AGN physics from synergism of Gaia and VLBI absolute astrometry

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Astrometry is a foundation of astronomy:

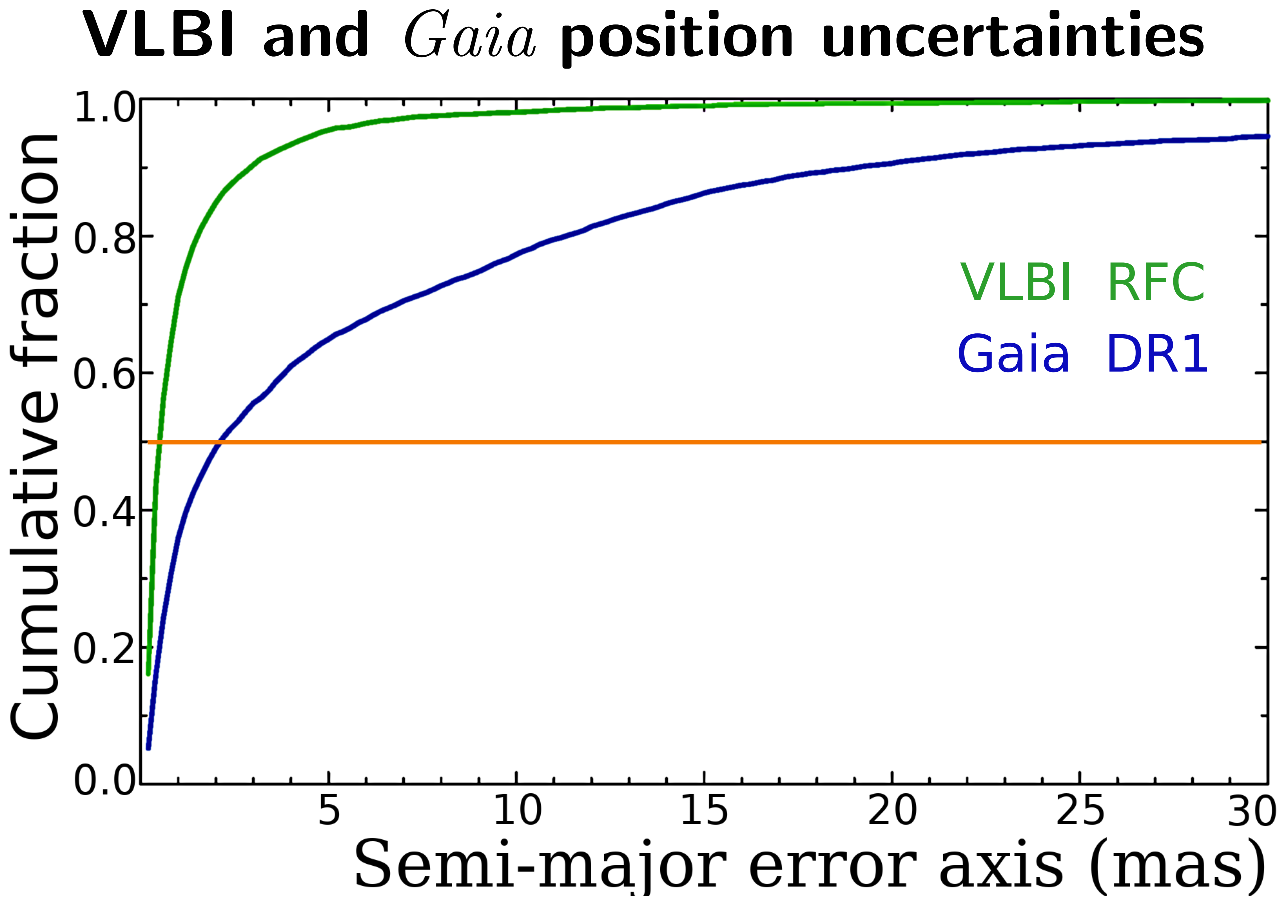
Foundation (astrometry):

Palace (physics):

How to build a palace on the foundation?

Is there anything which is more precise than *Gaia*?

Yes! — VLBI

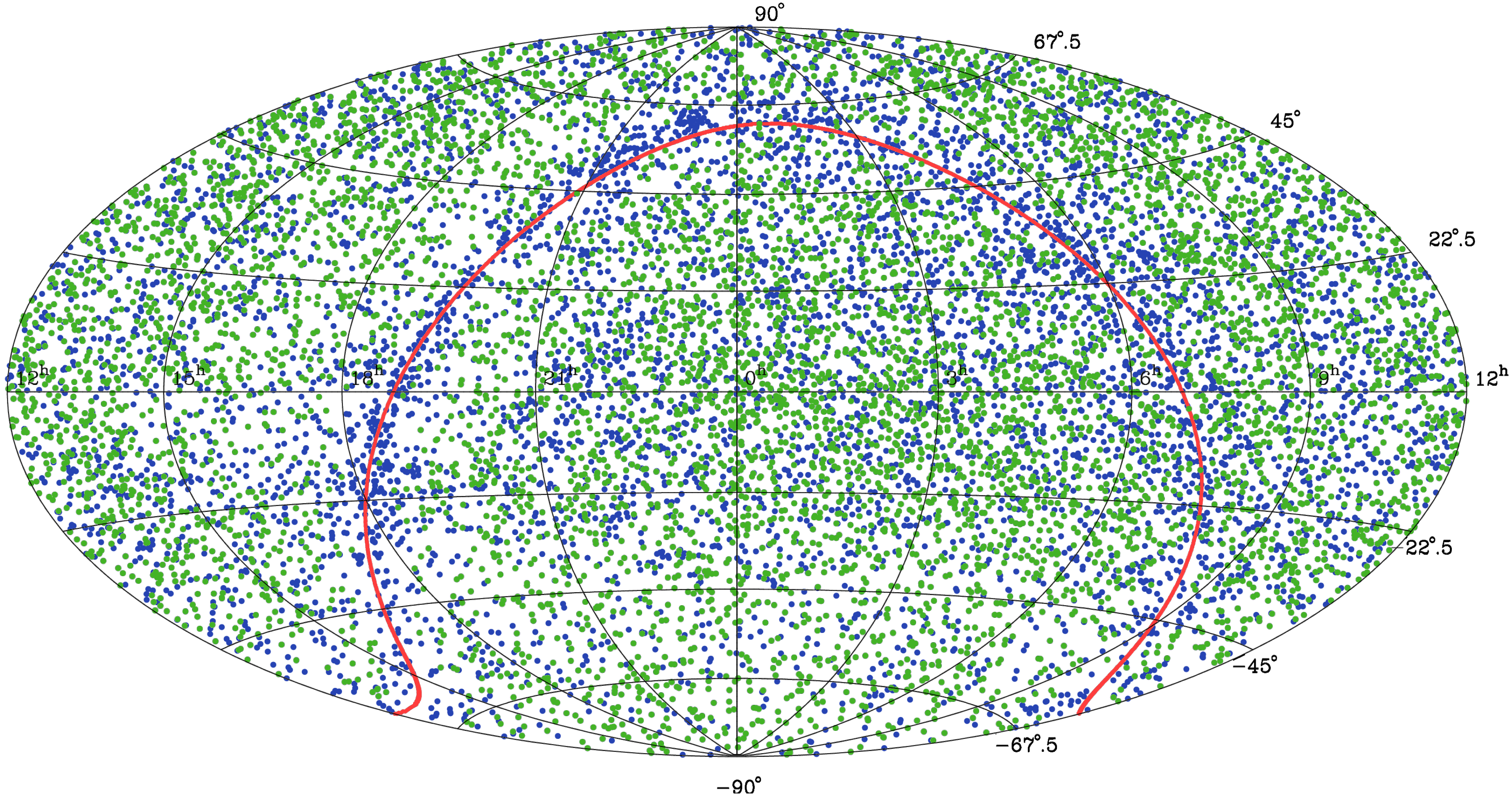


Median error: **VLBI RFC**: 0.5 mas

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

VLBI/*Gaia* comparison

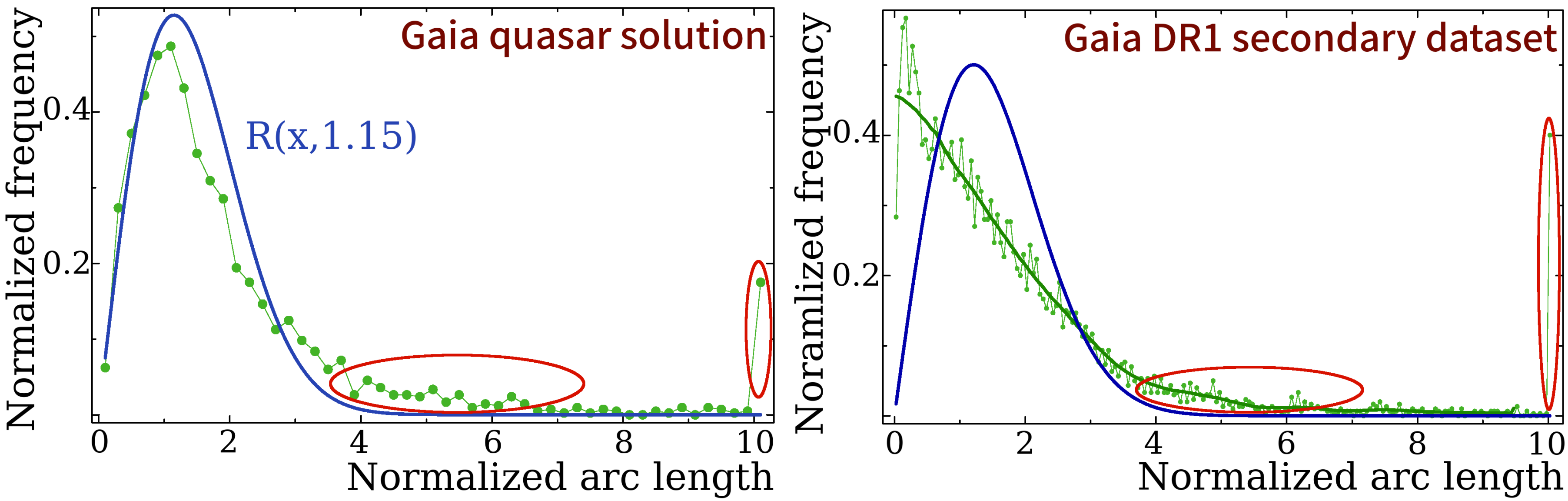
VLBI Radio Fundamental Catalogue (**14,786 sources**) on 2018.03.01 and *Gaia* DR1 ($1.14 \cdot 10^9$ objects)



Green: 7,716 VLBI/*Gaia* matches $P < 0.0002$

Blue: VLBI sources without *Gaia* matches

Distribution of VLBI/*Gaia* arc lengths

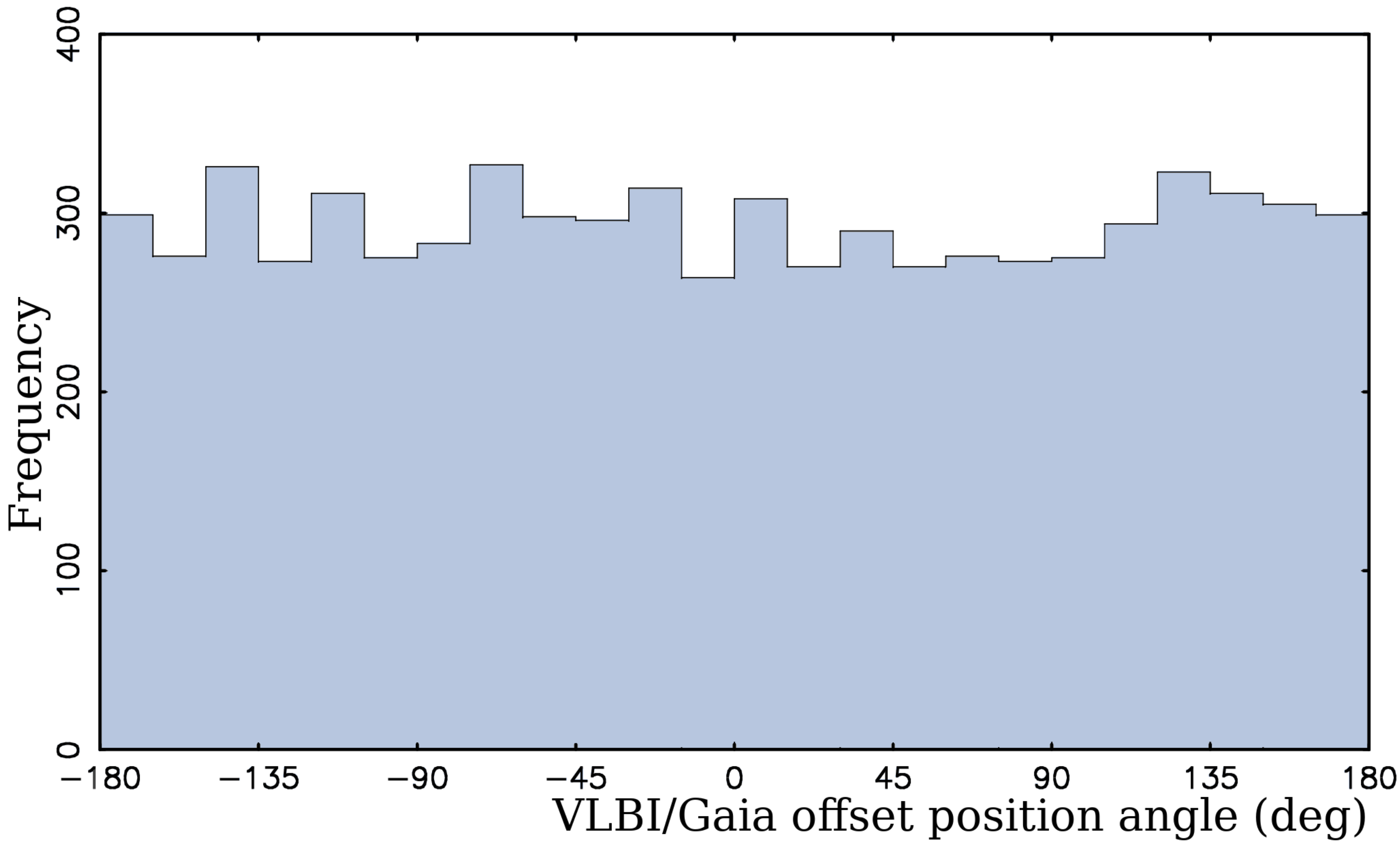


There are **486 outliers** (7%) at significance level 99%.

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

Is that it? What about offset directions?

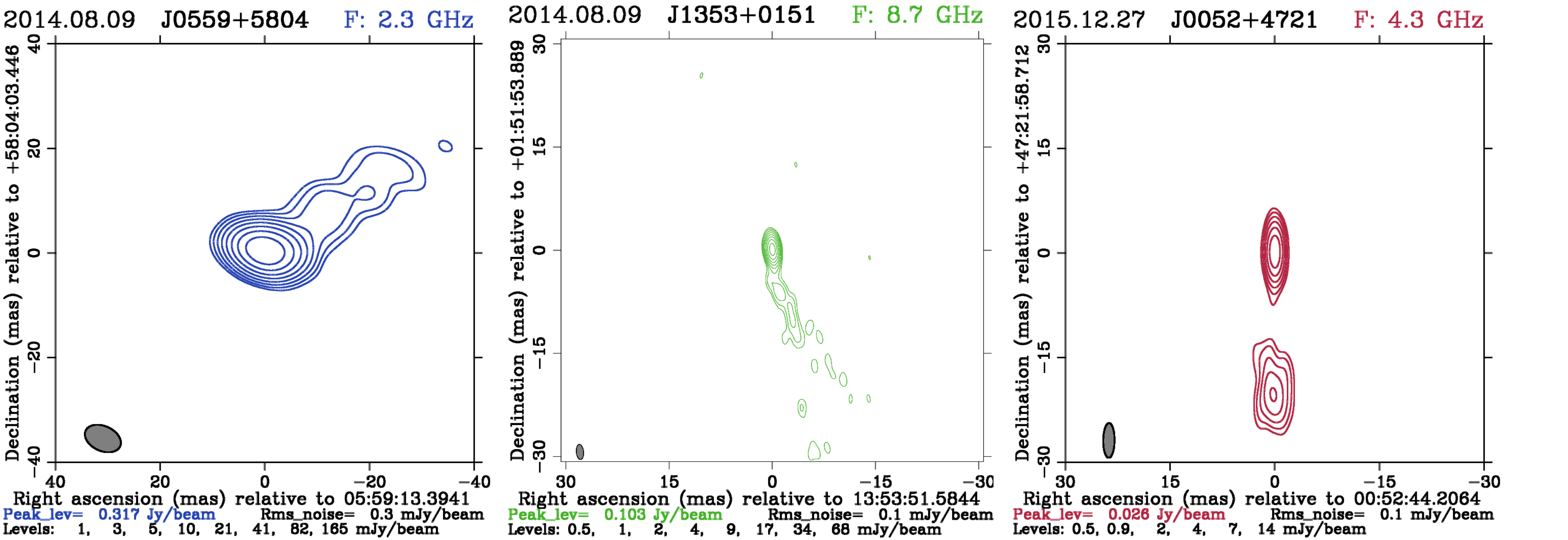
Distribution of VLBI/*Gaia* position offset angles



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?

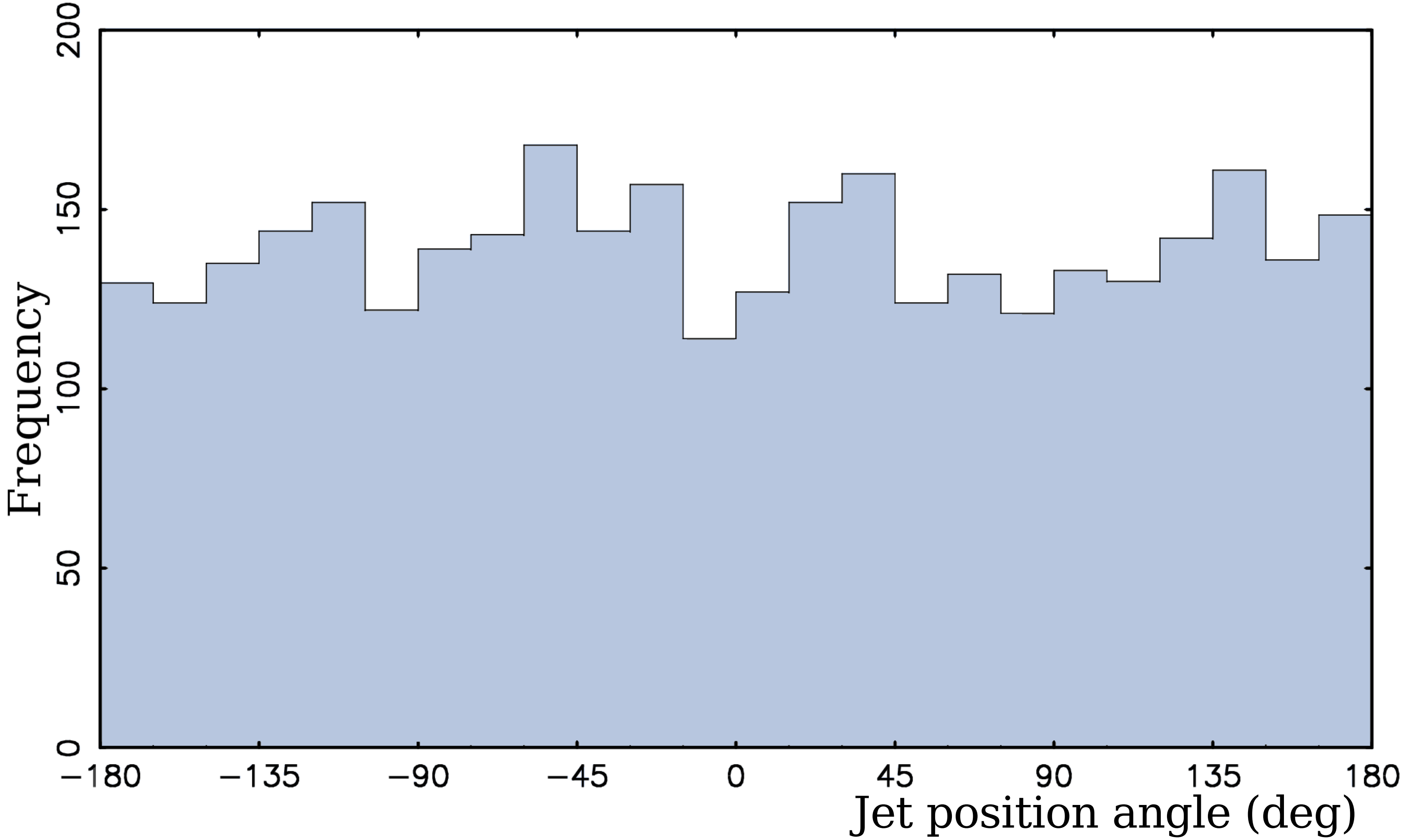
Generic property: core-jet morphology:



- Images are available for 86% sources (the number will increase)
- Jets can be reliably determined at 50% images (the share will raise)

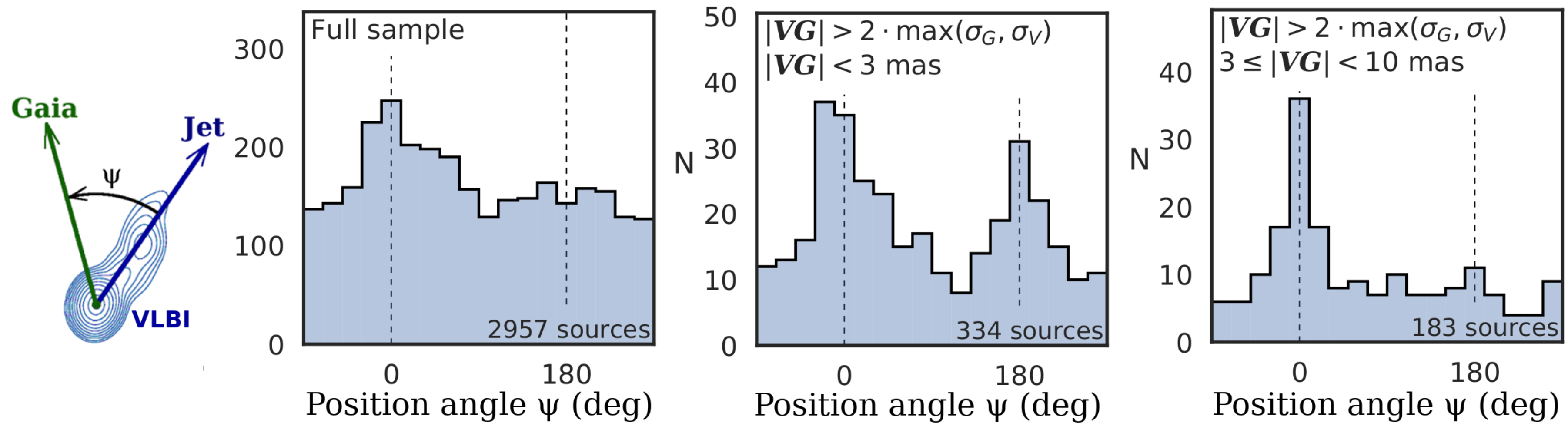
AGNs are intrinsically asymmetric sources!

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.

Systematic effects:

- Contribution of core-shift to dual-band positions: 0.02–0.05 mas.
- Contribution of source structure to VLBI positions: median 0.06 mas.
- Contribution of optical structure: may reach mas level.

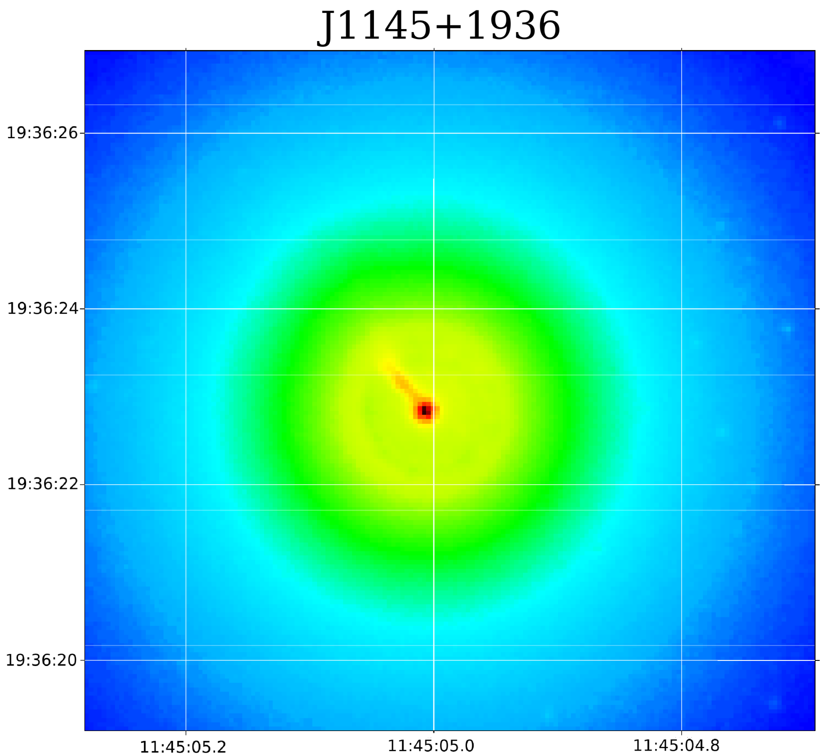
Interferometer (**VLBI**) and a power detector (*Gaia*) have a fundamentally different response to source structure.

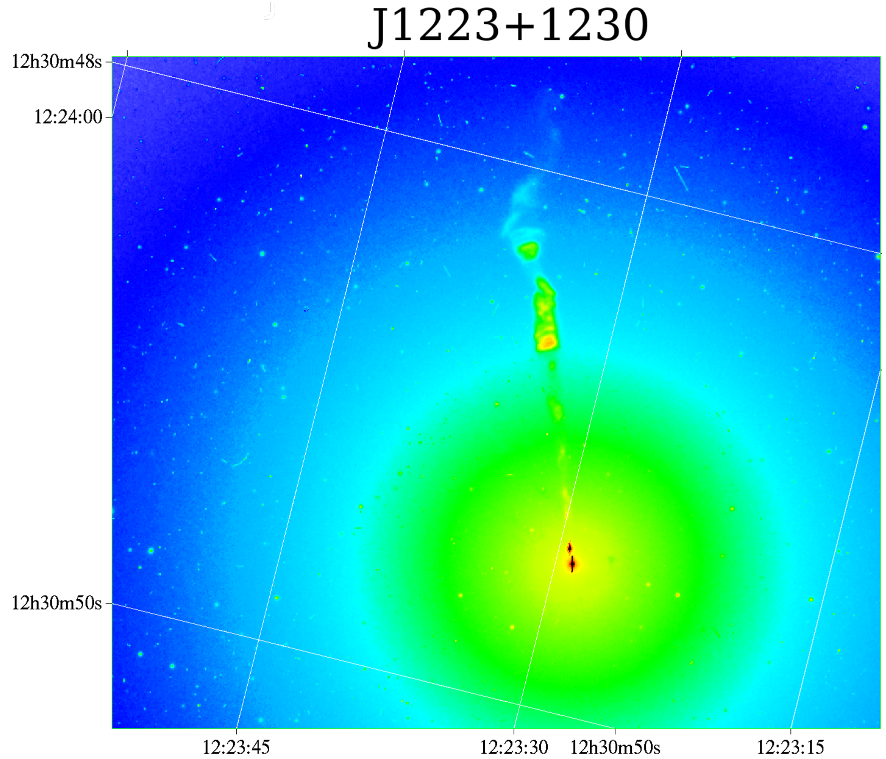
- **VLBI:** Sensitive to the position of the most compact component
- *Gaia*: Sensitive to the position of the centroid

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

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

Making science from VLBI/*Gaia* offsets

1. we establish discrepancy **VLBI**/*Gaia*;

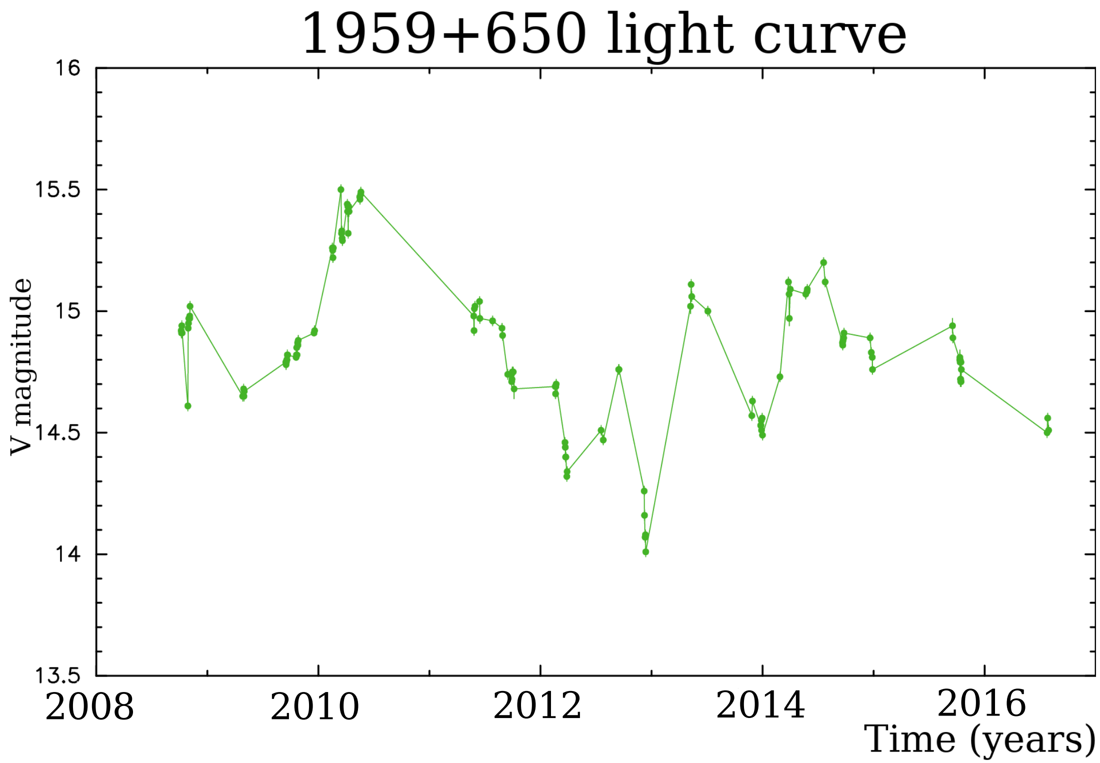
2. we formulate a hypothesis:
   optical jets at 1–100 mas scales are omnipresent;

3. we deduce verifiable predictions:
   - histogram of position offsets ψ will become clearer (**in 41 days**);
   - offset between AGN positions in polarization $\perp$ jet (**1–2 years**);
   - jitter in AGN *Gaia* positions (**late 2022**).

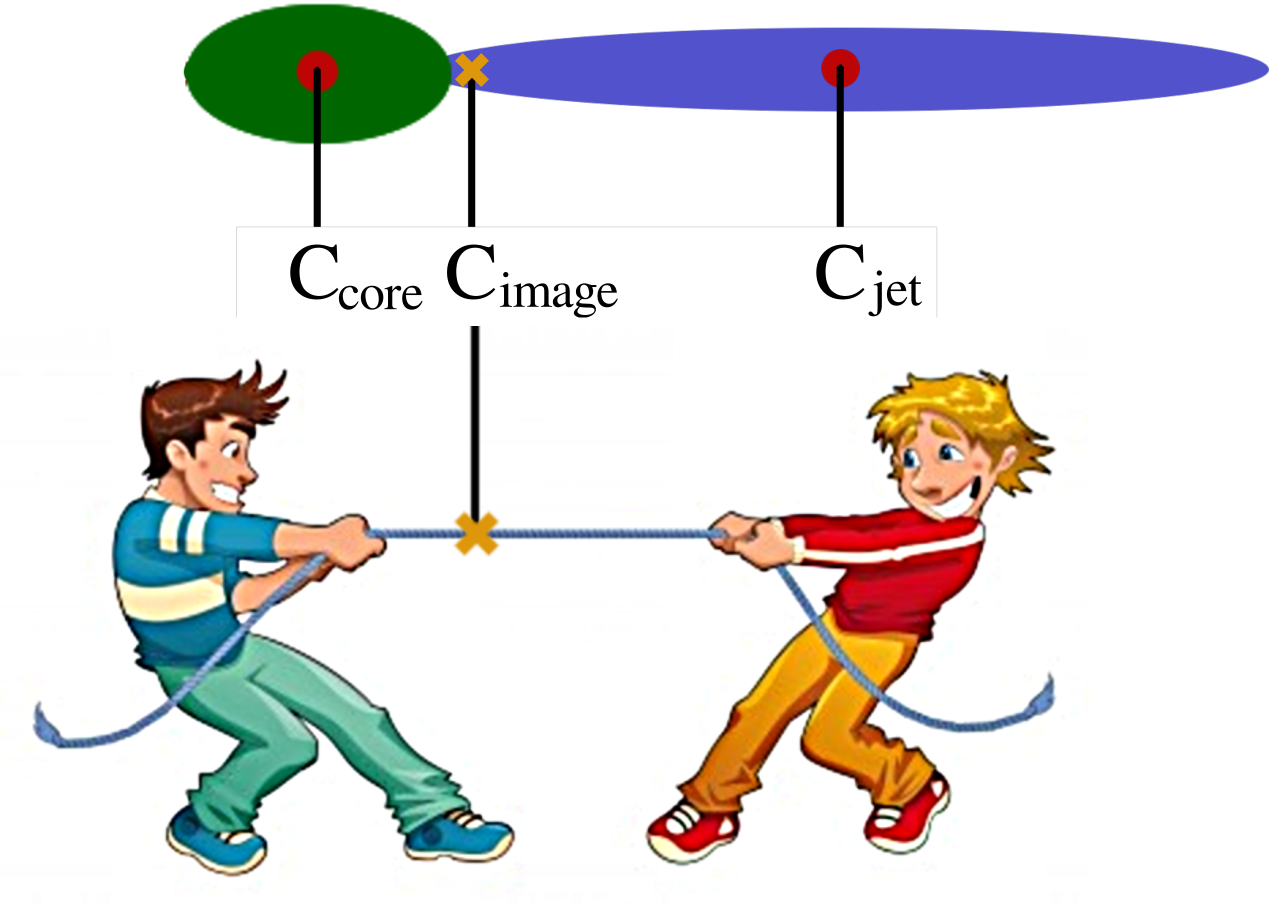
Impact of AGN variability

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

1. optical variability and
2. jet kinematics.

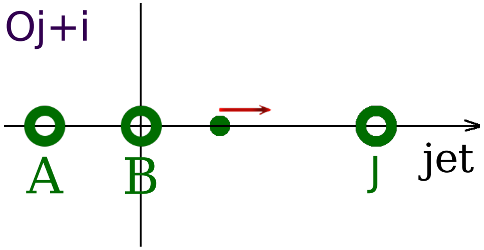


Centroid of a core-jet morphology

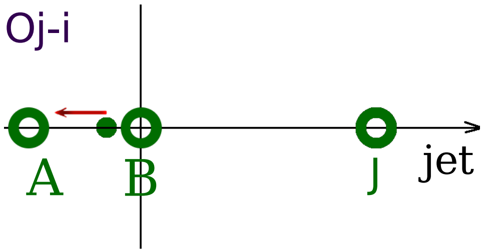


$$C_{\text{image}} = \frac{C_{\text{core}}\, F_{\text{core}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}} + \frac{C_{\text{jet}}\, F_{\text{jet}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}} + \frac{C_{\text{stars}}\, F_{\text{stars}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}}$$

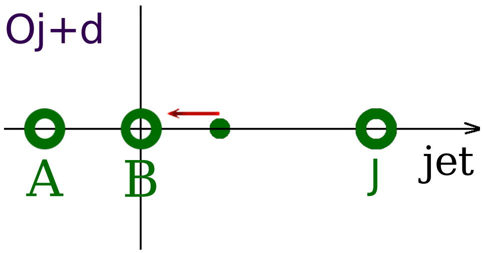
Direction of the centroid change after a flare

- 

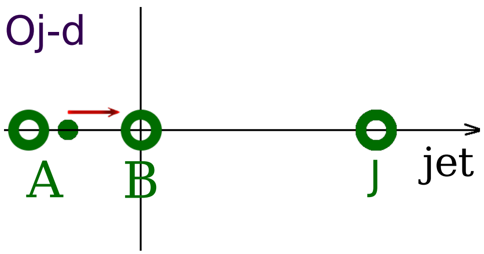
Flare happened at the jet

- 

Flare happened at the accretion disk

- 

Flare happened at the core or accretion disk

- 

Flare happened at the core 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!

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.

Objectives of VLBI/*Gaia* position offset study:

- Are optical jets omnipresent?
- To answer the question: where AGN flares happen:
  - at the accretion disk?
  - at the jet base?
  - at the hot spot on the jet?
- To get estimates of distance between the core jet and the accretion disk
- To measure optical jet dominance
- How optical jet dominance, i.e. presence of strong optical jet affect other AGN properties?
- Does optical jet dominance depend on the AGN class?
- Does optical jet dominance depend on the Doppler factor?
- Does $\mathcal{O}_{\rm j}$ depend on distance?

Summary:

- **VLBI**/*Gaia* residuals have systematics caused by core-jet morphology;
- **VLBI** and *Gaia* have different sensitivity to structure;
- The most plausible explanation: optical jets at scales 1–200 mas;
- Consequence of the optical jet presence: source position jitter;
- Position jitter + light curve = optical resolution at mas scale;
- *Gaia* - VLBI > *Gaia* + VLBI : we can determine the region of optical flares, its kinematics, and its flux density.

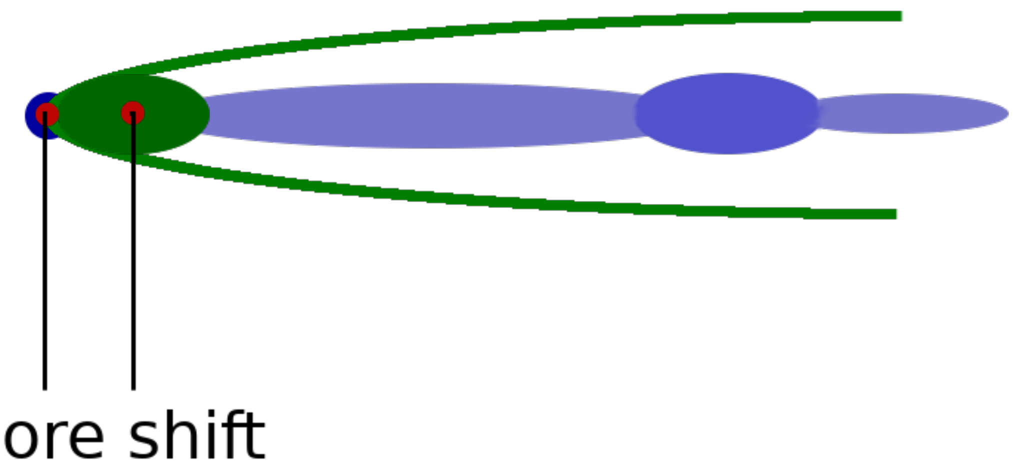
References: arxiv.org/abs 1611.02630, 1611.02632, 1704.07365

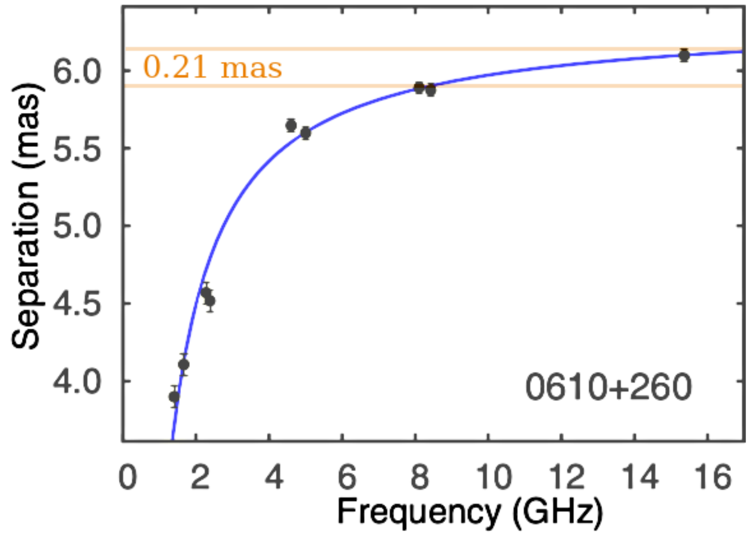
RFC preview: **http://astrogeo.org/rfc**

Backup slides

Core-shift

- Core is the optically thick part of the jet;





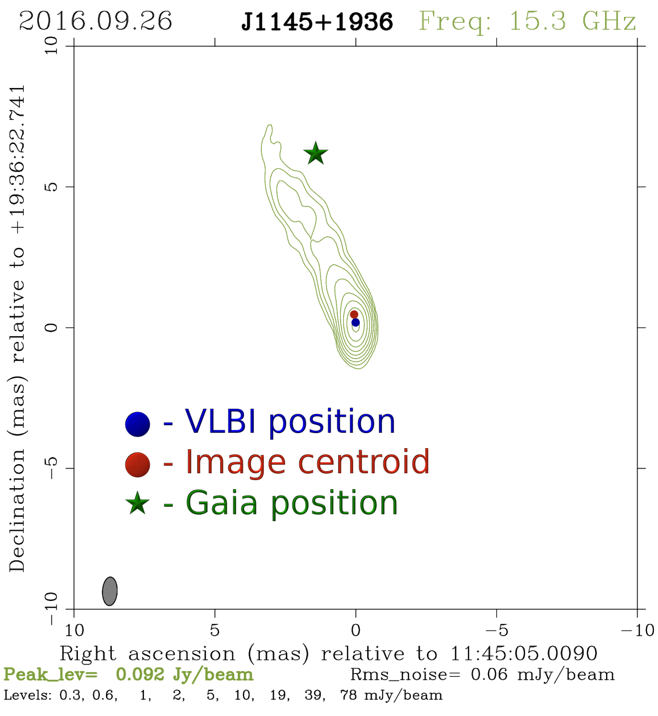
Sokolovsky et al. 2011

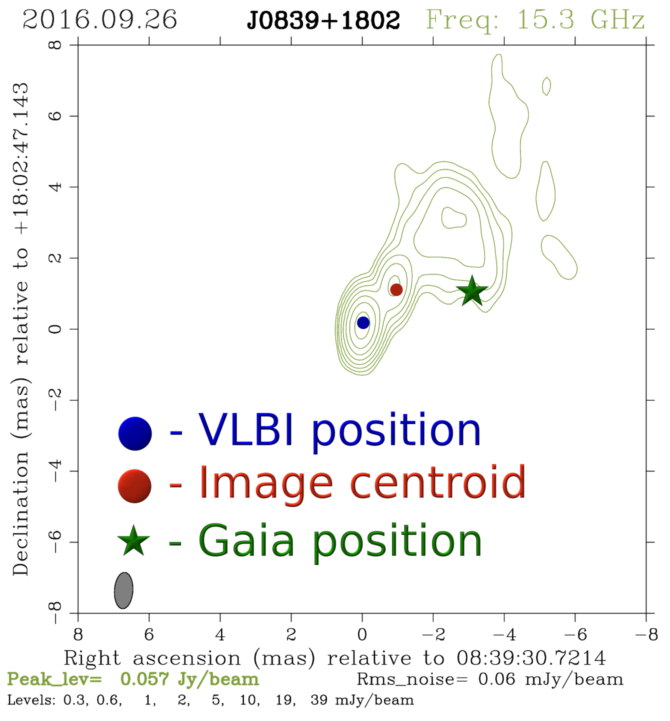
- Core centroid is shifted with respect to the jet base;
- The shift is frequency dependent;
- Results of core-shift measurements:
  - Contribution to 8 GHz positions: ~ 0.2 mas;
  - Contribution to dual-band positions: 0.02–0.05 mas.

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:



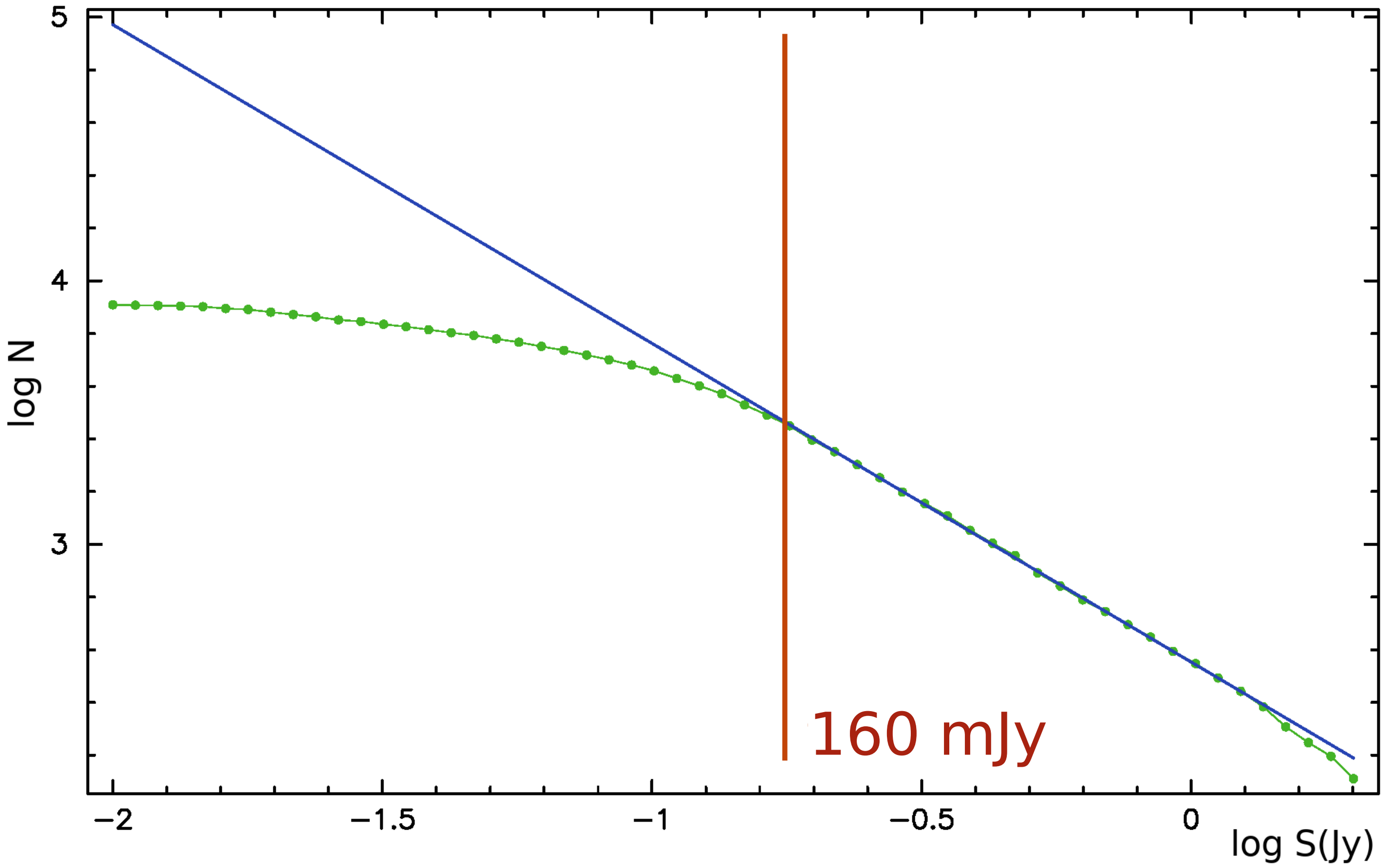


- Test VLBI experiment processed with source structure contribution applied:
  Median VLBI position bias: 0.06 mas
  Median image centroid offset: 0.25 mas

Conclusion: the effect is too small

Completeness of the RFC

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

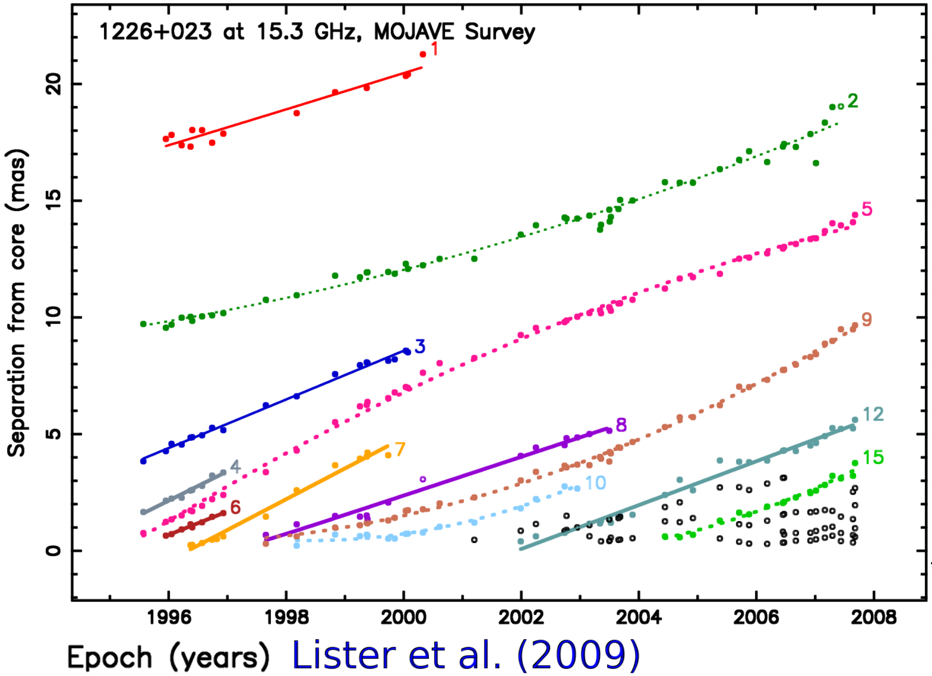


170 mJy 99%
160 mJy 97%
150 mJy 95%
100 mJy 80%
50 mJy 49%
10 mJy 10%

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