Relativity in Fundamental Astronomy: solved and unsolved problems

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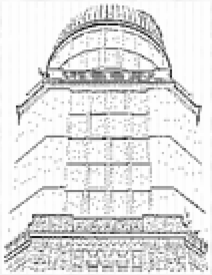


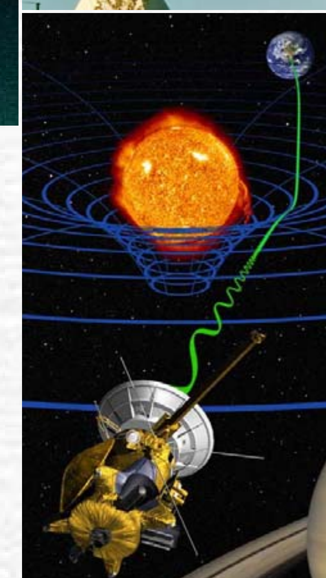
Journées 2007, Meudon, 18 September 2007

Relativistic effects in fundamental astronomy

Several general-relativistic effects are confirmed with the following precisions:


- VLBI ± 0.0003
- HIPPARCOS ± 0.003
- Viking radar ranging ± 0.002
- Cassini radar ranging ± 0.000023
- Planetary radar ranging ± 0.001
- Lunar laser ranging I ± 0.00045
- Lunar laser ranging II ± 0.005





No way to model all these kind of data without relativity

More precise data to come:

Gaia, BepiColombo, LLR with APOLLO, etc.

Why general relativity?

- Newtonian models cannot describe high-accuracy observations:
  - many relativistic effects are many orders of magnitude larger than the observational accuracy

- The simplest theory which successfully describes all available observational data:

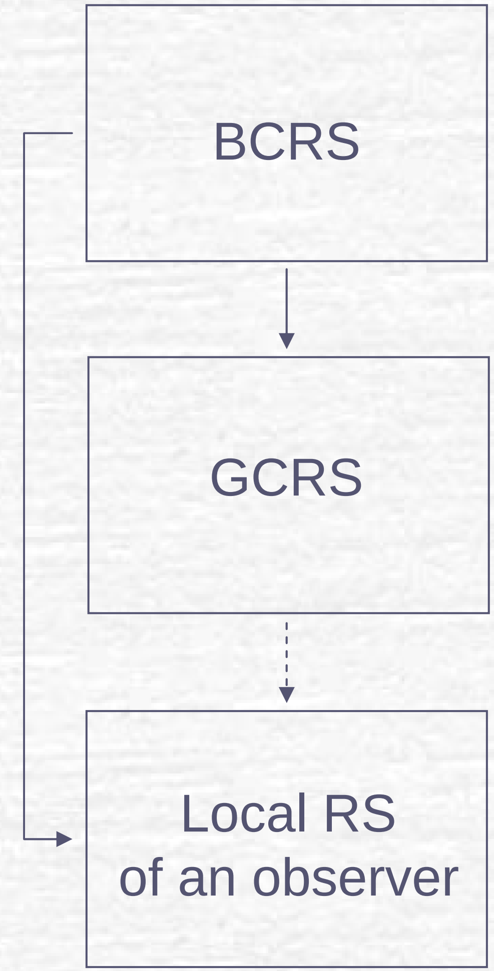
APPLIED RELATIVITY

a multidisciplinary research field

The IAU 2000 framework

- Three standard astronomical reference systems were defined

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

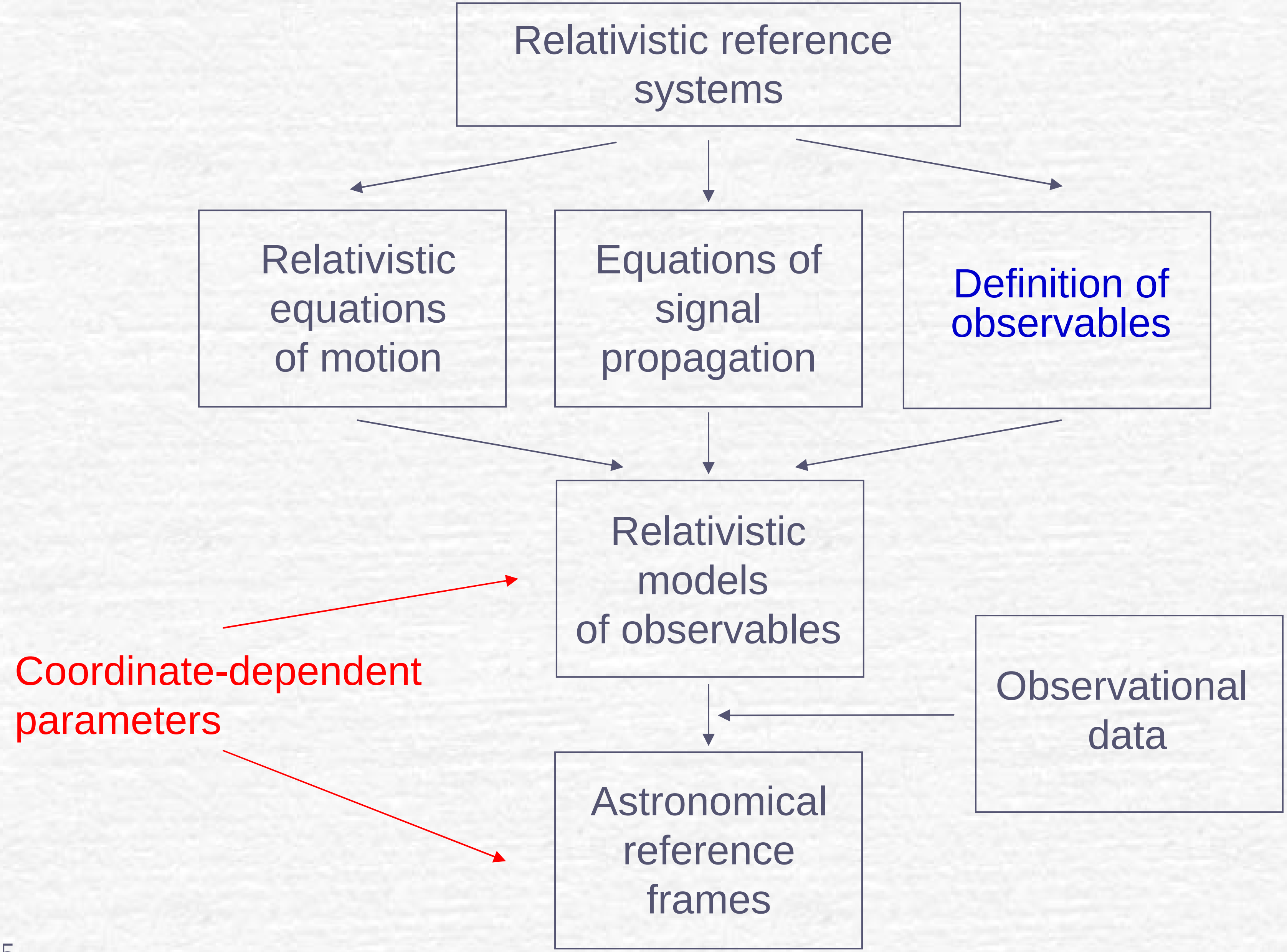


- All these reference systems are defined by

  the form of the corresponding metric tensors.

Technical details:
Brumberg, Kopeikin, 1988-1992
Damour, Soffel, Xu, 1991-1994
Klioner, Voinov, 1993
Klioner,Soffel, 2000
Soffel, Klioner,Petit et al., 2003

General relativity for space astrometry



Parametrized post-Newtonian (PPN) formalism

- K. Nordtvedt, C. Will (1970-)

  - covers a class of possible metric theories of gravity
    in the weak-field slow-motion (post-Newtonian) approximation:

    many metric theories of gravity were investigated and a generic form of the post-Newtonian metric tensor of a system of N bodies was derived.

  - the metric tensor contains 10 numerical ad hoc parameters.

  - two most important parameters are γ and β $(\gamma = \beta = 1$ in GRT$)$

  - all predictions of the theories can be expressed using these parameters

- Klioner, Soffel, 2000; Kopeikin, Vlasov, 2004: GCRS with PPN parameters

What is well known theoretically

- post-Newtonian relativistic reference systems
- post-Newtonian equations of motion for test particles and massive bodies having only masses
- multipole structure of the post-Newtonian gravitational field
- post-Newtonian equations of motion of bodies with multipole structure
- post-Newtonian equations of rotational motion
- post-Newtonian theory of light propagation

- some features of the post-post-Newtonian effects (by no means so detailed understanding as for the post-Newtonian approximation)

What is poorly known theoretically

- embedding of the post-Newtonian BCRS in the cosmological background

...could be important for the interpretation of high-accuracy observations (Gaia, VLBI, etc.)

Some efforts have been started by a number of people

- post-post-Newtonian relativistic reference systems (especially, GCRS)
- multipole structure of the post-post-Newtonian gravitational field
- detailed post-post-Newtonian equations of motion and their solution and analysis

…currently not interesting from the practical point of view…

What is thought to be clear theoretically, but represents a lot of difficulties in practice

- post-Newtonian equations of motion of bodies with multipole structure

very complicated and implicit algorithm for post-Newtonian approximation; never applied for numerical calculations

possibles source of “fly-by anomaly”?

unexpected additional increase of the velocity of several spacecrafts after close approach with the Earth

- post-Newtonian equations of rotational motion

complicated, but clear, explicit algorithm

first implemented by Klioner, Soffel, Le Poncin-Lafitte (2007)

What is thought to be clear theoretically, but represents a lot of difficulties in practice

Also much “simpler” issues…

- meaning of relativistic coordinate time scales

TCG is NOT “time at geocenter”!

TCB is NOT “time at barycenter”!

TT is NOT “time on the rotating geoid”!

- relativistic scaling of astronomical quantities

scaling does not mean changing of units

input: Klioner, 2007, A&A, accepted

Applied Relativity as multidisciplinary research topic

“Cultural” problems:

- Different mathematical languages

Example: STF tensors are used instead of spherical harmonics etc. to described the bodies’ structure in the equations of motion

$$\frac{d}{d\,\mathsf{TCG}}\left(C^{ab}\,\omega^b\right) = \sum_{l=1}^{\infty}\frac{1}{l!}\,\varepsilon_{abc}\,M_{bL}\,G_{cL} + \varepsilon_{abc}\,\Omega^b_{\text{iner}}\,C^{cd}\,\omega^d.$$

?

STF approach to compute the torque

1. For any STF tensor: $$T_L = \sum_{m=-l}^{l} T^{lm} \hat{Y}_L^{lm}$$

STF basis

$2l+1$ real numbers

2. For the multipole moments of the Earth: $$M_L = \sum_{m=-l}^{l} M^{lm} \hat{Y}_L^{lm}$$

equivalent to the $2l+1$ harmonic coefficients

3. For the tidal moments: $$G_L = \sum_{m=-l}^{l} G^{lm} \hat{Y}_L^{lm}$$

functions of the ephemeris data

STF approach to compute the torque

numbers

4. The torque:
$$\sum_{l=1}^{\infty}\frac{1}{l!}\varepsilon_{abc}M_{bL}G_{cL}=\sum_{l=1}^{\infty}\sum_{m=-l}^{l}\sum_{m'}\alpha^{a}_{lmm'}M^{lm}G^{lm'}$$

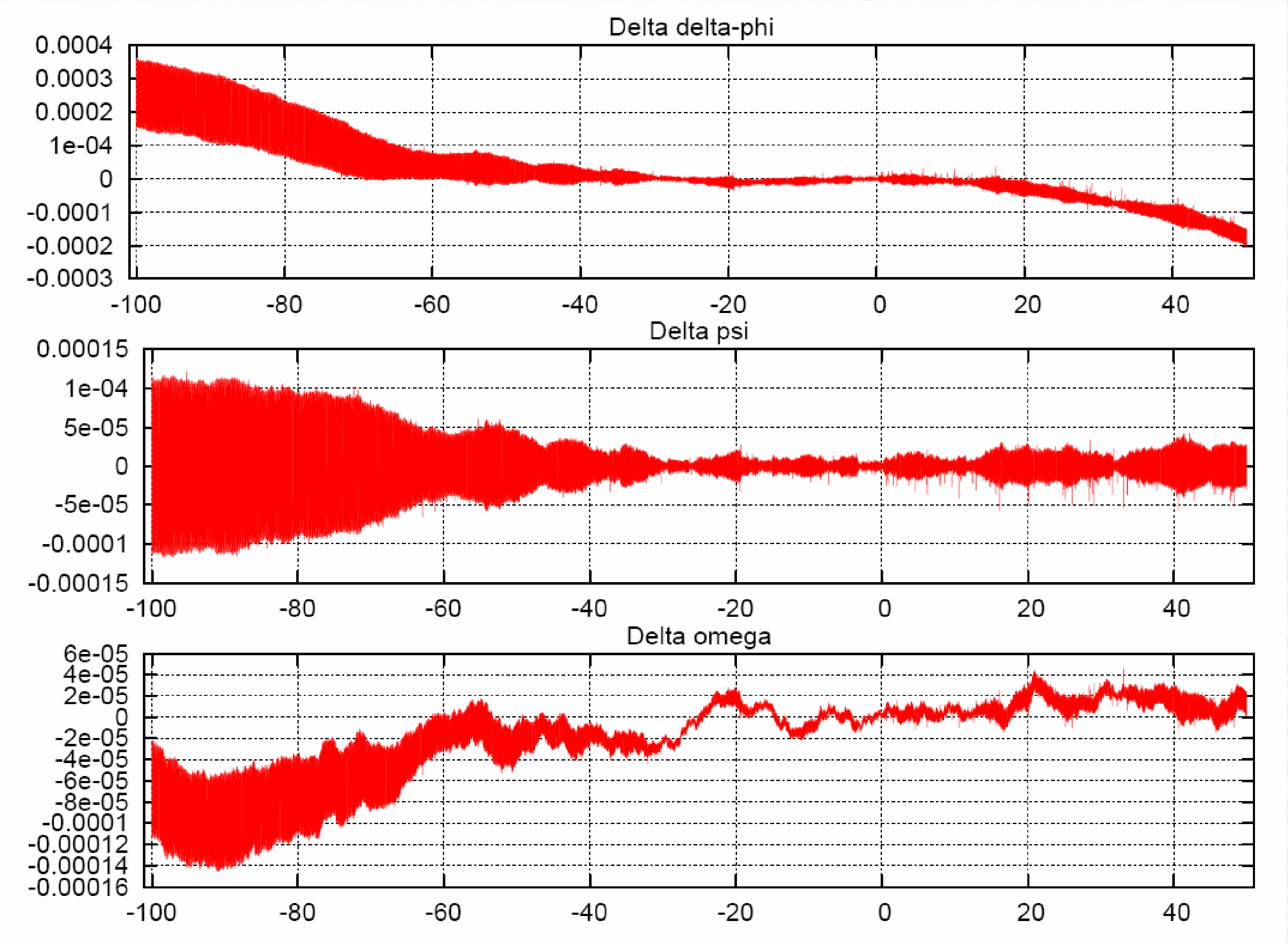
$$m'=-m-1,-m+1 \quad \text{for} \quad a=1,2$$

$$m'=-m \quad \text{for} \quad a=3$$

This is equivalent to the classical formulation with Legendre polynomials for Newtonian tidal potentials.

For relativistic tidal potential the STF tensor is the most efficient way also from the computational point of view.

Legendre polynomials vs. STF tensors for the Newtonian torque



μas

years from J2000

Applied Relativity as multidisciplinary research topic

Further “cultural” problems:

- only numerical magnitude is interesting for practical work
- in relativity analytical orders of magnitude are used

The situation is similar to “analytical expansions”
(e.g., in powers of eccentricities) in classical celestial mechanics…

$$c^{-2}, c^{-4}, e^{4}, \ldots$$

Post-post-Newtonian light propagation?

Full post-post-Newtonian expression for the Shapiro time delay with PPN parameters (Klioner, Zschocke, 2007):

$$
\begin{aligned}
c\,\tau = R \; + \; & (1+\gamma)\, m \, \log \frac{x + x_0 + R}{x + x_0 - R} \\
& + \frac{1}{8}\, \alpha\, \epsilon\, \frac{m^2}{R} \left(\frac{x_0^2 - x^2 - R^2}{x^2} + \frac{x^2 - x_0^2 - R^2}{x_0^2} \right) \\
& + \frac{1}{4}\, \alpha\, \left(8(1+\gamma) - 4\beta + 3\epsilon\right)\, m^2 \, \frac{R}{|\boldsymbol{x} \times \boldsymbol{x}_0|} \, \arctan \frac{x^2 - x_0^2 + R^2}{2|\boldsymbol{x} \times \boldsymbol{x}_0|} \\
& - \frac{1}{4}\, \alpha\, \left(8(1+\gamma) - 4\beta + 3\epsilon\right)\, m^2 \, \frac{R}{|\boldsymbol{x} \times \boldsymbol{x}_0|} \, \arctan \frac{x^2 - x_0^2 - R^2}{2|\boldsymbol{x} \times \boldsymbol{x}_0|} \\
& + \frac{1}{2}\, (1+\gamma)^2\, m^2 \, \frac{R}{|\boldsymbol{x} \times \boldsymbol{x}_0|^2} \, (x - x_0 - R)\,(x - x_0 + R)\,.
\end{aligned}
$$

$$m = \frac{GM}{c^2}$$

The higher-order terms give up to 10 meters. Are all these terms relevant?

Post-post-Newtonian light propagation?

NO!

The only numerically relevant term can be written as

$$c\,\tau = R + (1+\gamma)\,m\,\log\frac{x + x_0 + R + (1+\gamma)\,m}{x + x_0 - R + (1+\gamma)\,m}$$

This has already been derived by Moyer (2003) in a different way.

All other terms can be estimated as

$$c\,\delta\,\tau \le \frac{m^2}{d}\left(\frac{3}{4} + \frac{15}{4}\,\pi\right)$$

This gives maximally 4 cm for Sun-grazing ray,
and much less in typical cases…

Similar situation with light deflection,
with post-post-Newtonian equations of motion, etc.

Applied Relativity as multidisciplinary research topic

"Social" or educational problems:

- People doing "practical work" have limited knowledge of relativity and often cannot understand the details of the suggested relativistic models
- People working in relativity have limited experience with real data and often cannot judge if what they suggest is at all relevant

V.M.Lipunov

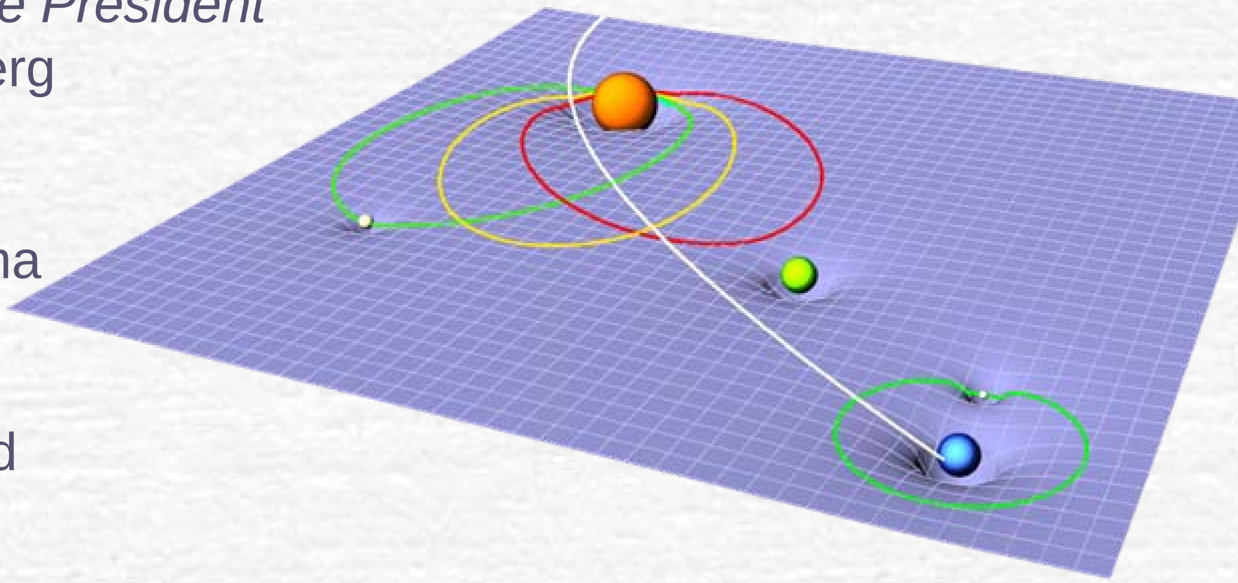
A. Basic education in relativity must be a part of astronomical education
B. Discussions are necessary

IAU Commission 52
“Relativity in Fundamental Astronomy”

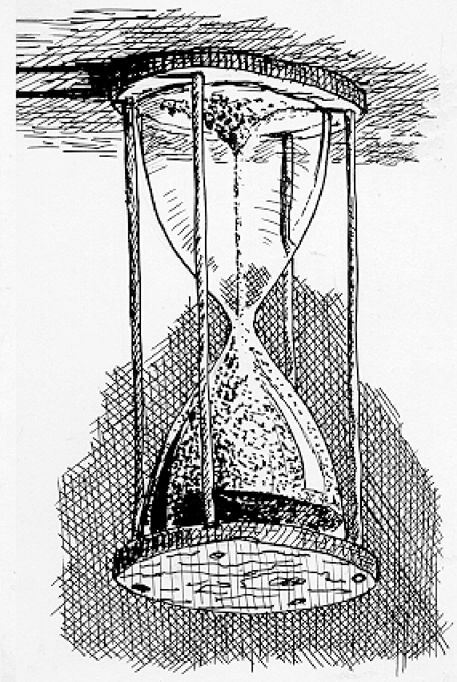
- Created by the IAU in 2006

- Present Organizing Committee:

Sergei A. Klioner, *President*
Gérard Petit, *Vice President*
Victor A. Brumberg
Nicole Capitaine
Agnès Fienga
Toshio Fukushima
Bernard Guinot
Cheng Huang
François Mignard
Ken Seidelmann
Michael Soffel
Patrick Wallace



IAU Commission 52
"Relativity in Fundamental Astronomy"



- is thought to provide a stimulate the exchange on relativistic issues
- Current projects:
  - Compile a list of unsolved problems
  - Frequently asked questions
  - Relativistic glossary for astronomers
  - "Task teams", an ad hoc discussion group for very well posed issues:
    - One task team is currently activated: "TDB units"

      Question: "What are the units of TDB?"

IAU Commission 52
“Relativity in Fundamental Astronomy”

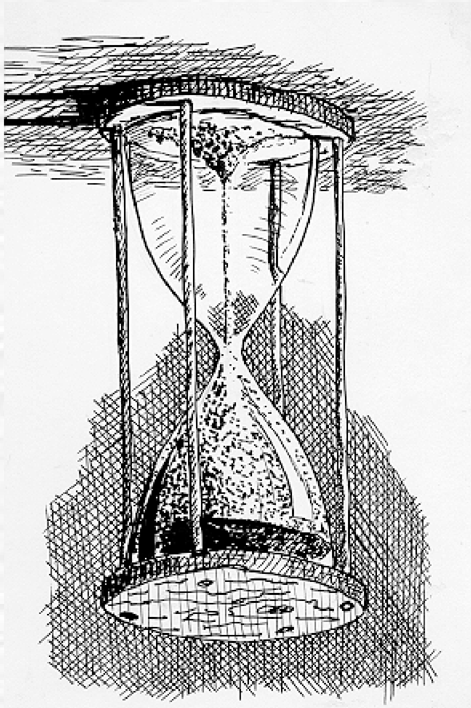
- Topics to be discussed in the future:

  1. Ecliptic or “ecliptic image” in the GCRS

     to be started soon with the input of
     the Earth rotation project in Dresden

  2. The system of astronomical units

     difficult subject that should be discussed by a broader community



Do we need astronomical units?

- The reason to introduce astronomical units was that angular measurements were many orders of magnitude more accurate than distance measurements.

- BUT

  - The situation has changed crucially since that time!
  - Solar mass is time-dependent just below current accuracy of ephemerides

$$\dot{M}_{Sun} / M_{Sun} \sim 10^{-13}\ \mathrm{yr}^{-1}$$

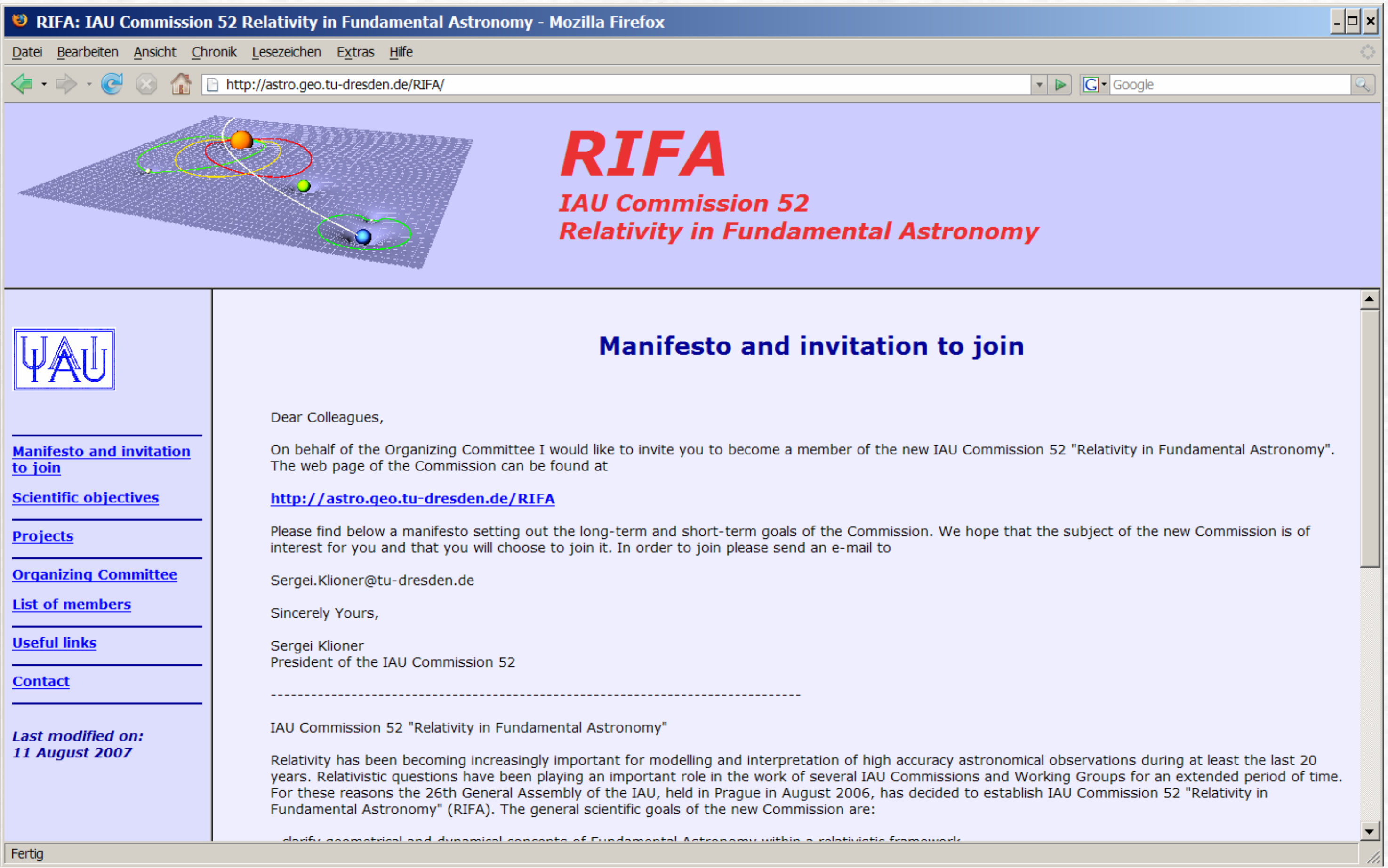
  - Very confusing situation with astronomical units in relativistic framework

- Why not to define AU conventionally as fixed number of meters?
- Do you see any good reasons for astronomical units in their current form?

IAU Commission 52
“Relativity in Fundamental Astronomy”

- All interested members of the IAU are kindly invited to join:

http://astro.geo.tu-dresden.de/RIFA


RIFA: IAU Commission 52 Relativity in Fundamental Astronomy - Mozilla Firefox

Datei Bearbeiten Ansicht Chronik Lesezeichen Extras Hilfe

http://astro.geo.tu-dresden.de/RIFA/

RIFA

IAU Commission 52
Relativity in Fundamental Astronomy

[Manifesto and invitation to join](#)
[Scientific objectives](#)
[Projects](#)
[Organizing Committee](#)
[List of members](#)
[Useful links](#)
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Last modified on: 11 August 2007

Manifesto and invitation to join

Dear Colleagues,

On behalf of the Organizing Committee I would like to invite you to become a member of the new IAU Commission 52 "Relativity in Fundamental Astronomy". The web page of the Commission can be found at

http://astro.geo.tu-dresden.de/RIFA

Please find below a manifesto setting out the long-term and short-term goals of the Commission. We hope that the subject of the new Commission is of interest for you and that you will choose to join it. In order to join please send an e-mail to

Sergei.Klioner@tu-dresden.de

Sincerely Yours,

Sergei Klioner
President of the IAU Commission 52

IAU Commission 52 "Relativity in Fundamental Astronomy"

Relativity has been becoming increasingly important for modelling and interpretation of high accuracy astronomical observations during at least the last 20 years. Relativistic questions have been playing an important role in the work of several IAU Commissions and Working Groups for an extended period of time. For these reasons the 26th General Assembly of the IAU, held in Prague in August 2006, has decided to establish IAU Commission 52 "Relativity in Fundamental Astronomy" (RIFA). The general scientific goals of the new Commission are:

Fertig

Backup

Content

1. No way to live without relativity
2. IAU 2000 Framework as a standard tool to model
3. PPN formalism as a standard tool to test
4. Is everything OK? Not quite: main problems
5. Example I: numerical magnitude vs. analytical order of magnitude
6. Example II: SFT tensors
7. Example III: scaling and units, astronomical units

Data analysis models compatible with IAU 2000

- Ephemeris construction (JPL, IMCCE, IAA)
- VLBI
- LLR
- SLR
- Hipparcos, Gaia
- time transfer algorithms
- pulsar timing
- GPS, standard model, according to Ashby (2003)
- Galileo (as a copy of GPS)

Some minor problems may still exist…

Observations against General Relativity?

- Are there some experimental evidences against General Relativity?

"Candidates":

"Pioneer anomaly": unexpected additional constant acceleration of two Pioneer spacecrafts directed towards the Sun 8.5 10-9 m/s^2

Criticism: "dirty" models of the spacecrafts (heat radiation from RTG, etc.)

"Fly-by anomaly": unexpected additional increase of the velocity of several spacecrafts

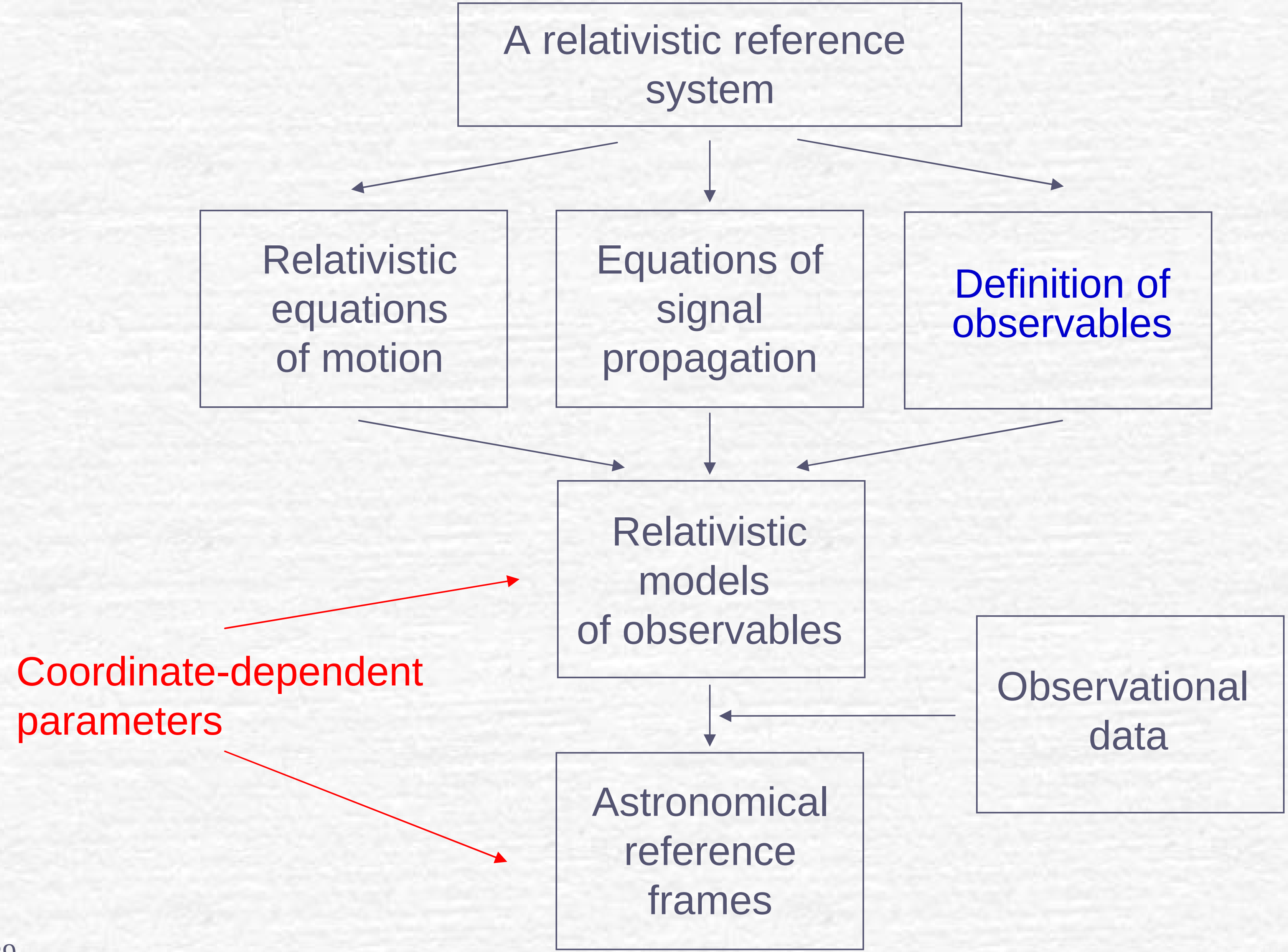
Criticism: the used model has not been checked from the relativistic point of view

Could the story of the Le Verrier's discovery of the perihelion advance repeat?
A lot of care should be taken in dealing with this delicate question…

Linear drifts between time scales

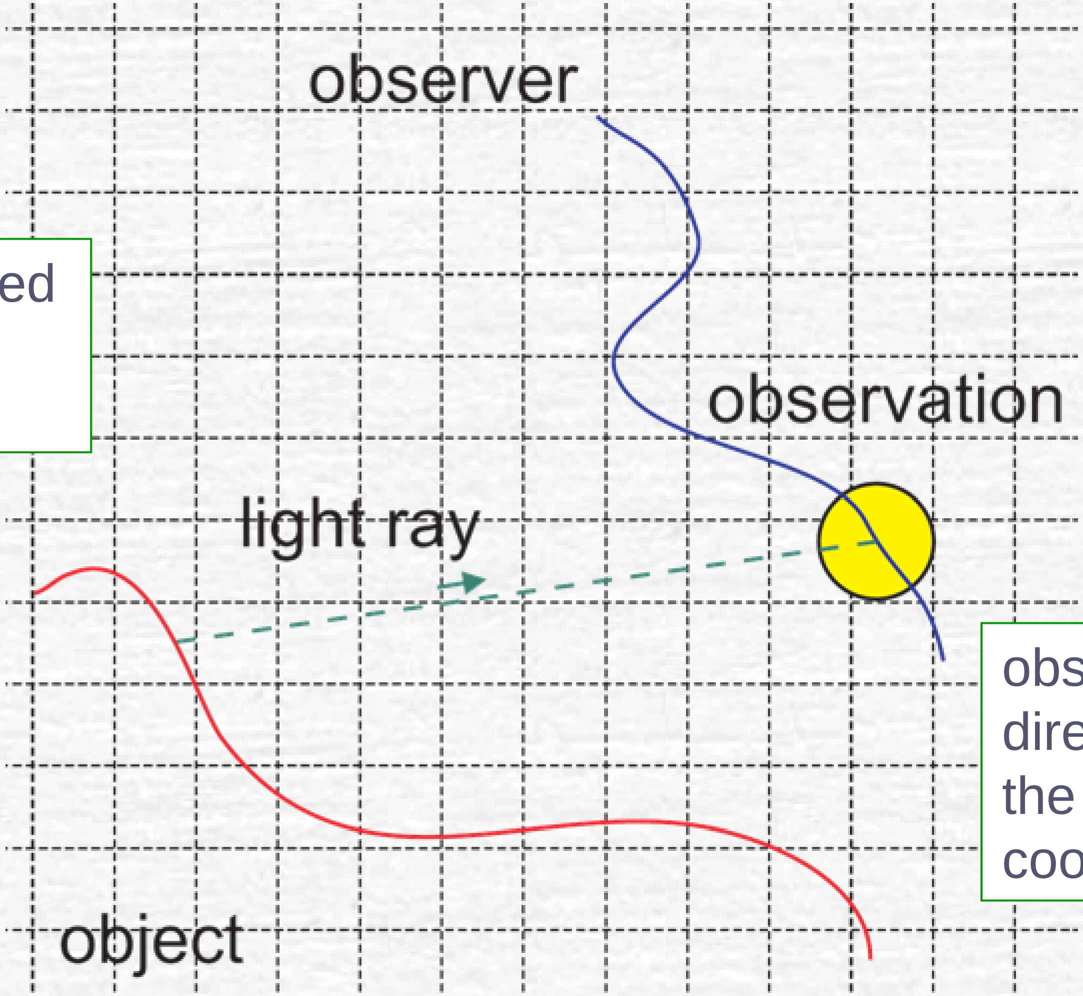
Pair	Drift per year (seconds)	Difference at J2007 (seconds)
TT-TCG	0.021993	0.65979
TDB-TCB	0.489307	14.67921
TCB-TCG	0.467313	14.01939

General relativity for space astrometry

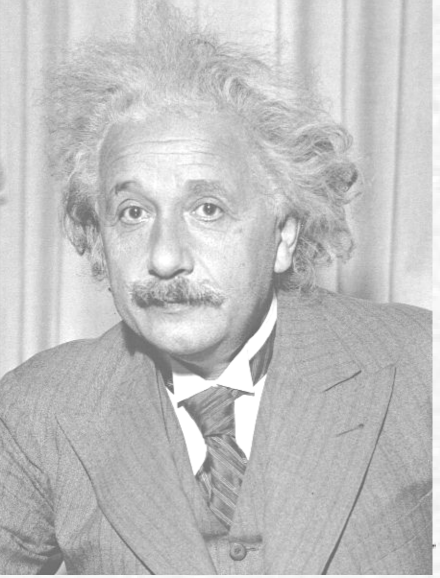


Astronomical observation

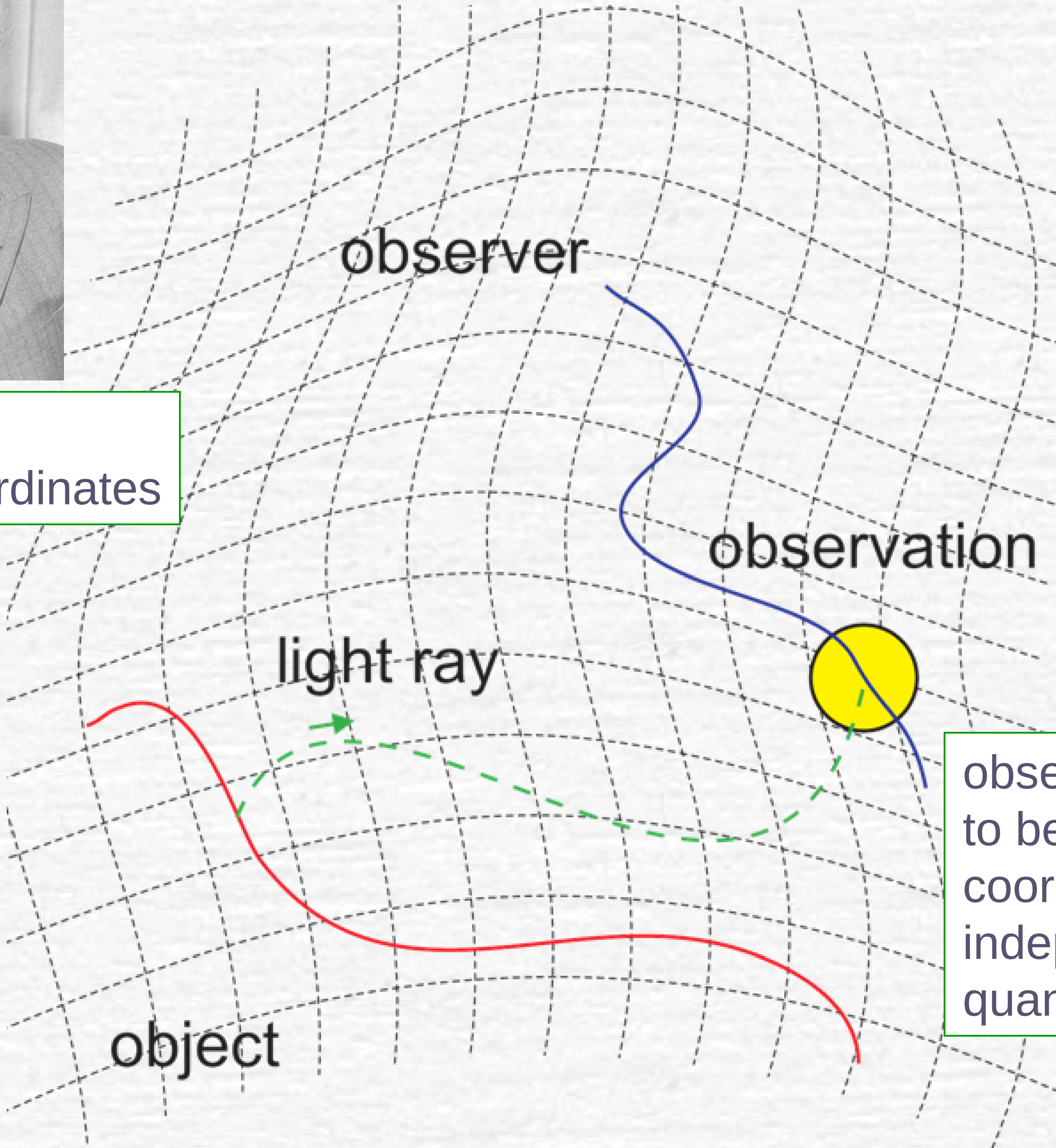
physically preferred global inertial coordinates



observables are directly related to the inertial coordinates



Astronomical observation



no physically preferred coordinates

observables have to be computed as coordinate independent quantities