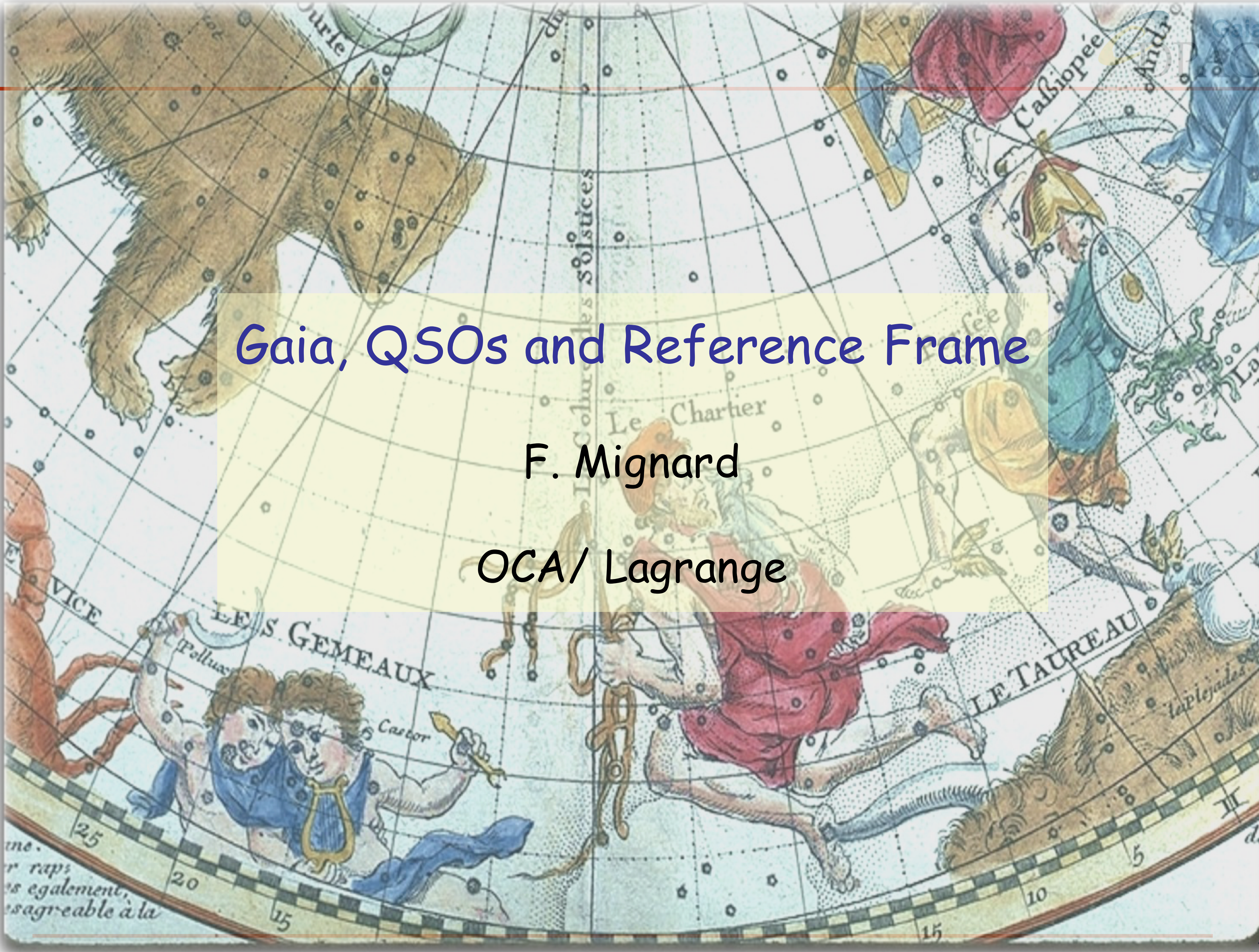


Gaia, QSOs and Reference Frame

F. Mignard

OCA/ Lagrange

Summary

- The general framework for the reference frame
- The DR1 Gaia frame
- The QSOs properties in the DR1
- Ultimate quality of the Gaia frame

The general framework

Why a reference frame ?

- To refer positions of fixed or moving sources
- To detect tiny motions
- To quantify without bias the motion of sources
  - modelling the galactic kinematics
  - investigate rotational and translational motion of external galaxies
- To monitor the rotation of the earth
  - fix the timescale
  - study the plate motions
- Angular positions (and distances) of quasars, galaxies, stars, planets, spacecraft

Need for Gaia and post-Gaia

- Materialising the RF is a science objective by its own
  - it lies at the heart of fundamental astrometry
  - survey missions are particularly well adapted to meet this goal
  - it is a major science goal of Gaia
- But this is also a technical requirements by itself
  - Any global astrometry mission needs a grid to refer secondary measurements
  - if small field astrometry is targeted the grid must be available, or built in parallel
  - the grid targets must very well selected as being 'clean' point sources
    - a minimum sample of distant QSOs should be in the grid for metrological continuity

Celestial Reference Frame

- One must distinguish between
  - The System:
    - Set of specifications defining the coordinate system, including origin, fundamental planes/axes, along with constants, models, and algorithms for transforming observables.
  - The Realisation(s):
    - Set of sources/points on the sky along with coordinates that serves as the practical materialisation of The System.

Gaia and future missions belong to this section

Key IAU Resolutions for ICRF

- 1988 Recommend the use of extragalactic sources for the Celestial Reference Frame
- 1991 IAU adopt General Relativity for the modelling
- 1997
  - As of Jan 1st 1998 the Reference System will be the ICRS described in the 1991 resolution
  - The Reference Frame will be the ICRF based on radio position of a set of extragalactic sources
  - HCRF (Hipparcos) will be a realisation of the ICRC in the optical domain
- 2009 Adoption of the ICRF2

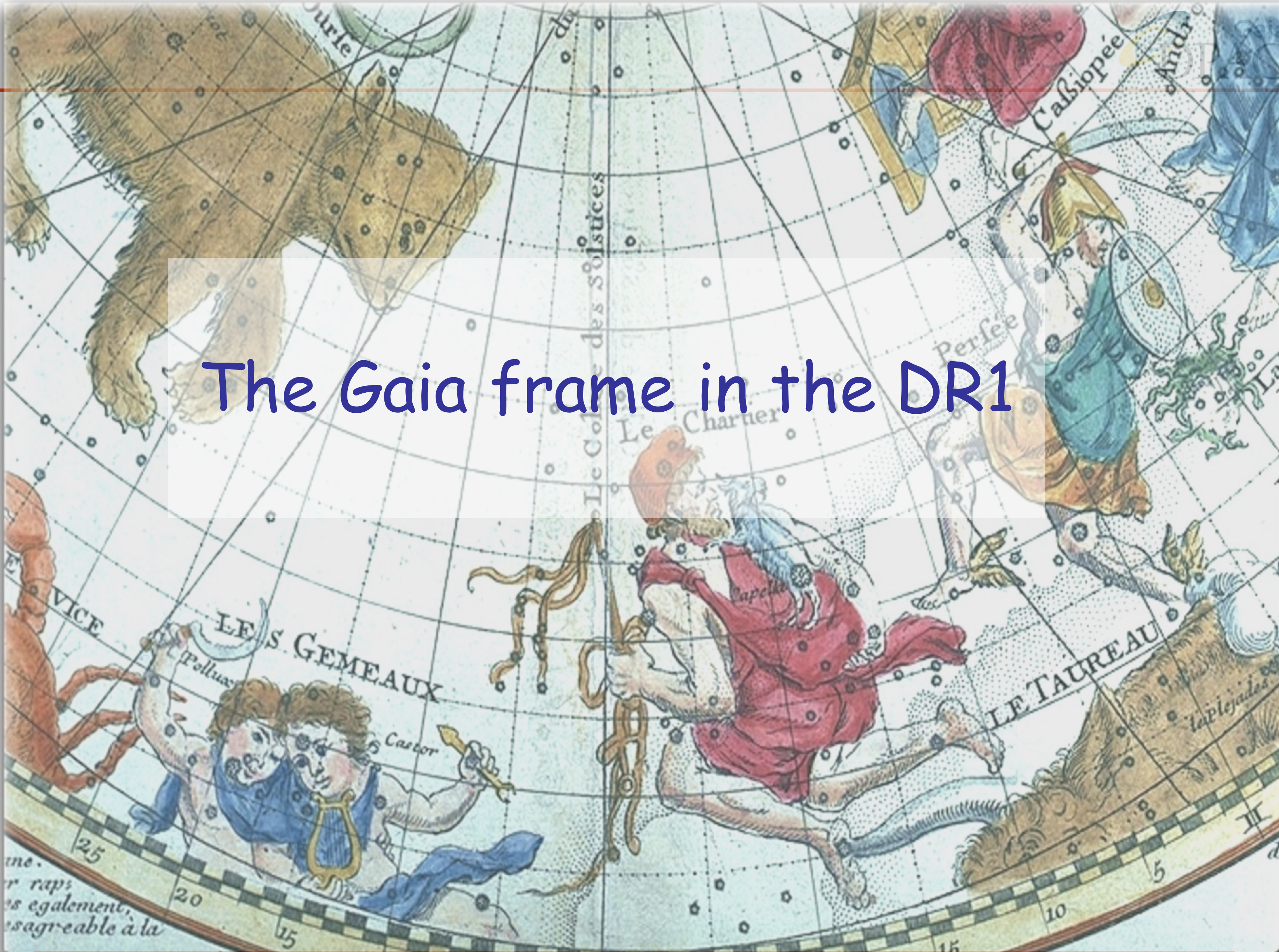
ICRF2 (2008)

- 20 years of VLBI observations
- 3414 sources, 295 defining (90 common with ICRF1 defining set)

Parameter	ICRF1	ICRF2
Observation dates	08/1979 – 07/1995	08/1979 – 03/2009
Observations	1.6M Group Delays	6.5M Group Delays
Defining Sources	212	295
Total Sources	608[1]	3414[2]
Noise Floor	~200 µas	~40 µas
Axis stability	20 µas	10 µas

Credit: R. Gaume

The Gaia frame in the DR1



Gaia Celestial Reference Frame - I

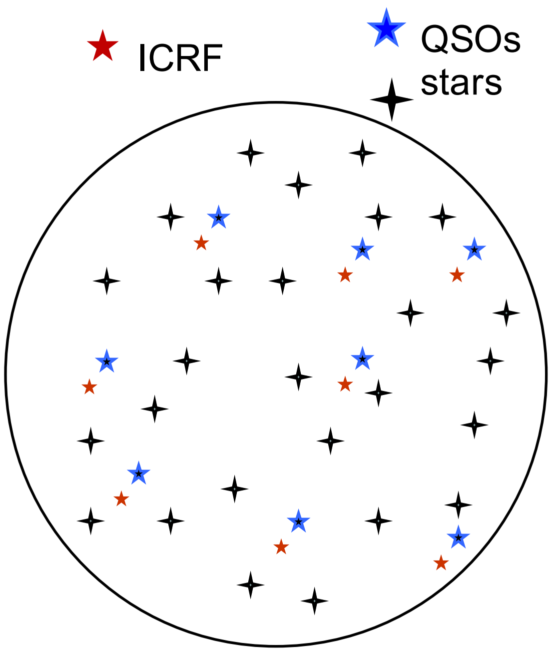
- Gaia astrometric solution provides simultaneously
  - a realisation of the primary frame with the QSOs
    - it meets the ICRS principles by construction
  - a very dense optical access with the ~1 billion stars
    - this is degrading with time due to the proper motion errors
- Metrological continuity with ICRF2 is ensured by the alignment
  - fundamental plane and origin are compatible within the combined uncertainties of each realisation
  - common sources are used for this purpose

Gaia Celestial Reference Frame - II

- AGIS natural frame has no strongly constrained orientation
- AGIS natural solution is not constrained to be inertial
  - proper motion are given in a rotating frame
- Two very different requirements for Gaia
  - Fix the orientation as close as possible to existing reference
    - small set of QSOs common to ICRF2 and Gaia to **align** the frames
  - Stop the residual rotation in agreement with the ICRS principles
    - large set of QSOs assumed to have **no global rotation**

Gaia alignment to ICRF

- Orientation is performed by minimizing the distances between Gaia positions and ICRF positions of common sources
  - Gaia-CRF needs to be aligned to ICRF
  - we have one infinitesimal rotations to fit(ε_x, ε_y, ε_z)
- ICRF sources are observed by Gaia
  - ~ 2500 G < 20 , 200 G < 18 - σ_{Gaia} < 100 μas
  - Gaia-CRF can be aligned to QSOs by a rotation
  - accuracy depend on radio-optical offset
  - at the best: $\sigma_{\text{align}} \approx \frac{\sqrt{\sigma_{\text{Gaia}}^2 + \sigma_{\text{ICRF}}^2}}{\sqrt{N_{\text{QSO}}}} < 10 \mu as$



Gaia alignment to ICRF in the DR1

Gaia DPAC

- Only the subset of defining sources has been used
  - 262 sources in common (out of 295 in ICRF2)
  - Done within the Quasar Auxiliary solution
  - Uncertainties estimated with bootstrap

$$\sigma_\epsilon \sim 40 \text{ muas}$$

Lindegren et al., A&A, 2016

  - Further alignments with different sets gave

$$|\epsilon| < 50 \text{ muas}$$

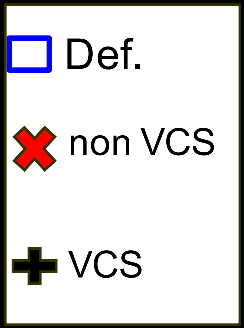
Mignard et al., A&A, 2016

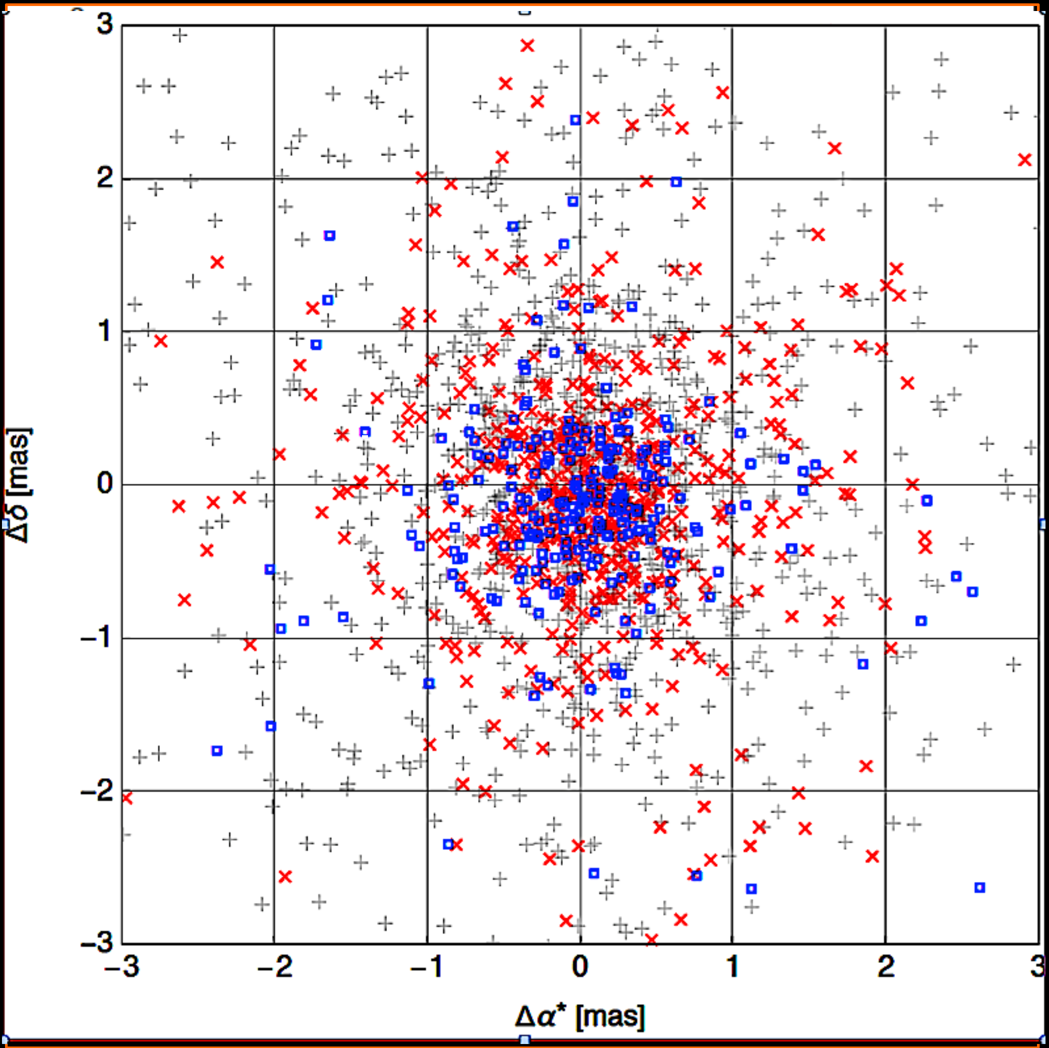
Gaia accuracy from ICRF2 sources

- The ICRF2 set provides outside Gaia the best astrometric reference
  - nominally better than Gaia for the defining sources
  - comparable for the others
- It was important to compare to Gaia DR1 solution to:
  - validate Gaia quoted precision
    - it applies to all other QSOs
  - detect possible systematic offset between radio and optical position
- Done on a set of 2191 sources from ICRF2 found in Quasar Aux Sol
  - 262 defining sources, 640 non-VCSs, 1289 VCS-only

Reference Frame

- Comparison to radio (VLBI) positions of ICRF2

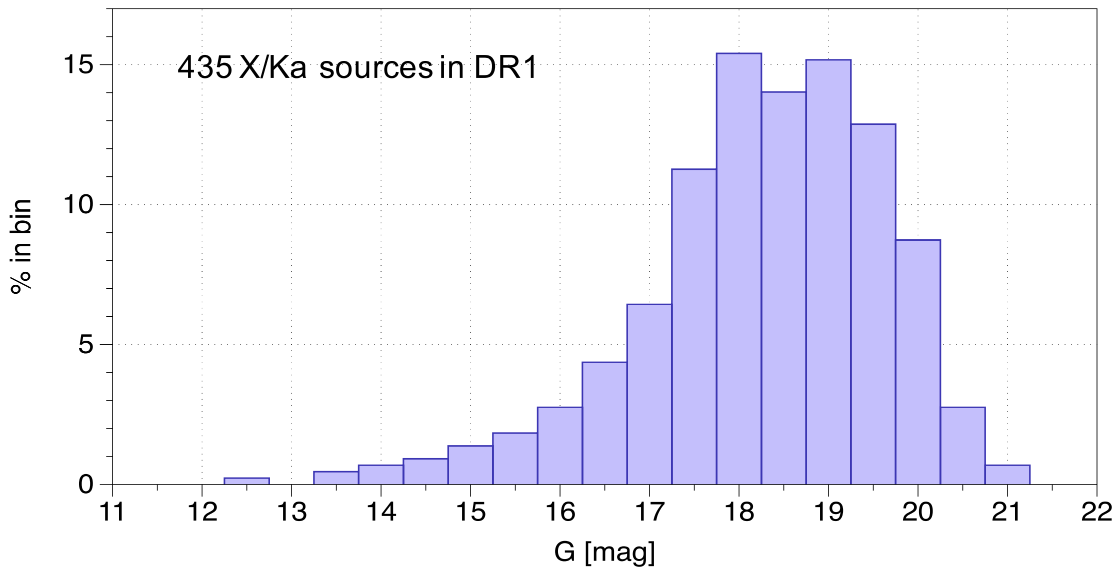




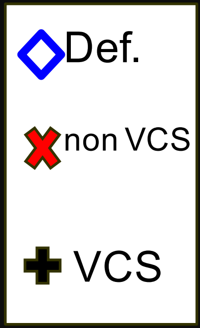
Mignard, Klioner, Lindegren et al., 2016

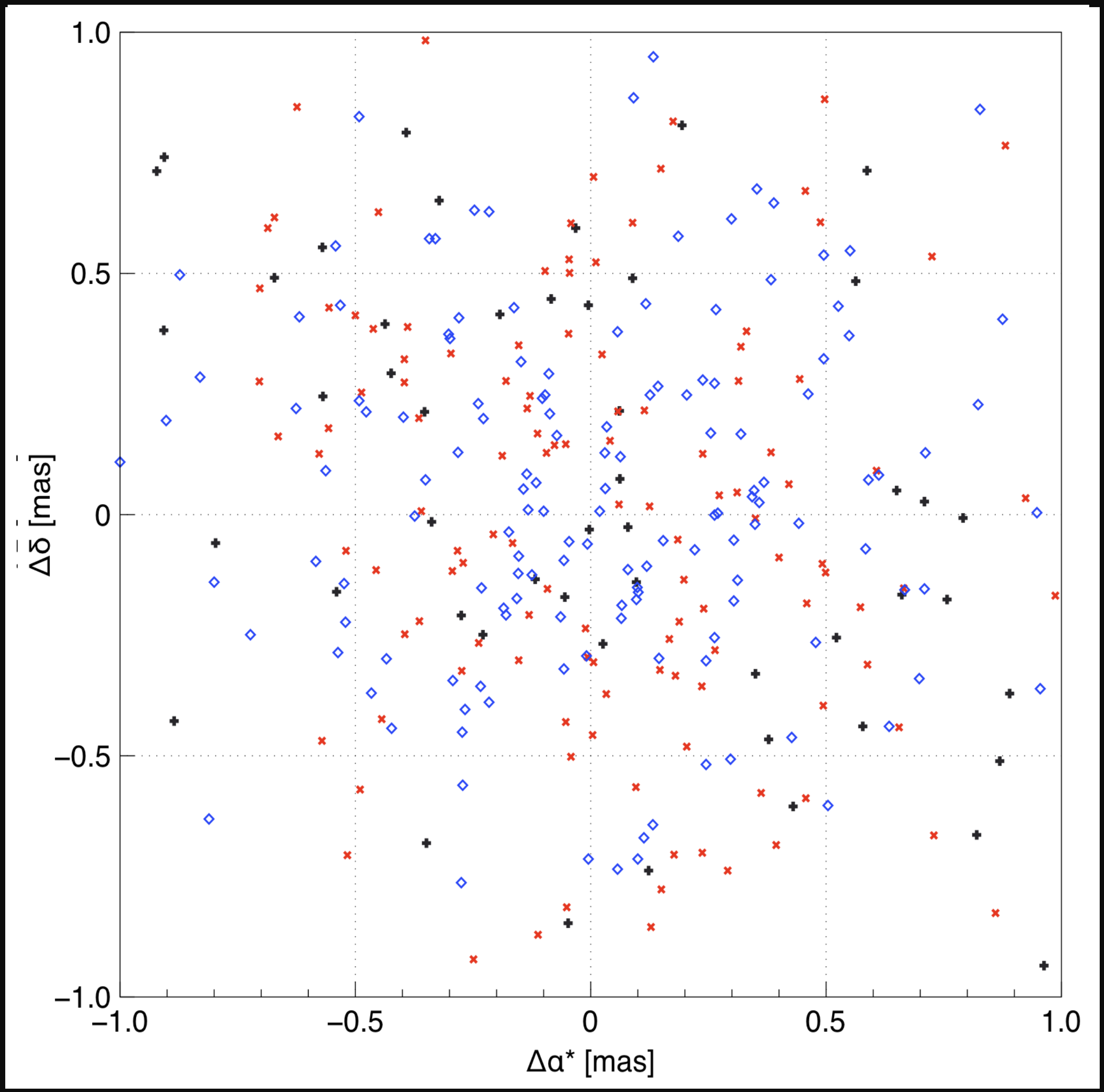
Comparison to X/Ka catalogue

- VLBI Observations on X/Ka band (higher frequencies than S/X)
- Data set independent of ICRF2 or GSF
- First solution by C. Garcia-Miro, C. Jacobs et al. 2015
  - 673 sources in the catalogue with $\sigma \sim 0.1 - 0.2$ mas
  - 435 found in the Gaia QSO good solutions
- Nominally better than Gaia DR1



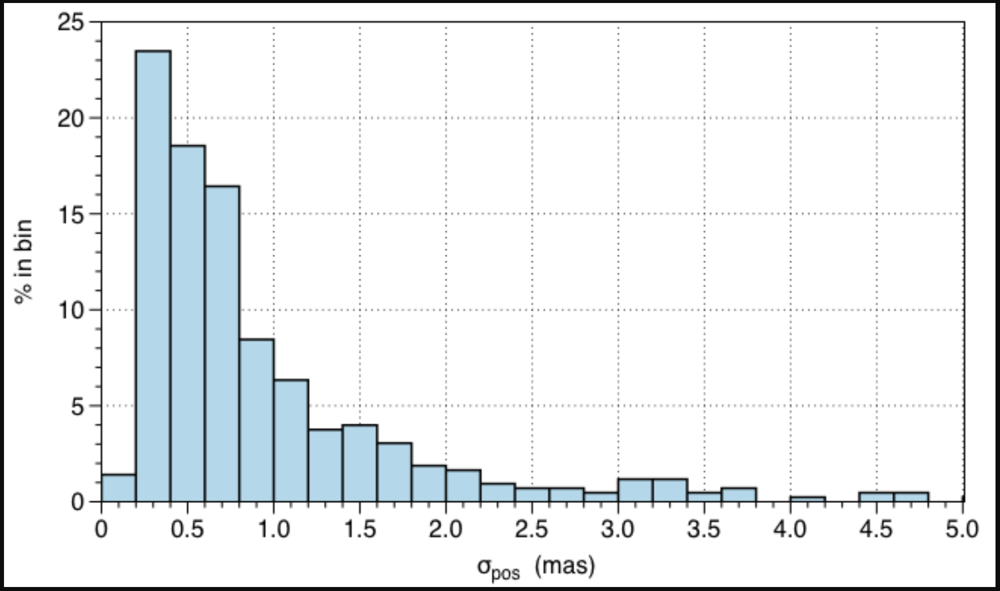
Comparison Gaia – X/Ka





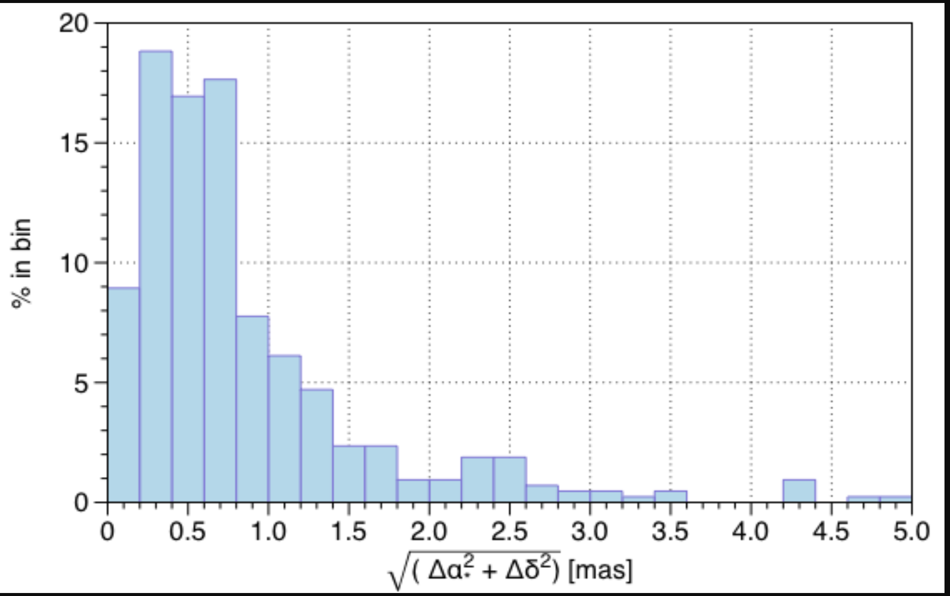
- no distinctive feature with ICRF categories
- remaining scatter shared between Gaia and X/Ka
- no bias in declination or RA
- Gaia formal uncertainties realistic

Gaia: realistic uncertainties



- Quoted uncertainties (max axis of error ellipse)

- Distances Gaia- X/Ka



The other QSOs

Number of QSOs available

- QSOs are observed like stars by Gaia
- The will be ultimately flagged by the CU8 General Classifier
  - not yet available for DR1 (and DR2)
- A list of known QSOs was available in the GIQC (Andrei et al, 2012)
  - 187,000 sources (136,000 well documented QSOs)
- Large compilation of existing material in the LQAC-3 (Souchay et aL; 2015) with 320,000 sources
  - SDSS is now the main contributor
- Very recently results of the ALLWISEAGN with 1.35 M sources
  - it provides the largest set and best nearly all-sky coverage
  - to be used in the DR2 for the reference frame

what we have learnt with the DR1

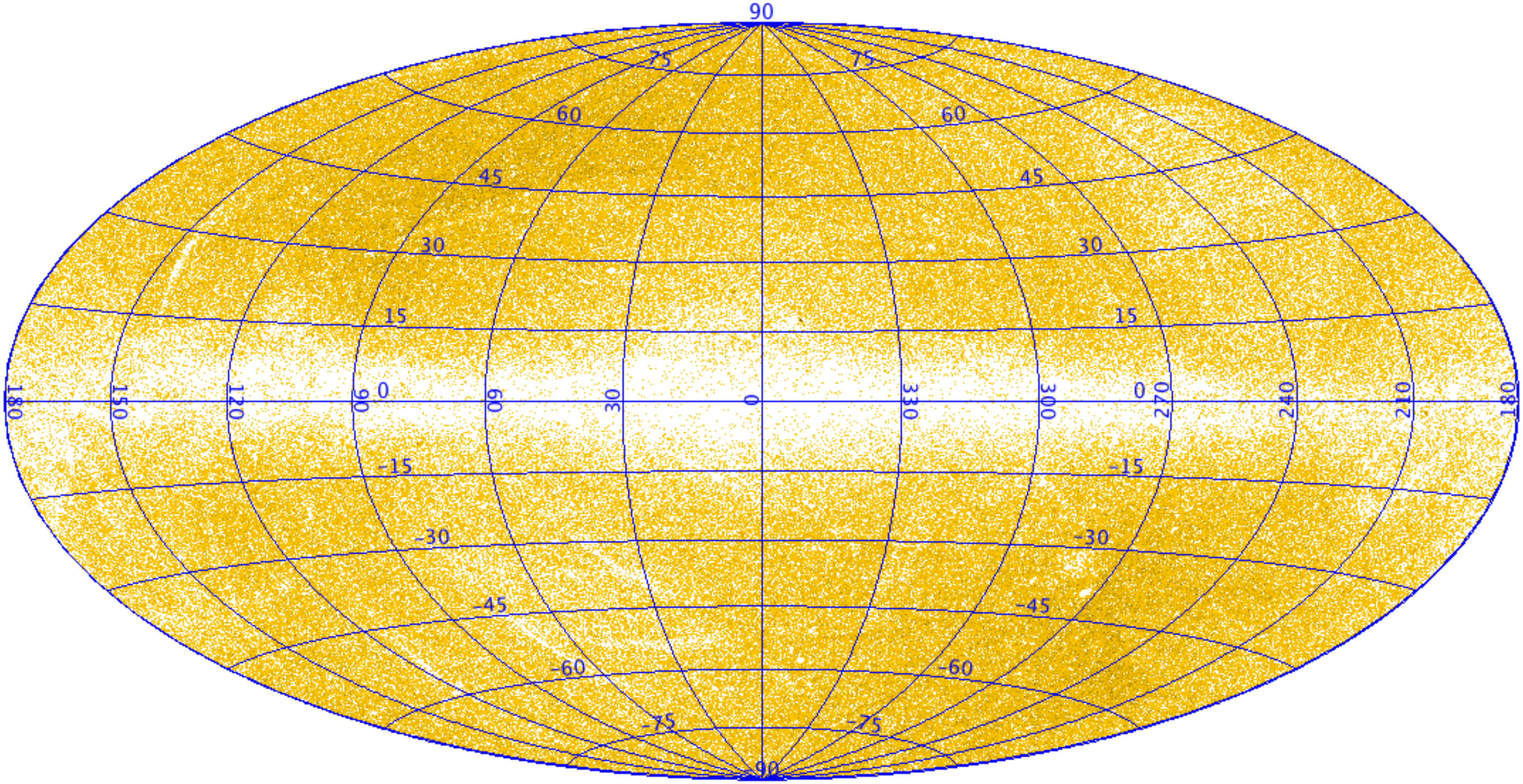
Number of QSOs available

- ALLWISEAGN (Secrest N.J. et al. ApJS , 2015)
  - WISE survey is an all-sky mid-IR survey at 3.4, 4.6, 12, and 22 microns
  - X-matched with SDSS-DR12 $\rho < 1''$, ➔ 424,366 matches
  - X-matched with LQAC-2 ➔ 187,504 matches
  - Typical positional accuracy 150 mas

– Total entries	1,355,000	
– Detected in IDT (Jul14-Sep15)	725,000	
• >= 5 transits	670,000	
• >= 10 transits	480,000	
– in Gaia-DR1 solution	570,000	(568,718)

Number of QSOs available

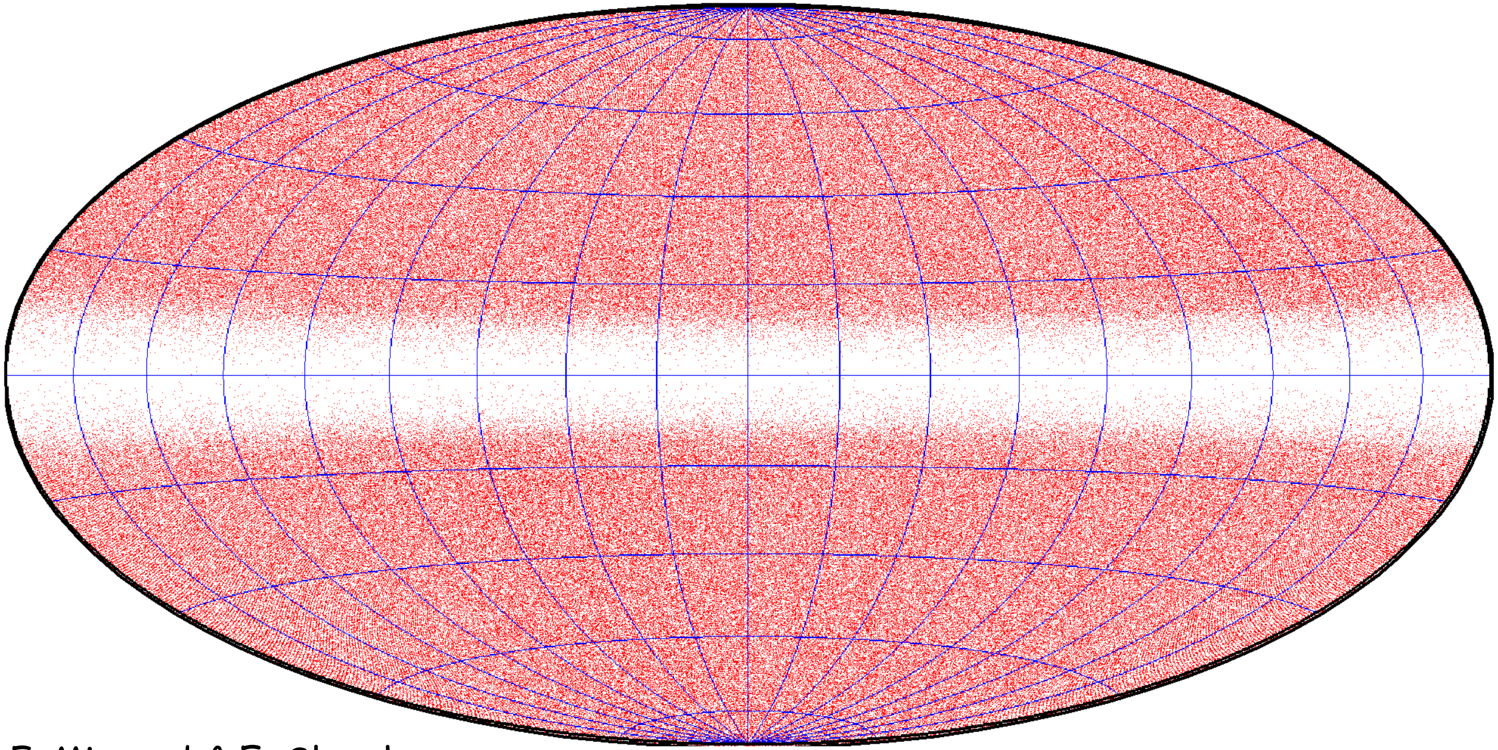
- ALLWISEAGN (Secrest N.J. et al. ApJS , 2015)
  - the 570,000 sources in the Gaia DR1 (galactic coordinates)



Sky distribution in GUM

- about 650,000 QSOs with G <20
  - based on Slezak & Mignard simulated catalogue (2007)
  - Simple probabilistic extinction model
  - magnitude cut to account for the detection inefficiency

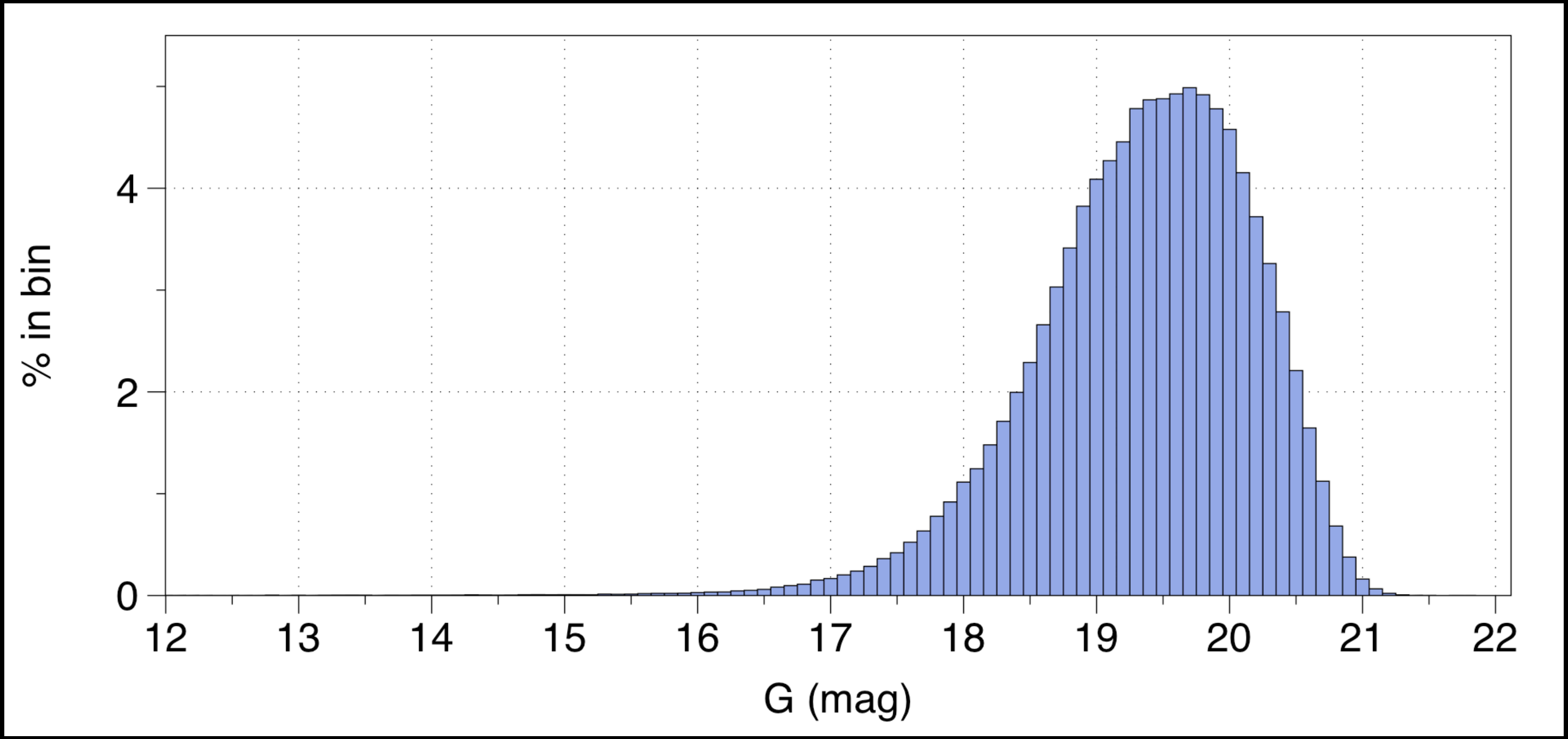
G < 20 – 630,000 QSOs



credit : F. Mignard & E. Slezak

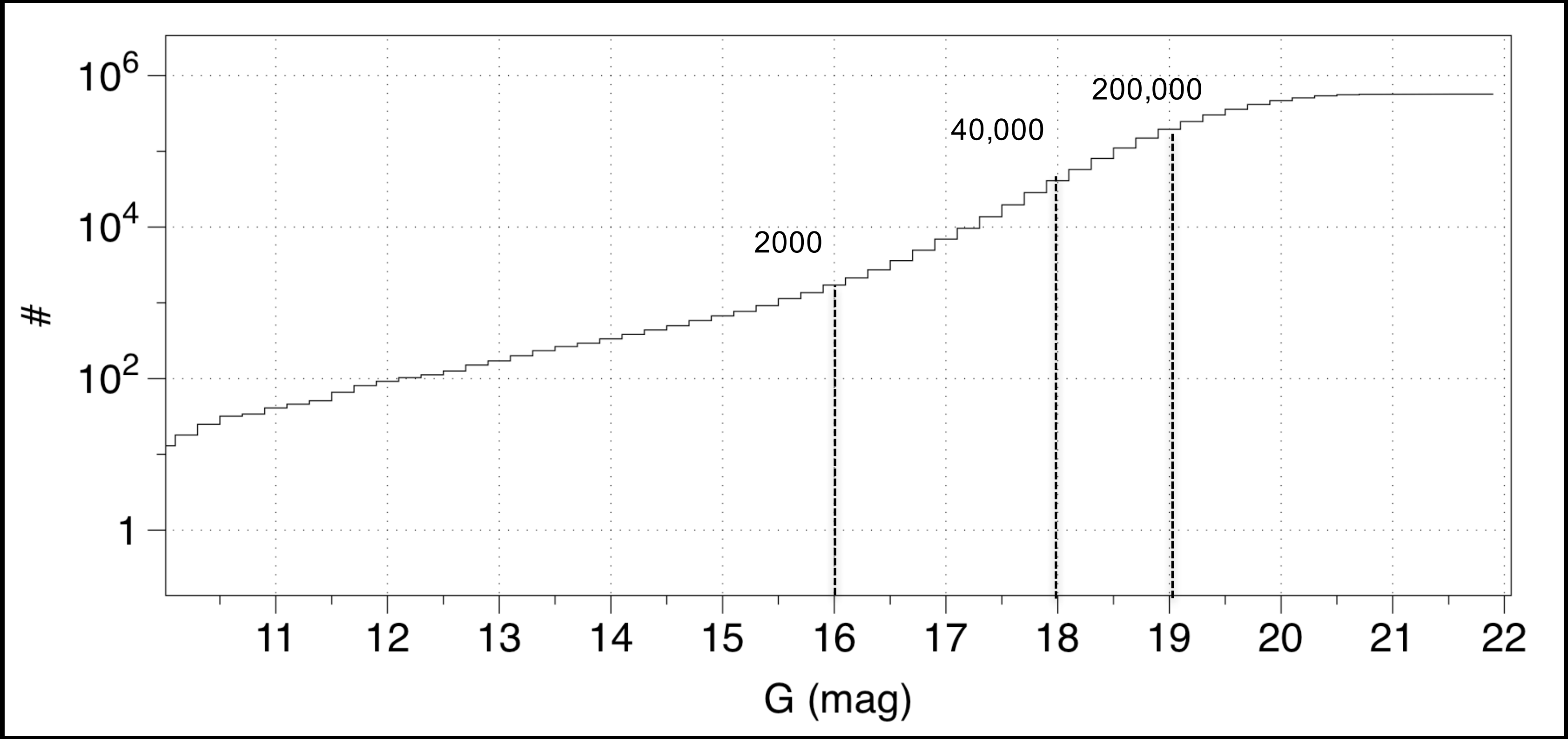
Magnitude distribution

- Measured for the first time with Gaia in the DR1

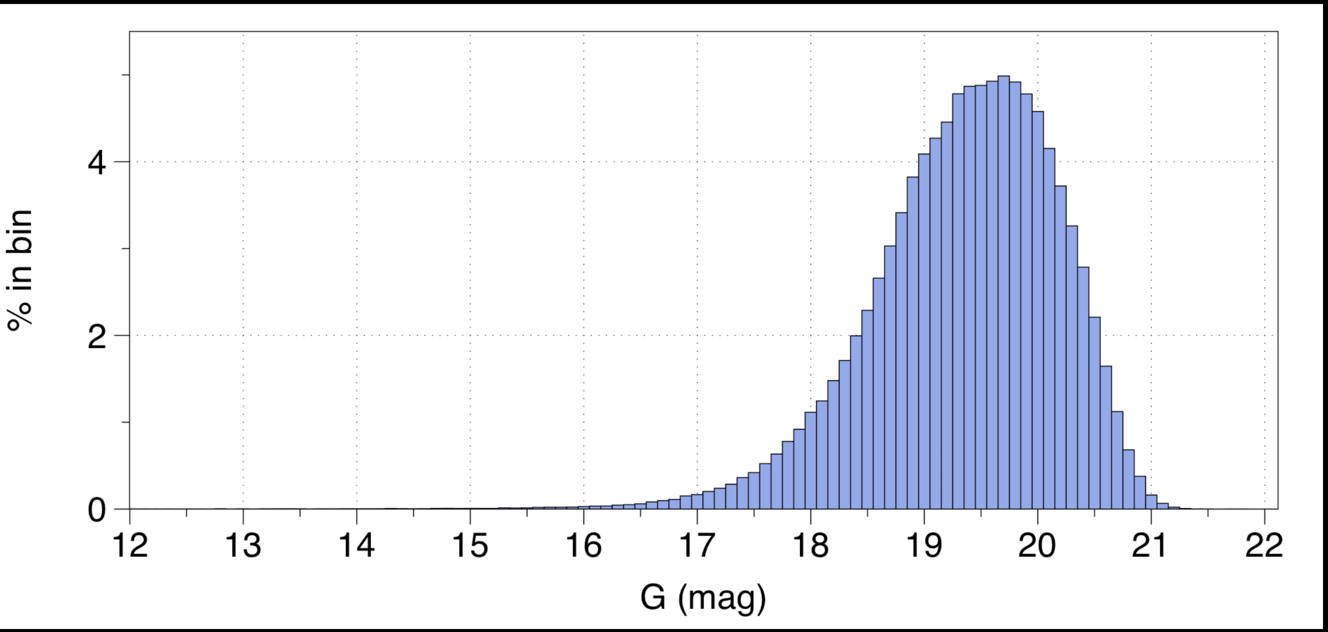


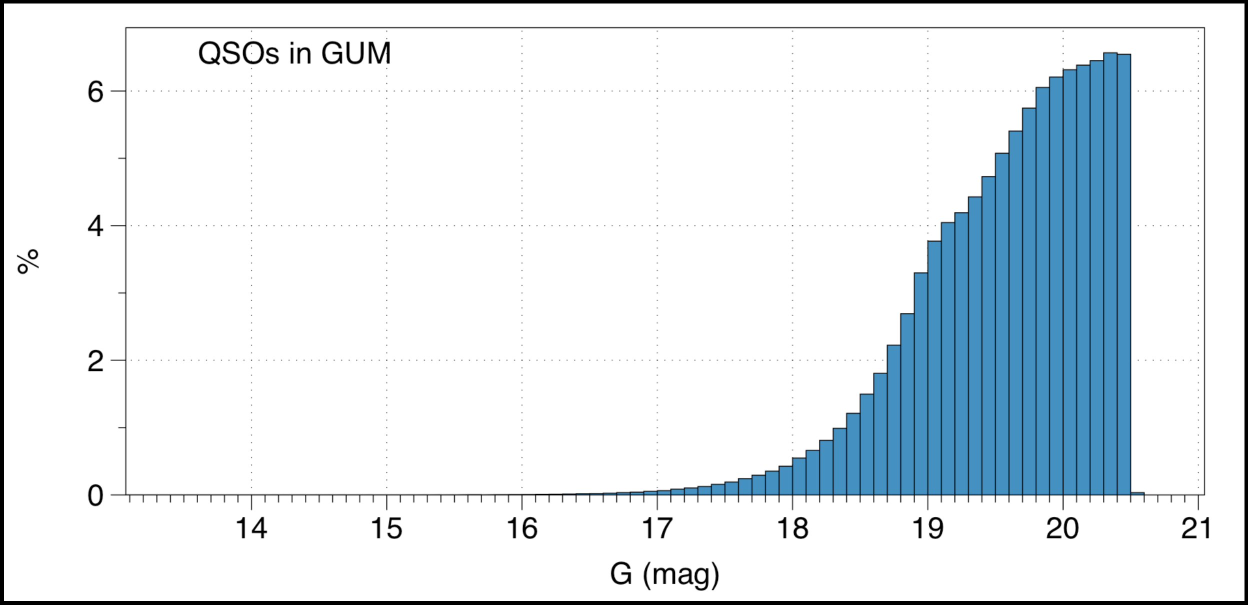
Magnitude distribution

- Good proportion of bright QSOs



Comparison to GUM

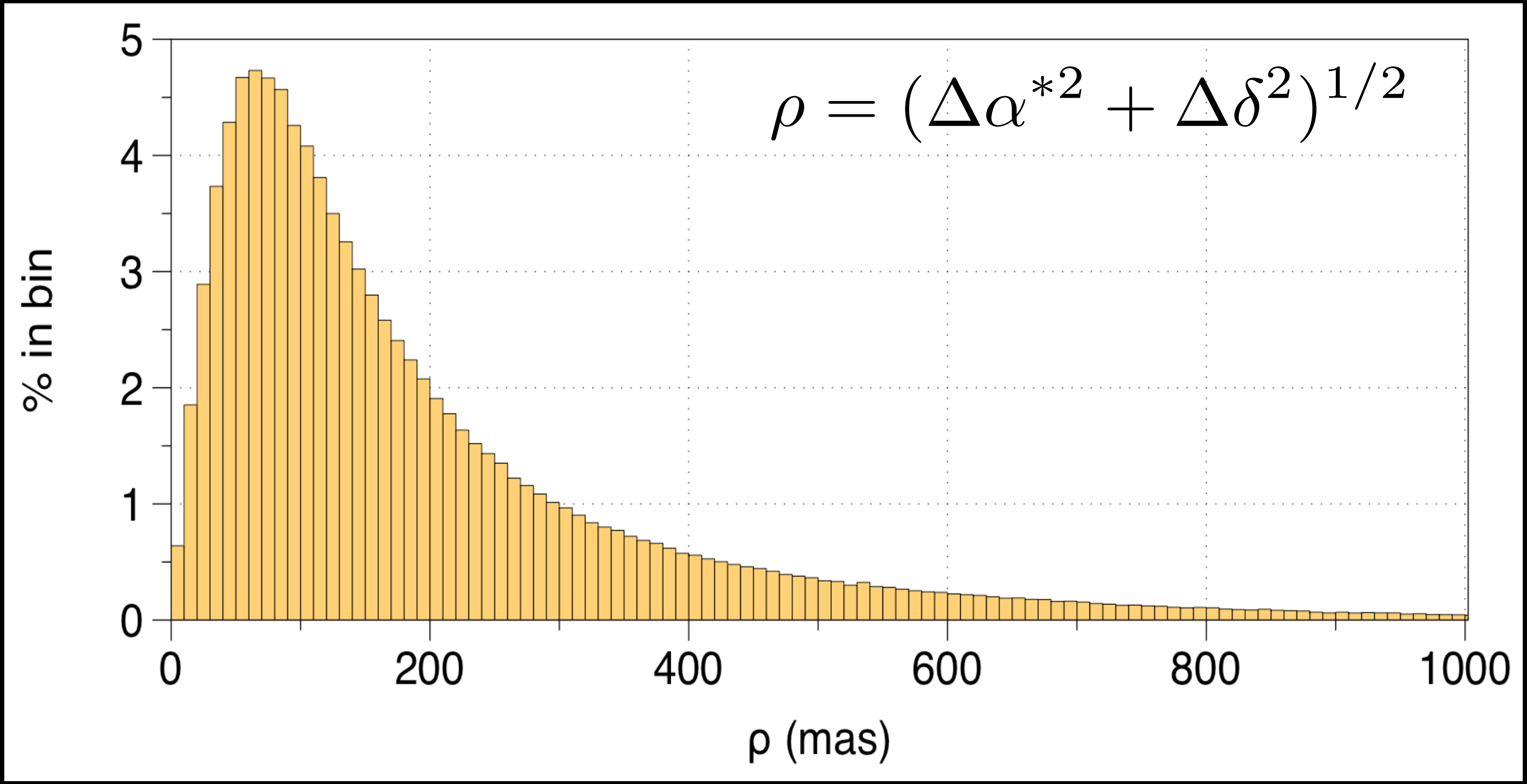




Slezak & Mignard , 2007

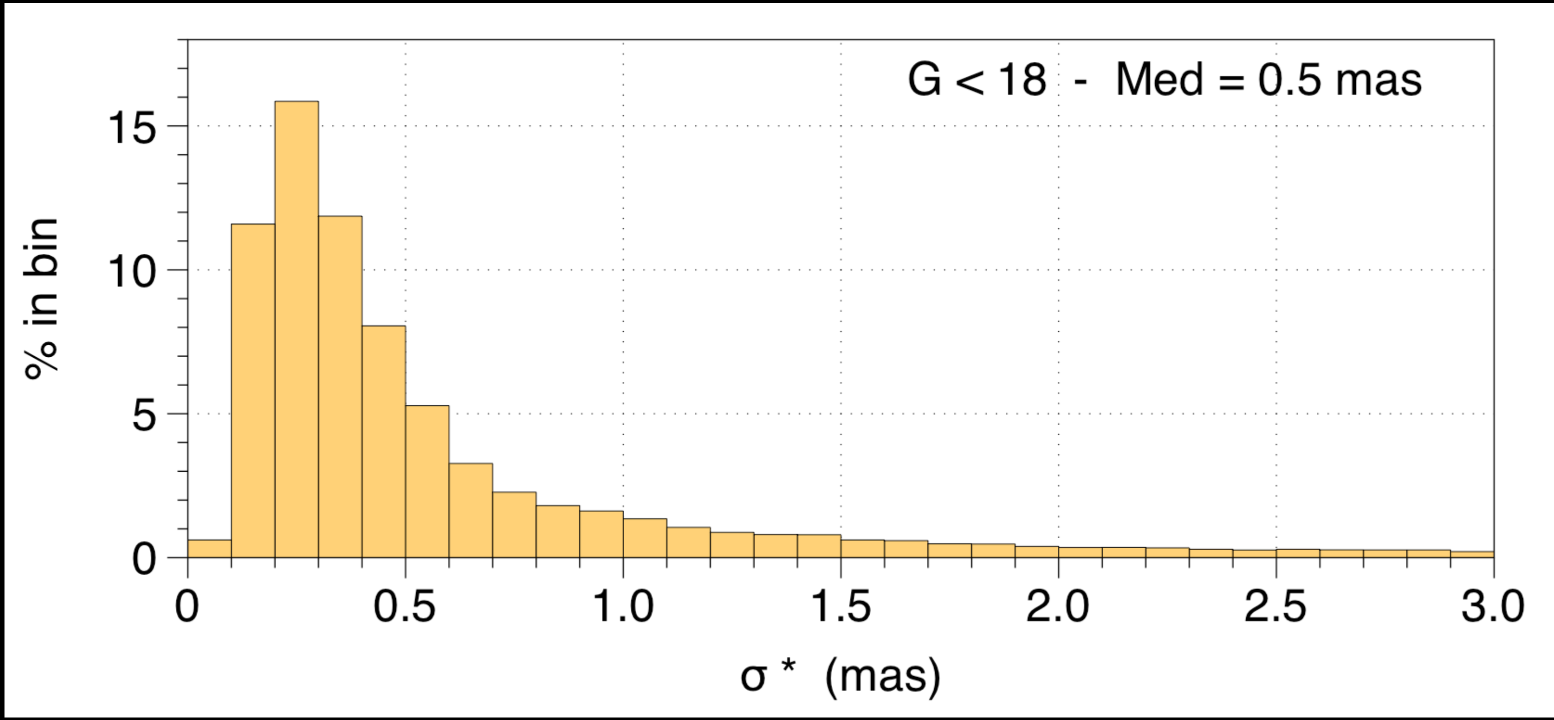
The Gaia sky achievement

- DR1 solution for AllWISE AGNs
  - 570,000 AGNS,
  - Pre- Gaia deep sky to ~150 mas



The Gaia sky achievement

- DR1 solution for AllWise AGNs
  - G < 20 & G < 18
  - Gaia formal uncertainty
  - access to the optical frame with > 1 source/deg^2 at sub-mas level

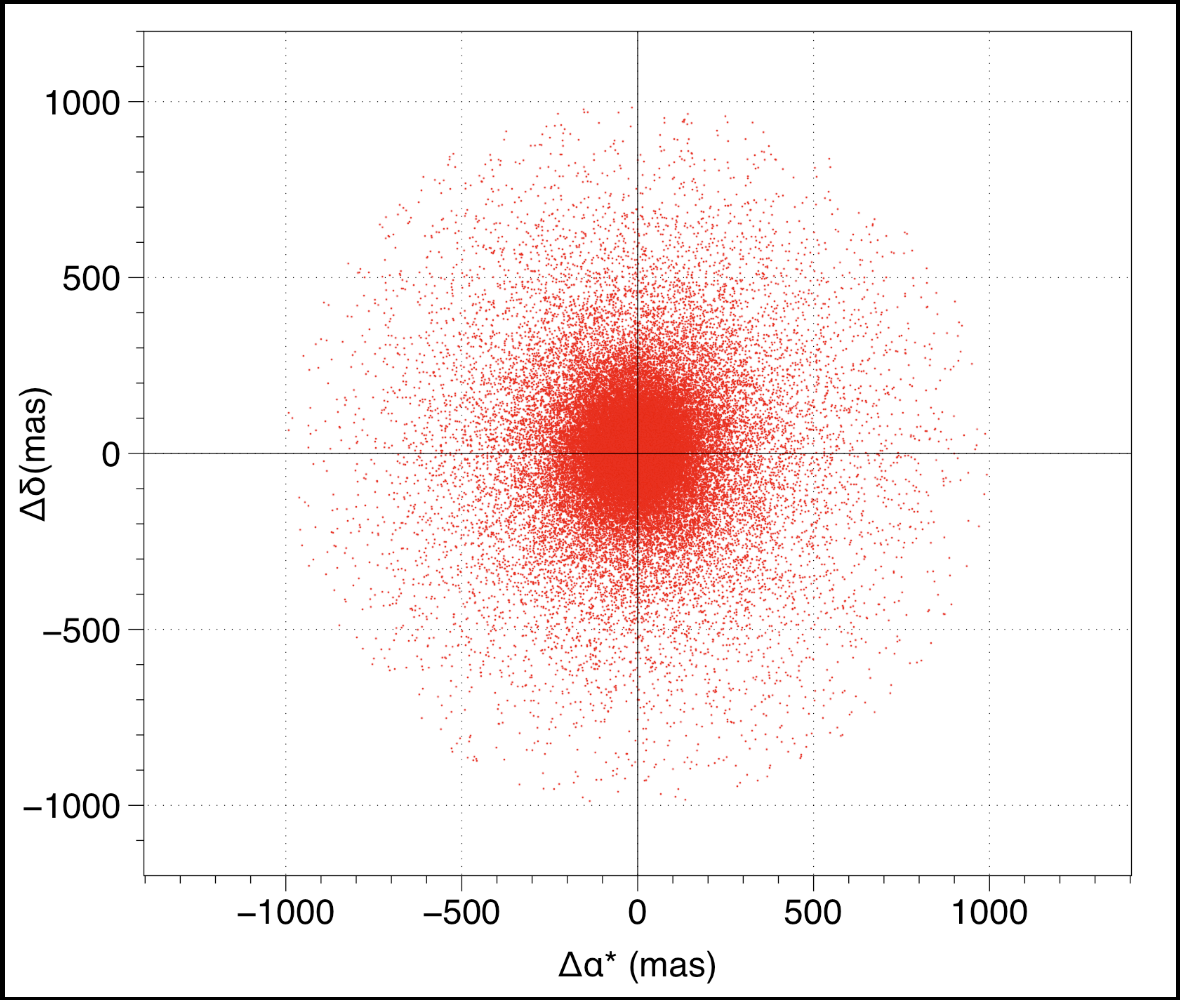


Astrometric accuracy

- Scatter distribution of $\Delta\alpha^* - \Delta\delta$ from the Gaia-DR1 solution
  - large central concentration
  - bias constant over magnitude ranges

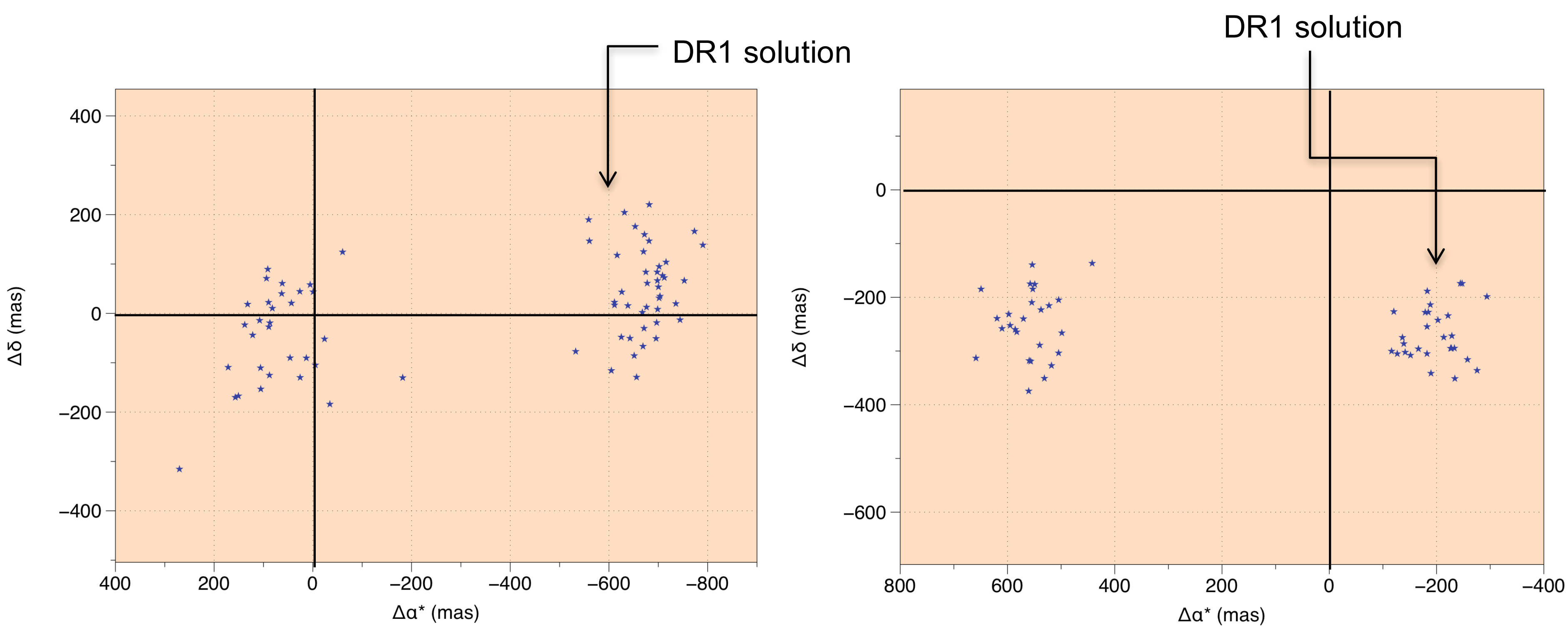
$$\mathrm{med}(\Delta\alpha^*) = -4\,\mathrm{mas}$$

$$\mathrm{med}(\Delta\delta) = 11\,\mathrm{mas}$$



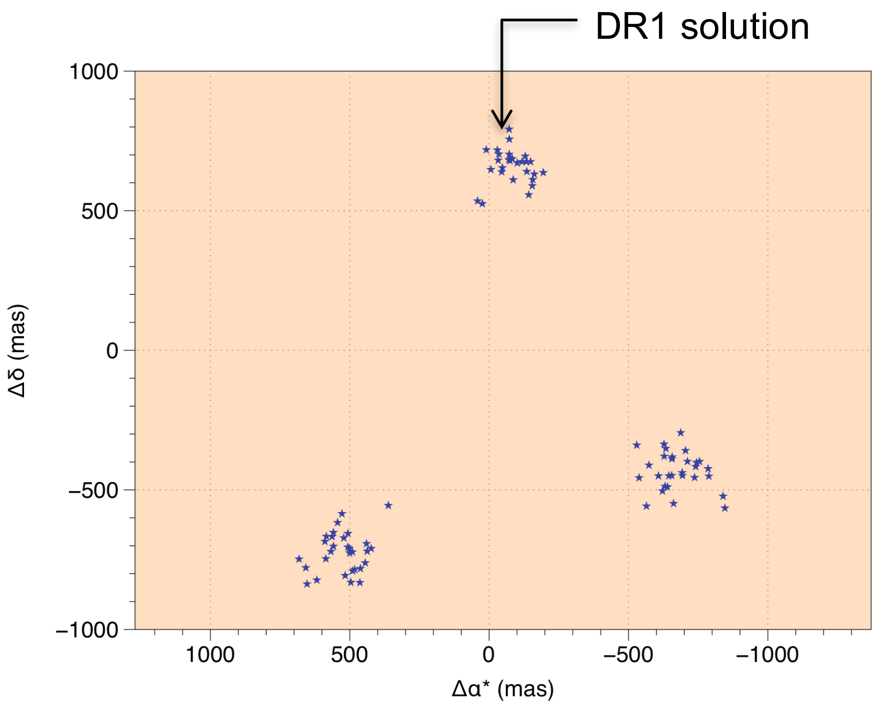
Contaminants in DR1 vs ALLWISE

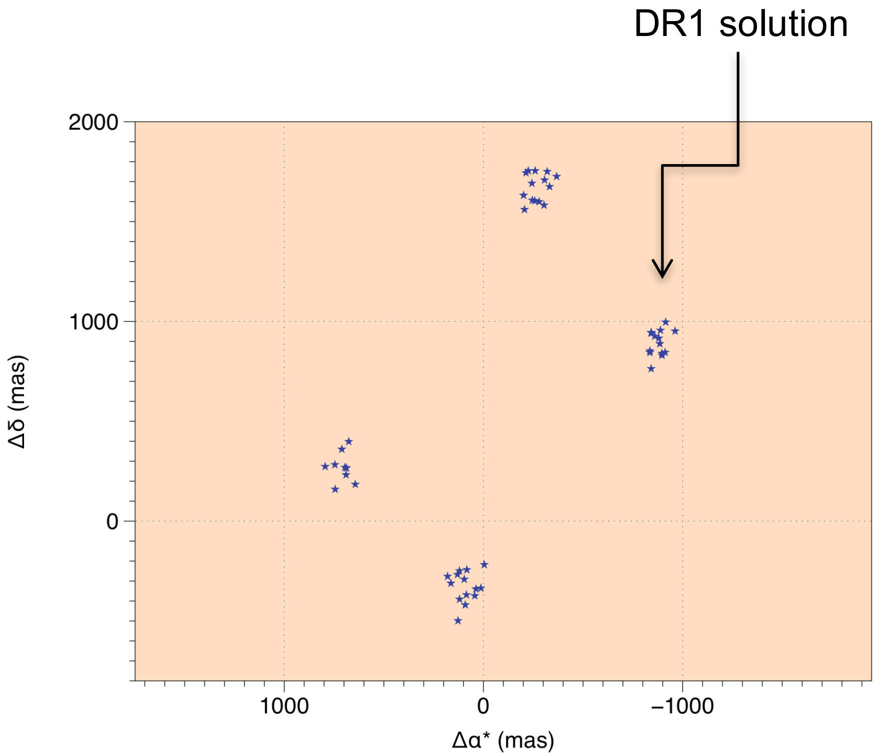
- ALLWISE in mid-IR has a limited spatial resolution
  - but less than 10,000 sources seen with double images (or more)
  - a star may be the DR1 solution instead of the AGN



Possible lenses ?

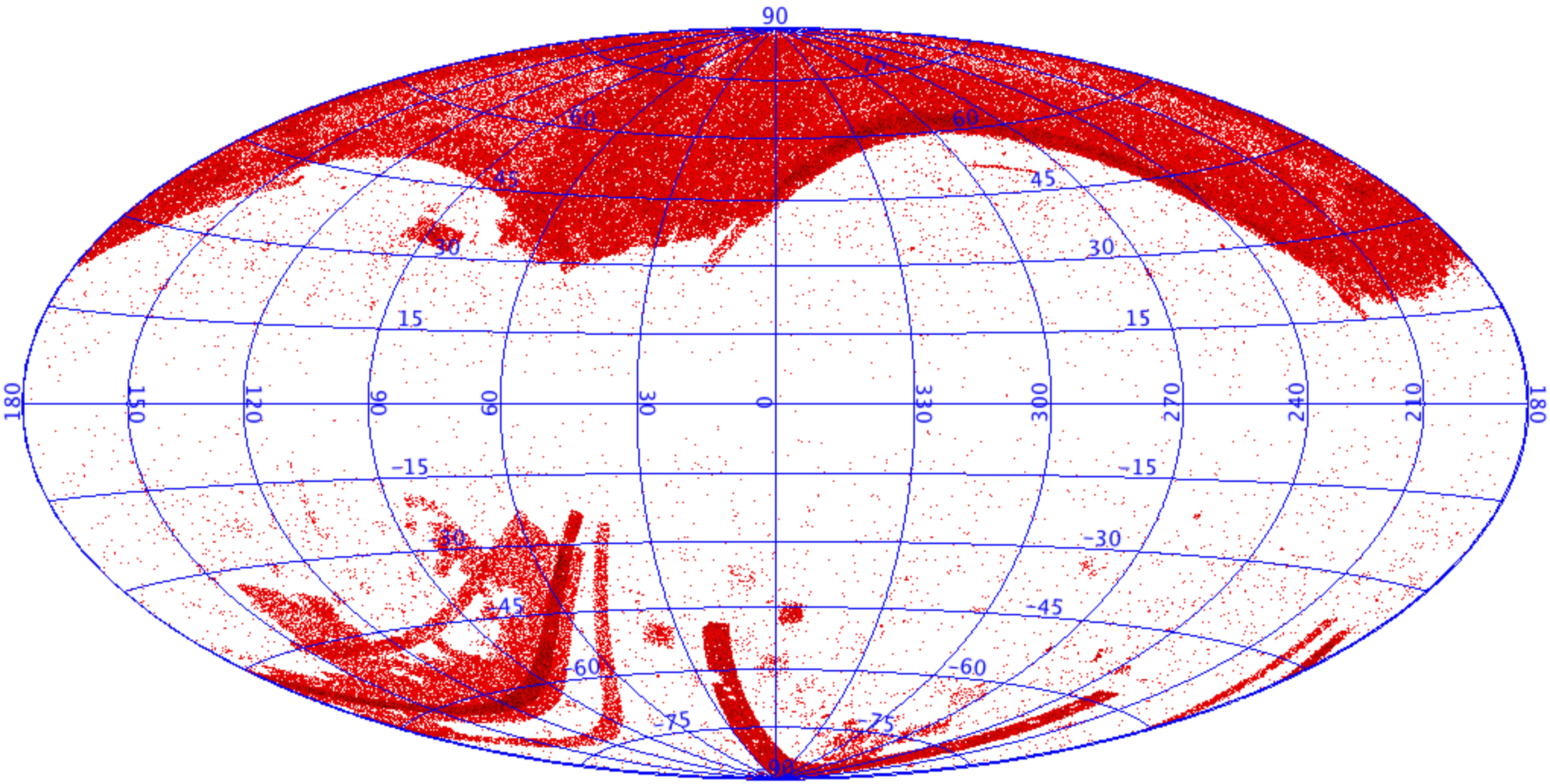
- Two cases from ALLWISE with multi images
  - both well outside the galactic plane
  - to be looked at in the gaia-DR2
  - not from known lenses





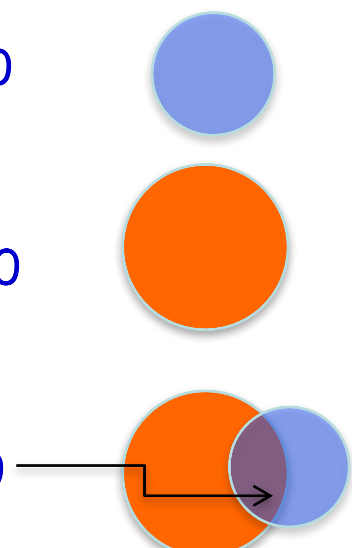
More known QSOs available

- LQAC3 (Souchay et al., 2015)) – 320,000 sources
  - distribution of the 240,000 sources seen with Gaia (Gal. coord.)



Number of QSOs available

- LQAC 3 (J. Souchay et al. , A&A, 2015)
  - general compilation taking over Véron- Cetty & Véron
  - cross identification from 9 catalogues
  - largely populated by SDSS
  - small proportion of AGNs ➔ so should be much different from ALLWISE
  - Total entries 320,000
  - Detected in IDT (G < 20.6) ~215,000
  -
  - ALLWISE in DR1 570,000
  - In common ~ 85,000
  - Therefore there are ~130,000 not used yet for the reference frame



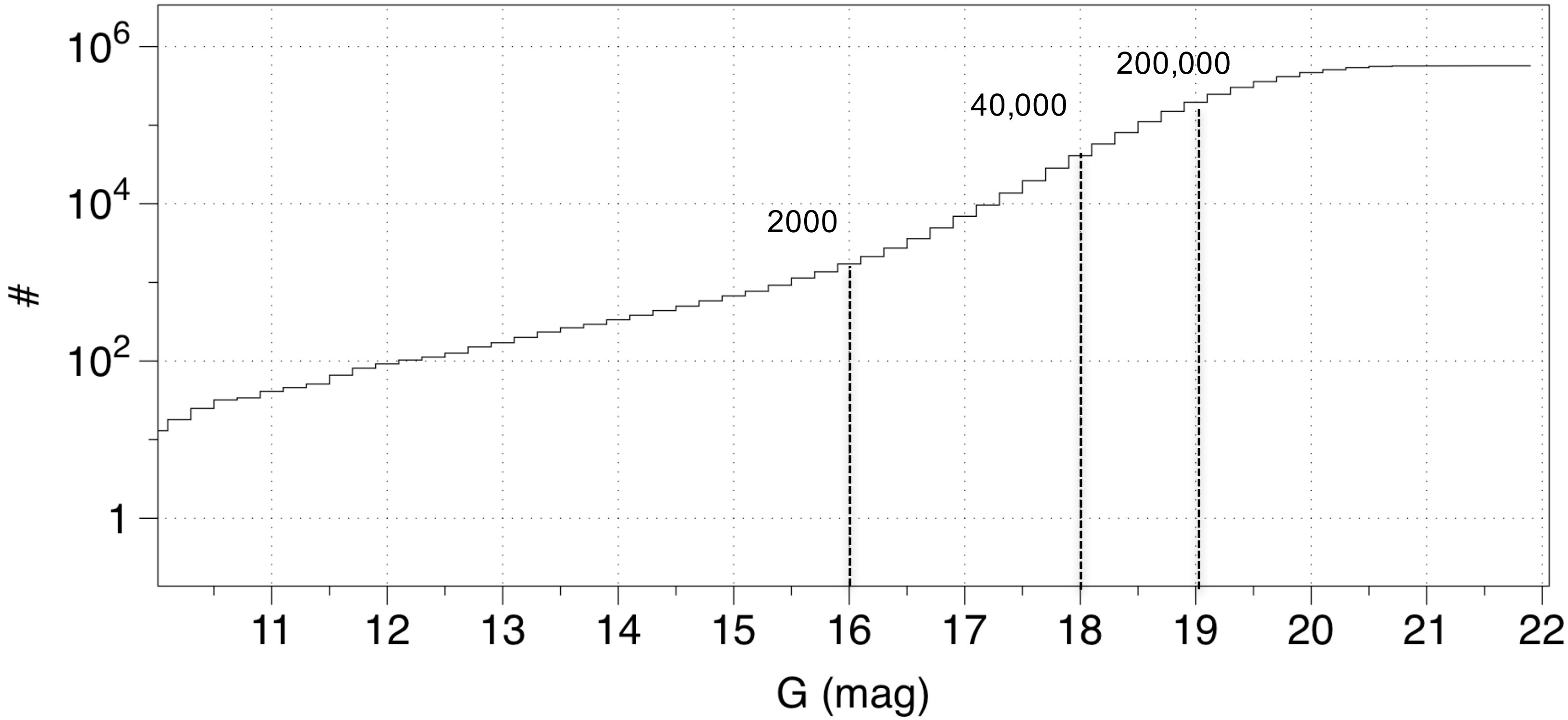
Quality of the Gaia frame

Quality of the Gaia frame

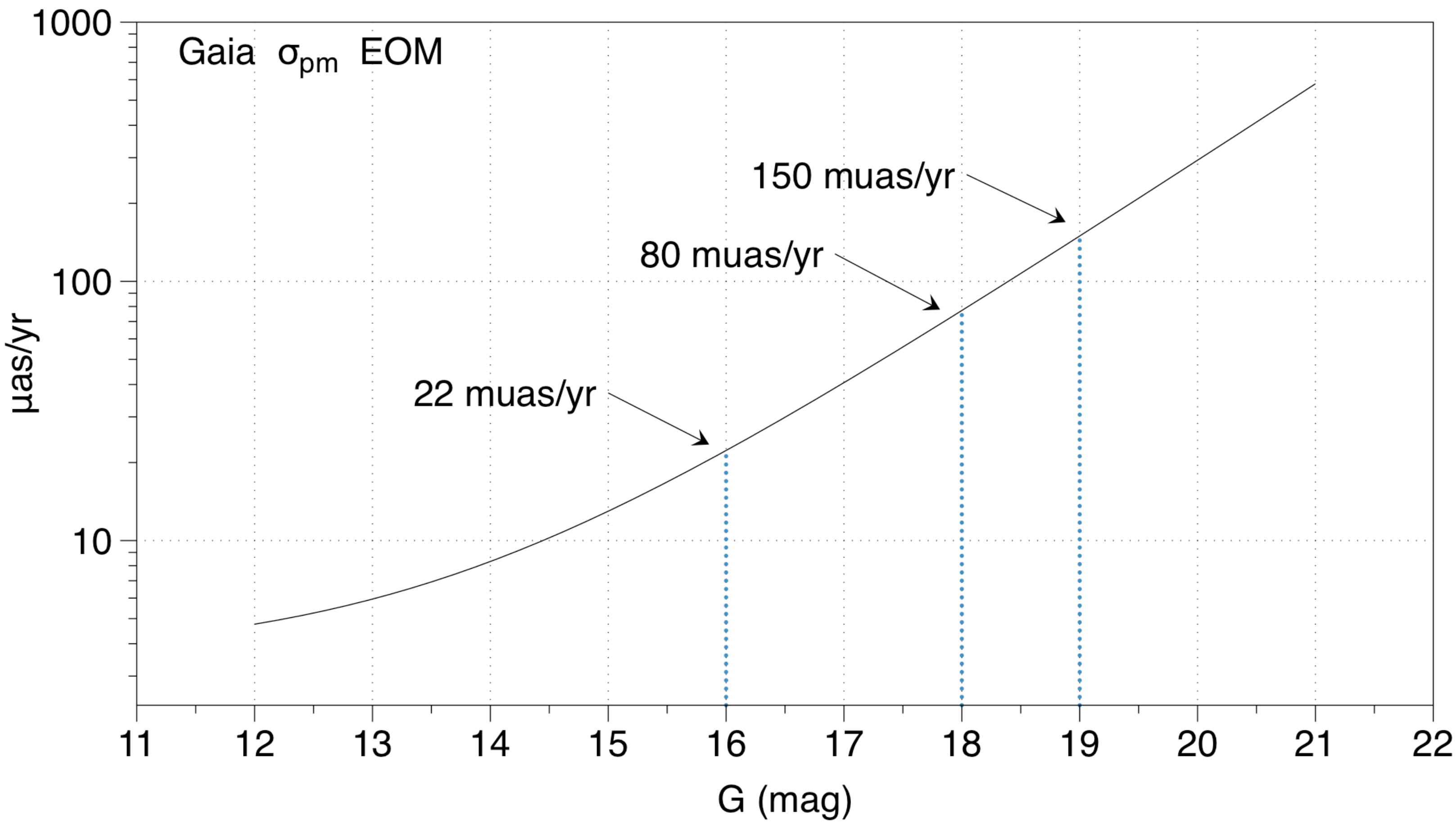
- Easy question but no easy answer
- How well a set of positions of QSOs fixes the fundamental directions (Oxyz)
- By how much can we rotate the frame so that it remains compatible with the uncertainties in the source position
- Orientation and spin are two different issues
  - very different number of sources involved
    - few 1000s for the orientation
    - few 100,000s for the spin

Number of QSOs available

- ALLWISEAGN DR1 sources only

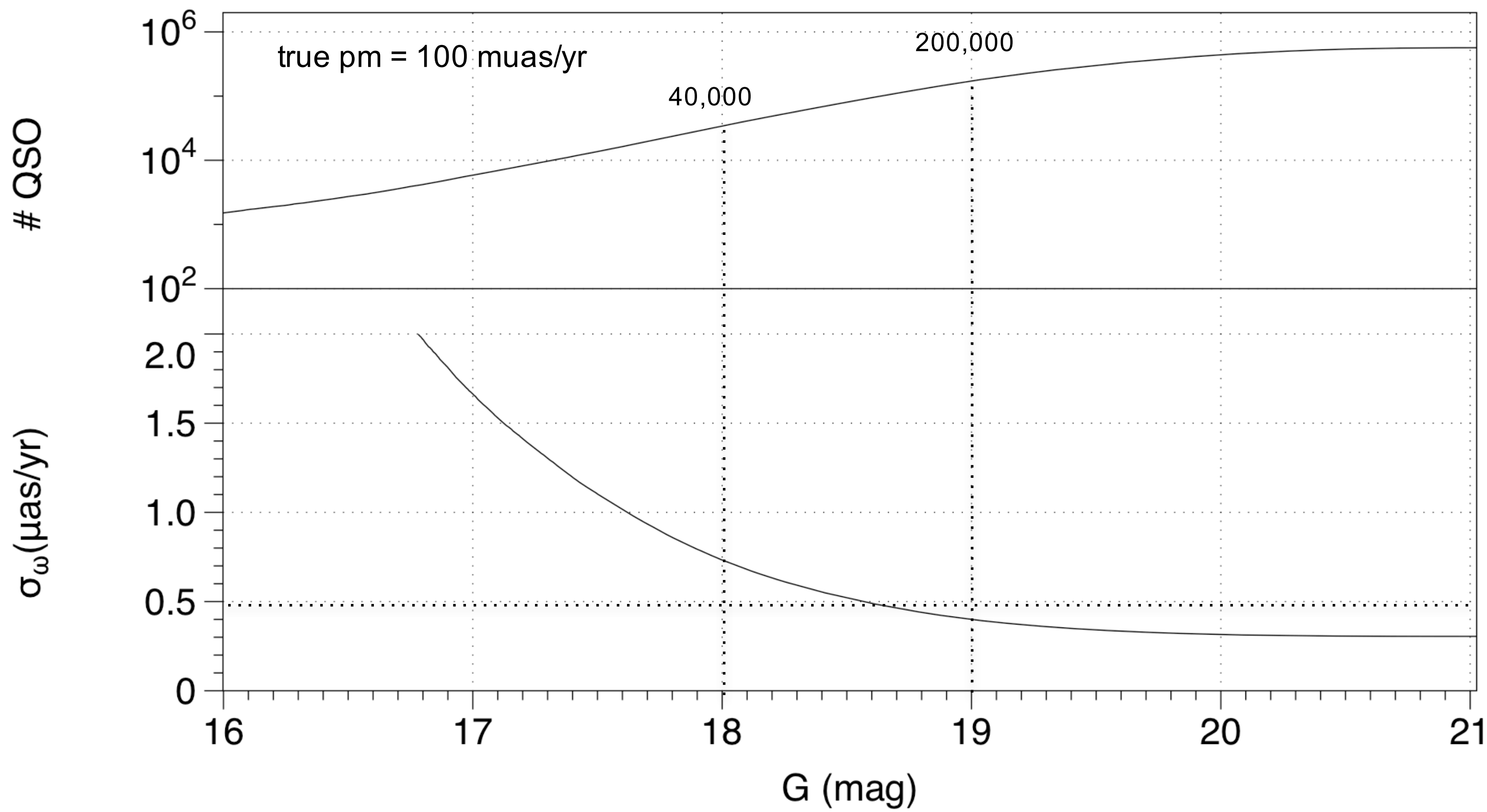


Astrometric Accuracy: proper motions



Best achievable performance

- ALLWISEAGN from DR1
- Spin covariance matrix computed with QSOs constrained to have no overall motion
- The plots show the standard error in ω(for a component)



Quite Challenging !

We potentially could reach a final result on the spin of the reference frame at 0.25 μas/yr level:

This is ~ 1/1000 of the astrometric accuracy of the faintest sources

but … many caveats

Thanks for your attention