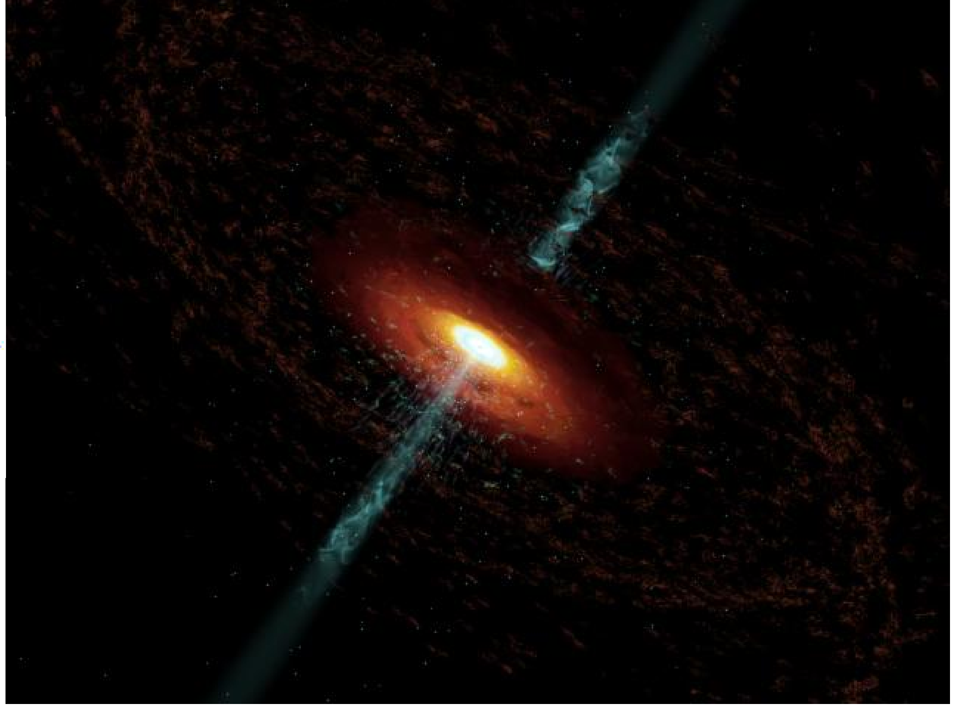


The Relationship between Radio and Higher Frequency Emission in AGNs

Alan Marscher
Boston University

Research Web Page: www.bu.edu/blazars

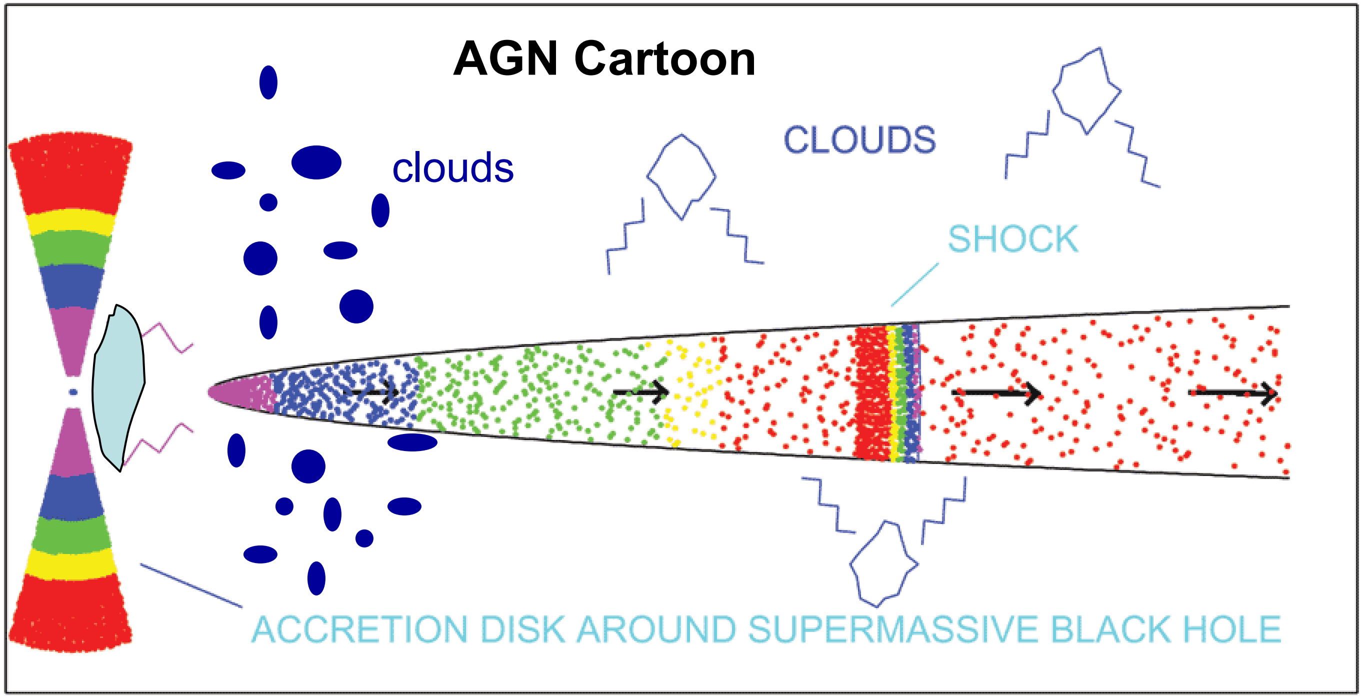
Sketch of an AGN

- 10^6 to > 10^9 M_{sun} black hole + accretion disk

- Dominant components of observed emission depend on direction of line of sight:

→ Viewed within about 40° of disk equator: non-blazar (jet is not as prominent, so accretion disk + clouds dominate)

→ Viewed within about 10° of jet axis: <u>blazar</u>



Emission Regions in an AGN

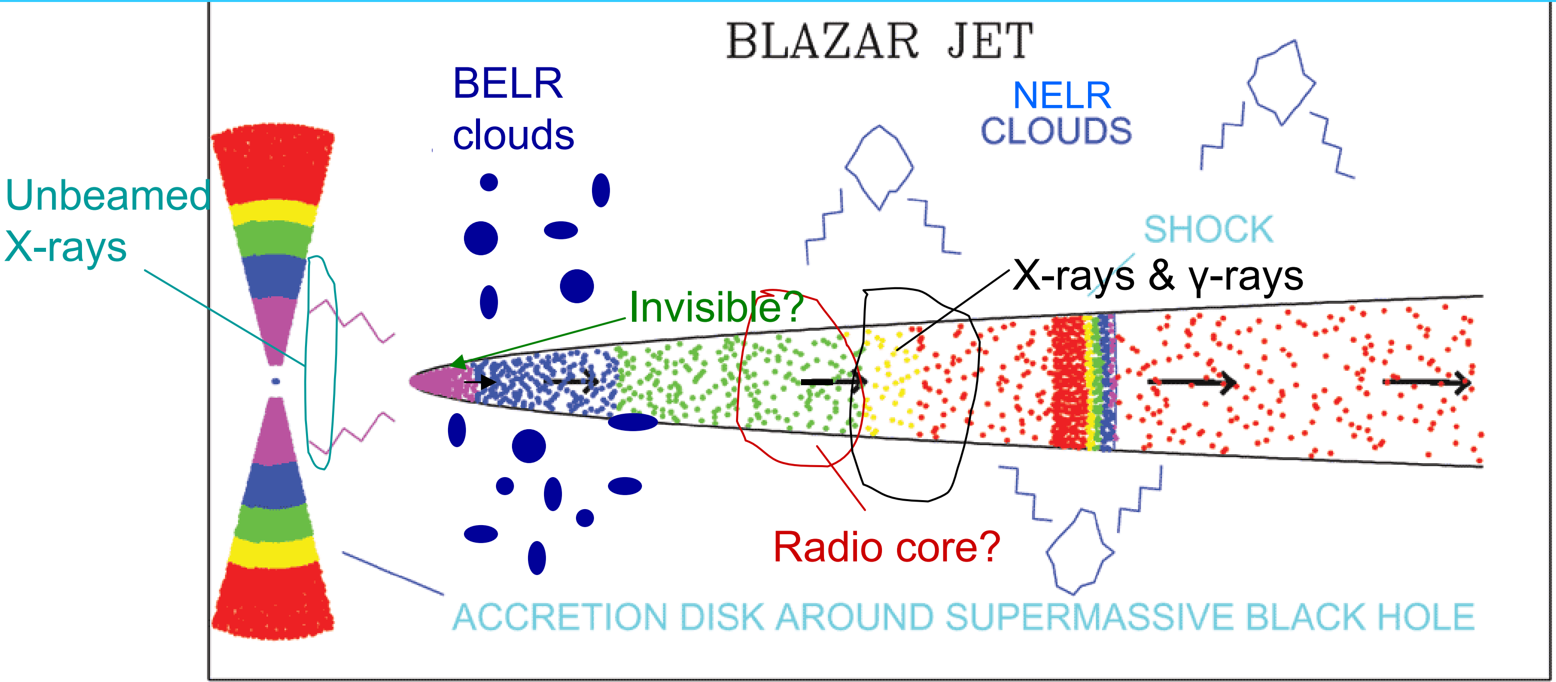
→ Unbeamed optical/uv/X-ray emission from accretion disk + corona

→ Broad & “narrow” optical emission lines from clouds

→ Optical absorption lines from outflows (funnel-shaped?)

→ Radio core & jet emission lie outside broad emission-line region

→ Beamed X-rays & gamma-rays come from jet



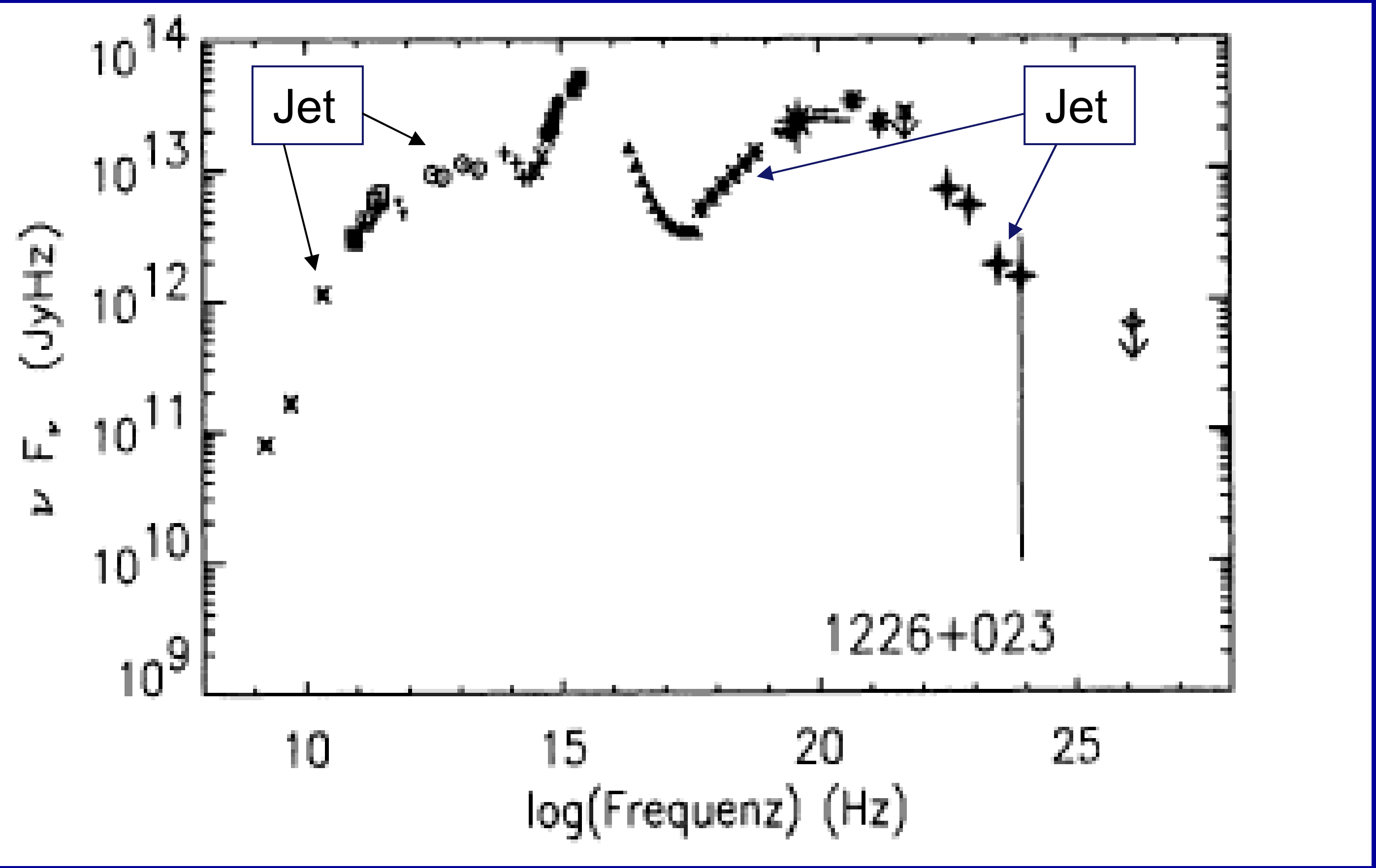
Basic Questions on the Nature of AGNs
that can be addressed by multi-waveband observations

- How are jets made by accreting black holes?
- How does jet L_{kin} compare with L_{total} of AGN?
- Where & how are jets accelerated to high Γs?
- Out to what distance does a relativistic jet retain high Γ?
- How/where are jets focused into narrow cones?
- Where & how are relativistic electrons accelerated?
- What causes the radio loud/quiet dichotomy (if there is one)?
- What is the physics of the jet flow (shocks, turbulence, interaction with gas, matter content, instabilities, magnetic field pattern, bending, precession)?
- Are high-frequency events related to the “ejection” of superluminal radio knots?

Multi-waveband Tools for Addressing Questions

1. Spectral energy distribution

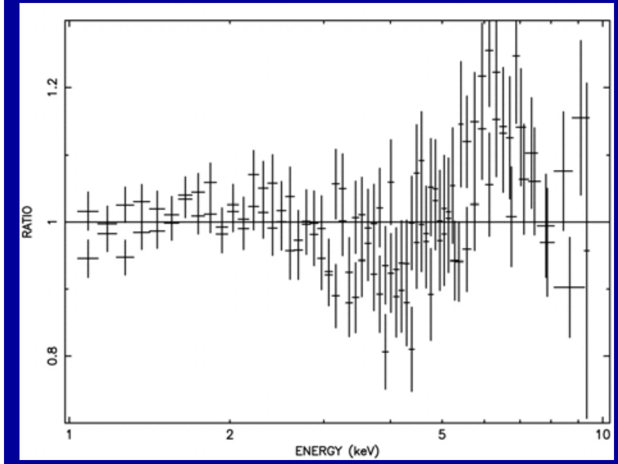
- Identification of separate components of emission



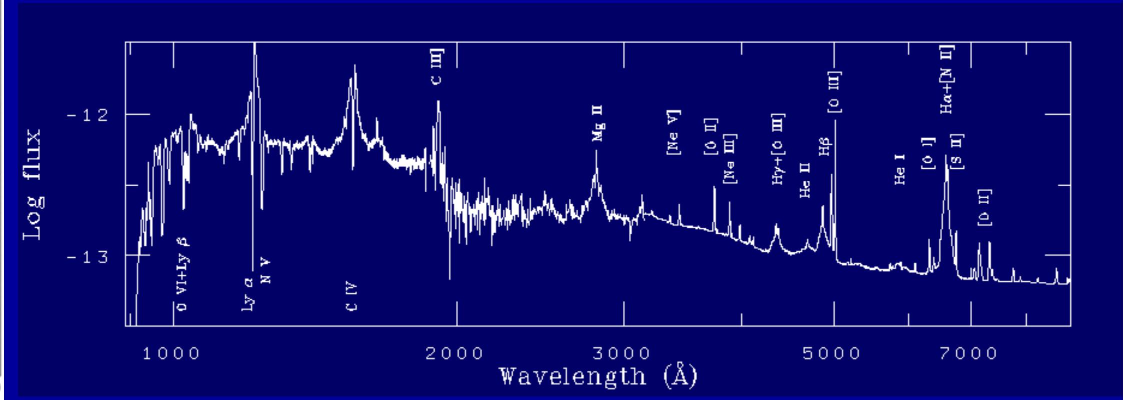
Multi-waveband Tools for Addressing Questions

2. Spectroscopy

- X-ray emission line indicates X-ray continuum from accretion disk region
- Broad optical emission lines require strong uv continuum from disk + neighborhood



3C 120 X-ray Fe Kα emission line (Grandi et al. 1997)

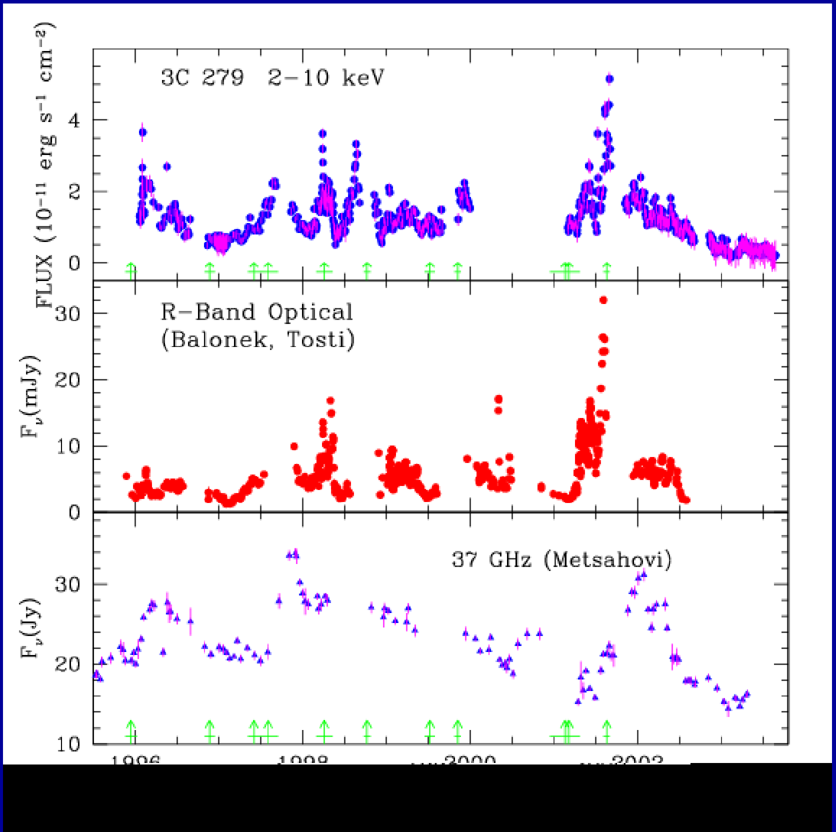


NGC4151 optical emission lines (W. Keel)

Multi-waveband Tools for Addressing Questions

3. Variability (good for all wavebands)

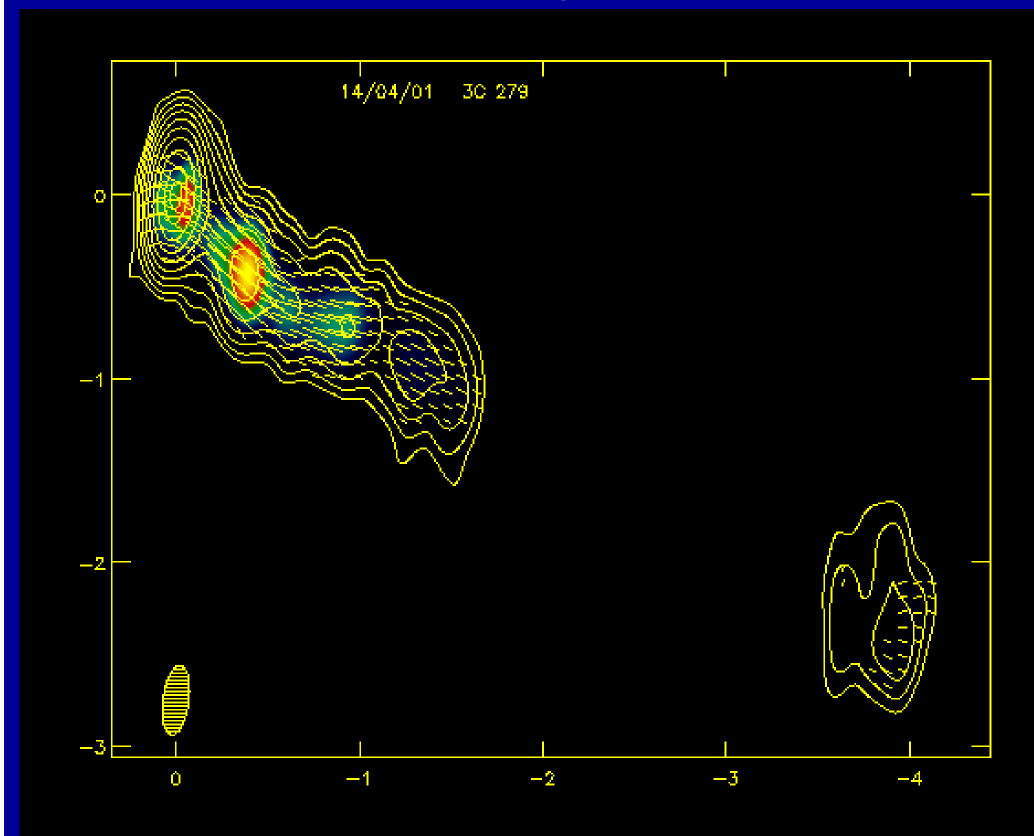
- Related to size of emission region
- Cross-frequency time lags help to locate sites of emission

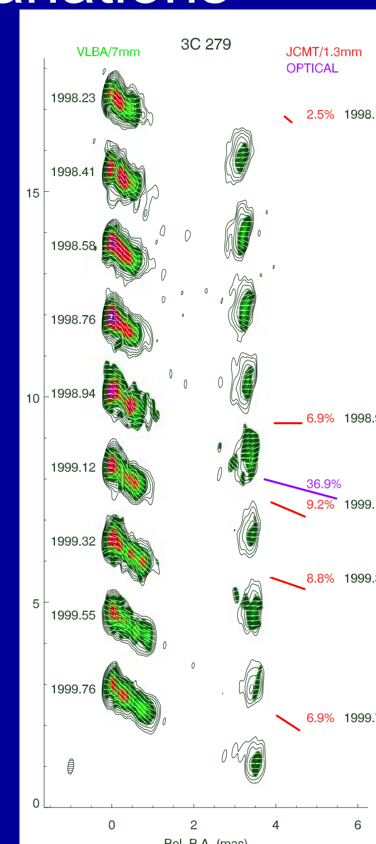


Multi-waveband Tools for Addressing Questions

4. Radio/mm-wave imaging: great resolution

- Picture of the jet (including polarization)
- Multi-epoch images allow us to watch variations





Limitations of Tools

- SEDs do not by themselves indicate location
- Spectral lines are reprocessed emission, not so straightforward to interpret
- Variability related to size but can occur at different locations
- High-frequency observations have spatial resolution much too coarse to image an AGN on parsec-scales and smaller
- Even mm-wave images are subject to opacity limiting how close to central engine we can explore

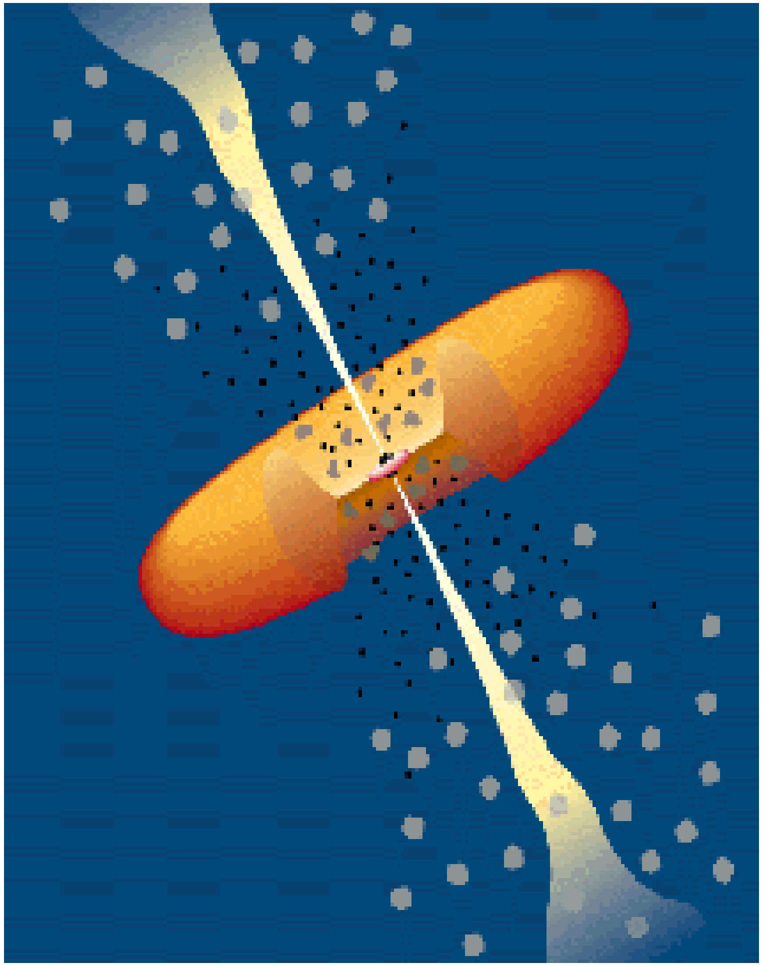
Overcoming Limitations: Combine tools

- Optical emission-line & continuum variability (reverberation mapping)
- Variability of SED (separate variable & non-variable components)
- Variability & VLBI (see what's changing directly or see the downstream effect of upstream variations)
- Multi-waveband polarization (identify high-frequency features on VLBI images by polarization signatures)

Unified Scheme of Active Galactic Nuclei

Lots of things going on: accretion, outflow, line emission & absorption, continuum emission across the E-M spectrum

To study region near the black hole, observe optical, uv, X-ray of AGNs with jets viewed from the side

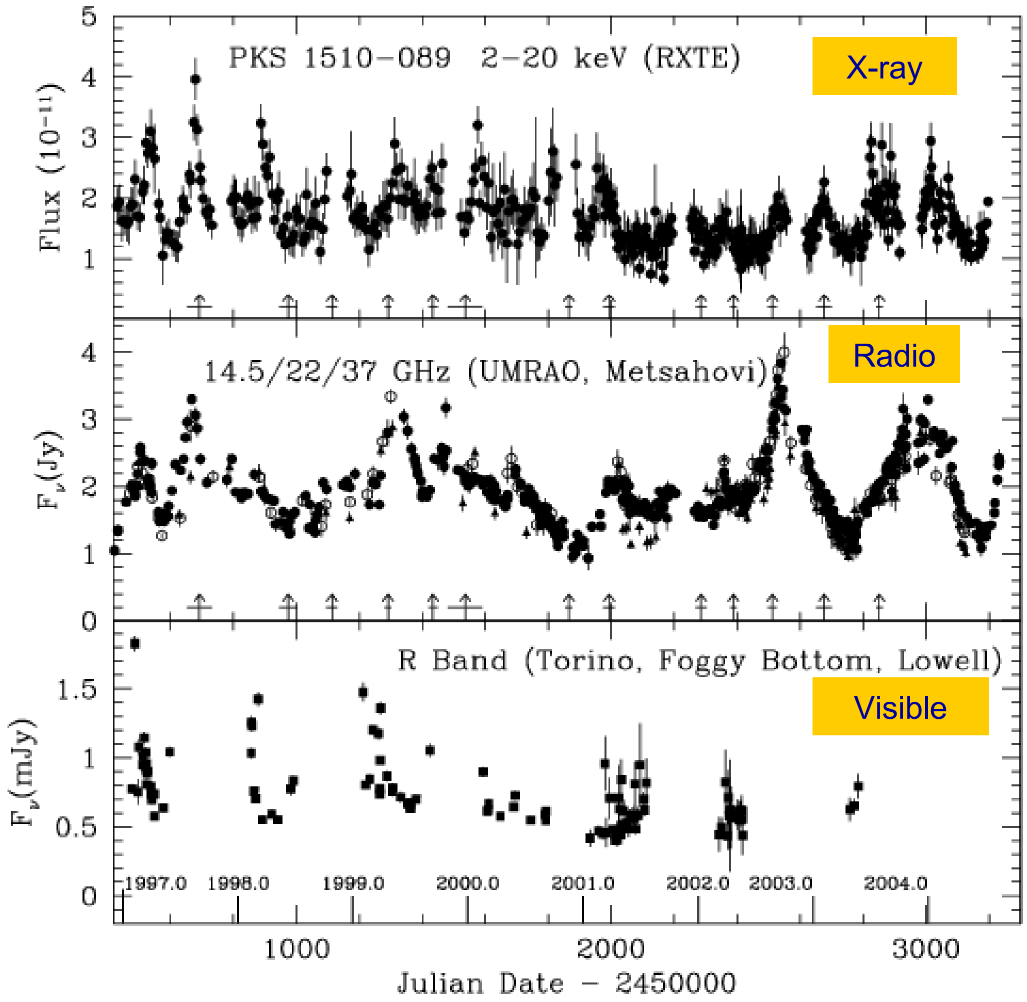


To study jets, observe AGNs with jets pointing at us (blazars)

Evidence that High & Low-ν Nonthermal Emission is Related:

Correlated Light Curves & Polarization Properties

The Quasar PKS 1510-089 (z=0.361) Radio/X-ray Correlation



(Optical too poorly sampled)

The Quasar PKS 1510-089 (cont.)

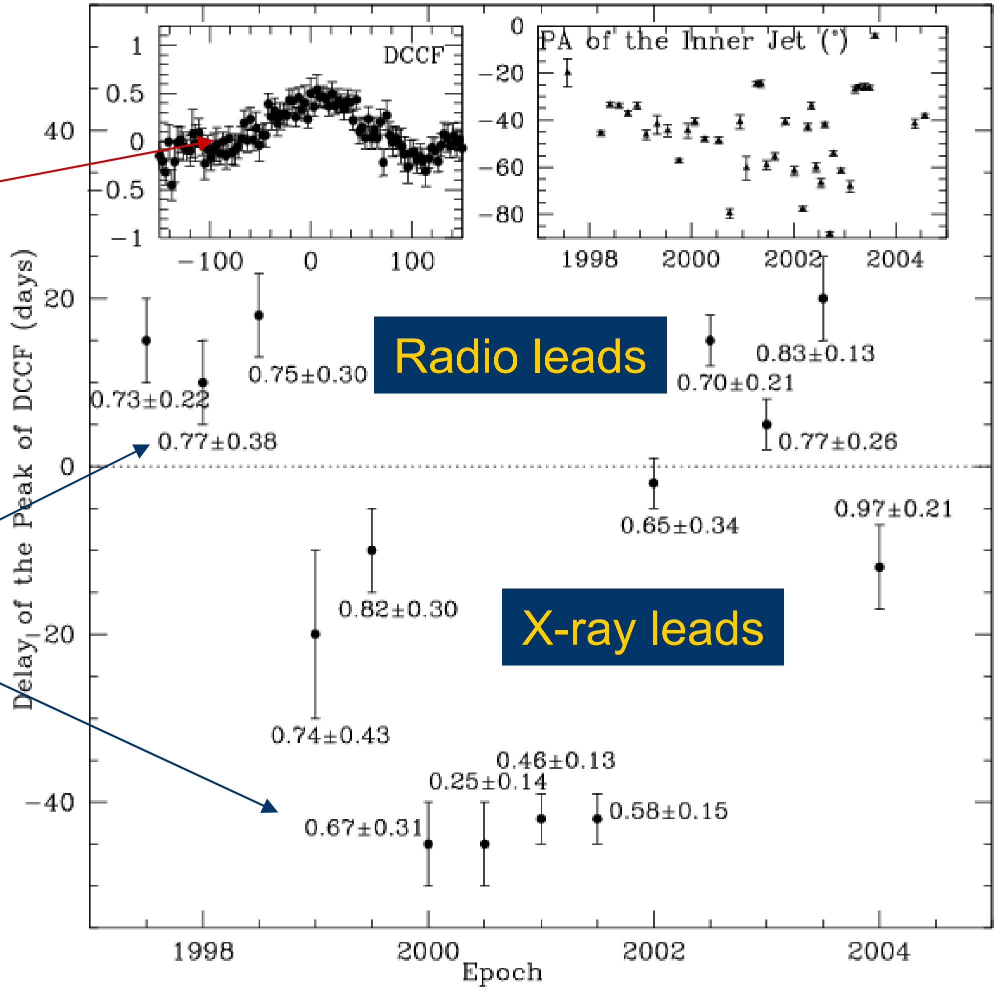
X-ray variations usually well-correlated with high-ν radio, with radio variations leading X-ray by an average of 6 days

X-ray/radio correlation is strongest when inner jet points near PA -20°

Discrete X-ray/radio Cross-Correlation Coefficient (x-axis is delay in days, > 0 means radio leads)

Numbers listed: peak of DCCF for 1 year of data centered on epoch of data point

When radio is optically thin, X-ray lags radio or is nearly simultaneous

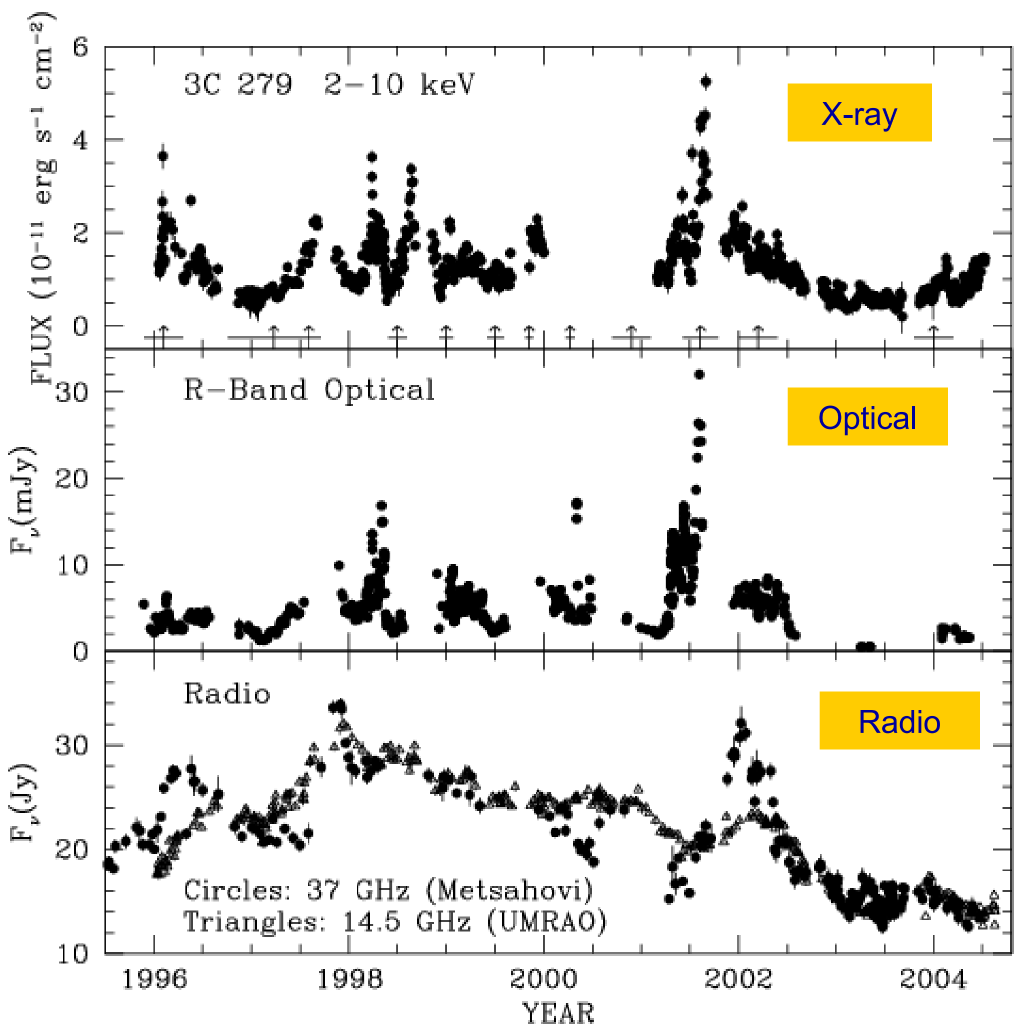


The Quasar 3C 279 (z=0.538)

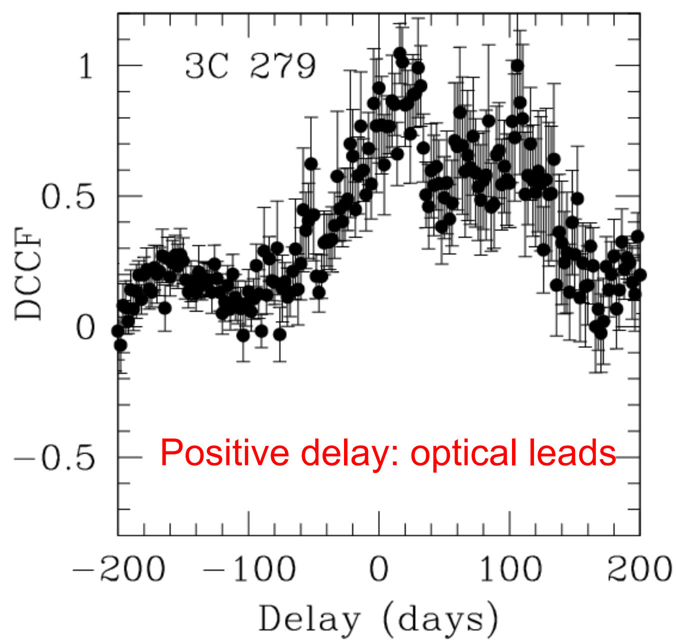
Extreme variations in flux at optical & X-ray (& γ-ray)

Variations in X-ray flux usually well-correlated with changes in optical brightness

→ time lag of 15±15 days, with optical leading



Discrete Cross-Correlation Coefficient (X-ray vs. optical)

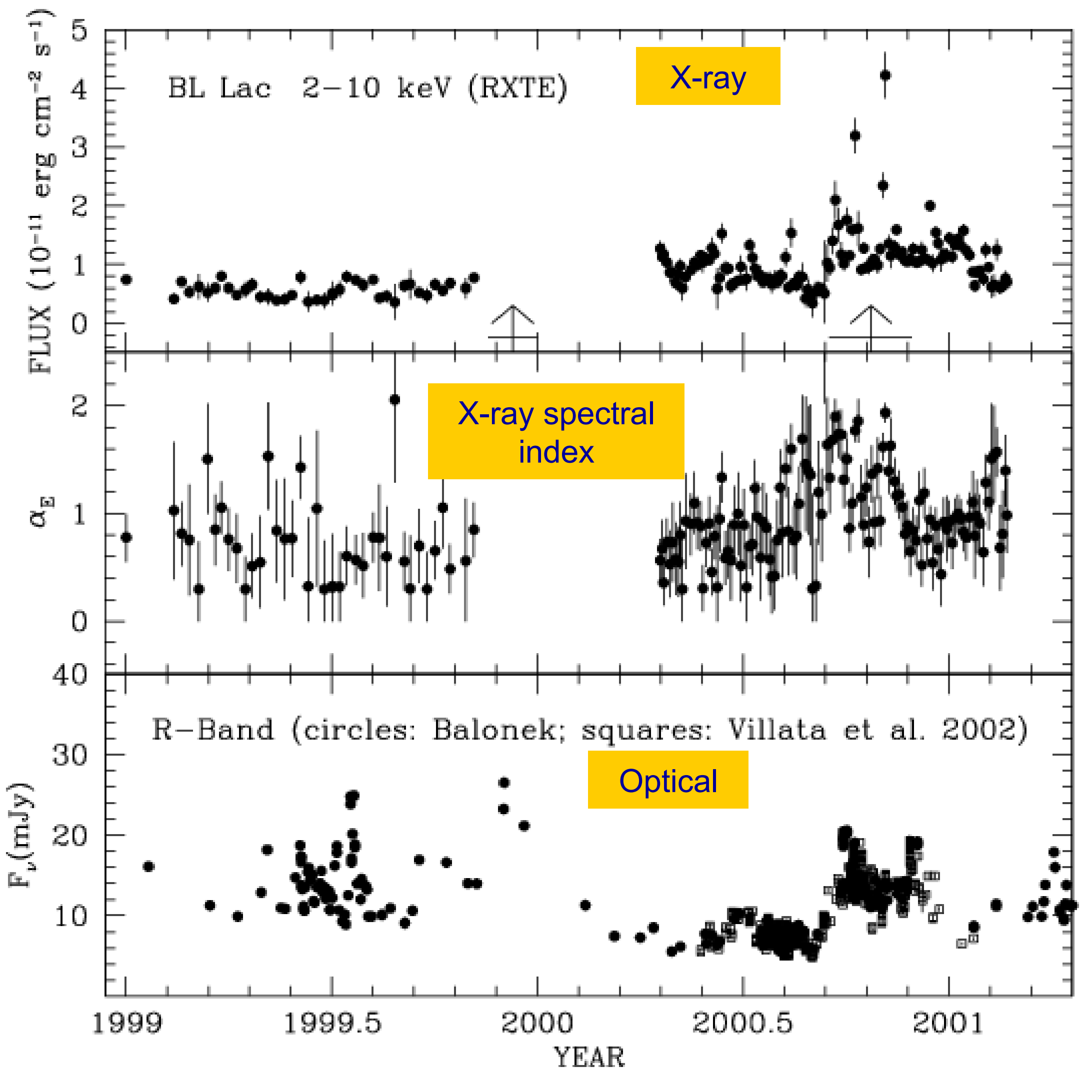


X-ray/radio correlation also quite strong, with radio lagging by 140±40 days

BL Lac (z=0.069)

Usually, X-ray continuum spectrum is too flat to be continuation of synchrotron spectrum

→ Probably synchrotron self-Compton



We find strong X-ray/optical correlation of long-term light curve with ~ zero lag

[Correlation not so good on short timescales (Böttcher et al. 2004)]

Note that period of strongest activity corresponds to steep X-ray spectral index → probably hihg-E tail of synchrotron emission

Superluminal ejection occurred during period of strongest activity

Why am I not talking about TeV Blazars?

Thus far, it appears that the radio jets of TeV blazars are rather slow & not highly variable on parsec scales (Marscher 1999, *Astroparticle Phys*.; Piner 2003 , *ApJ*)

Maybe they are e^--e^+ jets with flat E spectra such that the jet loses momentum when the electrons cool

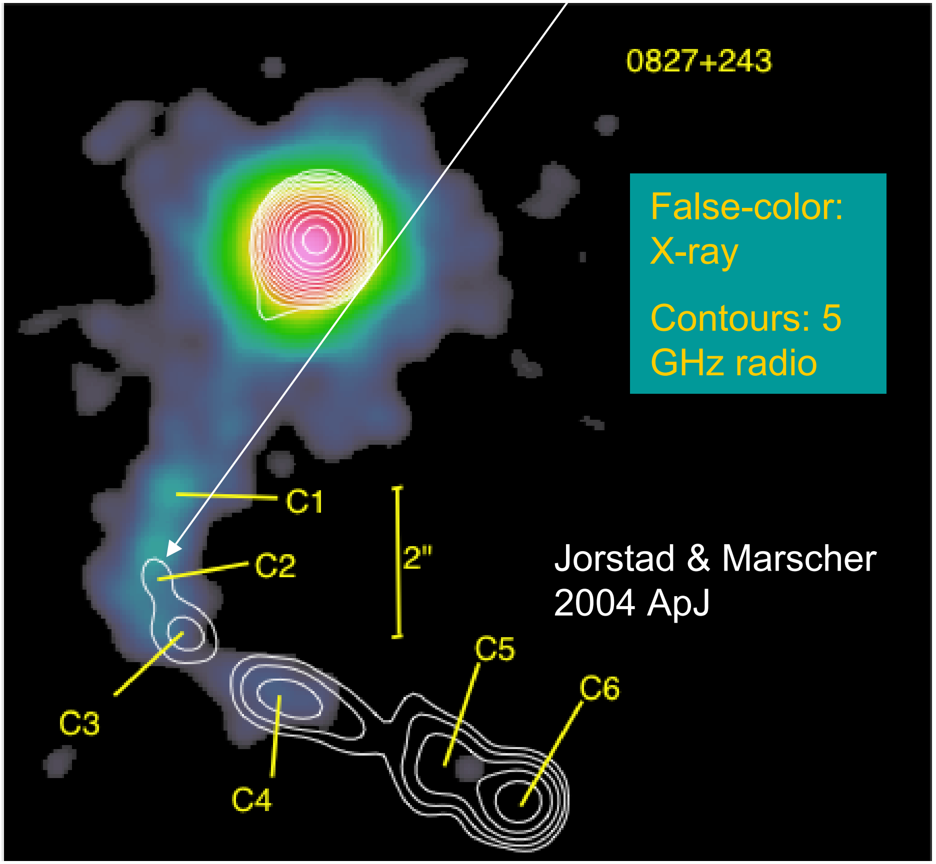
Wardle et al. (1998 *Nature*) infer from circular polarization that e^+ outnumber p^+ by ~5:1, but Ruszkowski & Begelman (2002, *ApJ*) disagree

Other attempts to decide e+/p+ ratio are not air-tight and lead to mixed results

Extended Jets of γ-ray Quasars: Ultrarelativistic out to 100's of kpc

0827+243: v_{app}=22c on pc scales

X-ray emission requires beaming factor δ ≈ 20 out to 100's of kpc

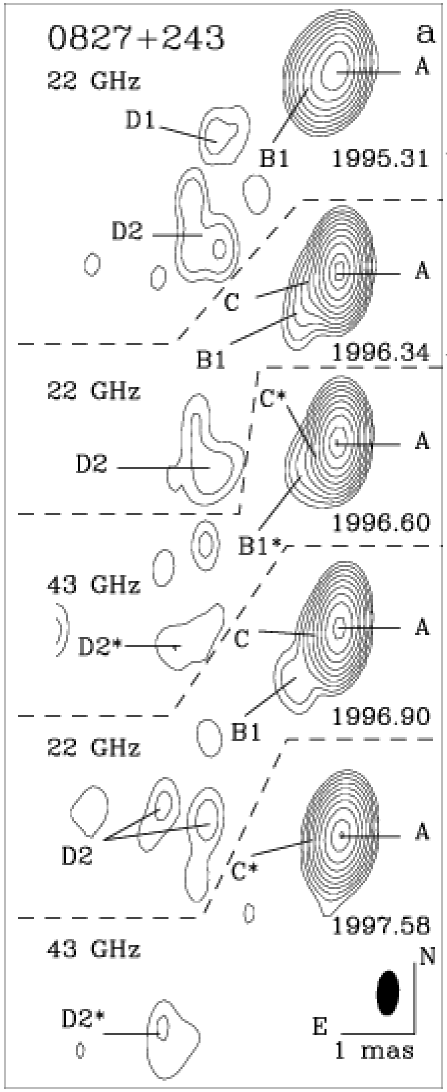


False-color: X-ray

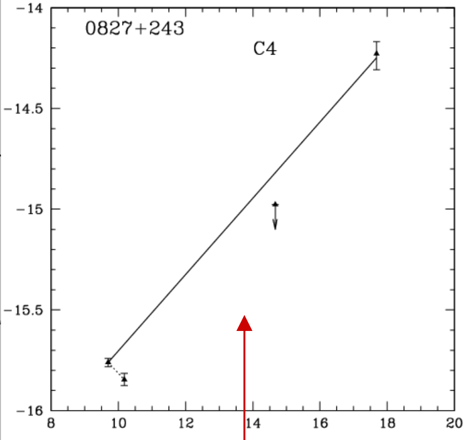
Contours: 5 GHz radio

Jorstad & Marscher 2004 ApJ

Scale: 1″ ≈ 120 kpc (7.8 kpc x 15 for de-projection)



(Jorstad et al. 2001 ApJS)



HST non-detection + radio spectrum imply that X-rays come from inverse Compton scattering of CMB

[For more on extended jets, see D. Worrall's talk]

Correlated Multiwaveband Polarization

⟶ suggests that mm-wave core region = site of optical emission

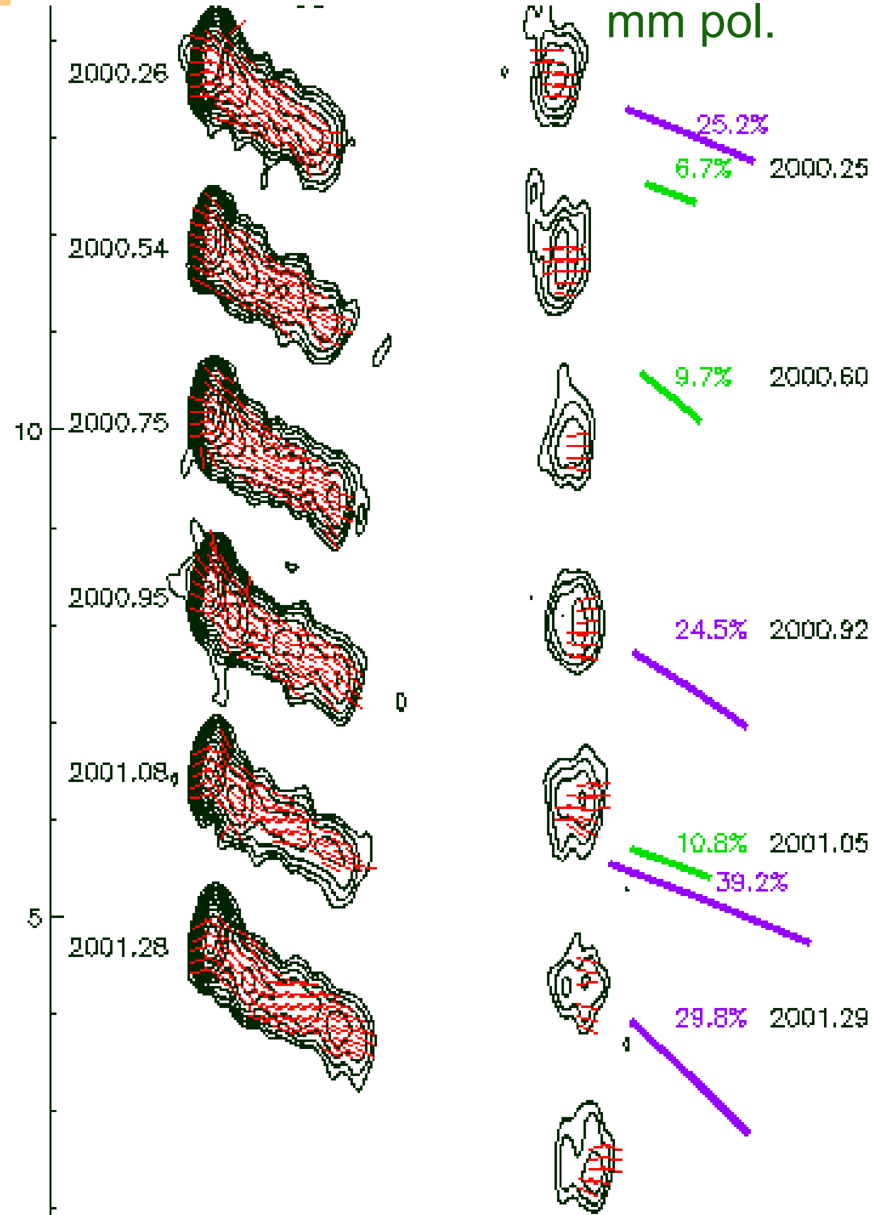
Purple: optical pol.

Green: ~ 1 mm pol.

Blazars: optical & mm-wave linear polarization often has similar E-vector direction (see also Gabuzda & Sitko 1994)

Degree of optical polarization is often higher

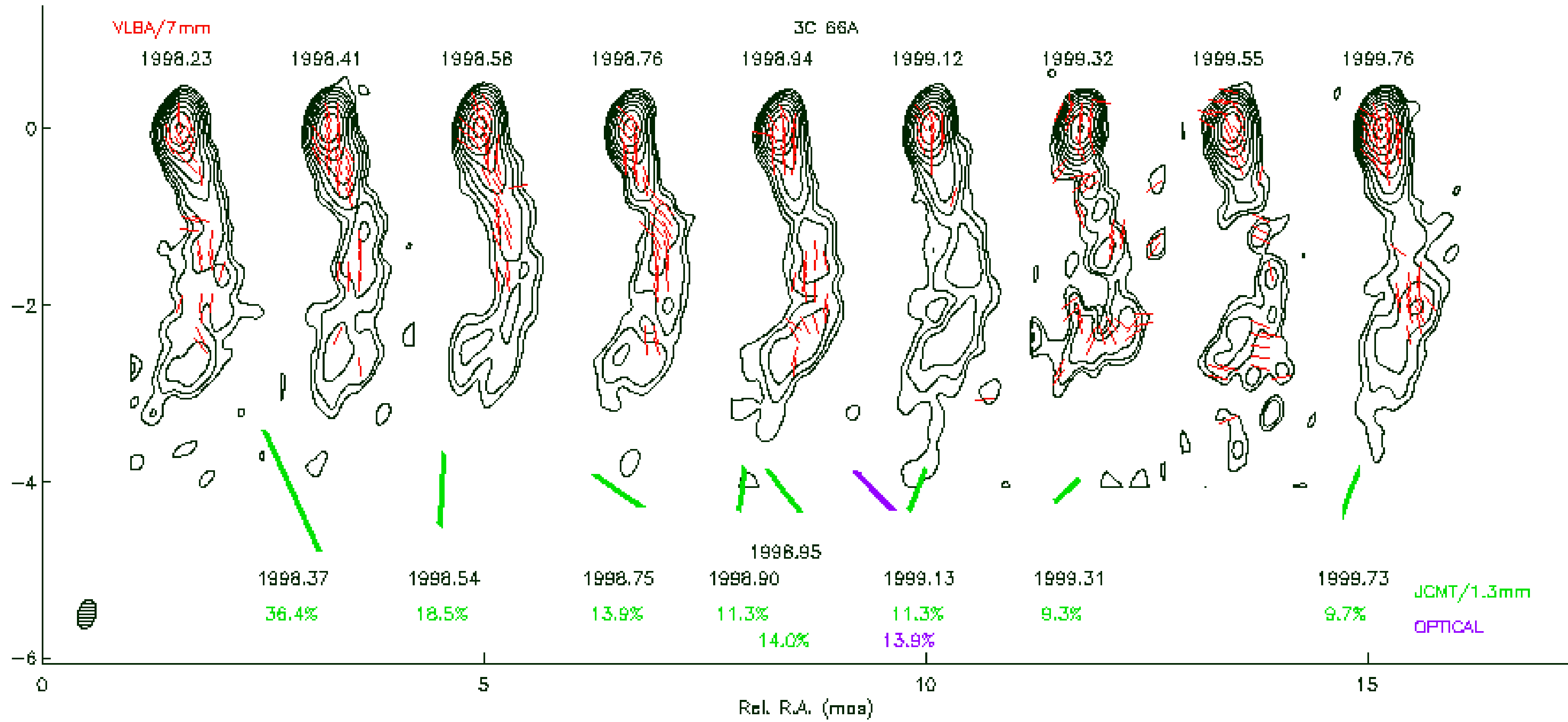
Lister & Smith (2000): quasars with low optical polarization also have low core polarization at 43 GHz



Correlated Multiwaveband Polarization Variability

7mm & 1.3 mm linear polarization often has similar E-vector direction

Degree of 1.3 mm polarization is often higher

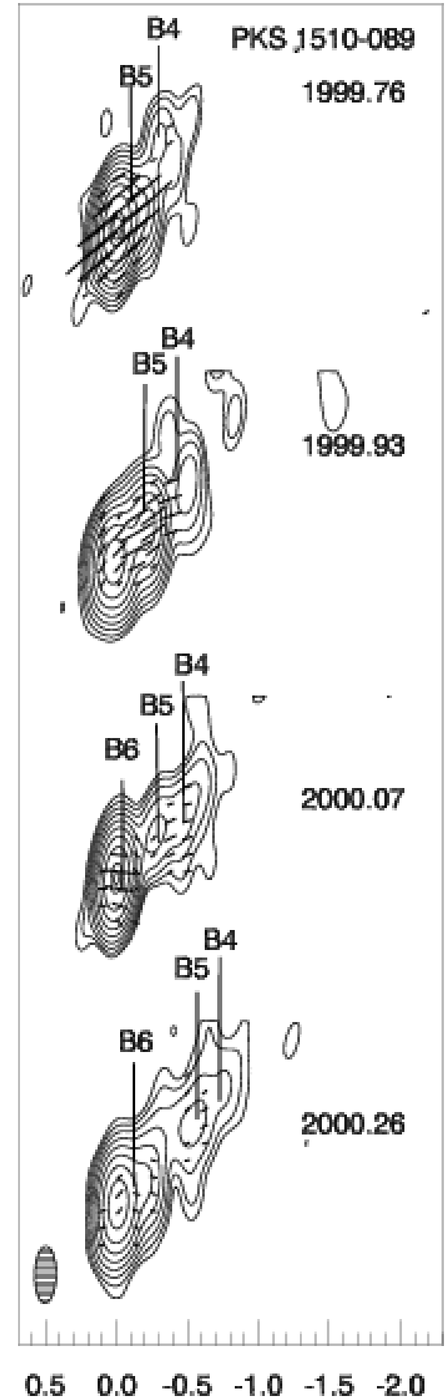


Identifying Knots by Polarization

Many superluminal knots have stable electric vector position angles (EVPAs) of linear polarization

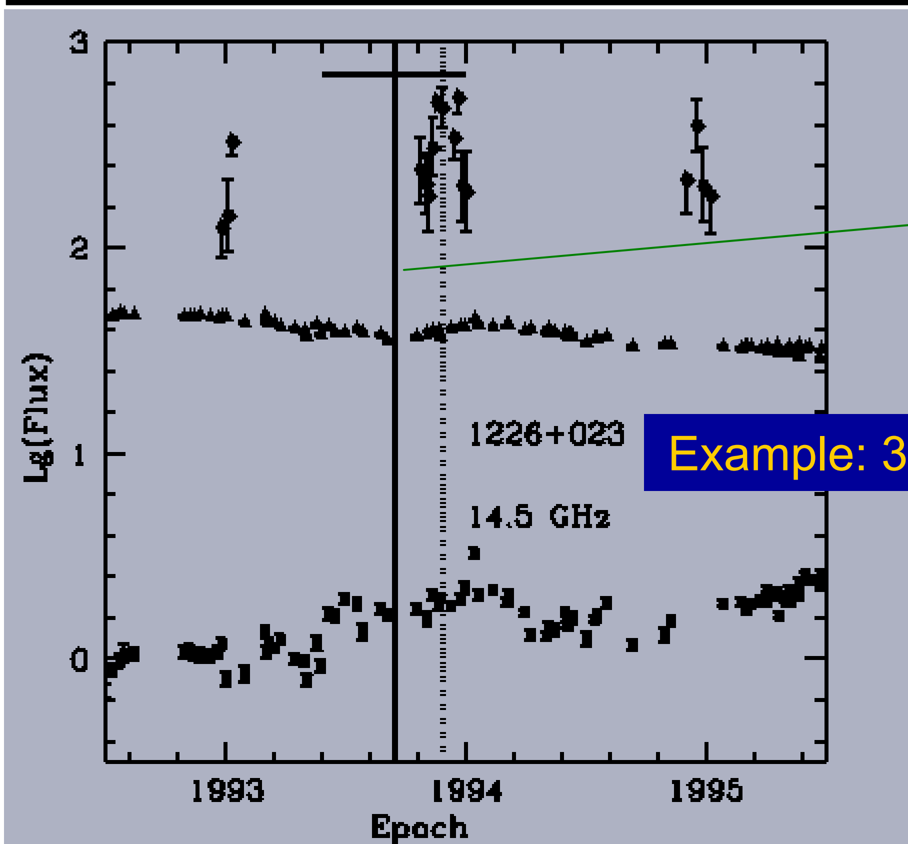
→ Might be able to identify knots responsible for optical/near-IR variations by similar EVPA as knots on VLBA images

Scale: 1 mas = 4.8 pc = 16 lt-yr (H_o=70)

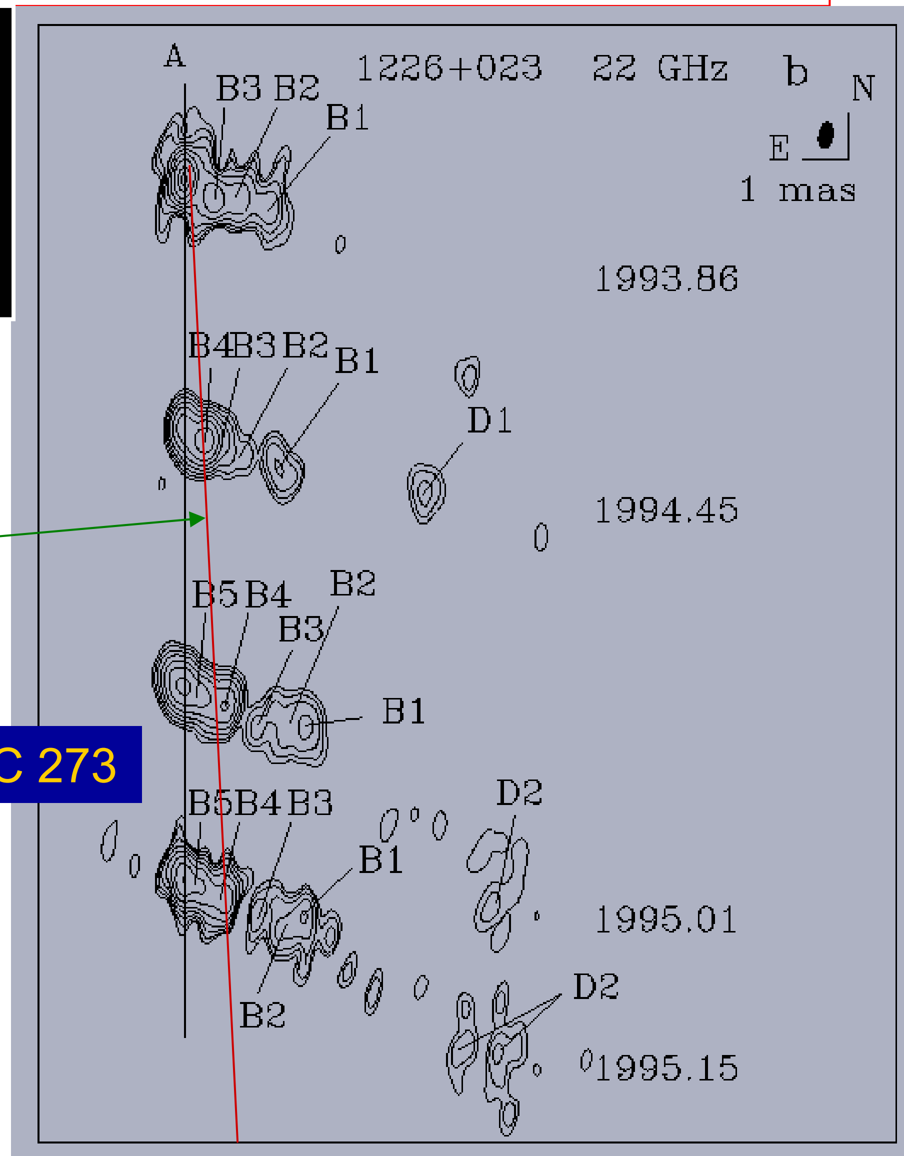


High γ-Ray Flux Tends to Occur <u>after</u> Ejections of Superluminal Radio Knots (Jorstad et al. 2001 ApJ)

23/28 γ-ray flares are contemporaneous with our VLBA data
11 superluminal jet components are associated with γ-ray flares (≤6 expected by chance)



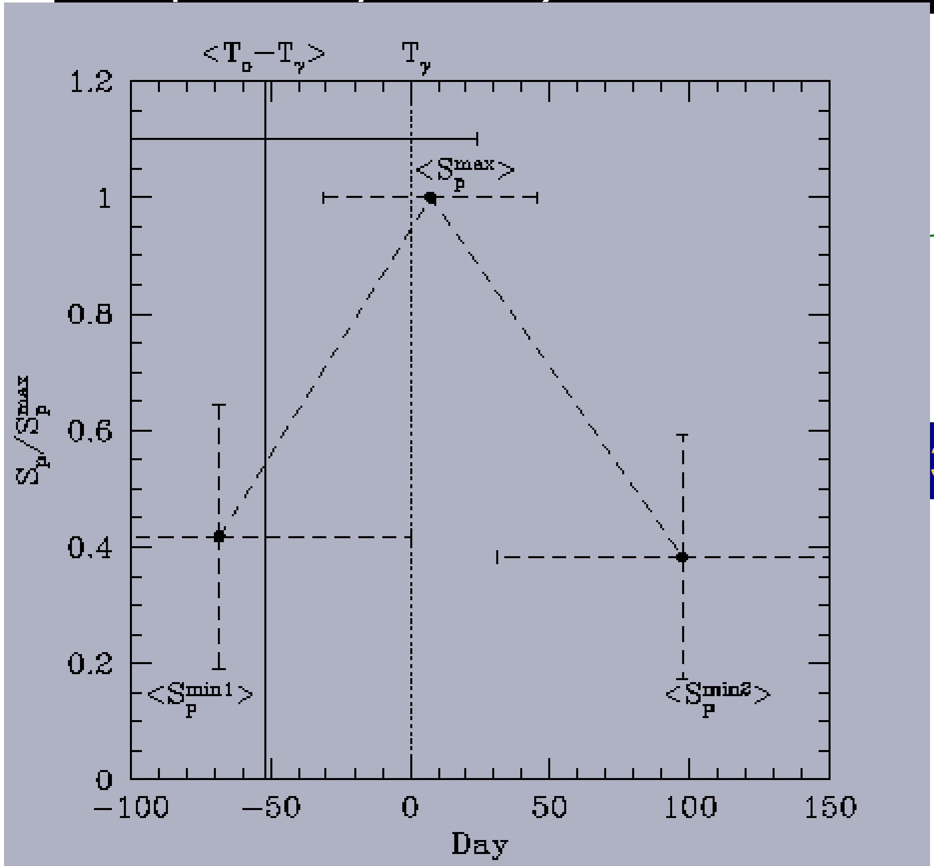
Example: 3C 273



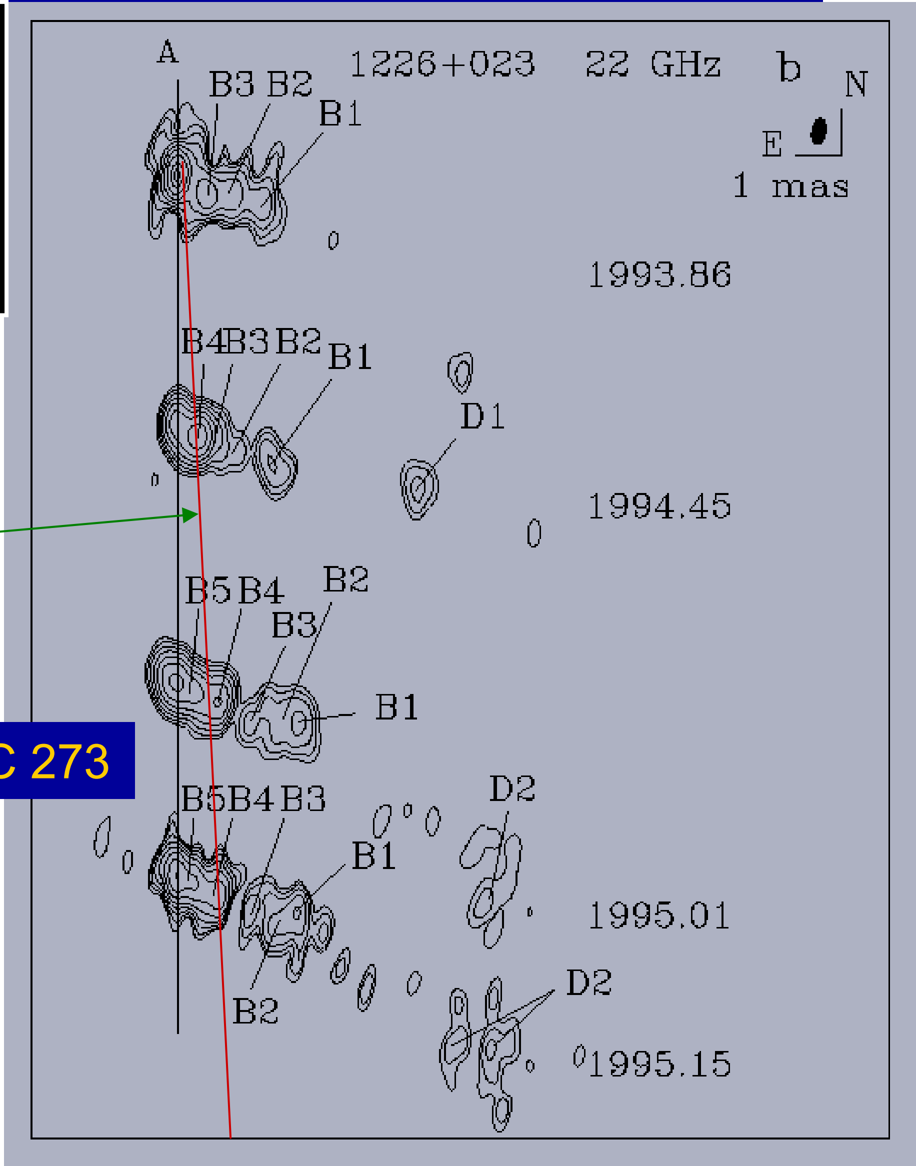
Increase in polarized radio flux accompanies high γ-ray flux + ejection of superluminal knot (Jorstad et al. 2001 ApJ)

23/28 γ-ray flares are contemporaneous with our VLBA data

11 superluminal jet components are associated with γ-ray flares (≤6 expected by chance)



3C 273



Proposed Method for Identifying Jet Features Responsible for High-frequency Variations

Look for correlated polarization variability in optical, IR, submm, & mm-wave

<u>Objective</u>: Locate sites of variable high-frequency emission on mm-wave VLBA images → relate optical/near-IR light

Relate to X-ray & γ-ray by correlating light curves (RXTE, Swift, AGILE, GLAST) with optical/near-IR, & mm-wave light curves

Observational Connection between Jet & Accretion Disk

Microquasars: X-ray dips precede appearance of knots in radio jet (see F. Mirabel's talk)

→ Might expect something similar in AGNs

Need AGNs with blazar-like jets in radio but main X-ray component from accretion disk/corona

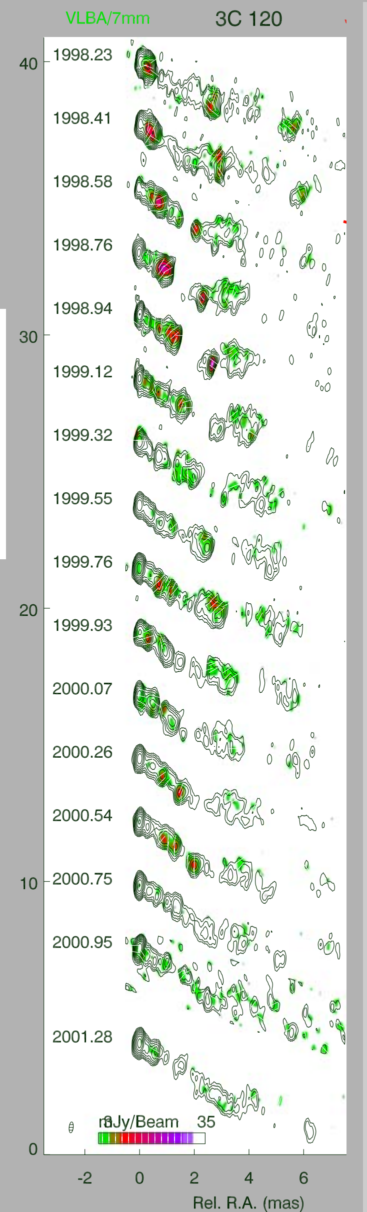
→ Blazar-like radio galaxies are good candidates

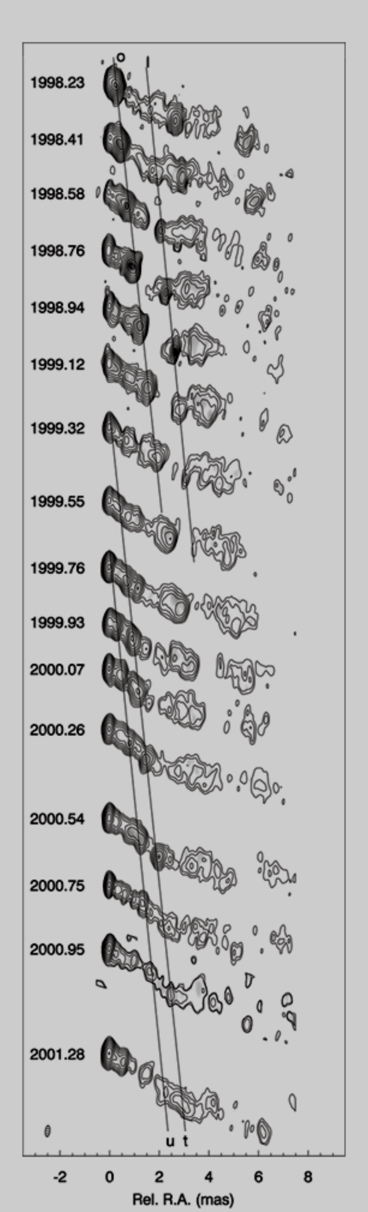
The FR I Radio Galaxy 3C 120 (z=0.033)

HST image (Harris & Cheung)

Sequence of VLBA images (Marscher et al. 2002)

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





- Superluminal apparent motion, 4-6c (1.8-2.8 milliarcsec/yr)
- X-ray spectrum similar to BH binaries & Seyferts
- Mass of central black hole ~ 3×10^7 solar masses (Marshall, Miller, & Marscher 2004; Wandel et al. 1999)

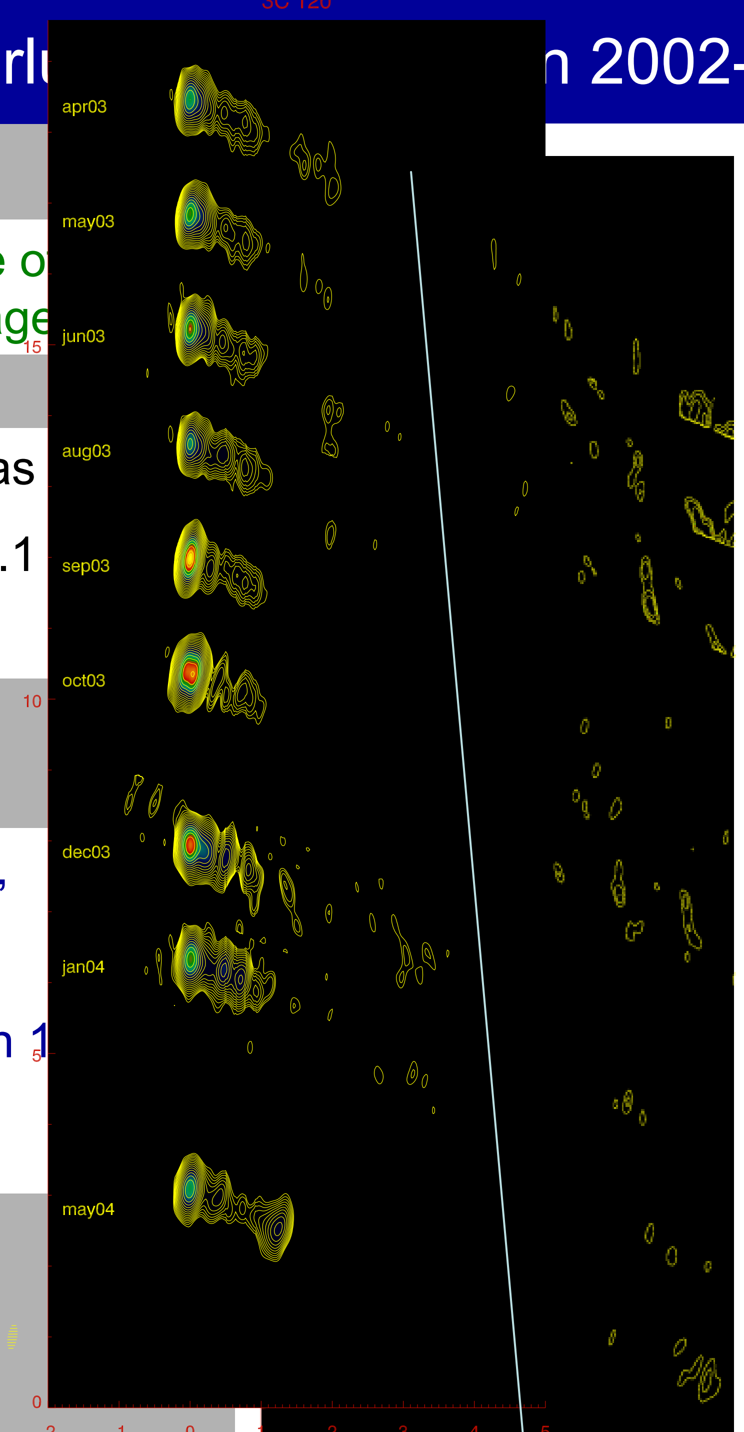
Superl… n 2002-03

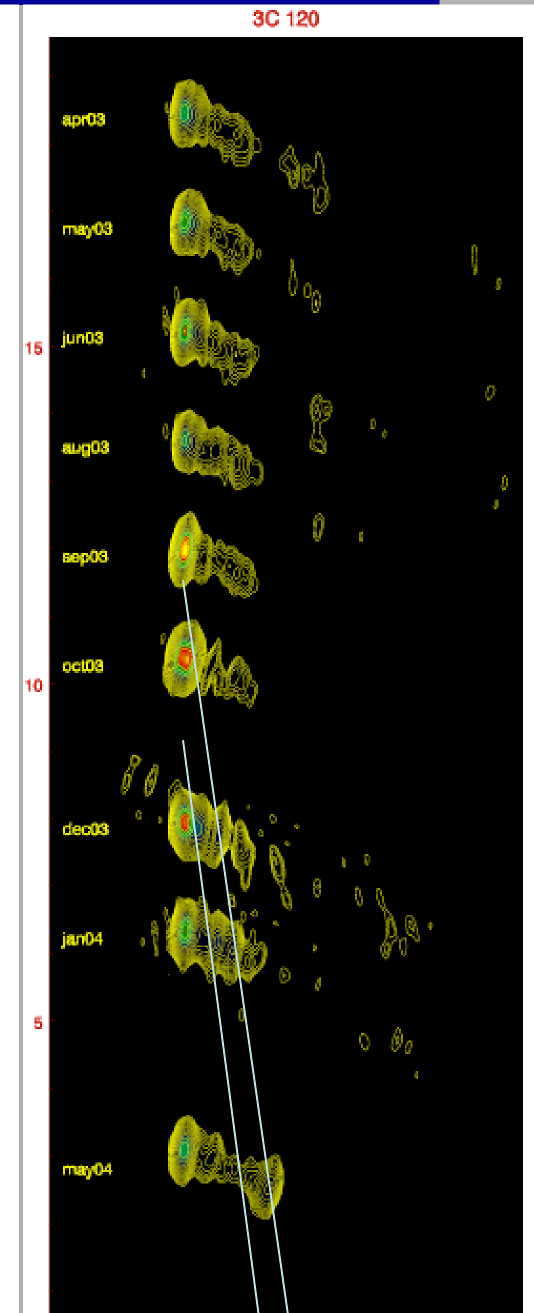
Sequence o…
VLBA image…

Scale: 1 mas …

0.64 pc = 2.1 …

(Ho=70)

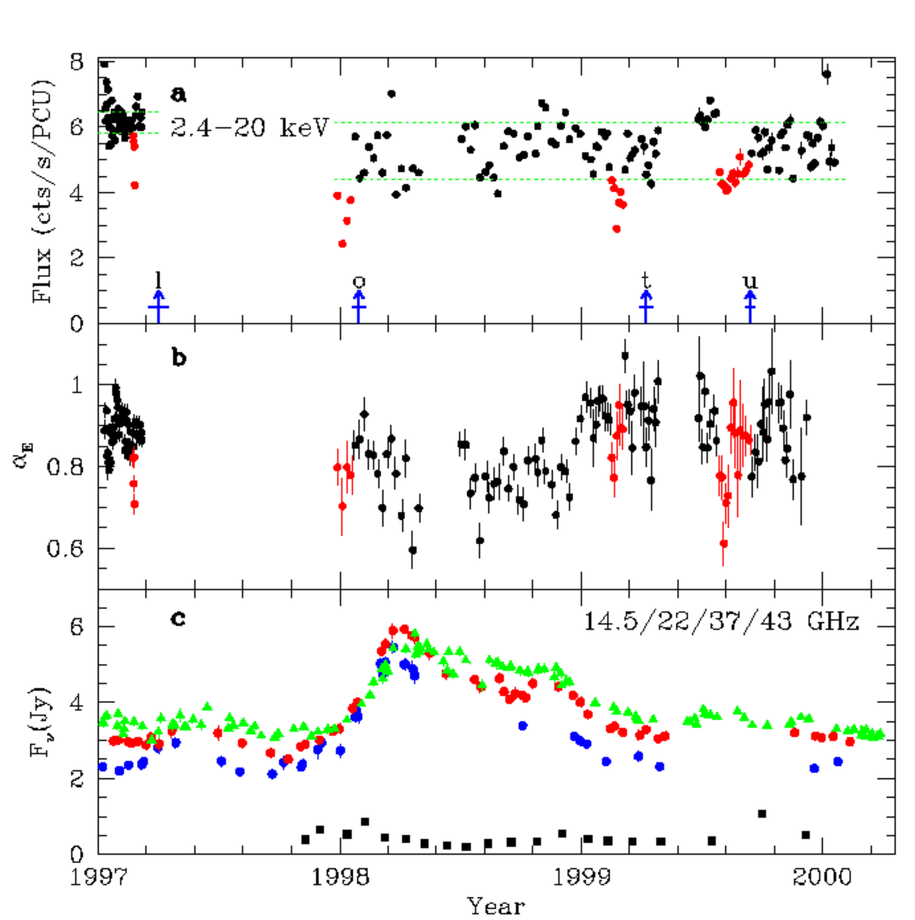


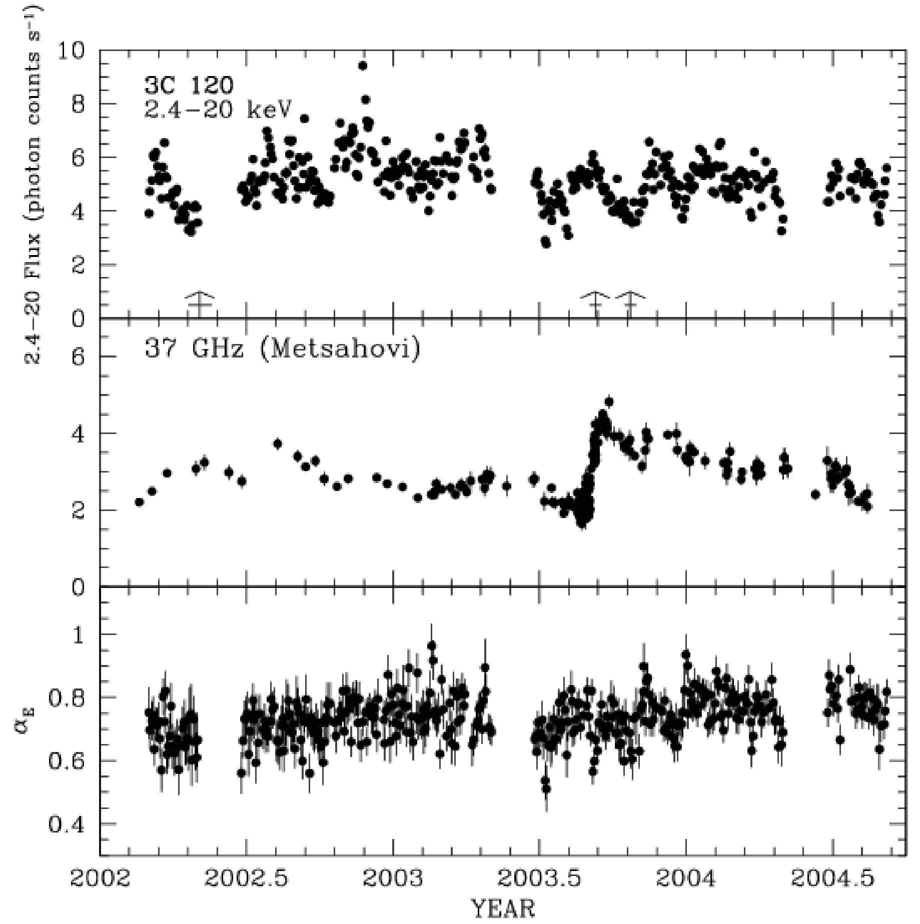


3 bright superluminal knots,
apparent motion = 4.5-5c

All other knots are less than 1…
core brightness beyond 0.5
milliarcsec from core

X-Ray Dips in 3C 120





Superluminal ejections follow X-ray dips

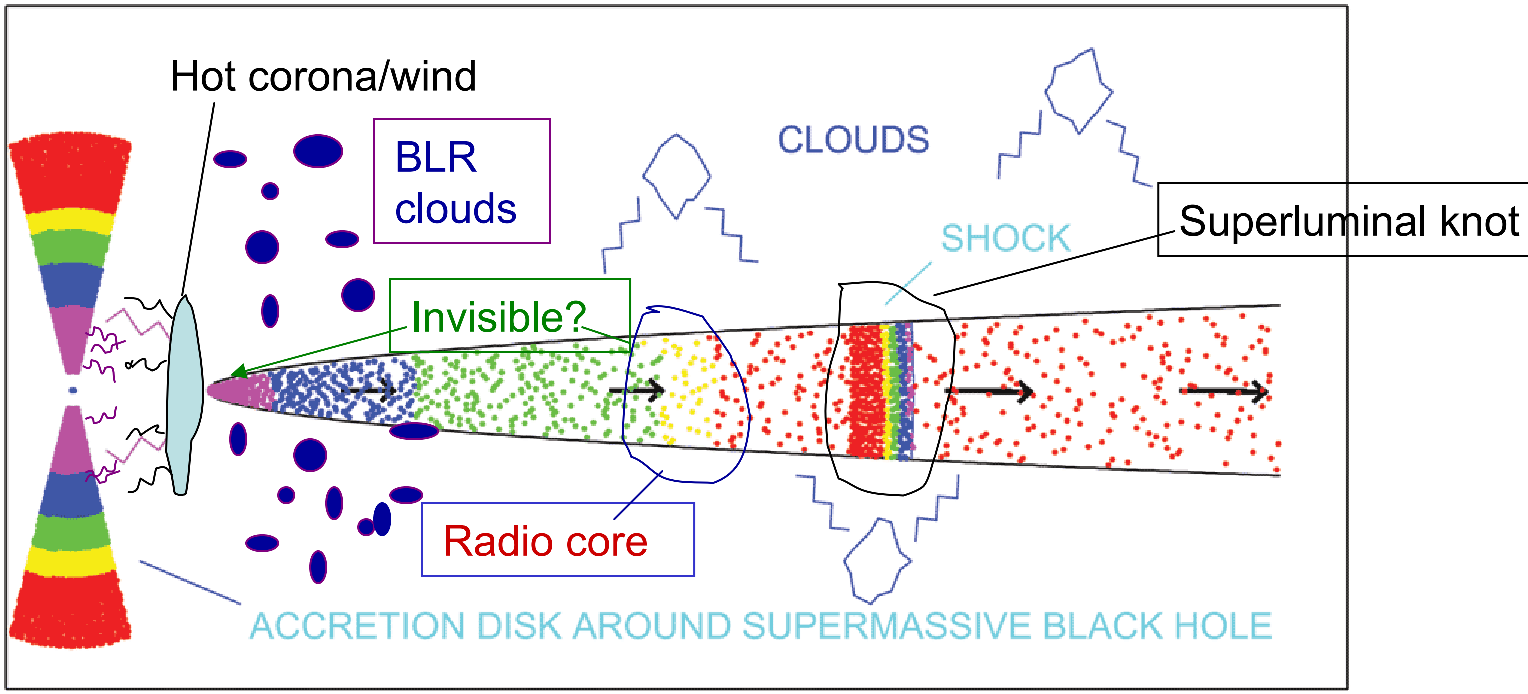
→ Similar to microquasar GRS 1915+105

Radio core must lie at least 1 lt-yr from black hole to produce the observed X-ray dip/superluminal ejection delay of ~ 60 days

Sketch of 3C 120 Nucleus

X-rays mainly from corona/wind, some probably from jet as well

Popular model: jet propelled by twisted poloidal magnetic field emanating from disk or ergosphere



Eikenberry & van Putin (2003), Livio et al. (2003), Tagger et al. (2004): More efficient outflow into jet when turbulent field becomes more poloidal

→ Gas in disk falls into BH more quickly, more advective, radiates less (dip)

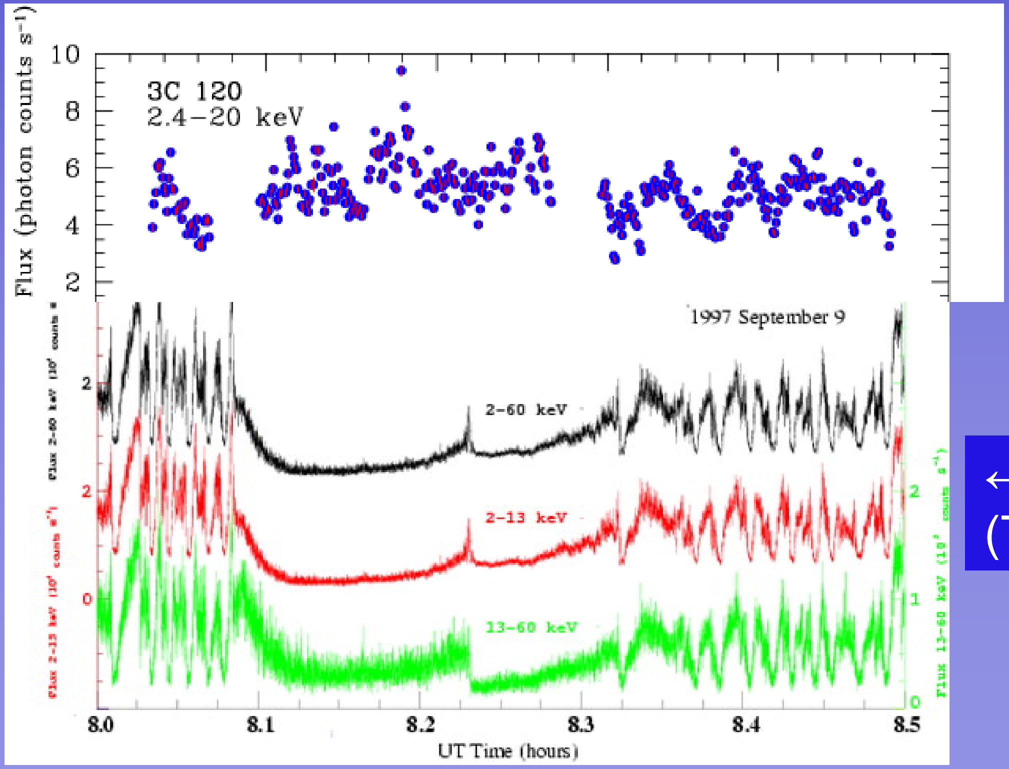
Comparison of GRS1915+105 with 3C 120 Light Curves

Dips in 3C 120 are not so deep & prolonged relative to other timescales as for GRS 1915+105

X-ray light curve is more similar to that of 1915+105 after long hard state, but with longer time between quick dips

Similar change in timescale of main fluctuations before & after low state

Recovery time from dip ~ 1 day in 3C 120, too short for scaling by M_{BH}, unless H/R of disk ~ 1/3 in 3C 120 and 1/10 in GRS 1915+105 (see Livio et al. 2003)

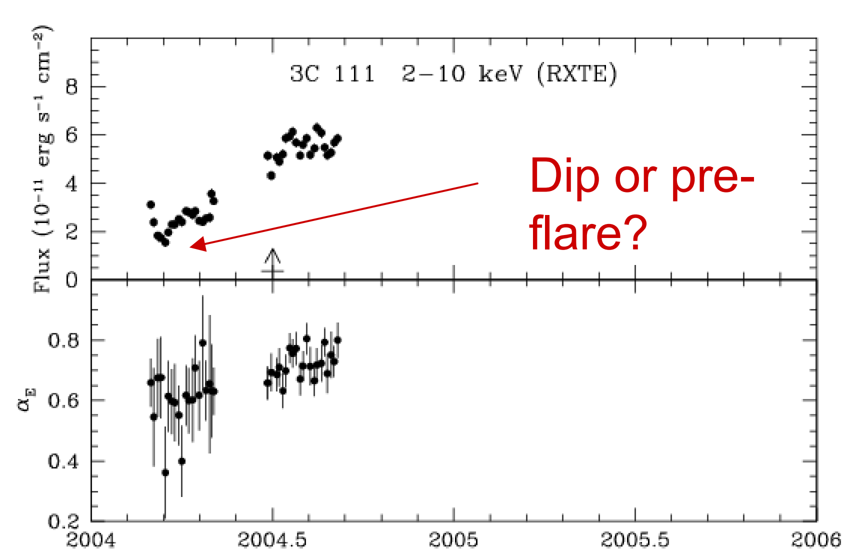


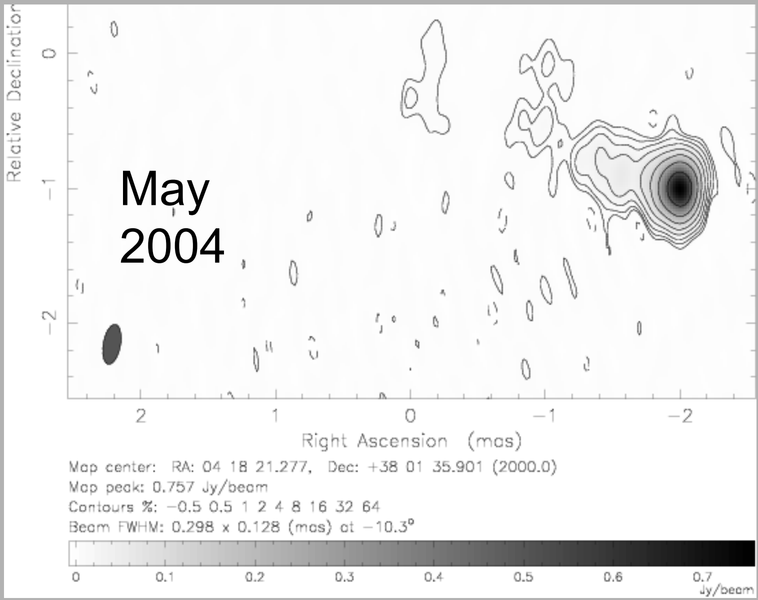
← GRS 1915+105 in 1997
(Taken from Tagger et al. 2004 ApJ)

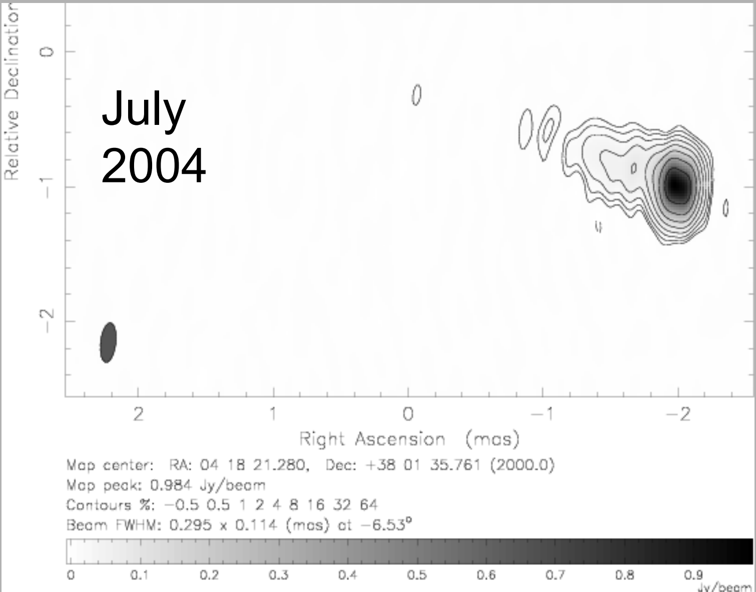
Does FR II Radio Galaxy 3C 111 (z=0.0485) Do the Same? Time will tell…

Similar to 3C 120 in radio & X-ray 5c (1.5 milliarcsec/yr)

Scale: 1 mas = 0.92 pc = 3.0 lt-yr (H_o=70)





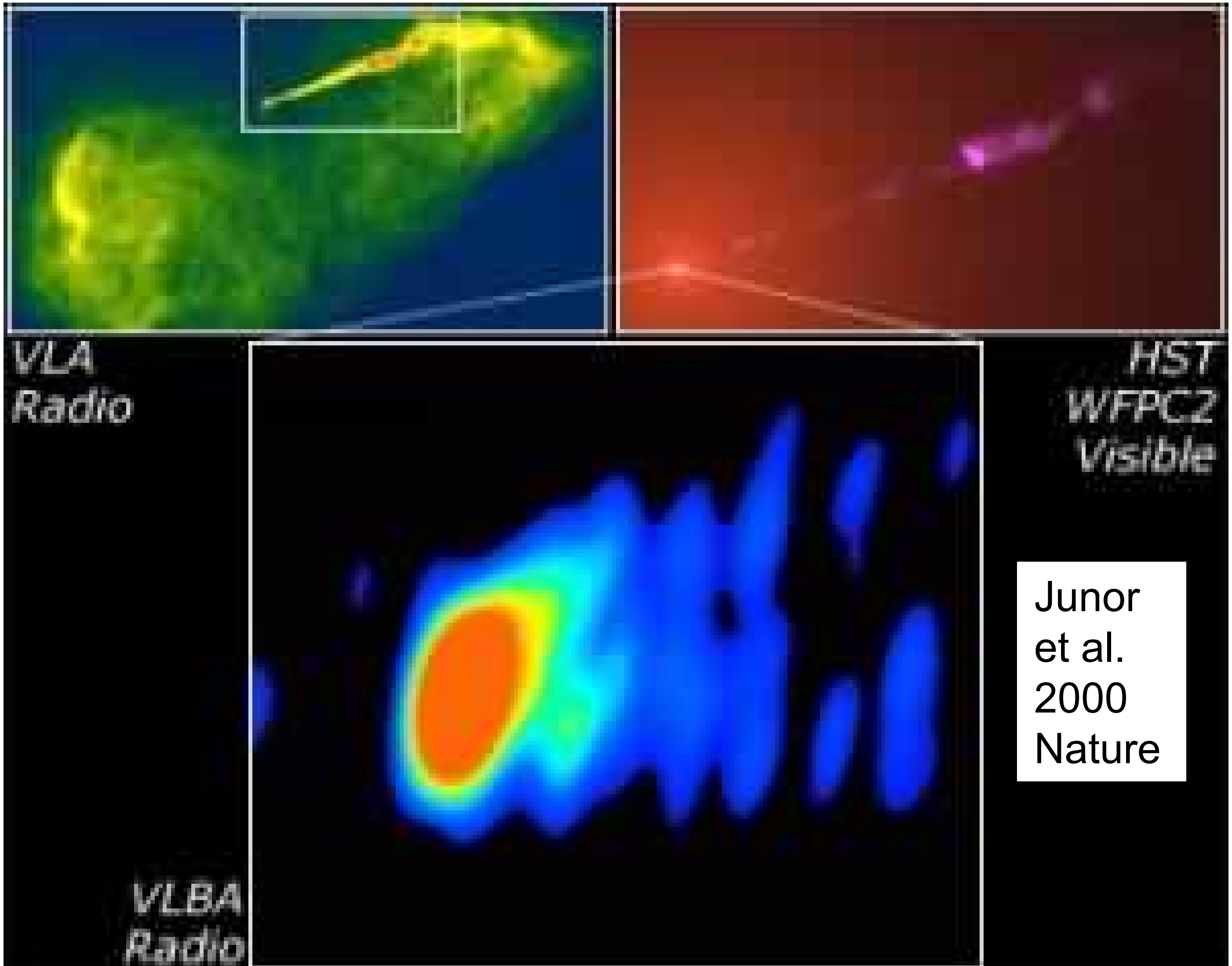


See M. Kadler's talk for a possible link between changes in X-ray Fe line & ejection of a radio knot in NGC1052

Evidence for Collimation of Jets Well Outside Central Engine

- **VLBA observations of M87: jet appears broad near core**

→ Flow may be collimated on scales ~1000 R_s

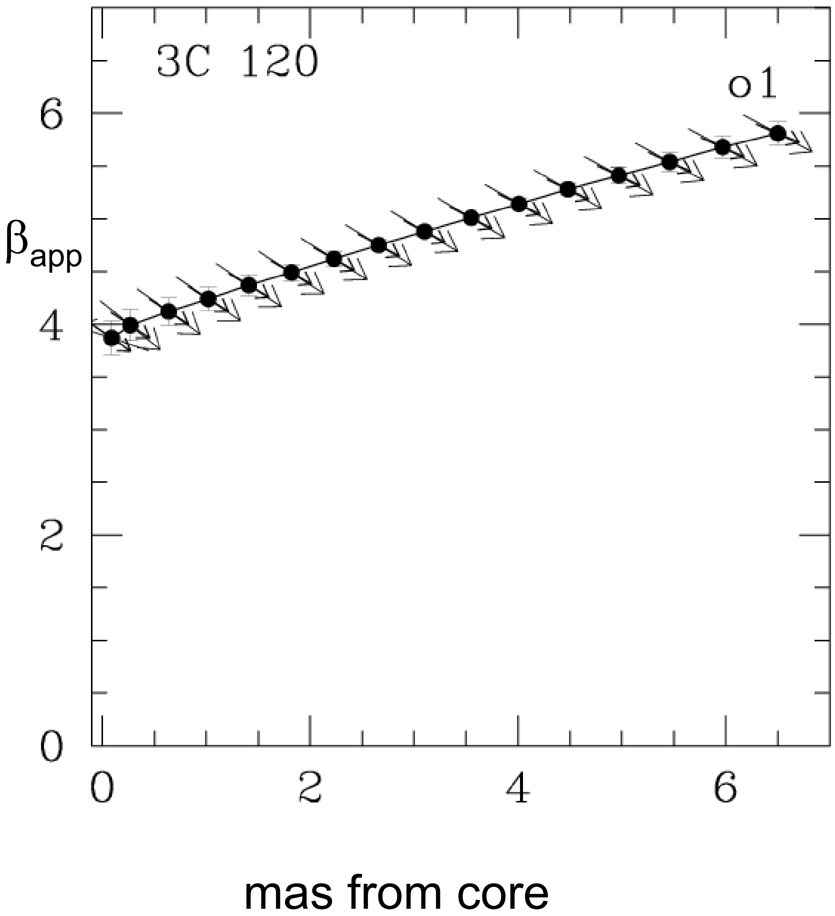


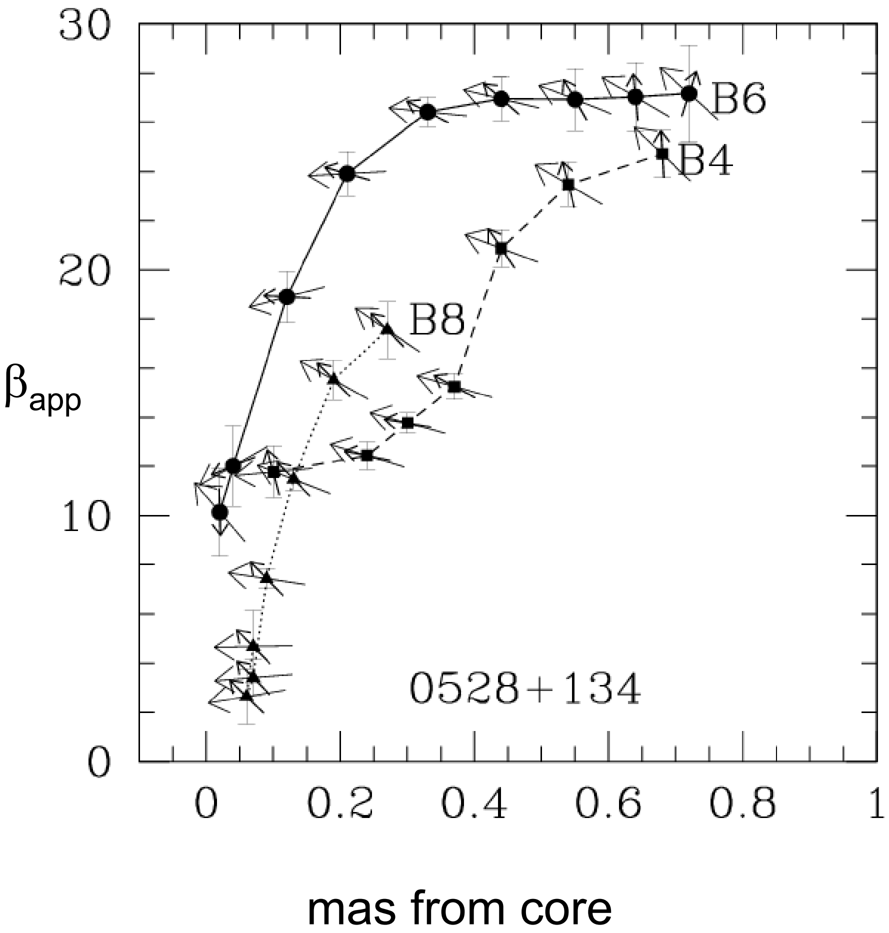
Junor et al. 2000 Nature

Evidence for Acceleration of Jet on Parsec Scales

Acceleration of proper motion near core (examples from Jorstad et al. 2005)

Can be caused by bending of trajectory or actual acceleration





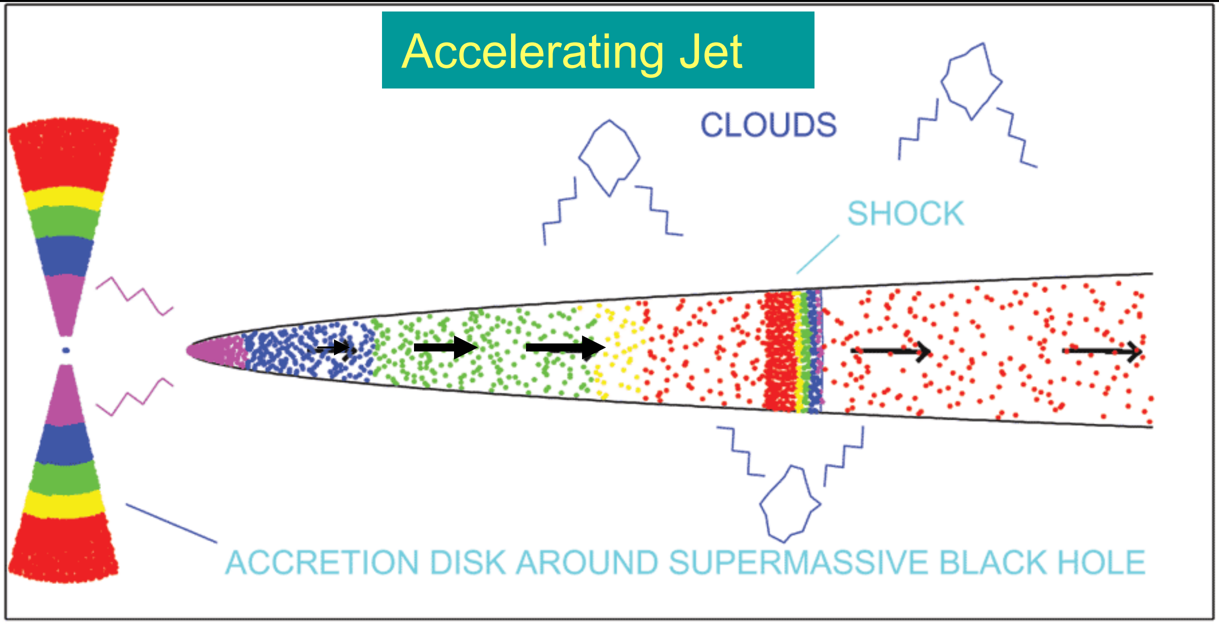
Evidence for Acceleration of Jet on Parsec Scales

Acceleration of proper motion near core in some jets

A jet with Γ > ~10 cannot propagate out of nuclear region (Phinney 1987)

How then can we have jets with observed apparent motions > 25*c*, implying Γ > 25 and focusing to within 0.5 degrees or less?

→ Models in which jet accelerates & collimates out to pc-scale radio core (Marscher 1980, ApJ; Vlahakis & Konigl 2004, ApJ)



Conclusions

Combining multi-waveband techniques is a powerful way to explore the most interesting physics of AGNs

The methods proposed here require a lot of observing time + patience from the observer, directors, & TACs

The proliferation of comprehensive multi-waveband studies is limited mainly by the amount of telescope time + astronomers' time available

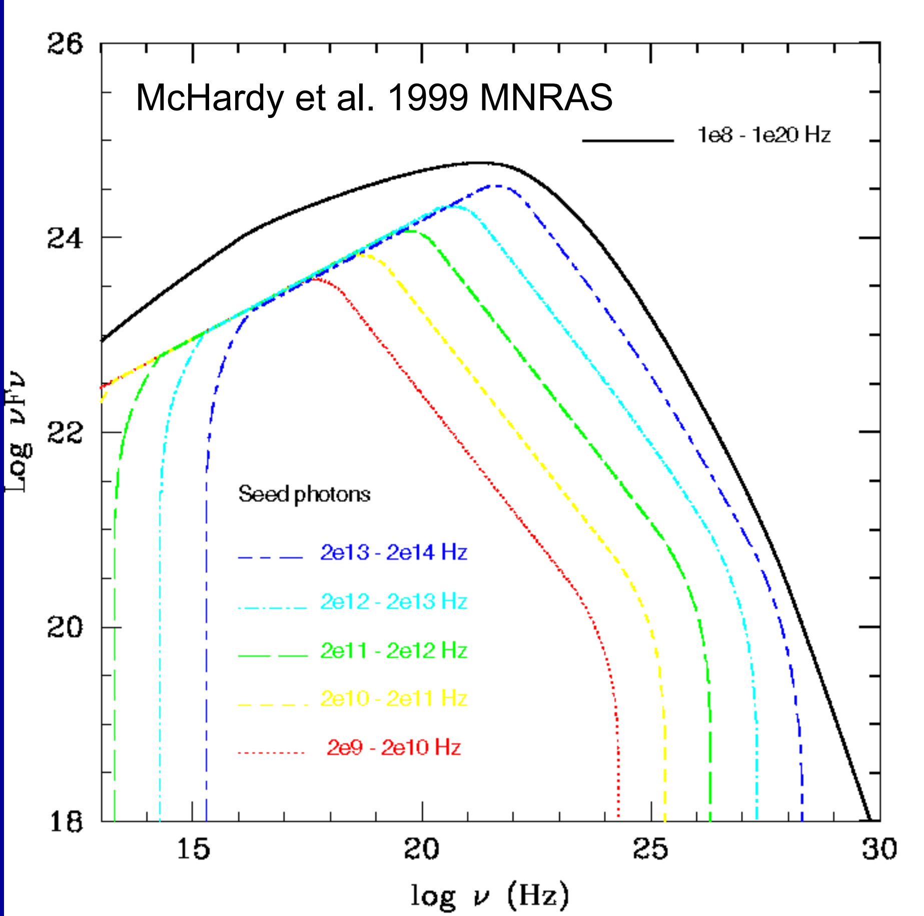
We look forward to GLAST, AGILE, VERITAS et al. (Cherenkov telescopes), Swift (in post-GRB-only phase), 1 & 2 mm VLBI, high-ν VLBI in space, & mo' better theory

END of TALK

…but not the end of the story!

Why Not One-to-One Correspondence between Radio or Optical/IR & X-ray?

SSC: All synchrotron photons that are in the right frequency range to scatter up to a given X-ray energy will contribute equally to the SSC X-ray/γ-ray flux



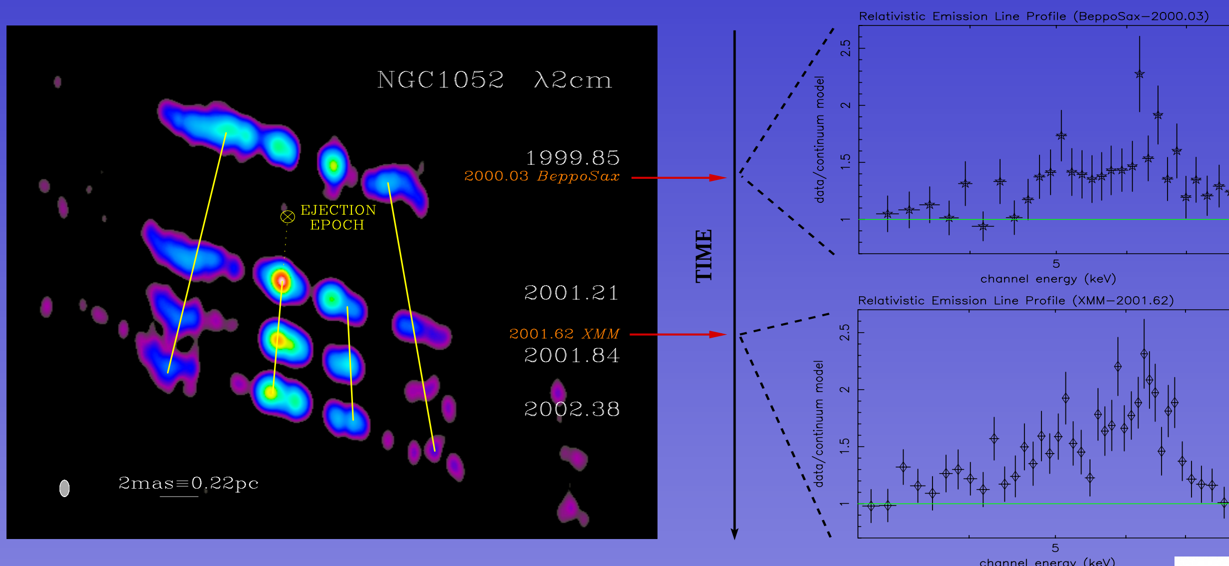
→ Relationship between SSC X-ray/γ-ray & synchrotron emission at any given frequency is simple only if source is uniform

→ Frequency-dependent time delays result from frequency stratification (e^-s accelerated at shock front, highest energy e^-s "die" quickly, lower-energy ones live longer → lower ν emitted over larger volume) + light-travel delays

The Radio Galaxy NGC1052 (z=0.0049)

M. Kadler et al. (2004)

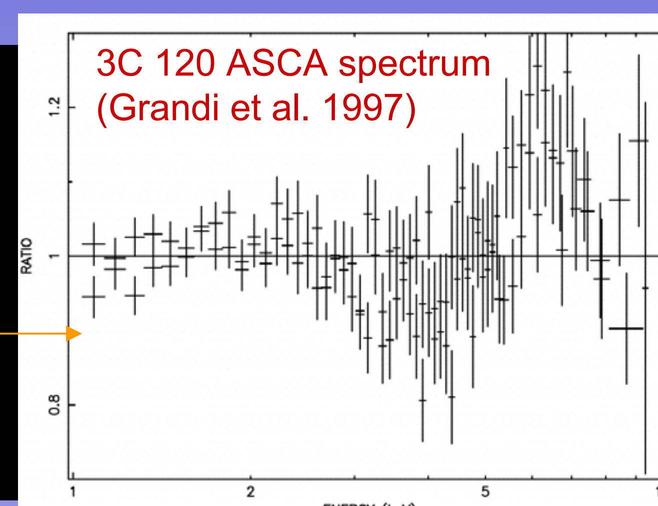
Apparent speed of radio knots ~ 0.25*c*



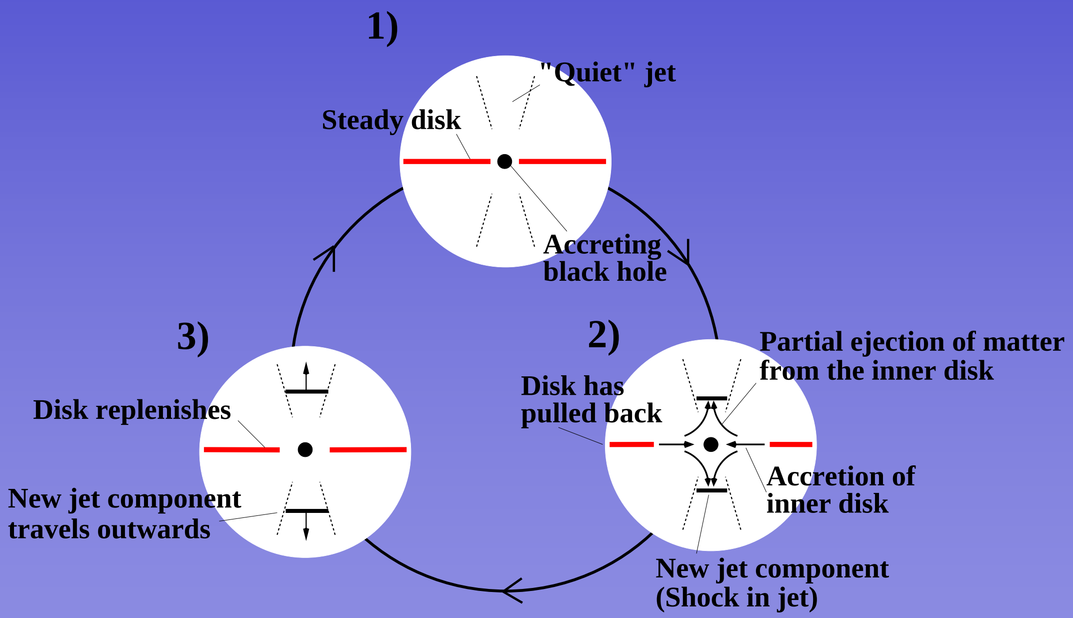
Iron line at 6.4 keV had more pronounced “red” wing prior to radio ejection event than at two other epochs

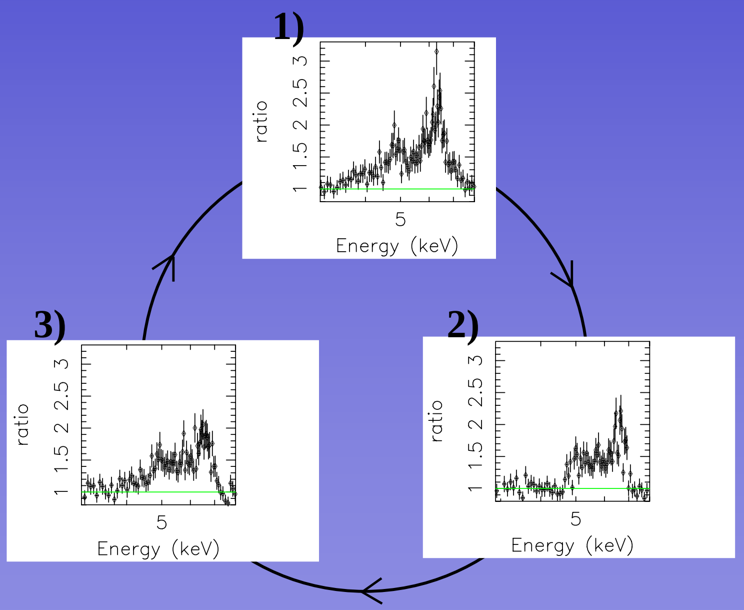
A major radio ejection event may be preceded by enhanced inflow in the relativistic region near the black hole in NGC1052

The iron line in 3C 120 is probably variable based on widely diverse reports of equivalent width; we are analyzing our RXTE observations in an effort to measure variability of the line & search for occasional broad wing



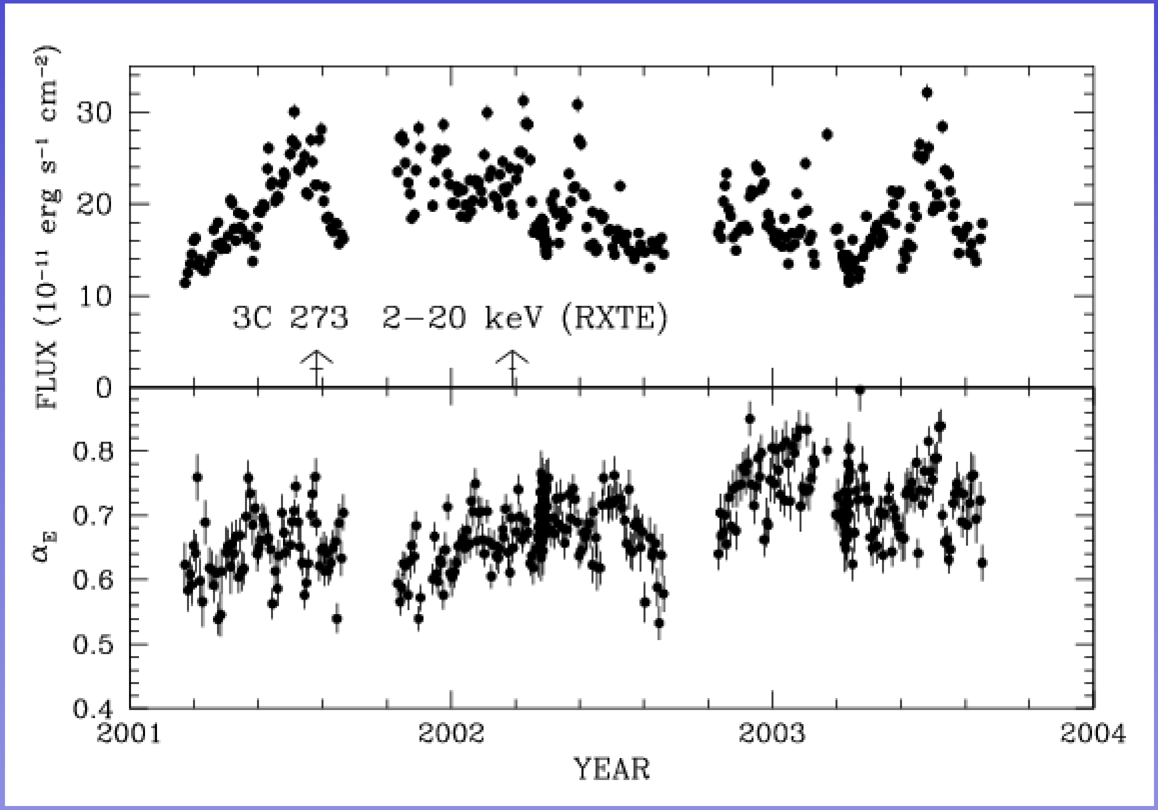
Kadler's Sketch of NGC1052





X-Ray Light Curve of 3C 273: 2001-2003

Somewhat similar to 3C 120; we will see whether X-ray dips occur, followed by superluminal ejections. Stay tuned …



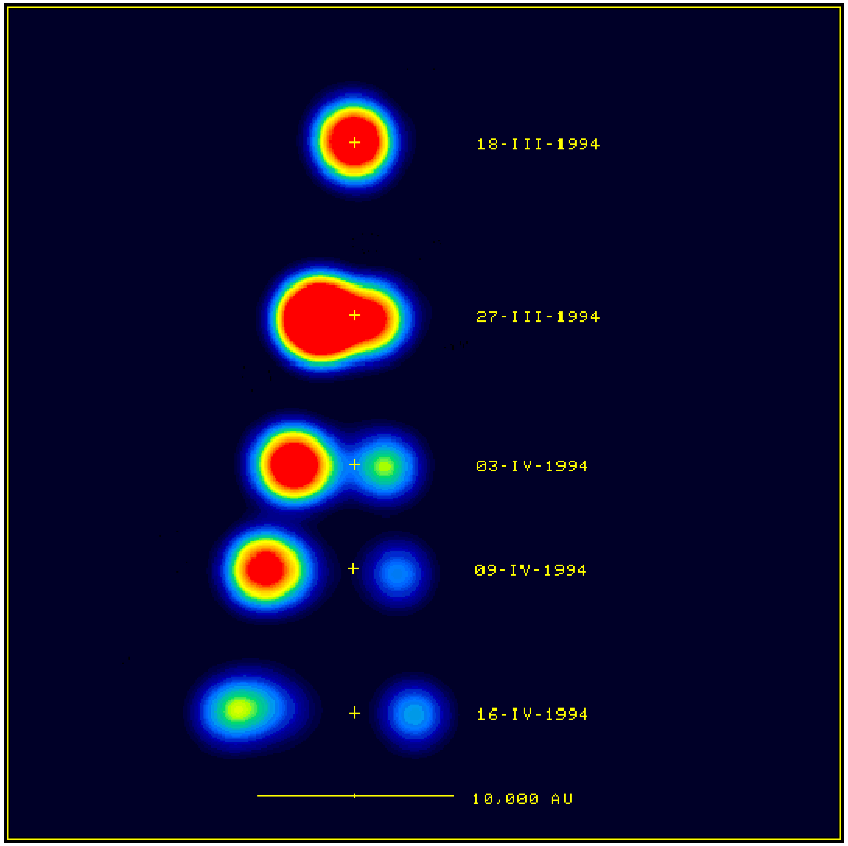
The “Microquasar” GRS 1915+105: A Faster-than-light Object in Our Galaxy

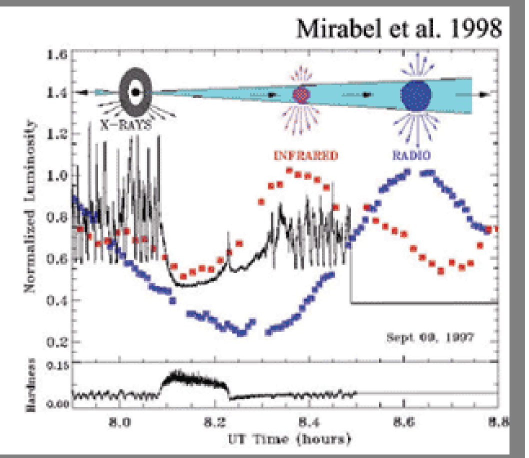
Apparent velocity 2-3c, but jet makes a large angle to line of sight
$\Gamma \sim 5$ (Fender et al. 1999)

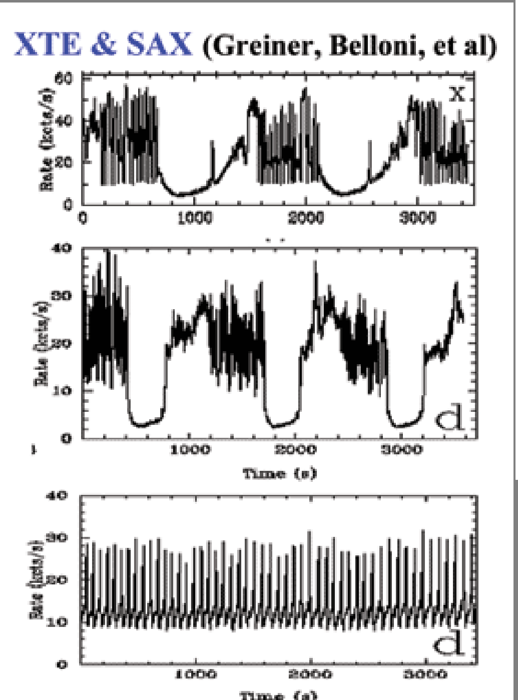
Binary system, giant star + black hole of 14 solar masses

Ejection of superluminal knots follows end of low, hard X-ray state

Mirabel & Rodriguez (1994 *Nature*)



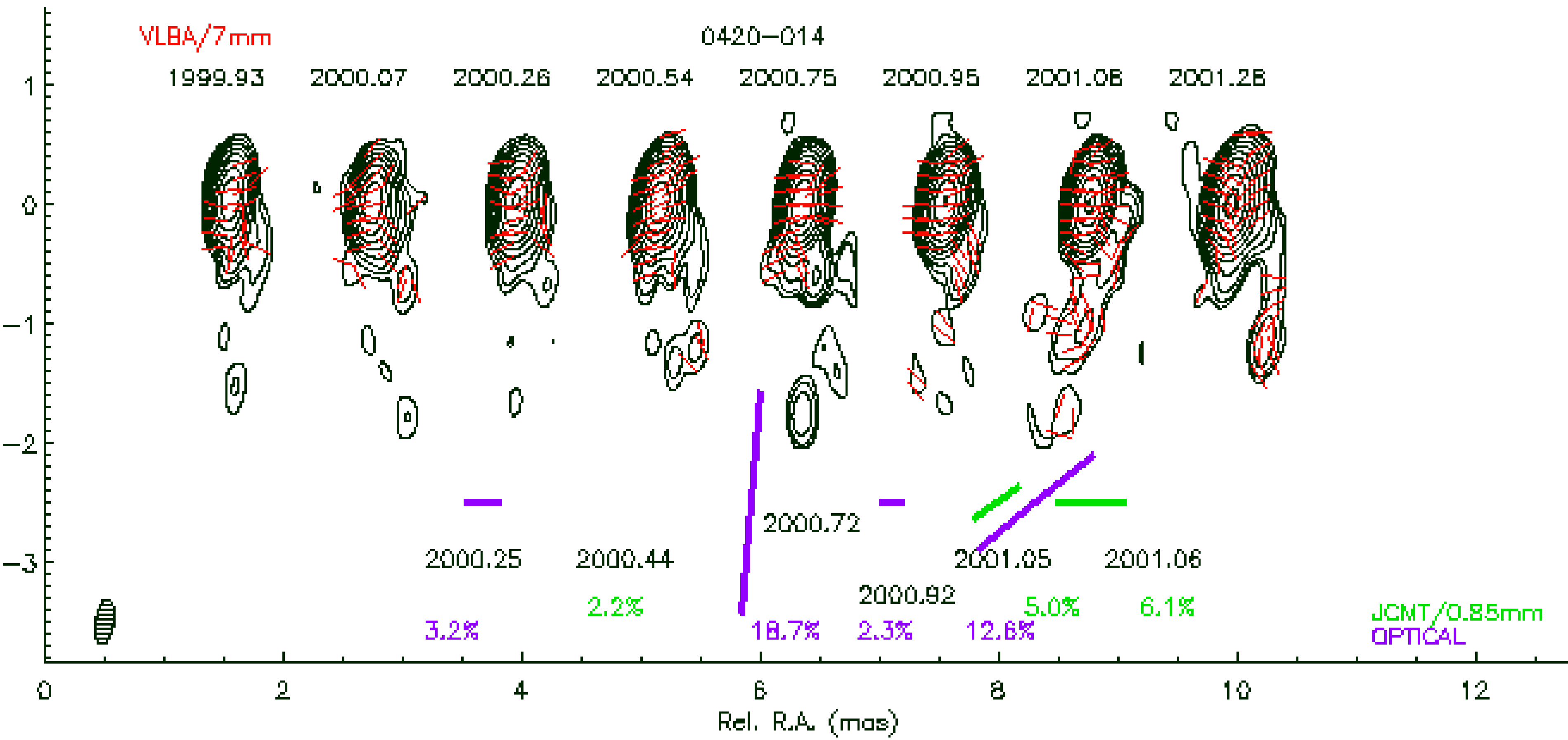




3 different types of behavior (Belloni et al. 2000)

Multiwaveband Polarization Variability

Quasar 0420–014: Note extremely rapid changes, possible linkages of directions of polarization at different wavebands

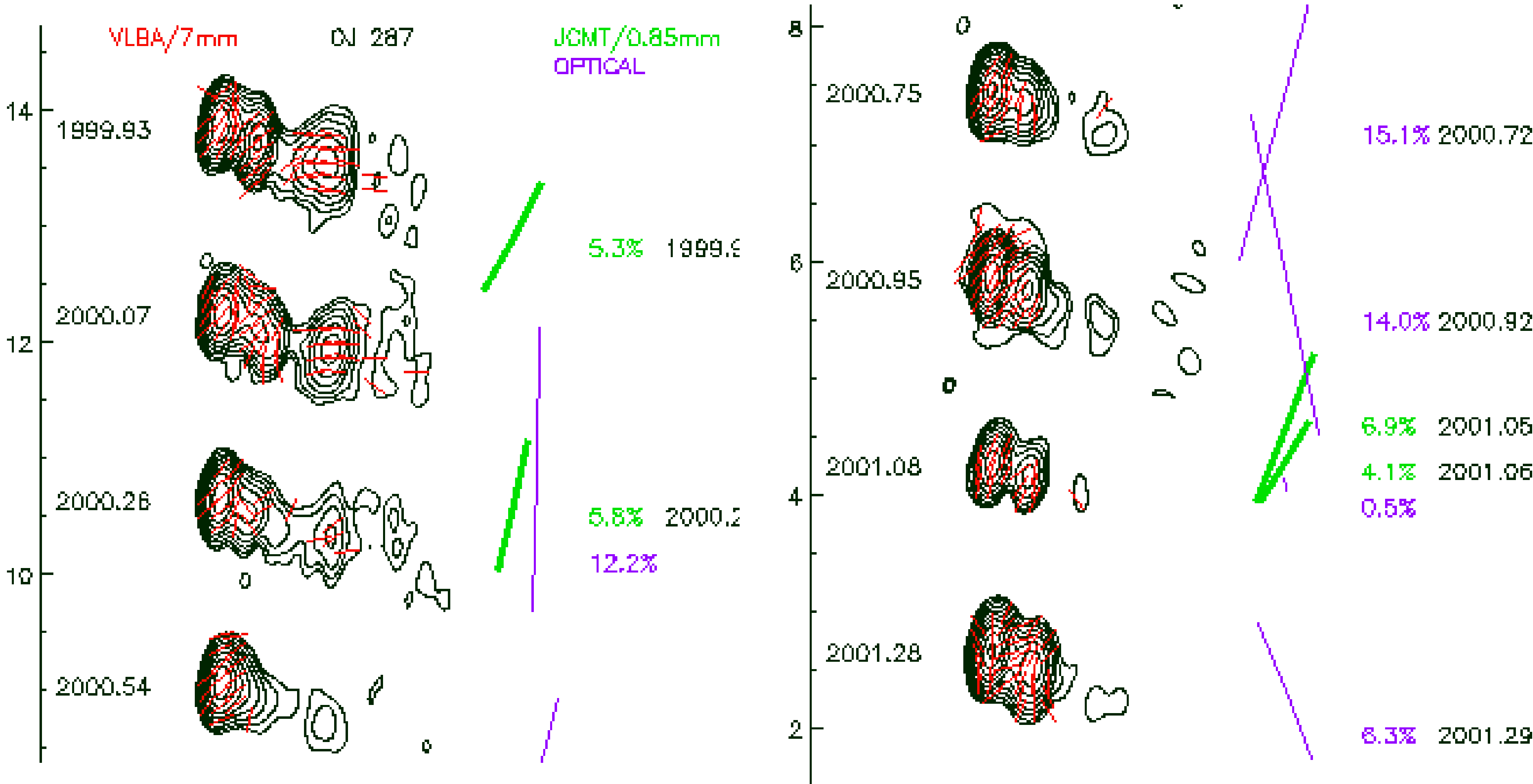


Multiwaveband Polarization Variability

Optical & mm-wave linear polarization often has similar E-vector direction

. . . but sometimes not – optical is more highly variable

Degree of optical polarization is often higher



BL Lac (z=0.069)

Jet does a hula dance:

~ 2-yr cycle of 24° swing in direction of jet near core

Scale: 1 mas = 1.3 pc = 4.1 lt-yr (H_o=70)