Physics of nuclei in active galaxies as revealed by high resolution radio and optical studies

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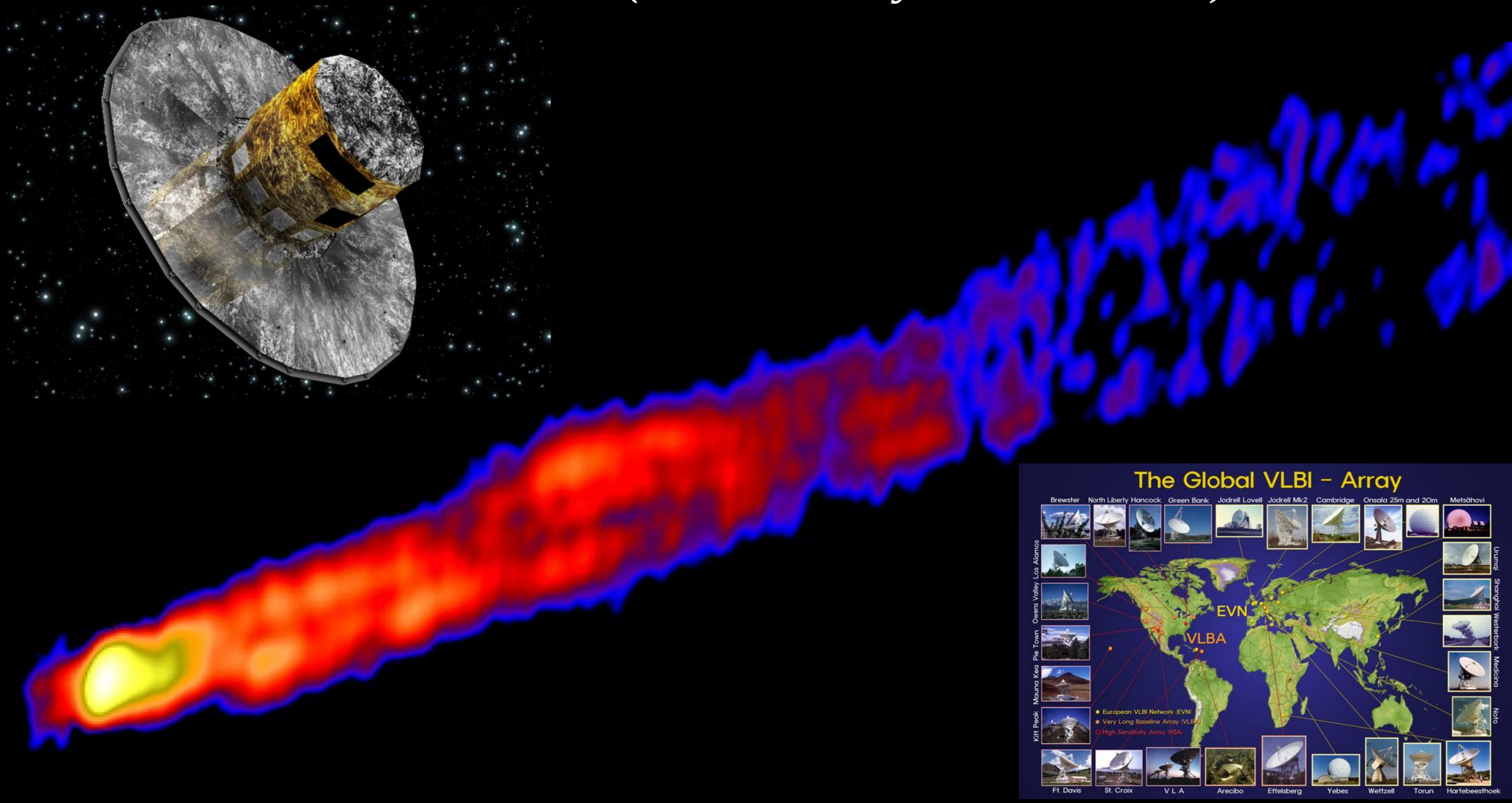


Talk plan: two parts

- A systematic study of geometry transition in AGN jets.

Pushkarev et al., MNRAS, 468, 4992 (2017);
Kovalev et al., MNRAS, 495, 3576 (2020).
See also the presentations at the meeting by Hada, Casadio, Nokhrina, Baczko.

- Astrophysics of the joint VLBI-Gaia analysis for AGN.

Petrov & Kovalev, MNRAS Letters, 467, 71L (2017);
Kovalev, Petrov, Plavin, A&A Letters, 598, 1L (2017);
Petrov & Kovalev, MNRAS, 471, 3775 (2017);
Petrov, Kovalev, Plavin, MNRAS, 482, 3023 (2019);
Plavin, Kovalev, Petrov, ApJ, 871, 143 (2019);
Kovalev, Zobnina, Plavin, Blinov, MNRAS Letters, 493, L54 (2020).

Jets geometry transition: a systematic study

- Geometry transition: critical to study formation and collimation of AGN jets. Properties of the break point (distance to the nucleus, width) allow to probe the mechanism of jet collimation and even determine properties of the central engine.

- Mostly targeted studies.

We decided to perform the first systematic study on stacked VLBI images for a large sample.

Data: 15 GHz VLBA monitoring observations of about 300 AGN (the MOJAVE program).

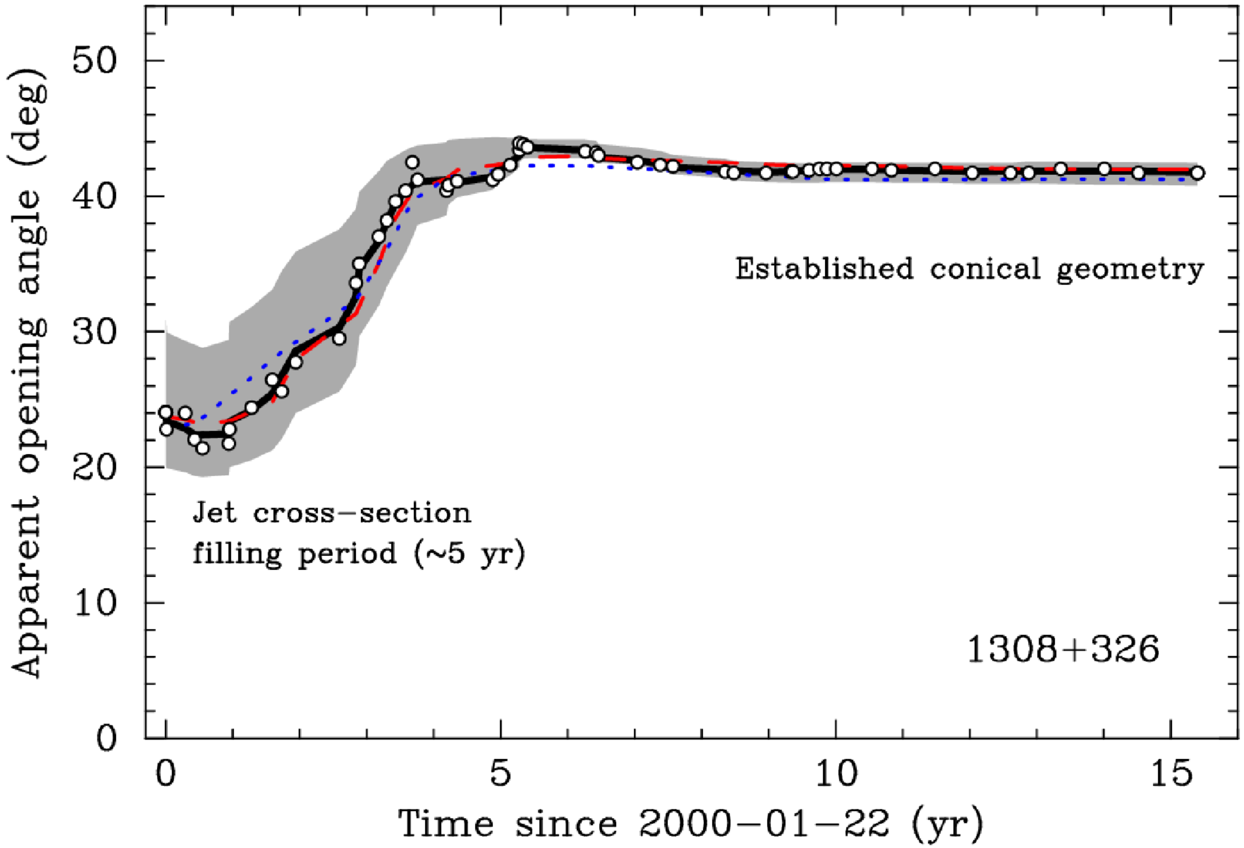
Why do we need stacked images?

Same analysis with lower time sampling by using

(i) every second (dashed red)

(ii) every third (dotted blue) epoch out of the 55 available

In both cases, the obtained dependence is close to the original.

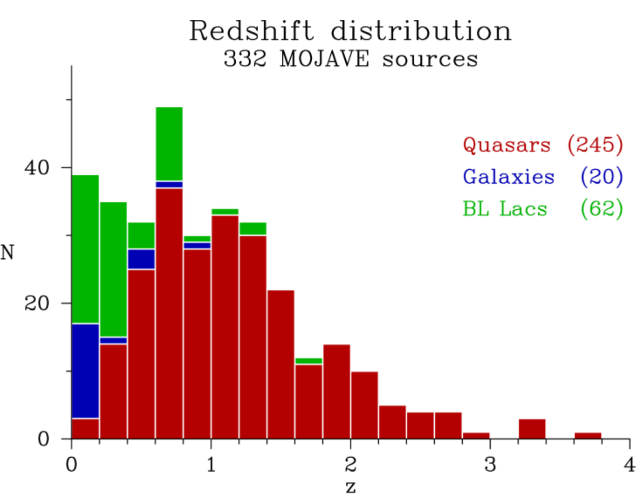


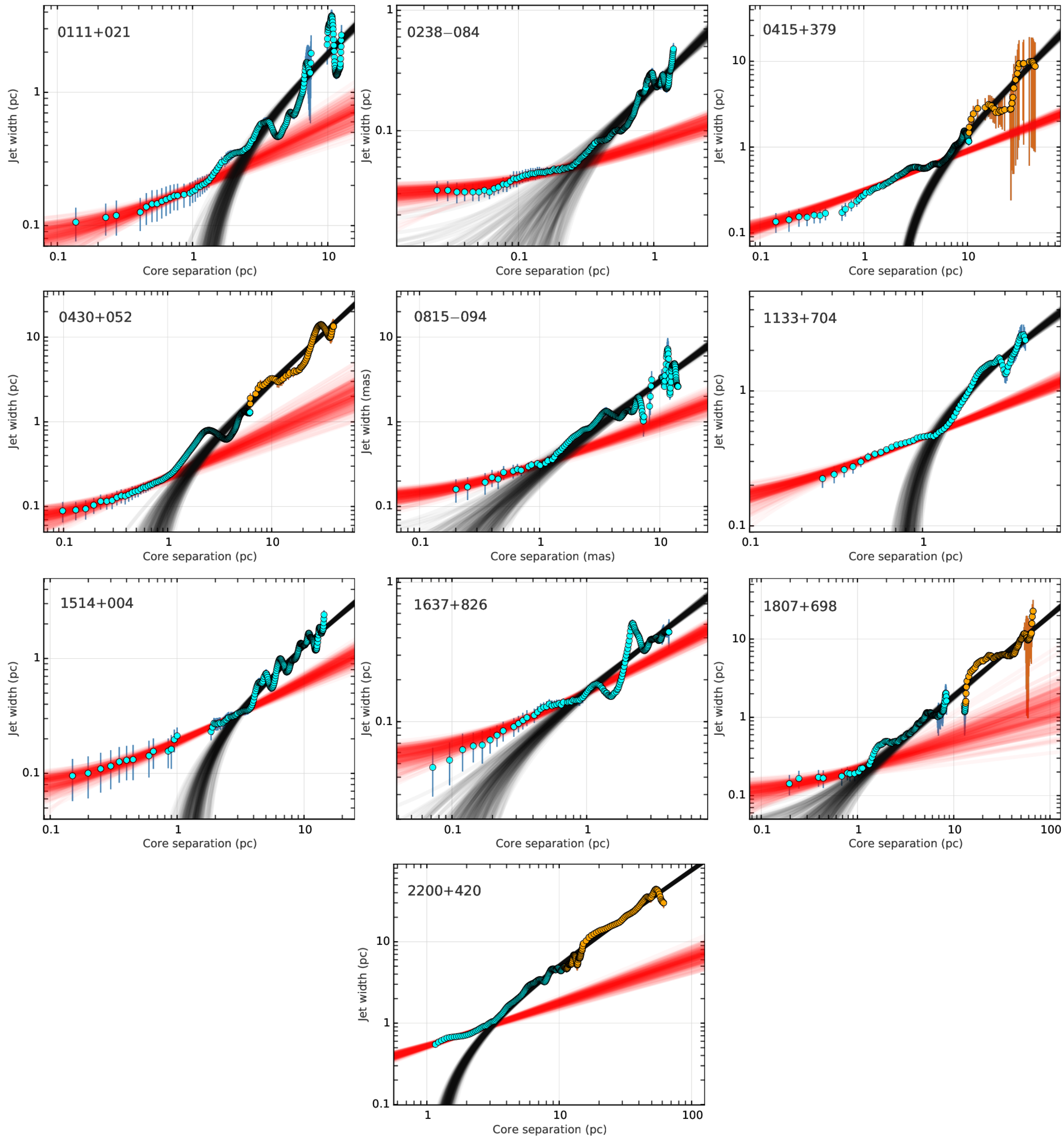
➔ The time period of ~ 5yr is not an observation specific bias, but rather a source specific characteristic

Emergence of a new bright jet feature in a different position angle widens apparent opening angle from 23 to 40 deg during 5 yr

New found AGN with geometry transition

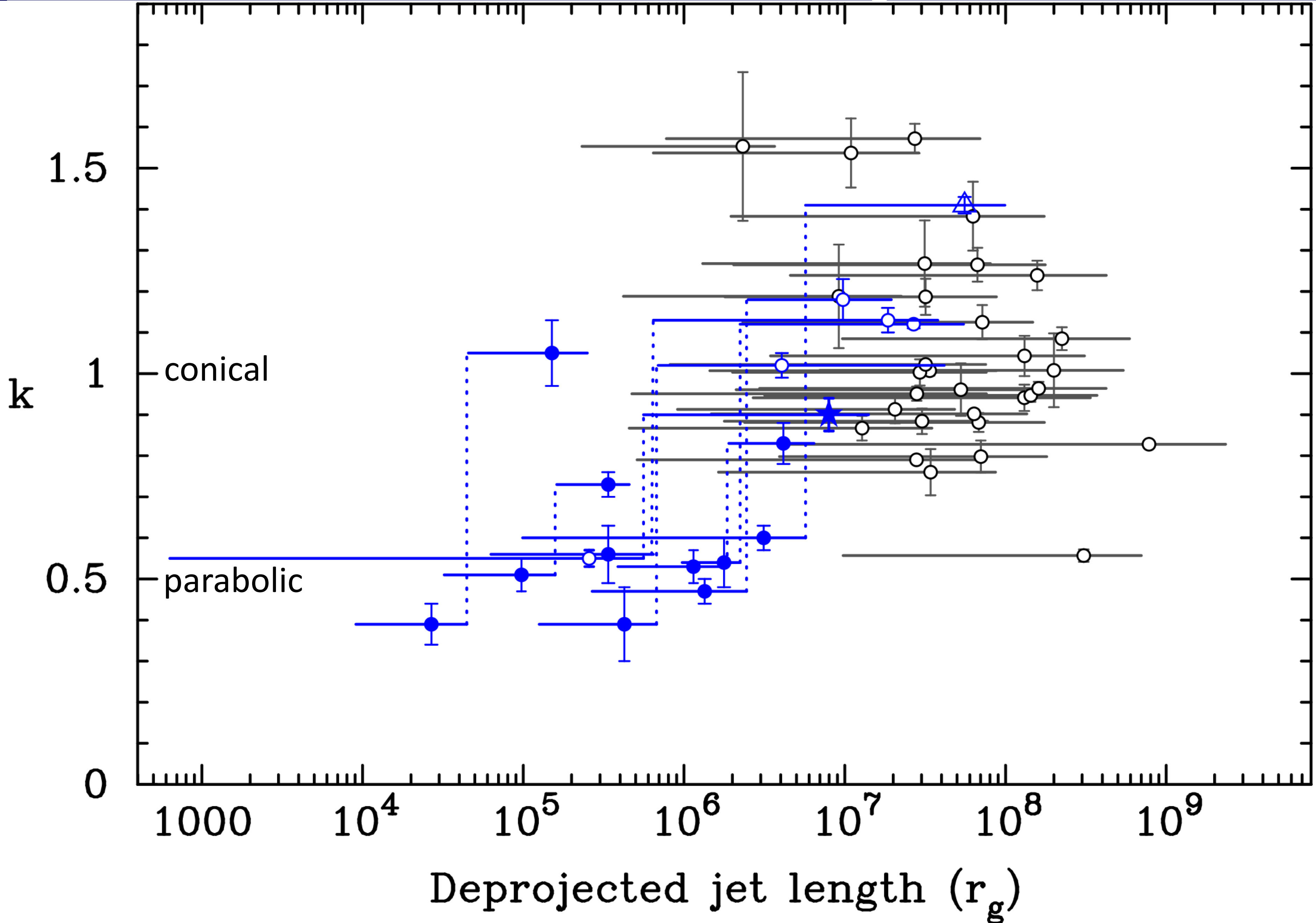
10 out of 330
Nine: z<0.07
One: z unknown.





Jet shape versus distance in grav radius

Transition happens at 10^5-10^6 r_g (Bondi radius)



Physics of the geometry transition

- Geometry transition is common for AGN jets.

- The accretion and collimation zone is within the Bondi radius. At this distance a recollimation (with a shock) occurs in the jet and converts much of the kinetic energy into the internal one. Parabolic expansion with acceleration transitions into the free conical expansion.

- External pressure affects this being governed by the Bondi accretion.

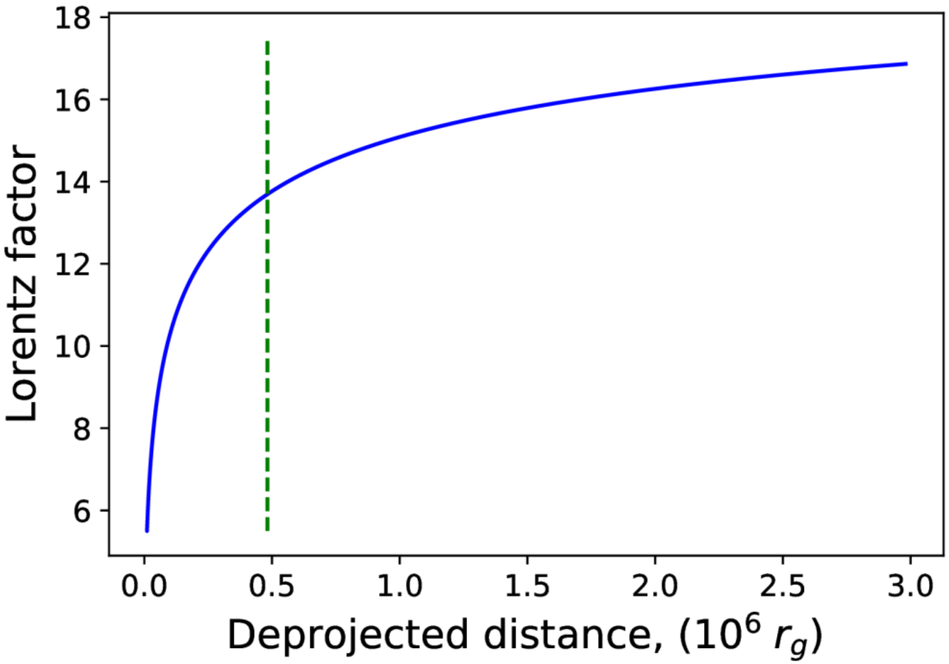
See also the talk by Elena Nokhrina.

Additional observational tests

➢ Half of AGN with geometry transition has standing features at their break point (MOJAVE) while only 1/5 of AGN in MOJAVE show standing features (Lister et al. 2019).

➢ Fitting for the non-zero distance between VLBI core and jet apex agrees with core-shift estimates.

➢ MOJAVE acceleration measurements agree with prediction of the model describing the change in Lorentz factor. However, direct comparison is very challenging.



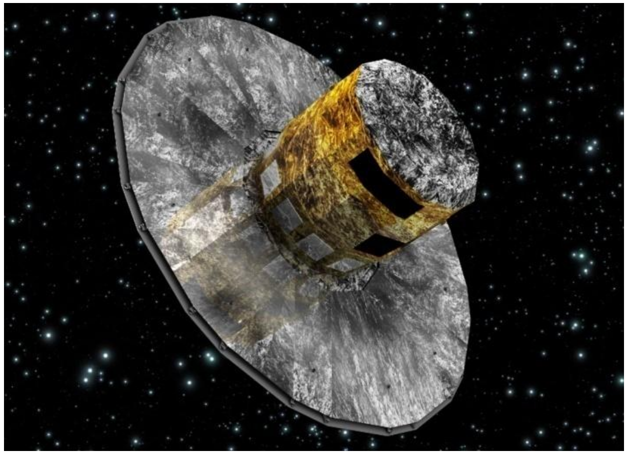
A dedicated systematic follow up study

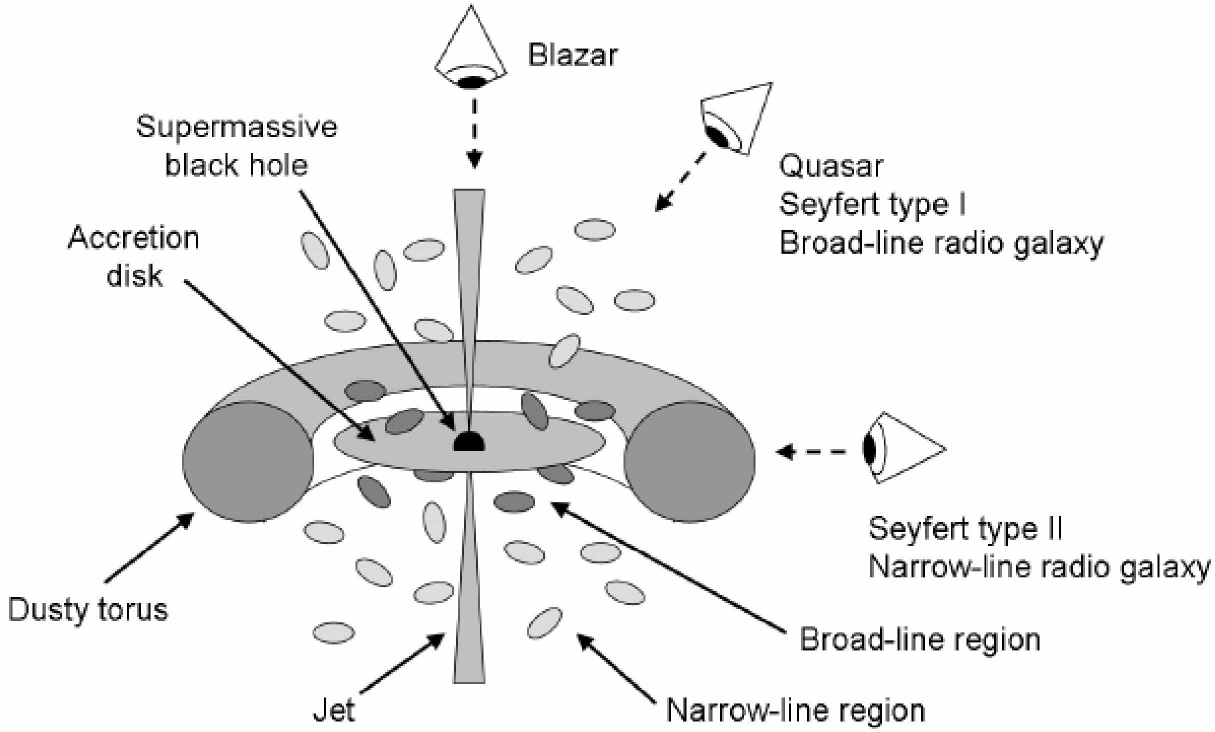
- 27 AGN with z<0.07 are selected for a dedicated follow up study with VLBA at 2 and 20 cm.

- The observations cover two years and will finish in late 2021. We will get kinematics (need to observing angle and Doppler boosting) and stacked images at 2 cm.

- We anticipate to increase the number of jets with geometry transition up to 30-40.

VLBI-Gaia: Why are we interested?
AGN schematics

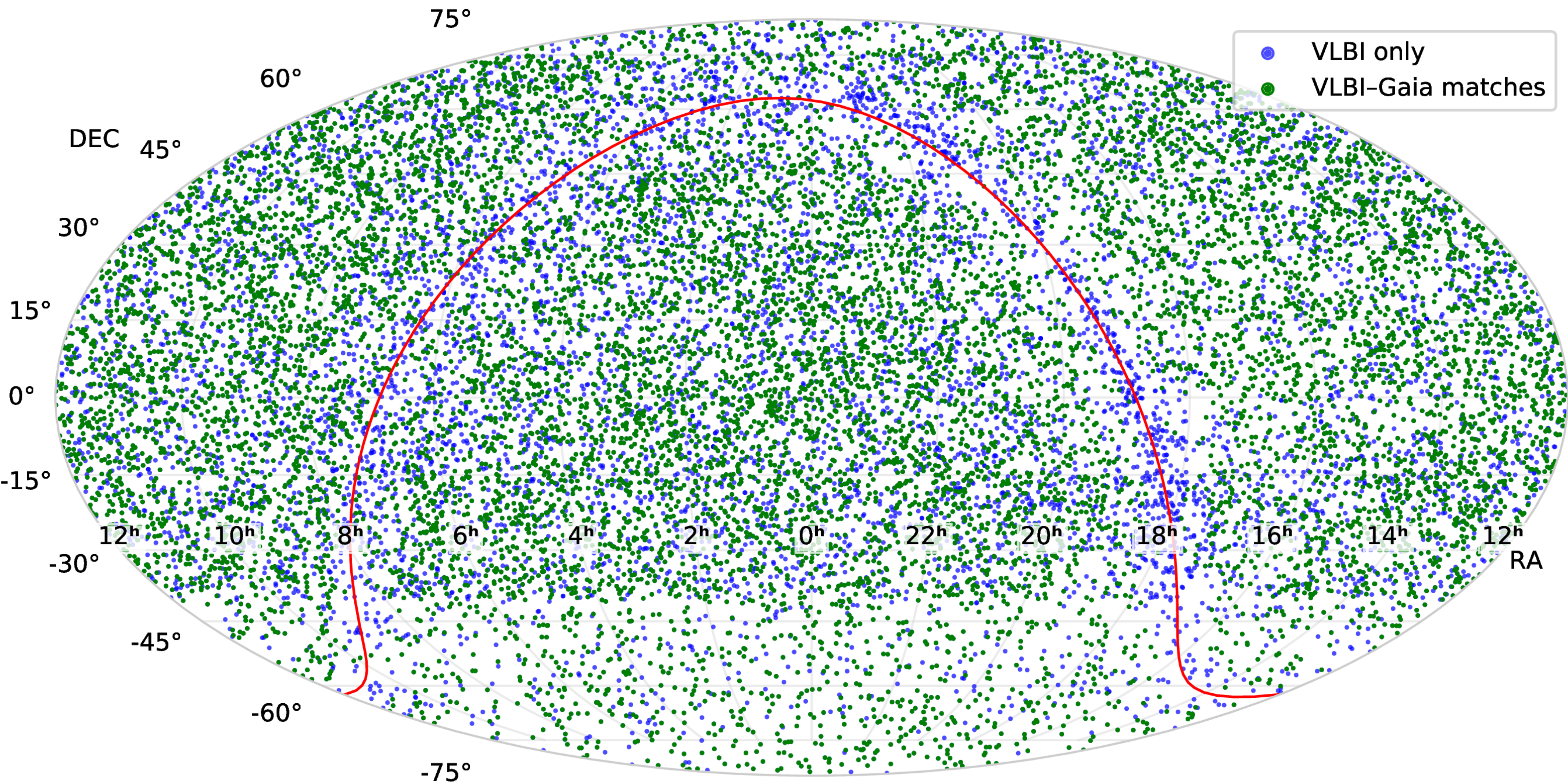




- ➢ To estimate systematics of reference frames
- ➢ To tie radio and optical reference frames

➢ **Astrophysical applications: study the disk-jet system and beyond.**

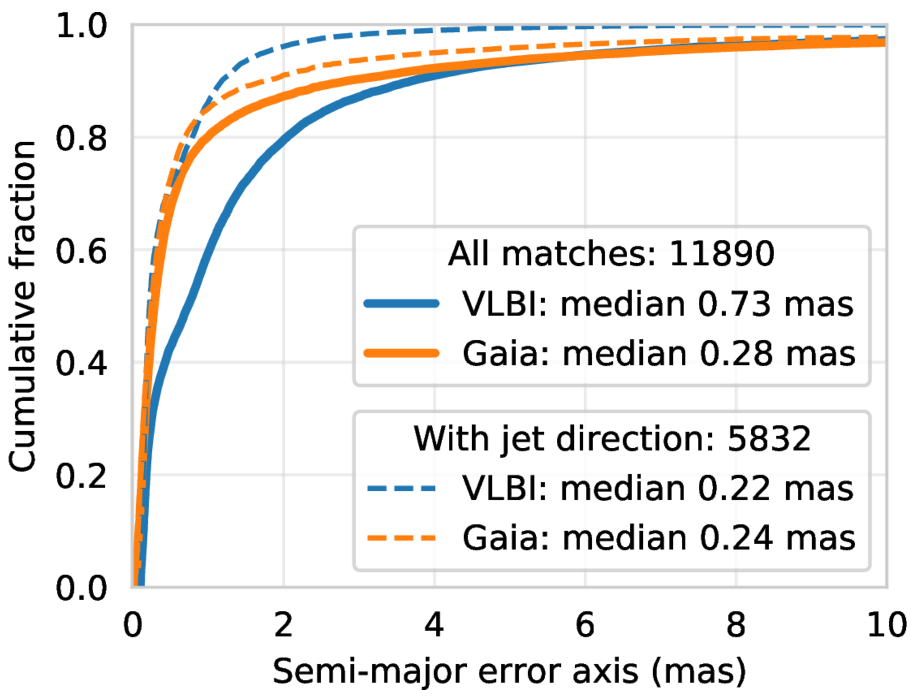
VLBI (RFC) - Gaia EDR3 counterparts



VLBI (RFC): 19 600 compact extragalactic objects – radio-loud AGNs.
12 thousand Gaia DR3 - VLBI counterparts are found (green), $p<0.0002$.

VLBI-Gaia EDR3 comparison

VLBI: Radio Fundamental Catalogue
http://astrogeo.org/rfc/
Median positional error 0.2-0.7 mas.



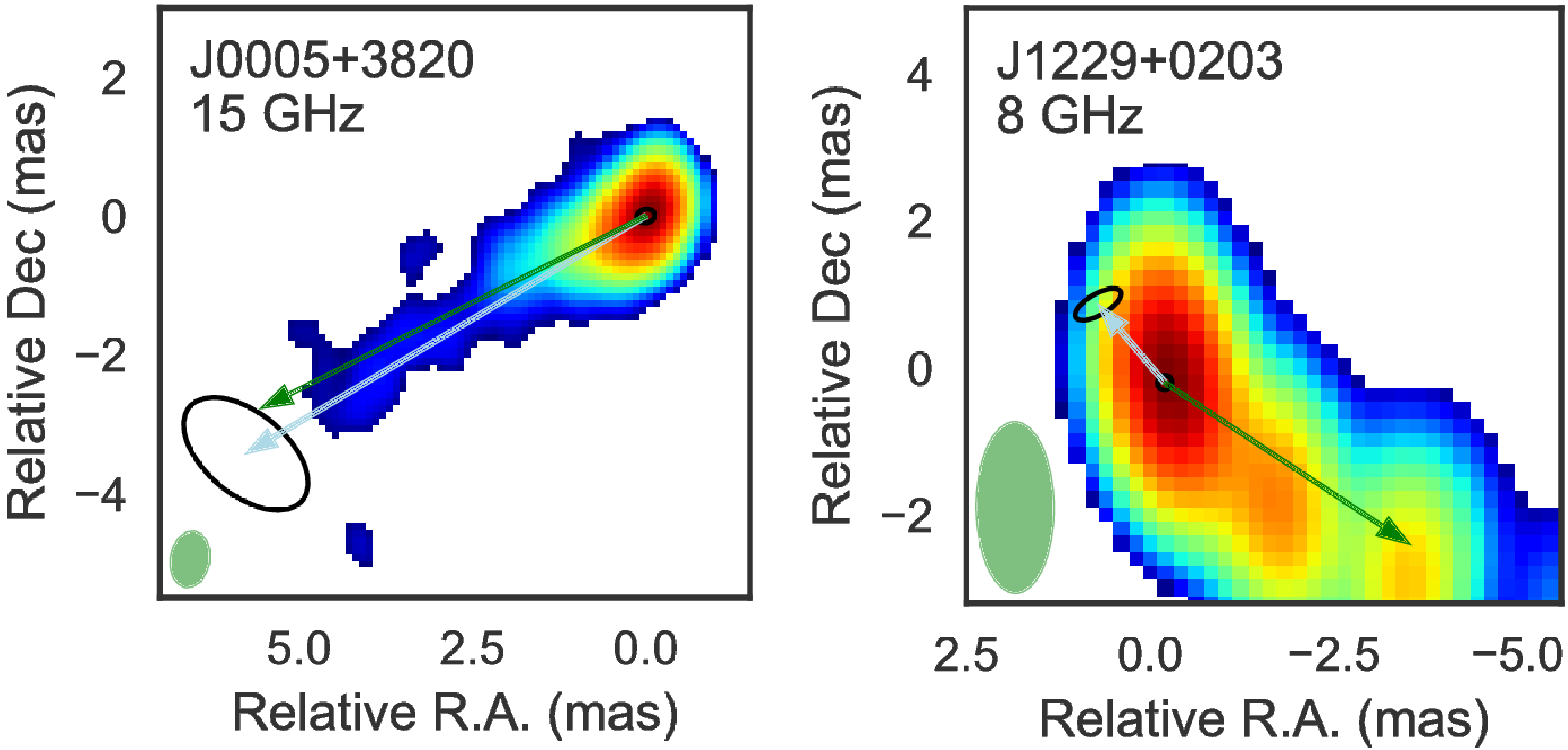
Gaia: DR3 catalog
Median positional error 0.2-0.3 mas.

About 9% of matches have significant offsets!

We compare jet and VLBI-Gaia offset directions

Extended optical jet

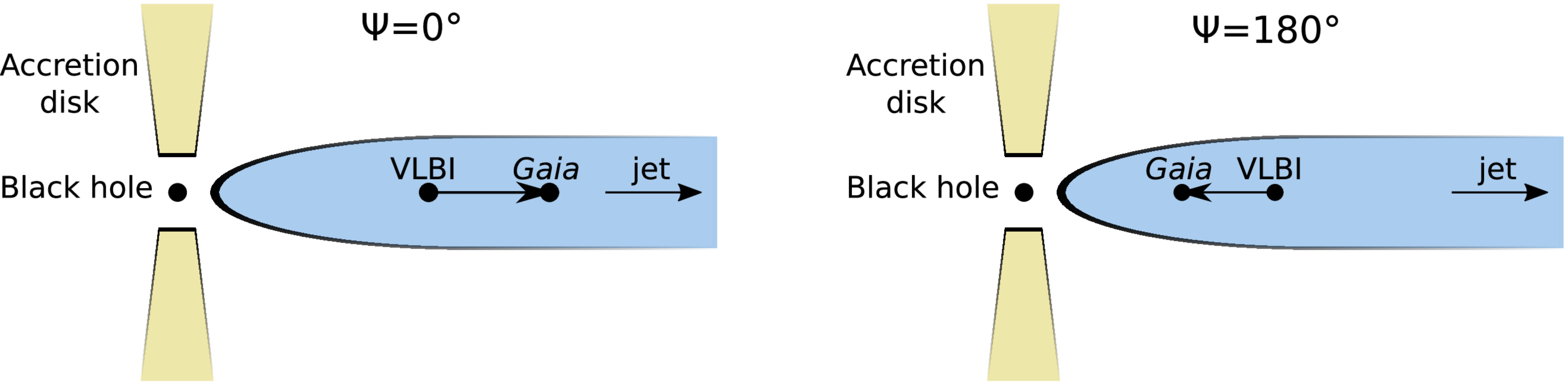
Core-shift or extended radio jet

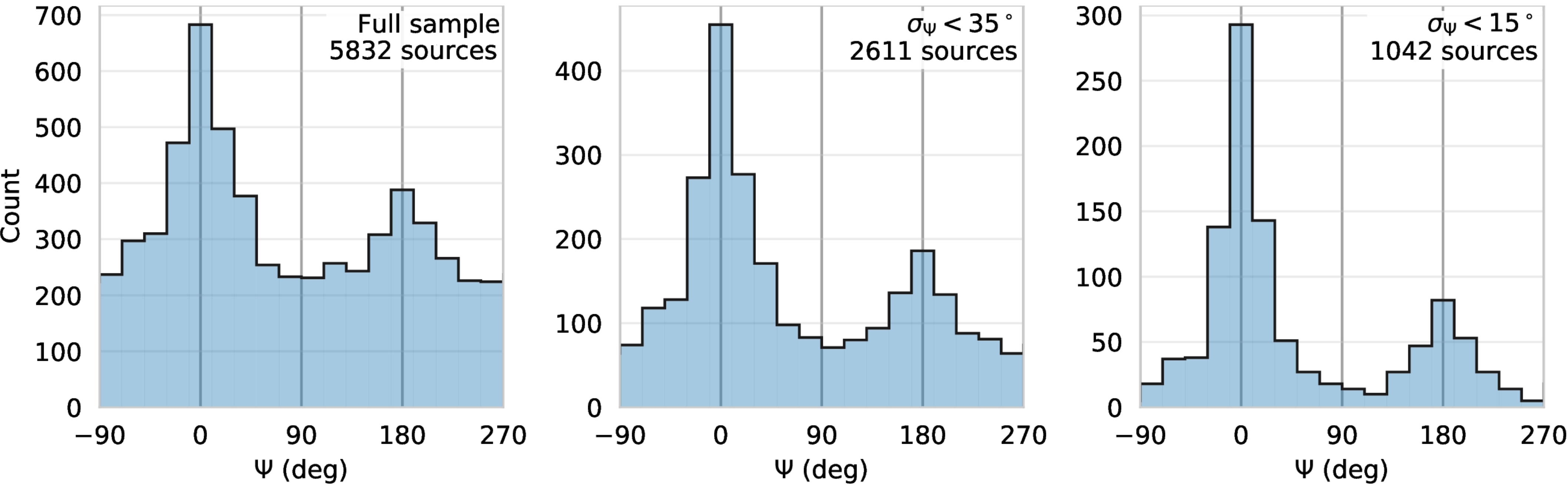


Jet direction (green vector) is measured for 5800 AGNs on the basis of their images.

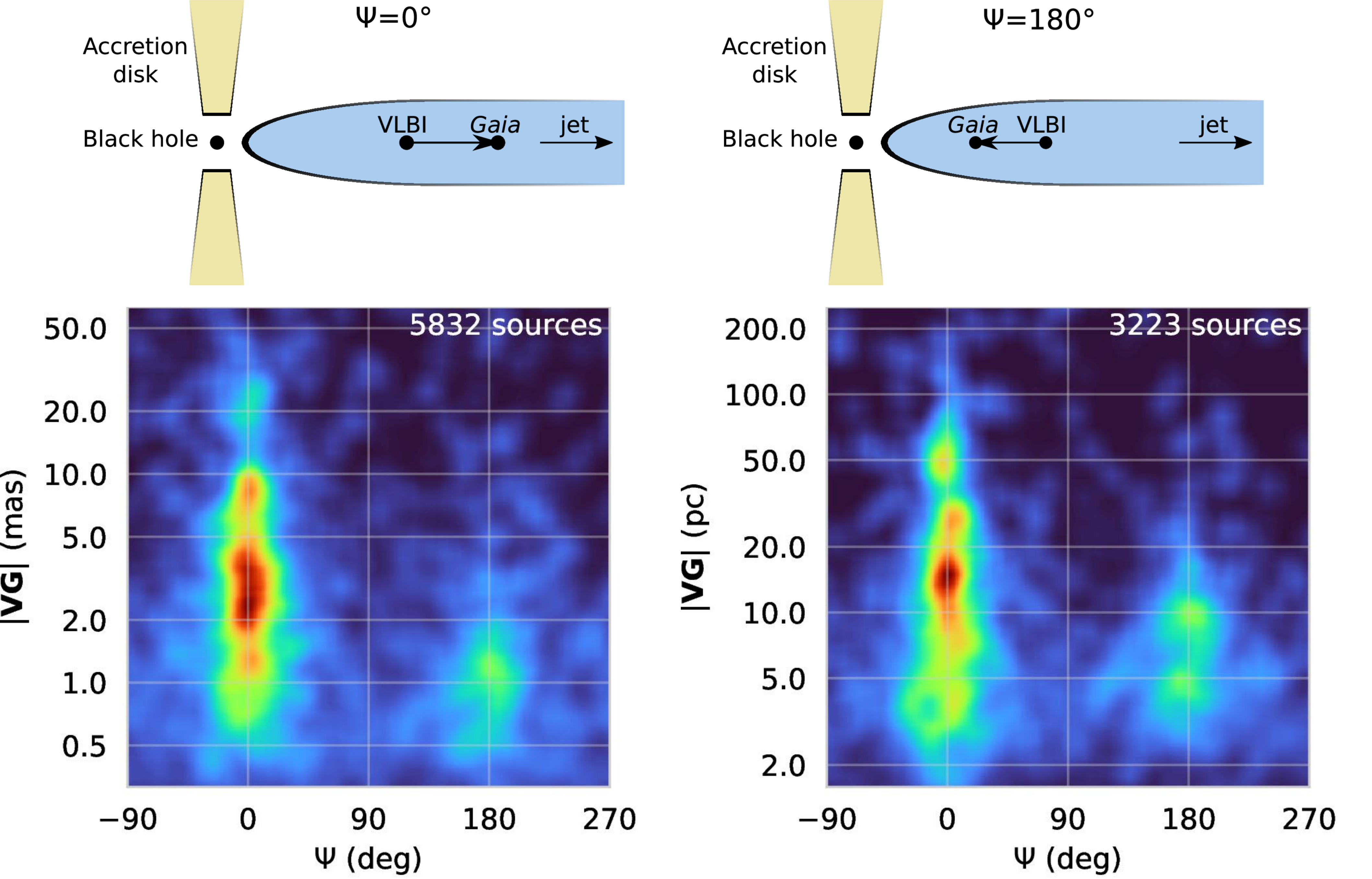
A dedicated paper on more that 8000 AGN jet directions is submitted to ApJS.

VLBI-Gaia EDR3 offsets: direction

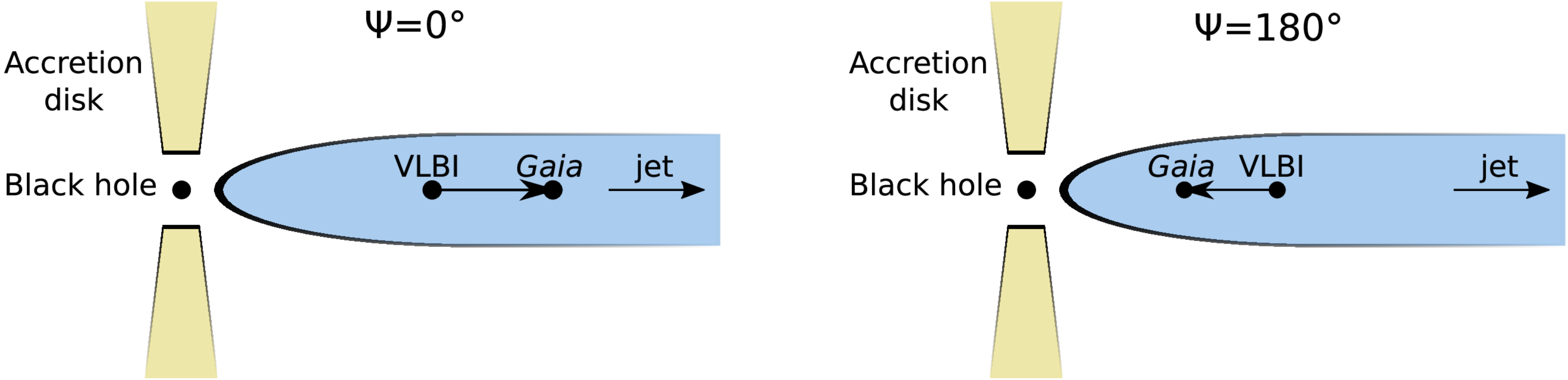




VLBI-Gaia EDR3 offsets: value and direction



Why do they shift?



Ψ=180°: up to 1-2 mas

VLBI is sensitive to most compact feature – the apparent core.

- ✓ Core-shift
- ✓ Non-compact jets

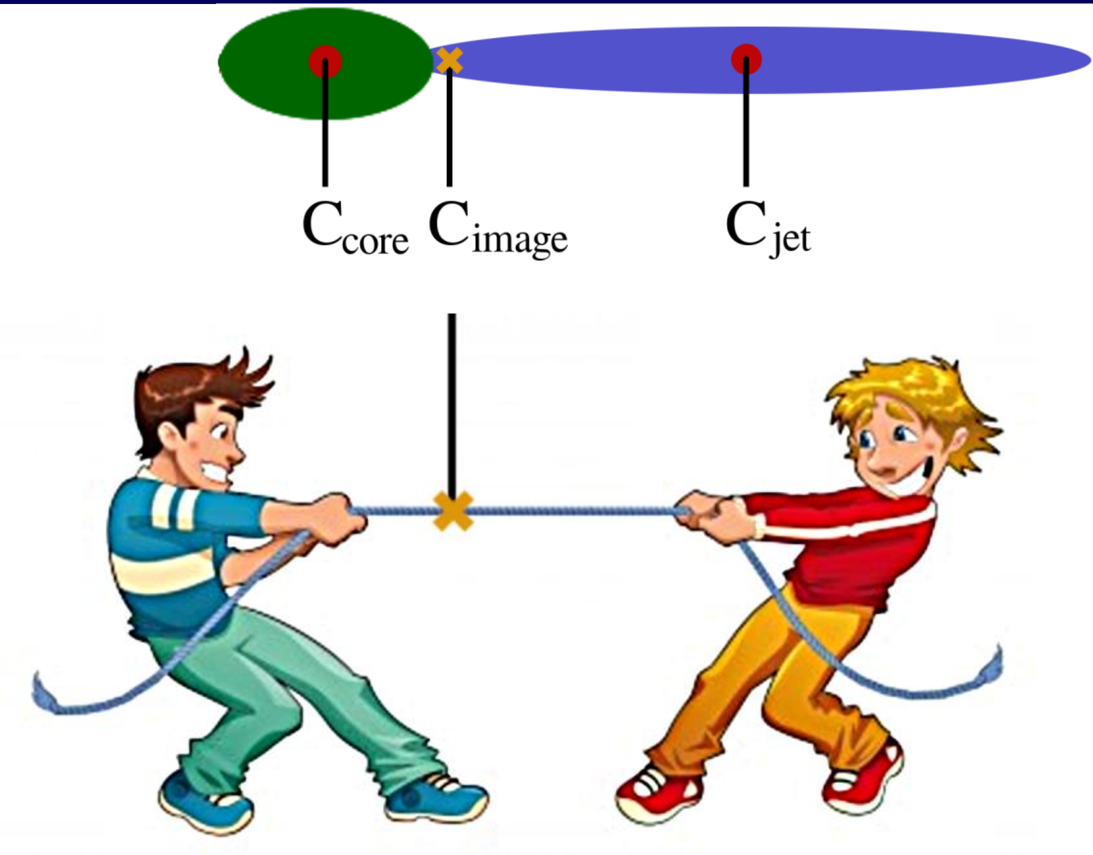
Ψ=0°: up to 10-20 mas

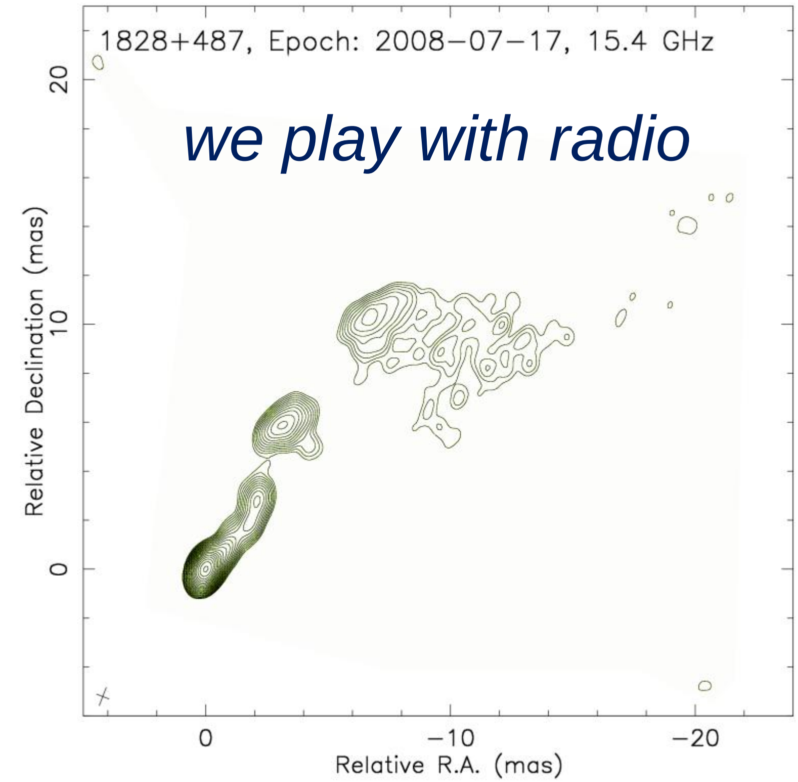
Gaia measures the true centroid of the image by CCD.

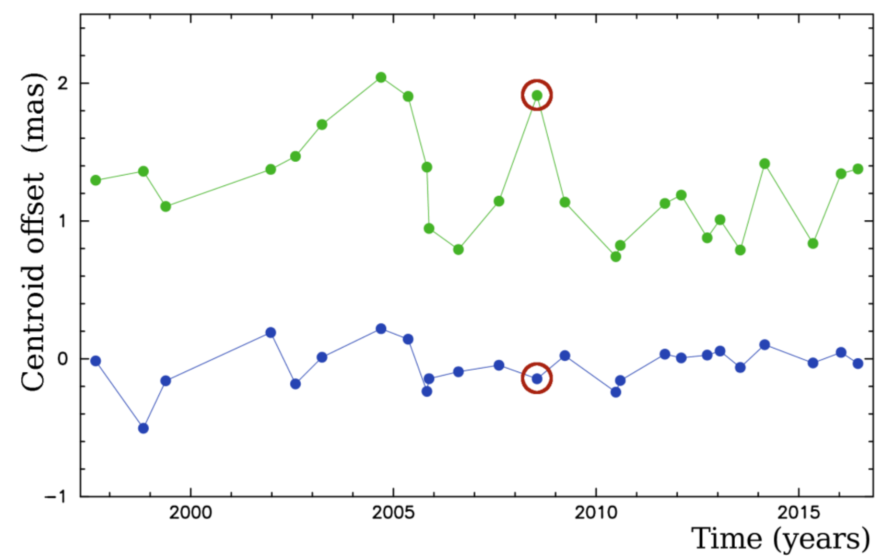
Optical jets can be strong and extended, they shift the centroid.

Interplay between the accretion disk and jet determines the optical centroid position.

Optical centroid variability predicted

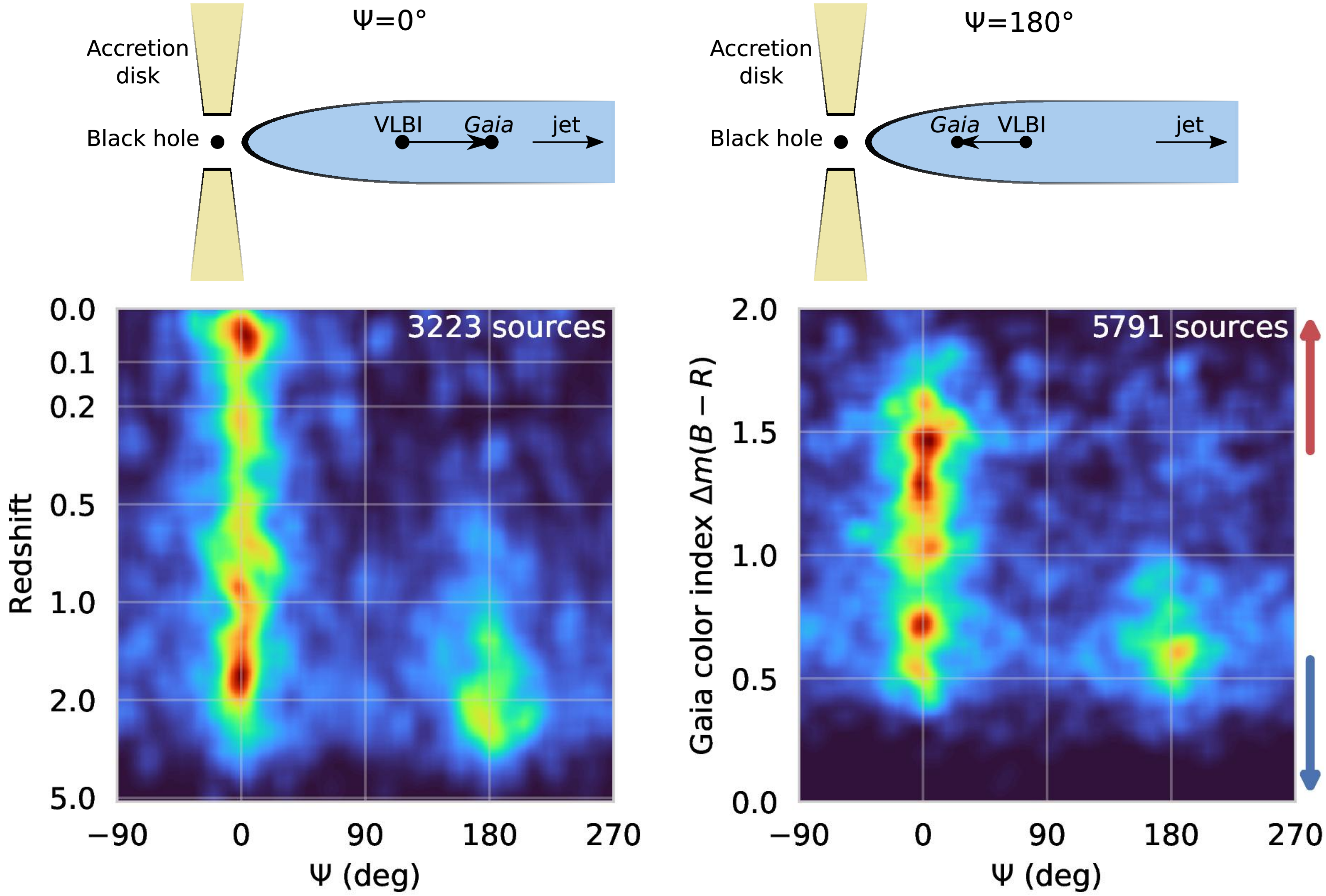




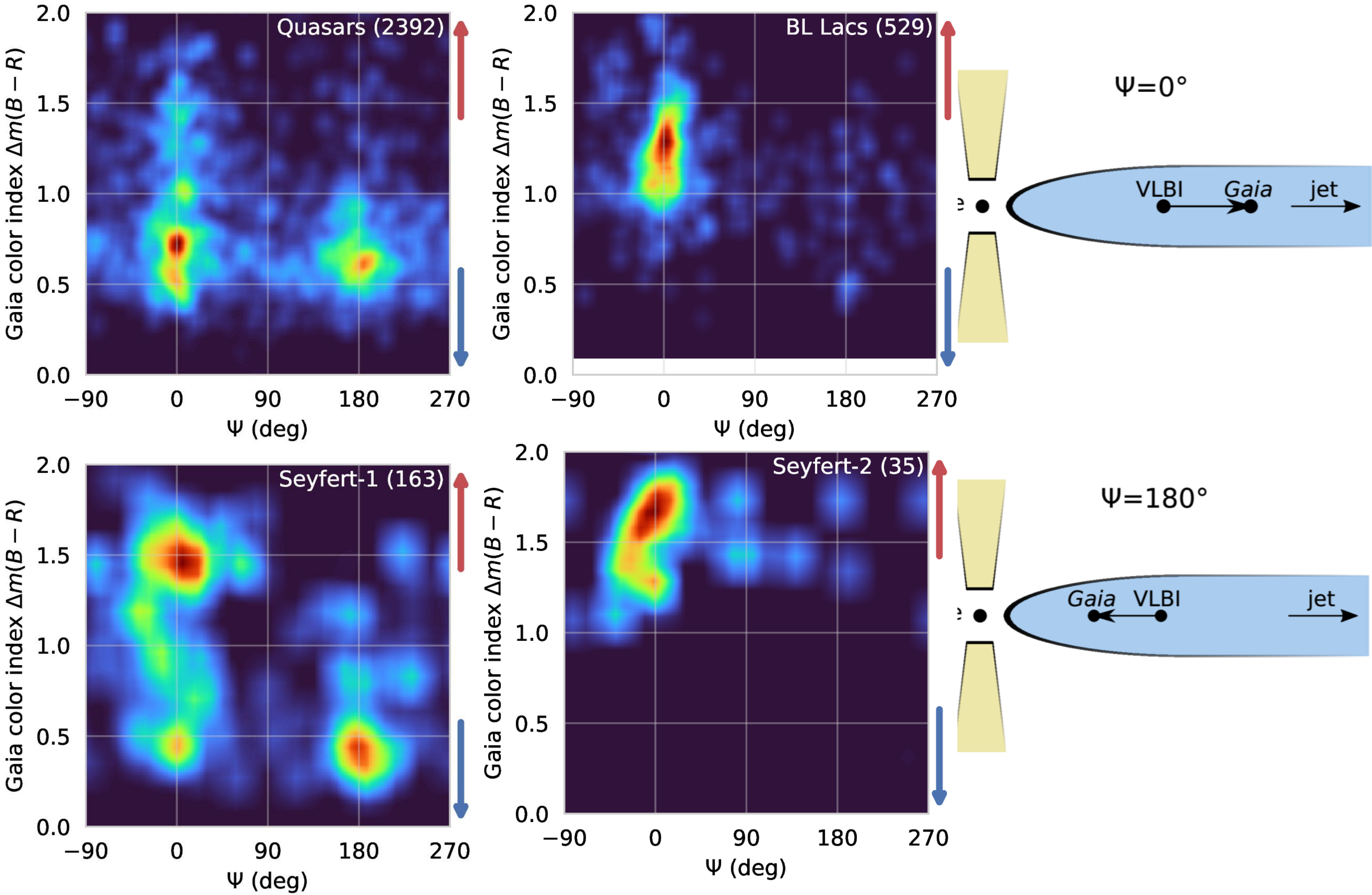


Centroid variations are defined by both the variability of the core brightness as well as by changes in the jet.
Most probably, core variations are the dominant cause of non-linear centroid variations.

VLBI-Gaia DR3 offsets: z, color and direction



VLBI-Gaia DR3 offsets: QSO, BL, Sy1&2



Challenges and opportunities

- Optical emission of extended jet seems to be comparable or stronger than the one of the accretion disk *and* the jet base for many radio-loud AGN

- VLBI and Gaia singe epoch astrometry (expected), images and colors supplemented by polarization data provide a great tool to probe the disk-jet system in hundreds of AGN.

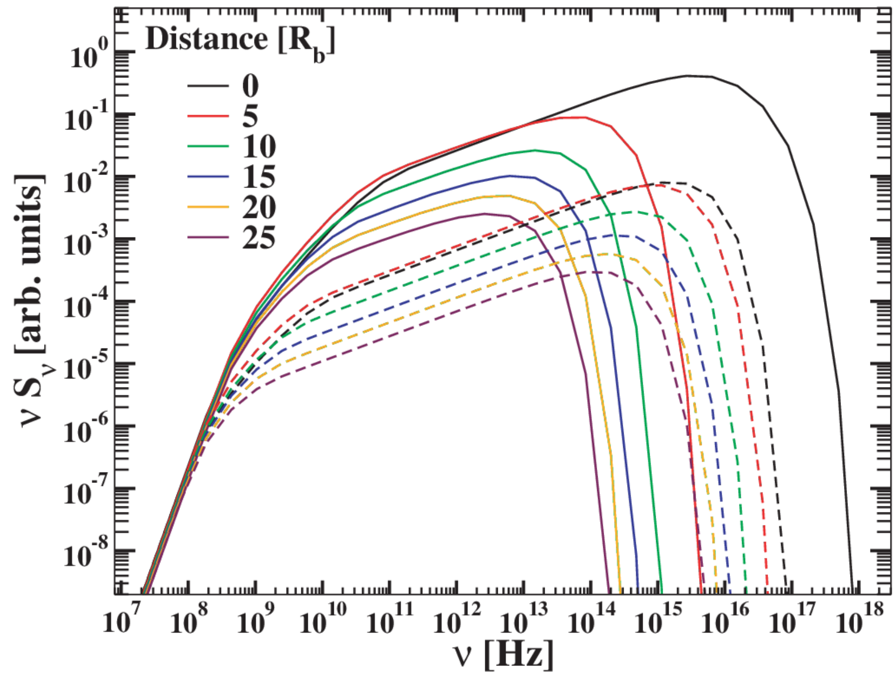


Figure 7. Different lines in the plot show the spectral energy distribution of selected points along the jet axis of model PM with two different magnetic fields. All the models have been computed using the SPEV method with the reference parameters of Section 5. Solid lines correspond to the PM-L model and dashed lines to the PM-S model. The distance to the nozzle (in R_b) to which each spectrum corresponds is provided in the legend. Synchrotron self-absorption is dominant at frequencies below few hundred MHz.

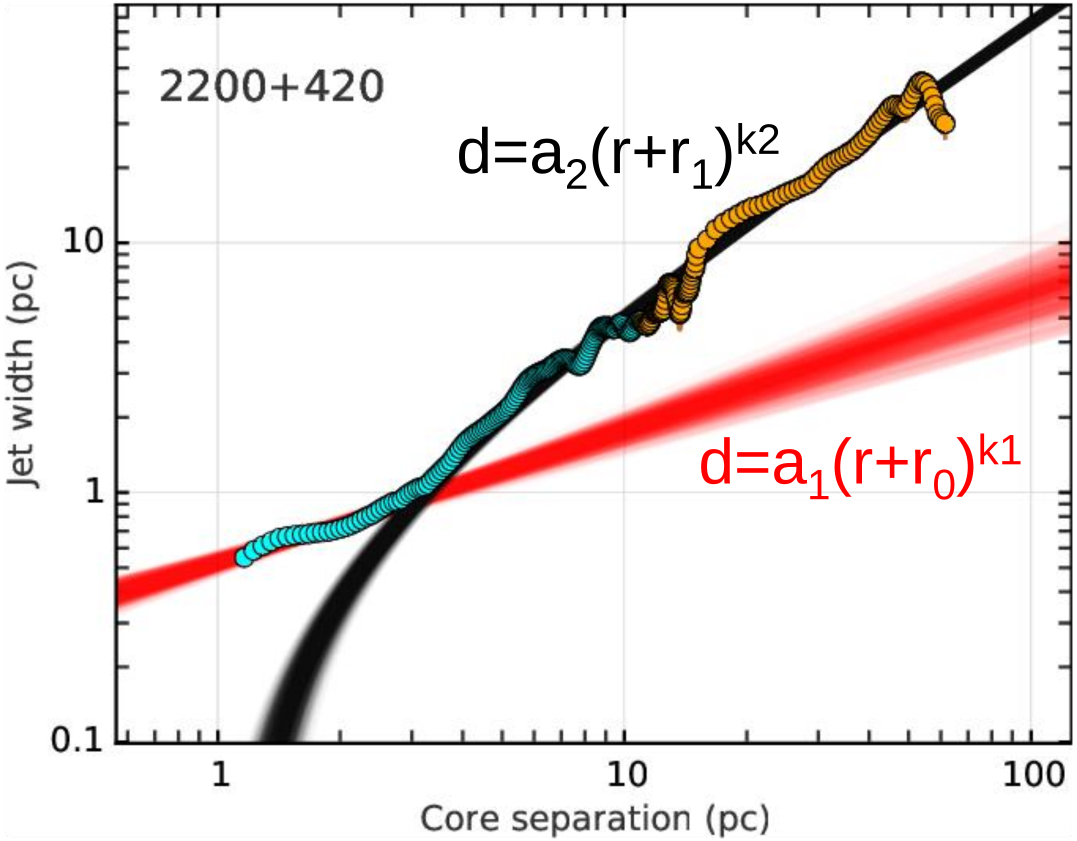
Mimica et al. 2009

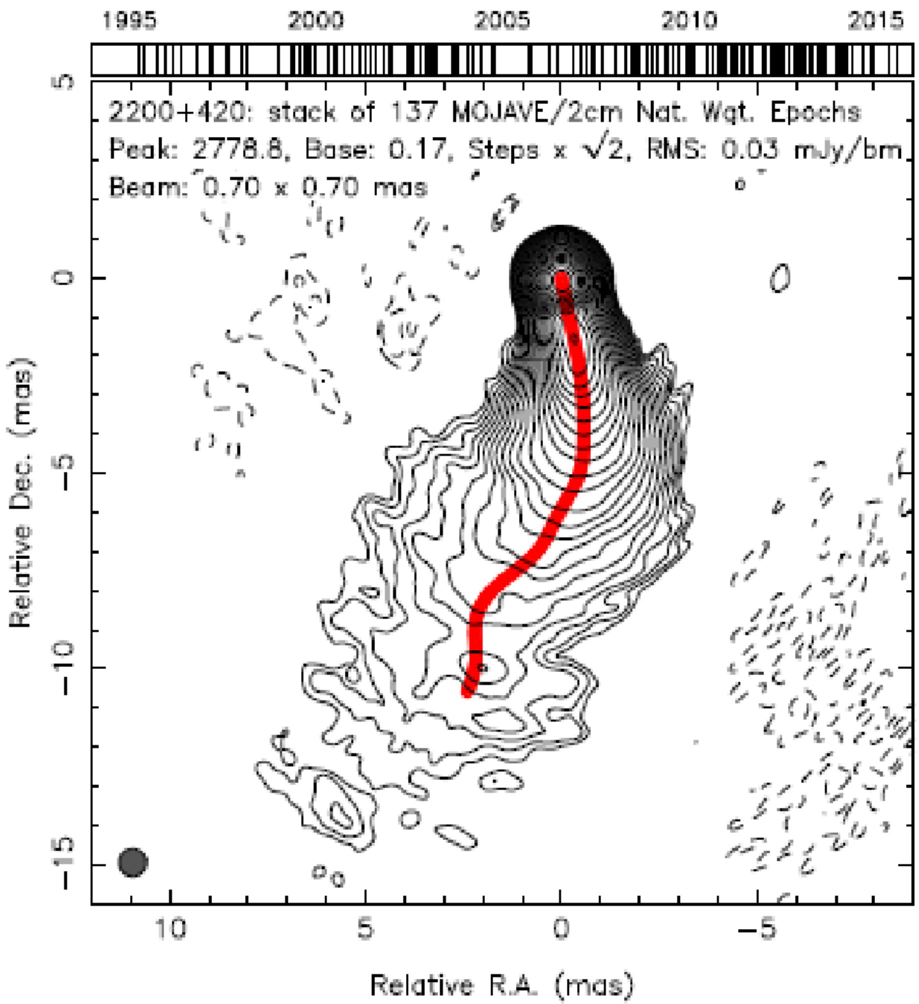
Summary

- Geometry transition (parabolic-conical) is a common effect in AGN jets, found systematically for nearby ones.
- It happens around 10^5-10^6 r_g from the nucleus when the bulk plasma kinetic energy flux becomes equal to the Poynting energy flux. The ambient medium pressure is assumed to be governed by the Bondi accretion.

- More than 800 AGN with statistically significant VLBI-Gaia offsets are found using Gaia DR3. These offsets prefer parsec-scale jet directions and are caused by accretion disks and jets.
- Strong differences for AGN classes can be understood within the unified scheme and used to constrain the disk-jet emission models as well as the size of the dusty torus.

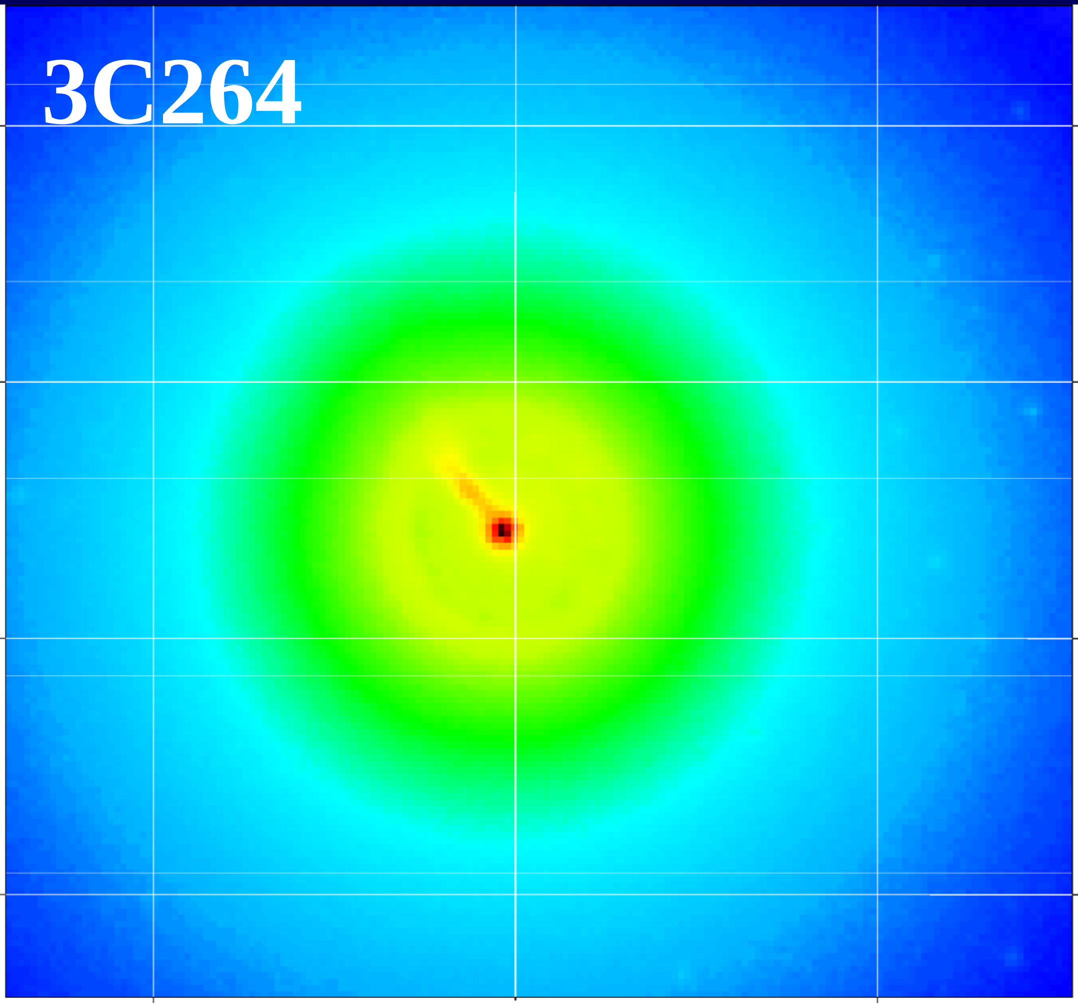
Fitting procedure

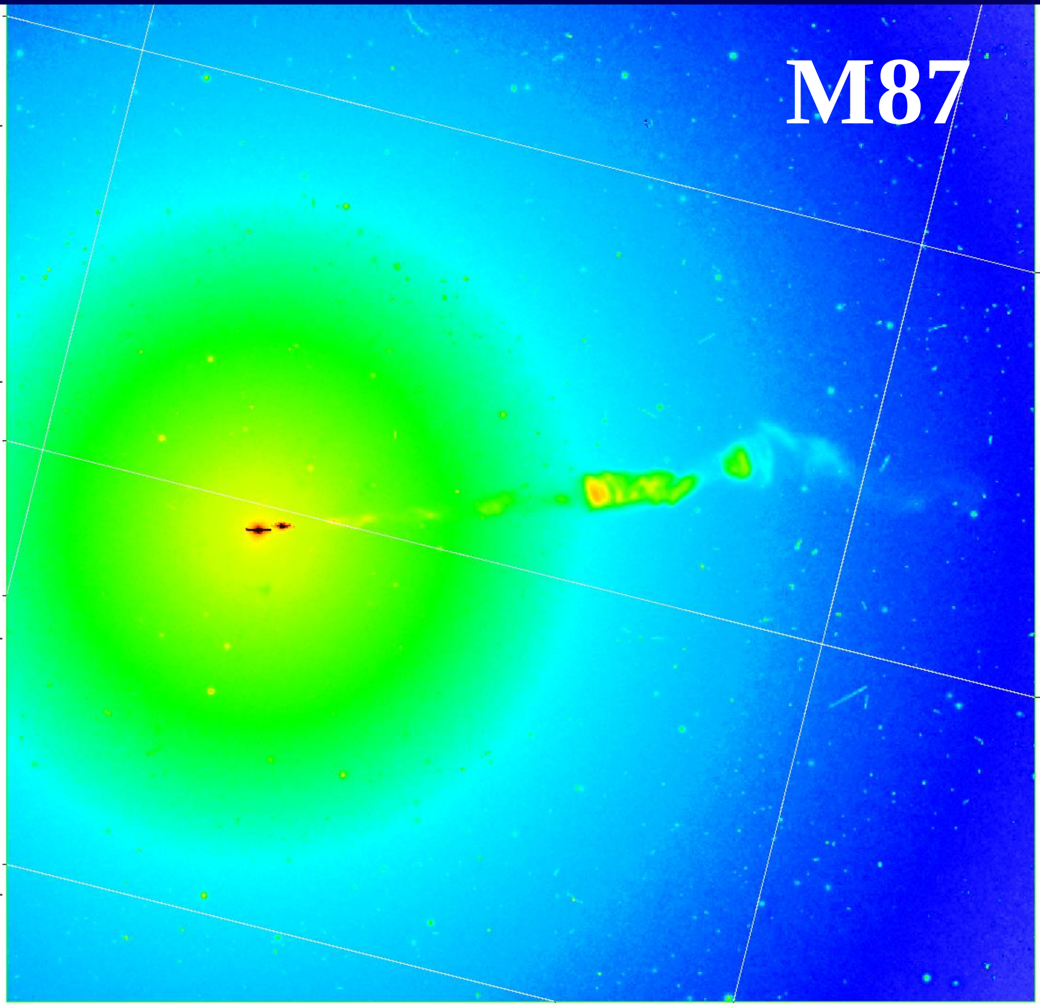




k1 & k2 describe the jet profile shape before and after the break.
r_0 is the distance from the apparent core to the true jet base.
d at the distance r=0 is the core width.

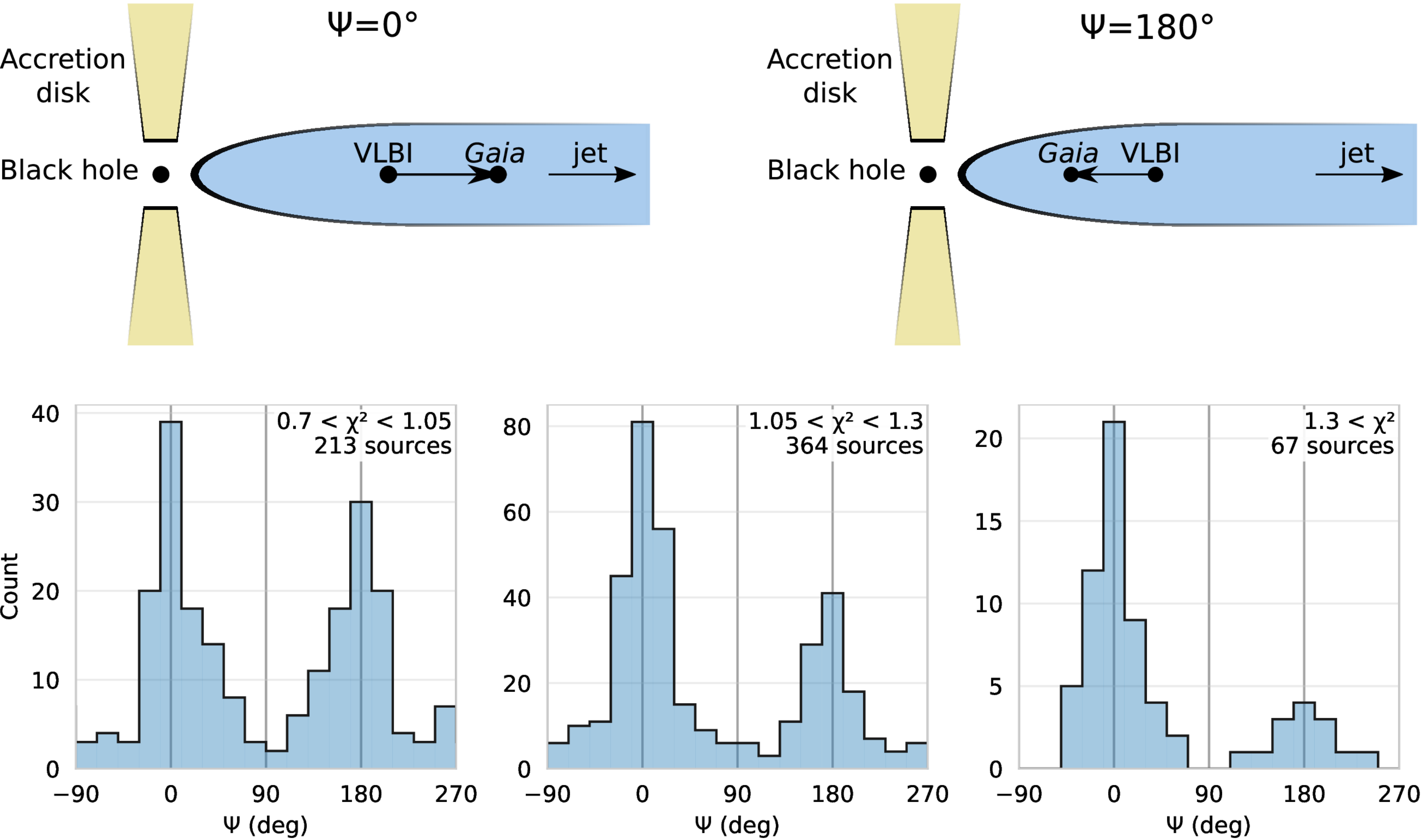
What do we know about optical jets?



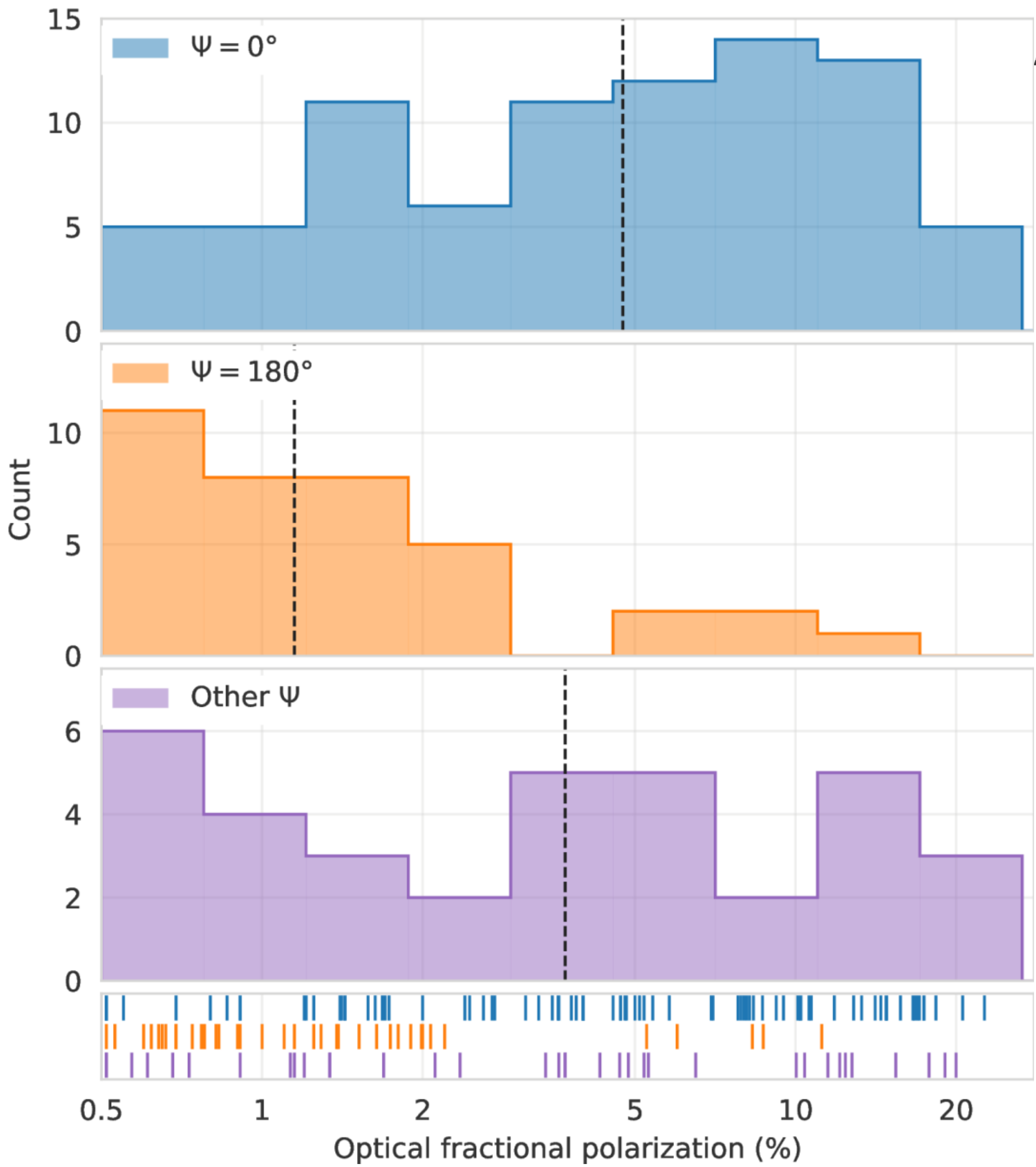


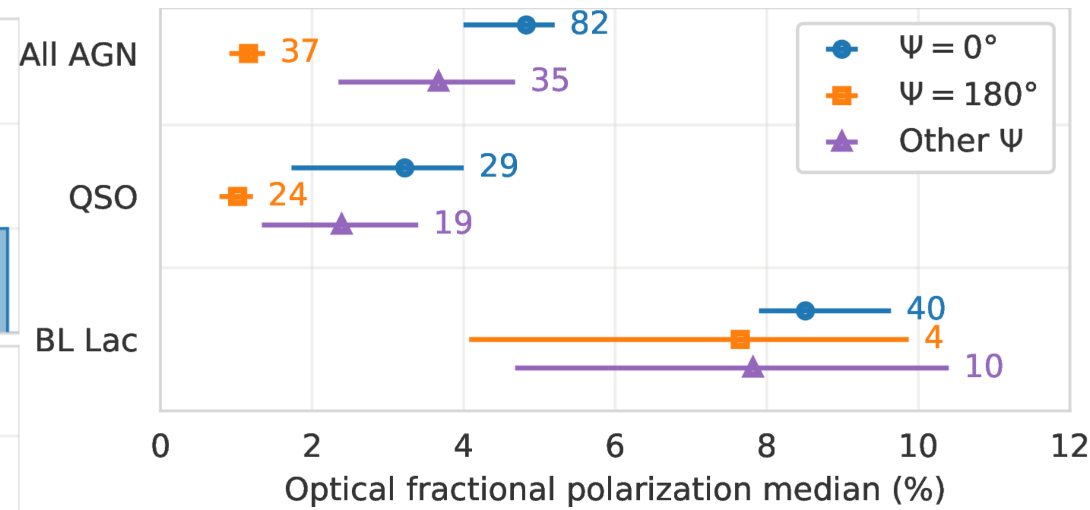
- To date, about 20 optical jets in AGNs are known with sizes from 0.5 to 20 arcsec.
- If we move them to typical quasar redshift, centroid is expected at several mas from the base.
- Yes, optical jets can cause the observed effect.

VLBI-Gaia DR3 offsets & Gaia jitter



VLBI-Gaia offsets: optical polarization





As expected for cases with dominant jet (synchrotron) versus disk (thermal) optical radiation:

<u>Ψ=0°</u>: high fractional linear polarization.
<u>Ψ=180°</u>: low fractional linear polarization.