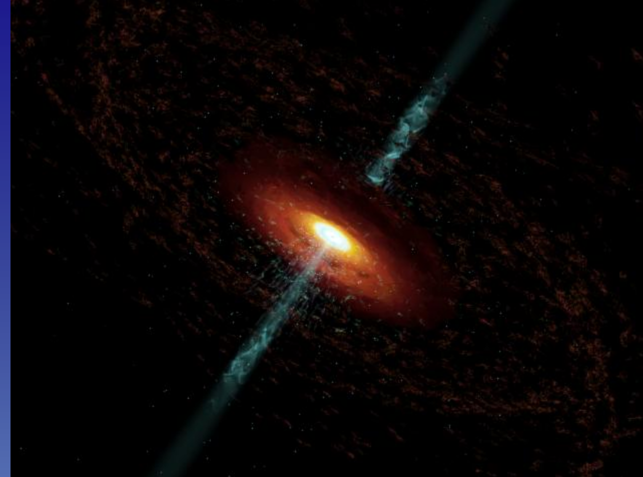


The Most Compact Regions of Jets in Active Galactic Nuclei

Alan Marscher
Boston University

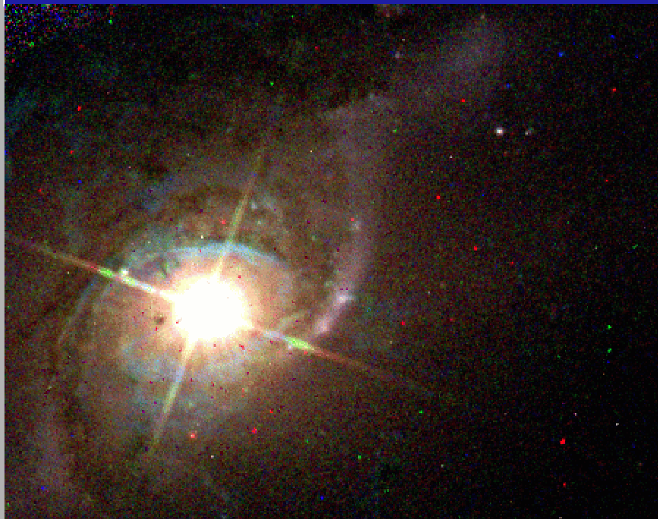
Research Web Page: www.bu.edu/blazars

Main Collaborators: Major International Effort

Svetlana Jorstad, Ritaban Chatterjee, Frannie D'Arcangelo (Boston U.)
José Luis Gómez & Iván Agudo (IAA, Granada, Spain)
Margo & Hugh Aller (University of Michigan)
Ian McHardy (U. Southampton, UK)
Vladimir A. Hagen-Thorn & Valeri Larionov (St. Petersburg State U., Russia)
Anne Lähteenmäki & Merja Tornikoski (Metsähovi Radio Observatory)
Walter Gear (Cardiff U., UK)
Esko Valtaoja (Turku U., Finland)
Thomas Balonek (Colgate U.)
Gino Tosti (U. of Perugia Observatory, Italy)
Omar Kurtanidze (Abastumani Observatory, Rep. of Georgia)
Martin Gaskell (U. of Texas)
H. R. Miller, Kevin Marshall, Wesley Ryle (Georgia St. U.)
Matthew Lister (Purdue U.)
Thomas Krichbaum, Lars Fuhrmann, Tuomas Savolainen, Yuri Kovalev (MPIfR)

Funded by NASA & NSF

Radio galaxies show a connection between X-rays from central engine region & activity in jet



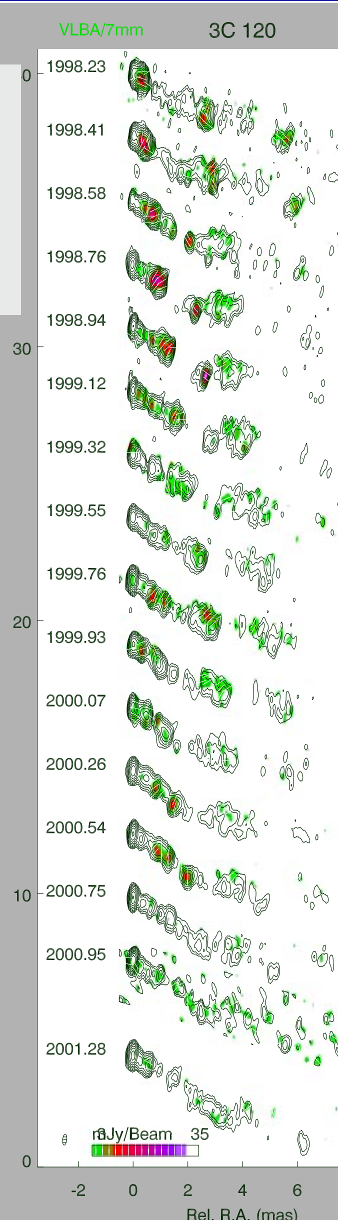
Sequence of VLBA images (Marscher et al. 2002, Nature)

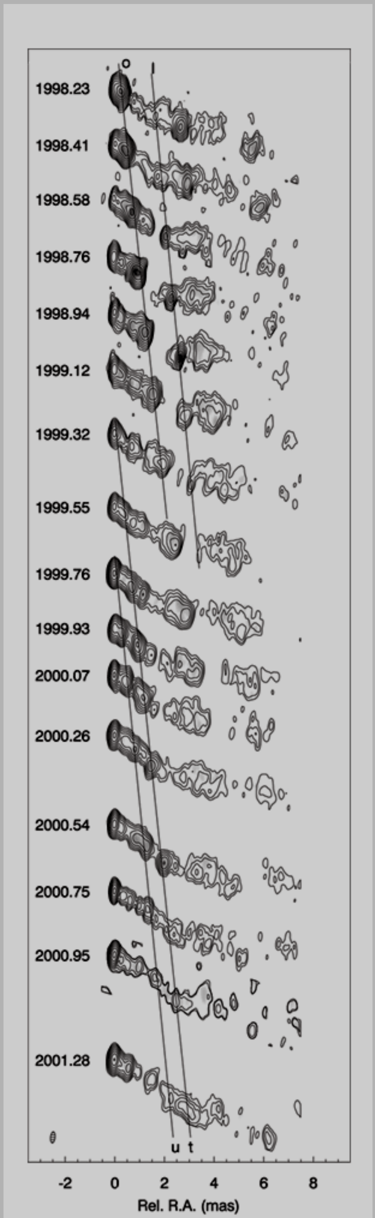
Scale: 1 mas = 0.64 pc = 2.1 lt-yr (Ho=70)

The FR I Radio Galaxy 3C 120 (z=0.033)

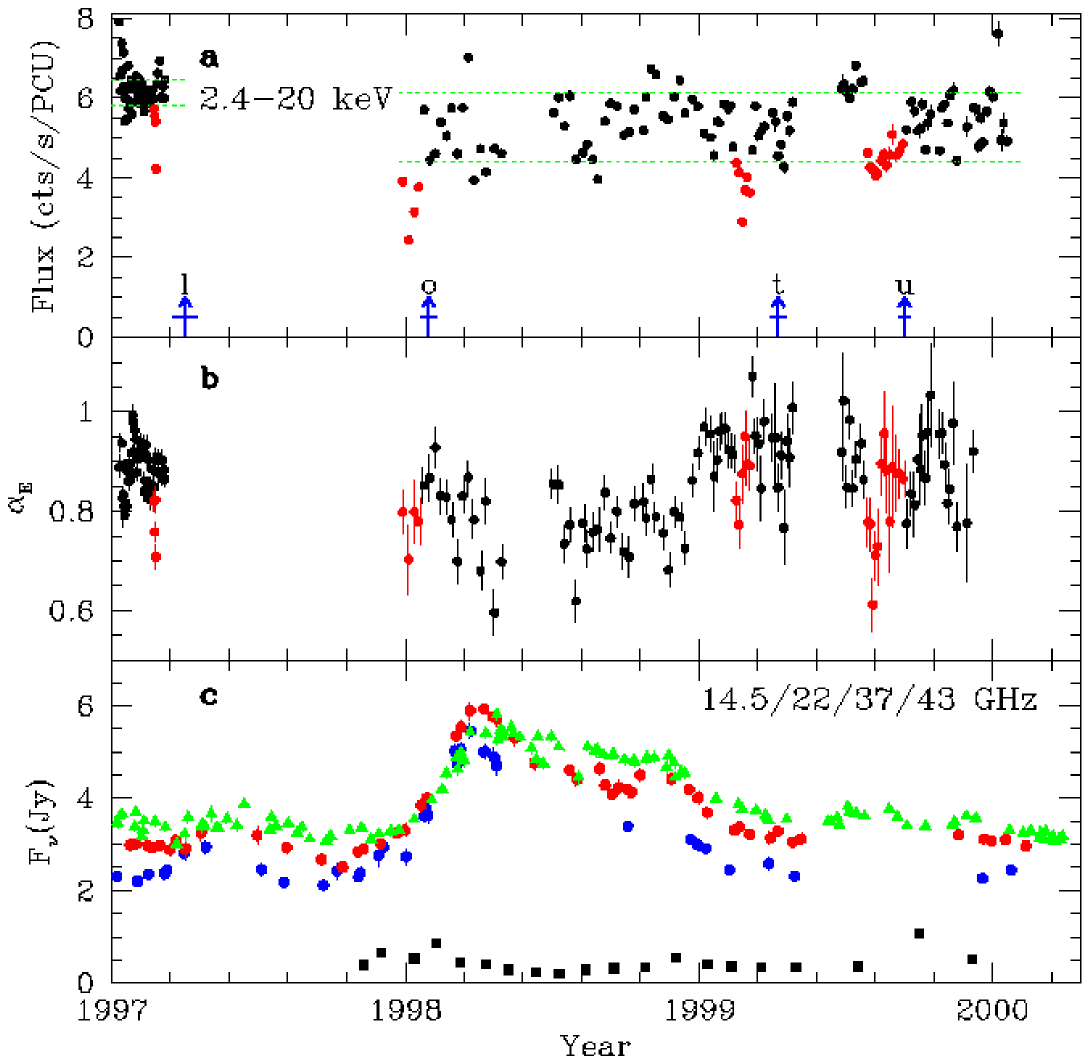
HST image (Harris & Cheung)

- Superluminal apparent motion, ~5c (~2 milliarcsec/yr)
- X-ray spectrum similar to Seyferts
- Mass of central black hole ~ 5×10^7 solar masses (Marshall et al. 2008; Peterson et al. 2004)





X-Ray Dip/Superluminal Ejection Connection in 3C 120: Older data

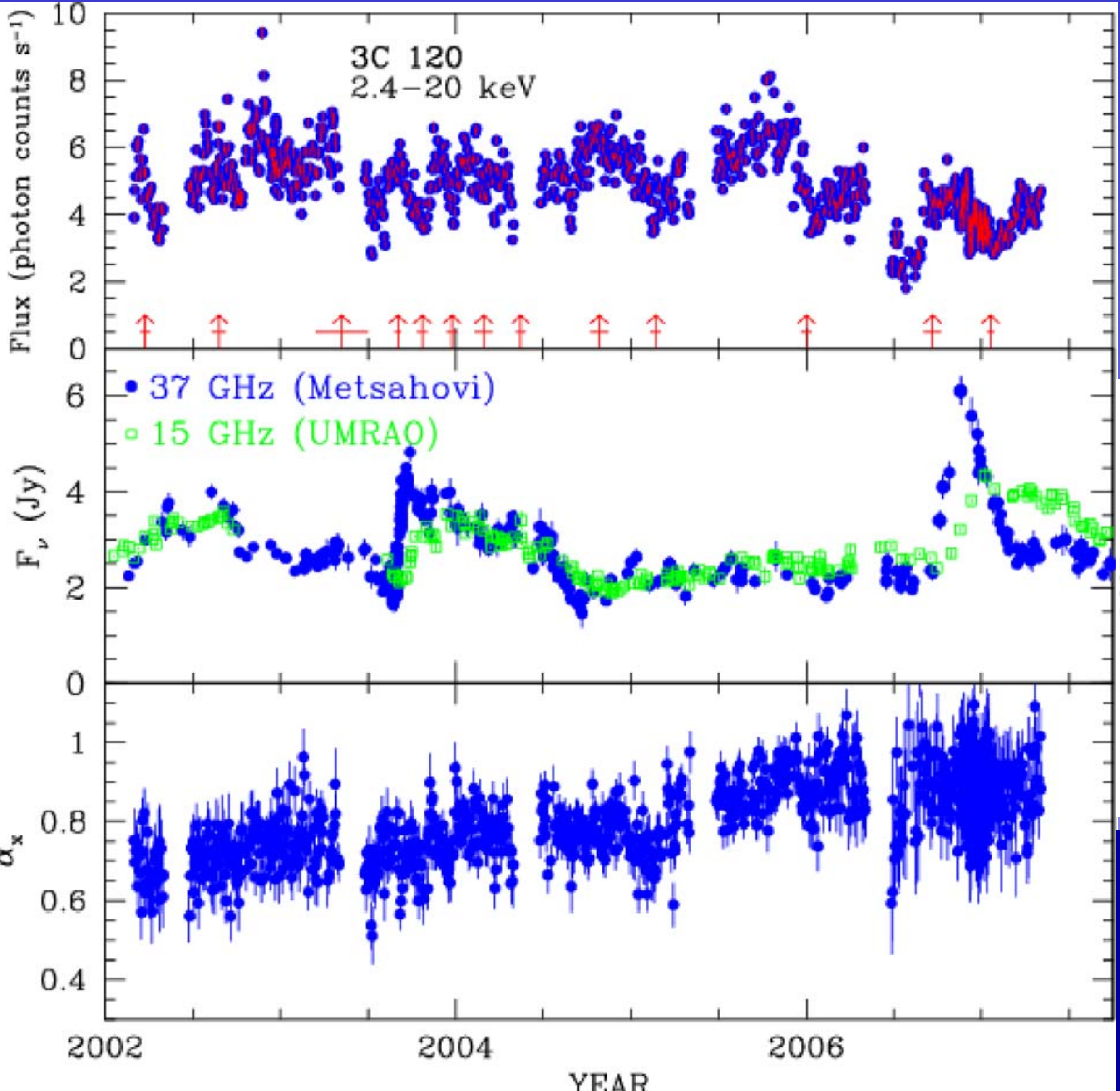


Superluminal ejections follow X-ray dips by ~ 60 days
→ Somewhat similar to microquasar GRS 1915+105

λ3mm core must lie at least 0.4 pc from black hole to produce the observed X-ray dip/superluminal ejection delay of ~ 60 days

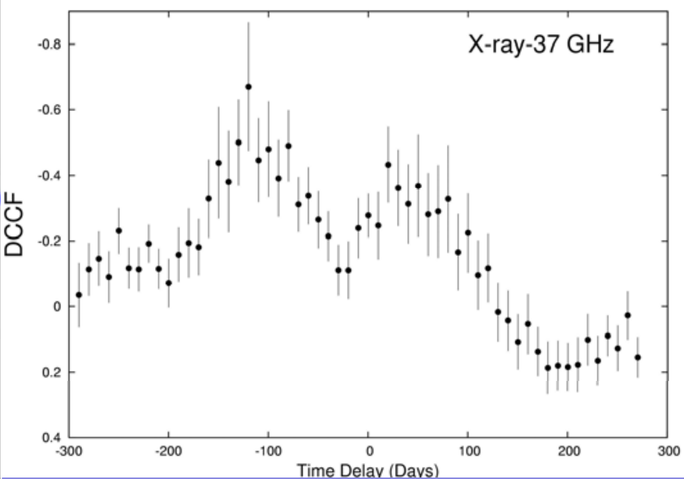
Marscher et al. 2002, Nature, **417**, 625

X-Ray Dips/Ejections in 3C 120: Data since 2002



Superluminal ejections still follow starts of X-ray dips by a few months

Anti-correlation between X-ray flux or spectral index & 37 GHz flux

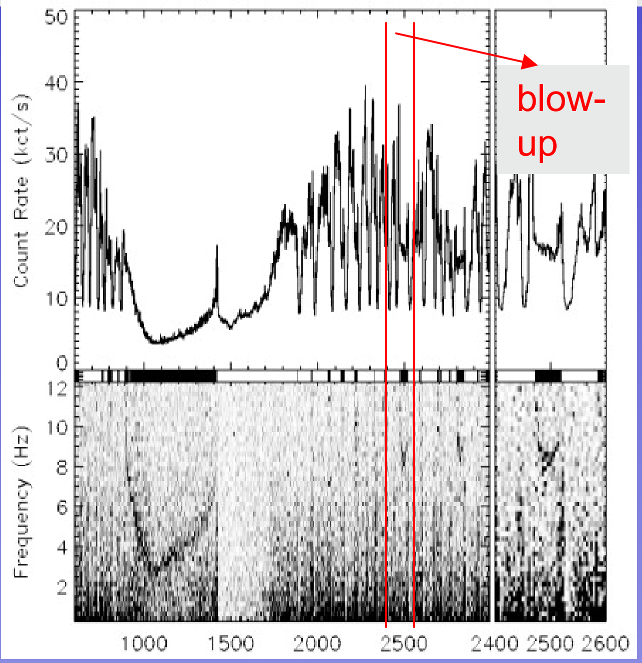


2002-05: X-ray leads by ~70 days

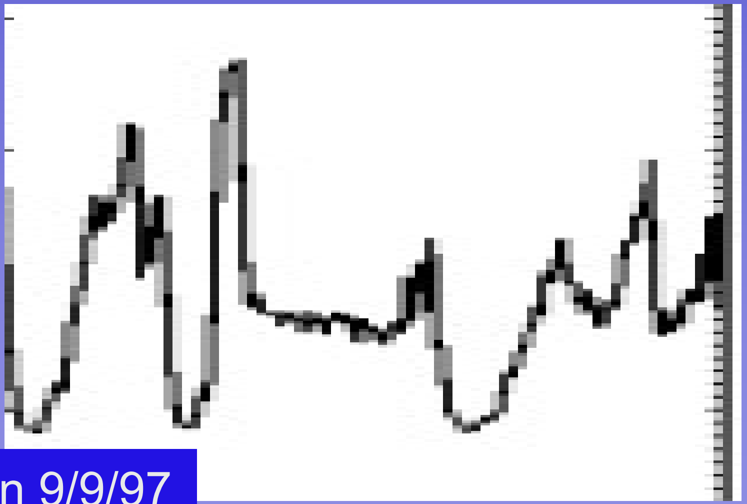
2006-07: X-ray leads by ~120 days (jet's τ = 1 surface moved downstream)

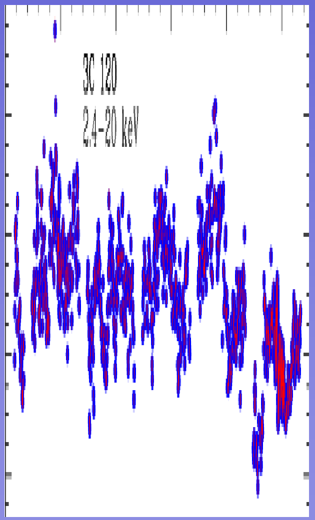
Comparison of GRS1915+105 with 3C 120 Light Curves

- M_{BH} of 3C 120 ~4×10^6 M_{BH} of GRS 1915+105 → timescales of hours to months in 3C 120 similar to scaled-up quasi-periods (0.15 to 10 s) of 1915+105
- PSD & typical fractional amplitude of dips similar, but no low/hard state in 3C 120
- Consistent with 3C 120 being near boundary of intermediate & high/soft state
- But jet of 3C 120 has not shut down during >40 yr of radio observations



150 s of blow-up should scale up to ~17 yr in 3C 120 if timescales ∝ M_{bh}

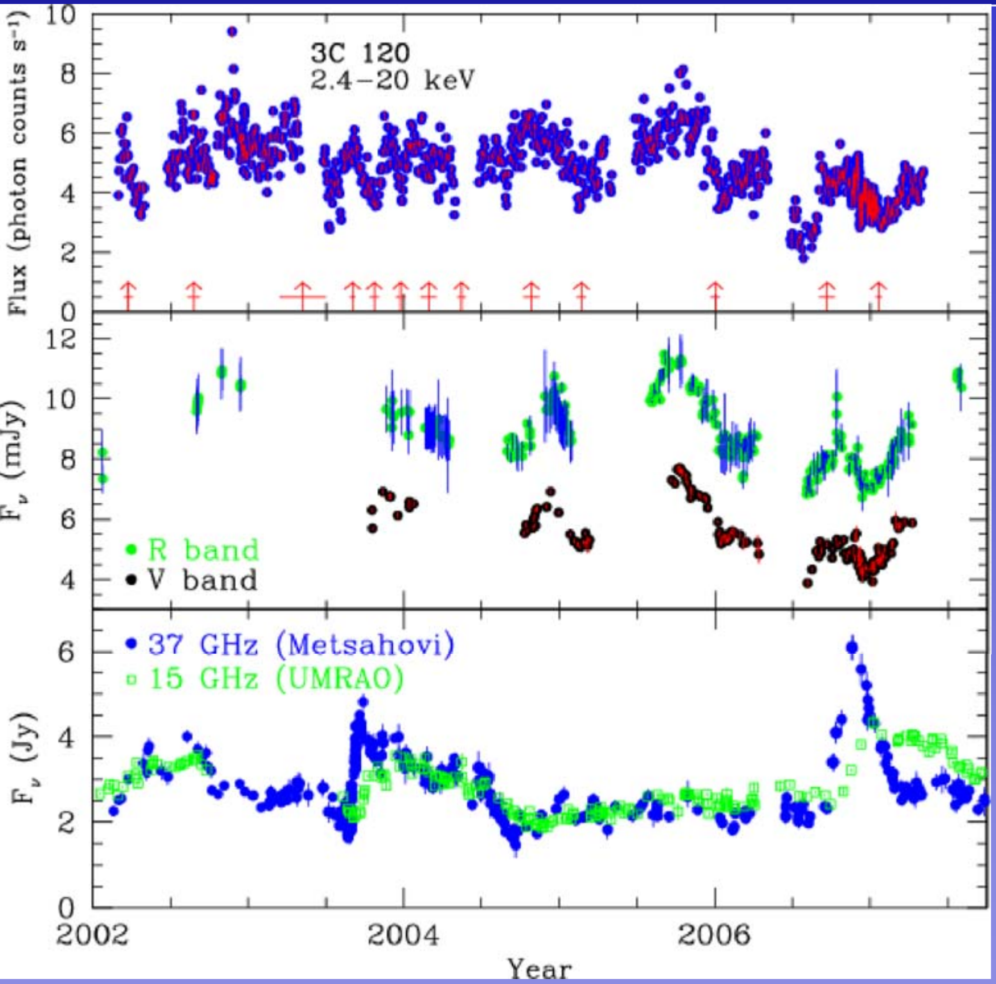




↑ GRS 1915+105 over 3000 s on 9/9/97
Light curve (top) & PSD (bottom)
(Taken from Markwardt et al. 1999 ApJL)

Above: X-ray light curves of GRS 1915+105 over 150 s & 3C 120 over 5 yr

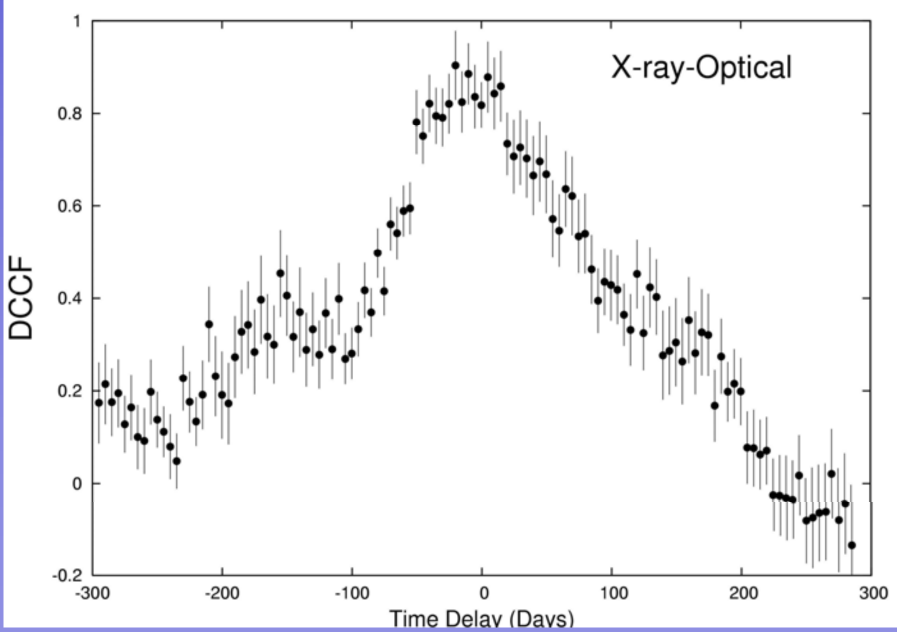
FR I Radio Galaxy 3C 120 X-ray/Optical Correlation



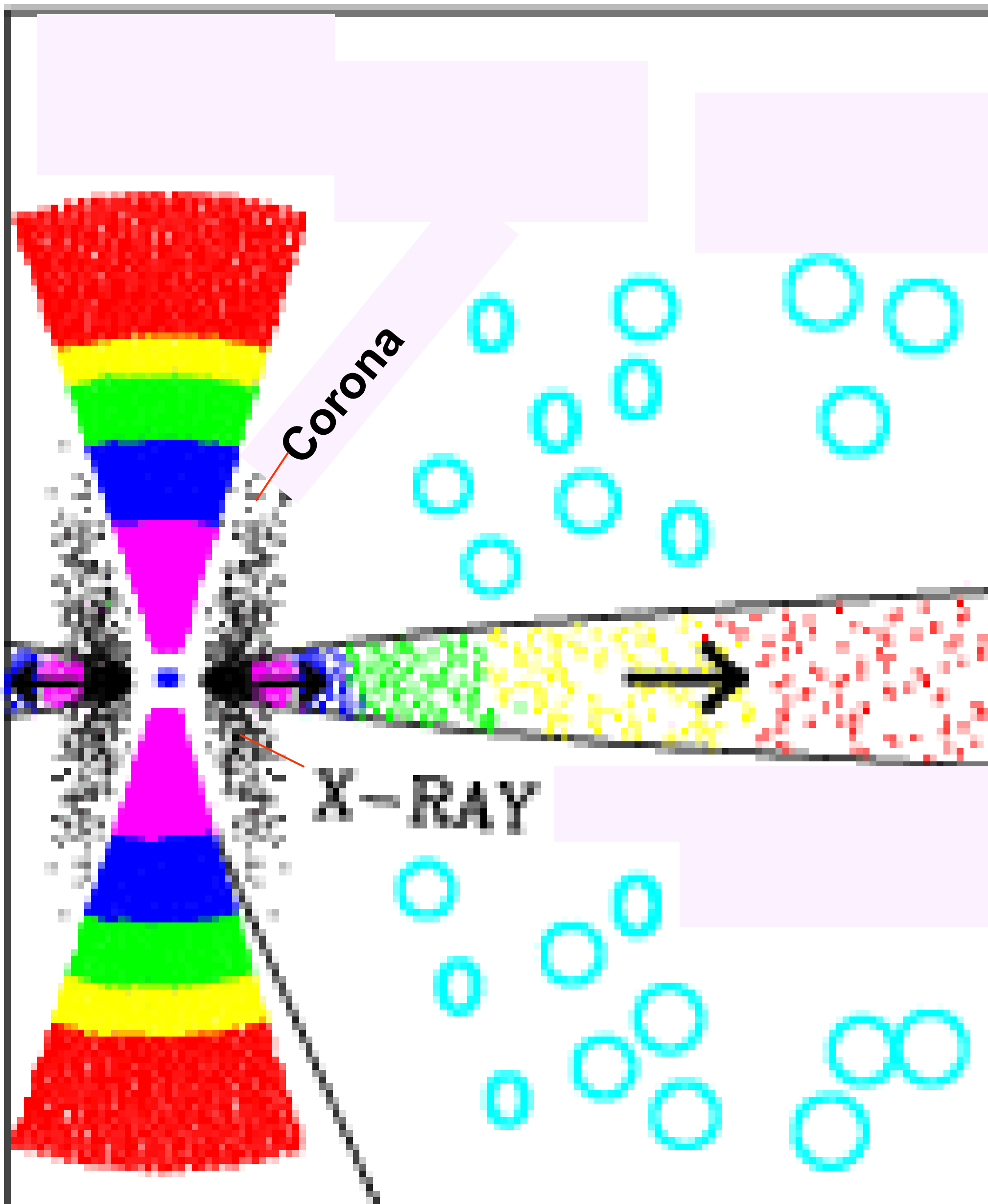
X-ray variations lead optical by 10±20 days

- lag expected if X-rays come from corona near black hole & optical from farther out in accretion disk

- 10 days ~ 10 times longer than usual scaling laws predict



Connection between Disk + Jet Events



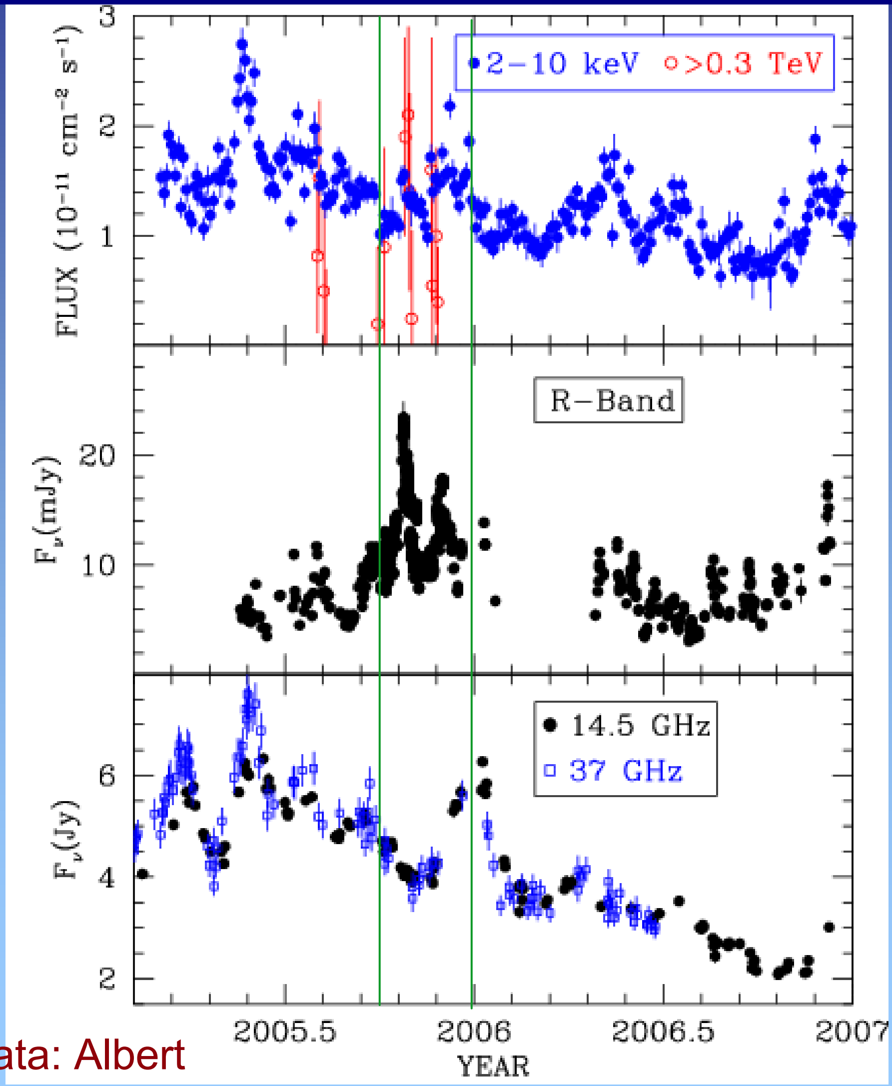
Possible scenarios of X-ray dip & hardening + faster jet flow → shock down jet:

1. Wind → jet; faster wind off disk → less dense corona, weaker X-ray, faster jet
2. **B** from ergosphere makes jet; fewer particles injected at base → weaker X-ray (if corona = base of jet), faster jet downstream (idea of G. Ghisellini)

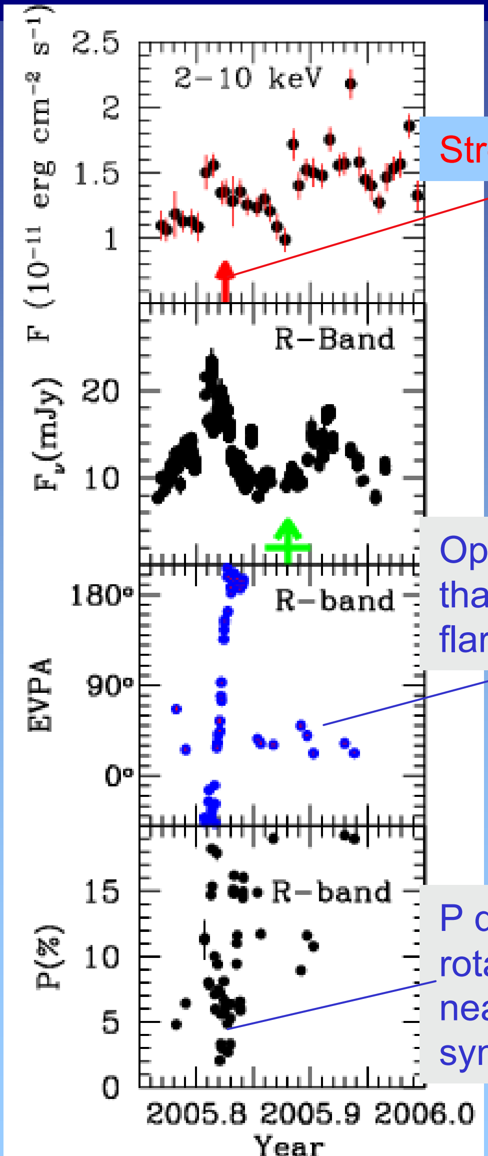
Flatter X-ray spectrum because downstream jet contributes higher fraction of X-rays when X-rays from base are weaker

BL Lac Reveals its Inner Jet (Marscher et al. 2008, *Nature*, 24/04/08)

Late 2005: Double optical/X-ray flare, detection at TeV energies, rotation of optical polarization vector during first flare, radio outburst starts during 2nd flare



TeV data: Albert et al. 2007 ApJL



Strong TeV detection

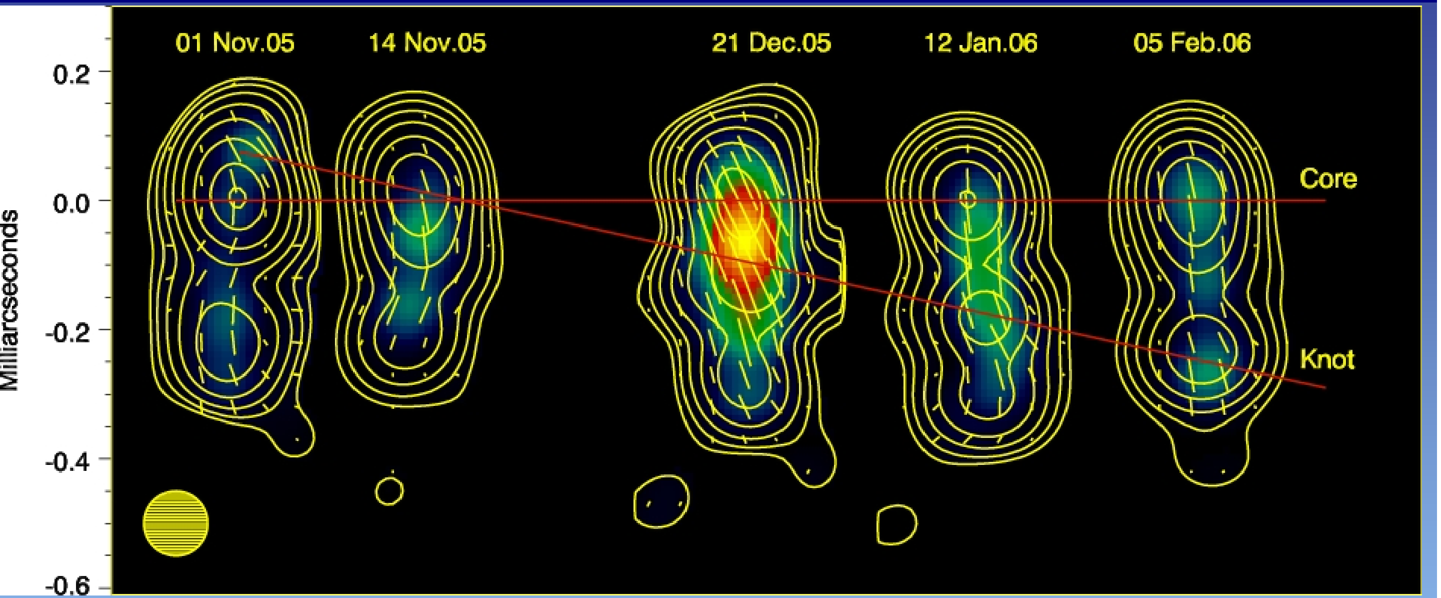
Optical EVPA matches that of knot during 2nd flare

P decreases during rotation → **B** is nearly circularly symmetric

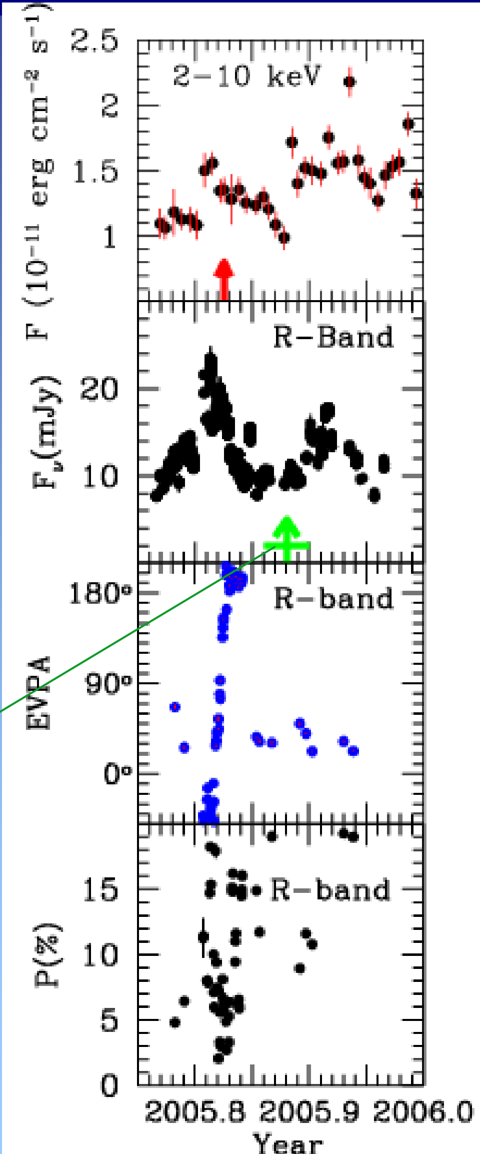
BL Lac: Superluminal Knot Responsible for Outburst

VLBA images reveal knot with distinct EVPA moving down jet at 5.0*c*

2nd flare occurs as knot passes stationary "core"



Scale:
1 mas = 1.2 pc



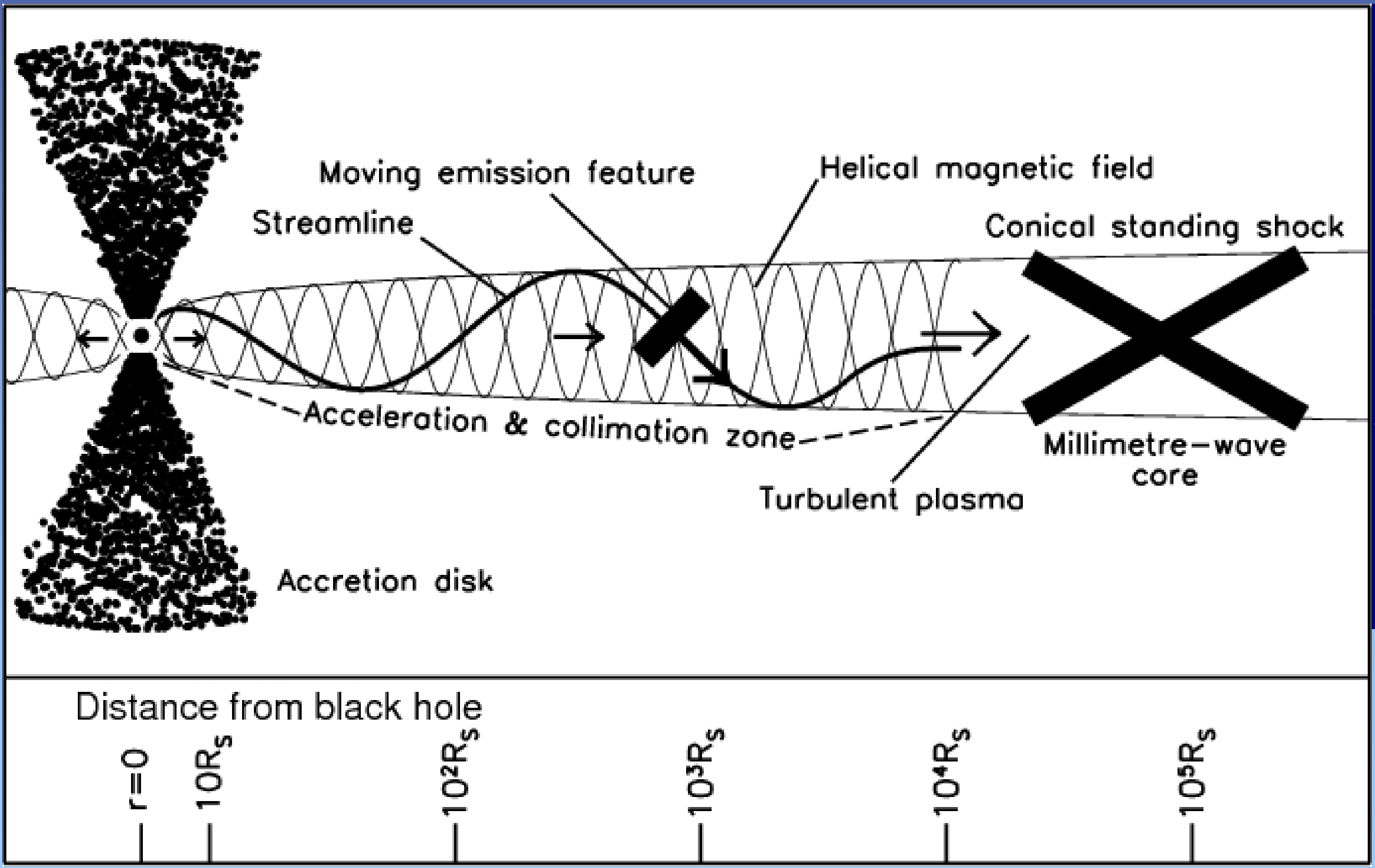
Superluminal knot coincident with core

Physical Picture of BL Lac: Exactly as Expected Theoretically* (It's a Miracle!)

Moving disturbance follows spiral streamline (does not cover entire jet cross-section)

Passes through helical field pattern in acceleration + collimation zone of jet

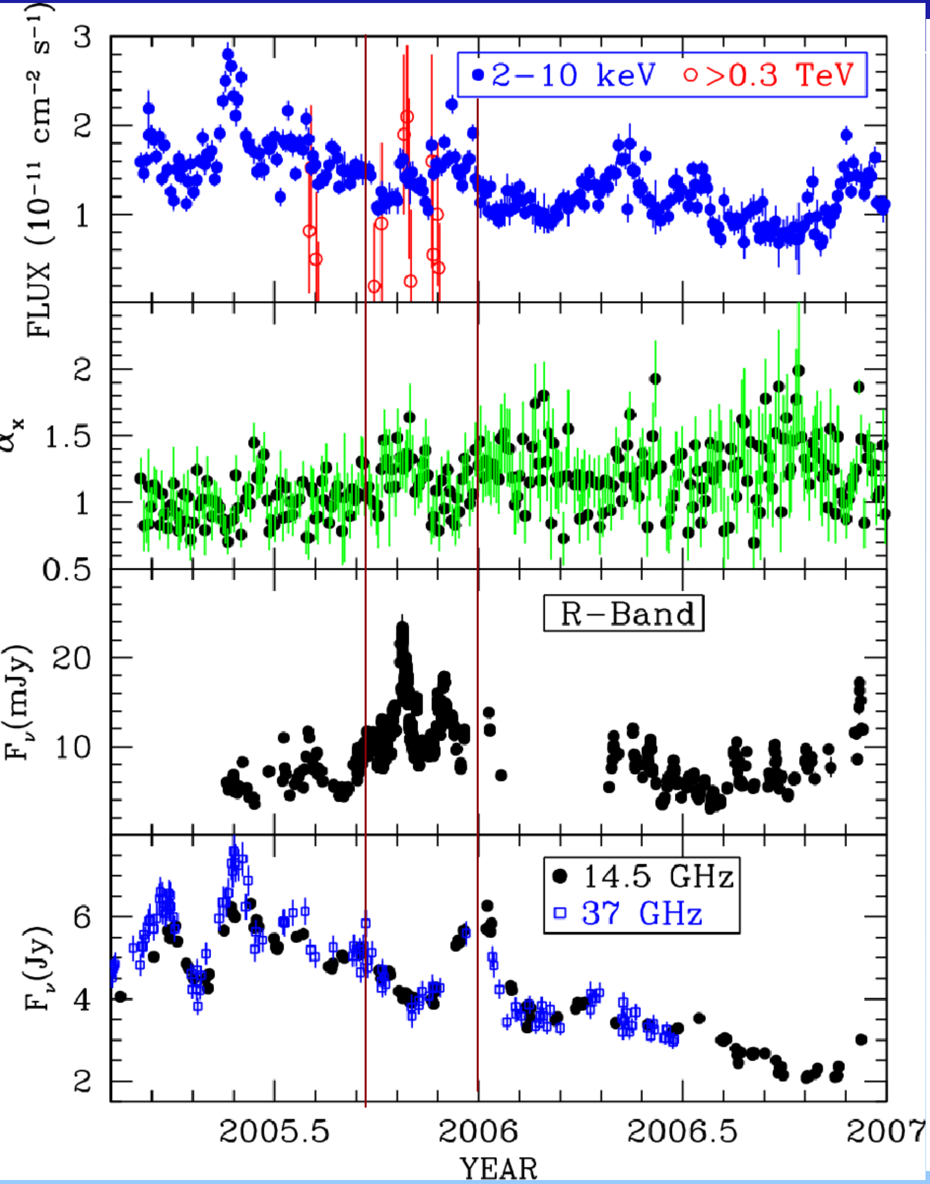
Becomes bright shortly before it emerges into zone of turbulent plasma

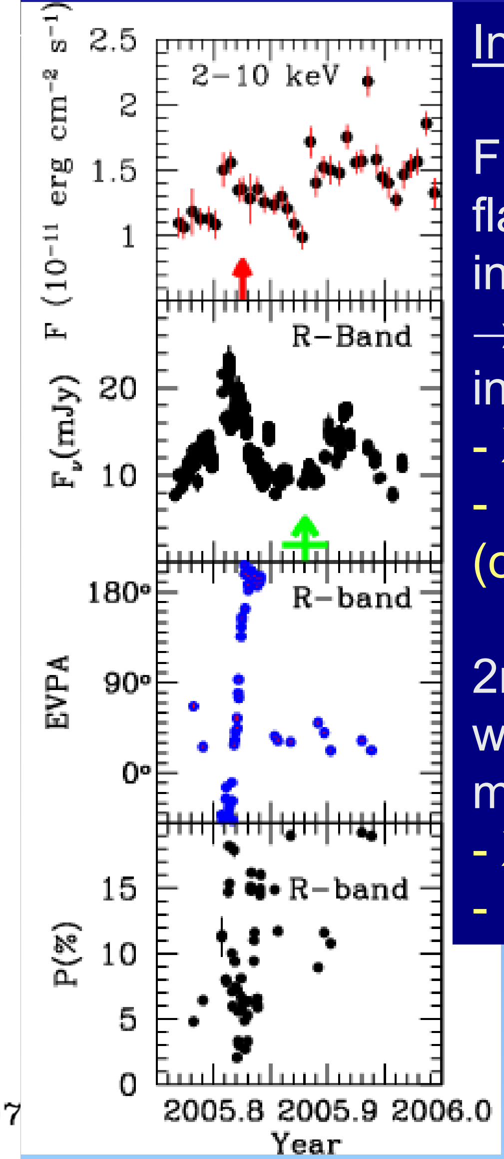


*Vlahakis (2006, in Variability of Blazars: Entering the GLAST Era)

- Similar to model for OJ287 by Kikuchi et al. 1988 A&A, 190, L8
&
Sillanpää et al. 1993, ApSS, 206, 55

BLLac in Late 2005: What Caused the Flares





Interpretation:

First optical/X-ray/TeV flare: knot Lorentz factor increases up to peak → Flare from increase in Doppler beaming
- X-rays: synchrotron
- No radio flare (opaque)

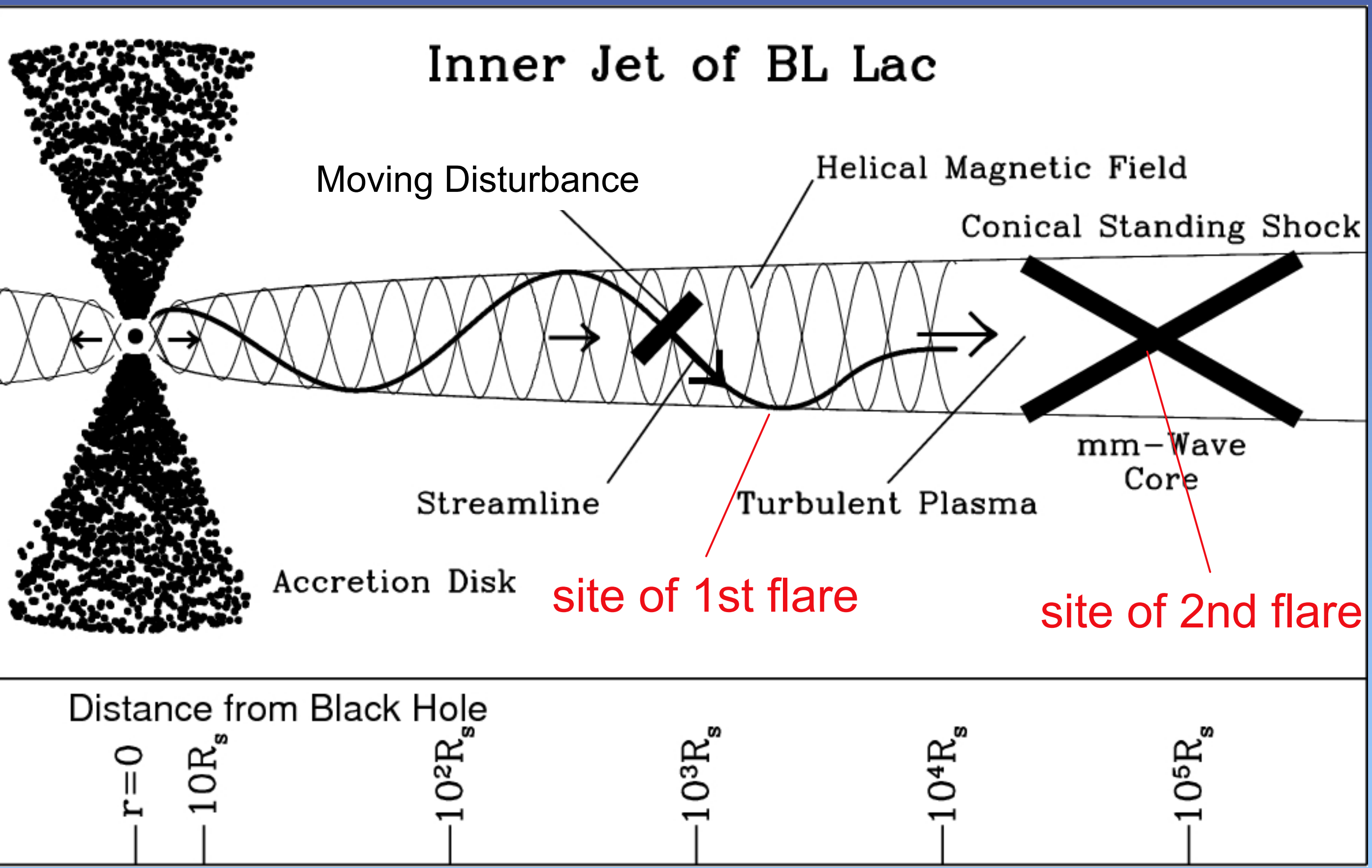
2nd flare: knot interacts with standing shock in 7 mm core
- X-rays: SSC
- Major radio flare

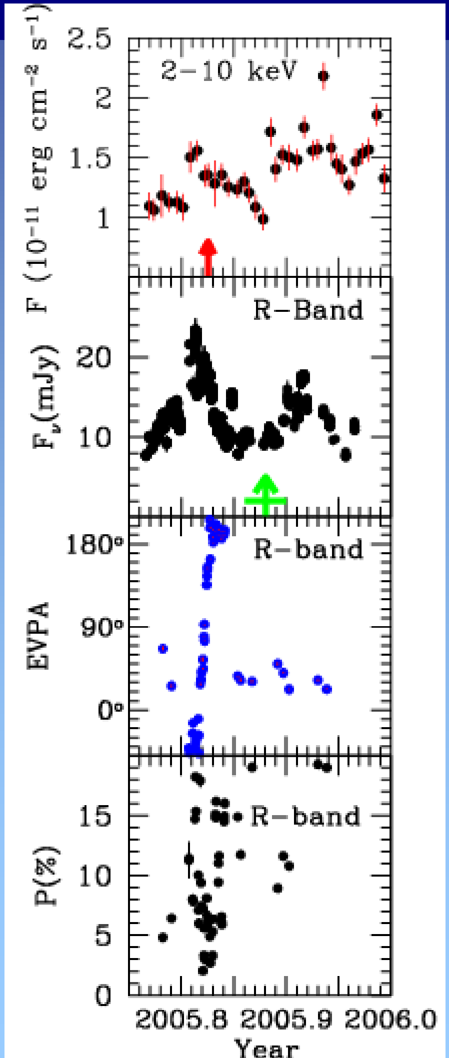
Interpretation of BL Lac Observations

Shock follows spiral streamlines until it exits region of coiled magnetic field

1st flare occurs just before disturbance exits acceleration & collimation zone

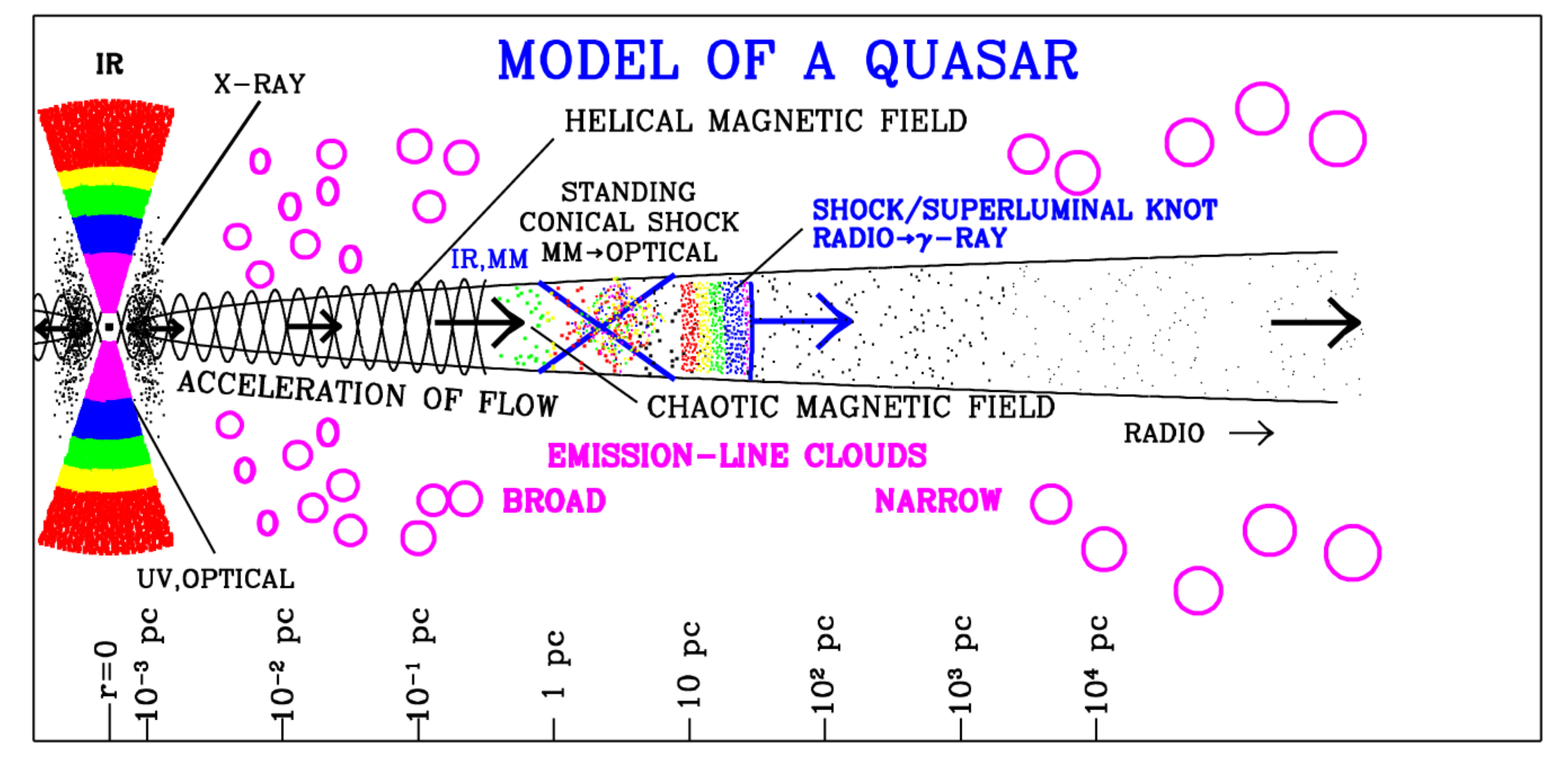
2nd flare caused by moving disturbance interacting with standing shock(s) in core



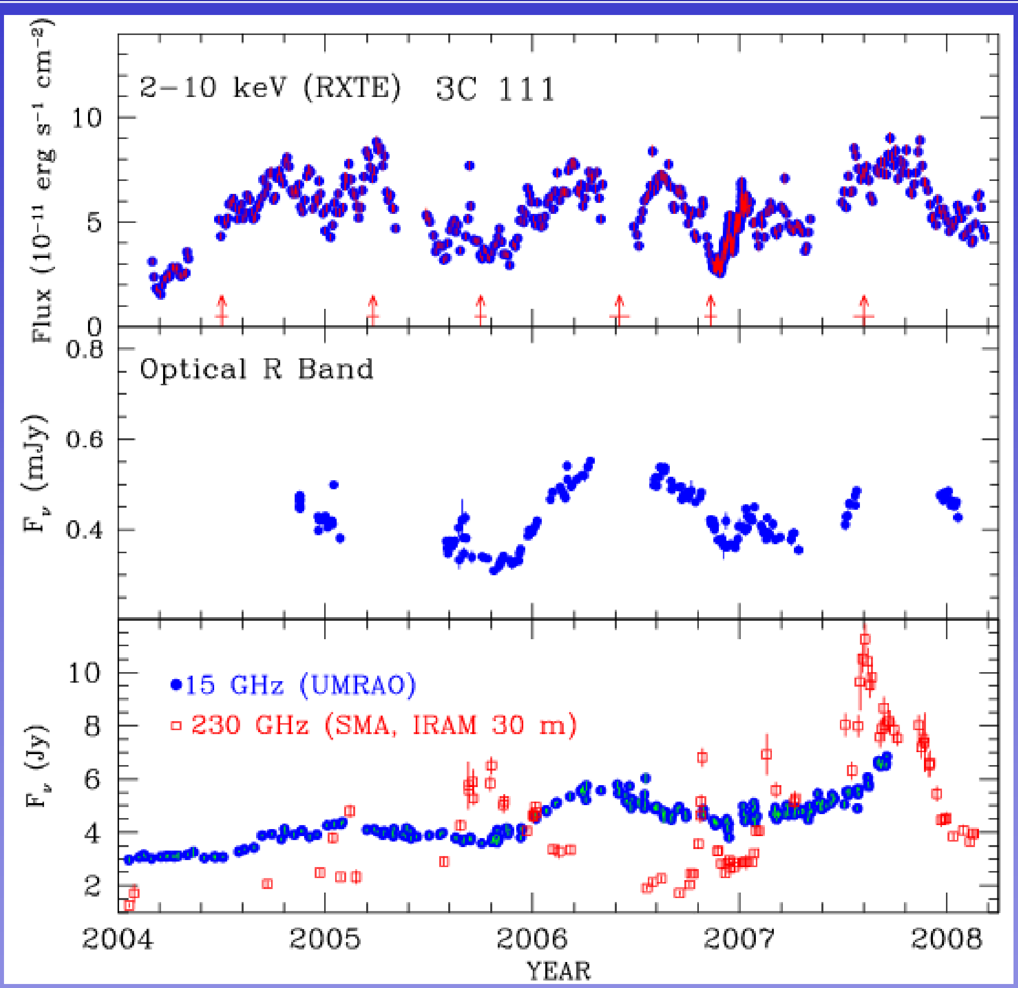


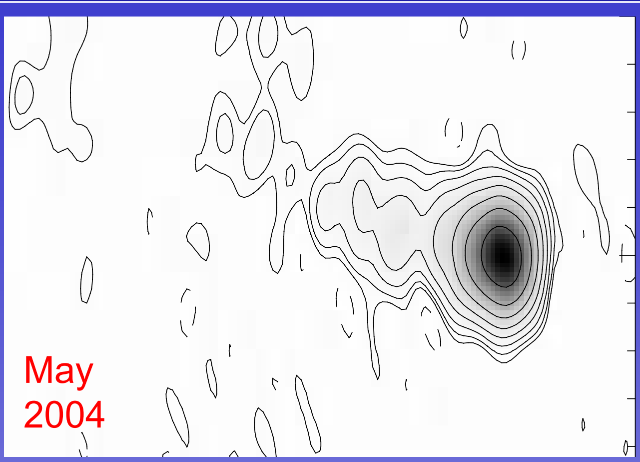
Conclusions

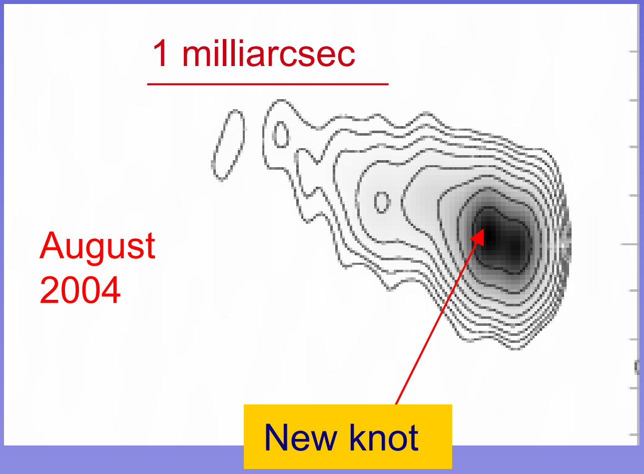
- Major emission events/superluminal knots in jet are triggered in the central engine
- Magnetic acceleration zone with helical field is site of some flares, mm-wave core (standing shock) is site of others
- Outbursts occur as moving disturbance passes through these regions
- Can explore inner jet with comprehensive monitoring of flux & polarization across all possible wavebands → These studies needed RXTE & VLBA… We still need them!



FR II Radio Galaxy 3C 111 (z=0.0485) Seems to Do the Same - But need a longer data train to confirm



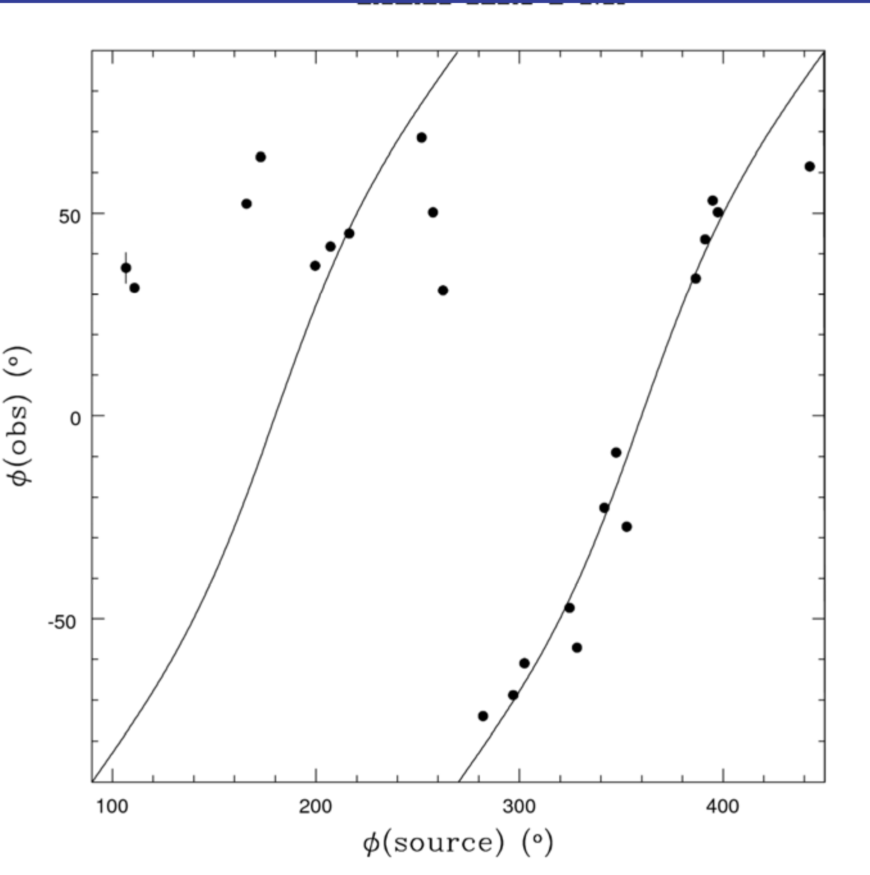




Ejection of bright superluminal knot follows start of X-ray dip by 0.35±0.2 yr

λ3mm core must lie at least 0.6 pc from black hole to produce the observed X-ray dip/superluminal ejection delay

BL Lac in Late 2005: Fit to Optical EVPA Rotation



Curvature of rotation: uniform rotation in source frame, axis at an angle of 45°

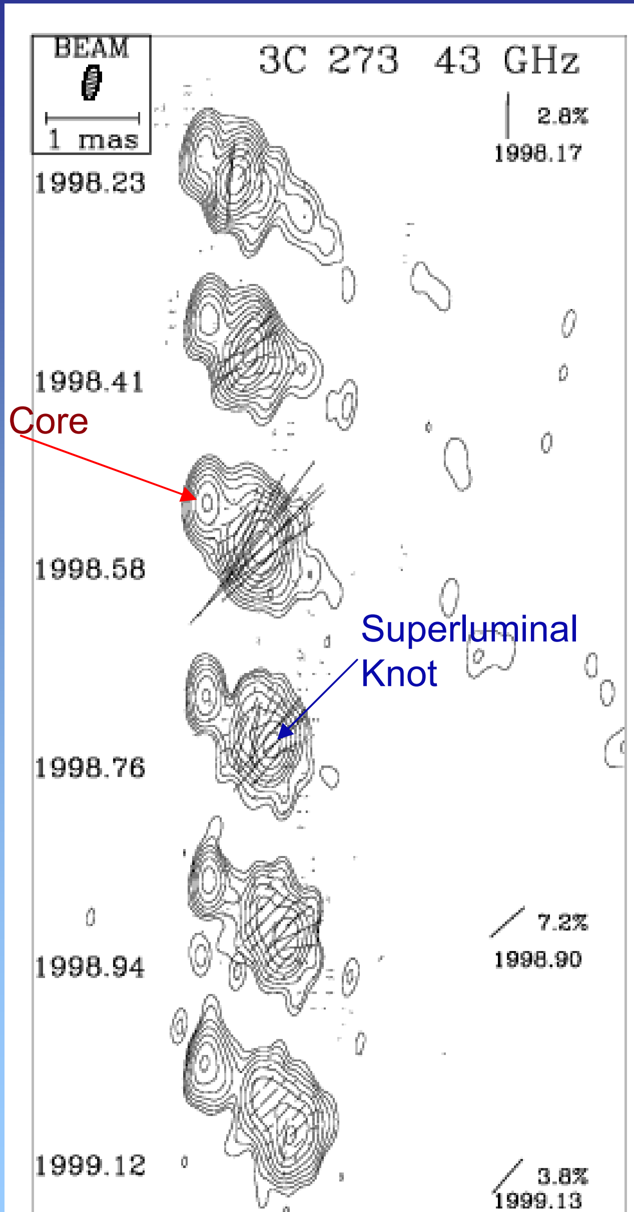
Can explain if streamline direction is aberrated (jet axis 7.7° from l.o.s.; Jorstad et al. 2005 - J05)

$\rightarrow$ Requires Lorentz factor ~ 7 (same as derived from knots by J05)

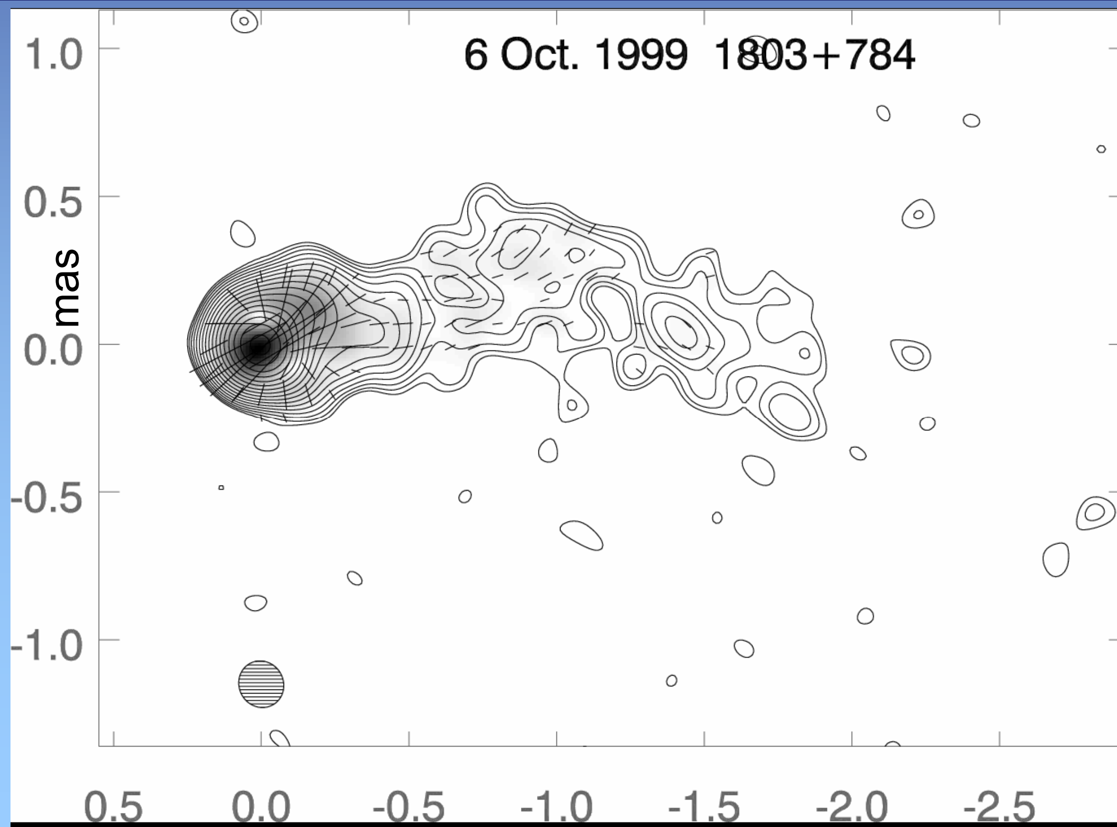
$\rightarrow$ Magnetic helical pattern cannot be aberrated (Poynting flux advection speed not highly relativistic) without causing dominant polarization parallel to axis

- consistent with stationary helical field pattern expected in MHD launched jets

The Core on VLBI Images



- At one end of jet
- Essentially stationary
- Usually low polarization (e.g., 3C 273 on left)
- Some cores: radial polarization (e.g., 1803+784 below): conical shock? (see Cawthorne 2006, MNRAS, 367, 851)



A Blazar Core Is <u>not</u> the Start of the Jet

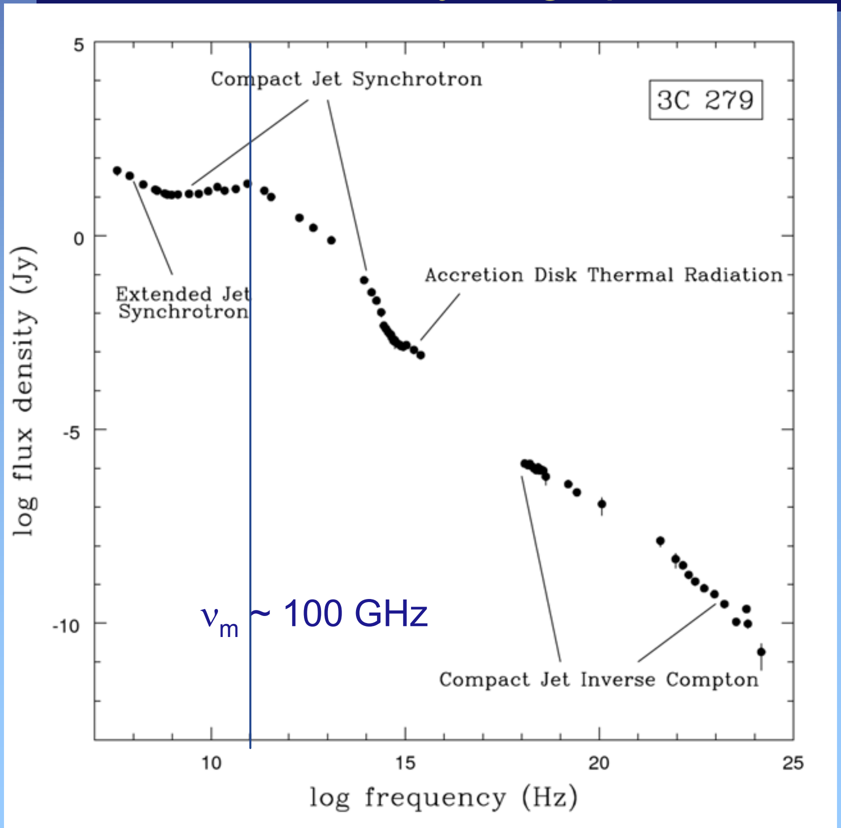
- Self-absorption turnover frequency > 43 GHz in many prominent blazars

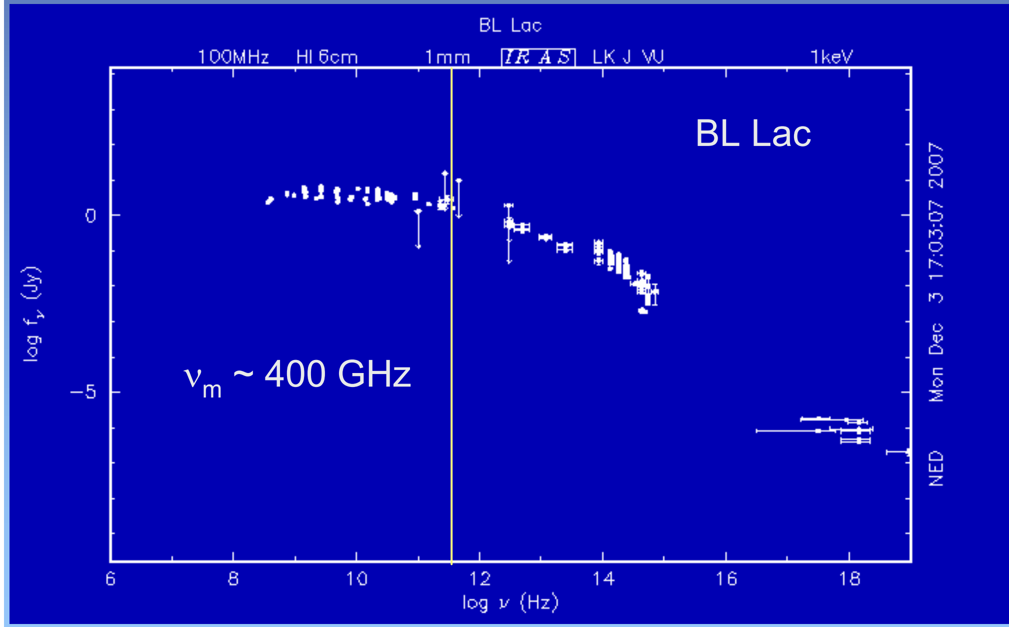
→ Self-similarity continues upstream of 43 GHz core

- Opacity gradients

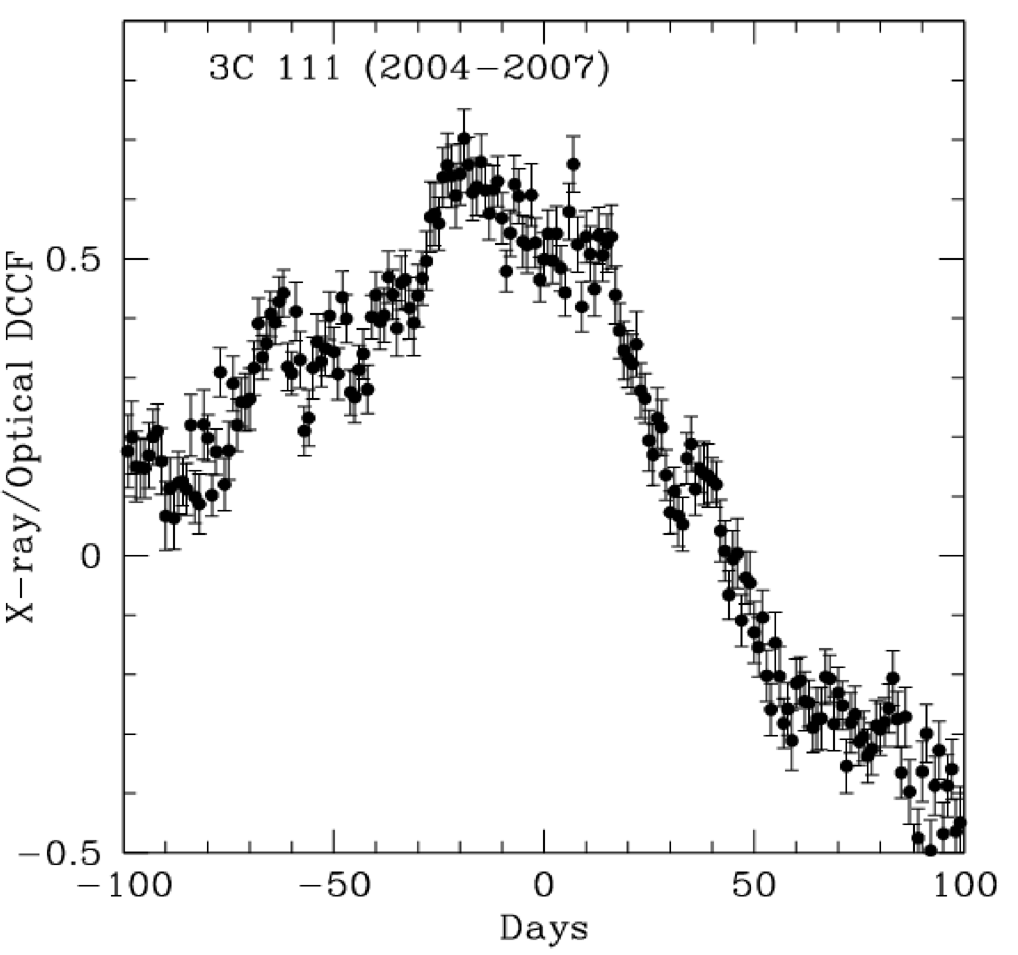
→ Core is farther downstream at longer λ (in steps?)

→ Can we see anything upstream of 43 GHz core?





FR II Radio Galaxy 3C 111 X-ray/Optical Correlation



X-ray variations lead optical by 20 days

- as expected if X-rays come from corona near black hole & optical from farther out in accretion disk