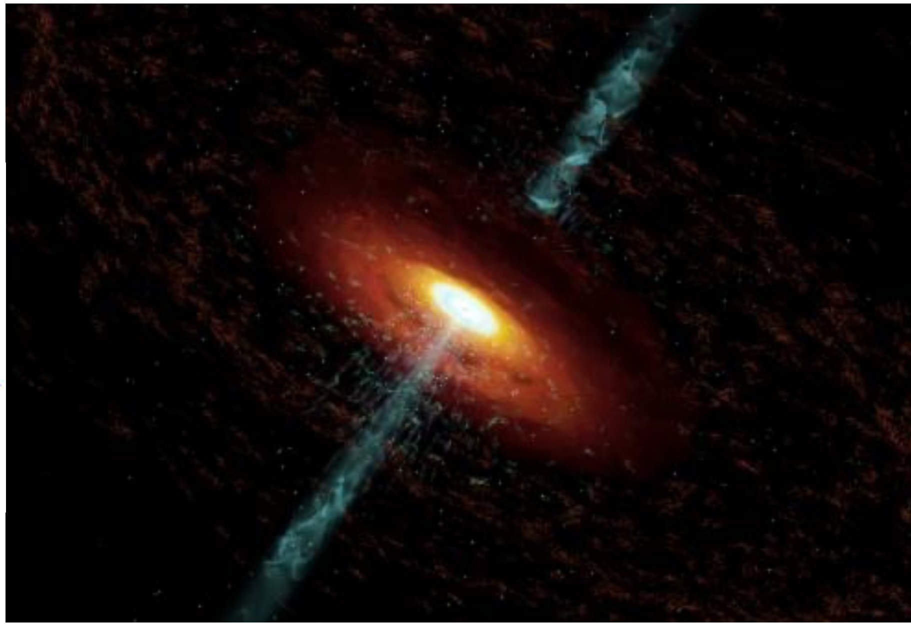


Multi-wavelength Polarization, Variability, and Energy Stratification in Blazar Jets

Prof. Alan Marscher

Institute for Astrophysical Research, Boston University

Research Web Page: www.bu.edu/blazars

Main Telescopes Used

mm-wave **VLBI: VLBA, GMVA, EHT**

mm/submm/IR: **Metsähovi, SMA, IRAM, Herschel**✝️

Optical: **Perkins (BU), Crimean Astrophysical Obs., St. Petersburg U. Obs., Calar Alto Obs., Steward Obs., et al.**

X-ray: **RXTE**✝️, **NuSTAR**, **IXPE, NICER**

γ-ray: **Fermi** Optical-UV-X-ray: **Swift**

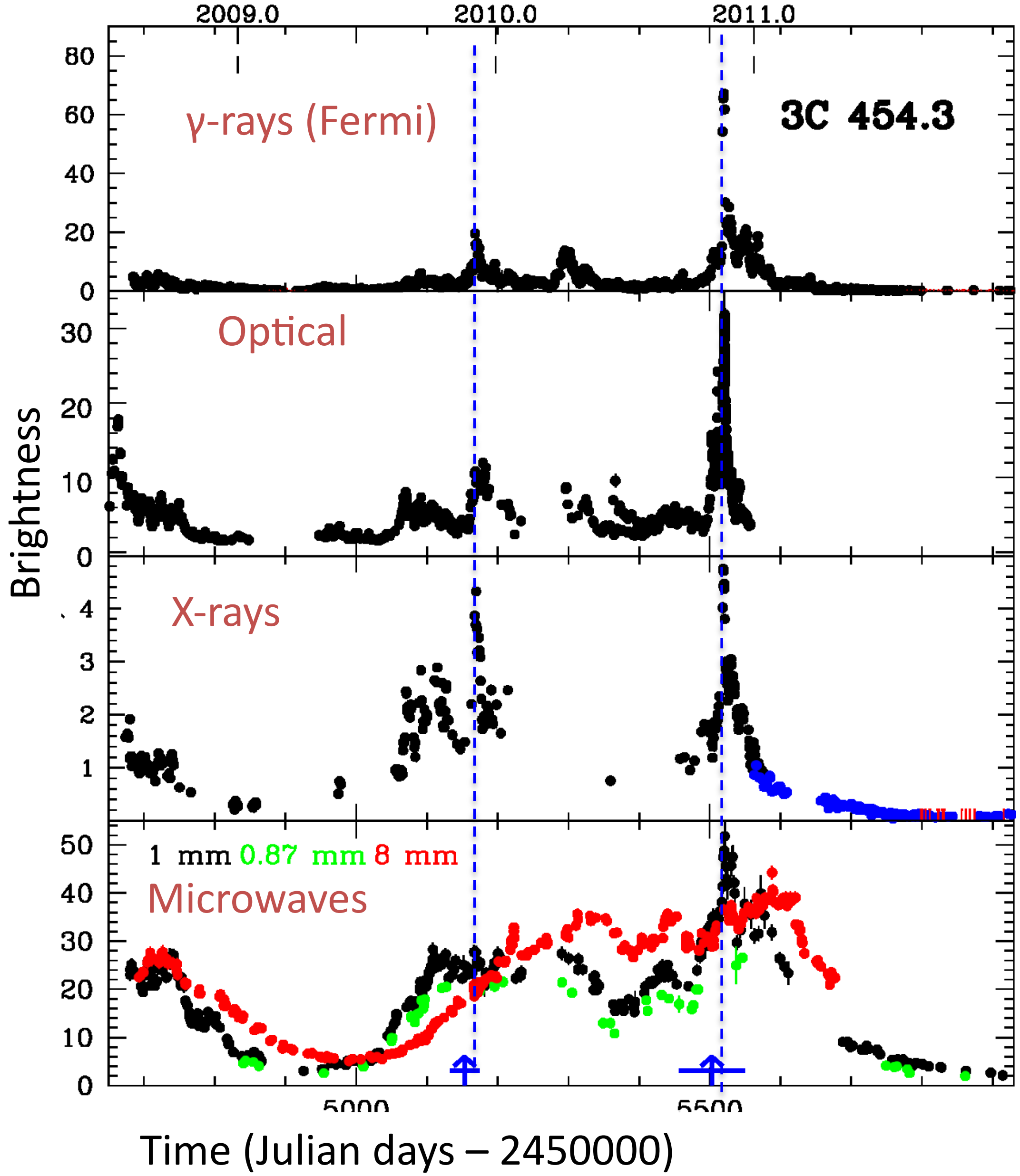
VHE γ-ray: **VERITAS, MAGIC, HESS**

Main collaborator: Dr. Svetlana Jorstad, Boston U.

Involves students + collaborators from around the world

Funded by NASA & NSF

Blazars



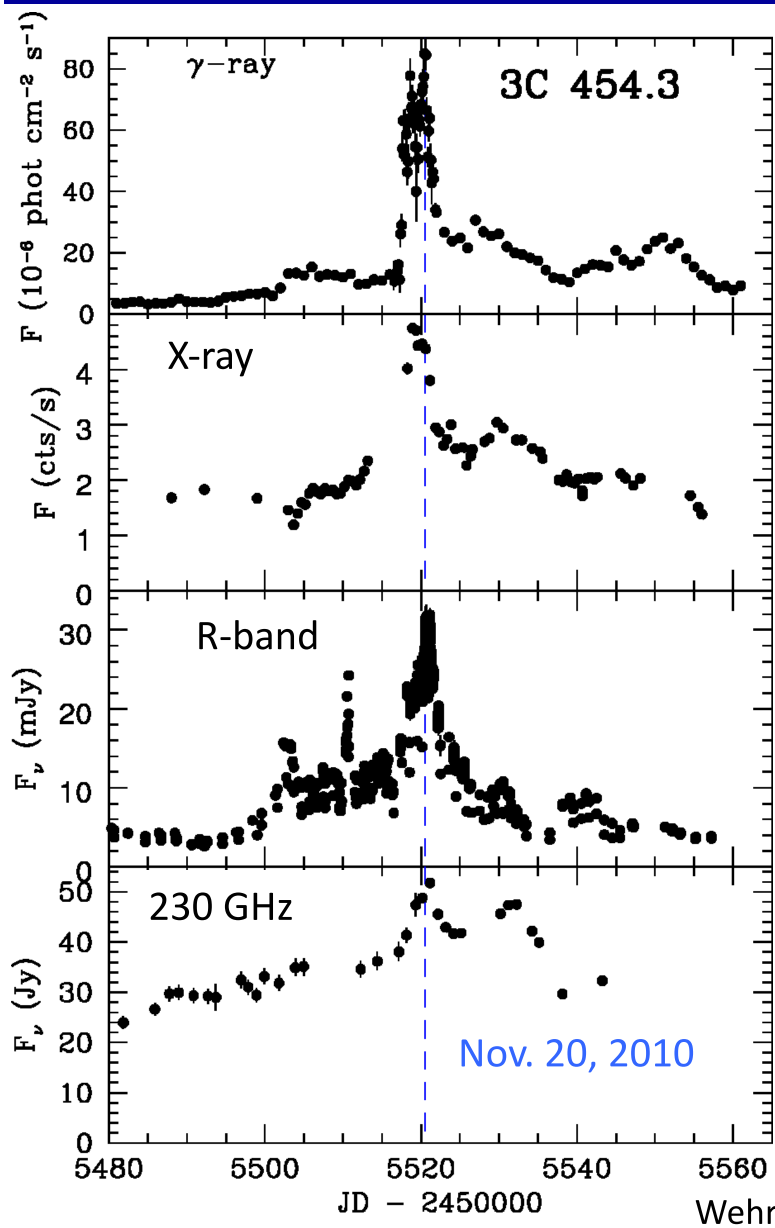
Rapidly changing flux

Highly relativistic electrons radiate across entire spectrum

Some events are simultaneous across wavebands

→ Can combine multi-waveband (MW) light curves, spectral energy distributions (SEDs), MW polarization, & mm-wave VLBI images to probe innermost regions of jets

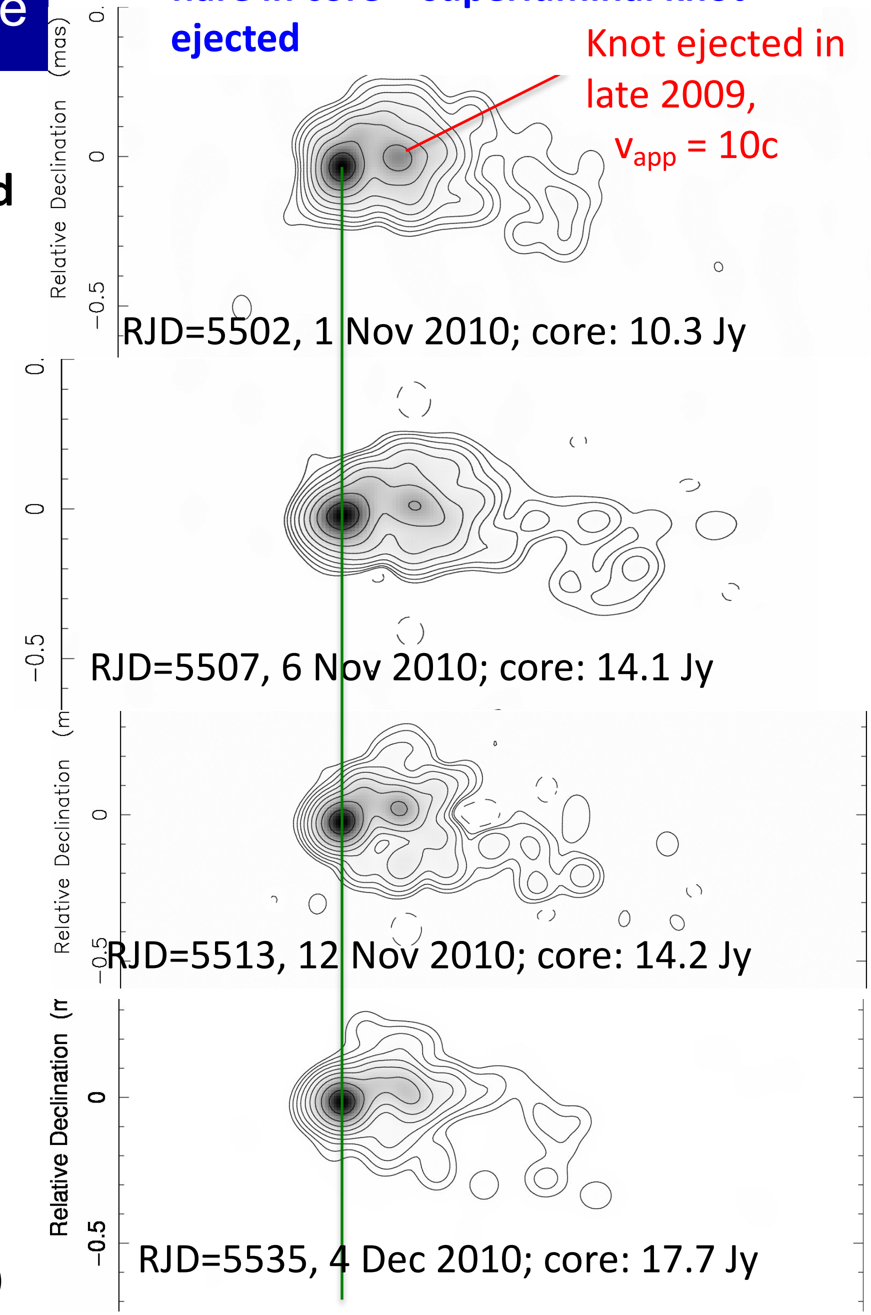
3C 454.3: All wavebands down to mm-wave peaked within 1 day during flare in VLBI core



γ-ray, etc. flare occurred on pc scales

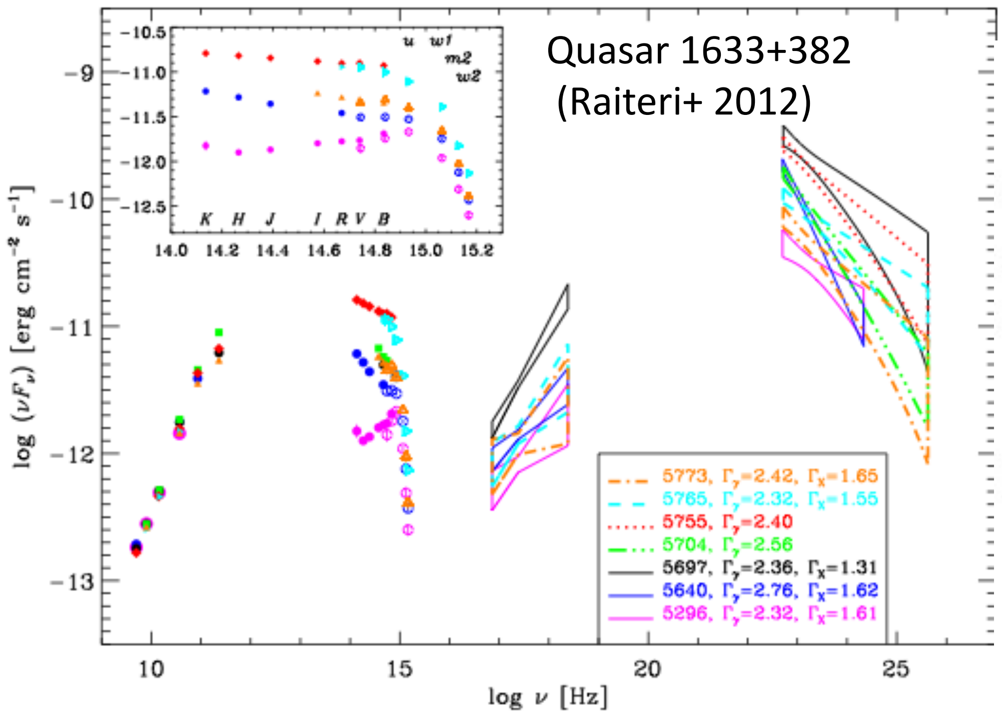
Wehrle et al. (2012 ApJ)

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

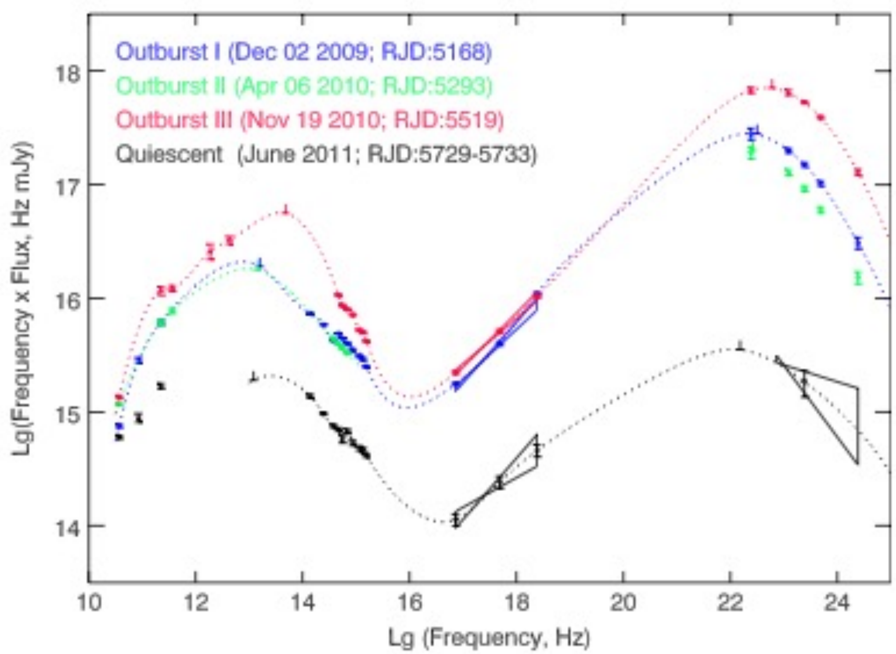


MW Connections: Spectral Energy Distributions

Low-synchrotron-peak (LSP) blazars



Quasar 3C 454.3 (Jorstad+ 2013)



All blazars have double-hump SEDs

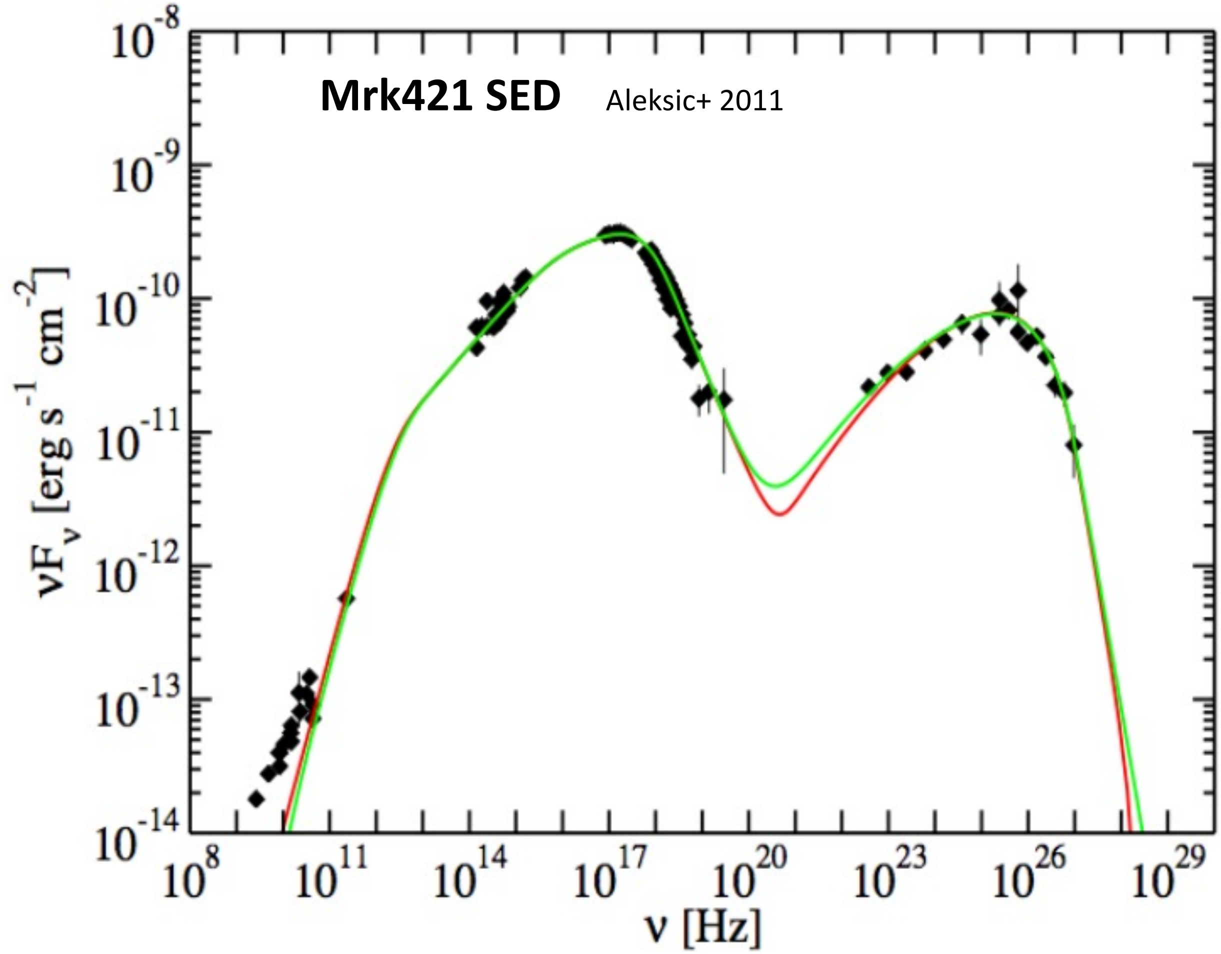
- Synchrotron at lower frequencies, probably Compton at high energies

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

→ Seed photons are from ~stationary source (not from fast jet)

MW Connections: Spectral Energy Distributions

High-synchrotron-peak (HSP) blazars



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

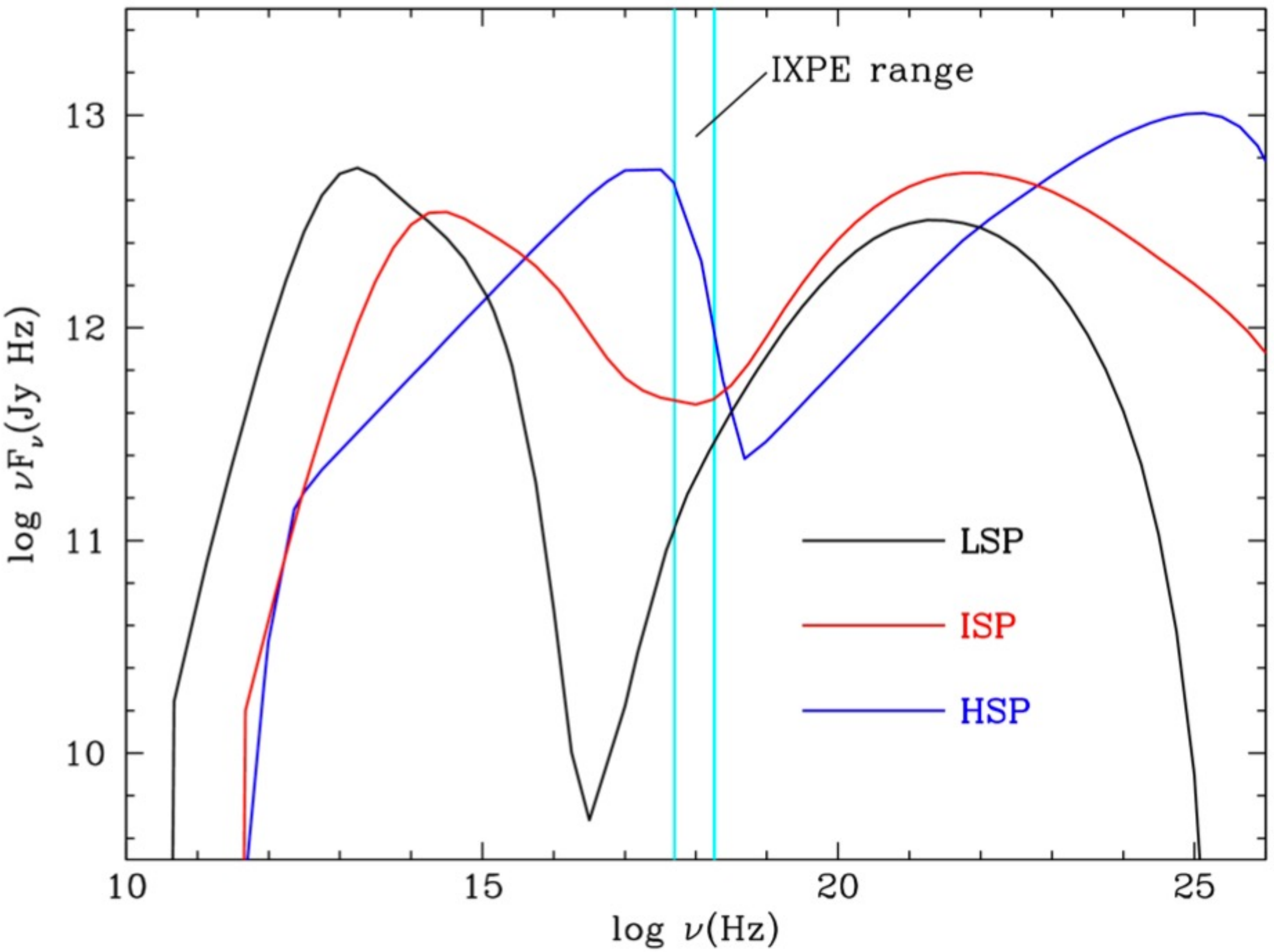
→ Seed photons can be from same region of jet (synchrotron self-Compton)

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

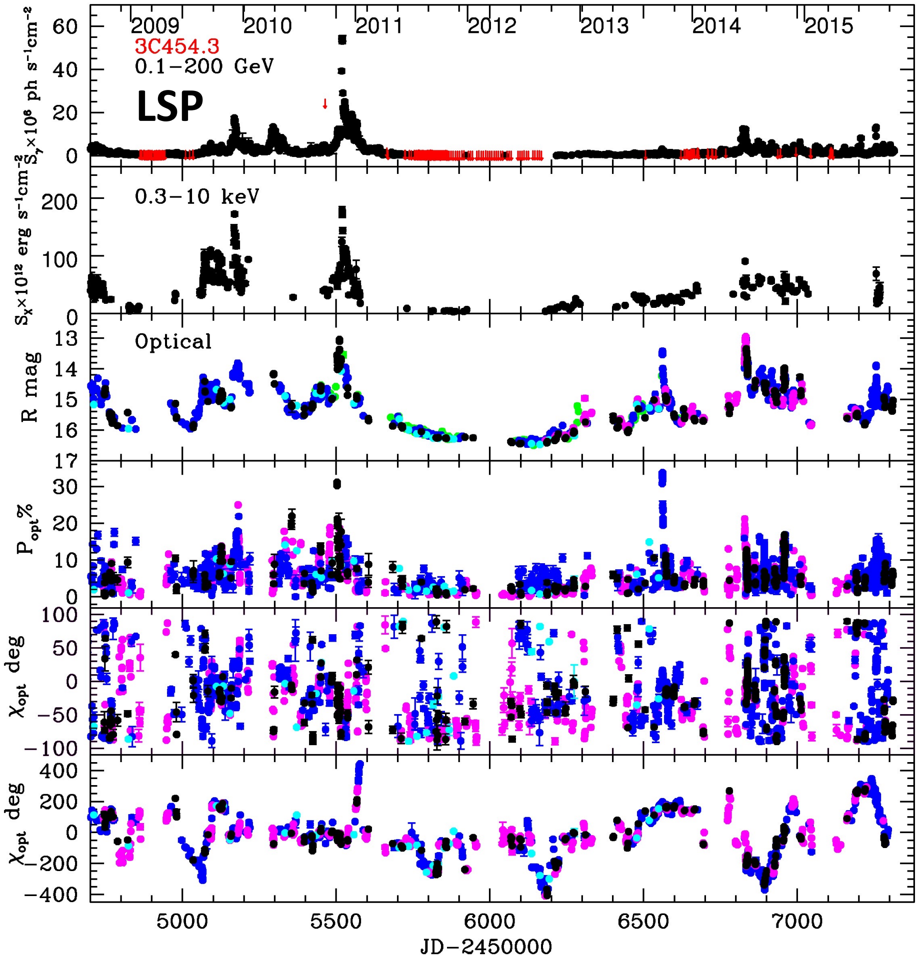
MW Connections: Spectral Energy Distributions

Comparison of LSP, ISP, & HSP blazars

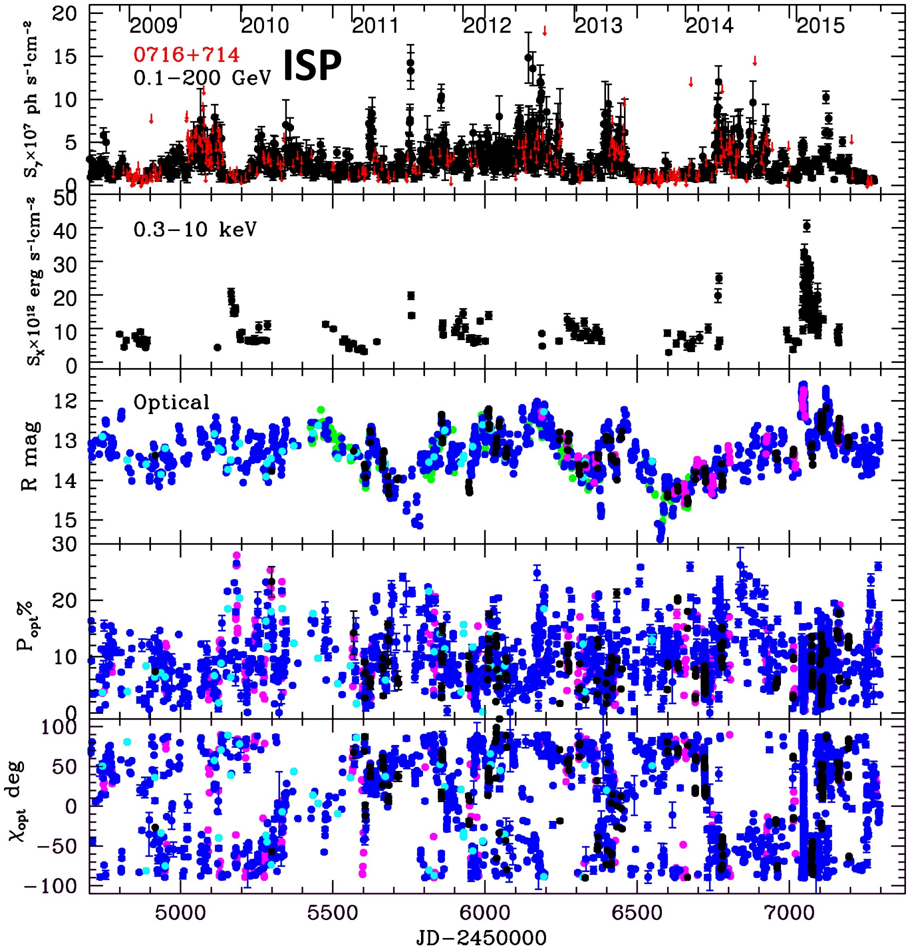
IXPE samples X-ray polarization from different parts of SED



Similarities & Diversity in Multi-waveband Light & Polarization Curves



Quasar 3C 454.3



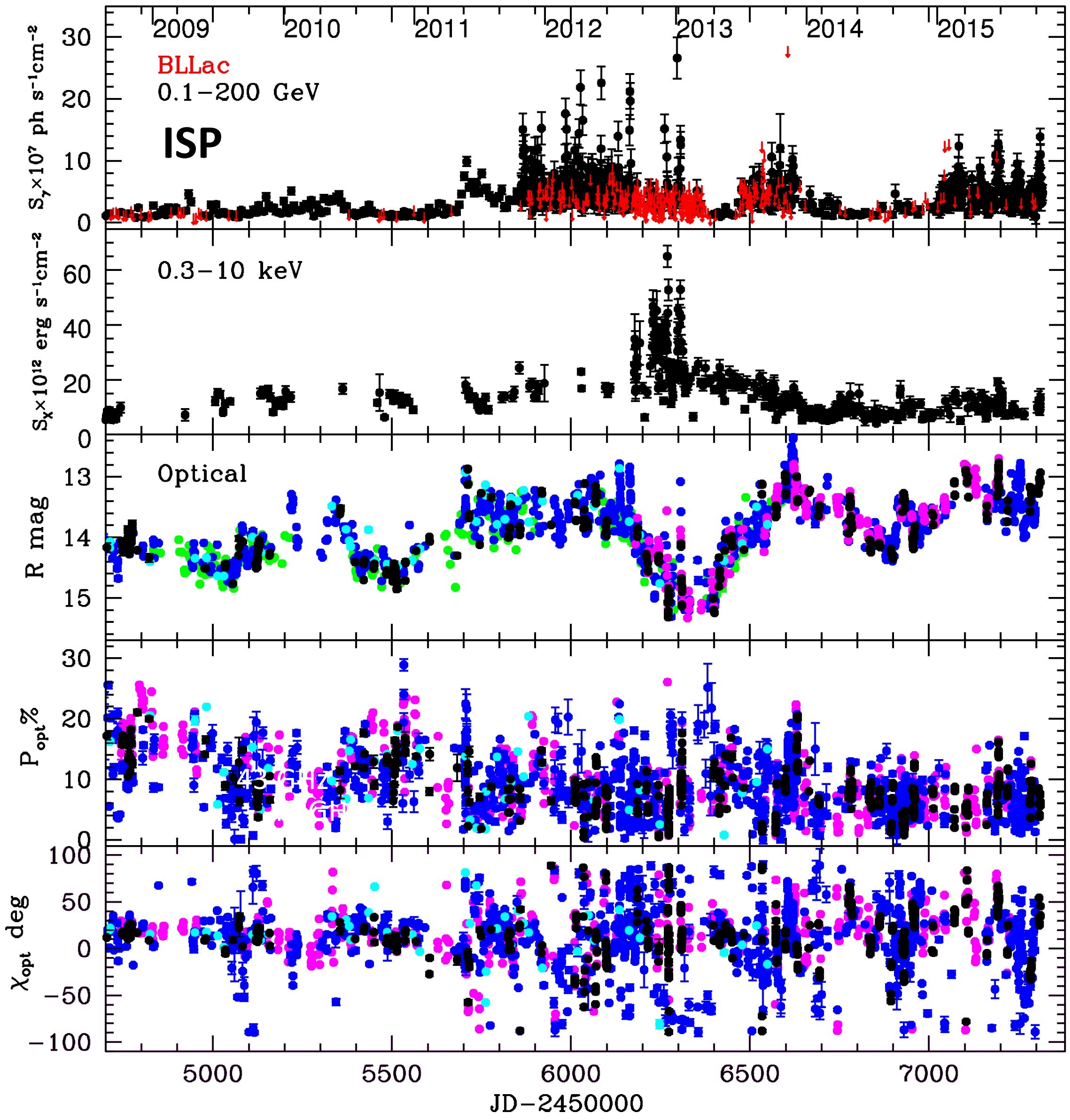
BL Lac object 0716+714

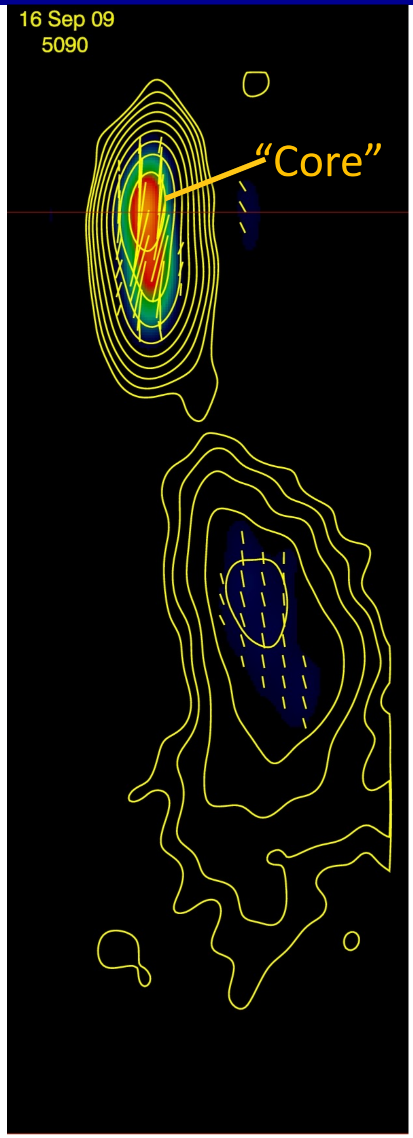
Quasar: "Floods" of multi-waveband flares separated by "droughts"

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

Both: wildly variable optical linear polarization

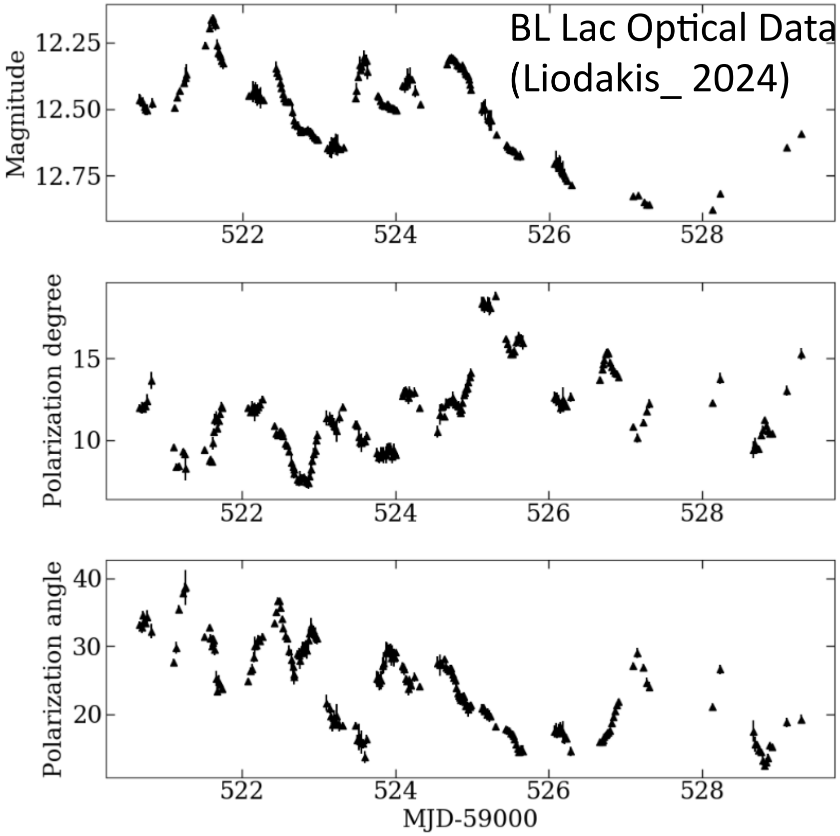
Another Case: BL Lacertae (ISP; switches from LSP to HSP)

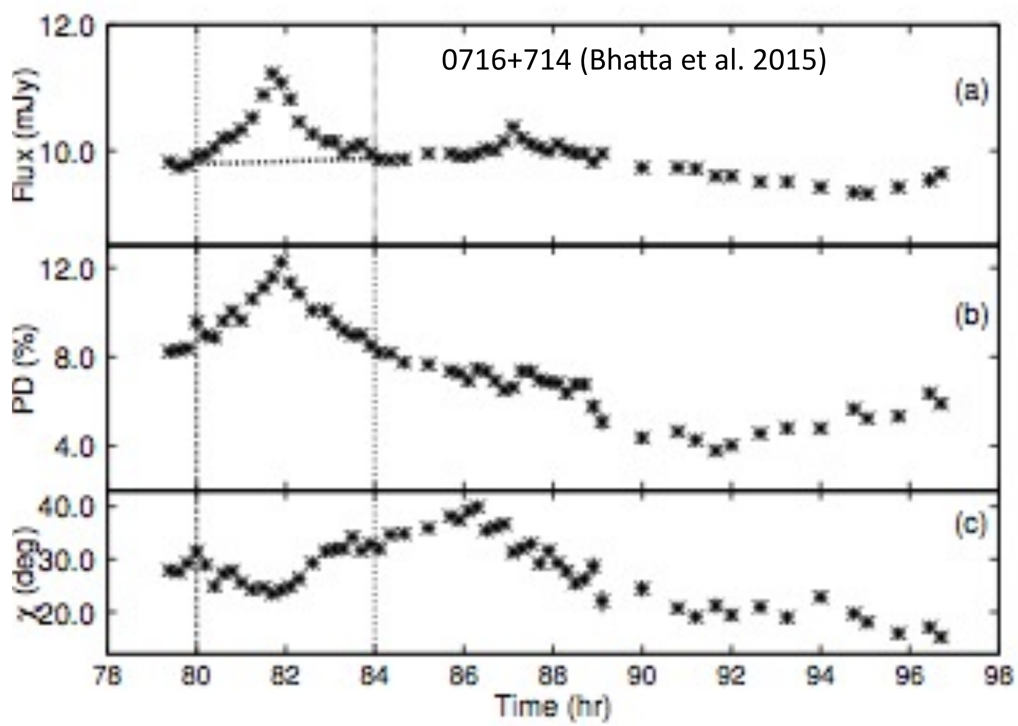




During quiescent periods, optical polarization position angle ~ stable along ~jet direction. During flares, polarization varies erratically, as expected if it results from turbulence (or some other magnetic field disordering)

Intra-day Variability of Optical Flux & Polarization





Polarization & flux vary significantly over hours, as expected if turbulence is involved

Polarization for a Turbulent Magnetic Field

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

<u>Mean polarization</u>: $<\Pi> = \Pi_{max}/N^{1/2}$ $\sigma_p \approx <\Pi>/2$ (Burn 1966)

Electric-vector position angle χ can have any value

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

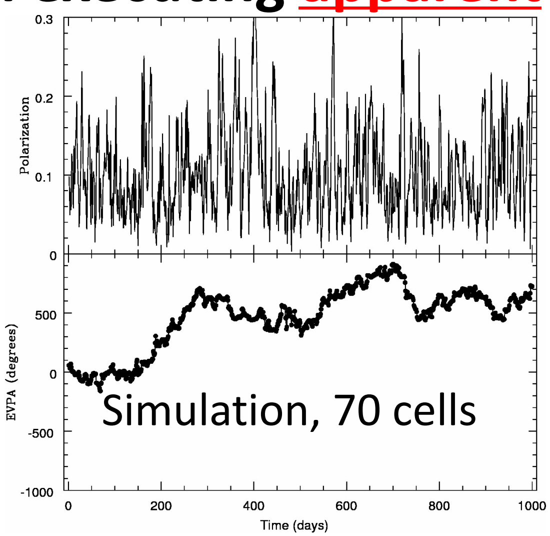
Π fluctuates about $<\Pi>$

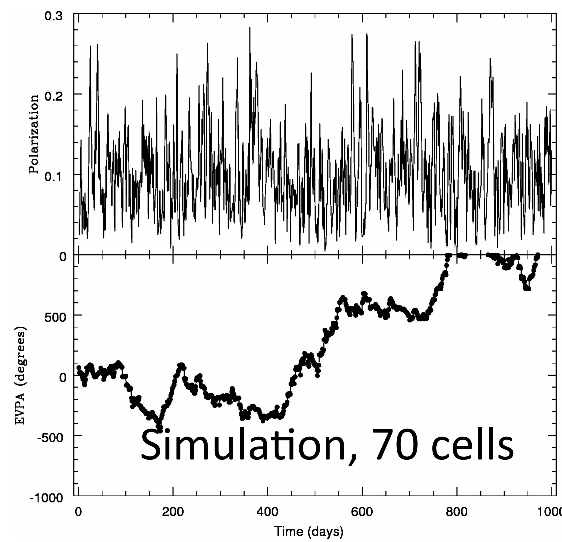
Π_{max} ~ 70-75%, so $<\Pi> \approx 7.5\%$, $\sigma_\Pi \approx 3.7\%$ *for N* ≈ 100

χ varies randomly, often executing <u>apparent</u> rotations that can be > 180°

- usually not very smooth, but sometimes quite smooth

(T.W. Jones 1988, ApJ; Zhang+ 2023)



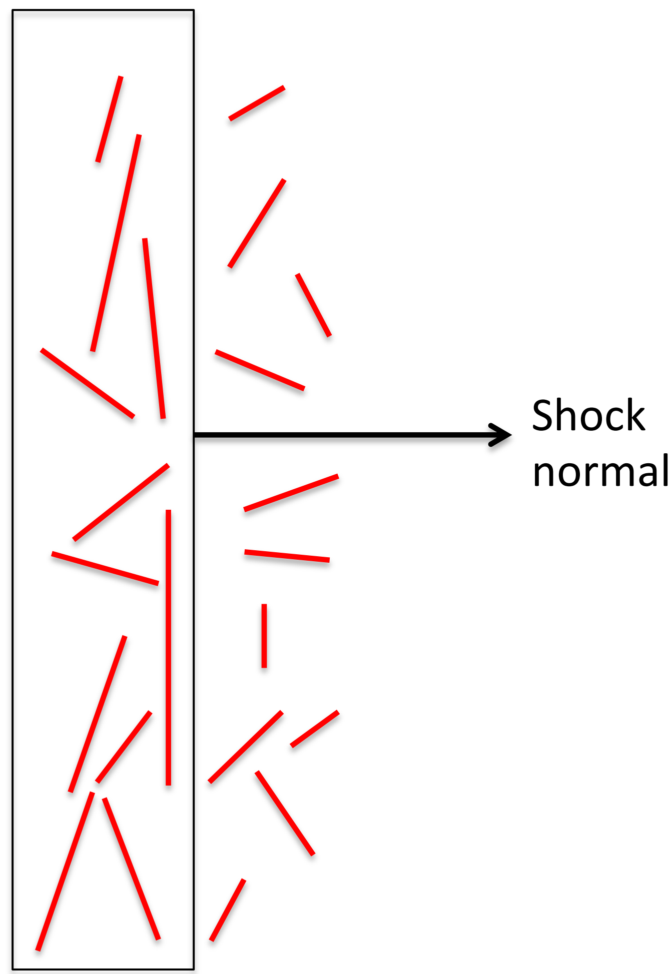


Stability of Mean EVPA → Partial Ordering of B Field

Possibility: Shock

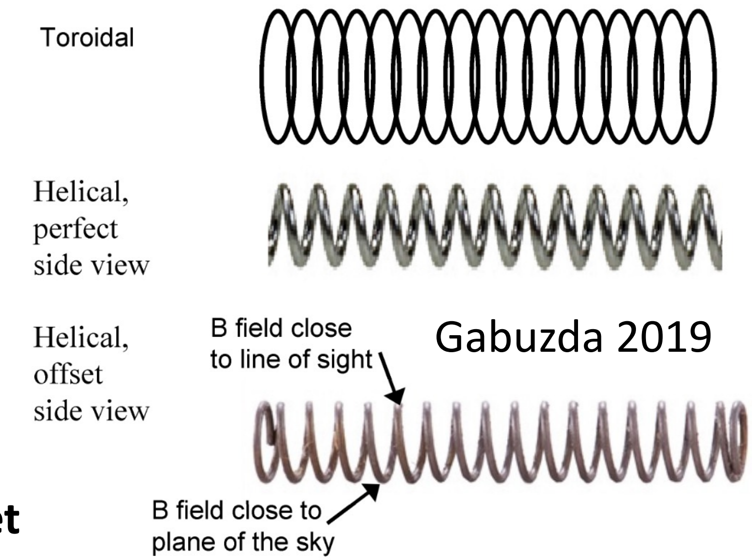
B field is amplified & stretched out perpendicular to shock normal
→Partial ordering parallel to shock front

If viewed side-on (after correction for aberration), polarization can be high, with EVPA || shock normal



Stability of Mean EVPA → Partial Ordering of B Field

Possibility: Helical or toroidal magnetic field (can also include turbulence & shocks)

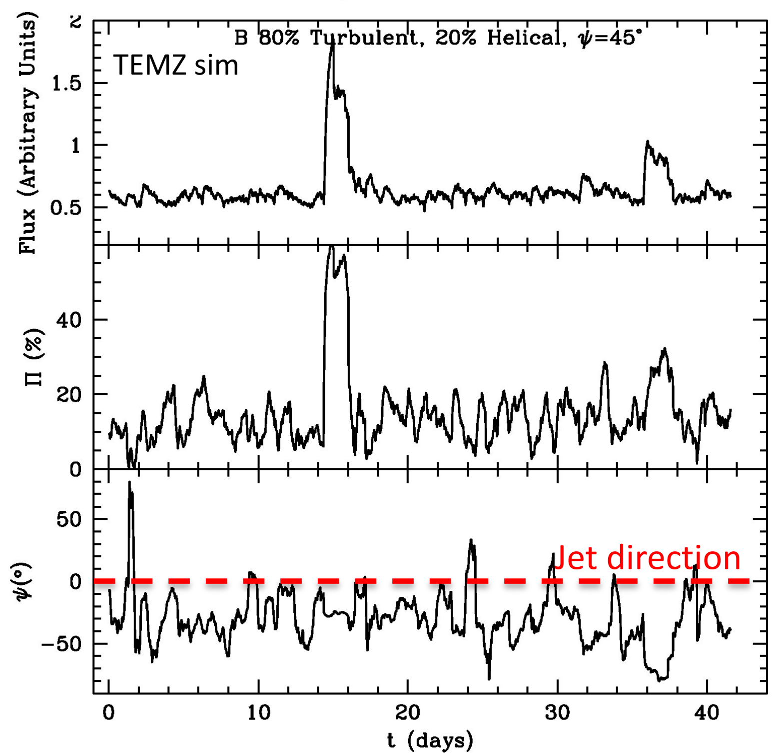


Jet plasma can be turbulent to produce random fluctuations superposed on the more ordered variations

→ For most viewing angles, mean EVPA is parallel to jet

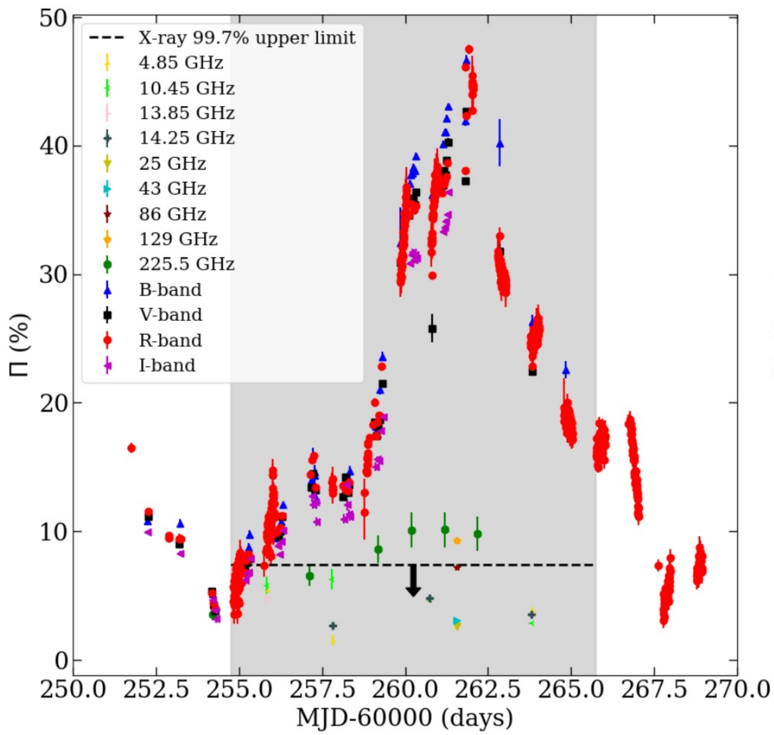
Shock will compress B field to make it more perpendicular to shock normal

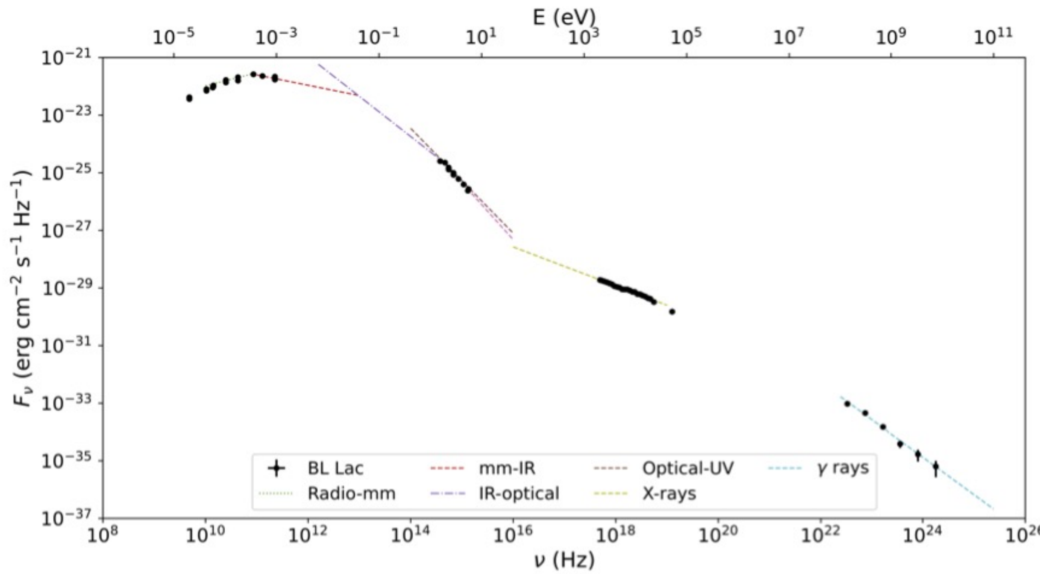
Right: Simulation of turbulence + helical field + conical shock (author's TEMZ model)



For conical shock, if pitch angle of helix is not close to 0° or 90°, <EVPA> can be offset from jet direction

BL Lac in Nov 2023: Huge optical polarization flare (Agudo+ 2025)





Optical polarization reached 47% (as high as blazars get)

X-ray polarization (IXPE, 2-8 keV): < 7.4% (3σ upper limit)

Slope of X-ray spectrum similar to far-IR

→ X-rays are almost surely from Compton of IR photons (LSP state)

Previous result (Peirson + 2023): Earlier observation (Nov 2022) measured steeper X-ray spectrum & detected X-ray polarization of 22±7% at 2-4 keV (not 4-8 keV)

→ X-ray transition from synchrotron to Compton at ~4 keV at this epoch (almost HSP state)

IXPE X-ray Polarization Measurements of HSP Blazars

From Marscher+ (2024)

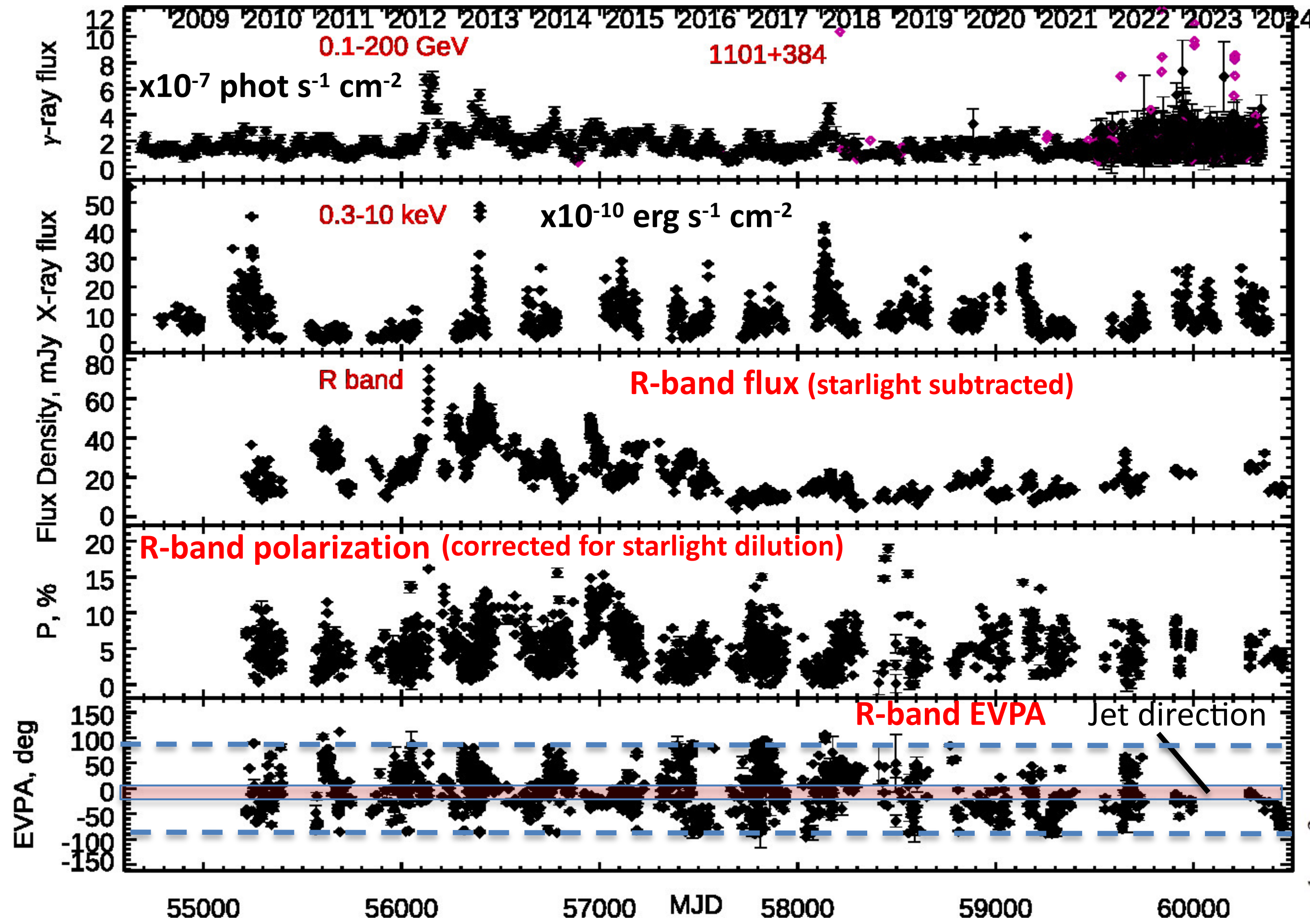
Object (Date)	X-ray		Optical R-Band [a]		Jet PA (°)
	Π_X (%)	ψ_X (°)	Π_O (%)	ψ_O (°)	at 43 GHz [b]
1ES0229 + 200 [c] (23 January 2023)	18 ± 3	$25 \pm 5°$	$2.4 \pm 0.7\%$	$2 \pm 8°$	163 ± 8
Mrk421 (5 May 2022)	$15 \pm 2\%$	35 ± 4	2.9 ± 0.5	32 ± 5	-29 ± 18
Mrk421 (5 June 2022)	10 ± 1	Rotation	4.4 ± 0.4	-40 ± 6	-29 ± 18
Mrk421 (8 June 2022)	10 ± 1	Rotation	5.4 ± 0.4	-35 ± 1	-29 ± 18
Mrk421 (17 December 2022)	14 ± 1	-73 ± 3	4.6 ± 1.3	26 ± 9	-29 ± 18
PG1553 + 113 (2 February 2023)	10 ± 2	86 ± 8	4.2 ± 0.5	Rotation	50 ± 10
Mrk501 (7 March 2022)	9.8 ± 1.7	136 ± 5	6.6 ± 0.4	110 ± 5	120 ± 12
Mrk501 (27 March 2022)	10.3 ± 1.4	115 ± 4	4.7 ± 0.3	120 ± 3	120 ± 12
Mrk501 (9 July 2022)	6.9 ± 1.8	134 ± 8	2.7 ± 0.5	109 ± 5	120 ± 12
Mrk501 (12 February 2023)	9.0 ± 2.4	110 ± 8	6.6 ± 0.9	150 ± 4	120 ± 12
Mrk501 (19 March 2023)	6.0 ± 2.1	107 ± 11	6.1 ± 0.7	125 ± 3	120 ± 12
Mrk501 (16 April 2023)	18.5 ± 2.2	103 ± 3	5.9 ± 1.5	108 ± 6	120 ± 12
1ES1959 + 650 (3 May 2022)	8.0 ± 2.3	123 ± 8	4.5 ± 0.2	159 ± 1	120–150
1ES1959 + 650 (10 June 2022)	< 5.1 [d]	—	4.7 ± 0.6	151 ± 19	120–150
1ES2155−304 (30 October 2023)	31 ± 2	129 ± 2	4.3 ± 0.7	116 ± 8	135 ± 45
1ES2155−304 (4 November 2023)	15 ± 2	125 ± 4	3.8 ± 0.9	116 ± 8	135 ± 45

$\Pi_x > \Pi_o$ by factor of 2-7

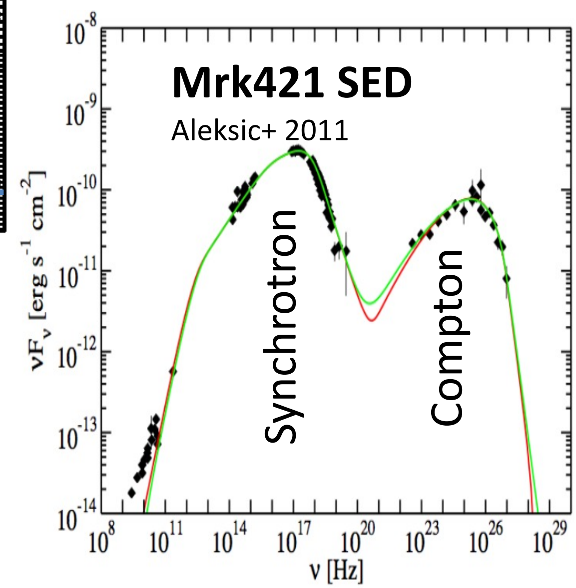
ψ_x sometimes similar to, sometimes different from ψ_o and jet direction

No X-ray polarization has yet been detected from a full-time LSP (Marshall+ 2024)

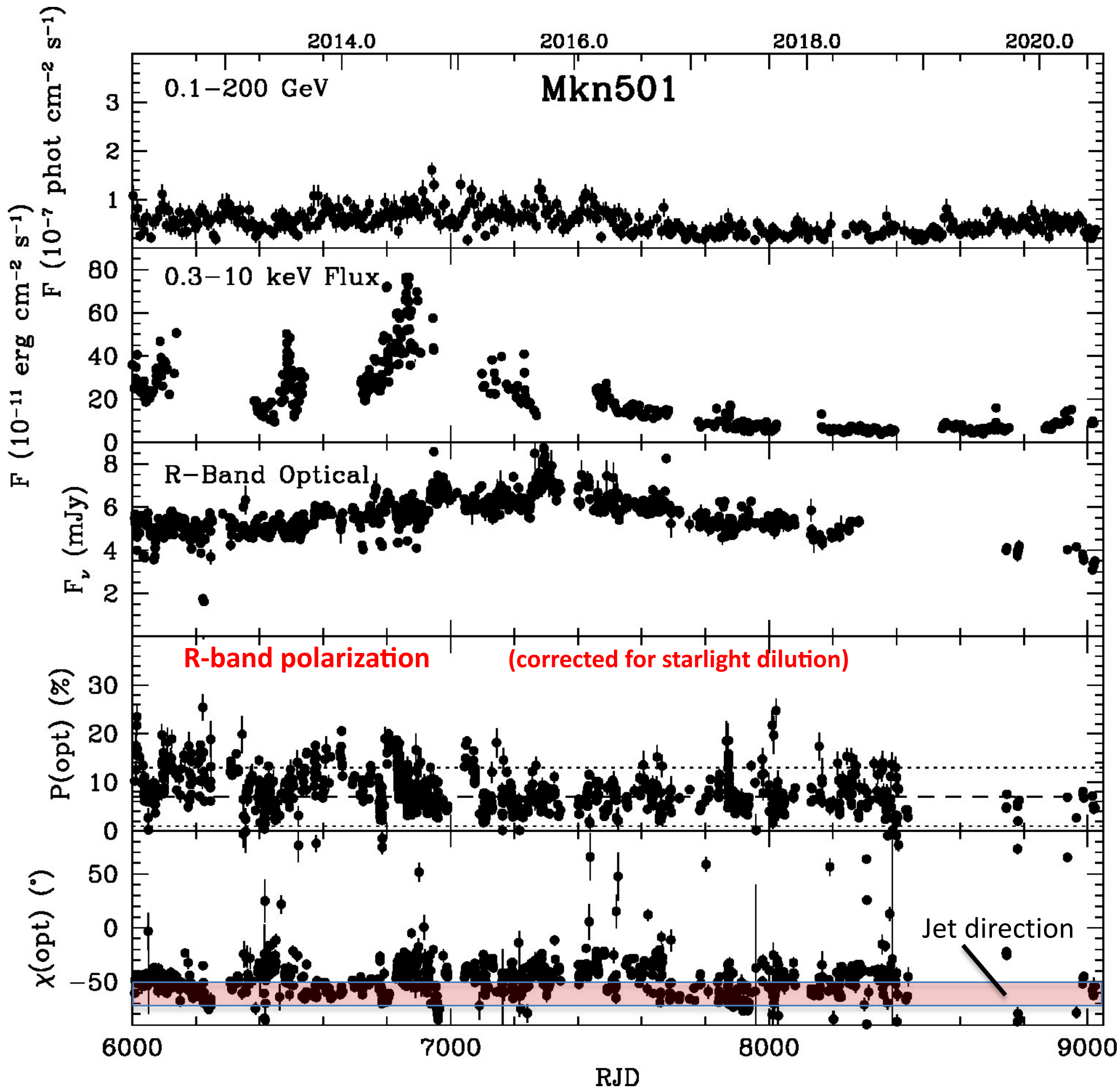
Long-term Variability of HSP Blazar Mrk421



Optical polarization = 0-14%, fluctuates about a mean direction 10-20^o from jet direction, but varies by ± 50-90^o during a given year



Long-term Variability of HSP Blazar Mrk501



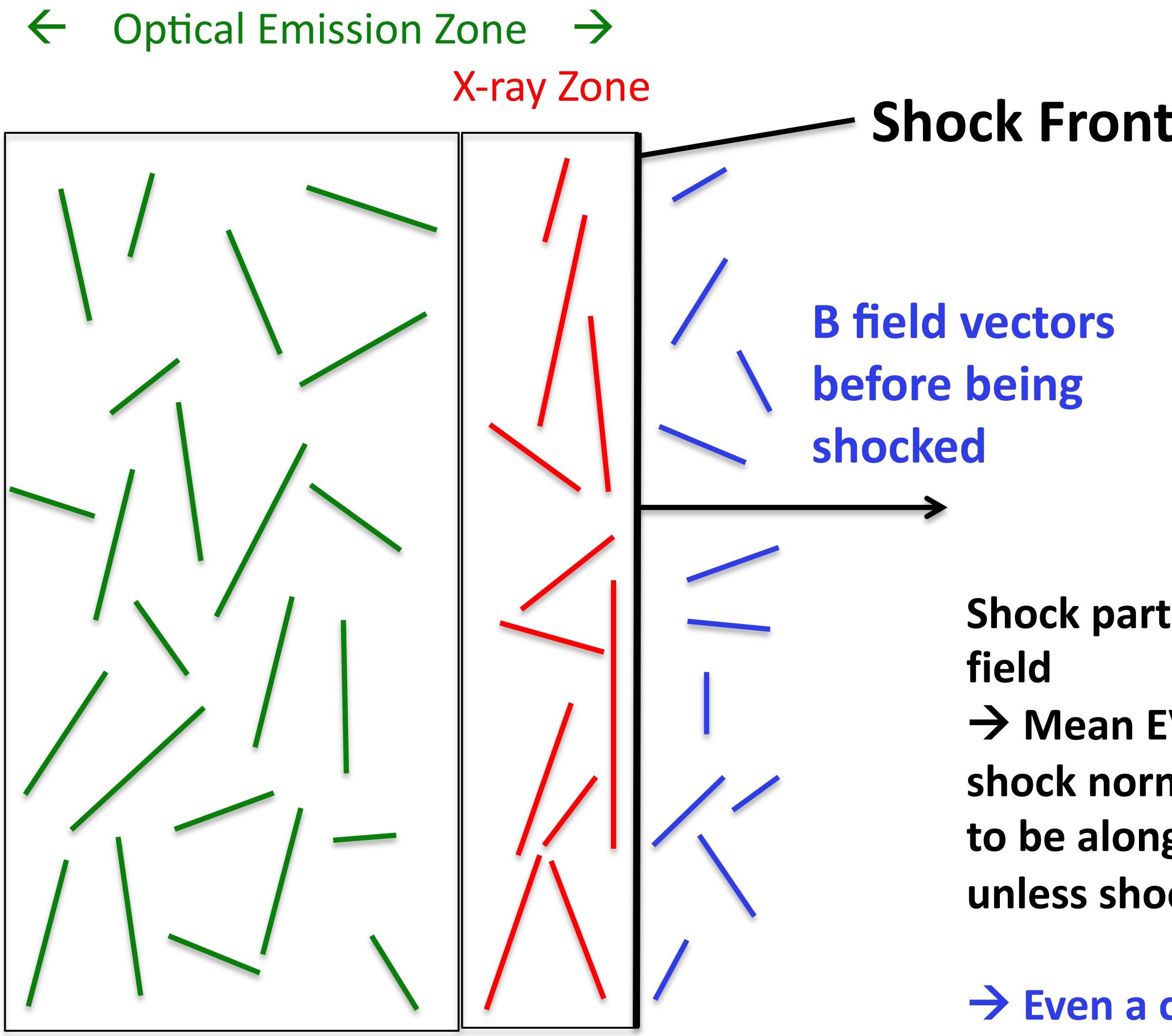
Optical polarization = 0-25%, fluctuates about a mean direction 10-20° from jet direction

Varies less than EVPA of Mrk421

→ Similar to most other HSPs that have similar data

Combination of ordered and random processes
→ Turbulence + shock or ordered B field

Polarization of an HSP Blazar: Turbulent Plasma Crossing a Shock



Frequency stratification from electrons losing energy to radiation as they propagate away from shock front that accelerates them

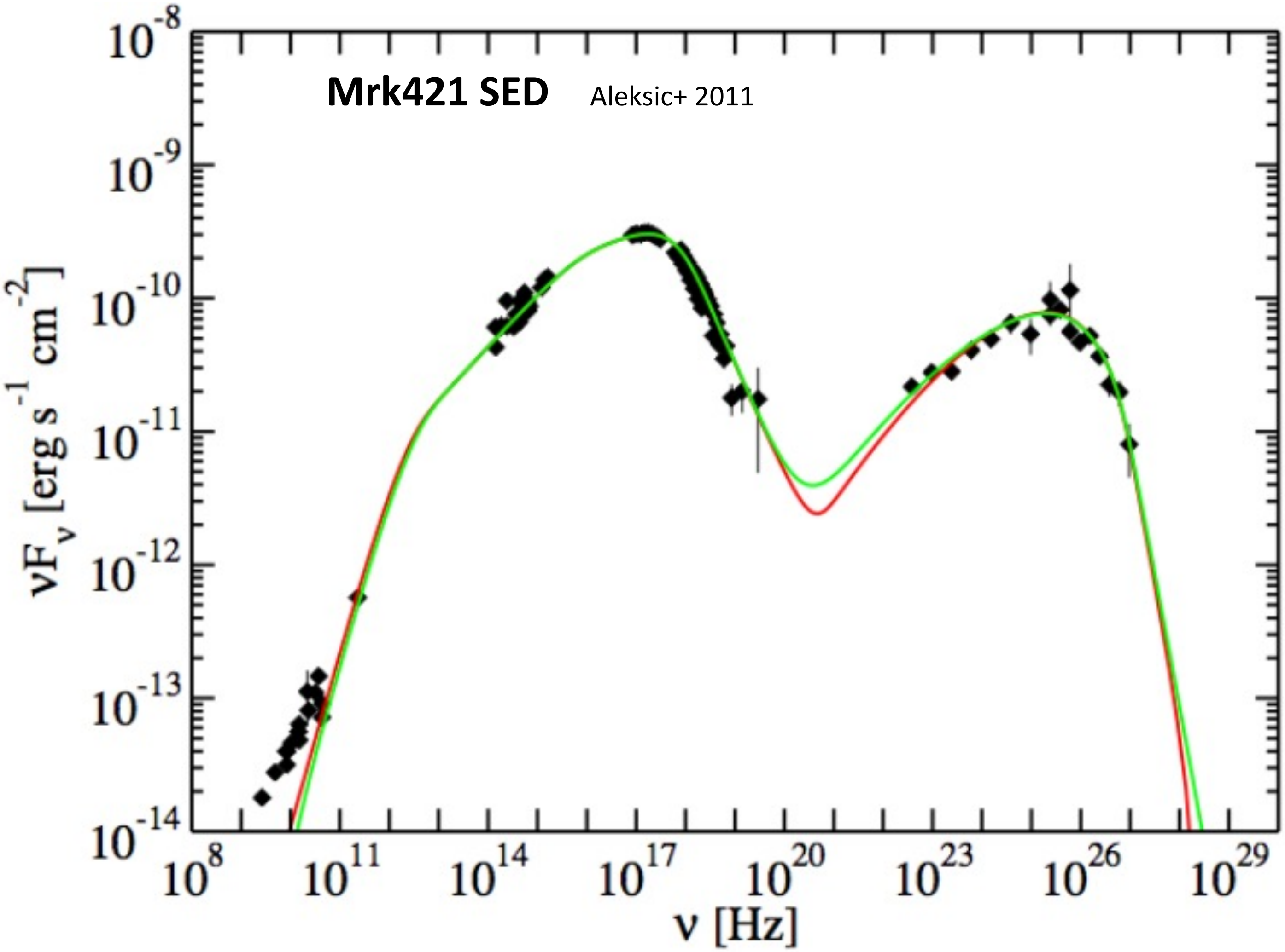
Increased level of turbulence farther from shock → lower polarization

Same B field vectors after being shocked

Shock partially orders B field
→ Mean EVPA parallel to shock normal, expected to be along jet direction unless shock is oblique

→ Even a cone-shaped standing shock produces a similar EVPA for most viewing angles

Advantage of Model: Continuity of SED



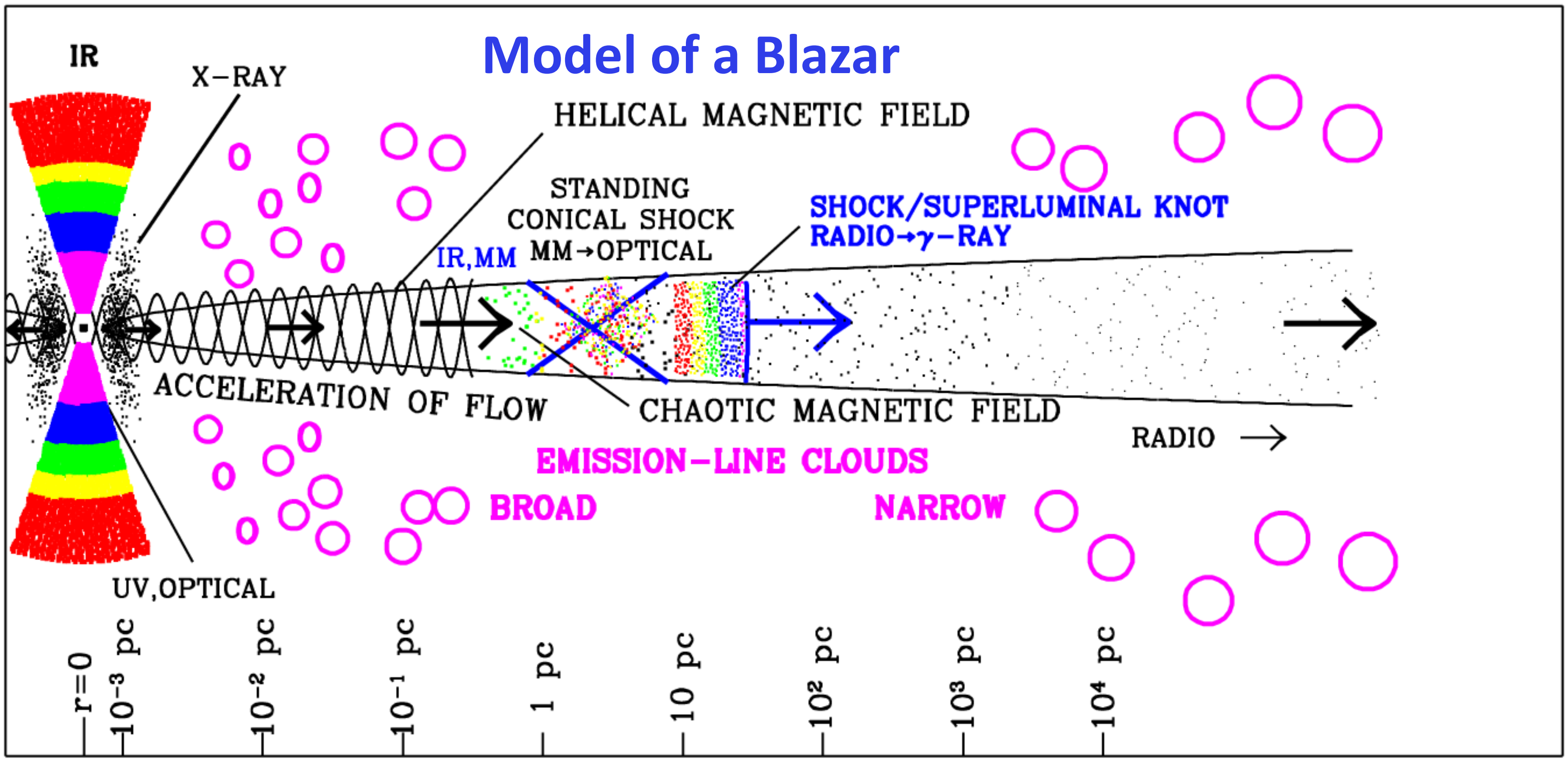
SED can connect smoothly across UV gap in data despite different X-ray & optical polarization

→ Implies that X-ray & optical regions connect smoothly, as in model

Not expected for spine-sheath model where there is a sudden drop in Lorentz factor between X-ray & optical regions (smooth gradient across jet might work)

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 B field accelerates particles via 2nd-order Fermi + many magnetic reconnections
- Shocks increase energies of particles, especially in locations where B direction is favorable

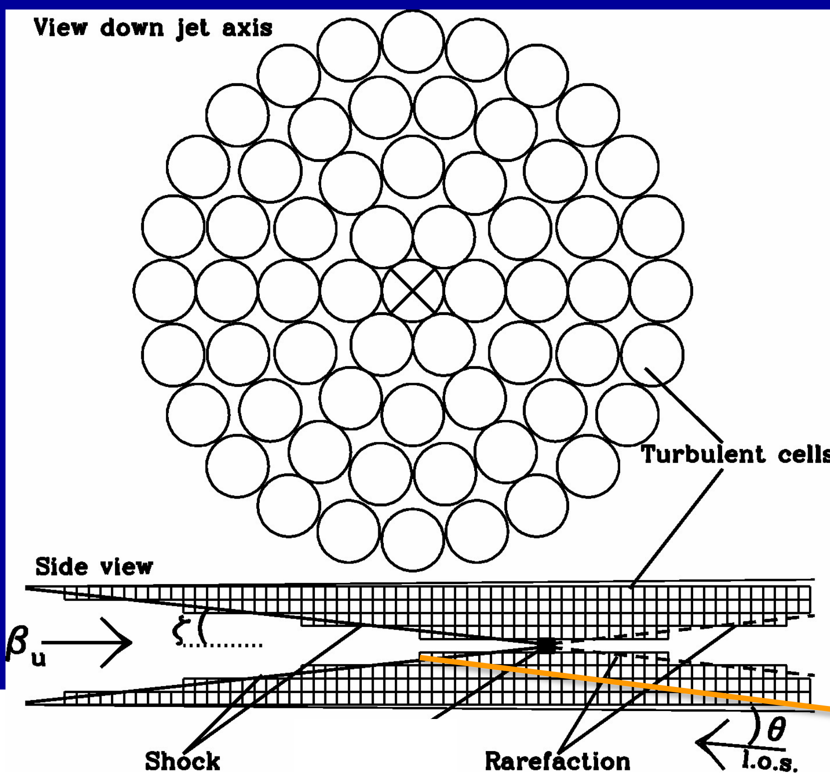


Turbulent Extreme Multi-zone (TEMZ) Model (Marscher 2014)

Many turbulent cells across jet cross-section, each followed after crossing shock, where e^-s are energized.

Each cell has turbulent & ordered B components; input flow energy varies

→ Flux & polarization fluctuate; major perturbations seen as superluminal knots (some of which may be moving shocks)



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

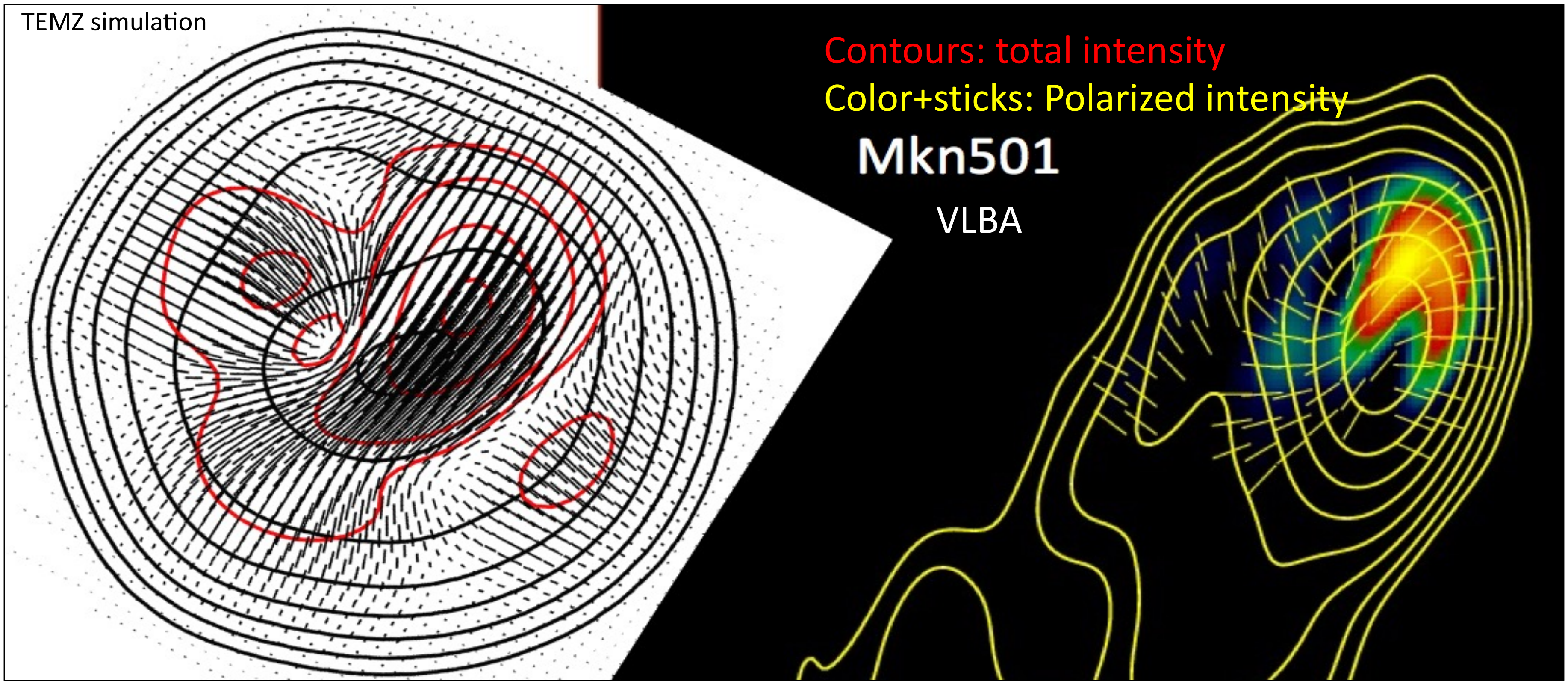
→ More rapid variability to explain intra-day flux changes

→ SED above peak frequency curves downward, similar to log-parabola

Conical standing shock

Polarization Pattern of Standing Shock

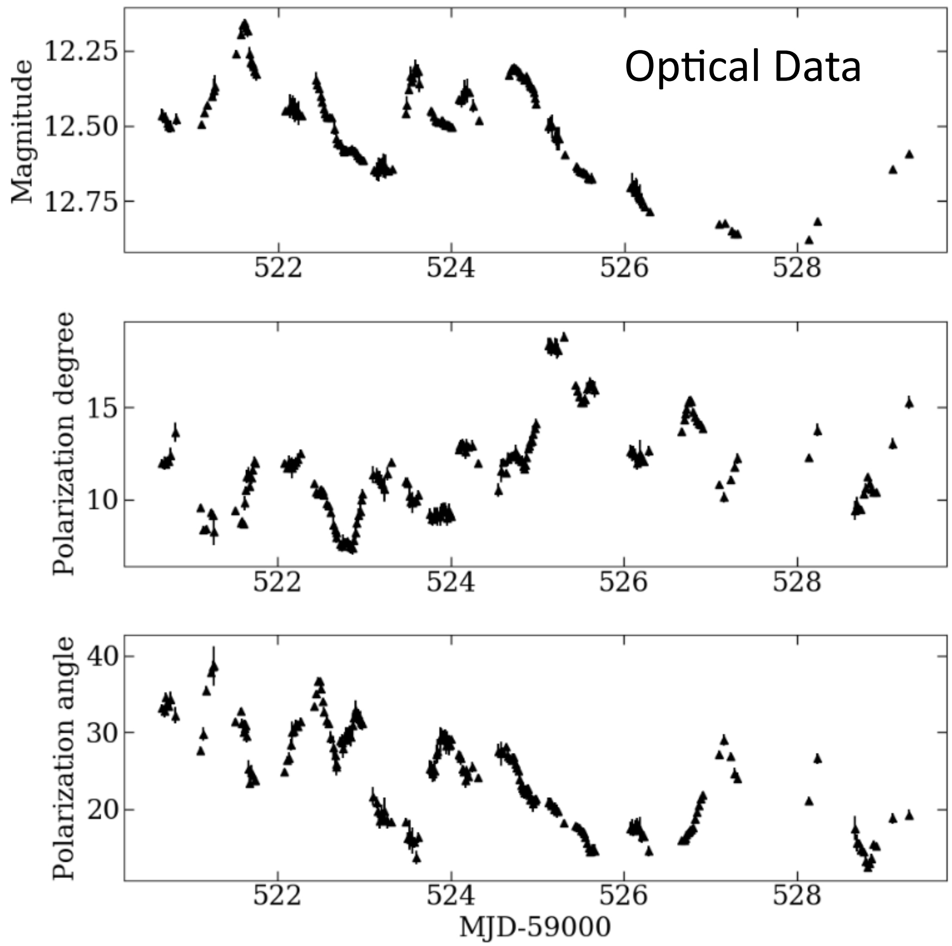
Turbulent plasma crossing a cone-shaped standing shock (TEMZ model) produces a radial EVPA pattern for viewing angles within a few degrees, as observed in some BL Lac objects

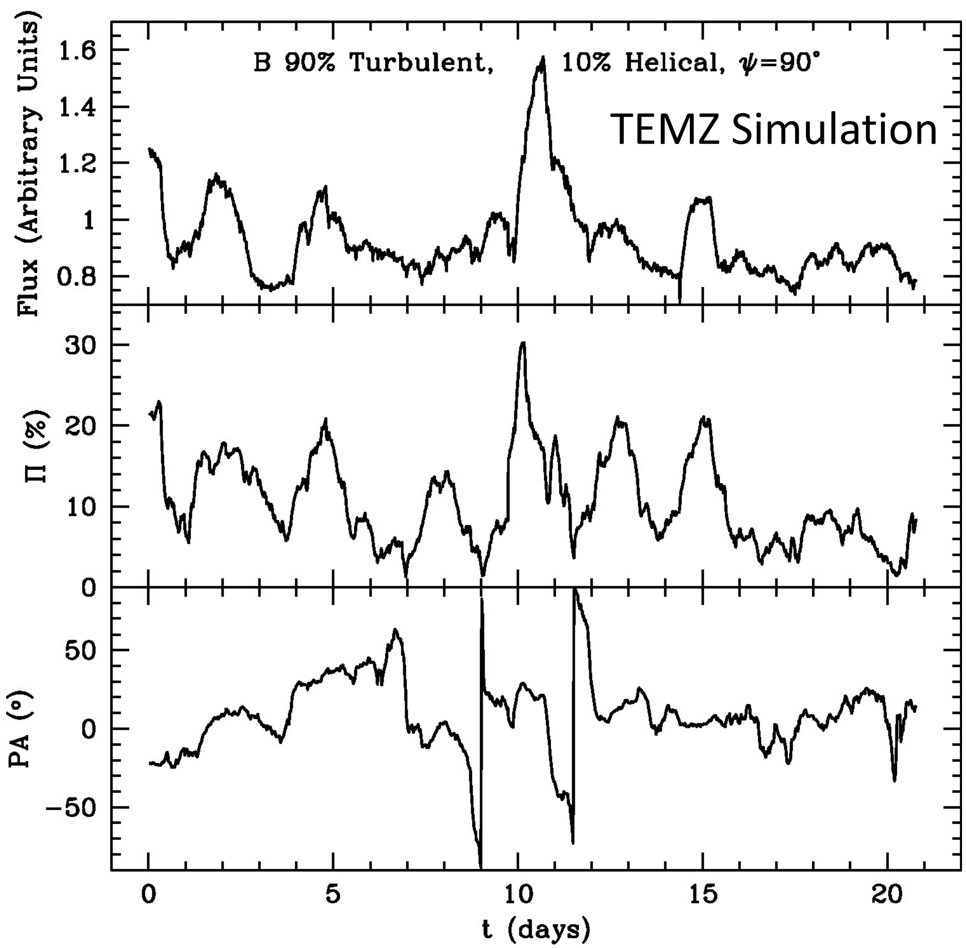


Red: polarized intensity
Black: Total intensity

Comparison of (left) sim of turbulent plasma crossing conical standing shock with (right) polarization in VLBA image

NOPE Campaign: Intraday Variations of BL Lac (Liodakis+ 2024)





TEMZ simulation has similar properties to actual data:

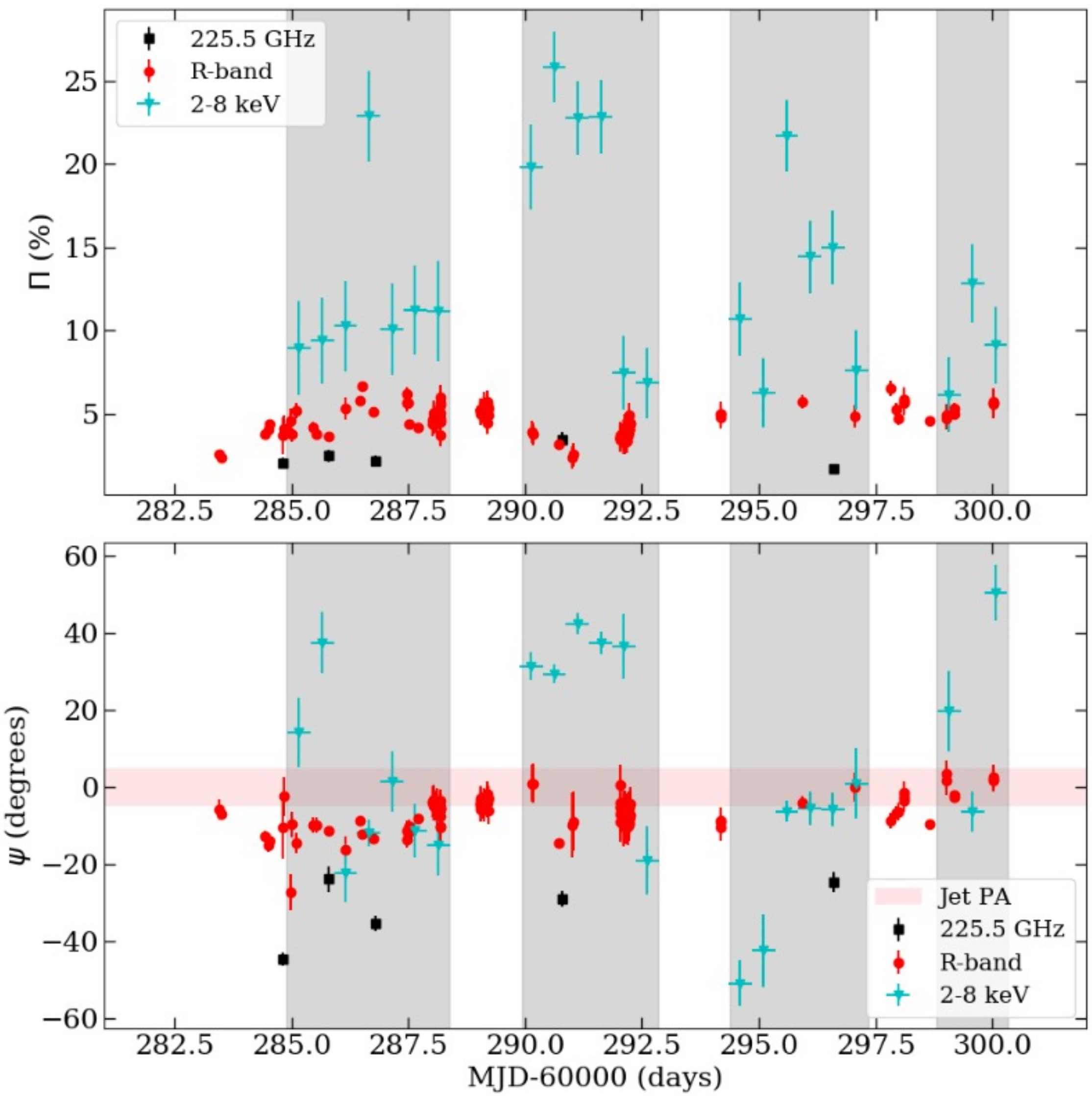
Range of variations of flux, polarization degree, and EVPA

Number of EVPA reversals

This sim does not, though, reproduce distribution of polarization degree values

Short-term Variability of Mrk421: Dec 2023

Maksym et al. (2025): Turbulence appears to dominate, but probably some ordering by shock; X-ray & optical EVPAs usually differ



Rapid fluctuation in Π_x and Ψ_x → There must be some depolarization from Ψ_x changing during integration

Optical EVPA remained ~ along jet direction

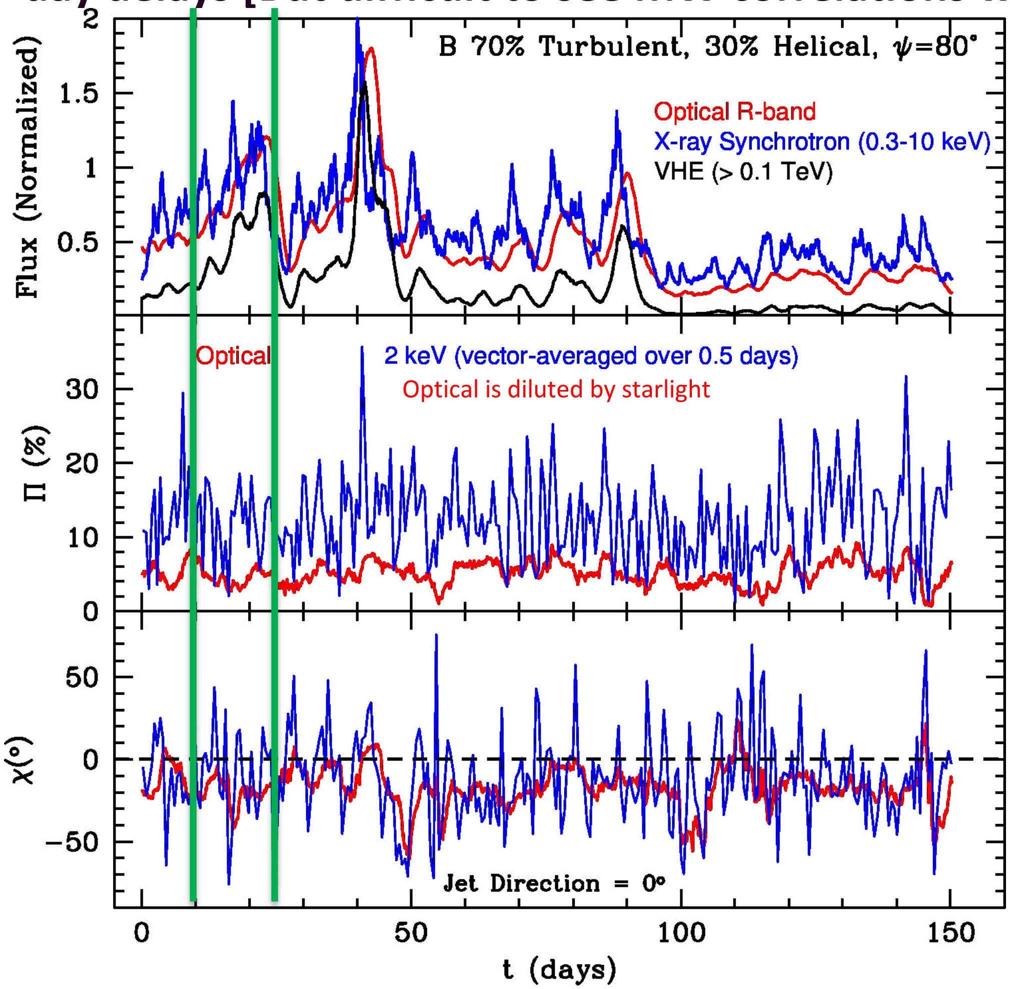
$\langle\Pi_x\rangle$ ~ 13% but intrinsically higher
$\langle\Pi_{opt}\rangle$ ~ 5%

Simulation: Superposition of Turbulent & Helical B Fields

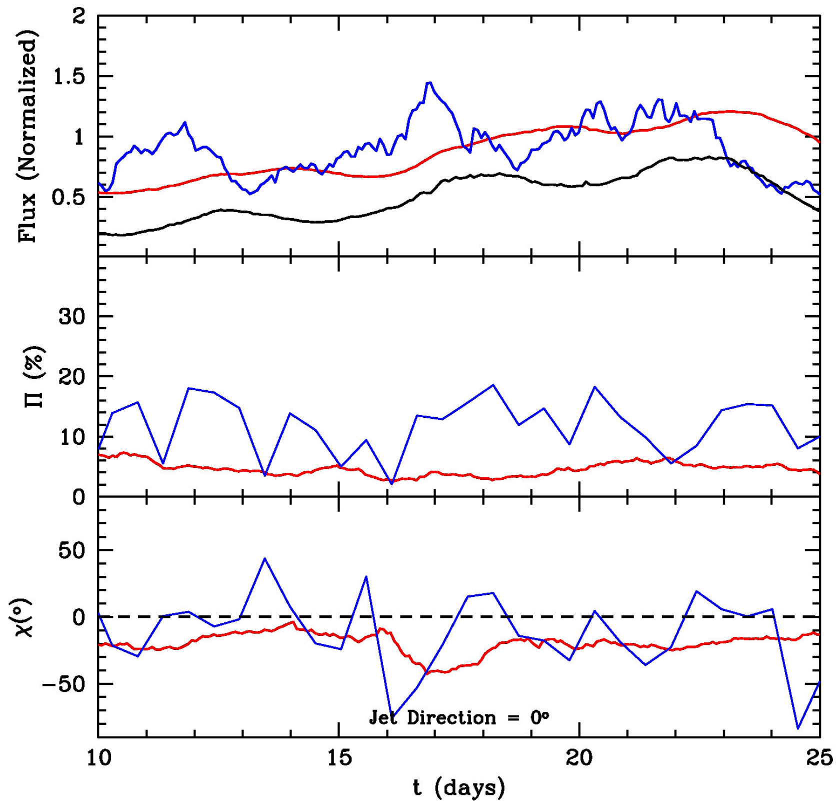
Turbulence in the jet can explain rapid fluctuations of flux & polarization, as well as X-ray/optical similarities & differences, but not major outbursts (accretion events?)

TEMZ model reproduces long-term similarities & short-term differences in X-ray & optical EVPA that are sometimes observed

In this simulation of Mrk421-like blazar, X-ray leads VHE, which leads optical variations, 1-2 day delays [But difficult to see MW correlations with 15-day observation]



15-day section of simulation



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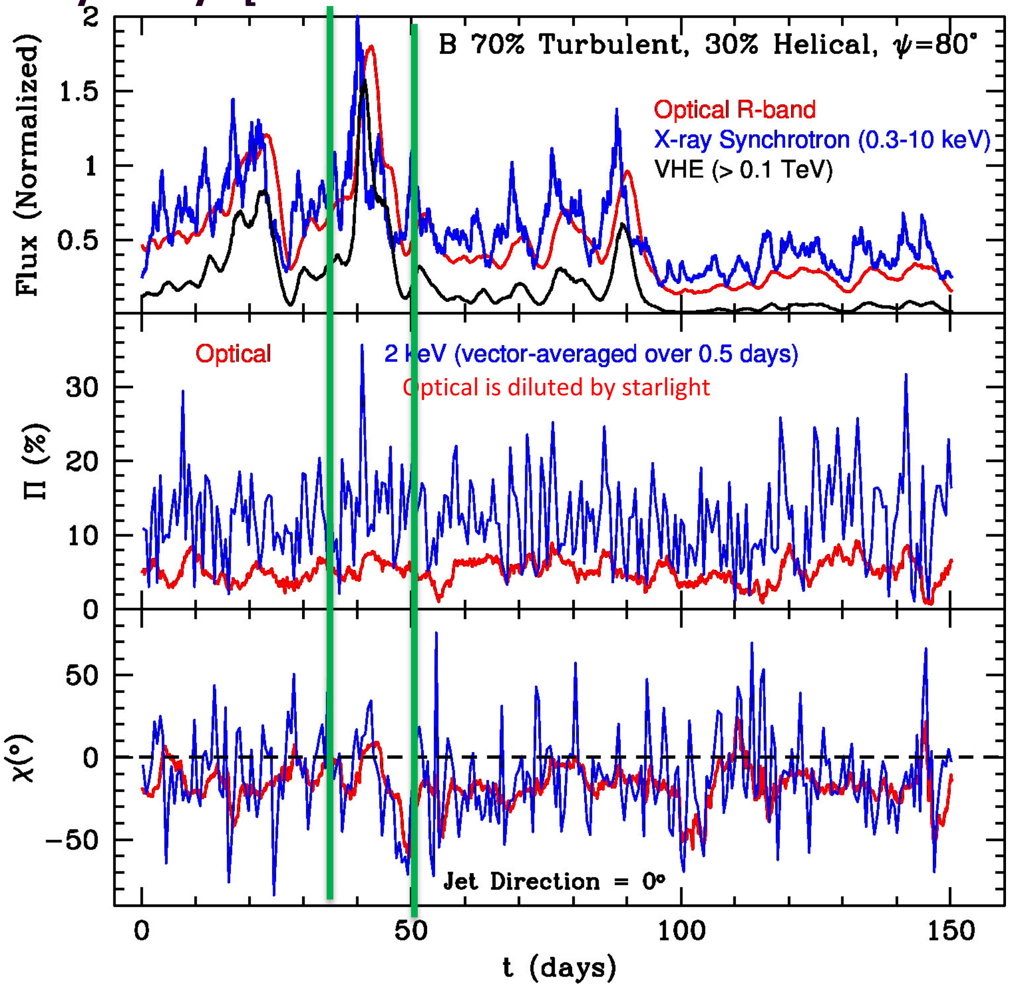

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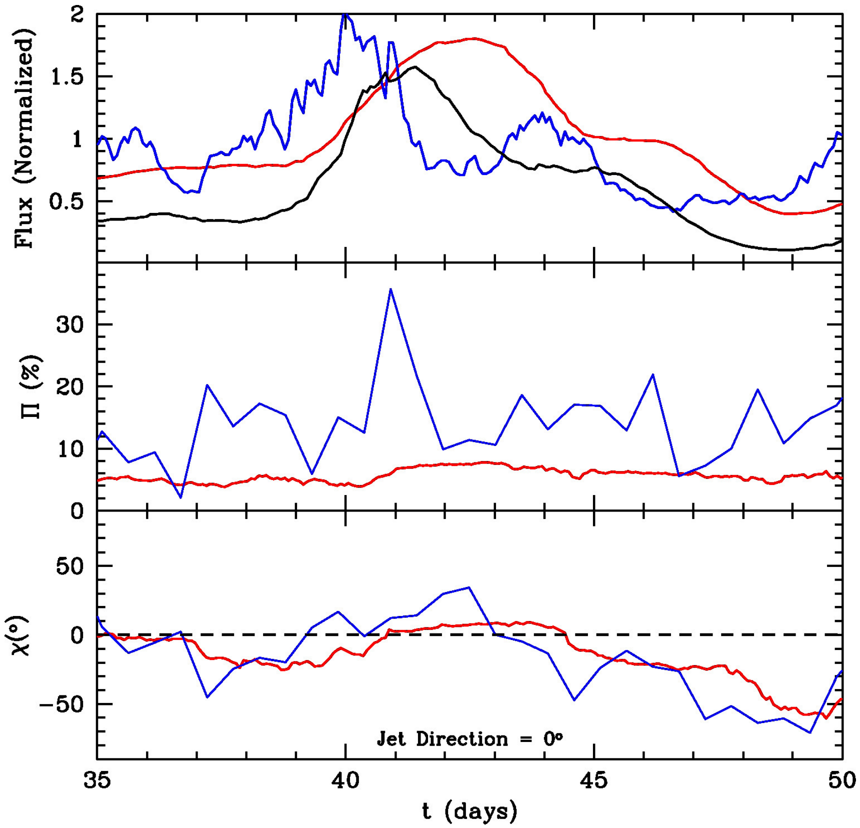

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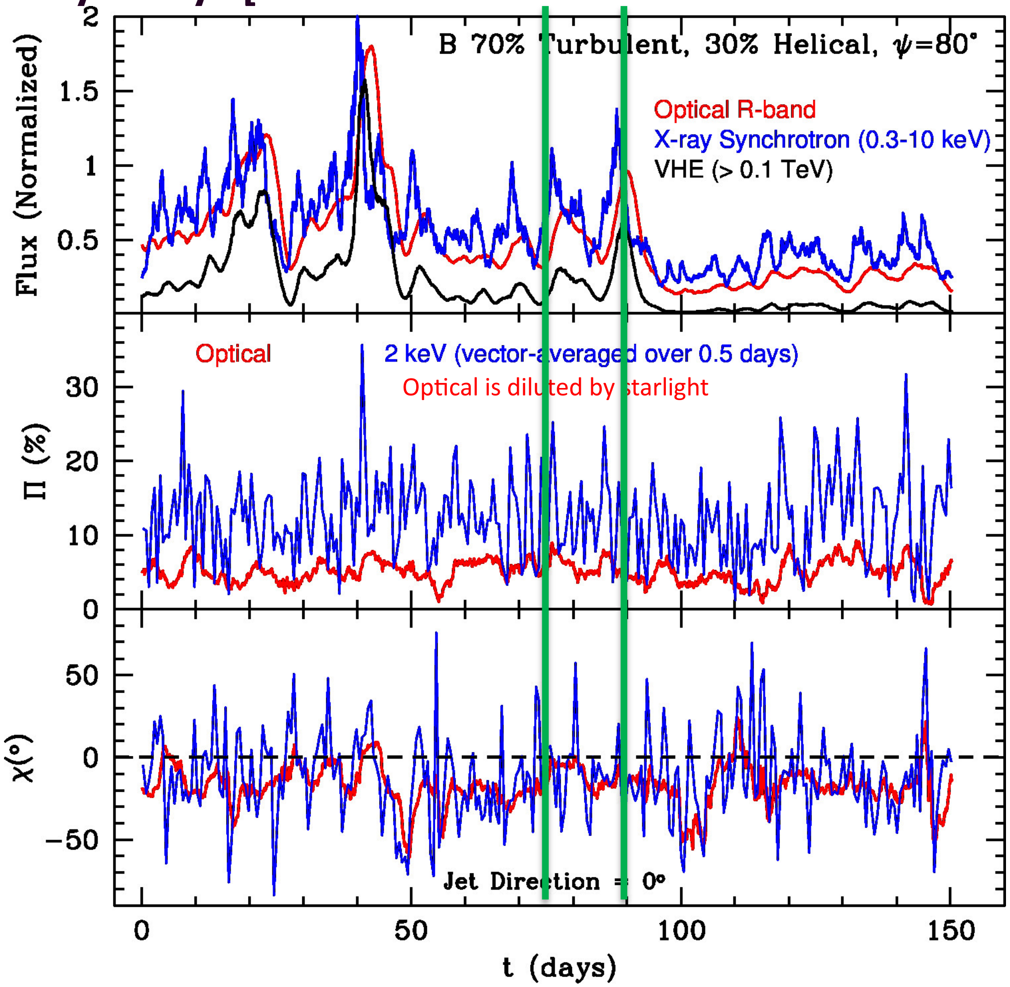
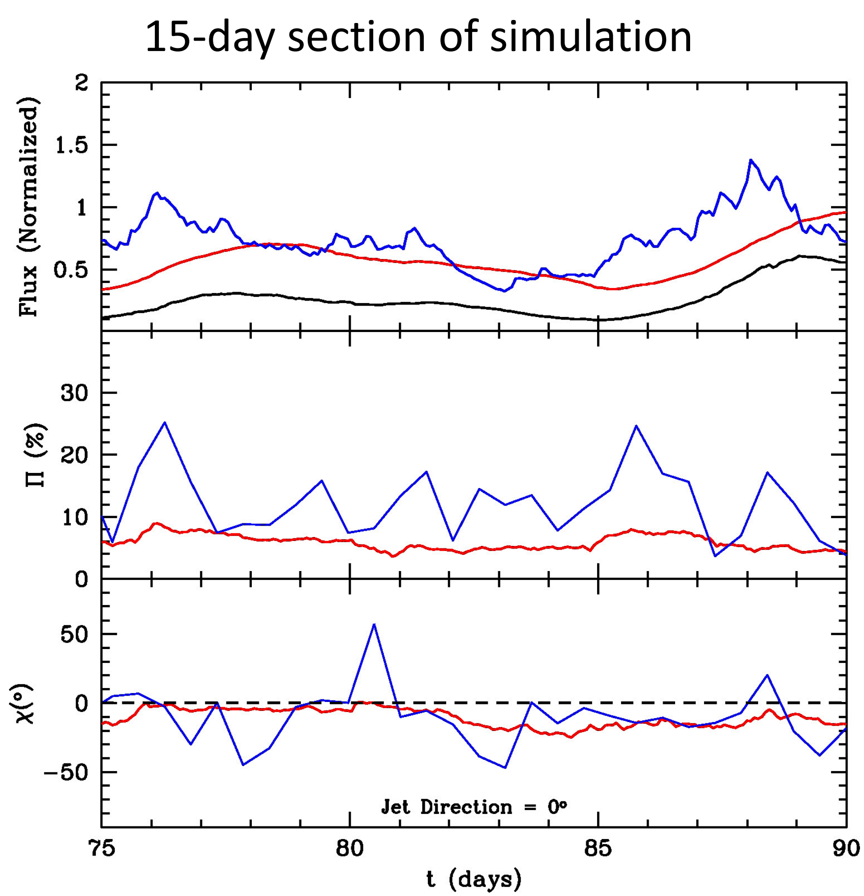
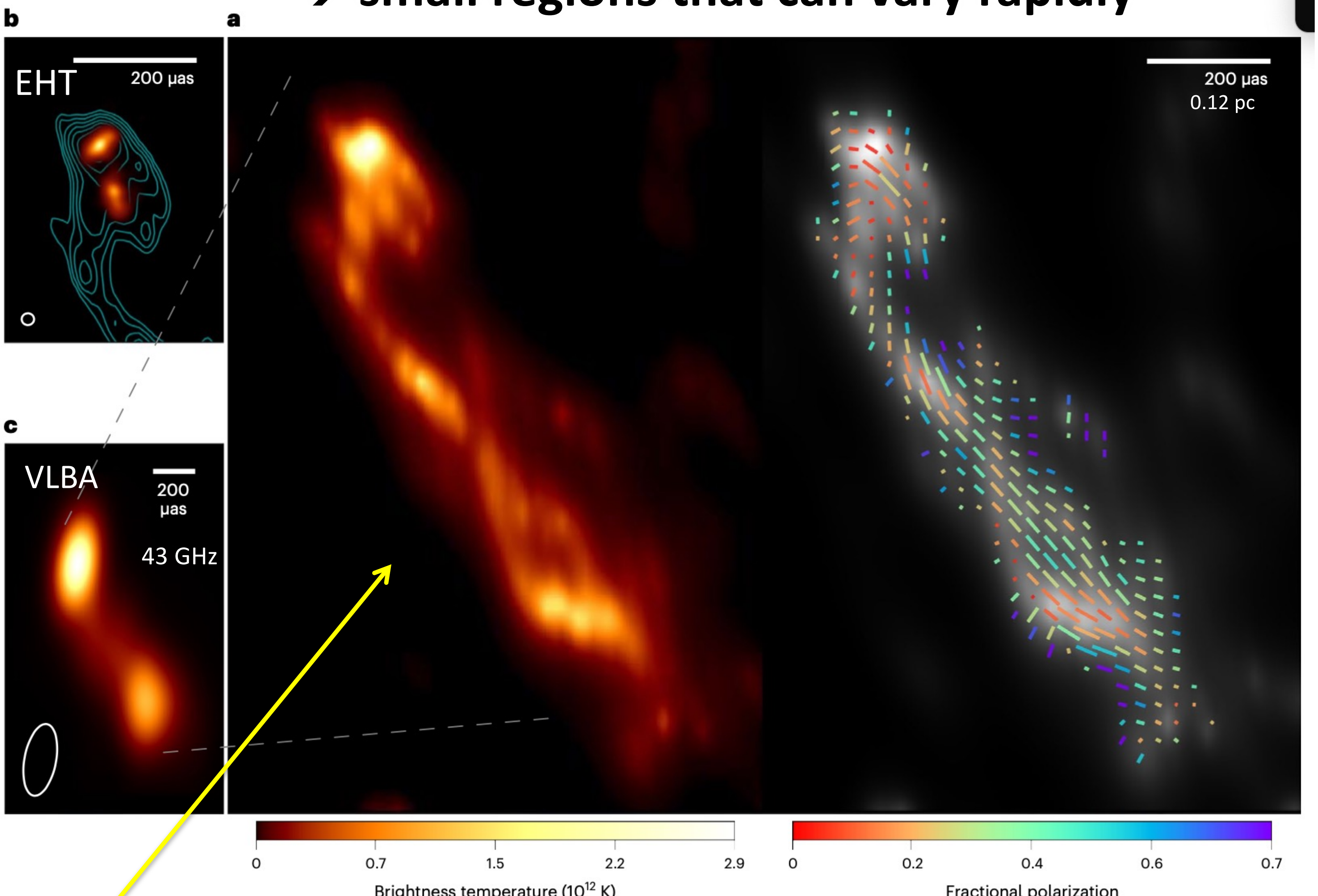




Complication: Filamentary Structure of Jet of Quasar 3C 279

→ Radiation comes from fraction of jet volume

→ small regions that can vary rapidly



VLBI at 1.3 cm including RadioASTRON space-based antenna (Fuentes+ 2023)

Conclusions

1. **Working jet model incorporating turbulence, shocks, & helical B fields can explain many general properties of blazars**

- Frequency (energy) stratification explains MWL similarities & differences

- Ratio of ordered to turbulent field determines level of variability

→ Electrons are accelerated at particular locations, lose energy as they propagate & radiate

2. **Data include features that strain the model**

→ There is room for phenomena such as changes in jet direction, magnetic reconnections, filamentation, kink instabilities, & other instabilities

3. **Despite complexities, data are providing more constraints on models**

→ Need to keep sampling variability to find more patterns

→ Repeat observations of the same objects as well as new ones

→ Future instruments need improved sensitivity & throughput

4. **More theoretical work is needed to develop models of jets that can be compared with the rich data**