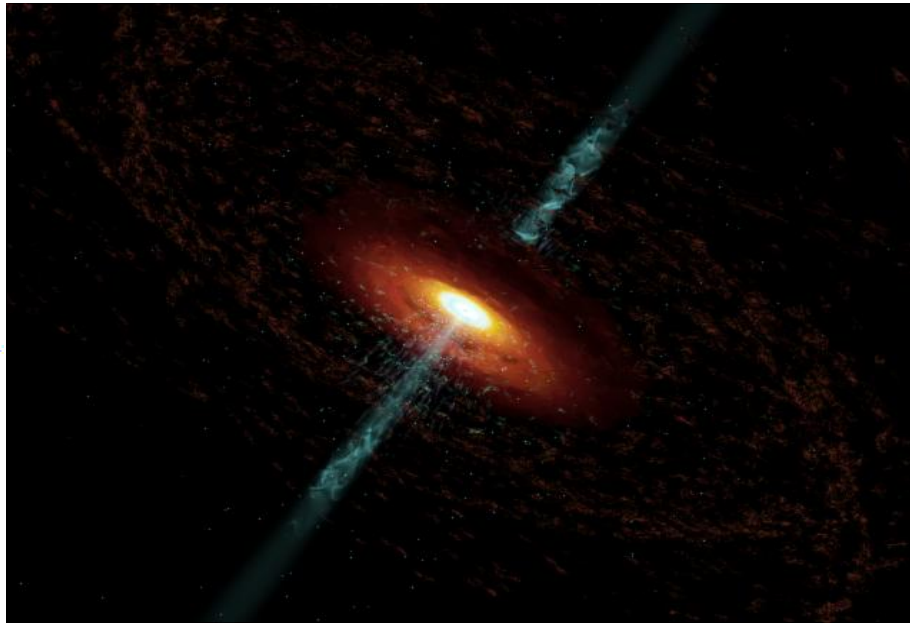

Modeling Variability of Blazar Jets with a Turbulent Magnetic Field

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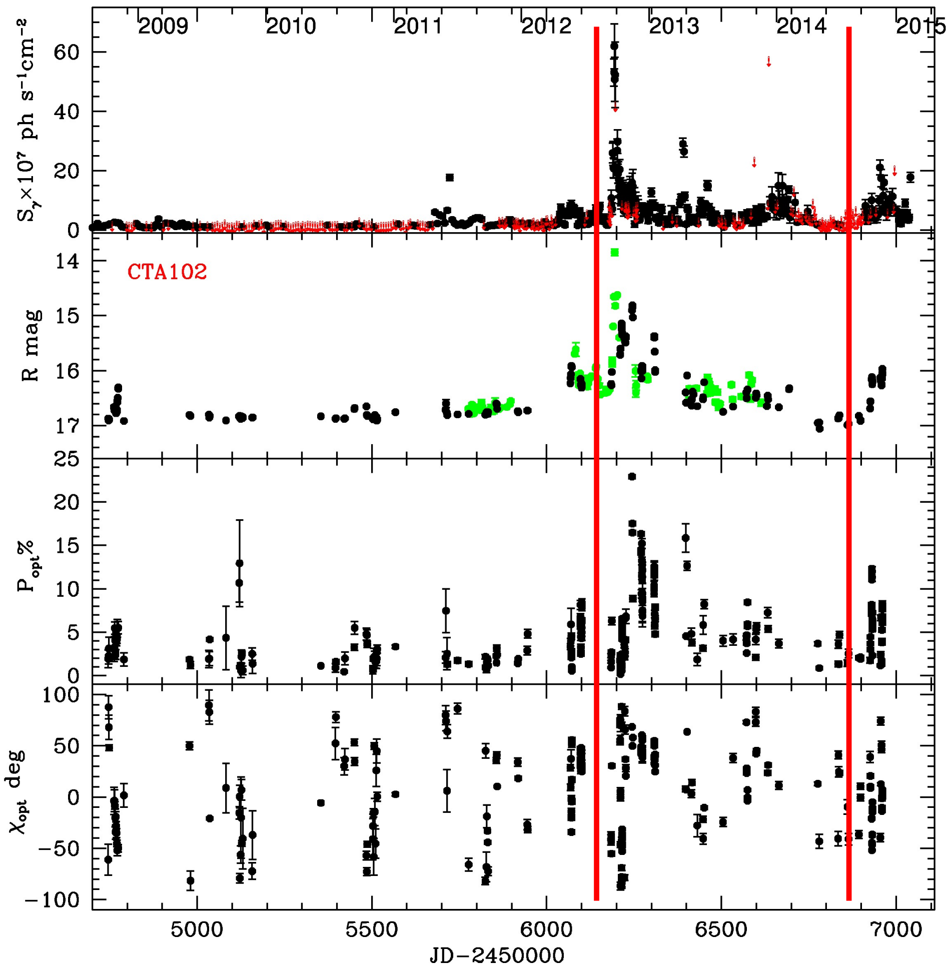
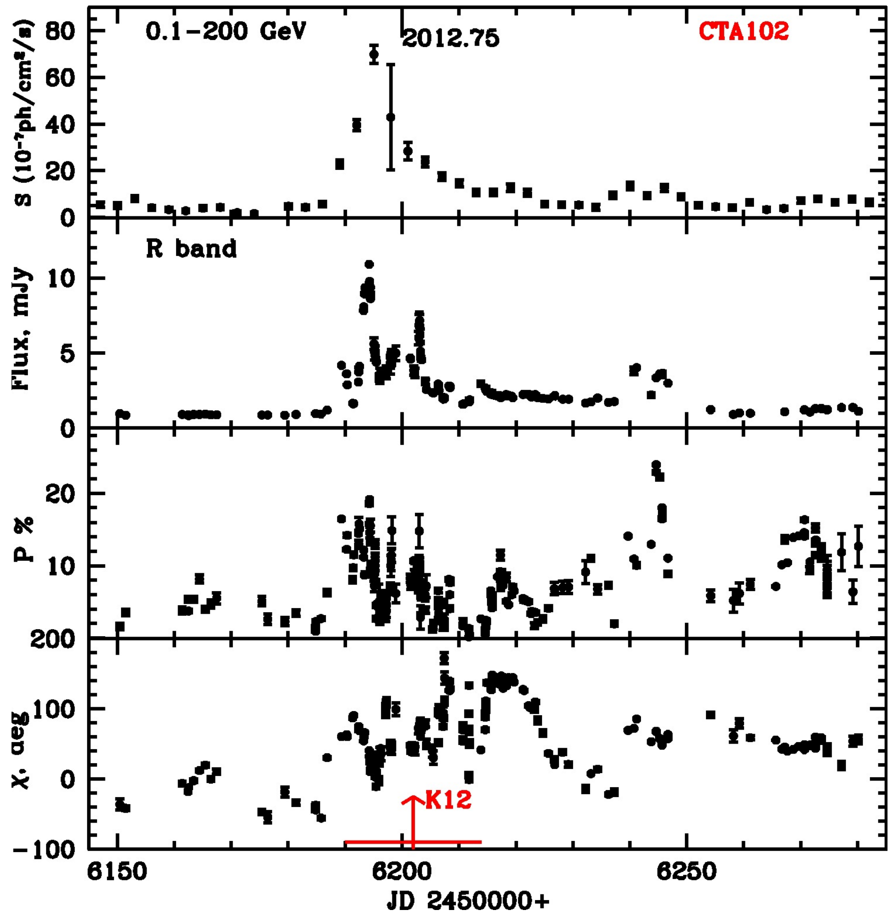
Variations in Linear Polarization: Evidence for a Disordered Magnetic Field Component: The Quasar CTA102





Polarization varies erratically, as expected if it results from turbulence (or some disordering similar to turbulence)

Linear Polarization from Turbulent Cells with Random Field Directions

Case of *N* cells, each with a uniform but randomly directed magnetic field of same magnitude

<u>Mean polarization</u>: $\langle p \rangle = p_{max}/N^{1/2}$ $\sigma_p \approx \langle p \rangle/2$ (Burn 1966, MNRAS)

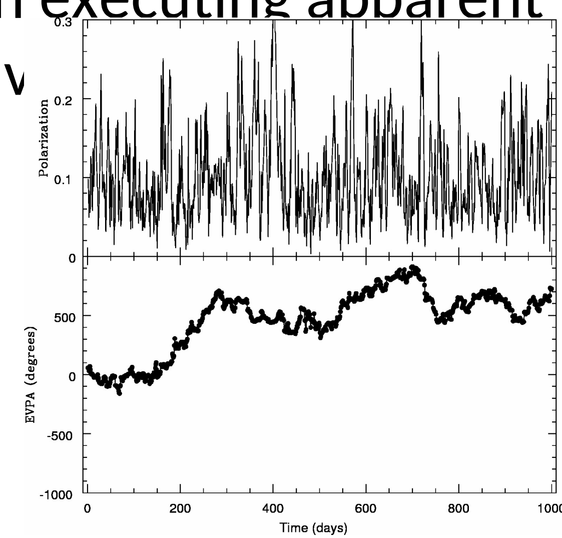
Electric-vector position angle χ can have any value

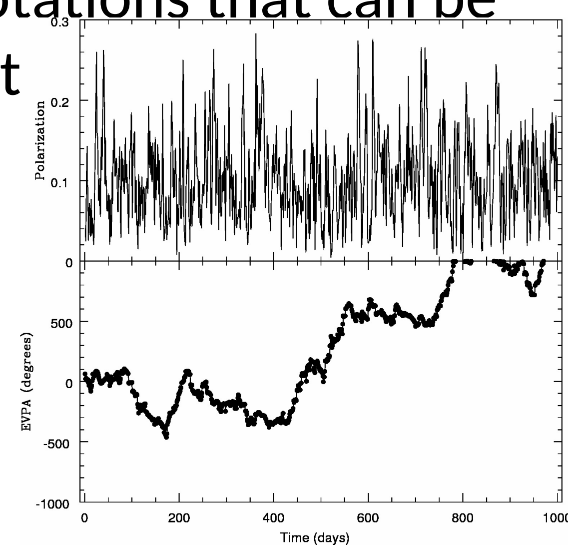
▭ If such cells pass in & out of emission region as time passes,

p fluctuates about $\langle p \rangle$

χ varies randomly, often executing apparent rotations that can be > 180°, usually not v … et

(T.W. Jones 1988, ApJ)





Linear Polarization from a Helical Magnetic Field

Assume that helical field propagates down the jet with the plasma (as in MHD models for jet acceleration & collimation)

$\mathbf{B}' = Bt' \cos\phi \, \boldsymbol{i}' + Bt' \sin\phi \, \boldsymbol{j}' + Bz' \, \boldsymbol{k}'$

Degree of polarization depends on viewing angle & Γ

(see Lyutikov, Pariev, & Gabuzda 2005, MNRAS)

Face-on ($\theta = \theta' = 0$): **p** = 0 (from symmetry) **if Iv is uniform across jet**

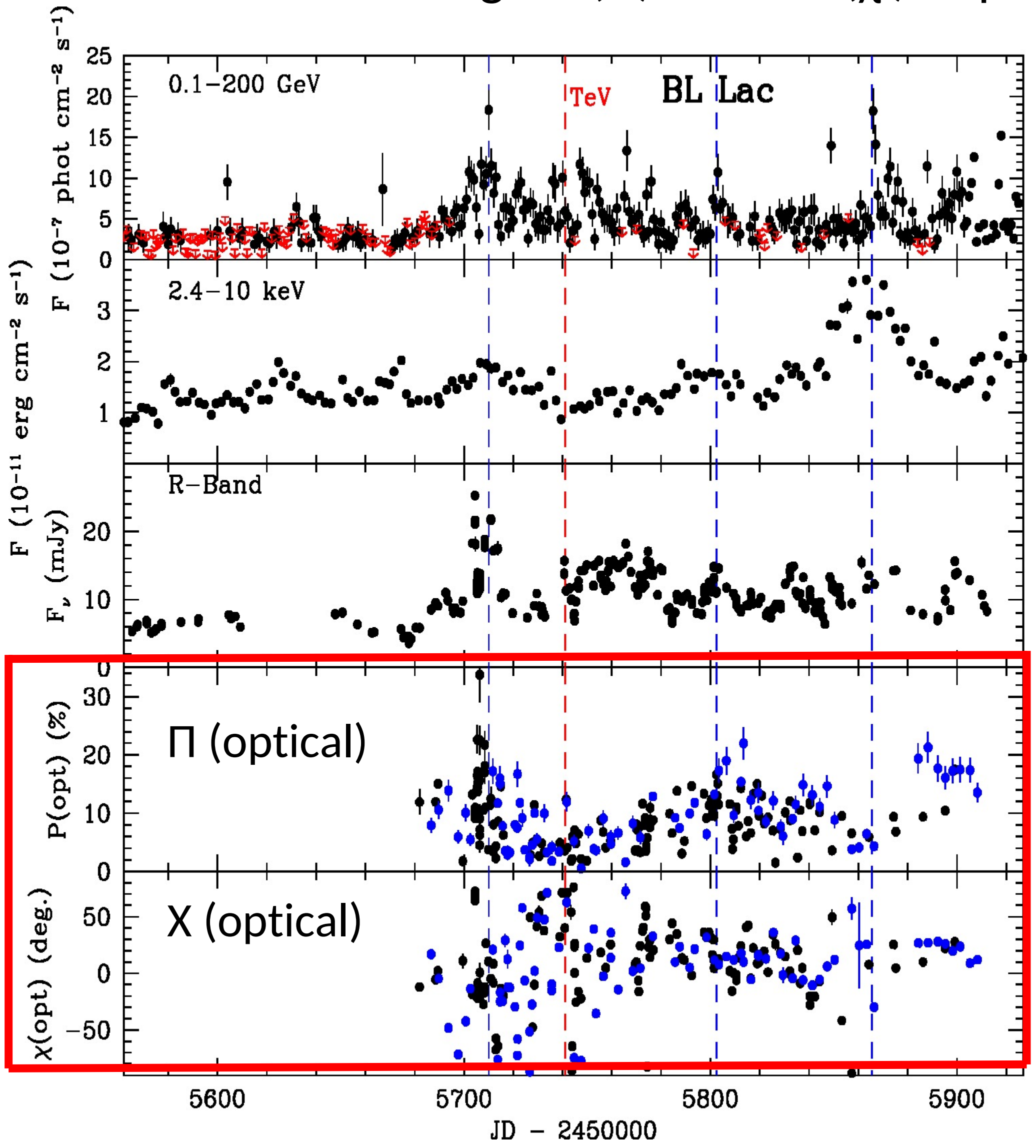
Side-on ($\theta' = 90°$): $\chi = 0°$ if $Bz' < Bt'$ & $\chi = 90°$ if $Bz' > Bt'$

p depends on Bt'/Bz'

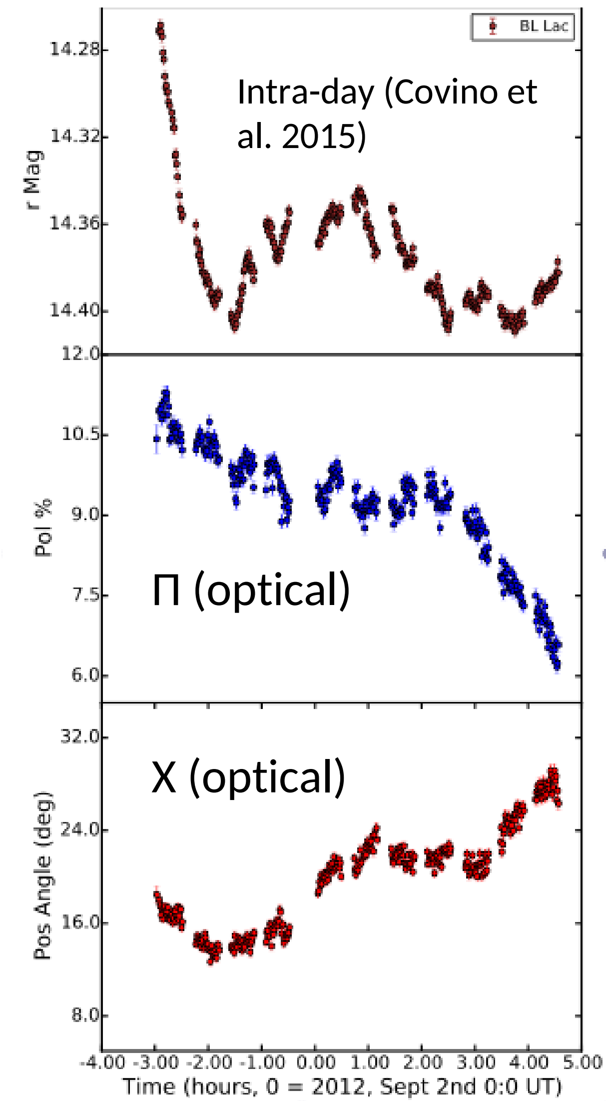
Other angles: qualitatively similar to side-on case

Variations in Linear Polarization: Evidence for a Disordered Magnetic Field Component: BL Lac

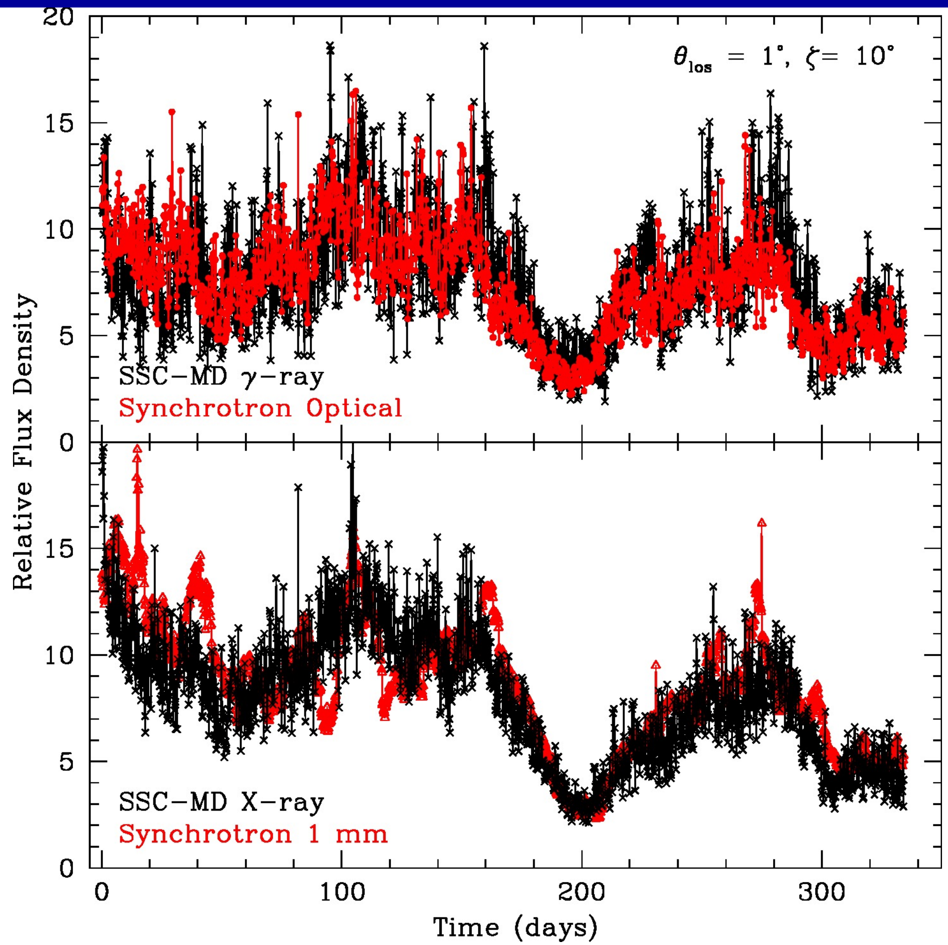
Erratic fluctuations in degree (Π) & EVPA (χ) of polarization

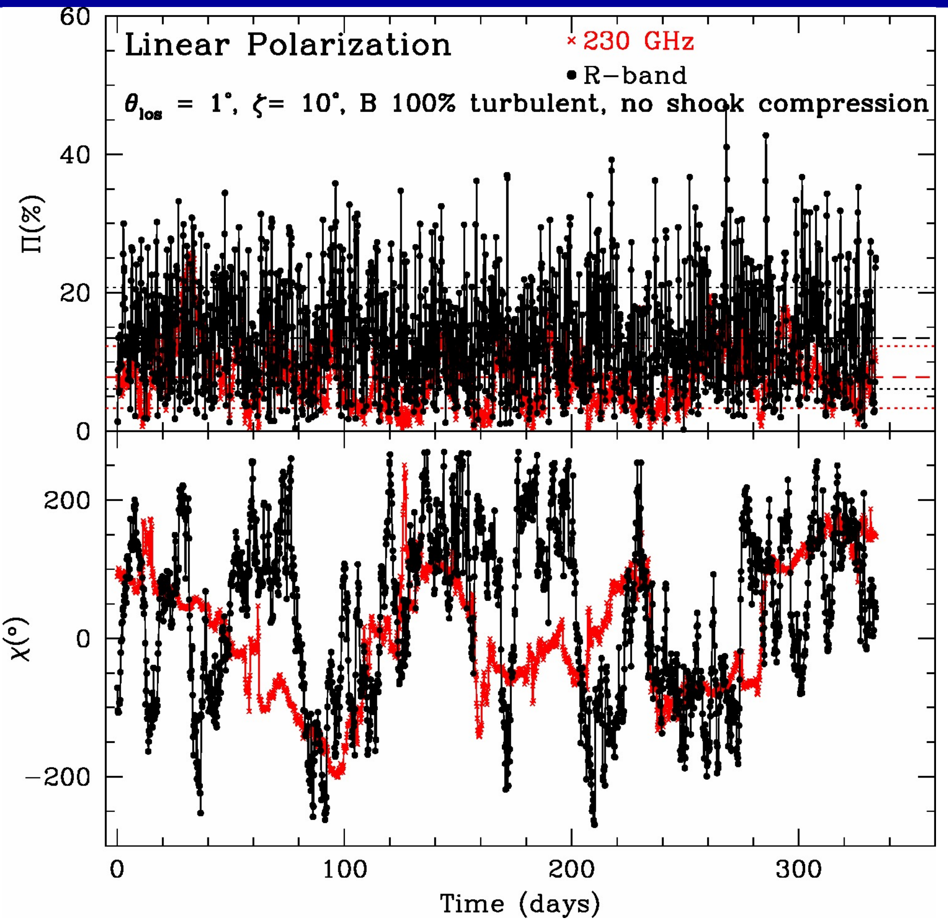


Marscher et al. (in prep)



Sample Simulated Light Curve from Turbulence - Case of 100% turbulent field with no shock





Outbursts & quiescent periods arise from variations in injected electron density

- **Random with red-noise probability distribution**

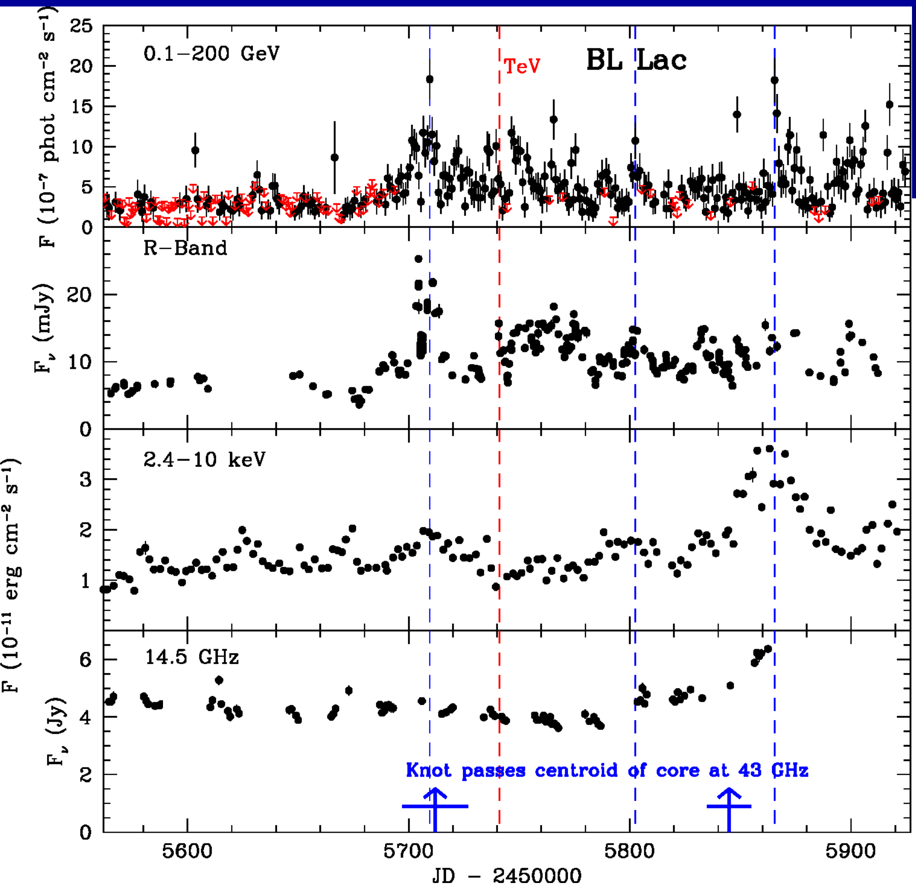
- **Very rapid fluctuations result from turbulence**

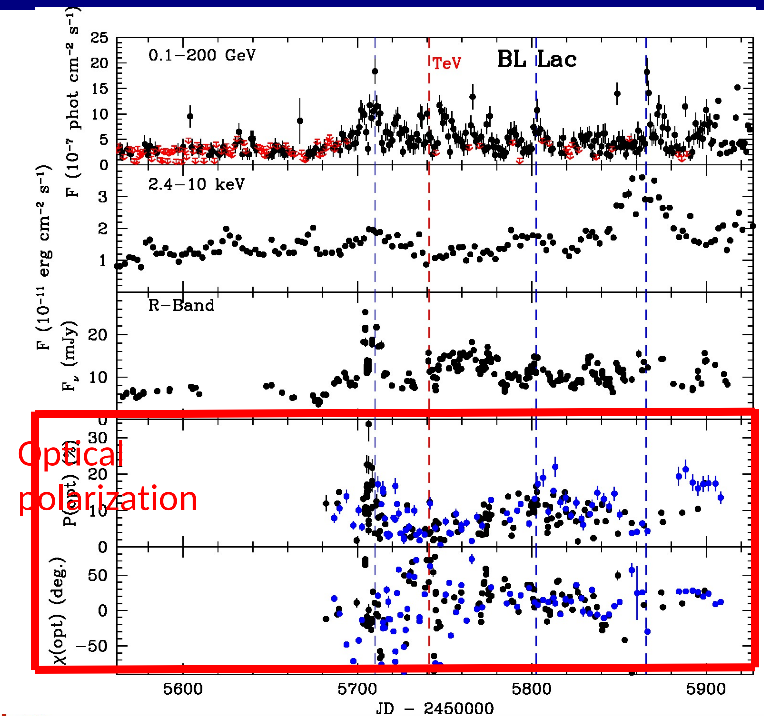
Polarization is stronger at higher frequencies, as generally observed

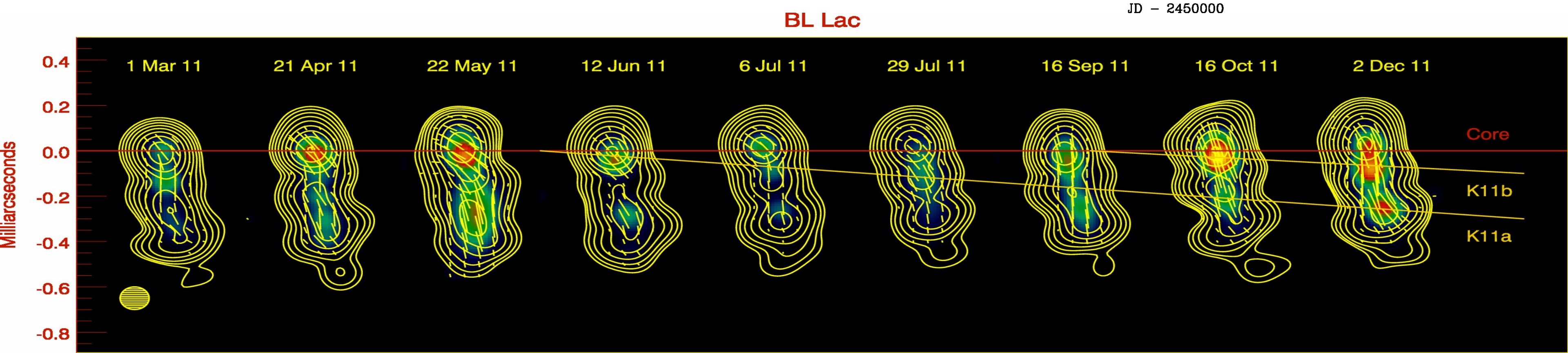
Position angle fluctuates randomly, with apparent rotations (usually not very smooth) in both directions

Where is the jet turbulent? Near the mm-wave “core”

Optical & γ-ray emission becomes bright as new superluminal knots pass through “core” + 2 other stationary emission features on the VLBA image





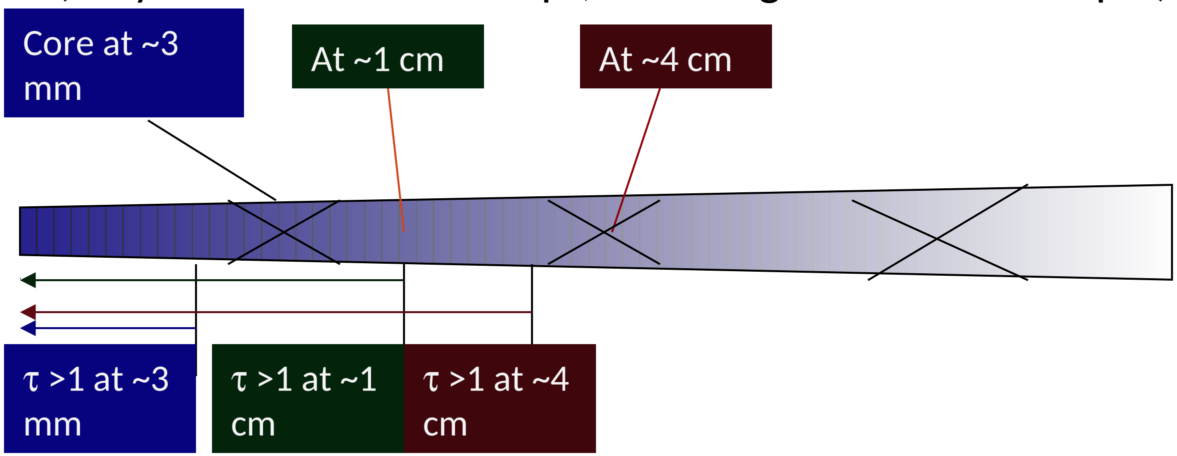


The “Core” of Blazar Jets

Observations suggest that core on VLBI images is either:

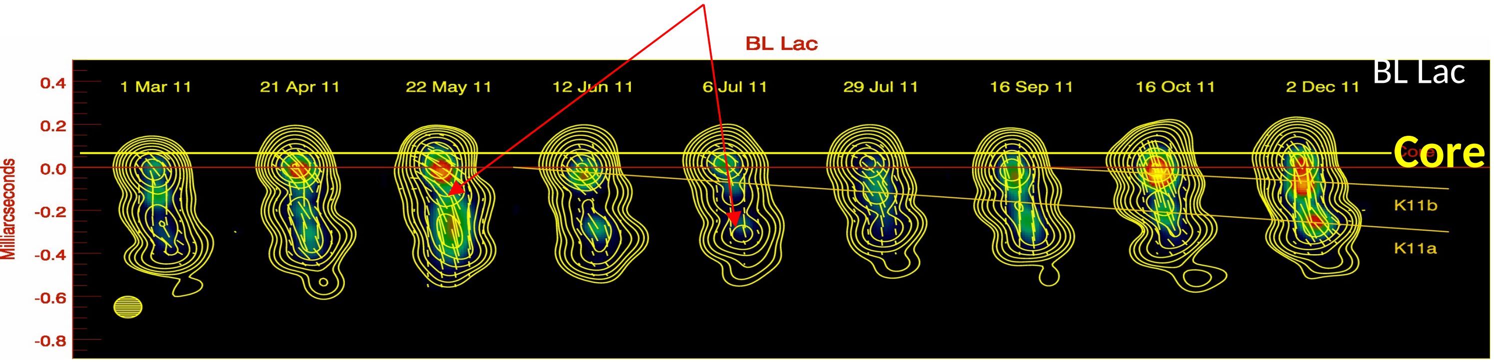
1. τ ~ 1 surface (τ = optical depth to synchrotron absorption)
2. First standing (oblique or conical) shock outside τ ~ 1 surface

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



HD simulation (Gómez et al. 1997)

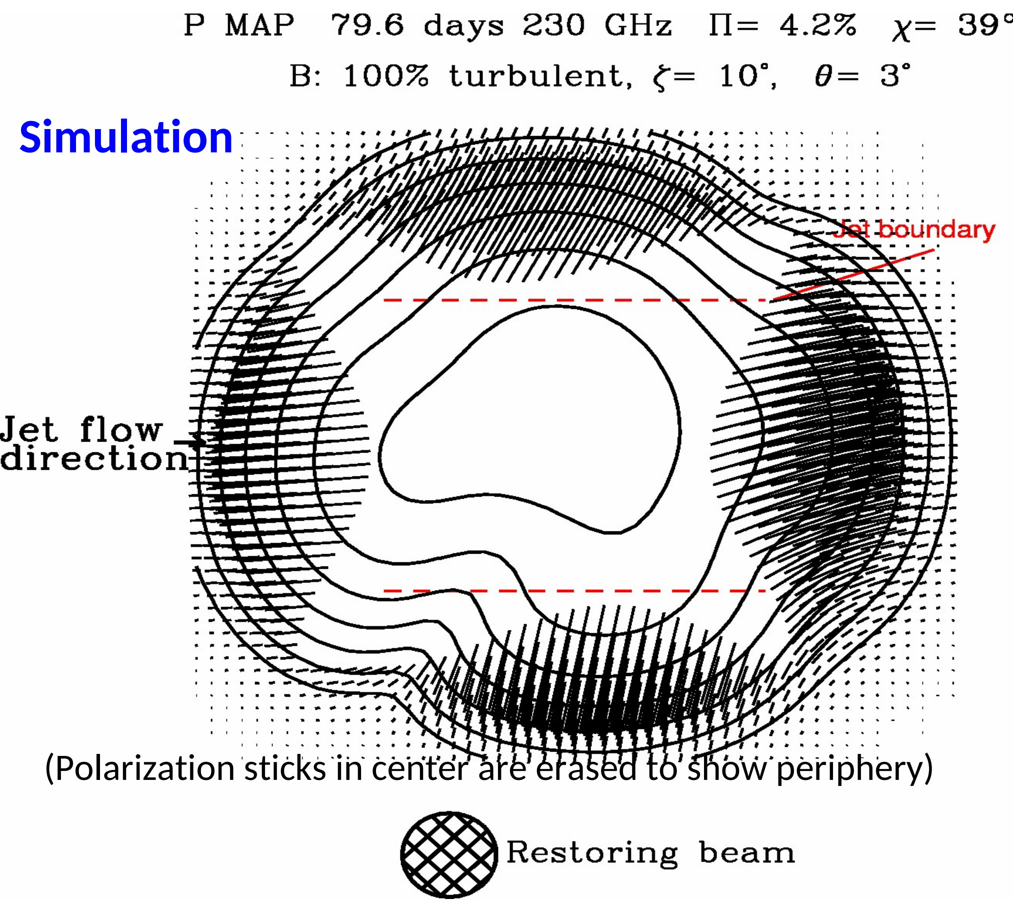
2 ~ stationary features with variable polarization downstream of core



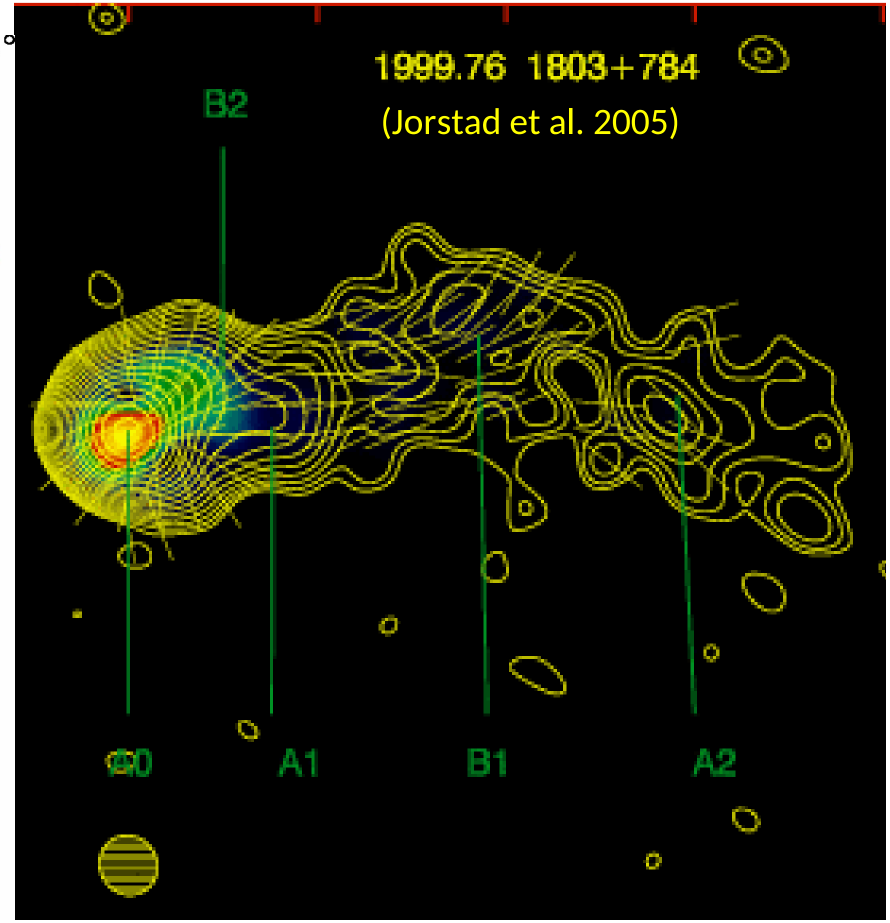
Turbulence in Blazar Jets

Cawthorne (2006, MNRAS), Cawthorne et al. (2013): "Core" seen on 43 GHz VLBA images has radial polarization pattern similar to that of turbulent plasma flowing through a standing, cone-shaped shock

Simulation

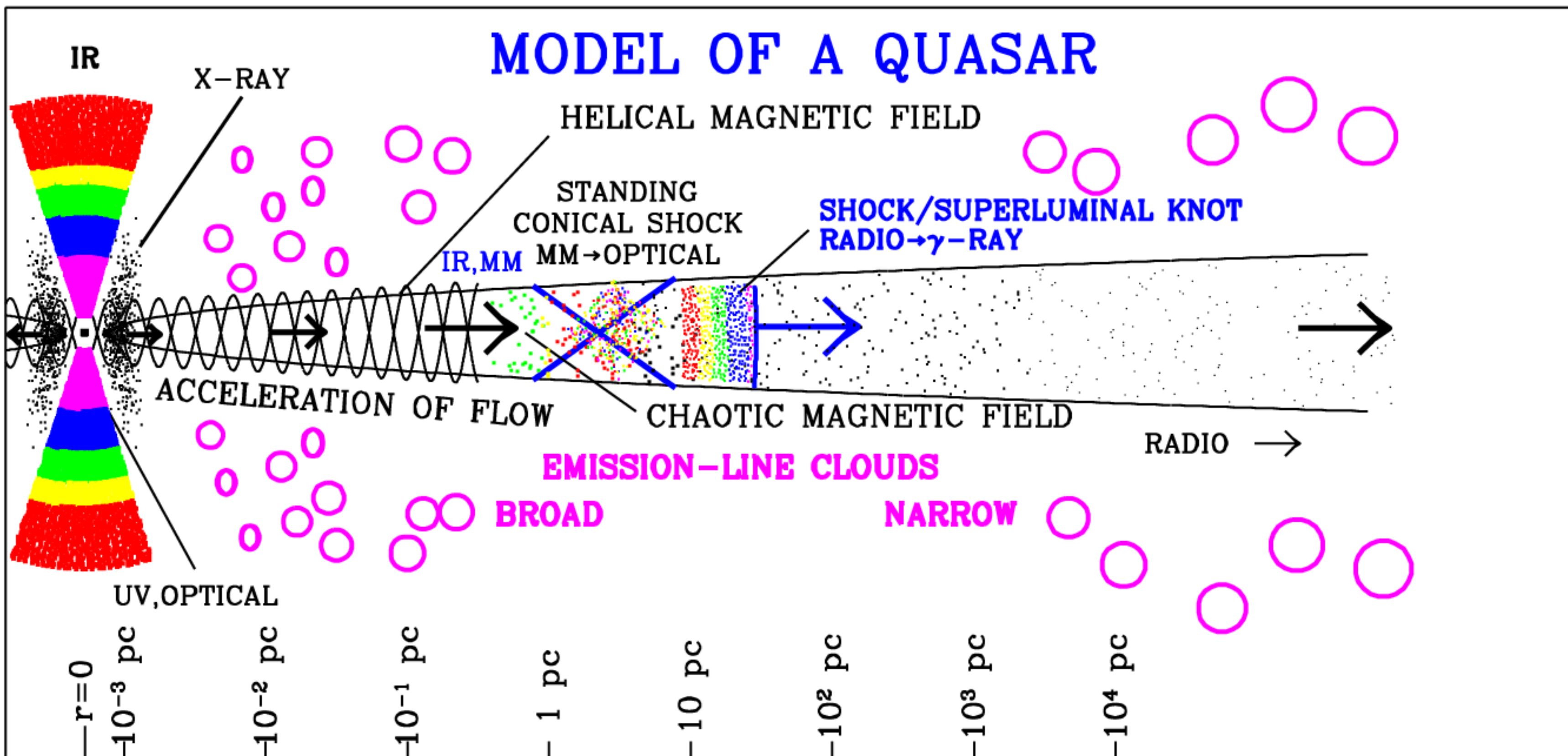


(Polarization sticks in center are erased to show periphery)



Proposed Blazar Model

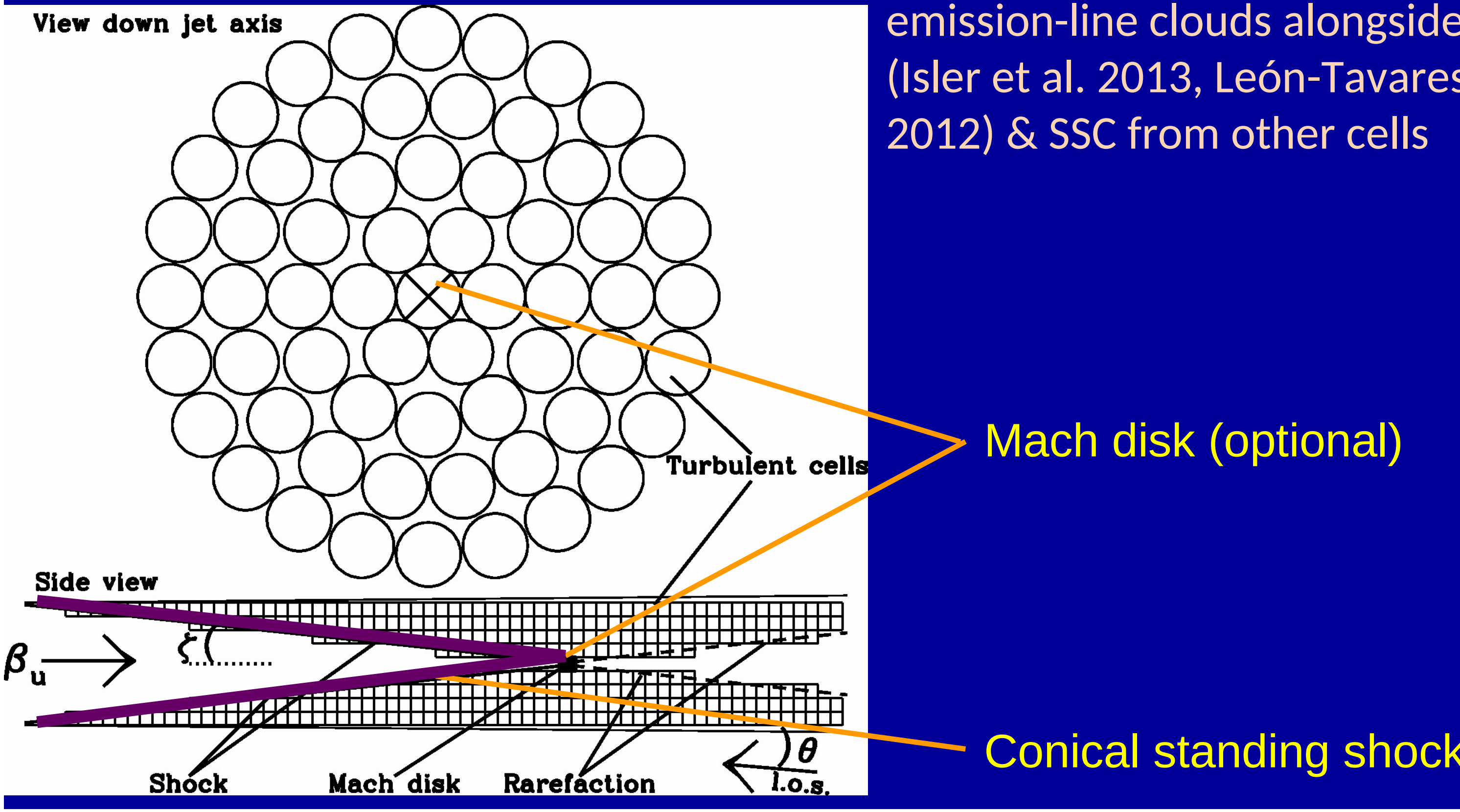
- Strong helical magnetic field in inner jet, turbulence becomes important on parsec scales
- Flares from moving shocks and denser-than-average plasma flowing across standing shock(s)
- Turbulent field accelerates particles via 2nd-order Fermi + magnetic reconnections
- Shocks increase energies of particles, especially in locations where B || shock normal



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

Many (e.g., 169) turbulent cells across jet cross-section, each followed after crossing shock, where e-s are energized & Compton scatter seed photons from dusty torus & Mach disk*; each cell has its own uniform magnetic field selected randomly from turbulent power spectrum + its own e- population

*Plan to add seed photons from emission-line clouds alongside the jet (Isler et al. 2013, León-Tavares et al. 2012) & SSC from other cells



Electron Energy Distribution in TEMZ Code

Power-law (slope= –*s*) injection into cell that is crossing the shock front

- From 2nd-order Fermi + magnetic reconnections upstream of shock

-Synchrotron & external Compton energy losses downstream of shock

-Maximum electron energy produced by shock depends on angle between magnetic field & shock normal

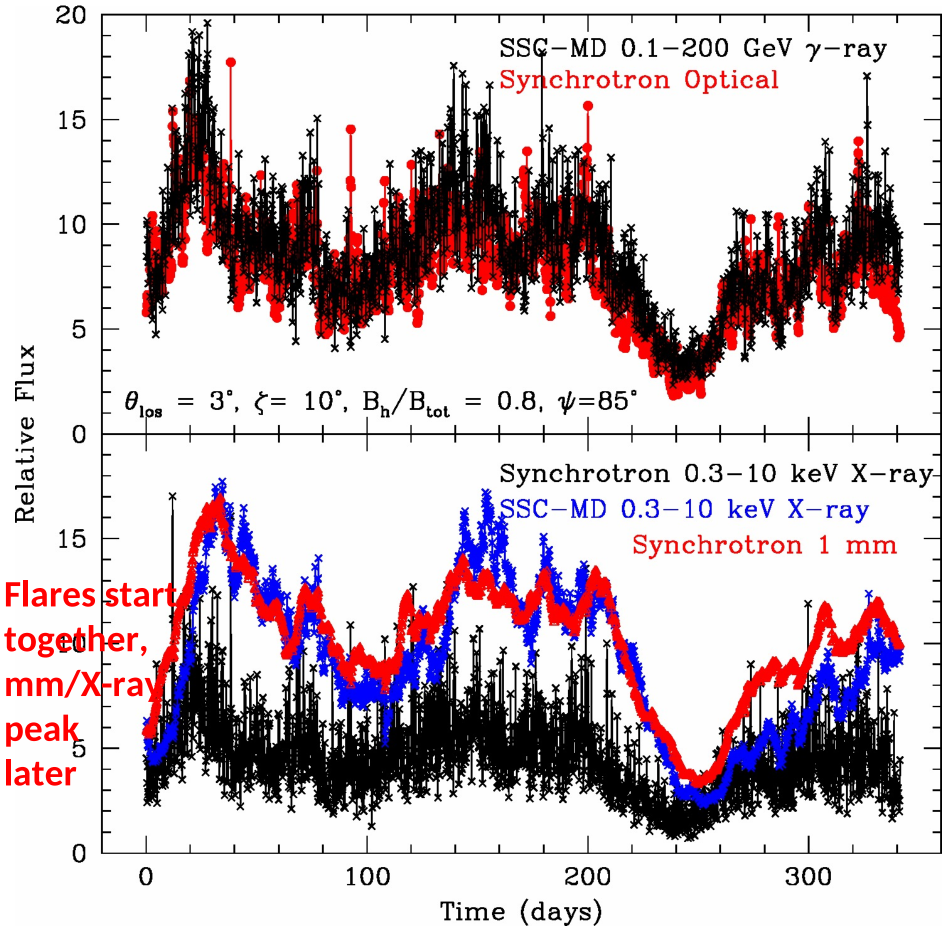
- This restricts optical & γ-ray emission to a small fraction of cells near shock front

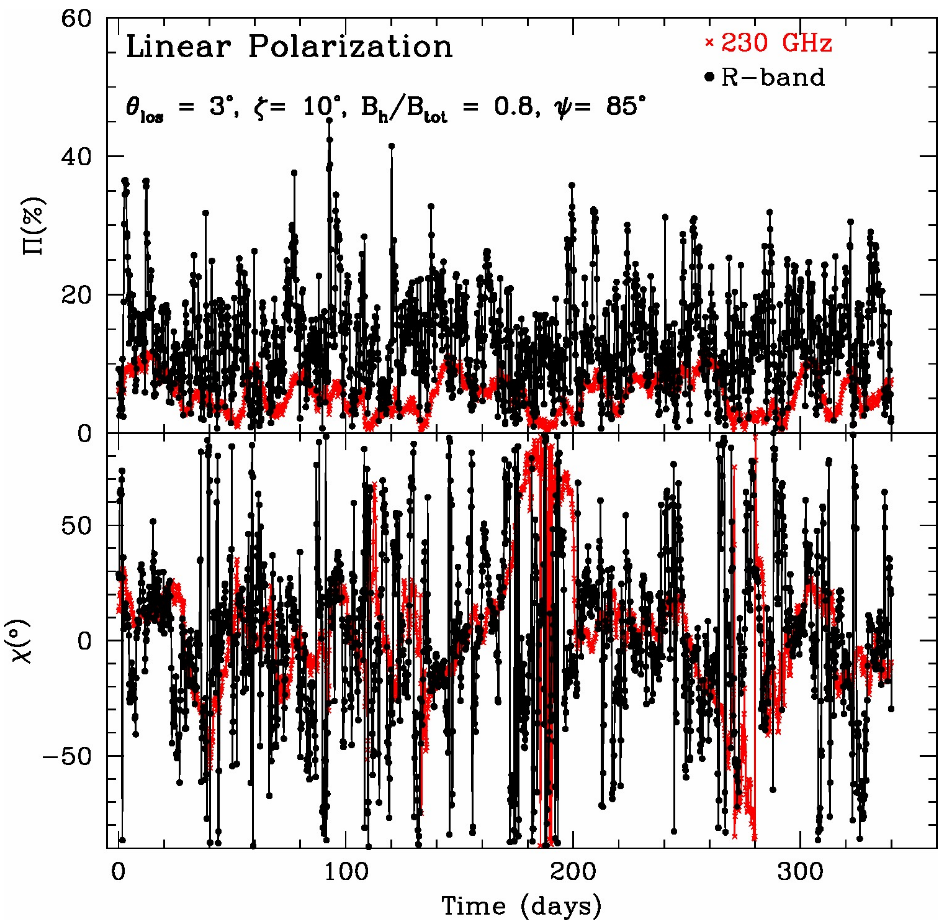
** Spectral index steeper than s/2 (radiative loss value), as observed**

** Mean polarization is higher & fluctuations greater at higher frequencies, as observed**

** Optical & γ-ray flux variability more pronounced than in mm-IR & X-ray**

Sample Simulated Light Curve Similar to BL Lac
Case of 20% turbulent, 80% helical field ahead of standing shock





Outbursts & quiescent periods arise from variations in injected electron density

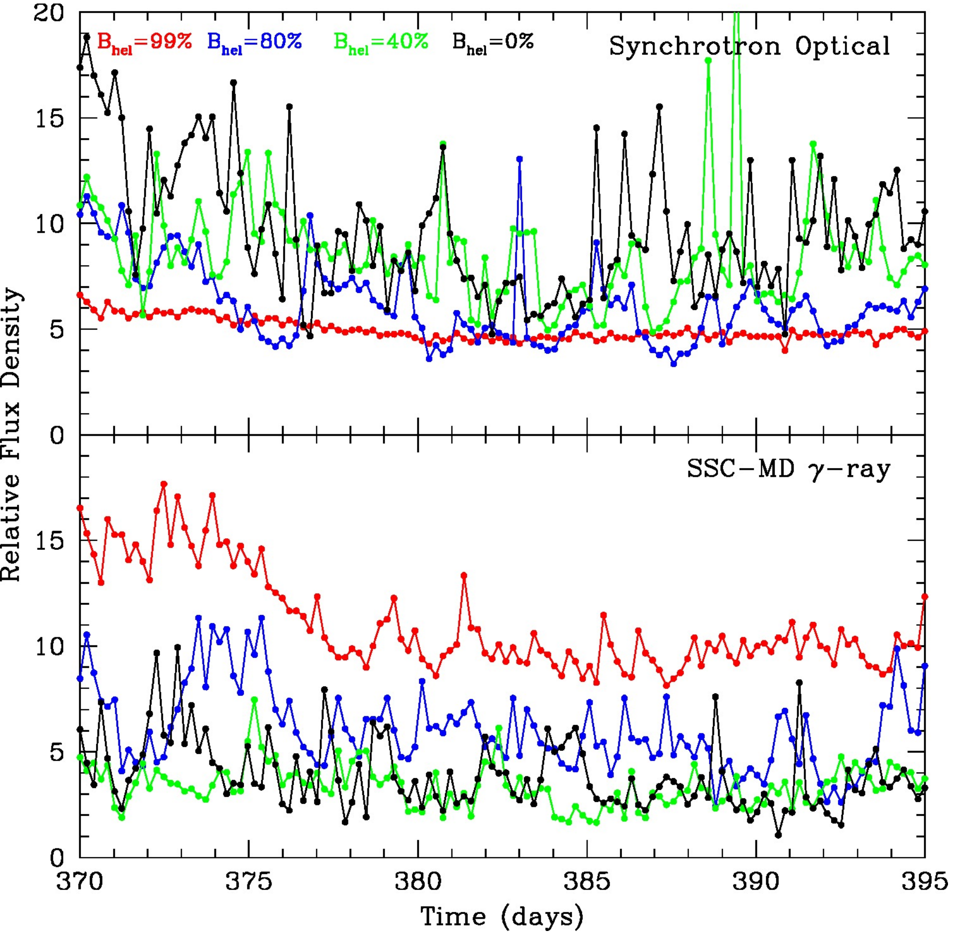
- Random with red-noise probability distribution

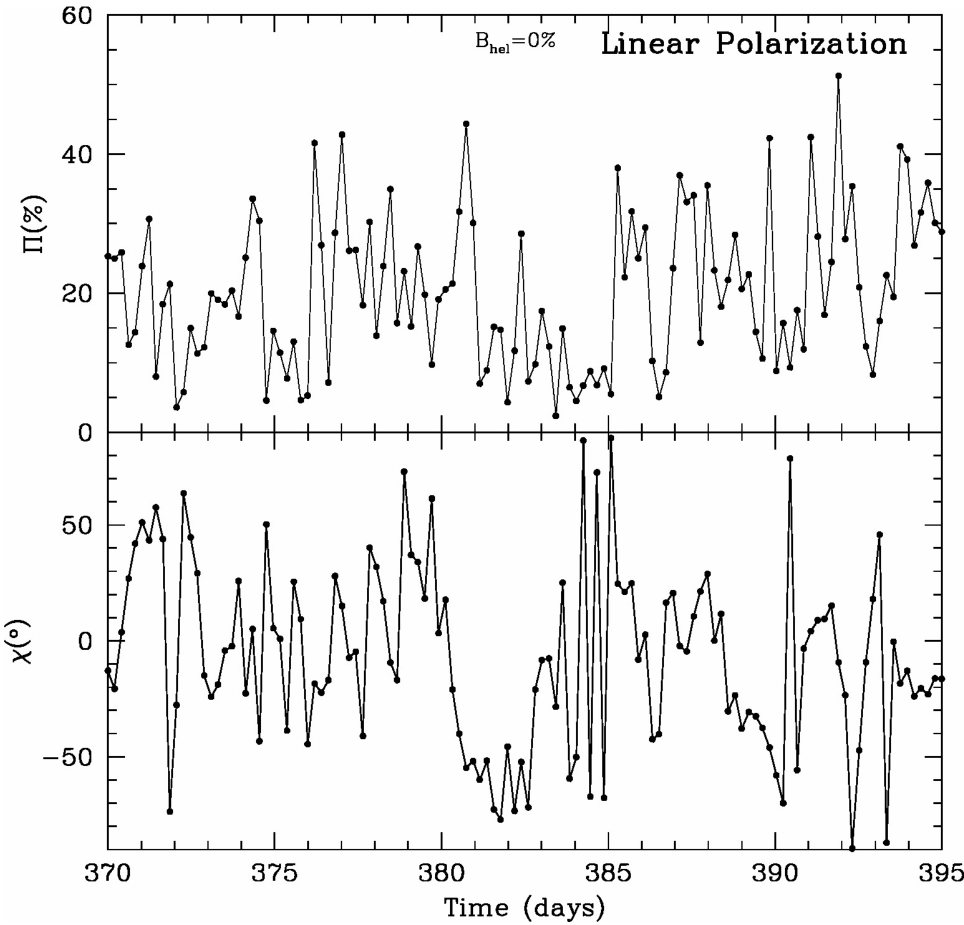
Most flares are sharply peaked, as often observed

Polarization is stronger at higher frequencies, as generally observed

Position angle fluctuates, but is usually within 50° of jet direction (as observed in BL Lac)

25-day Blow-up to See Details for Different Levels of Helical Field





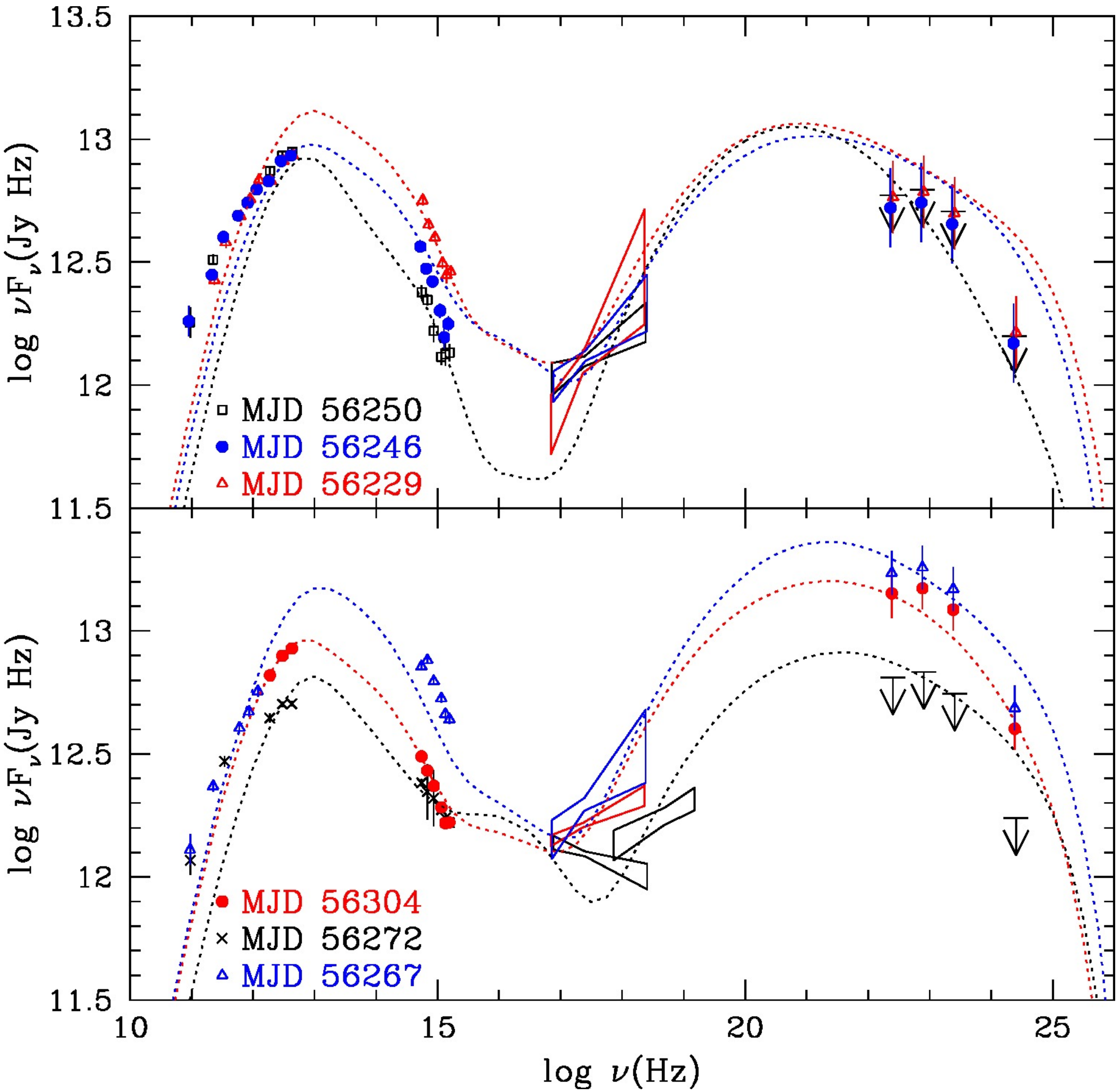
Up to ~50% of the magnetic field can be toroidal without strongly affecting the variability characteristics of either the multi-waveband flux or the optical polarization! Even 80% toroidal varies rapidly.

For viewing angles < 1/2Γ, helical field can decrease <Π> to match observed value

Sample Simulated Spectral Energy Distribution

Data: BL Lac at different times

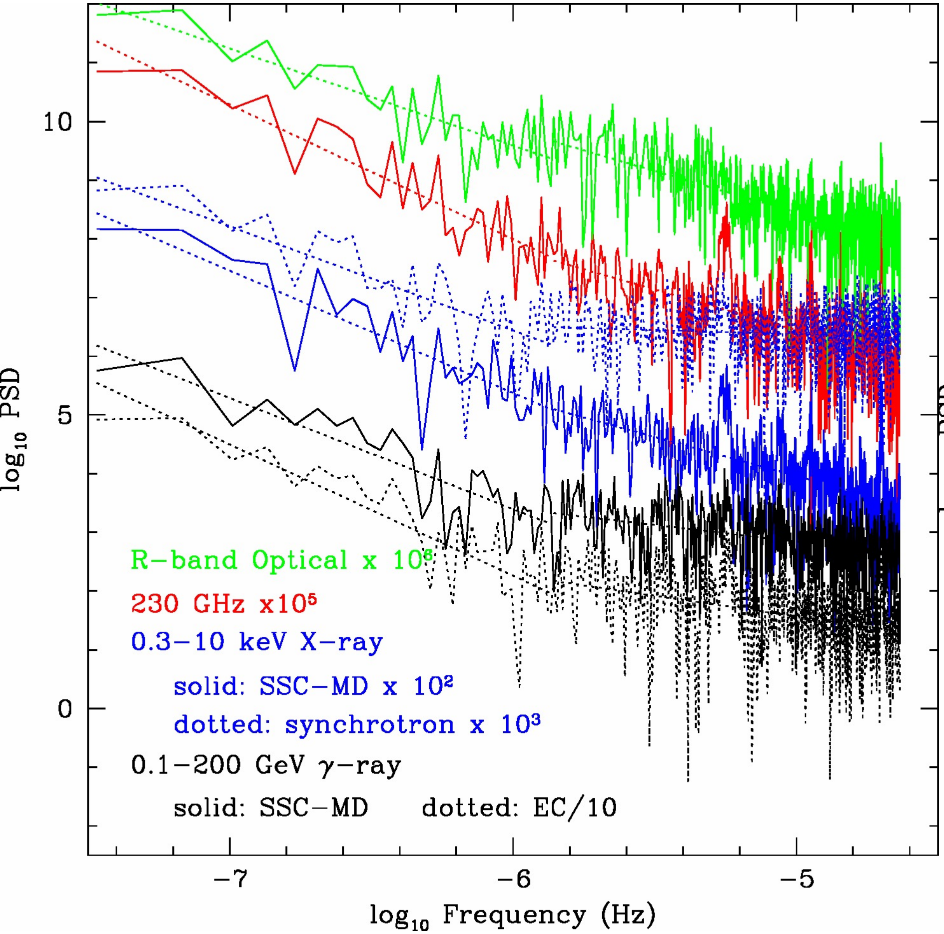
(Wehrle et al. 2015, ApJ, submitted)

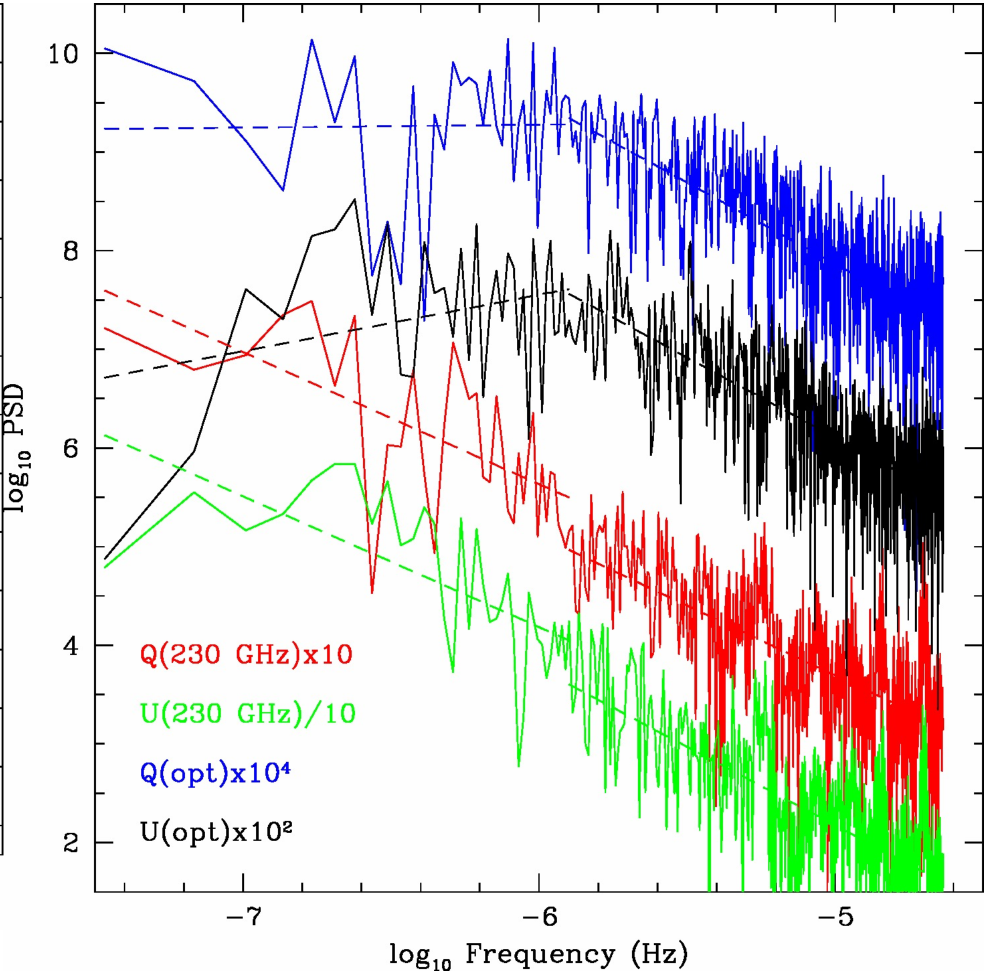


Power Spectra of Polarization Variations of Simulation

Flux Power spectrum slope -1.6 to -2.3 on long time-scales (low variational frequencies), flattens on shorter time-scales

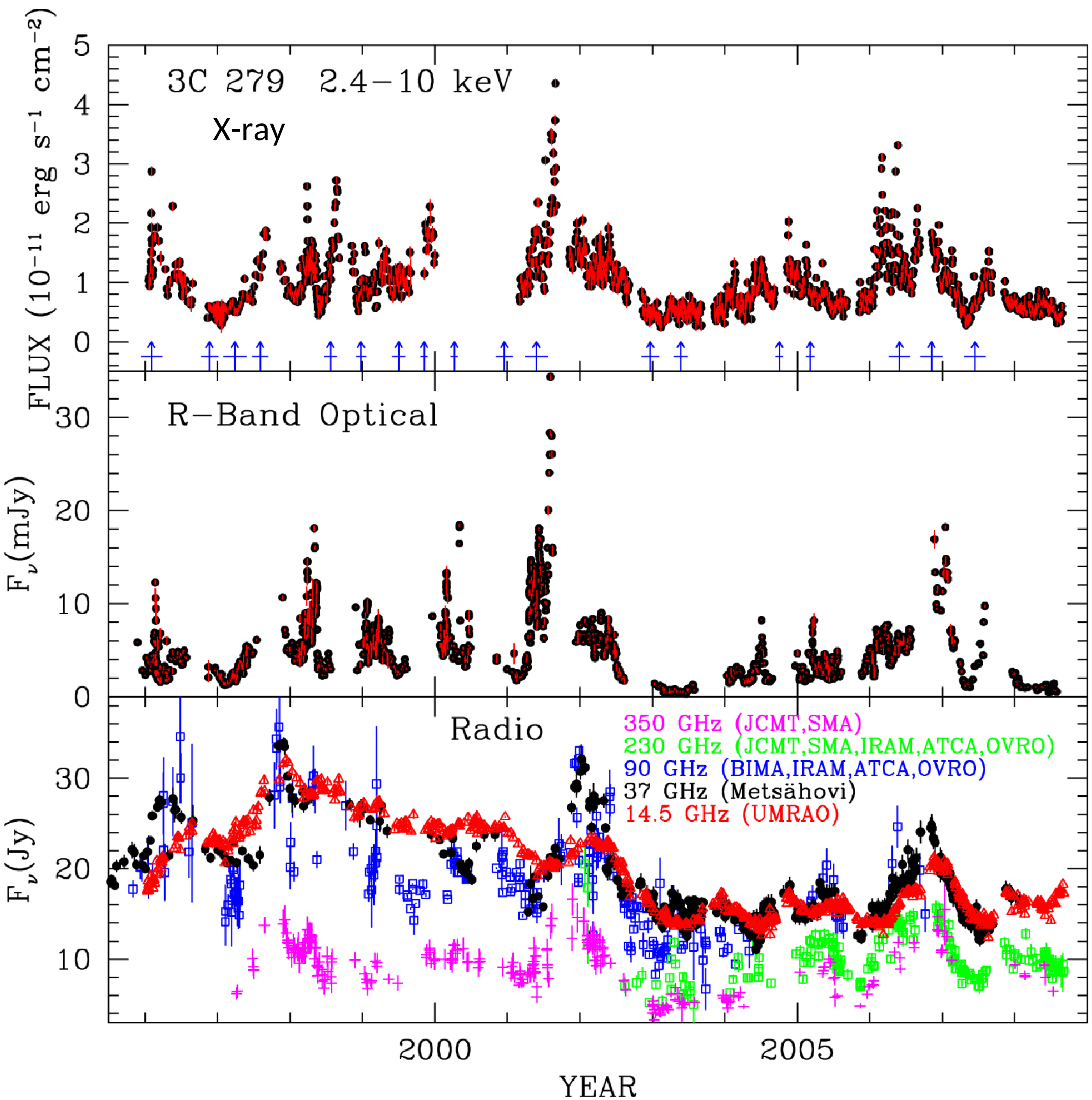
Stokes parameters: Power spectrum slope ~ -1.6 on short time-scales (high variational frequencies), flattens on longer time-scales



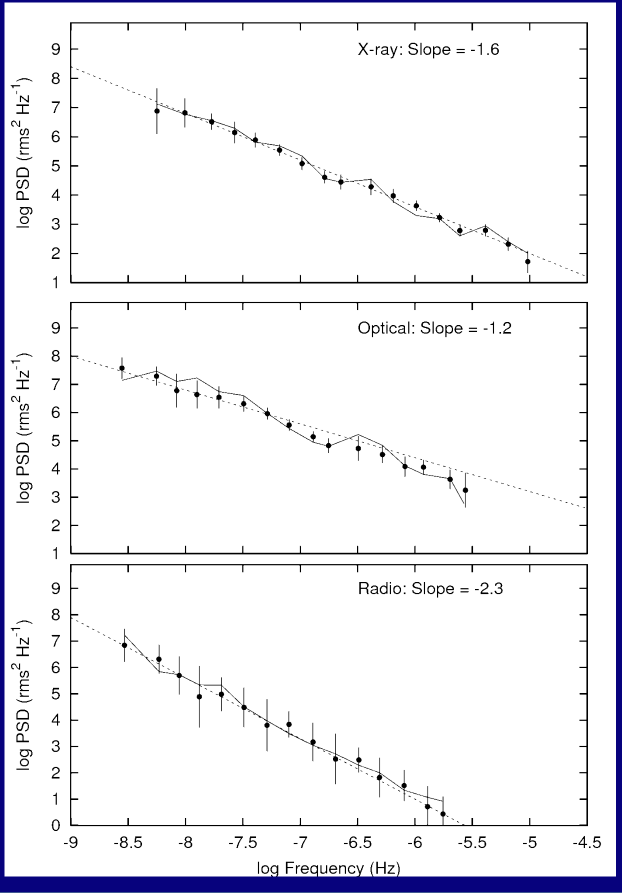


Break frequency higher for more turbulent field

Flux Variability of Blazars: Power-law Power Spectra

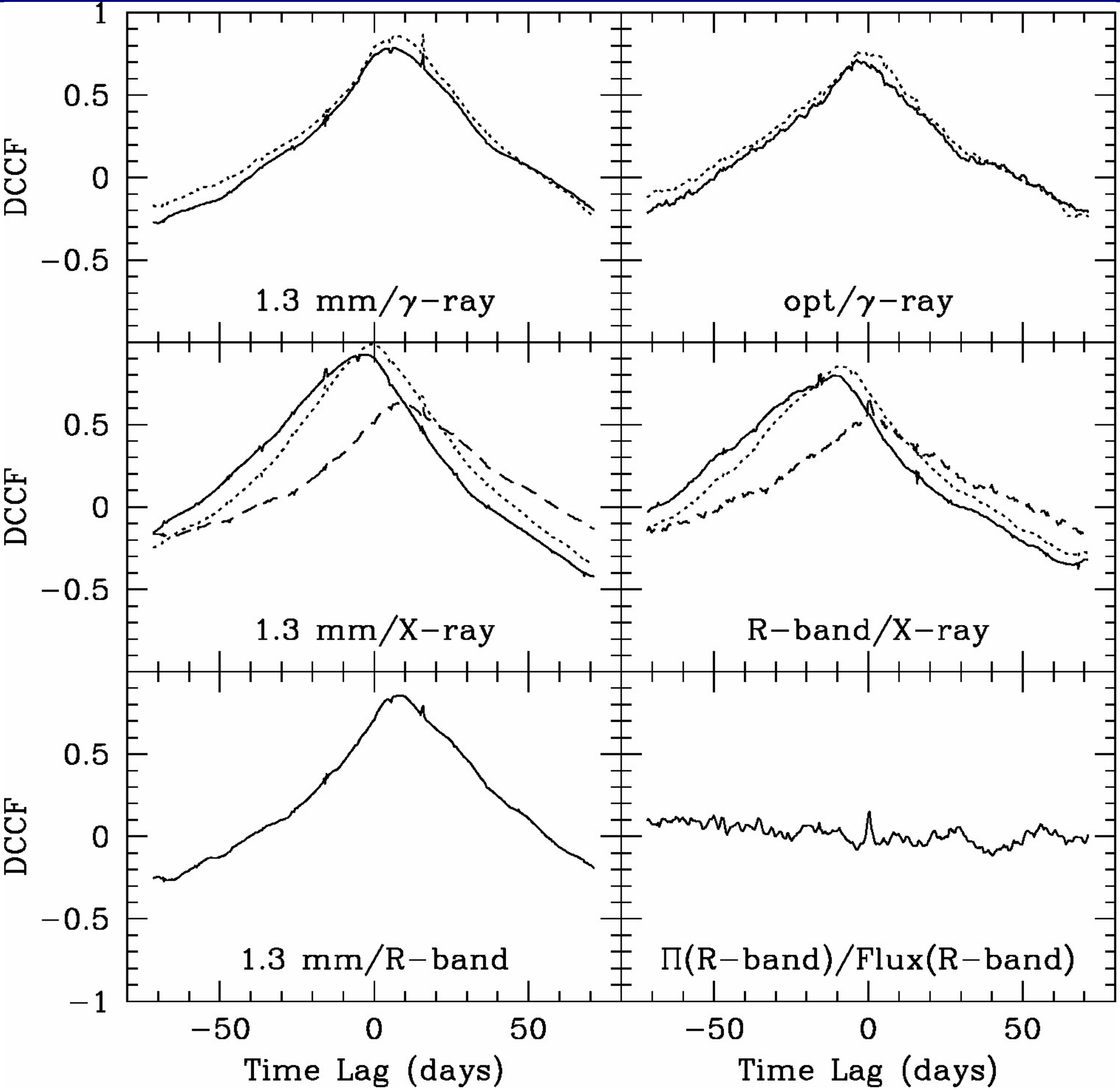


Power spectrum of flux changes follows a power law ⇒ random fluctuations dominate ⇒ turbulence?



Chatterjee et al. 2008 ApJ

Sample Correlations from Simulations



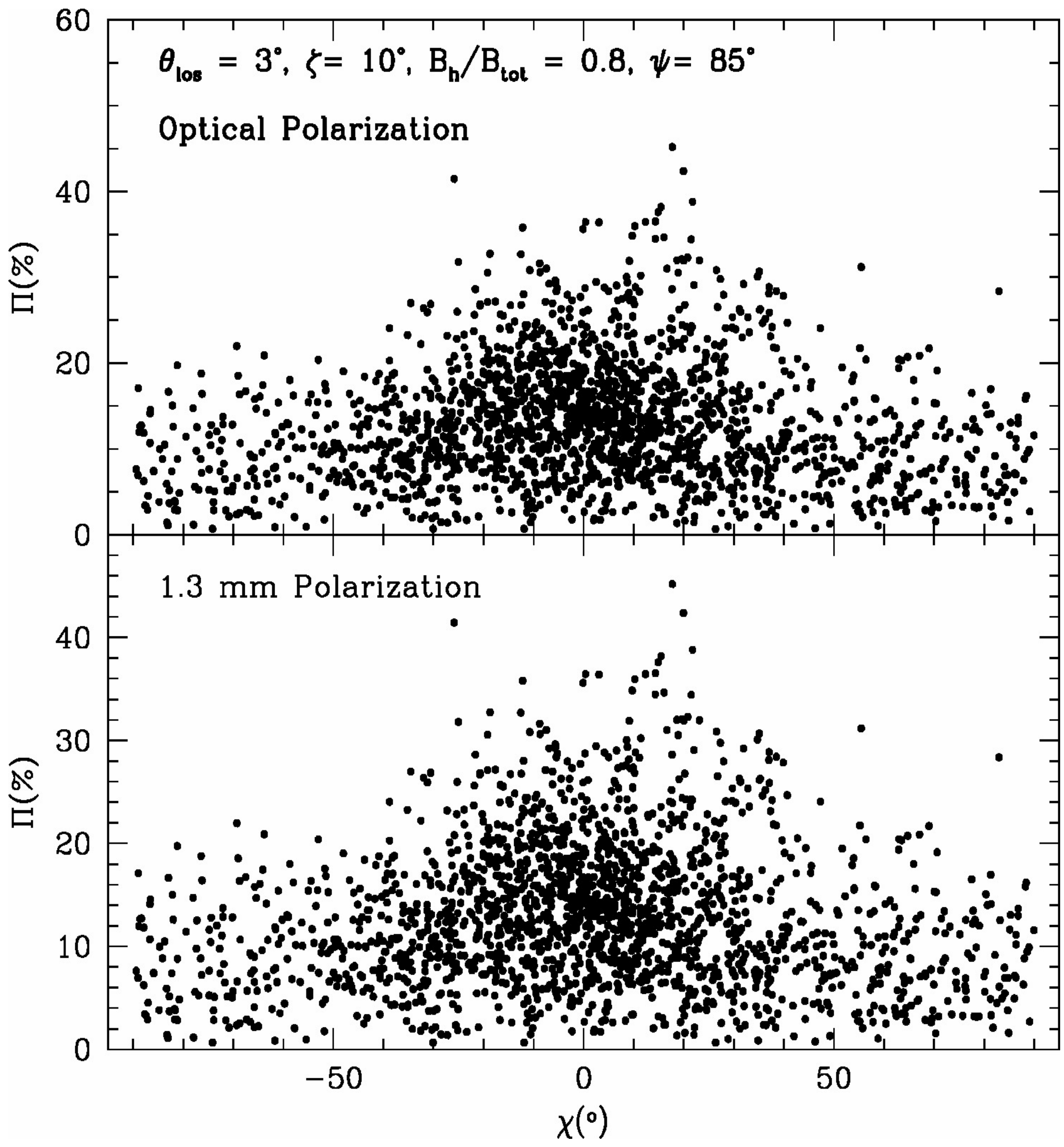
Positive lag: 2nd waveband leads

Solid: SSC-MD
Dotted: EC-dust
Dashed: Synchrotron

Note time lags up to 10 days despite all emission occurring in "core" = standing conical shock region parsecs from black hole

No Big Blue Bump emission included; otherwise there would be a stronger Π(opt) – Flux(opt) correlation

Difference between EVPA & Jet Direction vs. Degree of Pol.

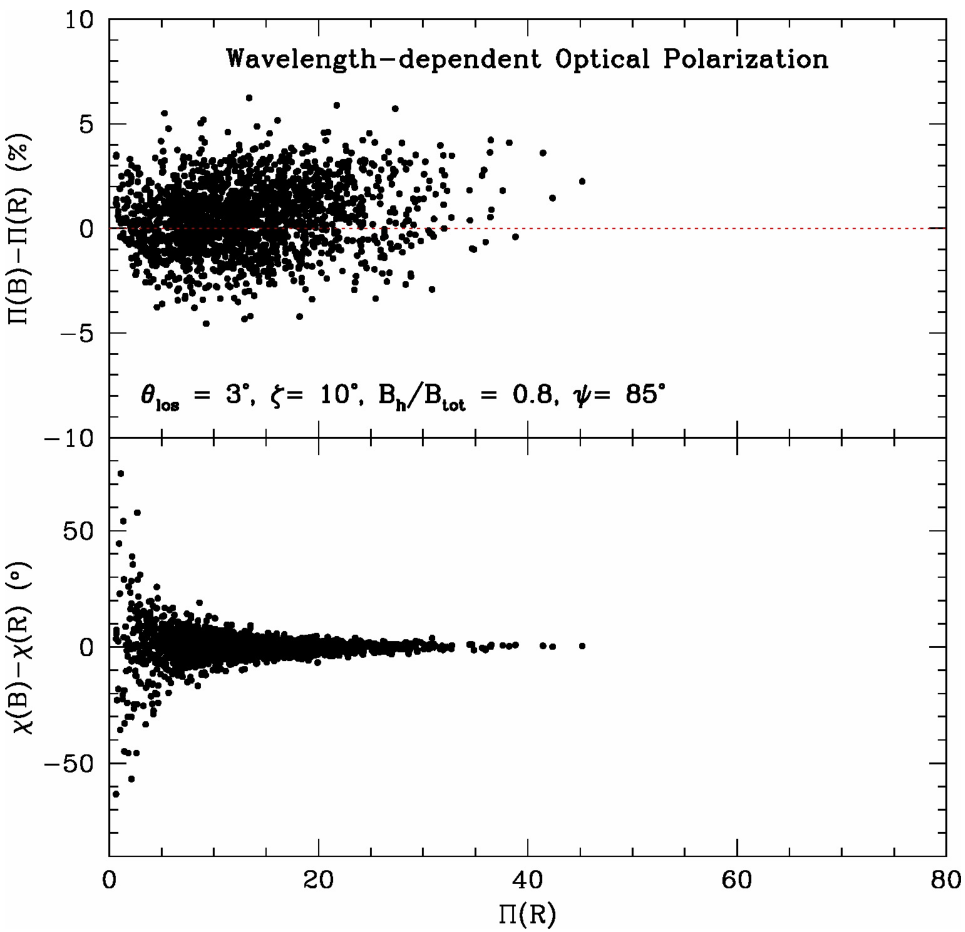


Difference larger at lower polarization levels

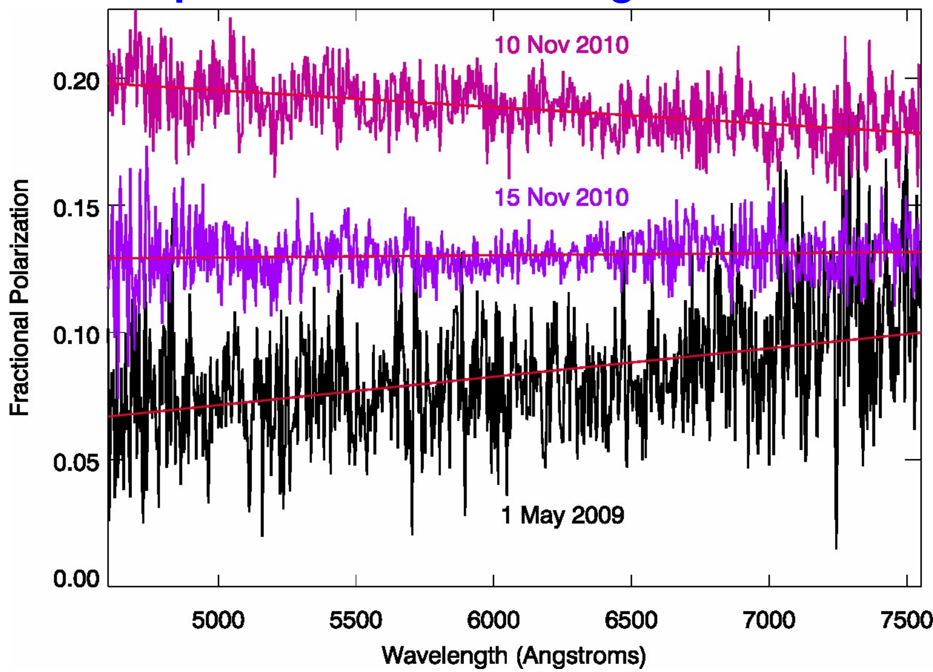
- **Can compare quantitatively to observations**

Wavelength Dependence of Optical Polarization

Simulated: More common: Π(B-band) > Π(R-band)
Large difference in χ only when Π < 3°



Sample observed wavelength



3C 454.3 during brightest state (Jorstad et al. 2013)
(Note that there is significant big blue bump emission at low flux levels.)

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/Γflow (Jorstad et al. 2005; Clausen-Brown et al. 2013)**
- **Half-width of jet at core ~ 0.1 *d*(core,pc) Γflow-1 pc (observed in typical quasar: ~0.1 pc)**

“Blob” is ~ 5-10 times smaller than cross-section

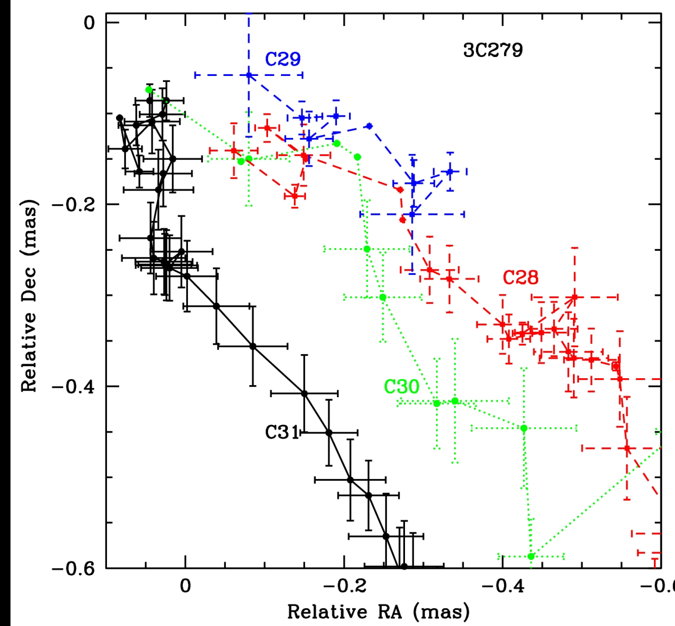
- **If filling factor *f* of cells with electrons of high enough energy to emit at at optical/gamma-ray frequencies is low, time-scale of variability can be very short:**

***t*var ~ 30 *f*1/2 (1+z) (Γflow δflow δturb)-1 *d*(core,pc) days**

For *f* ~ 0.1, z ~ 0.5, Γflow ~ δflow ~ 30, δturb ~ 2, *d*(core) ~ 10 pc,

***t*var ~ 2 hours**

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



CONCLUSIONS

Combined international effort is now producing multi-waveband flux & polarization data with sufficient time coverage to follow variations in dozens of blazars

Patterns are seen in data – some apparently systematic, others apparently random – that we can interpret in terms of physical properties of the jets

Erratic variations of flux & polarization indicate that turbulence is important, but there is also ordering of field relative to jet direction [illegible] shock(s)

Polarization of mm-wave "core" is consistent with conical shock

Acceleration of electrons can be combination of 2nd-order Fermi + reconnections from turbulence, with boost to highest energies in shocks

Model with turbulence + shock(s) shows promise in explaining much of the multi-waveband flux & polarization vs. time (as well as SEDs) of blazars

Statistics of flux & polarization variations are sensitive to level of turbulence

mm-wave VLBI polarized intensity images (e.g., with EHT) test "core" = conical shock scenario