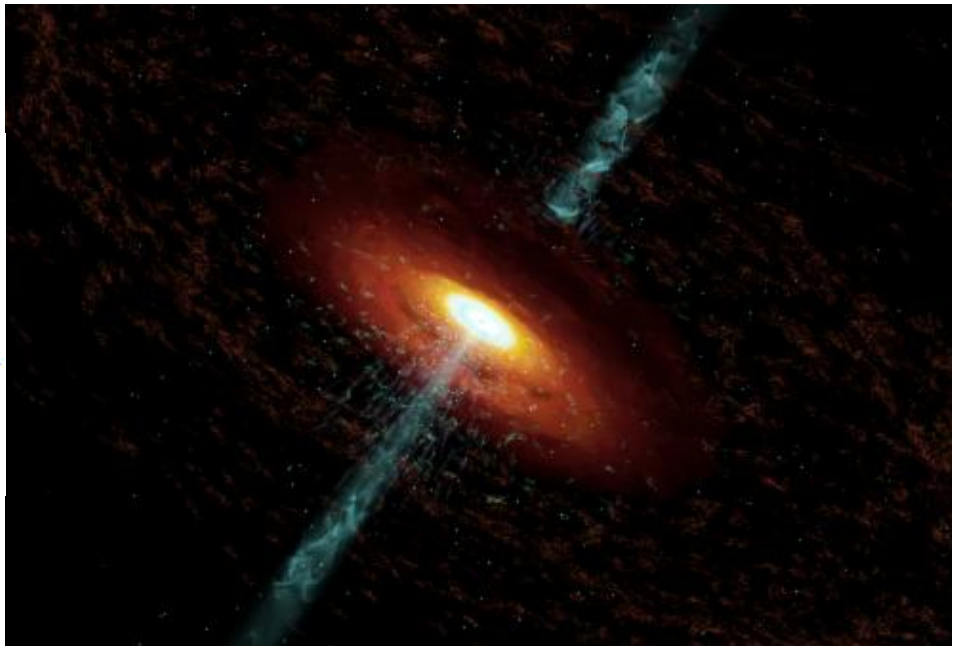


Multi-waveband Behavior of Blazars

Alan Marscher

Institute for Astrophysical Research, Boston University

Research Web Page: www.bu.edu/blazars

Disclaimer

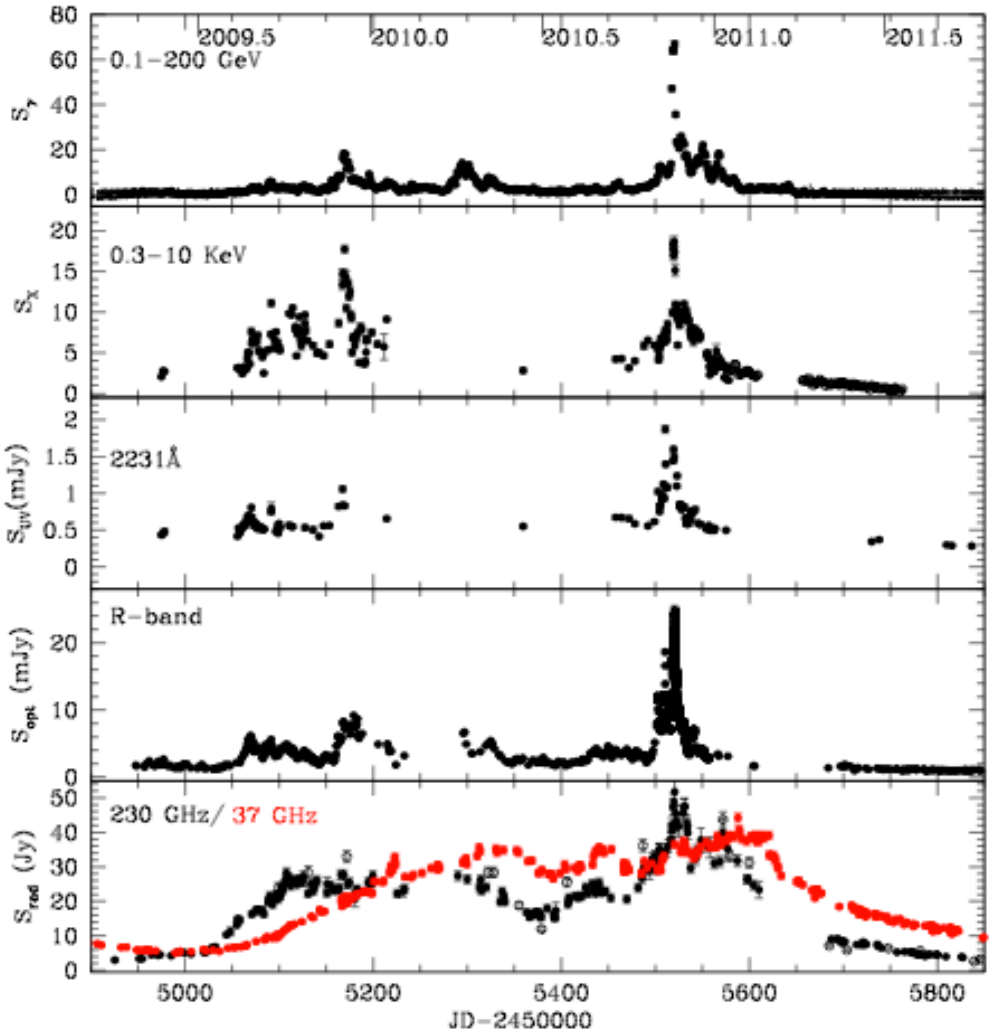
The data and discussion presented here are but a small subset of the huge number of both wonderful and not-so-wonderful multi-waveband studies.

Topics are selected to minimize overlap with other talks & posters at this meeting

The author apologizes to the many people whose wonderful studies are not mentioned here, and to those whose data are shown but to whom proper credit is not given.

The author is not to be held legally liable for any representations, misrepresentations, omissions, or emissions during this presentation.

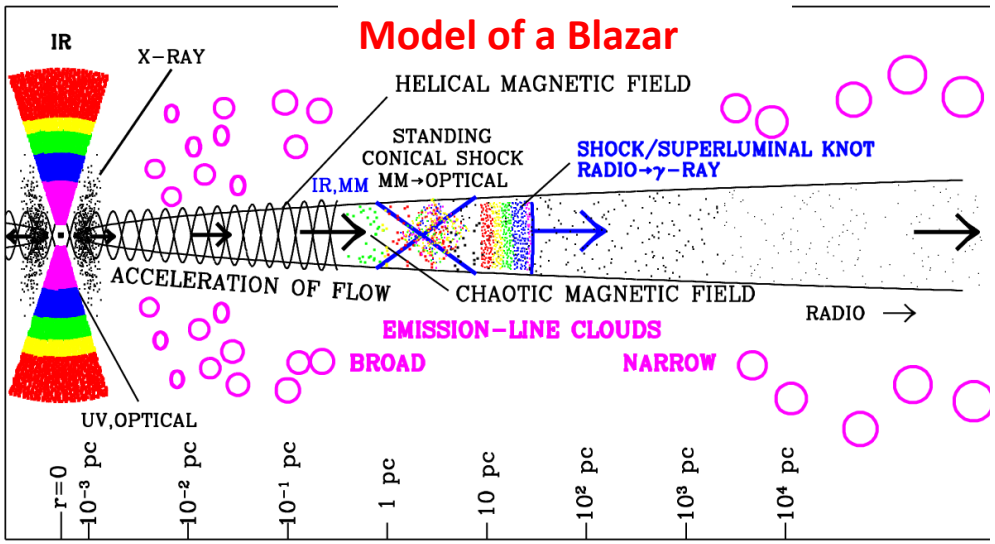
The Great Hope of Multi-waveband Variability Studies



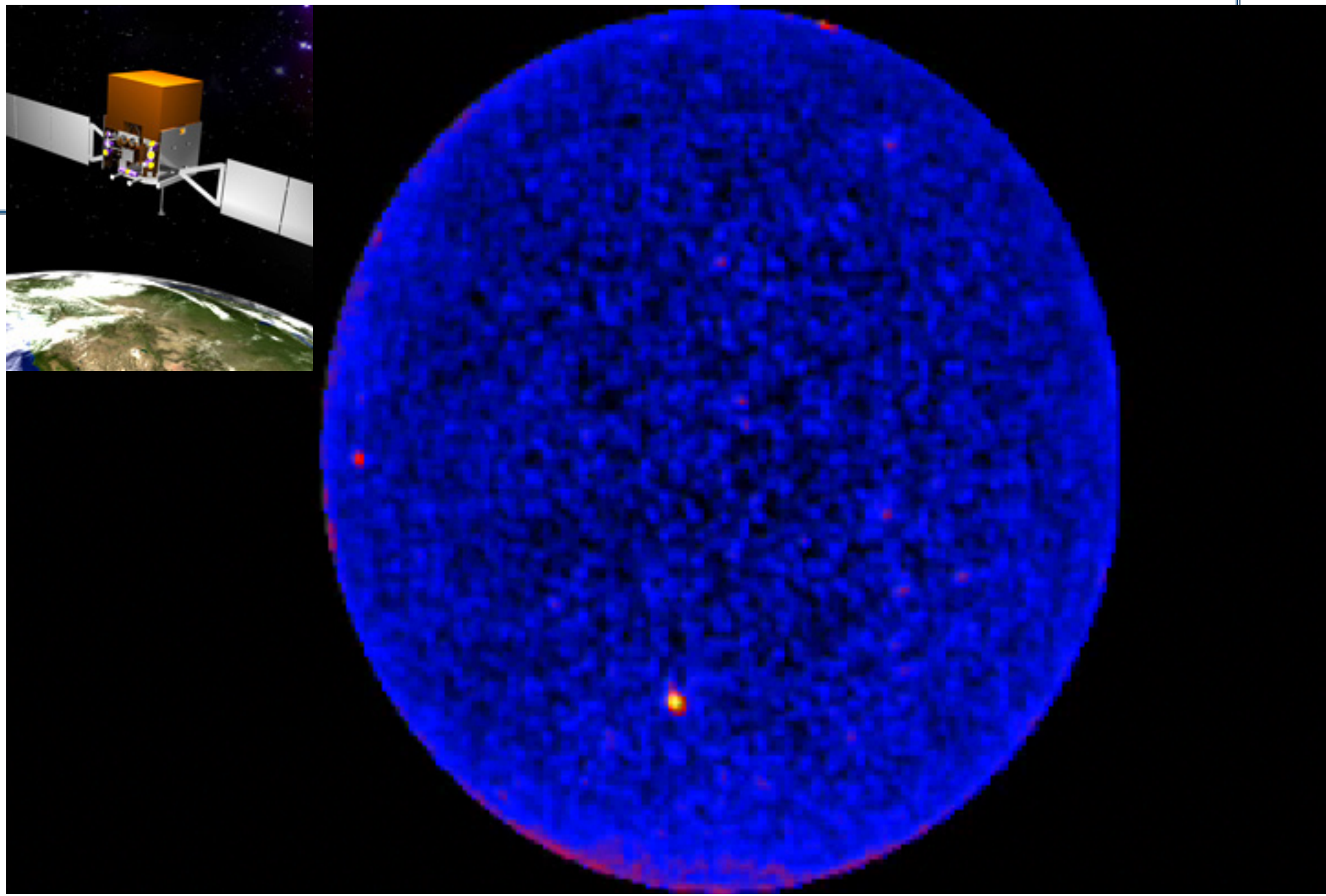
3C 454.3, from Jorstad et al. (ApJ, submitted)

Use details of variations & SEDs to probe structure & physics of jets close to the central engine (cf. our working model)

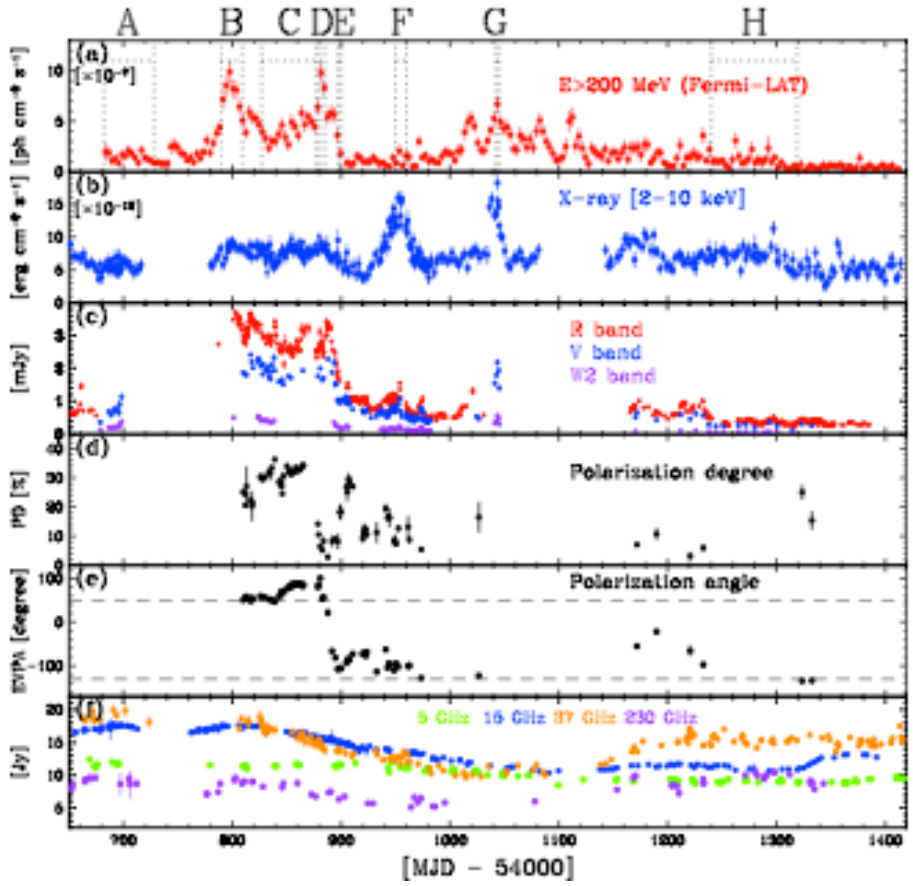
- Injection, acceleration, collimation of jet
- Energization of relativistic particles
- Dynamics of flow (shocks, stability, etc.)
- Which frequencies participate in flares?
- Cross-frequency correlations
- Cross-frequency time delays/simultaneity

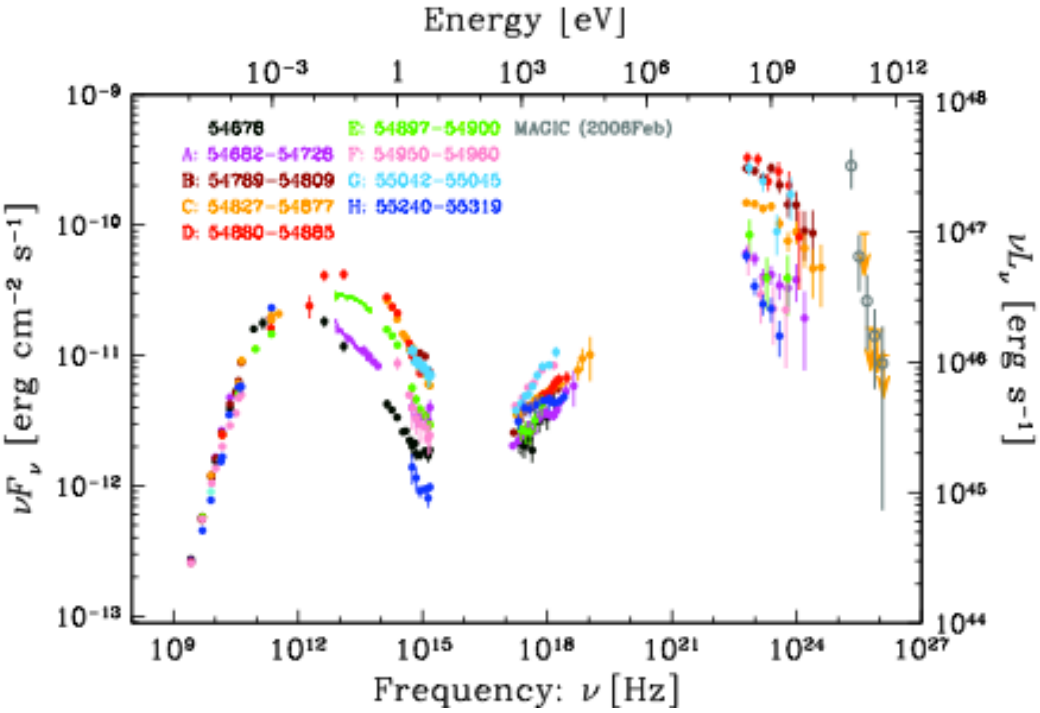


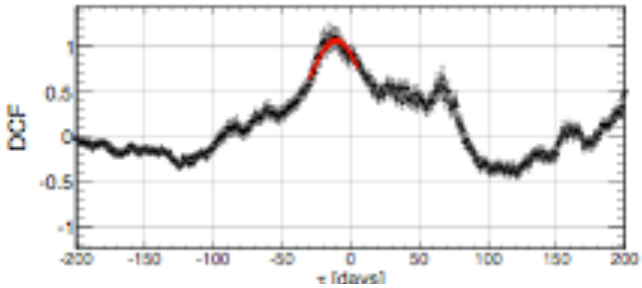
Fermi Light Curves: γ-ray Flux for Every Blazar Every 3 Hours



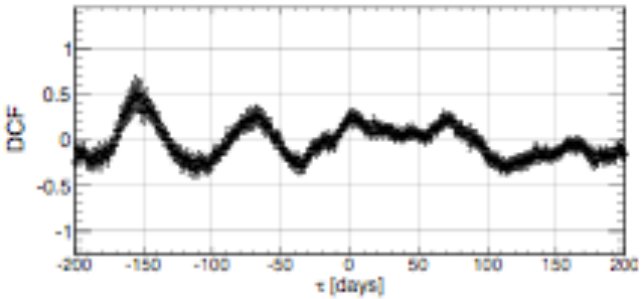
Example of Complexity: 3C 279 (Hayashida et al. 2012, ApJ)







Top: Gamma-optical DCF, <0 means gamma leads



Bottom: gamma/X-ray DCF

Correlations:
- Complex or very weak
- Time delays vary

SEDs:
- Double hump (synchrotron, IC)
- Gamma-ray flux can be ~ 2 orders of magnitude higher than X-ray

More Comprehensive Approach: Add VLBI Imaging

-We can use sequences of VLBA images to relate multi-waveband variations with physical structures in the jet
- Comes with polarization maps to compare with optical pol.

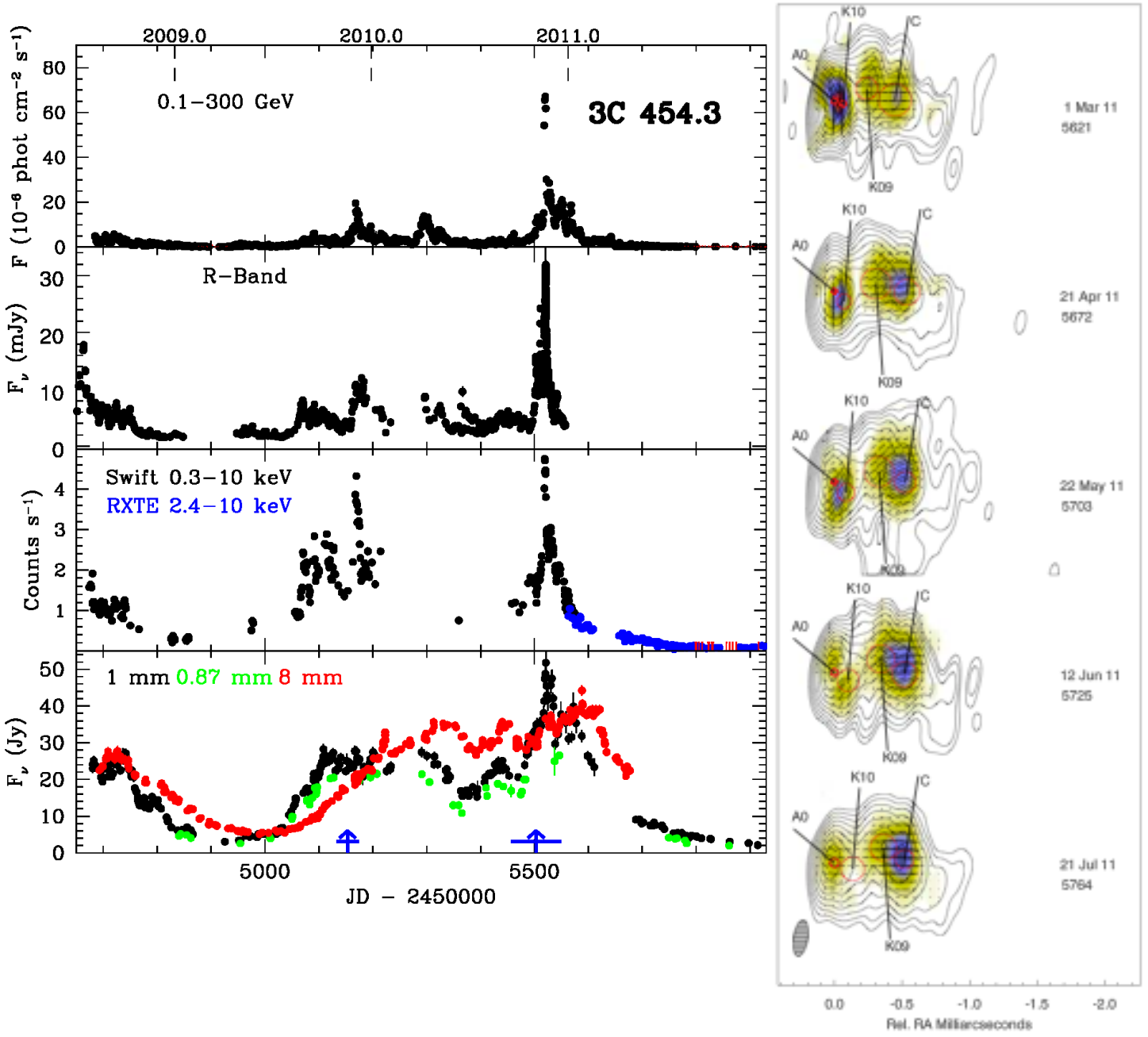
- Unfortunately, the NSF plans to "divest" the VLBA after this year, i.e., close it down & dismantle the antennas, unless non-NSF funds can be found for its operations (~ $5M/year)

- Also, Fermi is under serious financial stress, with a large cut in operations & guest investigator funds next year

- NASA has already shut down RXTE & U. Michigan has shut down UMRAO while they were still working well

→ We need to make an even stronger case for jet studies!

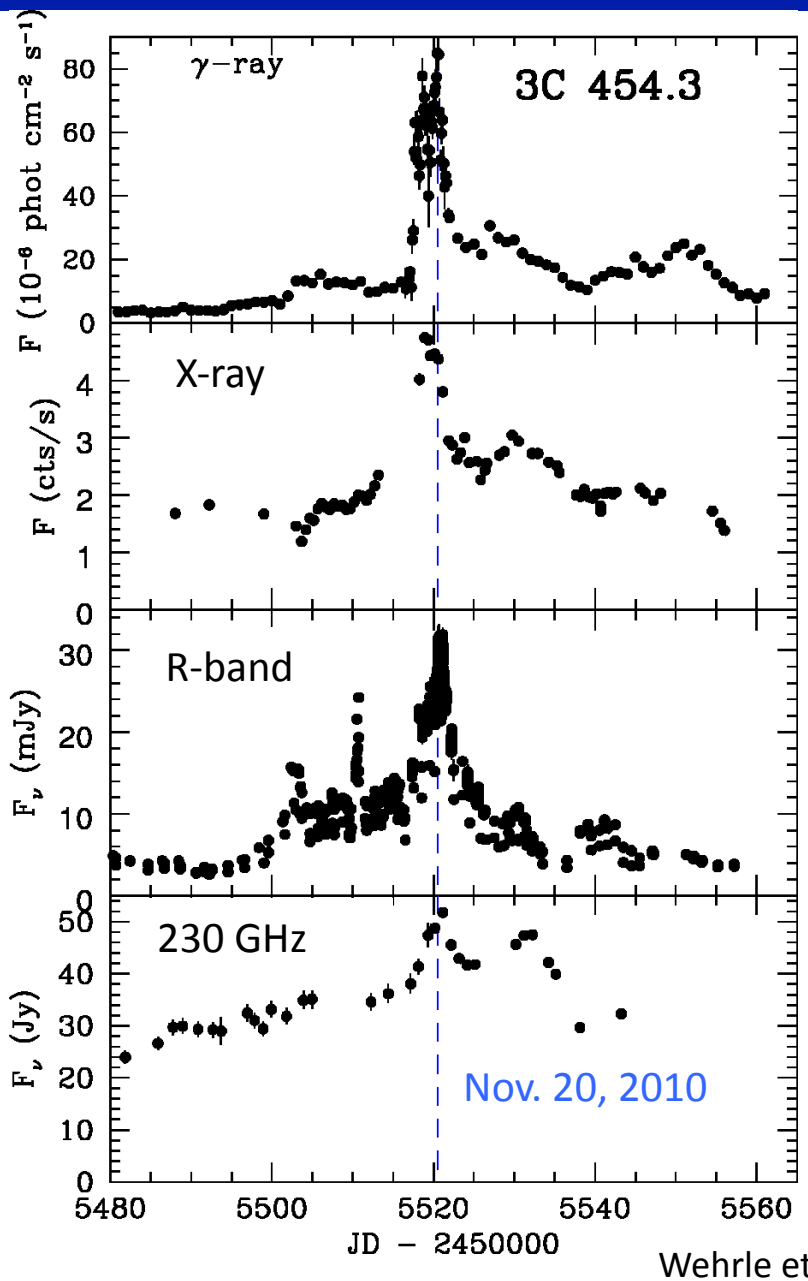
The VLBA Images Gamma-ray Emitting Region



8 mm outbursts start before gamma-ray flares (Lähteenmäki & Valtaoja 2003, León-Tavares et al. 2011)

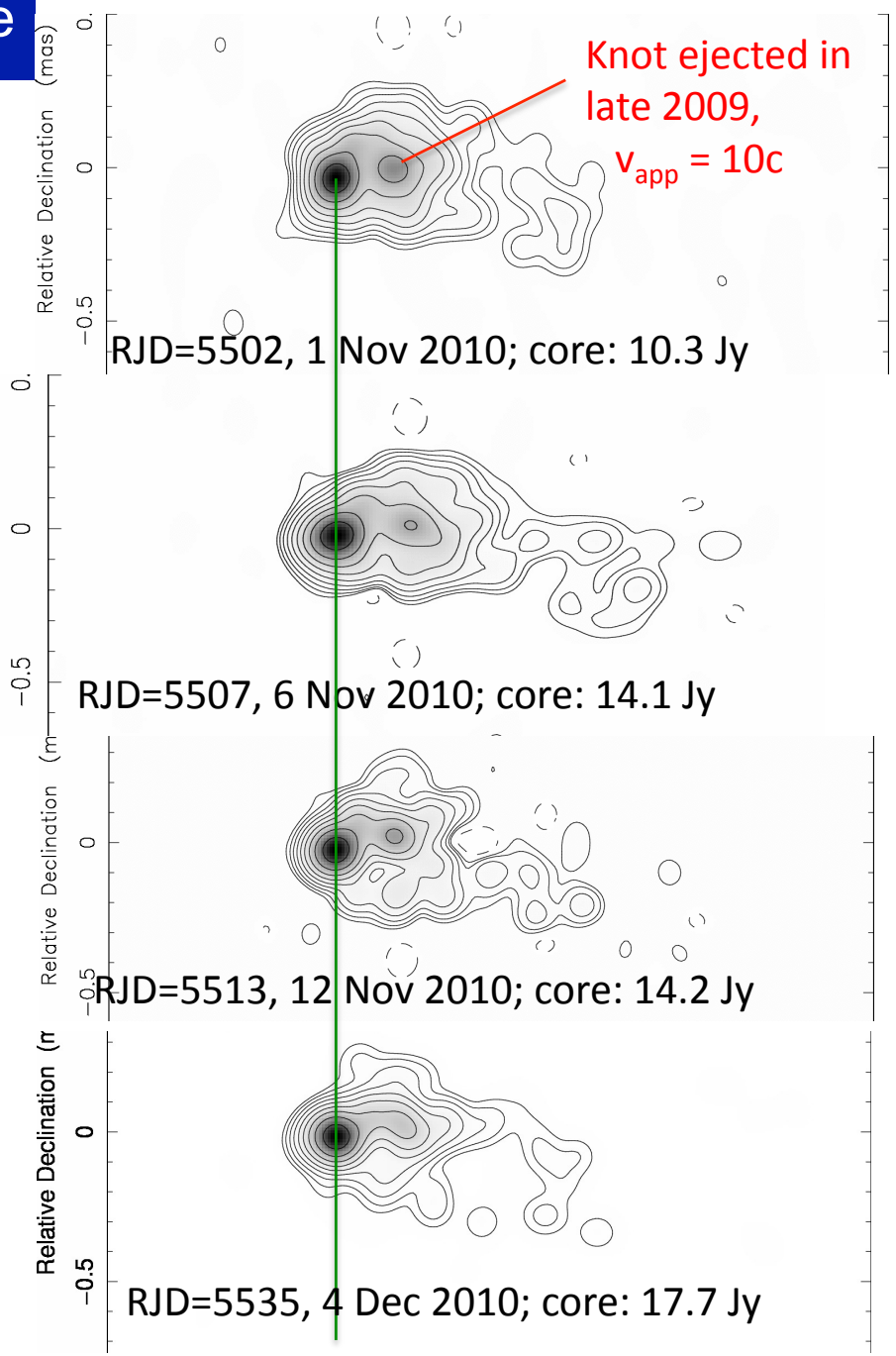
Events in VLBI core at 43 GHz occur before/during gamma-ray flares (Jorstad et al. 2001)

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



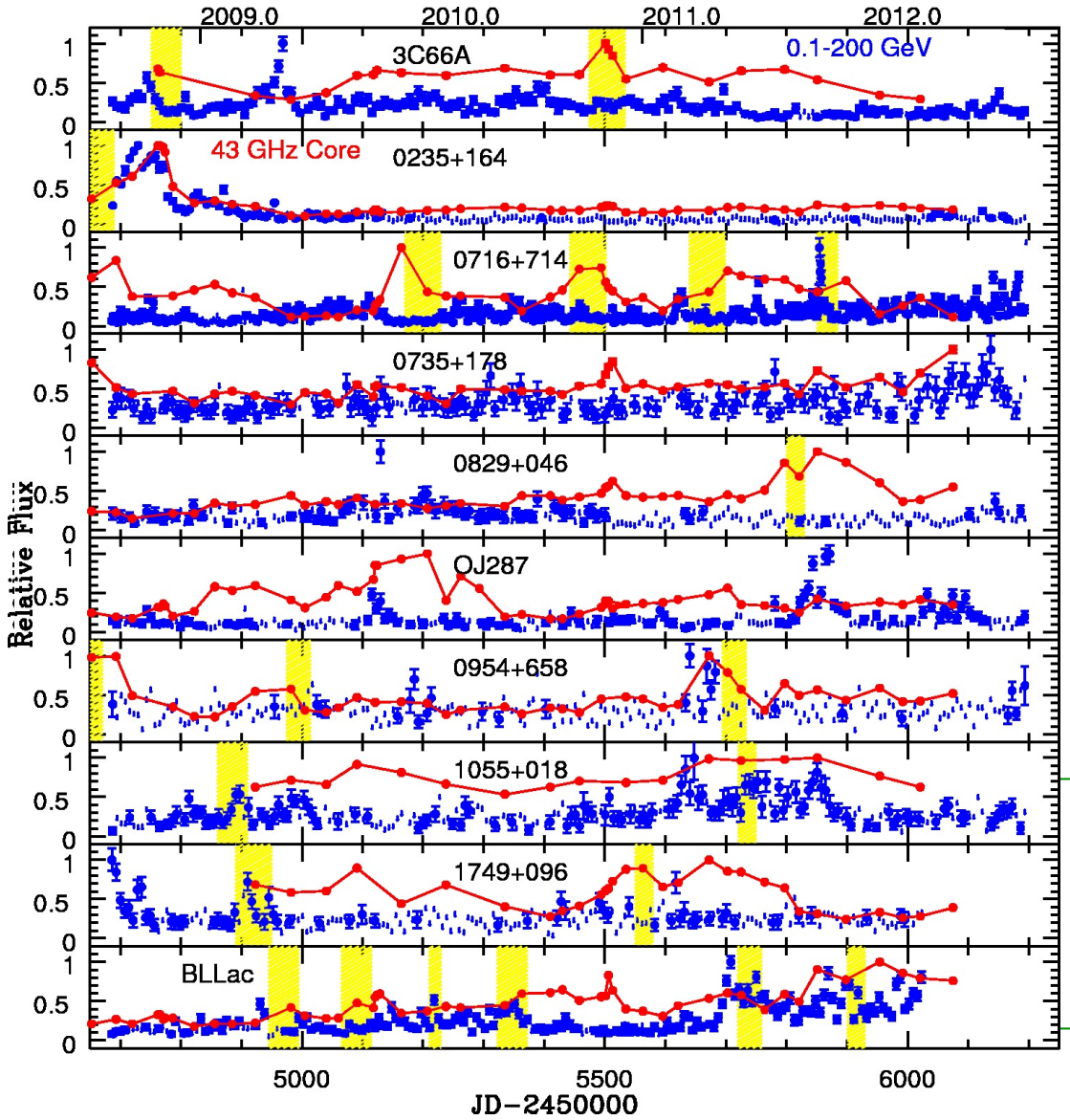
Wehrle et al. (2012 ApJ)

VLBA images at 7 mm wavelength



Behavior of Jet during γ-ray Flares in 34 Blazars over 4 Years

Blue: γ-ray flux **Red: mm-wave "core" flux** Yellow shading: new superluminal knot "ejected"



→ Of 62 γ-ray flares, 48 (77%) are simultaneous (within uncertainties) with a new superluminal knot or a major outburst in the core at 7 mm

(Both jet + gamma-ray emission are quiescent over 4 years in 5 sources & 86% of all sources have contemporaneous γ-ray & mm-wave quiescent periods)

→ Even accounting for chance coincidences, > 50% of γ-ray flares occur in the "core" seen in 7 mm images, parsecs from the black hole

← γ-ray light curves (blue), "core" light curve at 7 mm (red), & times of new superluminal knots (yellow) for 30 of the blazars in the sample

Marscher et al. 2012, Fermi & Jansky proc.

Location of Flares

Fermi + VLBA results: gamma-ray flares occur mostly on parsec scales, in mm-wave core or downstream

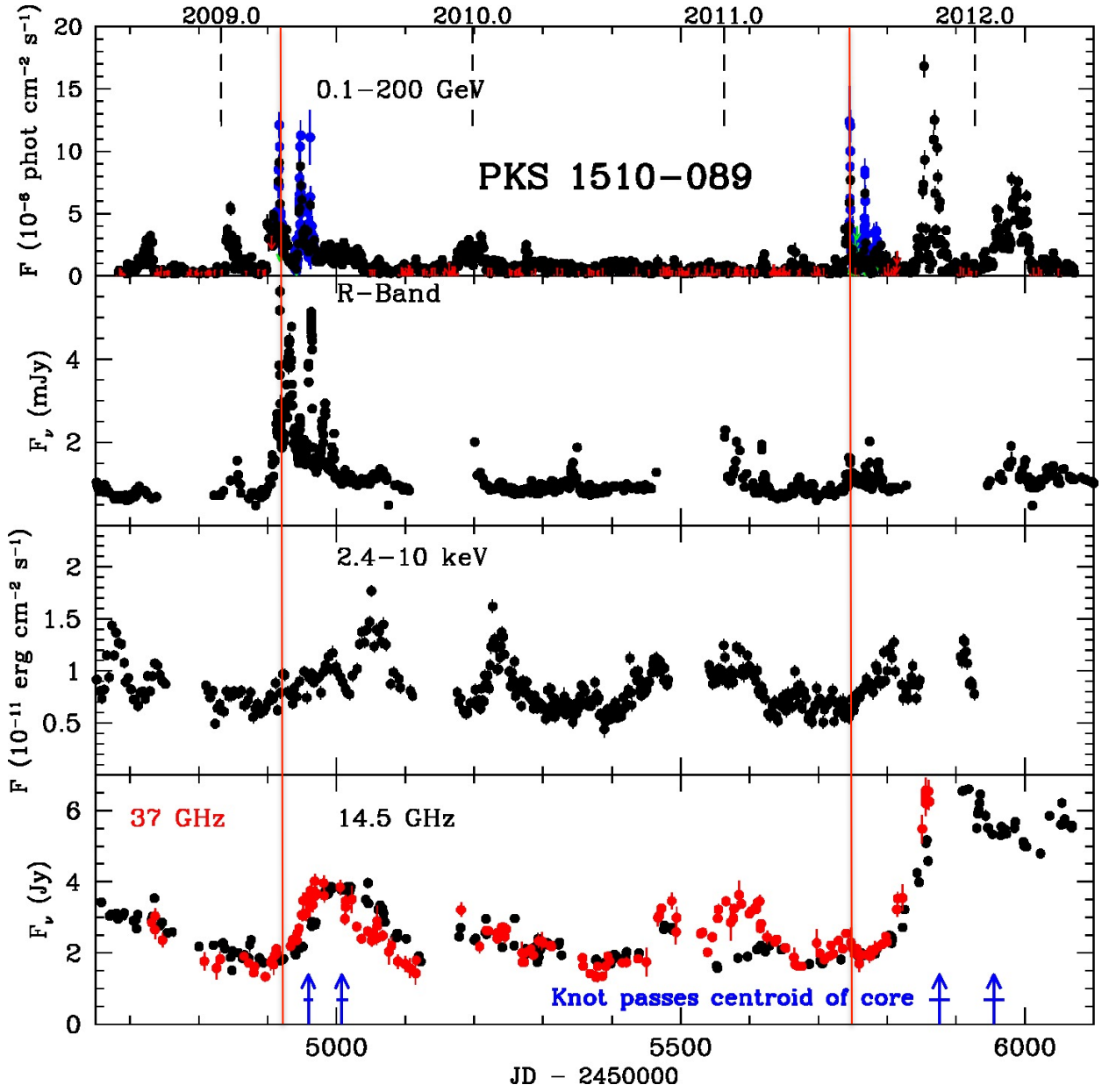
→ So do most optical flares, since gamma-ray/optical correlation is generally strong with ~ zero time delay

- Emission site outside BLR allows 10-500 GeV photons observed in some blazars to escape without pair producing off broad-line photons (e.g., 1222+216: Aleksic et al. 2011; PKS1424-418: Tavecchio et al. 2013)

- Are HBLs & IBLs like Mkn421, whose pc-scales jets are usually rather quiet, exceptions? → See talks by J. Richards, R. Lico, & K. Niinuma later in the week

Do any flares in quasars or LBLs occur between core & central engine?

PKS 1510-089



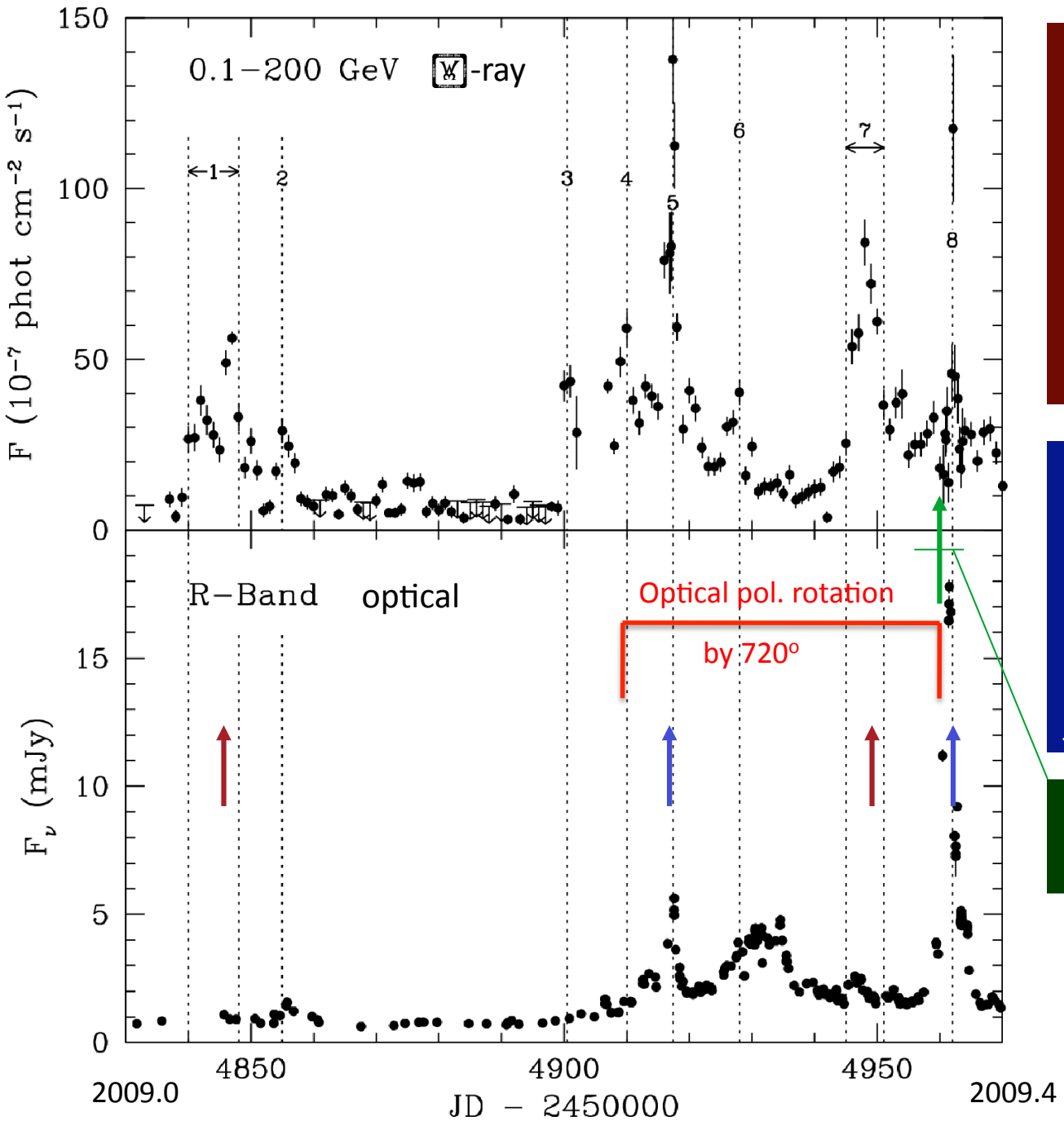
Two episodes of multi-flare outbursts

Nalewajko et al. (2012, ApJ): different location for different flares within each episode

Interesting note: emission at 14. 5 GHz already participates in outburst during first main gamma-ray flare

Both episodes included rotations of optical polarization vector

Quasar PKS 1510-089: first 140 days of 2009



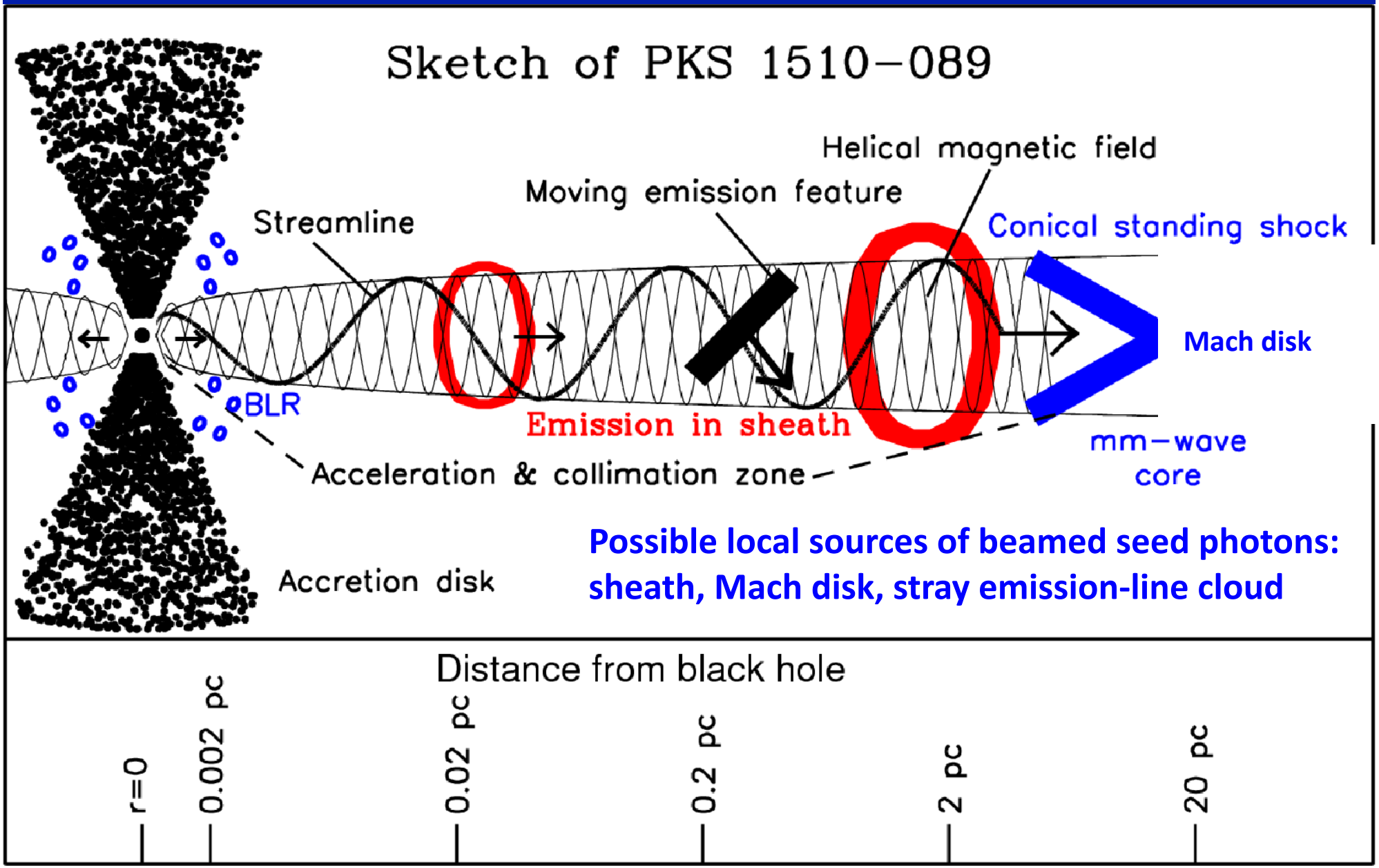
High gamma-ray to synchrotron luminosity ratio: knot passes local source (or variable source) of seed photons that get scattered to gamma-ray energies?

Lower ratio: gamma-rays could come mainly from inverse Compton scattering of synchrotron photons produced in same region of jet

Superluminal knot passes "core"

Marscher et al. (2010, Astrophysical Journal Letters, 710, L126)

Sites of γ-ray Flares in PKS 1510-089 (Marscher et al. 2010 ApJL)

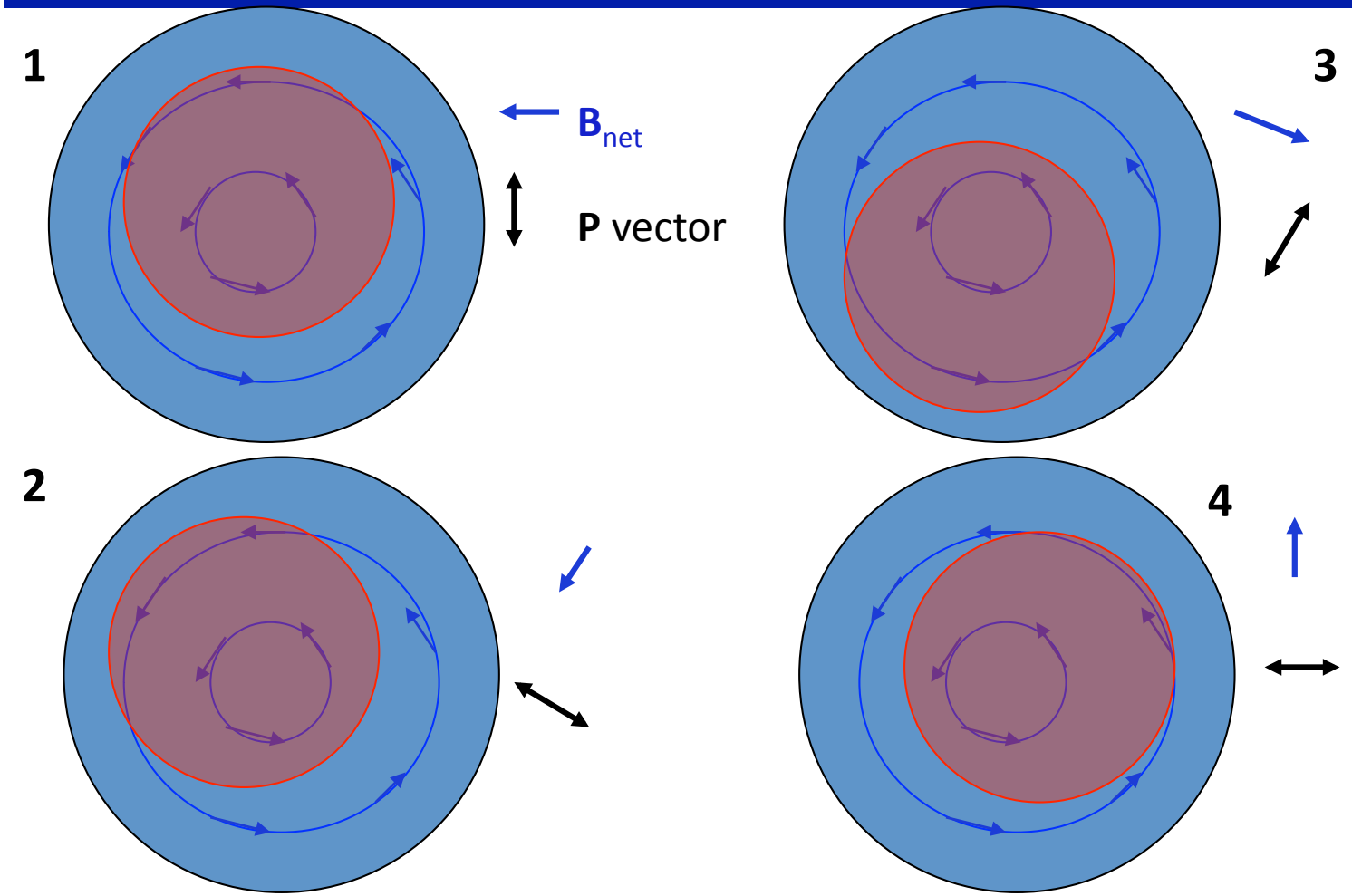


Emission feature following spiral path down jet

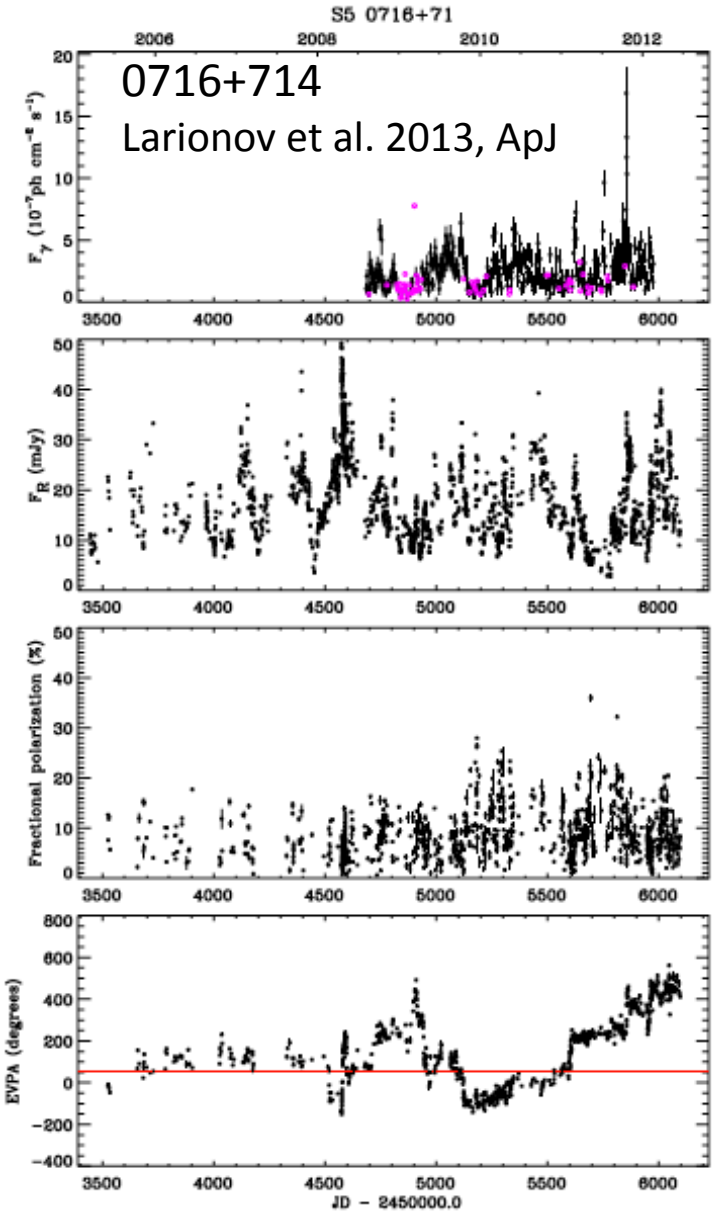
Feature (slow magnetosonic shock?) covers much of jet cross-section, but not all

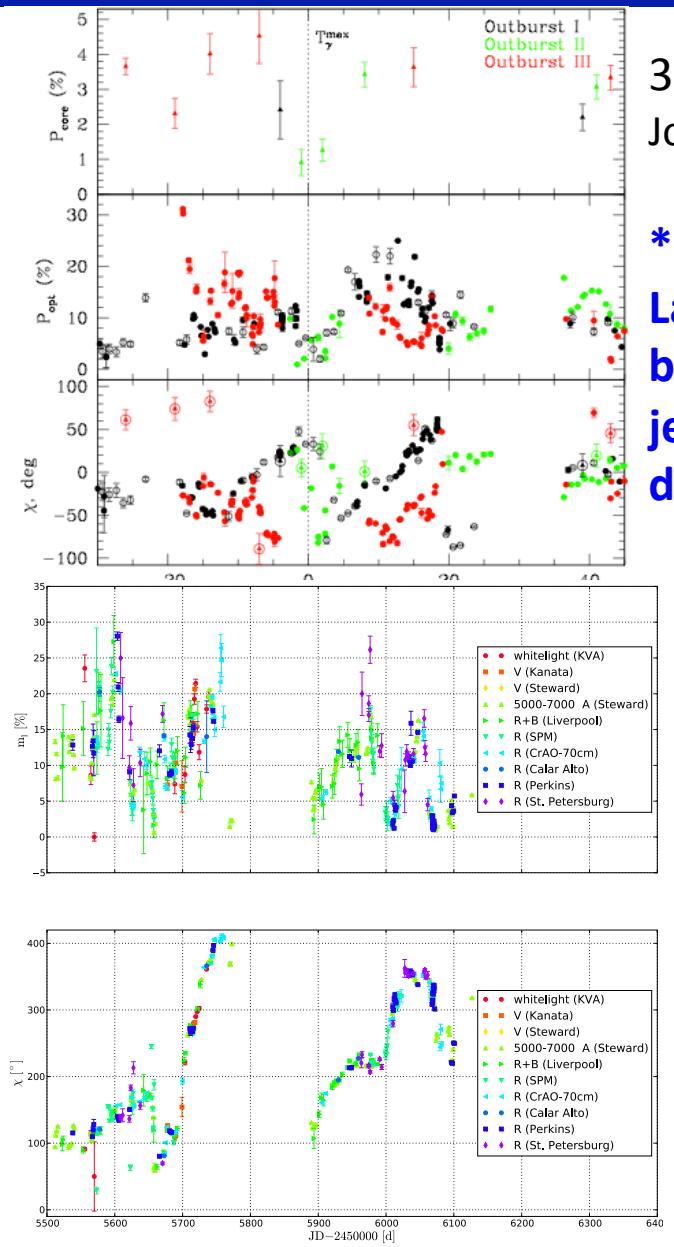
Centroid is off-center

Net **B** rotates as feature moves down jet, **P** perpendicular to **B**



Rotations of Polarization Vector Are Common
Can be helical magnetic field, twisted jet*, or random walk of turbulence





3C 454.3

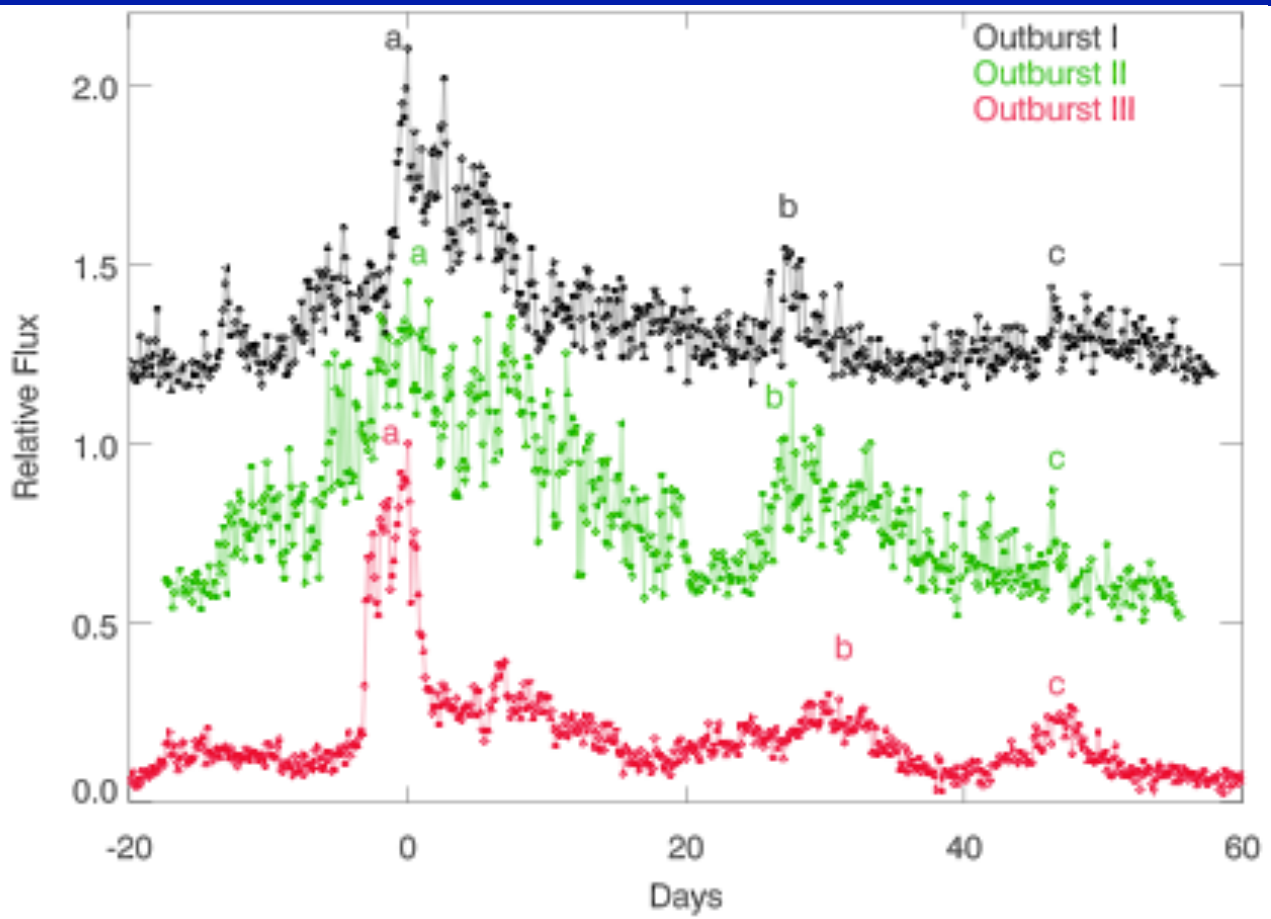
Jorstad et al. 2013, ApJ, subm.

***Raiteri et al. (2011) & Larionov et al. (2013) relate bent trajectory of twisted jet to flux variations in different blazars**

3C 279

Kiehlmann et al., in prep

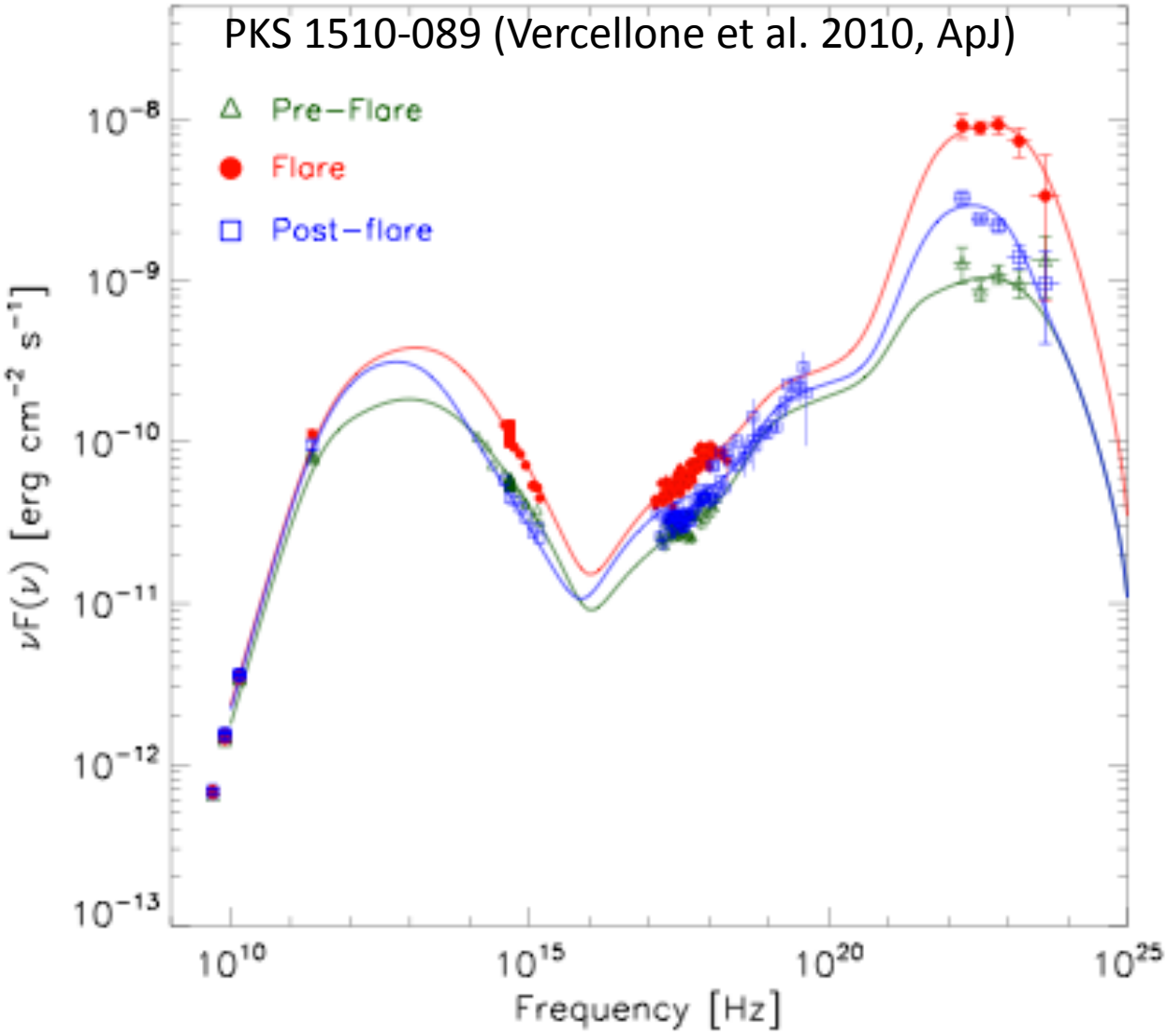
Repeated pattern in 3C 454.3 (Jorstad et al., ApJ, submitted)



Seems to be related to physical structures in the jet, within and near the mm-wave "core", whose "super-resolved" 43 GHz images contain a triple structure
(Jorstad et al. 2010, ApJ)

→ As we build a longer data train with Fermi & other time-domain telescopes, we can look for other repeated patterns that reveal physical structure of the jet

Spectral Energy Distributions (SEDs)



All authors of observational papers on multi-waveband variability hire a theorist to produce a model SED, usually single or 2 zones, to compare with data, usually single or 2-3 epochs

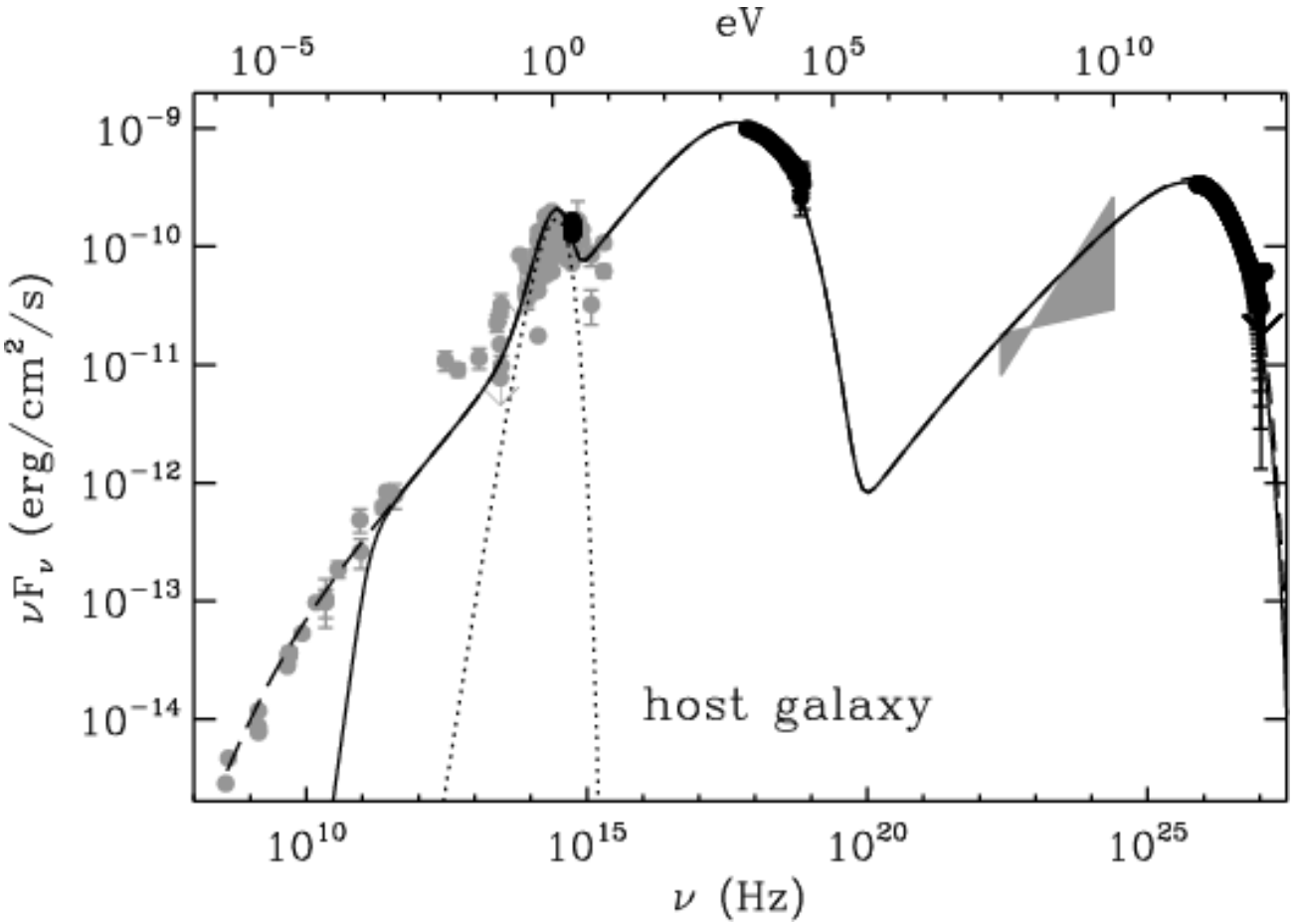
→Pretty useless **unless a model can't reproduce the SED**

Note in SED to left that
$L_\gamma \sim 100\ L_x$
→Very challenging for an SSC model

But usual conclusion is that outburst occurs inside BLR, not supported by observations
→ Thermal seed photons from torus or stray cloud near jet?

SED of an HBL/TeV Emitter

Mkn 421 (Giebels et al. 2007, A&A)



Consistent with synchrotron emission extending through X-rays, SSC in gamma-rays

Higher level of variability in these spectral regions than at radio frequencies

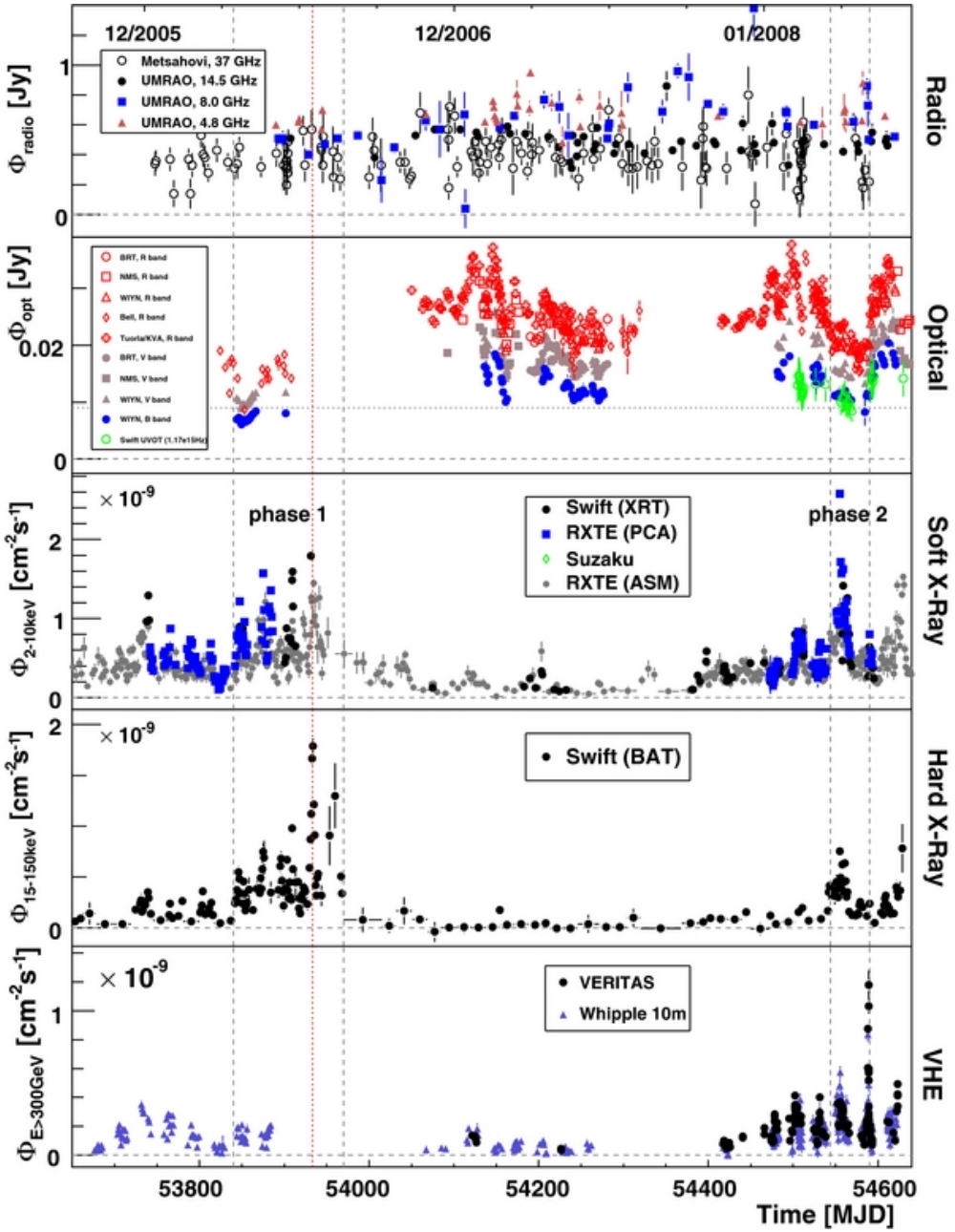
Intimate Relationship between X-ray and TeV Emission

- Radio-intermediate BL Lac objects

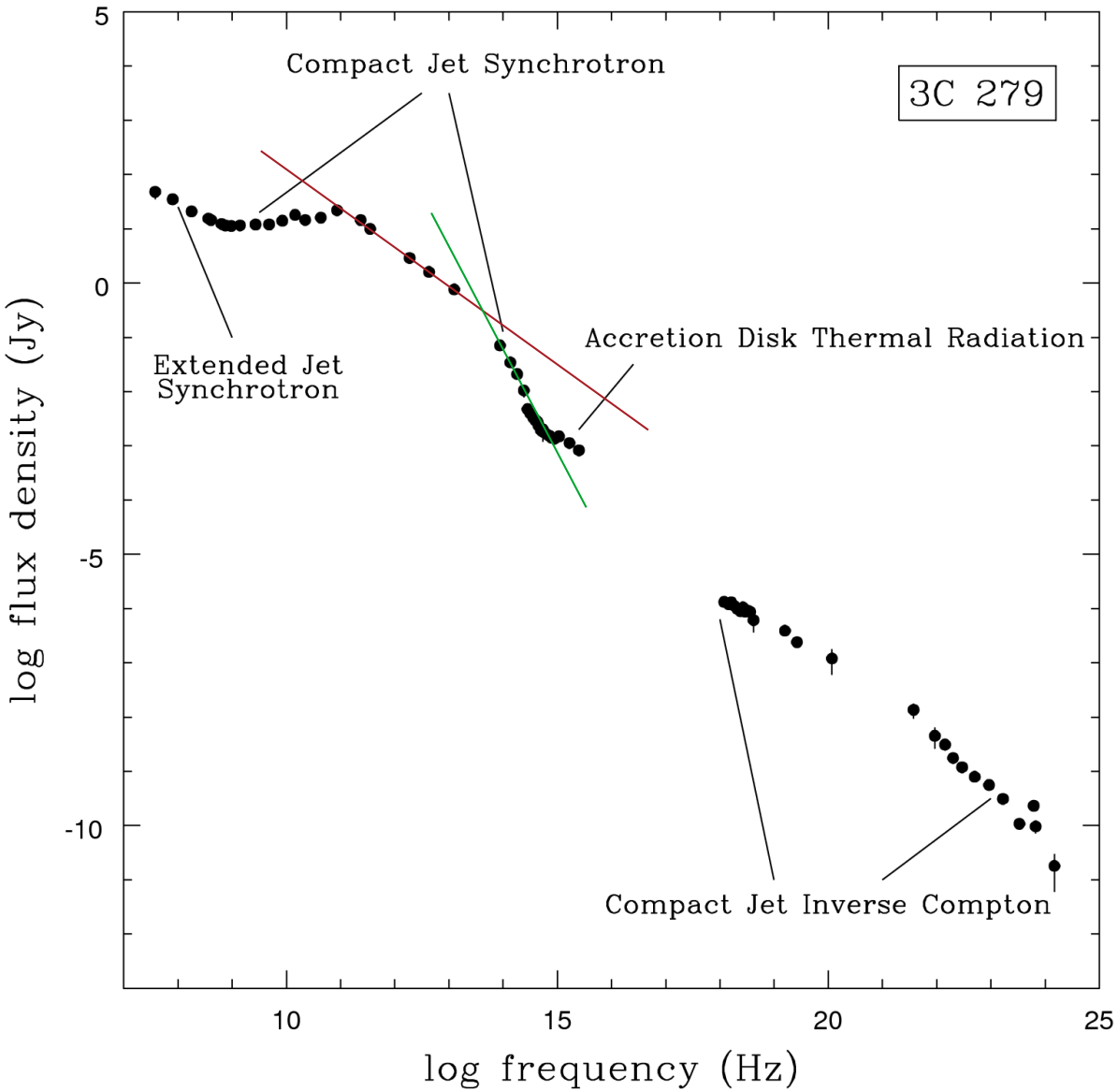
Mkn421 light curves →
(Acciari et al. 2011 ApJ, **738**, 25)

Typical TeV-emitting BL Lac object X-ray emission consistent with synchrotron radiation by ~TeV electrons

Usually – but not always – TeV variations are essentially simultaneous with X-ray variations



Break in Synchrotron Spectrum

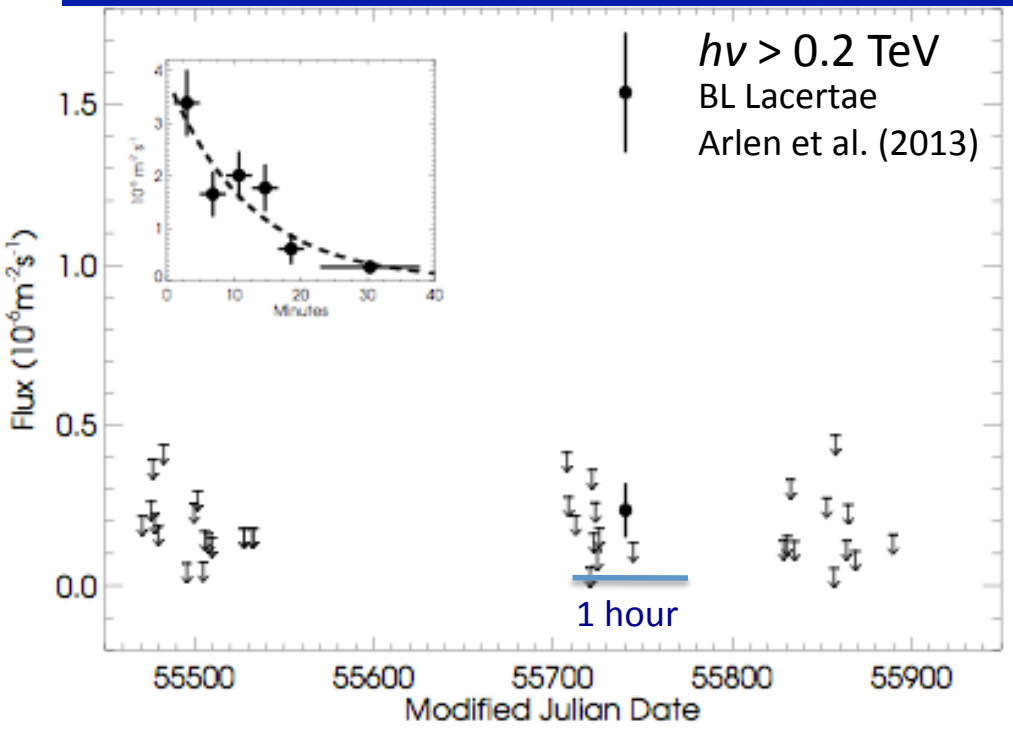


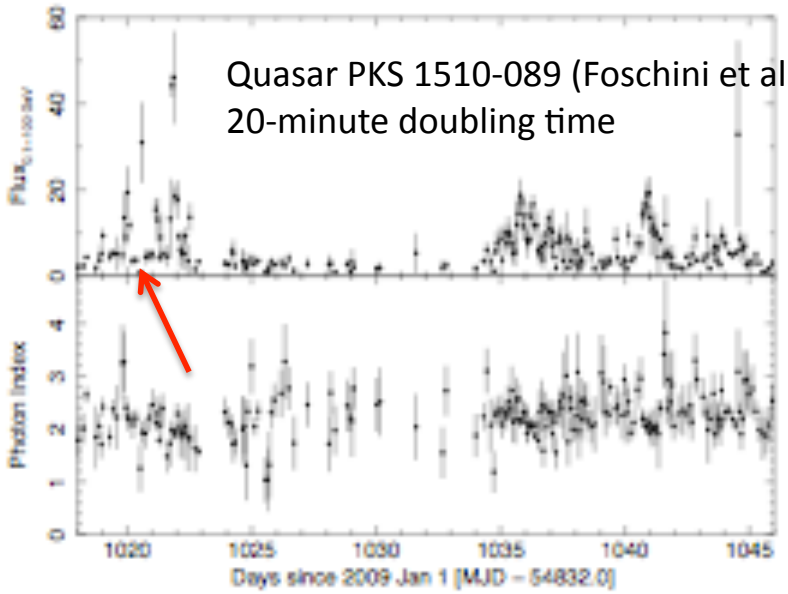
SED can be roughly described by broken power law

-break often by more or less than 1/2 expected from radiative losses

→ Volume filling factor decreases at higher electron energies/ higher frequencies

Problem: Intra-day Variability on Parsec Scales





Changes in flux are observed to occur on time-scales t_{var} as short as minutes

How can this occur parsecs from the black hole?

Size of region needs to smaller than ct_{var} $[\delta/(1+z)] \sim 2\times10^{14}\ t_{var,hr}\ \delta$ cm,

where z is the redshift of the host galaxy and δ is the Doppler factor (blueshift) from relativistic motion of plasma

Superluminal motion implies $\delta \sim 20 - 50$

+ Jet is very narrow (**$\sim 0.1/\Gamma_{flow}$** ; Jorstad et al. 2005, Clausen-Brown et al. 2013) so jet width 1 pc from black hole $\sim 10^{17}$ cm

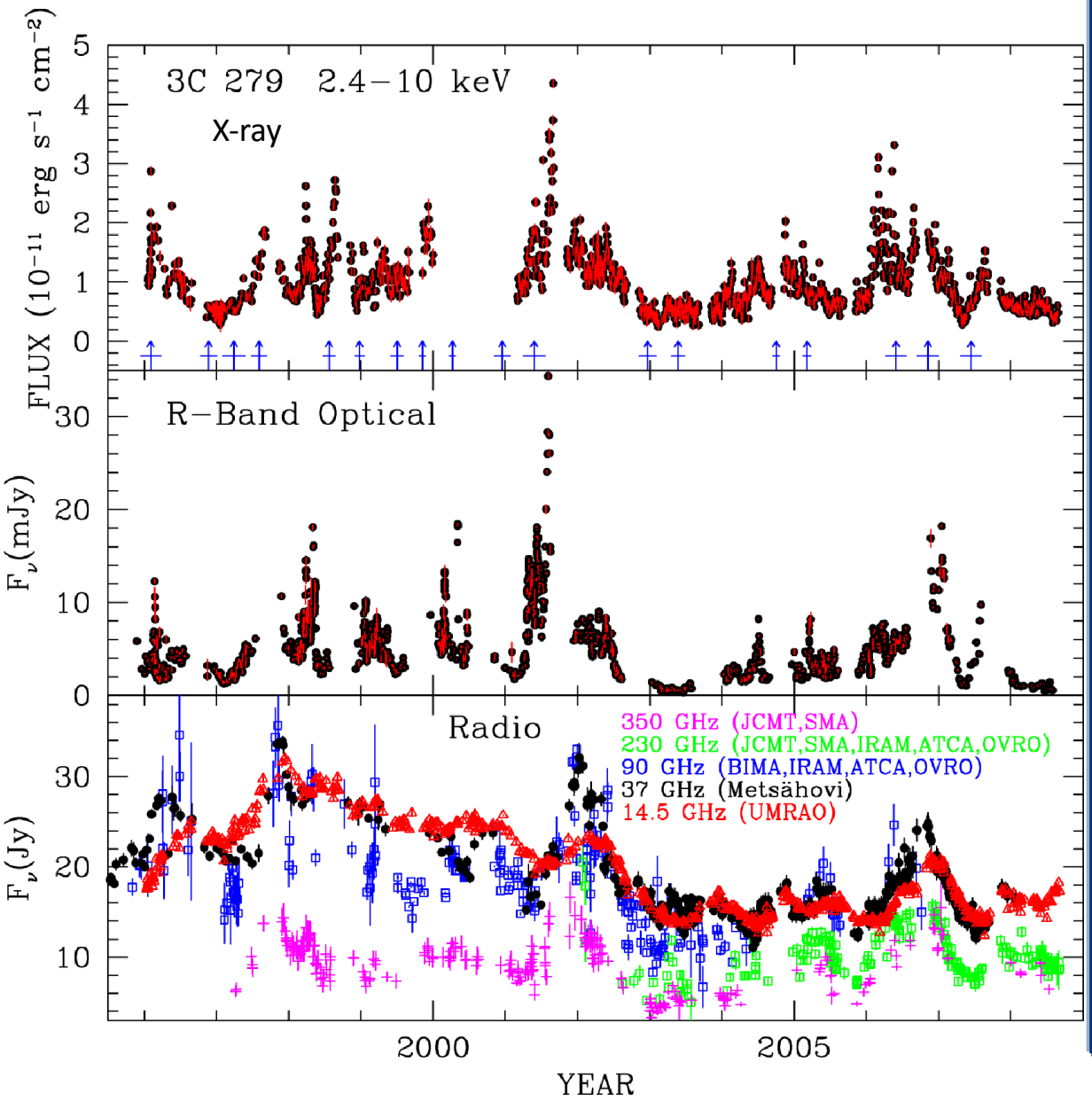
+ Only some fraction of jet x-section is bright at any given time

→Magnetic reconnection jet-in-jet model (Giannios 2013, MNRAS), or turbulence (Narayan & Piran 2012, MNRAS; Marscher 2012, Fermi and Jansky proc.)

The Case for Turbulence as a Major Factor in Blazar Jets

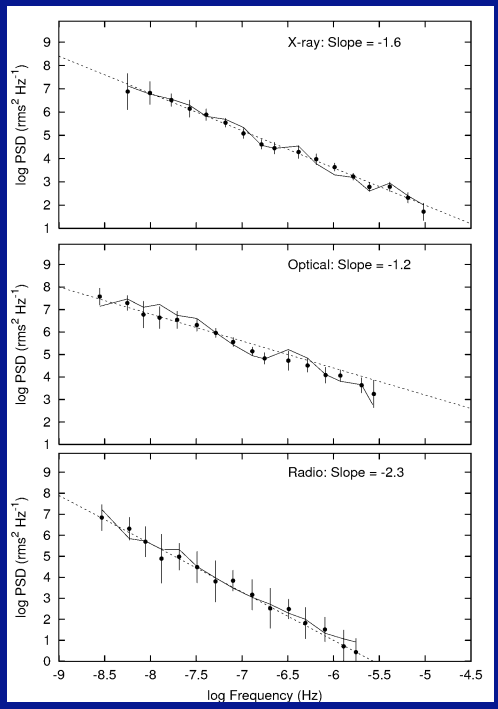
Possible source of turbulence: current-driven instabilities at end of acceleration/collimation zone (e.g., Nalewajko & Begelman 2012, MNRAS)

Blazars: Power-law PSDs → Noise process



- Rapidly changing brightness across the electromagnetic spectrum

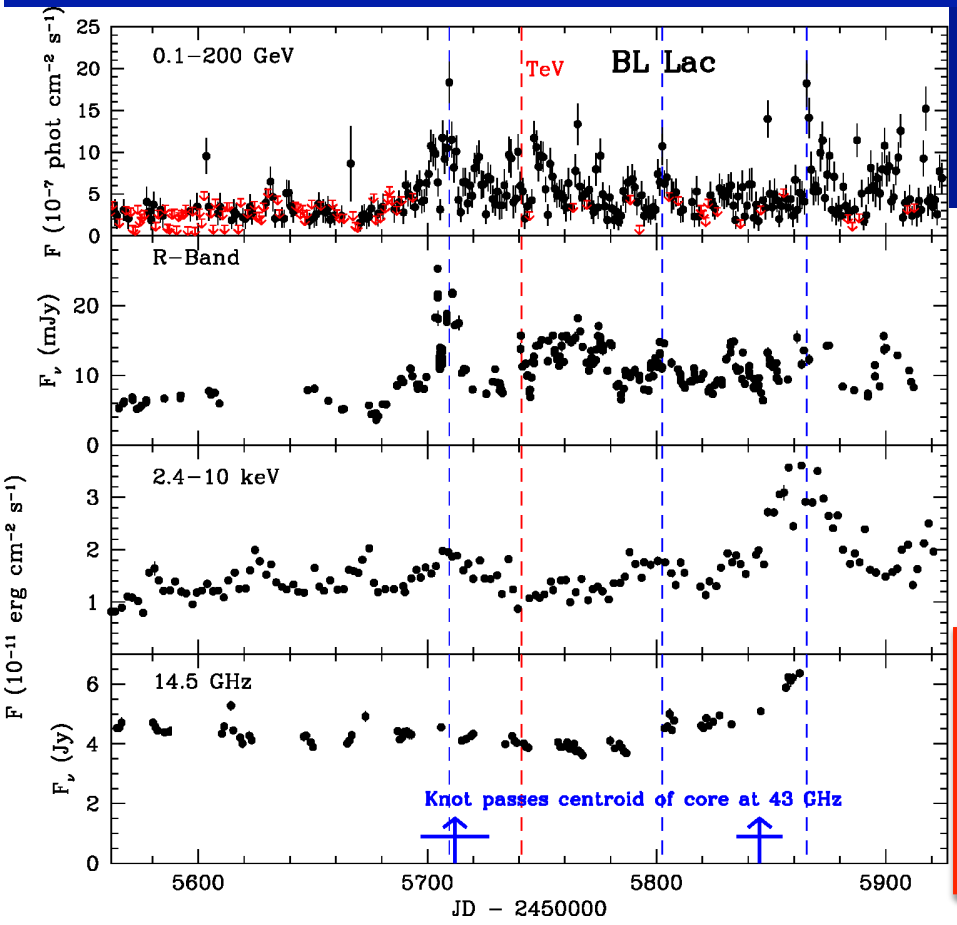
-Power spectrum of flux changes follows a power law → random fluctuations dominate

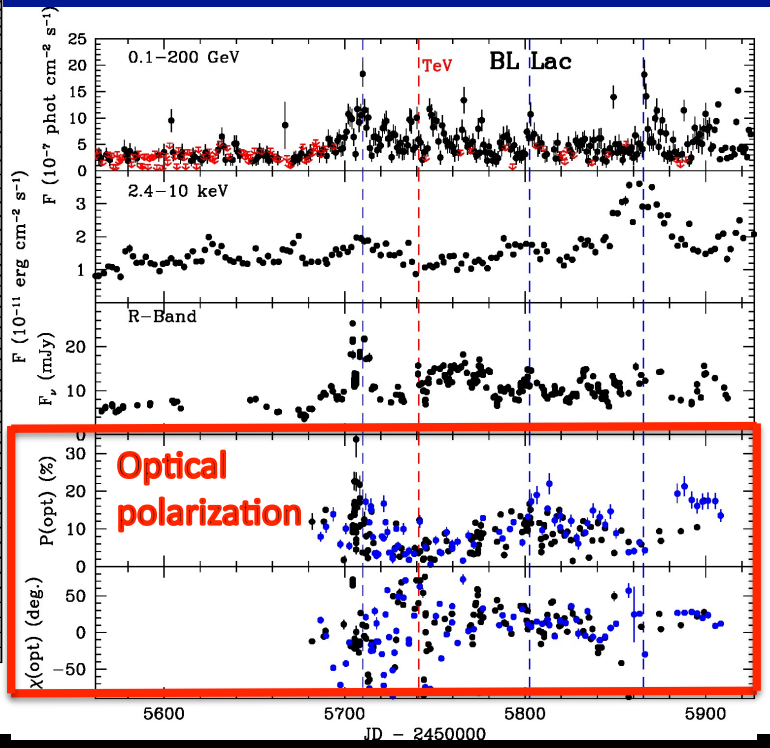


Chatterjee et al. 2008 ApJ

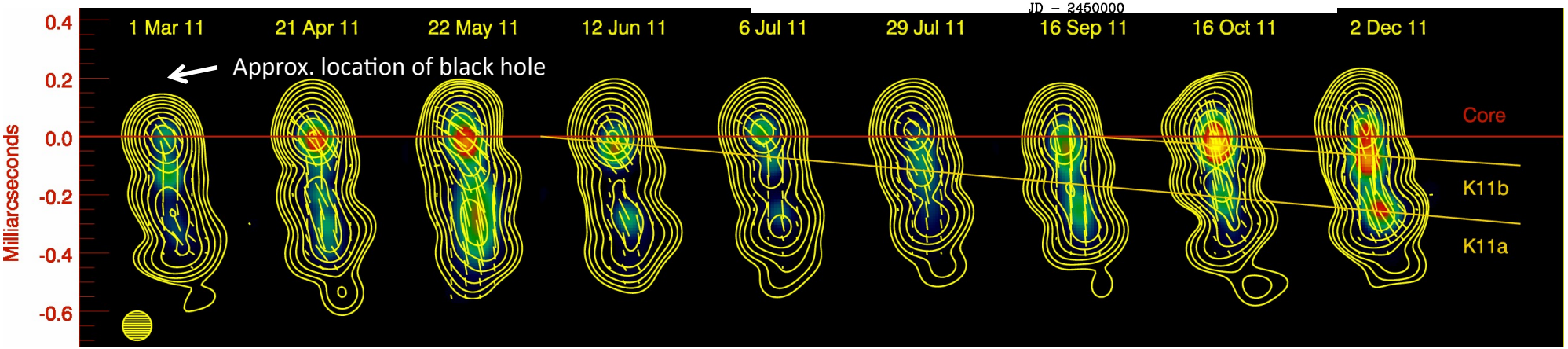
Blazar BL Lacertae in 2011

γ-rays become bright as new superluminal knots pass through "core" & through other stationary emission features on the VLBA image





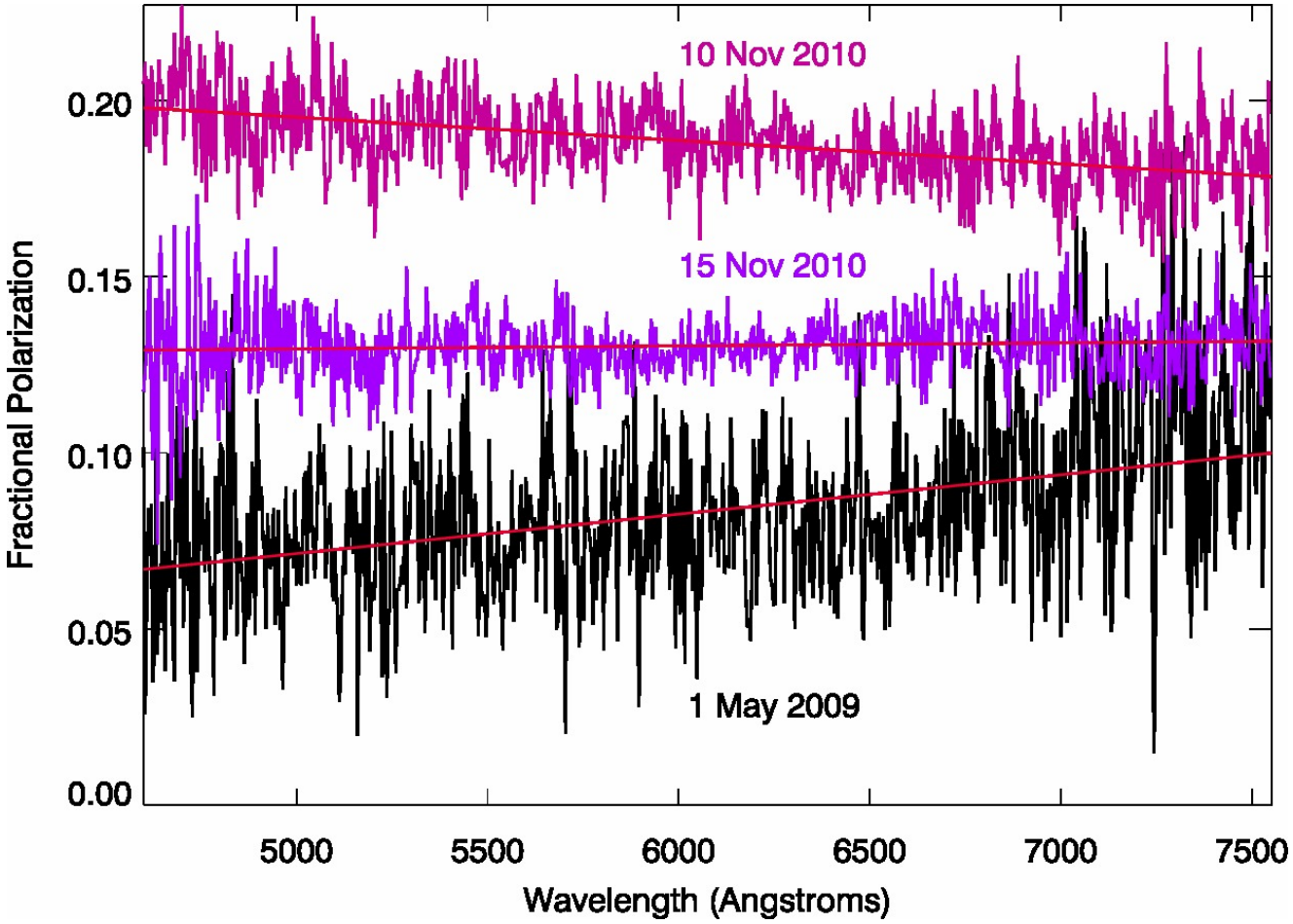
Degree of linear polarization & variations in degree & position angle suggest turbulence at work



Polarization Decreases with Wavelength

3C 454.3 during brightest state (Jorstad et al. 2013)

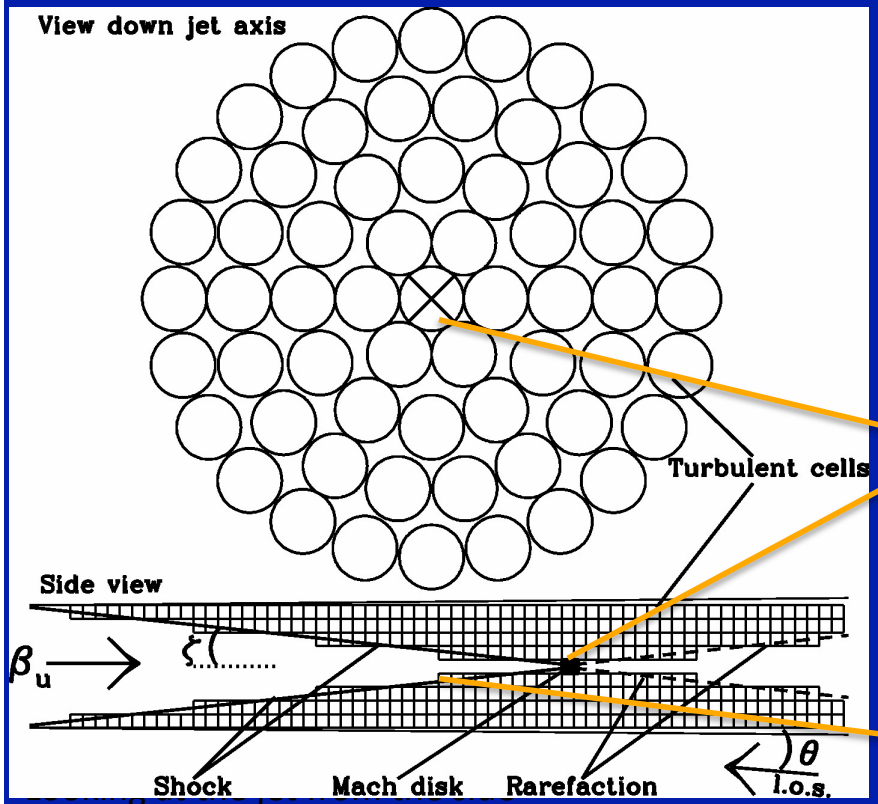
- Expected if fewer turbulent cells are involved in emission at shorter wavelengths



Turbulent Extreme Multi-zone (TEMZ) Model (Marscher 2012)

Many turbulent cells across jet cross-section, each followed after crossing shock, where e⁻s are energized; seed photons from dusty torus & Mach disk

Each cell has random B direction; B & number of e⁻s vary according to PSD



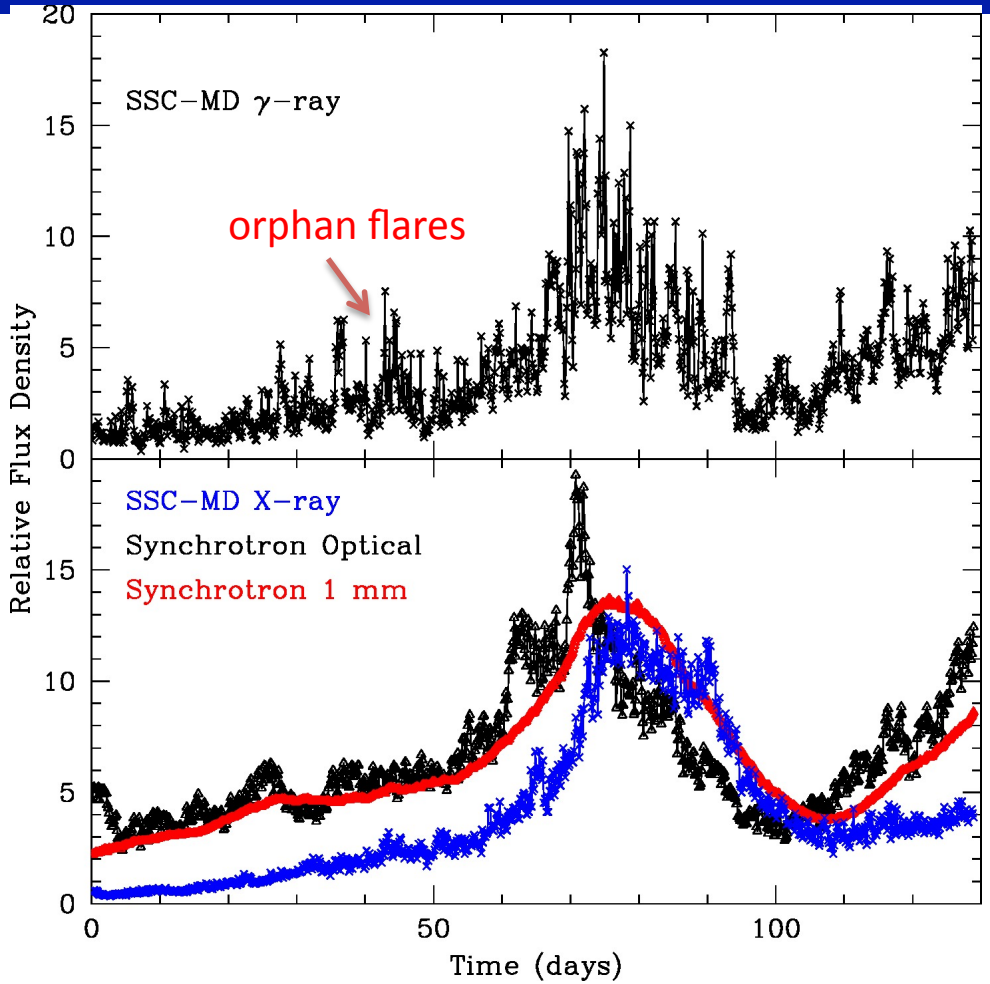
Important feature: only small fraction of cells can accelerate electrons up to energies high enough to produce optical & γ-ray emission

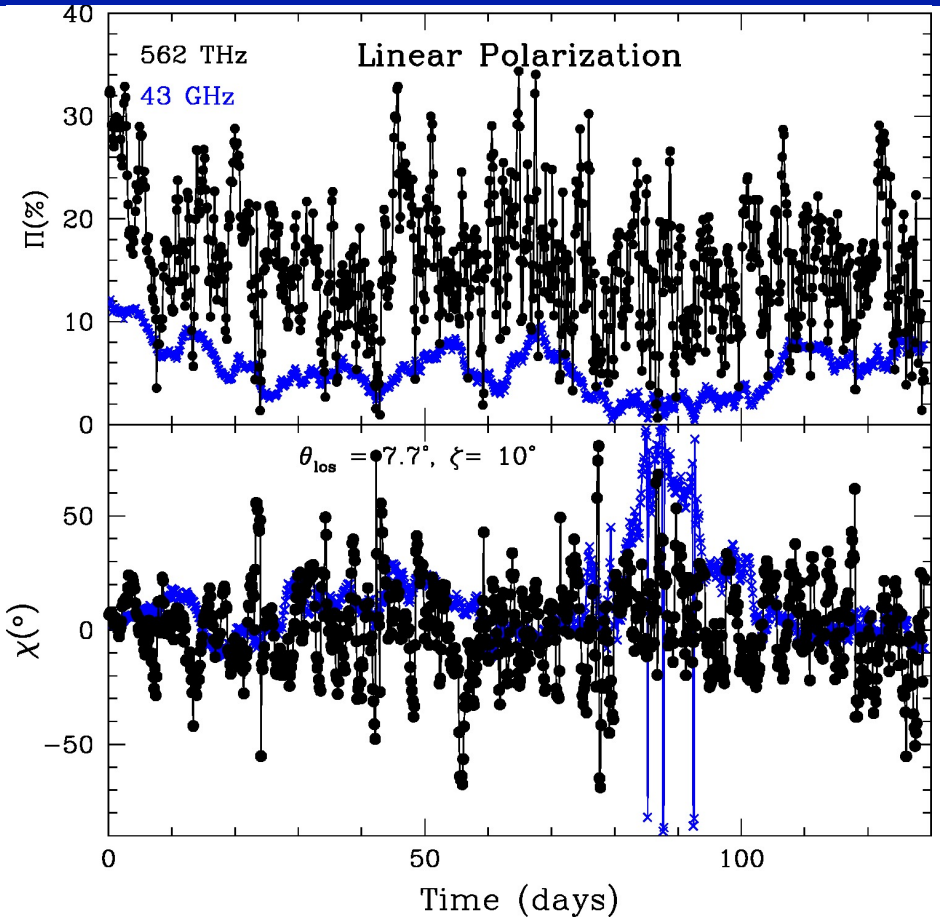
→ More rapid variability to explain intra-day flux changes

Mach disk (optional)

Conical standing shock

Sample Simulated Light Curve Similar to BL Lac





Outbursts & quiescent periods arise from variations in injected energy density
- Random with probability distribution determined by red-noise power spectrum

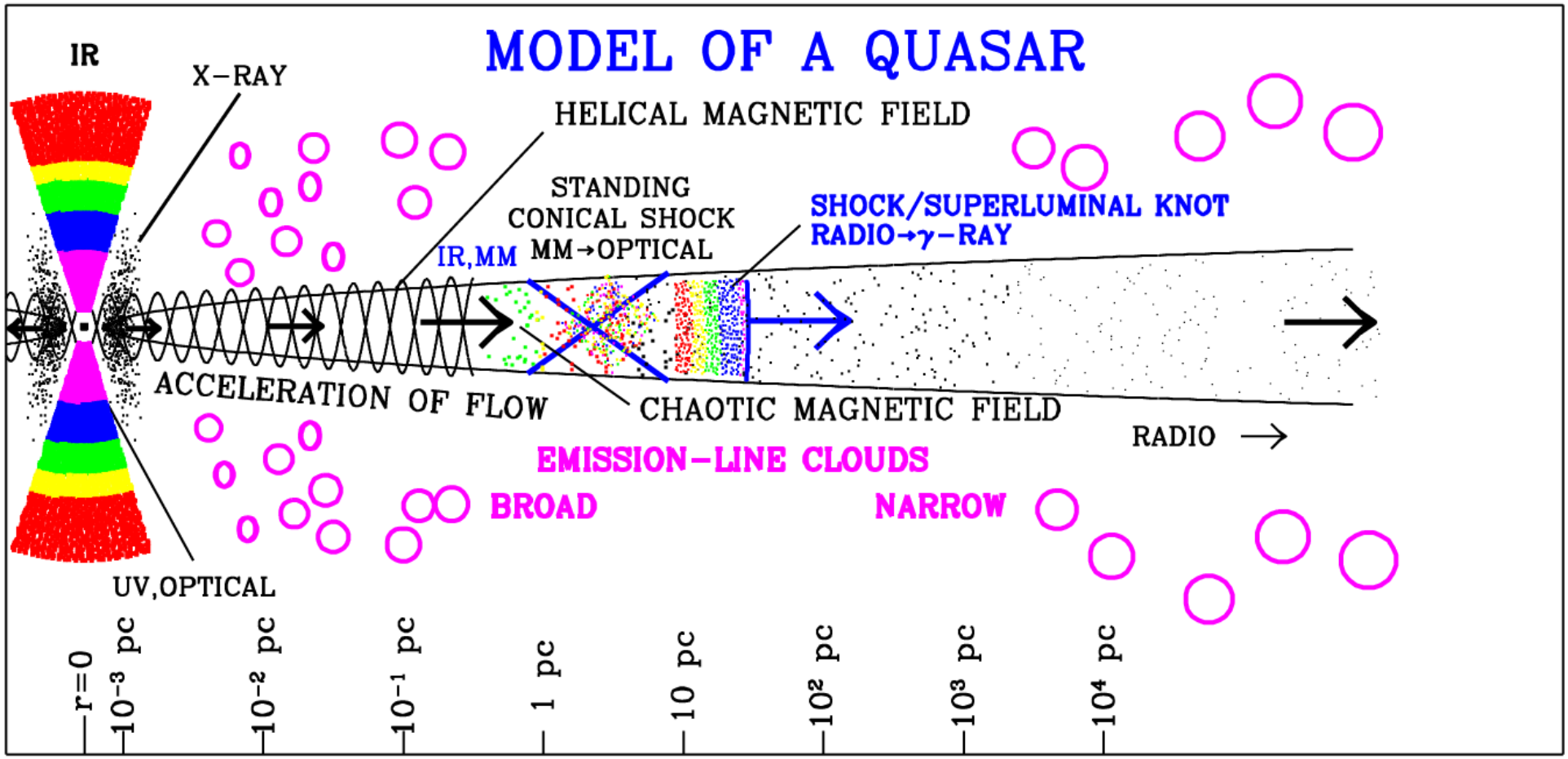
Polarization is stronger at higher frequencies

Position angle fluctuates, occasionally rotates at random times, but is usually within 20° of jet direction (as observed in BL Lac)

Sketch of a Quasar-Blazar

Components as indicated by theory & observations of SED, variability & polarization

Flares from moving shocks and denser-than-average plasma flowing across standing shock



Conclusions

- **We are now accumulating an extremely rich data set**

- **Theoretical models need to catch up to observations if they are to succeed in reproducing all of the characteristics of blazar emission**

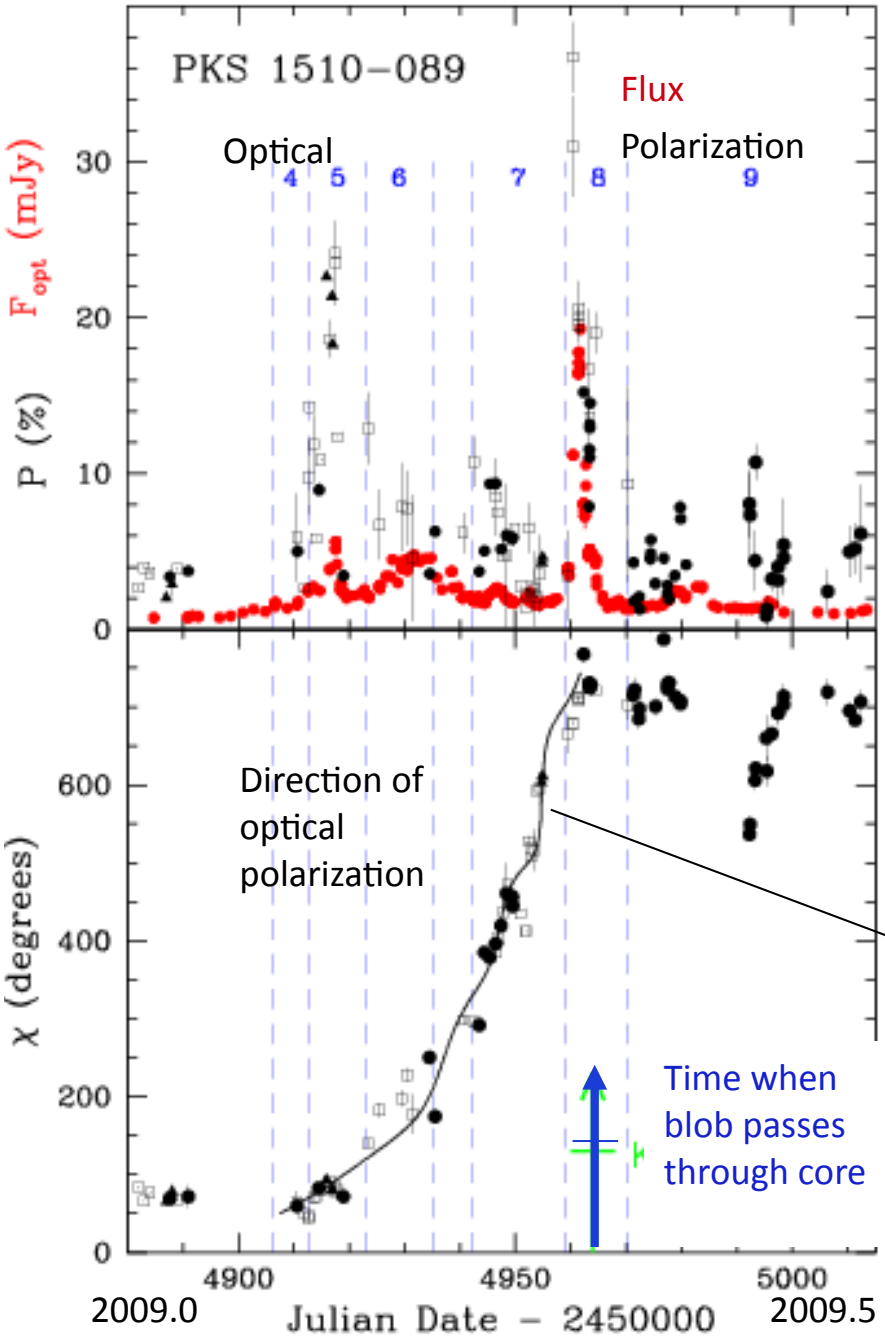
- **Most outbursts & flares occur on parsec scales**

→ **source(s) of seed photons for gamma-ray emission remains a difficult problem**

- **Emission-line clouds lying along jet (León-Tavares et al. 2012, ApJ; Isler et al. 2013, in prep.; revival of Ghisellini & Madau 1996 idea)?**

- **We need to find a way to keep our best time-domain instruments operating!!**

Rotation of Optical Polarization in PKS 1510-089



Rotations of optical (+ sometimes radio) polarization are common, especially during outbursts

In 1510-089 rotation starts when major optical activity begins, ends when major optical activity ends & superluminal blob passes through core

Model curve: blob following a spiral path through toroidal magnetic field in an accelerating flow

W increases from 8 to 24, W from 15 to 38
Blob moves 0.3 pc/day as it nears core

Core lies > 17 pc from central engine

Turbulence (or reconnection) Solution to Time-scales (see also Narayan & Piran 2012)

- **Need to understand that opening angle of jet is very narrow: ~ $0.1/\Gamma_{flow}$ (Jorstad et al. 2005; Clausen-Brown et al. 2013)**

→ Half-width of jet at core ~ 0.1 d(core,pc) Γ_{flow}^{-1} pc

- **If filling factor f of cells with electrons of high enough energy to emit at at optical/gamma-ray frequencies is low or blob doesn't cover entire jet cross-section, time-scale of variability can be very short:**

$$t_{var} \sim 120\, f^{1/2}\, (1+z)\, (\Gamma_{flow}\, \delta_{flow}\, \delta_{turb})^{-1}\, d(\text{core,pc})\ \text{days}$$

For f ~ 0.1, z ~ 0.5, $\Gamma_{flow} \sim \delta_{flow} \sim 30$, $\delta_{turb} \sim 2$, d(core) ~ 10 pc,

$$t_{var} \sim 0.3\ \text{days}$$

→ Minutes for smaller, less distant blazars like TeV BL Lac objects