VLBI in the Age of Fermi and Gaia

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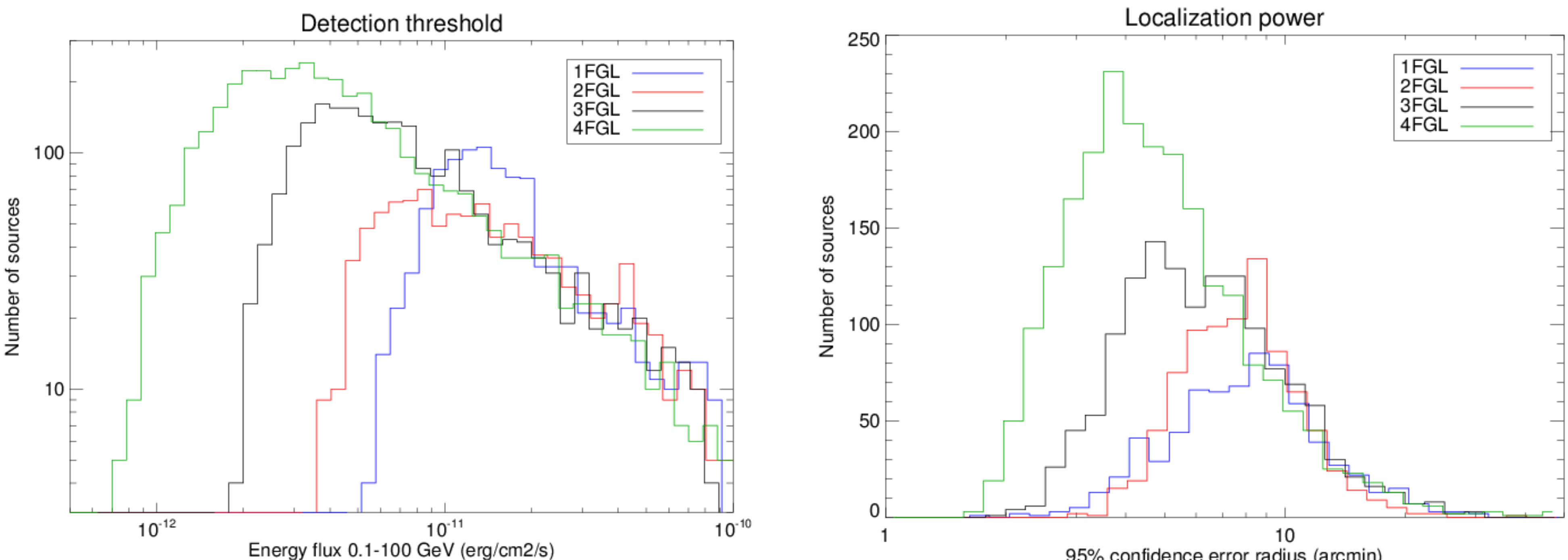
10 years of the Fermi Gamma-ray Space Telescope

- Launched: June 2008; Two instruments:
  Large Area Telescope (LAT) & Gamma-ray Burst Monitor (GBM)

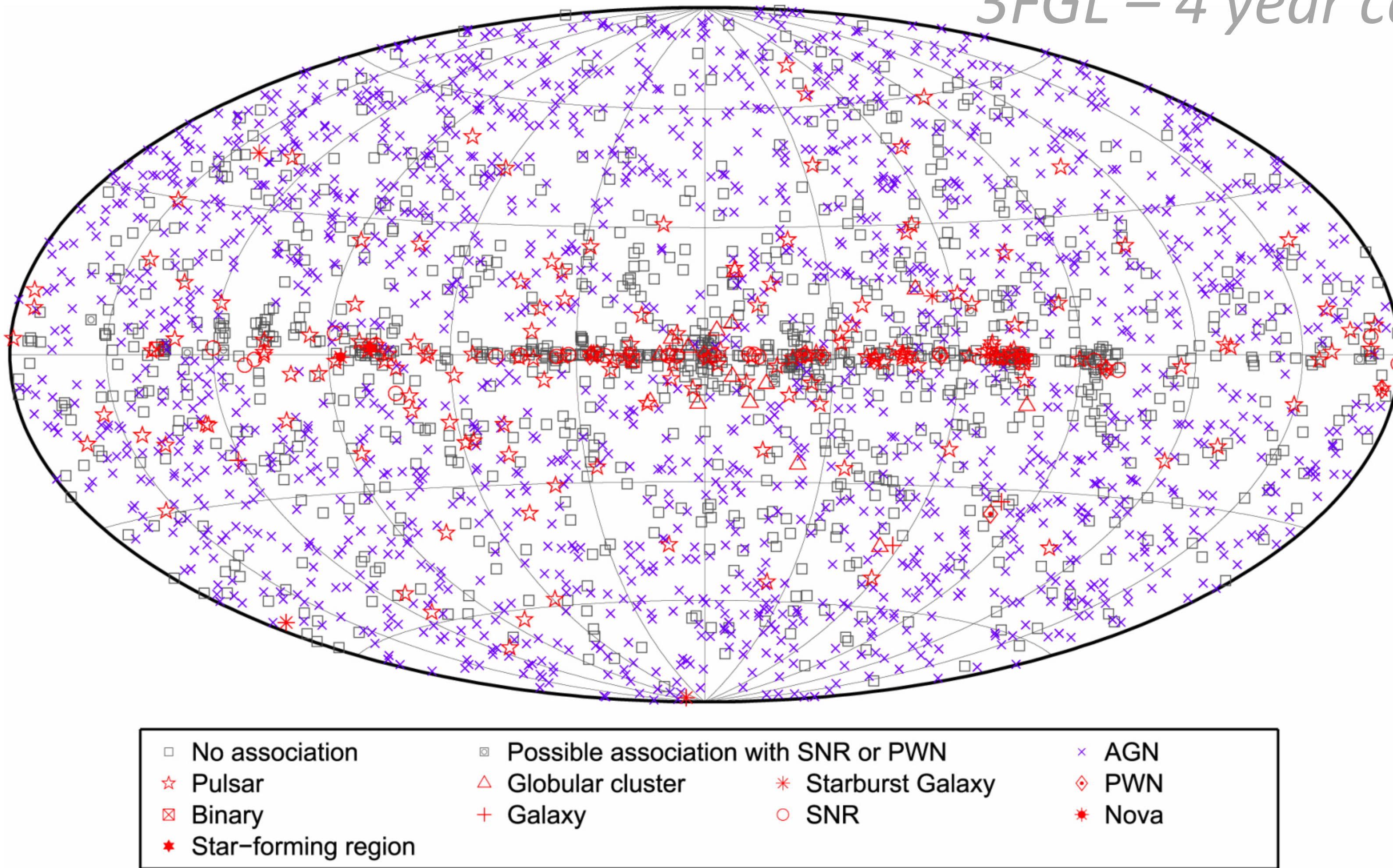
- Imaging gamma-ray detector (pair-conversion)/20 MeV – 300 GeV
- FOV ~20% of the sky
- default: full sky observed every 3 hours



J. Ballet (2017)

AGN dominate the γ-ray sky

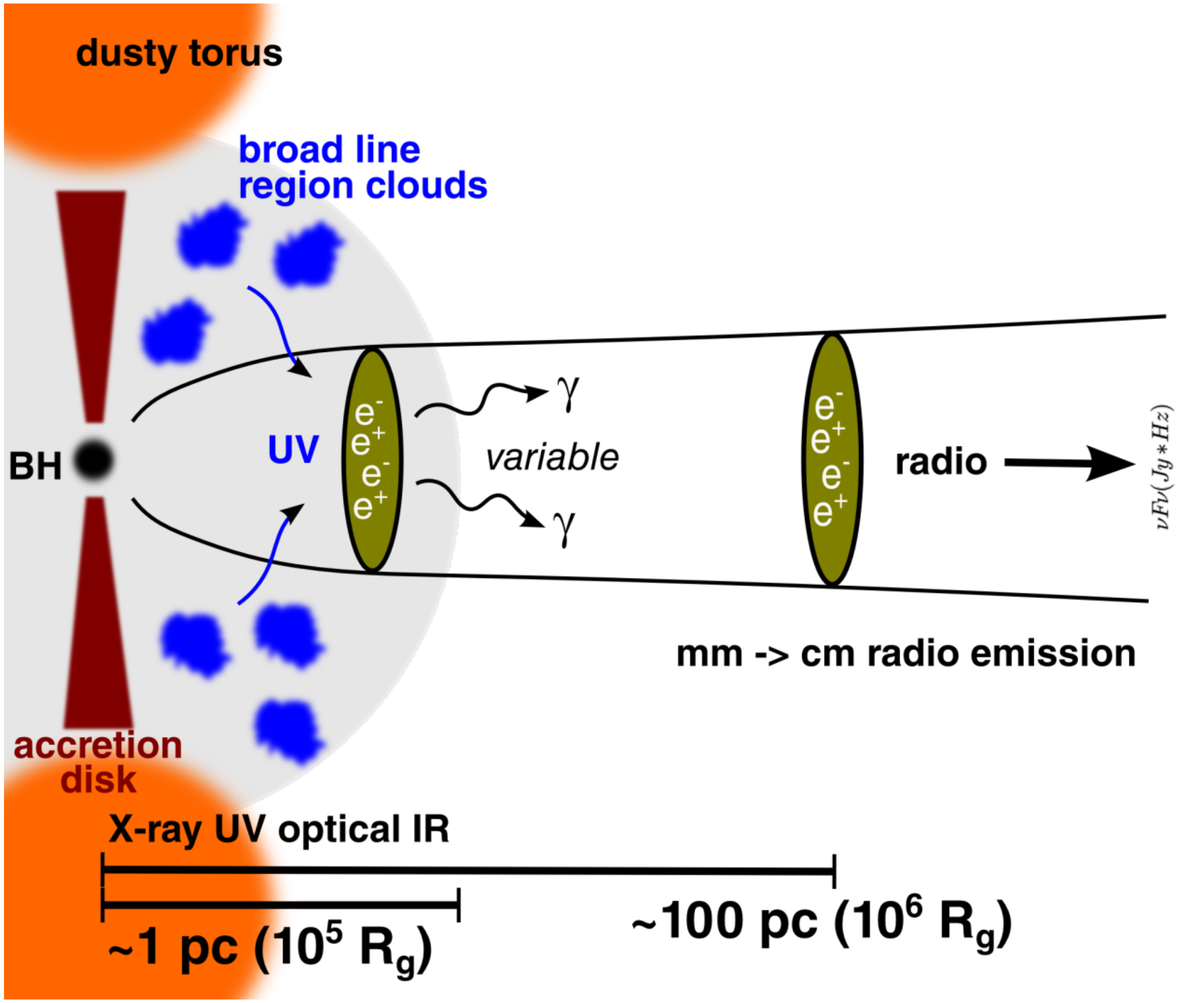
3FGL – 4 year catalog

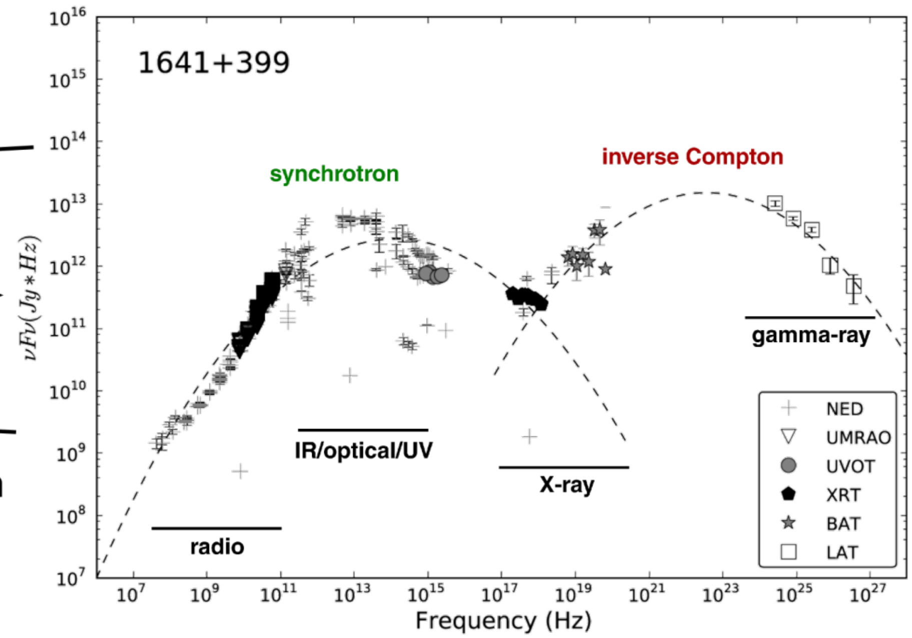


Acero et al. (2015)

>1100 (36%) are AGN out of 3033 γ-ray objects found integrating four years

Emission from AGN



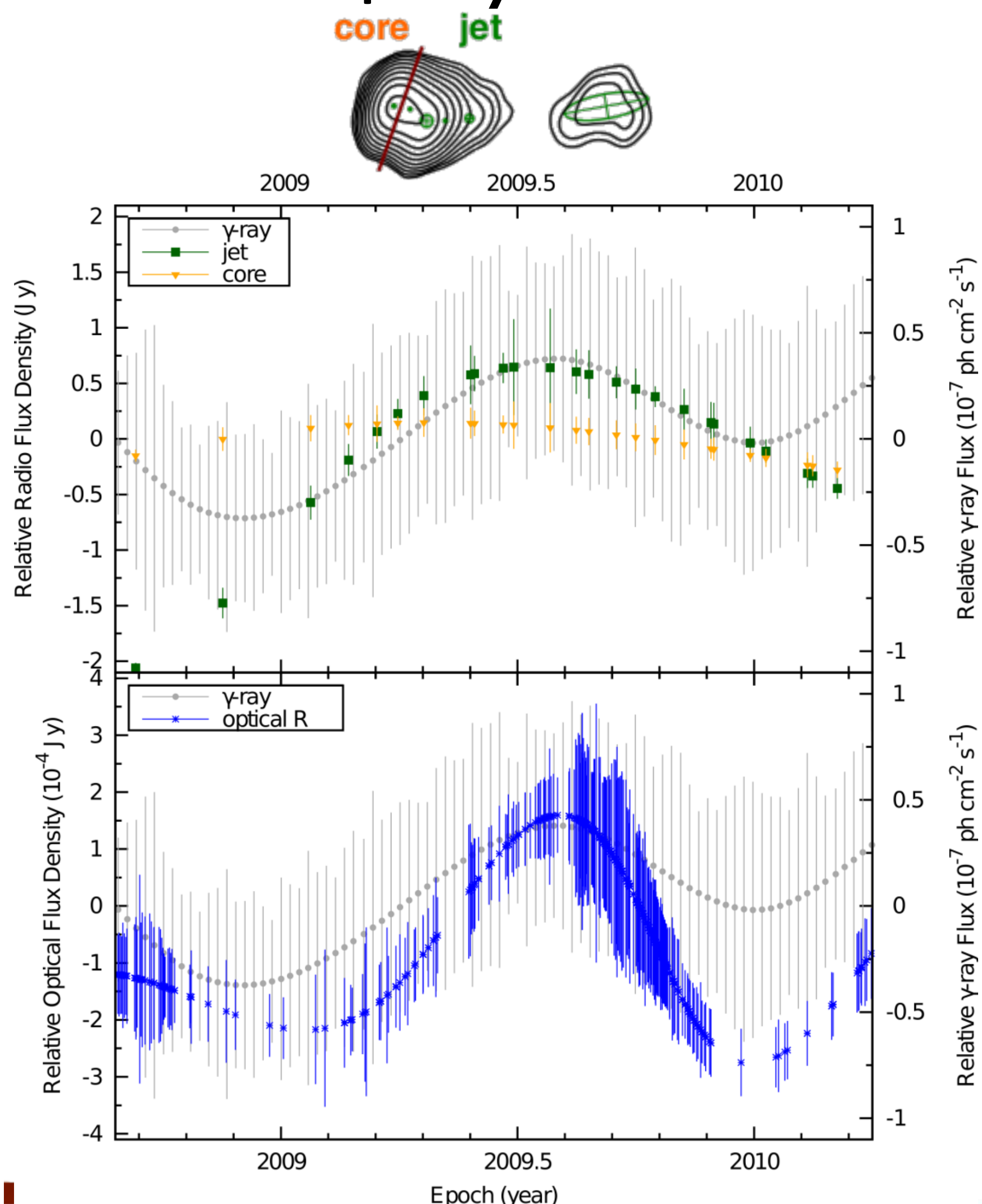


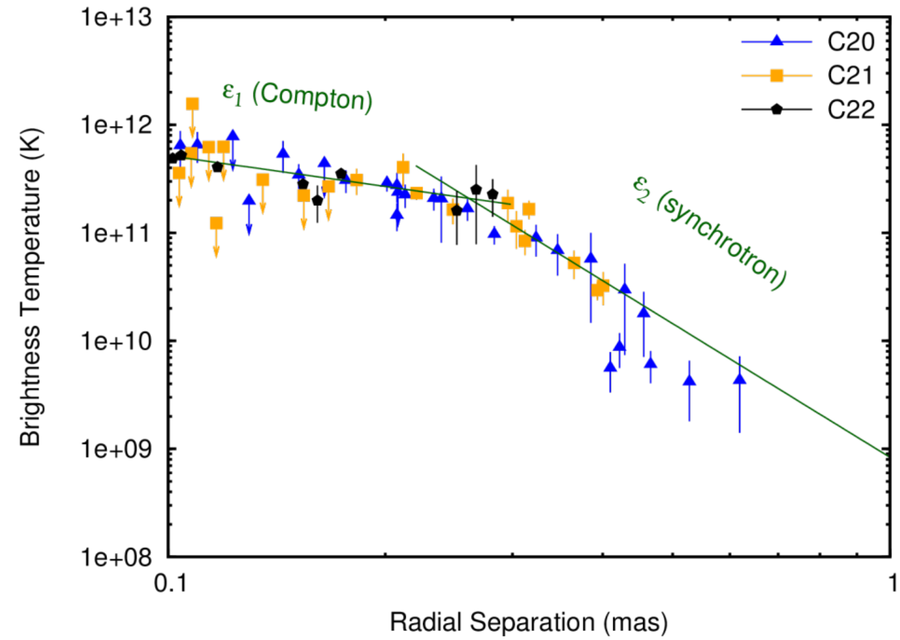
Chang (PhD, 2010)

Emission Mechanisms:

- Leptonic: SSC, EC
- Hadronic: p-p, etc.

3C345: γ-ray vs radio

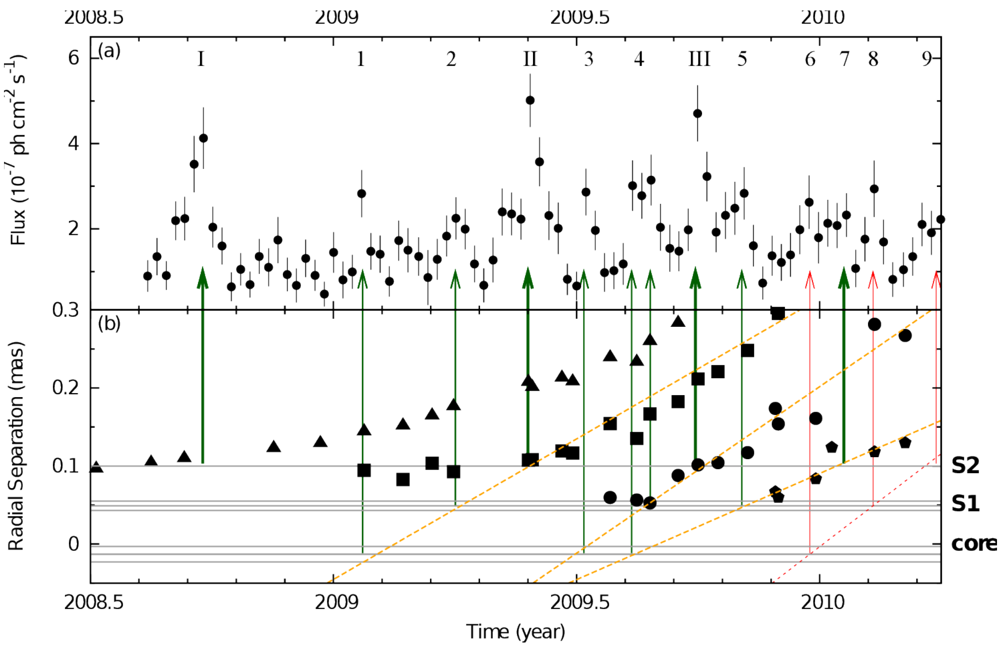


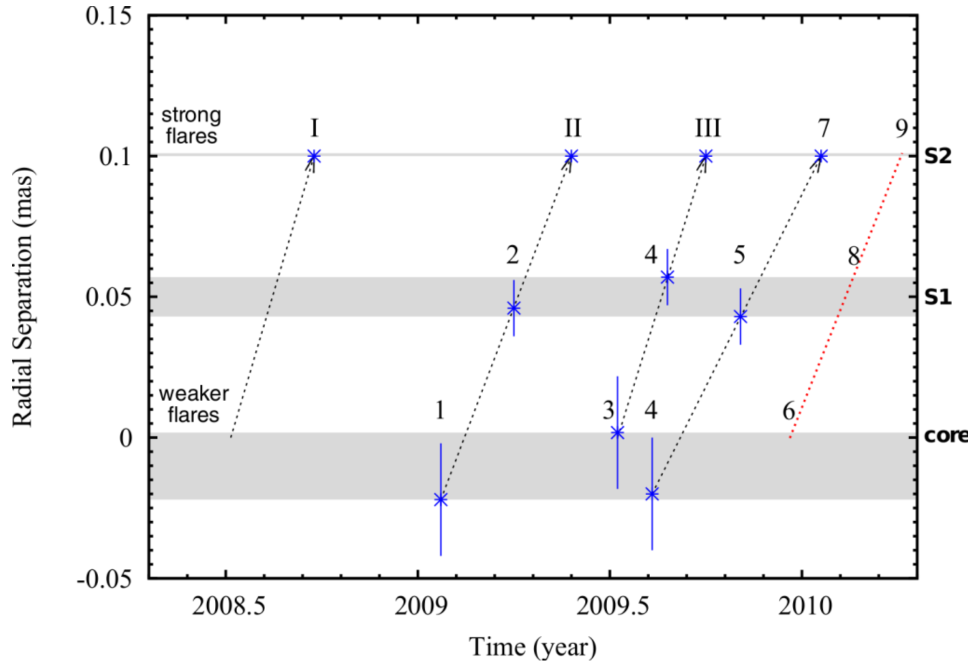


- Trends of jet radio and optical flux density evolution correlate with γ-rays.
- <=0.3 mas (~ 36 pc from the BH) from the 43 GHz core dominated by inverse Compton losses.

3C345: γ-ray vs radio

0.1-300 GeV

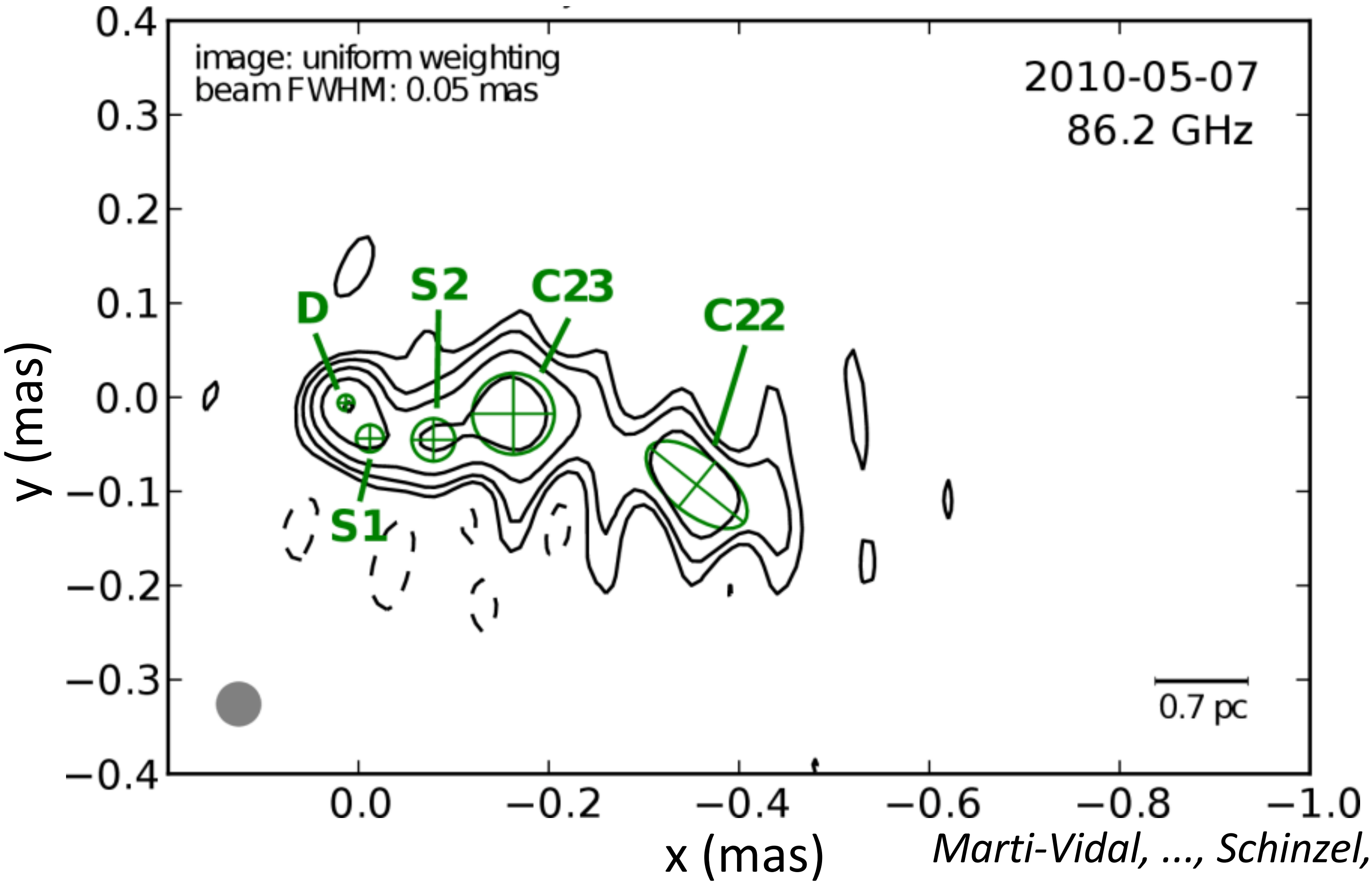




Distances calculated under the assumption of interaction of moving with stationary features in the jet, producing γ-ray flares during passage.

Predicts stationary jet features at the location of the "core", S1, and S2.

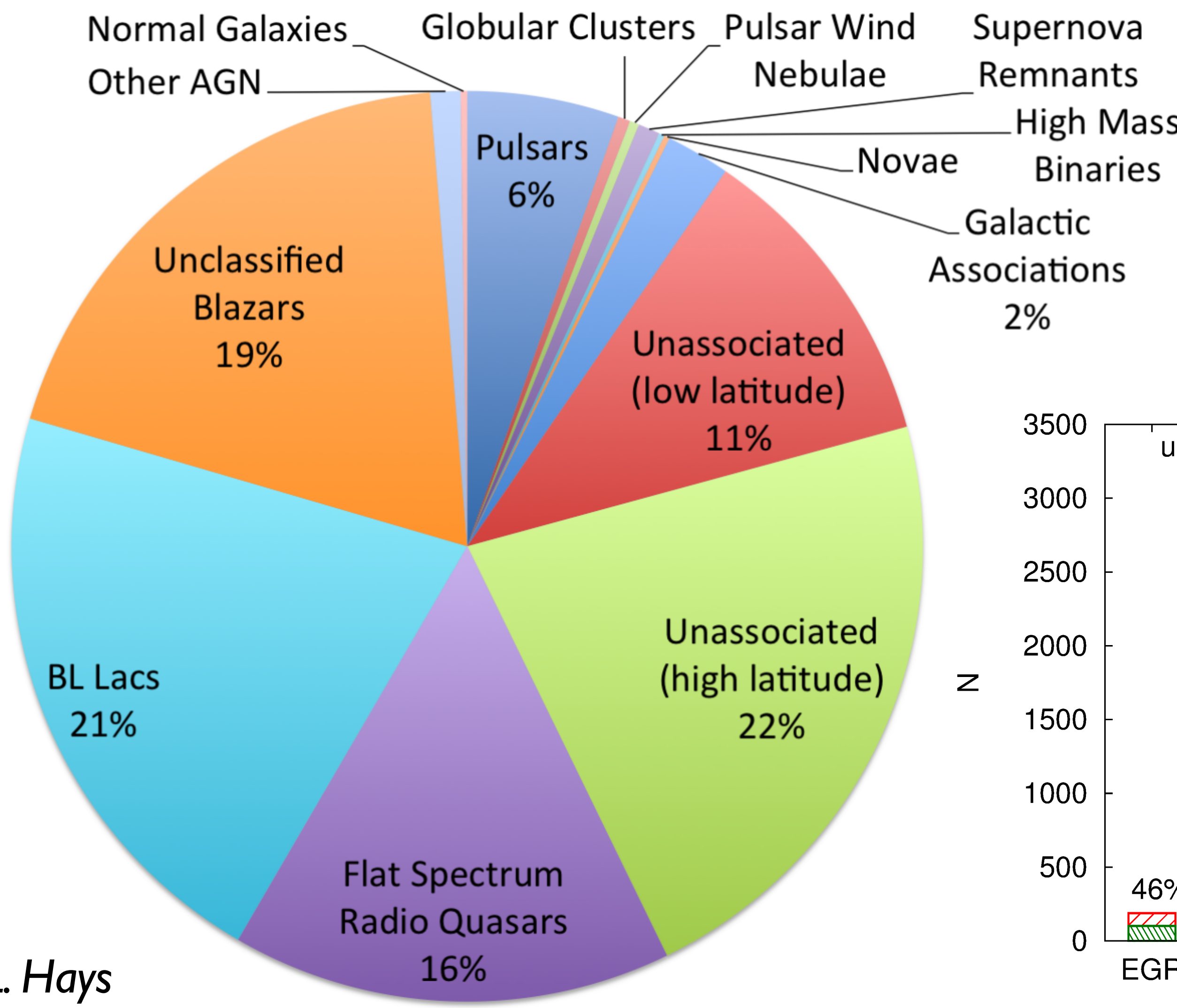
3C345: GMVA Image



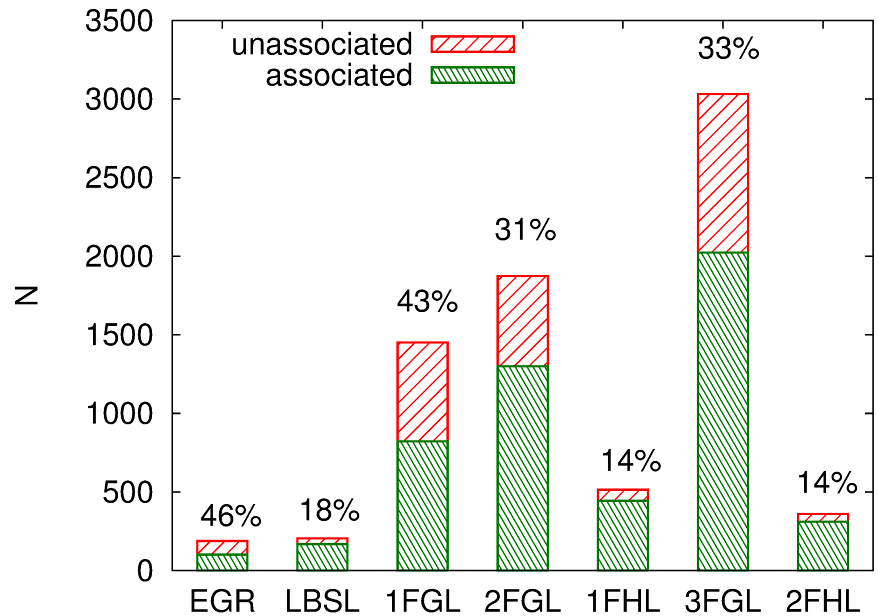
Marti-Vidal, ..., Schinzel, et al. (2012)

Confirms existence of predicted triple structure, D, S1, and S2!

3FGL



33% of detected point sources have no known multi-wavelength counterpart



L. Hays

Attempts to find counterparts

- Search for Pulsar counterparts (radio, gamma-ray data)
  e.g. Pleunis et al. (2017), Frail et al. (2017)

- Mining existing catalogs (WISE, NVSS, FIRST etc.)
  e.g. Maselli et al. (2013), Massaro et al. (2012)

- Machine Learning
  e.g. Saz Parkinson et al. (2016)

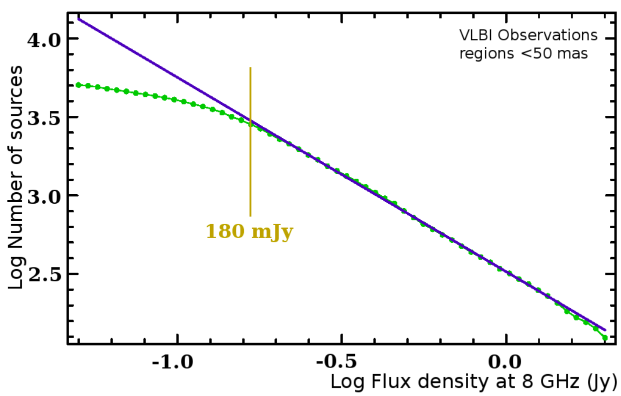
- **Radio surveys (VLA, VLBA, ATCA, LBA, ALMA, SPT)**
  e.g. Petrov et al. (2015), Schinzel et al. (2017), Giroletti et al. (2015)

VLBI + γ-ray -> new γ-ray loud AGN

Based on the distribution of known VLBI detected, γ-ray loud AGN we can derive a statistical likelihood that a detected mas-scale object is associated with a γ-ray source with arcmin localization.

Observation Program:

- **ATCA & VLA 5-10 GHz observations of *every* unassociated γ-ray source**
- **VLBI follow-up of VLA/ATCA detected radio sources**



In 2012:
Catalogs incomplete/flux limited for compact sources <180 mJy at 8 GHz.

About 7000 objects with mas scale emission known, almost all AGN.

VLBI + γ-ray -> new γ-ray loud AGN

Results:

- **~2 VLBI targets per γ-ray field**
- **Added >200 new AGN associations**
  (about same number as identified gamma-ray Pulsars)
  >50% of gamma-ray sources have a VLBI counterpart!
- **Found association candidates for Pulsars, Supernova Remnants/HII regions**

Fermi Catalog	Associated AGN	Unassociated	Share
2FGL (2 yrs)	1054	819	56%
3FGL (4 yrs)	1584	1423	52%
4FGL (7 yrs)	2175	3005	(>)42%

References: Petrov et al. (2013, 2015) , Schinzel et al. (2015, 2017)

Summary Fermi

- 1/3 of gamma-ray point sources are unassociated
- Expand radio/gamma-ray association work to 7-year catalog (~1700 target fields) -> VLA observations underway
- VLBA+Fermi provide a dynamic view into jet physics major programs:
  - MOJAVE (Lister et al.)
  - BU Blazar monitoring program (Marscher et al.)
  - TeV BL Lac monitoring (Piner et al.)

- **VLBA plays a crucial role in associating gamma-ray loud AGN!**
- **VLBA has been one of the most important (and one of the least recognized) observatories for the physical interpretation of gamma-ray emission from AGN!**

State of absolute astrometry by 01/01/2018

The state-of-the art catalog: the Radio Fundamental Catalogue

sources: 14786

Percentile of accuracy:

20%	< 0.30 mas
50% (median)	< 0.90 mas
80%	< 2.50 mas
90%	< 5.20 mas
94.8%	< 10.0 mas

Contributors:

VLBA:	**87%**
LBA:	8%
CVN:	4%
IVS:	1%

Flux density @ X-band: [0.003, 22] Jy, median: 101 mJy

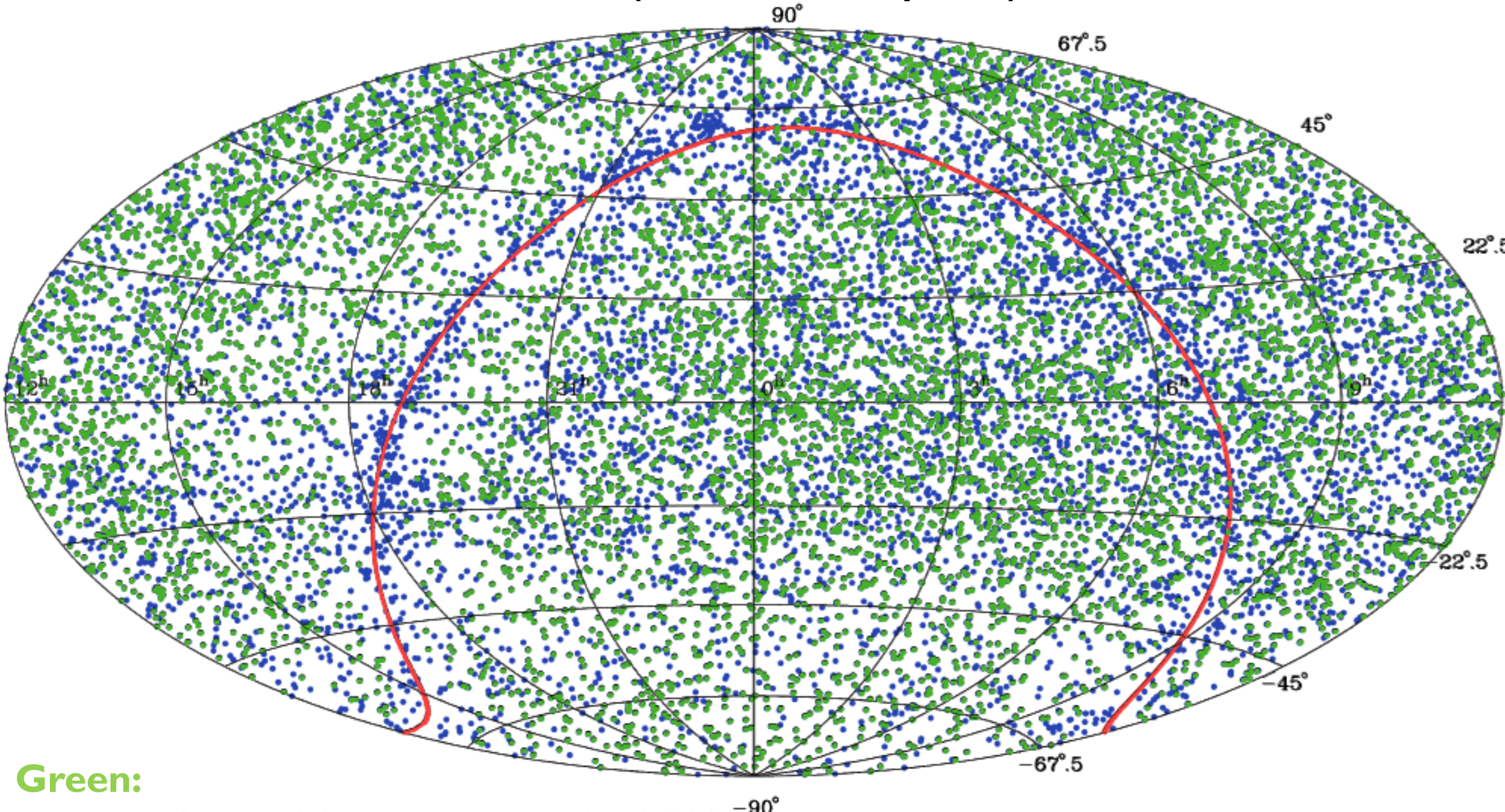
Results of ongoing dedicated VLBI absolute astrometry programs for 27000 sources since 1997 using over 8000 hours.

56,811 images of 9311 compact radio sources were generated

The number of matches of the RFC:

γ-ray	*Fermi*	15%
X-ray	*Chandra*	3%
infra-red	WISE	74%
infra-red	2MASS	36%
optic	*Gaia*	52%
optic	PanSTARRS	69% (78% at $\delta > -30°$)
optic	known redshifts	42%
radio	NVSS	91% (99.8% at $\delta > -40°$)
radio	TGSS	72% (76% at $\delta > -53°$)

VLBI Radio Fundamental Catalogue (**14,786 sources**) on 01/01/2018 and *Gaia* DR1 ($1.14 \cdot 10^9$ objects)

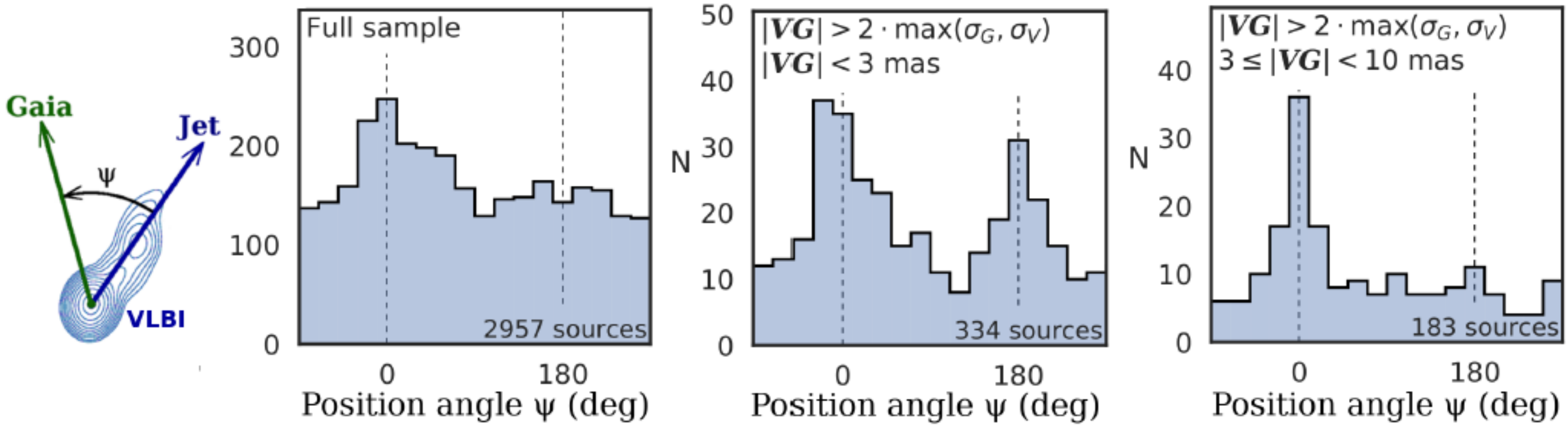


Green:

7,716 VLBI/*Gaia* matches (P<0.0002)

Blue: VLBI sources without *Gaia* matches

VLBI/Gaia offsets favor direction along the jet!



Mean *systematic* contribution: **1-2 mas**

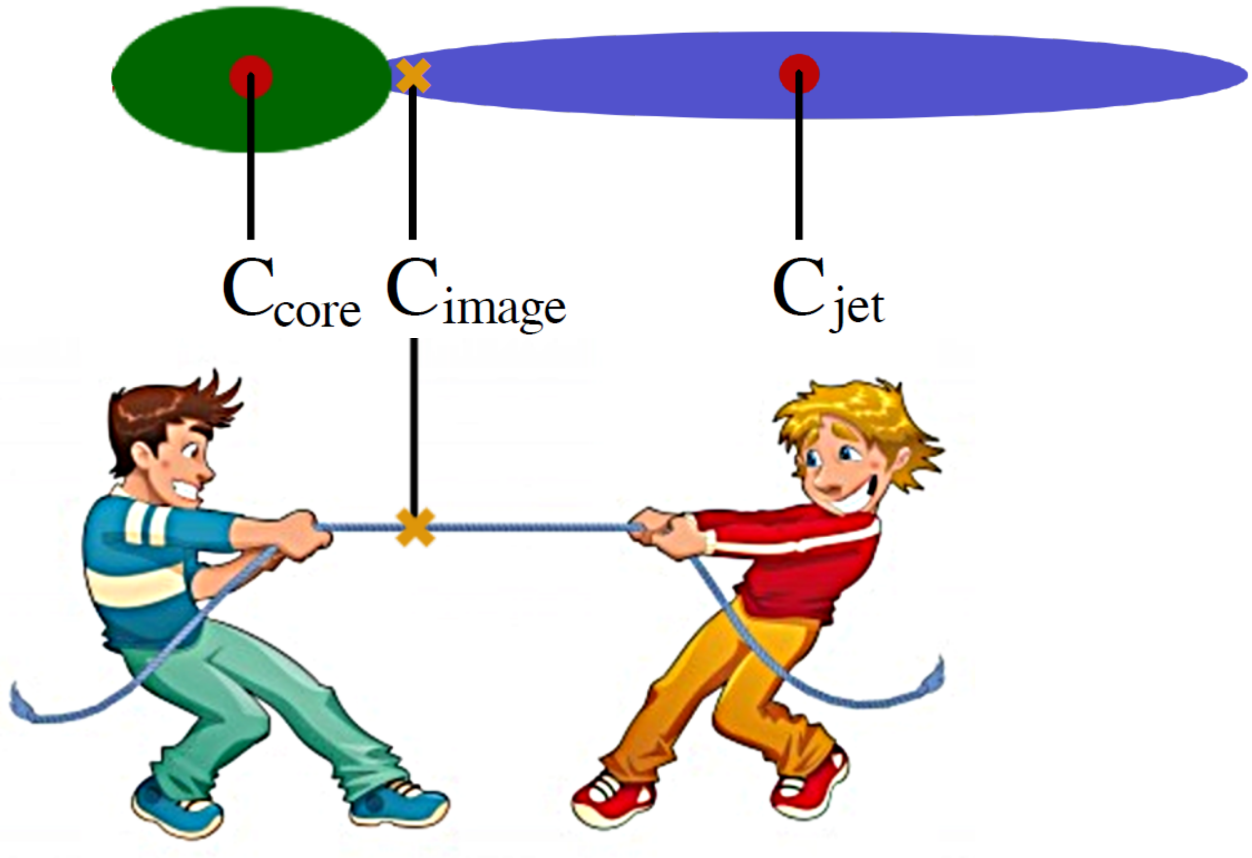
Explanation: presence of an optical jet at mas scales

Why **VLBI** and ***Gaia*** give different AGN positions?

	Gaia	**VLBI**
Records:	power	voltage
Position of an extended source	centroid	the most compact detail

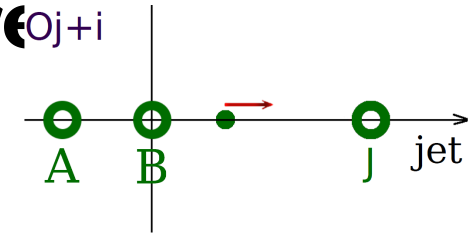
Gaia minus **VLBI** offset = position of the **centroid** wrt the **compact detail**

What will happen if one of the components becomes brighter?

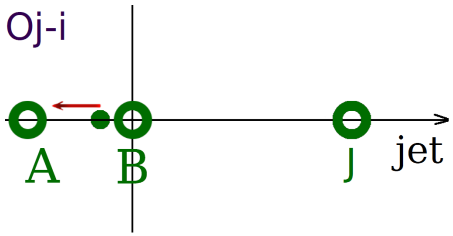


Prediction: ***Gaia*** centroid will jitter.

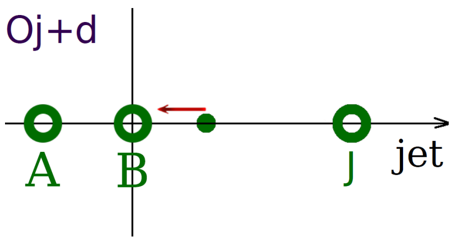
Direction of the centroid change after a flare



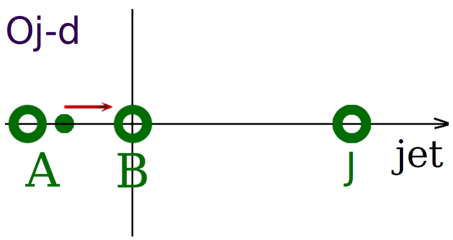
- Flare happened in the jet



- Flare happened at the accretion disk



- Flare happened at the core or accretion disk



- Flare happened at the core of the jet

Analysis of O_j time series will allow us to answer the question where the flare occurred

Summary *Gaia*

- VLBI/Gaia residuals have systematic 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;
- Consequences of the optical jet presence: source position jitter;
- Position jitter + light curve = optical resolution at mas scale;
- VLBI + Gaia -> 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**

Looking Ahead

- **Short-term (VLBA)**
  wider bandwidths, higher data rates -> increase sensitivity
  Benefit: All areas, especially AGN monitoring at high freq.
  and Gaia <-> VLBI comparison of radio-quiet AGN

- **Mid-term (eVLBA)**
  Real-time VLBI -> decrease response times
  Benefit: Rapid follow-up and feedback for e.g. gamma-ray & optical flares

- **Long-term (ngVLA)**
  filling in the *uv*-plane (baselines from 1000 km to a few km closing the 30-300 km gap)
  Benefit: All areas, better resolve spatial structure,
  increase sensitivity at the highest frequencies (3mm)

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