

# Status of the Celestial Reference Frame

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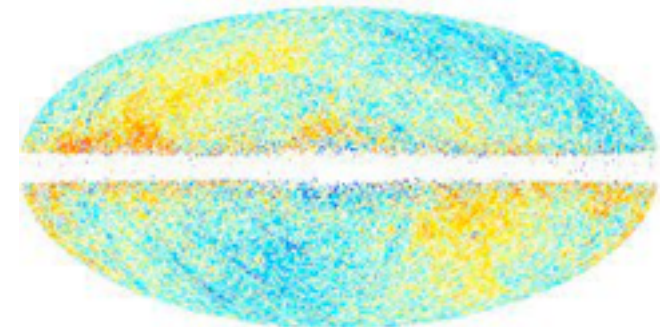
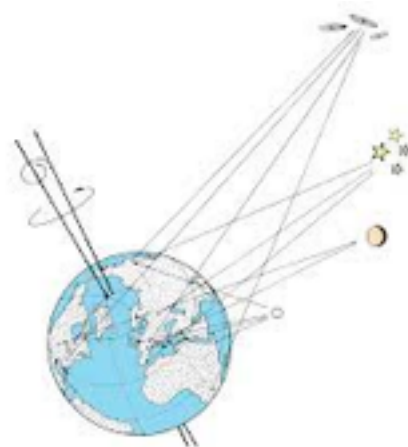
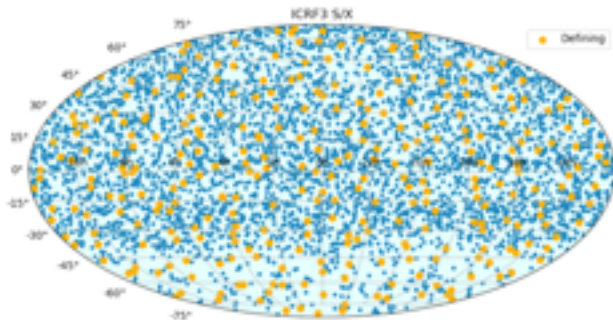
IAU 2022 FM 7

11 Aug 2022



# Outline

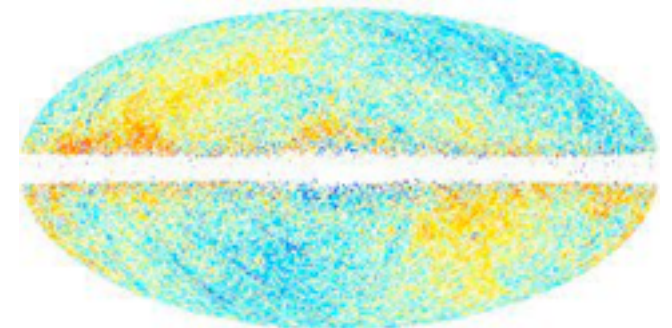
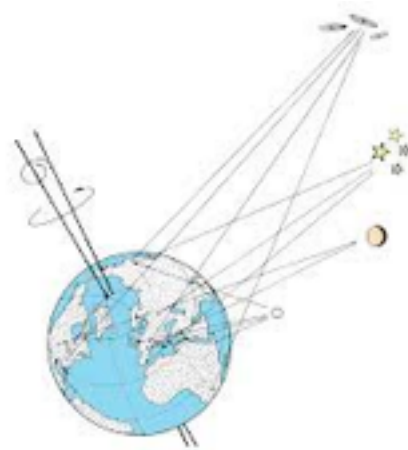
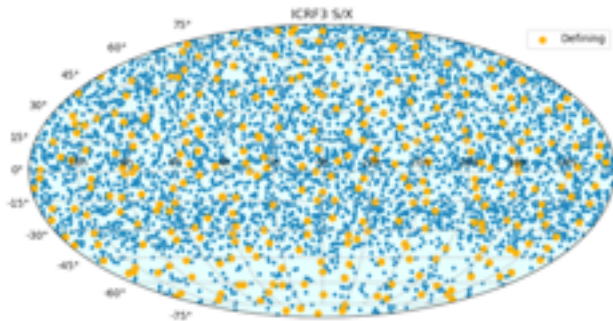
- Background
- The fundamental realisations in the radio domain: VLBI CRFs
- The fundamental realisations in the visible domain: Gaia CRFs
- Relationships between Radio and Optical CRF



# Outline

- **Background**

- The fundamental realisations in the radio domain : VLBI CRFs
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# 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

# 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

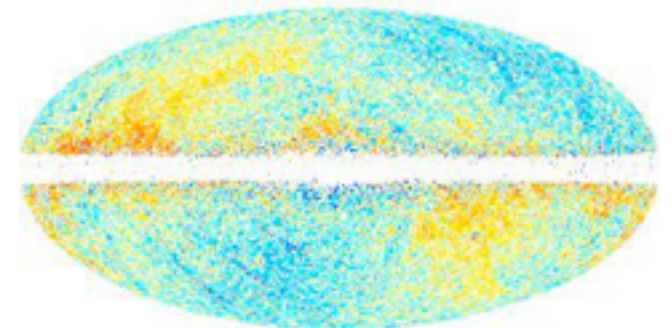
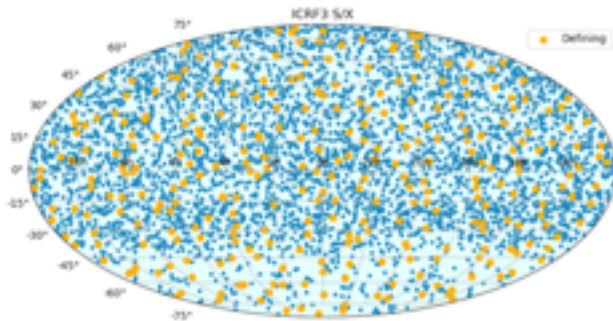
Name	Epoch	N. sources	mag <	Accuracy
Lacaille	1760	397	7	10 ''
Maskelyne	1774	36	5	5 ''
Piazzi	1818	220	6	2 ''
Bessel	1830	36	5	1 ''
Argelander	1869	160	6	1 ''
Auwers	1879	539	6	0.5 ''
FK3	1937	873	6.5	0.5 ''
FK4	1963	1535	7.5	0.2 ''
FK5	1988	1535	7.5	40 mas
Hipparcos <sup>1</sup>	1996	100 000	11.5	1 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
<b>Gaia</b> CRF2 QSOs	2018	550 000	21	0.5 mas
<b>Gaia</b> CRF3 QSOs	2021	1,620 000	21	0.4 mas
<b>Gaia</b> CRF3 $G < 18$	2021	35 000	18	0.09 mas

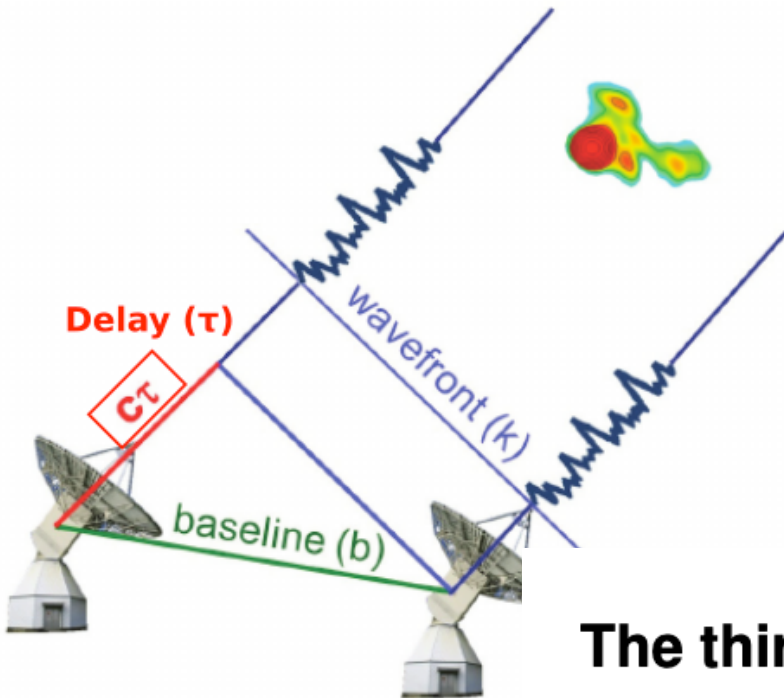
(1) quasi-fundamental



# 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





## ICRF radio – ICRF3

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

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

A&A 644, A159 (2020)

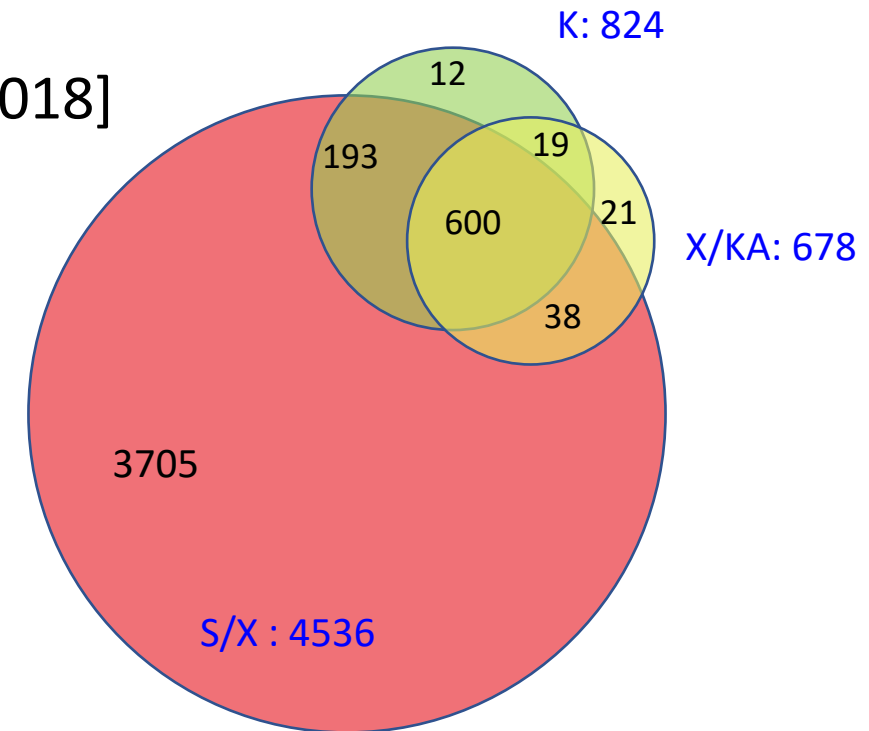
# VLBI CRFs

- 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

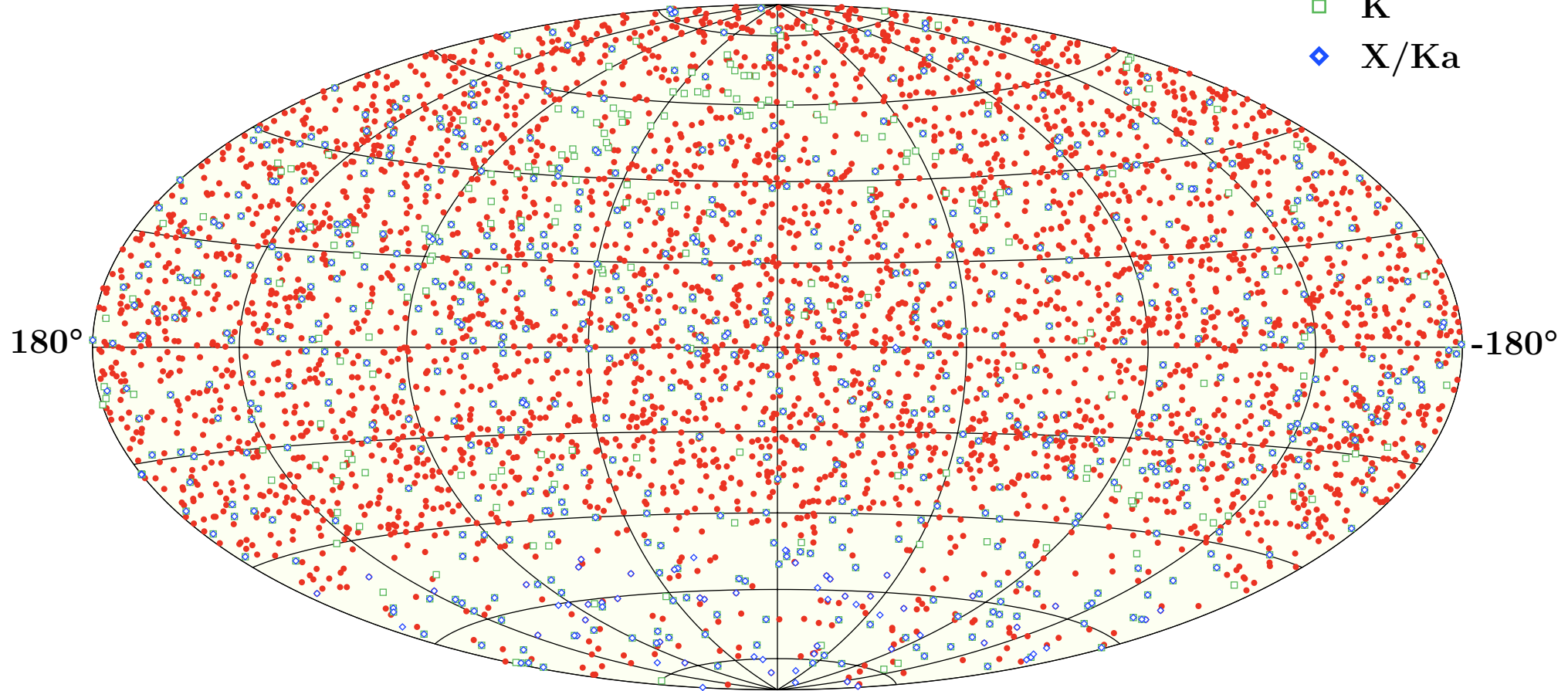
- International coordination with IAU
  - Three wavebands: S/X, K, X/KA [ 2.3, 8.5, 24, 32 GHz]
- VLBI observations in dedicated sessions
  - most of the VLBI network is used for geodetic purposes
- 13.6 million observations collected over ~ 40 years [1979-2018]
- global treatment for a set of sources
  - 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

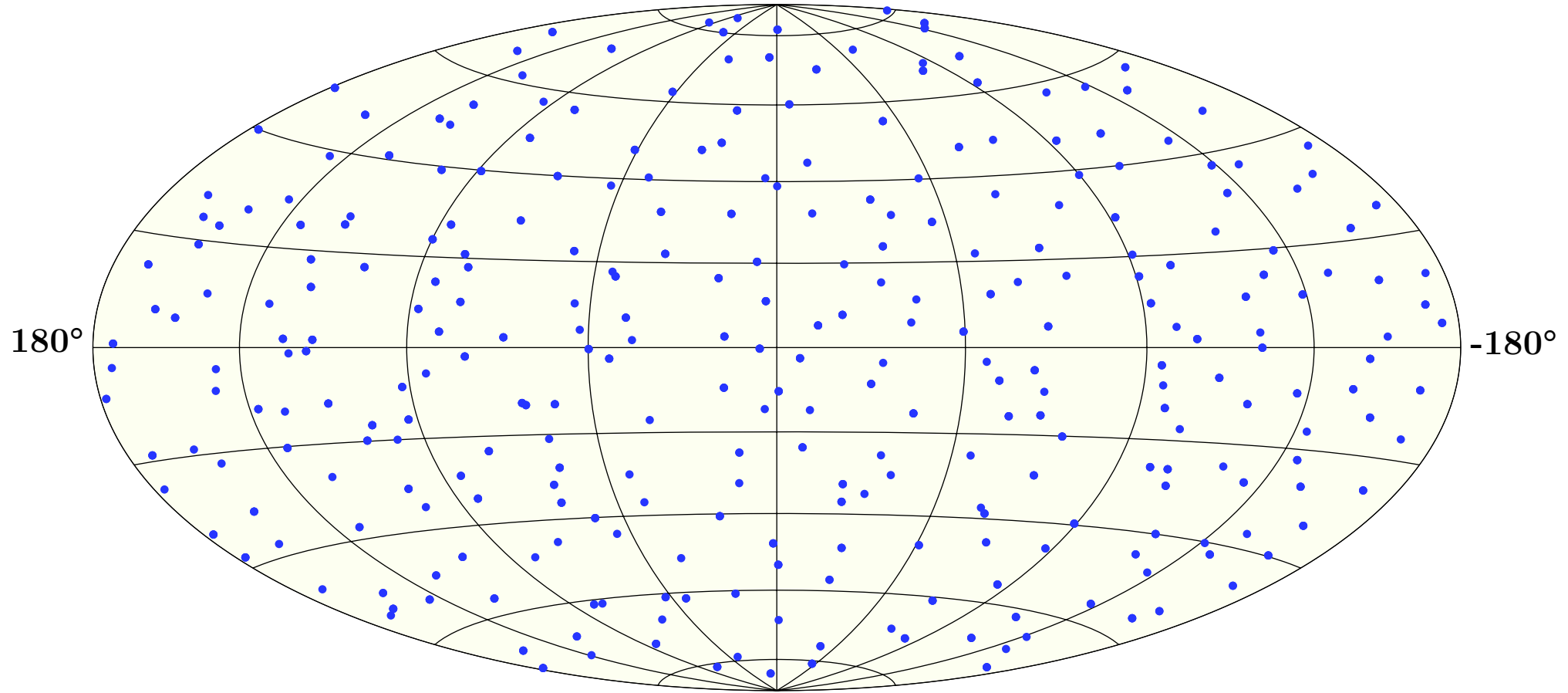
- S/X
- K
- ◆ X/Ka



# ICRF radio – ICRF3

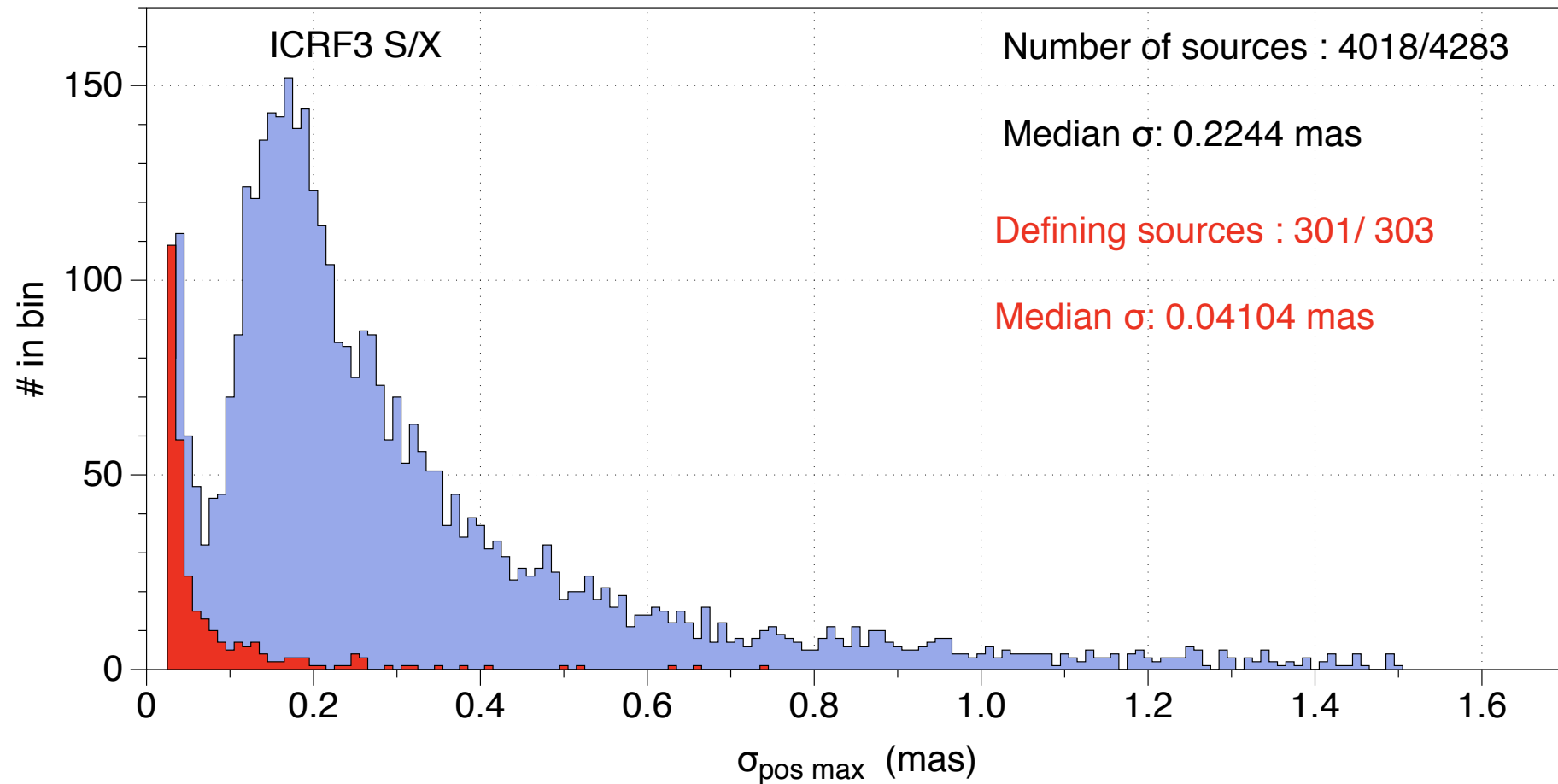
- S/X defining sources

• Defining sources (303)



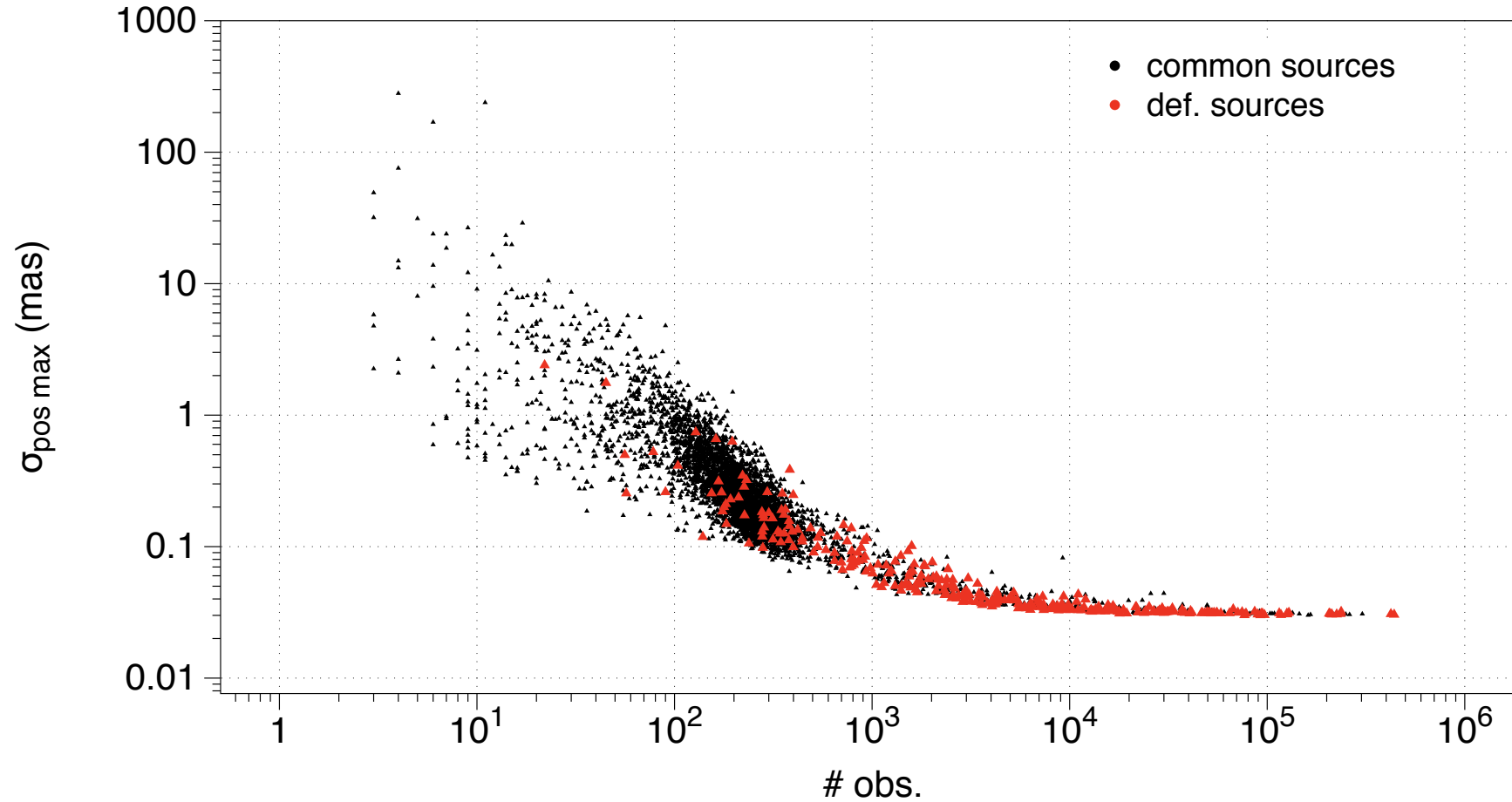
# ICRF radio – ICRF3

- Positional uncertainties



# ICRF radio – ICRF3

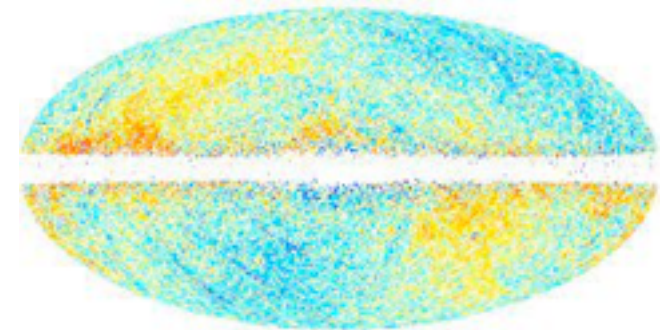
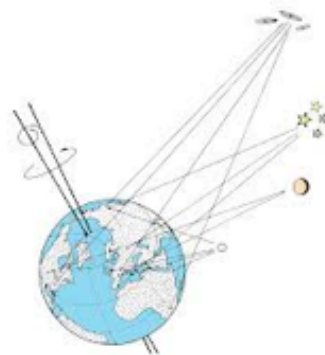
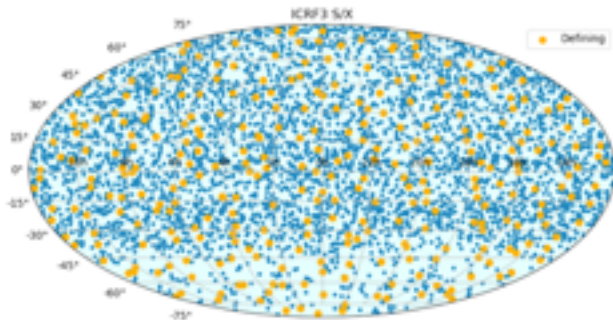
- Precision vs. number of delays

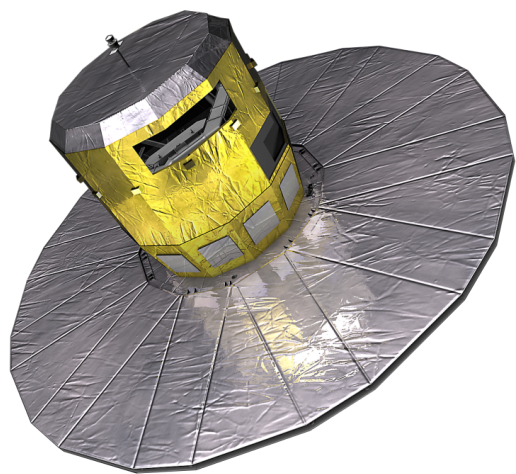




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# Gaia CRF3

## **Gaia Early Data Release 3**

### **The celestial reference frame (*Gaia*-CRF3)**

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

A&A 2022

# Gaia CRFs

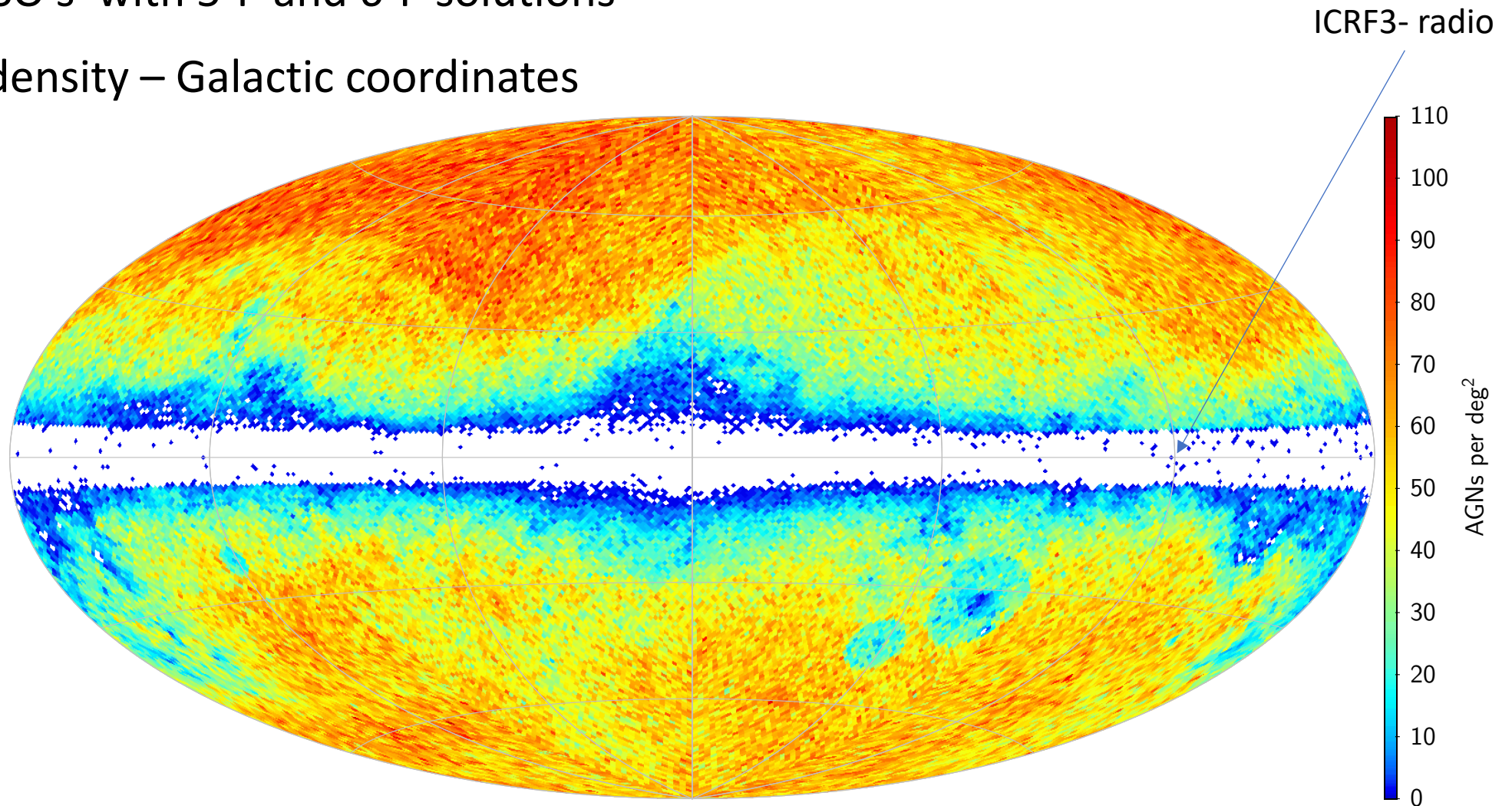
- One solution for each release
  - Gaia-CRF1 : Sep 2016      2191 sources (from 3414 ICRF2) - **0.5 mas @ G=18**
  - Gaia-CRF2 : Apr 2018    555,000 sources [2820 common to ICRF3 proto] ) - **0.15 mas @ G=18**
  - Gaia-CRF3 : Dec 2020    1.615 M sources [3142 common to ICRF3] ) - **0.11 mas @ G=18**
  - 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 :  $\varpi/\sigma_{\varpi} < 5$  → parallaxes should be 'zero'
  - $|\sin b| > 0.1$
  - cleanliness favoured over completeness
    - narrow match window
    - detection of pollution 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

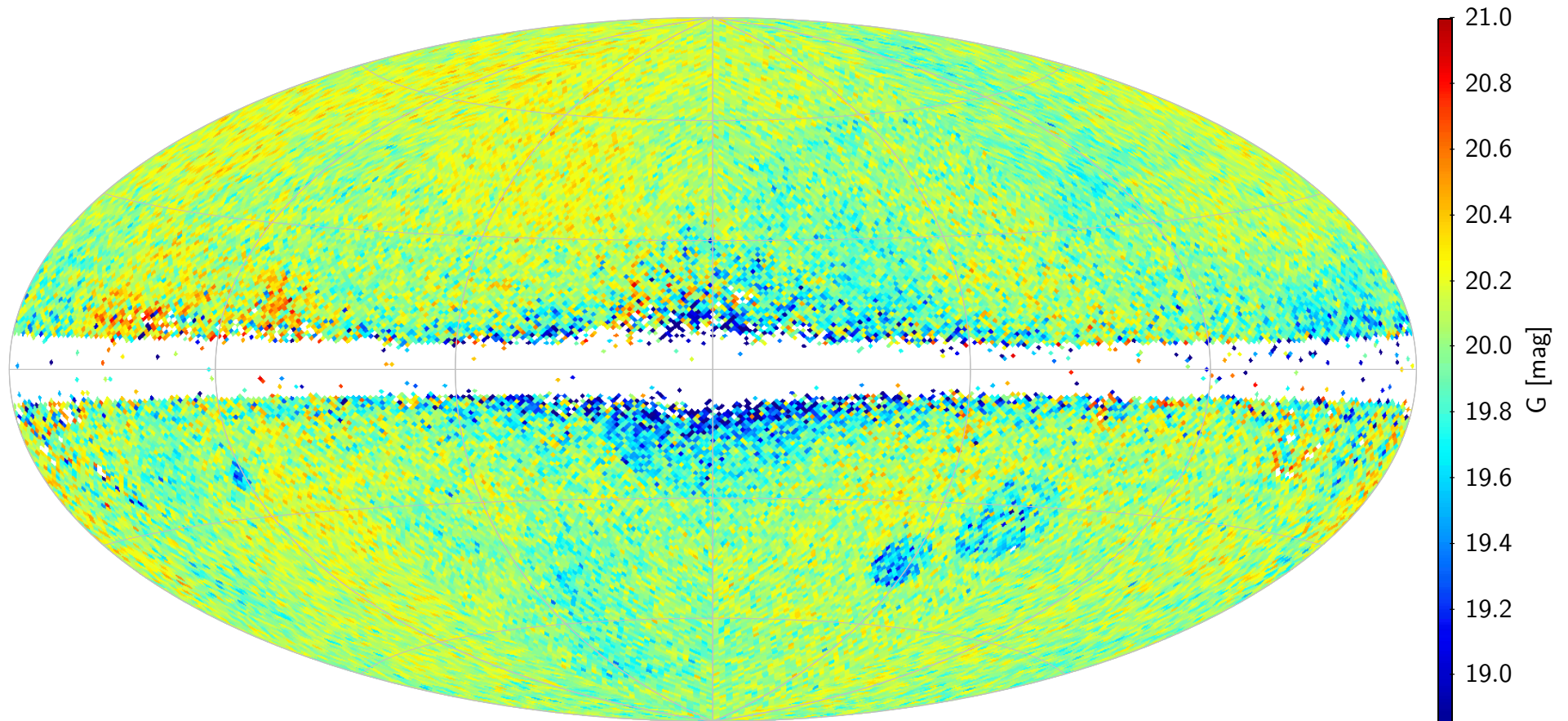


Klioner, Lindegren, Mignard et al. 2022



# Gaia-CRF3

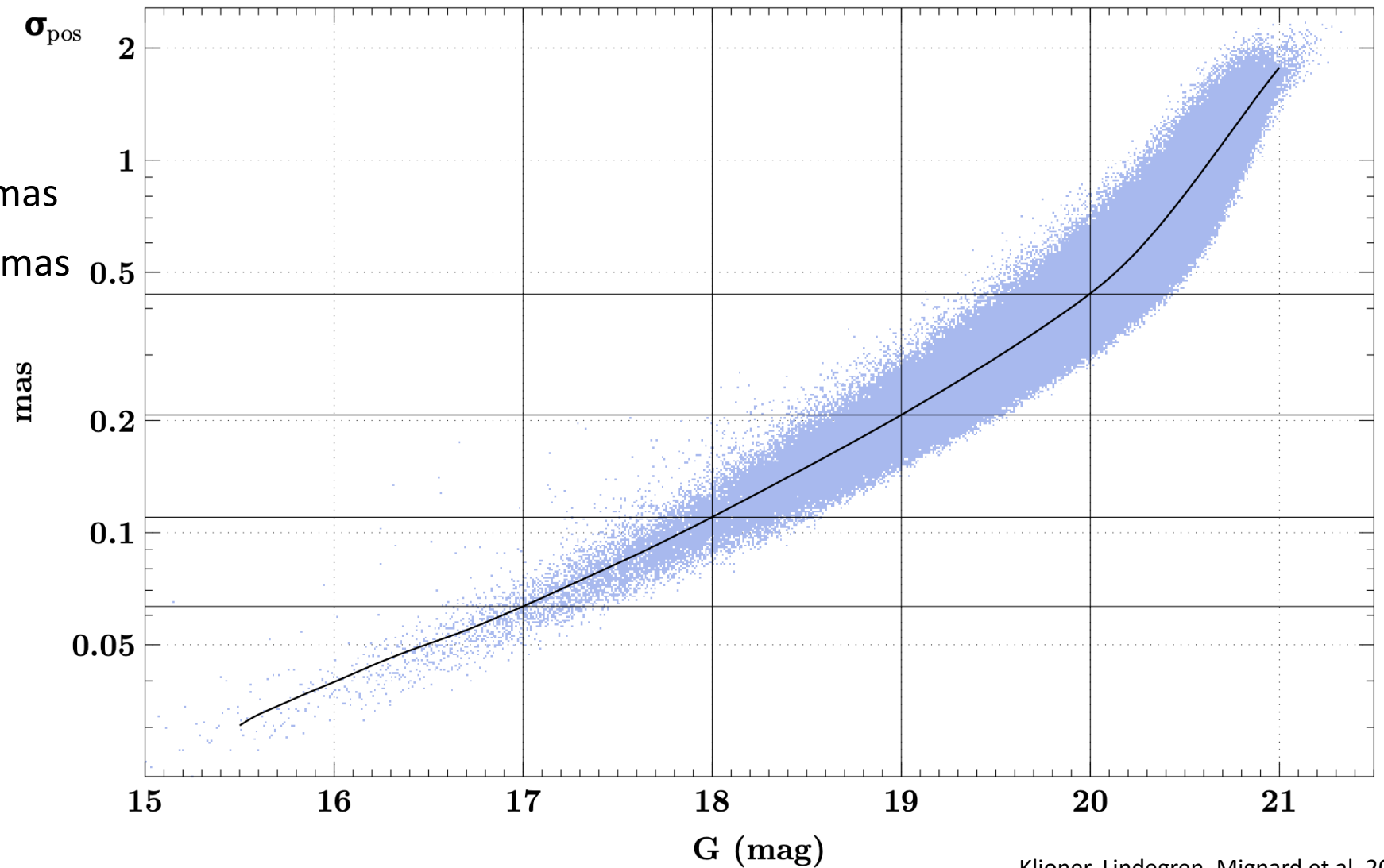
- 1.61 M QSO's with 5-P and 6-P solutions
- Median G-magnitude



Klioner, Lindegren, Mignard et al. 2022

# Gaia-CRF3 – Position uncertainties (in mas)

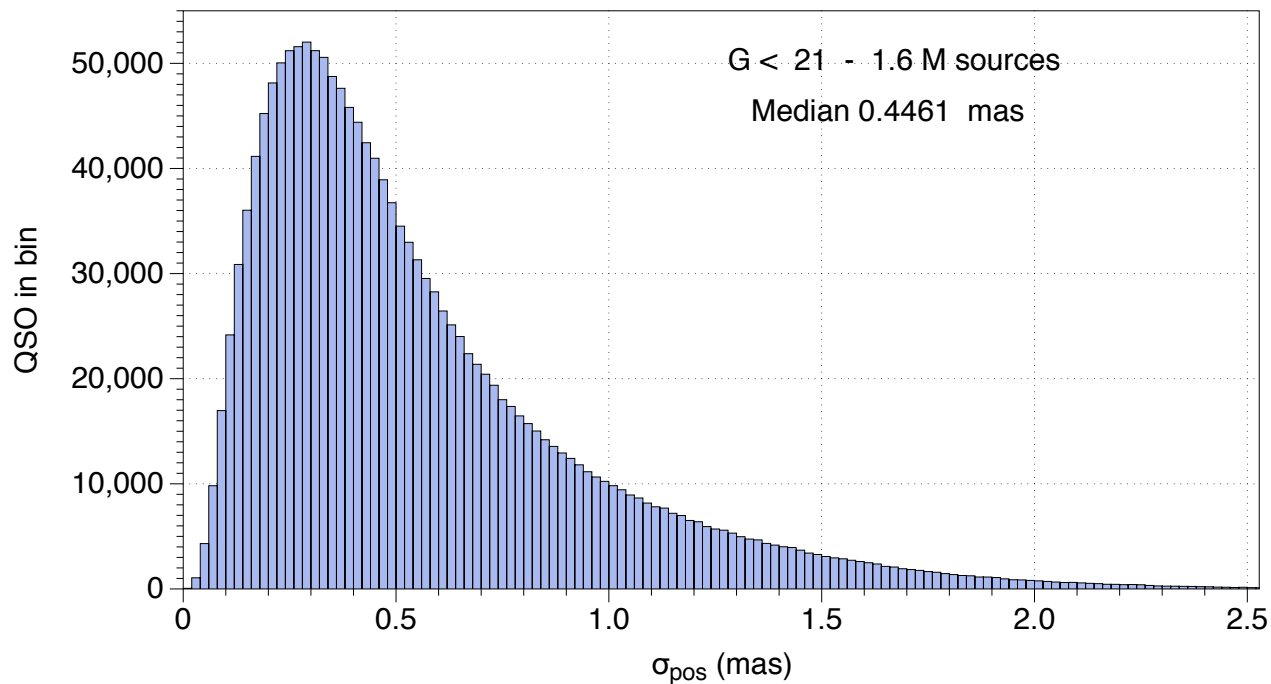
- 1.62 M QSOs to  $G = 21$ 
  - 32,000 with  $\langle \sigma_{\text{pos}} \rangle < 0.1$  mas
  - 210,000 with  $\langle \sigma_{\text{pos}} \rangle < 0.2$  mas



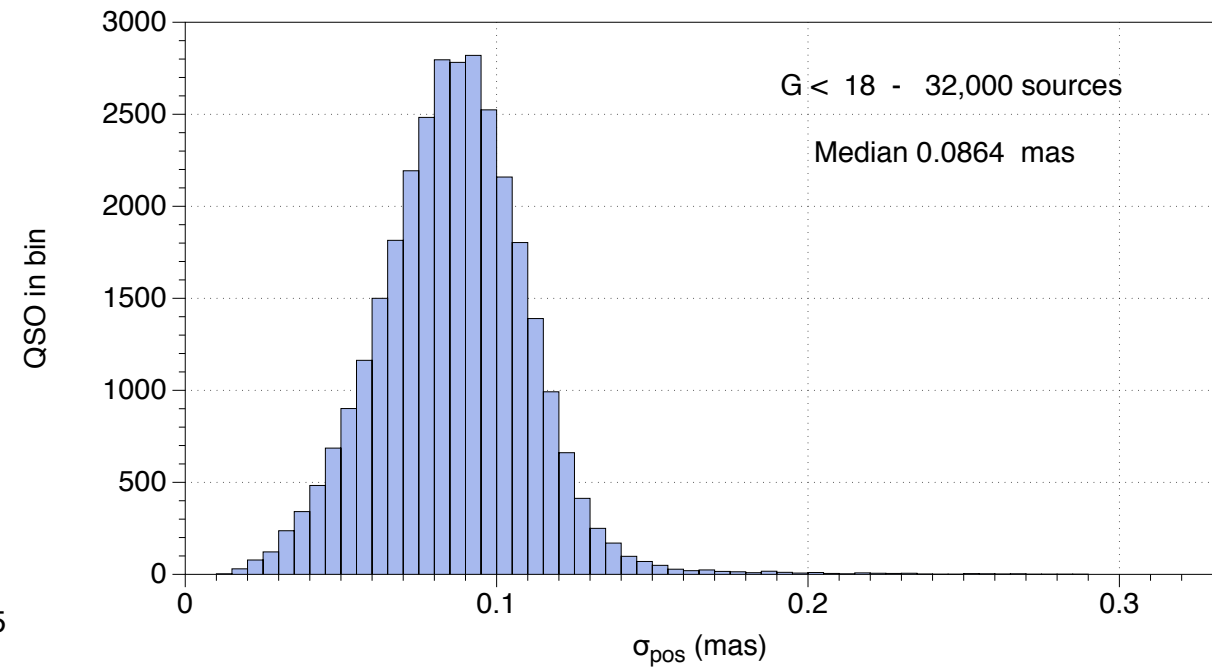
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# Gaia-CRF3 – Position uncertainties (in mas)

G < 21, 1.6 M QSOs



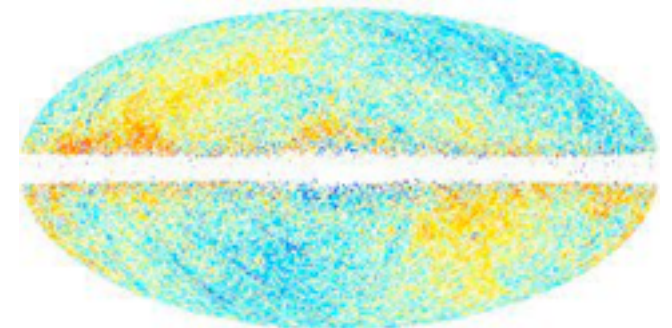
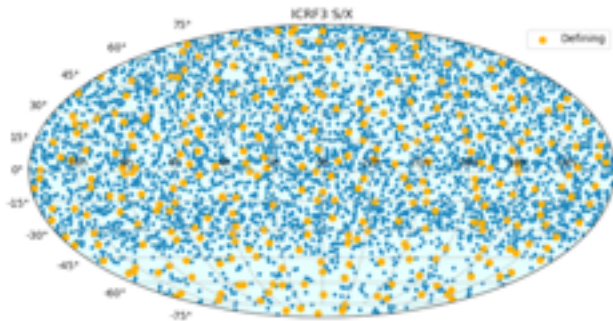
G < 18, 32 k QSOs



Klioner, Lindegren, Mignard et al. 2022

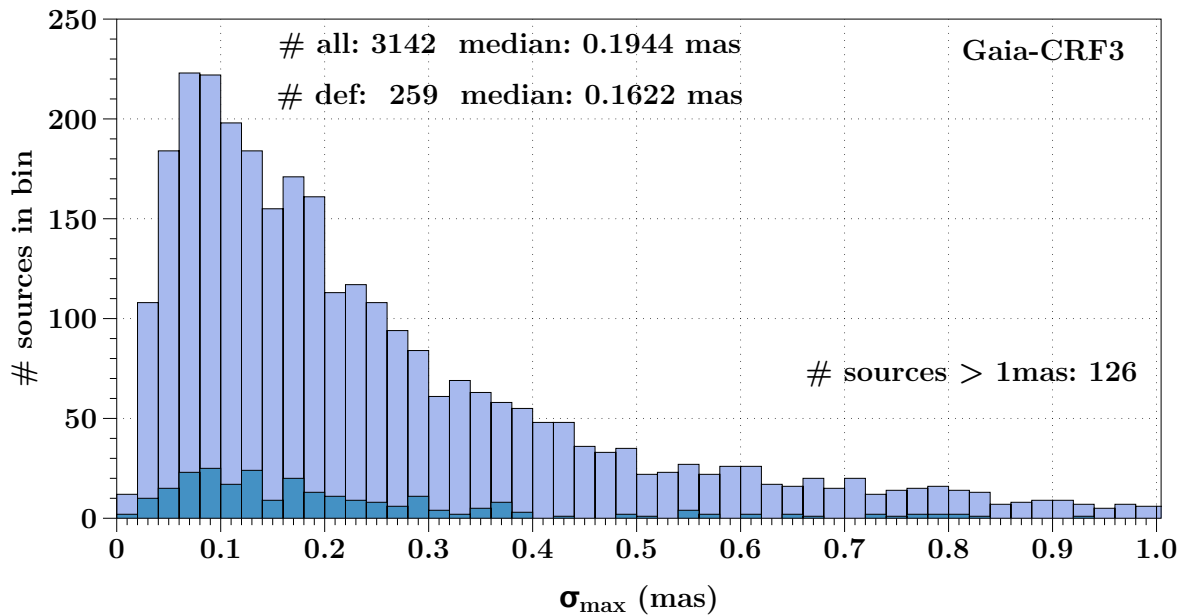
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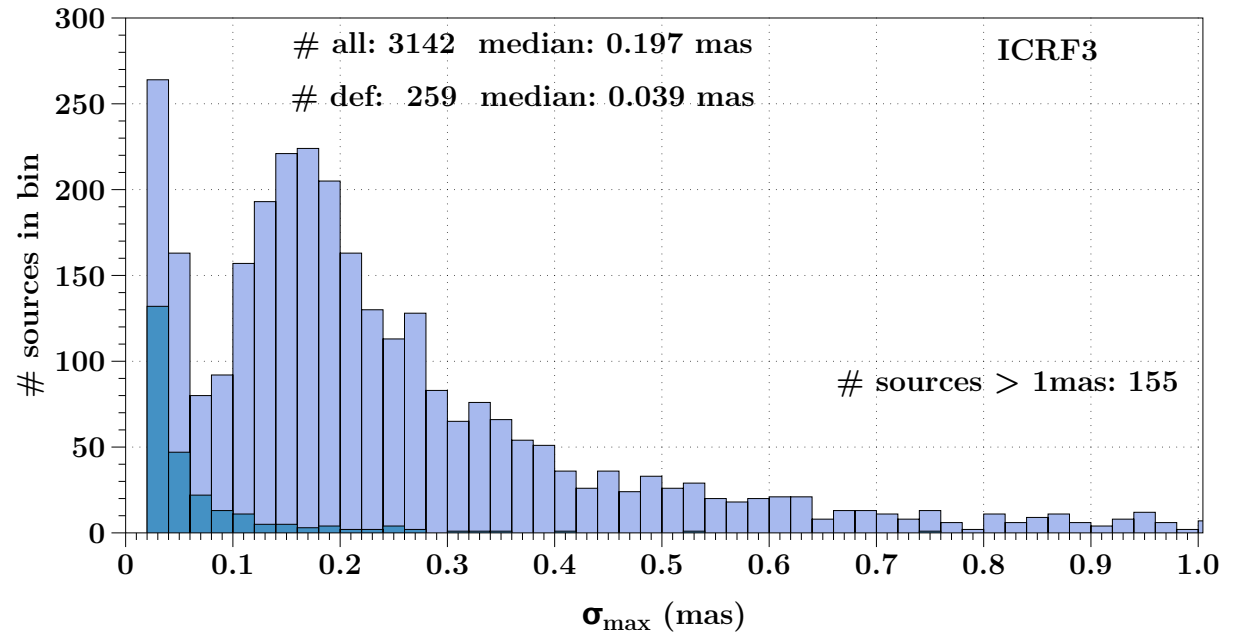


# Gaia-CRF3 & ICRF3 – 3142 Common sources

- Formal uncertainties



0.2 % of the Gaia CRF



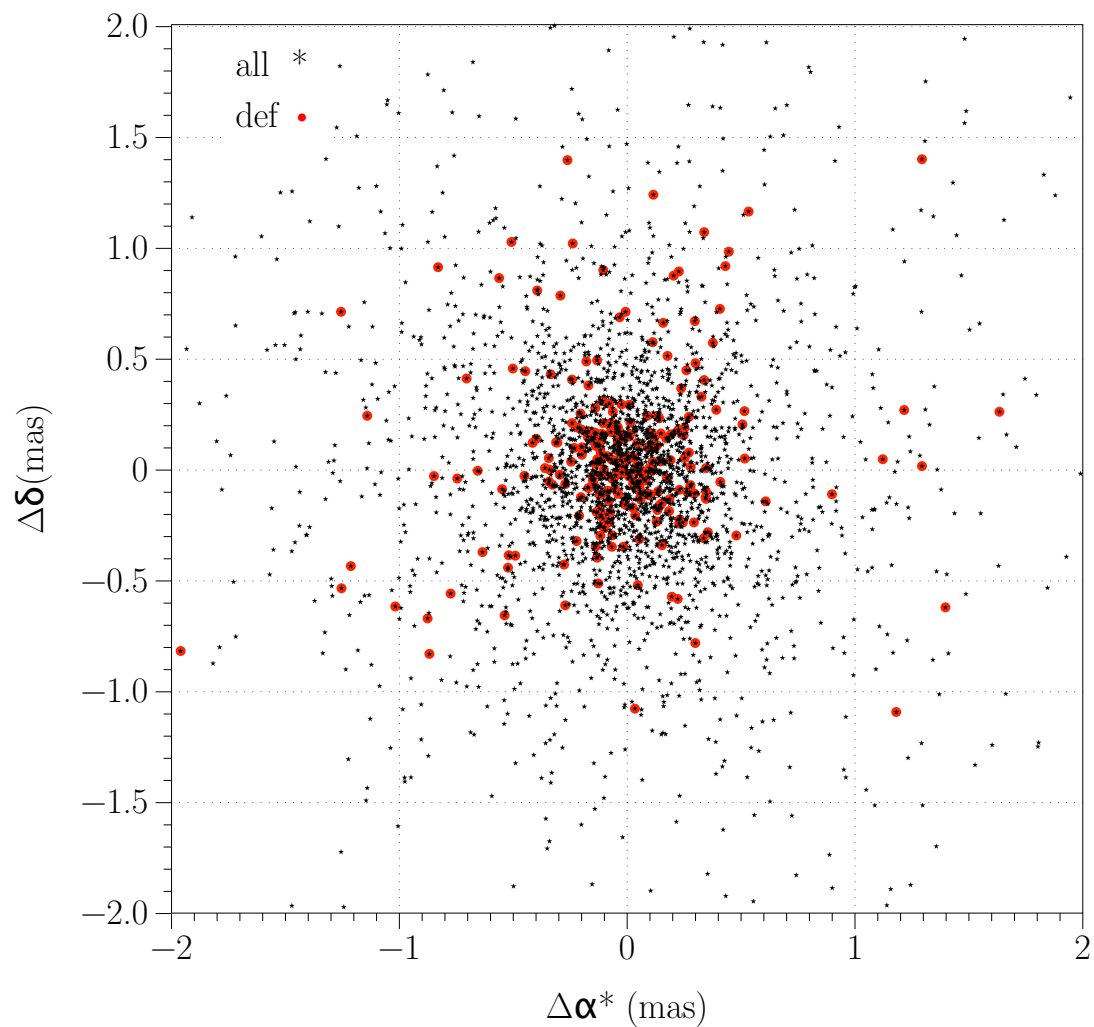
70% of the VLBI CRF

Remarkably similar distributions

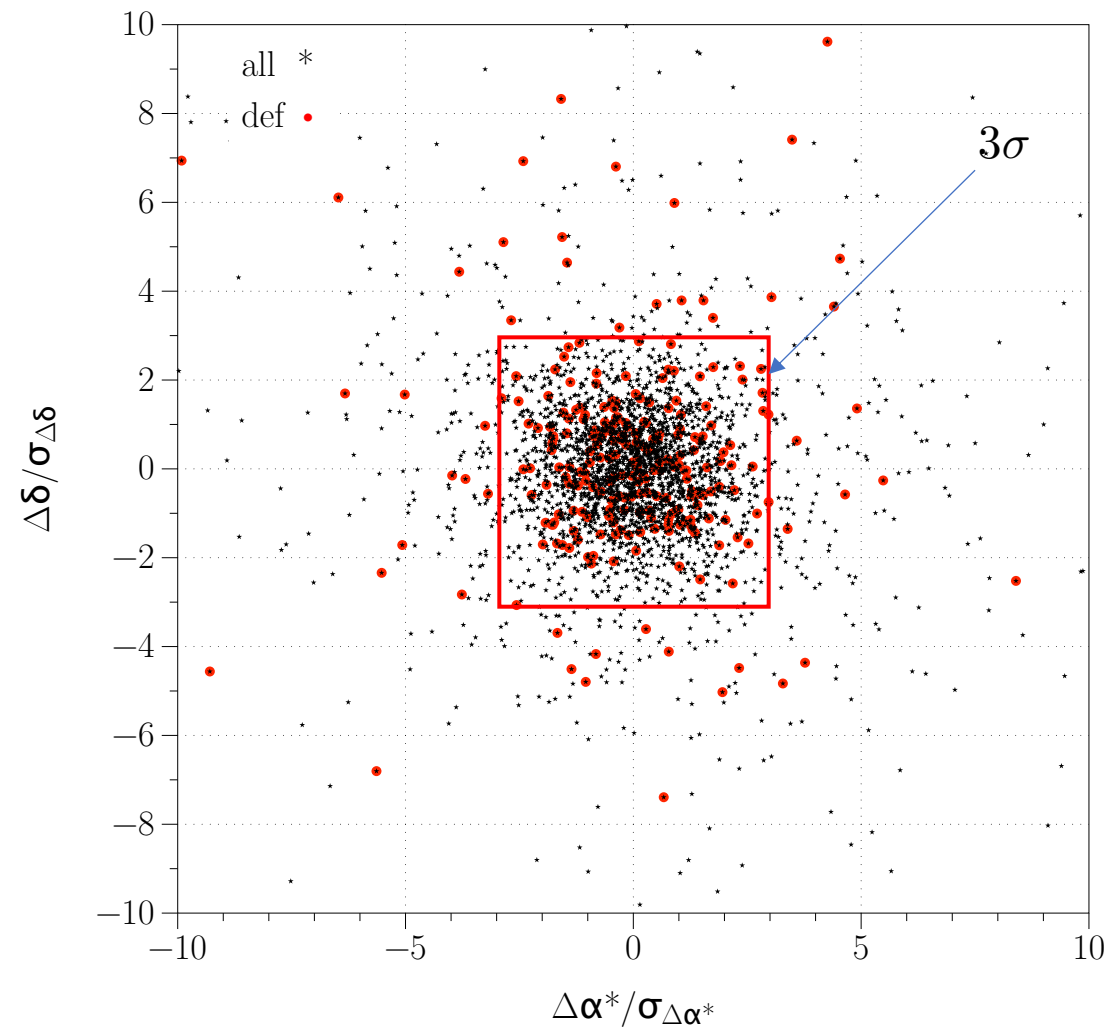
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### Absolute



### Normalised



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## 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**

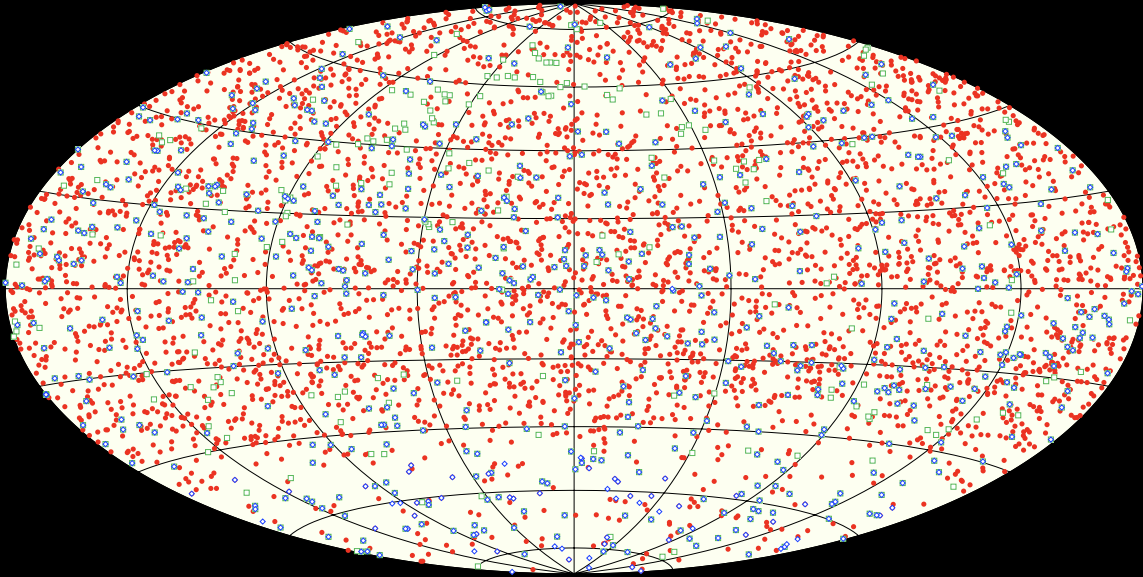
4. that since the establishment of the ICRF3, the ESA space telescope Gaia has conducted relevant optical observations of extragalactic sources and made available a high quality astrometric catalogue for these sources;

#### **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.

# IAU level structures

- WG **Third Realization of the International Celestial Reference Frame (ICRF3)** terminated in 2018 [P. Charlot]
- WG **Multi-waveband realizations of the International Celestial Reference System** terminated in 2021 [F. Mignard]
- New DIV A WG **Multi-waveband ICRF** established in 2021
  - Chaired by **P. Charlot**
  - 18 members
  - Terms of reference drafted
  - First full meeting in July 2022



*Thanks for your  
attention*

