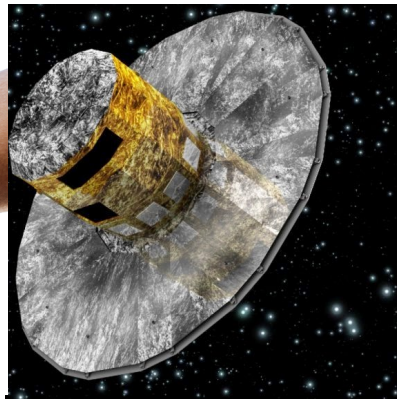
Use of VLBI/Gaia position offsets for AGN physics



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Astrometry is a foundation of astronomy:

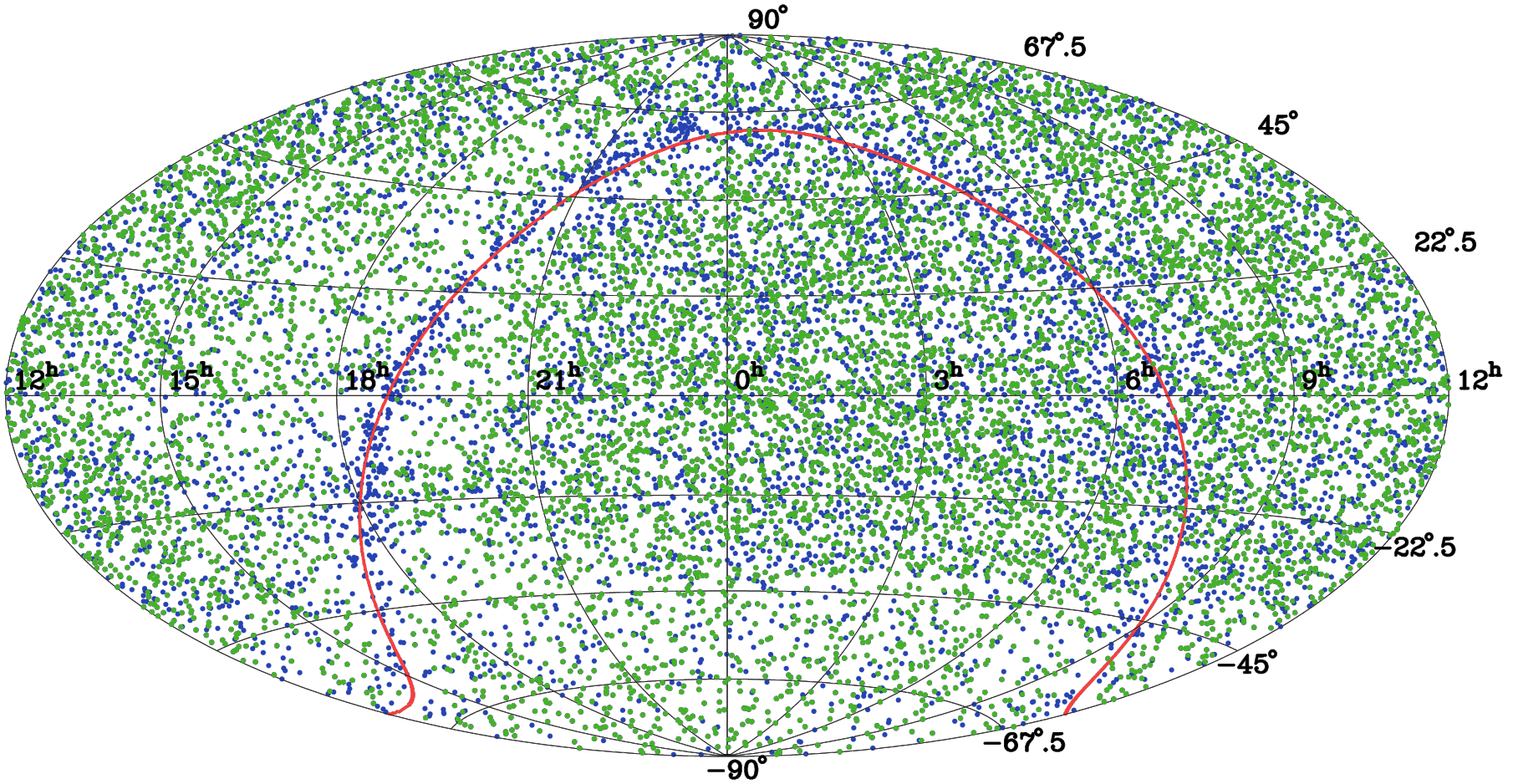
Foundation (astrometry):

Palace (physics):

How to build a palace on the foundation?

VLBI/Gaia comparison

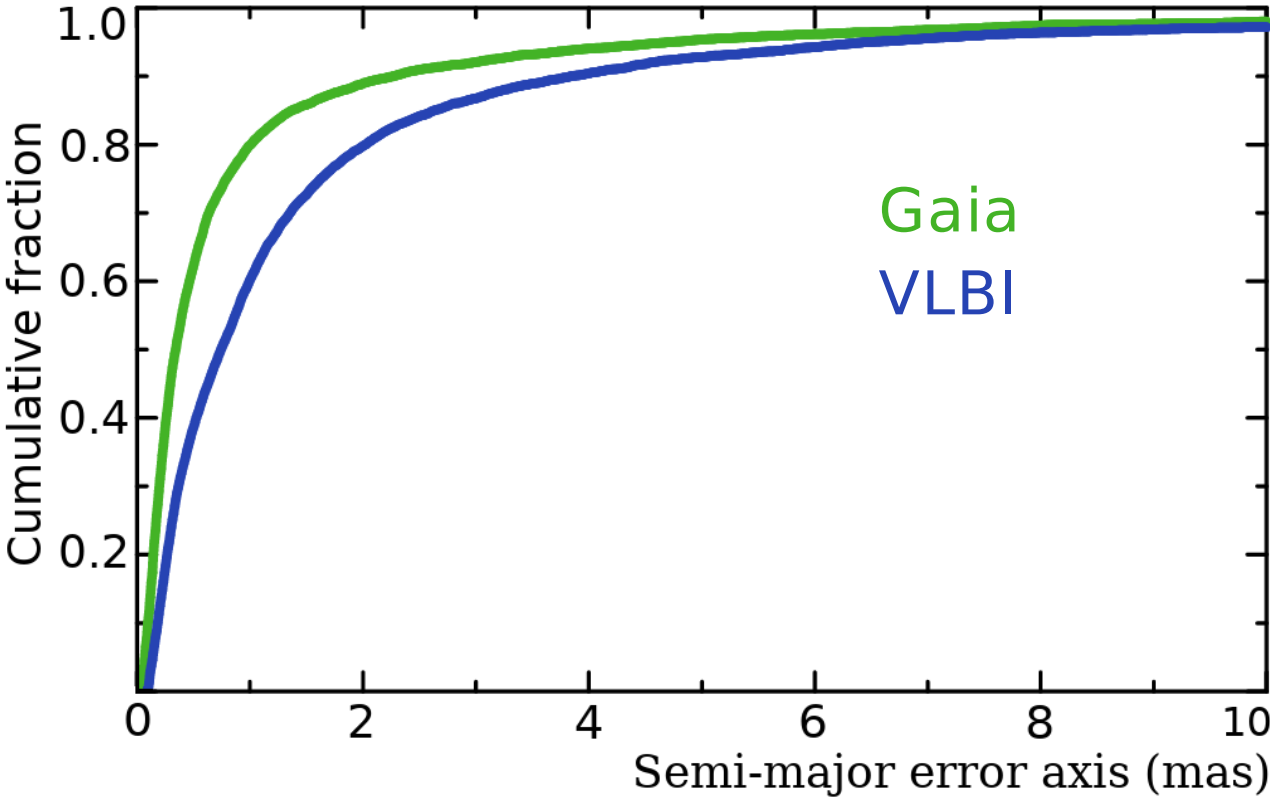
VLBI Radio Fundamental Catalogue (**15,155 sources**) on 2018.09.01 and Gaia DR2 ($1.69 \cdot 10^9$ objects)



Green: 9,081 VLBI/Gaia matches $P < 0.0002$

Blue: VLBI sources without Gaia matches

VLBI and Gaia position uncertainties

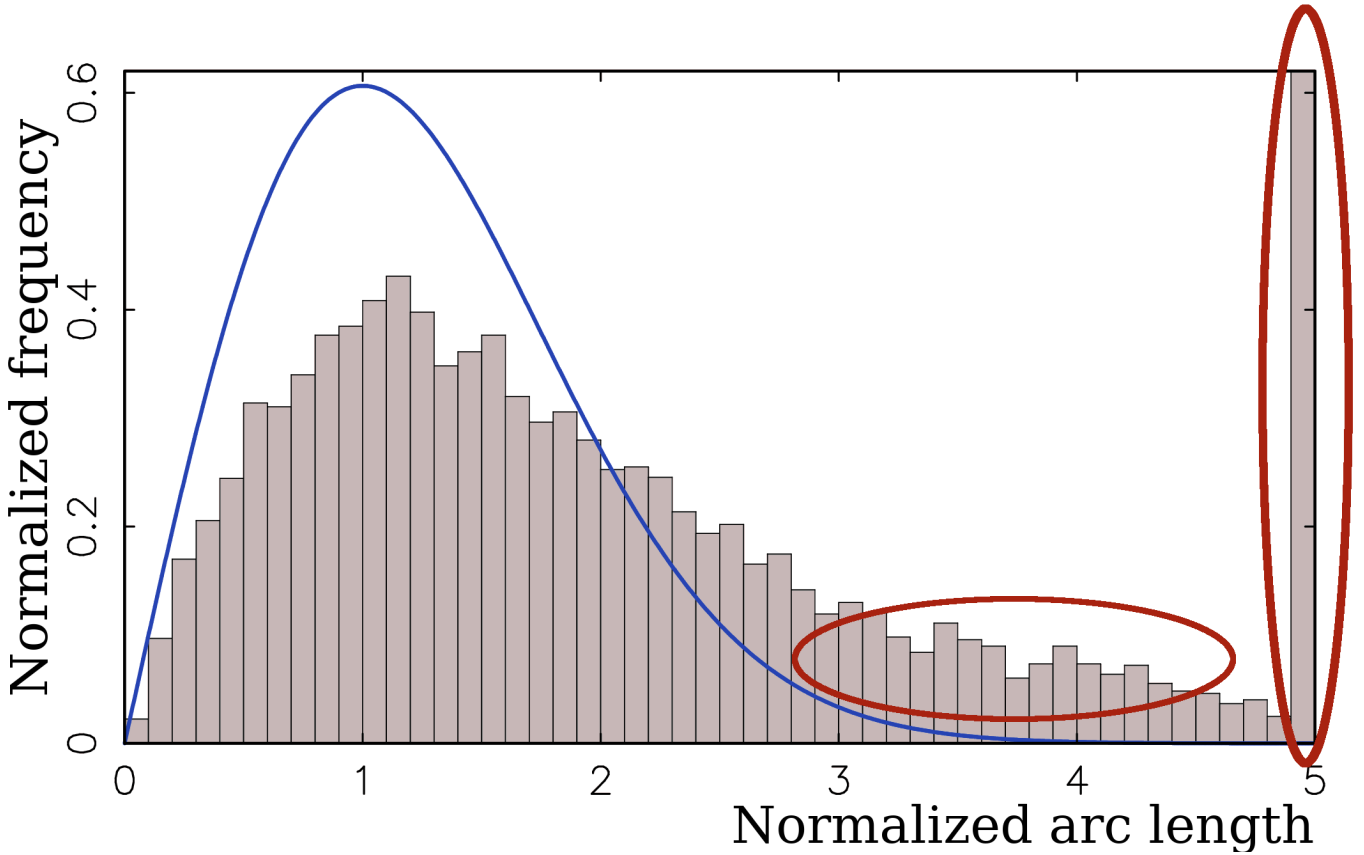


Median error: **Gaia DR2**: 0.34 mas

Median error: **VLBI RFC**: 0.74 mas

VLBI is not a king of absolute astrometry any more!

The distribution of normalized VLBI/Gaia arc-lengths over 9033 AGNs.

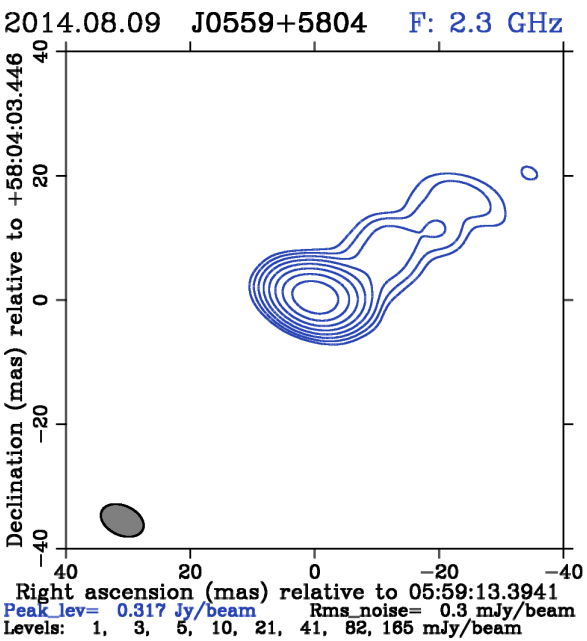


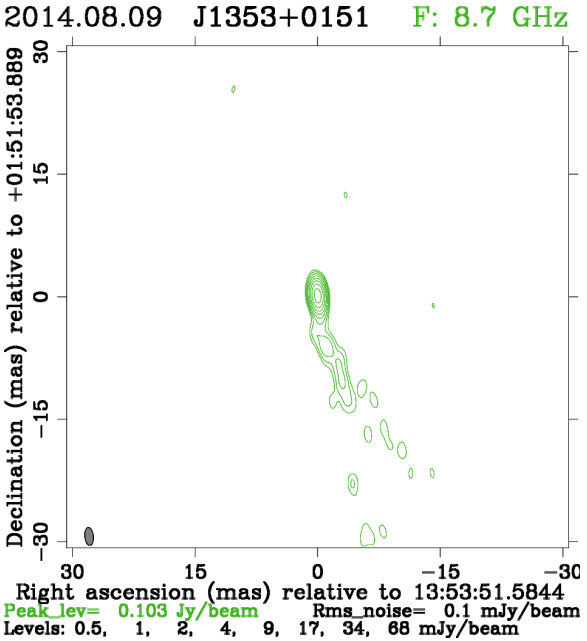
1/6 matched sources are outliers: $a/\sigma_a > 4$

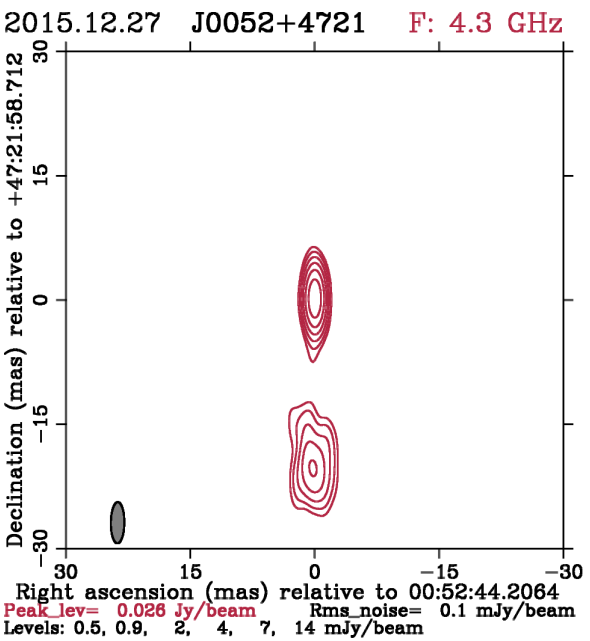
What is there nature?

How the AGNs look like at mas scale?

Generic property: core-jet morphology:



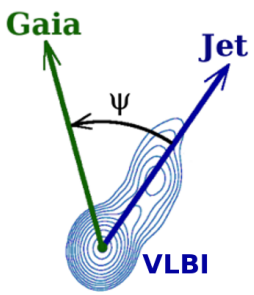


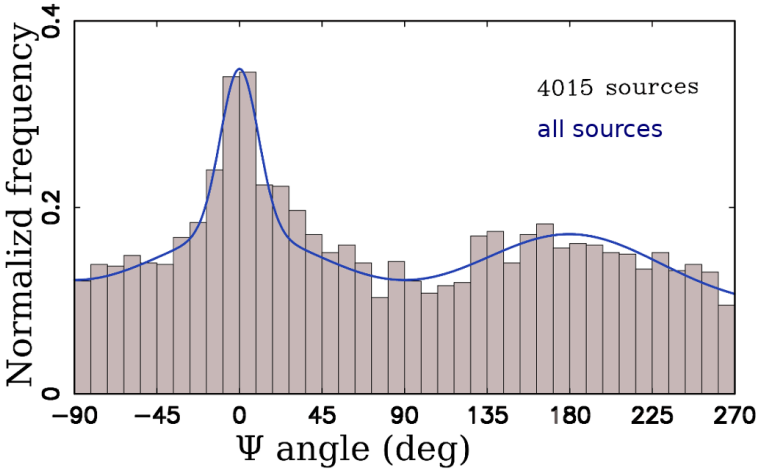


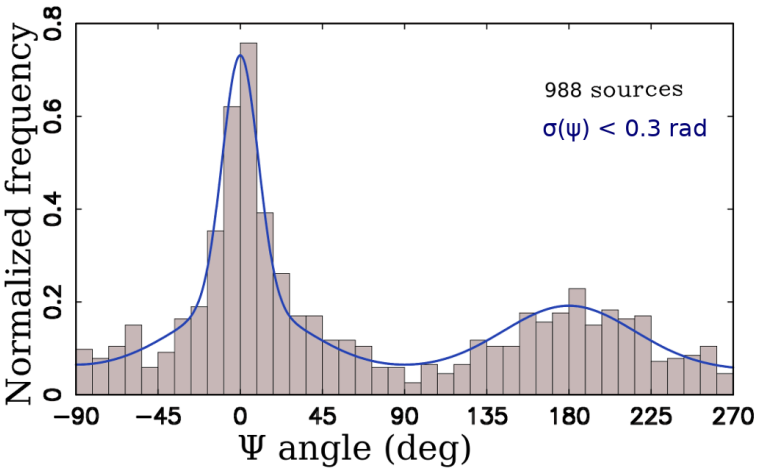
- Images are available for 88% sources (the number will increase)
- Jets can be reliably determined at 45% images (the share will raise)

AGNs are intrinsically asymmetric sources!

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.

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.

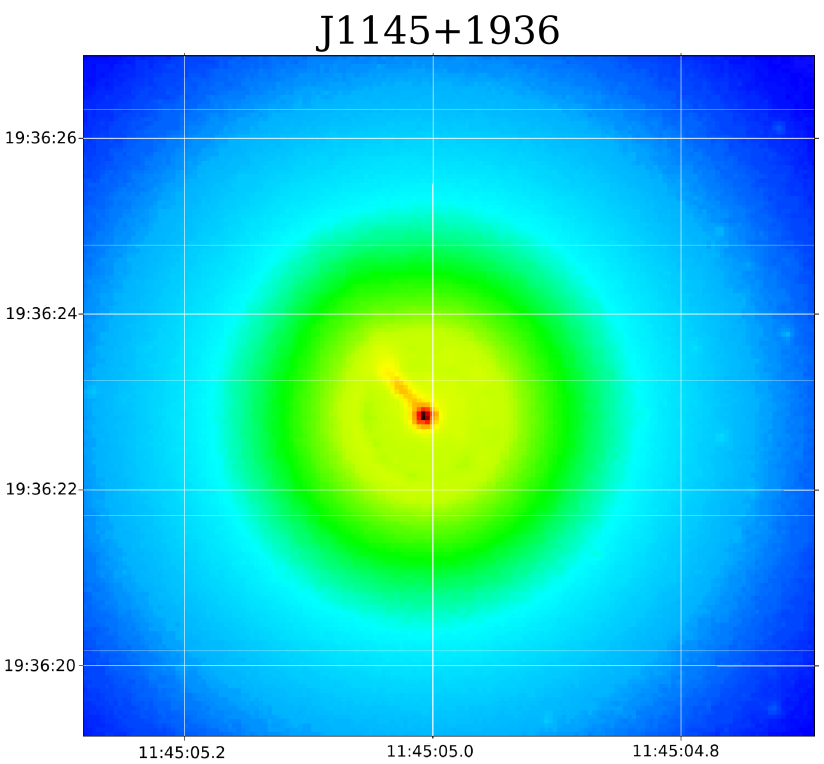
Interferometer (**VLBI**) and a power detector (**Gaia**) have a fundamentally different response to source structure.

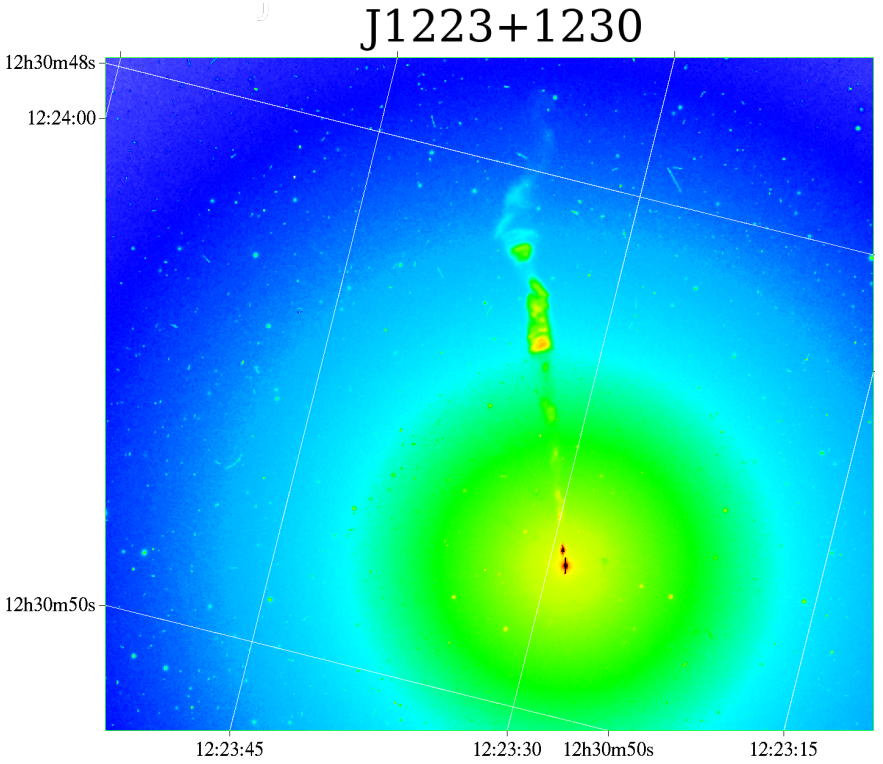
- **VLBI:** Sensitive to the position of the most compact component
- **Gaia:** Sensitive to the position of the centroid

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″



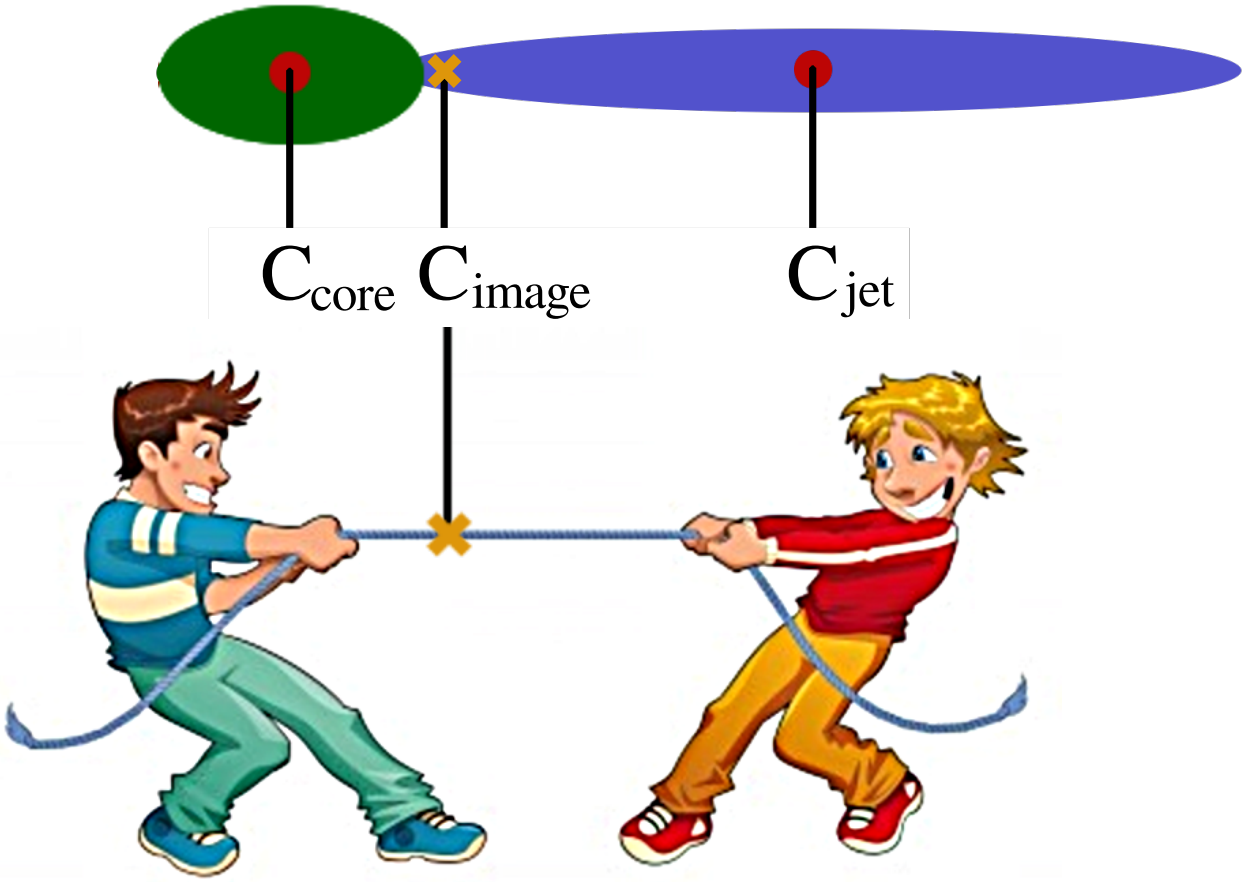


At z=0.07, visible optical jet of J1145+1936 would shift centroid at 5 mas

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

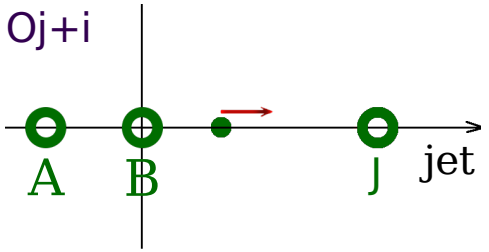
Conclusion: known optical jets at farther distance can cause centroid shifts at 1–2 mas level

Centroid of a core-jet morphology

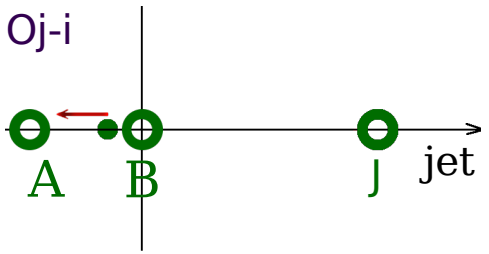


$$C_{\text{image}} = \frac{C_{\text{core}}\,F_{\text{core}}}{F_{\text{core}}+F_{\text{jet}}+F_{\text{stars}}} + \frac{C_{\text{jet}}\,F_{\text{jet}}}{F_{\text{core}}+F_{\text{jet}}+F_{\text{stars}}} + \frac{C_{\text{stars}}\,F_{\text{stars}}}{F_{\text{core}}+F_{\text{jet}}+F_{\text{stars}}}$$

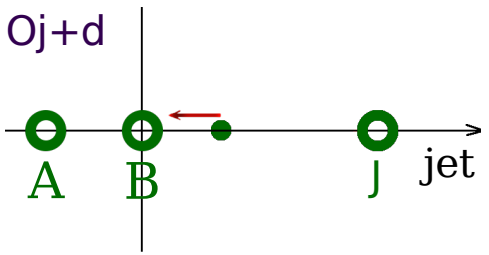
Direction of the centroid change after a flare

- 

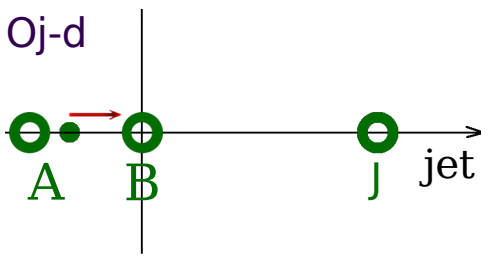
Flare happened at the jet

- 

Flare happened at the accretion disk

- 

Flare happened at the core or accretion disk

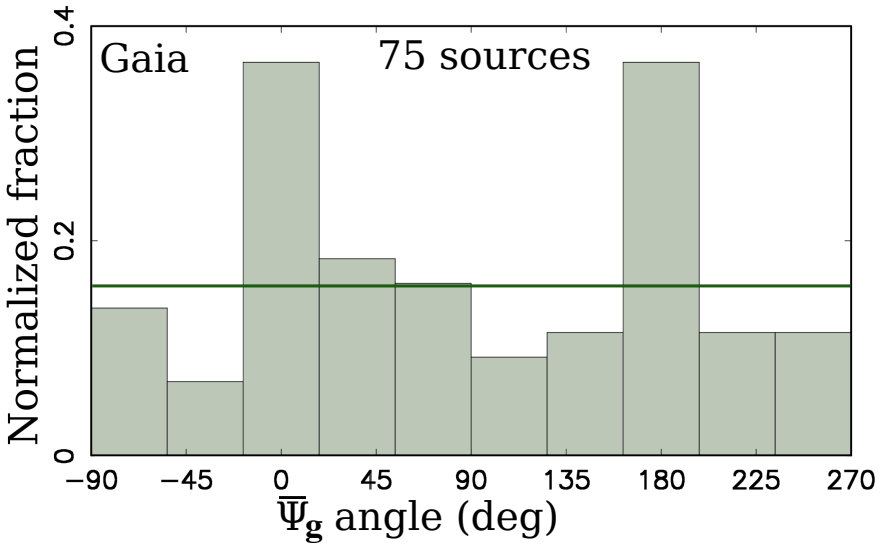
- 

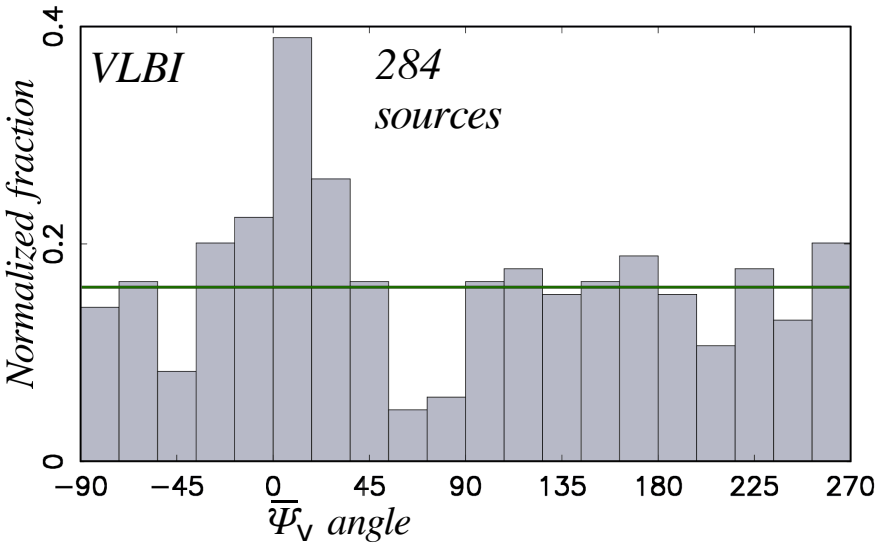
Flare happened at the core or the jet

Consequences of the optical jet interpretation for VLBI/Gaia offsets

1. Astrometry:
   - 1.1. **VLBI** and **Gaia** positions cannot be reconciled
   - 1.2. **Gaia** position accuracy cannot borrowed for radio applications
   - 1.3. A jitter in **Gaia** position is predicted
2. Astrophysics:
   - 2.1. Joint analysis of $\mathcal{O}_{\rm j}$ and Gaia time series will allow
     - 2.1.1. pin-point the region where flares occur
     - 2.1.2. estimate effective size of optic jet and its relative flux
   - 2.2. $\mathcal{O}_{\rm j}$ will correlate with color
   - 2.3. AGN optical image in original polarization wrt jet direction will have an offset

Direction of VLBI and Gaia proper motions





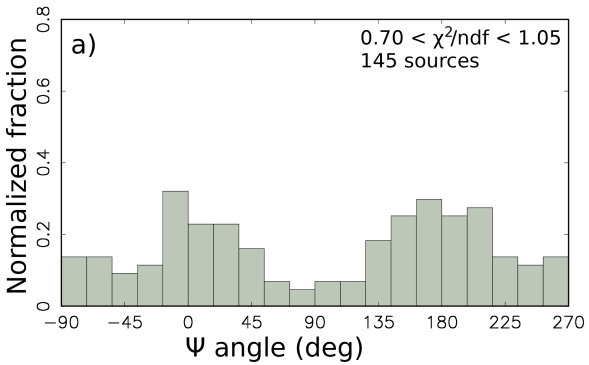
Only proper motions greater 4σ are accounted

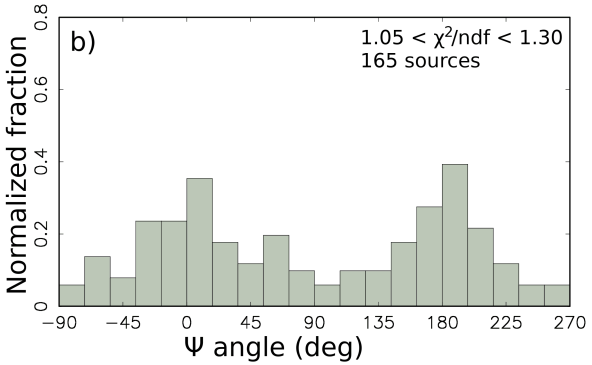
Median proper motions:

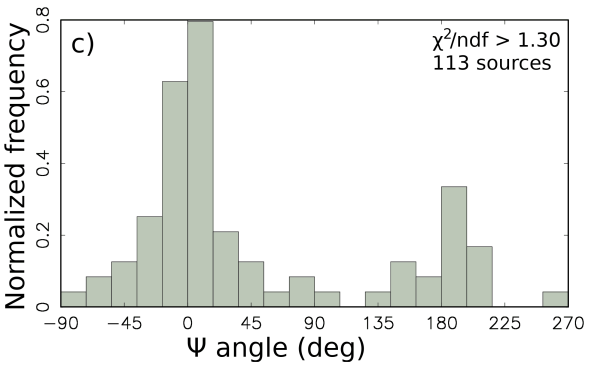
Gaia: 1.2 mas/yr

VLBI: 0.02 mas/yr

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





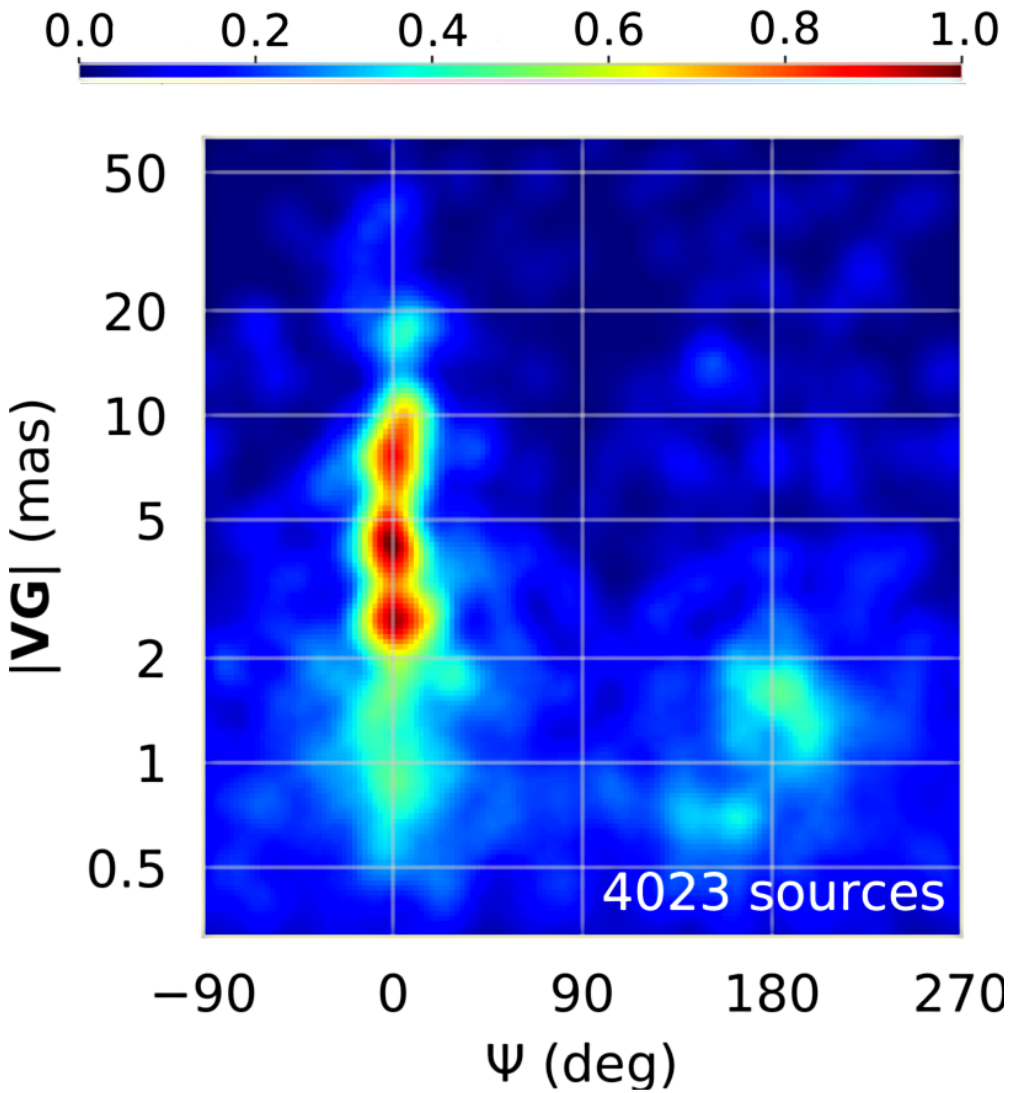


Only sources with $\sigma_{\bar{\psi}} < 0.3$ rad and arc-lengths < 2.5 mas are accounted

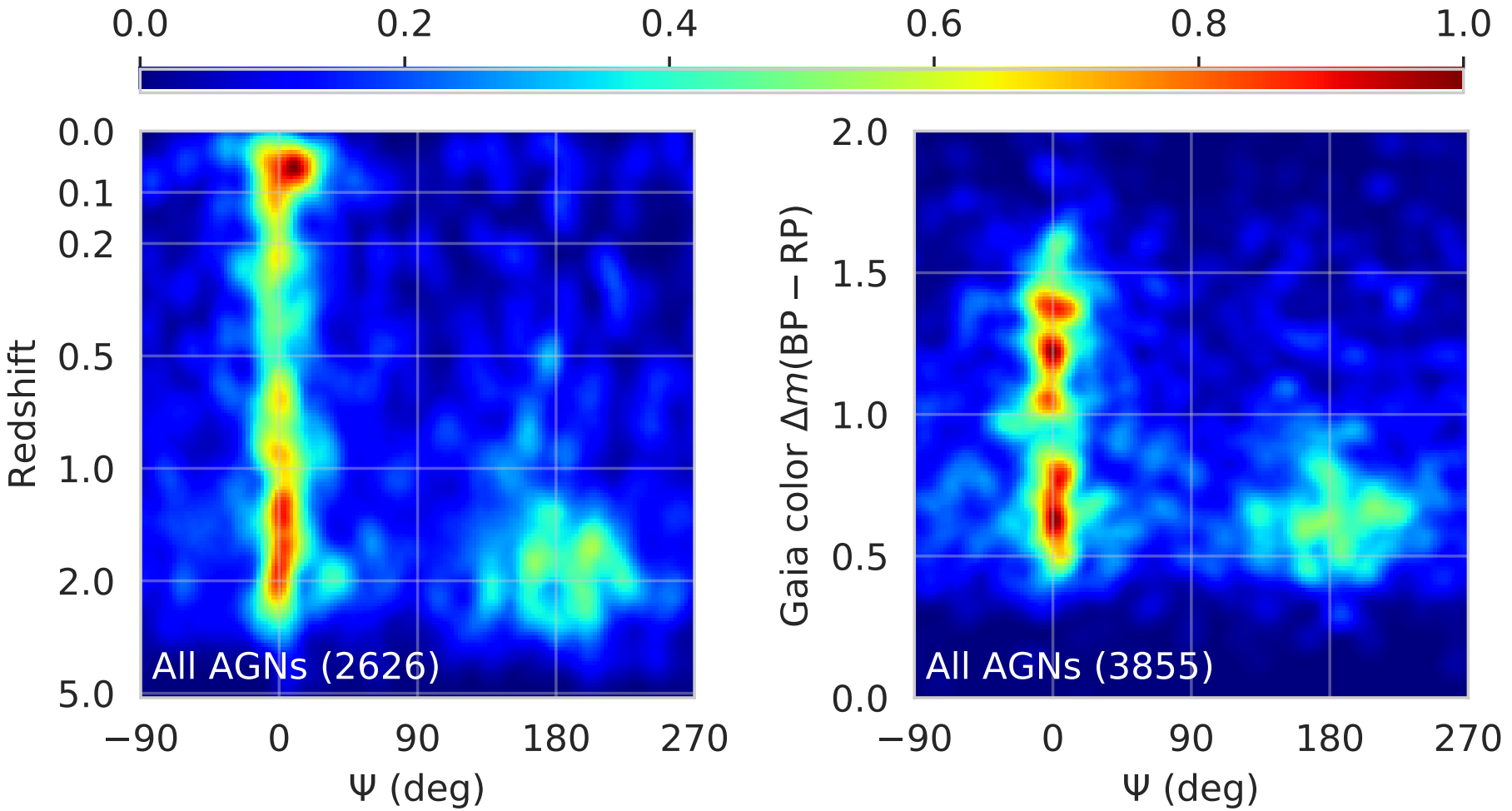
χ^2/ndf is a measure of non-linearity of AGN motion

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

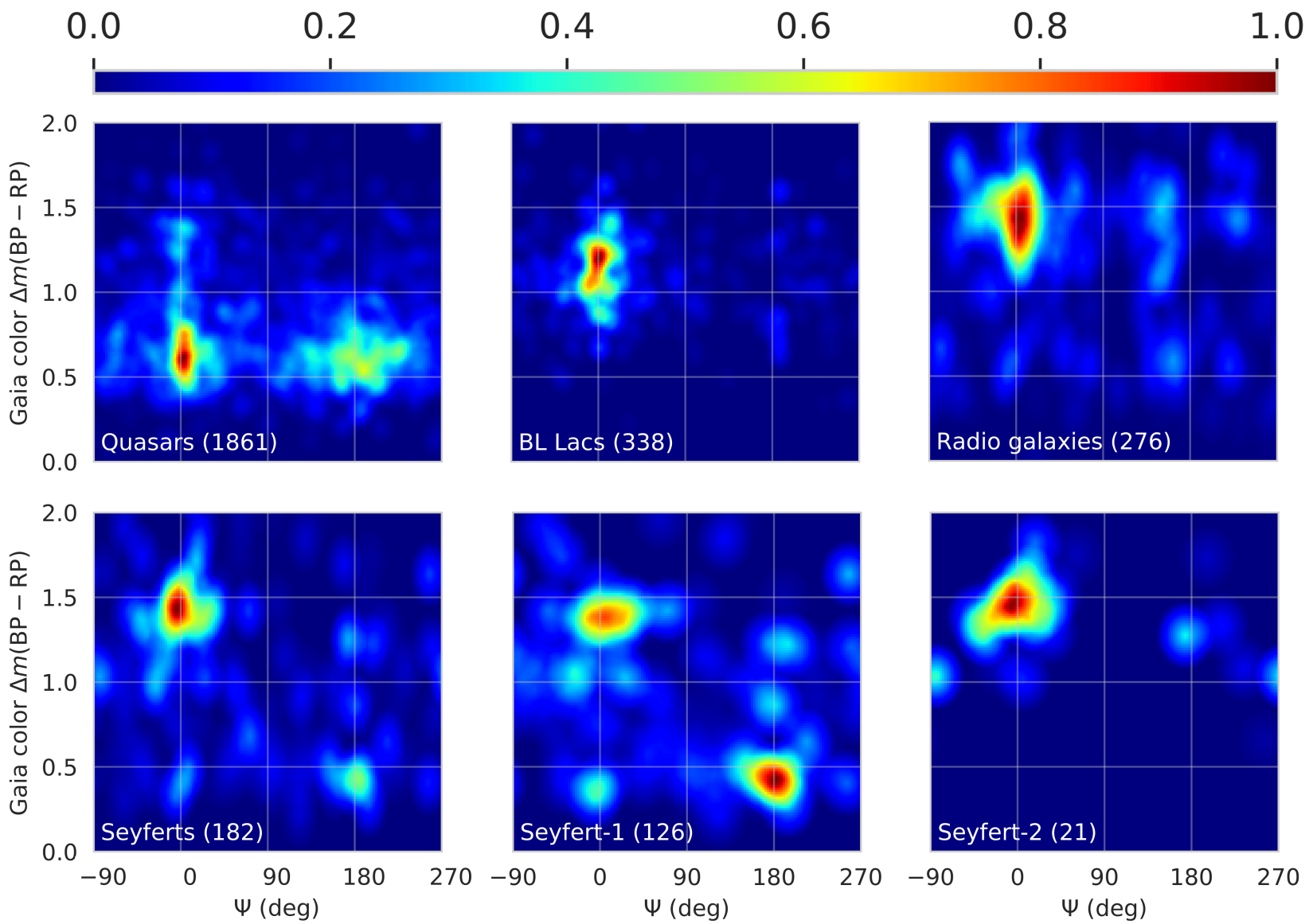
2D Ψ-angle/VG distance distribution



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



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



Conclusions:

- The main reason of VLBI/Gaia 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 different types of AGNs
- Time series VLBI/Gaia offsets will allow pin-point where flare occur
- VLBI/Gaia offset is a new rich observable for AGN physics

References: arxiv.org/abs 1611.02630, 1611.02632, 1704.07365, 1808.05114, 1808.05115

Future work:

- Improve VLBI position accuracy down to 0.2 mas level
- Improve VLBI images to determine jet direction
- Launch spectra-polarimetry observation program
- Correlate Ψ angles with SED at different wavelengths