The Celestial Reference Frame

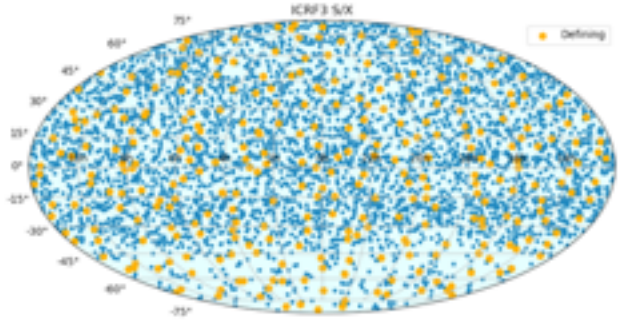
F. Mignard

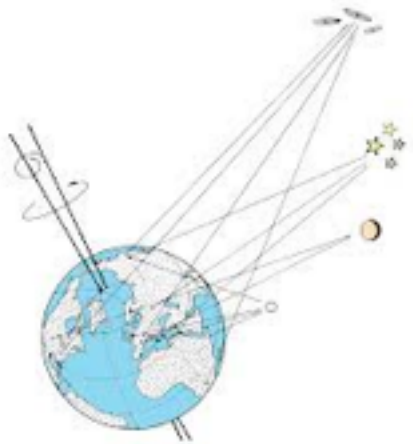
Observatoire de la Côte d'Azur/Lagrange

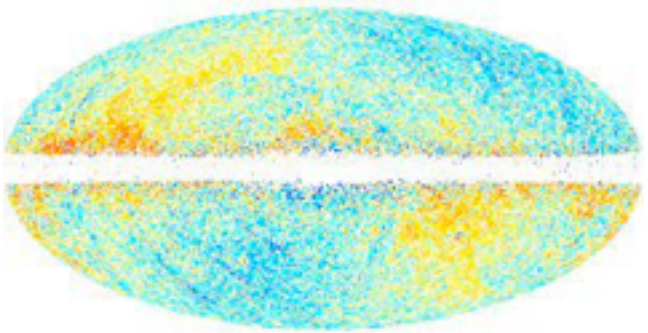
29 Sept 2022

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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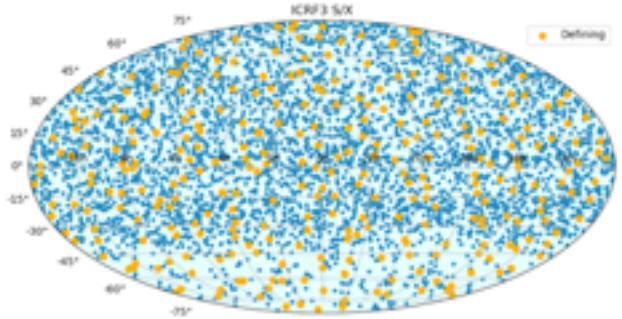
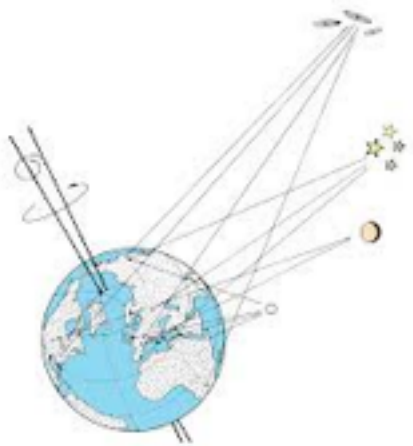
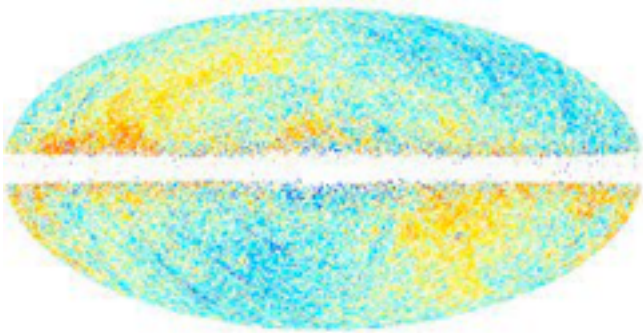




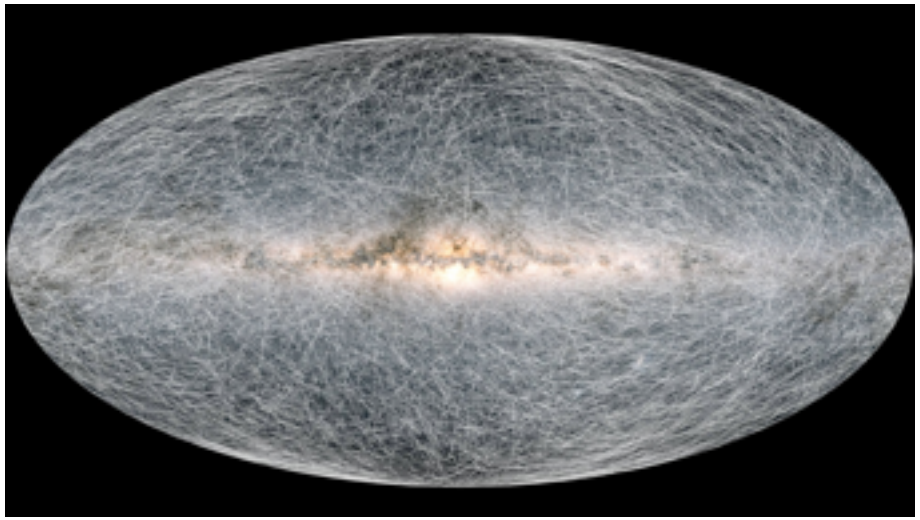


A Reference frame : what for?

- 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

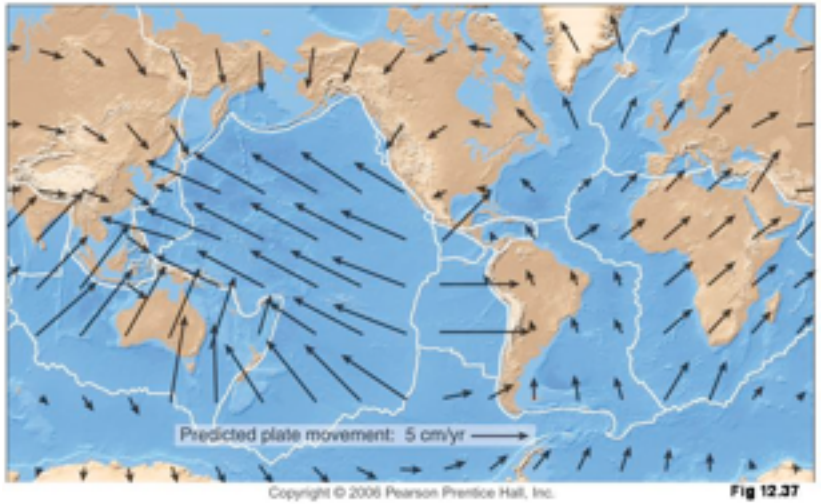
A more comprehensive list

- 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
  - UT1/UTC
  - lithospheric plate motions
  - sea level change
  - polar motion
  - satellites tracking
  - Earth and oceanic tides
  - hydrosphere (sea level, post-glacial rebound, …)
  - civil engineering and defense



A Reference frame : theory and practice

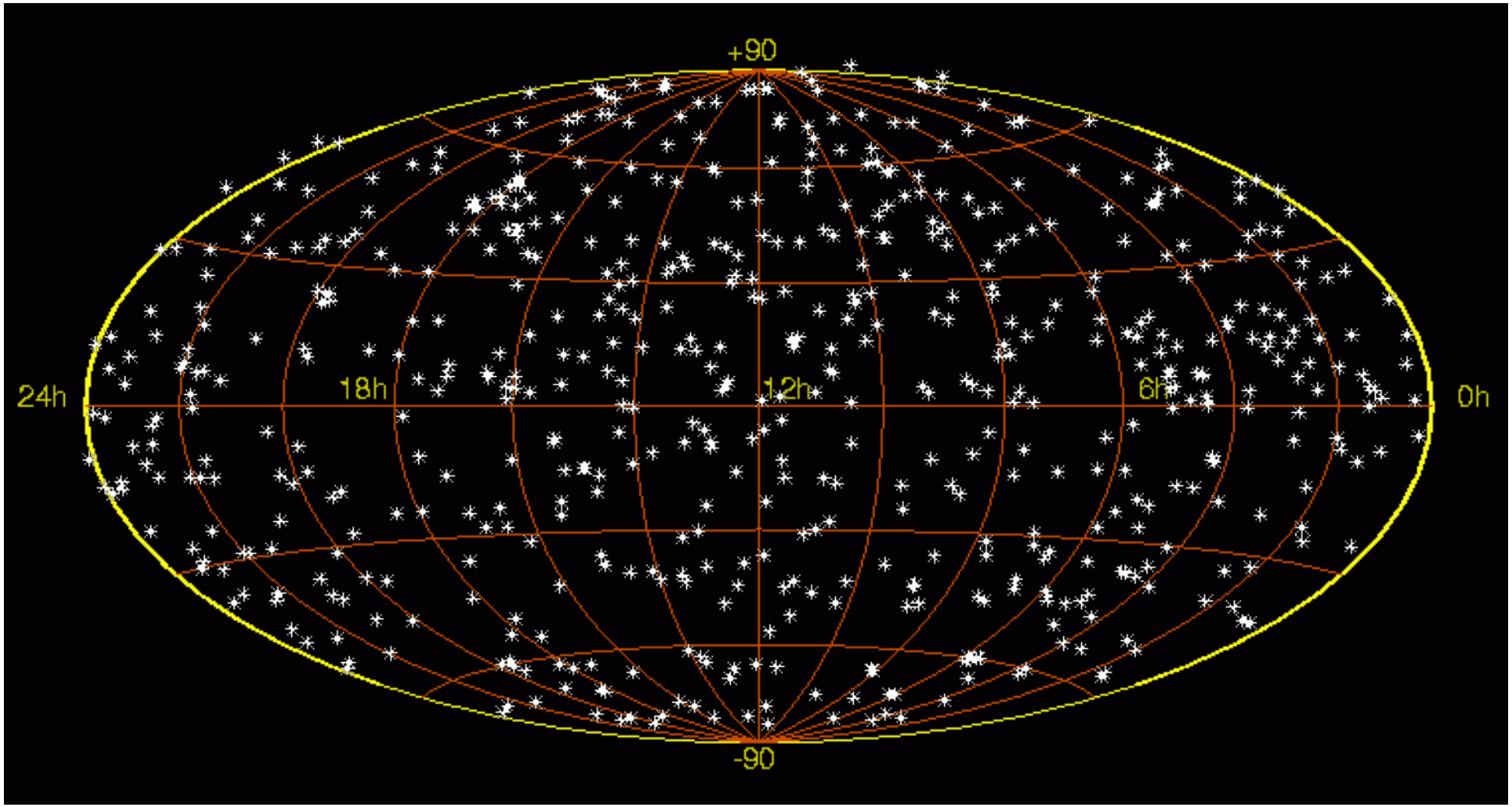
- One must distinguish between
  - **The System**: ICRS
    - Set of specifications defining the coordinate system, including origin, fundamental planes/axes, along with constants, models, and algorithms for transforming observables.
  - **The Realisation**(s): ICRF
    - Set of sources/points on the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

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

Observational technique(s) determined at any time by the state of the art

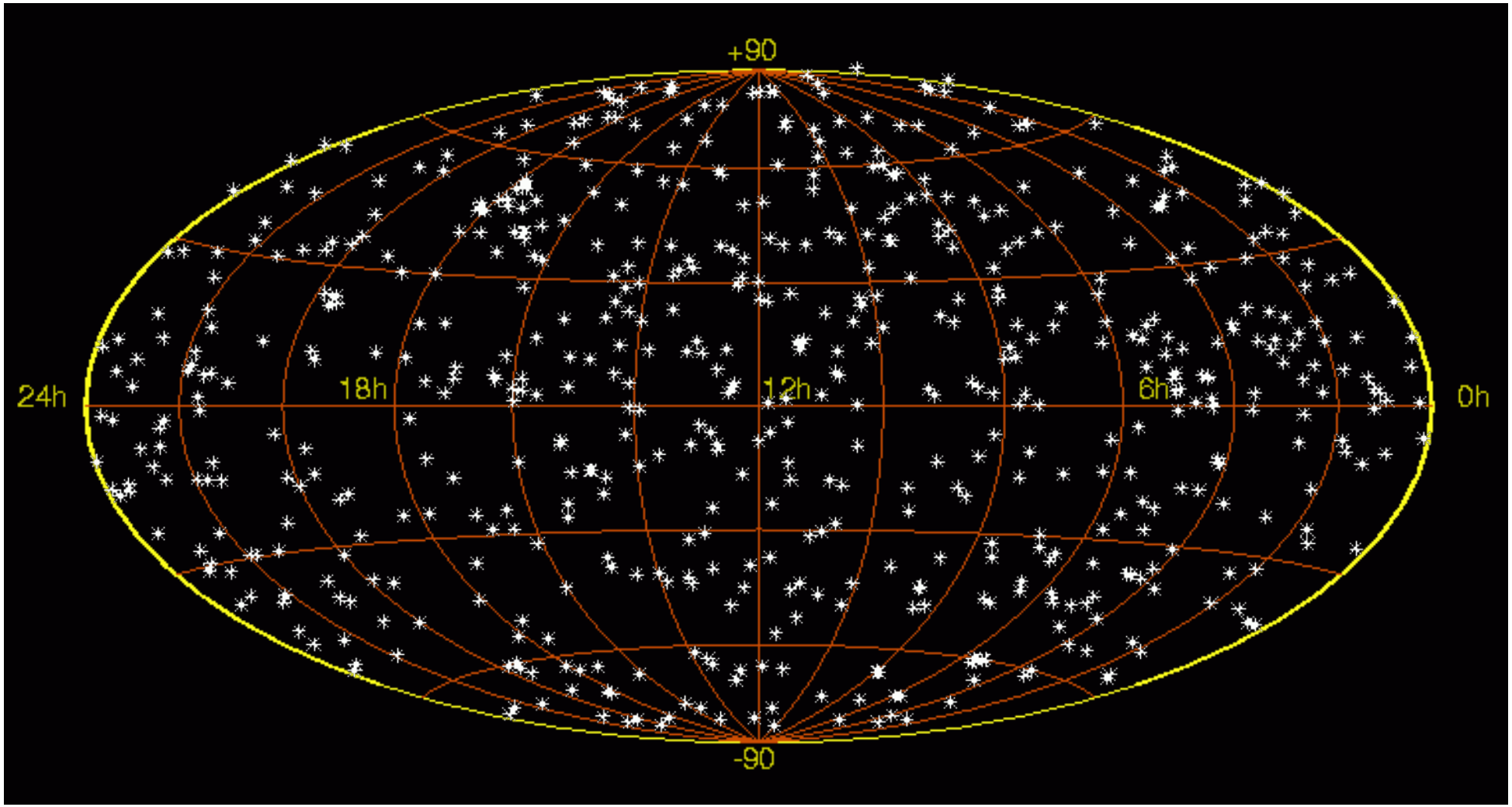
Reference frame : the user point of view

- 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

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

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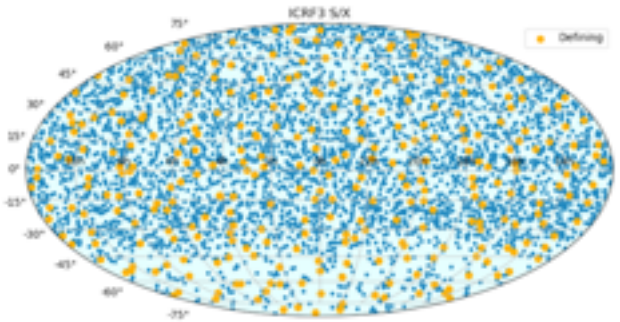
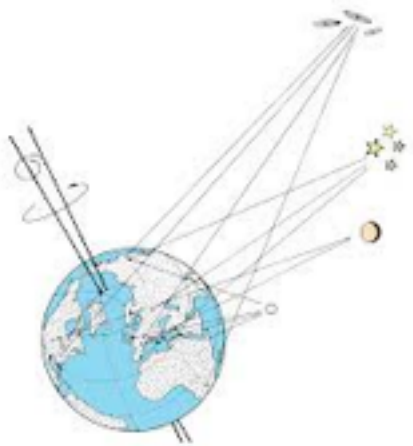
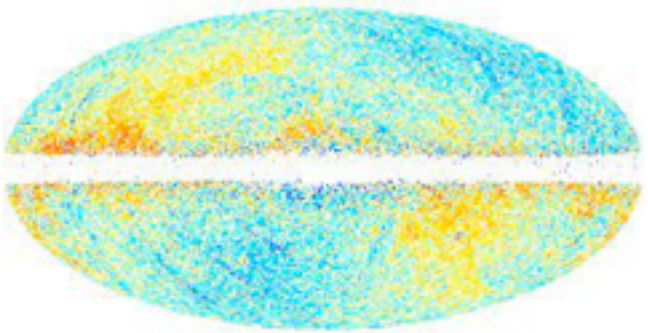
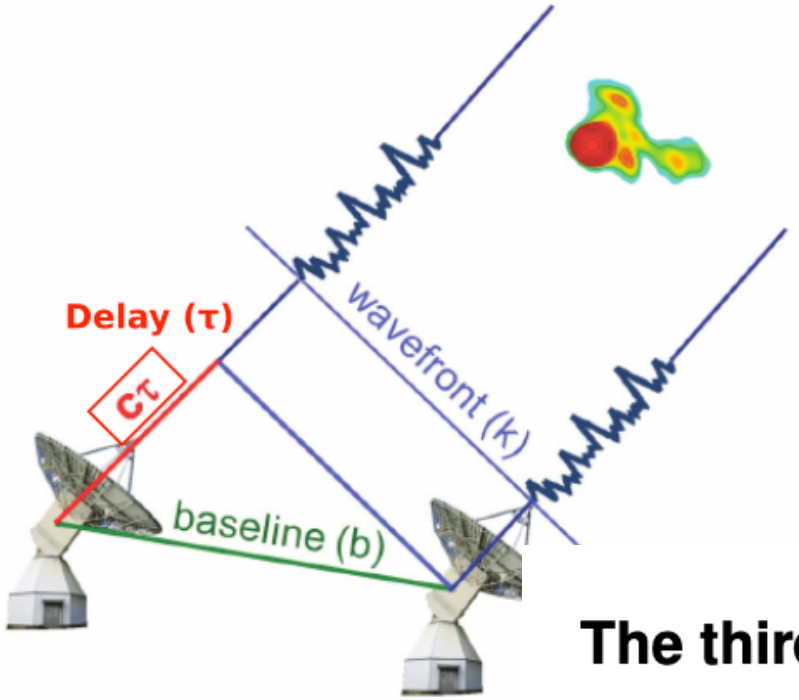








ICRF radio – ICRF3

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]

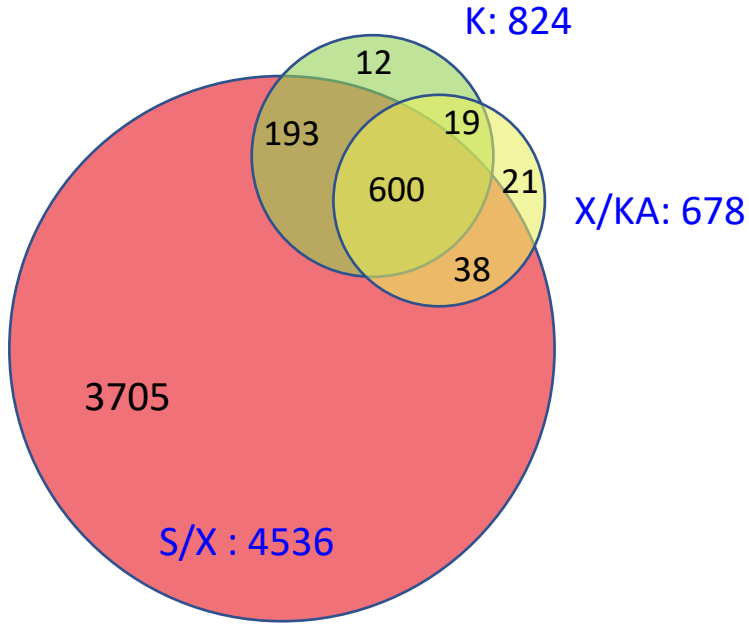
A&A 644, A159 (2020)

VLBI CRFs

- Three releases so far
  - ICRF1 : 1998 600 sources - **2 mas** [def < 0.5 mas]
  - ICRF2 : 2009 3400 sources - **0.2 mas to 5 mas** [def < 0.15 mas]
  - ICRF3 : 2018 4500 sources - **0.05 mas to 1 mas** [def : 0.05 mas]
  - ICRF4 : ?
- Three frequencies in ICRF3

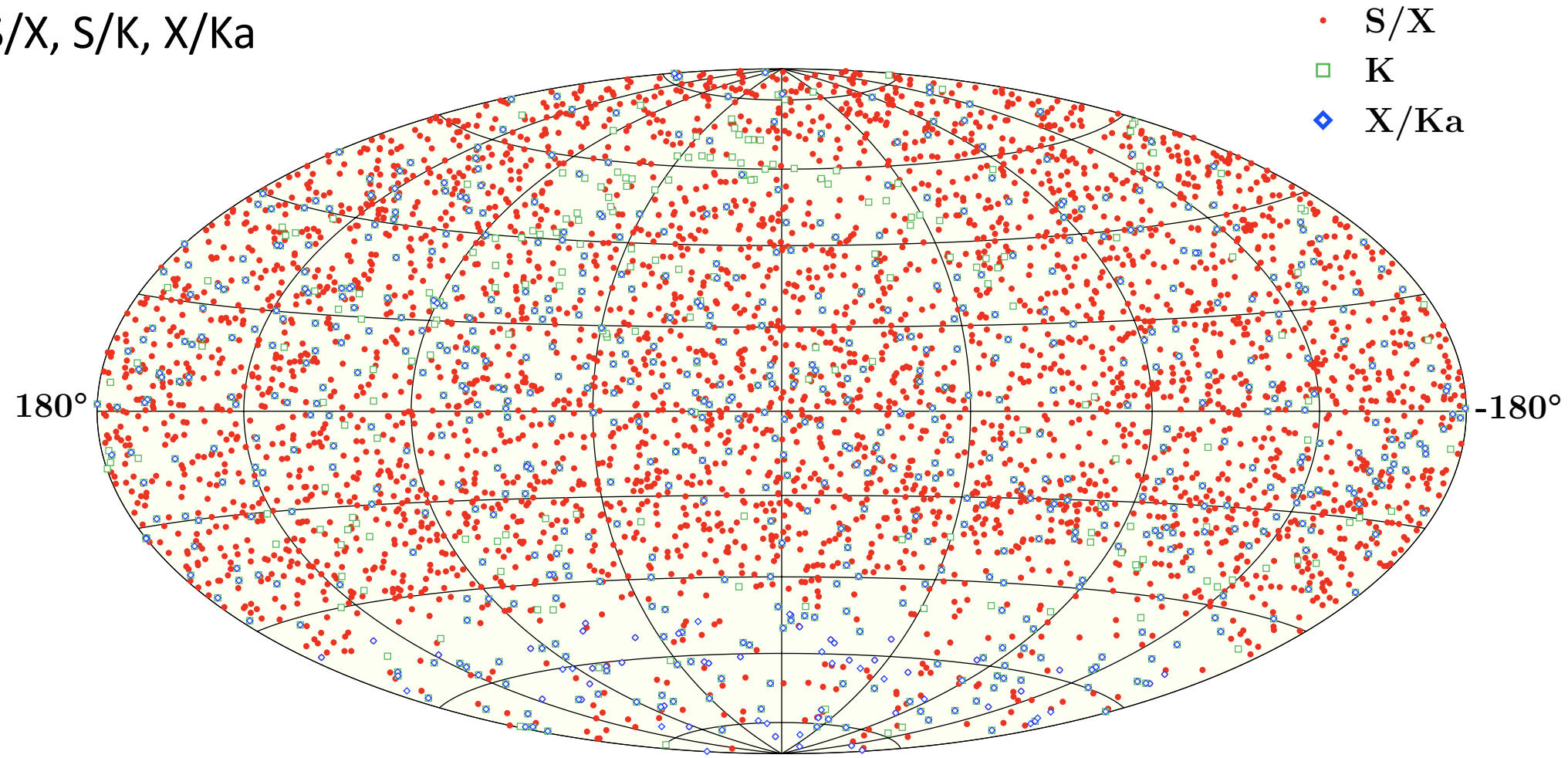
ICRF radio – ICRF3

- 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

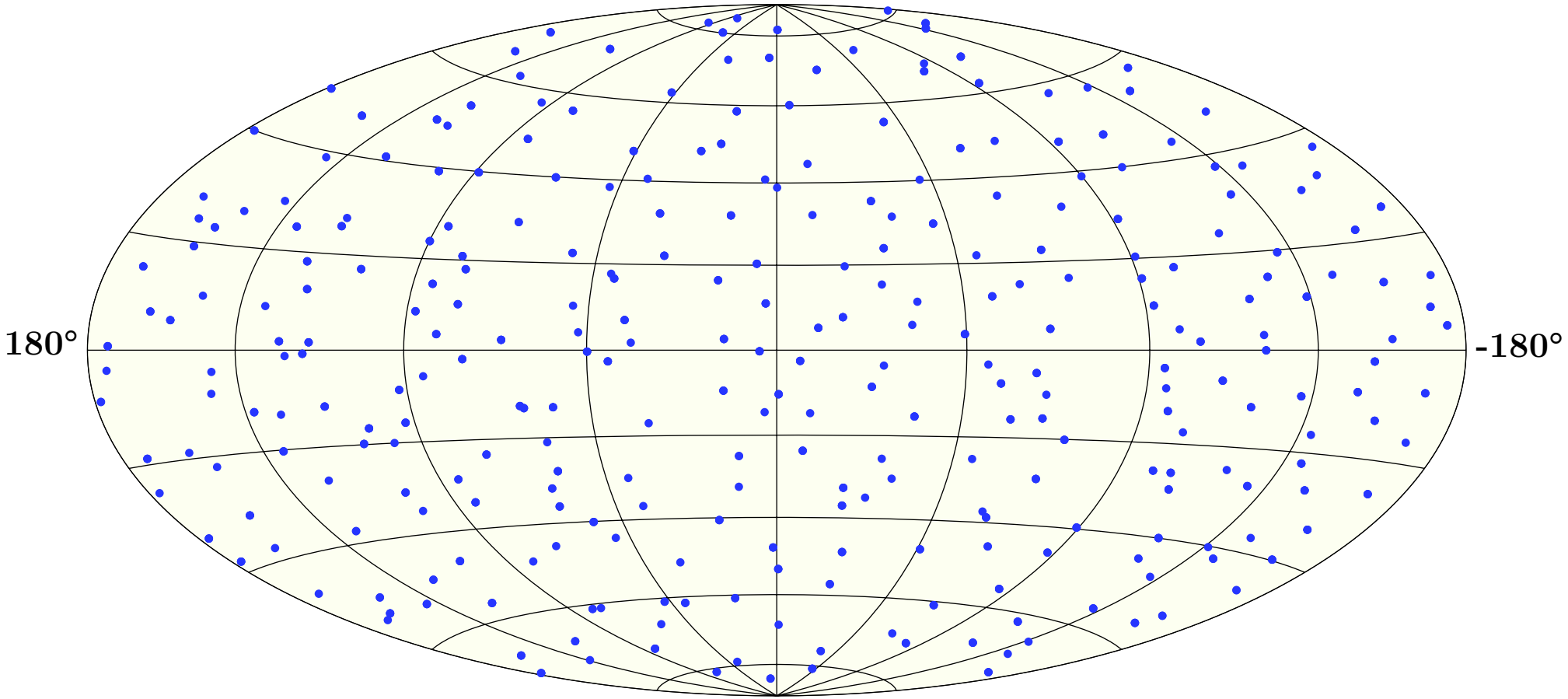
- S/X, S/K, X/Ka



ICRF radio – ICRF3

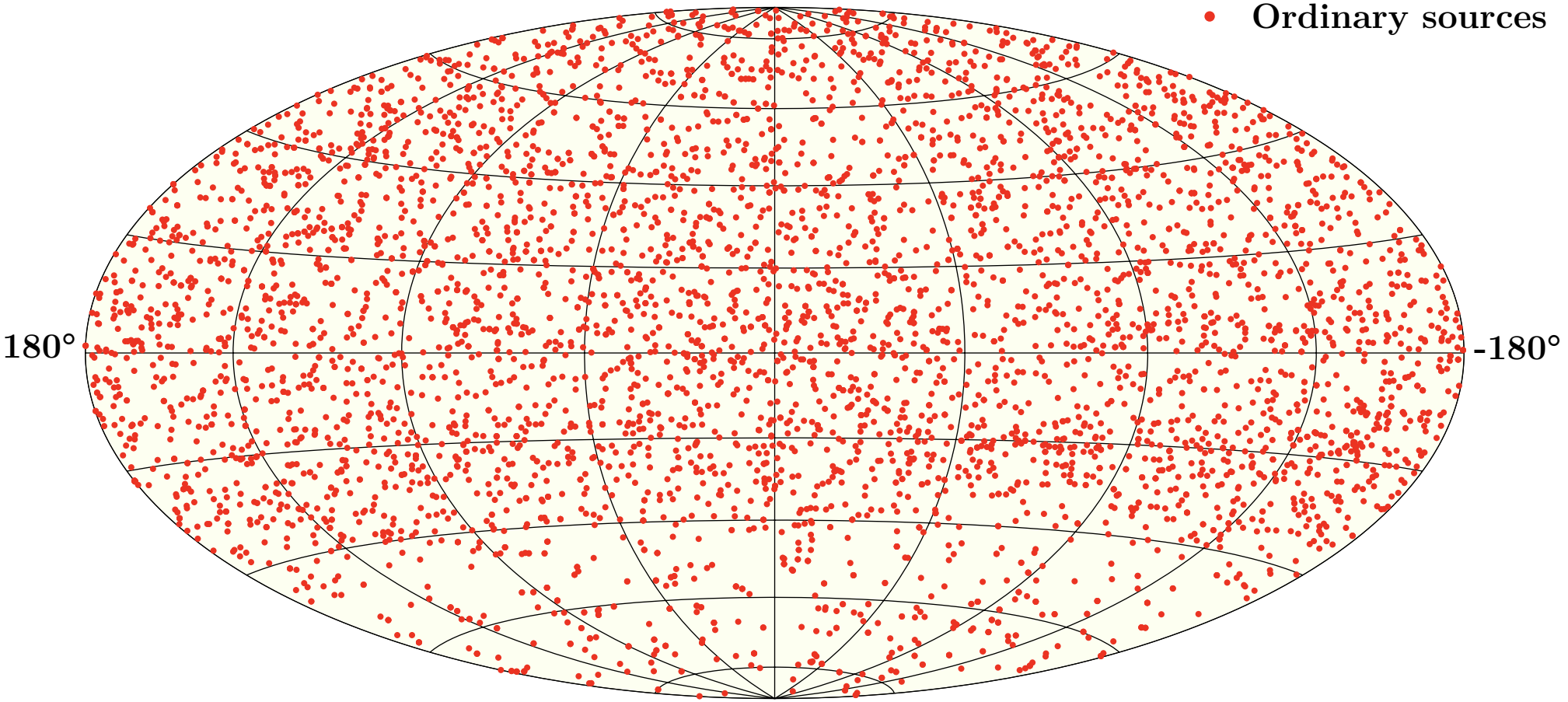
- S/X defining sources

- Defining sources (303)



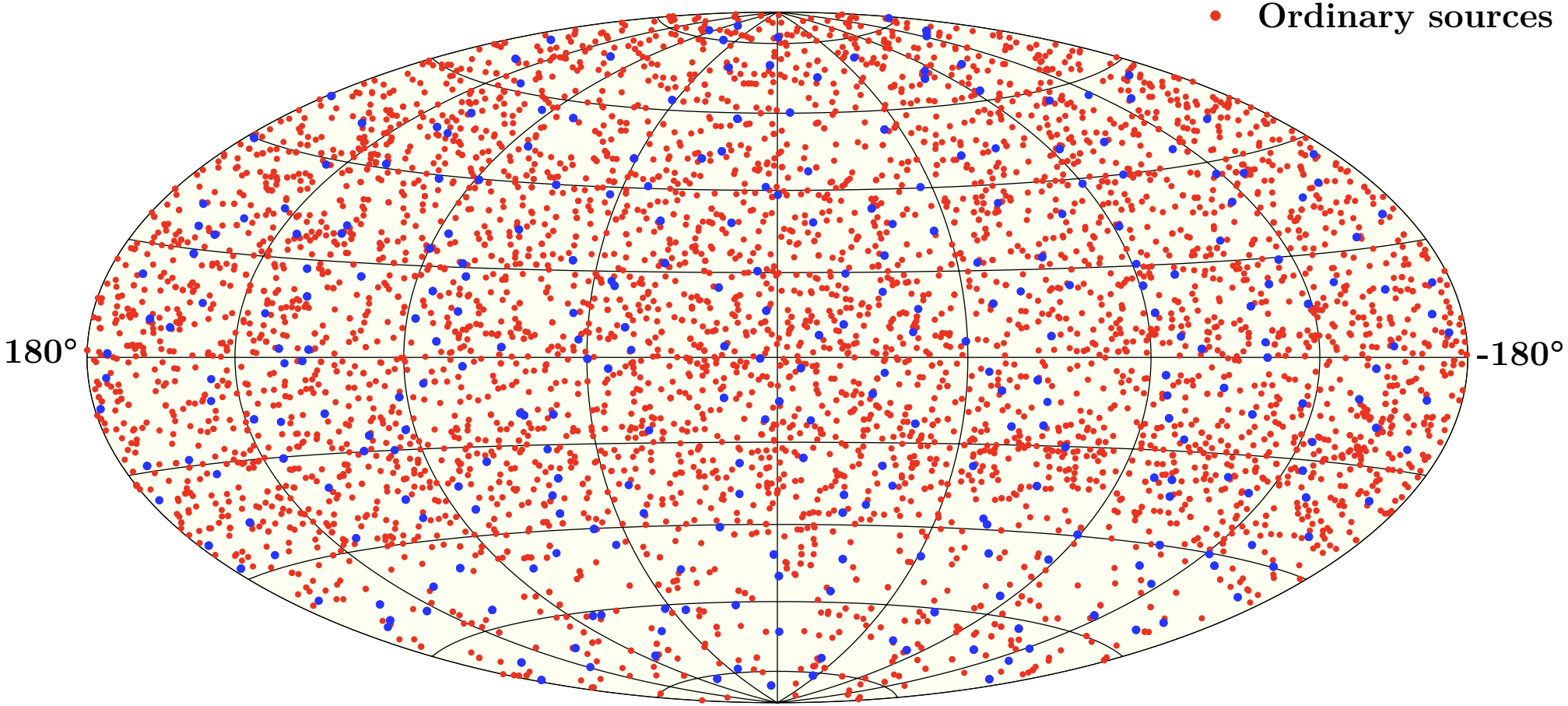
ICRF radio – ICRF3

- S/X secondary sources



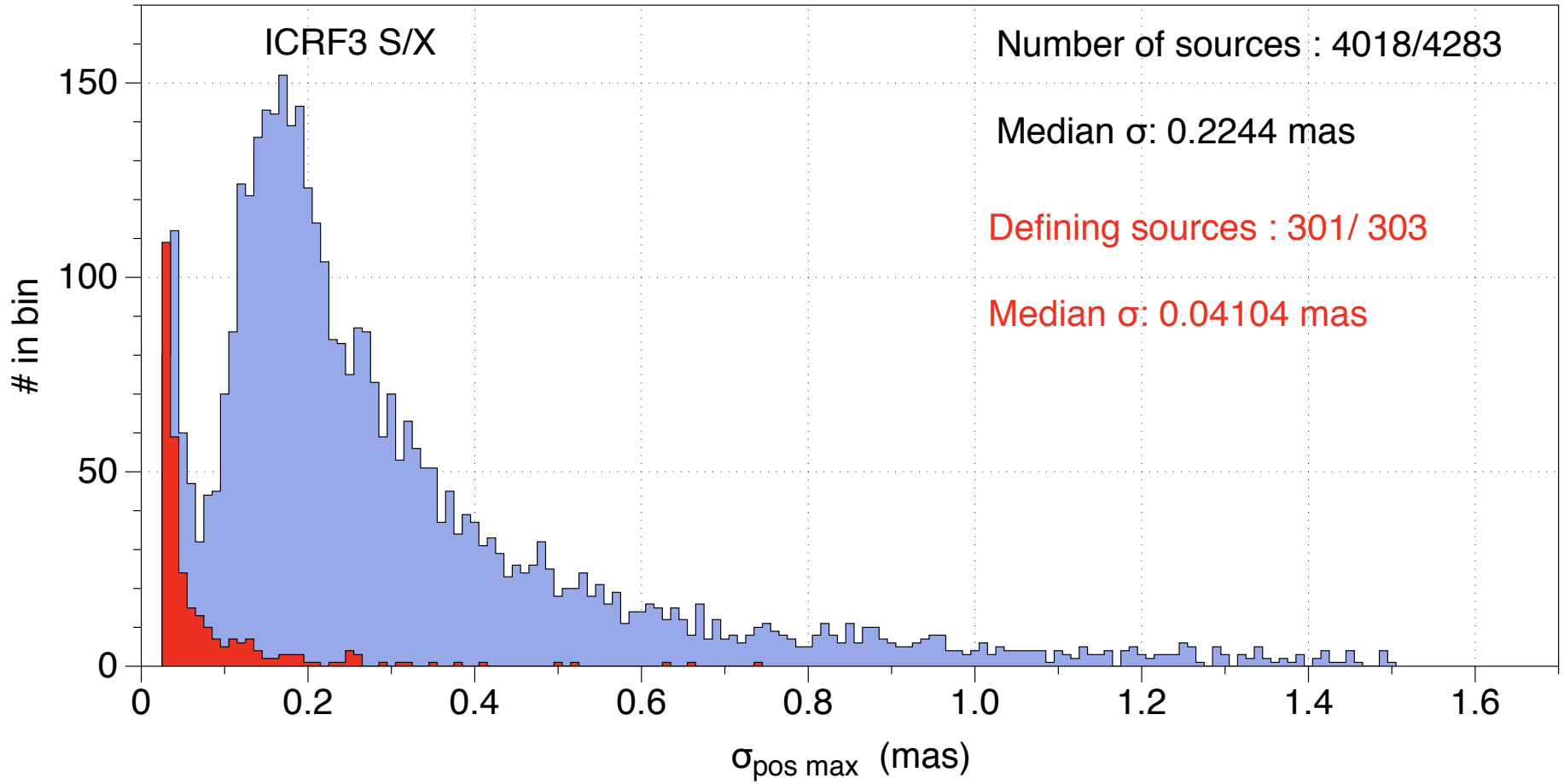
ICRF radio – ICRF3

- S/X : 4536 sources



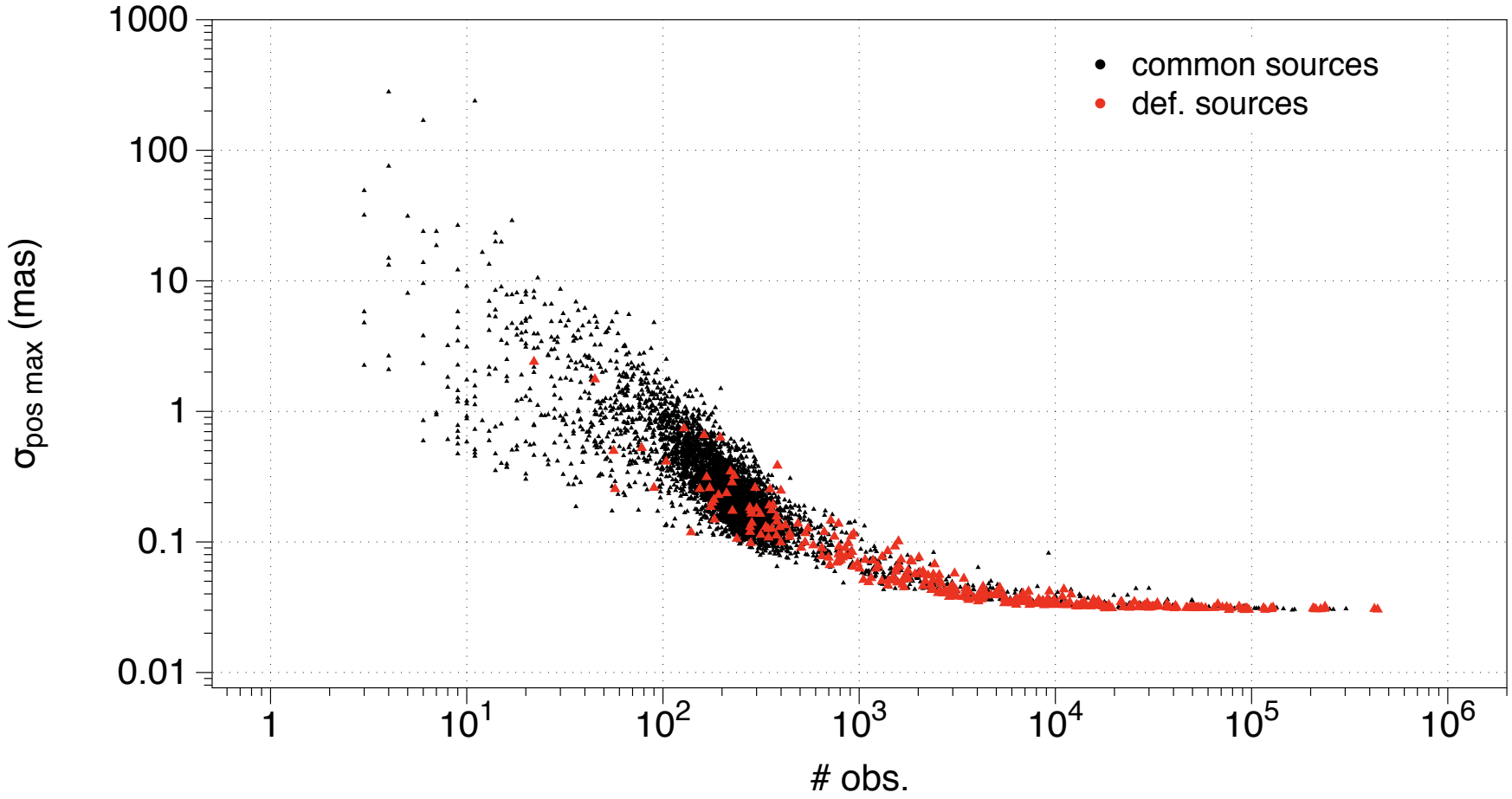
ICRF radio – ICRF3

- Positional uncertainties



ICRF radio – ICRF3

- Precision vs. number of delays



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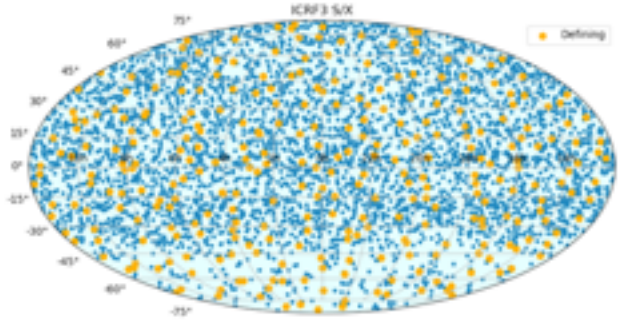
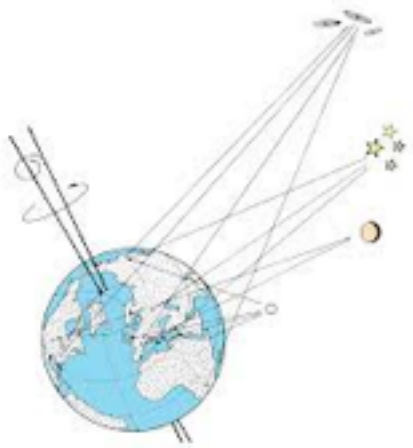
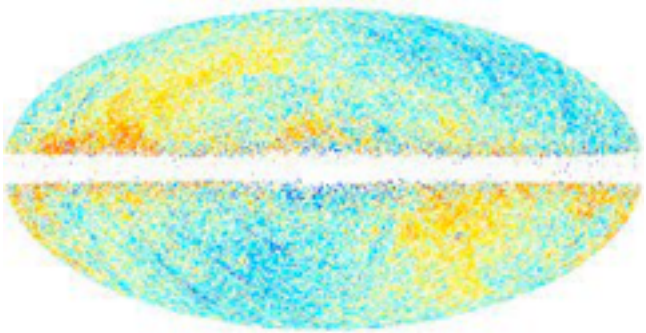
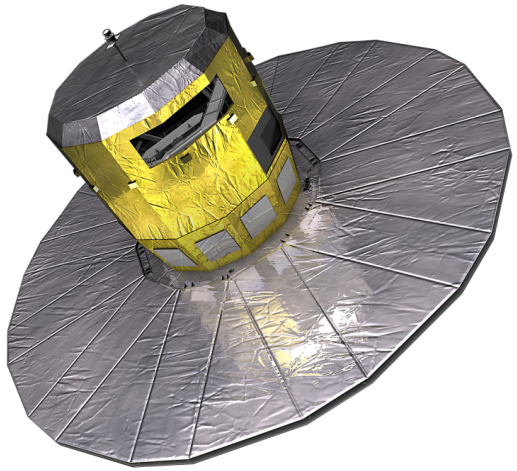








Gaia CRF3

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 CRFs

- One solution for each release
  - Gaia-CRF1 : Sep 2016 2191 sources (from 3414 ICRF2) - **0.5 mas** @ G=18
  - Gaia-CRF2 : Apr 2018 555,000 sources [2820 common to ICRF3 proto]) - **0.15 mas** @ G=18
  - Gaia-CRF3 : Dec 2020 1.615 M sources [3142 common to ICRF3]) - **0.11 mas** @ G=18
  - Gaia-CRF4 : ~ end 2025
- Global astrometry from Gaia

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 :
  - $|\sin b| > 0.1$
  - $\varpi/\sigma_{\varpi} < 5$ ➔ parallaxes should be 'zero'
  - $\mu/\sigma_{\mu} < 5$ ➔ PM should be 'zero'
  - cleanliness favoured over completeness
    - narrow match window
    - detection of polution by stellar contaminants
- Global astrometry from Gaia
- Remark : selecting sources only from Gaia + small parallax + small PM = 210 M sources in Gaia-DR3 ➔ more stringent selection criteria needed

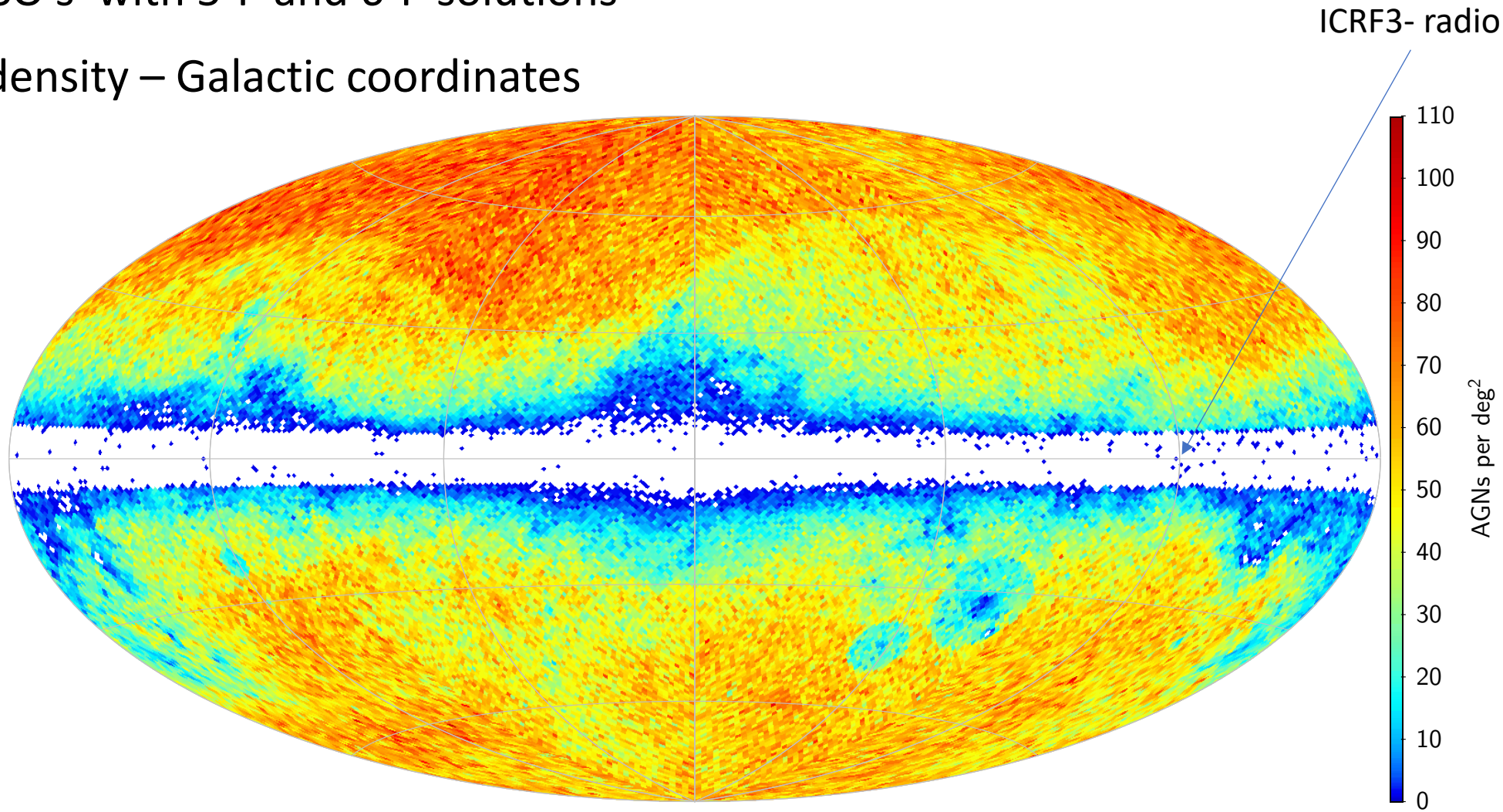
Gaia CRF3 : selection of sources

- X-matches from 17 external catalogues
- get rid of the stellar contaminants

catalogue		sources	unique matches	filtered sources	retained sources
ICRF3 S/X	V	4536	3477	3142	3142
ICRF3 K	L	824	715	660	660
ICRF3 X/Ka	B	678	611	576	576
OCARS	I	7607	5337	4723	4723
AllWISE		1 354 775	733 462	580 403	580 403
Milliquas v6.5		1 980 903	1 347 414	1 065 936*	1 039 610
R90		4 543 530	1 331 547	1 022 081	1 022 081
C75		20 907 127	2 068 813	1 265 419*	1 169 431
SDSS DR14Q		526 356	368 013	308 608	308 608
LQAC-5		592 809	421 289	348 085	348 085
LAMOST phase 1, DR1-5		42 578	42 255	39 886	39 886
LQRF		100 165	98 902	94 839	94 839
2QZ		28 495	24 192	21 569	21 569
Roma-BZCAT, release 5		3561	3343	2986	2986
2WHSP		1691	982	413	413
ALMA calibrators		3361	2746	2209	2209
Gaia-unWISE C75		2 734 464	2 726 201	2 061 253*	1 569 359
Final unique matches					**1 614 173**

EDR3 - Gaia-CRF3

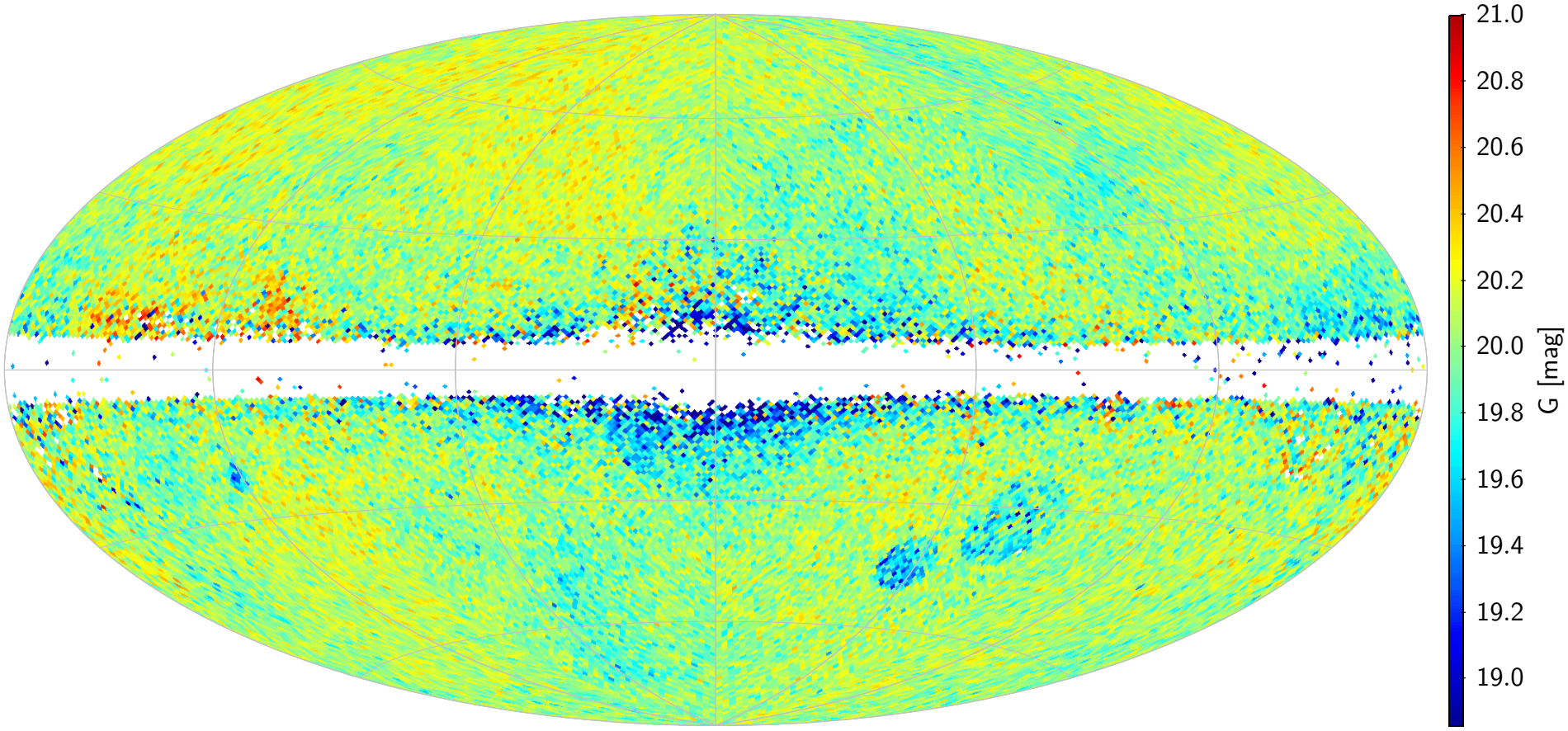
- 1.61 M QSO's with 5-P and 6-P solutions
- Sky map density – Galactic coordinates



Klioner, Lindegren, Mignard et al. 2022

Gaia-CRF3

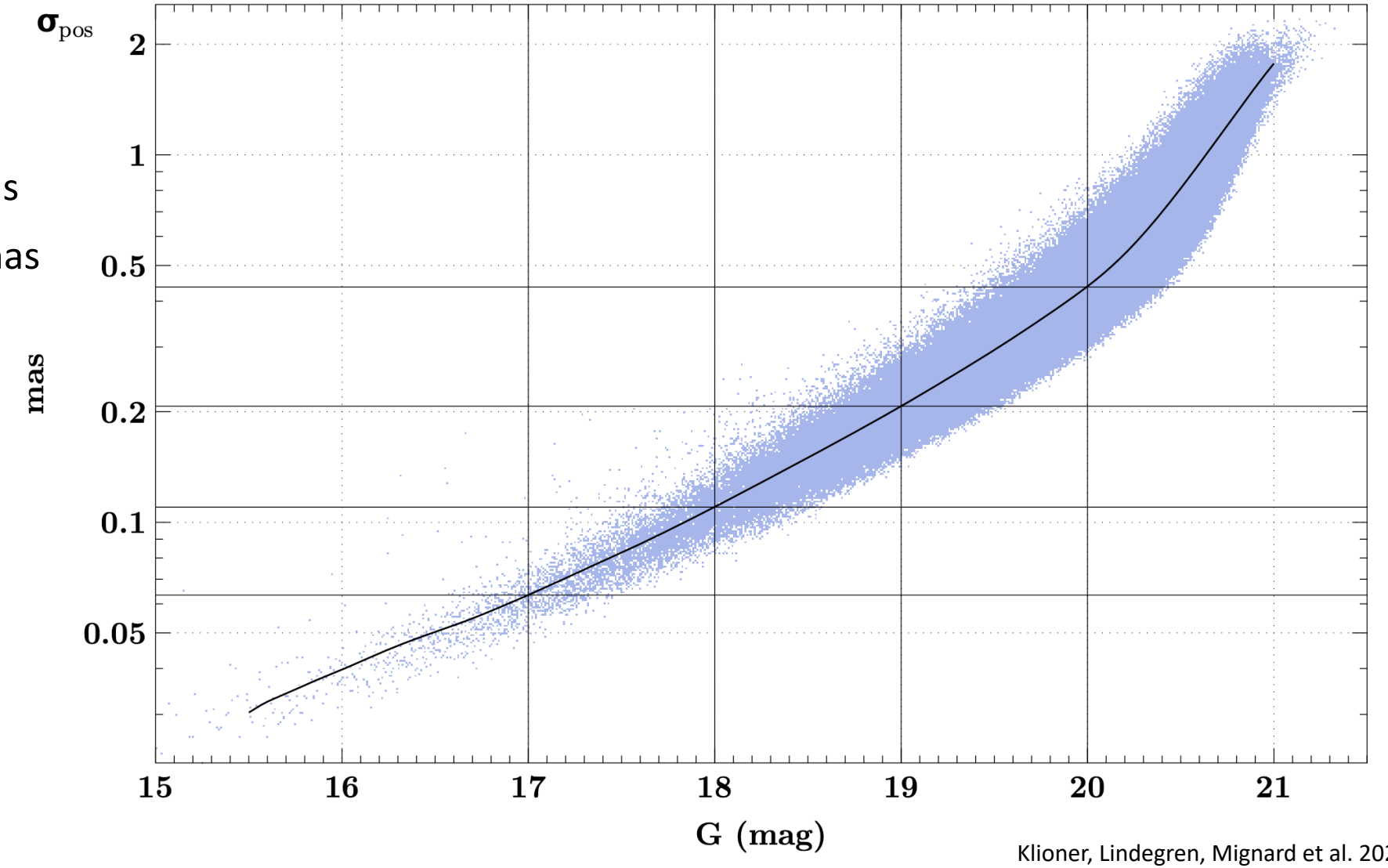
- 1.61 M QSO's with 5-P and 6-P solutions
- Median G-magnitude



Klioner, Lindegren, Mignard et al. 2022

Gaia-CRF3 – Position uncertainties (in mas)

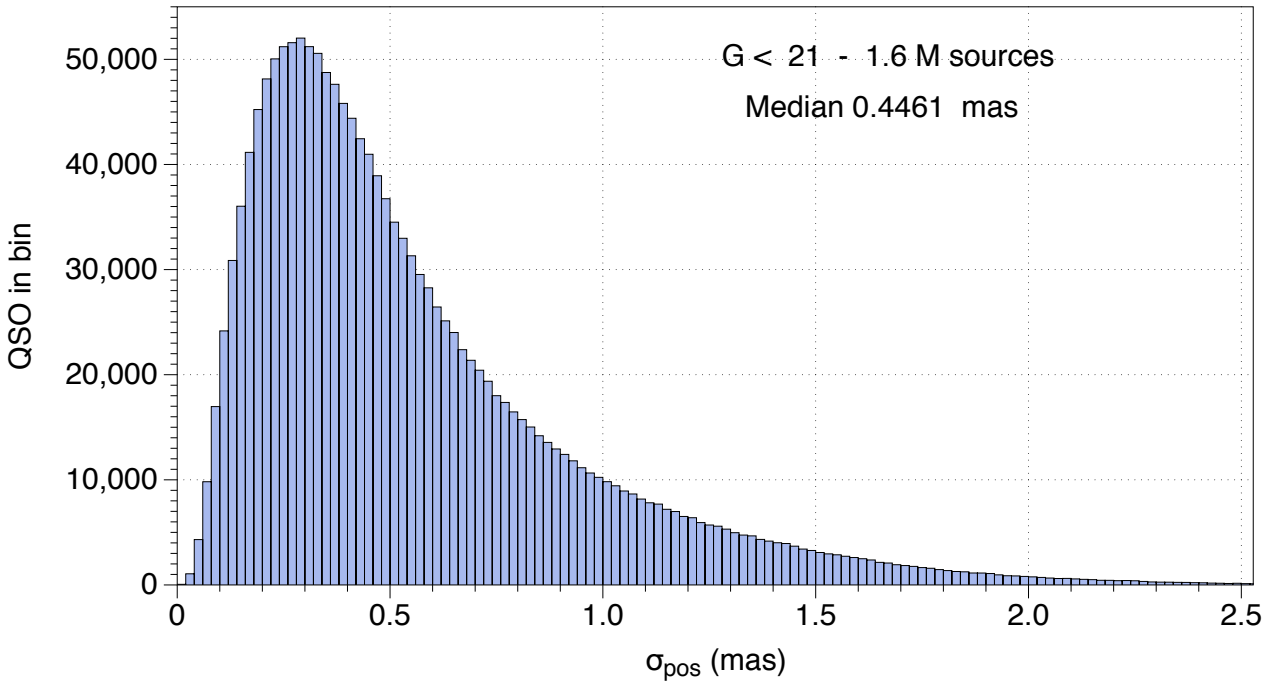
- 1.62 M QSOs to G = 21
  - 32,000 with $\sigma_{pos} < 0.1$ mas
  - 210,000 with $\sigma_{pos} < 0.2$ mas



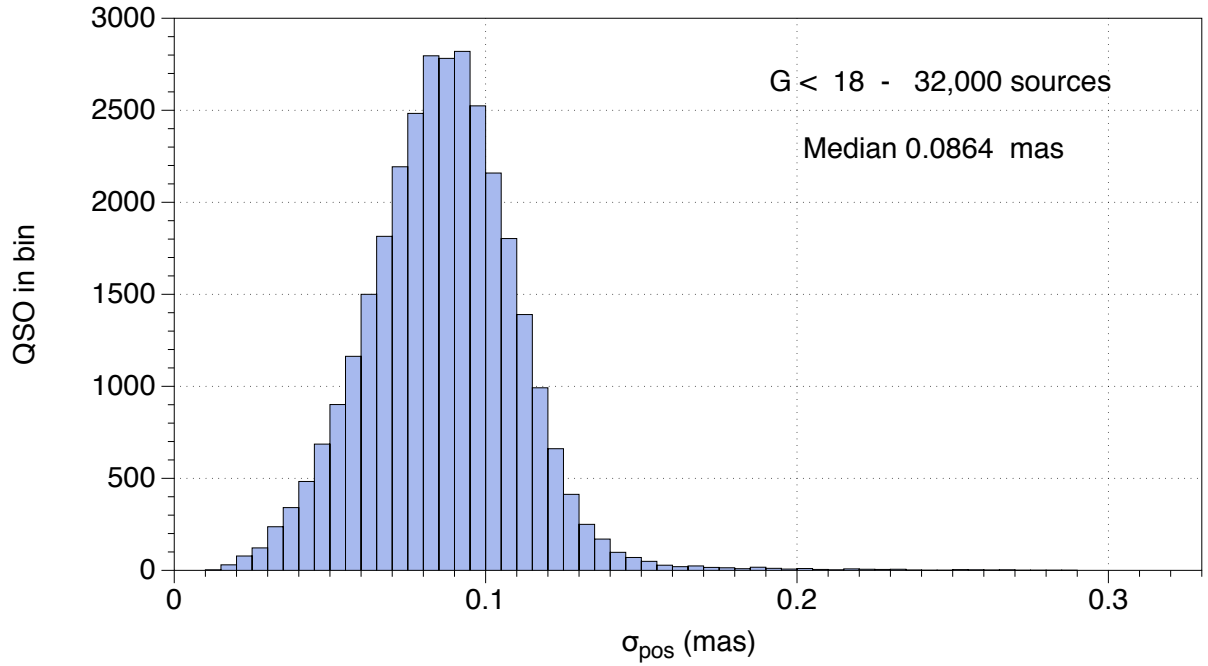
Klioner, Lindegren, Mignard et al. 2022

Gaia-CRF3 – Position uncertainties (in mas)

G < 21, 1.6 M QSOs



G < 18, 32 k QSOs



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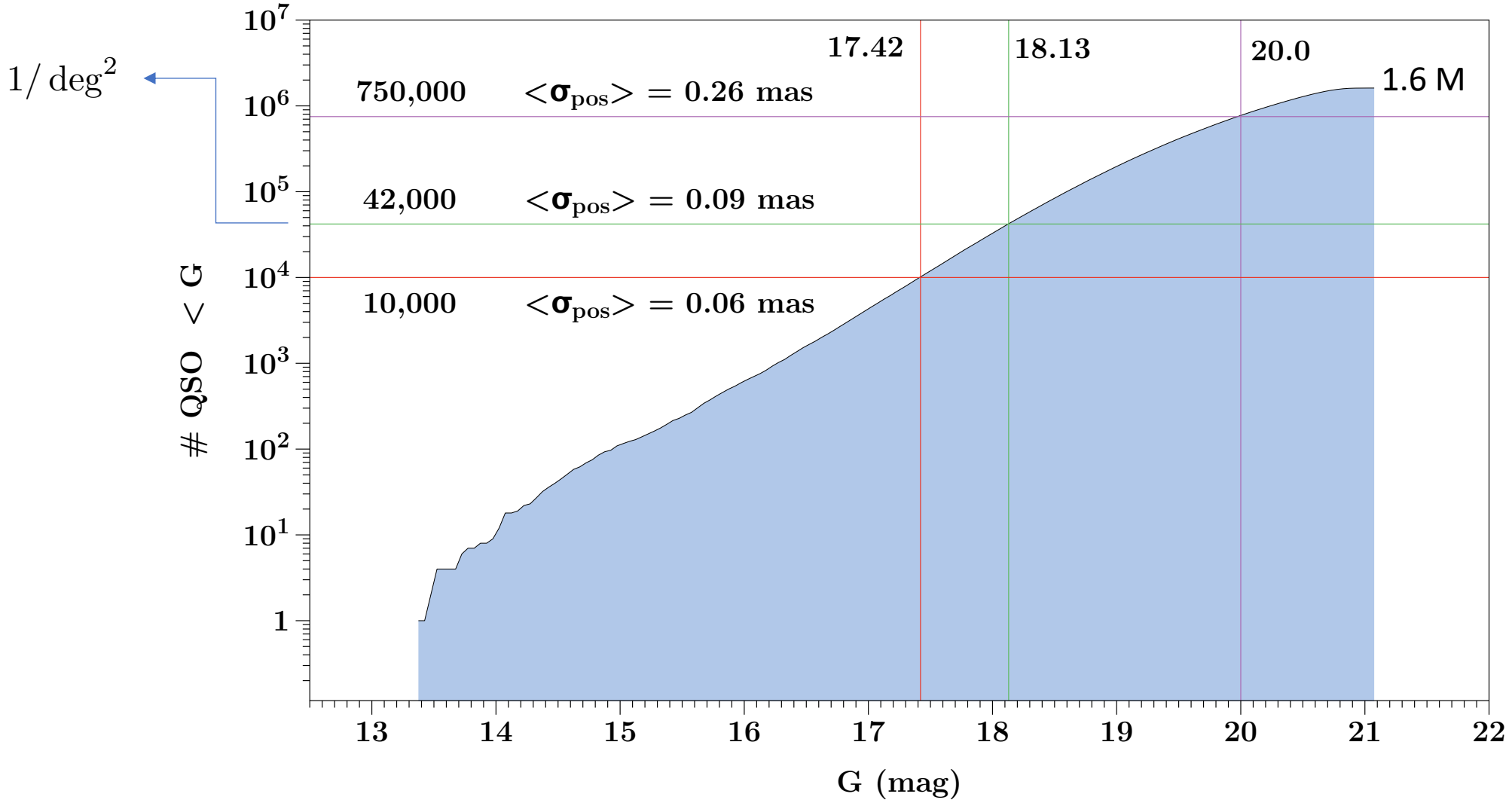
Gaia-CRF3

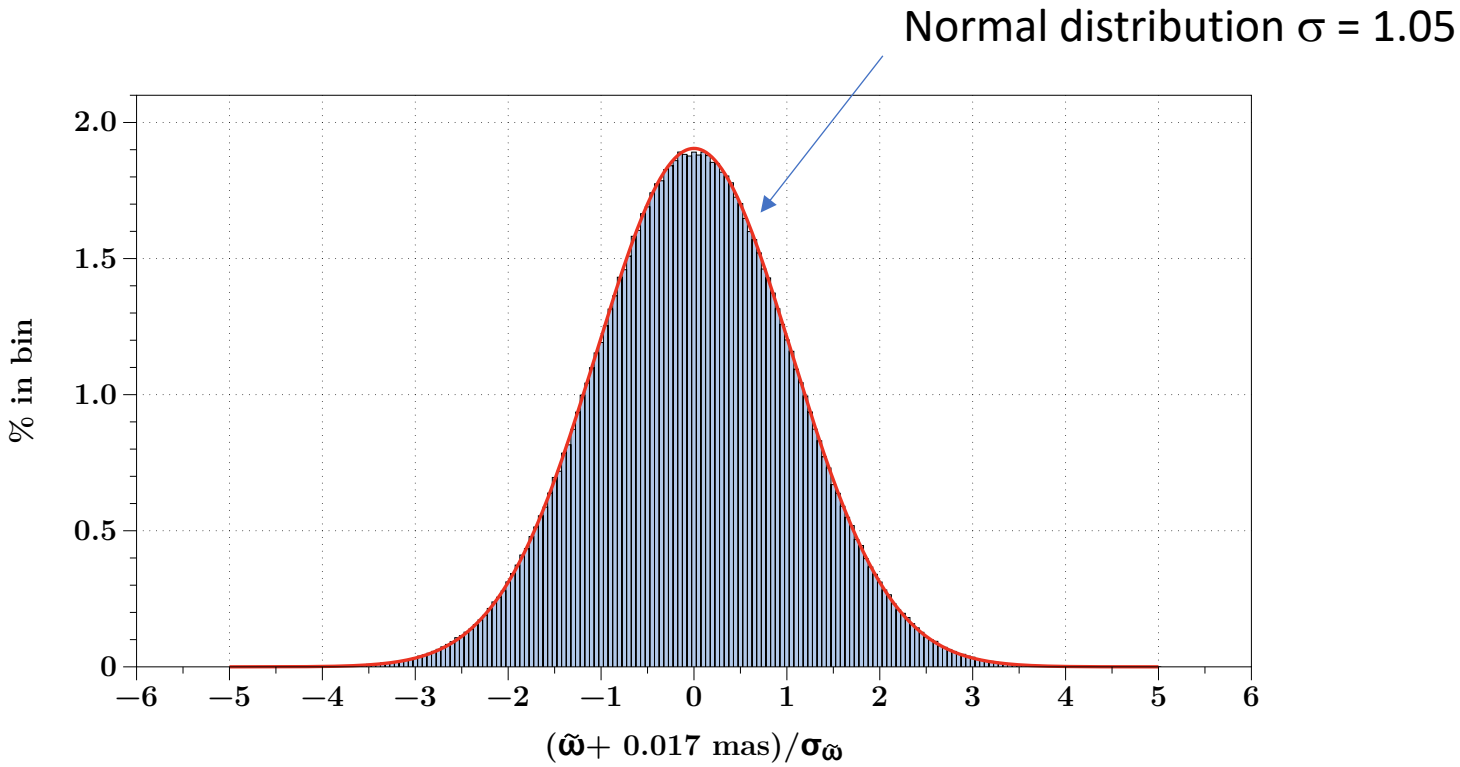
- Cumulative # sources/accuracy vs magnitude



Klioner, Lindegren, Mignard et al. 2022

EDR3 – Gaia-CRF3 – Normalised parallaxes

- 1.62 M QSOs to G = 21



linear scale

log scale

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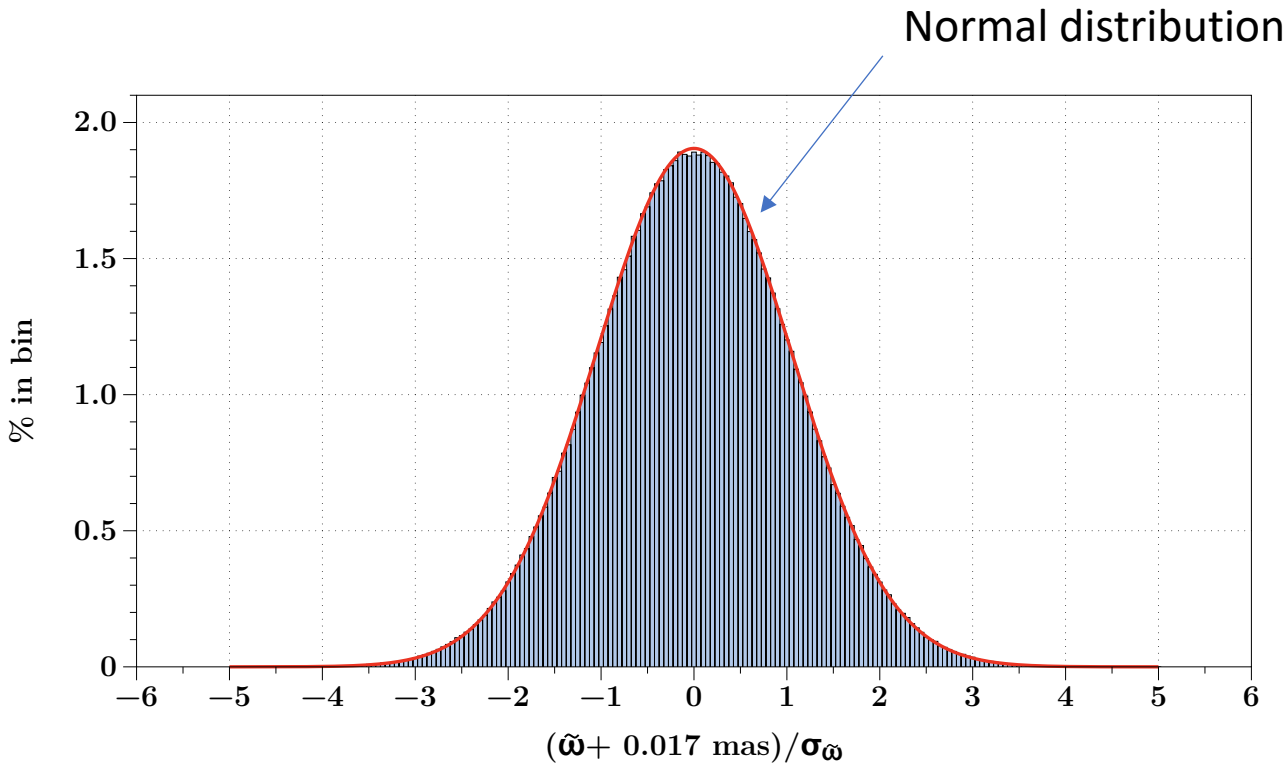
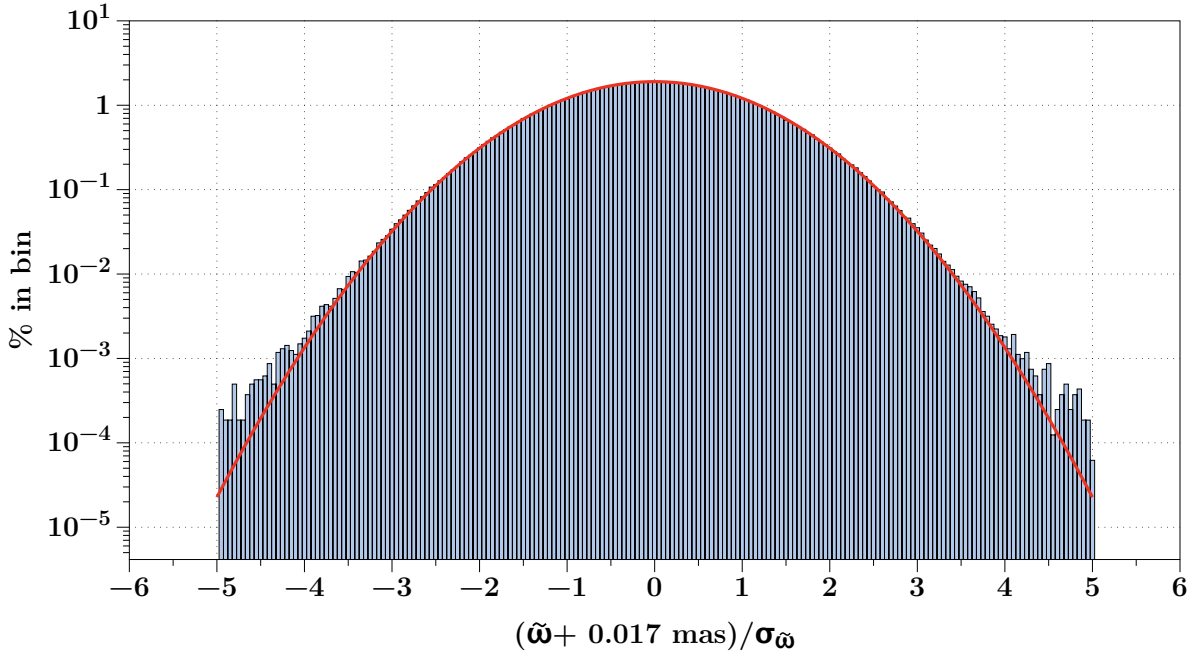


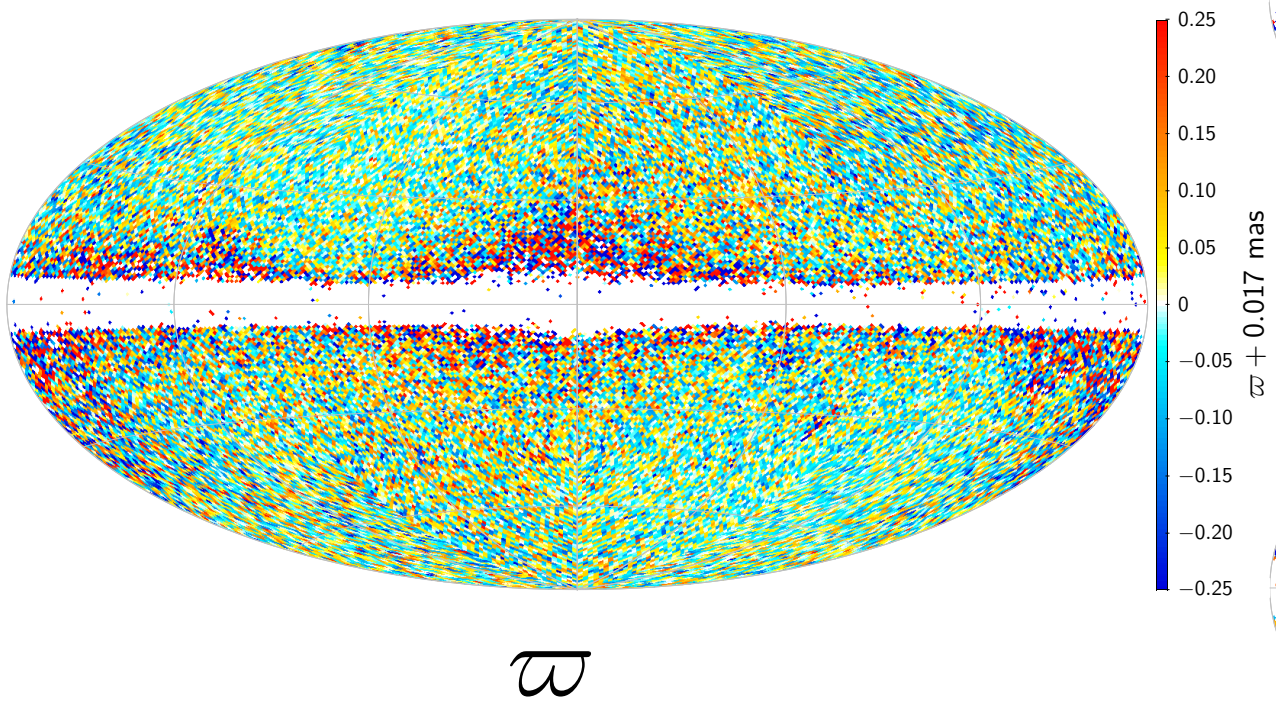
linear scale



log scale

Gaia-CRF3 – Parallaxes and PM (in mas, mas/yr)

- 1.62 M QSOs to G = 21



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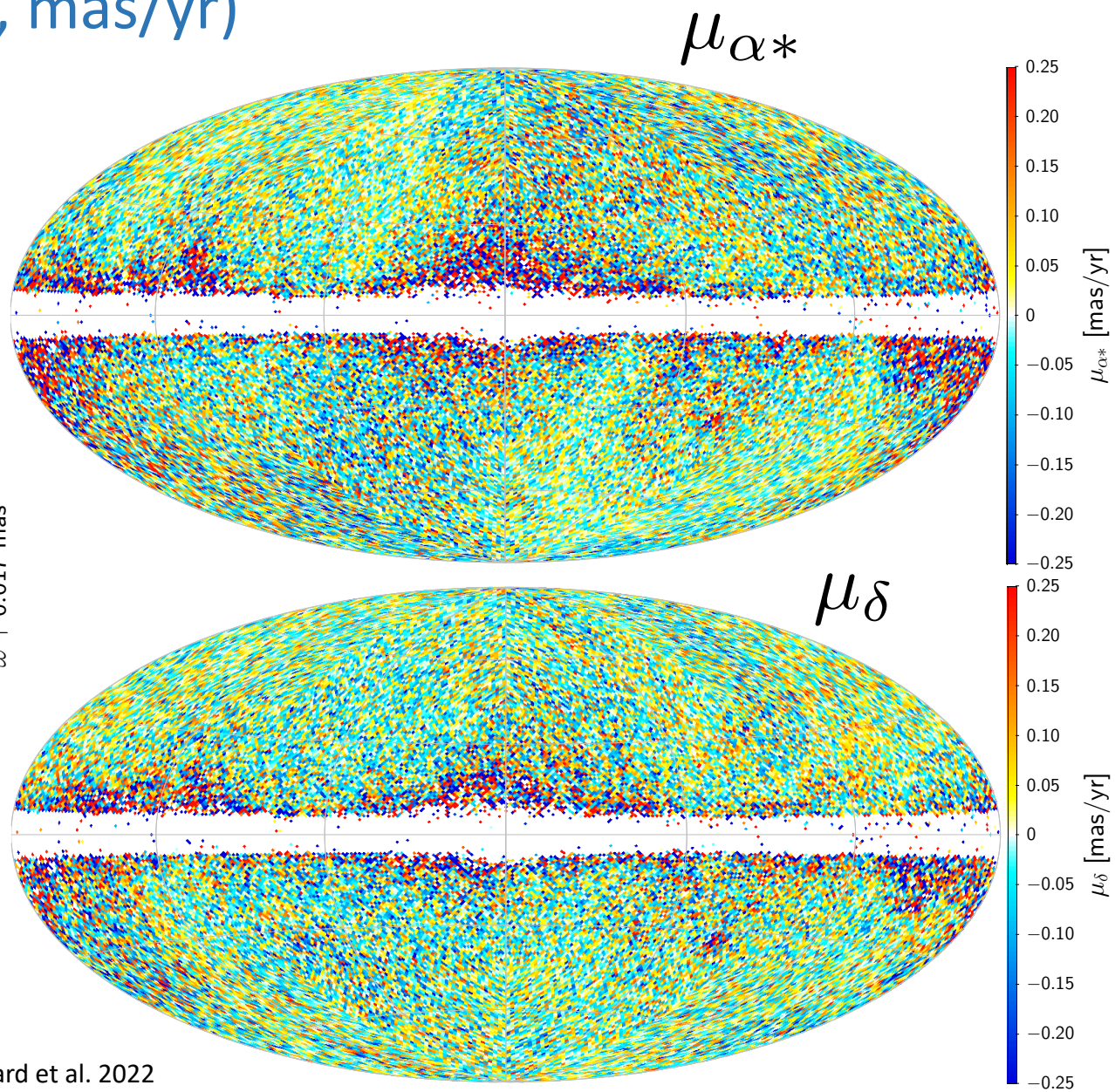

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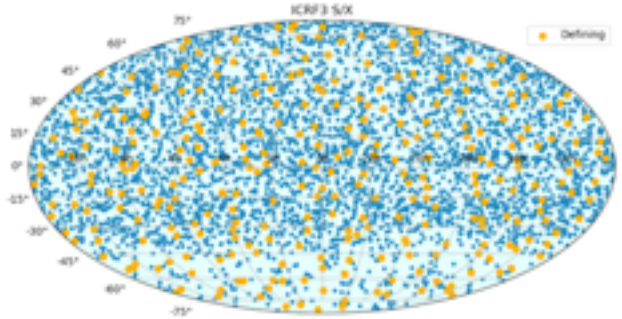
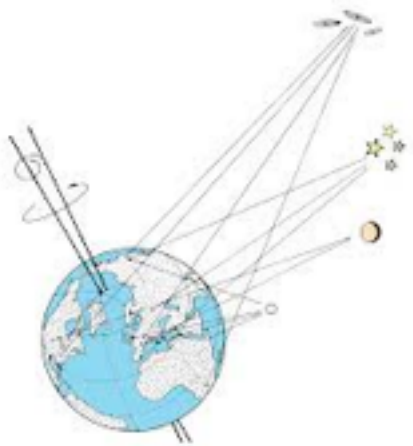
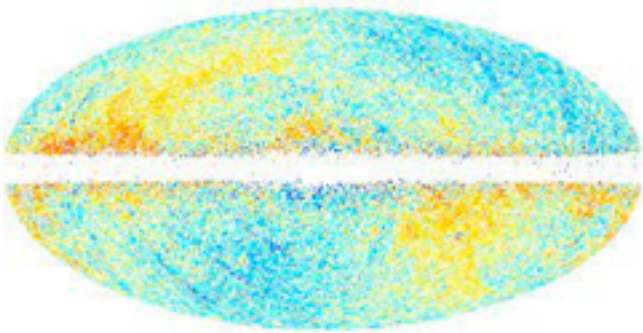
Outline

- 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
- **Relations between Radio and Optical CRF**





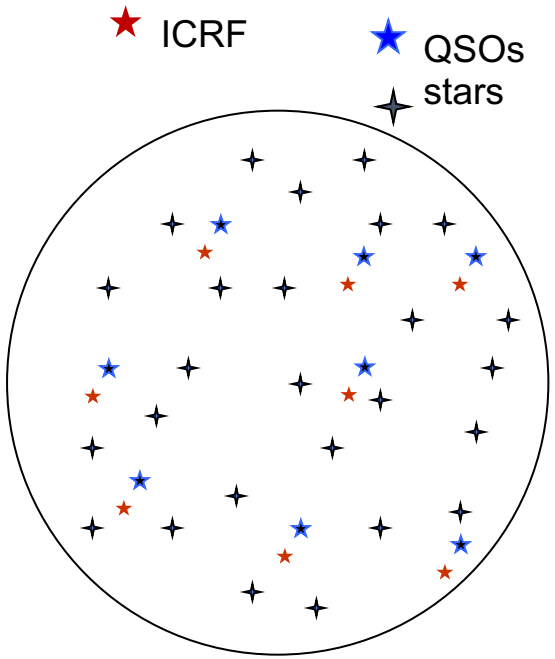


Alignment of radio and optical CRF

- 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:

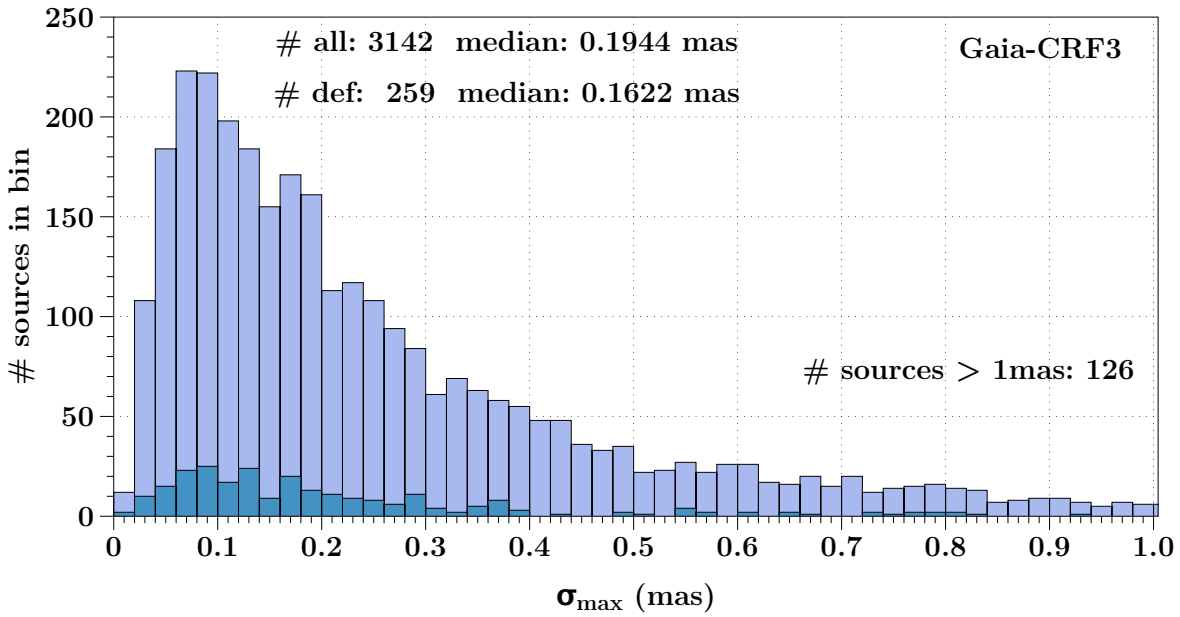
$$\sigma_{\rm align} \sim \sqrt{\frac{\sigma^2_{\rm Gaia} + \sigma^2_{\rm ICRF3}}{N_{\rm QSO}}} < 5\mu{\rm as}$$

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

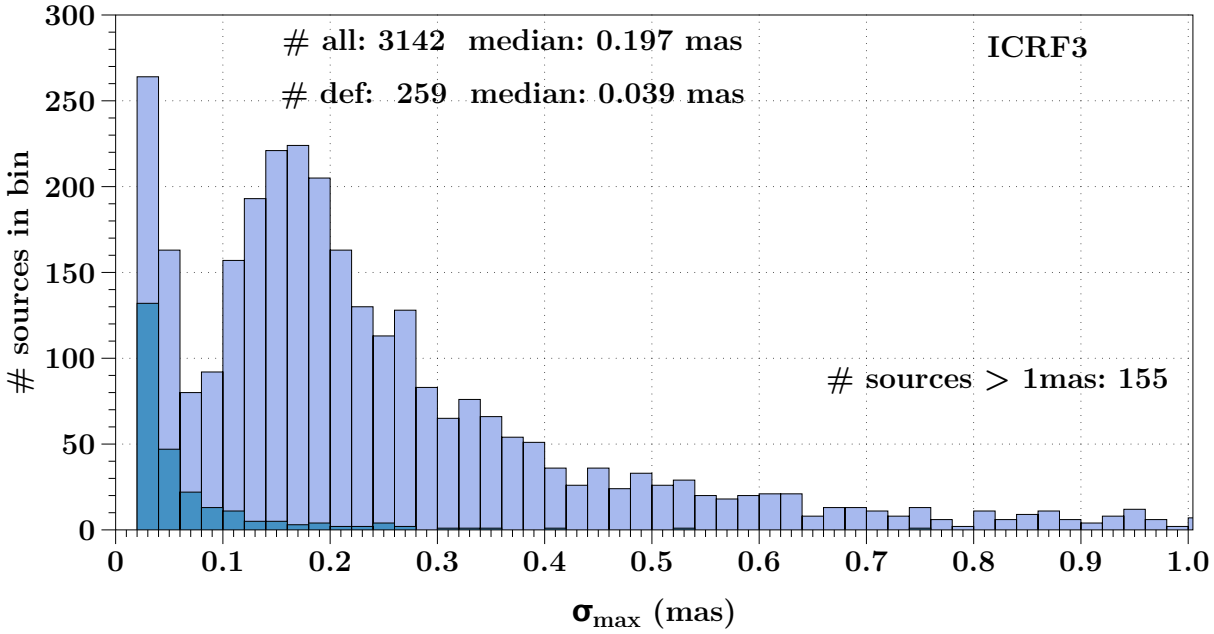


Gaia-CRF3 & ICR3 – 3142 Common sources

- Formal uncertainties



0.2 % of the Gaia CRF



70% of the VLBI CRF

Remarkably similar distributions

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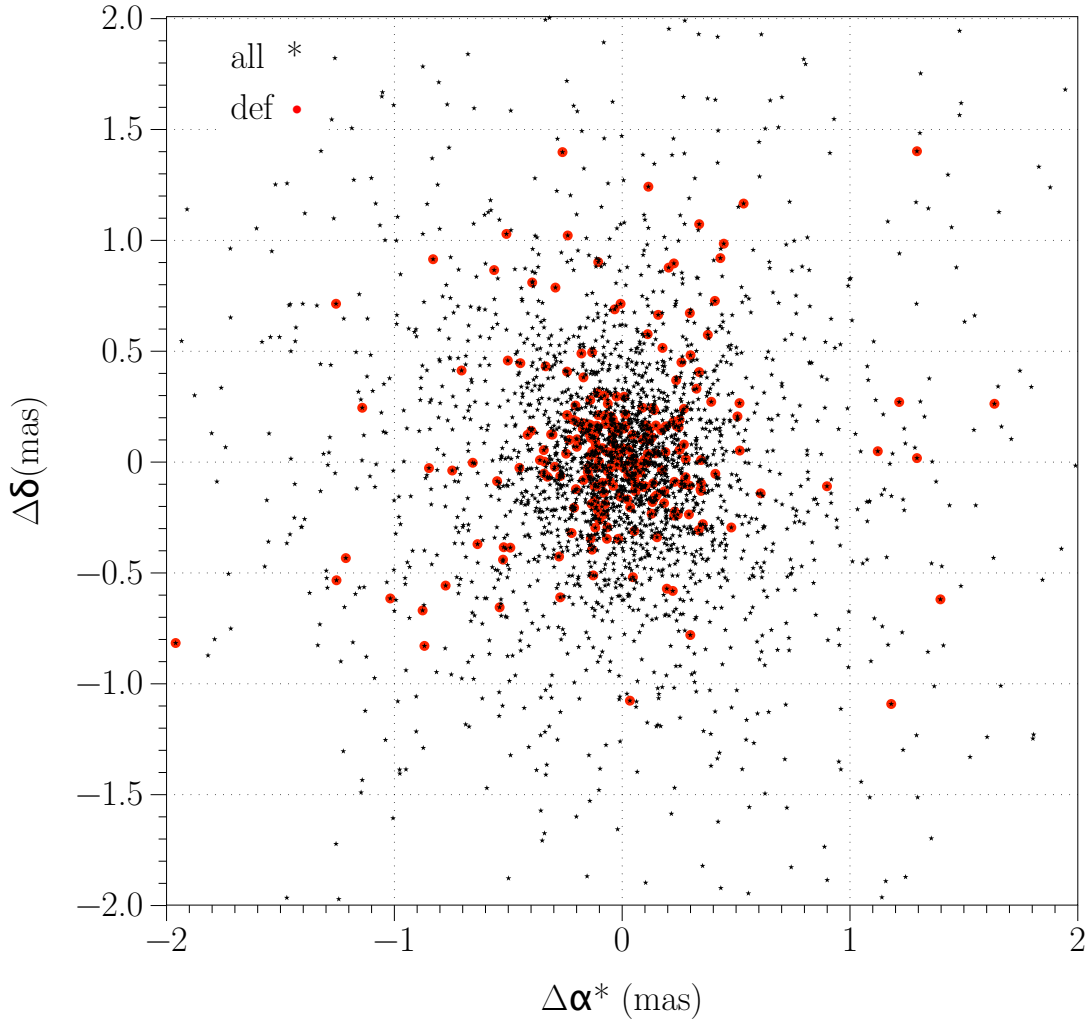
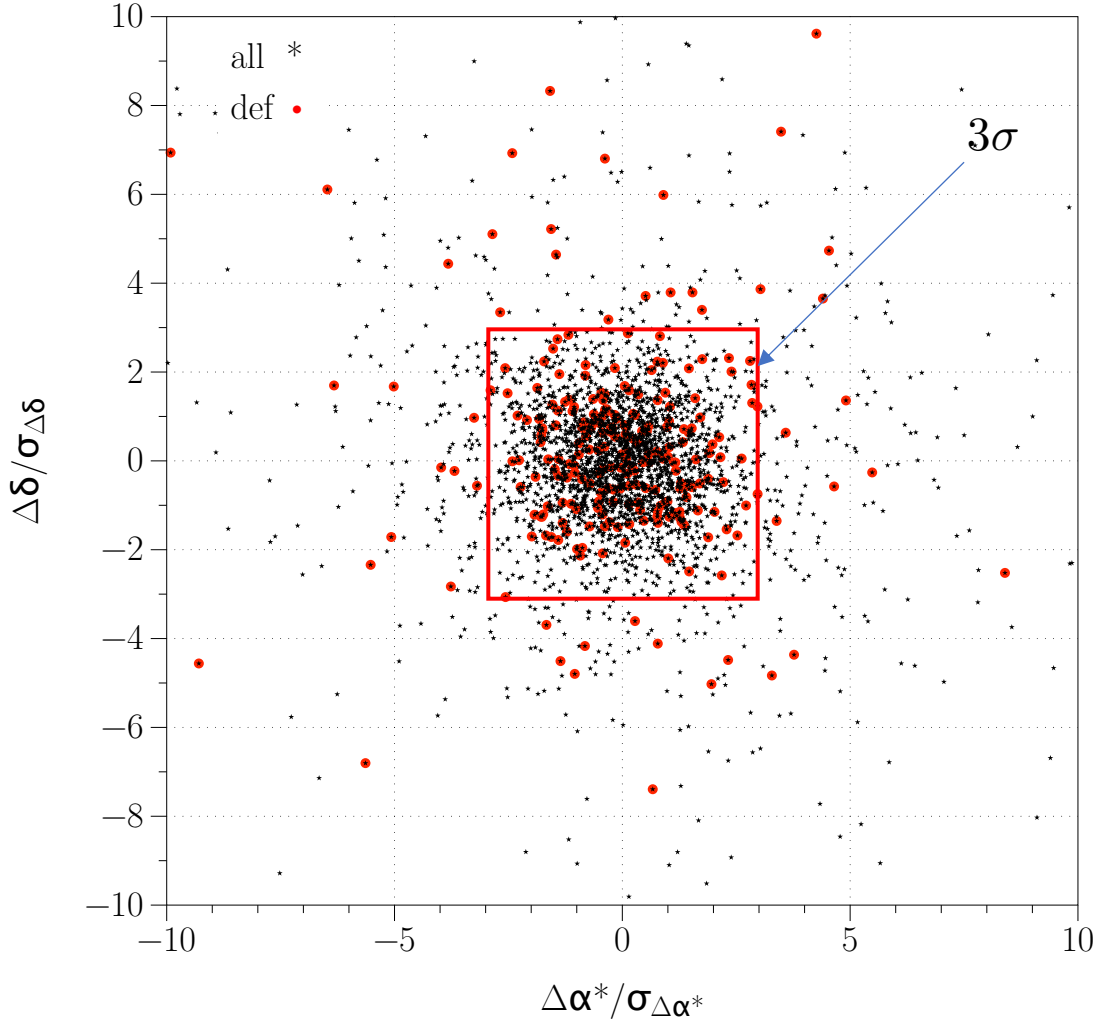
Gaia-CRF3

Positional differences

Absolute



Normalised



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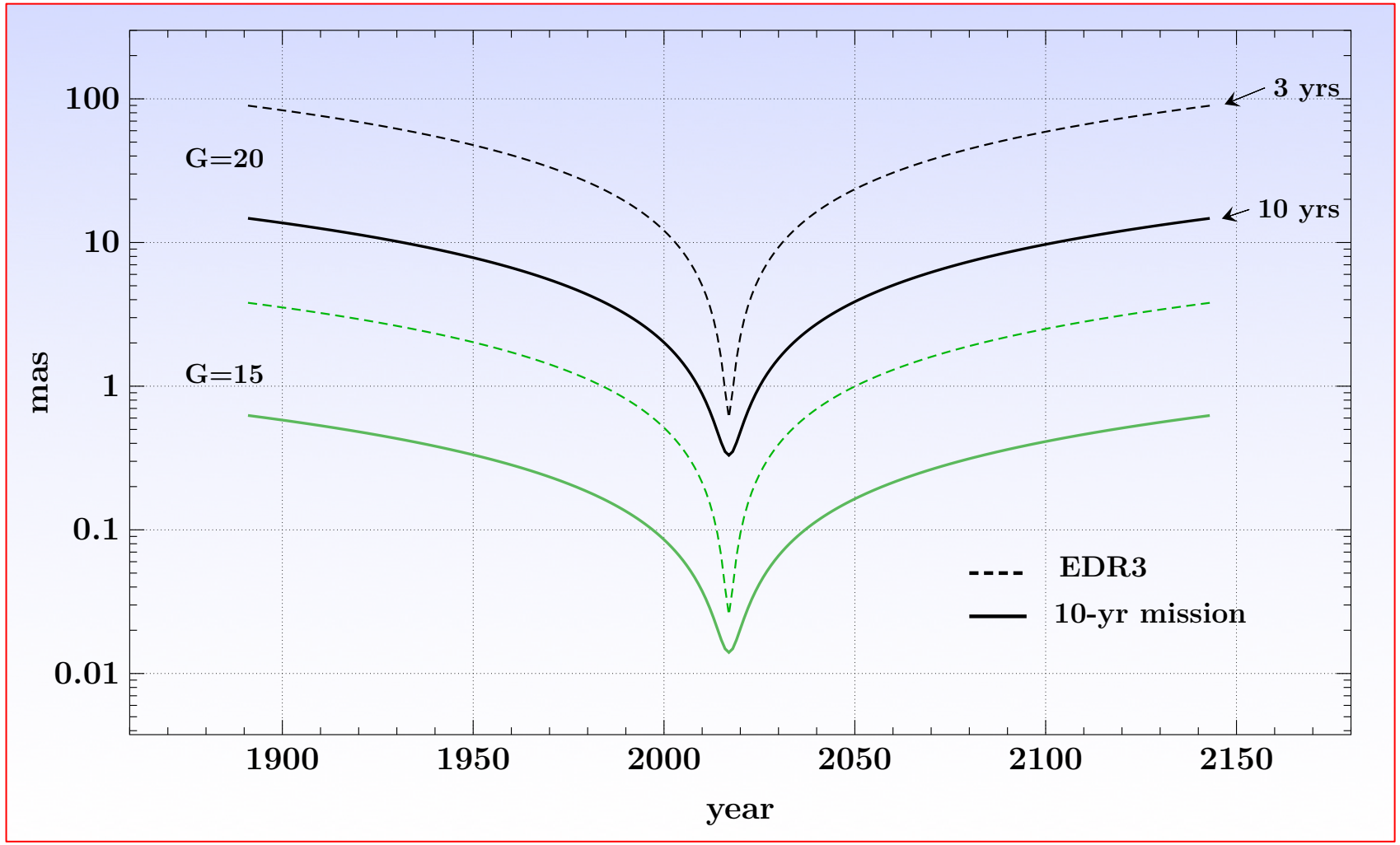
Reference frame : Gaia stellar frame

Gaia positional accuracy (stars) past and future



= EDR3

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'

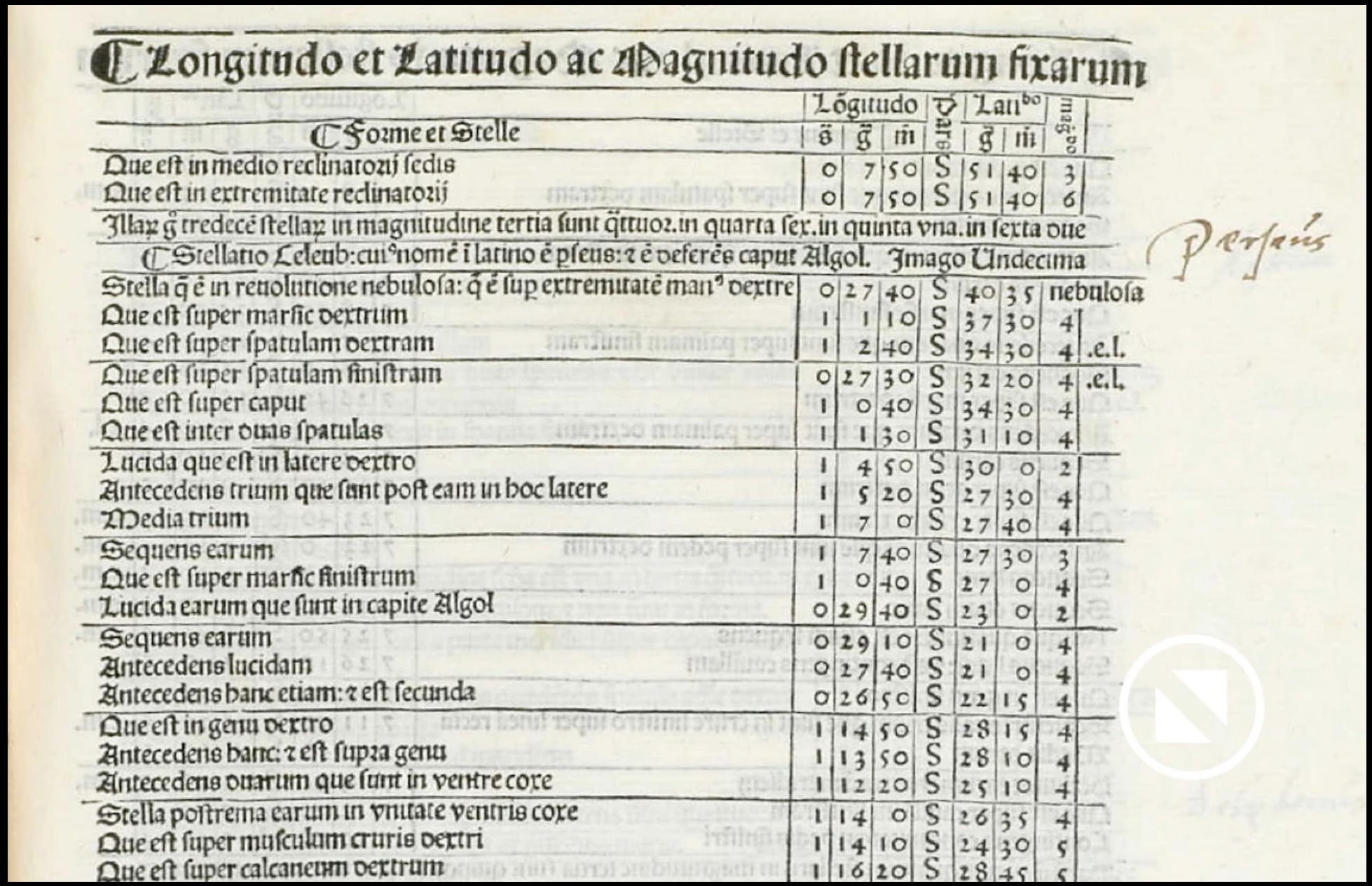
recognizing

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.

Ptolemy : Star Catalogue



Longitudo et Latitudo ac Magnitudo stellarum fixarum

Forme et Stelle	Lōgitudo ſ	g	m	Pars	Latᵒ g	m	Magᵒ	
Que eſt in medio reclinatorij ſedis	0	7	50	S	51	40	3	
Que eſt in extremitate reclinatorij	0	7	50	S	51	40	6	
Illaꝝ g̃ tredecē ſtellaꝝ in magnitudine tertia ſunt q̃ttuor.in quarta ſex.in quinta vna.in ſexta due								
Stellatio Celeub:cuiꝰ nomē i latino ē pſeus:ꝛ ē deferēs caput Algol. Imago Undecima								
Stella q̃ ē in reuolutione nebuloſa: q̃ ē ſup extremitatē manꝰ dextre	0	27	40	S	40	35	nebuloſa	
Que eſt ſuper marſic dextrum	1	1	10	S	37	30	4	
Que eſt ſuper ſpatulam dextram	1	2	40	S	34	30	4	.e.l.
Que eſt ſuper ſpatulam ſiniſtram	0	27	30	S	32	20	4	.e.l.
Que eſt ſuper caput	1	0	40	S	34	30	4	
Que eſt inter duas ſpatulas	1	1	30	S	31	10	4	
Lucida que eſt in latere dextro	1	4	50	S	30	0	2	
Antecedens trium que ſunt poſt eam in hoc latere	1	5	20	S	27	30	4	
Media trium	1	7	0	S	27	40	4	
Sequens earum	1	7	40	S	27	30	3	
Que eſt ſuper marſic ſiniſtrum	1	0	40	S	27	0	4	
Lucida earum que ſunt in capite Algol	0	29	40	S	23	0	2	
Sequens earum	0	29	10	S	21	0	4	
Antecedens lucidam	0	27	40	S	21	0	4	
Antecedens hanc etiam:ꝛ eſt ſecunda	0	26	50	S	22	15	4	
Que eſt in genu dextro	1	14	50	S	28	15	4	
Antecedens hanc:ꝛ eſt ſupra genu	1	13	50	S	28	10	4	
Antecedens duarum que ſunt in ventre coxe	1	12	20	S	25	10	4	
Stella poſtrema earum in vnitate ventris coxe	1	14	0	S	26	35	4	
Que eſt ſuper muſculum cruris dextri	1	14	10	S	24	30	5	
Que eſt ſuper calcaneum dextrum	1	16	20	S	28	45	5	

Perseus

Thanks for your attention