VLBI versus Gaia: science that emerges from the disagreement

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I. State of fundamental radio astrometry on 2021.06.24:

\# sources detected: 19514   # sources observed: 34003

percentiles of accuracy:

20%	< 0.18	mas
26%	< 0.30	mas
50% (median)	< 1.00	mas
80%	< 2.9	mas
90%	< 6.0	mas
94%	< 10	mas

Flux density @ X-band: [0.003, 22] Jy, median: 55 mJy

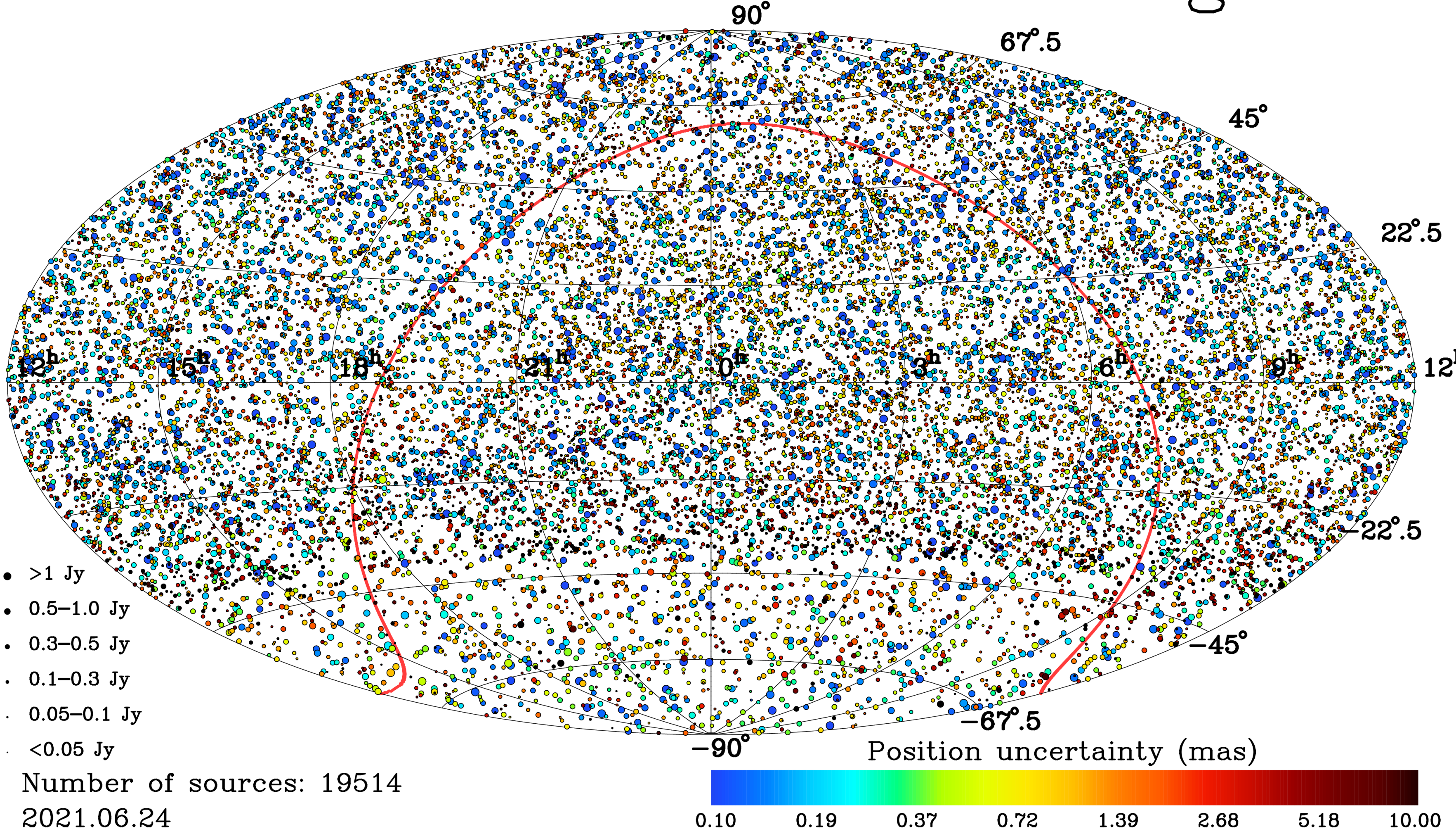
Observed band:

22 GHz	9%
8 GHz	92%
5 GHz	70%
2 GHz	33%
Dual-band:	81%

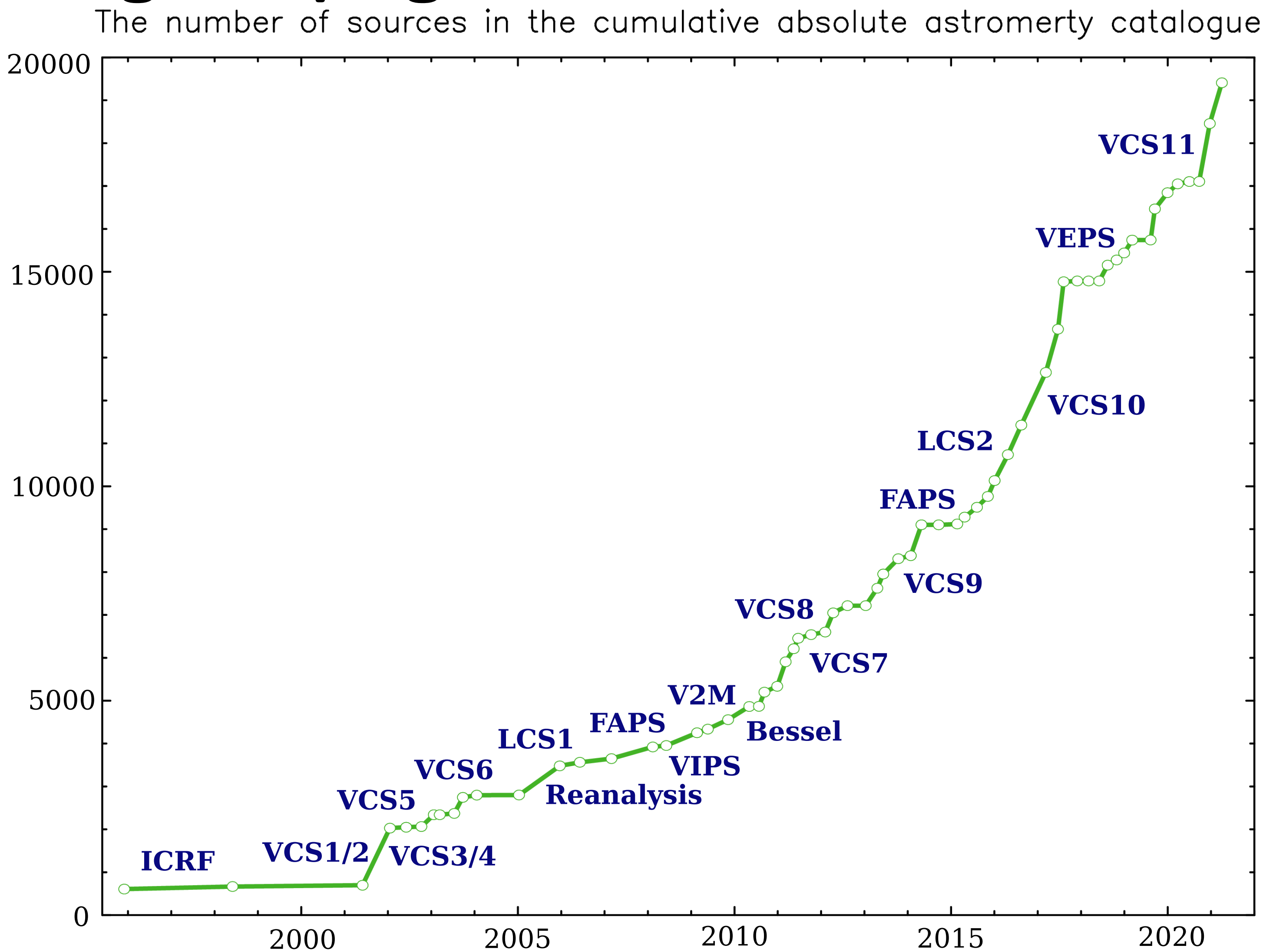
Number of observing sessions per source

1	64%
1–2	70%
1–5	91%
10+	5%
100+	2%

Radio Fundamental Catalogue

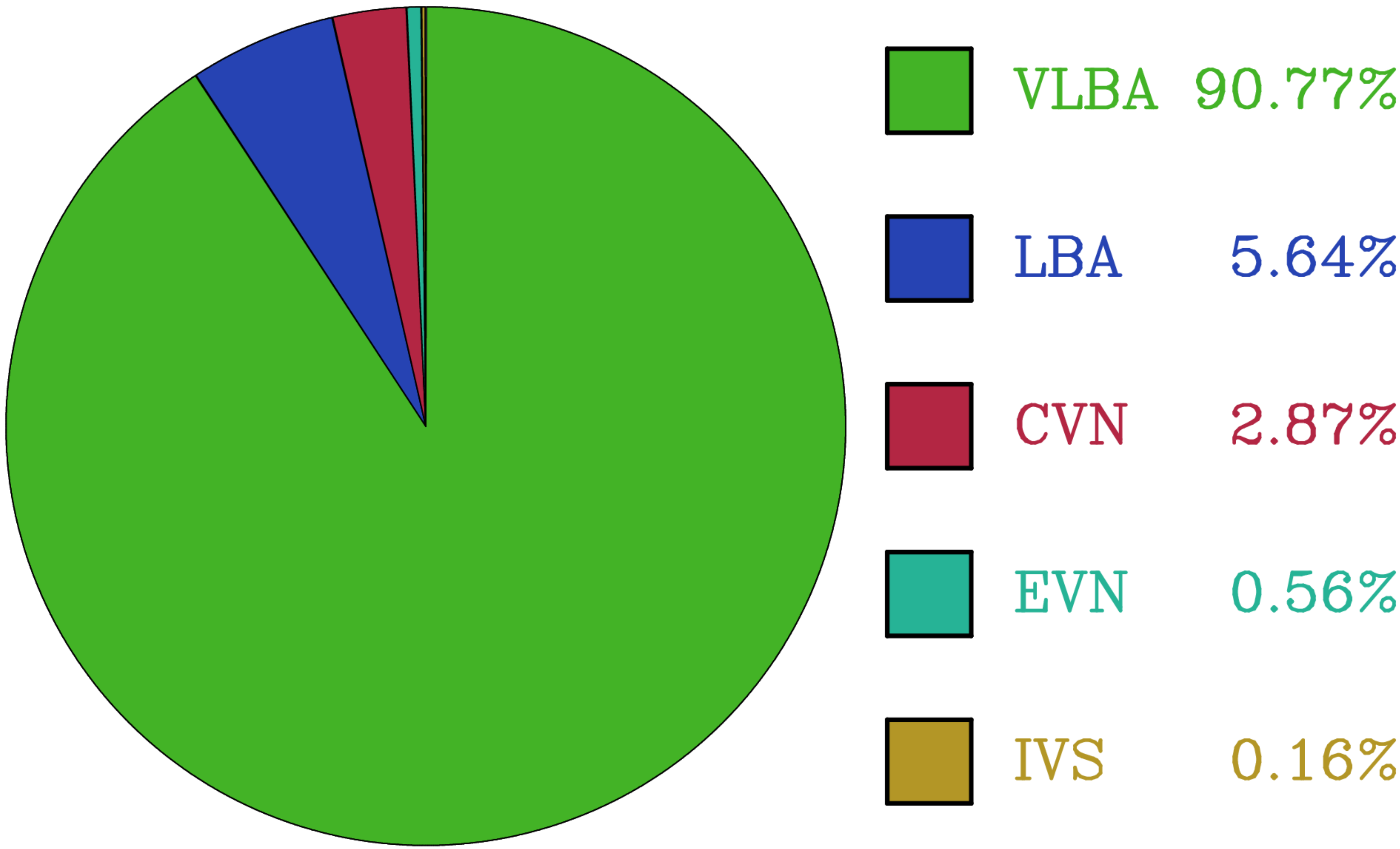


Observing campaigns



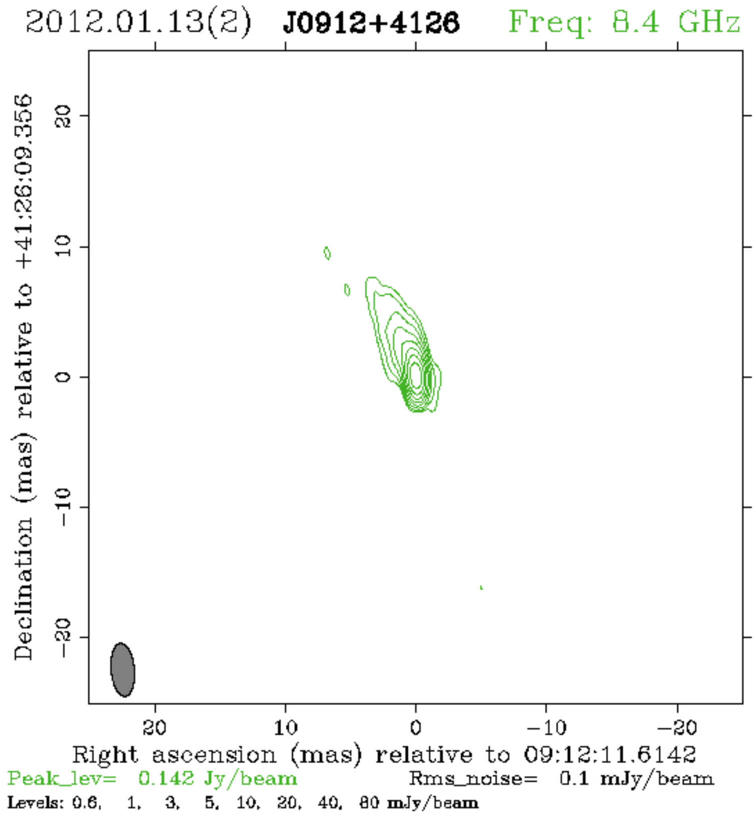
61 dedicated observing campaigns; 909 segments; 1.5 year observing time.
12 Pb raw data, 70 Tb visibility data.

Contribution of VLBI networks to the RFC

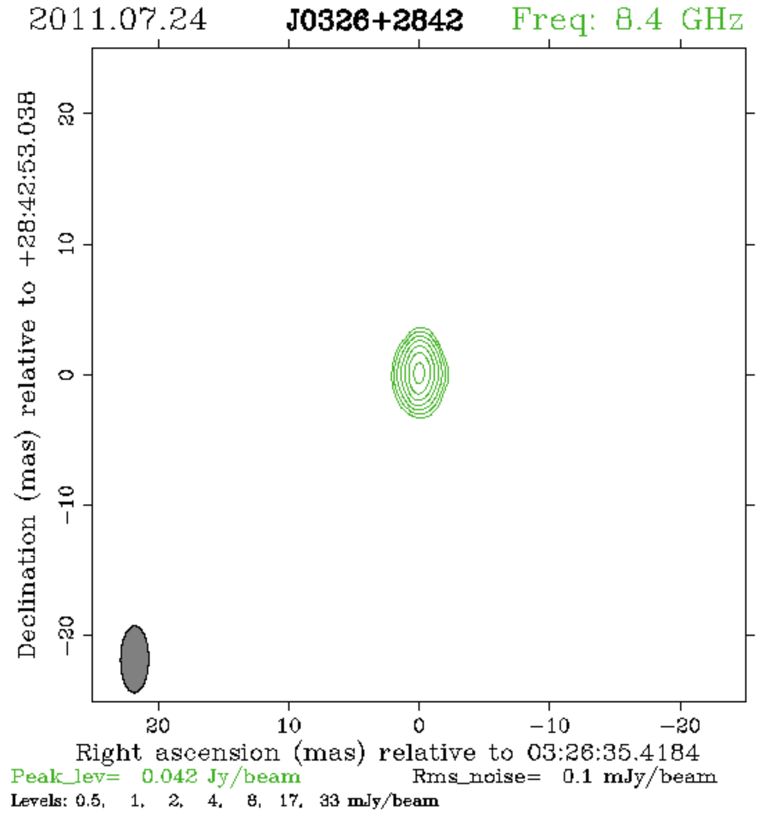


Observed objects

19495 Active galaxy nuclea

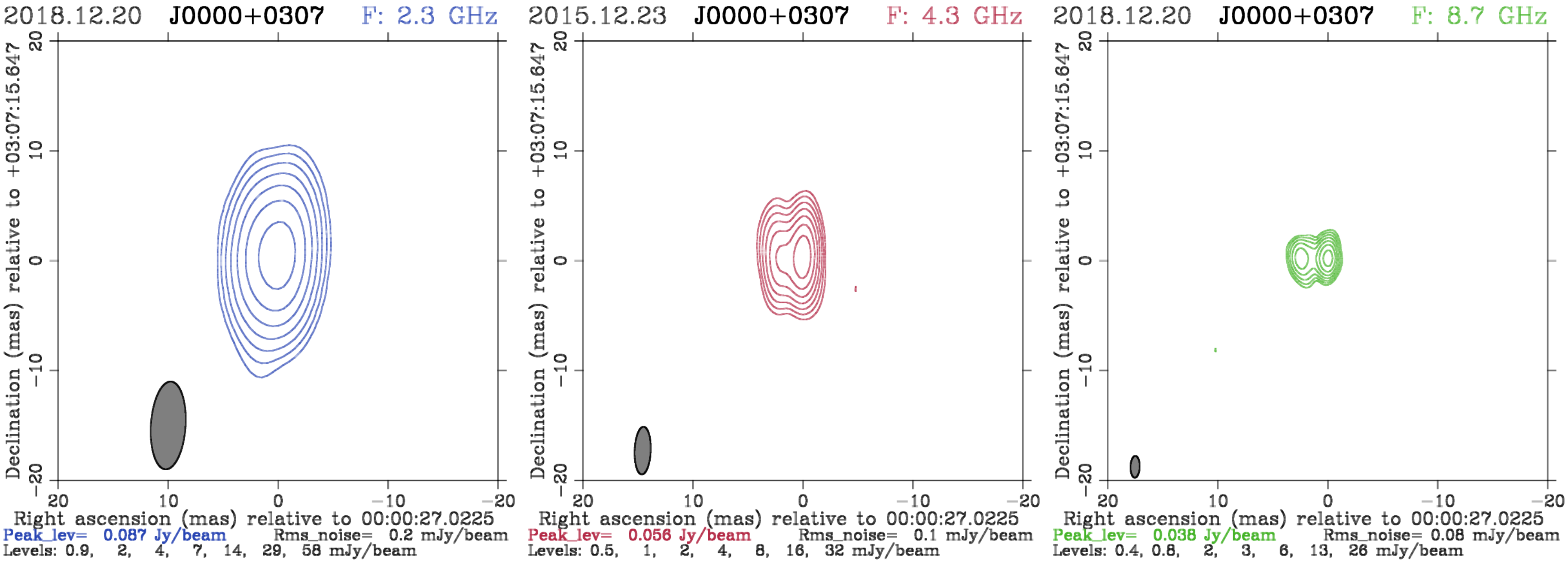


19 radio stars



Images are available for 17,411 sources (89%)

In total, 110943 images are available at **http://astrogeo.org/vlbi_images**



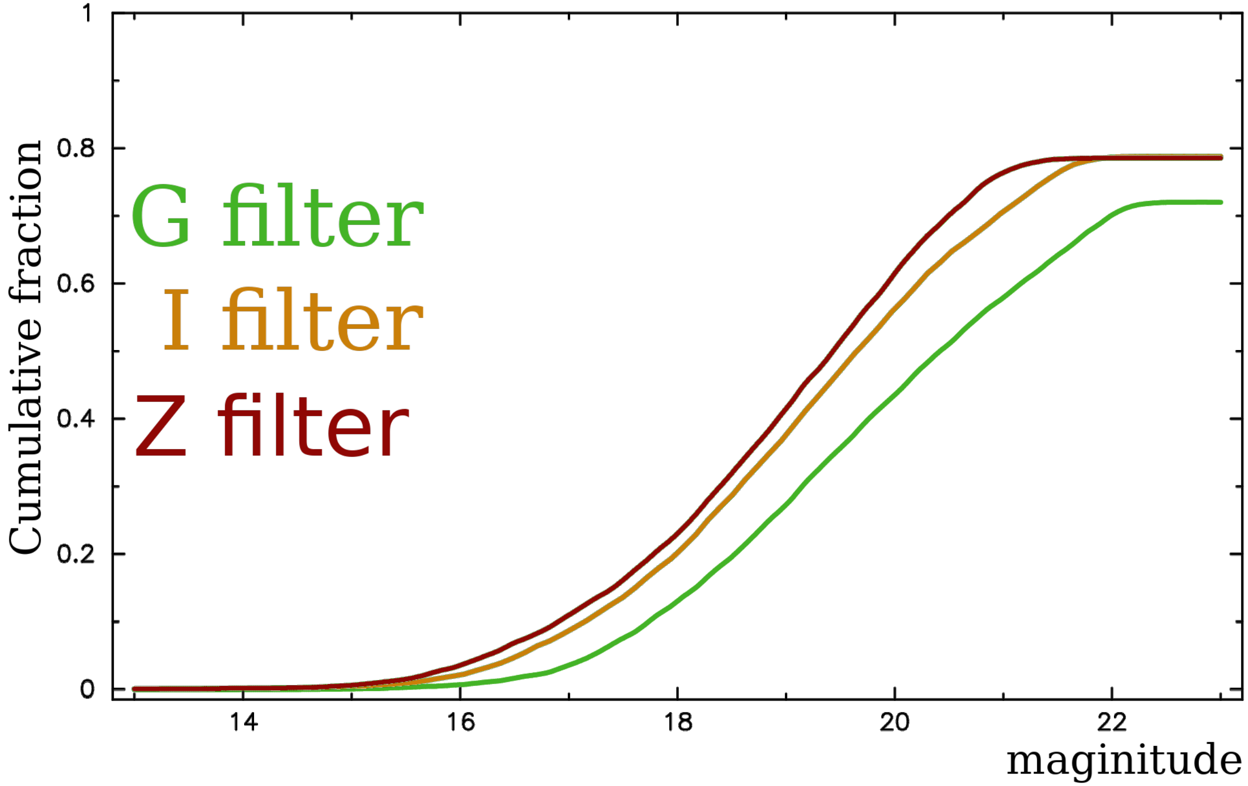
Technology of VLBI surveys

- Setting a goal of the survey
- Selection of a (wide) pool of candidates;
- Computing the probability of detection of each source;
- Maximization of the target function.
- Scheduling
- Several iterations of visibility analysis / astrometric data analysis
- Source imaging

Goals of astrometric surveys

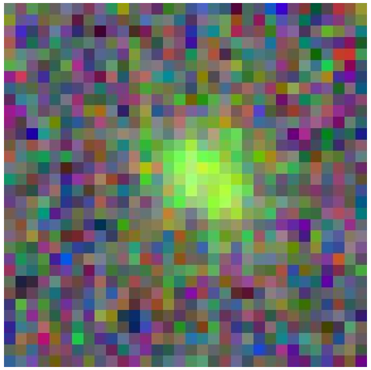
- To build a dense grid of phase calibrators
- To study a population of bright radio loud AGNs
- To associate a given population of radio sources with AGNs
- To improve position of sources observed at other wavelengths
- To investigate systematic differences with results of space astrometry

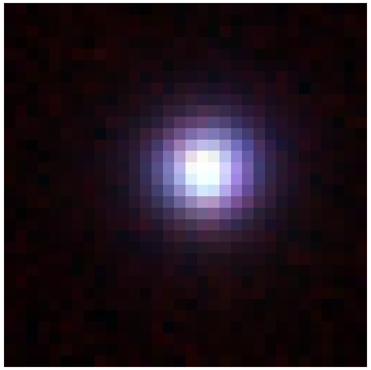
Comparison with Pan-STARRS catalogue

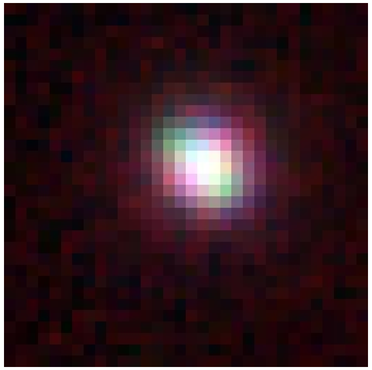


11618 RFC/PS matches

Flt	share	compl mag
g	65%	22.0
r	67%	21.8
i	68%	21.6
z	67%	21.0
y	65%	21.0





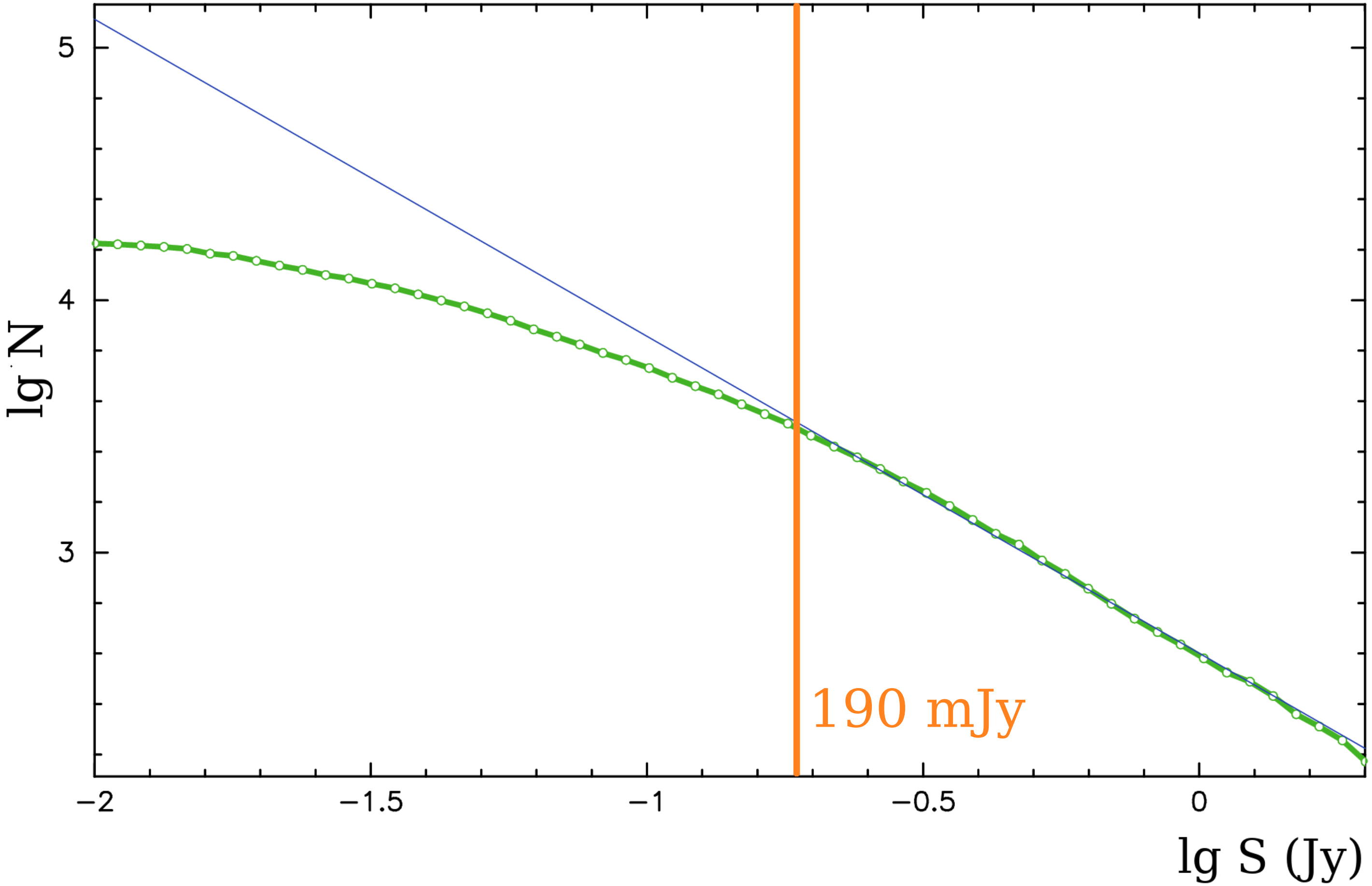


Number of matches

γ-ray	Fermi:	14%
X-ray	ROSAT	19%
UV	Galex	32%
optic	Gaia:	62%
optic	PanSTARRS:	79%
infra-red	WISE:	77%

Completeness of the RFC

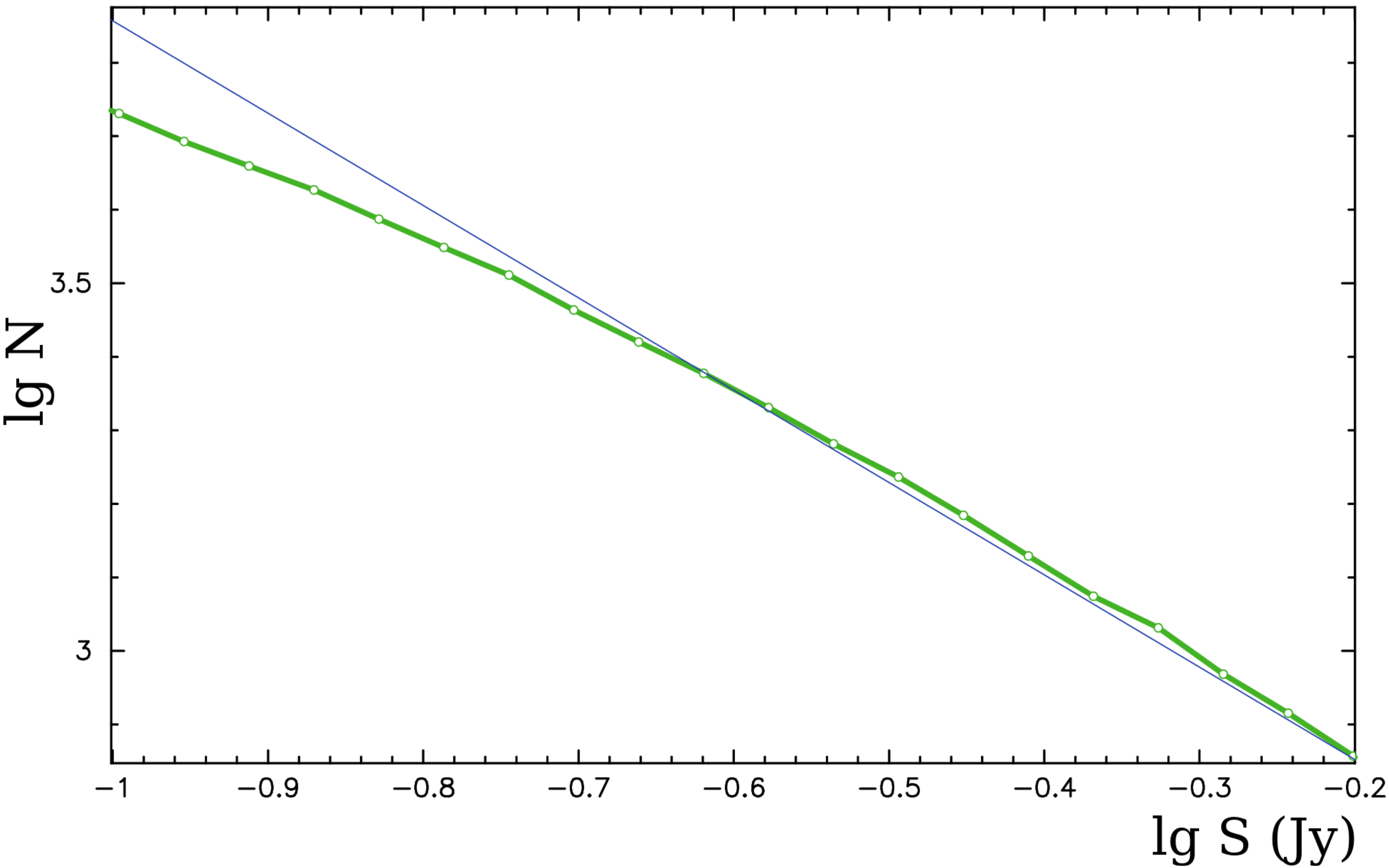
$\log N$ versus $\log S$ diagram. $S_{\rm corr}$ @ 8 GHz at baselines 200–1000 km



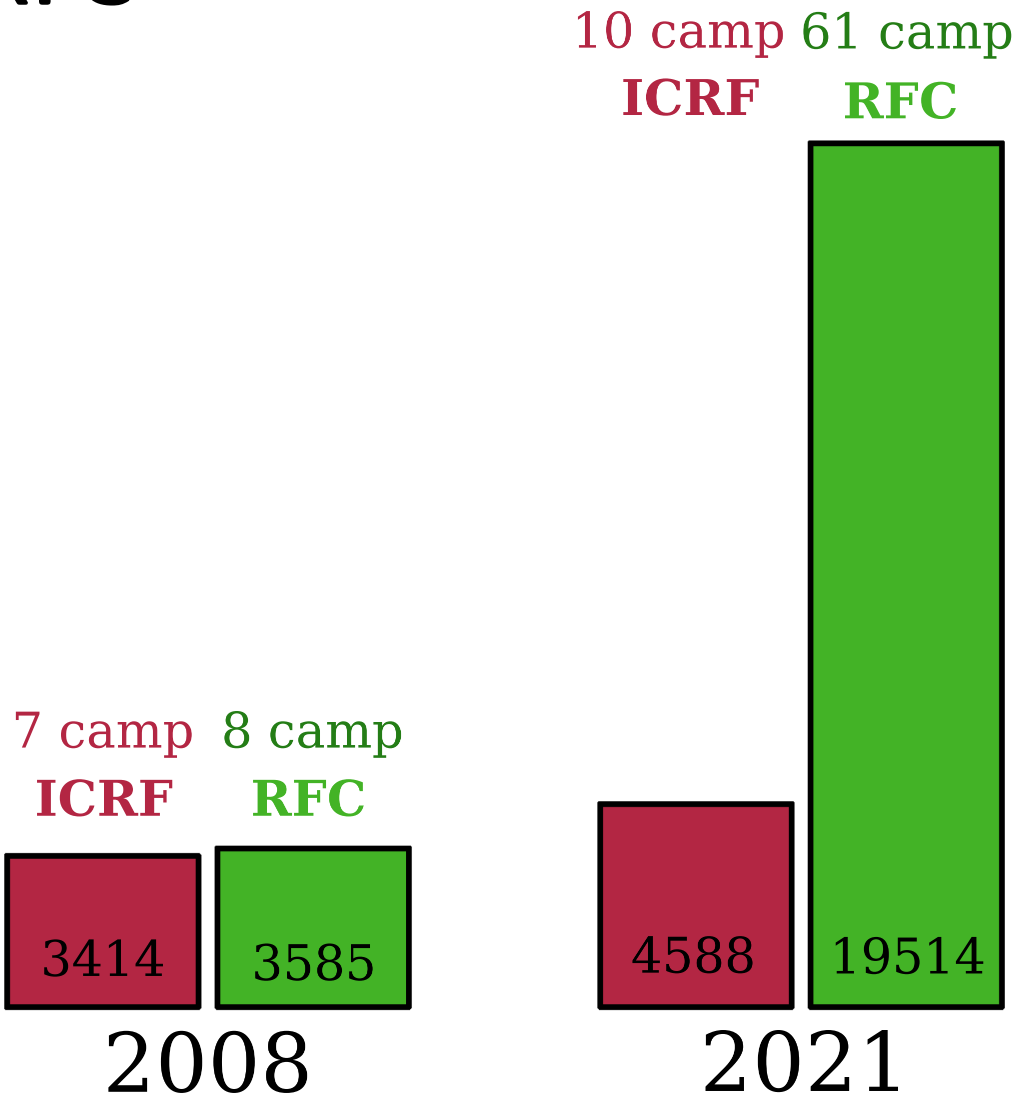
250 mJy	100%
200 mJy	96%
190 mJy	95%
150 mJy	86%
100 mJy	75%

Full sample at 190 mJy has 3200 objects, 16% of the RFC.

Lon N / Log S zoomed

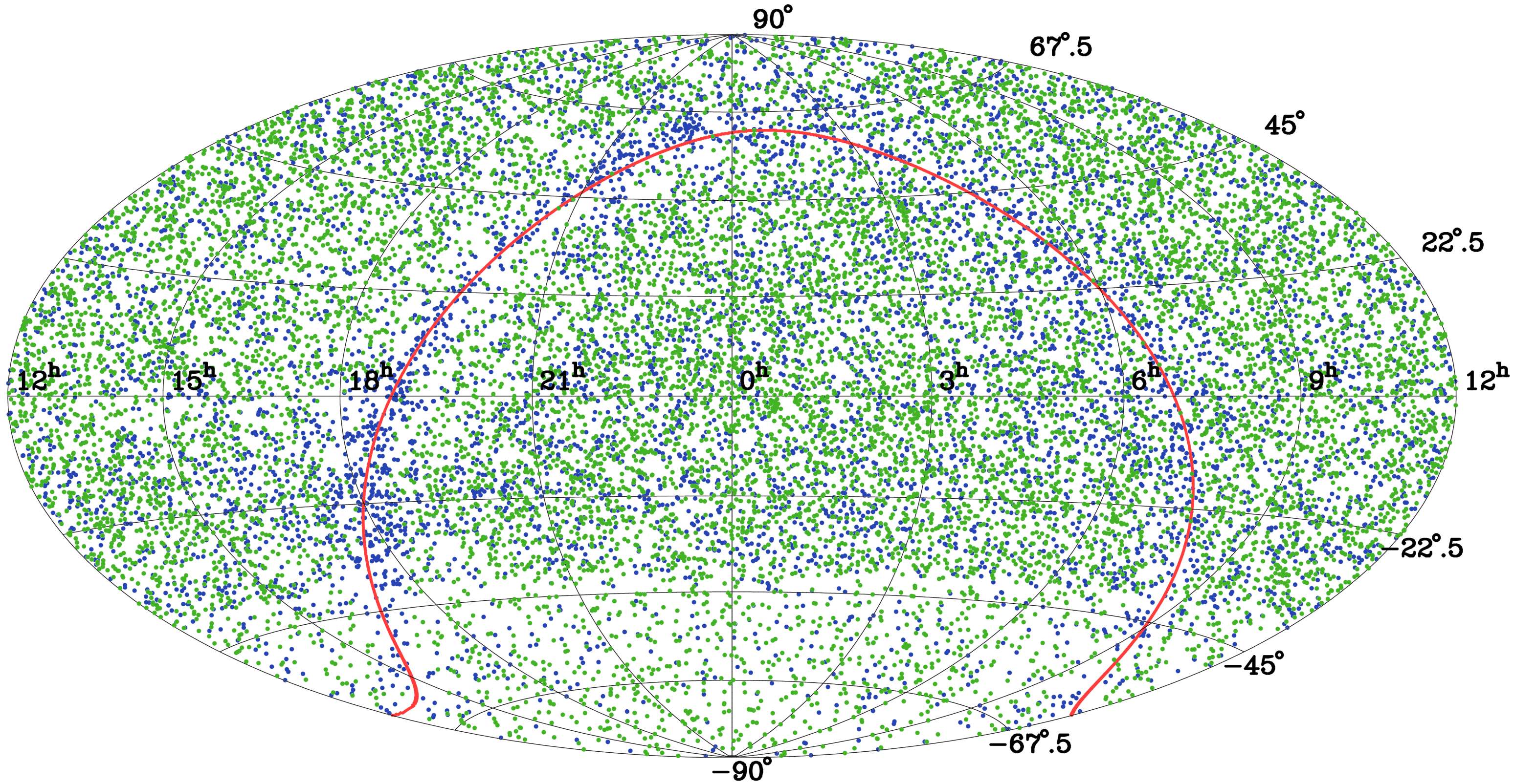


ICRF and RFC



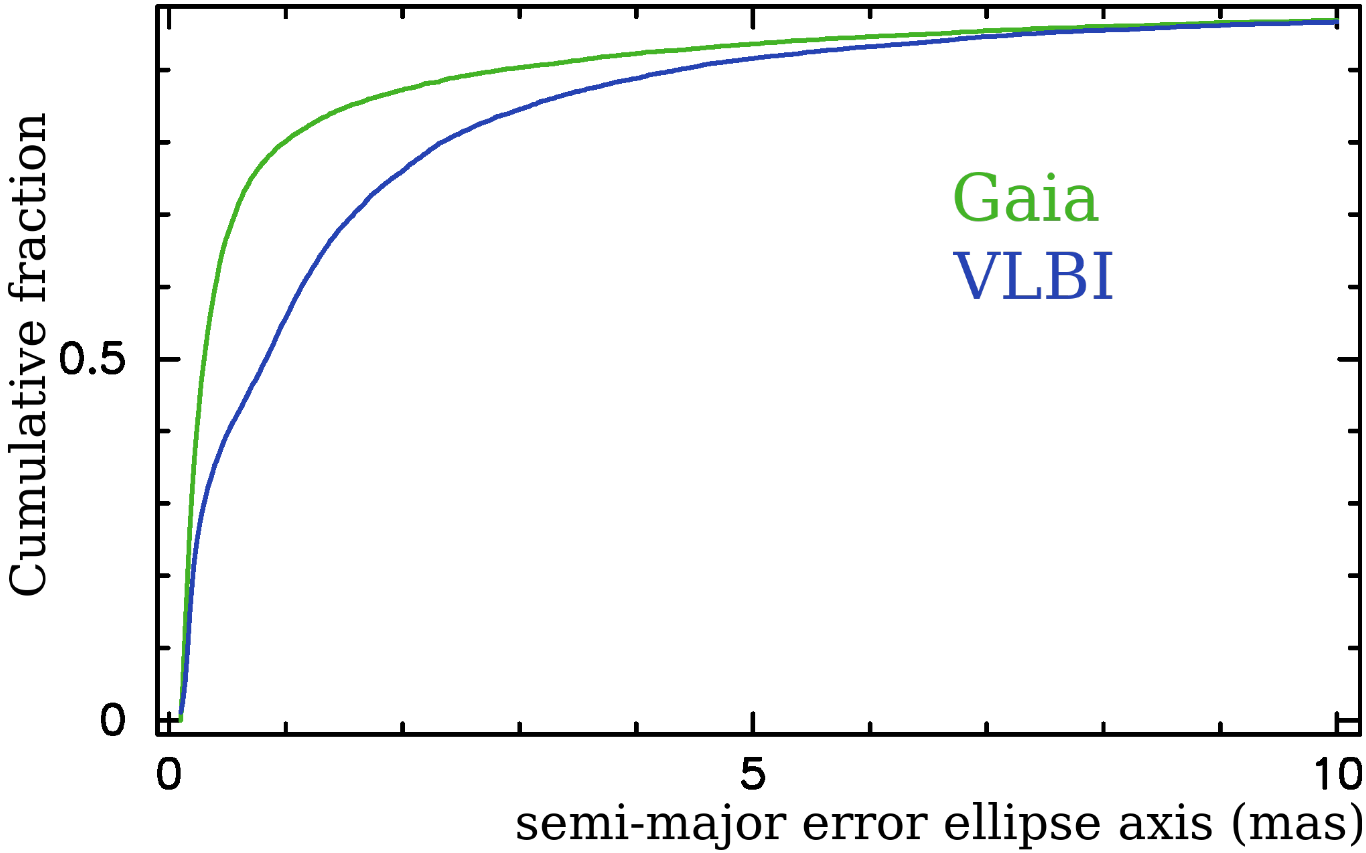
ICRF3 is a subset of RFC (23% sources)

VLBI Radio Fundamental Catalogue (**19,514 sources**) on 2021.06.24 and *Gaia* DR3 ($1.81 \cdot 10^9$ objects)



Green: 12,009 VLBI/*Gaia* matches $P < 0.0002$

Blue: VLBI sources without *Gaia* matches

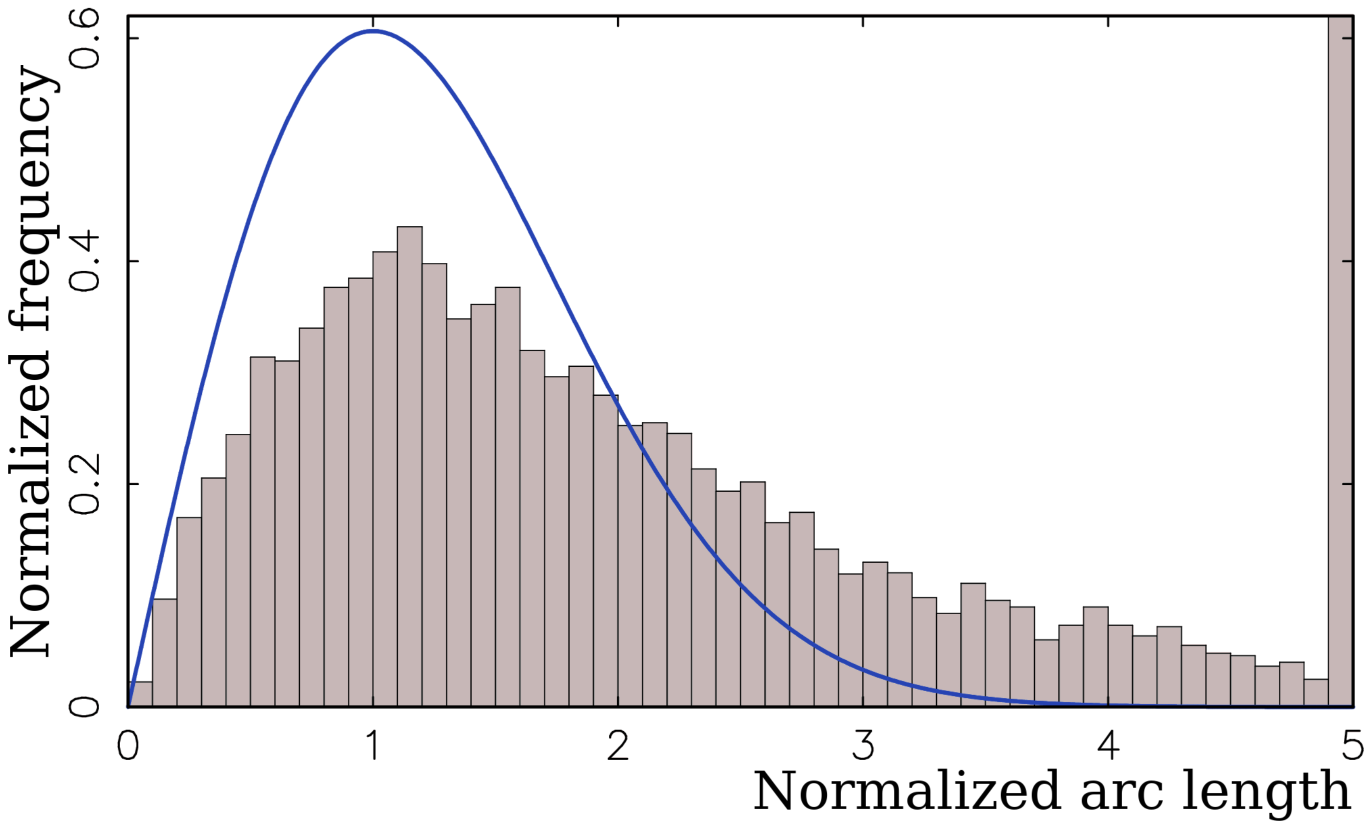


Median position error:

VLBI: 0.83 mas
Gaia: 0.30 mas

VLBI has lost its superiority to Gaia!

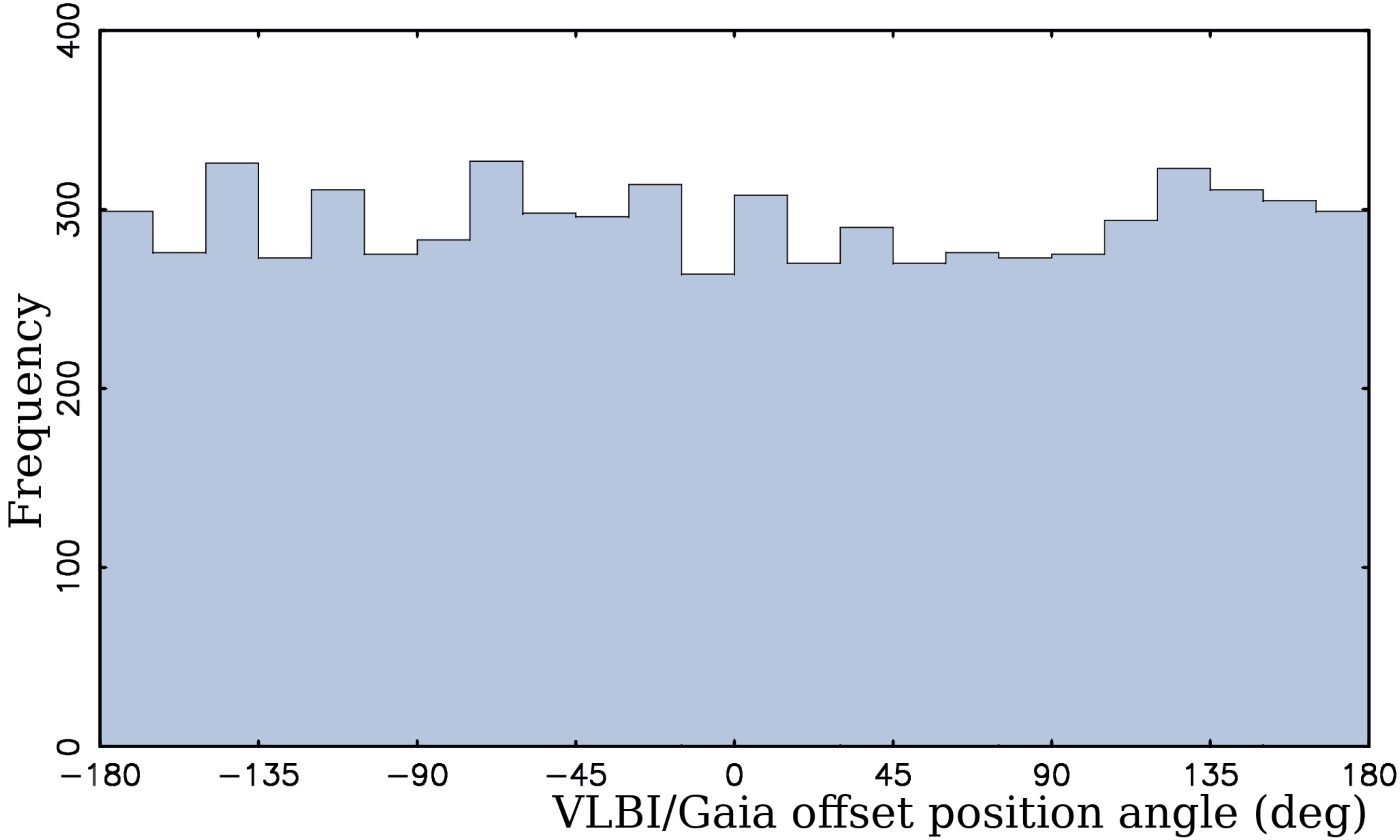
The distribution of normalized VLBI/Gaia arc-lengths over 9465 AGNs



1/6 matched sources are outliers: $a/\sigma_a > 4$

What is their nature?

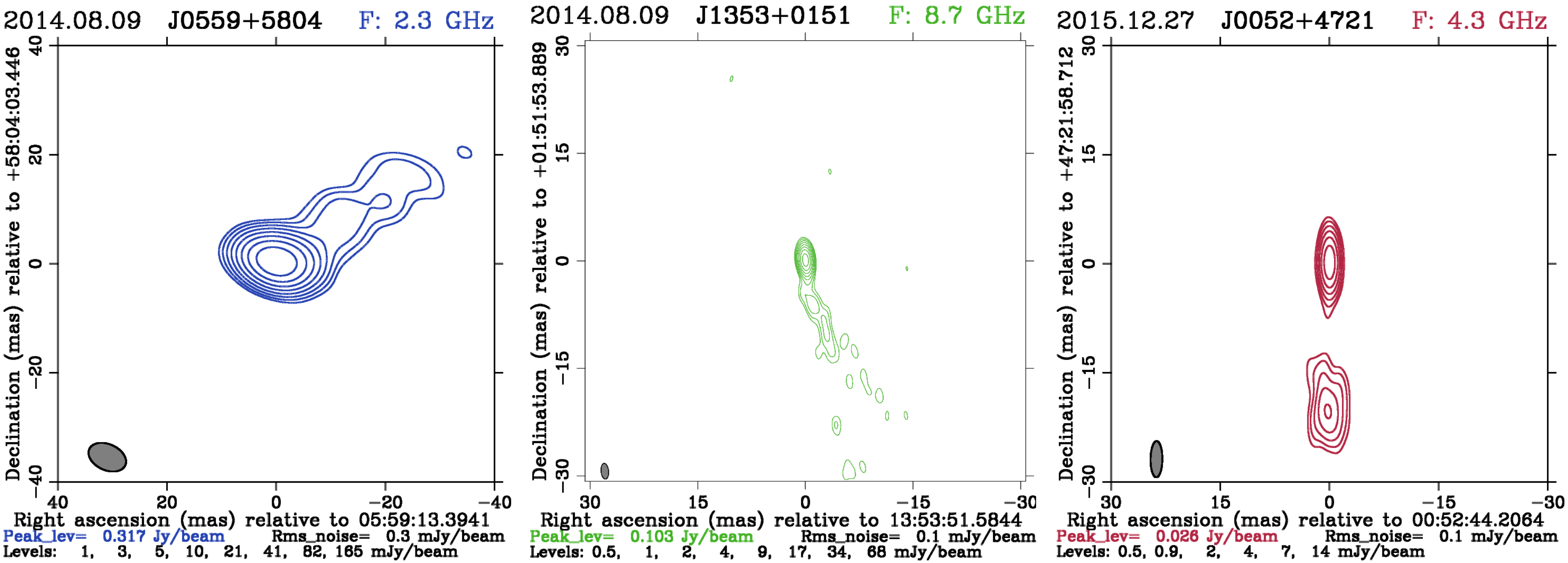
Distribution of VLBI/Gaia position offset angles



Main finding: no preference at $0^\circ, 180^\circ$ (VLBI declination errors)
No deviation from the isotropy.

How the AGNs look like at mas scale?

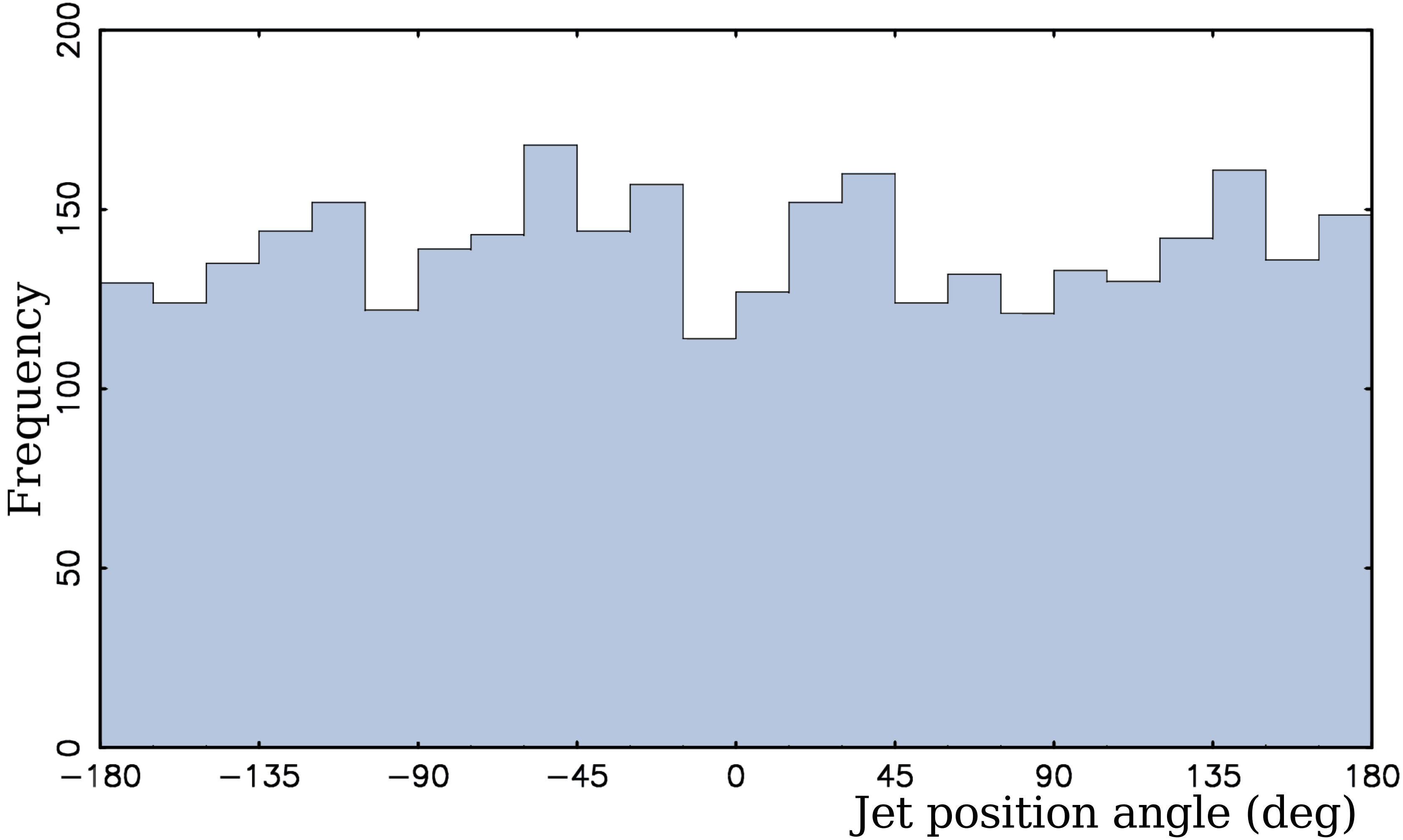
Generic property: core-jet morphology:



- Images are available for 89% sources (the number will increase)
- Jets are reliably determined for 25% sources (will be improved)

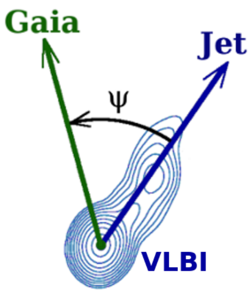
AGNs are intrinsically asymmetric sources!

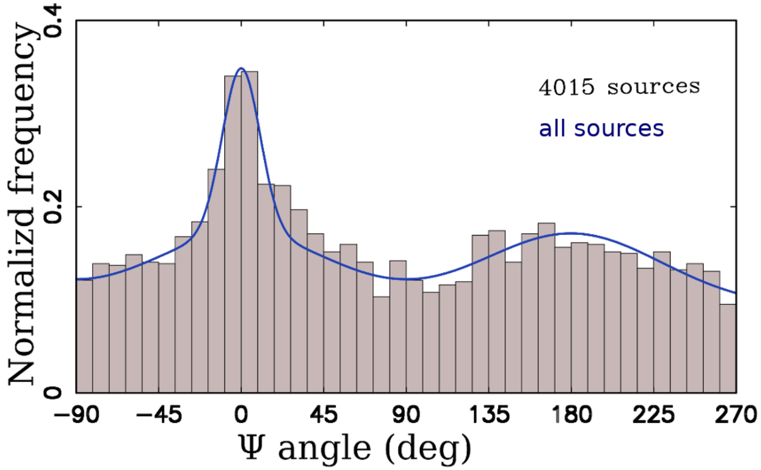
Distribution of AGN jet directions in the VLBI/Gaia sample

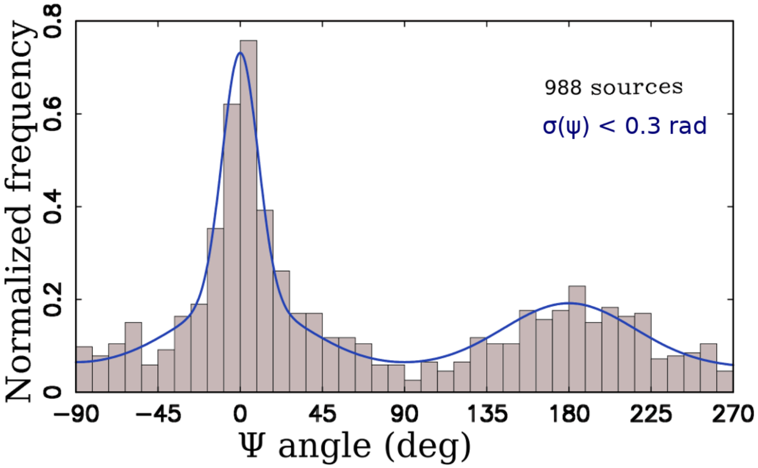


No deviation from the isotropy

Distribution of VLBI/Gaia position offset angles with respect to jet direction

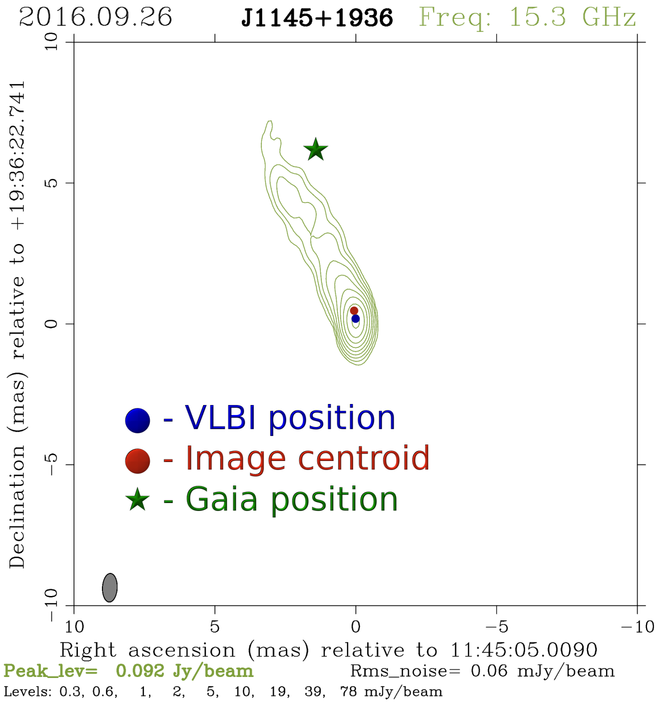


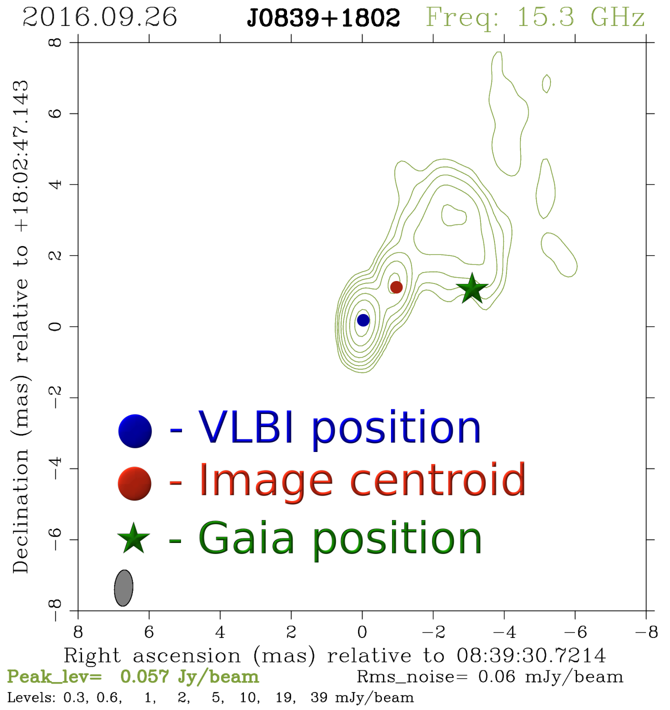




Contribution of source structure to VLBI position

- VLBI does not measure position of the centroid
- Source structure contribution depends on image Fourier transform
- The most compact image component has the greatest impact on position
- Examples:



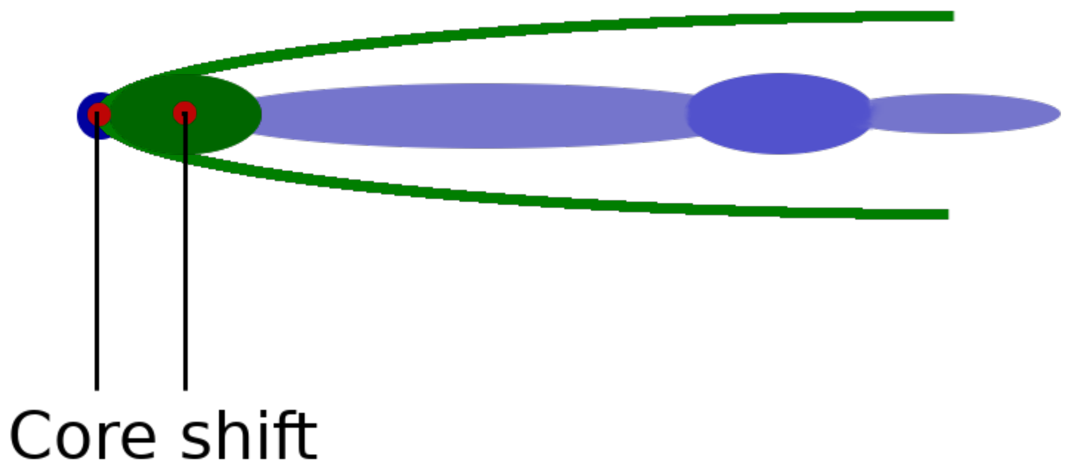


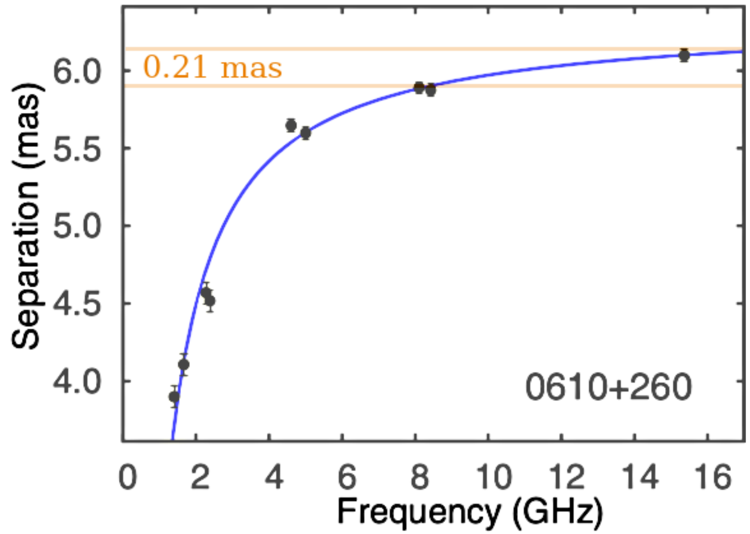
- Test VLBI experiment processed with source structure contribution applied:
  - Median VLBI position bias: 0.06 mas
  - Median image centroid offset: 0.25 mas

Conclusion: the effect is too small

Core-shift

- Core is the optically thick part of the jet;





Sokolovsky et al. 2011

- Core centroid is shifted with respect to the jet base;
- The shift is frequency dependent;
- Results of core-shift measurements:
  - Contribution to 8 GHz positions: ~ 0.2 mas;
  - Contribution to dual-band positions: 0.02–0.05 mas.

Conclusion: the effect is too small

Proposed explanation:

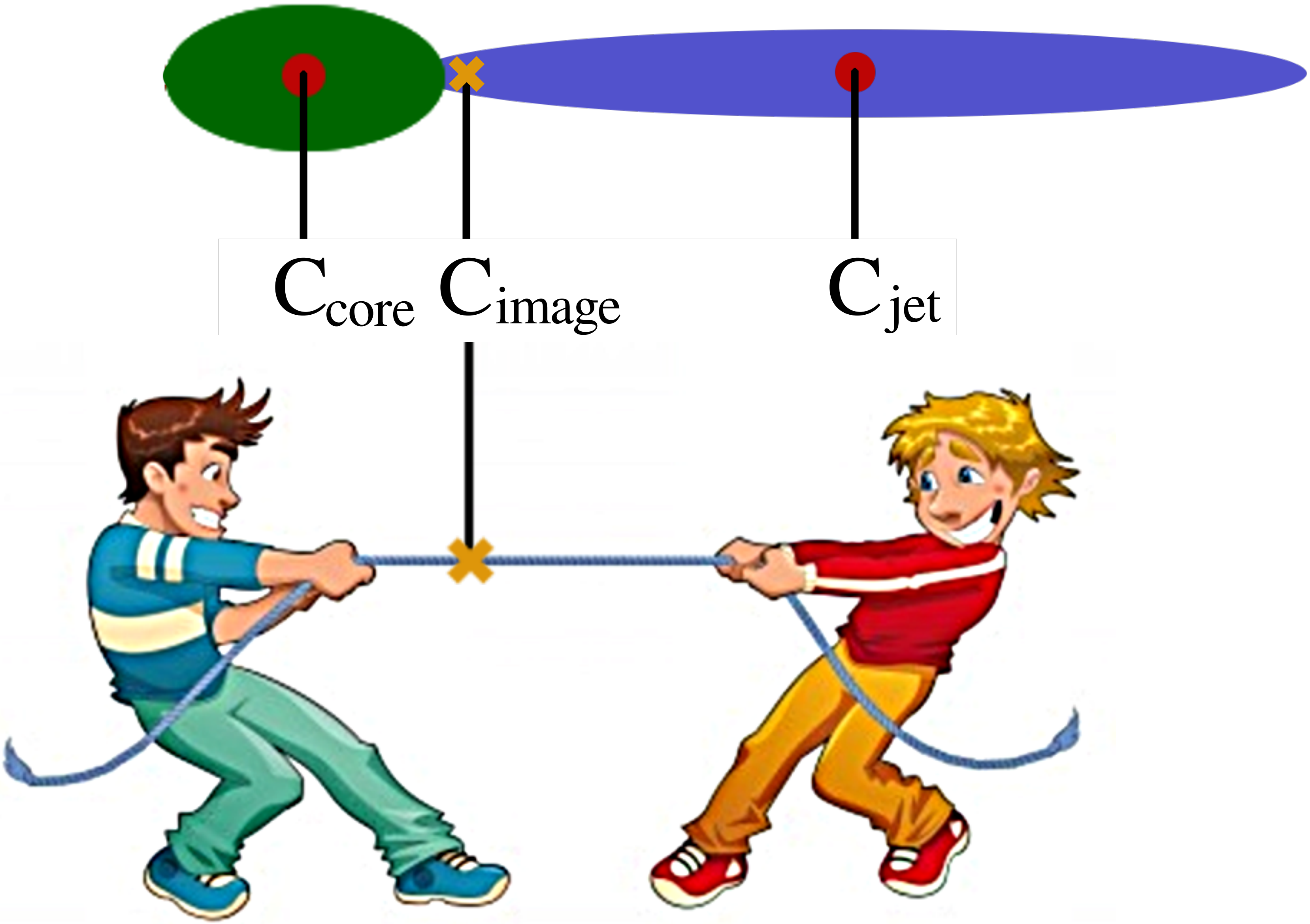
Presence of core-jet morphology in **optical range** at scales less than **Gaia PSF** (200 mas)

Interferometer (**VLBI**) and a power detector (**Gaia**) have a fundamentally different response to source structure.

- **VLBI:** Sensitive to the position of the most compact component
- **Gaia:** Sensitive to the position of the centroid

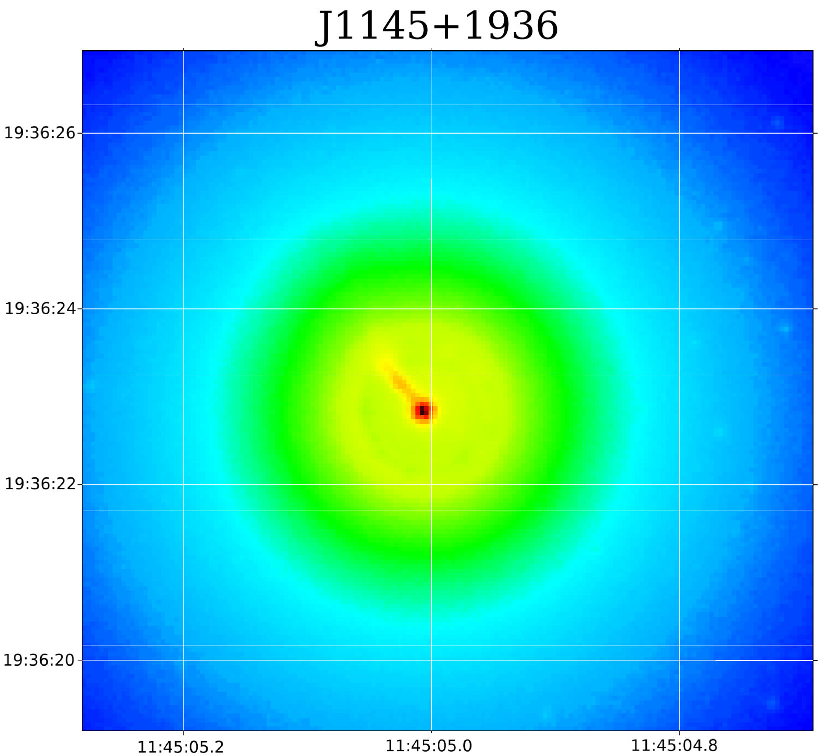
The differences **Gaia** minus **VLBI** provide offset of the centroid wrt jet base.

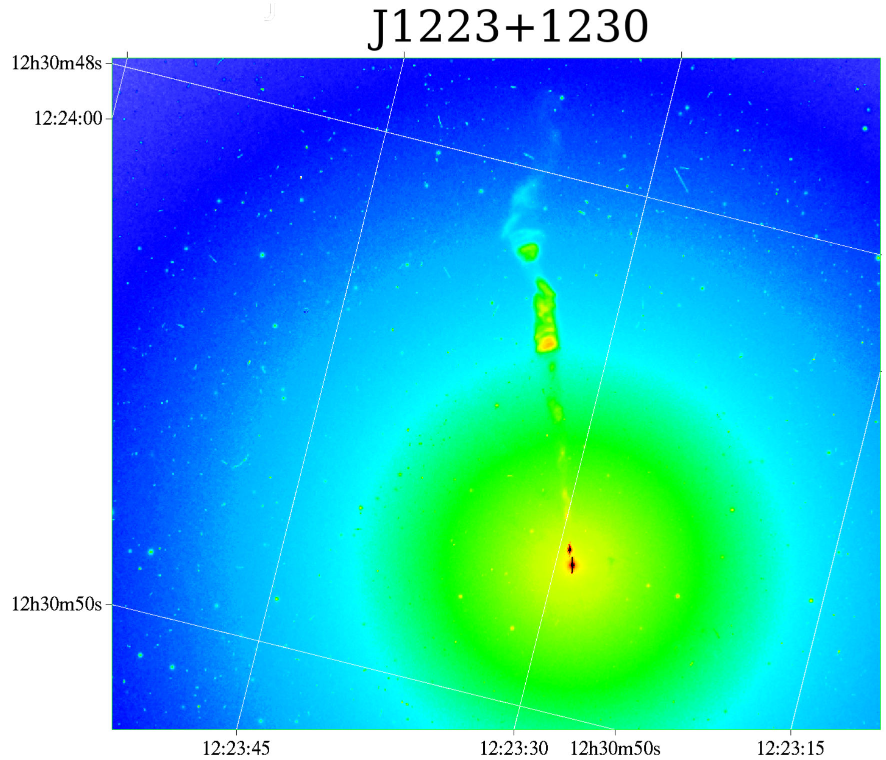
Centroid of a core-jet morphology



Contribution of optical structure

There are over 20 known optical jets with sizes 0.5–$20''$





At z=0.07, visible optical jet of J1145+1936 would shift centroid at 5 mas

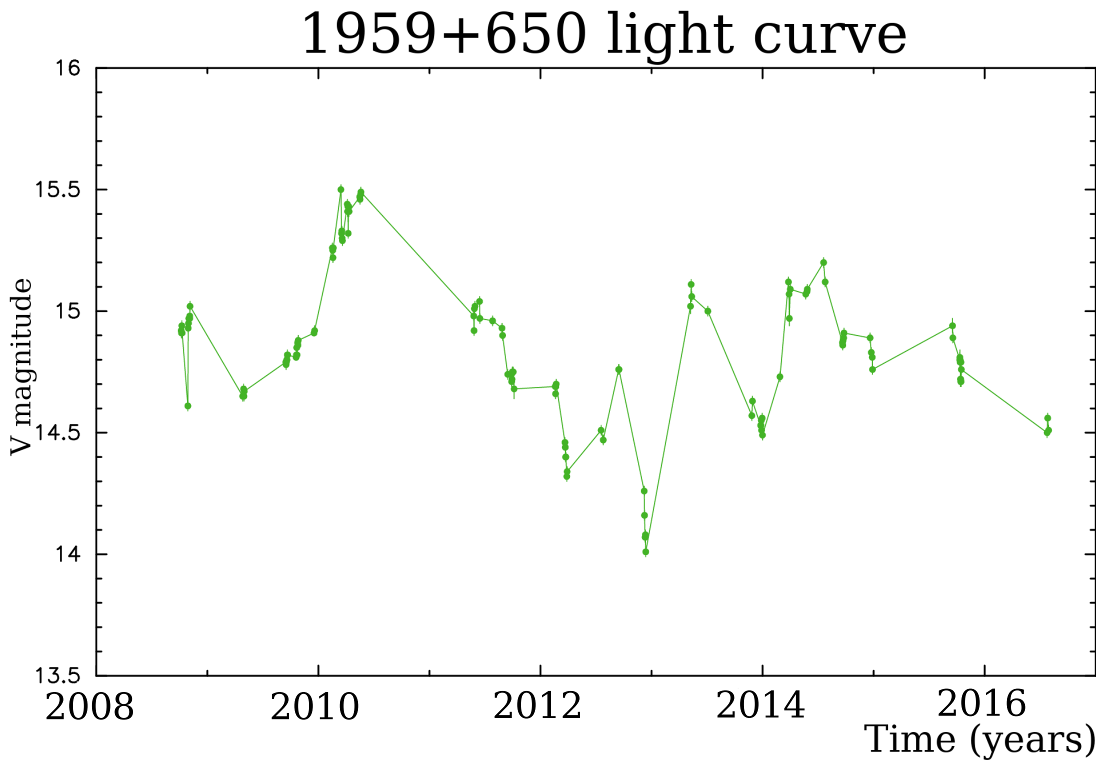
At z=0.3, visible optical jet of J1223+1230 would shift centroid at 1.2 mas

Conclusion: known optical jets at farther distance can cause centroid shifts at 1–2 mas level

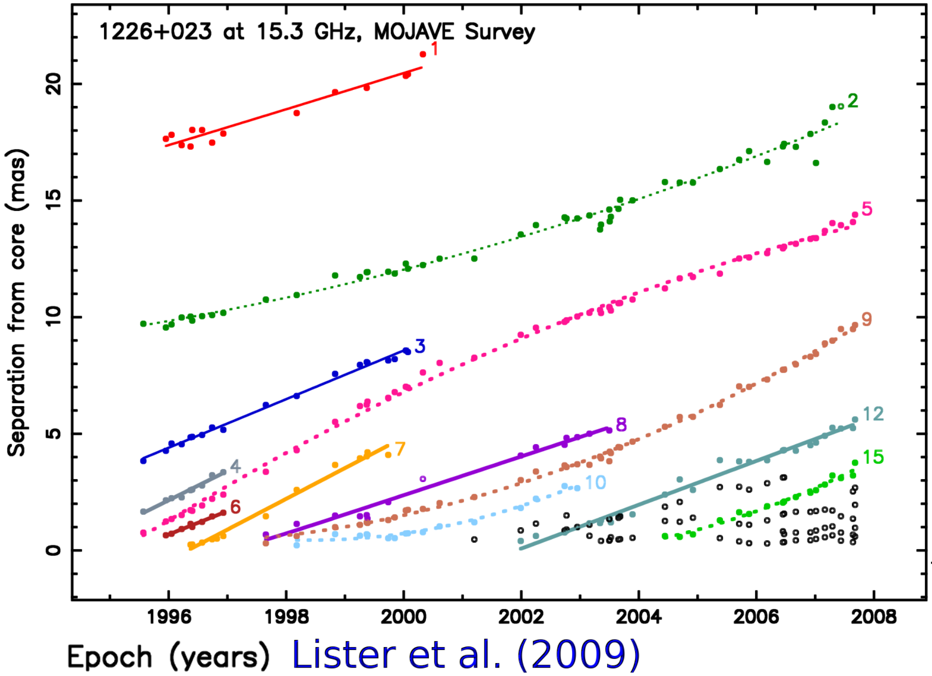
Impact of AGN variability

Image centroid and **VLBI**/*Gaia* offsets will change due to

1. optical variability and
2. jet kinematics.

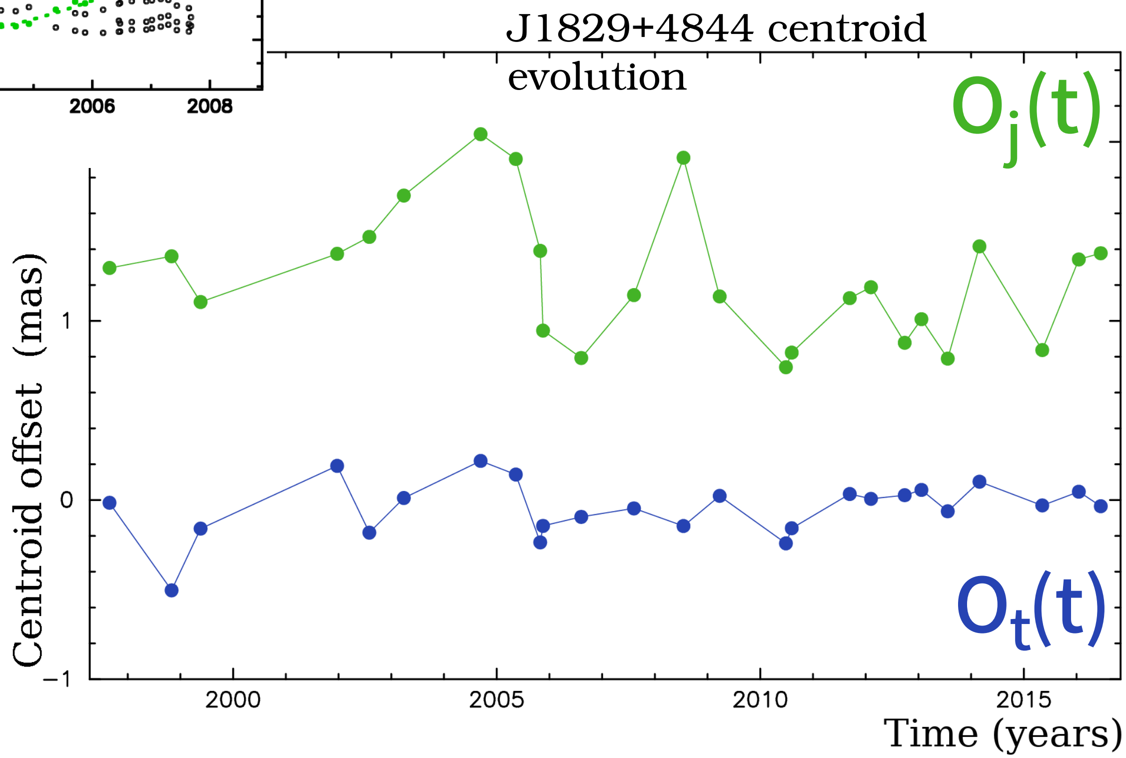


Jet kinematics

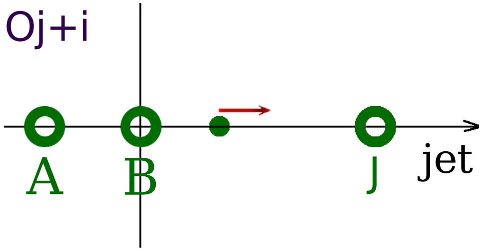


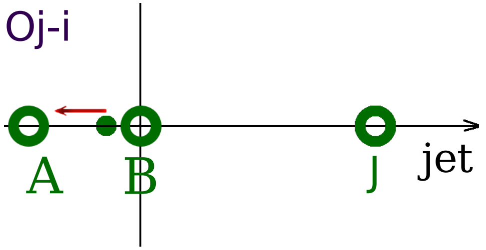
Lister et al. (2009)

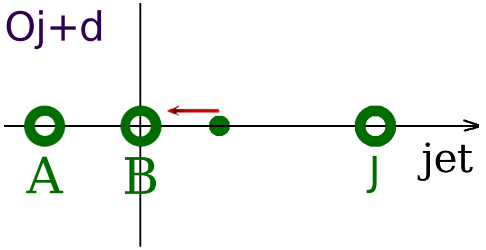
Core ejects components, they are moving, fainting, disappearing

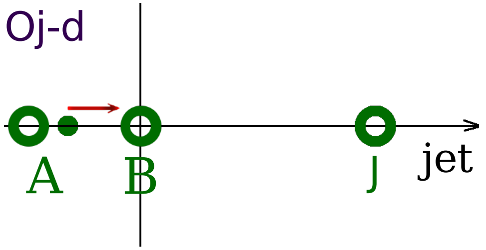


Direction of the centroid change after a flare

- 

Flare happened at the jet
- 

Flare happened at the accretion disk
- 

Flare happened at the core or the accretion disk
- 

Flare happened at the core or the jet

Correlation of the centroid wander and light curve

- Two component stationary model

$$C_f(t) \quad = \quad F(0)\,\frac{\mathcal{O}_{\rm j}(t) - \mathcal{O}_{\rm j}(0)}{F(t) - F(0)} + \mathcal{O}_{\rm j}(t)$$

$$F_f(t) \quad = \quad F(0)\,\frac{\mathcal{O}_{\rm j}(0)}{C_x(t)}$$

We can locate the position of the flaring component $C_f(t)$ and its flux density $F_f(t)$;

Stability of $C_x(t)$ provides a stationarity test.

- Two component stationary model

Solvable using jet kinematics from VLBI

A solution can by verified with spectropolarimetry!

Consequences of the optical jet interpretation for VLBI/Gaia offsets

Astrometry:

1. **VLBI** and **Gaia** positions cannot be reconciled
2. **Gaia** position accuracy cannot be used for radio applications
3. We predict a jitter in **Gaia** positions

Prediction of AGN position jitter

A consequence of **VLBI**/*Gaia* offset interpretation is a prediction of AGN jitter in *Gaia* time series at a level up to several milliarcseconds.

A jitter is

a) stochastic;
b) confined to a small region;
c) correlated with light curve;
d) occurs primarily along the jet;
e) mean value with respect to VLBI position is not zero;
f) first derivative (PM) is not zero.

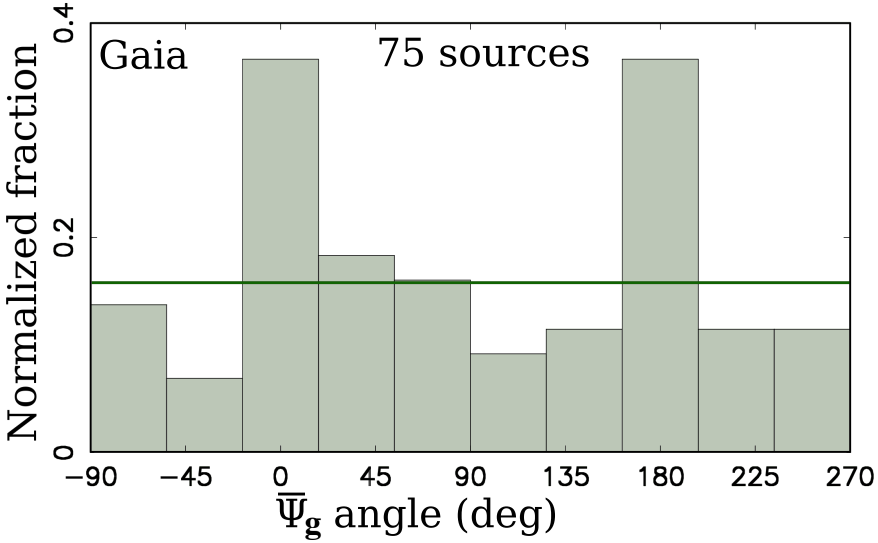
Naive model: AGNs are point-like and stable;
Realistic model: AGNs have variable structure and unstable.

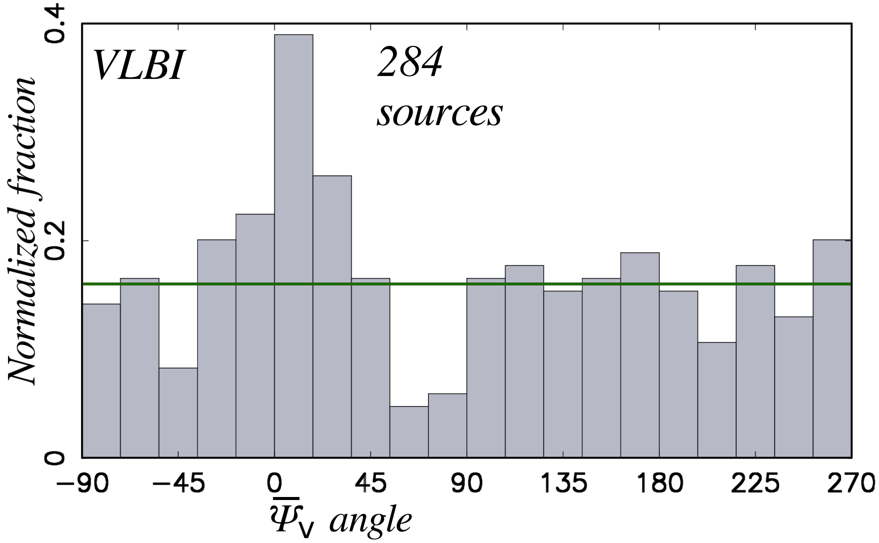
Consequences of the optical jet interpretation for VLBI/Gaia offsets

Astrophysics:

1. Joint analysis of **VLBI**/**Gaia** time series and **optical light curves** will allow
   1.1. pin-point the region where flares occur
   1.2. estimate effective size of optic jet and its relative flux
2. **VLBI**/**Gaia** offsets will correlate with color
3. AGN optical image in orthogonal polarizations wrt jet direction will have an offset
4. AGNs with large **VLBI**/**Gaia** will have higher fractional polarization in optical range

Directions of Gaia and VLBI proper motions





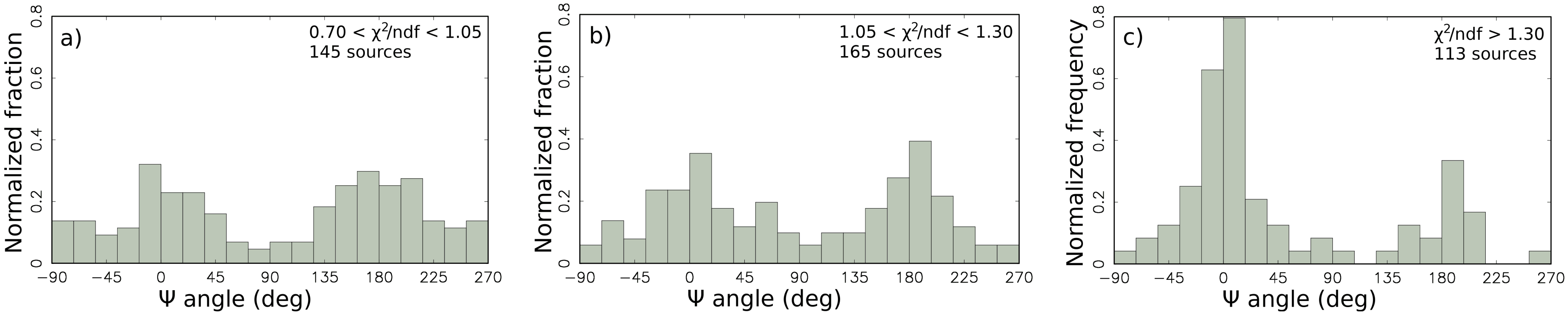
Only proper motions greater 4σ are accounted

Median proper motions:

Gaia: 1.2 mas/yr

VLBI: 0.02 mas/yr

Dependence of Gaia proper motion direction on χ^2/ndf

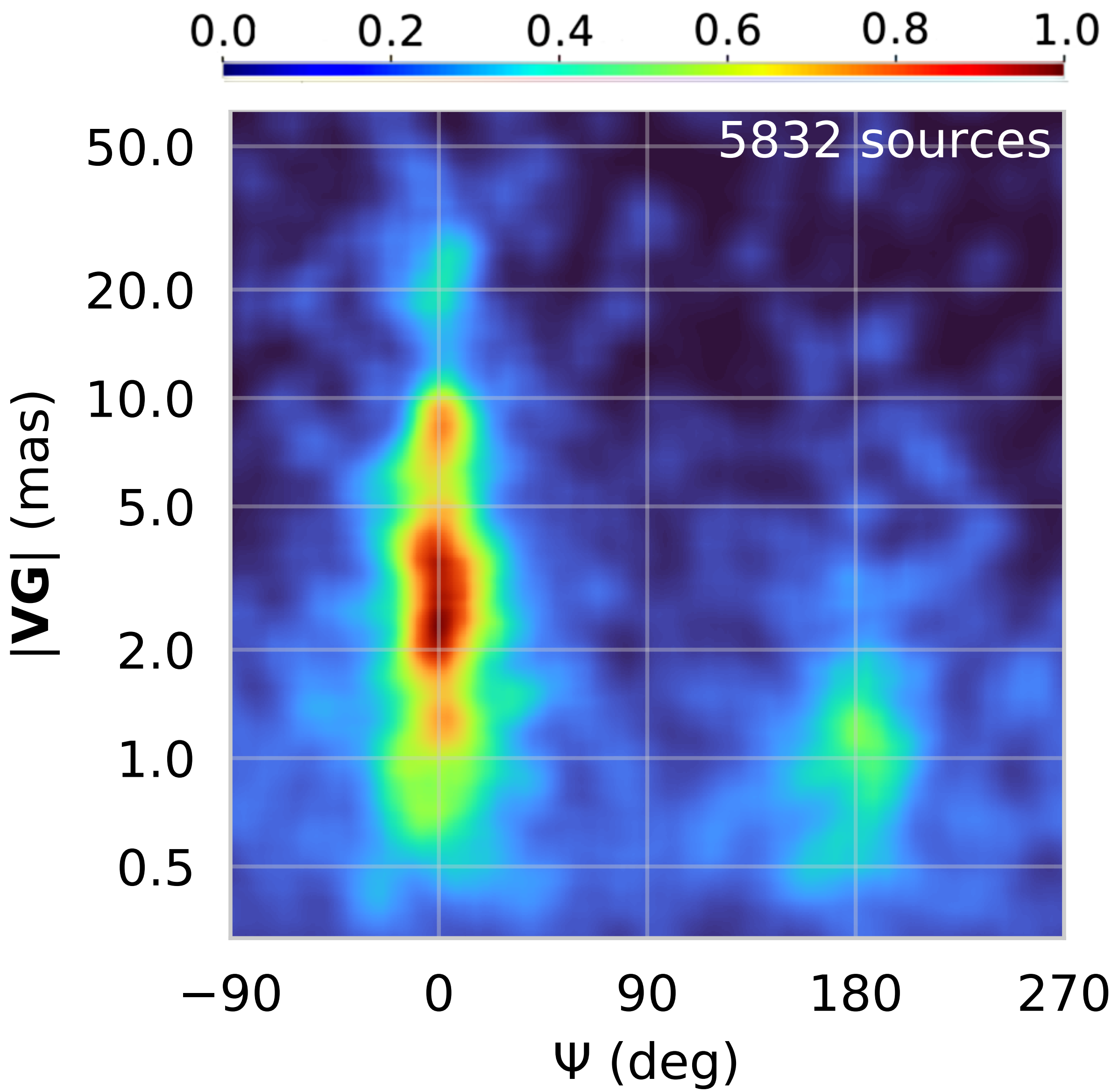


Only sources with $\sigma_{\bar{\psi}} < 0.3$ rad and arc-lengths < 2.5 mas are accounted

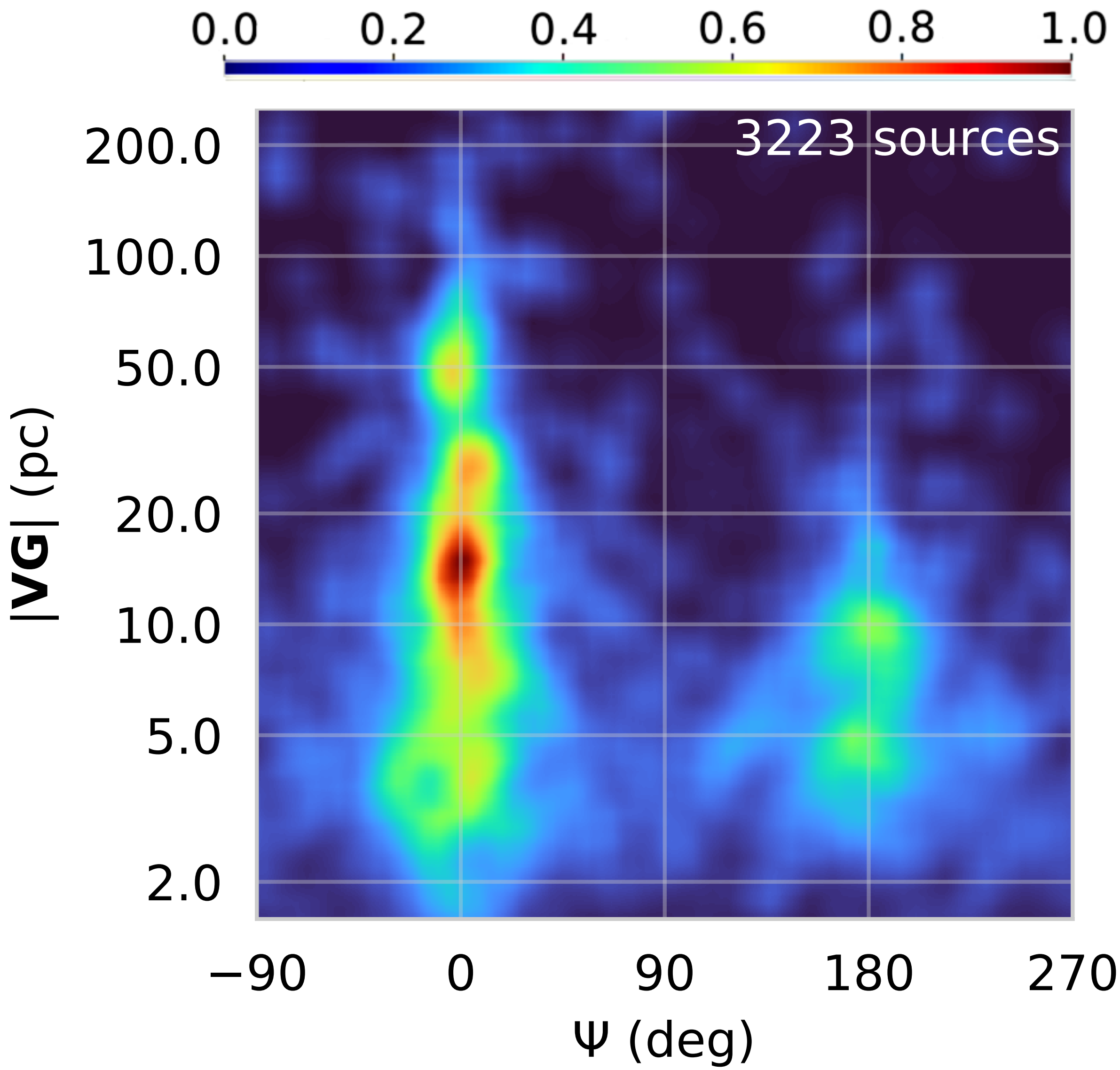
χ^2/ndf *is a measure of non-linearity of AGN motion*

Stronger non-linearity is associated with proper motion along the jet direction.

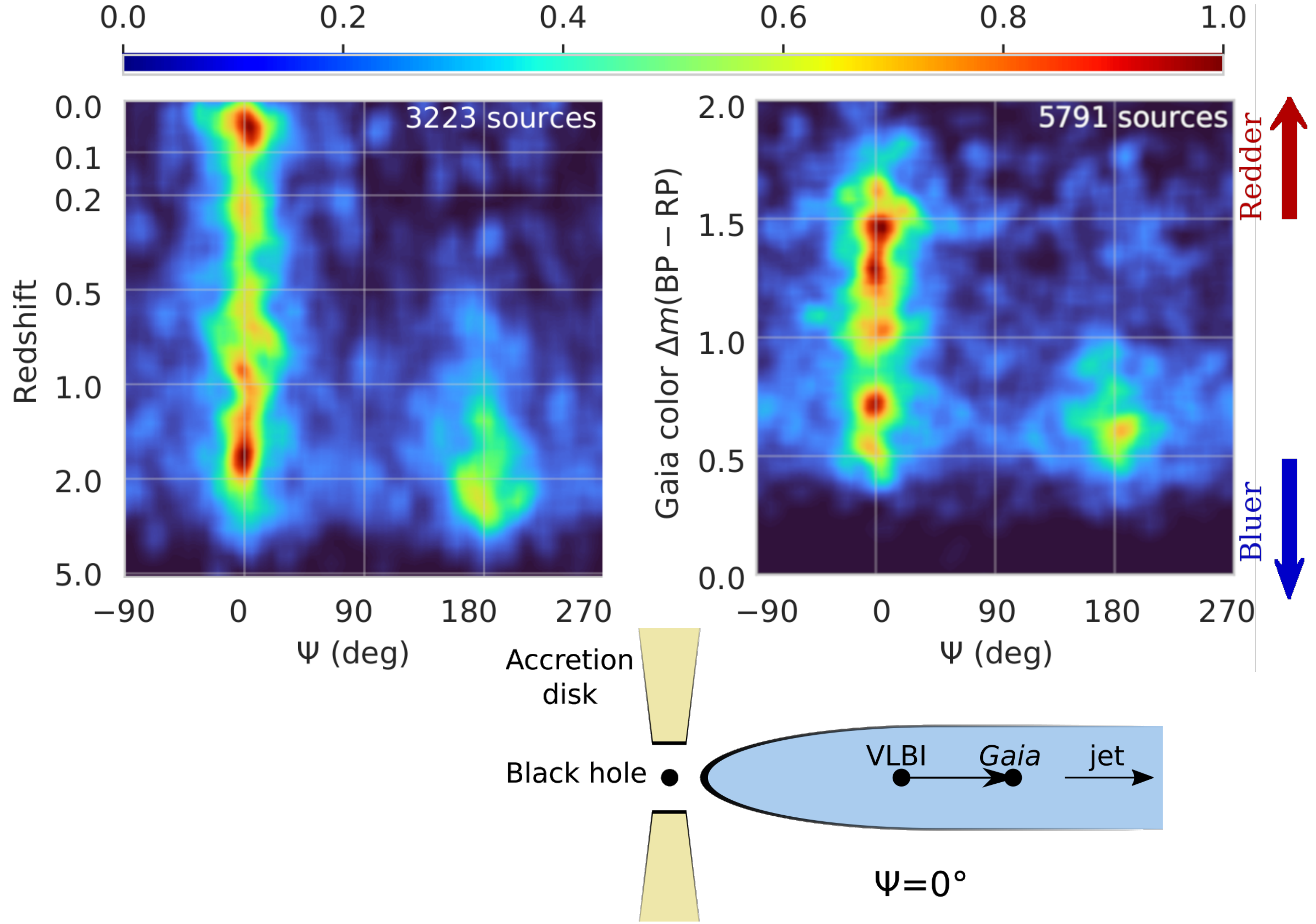
2D Ψ-angle/VG distance distribution



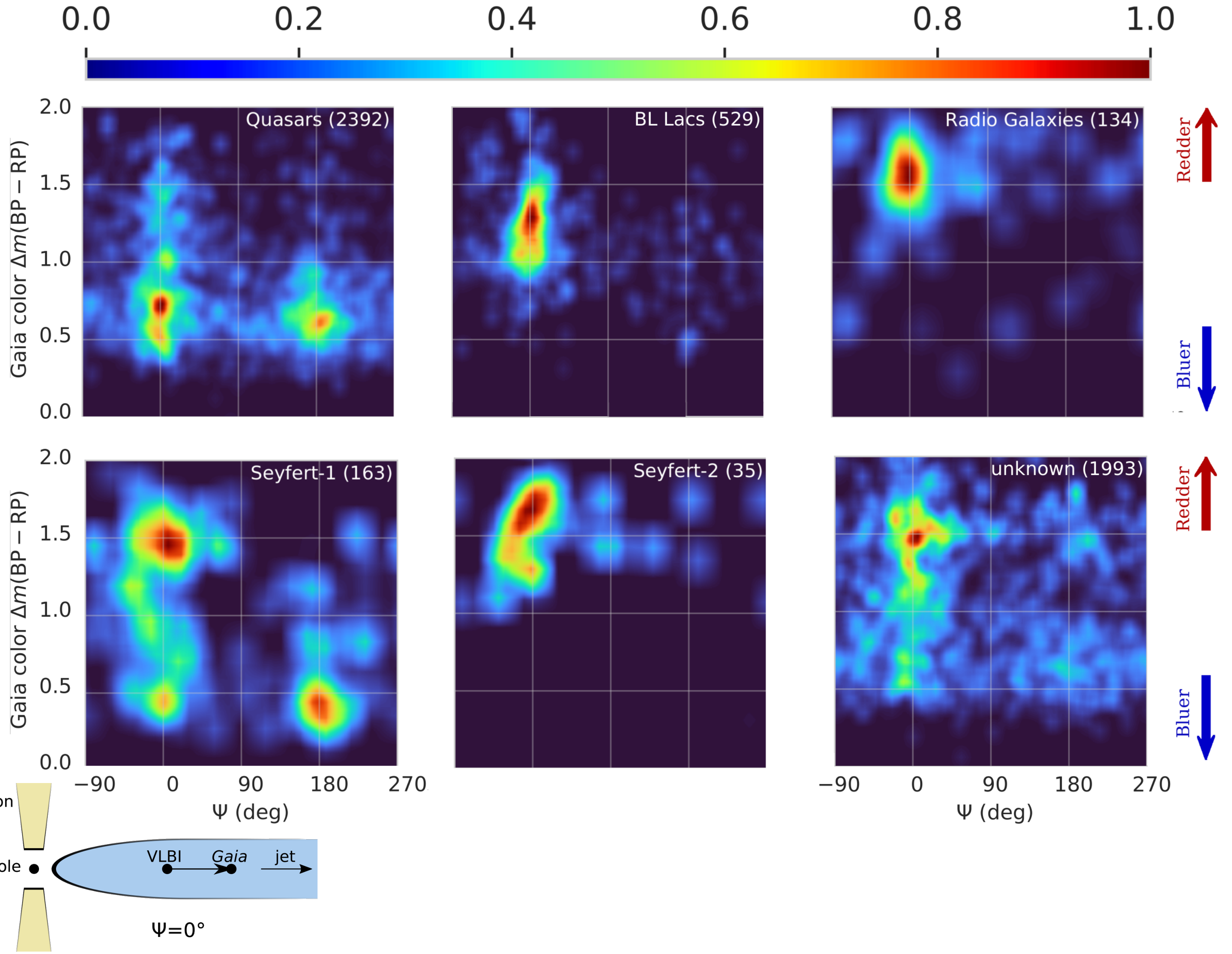
2D Ψ-angle/VG distance distribution



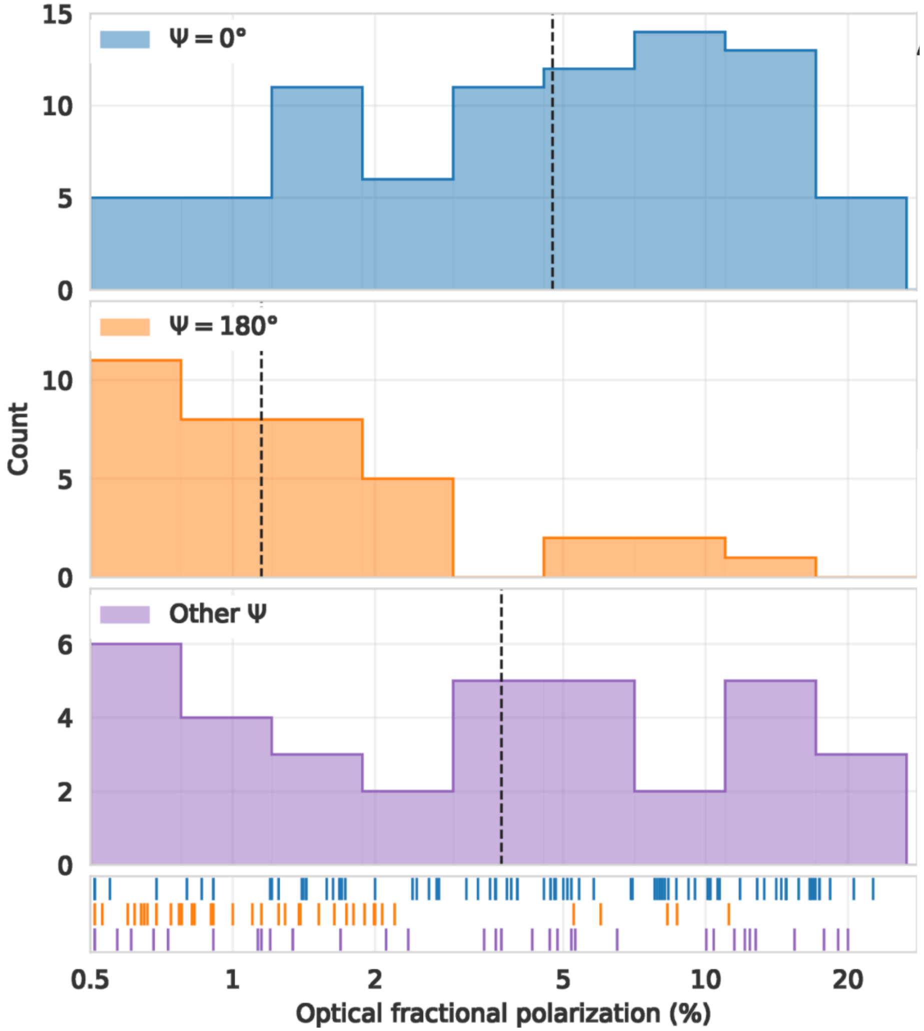
2D Ψ-angle/redshift and Ψ-angle/color distribution



2D Ψ-angle/color distribution for different AGN types



Optical polarization favours sources with $\psi = 0$



As expected for cases with dominant jet (synchrotron) versus disk (thermal) optical radiation:

Ψ=0°: high fractional linear polarization.
Ψ=180°: low fractional linear polarization.

Summary

There were 61 dedicated absolute astrometry campaigns

Their analysis yielded a catalogue of 19,500 AGNs, 17,411 images and 5823 jet directions.

Reach science emerged from **disagreement** of VLBI and Gaia source positions.

- The main reason of VLBI/Gaia offsets is a presence of optical jets
- Prediction that the share of outliers will grow **has been confirmed**
- Predicted AGN position jitter **has been indirectly confirmed**
- VLBI/Gaia offsets allow to discriminate sources with jet-dominated emission from accretion-disk dominated
- VLBI/Gaia offsets allow to discriminate different types of AGNs