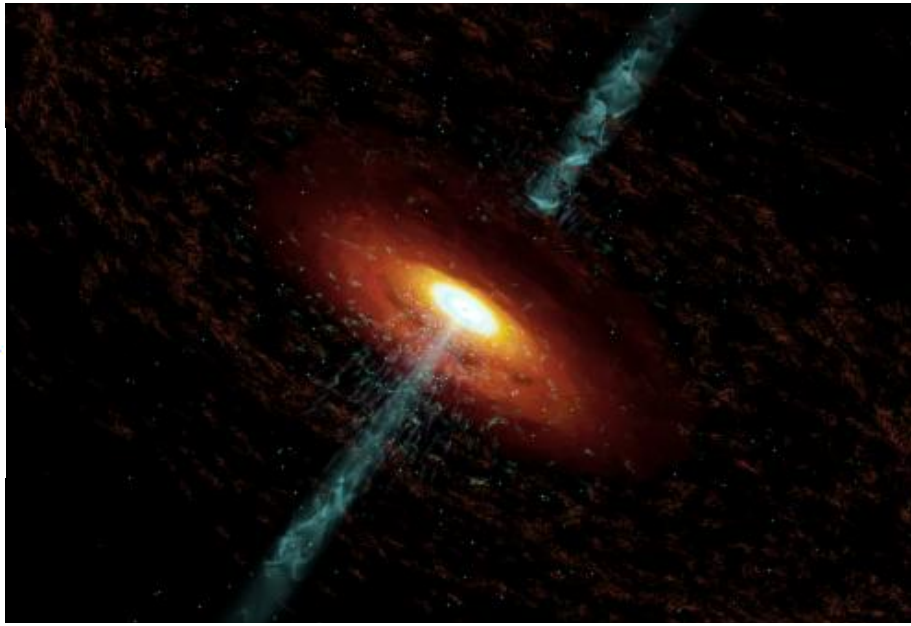

Probing Blazar Jets with Fermi and Multi-waveband Observations

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Research Web Page: www.bu.edu/blazars

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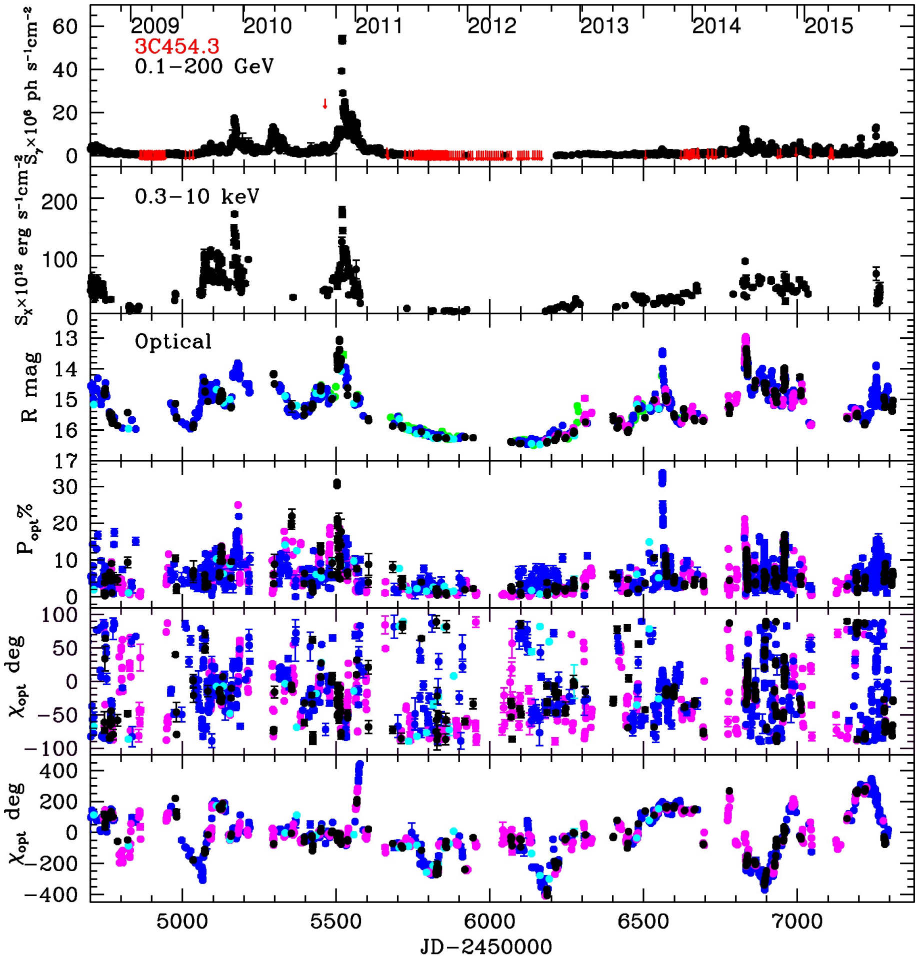
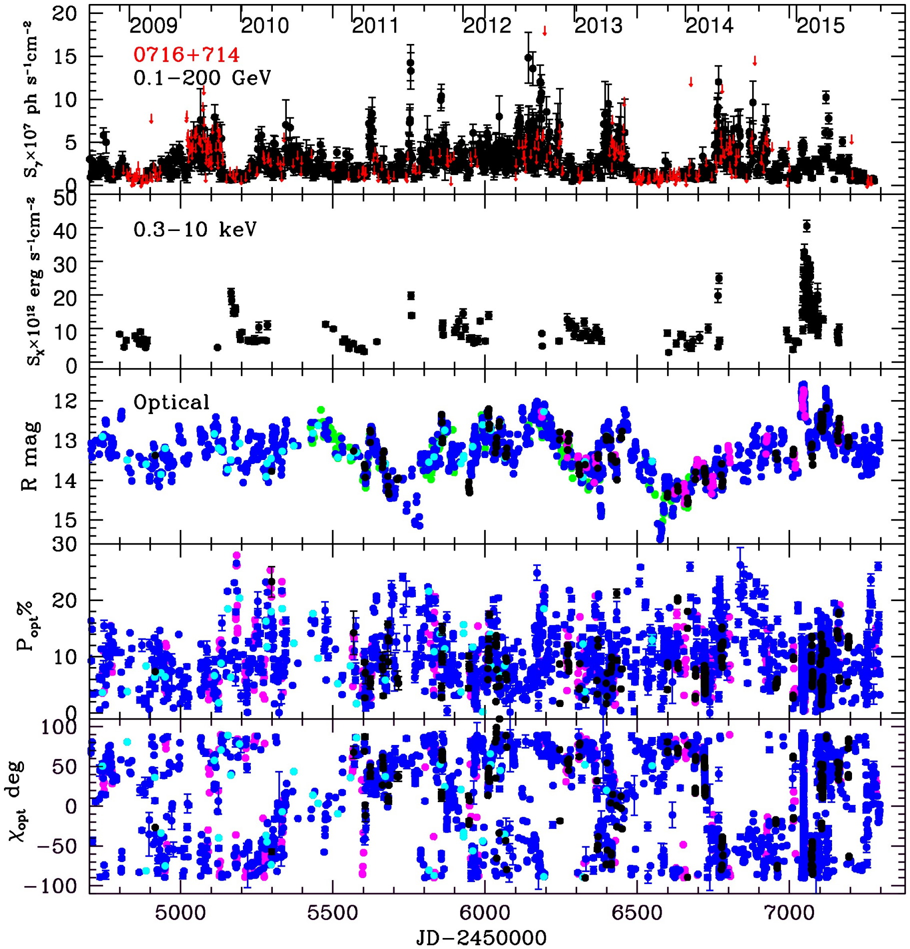
Multi-waveband Light & Polarization Curves (data: BU + collaborators)



Quasar 3C 454.3



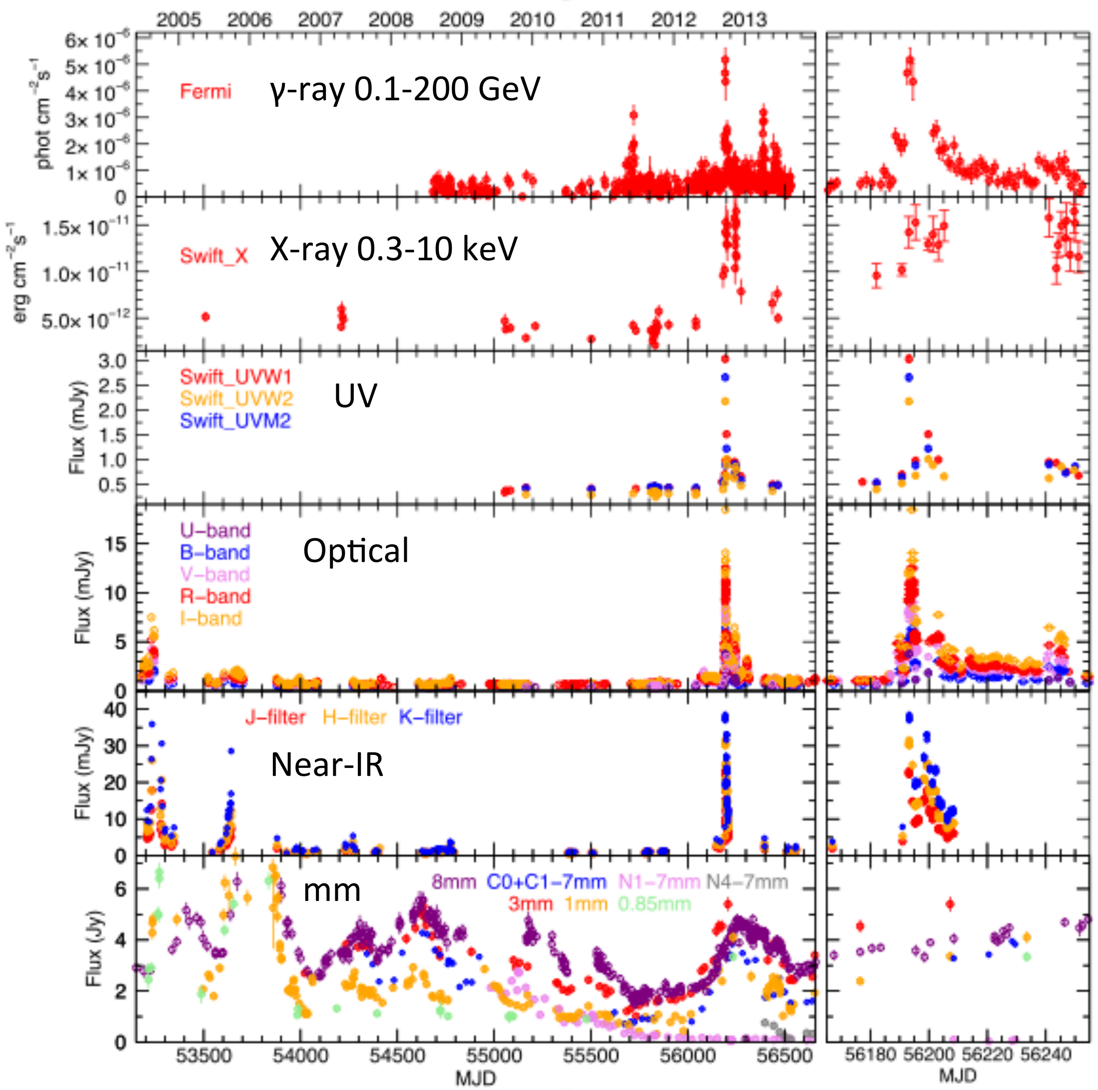
BL Lac object 0716+714

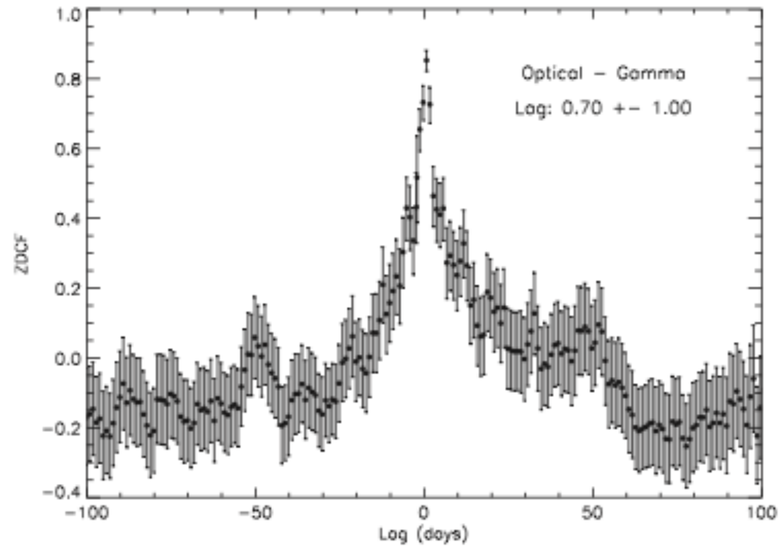
Quasar: Oases of outbursts separated by quiescent deserts

BL Lac object: wild fluctuations, not as wide flux range, γ-ray flares with & without optical flares

Both: wildly variable optical linear polarization

Quasar CTA 102 (Casadio et al. 2015)



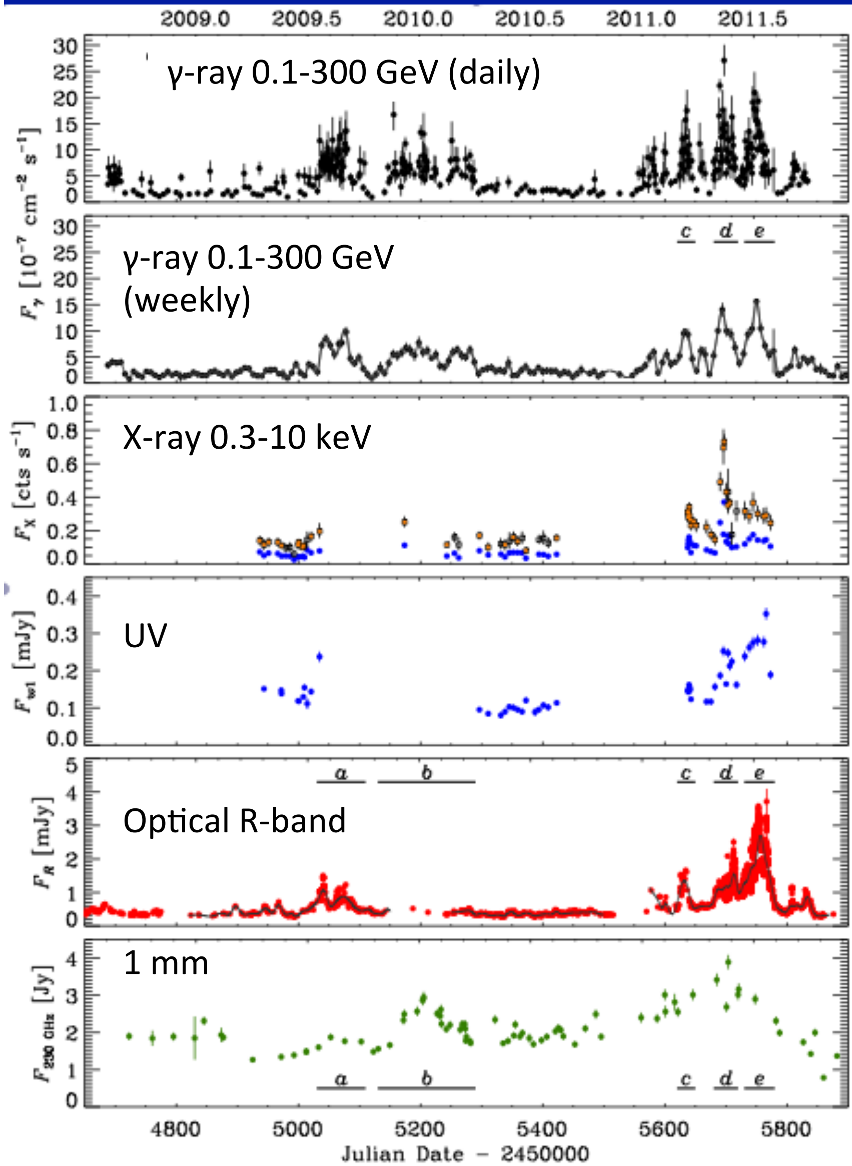


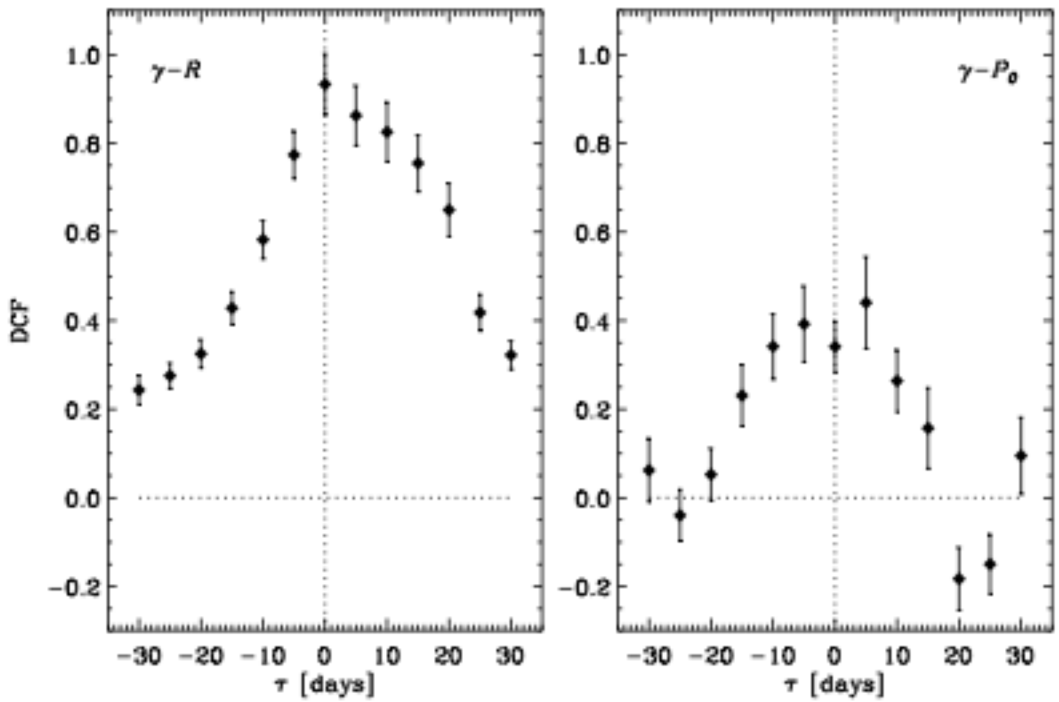
Strong γ-ray – optical correlation, ~ zero lag

But there are "orphan" γ-ray flares

Flares are often simultaneous across wavebands from short mm to γ-ray, but sometimes only appear at some λ's

Quasar 1633+382 (4C 38.41) (Raiteri et al. 2012)

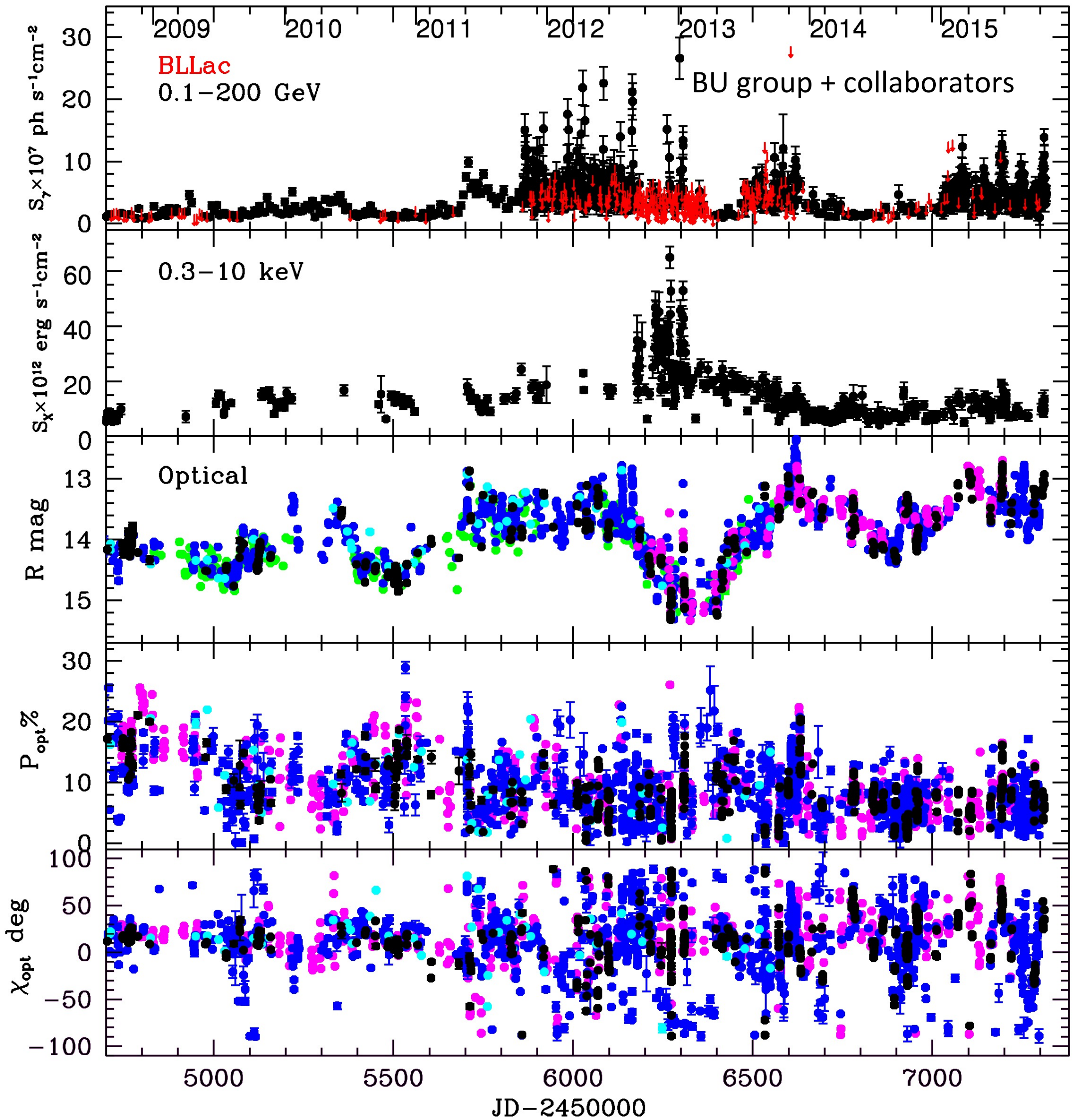


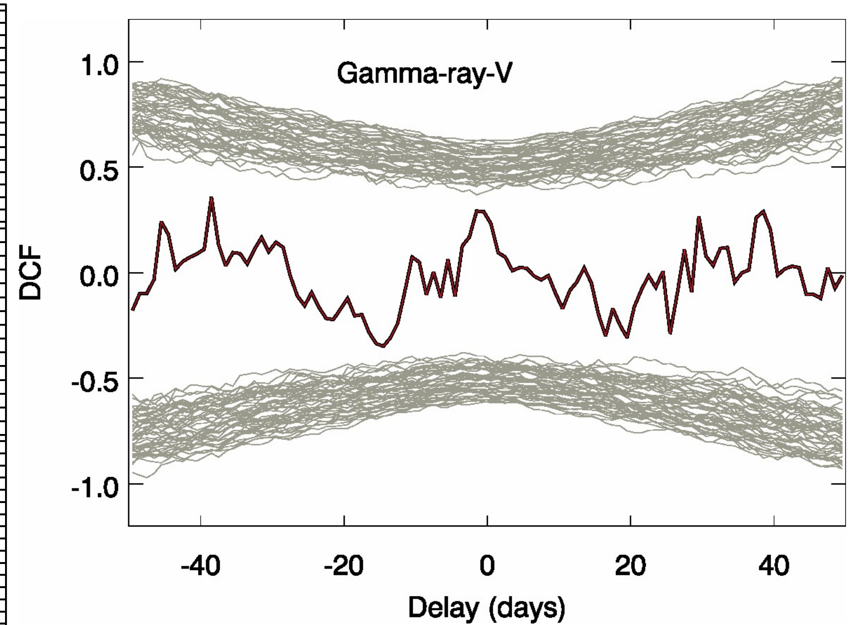


Strong γ-ray – optical correlation, ~ zero lag
Weaker correlation of γ-ray & optical polarization

Outburst in 2011 seen at all wavebands, but flux ratios change

BL Lacertae



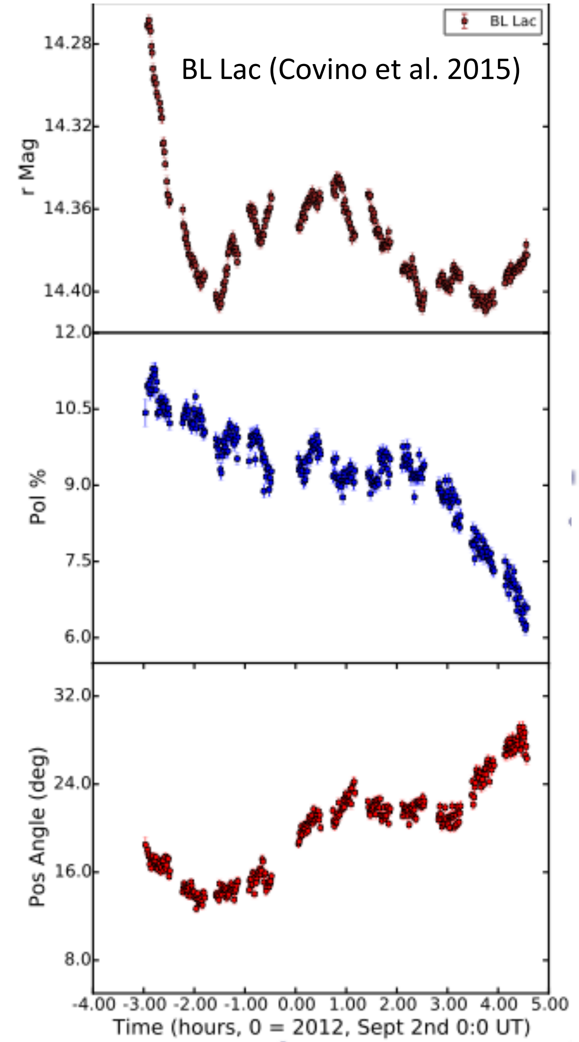


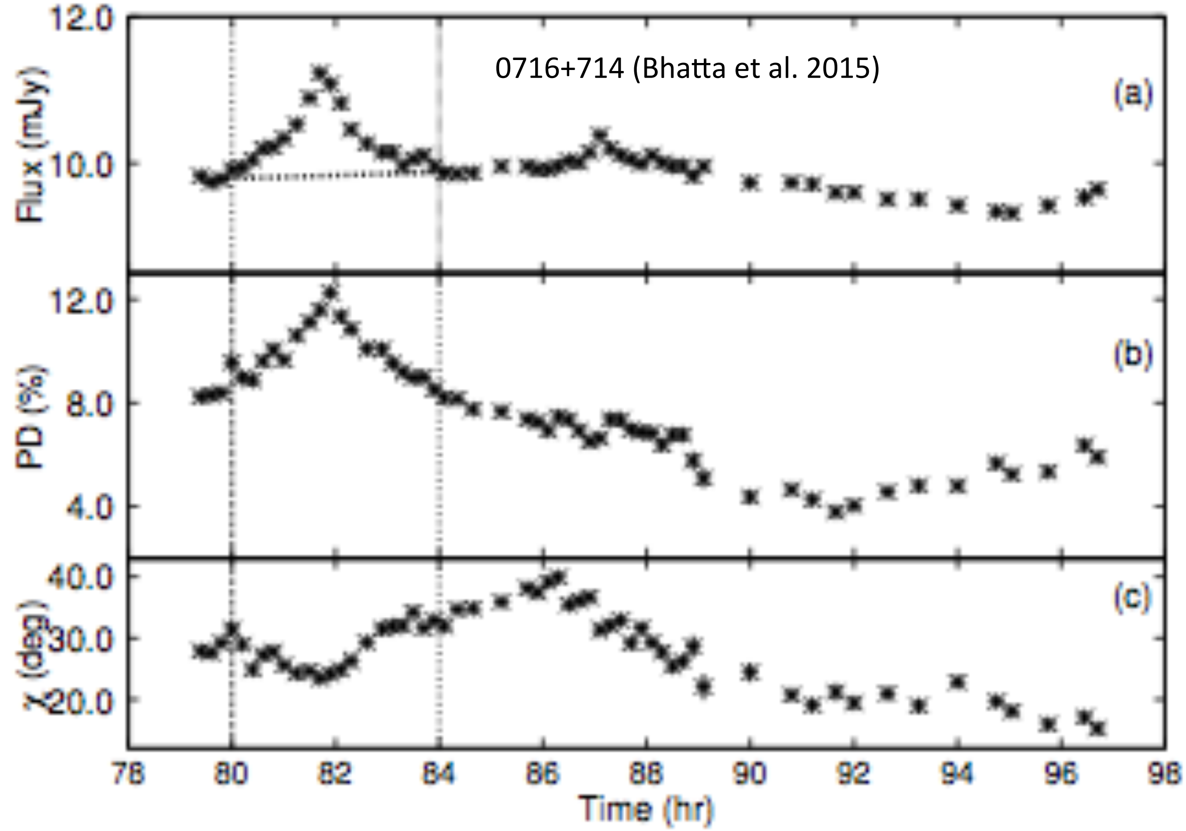
Weak γ-ray – optical correlation (data up to October 2013)
γ-ray leads by ~ 1 day

Yet every period of prolonged γ-ray flaring corresponds to a relatively high optical state

During quiesent periods, optical polarization position angle ~ stable along jet direction. During flares, polarization varies erratically, as expected if it results from turbulence (or some other magnetic field disordering)

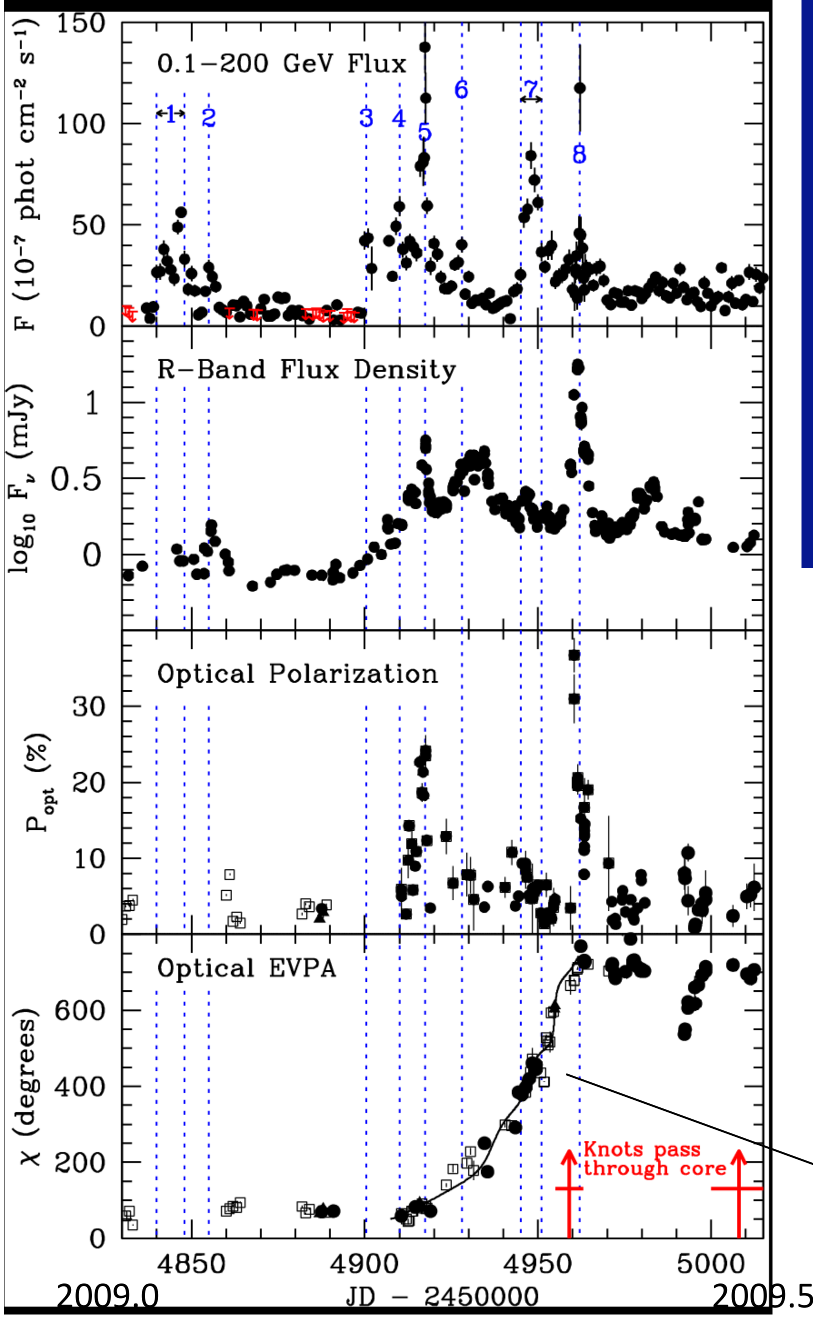
Intra-day Variability of Optical Flux & Polarization



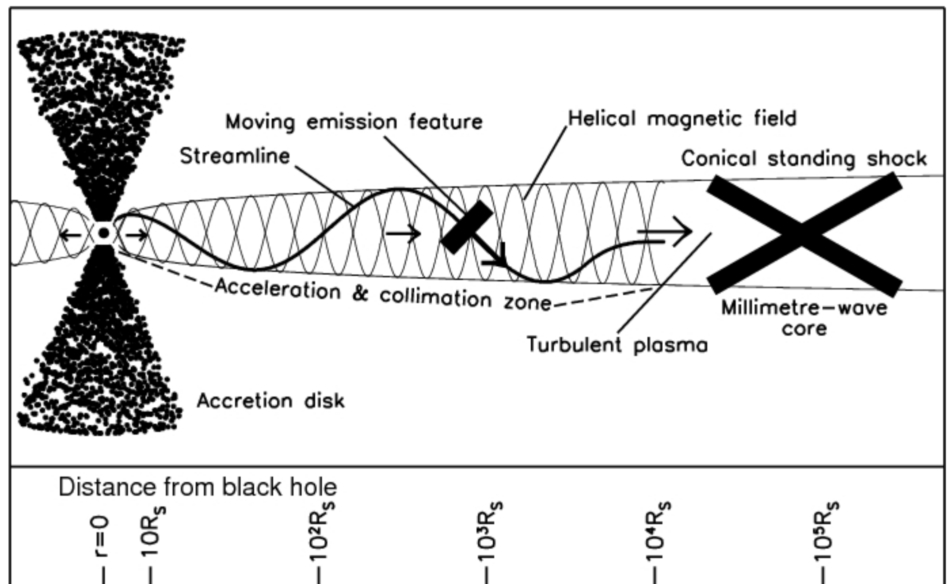


Polarization & flux varies significantly over hours, as expected if it results from turbulence

720° Rotation of Optical Polarization in PKS 1510-089 (Marscher et al. 2010)

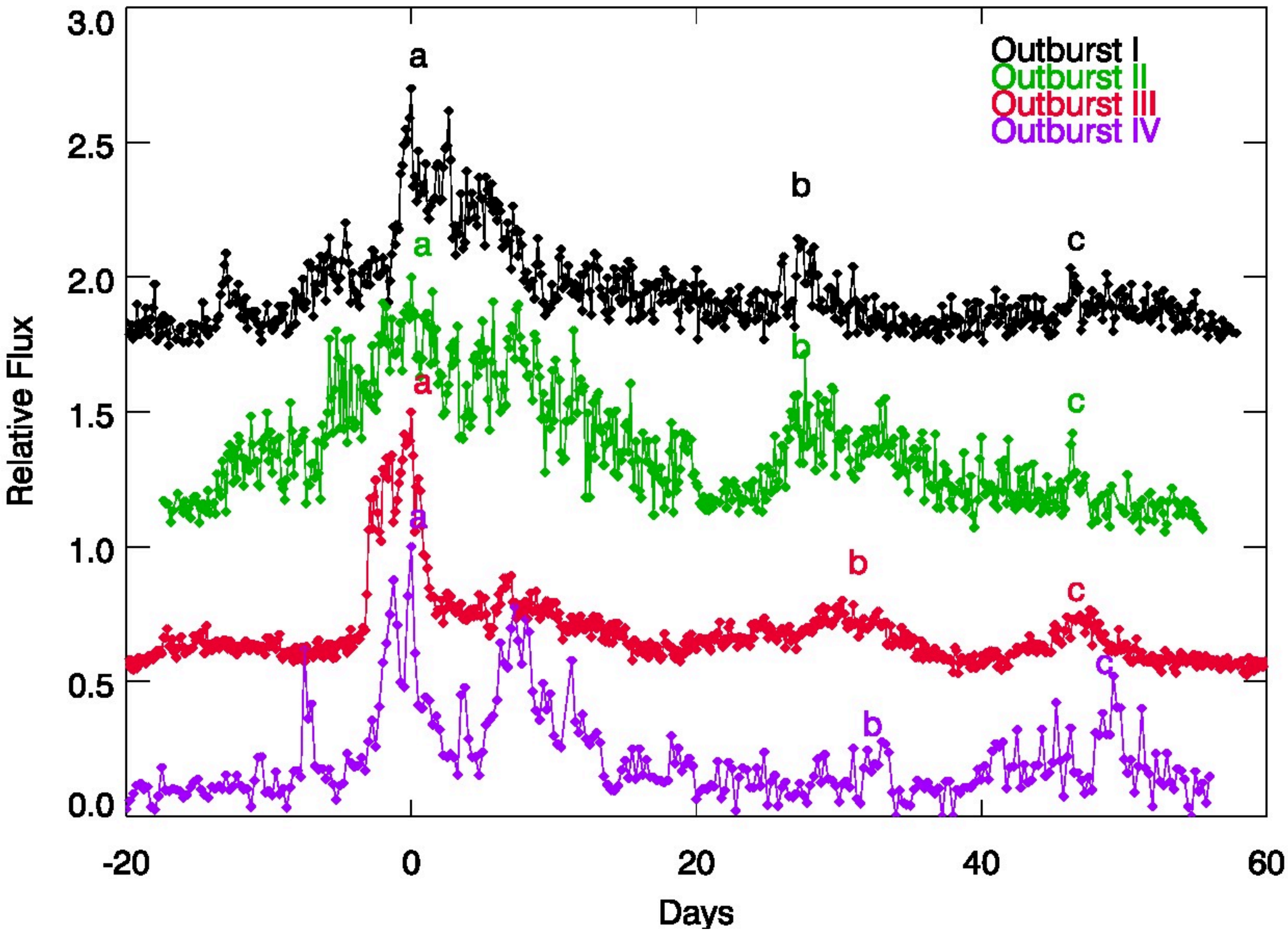


- Non-random timing argues against rotation resulting from random walk caused by turbulence → implies single blob did all
- Also, later polarization rotation similar to end of earlier rotation, as a weaker blob approaches core
- Blinov et al. (2015): statistics show that some rotations are connected with γ-ray flares
- Kiehlmann et al. (2015): some are random walks



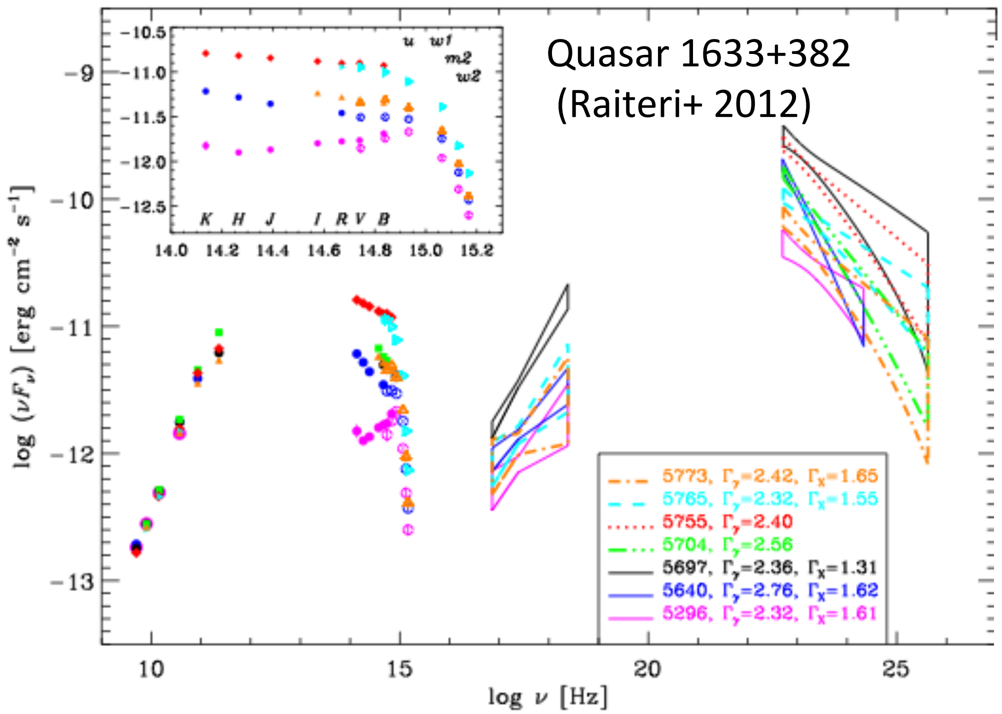
Model curve: blob following a helical path down **helical field** in accelerating flow

Observed Indication of Order: 3C 454.3 (Jorstad et al. 2013)

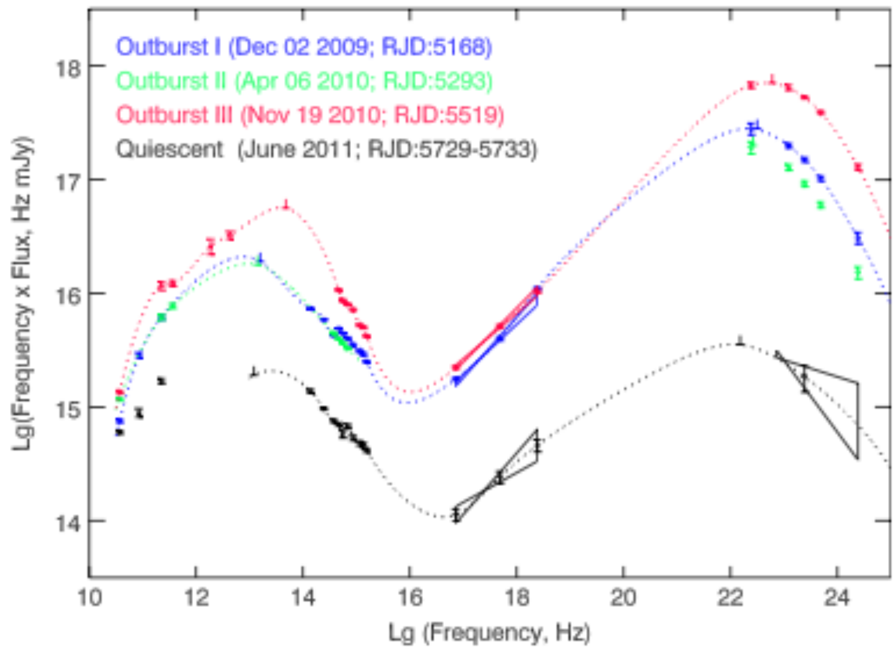


γ-ray light-curve profiles of 4 multi-flare outbursts are similar; possibly related to jet structure (Jorstad et al. 2013 & in prep)

Spectral Energy Distributions



Quasar 3C 454.3 (Jorstad+ 2013)



All blazars have double-hump SEDs

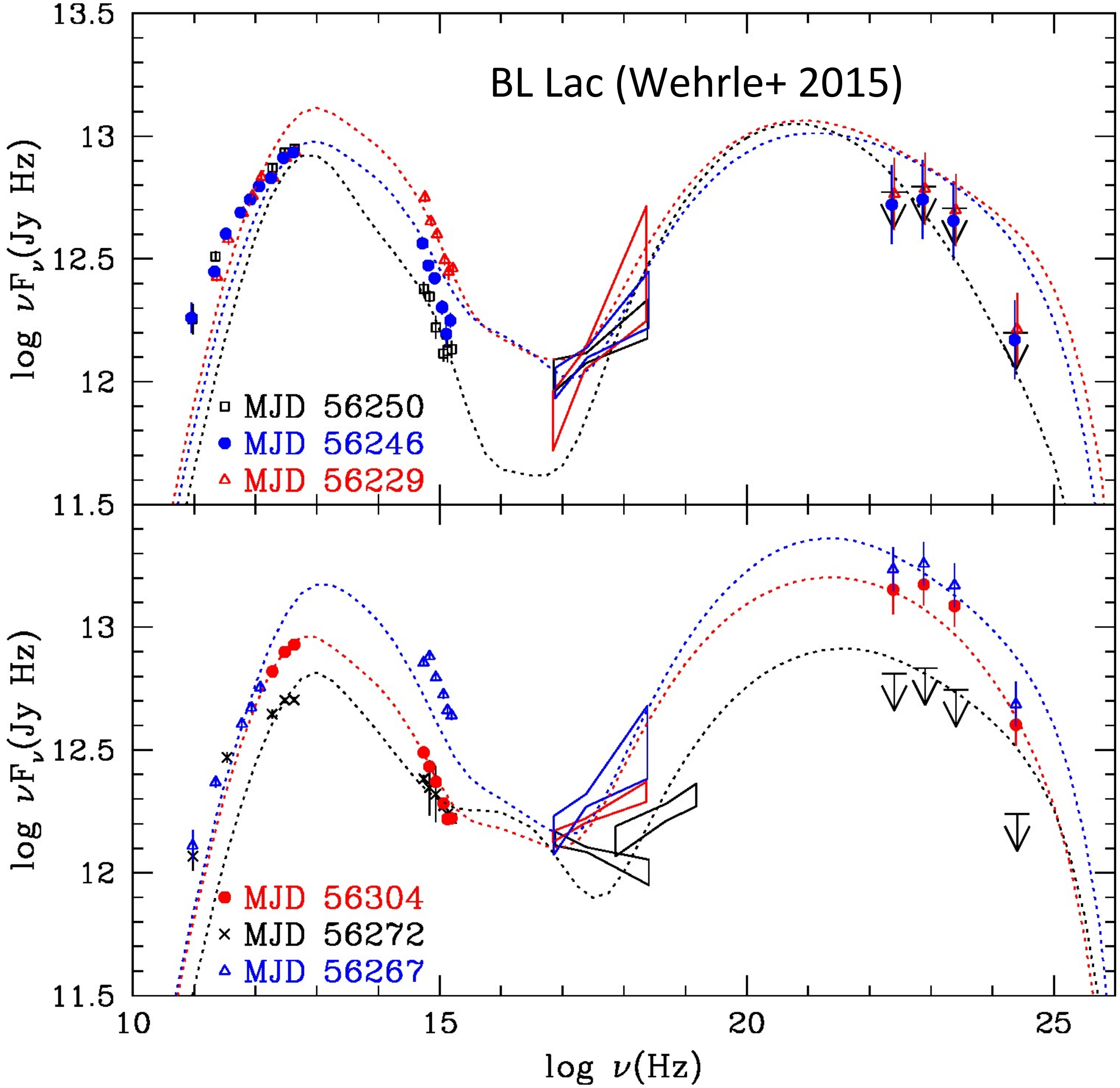
- Synchrotron at lower frequencies, probably inverse Compton at high energies

- In quasars, *L*(γ-ray) often >> *L*(synchrotron) during outbursts

→ Seed photons are from ~stationary source (not classic SSC)

Data here are consistent with single X-ray – γ-ray component

Spectral Energy Distributions

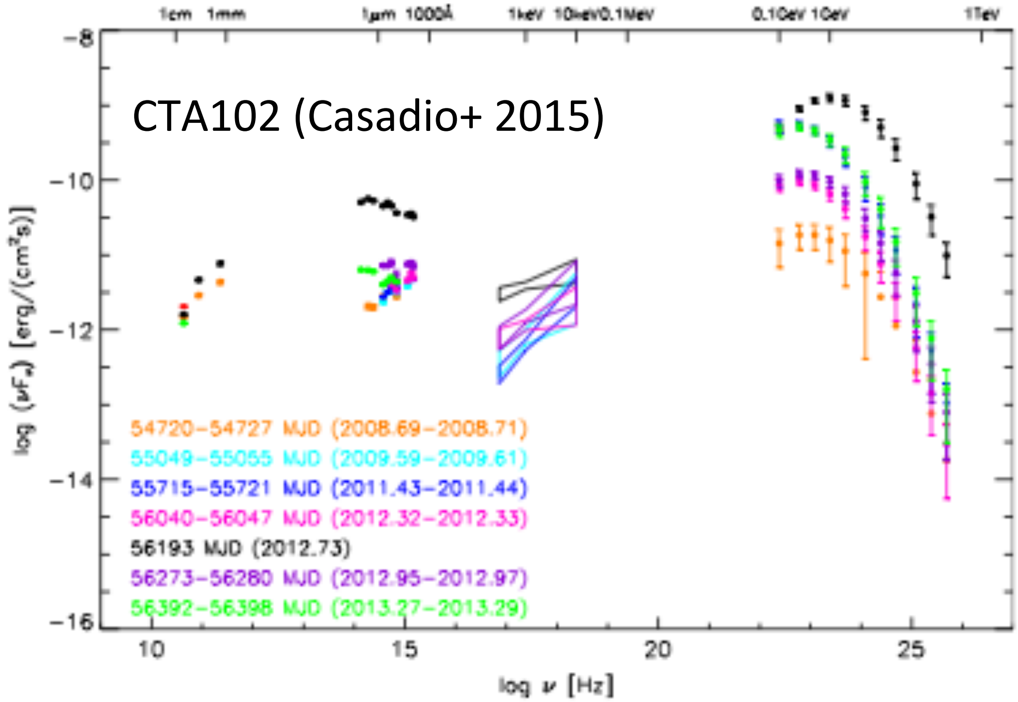


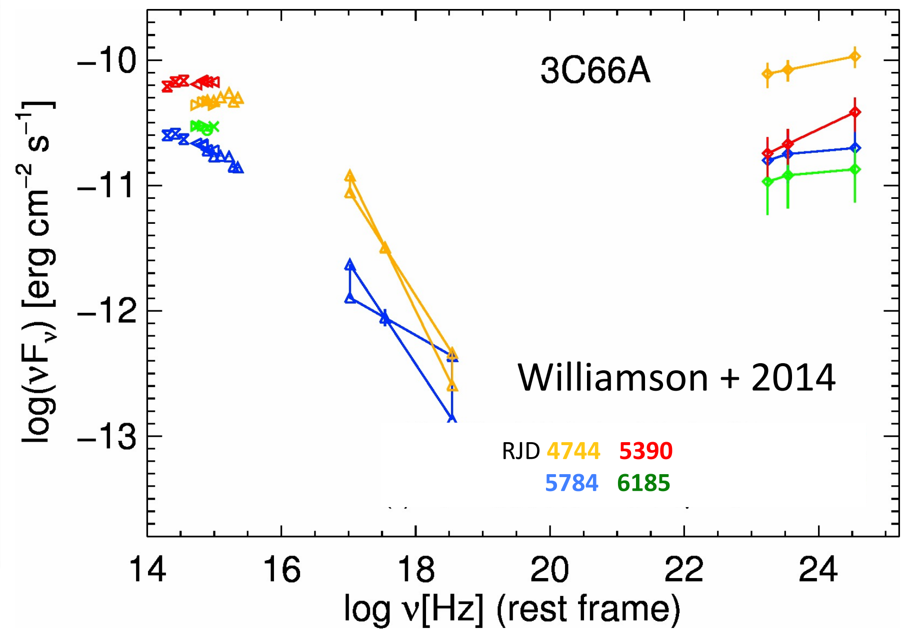
BL Lac objects: γ-ray peak usually similar to synchrotron peak

→ Can be SSC

TeV emitting BL Lacs: synchrotron component extends up to X-ray energies

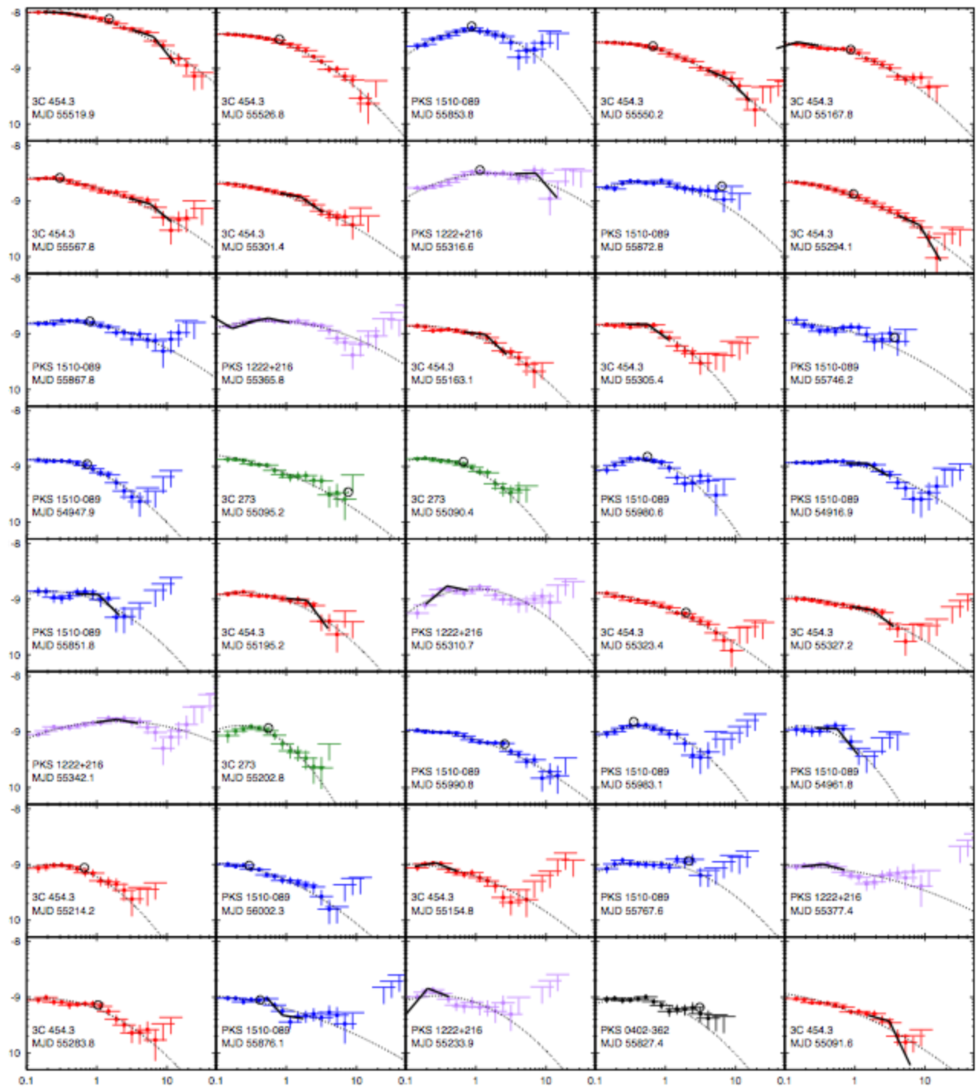
Spectral Energy Distributions





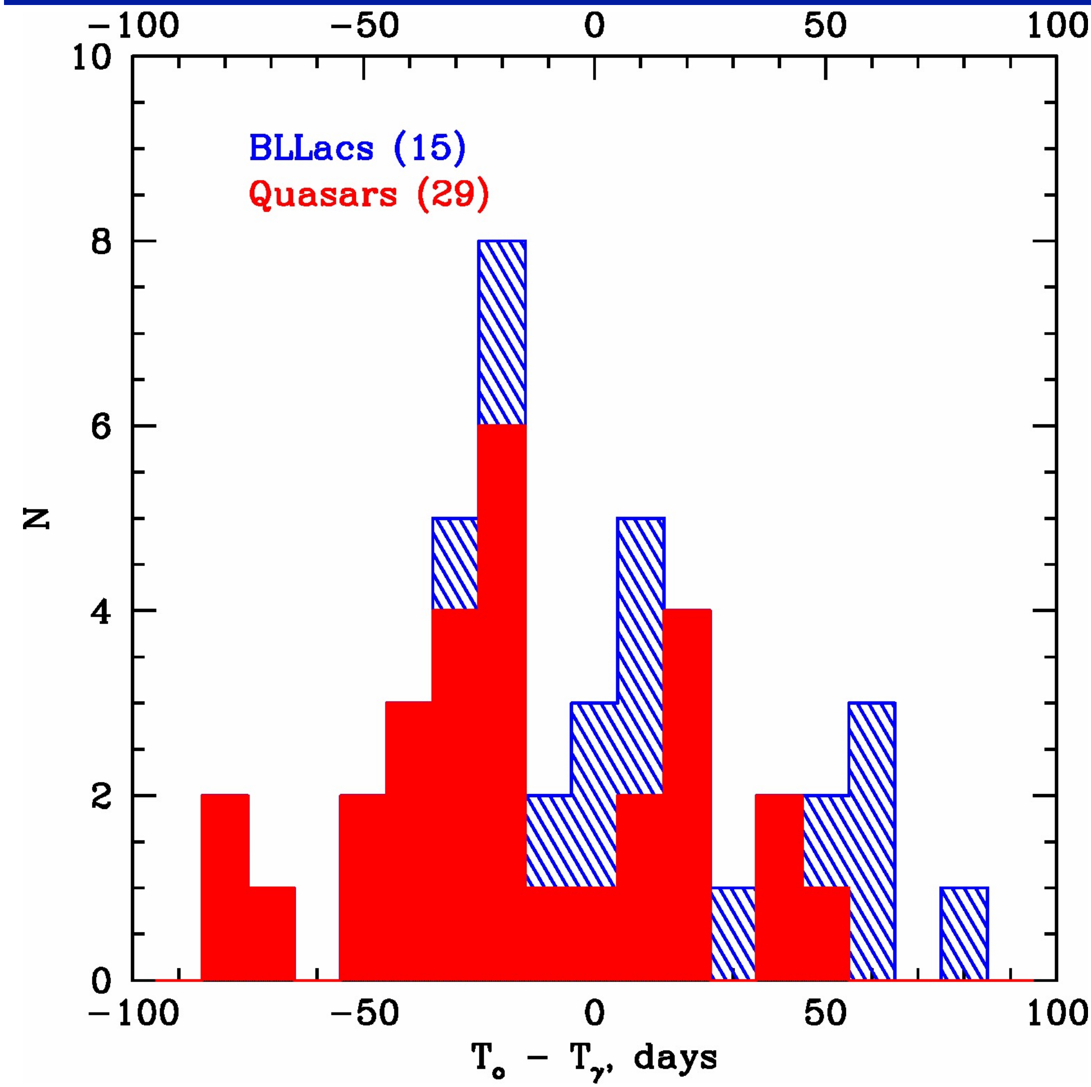
X-rays in 3C 66A + in high state of CTA102 do not extrapolate to γ-ray component → either seed photons have ~ thermal spectrum or minimum electron energy is quite high (~1000 mc^2)

Diversity in SEDs of Strongest Flares (Kohler & Nalewajko 2015)



Implies that a stochastic process – e.g., turbulence – controls the particle acceleration, etc., that causes flares

Gamma-ray Flares and Superluminal Radio Knots (Poster by Jorstad +)



33 blazars from VLBA-BU-BLAZAR monitoring program (Jorstad +, in prep)

44 out of 131 superluminal knots associated in time with major γ-ray flares

- another 9 similar flares were not accompanied by new knots

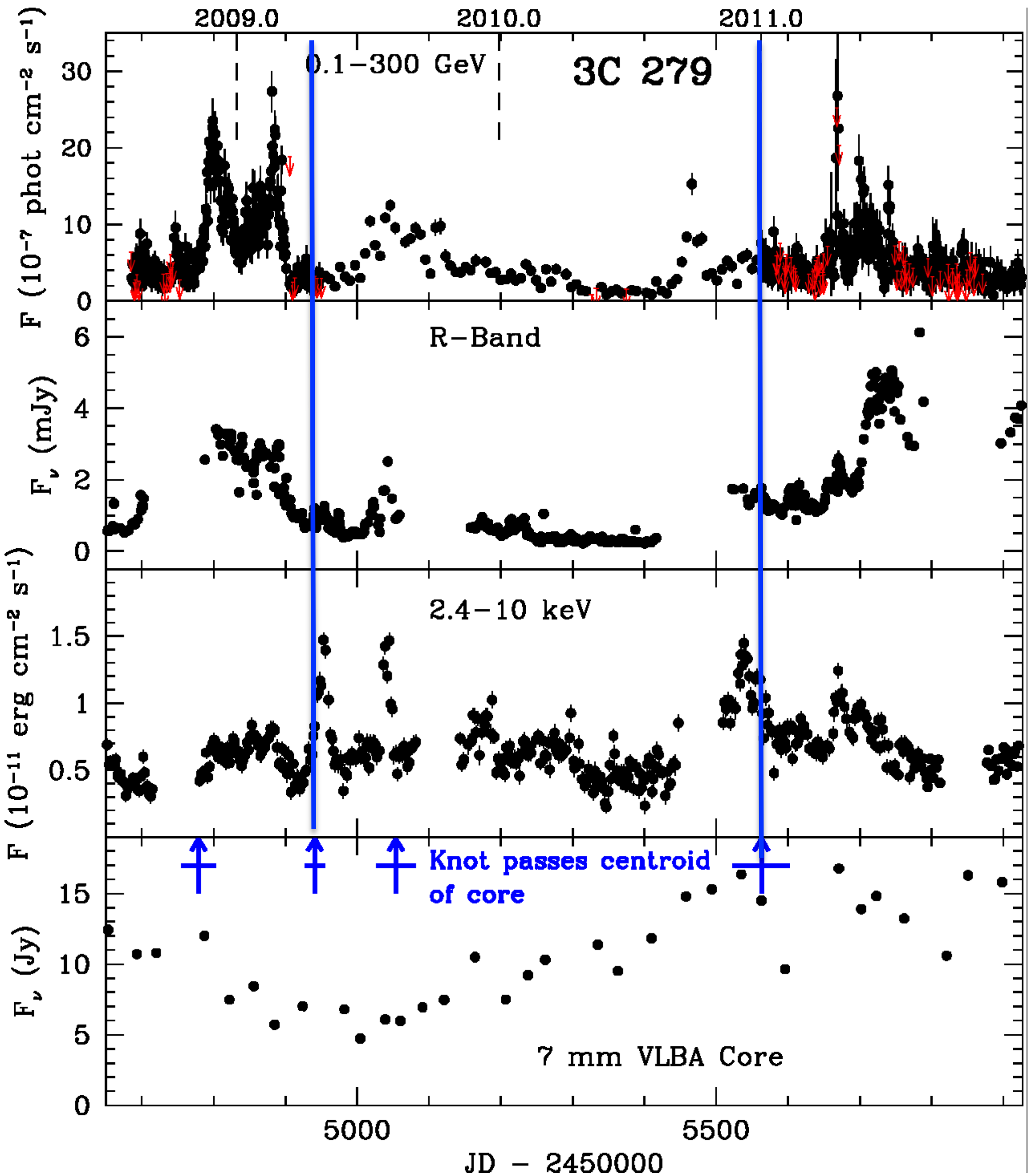
T_γ: peak of major γ-ray flare
T_o: superluminal knot crossed centroid of 7 mm VLBI "core"
-Typical uncertainty in T_o = 10-15 days

Some mm-wave cores have properties consistent with standing conical shock

83% of major γ-ray flares are contemporaneous with new knots crossing "core", 53% of these within 30 days

- Core has some extent, so knot is within it for > 30 days

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

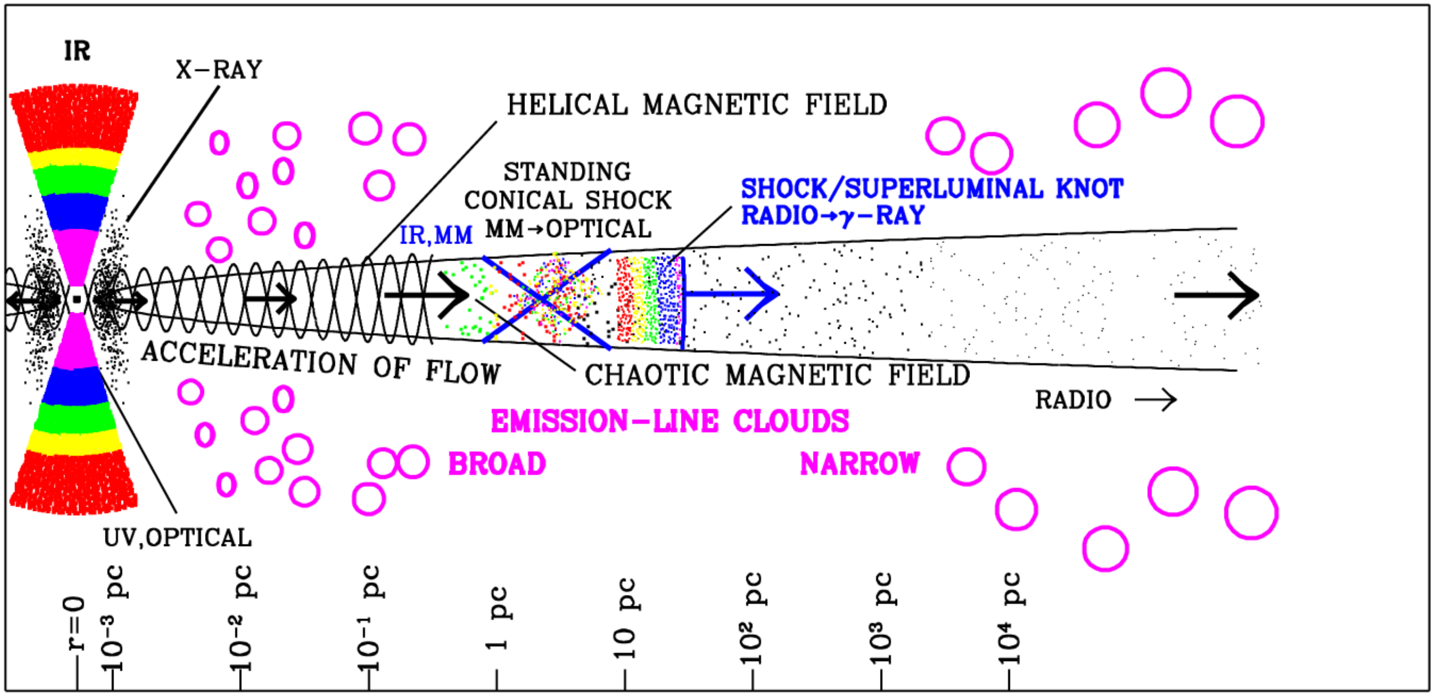


← Both types in Quasar 3C 279

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

Order + Disorder: The Blazar Theme

Likely case: jet flow, $\vec{B}$, shocks order; turbulence disorders



→Goal #1: determine order & its origin

- **Jet: nearly cylindrical flow → order || axis**
- **Shocks: order magnetic field along shock front**
- **Ordered component of magnetic field (e.g., helical)**

→ Goal #2: characterize disorder & determine its origin

Seed Photon Problem

The source of seed photons for IC scattering to γ-ray energies remains unresolved

Most theorists: Broad emission-line region (BLR) or dusty torus

+ Explains high-energy SED well

- BLR & torus are in disk, not spherical → not so intense in jet frame

- Most γ-ray flares occur on parsec scales where photon field is weak

? Stray emission-line clouds along jet? (e.g., Ghisellini & Madau 1996; Böttcher & Dermer 1998; León-Tavares + 2013; Vittorini + 2014; Tavani + 2015)

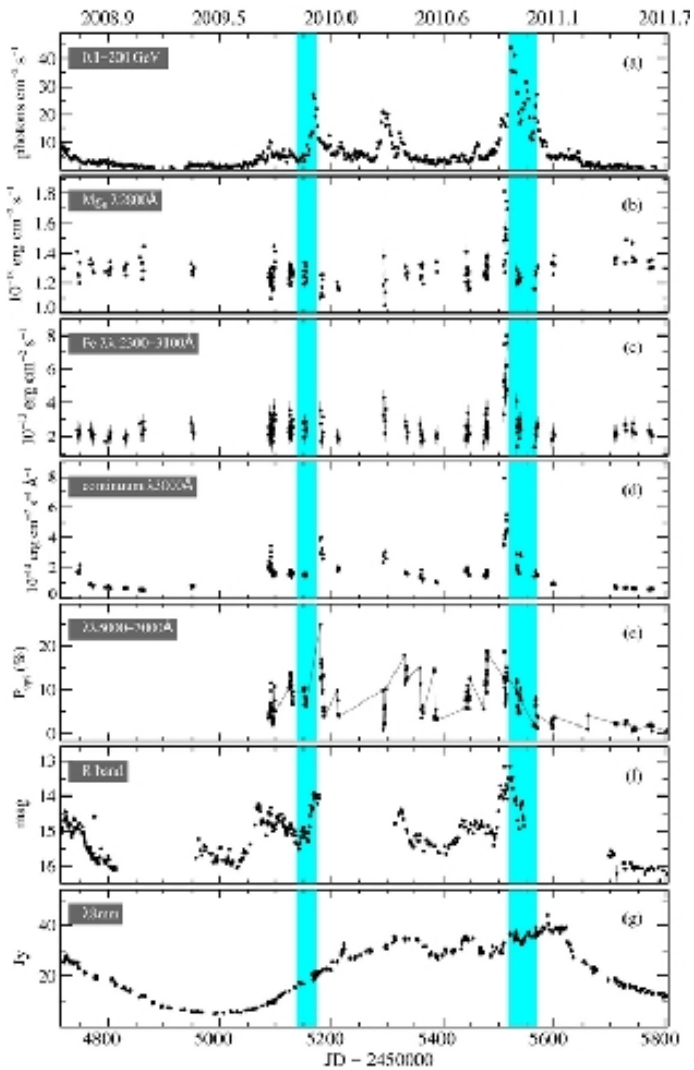
A few rebels: Jet sheath (e.g., MacDonald + 2015) or standing shock (Marscher 2014)

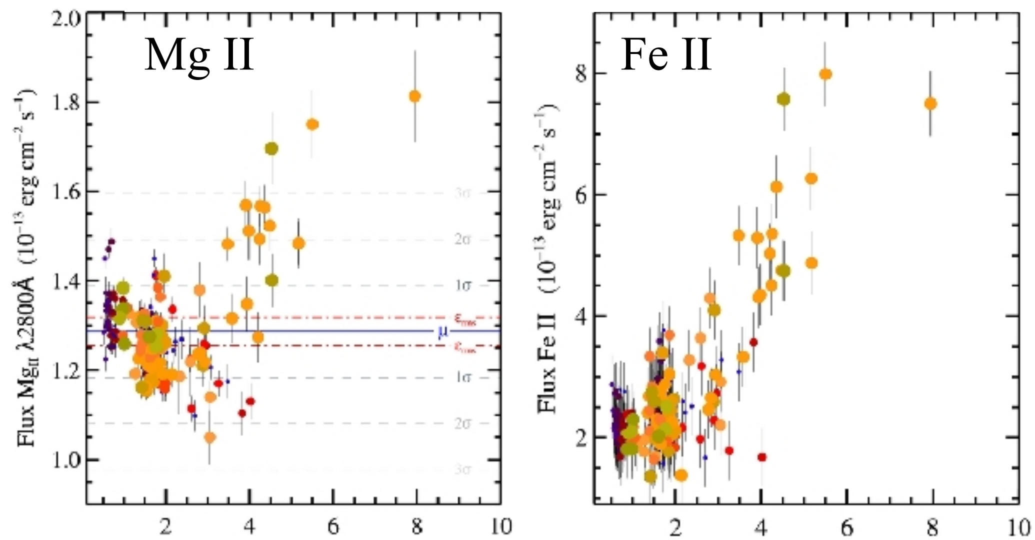
+ Present on parsec scales

+ Can be variable, explaining diversity of multi-waveband variability

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

Correlation between emission line and continuum variability in 3C 454.3 and ejection of superluminal knots



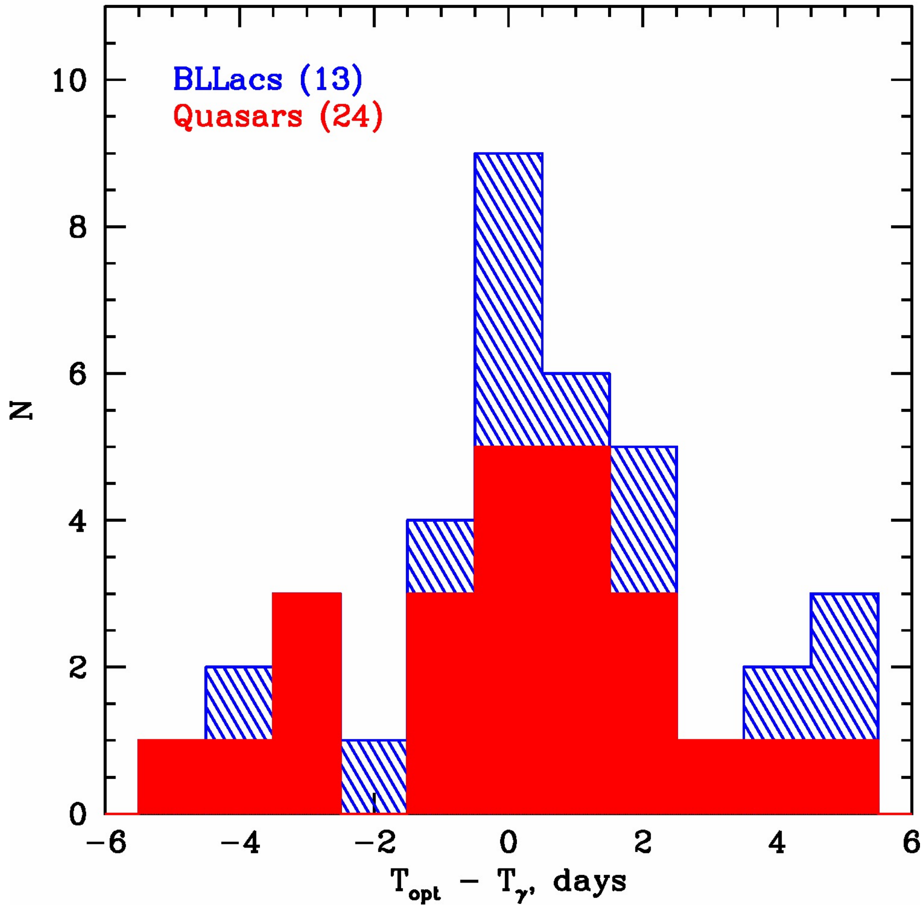


Emission-line flux vs.optical continuum flux

Leon-Tavares + 2013; see also Isler + 2013

Multi-waveband light curves of the quasar 3C~454.3; Leon-Tavares + 2013

Gamma-Optical Time Lags



33 blazars from VLBA-BU-BLAZAR monitoring program (Jorstad +, in prep)

Relative timing of peak of major γ-ray flares and local peaks of optical light curves

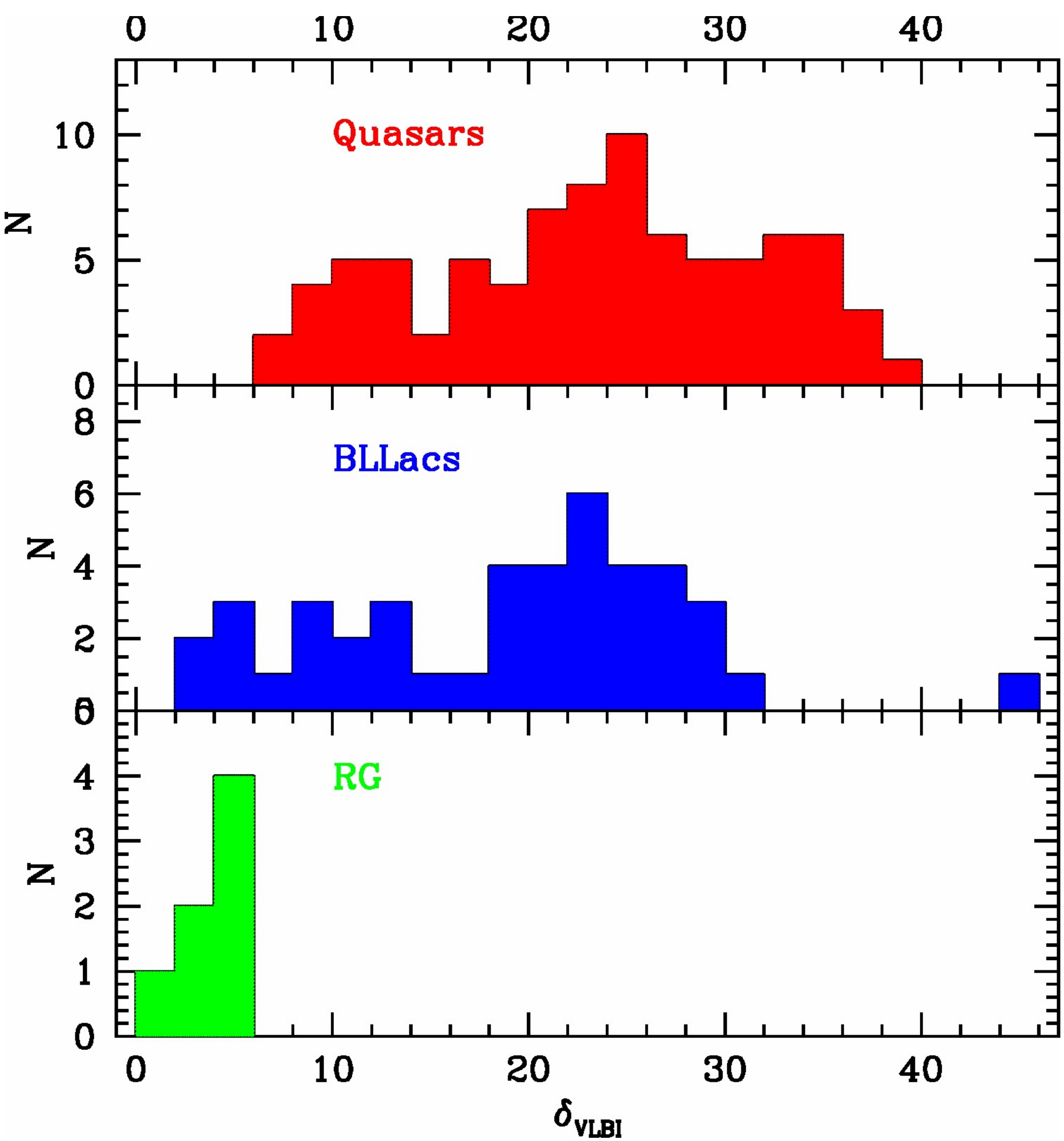
Majority of major γ-ray flares are simultaneous with local peaks of optical flux within 2 days

- Makes sense, since electron energies are similar

- Does not include orphan γ-ray flares, which are sometimes seen

→ Probably $\vec{B}$ & seed photon field vary from flare to flare

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



(Jorstad + in prep; see also Lister + 2011)

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

→Only a small fraction of jet kinetic power is "dissipated" to γ rays

→Filling factor of γ-ray emitting regions can be quite low

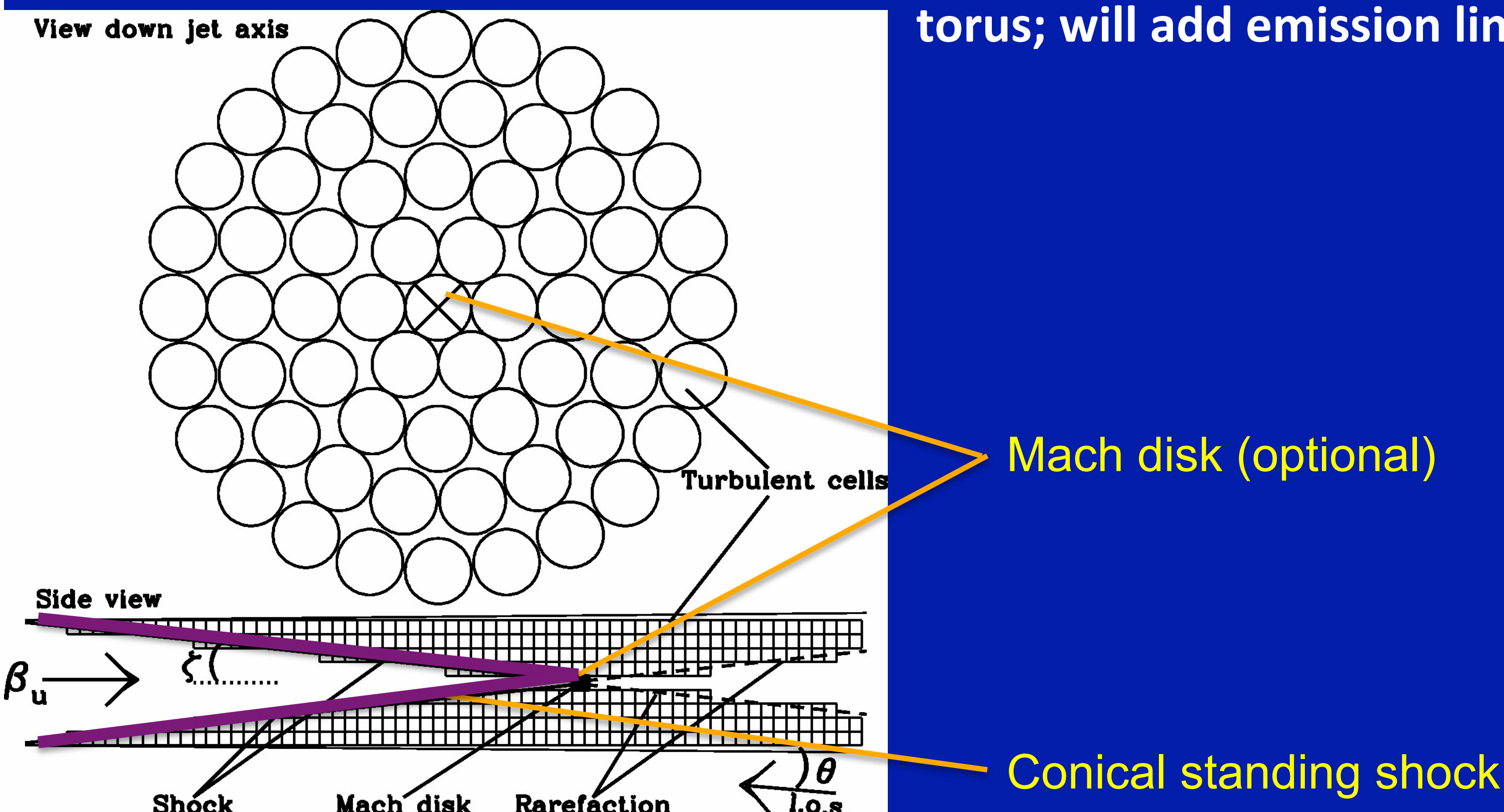
→Variability timescales can be short on pc scales

Turbulent Extreme Multi-Zone (TEMZ) Model (Marscher 2014, ApJ)

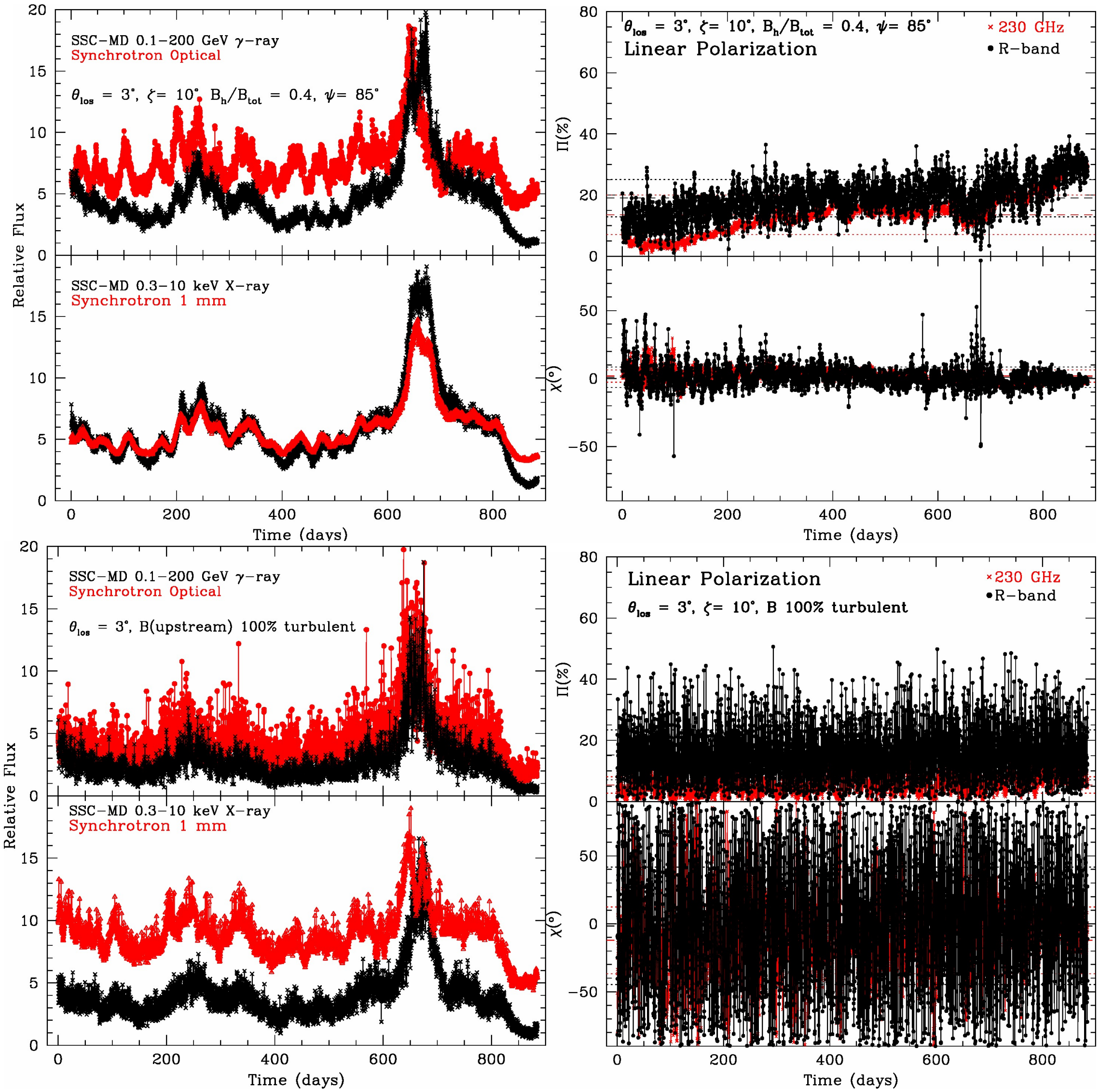
Many (thousands) turbulent cells, each followed after crossing a conical standing shock (= "core" or another ~ stationary feature)

e^-s accelerated by turbulence &/or reconnections upstream of shock, energized further by shock; <u>only some cells have very high E electrons</u>

Sources of seed photons: Mach disk at narrow end of conical shock, dusty torus; will add emission lines & SSC



Sample Simulated Light Curve – Parameters Similar to BL Lac



Upstream B field:

Top – 40% helical, 60% turbulent

Bottom – 100% turbulent

Statistical comparisons of simulated vs. observed flux & polarization curves + cross-wavelength correlations can determine which, if any, sets of parameters resemble actual blazars

Why We Need More Fermi, etc. Data + Theoretical Modeling

Blazars are the most luminous persistent coherent phenomena in the universe!

Presence of apparently random processes → need to characterize statistically
→ Need to observe multiple outbursts & quiescent periods in many sources
→ Important to determine full range of flux variations
→ Fermi both covers 0.1-300 GeV energies + provides continuous time coverage
→ Power spectra of variations & other statistics require long data trains

Identification of systematic behavior requires repetition of patterns
→Which superluminal radio knots are associated with γ-ray flares and why?
→What are differences between γ-ray flares at sub-parsec & parsec scales?

New types of multi-waveband observations

- **Variability of optical emission-line profiles alongside γ-ray flux**
- **Wavelength dependence of optical polarization (predicted by turbulence, not by "jet within jet" magnetic reconnection events)**
- **Event Horizon Telescope including ALMA (2017?) → higher-resolution images with ~ zero opacity**
- **ALMA circular polarization observations**

Need more analysis & theoretical modeling, e.g., multi-zone models
→ fund more theory!

The End

Particle Acceleration in Jets

Shocks: 1st-order Fermi process, shock-drift, or mere compression

• **Issue: particles cannot cross relativistic shock many times**

Turbulence: 2nd-order Fermi Process

- **Indicated by polarization (mean degree + variability)**

- **Expected from current-driven instabilities in jet**

• **Issue: problem generating rapid high-amplitude flares**

Magnetic Reconnection

- **Efficient acceleration of electrons**

- **Might result in extra relativistic motion → extra beaming**

• **Issues: Need high magnetization to be efficient, equipartition in emission zones, data suggest otherwise (Ghisellini & Tavecchio 2015)**

• **Not clear how oppositely directed fields can occur**