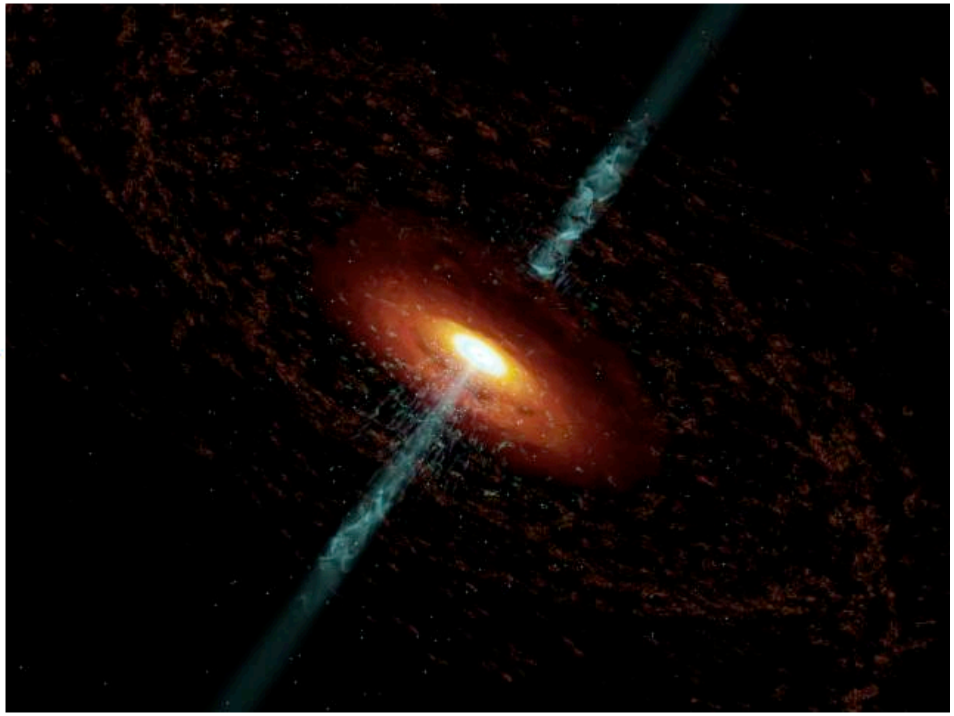

Radio & Gamma-ray Emission from Blazar Jets: Results from EGRET + the VLBA, and Prospects for GLAST

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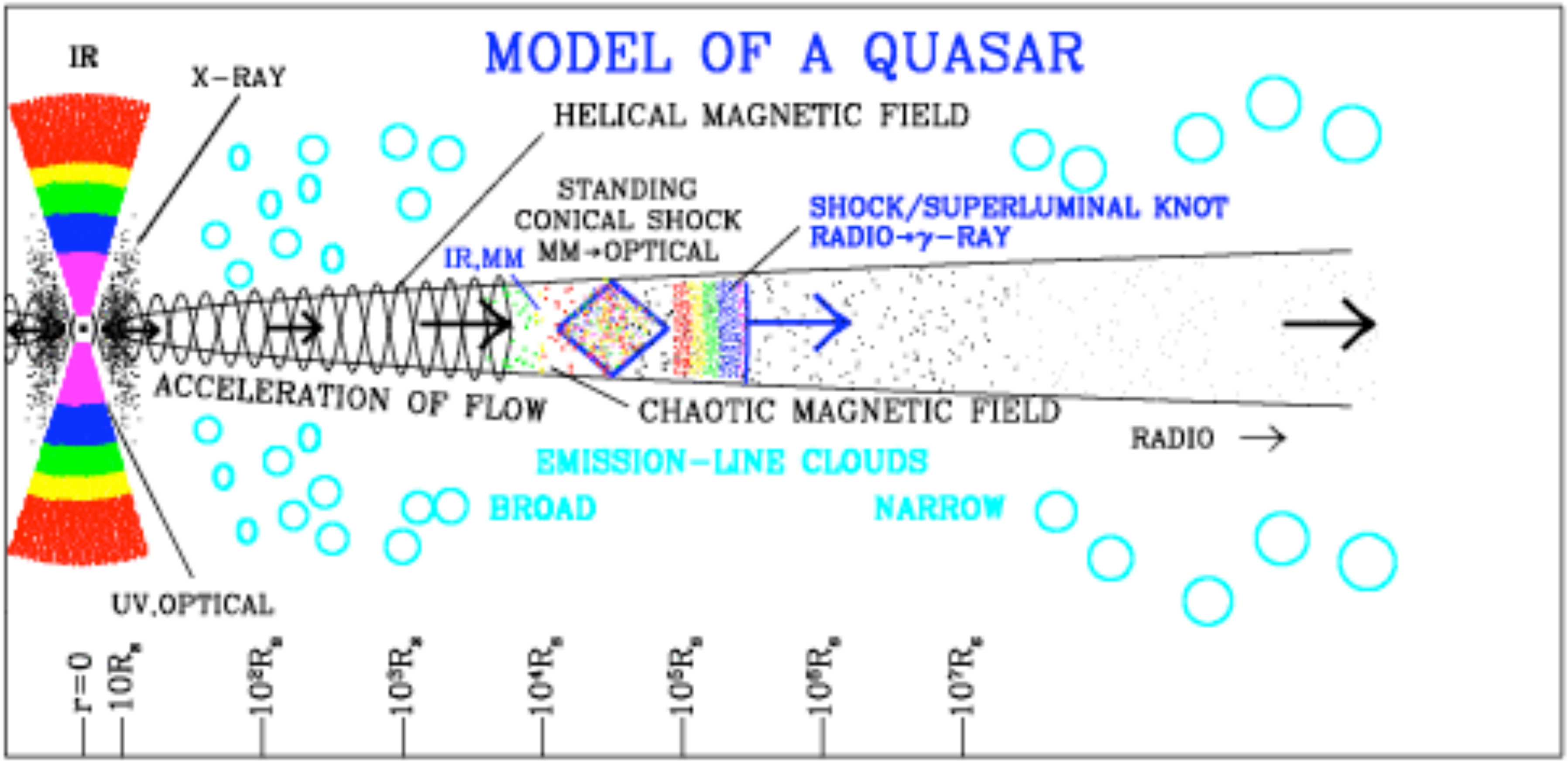
Research Web Page: www.bu.edu/blazars

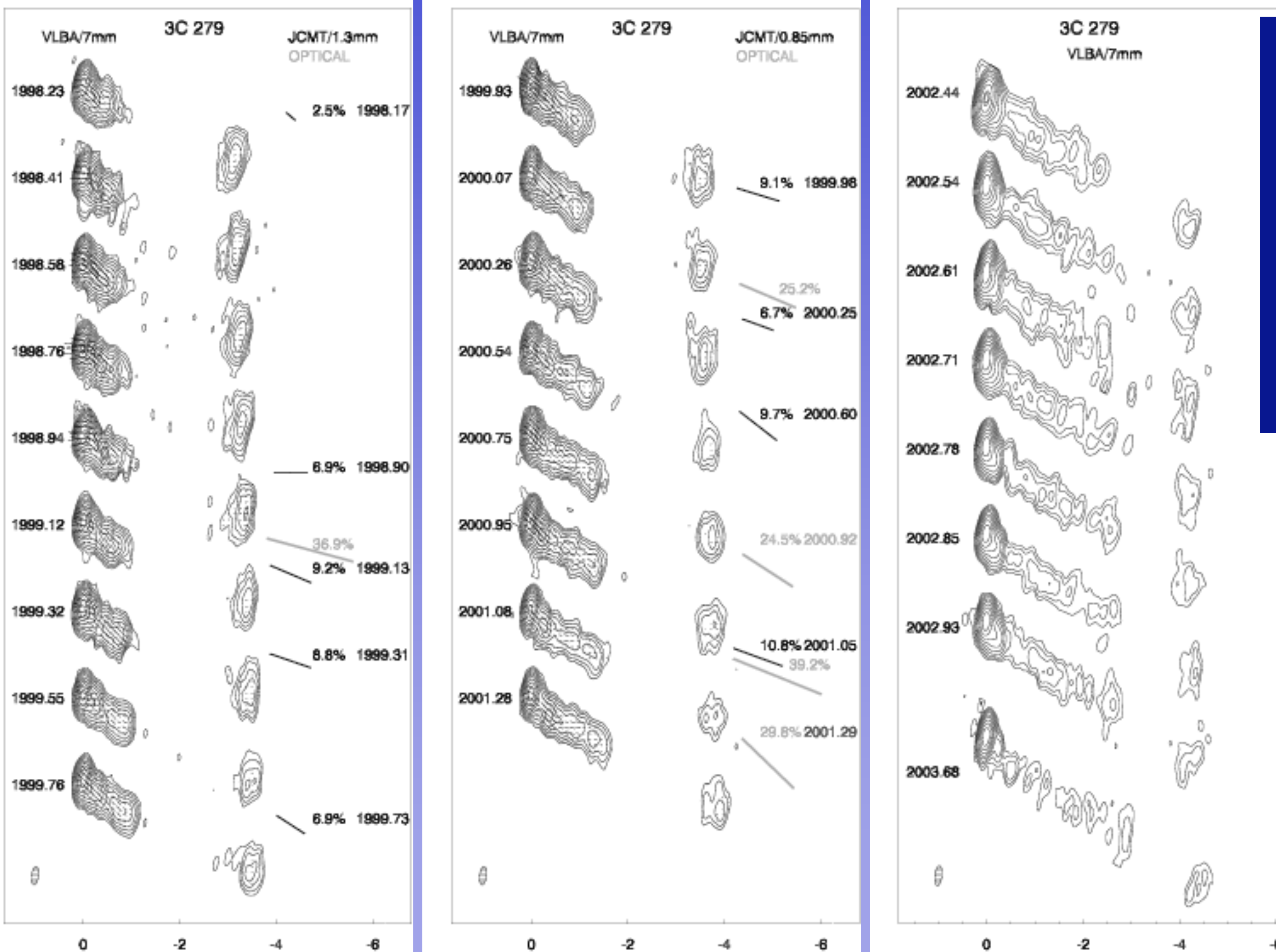
Sketch of Physical Structure of Jet, AGN Based on Current Observations & Theory

Goals: 1. Determine where & how gamma-ray emission originates

2. Use multiwaveband light curves + VLBI images to probe compact jet



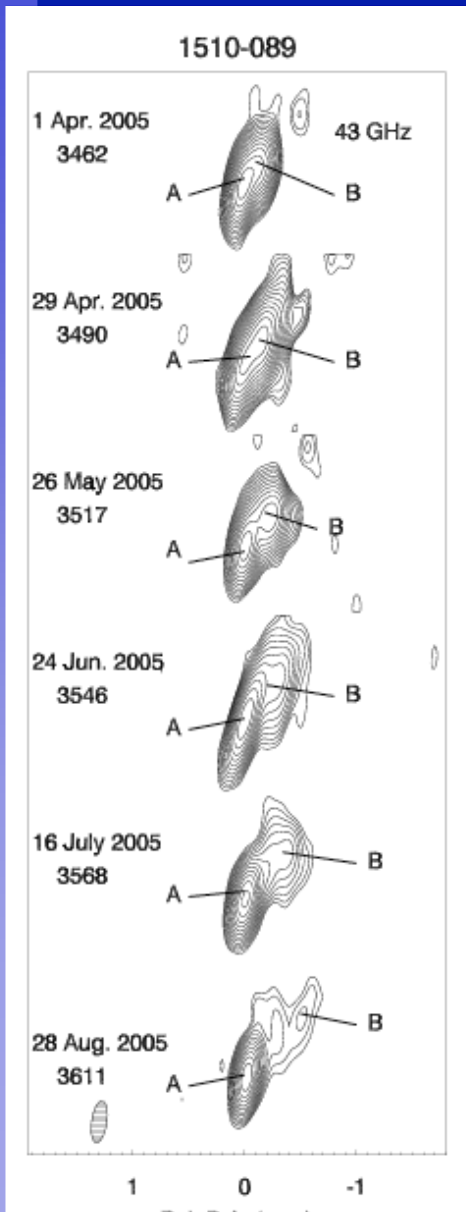
Jets of EGRET Blazars: Very Fast

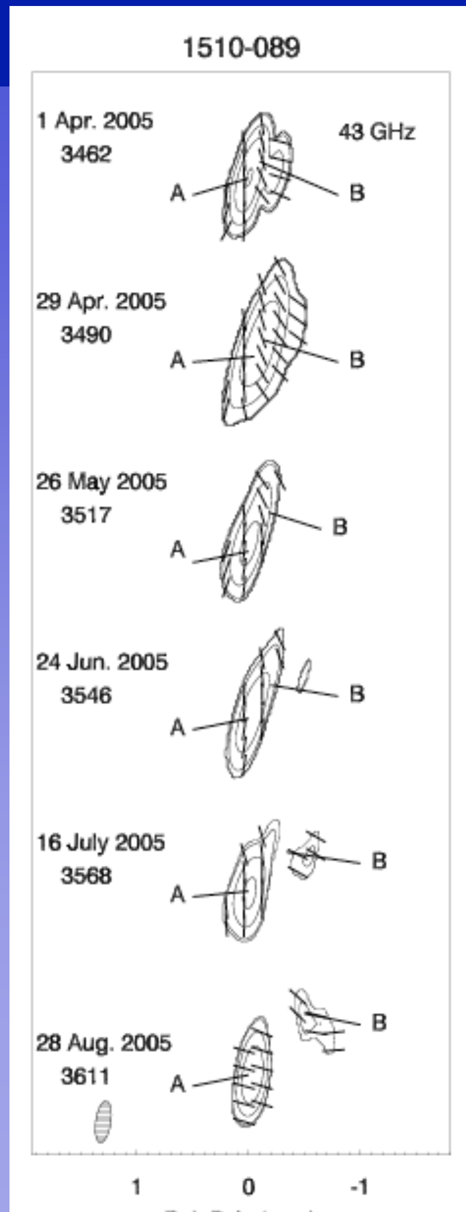


Superluminal motion as high as almost 50*c*
→Bulk Lorentz factor up to 50
→ Doppler factor can approach 100

3C 279: apparent speeds range from ~ 5*c* to >20*c*

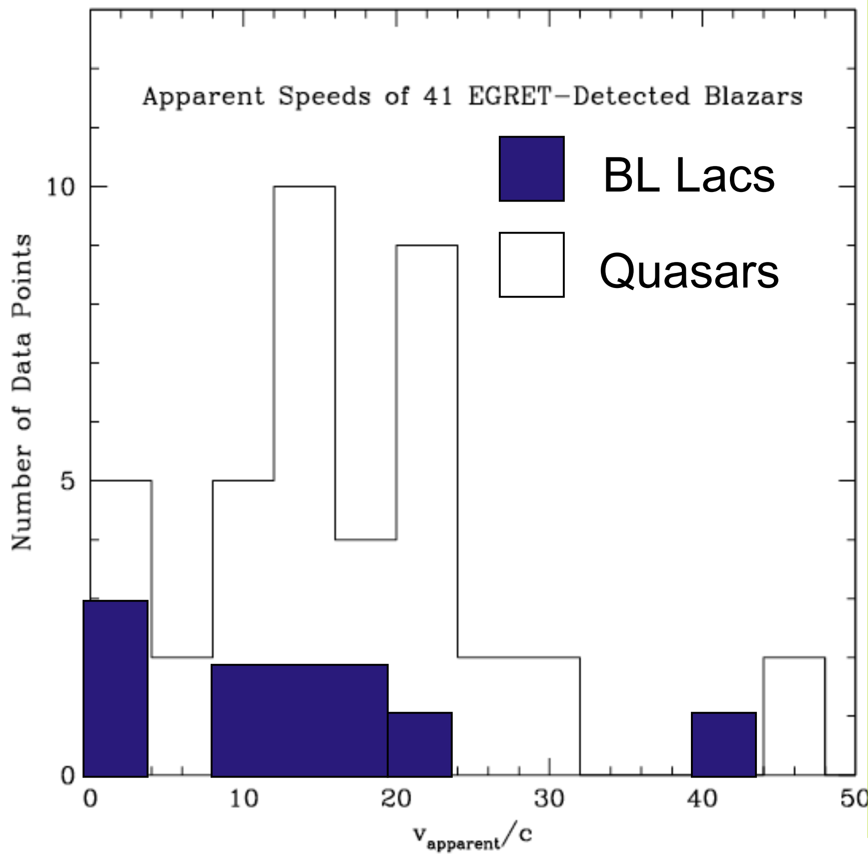
The Fastest Jet thus Far: PKS 1510-089





- Apparent speeds up to 46*c* (fastest known blazar containing well-defined superluminal knots) → bulk Lorentz factor of at least 45 in jet
- Can ID knot across epochs & across wavebands with polarization direction
- For blazars with such high apparent speeds, need to observe ~ monthly at 22 or 43 GHz

Superluminal Motions of Gamma-Ray Blazars

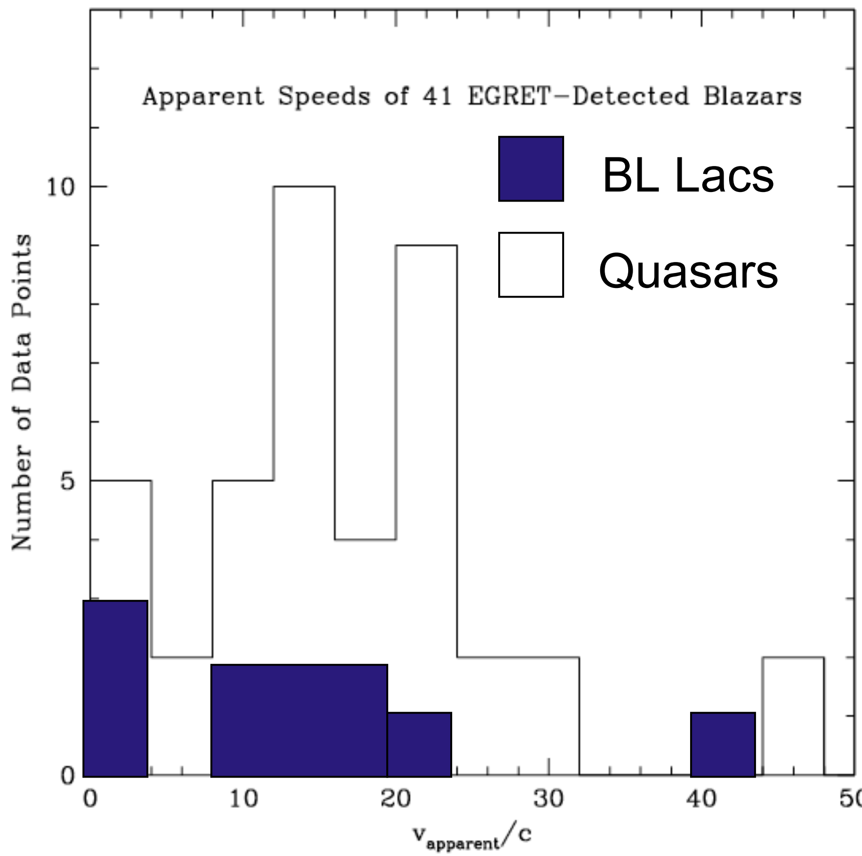


1. Jet velocities determined in 41 blazars by Jorstad et al. (2001,2005), Kellermann et al. (2004), Piner (2006), Gabuzda & Cawthorne (1996), & MOJAVE website.

2. Median value of fastest well-determined speed in a given source is 15*c*
(H_0=71 h_0 km s^{-1} Mpc^{-1}, Ω_Λ=0.7, Ω_M=0.3).

3. Median apparent speed is significantly higher than that in general population of strong compact radio sources (Kellermann et al. 2004).

Superluminal Motions of BL Lac Objects



1. A number of EGRET BL Lac objects have apparent speeds similar to those of quasars. Others have slow apparent speeds (histogram on left).

2. TeV-bright BL Lac objects have slow apparent speeds (Piner & Edwards 2002, 2003,2004), but not necessarily low bulk Lorentz factors (Mkn 510; Giroletti et al. 2004)

3. In many BL Lacs, faint, fast features pass through stronger, ~ stationary structure

Radio-Loud AGN: The General Population

Relativistic beaming causes strong selection effect in flux-limited radio surveys → Bias toward high-Γ jets pointing almost directly along line-of-sight

Population simulation (Lister & Marscher 1997): observed apparent-motion & redshift distribution reproduced if:

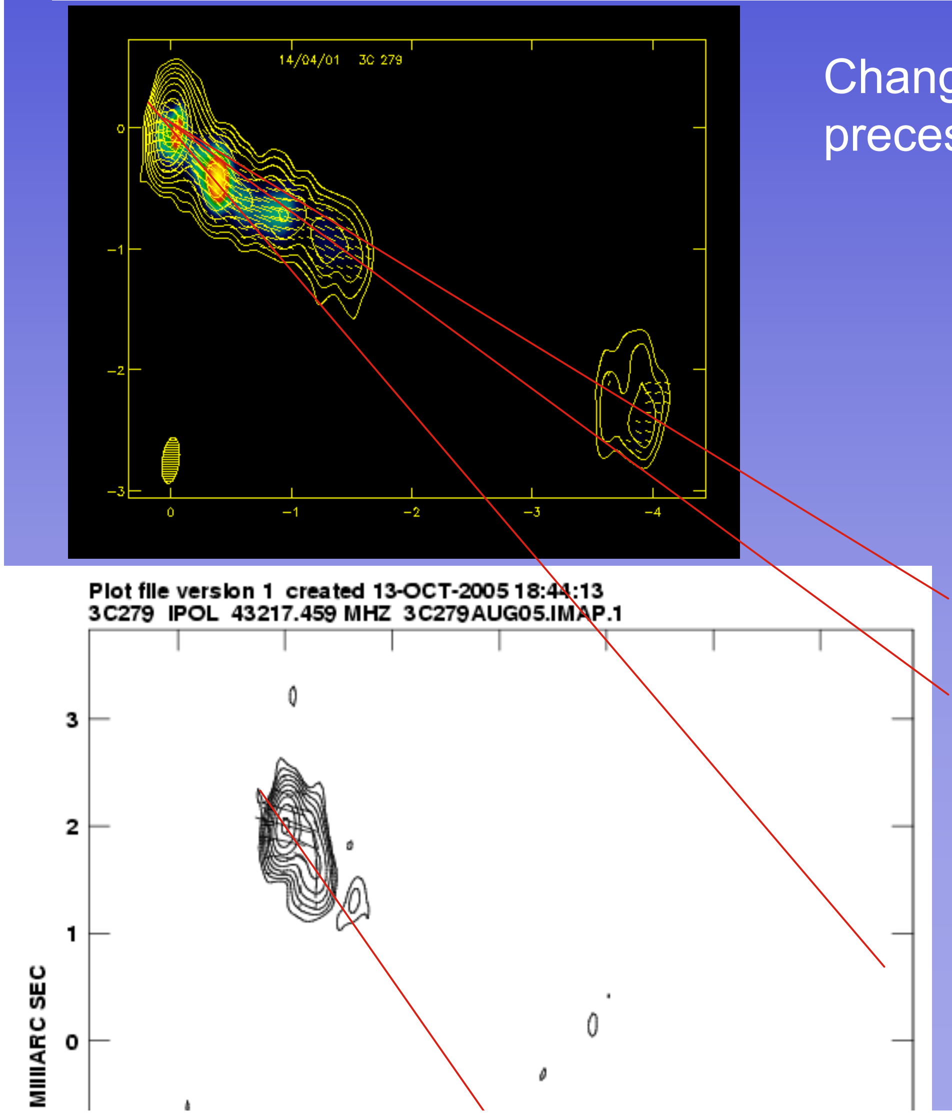
1. Radio-galaxy luminosity function measured at low z is valid at higher z

2. Lorentz factor distribution is a power law, $N(\Gamma) \propto \Gamma^{-a}$, a = 1.5-1.75, with a high-Γ cutoff of 45 (highest observed β_{app})

→ 12-17% of jets in population have Γ = 10-45
5-7% have Γ = 20-45, 2-3% have Γ = 30-45, 0.5-0.9% have Γ = 40-45

Changes in Direction

- •Change in apparent speed possible from change in direction even if Γ constant
- •Nonthermal luminosity seems to be related to direction of jet (see S. Jorstad's talk)
- •Changes amplified greatly by projection effects
- •Velocity seems ballistic in some jets but seems to follow twisting jet in many others

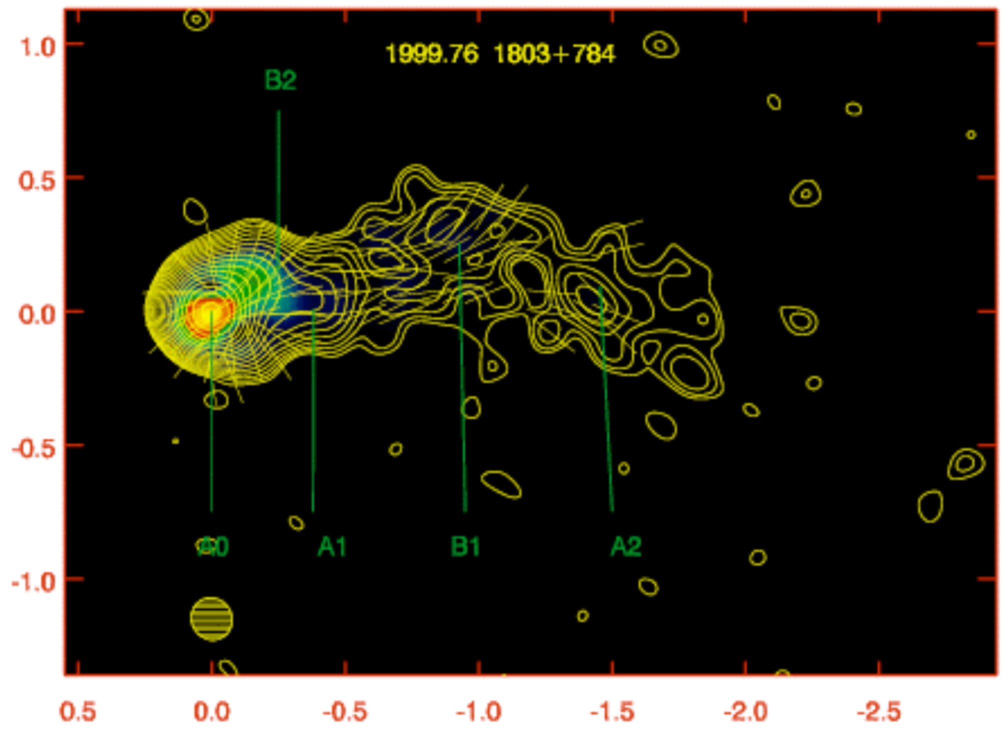


Changes in direction tend can be abrupt, unlike precession (more like an unstable firehose)

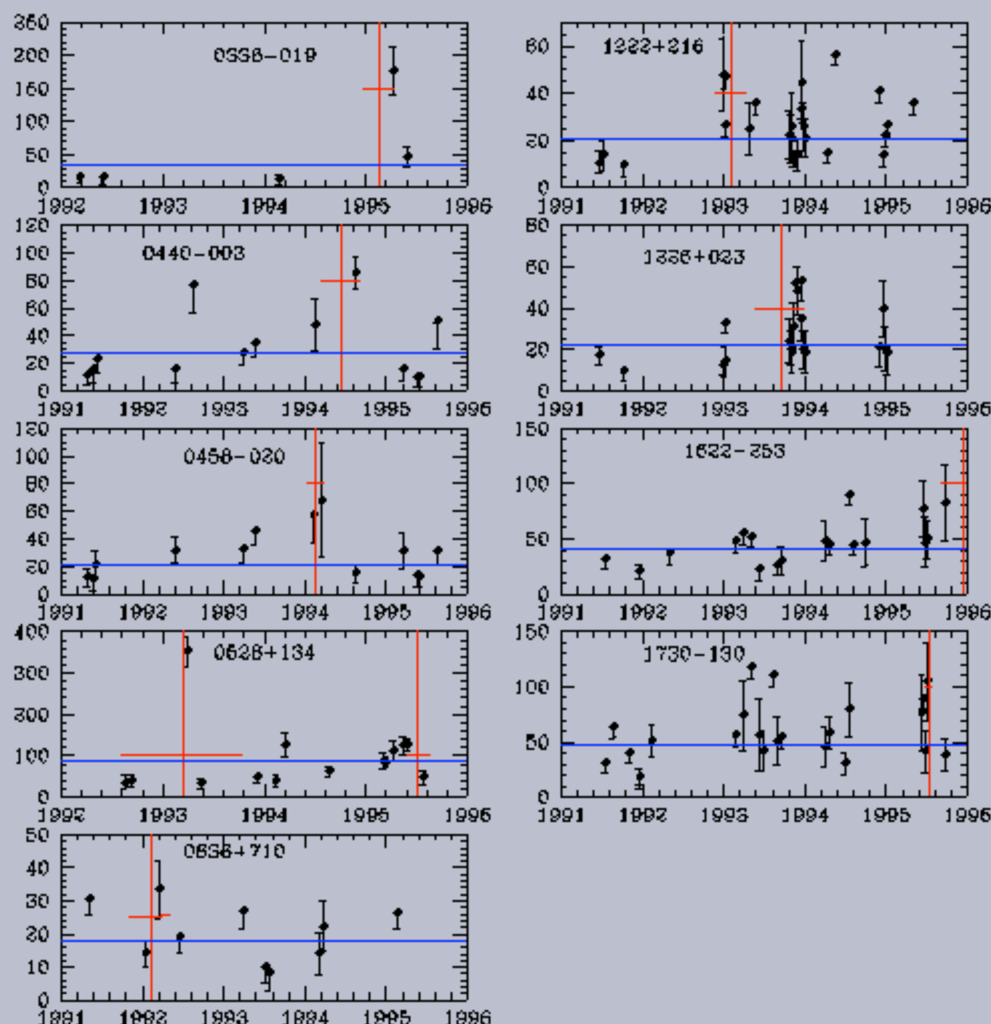
The Core of Blazar Jets

a. Frequencies below ~ 40 GHz: $\tau \sim 1$ surface (deeper at higher frequencies)
b. At higher frequencies, perhaps some lower frequencies:
Conical standing shock (Daly & Marscher 1988)
- Reproduces polarization pattern if randomly oriented B field is compressed by conical shock (Cawthorne 2006; e.g.; non-EGRET BL Lac object 1803+784 shown below)
- Observations of simultaneous optical & 43 GHz core polarization variations in 0420-014 explained by turbulence passing through a conical shock (D'Arcangelo et al. 2007)
c. Even higher frequencies (~300 GHz): End of zone of flow acceleration
- Where Doppler factor reaches asymptotic value

1803+784



Connection between γ-ray Flares and Superluminal Ejections



Jorstad et al. (2001): In 10 out of 23 cases the ejection of a superluminal component coincided to within 1σ with time of high state of the γ-ray flux. Flare in 15 GHz polarized flux occurs prior to time of high γ-ray flux

Lähteenmäki & Valtaoja (2003): high γ-ray flux occurs during rising phase of 37 GHz outbursts

Conclusion: mm-wave outburst + superluminal knot ejection occur before peak in γ-ray flux

→ γ-rays are produced in the knots, well beyond broad emission-line region

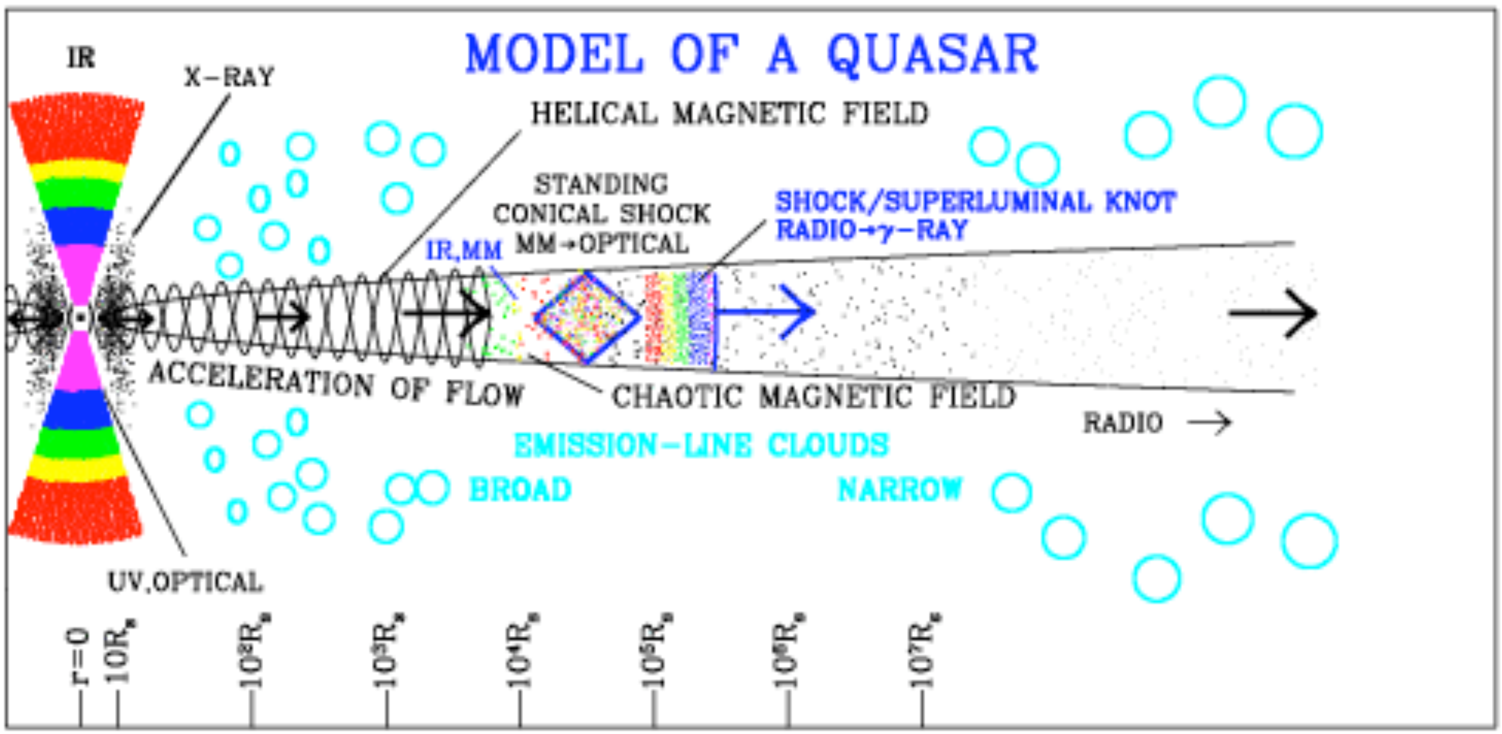
Need to test with better timing data: GLAST + well-sampled VLBI data

EGRET/VLBI: Likely Site(s) of Gamma-ray Emission

1. **Moving shock waves = superluminal knots**
   Signature: outburst lasting weeks/months with persistent polarization direction
2. **Standing (oblique/conical) shocks = core & other stationary features**
   Signature: steady but typically low polarization, usually parallel to jet axis

3. Combination of the two (see poster on M87 by Cheung)

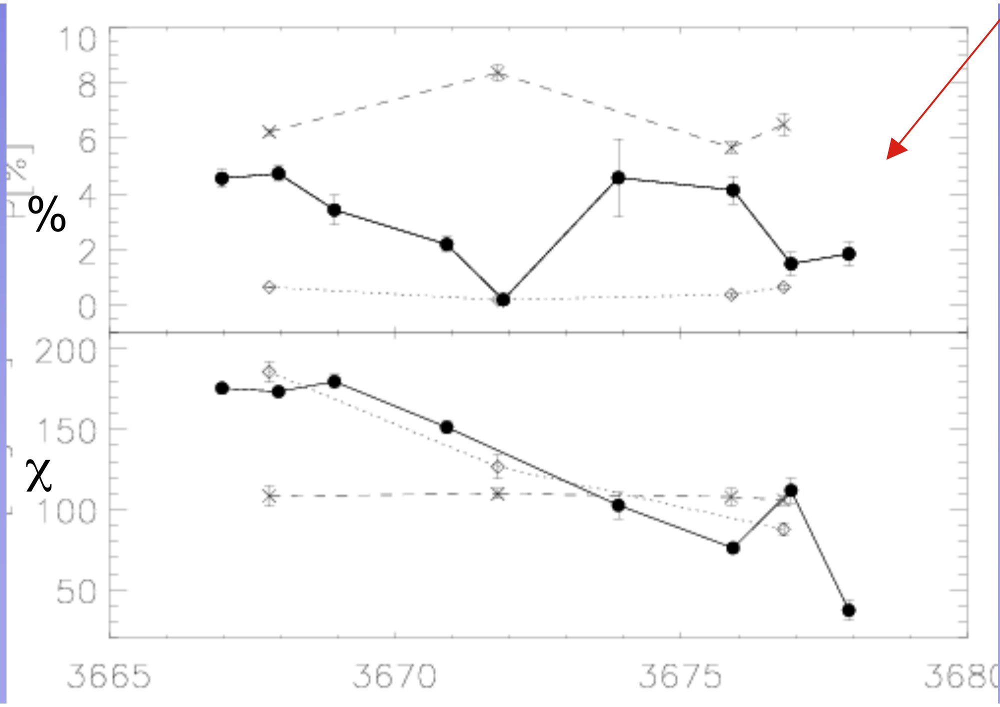
- Method for testing: (1) Well-sampled (monthly) time sequences of 43 GHz VLBI images, both total & polarized intensity; (2) polarization light curves from radio to optical; (3) total flux light curves from radio to gamma-ray



Variations from Turbulence (Not all flares are new shocks!)

1. **Shock waves moving through turbulent jet plasma**
   Signature: flux & polarization % and χ fluctuate about values that change more smoothly over weeks-months
2. **Turbulence passing through standing conical shock system** (e.g., 0420-014; D'Arcangelo et al. 2007)
   Signature: polarization % and χ fluctuate about low base polarization (see Cawthorne 2006)

- Method for observing: 10-20 day campaigns of daily polarization monitoring in optical & as frequently as possible (at least 3 times per week) with VLBA at 43 GHz; (2) polarization monitoring at intermediate frequencies if possible



Dark: optical

Light diamonds: core at 43 GHz

Light crosses: knot in jet for comparison

Guide to Combining VLBI Observations with GLAST Light Curves: Choice of VLBI Frequency

≤8.4 GHz:

Low frequency → – cannot probe deeply into jet

Coarse resolution (>0.5 mas) → + see knots long after ejection, out to tens of mas, – moving knots blend with stationary features

+ Very high sensitivity: good for surveys, weak sources (mJy range)

+ Do not need dense time coverage (less strain on resources)

15 GHz:

Medium frequency → probes 0.3-10 mas scale structure

Moderate resolution (0.4-0.8 μas) → – need to wait > 2 years after mm-wave outburst to measure apparent speed of moving knot in z>0.1 sources, – blending of moving & stationary features near core, + can image out to ~10 mas

+ Exellent sensitivity → good for surveys, strong to moderately weak (> 0.01 Jy) sources

+ Do not need dense time coverage for most blazars - 2-4 times/year

+ Densely sampled light curves available (UMRAO, OVRO)

Guide to Combining VLBI Observations with GLAST Light Curves: Choice of VLBI Frequency

43 & 22 GHz (VLBA, add Effelsberg et al. for better resolution):

+ High frequency → see deeper into jet
+ Fine resolution (0.1-0.2 mas) → see knots shortly after ejection, get apparent speeds & dates of ejection after several months
– Sensitive enough for > 1 Jy blazars, 0.1 Jy with phase referencing
+ Can get (& need) excellent time coverage (once per month)

86 GHz (Global Mm-VLBI Array):

+ Highest frequency → jet not as opaque
+ Finest resolution (40 μas)
– Lowest sensitivity → probes core region, not much else
– Poor time coverage - twice per year (unless core brighter than a few Jy so possible with stand-alone VLBA)

Most useful for highest resolution images to combine with sequences of 43 GHz images

> 100 GHz: Experimental, would be great if we can get it to supplement lower-frequency sequences of images

Guide to VLBI Observations of Gamma-ray Blazars: Number of Objects in a VLBA Session

Basic principles:

- Don't usually care about faint outer structure → can observe a given object for only 5-10 min per hour, cycle through 5-10 sources + calibrators
- 24 hours: can observe ~25 sources with flux > 1 Jy with dynamic range better than 100:1 (usually adequate to follow knots) even at 43 GHz
- Observe at as high a frequency as possible given brightness of source & dynamic range needs
- Surveys of basic properties (as opposed to monitoring changes): can observe >100 objects at lower frequencies in a single 24-hour session
- Difficult objects (e.g., TeV BL Lacs with weak knots): Observe more frequently during session to get better image fidelity
- Weak objects: sandwich program sources between scans of phase calibrator

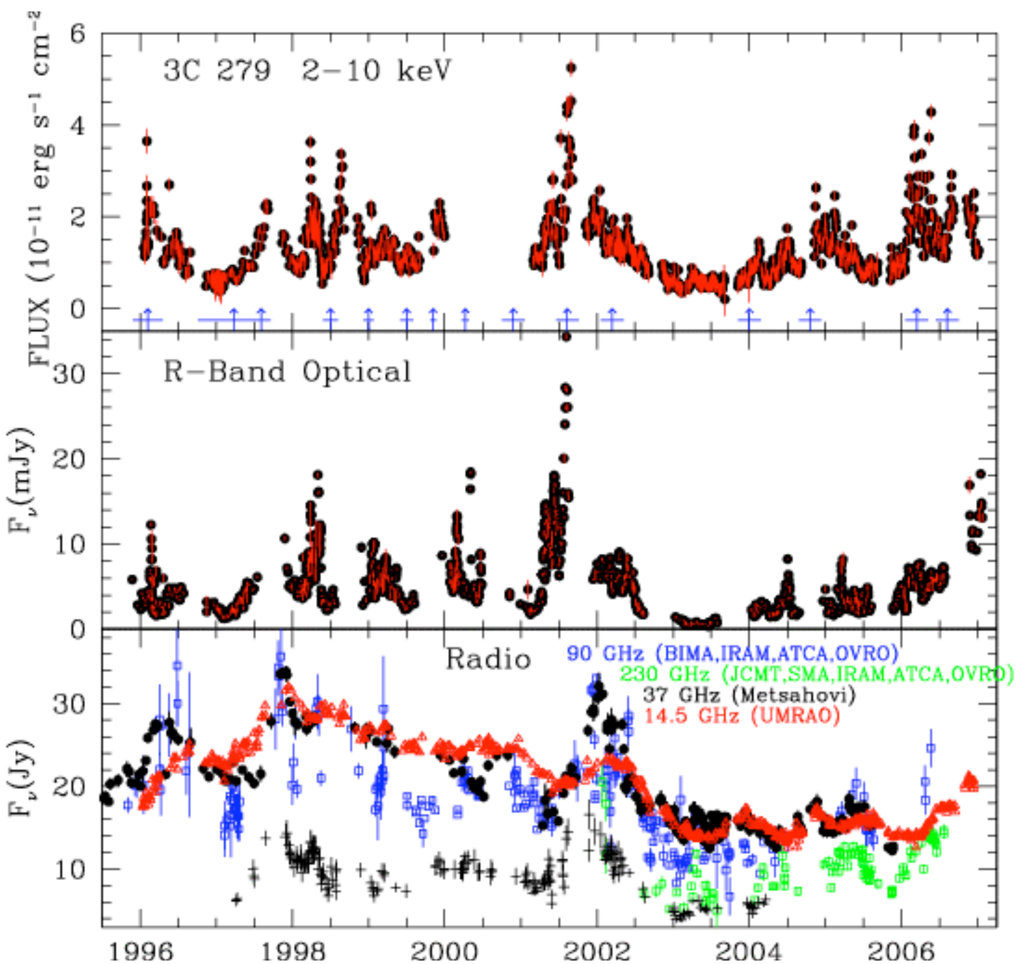
The Desired Observational Result

Densely sampled light curves from radio to gamma-ray for correlation analysis

Times of superluminal ejections and flux history of core & knots

ID of optically flaring features on VLBI images from polarization signature

Panchromatic emission maps from combination of the above

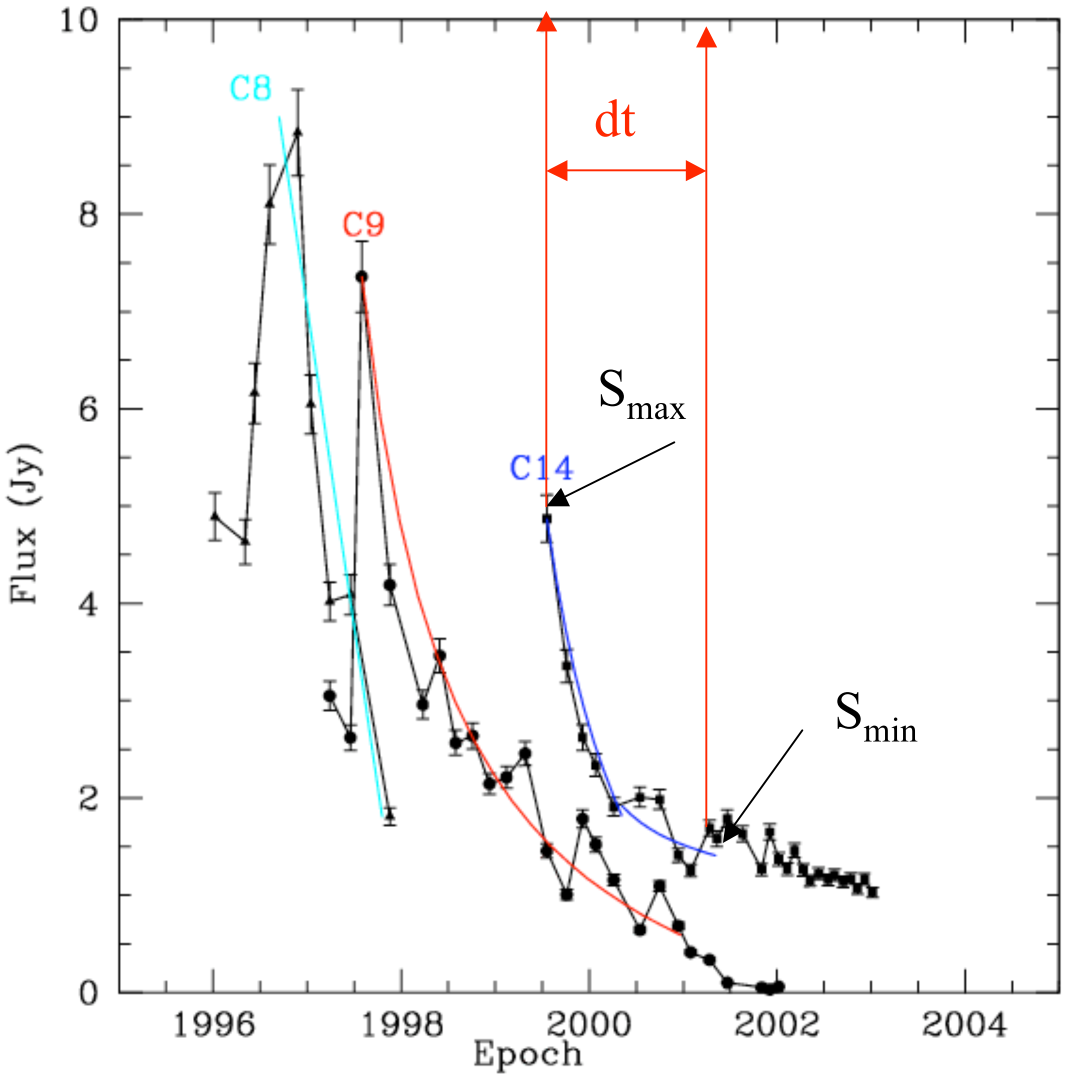


GLAST should be able to determine why some prominent, highly superluminal blazars were missing in action when EGRET observed them:

e.g., 3C 345, OJ 287, 3C 446

Tingay et al. 1998: EGRET detection seemed unrelated to brightness temperature → Doppler beaming factor of the core. Large samples observed with GLAST & VLBI should be able to determine why.

Derivation of Jet Parameters from Measurments of β_{app} & t_{var}



I. Time Scale of Variability
Burbidge, Jones, & O'Dell 1974, ApJ , 193, 43
$t_{var} = dt/\ln(S_{max}/S_{min})$

Variability Doppler Factor
$\delta_{var} = aD/[c\, t_{var}(1+z)]$
D - luminosity distance
a - size of feature (from model fitting of VLBI data)

II. $\beta_{app} = \beta\sin\Theta/(1-\beta\cos\Theta)$
$\beta = \sqrt{(1-\Gamma^{-2})}$
$\delta = \Gamma^{-1}(1-\beta\cos\Theta)^{-1}$

→ Can solve for Γ & Θ

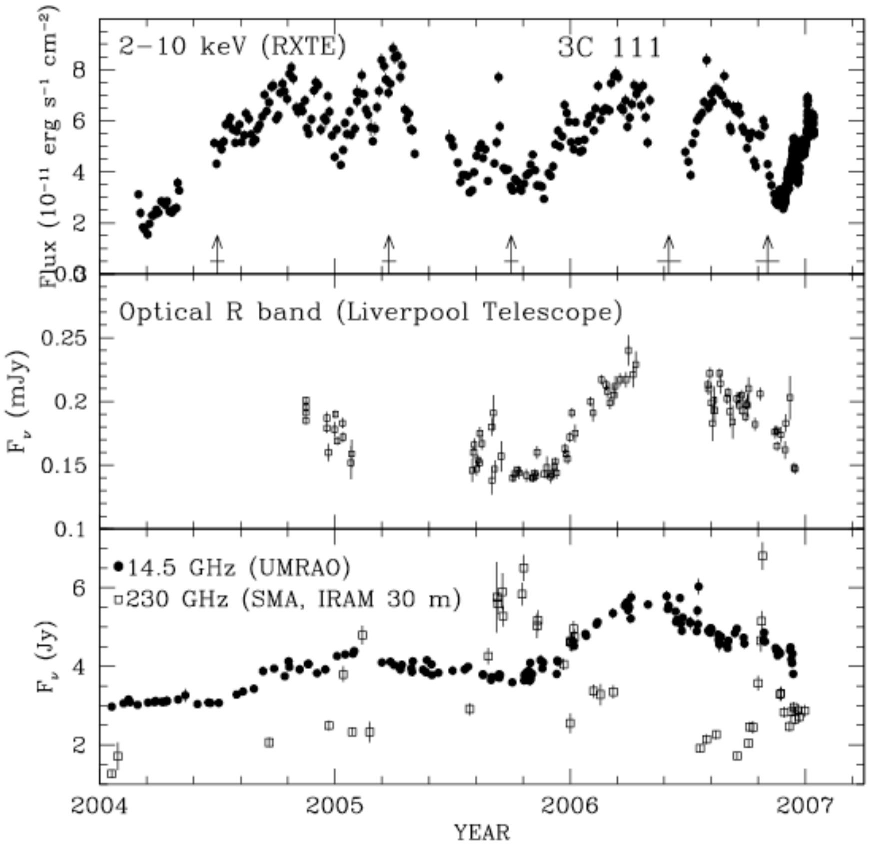
VLBI and GLAST: A Marriage Made in the Heavens

- VLBA provides images against which high-energy variations can be referenced
- Changes at short radio wavelengths correspond to at least some optical variations, which are related to high-E flux changes
- Polarization is very useful for connecting features on VLBI images to variable component at shorter wavelengths
- Comprehensive multiwaveband observations in concert with GLAST and the VLBA can provide multiwaveband emission maps of blazar jets

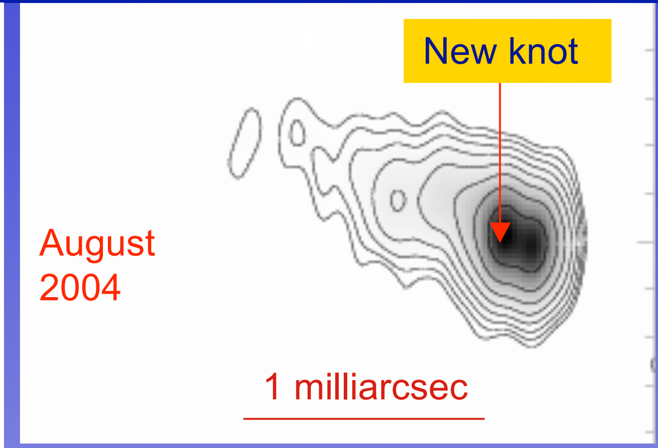
SAVE THE VLBA!!!

- Tell the NSF and the NRAO director how crucial the VLBA is!

FR II Radio Galaxy 3C 111 (z=0.0485): Probable EGRET Source



Superluminal ejections follow drops in hard X-ray flux



X-rays mainly from accretion disk region (Fe emission line at 6 keV)

X-ray dips indicate time of disturbance near black hole

Relative timing of X-ray dip, outbursts at different wavebands, & appearance of superluminal knot can determine distance of each emission region from the black hole