Discovery of optical jets from VLBI/*Gaia* comparison

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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%

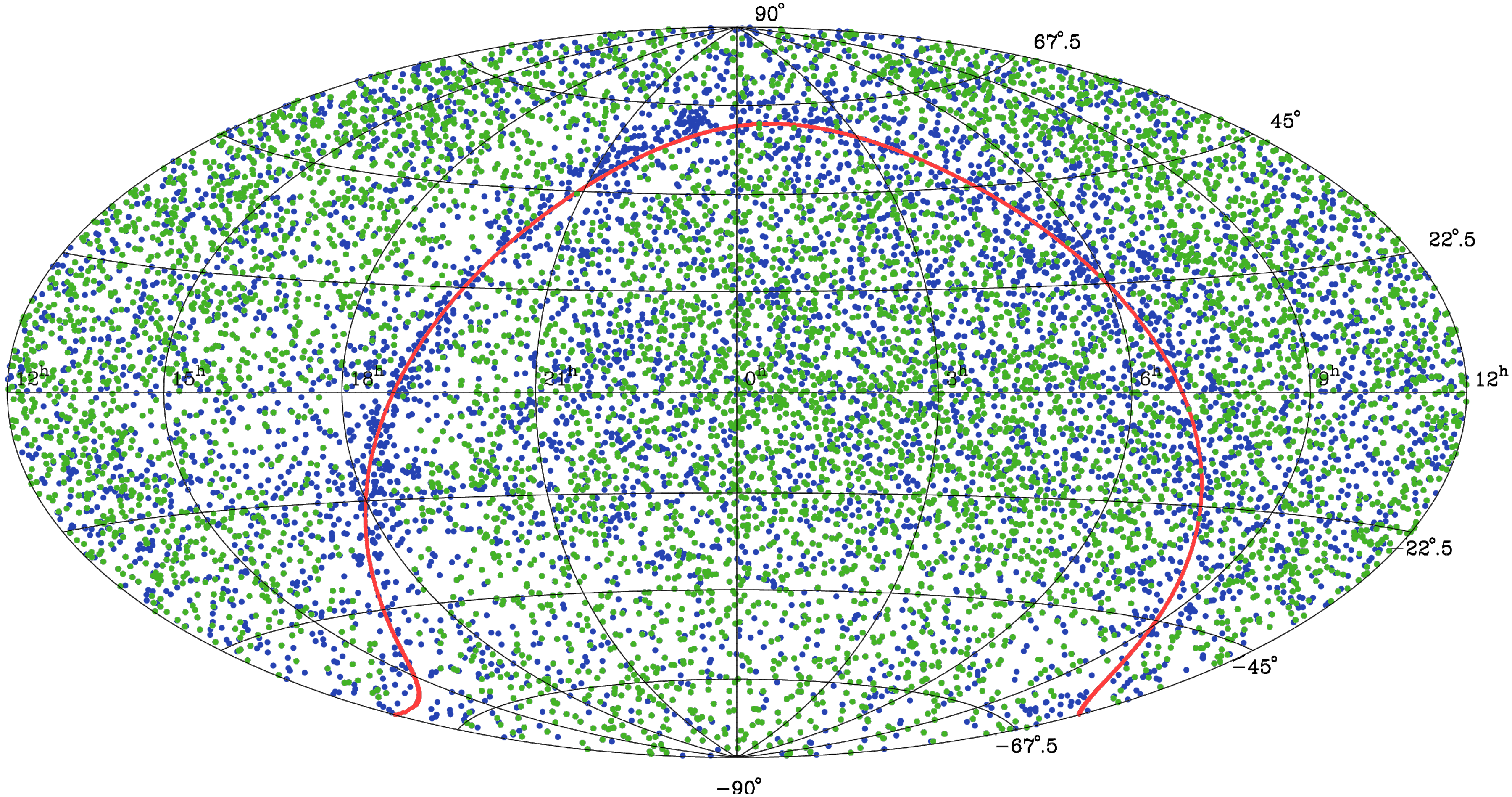
Number of observing sessions

1	45%
1–2	77%
1–5	90%
10+	8%
100+	3%

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

VLBI/*Gaia* comparison

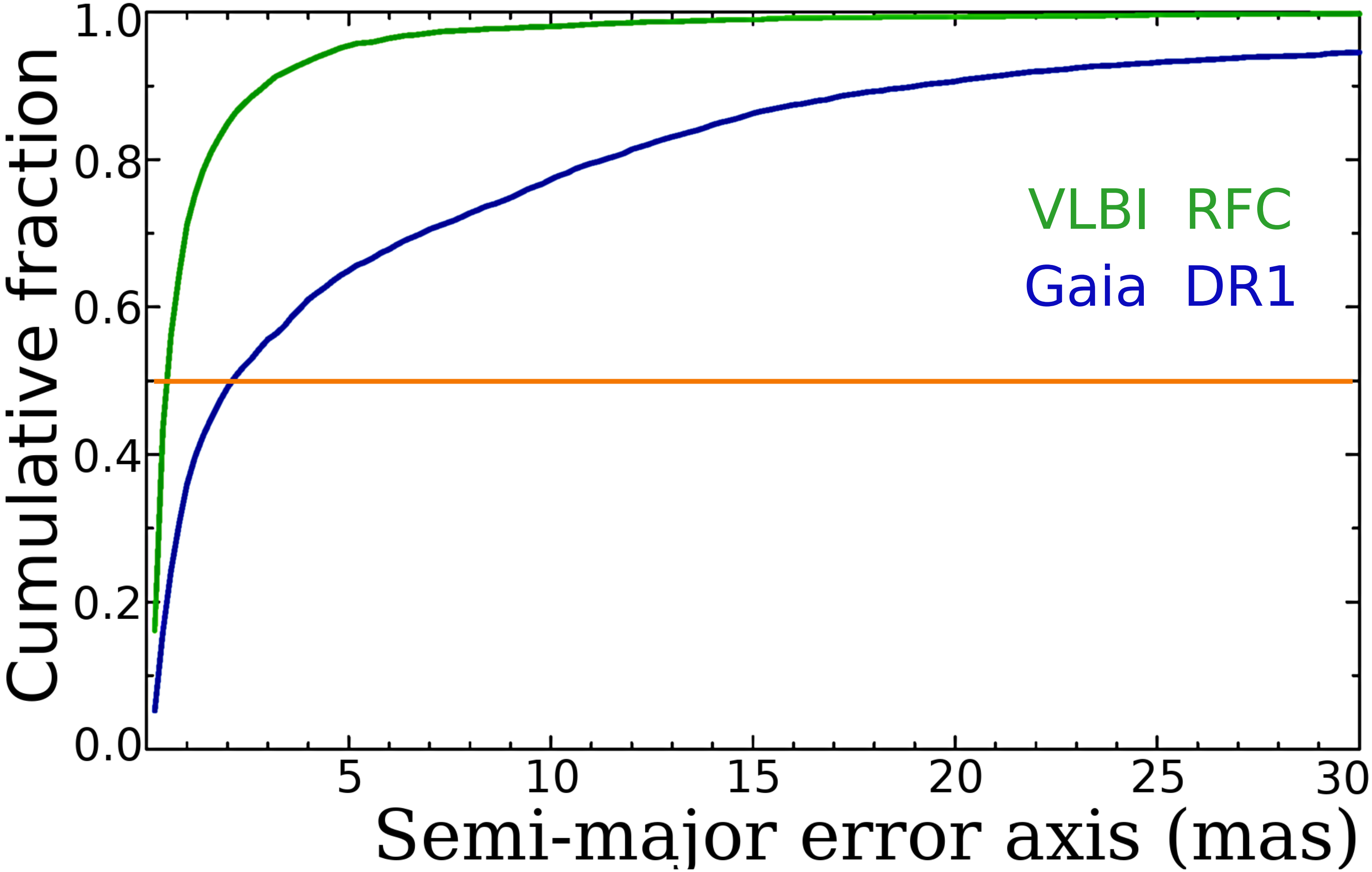
VLBI Radio Fundamental Catalogue (**14,768 sources**) on 2017.09.01 and *Gaia* DR1 ($1.14 \cdot 10^9$ objects)



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

Blue: VLBI sources without *Gaia* matches

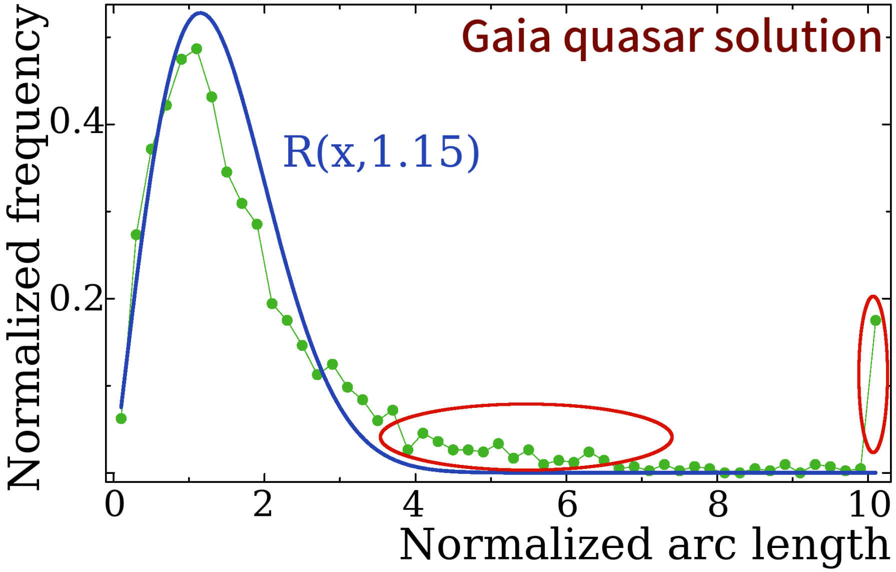
VLBI and *Gaia* position uncertainties

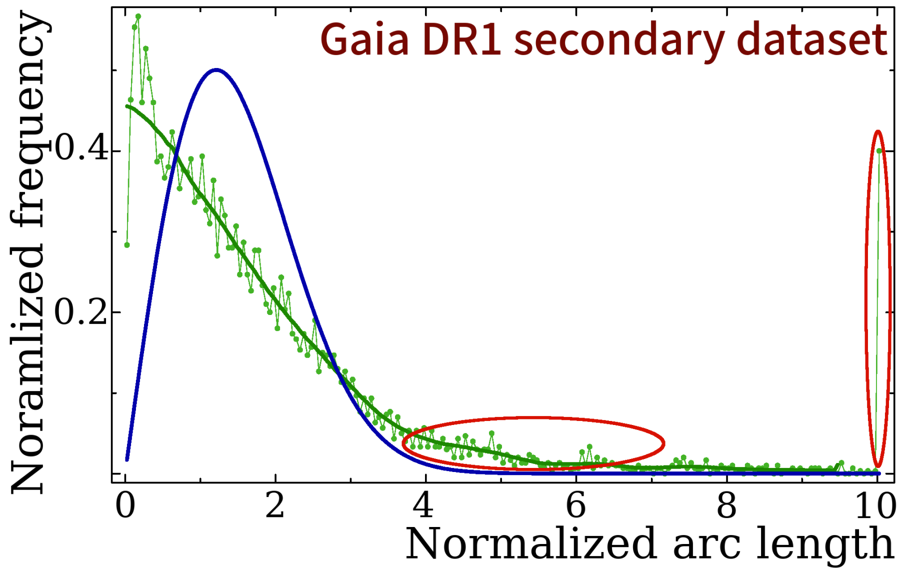


Median error: **VLBI RFC**: 0.5 mas

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

Distribution of VLBI/*Gaia* arc lengths

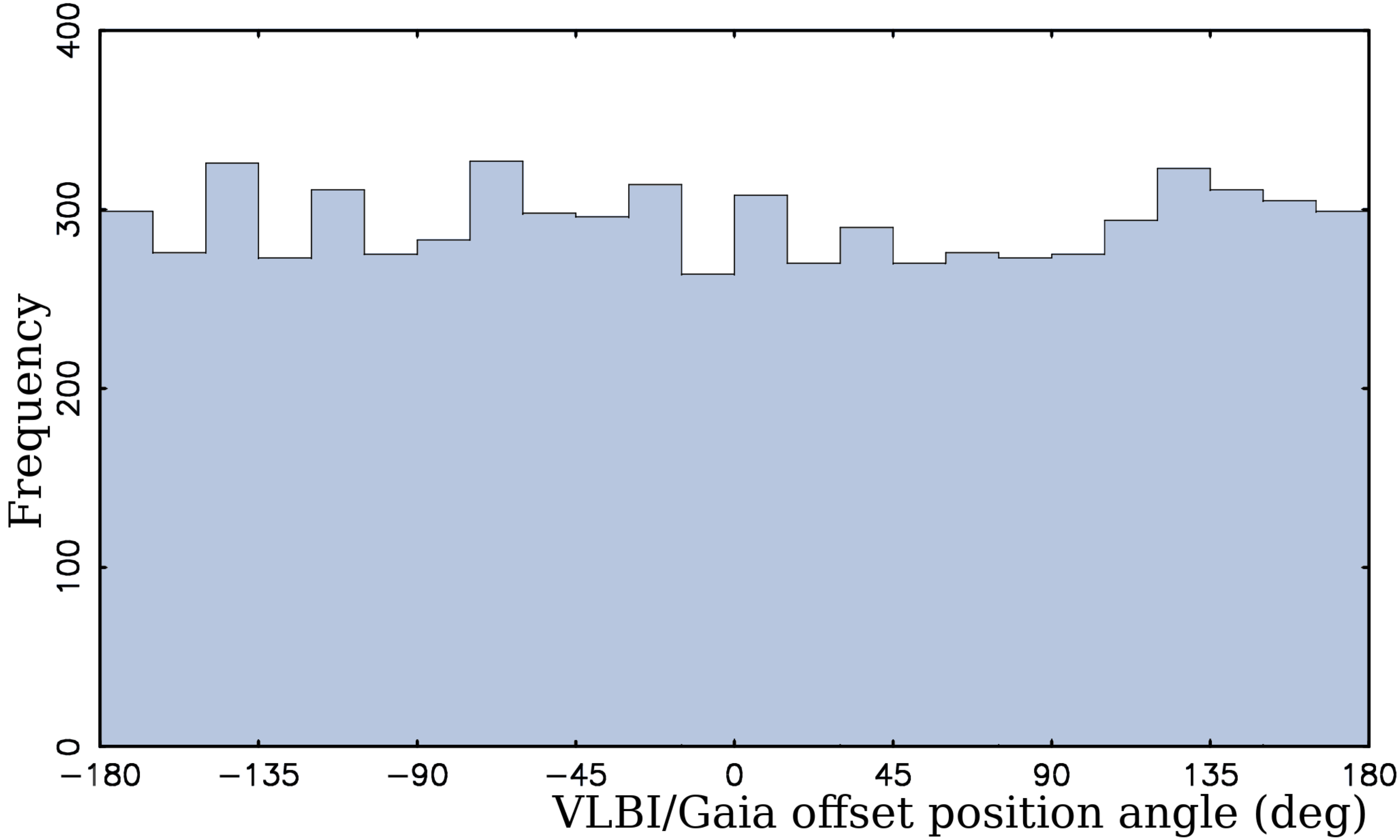




There are **486 outliers** (7%) at significance level 99%.

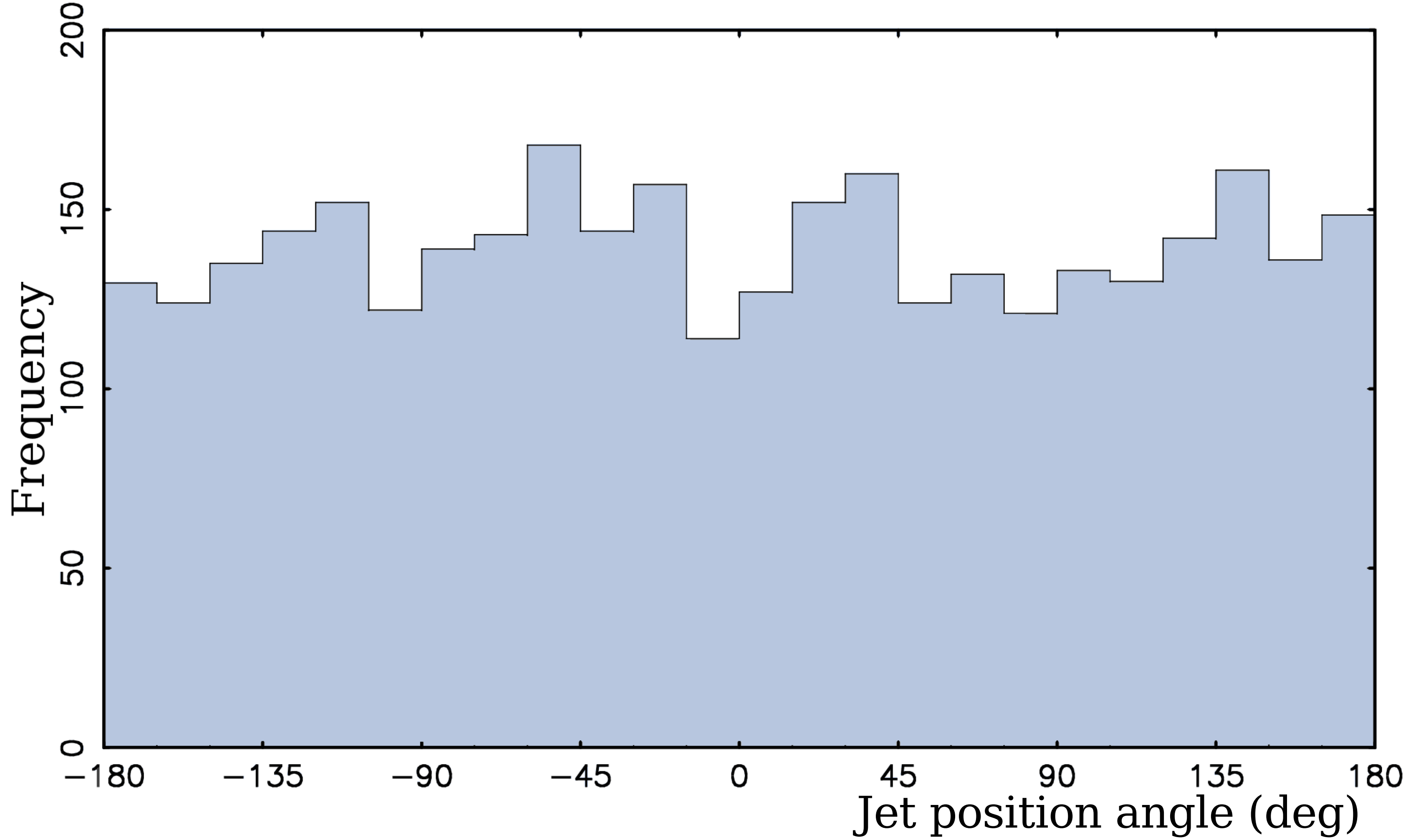
Outliers range: 1–400 mas (median: 10 mas).

Distribution of VLBI/*Gaia* position offset angles



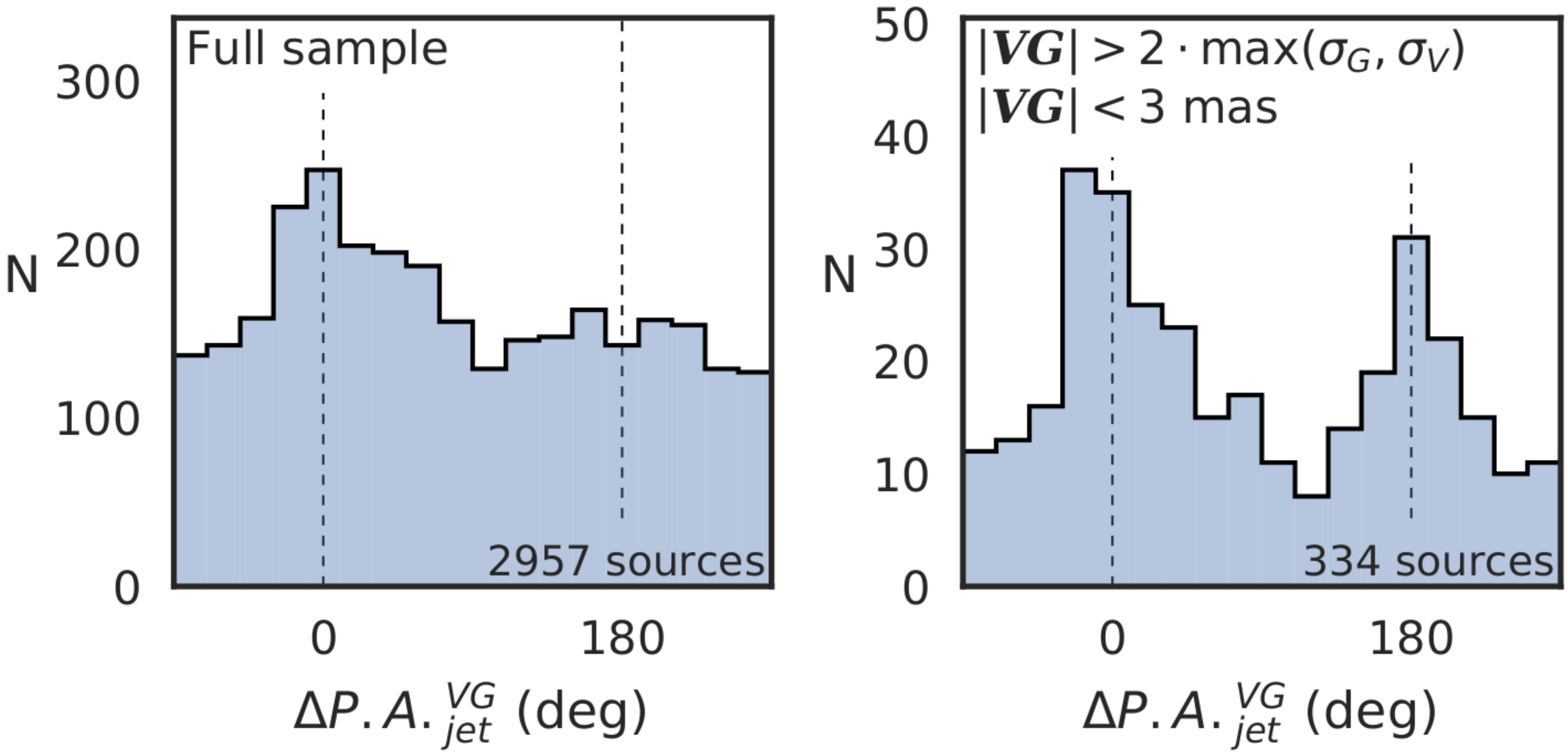
Main finding: no preference at $0^\circ, 180^\circ$ (VLBI declination errors)
No deviation from the isotropy.

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 only 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.

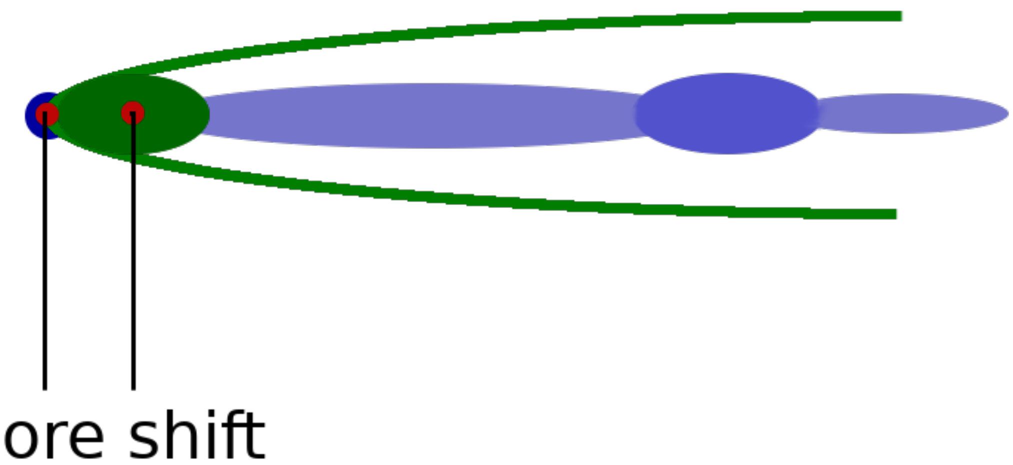
  To explain the pattern, systematic shifts VLBI/*Gaia* at **1–2 mas** level are required.

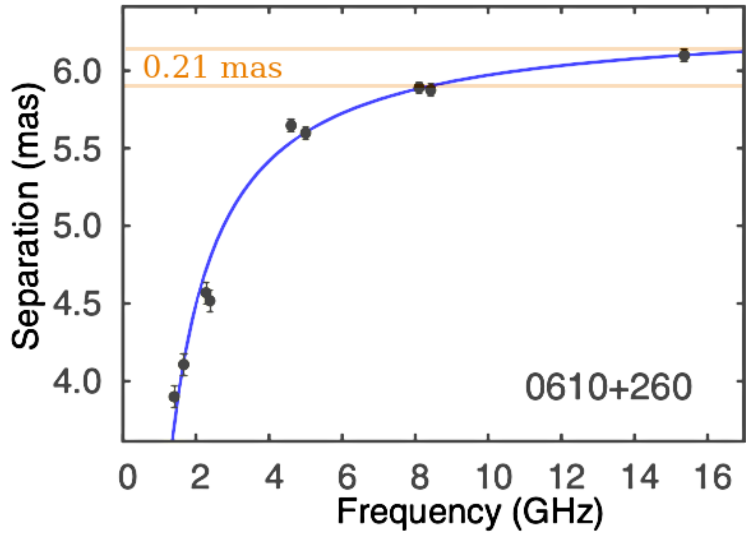
Possible explanations:

- **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;





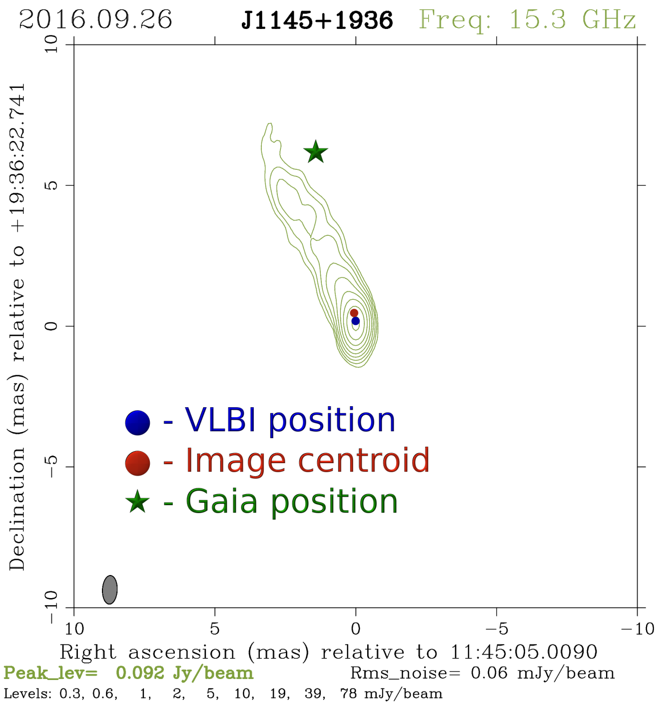
Sokolovsky et al. 2011

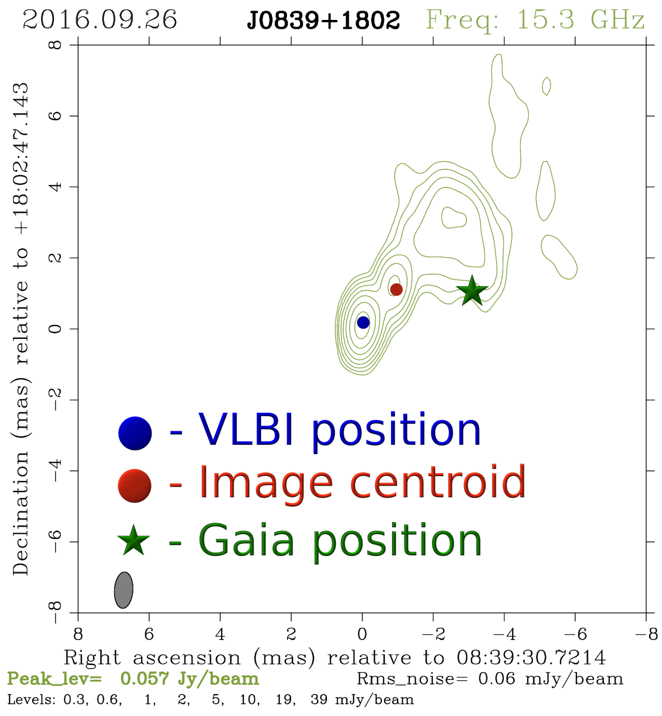
- Core centroid is shifted with respect to the jet base;
- The shift is frequency dependent;
- Results of core-shift measurements:
  - Contribution to 8 GHz positions: ~ 0.2 mas;
  - Contribution to dual-band positions: 0.02–0.05 mas.

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:



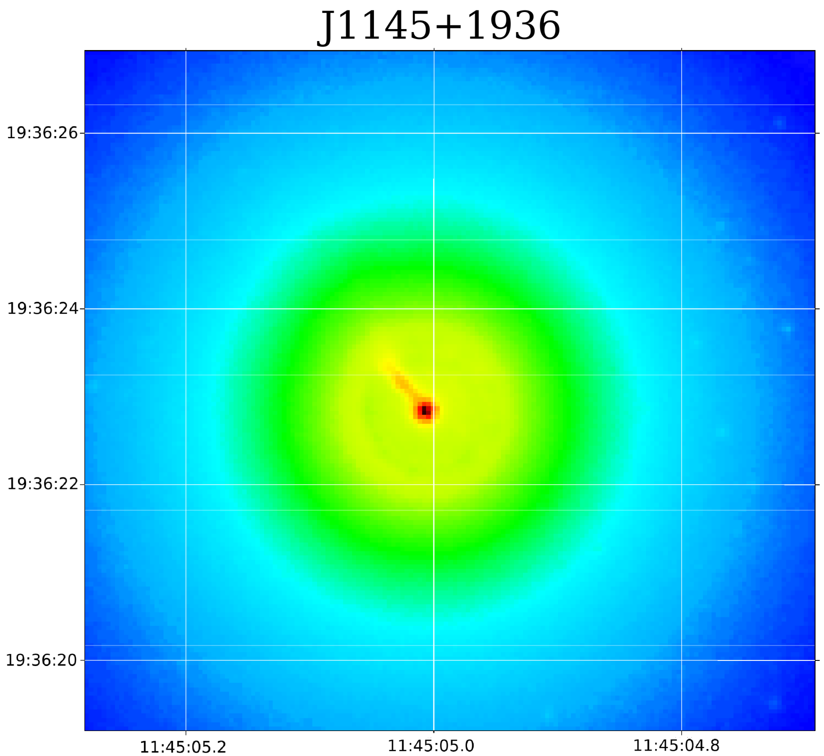


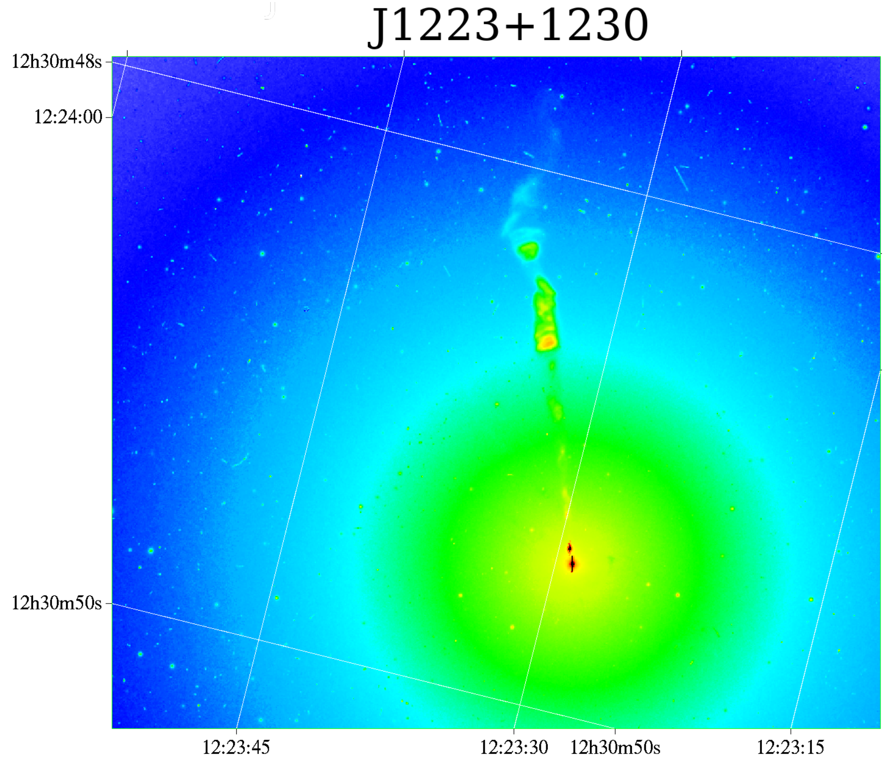
- Test VLBI experiment processed with source structure contribution applied:
  Median VLBI position bias: 0.06 mas
  Median image centroid offset: 0.25 mas

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

Argumentation:

1. Only core-jet morphology can cause preferable direction of VLBI/$Gaia$ offsets
2. Contribution of radio morphology is one order of magnitude too small
3. Optical jets are known
4. Known optical jets are co-spatial

So far, no direct proof:

- large optical jets that we see, do not affect $Gaia$.
- small optical jets that affect $Gaia$ we do not see

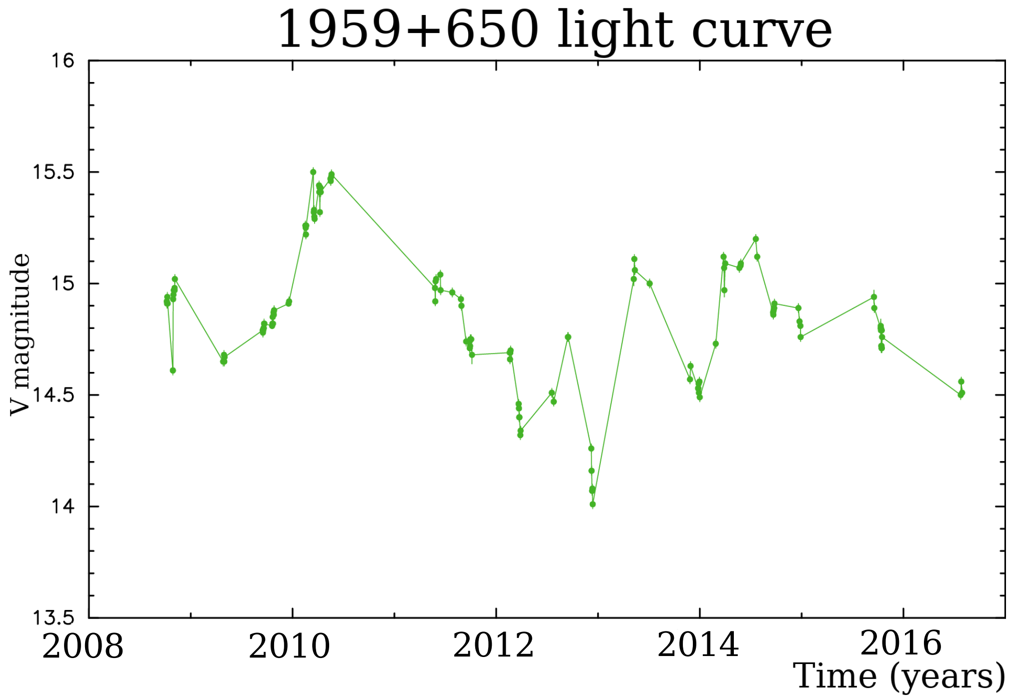
How to prove it?

To predict observational consequences.

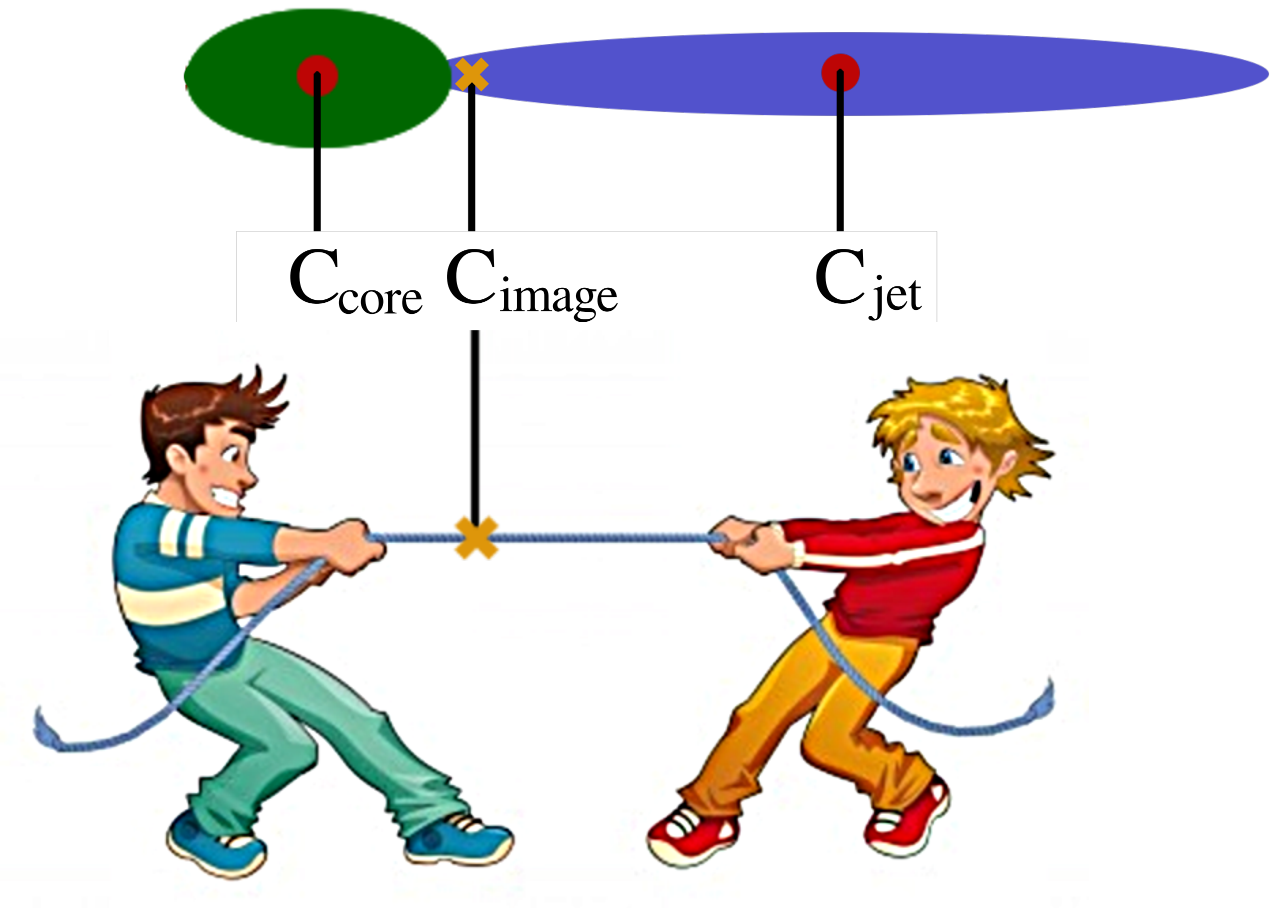
What are expected observational consequences?

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

1. optical variability and
2. jet kinematics.

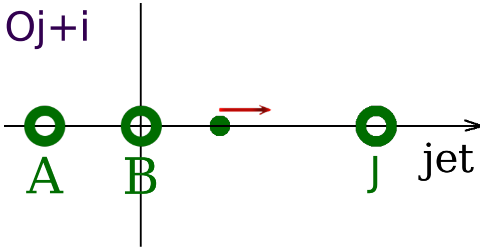


Centroid of a core-jet morphology

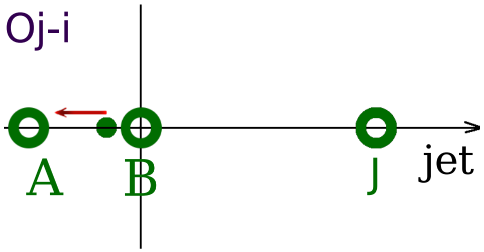


$$C_{image} = \frac{C_{core}\,F_{core}}{F_{core}+F_{jet}+F_{stars}} + \frac{C_{jet}\,F_{jet}}{F_{core}+F_{jet}+F_{stars}} + \frac{C_{stars}\,F_{stars}}{F_{core}+F_{jet}+F_{stars}}$$

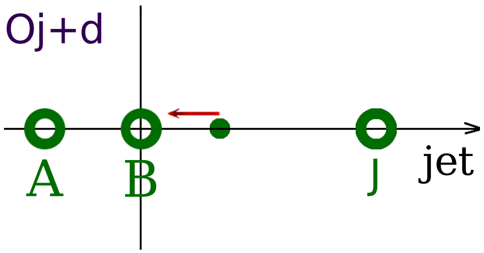
Direction of the centroid change after a flare

- 

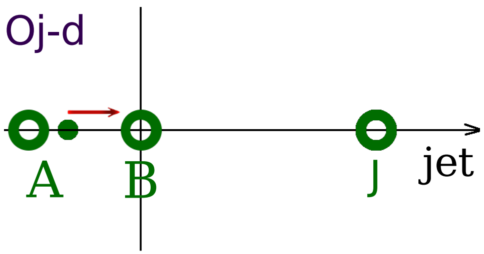
Flare happened at the jet

- 

Flare happened at the accretion disk

- 

Flare happened at the core or accretion disk

- 

Flare happened at the core or the jet

Correlation of the centroid wander and light curve

1. Two component stationary model

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

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

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.

Correlation of the centroid wander and light curve

2. A general non-stationary model

$$\mathcal{O}_{\mathrm{j}}(t) = \sum_i \frac{v(t-t_{0i})\,F_j(t) + C_i(t_{0i})\,F_j(t_{0i})}{F_c(t) + \sum_i F_j(t)}$$

$$F_t(t) = F_c(t) + \sum_i F_j(t)$$

$$F_j(t) = 0 \quad \forall\, t < t_{0i}$$

Not solvable without a use of addition information

3. Two-component non-stationary case

$$F_j(t) = \frac{\mathcal{O}_{\mathrm{j}}(t)\,F_t(t) - \mathcal{O}_{\mathrm{j}}(t_b)\,F_t(t_b)}{v\,(t-t_b)} + F_j(t_b)$$

$$F_c(t) = F_t(t) - F_j(t_b)$$

$$d_j(t) = d(t_b) + v(t-t_b)$$

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

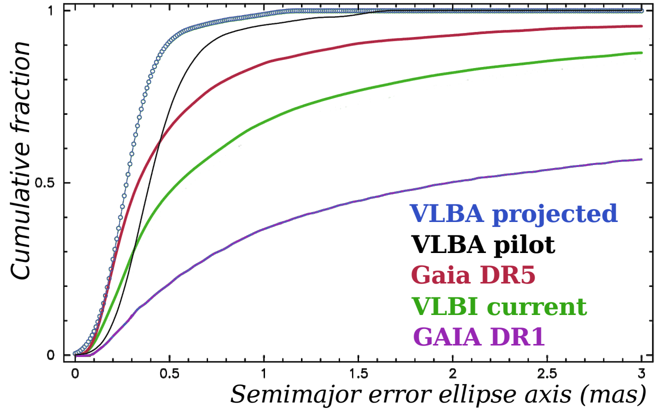
A jitter is

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

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

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: pilot.
- 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.

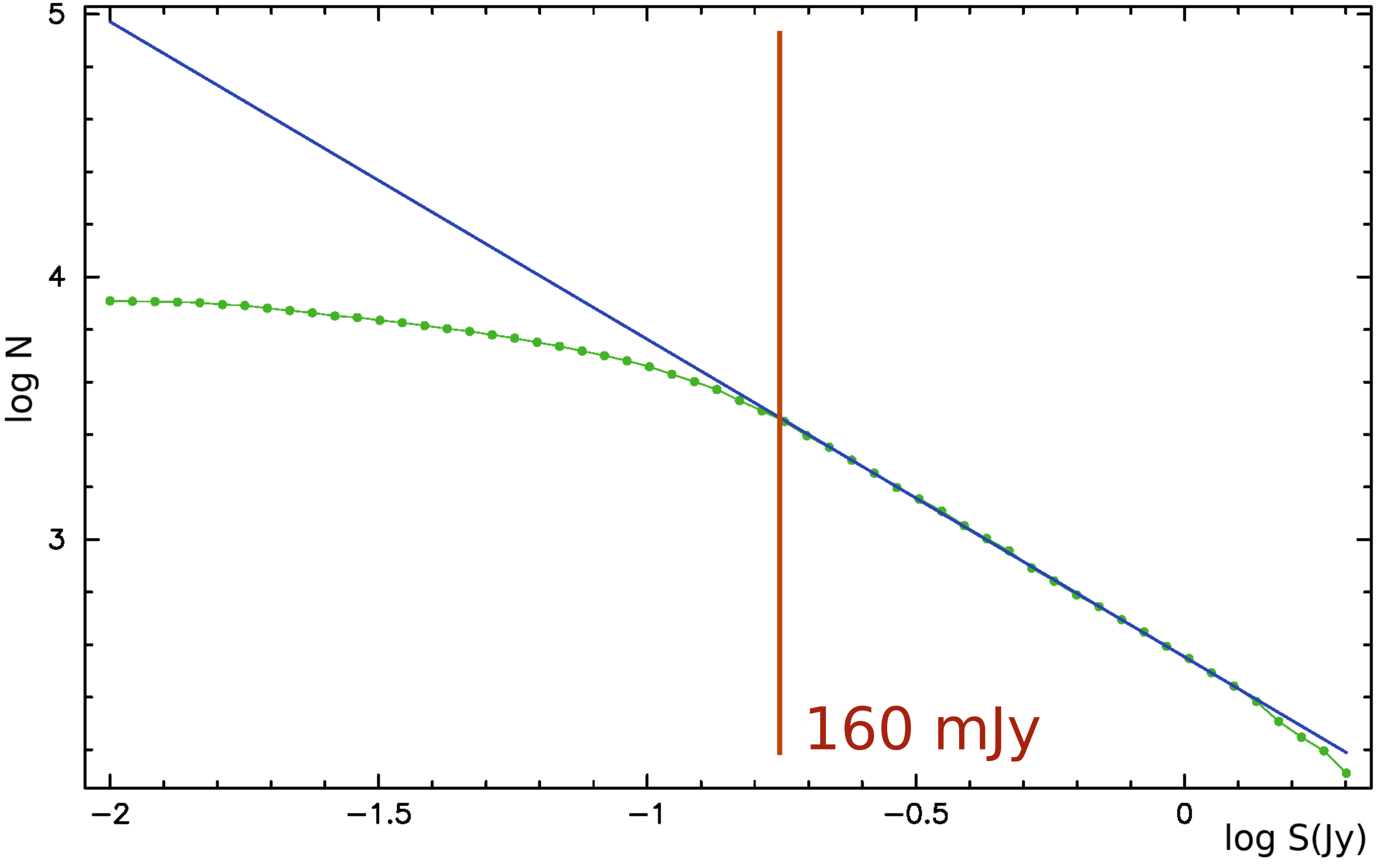
References: arxiv.org/abs 1611.02630, 1611.02632, 1704.07365

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

Backup slides

Completeness of the RFC

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

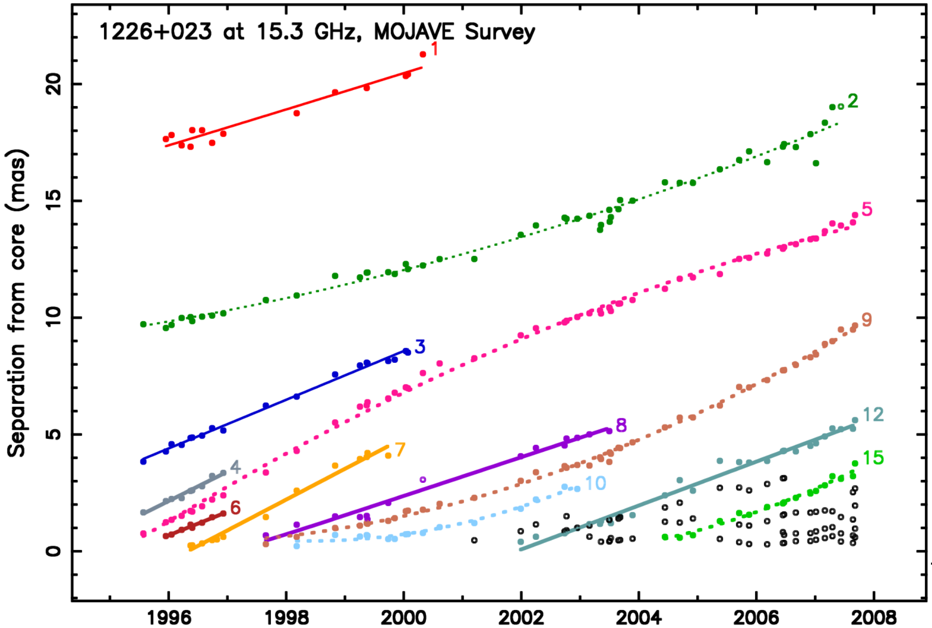


170 mJy	99%
160 mJy	97%
150 mJy	95%
100 mJy	80%
50 mJy	49%
10 mJy	10%

Number of matches

γ-ray	Fermi:	15%
X-ray	Chandra	3%
infra-red	WISE: 3.4 μm	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 1.4 GHz	91% (99.8%)
radio	TGSS 0.15 GHz	72% (76%)

Jet kinematics



Lister et al. (2009)

Core ejects components, they are moving, fainting, disappearing