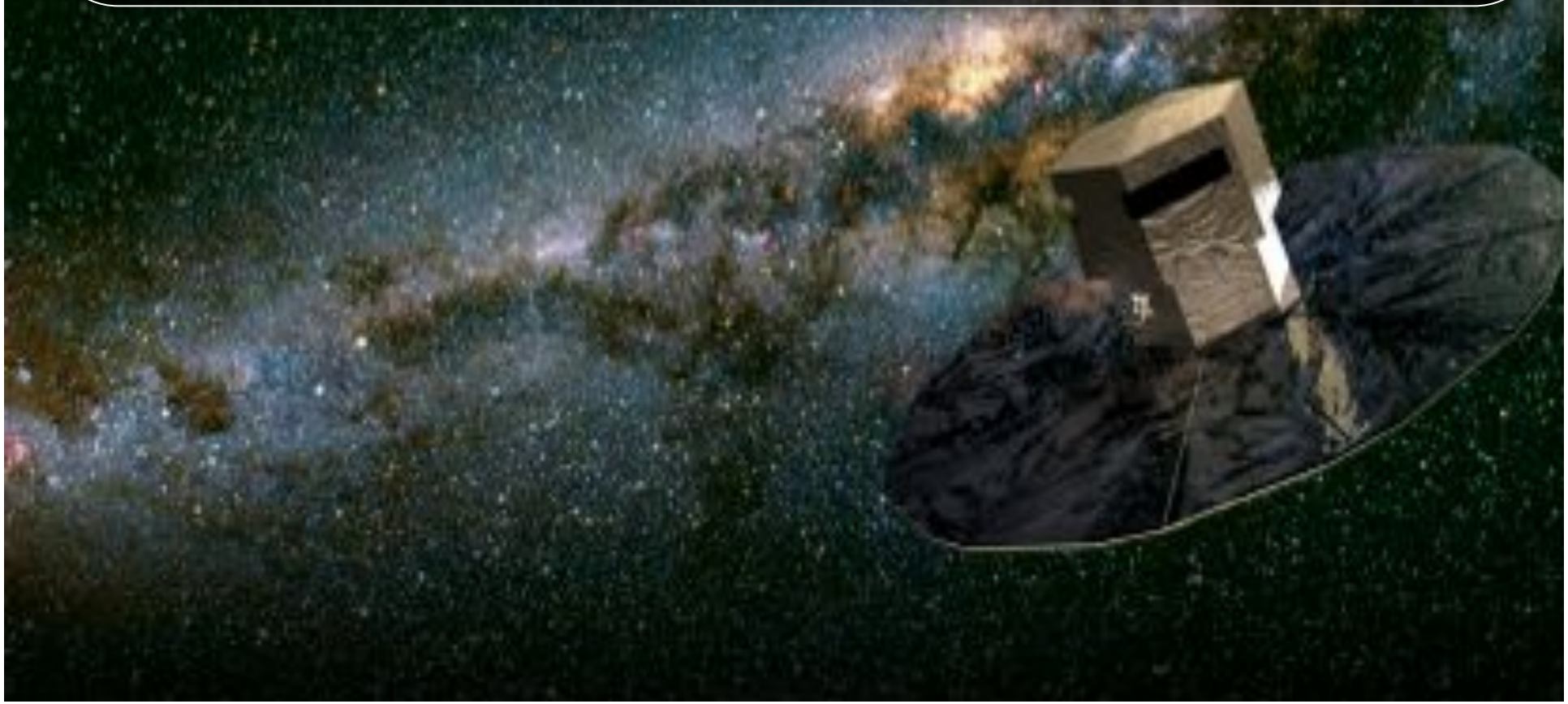
Relativistic modelling and fundamental physics with Gaia

Christophe Le Poncin- Lafitte
Observtoire de Paris, SYRTE

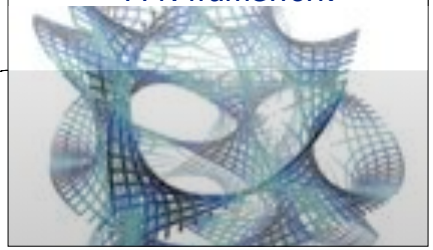


General overview

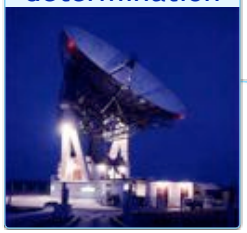
Parallaxe, proper motion :
LIGHT DEFLECTION

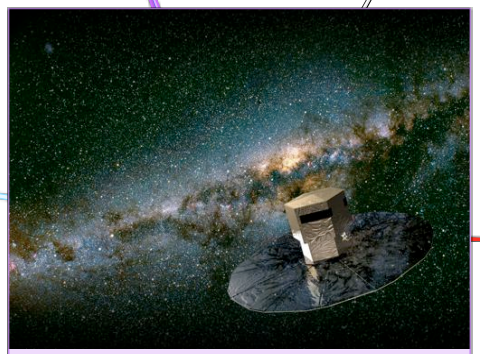
Abberation with satellite velocity

Choice of Reference Systems :
- General Relativity
- PPN framework



GAIA Orbit determination





Relativity and GAIA :
DPAC CU3 REMAT
(Relativistic modelling and tests)

Time scales

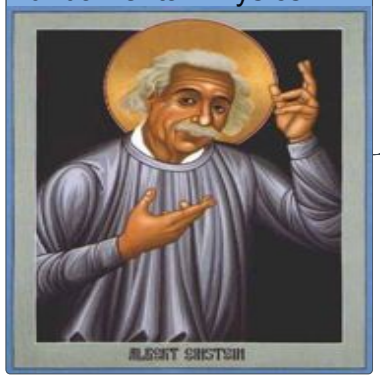
TCB of BCRS : conventional for the whole data processing

Relativistic GAIA proper time : TG
Practical realization : OBT

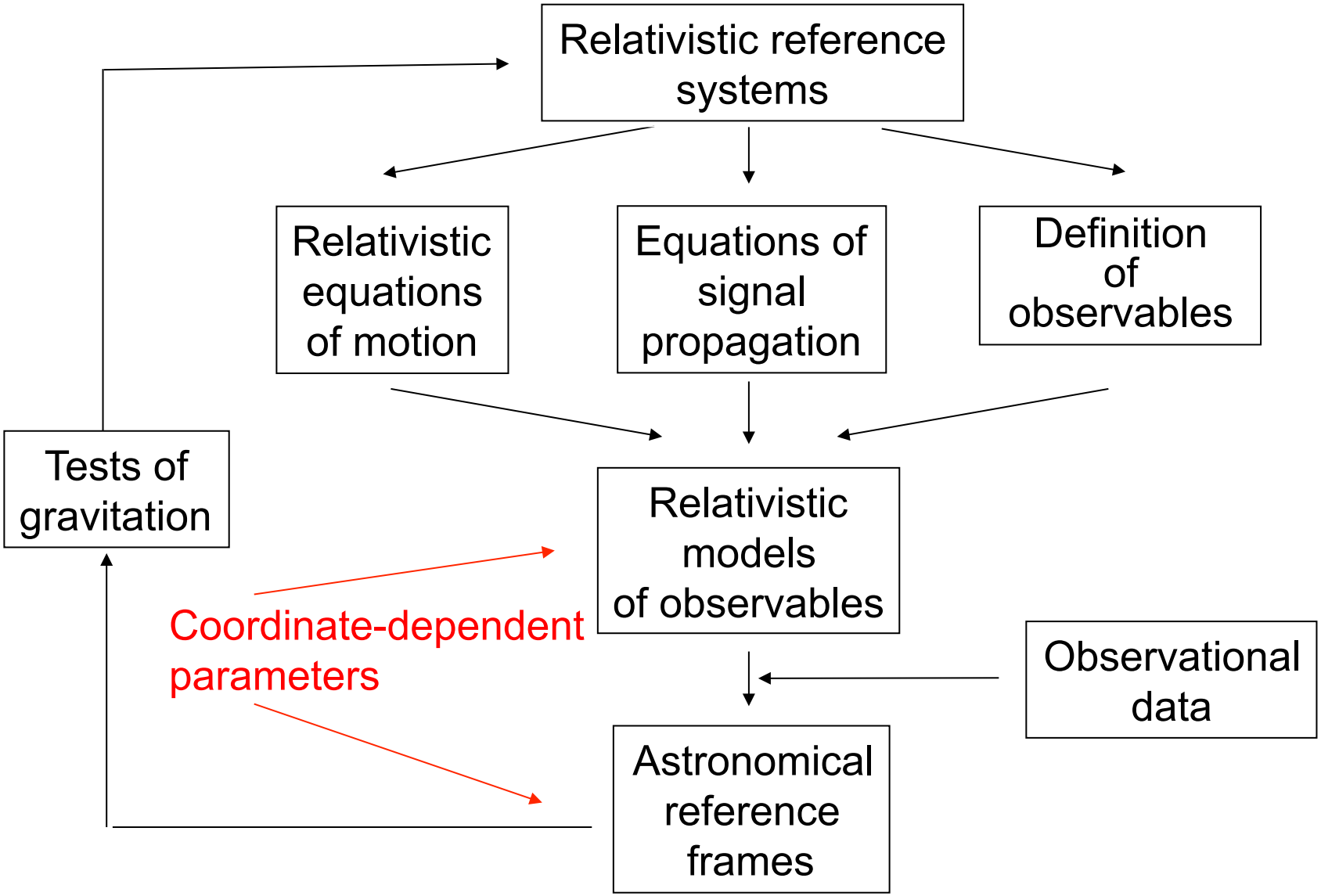
TCG of GCRS :
communication EARTH-GAIA

Relativistic Synchronization of clock

Reward :
Fundamental Physics ?

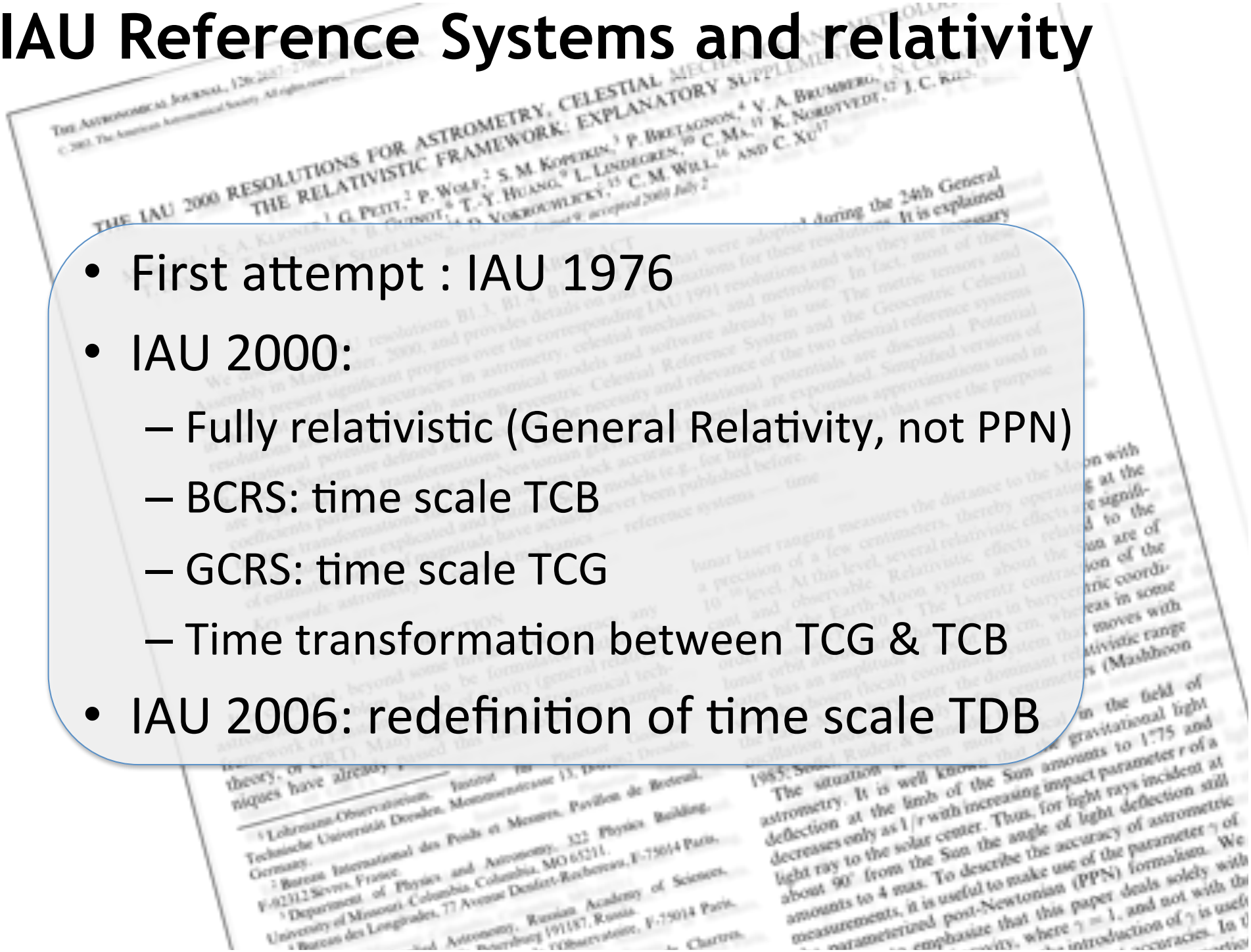


Relativistic Astronomy: basics



Klioner, 2003

IAU Reference Systems and relativity



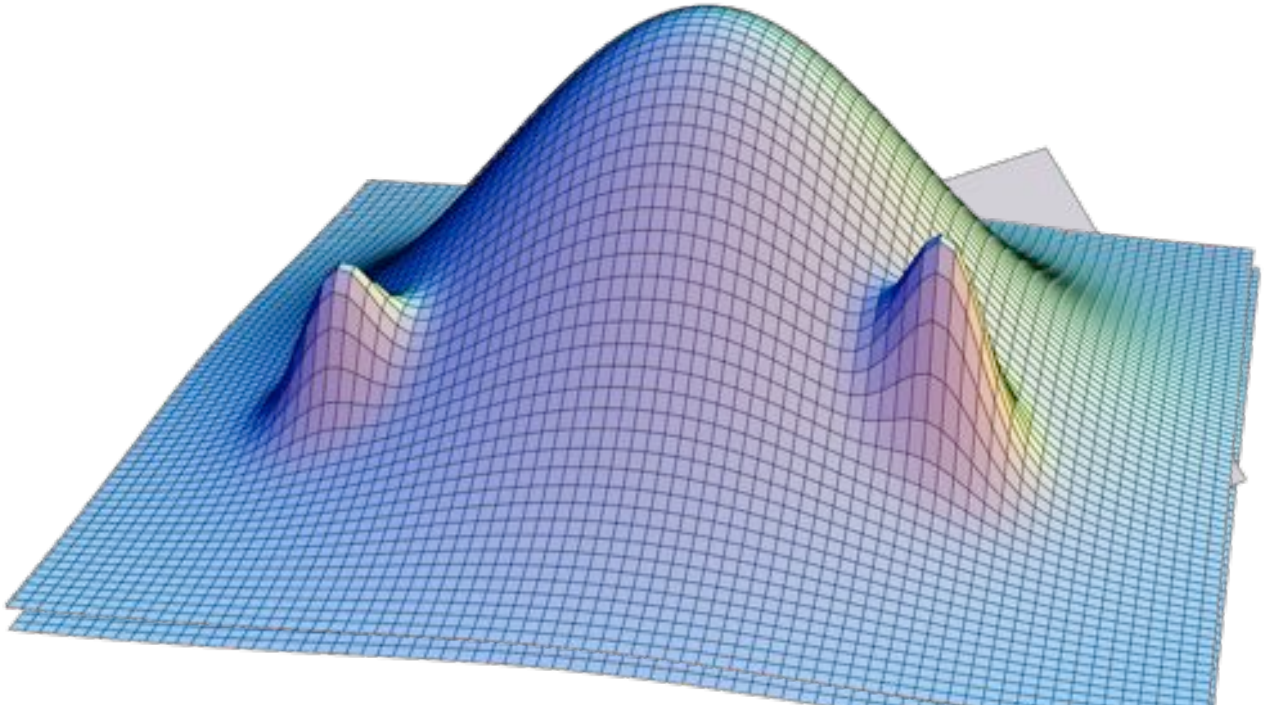
- First attempt : IAU 1976
- IAU 2000:
  - Fully relativistic (General Relativity, not PPN)
  - BCRS: time scale TCB
  - GCRS: time scale TCG
  - Time transformation between TCG & TCB
- IAU 2006: redefinition of time scale TDB

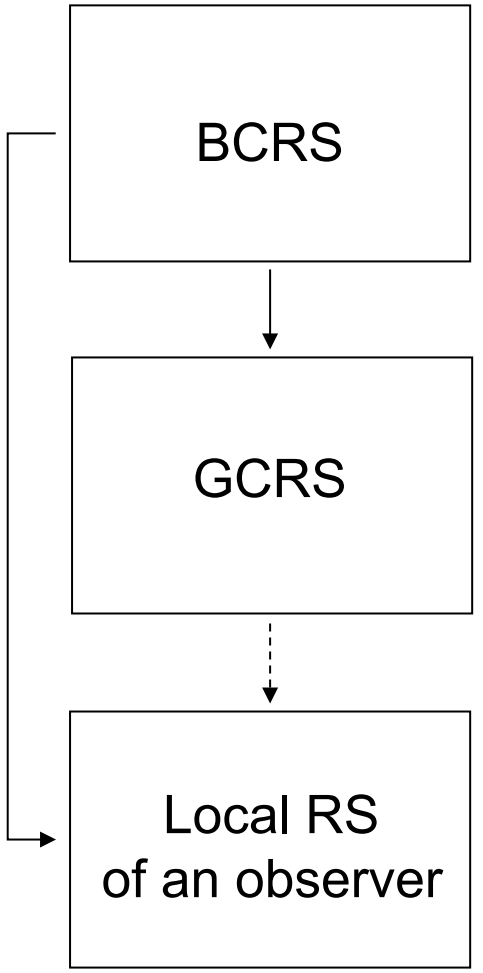
Reference systems theory

- In relativistic astronomy the
  - BCRS (Barycentric Celestial Reference System)
  - GCRS (Geocentric Celestial Reference System)
  - Local reference system of an observer

  play an important role.

- All these reference systems are defined by the form of the corresponding metric tensor.





Bini, 2003
Klioner, 2004

Barycentric Celestial Reference System

The BCRS is a particular reference system in the curved space-time of the Solar system

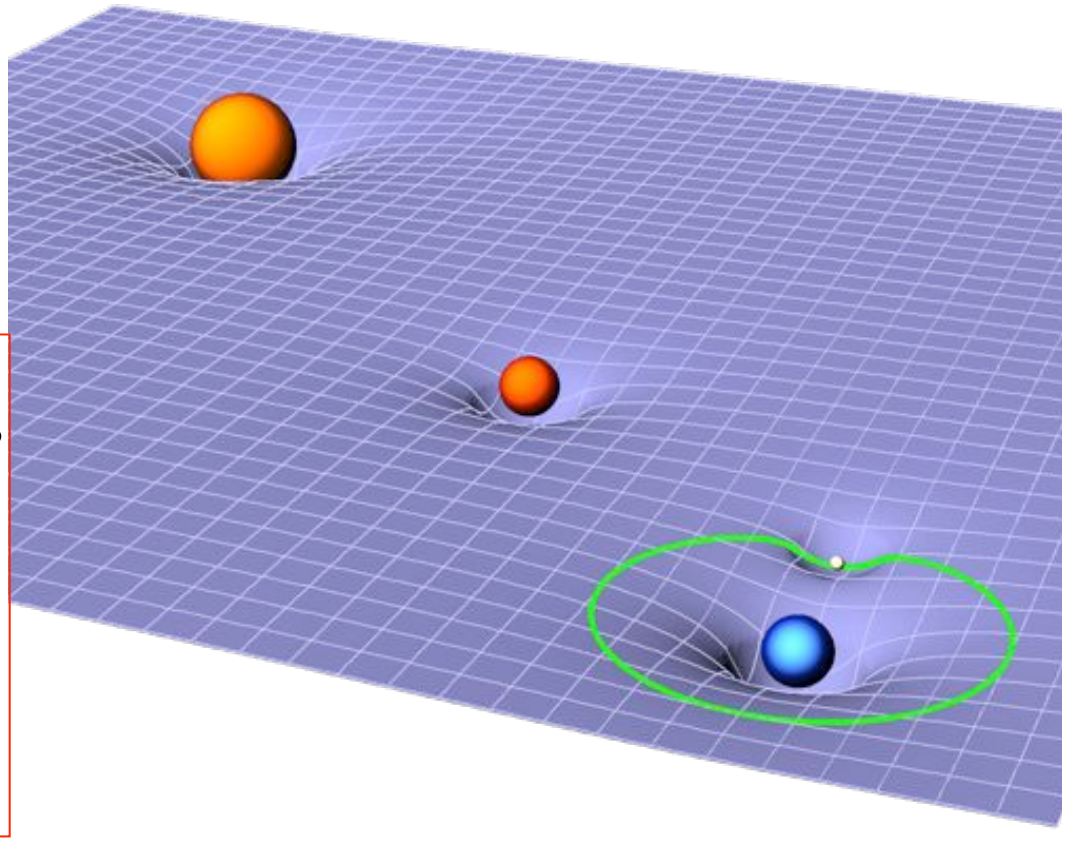
- One can use any
- but one should fix one :

ICRF by VLBI

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

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

$$g_{ij} = {}_{ij} \; 1 + \frac{2}{c^2} w(t,\boldsymbol{x}) \quad .$$

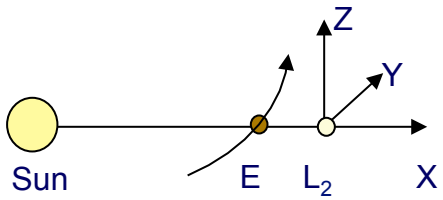


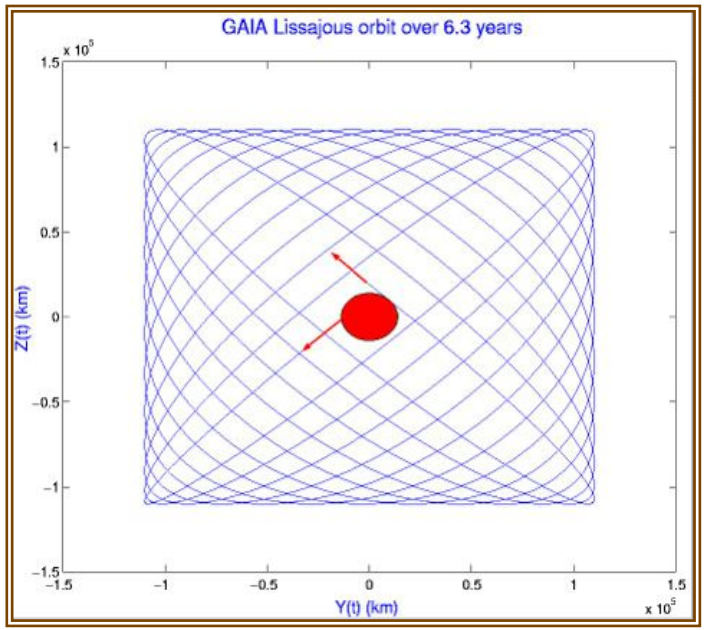
Used to describe motion of celestial body and description of light propagation

Ephemeride & Gaia orbit

Astrometry

GAIA orbit around Sun/Earth L2



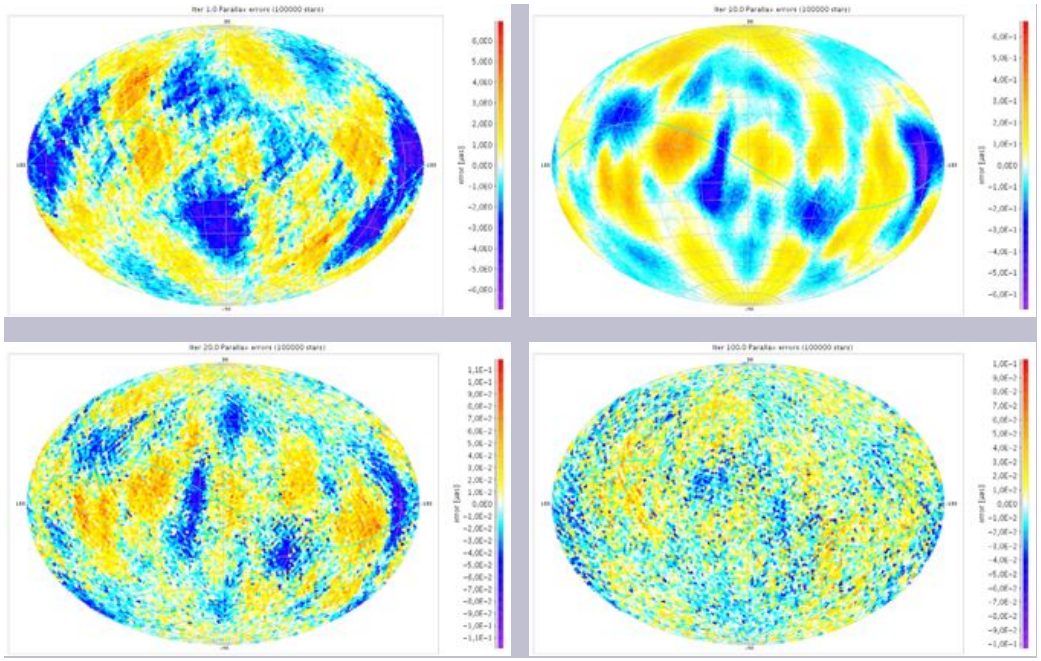


Usual modelling : Einstein-Infeld-Hoffman equations in BCRS

If relativistic effects are not taken into account, huge differences (several km in 200 days…)

Doppler tracking gives a good precision in radial distance -> 150m

Anyway, we need an accuracy of 1mm/s for the velocity = aberration…

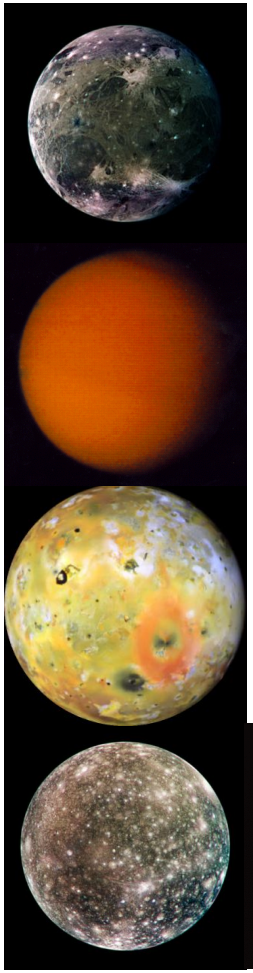


2 solutions :

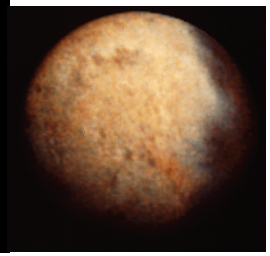
study of the aberration patterns

Observe Gaia from ground !!

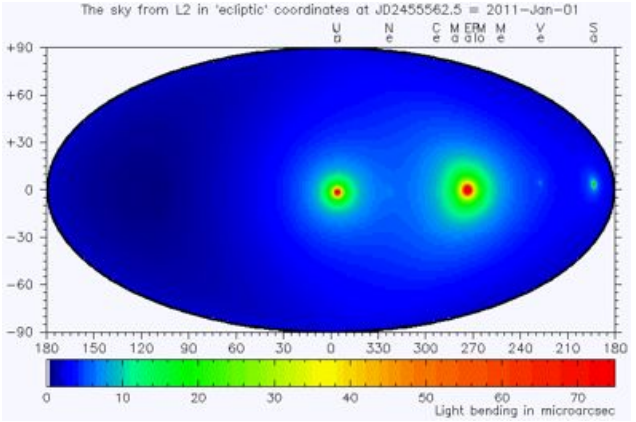
Light Deflection: How much?



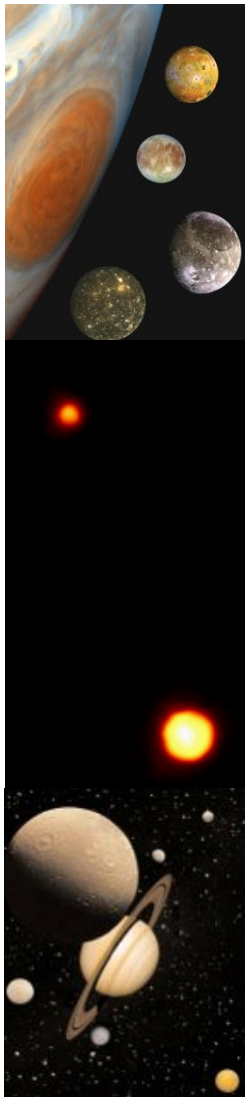
body	(muas)	>1muas
Sun	1.75 10^6	180°
Mercury	83	9°
Venus	493	4.5°
Earth	574	125°
Moon	26	5°
Mars	116	25°
Jupiter	16270	90°
Saturn	5780	17°
Uranus	2080	71°
Neptune	2533	51°



Order of magnitude for monopole light deflection.

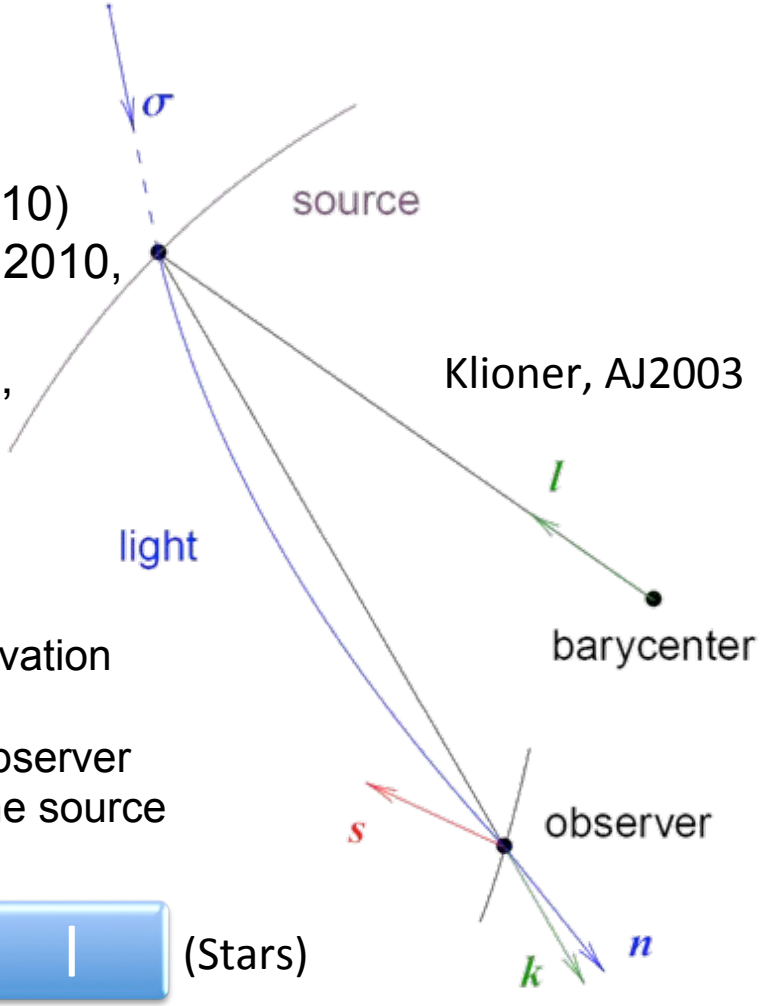


Minor bodies :	
Ganymede	35
Titan	32
Io	30
Callisto	28
Pluto	7
Charon	4
Titania	3
Ceres	1



Light Deflection: Modelling

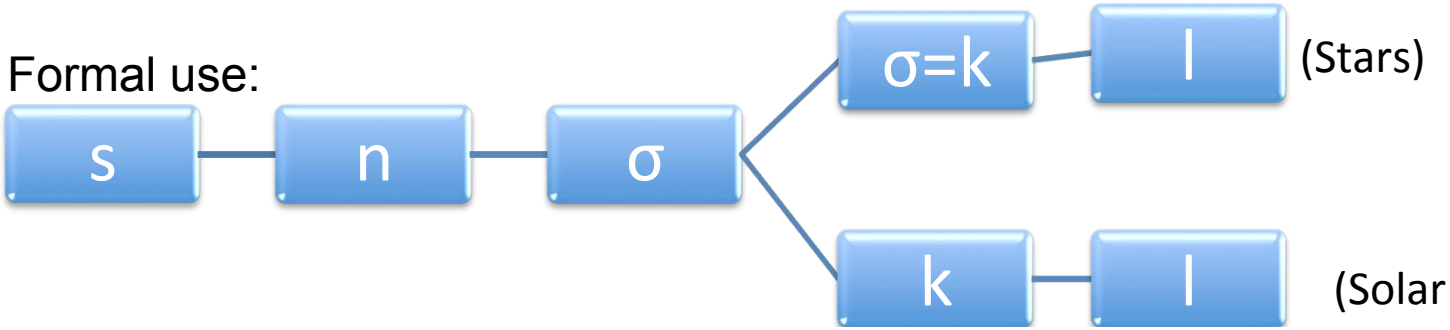
Basic modelling in BCRS:
-Mass monopole in uniform motion (Klioner, 2003)
-Quadrupole at moment of closest approach
-some « 2PN » effects (Klioner & Schocke, 2007, 2010)
-RAMOD (De Felice et al. 2006, Crosta & Vecchiato 2010, Crosta 2011)
-TTF (Le Poncin-Lafitte al. 2004, Bertone et al. 2013, Teyssandier & Le Poncin-Lafitte 2008)



Definition of basic quantities : GREM

- *s* the observed direction
- *n* tangential to the light ray at the moment of observation
- σ tangential to the light ray at past infinity
- *k* the coordinate direction from the source to the observer
- *l* the coordinate direction from the barycentre to the source
- π the parallax of the source in the BCRS

Formal use:



Gaia and relativistic timescales

Two fundamentals relativistic time scales : TCB (barycentric), TCG (geocentric, (let us say terrestrial)

Many others for practical use :

- TDB, barycentric, for planetary ephemerides
- TT, UTC, TAI, terrestrial (GCRS system comes back…)

And for Gaia ??

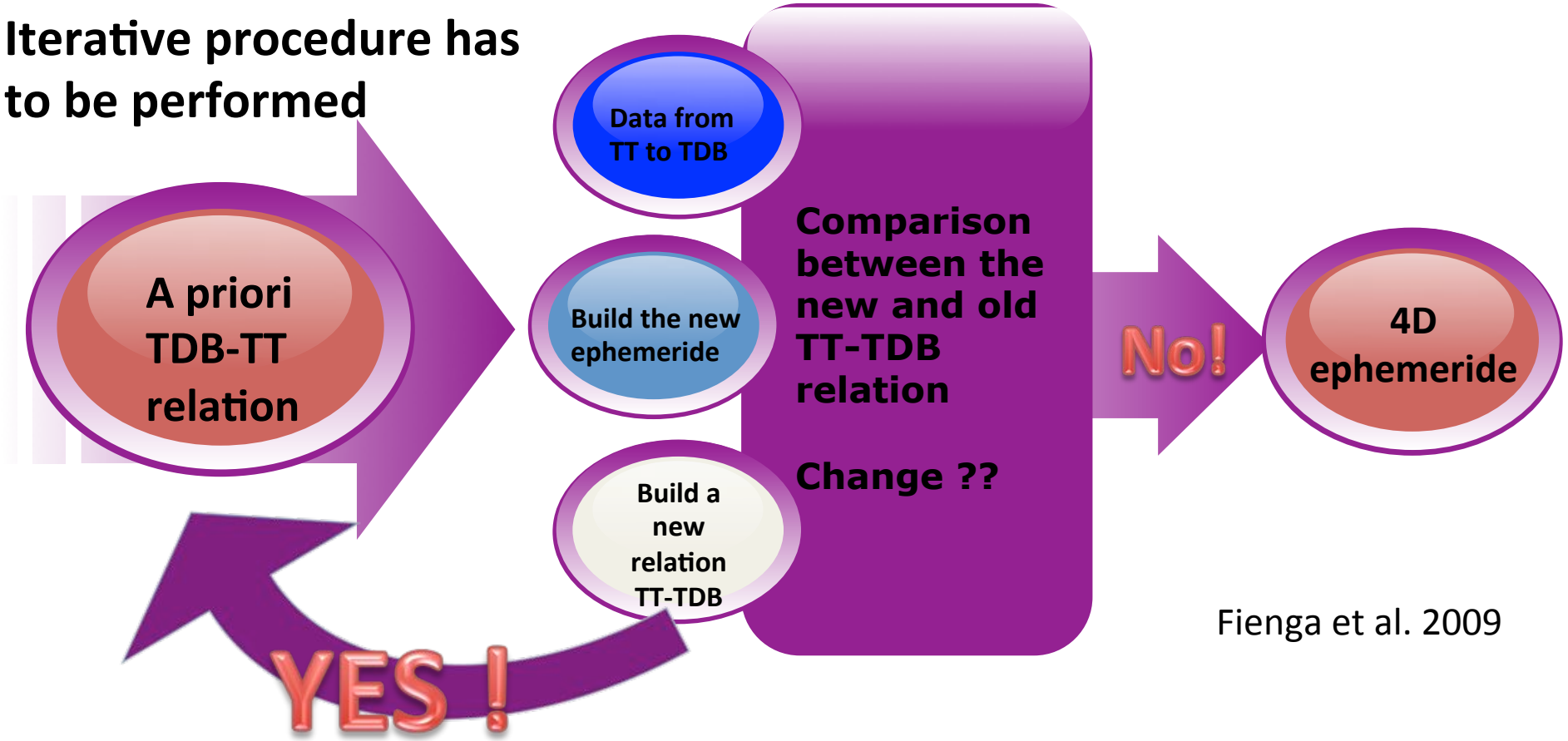
- Everything has to be done in BCRS, so time scale = TCB
- Usually ephemerides in TDB. But with IAU 2006, relation between TDB & TCB is a fixed linear function
- Proper time TG and TCB well known, idem for TCG & TCB (some integrals have to be calculated)
- OBT is the realization of TG. OBT & TCB have to be related: problem…

4D Planetary Ephemerides : INPOP

- Relativistic corrections in the motion. Very old in fact :

  Einstein (1917), Einstein, Infeld & Hoffmann, derived in the 30'

- Understood with multipole moments only by **Brumberg & Kopeikin (1988-1992), Damour, Soffel & Xu (1991-1994)**

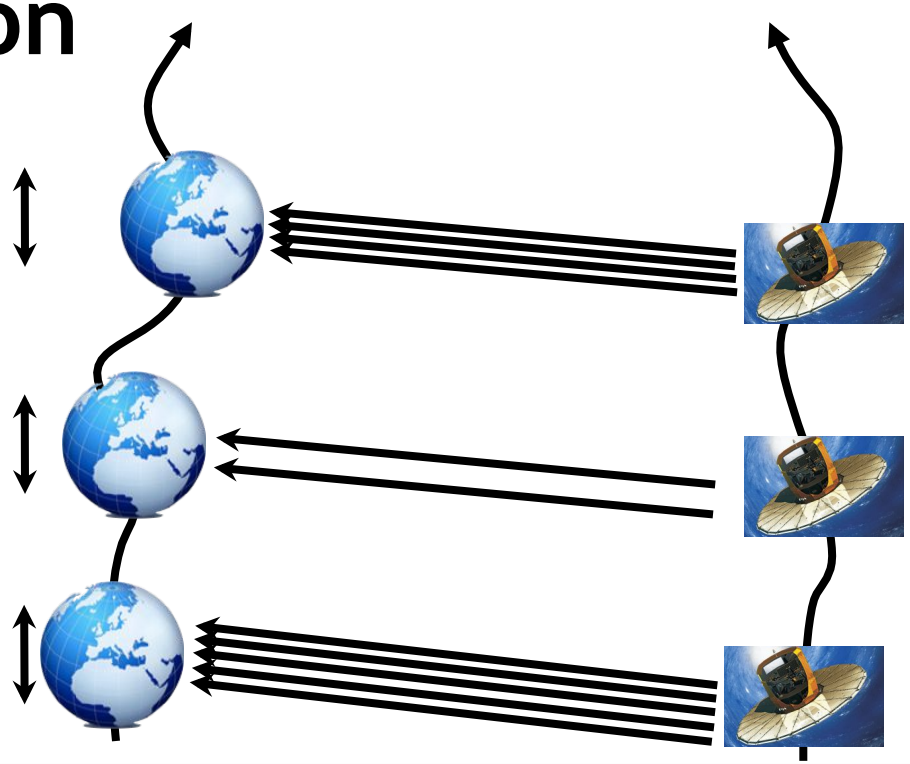


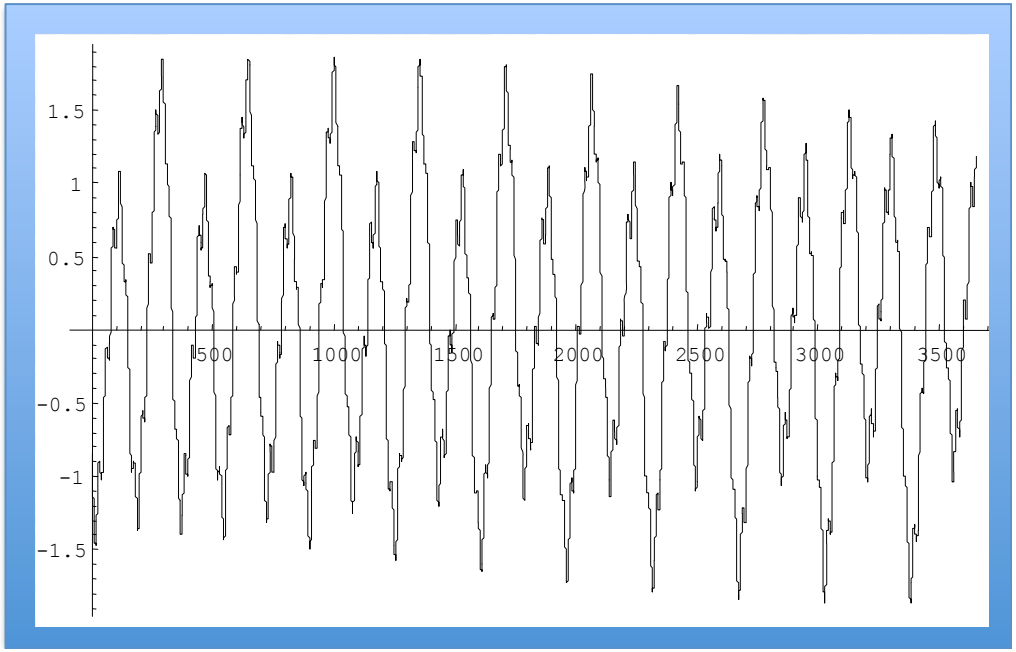
Fienga et al. 2009

Clock Synchronization

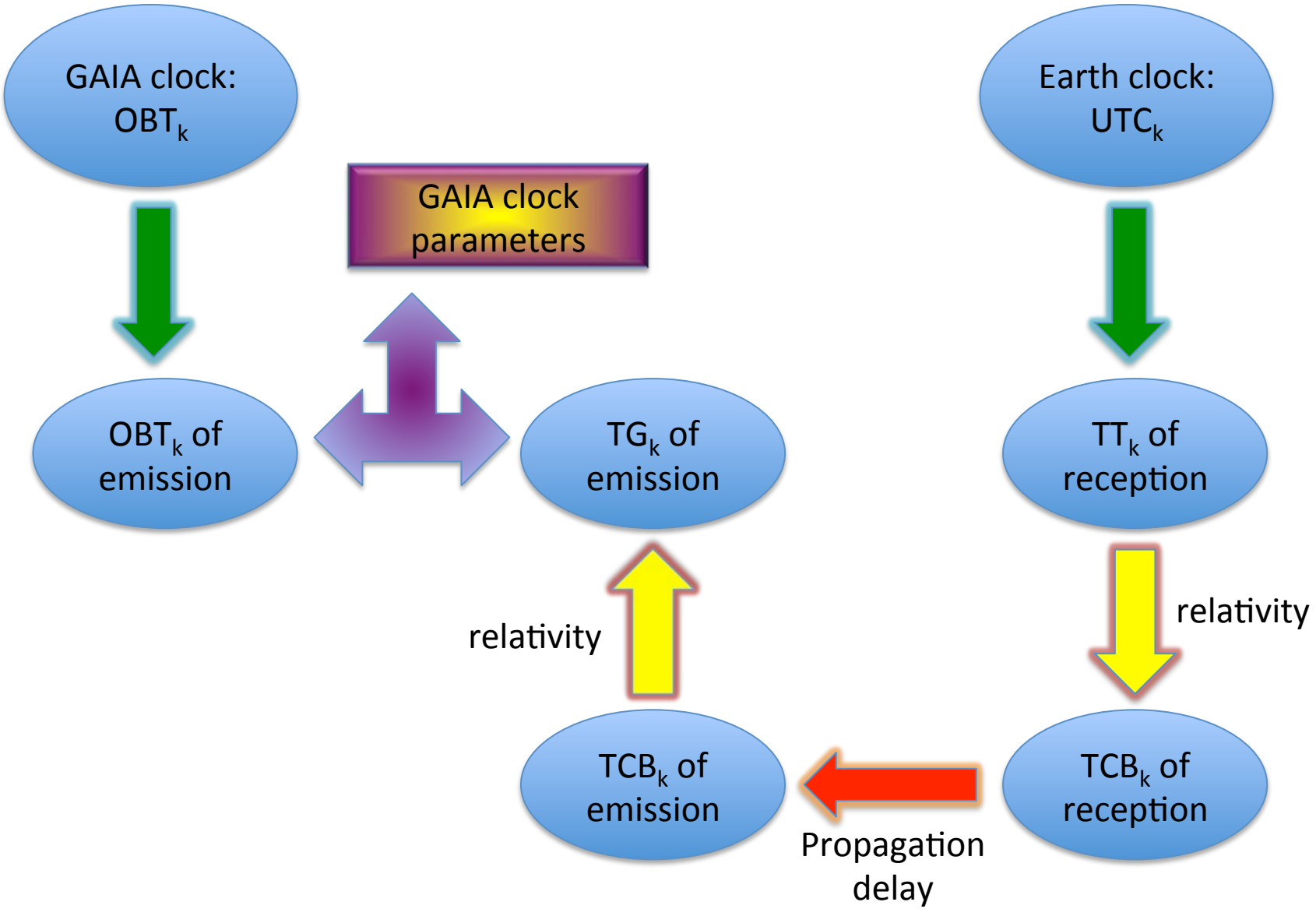
- Observations tagged in OBT
- Real clock can not be a pure realization of the proper time (technical errors)
- Need to synchronize the onboard clock with the ground
- But:
  - GAIA will not be observable from the ground all the time: 8h/day
  - Time telemetry procedure:
    - Stop sending of data at regular intervals
    - Send one OBT tag to the Earth

1mus == 1 muas in parallax !





Clock Synchronization



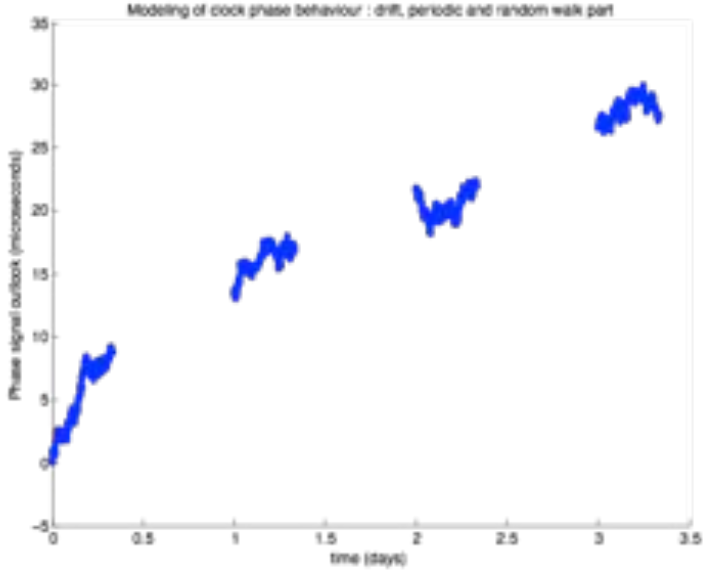
Le Poncin-Lafitte (TN2010)

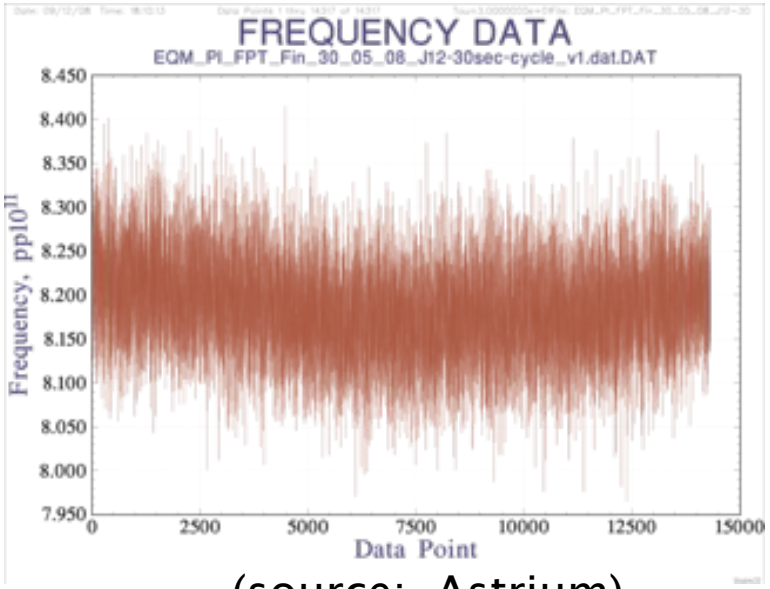
Basic frequency clock modeling

- ✓ Data from a test model on the frequency based on Astrium data:

$$\frac{d}{d\tau}(\tau - \tau_{Rb}) = \underbrace{A}_{\text{offset}} + \underbrace{B\tau}_{\text{drift}} + \underbrace{C\sin(2\pi f\tau)}_{\text{periodic}} + \frac{D}{\sqrt{\tau_0}}\underbrace{F(\tau_0)}_{\text{random distribution at } \tau_0 \text{ unitary standard deviation}}$$

- ✓ Assumptions:
  - ✓ the stochastic behaviour (F) of the clock is stationary → independent of which period of data is chosen. That is likely the case, except for malfunctions
  - ✓ A, B, C, D, f: to be determined in flight.
  - ✓ B and C: can be highly correlated.
  - ✓ No changes due to temperature variation (or magnetic) of clock's environment

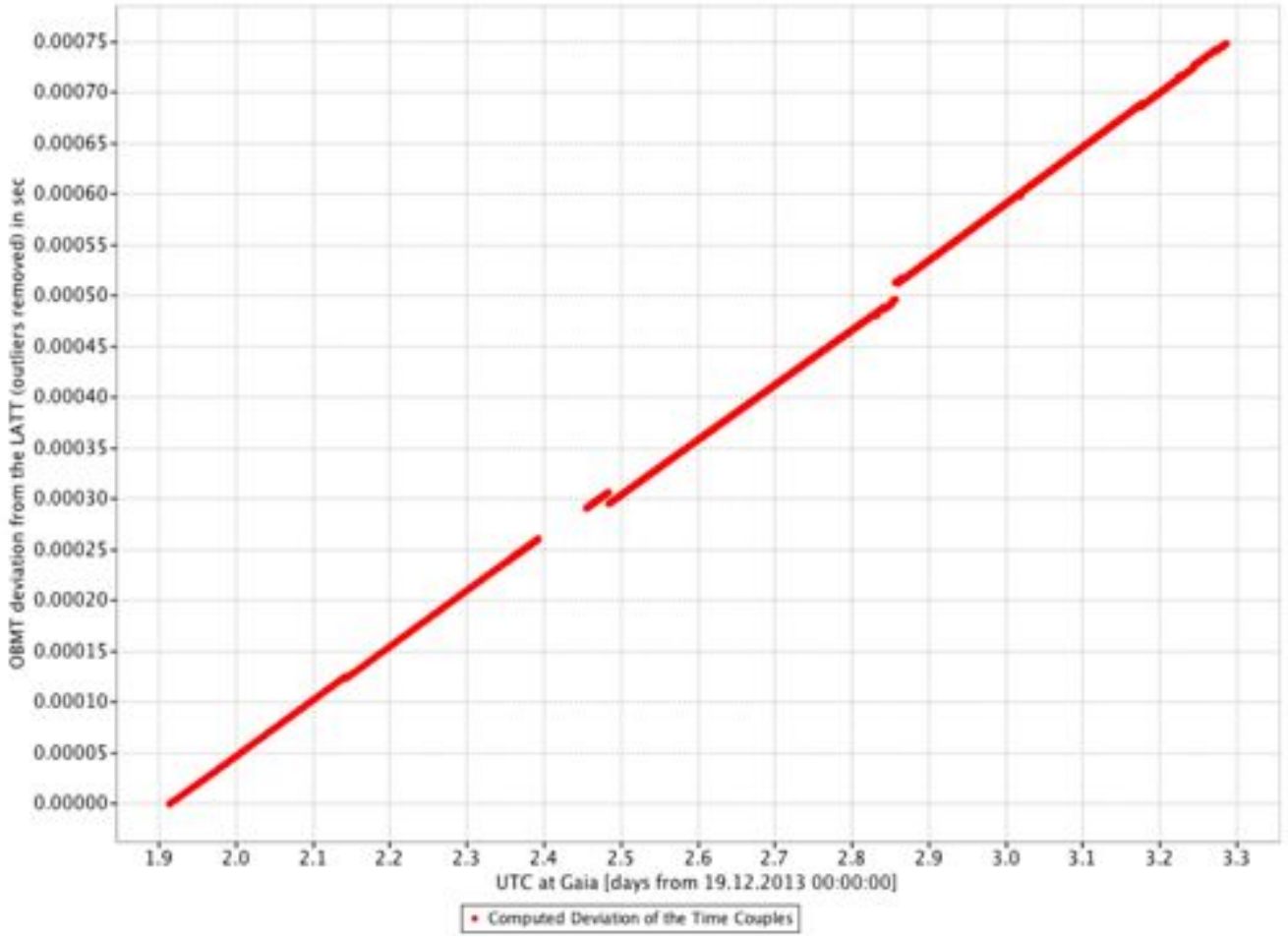




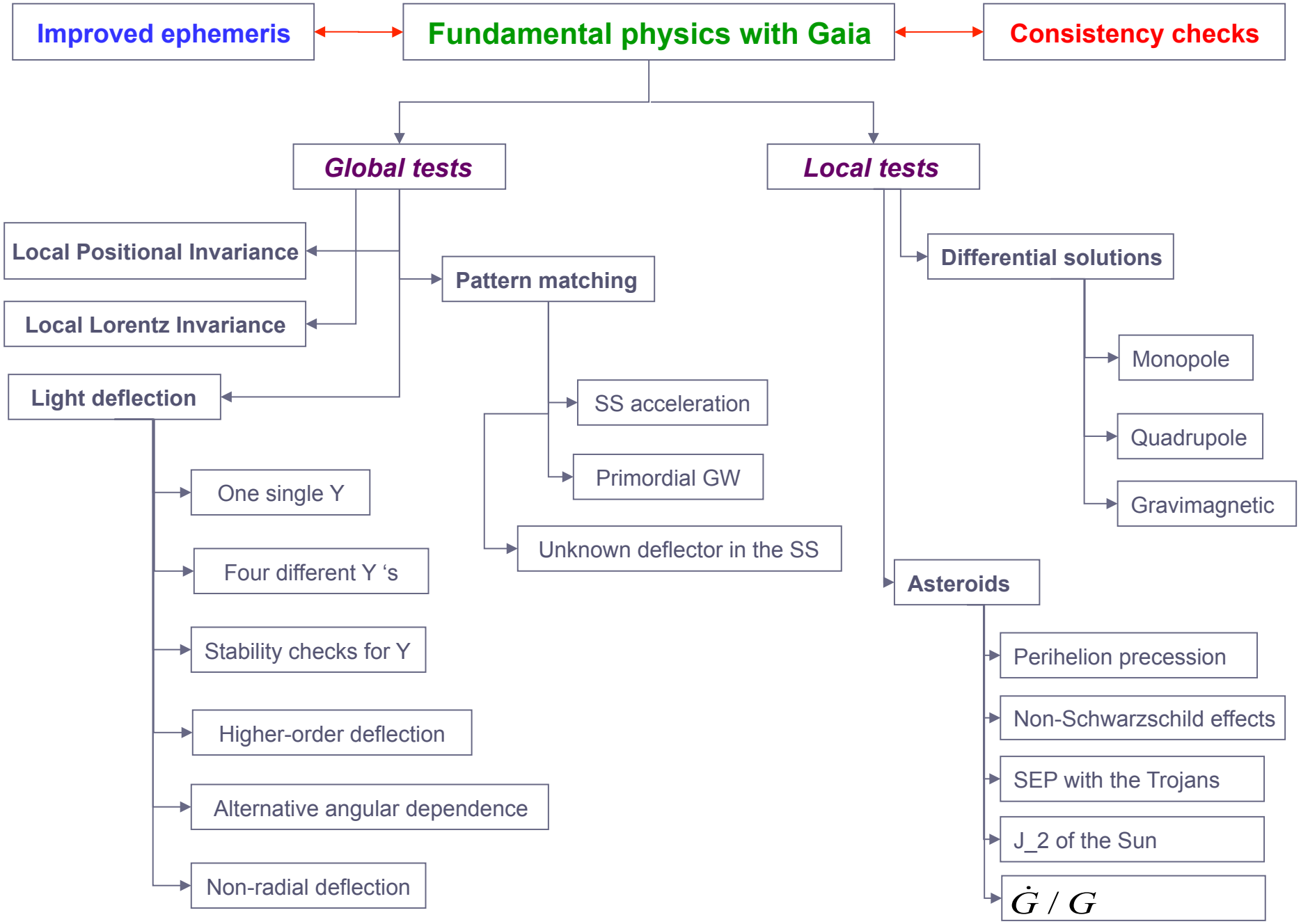
(source: Astrium)

Le Poncin-Lafitte (TN2011), Butkevith (TN2012)

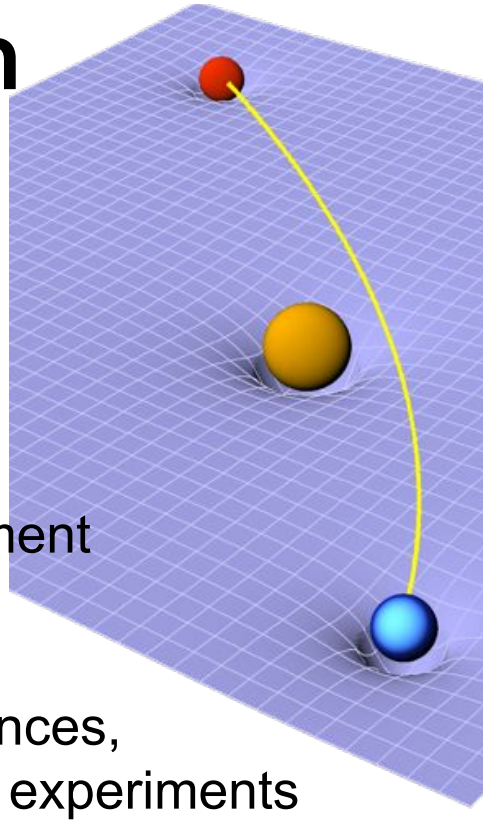
First relativistic effect detected : the clock…



Testing Fundamental Physics

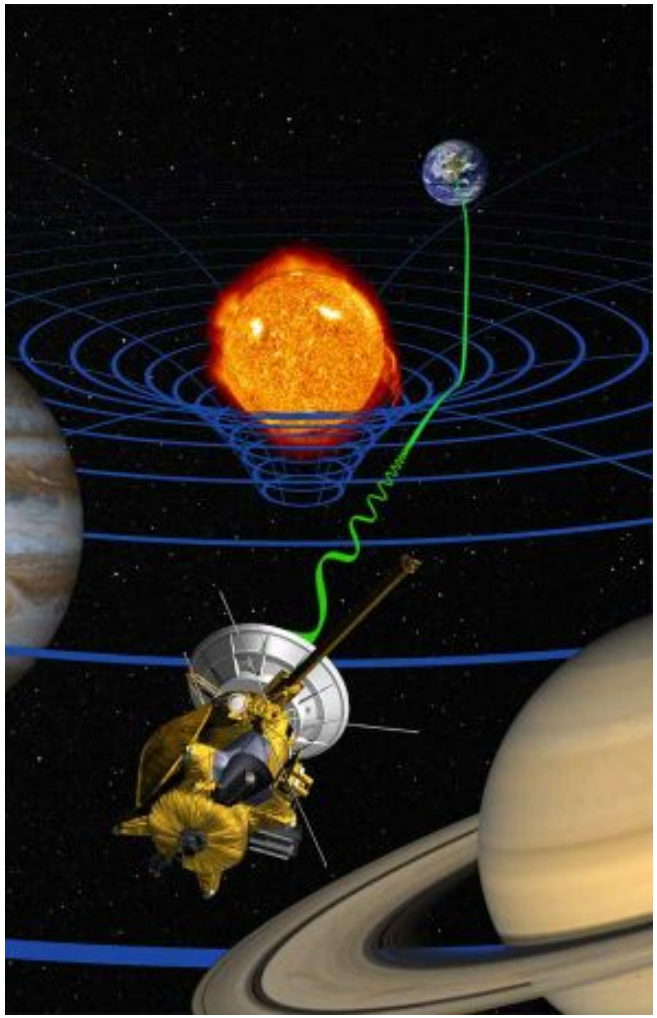


Global test from light deflection



- Most precise test possible with Gaia

Preliminary analysis: ESA, 2000; Mignard, 2001; Vecchiato et al., 2003, Hobbs 2010 : $< 10^{-6}$



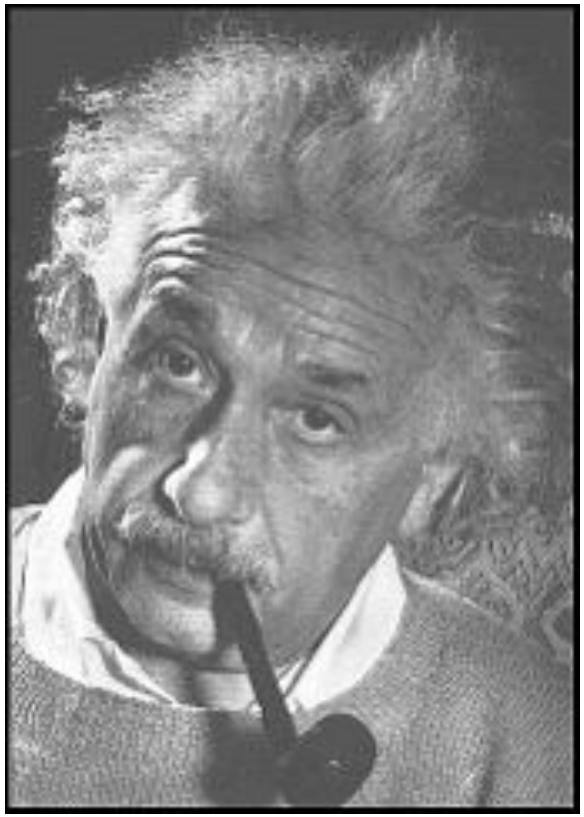
- Advantages of the Gaia experiment
  - optical,
  - deflection (not Shapiro),
  - wide range of angular distances,
  - full-scale simulations of the experiments

- Problems with some of the *current best estimates* of gamma (Cassini, 10^{-5})

1. special fits of the post-fit residuals of a standard solution (missed correlations lead to wrong estimates of the uncertainty);
2. no special simulations with simulated data to check what kind of effects we are really sensitive to.

Summary

- Relativity as a driven force for the whole data processing
- Necessity to add relativistic contributions and/or to check consistency of existing traditional issues :
  - Standard procedures of ESA/ESOC
  - Planetary ephemerides
- Sometimes, we even have to invent new procedures
- All this work is hidden in the core processing, but if we miss one detail, people will see it immediatly…
- Numerous tests of Relativity
- A new optical reference frame to be linked with ICRF2



« Everything should be made as simple as possible, but not simpler »

A.Einstein