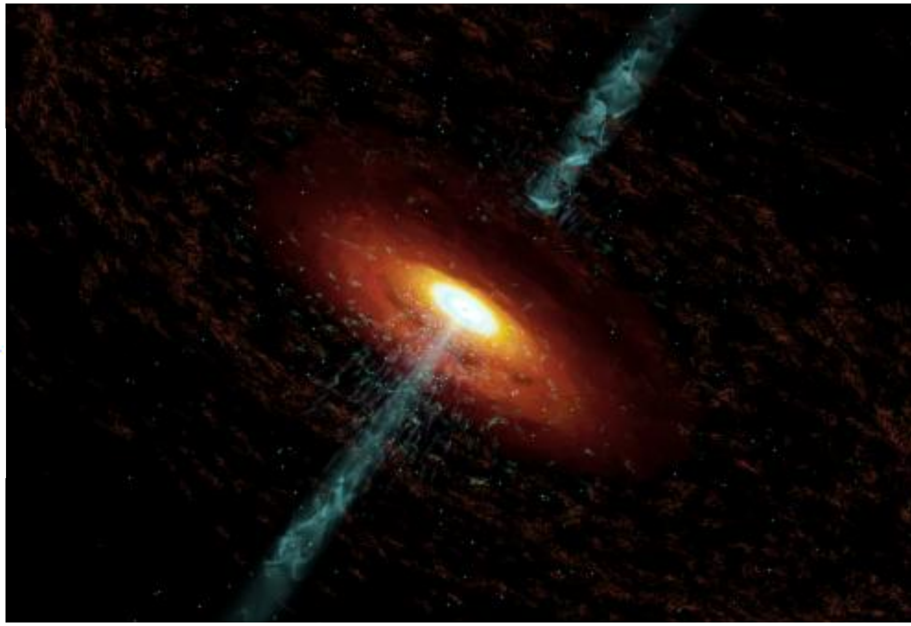


Very Long Baseline Inteferometry (VLBI) & Polarization of Blazars

Alan Marscher

Institute for Astrophysical Research, Boston University

Research Web Page: www.bu.edu/blazars

Free downloads of songs: www.soundclick.com/cosmosii

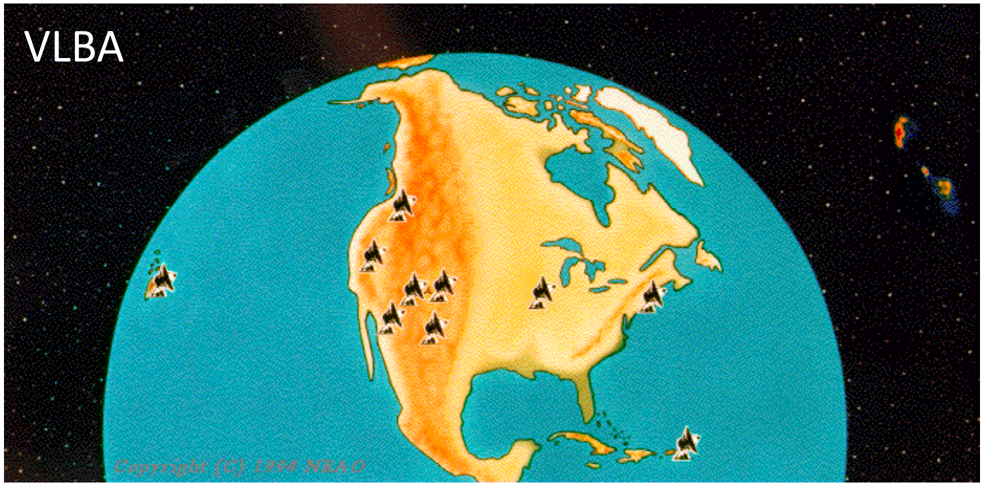
Imaging on Sub-milliarcsecond Scales with VLBI

VLBI: multiple radio antennas scattered across surface of Earth (+ sometimes one in space)

- **Observe same object at same time**
- **Resolution as fine as ~70 μarcsec at mm wavelengths**

Measures interference pattern of waves received by all permutations of *N*(*N*-1)/2 pairs of *N* antennas

Interference pattern represents Fourier transform of brightness distribution of the radio emission → Inverse Fourier transform produces image of source

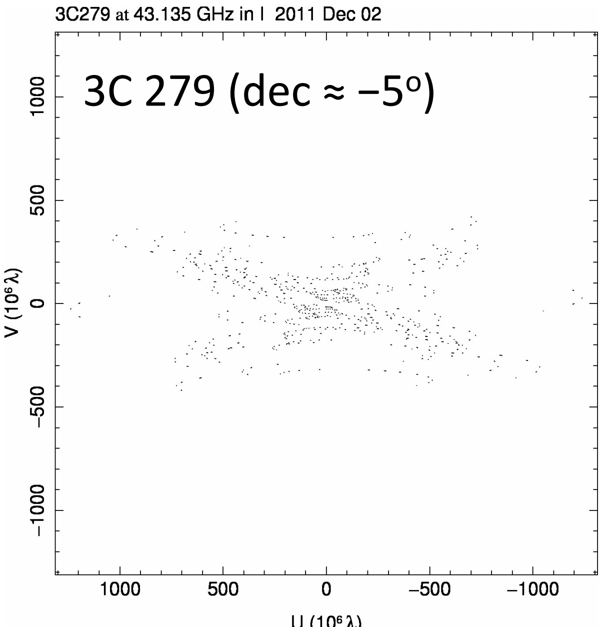


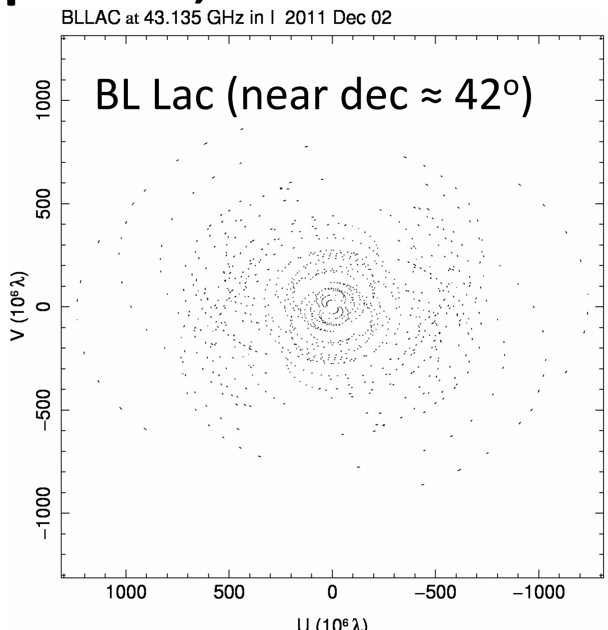
VLBI: Point-spread Function ("Beam")

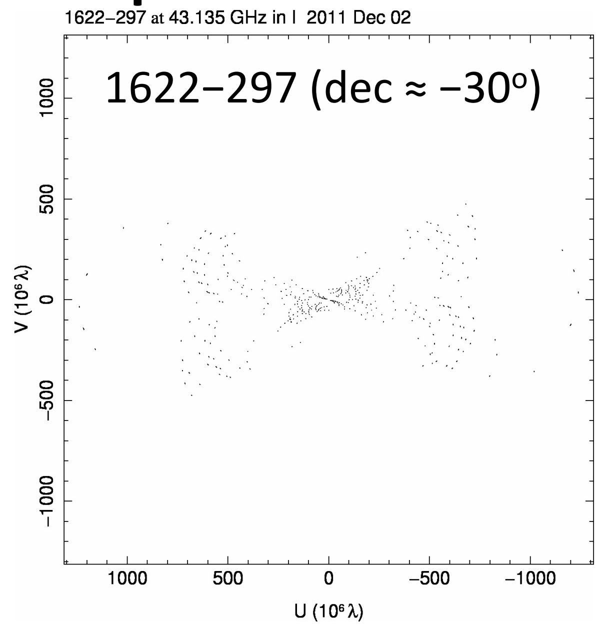
Resolution of any give pair of antennas depends on projected length & orientation of vector between antennas <u>as viewed by the celestial source</u> – this changes as Earth rotates

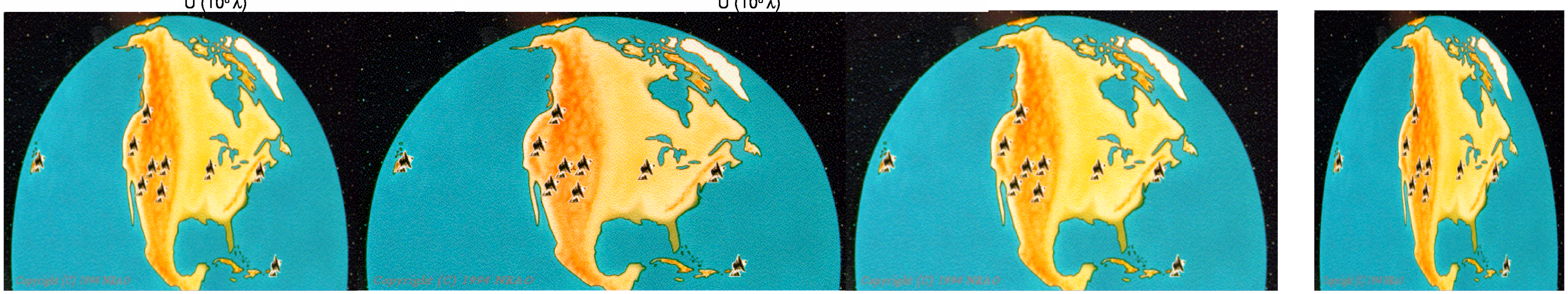
Baseline vectors follow arcs in (*u*,*v*) plane

u = east-west component, *v* = north-south component





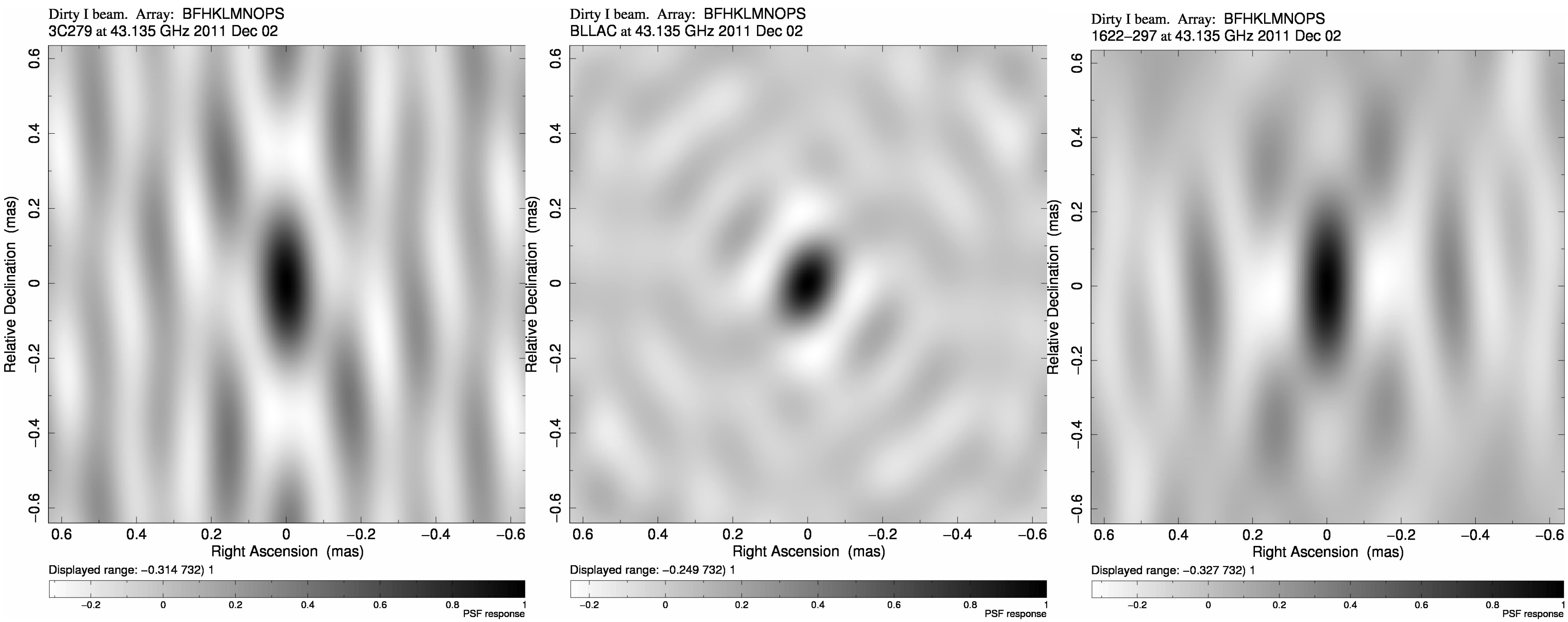




VLBI: Point-spread Function (“Beam”) (Part 2)

Angular resolution in a given direction corresponds to the projected maximum baseline length in that direction

Holes in (u,v) coverage cause bright (positive & negative) “side-lobes”

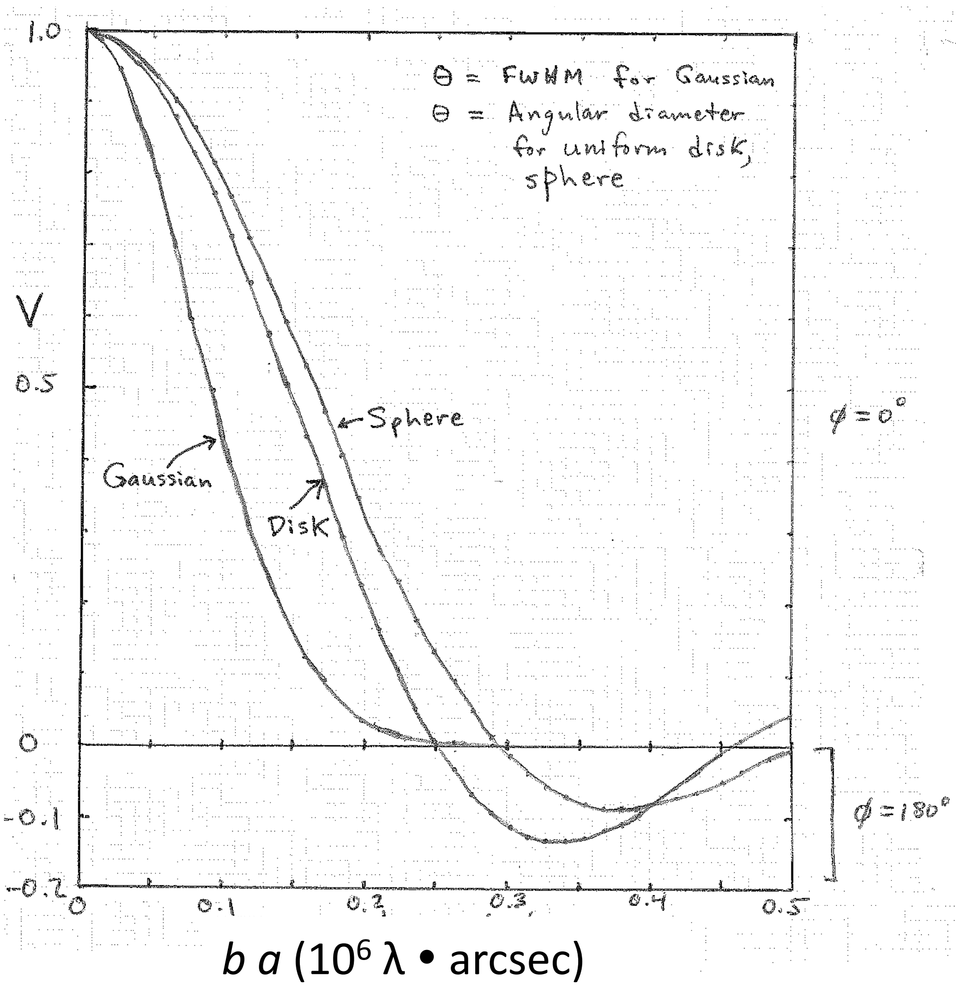


Because beam is complicated & data contain calibration errors, need to proceed slowly with imaging

- Iterative process creating image (with CLEAN) & using image to refine calibration (with many constraints!) – called “self-calibration”

Time-variable atmospheric delays of waves → loss of absolute position information

VLBI Visibility Curves of Model Sources



b = baseline length in units of 10^6 wavelengths

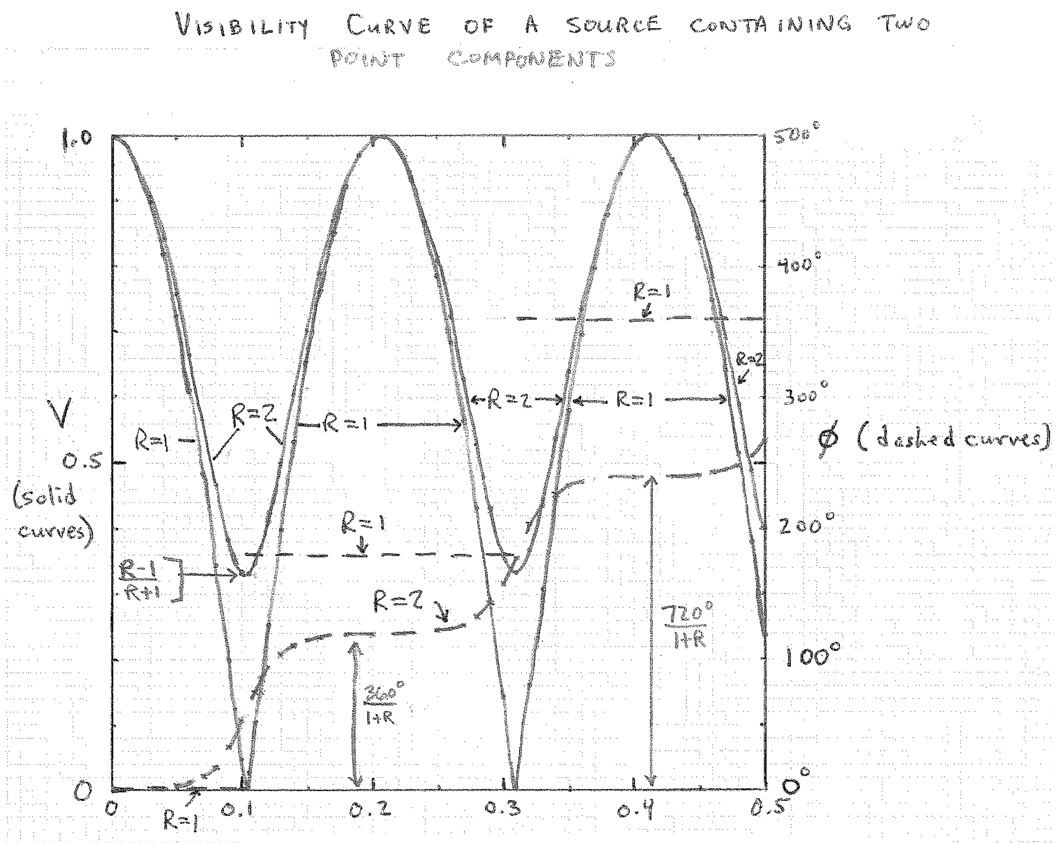
a = angular diameter or FWHM in arcsec

Visibility: amplitude *V* & phase ϕ of interference pattern

Shown are visibility curves of circularly symmetric brightness distributions

Point source: $V = 1$ and $\phi = 0$

VLBI Visibility Curves of Model Sources (Part 2)



$b\,s$ ($10^6\,\lambda$ • arcsec)

b = baseline length in units of 10^6 wavelengths
s = angular separation of components in arcsec
R = ratio of flux densities of two components

Visibility: amplitude V & phase ϕ of interference pattern

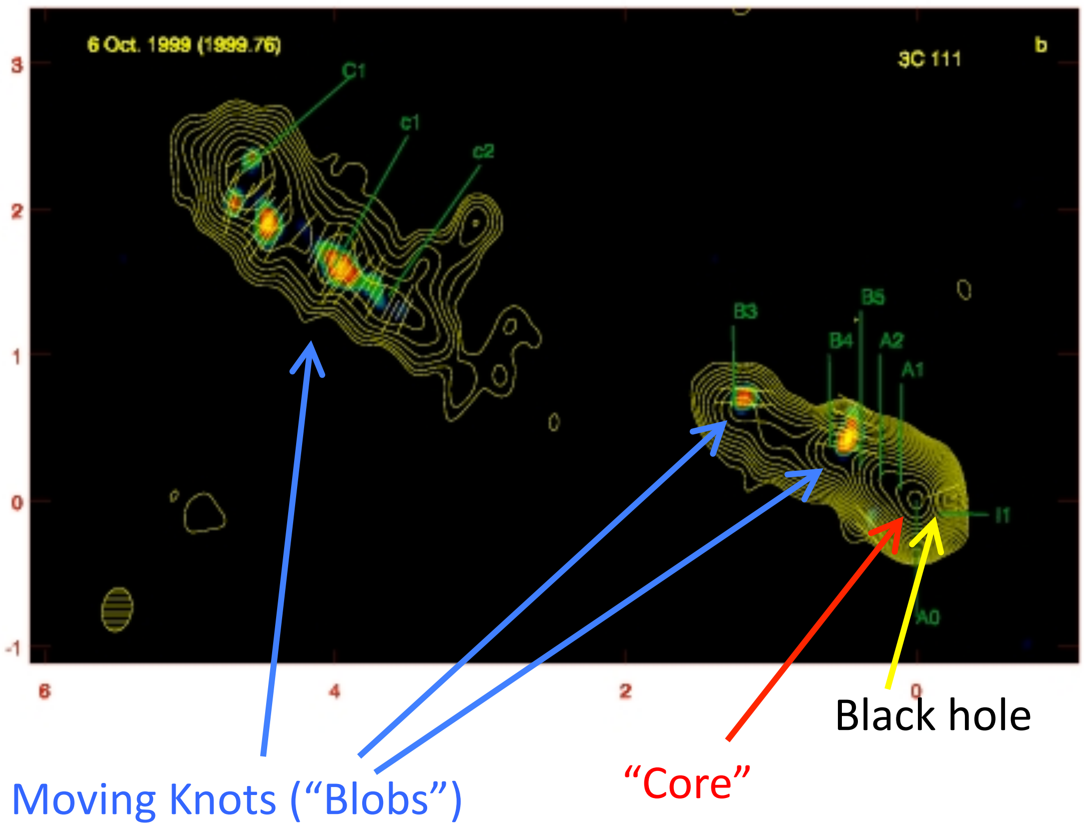
Shown are visibility curves of circularly symmetric brightness distributions

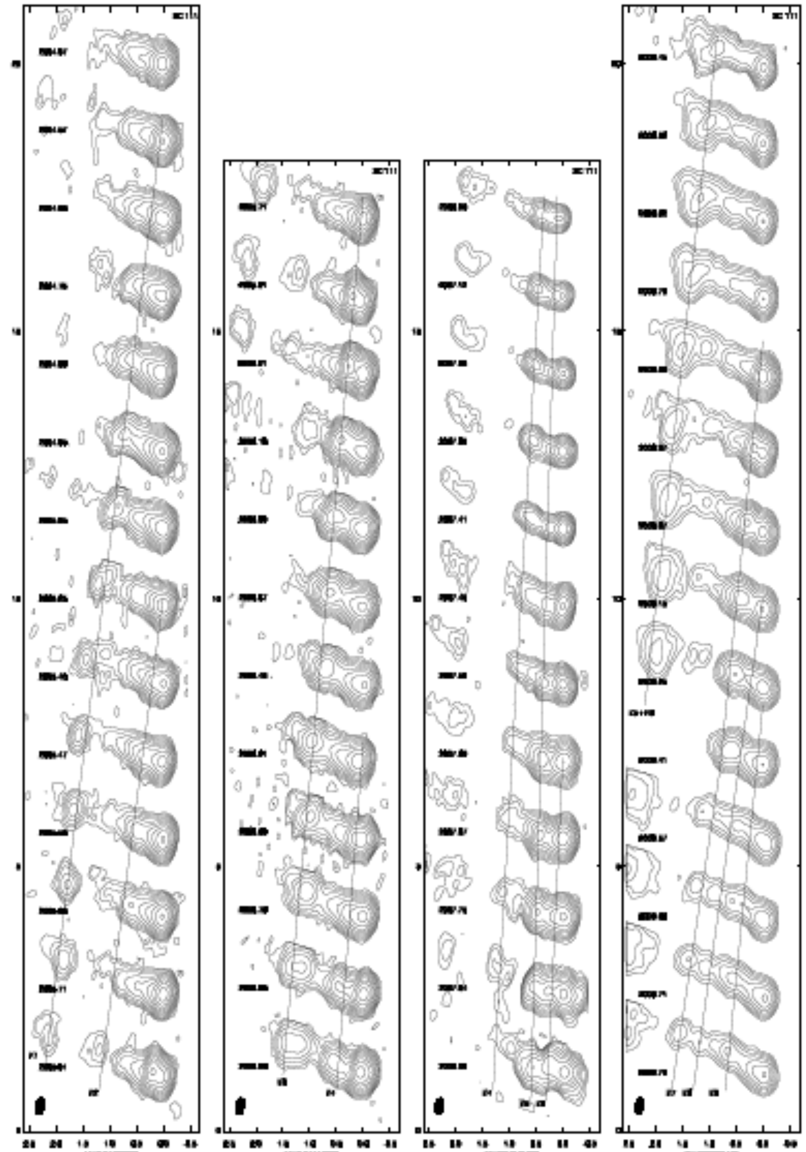
What do you expect if the components are extended rather than points?

Of course, real blazars are usually more complex, & so are visibilities

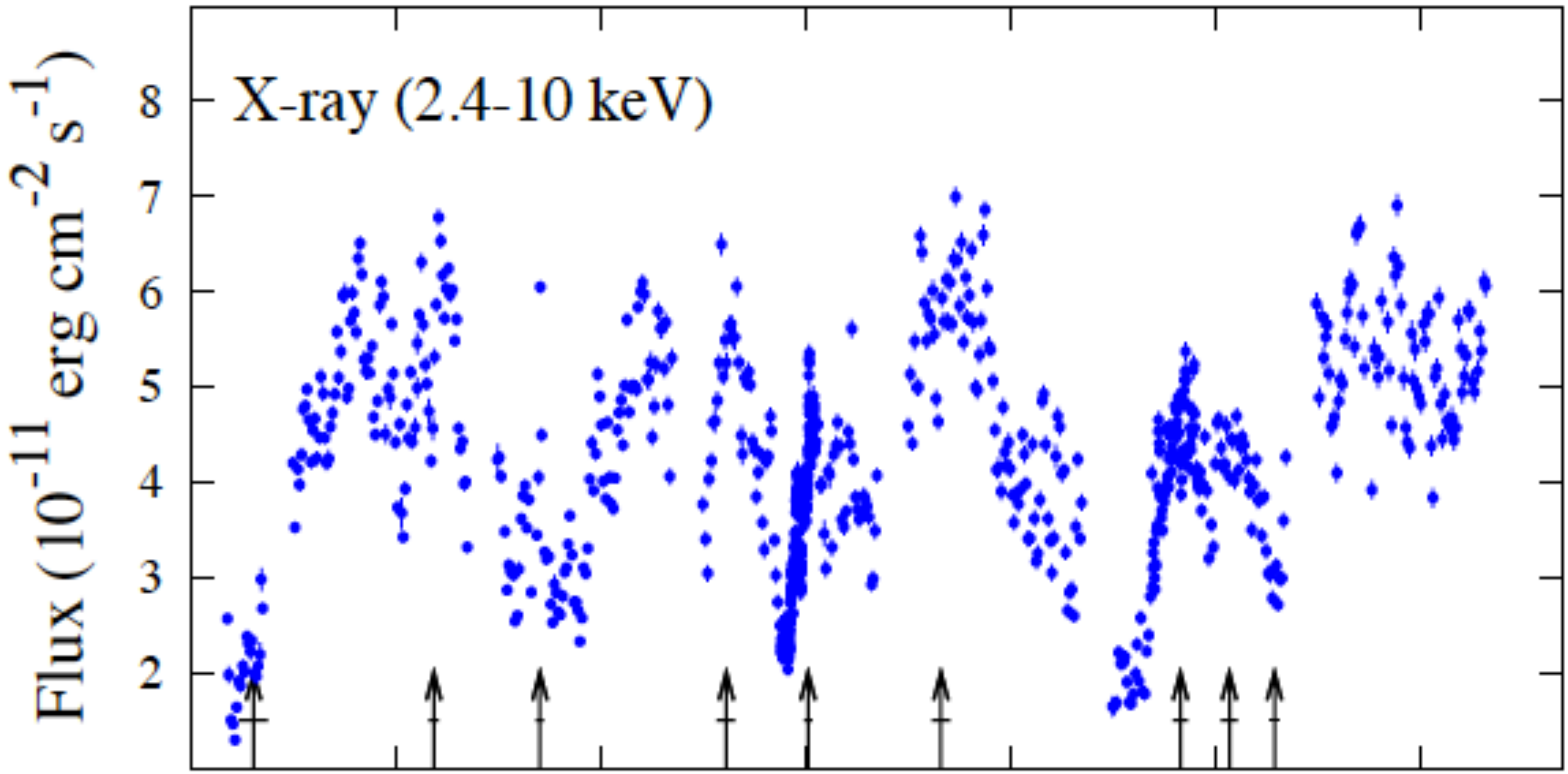
3C 111: Ejection & Superluminal Motion of Knots

VLBA images at 43 GHz (7 mm)



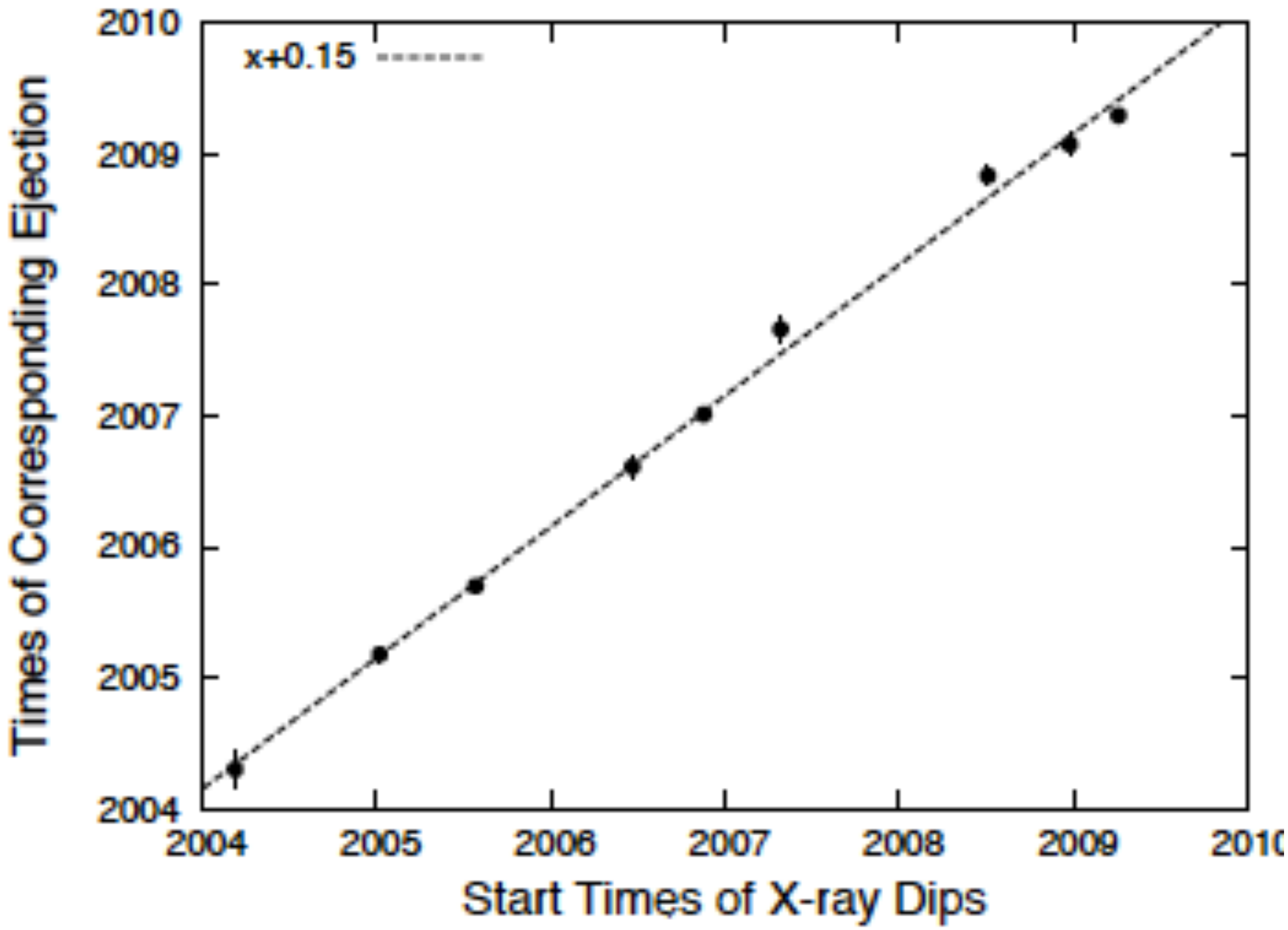


3C 111: X-rays from accretion disk/corona (see Fe line)
Minima in X-ray light curve precede passage of new blobs through “core”



Chatterjee et al. (2011, ApJ)

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



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

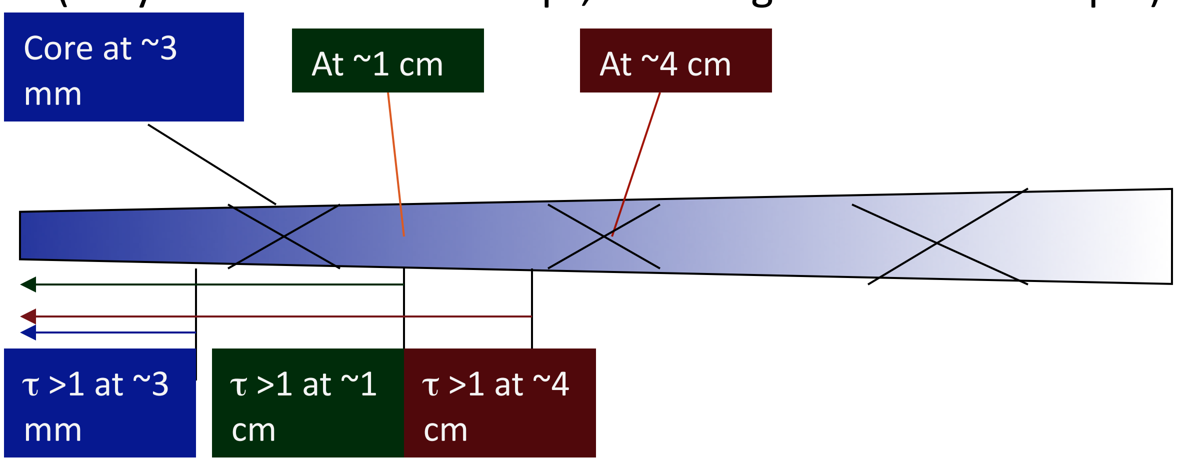
➔ Radio core must lie at 0.6±0.3 pc (0.2 mas, projected) from black hole

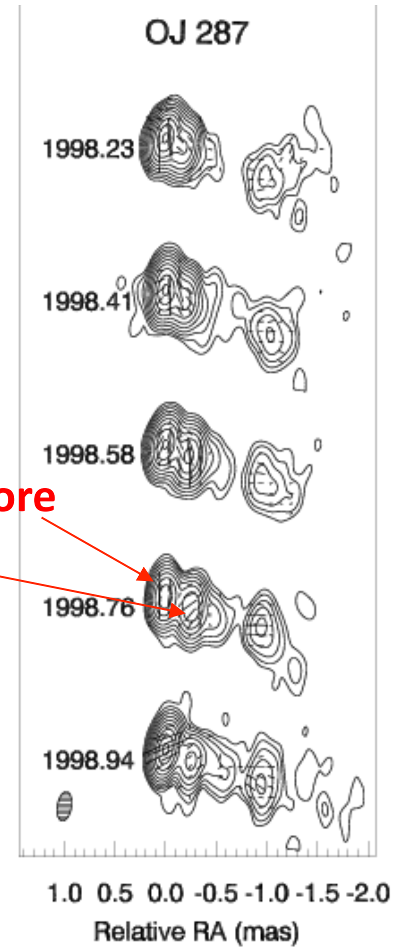
The “Core” of Blazar Jets

Observations suggest that core on VLBI images is <u>either</u>:

1. $\tau \sim 1$ surface (opacity is from synchrotron self-absorption)
2. First standing (oblique or conical) shock outside $\tau \sim 1$ surface

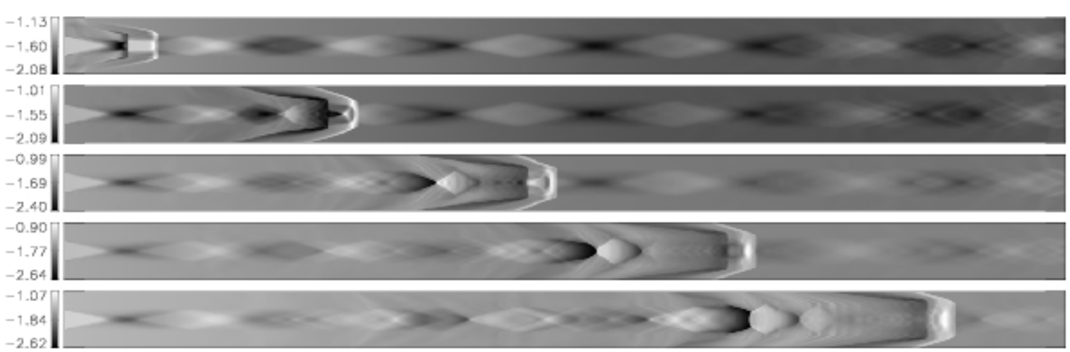
(Daly & Marscher 1988 ApJ, D’Arcangelo et al. 2007 ApJL)





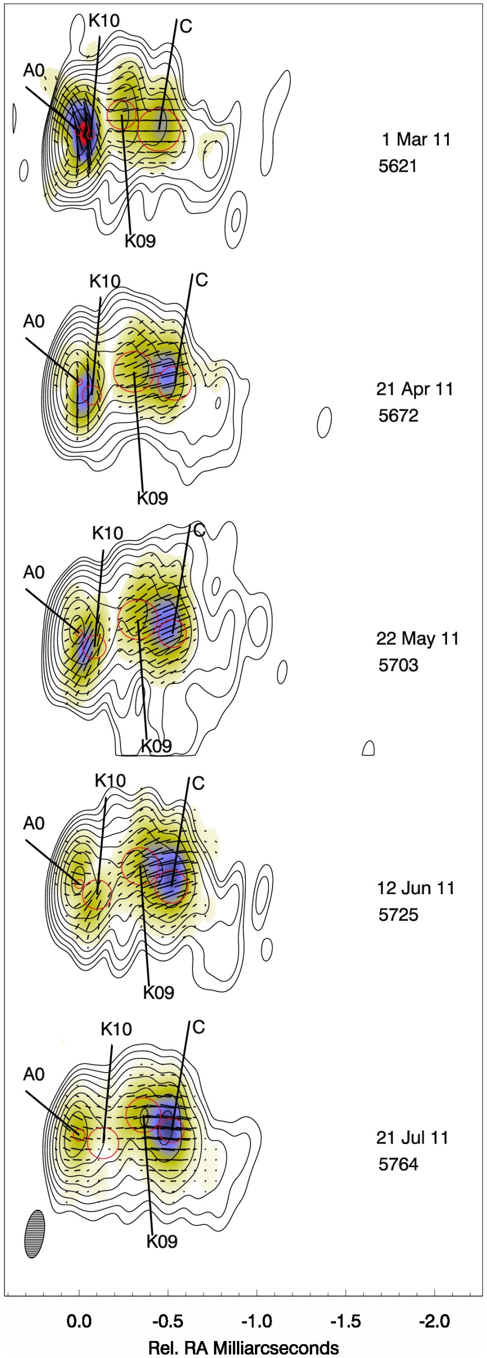
Core

Stationary feature with variable polarization



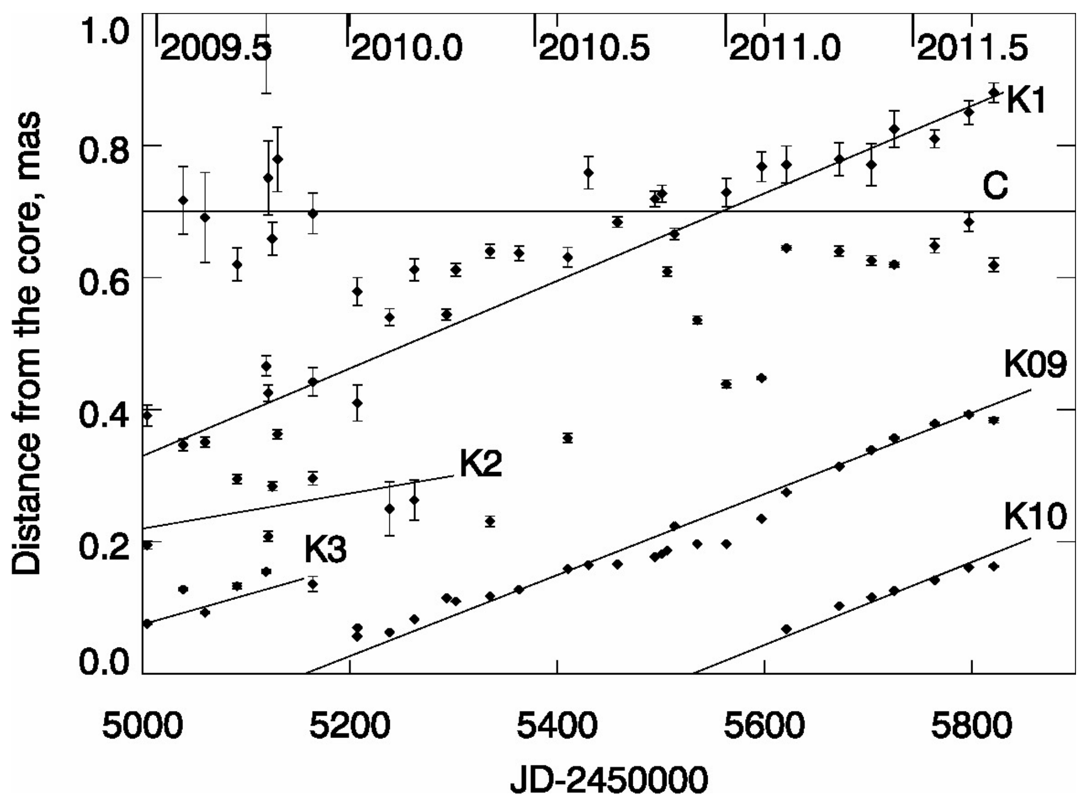
HD simulation (Gómez et al. 1997)

VLBI for Fun & Profit: 3C 454.3

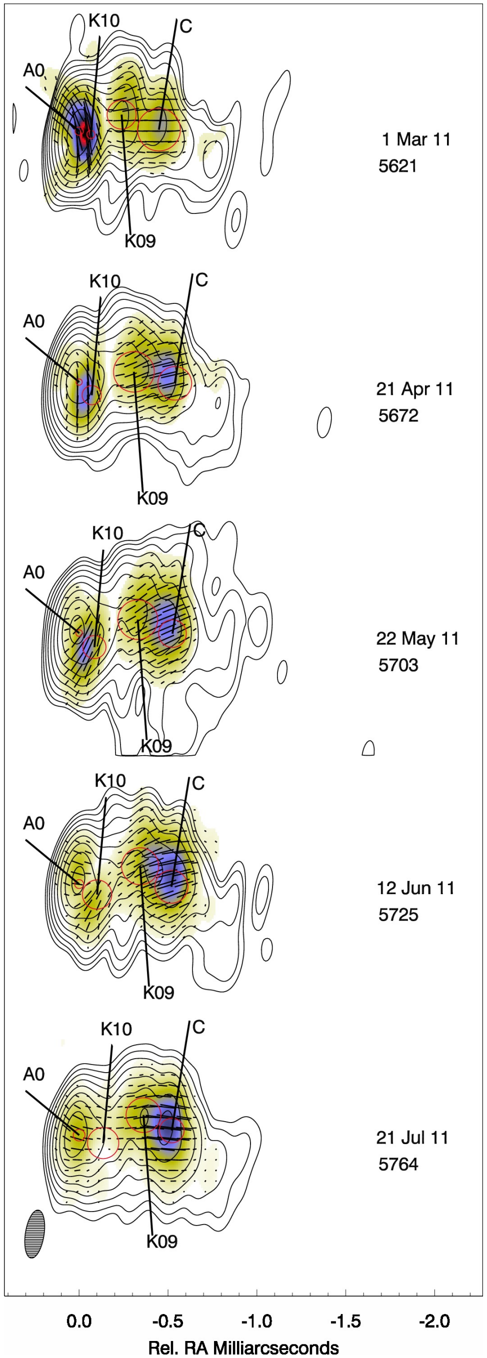


Model fit in Difmap to measure flux, angular size, & position (relative to "core") of knots of interest

- **We use circular Gaussian brightness distributions of components of image (can use elliptical Gaussians, but this often provides too few constraints) to get FWHM sizes**
- **Conversion of FWHM to diameter of sphere: multiply by 1.8**
- **Conversion of FWHM to diameter of disk: multiply by 1.6**



VLBI of 3C 454.3 (Part 2)



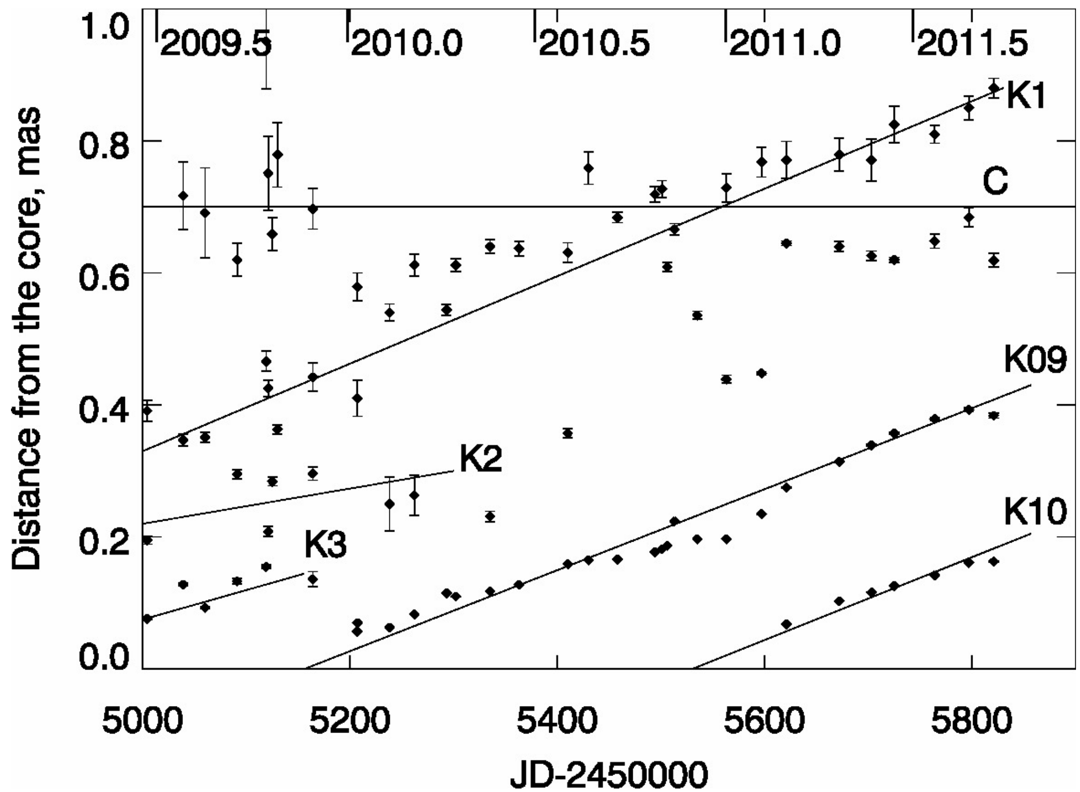
Results of model fit in Difmap: knot K10 passed through "core" very close to peak of late-2010 flare

z = 0.859 → 1 milliarcsec = 7.7 pc

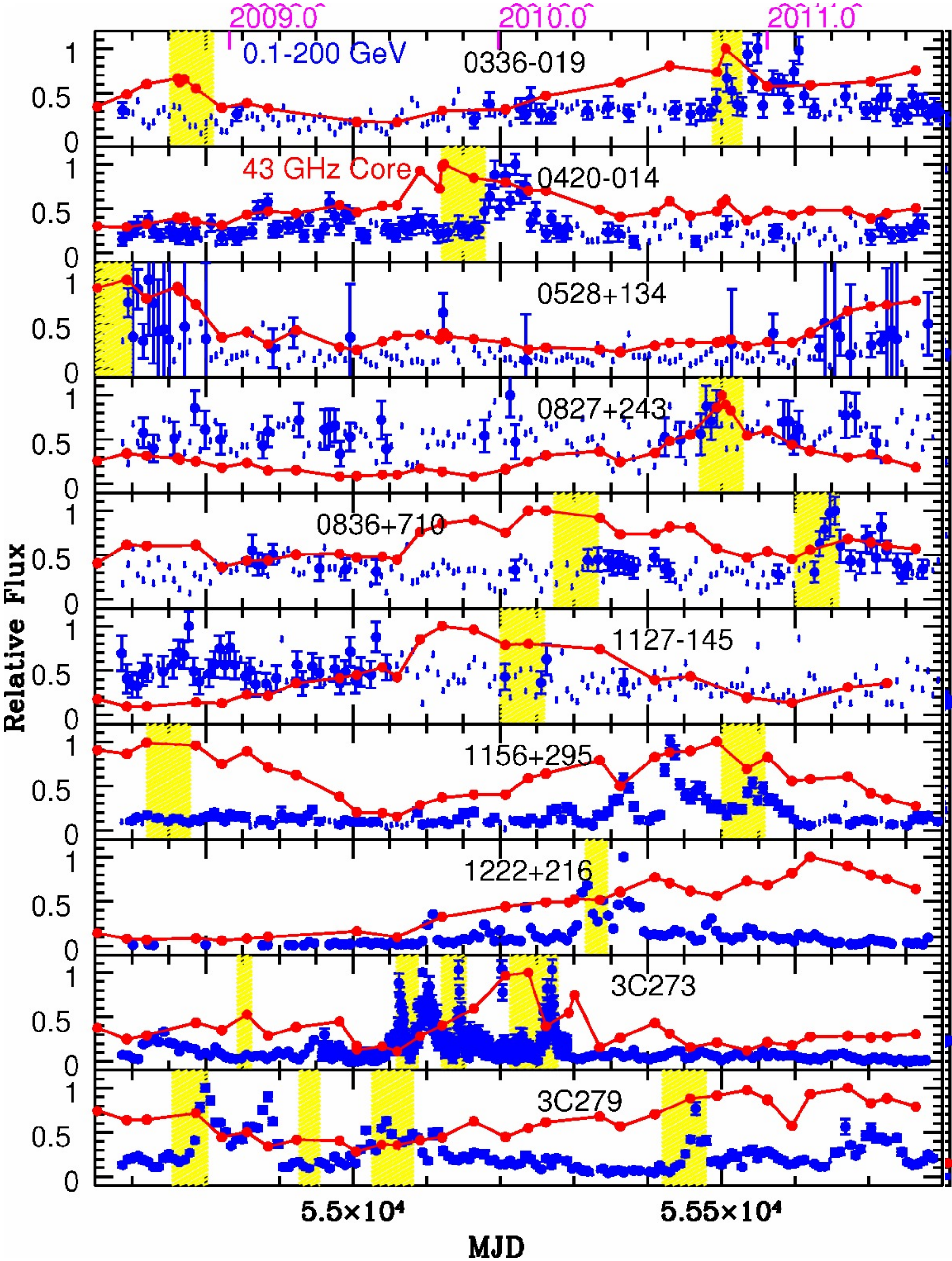
β_{app} = 9c, a(FWHM) = 0.11 milliarcsec → R = 0.80 pc

t_{var} = 0.12 yr → δ_{var} = (1+z) R/t_{var} = 40

→ γ = 21, θ = 0.6°



Behavior of Jet during γ-ray Flares in 34 Blazars



→ Of 64 γ-ray flares, 43 are simultaneous (within errors) with a new superluminal knot or a major outburst in the core at 7 mm

(Both jet + gamma-ray emission are quiescent over 3 years in 5 sources)

→ Even accounting for chance coincidences, > 50% of γ-ray flares occur in the "core" seen in 7 mm images, parsecs from the black hole

→However, some flares seem to be unassociated with major mm-wave events

← γ-ray light curves (blue), "core" light curve at 7 mm (red), & times of new superluminal knots (yellow) for 30 of the blazars in the sample

Linear Polarization

For optically thin synchrotron radiation with a uniform B field, degree of polarization has its maximum value at

$p_{max} = 3(1+\alpha)/(5+3\alpha)$ where α is the spectral index, $F_\nu \sim \nu^{-\alpha}$

For typical values of α (0.5-2), this is in range of 70-80%

E-vector position angle χ transverse to projected direction of B

Optically thick case: $p \sim p_{max}/7$, χ parallel to projected direction of B

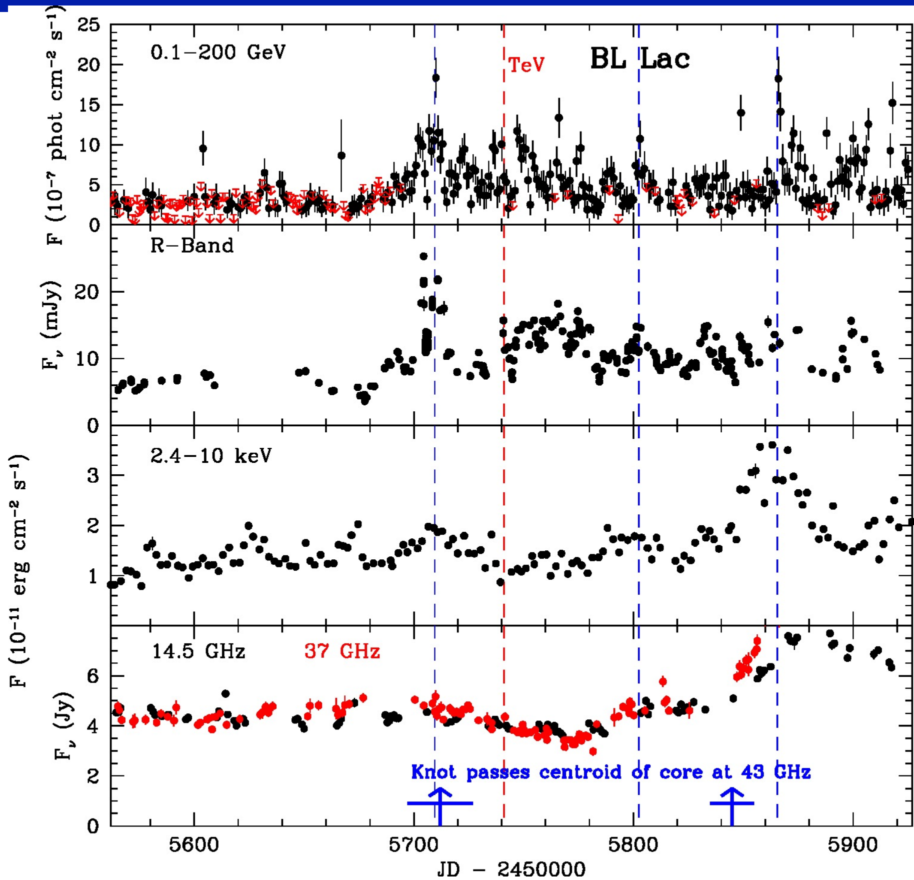
<u>But</u> p is not observed to be so high → can model as 2 cross-polarized components or by N cells with random field directions:

$\langle p \rangle = p_{max} N^{-1/2}$ with standard deviation $\sigma(p) = \langle p \rangle / 2^{1/2}$

$\langle \chi \rangle$ transverse to mean projected B direction

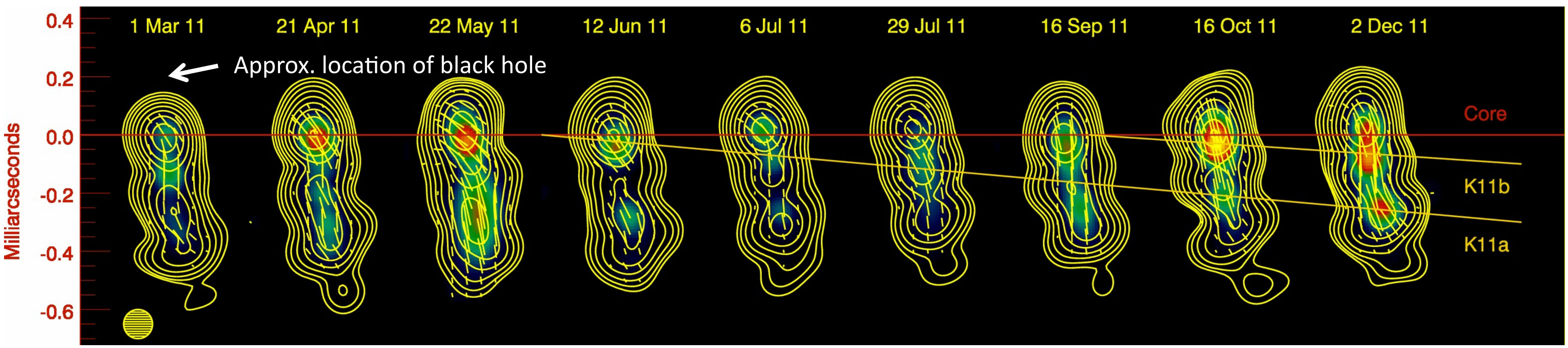
<u>Warning</u>: when measuring polarization, need to correct for statistical bias, especially when p is low; see Wardle & Kronberg (1974, ApJ, 194, 249)

Polarization in VLBI Images: BL Lac in 2011

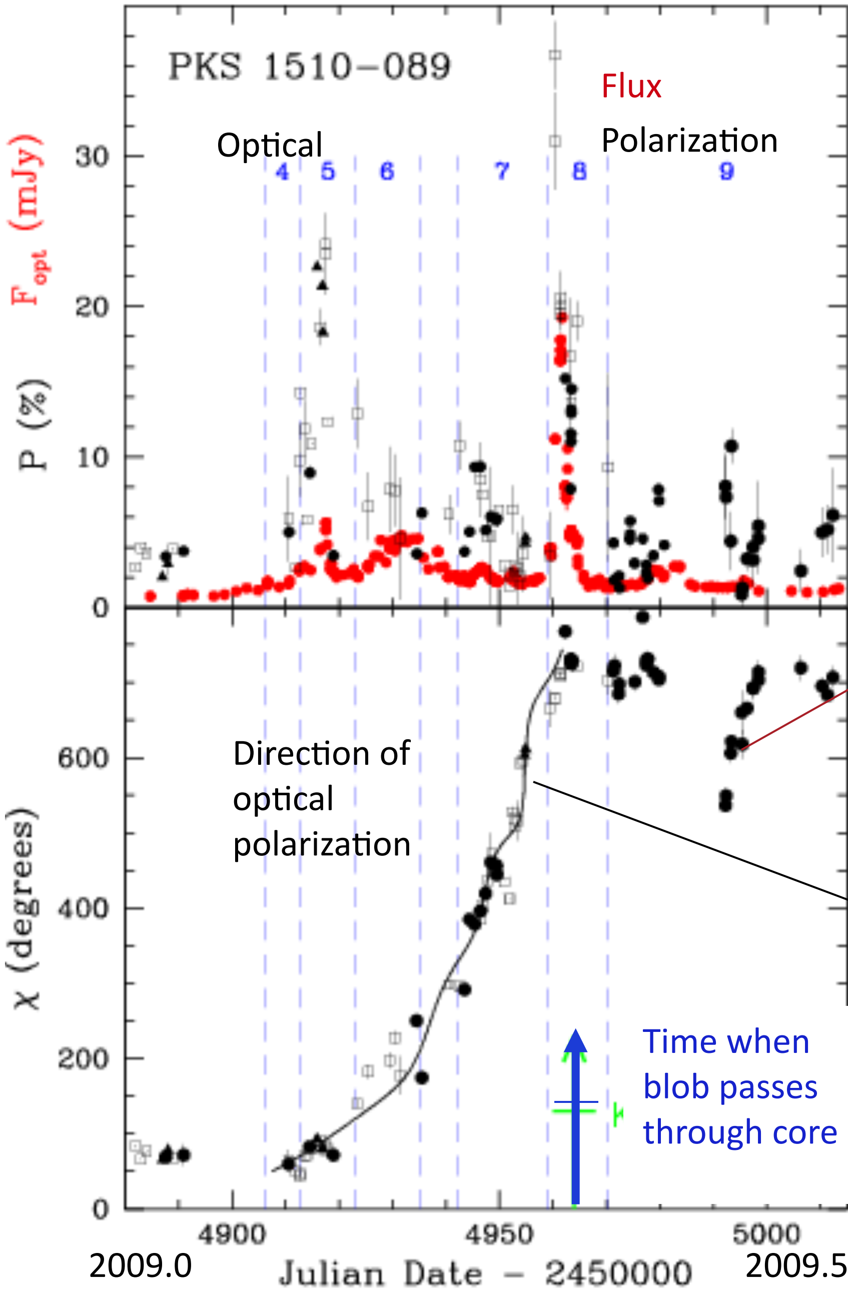


New blobs are best seen in polarized intensity, especially if χ differs from previous value in core

In BL Lac, γ-rays become bright as new superluminal blobs pass through "core" & through other stationary emission features on the VLBA images



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, as expected if caused by geometry of mag. field; event occurs as a weaker blob approaches core

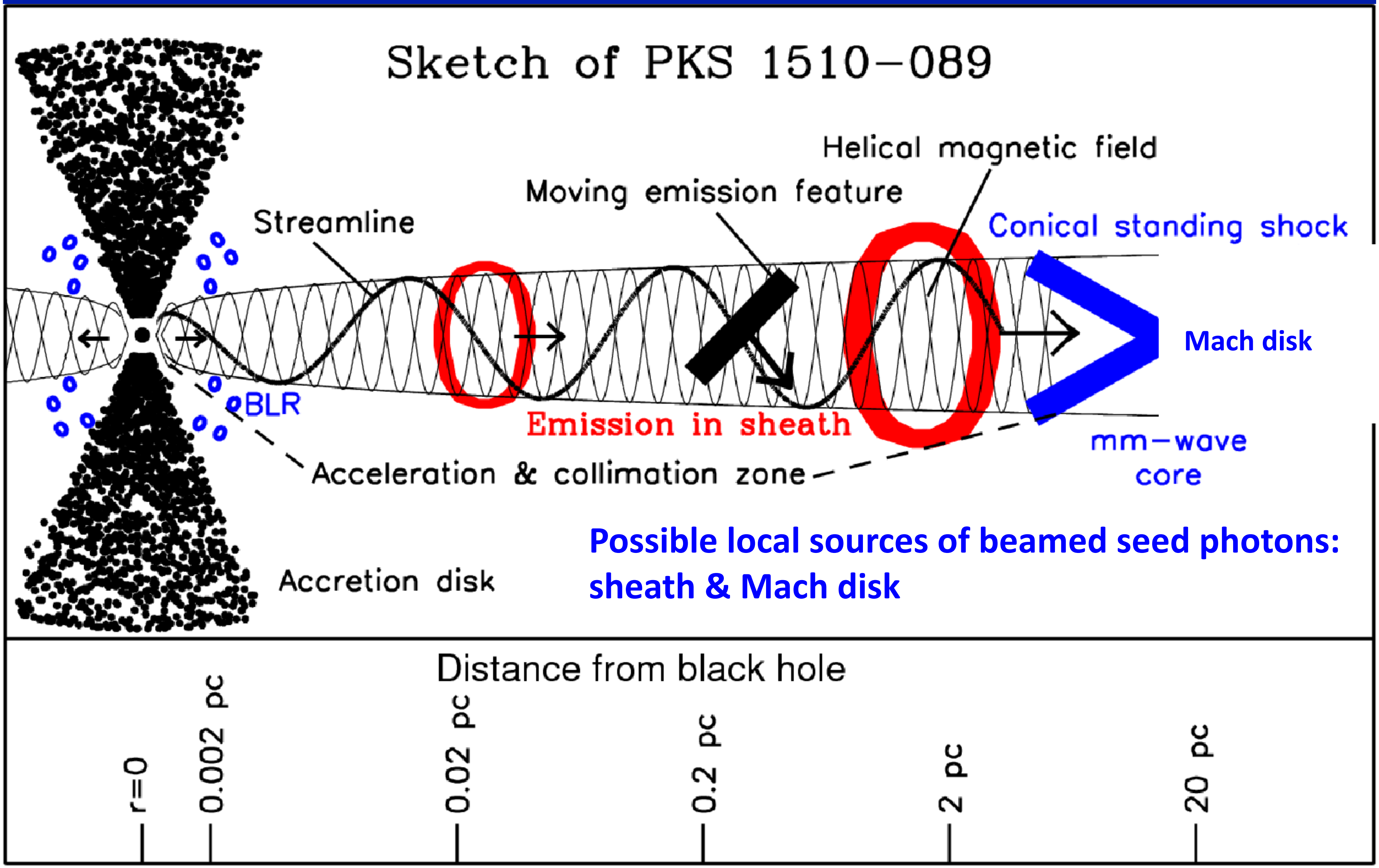
Model curve: blob following a spiral path through coiled magnetic field in an accelerating flow

Γ increases from 8 to 24, δ from 15 to 38

Blob moves 0.3 pc/day as it nears core

Core lies > 17 pc from central engine

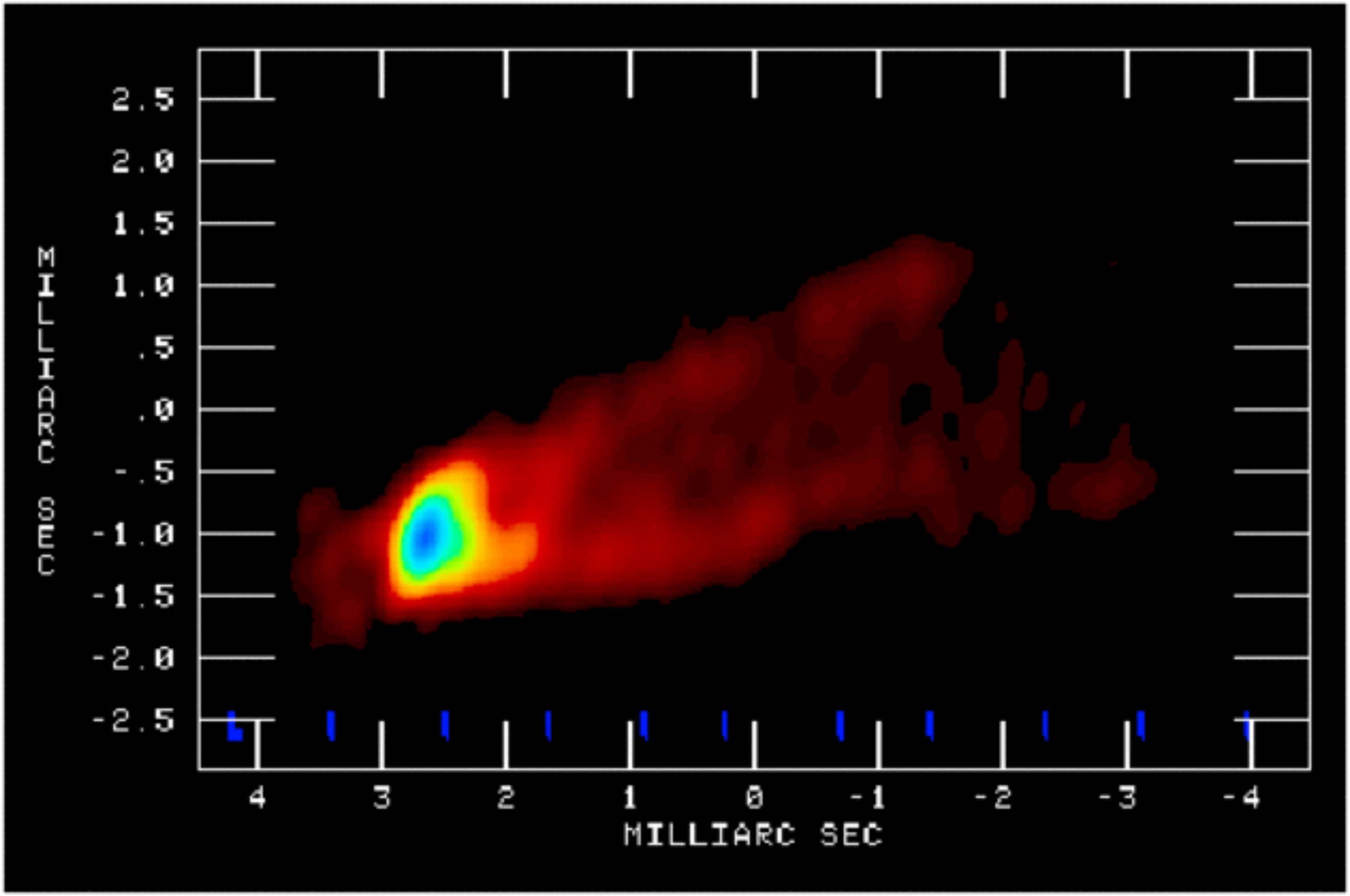
Sites of γ-ray Flares in PKS 1510-089 (Marscher et al. 2010 ApJL)



Evidence for Collimation of Jets Well Outside Central Engine

- VLBA observations of M87: jet appears broad near core

→ Sheath? Or flow collimates on scales ~1000 R_s



Walker et al.

NRAO website

Behavior of Jet during γ-ray Flares in 34 Blazars

Ejection of <u>bright</u> superluminal knot:

***** Knot passes core near peak of flare within error bars: 27 events in 14 sources**

- Flare prior to knot passing through core: 5 in 4 sources [3 included in *]**

- Flare after knot passes through core: 7 in 6 sources [all different from *]**

-[4 of these (3 sources) are associated with polarization increase in knot]

Contemporaneous outburst in core region with no bright knot (yet) confirmed: 12 in 11 sources (6 included in *)**

Gamma-ray flare with no jet event observed: 5 in 4 sources (2 included in *)**

Superluminal ejection or major core flare without observed gamma-ray flare: 8 in 7 sources (2 included in *)**

Quiescent jet + quiescent in gamma-rays: 5 sources

→ Of 64 γ-ray flares, 43 are simultaneous within errors with a new superluminal knot or a major outburst in the core at 7 mm

→ Even accounting for chance coincidences, > 50% of γ-ray flares occur in the "core" seen in 7 mm images