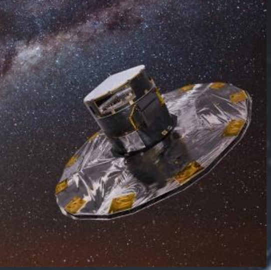


Locating the blazar γ-ray zone from astrometric VLBI and Gaia data?

Lambert, S., Pierron, A., Sol, H.
Observatoire de Paris, CNRS

GAMMA2022 - Barcelona - July 4-8, 20212

Locating the γ-ray emitting zone(s): a critical open question

- Several possible sites: Black Hole magnetosphere, base of jet, 'inside' or 'outside' BLR, VLBI knot, large scale jet component *cf Rieger's talk*

- Yet still tensions in some cases.
  – Lack of BLR γ-γ absorption features *(cf Foffano's talk)* suggests emission from 'outside' the BLR, not easy to reconcile with severe constraints imposed on the size of the emitting zones for fast varying VHE sources as 3C 279, PKS 1222+216 *(Abdalla et al. 2019, Meyer et al. 2019)*

- Identifying the true location should better constraint the properties of the emitting zone and could break degeneracies between various scenarios of blazar emission:
  - intensity and order of magnetic field,
  - nature of emitting particles (leptonic versus hadronic models),
  - dominant particle acceleration mechanisms,
  - origine of variability

- MWL approach important to explore blazars at very small angular scales, in particular in radio and optical ranges.

Radio VLBI versus γ-rays

- Growing evidences for correlation between some HE and VHE flares and events seen by VLBI: radio core flux variations, emergence of new knots at jet base, appearance of stationary features *(Akiyama et al, 2012; Jorstad, Marscher, 2018; Rani et al, 2018; Larionov et al, 2020; Kim et al, 2020; Lico et al, 2022)*

- Beyond studies of individual sources, interest of statistical approach to better identify general trends

- Long term joint VLBI-Fermi monitoring of 331 AGN: strong correlation between Fermi LAT flux and

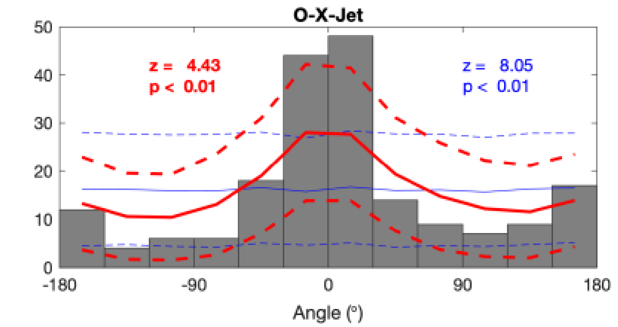
  (1) radio flux from the radio core, delayed by 3-5 months in observer's frame,
  (2) radio flux from radio jet without the core, delayed by 5-9 months
  (Kramarenko et al, 2022)

- Temporal correlation between optical, X, and γ fluxes *(cf Otero-Santos's talk)* suggests a common emission region and correlated mechanisms

Synergy radio VLBI – optical Gaia data

Analysis of VLBI-Gaia offsets over last years:

- Optical centroid preferably in the jet *(Kovalev et al. 2017, Petrov et al. 2018, Lambert et al. 2021)*
- Coincidence of some optical centroids with VLBI knots often stationary and with high linear polarization, up to 20% *(Kovalev et al. 2020, Lambert et al. 2021)*

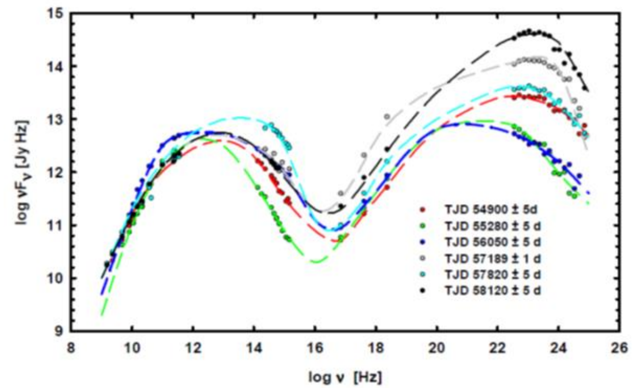


Angle ‘Gaia centroid versus jet’
(Lambert et al, 2021)

Suggests that:

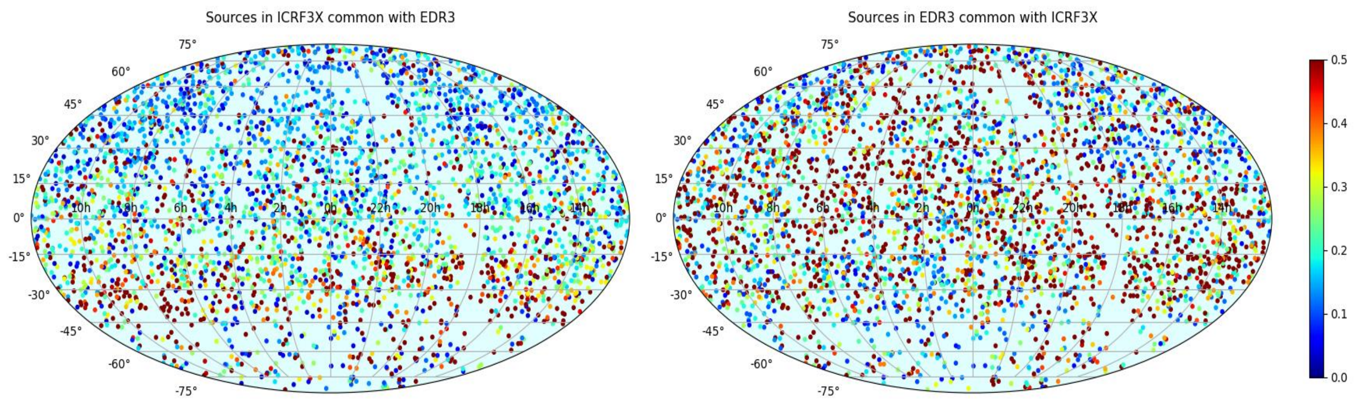
- optical centroids are dominated by non-thermal (NT) synchrotron emission at least in some sources
- γ-rays expected from same site by IC emission in leptonic models, or if optical synchrotron emission is due to secondary particles in hadronic models
- optical centroids could locate the γ-ray site
- WARNING: complexity of optical sky *(cf Padovani’s talk)*

  ---> Disk emission *(Plavin et al, 2019)*, BLR/NLR, stellar halo, gaseous component, host galaxy + obscuration effects can dominate or contaminate the NT optical emission.



Evolution of the SED of 3C 279
(Larionov et al. 2020)

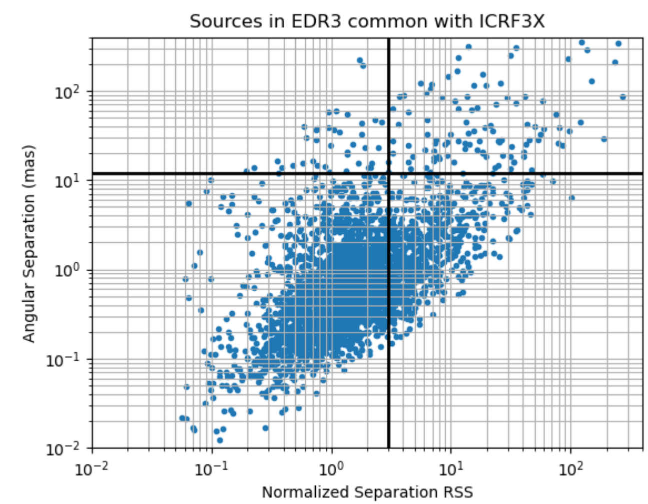
The International Celestial Reference Frame ICRF3 and the GAIA Early Data Release EDR3



- Absolute sub-mas astrometry, at 3 radio frequencies (ICRF3) and in the optical range (Gaia)
- Two challenging achievements
  - ICRF3 *(Charlot et al. 2020)*
  - Gaia EDR3 (*Prusti et al. 2016, Brown et al. 2021)*

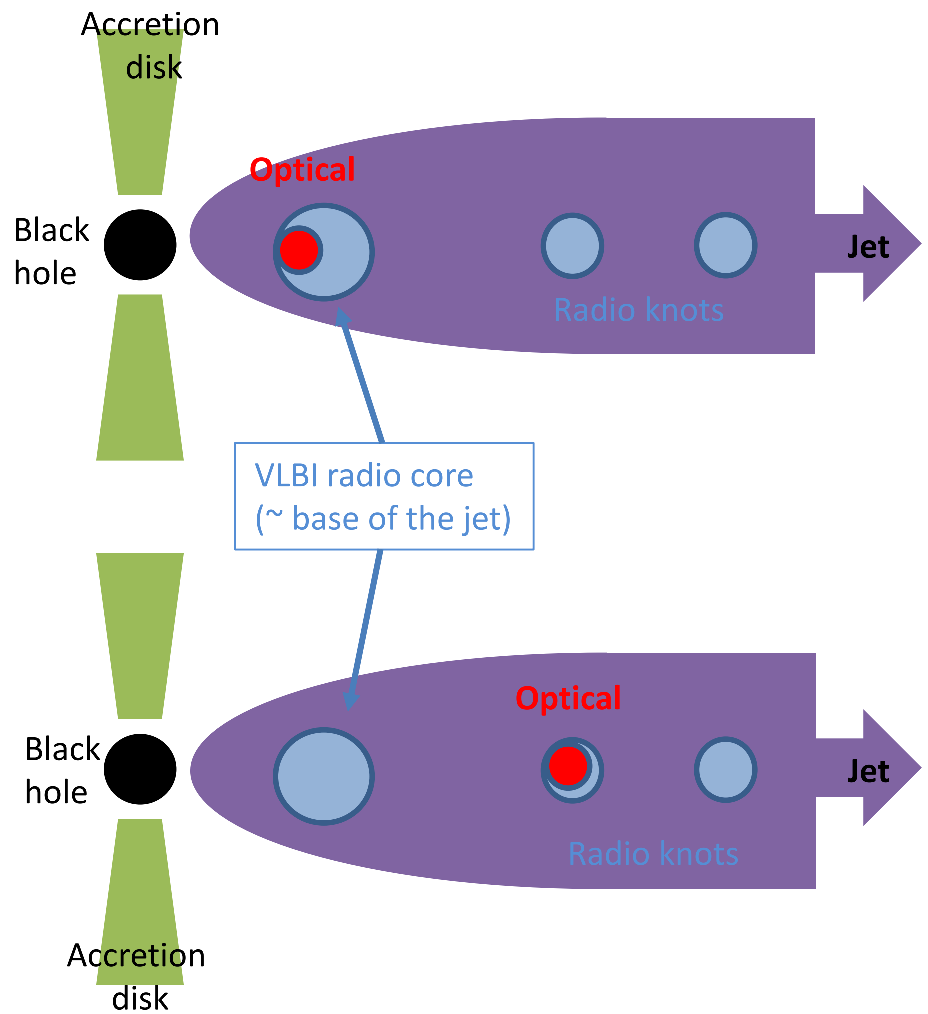
- ICRF and Gaia precisions are comparable: ~ 0.1 mas
- Positional differences reveal significant offsets between radio and optical centroids at the mas level

Cross-id 3500+ sources:



1 - AGN sample from ICRF/Gaia/MOJAVE

- Pierron et al. 2021: study ~ 350 AGN
  - Gaia EDR3 positions *(Prusti et al, 2016, Brown et al, 2021)*
  - ICRF3 positions at 'X-band' at 8.4 GHz *(Charlot et al, 2020)*
  - MOJAVE modelfit at 15 GHz *(Lister et al, 2019)*
  - Complementary to previous studies
- Coincidence between Gaia centroid and MOJAVE components:
  - 45% associated with the VLBI radio core
  - 45% associated with a knot downstream in the VLBI jet
  - Only ~ 10% cases with no apparent coincidence



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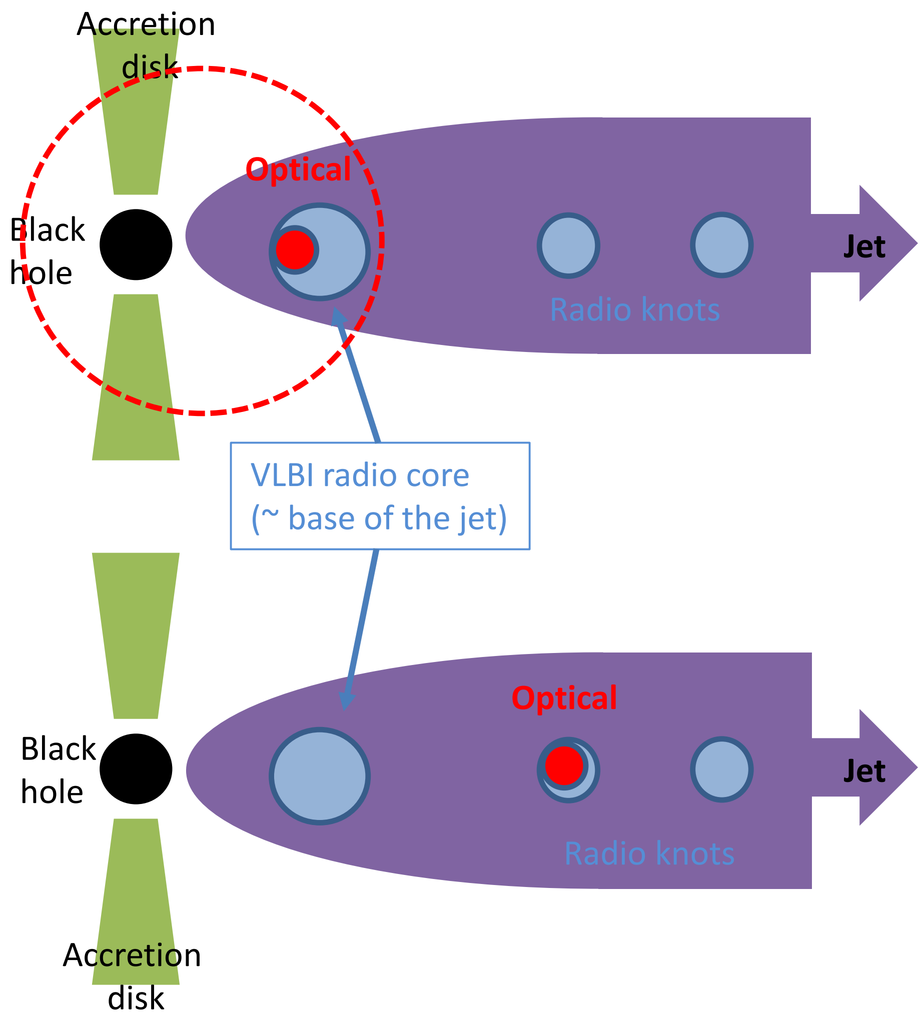
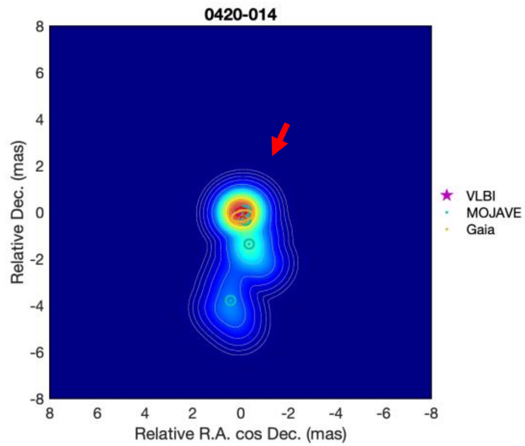
  - Complementary to previous studies

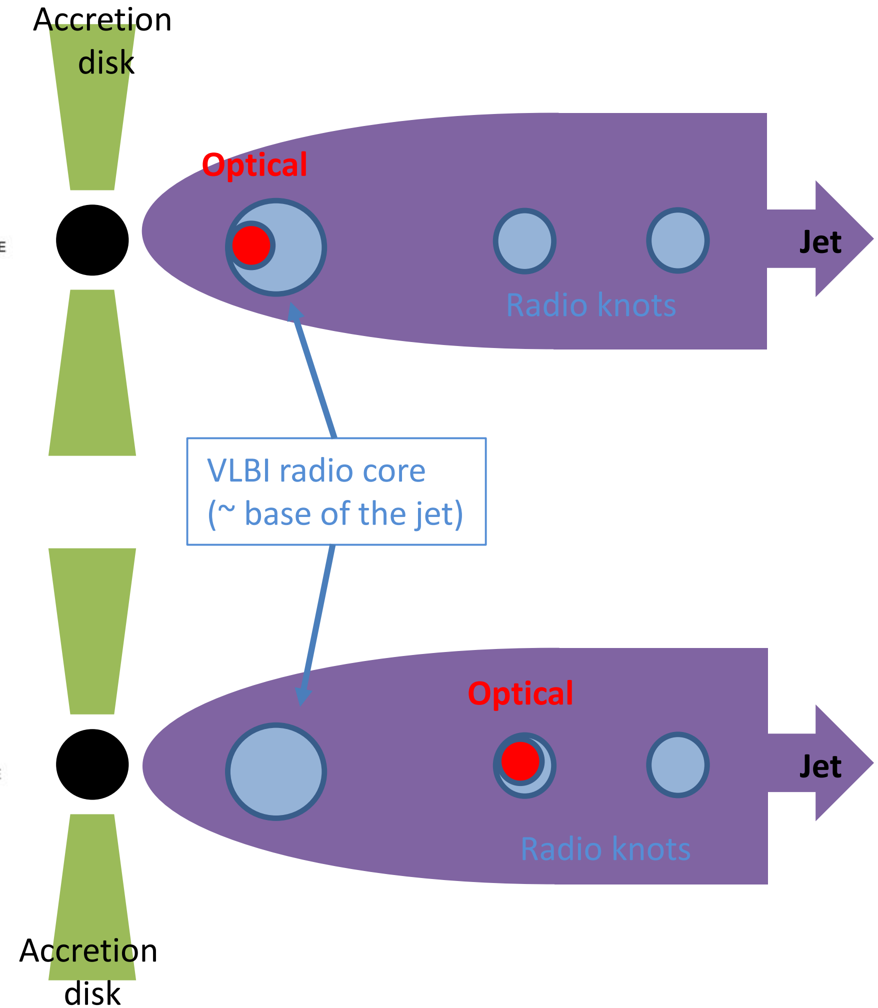
- Coincidence between Gaia centroid and MOJAVE components:
  - 45% associated with the VLBI radio core → optical from disk or jet?
  - 45% associated with a knot downstream in the VLBI jet
  - Only ~ 10% cases with no apparent coincidence

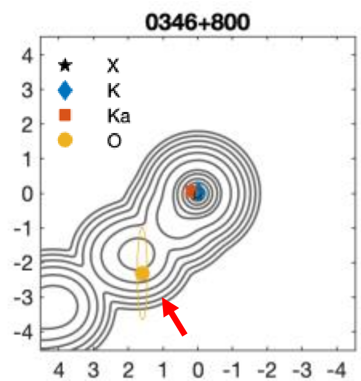


2 main populations of radio-VLBI « Gaia AGN »

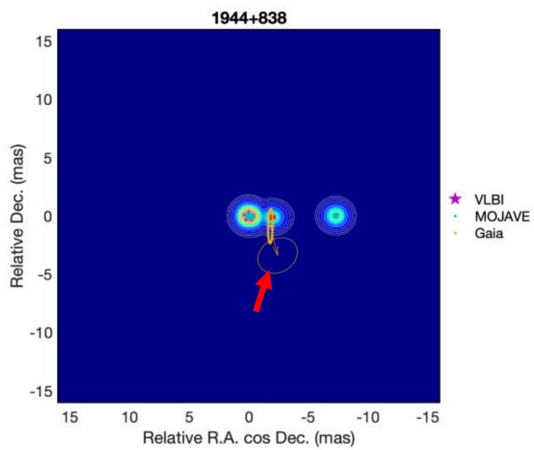


(Pierron et al, 2021)



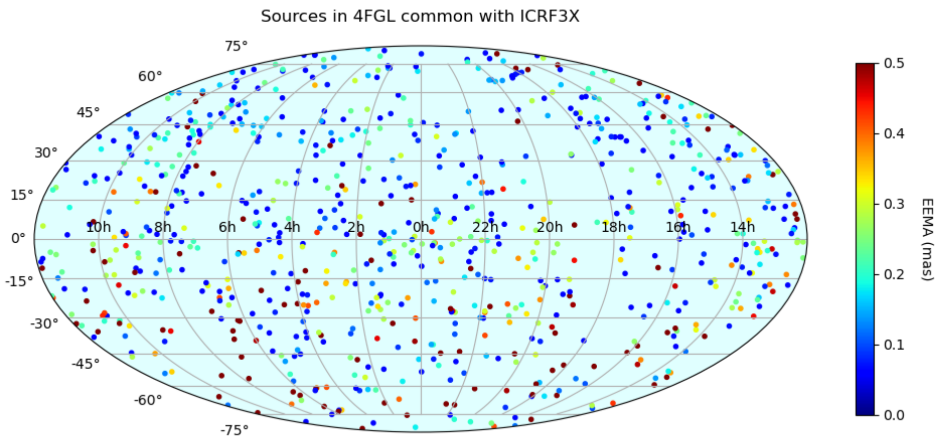


(Lambert et al, 2021)



Hereafter use the **angular distance r (radio-optical, or VLBI core-Gaia separation)** between the positions of the radio centroid ('X'-band VLBI at 8.4 GHz) and the optical centroid (Gaia) as the main parameter of the study

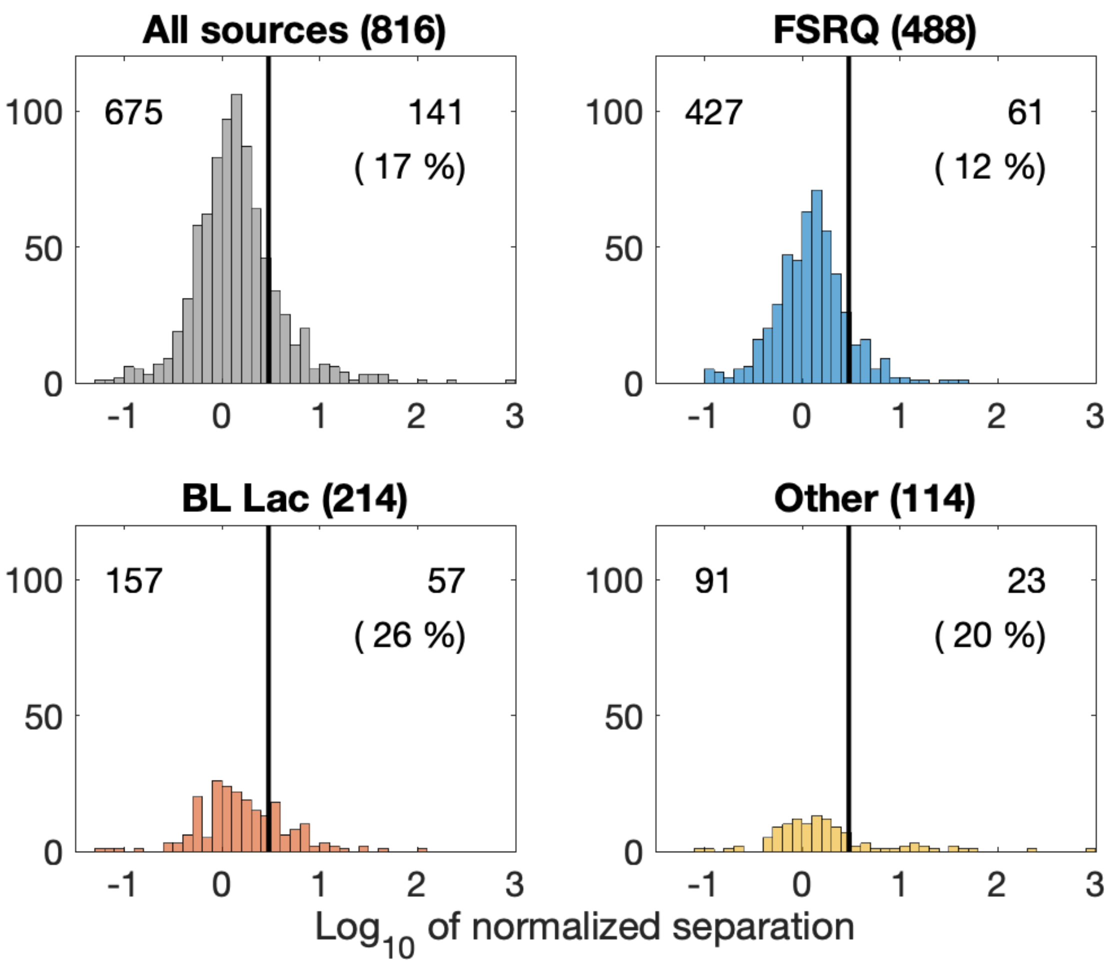
AGN sample from ICRF/Gaia/Fermi LAT



816 sources among which:
488 FSRQ
214 BL Lac

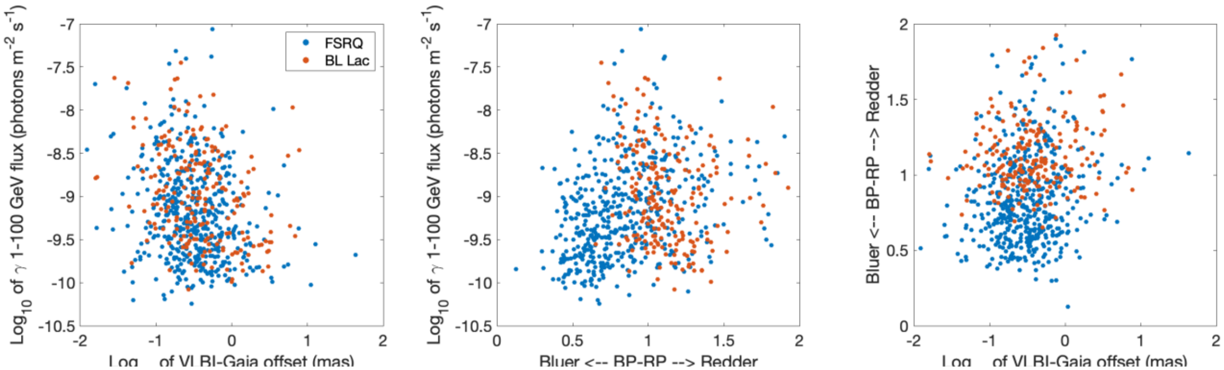
- Positions:
  - X-band at 8.4 GHz: ICRF3 (Charlot et al. 2020)
  - Optical: Gaia EDR3 (Prusti et al. 2016, Brown et al. 2021)
- 1-100 GeV γ fluxes: Fermi-LAT 4FGL-DR3 (Abdollahi et al, 2020, 2022)
- Other information
  - Object class: Fermi-LAT
  - Color index: Gaia EDR3 BP-RP

Distribution of the radio-optical normalized separation

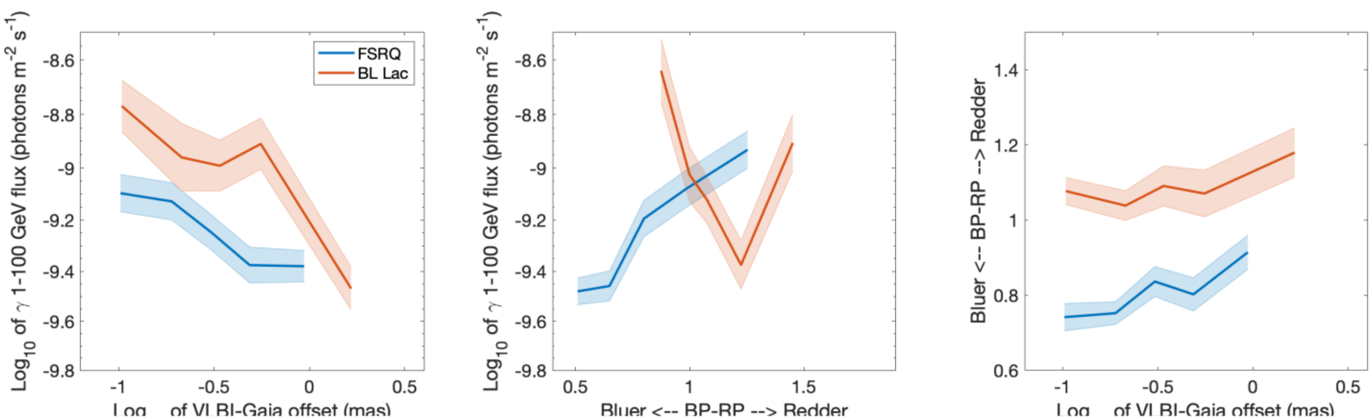


Black vertical lines = separation of 3σ

Search for trends between separation r, F_γ and Gaia color index



All AGN in sample



Median of y-quantity in bins of x-quantity with equal nb of AGN

FSRQ : globally bluer than BL Lac --- > expected at least from disk emission

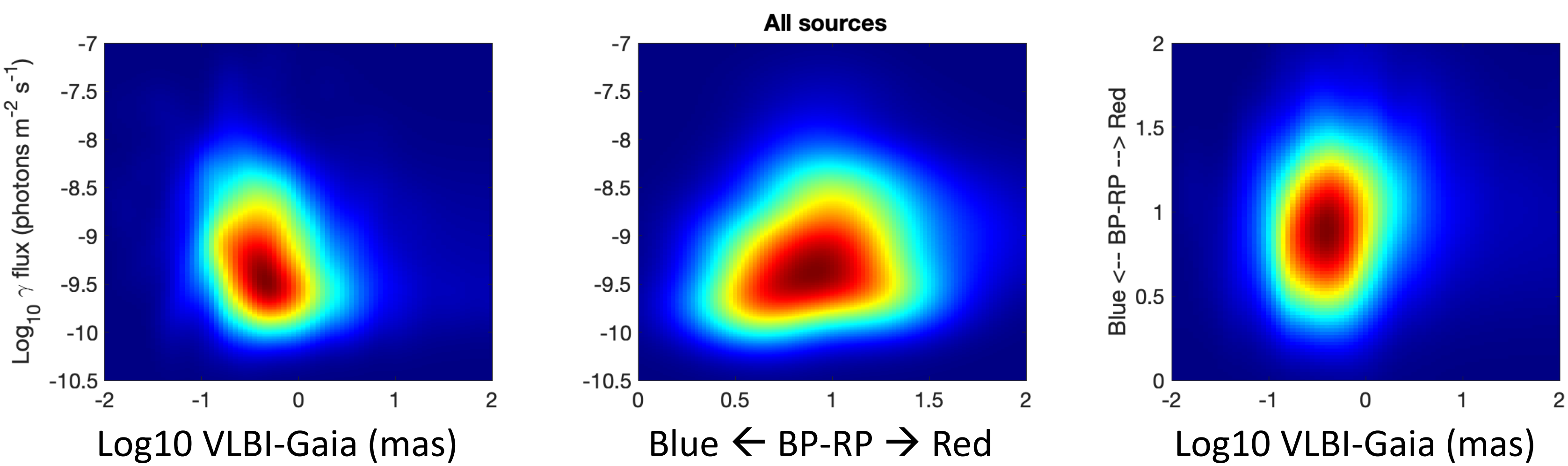
Global decrease of F_γ with increasing separation r

BL Lacs : possible two sub-groups ?

- Short-to-moderate separation r, globally higher F_γ flux, intermediate color index
- Longer separation r, globally weaker F_γ, redder color index

Kernel Smoothing Density (KSD) of distribution patterns

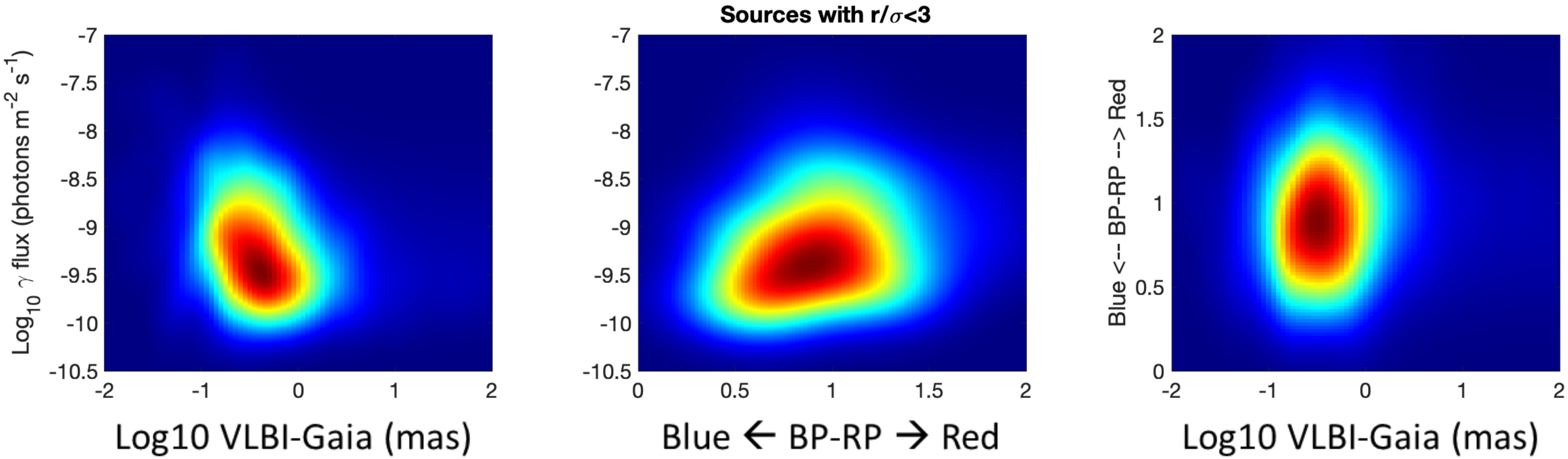
- Whole ICRF/Gaia/Fermi-LAT sample



- As the separation r increases: F_γ globally decreases and sources become redder
- Highest F_γ are for intermediate color indices
- Strongest γ-ray sources globally correspond to optical emission close to the base of the jet (small r).

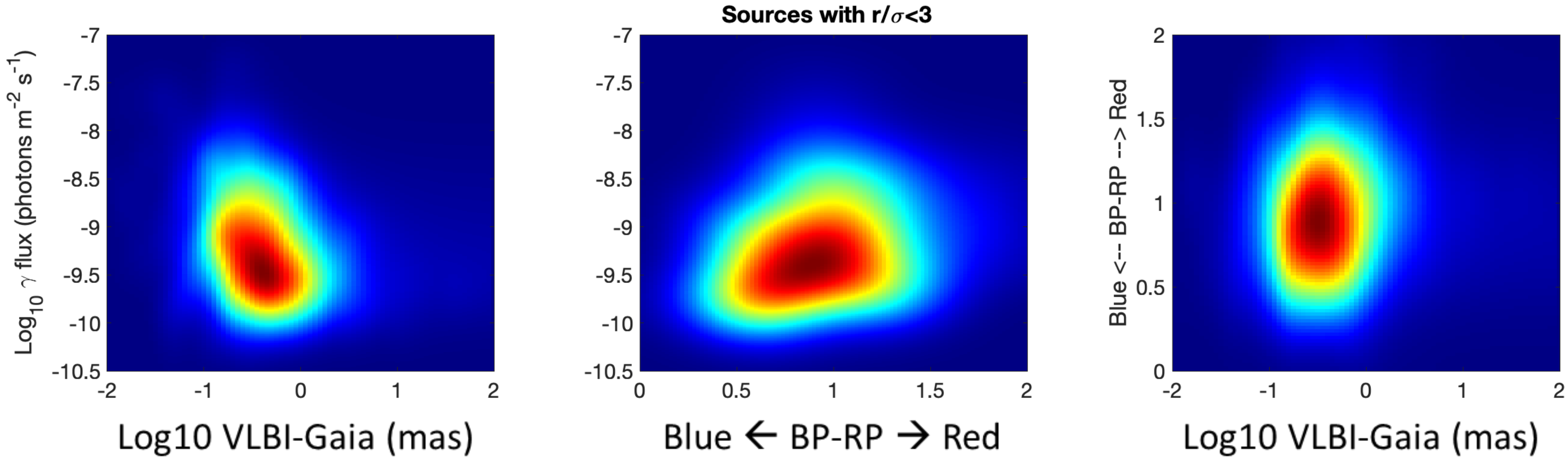
At small r, optical emission can be from disk or jet depending on synchrotron peak

- Sources with low or non-significant r (r/σ < 3):   optical < -- > core/disk



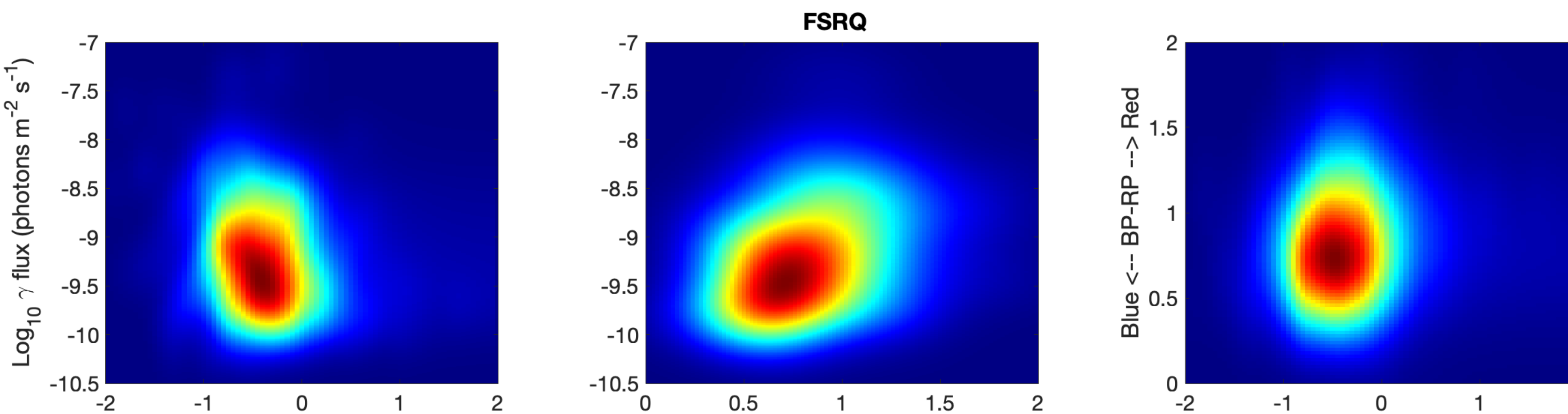
- F_{γ} globally decreases with increasing r and with bluer color index
- Color index becomes redder with increasing r (possible disk effect)

- Sources with low or non-significant r (r/σ < 3): optical < -- > core/disk

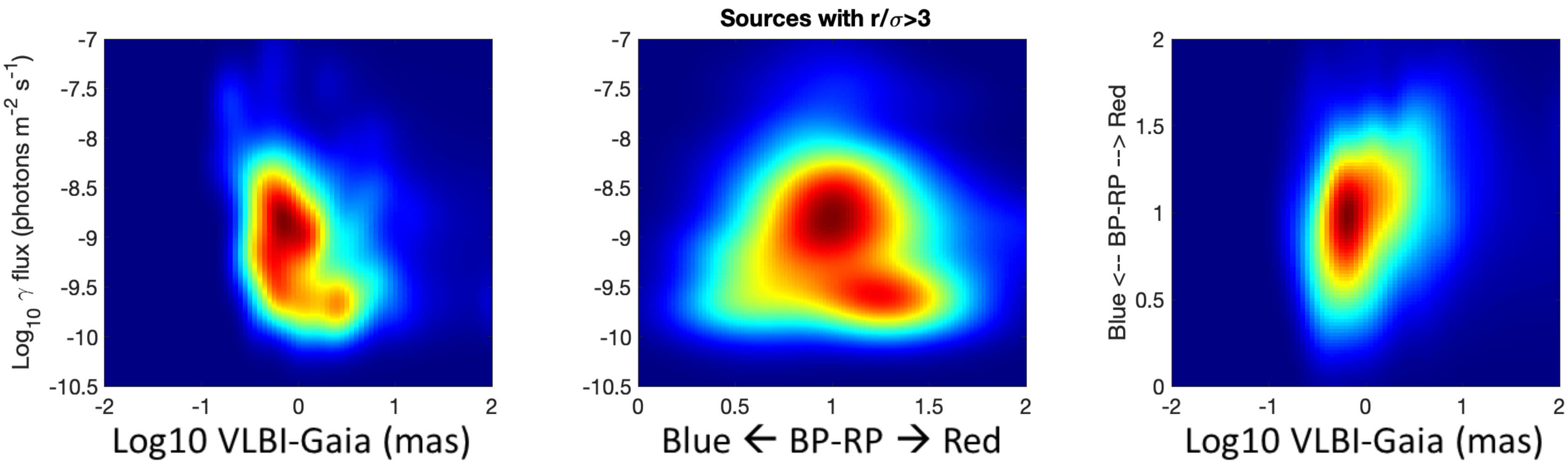


- F_γ globally decreases with increasing r and with bluer color index
- Color index becomes redder with increasing r (possible disk effect)

- Population of FSRQ: no strict overlap but strong similarities



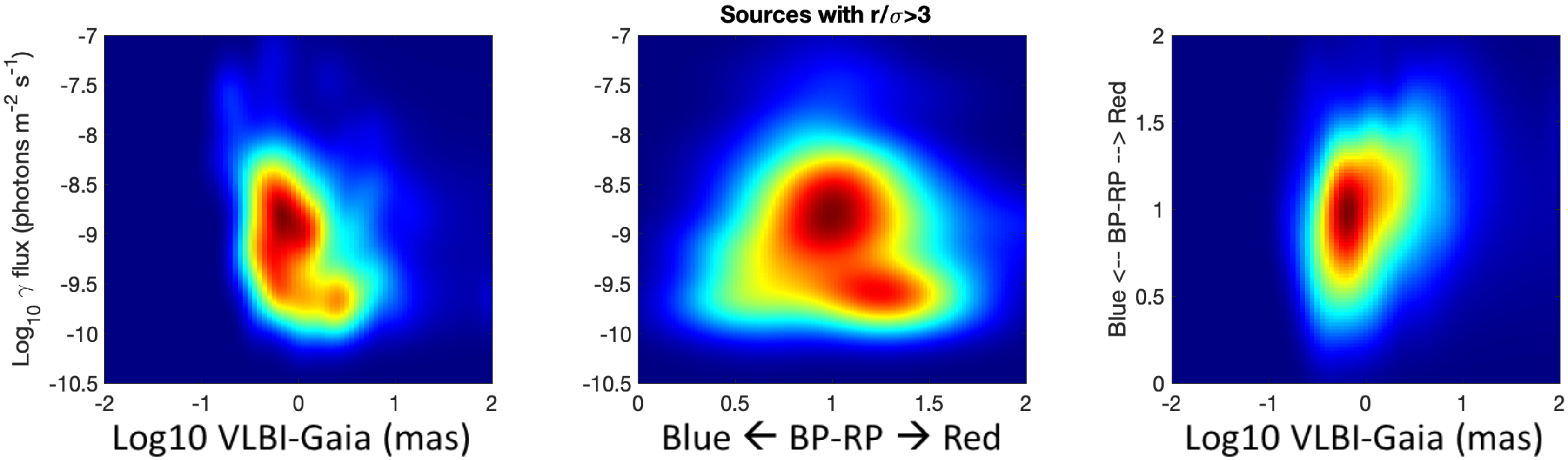
- Sources with high r (r/σ >3): optical < -- > jet components



Two sub-groups:

- Intermediate r, globally highest F_γ, intermediate color
- Large r, globally weaker F_γ, reddest sources at largest r

- Sources with high r ($r/\sigma > 3$): optical < -- > jet components



Two sub-groups:

- Intermediate r, globally highest F_γ, intermediate color
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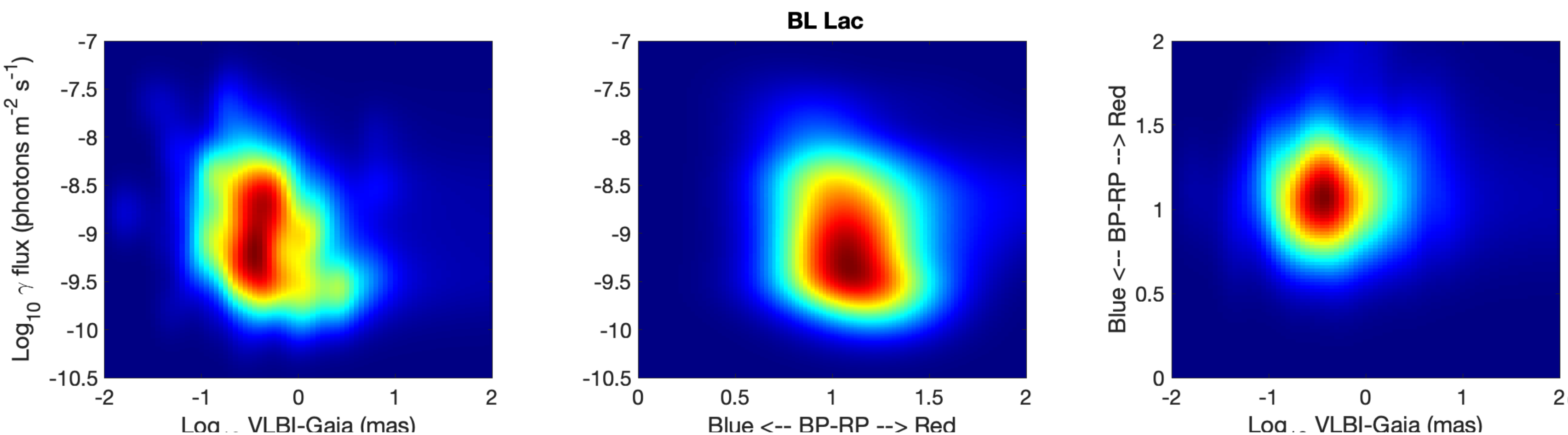
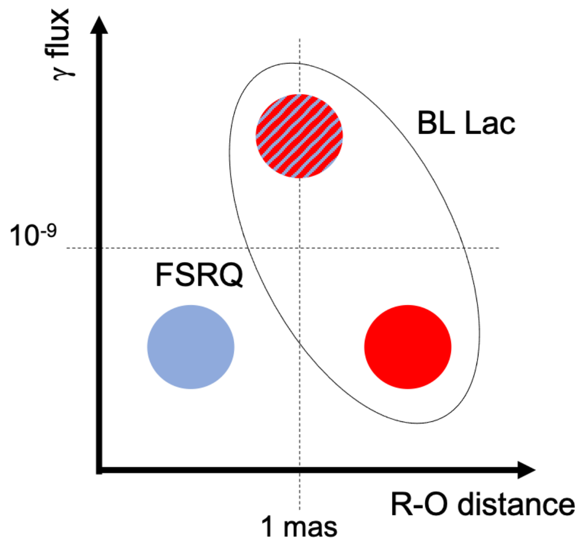
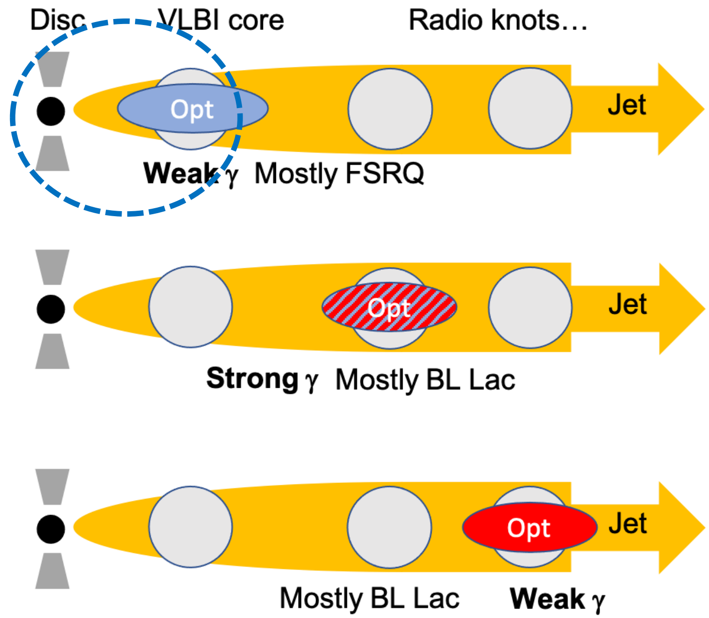
- Population of BL Lacs: no strict overlap but similarities



Possible sketch between r, Fγ and color index





- γ flux linked to the location and color index of the optical centroid
- Bluer optical, small or non significant r, mostly FSRQ : disk emission + globally weaker γ flux due to absorption by ambient photons (disk and BLR)?
- Intermediate color index and relatively small r, mostly BL Lac with emission in the first 1 mas of the jet : strong γ emission from particle acceleration in BH magnetosphere and jet base
- Redder optical, mostly BL Lac with jet influence : weaker γ flux possibly due to reacceleration of particles in weaker reconfinement shocks
- Possible signature of perturbation propagating along successive stationary shocks, as observed in several BL Lacs *(Hervet et al, 2019, Kramarenko et al, 2022)* *cf Hervet's talk*

Conclusion

- Detailed studies combining astrometric VLBI and Gaia data with MOJAVE data showed that 45% of Gaia centroids are coincident with the VLBI radio core (or disk), and 45% at large r are coincident with a radio knot in the VLBI jet
- The "ICRF3/Gaia/LAT" sample brings together fairly homogeneous populations (existence of scaling laws)
- In the parameter space ‘separation r’, ‘F_γ‘and ‘optical color index’: similarities between “low r sources” and “FSRQ”, and between “large r sources” and “BL Lacs”, but no strict overlap
- For large r sources : **the Gaia centroid provides an interesting tool to locate the gamma-ray emitting site**. Two sub-groups appear, at intermediate and larger r, with decreasing activity along the jet.
- For low r sources : Gaia centroid can also locate the dominant γ site for BL Lacs (or weak disk sources). More difficult situation for FSRQ, analysis in progress. Need a way to disentangle the optical NT synchrotron emission from the optical bright disk emission

  --- > future astrometric accuracies from both VLBI and Gaia able to distinguish between the disk and the radio core positions?

  --- > optical data (spectra, polarization) able to distinguish between disk or NT synchrotron emission for the optical emission located by Gaia

Perspectives

- Next steps
  - Introduce redshifts and other individual characteristics of the sources, including more detailed classifications of BL Lacs (HBL, IBL, LBL)
  - New samples from new Gaia releases and improved VLBI catalogs with improved accuracy and increased number of sources
  - Consider temporal evolution of astrometric and photometric quantities. Take proper motions into account when available
- Future needs coordination between simultaneous observations in optical, radio, and γ

Improving reference frames will improve the modeling of AGN jets
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