Space astrometry with Gaia
and
relativistic astrophysics

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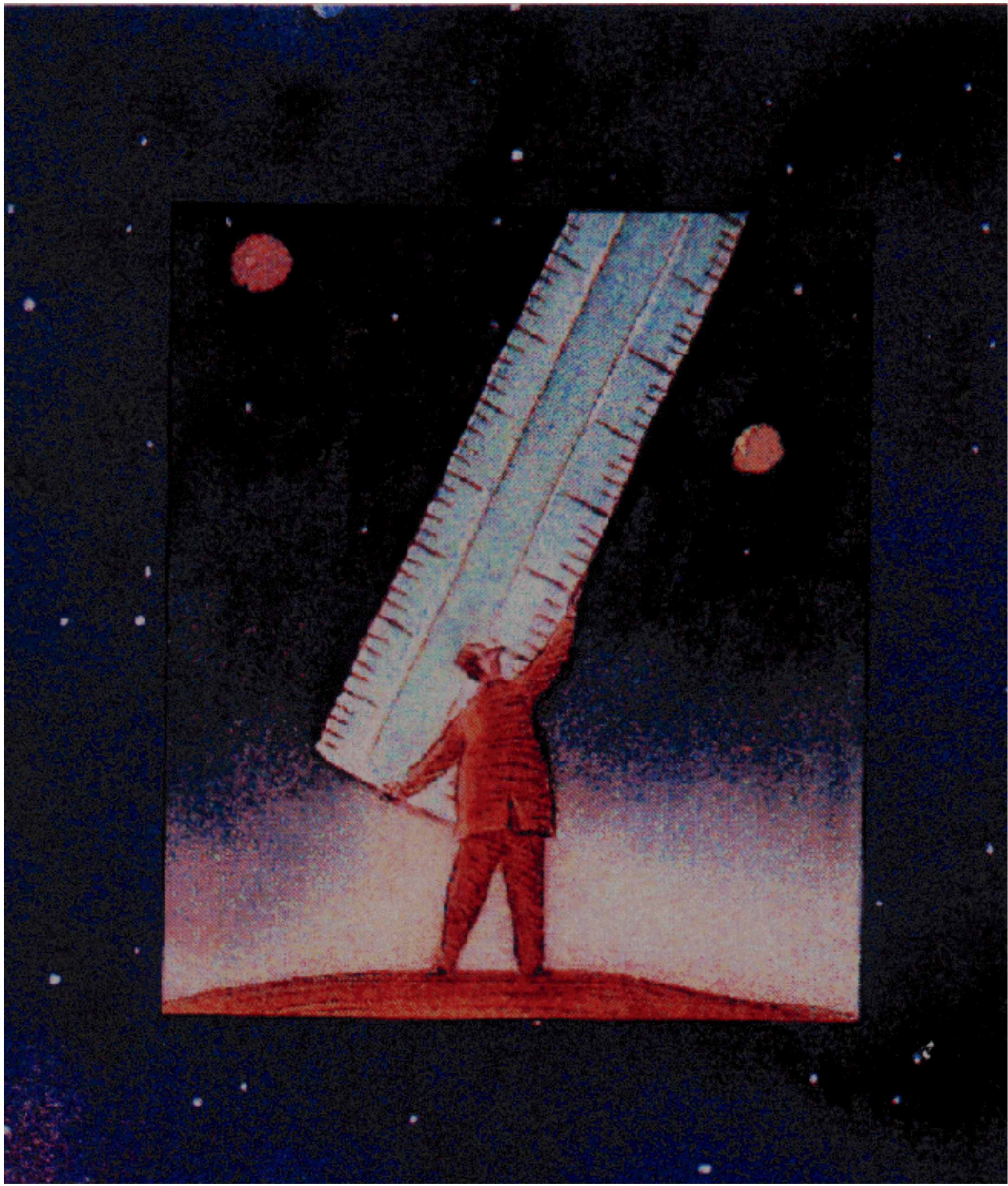
TEXAS 2015, Geneva, Switzerland, 17 December 2015

Astrometry: the art of measuring stellar positions



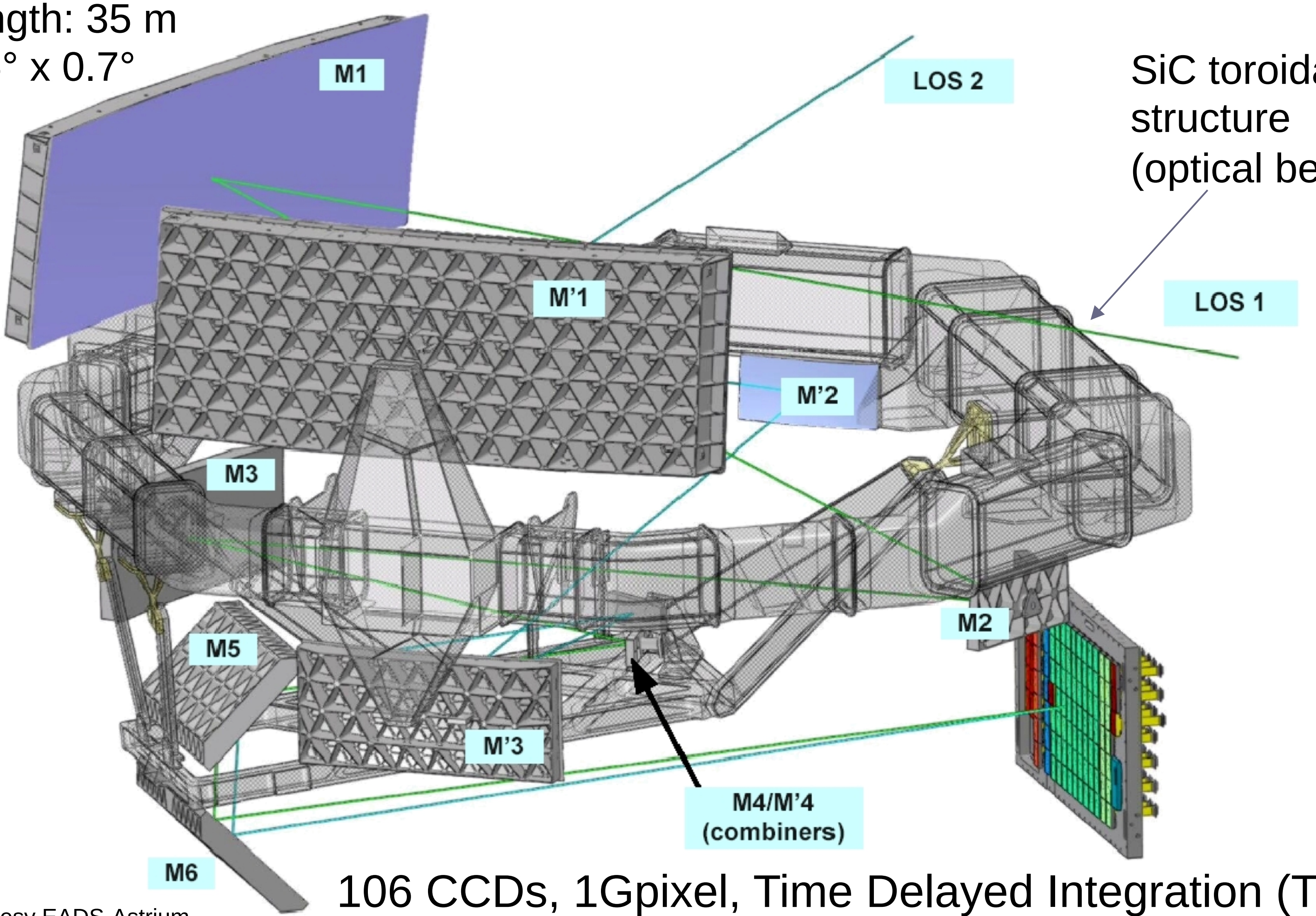
Astronomy analyses stellar light:

Astrometry – direction
Photometry – quantity
Spectroscopy – wave length
Polarimetry – polarization

Gaia: a space telescope

Astrometry+photometry of 10^9 sources up to 20 mag (+radial velocities)

2 SiC primary mirrors at 106.5°
Aperture:1.45 m x 0.5 m
Focal length: 35 m
FOV: 1.6° x 0.7°

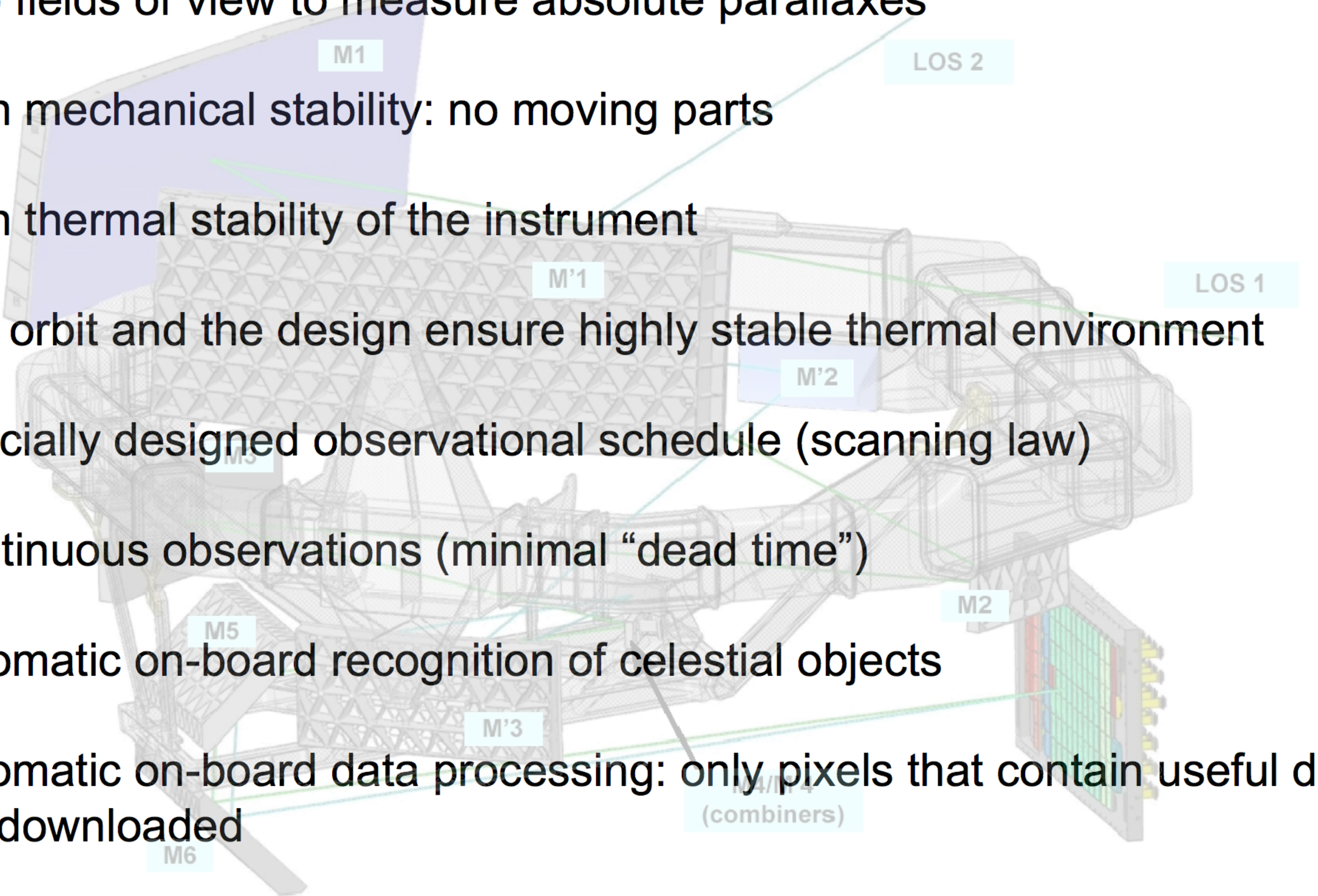


SiC toroidal structure (optical bench)

106 CCDs, 1Gpixel, Time Delayed Integration (TDI)

Figure courtesy EADS-Astrium

Gaia: tuned for high-accuracy astrometry

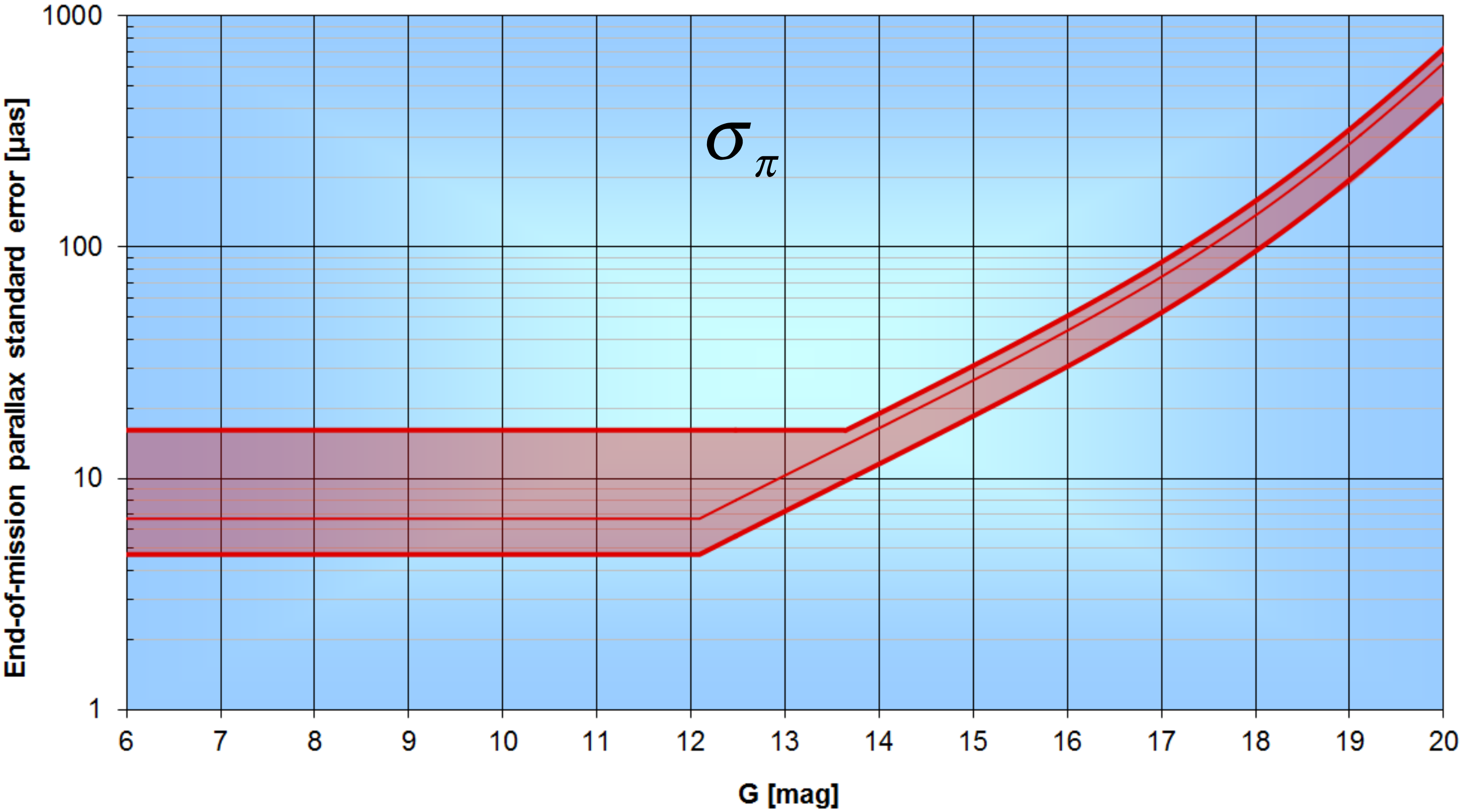


1. Two fields of view to measure absolute parallaxes
2. High mechanical stability: no moving parts
3. High thermal stability of the instrument
4. The orbit and the design ensure highly stable thermal environment
5. Specially designed observational schedule (scanning law)
6. Continuous observations (minimal “dead time”)
7. Automatic on-board recognition of celestial objects
8. Automatic on-board data processing: only pixels that contain useful data are downloaded

1 PB of raw data; 800 observations for each of 10^9 objects; 10^{10} unknowns

Gaia: expected uncertainties of astrometry

Predicted uncertainty depends of the brightness and varies over the sky



$$\sigma_{\alpha*} = 0.787\,\sigma_\pi$$
$$\sigma_{\delta} = 0.699\,\sigma_\pi$$
$$\sigma_{\mu\alpha*} = 0.556\,\sigma_\pi$$
$$\sigma_{\mu\delta} = 0.496\,\sigma_\pi$$

$$G = V - 0.0257 - 0.0924(V - I_C) - 0.1623\,(V - I_C)^2 + 0.0090(V - I_C)^3$$

(α,δ) position; $(\mu_{\alpha*},\mu_\delta)$ proper motion; π parallax

Gaia payload ready for launch (2013)

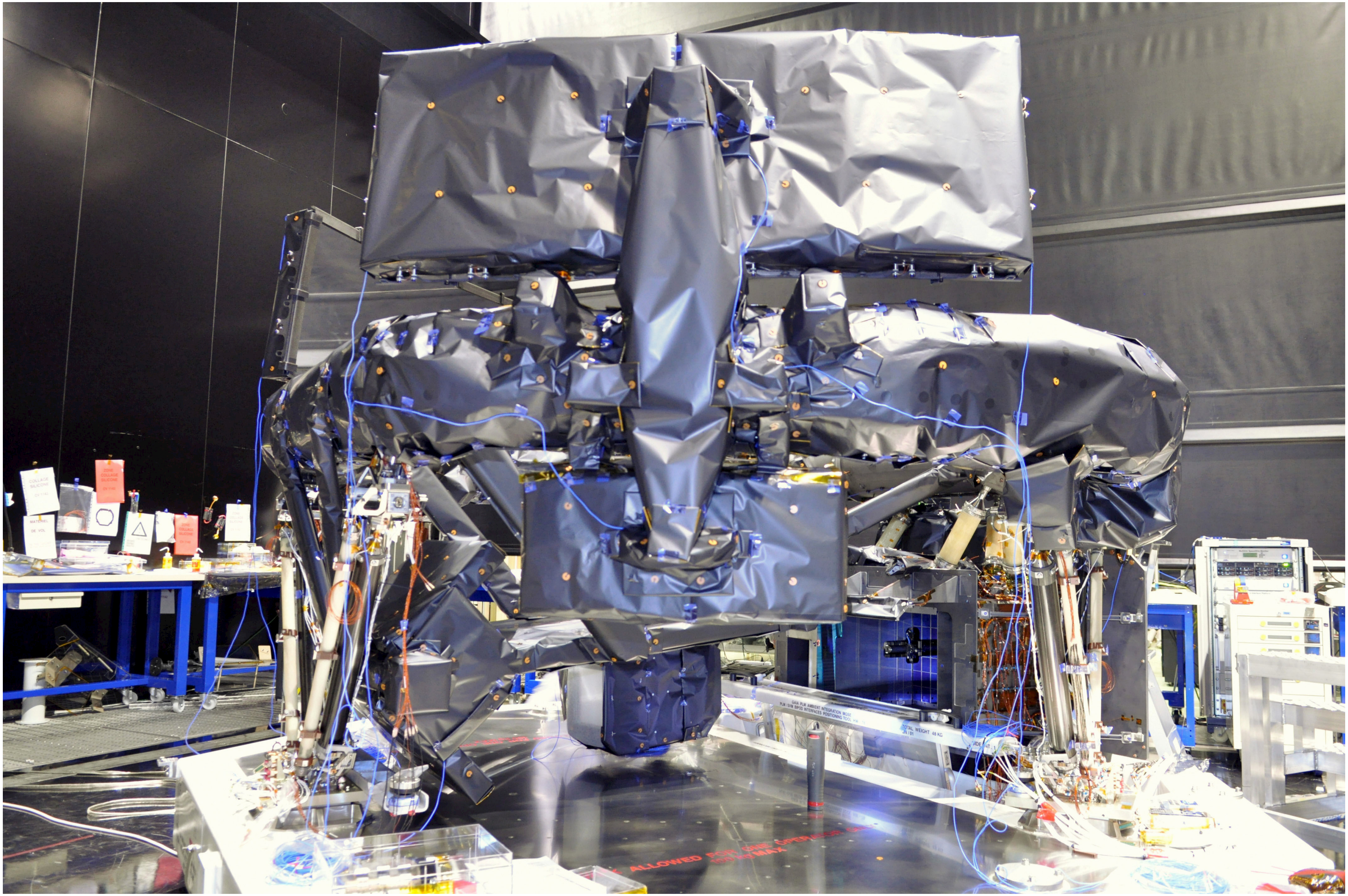
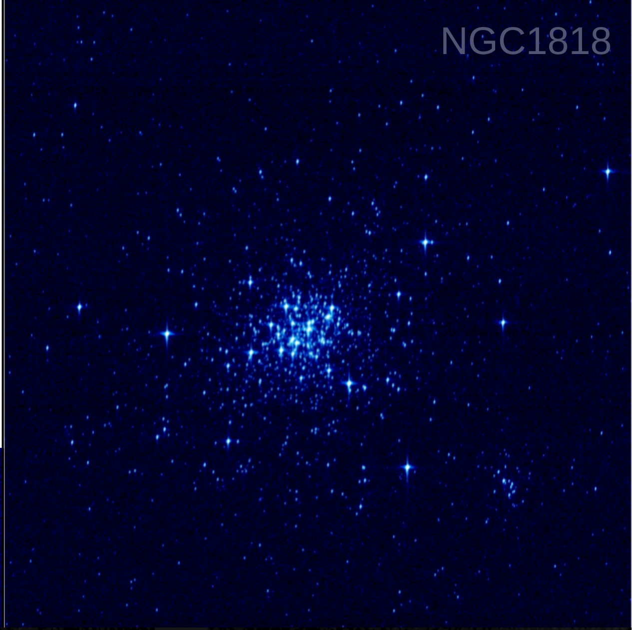


Figure courtesy EADS-Astrium

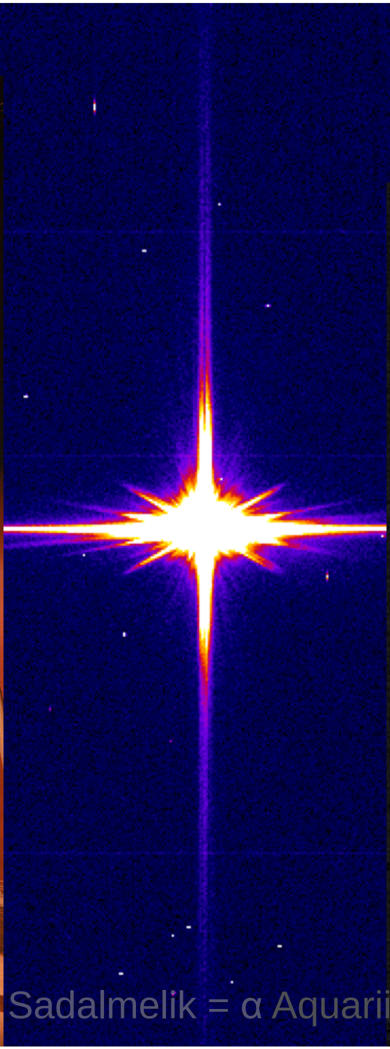
Gaia:

- launched 19 December 2013
- extensive commissioning until July 2014
- 517 days in routine science operations

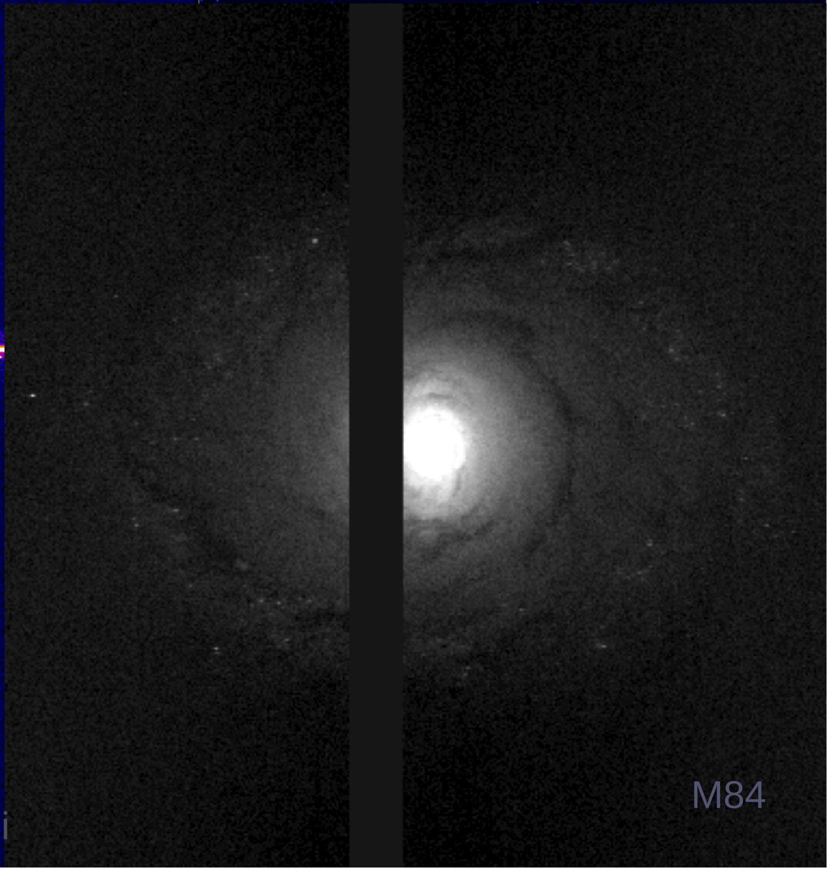


NGC1818

Figure courtesy Arianespace

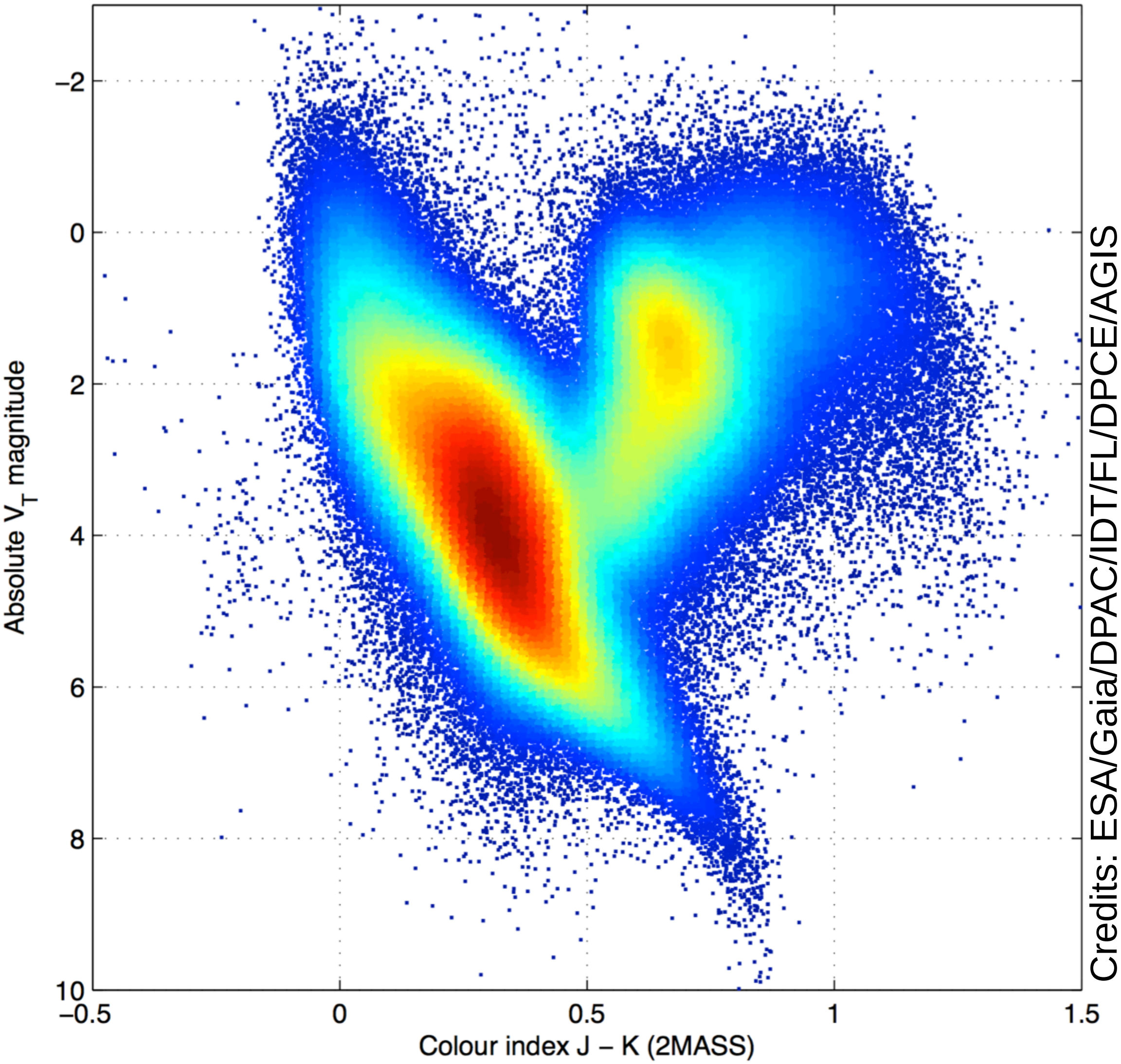


Sadalmelik = α Aquarii



M84

The first Hertzsprung-Russel diagram

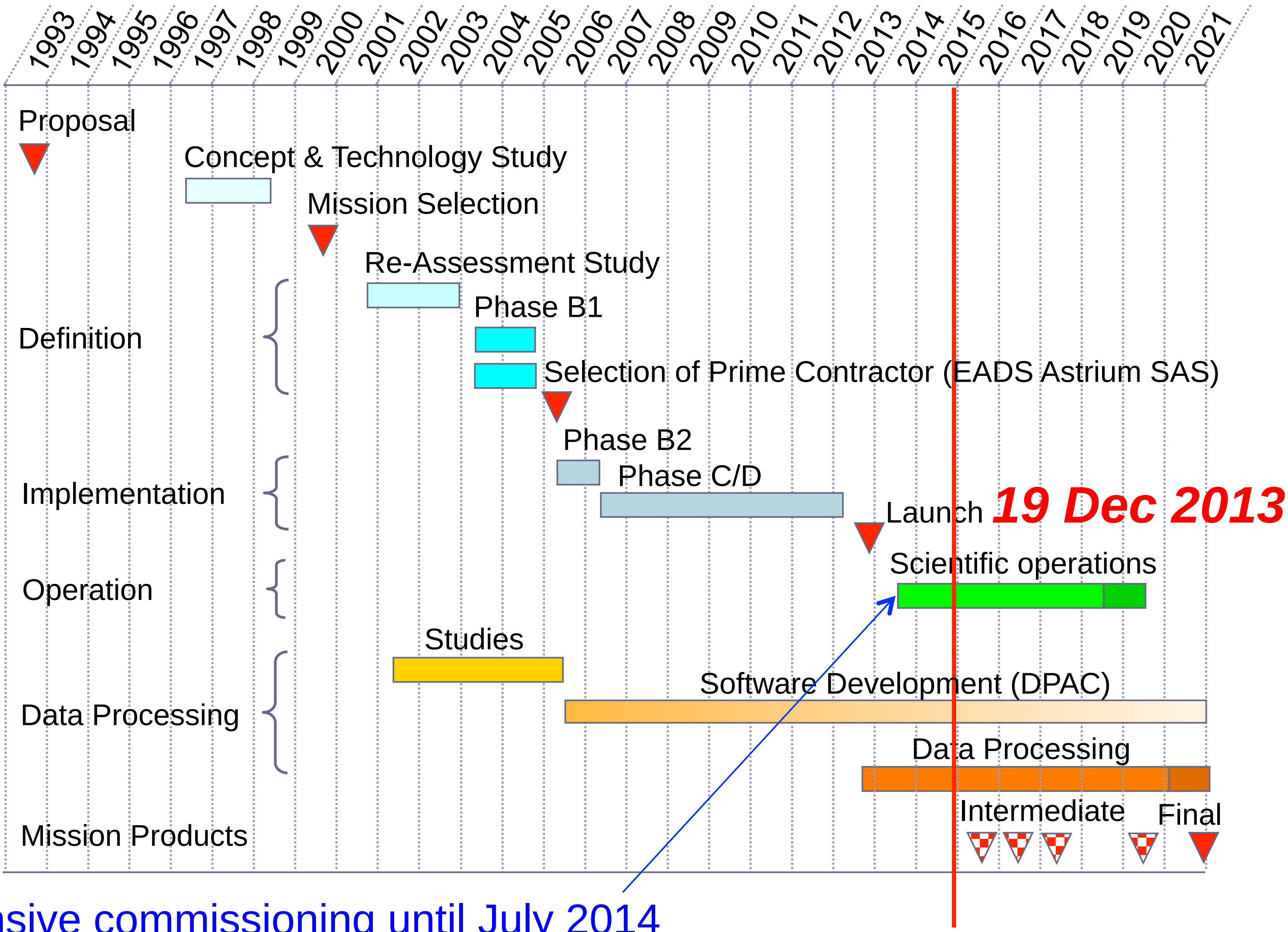


Credits: ESA/Gaia/DPAC/IDT/FL/DPCE/AGIS

- done in July 2015
- for testing only
- colours from 2MASS since Gaia colours were not yet available in July 2015

Ugly? Plotted with the very first trial solution of about a million stars to see that what we get from our data processing makes some sense.

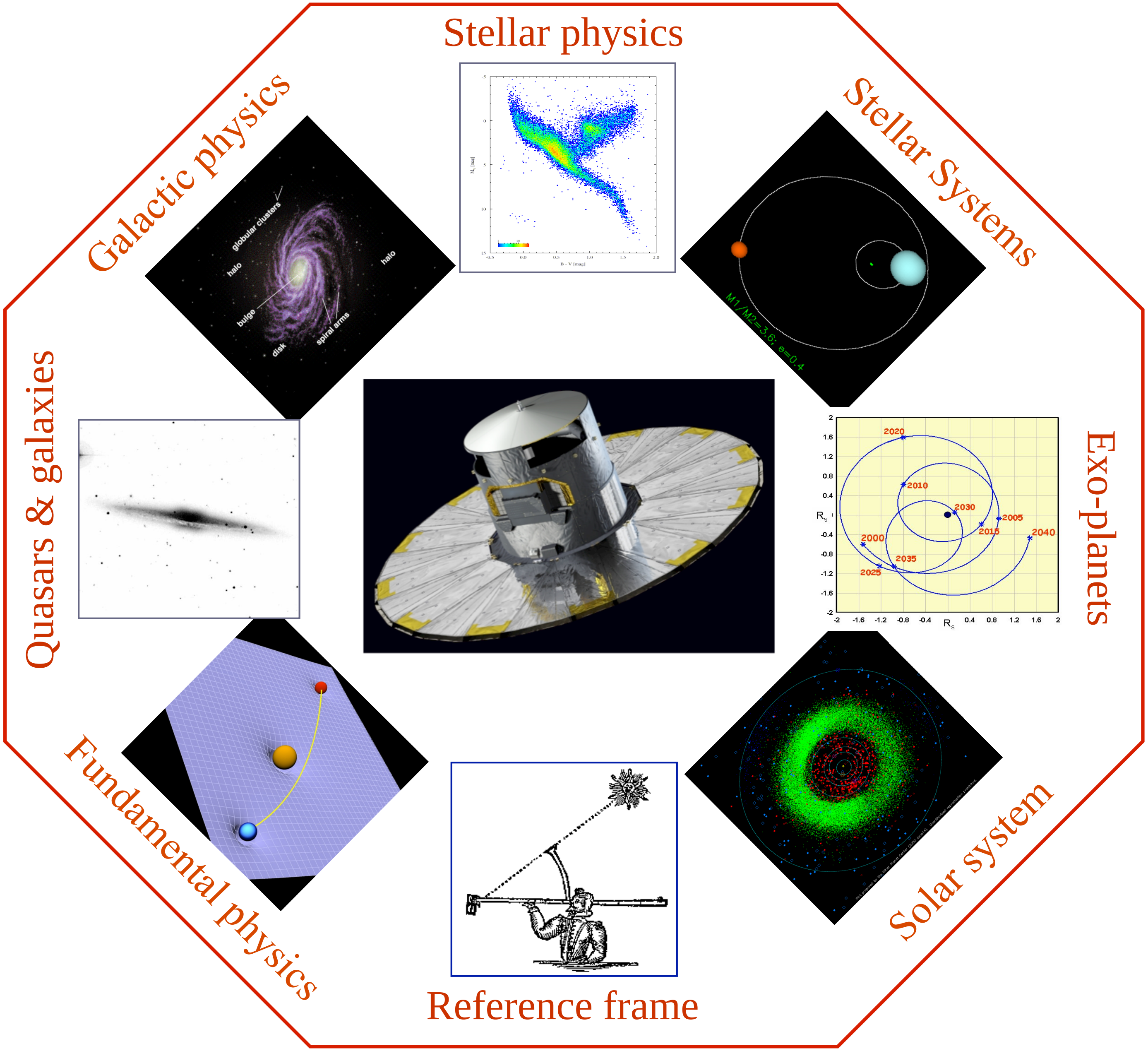
Schedule



extensive commissioning until July 2014

Today = day 517 of science operations

Gaia: goals



Stellar physics

Stellar Systems

Exo-planets

Solar system

Reference frame

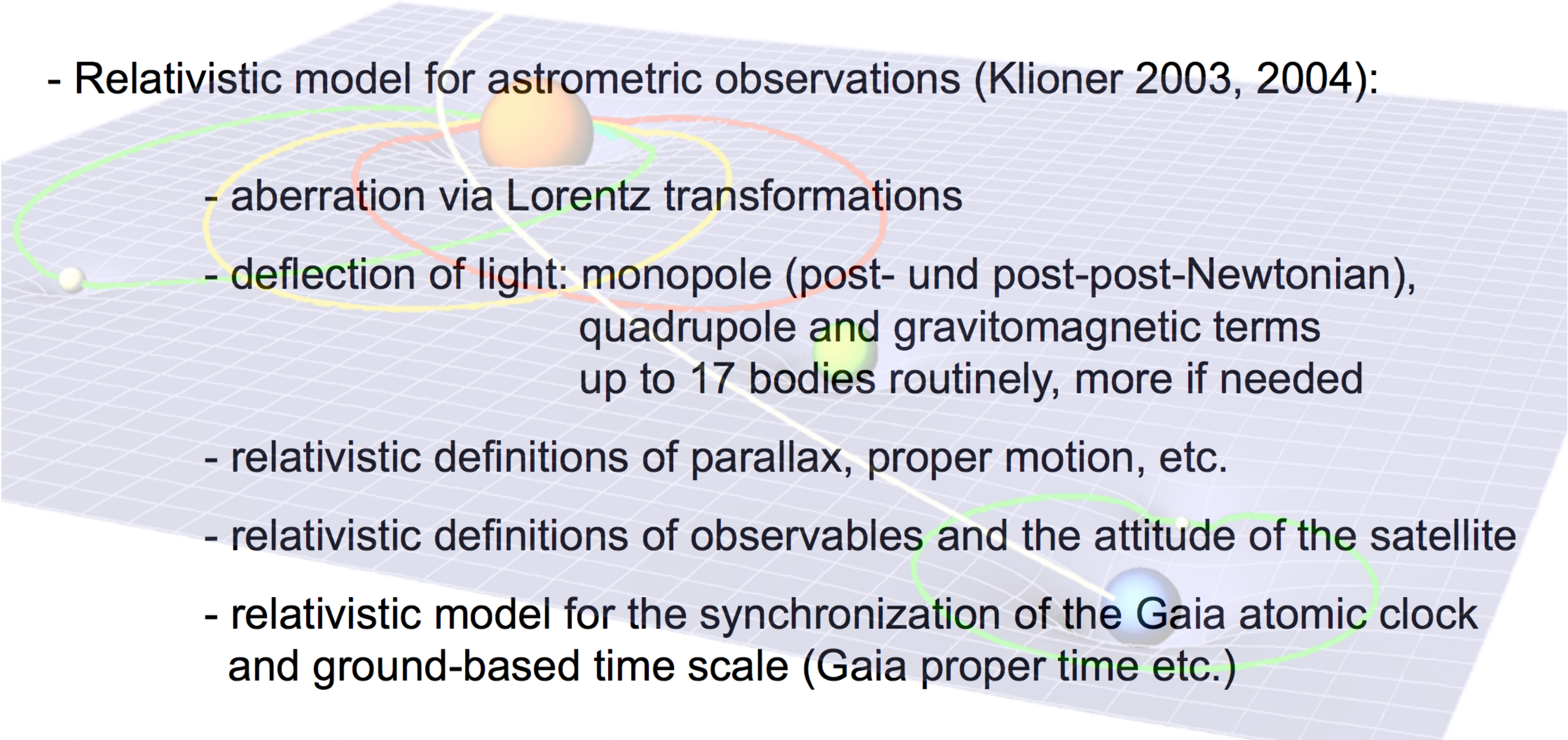
Fundamental physics

Quasars & galaxies

Galactic physics

Prerequisite for all applications: the model

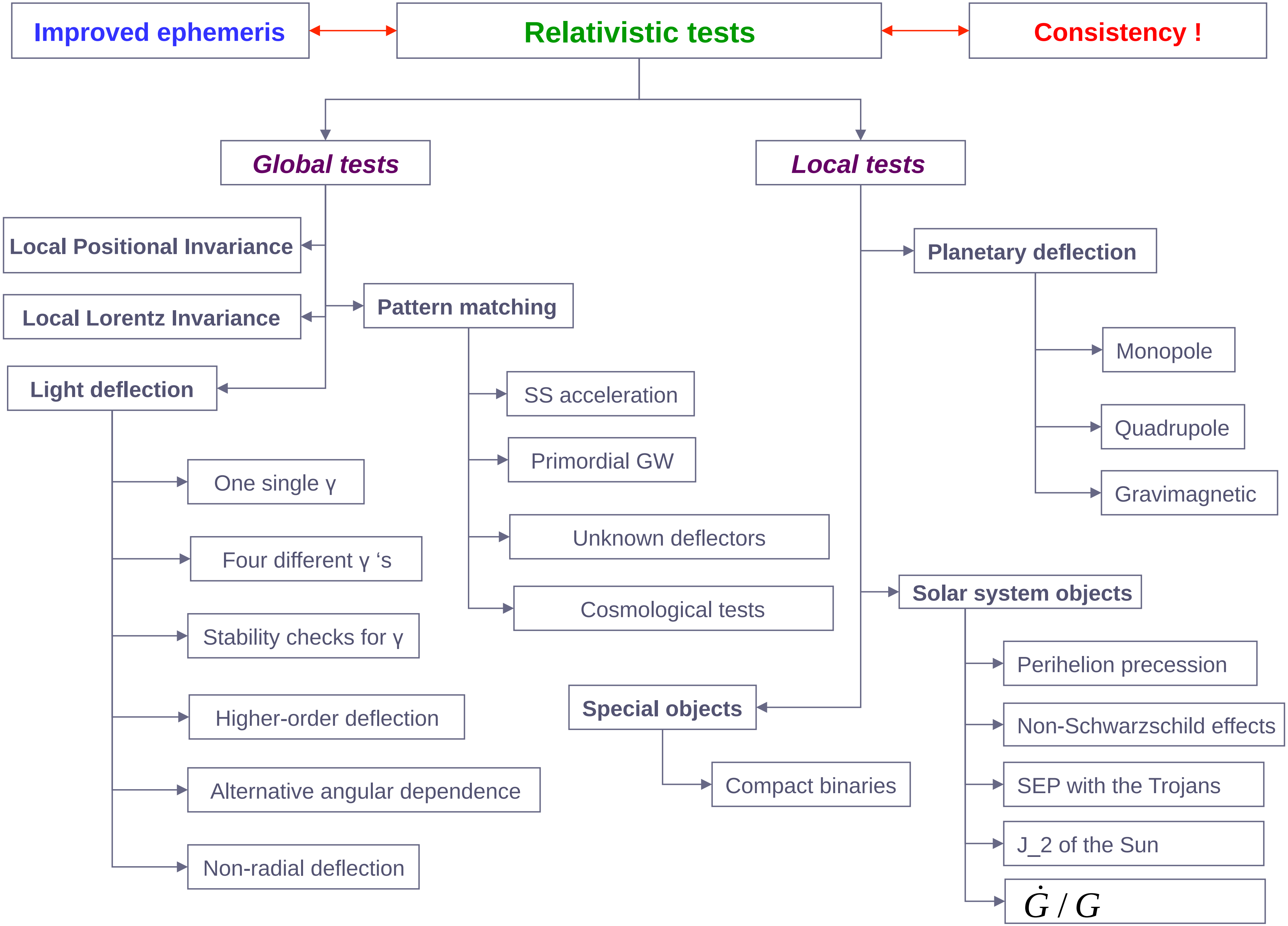
- Standard IAU relativistic reference systems (Soffel et al. 2003) form the basis for the Gaia data processing



- Relativistic model for astrometric observations (Klioner 2003, 2004):
  - aberration via Lorentz transformations
  - deflection of light: monopole (post- und post-post-Newtonian),
    quadrupole and gravitomagnetic terms
    up to 17 bodies routinely, more if needed
  - relativistic definitions of parallax, proper motion, etc.
  - relativistic definitions of observables and the attitude of the satellite
  - relativistic model for the synchronization of the Gaia atomic clock and ground-based time scale (Gaia proper time etc.)

Consistency of all aspects of the modelling (constants, ephemerides, etc.) should be ensured and monitored

Efficiency! 10^9 objects, 1 sec per object = 30 years!



Improved ephemeris ↔ **Relativistic tests** ↔ **Consistency !**

- ***Global tests***
  - **Local Positional Invariance**
  - **Local Lorentz Invariance**
  - **Pattern matching**
    - SS acceleration
    - Primordial GW
    - Unknown deflectors
    - Cosmological tests
  - **Light deflection**
    - One single γ
    - Four different γ ‘s
    - Stability checks for γ
    - Higher-order deflection
    - Alternative angular dependence
    - Non-radial deflection
- ***Local tests***
  - **Planetary deflection**
    - Monopole
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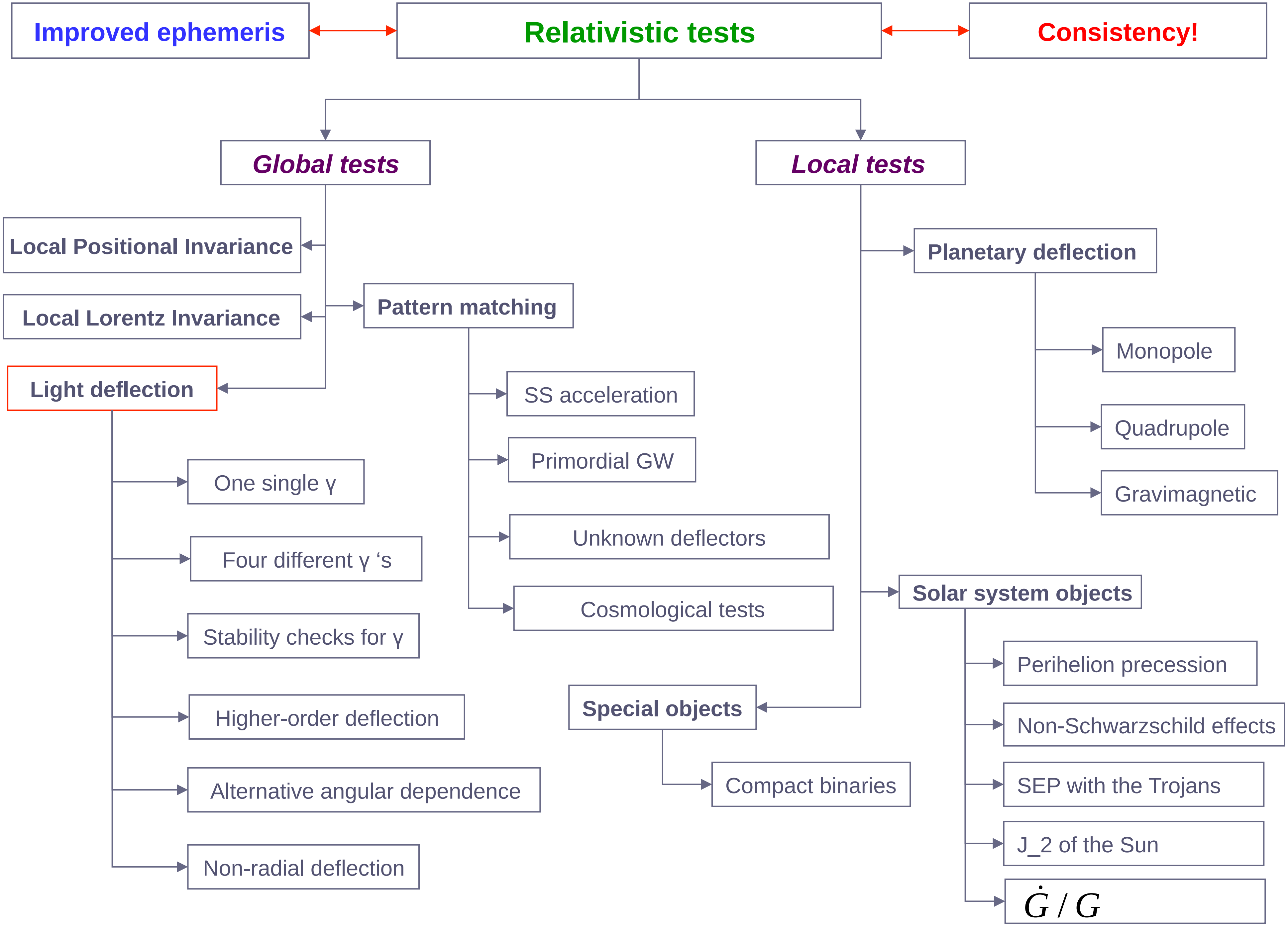
    - Gravimagnetic
  - **Solar system objects**
    - Perihelion precession
    - Non-Schwarzschild effects
    - SEP with the Trojans
    - J_2 of the Sun
    - $\dot{G} / G$
  - **Special objects**
    - Compact binaries



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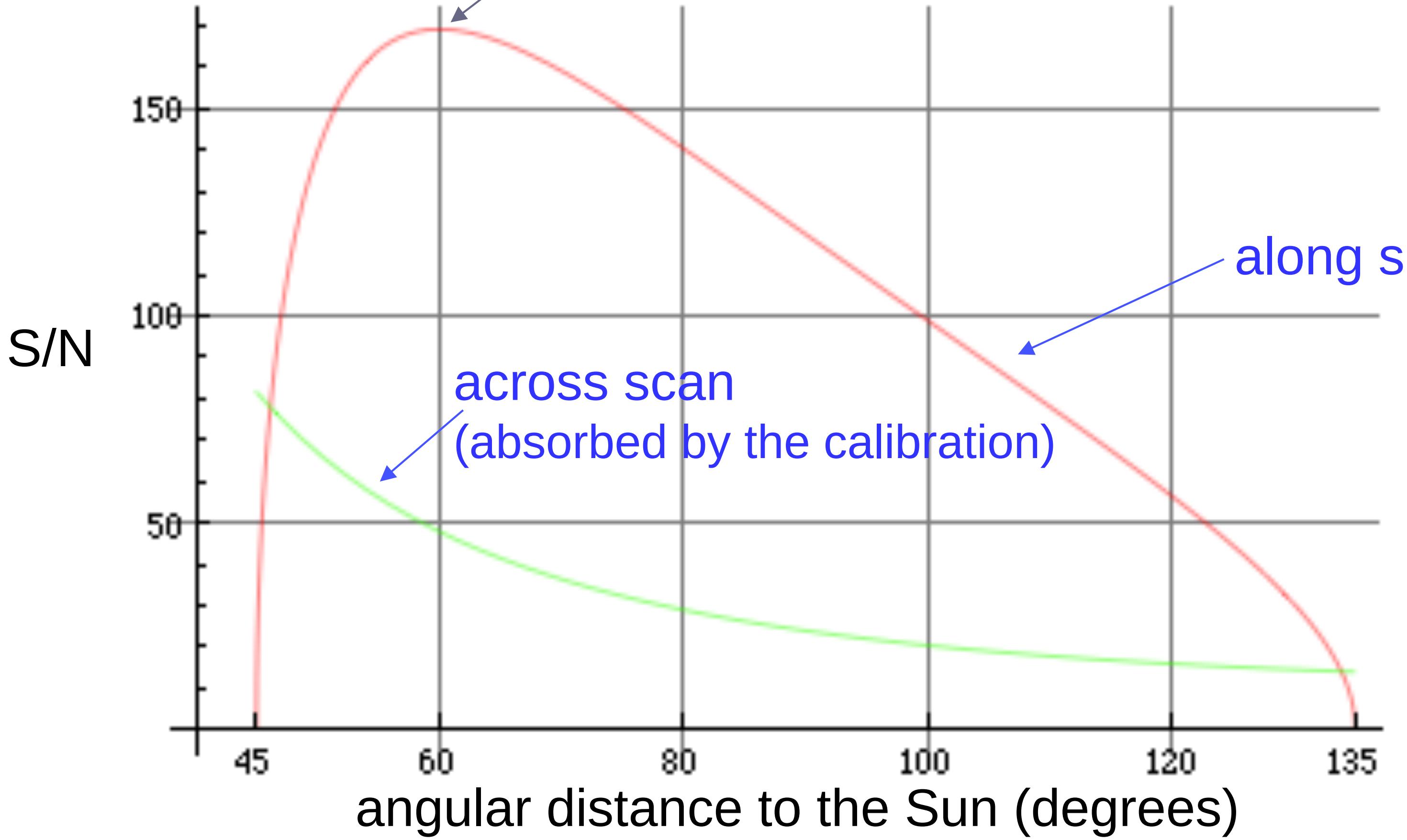
Light bending with Gaia

- Potentially the most precise test with Gaia
- Gaia sensitivity for one transit of an optimal star:



169 @ 60°

along scan

across scan
(absorbed by the calibration)

about 80 transits for each of 10^9 sources…

Light bending with Gaia

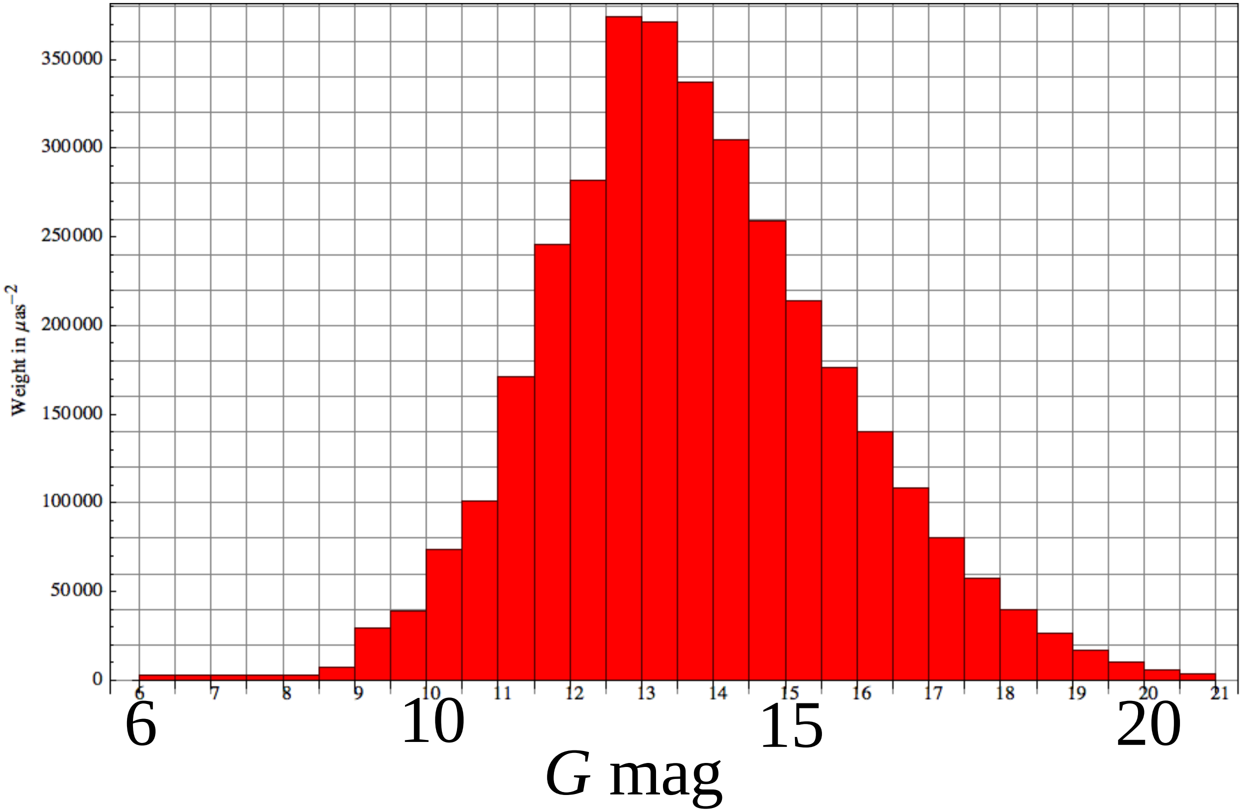
- The post-launch model for the observational noise and the Besançon model for the Galaxy

all stars with G<20:

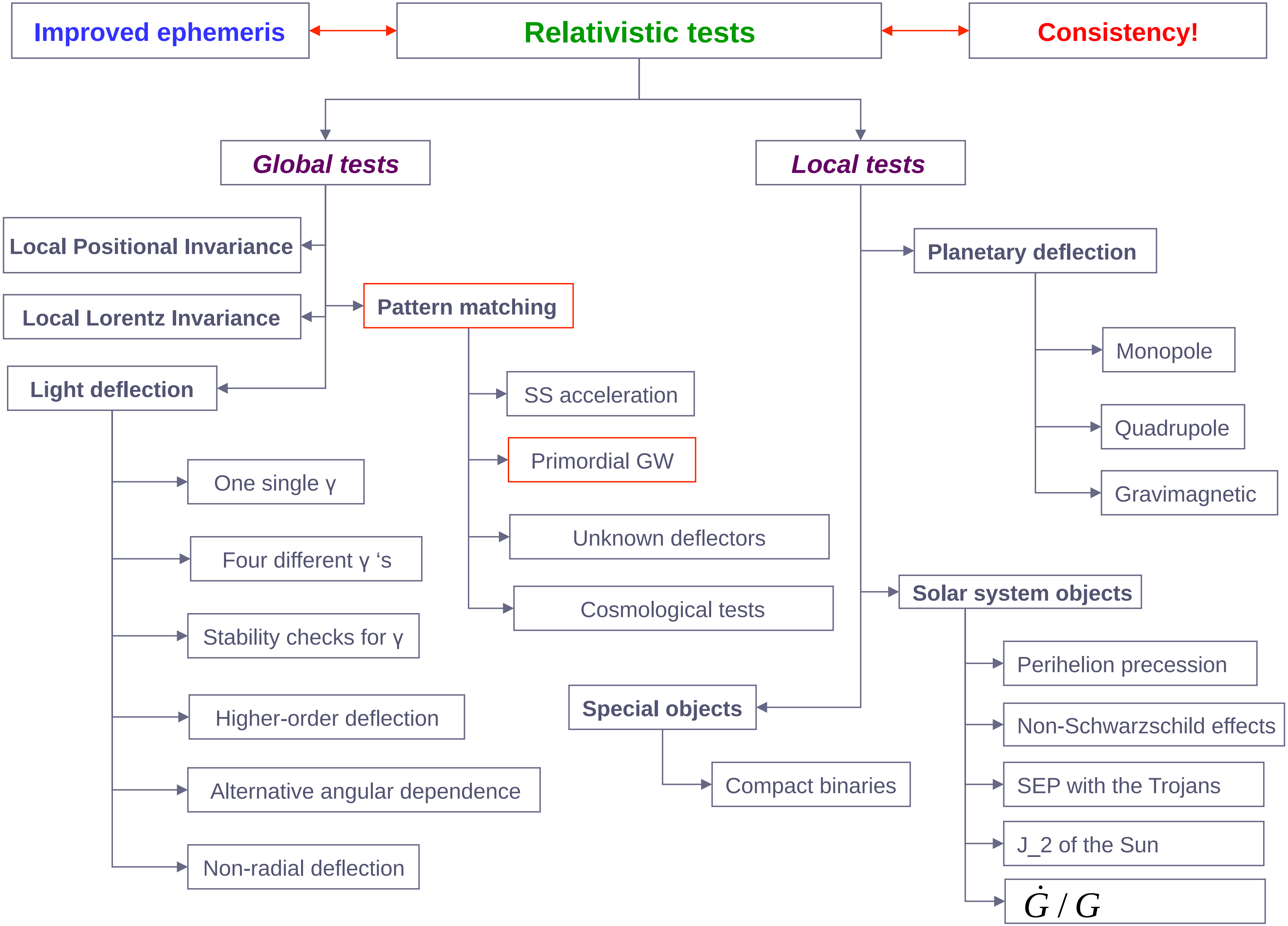
$$\sigma_\gamma > 1.3\times10^{-6}$$

if no bright stars (G<15) are used:

$$\sigma_\gamma > 2.5\times10^{-6}$$



- Systematic errors are a challenge and may even completely ruin this promise!



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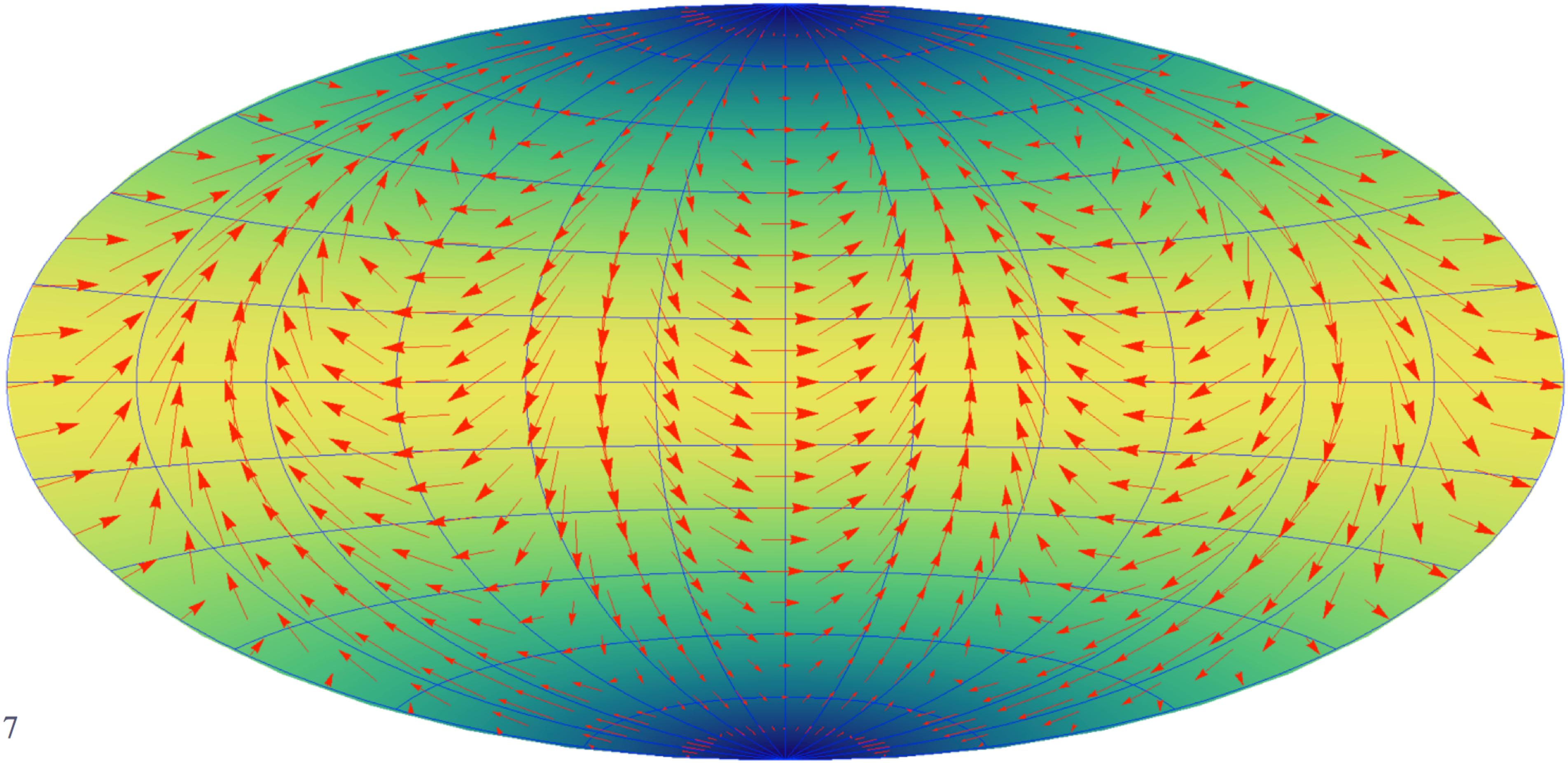
Gravitational waves and astrometry

- At each moment of time a GW produces a deflection pattern on the sky: it is not a pure quadrupole, but rather close to it (Pyne et al, 2006; Gwinn et al, 2006; Book, Flanagan, 2011; Klioner, 2014)

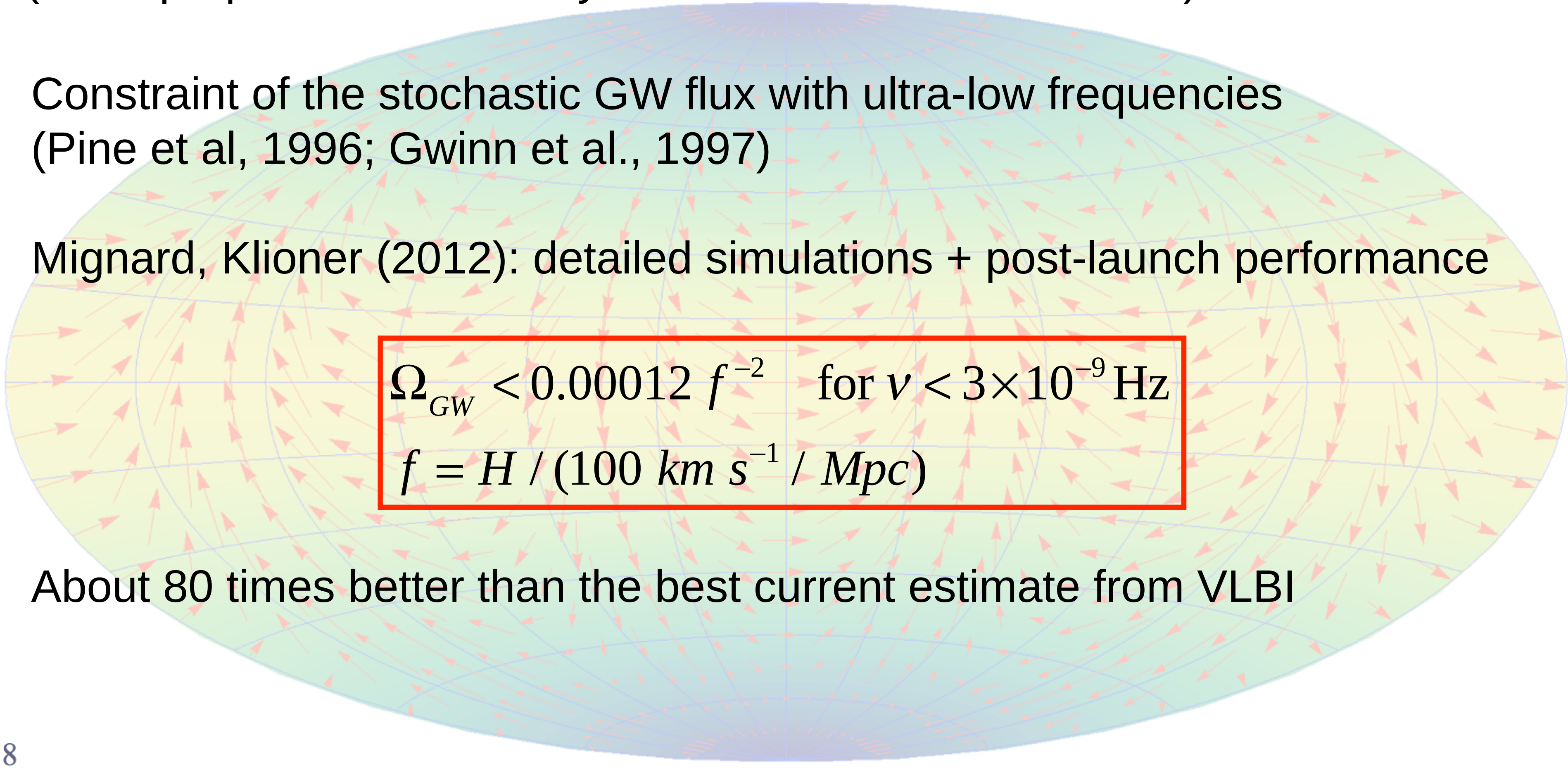
  This is for a GW propagating in the direction δ=90°:



Application 1: ultra-low-frequency GWs

If the frequency of the GW is so small that the period of the wave is substantially larger than the time span covered with observations, the GW deflection pattern is absorbed by proper motion parameters.

This is now the pattern in the proper motions of QSOs in the final catalogue (stars’ proper motions are systematic and cannot be used):



Constraint of the stochastic GW flux with ultra-low frequencies (Pine et al, 1996; Gwinn et al., 1997)

Mignard, Klioner (2012): detailed simulations + post-launch performance

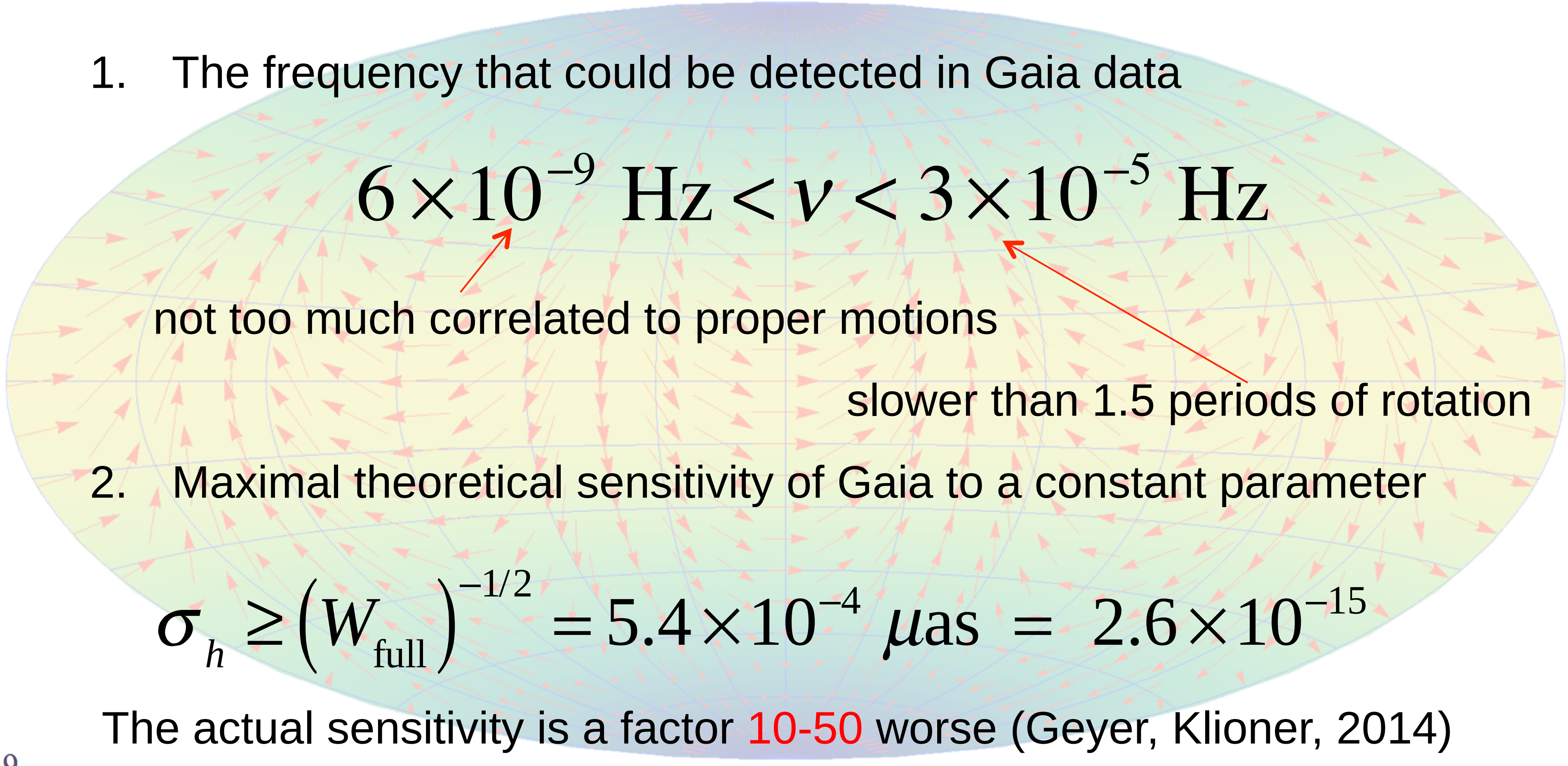
$$\boxed{\begin{aligned}&\Omega_{GW} < 0.00012\, f^{-2} \quad \text{for } \nu < 3\times 10^{-9}\,\mathrm{Hz}\\ &f = H/(100\; km\; s^{-1}/Mpc)\end{aligned}}$$

About 80 times better than the best current estimate from VLBI

Application 2: low-frequency GWs

If the frequency of the GW is large enough, the time-dependence of the deflection does not allow the effect to be absorbed by proper motion.

This is now a time-dependent pattern in the residuals of the solution (at each moment of time only certain directions are observed):



1. The frequency that could be detected in Gaia data

$$6\times10^{-9}\ \text{Hz} < \nu < 3\times10^{-5}\ \text{Hz}$$

not too much correlated to proper motions

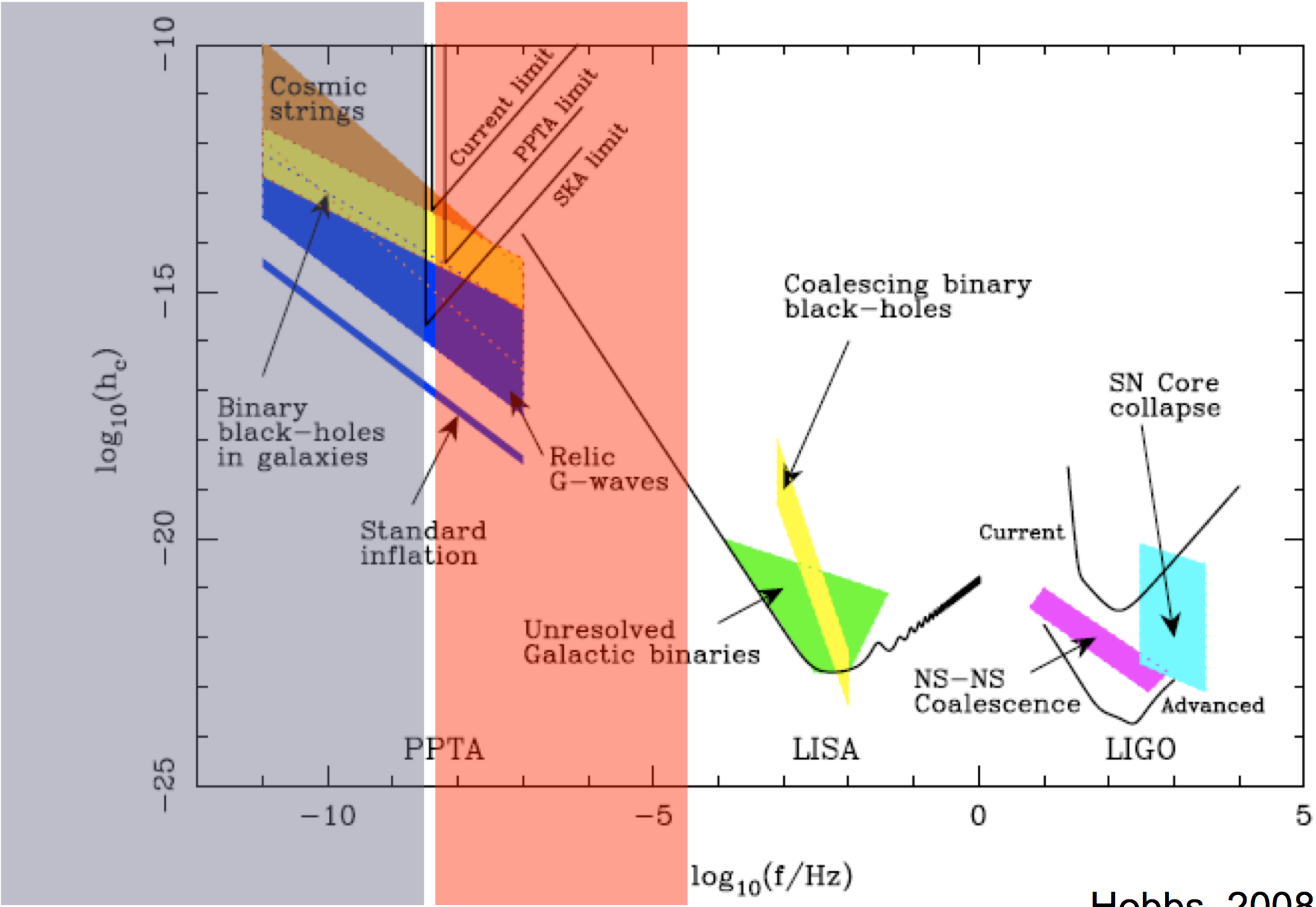
slower than 1.5 periods of rotation

2. Maximal theoretical sensitivity of Gaia to a constant parameter

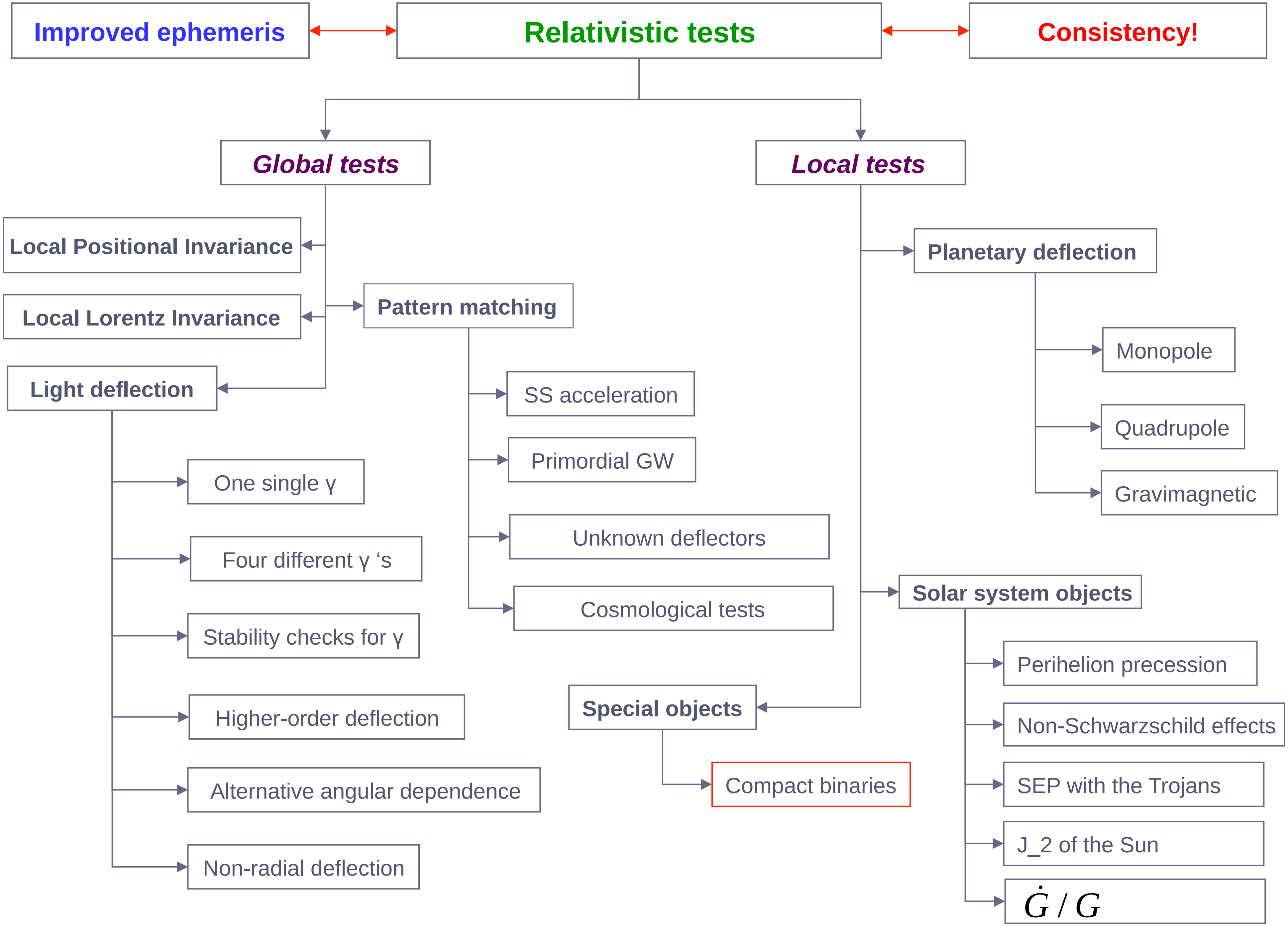
$$\sigma_h \ge \left(W_{\text{full}}\right)^{-1/2} = 5.4\times10^{-4}\ \mu\text{as} \ =\ 2.6\times10^{-15}$$

The actual sensitivity is a factor 10-50 worse (Geyer, Klioner, 2014)

Gravitational Wave Spectrum



Hobbs, 2008



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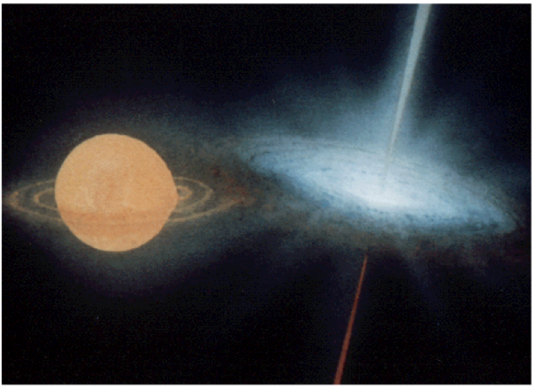
Masses and orbital inclination of neutron stars and black hole in X-ray binaries

- Astrometric wobble of the visible companions
- distance and 3d velocity of the whole system

Many systems with astrometric signatures larger than 20-30 μas:



Bastian, Fuchs, 2004;
Unwin et al., 2008;

Cyg X1 (40 μas), SS433 (30 μas), …

e.g. Cyg X1 – 10%

- BH: Mass function of BH candidates ($M<5M_\odot$? $M>20M_\odot$?)
- neutron stars: constraints on the nuclear equation of state (maximal mass)
- source luminosities, mass accretion rates, sizes of accretion disks…
- proper motions to determine their birthplaces
  (e.g. whether a supernova is required for the formation of a black hole)

What is left out in this presentation

The core science of Gaia will contribute to clarification of the nature of

- Dark energy

  precise calibration of the distance scale

  quantify dispersion in tracers

- Dark matter

  dark matter distribution in various components of the Galaxy

  is the dark matter distribution compatible with MOND, …

Backup slides

Gaia and fundamental physics: a summary

- All the Einsteinian effects that were used in the model can be tested:
  - light-bending effect from several kinds of gravitational fields:
    - monopole
    - quadrupole
    - translational gravitomagnetic
  - relativistic effects in the motion of solar-system objects (e.g., perihelia)

- Tentative non-Einsteinian effects will also be tested:
  - relativistic aberration (Local Lorentz Invariance – a big MM experiment)
  - violation of the Strong Equivalence Principles from asteroids
  - time-dependence of the Newtonian gravitational constant
  - non-Einsteinian light-deflection laws

- Special data processing for certain celestial objects will be used to estimate a number of quantities of high interest for fundamental physics:
  - the acceleration of the solar system relative to QSOs
  - the energy flux of primordial gravitational waves
  - Upper estimates of higher-frequency gravitational waves
  - the masses of a number of black hole candidates in compact binary systems (from astrometric wobbling of the components)

Problems: correlations and systematic errors

- Correlation with the parallax zero point $\rho_{\gamma\pi} \approx -0.89$

  → increases the uncertainty of γ by a factor of $\left(1-\rho_{\gamma\pi}^2\right)^{-1/2} \approx 2.2$
  → impossible to determine γ without good parallaxes

- Very complex data processing: Astrometric Global Iterative Solution

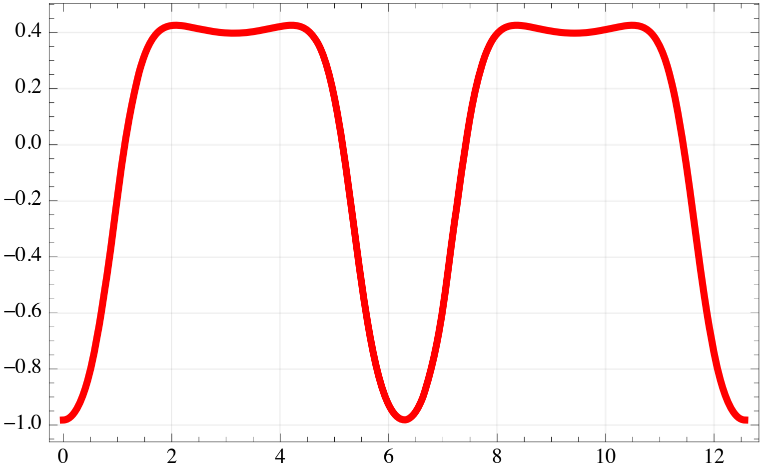
  → no full variance-covariance matrix possible,
  → no realistic uncertainty from the fit

→ Statistical bootstrapping to take into account “unknown” correlations:

$$\boxed{\sigma_\gamma^{\text{realistic}} / \sigma_\gamma^{\text{formal}} = 3.33 \pm 0.07}$$

- Systematic errors in calibration parameters (e.g, in the basic angle) can seriously bias the estimate of γ

  → no γ without good calibrations



Gaia: hardware problems

- Gradual throughput decrease

reason: unexpected water in the spacecraft which slowly
evaporates and condenses as ice on the (cold) mirrors
remedy: periodic (max. twice per year) heating of the payload
consequences: <1 month of additional dead time per year

- Excessive stray light in some parts of the focal plane

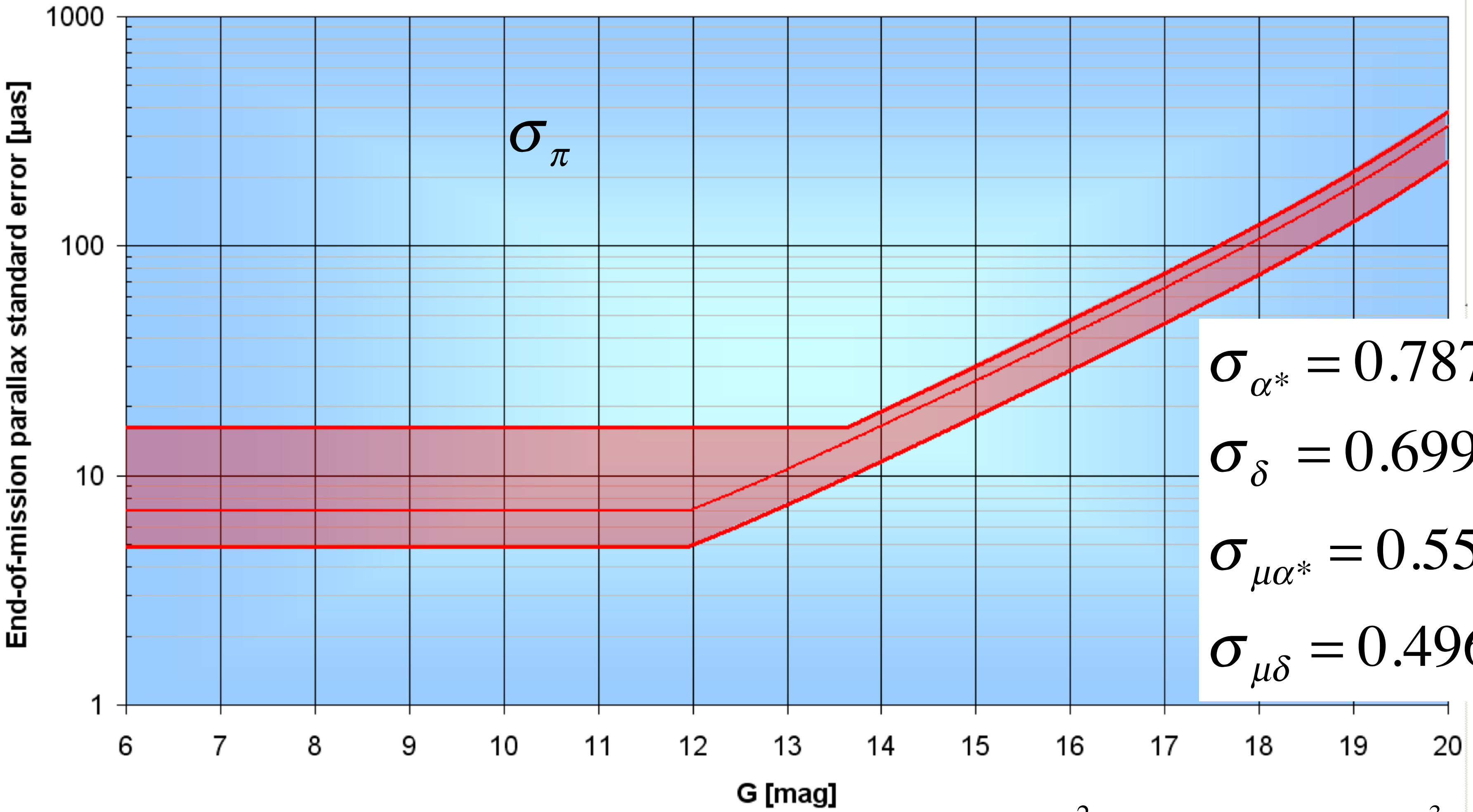
reason: manufacturing errors of the sunshield
remedy: none
consequences: lower accuracies for stars G>16 (factor 2 at G=20)

- Large variations of the BA (basic angle) are measured by the BA monitor

reason: unknown
remedy: BA monitor; studies ongoing
consequences: hopefully none, but…; much more complex calibration

Gaia: no longer expected astrometric accuracy

Predicted uncertainty depends of the brightness and varies over the sky



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$$\sigma_{\mu\alpha*} = 0.556\,\sigma_\pi$$

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$$G = V - 0.0257 - 0.0924\left(V - I_C\right) - 0.1623\left(V - I_C\right)^2 + 0.0090\left(V - I_C\right)^3$$

(α,δ) position; $(\mu_{\alpha*},\mu_\delta)$ proper motion; π parallax

Gaia: expected uncertainties of astrometry

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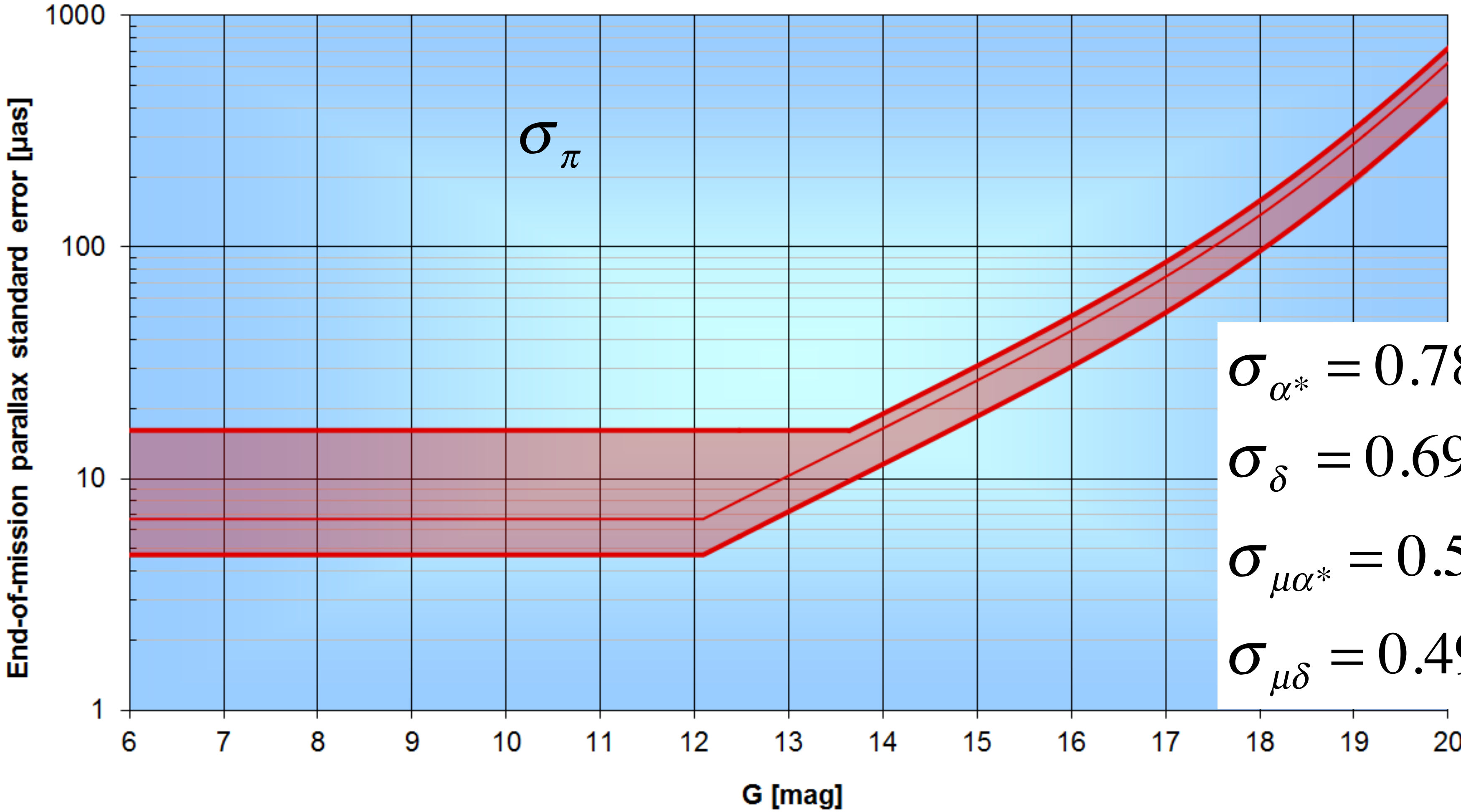

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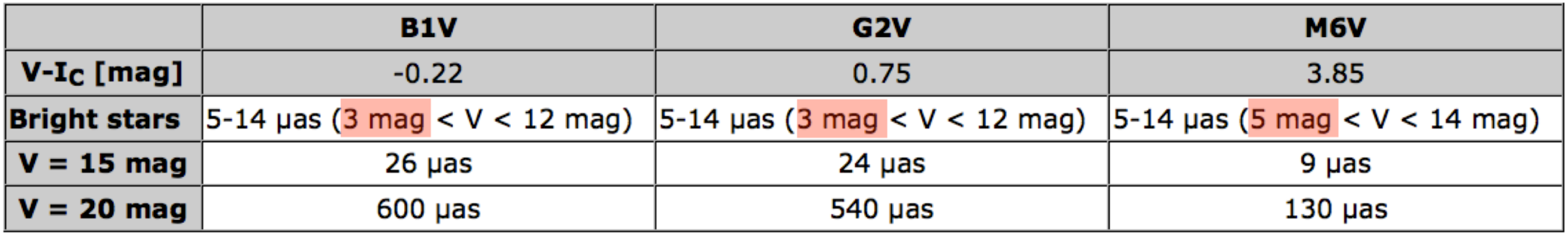
(α, δ) position; $(\mu_{\alpha*}, \mu_\delta)$ proper motion; π parallax

Gaia: expected astrometric accuracy

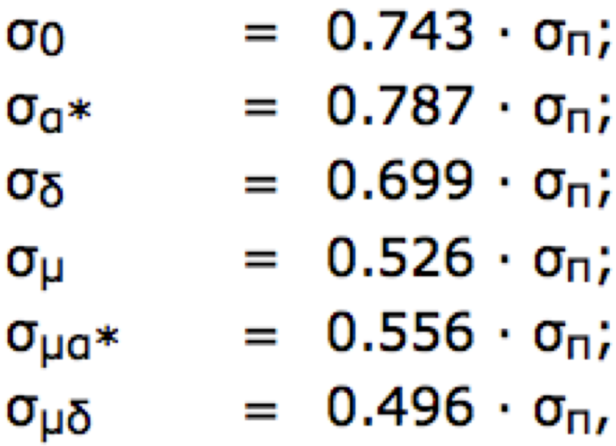
http://www.cosmos.esa.int/web/gaia/science-performance

End-of-mission parallax:



	B1V	G2V	M6V
V-I$_C$ [mag]	-0.22	0.75	3.85
Bright stars	5-14 µas (3 mag < V < 12 mag)	5-14 µas (3 mag < V < 12 mag)	5-14 µas (5 mag < V < 14 mag)
V = 15 mag	26 µas	24 µas	9 µas
V = 20 mag	600 µas	540 µas	130 µas

Other parameters:

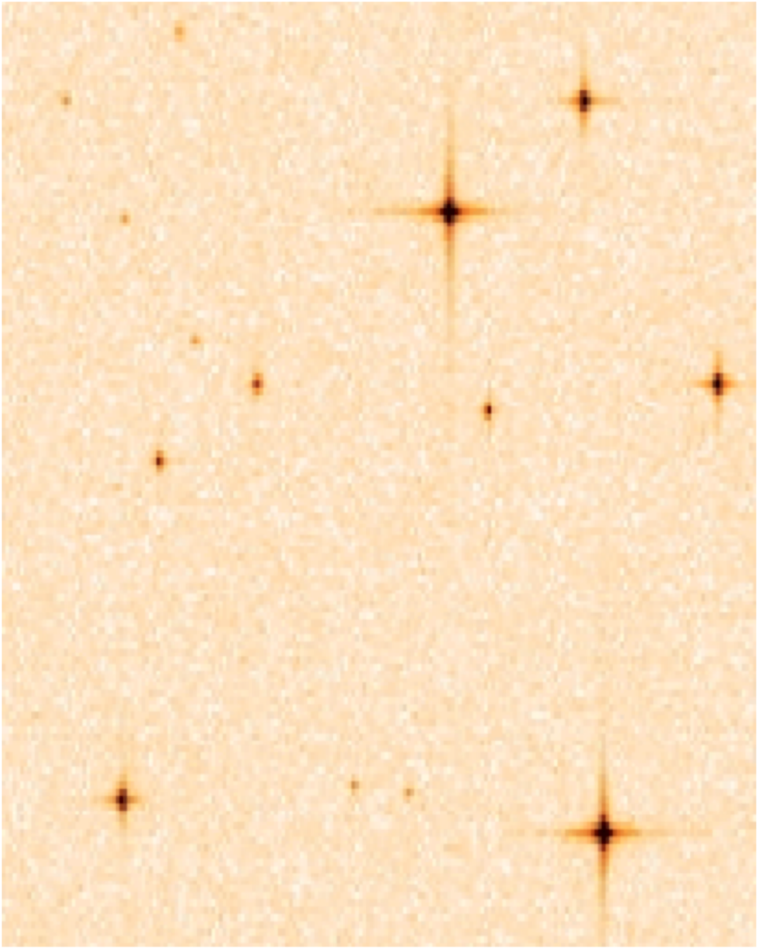


$$
\begin{aligned}
\sigma_0 &= 0.743 \cdot \sigma_\pi; \\
\sigma_{\alpha*} &= 0.787 \cdot \sigma_\pi; \\
\sigma_\delta &= 0.699 \cdot \sigma_\pi; \\
\sigma_\mu &= 0.526 \cdot \sigma_\pi; \\
\sigma_{\mu\alpha*} &= 0.556 \cdot \sigma_\pi; \\
\sigma_{\mu\delta} &= 0.496 \cdot \sigma_\pi,
\end{aligned}
$$

The predicted errors vary over the sky…

Gaia raw observations: 10^{12} stellar “images”

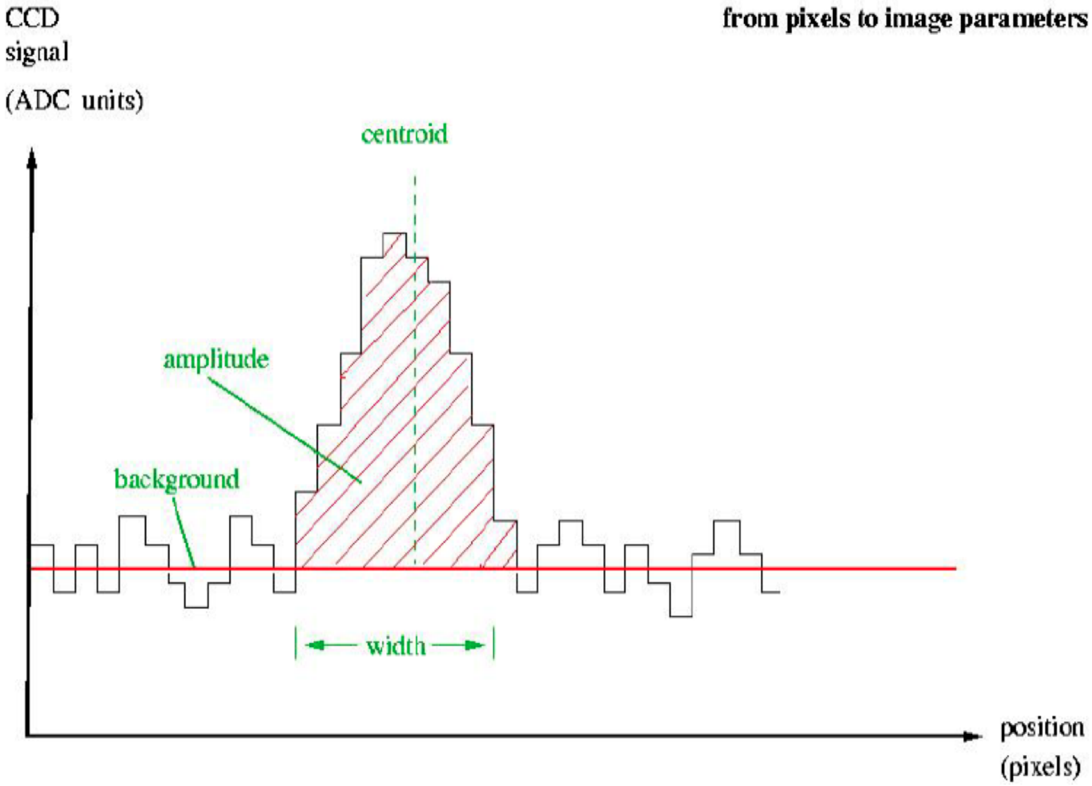
CCD pixel count read off a certain CCD at a certain moment of time



(binned) CCD pixels with time-tags for each pixel

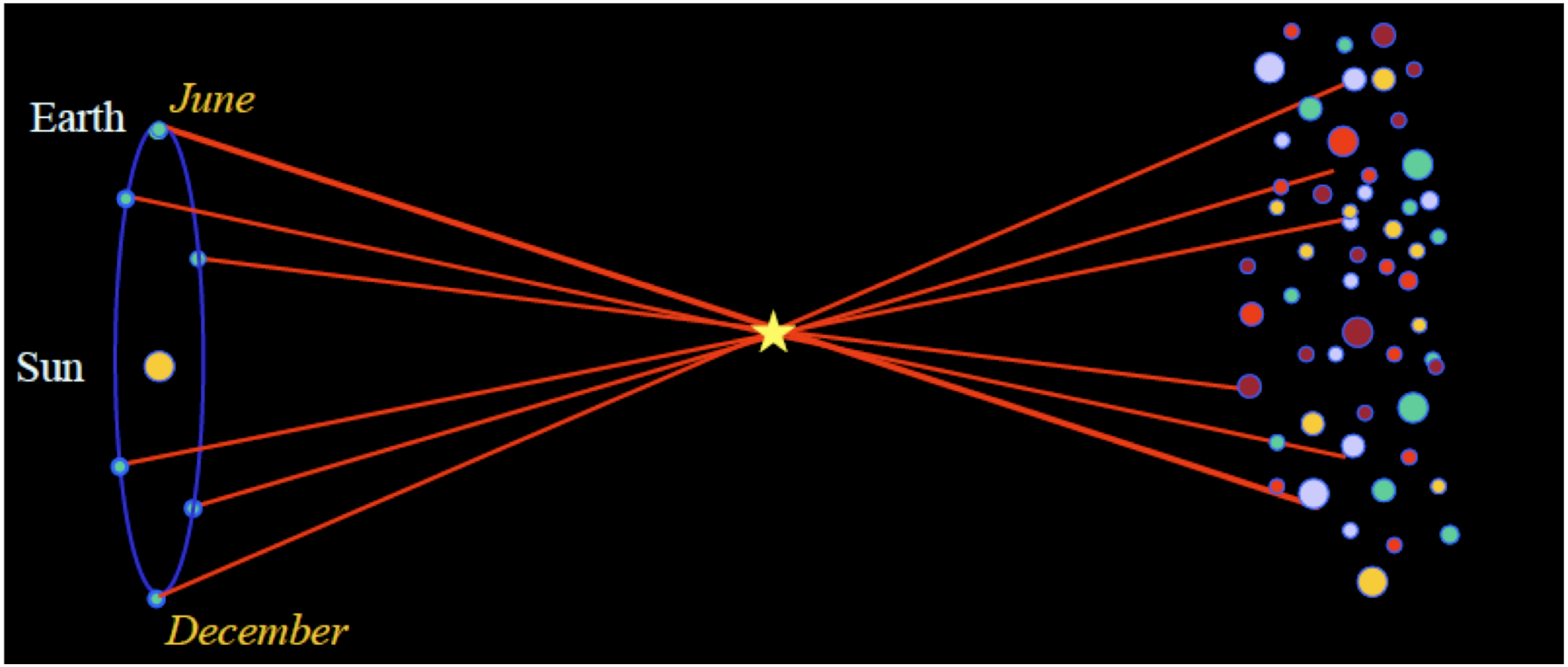
Windows for each observed object

Centroiding accuracy: millipixels

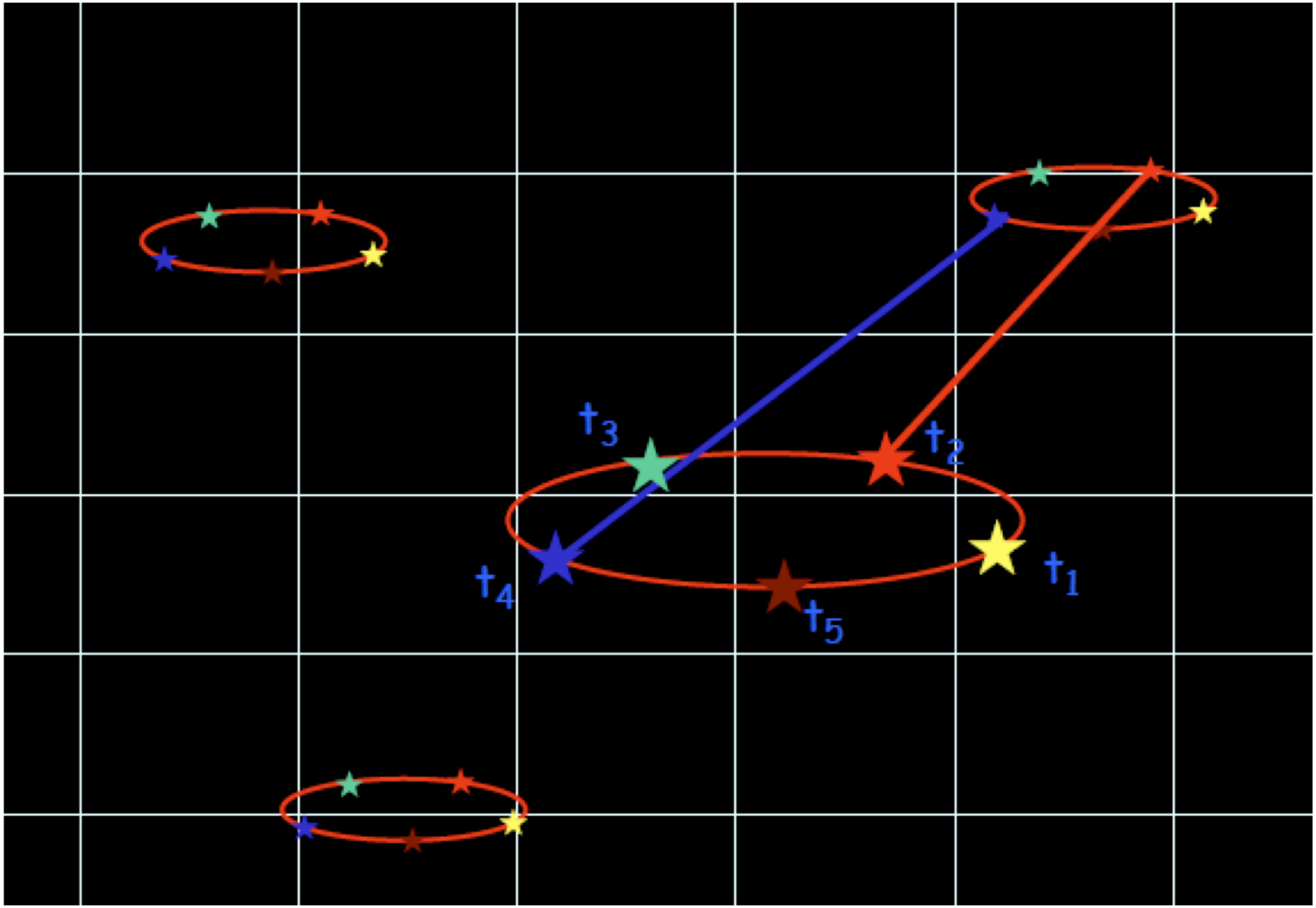


Stellar parallaxes

Earth's orbit a closer star very distant stars



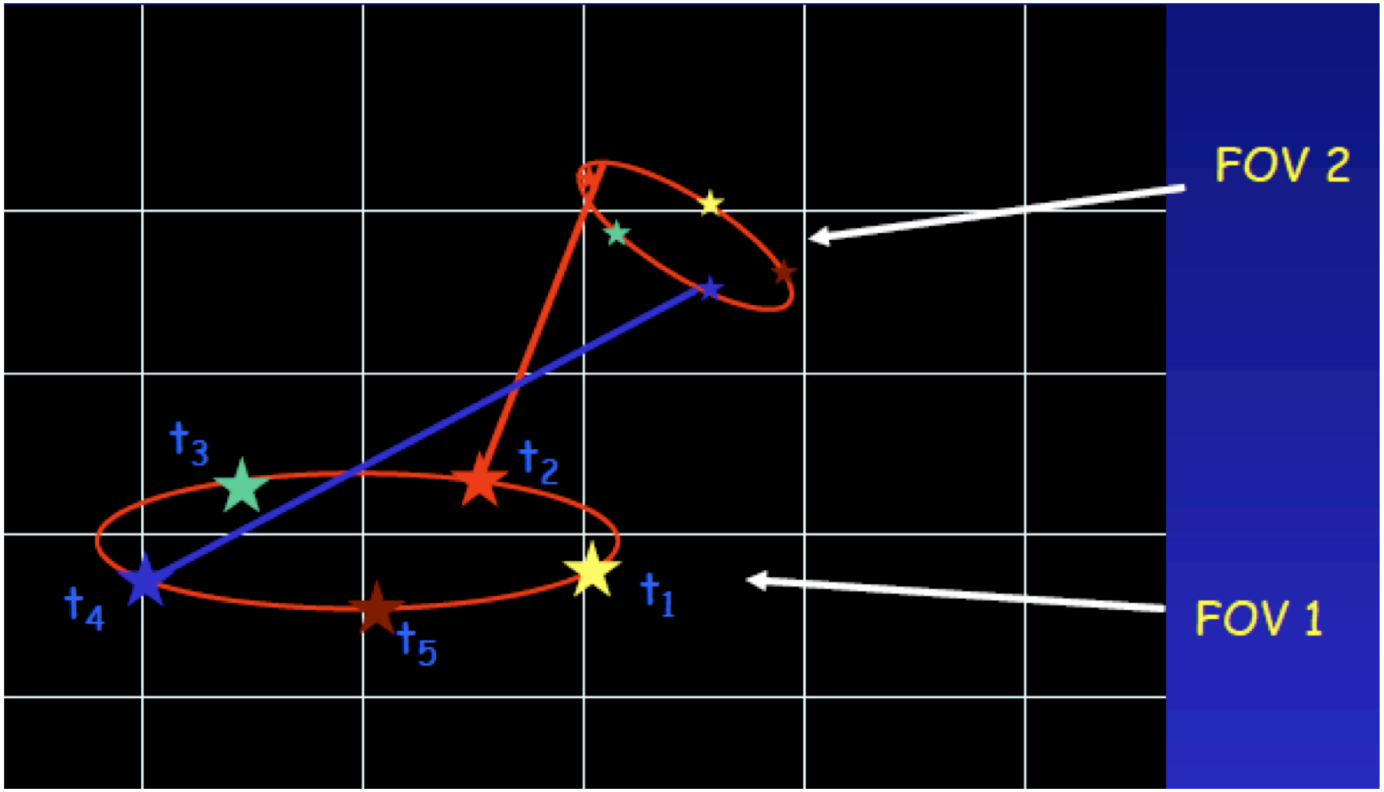
One field of view: relative parallaxes



Measurable quantity: $f(t)\times(\pi_2-\pi_1) \quad \Rightarrow \quad \pi_2-\pi_1$

Two fields of view: absolute parallaxes

Pierre Lacrout, 1968:



Measurable quantity: $f_2(t)\pi_2 - f_1(t)\pi_1 \quad \Rightarrow \quad \pi_2$ and π_1

Implemented by ESA twice: Hipparcos (1989-1993), Gaia (2013-)