Radio astrometry in the post-*Gaia* epoch

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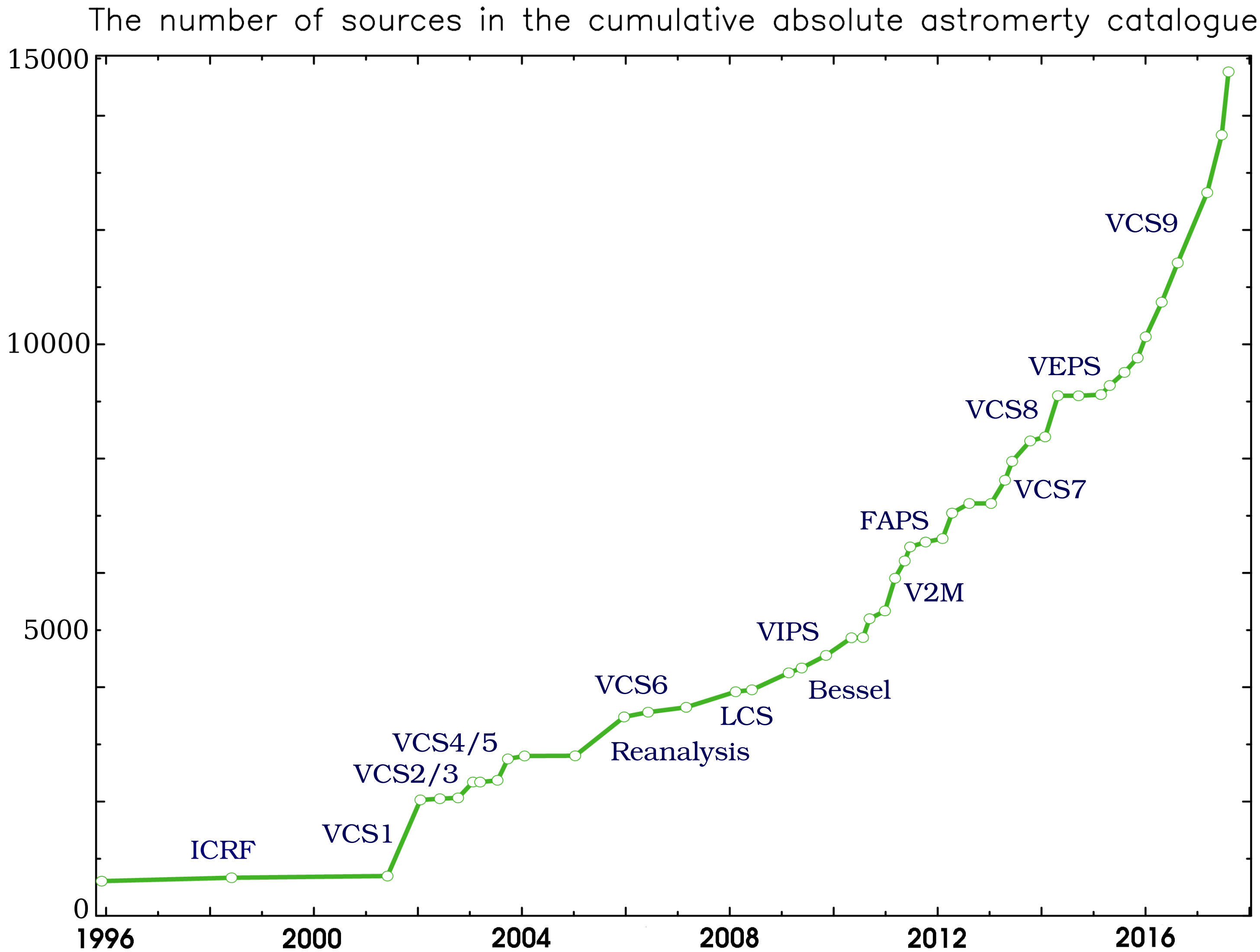
1. Recent VLBI surveys

2. Present state of absolute radio astrometry: the Radio Fundamental Catalogue

3. What did we learn from VLBI/$Gaia$ comparison?

4. Where do we go?

Observing campaigns



589 dedicated observing sessions. Approximately 1 year on-source time.

10 Pb raw data, 64 Tb visibility data.

Summary: Major geodesy/astrometry programs

	Dur (h)	C		X		X/S or X/C	
VCS9	530	**5680**	(10766)	**5086**	(10766)	**5021**	(10766)
VCS8	48	**924**	(1386)	**878**	(1386)	**871**	(1386)
VCS7	72	**811**	(1436)	**754**	(1436)	**750**	(1436)
V2M	654			**1865**	(2702)		
FAPS*	224			**699**	(898)		
VEPS*	334			**756**	(3628)		
LCS	334			**1347**	(1742)		
VCS-ii	246			**2586**	(2596)	**2549**	(2596)
VCS1-6	588			**3696**	(4133)	**3497**	(3800)
RDV*	3,720			**1424**	(1462)	**1422**	(1462)
VIPS	176	**857**	(858)				
VIPS+	48	**193**	(193)				
NPCS	72			**133**	(521)	**177**	(521)
BESSEL	193			**439**	(1967)		
OBRS	240			**400**	(411)	**373**	(411)
IVS	134,000					**1067**	(1181)
Total		**8376**	(14801)	**13497**	(26477)	**10653**	(18328)

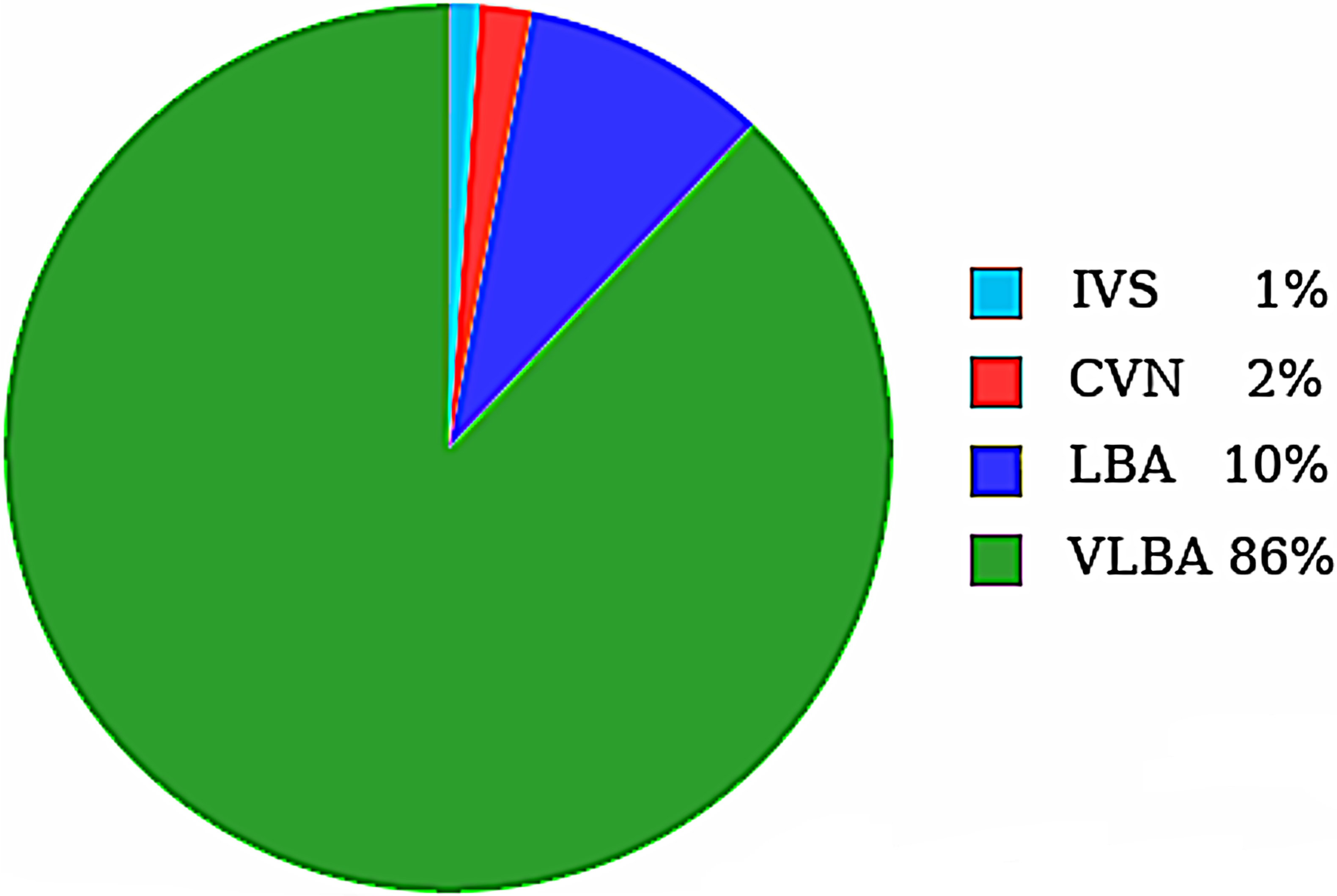
$*$ — ongoing.

The total number of observed sources is shown in brackets.

Grand total: **14768 (26769) sources**.

Statistics are computed on 2017.09.01

Participating VLBI networks



What is new in modern surveys:

- Gradual increase of field of view from $2''$ to $5'$ (whole beam)
- Gradual lifting selection bias towards flat spectrum
- Wider bandwidth. Detection limit: 6–20 mJy
- Automatic scheduling
- (semi)Automatic imaging
- Including X/C, K-only, X-only, C-only, S-only data

Goals of surveys:

- Full sky surveys with the goal of reaching completeness at a given flux denisity limit
- Full-in surveys for improvement of the spacial coverage
- Observations of a dedicated zone
  - ecliptic plane
  - Galactic plane
  - polar cap
  - southern zone
- Observations of a dedicated class of sources (γ-ray loud)
- Follow-up surveys (VCS-i-i, VEPS-F)

II. State of fundamental radio astrometry on 2017.09.01

The Radio Fundamental Catalogue

sources: 14768

percentile of accuracy:

20%	< 0.30	mas
50% (median)	< 0.90	mas
80%	< 2.5	mas
90%	< 5.2	mas
94.8%	< 10	mas

Flux density @ X-band: [0.003, 22] Jy, median: 101 mJy

Used type of observations:

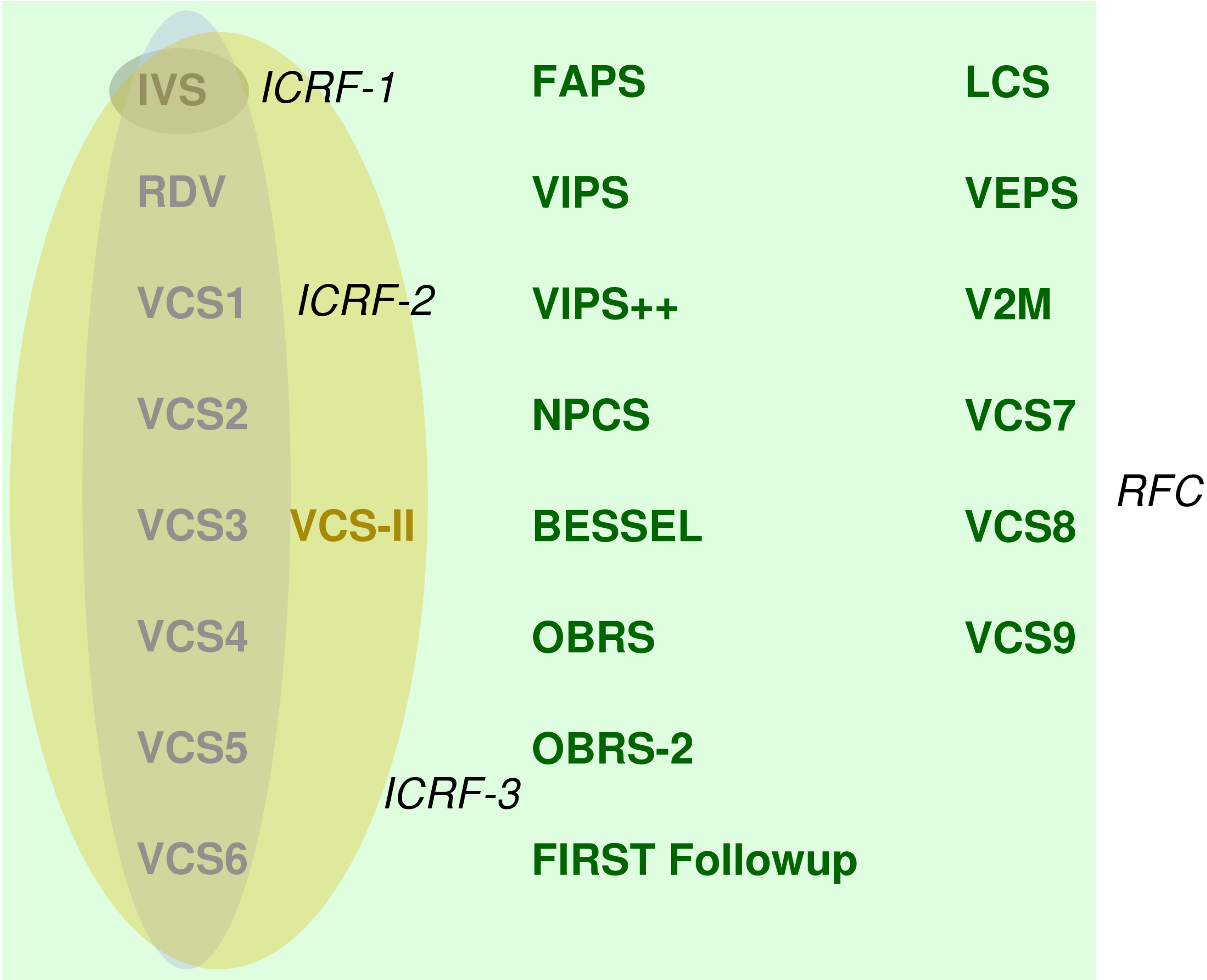
Dual-band:	55%
8 GHz	33%
5 GHz	10%
22 GHz	2%
2 GHz	1%

Number of observing sessions

1	45%
1–2	77%
1–5	90%
10+	8%
100+	3%

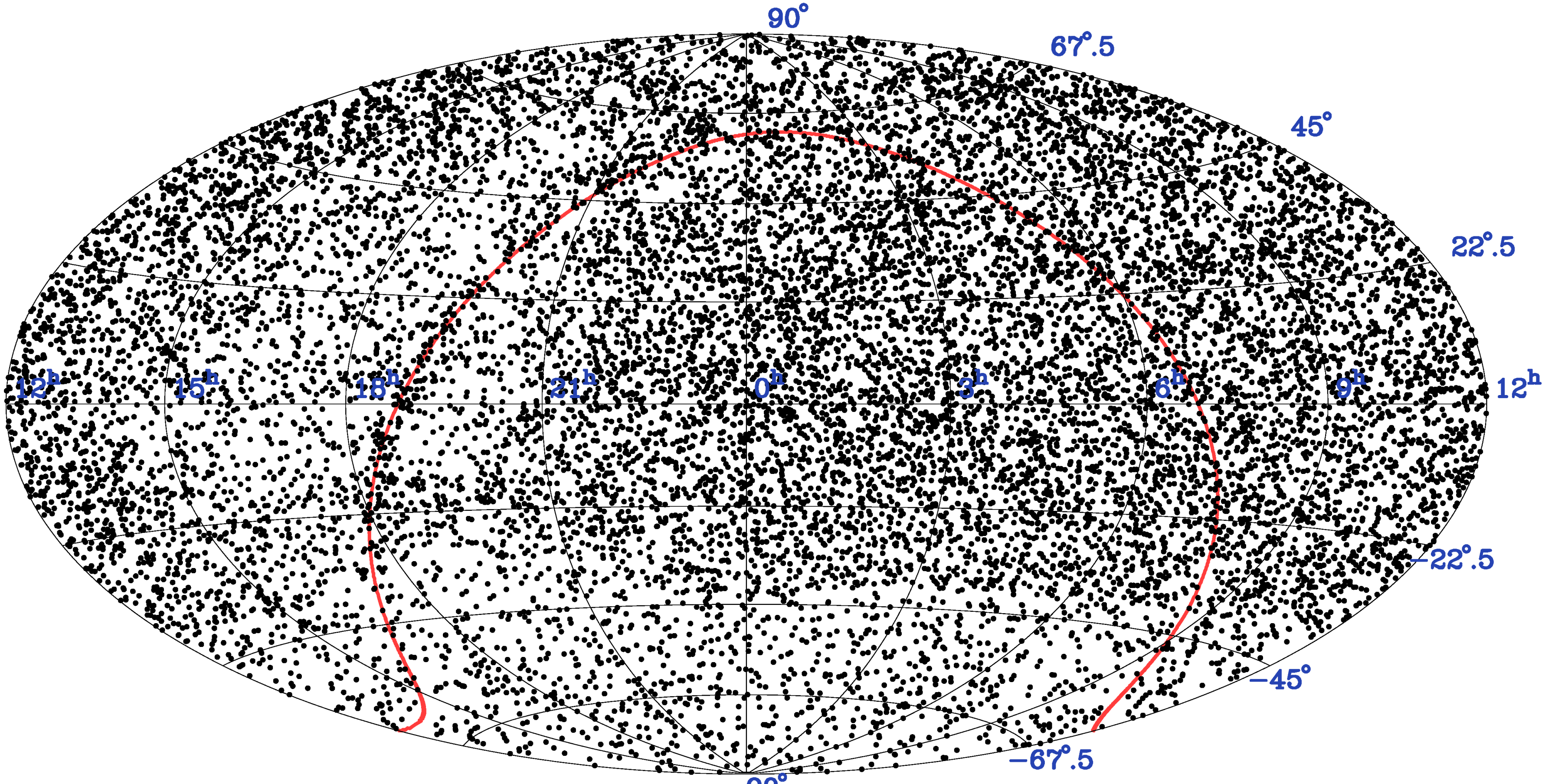
56,147 images in FITS format of 9304 compact radio sources

RFC input observing campaigns:



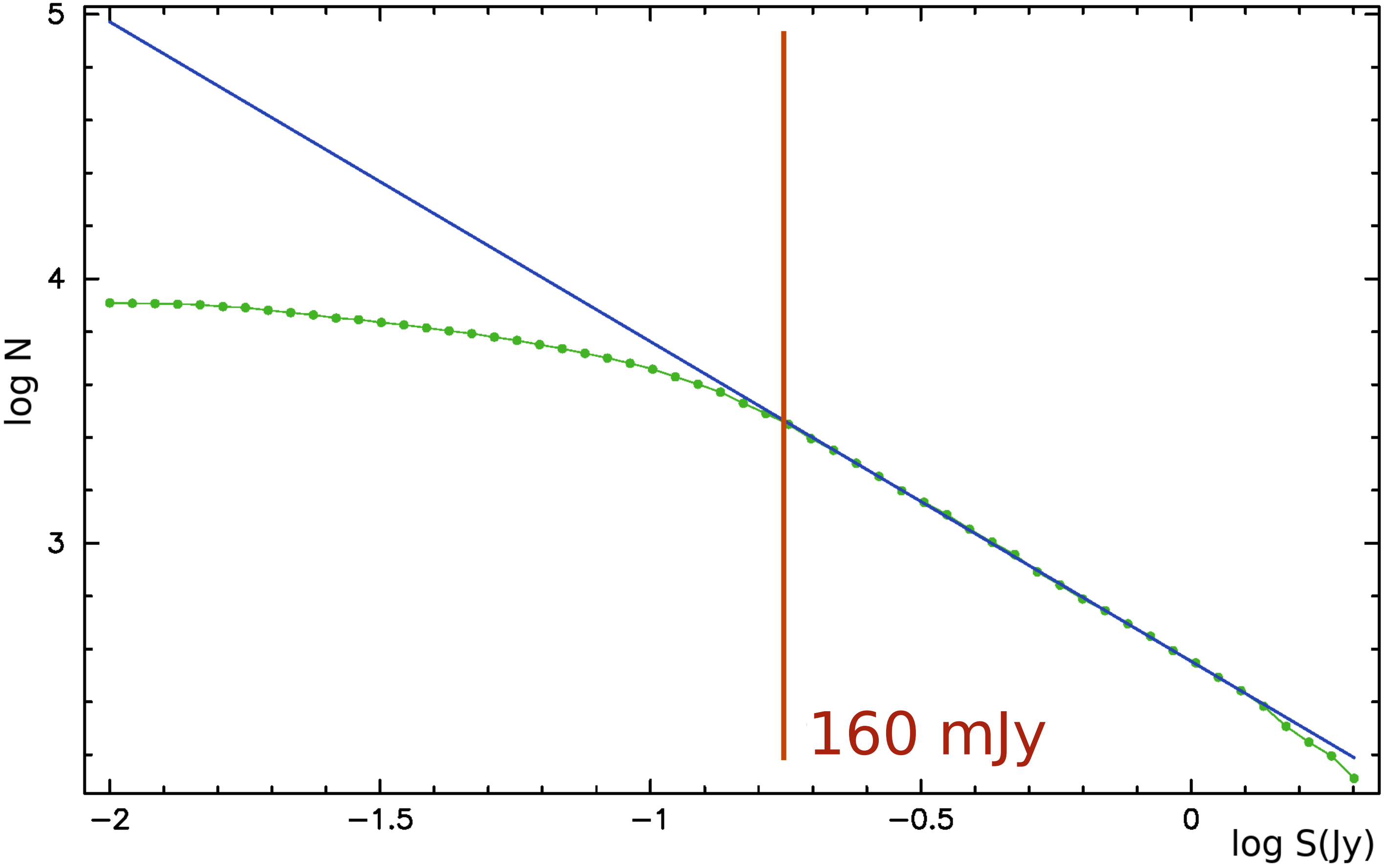
Sky distribution: 14768 objects

RFC 2017b



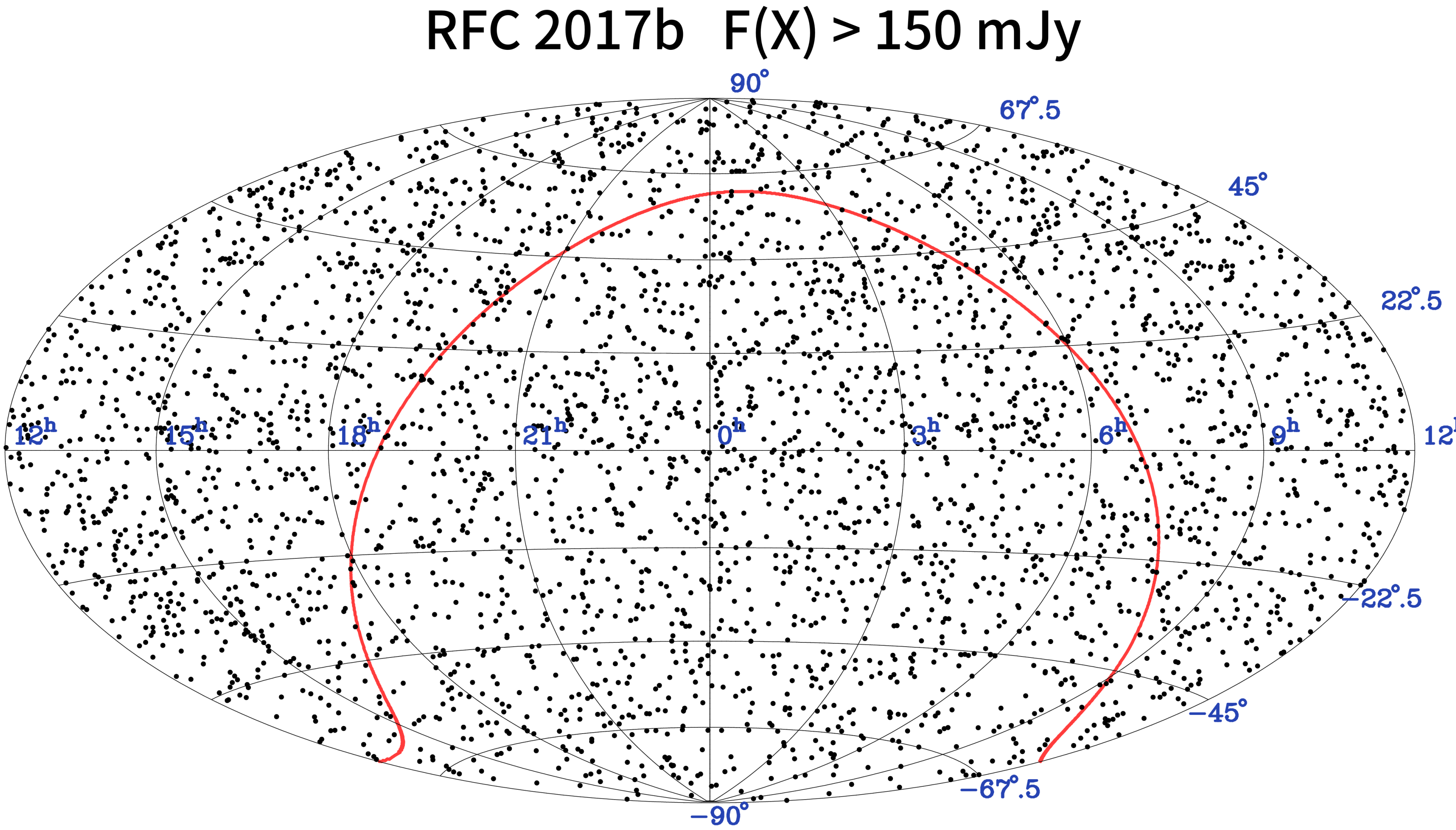
Completeness of the RFC

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

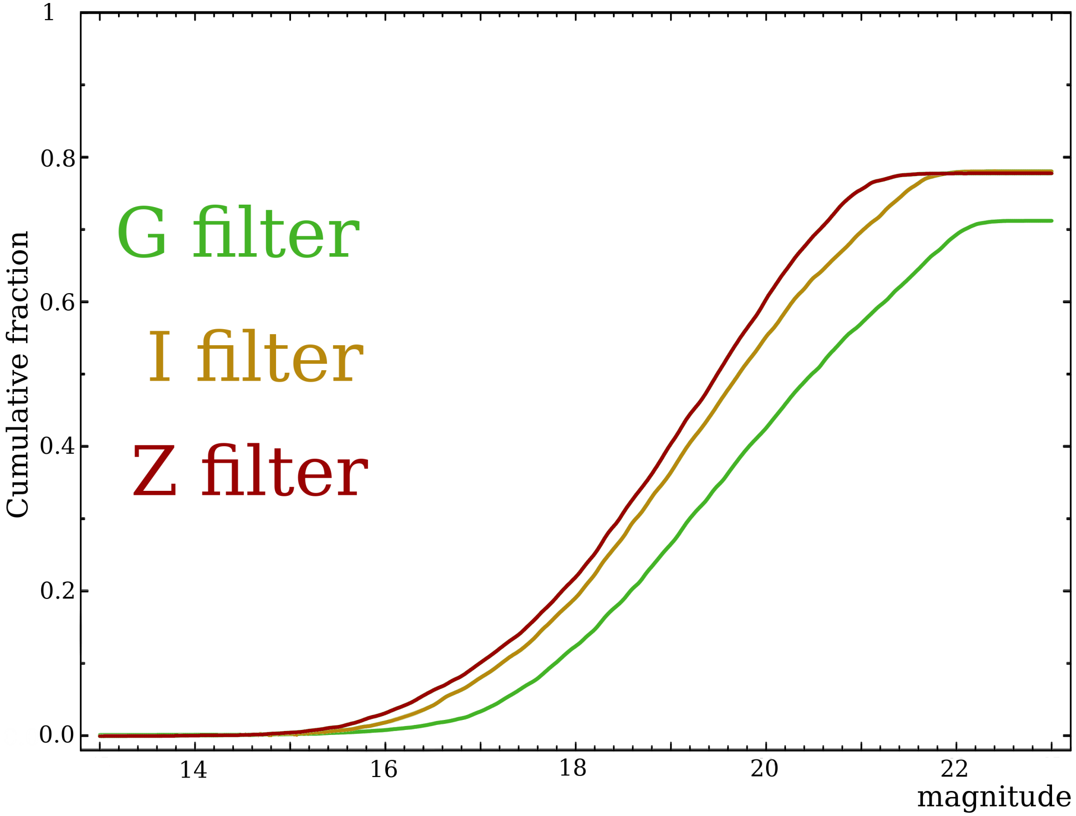


170 mJy	99%
160 mJy	97%
150 mJy	95%
100 mJy	80%
50 mJy	49%
10 mJy	10%

Source sky distribution (complete subsample of 3500 objects)

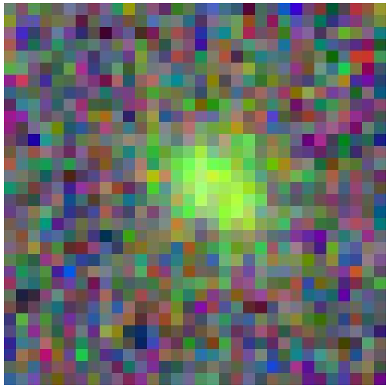


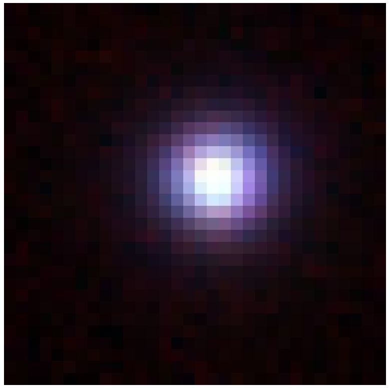
Comparison with Pan-STARRS catalogue

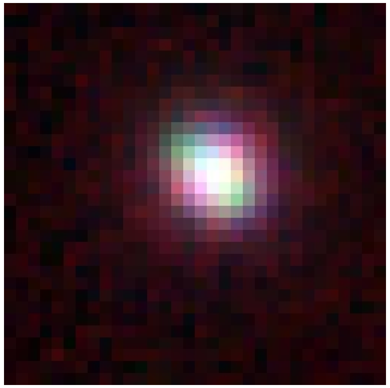


10202 RFC/PS matches

Flt	share	compl mag
g	71%	22.0
r	76%	21.8
i	78%	21.6
z	78%	21.0
y	76%	21.0







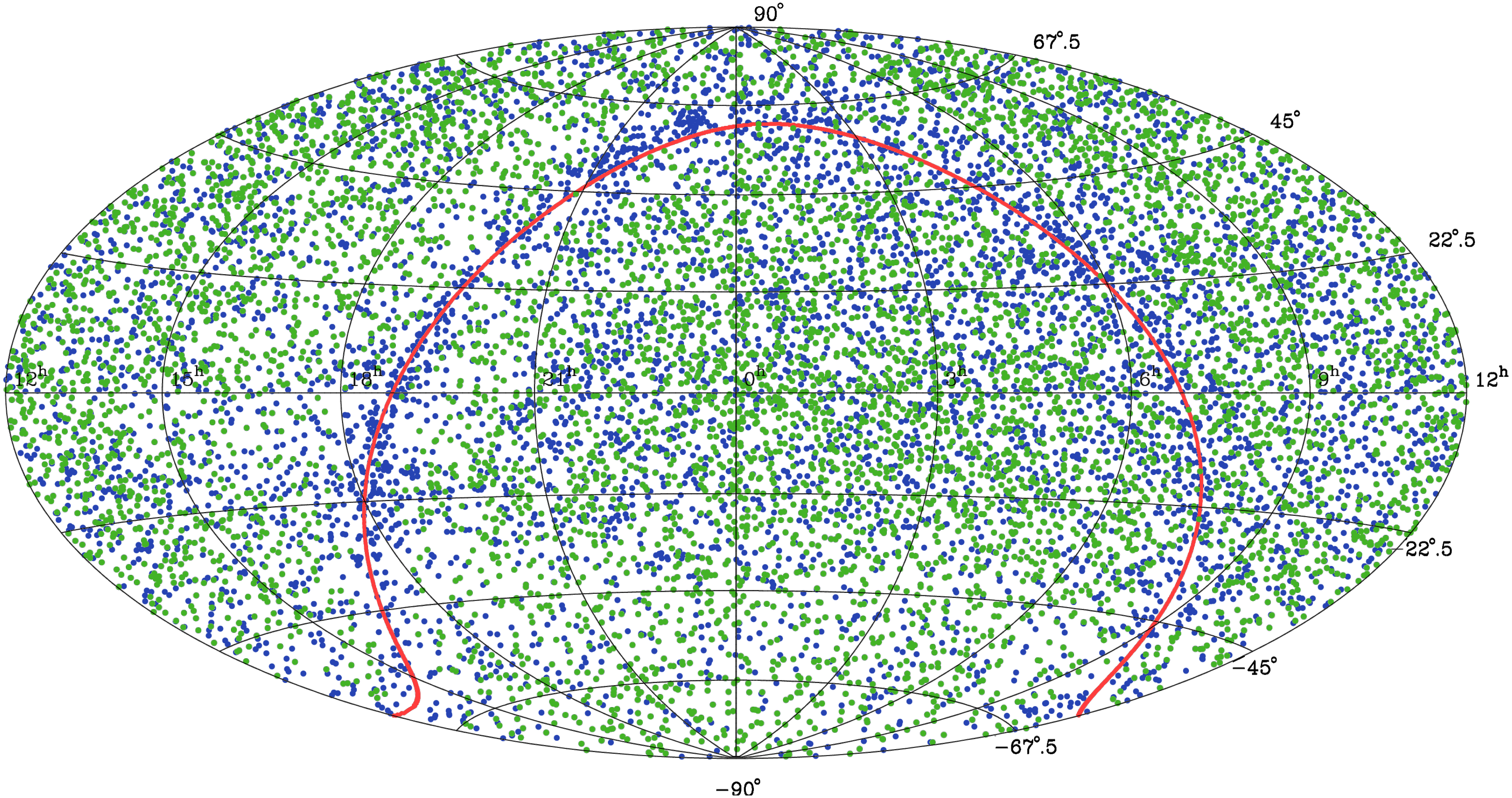
Number of matches

γ-ray	Fermi:	15%
X-ray	Chandra	3%
infra-red	WISE:	74%
infra-red	2MASS:	36% (point sources)
infra-red	2MASS:	11% (extended sources)
optic	*Gaia*:	53%
optic	PanSTARRS:	69% (78%)
optic	known redshifts	42%
radio	NVSS	91% (99.8%)
radio	TGSS	72% (76%)

III. VLBI/*Gaia* comparison

Data

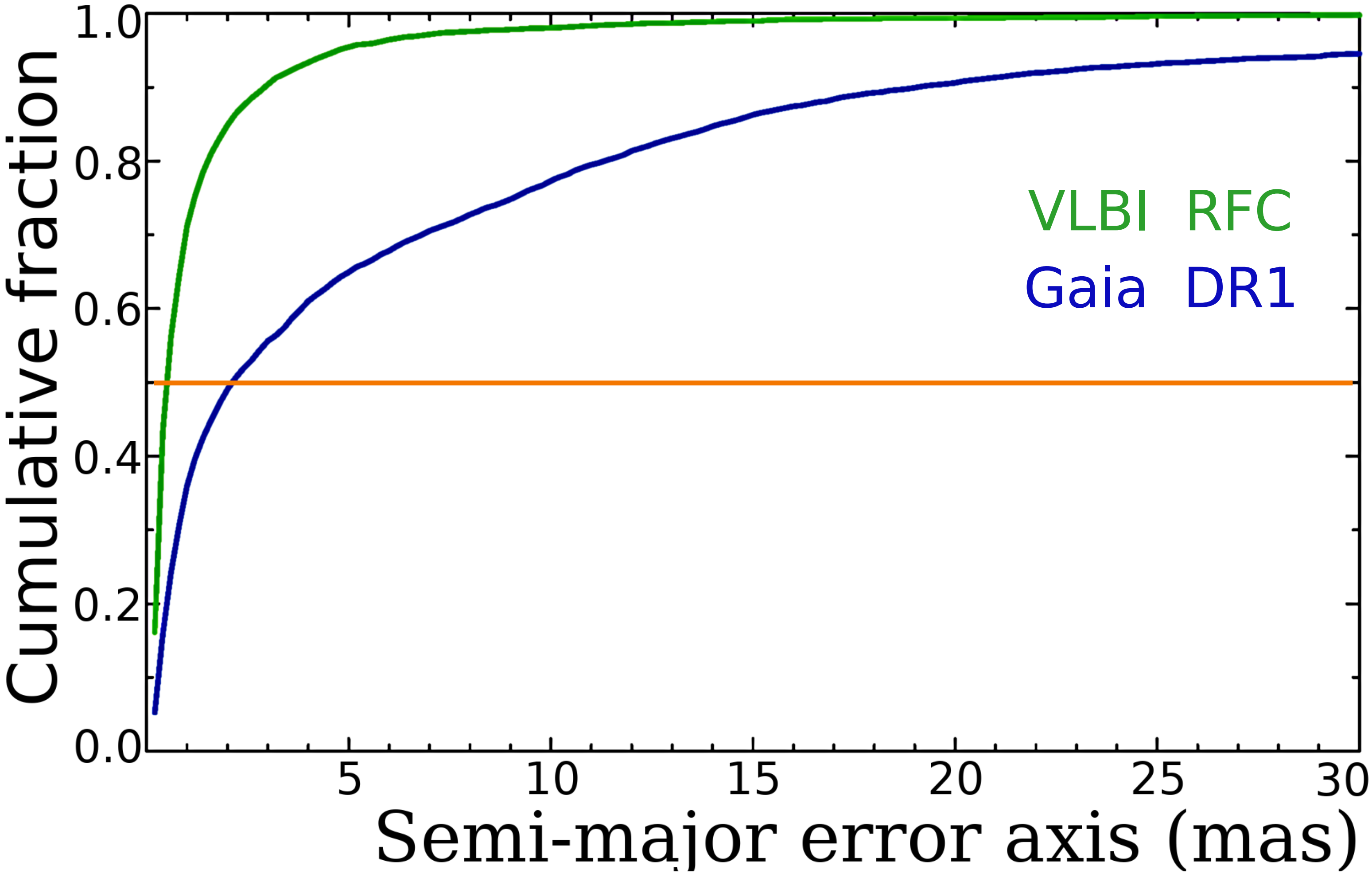
VLBI Radio Fundamental Catalogue (**14,768 sources**) on 2017.09.01 and *Gaia* DR1 ($1.14 \cdot 10^9$ objects)



Green: 7,669 VLBI/*Gaia* matches $P < 0.0002$

Blue: VLBI sources without *Gaia* matches

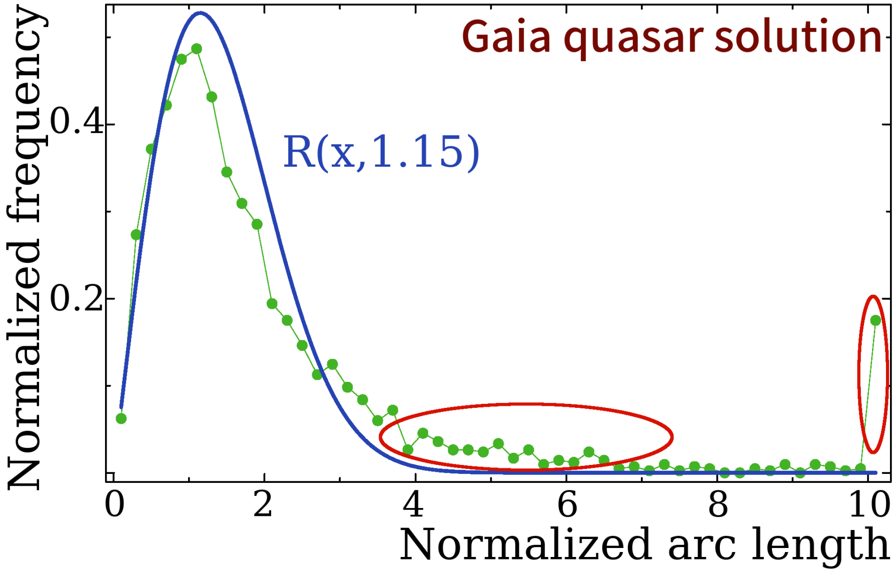
VLBI and *Gaia* position uncertainties

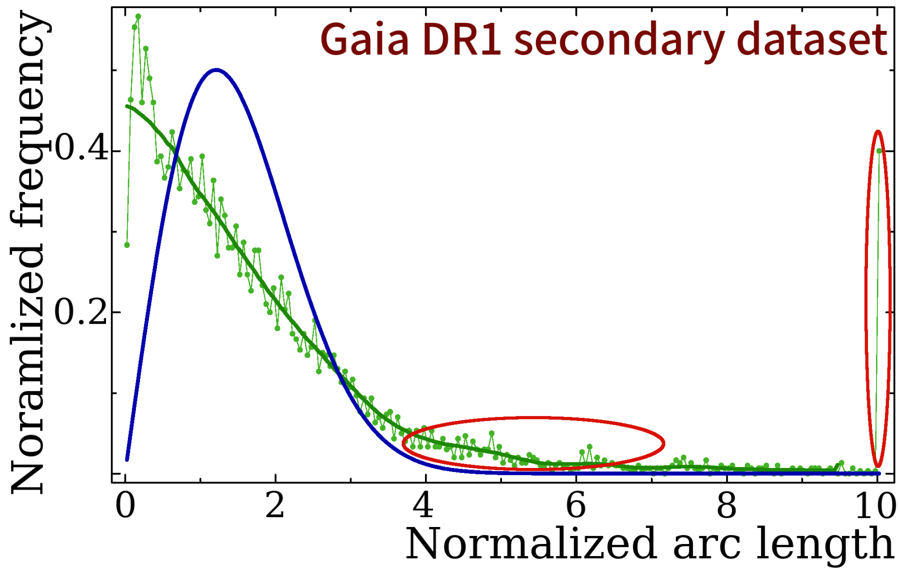


Median error: **VLBI RFC**: 0.5 mas

Median error: *Gaia* **DR1**: 2.2 mas

Distribution of VLBI/*Gaia* arc lengths

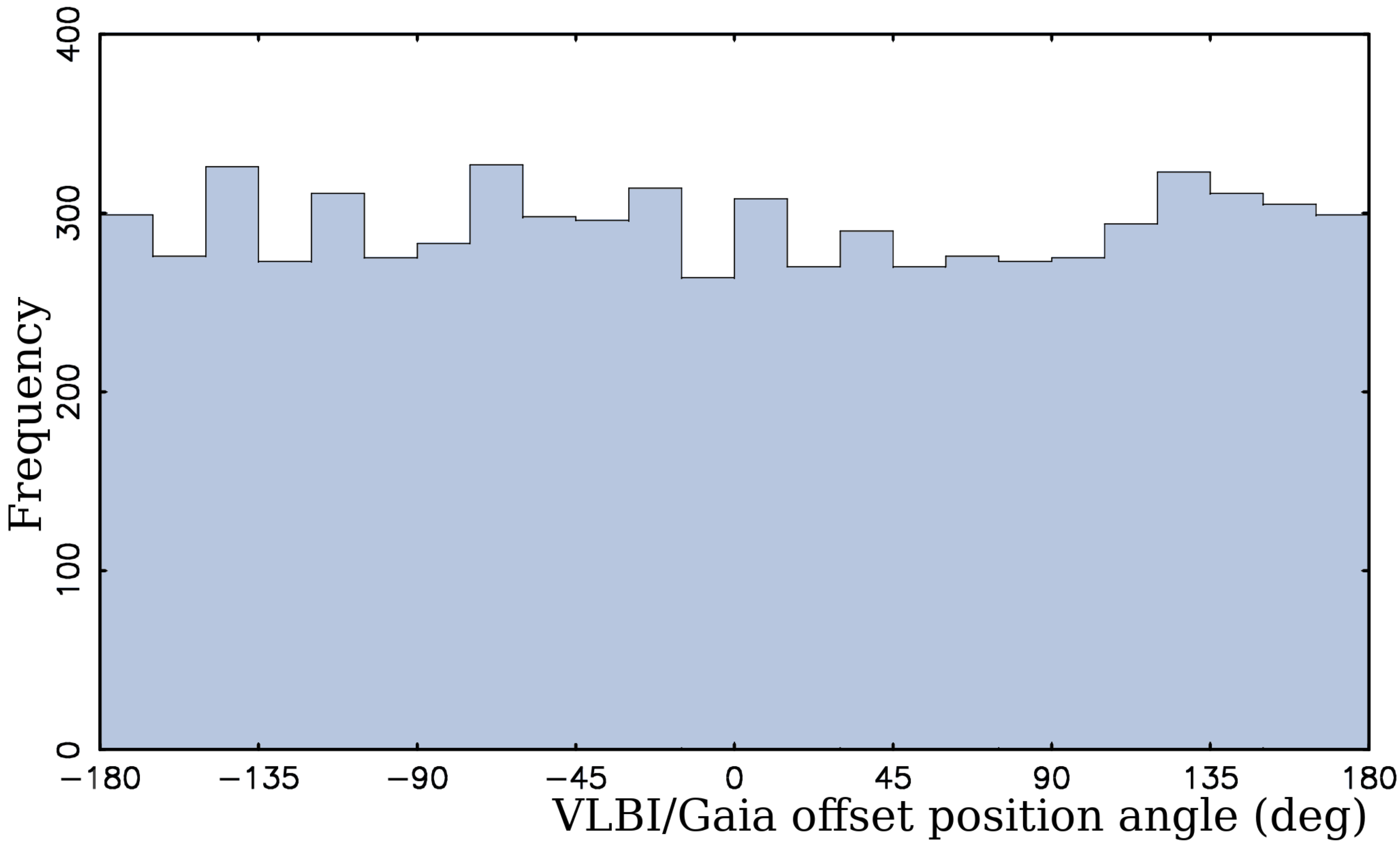




There are **486 outliers** (7%) at significance level 99%.

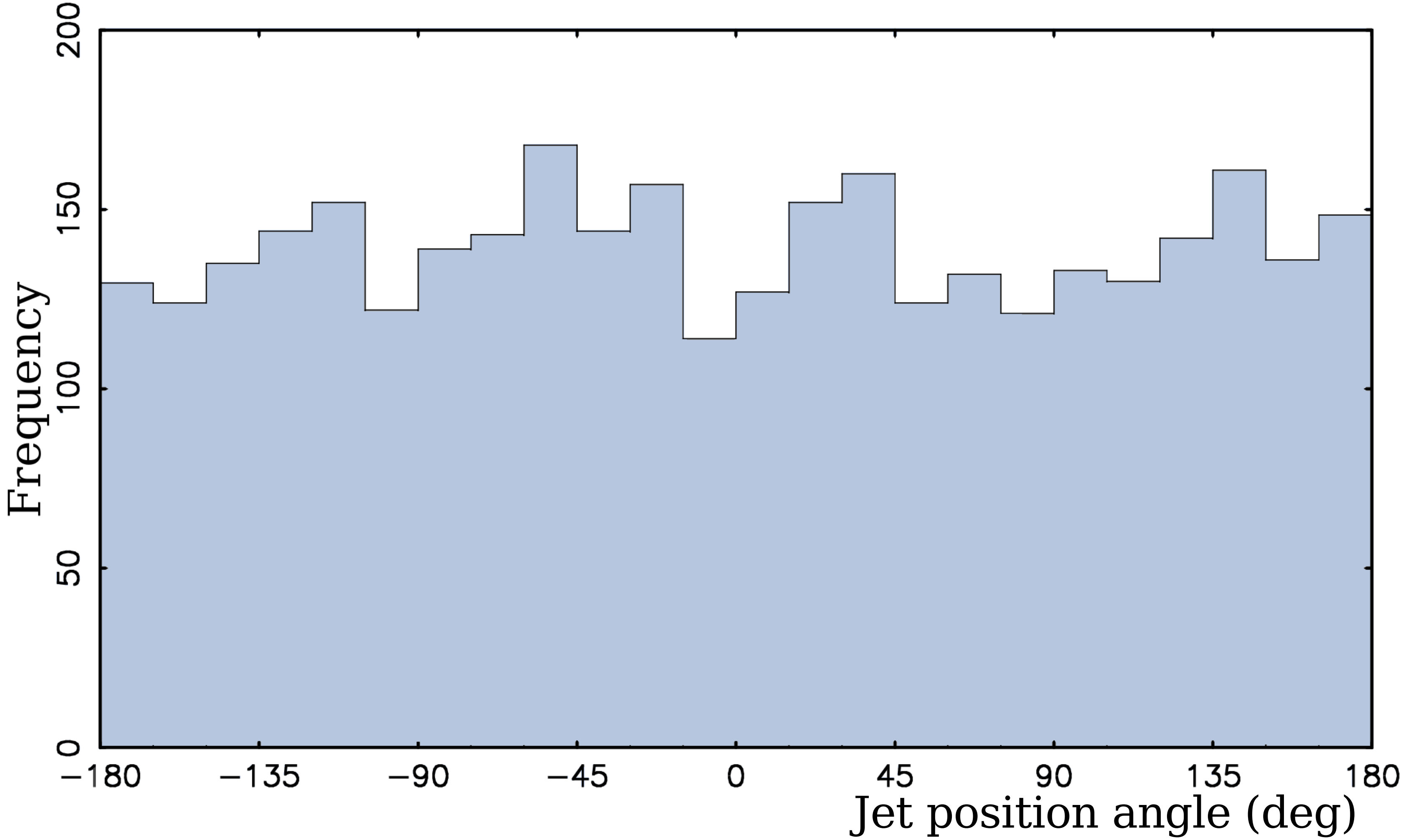
Outliers range: 1–400 mas (median: 10 mas).

Distribution of VLBI/*Gaia* position offset angles



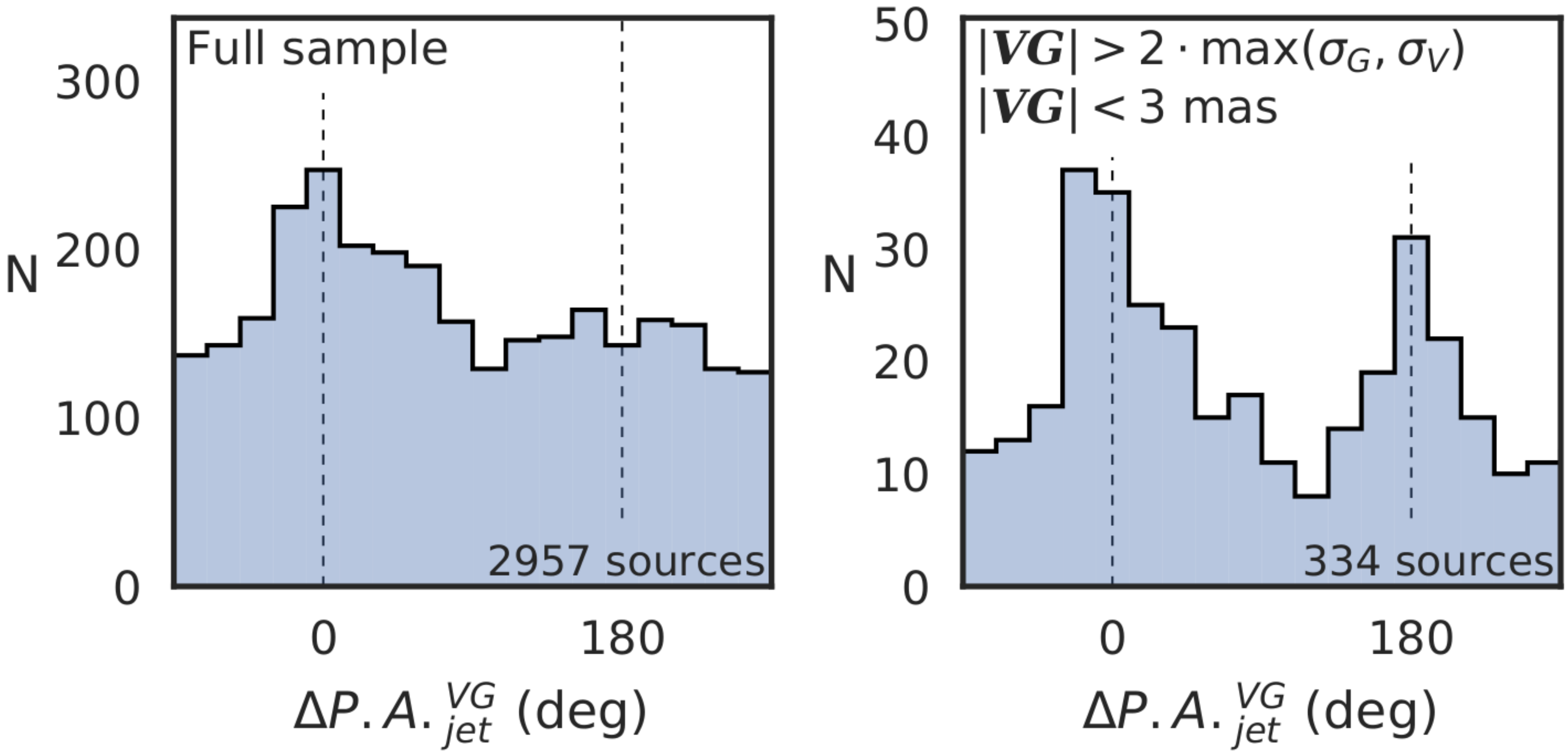
Main finding: no preference at $0°, 180°$ (VLBI declination errors)
No deviation from the isotropy.

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



VLBI/*Gaia* offsets prefer directions along the jet!!

The pattern can be explained <u>only</u> by core-jet morphology

VLBI/*Gaia* differences: explanation

Facts:

- There are 7% sources with significant VLBI/*Gaia* offsets (**1–400 mas**).
- While position angles of VLBI/*Gaia* offsets and jet position angles, taken separately, are distributed uniformly, their difference has significant peaks at 0 and 180 degrees.

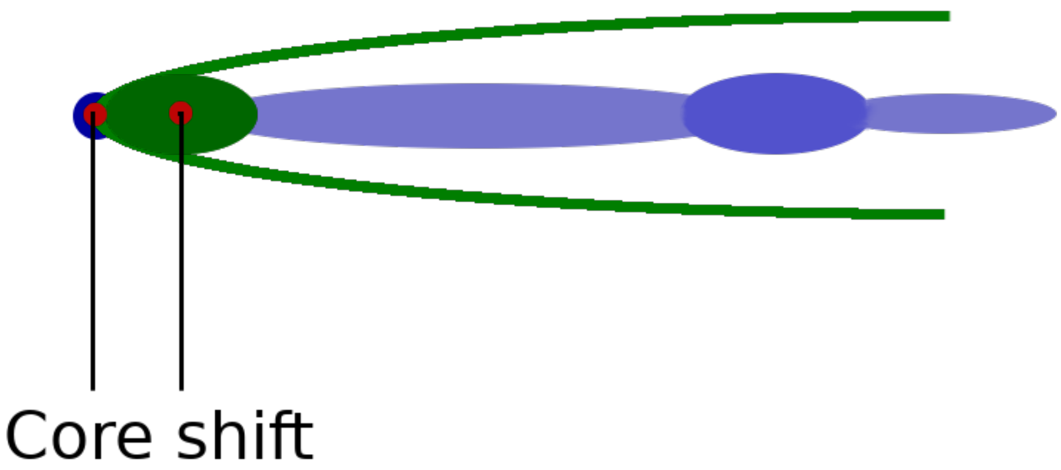
  To explain the pattern, systematic shifts VLBI/*Gaia* at **1–2 mas** level are required.

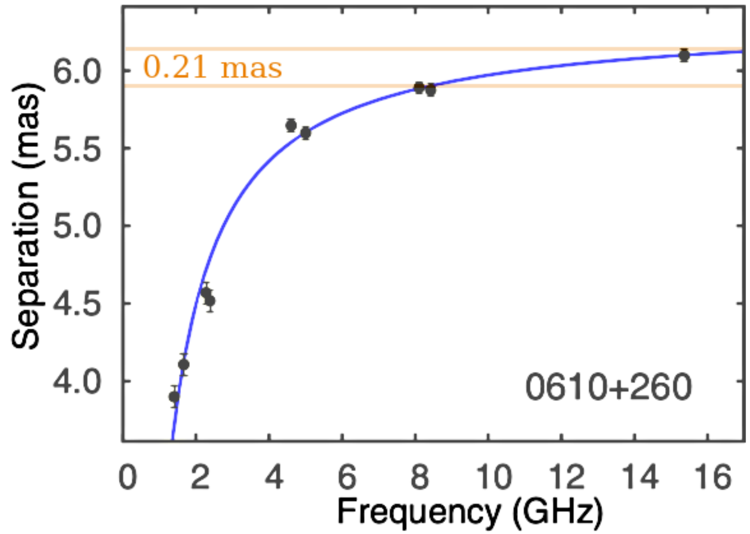
Possible explanations:

- **Blame radio:** core-shift;
- **Blame radio:** the contribution of source structure to VLBI positions;
- **Blame *Gaia*:** the contribution of optical jets or the accretion disks to centroid positions.

Core-shift

- Core is the optically thick part of the jet;





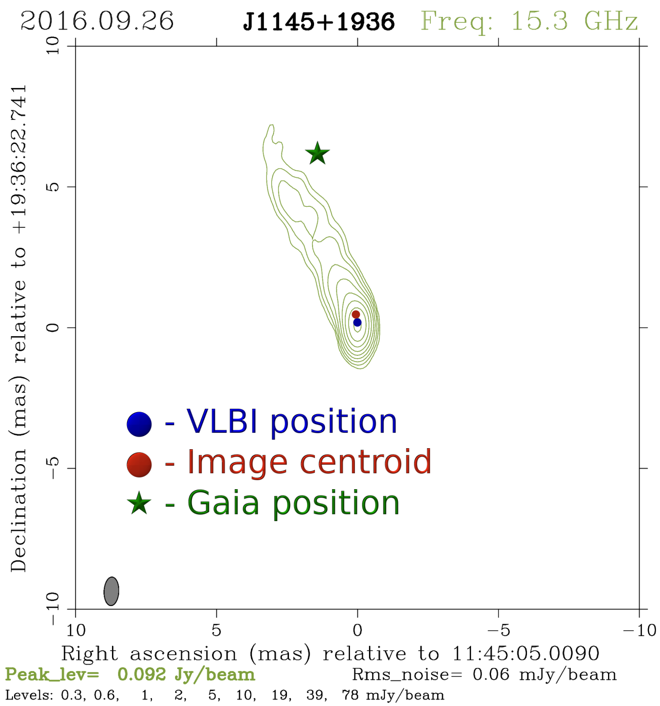
Sokolovsky et al. 2011

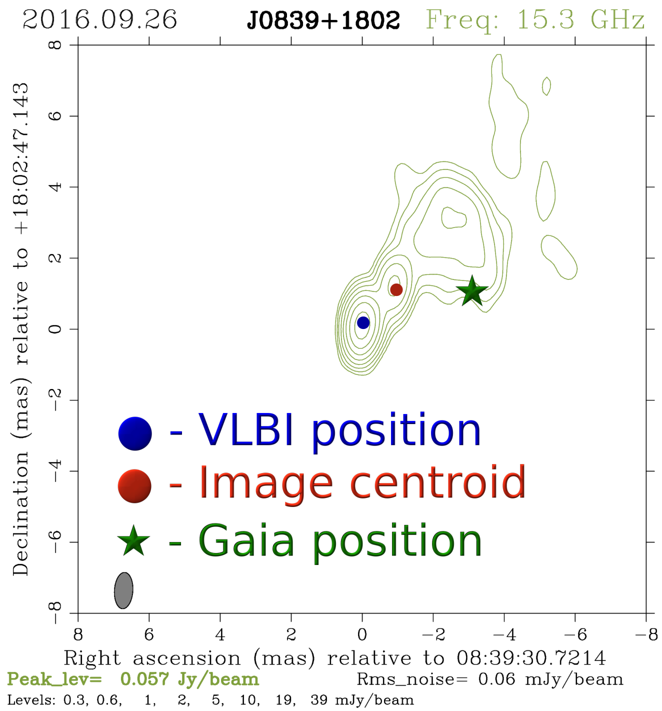
- Core centroid is shifted with respect to the jet base;
- The shift is frequency dependent;
- Results of core-shift measurements:
  - Contribution to 8 GHz positions: ~ 0.2 mas;
  - Contribution to dual-band positions: 0.02–0.05 mas.

Conclusion: the effect is too small

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:

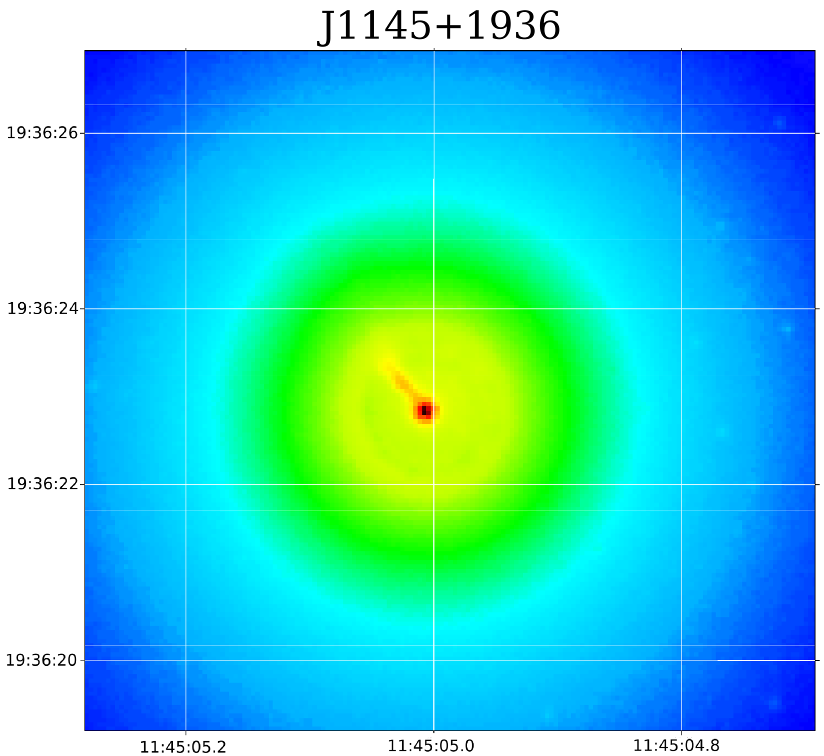
  Median VLBI position bias: 0.06 mas

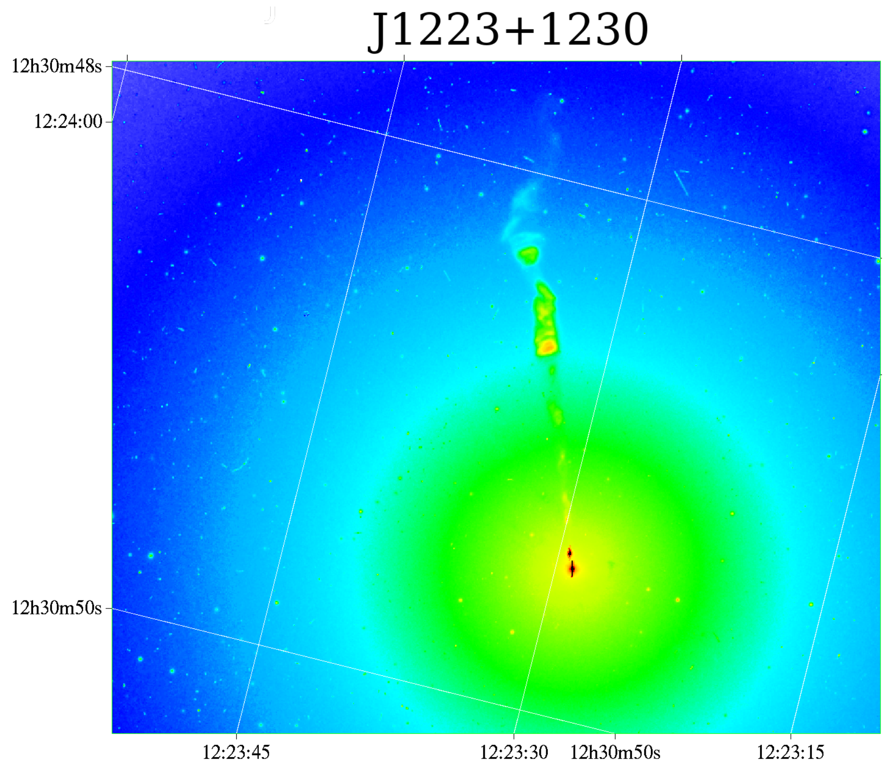
  Median image centroid offset: 0.25 mas

Conclusion: the effect is too small

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

Optical jets interpretation

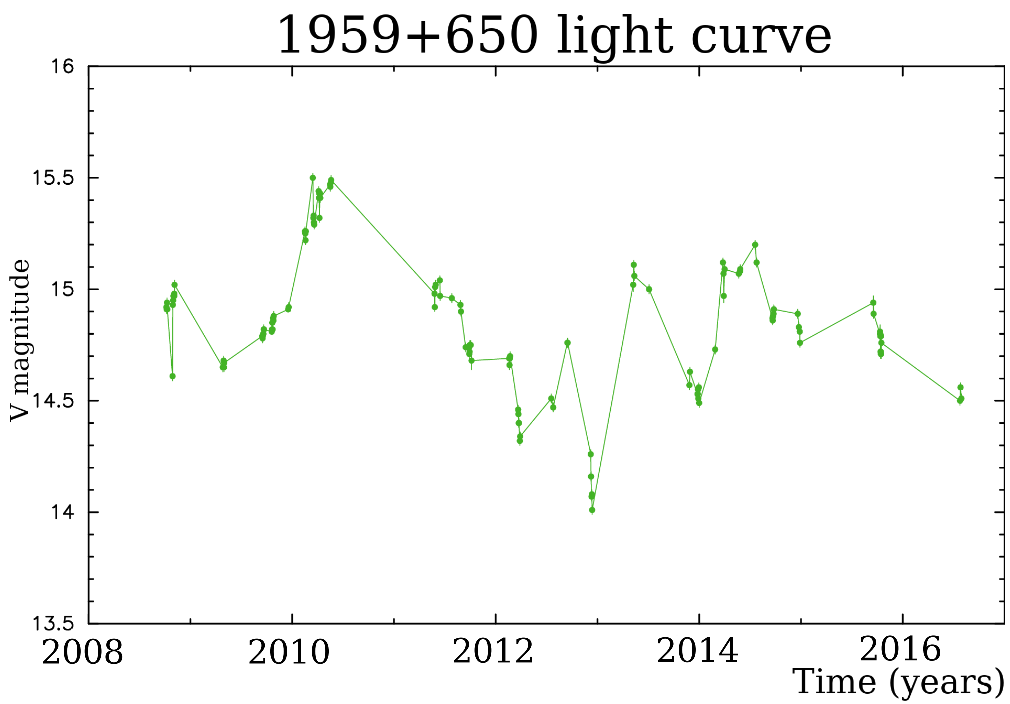
Dilemma:

- large optical jet that we see, do not affect *Gaia*.
- small optical jet that we do not see, affect *Gaia*.

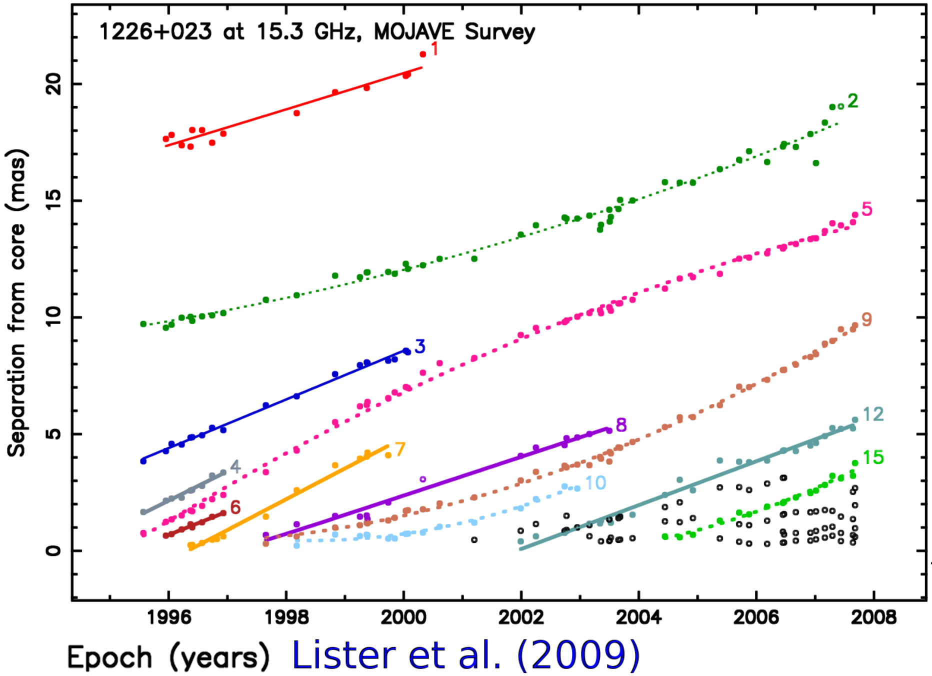
What are observational consequences?

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

1. optical variability and
2. jet kinematics.

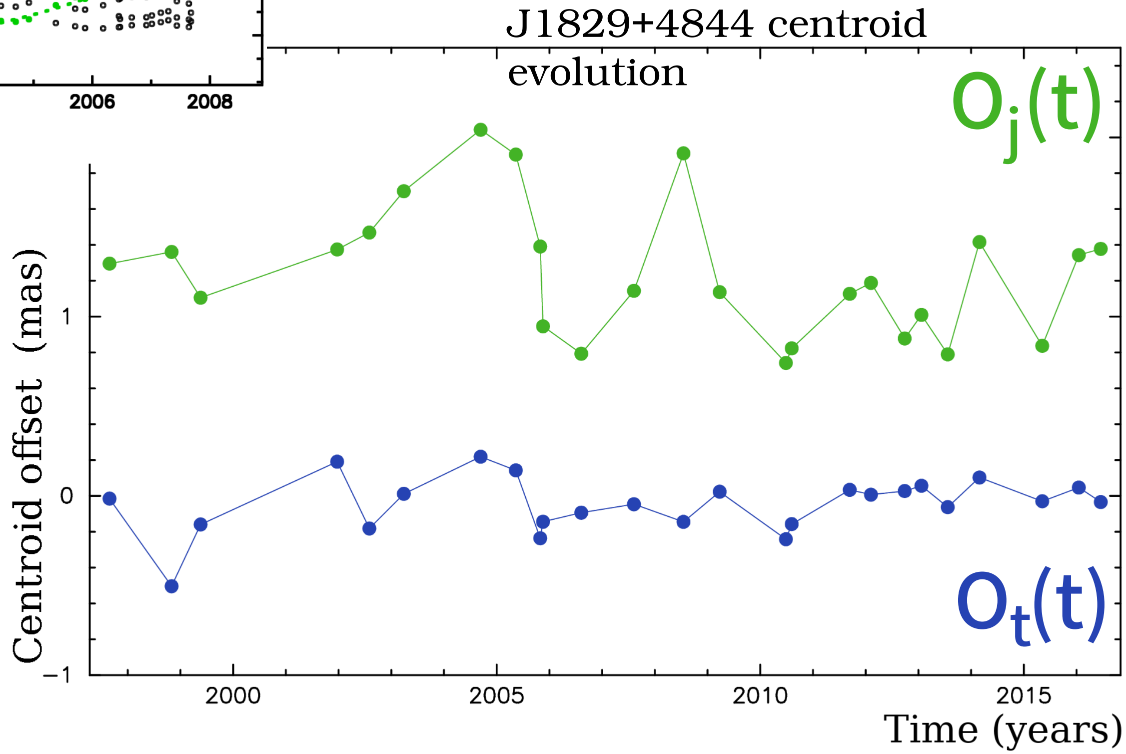


Jet kinematics

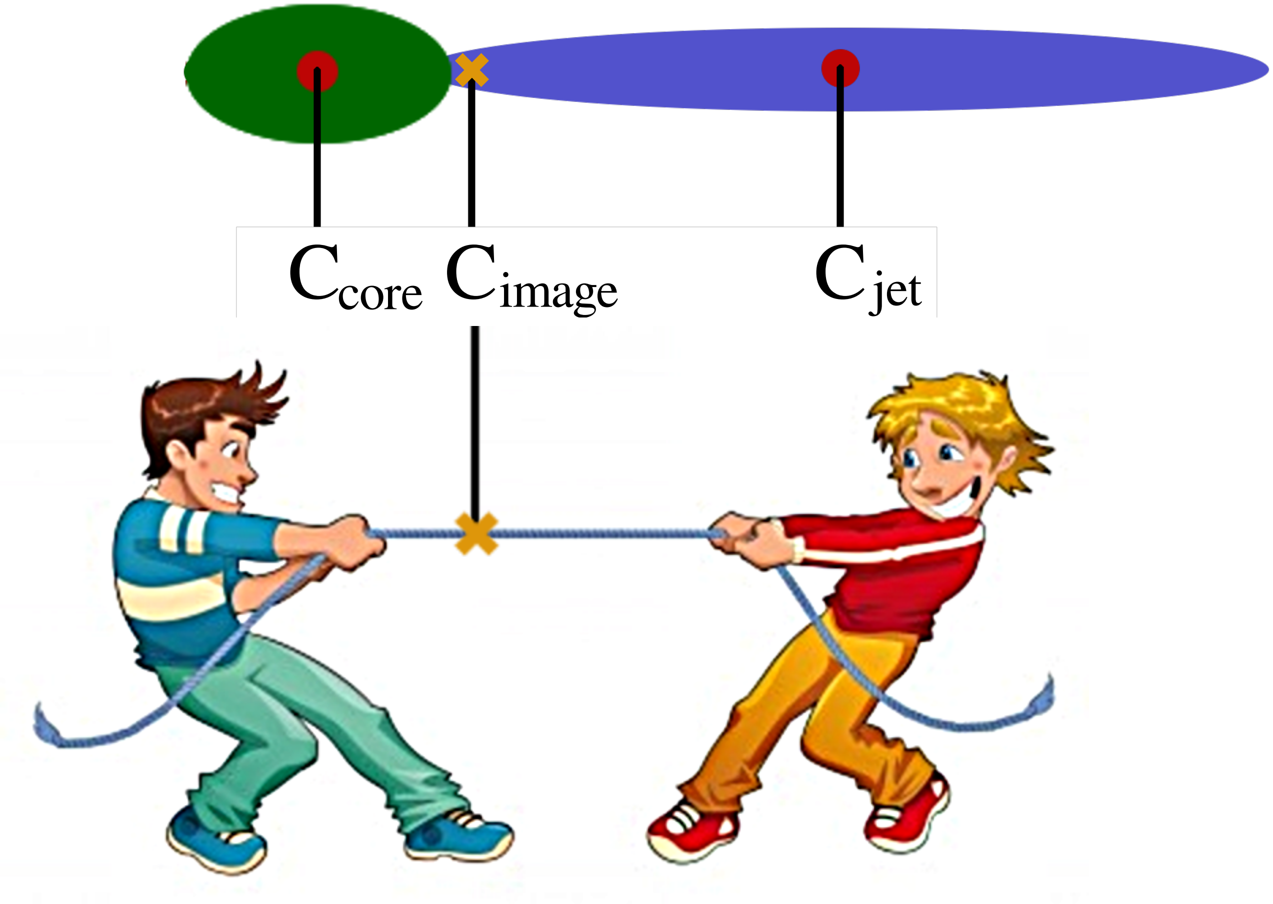


Lister et al. (2009)

Core ejects components, they are moving, fainting, disappearing

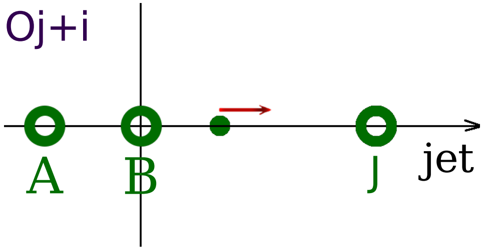


Centroid of a core-jet morphology

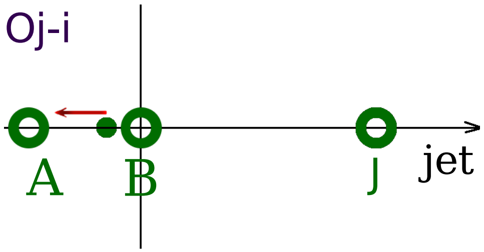


$$C_{\text{image}} = \frac{C_{\text{core}}\,F_{\text{core}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}} + \frac{C_{\text{jet}}\,F_{\text{jet}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}} + \frac{C_{\text{stars}}\,F_{\text{stars}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}}$$

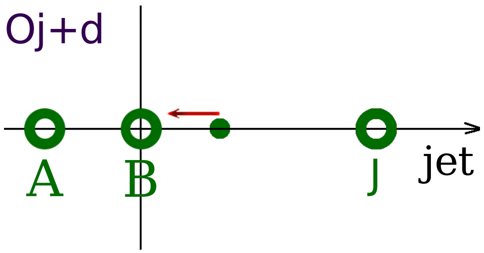
Direction of the centroid change after a flare

- 

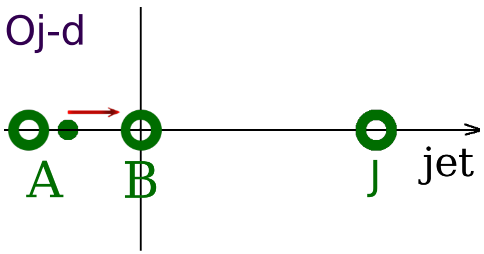
Flare happened at the jet

- 

Flare happened at the accretion disk

- 

Flare happened at the core or accretion disk

- 

Flare happened at the core and the jet

Correlation of the centroid wander and light curve

1. Two component stationary model

$$
\begin{aligned}
C_f(t) &= F(0)\,\frac{\mathcal{O}_{\rm j}(t)-\mathcal{O}_{\rm j}(0)}{F(t)-F(0)}+\mathcal{O}_{\rm j}(t)\\
F_f(t) &= F(0)\,\frac{\mathcal{O}_{\rm j}(0)}{C_x(t)}
\end{aligned}
$$

We can locate the position of the flaring component and its flux density;

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

Correlation of the centroid wander and light curve

2. A general non-stationary model

$$
\begin{aligned}
\mathcal{O}_\mathrm{j}(t) &= \sum_i \frac{v(t-t_{0i})\,F_j(t) + C_i(t_{0i})\,F_j(t_{0i})}{F_c(t) + \sum_i F_j(t)} \\
F_t(t) &= F_c(t) + \sum_i F_j(t) \\
F_j(t) &= 0 \quad \forall\, t < t_{0i}
\end{aligned}
$$

Not solvable without a use of addition information

3. Two-component non-stationary case

$$
\begin{aligned}
F_j(t) &= \frac{\mathcal{O}_\mathrm{j}(t)\,F_t(t) - \mathcal{O}_\mathrm{j}(t_b)\,F_t(t_b)}{v\,(t-t_b)} + F_j(t_b) \\
F_c(t) &= F_t(t) - F_j(t_b) \\
d_j(t) &= d(t_b) + v(t-t_b)
\end{aligned}
$$

If ejection start time t_b and component speed v are known, we can

- locate the **position** of the jet component
- determine its **flux density** as function of time
- determine **flux density** of the core as a function of time

AGN position jitter

A consequence of VLBI/*Gaia* offset optical jet interpretation is prediction of AGN jitter in *Gaia* time series at a level of 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 with respect to VLBI position is not zero.

Naive model: an AGNs is point-like and stable;
Realistic model: AGN has variable structure and it has jitter.

In VLBI world we got used to that.

How to live with AGN position jitter?

Two cases:

- Radio-loud AGNs:

  weak remedy: determine VLBI jet direction, $\mathcal{O}_\mathrm{j}(t)$, $\mathcal{O}_\mathrm{t}(t)$;
  strong remedy: centroid modeling, determination of the invariant core;

- AGNs without detected parsec-scale emission:

  determination of jet direction for position jitter;

Good news: position jitter converges with time to some (biased) mean position.

IV. Consequences to fundamental astronomy

- We still do not know unmovable sources (AGNs are not);
- There is a limit beyond that positions from technique A and B are not comparable;
- For VLBI/$Gaia$ this limit is 1–2 mas;
- Even for VLA/VLBA positions may be different;
- The fundamental coordinate systems from different techniques have to coexist;
- Impossible to say which is the best: $Gaia$-DR99, or RFC, or ICRF-2100;
- Future comparison of VLBI/optic will focus on astrophysics interpretation.

Wide impact of *Gaia* on fundamental astronomy

- VLBI astrometry for study of Galaxy kinematics is on a brink of extinction:
  - VLBI stellar parallax determination — **GONE!**
  - VLBI maser parallax/proper motion determination — **GONE!**
- Ground astrometry of Galactic plane objects is limited to
  - objects weaker 21 mag (telescope larger 2m);
  - objects not visible in optical range, like pulsars, masers
- VLBI/*Gaia* AGN program is emerging;

Radio absolute astrometry: where to go

- Field of "extensive astrometry":
  - ecliptic plane (50 and 30 mJy);
  - unassociated sources (f.e. *Fermi*)

  Expected growth rate: 200–500 new sources per year.

- Extensive era of radio astrometry is followed by with intensive era

  The areas that need nanorad level accuracy:

  1. $\mathcal{O}_\mathrm{j}$, $\mathcal{O}_\mathrm{t}$ observables;
  2. space navigation;
  3. pulsar timing/VLBI differences.

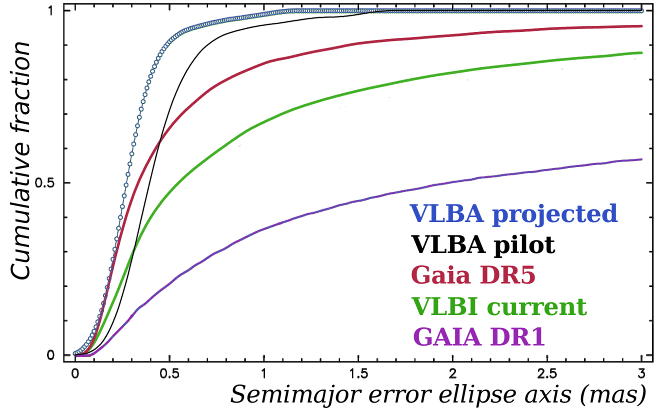
  Goals:
  - improve positions of ~ 9000 VLBI/$Gaia$ matches down to 0.2–0.3 mas.
  - derive source images, apply source structure correction.
  - determine jet direction

- Derive images/ determine flux densities at high frequencies (22–129 GHz).

Absolute astrometry without imaging is *junk* in post-*Gaia* era.

Future observing programs

- improve VLBI positions of ~ 6000 matches at $\delta > -40^\circ$ and get jet directions. Goal: 0.2 mas. Status: pending.



- improve VLBI positions of 758 matches at $\delta < -40^\circ$, get jet directions. Goal: 0.3 mas. Status: **ongoing**
- Imaging peculiar VLBI/*Gaia* matches with ROBO AO. Status: **ongoing**
- Imaging VLBI/*Gaia* matches with large offsets with HST. Status: pending
- Getting spectra of peculiar VLBI/*Gaia* matches. Status: pilot
- Specta-polarimetric observations of VLBI/*Gaia* matches. Status: pending
- Redshift determination. Status: discussed.
- Ecliptic plane survey. Status: **ongoing**.

Summary:

- VLBI/*Gaia* residuals have systematic caused by core-jet morphology;
- VLBI position is related to the most compact detail, an AGN core;
- *Gaia* position is related to the image centroid within the PSF;
- The most plausible explanation: optical jet at scales 1–200 mas;
- Consequence of the optical jet presence: source position jitter;
- Position jitter + light curve = optical resolution at mas scale;
- VLBI + *Gaia* $\longrightarrow$ we can determine the region of optical flares its kinematics and its flux density.

References: arxiv.org/abs 1611.02630, 1611.02632, 1704.07365

RFC preview: **http://astrogeo.org/rfc**