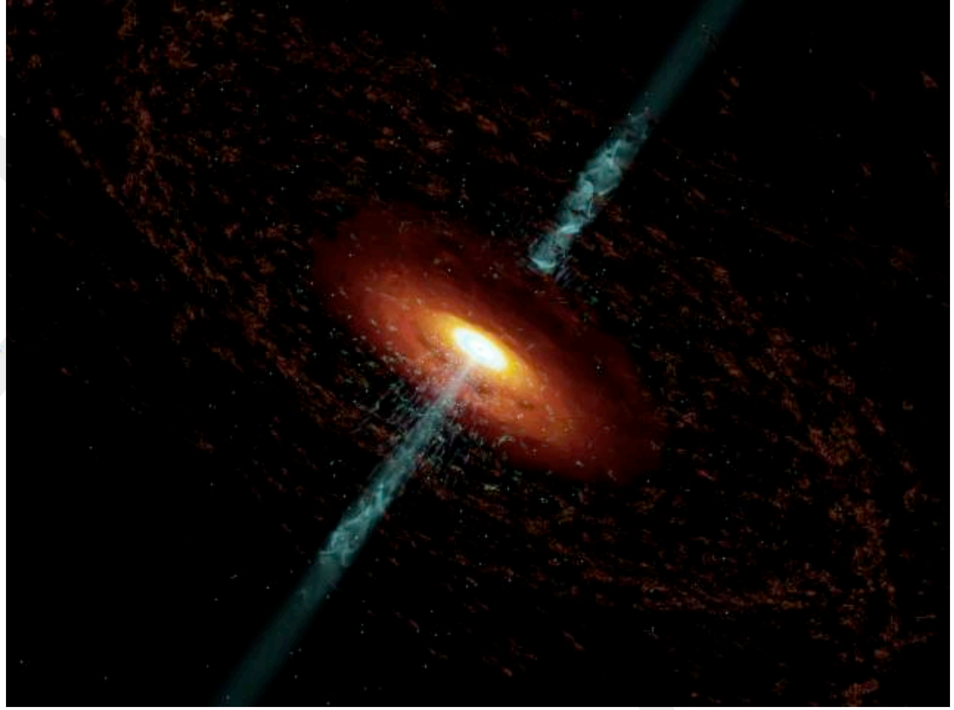


Rapid Variability of Gamma-Ray Emission from Sites near the 43 GHz Cores of Blazar Jets

Alan Marscher & Svetlana Jorstad

Boston University

Research Web Page: www.bu.edu/blazars

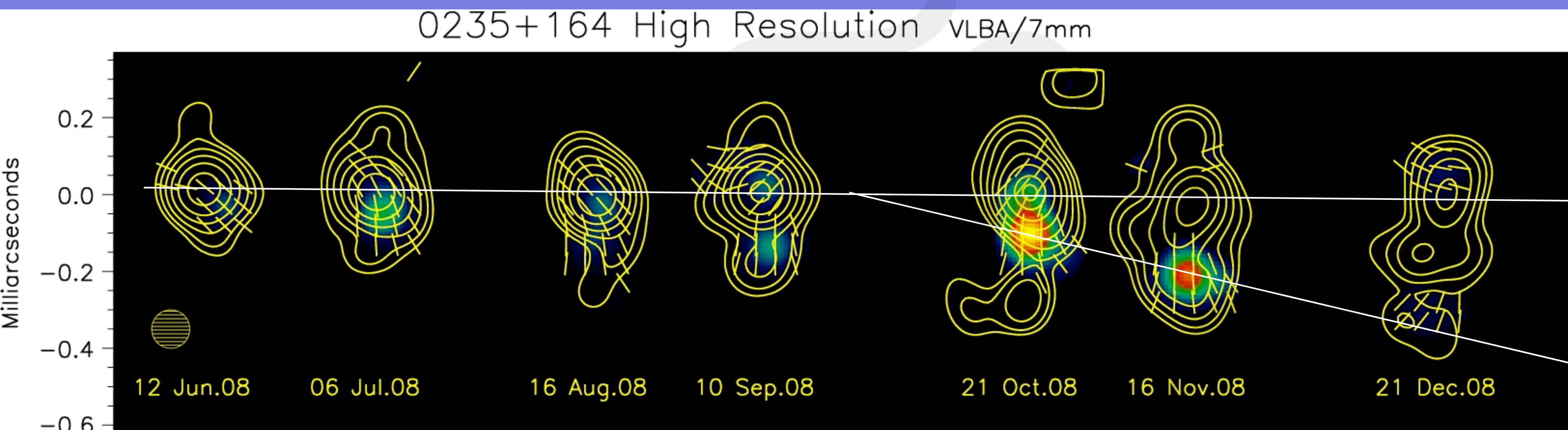
Ultra-fast Superluminal Motion in AO 0235+164

Apparent speed β_{app} = 70±10*c*

Bulk Lorentz factor $\Gamma > \beta_{app}$

Opening angles of blazar jets: $\phi \sim 10°/\Gamma$ (Jorstad et al. 2005)

→ Jets with high Γ are extremely narrow intrinsically

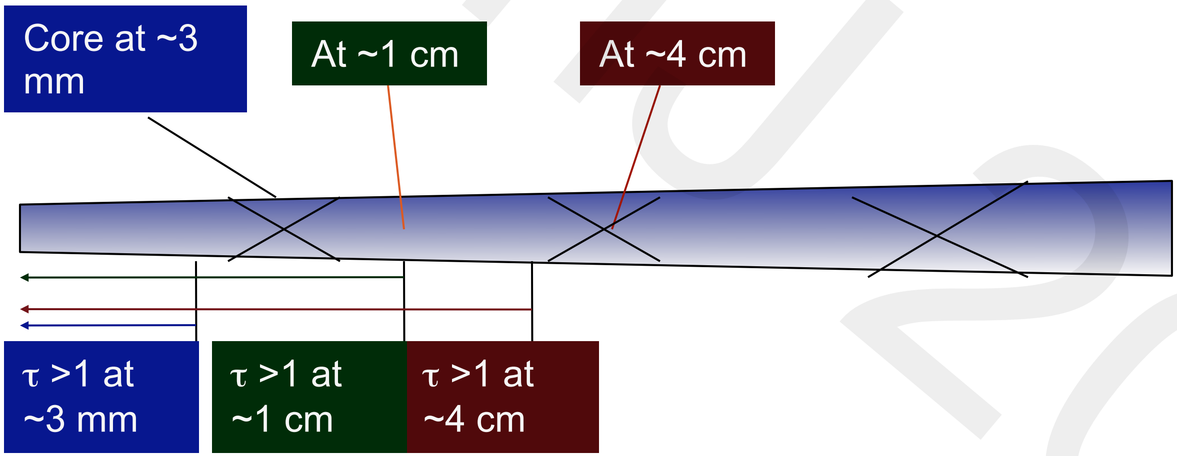


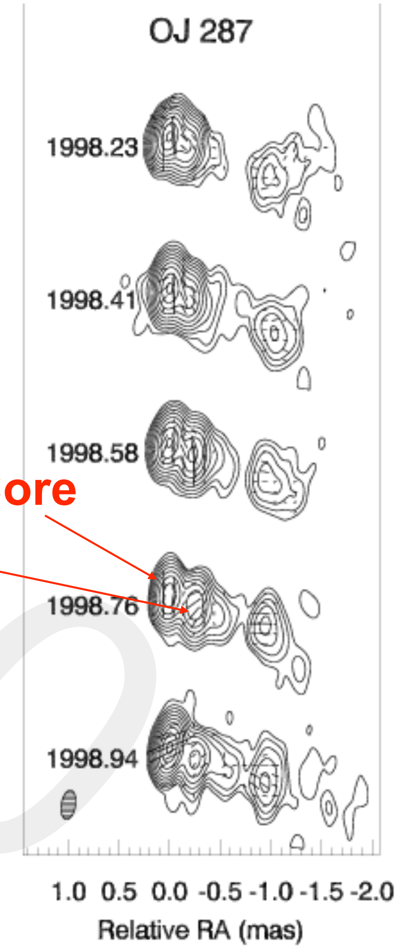
Standing Shocks in Blazar Jets

Observations suggest that core on VLBI images is <u>either</u>:

1. $\tau \sim 1$ surface (τ = optical depth to synchrotron absorption)
2. First standing (oblique or conical) shock outside $\tau \sim 1$ surface

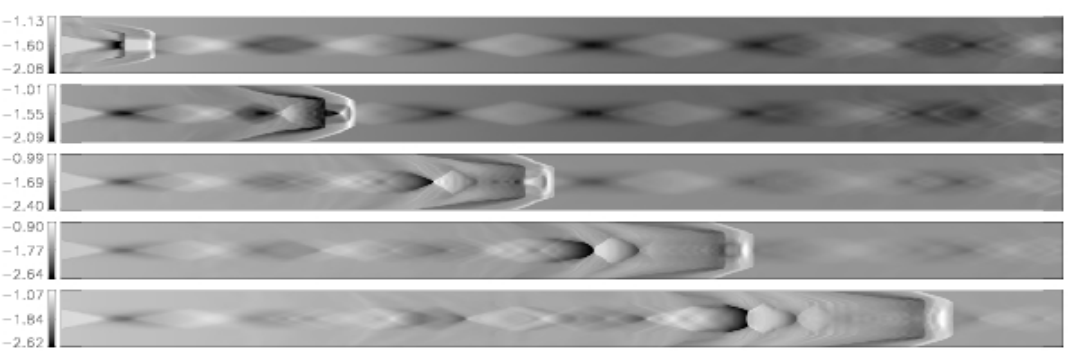
(Daly & Marscher 1988 ApJ, D'Arcangelo et al. 2007 ApJL)





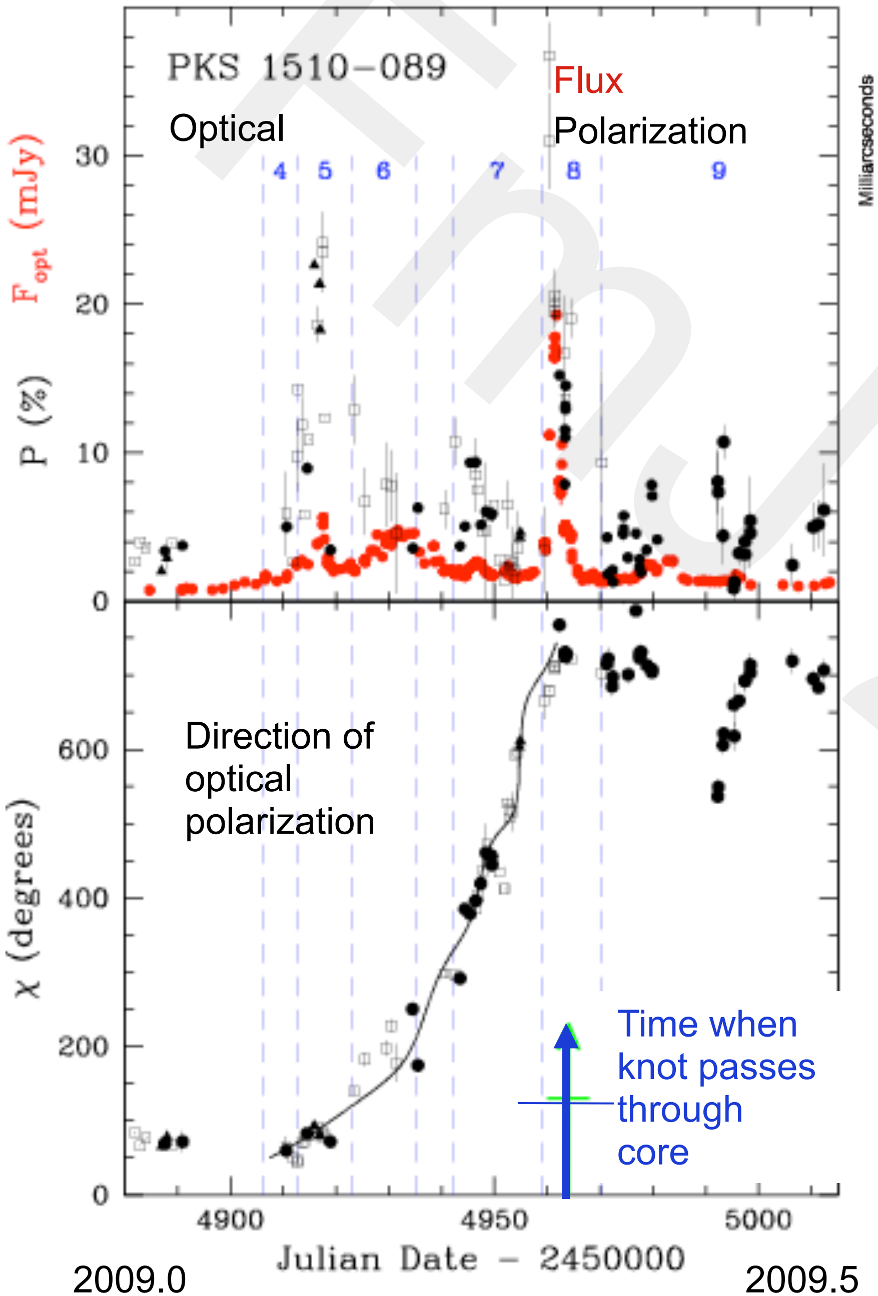
Core

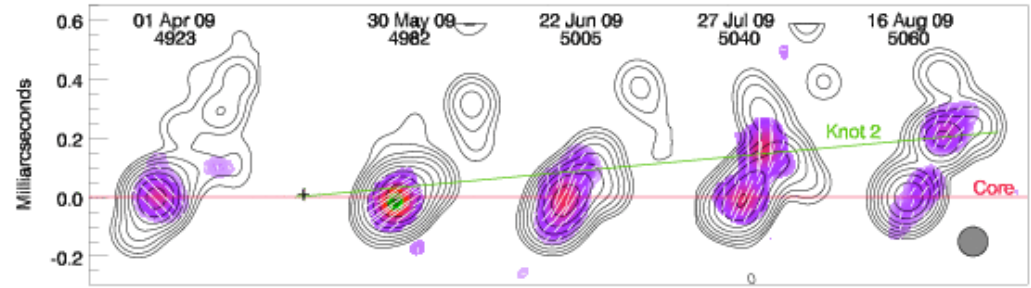
Stationary feature with variable polarization



HD simulation (Gómez et al. 1997)

Rotation of Optical Polarization in PKS 1510-089





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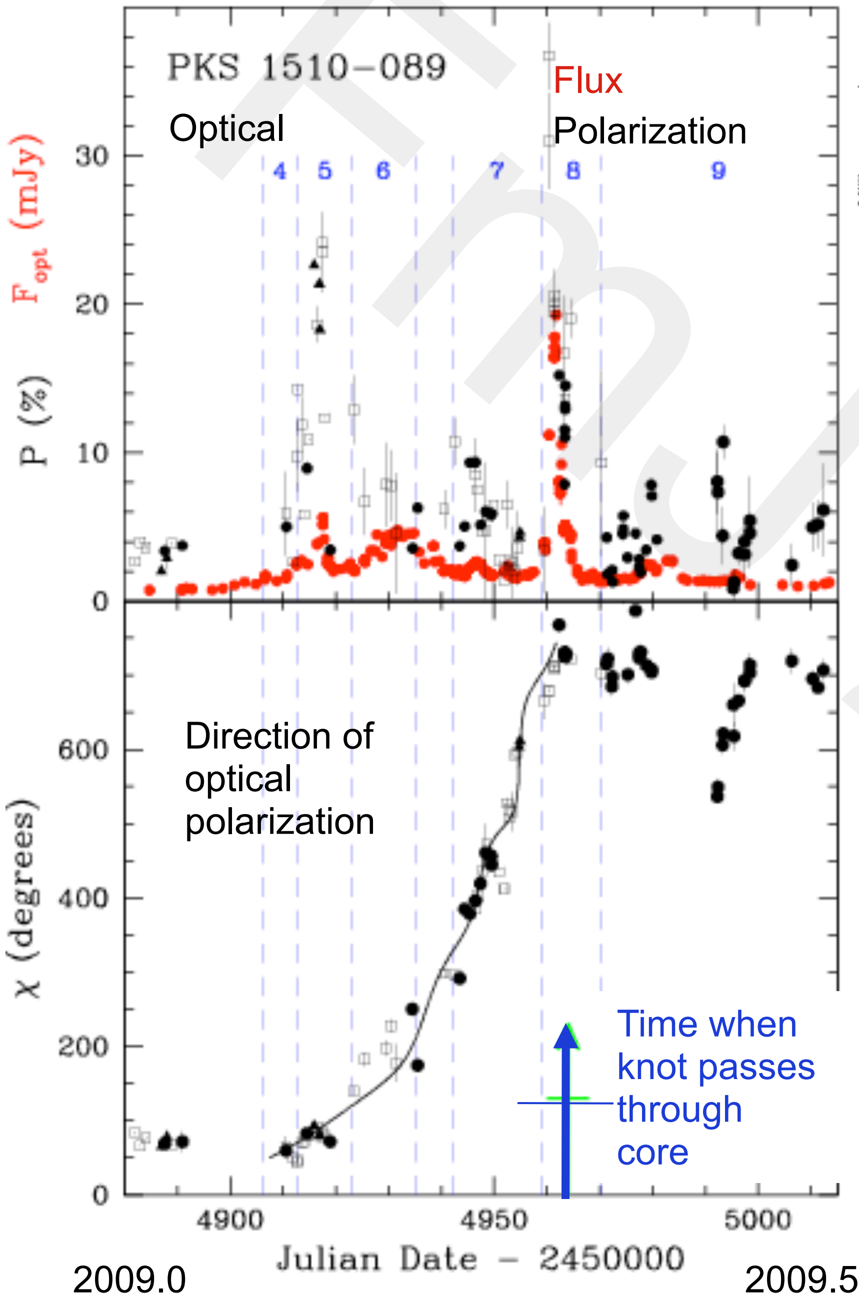

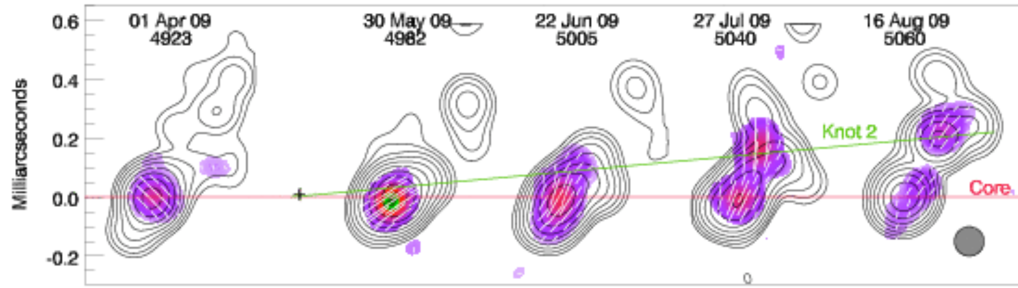

Non-random timing & 2nd similar rotation argue against random walk (Jones 1988) caused by turbulence → implies single knot responsible for entire outburst

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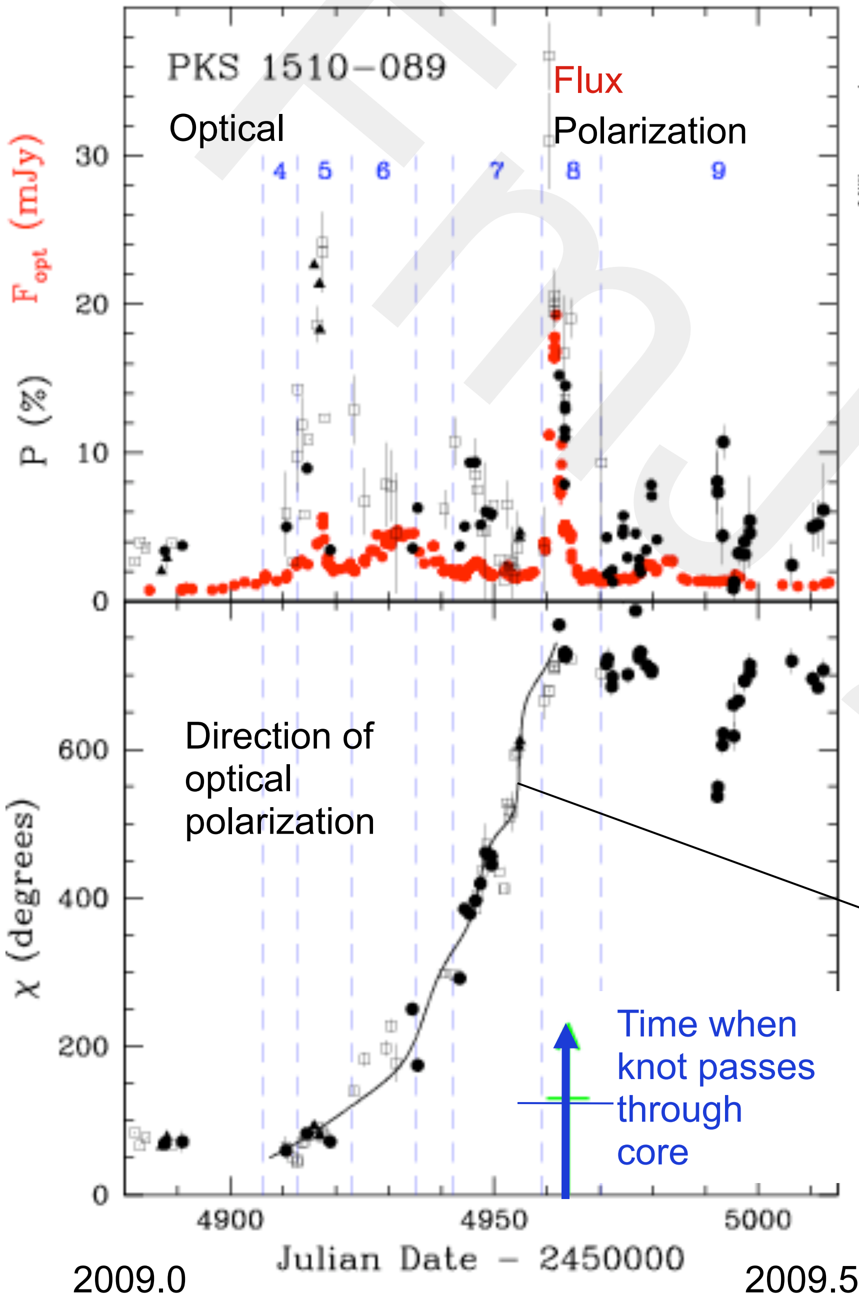

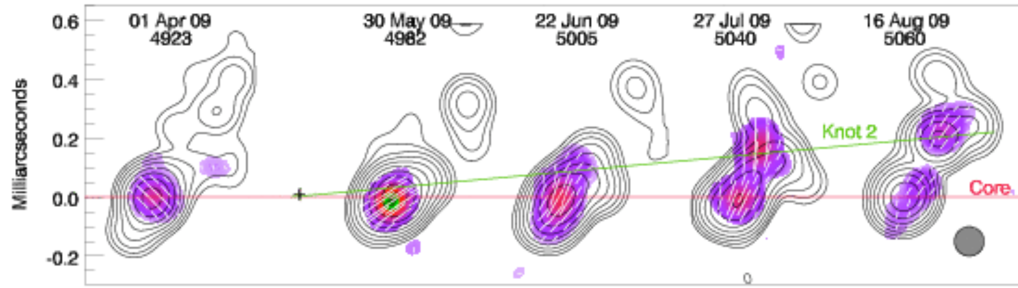

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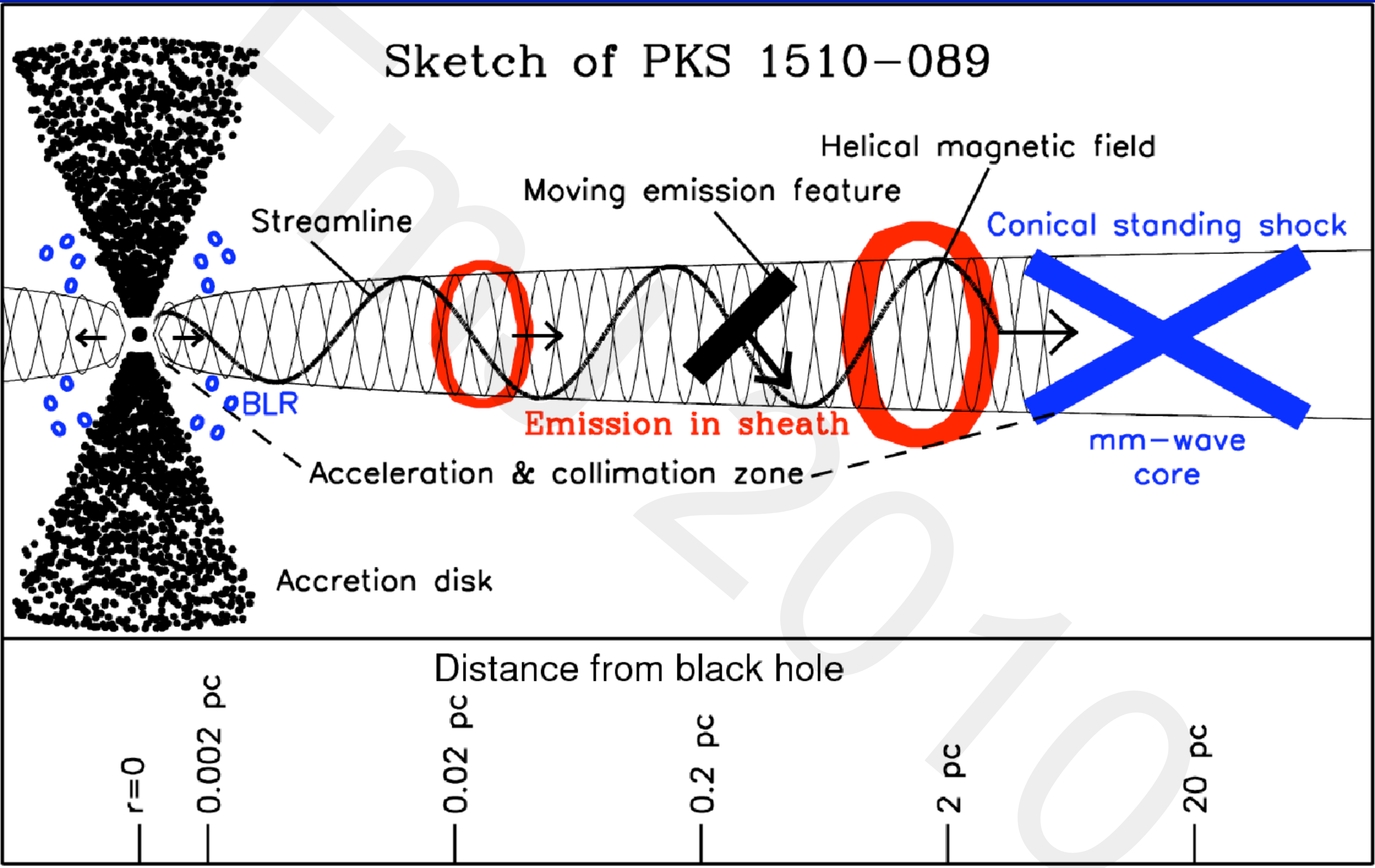
Model curve: knot following a spiral path through toroidal **B** in an accelerating flow

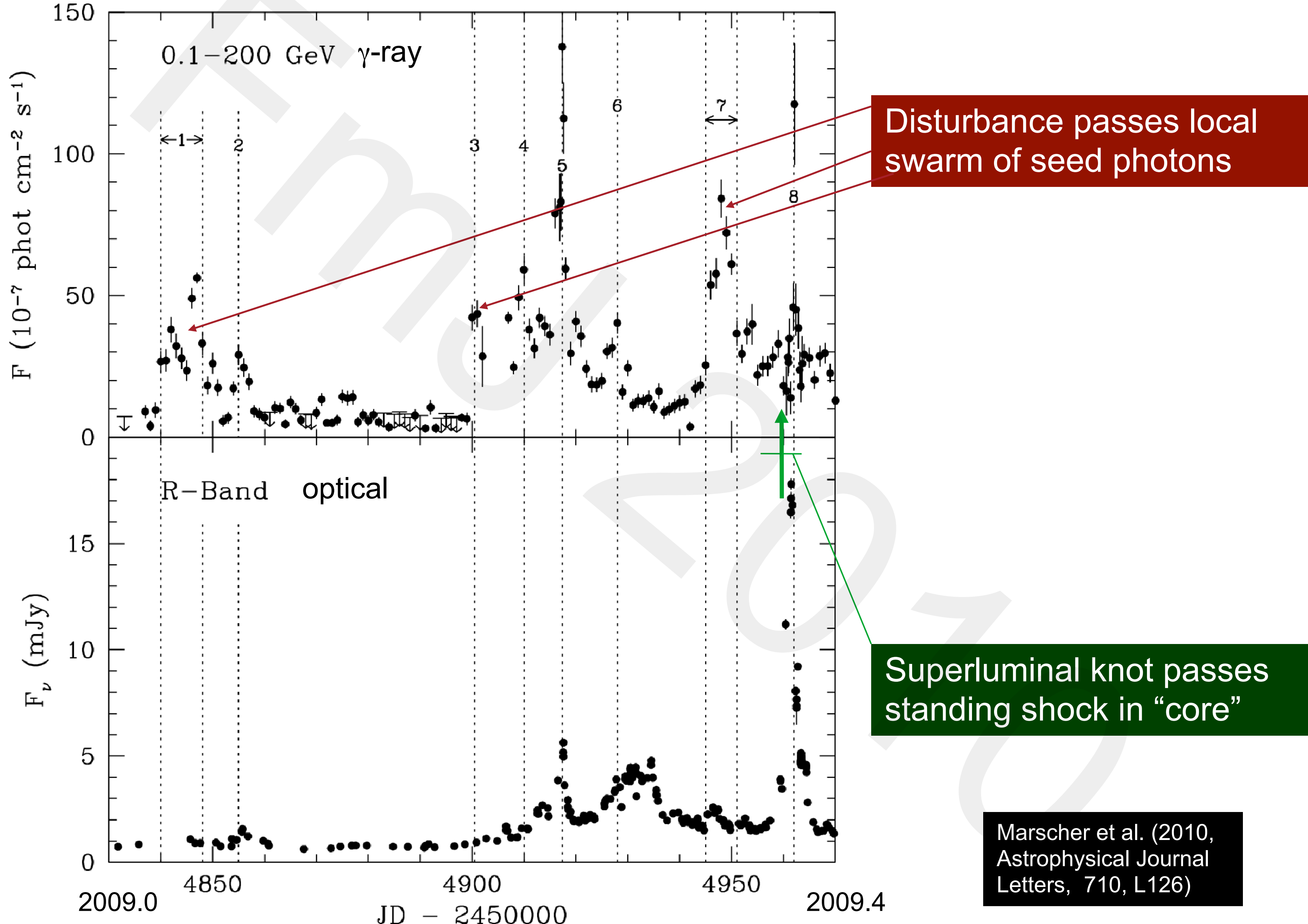
Γ increases from 8 to 24, δ from 15 to 38
Blob moves 0.3 pc/day as it nears core

Core lies 17 pc from central engine

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



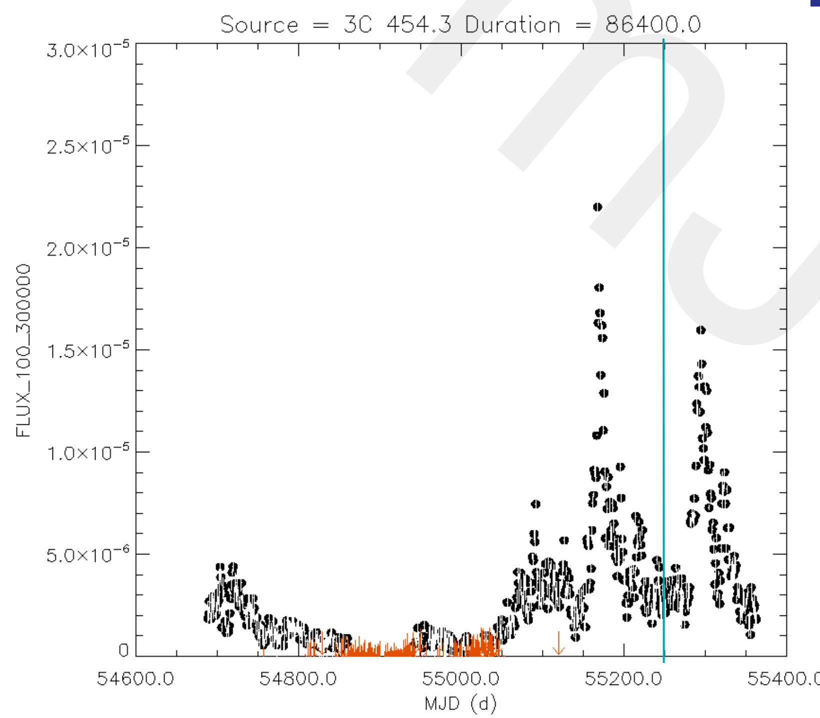
Quasar PKS 1510-089 (z=0.361): first 140 days of 2009

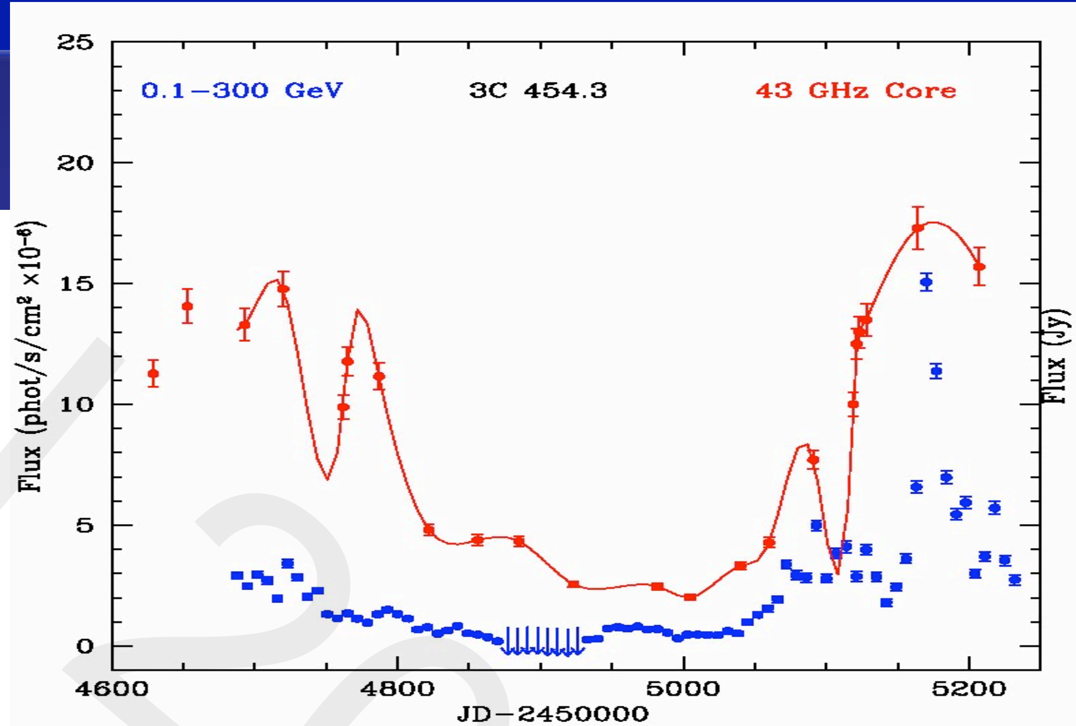


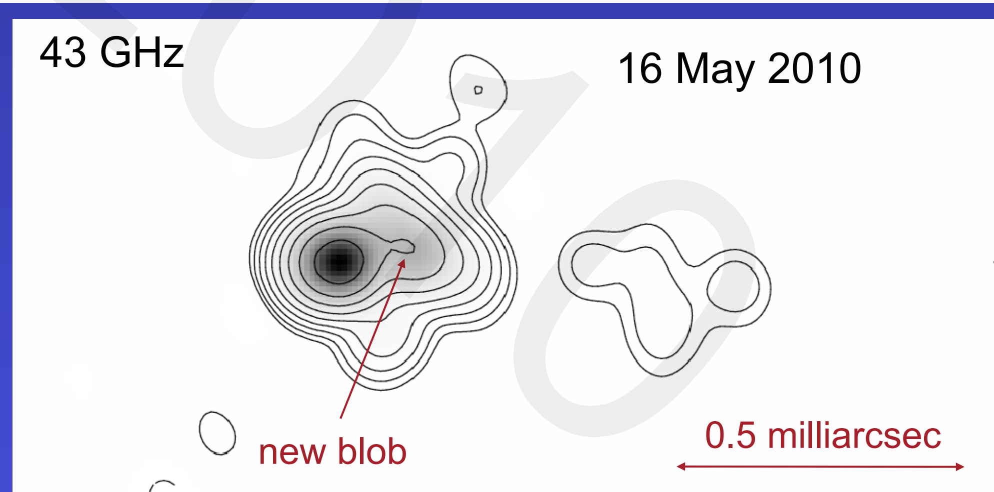
Marscher et al. (2010, Astrophysical Journal Letters, 710, L126)

Quasar 3C 454.3: Outburst seen first at mm wavelengths

- **Highest γ-ray fluxes from a blazar thus far**





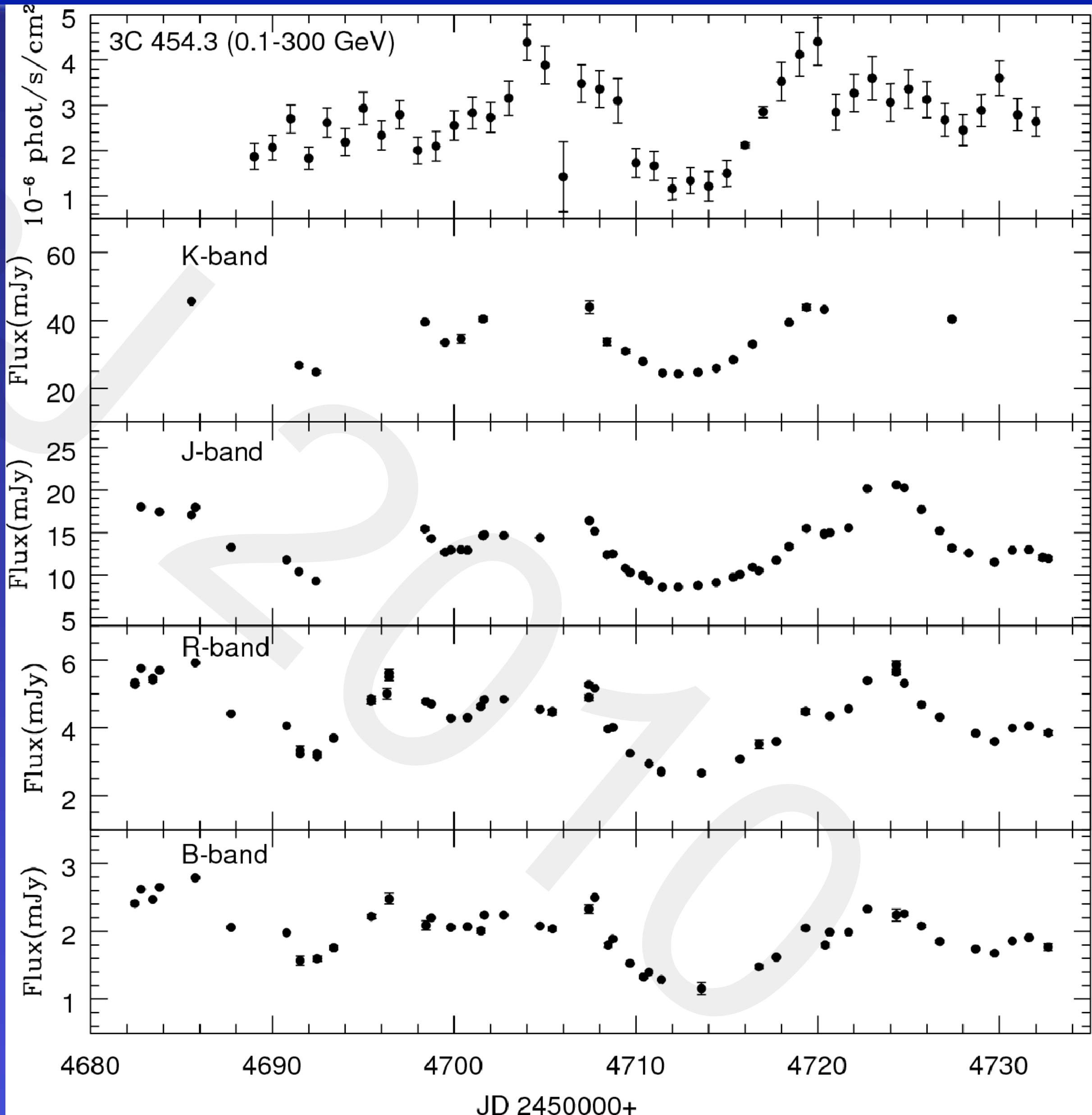


Jorstad et al. (2010 ApJ, 715, 362 & arXiv:0912.5230)

Quasar 3C 454.3: Gamma-ray/optical/near-IR correlation

Variations smoother at longer wavelengths

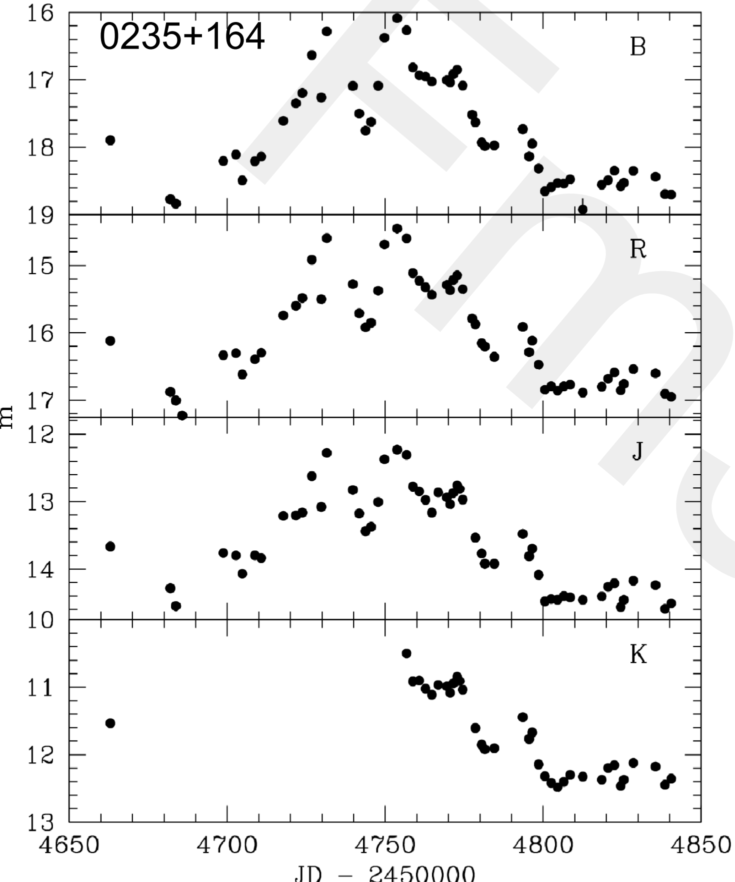
Bonning et al. 2009 ApJ

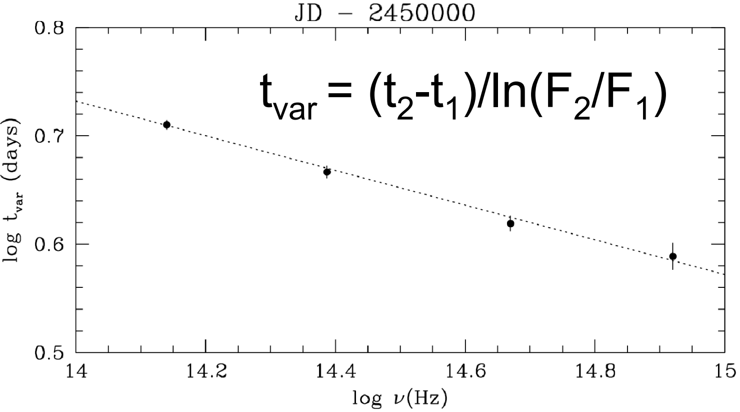


Variations in Flux vs. Frequency

Gamma-ray + optical variations usually faster than X-ray, IR, & mm-wave variations

Optical/near-IR: higher $\nu \rightarrow$ shorter time-scale





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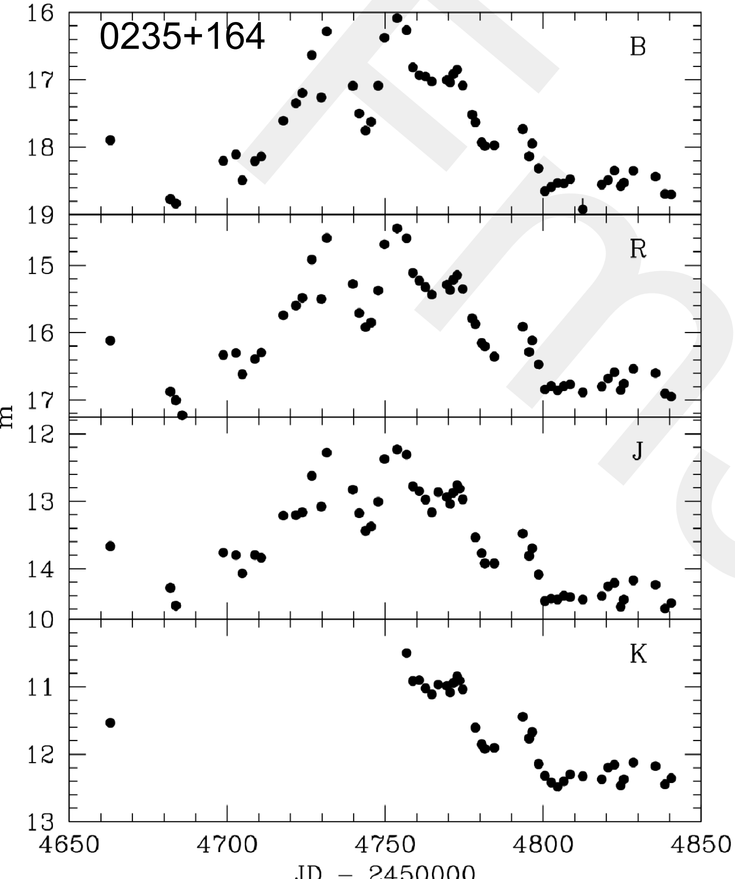

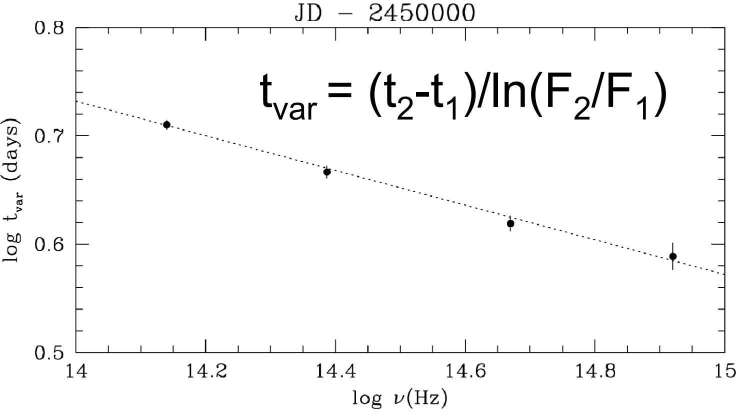

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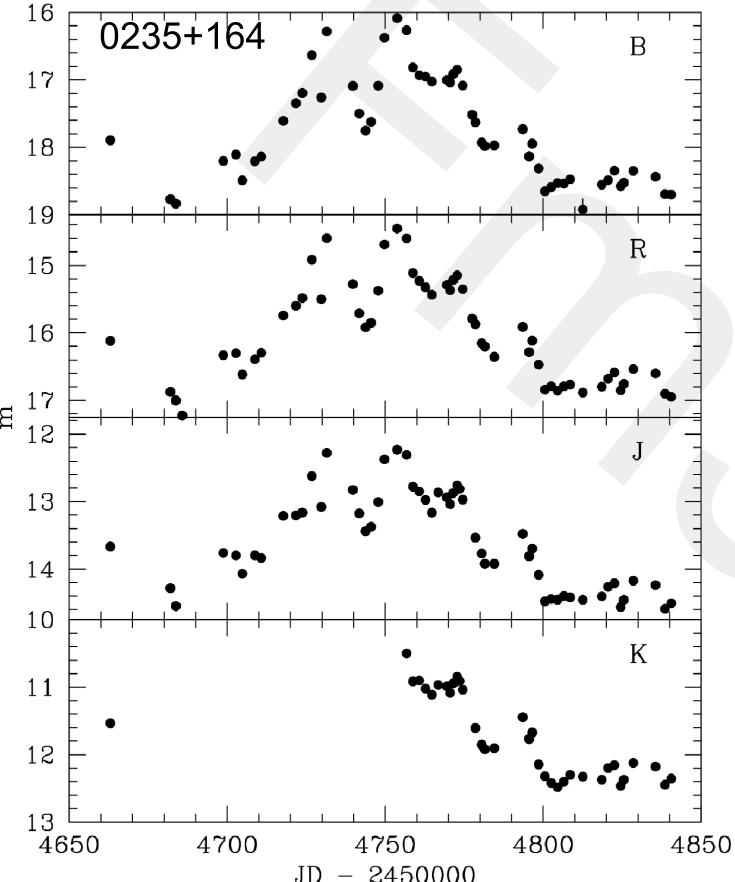

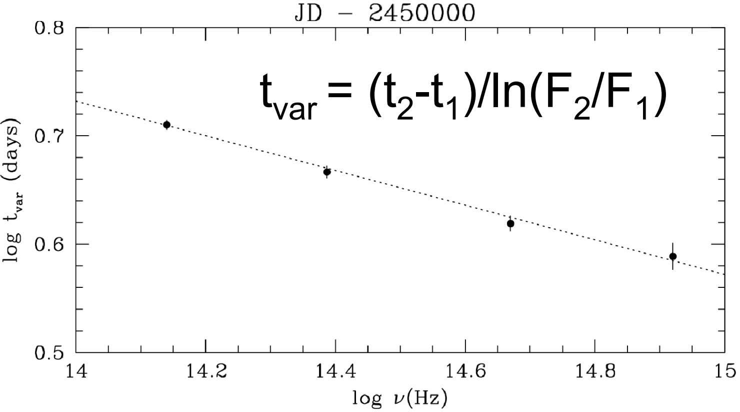

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Smaller = closer to black hole?

Problems:

- Observed coincidence of γ-ray flares with events in radio jet

- If too close to black hole, high-E gamma-rays cannot escape before producing e^+-e^- pairs

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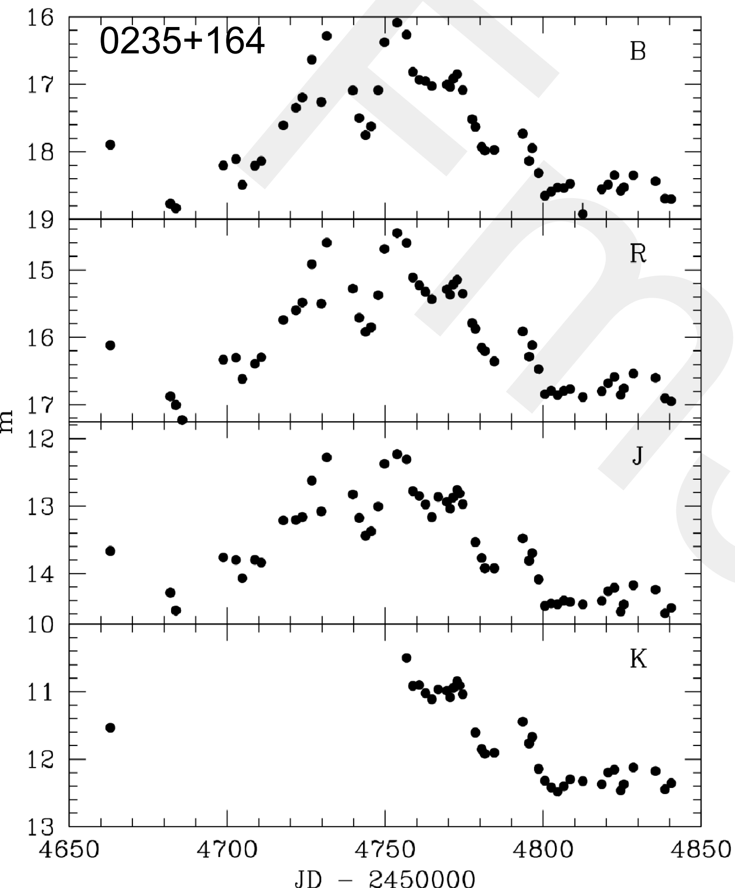

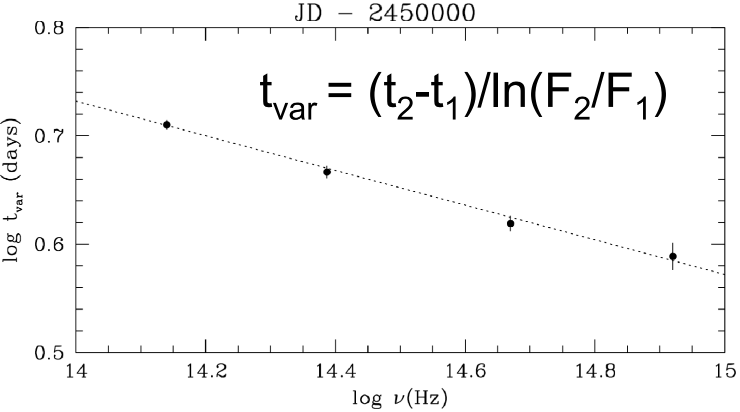

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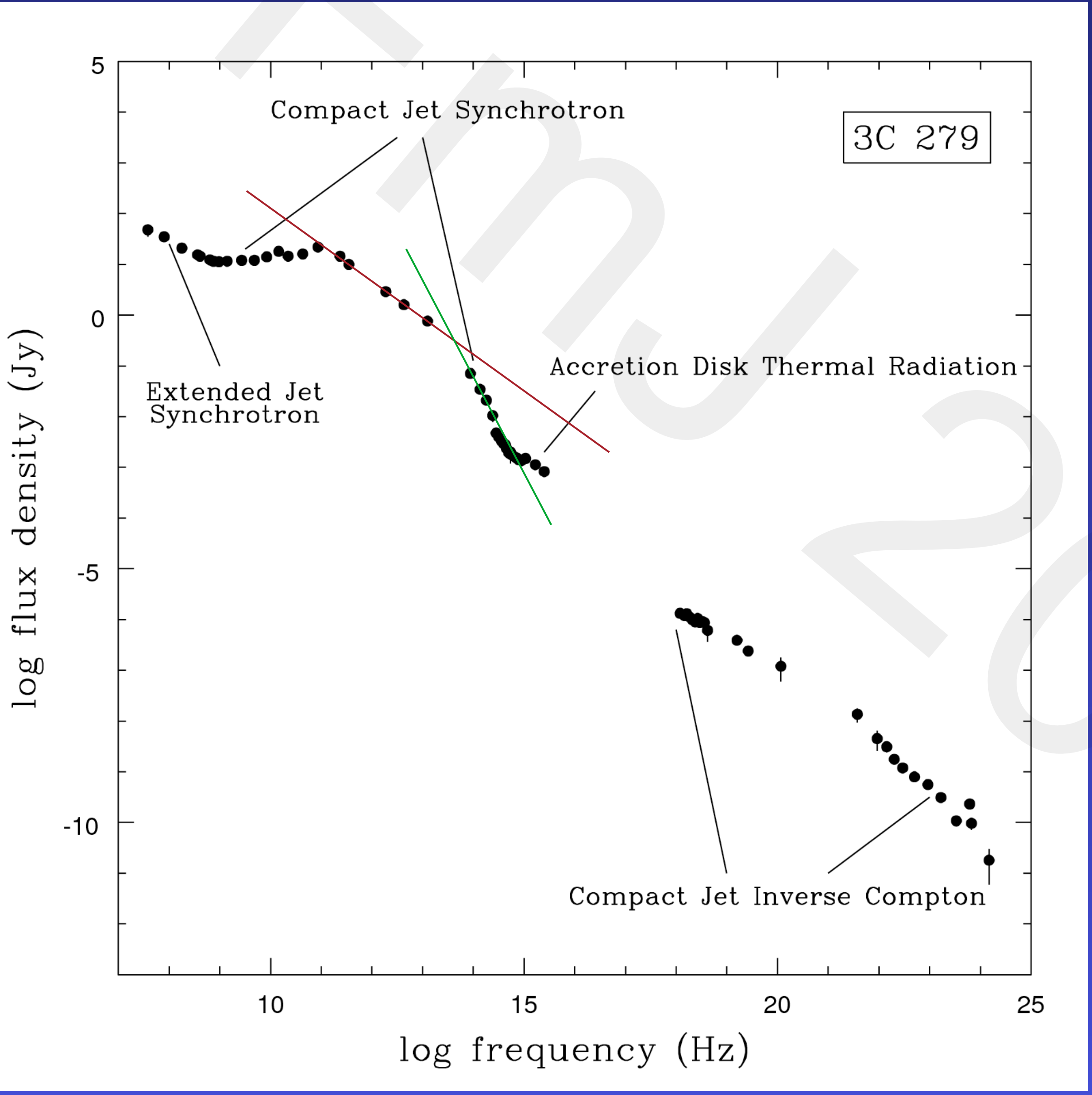
In our proposed model:

Particle acceleration efficiency in jet varies with position & time

- Only some small fraction of emission region contains highest E electrons

- Related to direction of magnetic field?

Break in Synchrotron Spectrum



Spectral energy distribution can be described by broken power law

- break often by more or less than 1/2 expected from radiative losses (e.g, Marscher & Gear 1985)

- Break now seen in γ-ray spectra as well

Working toward a Modified Model

Imagine that blobs are just random fluctuations in turbulent jet flow (agrees with power-law PSD)

Electrons in blob are accelerated when blob passes through standing shock in core or elsewhere

- Maximum energy achieved varies from one turbulent cell to another → number of cells with energies as high as E depends on E

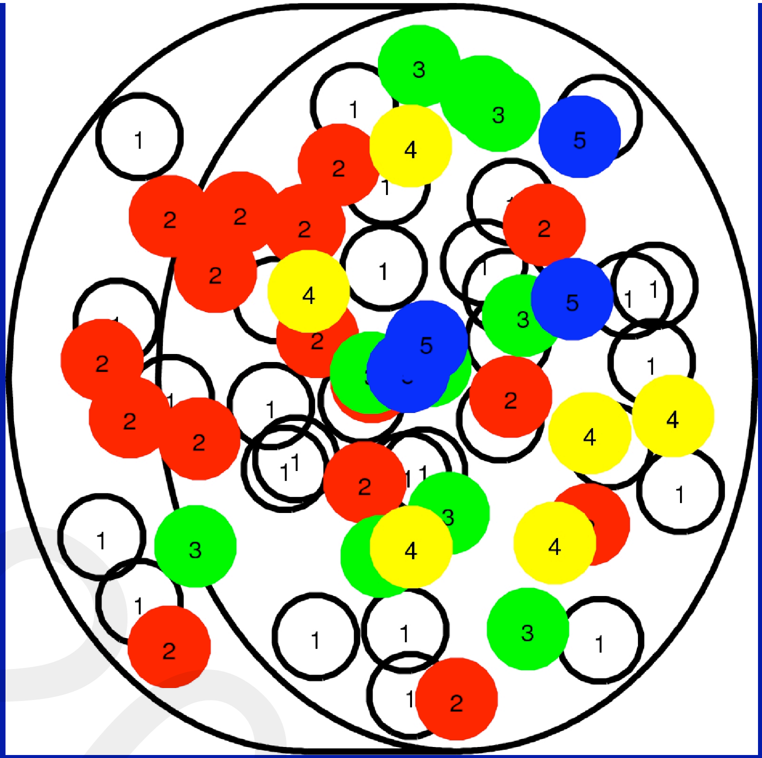
→ Frequency-dependent volume of emission $V(\nu) \propto \nu^{-p}$

Flux density $F_\nu \propto \nu^{-(s-1)/2}\, V(\nu) \propto \nu^{-[p+(s-1)/2]}$

Radiative losses can steepen this further

Advantages of Model

Smaller number of turbulent cells are involved in emission at higher frequencies



® **Variability time scale shorter (approx. $\propto \nu^{-p/2}$)**

  - **Helps to explain short time scales of variability**

® **Linear polarization higher & more highly variable in degree & position angle (as observed)**

Works well for blazar AO 0235+164, $V(\nu) \propto \nu^{-0.32}$

Sample Runs of Simplified Numerical Model

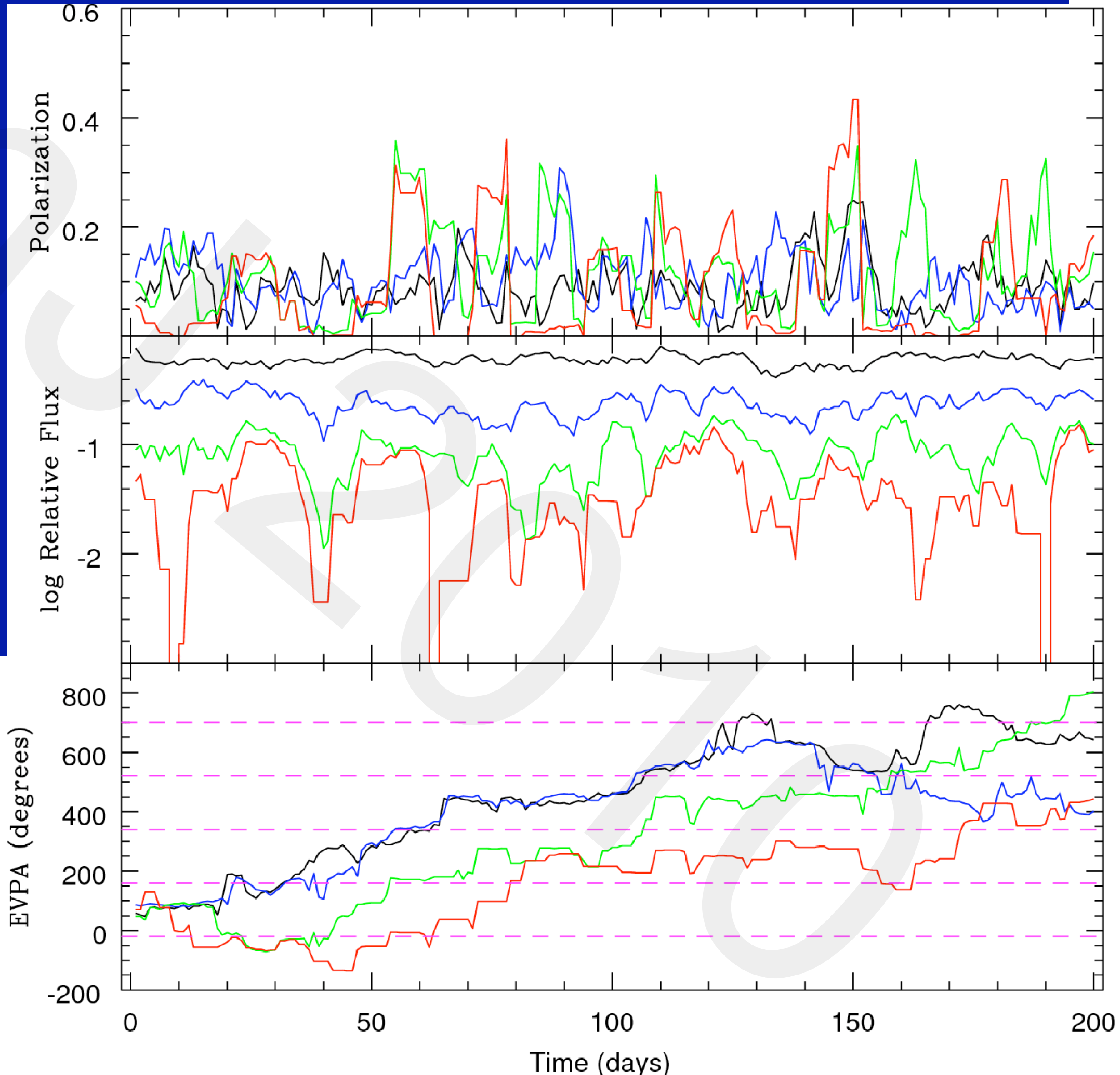
49 cells, 7 removed, 7 added at each time step with randomly oriented $\vec{B}$

<no. cells > $\propto \nu^{-0.4}$

Black: ~10^{13} Hz

Blue: ~10^{14} Hz

Green: ~10^{15} Hz



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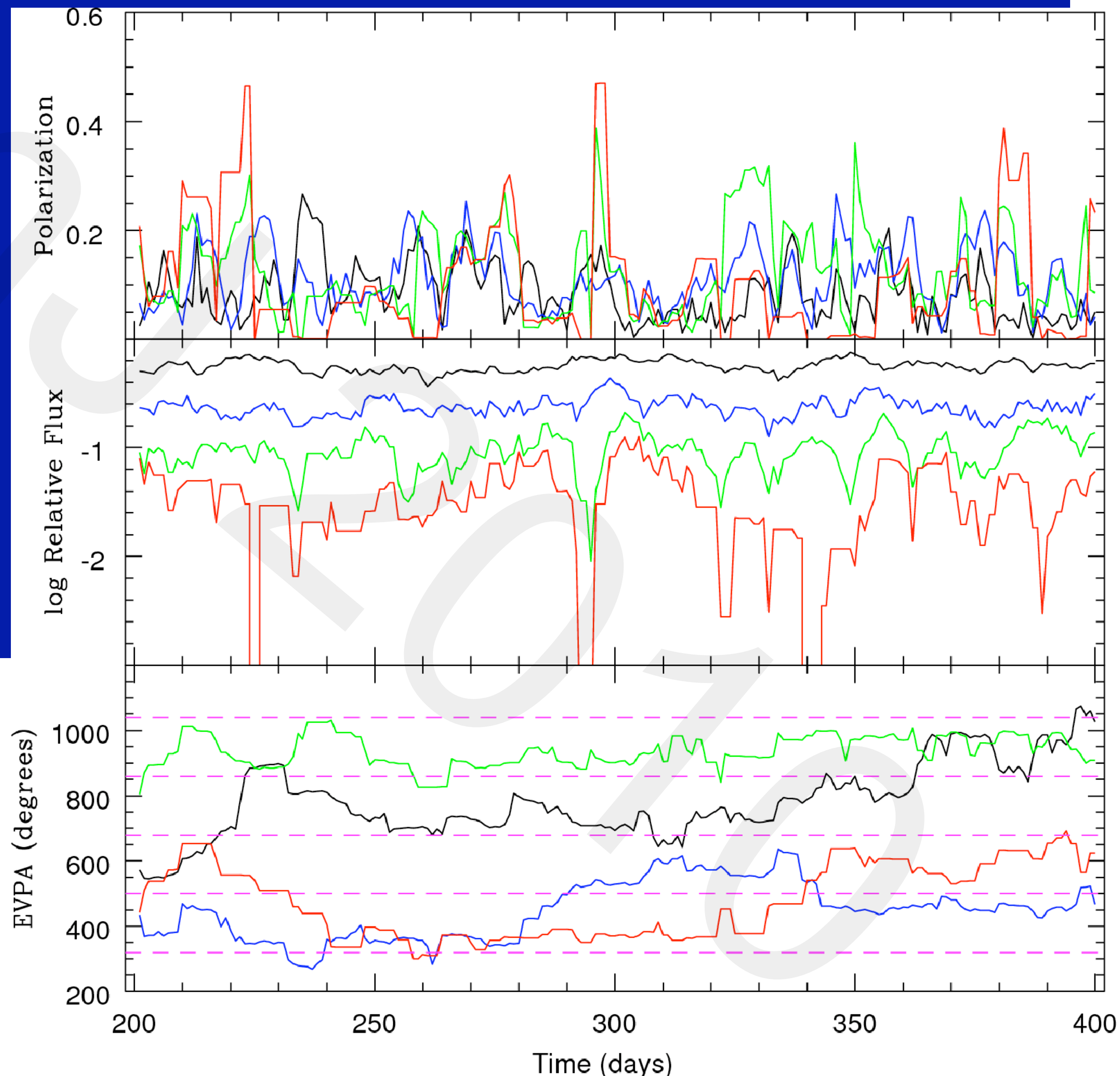

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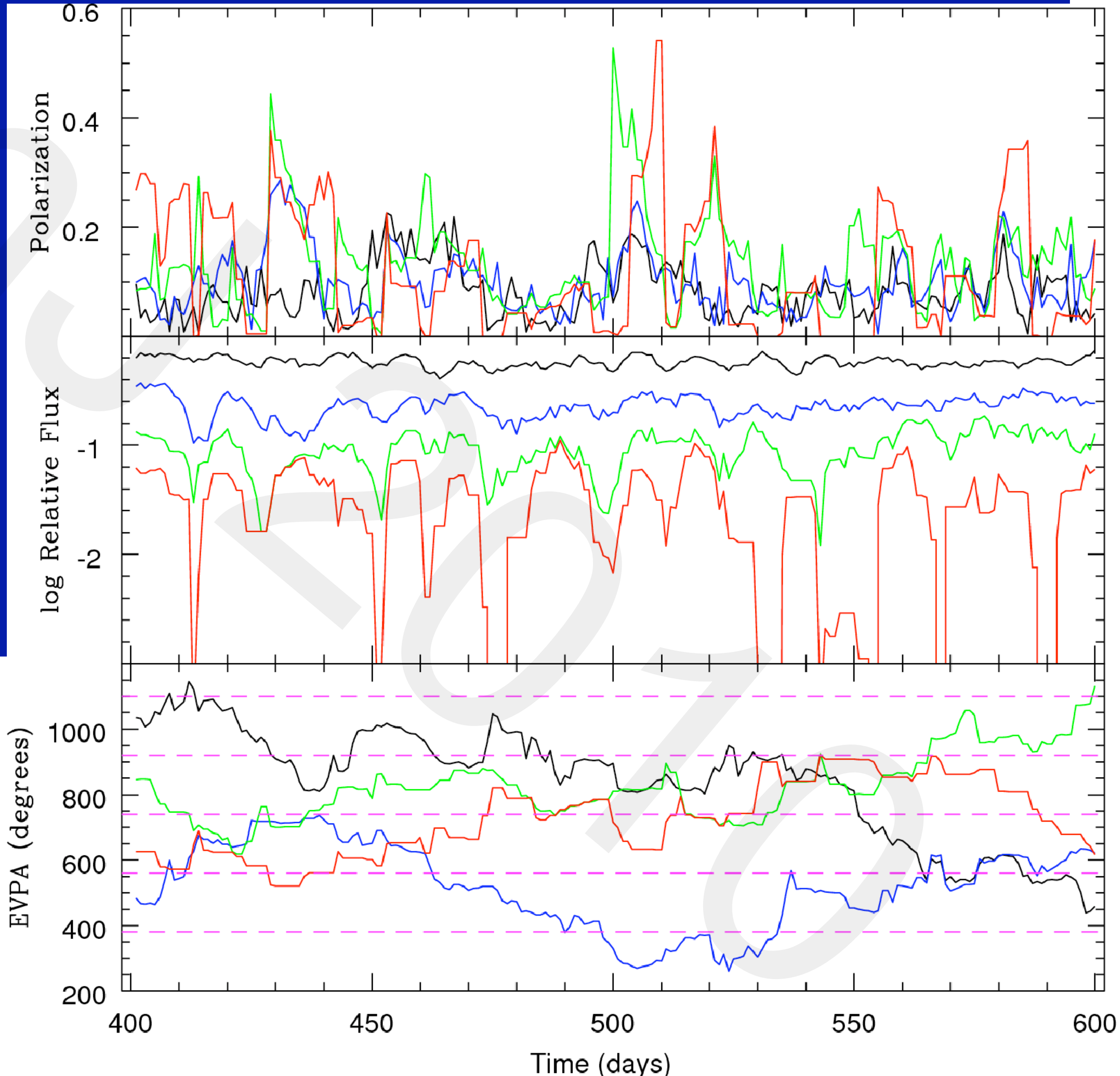

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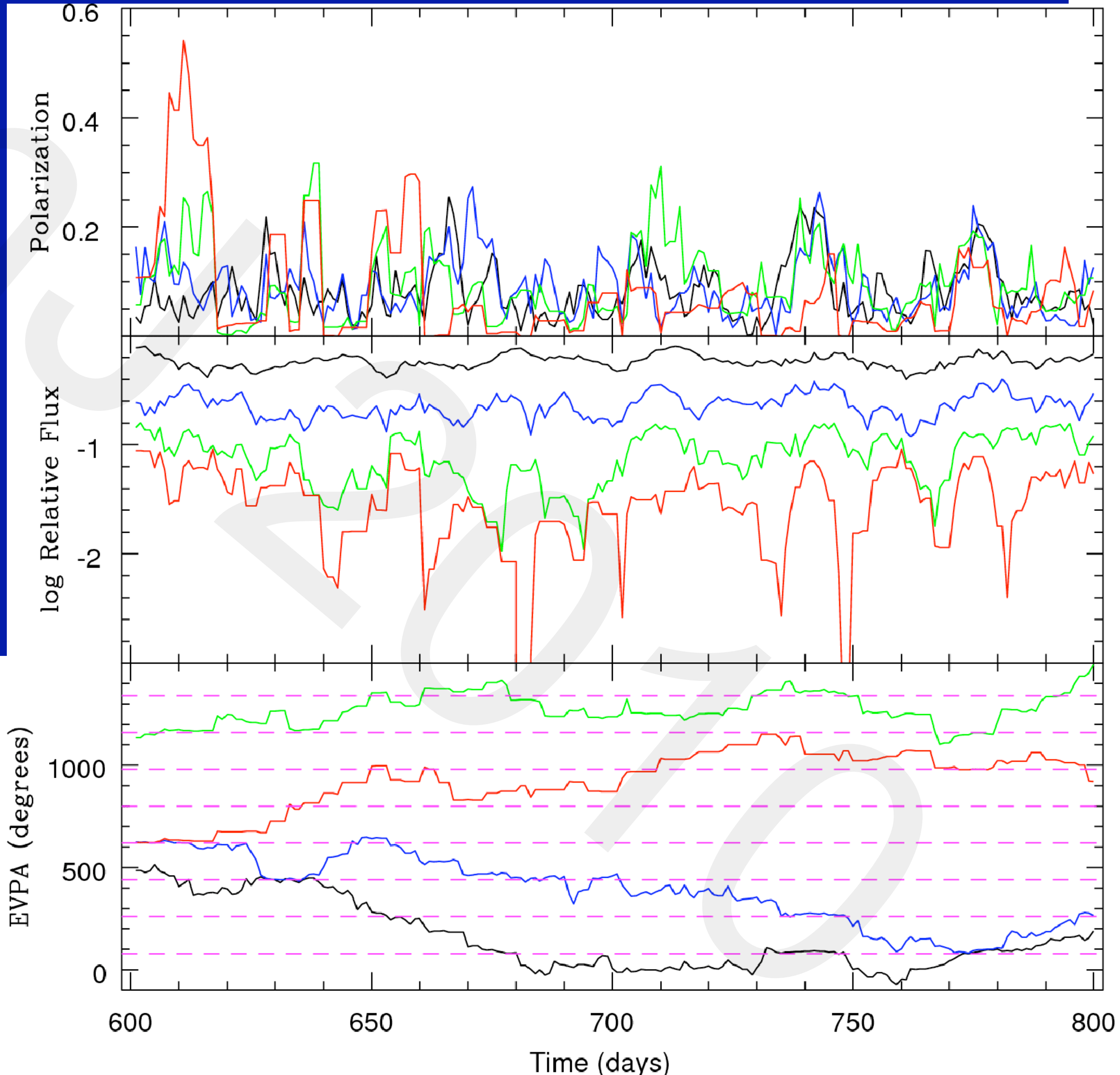

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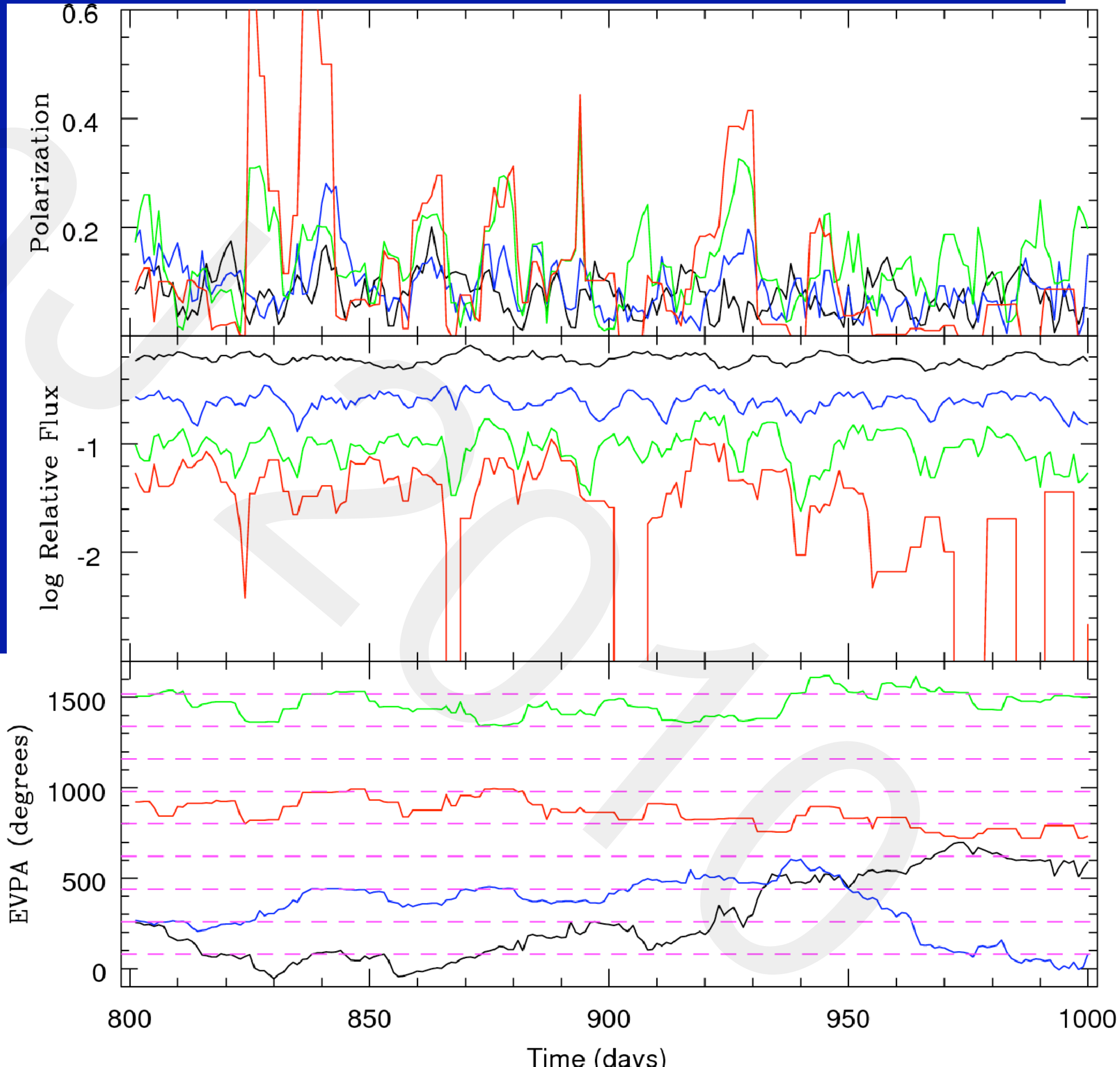

Conclusions

Data: γ-ray flares occur as a blob (1) passes a local source of seed photons or (2) interacts with the core or stationary emission feature downstream of core, parsecs from the central engine

Power-law PSDs, spectral breaks, and frequency-dependent time scales of variations & polarization imply that turbulence (or some other stochastic process) is a major factor in the variable emission

Frequency-dependent volume of turbulent emission regions (in combination with very narrow jet opening angles) consistent with

1. Power-law PSDs of flux variations

2. Shorter time-scales of variability at shorter wavelengths

3. Higher mean value & variation of polarization at shorter wavelengths

3. Breaks in SEDs

4. High-frequency (optical, γ-ray) variations that occur on time-scales

Emission feature following spiral path down jet

Feature 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**