory



Doppler ⇒ Cassini trajectory: estimated by segments ~ 15-30 passes

DSN station

calibration error: shared by range observations from the same pass (100% correlated)

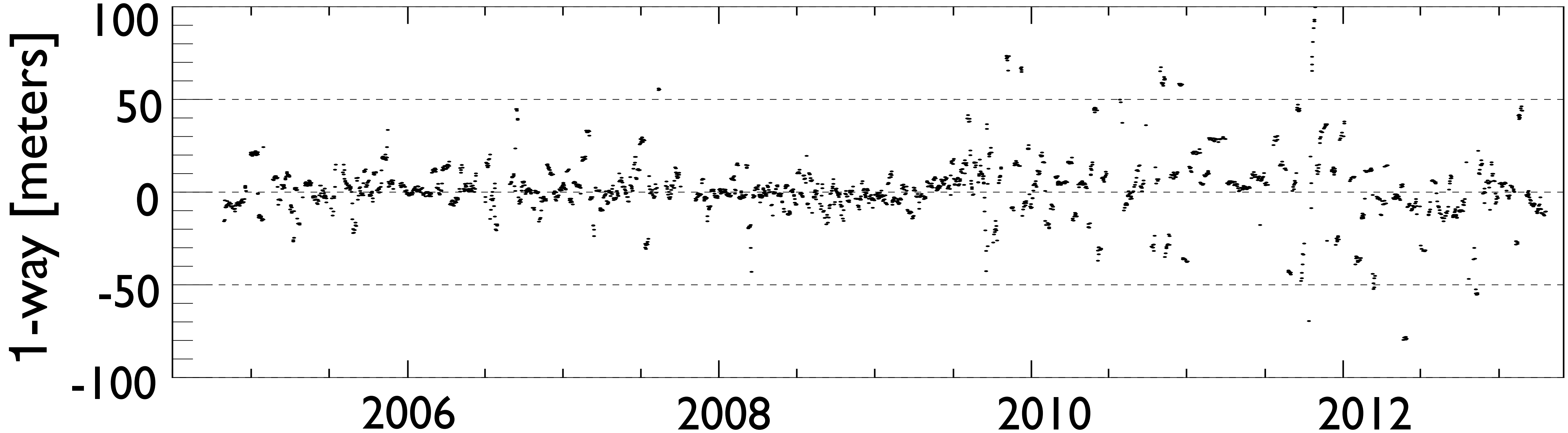
- weighting of the data in the fit - Gauss Markov theorem: weight = the individual standard deviation of the individual measurements if they are independent
  ⇒ consideration of one range observation per pass

[1] L. Blanchet, A. Le Tiec, MNRAS, 2011

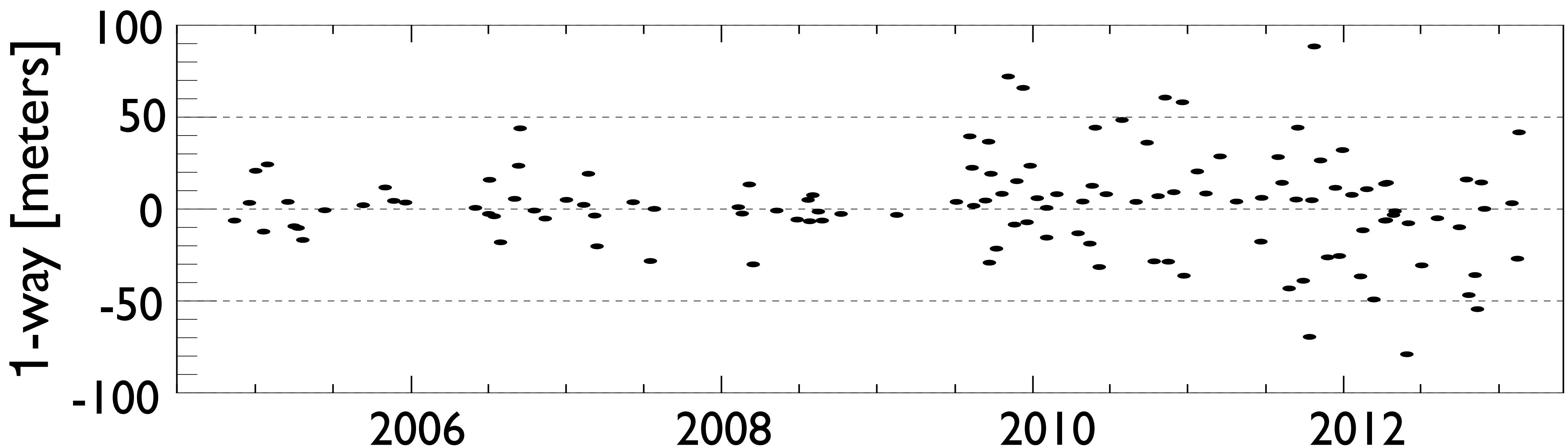
[2] A. Hees, W. Folkner, et al, submitted to A&A, 2013

Analysis

- range residuals (one per pass)



- study of the systematics of the results obtained (considering different subsets of the data) show our uncertainty was too optimistic: measurements in the same orbit segment not independent (same error)
  ⇒ consideration of one range observation per orbit segment



Results

- analysis of the systematics (considering different subsets of the data): coherent !
- Result of the fit[1] :

$$Q_2 = (3 \pm 3) \times 10^{-27} s^{-2}$$

- NO deviation from GR observed at the 1σ confidence level
- severe constraint on theoretical models that predict[2]

$$2.1 \times 10^{-27} s^{-2} \leq Q_2 \leq 4.1 \times 10^{-26} s^{-2}$$

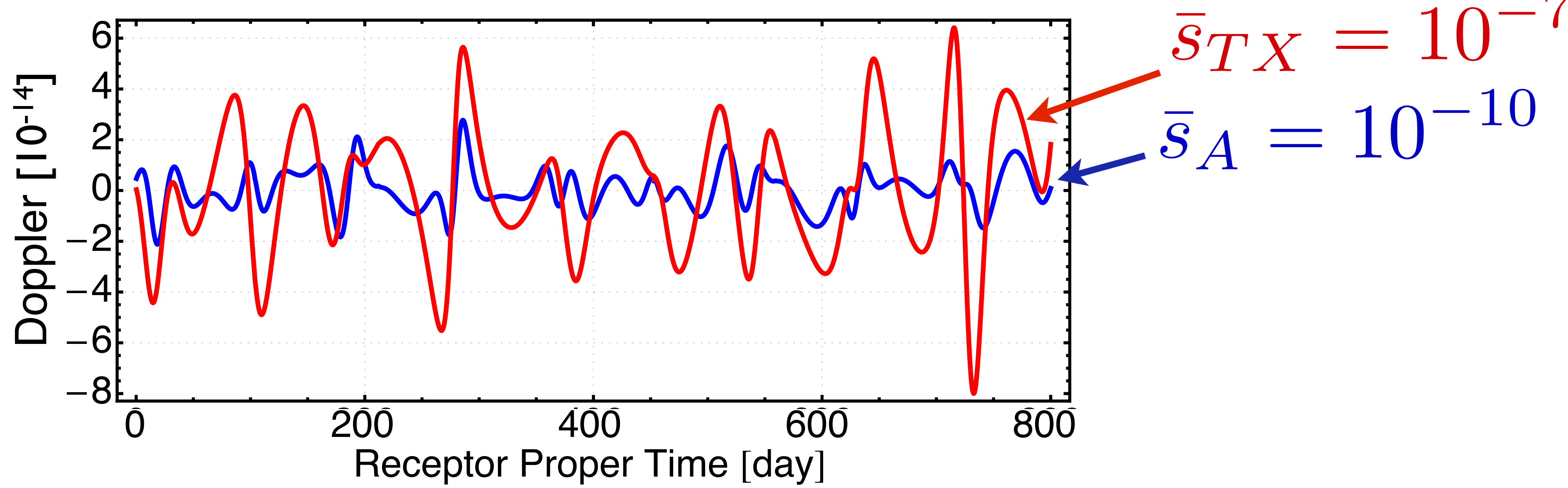
[1] A. Hees, W. Folkner, et al, submitted to A&A, 2013

[2] L. Blanchet, J. Novak, MNRAS, 2011

SME sensitivity analysis

- simulations[1] of radioscience data within SME for: Messenger (2 years around Mercury) and Cassini (9 years around Saturn)

SME signature on Messenger Doppler:



Expected sensitivities[2]:

Messenger

Par.	Uncertainties
$\bar{s}_A$	1.1×10^{-10}
$\bar{s}_{TX}$	3.1×10^{-8}
$\bar{s}_B$	1.4×10^{-8}
$\bar{s}_C$	3.2×10^{-11}

Cassini (Saturn)

Par.	Uncertainties
$\bar{s}_F$	8.6×10^{-11}
$\bar{s}_{TX}$	1.2×10^{-8}
$\bar{s}_G$	1.5×10^{-8}
$\bar{s}_H$	2.3×10^{-11}

- very good constraints expected compared to current limit[2]

⇒ results are promising and give motivations to do the analysis on real data...

[1] A. Hees, B. Lamine et al, CQG, 29/235027, 2012

[2] A. Hees, B. Lamine et al, proceedings CPT'13, 2013

Conclusion

- Testing GR in the solar system is very challenging but very important:
  - search for small deviations (smaller than present PPN accuracy)
  - search for deviations in extended frameworks

- Test of MOND External Field Effect with Cassini data[1]:

$$Q_2 = (3 \pm 3) \times 10^{-27}\ s^{-2}$$

Exclude a large part of relativistic MOND theories

- Simulations of SME for 2 situations[2,3]: Messenger and Cassini
  - sensitivity analysis performed: gives an idea of order of magnitude of constraints on SME parameters

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[1] A. Hees, W. Folkner et al, submitted, 2013
[2] A. Hees, B. Lamine et al, CQG, 29/235027, 2012
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