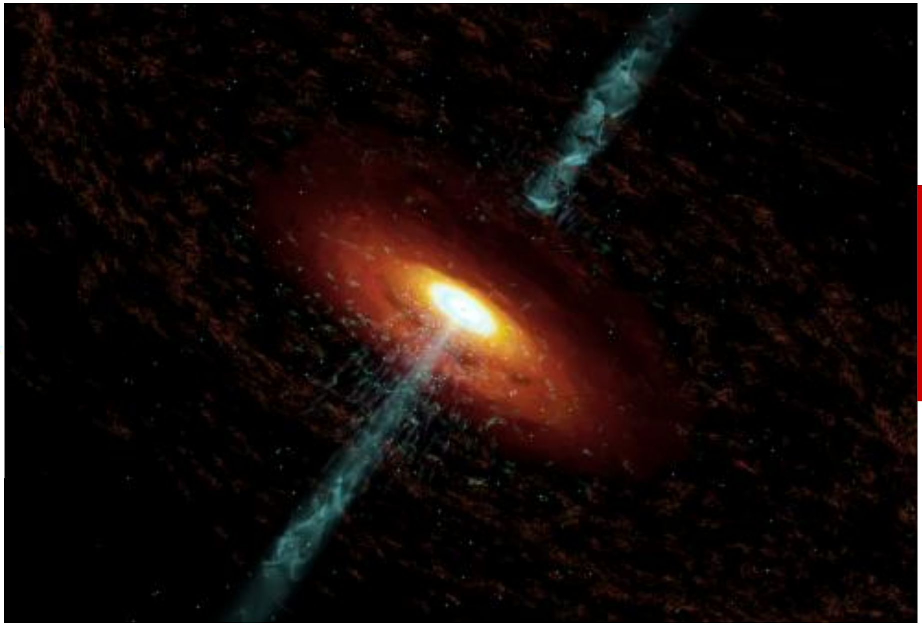

10 Years of VLBA-BU-BLAZAR Monitoring: Relationship between γ-ray & Microwave Events in Blazar Jets

Alan Marscher

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Research Web Page: www.bu.edu/blazars

Main Collaborators

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*****See posters by Jorstad et al. & by Weaver et al.*****

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Valeri Larionov

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Aalto University Metsähovi Radio Obs. (Finland):

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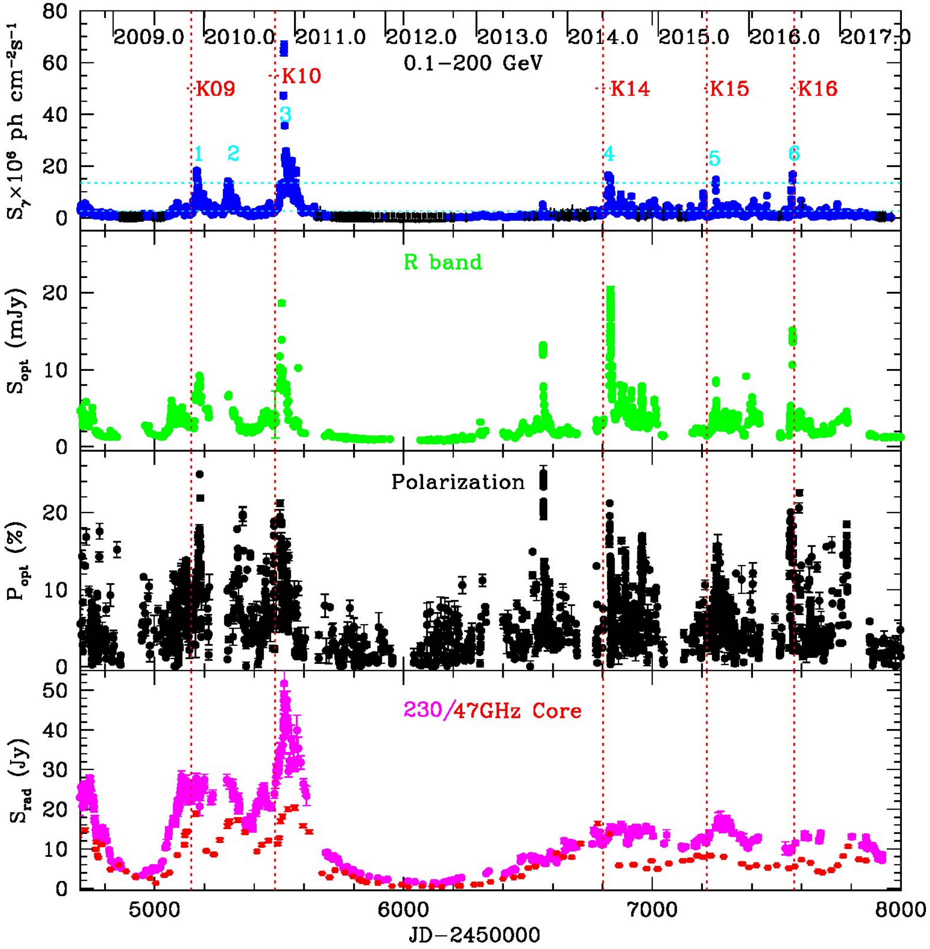
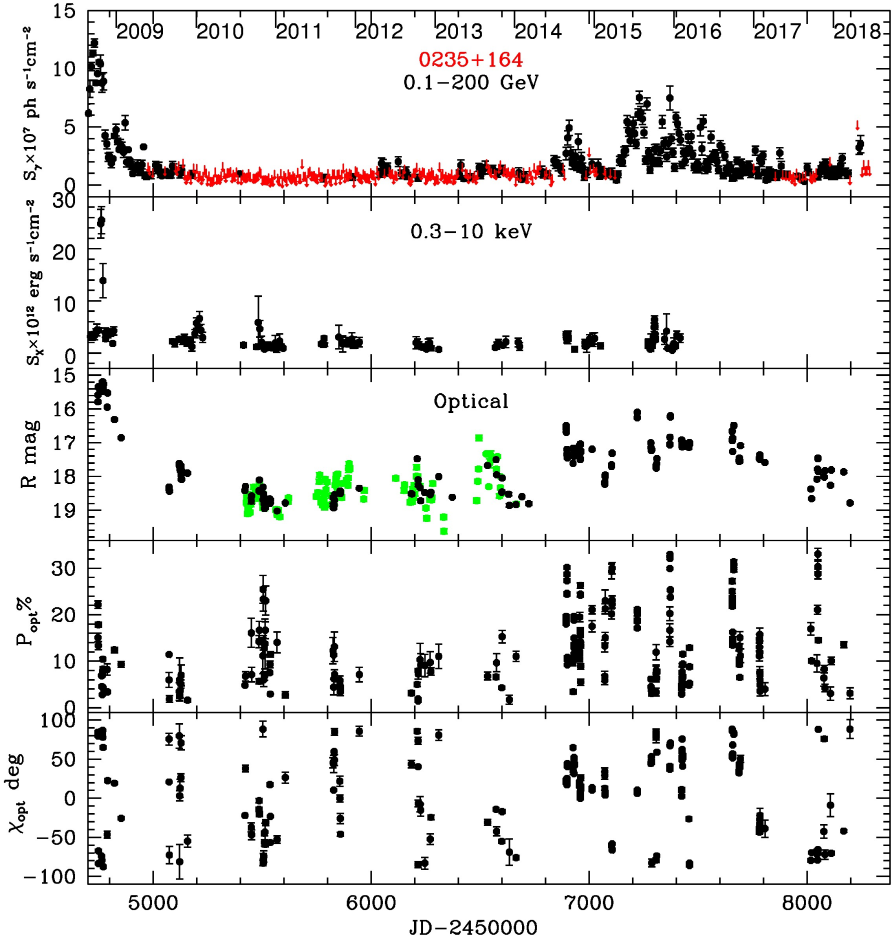
Funded by NASA Fermi & US National Science Foundation

Multi-waveband Light & Polarization Curves



Quasar 3C 454.3



BL Lac object 0235+164

Flux & polarization vs. time are difficult to interpret without images of the jet of the blazar

VLBA-BU-BLAZAR & Multi-waveband Monitoring Program

1. Monthly VLBA monitoring at 43 GHz (37 γ-ray blazars)

2. Multi-waveband light curves
   a) γ-ray (0.1-200 GeV): Fermi LAT

   b) Optical (BVRI) light curves (1.8 m Perkins Telescope)

   c) Optical polarization vs. time (Perkins Tel. + collaborators)

   d) Optical emission-line monitoring (4.3m DCT)

   e) UV & X-ray (0.3-10 keV) light curves: Swift

   f) Radio light curves: 230 & 350 GHz (SMA); 37 GHz (Metsähovi) from collaborators

The VLBA-BU-BLAZAR Sample

- Flux density at 43 GHz > 0.5 Jy (usually)
- Declination > -30^o
- Optical magnitude in R band < 18.5^m
- Detection by EGRET

→ 37 objects ($z = 0.017 – 2.17$): 21 FSRQs, 13 BL Lacs, 3 RGs

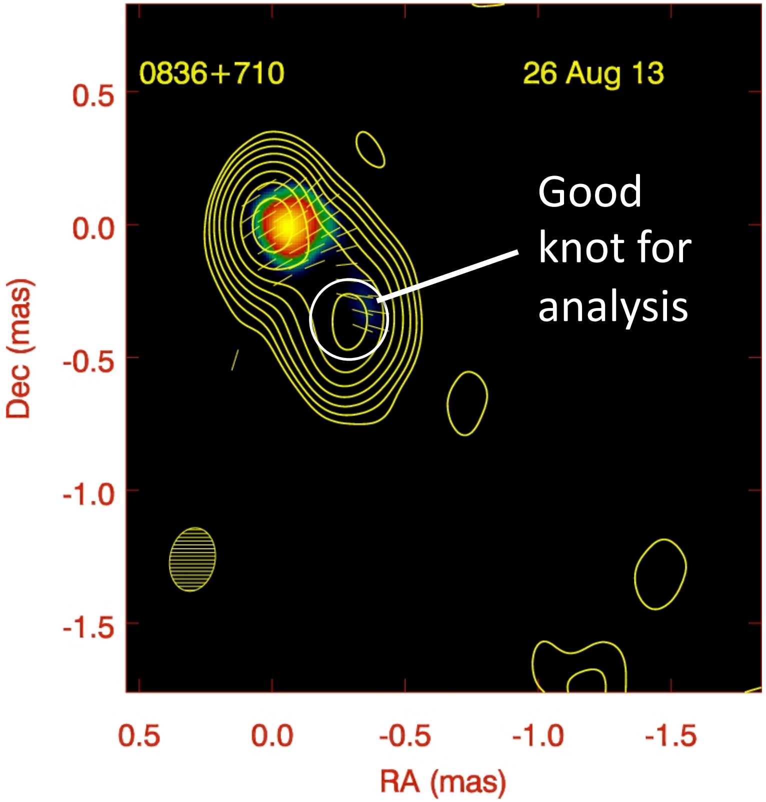
Goals of the Program:

- Monitor jet structure to relate changes to γ-ray (etc.) events (Jorstad & Marscher 2016)

  → Determine location(s) of high-energy emission sites
  → Determine Doppler & Lorentz factors, viewing & opening angles
  → Constrain emission mechanisms (e.g., source of seed photons)

- Study jets of blazars on (sub-)parsec scales (Jorstad et al. 2017)

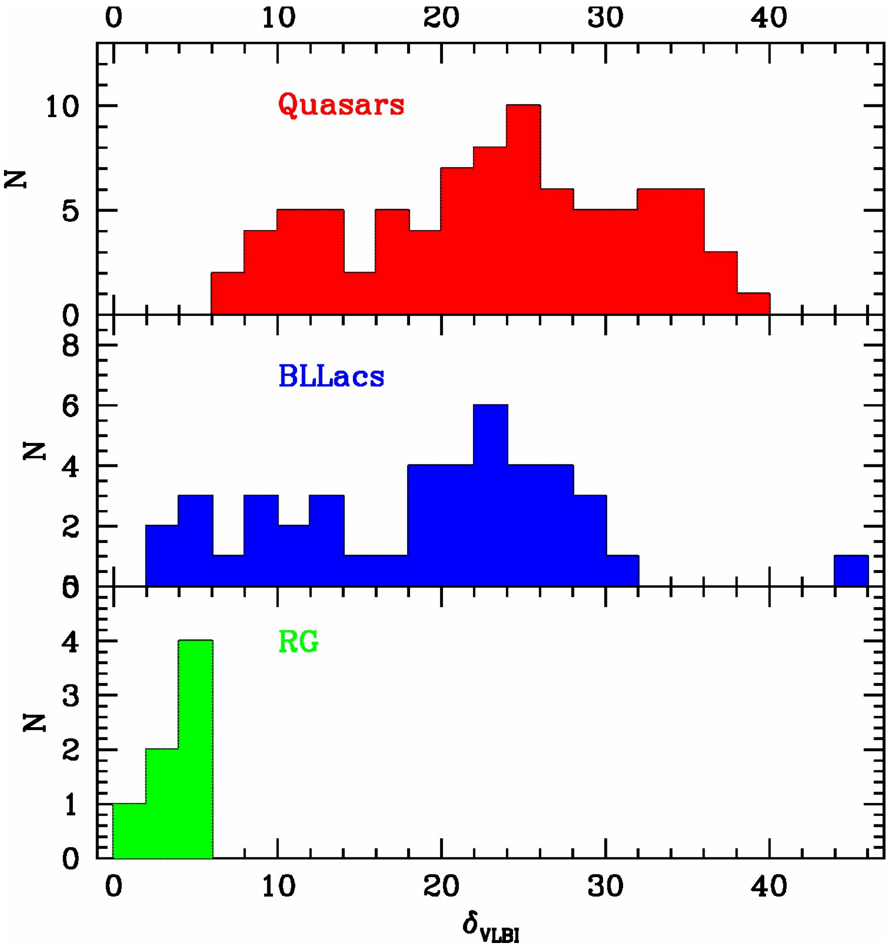
Doppler Factors of Bright γ-ray Blazars from VLBA-BU-BLAZAR Sample



Good knot for analysis

Method: For well-defined moving knots, measure v_{app}, size a, & flux decay time t_{var}

$$\rightarrow \delta \approx [a/(v_{app}\, t_{var})](1+z)$$



Most prominent γ-ray blazars have Doppler factors of 10-40 → γ-rays are beamed by factor ~10^4 – 10^6

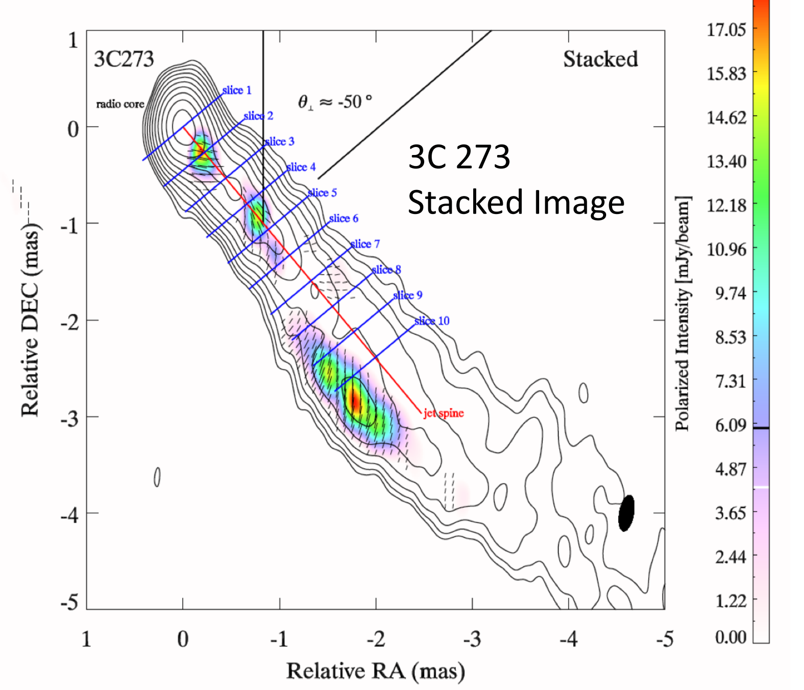
(Jorstad + 2017; see also Lister + 2011)

Intrinsic Jet Opening Angle

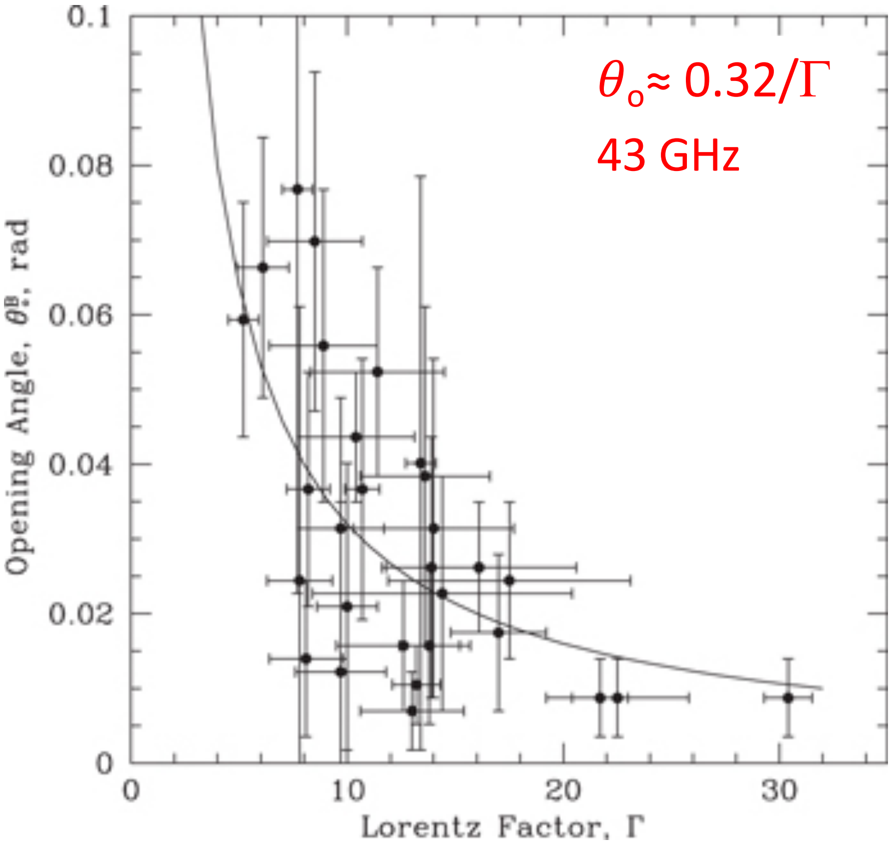
Our 43 GHz + MOJAVE 15 GHz:

High-Γ blazar jets are extremely narrow, ~20°/Γ

(Emission concentrated over even narrower angle at any given time → shorter t_{var})

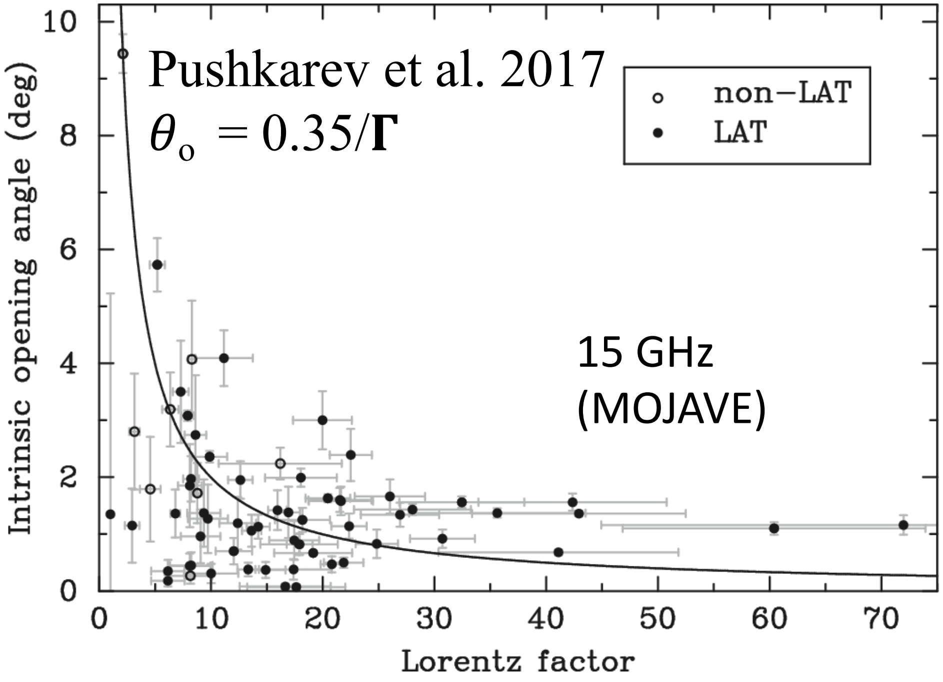


3C 273 Stacked Image



$\theta_o \approx 0.32/\Gamma$

43 GHz



Pushkarev et al. 2017

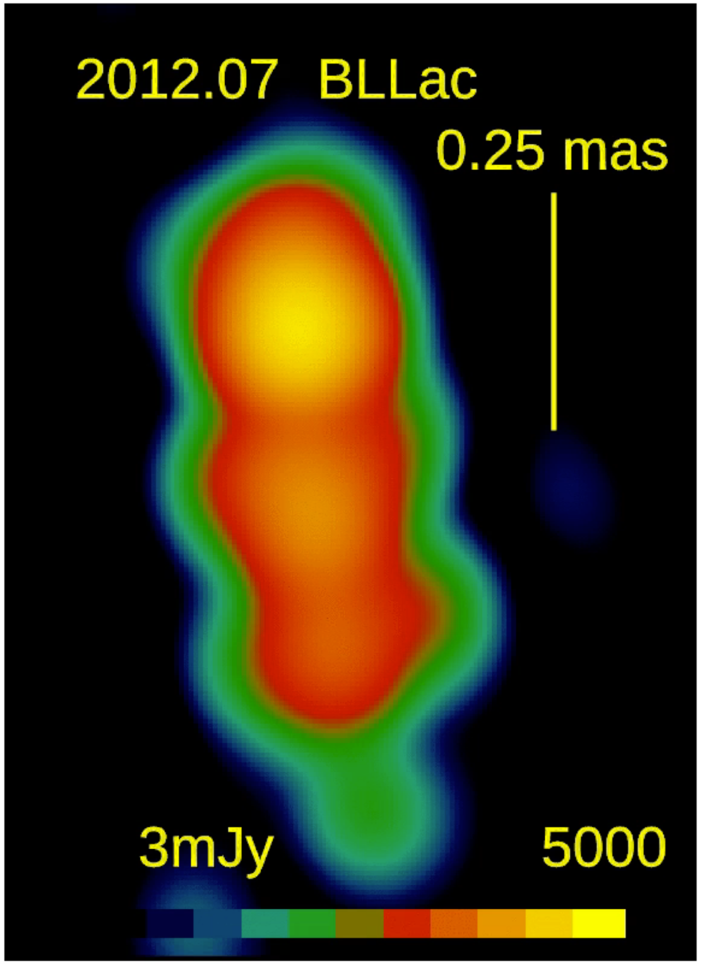
$\theta_o = 0.35/\Gamma$

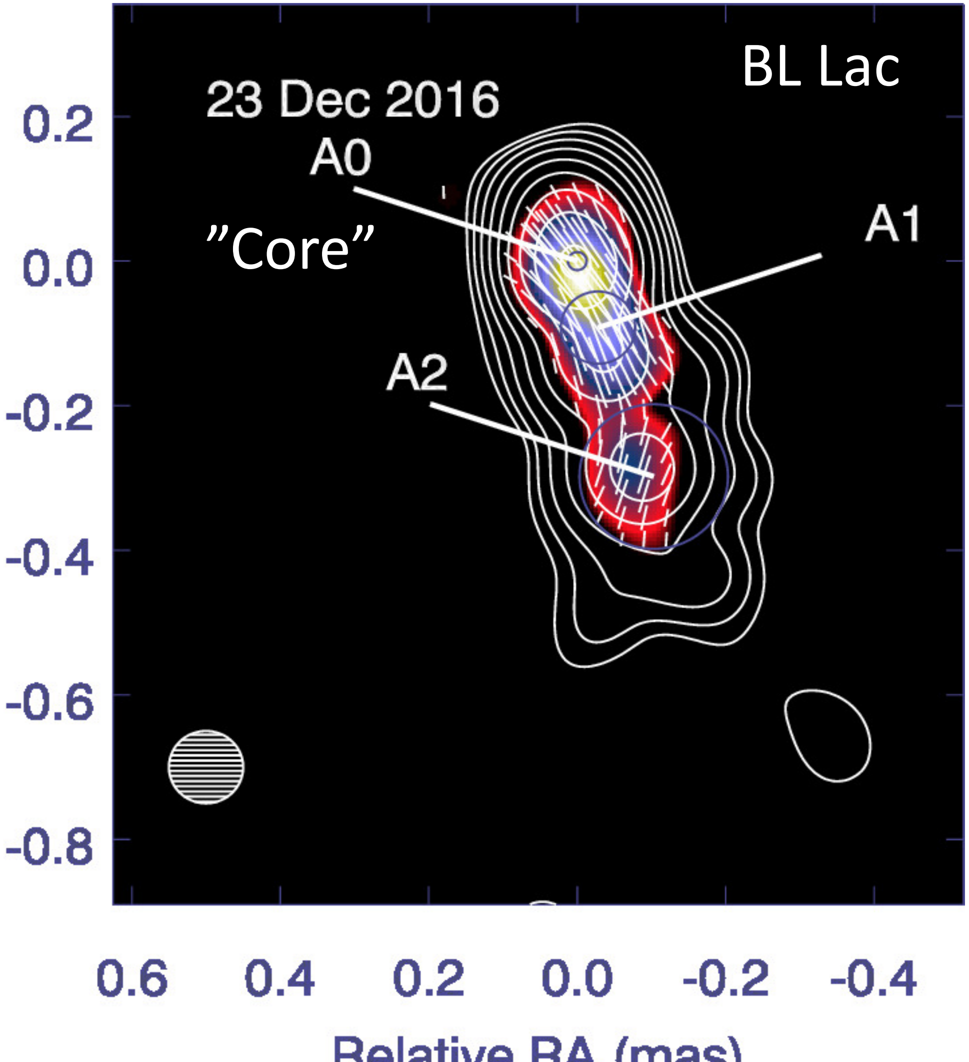
15 GHz (MOJAVE)

~ Stationary Features in Most Blazar Jets (Standing shocks?)

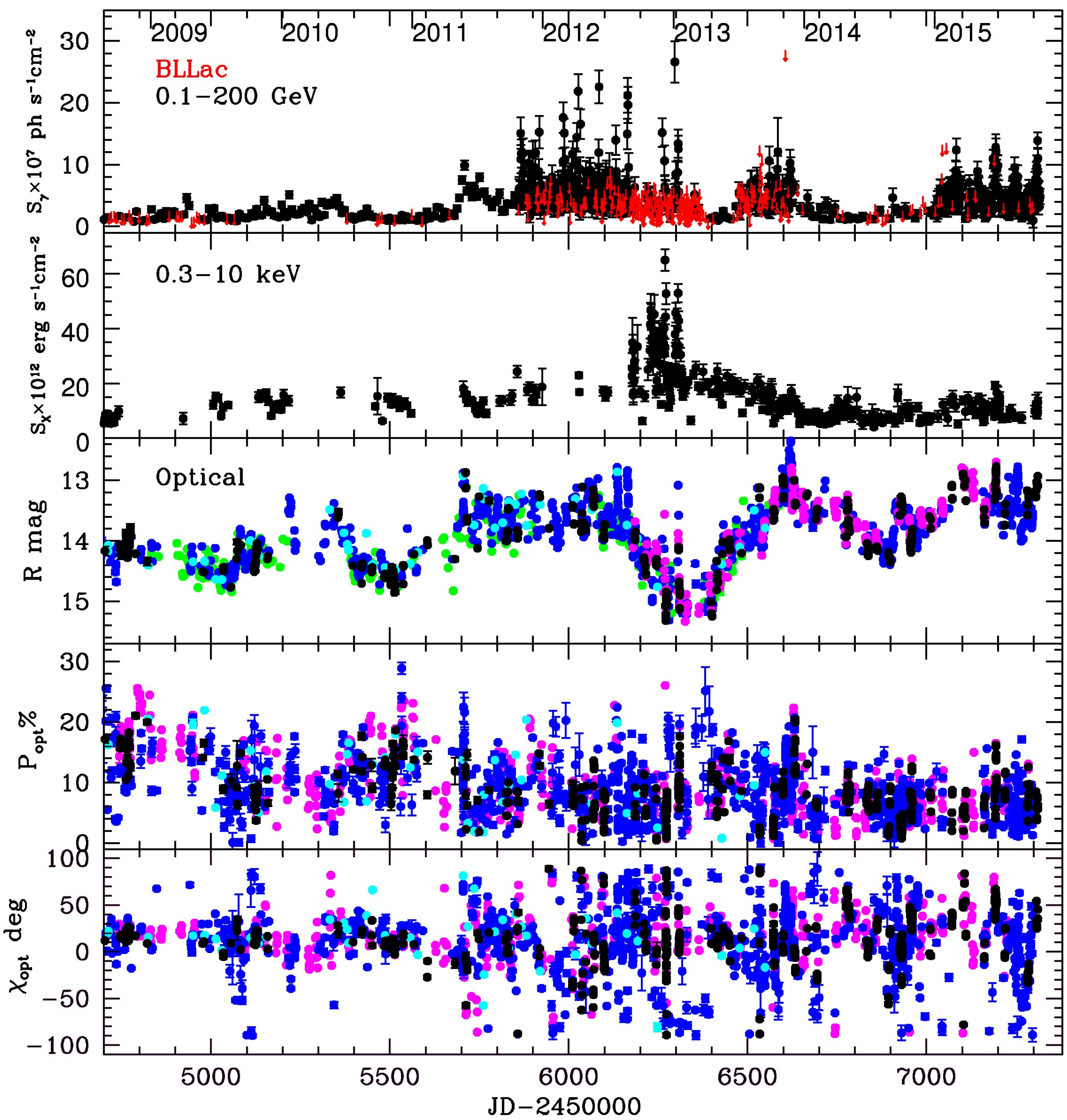
- Especially prominent in BL Lac objects

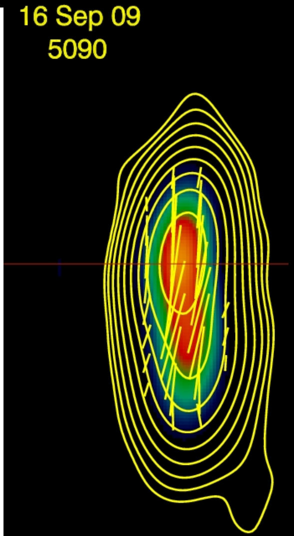
BL Lac: knots crossing stationary features coincide with VHE flares (e.g., Abeysekara + 2018; more examples: see poster by Jorstad et al.)





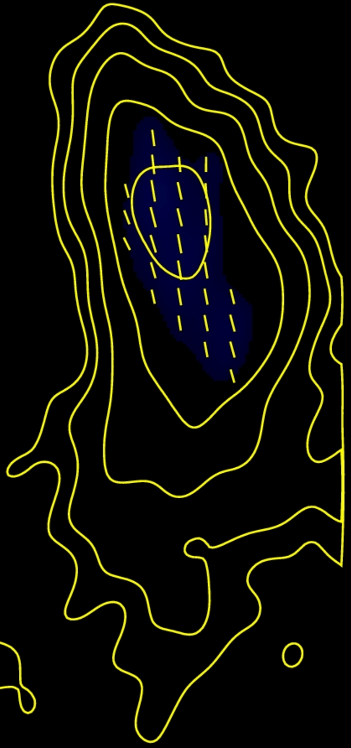
Magnetic Field: Some order, mostly disorder (turbulence)



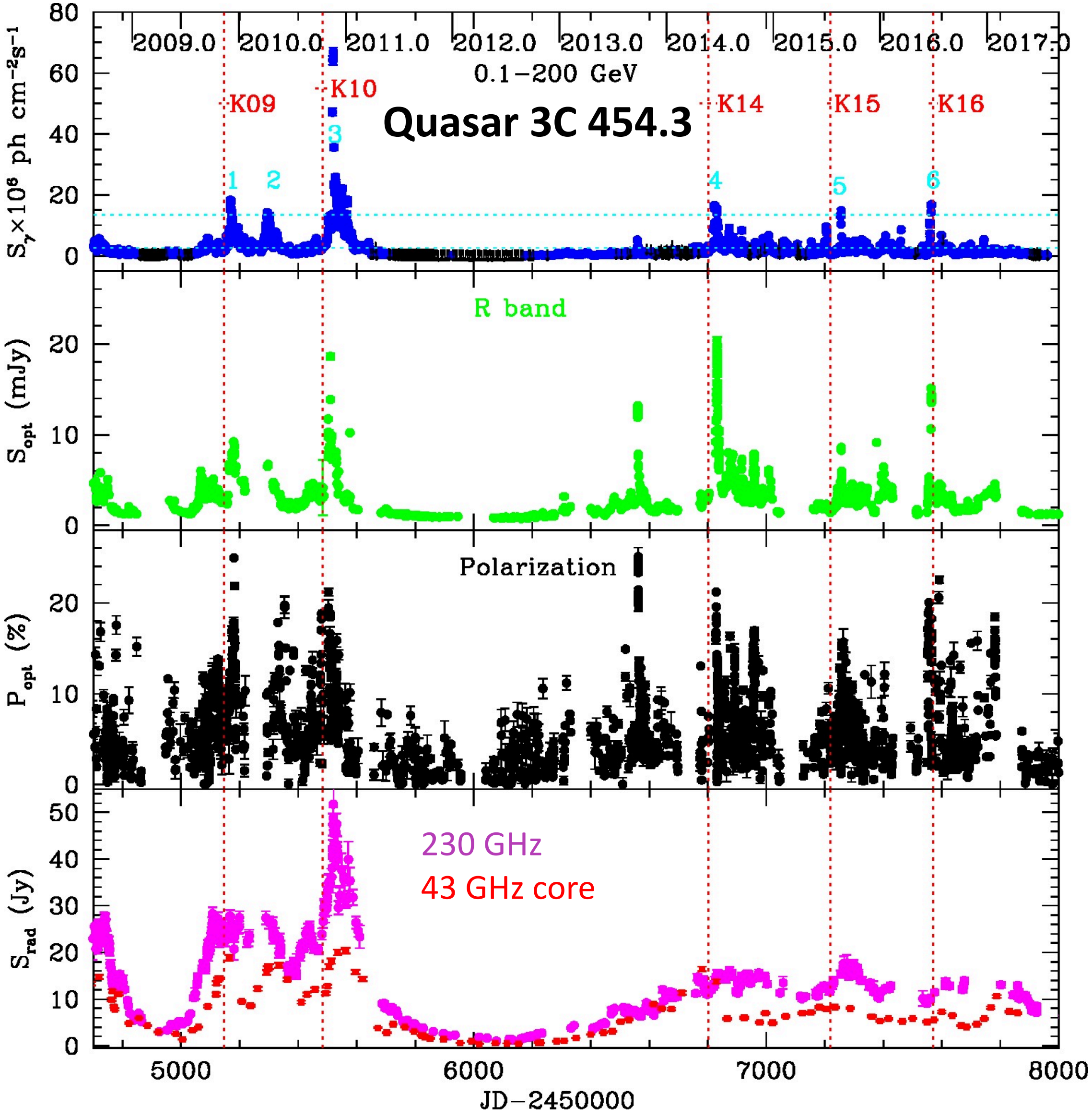


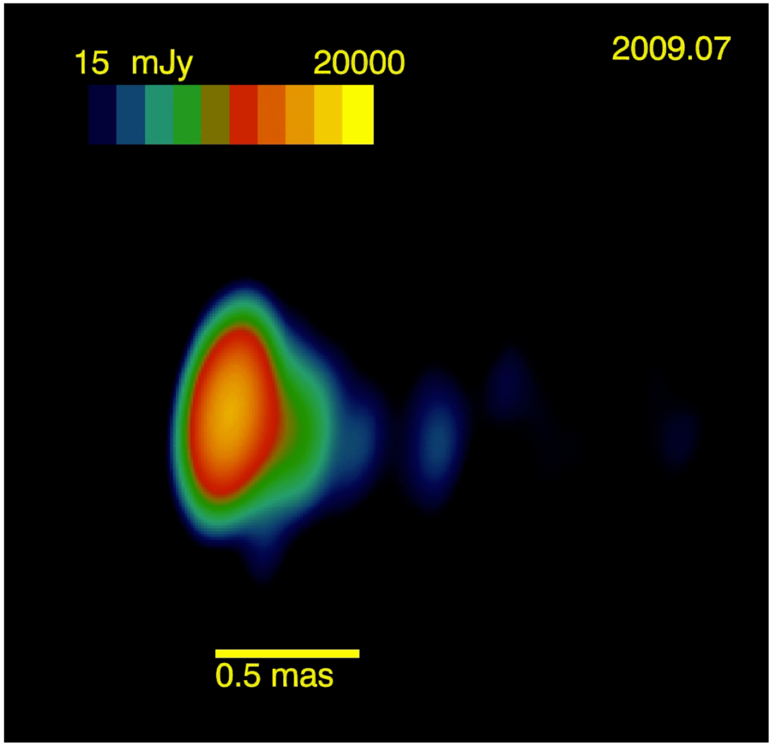
BL Lac

Pol. Of core ~ 7%
→ ~100 turbulent cells



Time Sequences of VLBA Images: What happens in jet during γ-ray outbursts & quiescence

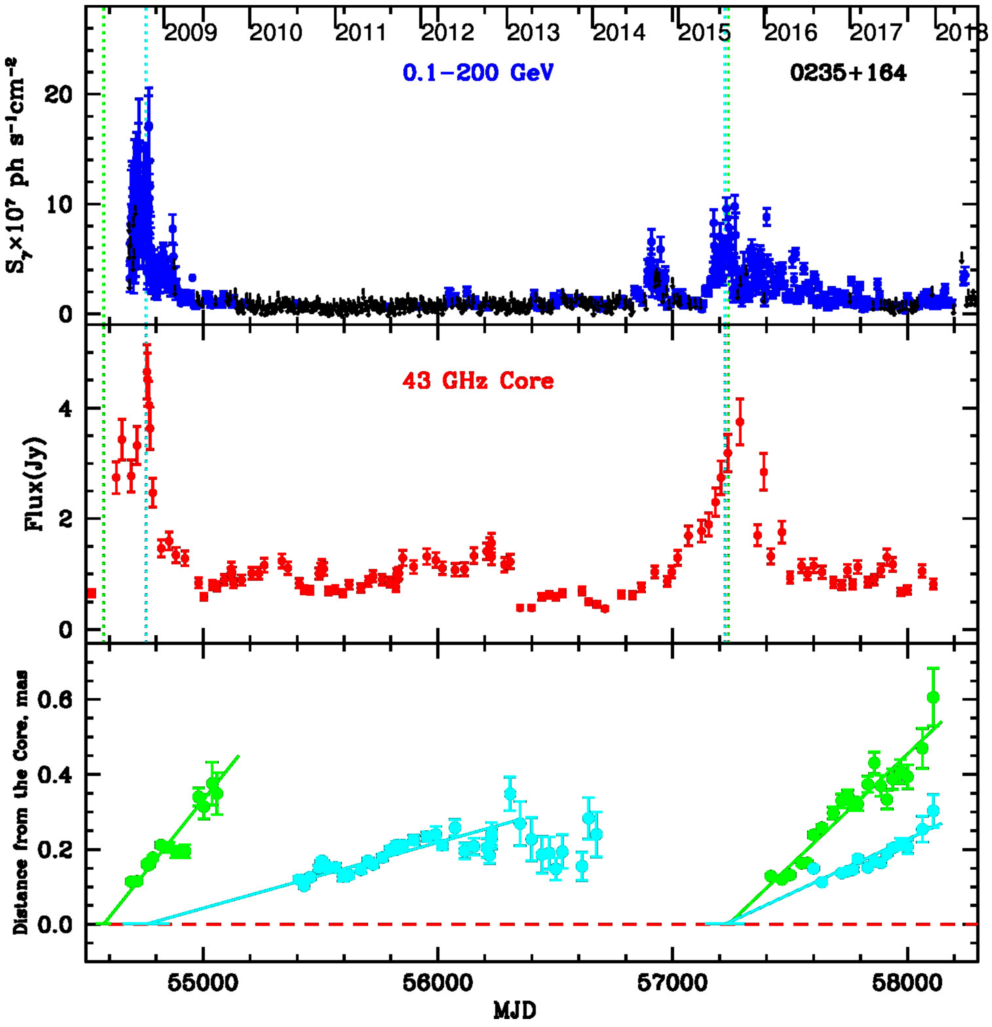


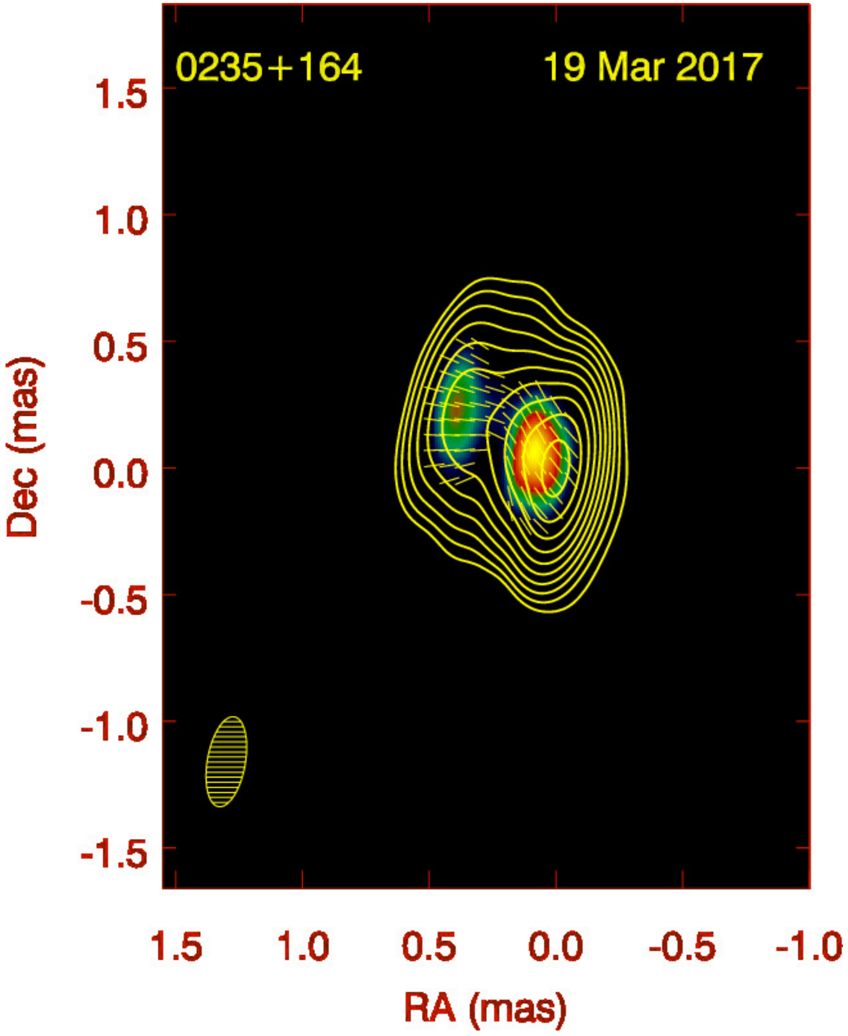


γ rays quiescent when radio jet is quiescent, & γ-ray outbursts occur when radio jet is very active

(Jorstad et al. 2010, 2013, 2016)
See also poster by Weaver et al.

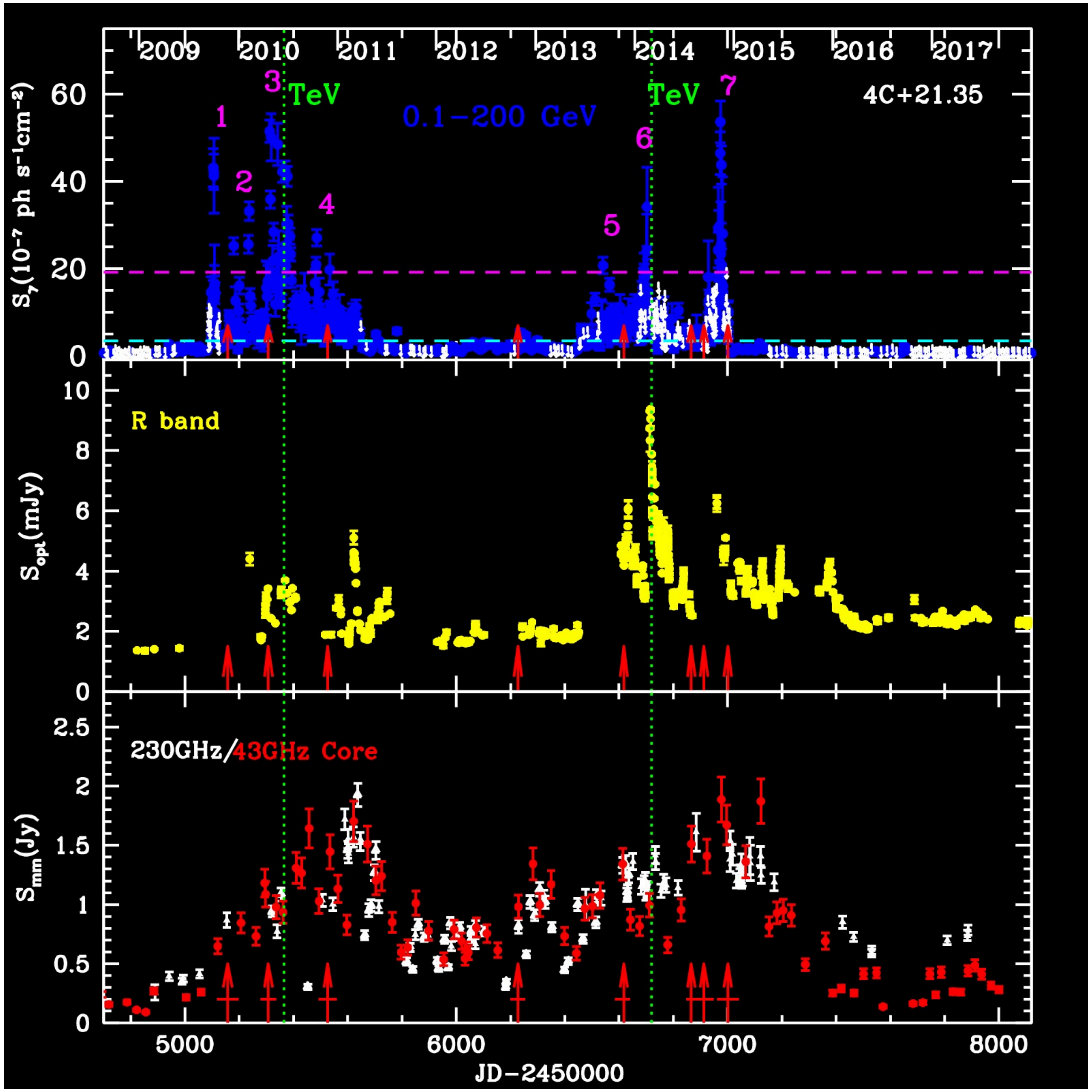
γ-ray outbursts only occur during strong activity in jet at millimeter wavelengths Example: BL Lac object 0235+164

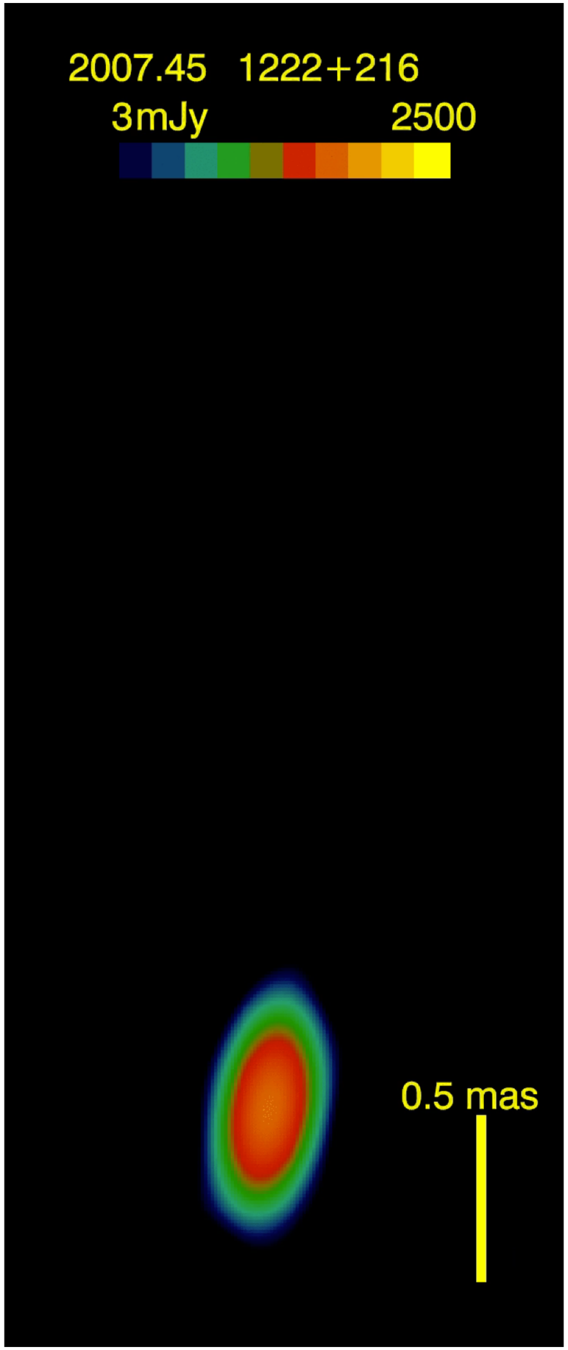




Variability of 1222+216 (4C+21.35)

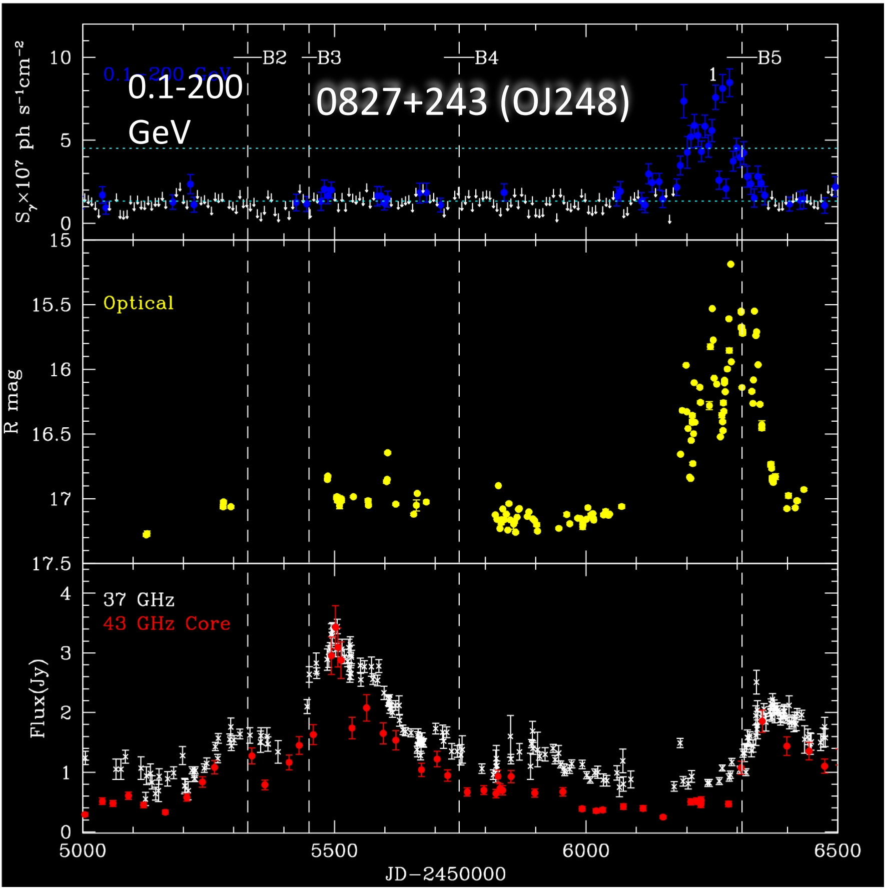
- Note optical flares with & without γ counterpart

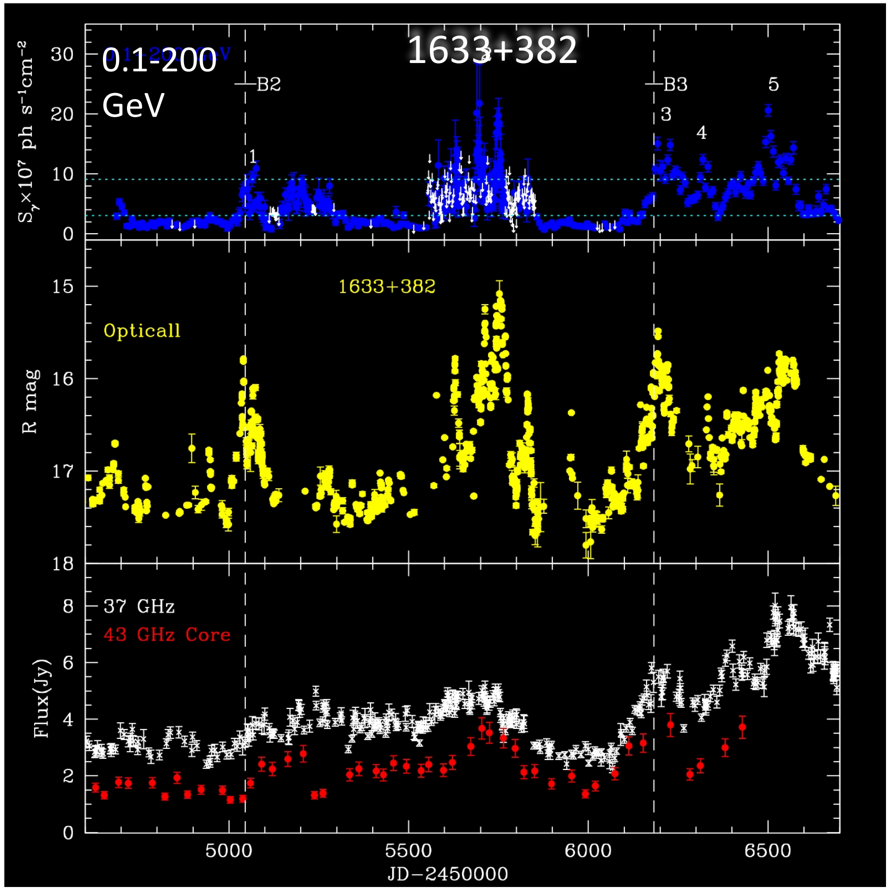




New superluminal knot (83%) and/or brightening of "core" at 43 GHz coincides with every γ-ray flare

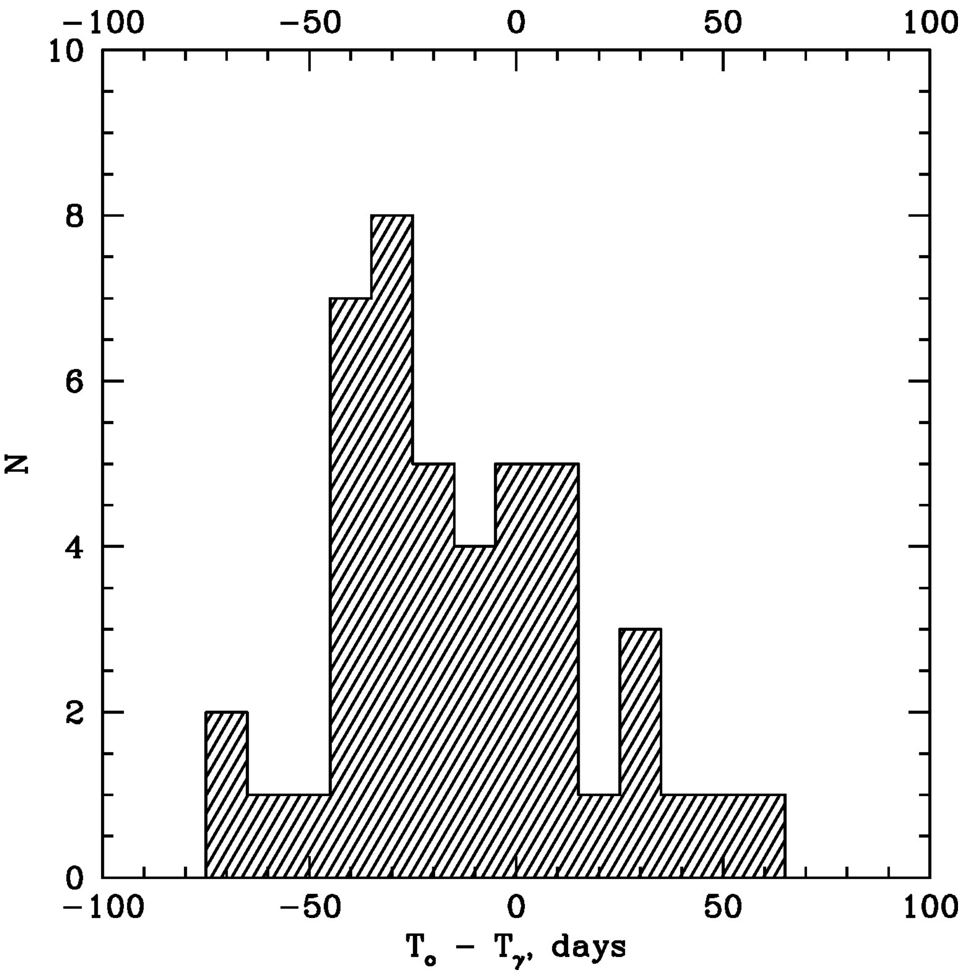
But only 35% of superluminal knots are associated with γ-ray flares → Either acceleration of e$^-$s to >10 GeV only occurs in 35% of knots or seed photon field is variable





Timing of Gamma-Ray/Jet Events

→ γ-ray flares mostly occur on parsec scales



Even when $T_\gamma > T_o$ by < 60 days, most knots have not yet fully exited from "core"

T_o: Time when centroid of knot crosses centroid of "core"

- Note that a blazar "core" is 2-20 pc from black hole

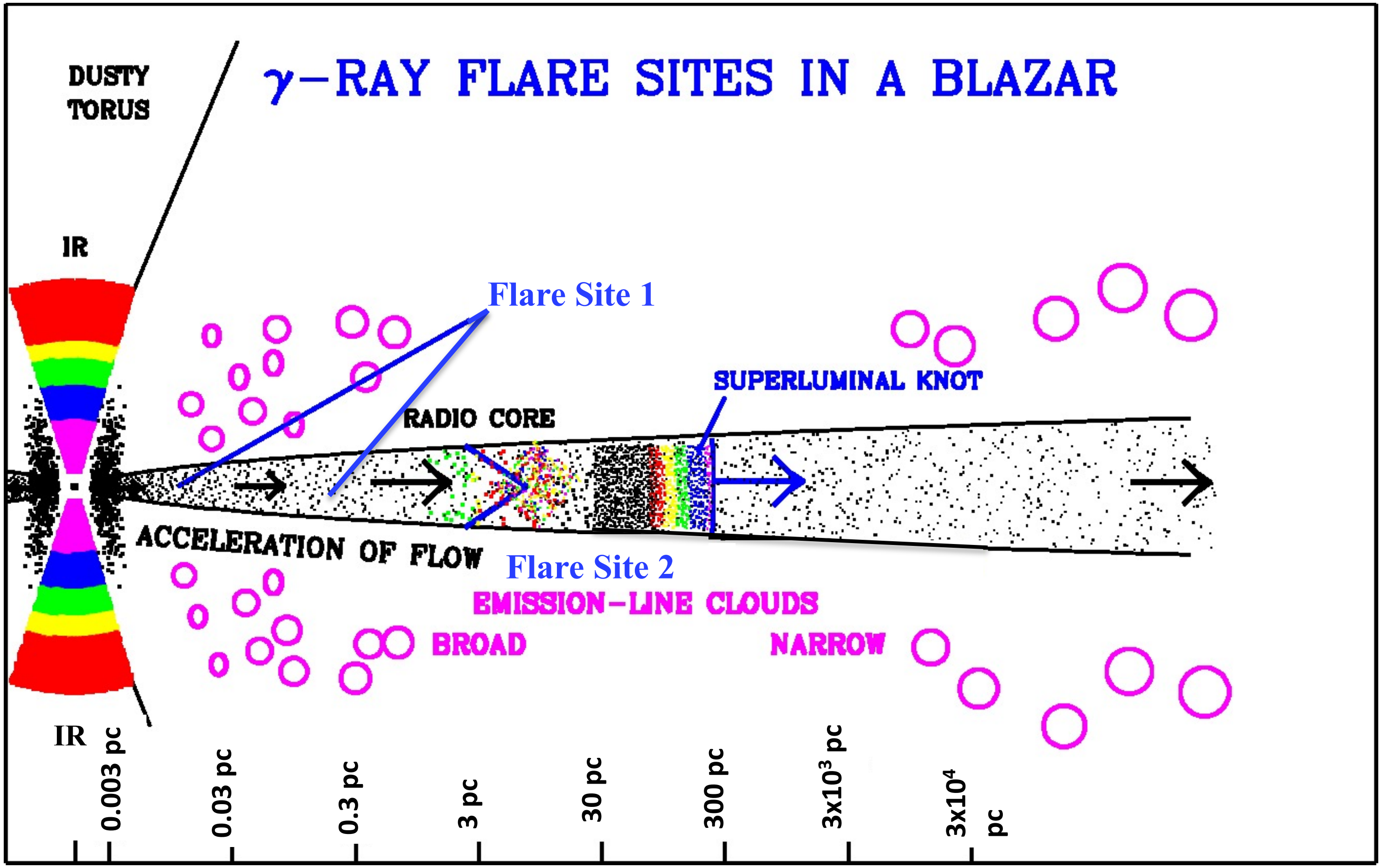
- At 43 GHz, "core" is usually consistent with a standing shock

T_γ: Time of peak of γ-ray flare

Peak of (T_o- T_γ) distribution corresponds to the centroid of knot crossing centroid of core 25-35 days before γ-ray flare peak

Monte Carlo simulations → association of knots & flares significant at 1% confidence level

Possible Flare Sites in Blazars



Flare site 1: Inner jet, inside radii of BLR, dusty torus

Advantages: Dense seed photon field, small region → rapid variability

Disadvantages: Conflicts with flare vs. knot timing, Γ probably not yet at maximum value

Flare site 2: pc scale - moving knot crosses "core" or other stationary feature

Advantages: Agrees with flare vs. knot timing, Γ near maximum value

Disadvantages: Not as dense seed photon field, short t_{var} → only small fraction of jet involved

Seed Photons for γ-ray Production via Inverse Compton Scattering

Flare site 1: Broad emission lines from BLR or IR from dusty torus

+ Explains high-energy SED well

- BLR & torus photons not important on > few pc scales
- Unlikely to be strongly variable in a luminous blazar

Flare site 2: Synchrotron photons – SSC or from sheath or Mach disk

+ Highly variable

- SSC unlikely to give $L_\gamma/L_{synchrotron} > 10$ (good for most BL Lacs, though)

Polar clouds of gas + free electrons? (León-Tavares + 2013; Vittorini + 2014; Tavani + 2015; see poster by Jorstad et al.)

+ Variable in response to flares from jet → could explain diversity of flare behaviors

Nonthermal: Jet sheath (e.g., MacDonald + 2015) or standing shock (Marscher 2014)

+ Evidence for presence on parsec scales
+ Can be variable, explaining diversity of multi-waveband variability

- Fitting X-ray emission requires high minimum energy of electrons

Conclusions

VLBA images guide interpretation of light curves + polarization vs. time

γ-ray outbursts coincide with mm-wave activity in jet

→ γ rays are mainly produced on parsec scales

Only 35% of new knots/core flares associated with γ-ray flares → either seed photon field or E_{max} of e^-s varies

Timing: γ-ray flares peak as moving knot crosses “core” or other stationary feature

Magnetic field in jet is mostly disordered → turbulence

Jets of most γ-ray bright blazars are very narrow with high Doppler factors → short time-scales of variability

Extra Slides Follow

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

I. Brightest γ-ray flares (3σ events):
$S_\gamma > (<S_\gamma> +3\sigma)$ for ≥2 consecutive measurements with 7-day binning

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

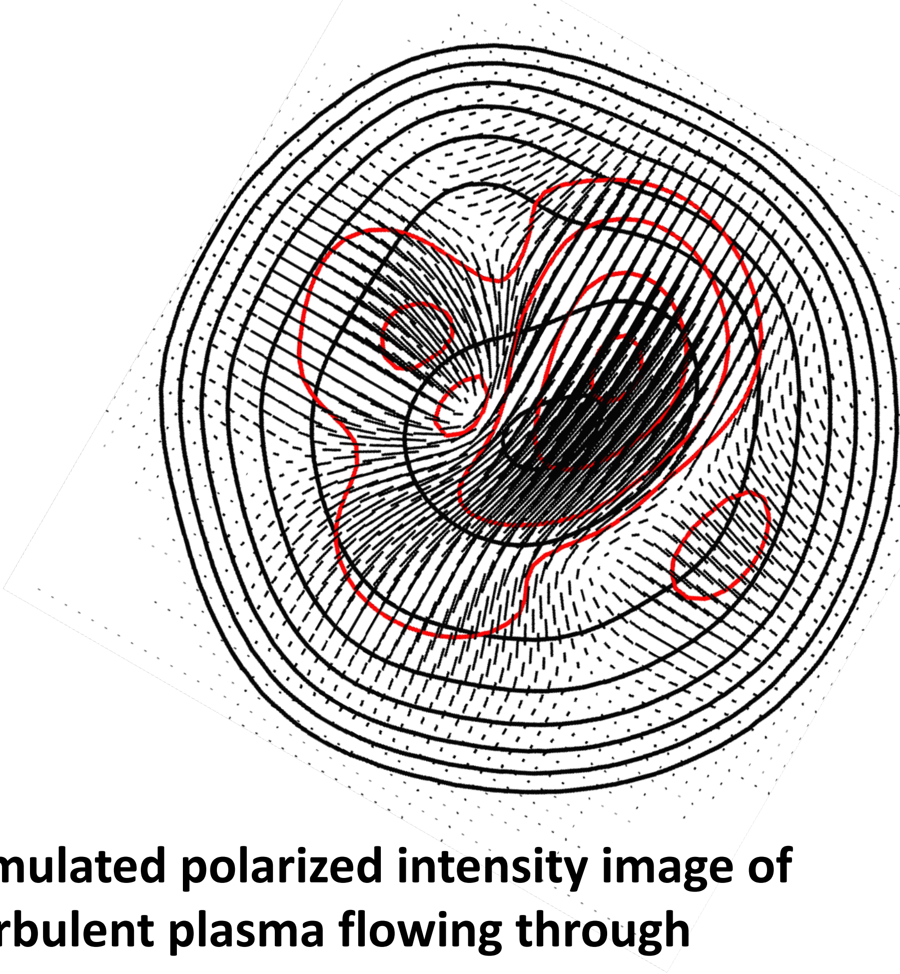
III. For each event a γ-ray light curve with a shorter binning interval (1-3 days) is produced to find ``true'' γ-ray peak, $S_\gamma^{\max}$

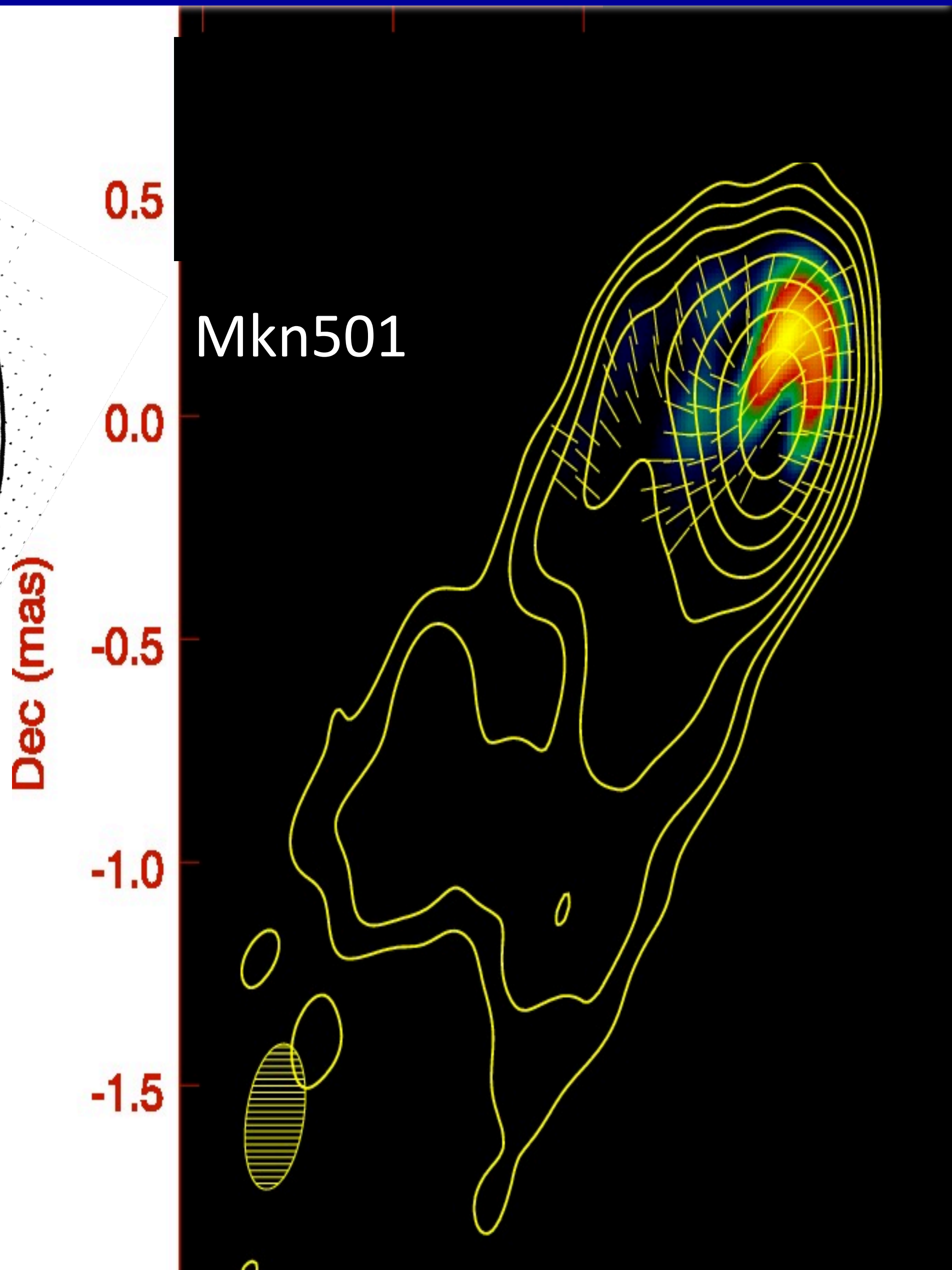
III. Duration of a flare: FWHM of $S_\gamma^{\max}$

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

Model of “Core”: Turbulent Plasma Crossing Conical Standing Shock (see also Cawthorne et al. 2013 ApJ)

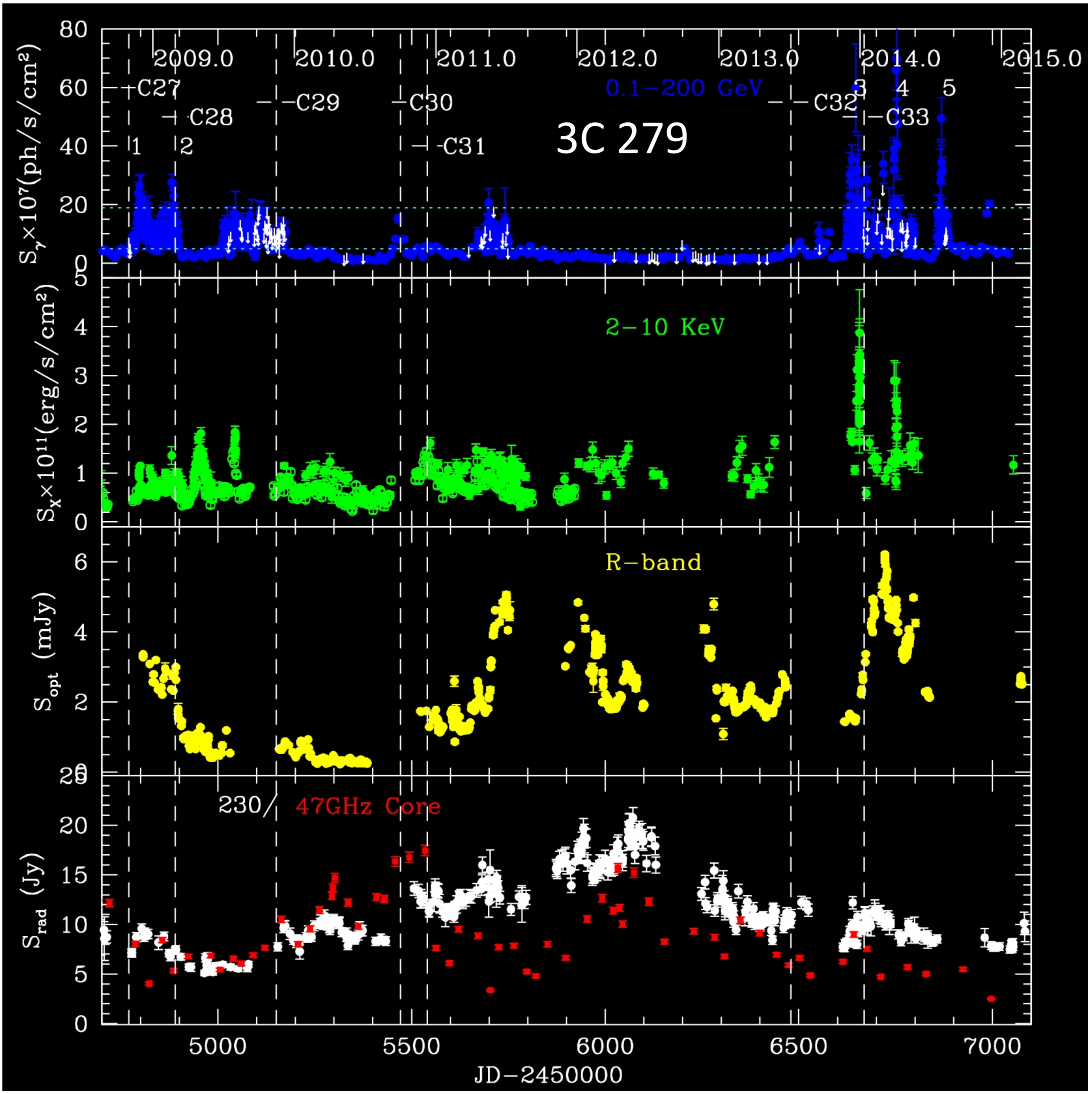


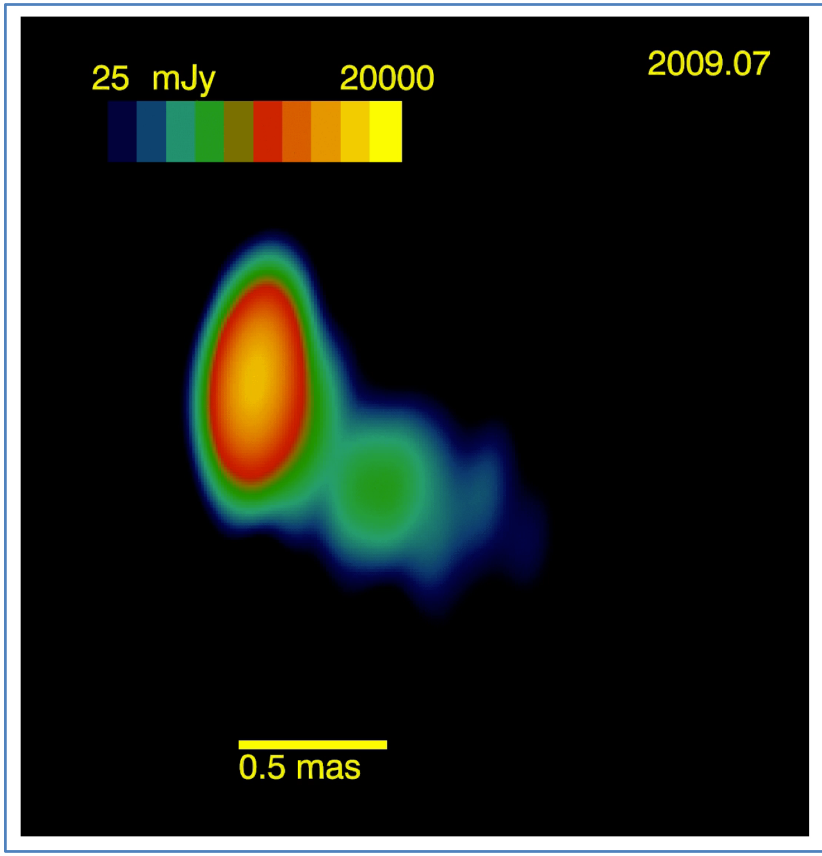


Simulated polarized intensity image of turbulent plasma flowing through standing conical shock

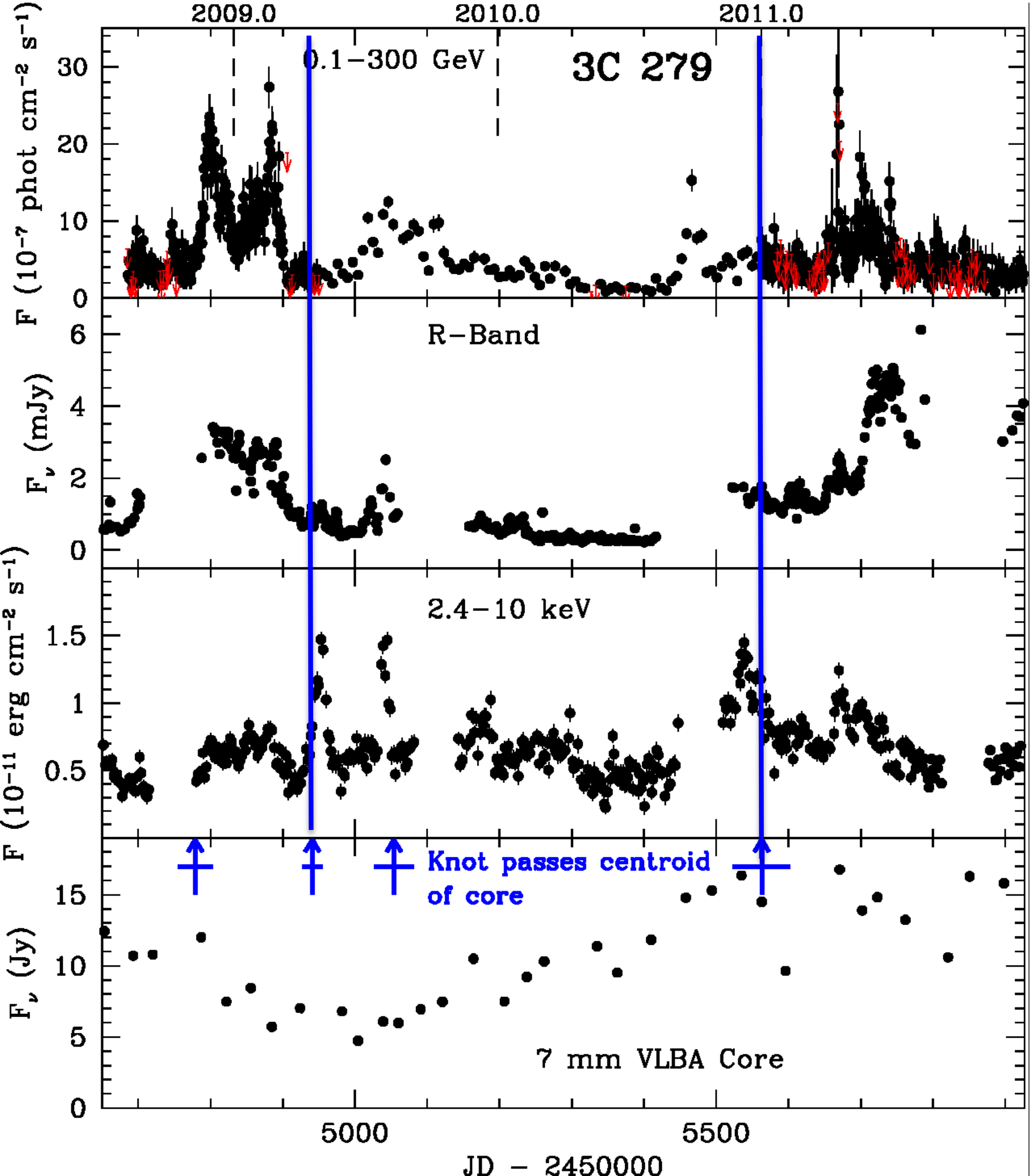
- Pattern of polarization & total polarization similar to blazar core

What happens in jet during γ-ray outbursts & quiescence





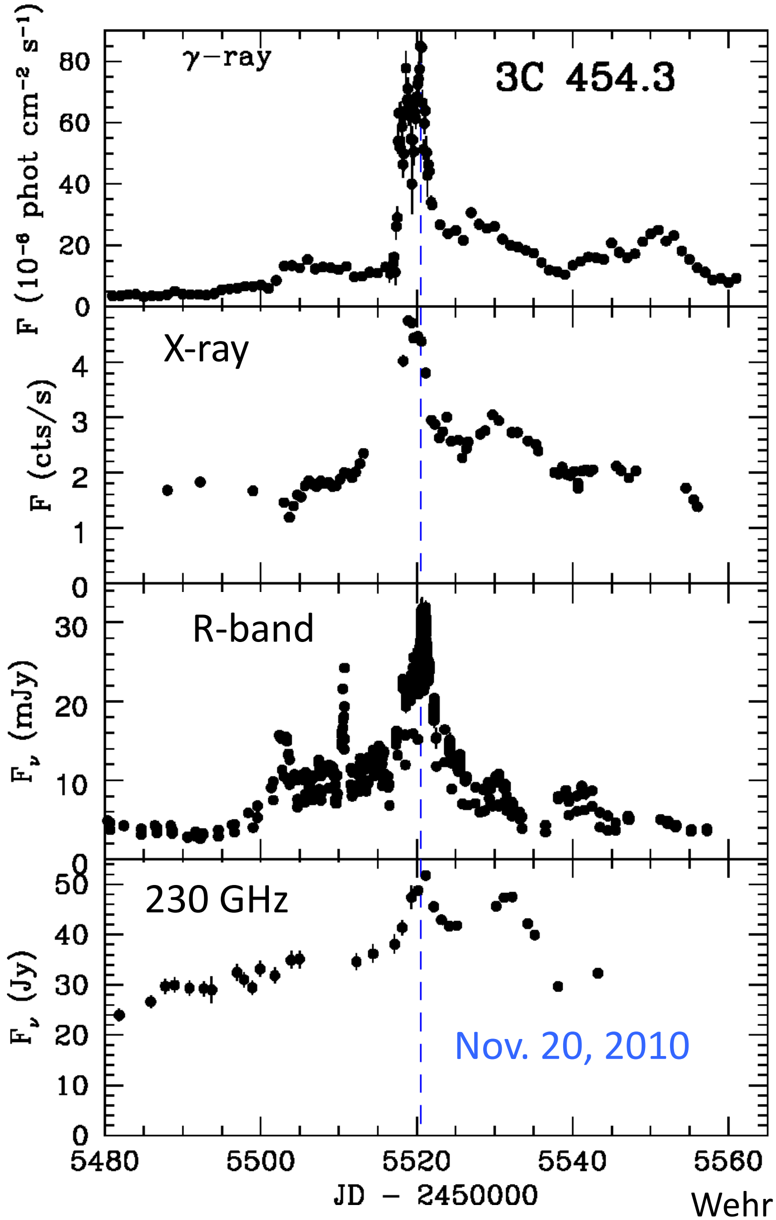
Knots with & without γ-ray Flares (Jorstad + in prep)



← **Both types in Quasar 3C 279**

Knots without γ-ray & optical flares must only energize electrons to ~1000 mc²

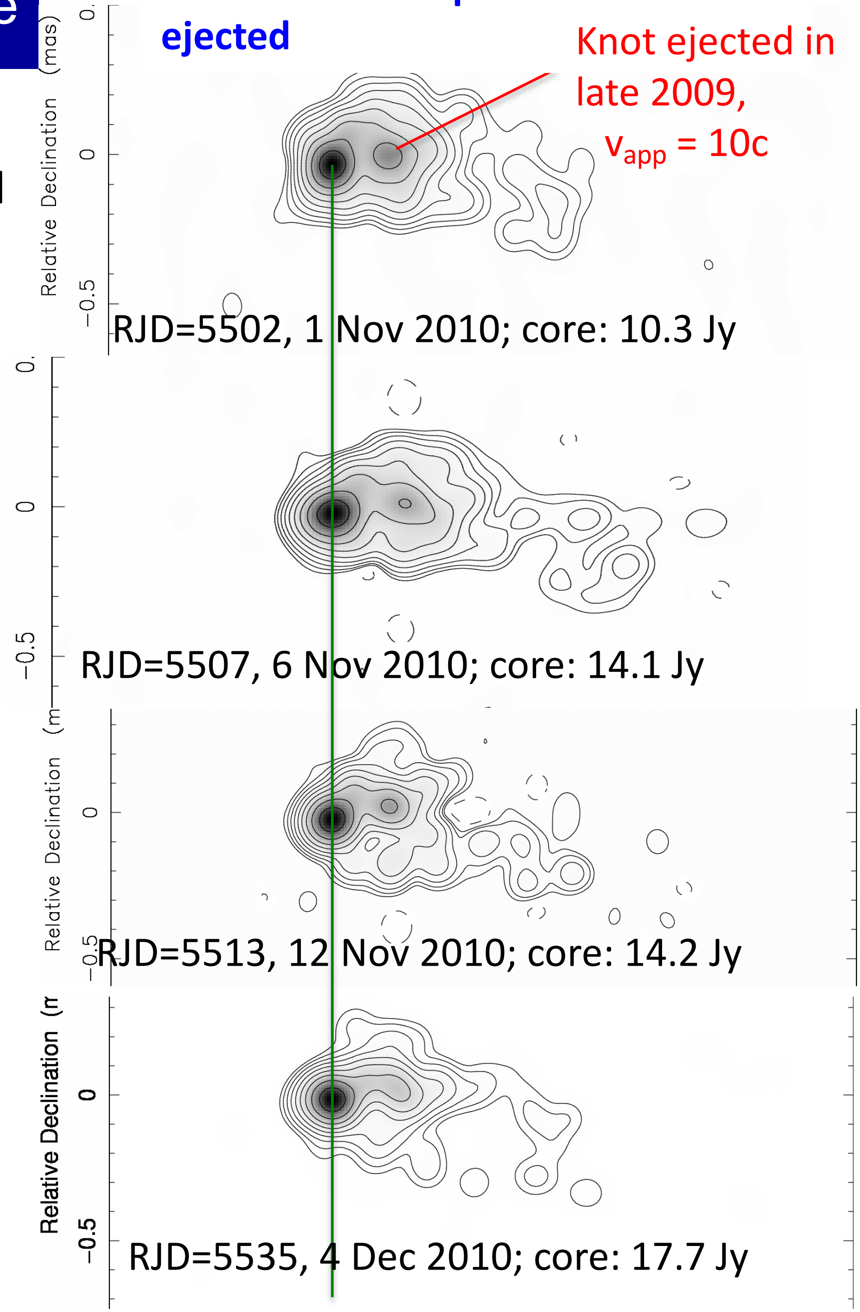
3C 454.3: All wavebands down to mm-wave peaked within 1 day during flare in VLBI core



γ-ray, etc. flare occurred on pc scales

Wehrle et al. (2012 ApJ)

VLBA images at 7 mm wavelength: flare in core + superluminal knot ejected



Knot ejected in late 2009, v_{app} = 10c

RJD=5502, 1 Nov 2010; core: 10.3 Jy

RJD=5507, 6 Nov 2010; core: 14.1 Jy

RJD=5513, 12 Nov 2010; core: 14.2 Jy

RJD=5535, 4 Dec 2010; core: 17.7 Jy