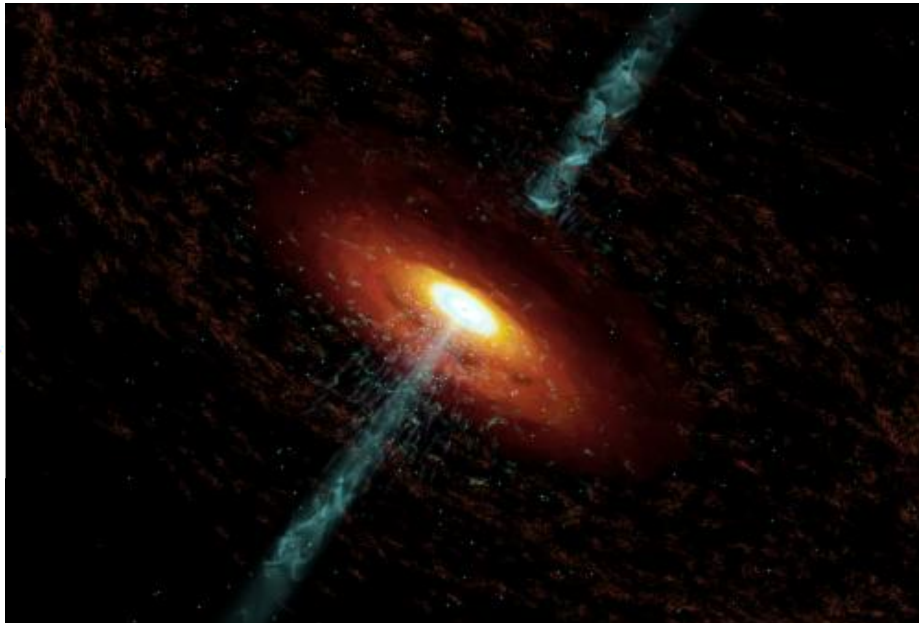
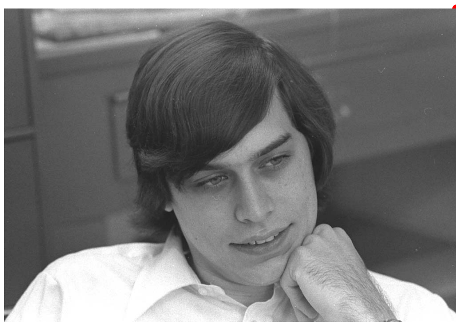
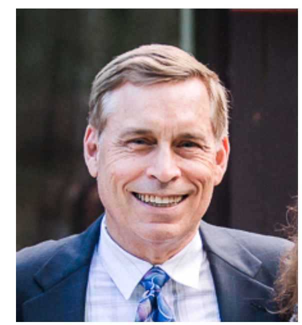


Variability of Blazars & Blazar Models over 38 Years





Alan Marscher

Institute for Astrophysical Research, Boston University

Research Web Page: www.bu.edu/blazars

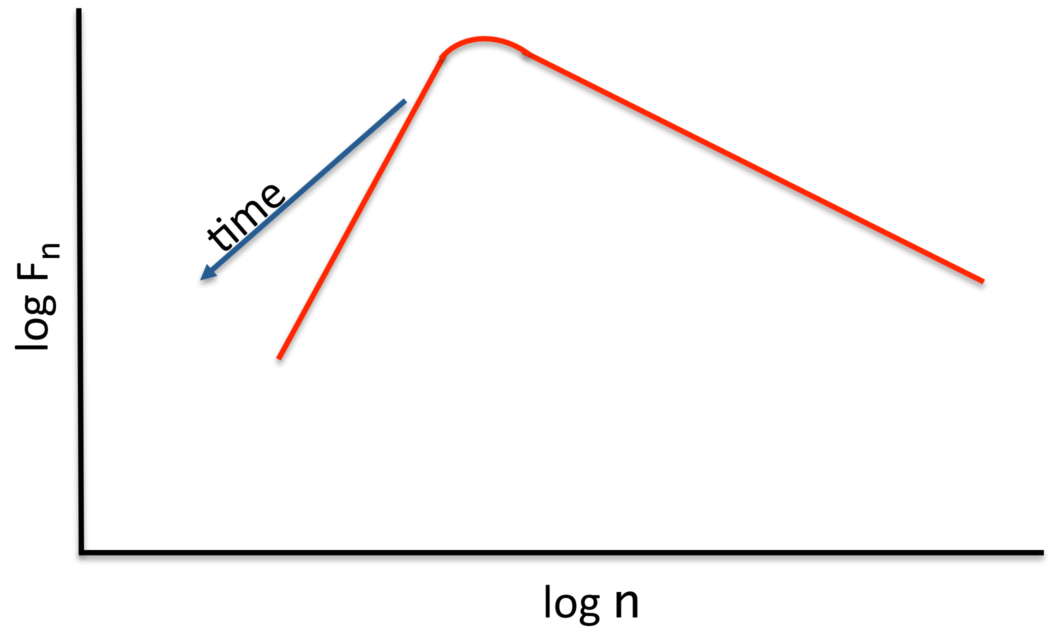
Recordings of original songs: www.soundclick.com/cosmosii

Blazar Models: The Early Years

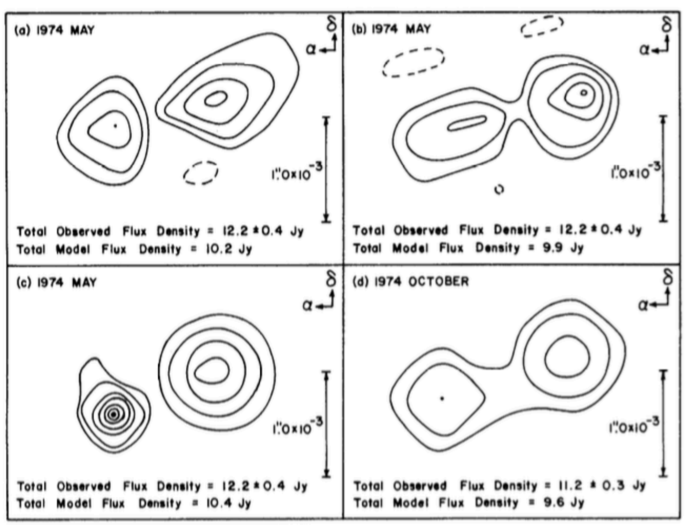
Expanding blobs (Kardashev, Shklovsky, van der Laan)

- **Energy losses → decreasing flux & peak (SSA) frequency**

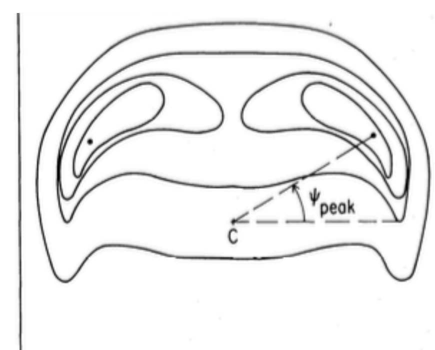
Altschuler & Wardle; Aller & Aller; Odea, Dent, & Balonek:
Radio variations rarely follow predicted spectral changes



VLBI: double sources separating superluminally

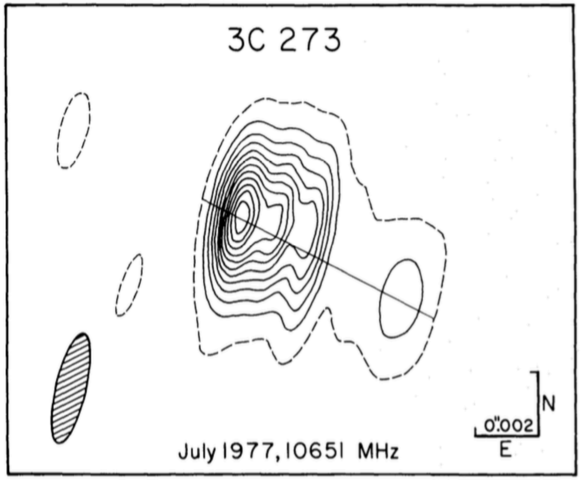


Marscher 1978: Relativistic blast wave in equatorial wind



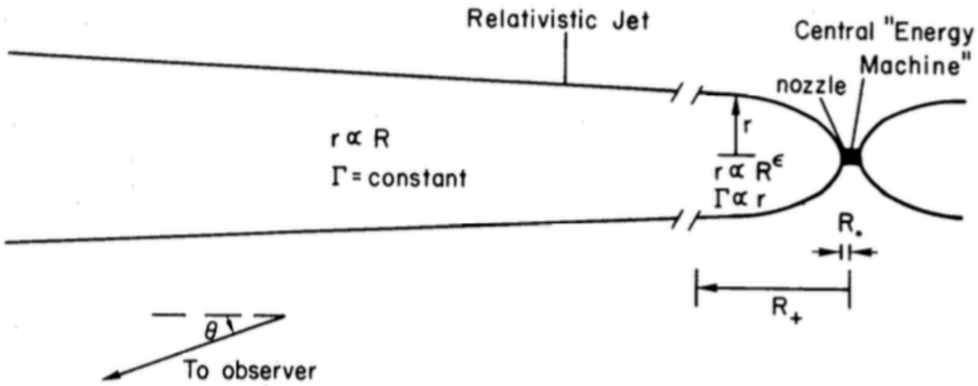
Blazar Science: Jets

1978 Pittsburgh conference on BL Lac Objects: term "blazars" coined
- Blandford & Rees: blazars are compact relativistic jets



1979: Readhead, Cohen, et al.:
hybrid VLBI images → they are jets!

Jet Models
Blandford & Znajek 1977: BH spin→jet
Blandford & Königl 1979: knots are shocks
Marscher 1980: energy losses after particles injected at base → Frequency stratification
Königl 1981: cone; no cooling
Ghisellini+ 1985: generalized
Blandford & Payne 1982: disk-launched jets



Blazar Science: Multi-wavelength Observations

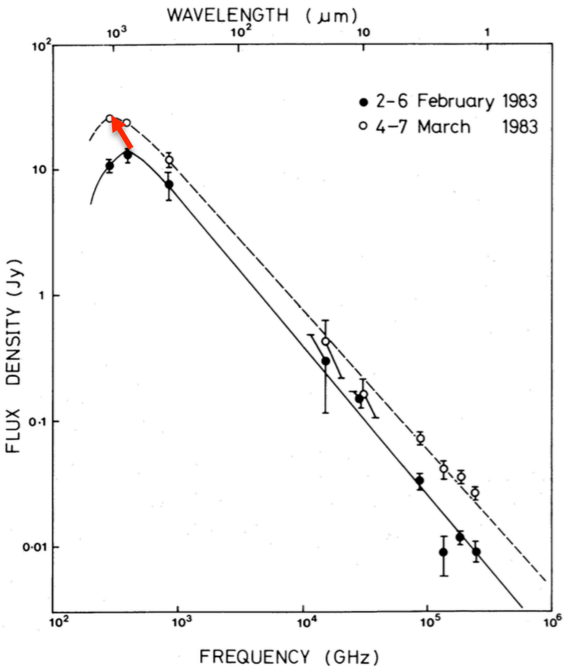
Jet models differed in predictions of SEDs & multi-wavelength variability

Miller (1982): Multi-color optical variability agreed with my jet model!

1981-1988 (Marscher & Broderick): Combined X-ray & VLBI observations of quasar NRAO140: superluminal motion predicted + detected

1982 (Balonek & Dent): repeated radio + optical flares in AO 0235+164

1983 (Robson et al.): cm, mm submm, IR, optical flare of 3C 273



Caught rising portion of outburst

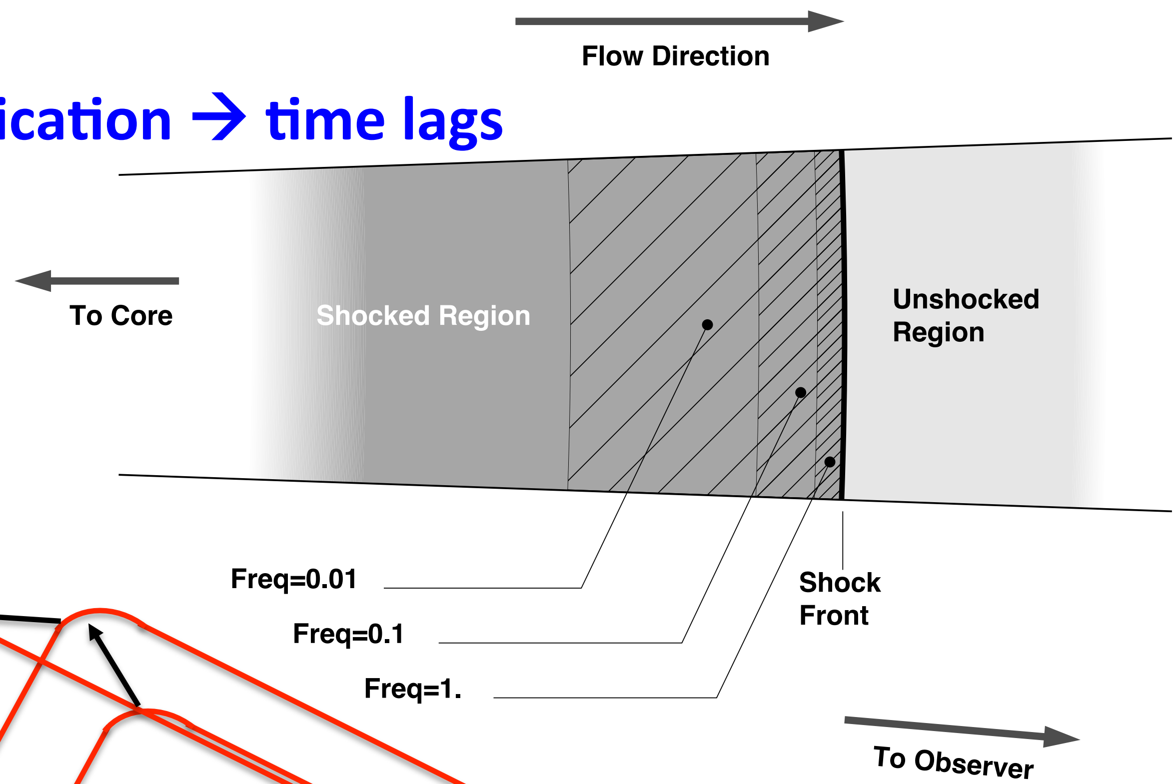
Completely different from expanding blob model

How about a shock?

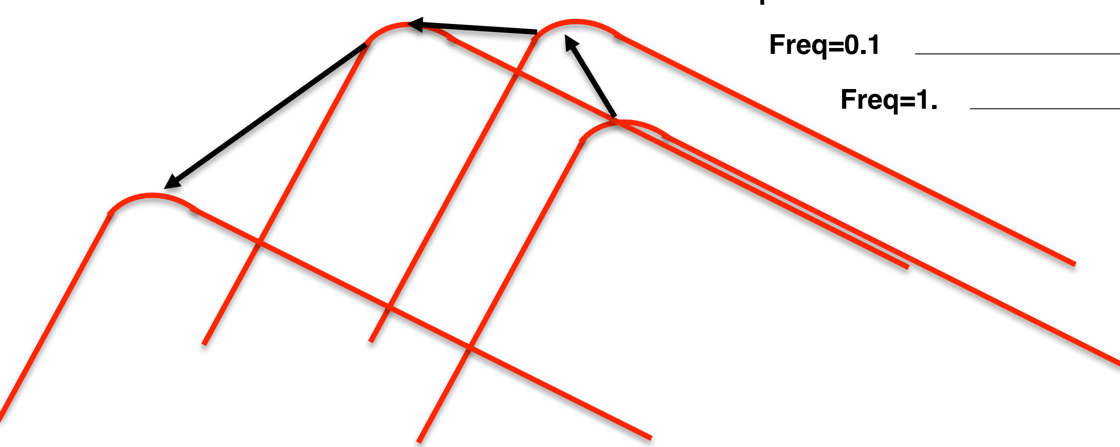
Shocking Blazars

1985 (Marscher & Gear; Hughes, Aller, & Aller; Lind & Blandford): outbursts + superluminal knots are moving ("internal") shocks

Frequency stratification → time lags



Spectral evolution



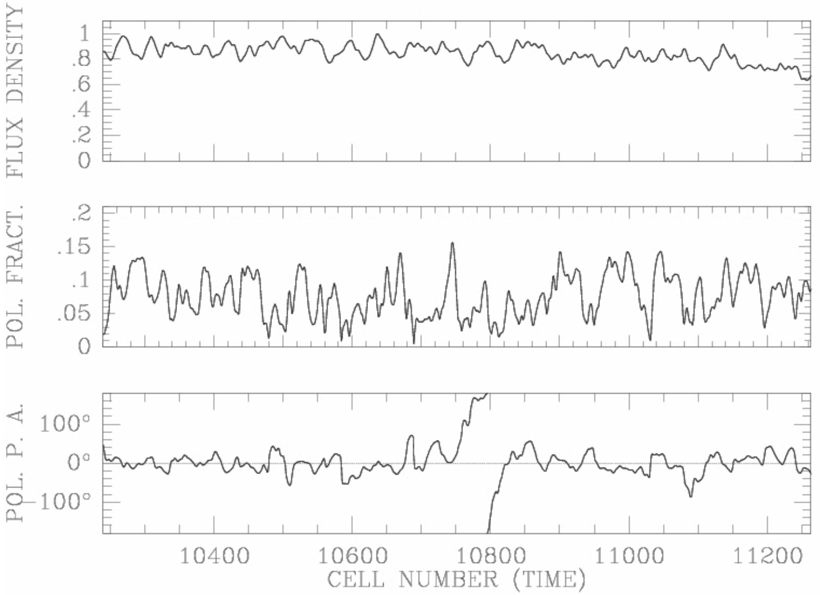
HA&A: Reproduces radio polarization observations

Blazars: Turbulent Inside

1980s: Rotations of radio & optical polarization vectors reported

1985-88 (Jones et al.): polarization variability (Allers) → turbulent B
→ Can cause apparent polarization swings, often rather smooth

1992 (Marscher, Gear, & Travis): omni-present minor fluctuations in flux & pol. caused by turbulent plasma passing into shock waves

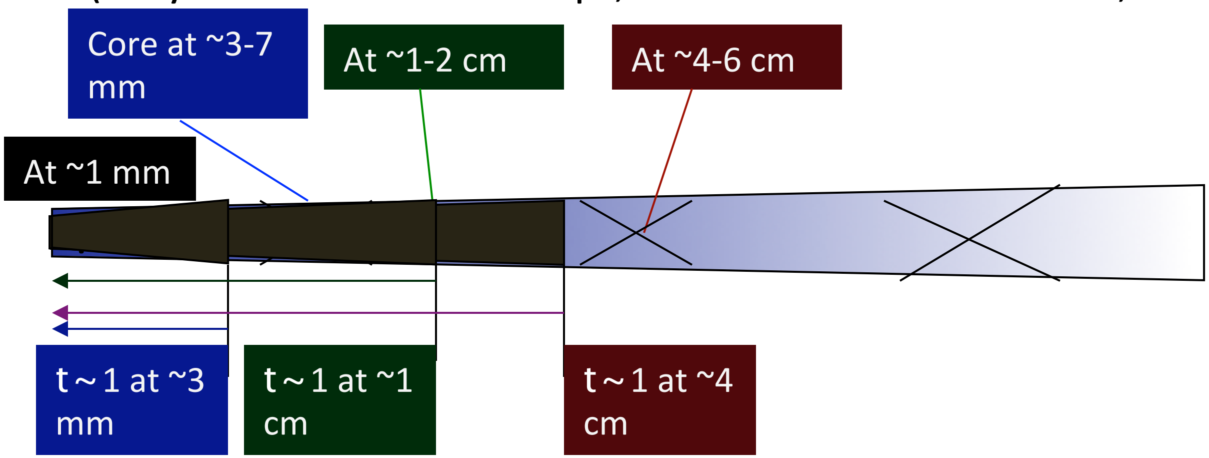


What Is the “Core” of Blazar Jets?

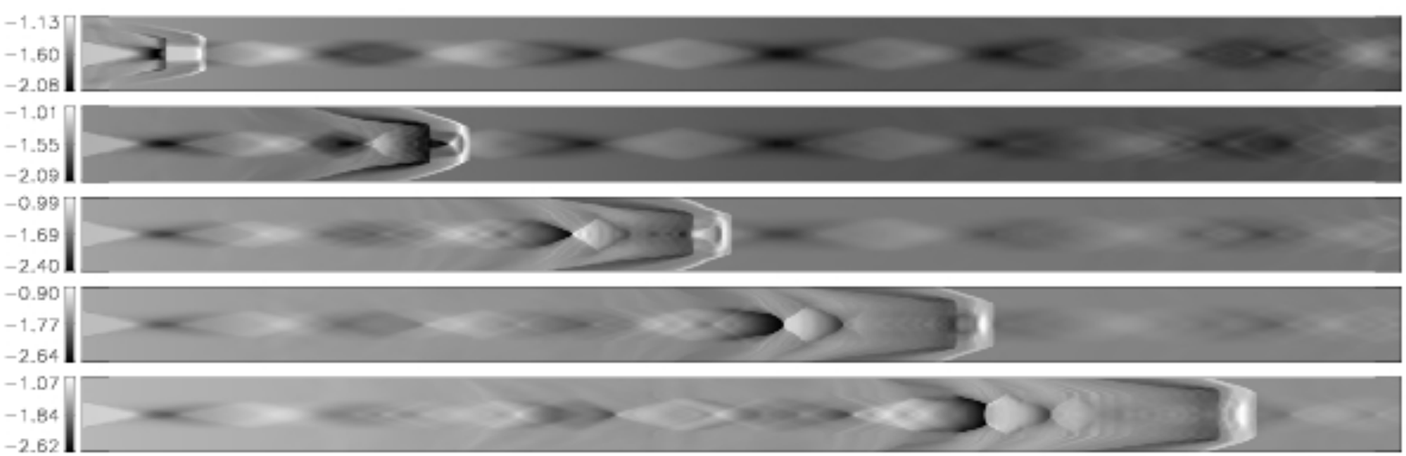
Observations suggest that core on VLBI images is either:

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

(Daly & Marscher 1988 ApJ; Cawthorne & Cobb 1990; Cawthorne 2006; Cawthorne + 2013)



Lobanov (1998): Can determine B from core shift)



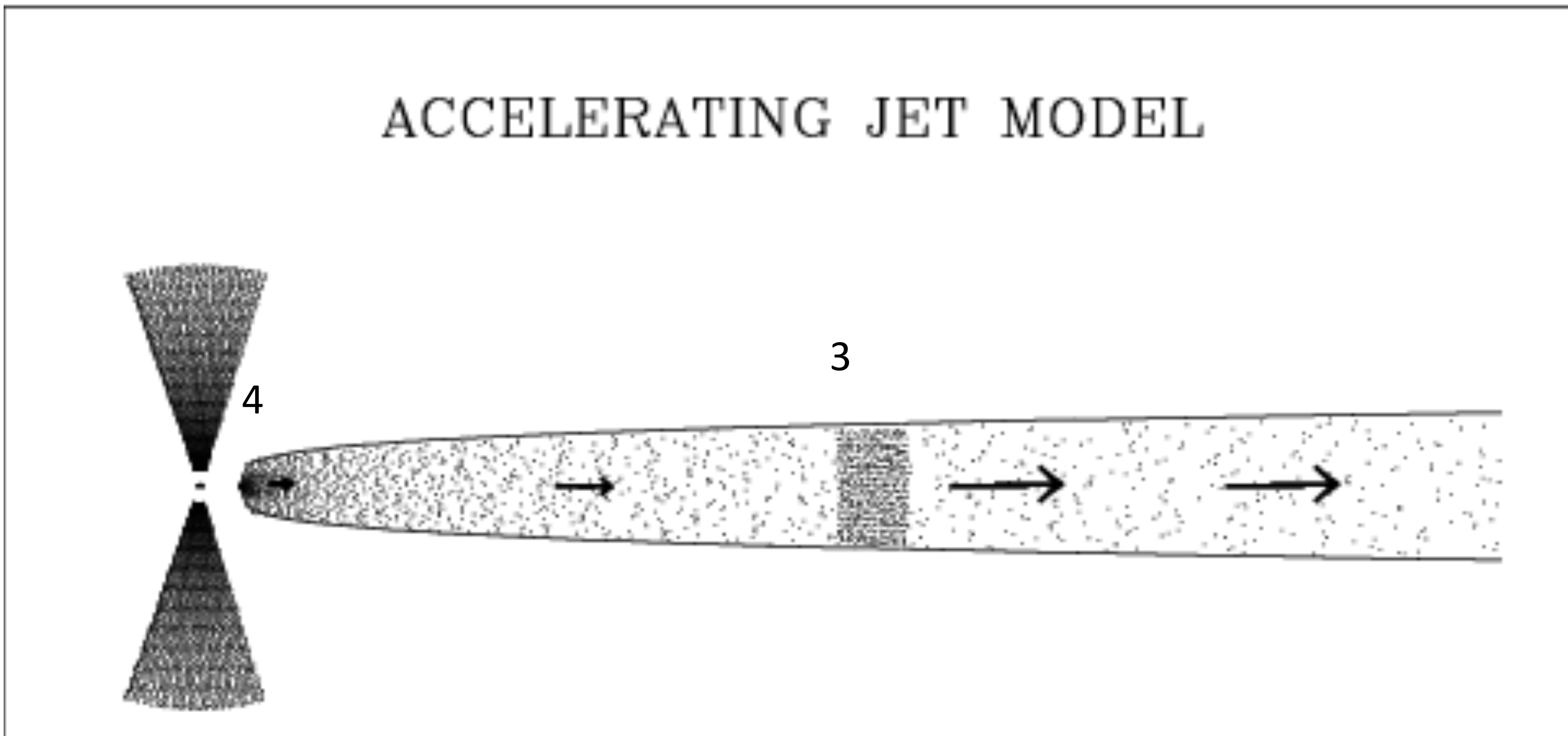
HD simulation (Gómez et al. 1997)

The "Core" of Blazar Jets (continued)

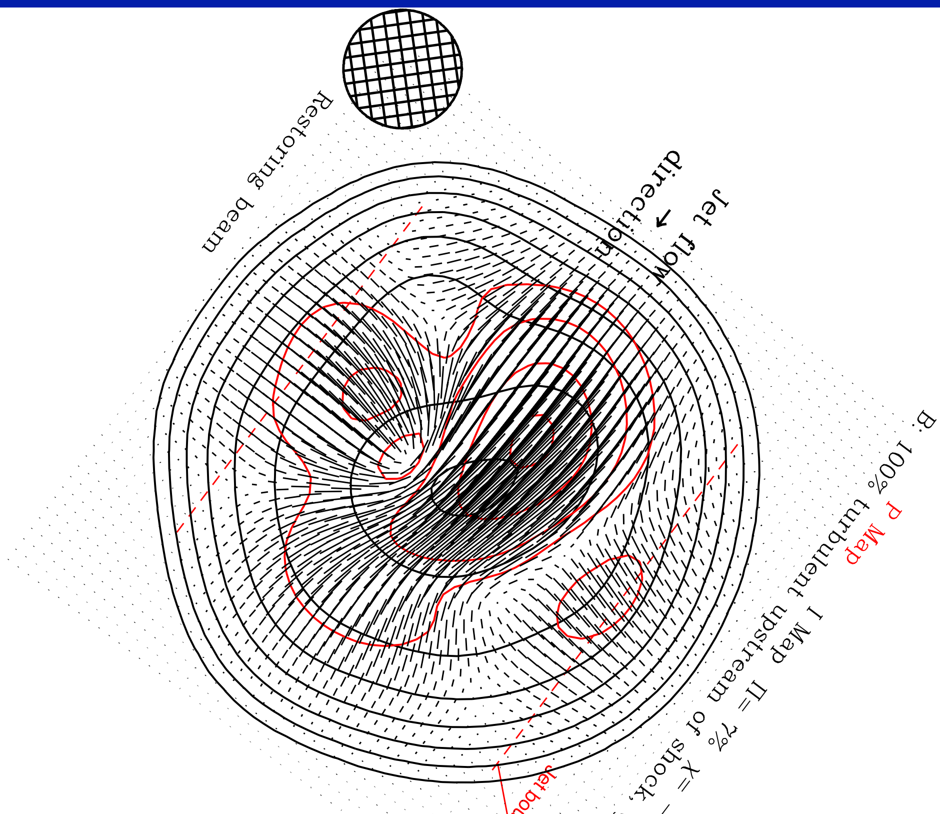
3. If <u>accelerating</u> relativistic jet is viewed within ~ 10° of axis, core can be location where Doppler factor approaches its ultimate value

4. If viewed from a wider angle, base of jet can be seen as the core <u>if</u> a sufficient number of relativistic electrons are present there

- Appears to be the case in M87, Cyg A, NGC1052, 3C 84



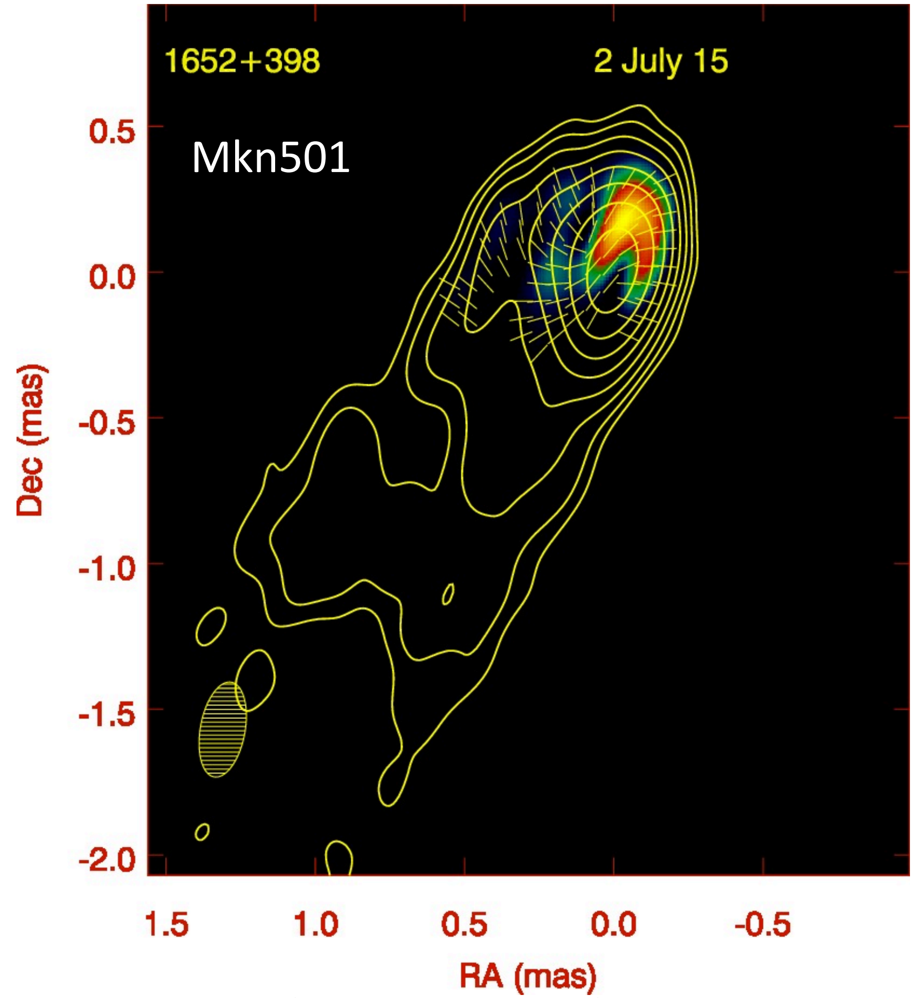
Turbulence + Conical Shock Model vs. Image of Mkn501



Simulated polarized intensity image of turbulent plasma flowing through standing conical shock

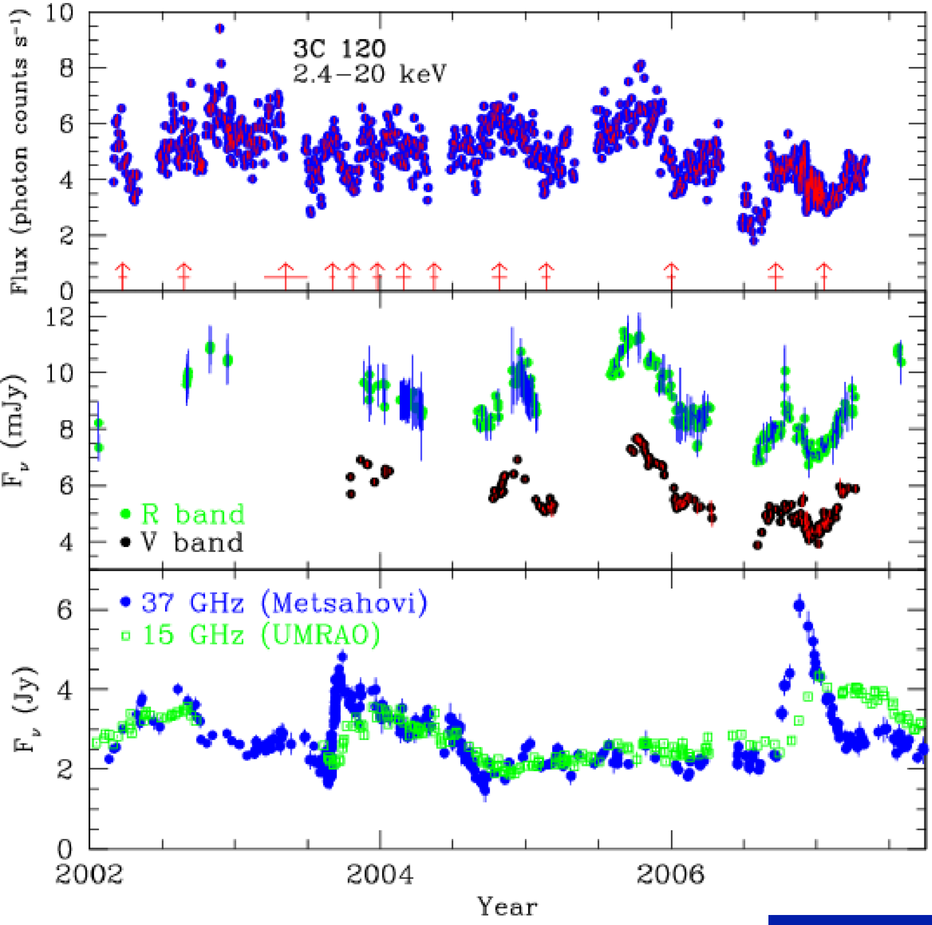
- Symmetry causes near-cancellation of polarized components parallel & perpendicular to jet axis

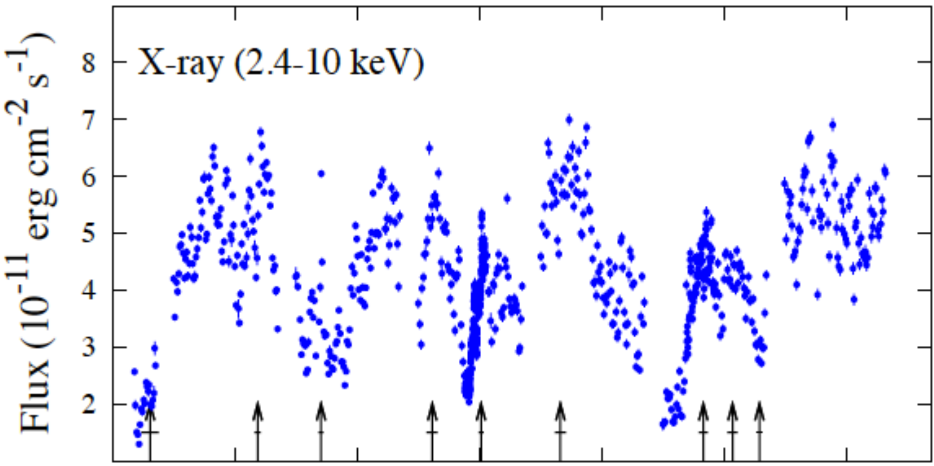
- Net polarization direction corresponds to random variation of mean field direction



Actual 43 GHz VLBA polarized intensity image of Mkn501

X-Ray Dips/Superluminal Ejections in Radio Galaxies 3C 120 & 3C 111



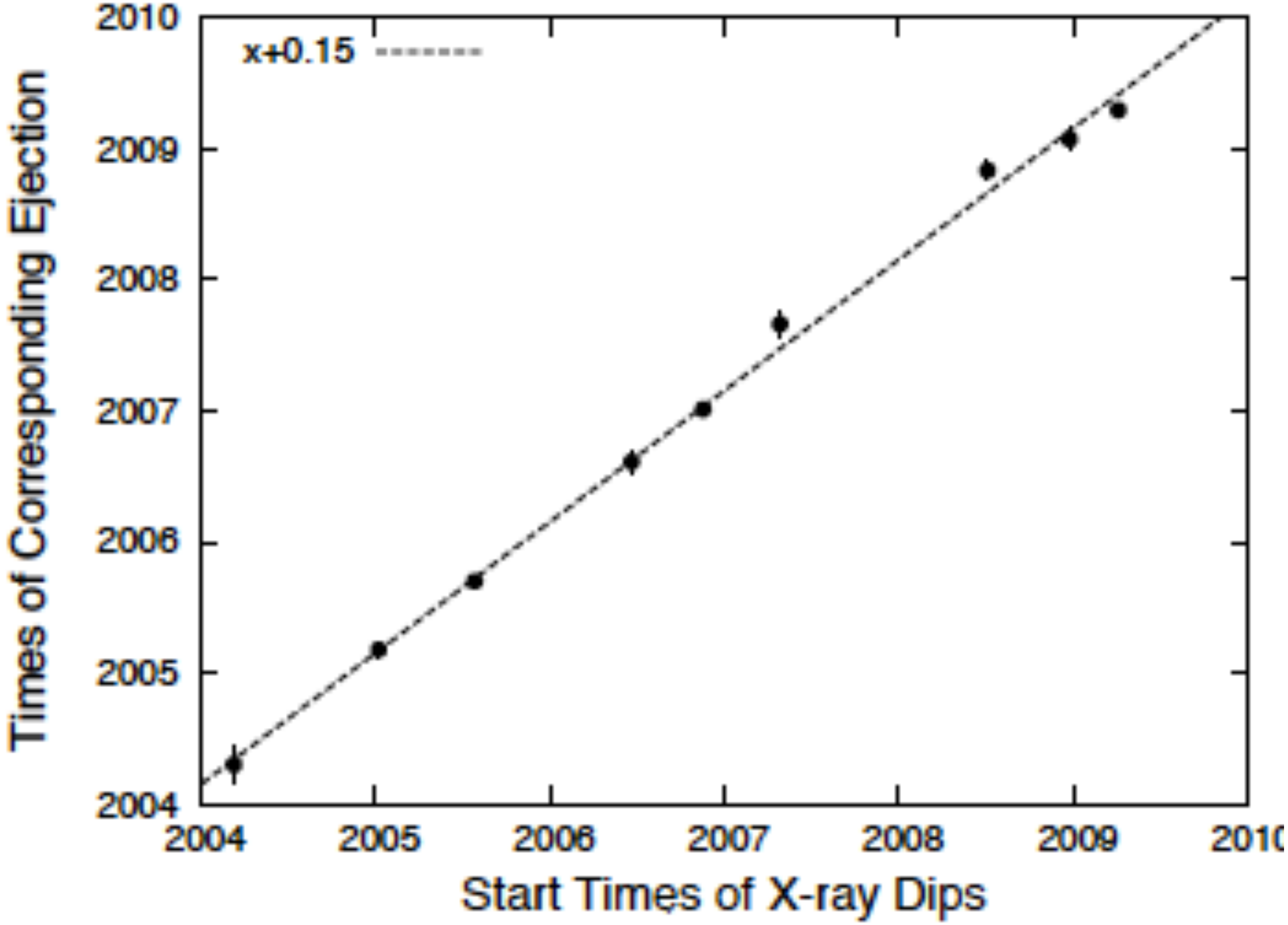


Superluminal ejections/37 GHz flares follow X-ray dips

Radio core must lie at least 0.5 pc from black hole to produce the observed X-ray dip/superluminal ejection delay of ~ 60 days (Marscher et al. 2002 Nature; Chatterjee et al. 2008, 2011 ApJ)

Strong optical/X-ray correlation: optical from disk

3C 111: Distance of 43 GHz "Core" from Central Engine



Superluminal ejections follow X-ray dips by mean time of 55 days

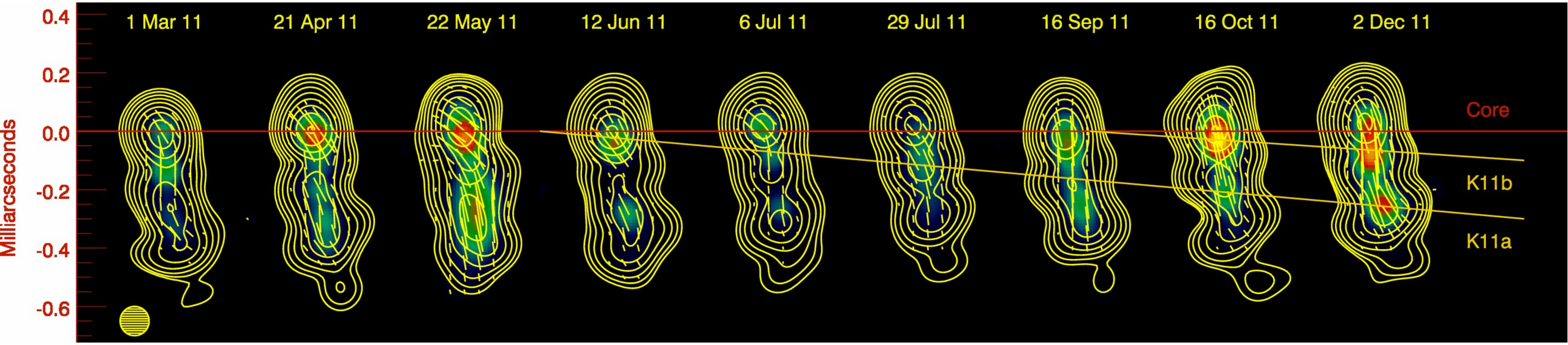
→ Radio core must lie at 0.6±0.3 pc (0.2 mas, projected) from black hole

Progress in Polarization

All along (Allers): Multi-frequency radio polarization vs. time

Late 80s (Wardle & Roberts): Polarized intensity VLBI

1995: VLBA begins full operations with polarization capabilities



Late 1990s:

- **(Wardle & Homan): Circular polarization with VLBA → positrons**
- **Gabuzda, Sitko, Smith: Connection between optical & radio pol.**
- **1998: S. Wagner showed me extensive optical pol. curves → ideas**

- **Jorstad et al.: monitoring of mm VLBA, 1+3 mm, & optical flux + pol.**

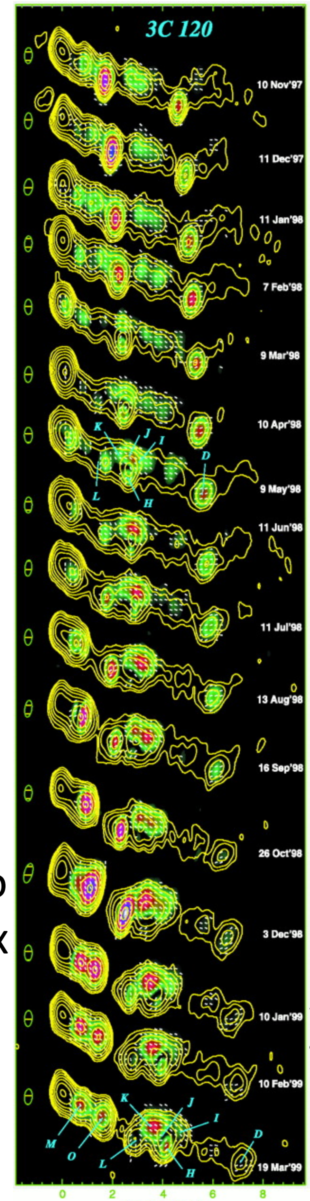
→ Connection often close → Larger monitoring programs justified

Productivity Increase in Late ‘90s: The Full Story

3 wonderful events in the late ‘90s:

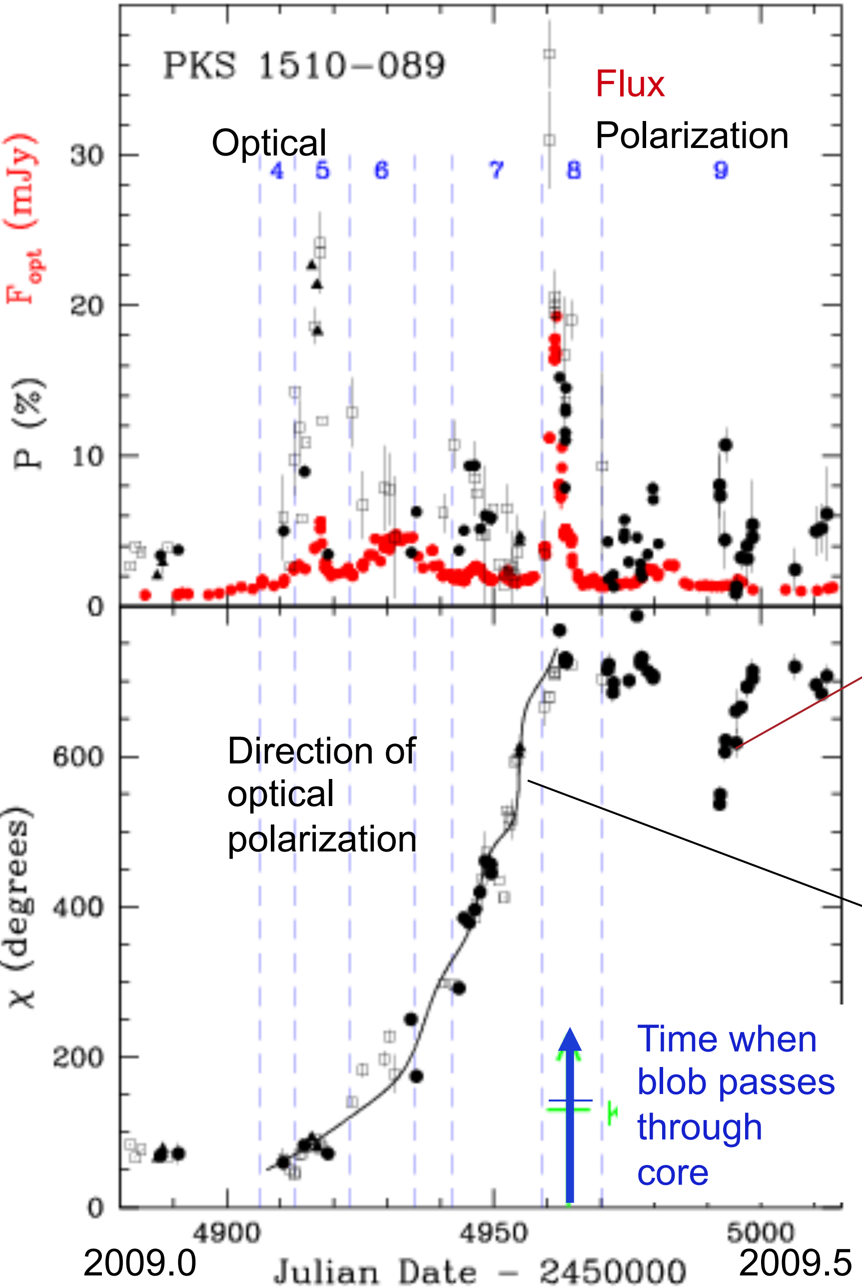
1995: The VLBA was completed

BU became partners with Lowell Observatory → guaranteed telescope time to monitor blazars in optical flux & polarization



Svetlana arrived in the US . . .
And immediately started working on the observations

Rotation of Optical Polarization in PKS 1510-089



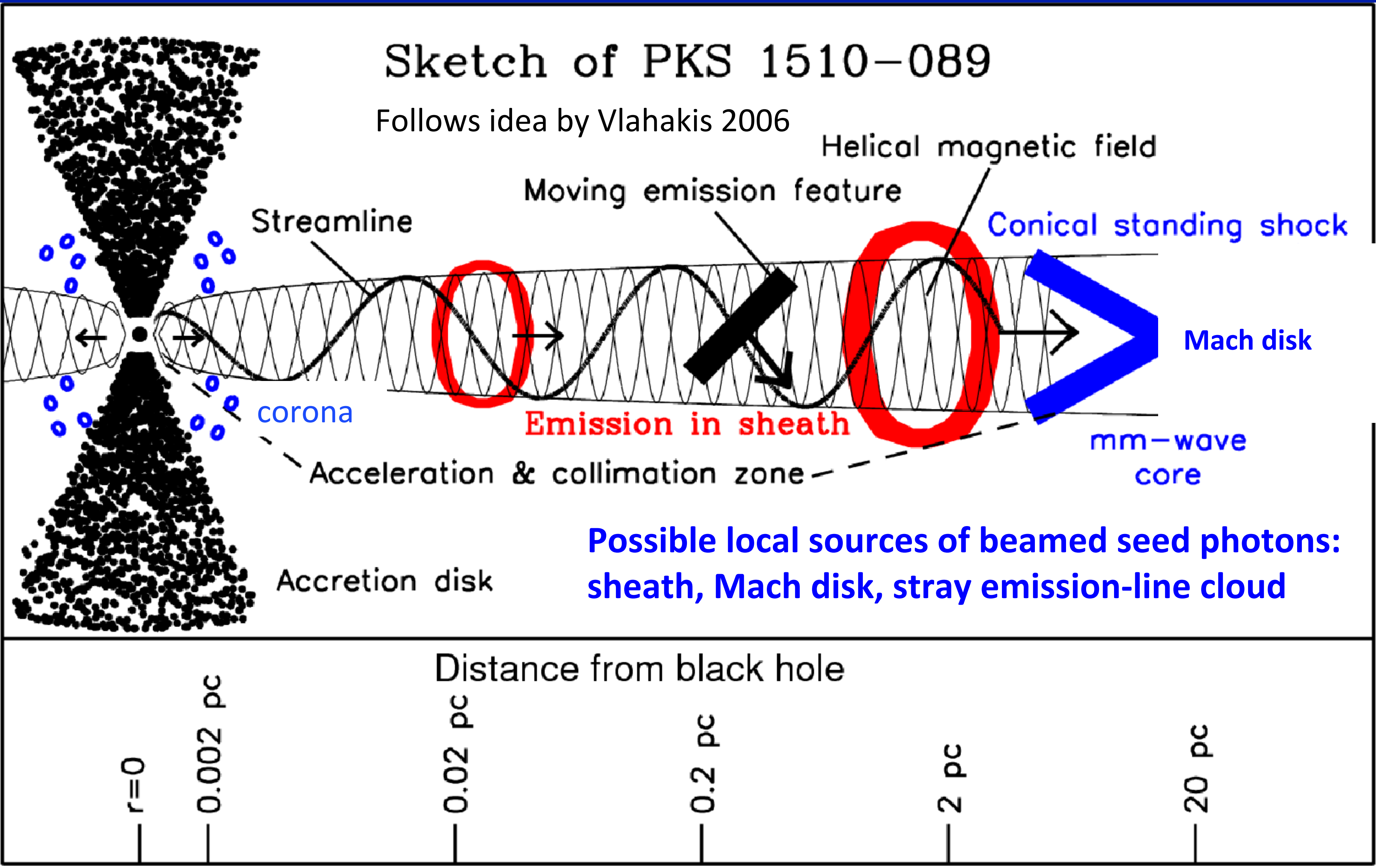
Rotation starts when major optical activity begins, ends when major optical activity ends & superluminal blob passes through core

- 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 → related to geometry of mag. field

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

Some polarization rotations in blazars are similar, others resemble turbulence

Polarization Rotation in PKS 1510-089 (Marscher et al. 2010 ApJL)



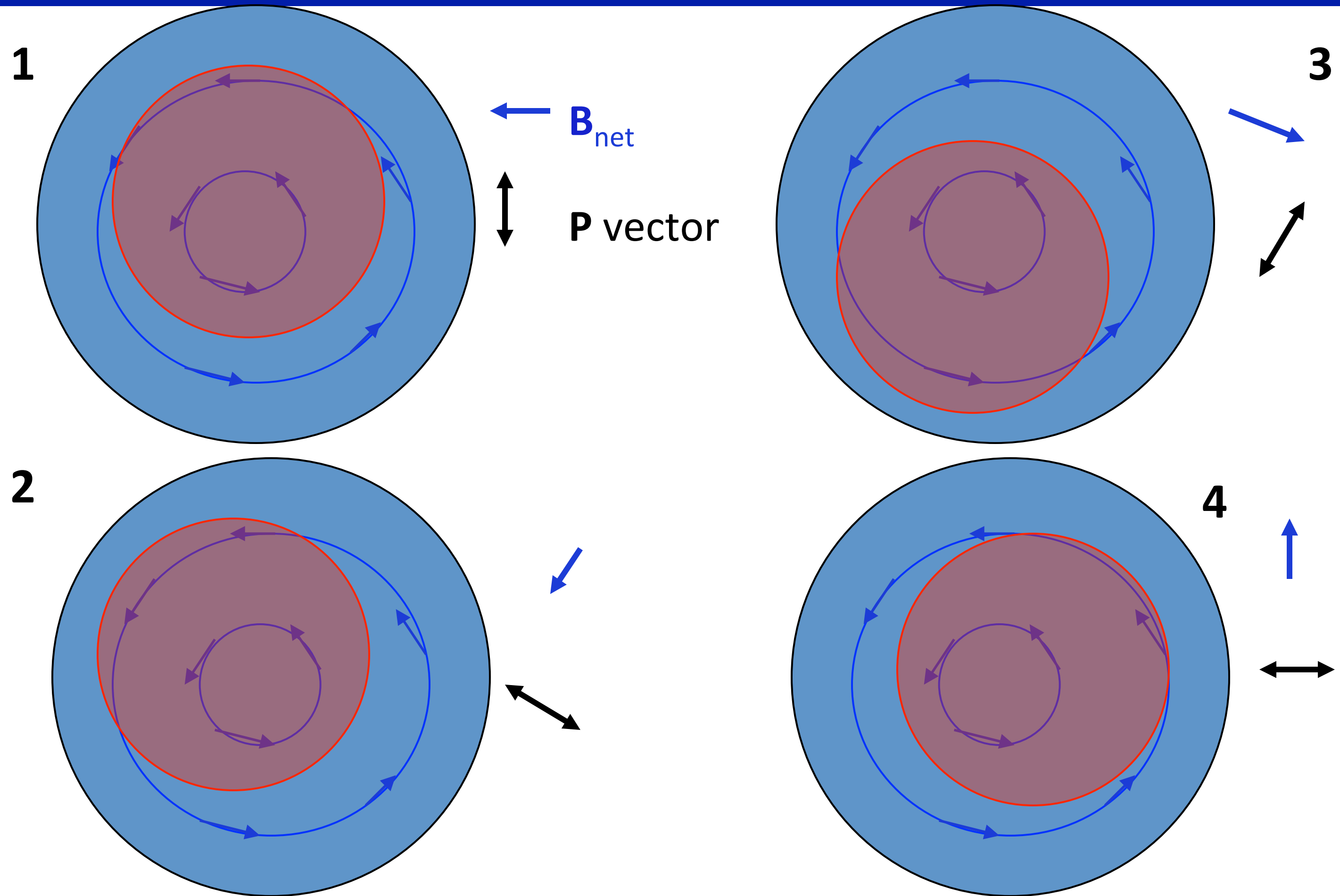
Possible local sources of beamed seed photons: sheath, Mach disk, stray emission-line cloud

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**



High Photon Energies from Blazars

1980s: Einstein Observatory → many blazars detected in X-rays

1996-2012: RXTE → dense X-ray monitoring of some blazars

2004-present: Swift → X-ray + optical-UV, some monitoring

1991-2000: CGRO (EGRET detector): many blazars detected in g-rays

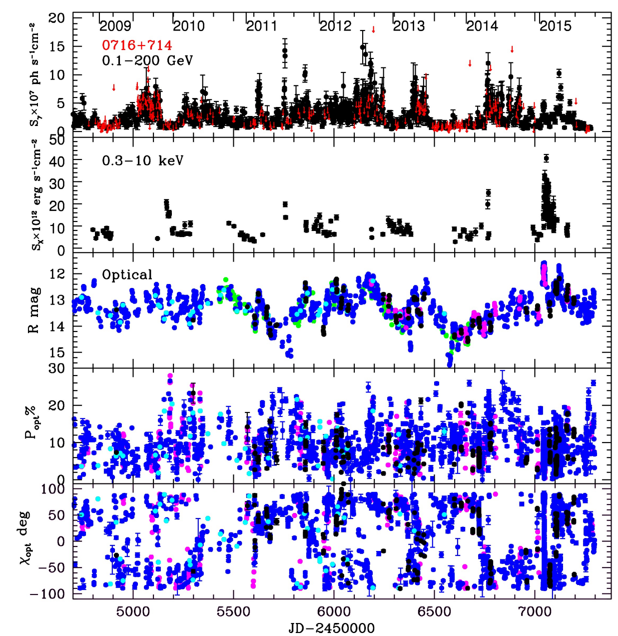
2007-present: AGILE

2008-present: Fermi (LAT detector)

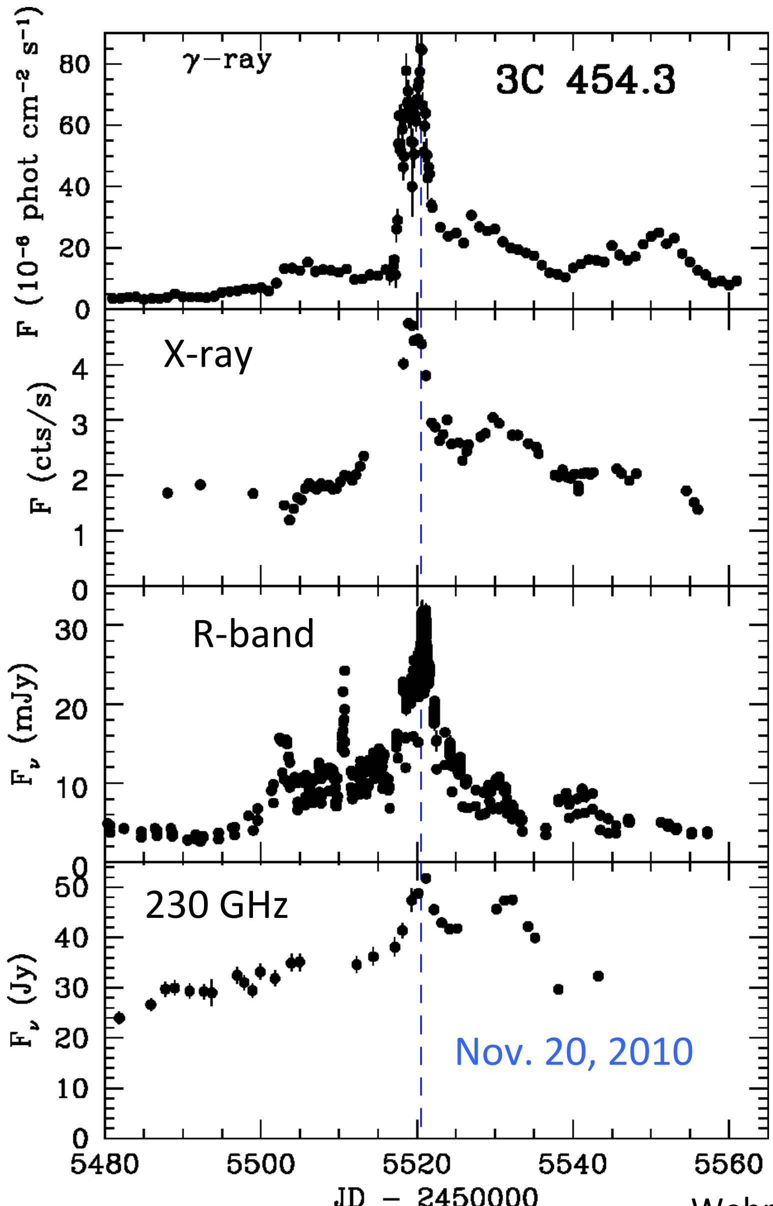
→ Thousands of blazars detected, densely sample light curves

→ Many multi-waveband monitoring programs

Collaborators have included many people at this conference, as well as others who could not come



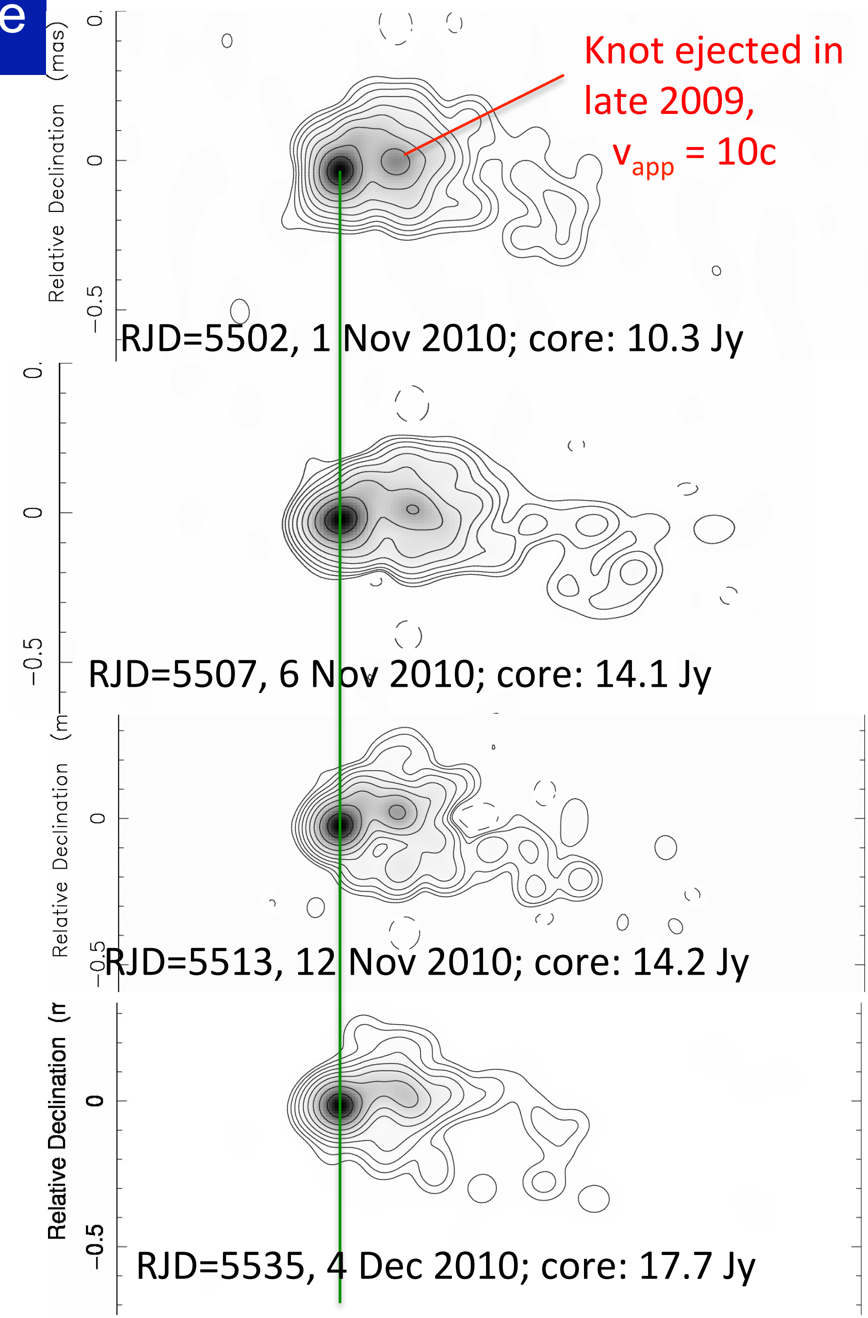
3C 454.3: All wavebands down to mm-wave peaked within 1 day during flare in VLBI core

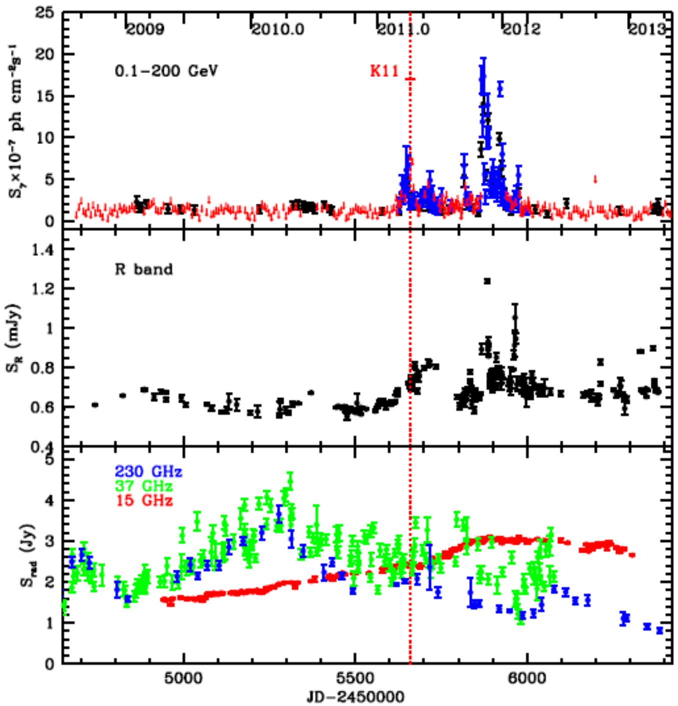


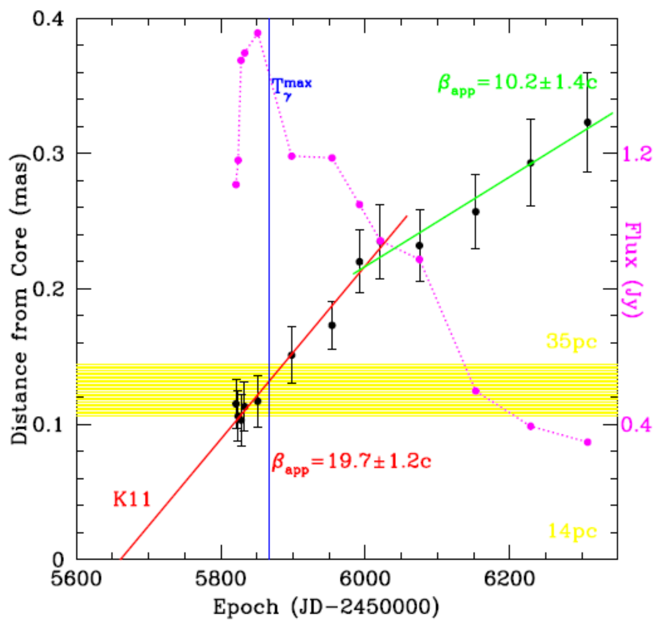
~70% of g-ray flares occur on pc scales

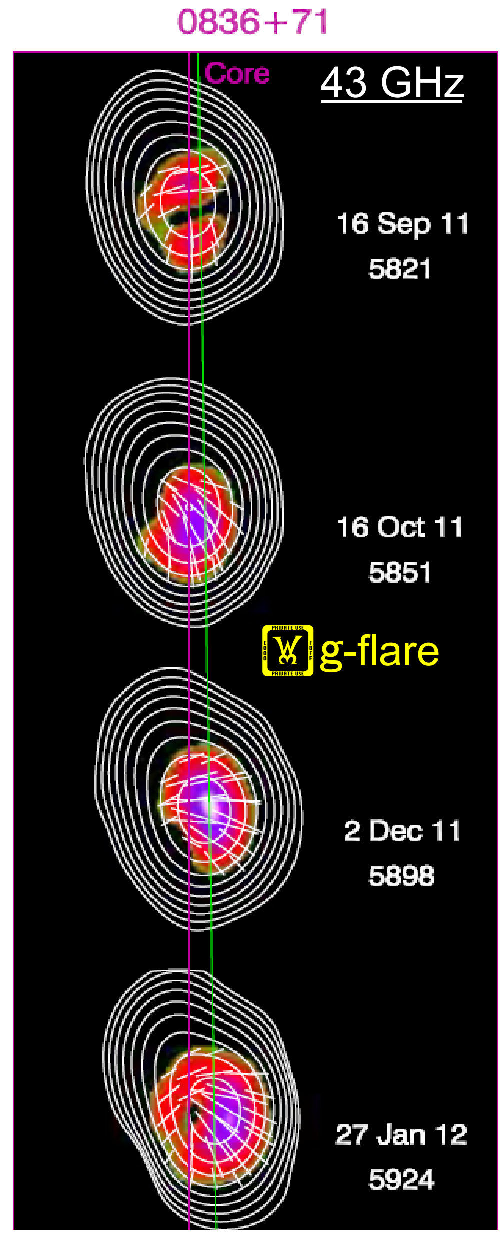
Wehrle et al. (2012 ApJ)

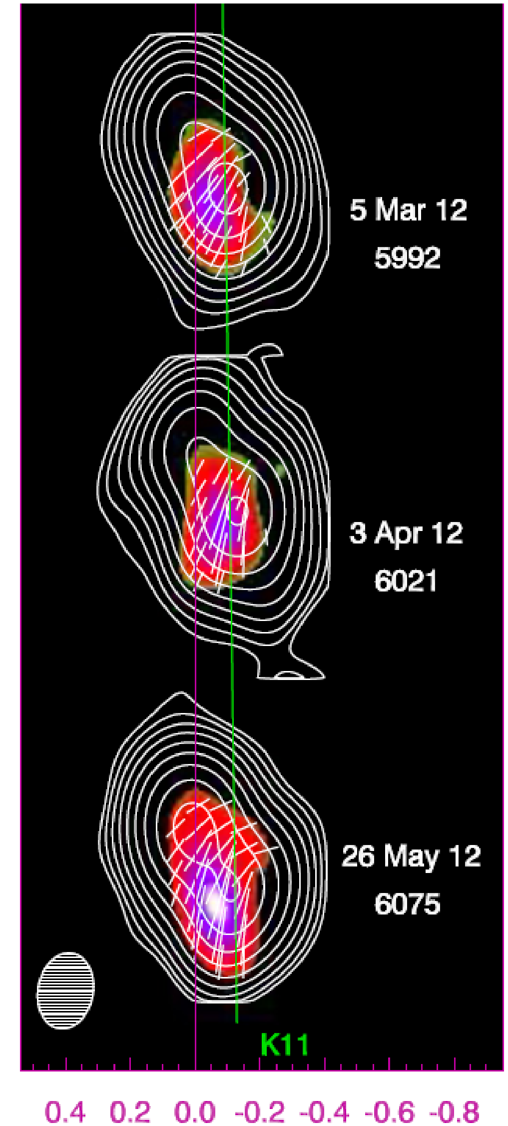
VLBA images at 7 mm wavelength







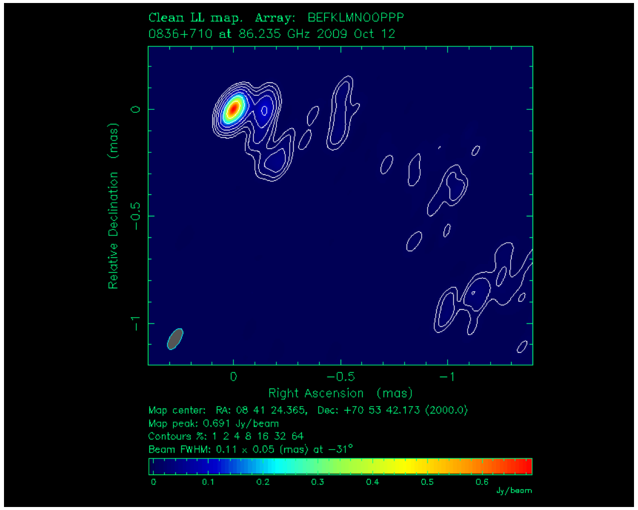




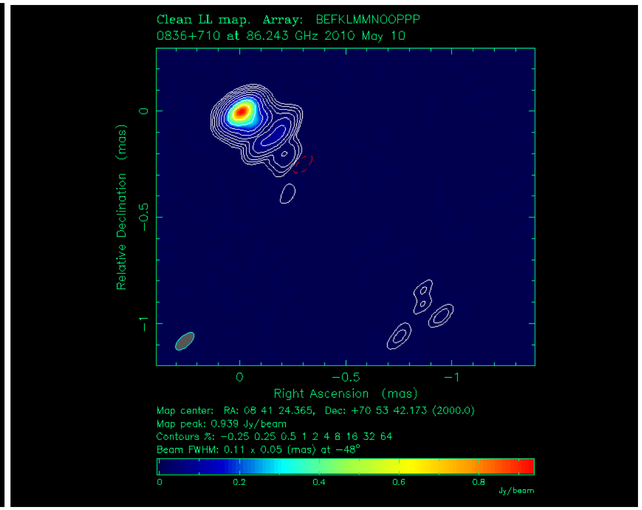
Jorstad+ 2013

The structural evolution of 0836+714 at 86 GHz

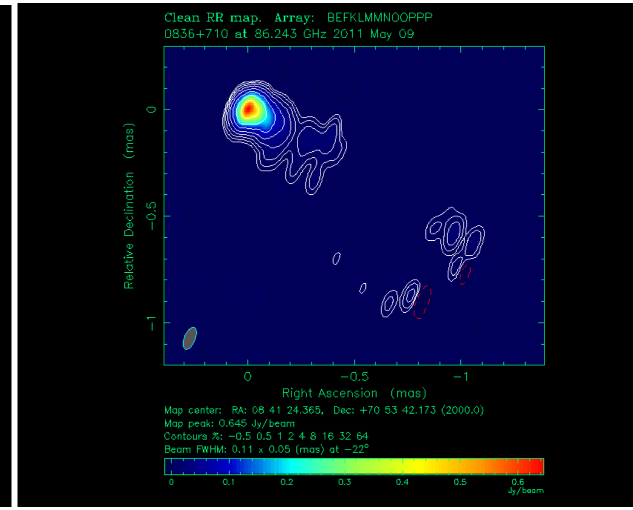
Oct. 2009



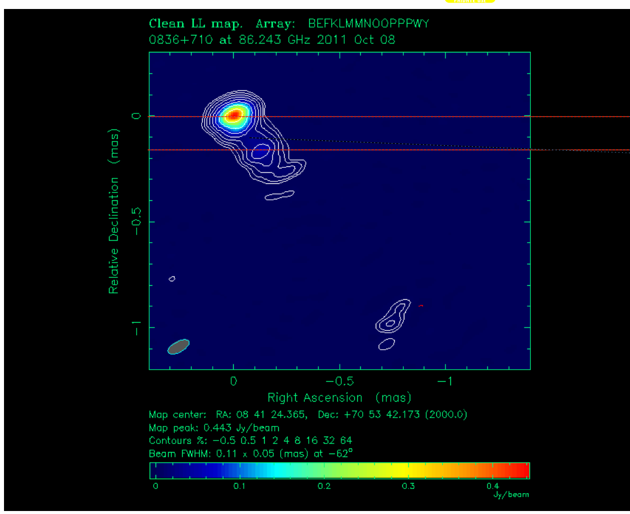
May 2010



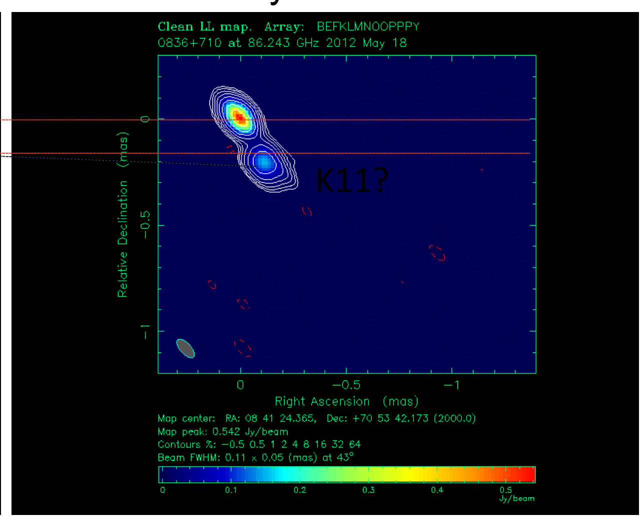
May 2011



Oct. 2011 g-flare



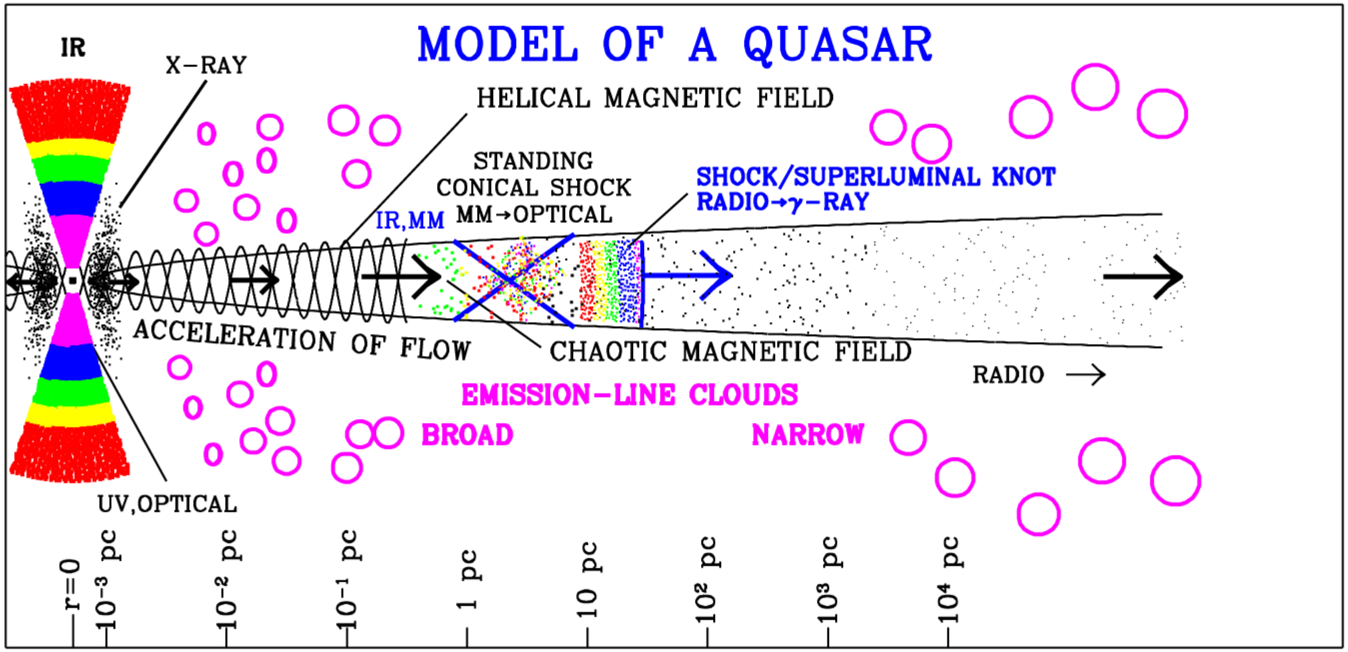
May 2012



more epochs to come....

(K11: b_{app} = ~20)

The Dilemma of Parsec-Scale Gamma-ray Flares



Seed photon crisis: > few pc outside main emission line & dust regions

Synchrotron photon field of g-ray emitting region too weak

Stray clouds (León-Tavares+)? Slow sheath or Mach disk? Polar dust?

Time-scale crisis: High-L flares on time-scales < 1 hr on parsec scales?

G > 100 could solve, but parent population is too small

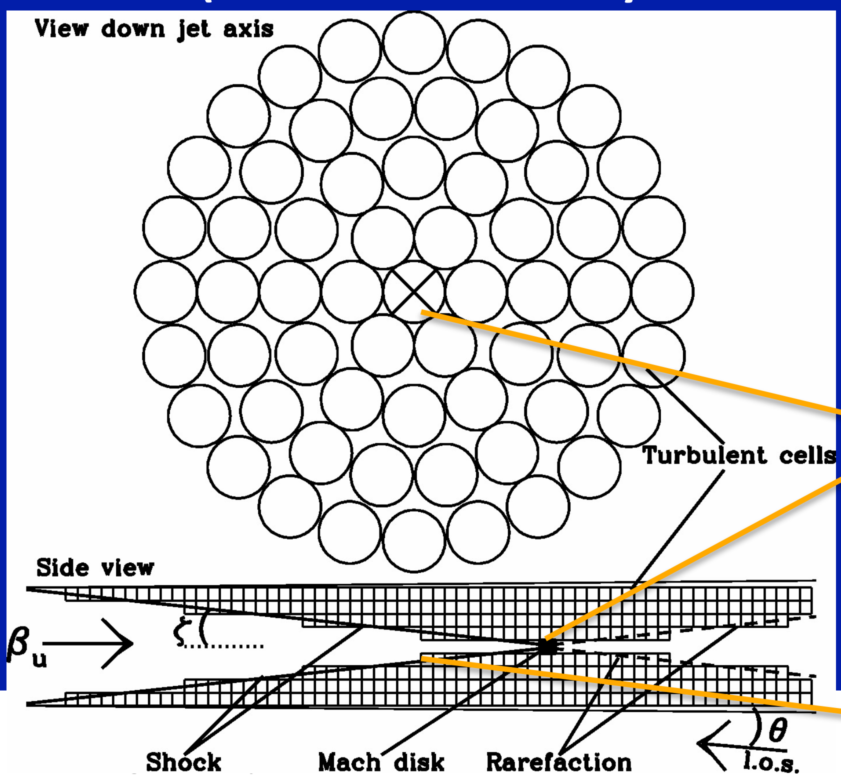
SCANDALS!!

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)



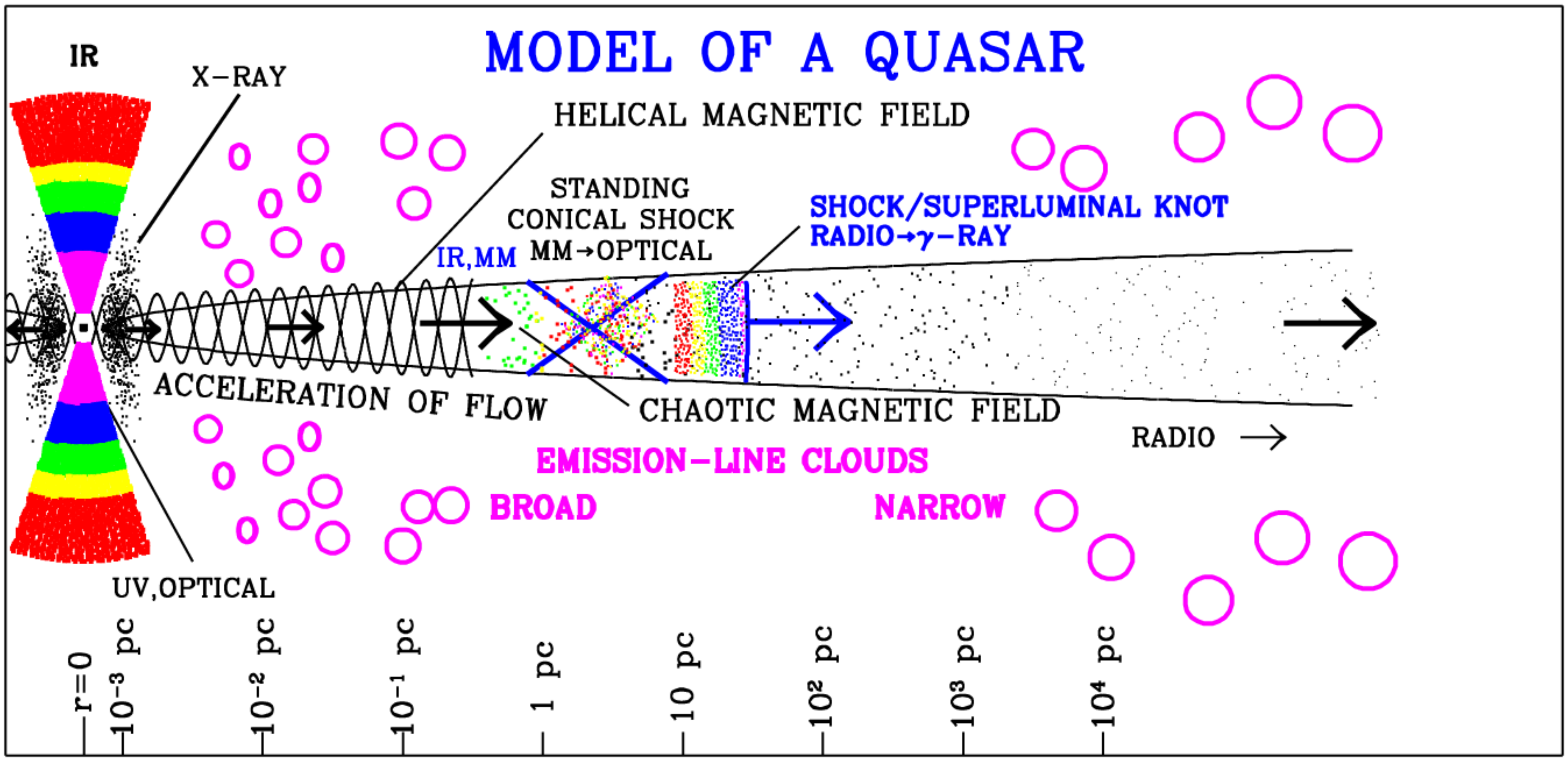
Important feature: only small fraction of cells can accelerate electrons up to energies high enough to produce optical & γ-ray emission
→ More rapid variability to explain intra-day flux changes

Mach disk (optional)

Conical standing shock

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 direction is favorable



Not The End (Yet)

Assignments to the blazar community:

1. Solve brightness temperature problem
2. Solve time-scale problem
3. Determine sources of seed photons near the parsec-scale jet
4. Develop more models for multi-waveband flux & polarization variations
5. Improve simulations of magnetic reconnection
6. Participate in decadal surveys, etc., to argue for new facilities that can study blazars
7. Win the lottery and donate the money to the VLBA & other worthy endangered or proposed-but-unfunded instruments
8. Use new facilities (e.g., Event Horizon Telescope/Black Hole Camera, Cherenkov Telescope Array) to explore regions very close to (as well as farther from) the black hole

This is the End

Many thanks to . . .

everyone who made this great conference possible

Special thanks to Ivan Troitsky & Carolina Casadio for technical assistance

& especially to José Luis for initiating it & leading the organization!!!

Extra Slides Follow

The Birth of Blazars: Pre-natal Period (before 1978)

1963 (Schmidt): 3C 273 recognized as a high-redshift object: quasar
1965 (Sholometsky; Dent): Variability problem: radio sources too compact
1962-66 (Khardashev; Shklovsky; van der Laan): expanding blob model
1966 (Rees): Variability problem can be solved with relativistic motion → predicted apparent superluminal motions
1969 (Kellermann & Pauliny-Toth): ~10^{12} K brightness temp. limit
1969 (Lynden-Bell): Accretion onto supermassive black holes power quasars → considered too extreme at first
1970s (H&M Aller; Altschuler & Wardle): multi-● radio monitoring → expanding blob models don't fit data well
1971 (VLBI; Whitney et al.): Superluminal motion (~10c) in 3C 279
Early 1970s (Scheuer; Blandford & Rees): jets feed extended lobes
1973-74 (Jones et al.): Synchrotron & inverse Compton theory
1977 (Marscher): Synchrotron sources with gradients (wind?)
1977 (Blandford & Znajek): Extraction of energy from rotating BH

The Birth of Blazars: 1978-82

1978 BL Lac Conference in Pittsburgh (organized by Arthur Wolfe)
- After-banquet speech by Ed Siegel (Columbia U.): coined "Blazars"
- Blandford & Rees: blazars are compact relativistic jets

1978 (Marchenko & Hagen-Thorn): BL Lac has preferred ♍$_{optical}$
1979 (Readhead et al.): VLBI with closure phases → Compact jets
1979 (Blandford & Königl): Compact jet model: knots are shocks
1980 (Cotton et al.): Flat radio spectra as "conspiracy" of many knots
1980 (Marscher): Relativistic jet model with acceleration of flow + radiative energy losses
1980 (Balonek & Dent): Simultaneous radio-optical outburst in 0235+164 (2nd such event in same object)
1981 (Miller): Multi-color optical variations of 3C 446 agree w/ model
1981 (Königl): Relativistic jet model without losses → flat spectra
1981-82 (Marscher & Broderick): combined VLBI + X-ray (Einstein Obs.) → relativistic motion needed, superluminal motion observed

Blazar Studies: 1982-97

1983 (Robson et al.): mm to optical outburst of 3C 273
1983 (Antonucci & Miller): polarized light reveals hidden Type I nucleus in Seyfert II galaxies → unified scheme
1984: Esko Valtaoja lays plans for Metsähovi mm-wave monitoring
1985 (Marscher & Gear; Hughes, Aller, & Aller): shock models for multi-wavelength flux & polarization variability, comparison w/ data
1988 (Jones): Turbulent magnetic fields → rotations of polarization
1988 (Daly & Marscher): mm-wave VLBI "core" as a standing shock
Late 1980s through 1990s (Bregman + many others): multi-wavelength campaigns from radio to ♑-ray → connections & complexities revealed
1991-99: EGRET detections of ♑-rays from many blazars
1994 (Readhead): Brightness temperatures suggest equipartition
1995: VLBA began full operations (♑-ray blazar monitoring w/ Wehrle)
1995-97 (Gómez et al.): HD simulations applied to compact jets

Location of Flares

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

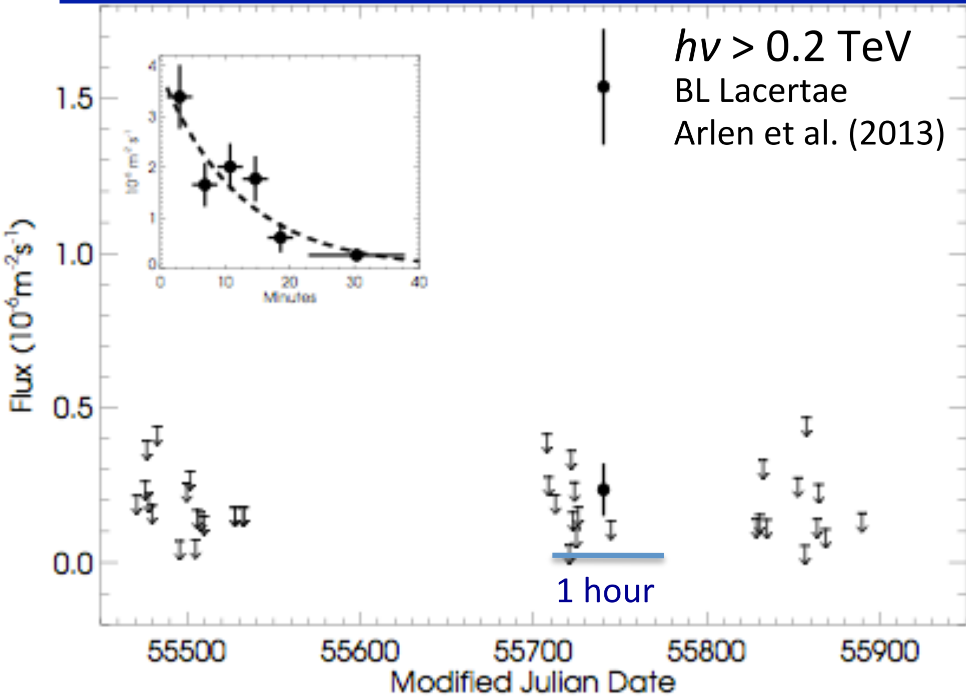
→ So do most optical flares, since gamma-ray/optical correlation is generally strong with ~ zero time delay

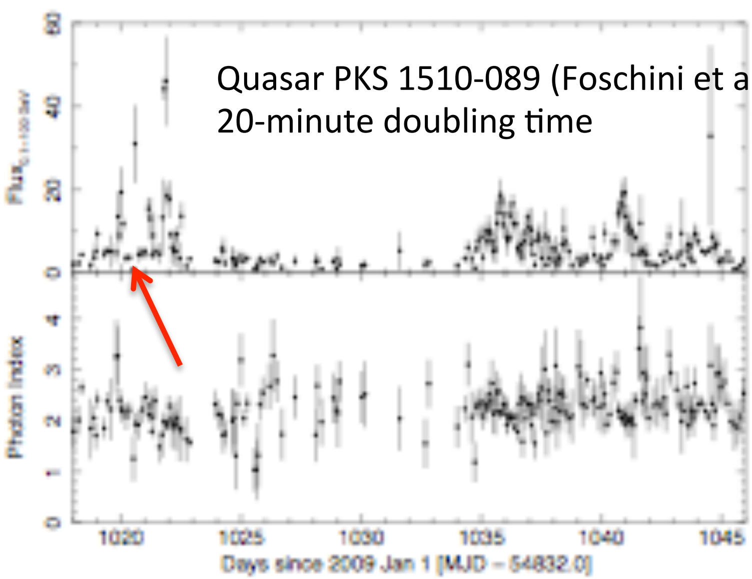
- Emission site outside BLR allows 10-500 GeV photons observed in some blazars to escape without pair producing off broad-line photons (e.g., 1222+216: Aleksic et al. 2011; PKS1424-418: Tavecchio et al. 2013)

- 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?

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} $[\delta/(1+z)]$ ~ $2x10^{14}$ $t_{var,hr}$ δ cm,

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

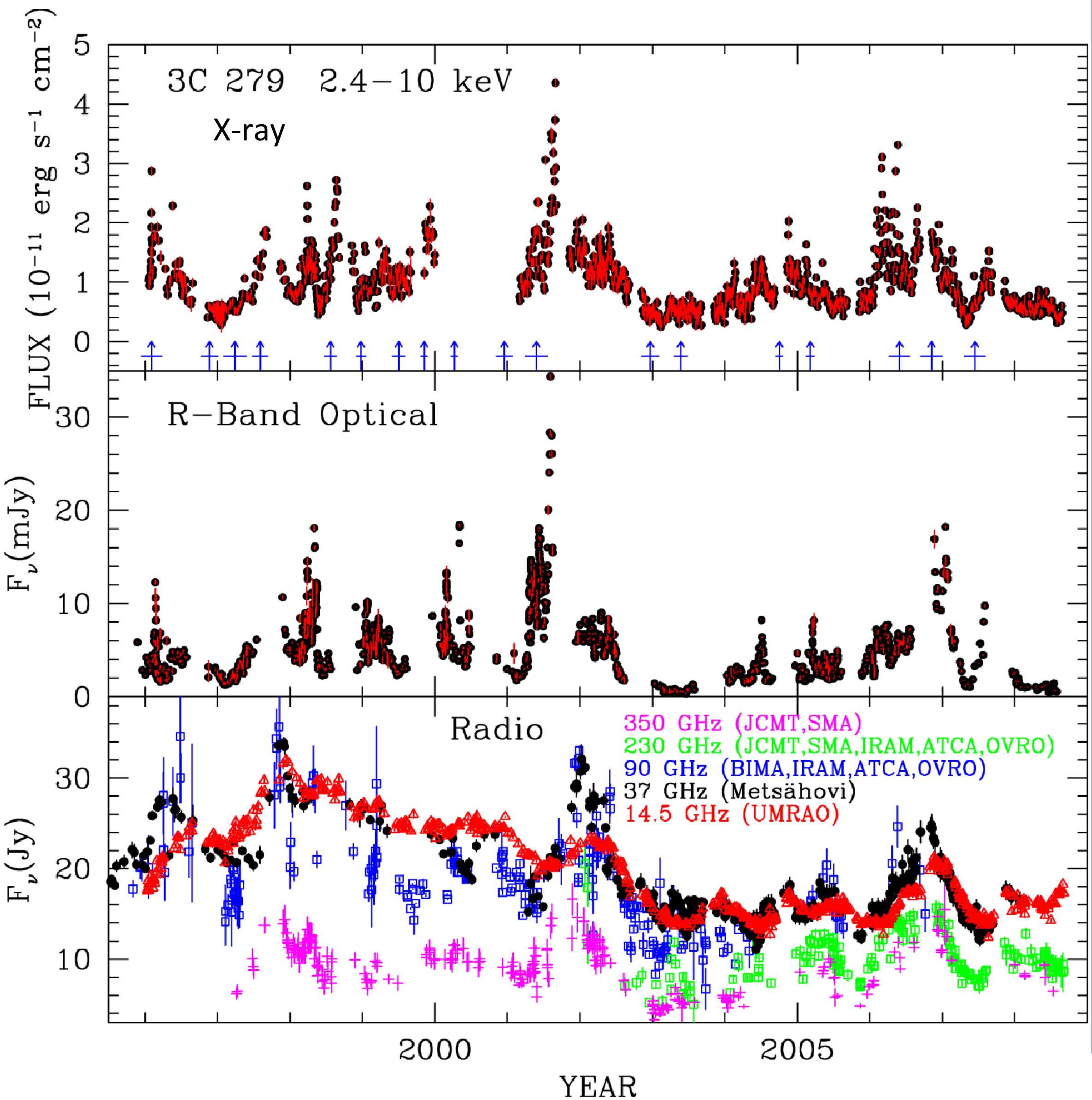
Superluminal motion implies δ ~ 20 - 50

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

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

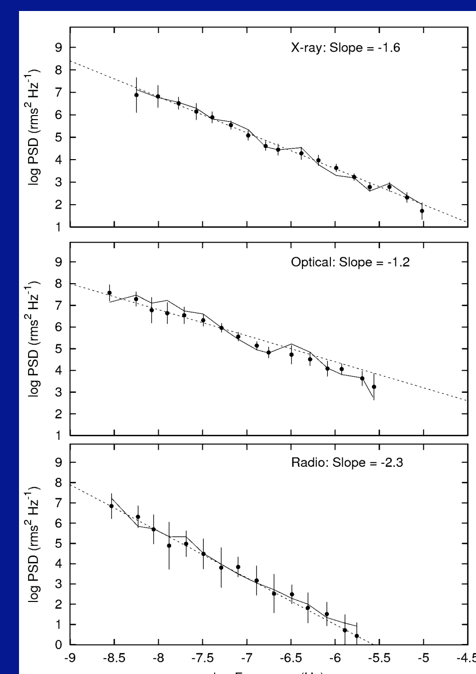
→Magnetic reconnection jet-in-jet model (Giannios 2013, MNRAS), or turbulence (Narayan & Piran 2012, MNRAS; Marscher 2012, Fermi and Jansky proc.)

Blazars: Power-law PSDs → Noise process



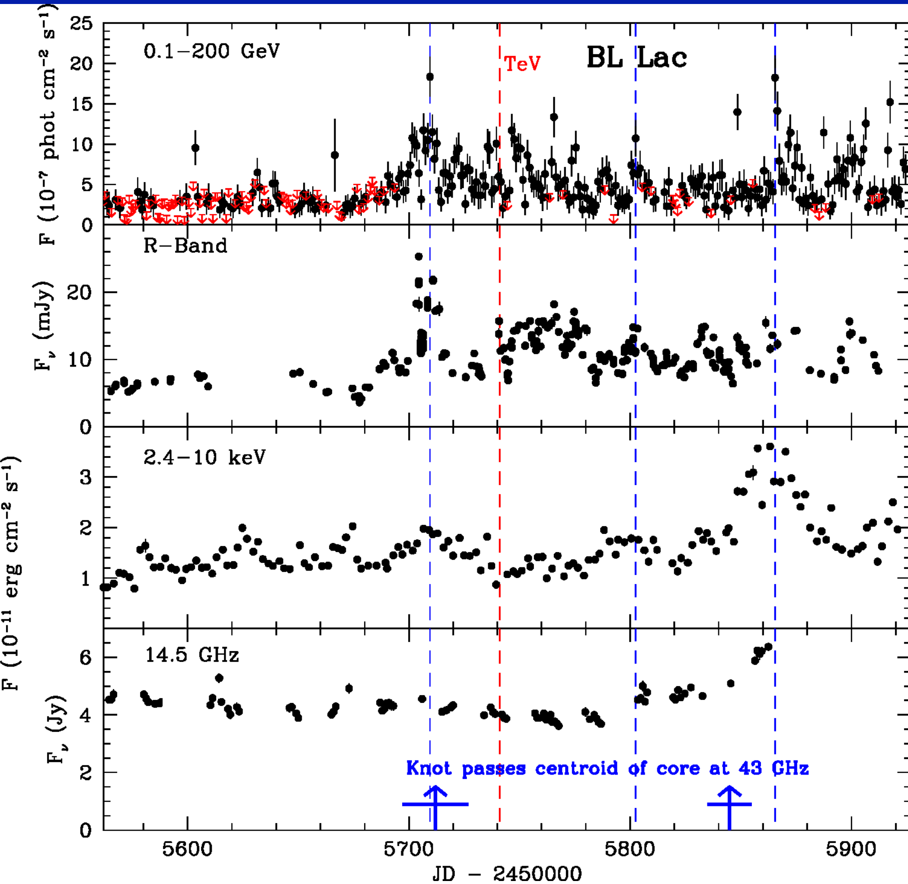
- Rapidly changing brightness across the electromagnetic spectrum

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

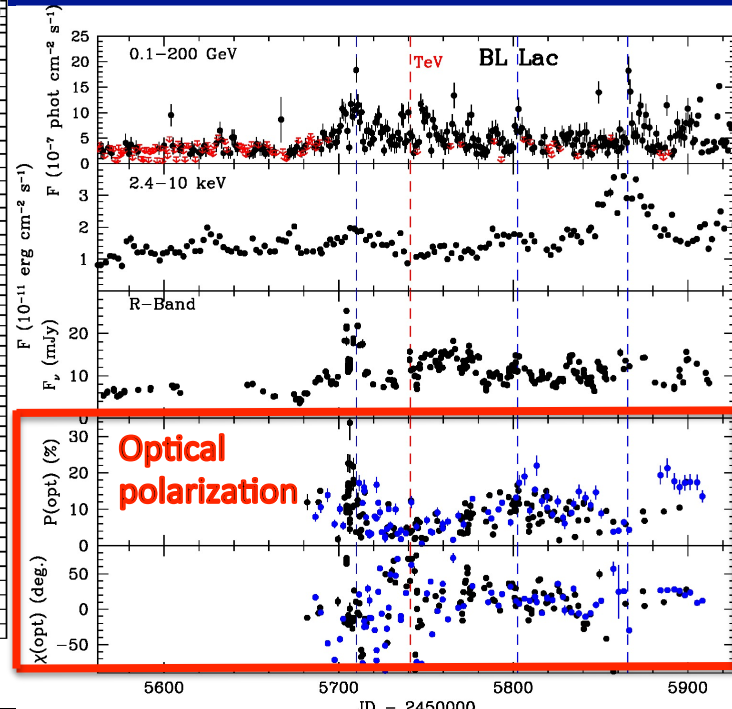


Chatterjee et al. 2008 ApJ

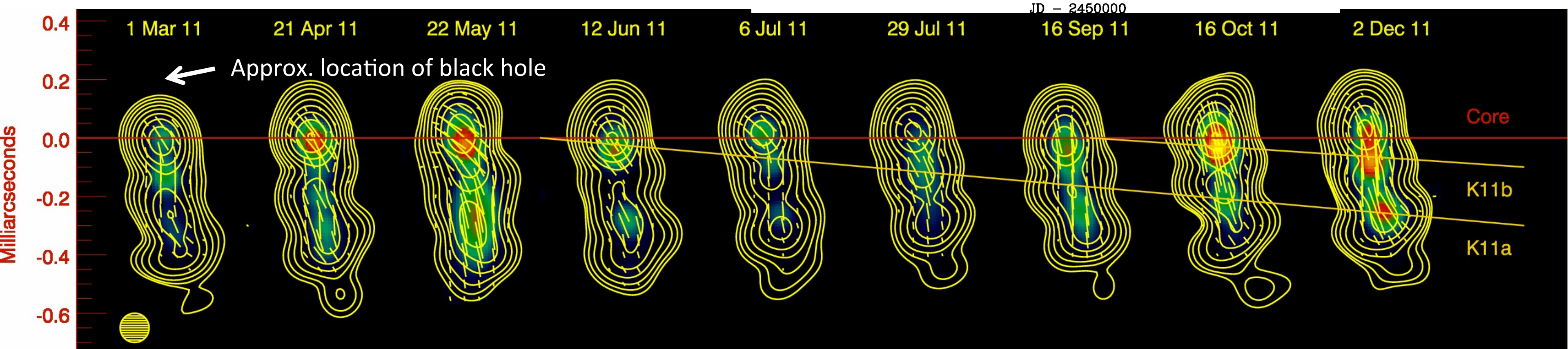
Blazar BL Lacertae in 2011



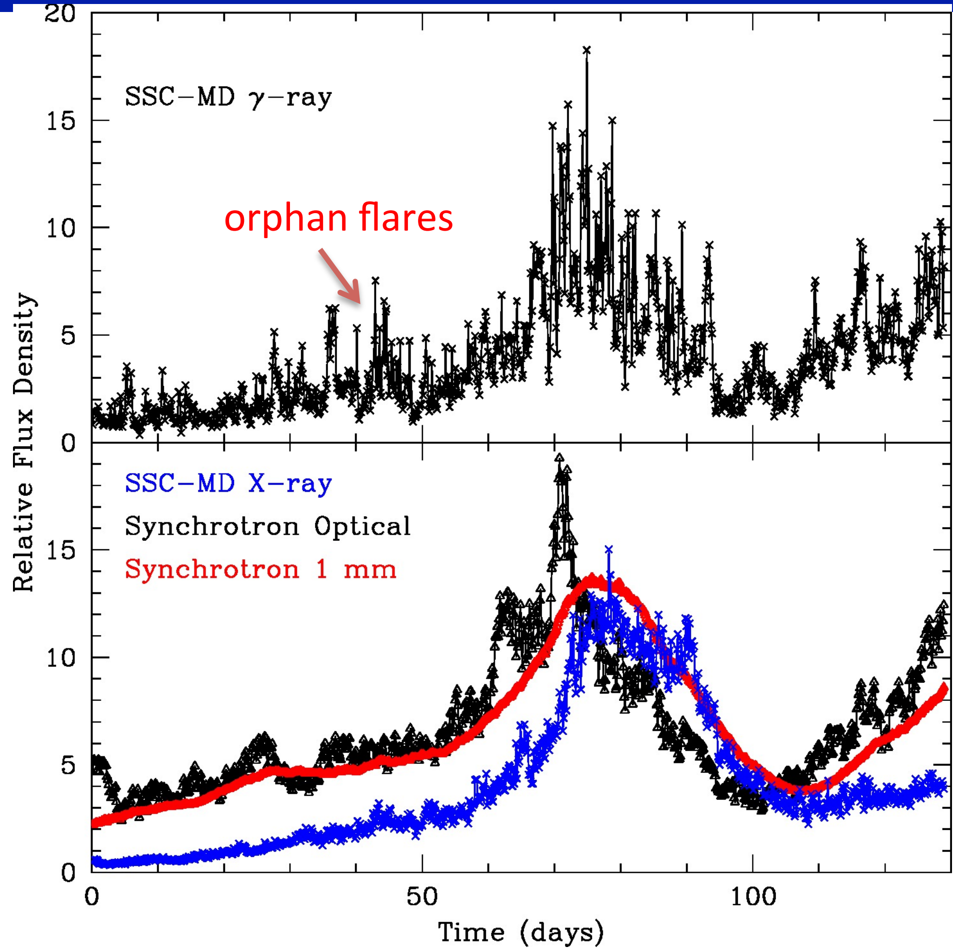
γ-rays become bright as new superluminal knots pass through "core" & through other stationary emission features on the VLBA image

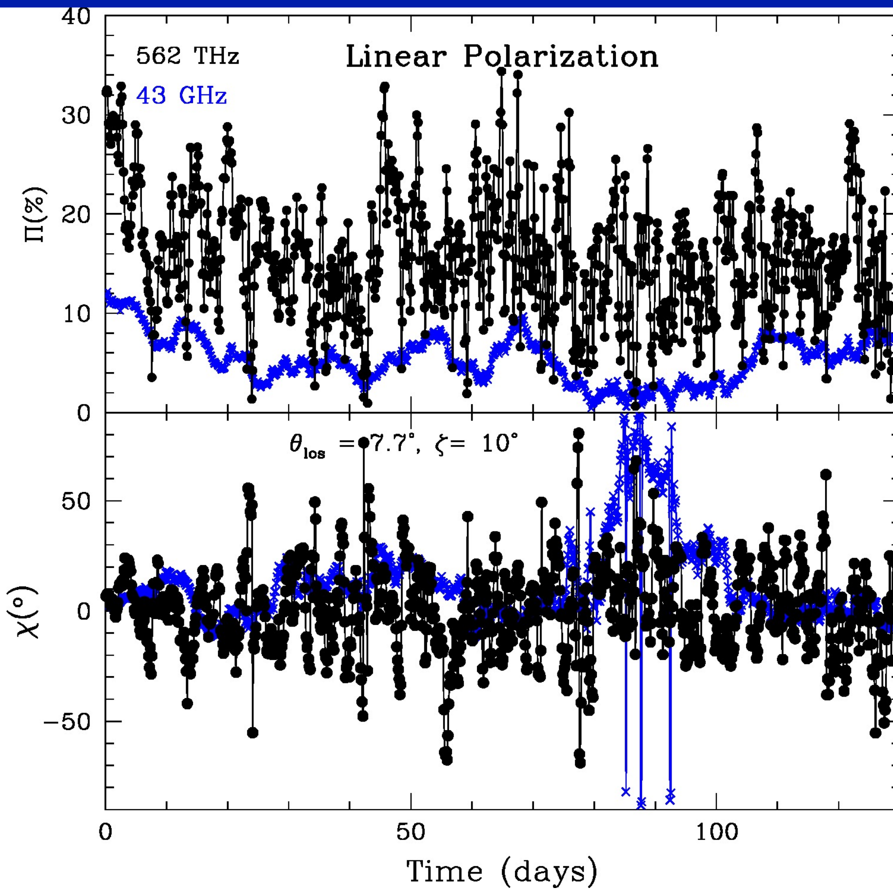


Degree of linear polarization & variations in degree & position angle suggest turbulence at work



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

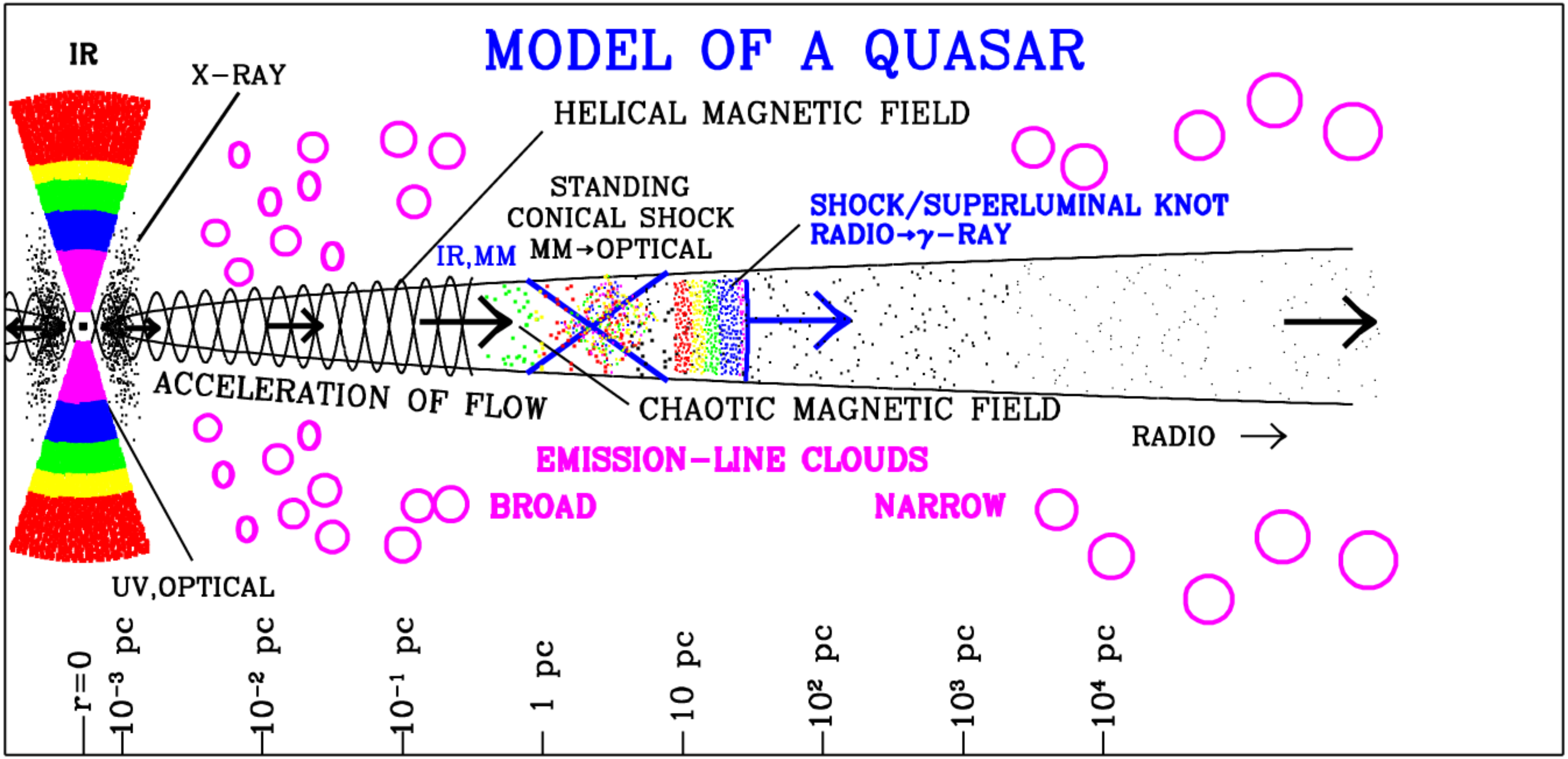
Polarization is stronger at higher frequencies

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**

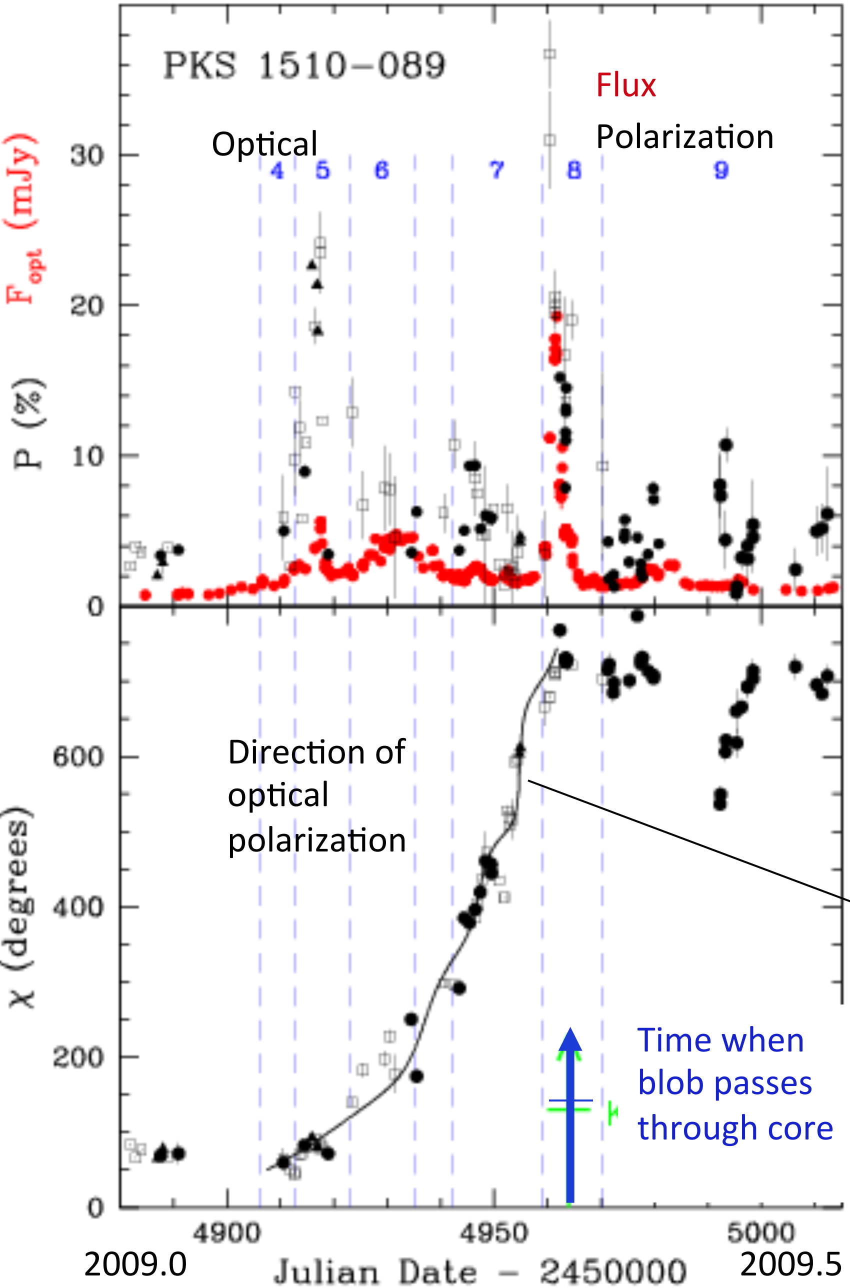
- **Most outbursts & flares occur on parsec scales**

→ **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

[illegible] increases from 8 to 24, [illegible] 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:**

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

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

$t_{var} \sim 0.3$ days

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