RHODES UNIVERSITY
Where leaders learn

Testing gravitation using asteroids observations with Gaia

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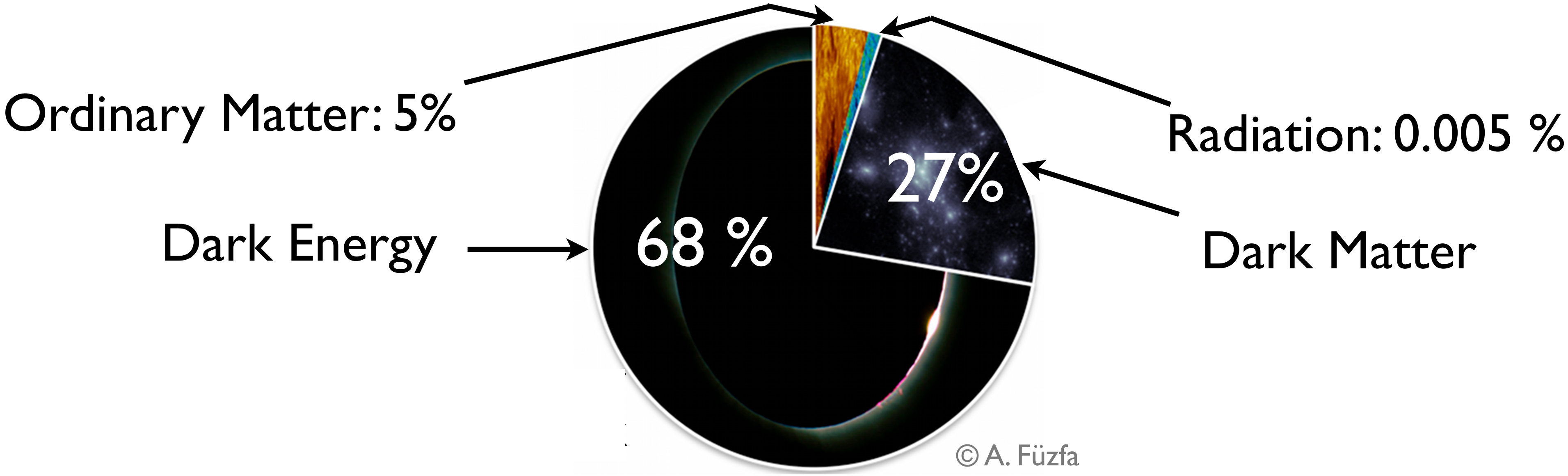
SF2A, GRAM session 2015
02/06/2015

l'Observatoire de Paris | SYRTE
Systèmes de Référence Temps-Espace

Motivations to test GR

- Quantum theory of gravity:
  - GR: classic theory (not a quantum theory)
  - at high energy: quantum effects should appear
  - useful to study black holes and the Planck Era
- Unification of all fundamental interactions: unify Standard model of particles with gravitation
- Cosmological and galactic observations required Dark Matter and Dark Energy: not directly observed so far ⇒ hints of a deviation from GR ?



Basic principles of GR

1) Equivalence Principle:

- 3 facets: Universality of free fall, Local Position/Lorentz Invariance
- very well tested (10^{-13} with Eötwash experiments and with Lunar Laser Ranging ; 10^{-4} with grav. redshift ; no variation of constants)[1]
- more accurate measurement needed: alternative (string) theories predict violation smaller[2] → MICROSCOPE accuracy 10^{-15}

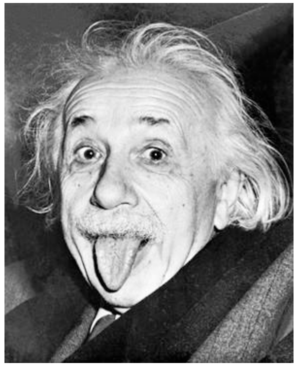
- Gravitation ⇔ space-time curvature (described by a metric $g_{\mu\nu}$)
- free-falling masses follow geodesics of this metric and ideal clocks measure proper time

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

[1] C. Will, LRR, 9, 2006

[2] T. Damour, CQG, 29-184001, 2012

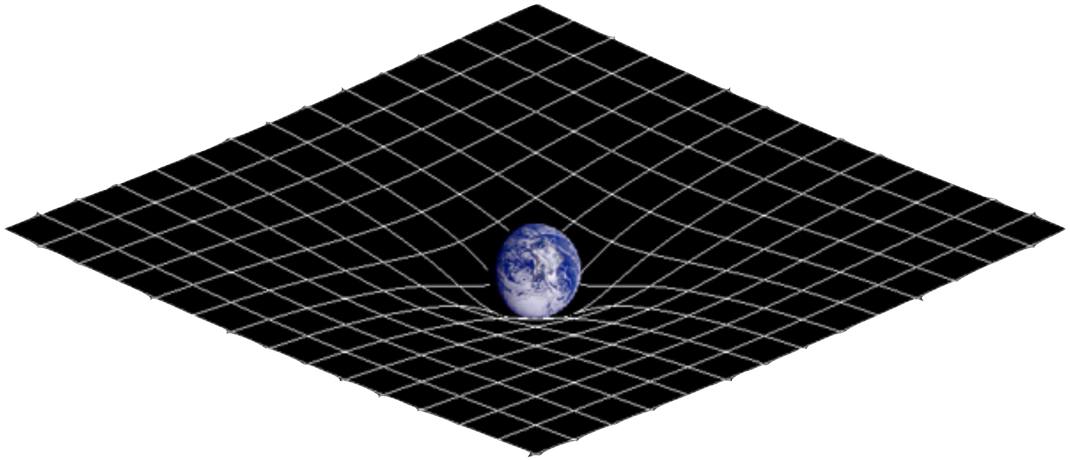
Basic principles of GR



II) Field equations (determination of the metric):

- Einstein Equations: $$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

space-time curvature (metric) ⇔ matter-energy content



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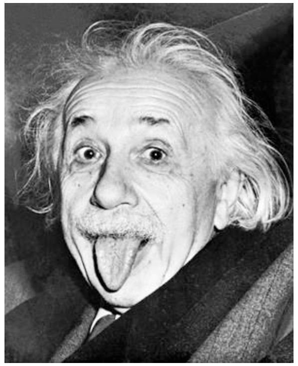

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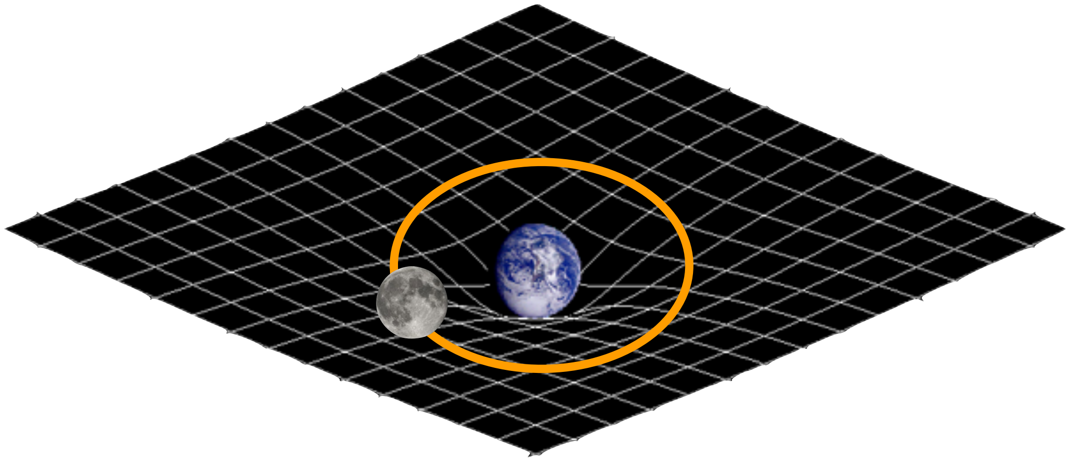

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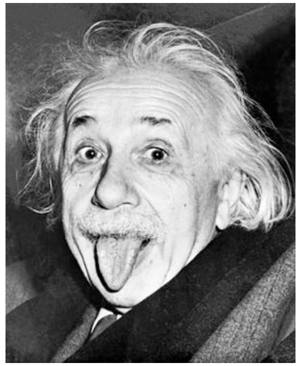

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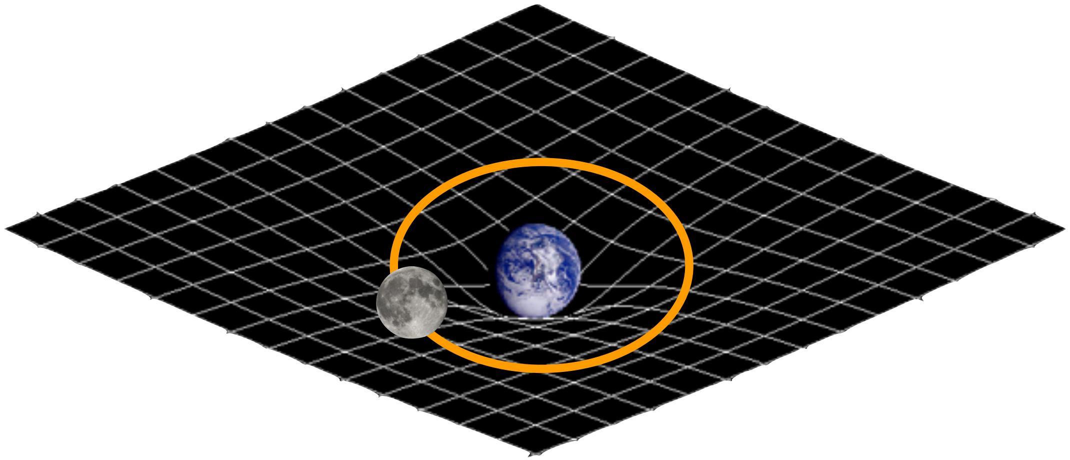

- important effects for space-mission:
  - dynamics ≠ from Newton (ex.: advance of the perihelion)
  - proper time (measured by ideal clocks) ≠ coordinate time
  - coordinate time delay for light propagation (Range/Doppler)
  - light deflection (VLBI, astrometry)

Tests of the gravitational dynamics

- How to test the form of the metric/the Einstein field equations ? Two frameworks widely used so far:

[1] C. Will, LRR, 9, 2006
"Theory and Experiment in Grav. Physics", C. Will, 1993

[2] E.G. Adelberger, Progress in Part. and Nucl. Phys., 62/102, 2009
"The Search for Non-Newtonian gravity", E. Fischbach, C. Talmadge, 1998

Tests of the gravitational dynamics

- How to test the form of the metric/the Einstein field equations ? Two frameworks widely used so far:

1) Parametrized Post-Newtonian Formalism[1]

  - powerful phenomenology making an interface between theoretical development and experiments
  - metric parametrized by 10 dimensionless coefficients
  - γ and β whose values are1 in GR

$$ds^2 = (1 + 2\phi_N + 2\beta\phi_N^2 + \dots)dt^2 - (1 - 2\gamma\phi_N + \dots)d\vec{x}^2$$

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II) Fifth force formalism[2]

- modification of Newton potential of the form of a Yukawa potential

$$\phi(r) = \frac{GM}{c^2 r}\left(1 + \alpha e^{-r/\lambda}\right)$$

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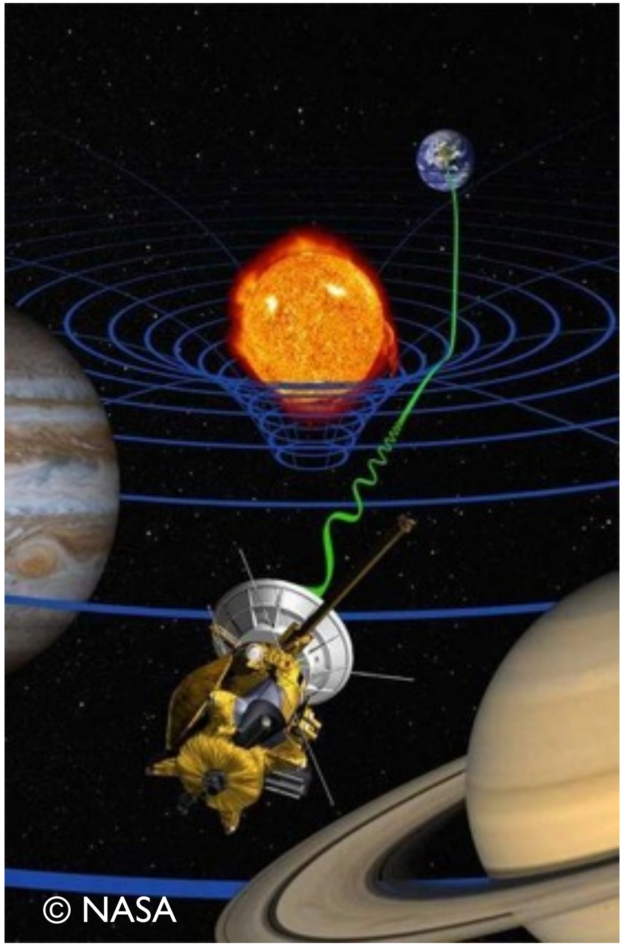
Constraints on PPN parameters

- Measurement of the Shapiro time delay with Cassini[1]

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



- Planetary ephemerides INPOP[2]

$$\beta - 1 = (0.2 \pm 2.5) \times 10^{-5}$$

- Dynamic of the orbit of the Moon with LLR[3]

$$\beta - 1 = (2.1 \pm 1.1) \times 10^{-4}$$

[1] B. Bertotti, L. Iess, P. Tortora, Nature, 425/374, 2003

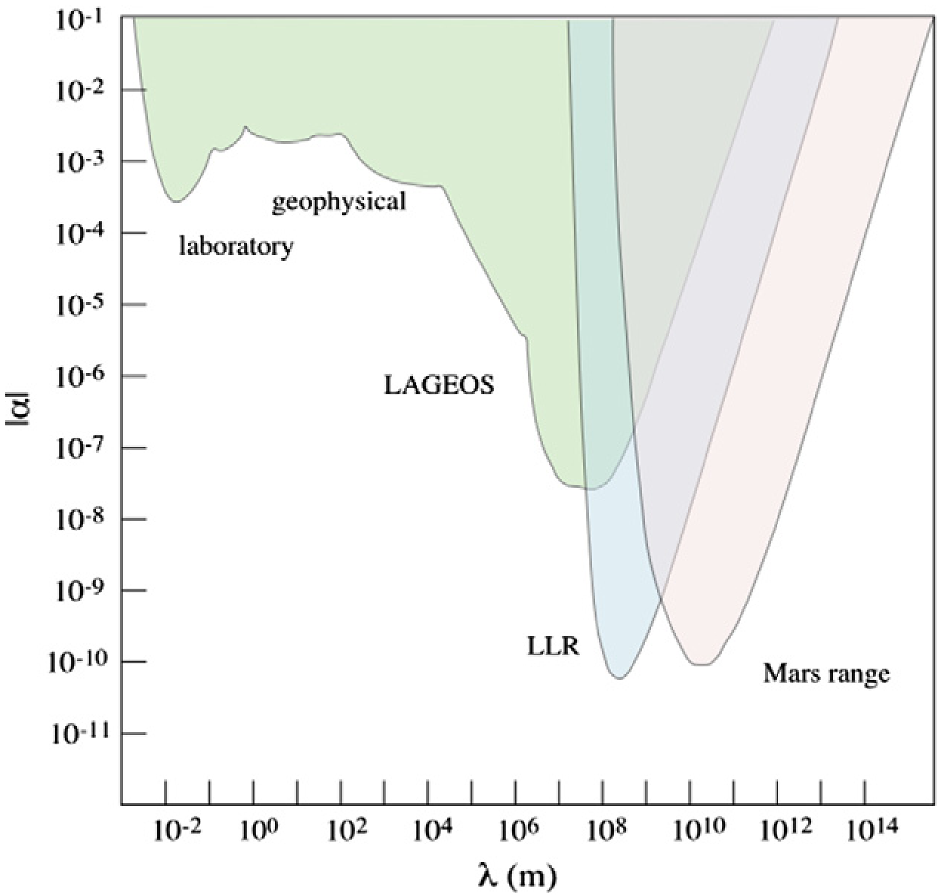
[2] A. Verma et al, A & A, 561, A115, 2014

[3] J. Williams, S. Turyshev, D. Boggs, IJMP D, 18/1129, 2009

Fifth force formalism

- Search for a deviation of the Newton potential of the form of a Yukawa potential[1] $\phi(r) = \frac{GM}{c^2 r}\left(1 + \alpha e^{-r/\lambda}\right)$

Excluded area for fifth force



- Very good constraints in this formalism except at small and large distances

from A.Konopliv et al, Icarus, 211/401, 2011

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Is it enough ?

- Still strong motivations to improve the current tests:
  - tensor-scalar theories "naturally" converging towards GR[1]
  - screening theories: modification of GR "hidden" in certain region of space-time: chameleons[2], symmetron[3], Vainshtein mechanism[4]
  - tensor-scalar theories with a decoupling of the scalar field[5]

We have strong motivations to pursue this kind of tests!

[1] T. Damour, K. Nordtvedt, PRD 48/3436 and PRL 70/2217, 1993
[2] J. Khoury, A. Weltman, PRD 69/044026 and PRL 93/171104, 2004
[3] K. Hinterbichler, et al, PRD84/103521 and PRL104/231301, 2010
[4] A. Vainshtein, Phys. Let. B, 39/393, 1972
[5] T. Damour, A. Polyakov, Nucl. Phys. B, 1994
O. Minazzoli, A. Hees, PRD 88/1504, 2013

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 : $\gamma, \beta, \ldots$~~

~~5th force formalism: α, λ~~

Is it necessary to go beyond ?

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

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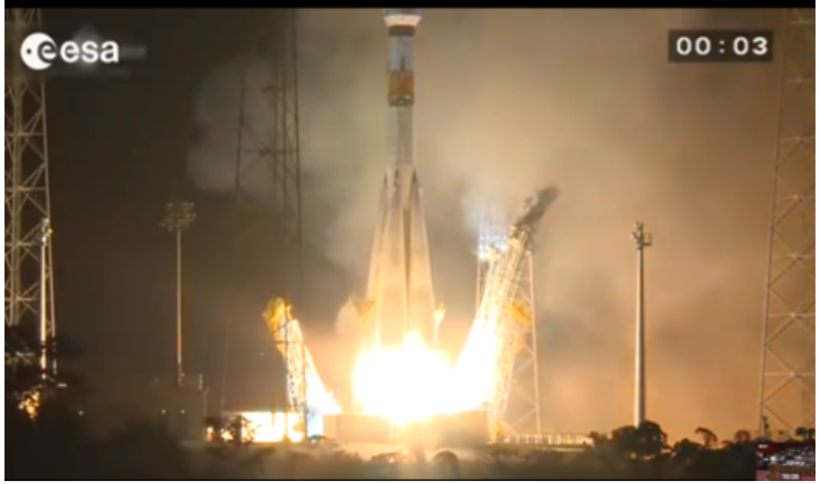
GAIA

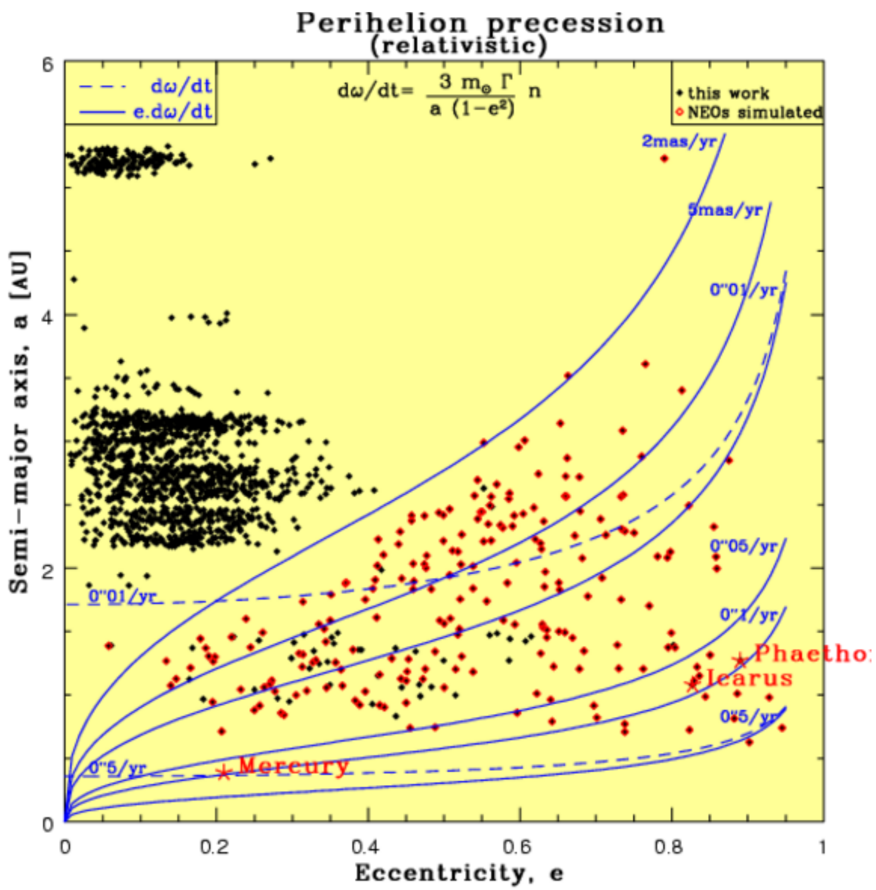


- Launched in December 19 2013
- Successor of Hipparcos, it will bring some huge improvements:
  - observation of ~ 1 billion stars, 3D mapping of our galaxy
  - parallax to 25 μas and proper motion to 15 μas/yr
  - colours from low resolution spectro-photometry
  - radial velocities from spectrometer
  - astrometric and photometric measurements for a large number of SSOs, mainly asteroids: high precision on a CCD basis

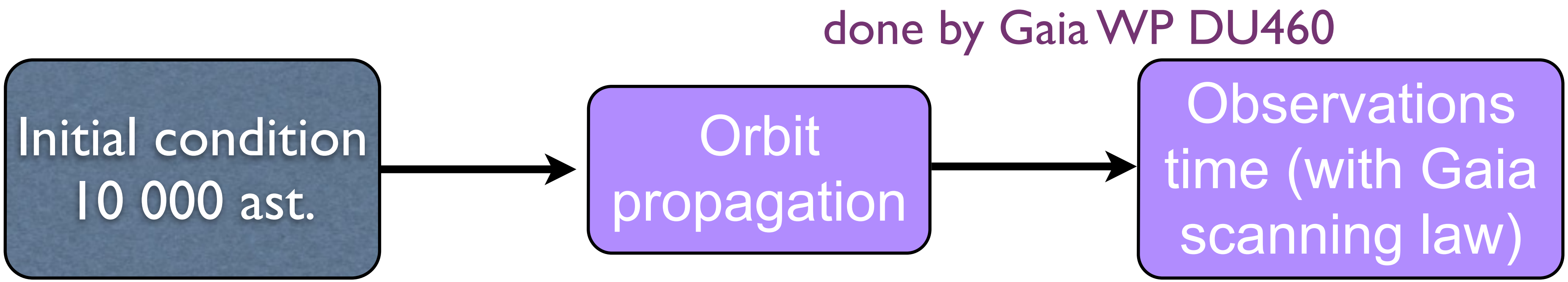
Asteroids: Gaia

- Use GAIA asteroid observations to test GR: advantage of a large samples of different orbital parameters (300 000 objects)
  - decorrelation of parameters
  - complementary to planetary ephemerides (different bodies, different type of observations, different method to analyze the data)

- accuracy ~ 0.2-0.5 mas



Simulations of Gaia observations



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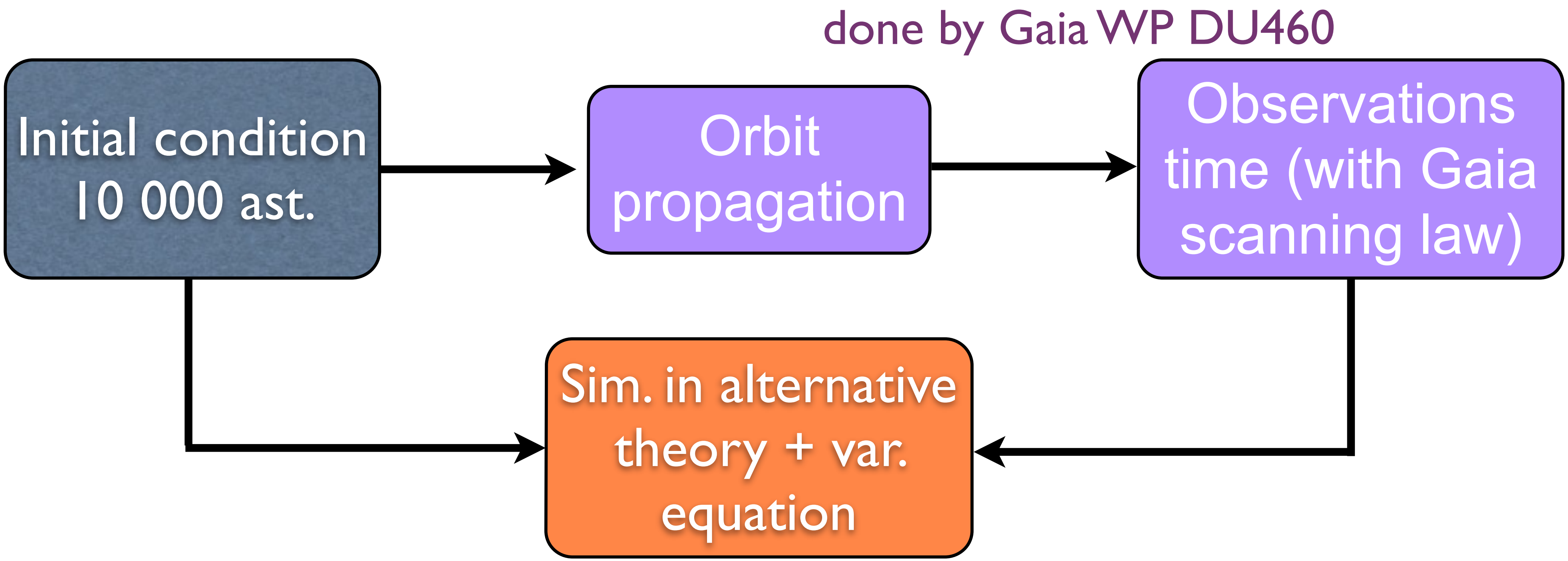

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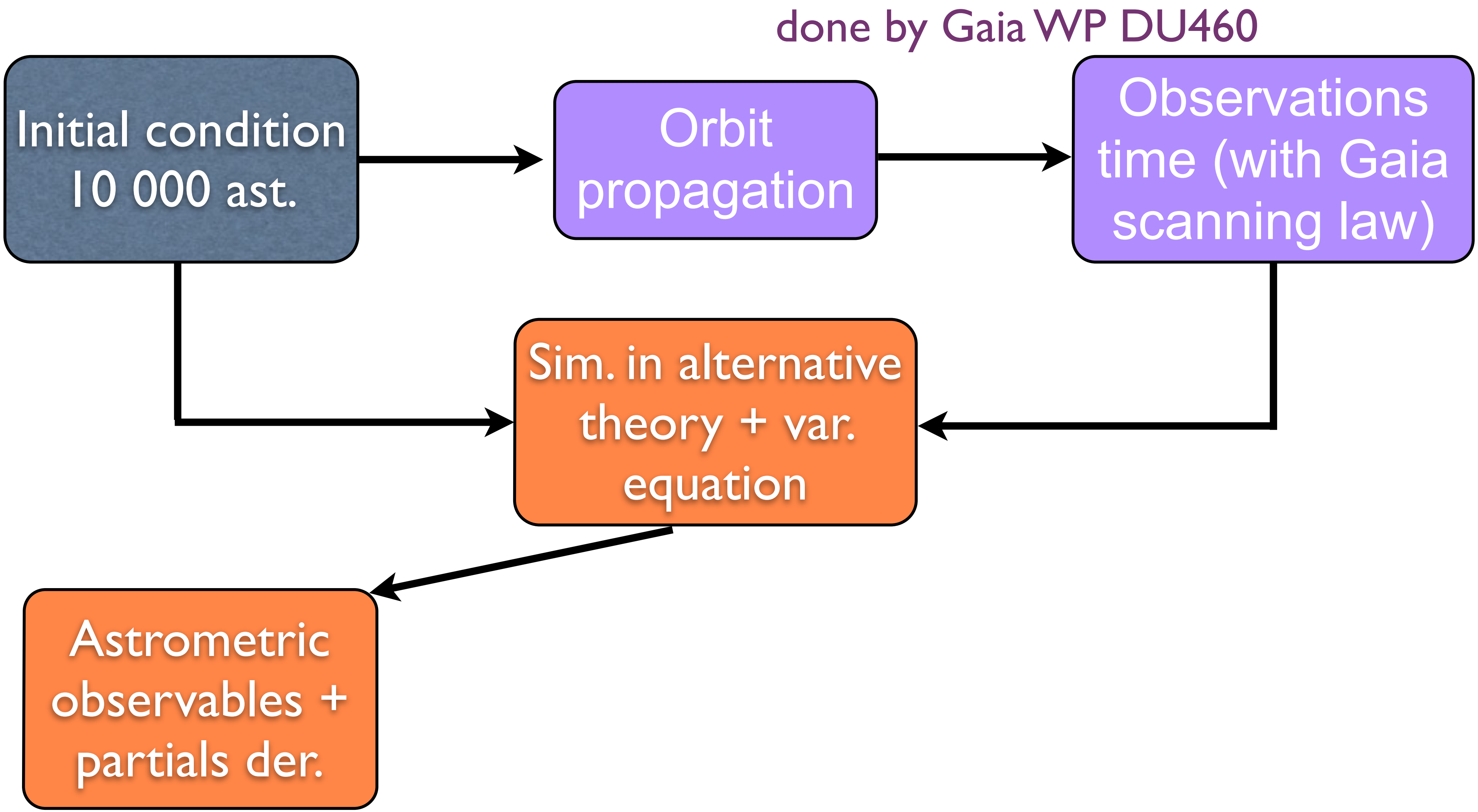
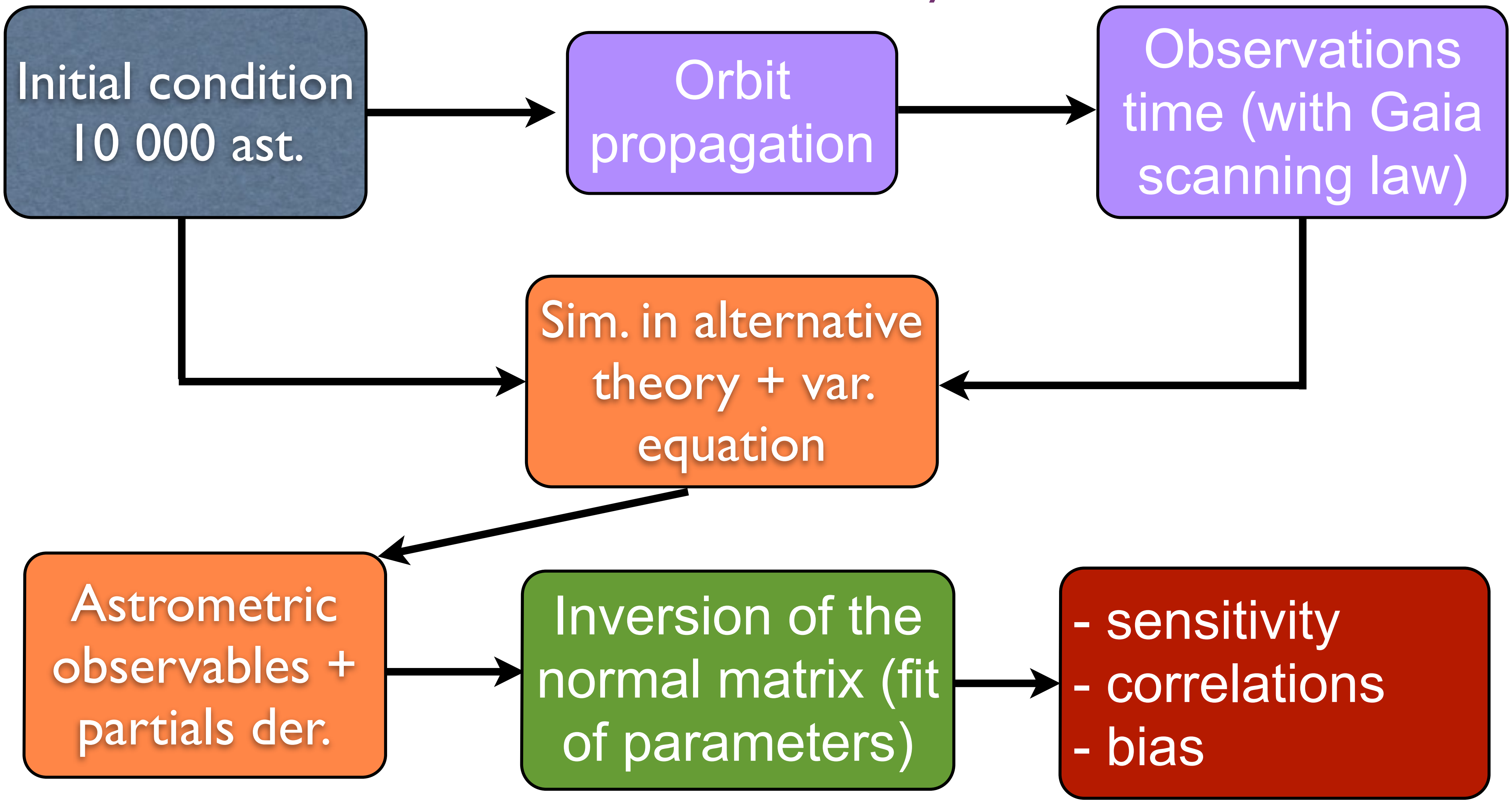


Simulations of Gaia observations

done by Gaia WP DU460



- local parameters (IC)
- global parameters (grav. theory, J_2, …)

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

PPN formalism and Sun J_2

- highly correlated parameters: one secular effect on orbital dynamics (advance of the perihelion)

$$\left\langle \frac{d\omega}{dt} \right\rangle = (2 + 2\gamma - \beta) n \frac{GM}{c^2 a(1-e^2)} + \frac{3}{2} n \frac{J_2 R^2}{a^2(1-e^2)^2}$$

- various asteroids orbital parameters help to decorrelate

- sensitivity:

	J_2	β
GAIA	$\sigma_{J_2} \sim 10^{-7}$	$\sigma_\beta \sim 7 \times 10^{-4}$
INPOP	$(2.24 \pm 0.15) \times 10^{-7}$	$(-0.25 \pm 6.7) \times 10^{-5}$

INPOP results from A. Fienga et al, arXiv:1409.4932, 2014

- correlation ~ 0.56

- Not as good as planetary ephemerides but: independent analysis, not suffering from the same systematics ⇒ interesting complementary check

Violations of the SEP

- All alternative theories of gravitation violate the Strong Equivalence Principle (SEP)
- The Universality of Free Fall is violated for self-gravitating bodies
- Nordtvedt effect parametrized by η

$$m_p = m_i + \eta \frac{E_{\text{grav}}}{c^2} \qquad\qquad m_i \vec{a} = m_p \vec{\nabla} U$$

see K. Nordtvedt, Phys. Rev., 169, 1014, 1968

- sensitivity: 9x10-4 . The only actual constraint comes from LLR

$$\eta = (4.4 \pm 4.5) \times 10^{-4}$$

see J. Williams et al, IJMPD, 18, 1129, 2009

- NO correlation with J_2 or β PPN

The SEP can help to decorelate J_2 and β

- In the PPN framework $$\eta = 4\beta - \gamma - 3$$

see C. Will, "Theory and Experiment in Gravitational Physics", 1993

- Instead of estimating 3 independent parameters: J_2, β, η, we can use the above relation to estimate only 2 parameters: J_2 and β

	J_2	β	ρ
GAIA (no SEP)	$\sigma_{J_2} \sim 10^{-7}$	$\sigma_\beta \sim 7 \times 10^{-4}$	0.55
GAIA (with SEP)	$\sigma_{J_2} \sim 9 \times 10^{-8}$	$\sigma_\beta \sim 2 \times 10^{-4}$	0.18
INPOP	$(2.24 \pm 0.15) \times 10^{-7}$	$(-0.25 \pm 6.7) \times 10^{-5}$	-

- using the relation between η and β allows to improve the sensitivity but reduce significantly the correlation !

- Similar result expected for planetary ephemerides (η never been considered so far)

Lense-Thirring effect

- Relativistic frame dragging effect produced by the rotation of a body (Sun or Earth)
- Detected with the orbit of LAGEOS spacecraft @ the level of 10% (controversy between L. Iorio and I. Ciufolini)

see Ciufolini et al, Nature 431, 958, 2004
L. Iorio et al, APSS 331, 351, 2011

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- Lense-Thirring impossible to be estimated in planetary ephemerides: completely correlated with J_2

  see W. Folkner et al, IPN Prog. Rep. 42, 196, 2014

- Asteroids can decorrelate but Gaia does not have enough accuracy!
- But… not including the LT in the modeling leads to bias:

- 10^{-8} on the J_2 (i.e. 10% of its value)

- 5×10^{-5} on the β PPN

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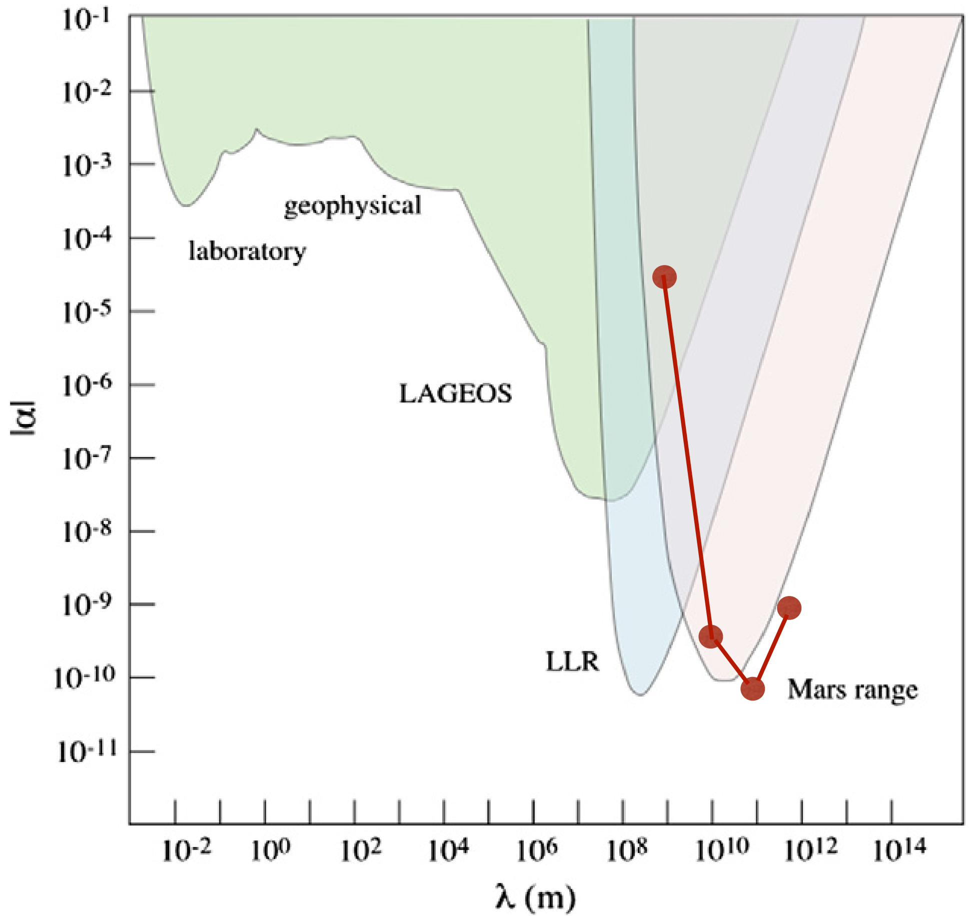
- 10^{-8} on the J_2 (i.e. 10% of its value)

- $5\mathrm{x}10^{-5}$ on the β PPN

Similar conclusions seem to hold for planet. ephem. !

Fifth force

- Use GAIA asteroid observations to constrain the 5th force parameters



- correlation with Sun mass to be assessed

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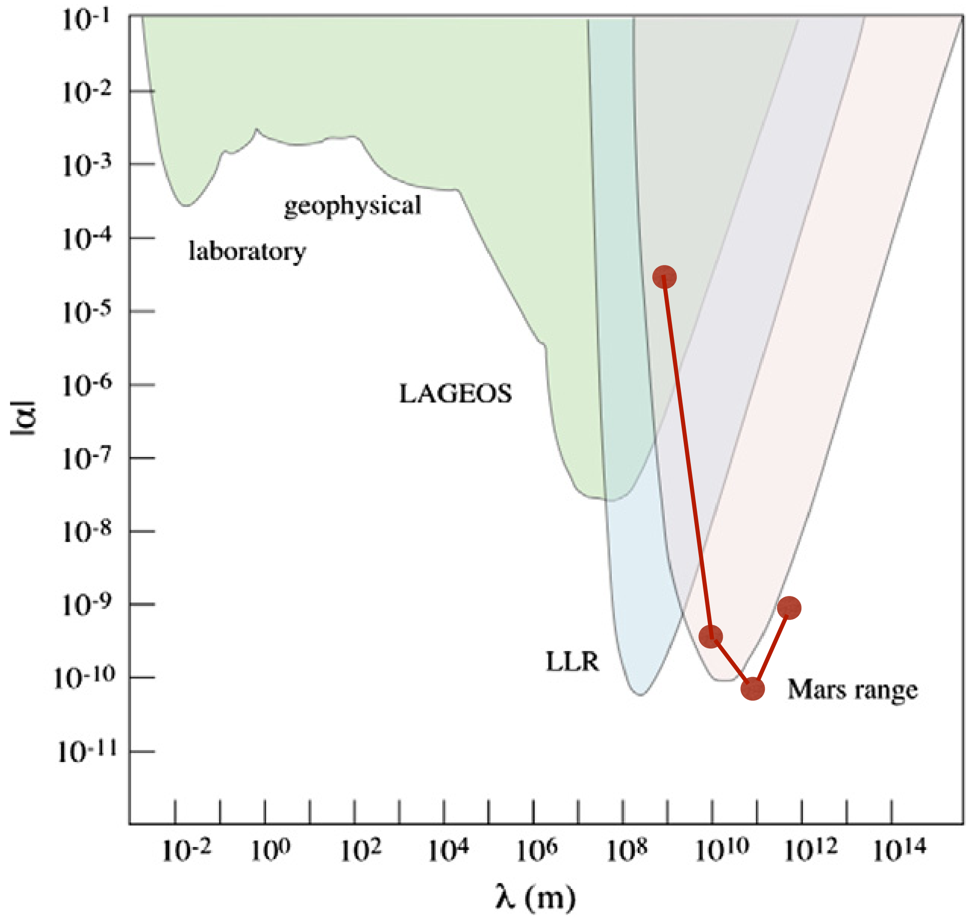

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Standard Model Extension (SME)

- Recent phenomenology developed to consider hypothetical violations of the Lorentz invariance in all sector of physics — violations coming from a more fundamental theory (string theory, loop quantum gravity, non-commutative theory, …)

- Pure gravity sector[1] depends on 8 parameters $\bar{s}^{\mu\nu}$: Lagrangian based approach (vs PPN based on the metric). The metric does not enter PPN formalism

- Quite few analysis in SME framework: LLR and atom interferometry[2]

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}	$(-1.3 \pm 4.1) \times 10^{-7}$

[1] Q. Bailey, V.A. Kostelecky, PRD, 74/045001, 2006

[2] J. Battat, J. Chandler, C. Stubbs, PRL, 99/241103, 2007
K. Chung, et al, PRD, 80/016002, 2009

SME and asteroids

- Main advantage: decorrelation of the SME parameters
- Sensitivity on the 8 independent parameters

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 constraints

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- Correlations between 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

reasonnable correlations

SME and asteroids

- First possibility to decorrelate all parameters
- Analysis done including the Sun J_2: similar results ; J_2 decorrelates as well
- Improvement by ~ 1 order of magnitude wrt current constraints
- Need to extend the study to include "gravity-matter SME coupling" (more parameters that include violation of the equivalence principle)

Very promising results expected

Time variation of G

- A lot of alternative theories of gravitation induce a time variation of G (tensor-scalar theory for example)
- Constraining a linear variation in G is standard: $\dot{G}/G$
- Sensitivity for GAIA: 10^{-12} per year
- Current constraint: $\dot{G}/G = (0.5 \pm 1.6) \times 10^{-13} \mathrm{yr}^{-1}$

INPOP results from A. Fienga et al, arXiv:1409.4932, 2014

$$\dot{G}/G = (0.1 \pm 1.6) \times 10^{-13} \mathrm{yr}^{-1}$$

DE results from A. Konopliv et al, Icarus 211, 401, 2011

Periodic variation of G

- Very recent temporal analysis of G measurements seem to indicate a periodic variation

$$G(t) = \bar{G} + A \sin\left(2\pi \frac{t - t_0}{T}\right)$$

- first estimation by Anderson et al — J. Anderson, et al, Eur. Phys. Letters 110, 10002, 2015
- more careful analysis by Schlamminger et al — S. Schlamminger et al, arXiv:1505.01774, 2015

Fit function	T (years)	$A \times 10^{15}$ ($\mathrm{m^3\,kg^{-1}\,s^{-2}}$)	$\bar{G} \times 10^{11}$ ($\mathrm{m^3\,kg^{-1}\,s^{-2}}$)	Maximum
from Fig. 1 in [1]	5.93	16.1	6.673 88	09/13/01
sine, fixed T	5.93	10.7	6.673 59	03/14/01
sine, T free	0.77	11.2	6.673 58	02/21/00
sine, T free	6.17	11.0	6.673 54	02/13/01
straight line	n.a.	n.a.	6.674 13	n.a.

- Gaia sensitivity around ~ 10^{-20} for the amplitude, no correlation with Sun J_2.

- Planetary ephemerides can be used to constrain severely this effect

L. Iorio, arXiv:1504.07233, 2015

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 (SME is one of them)

- Asteroids observations with GAIA offer nice opportunities to probe orbital dynamics
  - large number of orbital parameters: nice to deal with correlations
  - different and independent constraints from planetary ephemerides

- Sensitivity assessed for different alternative gravity framework: PPN parameters, fifth force, SME, variation of G, …

- In the longer term, combining GAIA observations with UCLA radar data may improve the results: complementary observations — currently under investigation

see J.L. Margot and J. Giorgini, proceedings of IAU symp. 261, 2010

BACK UP SLIDES

Basic principles of GR

1) Equivalence Principle: the future…

- theoretical motivations to improve these: string theory, Kaluza-Klein, theories with variable fundamental constants ("principle of absence of absolute structure"), "anthropic principle", ...

for a review, see T. Damour, CQG, 29-184001, 2012

- Universality of Free Fall:
  - Microscope: launch in April 2016; test at 10^{-15} see G. Metris's talk
  - Galileo Galilei: Italian proposal; test at 10^{-17}
  - STE-QUEST: ESA proposal; quantum test at the level of 10^{-15}

- Local Position Invariance - gravitational redshift:
  - ACES: launch in 2016; test at 10^{-6}
  - Galileo 5 and 6 GNSS satellites: failed launched eccentric orbit appropriate for redshift tests (comparison of onboard clocks to clocks on Earth). Full sensitivity study (stochastic noise and systematics): sensitivity at 2×10^{-5} with one year of data

see Delva P., Hees A., et al, proceedings of Moriond 2015 and coming publication