Gaia Celestial Reference Frame:

Properties and relations to ICRF3

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Gaia and the Reference Frame

- Effectively, Gaia observes apparent angular distances between pairs of sources

- Therefore, Gaia astrometry has almost perfect 6-dimensional degeneracy:

  – an arbitrary constant (time-independent) rotation of all position
  – an arbitrary rotation of all proper motions (constant angular velocity)

=> strictly speaking, the degeneracy is not perfect since Gaia uses particularly-oriented ephemerides to compute aberration, light deflection, etc.

However, these effects are too week to have practical relevance.
The corresponding rotations should be, however, small.

Gaia and the Reference Frame

- Therefore, a Gaia astrometric catalogue can be rotated
    i. by a (small) constant angle and
    ii. using a (small) constant angular velocity

- The orientation (case “i.”) is a pure convention.

  The choice for Gaia: aligned as the VLBI-based ICRF.

- The rotational state (case ”ii.”) is a physical property of the resulting reference frame.

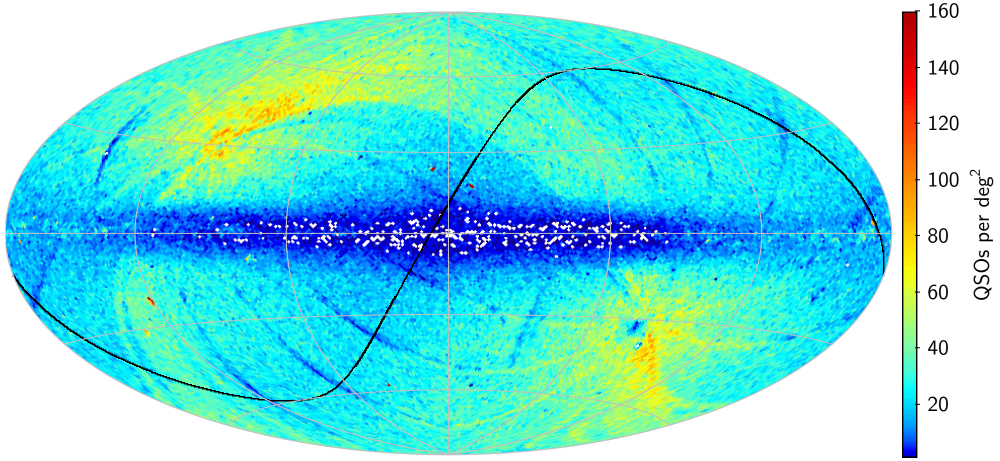
  The choice for Gaia: implement the concept of ICRS – no global rotation with respect to a set of extragalactic objects.

The usefulness of the ICRS concept is a cosmological assumption.

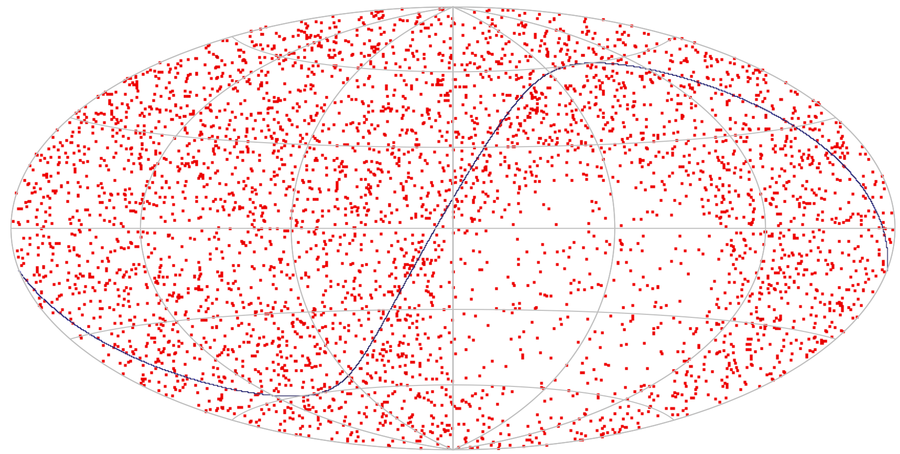
Selection of QSOs in Gaia DR2

- In future releases Gaia will be able to classify objects as extragalactic (e.g. as QSOs) from its own observations.
- For Gaia DR2, two external AGN catalogues were taken:
  - allWISE AGN catalogue (Secrest et al. 2015)
  - ICRF3 prototype catalogue provided by the IAU WG on ICRF3 in July 2017

allWISE AGN: 1 354 775 sources

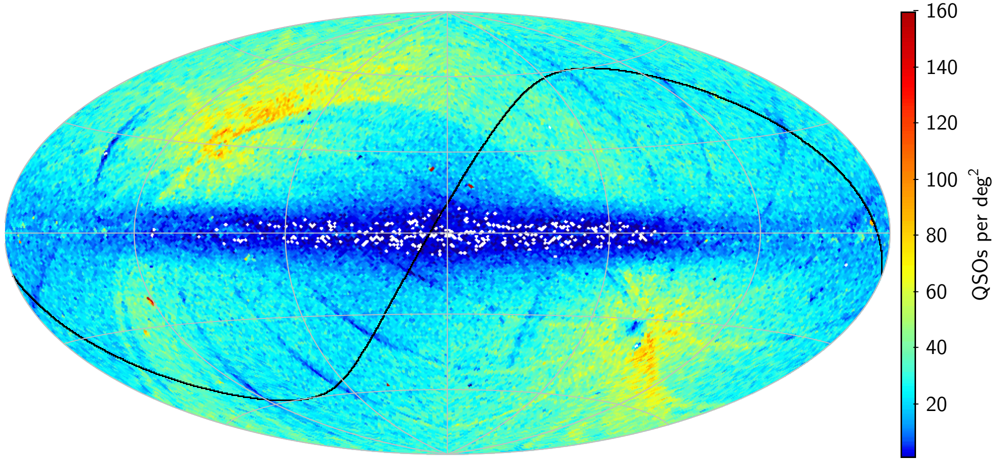


ICRF3 prototype: 4 262 sources



Selection of the sources in Gaia-CRF2

allWISE AGN: 1 354 775 sources



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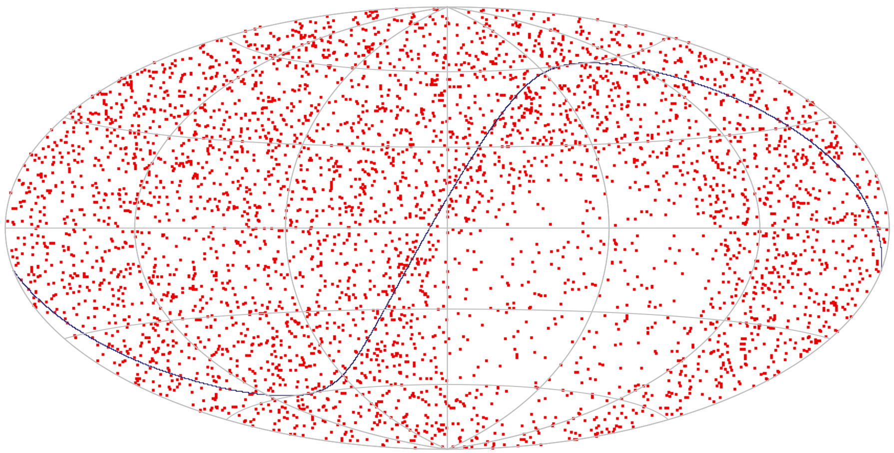
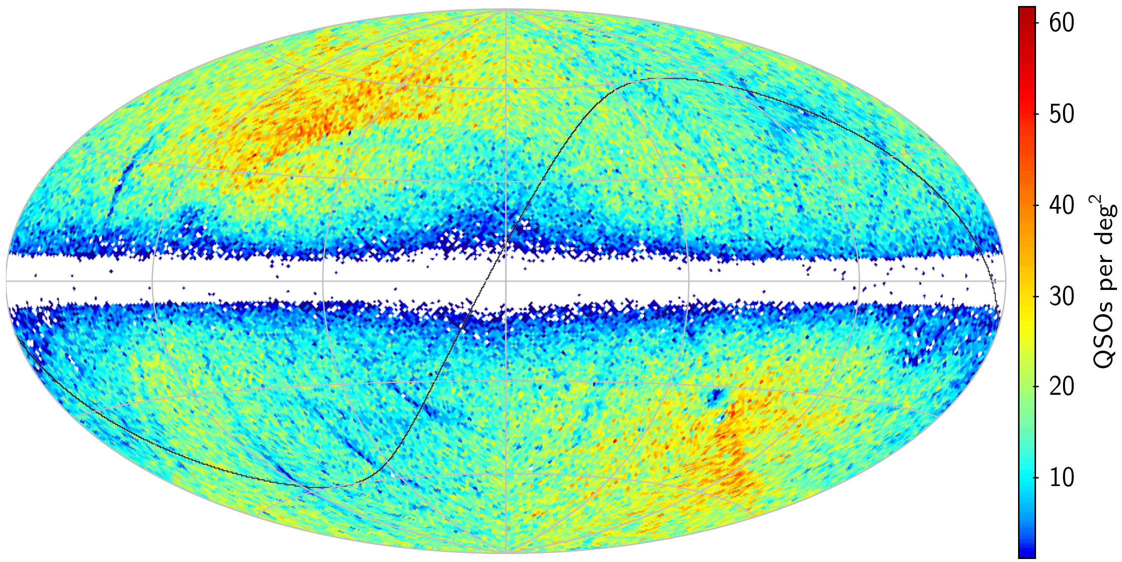


Gaia-CRF2: 556 869 sources



Gaia-CRF2:

total number of sources: 556 869

number of ICRF3 sources: 2820

number of allWISE AGNs: 555 934

(1885 sources are both in ICRF3 and allWISE)

Selection of the sources in Gaia-CRF2

1) Cross match with Gaia DR2 with the distance `rho < X`

   `X=100 mas` for the ICRF3 prototype

   `X=2000 mas` for the allWISE AGN catalogue

   the difference reflects the astrometric quality of the catalogues

2) Filtering: quality of Gaia astrometry and possible star contaminations

```
astrometric_params_solved == 31  # full astrometric solution
astrometric_matched_observations >= 8
abs( (parallax + 0.029) / parallax_error ) < 5
sqrt( (pmra/pmra_error)^2 + (pmdec/pmdec_error)^2 ) < 5
```

3) Additional filtering of star contaminations in the match with the allWISE AGNs :

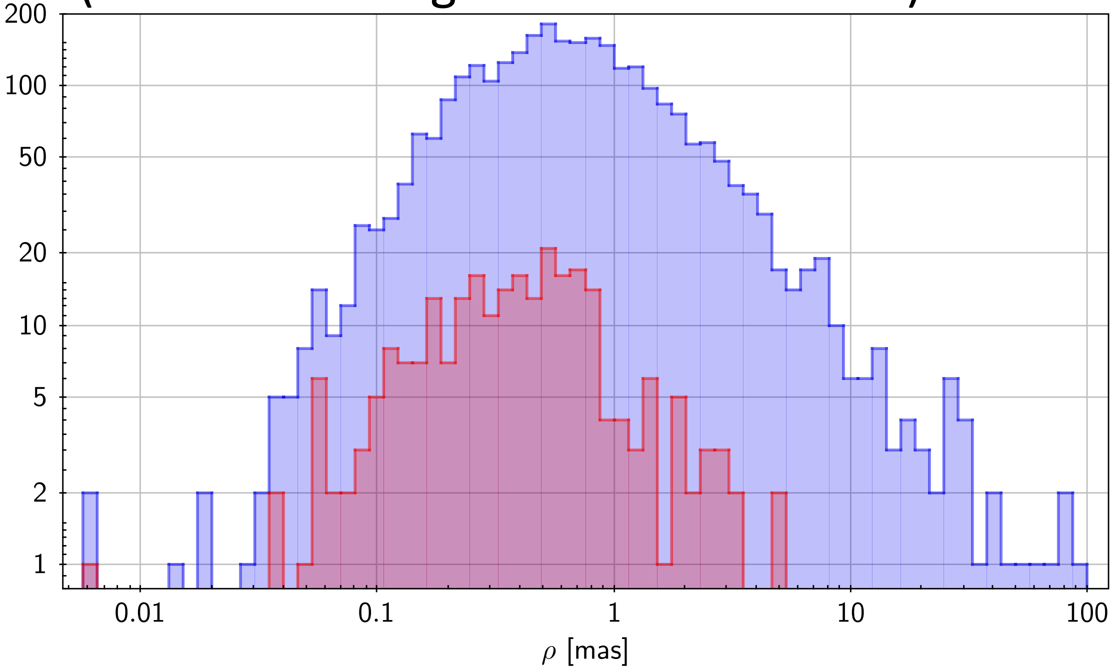
```
abs(sin(b)) > 0.1          # b is the galactic latitude
rho < 2*abs(sin(b))        # rho is the separation in arcseconds

++ manual elimination of a few sources known to be stars
```

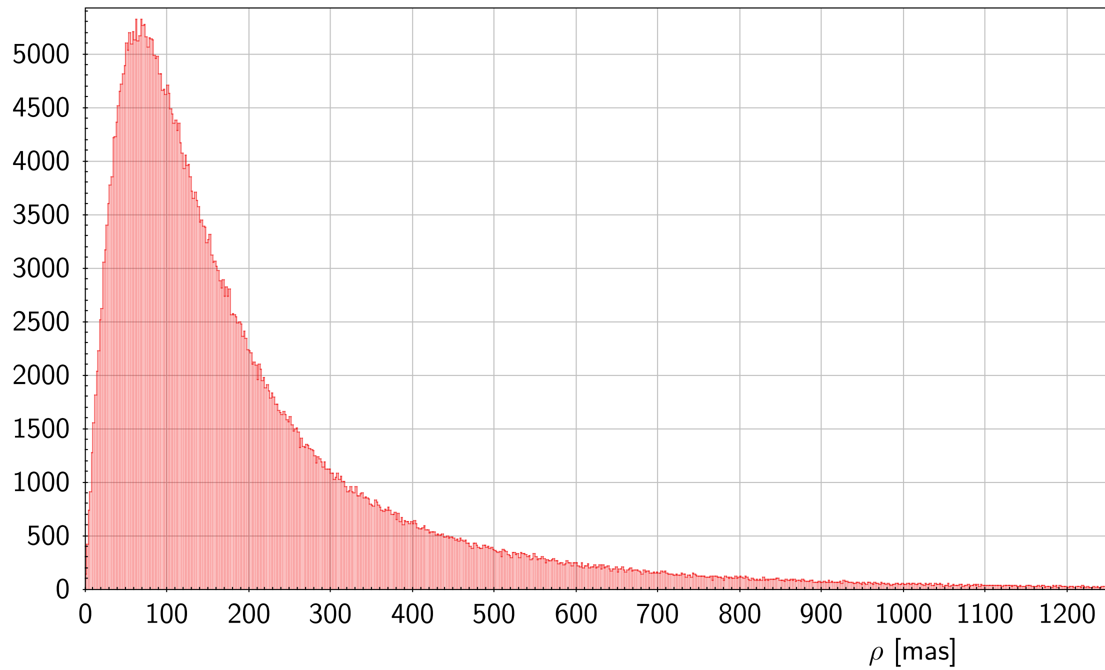
** Do expect small differences if you repeat this procedure with the published data.

Selection of QSOs in Gaia-CRF2: distances

ICRF3 prototype (2820 matches)
Median distance: 0.622 mas
(for 250 defining sources: 0.407 mas)

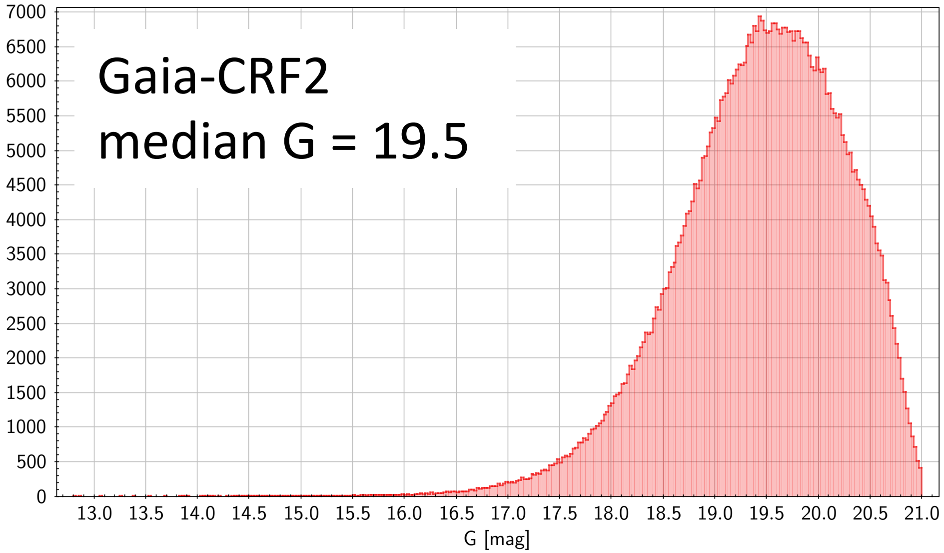


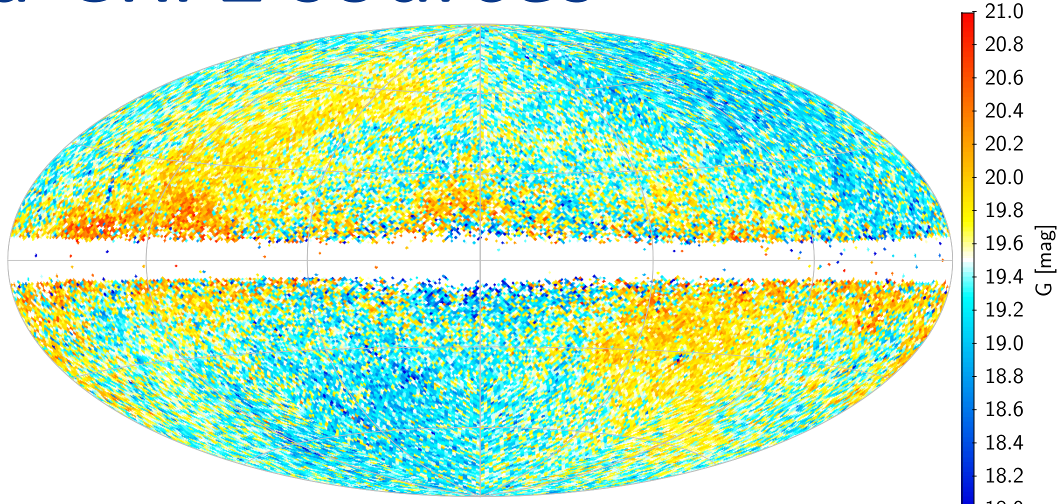
allWISE AGNs (555 934 matches)
Median distance: 138 mas



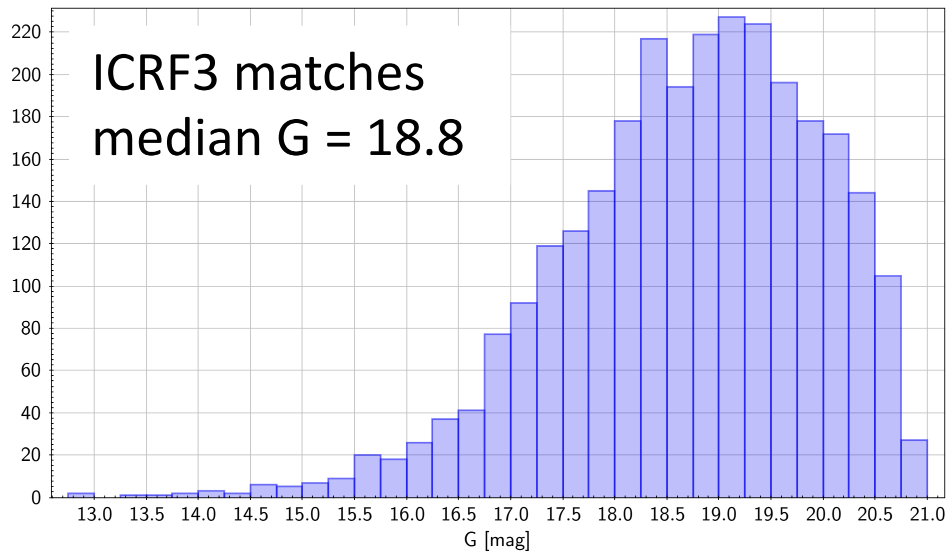
Astrometric quality of ICRF3 is obviously much better than that of the allWISE catalogue.
No special treatment of ICRF3 sources in Gaia. Small distances show the quality of Gaia data.

Magnitude of the Gaia-CRF2 sources



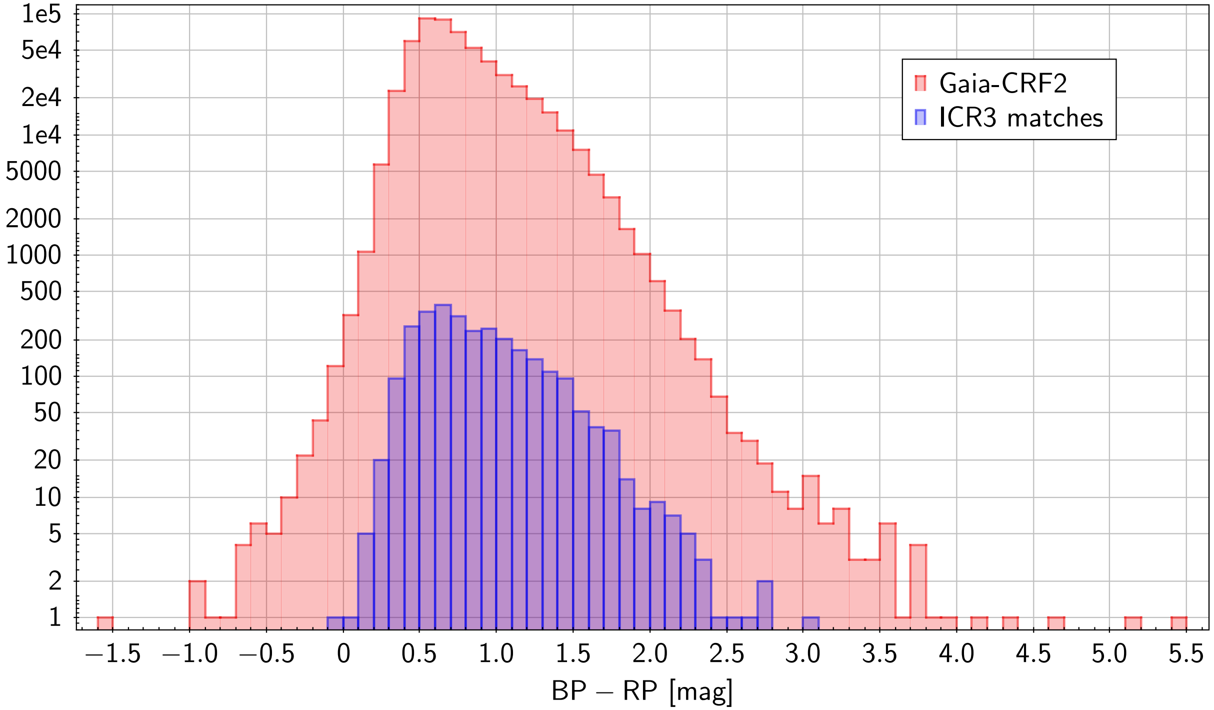


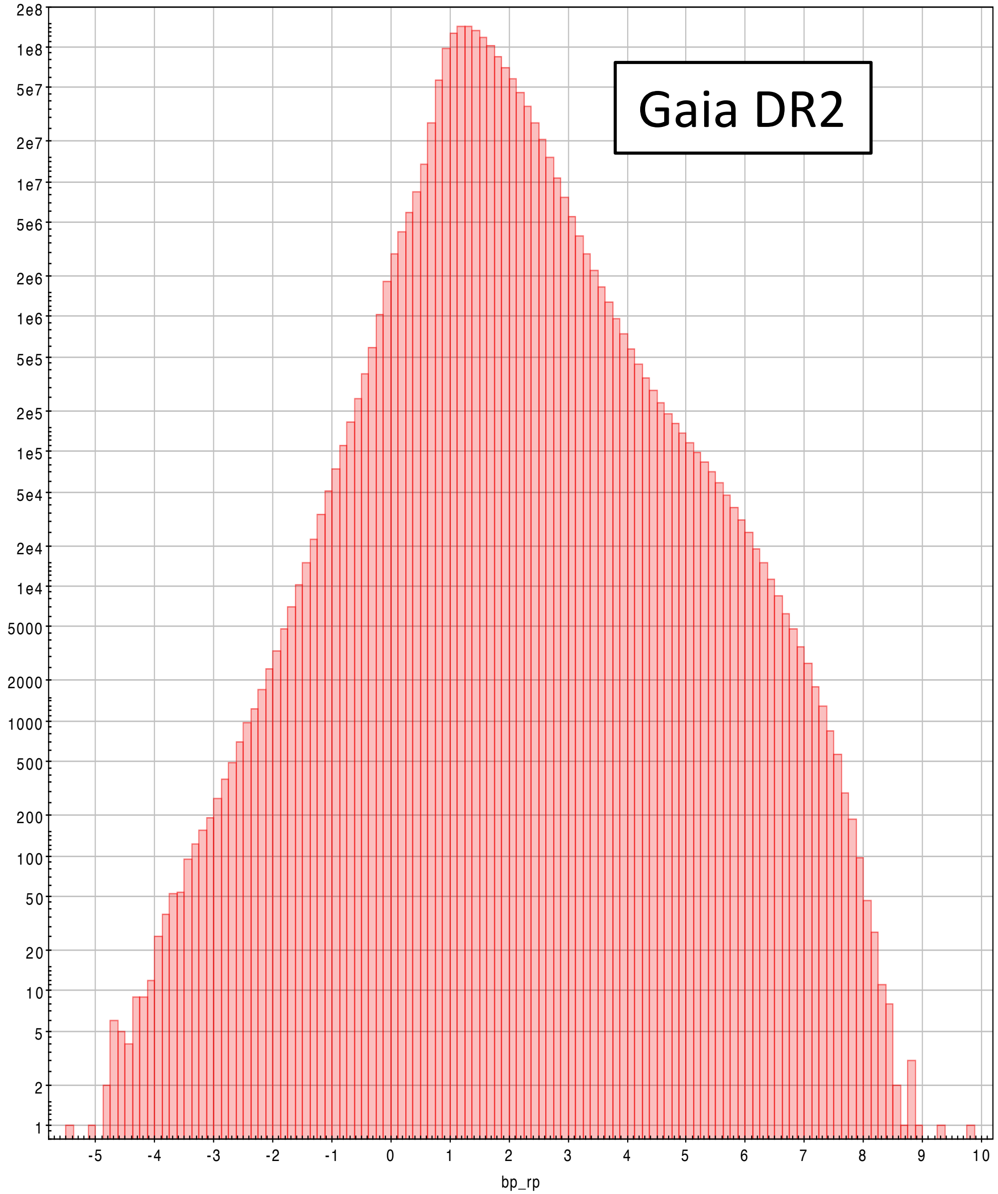
Gaia-CRF2: median G magnitude per pixel



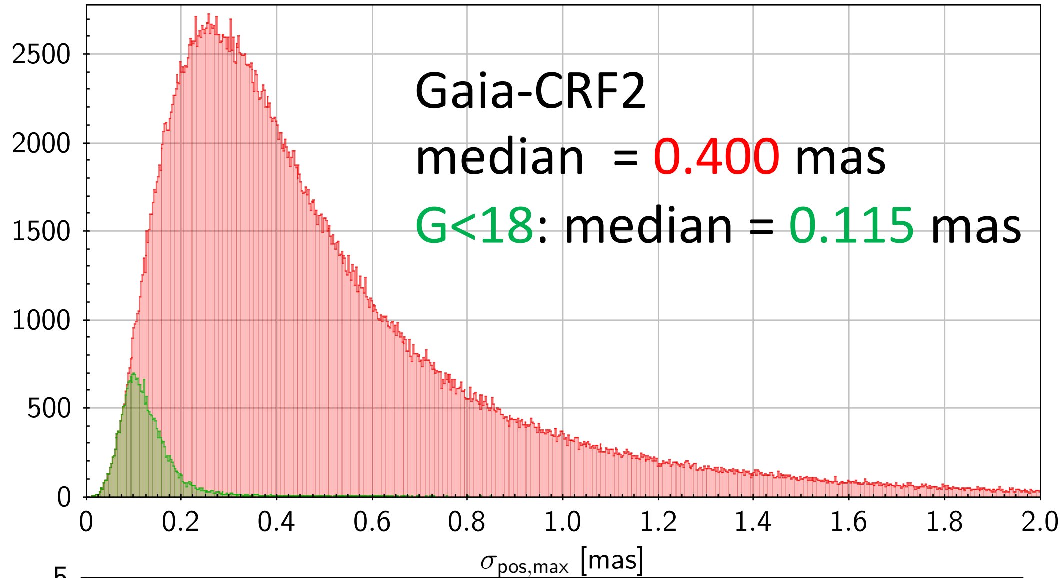
Colour of the sources

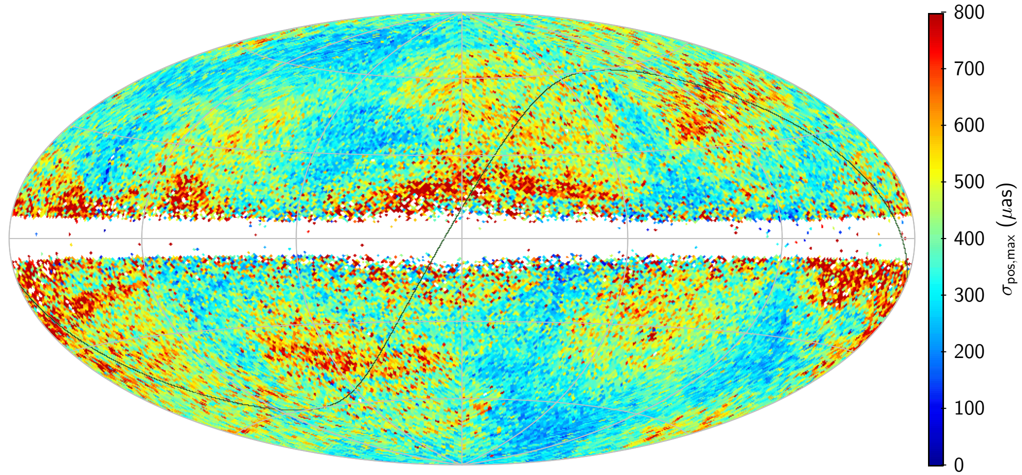
- A bit bluer than an average of Gaia DR2: median BP-RP = 0.71 (0.79 for ICRF3 matches)

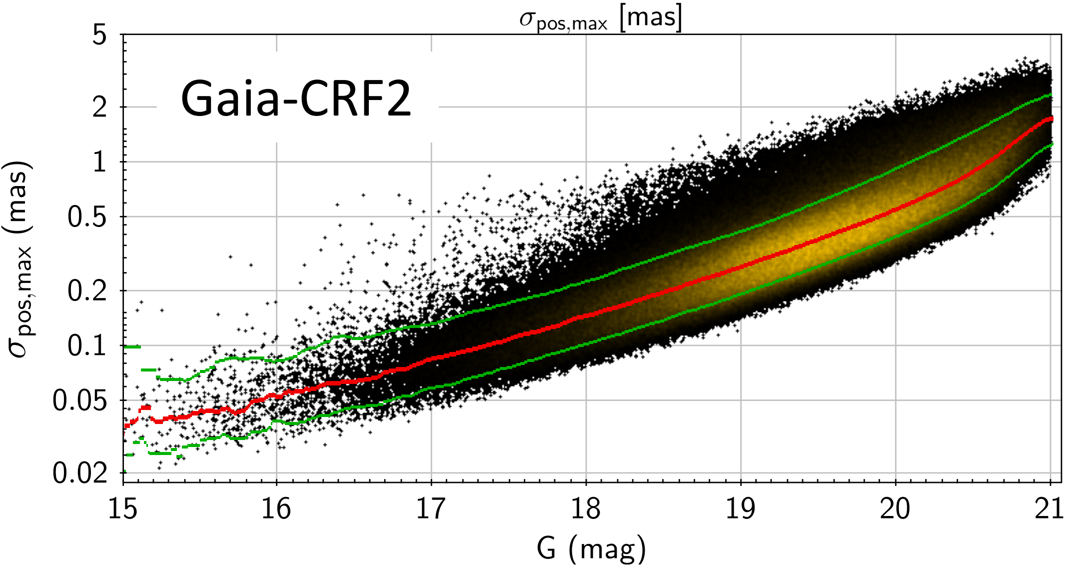


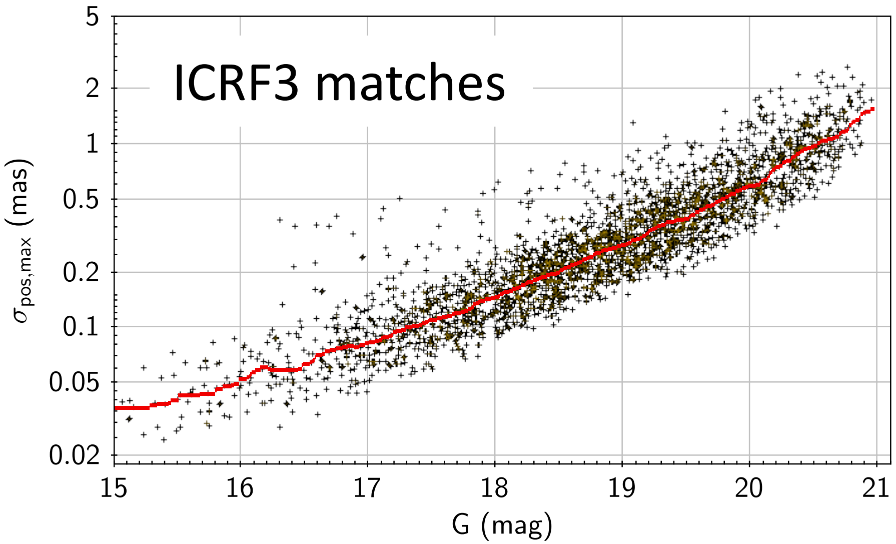


Positional accuracy





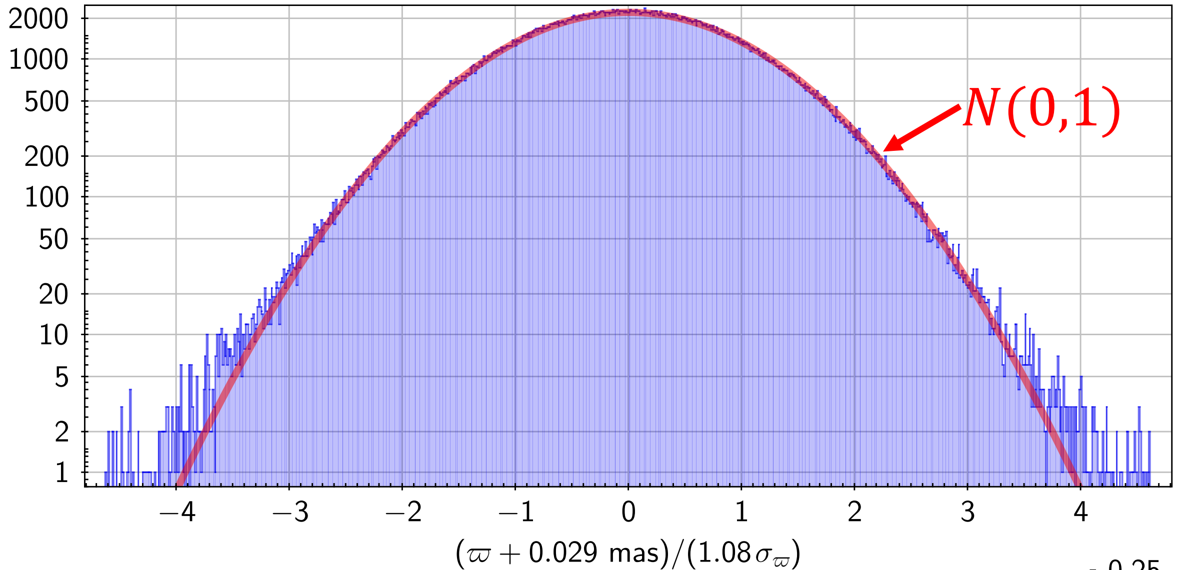


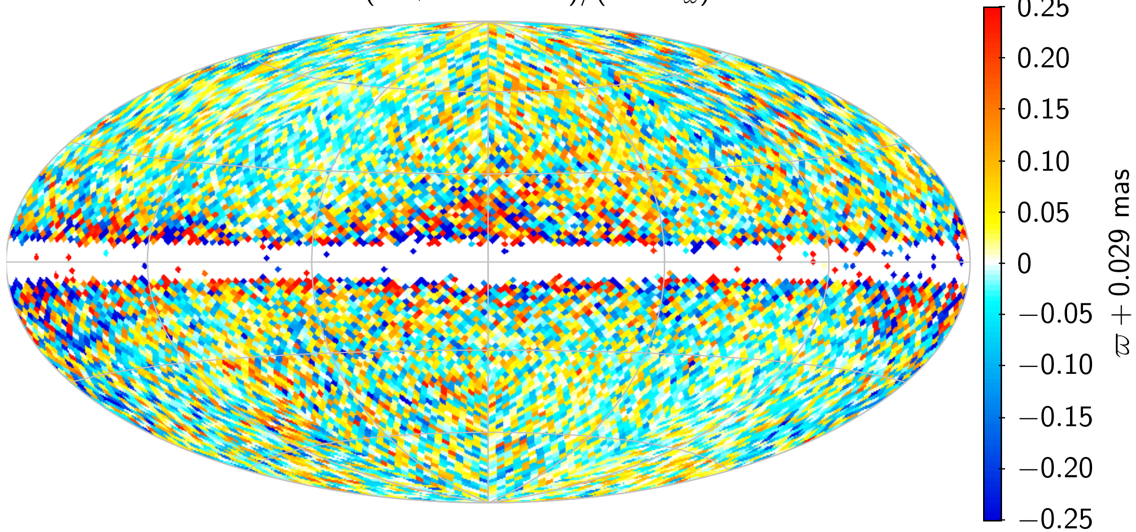


Parallaxes and proper motions as quality indicators

Parallaxes:

median = −0.029 mas
RSE = 0.566 mas
scaling of the formal errors: **1.08**





Parallaxes and proper motions as quality indicators

Proper motions:

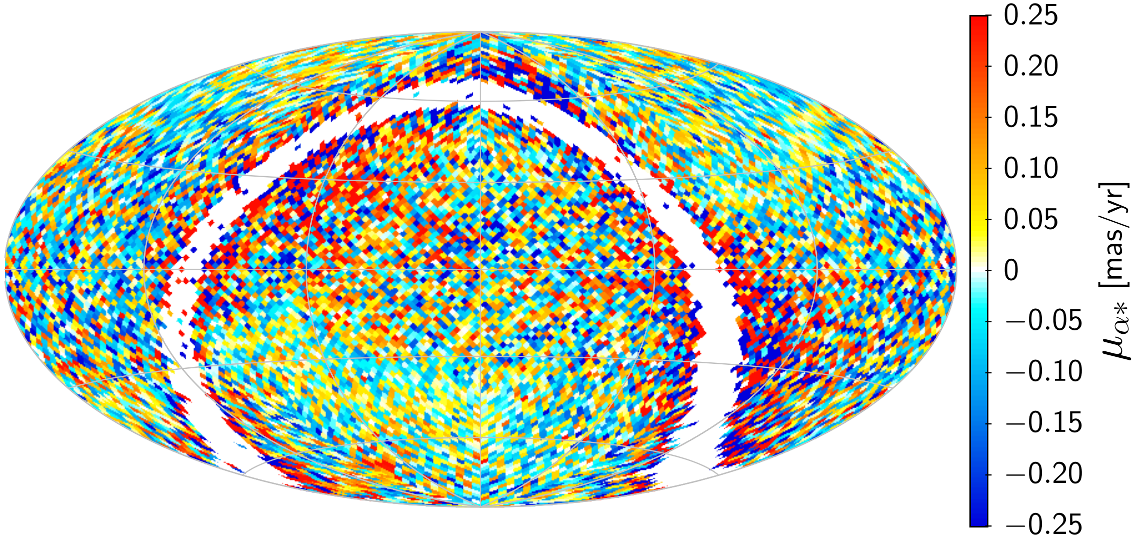
in right ascension

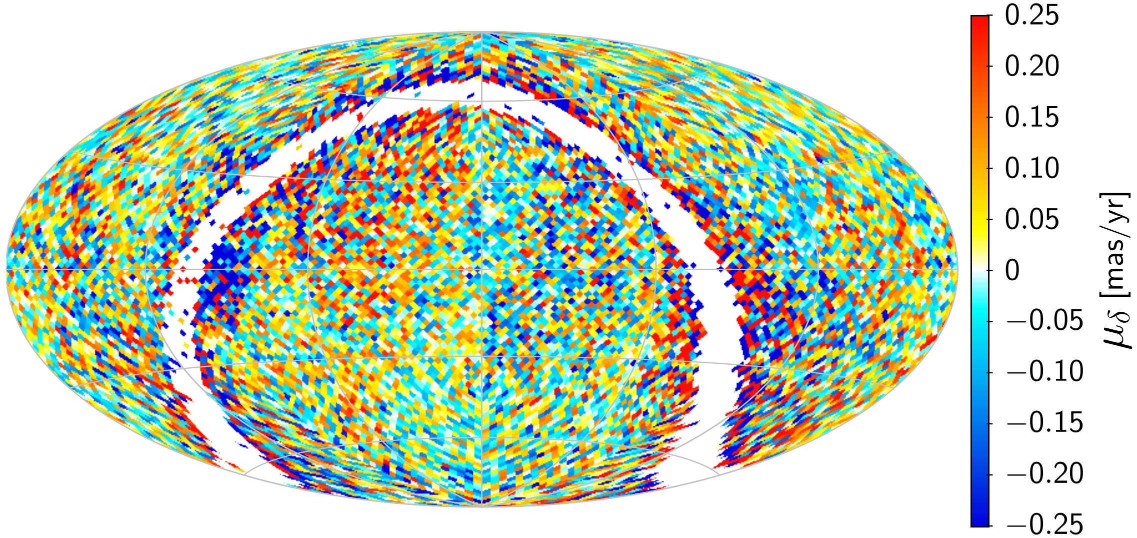
median = −0.001 mas/yr
RSE = 0.953 mas/yr
scaling of the formal errors: **1.09**

in declination

median = +0.012 mas/yr
RSE = 0.902 mas/yr
scaling of the formal errors: **1.11**

Typical size of the systematics: see also the presentation of L. Lindegren

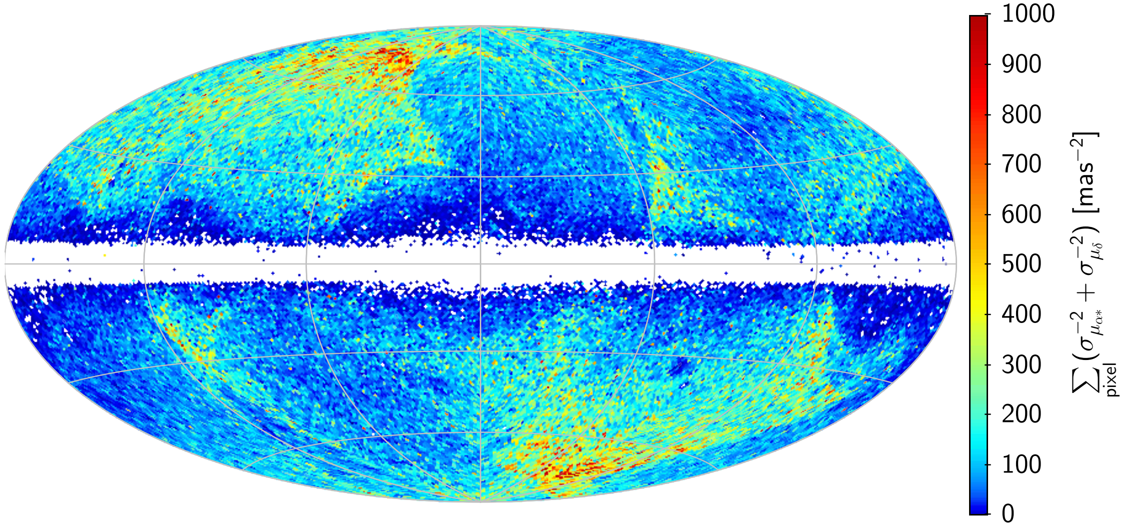




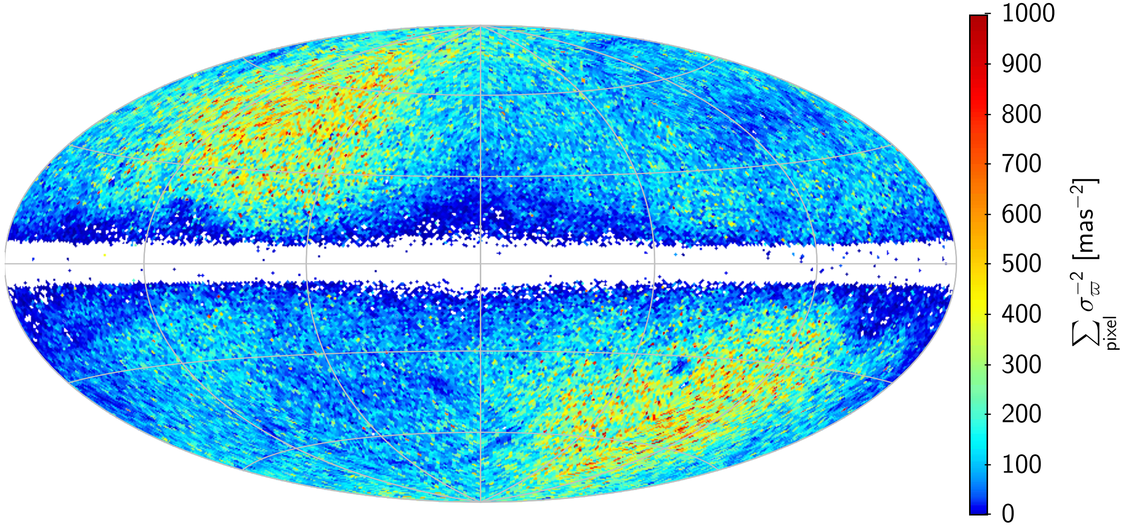
Global (V)SH analysis: the information distribution

- (Vector) Spherical Harmonics - (V)SH - are orthogonal only if statistical information is distributed homogeneously.
- The statistical weight per pixel for the Gaia-CRF2 sources:

proper motion



parallax



Global (V)SH analysis: the alignment to ICRF3

Various versions of the VSH fit to compute the mutual rotation of the catalogues:

Fit	Source selection	W	l_{max}	N	Orientation (μas) x	Orientation (μas) y	Orientation (μas) z	Glide (μas) x	Glide (μas) y	Glide (μas) z
1	all	y	1	2820	−9 ± 29	4 ± 27	3 ± 28	–	–	–
2	all	y	1	2820	−28 ± 31	−8 ± 29	10 ± 28	47 ± 29	−69 ± 28	−72 ± 29
3	$\rho < 10$ mas	y	1	2773	−17 ± 16	22 ± 15	−23 ± 16	–	–	–
4	$\rho < 2$ mas	y	1	2423	−35 ± 9	21 ± 8	−24 ± 9	–	–	–
5	$\rho < 2$ mas	n	1	2423	−13 ± 14	5 ± 14	−5 ± 13	–	–	–
6	$\rho < 2$ mas	y	5	2423	−47 ± 12	30 ± 10	0 ± 11	2 ± 12	−40 ± 10	−25 ± 11
7	$\rho < 1$ mas	y	5	1932	−47 ± 10	12 ± 9	−10 ± 9	−2 ± 10	−42 ± 9	−18 ± 9
8	$\rho < 1$ mas	n	5	1932	−15 ± 12	2 ± 12	−14 ± 11	−6 ± 12	1 ± 12	11 ± 11
9	$\rho < 2$ mas, $G < 19$	y	5	1382	−57 ± 16	33 ± 13	9 ± 14	3 ± 15	−48 ± 13	−24 ± 14
10	$\rho < 2$ mas, $G < 19$	n	5	1382	−65 ± 20	0 ± 18	22 ± 17	5 ± 20	−30 ± 18	24 ± 17
11a	$\rho < 2$ mas, $\lfloor 10^5\alpha \rfloor$ mod $2 = 0$	y	5	1255	−19 ± 18	34 ± 15	−10 ± 16	28 ± 17	−10 ± 15	−22 ± 16
11b	$\rho < 2$ mas, $\lfloor 10^5\alpha \rfloor$ mod $2 = 1$	y	5	1168	−61 ± 17	33 ± 15	17 ± 15	−31 ± 17	−64 ± 15	−18 ± 15

The alignment with the ICRF3 (prototype) at the level of 20-30 μas.
Higher accuracy is only possible if the alignment procedure is fully mathematically fixed.

Global (V)SH analysis: the rotational state

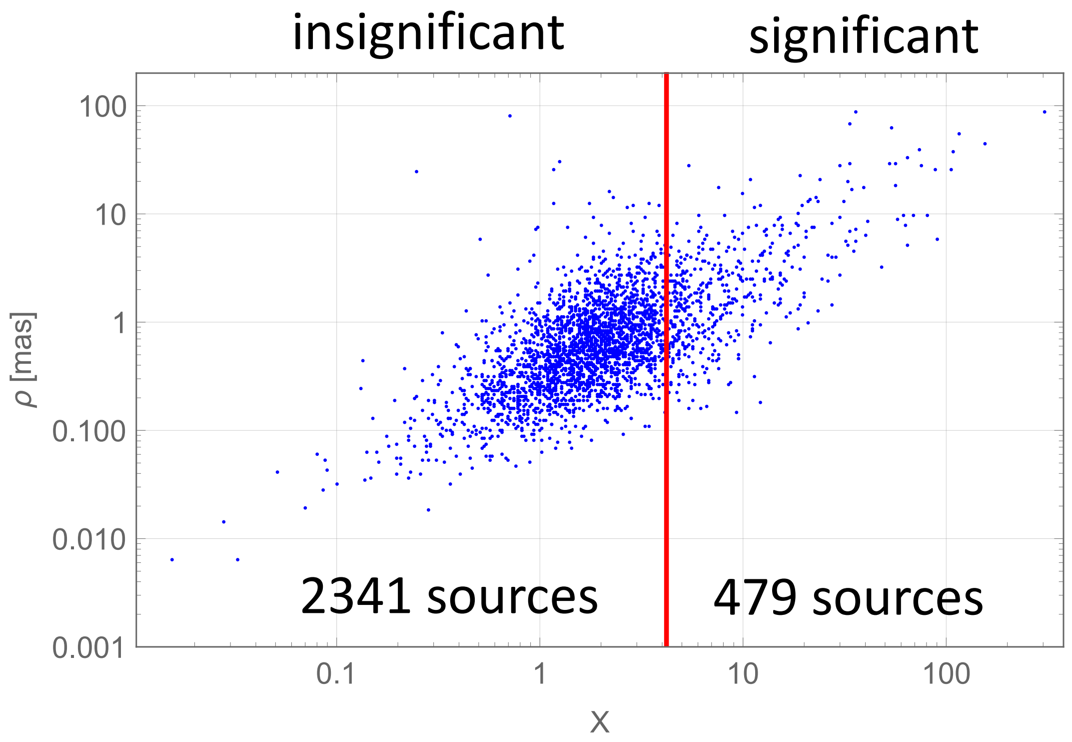
Various versions of the VSH fit to get the "spin" and the glide (galactic acceleration) patterns:

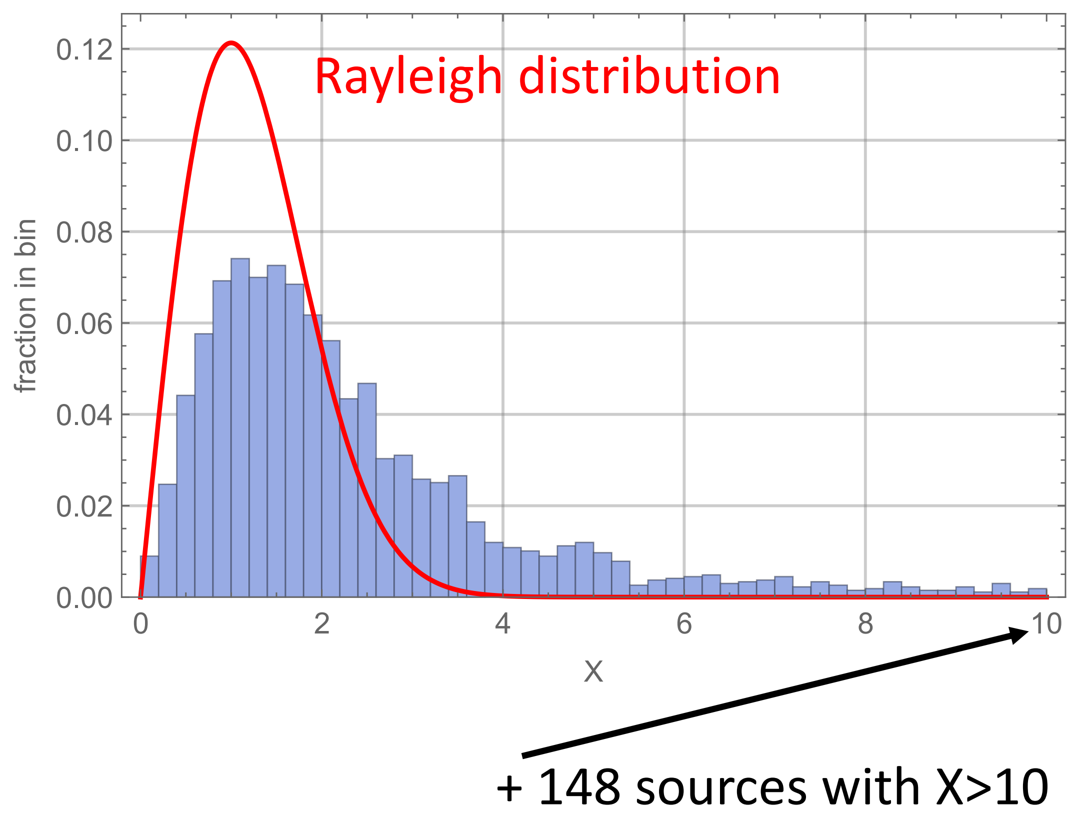
					Rotation [μas yr^{-1}]			Glide [μas yr^{-1}]		
Fit	Source selection	W	l_{max}	N	x	y	z	x	y	z
1	all	y	1	556869	-3.1 ± 0.8	-1.9 ± 0.7	-1.0 ± 0.9	–	–	–
2	all	y	1	556869	-3.6 ± 0.8	-2.2 ± 0.7	-0.9 ± 0.9	-7.0 ± 0.8	4.7 ± 0.7	12.1 ± 0.7
3	all	y	5	556869	-5.5 ± 1.1	-7.4 ± 0.9	5.6 ± 1.2	-9.2 ± 1.2	4.7 ± 1.0	11.6 ± 1.0
4	$\mu < 2$ mas yr^{-1}, $G < 18$	y	5	27189	-13.8 ± 2.0	-13.2 ± 1.7	4.0 ± 2.2	-7.9 ± 2.2	4.7 ± 1.8	10.3 ± 1.7
5	$\mu < 2$ mas yr^{-1}, $G < 18$	n	5	27189	-8.9 ± 2.9	-12.1 ± 2.4	2.8 ± 2.5	-10.4 ± 2.9	5.7 ± 2.4	16.6 ± 2.5
6	$\mu < 2$ mas yr^{-1}, $G < 19$	y	5	149146	-11.2 ± 1.3	-12.0 ± 1.1	4.4 ± 1.4	-9.8 ± 1.5	4.6 ± 1.2	10.4 ± 1.1
7	$\mu < 3$ mas yr^{-1}, $G < 20$	y	5	400472	-5.9 ± 1.1	-8.6 ± 0.9	5.1 ± 1.2	-9.0 ± 1.2	4.1 ± 1.0	11.9 ± 1.0
8	$\mu < 3$ mas yr^{-1}	y	5	513270	-5.7 ± 1.1	-7.9 ± 0.9	5.2 ± 1.2	-8.8 ± 1.2	4.1 ± 1.0	11.6 ± 0.9
9a	$\lfloor 10^5\alpha \rfloor \bmod 2 = 0$	y	5	278170	-5.8 ± 1.6	-8.9 ± 1.3	6.4 ± 1.7	-8.5 ± 1.7	3.0 ± 1.4	12.5 ± 1.4
9b	$\lfloor 10^5\alpha \rfloor \bmod 2 = 1$	y	5	278699	-5.1 ± 1.6	-5.8 ± 1.3	4.8 ± 1.7	-9.8 ± 1.7	6.6 ± 1.4	10.7 ± 1.4
10	$G > 19$	y	5	406356	9.8 ± 2.1	6.2 ± 1.8	7.0 ± 2.4	-8.3 ± 2.3	3.3 ± 1.9	15.6 ± 1.9

1. Gaia-CRF2 has no rotation with respect to QSOs at the level of ±20 μas/yr.
   Higher accuracy needs exact definition of what "no rotation" means.
2. Magnitude dependence of the "spin" at the level of ± 10-20 μas/yr.
3. Systematic errors are too high to allow a measurement of the galactic acceleration.

ICRF3 vs. Gaia-CRF2: astrophysics of the QSOs

- The observed distances ρ between ICRF3 and Gaia-CRF2 cannot be explained by the given statistical uncertainties: confusing sources(?), astrophysics of the QSOs(?), …
- X is the distance ρ normalized using combined covariances from both catalogues.

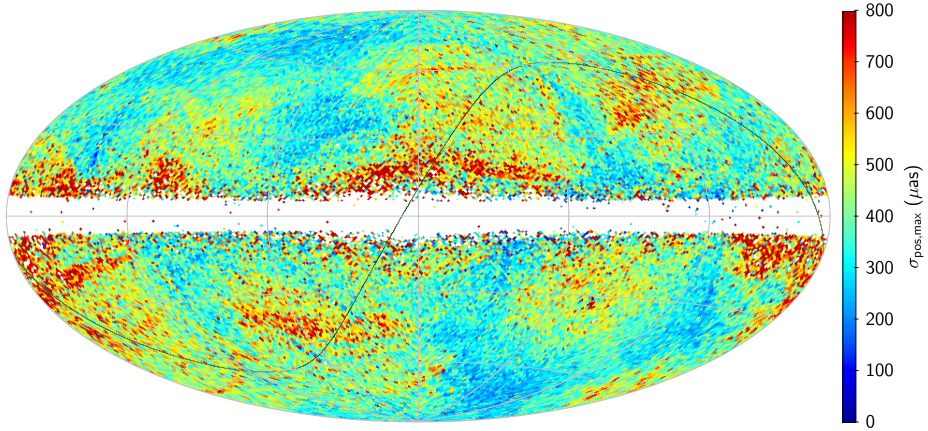


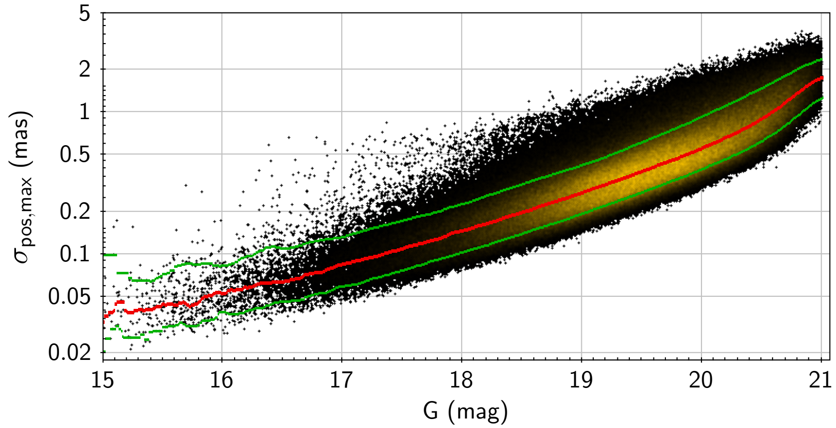


the probability to get X > 4.1 in a sample of size 2820 is < 0.5.

Summary of Gaia-CRF2

- Gaia-CRF2 contains 557000 extragalactic sources with full astrometric solution.
- About 13.5 extragalactic sources per deg^2 at a sub-milliarcsec accuracy:
  0.4 mas in position and parallax, 0.9 mas/yr in proper motion
- About 27000 bright sources (G<18) have positional errors of 0.12 mas (median)
- Accuracy of the ICRF alignment: about 0.02 mas
- Rotation with respect to QSOs: 0 ± 0.02 mas/yr
- Be aware of systematic errors causing e.g. magnitude-dependent spin.
- Gaia-CRF2 is the best optical reference frame to replace the Hipparcos-CRF.





Other extragalactic objects in Gaia DR2

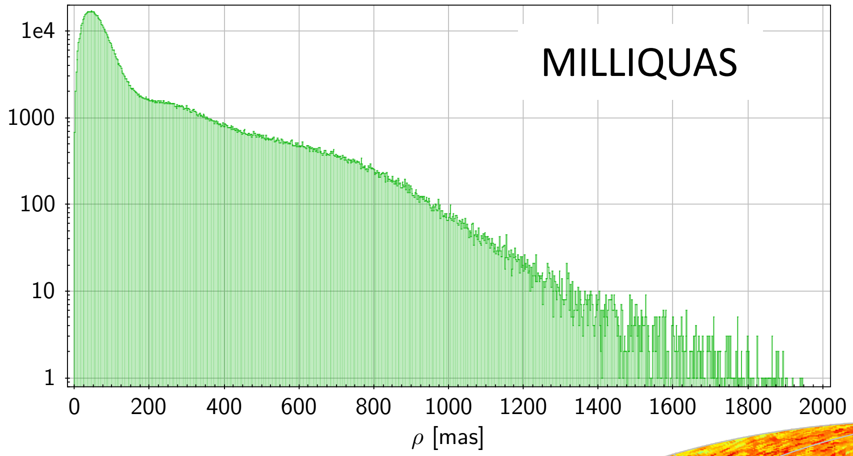
- Only the allWISE AGN catalogue (Secrest et al. 2015) and the ICRF3 prototype were used to find extragalactic sources in Gaia DR2.
- Other catalogues could be used as well, but, as of 2017, seemed to be less consistent, reliable and homogeneous.
- One example of such an additional crossmatch is given in the Gaia-CRF2 paper:

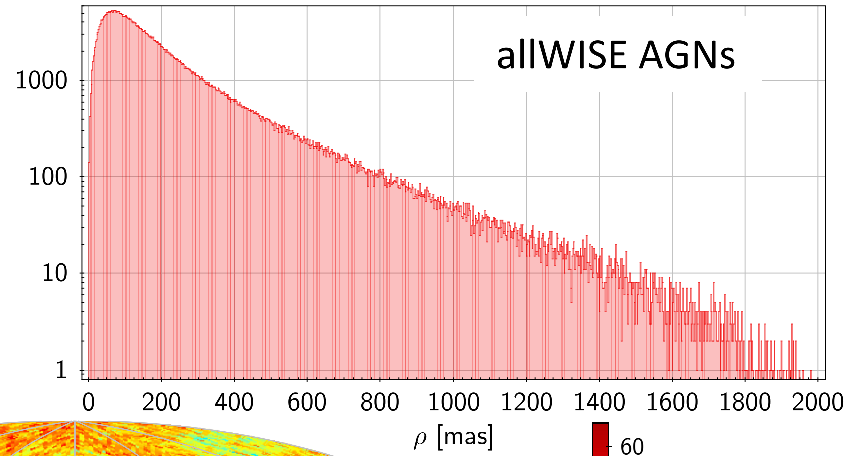
  a crossmatch with MILLIQUAS 5.2 (Flesh 2017) gives ~500 000 additional AGN matches

Other extragalactic objects in Gaia DR2

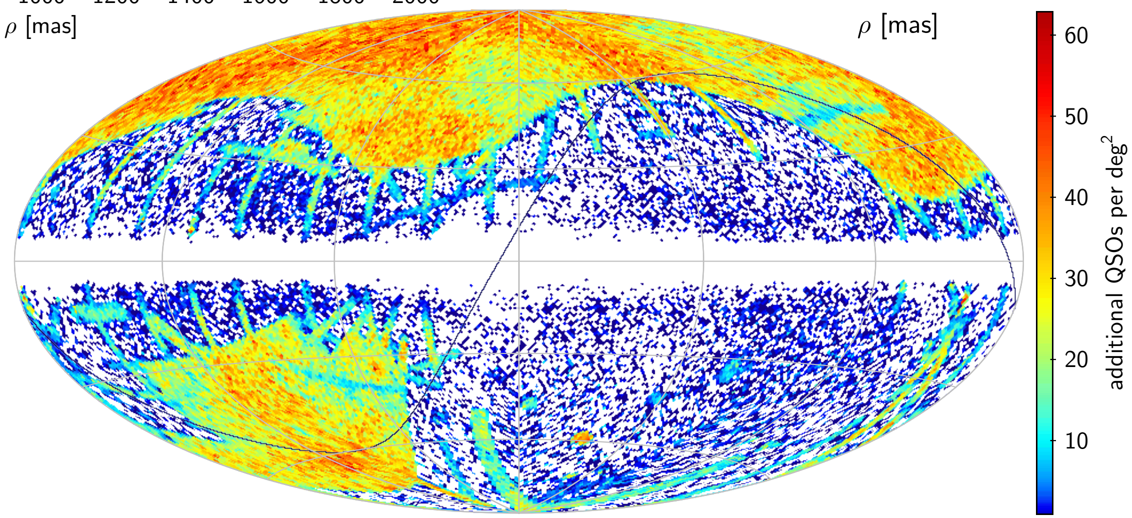
A crossmatch with MILLIQUAS 5.2 (Flesh 2017) gives ~500 000 additional AGN matches.

MILLIQUAS is astrometrically less homogeneous. Distances to the matched Gaia DR2 sources:





The sky distribution of the ~500 000 additional AGNs from MILLIQUAS 5.2



Other extragalactic objects in Gaia DR2

- One example of such an additional crossmatch is given in the Gaia-CRF2 paper:

  a crossmatch with MILLIQUAS 5.2 (Flesh 2017) gives ~500 000 additional AGN matches.

- Another example: Liao et al. 2018 claiming to get ~220 000 additional AGNs.

- A promising option is given by the WISE AGN catalogues of Assef et al. 2018:

  R90: a catalogue of > 4 500 000 AGNs with 90% reliability
  C75: a catalogue of ~21 000 000 AGNs with 75% completeness

  Problem: non-uniform distribution (large areas of the sky were explicitly excluded)

Next versions of the Gaia-CRF

- More sources:

  crossmatches with newest external catalogues
  - MILLIQUAS (Flesh 2017), the WISE AGN catalogue (Assef et al 2018), … -
  fosters the hope that the future versions of Gaia-CRF
  will have more than 1 million sources

- Better accuracies:

  position and parallax $\propto T^{-1/2}$, T is the time span of observations

  proper motions $\propto T^{-3/2}$

  systematic errors can be expected to become considerably smaller

- Gaia-based classification of extragalactic sources!

- Future versions of the Gaia-CRF will probably contain more classification indicators:
  user can decide which reliability, completeness, etc. to choose

On the future of multi-waveband ICRF

- Radio ICRF3 comes in three wavebands: S/X, K and X/Ka: 8.4, 24 and 32 GHz
- Optical Gaia-CRF (@ about 500 000 GHz :-) has comparable accuracies already now
- Both realizations of the ICRS concept are needed

  * only radio ICRF can be readily used to monitor Earth orientation parameters and provide high-accuracy position of spacecrafts in the plane of view

  * only optical (Gaia) CRF can have million(s) of sources and can be readily used e.g. for the coming huge astronomical telescopes in the optics and IR

- Multi-waveband CRF allows for new science:

  e.g. astrometry-driven astrophysics of extragalactic source

On the future of multi-waveband ICRF

- The arrival of a dense and accurate optical ICRF raises the issue of the terminology:

  Is the name "ICRF" reserved for the radio CRFs?

  Should the proposed "ICRF3" be renamed into "Radio-CRF3" or "VLBI-CRF3"?

  Should both "VLBI-CRF3" and "Gaia-CRF2" be considered as realizations of ICRF/ICRS?

- Since ICRF3 already has 3 wavebands, the optical can be added to a future ICRF…
  at the XXXI GA in 2021?