Astrométrie Spatiale avec Gaia

Relations avec la physique fondamentale

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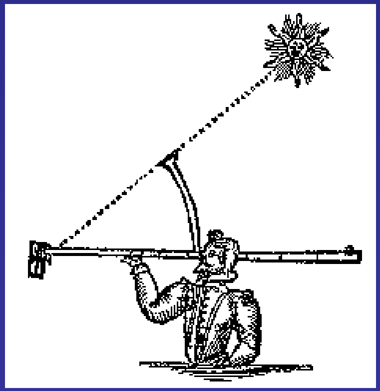
Outline

- Global Astrometry
- The Gaia mission
  - principles
  - performances
- Fundamental physics with astrometry
  - light deflection
  - planetary motions

What is meant by Astrometry ?

- Astrometry deals with the measurement of the positions and motions of astronomical objects on the celestial sphere.
  - Global or wide field astrometry
  - Local or small field astrometry
- Astrometry relies on specialized instrumentation and observational and analysis techniques.
- It is fundamental to all other fields of astronomy.



Goals of Global Space Astrometry

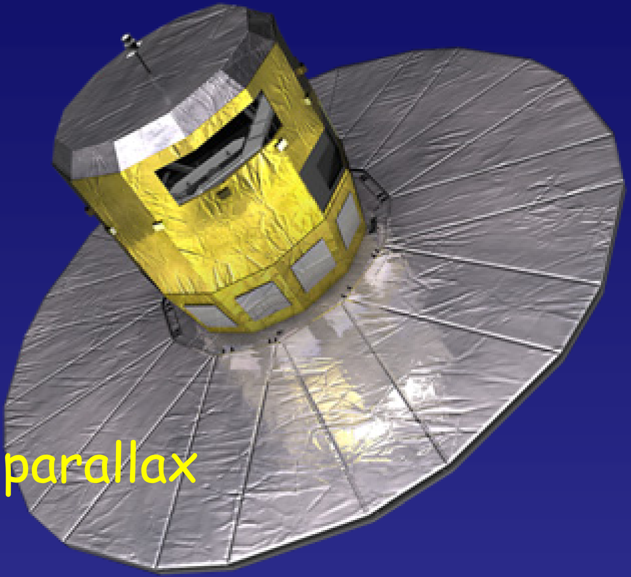
- Primary Objectives not achievable from Earth
  - Ascertain the distances of the stars
    - **absolute** stellar parallaxes for astronomers
  - Define and materialise the inertial frame
    - now based on extragalactic sources
- Secondary objectives
  - Astrophysics with astrometry, photometry, spectroscopy
    - stellar and galactic physics
    - detection of extrasolar planets
    - solar system dynamics
  - Tests of fundamental physics in space
    - based on light path geometry

Gaia: Mission requirements summary

- A Stereoscopic Census of Our Galaxy
- Astrometry (V < 20):
  - completeness to 20 mag (on-board detection) 10^9 stars
  - parallax accuracy: 7 μas at <10 mag; 12–25 μas at 15 mag 100–300 μas at 20 mag
- Photometry (V < 20):
  - astrophysical diagnostics (low-dispersion photometry) + chromaticity
  - 8–20 mmag at 15 mag: Teff ~ 200 K, log g, [Fe/H] to 0.2 dex, extinction
- Radial velocity (V < 16.5–17):
  - Third component of space motion, perspective acceleration
  - <1 km/s at 13-13.5 mag and <15 km/s at 16.5-17 mag

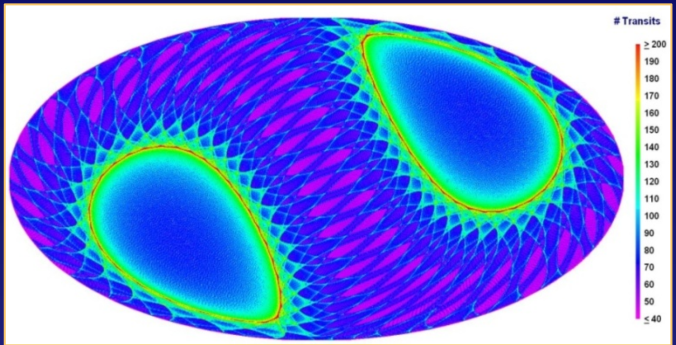
Gaia quick fact sheet

- Main goal : astrometry and photometric survey to V = 20
  - ~ 10^9 sources
    - stars, QSOs, Solar system, galaxies



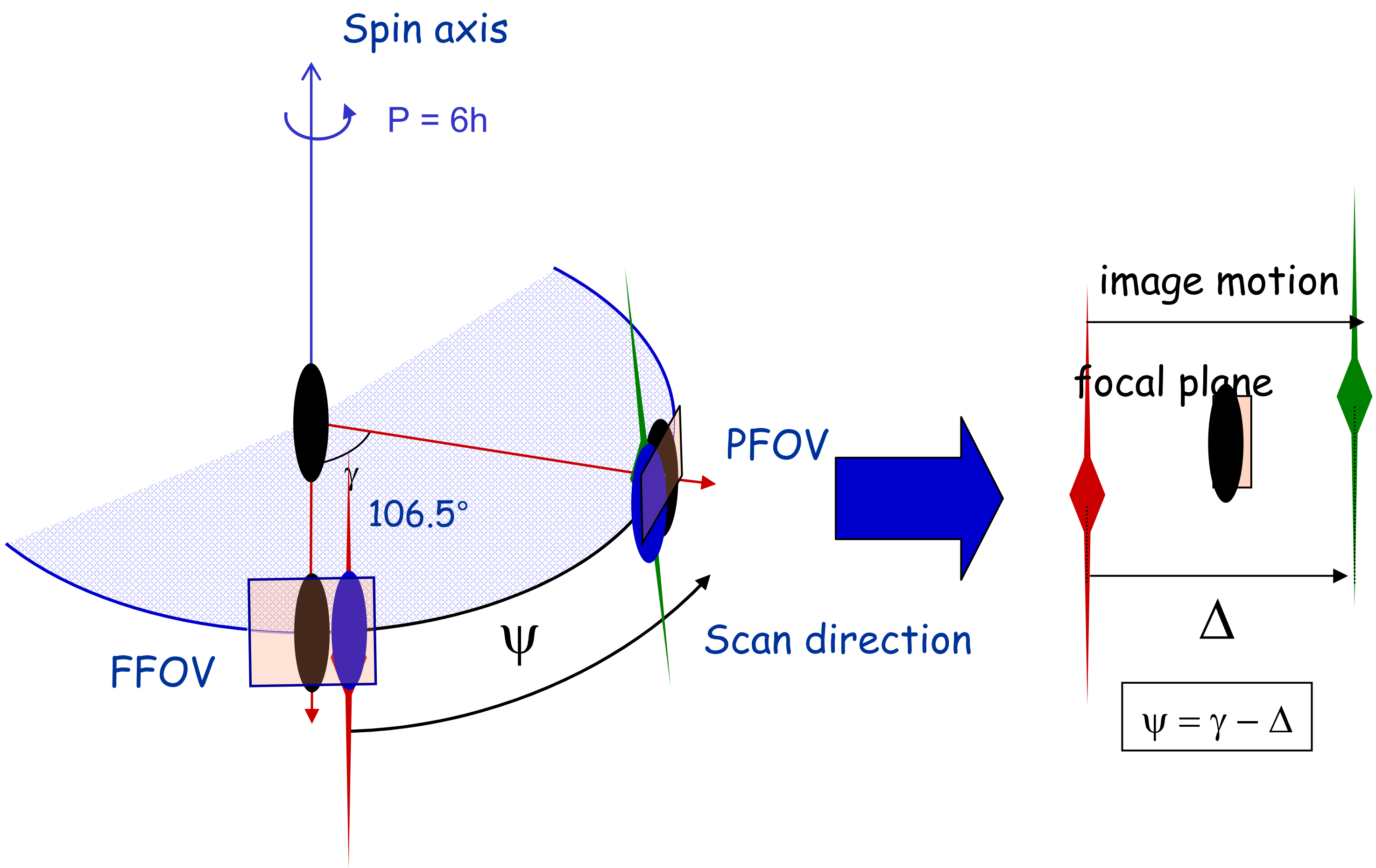
- Accuracy in astrometry : 25 μas @ V = 15 for parallax
  - 10 μas V < 13 - 300 μas V = 20
- Regular scan of sky over 5 yrs
  - each source observed about ~80 times
  - internal autonomous detection system
- Launch October 2013 from Kourou
- Current integration of P/L and S/M advancing smoothly

Observation principles



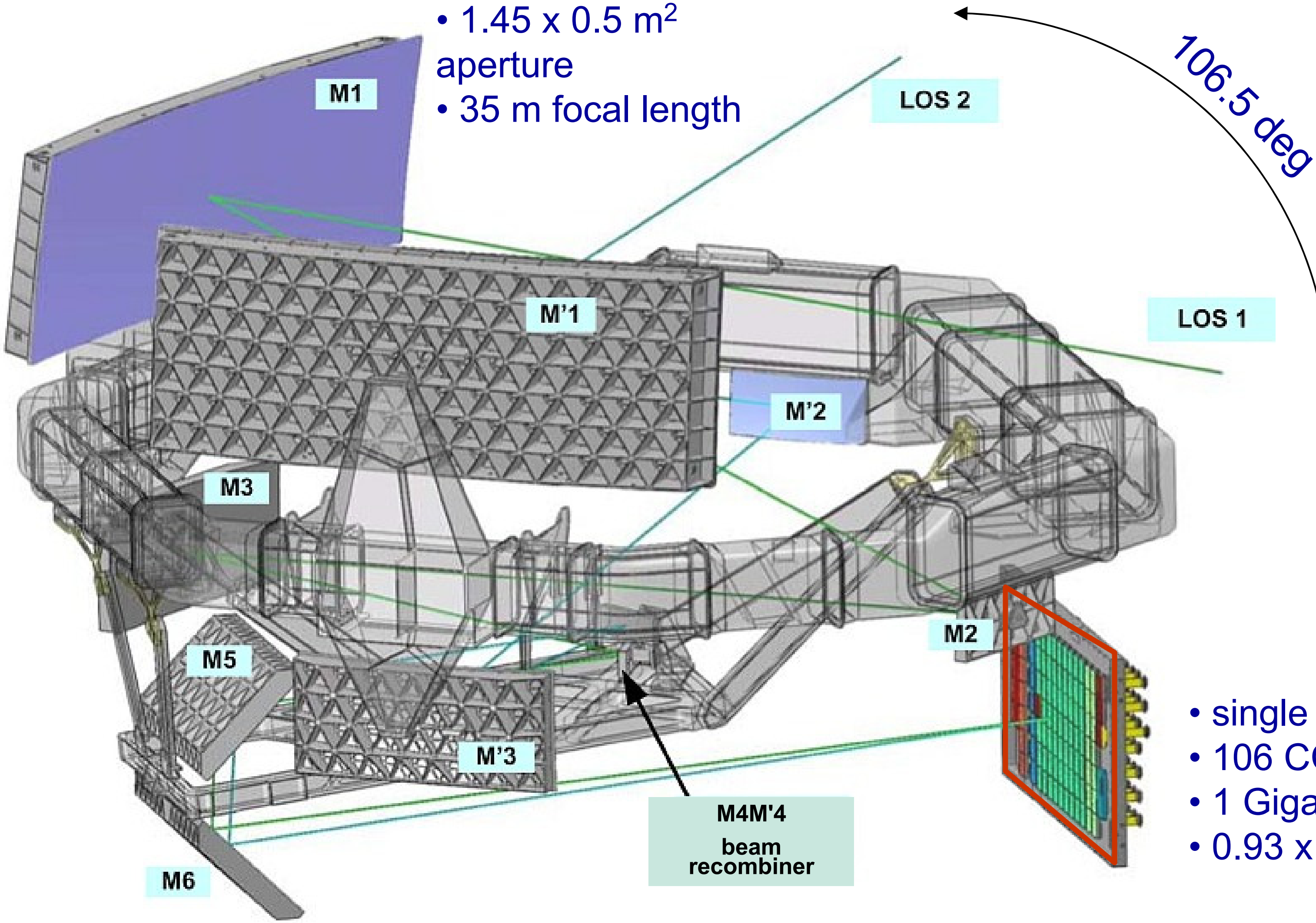
- Gaia is a scanning mission
  - no pointing, no change in the schedule
- Gaia gathers astrometric, photometric and spectroscopic data
  - each source is observed ~ 75 times in astrometry & photom. , 50 in spectroscopy
- Gaia has an internal system of detection
  - sensitivity limited detection at G ~ R = 20
- Objects are reasonably regularly measured during the mission
  - orbit reconstruction
  - light curves

- Wide angle measurements with overlapping fields



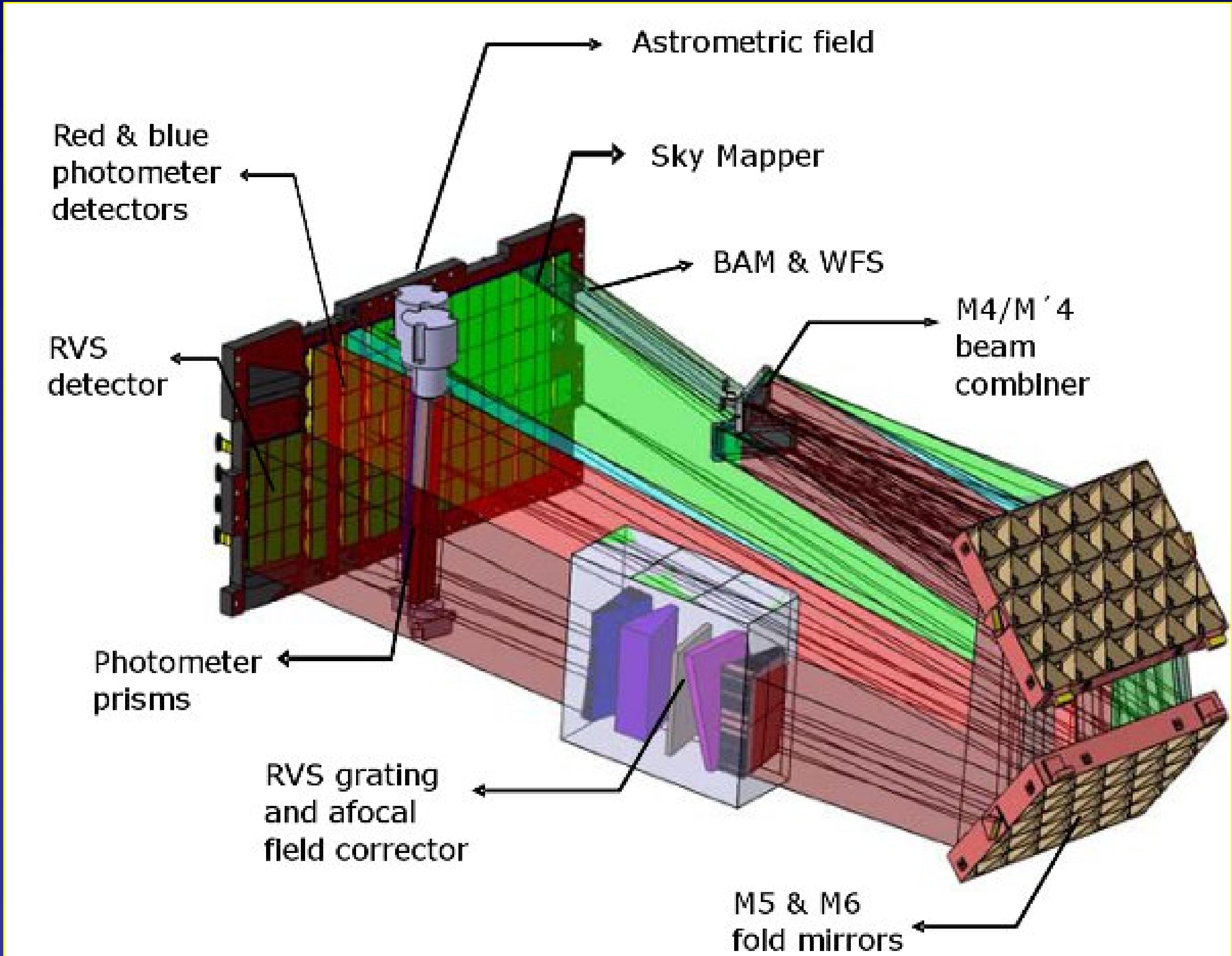
Gaia : telescopes and detector

- 2 off-axis telescope
- 1.45 x 0.5 m^2 aperture
- 35 m focal length

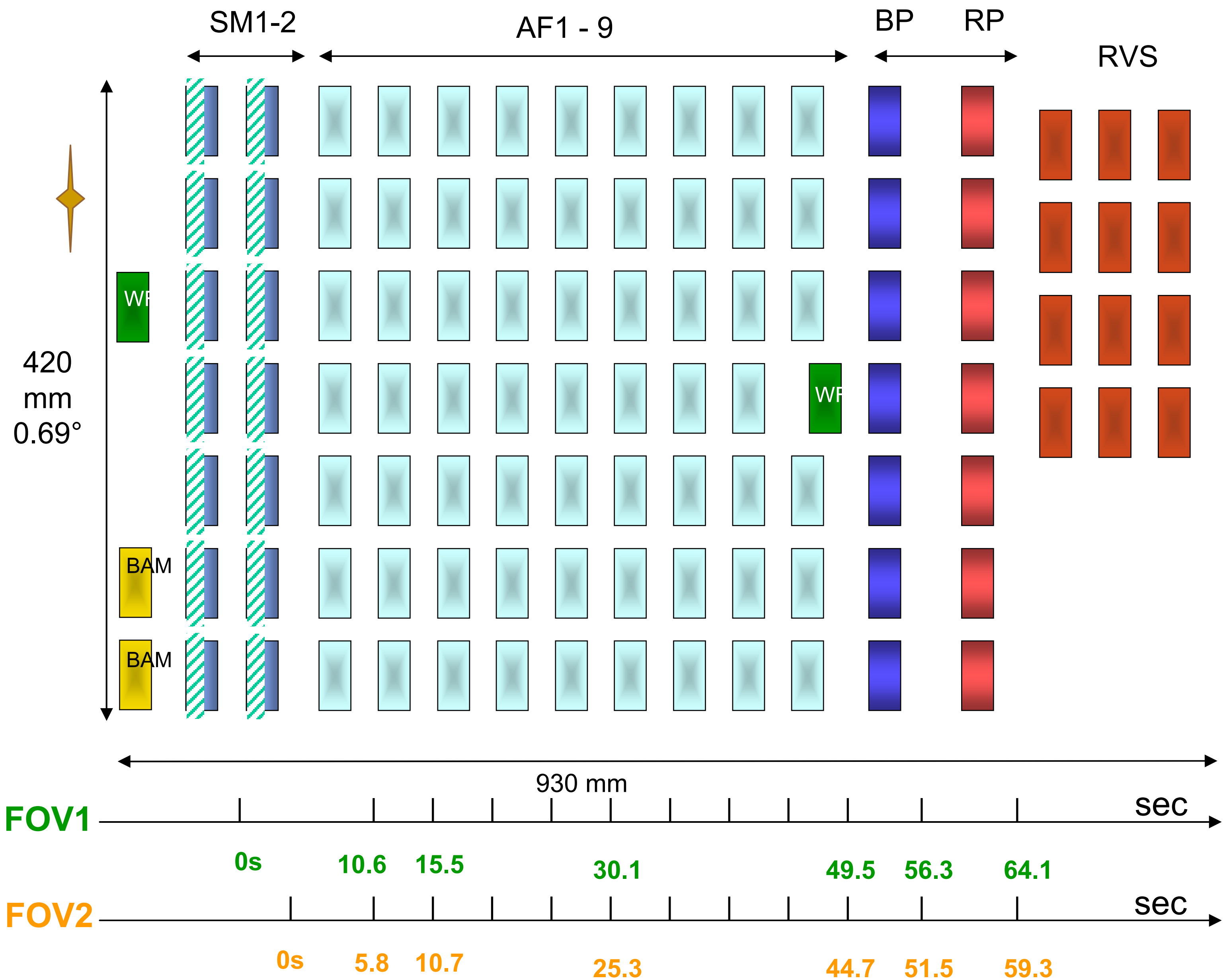


- single focal plane
- 106 CCDs
- 1 Gigapixel
- 0.93 x 0.42 m^2

Photometry & Spectroscopy



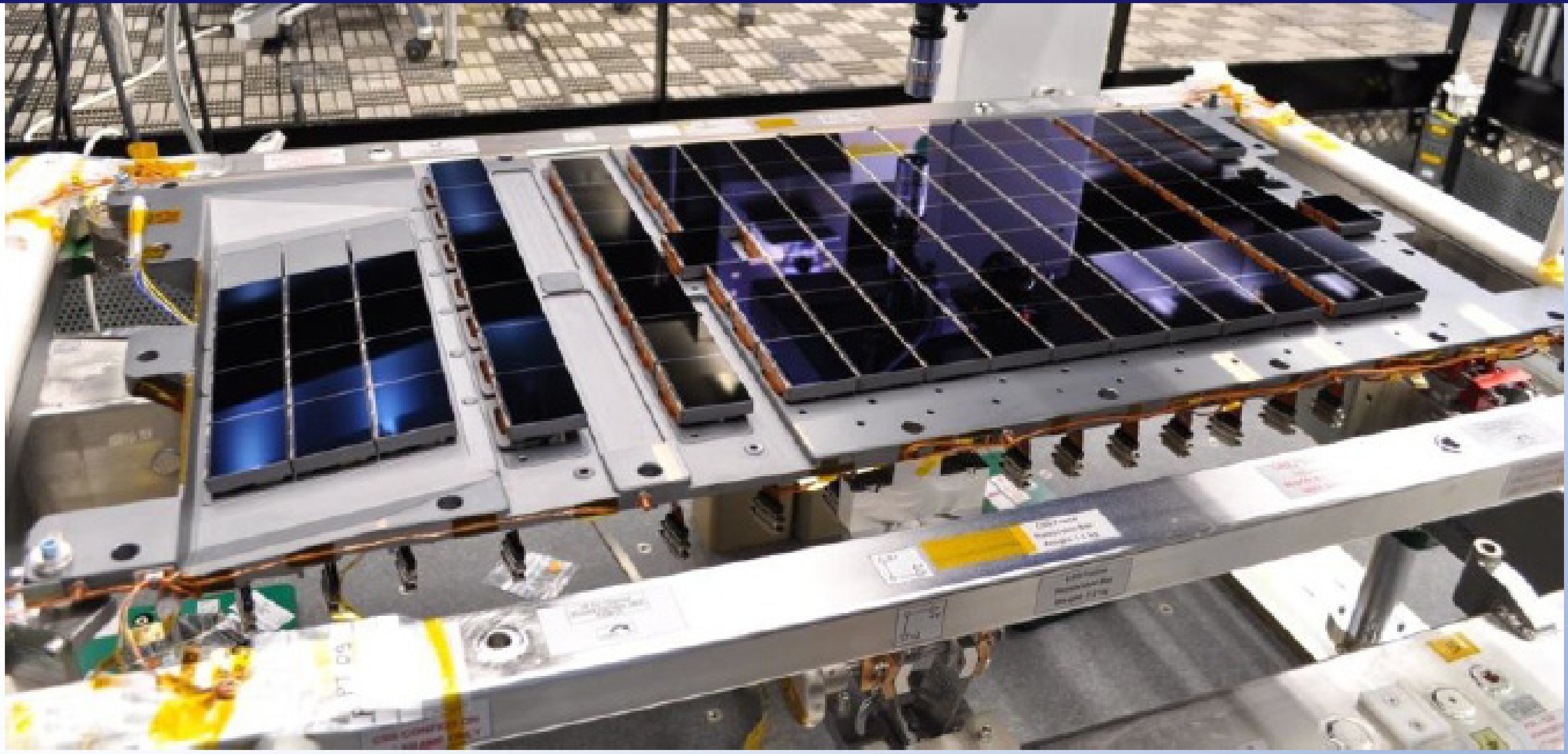
Focal Plane Assembly



106 CCDs , 938 million pixels, 2800 cm2

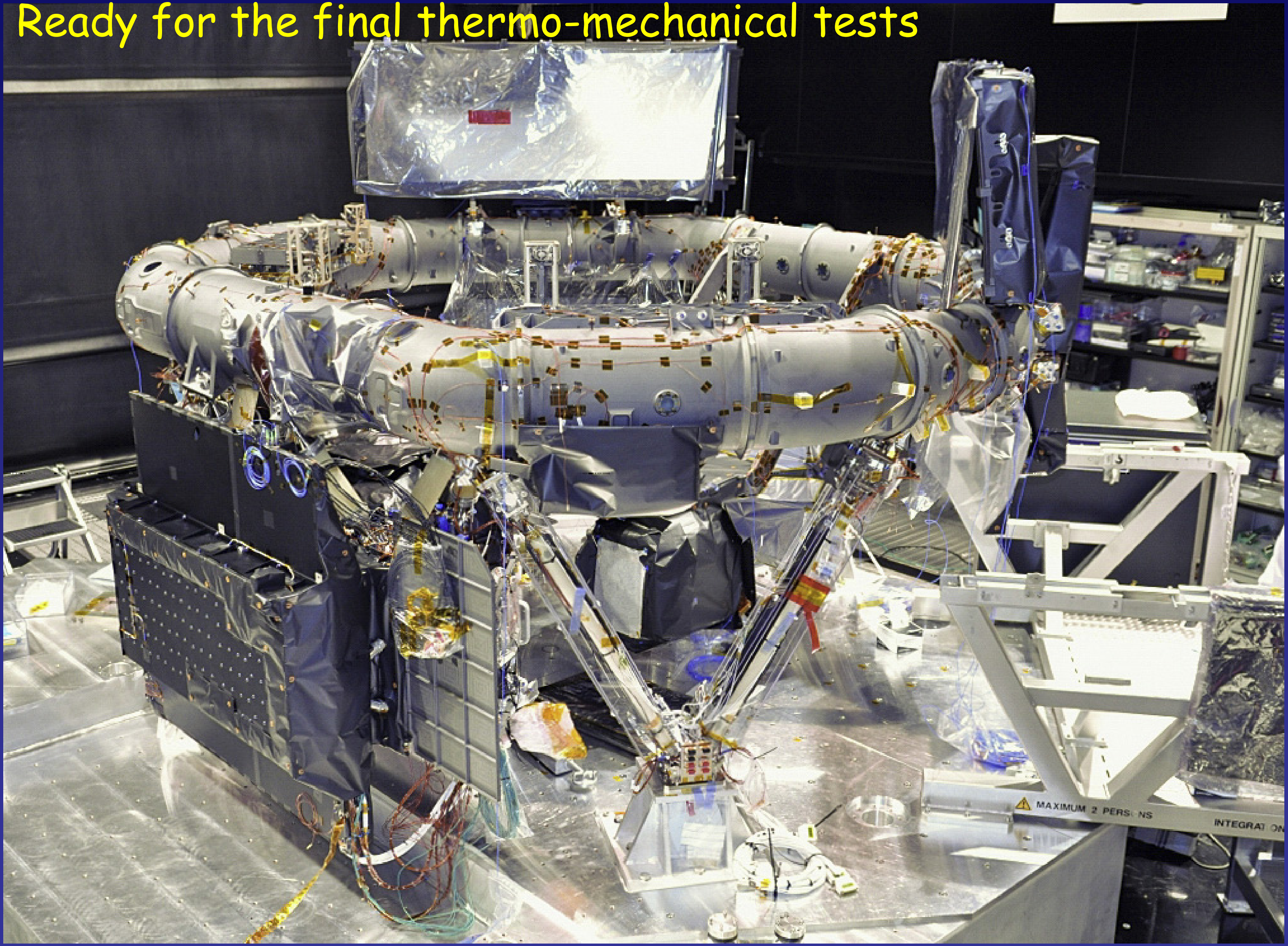
The True Focal Plane Assembly

- System fully integrated now in the P/L
- All tests completed



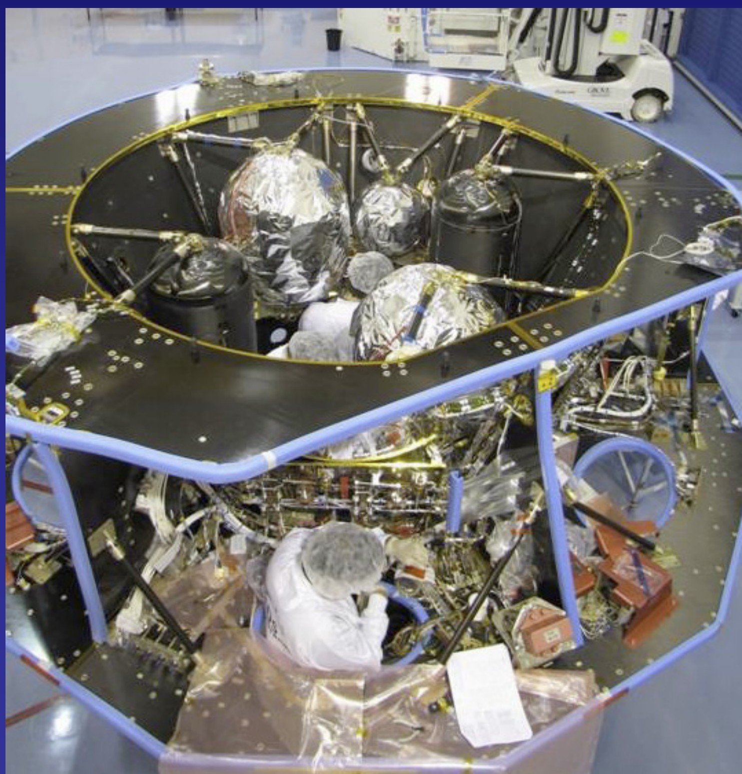
Gaia Payload Module

- Ready for the final thermo-mechanical tests



Main Activities on the S/C

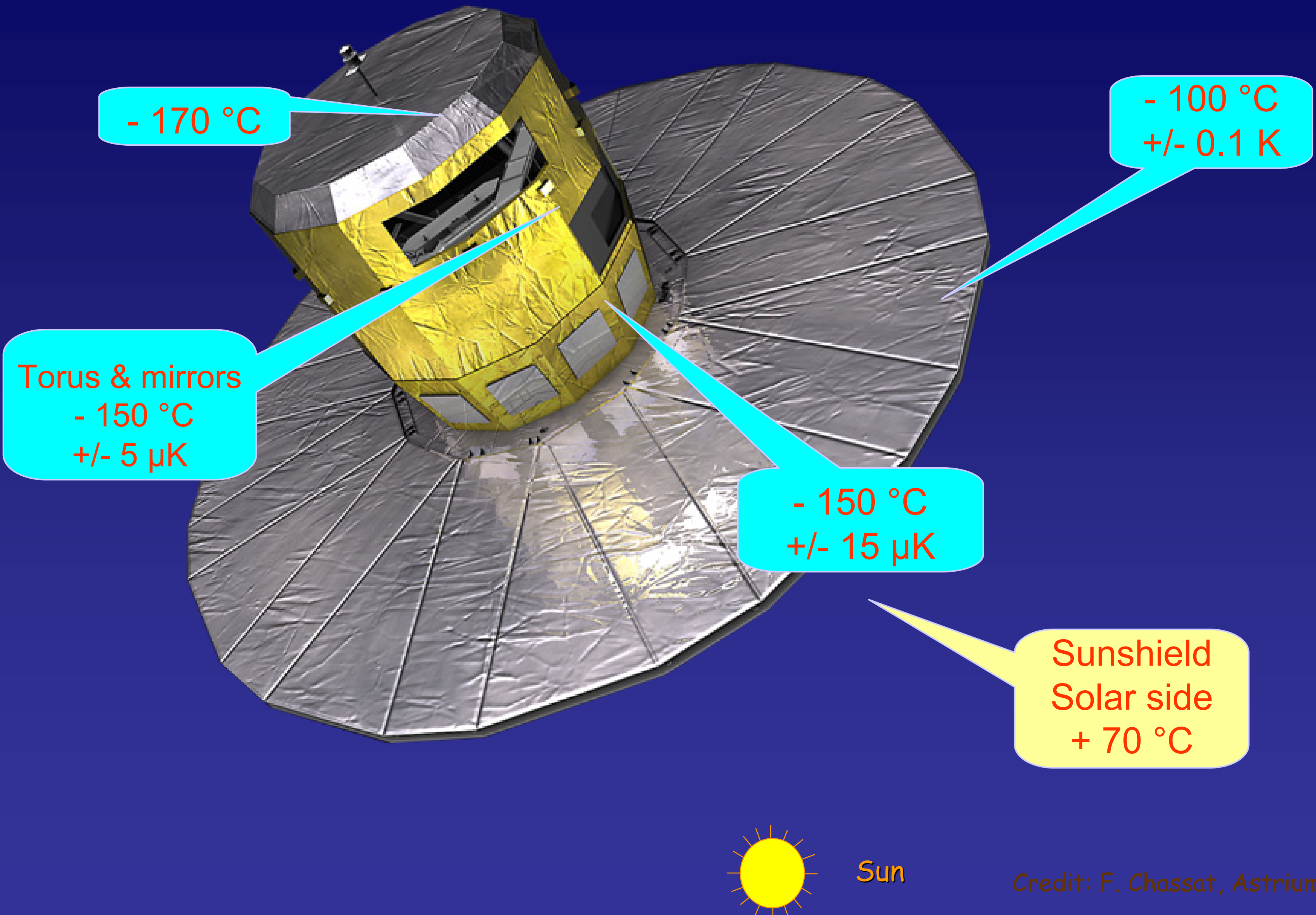
- Service Module finalised
- Thermal/vacuum tests during summer



- Deployable Sunshield qualified
- Put into storage

Fully Deployed Sunshield

Thermal Insulation

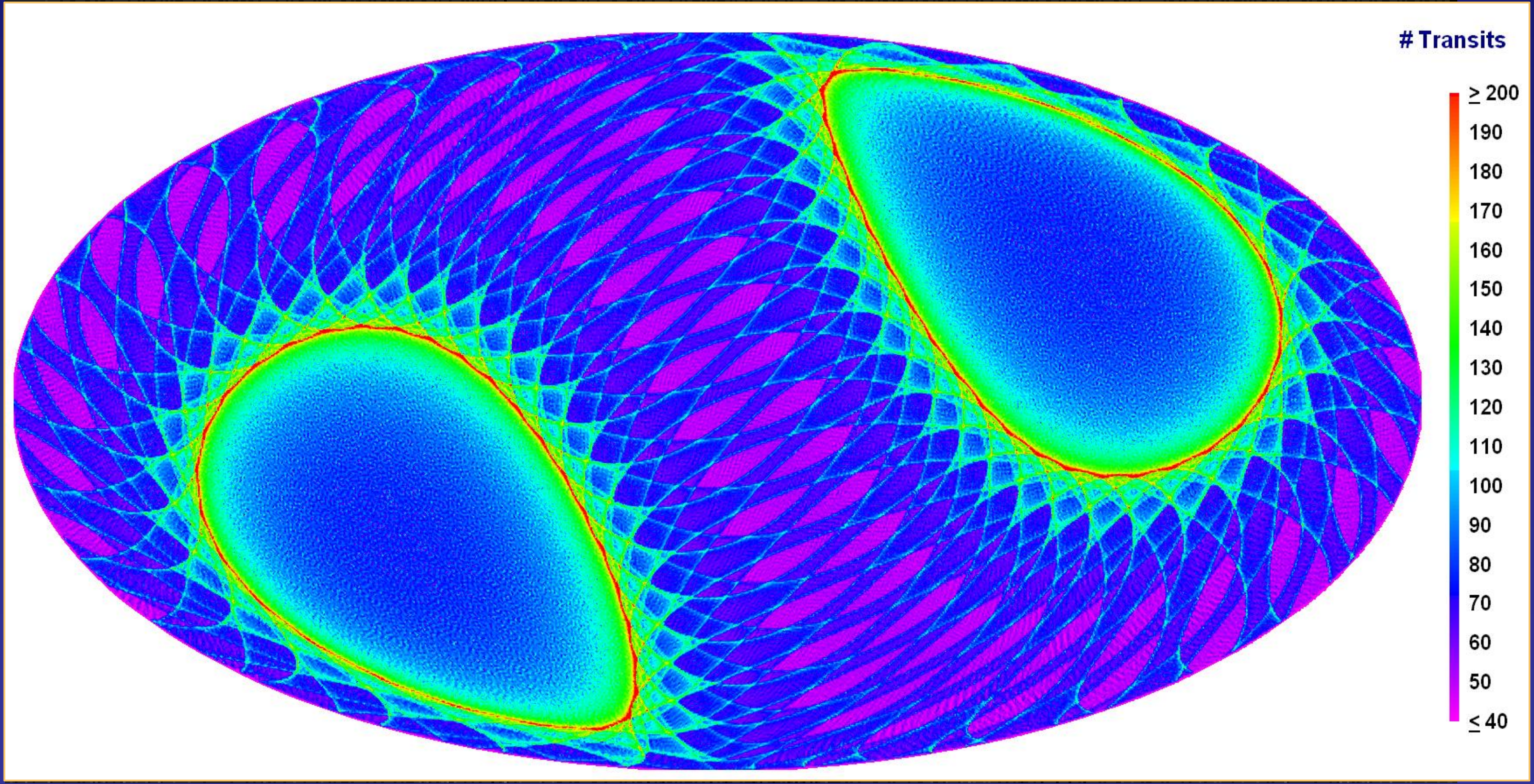


Sky coverage

- The Scanning law is optimized to explore the same area at more or less regular intervals:
  - parallax, proper motion, variability, orbits
- The scan direction must allow alpha and dec measurements
- The along-scan speed must be constant
- Mathematically: a set of two differential equations
  - Three independent rotational motions

Sky coverage

- Time average is a combination of the sky distribution and the scanning law
  - two different symmetries: galactic plane and eclitpic plane

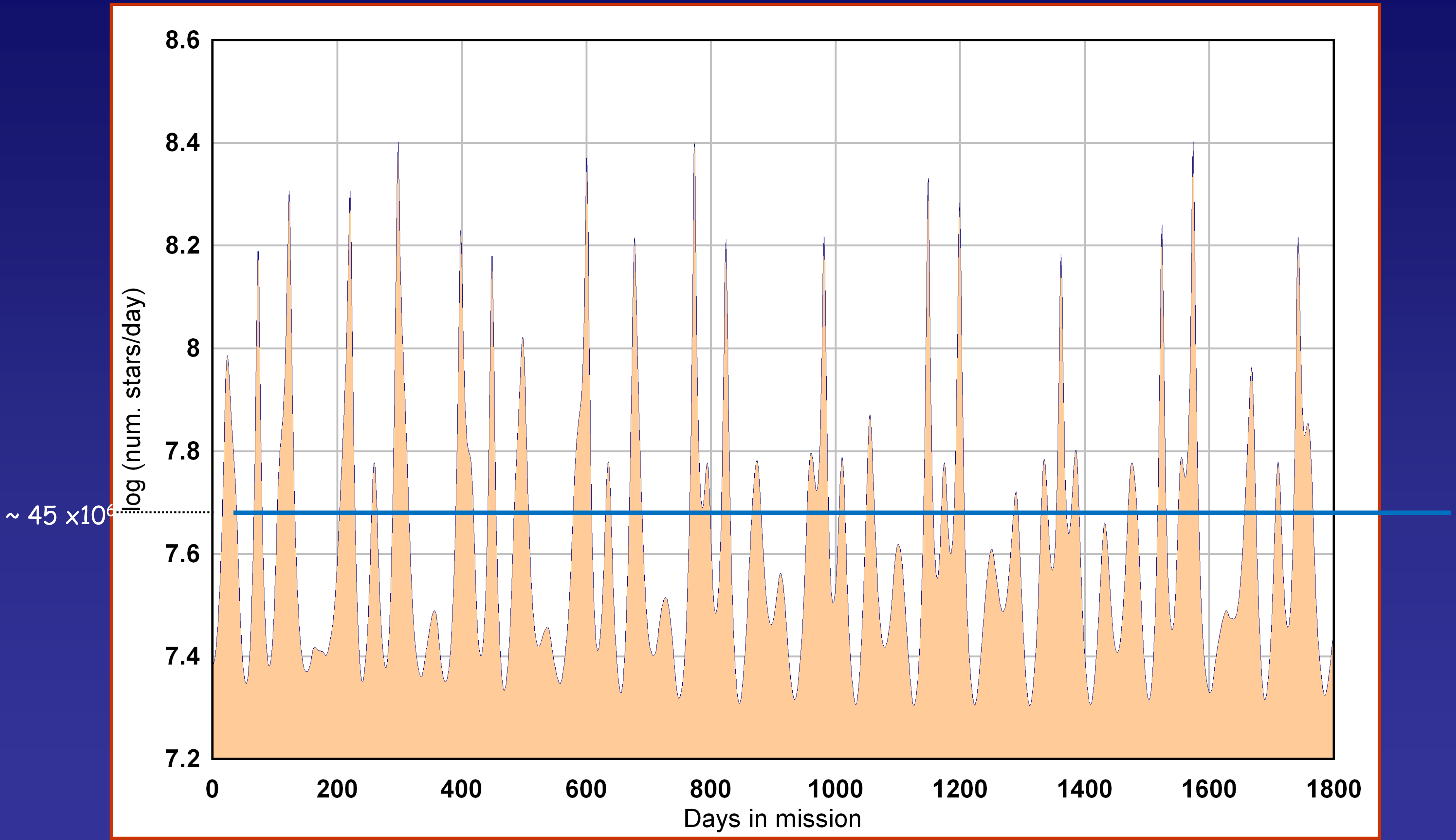


Number of sources per day

- How many sources per day to be processed on board ?
  - number of sources brighter than 20 mag — $\sim 10^9$
  - duration of the nominal mission — 1800 days
  - average number of field transits per source — ~ 80 *(no dead time)*
  - average number per day — $\sim 10^9 * 80/1800 = \sim 45 \times 10^6$
- But large scatter with the orientation of the scan wrt the Galactic plane.
- Detailed study done with a simulation using the nominal scanning law and a galactic model

Number of sources per day

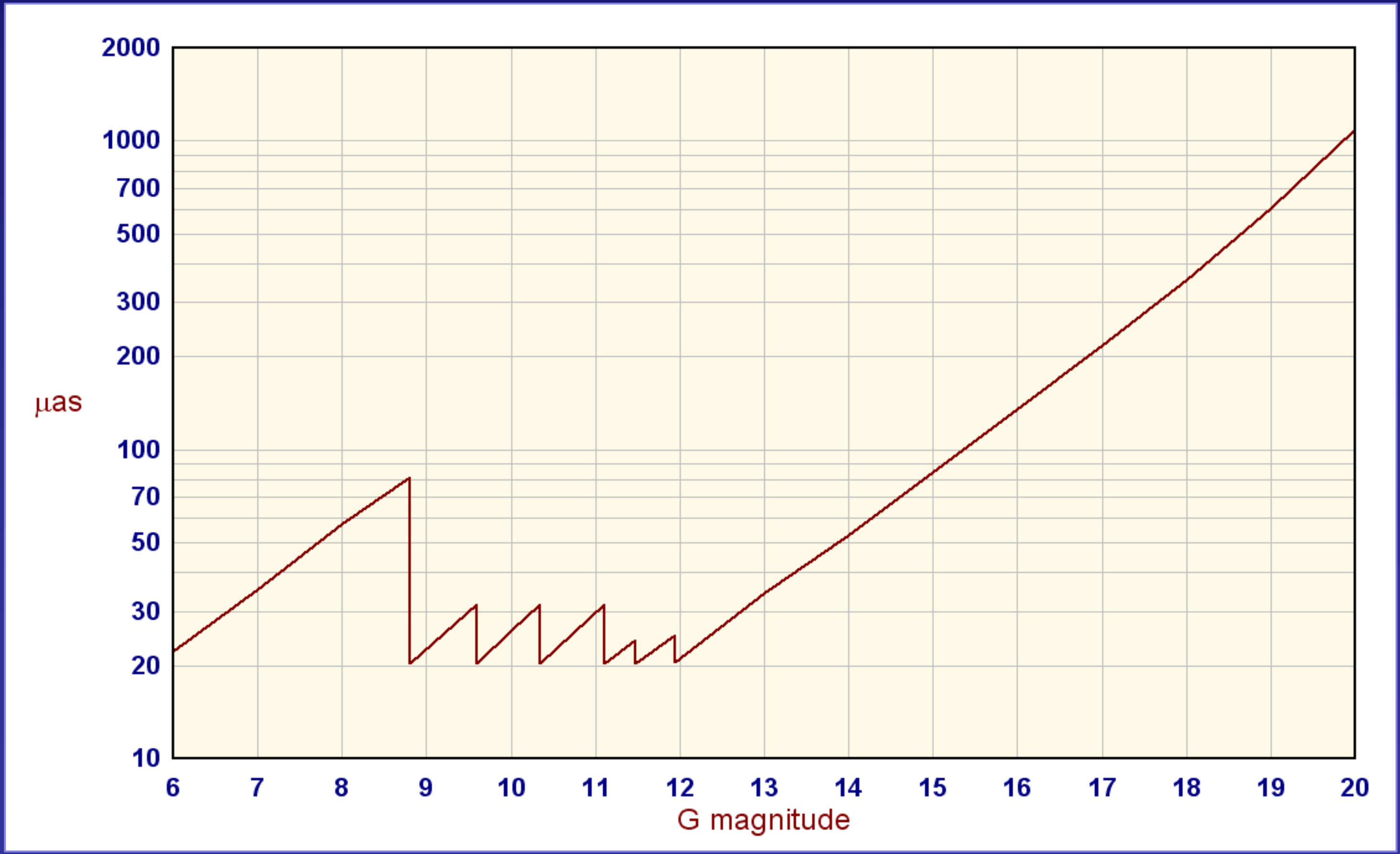
- Number of sources detected per day (log scale) during the mission



Performances

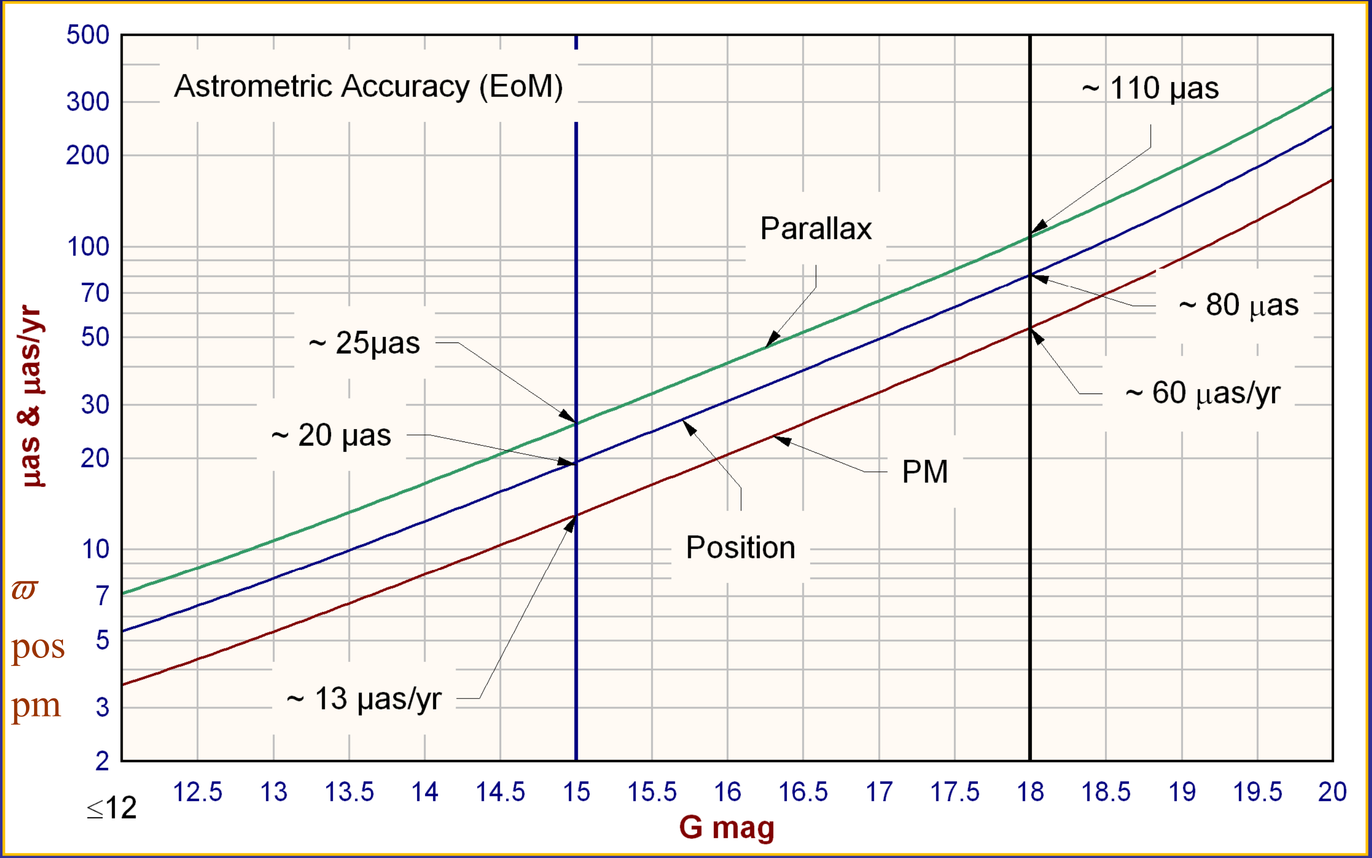
Astrometric accuracy: single transit

- Single observation accuracy ➔ orbit, solar system
  - one field transit: integration over 9 AF CCDs
  - point source



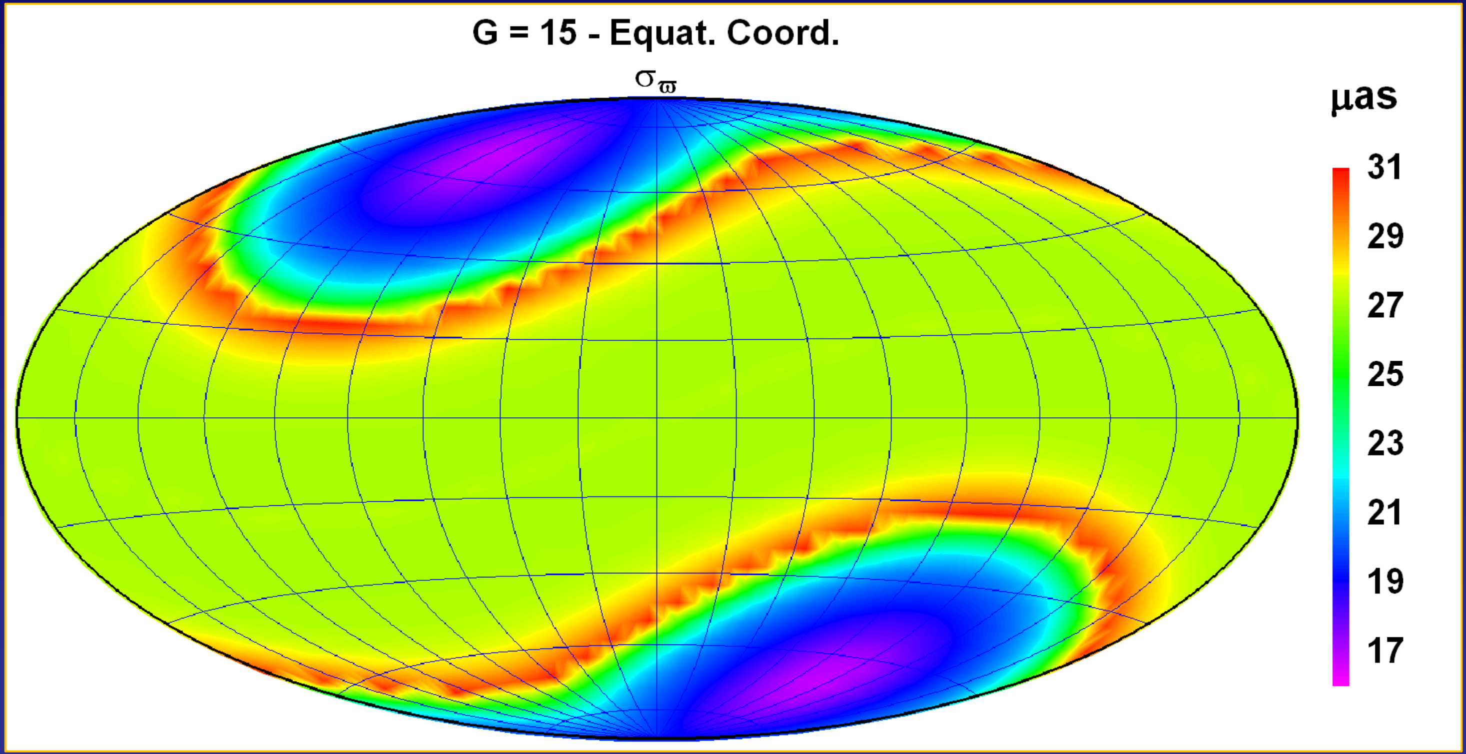
Gaia Accuracy at mean epoch

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



Sky distribution – Parallaxes

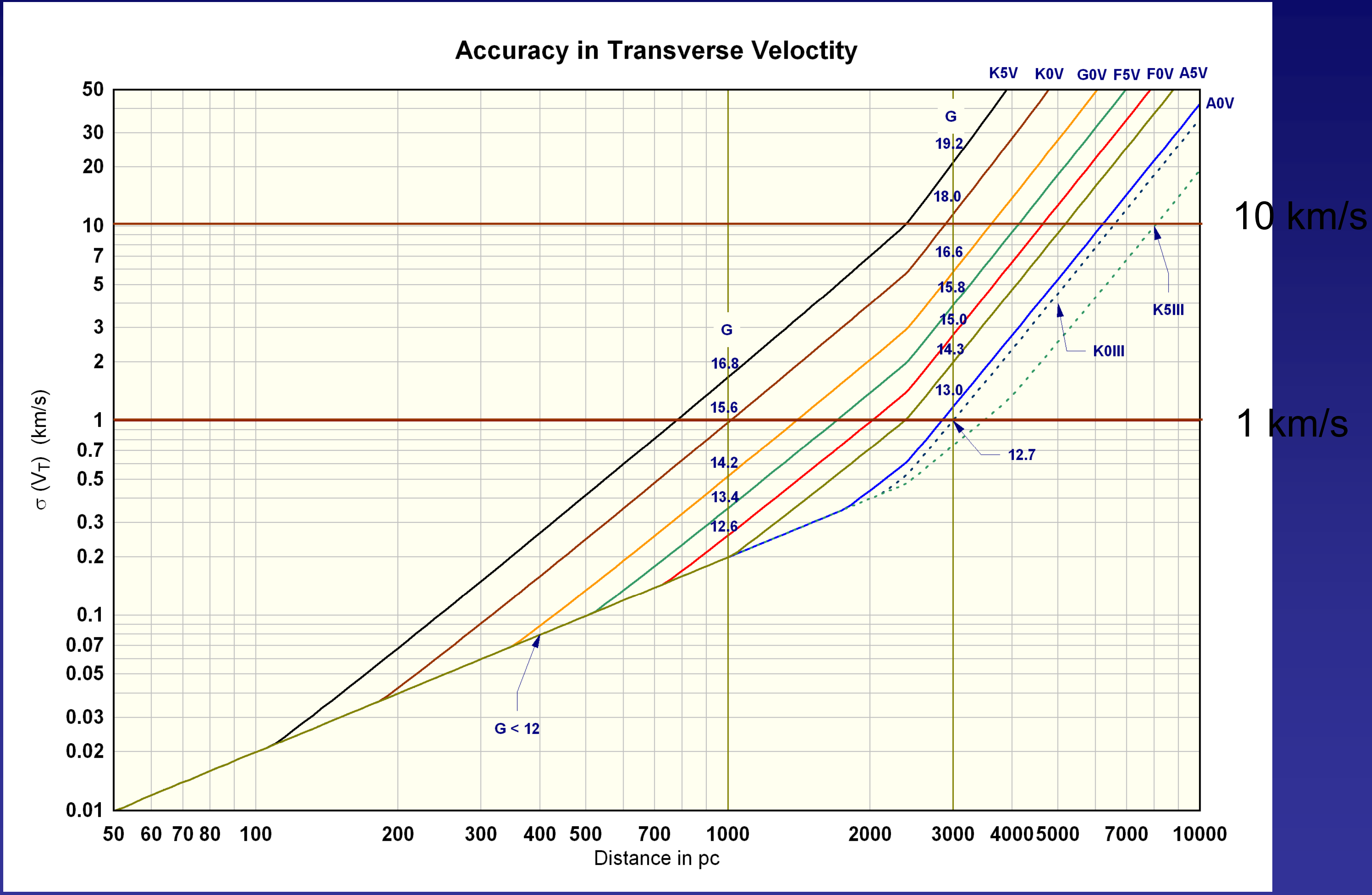
- Plot for G =15, but scalable to other magnitudes



σ_{ϖ} – μas

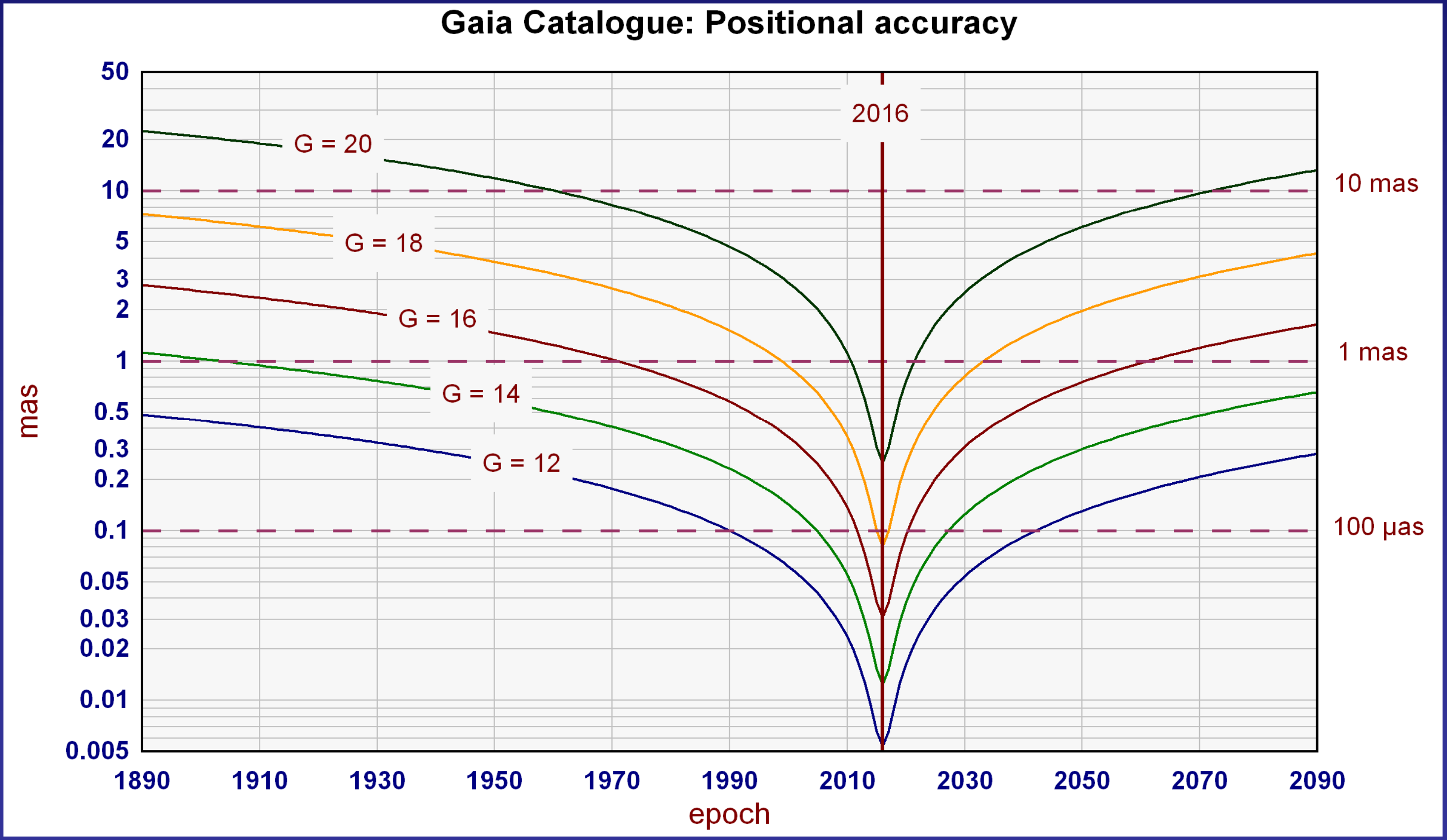
$$< \sigma_{\varpi} > = 25\ \mu\text{as}$$

Transverse velocity estimate with Gaia



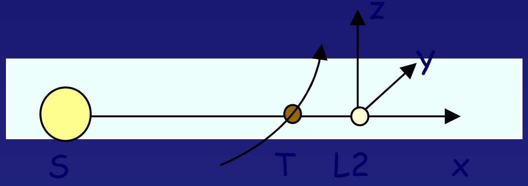
Gaia Accuracy in the past and future

- Covariance matrix fully propagated at t = 1890..2090 step 1 yr
  - sky averaged accuracy
  - mean accuracy between α and δ



Timeline of the mission

- Selection by ESA in 2000 (and confirmed in 2002)
- Prime contractor selected in February 2006
- Data analysis consortium formed in June 2006
  - selected by ESA SPC in March 2007
- Launch : October 2013
  - from Kourou with a Soyuz + Fregat
- Orbit around L2



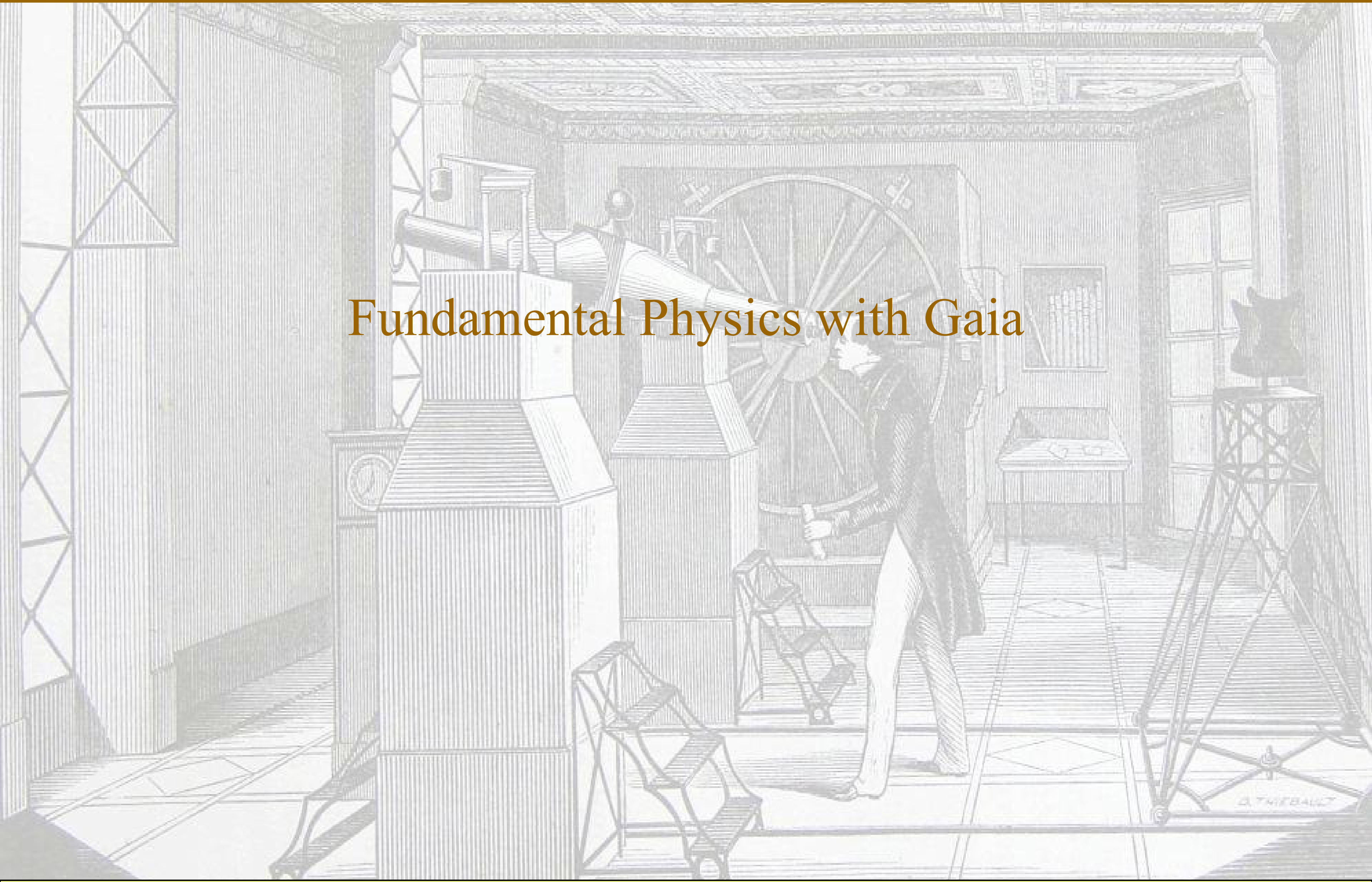
Routine operations start at L + 6 months

- Continuous observation to 2019
- End of data processing to 2020
- Results and data available in 2021
  - intermediate releases planned during the mission

First Soyuz launch from Kourou, 20 October 2011

Gaia launcher manufacturing has started

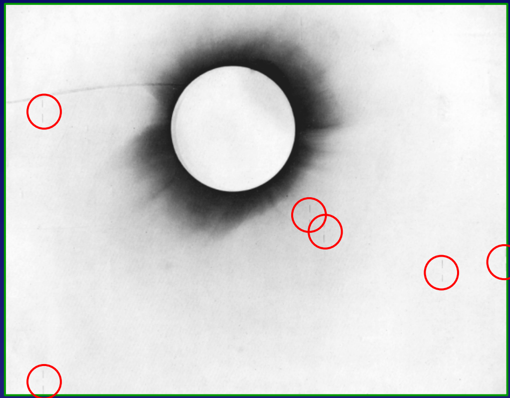
- Soyuz rocket Sz-013



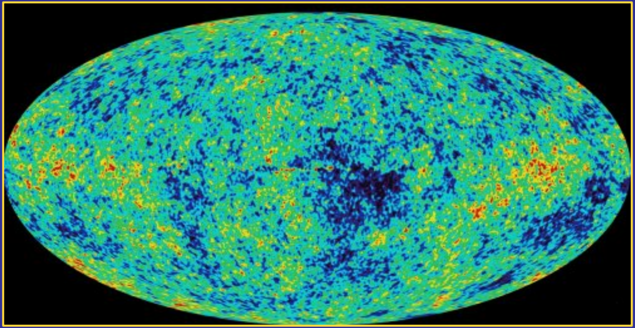
Fundamental Physics with Gaia

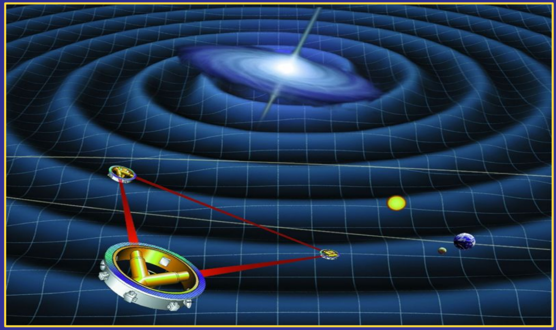
Fundamental Physics & Astronomy

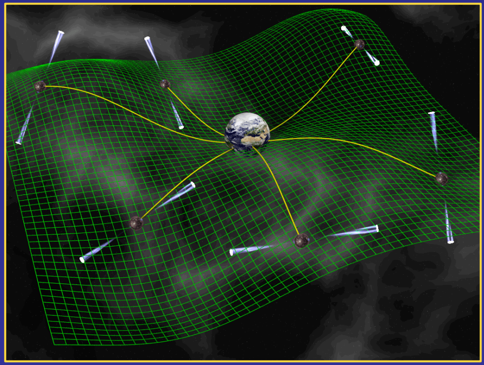
- Relevant topics
  - Very variable according to historical periods
    - dominated by the law of motion, covariance of physical laws under reference frame transformation
  - Closely associated to astrometric accuracy
    - but not only ➔ eg COBE/WMAPS/PLANCK



- 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





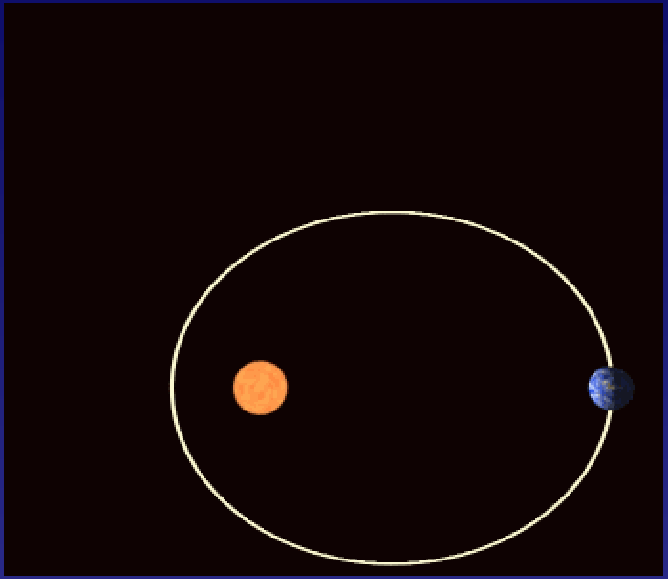


Astrometry → Fundamental laws

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	

- 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

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

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

$$G \neq G(t) \qquad G \neq G(\mathrm{x})$$

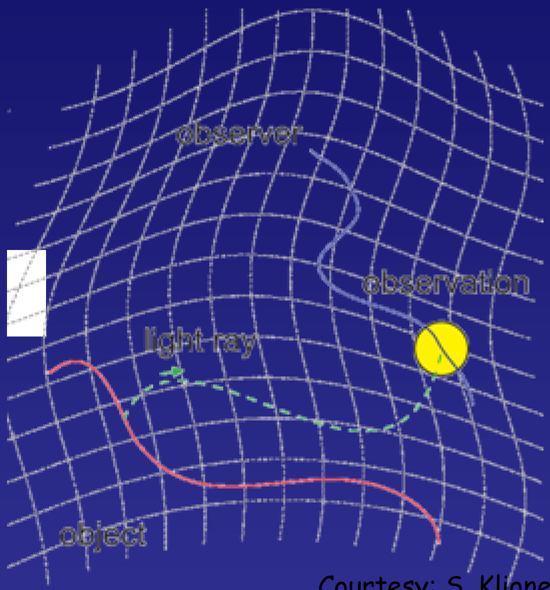
Astronomy can help check these assumptions in the large scale domain

A dual relationship with mutual benefit

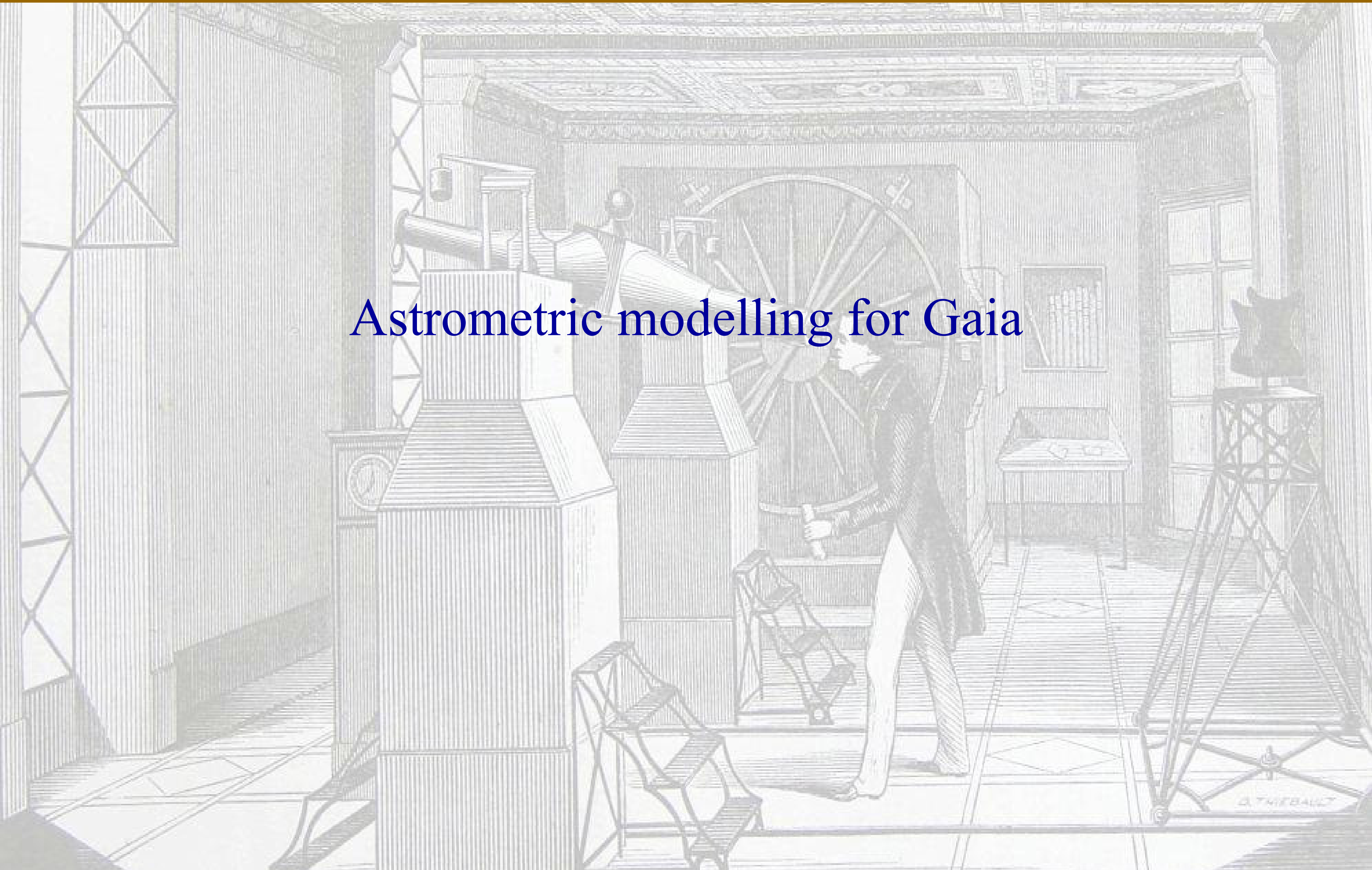
- Astronomy has been the source of early thinking about space and time fundamental properties

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

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



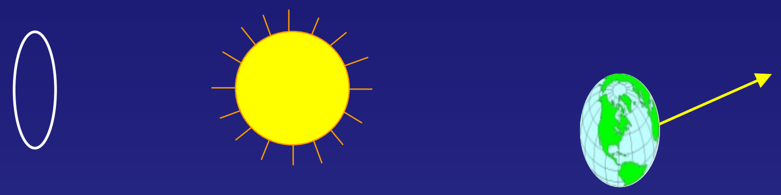
Courtesy: S. Klioner



Astrometric modelling for Gaia

Relativity in Astrometry : when and where ?

- Effects due to motion



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

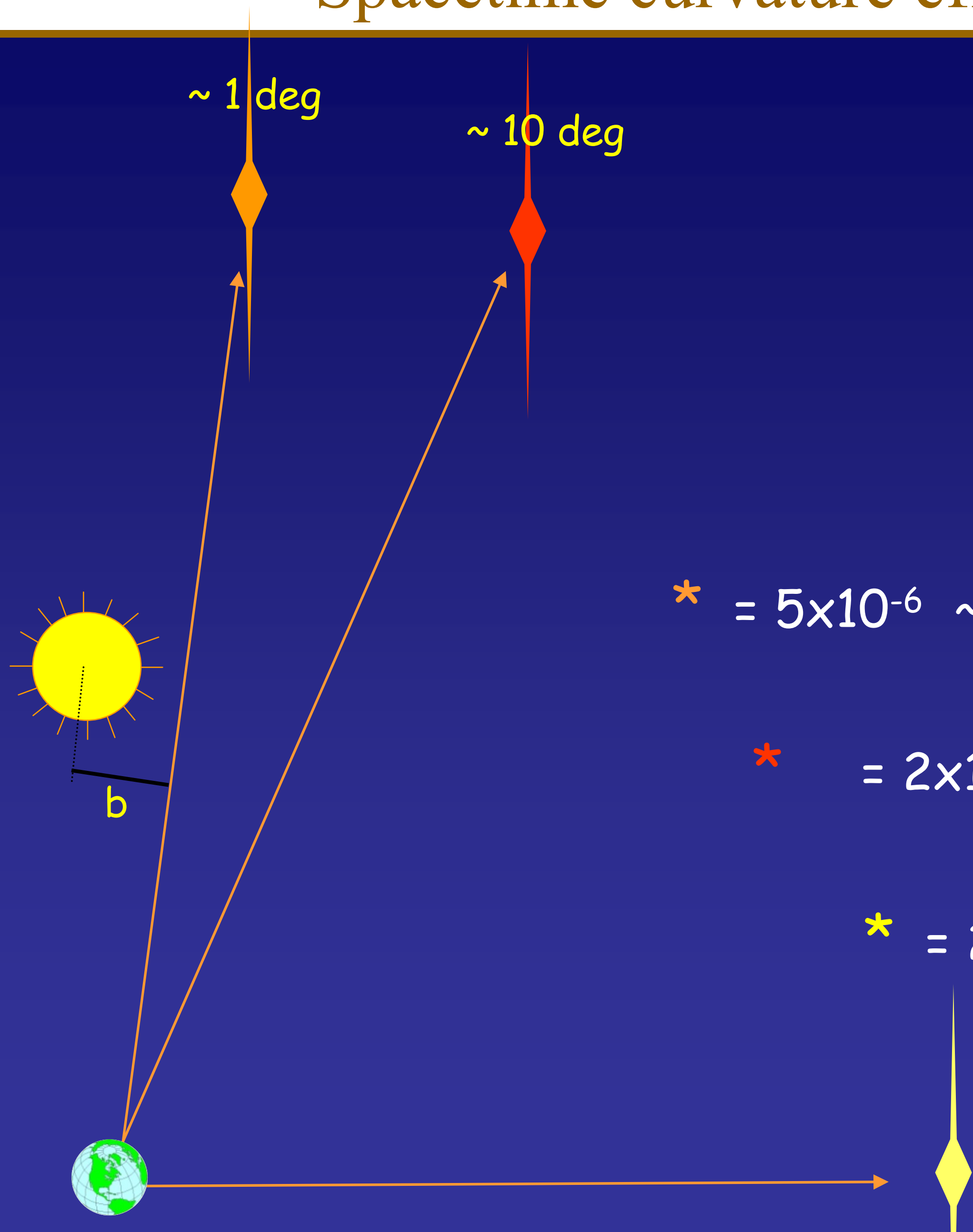
$v^2/c^2 = 10^{-8} \sim 1$ mas

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

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

Test of Local Lorentz Invariance ?

Spacetime curvature effects



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

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

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

* $= 2\times10^{-8} \sim 5$ 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

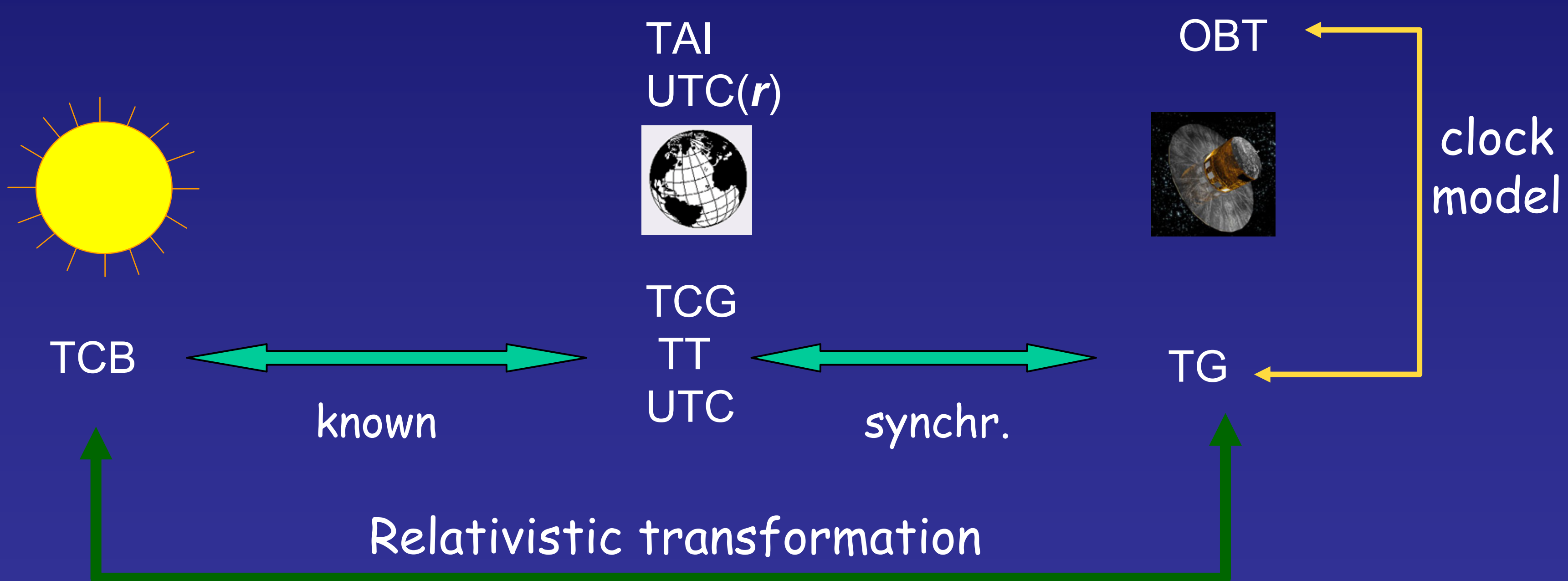
Implementation for Gaia

- 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
- Comparisons are under way to check respective properties
- Solar system ephemeris (INPOP) are consistent with the model

Time Modelling

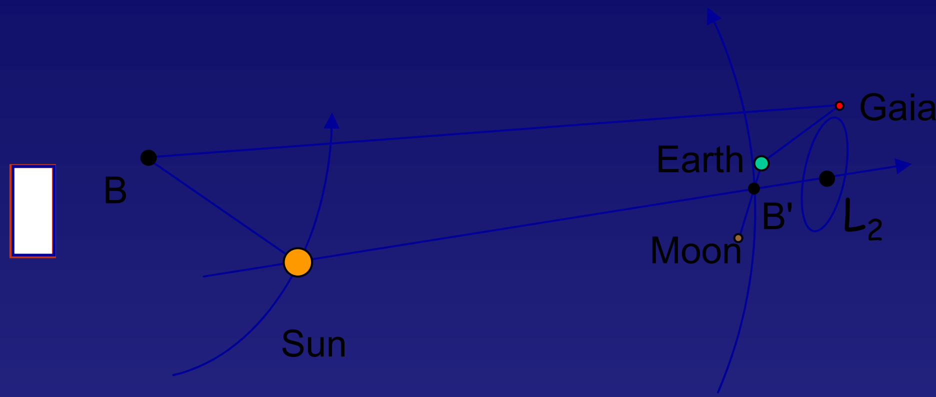
Relevant timescales for Gaia

- Modelling and data processing in TCB
- on-board clock delivering a realisation of TG (→ OBT)
- tracking and ground-based timing in UTC



Mignard, Crosta, Klioner, 2004

- Orbit of Gaia around L2



$$\frac{d\tau}{dt} \approx 1 - \frac{1}{c^2}\left[\frac{V^2}{2} + U\right] + \frac{1}{c^4}\left[-\frac{V^4}{8} - \frac{3}{2}V^2U + \frac{U^2}{2} + 4\mathbf{V.W}\right]$$

$$t - \tau = \int\left(\frac{V^2}{2c^2} + \frac{U}{c^2}\right)dt + \int\left(\frac{1}{8}\frac{V^4}{c^4} + \frac{3}{2}\frac{V^2U}{c^4} - \frac{U^2}{2c^4} - 4\mathbf{V.W}\right)dt$$

- Numerical quadrature + solar system ephemerides

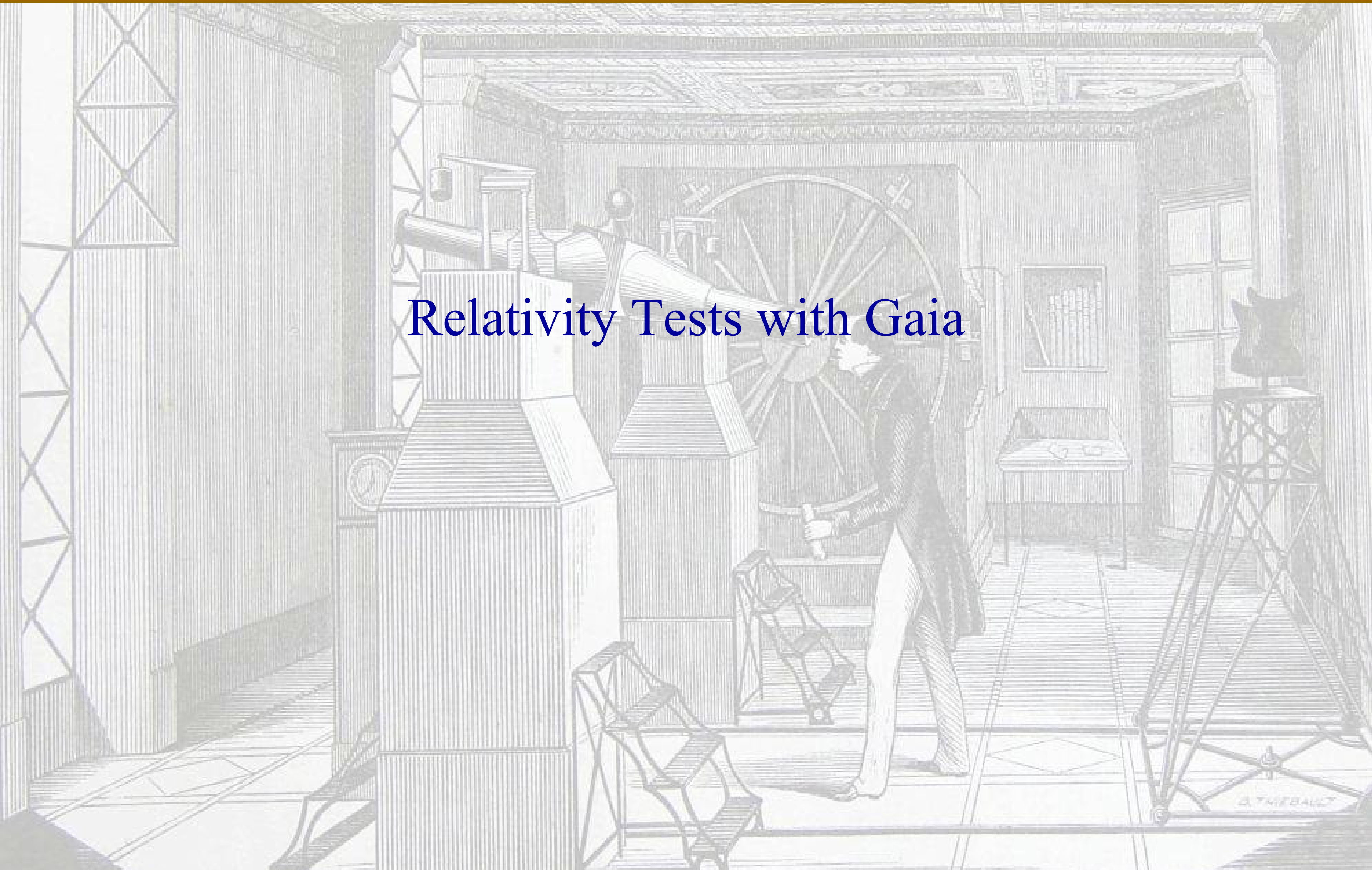
Solution for GAIA

Secular term

	TCG	Gaia	
L_c	$1.480\,826\,867 \times 10^{-8}$	$1.481\,259\,949 \times 10^{-8}$	day/day
		$1.481\,259\,960 \times 10^{-8}$	with $1/c^4$ terms

Periodic terms

P(yr)	TCG μs	Gaia μs	
1.00	1656.68	1664.74	Sun
0.486	-	121.74	Lissajous
1.09	22.42	22.63	J-S
0.5	13.84	13.83	2S
11.8	4.77	4.76	J
1.04	4.68	4.63	Sa-S
29.5	2.26	2.28	Sa
0.95	-	1.33	Lis- S



Relativity Tests with Gaia

Relativity tests with astrometry

light deflection

spacetime curvature

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 $\sigma_{\gamma} < 1\times10^{-6}$

Orbits of minor planets $\sigma_{\beta} < 5\times10^{-4}$

Orbits of minor planets $\sigma_{\dot{G}/G} < 5\times10^{-13}\,\mathrm{yr}^{-1}$

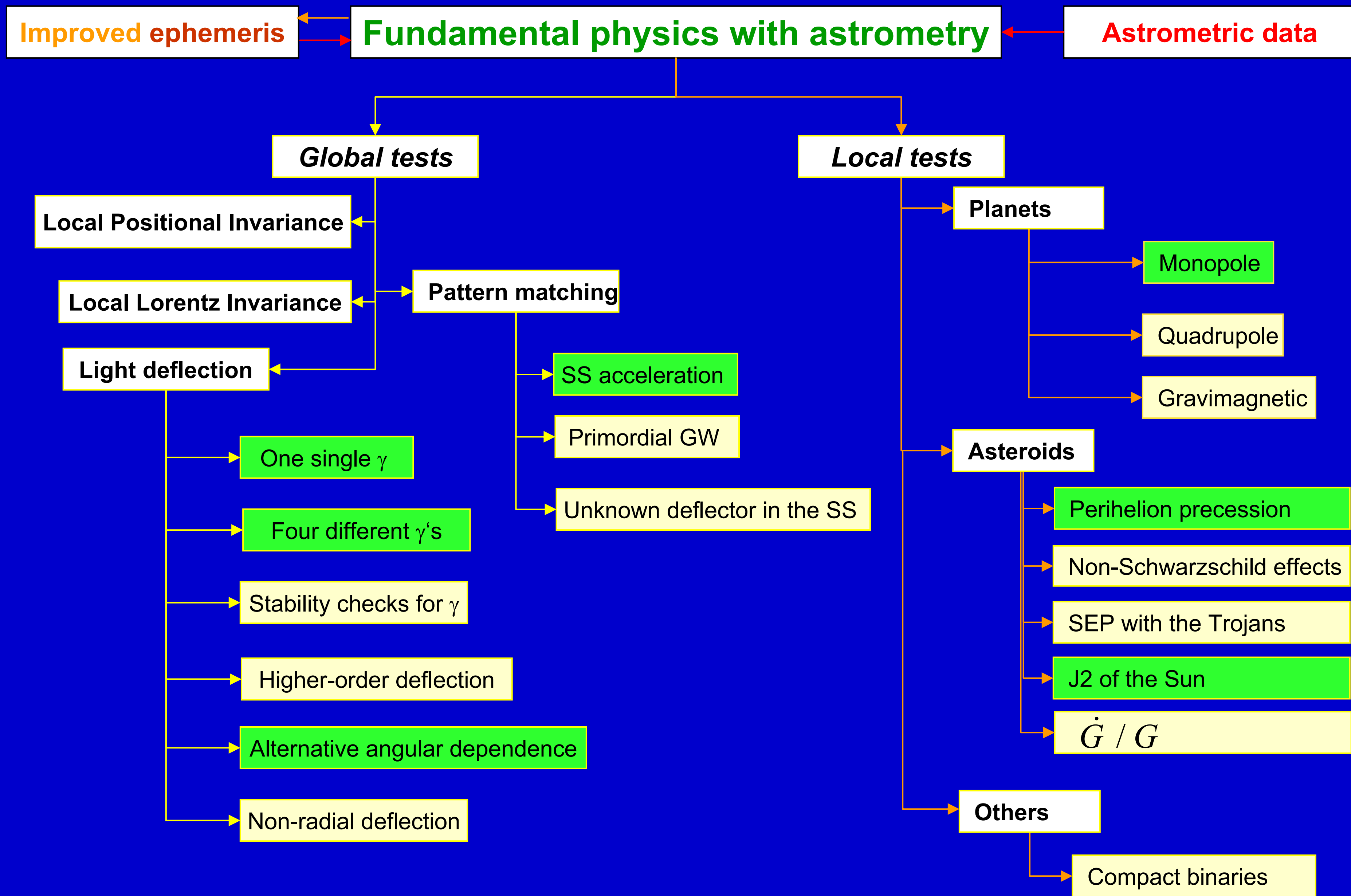
Jupiter light deflection $Q_{\mathrm{deflect}} > 3\sigma$

Relativity tests with accurate astrometry

Improved ephemeris ⇄ **Fundamental physics with astrometry** ← **Astrometric data**

- ***Global tests***
  - **Local Positional Invariance**
  - **Local Lorentz Invariance**
  - **Pattern matching**
    - SS acceleration
    - Primordial GW
    - Unknown deflector in the SS
  - **Light deflection**
    - One single γ
    - Four different γ's
    - Stability checks for γ
    - Higher-order deflection
    - Alternative angular dependence
    - Non-radial deflection
- ***Local tests***
  - **Planets**
    - Monopole
    - Quadrupole
    - Gravimagnetic
  - **Asteroids**
    - Perihelion precession
    - Non-Schwarzschild effects
    - SEP with the Trojans
    - J2 of the Sun
    - $\dot{G} / G$
  - **Others**
    - Compact binaries

Gaia : Core tests – good results expected



Gaia: complementary tests with parameter fitting

Gaia DPAC

- Improved ephemeris
- Astrometric data
- **Fundamental physics with astrometry**
  - ***Global tests***
    - **Local Positional Invariance**
    - **Local Lorentz Invariance**
    - **Pattern matching**
      - SS acceleration
      - Primordial GW
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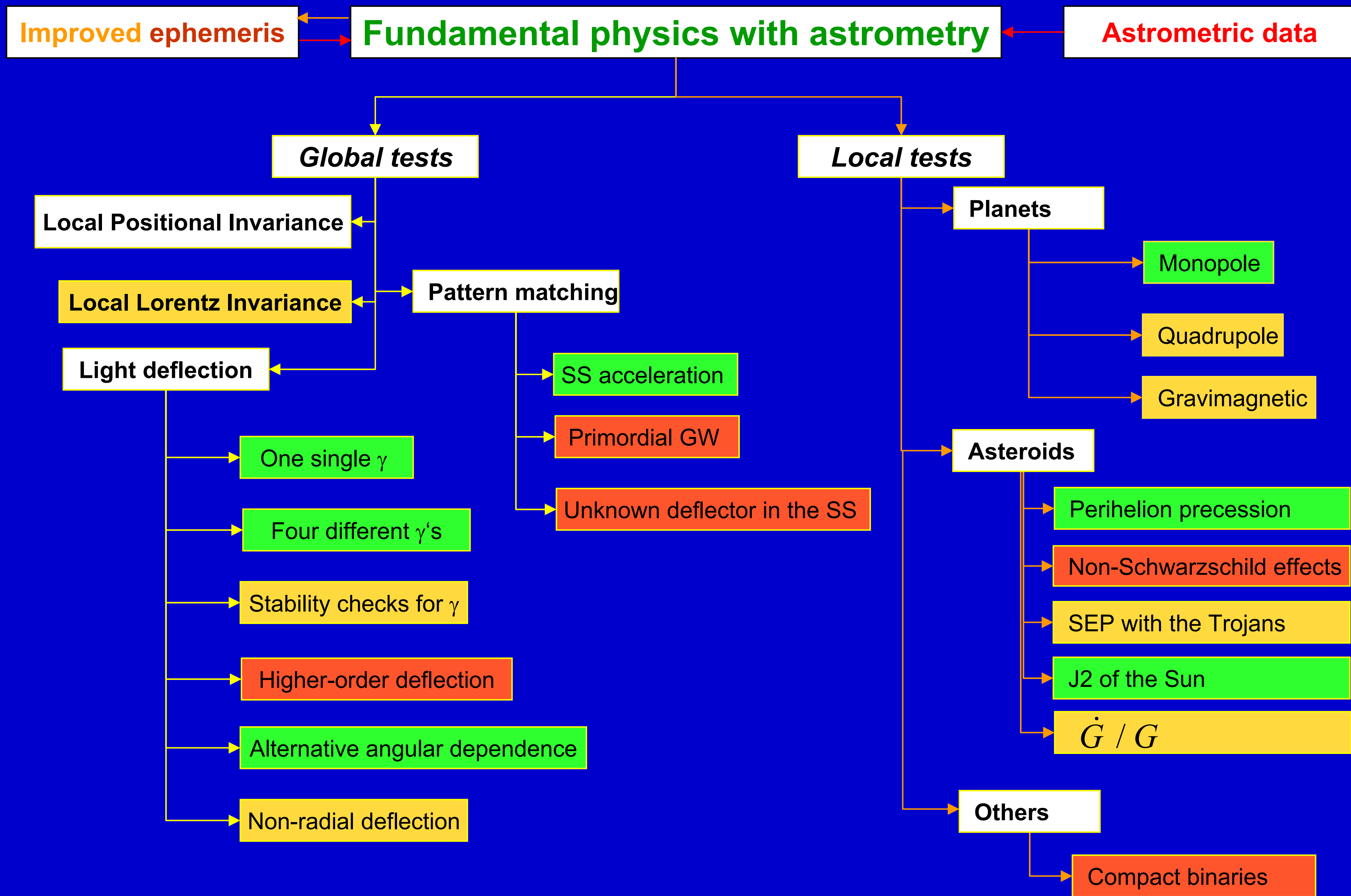
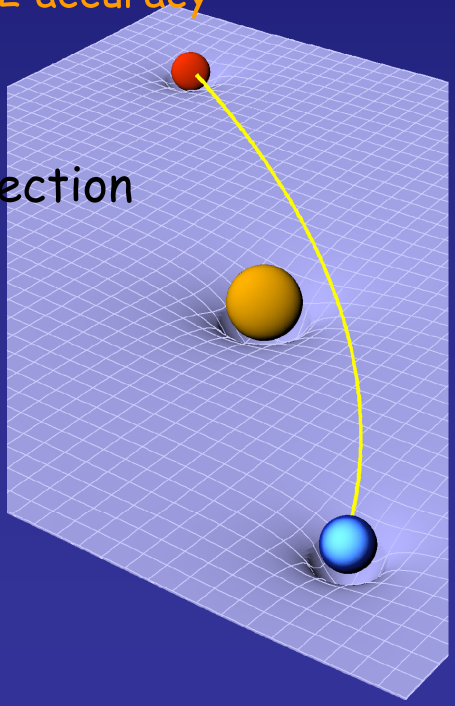
      - Compact binaries

Gaia: tests on residuals



Solar light deflection

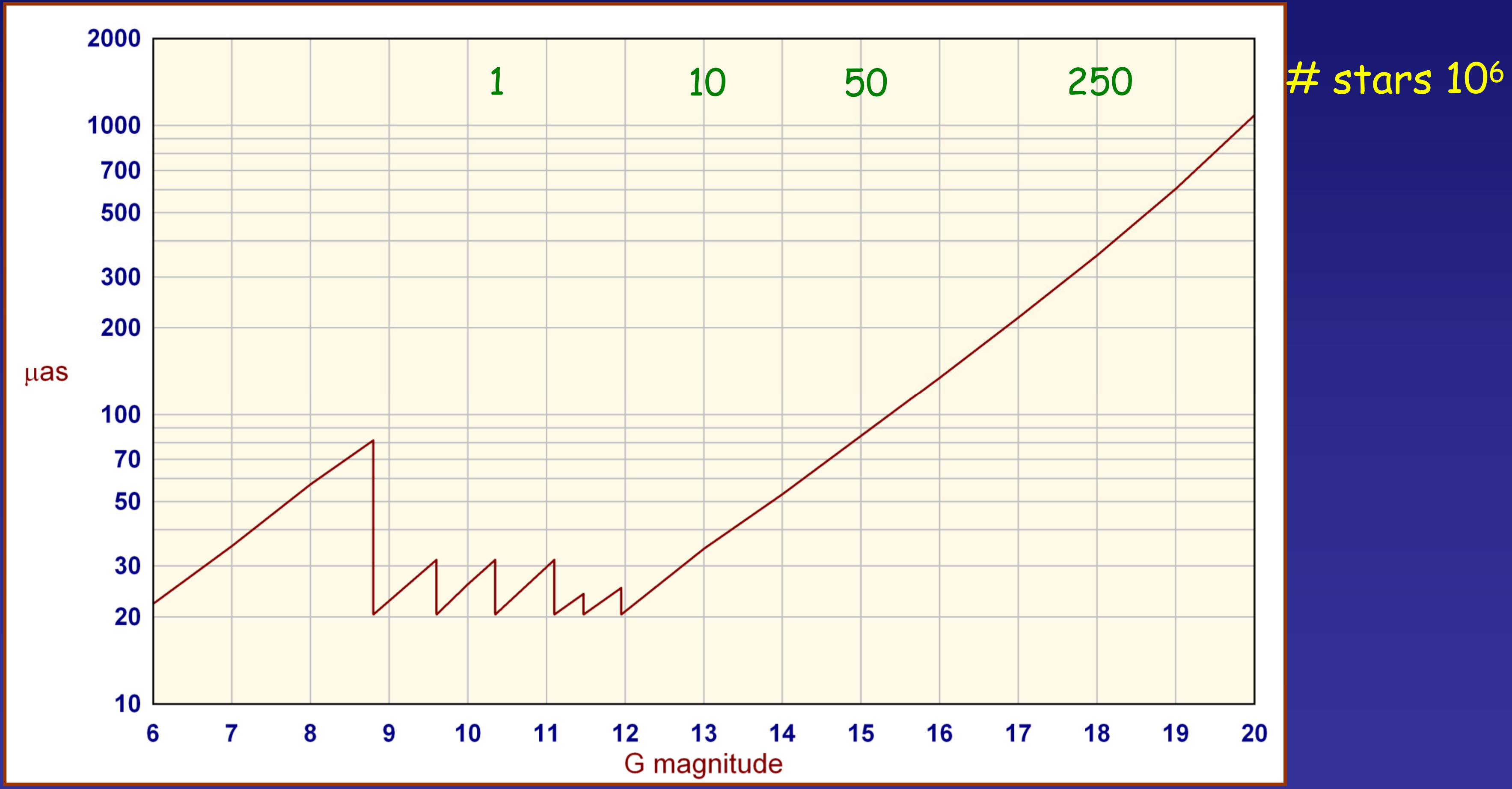
- Most precise test on γ with Gaia
  - Preliminary analysis (ESA, 2000, Mignard, 2001, Vecchiato et al., 2003)
- Advantages of Gaia experiment
  - Optical with accurate astrometry
    - One individual observation at 90° from the Sun ➔ γ to 0.02 accuracy
  - Deflection (not time delay involving nearly 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



Gaia single observation accuracy

- One transit over the field-of-view
- Integration over 9 Astro CCDs

Solar deflection→ 4mas @ 90°



Photon path in a gravitational field

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

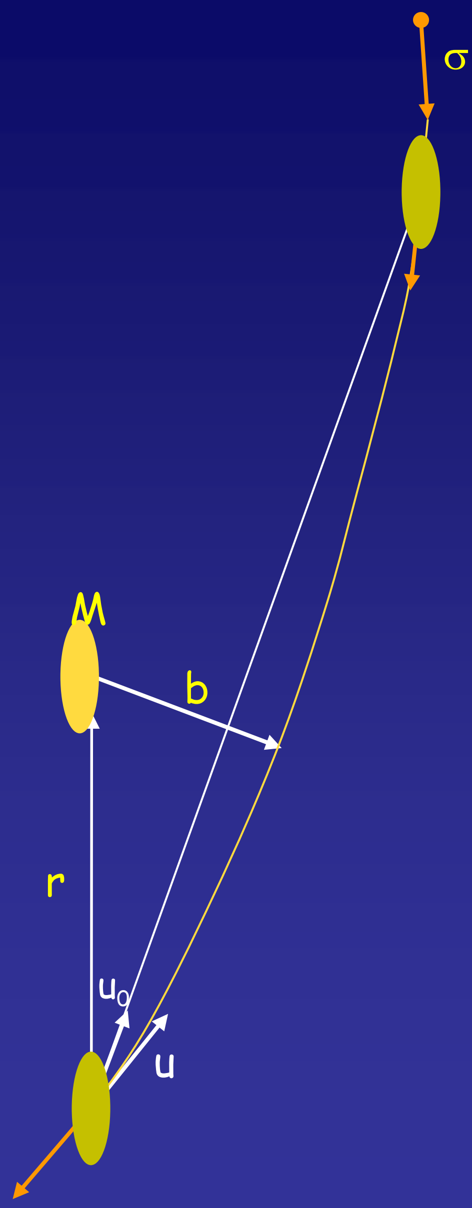
$$g_{0i} = -\frac{4}{c^3} w^i(x,t)$$

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

$$\mathbf{x}(t) = \mathbf{x}_0(t) + \boldsymbol{\sigma}(t - t_0) + \Delta\mathbf{x}(t) / c^2$$

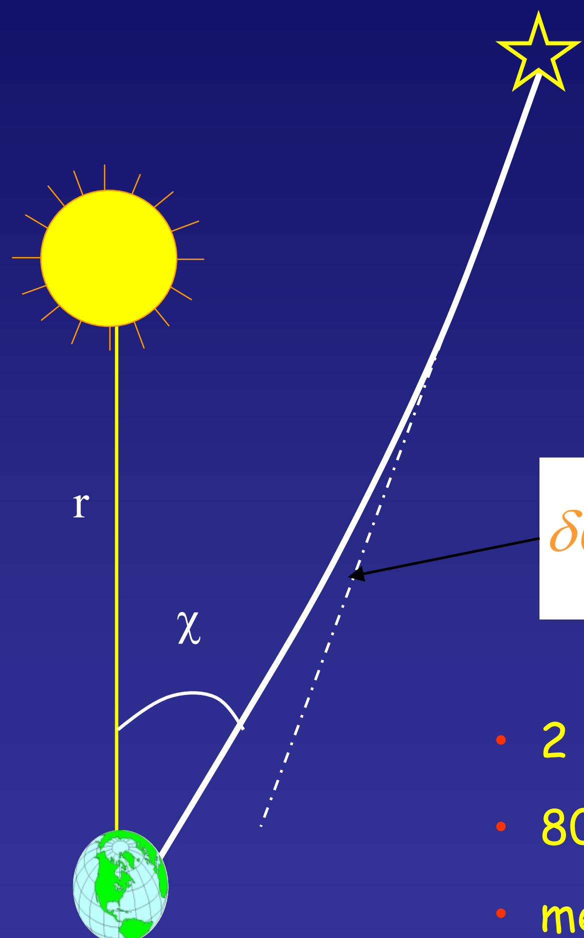
$$\boxed{\mathbf{u} = \mathbf{u}_0 + \frac{(1+\gamma) GM}{c^2} \frac{\left[1 + (\mathbf{u}_0 . \mathbf{r}) / r\right] \mathbf{b}}{b^2}}$$

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



Relativity Experiments

- Light Deflection : determination of γ



Light deflection in mas

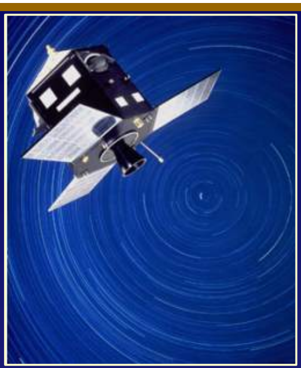
	min χ	$\chi = 45$ deg
Sun	10 mas	10 mas
Jupiter	16 mas	2 μas
Saturn	6 mas	0.8 μas

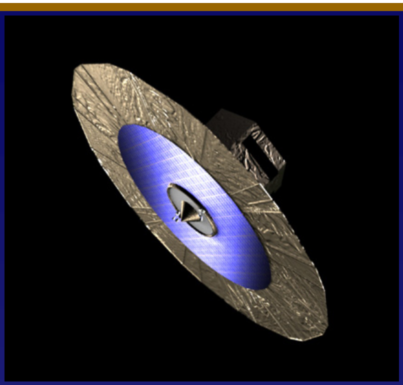
$$\delta\theta = \frac{2GM}{rc^2}\frac{1+\gamma}{2}\frac{\sin\chi}{1-\cos\chi}$$

Observable quantity

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

Expected Performance on γ





Hipparcos	GAIA	σ_H/σ_G
• 10^5 stars V < 10	• 8×10^6 stars V < 13	
• 2.5×10^6 abscissas	• 6×10^8 FOV transits	➔ x 15
• $\sigma \sim 3$ to 8 mas	• $\sigma \sim 40$ μas	➔ x 125
• χ > 47 degrees	• χ > 45 degrees	
	• + 10^9 fainter stars	
		> 2000

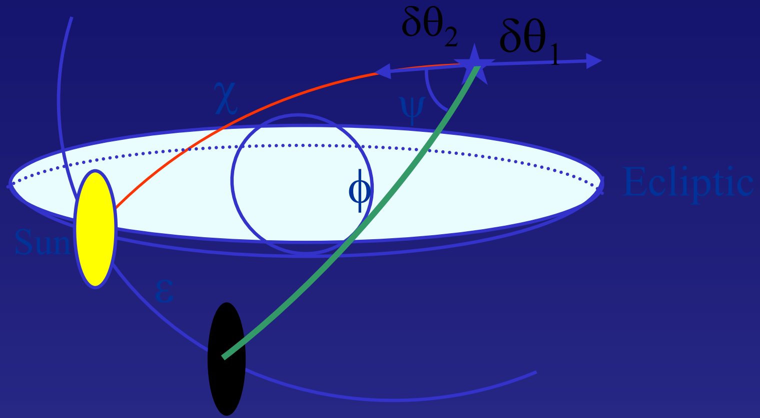
$$\gamma = 1 \pm 3 \times 10^{-3}$$

$$\sigma_\gamma \approx 2 \times 10^{-6} \text{ to } 6 \times 10^{-7}$$

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

Link with parallax



Deflection : $\delta\theta_1$

$$\delta\theta_1 = \frac{2GM}{ac^2}\frac{1+\gamma}{2}\frac{\sin\chi}{1-\cos\chi}$$

Parallax : $\delta\theta_2$

$$\delta\theta_2 = \pi\sin\chi$$

- Abscissa change : $\delta\phi_1 = \delta\theta_1\cos\psi = \frac{2GM}{ac^2}\frac{1+\gamma}{2}\frac{\cos\varepsilon\sin\phi}{1-\cos\varepsilon\cos\phi}$

$$\delta\phi_2 = -\delta\theta_2\cos\psi = -\pi\cos\varepsilon\sin\phi$$

- Correlation : 0.88 (0.92 with Hipparcos)

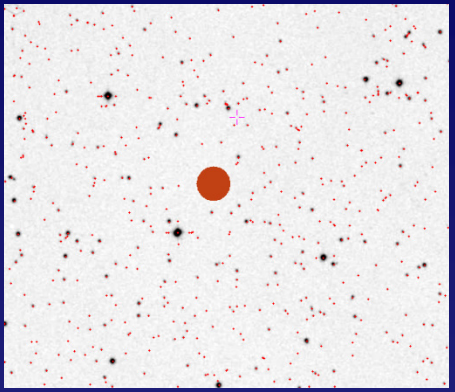
Beyond plain γ

- 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

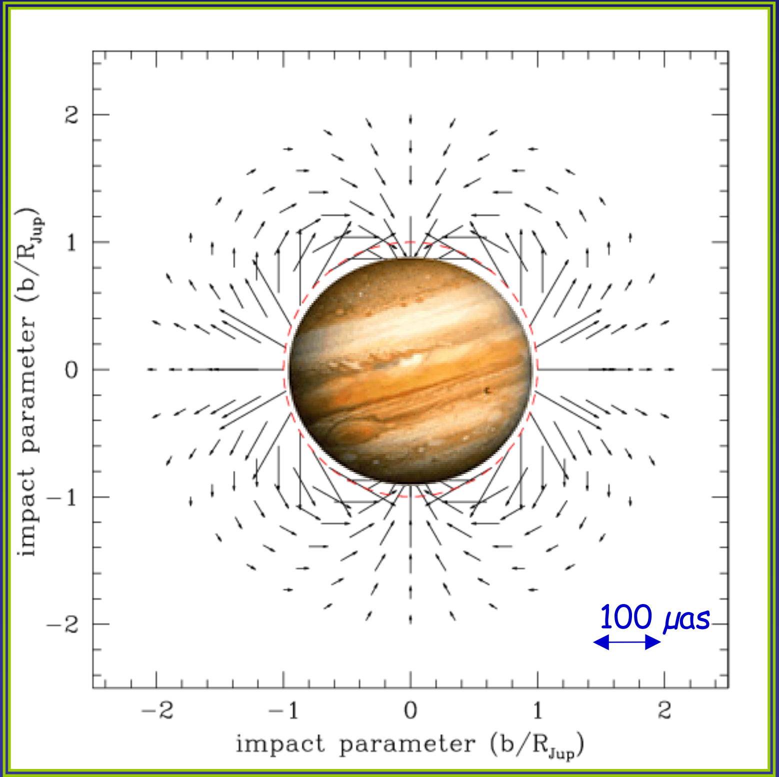
Light deflection by giant planets

		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

- Jupiter light deflection
  - Small field astrometry with Gaia
  - Relative measurements of star position around Jupiter
  - Same field observed earlier or later



Jupiter in 2013



Deflection from Jupiter quadrupole

$$\delta\phi_Q = \frac{4GM_J}{c^2}\frac{J_2 R_J^2}{b^3}$$

- On-going work
  - optimize the mission parameters
  - search for observations close to bright stars
  - method of reduction

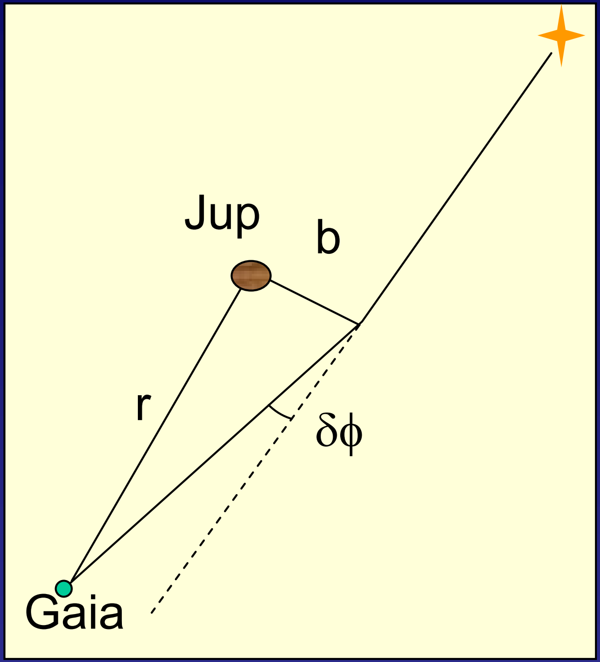
Crosta & Mignard, 2006, CQG

Small field light deflection

- Simplified formula for the quadrupole deflection

$$\delta\phi_M = \frac{4GM_J}{c^2 b}\frac{1+\gamma}{2}$$

$$\delta\phi_Q = \frac{4GM_J}{c^2}\frac{J_2 R_J^2}{b^3}$$



Exact expression with radial and non radial deflection

- Full derivation includes radial and non-radial deflection
  - Klioner, 2003 ; Crosta & Mignard, 2006 ; Leponcin-Lafitte & Teysandier.

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

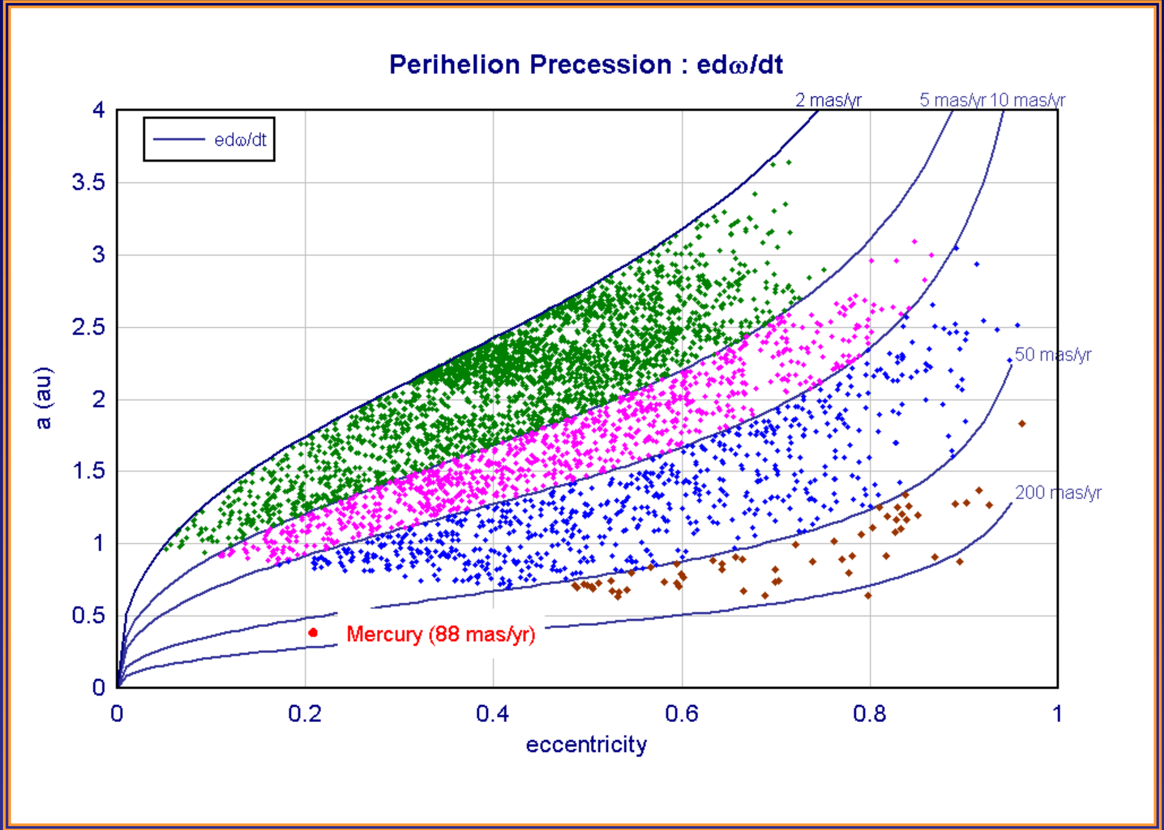
Determination of β : Orbits of minor planets

- About 300,000 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

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

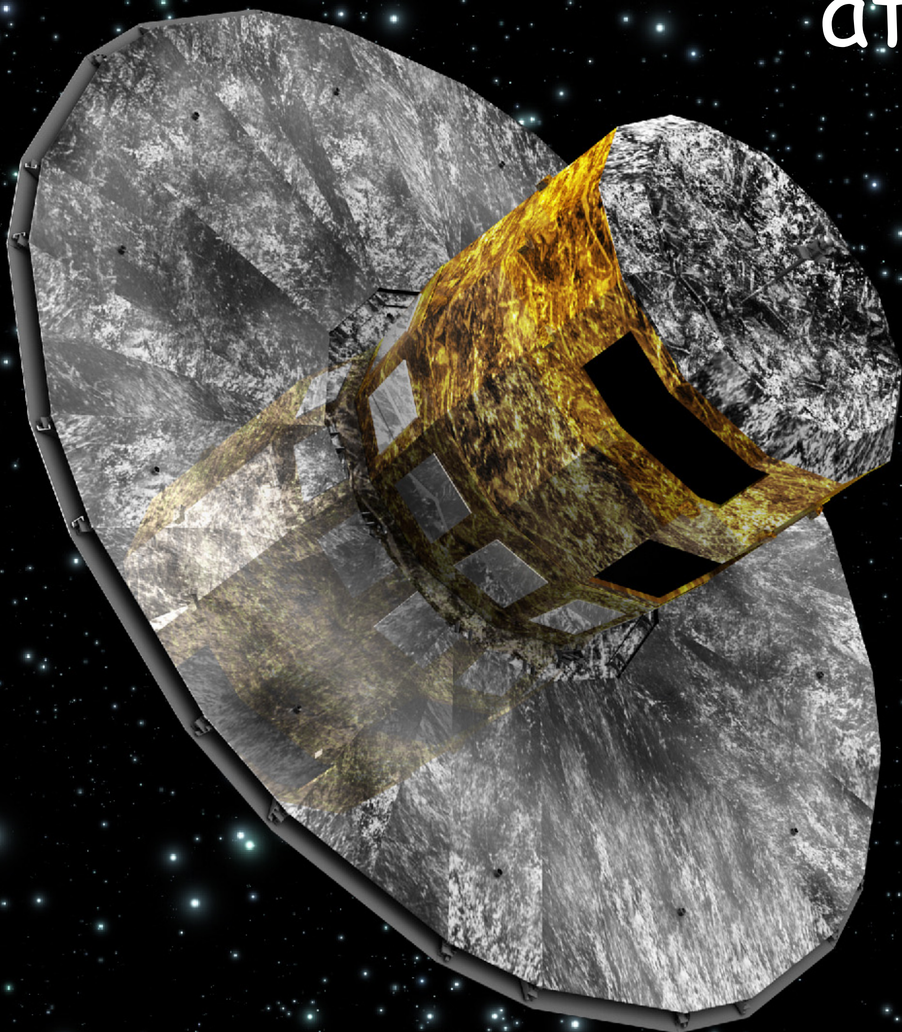
$$\dot{\omega} = \frac{38\lambda}{a^{5/2}(1-e^2)} + \frac{0.04(J_2/10^{-6})}{a^{7/2}(1-e^2)^2} \qquad \text{mas/yr} \ \ (a \text{ in AU})$$

Perihelion precession : edϖ/dt



- Parameters fitted with Gaia
  - PPN β , Solar J2, $\dot{G}/G$
- Expected precision $\sigma(\beta) \sim 2 \times 10^{-4}$

Thanks for your attention



Sky coverage: Galactic coordinates

Transits during the mission