High Accuracy Astrometry and fundamental physics with Gaia

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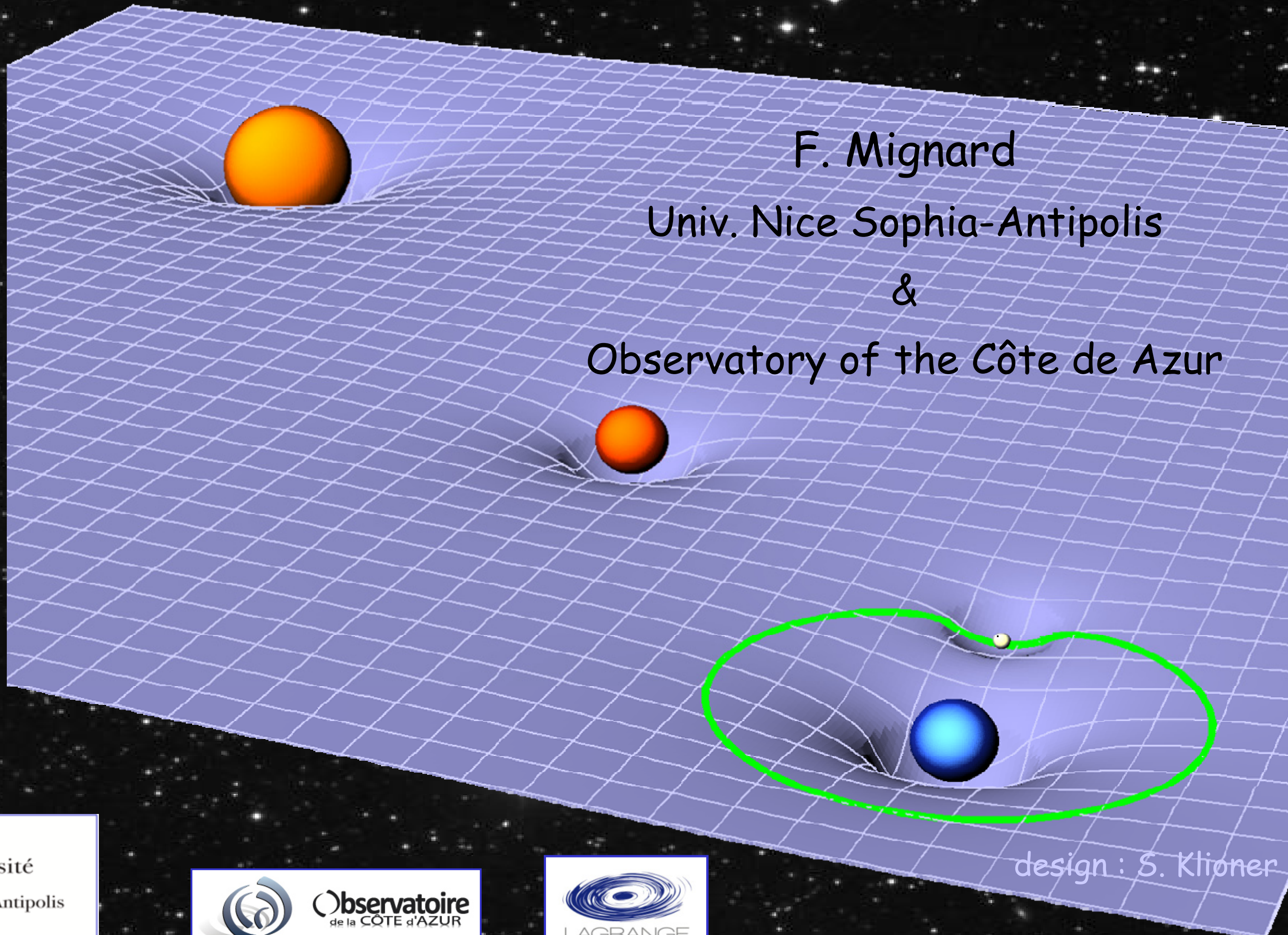
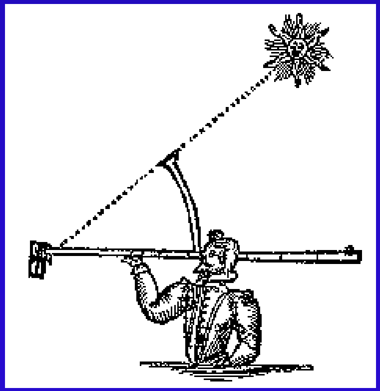
&

Observatory of the Côte de Azur



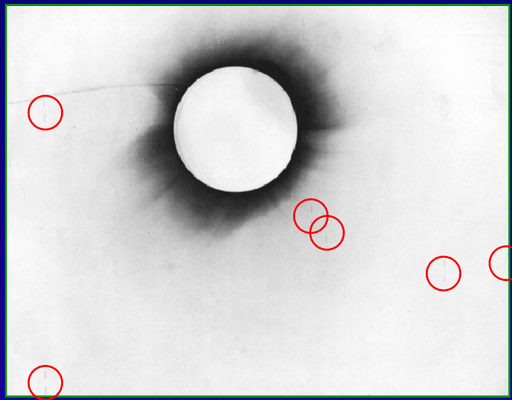
What is meant by Astrometry ?

- Astrometry deals with the measurement of the positions and motions of astronomical objects on the celestial sphere.
- Astrometry relies on specialized instrumentation, observational and analysis techniques.
- It is fundamental to all other fields of astronomy
- It is as old as astronomy !
- The field is totally renewed by access to space
  - Hipparcos and soon Gaia

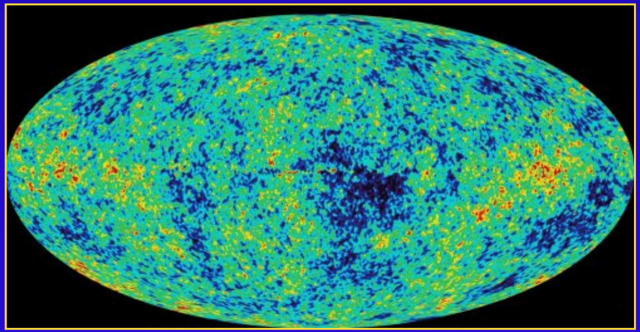


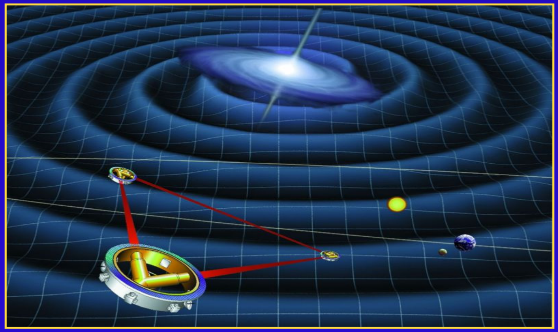
Fundamental Physics

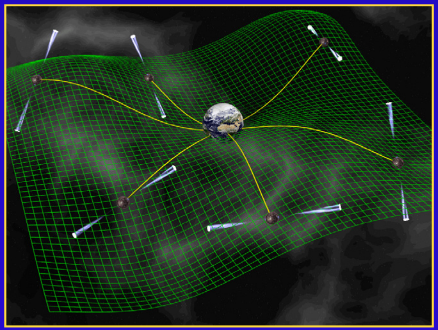
- Relevant topics
  - Very variable according to historical periods
    - dominated by the law of motion, covariance of physical laws under reference frame transformation
  - Closely associated to astrometric accuracy
    - but not only ➔ eg COBE/WMAPS/PLANCK

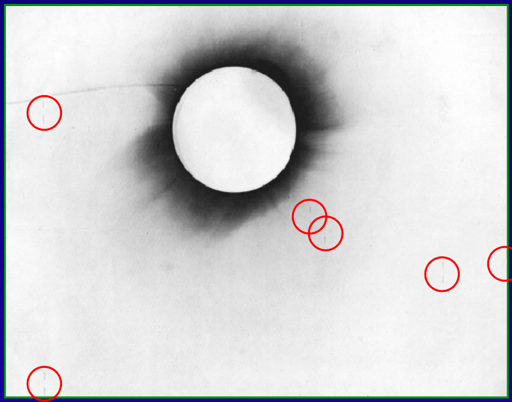


- Astronomy can provide clues only on large distance scale
  - 100 -1000 km — Earth satellites
  - 10^8 – 10^9 km — Solar System
  - pc – kpc — Stellar system in the MW
  - Mpc — Local group
  - Gpc — QSOs, CMB, SN1a









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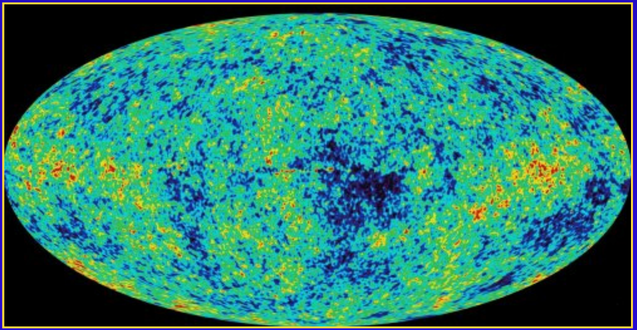
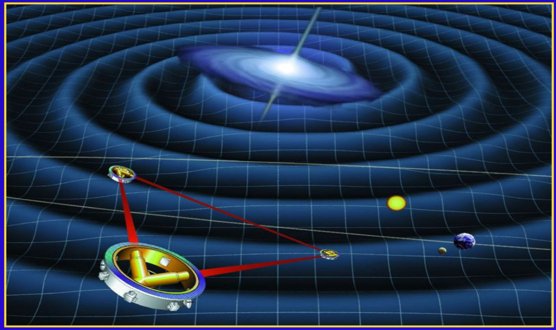
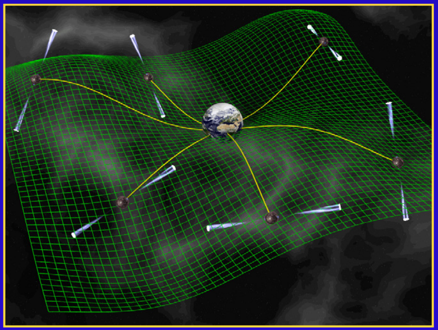






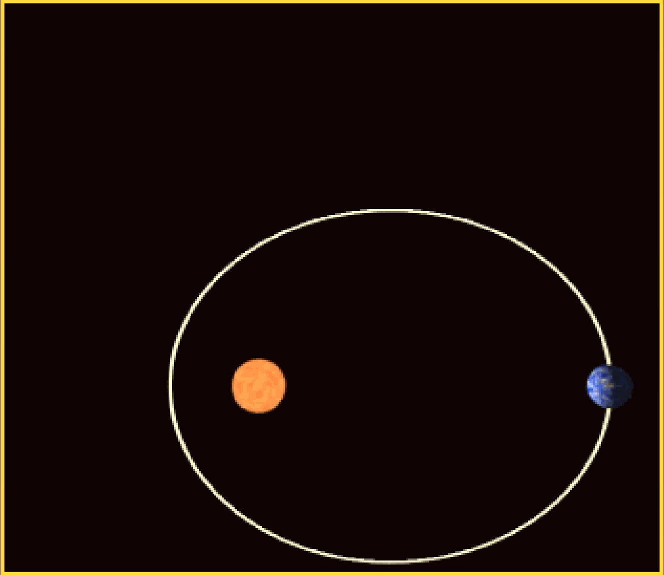
Astrometry ➔ Fundamental laws

Kepler Laws	1610	Kepler
Finite speed of light	1676	Roemer →
Gravitation theory – $1/r^2$ law	1700	Newton
Aberration of Light	1727	Bradley
Universal Gravitation	1827	Savary
Orbit of Mercury	1850	LeVerrier
Light deflection by the Sun	1919	Eddington
Recession of galaxies	1925	Hubble
Radar echo delay	1970	
Superluminuous radiation	1980	
Einstein rings and lensing.	1980	
Orbital evolution of the binary pulsar	1982	
Strong Equivalence Principle (LLR)	1990	
Dark matter in Galactic clusters	1990	

Assumptions in Newtonian Gravity

- Laws of motion

$$m_a \frac{d^2 \mathbf{x}_a}{dt^2} = -\sum_{b \neq a} G m_a m_b \frac{\mathbf{x}_a - \mathbf{x}_b}{\left|\mathbf{x}_a - \mathbf{x}_b\right|^3}$$

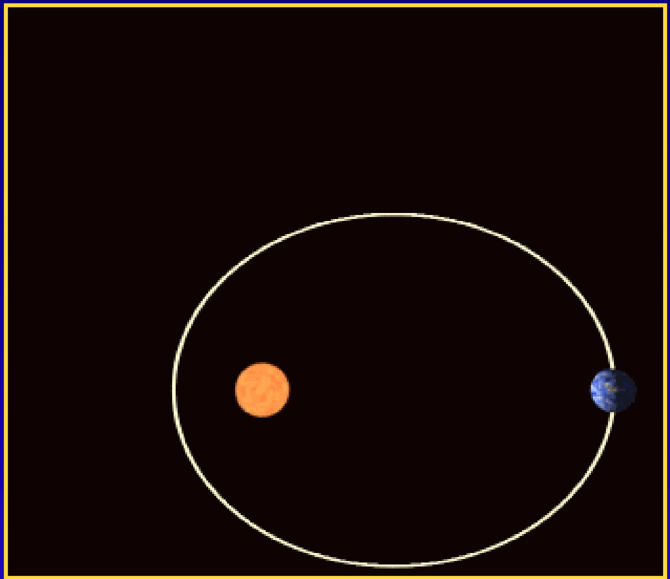


- … few subtleties

Assumptions in Newtonian Gravity

- Laws of motion

$$m_a \frac{d^2 \mathrm{x}_a}{dt^2} = -\sum_{b \neq a} G m_a m_b \frac{\mathrm{x}_a - \mathrm{x}_b}{\left|\mathrm{x}_a - \mathrm{x}_b\right|^3}$$



- … few subtleties

$$m_a^I \frac{d^2 \mathrm{x}_a}{dt^2} = -\sum_{b \neq a} G\, m_a^G\, m_b^G \frac{\mathrm{x}_a - \mathrm{x}_b}{\left|\mathrm{x}_a - \mathrm{x}_b\right|^3}$$

Assumptions in Newtonian Gravity

- There is an inertial frame
  - F = mg
- There is an absolute time
  - t is absolute and 'flows uniformly'
- Equivalence principle

$$m_a^I = m_a^G$$

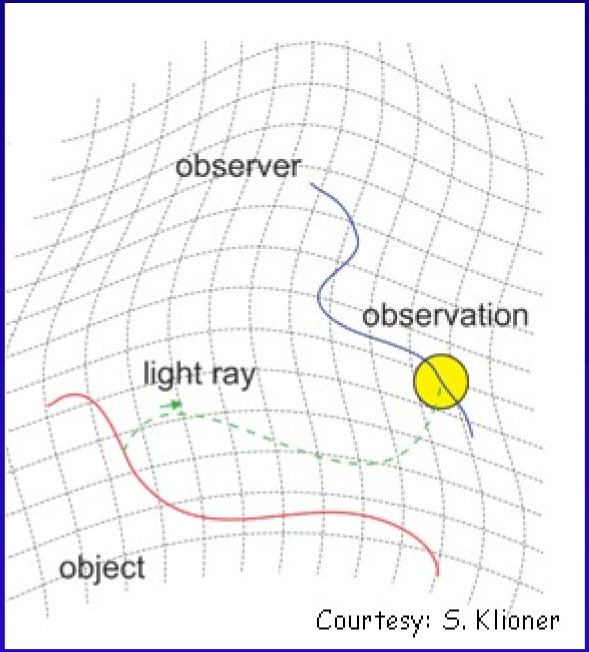
- G is a fundamental coupling constant

$$G \neq G(t) \qquad G \neq G(x)$$

Astronomy can help check these assumptions in the large scale domain

A dual relationship with mutual benefit

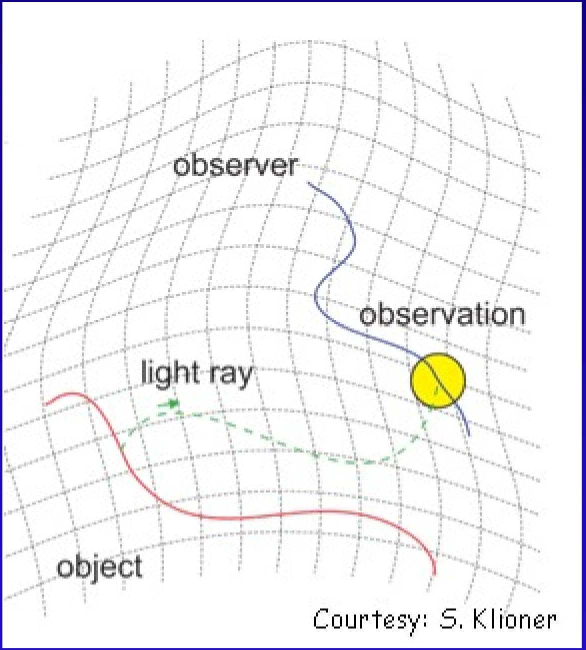
- Astronomy has been the source of early thinking about space and time fundamental properties



Gaia DPAC

- Astronomy has been the source of early thinking about space and time fundamental properties

- Fundamental physics provides astronomers with tools to model space-time observations



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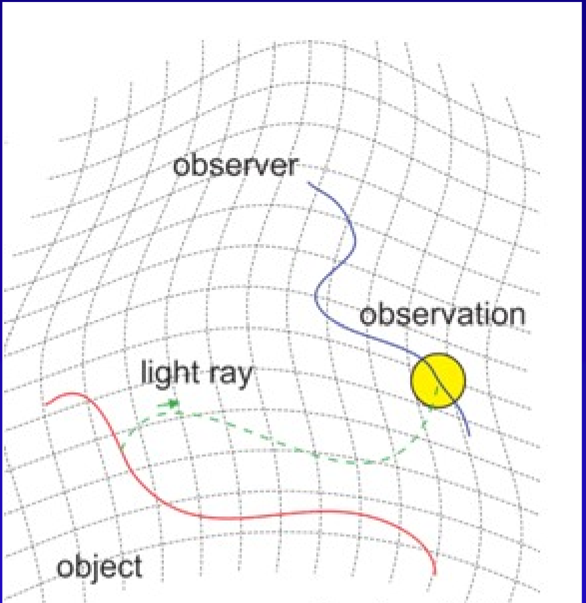
- Accurate astronomy is a playground to put physical theories under tests



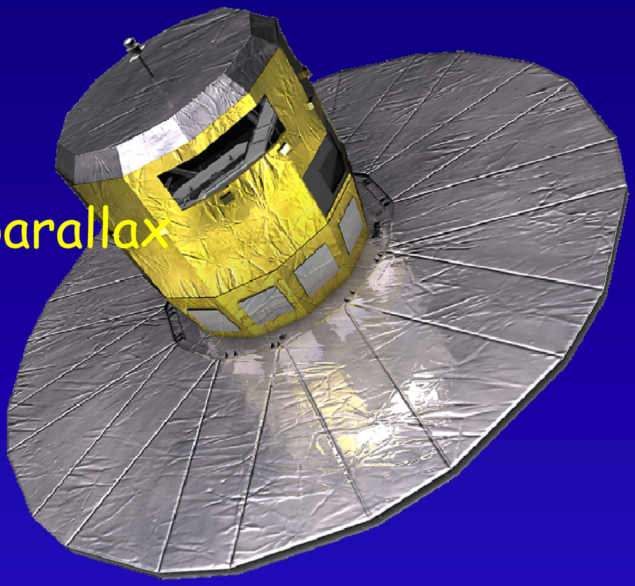
Courtesy: S. Klioner


Space Astrometry with Gaia

Gaia quick fact sheet

- Main goal : astrometry and photometric survey to V = 20
  - ~ 10^9 sources
    - stars, QSOs, Solar system, galaxies
- Accuracy in astrometry : 25 µas @ V = 15 for parallax
  - 10 µas V < 13 - 300 µas V = 20

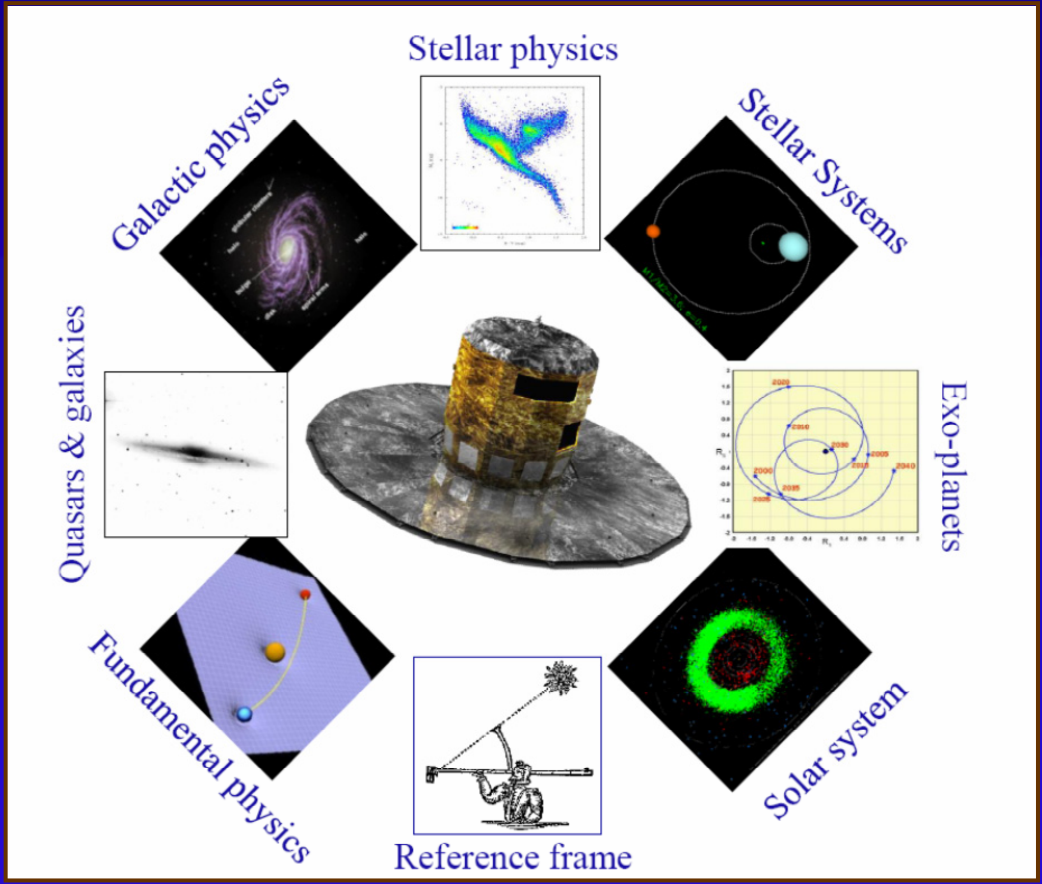
  10 µas = 1human hair at 1000 km!



- Regular scan of sky over 5 yrs
  - each source observed about ~75 times
  - internal autonomous detection system
- <u>Launch 20 November 2013 from Kourou</u>
- Five year nominal mission + 1 yr possible extension

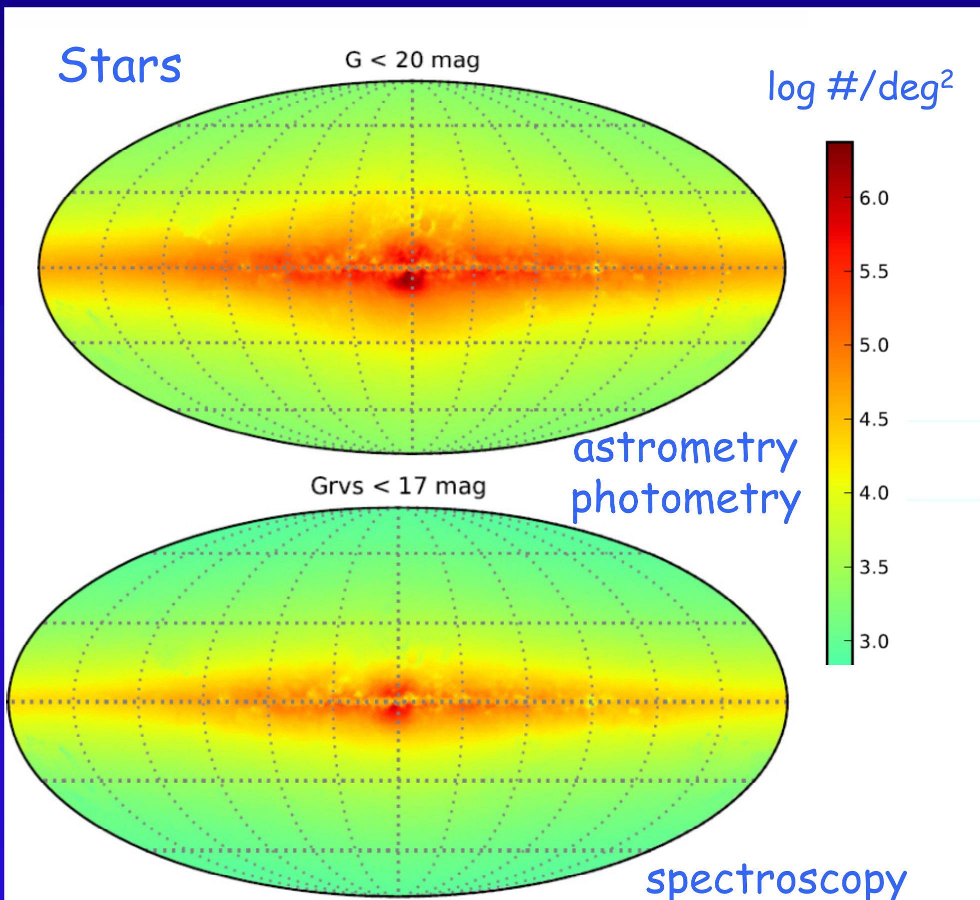
Driven by Astrometry,

designed for astrophysics



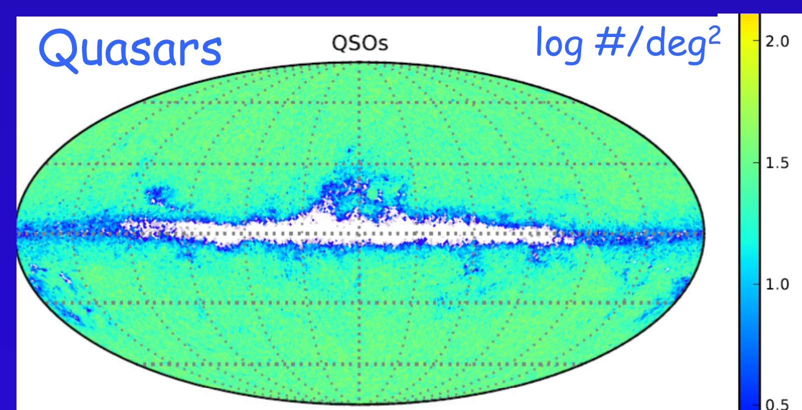
The Gaia Sky

- All-sky survey to 20 mag
- 70 observations per source, 5 years



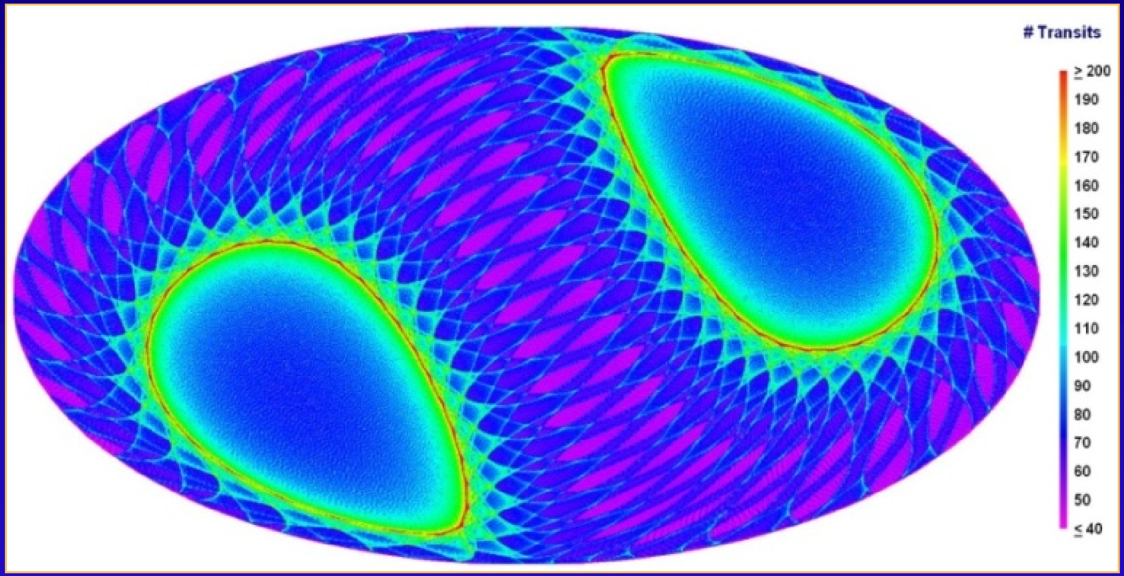
from Robin et al., 2012

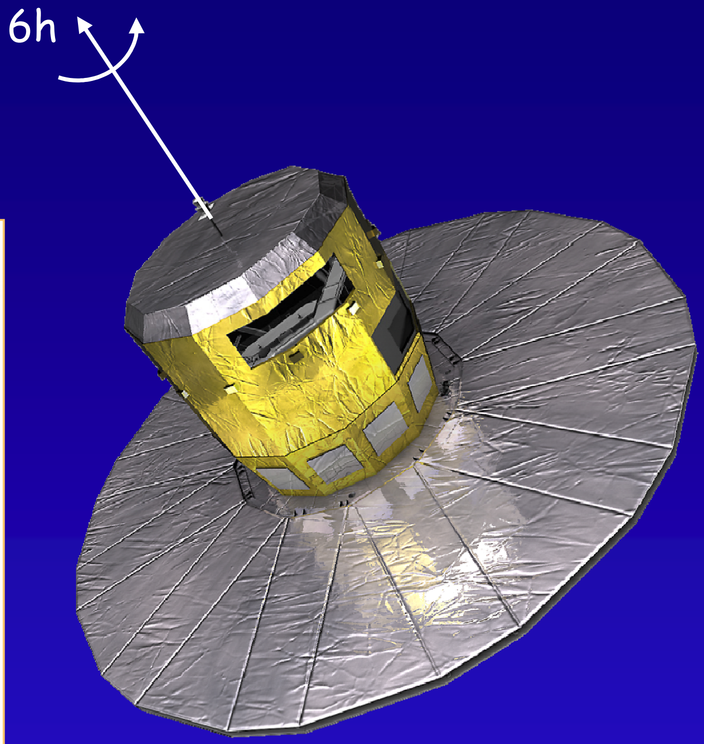
- > 1 billion stars
- 600,000 quasars
- 350,000 asteroids
- 1-10 million galaxies
- >10,000 exoplanets



Observation principles

- Gaia is a scanning mission
  - no pointing, no change in the schedule

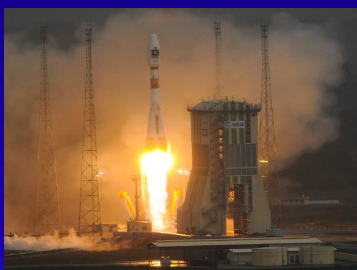


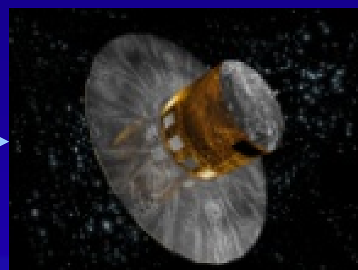


- Sources are reasonably regularly measured during the mission
  - orbit reconstruction
  - light curves

Gaia: Mission Components

Industry/ESA CSG/ESOC/ESAC





(20/11/2013)

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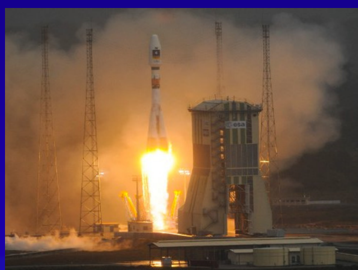

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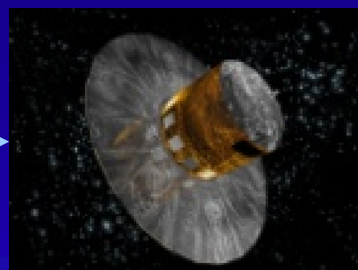
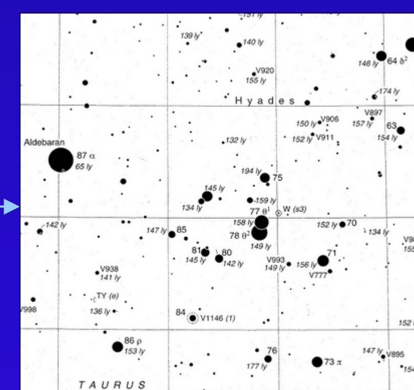
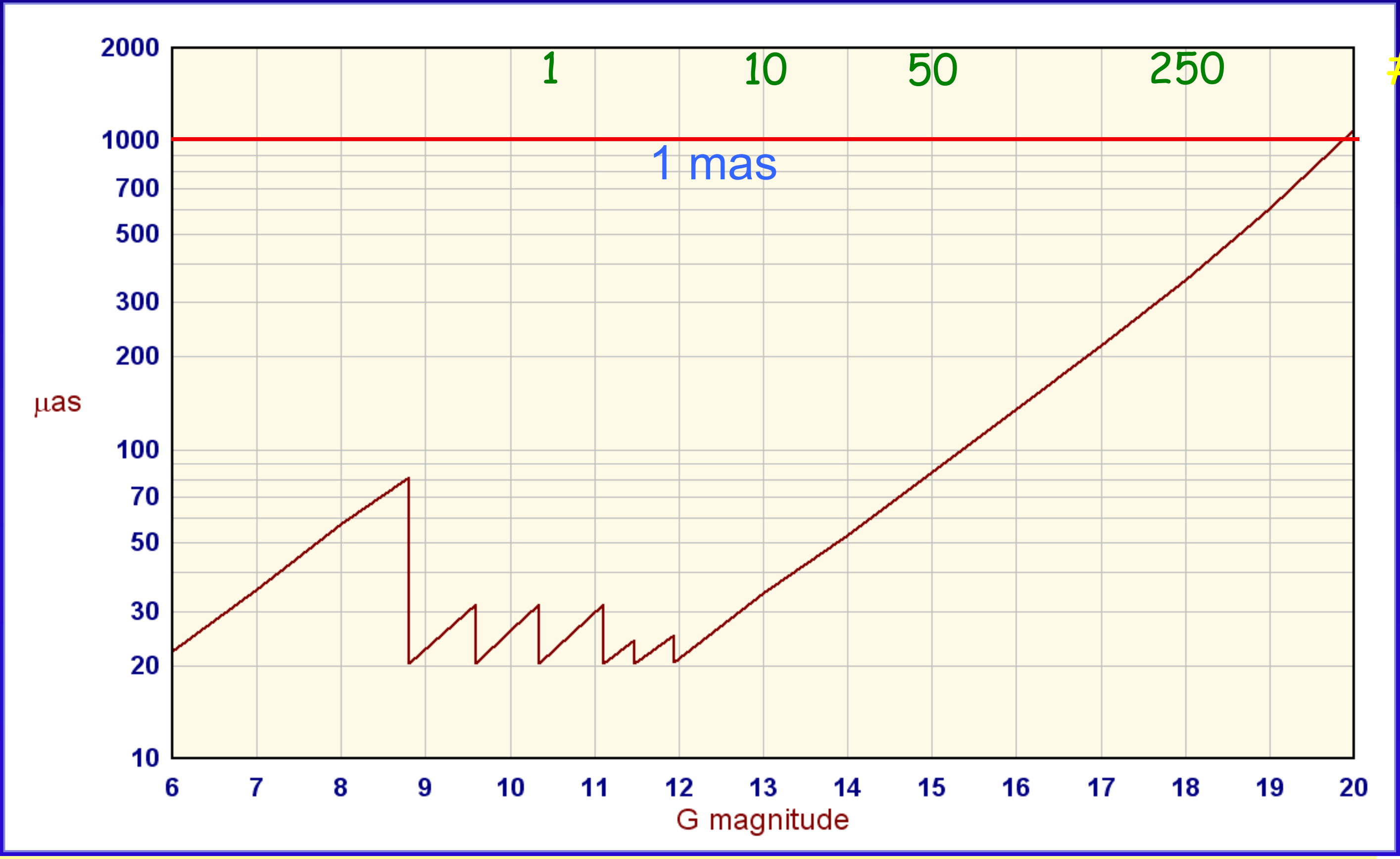


One consortium for the Processing: the DPAC



Astrometric accuracy: single observation

- Small field accuracy with final attitude
- Single observation accuracy ➔ orbit, solar system
  - one field transit, final attitude
  - point source



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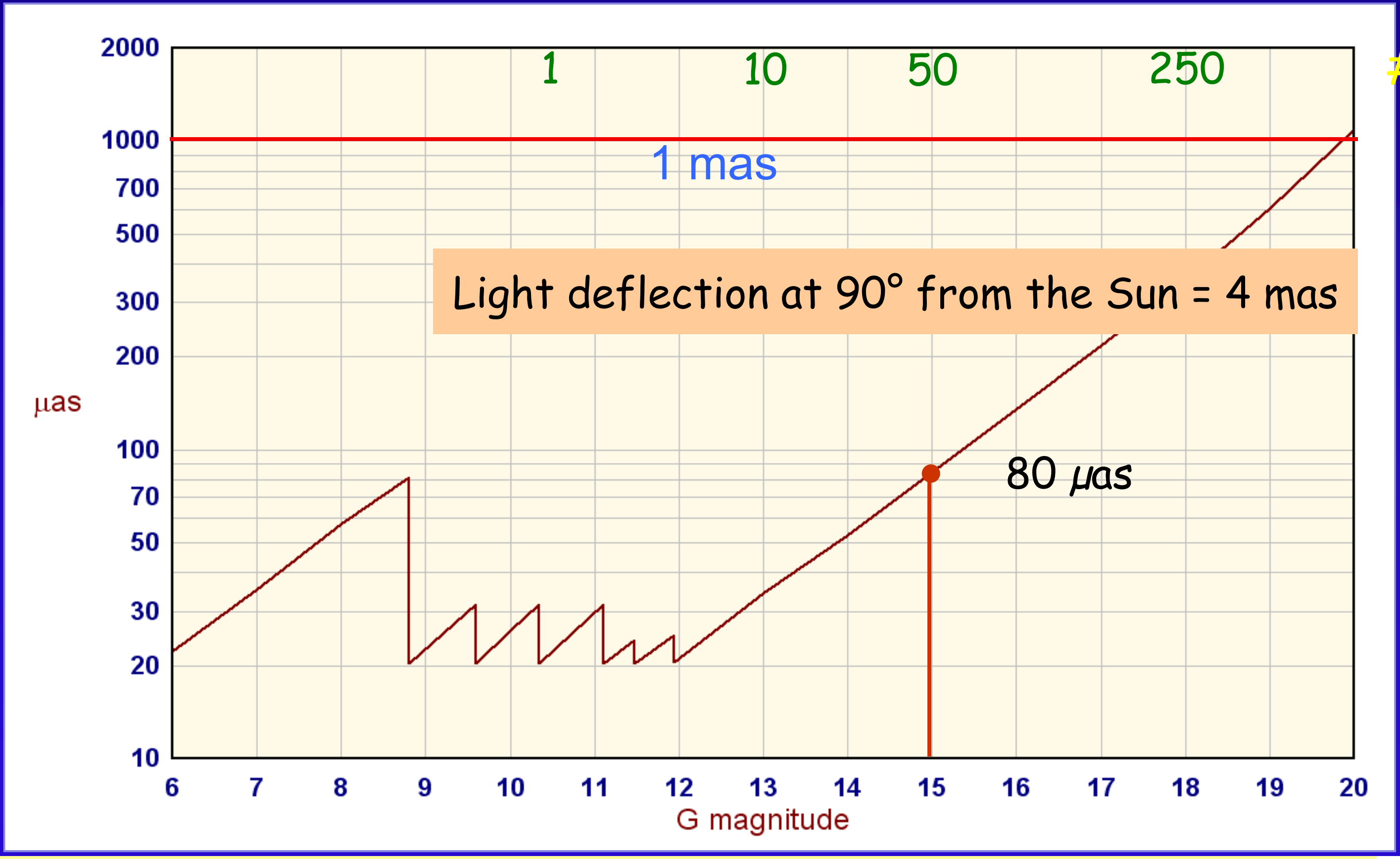
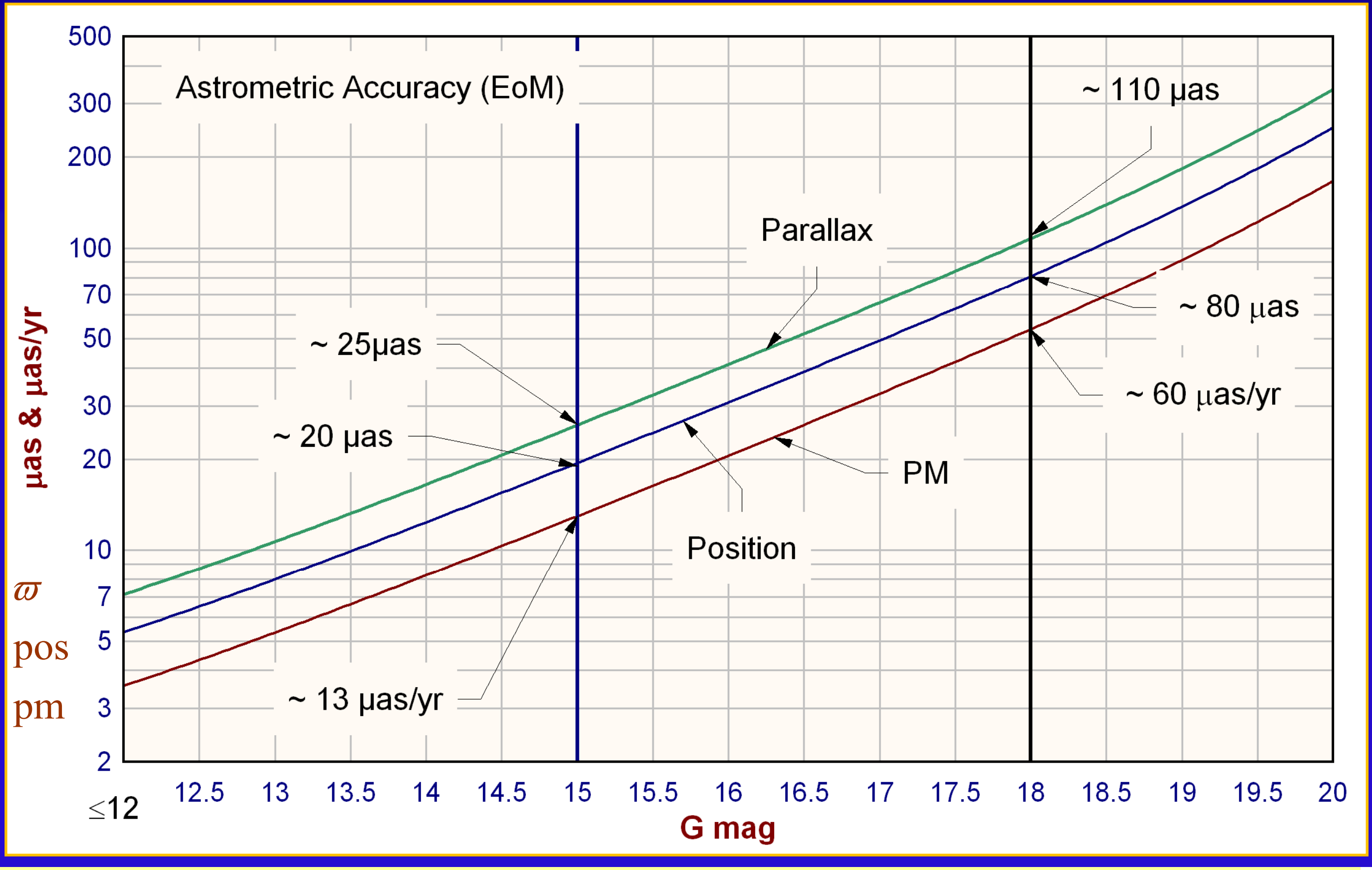
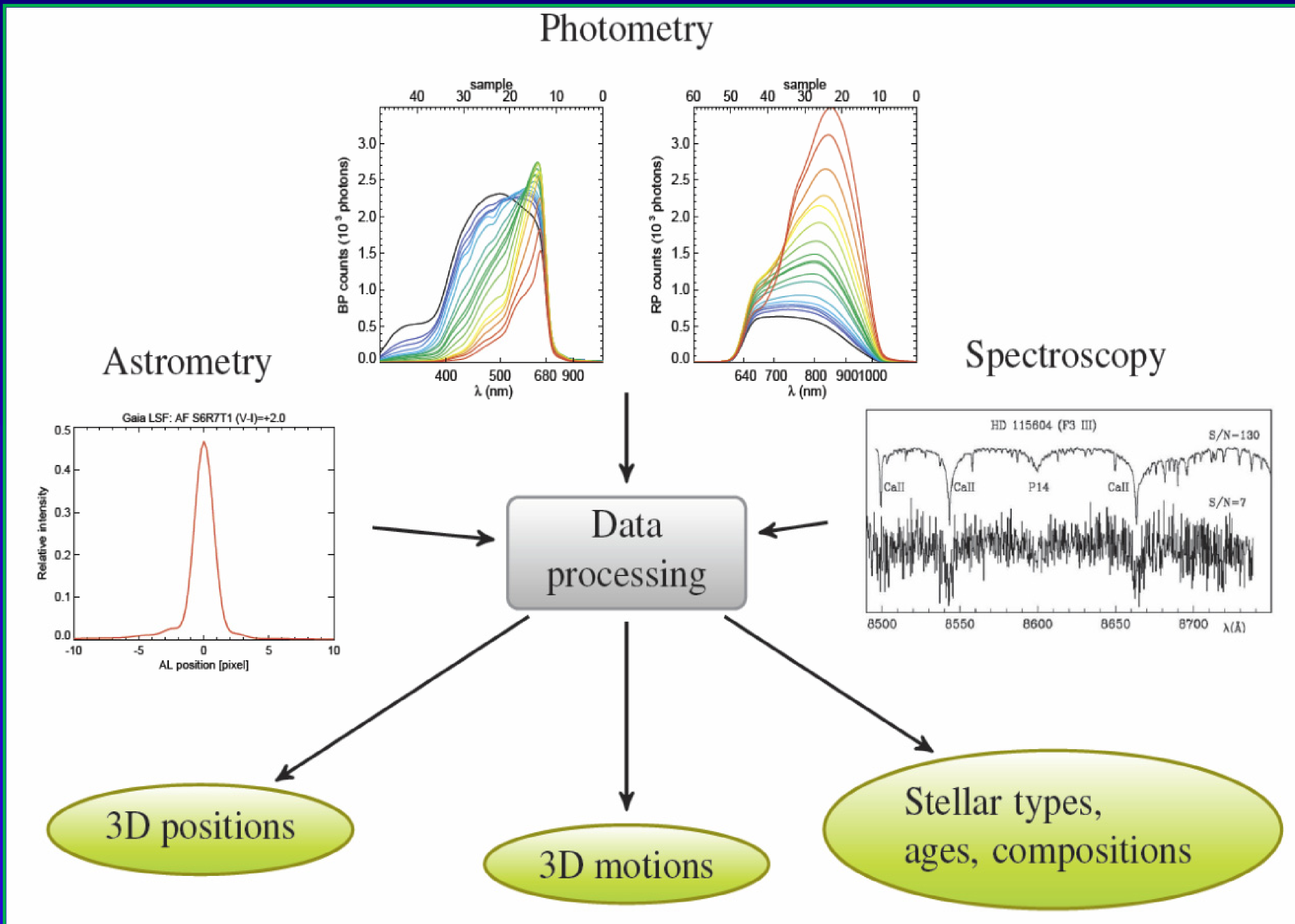


Gaia Accuracy at mean epoch

- Five year mission, sky –averaged
  - reference value: σ_ω = 25 µas @ G = 15
  - based on data from J. De Bruijne (ESA)



What Gaia will deliver

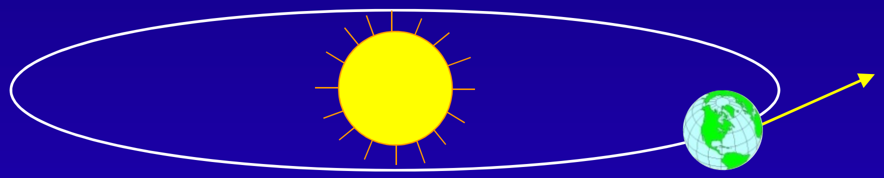


cartoon: A. Brown

Astrometric modelling

Relativity in Astrometry : when and where ?

- Effects due to motion



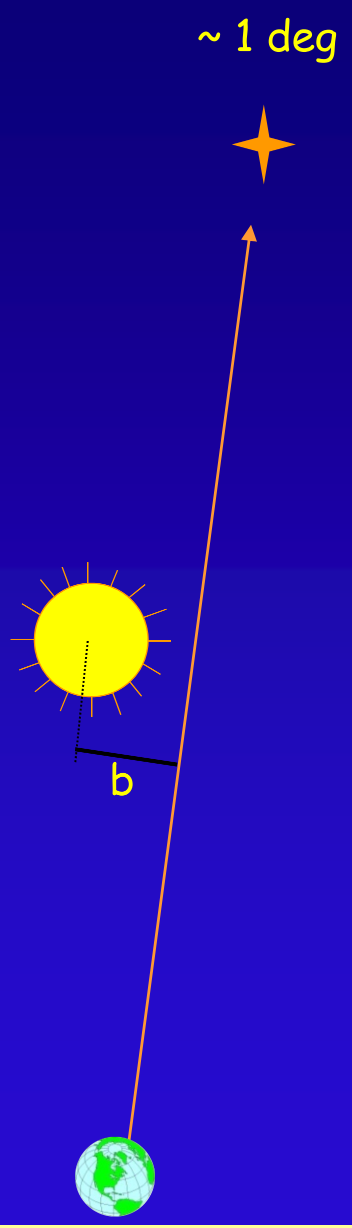
$v/c = 10^{-4} \sim 20''$

$v^2/c^2 = 10^{-8} \sim 1$ mas

$v^3/c^3 = 10^{-12} \sim 0.1\ \mu as$

- v/c Astrometry ~ 1700 ➔ 20" = discovery of aberration
- Ground based astrometry < 1980 ➔ Newtonian aberration
- v^2/c^2 Hipparcos (~ 1mas) ➔ v^2/c^2 terms
- v^3/c^3 Gaia, (~ 1-10 μas) ➔ full relativistic formulation

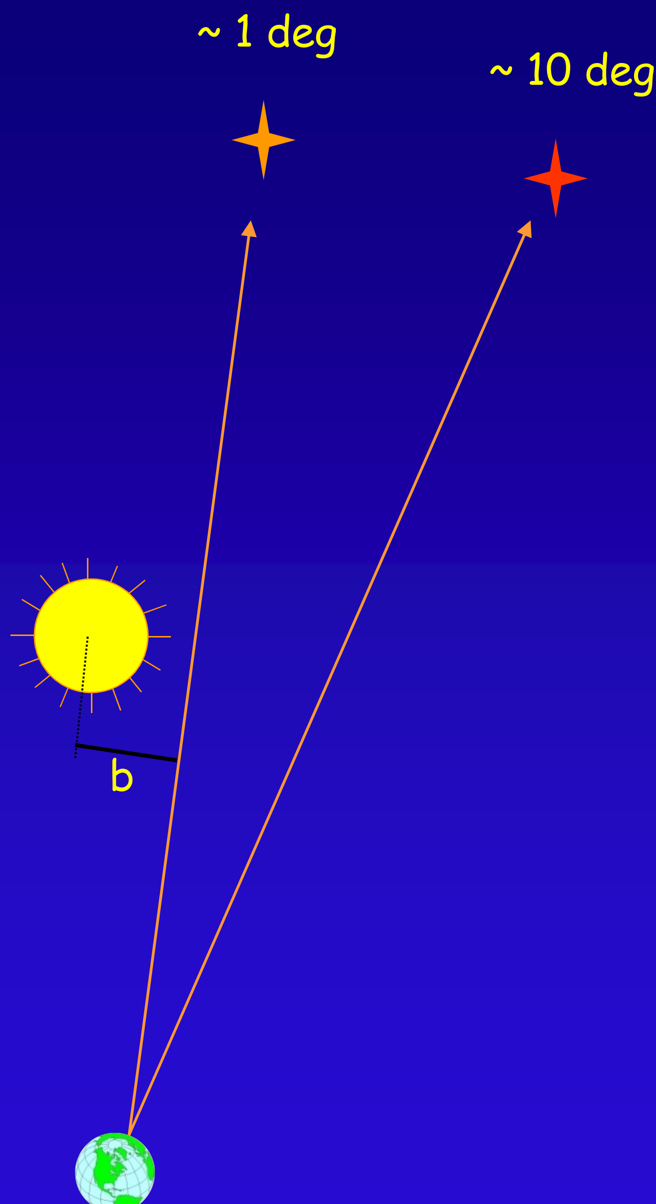
Test of Local Lorentz Invariance ?



$$\frac{4GM}{c^2 b}$$

* = 5×10^{-6} ~ 1 "   1915

Spacetime curvature effects

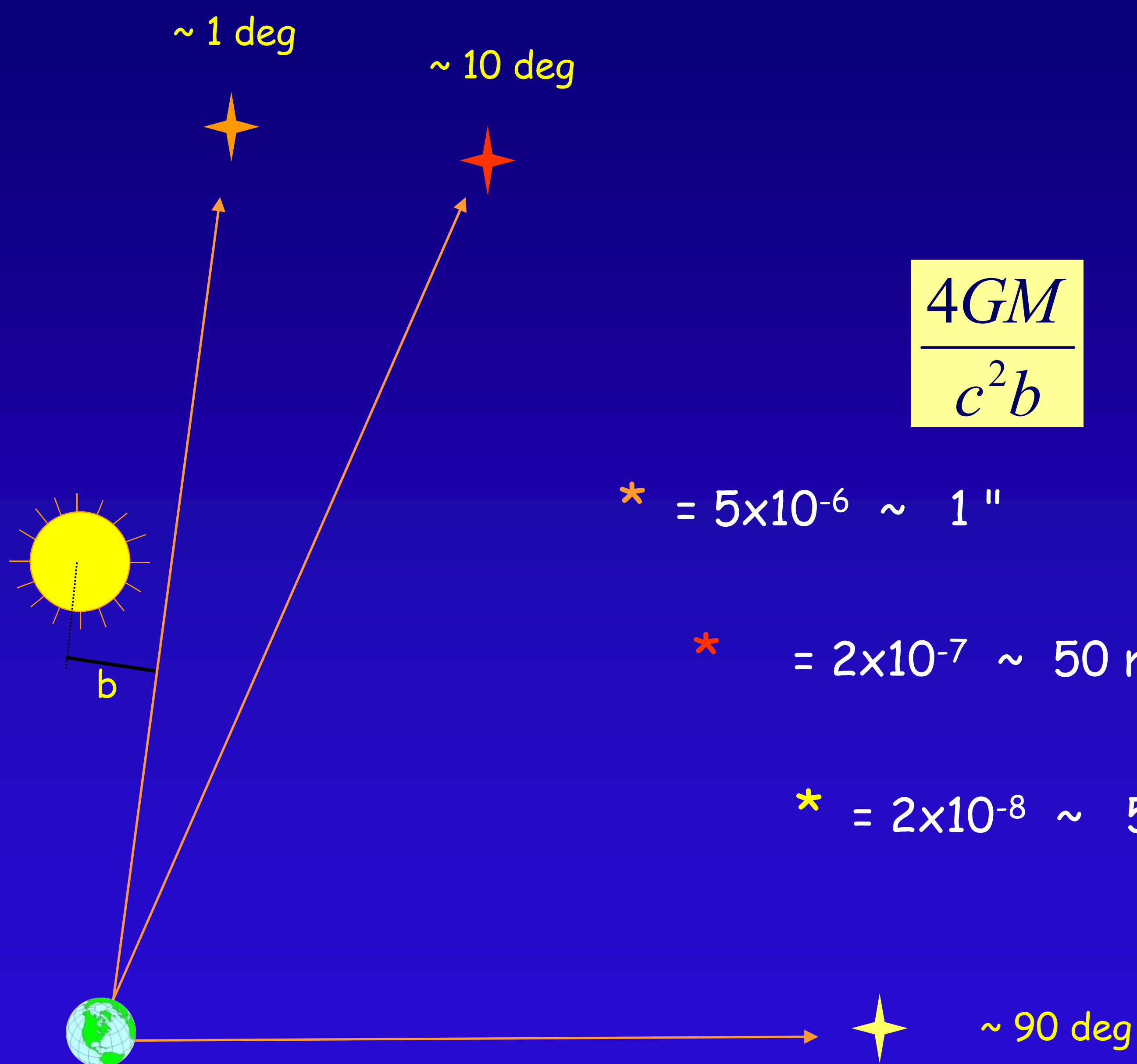


$$\frac{4GM}{c^2 b}$$

* $= 5\times10^{-6} \sim 1''$ 1915

* $= 2\times10^{-7} \sim 50$ mas 1960

Spacetime curvature effects



$$\frac{4GM}{c^2 b}$$

* $= 5\times10^{-6}$ ~ 1 " 1915

* $= 2\times10^{-7}$ ~ 50 mas 1960

* $= 2\times10^{-8}$ ~ 5 mas 1980

Astrometric modeling

- Newtonian models cannot describe high-accuracy observations:
  - many relativistic effects are several orders of magnitude larger than the observational accuracy
  - space astrometry missions would not work without relativistic modelling
    - both for space and time ➔ 4D modelling
- The simplest theory which successfully describes all available observational data:

GENERAL RELATIVITY

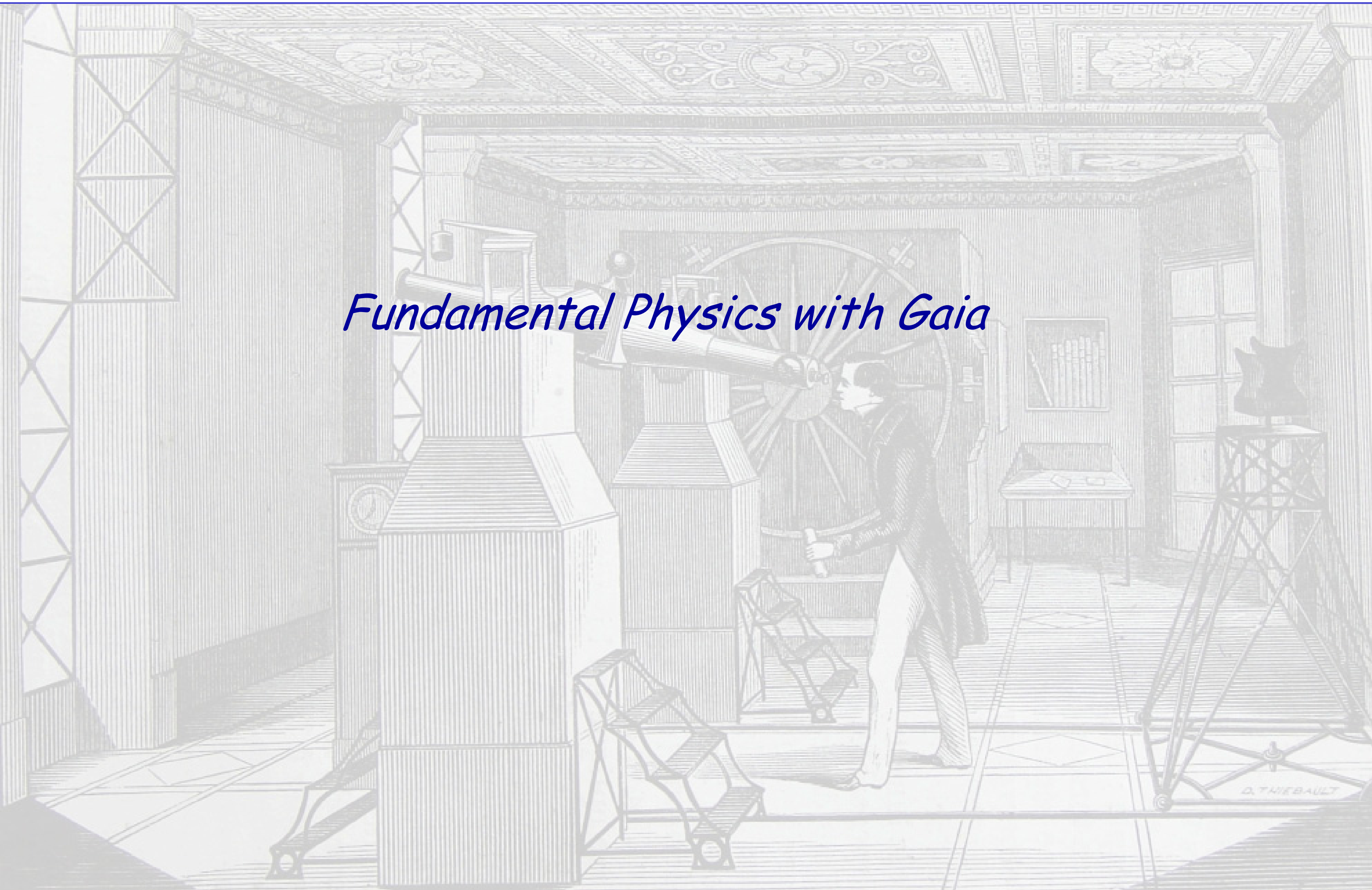
" Astrometry is the measurement of space-time coordinates of photon events "

A. Murray

Implementation for Gaia

- The astrometric model is a key element in the DP
  - a modeling accuracy of 0.1 μas is the requirement
- Two independent models have been developed
  - GREM by Klioner et al.
  - RAMOD by Vecchiato, Crosta et al.
- They will be used in different context in the data processing
  - GREM is the baseline for the pipeline reduction
  - it is implemented in the Gaia Tool library
  - it has a direct (➔ proper directions) and a reverse mode
  - both stellar and solar system sources
  - accuracy can be controlled by the user ➔ CPU-effective
  - partial derivatives are optional
- Solar system ephemeris (INPOP) are consistent with the model
- Timescale transformations done in accordance with GR

Fundamental Physics with Gaia



Relativity tests with astrometry

- light deflection → spacetime curvature
- light deflection → planetary J2
- orbital precession → non linearity of gravitation
- Lunar orbit → equivalence principle
- Pulsars → strong fields and gravitational waves

Gaia ambitions for testing relativity

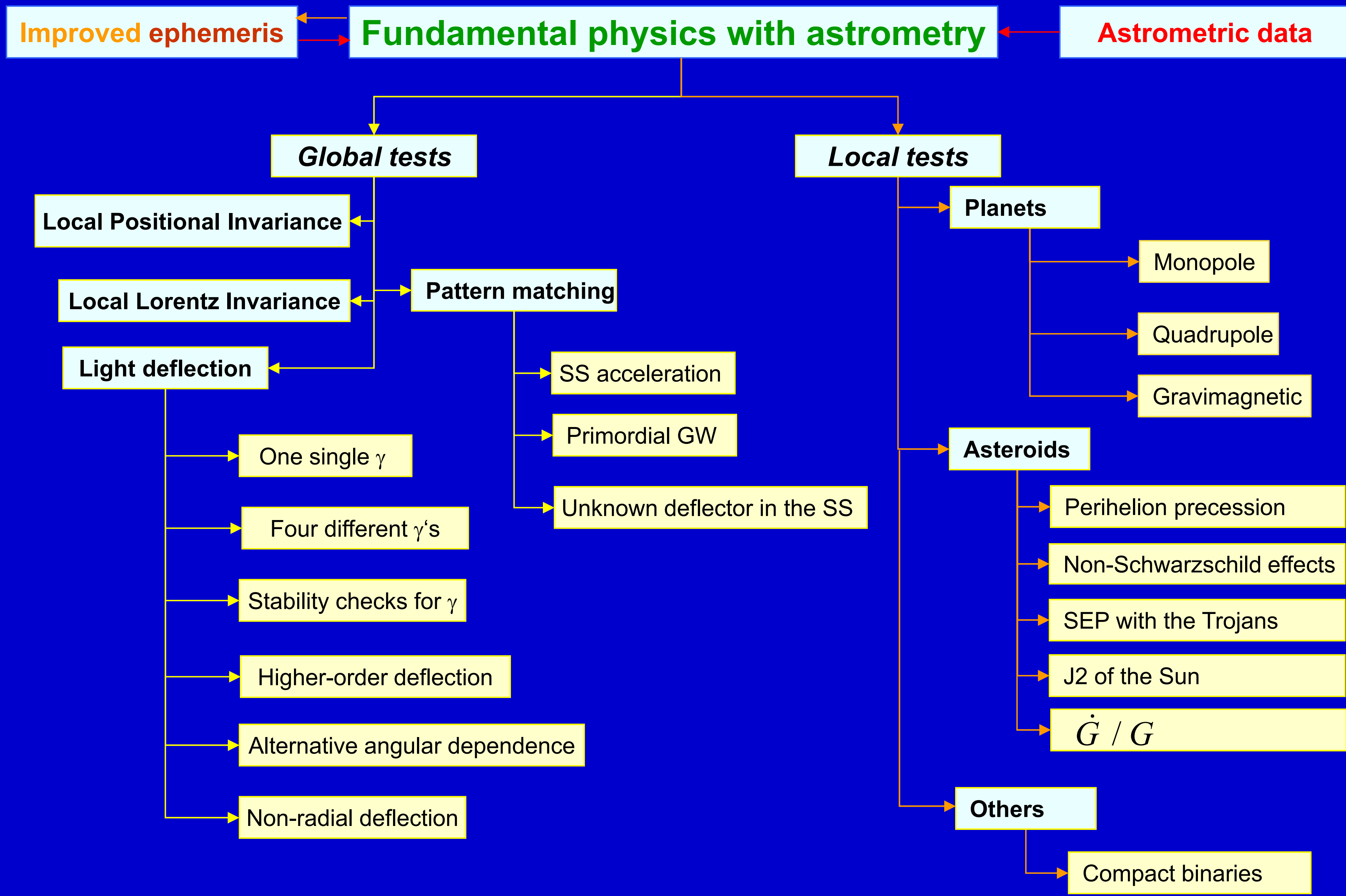
Solar Light deflection $\sigma_{\gamma} < 1 \times 10^{-6}$

Orbits of minor planets $\sigma_{\beta} < 5 \times 10^{-4}$

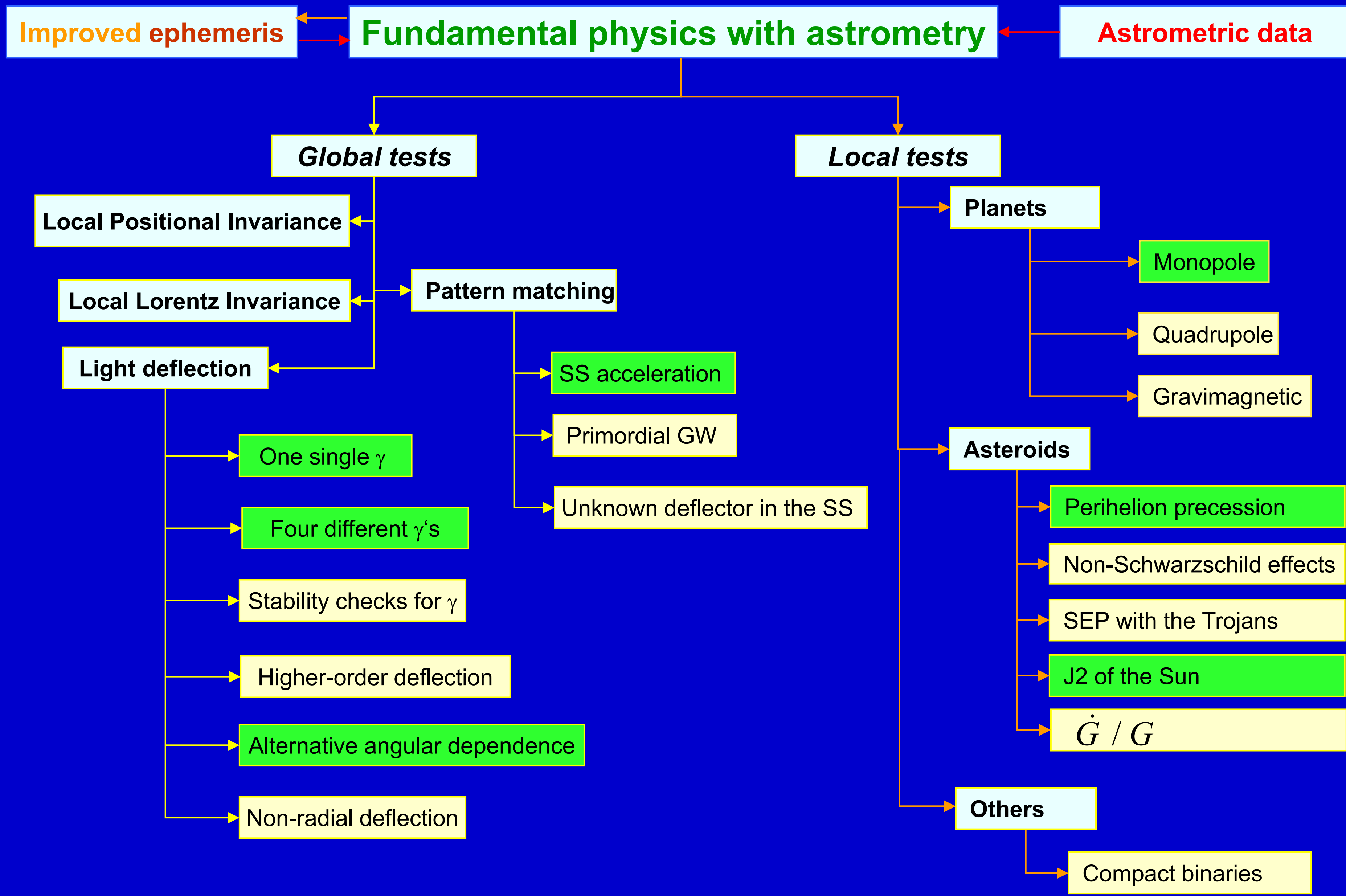
Orbits of minor planets $\sigma_{\dot{G}/G} < 5 \times 10^{-13}\,\mathrm{yr}^{-1}$

Jupiter light deflection $Q_{\mathrm{deflect}} > 5\sigma$

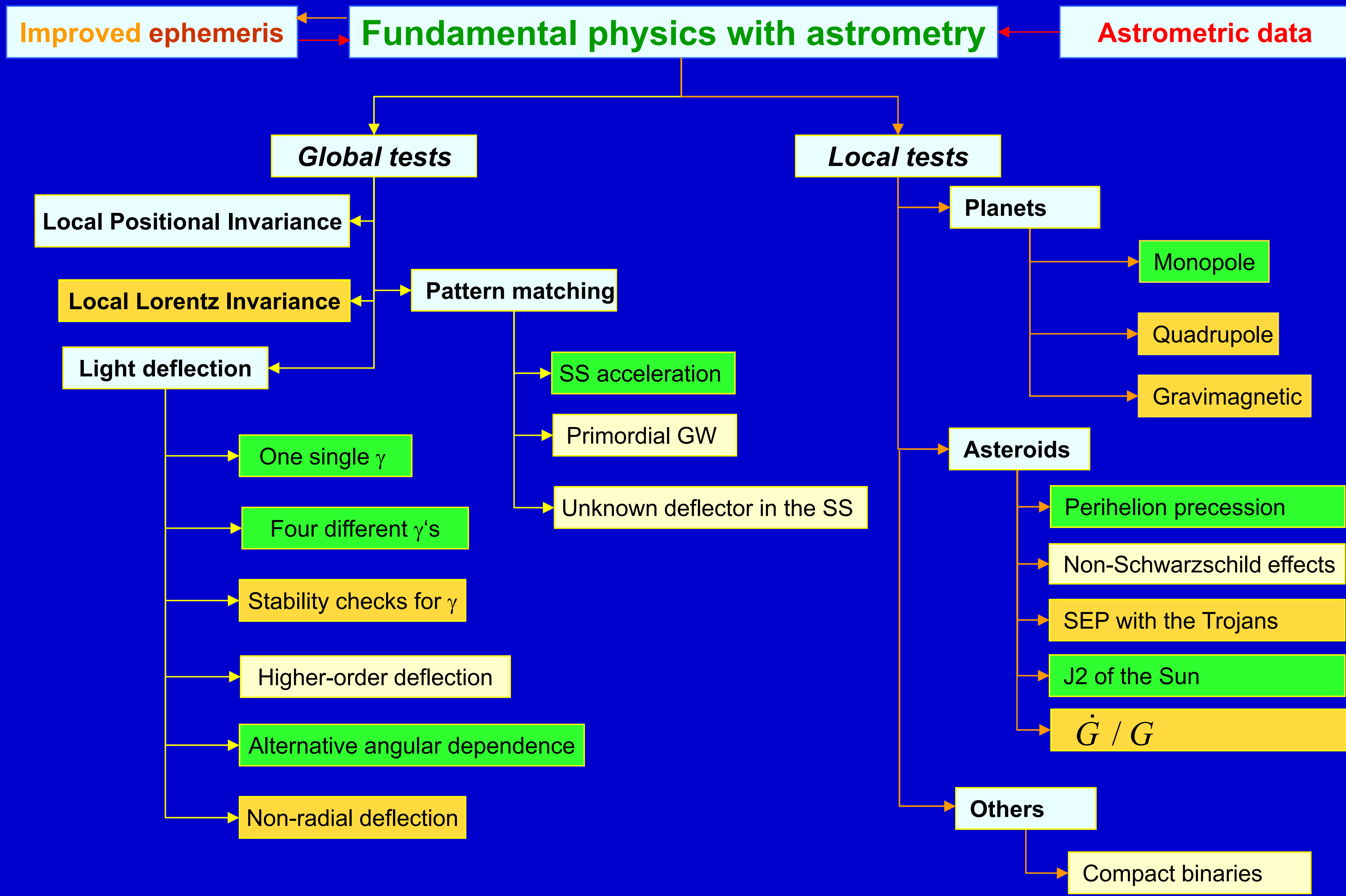
Relativity tests with accurate astrometry



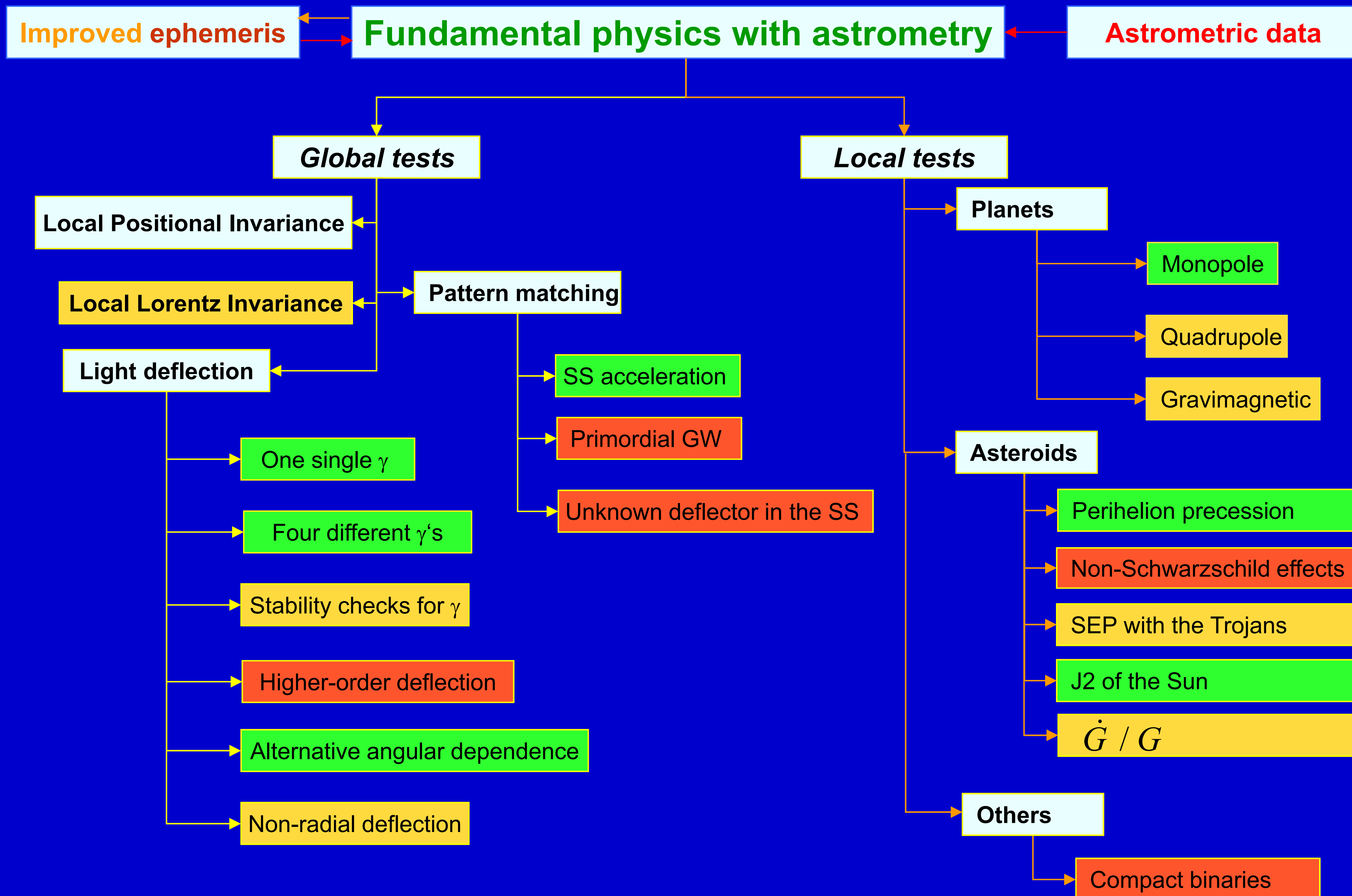
Gaia : Core tests - good results expected



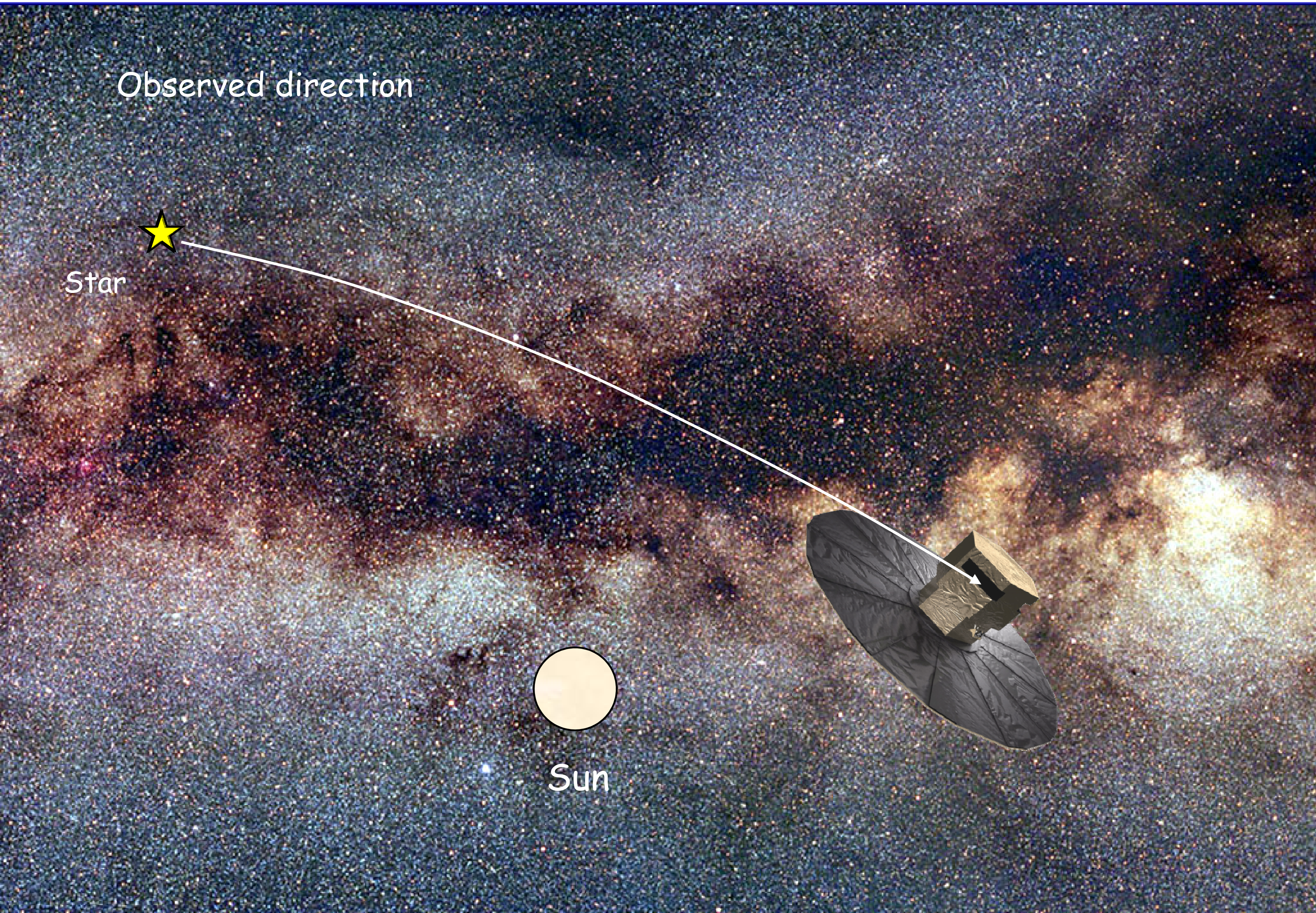
Gaia: complementary tests with parameter fitting



Gaia: tests on residuals



Einstein Light Bending



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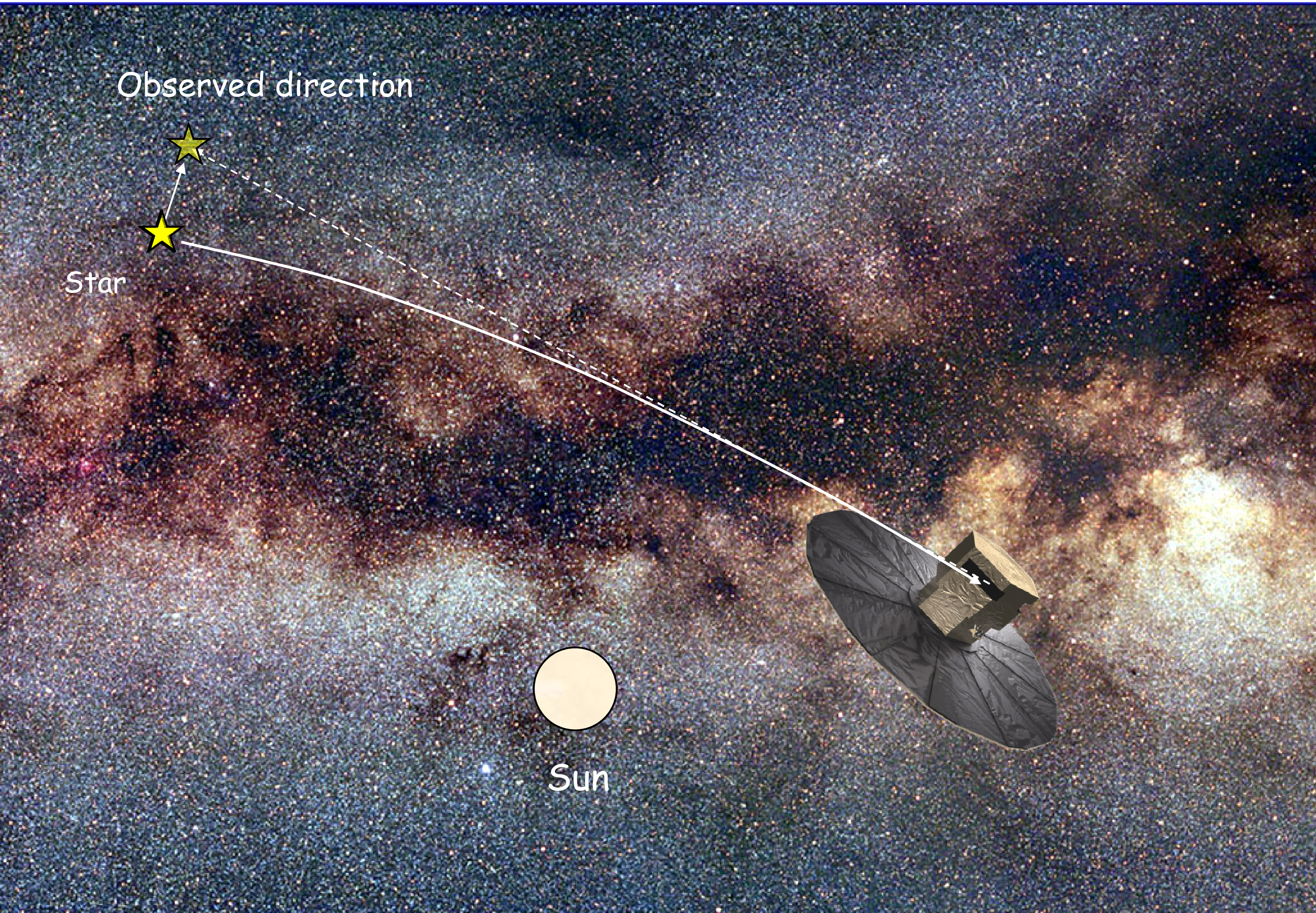
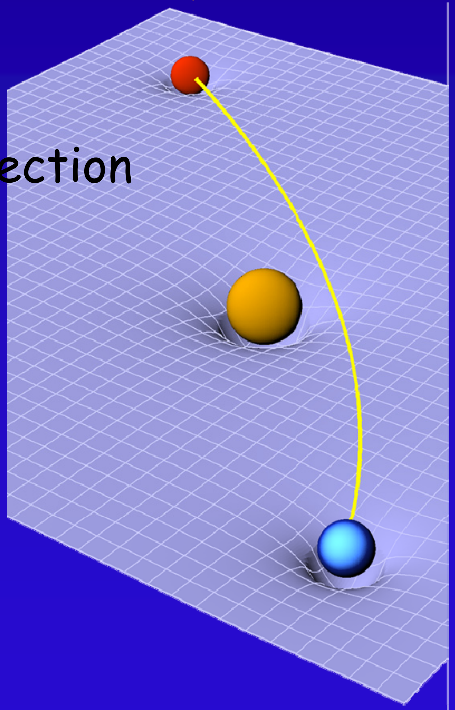


Solar light deflection

- Most precise test on γ with Gaia
  - Preliminary analysis (ESA, 2000- Mignard, 2001 - Vecchiato et al., 2003)
- Advantages of Gaia experiment
  - Optical with accurate astrometry
    - One individual observation at 90° from the Sun ➔ γ to 0.02 accuracy
  - Deflection (not time delay involving nearly sun grazing)
  - Wide range of angular coverage ➔ mapping of the deflection
    - Test of alternate deflection law
  - No problem with solar corona
  - Full-scale simulation of the experiments
    - sensitivity analysis, systematic effects
  - Testing could be wider than PPN formulation



Photon path in a gravitational field

$$g_{00} = -1 + \frac{2}{c^2} w(x,t) - \frac{2}{c^4} \beta w^2(x,t)$$

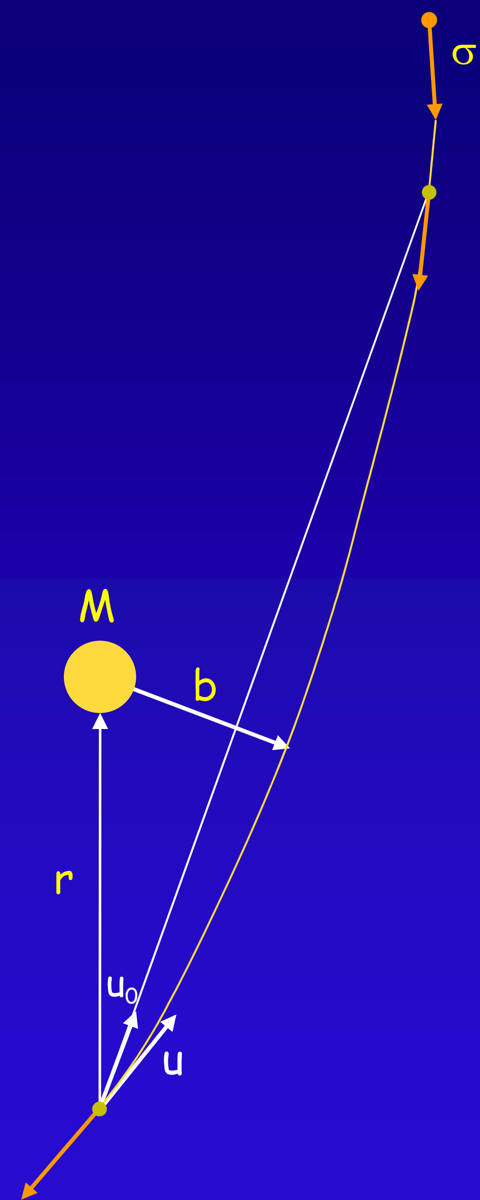
$$g_{0i} = -\frac{4}{c^3} w^i(x,t)$$

$$g_{ij} = \left(1 + \frac{2}{c^2} \gamma w(x,t)\right) \delta_{ij}$$

$$\mathbf{x}(t) = \mathbf{x_0}(t) + \boldsymbol{\sigma}(t - t_0) + \Delta\mathbf{x}(t) / c^2$$

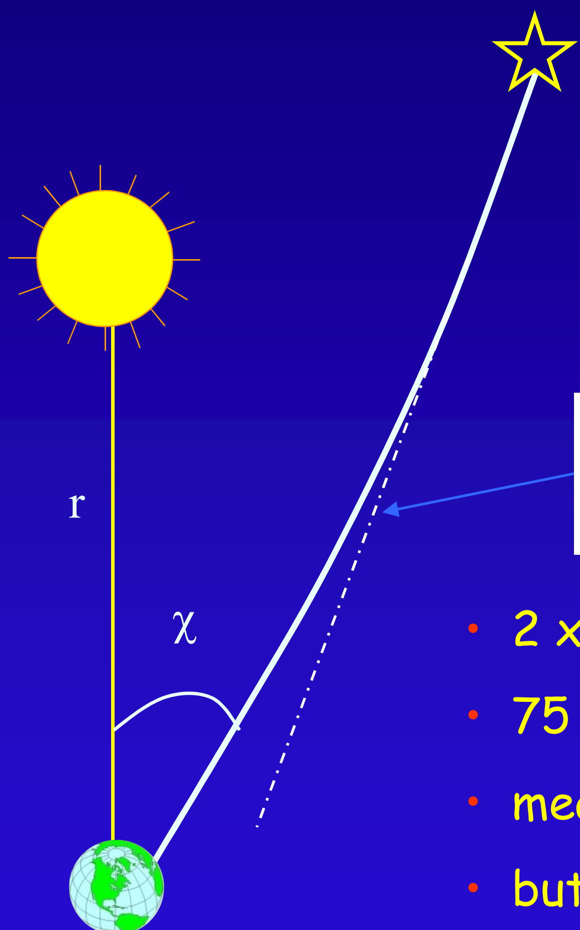
$$\mathbf{u} = \mathbf{u_0} + \frac{(1+\gamma) GM}{c^2} \frac{\left[1 + (\mathbf{u}_0 . \mathbf{r}) / r\right] \mathbf{b}}{b^2}$$

$$\delta\phi = \frac{(1+\gamma) GM}{c^2} \frac{1 + \cos\chi}{b}$$



Gaia DPAC

- Light Deflection : determination of γ



Light deflection in mas

	min χ	$\chi = 45$ deg
Sun	10 mas	10 mas
Jupiter	16 mas	2 µas
Saturn	6 mas	0.8 µas

$$\delta\theta = \frac{2GM}{rc^2}\frac{1+\gamma}{2}\frac{\sin\chi}{1-\cos\chi}$$

Observable quantity

- 2×10^7 stars V < 14
- 75 observations per star
- measurable effect even at 135° from the Sun
- but large correlation with zero-point parallax (~ -0.85)

$$\sigma_\gamma \approx 2\times10^{-6} \text{ to } 6\times10^{-7}$$

Observatoire de la CÔTE d'AZUR

Potential problems

- Special problems related to the procedure
  - many measurements are used and averaged out to get gamma
    - improvement in $1/n^{1/2}$ if no other unknown instrumental or physical effect is correlated with the deflection
    - very hard to establish at this level of accuracy
  - but these effects become significant only if constant over five years
- Known effects already identified
  - global parallax shift strongly correlated with γ
    - itself linked to instrument thermo-mechanical behaviour
  - relation with the velocity and aberration correction

But remember the lessons from GPB !

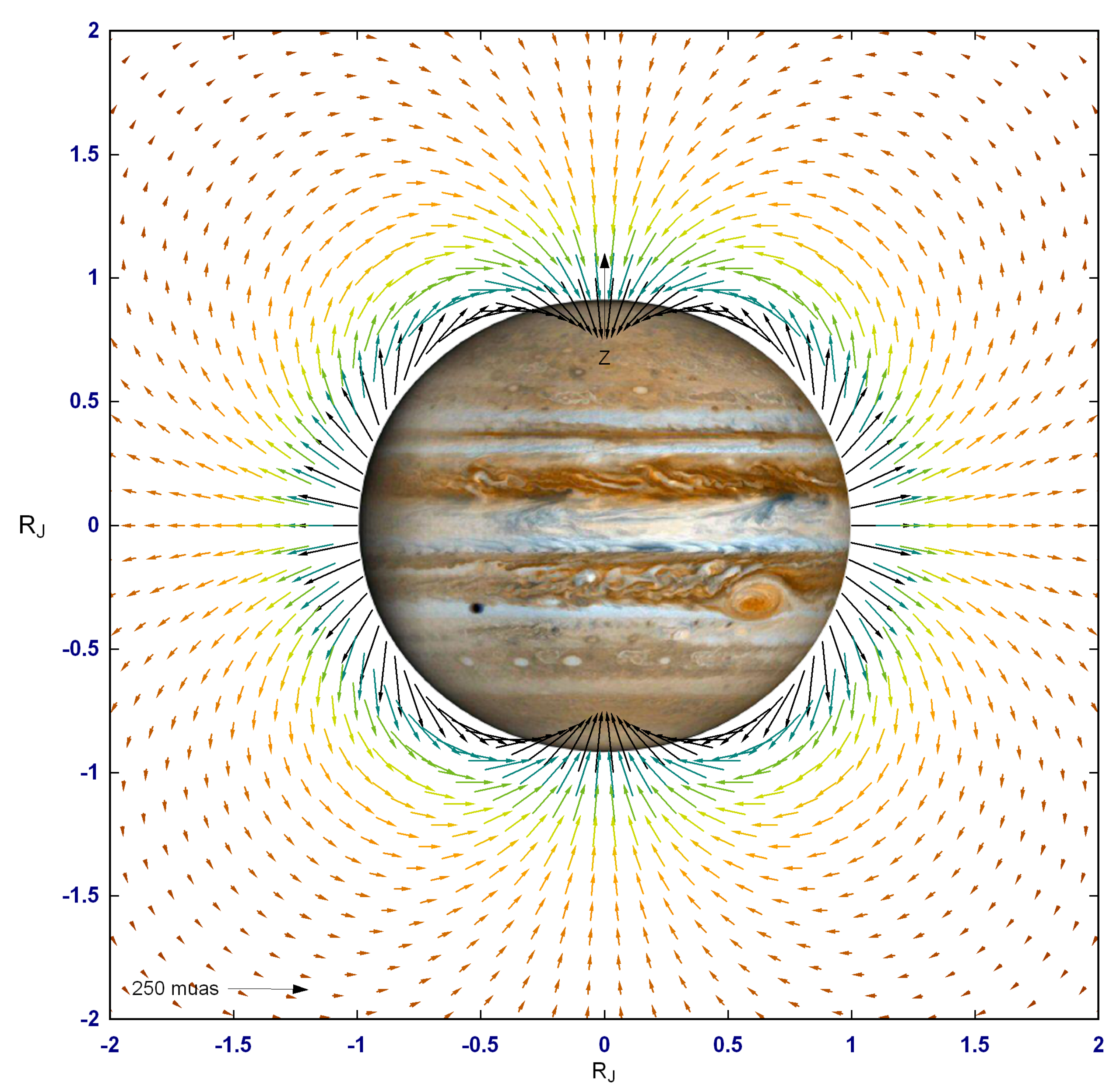
Beyond plain γ

- Observations over five years
  - processing over independent time intervals
  - check for systematic effects
- Repeated observations over many stars
  - Stability check: dependence of γ on various parameters
    - brightness, color, geometry
- Sampling of the angular distance to the Sun
  - mapping of the actual angular dependence
    - blind decomposition on spherical harmonics
- Higher order PPN terms could be included

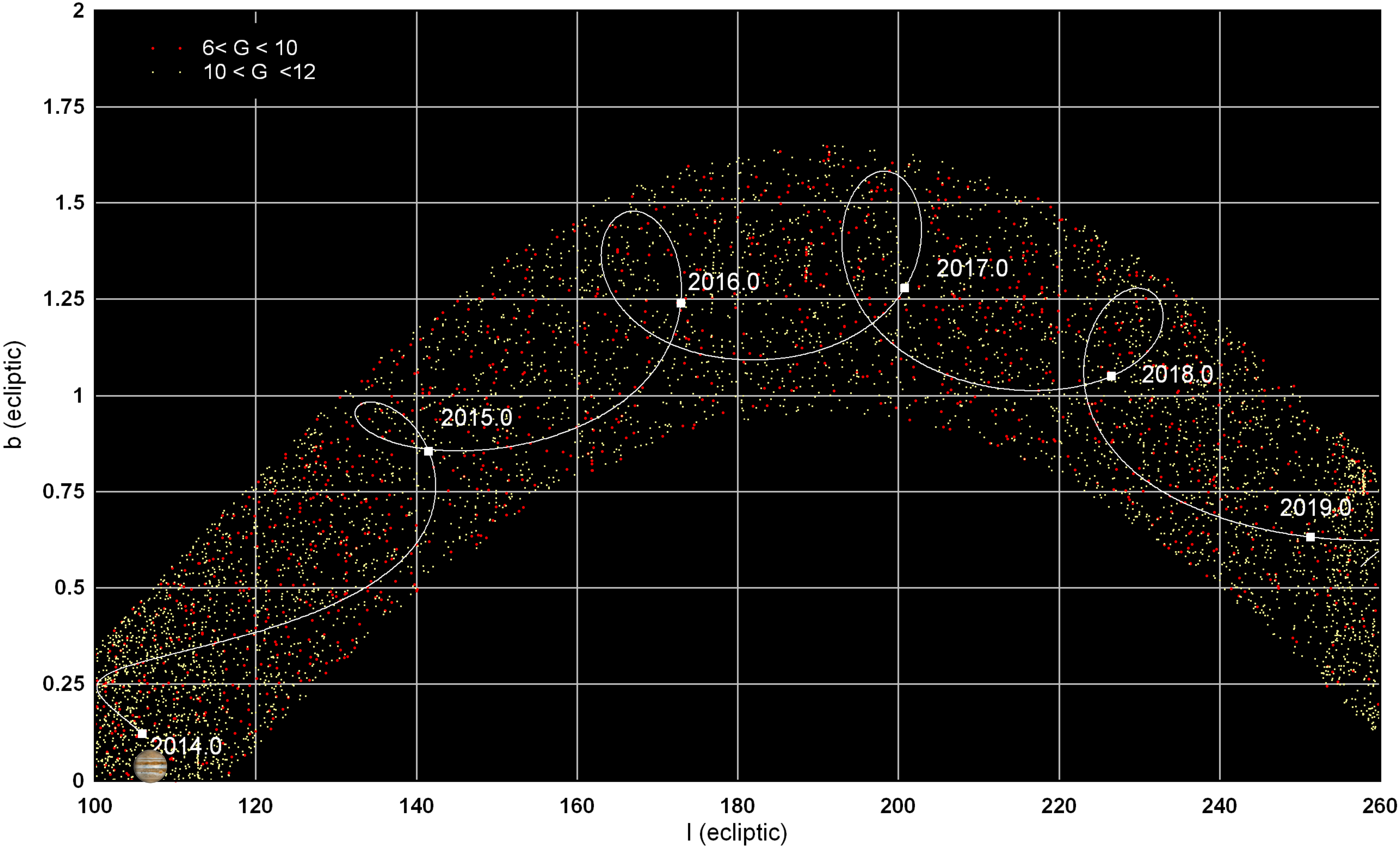
Light deflection by giant planets

	Monopole mas	Quadrupole μas
$1R_j$	16	240
$2R_j$	8	30
$5R_j$	3	2
$10R_j$	2	0.2
$1R_s$	6	95
$2R_s$	3	12
$5R_s$	1	0.8
$10R_s$	0.6	0.01

Light bending by Jupiter quadrupole



Jupiter among the stars 2014-2019



Jupiter relativity experiment with Gaia

Gaia DPAC

- Objectives
  - Evidence the quadrupole light deflection on stars seen around Jupiter
- Stars can be observed very close to the limb of Jupiter
  - $d_{min} < 5$ arcsec
- Same stars are observed at other epochs without Jupiter
- Astrometric effect is included in the data modelling
  - it is superimposed to the monopole deflection

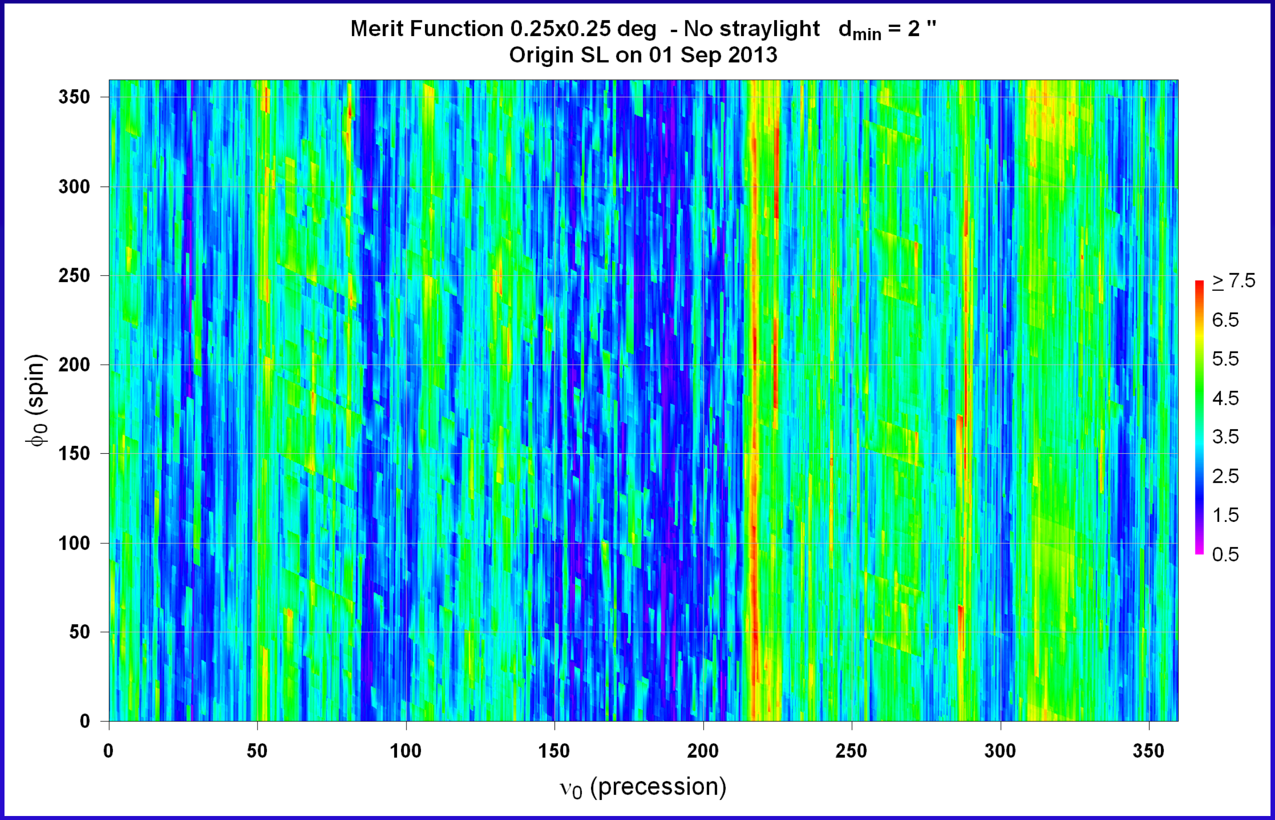
$$\delta\phi_M = \frac{4GM_J}{c^2 b}\frac{1+\gamma}{2} \qquad \delta\phi_Q = \frac{4GM_J}{c^2}\frac{J_2 R_J^2}{b^3} \quad \text{(simplified formula)}$$

- Some mission parameters are optimised for this experiment

We hope to detect the deflection to 5σ

Selection of free scan parameters

- Two free initial conditions
- Extensive simulations of Jupiter observation
- Analysis of the nearby starfield



Proper Motions global patterns

- Proper motions seen as a vector field on S_2
- Applicable to stars and QSOs
- Expansion in Vector Spherical Harmonics T_{lm} , S_{lm}

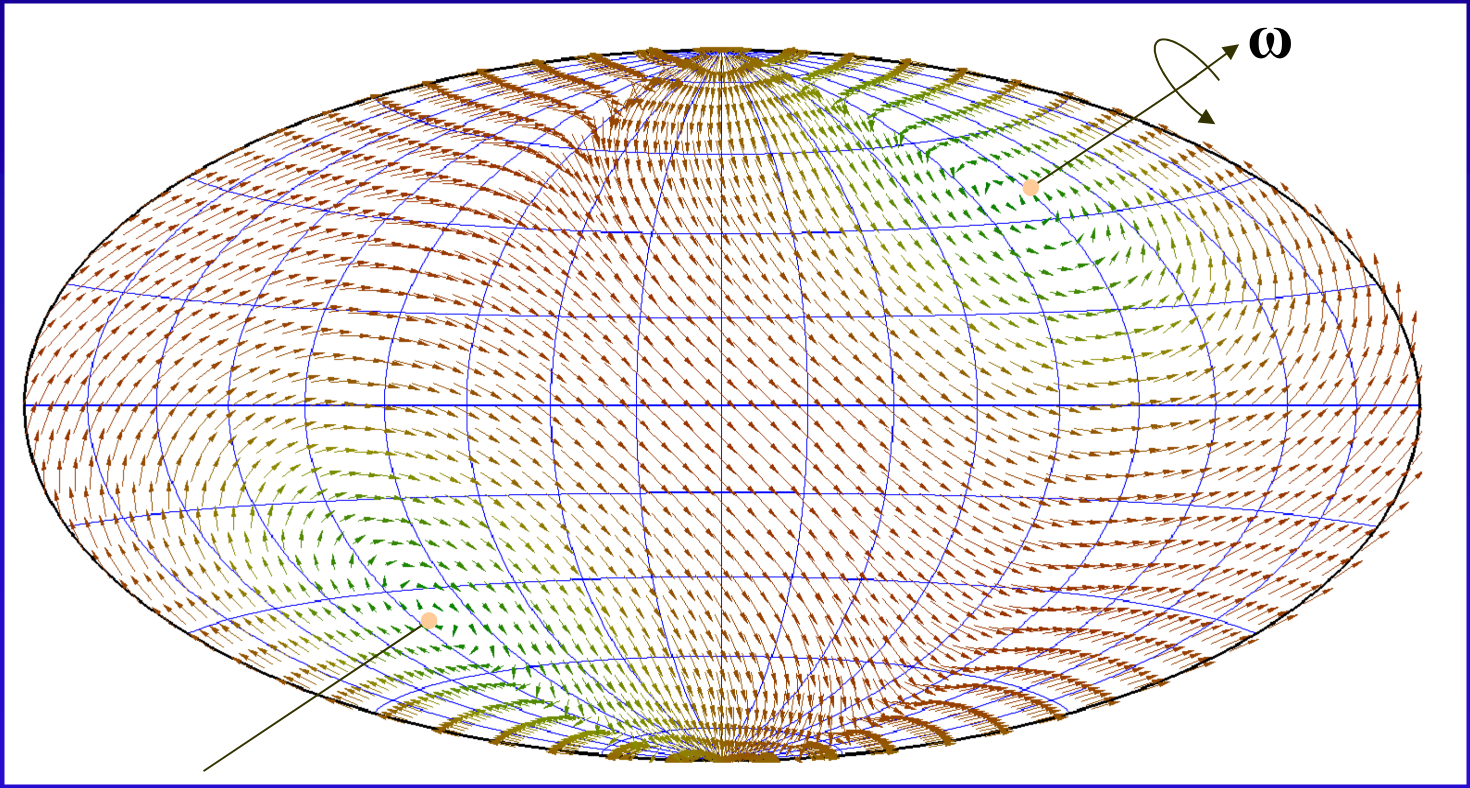
$$\mathbf{V}(\alpha,\delta) = V_\alpha \mathbf{e}_\alpha + V_\delta \mathbf{e}_\delta = \sum_{l=1}^{l=L} \sum_{m=-l}^{m=l} (t_{lm}\mathbf{T}_{lm} + s_{lm}\mathbf{S}_{lm})$$

$l = 1 - \mathbf{S}_{1m}$	Global rotation
$l = 1 - \mathbf{T}_{1m}$	Solar system acceleration
$l > 1 - \mathbf{S}_{1m}\ \&\ \mathbf{T}_{1m}$	Stochastic field of GW

Global Rotation on QSOs - S_{1m}

- Inertial system materialised to 0.2 μas/yr

$$\mu_\alpha \cos\delta = \omega_x \sin\delta\cos\alpha + \omega_y \sin\delta\sin\alpha - \omega_z \cos\delta$$
$$\mu_\delta = -\omega_x \sin\alpha + \omega_y \cos\alpha$$

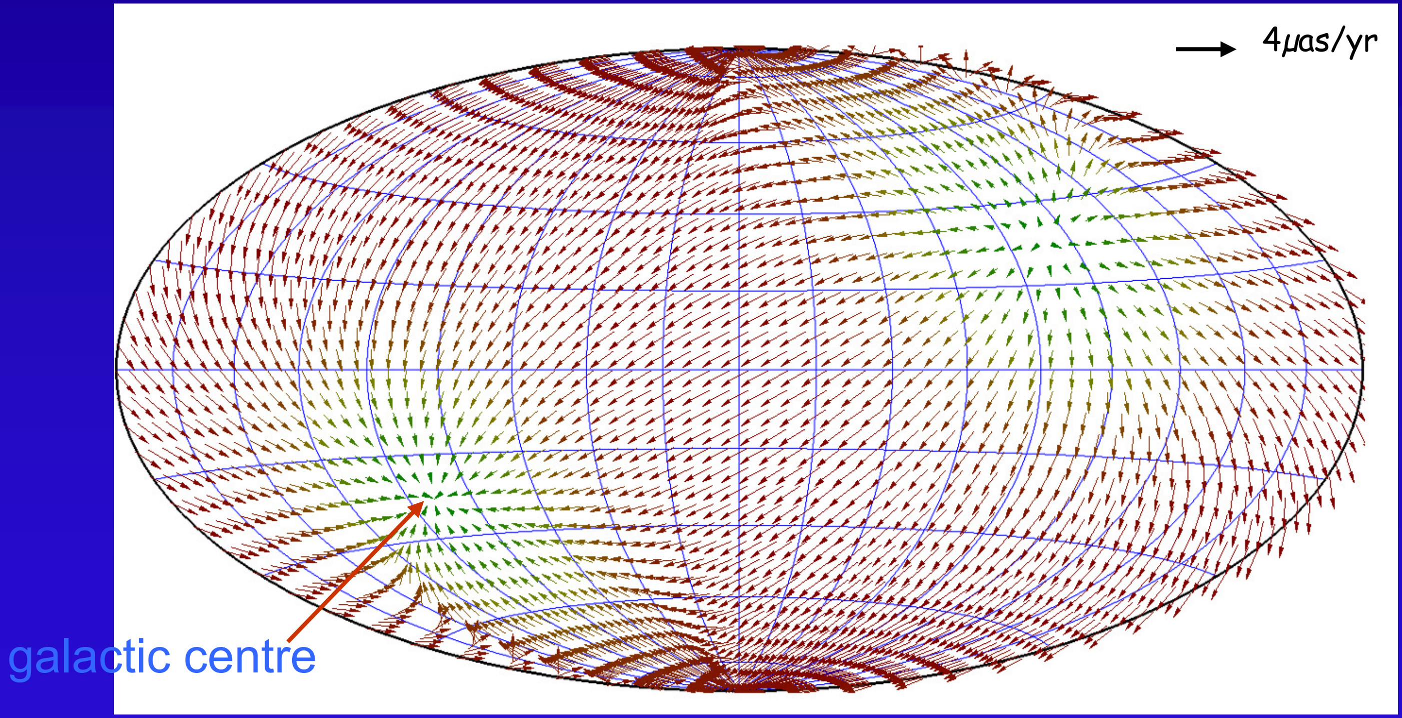


Acceleration of the solar system – T_{1m}

- Γ/c to 0.2 μas/yr - Γ to 1×10^{-11} m/s^2 ~ 1/100 of Pioneer acceleration

$$\mu_\alpha \cos\delta = -\frac{\Gamma_x}{c}\sin\alpha + \frac{\Gamma_y}{c}\cos\alpha$$

$$\mu_\delta = -\frac{\Gamma_x}{c}\sin\delta\cos\alpha - \frac{\Gamma_y}{c}\sin\delta\sin\alpha + \frac{\Gamma_z}{c}\cos\delta$$

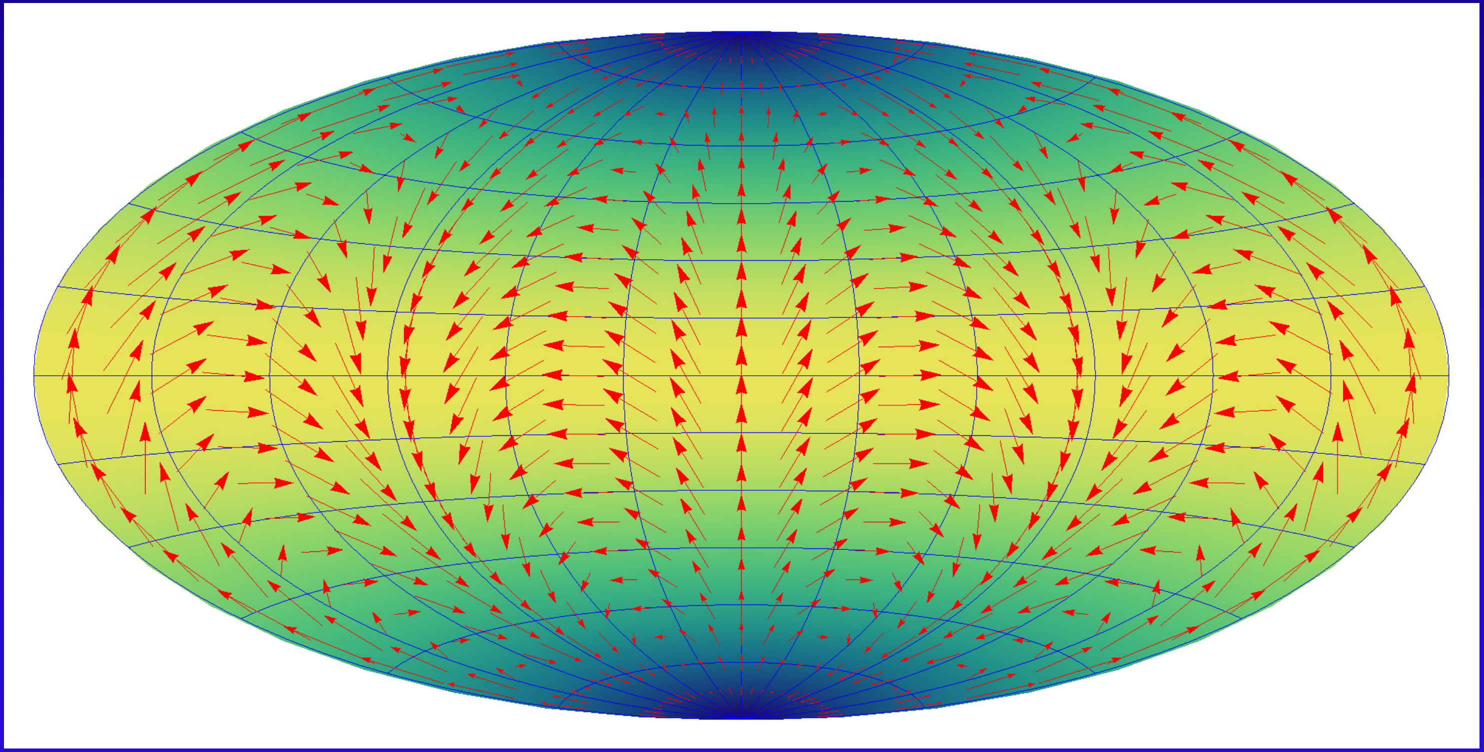


Diffuse background of GW

- A GW of strain *h* and frequency *ω* propagating in the direction δ= 90°

$$\vec{\mu} = \frac{1}{2}\omega h \sin \omega T \cos \delta \left(\cos 2\alpha\, \mathbf{\vec{e}}_\delta + \sin 2\alpha\, \mathbf{\vec{e}}_\alpha \right)$$

- Gaia can constrain the flux at very low frequencies ($<10^{-8}$ Hz)



credit : S. Klioner

Equations of Motion for a test body

- EIH equations with $M_s \gg M_p$, $V_s \ll V_p$
  - Heliocentric form
  - good for gravitation on asteroids and comets

$$\frac{d^2\mathrm{r}}{dt^2} = -\frac{k^2\,\mathrm{r}}{r^3}$$

Newton Sun

$$-k^2 \sum_p M_p \left[\frac{\mathrm{r}-\mathrm{r}_p}{\left|\mathrm{r}-\mathrm{r}_p\right|^3} + \frac{\mathrm{r}_p}{r_p^3} \right]$$

Newton planets

$$+\frac{k^2}{c^2 r^3}\left[2(\gamma+\beta)\frac{k^2\mathrm{r}}{r} - \gamma(\dot{\mathrm{r}}\cdot\dot{\mathrm{r}})\mathrm{r} + 2(1+\gamma)(\dot{\mathrm{r}}\cdot\mathrm{r})\dot{\mathrm{r}} \right]$$

Einstein + PPN

$$\Delta\varpi = \frac{2\pi GM}{a(1-e^2)c^2}\left[-(\gamma+\beta) \qquad +\gamma \qquad +2(1+\gamma) \right]$$

Precession per orbit

Determination of β : Orbits of minor planets

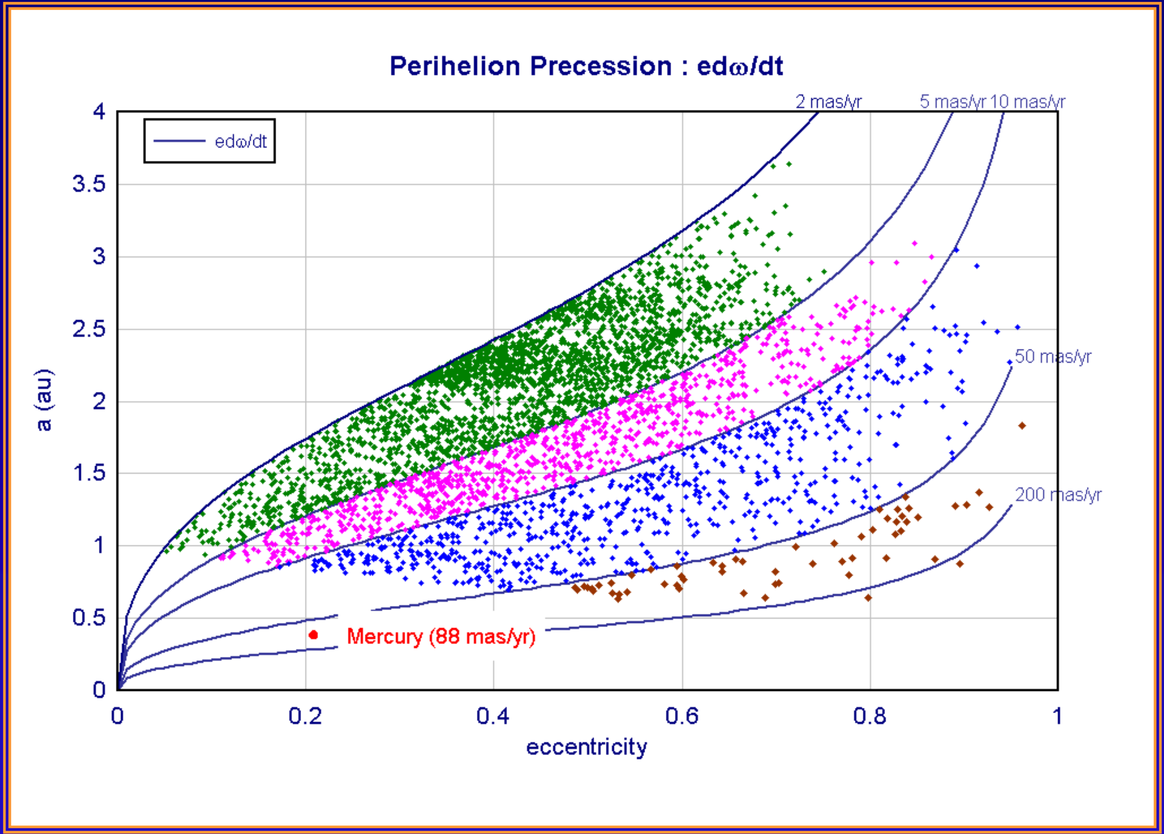
- About 350,000 planets observable with Gaia
- Accurate astrometry corrected for phase effect
- ~ 60 observations each over 5 years
- Accurate orbits determined with Gaia data
- Perihelion precession included in the dynamical model

$$\Delta\varpi = \frac{6\pi\lambda\, GM}{a(1-e^2)c^2} + \frac{3\pi\, J_2 R^2}{a^2(1-e^2)^2}$$

$$\lambda = (2\gamma - \beta + 2)/3$$

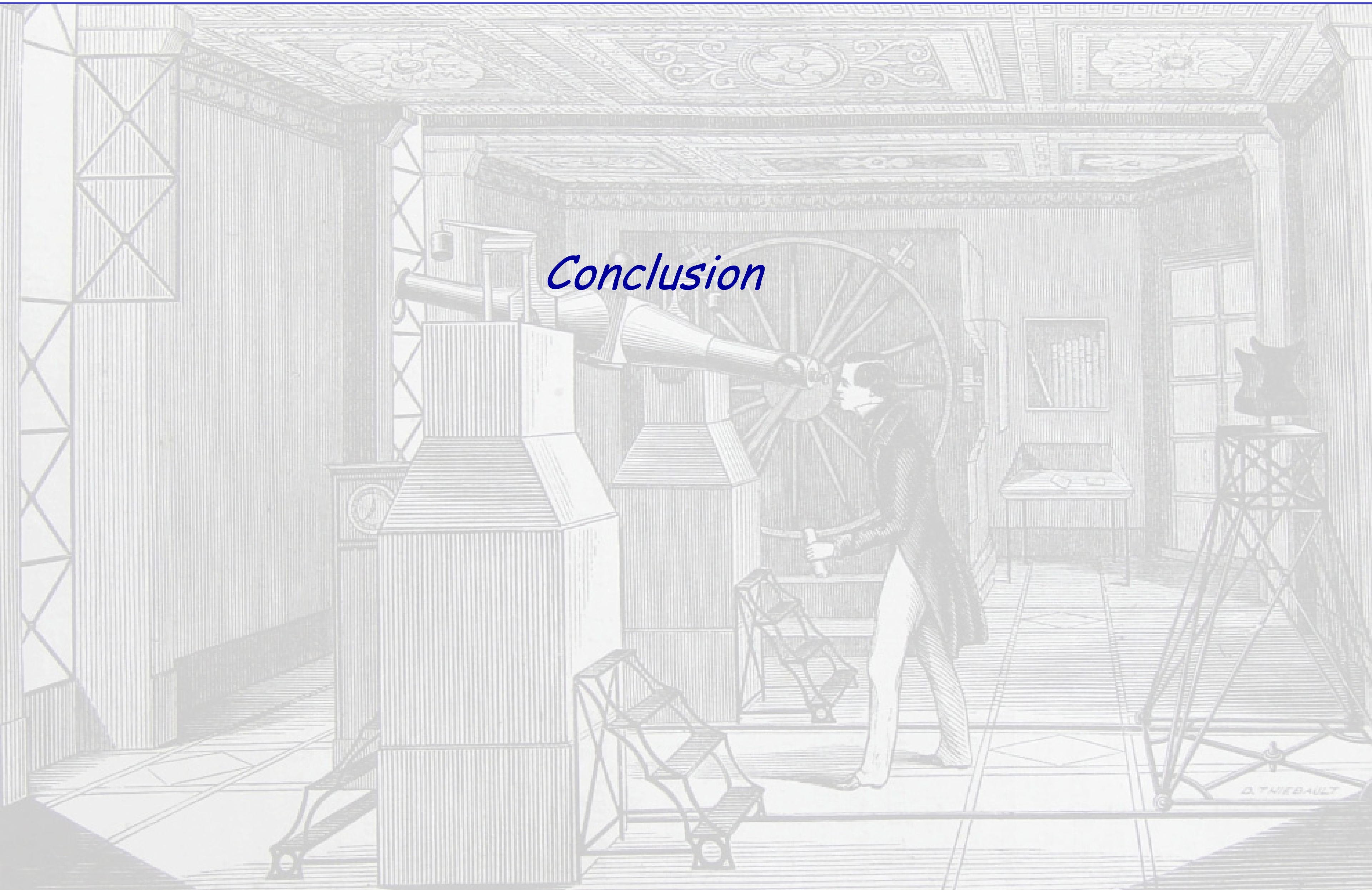
$$\dot{\omega} = \frac{38\lambda}{a^{5/2}(1-e^2)} + \frac{0.04(J_2/10^{-6})}{a^{7/2}(1-e^2)^2} \quad \text{mas/yr} \; (a \text{ in AU})$$

Perihelion precession : $e d\varpi/dt$



- Parameters fitted with Gaia
  - PPN β , Solar J2, $\dot{G}/G$
- Expected precision $\sigma(\beta) \sim 10^{-3}$ to 5×10^{-4} (Hestroffer et al.)

Conclusion



Summary: Promises with Gaia

- Deflection of Light
  - Monopole from the Sun : σ_γ ~ 10^{-6} factor 20 improvement
  - First detection around planets of relativistic effect
    - Monopole from Jupiter to 10^{-3} , quadrupole light deflection to S/N~ 5
- Precession of perihelion of minor planets
  - several 10s planets with large eccentricity
  - $\sigma_\beta \sim 10^{-3}$ $\sigma_{J2/sun} \sim 10^{-7}$ $\dot{G}/G \sim 10^{-12}$ /yr
- Global pattern with proper motion of quasars
  - acceleration of the solar system wrt QSOs → $\sigma_a/a < 0.1$
  - improved estimates of the stochastic background of low frequency GW : a 100 times improvement to best estimates
- Astrometry of relevant source for relativistic modeling
  - QSOs, CygX1


Gaia launch: 20 November 2013
@ 08:57:30 UTC
esa
http://www.esa.int/esatv/Television + web streaming