VLBA and GLAST Observations of AGNs

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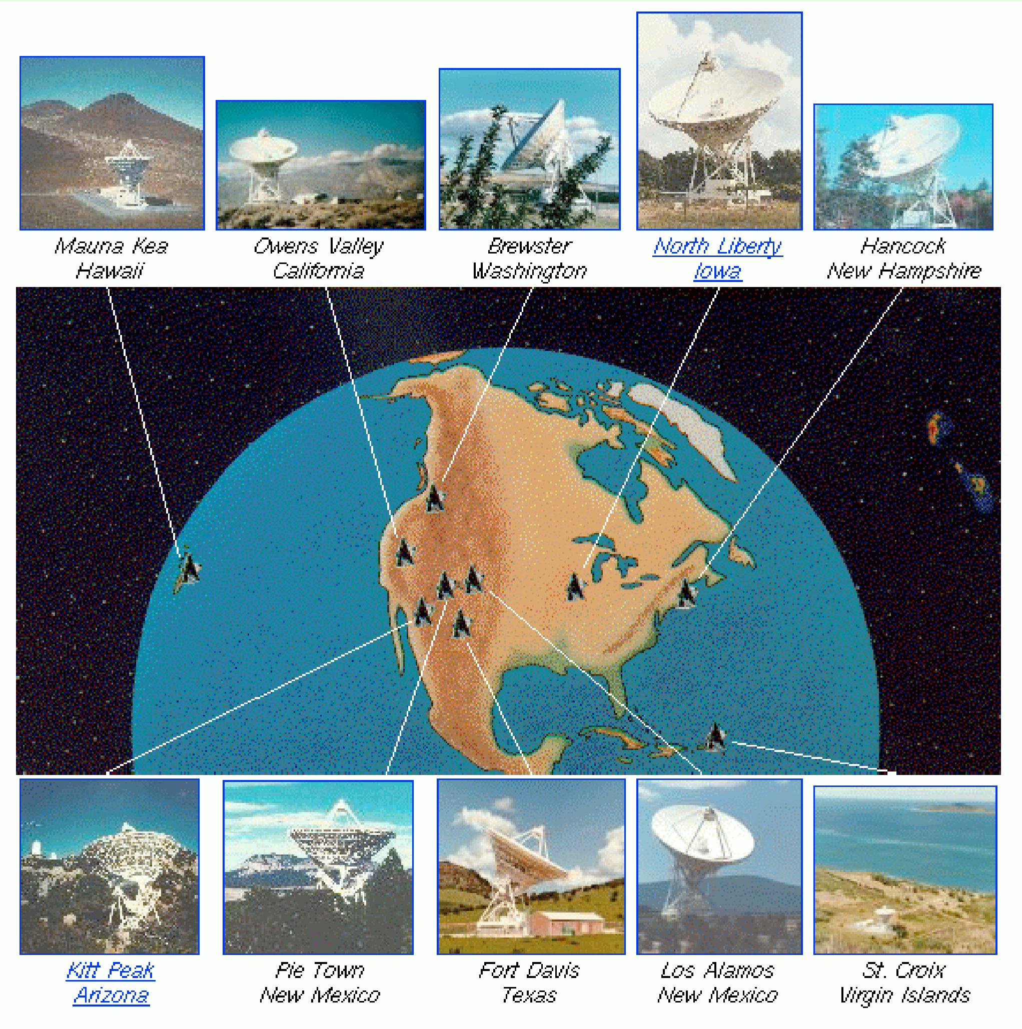
Outline

- VLBA Background
- Blazar Physics
- Seyferts and Low-Luminosity AGNs
- Extragalactic Source Identification
- Summary

Very Long Baseline Array

- World's only dedicated VLBI array
- Baselines 200 km to 8600 km
- Resolution as high as 0.1 mas
- Part of NRAO (NSF-funded)



Frequency Coverage and Sensitivity

Wavelength (cm)	Freq. Range (GHz)	2 ant. RMS (2 min)	Image RMS (8 hr)
90	0.312-0.342	150 mJy	2 mJy/beam
50	0.596-0.626	150 mJy	2 mJy/beam
18-21	1.35-1.75	4.7 mJy	46 uJy/beam
13	2.15-2.35	5.2 mJy	50 uJy/beam
6	4.6-5.1	4.7 mJy	45 uJy/beam
4	8.0-8.8	4.8 mJy	46 uJy/beam
2	12.0-15.4	8.7 mJy	84 uJy/beam
1.3	21.7-24.1	15.7 mJy	151 uJy/beam
0.7	41.0-45.0	50 mJy (30 s)	237 uJy/beam
0.3	80-96	200 mJy (15 s)	>1 mJy/beam

Angular Resolution

Wavelength (cm)	***Beam FWHM (mas)***	***Beam (at z=1) (H_0=65, q_0=0.5)***
90	21	140 pc
50	12	80 pc
18-21	5	33 pc
13	3	20 pc
6	1.4	9 pc
4	0.8	5 pc
2	0.5	3.3 pc
1.3	0.3	2.0 pc
0.7	0.2	1.3 pc
0.3	0.1	0.7 pc

VLBA Observing Availability

- 4500-5000 hours of scientific observations/yr
- Peer-reviewed proposals with 3 deadlines/yr
- More than 50% of VLBA scientific observing hours are dynamically scheduled
  – Potentially important for gamma-ray flares
- Polarimetric imaging capability
  – 1-2 hours provides decent imaging
  – Sources as weak as 0.5 mJy can be imaged at cm 8

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THANKS TO ALAN MARSCHER FOR SUPPLYING SOME BLAZAR SLIDES!

EGRET Blazars

- 3rd EGRET catalog has 191 sources more than 10 degrees from Galactic plane (Hartman et al. 1999)
  - 66 identified with blazars, plus 1 radio galaxy
    - Most are superluminal, highly variable
  - 27 possible AGNs
  - 96 unidentified sources
- LAT surely will detect many more blazars

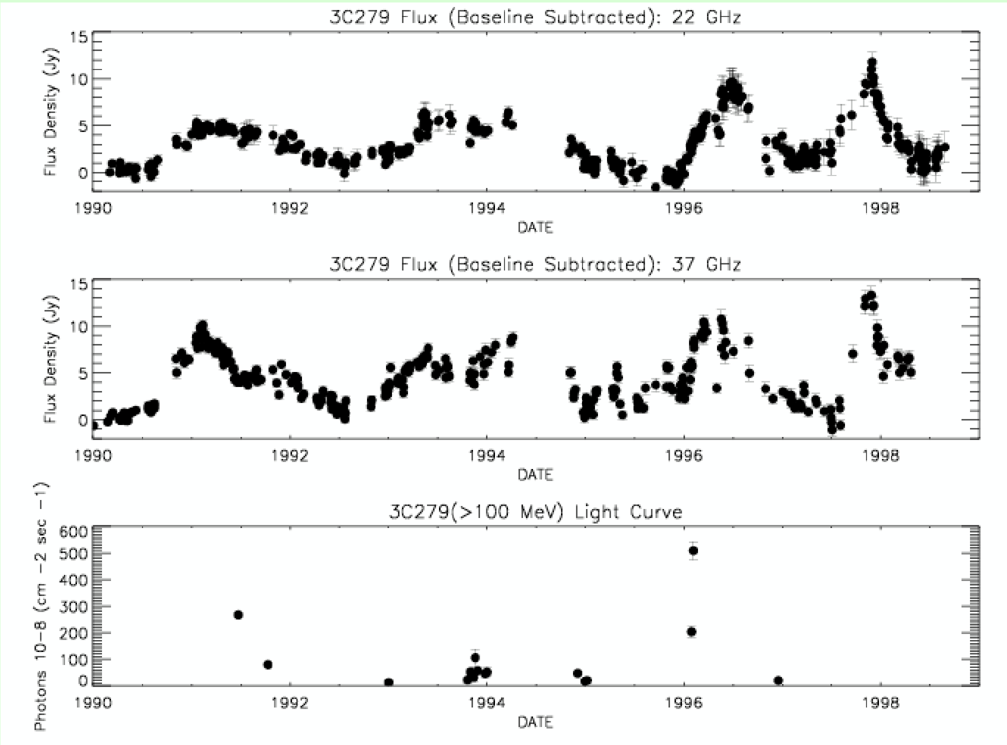
X-Rays & _-Rays from Blazars

and Relationship to Lower-Frequency Emission (AM)

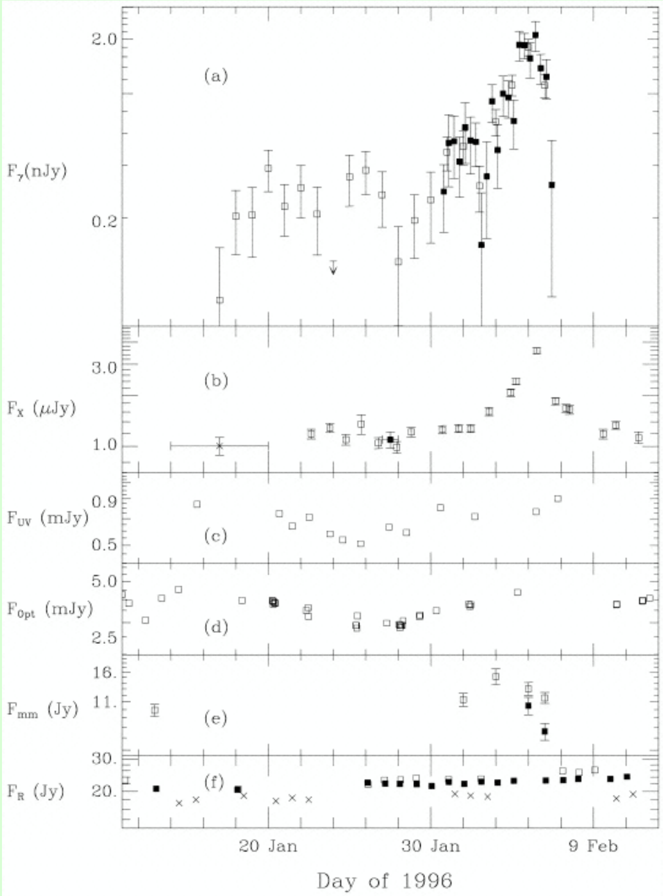
- Are high-energy and lower-frequency variations correlated?
- Do X-ray & _-ray events correspond to the ejection of superluminal knots?
- Where are the X-rays & _-rays produced?
  - The accretion disk?
  - The inner jet (between the central engine and the core of radio jet)?
  - At – or downstream of – the core of the radio jet?
- What can we learn about reason for ultra-high values of T_B?

3C 279 radio/gamma flares

Wehrle et al. (p.c.)

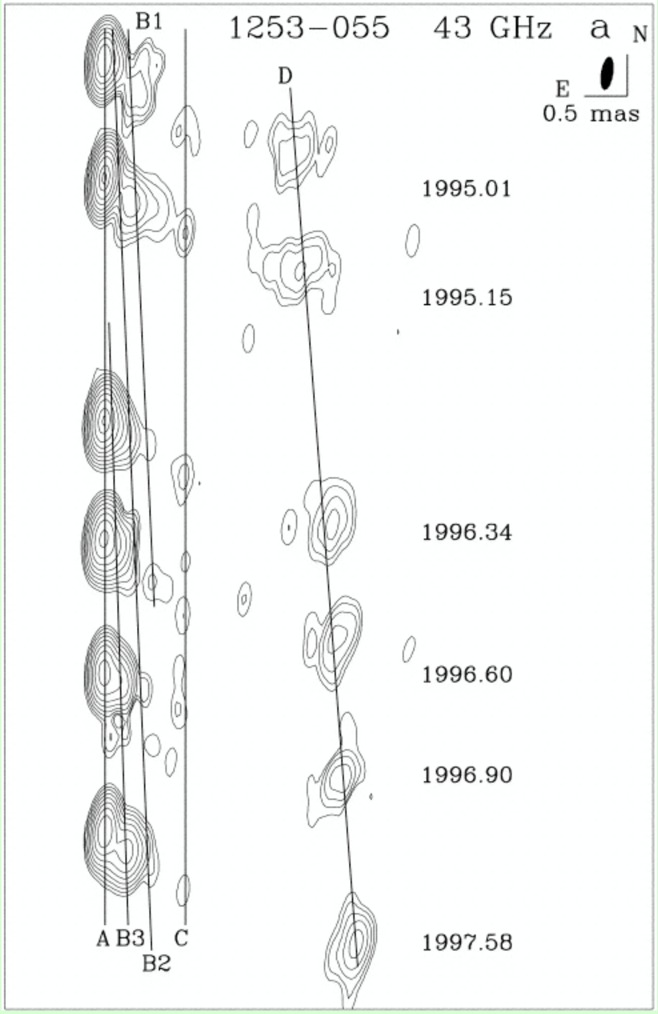


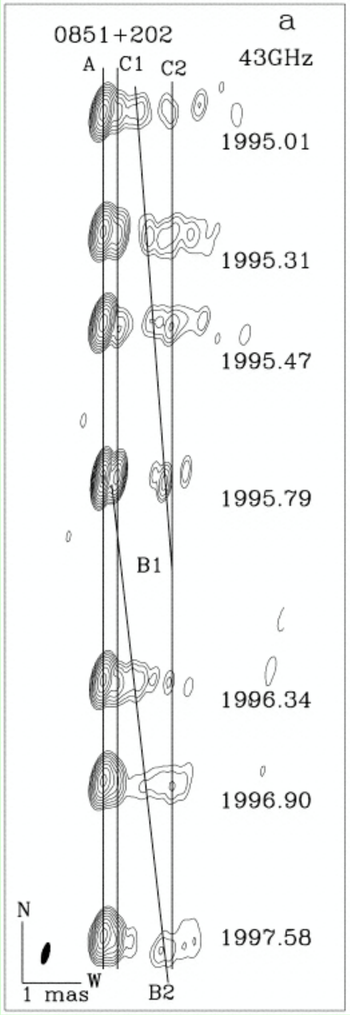
Wehrle et al. (2001)



Multi-epoch Imaging (Jorstad et al. 2001)

- Inner components of EGRET blazars may have v_{app}~20c
- Ejection at gamma-ray flares?





The Quasar PKS 1510-089 (z=0.361)

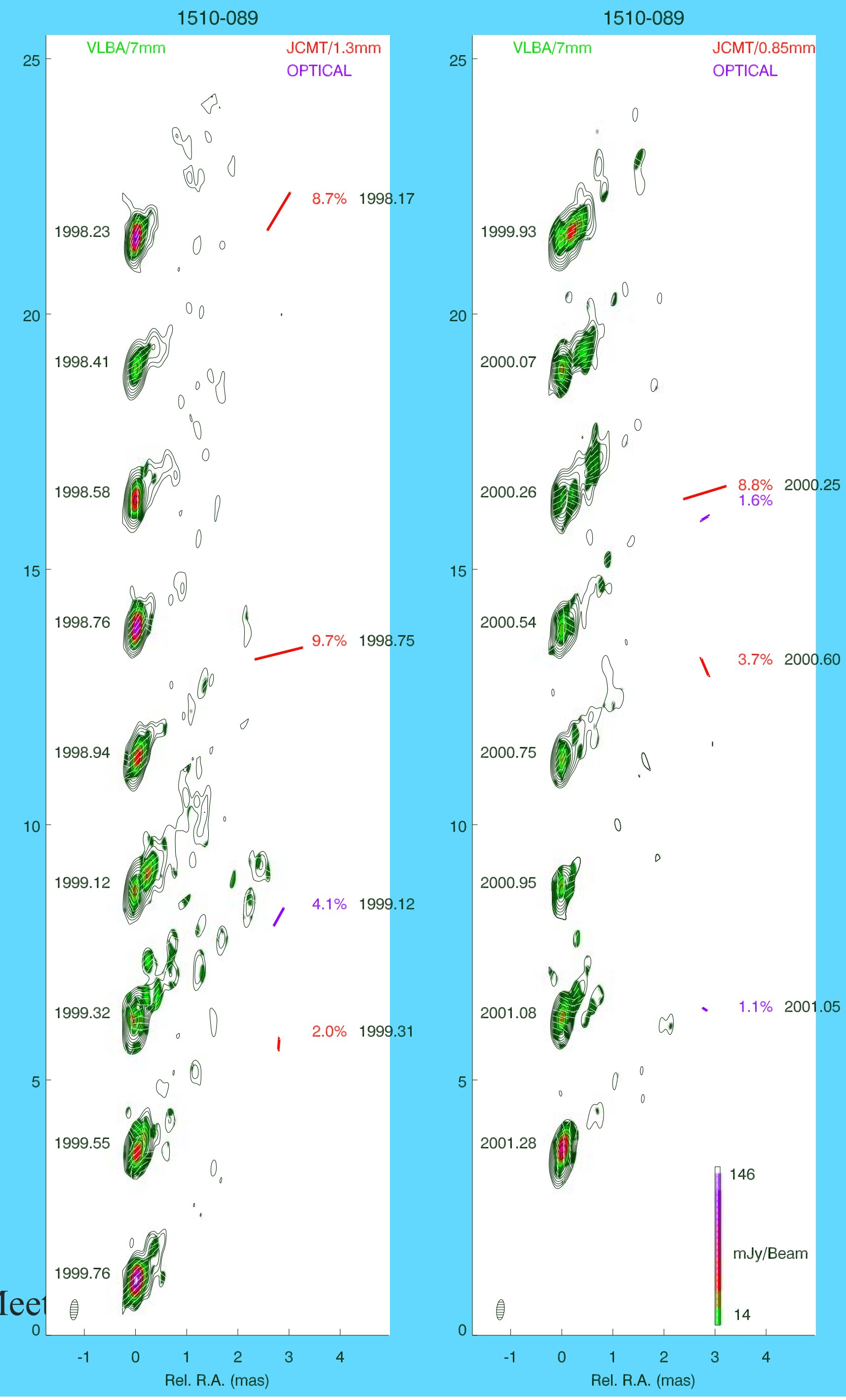
Bright X-ray source with highly variable flux
+ flat spectrum

Bright source of 0.1-3 GeV _-rays

VLBA images

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

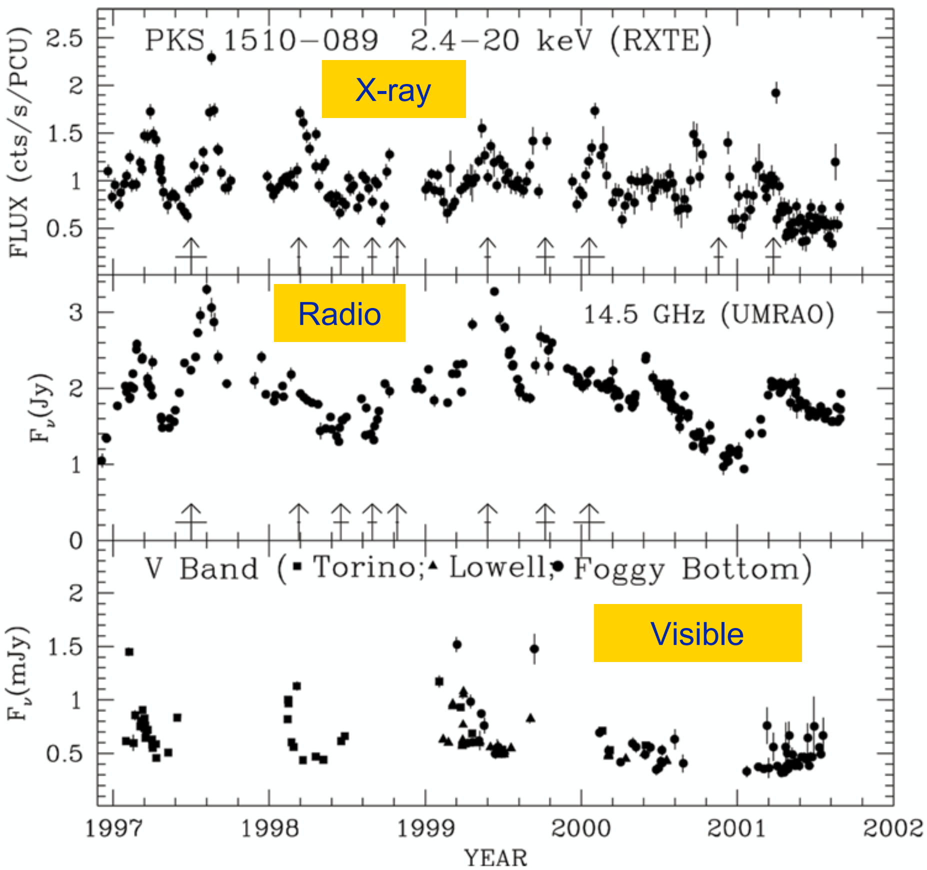
Next 4 slides courtesy of Alan Marscher et al.



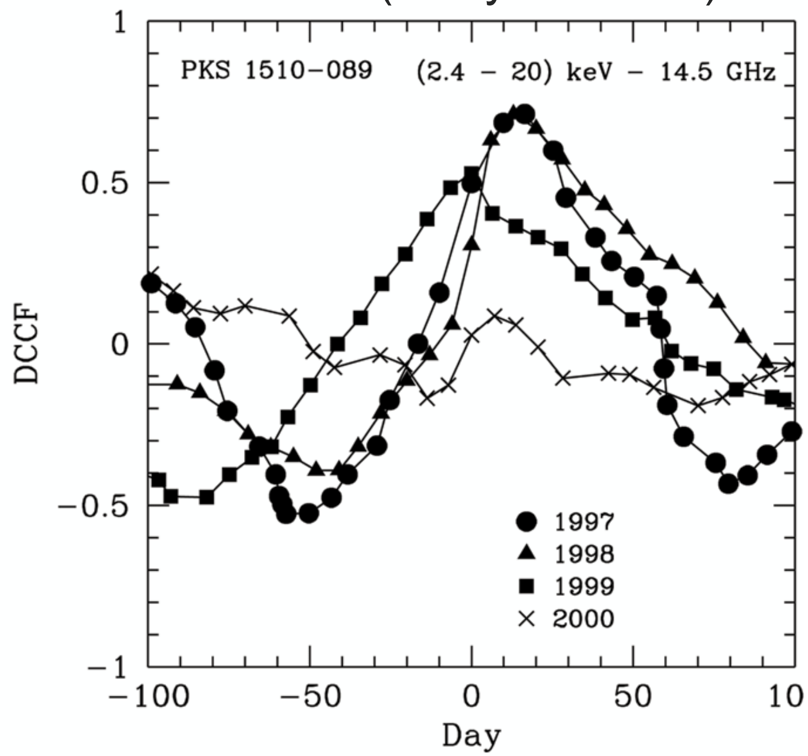
The Quasar PKS 1510-089 (cont.)

X-ray flares well-correlated with radio (14.5 GHz) in 1997 & 1998, with radio variations leading X-ray by ~ 2 weeks ("reverse time lag"); ejections of superluminal knots tend to coincide with X-ray flares (but difficult to establish connection statistically)

→ **X-rays come from superluminal knots in jet (*not* from accretion disk)**



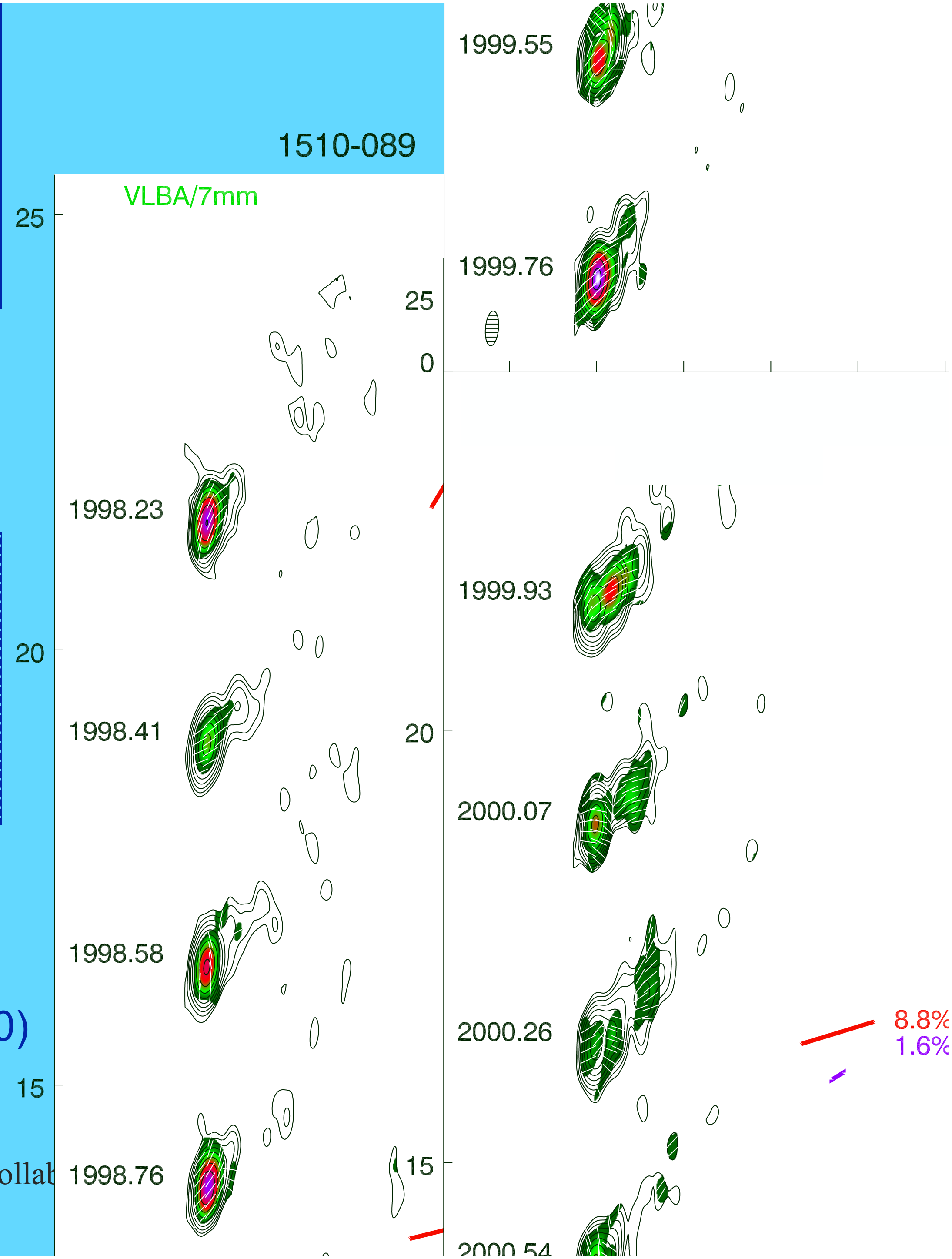
Discrete Cross-Correlation Coefficient (X-ray vs. radio)



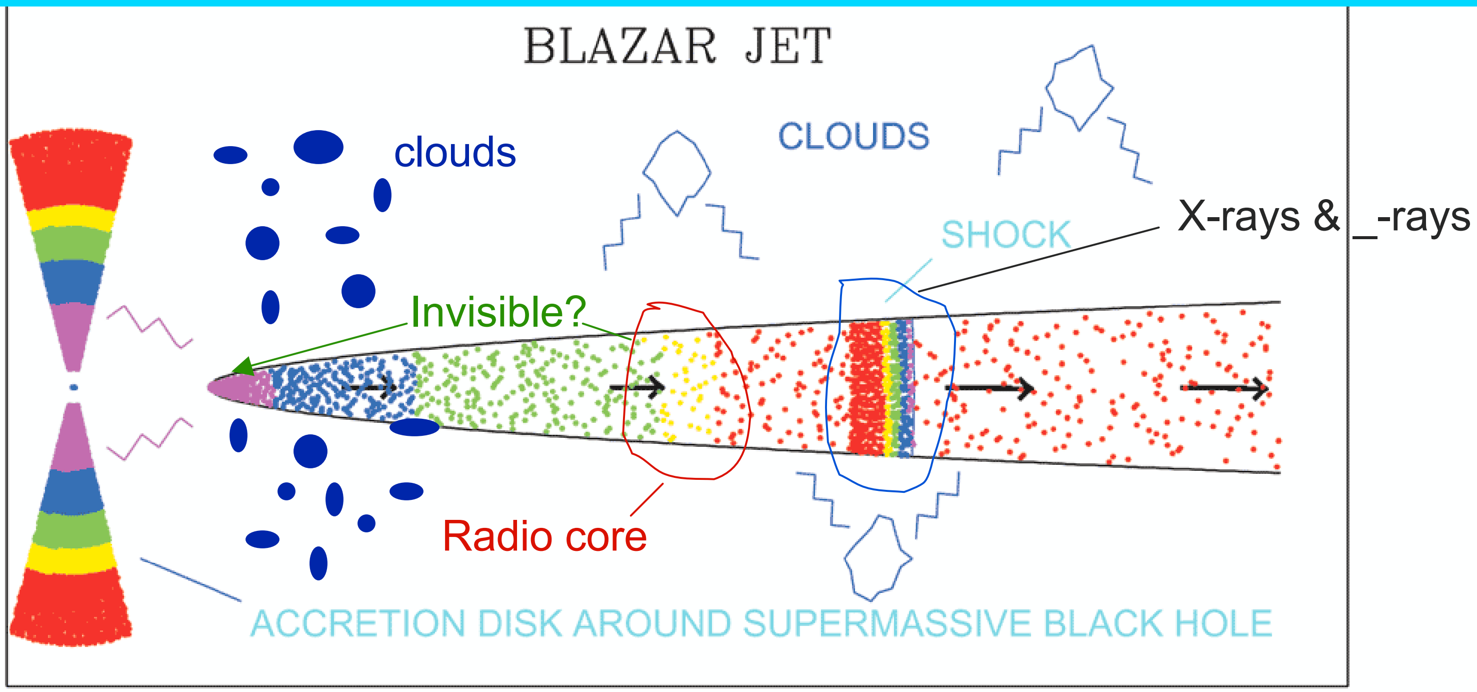
PKS 1510-089

Superluminal apparent motion
greater than 40c (2.1 milliarcsec/yr) (fastest confirmed speed)

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



Where Most X-rays & _-rays Are Emitted



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Seyferts, Low-Luminosity AGNs

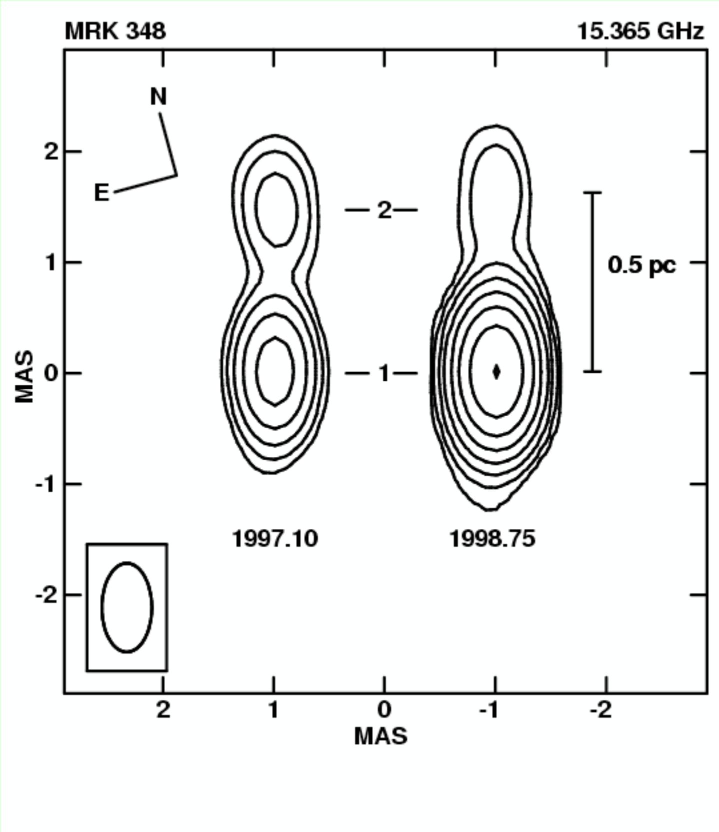
- Low-luminosity sources in nearby galaxies
  - Radio powers may be 10^{18} to 10^{22} W/Hz, while strong blazars are 10^{26} W/Hz or greater
  - Typical z=0.002 to 0.02, vs. z=0.2 to 2 for blazars
  - At d=16 Mpc, 7mm resolution is 0.013 pc
    - 2700 AU, or $1300r_g$ for 10^8M_{sun} black hole
  - Apparent speeds usually are subluminal
  - Radio variability may be 20-100% over year time scales

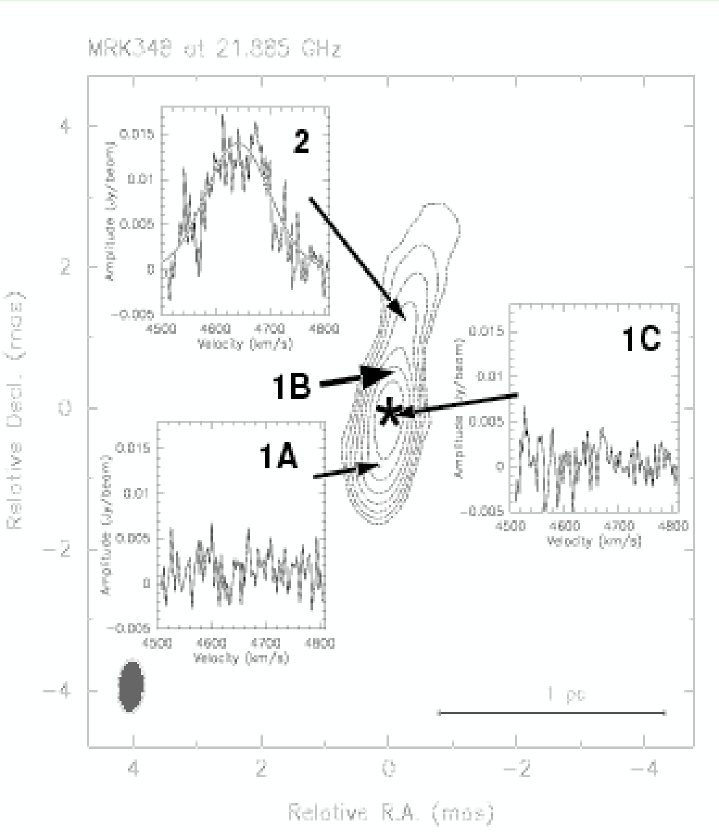
Seyfert, LLAGN Cores

- Why are Seyferts and LLAGNs different from radio quasars and radio galaxies?
  - Typical black hole masses are a few X 10^7 solar masses, 10-100 times lower than radio galaxies
  - Radiative efficiency must be reduced considerably
    - Advection-Dominated Accretion Flows? ADAF+Jet?
  - Mostly unresolved VLBA cores (Falcke et al. 2000; Ulvestad & Ho 2001b; Nagar et al. 2002)
  - VLA radio cores have flat spectra, unlike classical Seyferts (Ulvestad & Ho 2001a)
- At what level are they gamma-ray sources?

Mrk 348 (z=0.016)

- Continuum flared by factor 5
  - Speed 0.2c or less
  - (Ulvestad et al. 1999)
- Water maser flare in March 2000 (Peck et al. 2003)
- Component separation at 0.4c



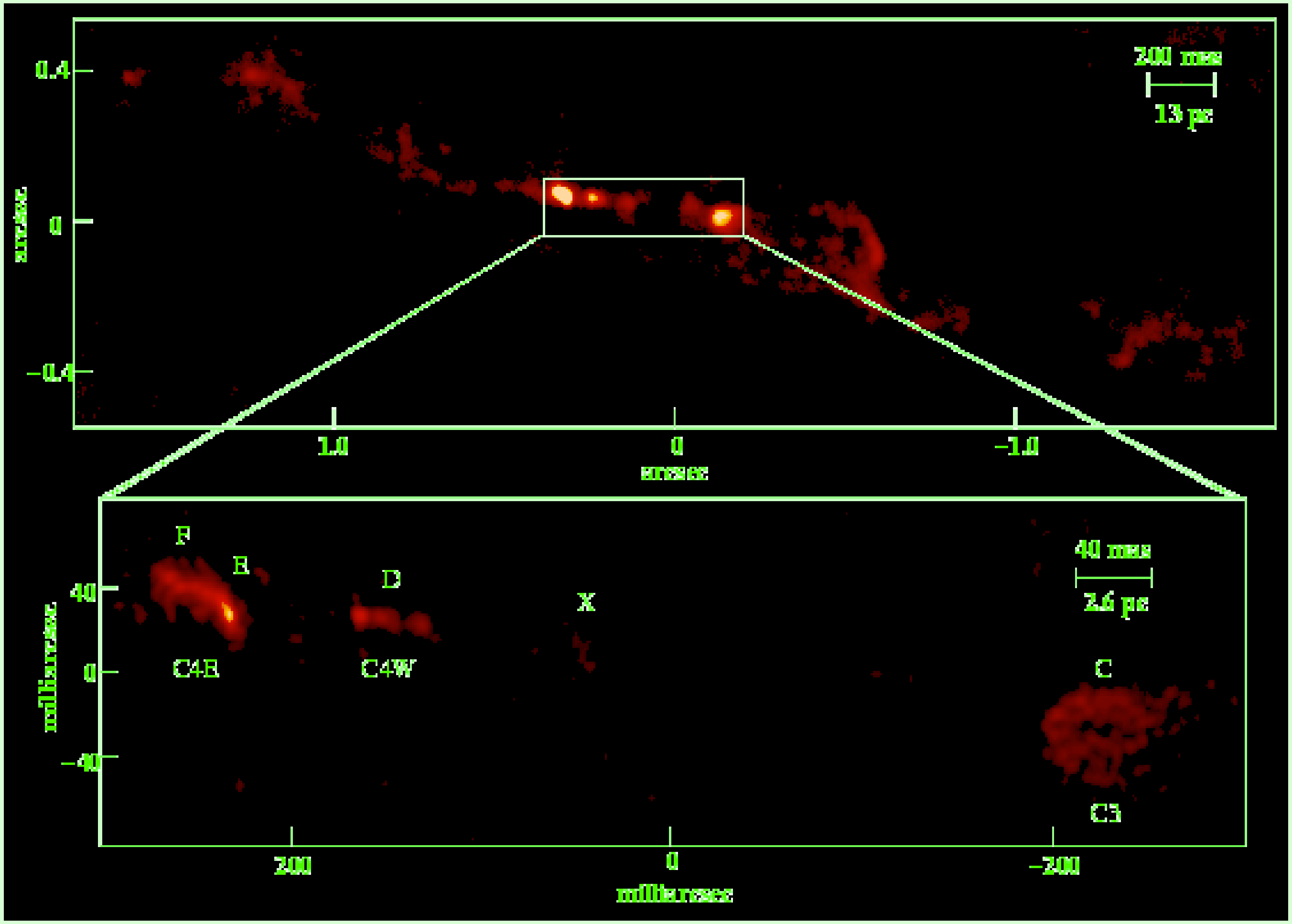


NGC 4151 ($z=0.003$)

- Nearby classical Seyfert galaxy reportedly detected in soft gamma rays by balloon flights in late 1970s (Perotti et al. 1979, 1981)
  - L(0.5-5 MeV) ~ $10^{44.5}$ to 10^{45} ergs/s?
  - Variability by factors of a few in hard X-rays and gamma rays, over a year
  - Hard photons originate within 0.1 pc of AGN?
- Will Seyfert class be detected by LAT?

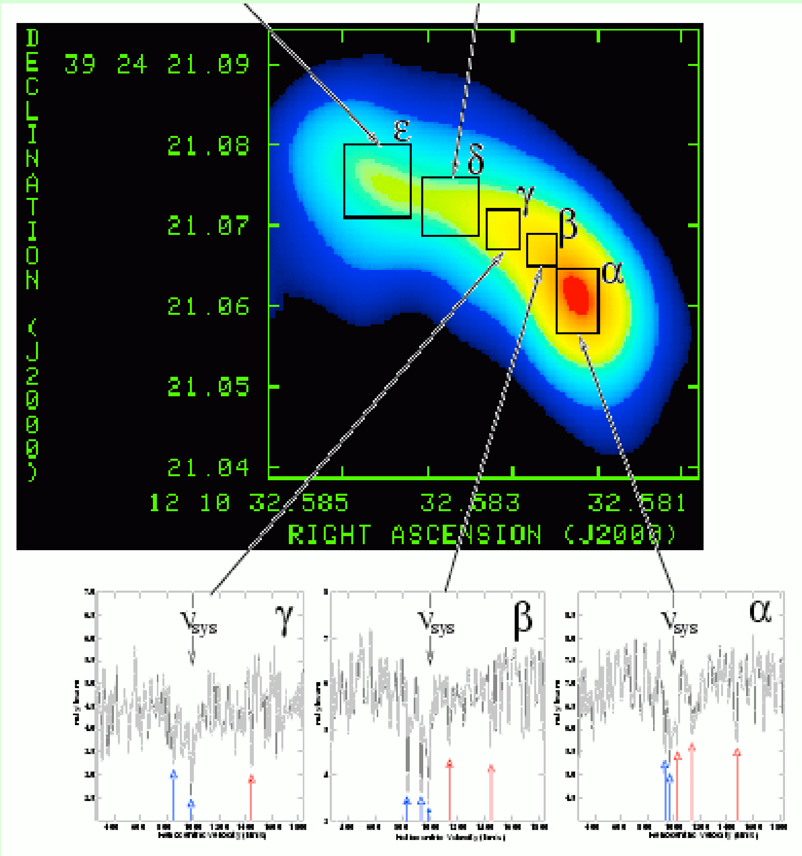
Jet-Cloud Interactions in N4151

- VLBA 21cm continuum (Mundell et al. 2003)

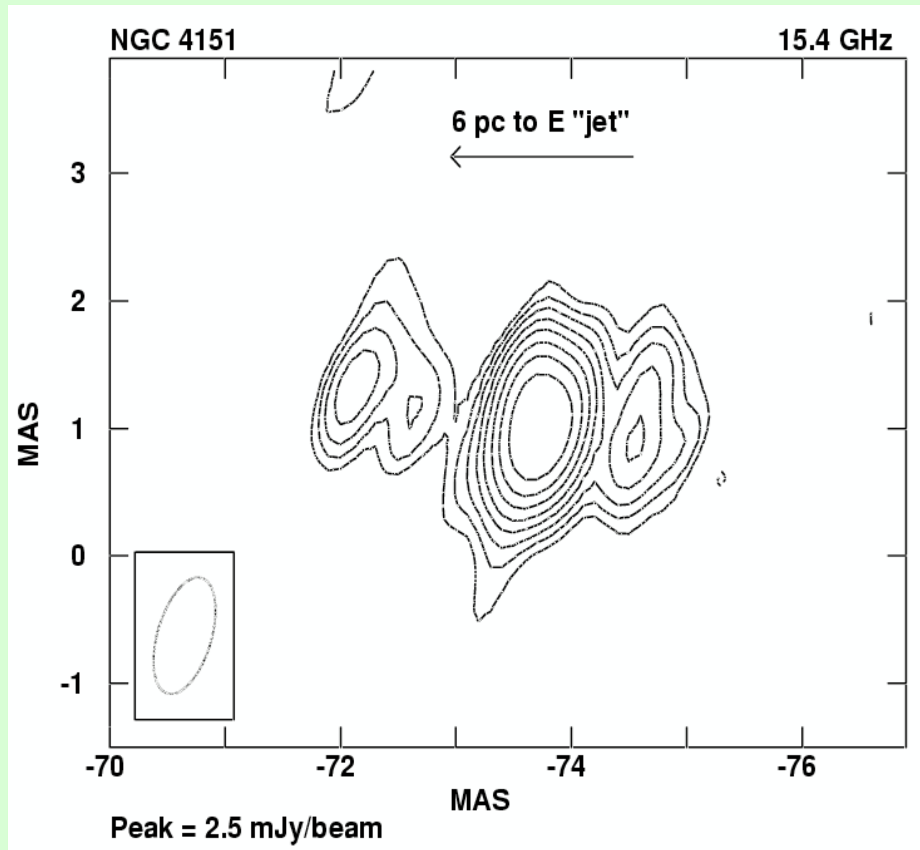


The Jet and Nucleus of NGC 4151

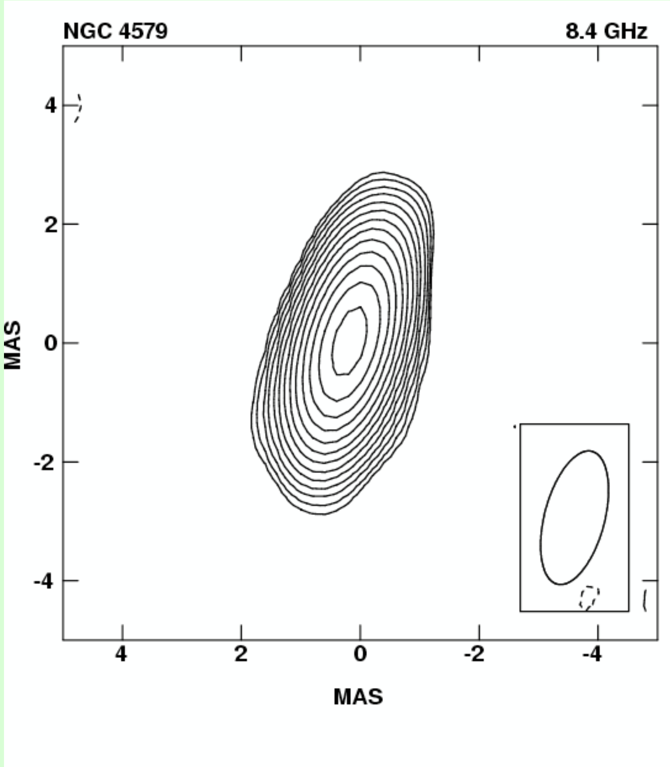
Mundell et al. 2003
Comp. "C4E" or "E"

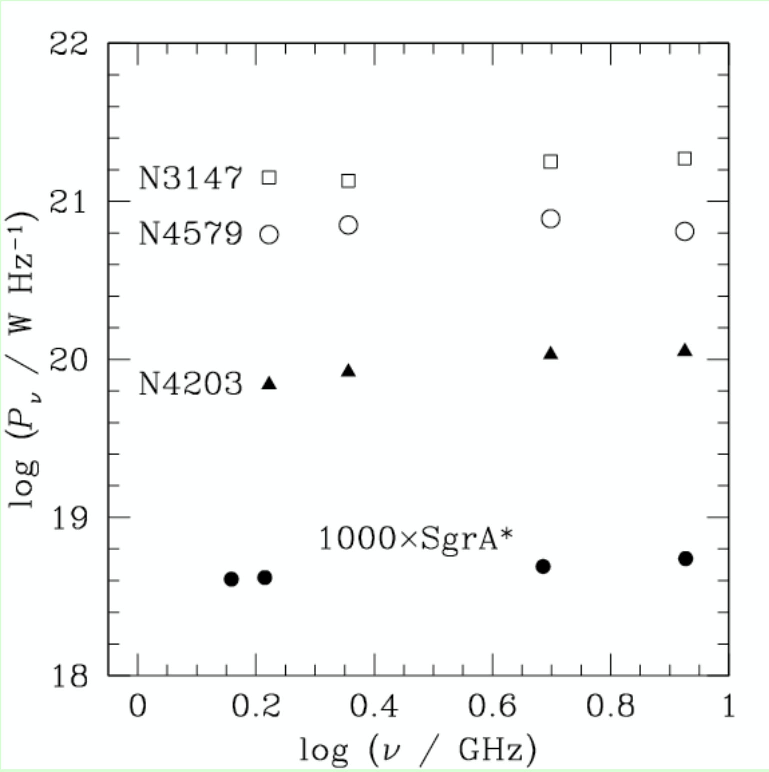


Ulvestad et al. 2003
Comp. "C4W" or "D"



Low-Lum. Seyfert VLBA Cores

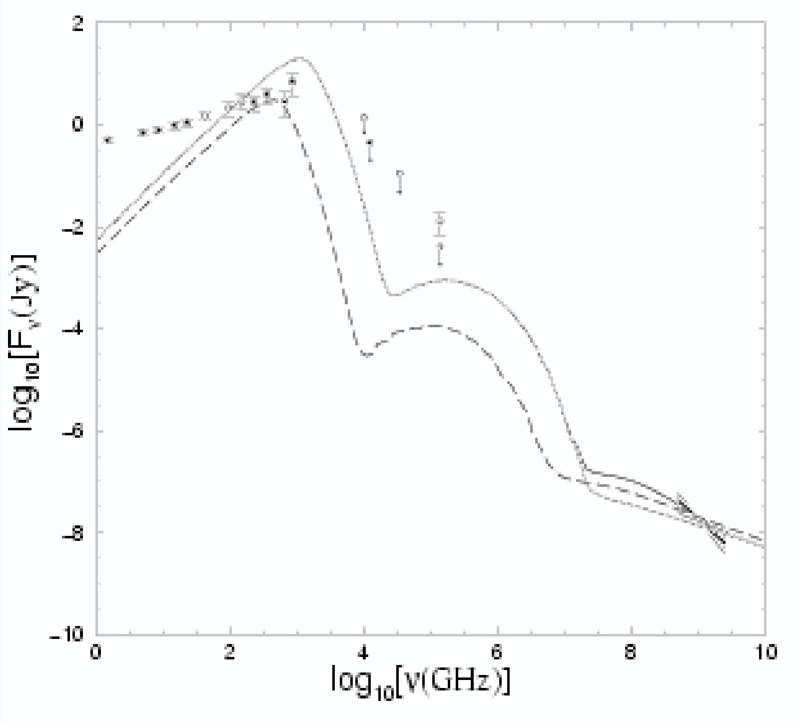




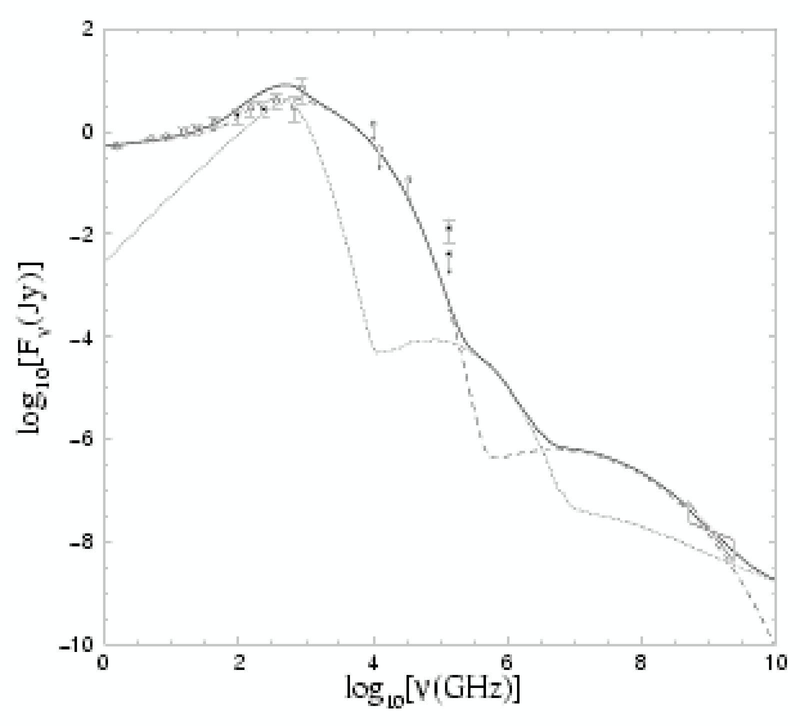
- Unresolved, rising spectra (Ulvestad & Ho 2001b)
  - Radio/X-ray wrong for ADAFs
  - Size upper limits of a few thousand R_g

Comparison of ADAF and Jet Models for Sgr A* (Yuan et al. 2001)

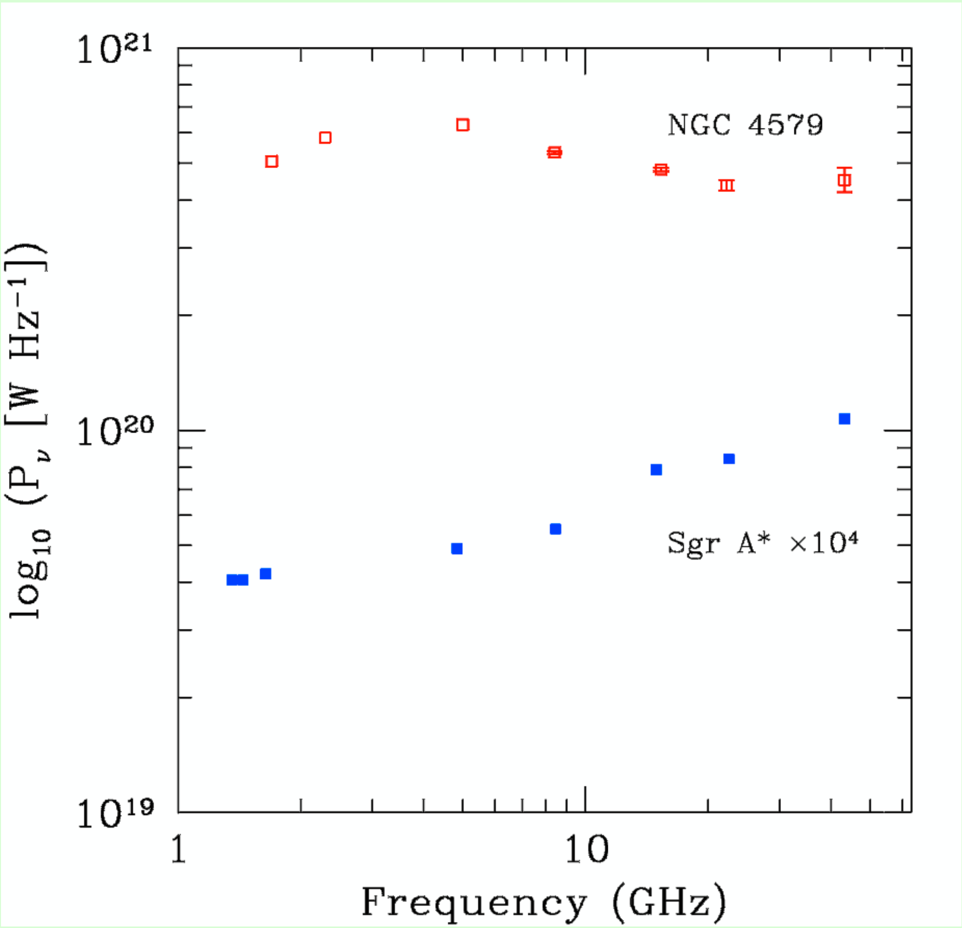
ADAF only



ADAF + Compact Jet



VLBA Spectral Analysis



- NGC 4579 luminosity turns over at 5 GHz
- $\alpha^{5.0}{}_{1.7} \approx +0.2$
- $\alpha^{22}{}_{5.0} \approx -0.25$
- Inconsistent with ADAF spectrum
- 8 GHz luminosity suggests accretion at half the Eddington rate, violating the ADAF assumptions
- May be consistent with jet model???
- J. Anderson, thesis, in prep.

Gamma Rays from LLAGNs

- LLAGNs probably harbor compact jets
  - Sizes of a few tens of Schwarzschild radii (tens of microarcseconds)
  - Jets may or may not be beamed, but are quite nearby
  - If gamma-ray/radio ratio is similar to EGRET blazars, expect that gamma-ray emission from some LLAGN cores will be detectable

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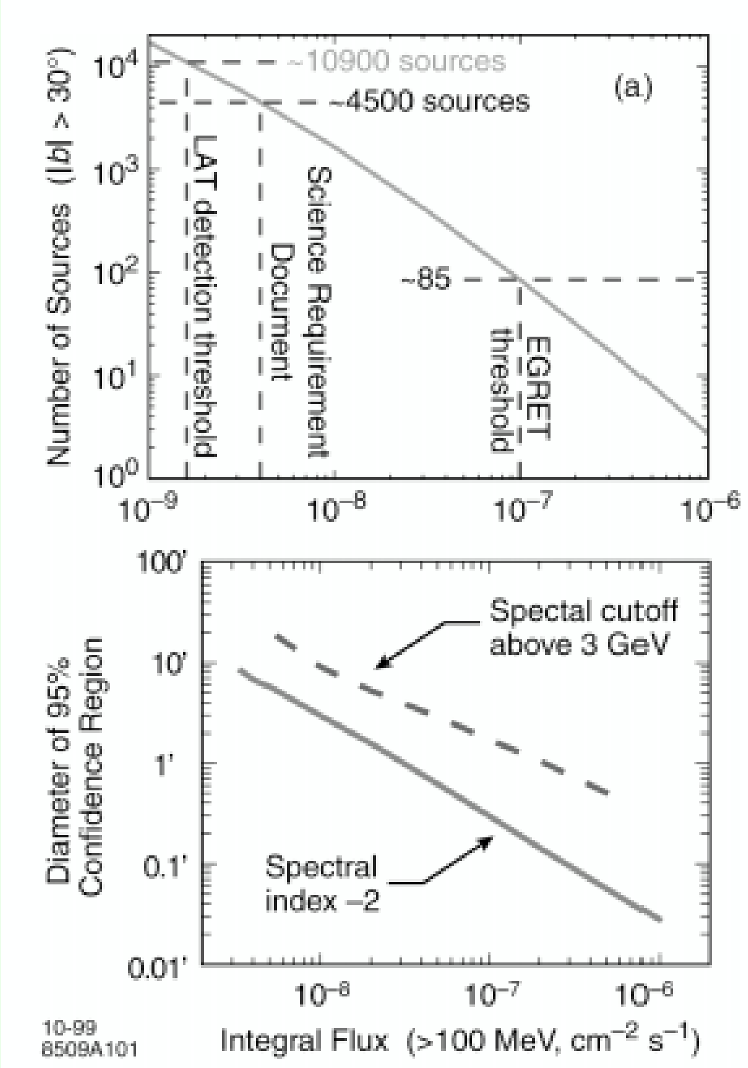
Identification of LAT sources

- Large Area Telescope aboard GLAST should detect ~5,000 extragalactic sources
  - Sources likely will show strong gamma-ray variability
  - How can accurate positions be derived, and identification with objects seen at other wavelengths?
    - Key may be compact, optically thick radio emission
    - Sub-arcsecond radio positions easily obtained

LAT Source Count Predictions

- LAT will detect several thousand sources with 1-10 arcmin position errors
- Density of flat-spectrum radio sources above 30 mJy is 1-2 per square degree



AGN Number Density

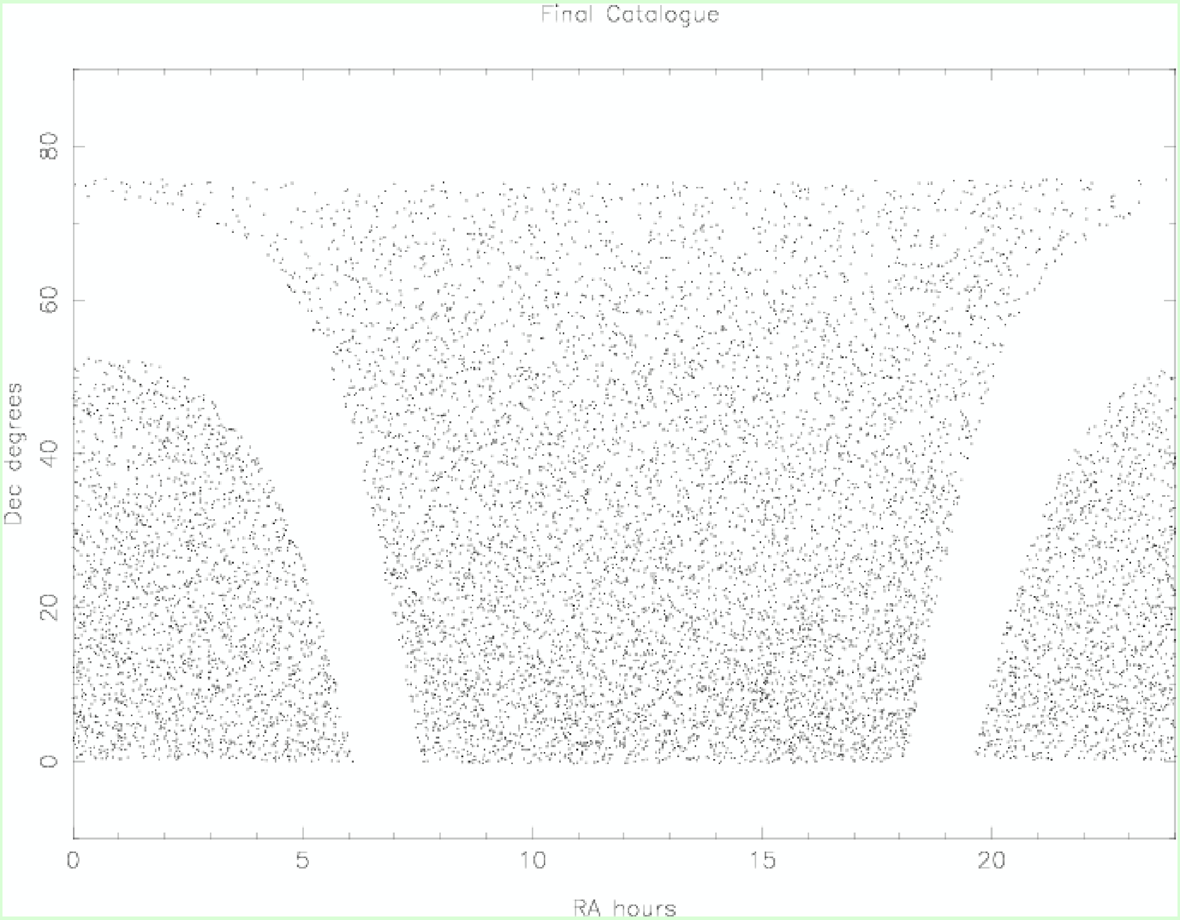
- Sloan Digital Sky Survey—1st release in January 2003
  - 3000 square degrees
  - 30,000 quasars: 10 per square degree
  - 120,000 galaxies: 40 per square degree
    - 26,000 active galaxies
- Aim to survey 10,000 square degrees
- Significant “confusion” likely in identification of LAT sources near detection threshold

Gamma Ray/Radio Correlation?

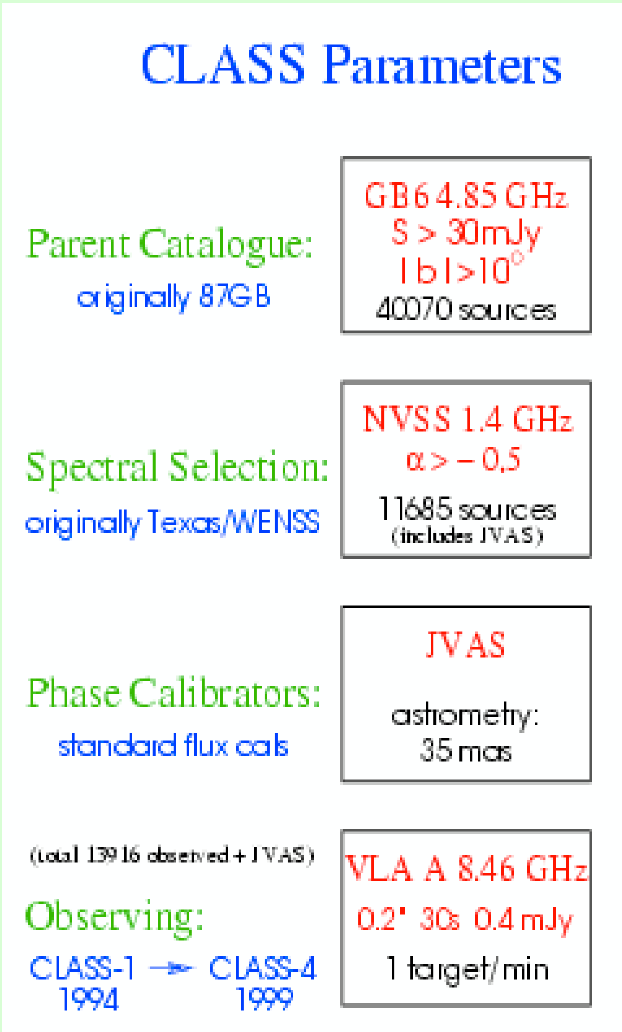
- EGRET blazars show correlation with flat-spectrum radio sources above 1 Jy (Mattox et al. 1997)
  - Radio vs. gamma-ray flux density for high-confidence identifications is a scatter plot
  - However, at a given radio flux density, peak gamma-ray flux varies by 1.5 orders of magnitude, and vice versa
  - Possible correlation of gamma-ray peak with compact VLBI flux
- For 30 times weaker gamma-ray sources, is there a correlation with flat-spectrum radio sources above 30 mJy?

Flat-Spectrum Radio Sources

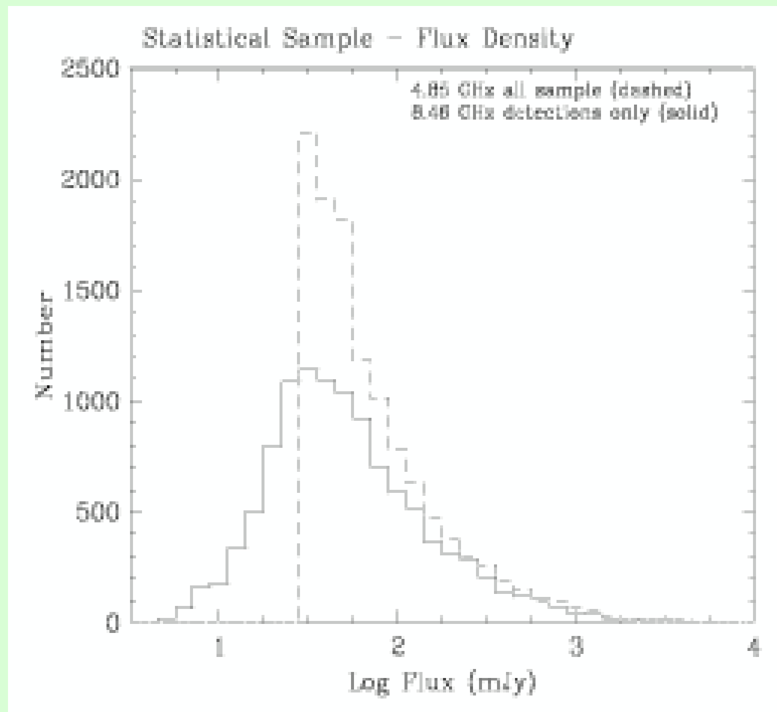
- CLASS gravitational lens search surveyed 16,521 sources (Myers et al. 2003)
- Complete sample of 11,668 flat-spectrum sources above 30 mJy



Compact CLASS Sources



- Many CLASS candidates have sub-arcsecond components
- Compact flux densities permit routine VLBA imaging



Will CLASS Flat-Spectrum Sources be Gamma-Ray Sources?

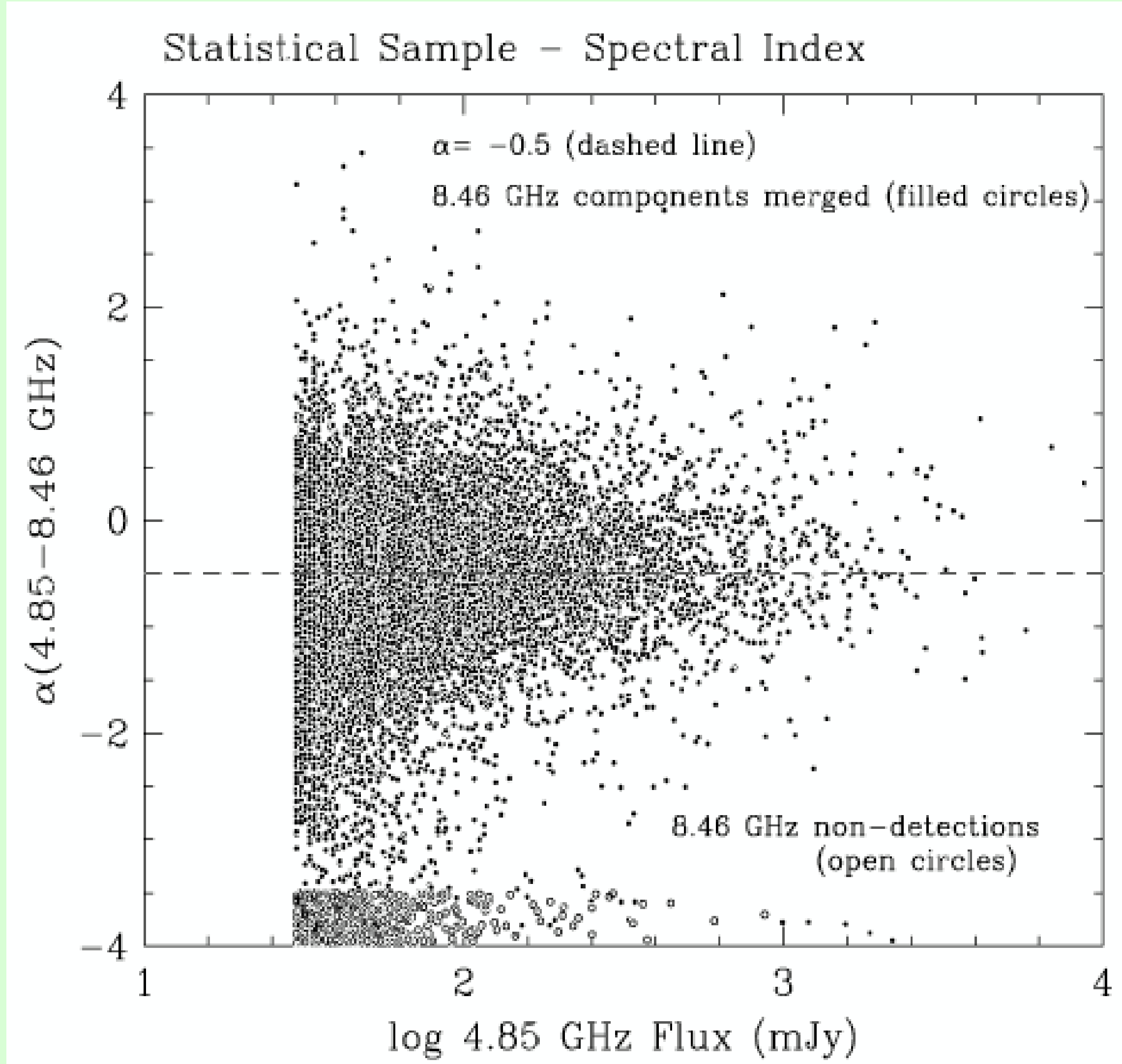
- Many CLASS candidates are likely to be counterparts to LAT sources, but which ones?
  - Beamed sources are most likely
  - Expect one-sided milliarcsecond jets, not CSOs
  - Highly polarized jets
- Remember, we don't really know what AGN types the LAT will detect!

VLBA Imaging and Polarimetry Survey (VIPS)

- Multifrequency polarimetric VLBA imaging of 1000 CLASS sources above 50 mJy, with dynamic range of 100:1 or better
  - 5 and 15 GHz observations, 1.5 hours total per source, spread over several years
  - Single epoch
  - In sky region covered by Sloan Digital Sky Survey, so optical information will be available
  - Envision completion by 2006

Sources Available for VIPS

- About 1500 CLASS targets are available in the region to be covered by the SDSS
  - ∗ > 20 deg. so good VLBA imaging is possible
- Expect ~600 LAT sources in the same region



Some VIPS/LAT Connections

- Wealth of information for modeling and follow-up
- Full-Stokes reference images
  - Predictions of likely gamma-ray detections?
  - Useful for follow-up (e.g., jet speed measurements) after gamma-ray flares
  - Faraday rotation and intrinsic magnetic fields
- Efficient study of optical (and other) counterparts
  - Quantitative comparisons of quasars, galaxies, and BL Lac objects
  - Multi-band spectral energy distributions
  - Gamma-ray luminosity functions (needs redshifts)

VIPS Status/Timeline

- Pilot proposal submitted October 1 to image 100 sources in 150 hours of VLBA observations
  - PI: Chris Fassnacht, UC Davis
    - Co-Is: Gehrels (GSFC); Michelson (Stanford); Fomalont, Myers, Sjouwerman, Taylor, Ulvestad, Walker, Wrobel (NRAO); Readhead, Pearson (Caltech);
  - Requested 8 x 19 hours in 2003
  - Test pipeline processing, observing strategy
- Large proposal submission in October 2003
  - Anticipate request for 850-1000 hours in 2004/’05/’06
  - Pre-launch follow-up of most interesting sources?
  - Rich data source for Ph.D. dissertations …

Summary

- VLBA is the only full-time milliarcsecond imaging tool available for high-energy sources
  - Can image near scale of the gamma ray emission
  - Distinguish gamma-ray emission models
  - Follow up new classes of extragalactic gamma-ray emitters (e.g., LLAGNs)
  - Enable identification and study of many weak gamma-ray sources
  - Multi-year VIPS program necessary to be “ready” for GLAST launch
- Large potential for a variety of combined GLAST/VLBA programs