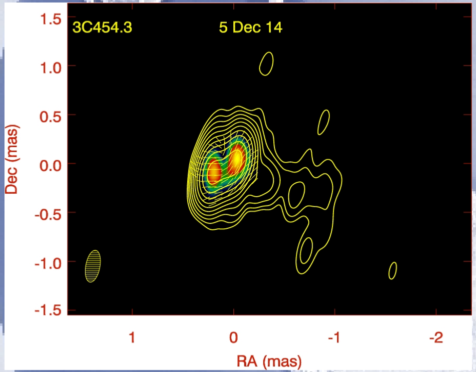
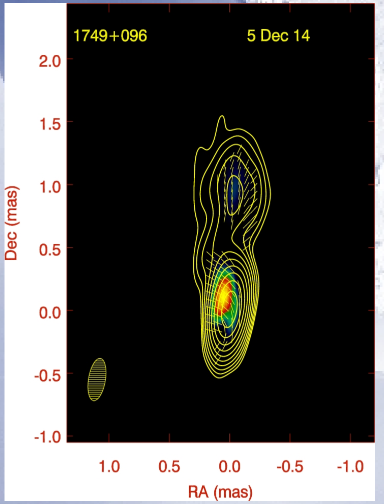
Kinematics of Jets of Gamma-Ray Blazars from VLBA Monitoring at 43 GHz

Svetlana Jorstad
Boston University, USA
St.Petersburg State University, Russia

VLBA-BU- BLAZAR





Quasars

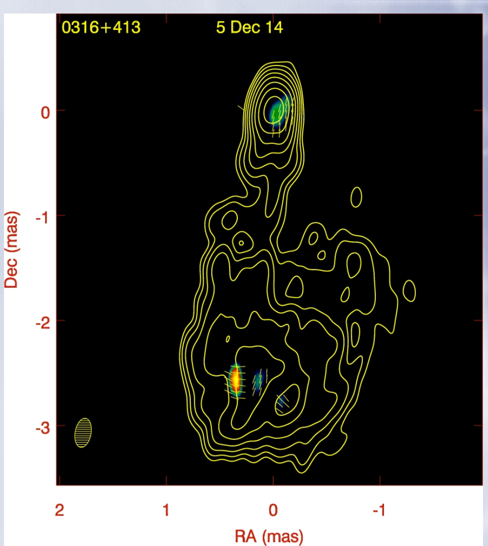
0336-019
0420-014
0528+134
0827+243
0836+710
1127-145
1156+295
1222+216
1226+023
1253-055
1308+326
1406-076
1510-089
1611+343
1622-297
1633+382
1641+399
1730-130
2223-052
2230+114
2251+158

BL Lacs

0219+428
0235+164
0716+714
0735+178
0829+046
0851+202
0954+658
1055+018
1101+384
1219+285
1749+096
2200+420

Radio G

0316+41 (3C84)
0415+37 (3C111)
0430+05 (3C120)



Collaborators

Boston University group (USA):
Alan Marscher, Nicholas MacDonald, Vishal Bala,
Karen Willamson. Michael Malmrose, Manasvita Joshi
St.Petersburg University group (Russia):
Valeri Larionov, Daria Morozova, Ivan Troitsky
Ludmila Larionova, Evguenia Kopatskaya, Yulia Troitskaya
Instituto de Astrofísica de Andalucía group (Spain):
Jose-Luis Gómez, Ivan Agudo, Carolina Casadio
Aalto University Metsähovi Radio Obs. group (Finland):
Anne Lähteenmäki, Merja Tornikoski, Venkatessh Ramakrishnan
Harvard-Smithsonian Center for Astrophysics (USA):
Mark Gurwell

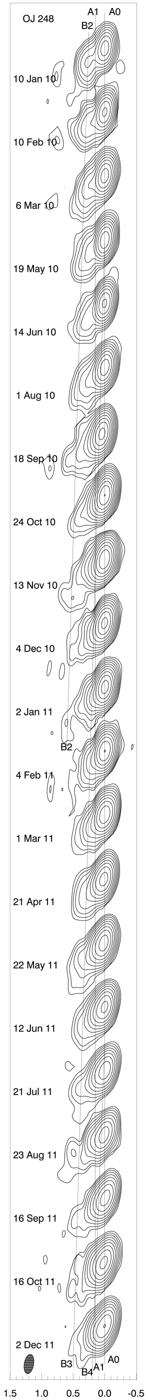
Outline

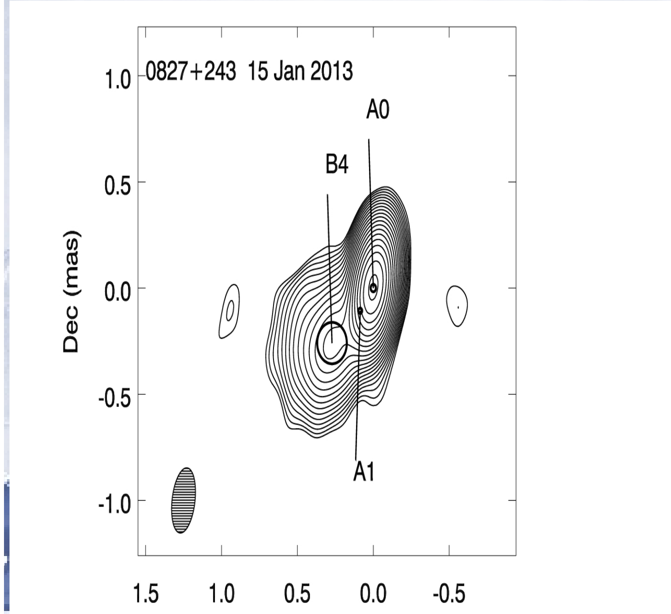
I. Apparent speed, brightness, and size of features in the parsec scale jets of gamma-ray blazars based on monthly monitoring with the VLBA at 43 GHz from 2007 June to 2013 December

II. Physical parameters (Lorentz and Doppler factors, viewing angles) of the features in compact jets derived from kinematics

III. Connections between gamma-ray outbursts and activity in the parsec-scale jets

IV. Comparison of the physical parameters of features related to high energy events with those have no apparent connection

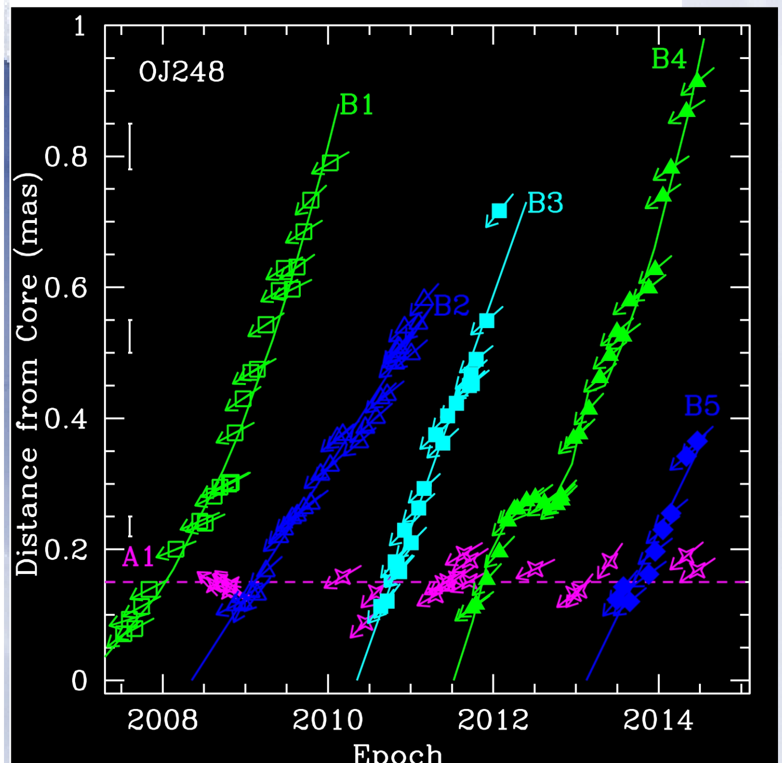


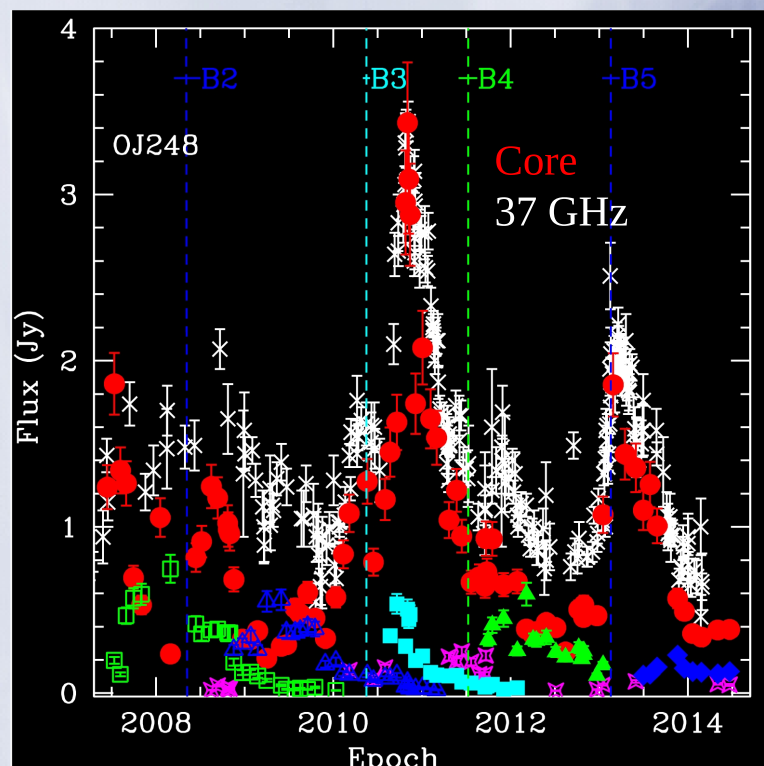


An Example of the VLBA data for Kinematical Analysis {quasar 0827+243 (OJ248)}

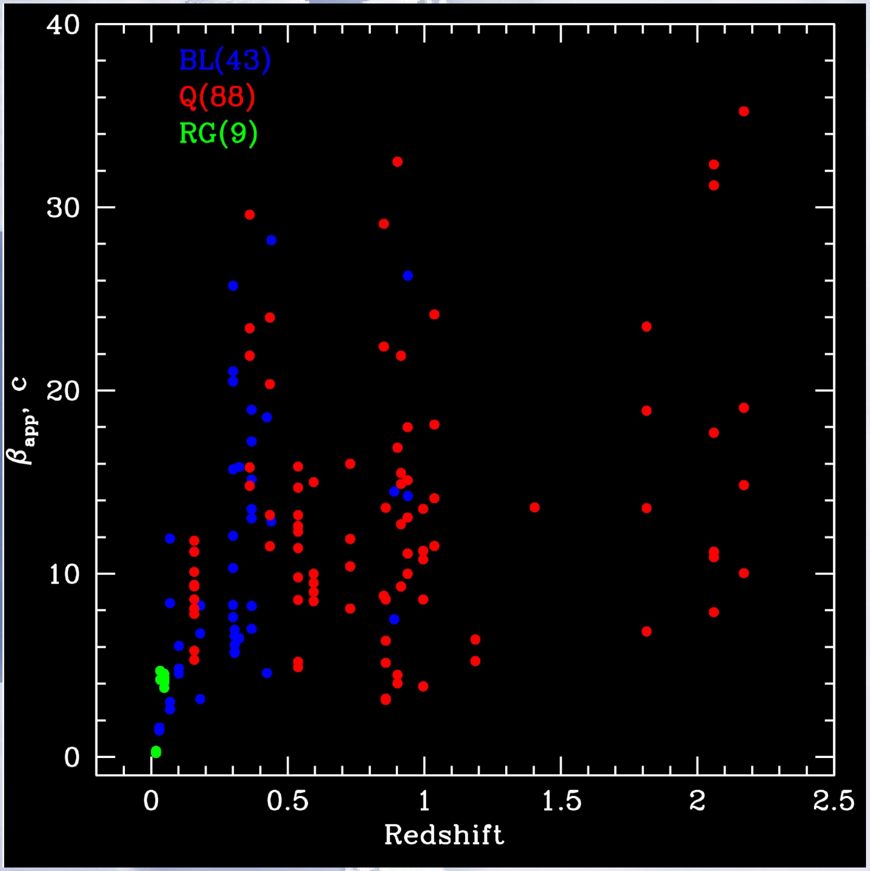
79 epochs from 2007 June to 2013 Dec

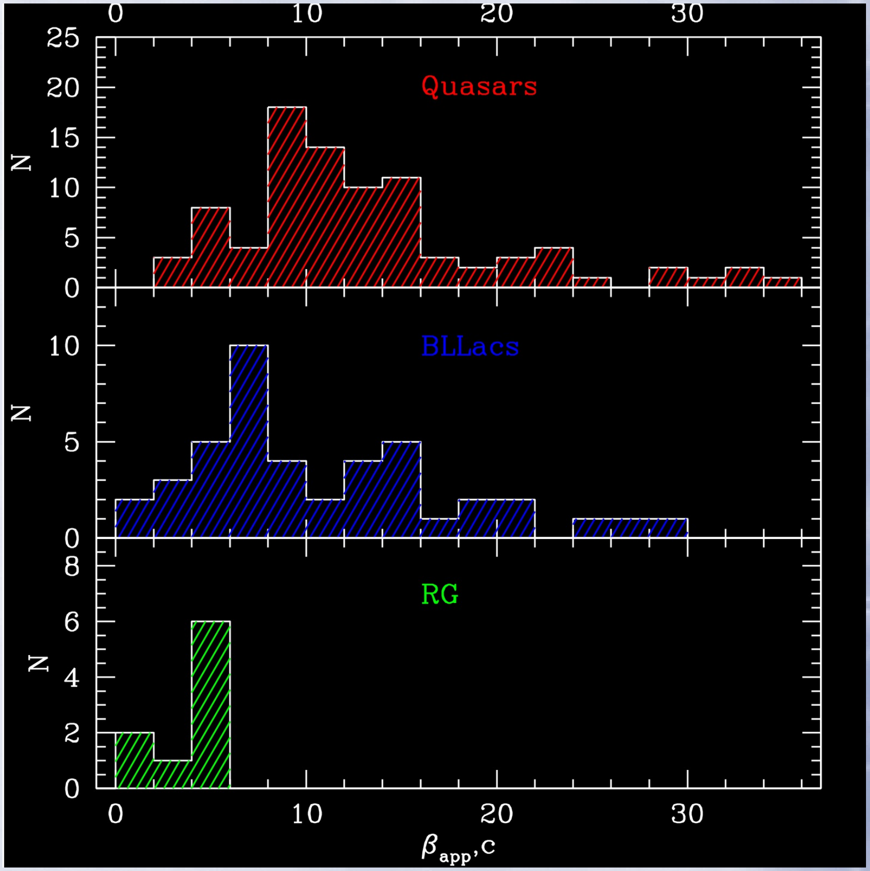
For each object: from 43 to 79 (3C120: 24)
Classification of features: Core (A0), Stationary knots (A#), Moving knots (B#)





Apparent Speeds of Moving Features



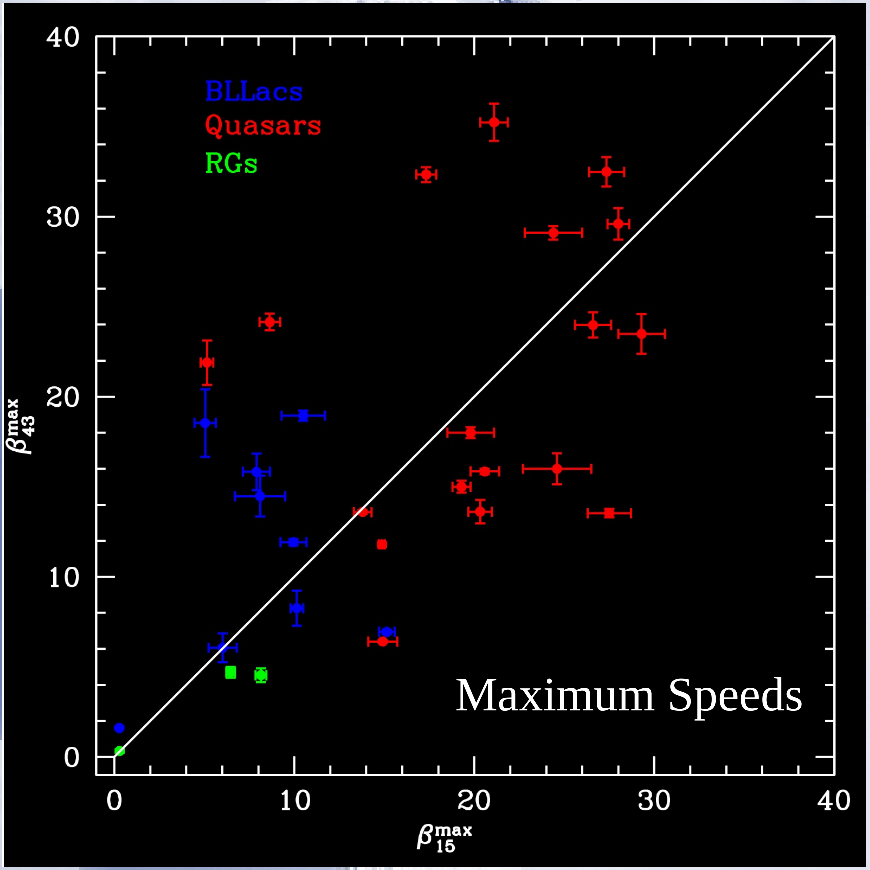


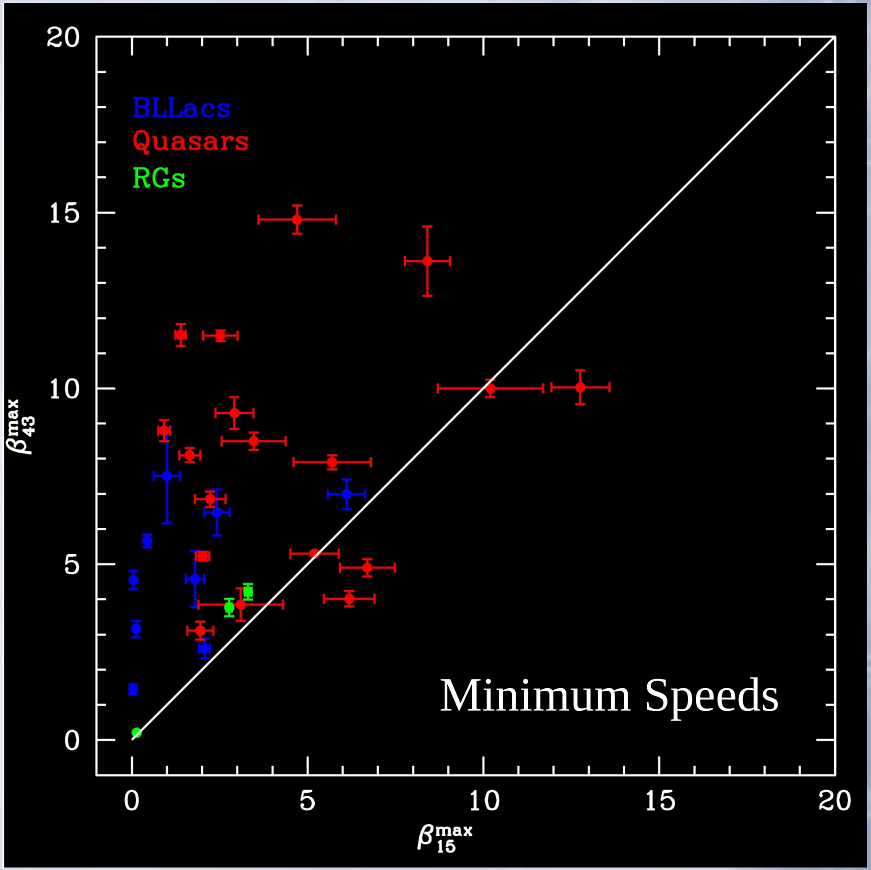
Quasars: 8-10c

BLLacs: 6-8c; RG: 4-6c

No reliable moving features in 3 quasars: 1406-076, 1611+343, 1622-279

VLBA-BU-BLAZAR vs MOJAVE





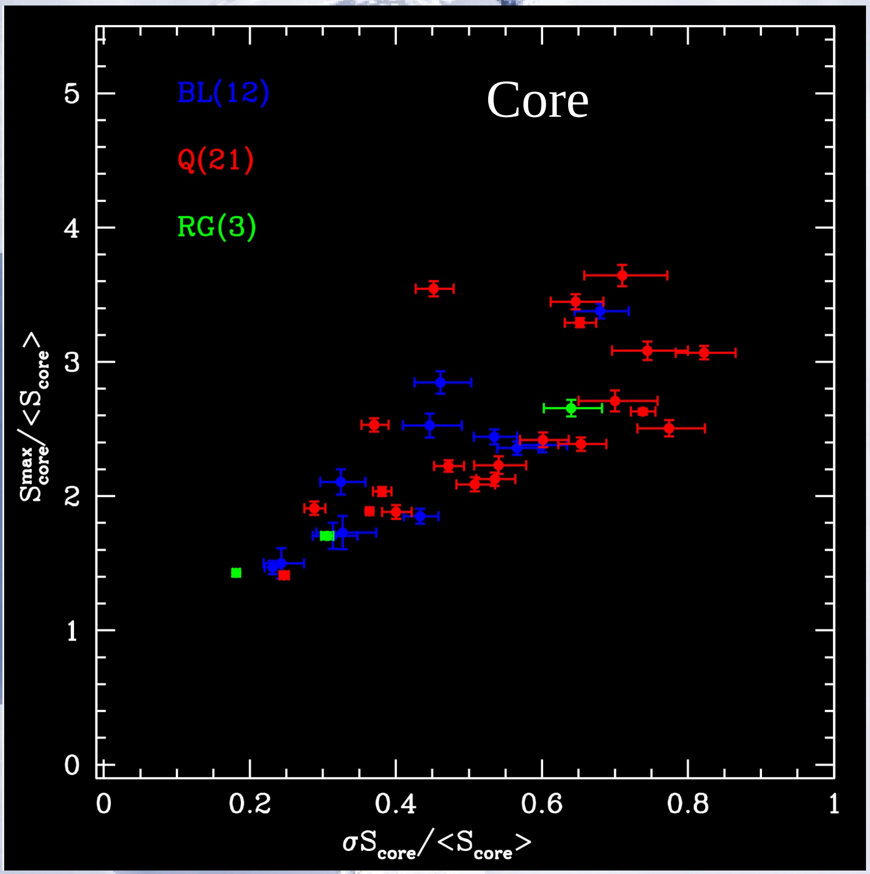
Lister et al. 2013, AJ, 146, 5

Cohen et al. 2014, ApJ, 787, 151

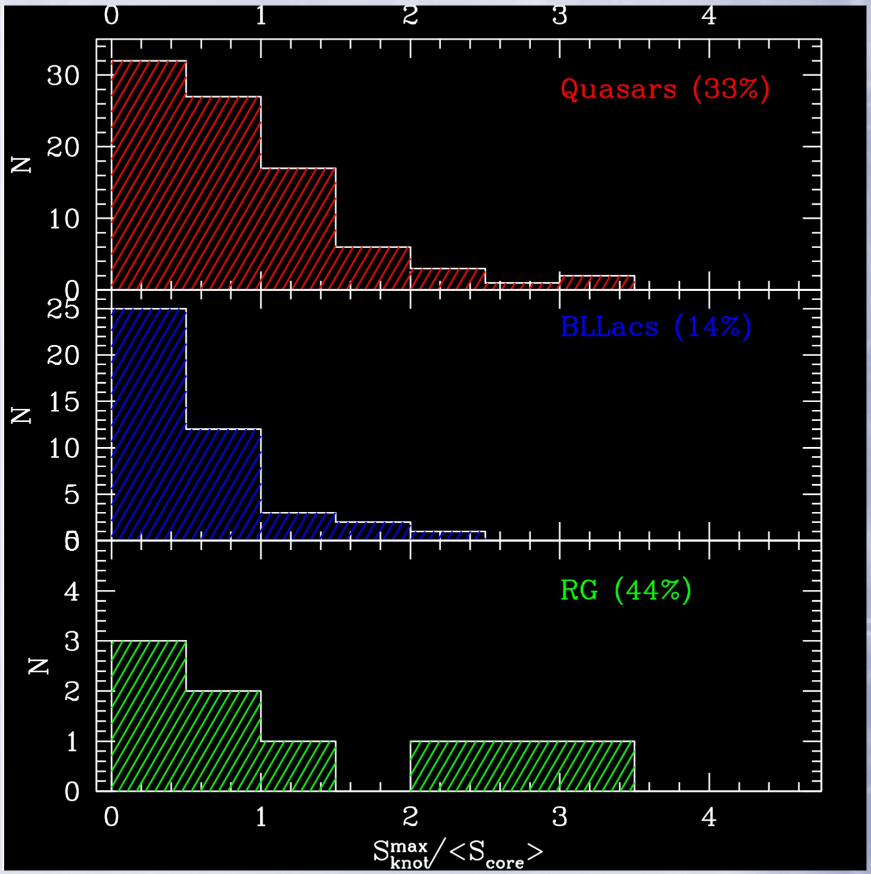
30 sources: 18 Quasars, 9 BLLacs, 3 RGs

No speeds at 15 GHz for 3 BLLacs: 3C66A, 0235+16, and 0716+71

Brightness of Jet Features



Moving Knots



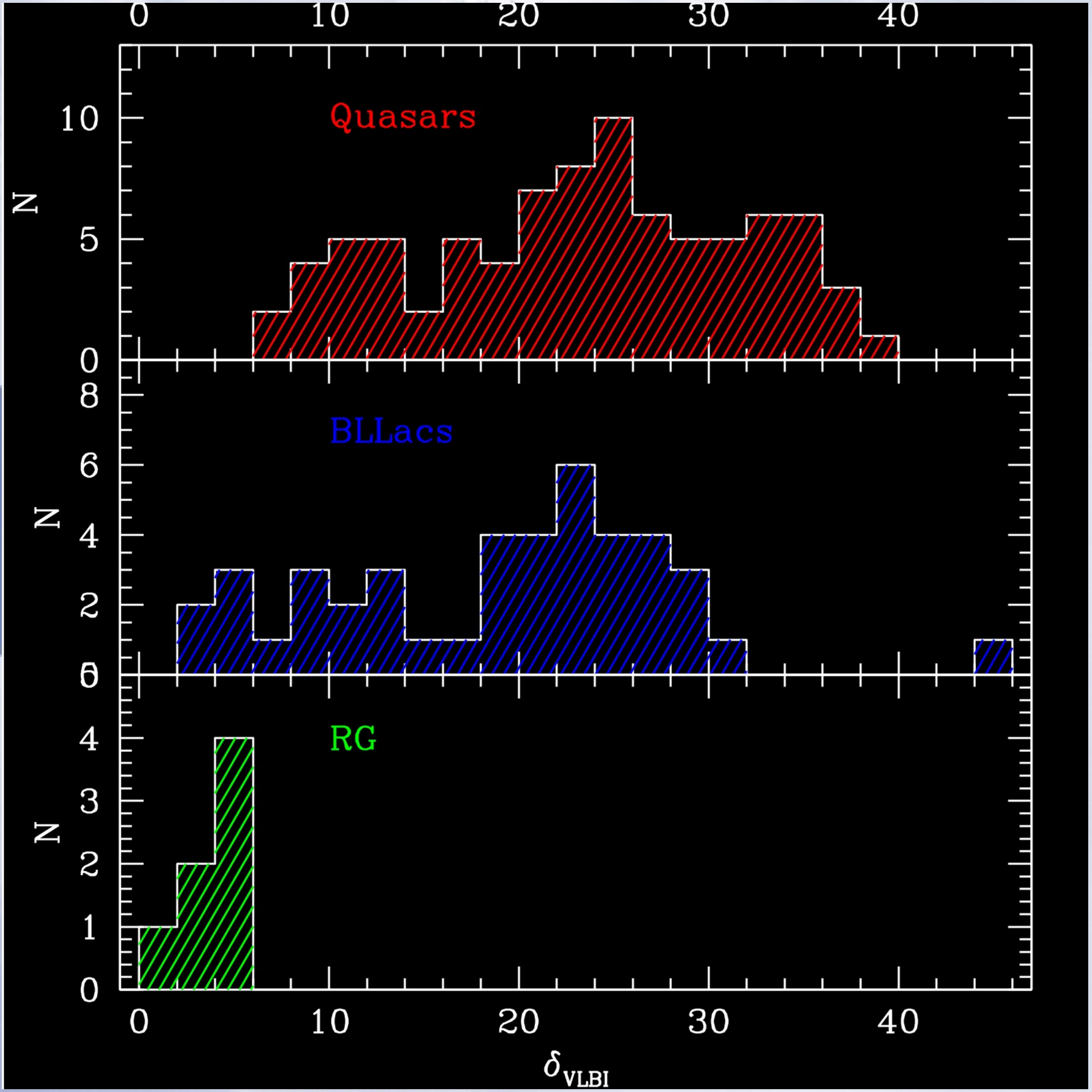
Average Core Flux Densities, $<S_{core}>$:

Quasars: 0.76 – 9.24 Jy

BLLacs: 0.16 - 2.47 Jy

RGs: 0.72 - 4.08 Jy

Doppler Factors

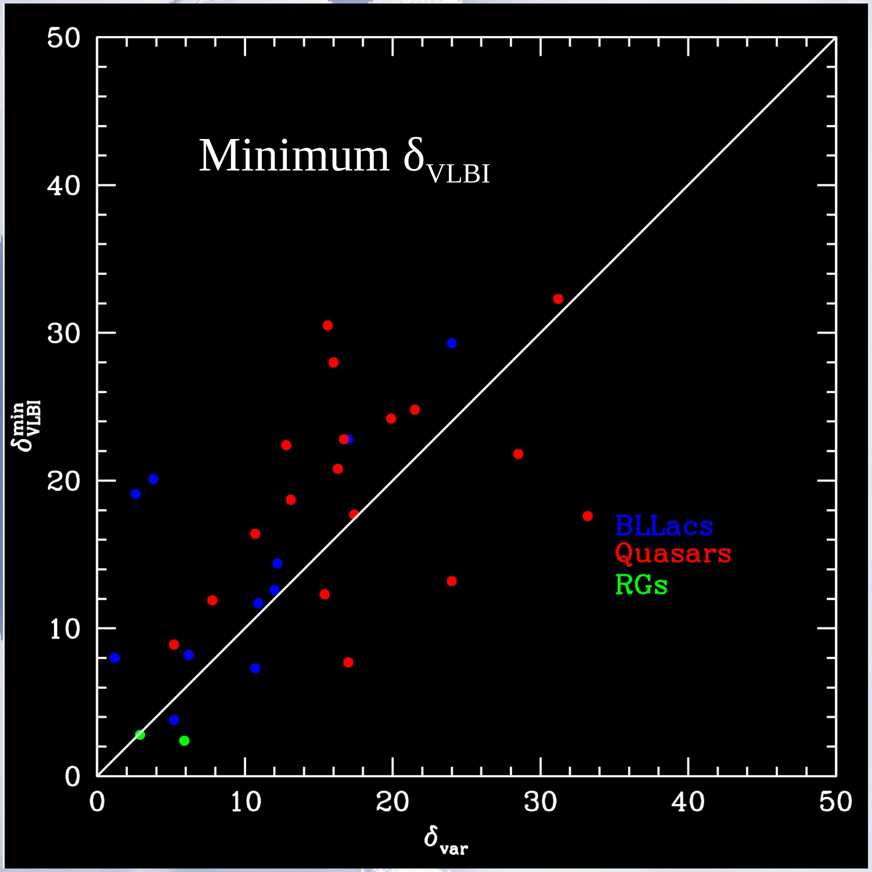


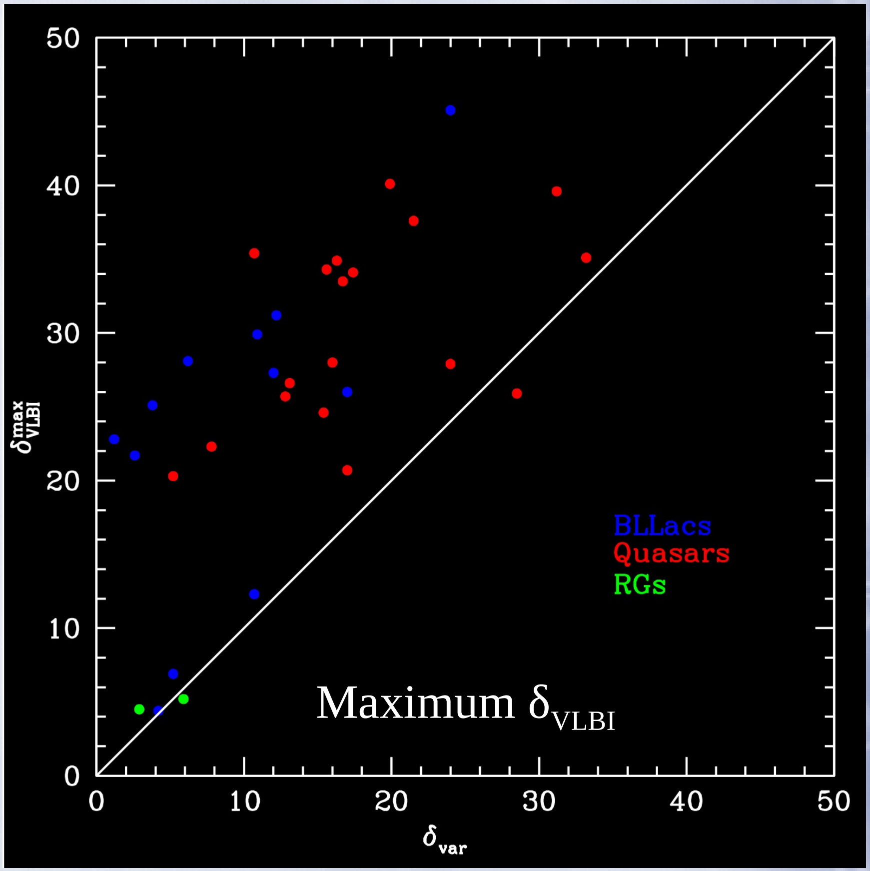
VLBI Time Scale of Variability
Burbidge, Jones, & O'Dell 1974, ApJ , 193, 43
$\Delta t_{var} = dt/\ln(S_{max}/S_{min})$

Variability Doppler Factor
$\delta_{var} = a_{mod}\, D/[c\, \Delta t_{var}\, (1+z)]$
D - luminosity distance
a - VLBI size of component
$a_{mod} = 1.6\times a$
c - speed of light
z – redshift
Jorstad et al. 2005, AJ, 130

Quasars: ~24-26
BLLacs: ~ 22-24
RGs: ~ 4-6

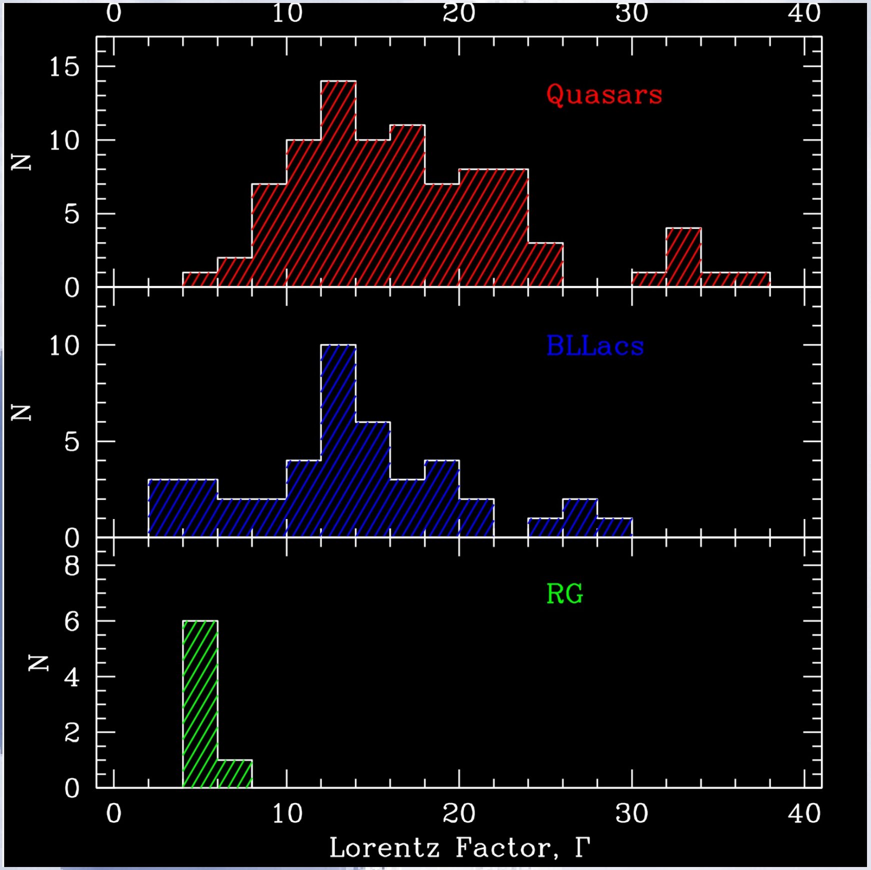
VLBI Doppler Factor vs mm-Wave Variability Doppler Factor

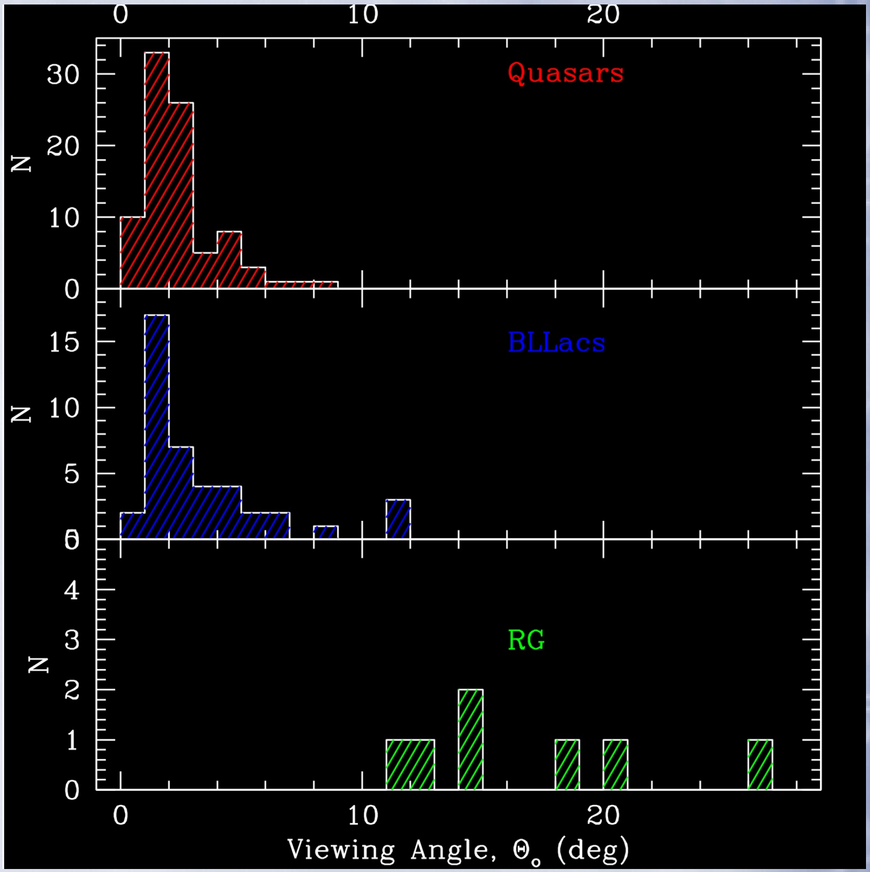




Hovatta et al. 2009, A&A, 494, 527

Lorentz Factor & Viewing Angle





Lorentz Factor
Quasars: 12-14, $\Gamma > 14$ in 61%
BLLacs: 12-14, $\Gamma > 14$ in 44%
RG: ~5

Viewing angle
Quasars: 1° -3°, $\Theta_o > 3$ in 22%
BLLacs: 1° -3°, Θo > 3 in 37%
RG: 11°- 26°

Rules for Establishing Connection between Gamma-Ray/Radio Jet Events

I. The brightest Gamma-Ray Flares (3σ events):
$S_\gamma > (< S_\gamma > + 3\sigma)$ at least for 2 consecutive measurements in γ-ray light curve with 7-day binning

II. Two such events are different flares if separated by > 1 month

III. For each event a γ-ray light curve with a shorter binning interval (1-3 days) is produced to find ``true'' γ-ray peak, S_γ^{max}

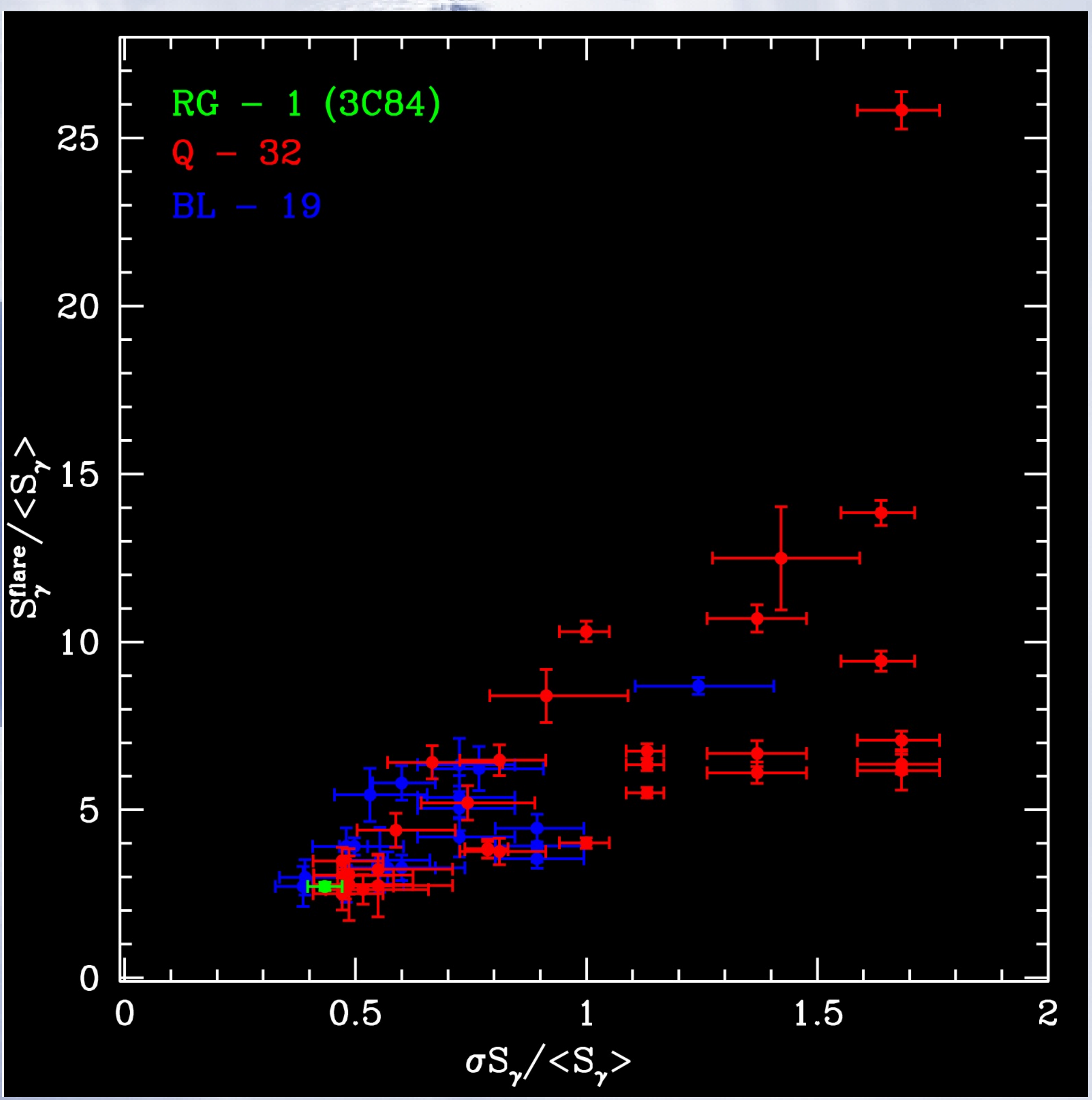
III. Duration of a flare: period of time when $S_\gamma > 0.5 \times S_\gamma^{max}$ (Nalewajko et al. 2012, MNRAS, 430, 1324)

IV. Detection in the jet of a superluminal knot (at least at 6 epochs) with the ejection time, $T_o \pm 1\sigma(T_o)$, within the flare duration

V. 3σ flares of the VLBI core, mm-wave, and optical fluxes during the γ-ray flare

Establishing Connection does NOT determine yet the location of γ-ray flares

Gamma-Ray Events



52 3σ events in 36 blazars during 2008-2013

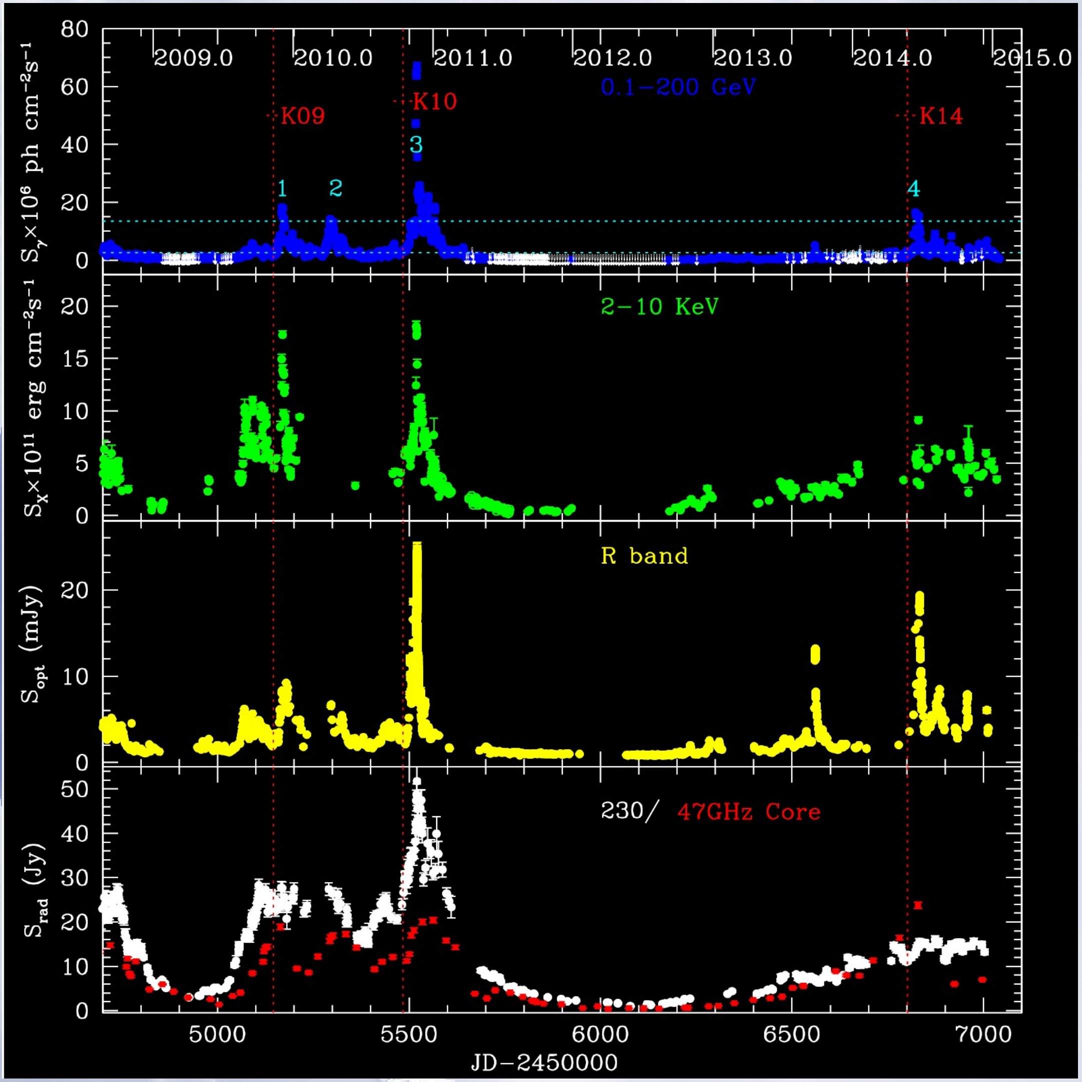
No 3σ events for 4 Qs:

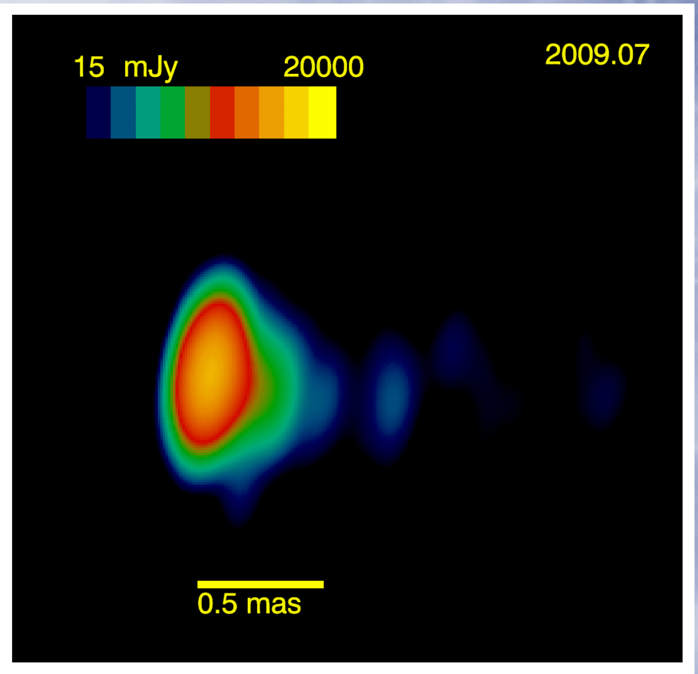
1127-145
1406-076
1611+343
1622-027

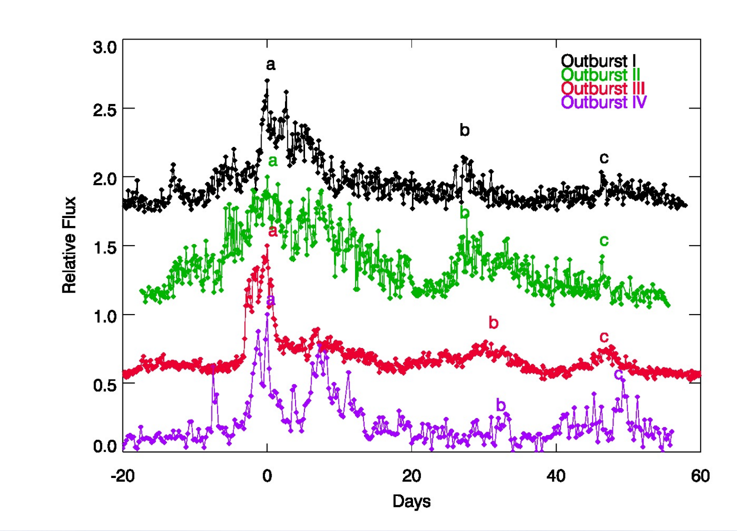
and 2 RGs:

3C111 and 3C120 but see:
Tanaka et al. arXiv:1503.04248

Quasar 3C454.3

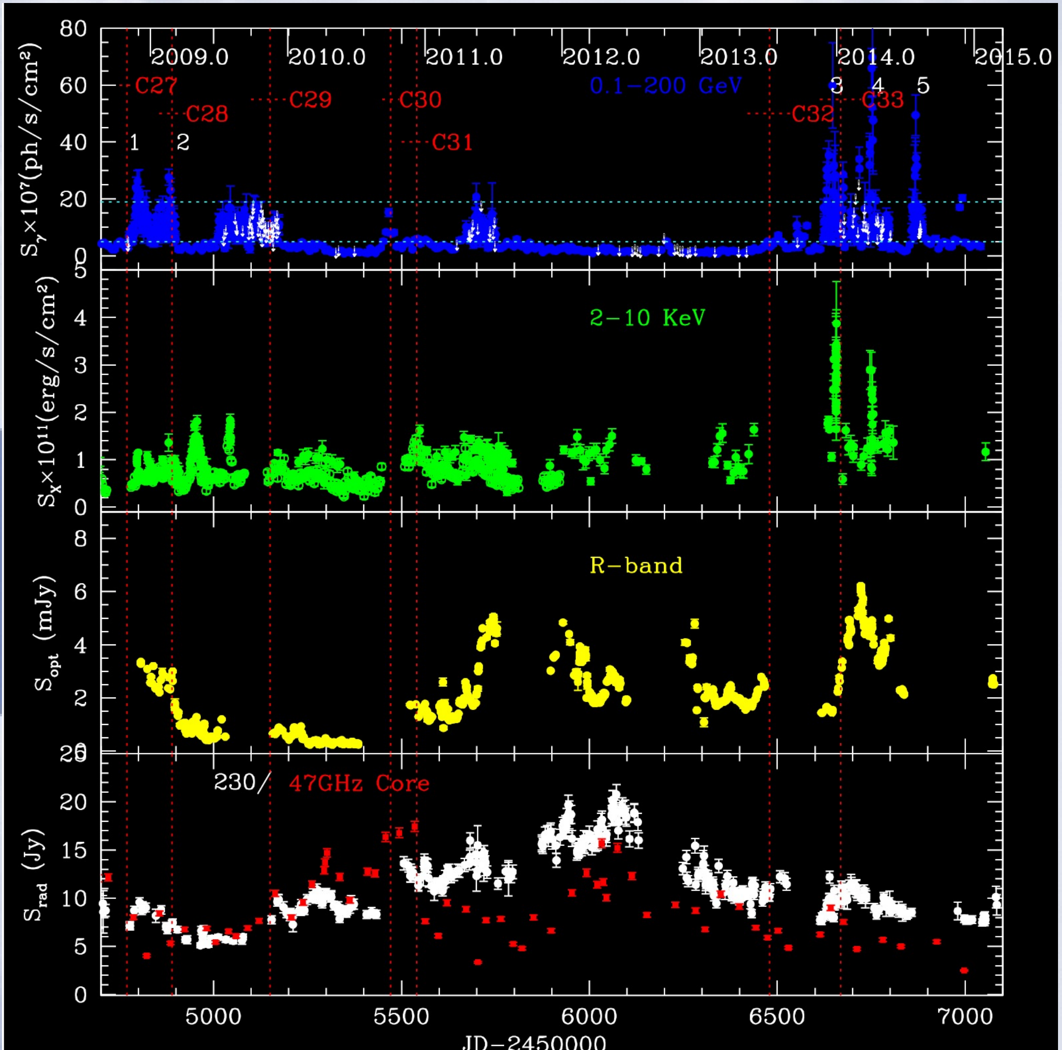


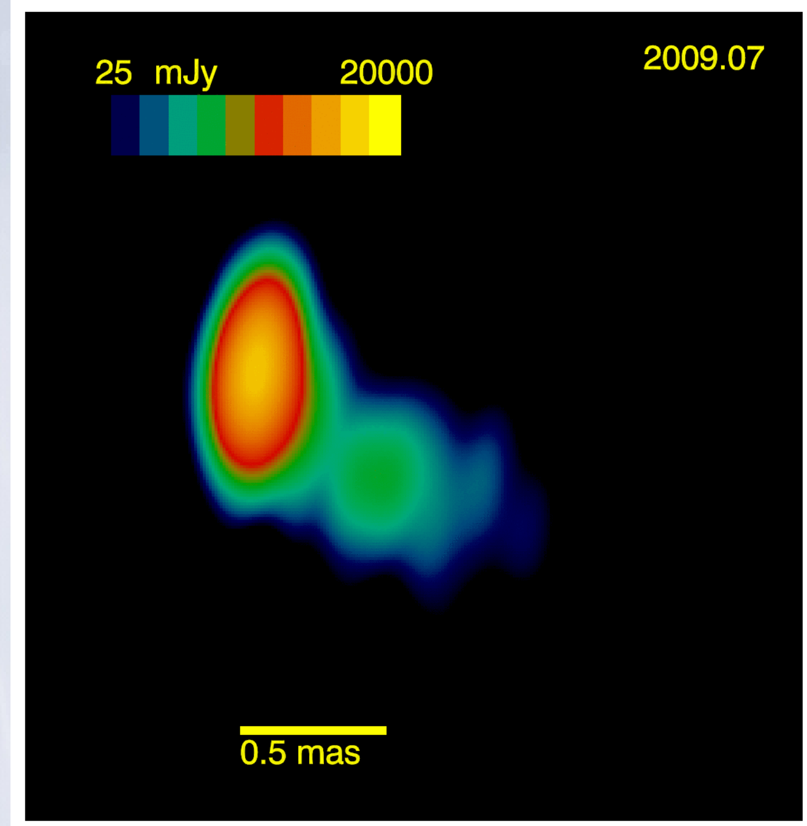


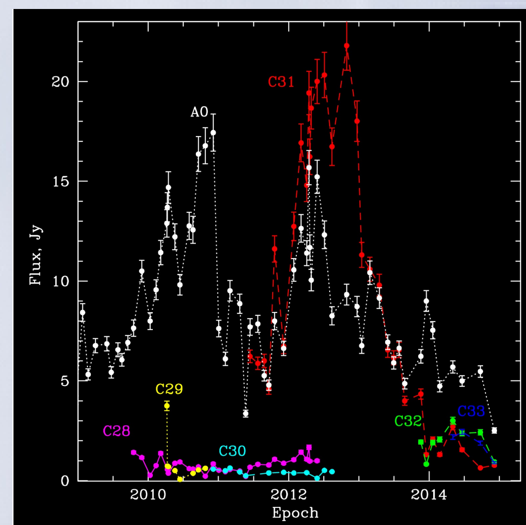


Wehrle et al. 2012, ApJ, 758, 72
Jorstad et al. 2013, ApJ, 773, 147
Morozova et al. Poster # 52

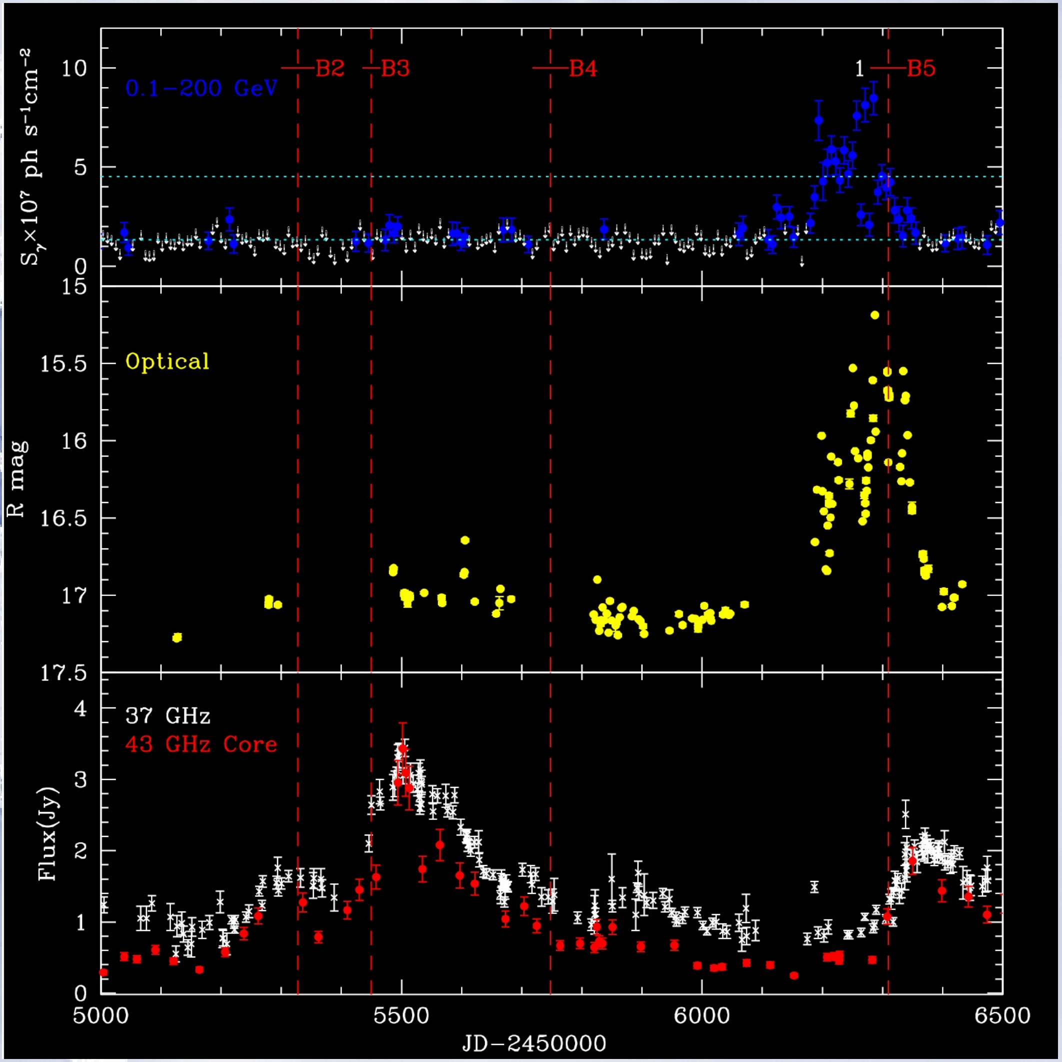
Quasar 3C279







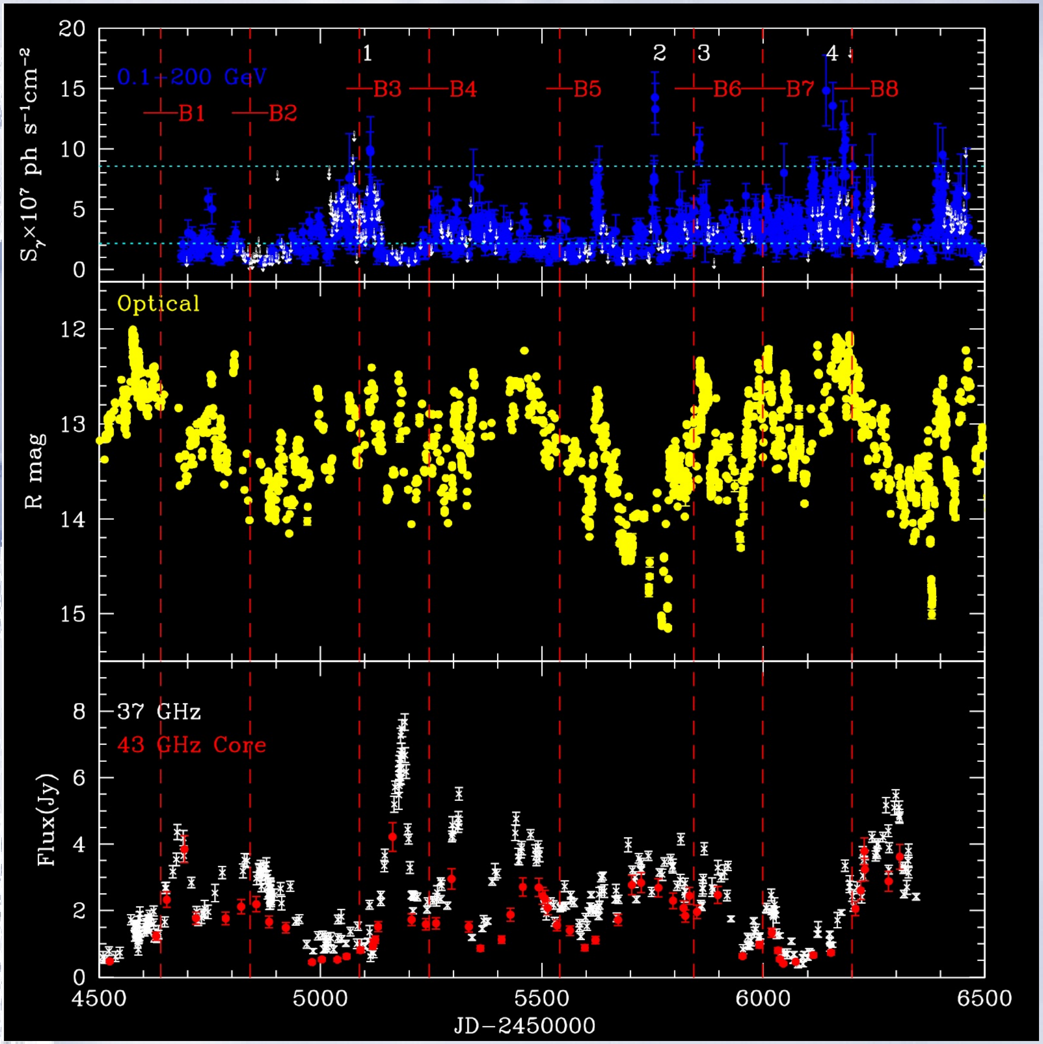
The Quasar 0827+243 (OJ248)



Ramakrishnan et al. 2014, MNRAS, 445, 1636: 1156+295

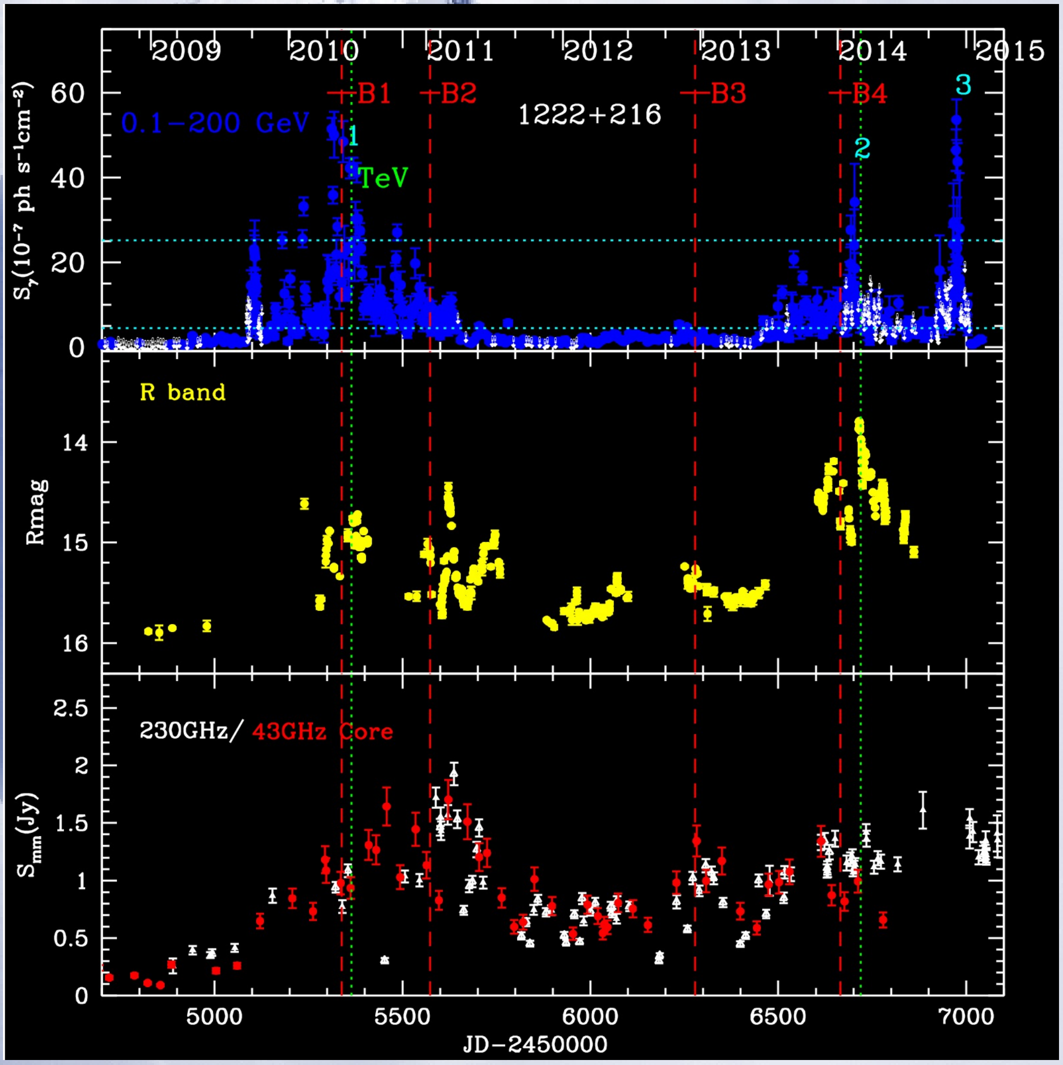
Aller et al. Poster

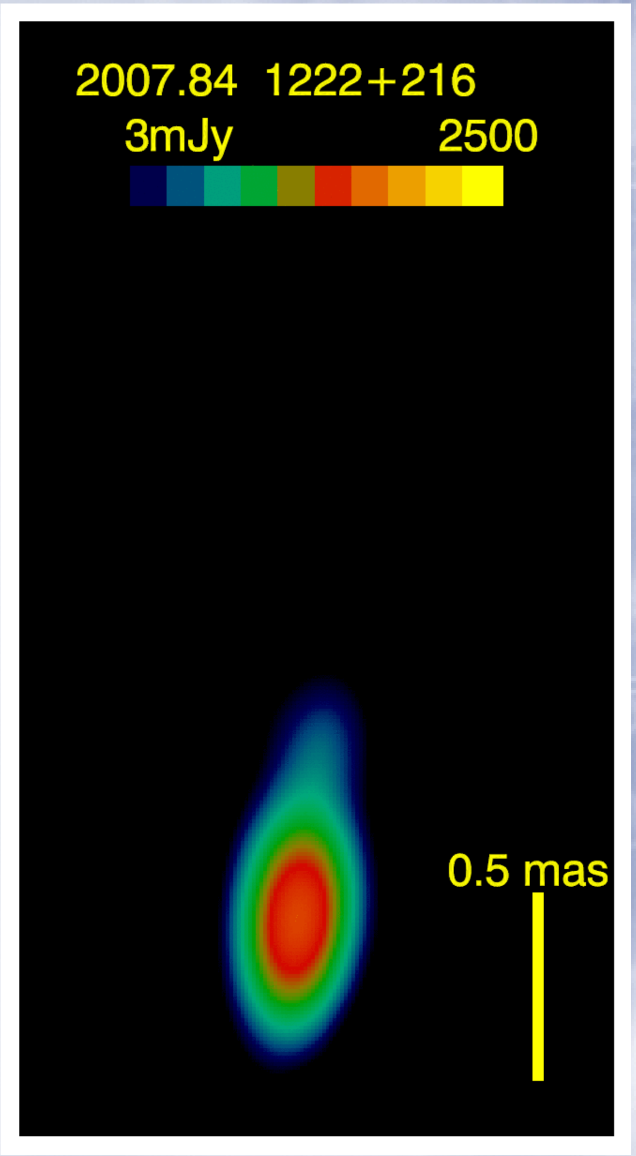
The BL Lac Object S5 0716+714



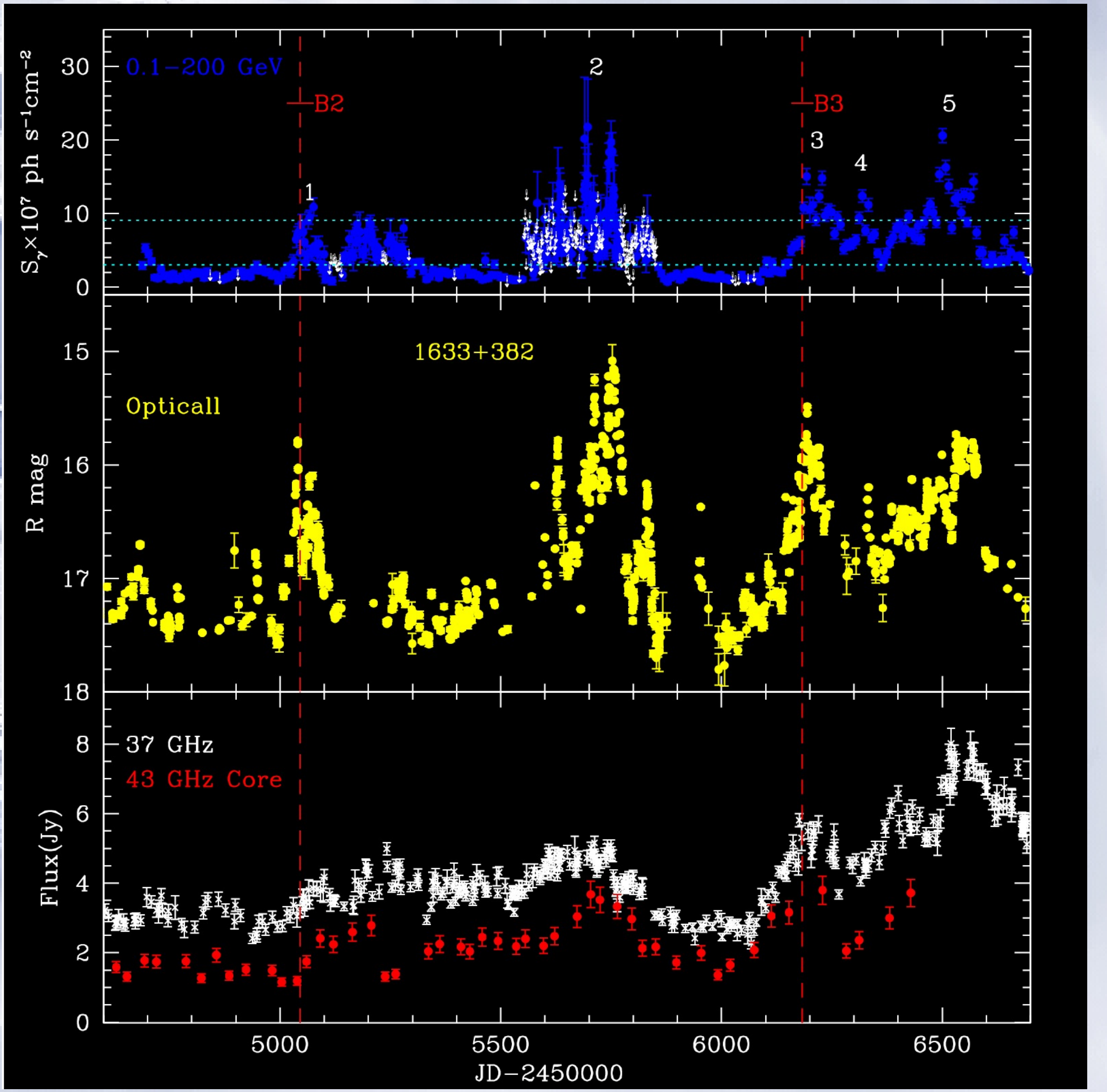
Larionov et al. 2013, ApJ , 768, 40
Aller et al. Poster

The Quasar 1222+216

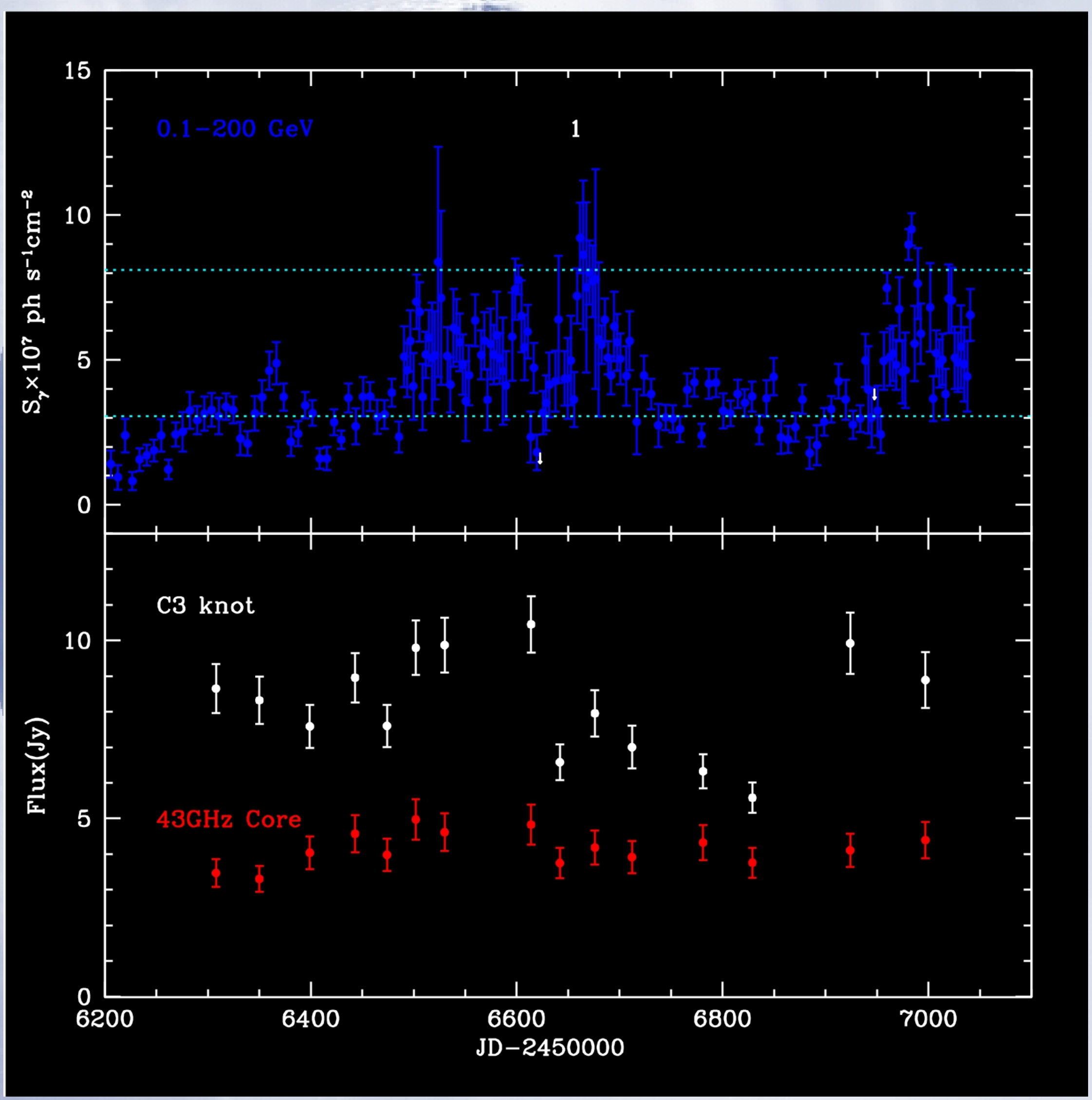


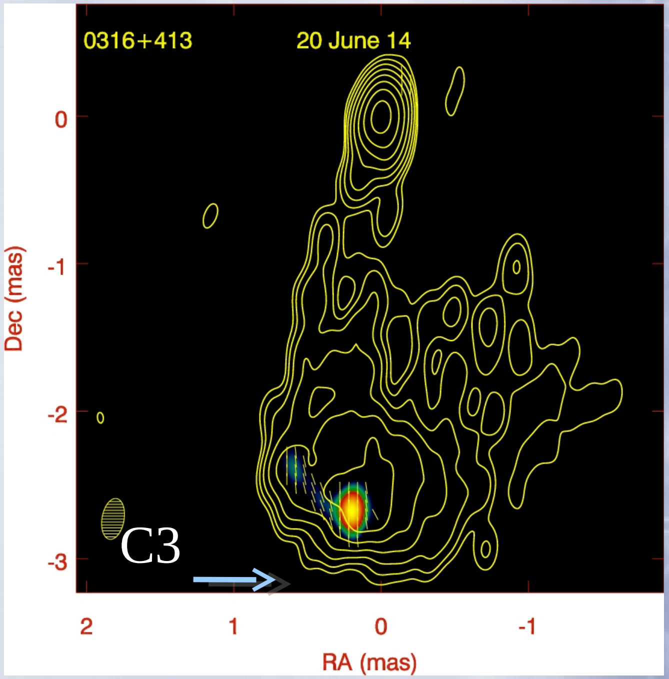


The Quasar 1633+382

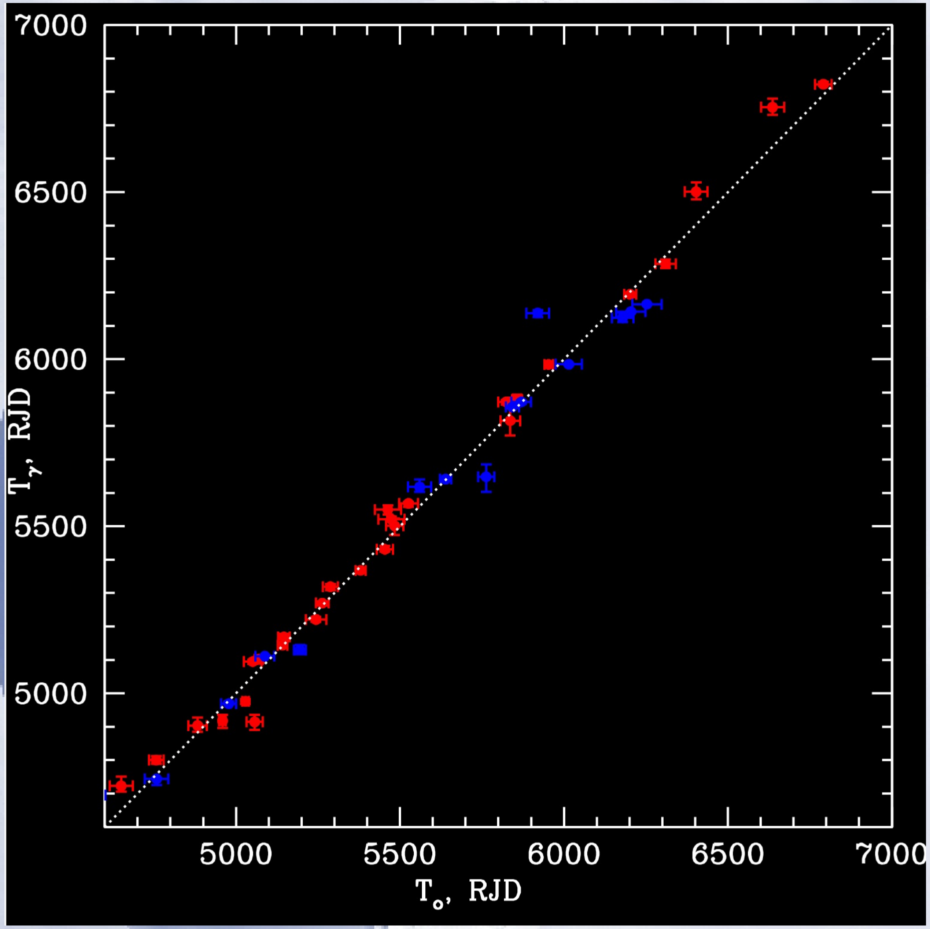


The Radio Galaxy 3C 84





Statistics of Gamma-Ray/Jet Events



During 2008-2013 we detected in
18 quasars and 12 BLLacs

I. 32 and 19 3σ γ-ray flares

II. 88 and 43 superluminal components

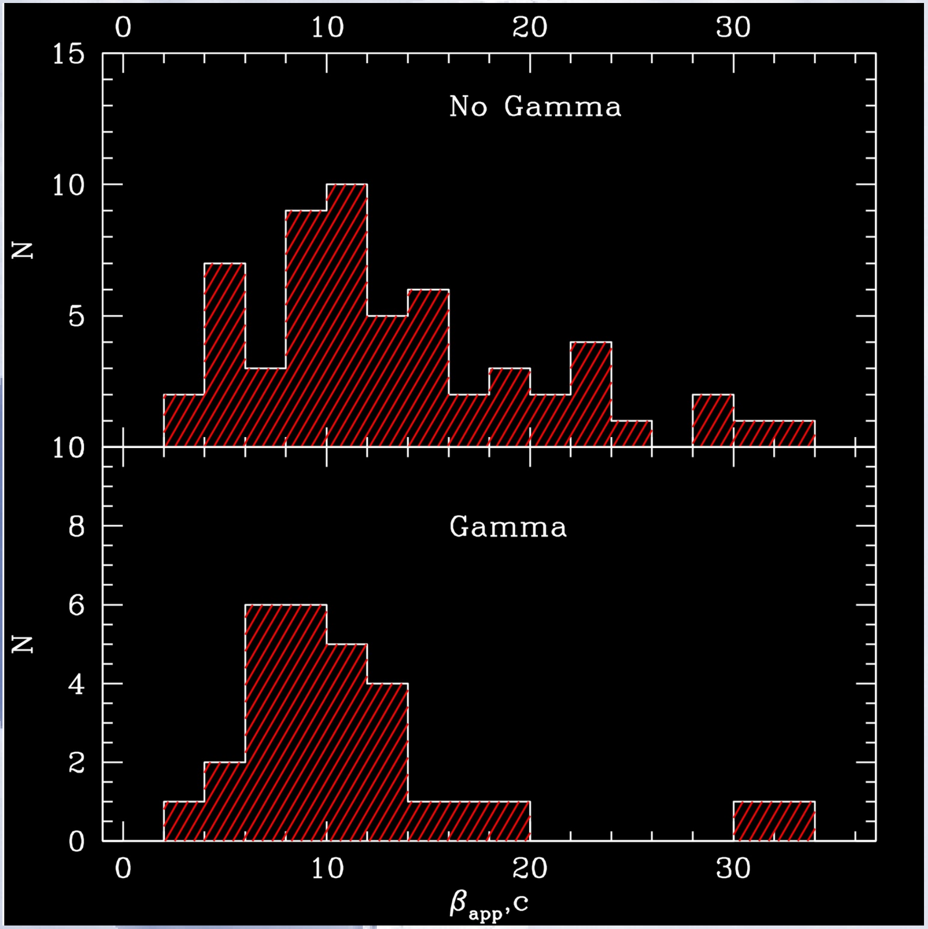
III. 100% of the γ-ray events are accompanied by brightening of the 43 GHz VLBI core

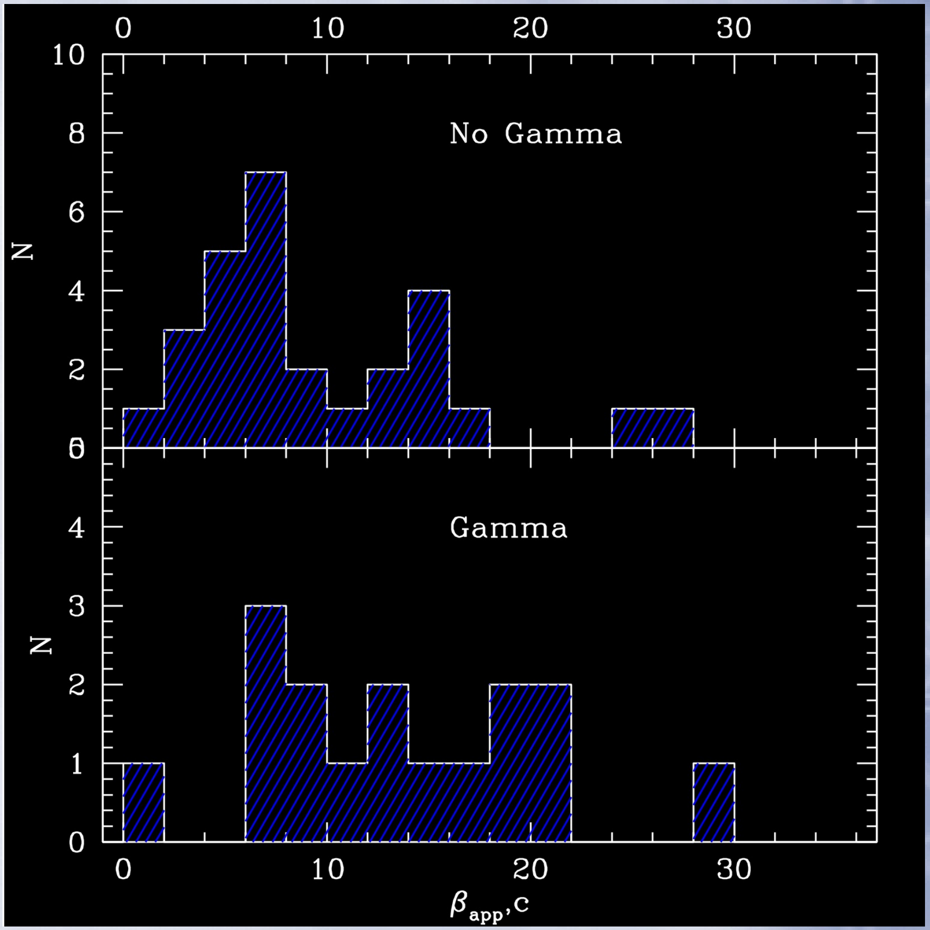
IV. 90% of the γ-ray events are associated with the ejection of a super-luminal knot within the flare duration

V. 65% of superluminal knots do NOT produce prominent γ-ray flares

Can we determine differences in properties of knots associated with sγ-ray flares and those which are not connected with prominent γ-ray events?

Are Apparent Speeds Faster?





Quasars

No γ Knots: 10-12c, β_{app} > 10 in 64%

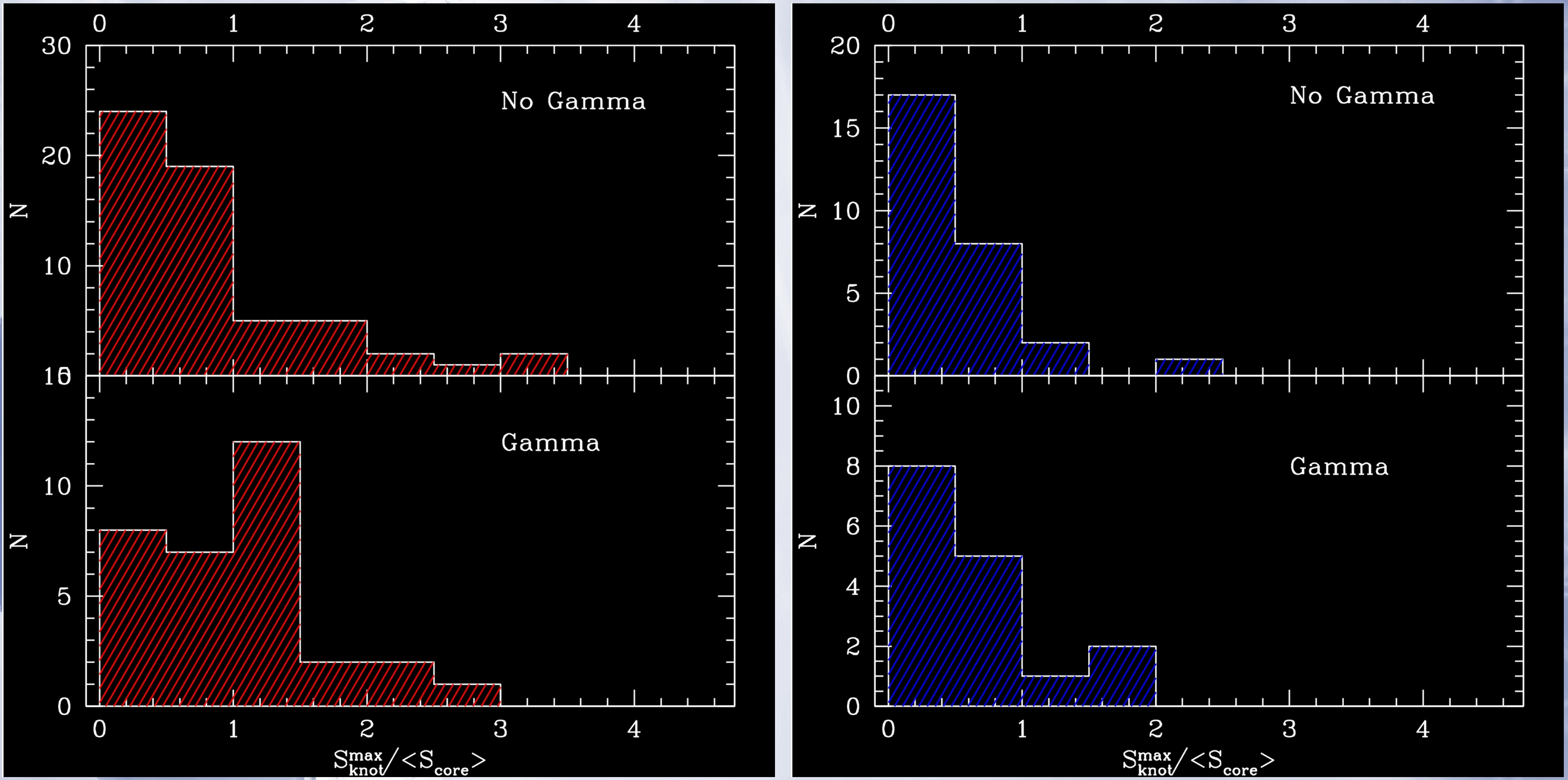
γ Knots: 6-10c, β_{app} > 10 in 45%

BLLacs

No γ Knots: 6-8c, β_{app} > 10 in 37%

γ Knots: 6-8c, β_{app} > 10 in 62.5%

Are Gamma Knots Brighter?



Quasars

No γ Knots: $S_{knot}^{max} > <S_{core}>$ in 26%

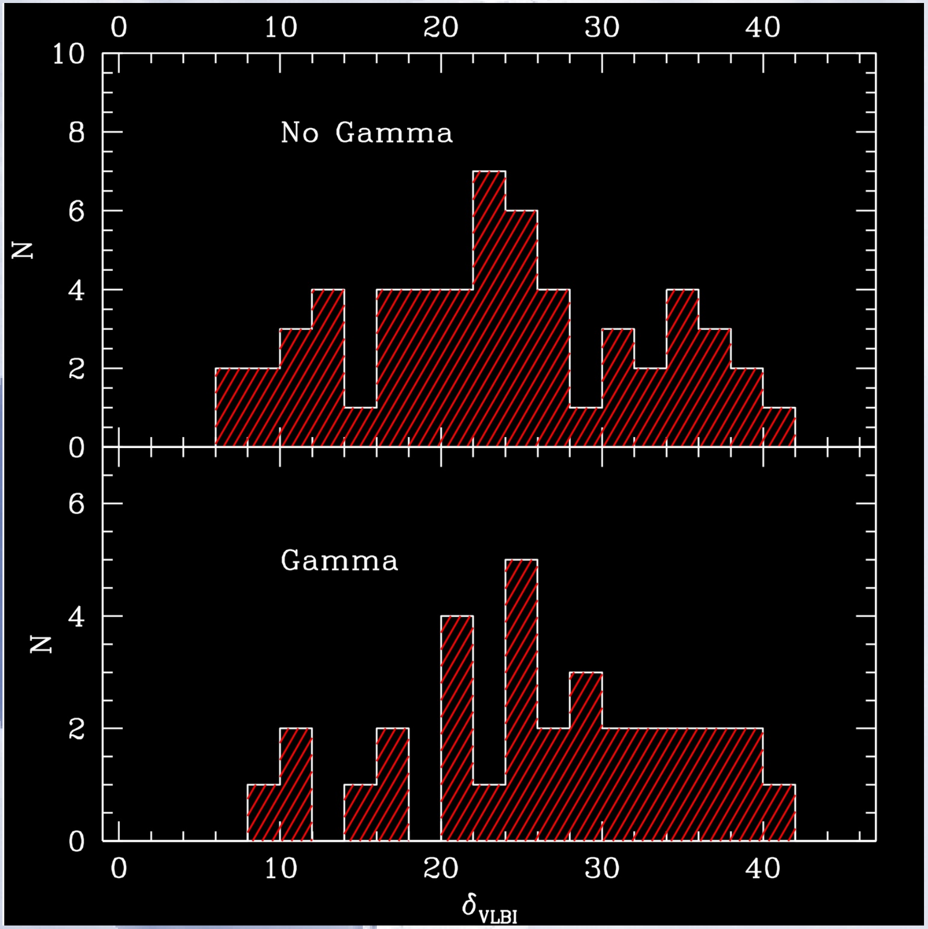
γ Knots: $S_{knot}^{max} > <S_{core}>$ in 57%

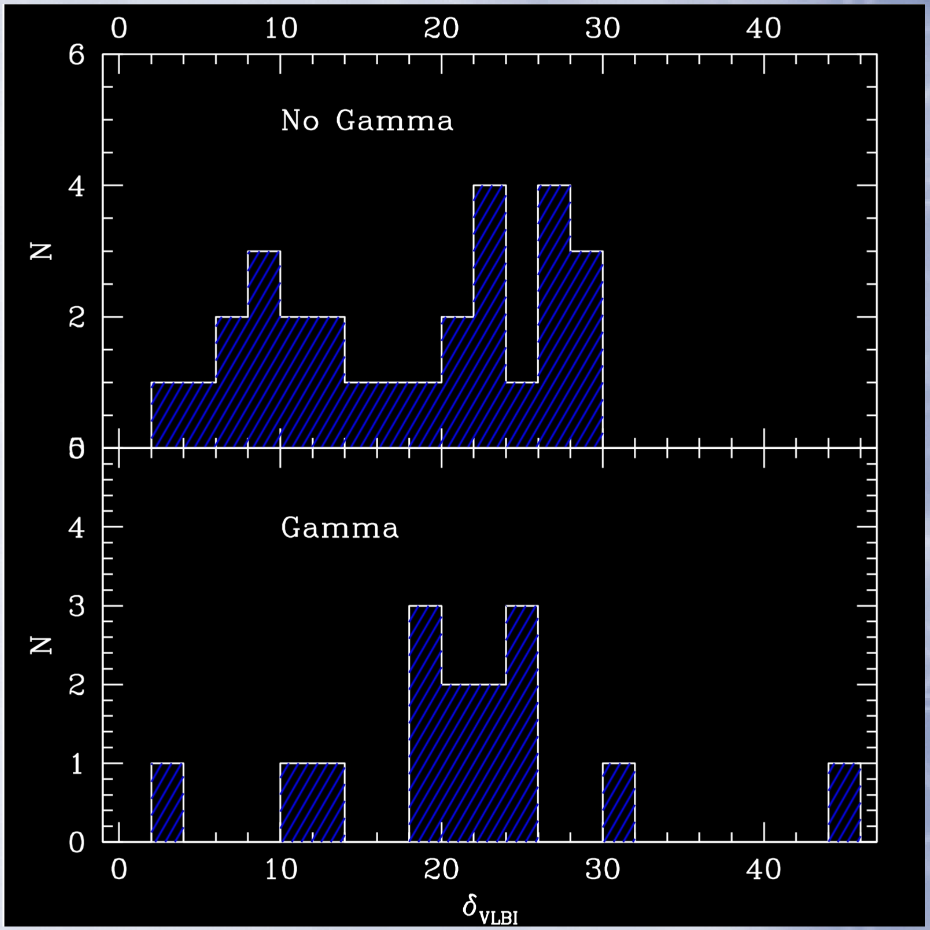
BLLacs

No γ Knots: $S_{knot}^{max} > <S_{core}>/2$ in 39%

γ Knots: $S_{knot}^{max} > <S_{core}>/2$ in 50%

The Doppler Factor should be Higher for γ Knots





Quasars

No γ Knots: $\delta_{VLBI} > 20$ in 64%

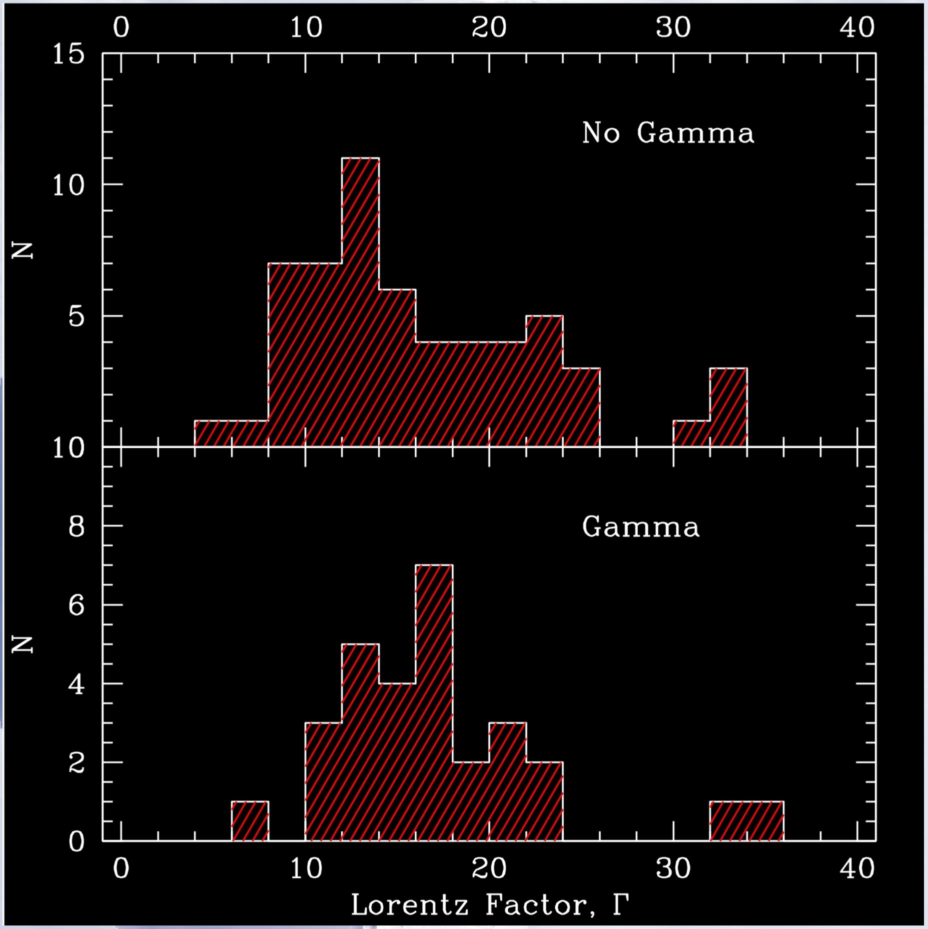
γ Knots: $\delta_{VLBI} > 20$ in 79%

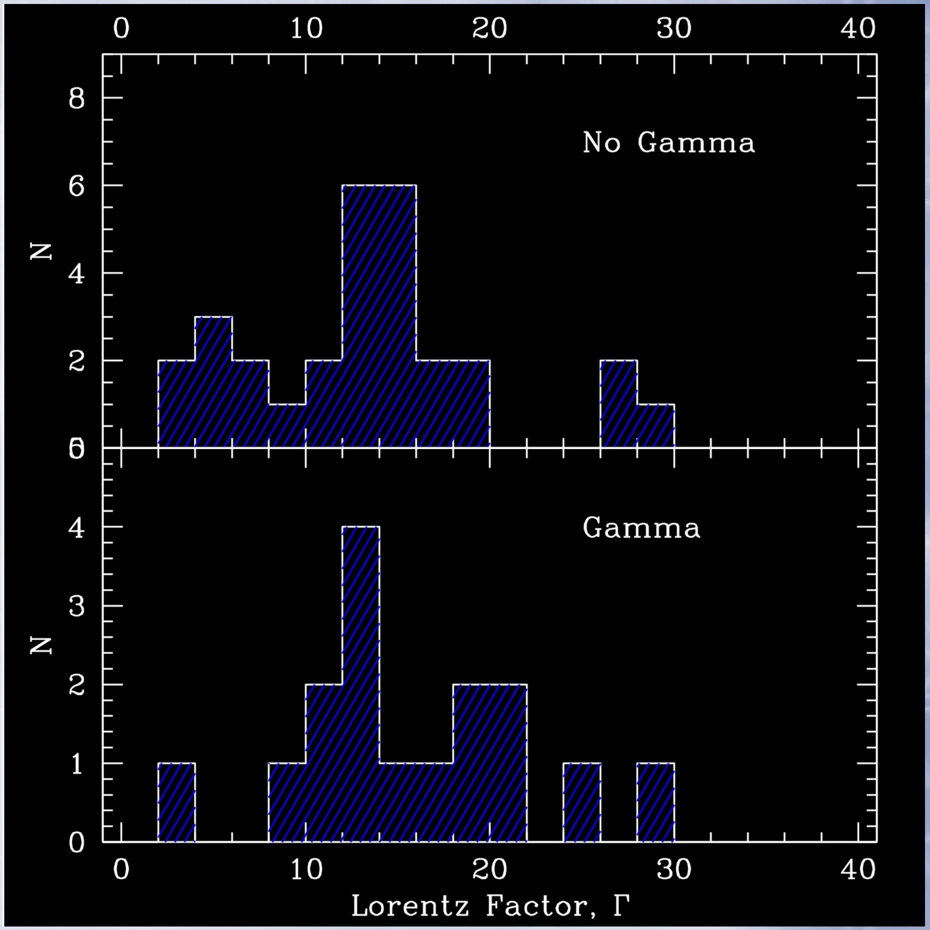
BLLacs

No γ Knots: $\delta_{VLBI} > 20$ in 50%

γ Knots: $\delta_{VLBI} > 20$ in 56%

What is the Lorentz Factor Difference?





Quasars

No γ Knots: $\Gamma_{VLBI} > 16$ in 42%

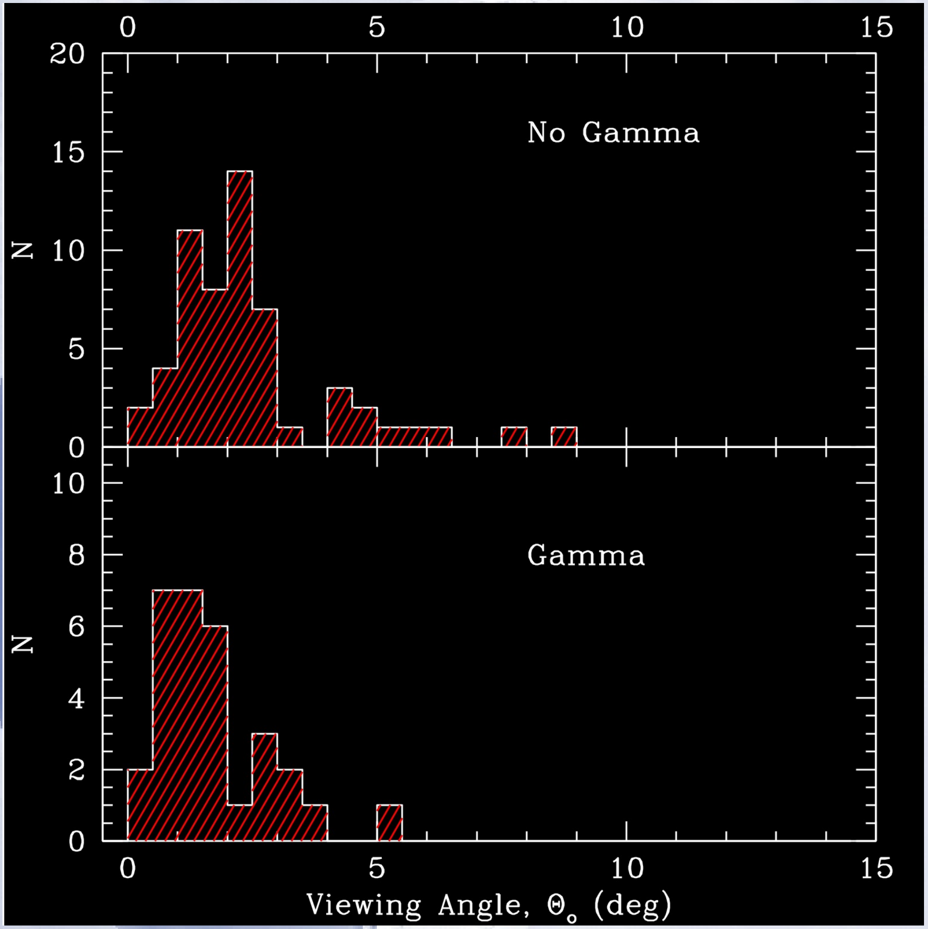
γ Knots: $\Gamma_{VLBI} > 16$ in 53%

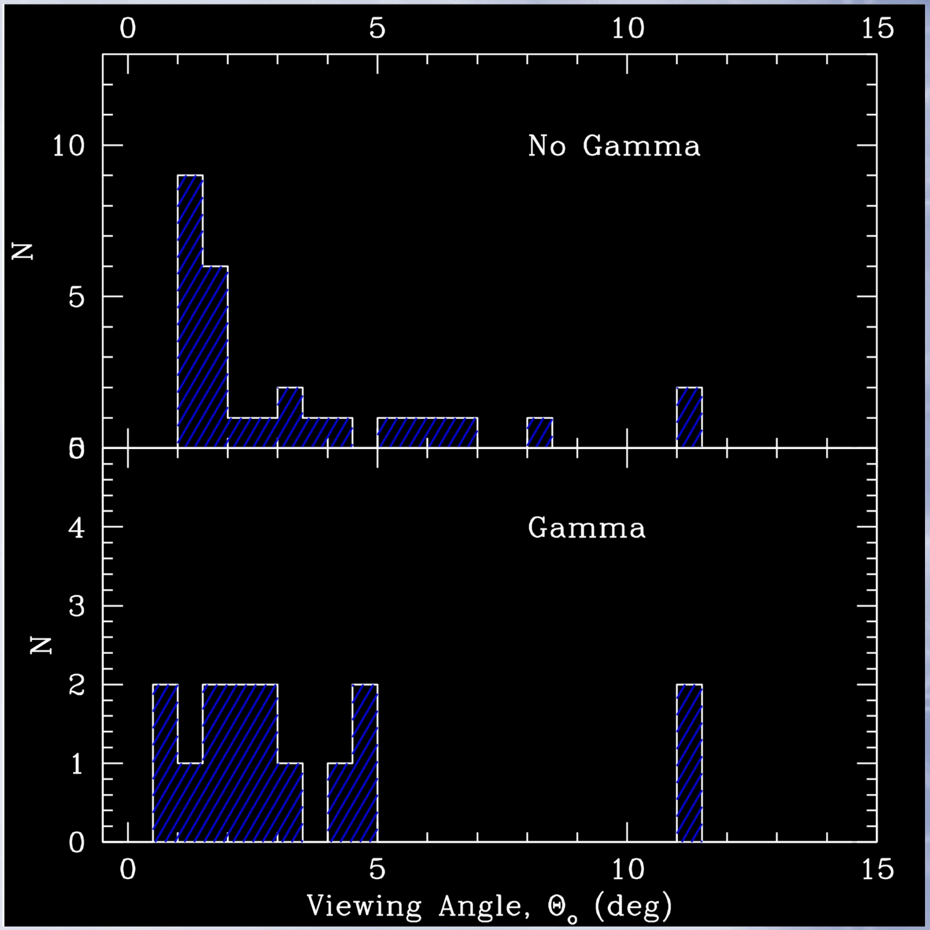
BLLacs

No γ Knots: $\Gamma_{VLBI} > 16$ in 25%

γ Knots: $\Gamma_{VLBI} > 16$ in 47%

What is the Viewing Angle Difference?





Quasars

No γ Knots: $\Theta_o \leq 2°$ in 44%

γ Knots: $\Theta_o \leq 2°$ in 73%

BLLacs

No γ Knots: $\Theta_o \leq 2°$ in 54%

γ Knots: $\Theta_o \leq 2°$ in 33%

Summary

I. Ejections of 131 superluminal knots were detected from 2008 August to 2014 January in the 21 quasars and 12 BL Lac objects which form the majority of the BU-VLBA-BLAZAR sample of bright γ-ray blazars.

II. 51 prominent γ-ray outbursts were counted in these sources during the same period.

III. All γ-ray outbursts are contemporaneous with an increase of the flux in the 43 GHz VLBI core, which suggests that a disturbance propagating in the jet is necessary to produce a strong γ-ray outburst.

IV. 90% of the γ-ray outbursts have an intimate connection between timing of the outbursts and passage of superluminal knots through the VLBI core.

V. 65% of superluminal knots do not trigger prominent γ-ray events.

VI. We have found a possible difference in properties of knots in jet associated with γ-ray outbursts (γ Knots) and those which do not show such a relation (non-γ Knots).

VII. In both the quasars and BL Lac objects γ Knots tend to have a higher Doppler factor, but in the quasars this requires a smaller viewing angle, while in BL Lac objects a higher Lorentz factor is needed.