Local tests of gravitation with Solar System Objects

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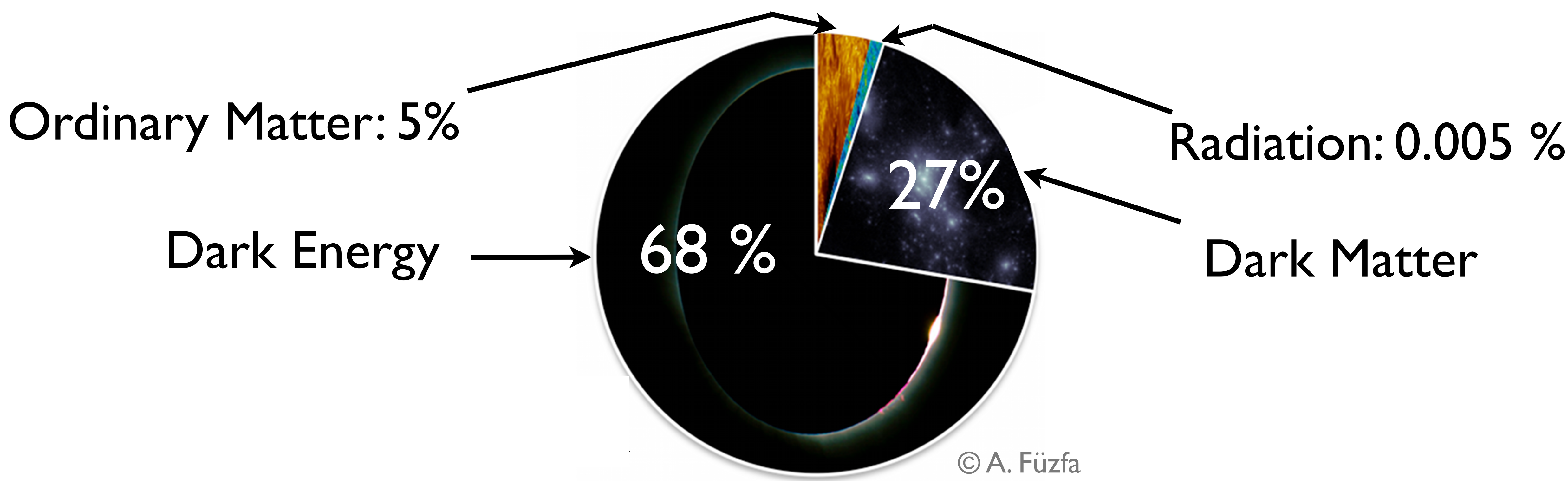
Systèmes de Référence Temps-Espace

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 ?



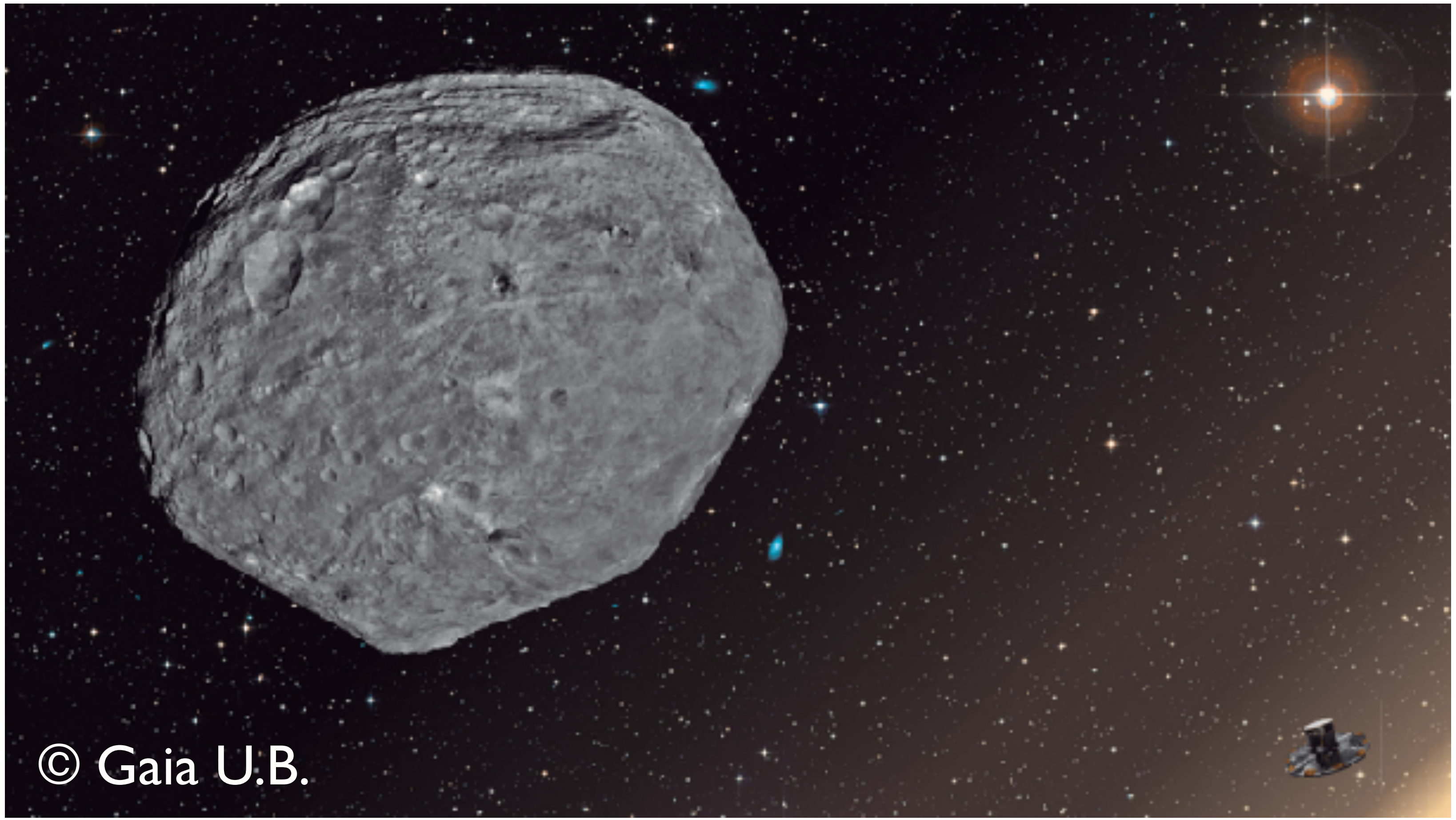
Gaia will offer two ways to test GR

measurement of the light deflection by the Sun & planets

probing space-time with massless particles: spatial and temporal part of metric

orbital dynamics of Solar System Objects

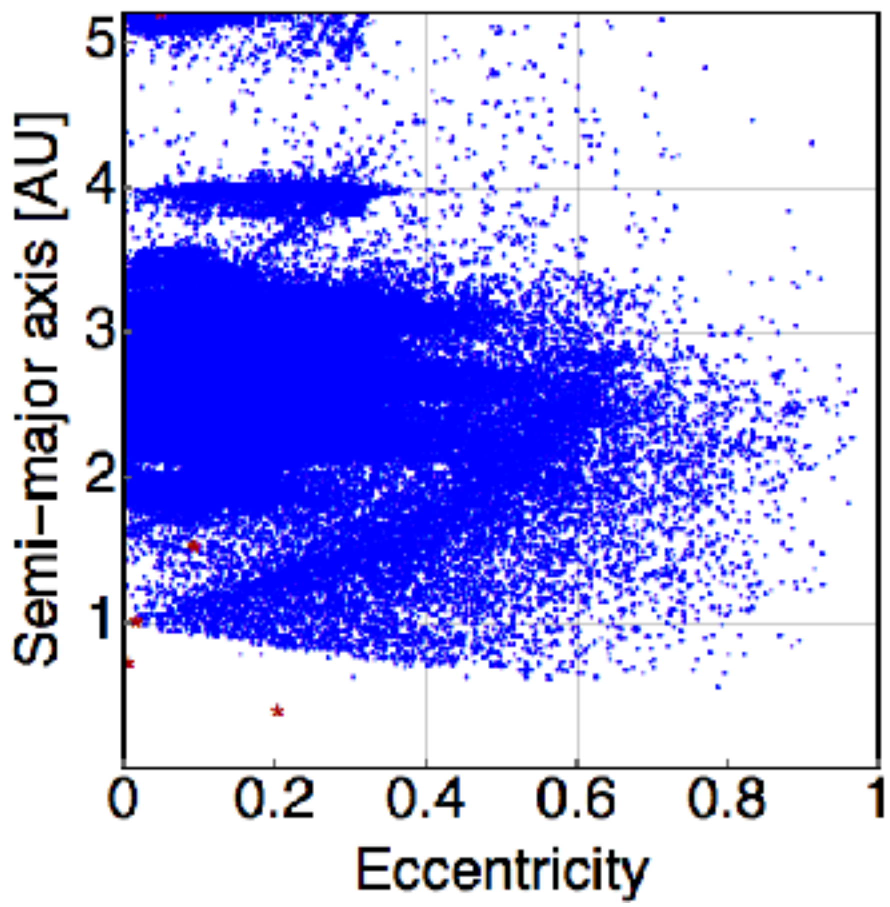
probing space-time with massive test bodies: mainly spatial part of metric

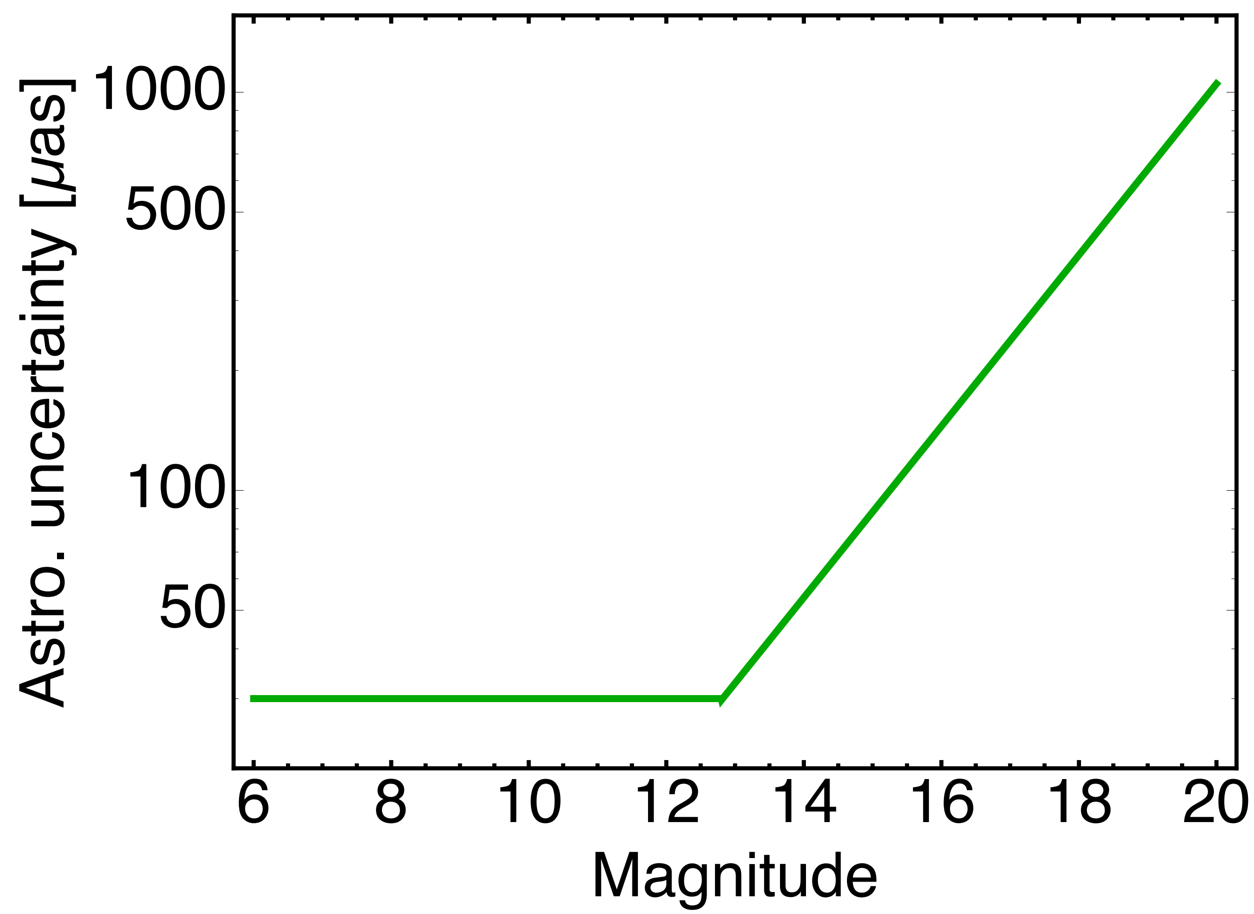


Gaia will observe ~400 000 SSO's

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

- Uncertainty used in simulations depends on magnitude

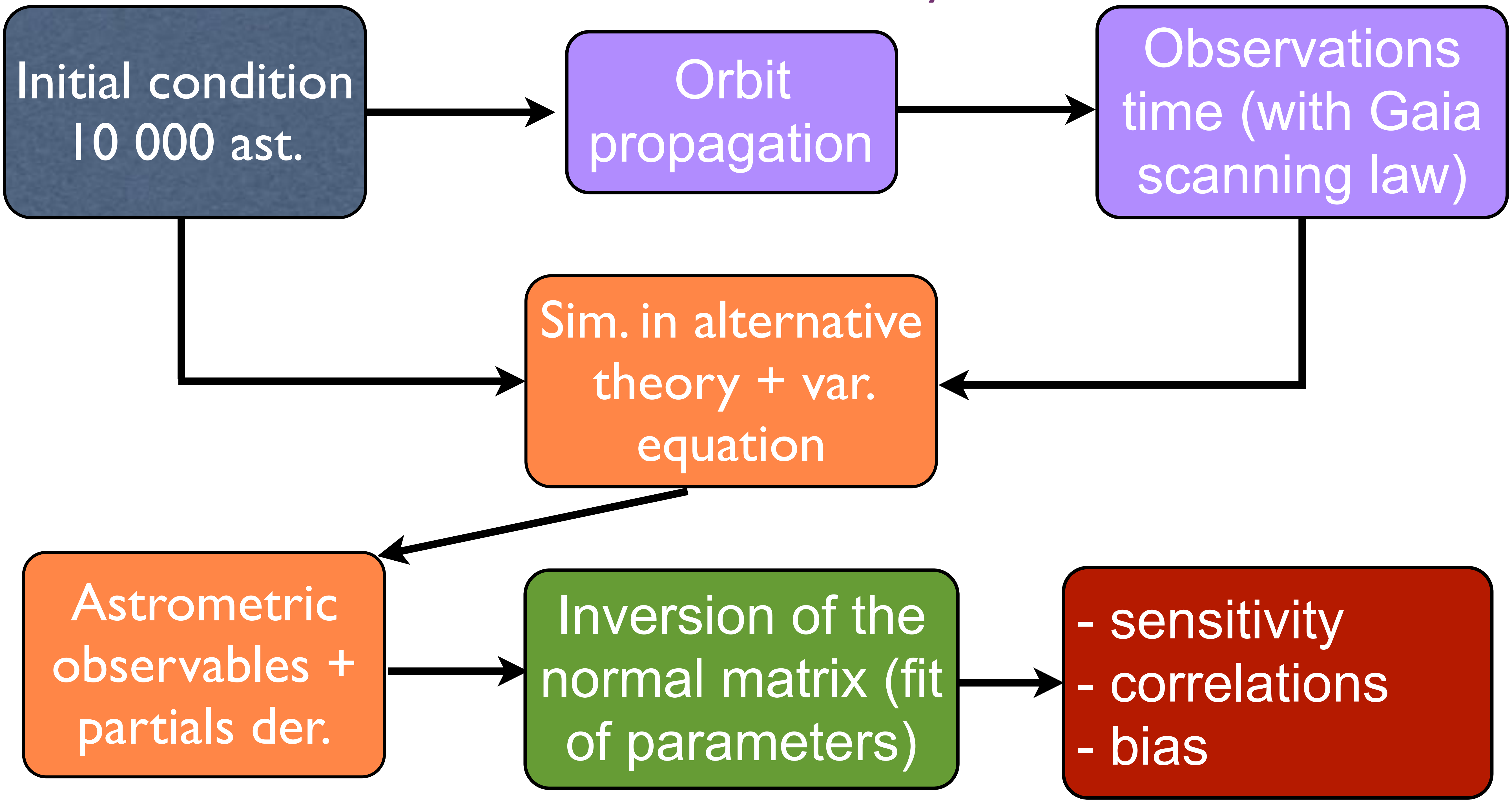




- Simulations done for 5 years and also for 10 years (extended mission)

Simulations of Gaia observations

done by Gaia WP DU460



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

Similar to what is done in Mouret, PRD, 2011

Different ways to test GR with Gaia

- With the Parametrized Post-Newtonian formalism (PPN)
- Using the fifth force formalism
- Testing Lorentz symmetry
- The Lense-Thirring effect

The PPN formalism has been widely used to test GR in weak field

see C. Will, LRR, 2014

- Powerful phenomenology: interface between theoretical development and observations
- metric parametrized by 10 dimensionless coefficients
- these coefficients can be matched in some alternative theories of gravitation: Brans-Dicke, Tensor-Vector-Scalar, …

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

Orbital dynamics

Gaia: @10^{-6} with light deflection

PPN formalism and Sun J_2

- highly correlated parameters: secular effect on orbital dynamics

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

- various asteroids orbital parameters help to decorrelate

- sensitivity:

	J_2	β
GAIA [5yr]	$\sigma_{J_2} \sim 5 \times 10^{-8}$	$\sigma_\beta \sim 4 \times 10^{-4}$
GAIA [10yr]	$\sigma_{J_2} \sim 1.5 \times 10^{-8}$	$\sigma_\beta \sim 10^{-4}$
INPOP	$(2.22 \pm 0.13) \times 10^{-7}$	$(0.0 \pm 6.9) \times 10^{-5}$

- correlation ~ 0.4

INPOP results from A. Fienga et al, Cel. Mech. Dyn. Astro. 2015

- complementary to planetary ephemerides: different analysis, not the same systematics

- Interesting: combined fit Gaia + planets

Test of the SEP can help to decorrelate β and J_2

- SEP: Universality of free fall violated for self-gravitating body

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

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

- Gaia can constrain η at 3×10^{-4} [3×10^{-5} if extended mission] while the current best constraint from LLR is $\eta = (4.4 \pm 4.5) \times 10^{-4}$

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

- In the PPN formalism $\eta = 4\beta - \gamma - 3$ helps to estimate β

	J_2	β
GAIA [5yr]	$\sigma_{J_2} \sim 4 \times 10^{-8}$	$\sigma_\beta \sim 8 \times 10^{-5}$
GAIA [10yr]	$\sigma_{J_2} \sim 1.3 \times 10^{-8}$	$\sigma_\beta \sim 8 \times 10^{-6}$
INPOP	$(2.22 \pm 0.13) \times 10^{-7}$	$(0.0 \pm 6.9) \times 10^{-5}$

no correlation remaining

INPOP results from A. Fienga et al, Cel. Mech. Dyn. Astro. 2015

- Considering a violation of the SEP reduces σ_β by a factor 5

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A fifth force is a well motivated phenomenology

- deviation from Newtonian gravity characterized by a Yukawa potential

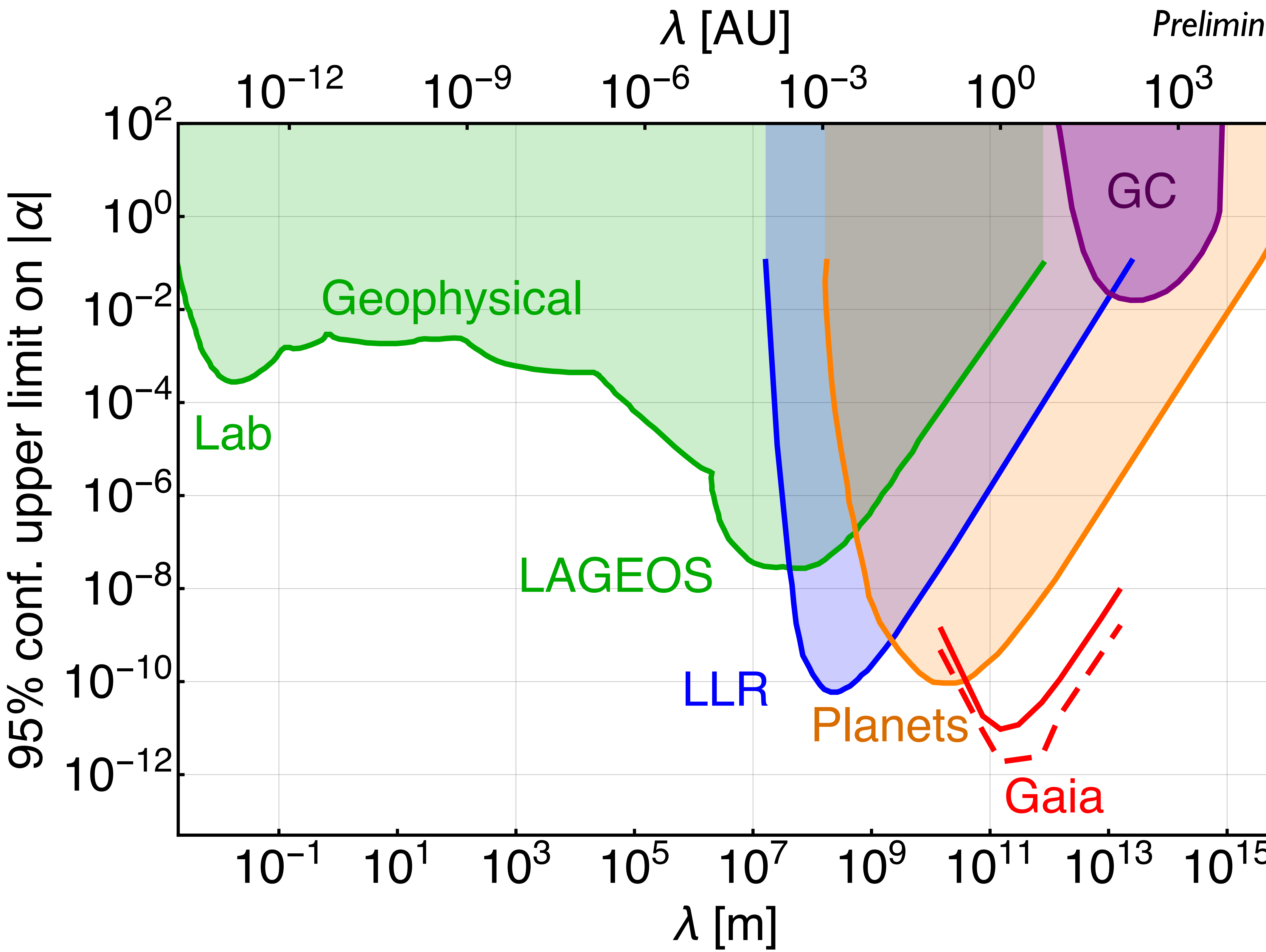
$$\phi(r) = \frac{GM}{c^2 r}\left(1 + \alpha e^{-r/\lambda}\right)$$

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

- Phenomenology motivated by
  - new interaction with a massive gauge boson   Fischbach and Talmadge, Nature, 1989
  - high dimension theories   Krause and Fischbach, arXiv: hep-ph/9912276
  - Braneworld scenarios   Arkani-Hamed, et al, PRD, 1999
  - massive gravity   Will, PRD, 1998
  - massive tensor-scalar theory   Alsing, et al, PRD, 2012
  - ...

A fifth force can be tested with Gaia

Preliminary results



correlation with the Sun GM needs to be assessed carefully

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Some fundamental unified theories break Lorentz symmetry

- like e.g.: strings, noncommutative space-time, loop quan. theory
- General framework to study Lorentz violation:

  Standard-Model Extension (SME)

  developped by Kostelecky and collaborators in the 90ies

- SME is an effective field theory developed from a Lagrangian

$$\mathcal{L} = \underbrace{\mathcal{L}_{\mathrm{SM}}}_{\text{standard model}} + \underbrace{\mathcal{L}_{\mathrm{GR}}}_{\text{General Relativity}} + \mathcal{L}_{\mathrm{LV}}$$

All possible Lorentz violating terms constructed from SM & GR fields and background coefficients

Credit to Q. Bailey

The gravity sector of the minimal SME introduces 9 coefficients

- minimal SME = linearized gravity limit $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

$$\mathcal{L}_{\rm LV} = \frac{c^3}{32\pi G} h^{\mu\nu} \bar{s}^{\alpha\beta} \mathcal{G}_{\alpha\mu\nu\beta} + \dots$$

STF tensor: 9 Lorentz-violating coefficients

non-minimal higher order terms

See Kostelecky, PRD, 04 - Bailey and Kostelecky, PRD, 06 - Kostelecky and Mewes, PLB, 16

- this modifies the equations of motion

$$\left[\frac{d^2x^j}{dt^2}\right]_{\rm SME} = \frac{GM}{r^3}\left[\bar{s}^{jk} r^k - \frac{3}{2}\bar{s}^{kl}\frac{r^k r^l}{r^2} r^j + 2\bar{s}^{0k}\frac{v^k}{c} r^j - 2\bar{s}^{0j}\frac{v^k}{c} r^k + \dots\right]$$

- Already constrained by: LLR, pulsars, VLBI, atom interferometry, etc ...

Bourgoin et al., PRL, 2016

Le Poncin-Lafitte at al., PRD, 2016

for a review of the tests of SME in gravity sector, see Hees et al, Universe, 2016

Gaia is very powerful to constrain SME

- Main advantage: decorrelation of the 9 SME parameters because of the variety of orbital parameters (not feasible with planets)

SME Parameter	1σ - 5yr	1σ - 10yr
$\bar{s}^{XX} - \bar{s}^{YY}$	3.7×10^{-12}	6.5×10^{-12}
$\bar{s}^{XX} + \bar{s}^{YY} - \bar{s}^{ZZ}$	6.4×10^{-12}	2.1×10^{-12}
$\bar{s}^{XY}$	1.6×10^{-12}	7.0×10^{-13}
$\bar{s}^{XZ}$	9.2×10^{-13}	3.7×10^{-13}
$\bar{s}^{YZ}$	1.7×10^{-12}	5.8×10^{-13}
$\bar{s}^{TX}$	5.6×10^{-9}	1.1×10^{-9}
$\bar{s}^{TY}$	8.8×10^{-9}	2.0×10^{-9}
$\bar{s}^{TZ}$	1.6×10^{-8}	4.0×10^{-9}

1 order of magnitude improvement wrt current constraints

- To be extended to take into account violations of the Einstein Equivalence Principle (gravity-matter Lorentz violating terms)

Extremely promising results !

see Hees et al, Universe, 2016

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Lense-Thirring effect due to the Sun

- Relativistic frame dragging effect produced by the rotation of a body (due to the Spin S)

- impossible to estimate the Sun Lense-Thirring with planetary ephemerides: completely correlated with J_2 see W. Folkner et al, IPN, 2014

- Asteroids can decorrelate but Gaia not powerful enough

$$\frac{\sigma_S}{S} \sim 6.5 \quad [1.7 \text{ for } 10\text{yr}]$$

- Combination with radar observations to be considered

- 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

Conclusion

- GR is probably not the ultimate theory of gravitation
  Need for observations to constrain/detect new physics
- SSO's observations with Gaia offer a new opportunity to probe spacetime (PPN, fifth force and SME formalisms considered)
  large number of orbital par. reduce some correlations
- In the longer term, combining *GAIA observations with UCLA radar data* may improve the results: complementary observations in time but also gives access to the 3rd dimension

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

Interesting GR tests can be expected from these observations