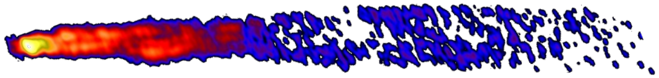

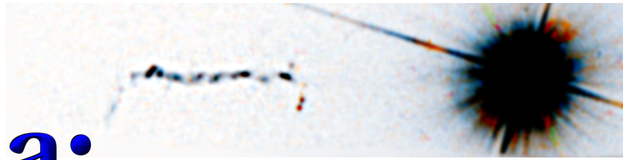

VLBI and Gaia: a new window to study physics of active galactic nuclea

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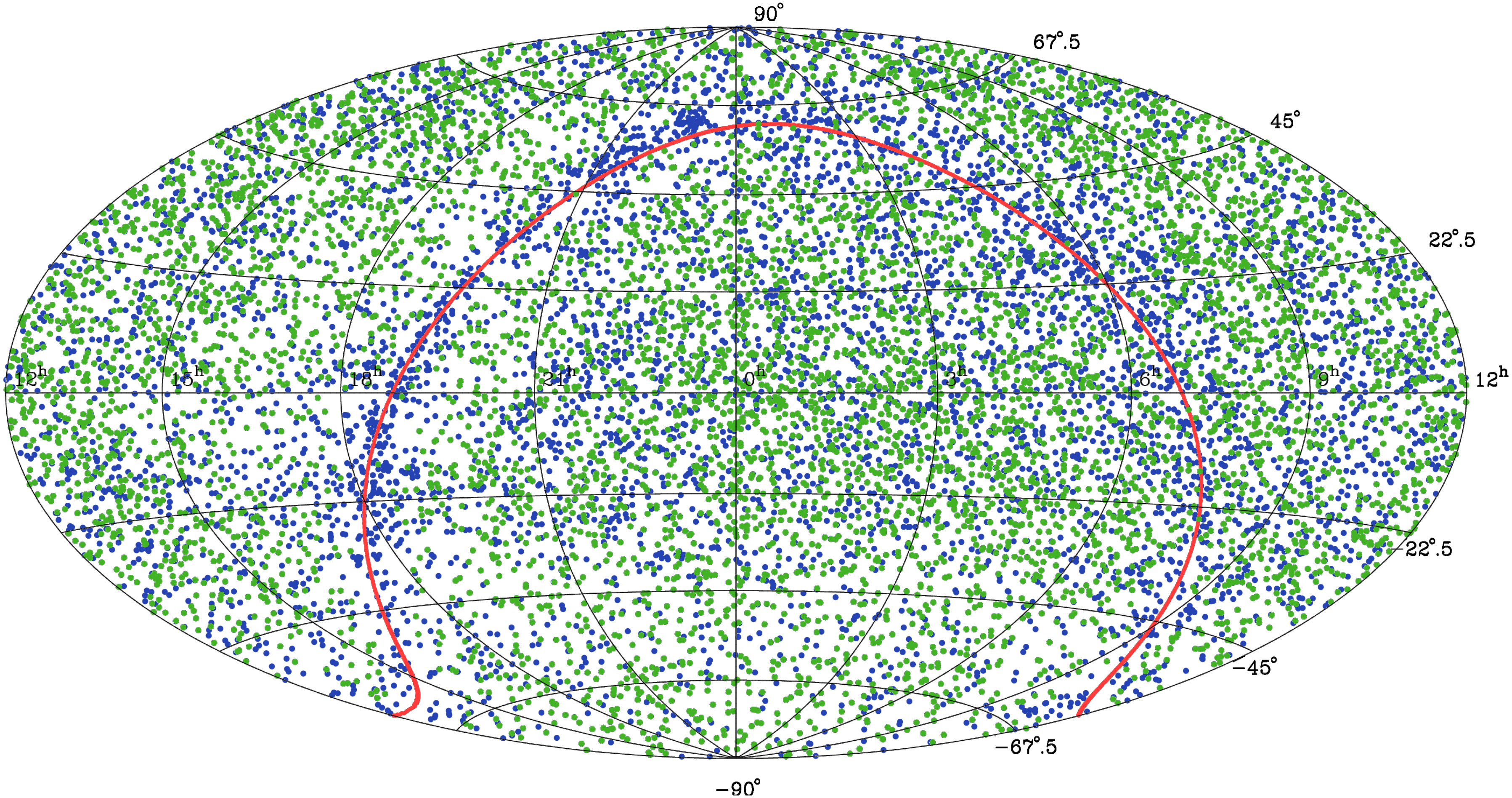
Data

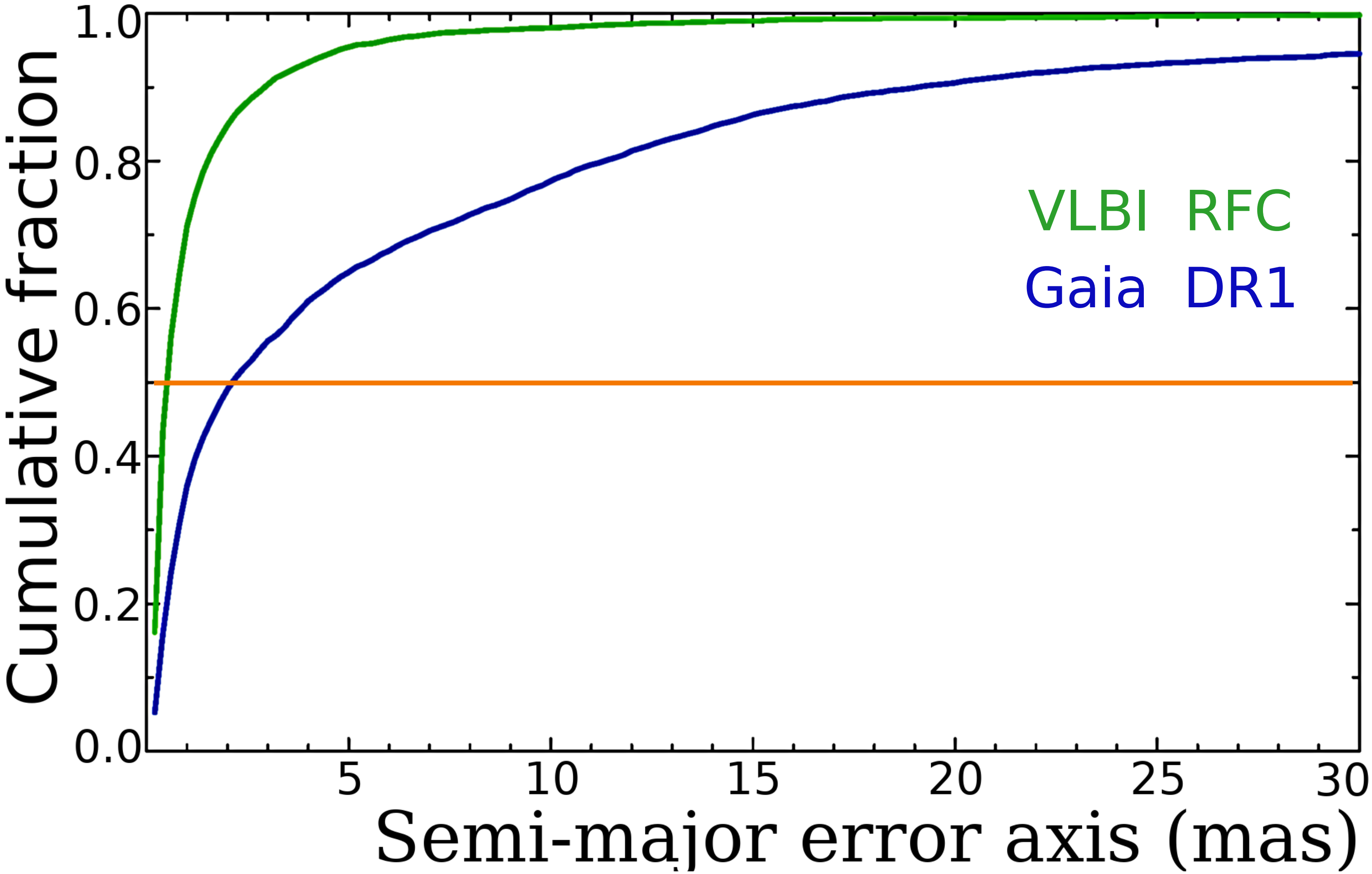
VLBI Radio Fundamental Catalogue (**13,036 sources**) on 2017.04.15 and Gaia DR1 ($1.14 \cdot 10^9$ objects)



Green: 6,907 VLBI/Gaia matches $P < 0.0002$

Blue: VLBI sources without Gaia matches

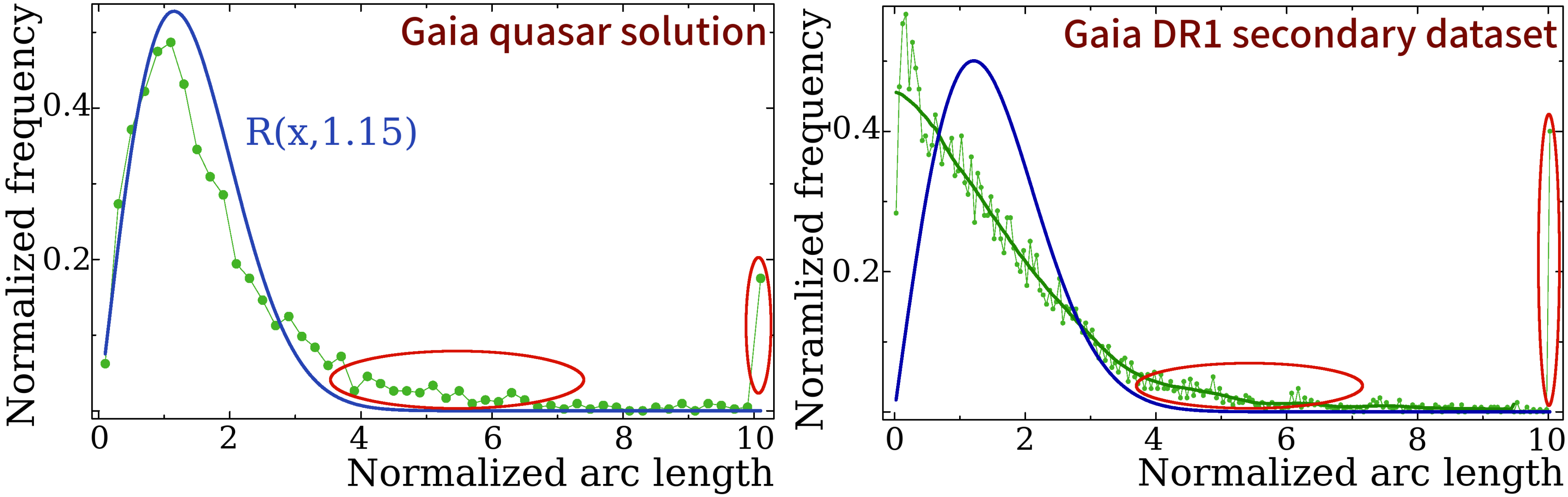
VLBI and Gaia position uncertainties



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

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

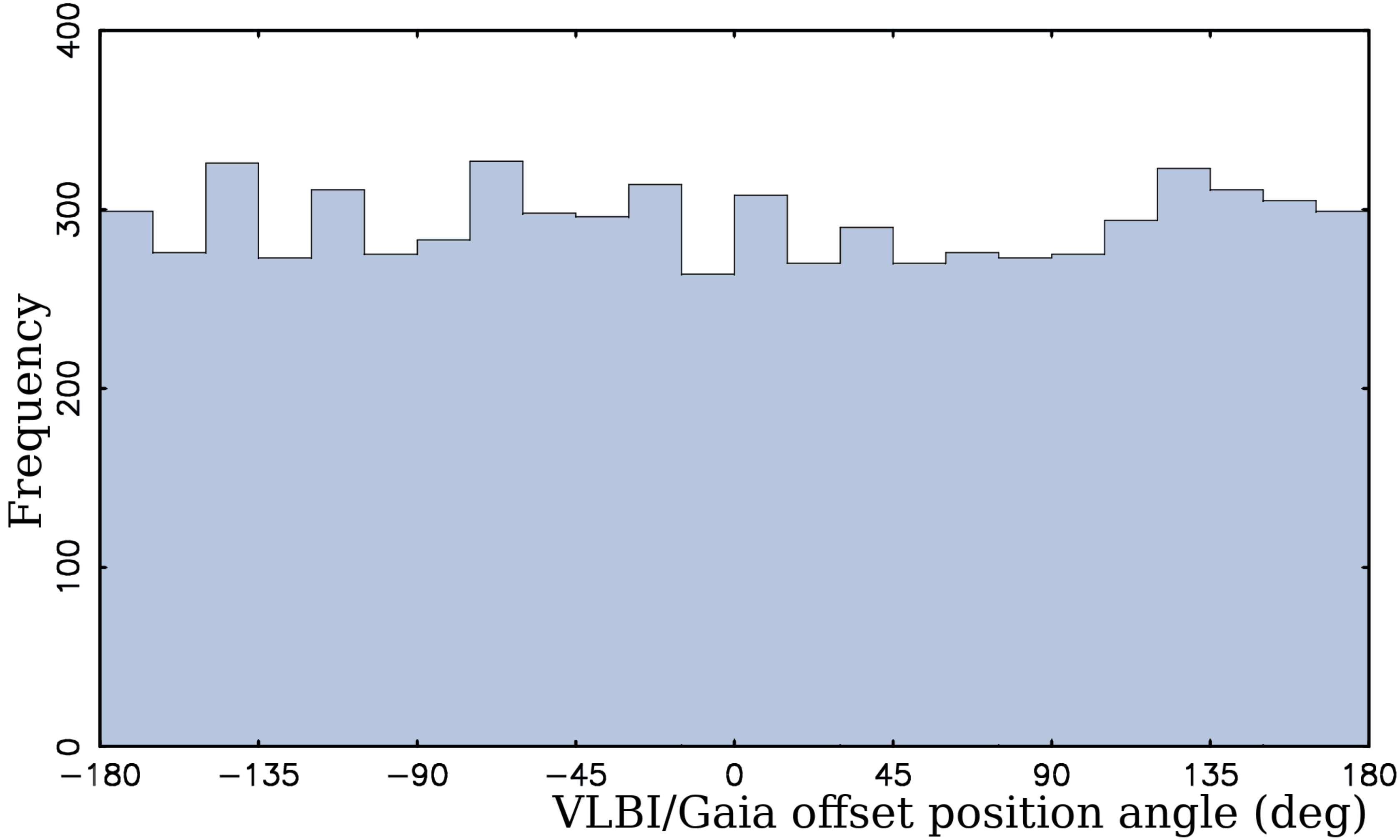
Distribution of VLBI/Gaia arc lengths



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

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

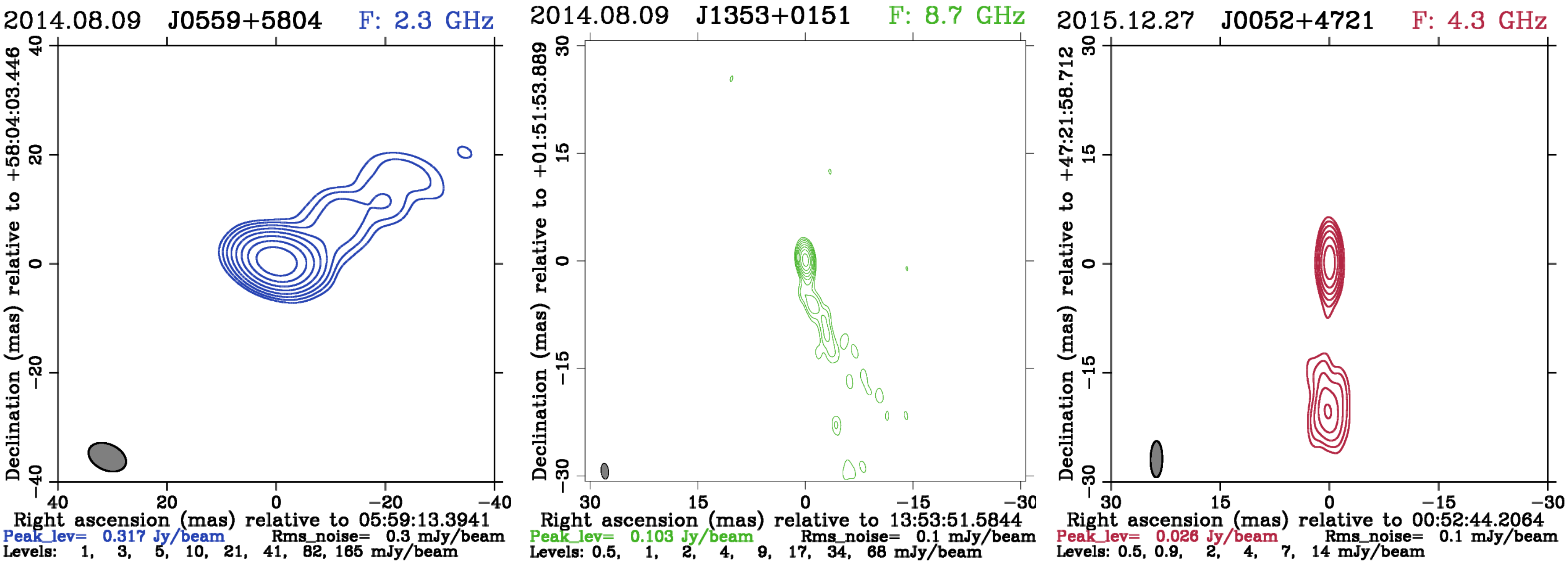
Distribution of VLBI/Gaia position offset angles



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

How the AGNs look like at mas scale?

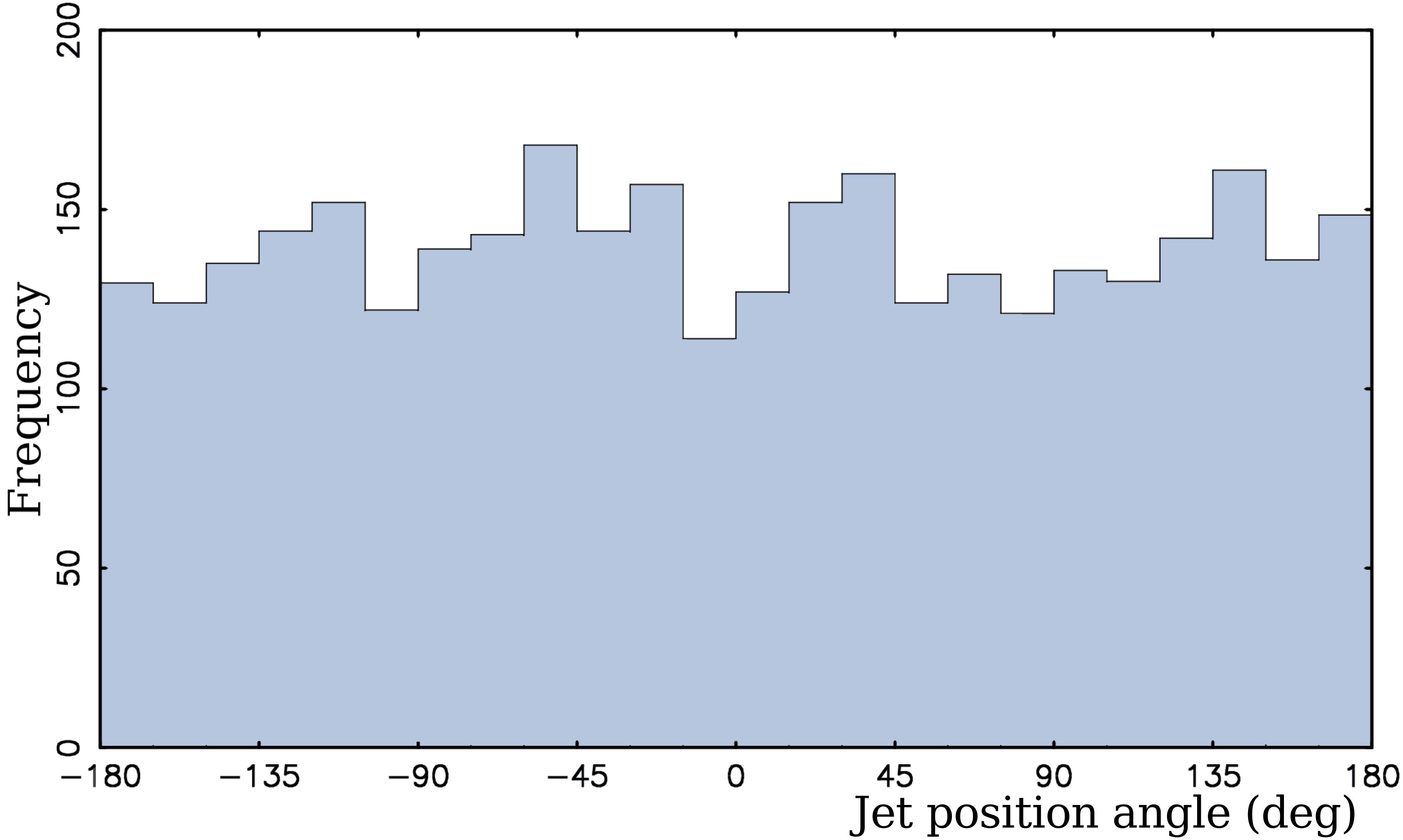
Generic property: core-jet morphology:



- Images are available for 74% sources (the number will increase)
- Jets can be reliably determined at 50% images (can be improved)

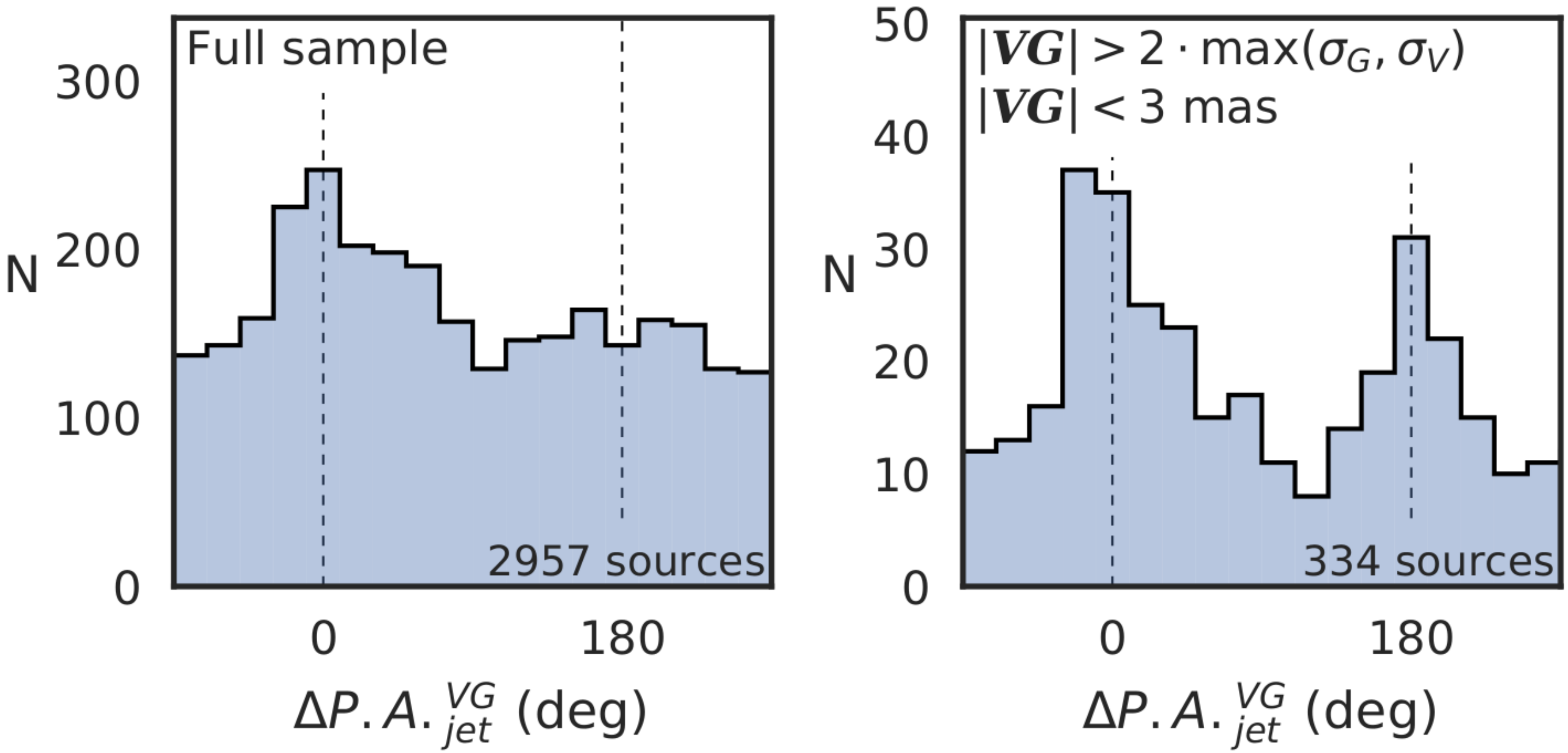
AGNs are intrinsically asymmetric sources!

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



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.

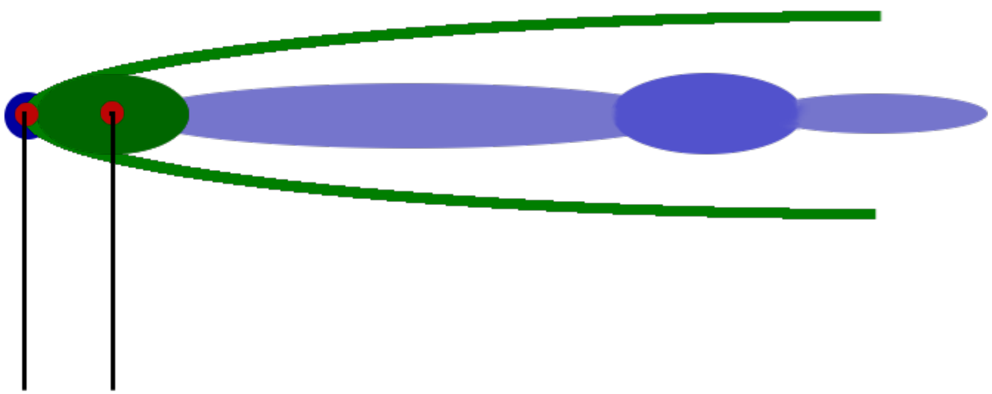
  To explain the pattern, systematic shifts VLBI/Gaia at **1–2 mas** level are required.

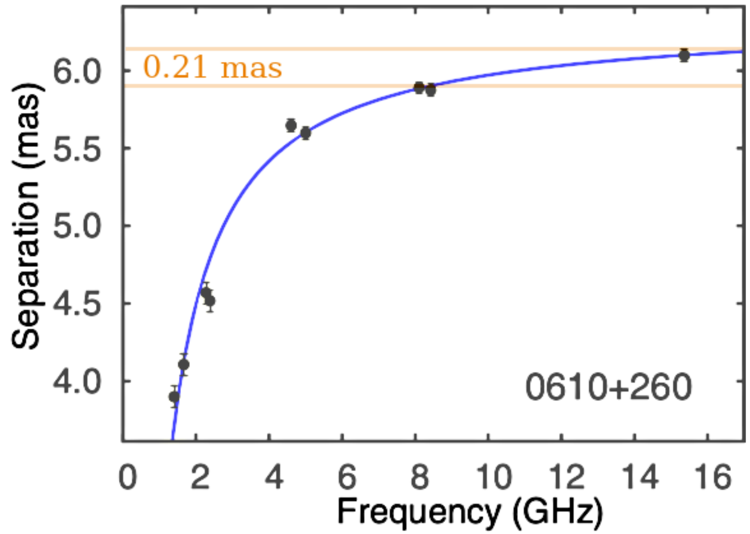
Possible explanations:

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

Core-shift

- Core is the optically thick part of the jet;





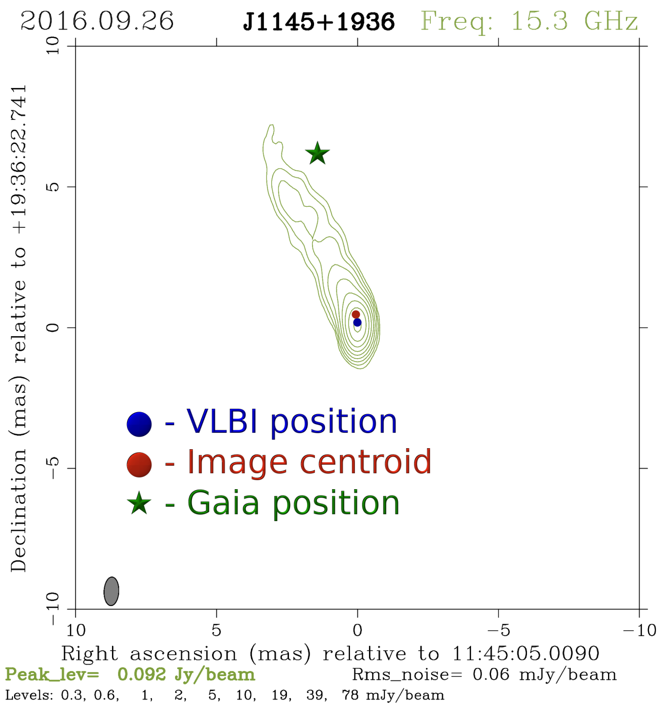
Sokolovsky et al. 2011

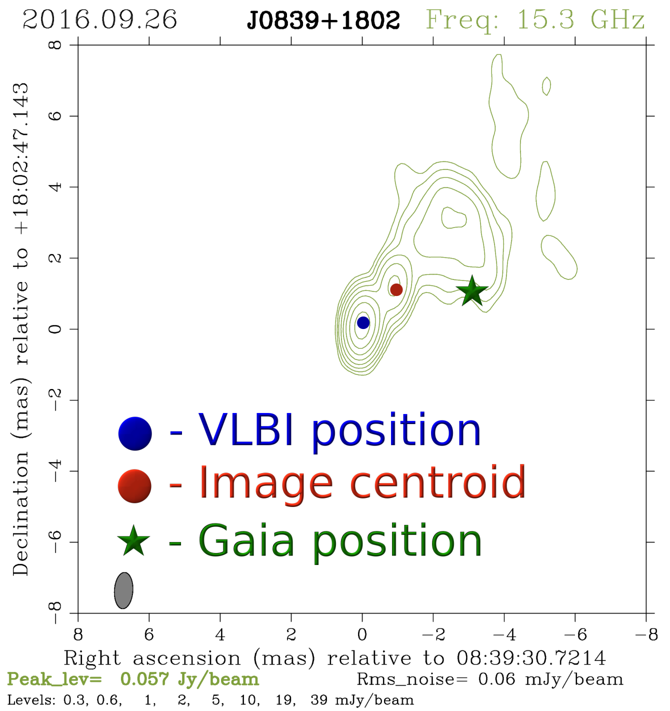
- Core centroid is shifted with respect to the jet base;
- The shift is frequency dependent;
- Results of core-shift measurements:
  - Contribution to 8 GHz positions: ~ 0.2 mas;
  - Contribution to dual-band positions: 0.02–0.05 mas.

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:

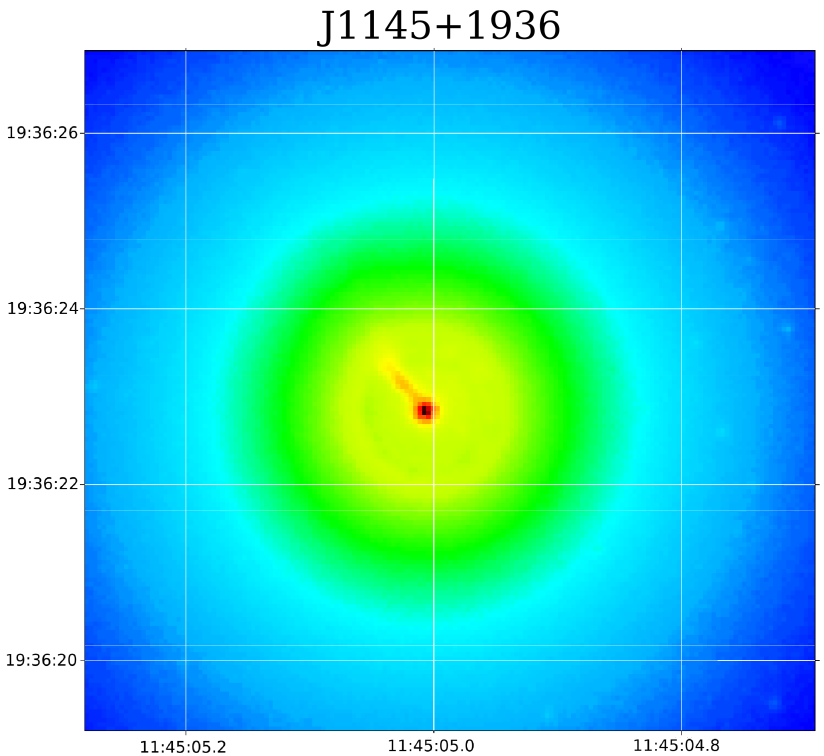
  Median VLBI position bias: 0.06 mas

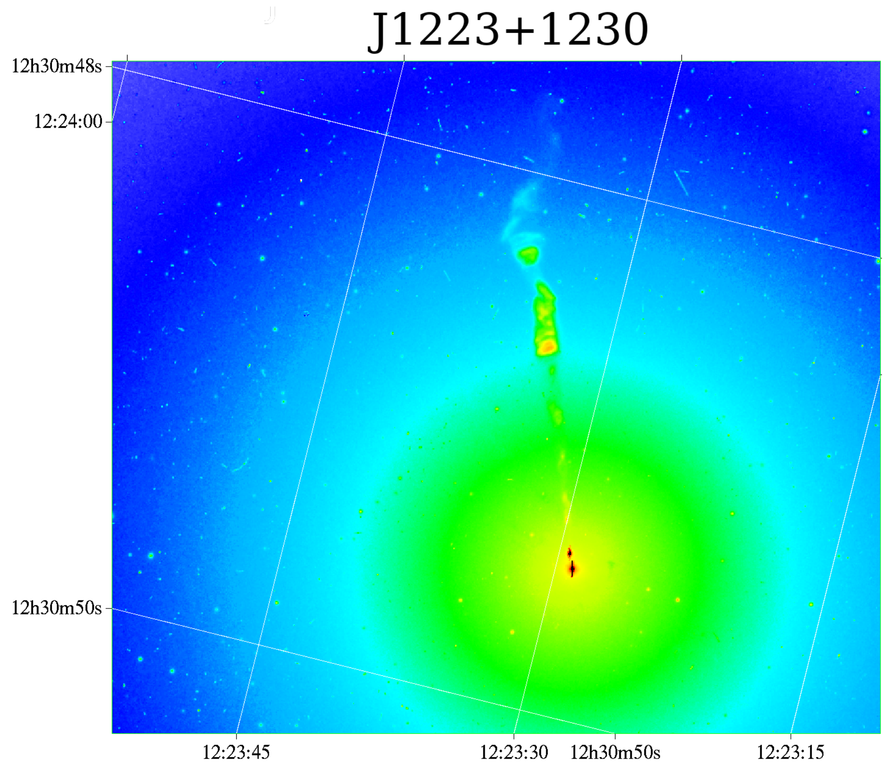
  Median image centroid offset: 0.25 mas

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

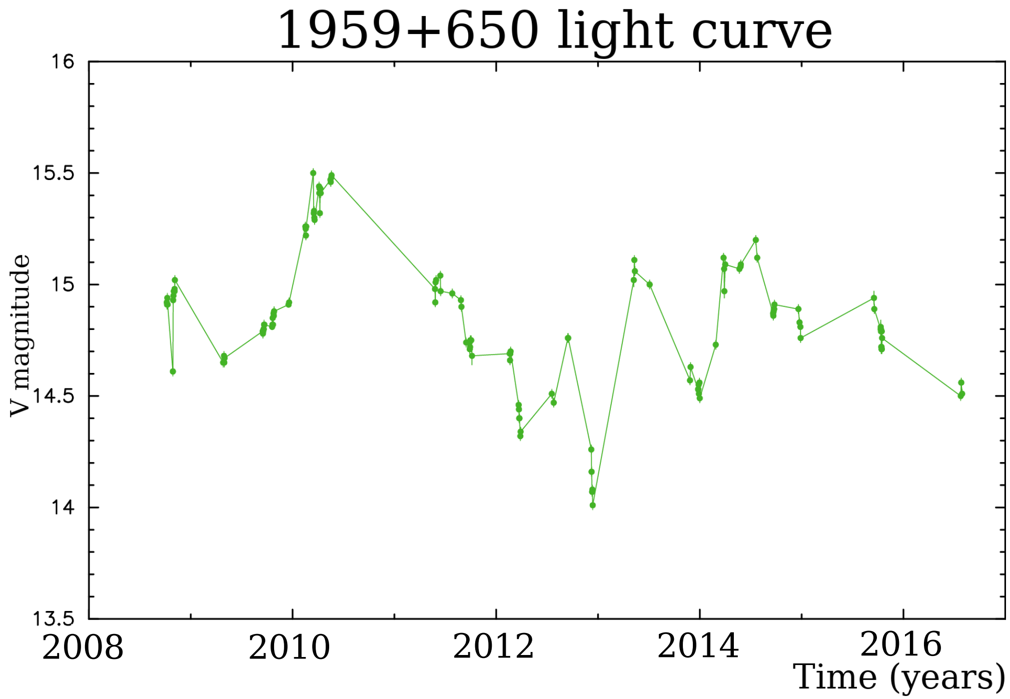
Optical jets interpretation

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

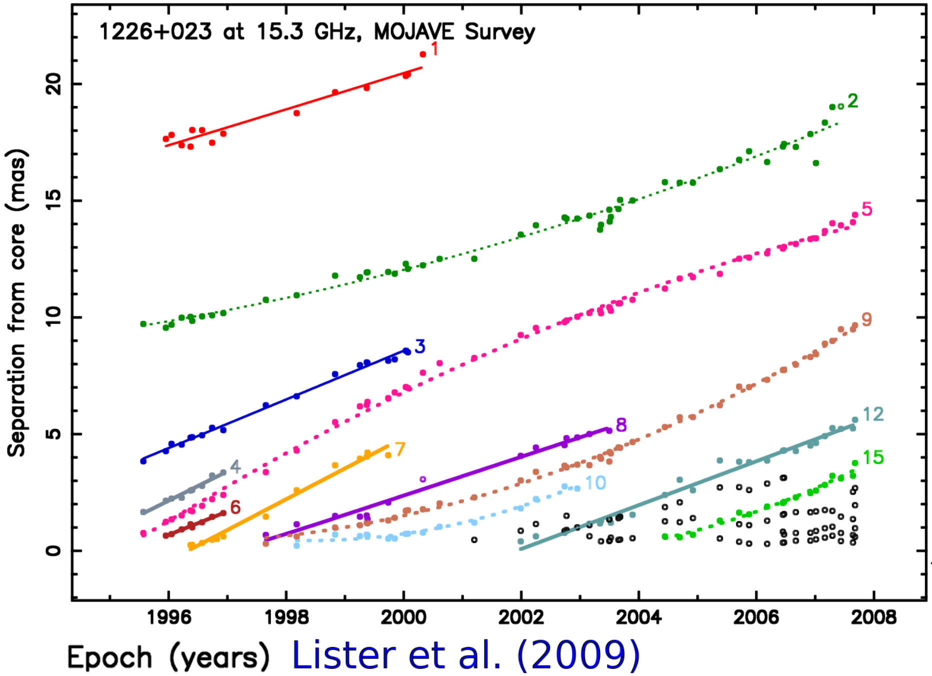
What are observational consequences?

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

1. optical variability and
2. jet kinematics.

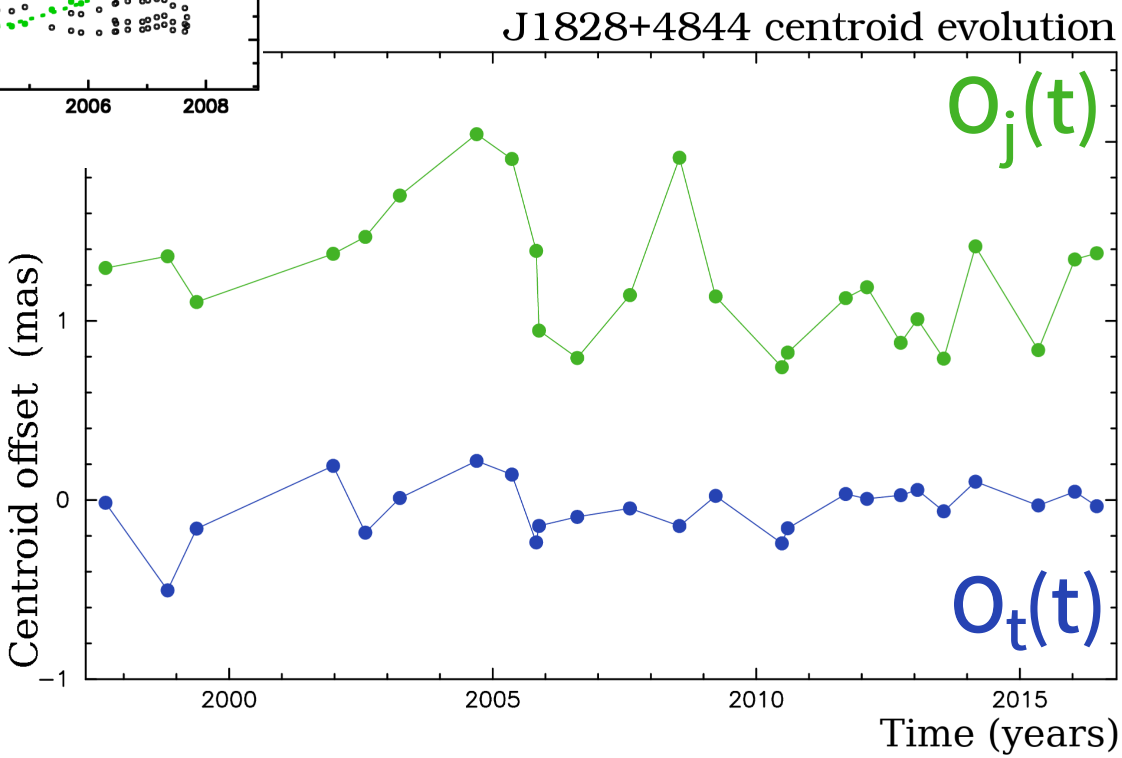


Jet kinematics

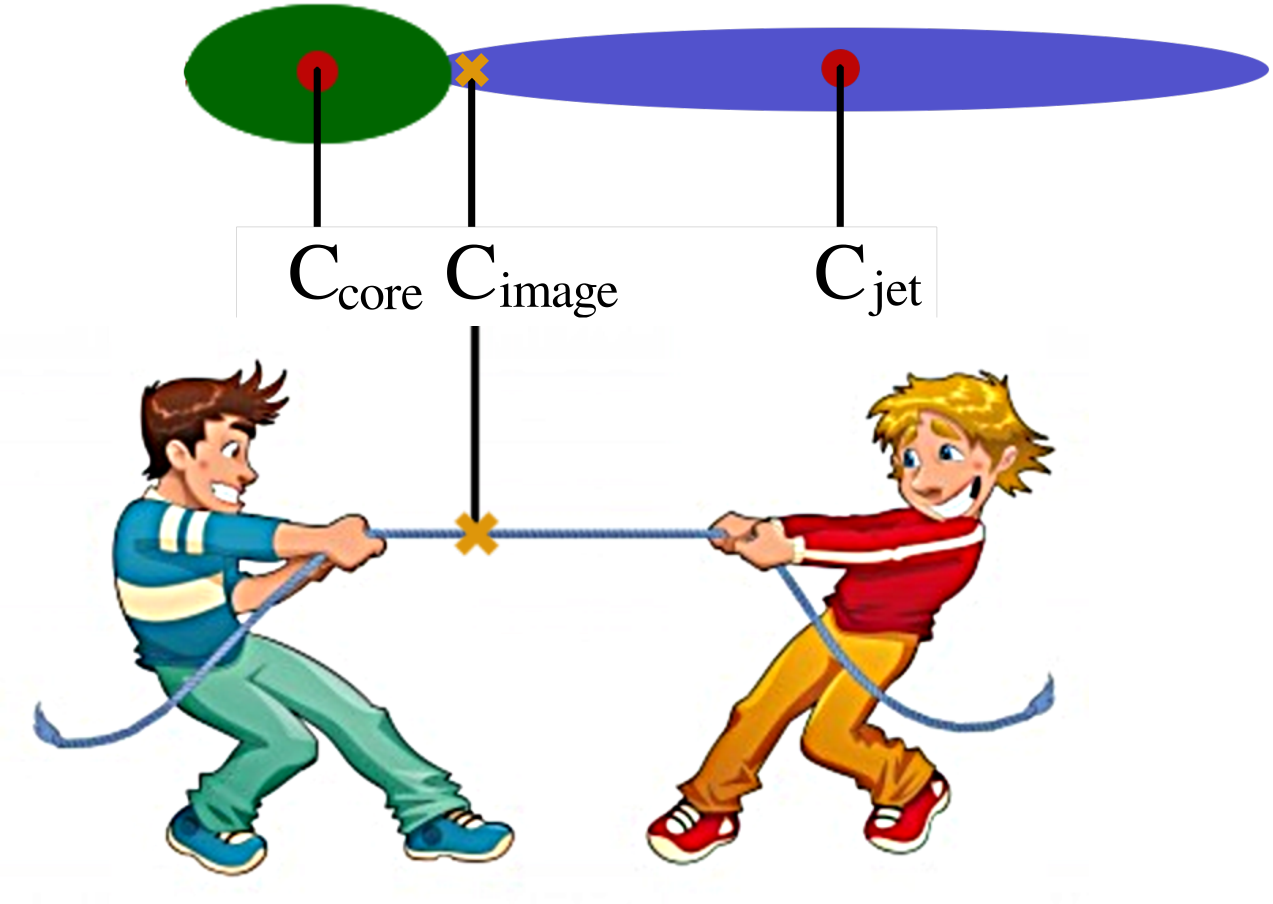


Lister et al. (2009)

Core ejects components,
they are moving,
fainting,
disappearing

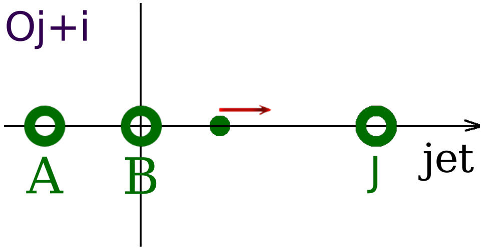


Centroid of a core-jet morphology

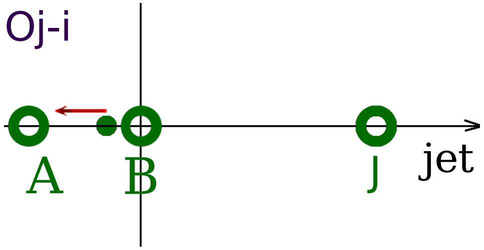


$$C_{\text{image}} = \frac{C_{\text{core}}\, F_{\text{core}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}} + \frac{C_{\text{jet}}\, F_{\text{jet}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}} + \frac{C_{\text{stars}}\, F_{\text{stars}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}}$$

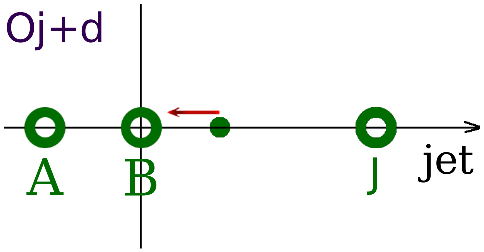
Direction of the centroid change after a flare



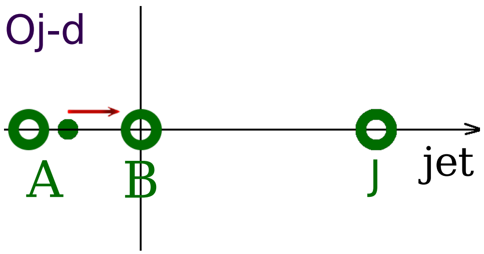
- Flare happened at the jet



- 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

$$C_f(t) = F(0)\,\frac{O_j(t) - O_j(0)}{F(t) - F(0)} + O_j(t)$$

$$F_f(t) = F(0)\,\frac{O_j(0)}{C_x(t)}$$

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

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

Not solvable without a use of addition information

3. ## Two-component non-stationary case

$$
\begin{aligned}
F_j(t) &= \frac{O_j(t)\,F_t(t) - O_j(t_b)\,F_t(t_b)}{v\,(t-t_b)} + F_j(t_b) \\
F_c(t) &= F_t(t) - F_j(t_b) \\
d_j(t) &= d(t_b) + v(t-t_b)
\end{aligned}
$$

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, $O_j(t)$, $O_t(t)$, strong remedy: centroid modeling, determination of the invariant core;

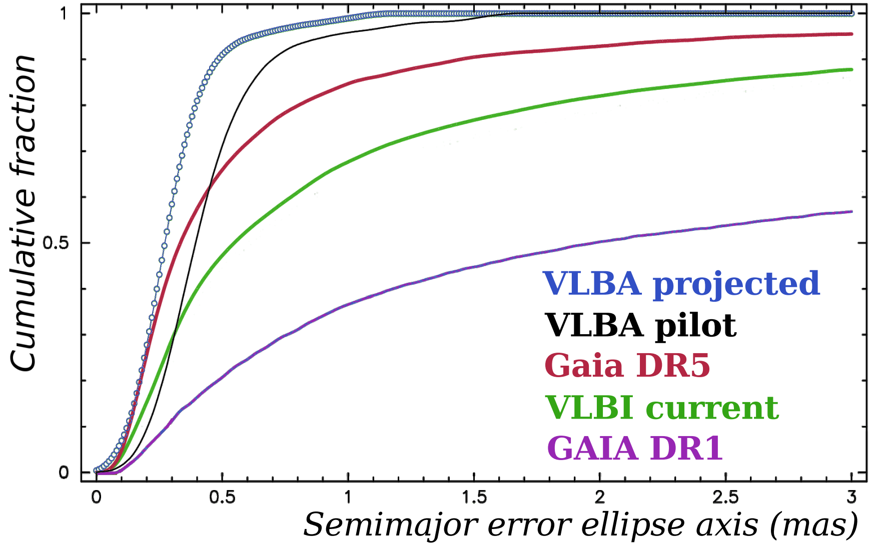
- AGNs without detected parsec-scale emission:

  determination of jet direction for position jitter;

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

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 ~ 2000 matches at $\delta < -40^\circ$, get jet directions. Goal: 0.4 mas. Status: approved.

- Imaging peculiar VLBI/Gaia matches with ROBO AO telescope. Status: ongoing.

- Getting spectra of peculiar VLBI/Gaia matches. Status: pilot.

Summary:

- VLBI/Gaia residuals have systematics 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;
- Can determine the region of optical flares its kinematics and its flux density.

References: arxiv.org/abs 1611.02630, 1611.02632, 1870281
http://astrogeo.org/rfc