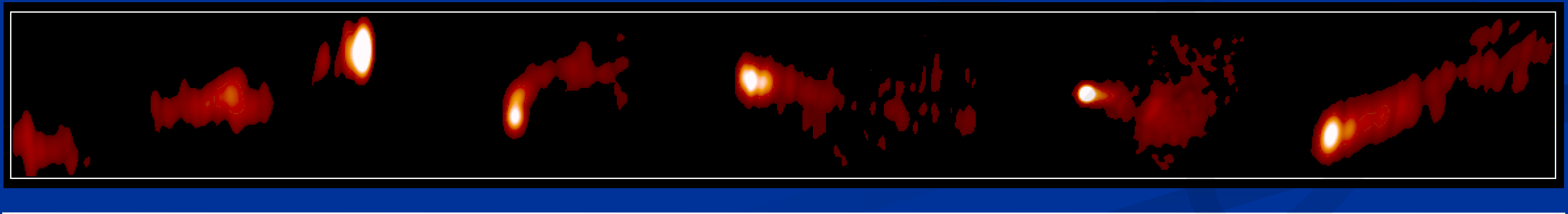
Radio/gamma-ray time delay in the parsec-scale cores of AGN

A.B. Pushkarev[1,2,3], Y.Y. Kovalev[4,1], M.L. Lister[5]

[1]Max-Planck-Institute für Radioastronomie
[2]Pulkovo Astronomical Observatory, [3]Crimean Astrophysical Observatory,
[4]Astro Space Center, [5]Purdue University



Fermi meets Jansky – AGN at Radio and Gamma-Rays
Bonn, June 22, 2010

Motivation

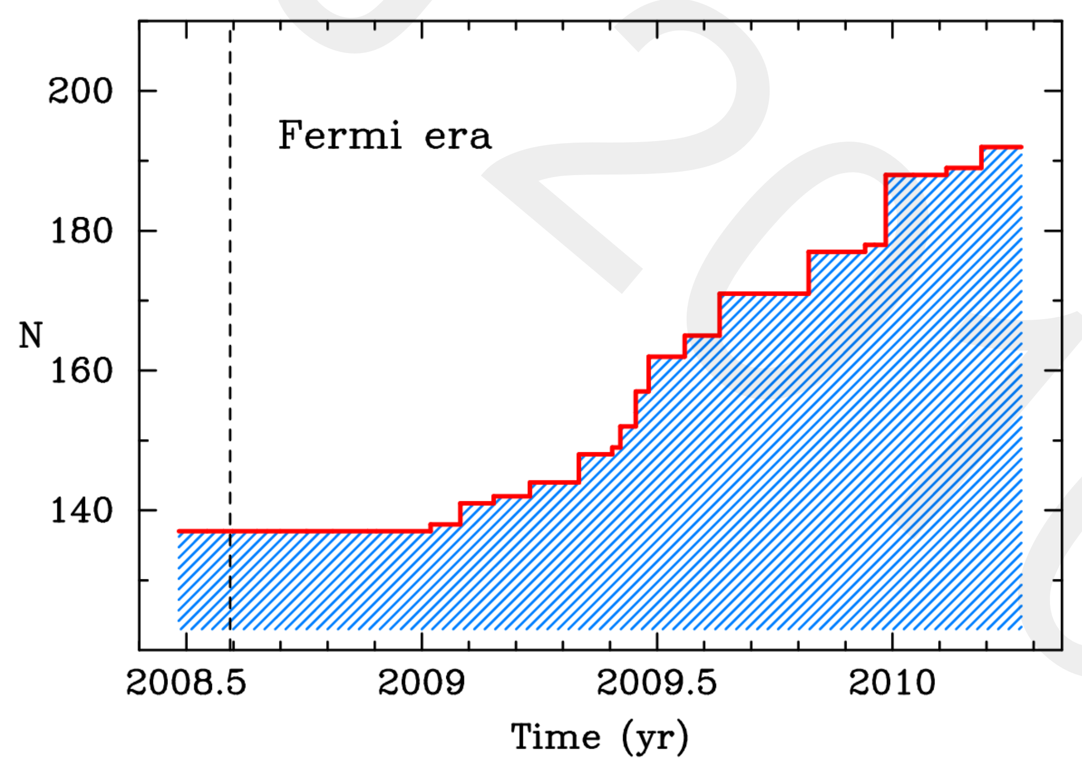
- Some fundamental questions remain open
  - HOW → acceleration mechanisms
  - WHAT → origin of gamma-ray variability
  - WHERE → site of gamma-ray emission in AGN
- Important for constructing the models and also for planning multi-wavelengths campaigns

Introduction

- Comparison of long-term records of radio (10.7 GHz) and optical fluxes (Pomphrey et al. 1976) for a sample of 24 AGN → correlation is found for 13 sources; optical events preceding radio by intervals ranging from 0 to 14 months
- Analysis for internally consistent light curves for 18 AGN in the optical and radio (4.6-14.5 GHz) domains (Clements et al. 1995) → 9 sources exhibited positive correlation with a time lag 0-14 months
- Optical and radio (22-230 GHz) obs. (Tornikoski et al. 1994) for a sample of 22 AGN → correlation is found for 10 sources; in 6 sources no delay was detected
- A time delay study of individual cm- and mm-wave flare peaks for a sample of 55 sources (Hovatta et al. 2008) → delays ranged up to hundreds of days between 4.5 and 220 GHz
- Optical outbursts led 230 GHz flares by 15-50 days in 3C454.3 (Jorstad et al. 2008)
- A longer delay of ~10 months between optical and 37 GHz flux variations in 3C454.3 was reported by Volvach et al. 2008

Gamma-ray bright AGN in MOJAVE

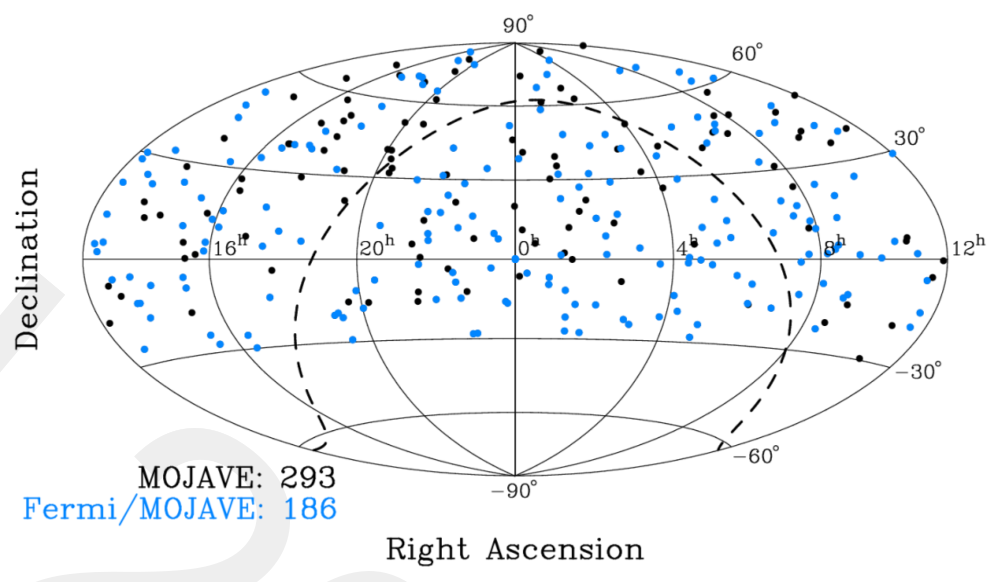
- ~25% of MOJAVE-1 was in the 3 month list (75% in the 1FGL)
- 55 sources with TS > 100 positionally associated with bright radio-loud blazars (Abdo et al. 2009; Kovalev 2009) have been incrementally added to the program
- MOJAVE-2 sample currently comprises 186 1FGL AGN

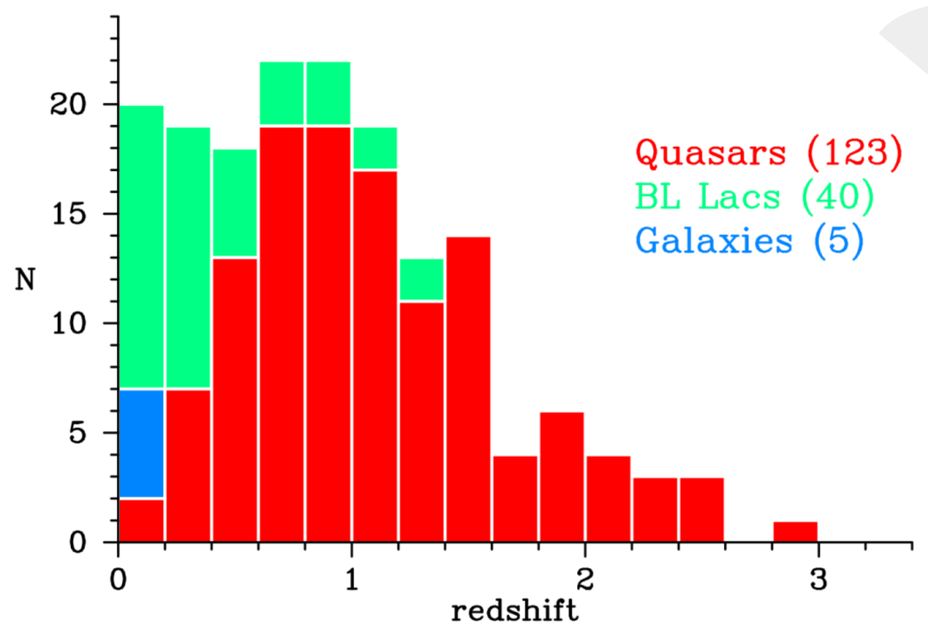


Gamma-ray bright AGN in MOJAVE

Sky distribution

- 186 1FGL AGN are currently being monitored with MOJAVE

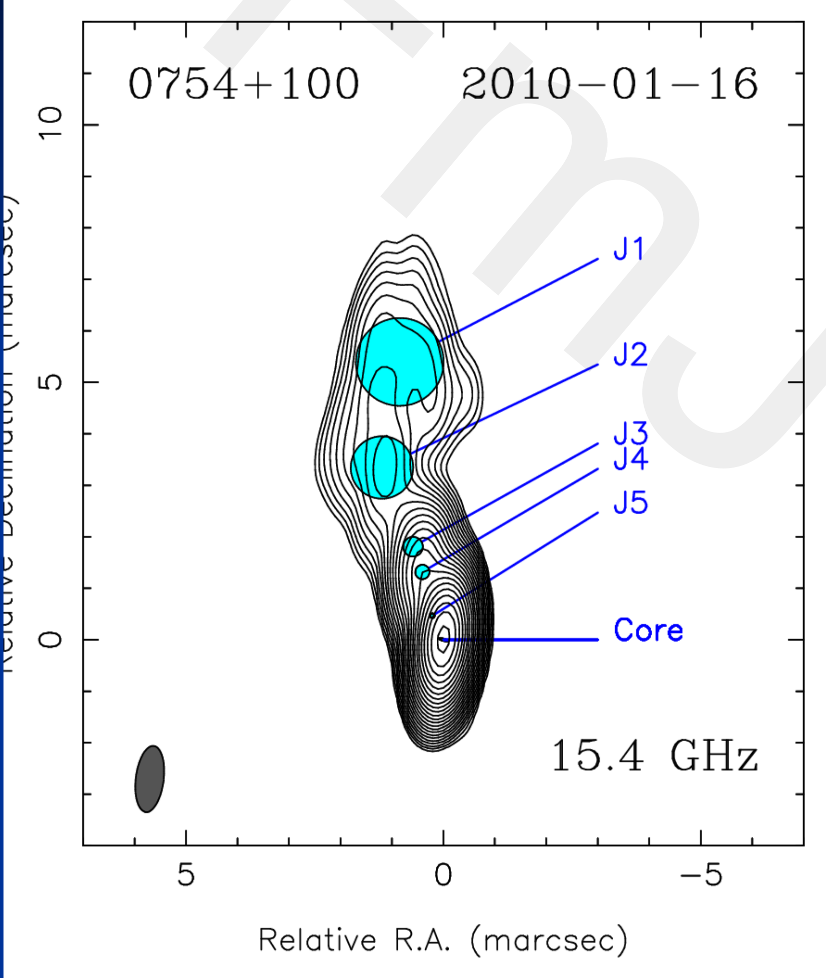




Redshift distribution

- 168 (90%) with known z
- dominated by quasars (73%)
- high fraction of BL Lacs (21%)

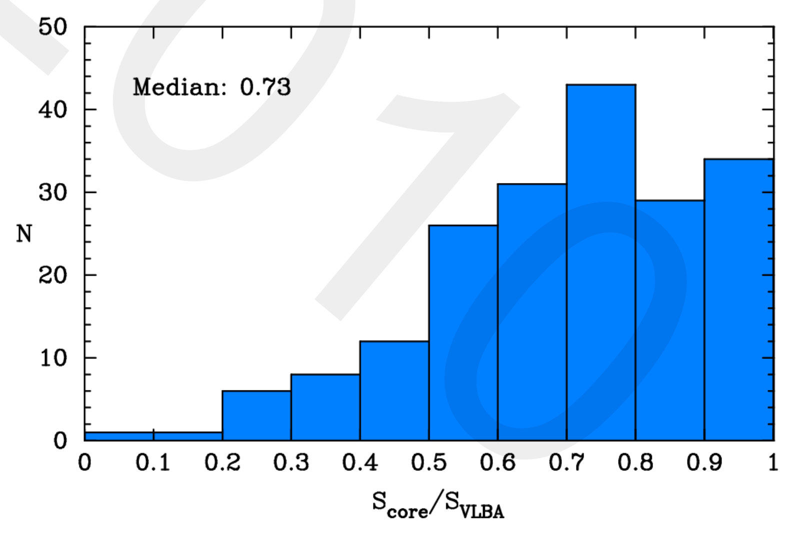
Parsec-scale radio structure modelfitting



Core dominance = 0.85

A limited number of circular/elliptical Gaussian components, for which we fit

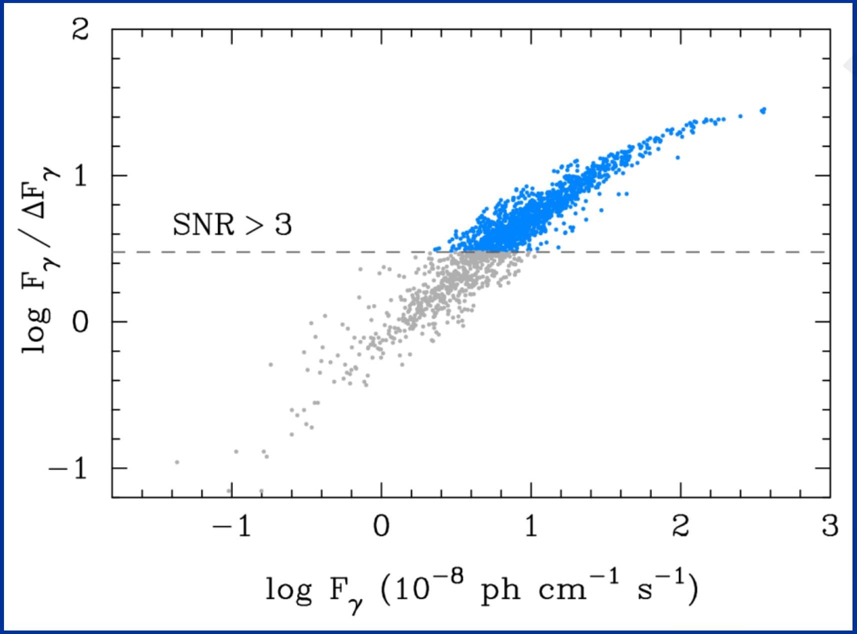
	flux [mJy]	r [mas]	θ [deg]	size [mas]
Core	1385	0.01	86.4	0.18
J5	51	0.51	24.3	0.09
J4	100	1.38	17.1	0.28
J3	20	1.90	18.0	0.38
J2	28	3.55	19.5	1.21
J1	36	5.46	8.9	1.70



Data in use

Radio

- MOJAVE program (Lister et al. 2009) – a long-term VLBA project
- Flux density at 15 GHz (core, total, jet = total – core)
- 183 sources
- 564 VLBA images and corresponding modelfits



Gamma-ray

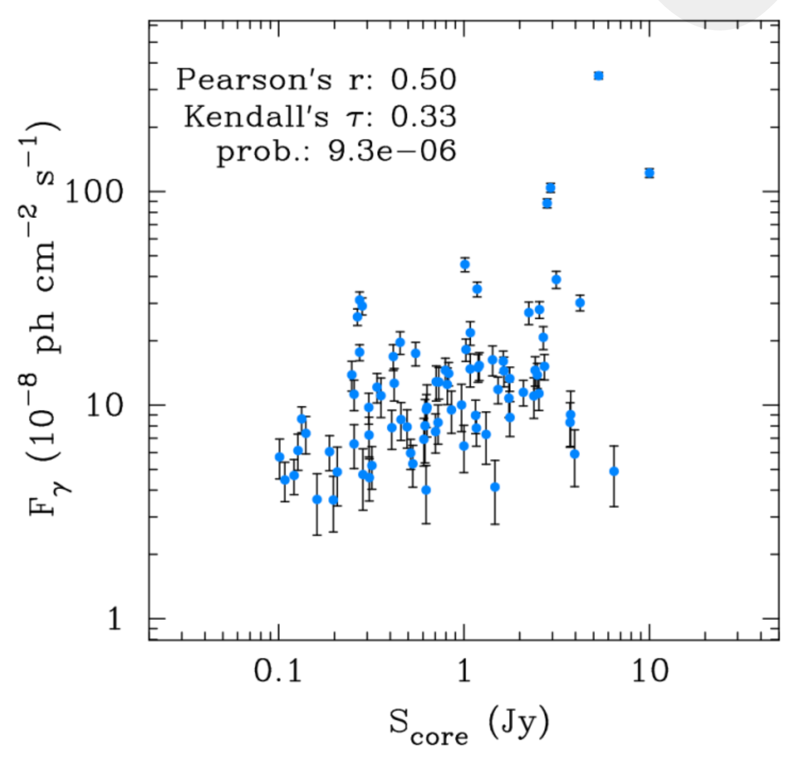
- 1FGL
- 0.1-100 GeV photon flux
- monthly binned →
  11 measurements per source
- SNR = 3 cutoff used

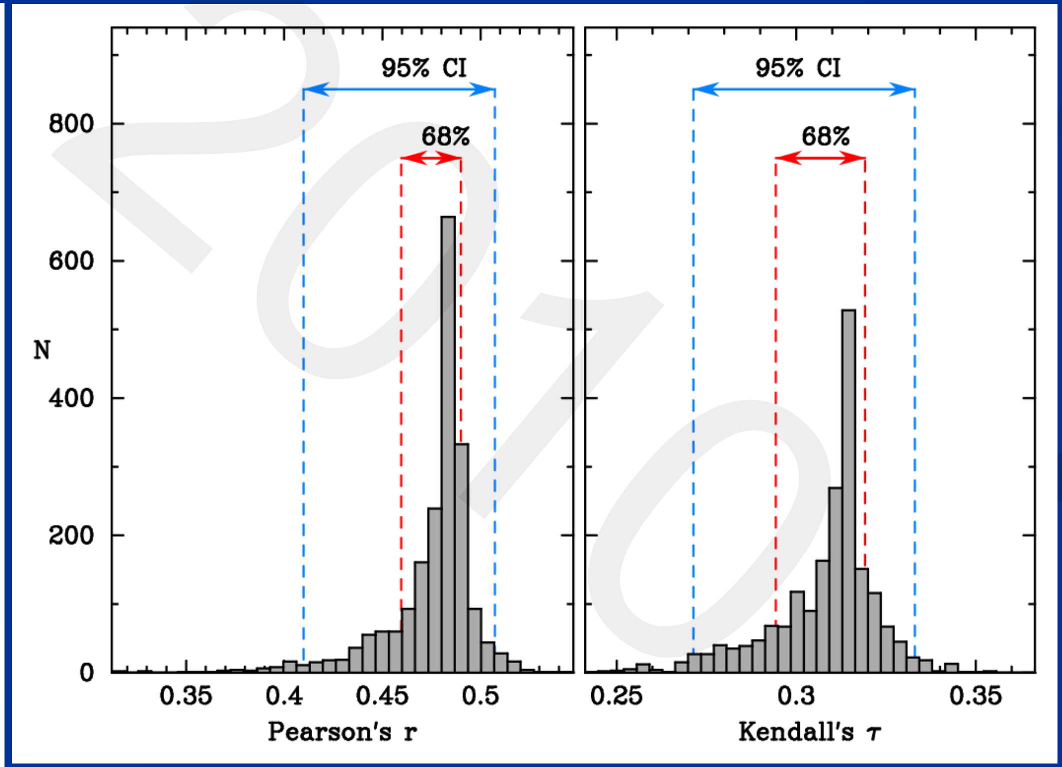
Method

Construction the data sets: by selecting radio and gamma-ray measurements within an epoch difference window of 1 month, e.g. [-0.5, +0.5] months; shift the window by 0.5 months

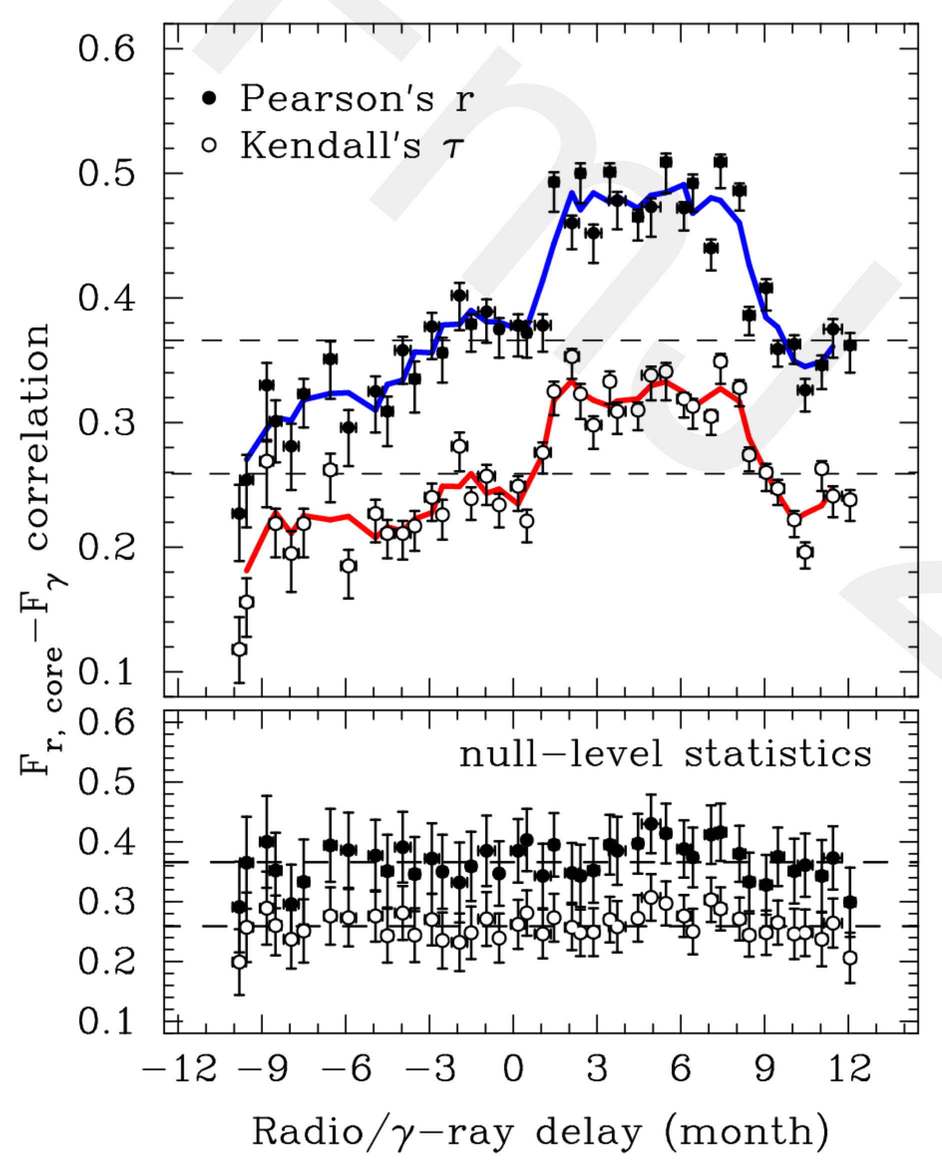
Calculation correlation coefficients: Pearson's r and Kendall's tau

Estimation the errors: (i) swapping radio flux densities for a randomly selected pair of sources, (ii) calculating the Pearson's r and Kendall's tau, (iii) repeating (i) and (ii) 2000 times; estimating 95% (68%) CI





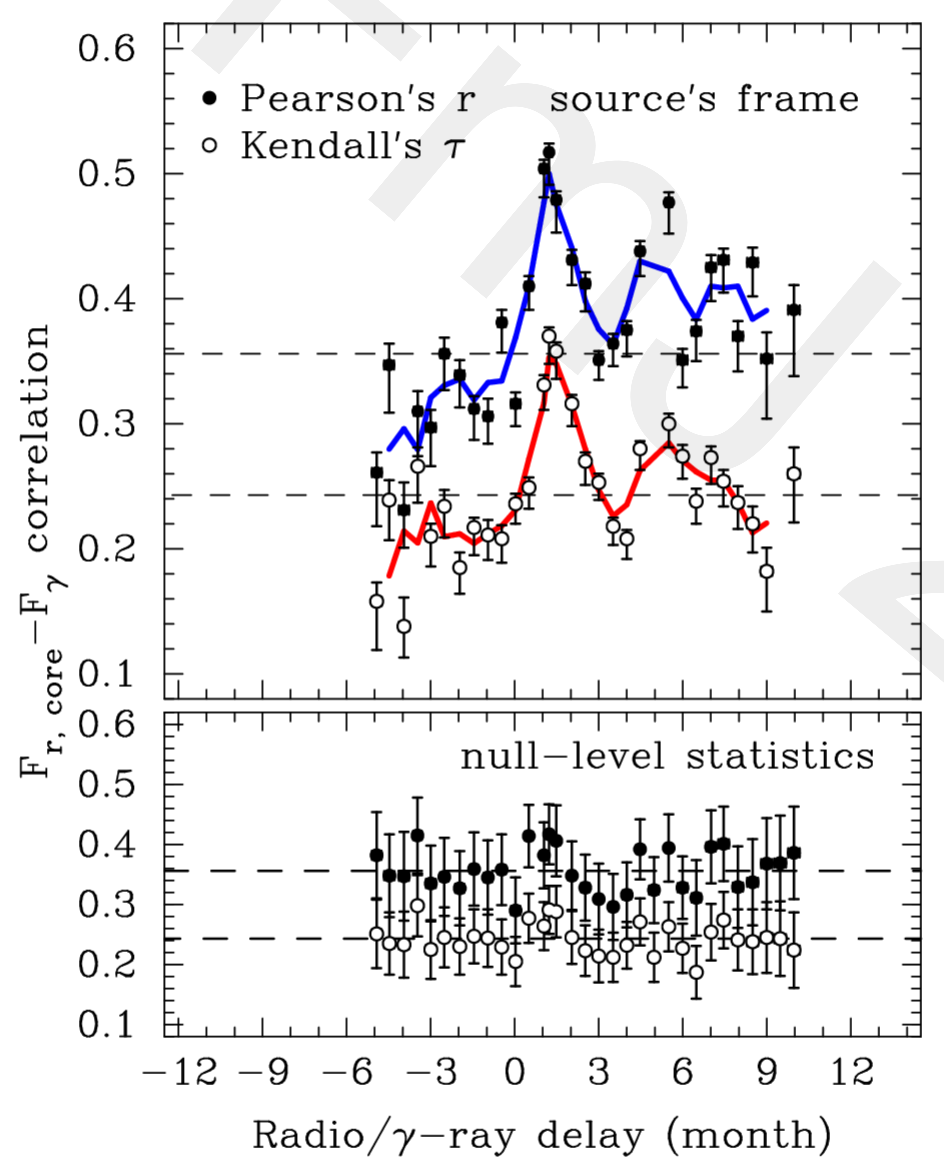
Radio/gamma-ray time delay



Observer’s frame

- γ-ray leads radio
- Delay ranges from 1 to 8 m
- Smearing in delay due to different conditions
  - in nucleus (M_{BH}, spin, M dot)
  - in nearby ISM
  - geometry (angle to LOS)
  - wide range of redshifts
- Null-level statistics is taken from shuffling photon fluxes, keeping radio flux densities the same

Radio/gamma-ray time delay

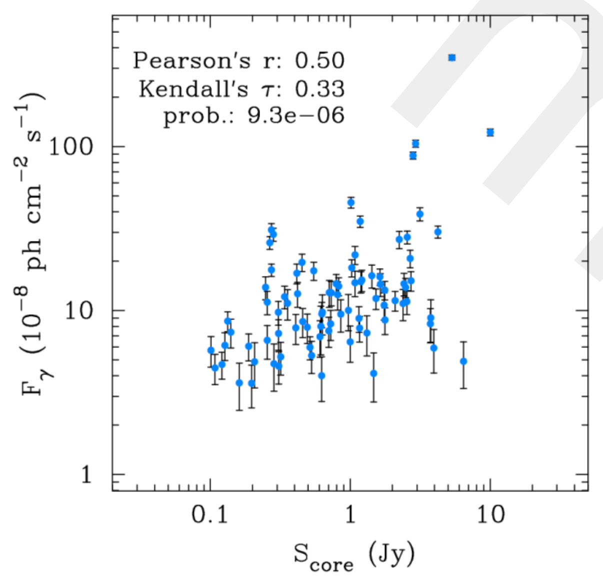


Source frame

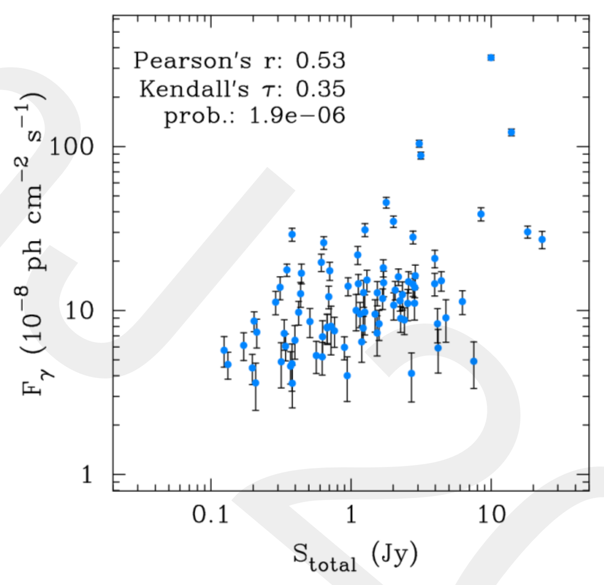
- Dividing radio/γ-ray epoch time difference by (1+z)
- Peaks at ~1.2 months → 2.5 months in the observer's frame
- Other subpeaks may indicate longer delays in a smaller number of sources

Localization of the gamma-ray site

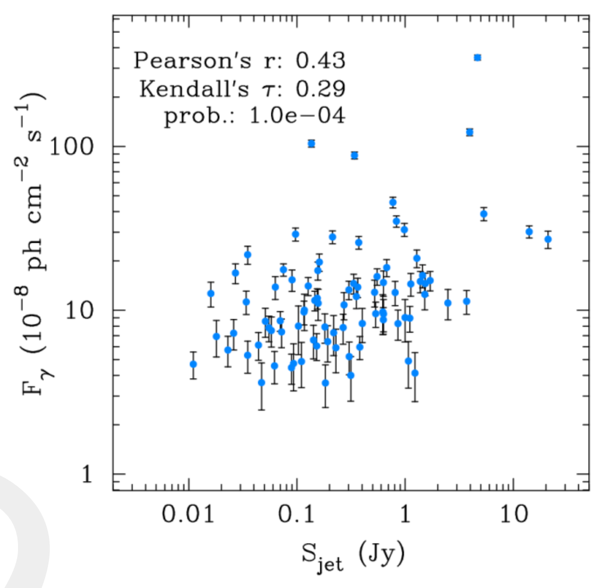
Core



Total



Jet (Total - Core)

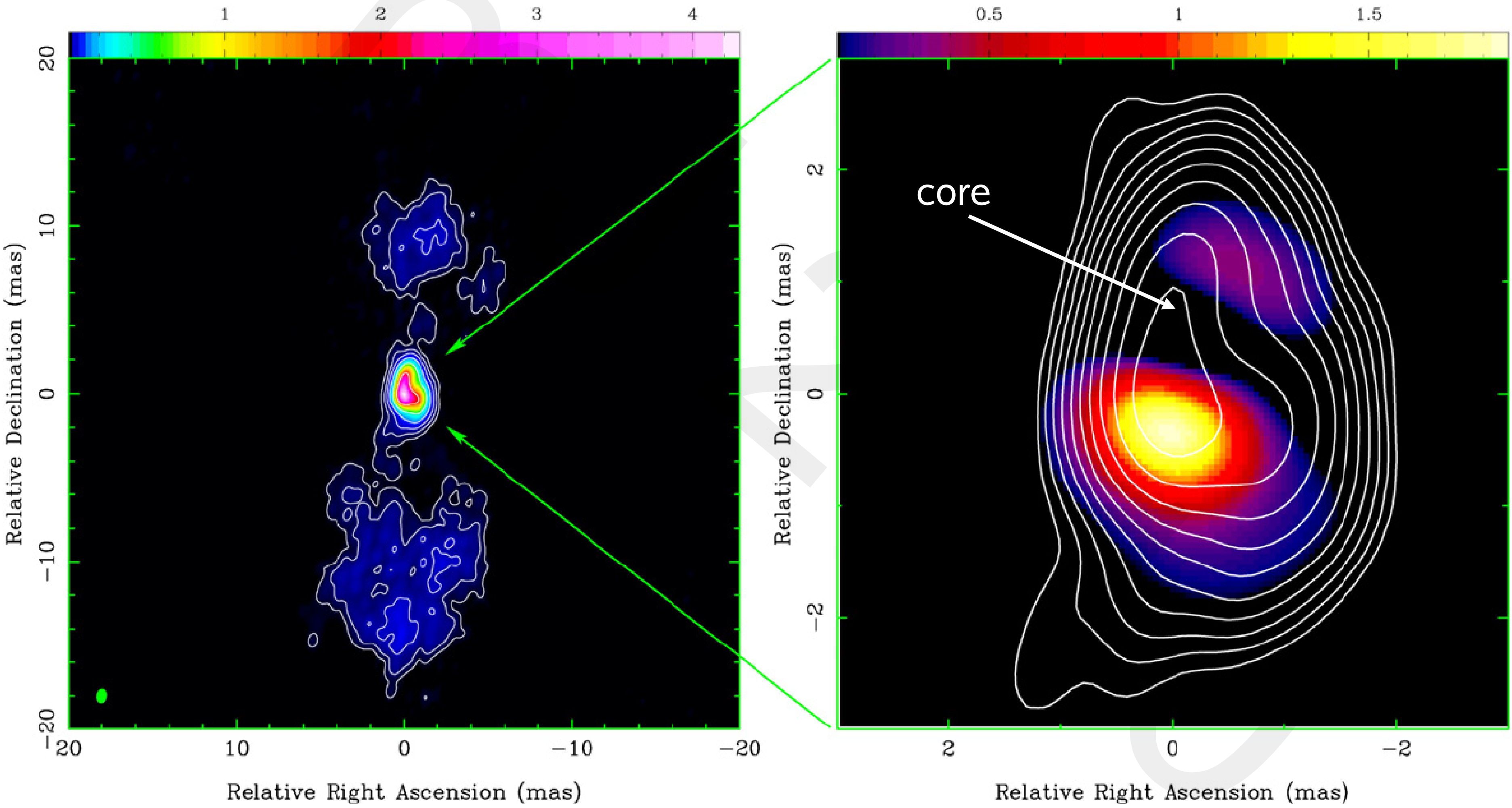


- Pearson’s r and Kendall’s tau agree within the errors for the core and total flux densities, most probably, due to a strong core dominance with the median of S_core/S_total = 0.73
- Correlation for the jet flux density is weaker but significant
  - The correlation can be driven by the same Doppler factor in the jet and in the core (app. jet base)
  - Gamma-ray emission originates in the resolved jets?

Gamma-ray activity & radio flare in 3C 84

15 GHz MOJAVE I-map on 2008.65

Color: a difference image (2008.65–2007.67)



z = 0.0176 1 mas = 0.35 pc (~2 pc of de-projected dist.)

Abdo et al., 2009

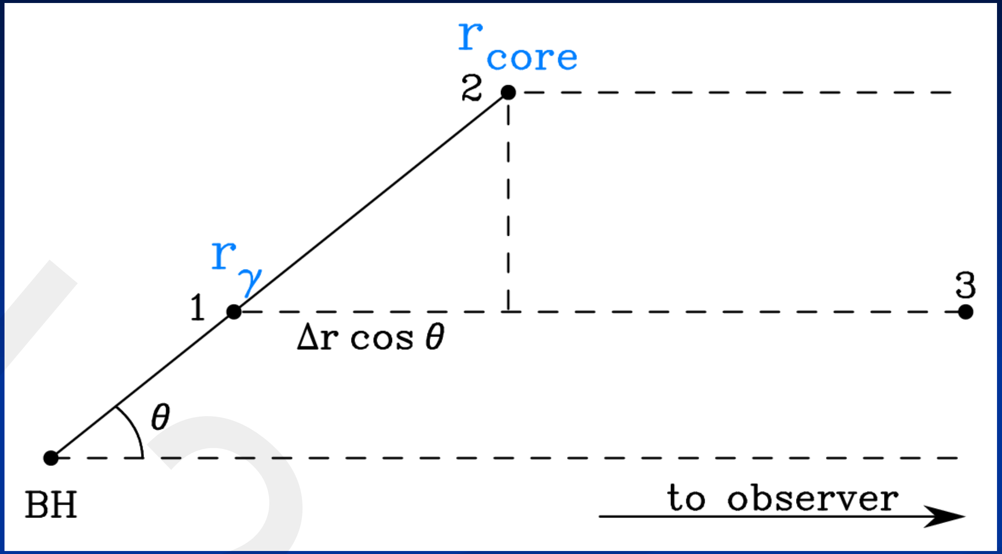
Time lag as a result of syn. nuclear opacity

- A disturbance at a distance r_γ upstream to the apparent 15 GHz core position induces both γ-ray and radio emission

- A γ-ray photon escapes immediately, while radio emission is opaque

- It takes several months for a perturbation to propagate farther along the jet to become detectable at r_core, where τ~1

- Travelled distance along the jet



$$\Delta r = r_{\mathrm{c}} - r_\gamma = \frac{\delta \Gamma \beta c \Delta t^{\mathrm{obs}}_{\mathrm{R}-\gamma}}{1+z}$$

$$\beta_{\mathrm{app}} = \frac{\beta \sin\theta}{1-\beta\cos\theta}, \qquad \delta = \Gamma^{-1}(1-\beta\cos\theta)^{-1}$$

$$\Delta r = \frac{\beta_{\mathrm{app}} c \Delta t^{\mathrm{sour}}_{\mathrm{R}-\gamma}}{\sin\theta}$$

Time lag as a result of syn. nuclear opacity

- Consider a source with a set of parameters typical for a LAT-detected blazar

$$\Delta r = \frac{\beta_{\mathrm{app}}\, c \Delta t^{\mathrm{sour}}_{\mathrm{R}-\gamma}}{\sin\theta}$$

  - radio/γ-ray time lag in a source frame $\Delta t \sim 1.2$ months
  - apparent jet speed $\beta_{\mathrm{app}} \sim 15$ (Lister et al. 2009)
  - viewing angle $\theta \sim 3.6$ deg (Pushkarev et al. 2009)

Δr ~ 7 pc (de-projected)

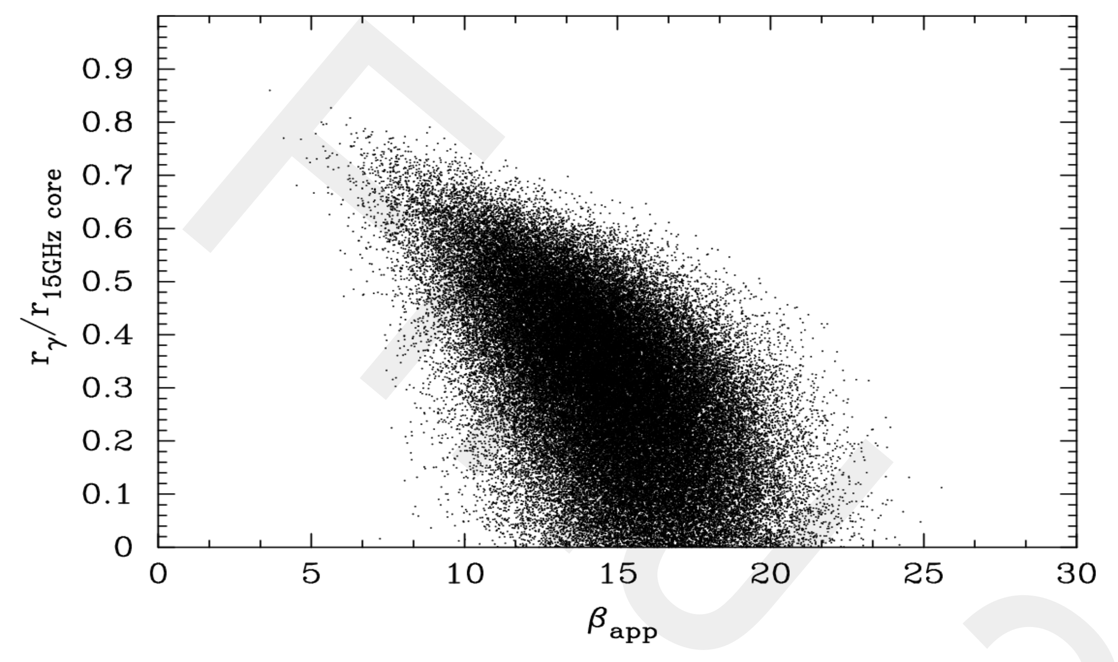
or ~ 0.9 pc (projected)

or ~ 0.1 mas (z ~ 1)

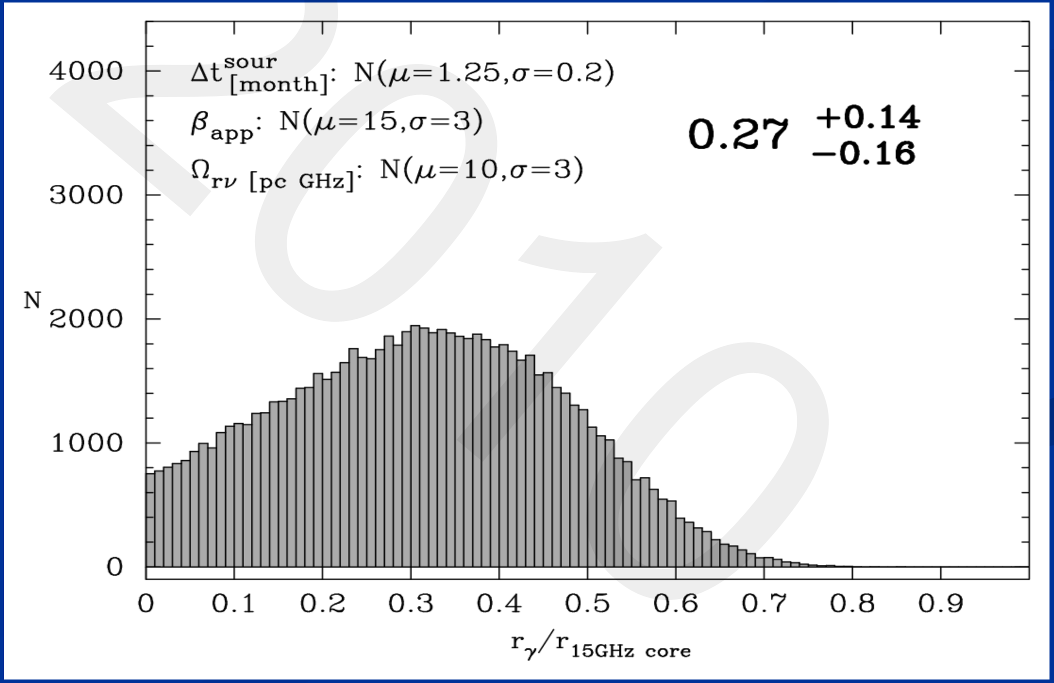
- These estimates are consistent with the core radius at 15 GHz obtained from the frequency dependent core shift measurements (Lobanov 1998, Kovalev et al. 2008, O'Sullivan & Gabuzda 2009)
- VLBI observations at higher frequencies (e.g. 43 or 86 GHz) should register shorter delay or even quasi-simultaneous flux variations with γ-ray at least for some sources, and might even resolve the region of the jet where γ-ray emission is generated (e.g. 3C345, Schinzel et al. 2010, Jorstad et al. 2010)

Summary

- Correlation between gamma-ray photon flux and radio flux density is found to be highly significant
  - correlation results for core and total VLBA flux are indistinguishable
  - correlation is systematically weaker (but significant) if the jet flux is used
- A non-zero radio/gamma-ray delay is detected
  - ranges from 1 to 8 months in the observer's frame
  - peaks at ~1.2 months in the source's frame
  - most probably connected to the synchrotron opacity
  - radio is lagging gamma-ray (*at their flare peaks*)
- The region, where most of gamma-ray photons are produced, is found to be located within the compact opaque parsec-scale core
  - de-projected distance $(r_{\mathrm{core}} - r_{\mathrm{gamma}}) \sim 7$ pc or 0.1 mas in a projected angular scale, which is consistent with the typical core radius derived from the frequency dependent core shift measurements



$r_\gamma / r_{15\mathrm{GHz\ core}}$
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
β_{app}



$\Delta t^{\mathrm{sour}}_{[\mathrm{month}]}$: $N(\mu=1.25,\sigma=0.2)$
β_{app}: $N(\mu=15,\sigma=3)$
$\Omega_{r\nu\ [\mathrm{pc\ GHz}]}$: $N(\mu=10,\sigma=3)$
$0.27^{+0.14}_{-0.16}$
N
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
$r_\gamma / r_{15\mathrm{GHz\ core}}$