Relativistic model and reference frame for next generation astrometry

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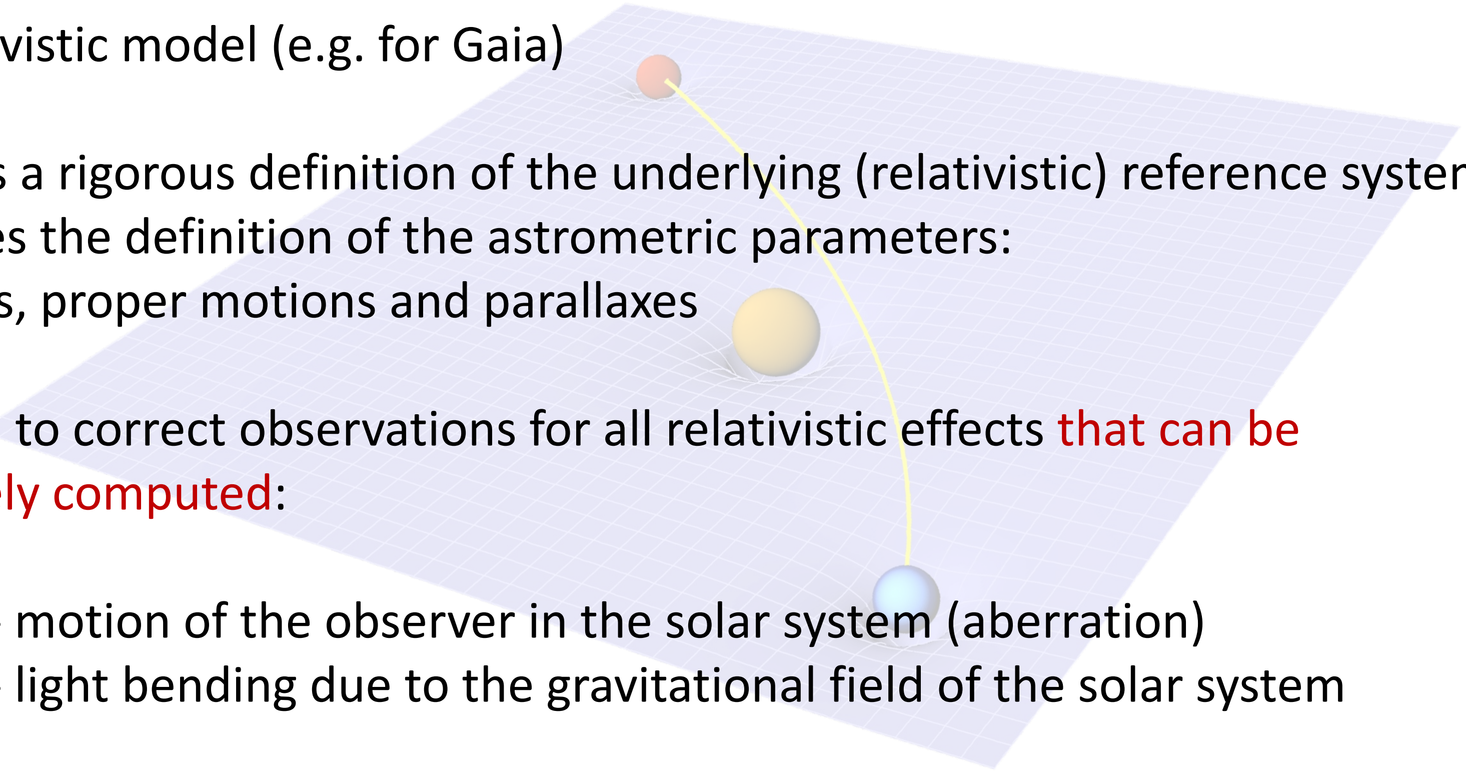
Relativistic model

Relativity for astrometry: the model



The relativistic model (e.g. for Gaia)

- provides a rigorous definition of the underlying (relativistic) reference system that gives the definition of the astrometric parameters: positions, proper motions and parallaxes

- is aimed to correct observations for all relativistic effects that can be accurately computed:

  - motion of the observer in the solar system (aberration)
  - light bending due to the gravitational field of the solar system

The idea of the Gaia model was to consider ALL effects that can exceed 1 μas even if it would be a rare case…

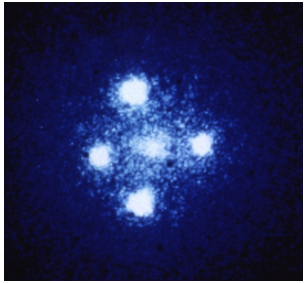
Outline of the relativistic model for Gaia

- 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, 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.)

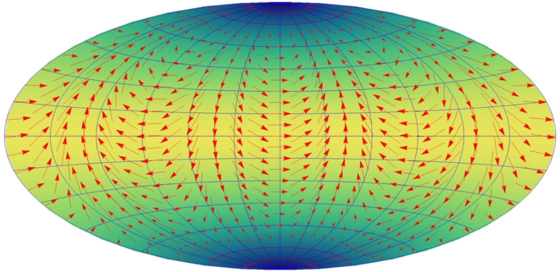
Relativity for astrometry: beyond the model

It is important to understand that there are a number of known relativistic effects that cannot be computed apriori:



1. Microlensing: light bending due to the bodies of our Galaxy

2. Macrolensing



3. Effects of gravitational waves
   (individual ones and the stochastic background)

All these effect can be investigated in the epoch astrometry or in the residuals of the astrometric solution!

For the astrometric solution these are additional sources of noise!

Relativity for astrometry: input data for the model

The model is a set of formulas, in which some quantities appear.
Those quantities must be known with a certain accuracy. For Gaia:

1. Barycentric position of the observer: 150 km (parallaxes)

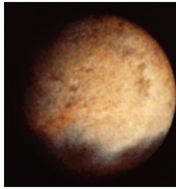
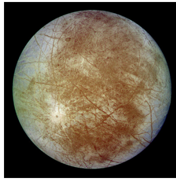
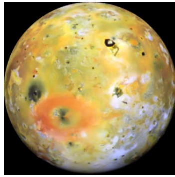
$$\delta x < 1\,\mathrm{au} \times \delta\varpi \quad \Rightarrow \quad \delta x < 1.5\times 10^5\,\mathrm{m} \times \left(\frac{\delta\varpi}{1\,\mu\mathrm{as}} \right)$$

2. Barycentric velocity of the observer: about 1.4 mm/s (Newtonian aberration)

$$\delta v < c\,\delta \quad \Rightarrow \quad \delta v < 1.4\,\mathrm{mm/s} \times \left(\frac{\delta}{1\,\mu\mathrm{as}} \right)^{1/2}$$

These requirements should be remembered when planning a new mission!

Relativity for astrometry: input data for the model

3. Ephemerides and masses of all solar system bodies with a radius

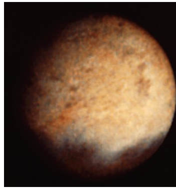
$$R \geq \left(\frac{\rho}{1\,\mathrm{g/cm^3}}\right)^{-1/2} \times \left(\frac{\delta}{1\,\mu\mathrm{as}}\right)^{1/2} \times 650\,\mathrm{km}$$

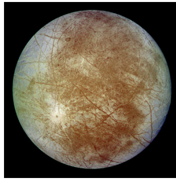
this gives a limited number of bodies for Gaia:

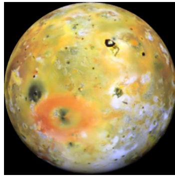
the Sun, the major planets, the Moon

Ganymede	35				
Titan	32	Pluto	7	Rea	2
Io	30	Charon	4	Dione	1
Callisto	28	Titania	3	Ariel	1
Triton	20	Oberon	3	Umbriel	1
Europe	19	Iapetus	2	Ceres	1

Relativity for astrometry: input data for the model







4. The required accuracy of the ephemerides:

$$\delta_{pN} = \frac{(1+\gamma)GM_A}{c^2\,|\boldsymbol{r}_{oA}|}\cot\frac{\psi_A}{2} \quad \Longrightarrow \quad \sigma_{\delta_{pN}} < 2\,\delta_{pN}\,\frac{\sqrt{\sigma^2_{x_o}+\sigma^2_{x_A}}}{d_A}$$

e.g. for Gaia, Jupiter: 600 m.

Increasing the accuracy of the relativistic model?

To increase the accuracy by 1-2 orders of magnitude while taking all effects that potentially exceed a given magnitude is difficult:

- too many bodies should be taken into account (not all are even known!)

- too accurate ephemerides and masses are needed

- still unresolved problems with higher post-Newtonian approximation in the propagation of light:

  light propagation in the field of N arbitrarily moving bodies with arbitrary multipole structure to second order in G (= post-post-Minkowskian)

Which deficiencies of the model be tolerated?

1. The idea is to drop the minor effects that affect very few observations.
   For example:
   - Deflection due to most of the minor bodies
   - Multipole deflection (non-sphericity of the bodies)
   - Post-post-Newtonian effects
   - …

   A dedicated study is needed to see:

   (a) what errors the astrometric solution gets when those effects are ignored

   (b) how to find the sources affected by the dropped effects

2. One needs to clarify if a (chaotic/unpredictable) microlensing on galactic stars and/or asteroids in the solar system prohibits reaching the accuracies of $< 0.1\ \mu$as/yr

Reference frame

Fixing the reference frame

- Scanning satellites effectively measure angular distances between sources

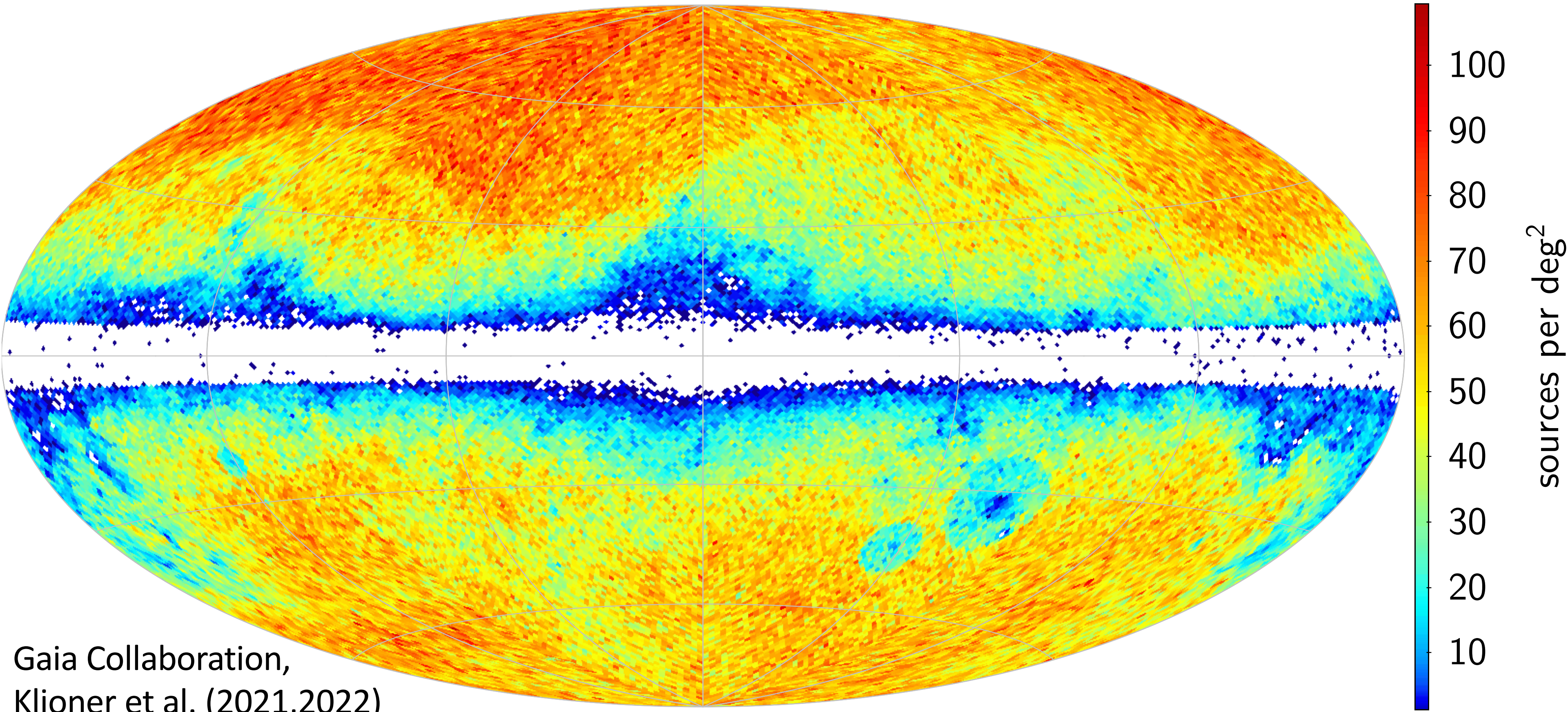
- The observations define an astrometric solution up to a free constant rotation (orientation) and a free constant angular velocity (“spin”)

- To fix the orientation in Gaia one takes an external radio catalogue of quasars ICRF3 S/X and removes mutual rotation: a pure convention

- To fix the spin in Gaia one takes a large set of observed QSOs and require that the average proper motion of that set of QSOs vanishes: an important physical principle

Gaia-CRF3, 2020

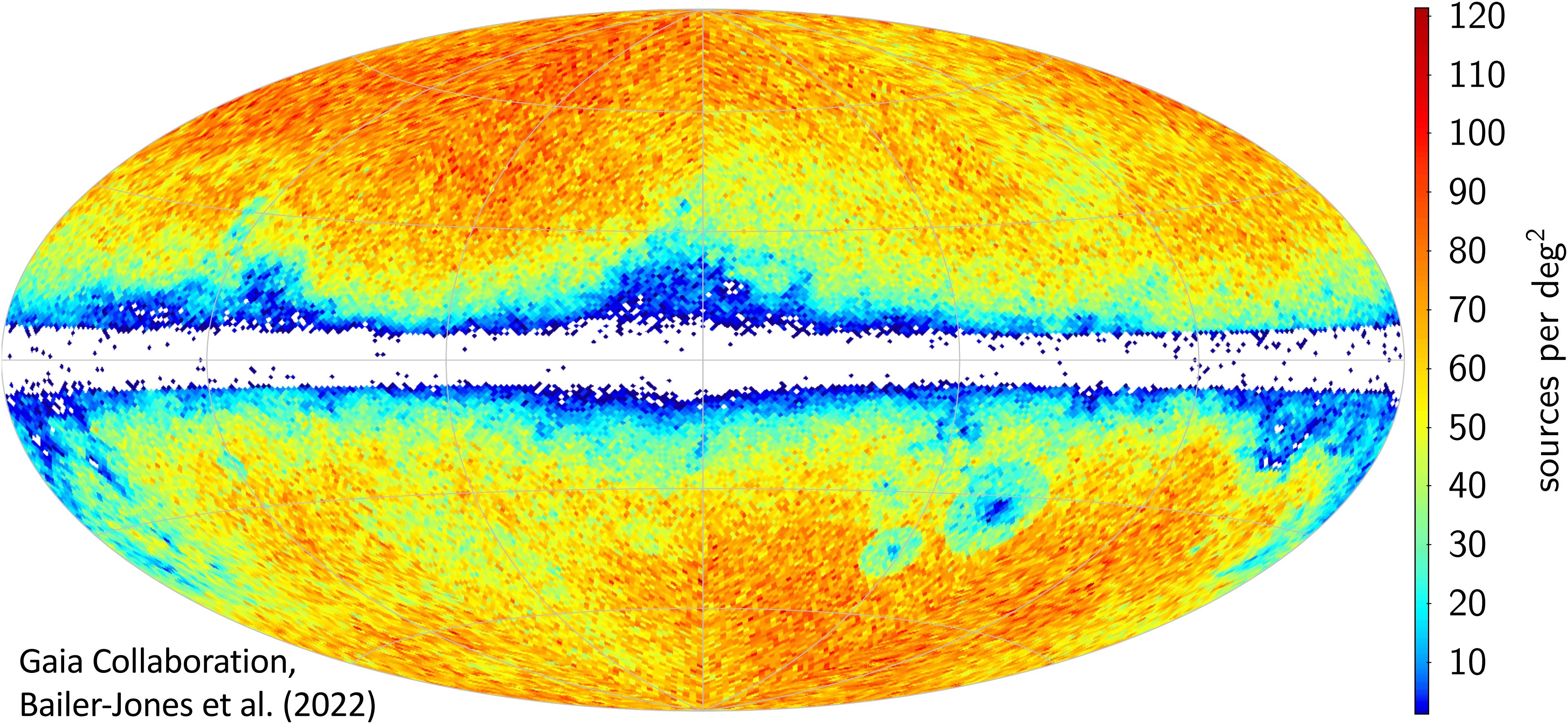
1 614 173 QSOs



Gaia Collaboration,
Klioner et al. (2021,2022)

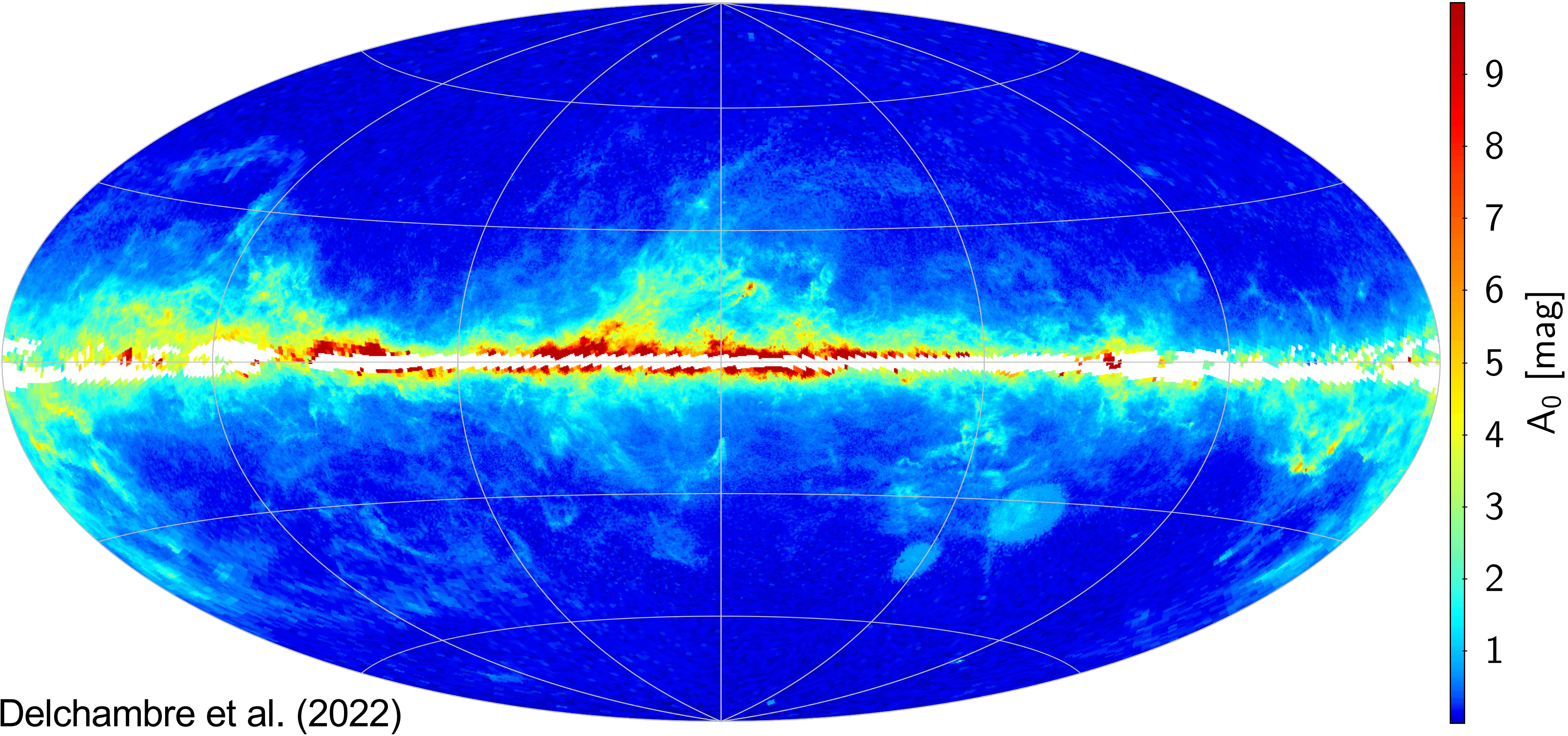
The astrometric selection of QSOs in Gaia DR3, 2022

1.614.173 + 283.581 = 1.897.754 QSOs



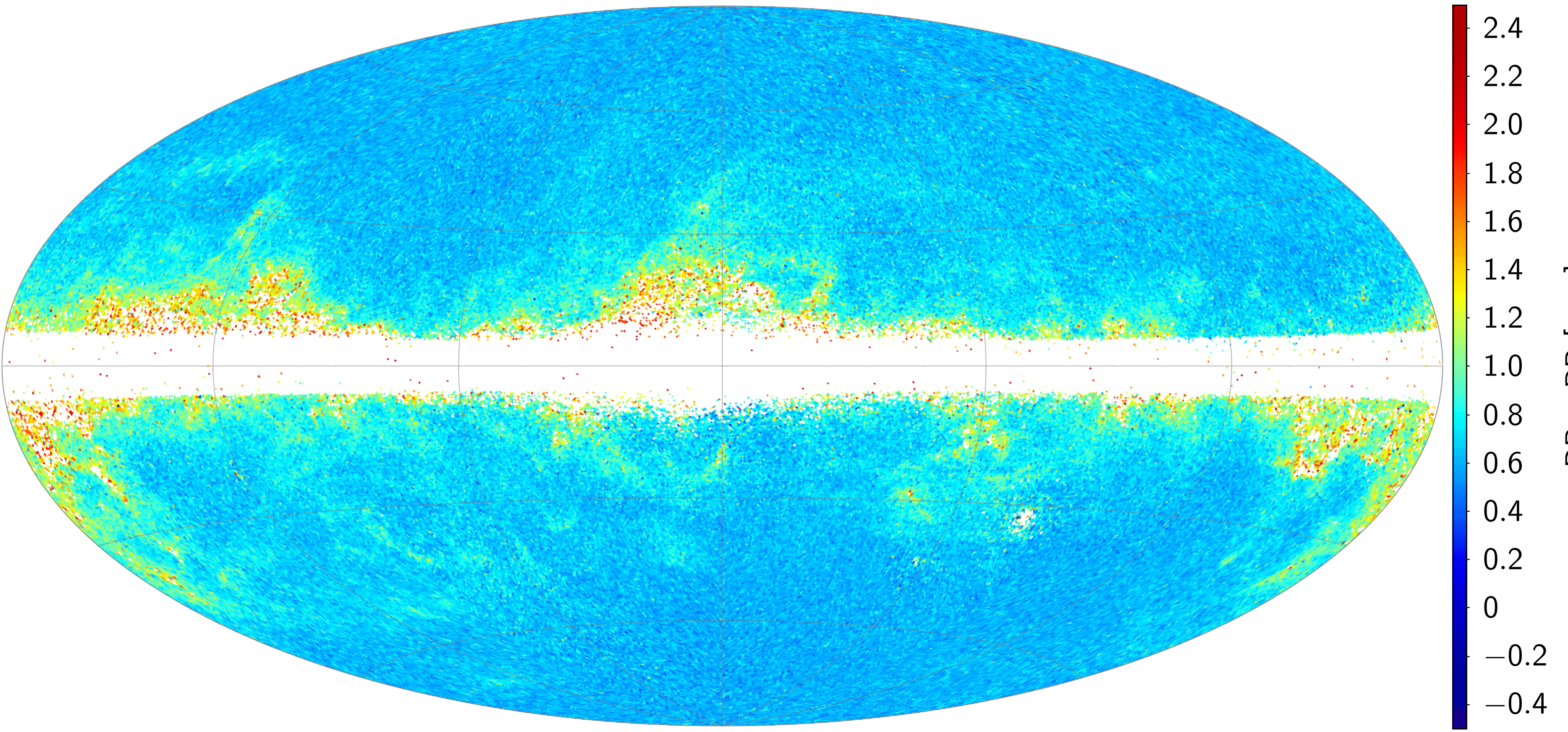
Gaia Collaboration,
Bailer-Jones et al. (2022)

Galactic Extinction in Gaia DR3



Delchambre et al. (2022)

Colour index BP−RP of the QSOs in Gaia DR3

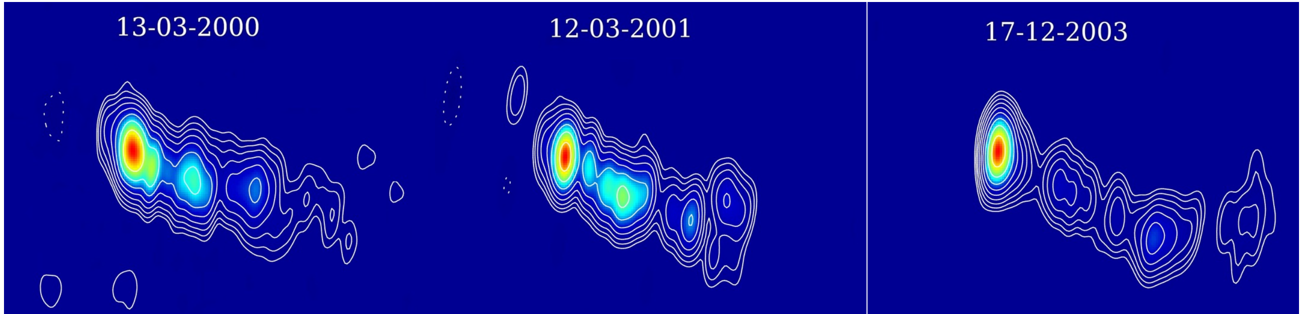


QSOs of different astrometric quality: radioastrometry

- The problem of source structure is well known in the radio!

- Remedies: high-resolution imaging and monitoring of the structure
  or derived measures of the source-structure effects
  (e.g. closure amplitude root-mean-square, CARMS; Xu et al 2021)

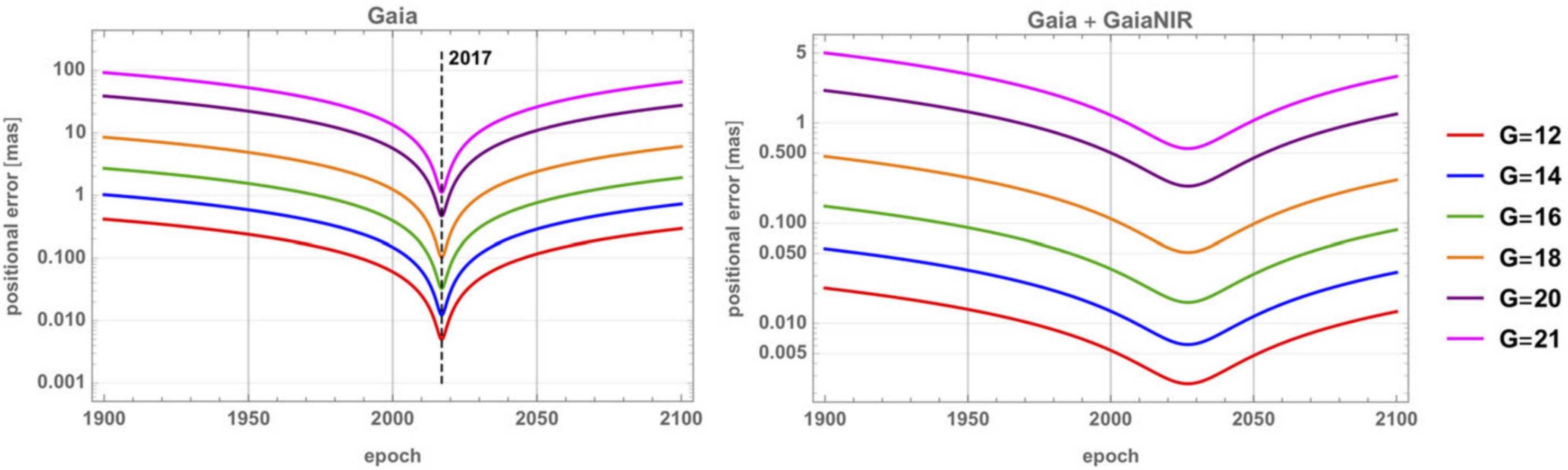
- Classification of the sources according to the compactness of the structure
  and its stability; only best sources are used as "defining" the Reference Frame



Images
from BVID

10x15 mas

Sources of low astrometric quality can quickly destroy the RF



Hobbs et al., 2021: Exp. Ast., 51, 783, Fig 3

This promise can only hold if the sources follow the fitted model with position and linear proper motion!

→ A selection of "good" sources is important

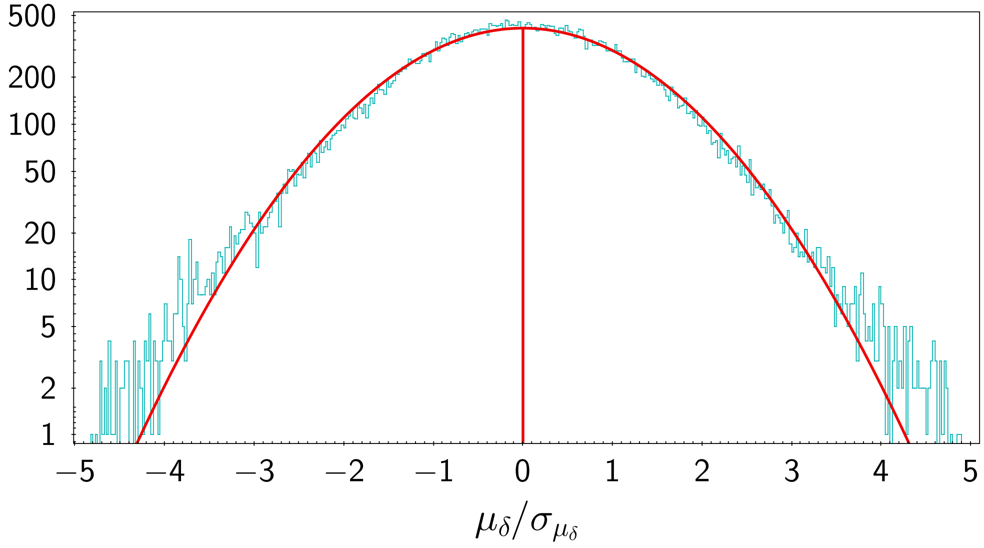
QSOs of different astrometric quality: Gaia(NIR)

- Subsamples of QSOs of lower astrometric quality were found in Gaia DR3

  - QSOs for which traces of the host galaxy was found
  - QSOs of extreme colours
  - QSOs identified as such only by certain external catalogues
  -...

  Various statistical criteria can be used here:

  e.g. larger scaling needed to meet the distribution of the normalized astrometric parameters...



QSOs of different astrometric quality: Gaia(NIR)

- Careful search for pro sources is needed with an ultimate goal to introduce "**source quality index**" for all QSOs

  Investigate samples:

  - different areas on the sky
  - different bins in magnitude, colours,
  - different physical type of sources (blasars), etc.

→ the selected best sources can be used to define the Reference Frame

This is especially important for the future GaiaNIR reference frame that aimed at much higher accuracies in proper motions!