High-energy view of AGN

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High-energy emission the defining characteristic of an AGN.
But emission complicated, many unanswered questions

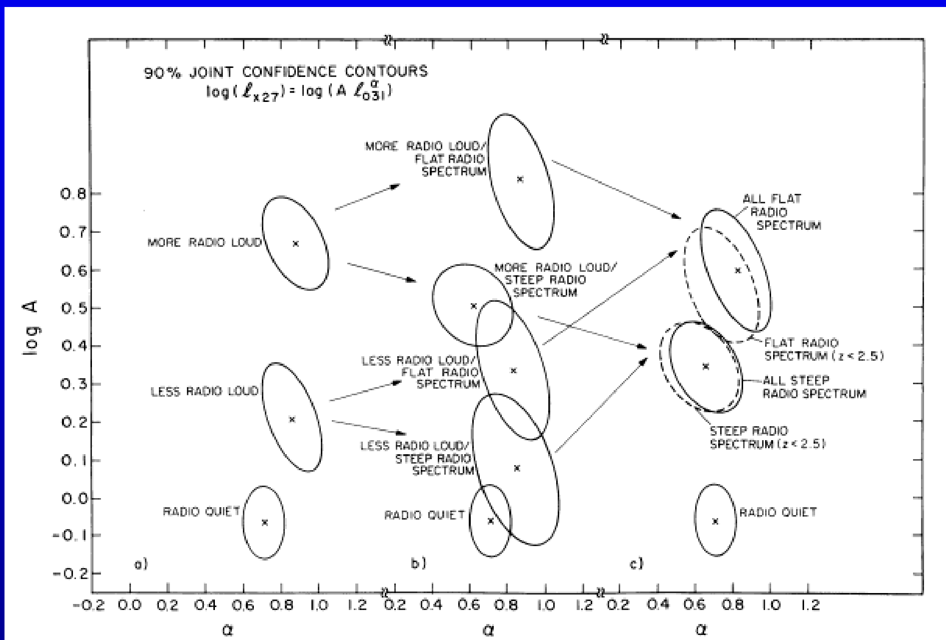
Most complicated – those with radio jets.
Need to peel off the jet to reveal central engine.

Chandra-resolved jet components inform interpretation of the unresolved structures

Two important discoveries of late '70s

First: Radio-loud quasars brighter X-ray sources than radio-quiet for given optical luminosity

Ku et al. 1980, Zamorani et al. 1981



Dependence of X-ray luminosity & spectrum on beaming angle:

$$X = X_{RQ} + X_{RL}$$

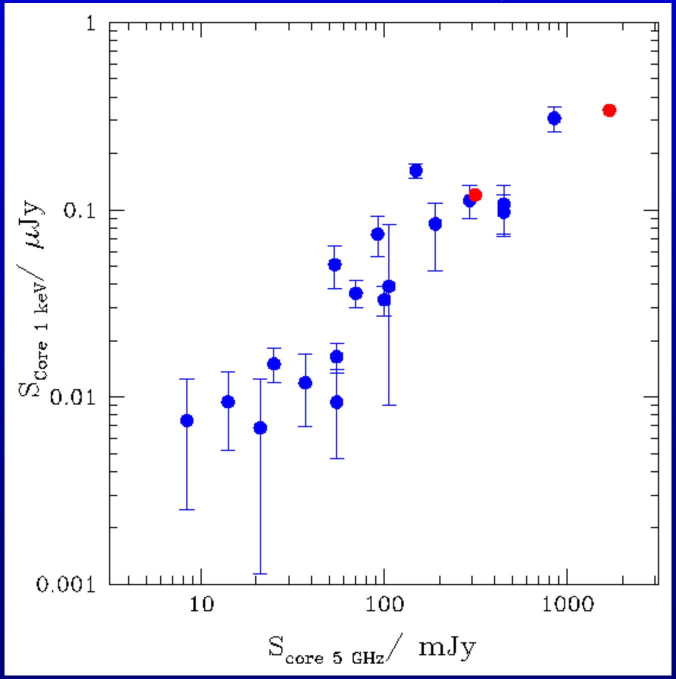
Zamorani 1984, Browne & Murphy 1987, Worrall et al. 1987, Wilkes & Elvis 1987, Canizares & White 1989, Kembhavi 1993, Shastri et al. 1993

Accretion-related X-rays different in radio-loud & radio-quiet quasars, even if both are at high Eddington accretion effic?

Second: Radio-X-ray correlation in fainter non-beamed objects. Fabbiano et al. 1984

Supported by ROSAT observations that largely separated out thermal emission from host galaxies & clusters
Worrall & Birkinshaw 1994, Canosa et al. 1999

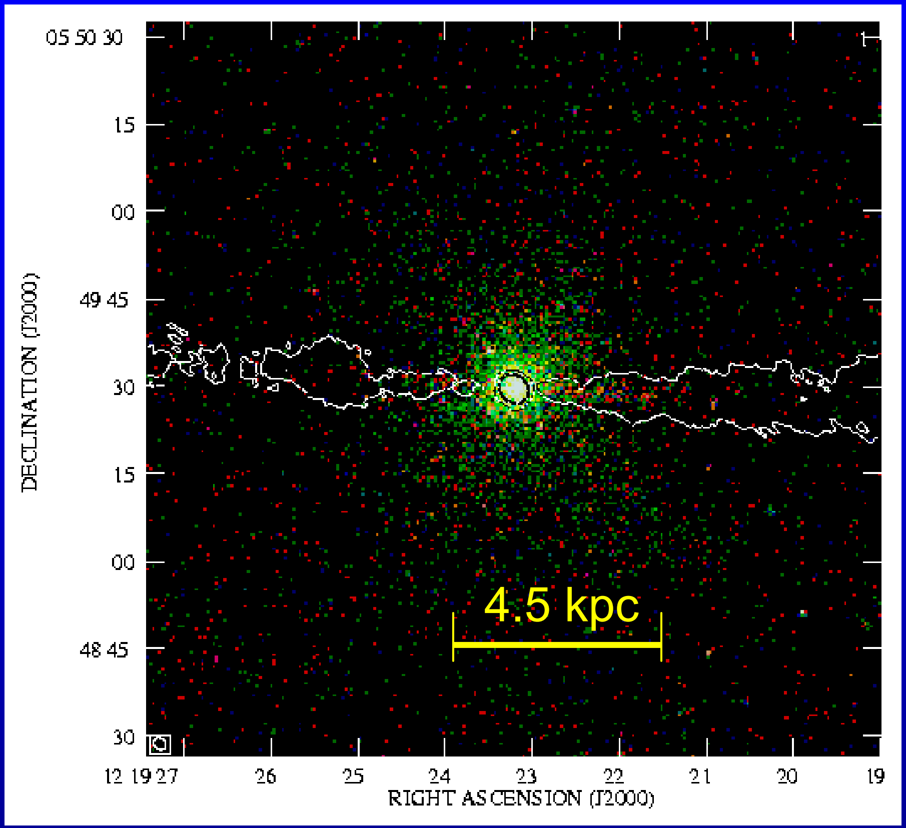
- central-engine X-rays correlated to radio loudness, or
- observing inner jet emission and
    - central engine obscured, or
    - central engine weak



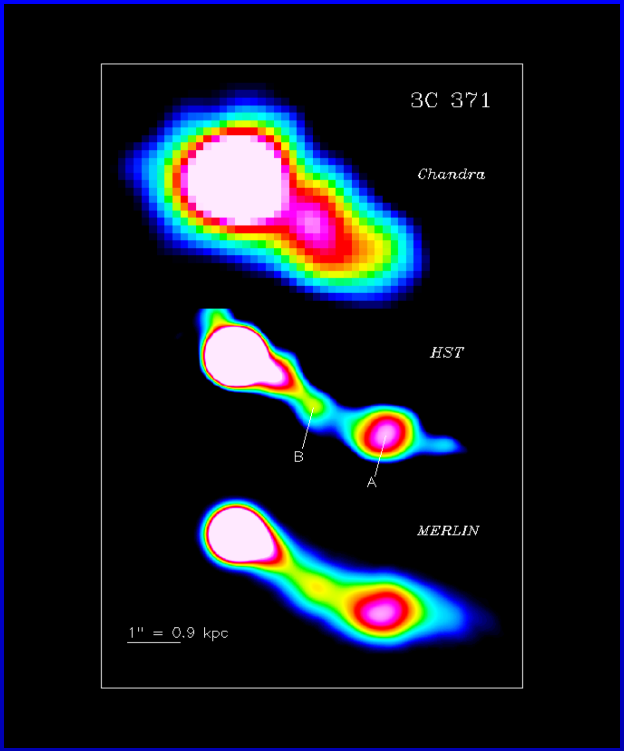
Low-redshift sources provide the best linear resolution

BL Lac objects

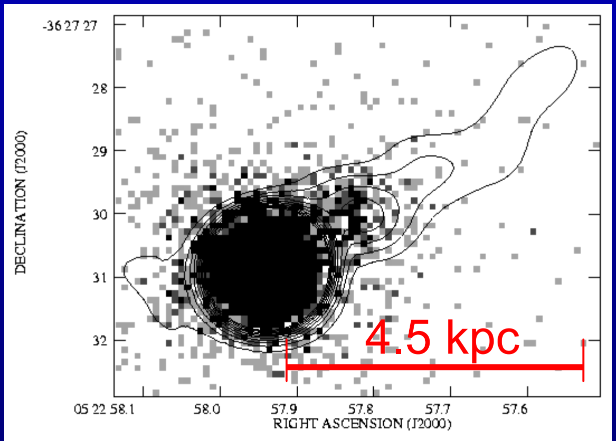
Twin-jet radio galaxy



e.g., NGC 4261
Chiaberge et al. 2003
Zezas et al. 2003



e.g., 3C 371
Pesce et al. 2001



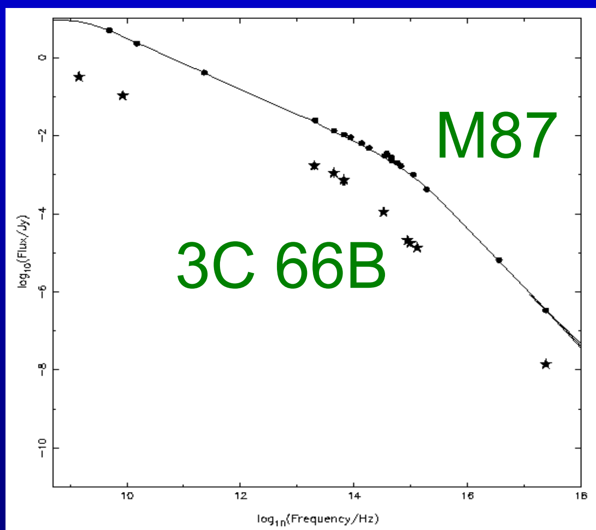
e.g., PKS 0521-365
Birkinshaw et al. 2002

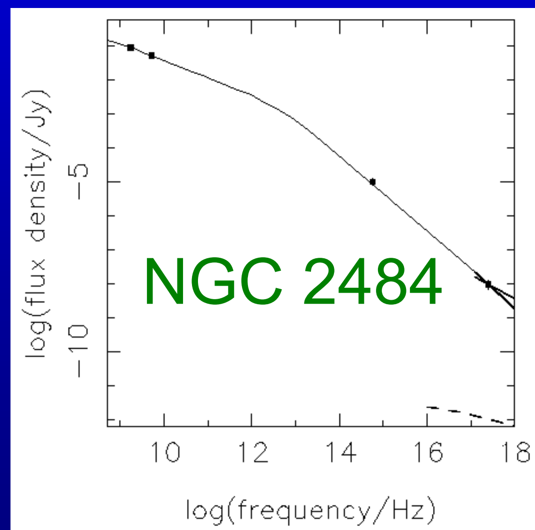
Selection effects: mostly predominantly one-sided jet sources. Known optical jet sources over-represented

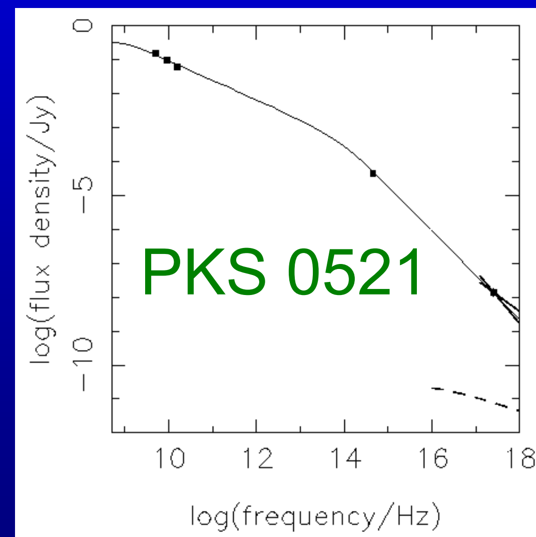
Chandra results

- Resolved X-ray jets typically found. Better contrast with galaxy emission than in optical to depth of HST snapshots.
- Broken power law fits spectrum interpolated through radio, optical, X-ray, integrating over X-ray region.

X-ray spectrum typically too steep for iC → synchrotron





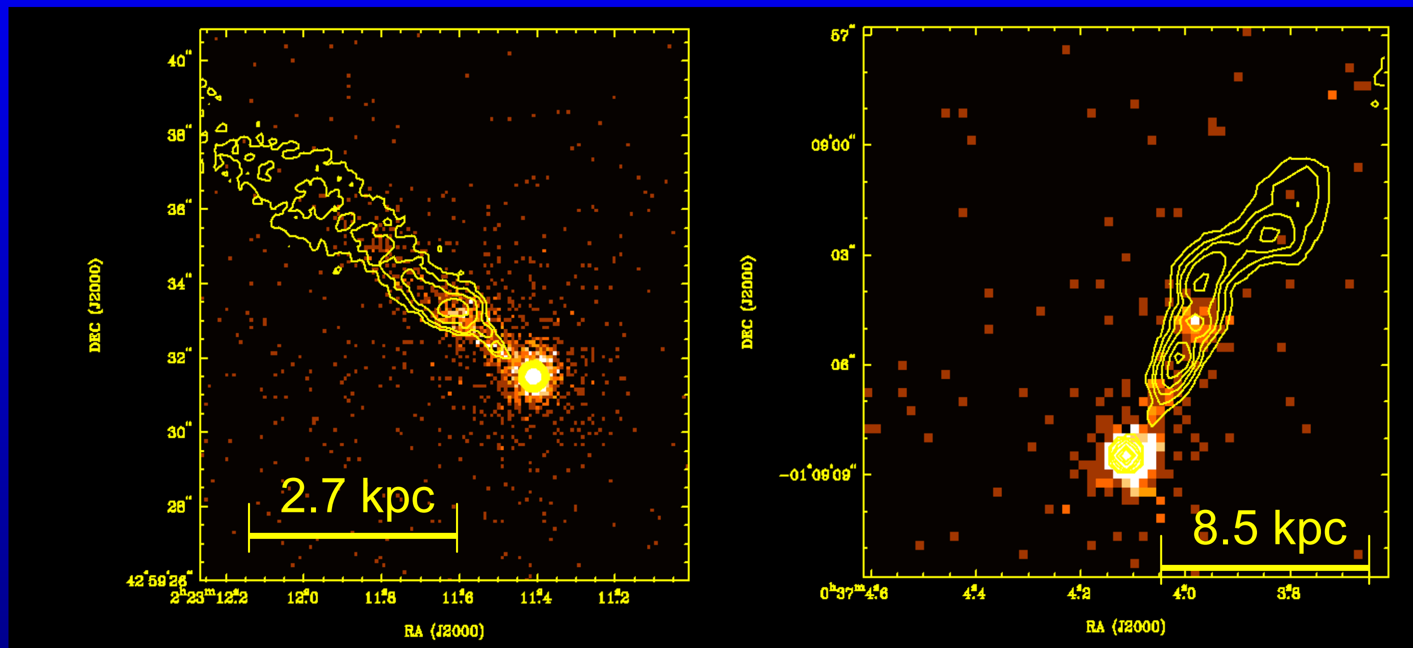


Böhringer et al., Hardcastle et al., Worrall et al. 2001, Birkinshaw et al. 2002.

But,

- Spectral break too large for simple continuous injection & energy-loss model
- Distinct offsets between X-ray & radio peaks, with X-rays typically closer to the core

e.g., Hardcastle et al. 2001, Kataoka et al. 2003

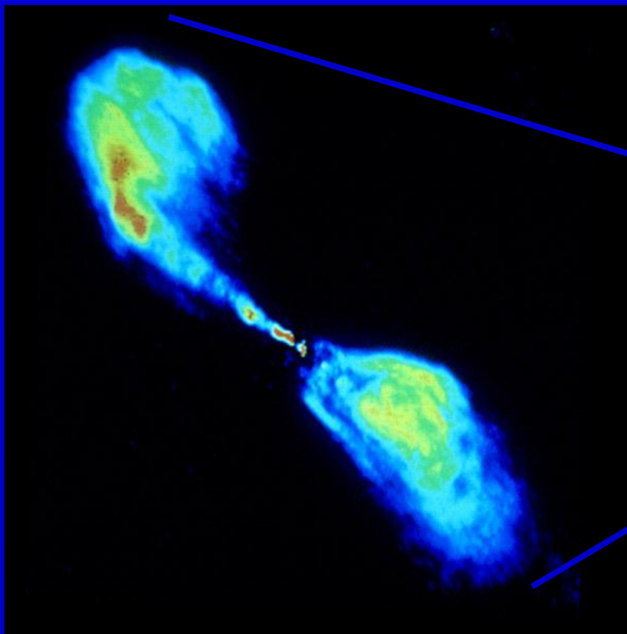


Points related. B_{min}~ 100μG. Electron lifetime tens of years $\rightarrow$ in situ (shock) acceleration. Spectra & images integrations

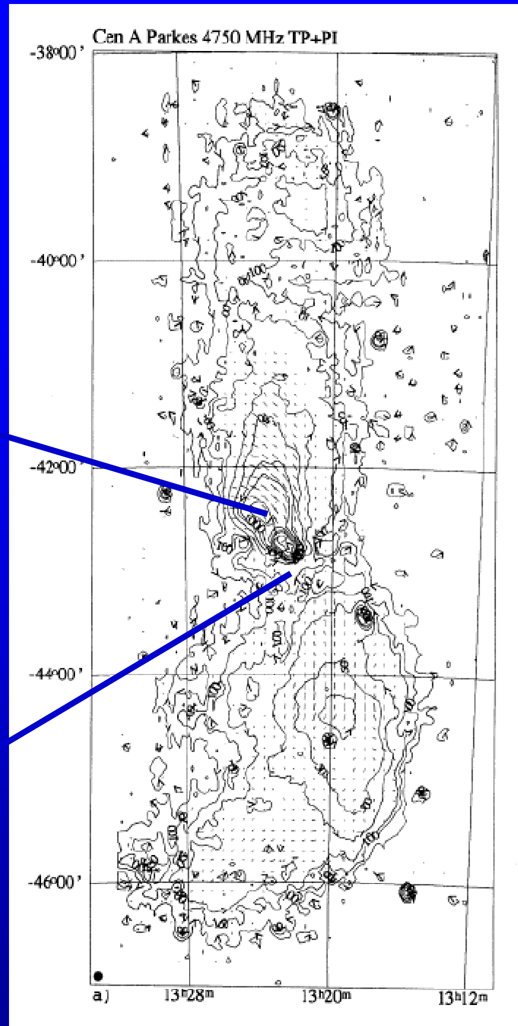
Burns et al. 1983, Junkes et al. 1993.

Cen A

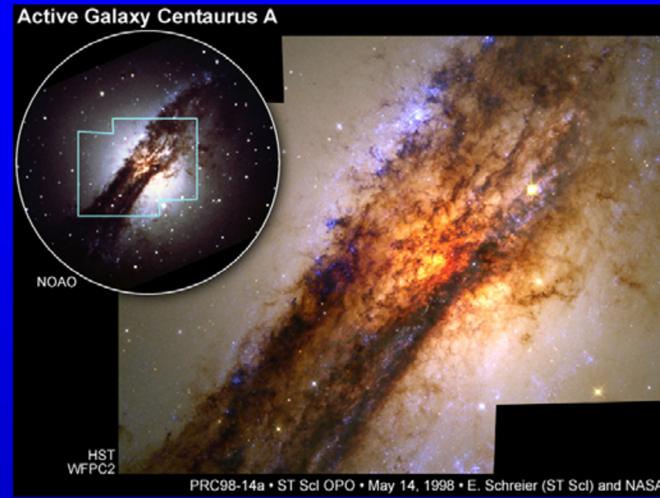
1 arcsec = 17 pc

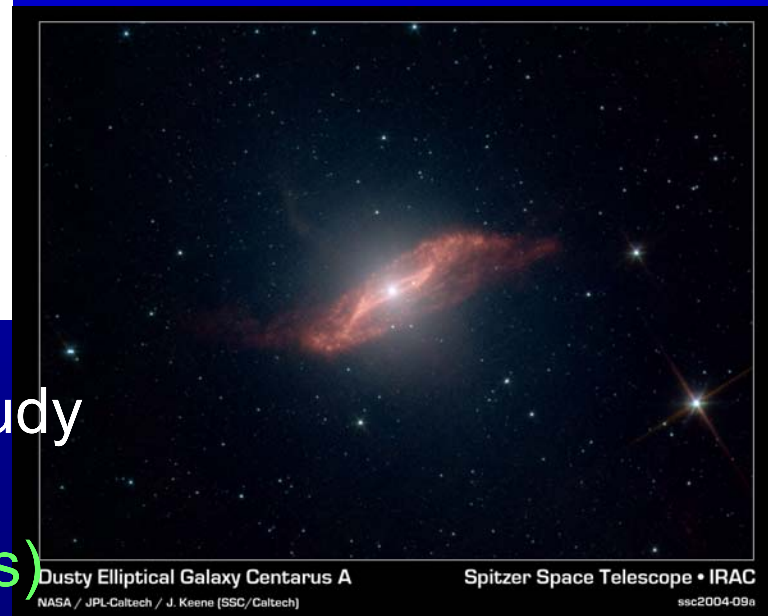


12 kpc



500 kpc



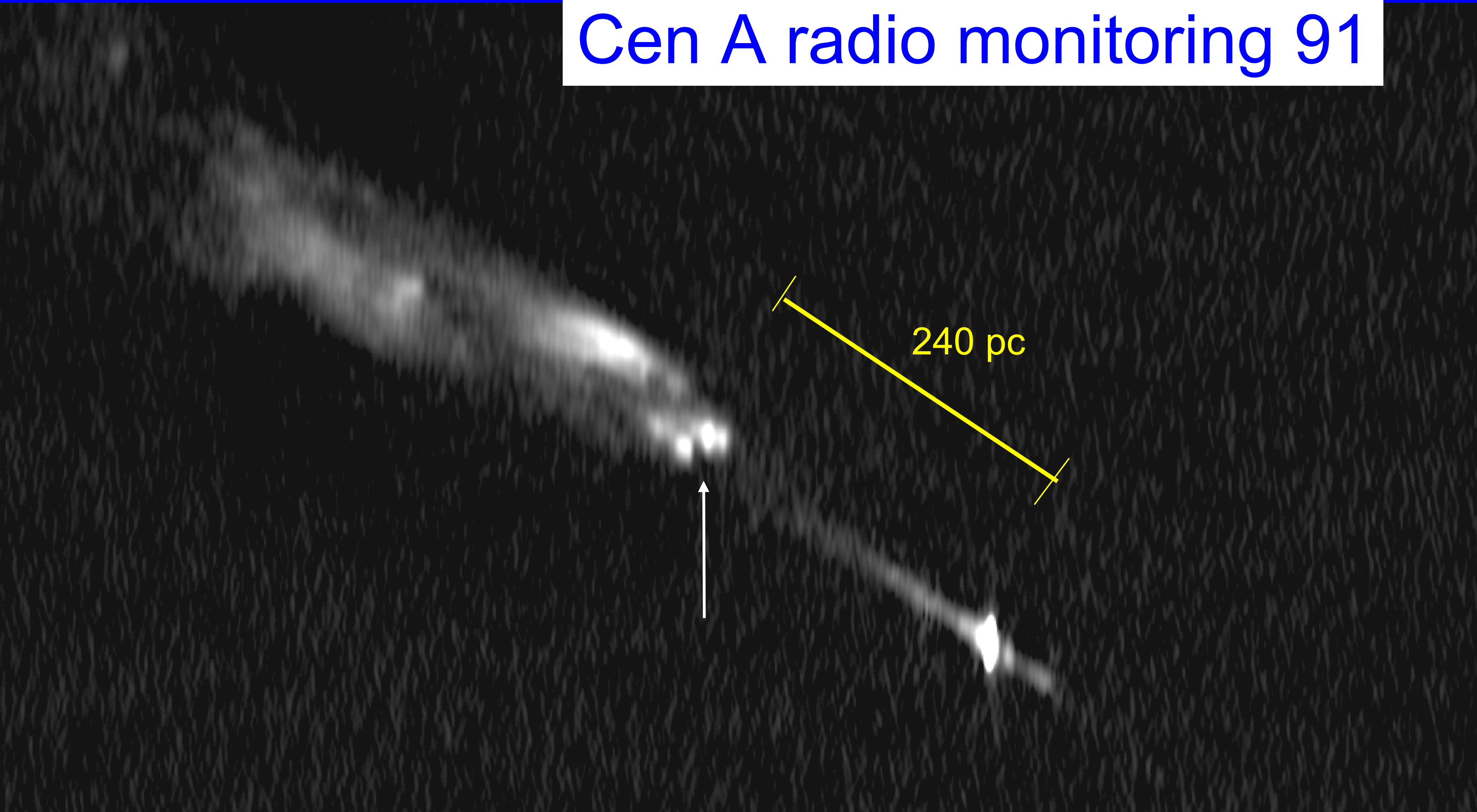


Ongoing comprehensive multi-wavelength study

Kraft, Jones, Forman, Murray (SAO)

Birkinshaw, Worrall (Bristol) Hardcastle (Herts)

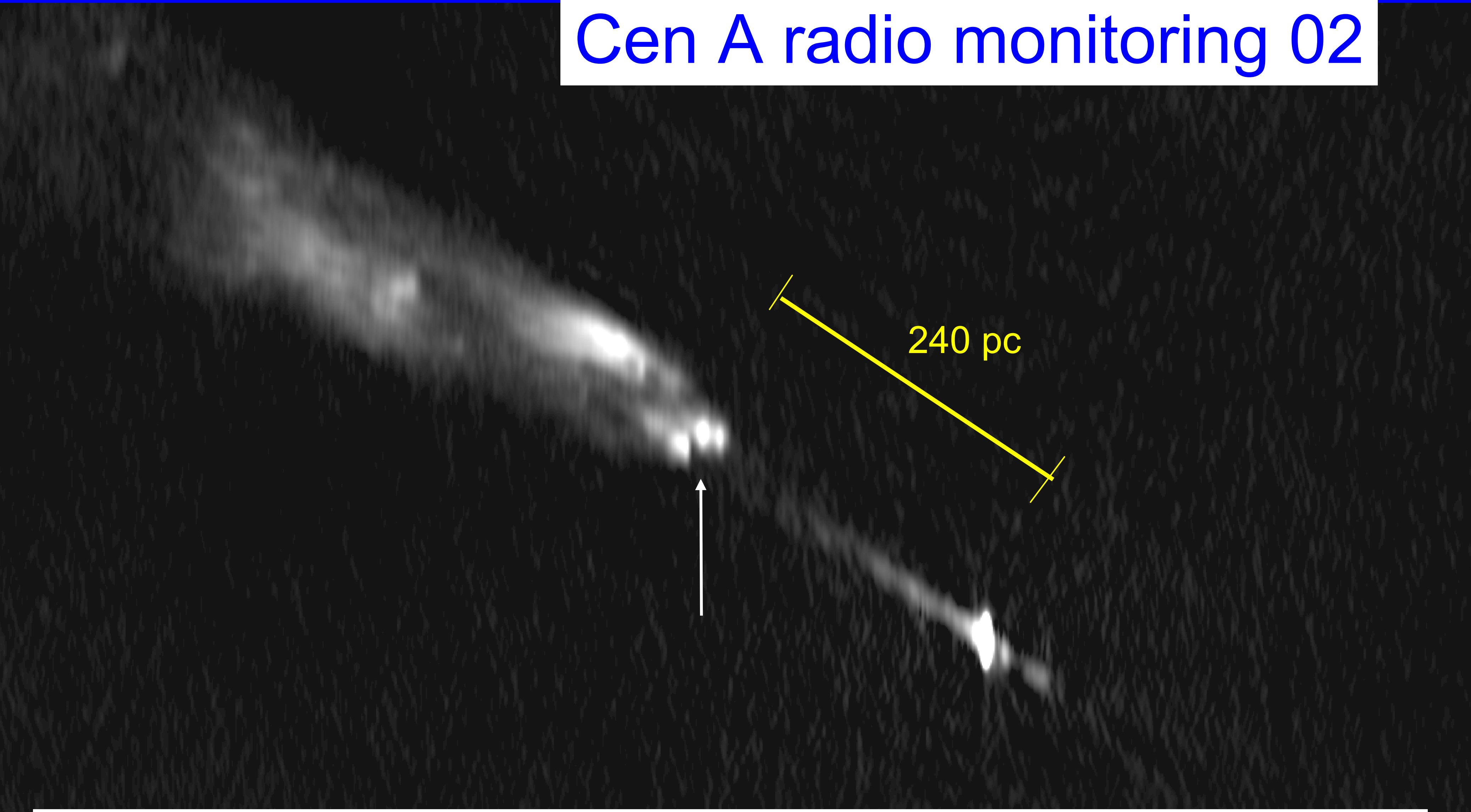
Cen A radio monitoring 91



VLA 8.4 GHz A & B array: 1991 archival, 2002 new. Dynamic range 120,000:1. Proper motions: v_{app} ~ 0.5c. If θ ~ 50°, jets asymmetric.

Hardcastle et al. (2003).

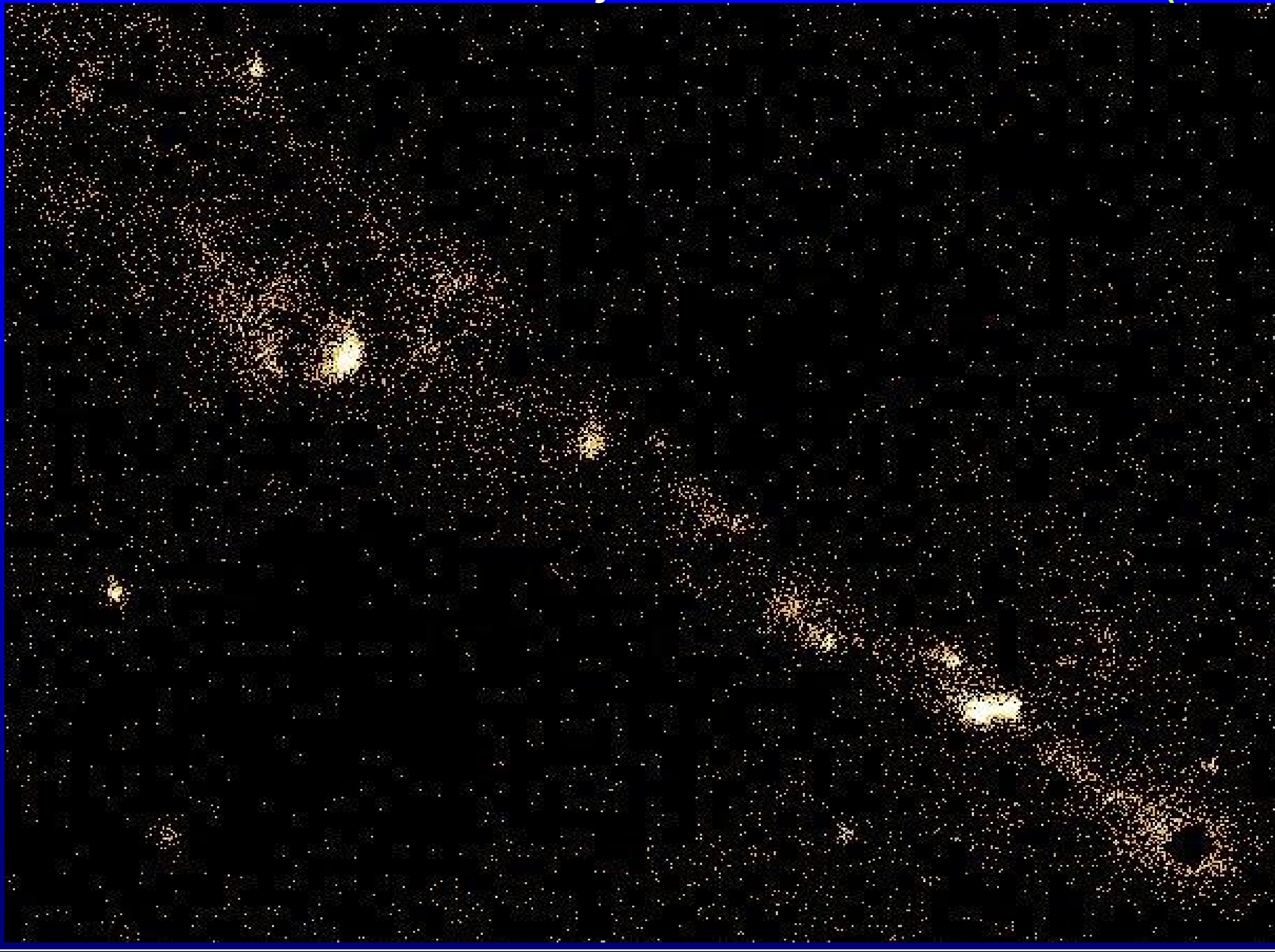
Cen A radio monitoring 02



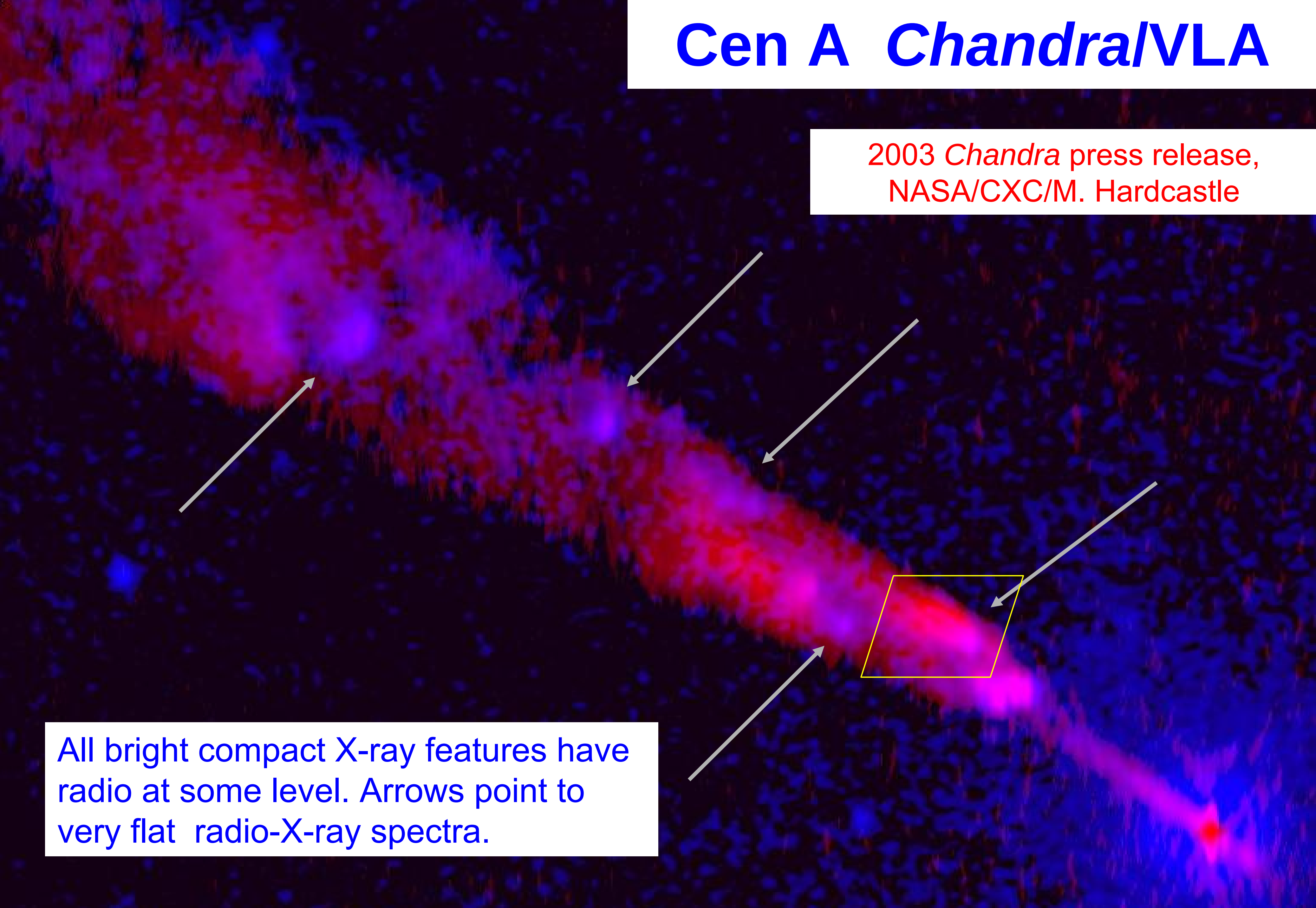
VLA 8.4 GHz A & B array: 1991 archival, 2002 new. Dynamic range 120,000:1. Proper motions: v_{app} ~ 0.5c. If θ ~ 50°, jets asymmetric.
Hardcastle et al. (2003).

Chandra ACIS-S 45 ks X-ray

Jet and weak counter-jet Hardcastle et al. (2003)



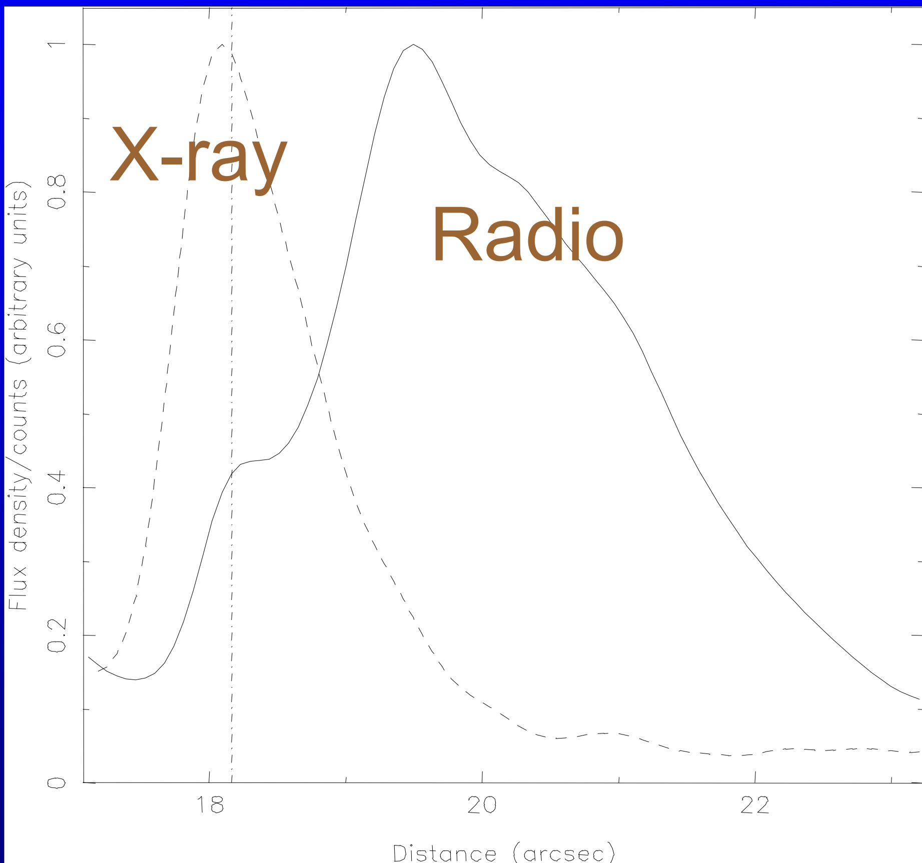
Cen A *Chandra*/VLA



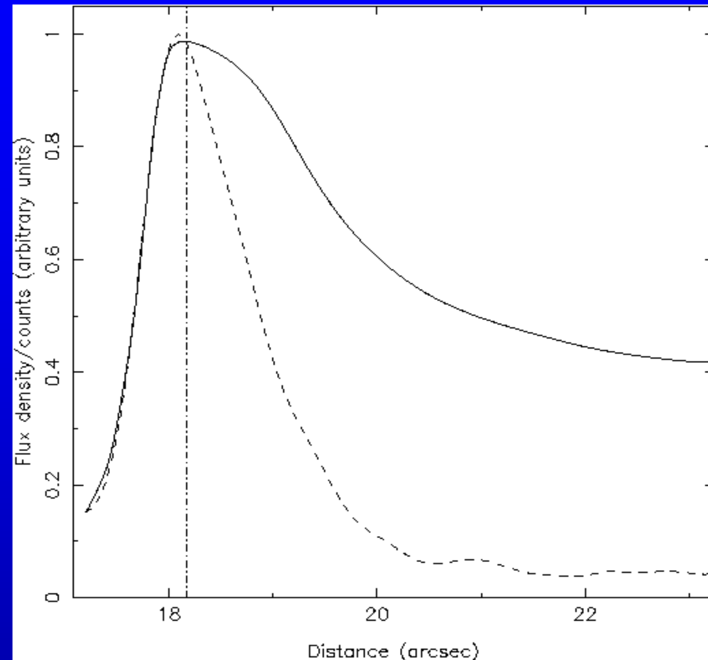
2003 *Chandra* press release,
NASA/CXC/M. Hardcastle

All bright compact X-ray features have radio at some level. Arrows point to very flat radio-X-ray spectra.

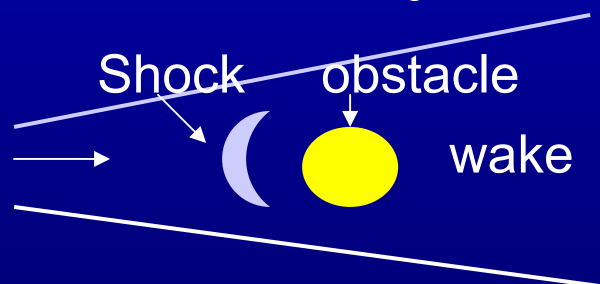
Knot profile



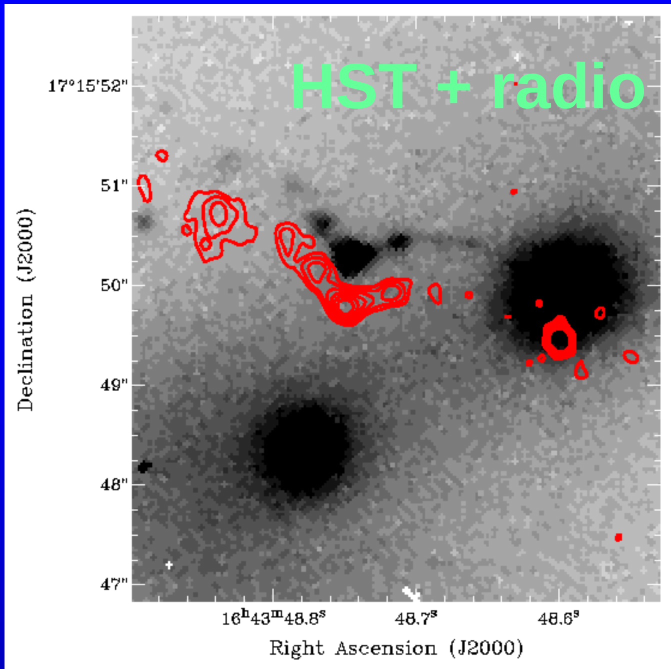
Acceleration and advection (toy profile)

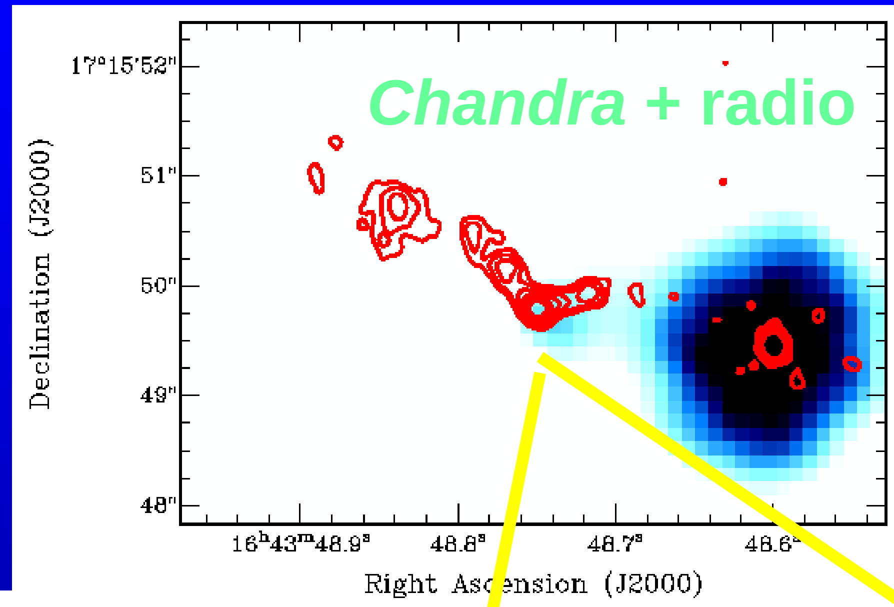


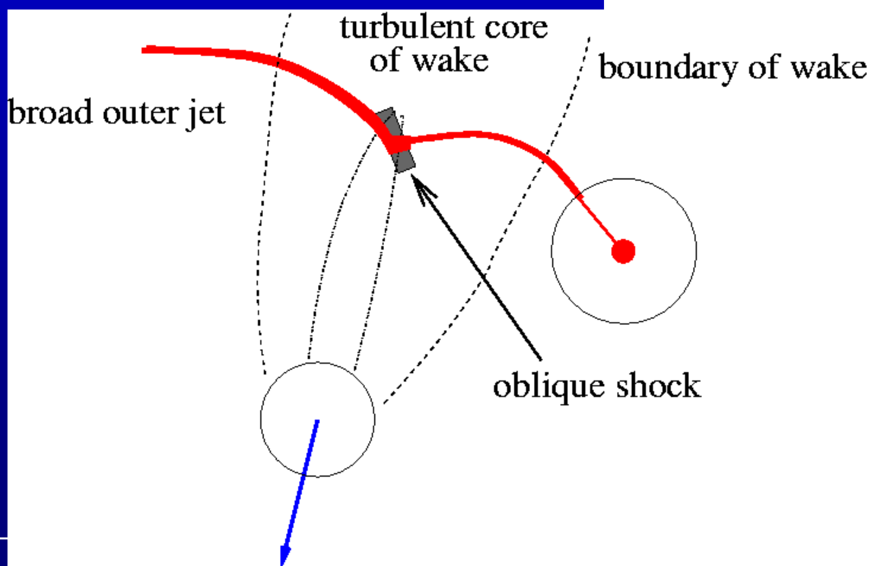
Alternative toy model

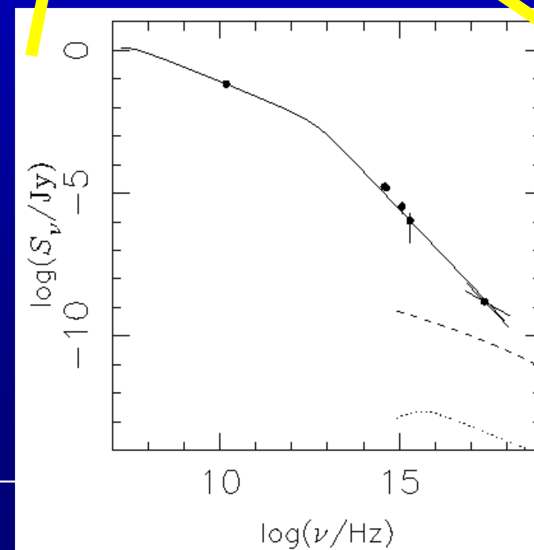


Synchrotron knot in high-power FRII 3C 346





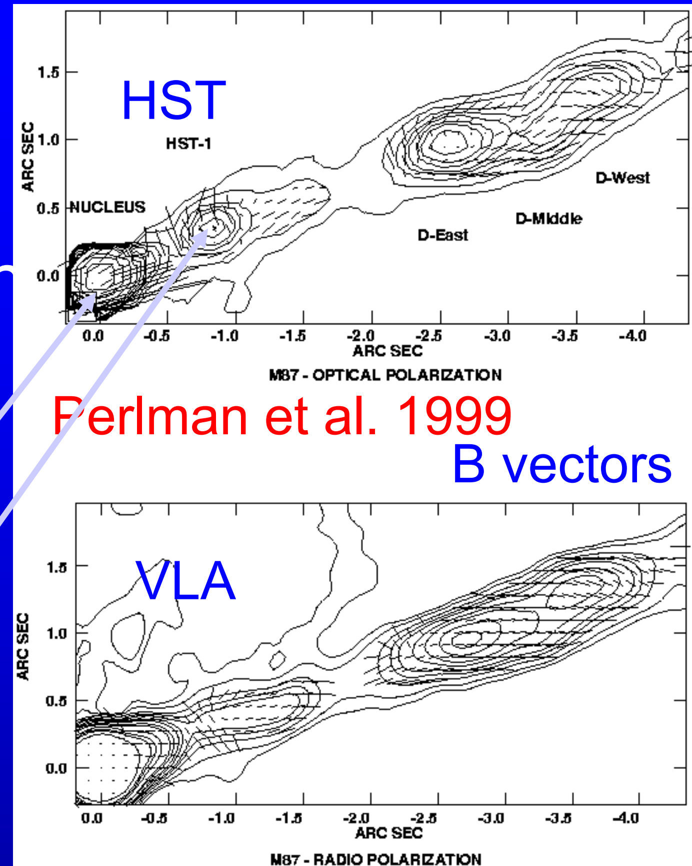




Worrall & Birkinshaw 2004

Optical Polarization

e.g. M 87. Optical narrower than radio. Strong optical polarization with *B* vectors perpendicular to jet marking strong shock acceleration. Lower-energy electrons concentrated in a sheath.



Variability

X-ray and optical variability on timescale of months consistent with shock acceleration, expansion and energy losses Harris et al. 2003; Perlman et al. 2003.

Intermediate Conclusions

• Low-power jets with resolved X-ray emission must be relativistic (more than a few tenths of c, from proper-motion and sidedness arguments).

•Shocks accelerate particles and change *B*-field directions, but don't fully disrupt jets.

•If happening on large scale, can presumably happen on small, in the faster jets within the cores.

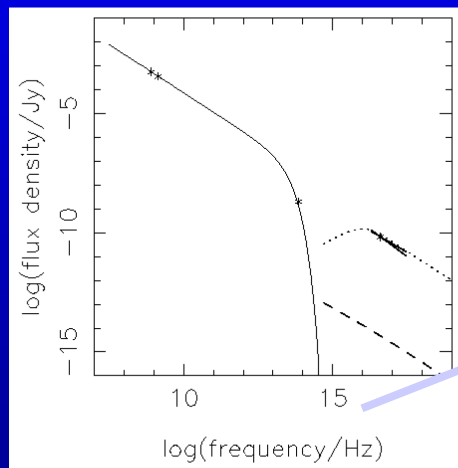
Beware simple one-zone emission models applied to blazar jets!

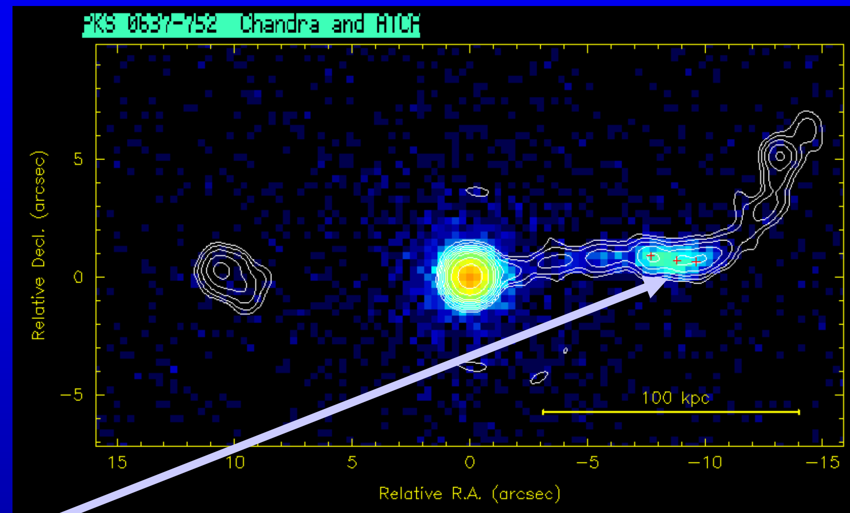
Boosted high-power, FRII, jets

High-power rarer, more distant. Boosted → quasars PKS 0637-752. Now surveys.

Optical rules our synchrotron from single electron population

Single-zone SSC→ large departure from minimum energy





Schwartz et al. 2000

iC-CMB with B_{eq}, θ ~ 5 deg, Γ~ 20, i.e., v ~ 0.9987c

Beamed ic-CMB with B_{min} is favored model

Tavecchio et al. 2000, Celotti et al. 2001

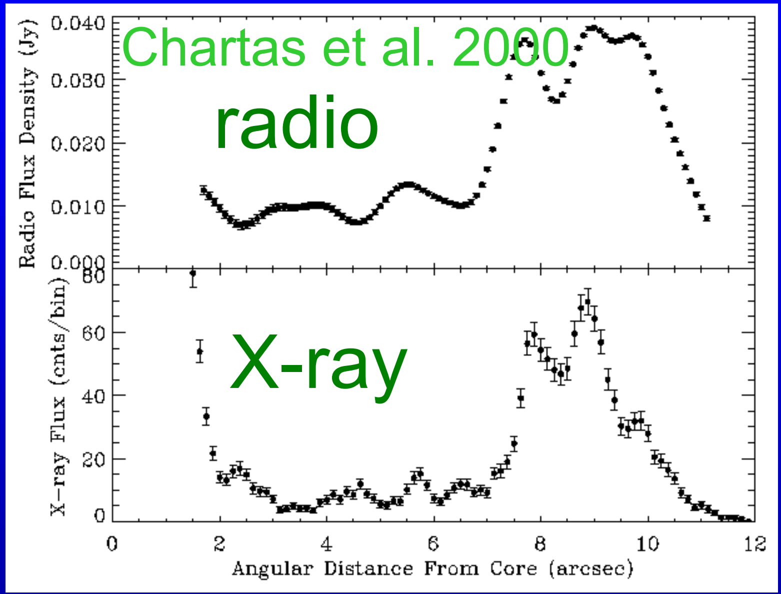
Problems with beamed iC-CMB interpretation?

Sharp gradients in X-ray surface brightness at the edge of the knots unexpected since X-rays are from low-energy electrons with long lifetimes.

May suggest jets are clumpy

Tavecchio et al. 2003

But, if clumpy SSC can be higher & may not need fast speeds Schwartz et al. 2000

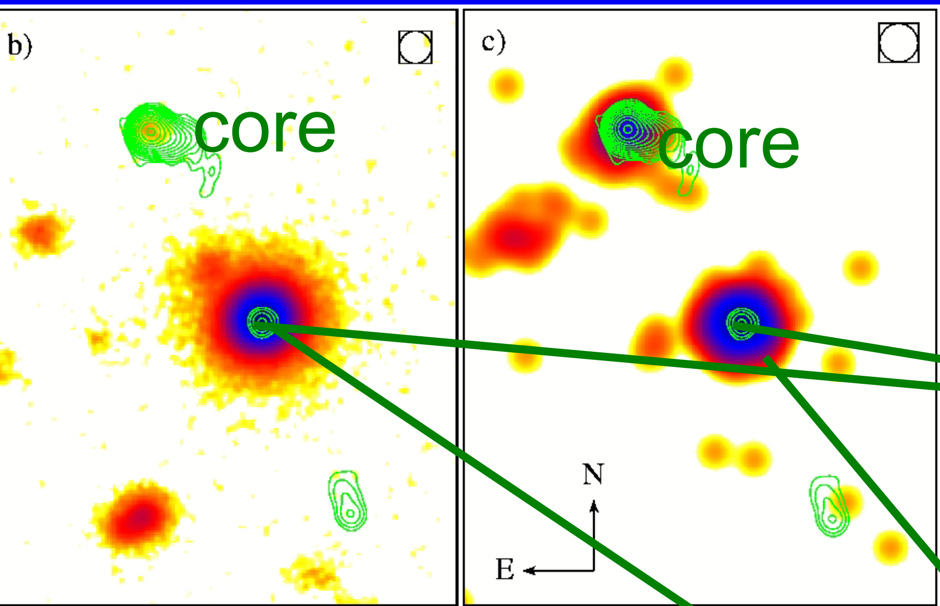


May suggest decelerations Georganopoulos & Kazanas 2004

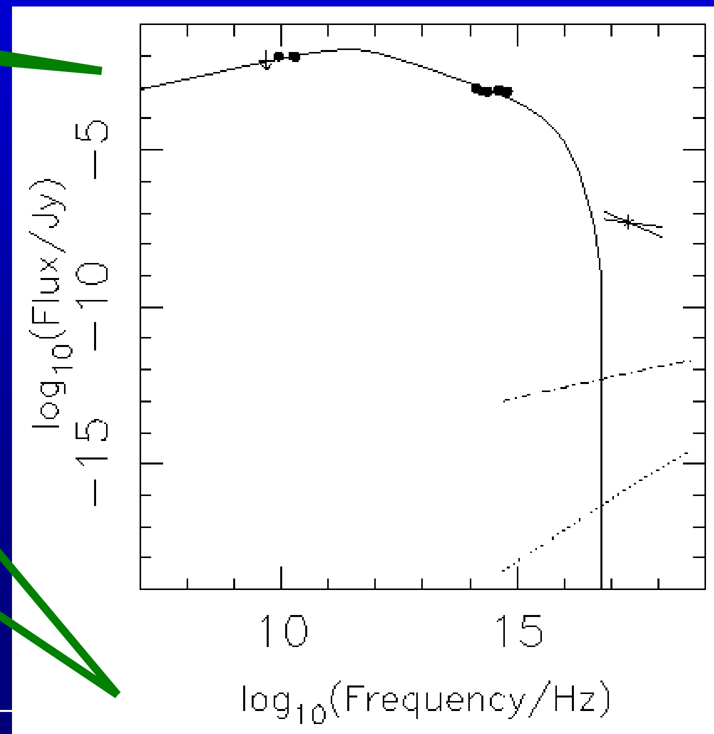
But, X-rays may be dominated by synchrotron emission from high-energy electrons in the Klein-Nishina regime Dermer & Atoyan 2002, or separate population.

PKS 1421-490

radio/optical radio/X-ray



Assuming middle knot not a BL Lac interloper, difficult to explain except by synchrotron.

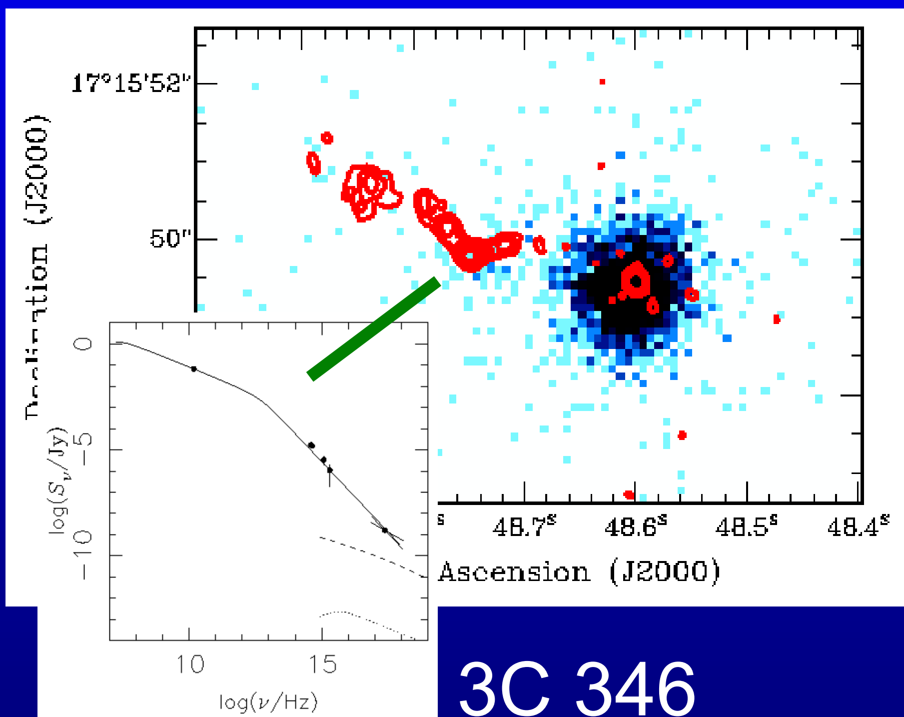


Gelbord et al. 2004

See also QSO 0827+243
Jorstad and Marscher 2004

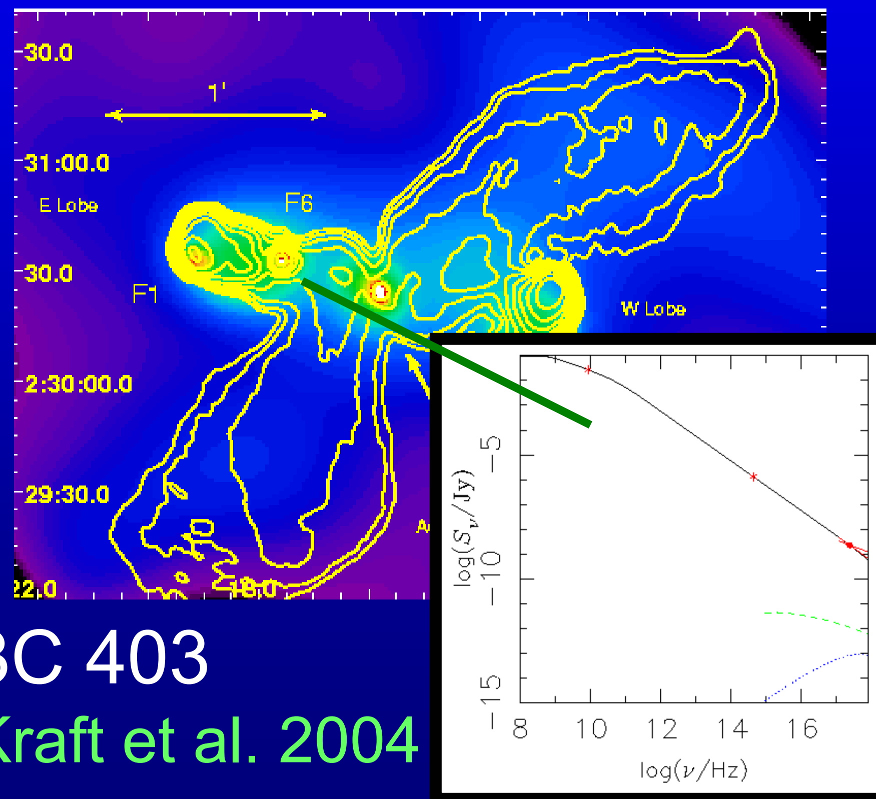
Unboosted high-power, FRII, jets

Jets in unboosted counterparts of high-power sources have been hard to detect.
Two examples show good evidence for synchrotron X-ray emission, indicating localized shocks



3C 346

Worrall & Birkinshaw 2004



3C 403

Kraft et al. 2004

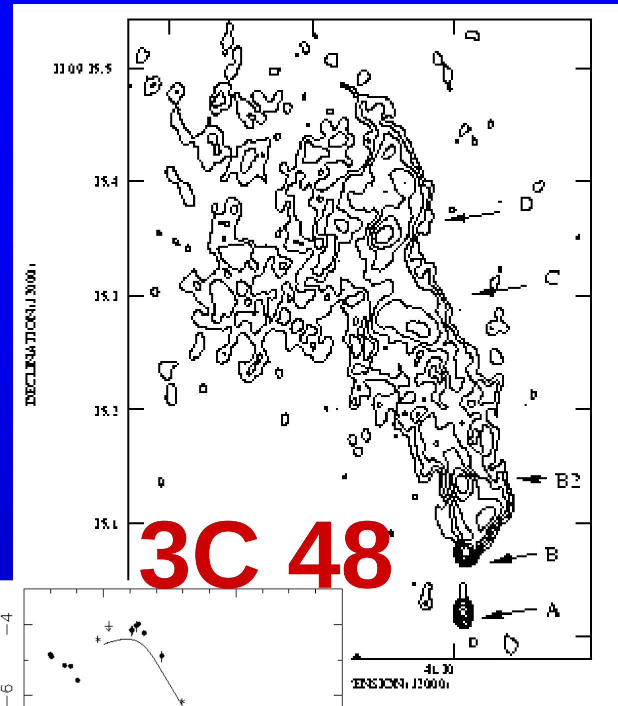
Modeling jet emission in cores. Powerful boosted sources.

Common to assume jet emission dominates at all energies, sometimes up to TeV. One-zone SSC models.

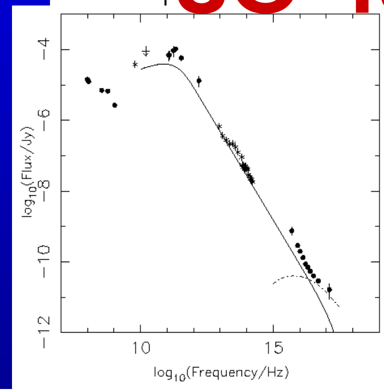
e.g., Ghisellini et al. 1998, Krawczynski et al. 2001, Tagliaferri et al. 2003

Sometimes correlated flares support dominant emission region

e.g., Urry et al. 1997, Takahashi et al. 2000



3C 48



Resolved scales → shocks don't necessarily disrupt fast flow.
Multiple synchrotron components.
Beware one-zone models.

SSC model within A
Size ~10^{16} cm, B ~ 1.3 G

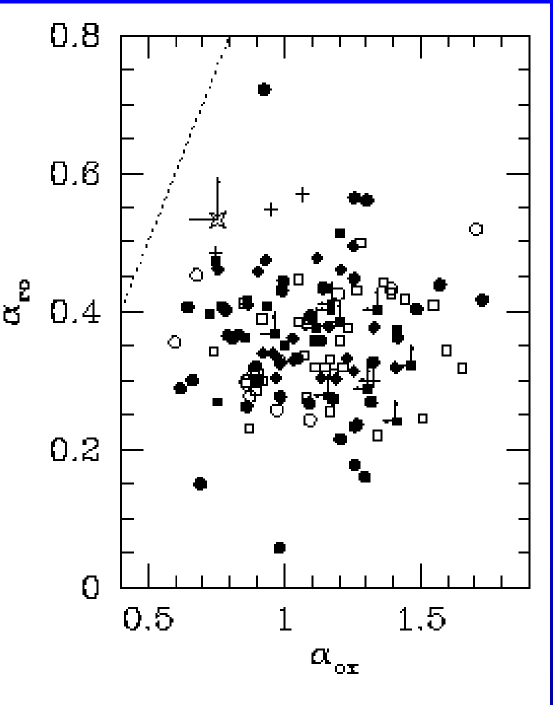
Worrall et al. 2003

Modeling jet emission in cores. Powerful un-boosted sources.

Generally distant. kpc-scale jet emission will be in the unresolved cores. Obscuring torus invoked by unified models should weaken nuclear flux.

Low-power boosted sources.

PKS J2310-437



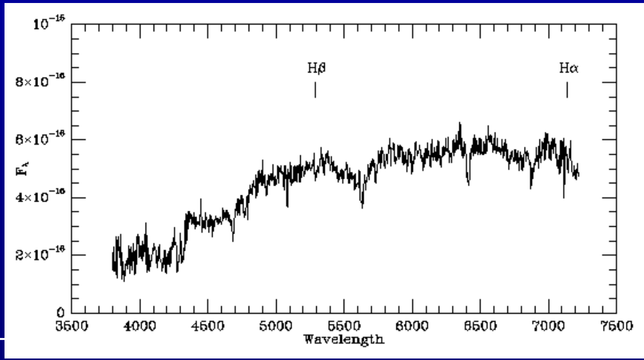
BL Lacs cover large area in α_{ro}/ α_{ox} plane. Not clear plane fully sampled.

PKS J2310-437 extreme -→ boosted radio/X-ray jetted source where any optical jet well buried in the galaxy

Murray et al. 2004

Could there be radio-quiet jets?

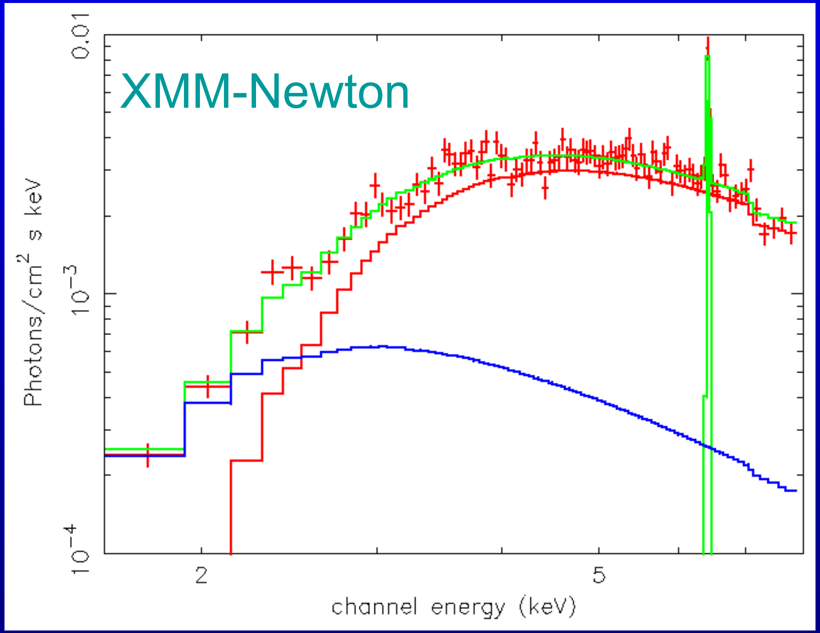
Londish et al. 2004



Low-power un-boosted sources.

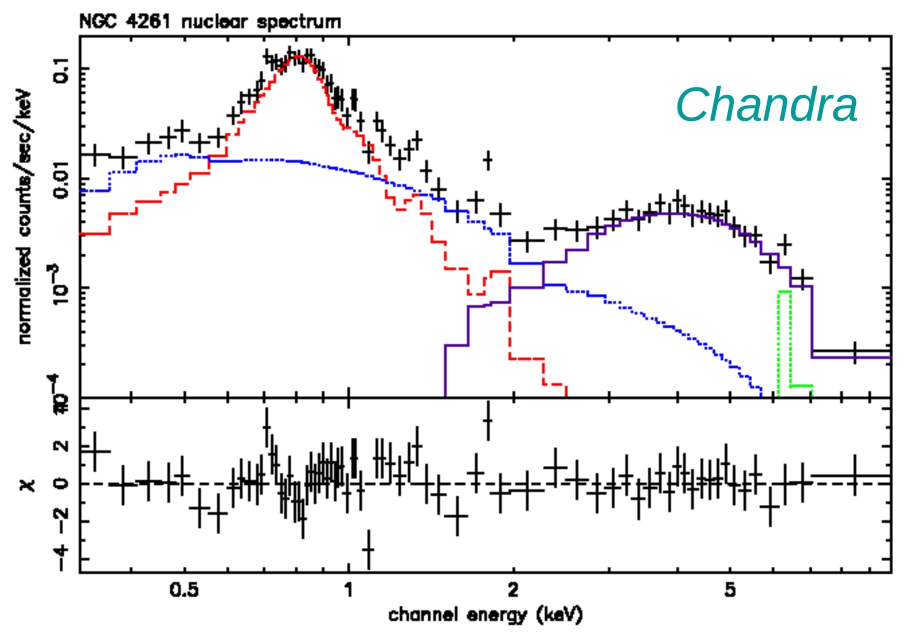
Low-power radio-galaxy cores interpreted either as SSC based on SEDs e.g. Capetti et al. 2000 or thick/thin accretion disk based on variability or FeK emission e.g. Gliozzi et al. 2003. Both in

Cen A



Evans et al. 2004

NGC 4261



Zezas et al. 2003

also Chiaberge et al., Sambruna et al., Gliozzi et al 2003

Reflections

- Much physics possible from study of resolved jets
- Shocks prevalent, & don’t necessarily disrupt jets
- One-zone models of emission near shocks are an over-simplification
- Beware one-zone models for small-scale jets embedded in cores
- Association of soft X-ray components with jet emission looks good, but closest radio galaxy (Cen A) & best twin-jet X-ray source (NGC 4261) both show clear evidence of additional absorbed hard components. Data don’t exclude $\sim 10^{41}$ erg s^{-1} obscured emission in other sources
- X-ray selection biases must be corrected