Challenges of fundamental physics in the context of Gaia astrometry

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A disclaimer

The core science of Gaia will contribute to clarification of two biggest mysteries of modern physics:

- Dark energy

    precise calibration of the distance scale

    quantify dispersion in tracers

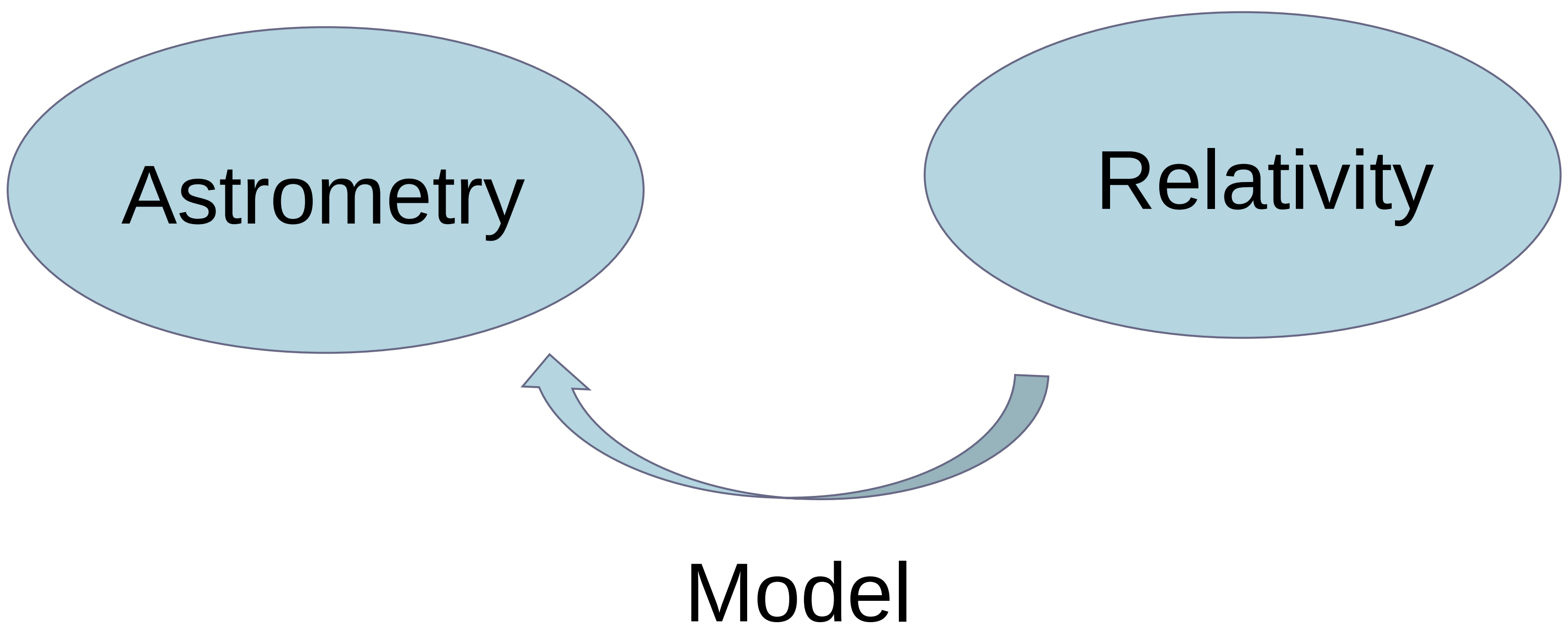
- Dark matter

    dark matter distribution in various components of the Galaxy

    is the dark matter distribution compatible with MOND, …

This is completely left out of this presentation!
See >15 other presentations at this Symposium dealing with the subject….

Gaia astrometry needs a relativistic model



Prerequisite for all applications and tests: Gaia Relativity Model (GREM)

- 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

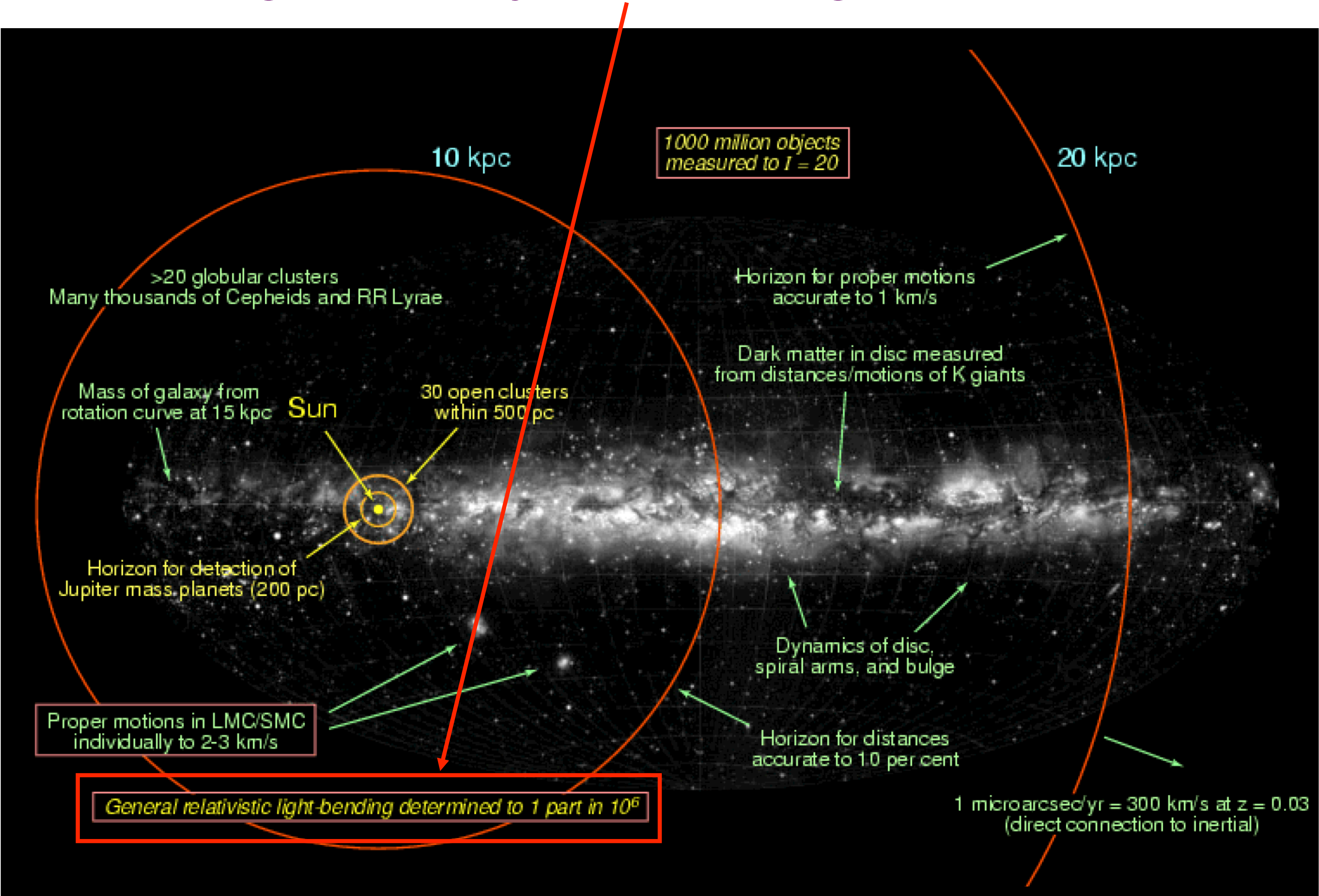
    - relativistic definitions of parallax, proper motion, etc.

    - relativistic definitions of observables and the attitude of the satellite

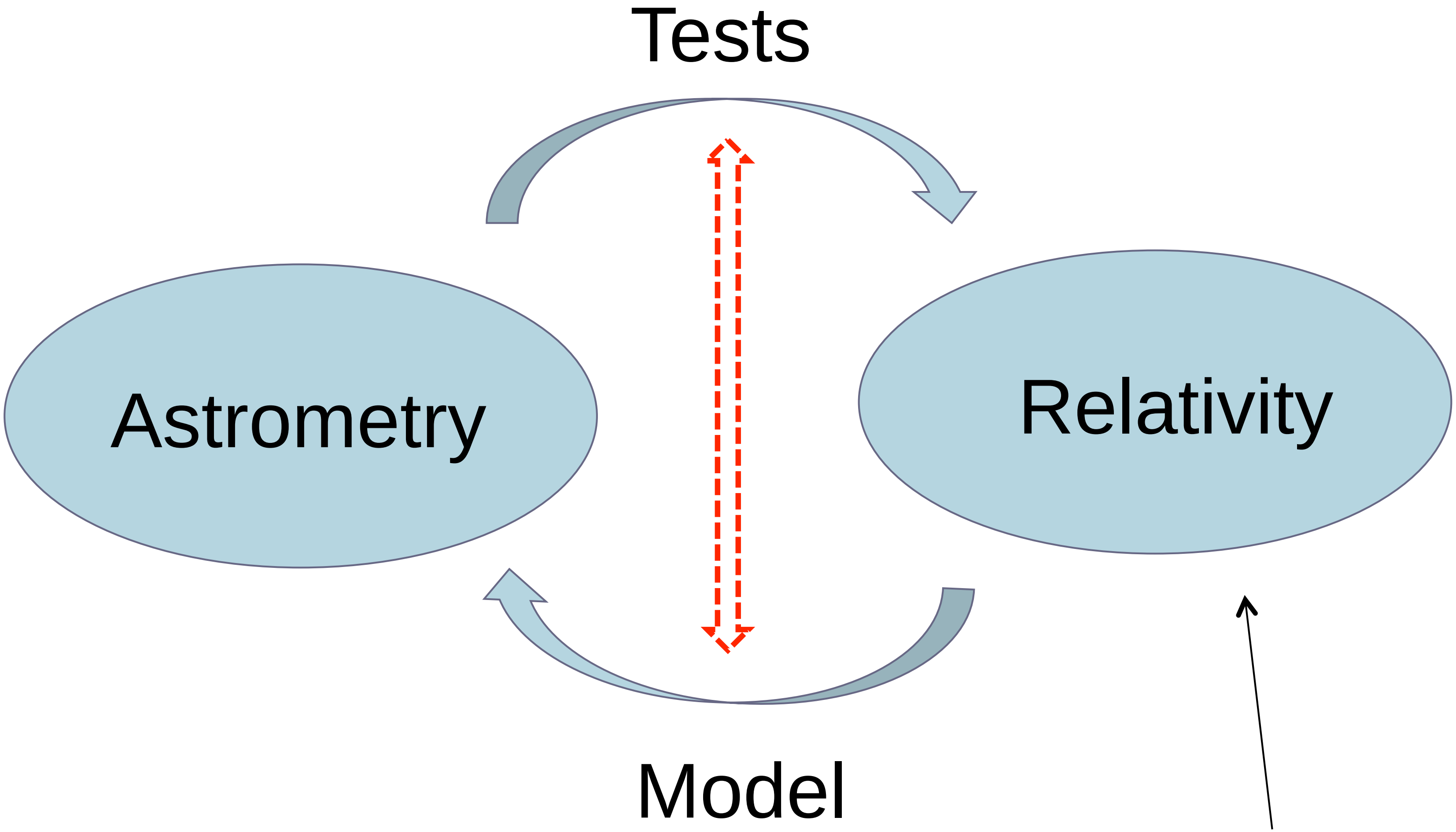
    - relativistic model for the synchronization of the Gaia atomic clock and ground-based time scale (Gaia proper time etc.)

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

Testing Relativity as a driving force for Gaia



Gaia astrometry can be used to test Relativity



More than just “Relativity”!

Possible tests: an attempt of classification

I. Effects in the standard relativistic model (e.g. deflection of light)

II. Additional global effects:

(1) not in GR;

(2) can’t be modelled systematically (e.g. transient or unknown)

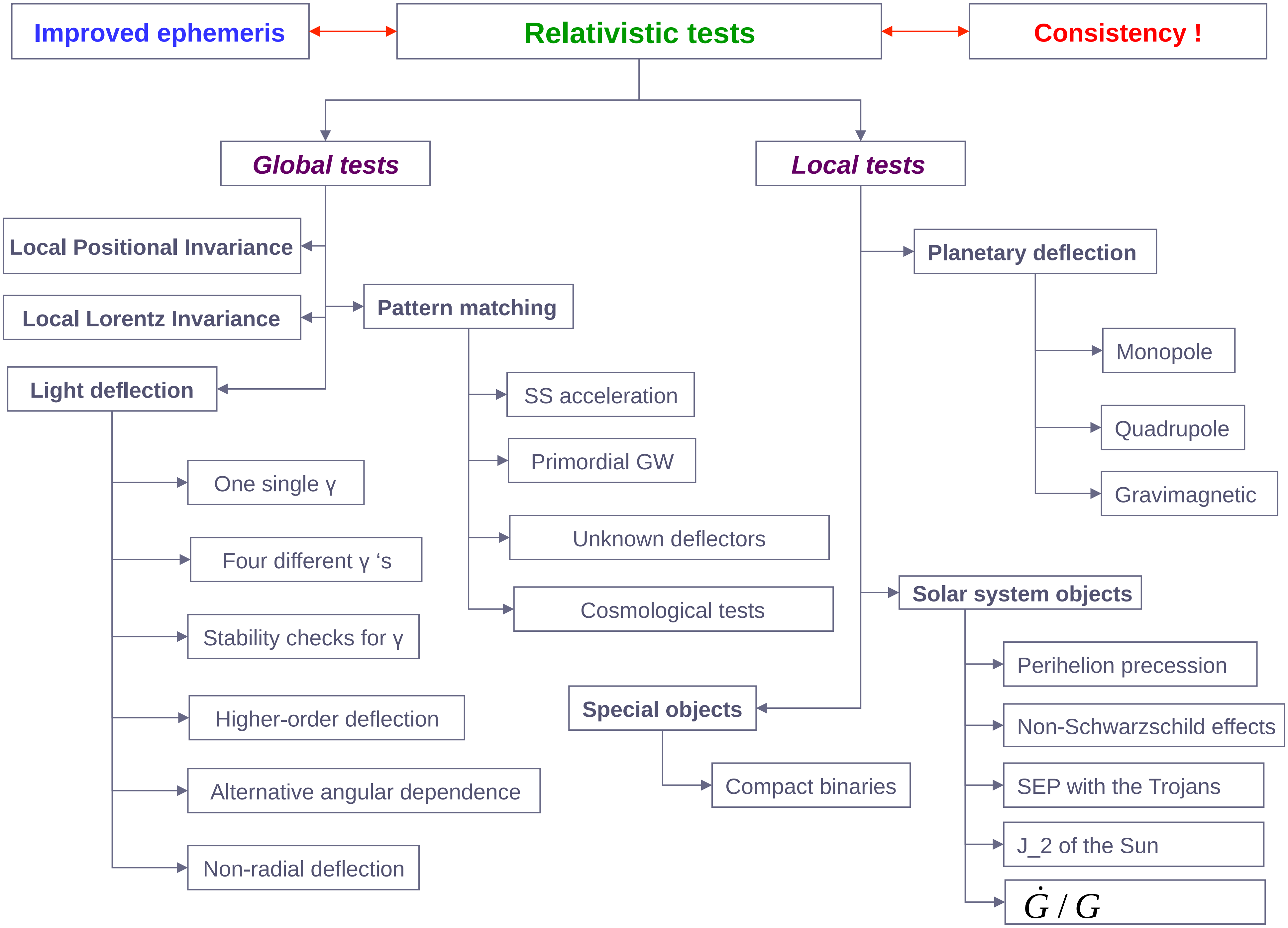
III. Observations of individual objects of special interest

A. Not related to gravitational fields

B. Gravitational field of the Solar System

C. Gravitational field generated by remote objects, but measured in the Solar System

D. Gravitational fields at remote objects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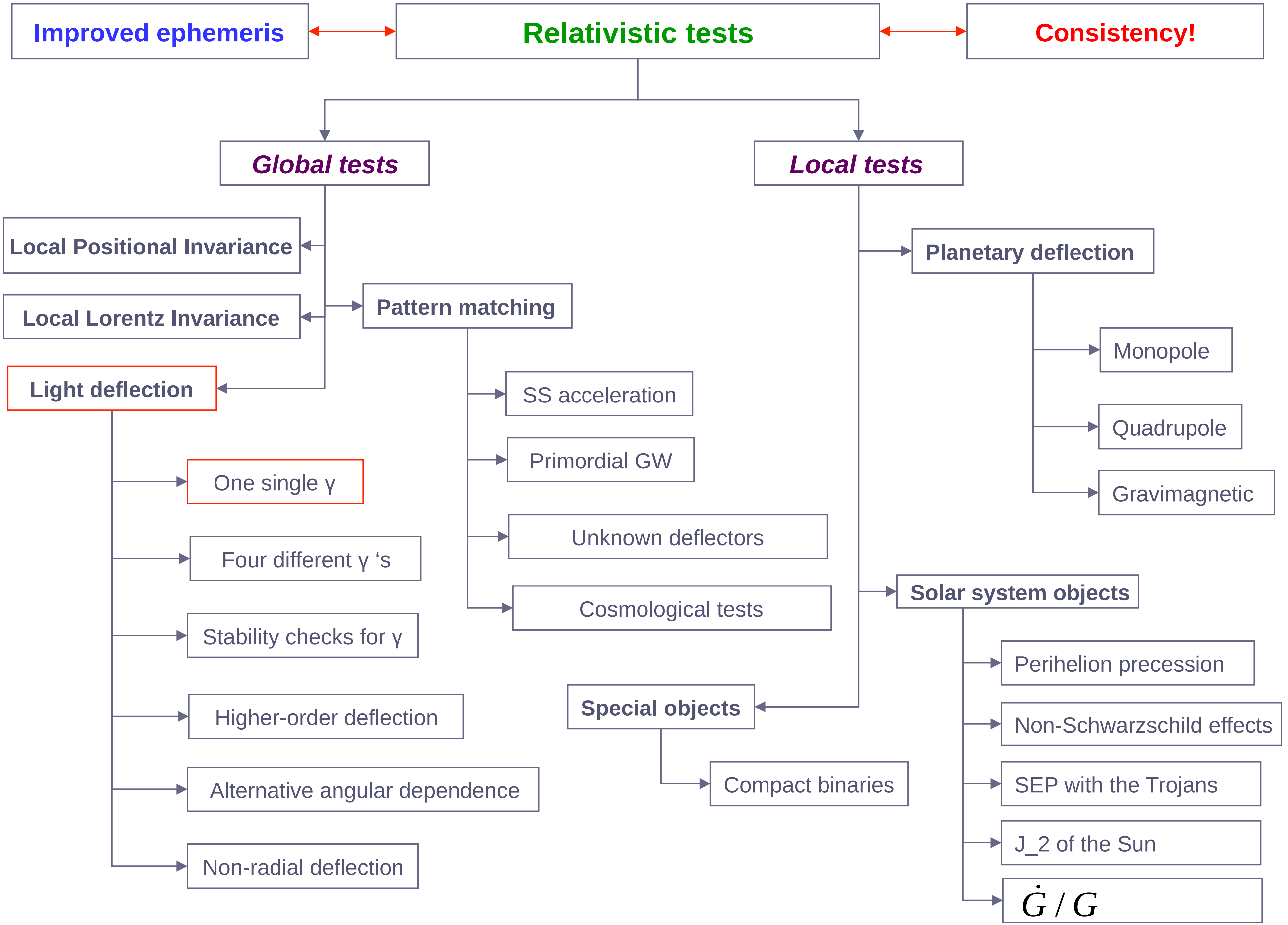
Compact binaries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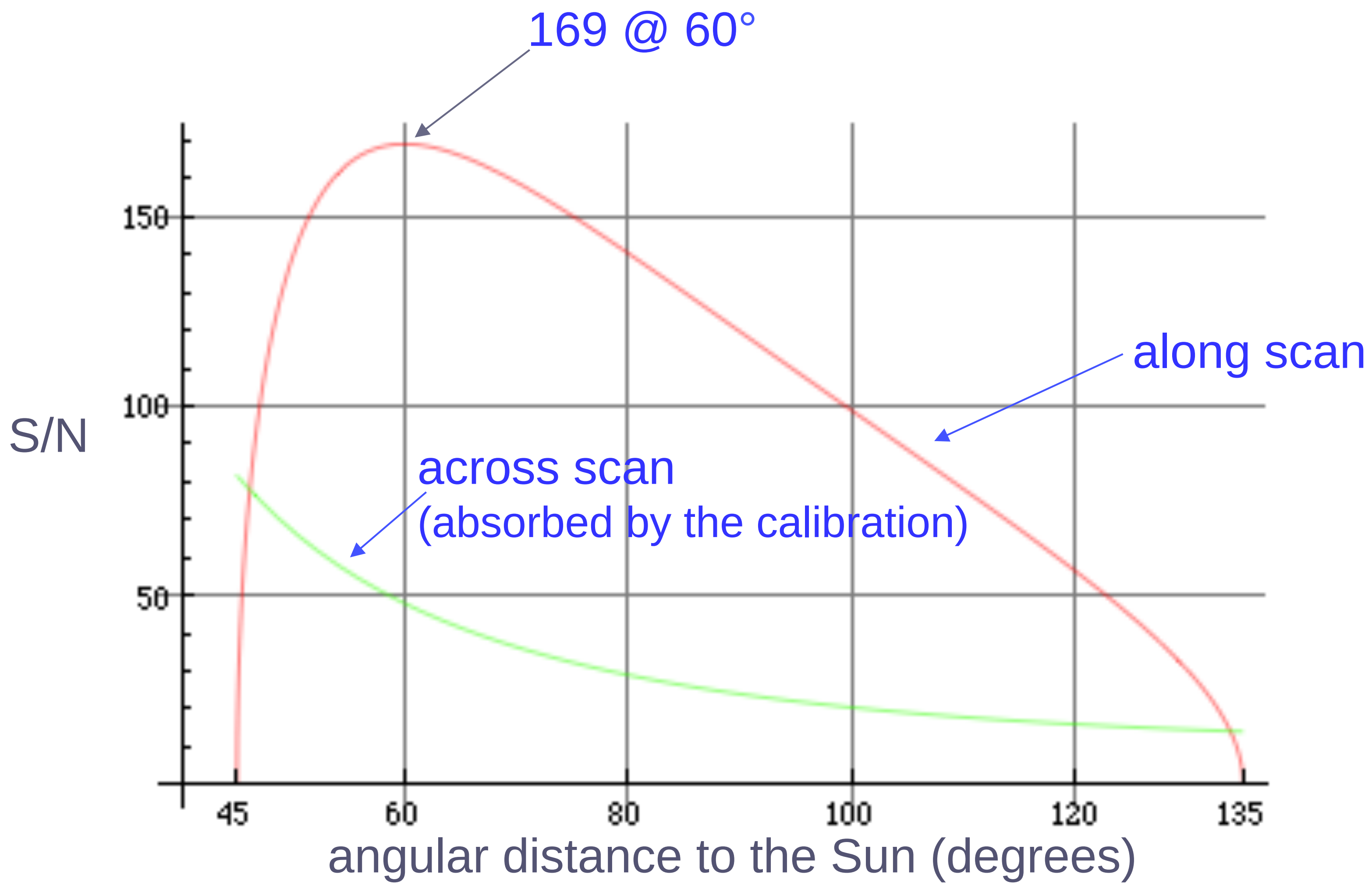
Light-bending with Gaia

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

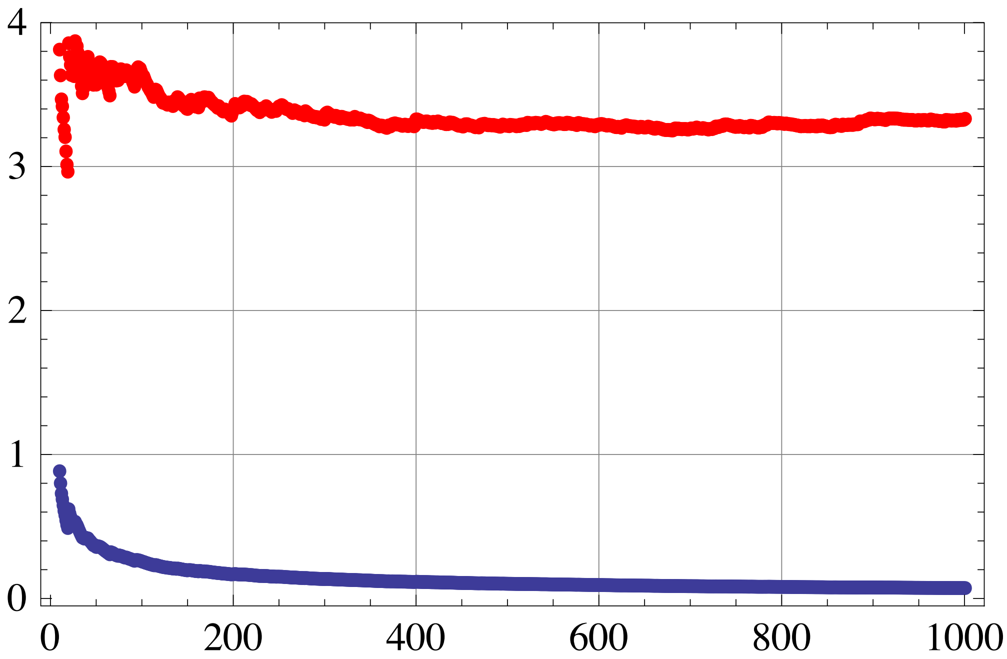


Problem I : unknown correlations in AGIS

- Very complex astrometric data processing:
  no single variance-covariance matrix possible,
  no realistic uncertainty from the fit

- Statistical bootstrapping is needed to take into account hidden correlations

>1000 test runs of AGIS solution with a realistic Gaia setup:



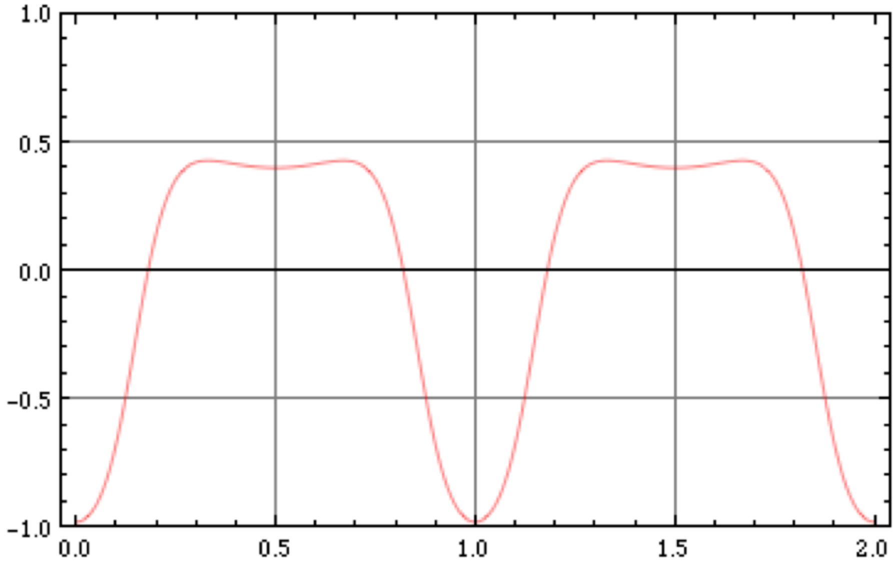
$$\frac{\sigma_\gamma^{\text{realistic}}}{\sigma_\gamma^{\text{formal}}} = 3.33 \pm 0.07$$

Only a part can be modelled analytically: the known correlation with parallax zero point

Problem II : systematic errors in calibrations

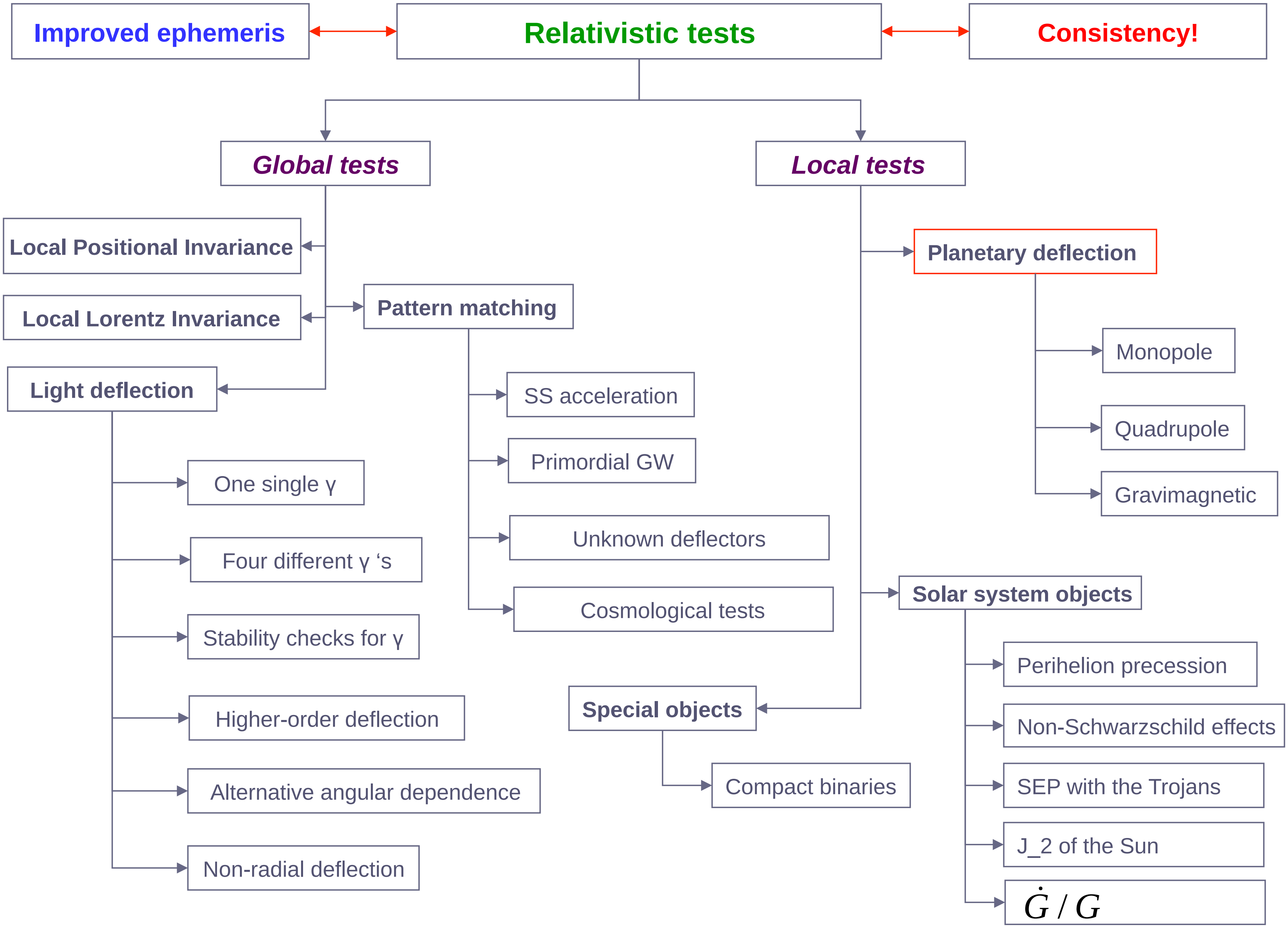
- Systematic errors in calibration can substantially bias the estimate. E.g. a variation in γ is (almost) equivalent to a certain variation of the basic angle (Ω is the heliotropic phase of Gaia):

$$\delta\,\Gamma_\gamma = \delta\gamma\,\frac{2m_\odot}{R}\,f(t) = \delta\gamma\sum_{k=1}^{\infty} C_k^{(\gamma)}\cos(k\Omega)$$



heliotropic rotational phase

- Possible calibration problems can ruin the promise for γ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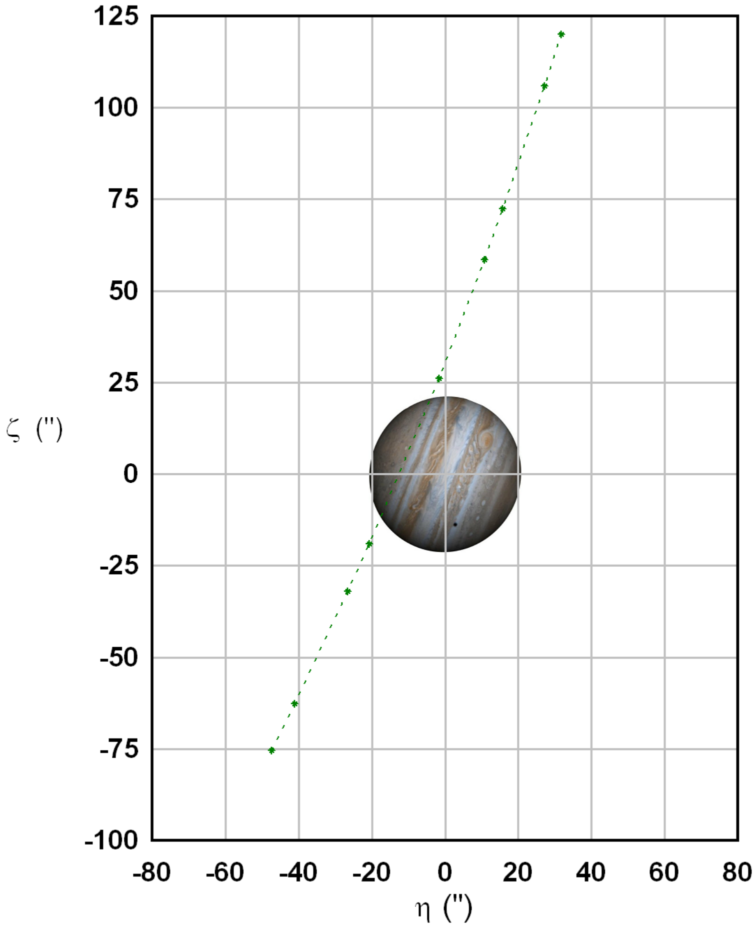
Non-solar light bending

Stars close to the giant planets allow one to trace also smaller effects:

- quadrupole deflection of light
- enhanced post-post-Newtonian deflection terms
- translational gravitomagnetic deflection

Optimal stars close to e.g. Jupiter are needed!

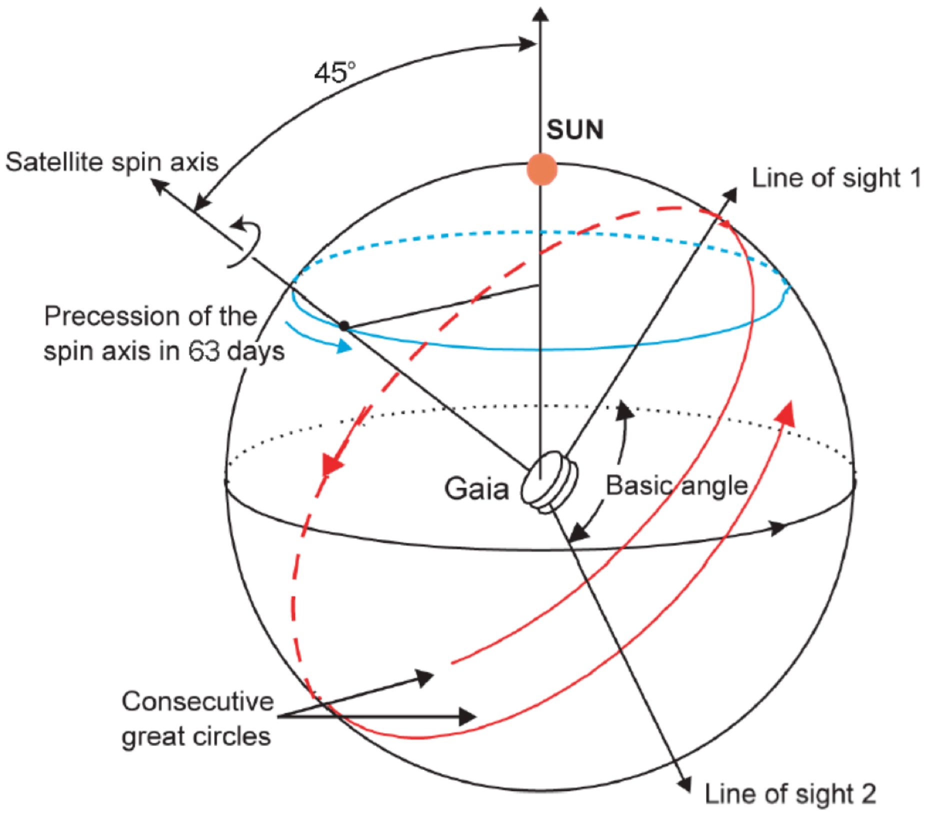


Klioner, Mignard, 2014

Close approaches of bright stars and Jupiter

Several rare events contribute to the sensitivity to the quadrupole deflection

to be observed by Gaia at the optimal moment and in the optimal direction

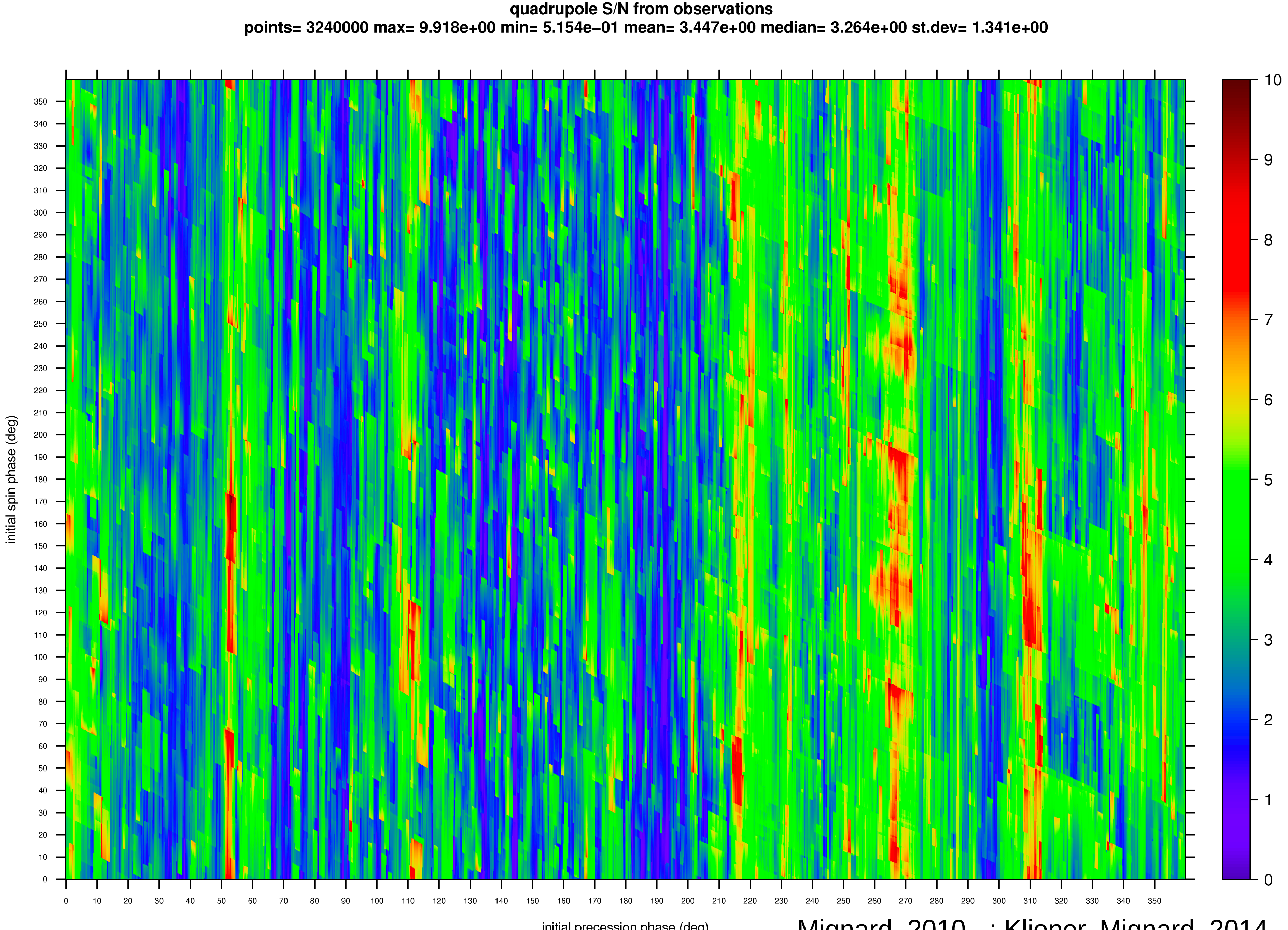


The scanning law of Gaia has two free parameters:

- initial precession phase
- initial spin phase

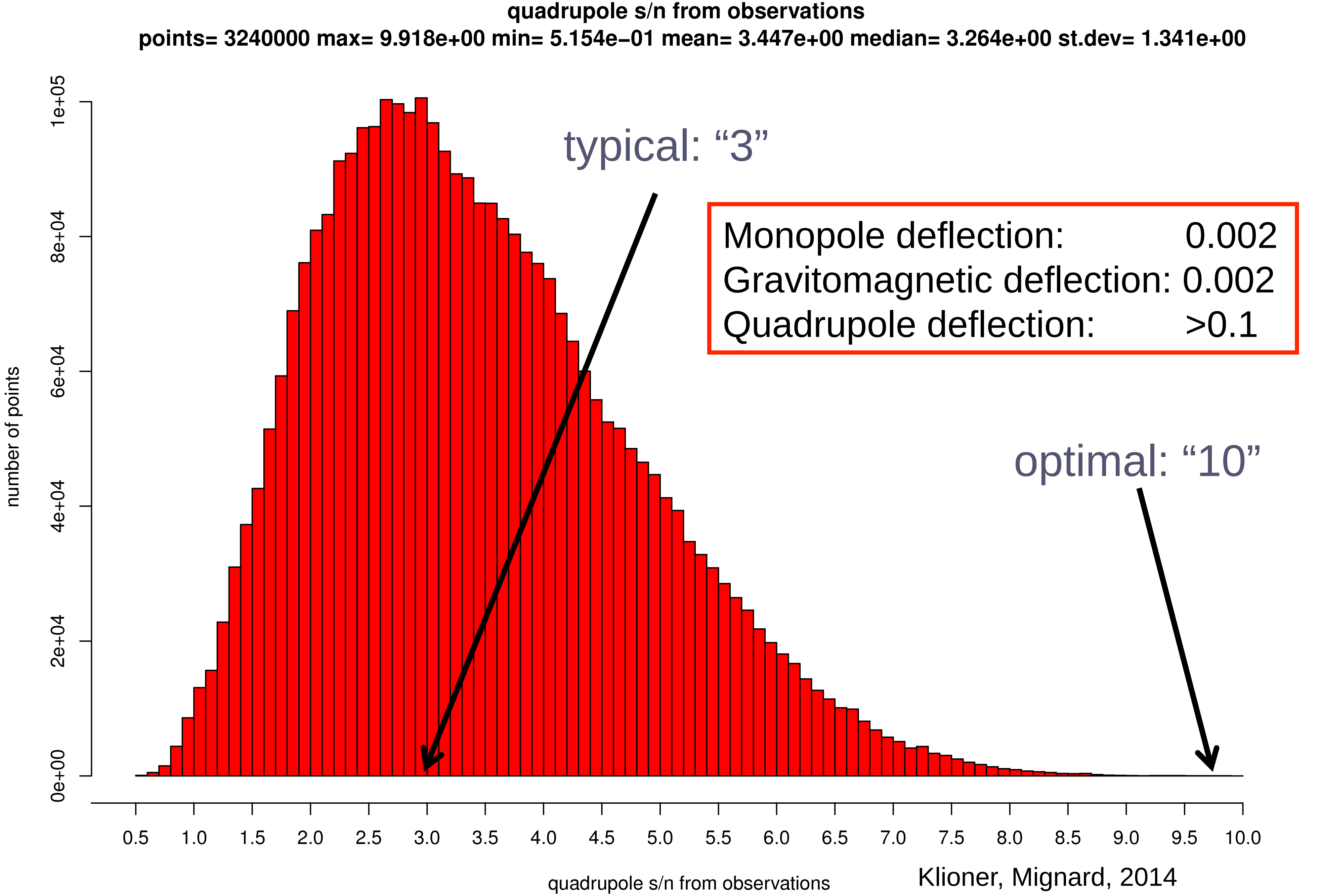
These parameters can be optimized for the test of quadrupole deflection

Color-coded sensitivity as function of two initial phases

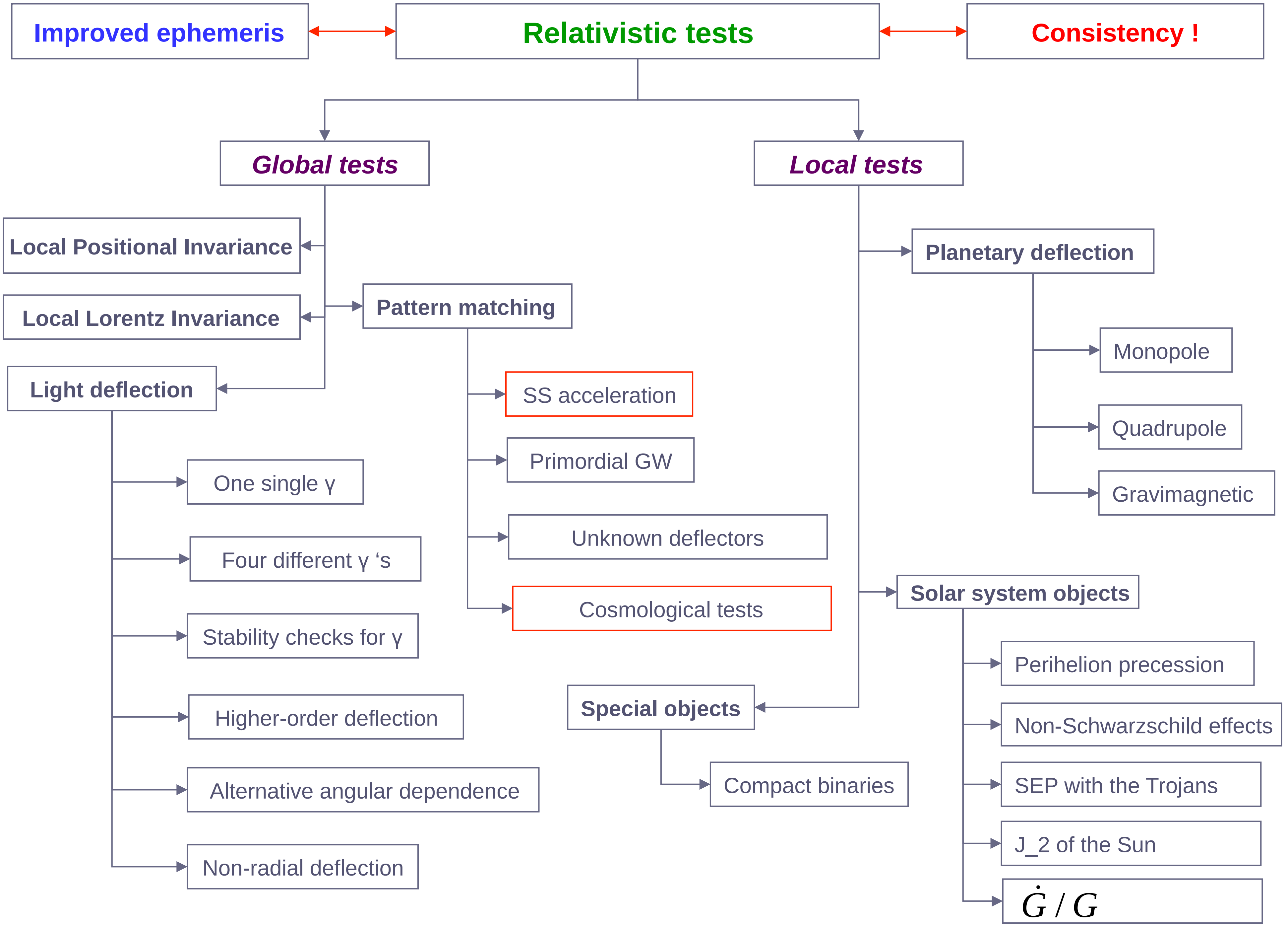


Mignard, 2010 - ; Klioner, Mignard, 2014

This optimization does bring a major improvement



Klioner, Mignard, 2014



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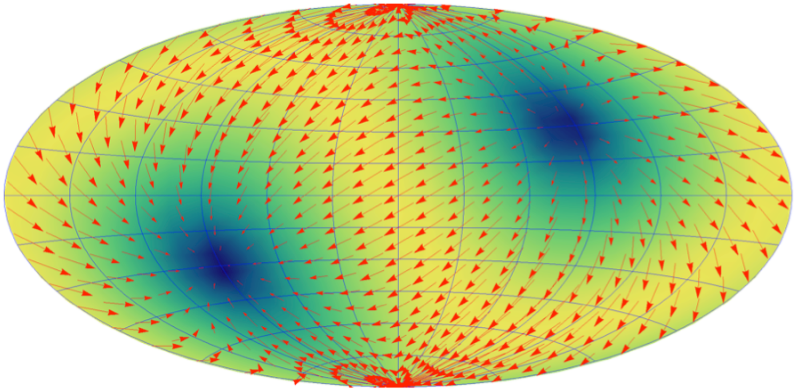
Patterns in proper motions of extragalactic objects

1. Drift of secular aberration due to acceleration of the Solar system relative to remote sources: about 5 μas/yr; independent of source distances

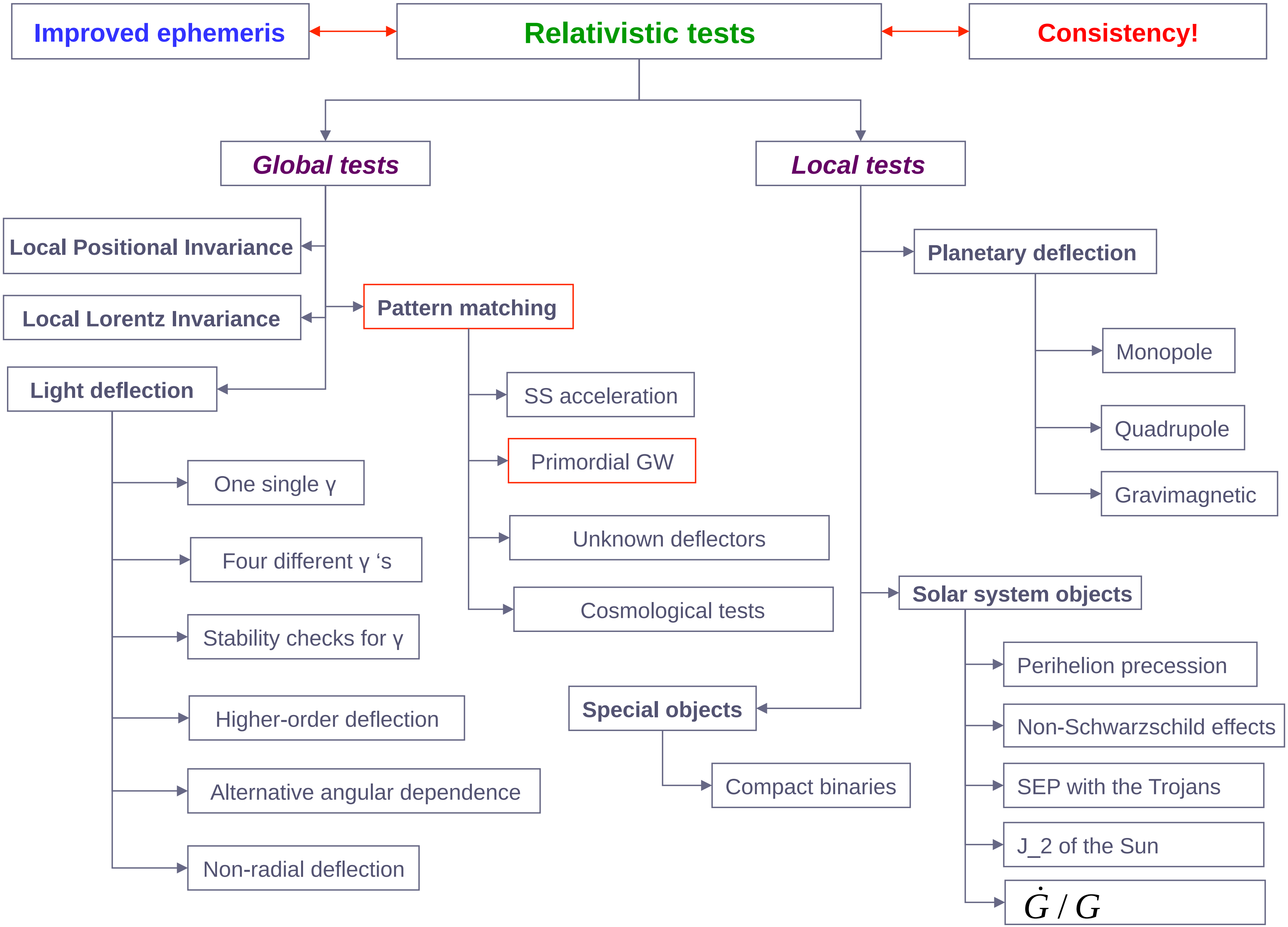
    - important for the binary pulsar test of relativity (at 1% level)

Gaia will measure the acceleration with <10% accuracy (Mignard, Klioner, 2012; Bachchan et al 2016)



2. Linear parallactic shifts of nearby galaxies (z<0.03) due to motion of the Solar System relative to the CMBR (80 AU per year! Kardashev, 1986): a few μas/yr for closest galaxies; dependent on the source distance

    Different interpretations are possible. E.g. Gaia may be able to measure the Hubble constant to 10% (Bachchan et al 2016)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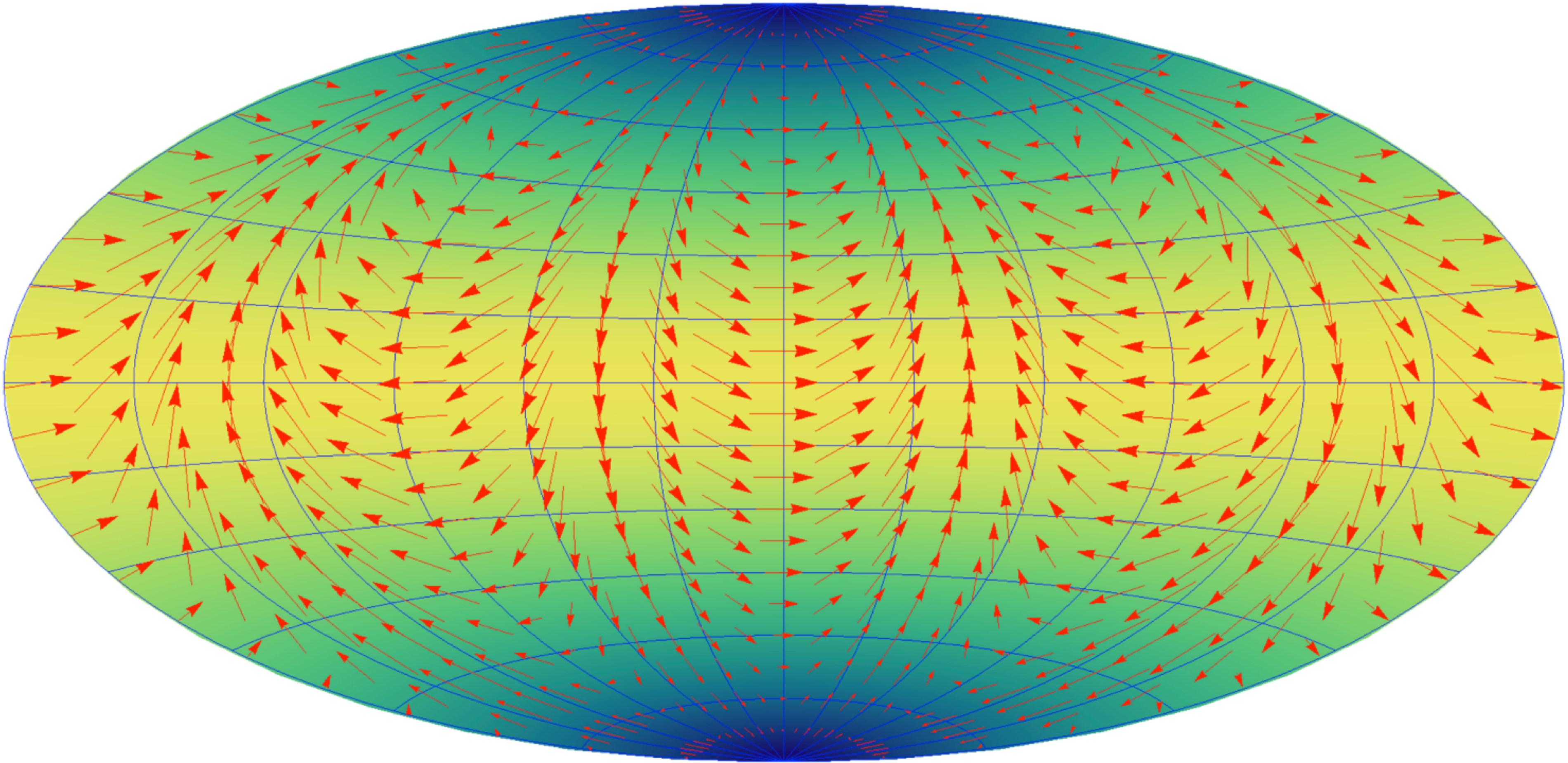
Gravitational waves and astrometry

- 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)

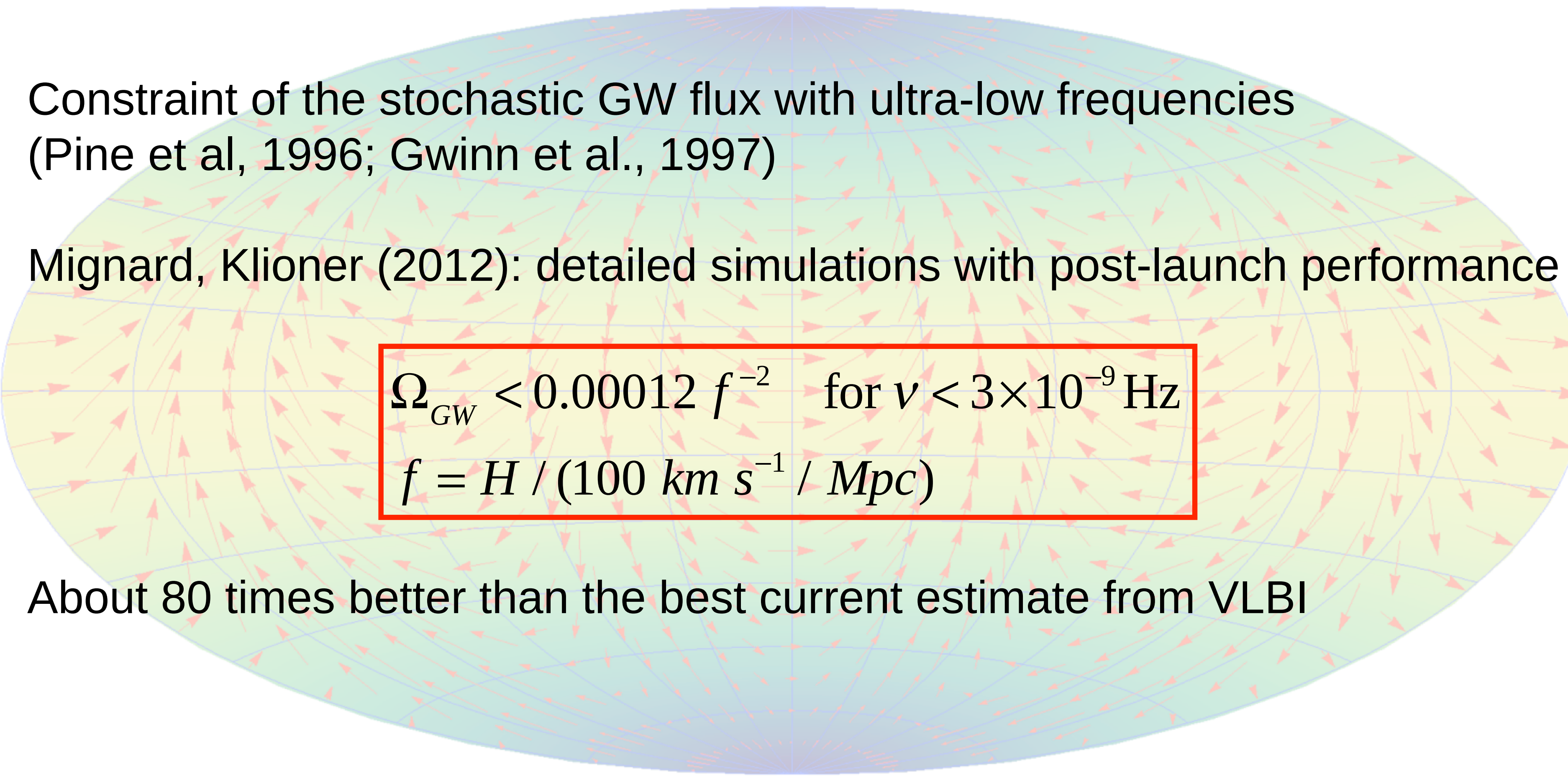
  For a GW propagating in the direction δ=90°:



Application 1: ultra-low-frequency GWs

If the period of the GW is substantially larger than the time span covered with observations, the GW deflection pattern is absorbed by the proper motion.

This plot shows now the pattern in the proper motions of QSOs in the final catalogue (stellar 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 with post-launch performance

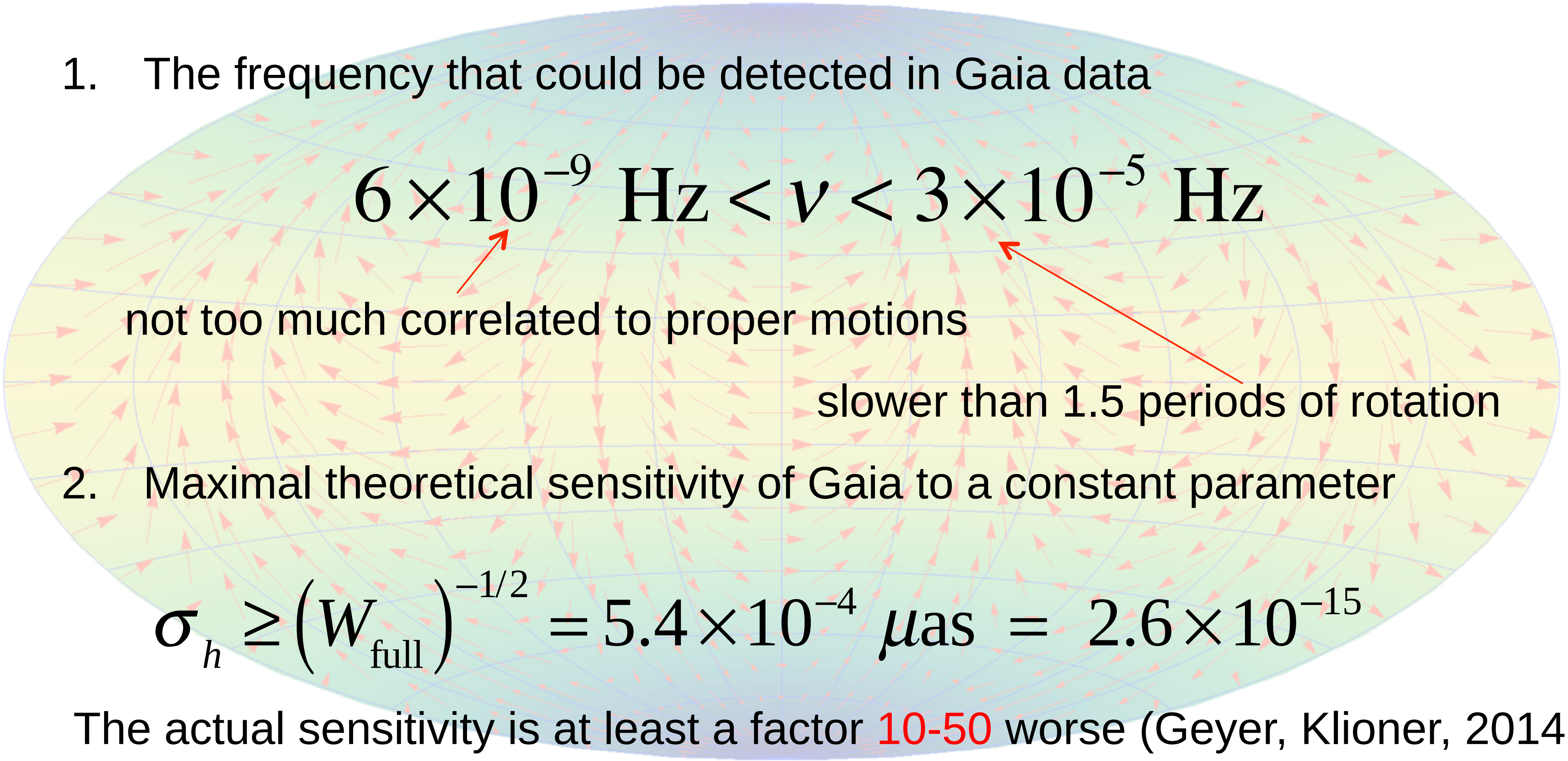
$$\boxed{\begin{array}{l} \Omega_{GW} < 0.00012\, f^{-2} \quad \text{for } \nu < 3\times 10^{-9}\,\text{Hz} \\ f = H\,/\,(100\ km\ s^{-1}\,/\,Mpc) \end{array}}$$

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.

The plot shows now <u>a time-dependent pattern in the residuals of the solution</u> (at each moment of time only two directions are observed):



1. The frequency that could be detected in Gaia data

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

not too much correlated to proper motions

slower than 1.5 periods of rotation

2. Maximal theoretical sensitivity of Gaia to a constant parameter

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

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

GW sources for astrometry: realistic sources

- Example: M87, a SMBH of 6.6x10^9 solar masses at 18.4 Mpc; suspected binary! Assuming two components of the equal masses:

$$h_{\mathrm{M87}} = 6.7\times 10^{-13}\left(\frac{P_{gw}^{\mathrm{M87}}}{1\ \mathrm{yr}}\right)^{-2/3}$$

- This could be within the reach of Gaia if the orbital period is not [much] more than 2 yr ($P_{gw}^{\mathrm{M87}} < 1\ \mathrm{yr}$)

The lifetime of such a system would only be about 30 years …

BUT ONLY IF WE CAN CALIBRATE OUR INSTRUMENT WELL TO 1 μas!

- Other examples: OJ287, PG 1302−102 (both longer-living)

$h_{\mathrm{OJ287}} \approx 2.0\times 10^{-14}$ at 6 yr, $h_{\mathrm{PG1302\text{-}102}} \le 2.0\times 10^{-15}$ at 2.6 yr

Gravitational Wave Spectrum

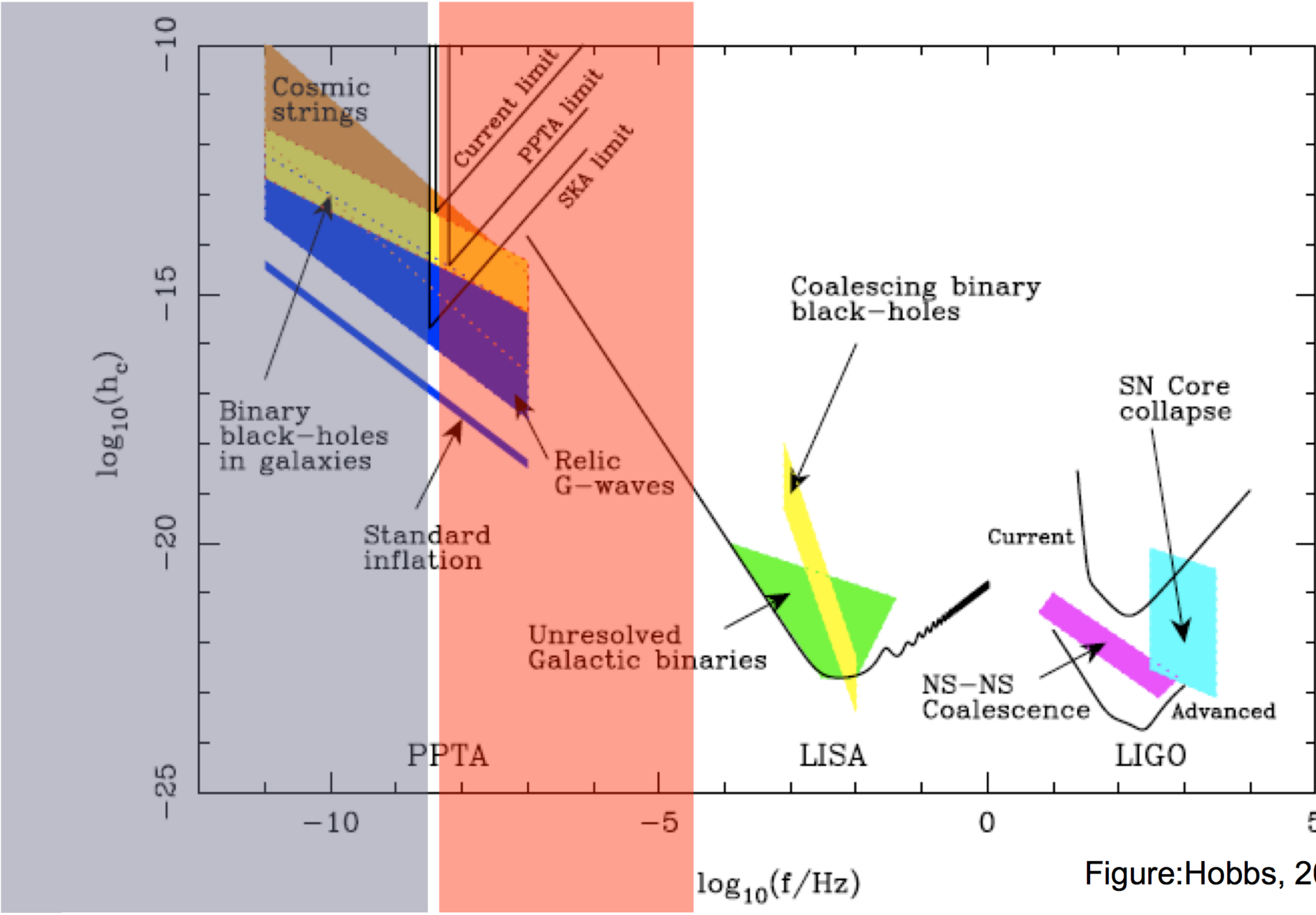
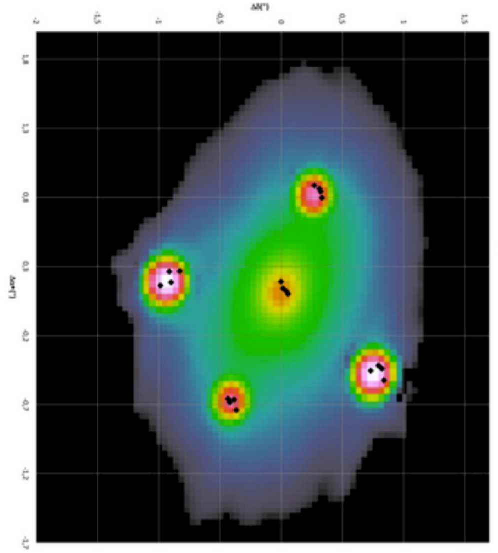


Figure:Hobbs, 2008

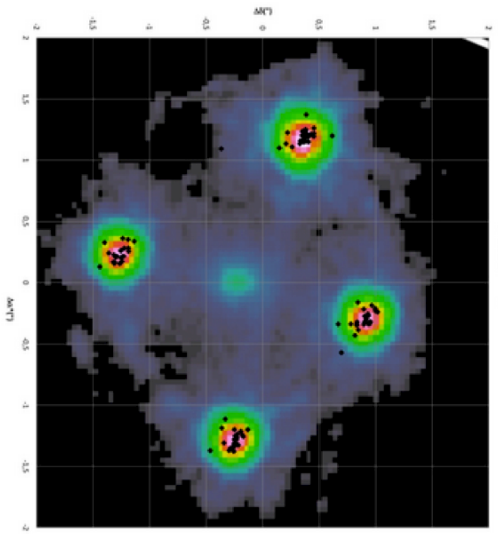
Individual objects of special interest

1) Visible companion of compact binaries:
model-independent masses of invisible components from astrometric wobble of the visible
(Bastian, Fuchs, 2004; Unwin et al., 2008)
Cyg X1 (40 μas), SS433 (30 μas), …



2) Wide astrometric binaries: possible test of the MOND
(e.g. Hernandez et al. 2012)

2) Macrolensing: possible test of the light bending
at kpc scale (e.g. Bolton et al., 2006);
see the presentation of Christine Ducourant et al.



ESA/Gaia/DPAC/Christine Ducourant, Jean-Francois Lecampion (LAB/Observatoire de Bordeaux), Alberto Krone-Martins (SIM/Universidade de Lisboa, LAB/Observatoire de Bordeaux), Laurent Galluccio, Francois Mignard (Observatoire de la Côte d'Azur, Nice)

GR-relevant tests with Gaia: solar system and beyond

1. Monopole light deflection

2. Quadrupole light deflection (a few sigmas – detection)

3. Local Lorentz Invariance – a big (and expensive ☺) “Michelson-Morley”

4. post-Newtonian equations of motion with asteroids;
   see the presentation of Hees et al!

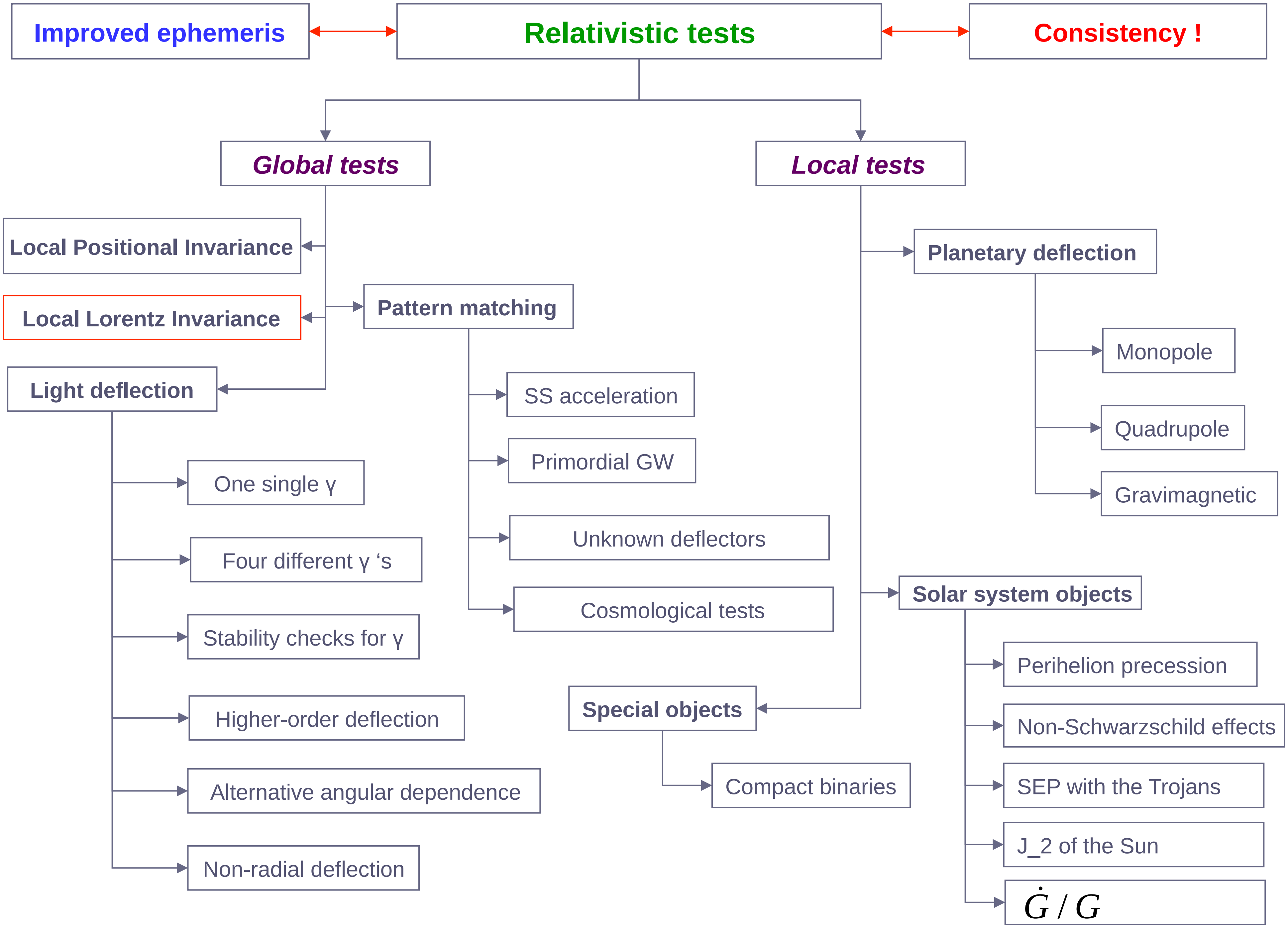
5. acceleration of the solar system

6. masses of black holes and neutron stars in binaries

7. ultra-low frequency gravitational waves: $v < 6$ nHz

8. gravitational waves from quasi-stationary (continuous) sources
   (binary supermassive black holes): $6 \text{ nHz} < v < 0.03 \text{ mHz}$

Backup slides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Local Lorentz Invariance and aberration

- Special-relativistic aberration is given by

$$\left.\begin{aligned} \boldsymbol{s}'' &= \left(\boldsymbol{s} - \left[\frac{\gamma}{c} - (\gamma - 1)\,\frac{\boldsymbol{v}\cdot\boldsymbol{s}}{v^2} \right] \boldsymbol{v} \right) \frac{1}{\gamma(1 - \boldsymbol{v}\cdot\boldsymbol{s}/c)}, \\ \gamma &= \left(1 - v^2/c^2\right)^{-1/2}, \\ \boldsymbol{v} &= \dot{x}_o \left(1 + \frac{2}{c^2} U(t, \boldsymbol{x}_o) \right) \end{aligned}\right\} \text{standard Lorentz transformations}$$

- Expanding in powers of $\boldsymbol{k} = \boldsymbol{v}/c$

$$\boldsymbol{s}'' = \boldsymbol{s}$$

$$+ (\boldsymbol{s}\cdot\boldsymbol{k})\,\boldsymbol{s} - \boldsymbol{k}$$

$$-\frac{1}{2}(\boldsymbol{s}\cdot\boldsymbol{k})\,\boldsymbol{k} - \frac{1}{2}k^2\,\boldsymbol{s} + (\boldsymbol{s}\cdot\boldsymbol{k})^2\ \boldsymbol{s}$$

Local Lorentz Invariance and aberration

- Using the Mansouri-Sexl generalization of the Lorentz transformation

  (Klioner, Zschocke, et al. 2008)

$$\boldsymbol{s}'' = \boldsymbol{s}$$

$$+(\boldsymbol{s}\cdot\boldsymbol{k})\,\boldsymbol{s} - \boldsymbol{k}$$

$$-\frac{1}{2}(\boldsymbol{s}\cdot\boldsymbol{k})\,\boldsymbol{k} - \frac{1}{2}k^2\,\boldsymbol{s} + (\boldsymbol{s}\cdot\boldsymbol{k})^2\;\boldsymbol{s}$$

$$\boxed{-\eta\,(\boldsymbol{s}\cdot\boldsymbol{K})\,\boldsymbol{k} - \eta\,(\boldsymbol{s}\cdot\boldsymbol{k})\,(\boldsymbol{k}+\boldsymbol{K}) + \eta\,(\boldsymbol{s}\cdot\boldsymbol{k})^2\;\boldsymbol{s} + 2\eta\,(\boldsymbol{s}\cdot\boldsymbol{k})\,(\boldsymbol{s}\cdot\boldsymbol{K})\,\boldsymbol{s}}$$

The same parameter as in the Michelson-Morley experiment

$$\eta \equiv P_{MM} = 1/2 - \beta + \delta$$

$$\boldsymbol{K} = \boldsymbol{V}\,/\,c$$

$\boldsymbol{V}$ is the velocity of the solar system (BCRS) relative to the preferred frame