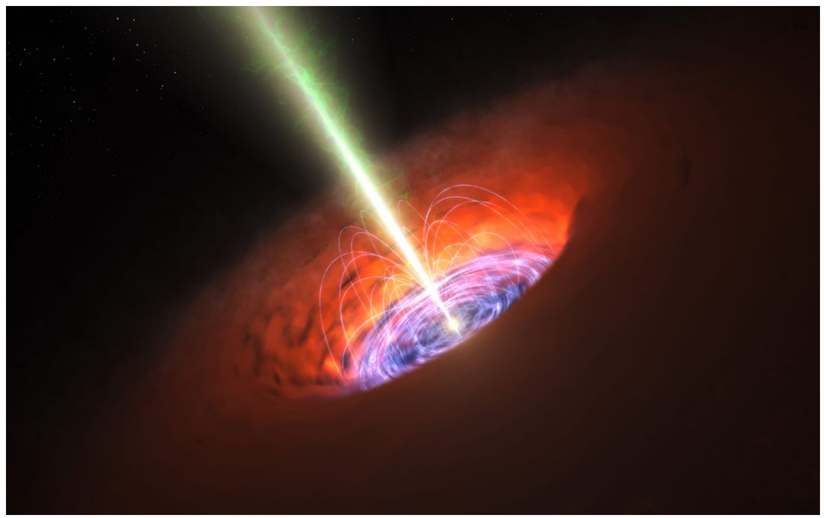
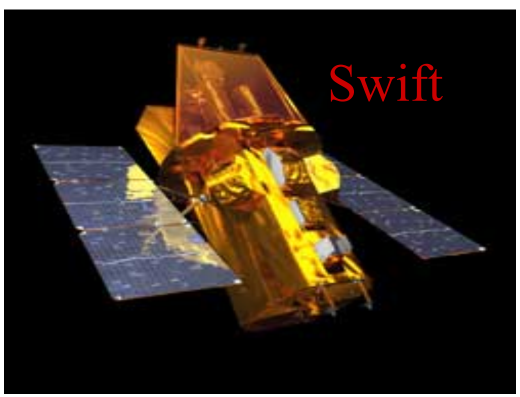
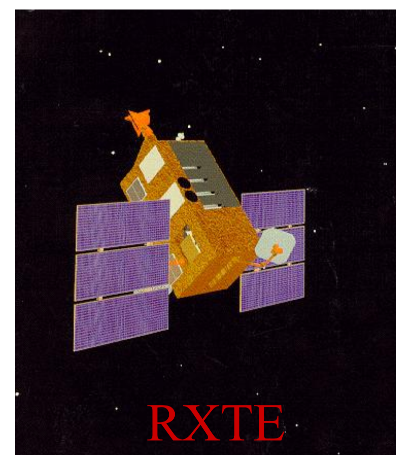
VLBA-BU-BLAZAR PROGRAM

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







Collaborators

Boston University group (USA):   *Alan Marscher*
Vishal Bala, Manasvita Joshi, Mason Keck, Nicholas MacDonald, Michael Malmrose, Mahito Sasada, Karen Williamson

St.Petersburg University group (Russia):
Valeri Larionov, Vladimir Hagen-Thorn, Daria Morozova, Ivan Troitsky, Ludmila Larionova, Evguenia Kopatskaya, Yulia Troitskaya

Instituto de Astrofísica de Andalucía group (Spain):
Jose-Luis Gómez, Ivan Agudo, Carolina Casadio, Sol Molina

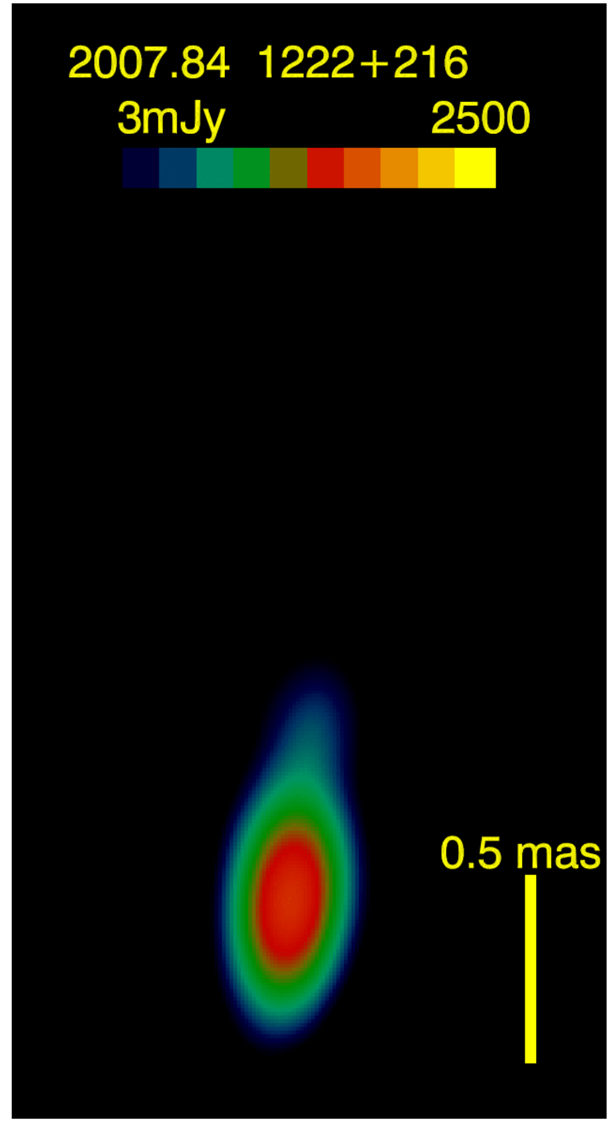
Steward Observatory (USA):
Paul Smith

Aalto University Metsähovi Radio Obs. group (Finland):
Anne Lähteenmäki, Merja Tornikoski, Esko Valtaoja, Venkatessh Ramakrishnan

Goals of the Program:

I. Studying Kinematics of the innermost parsec-scale jet behavior of bright γ-ray blazars

II. Determining locations and mechanisms of high energy production in blazars



The Sample:

I. DEC > -30°

II. Flux density at 37 GHz > 0.5 Jy

III. Optical magnitude in R band < 18.5

IV. Detection by EGRET

36 blazars z=0.017 – 2.17

21 quasars + 12 BLLacs + 3 RG

THE PROGRAM

I. Monthly monitoring with the VLBA at 43 GHz of the sample of γ-ray blazars

II. Optical photometric (BVRI) and polarimetric (R-band) monitoring of the sample at the Perkins Telescope, Lowell Obs. (5-10 nights per month)

III. Construction of UV and X-ray light curves from Swift UVOT & RXTE observations

IV. Construction of γ-ray light curves using Fermi LAT data

V. Analysis of multi-wavelength data (posters by Mason Keck, Michael Malmrose, Daria Morozova, Mahito Sasada, Ivan Troitskiy, Yulia Troitskaya, and Karen Williamson)

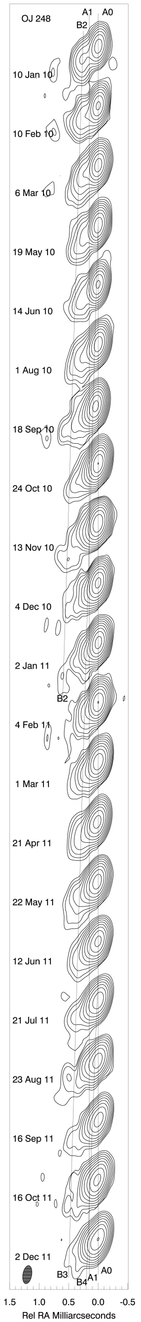
IV. Theoretical models of multi-wavelength blazar emission (TEMZ, Marscher 2014; MUZORF, Joshi et al. 2014; Ring of Fire, MacDonald et al. 2015)

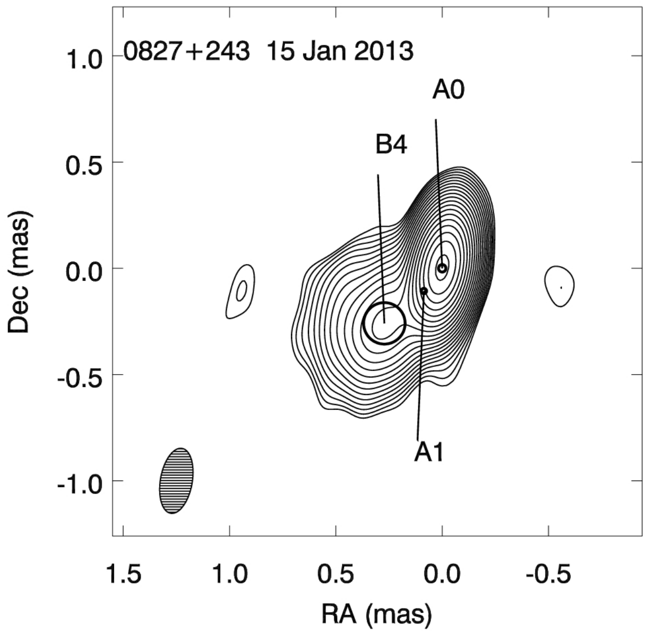
http://www.bu.edu/blazars/VLBAproject.html

VLBA Monitoring

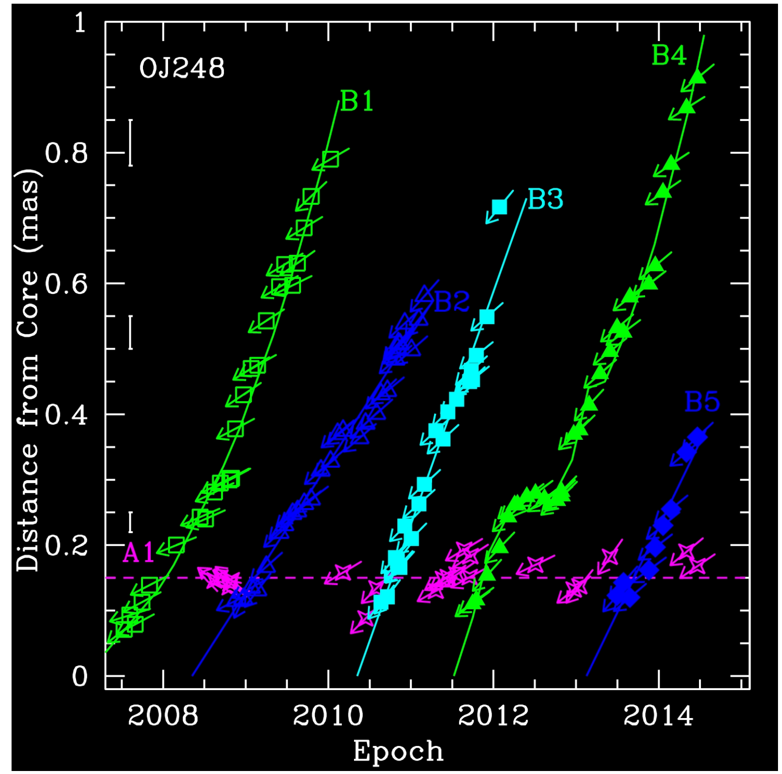
From 2007 June to 2013 January
58 epochs (24 hrs each, 30-33 sources) plus
7 campaigns over 2 weeks with 3 epochs
(16 hrs & 16 sources along with one VLA epoch each)

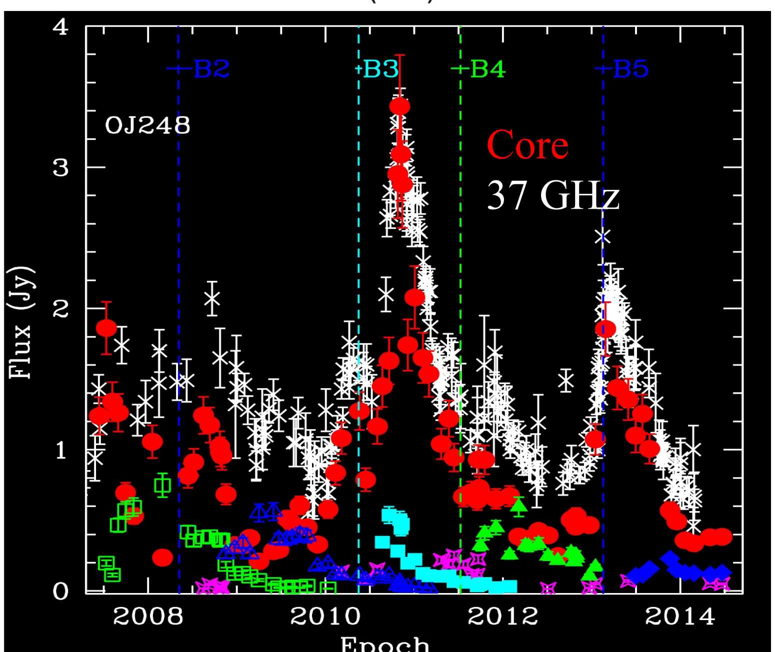
I. 2349 images at 43 GHz in total and polarized intensity
II. 234 jet features are identified at least at 6 epochs
III. 41 features are classified as stationary knots
(a stationary knot has a sub-luminal speed comparable with the speed uncertainty)
IV. 147 moving knots are ejected from 2008 August to 2013 January (the Fermi era) with the time of ejection determining with an accuracy from several days to a month.





Moving Features





B1: $<\beta_{app}> = 15.1 \pm 0.5c$

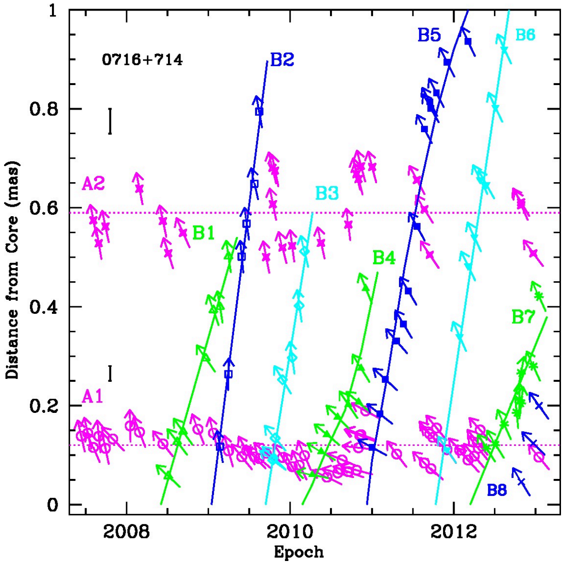
B2: $\beta_{app} = 10.0 \pm 0.3c$

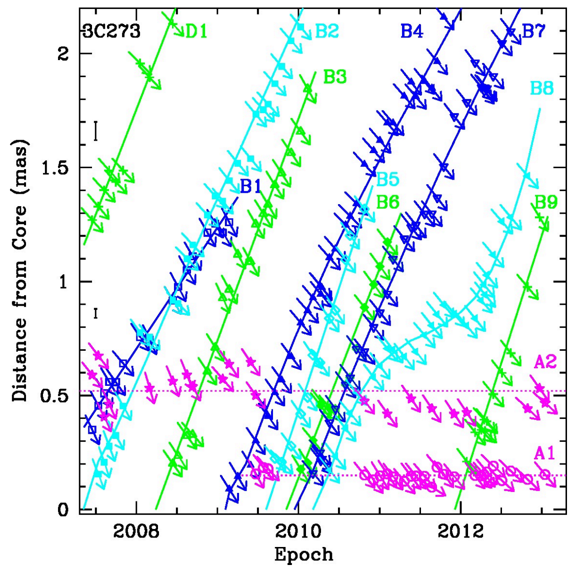
B3: $\beta_{app} = 18.0 \pm 0.2c$

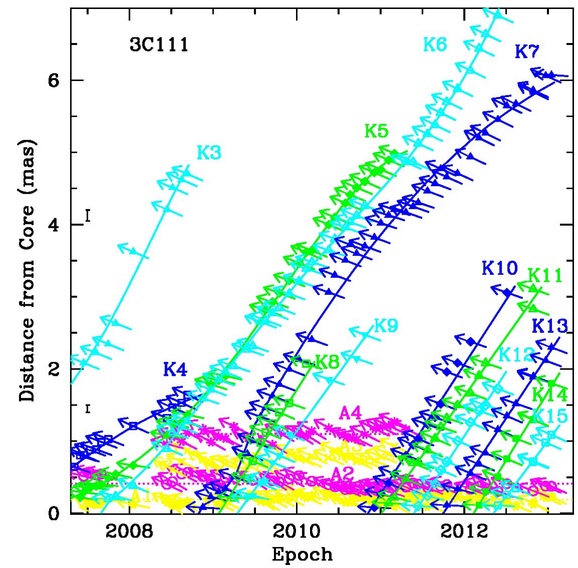
B4: $<\beta_{app}> = 11.1 \pm 2.8c$

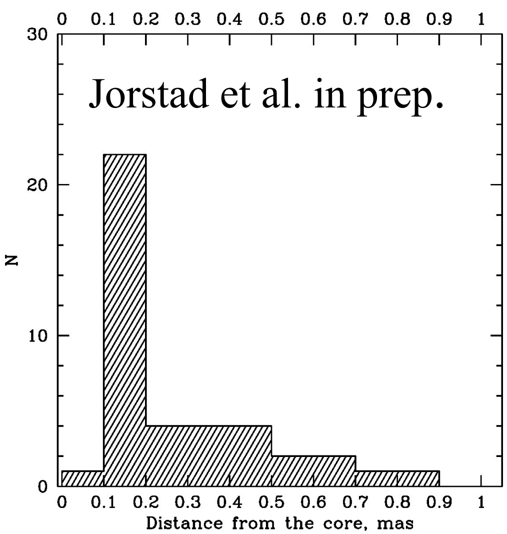
B5: $\beta_{app} = 13.7 \pm 0.3c$

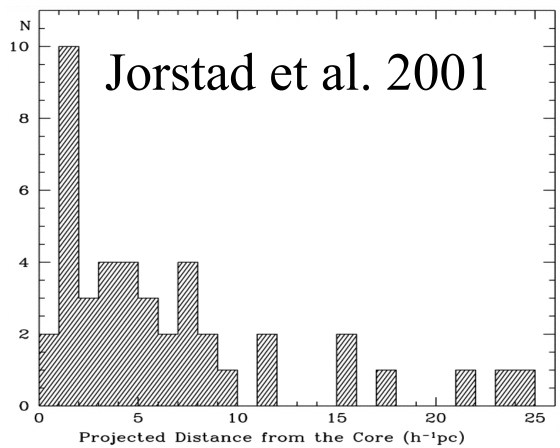
Stationary Features within 1 mas from the Core





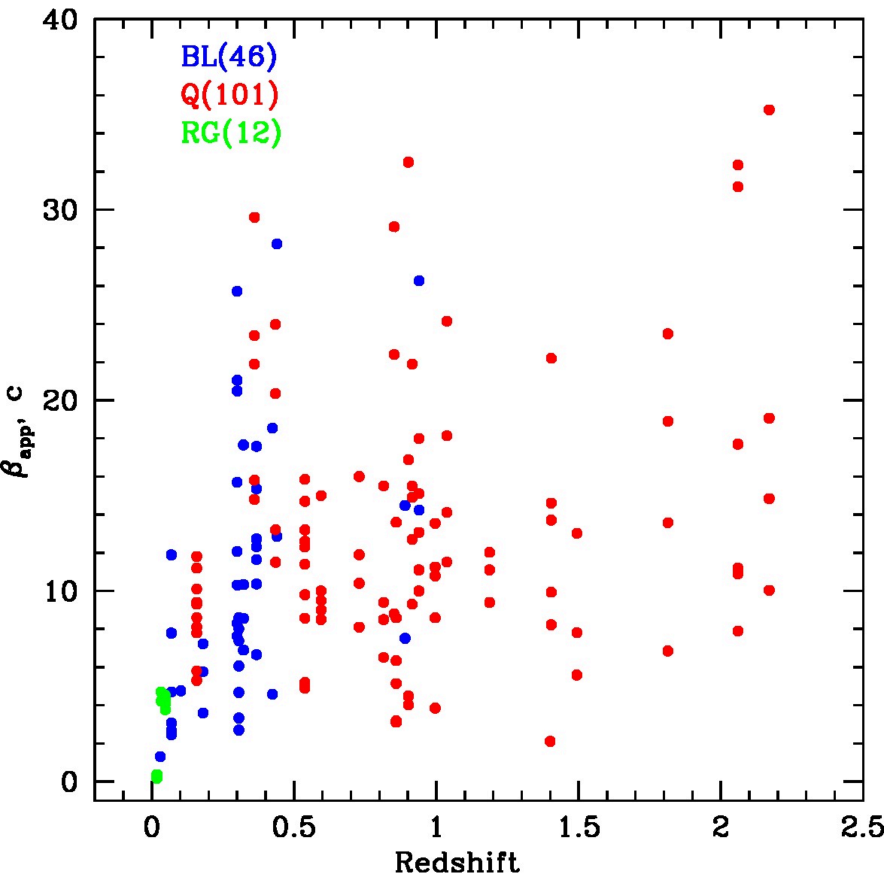


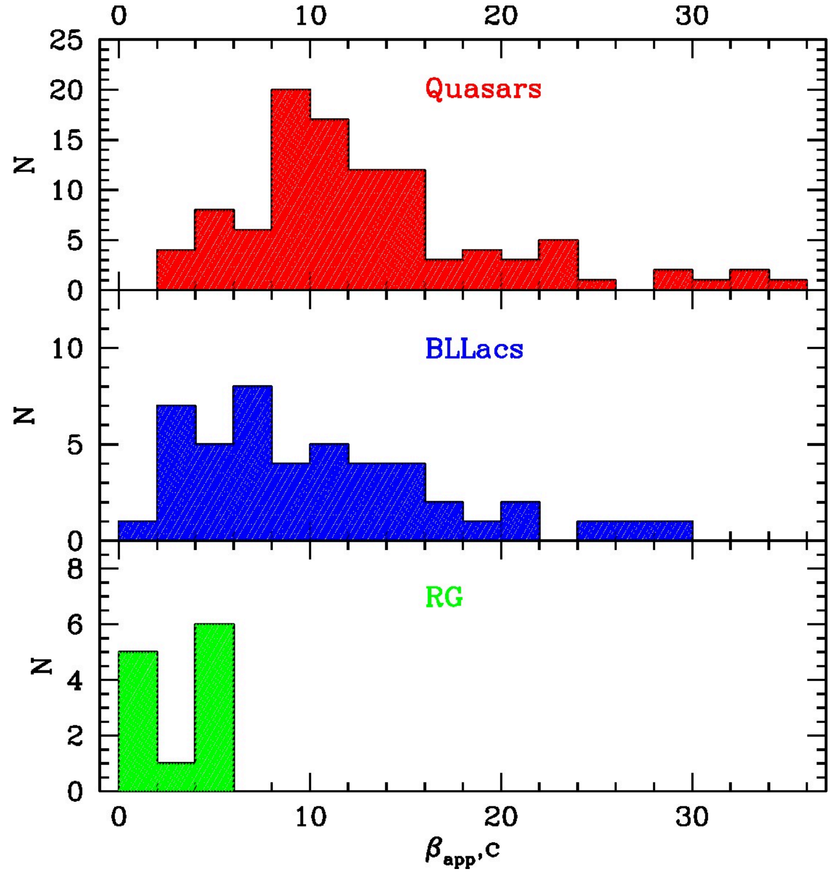




100% of BLLacs,
67% of quasars,
and all 3 RG have 1
or more stationary
features within 0.5 mas
from the core

Apparent Speeds of Moving Features

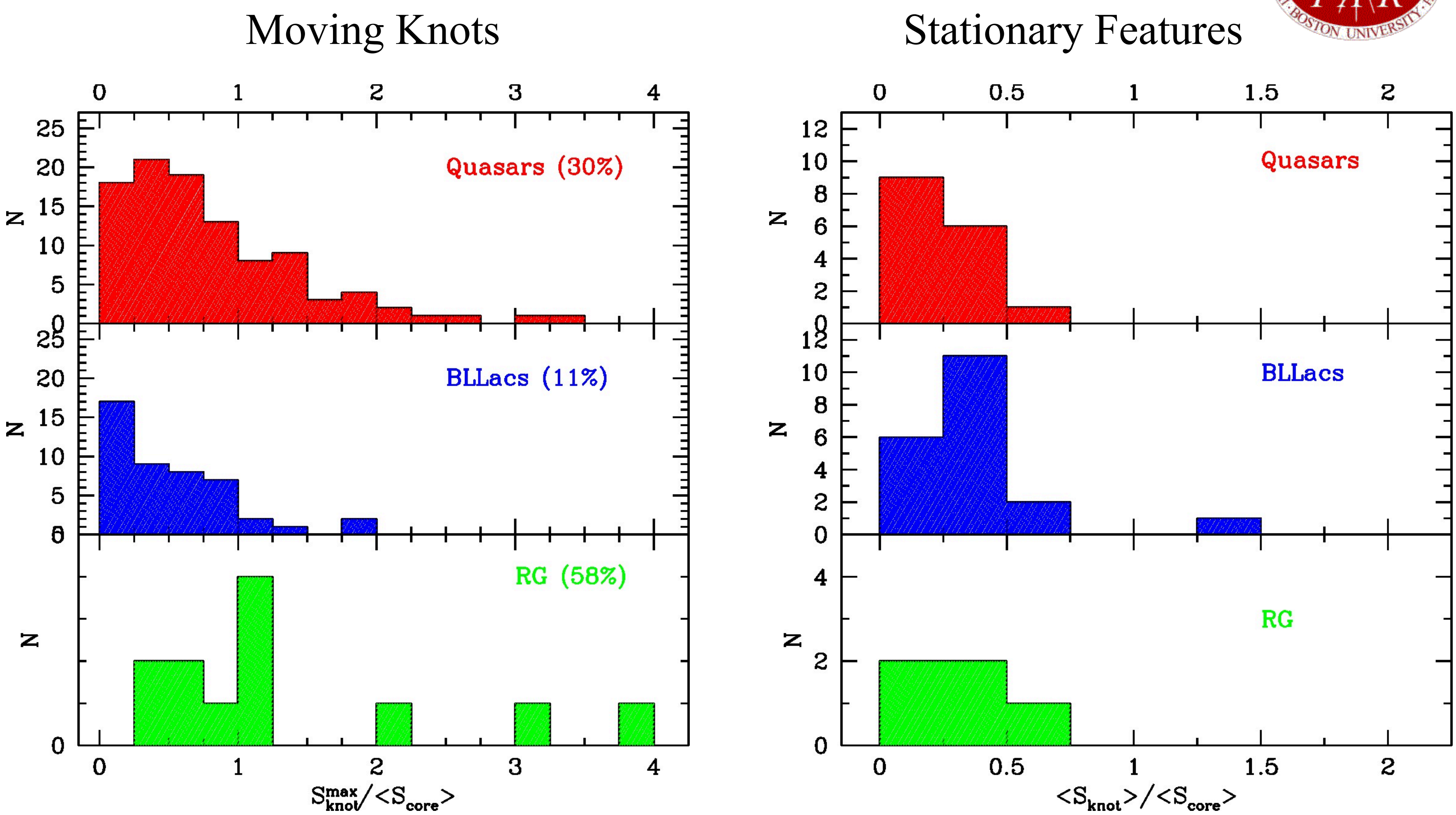




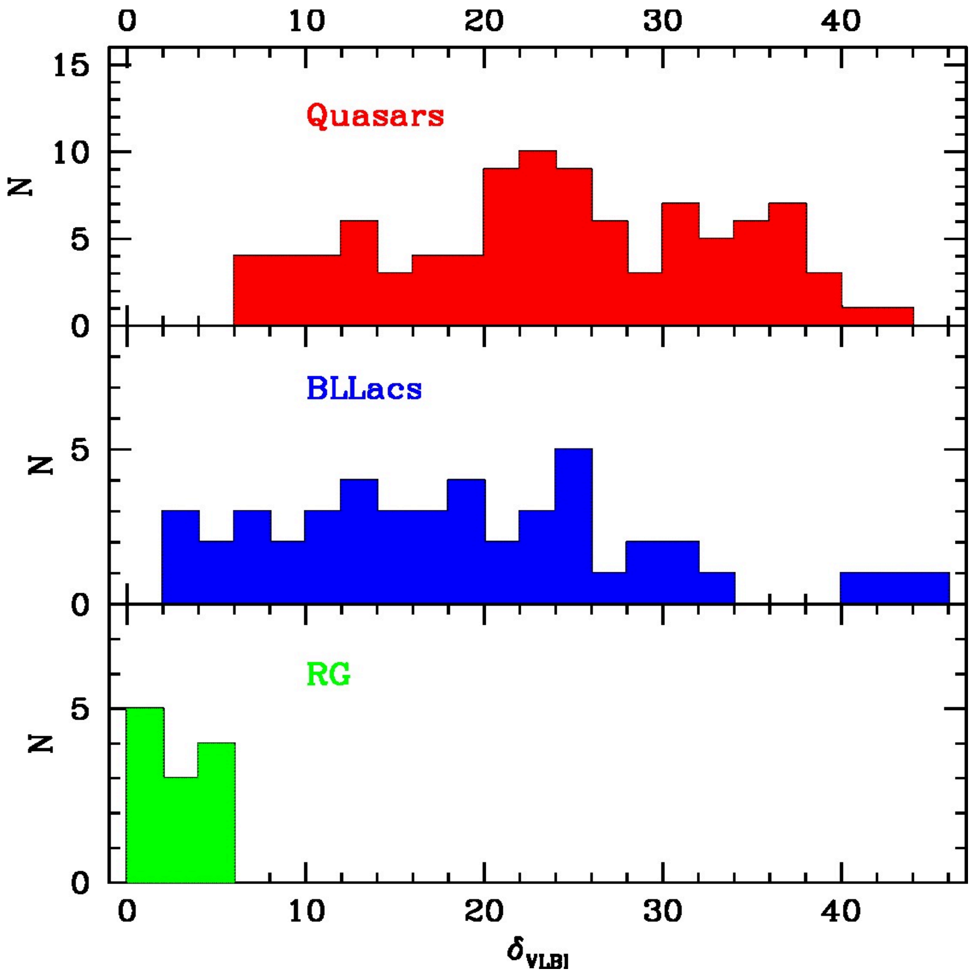
Quasars: 8-10c

BLLacs: 6-8c; RG: 0-2c & 4-6c

Brightness of Jet Features



Doppler Factors

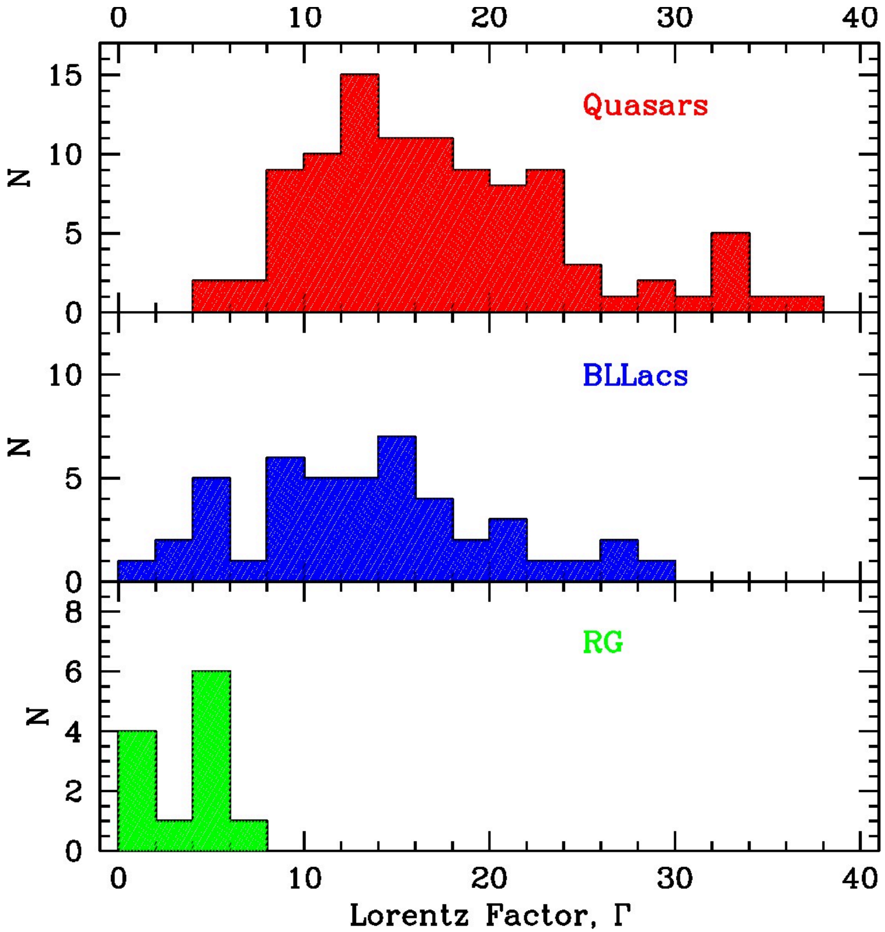


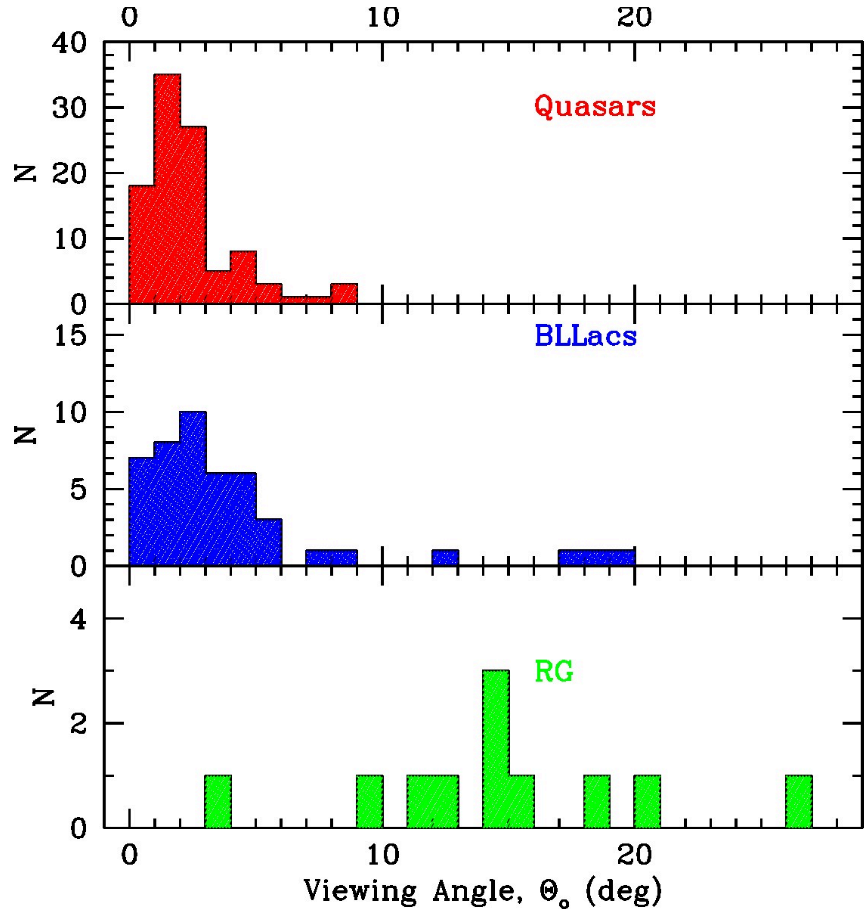
VLBI Time Scale of Variability
Burbidge, Jones, & O' Dell
1974, ApJ , 193, 43
□$t_{var} = dt/\ln(S_{max}/S_{min})$

Variability Doppler Factor
□$_{var} = a_{mod}$ D/[c □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: ~20-26
BLLacs: ~ 2-26
RGs: ~ 1-6

Lorentz Factor & Viewing Angle





Lorentz Factor

Quasars: 12-14, $\Gamma > 20$ in 30.6%

BLLacs: 8-16, $\Gamma > 20$ in 17.4%

RG: ~1 & ~5

Viewing angle

Quasars: 1° -2°, $\Theta_o > 5$ in 8%

BLLacs: 2° -3°, $\Theta_o > 5$ in 20%

RG: 15°- 16°

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 (Williamson et al. 2014)*

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

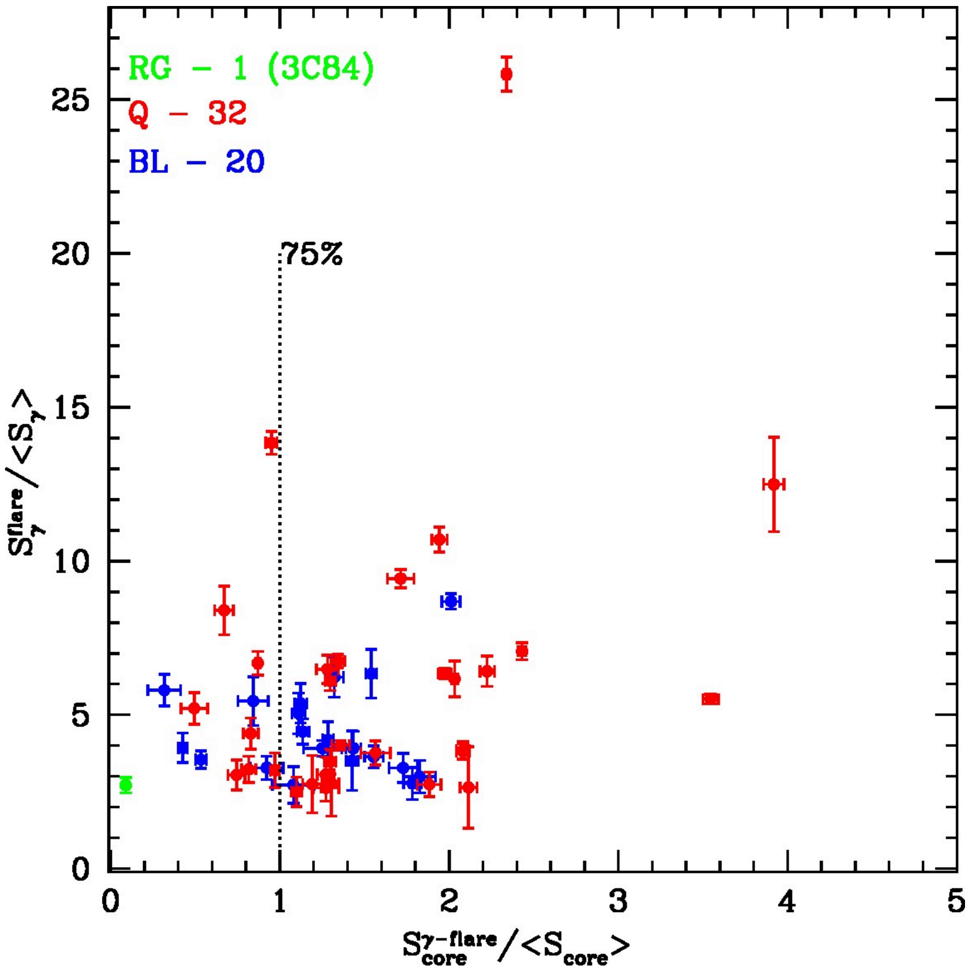
III. For each event a γ-ray light curve with a shorter binning interval (1-3 days) is produced to find ``true'' γ-ray peak, S_γ^{max}

III. Duration of a flare: FWHM of S_γ^{max}

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*

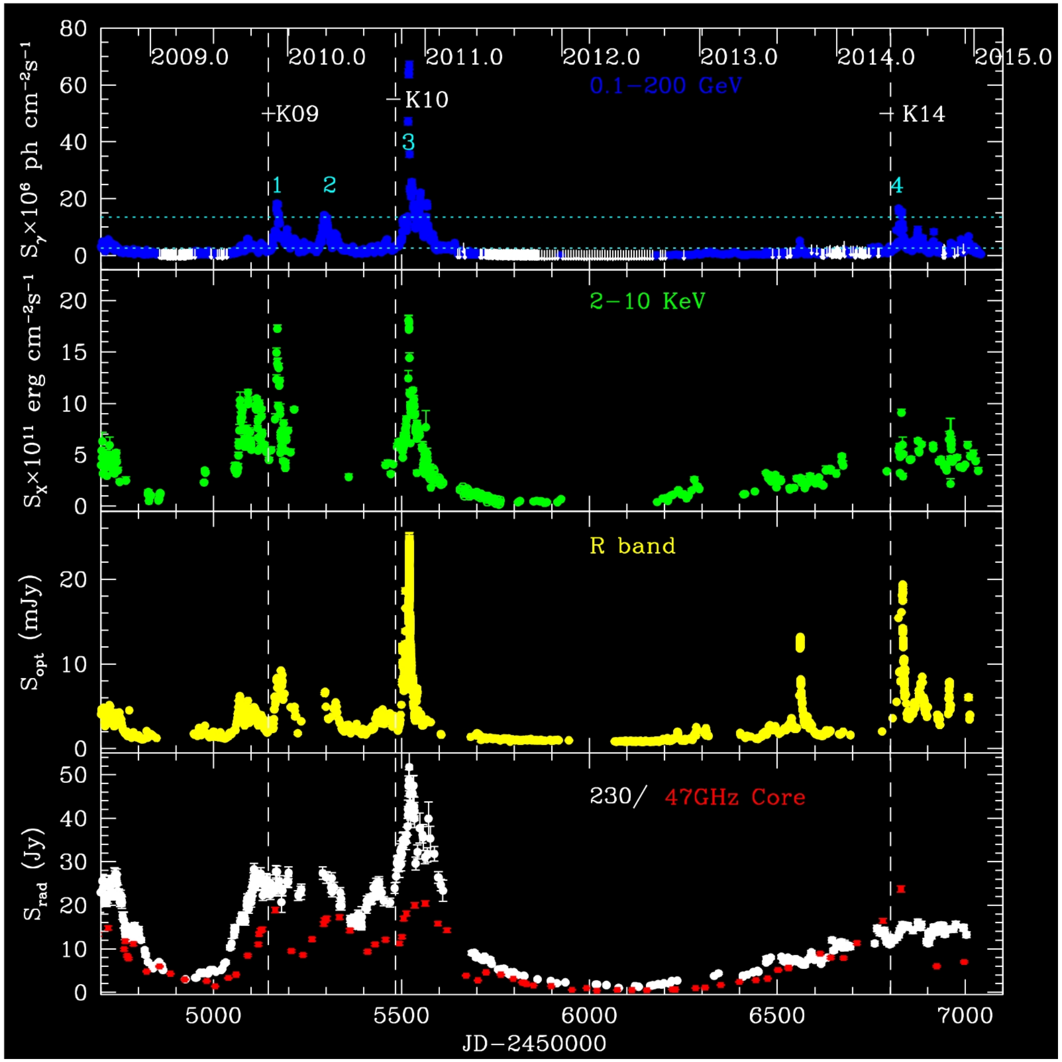
V. 3σ flares of the VLBI core and mm-wave

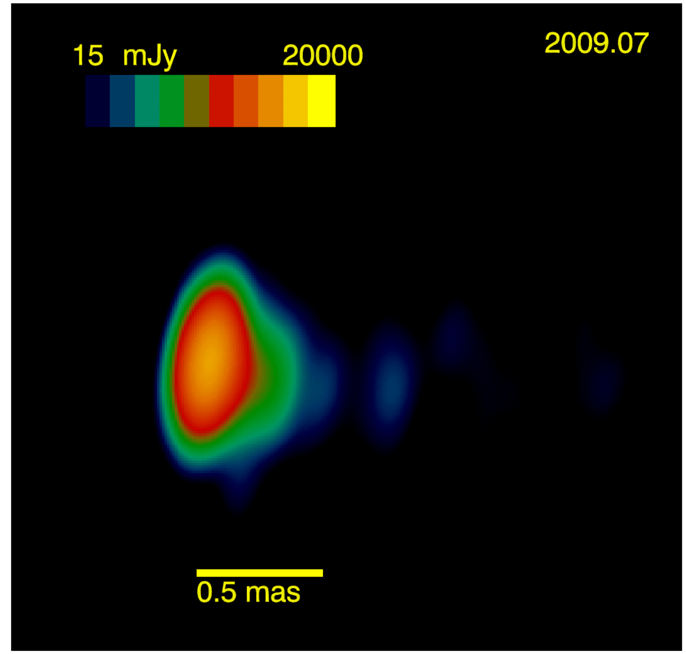
Gamma-Ray Events

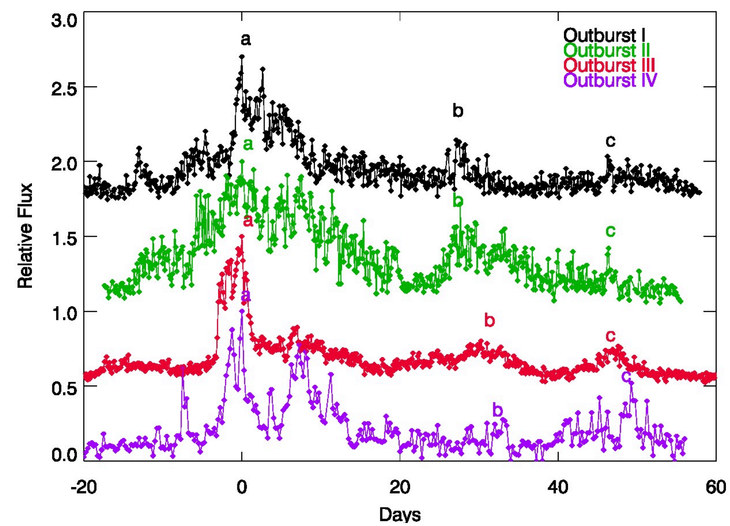


53 3σ γ-ray events
during 2008-2013
No 3σ events for 3 Qs:
1406-076
1611+343
1622-027
and 2 RGs:
3C111 and 3C120 but see:
Tanaka et al. 2015, ApJ 799L
Casadio et al. 2015, ApJ 808

Quasar 3C454.3



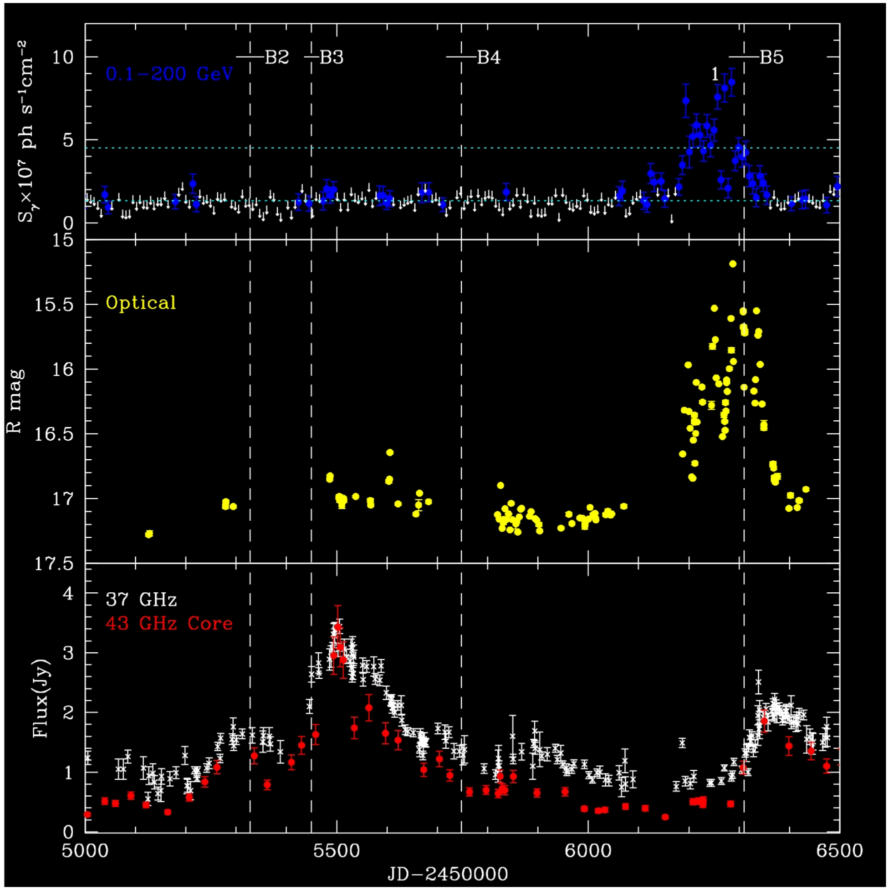




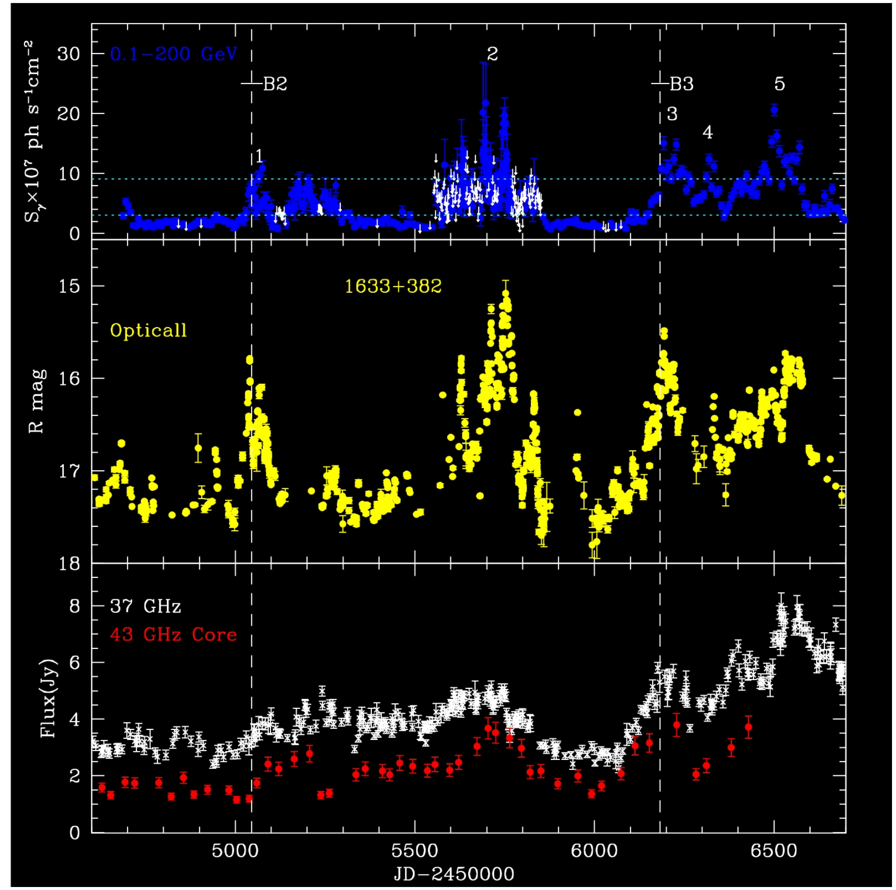
Wehrle et al. 2012, ApJ, 758, 72

Jorstad et al. 2013, ApJ, 773, 147

0827+243 (OJ248)

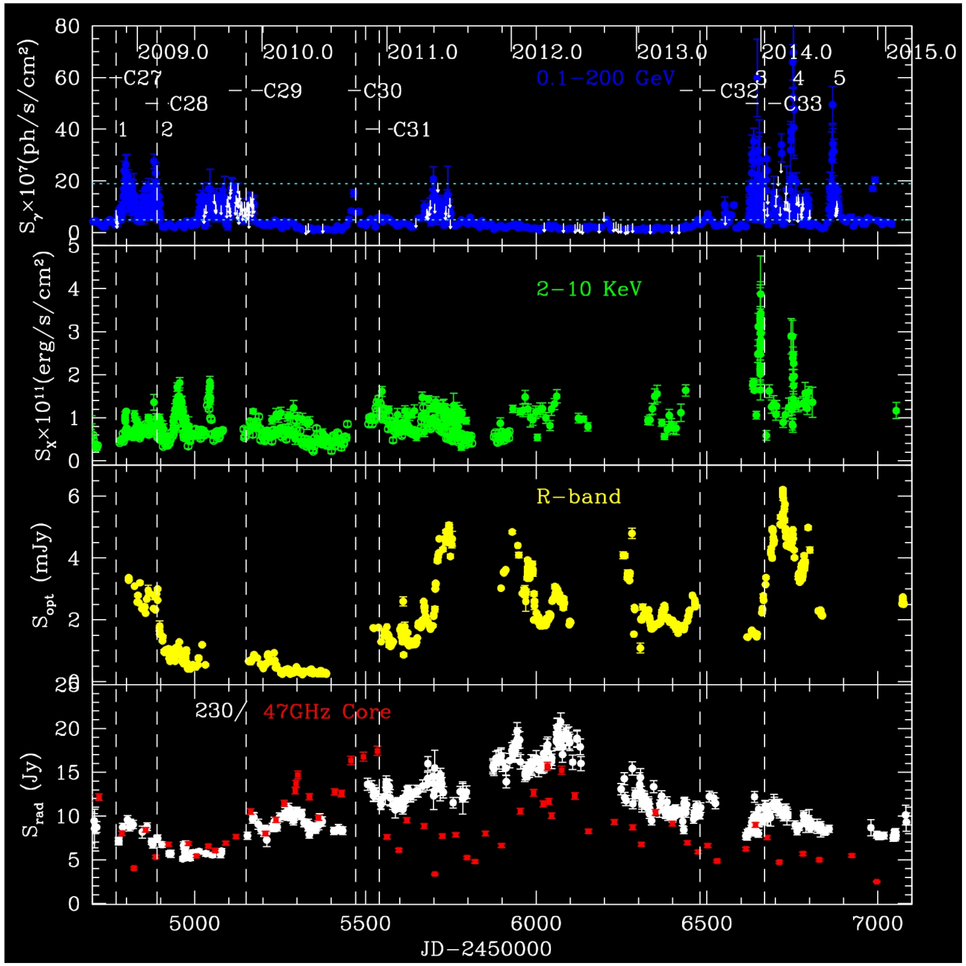


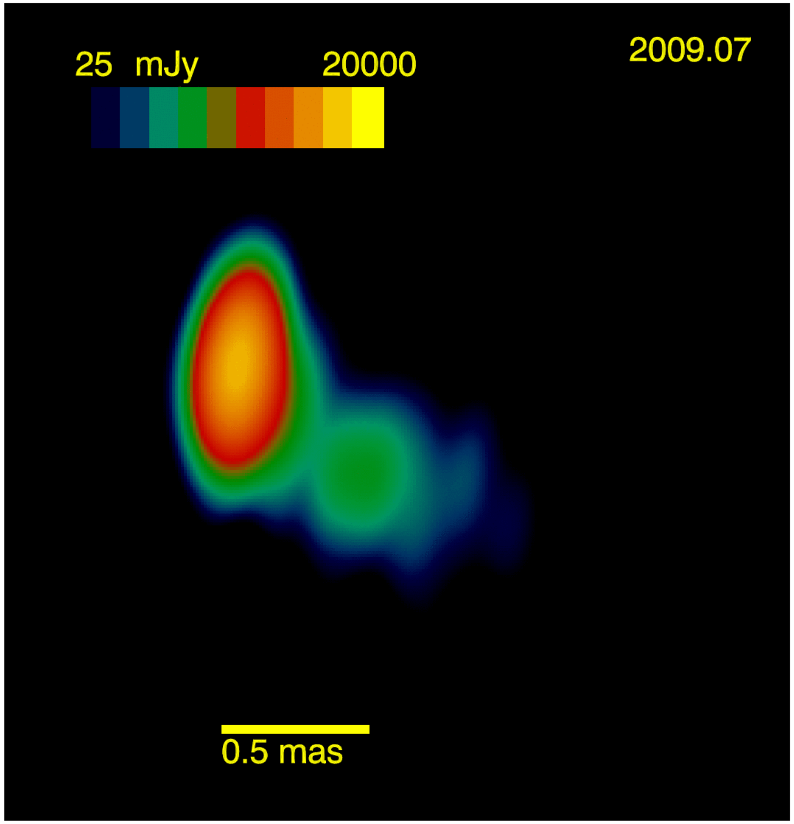
1633+382

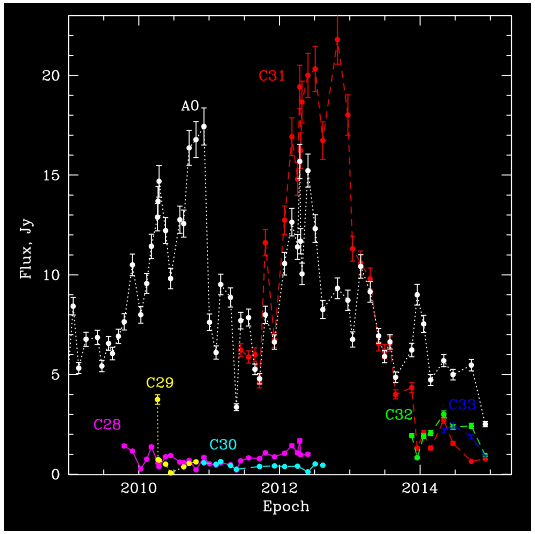


For most recent connection between γ-ray outbursts and jet events see posters by Morozova et al. (0954+65) and Troitskiy et al. (1222+216)

Quasar 3C279

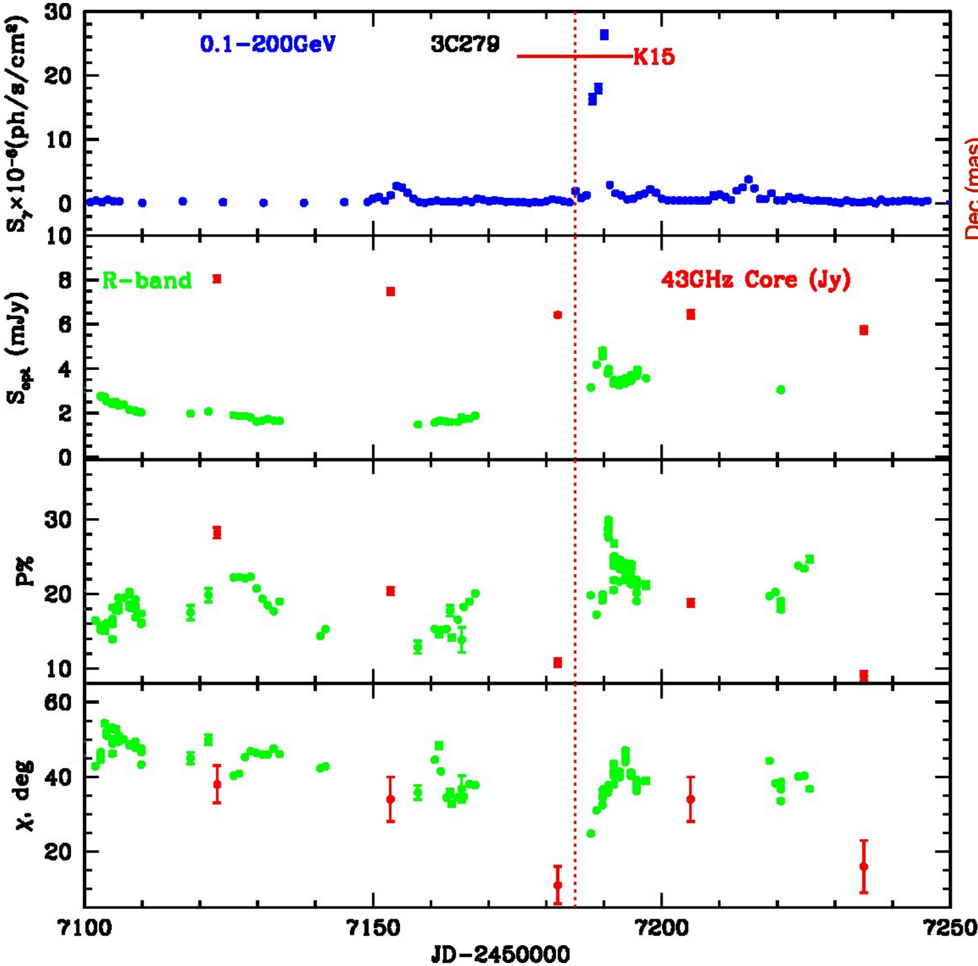


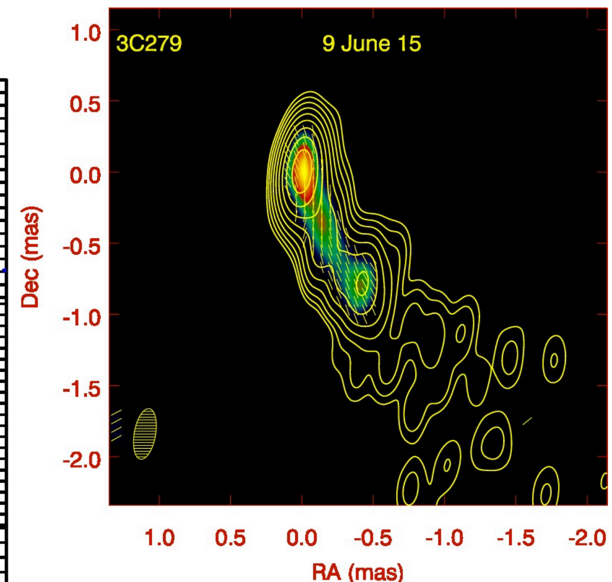


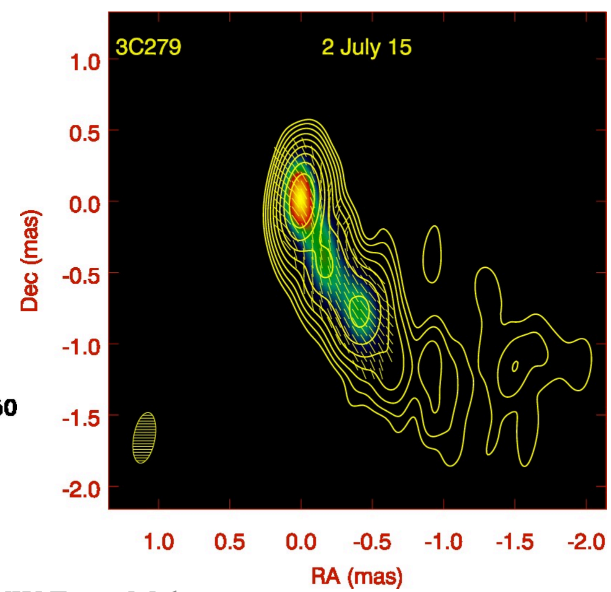


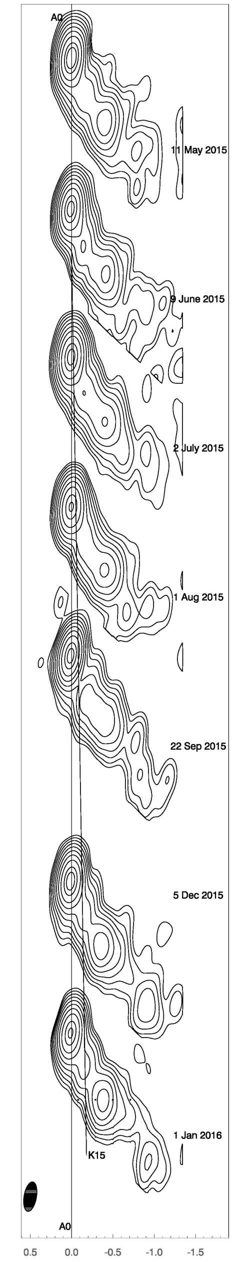
Correlation between γ-ray and optical light curves see poster by Williamson et al.

Quasar 3C279 in the 2015 Flare

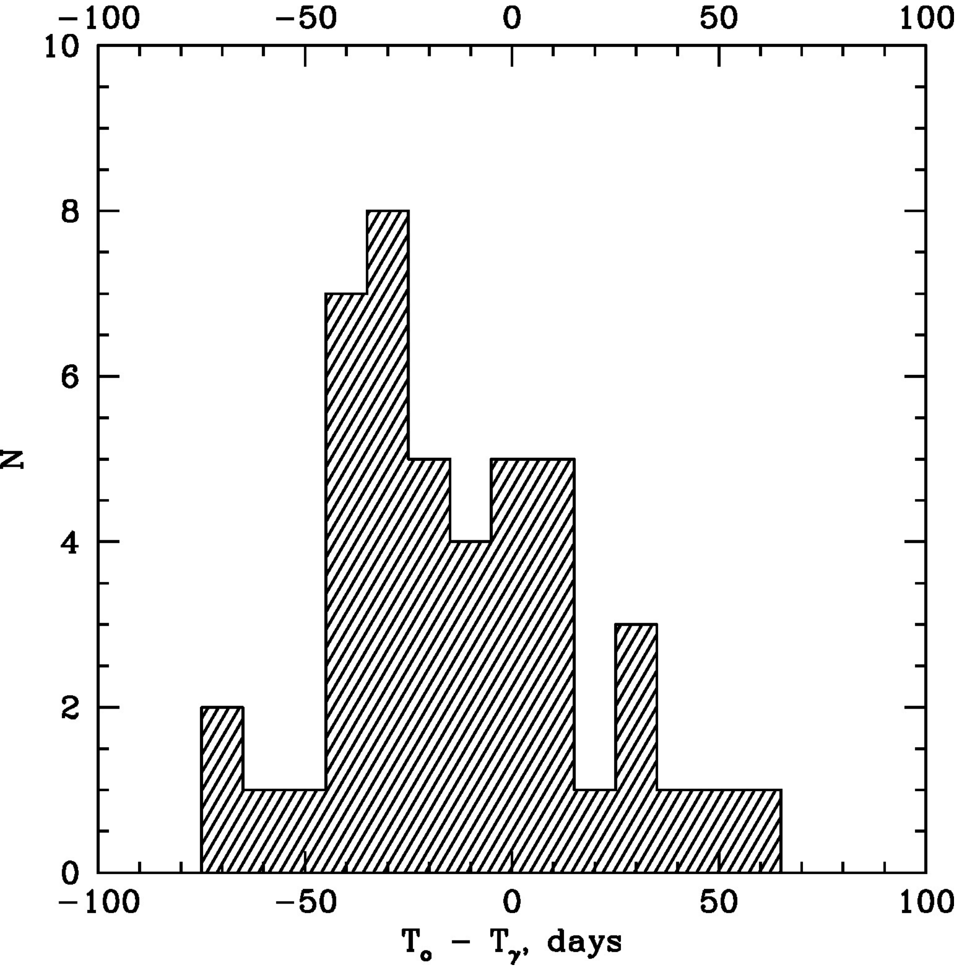








Statistics of Gamma-Ray/Jet Events



During 2008-2013 we detected :

I. 147 superluminal knots in 21 quasars (101) and 12 BLLacs (46)

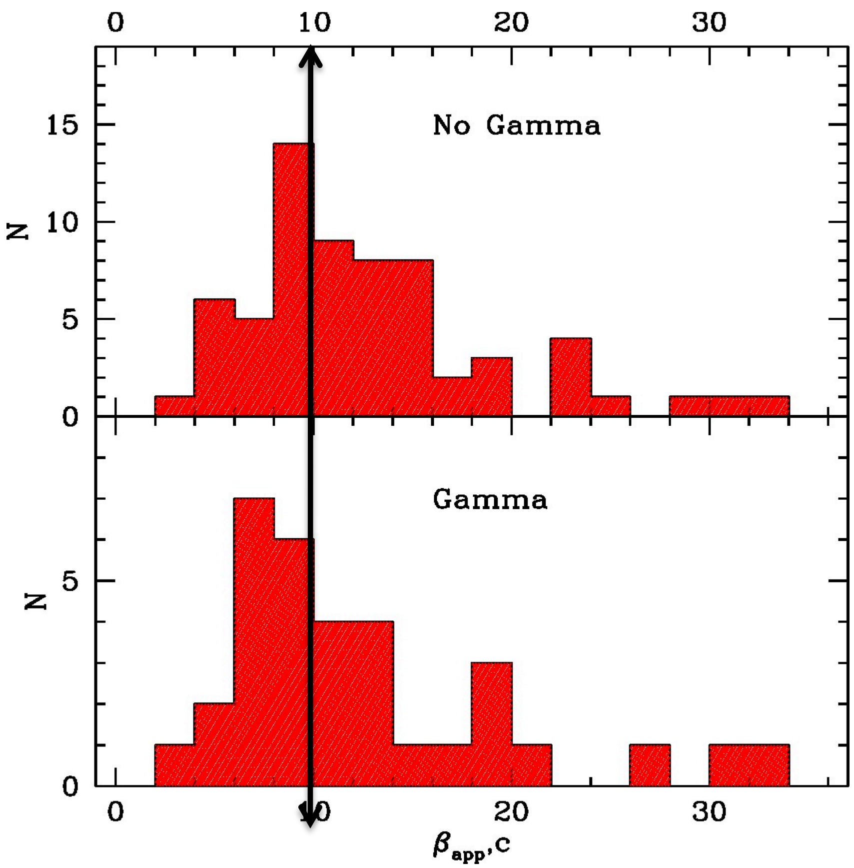
II. 3σ γ-ray flares in 32 (quasars) and 20 (BLLacs)

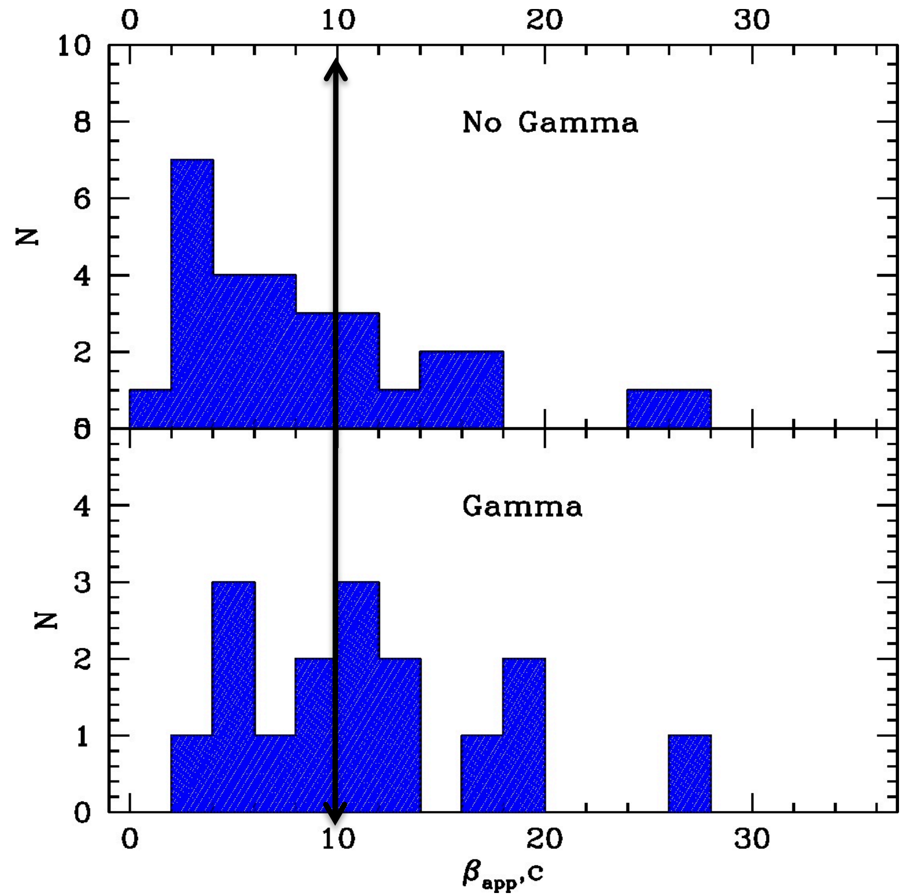
III. 83 % the γ-ray events (29 and 16) are associated with the ejection of a superluminal knot within the flare duration with the peak of the distribution corresponding to the radio events leading the peaks of γ-ray outbursts by 25-35 days

IV. 70% of superluminal knots do NOT produce prominent γ-ray flares.

V. Correlation between γ-ray and mm wave light curves Nieppola et al. 2011, Fuhrmann et al. 2014

Are the Gamma Knots Faster?





Quasars

No γ Knots: 8-10c, $\beta_{app} < 10$ in 64%

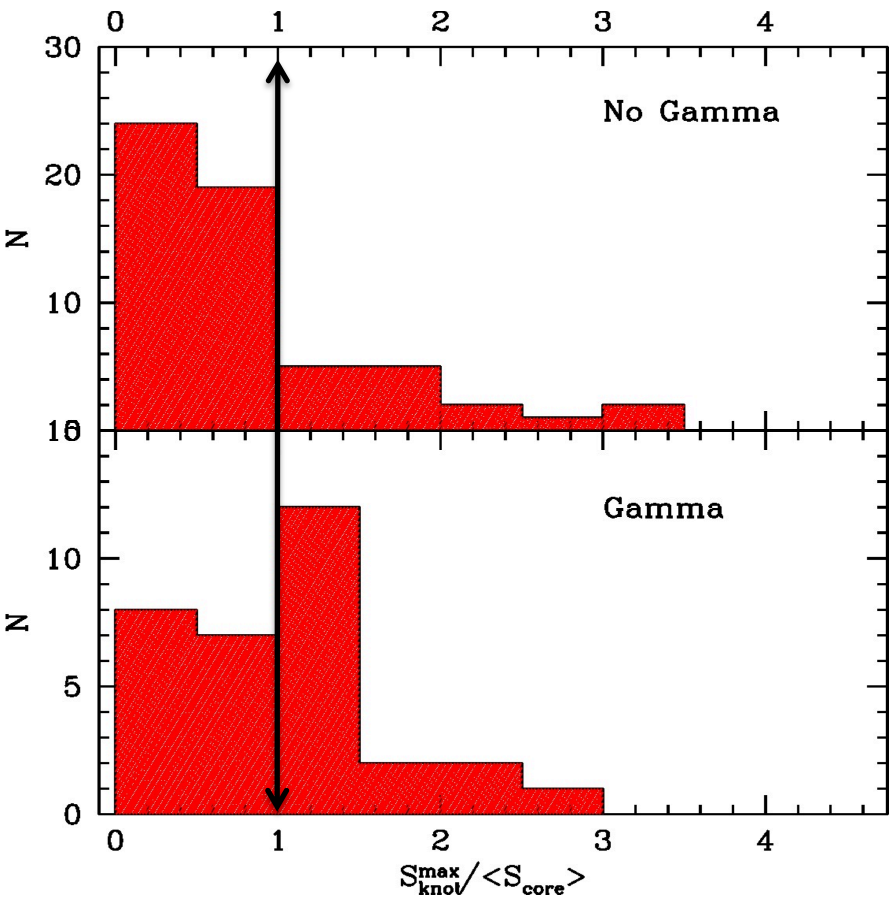
γ Knots: 6-10c, $\beta_{app} < 10$ in 49%

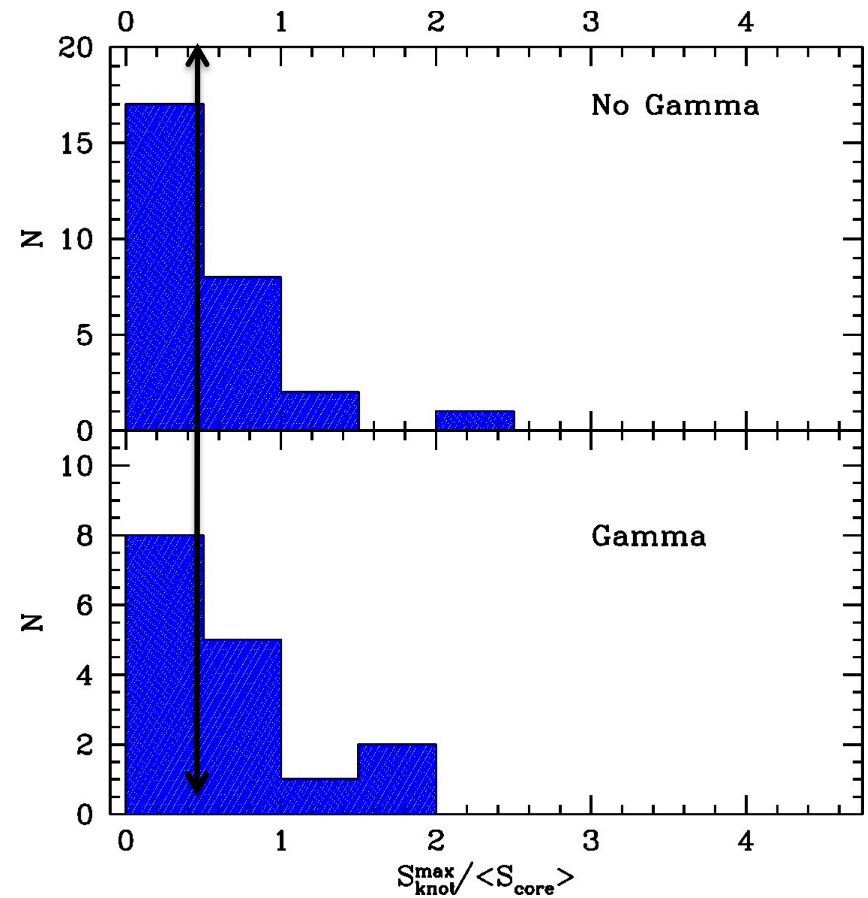
BLLacs

No γ Knots: 2-4c, $\beta_{app} > 10$ in 34%

γ Knots: 10-12c, $\beta_{app} > 10$ in 69%

Are the Gamma Knots Brighter?





Quasars

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

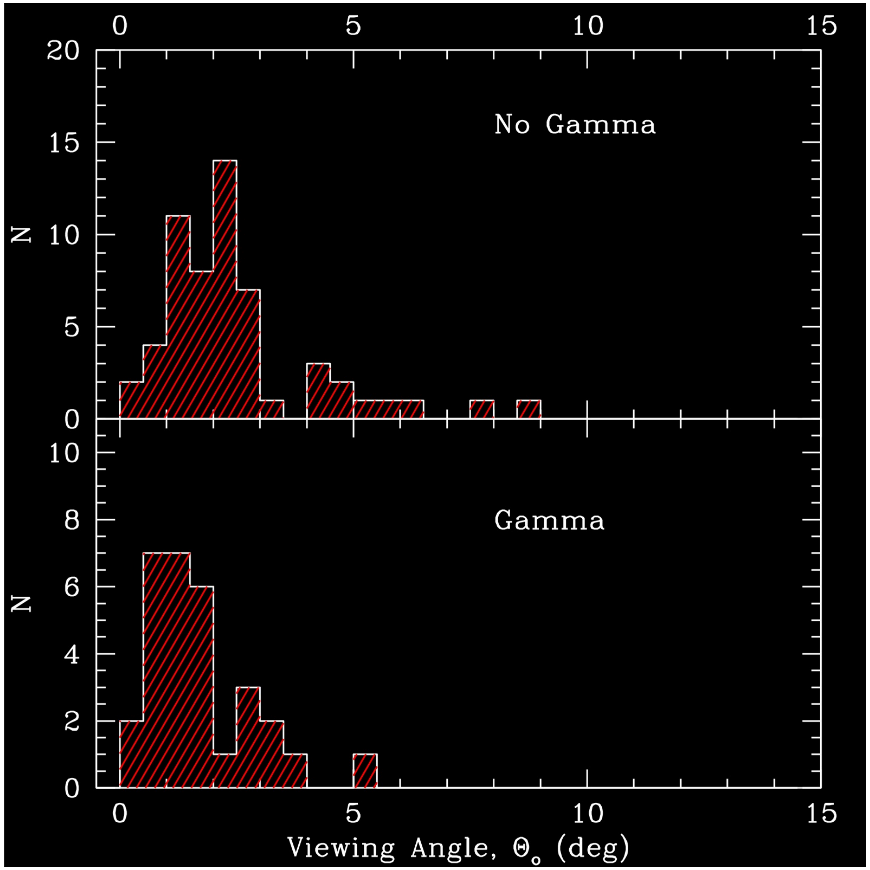
γ Knots: $S_{knot}^{max} > \langle S_{core} \rangle$ in 57%

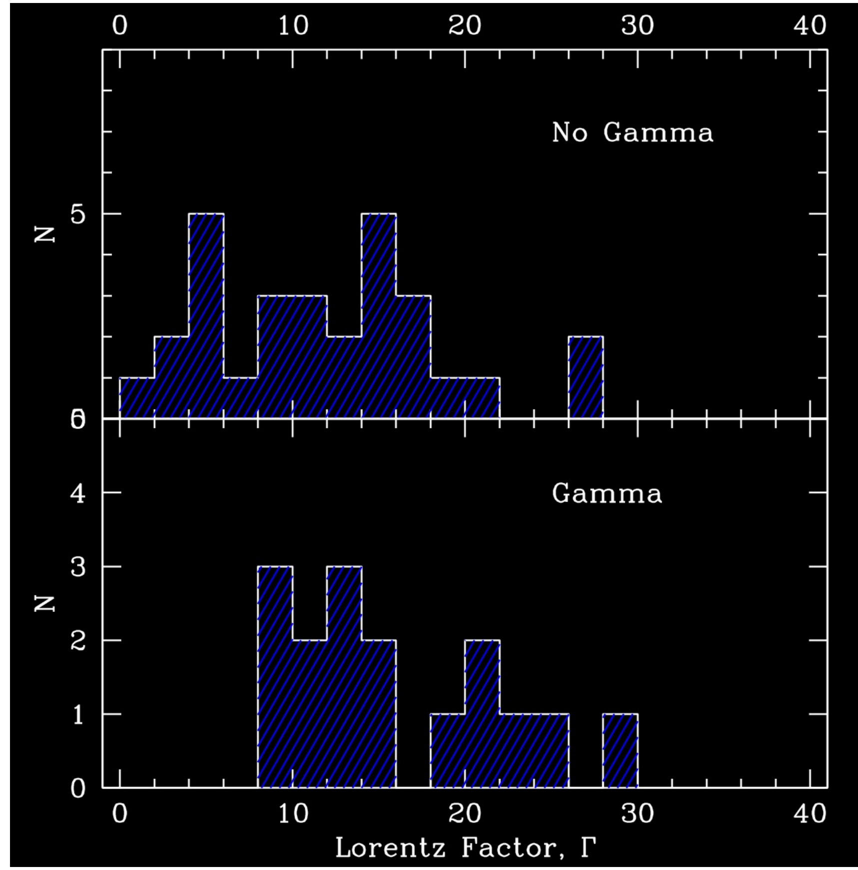
BLLacs

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

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

The Lorentz Factor and Viewing Angle of γ Knots





Quasars

No γ Knots: $\Theta_o \leq 2°$ in 44%

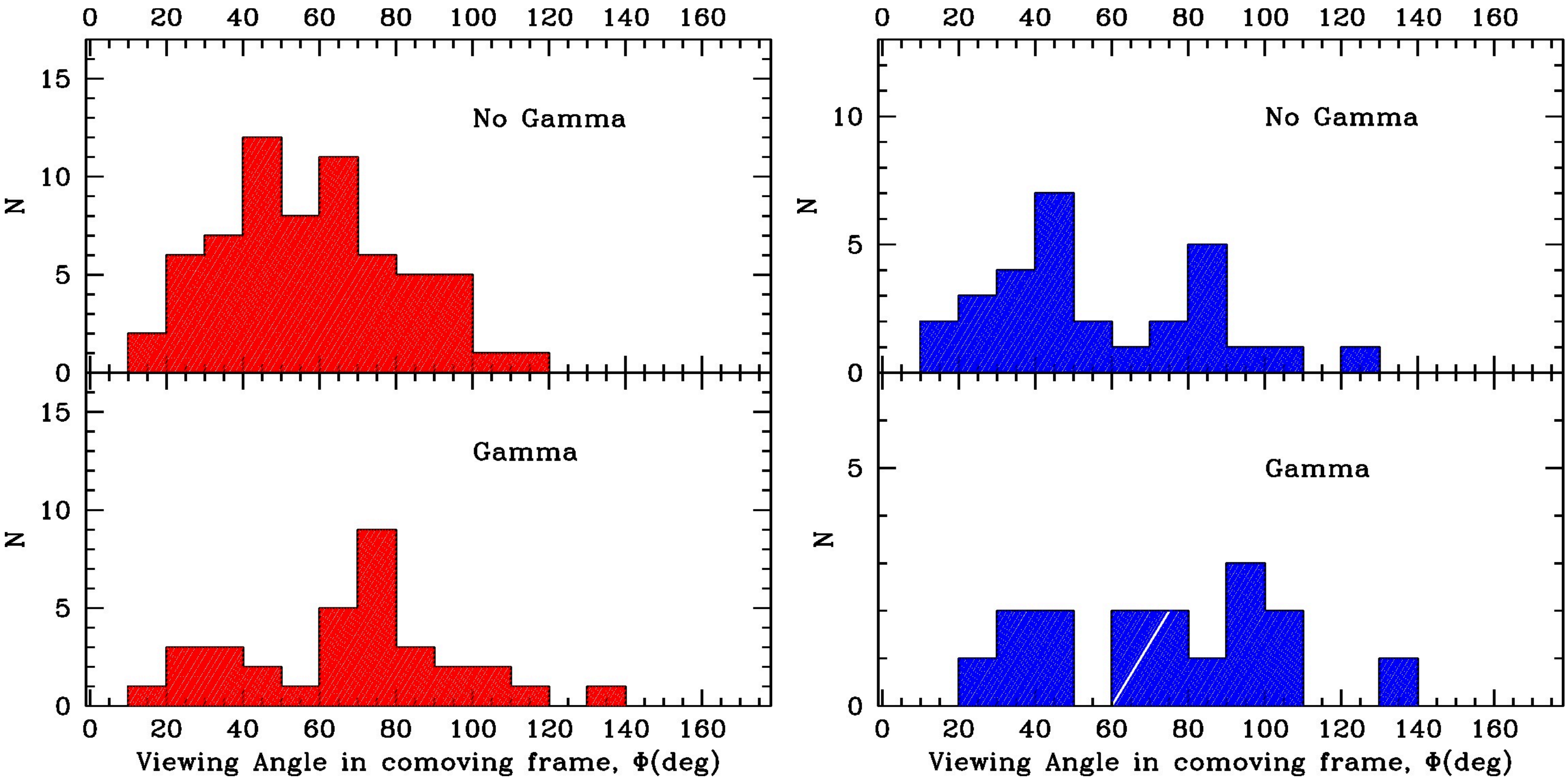
γ Knots: $\Theta_o \leq 2°$ in 73%

BLLacs

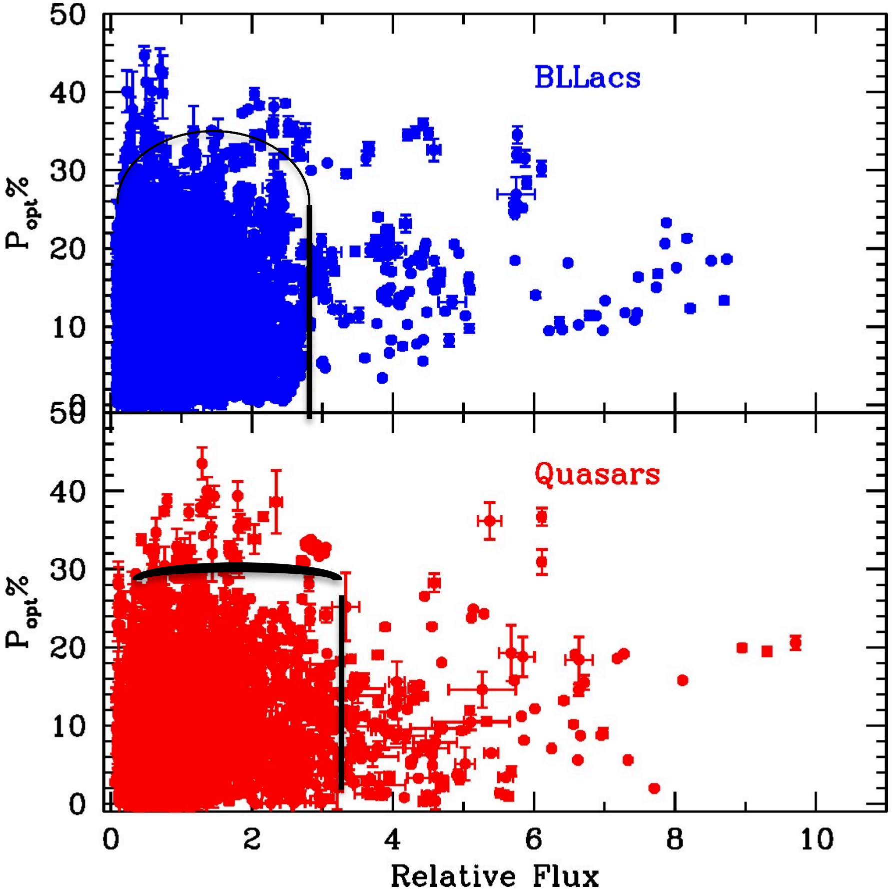
No γ Knots: $\Gamma > 10$ in 55%

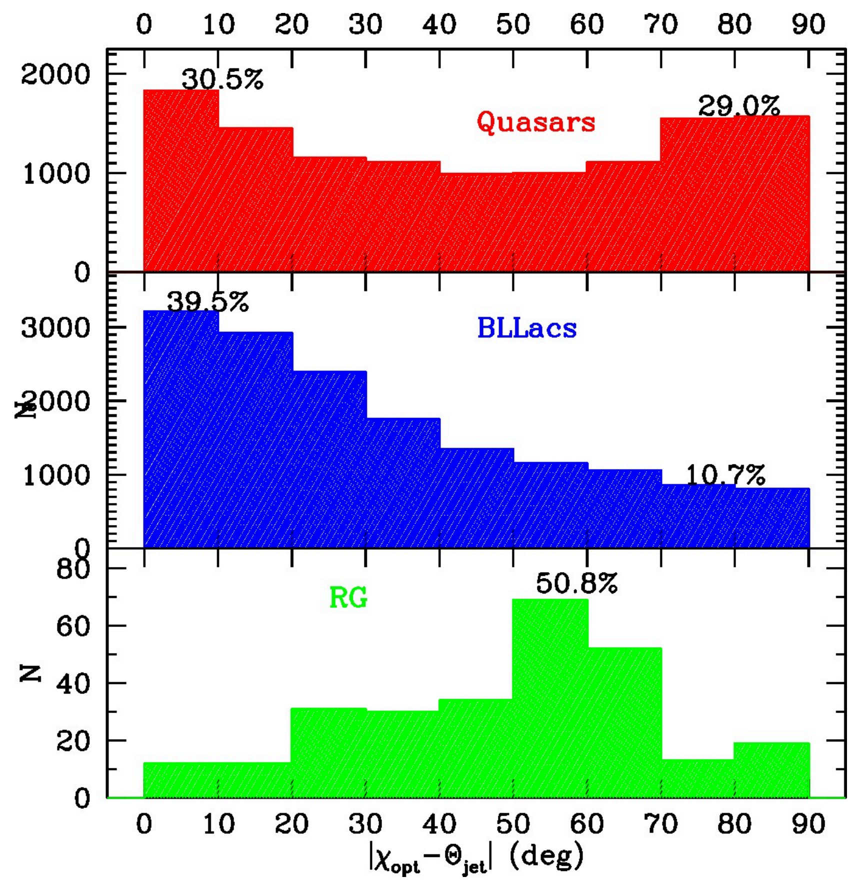
γ Knots: $\Gamma > 10$ in 81%

The Viewing Angle in the Comoving Frame



Degree and Position Angle of Optical Polarization Behavior





Gabuzda et al. 1996

Turbulence + Shocks+ Ordered Component

Helical or Poloidal Field

Future Direction

I. To continue monthly monitoring at 43 GHz with the VLBA of our sample of γ-ray blazars to assemble more γ-ray and jet events

II. To study spectral properties and rotation measures of the jet at mm-waves incorporating observations at 3 mm with the GMVA, at 1 mm with the EHT, and at 22 GHz with the RadioAstron

III. To continue optical photometric and polarimetric observations including multi-band polarization measurements and near-IR observations

IV. To add monitoring of emission line's behavior of the γ-ray blazars during quiescent and active states using the 4-m DCT at Lowell Obs. AZ