Sagan Summer Workshop

NExScI

The Celestial Reference Frame

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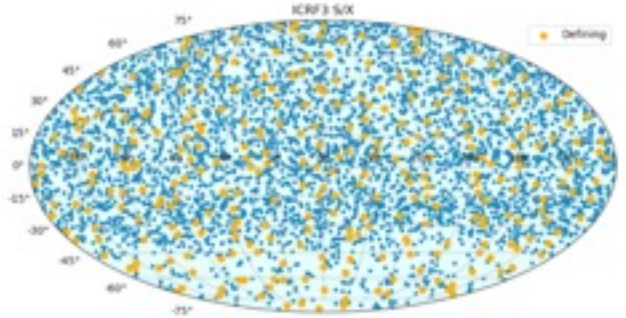
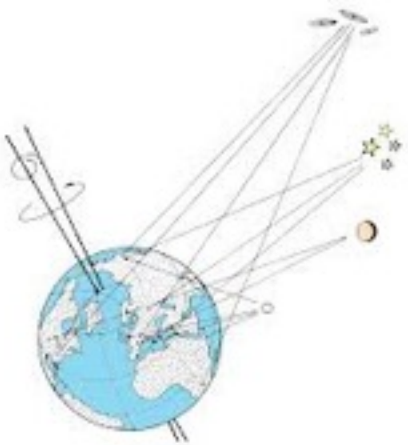
Observatoire de la Côte d'Azur/Lagrange

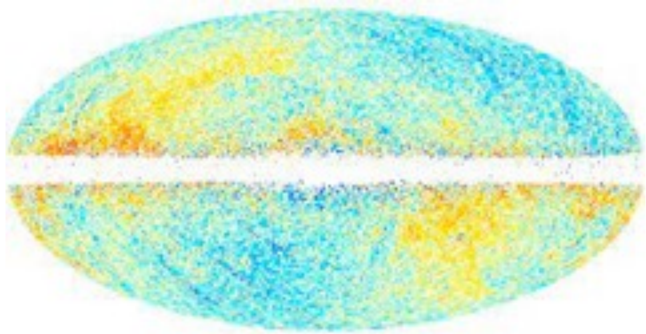
29 July 2022

Outline

- Reference frames : why, for what, for whom
- The fundamental realisations in the radio domain: VLBI CRFs
- The fundamental realisations in the visible domain: Gaia CRFs
- Relationships between Radio and Optical CRF







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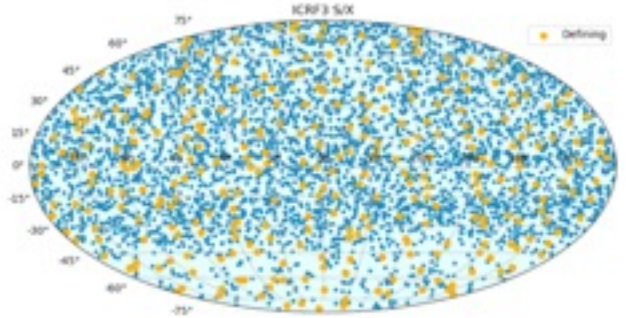
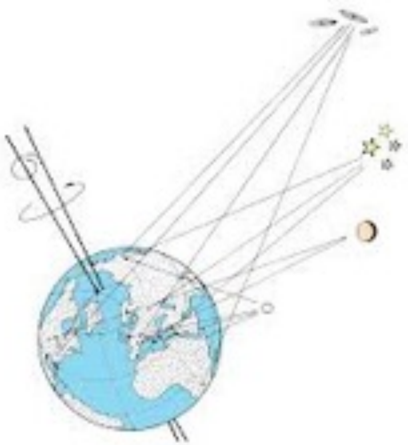
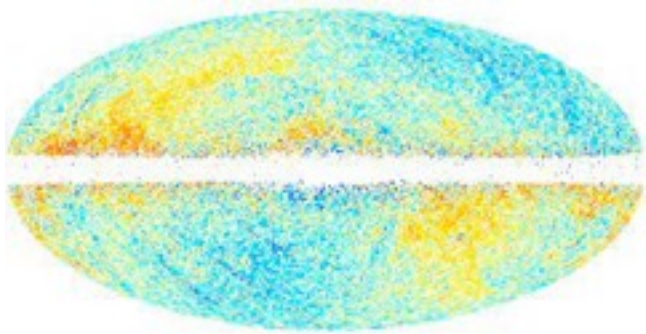






A Reference frame : what for?

- At the very first level : to map the sky and tell where the stars are !
- To refer positions of fixed or moving sources
- To **detect** tiny motions ➔ E. Halley 1717
- 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

A Reference frame : theory and practice

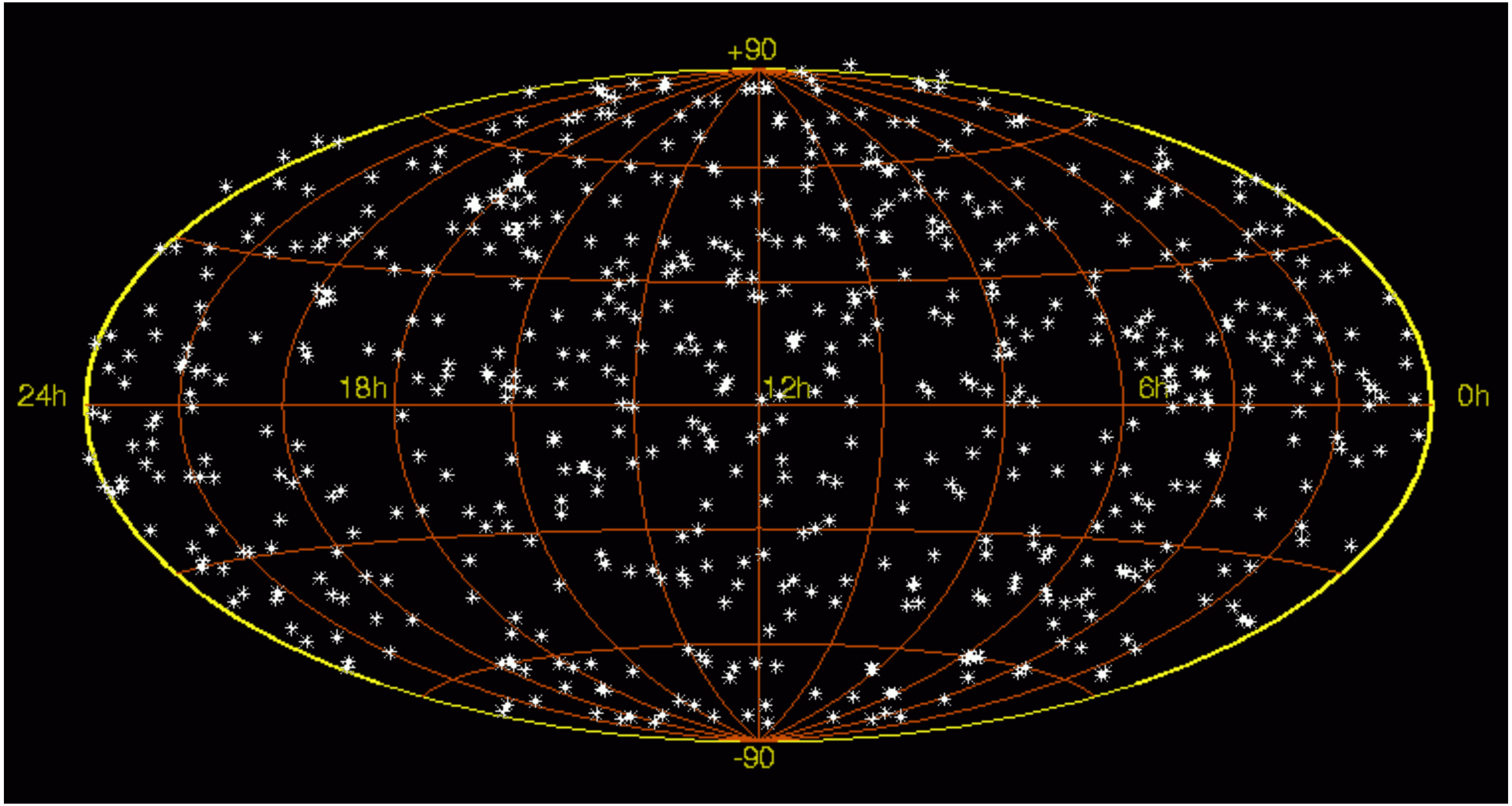
- One must distinguish between
  - **The System**: ICRS
    - Set of specifications defining the coordinate system, including origin, fundamental planes/axes, along with constants, models, and algorithms for transforming observables.
  - **The Realisation**(s): ICRF
    - Set of sources/points on the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

Gaia and future missions belong to this section

Gaia-CRFs and ICRF-x radio are Realisations of ICRS

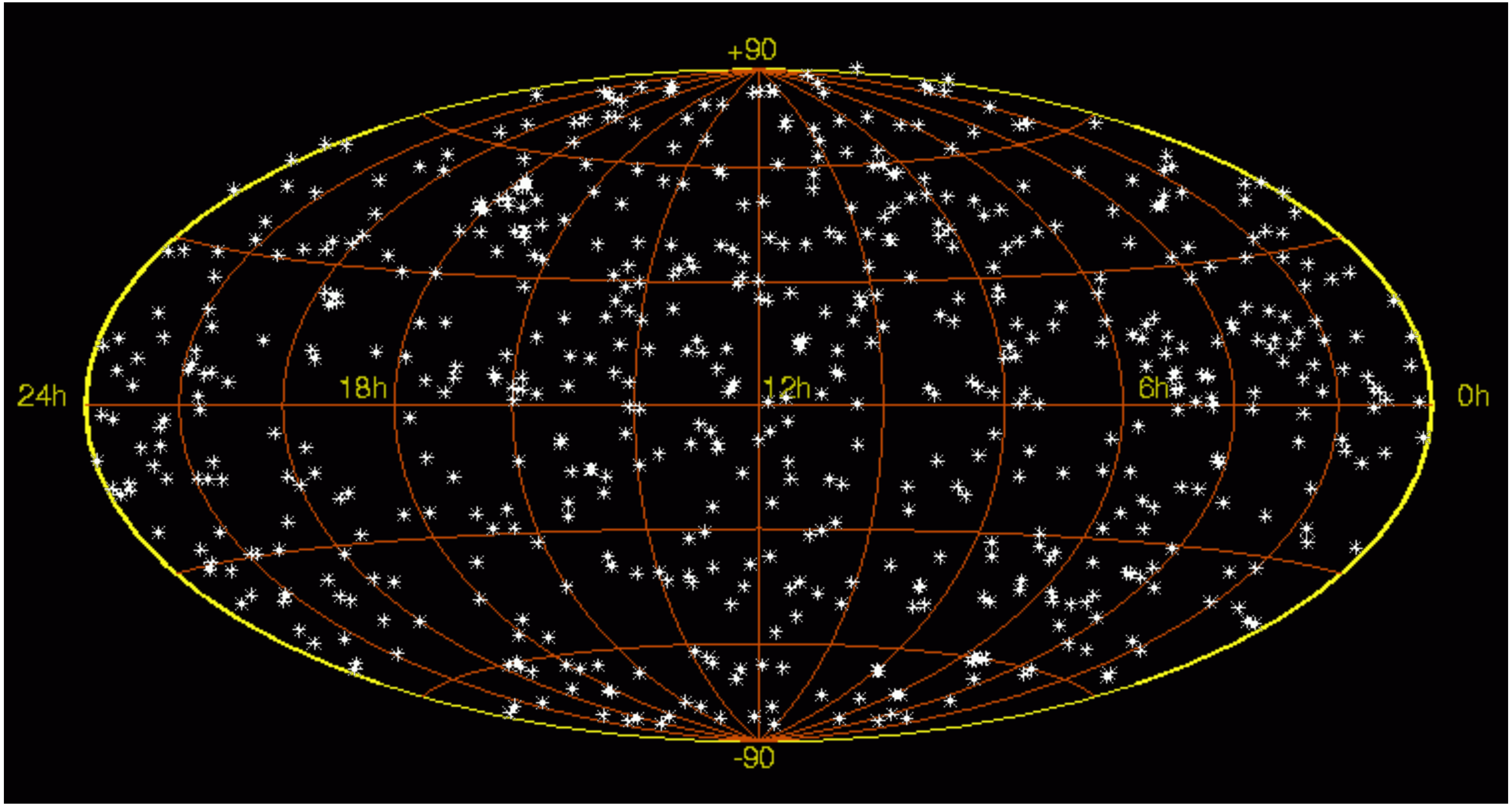
Reference frame : the user point of view

- Pre-existing reference graticule



Reference frame : the fundamental point of view (Gaia, VLBI)

- Use stellar sources as fiducial points



A Reference frame : Relevance for 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 requirement** 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

Fundamental catalogues: timeline

- Relatively recent history
- Small catalogues relative to surveys
- Absolute observations
- Old **system** : stars, celestial equator, equinox at epoch, inertial
- Current **system** : QSOs, arbitrary fundamental plane and origin, kinematically non rotating system

Name	Epoch	N. sources	mag <	Accuracy
Lacaille	1760	397	7	10 ″
Maskelyne	1774	36	5	5 ″
Piazzi	1818	220	6	2 ″
Bessel	1830	36	5	1 ″
Argelander	1869	160	6	1 ″
Auwers	1879	539	6	0.5 ″
FK3	1937	873	6.5	0.5 ″
FK4	1963	1535	7.5	0.2 ″
FK5	1988	1535	7.5	40 mas
Hipparcos[1]	1996	100 000	11.5	1 mas
ICRF1 (Radio)	1998	620	-	2 mas
ICRF2 (Radio)	2009	3400	-	0.6 mas
ICRF3 (Radio)	2018	4500	-	0.2 mas
ICRF3 def. sources	2018	303	-	0.05 mas
Gaia CRF2 QSOs	2018	550 000	21	0.5 mas
Gaia CRF3 QSOs	2021	1,620 000	21	0.4 mas
Gaia CRF3 $G < 18$	2021	35 000	18	0.09 mas

(1) quasi-fundamental

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
- 1998 ICRF1 (radio) replaces FK5 as fundamental frame
- 2009 Adoption of the ICRF2
- 2018 Adoption of ICRF3 IAU XXXth GA
- 2021 ICRF reshaped to include Gaia-CRF3 IAU XXIth GA

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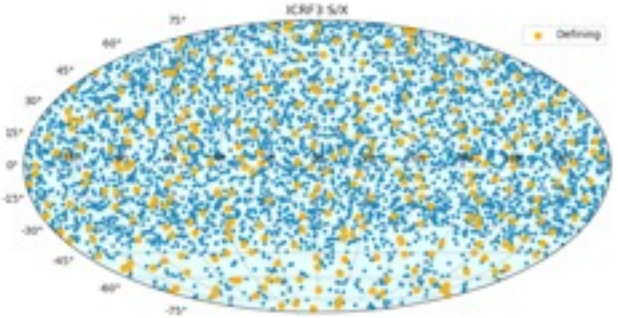
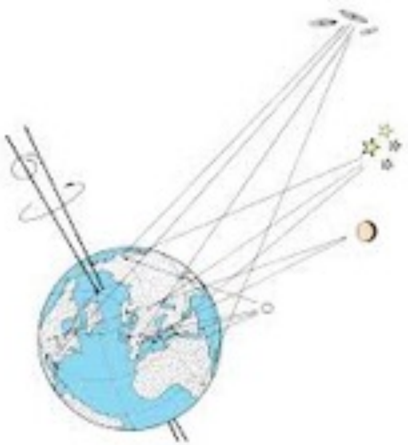
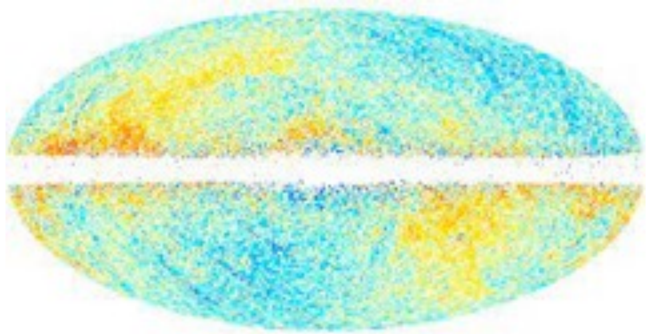






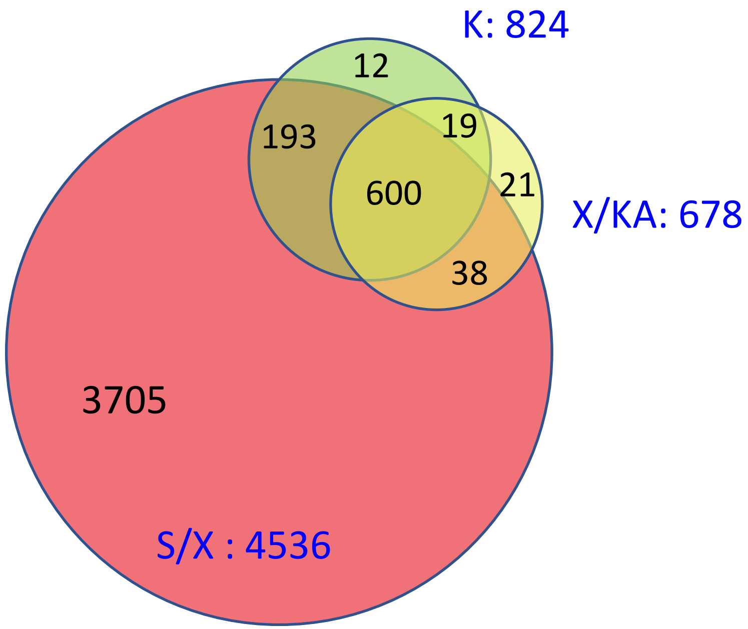
ICRF radio – ICRF3

The third realization of the International Celestial Reference Frame by very long baseline interferometry★

P. Charlot[1], C. S. Jacobs[2], D. Gordon[3], S. Lambert[4], A. de Witt[5], J. Böhm[6], A. L. Fey[7], R. Heinkelmann[8], E. Skurikhina[9], O. Titov[10], E. F. Arias[4], S. Bolotin[3], G. Bourda[1], C. Ma[11,★★], Z. Malkin[12,13], A. Nothnagel[14,★★★], D. Mayer[6,★★★★], D. S. MacMillan[3], T. Nilsson[8,†], and R. Gaume[15]

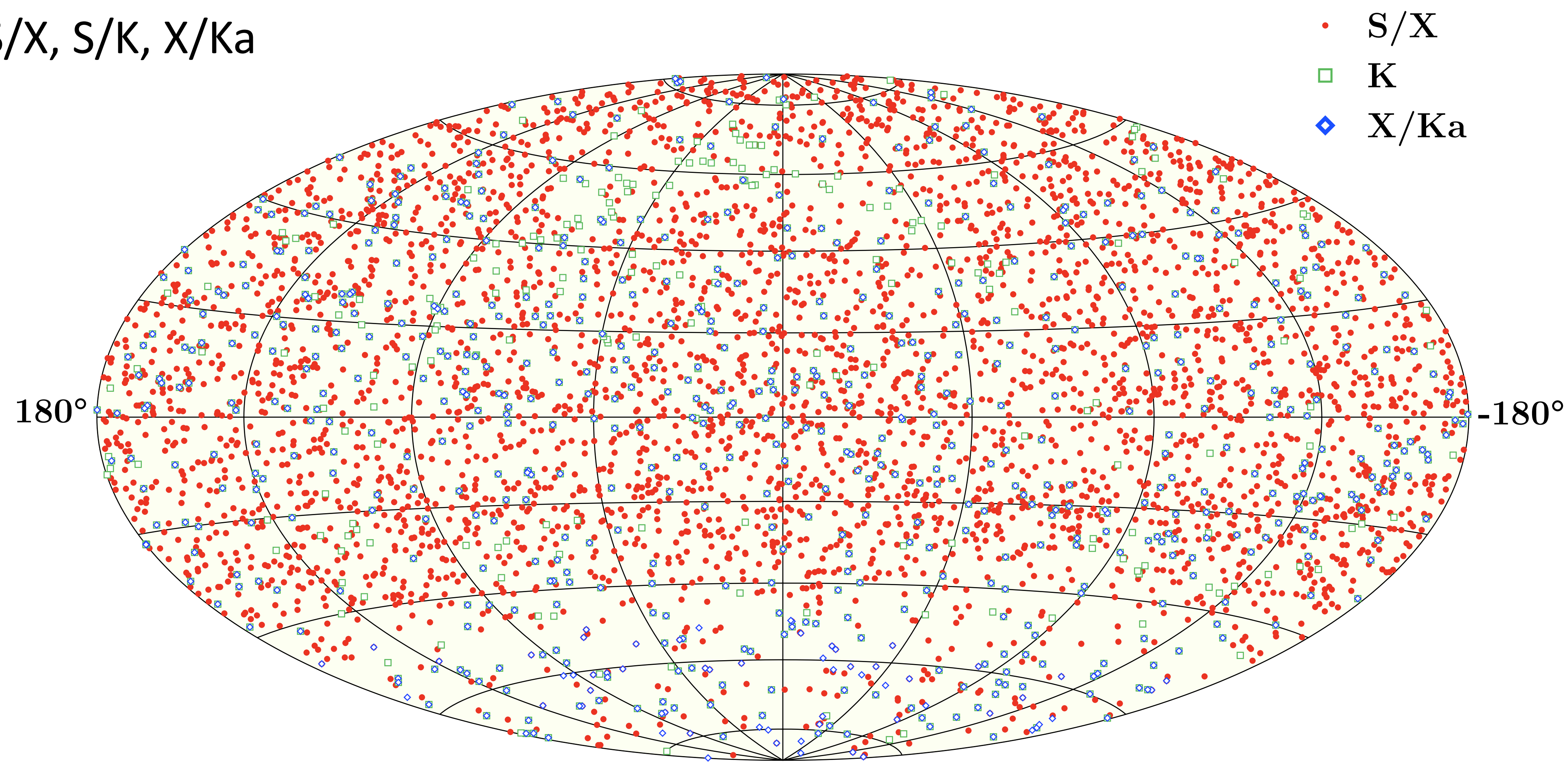
A&A 644, A159 (2020)

- International coordination with IAU
- VLBI observations in dedicated sessions
  - most of the VLBI network is used for geodetic purposes
- 13.6 million observations collected over ~ 40 years [1979-2018]
- global treatment for a set of sources
  - final subset based on the most stable and best observed
- 4588 sources selected
  - 4536 sources (S/X), 824 (K), 678 (X/KA)
  - 303 defining sources used to determine the system



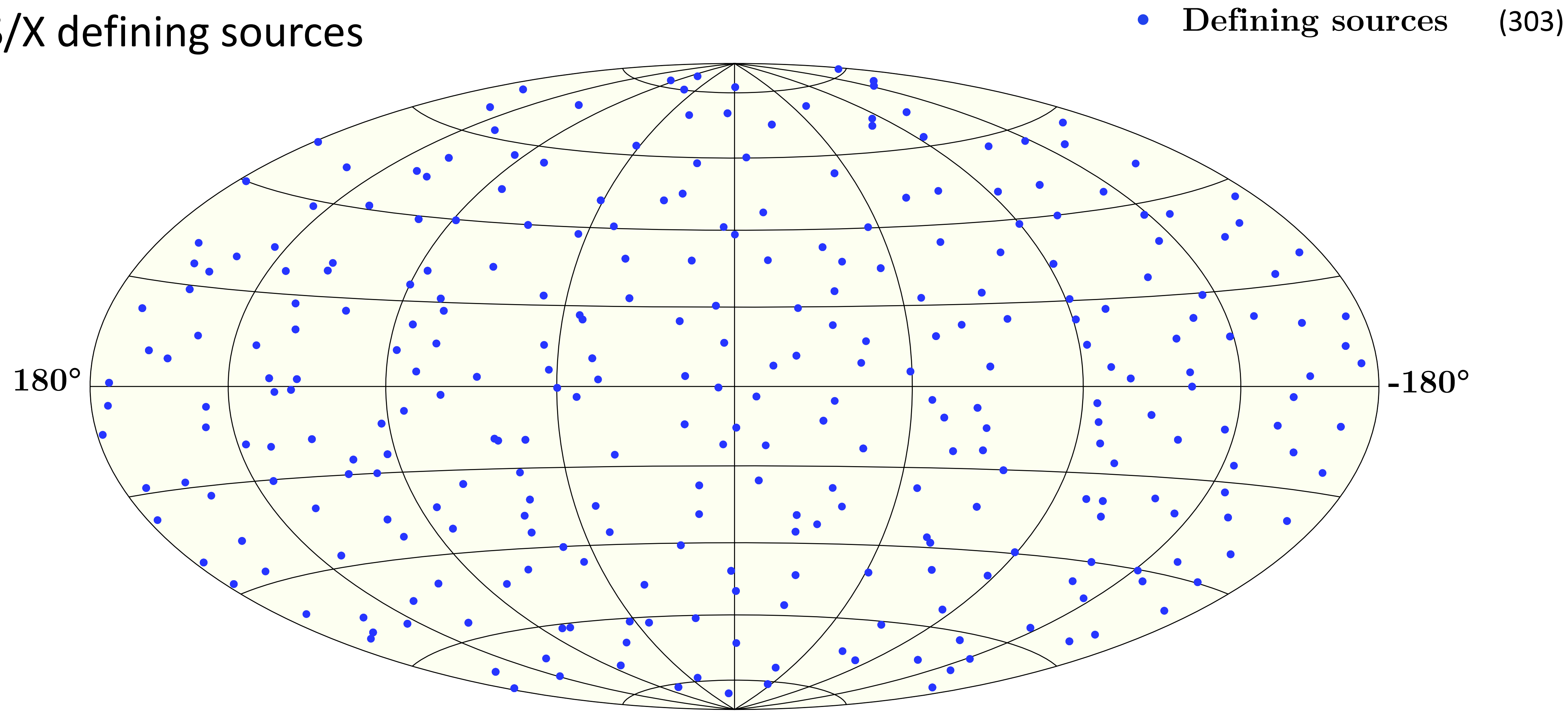
ICRF radio – ICRF3

- S/X, S/K, X/Ka



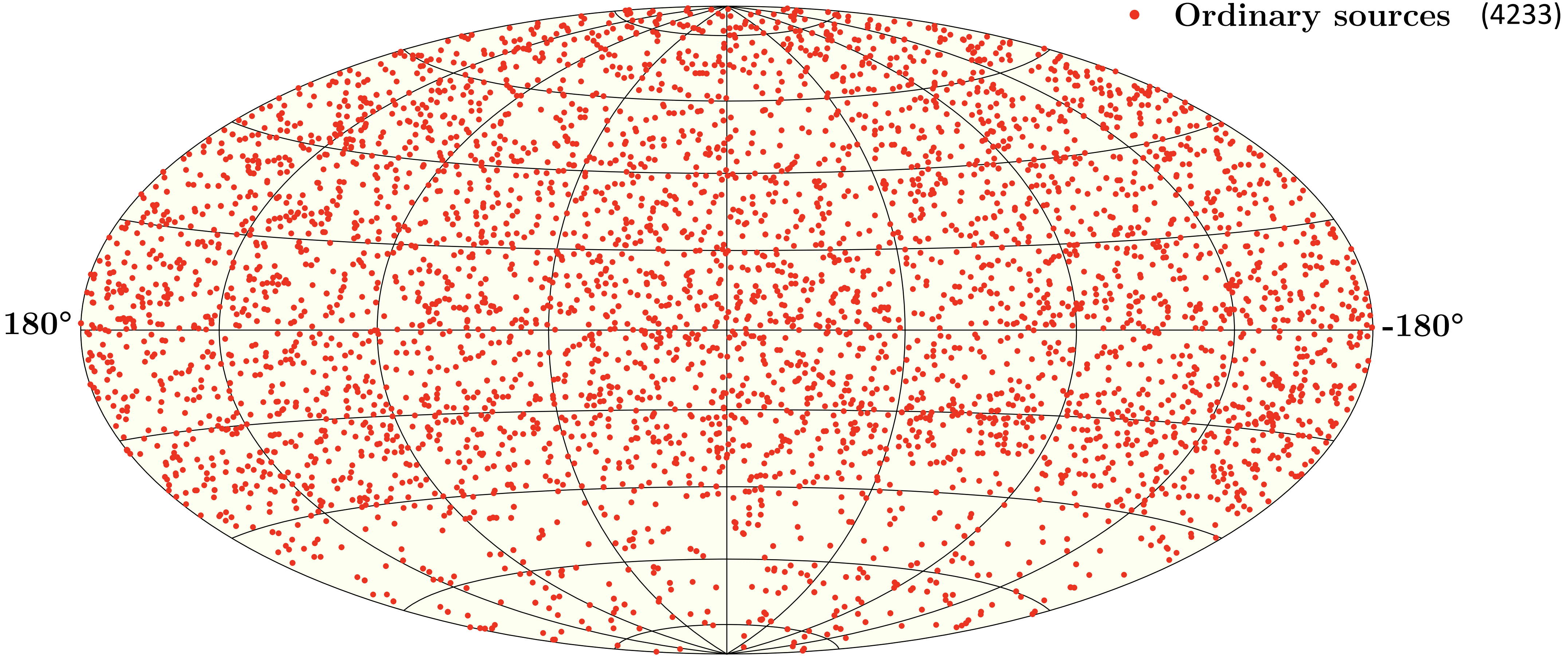
ICRF radio – ICRF3

- S/X defining sources



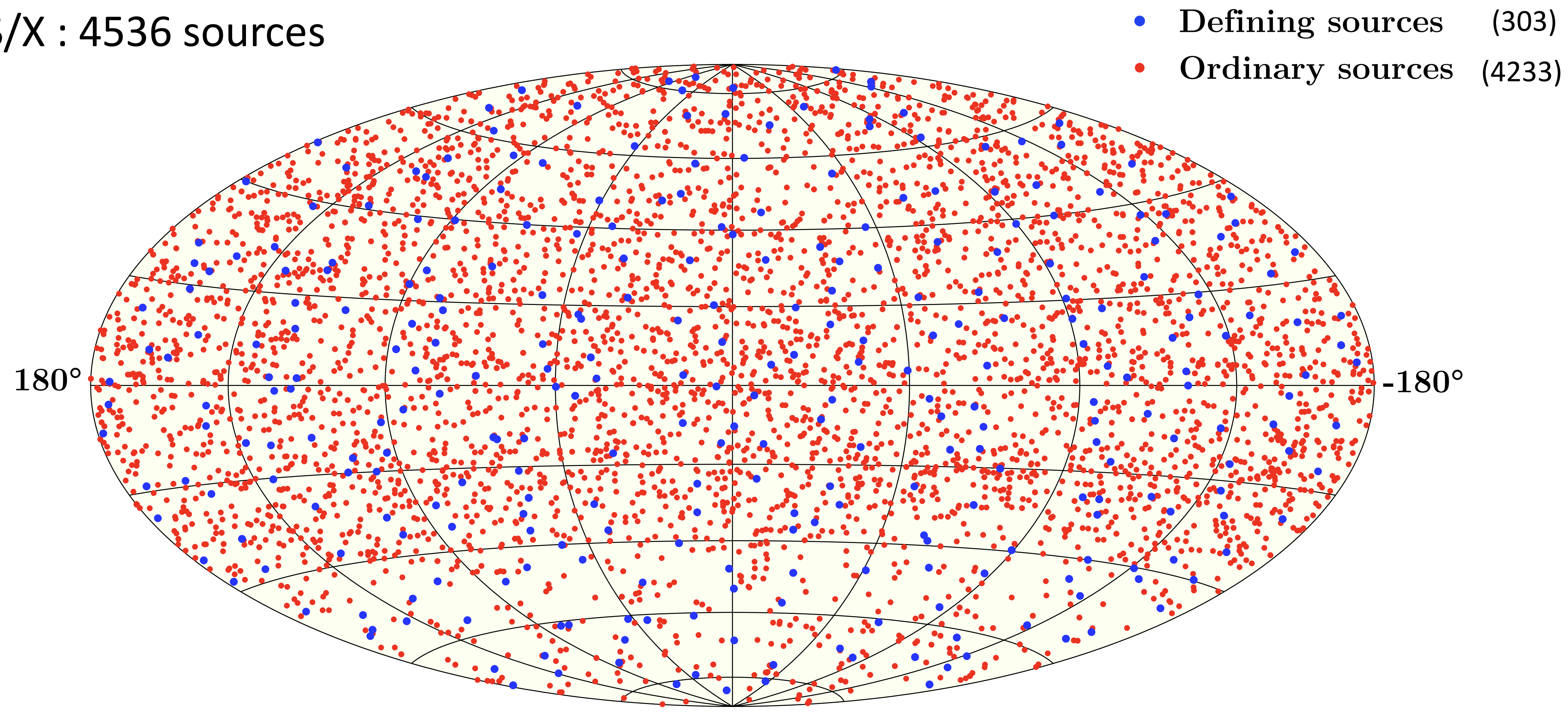
ICRF radio – ICRF3

- S/X secondary sources



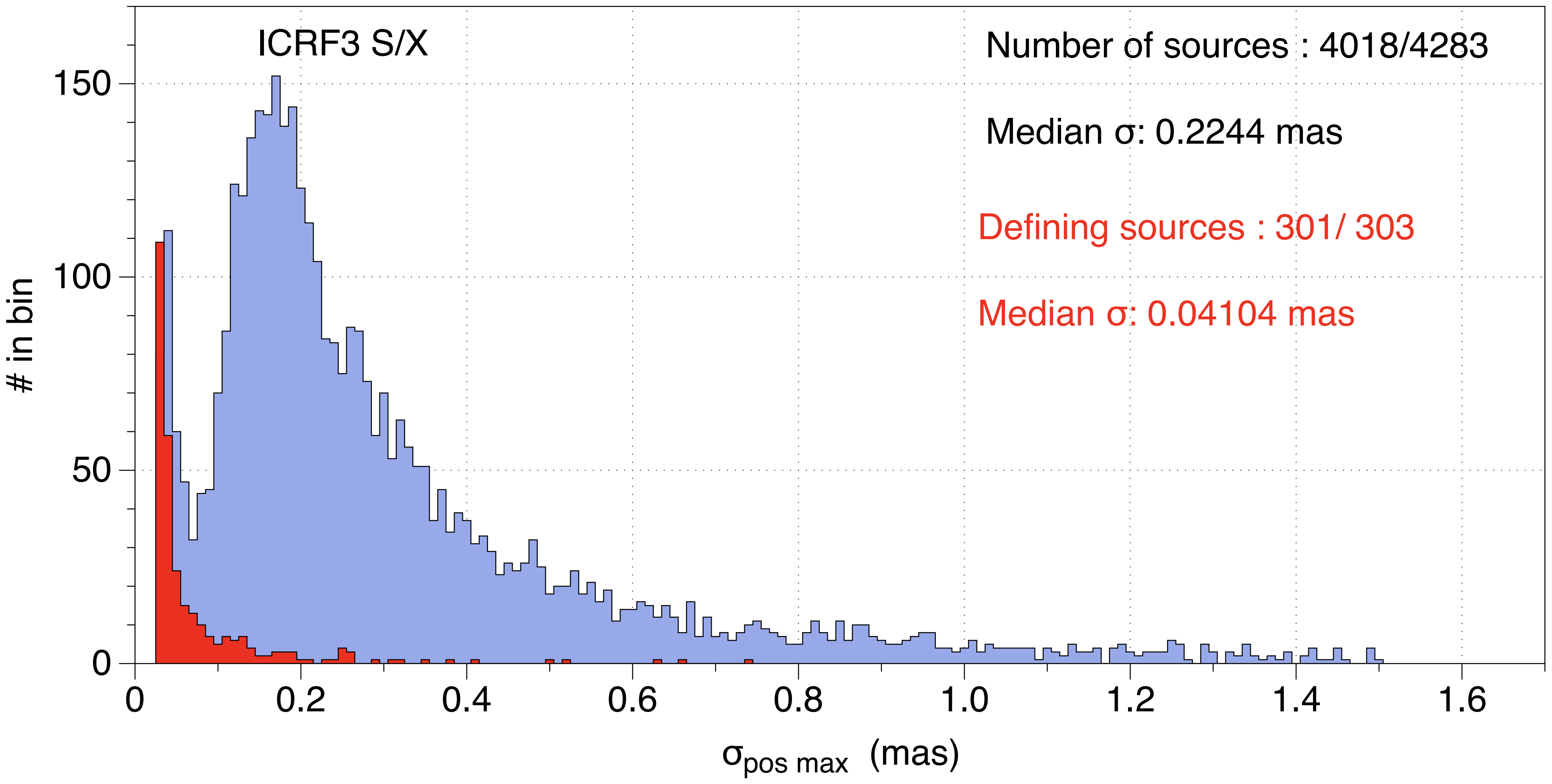
ICRF radio – ICRF3

- S/X : 4536 sources



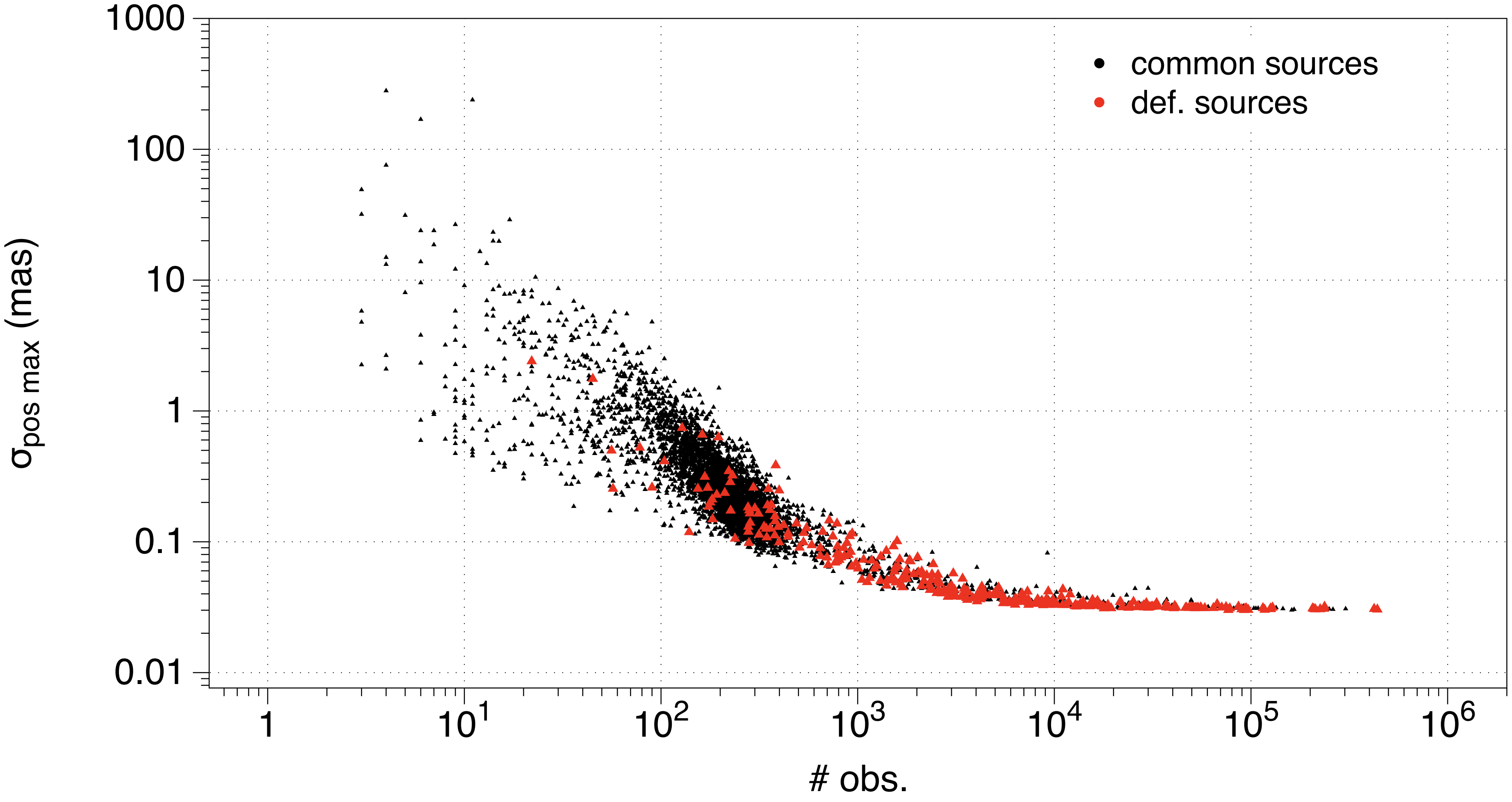
ICRF radio – ICRF3

- Positional uncertainties



ICRF radio – ICRF3

- Precision vs. number of delays



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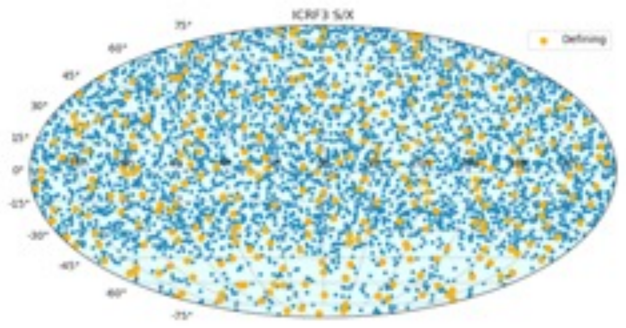
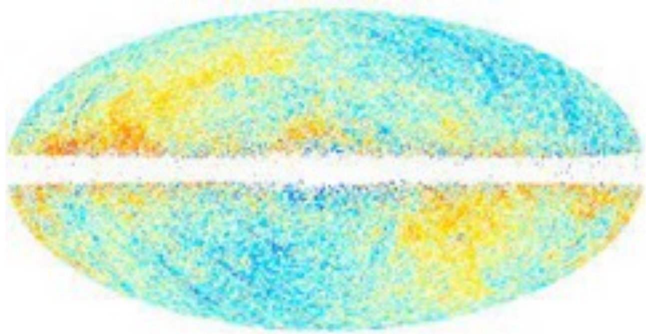
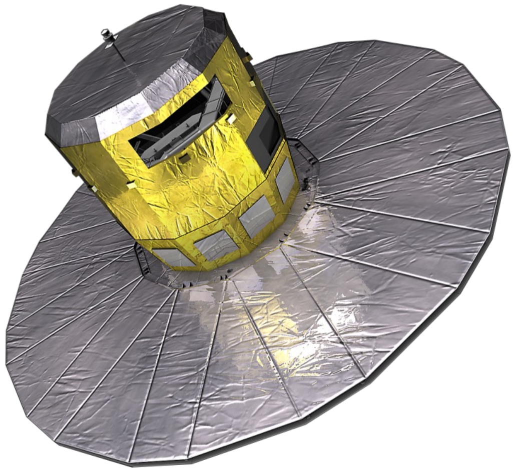






Gaia CRF3

Gaia Early Data Release 3

The celestial reference frame (*Gaia*-CRF3)

Gaia Collaboration, S.A. Klioner[1], L. Lindegren[2], F. Mignard[3], J. Hernández[4], M. Ramos-Lerate[5], U. Bastian[6], M. Biermann[6], A. Bombrun[7], A. de Torres[7], E. Gerlach[1], R. Geyer[1], T. Hilger[1], D. Hobbs[2], U.L. Lammers[4],

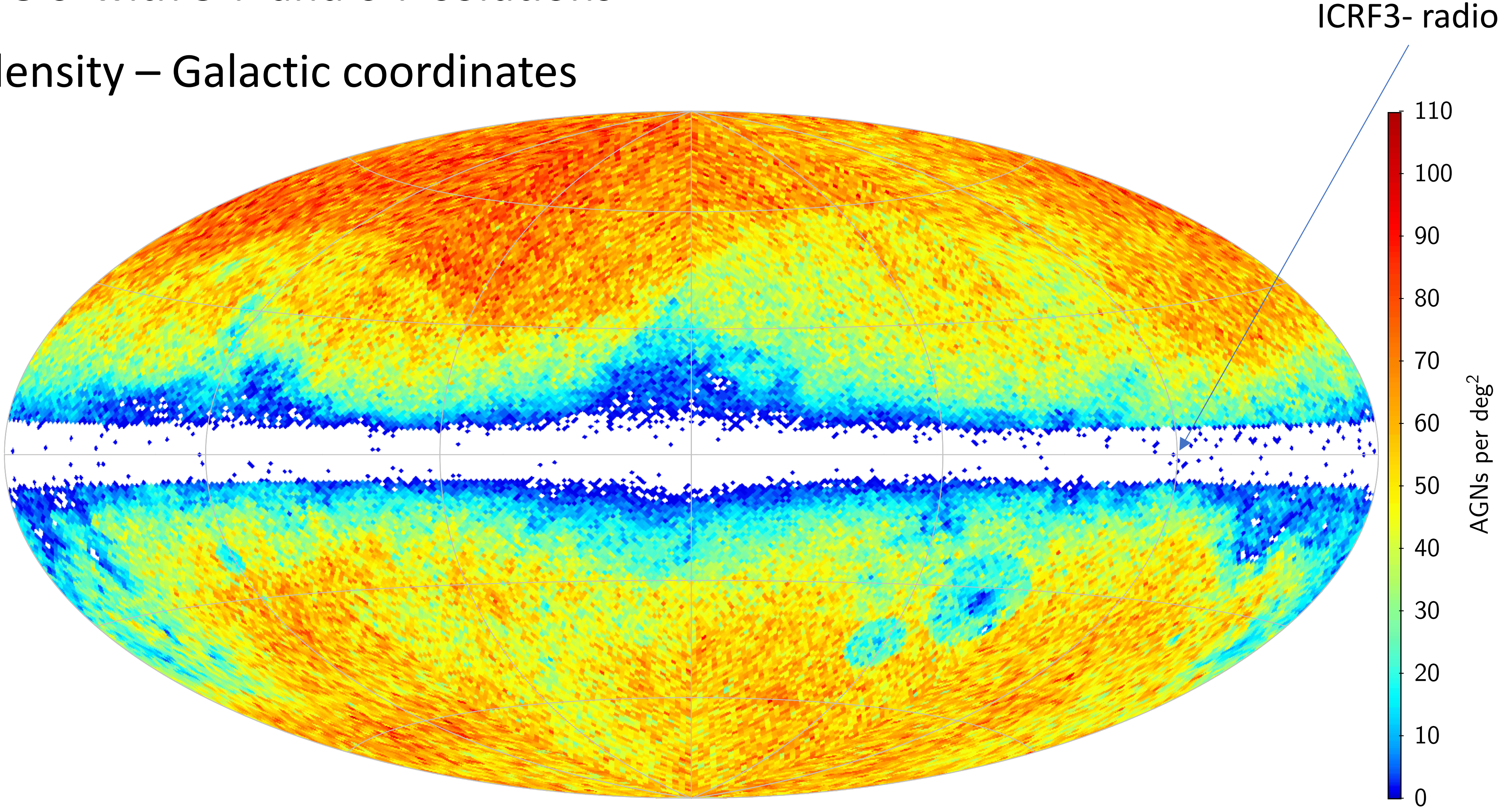
A&A 2022

Gaia CRF3

- Based on 34 months of Gaia data [Jul 2014 - May 2017]
- Sources selected from 17 external catalogues of compact sources
- 1.615 M sources (QSOs, AGNs) in the final selection
  - astrometric filters e.g : $\varpi/\sigma_\varpi < 5$ ➔ parallaxes should be 'zero'
  - $|\sin b| > 0.1$
  - cleanliness favoured over completeness
    - narrow match window
    - detection of polution by stellar contaminants
- Global astrometry from Gaia

EDR3 - Gaia-CRF3

- 1.61 M QSO's with 5-P and 6-P solutions
- Sky map density – Galactic coordinates



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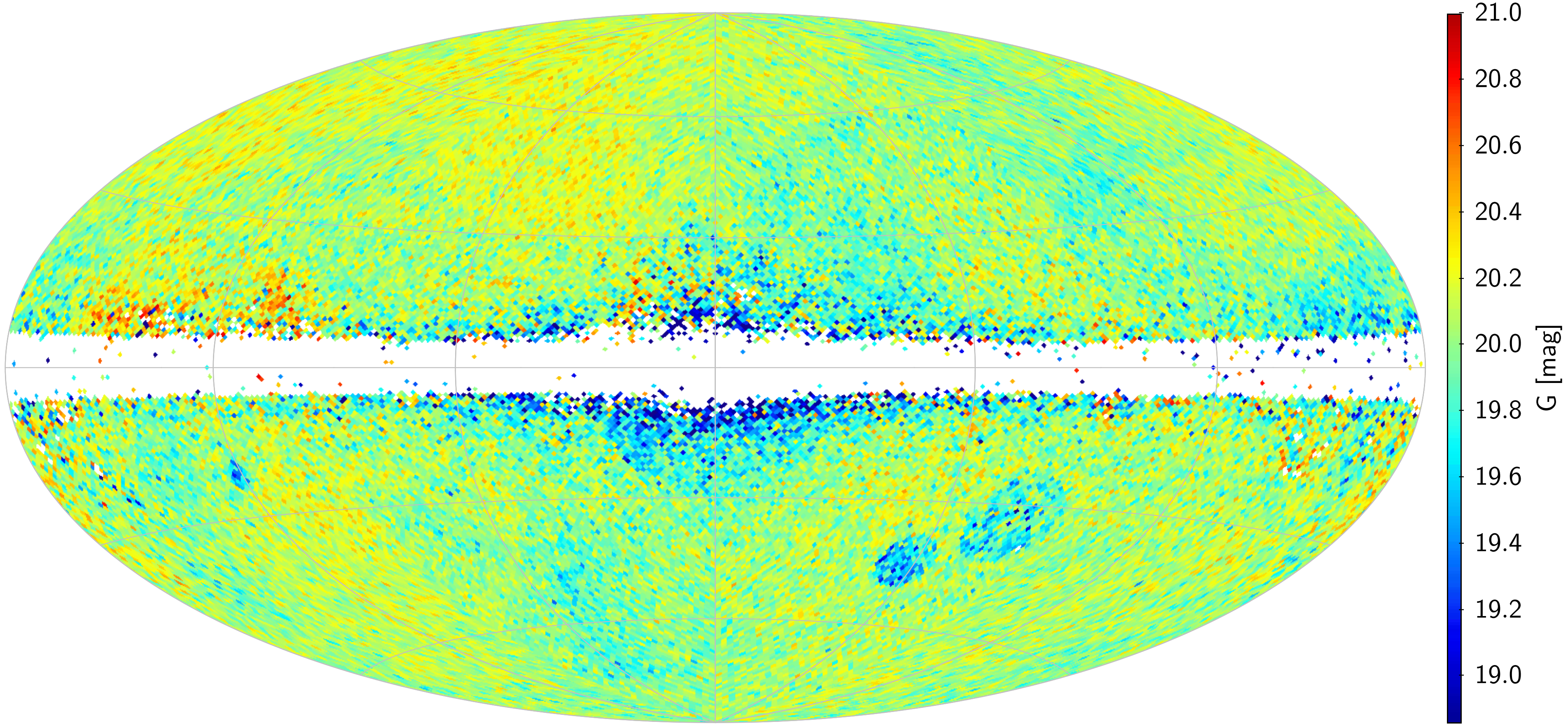
Gaia-CRF3

- 1.61 M QSO's with 5-P and 6-P solutions
- Median G-magnitude



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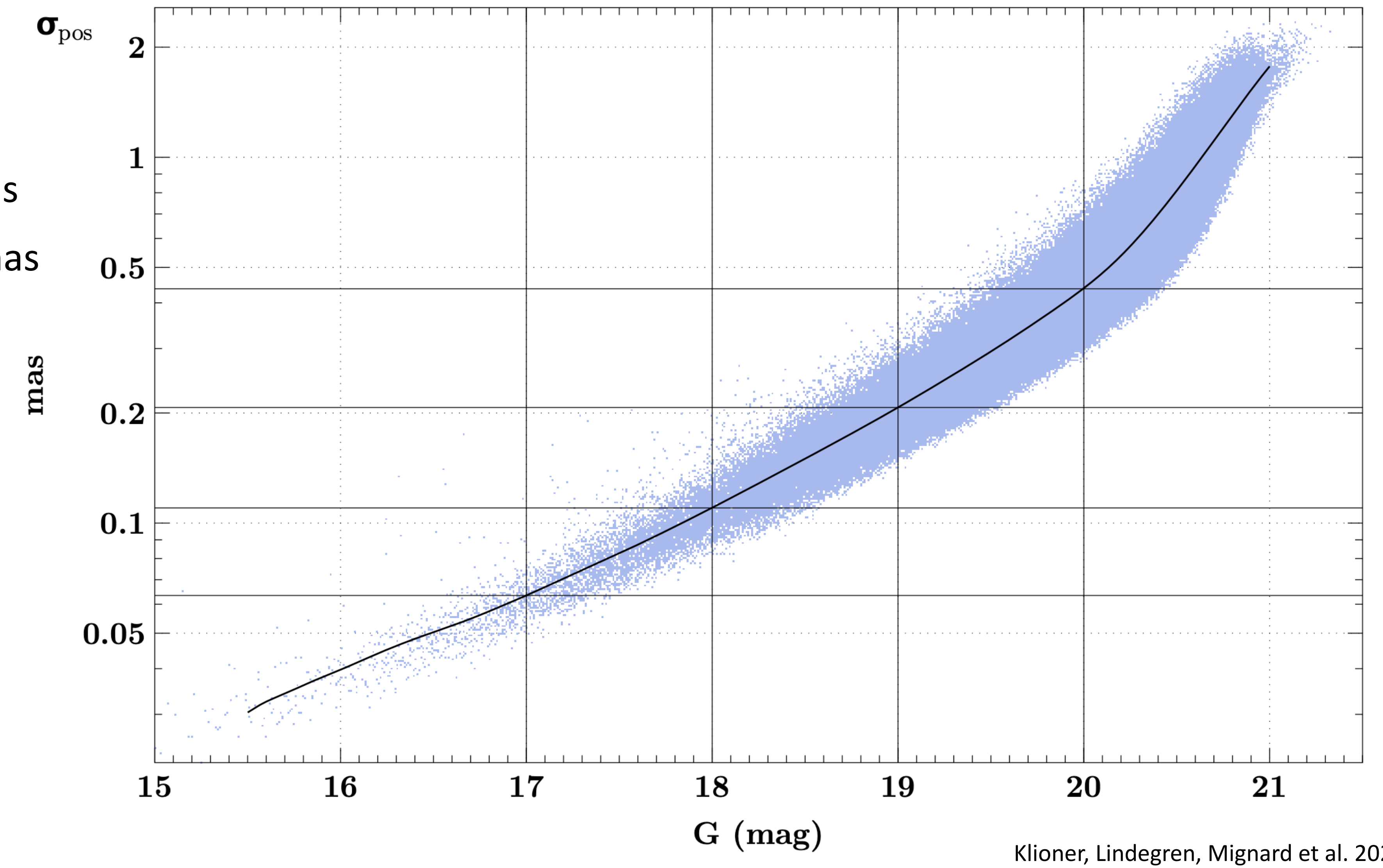
Gaia-CRF3 – Position uncertainties (in mas)

- 1.62 M QSOs to G = 21
  - 32,000 with σ_{pos} < 0.1 mas
  - 210,000 with σ_{pos} < 0.2 mas



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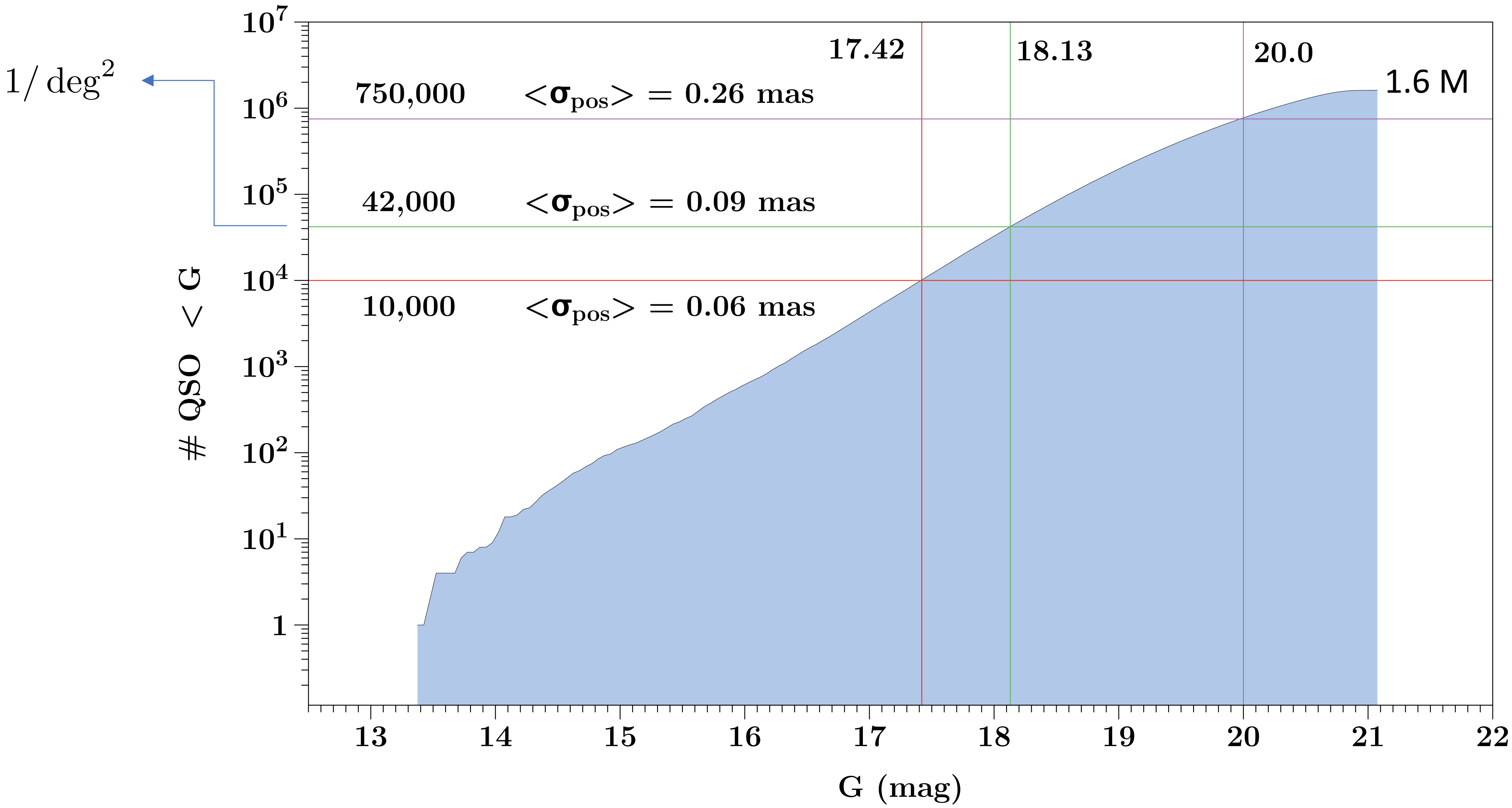
Gaia-CRF3

- Cumulative # sources/accuracy vs magnitude



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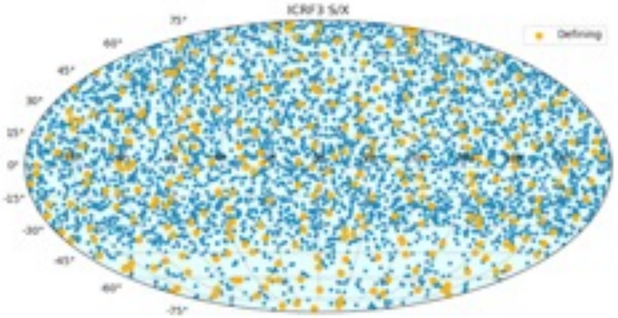
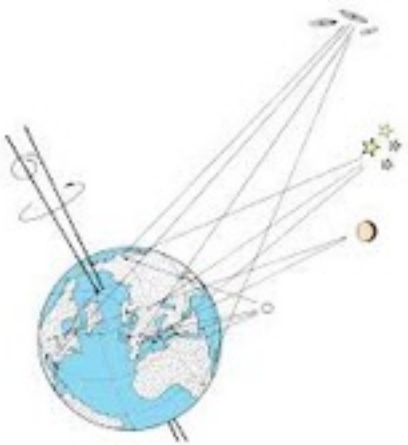
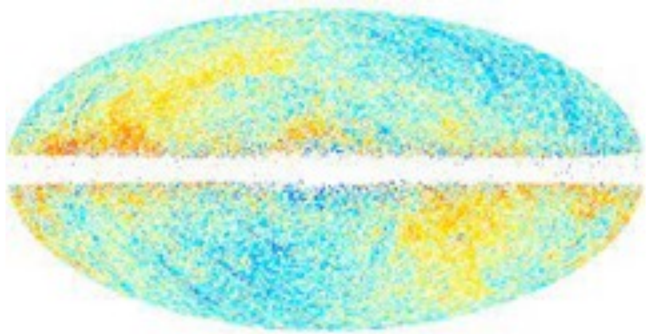




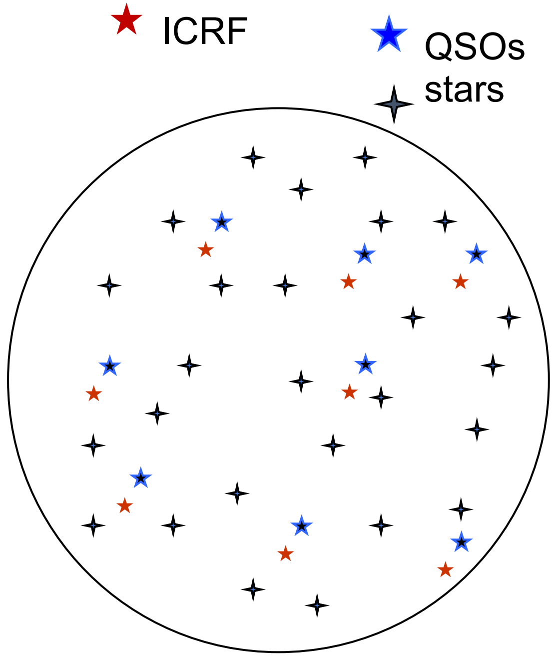


Alignment of radio and optical CRF

- Orientation is performed by minimizing the distances between Gaia positions and ICRF positions of common sources
  - GCRF needs to be aligned to ICRF
  - we have one infinitesimal rotations to fit $(\epsilon_x, \epsilon_y, \epsilon_z)$
- Many ICRF3 sources are observed by Gaia
  - 3142 G < 21 , 259 def. sources, σ_{Gaia} < 200 µas
  - Gaia-CRF and ICRF3 can be aligned to QSOs by a rotation
- ideally:

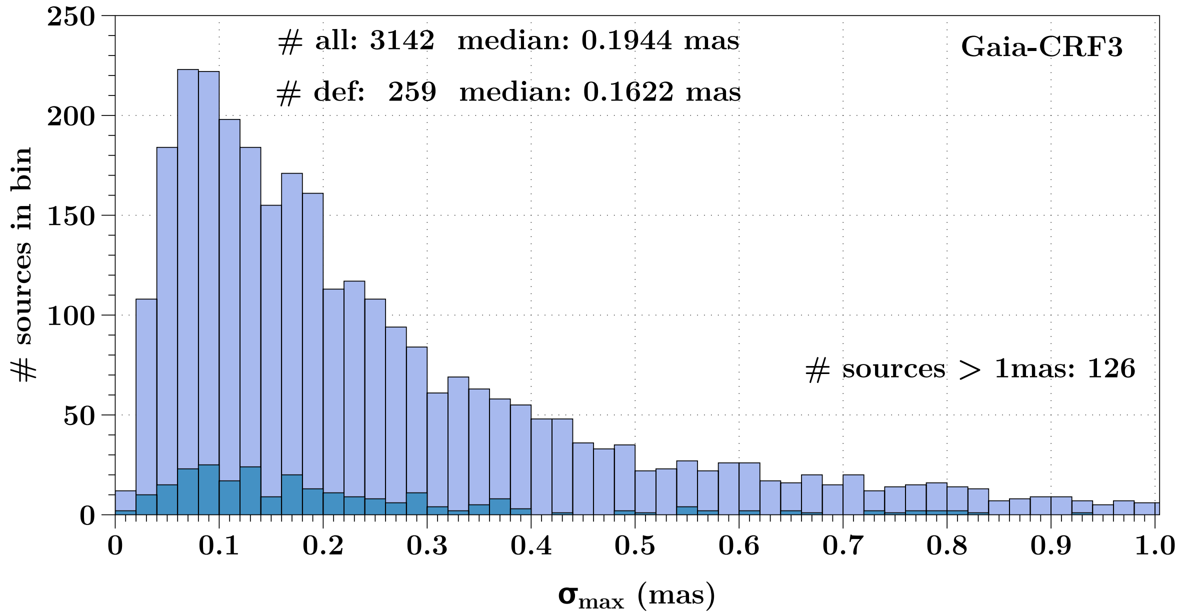
$$\sigma_{\rm align} \sim \sqrt{\frac{\sigma^2_{\rm Gaia} + \sigma^2_{\rm ICRF3}}{N_{\rm QSO}}} < 5\mu{\rm as}$$

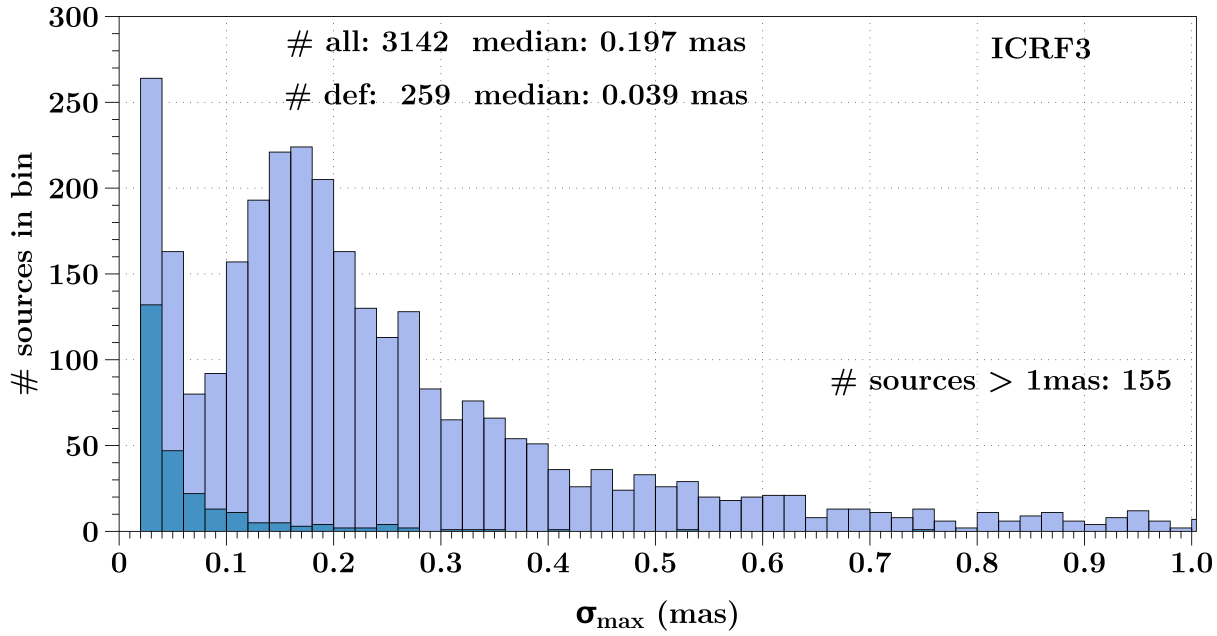
- but true accuracy depends on radio-optical offset
  - non random effect



Gaia-CRF3 & ICR3 – 3142 Common sources

- Formal uncertainties





0.2 % of the Gaia CRF

70% of the VLBI CRF

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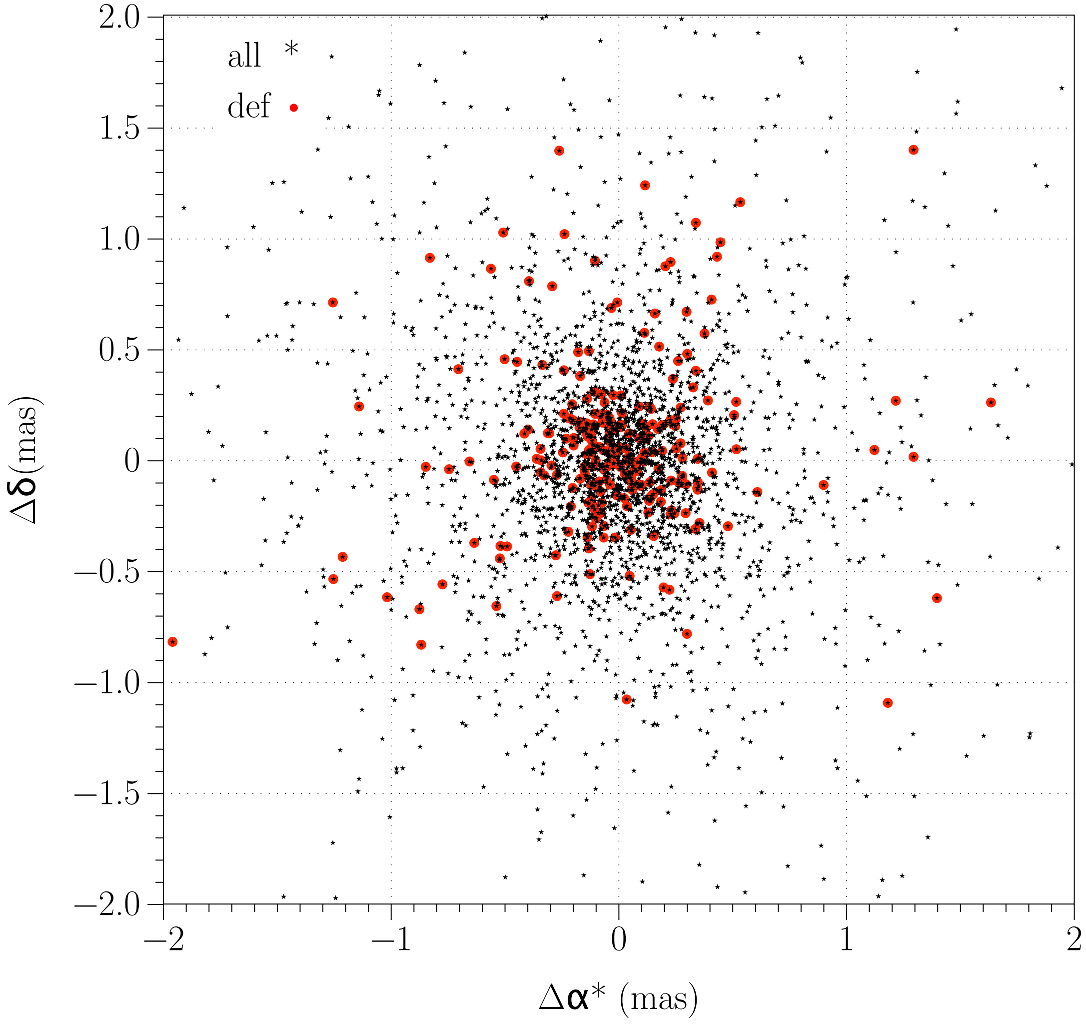
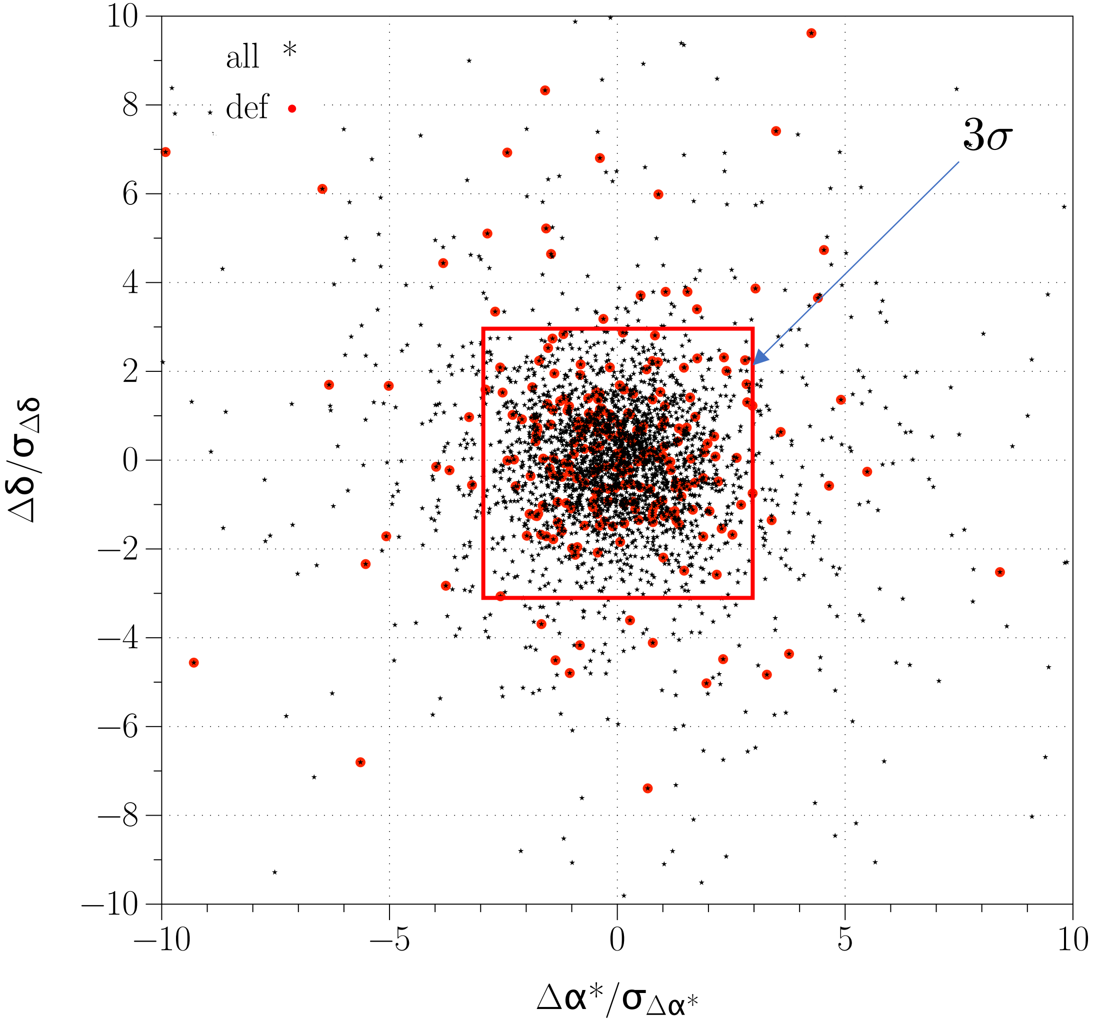
Gaia-CRF3

Positional differences

Absolute



Normalised



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IAU 2021

XXXIst GENERAL ASSEMBLY

RESOLUTIONS PRESENTED TO THE XXXIst GENERAL ASSEMBLY

RESOLUTION B3

On the Gaia Celestial Reference Frame

Proposed by the IAU Division A WG 'Multi-waveband Realizations of the International Celestial Reference System'

recognizing

4. that since the establishment of the ICRF3, the ESA space telescope Gaia has conducted relevant optical observations of extragalactic sources and made available a high quality astrometric catalogue for these sources;

resolves

10. that as from 1 January 2022, the fundamental realization of the International Celestial Reference System (ICRS) shall comprise the Third Realization of the International Celestial Reference Frame (ICRF3) for the radio domain and the Gaia-CRF3 for the optical domain.


Thanks for
your attention

Spare slides

Gaia frame ageing : principles

- FK5 had an epoch and degraded with time
  - primarily because of the **uncertainty** in the PM
- Initial ICRF have no epoch (ICRF1, 2)
- There is no reference to any moving pole or origin
- Positions of fiducial sources are in principle defined for ever
  - they are replaced only when a better realisation is available
  - not because the realisation has degraded
- However, with the time one sees positional instability in defining sources
  - structure is also evidenced with high resolution radio maps

Gaia frame ageing: model

- A stellar frame degrades with time because of the star proper motions
  - true limitation : not the PM themselves but how well they are known

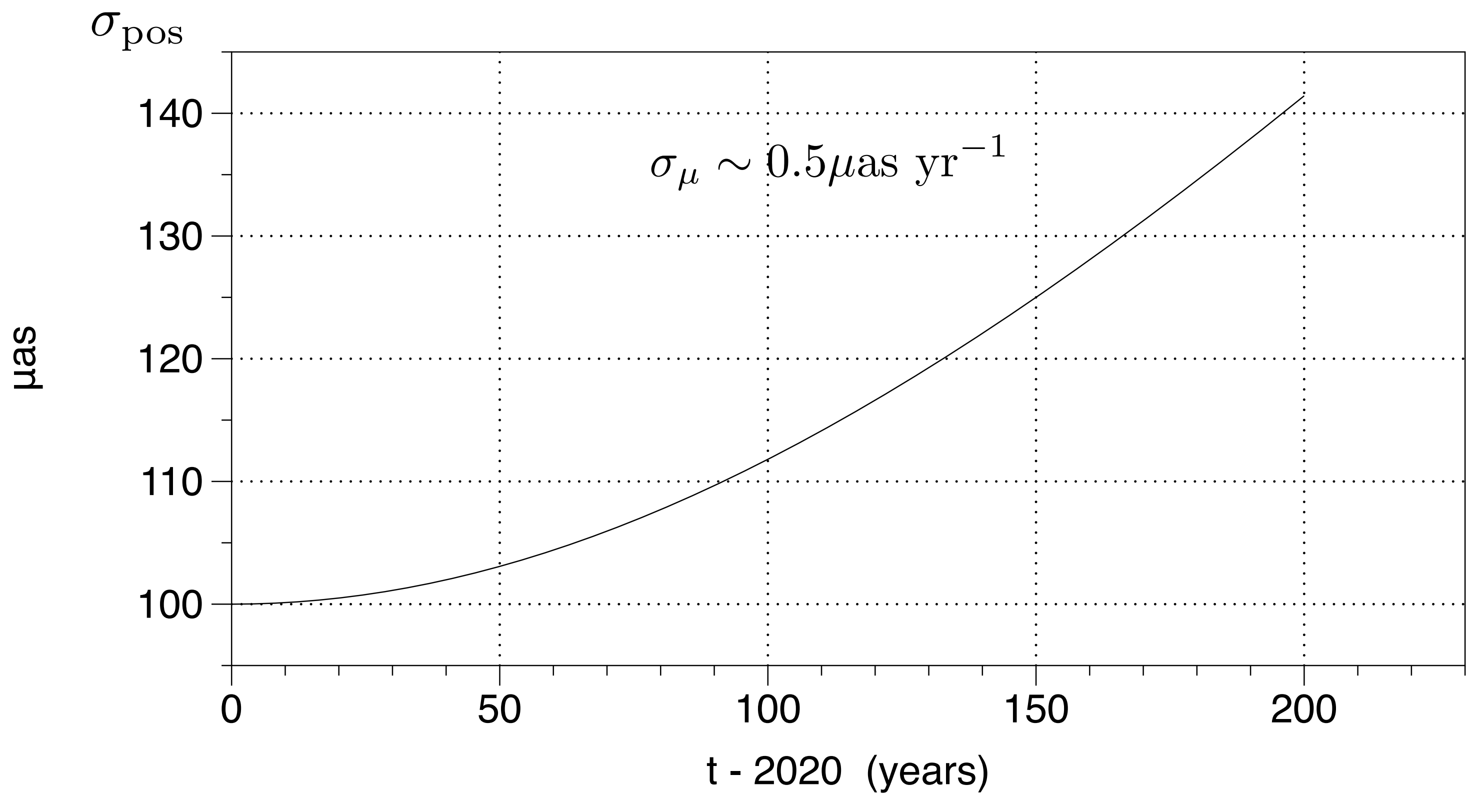
$$\sigma^2_{\alpha*}(t) = \sigma^2_{\alpha*}(t_0) + \sigma^2_{\mu_{\alpha*}}(t-t_0)^2$$

after a while : $\sigma_{\alpha*}(t) \approx \sigma_{\mu_{\alpha*}}(t-t_0)$

- QSOs have in principle no individual sensible proper motion
  - but galactic acceleration gives a systematic motion of $\sim 5 \pm 0.5\ \mu\mathrm{as\ yr}^{-1}$
- there is no need to plan the maintenance FOR THAT FEATURE
  - the denser optical access with the stars will degrade much faster
- In addition the acceleration parameter will be improved
- But other transverse motions will show up with the time

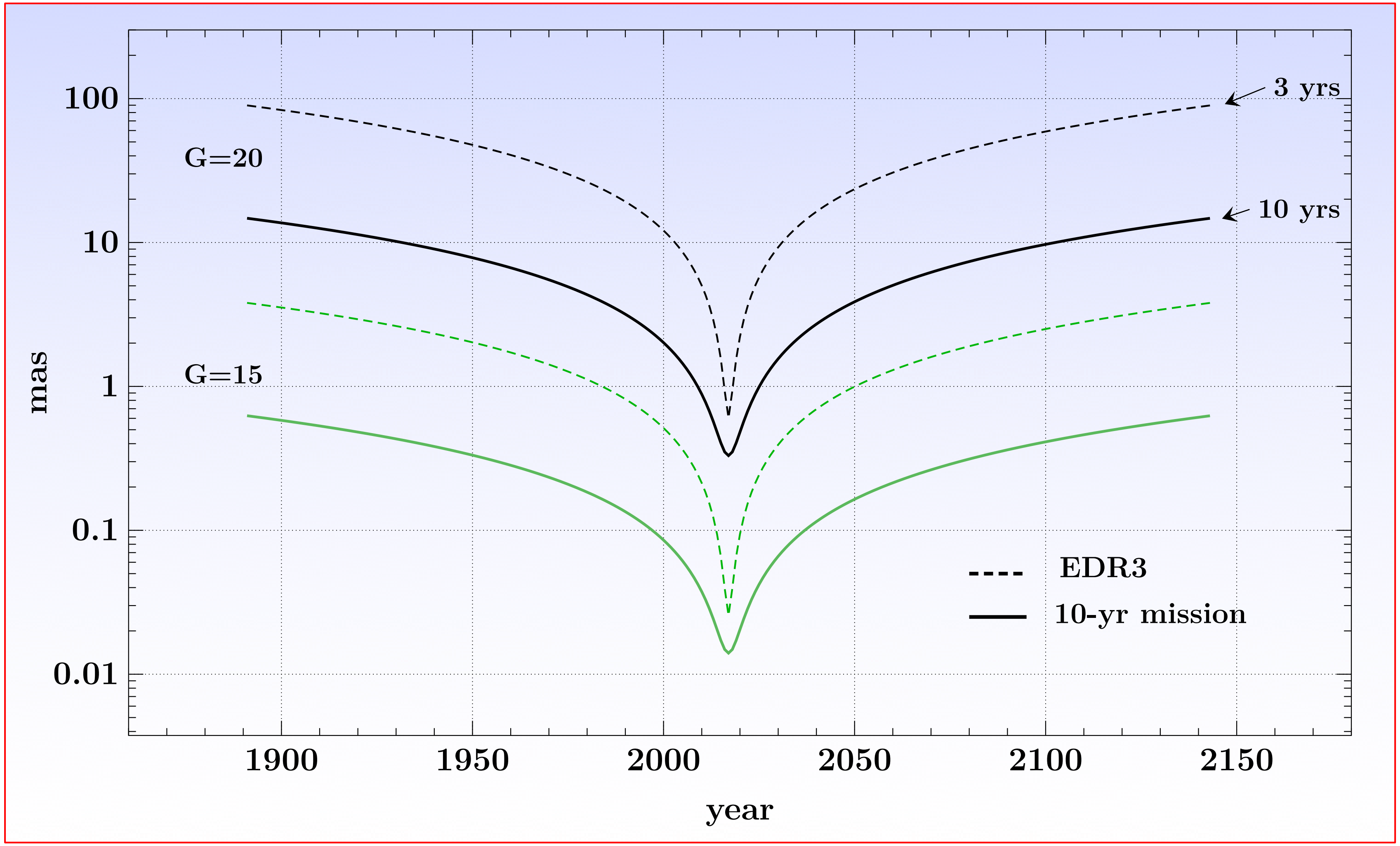
Gaia frame ageing: size

- Change of the positional uncertainty with time due to the limited knowledge of the galactic acceleration
  - very slow degradation



Reference frame : Gaia stellar frame

Gaia positional accuracy (stars) past and future

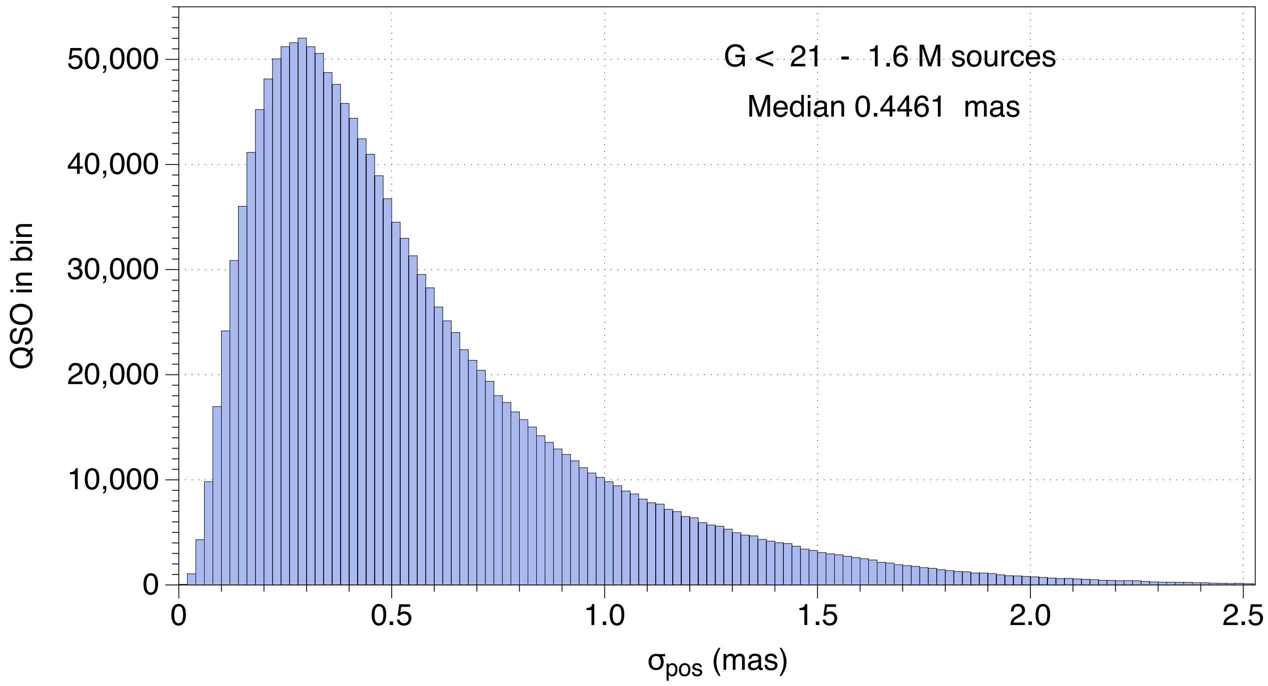


ICRS/ICRF today

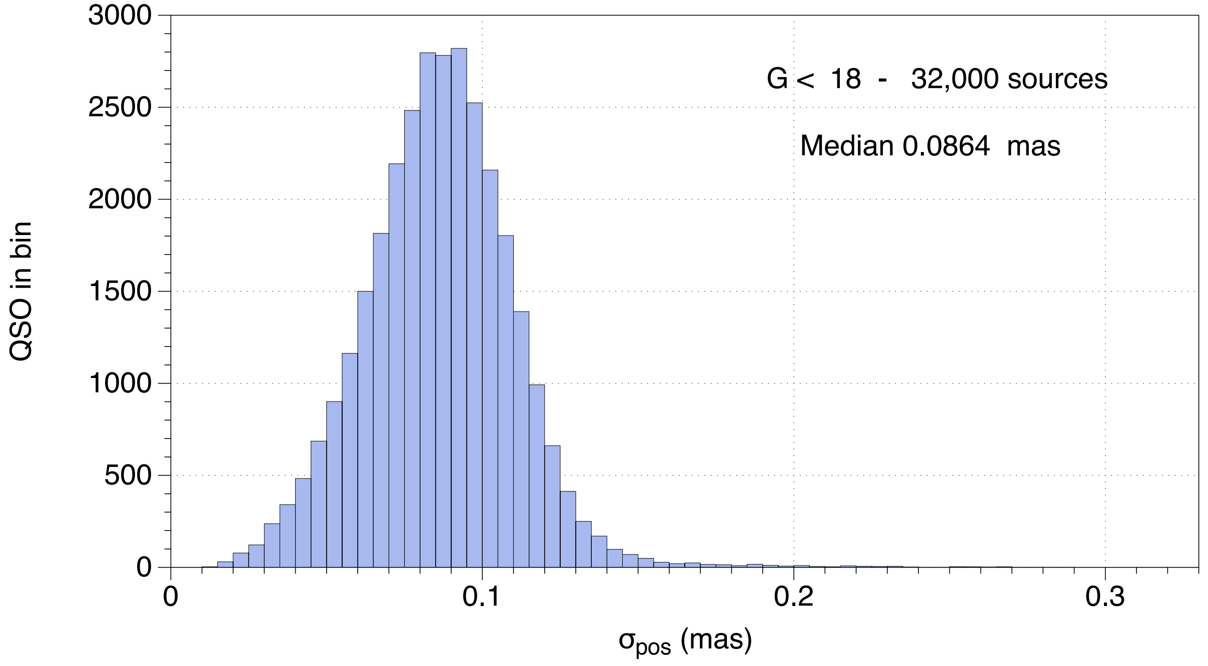
- Kinematical system with basic assumption :
    - the most distant sources exhibit no global rotation
    - globally at rest with respect to CMB
    - QSOs have no sizeable transverse motion
- Origin : should be the solar system barycentre
- Pole : should be close to the J2000 celestial pole
- Origin of right ascension : should be consistent with the FK5 equinox
- Realisation : from a set of stable QSOs
    - Observational technique determined at any time by the state of the art

Gaia-CRF3 – Position uncertainties (in mas)

G < 21, 1.6 M QSOs



G < 18, 32 k QSOs



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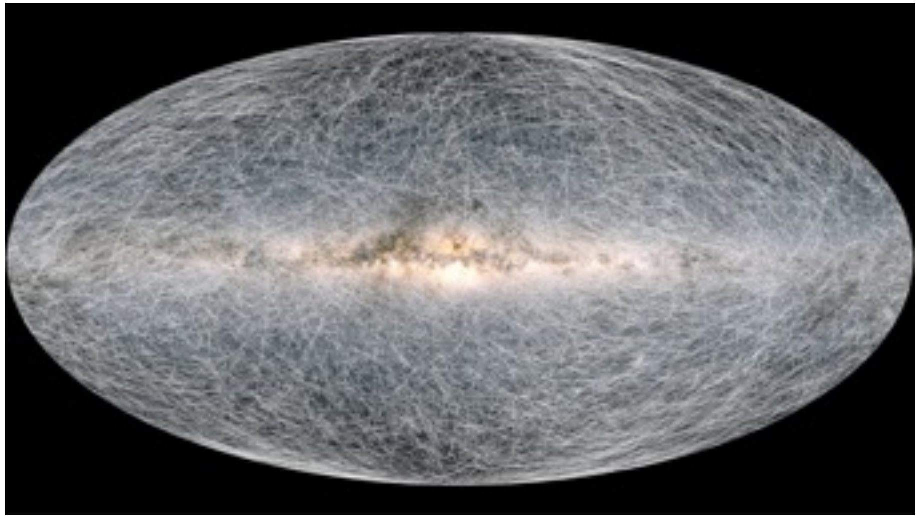
Gaia Data Releases

- DR1 : 14 September 2016 (data : 14 months)
- DR2 : 25 April 2018 (data : 22 months)
- EDR3 : 03 December 2020 (data : 34 months)
- DR3 : 13 June 2022 (data : 34 months)
- DR4 : ~ 2024-2025 (data : 66 months) → data on-ground
- DR5 : ~ 2029 (120 months) → 96 months already acquired

A more comprehensive list

- Celestial frames
  - differential rotation of the Galaxy
  - Motion of stars in the Galaxy
  - dynamics of star clusters
  - source cross-identification in γ, X, visible, IR, radio wavelengths
  - dynamics of the solar system
  - motion and rotation of galaxies in general
  - Earth rotation
  - Space navigation
  - civil engineering and defense
  - GNSS maintenance



A more comprehensive list

- Terrestrial frames
  - global positioning
  - lithospheric plate motions
  - sea level change
  - polar motion
  - satellites tracking
  - Earth and oceanic tides
  - hydrosphere (sea level, post-glacial rebound, …)
  - civil engineering and defense