Active-Galaxy Jets with X-rays

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Aktive Galaxie-Jets mit Röntgenstrahlung

Aktive Galaxie-Jets mit RS

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- Resolved Jets (numbers, mechanisms)

- Global properties (spectral distributions, offs
variability, optical polarization).
Detailed look at Cen A.

- Magnetic field measurements.

- Interactions with the X-ray-emitting medium

- Surprises, successes, TBDs

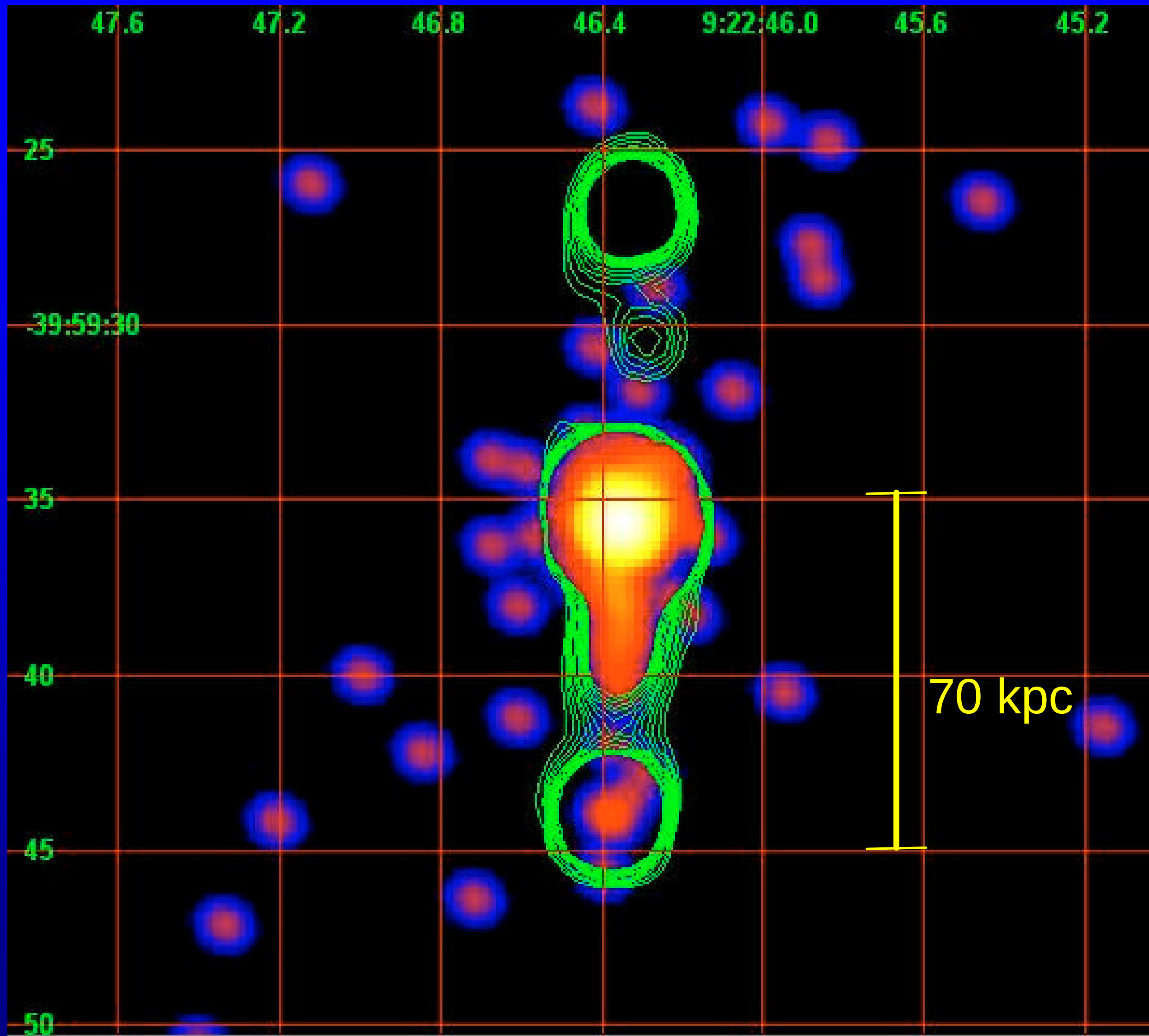
Resolved X-ray Jets (not hotspots or lobes)

High Radio Power (Pre *Chandra*: 3C 273)

Mostly quasars detected (but Pic A & possibly Cyg A: Wilson et al. 2001)

One-sided, corresponding to brighter radio jet
→beaming important (but see 3C 9: Fabian et al. 2003)

e.g., PKS 0920-397
(Marshall et al. 2004;
Schwartz et al. 2004)



Chandra image with ATCA 8.6 GHz contours (J. Lovell)

Resolved X-ray Jets (not hotspots or lobes)

High Radio Power

Mostly quasars detected

One-sided, corresponding to brighter radio jet

→beaming important

Currently at least 26 quasar jet detections. Targeted programs.
Generally no pre-existing optical detections.

(e.g., Sambruna et al. 2003; Siemiginowska et al. 2003; Marshall et al 2004)

Resolved X-ray Jets (not hotspots or lobes)

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→beaming important

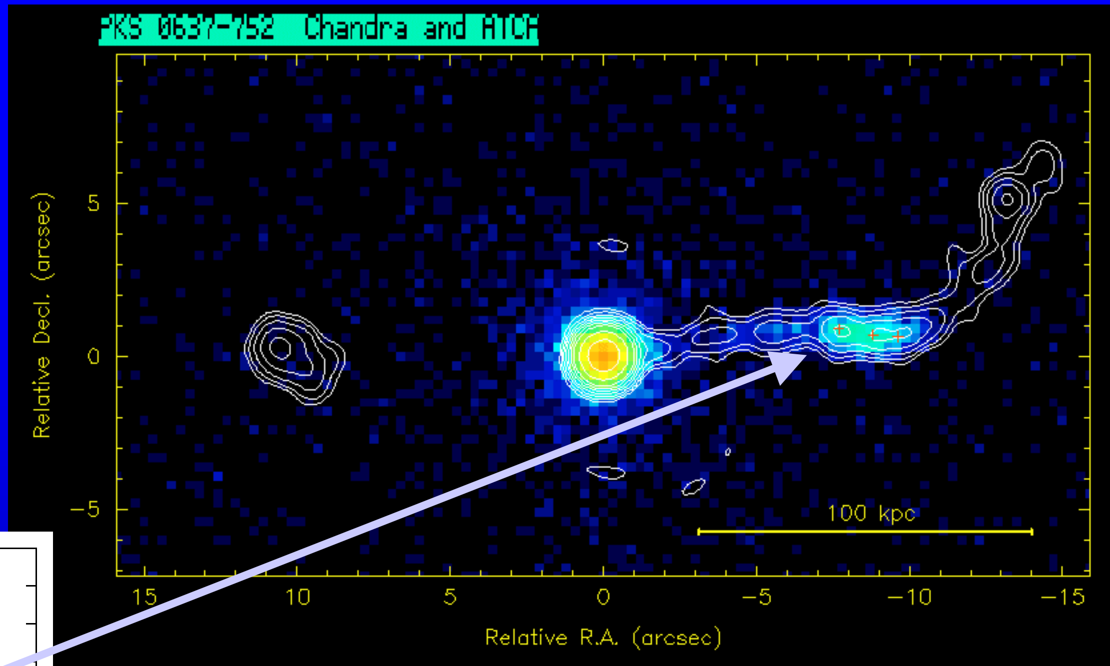
Currently at least 26 quasar jet detections. Targeted programs. Generally no pre-existing optical detections.

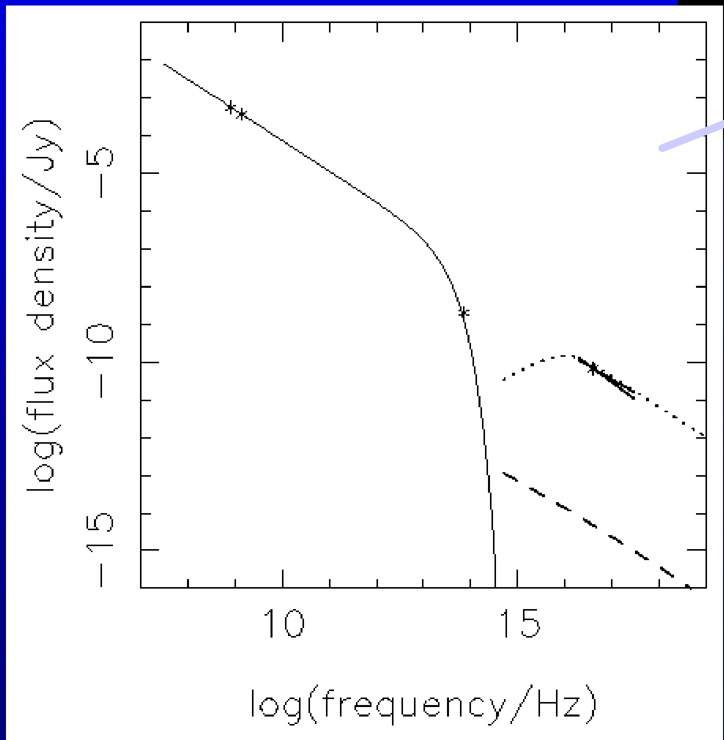
Optical key in ruling out synchrotron X-ray origin

SSC → uncomfortably large departure from B_{eq}
(Schwartz et al. 2000; Sambruna et al. 2002)

Beamed iC-CMB with B_{eq} is favored model
(Tavecchio et al. 2000; Celotti et al. 2001)

SSC would need total energy 1000x minimum energy





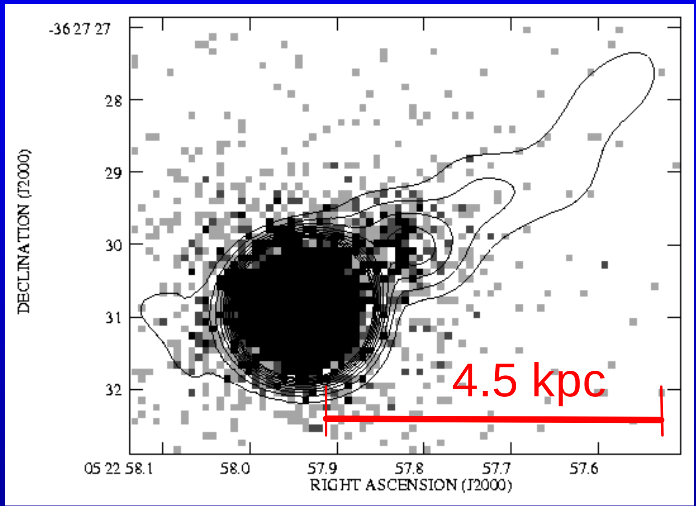
Schwartz et al. 2000

iC-CMB with B_{eq}, ? ~ 5 deg, G~ 20, i.e., *v* ~ 0.9987c

Low Radio Power (Pre *Chandra*: Cen A & M 87)

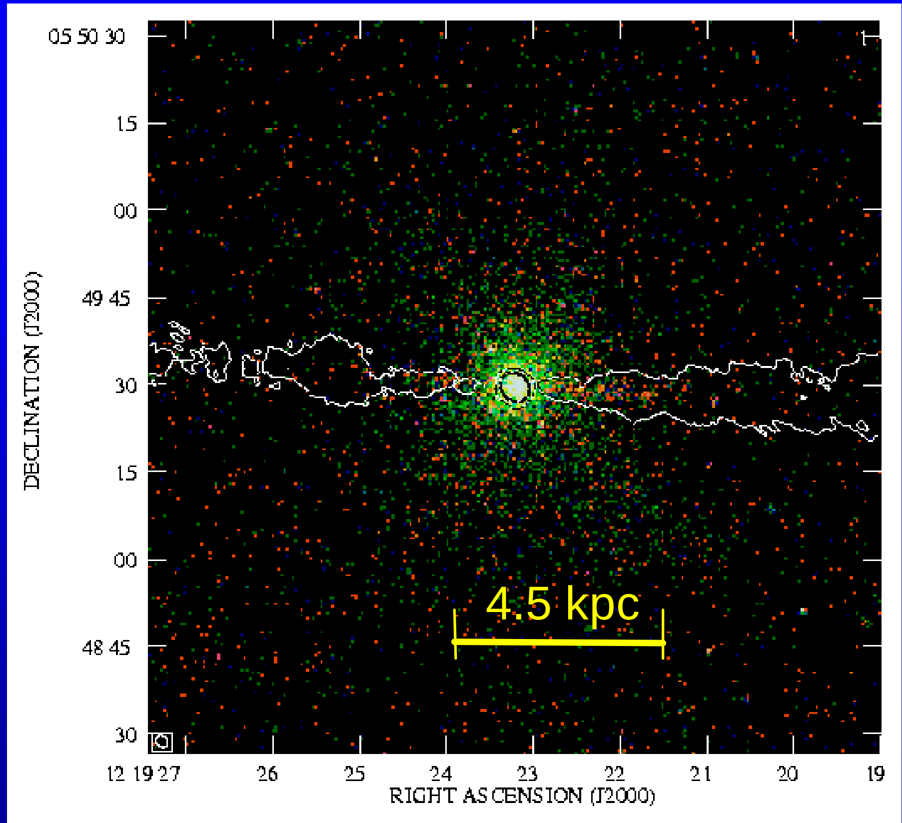
All orientations: BL Lacs + FRI radio galaxies → beaming much less important

BL Lac object



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

Twin-jet radio galaxy



e.g., NGC 4261
(Chiaberge et al. 2003;
Zezas et al. 2003)

Low Radio Power

All orientations: BL Lacs + FRI radio galaxies → beaming much less important

Currently at least 19 detections. Several pre-existing optical jet detections; otherwise X-rays easier to detect – better contrast with galaxy.

(Kraft et al. 2000; Worrall et al. 2001,2003; Hardcastle et al. 2001, 2002; Pesce et al. 2001; Birkinshaw et al. 2002; Marshall et al. 2002; Harris et al. 2002 …)

Low Radio Power

All orientations: BL Lacs + FRI radio galaxies → beaming much less important

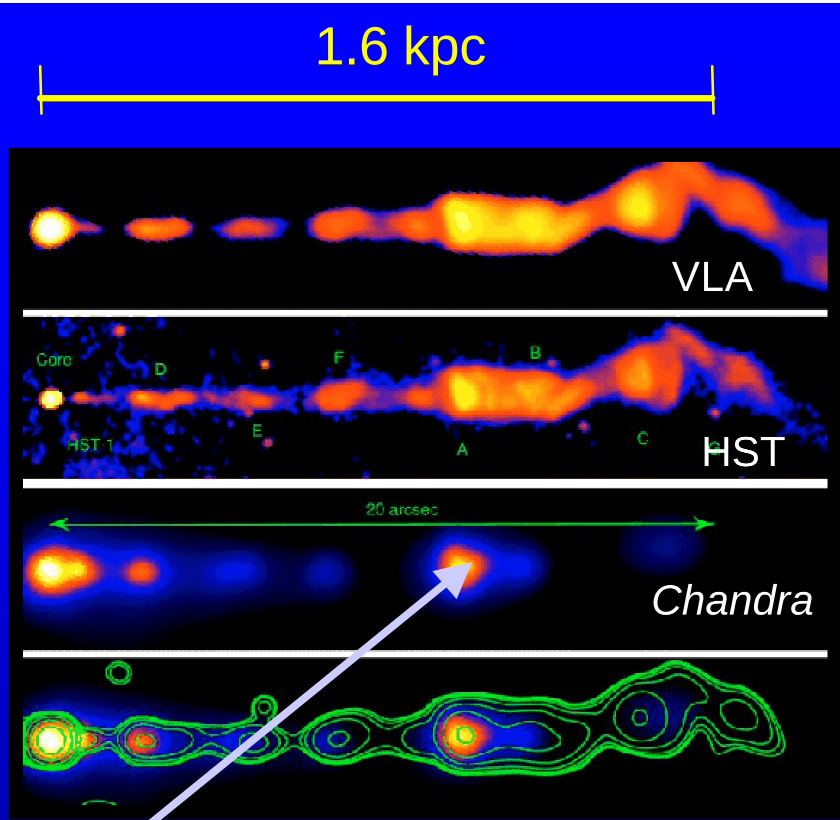
Currently at least 19 detections. Several pre-existing optical jet detections; otherwise X-rays easier to detect – better contrast with galaxy.

iC → uncomfortably large departure from B_{eq}

Steep X-ray spectra + SED → synchrotron from single electron population (usually broken power law) plausible

SSC with B_{eq} severely under-predicts X-ray. SSS with any B has wrong X-ray spectrum (well measured with XMM-Newton).

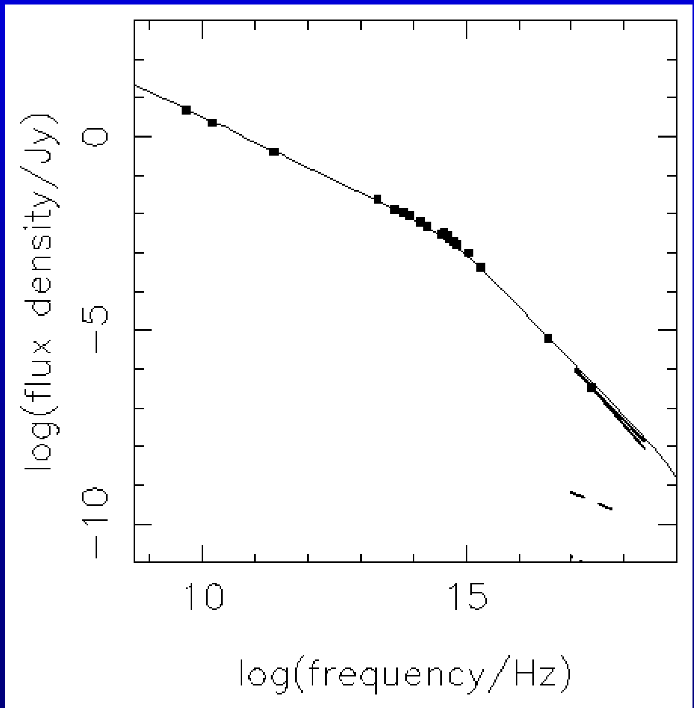
Synchrotron with broken power law fits X-ray spectrum



Marshall et al. 2002

M 87 Knot A

TeV electrons → in situ acceleration required.

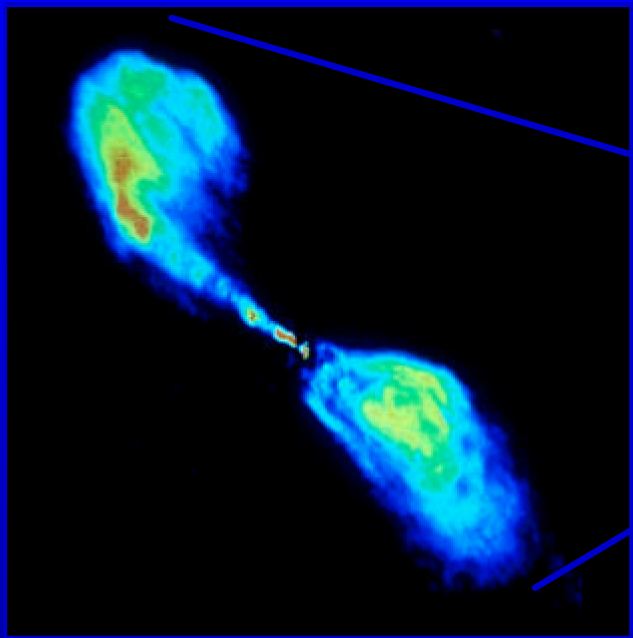


Böhringer et al. 2001

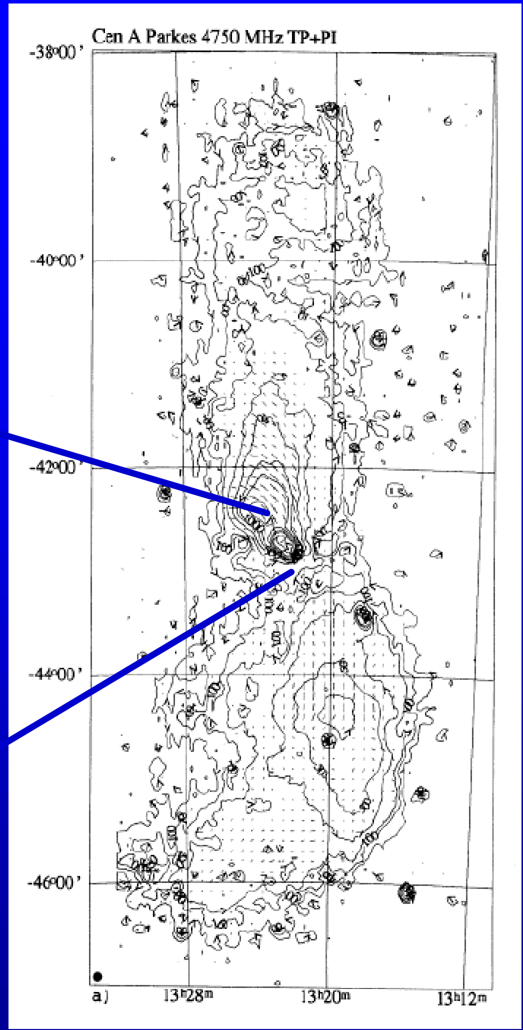
Cen A

1 arcsec = 17 pc

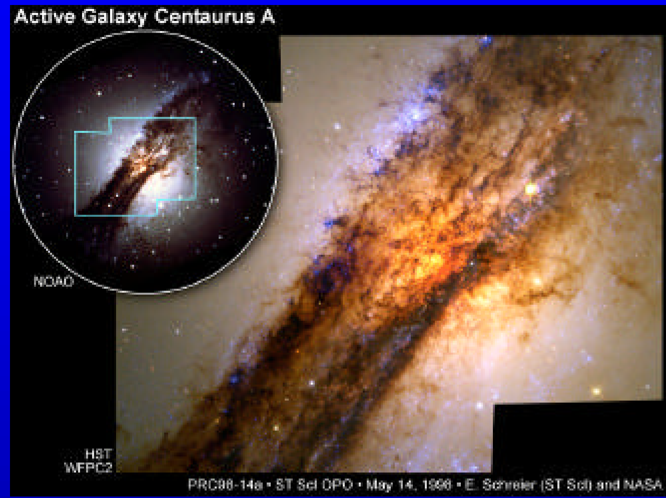
5 GHz VLA image of Burns et al. (1983) and full radio extent (Junkes et al. 1993).



12 kpc



500 kpc



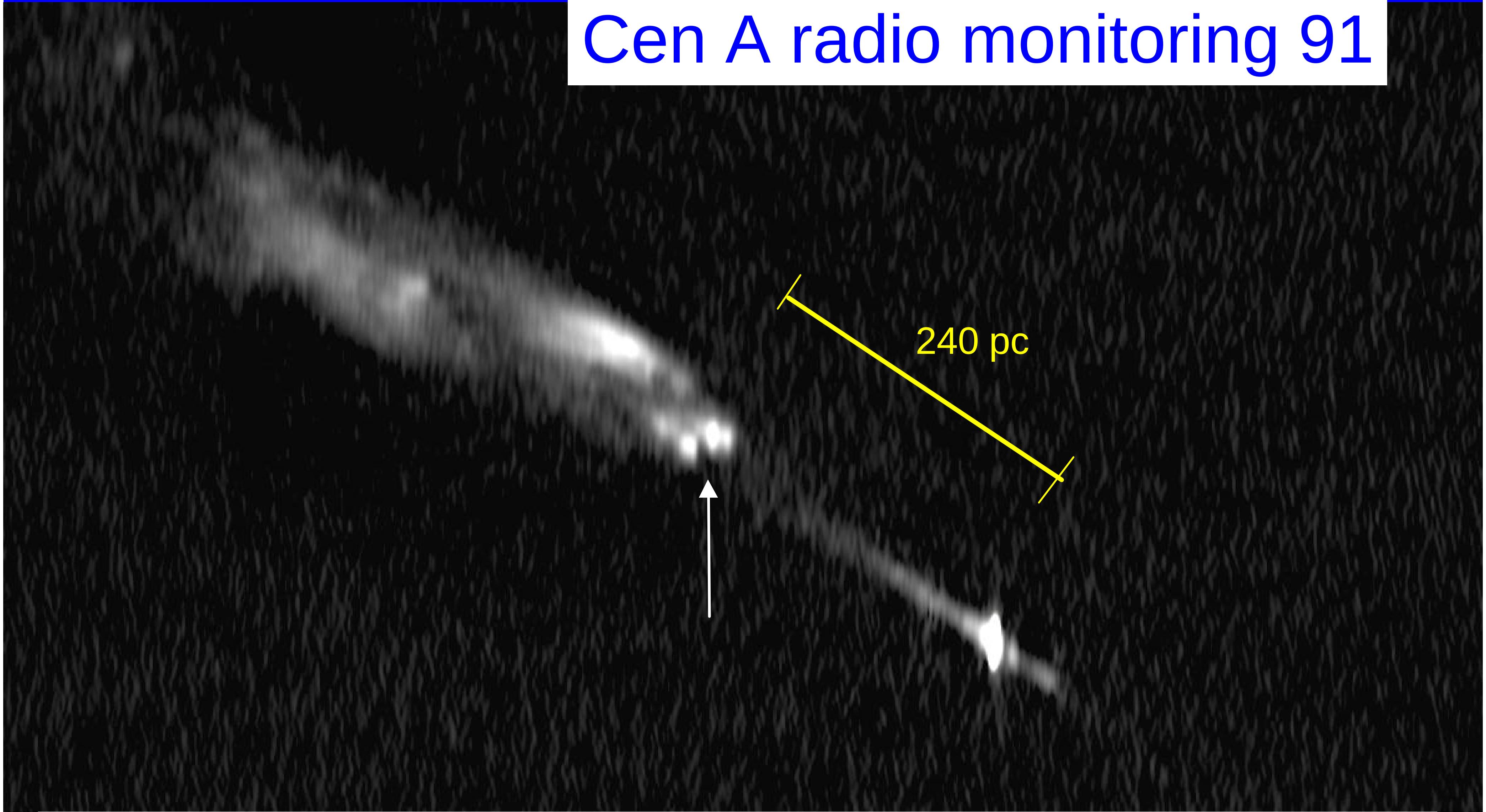
1998 HST press release, NASA/STScI/E. Schreier

Chandra/XMM-Newton/VLA/ATCA study.

R. Kraft, C. Jones, W. Forman, W. Murray (CfA)

M. Hardcastle, D. Worrall (Bristol)

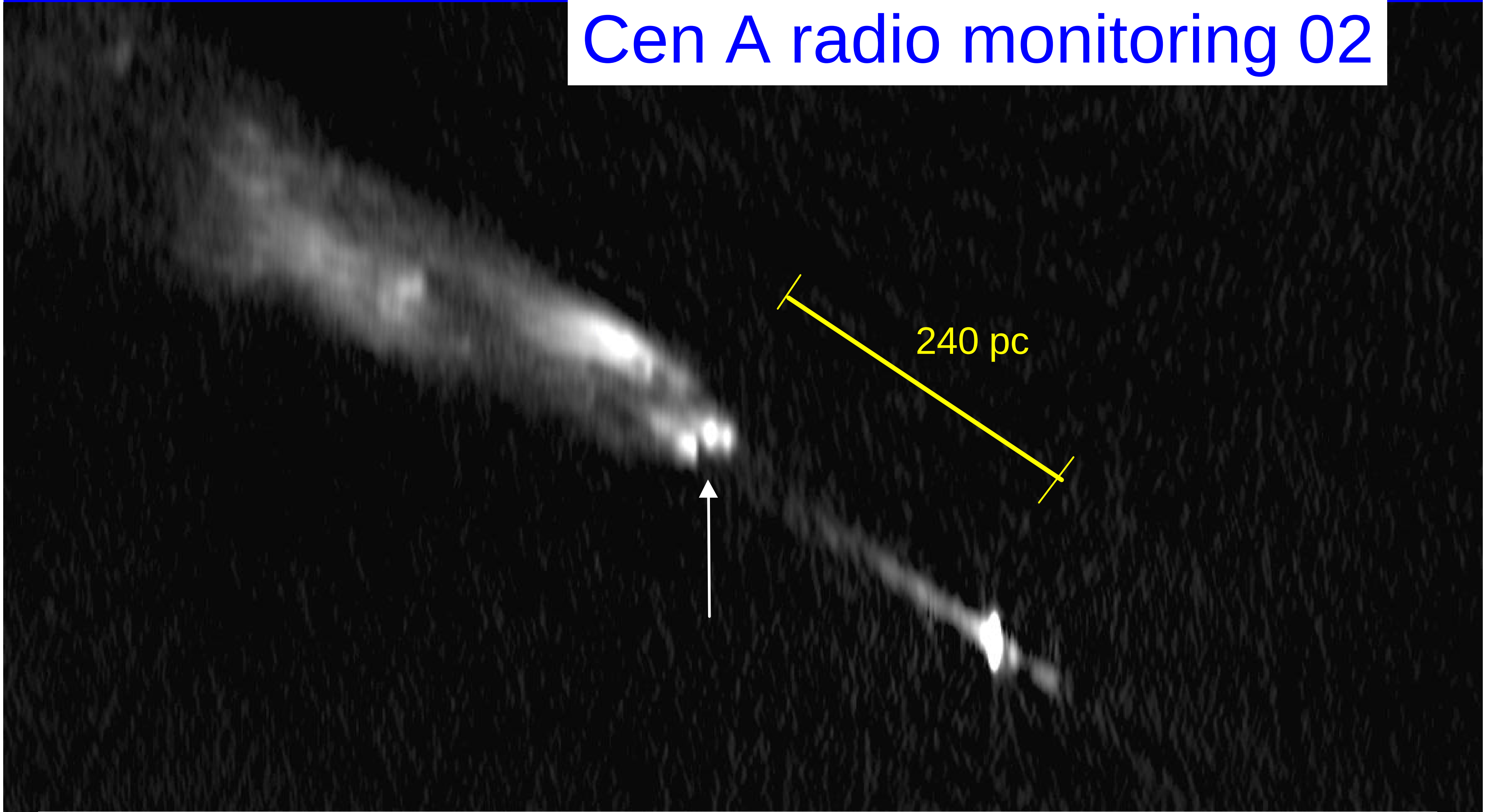
Cen A radio monitoring 91



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

Hardcastle et al. (2003).

Cen A radio monitoring 02

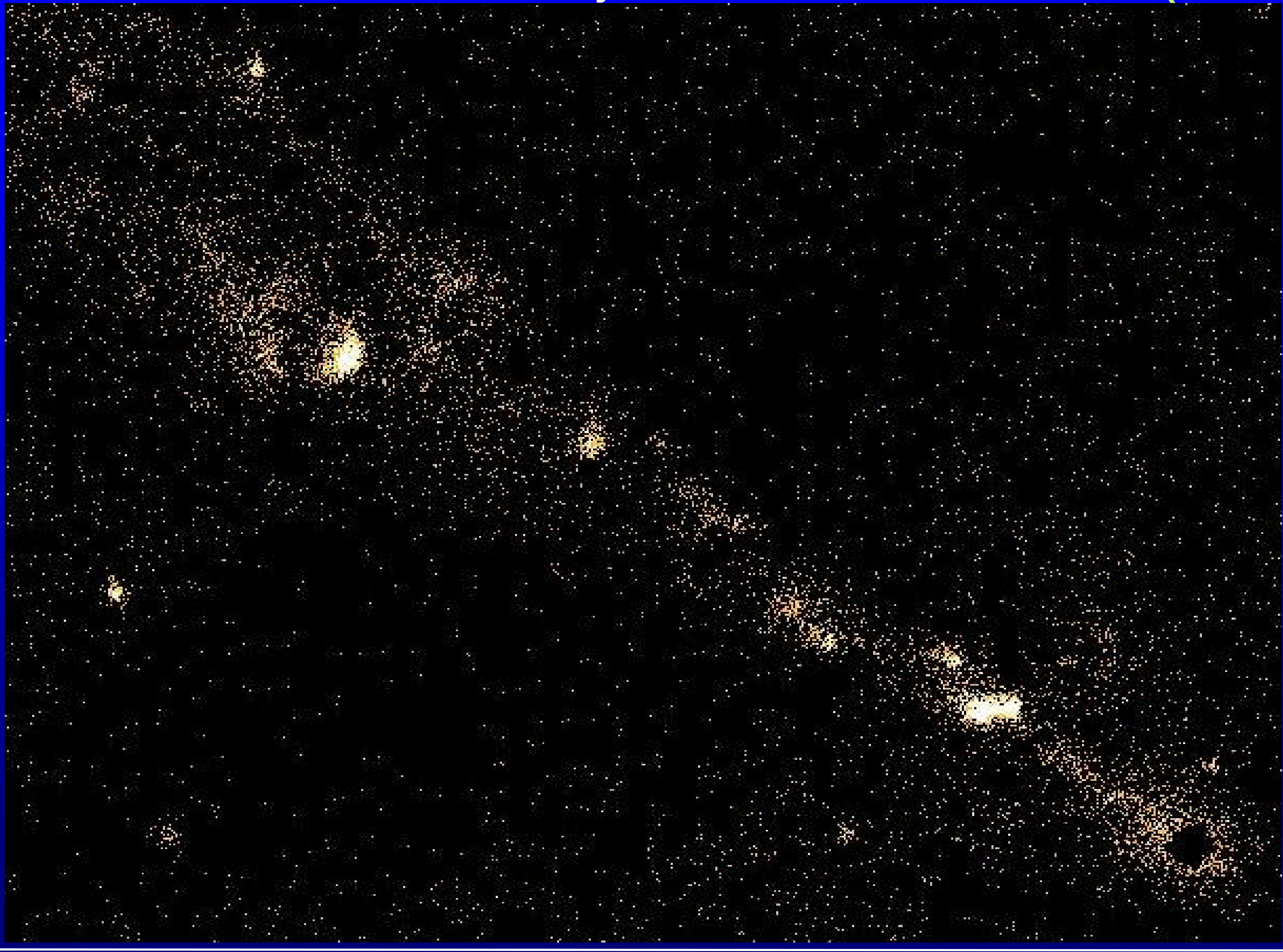


VLA 8.4 GHz A & B array: 1991 archival, 2002 new. Dynamic range 120,000:1. Proper motions: v_{app} ~ 0.5c. If ? ~ 50°, jets asymmetric.

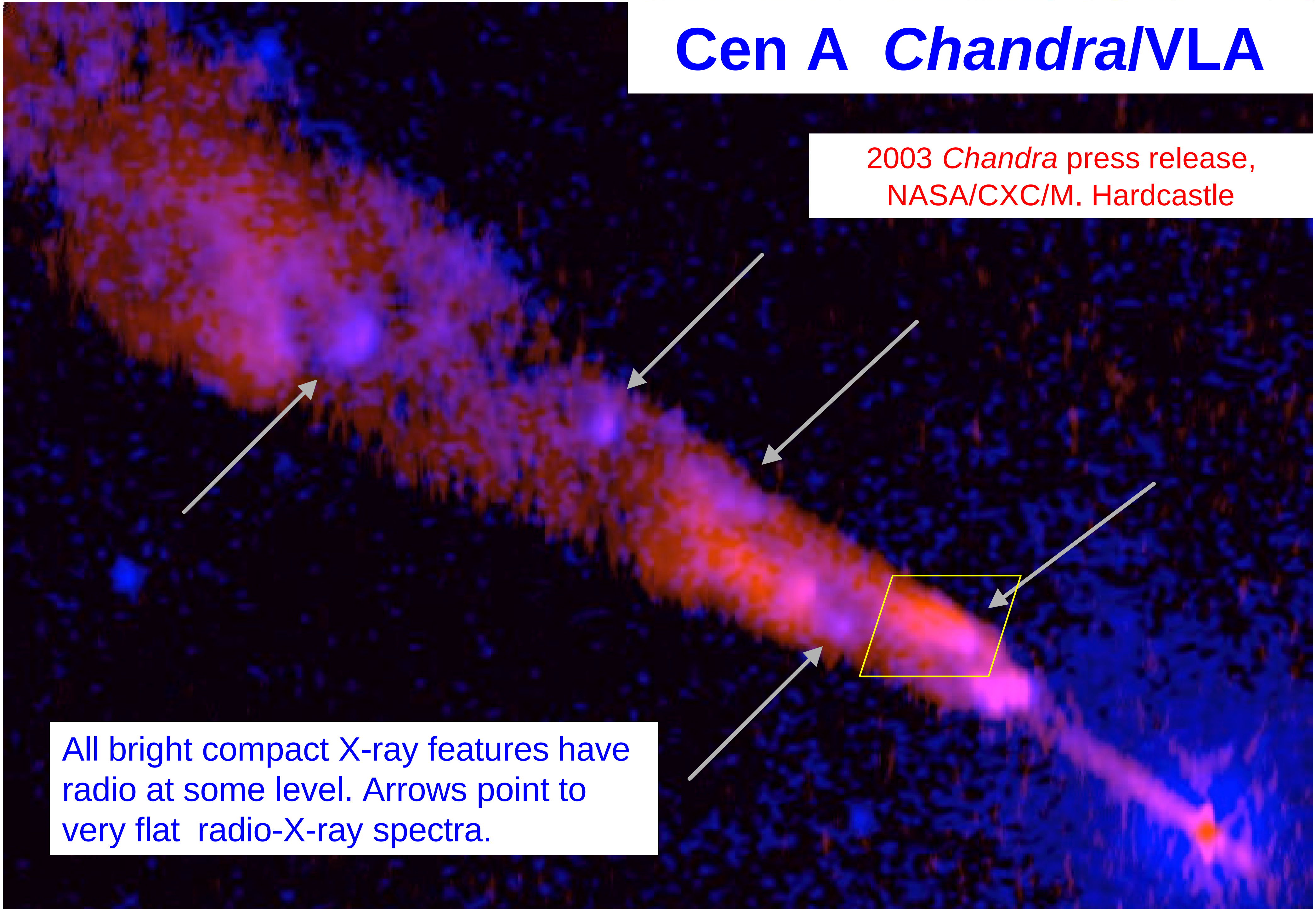
Hardcastle et al. (2003).

Chandra ACIS-S 45 ks X-ray

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

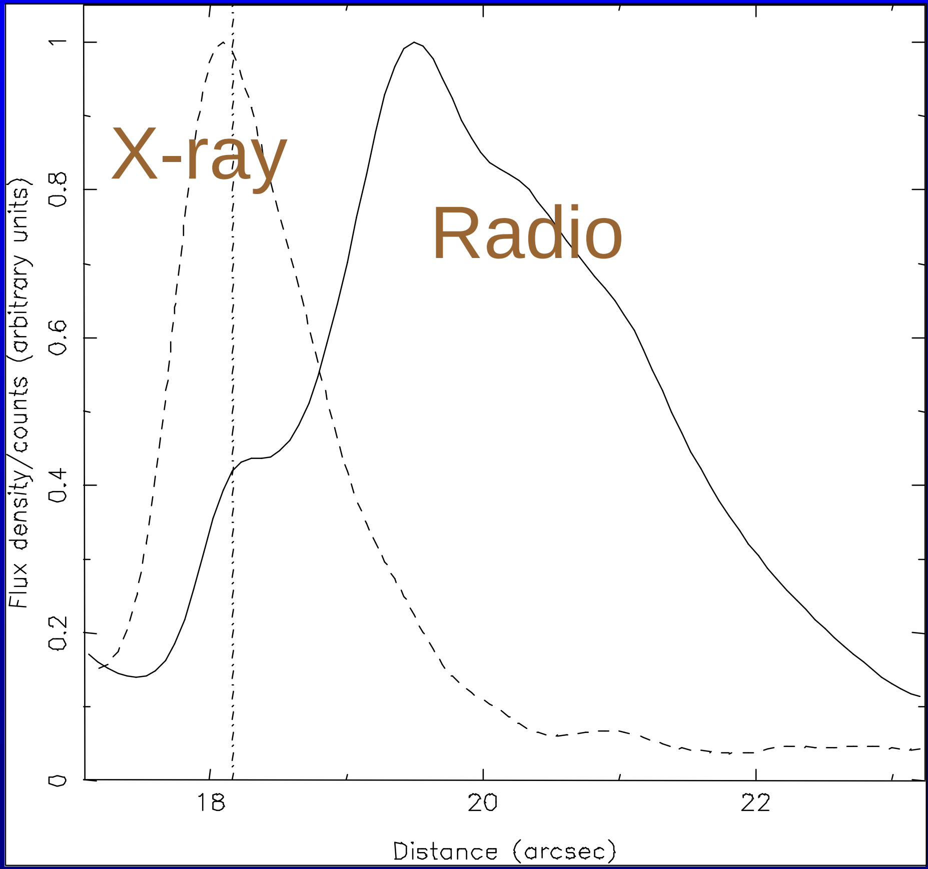


Cen A *Chandra*/VLA

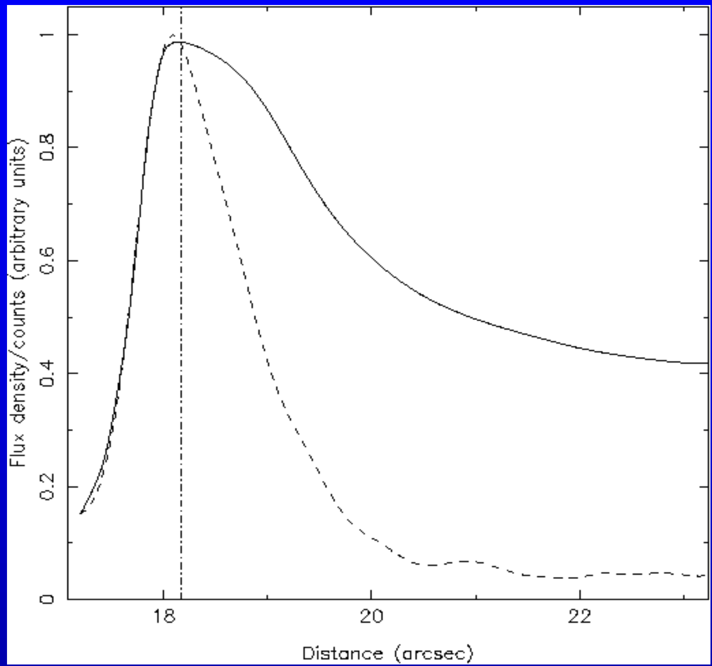


All bright compact X-ray features have radio at some level. Arrows point to very flat radio-X-ray spectra.

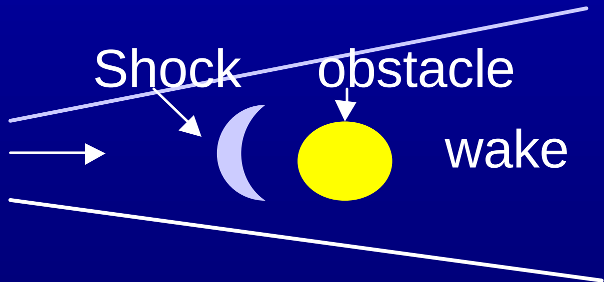
Knot profile



Acceleration and advection (toy profile)

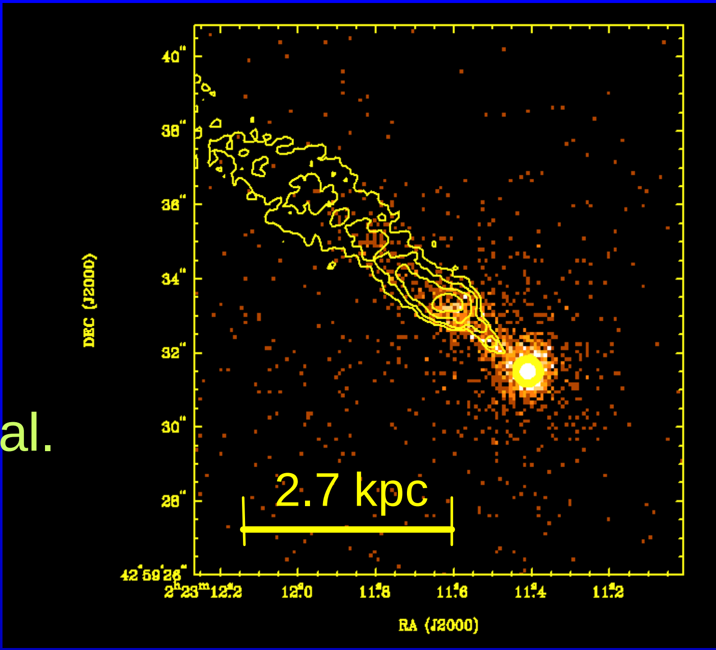


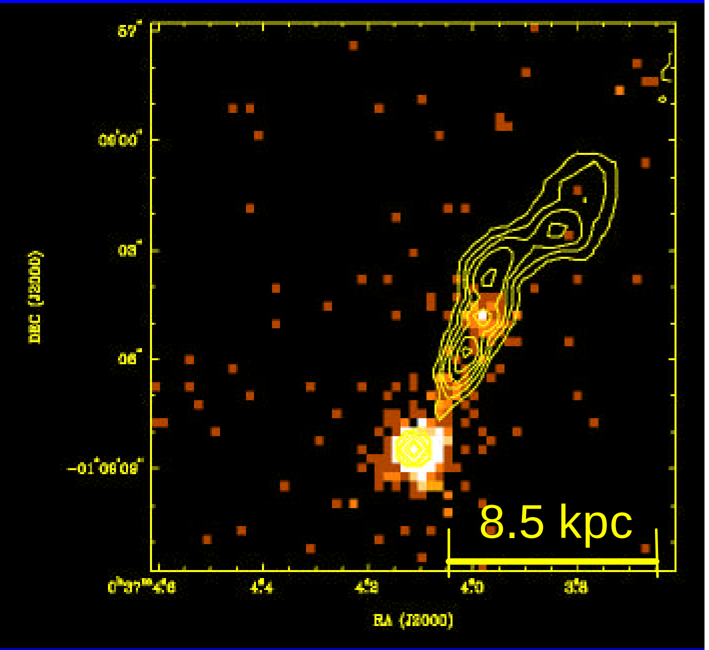
Alternative toy model



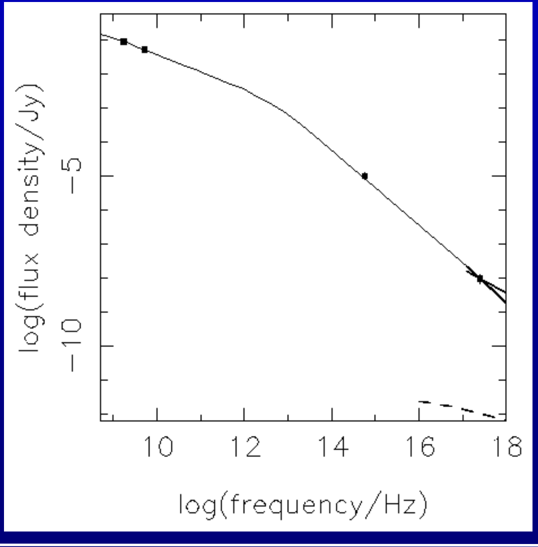
Global properties of low-power sources

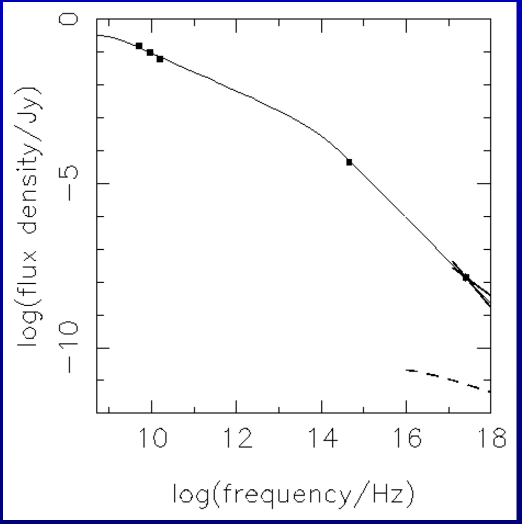
Offsets,
e.g., 3C 66B
(Hardcastle et al. 2001)
and 3C 15 (Kataoka et al. 2003).

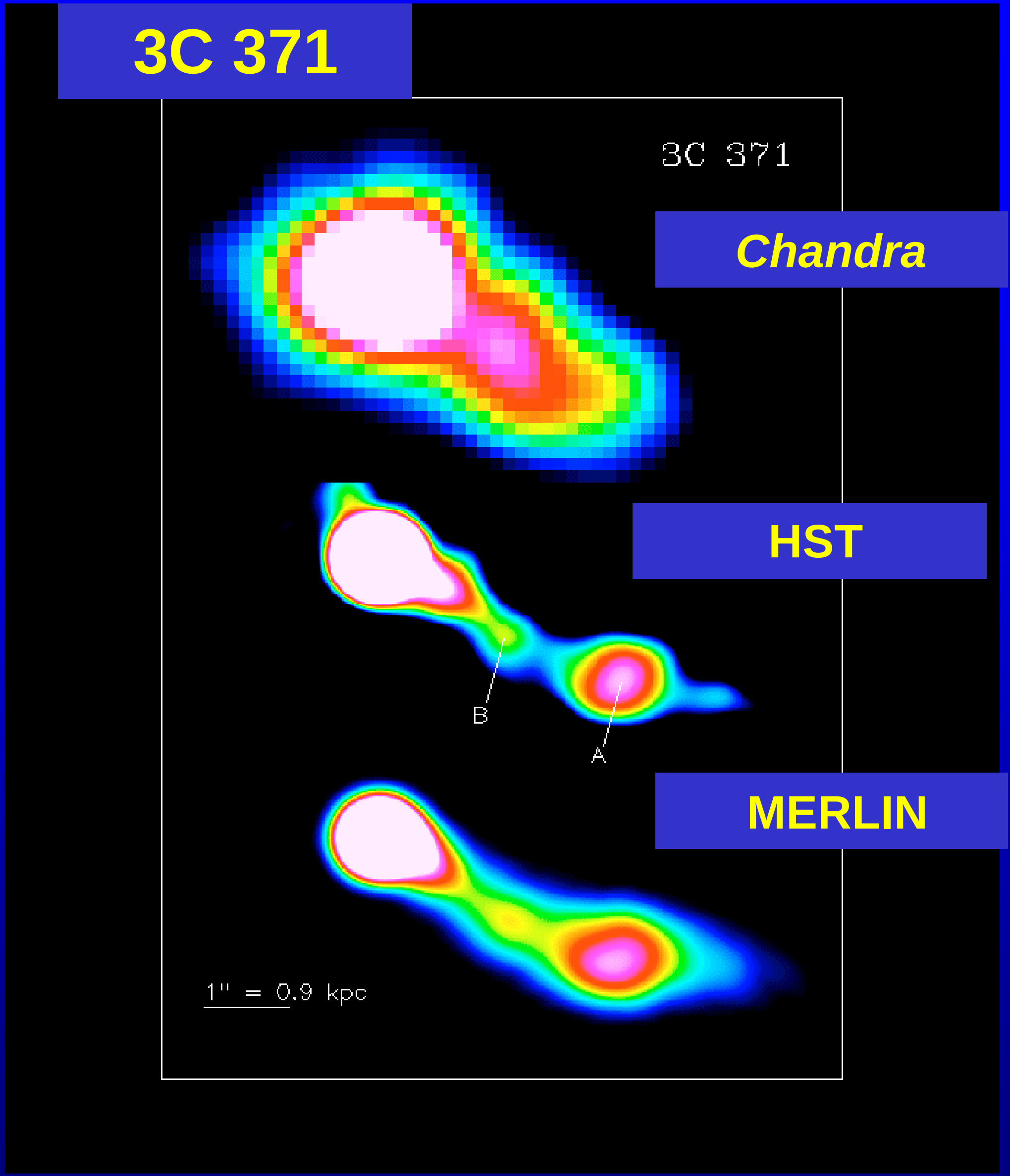




Spectral breaks,
e.g., NGC 2484
(Worrall et al. 2001)
and PKS 0521-365
(Birkinshaw et al. 2002).



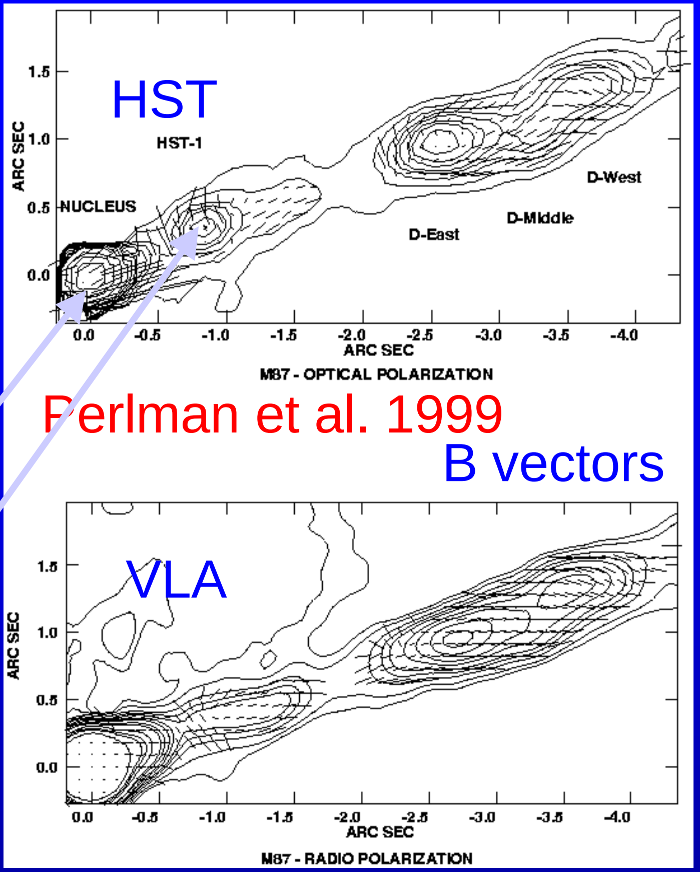




Pesce et al. (2001)

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).

Knot X-ray variability possibly seen in Cen A (Kraft et al. in prep).

Measurements of *B*

If both L_{syn} and L_{iC} from same electrons → 2 equations, 2 unknowns. Can measure *B* and test equipartition.

Hotspots: *V* and $u_g = u_{syn}$ well known.

Hotspots agreeing with equipartition to within factor of about 2:

Cygnus A (before Chandra)

3C 295, 3C 123, 3C 263, 3C 330

No hotspots under-bright in X-ray

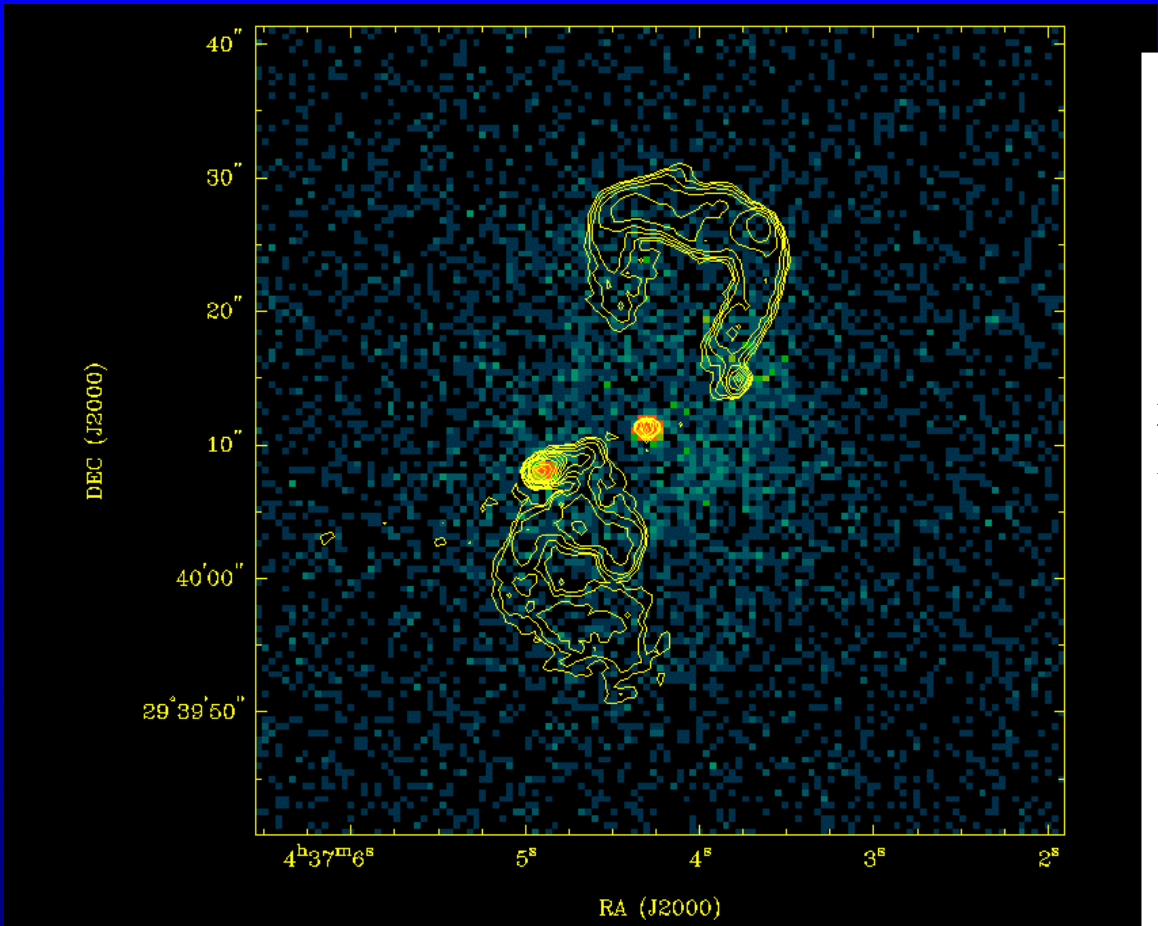
(over-bright: Pic A, 3C 390.3, 3C 120, 3C 351)

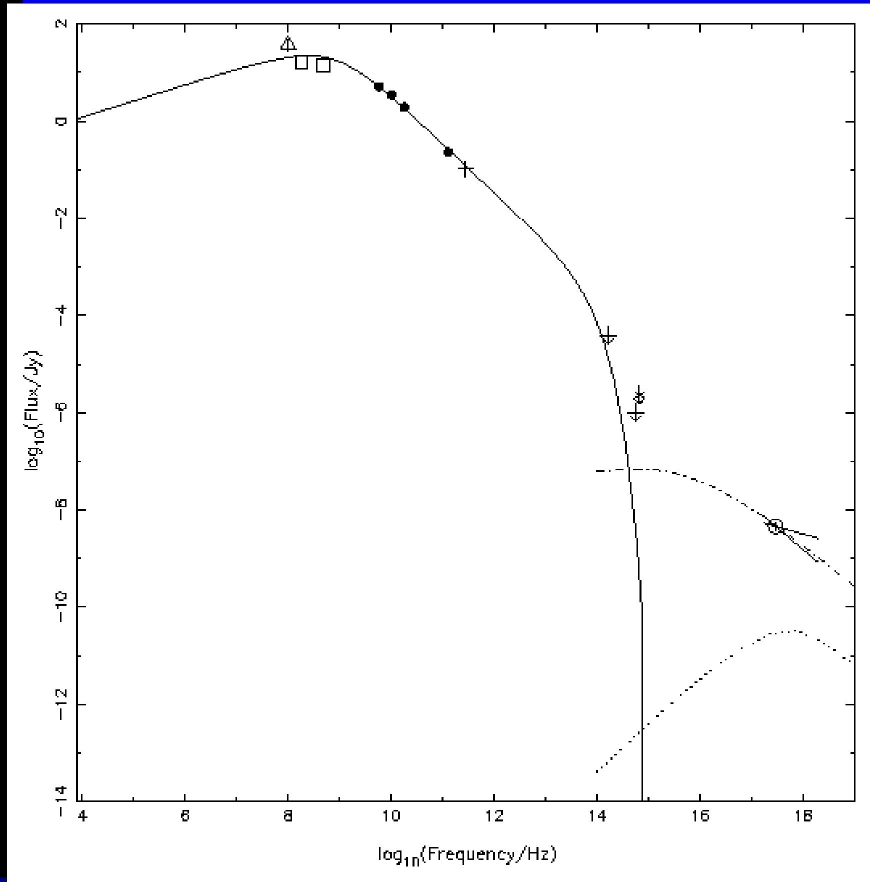
Work in progress on a sample of about 35

3C 123

z~0.22 radio galaxy

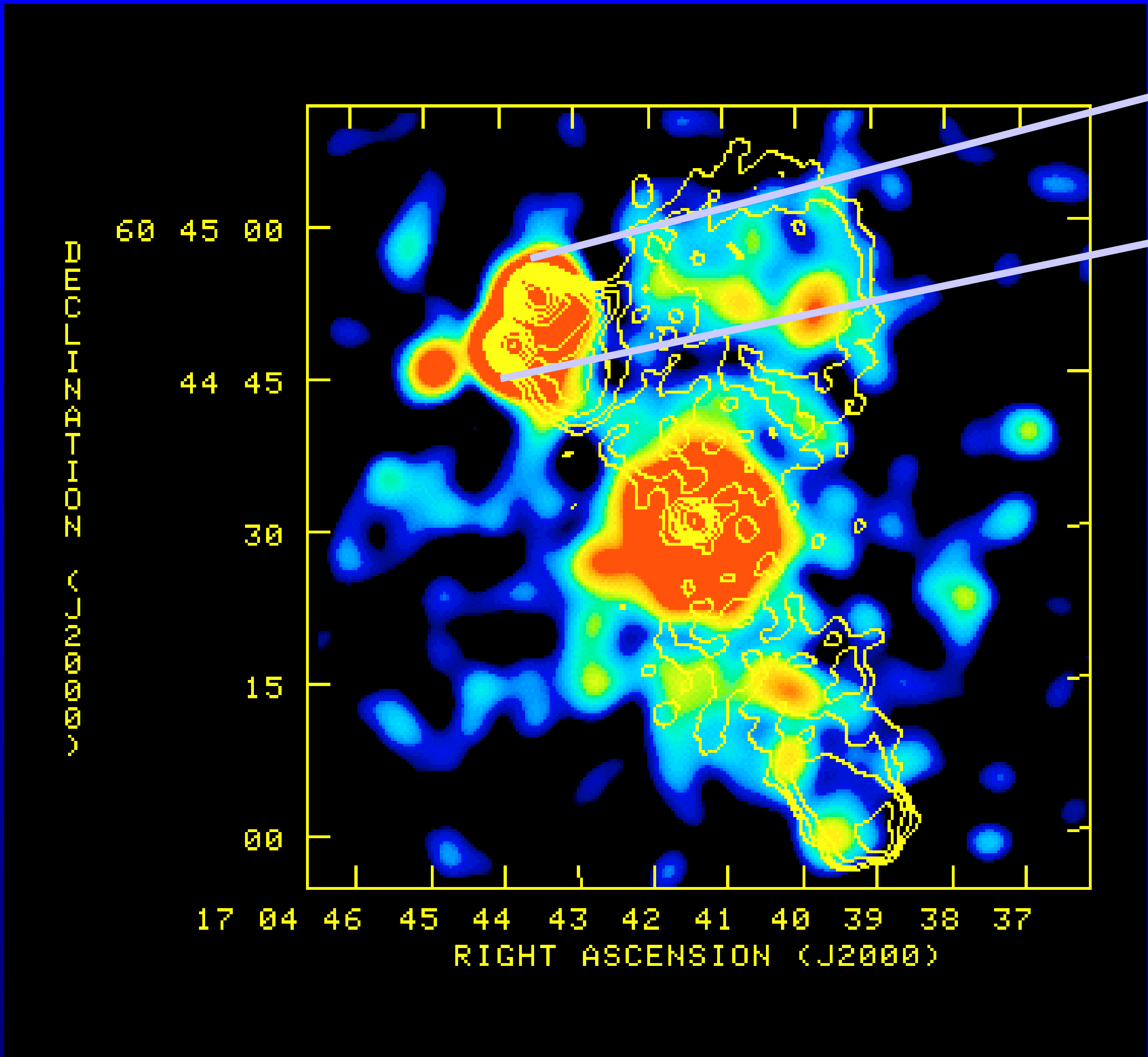
B~$0.7B_{eq}$

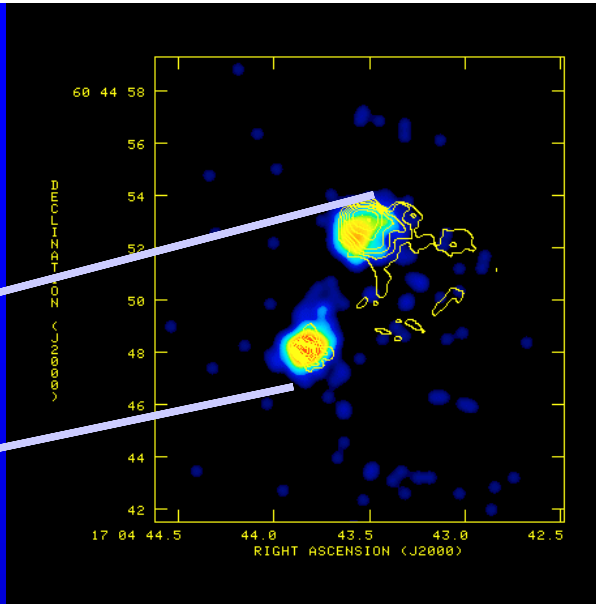




Hardcastle, Birkinshaw & Worrall (2001)

3C 351





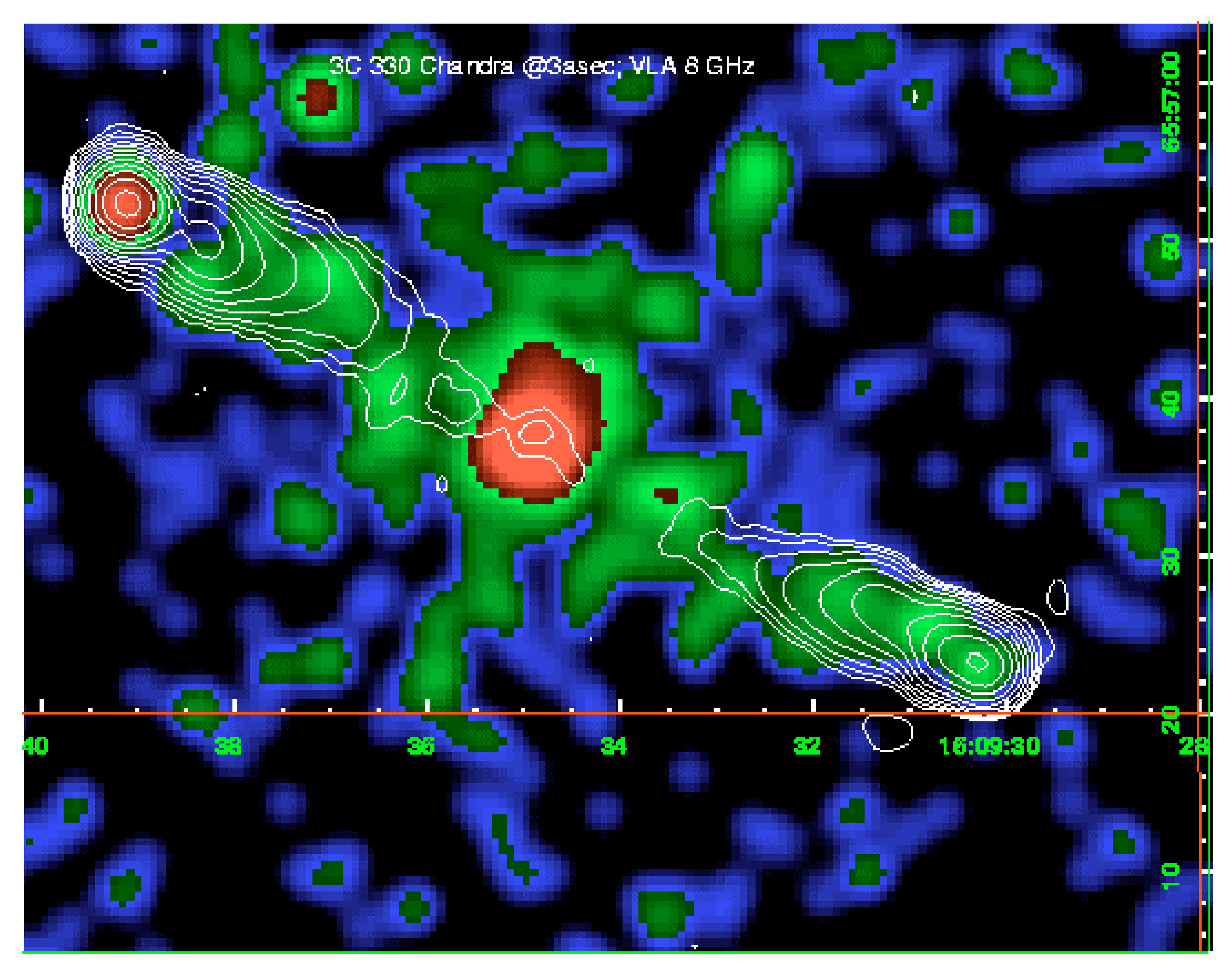
$B \sim 0.4 B_{eq}$ in lobes (0.1 in hotspots)

Hardcastle et al. (2002)

z=0.371

quasar

3C 330



$B \sim B_{eq}$ in lobes and hotspots

Hardcastle et al. (2002)

$z = 0.549$

Radio galaxy

X-ray Cores

Expect jet-related X-ray emission at some level in the cores of objects with resolved X-ray jets.

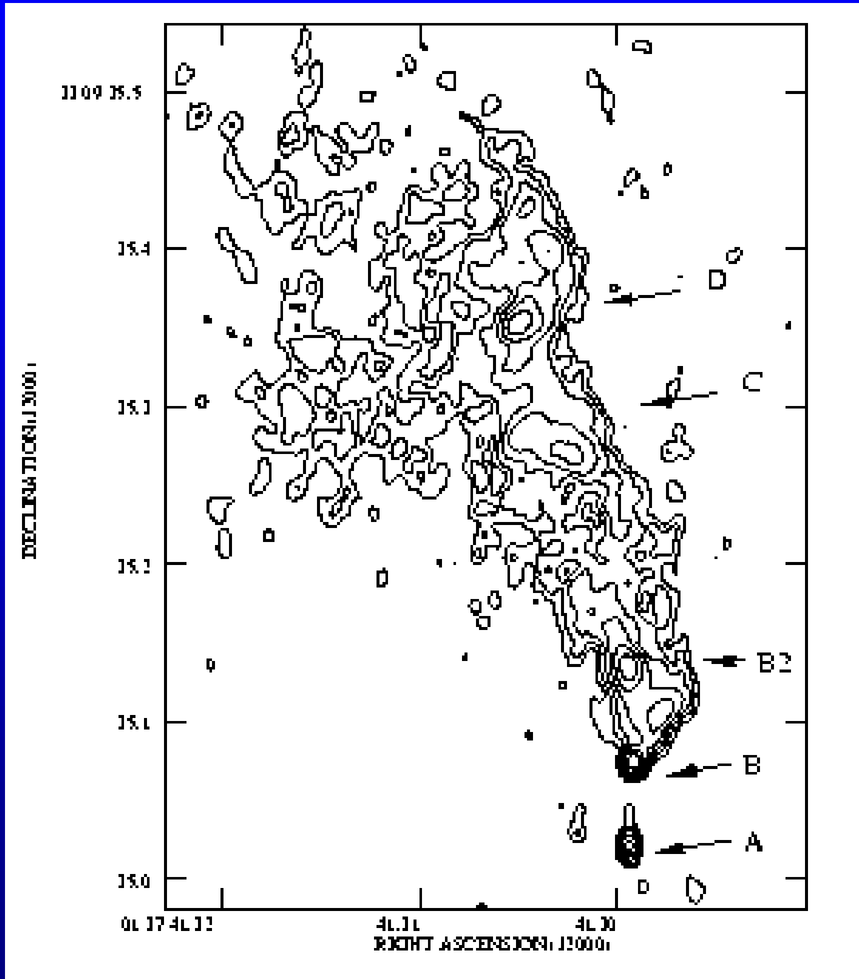
Statistical evidence from radio-loud quasars having higher X-ray fluxes and flatter spectra (Brunner, Staubert et al.)

Radio/Soft X-ray core correlation has been used to argue that **soft-X-ray** emission from the cores of radio galaxies is dominated by radio-related emission.

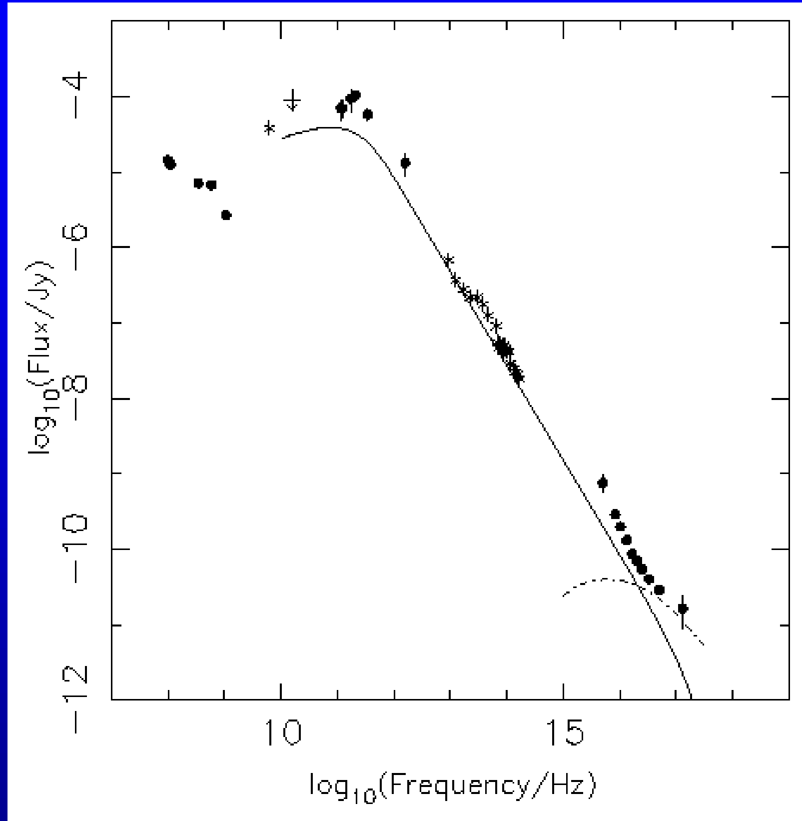
γ-ray emission used to point to strong contribution from blazar jets, but otherwise hard to separate quasar core X-rays into nuclear and small-scale jet-related components. e.g. 3C 48

3C 48

Second quasar to be recognized. Compact-steep spectrum radio source all within VLBI scales. z=0.367



Worrall et al. 2003

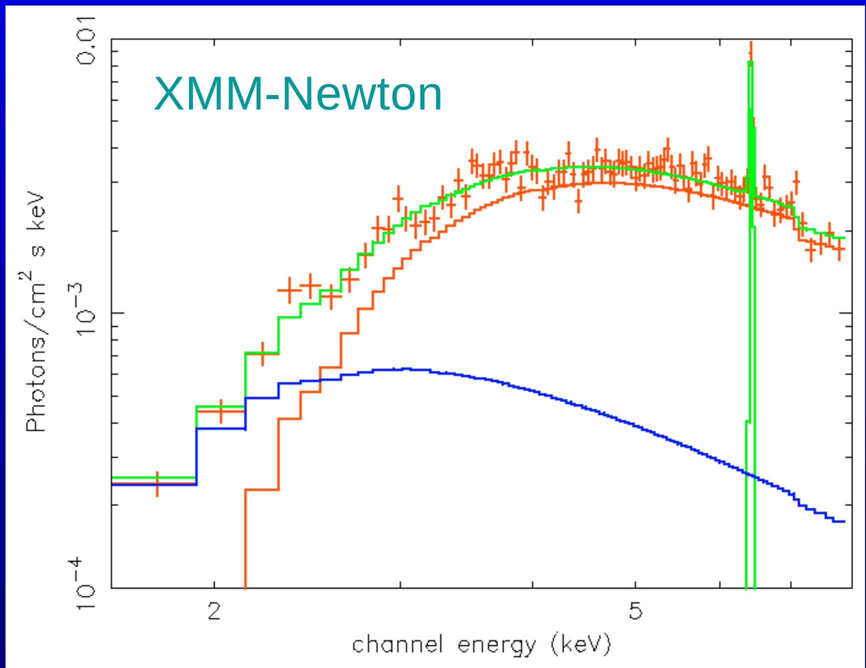


SSC model within comp. A

Size ~10^{16} cm, B ~ 130,000 nT

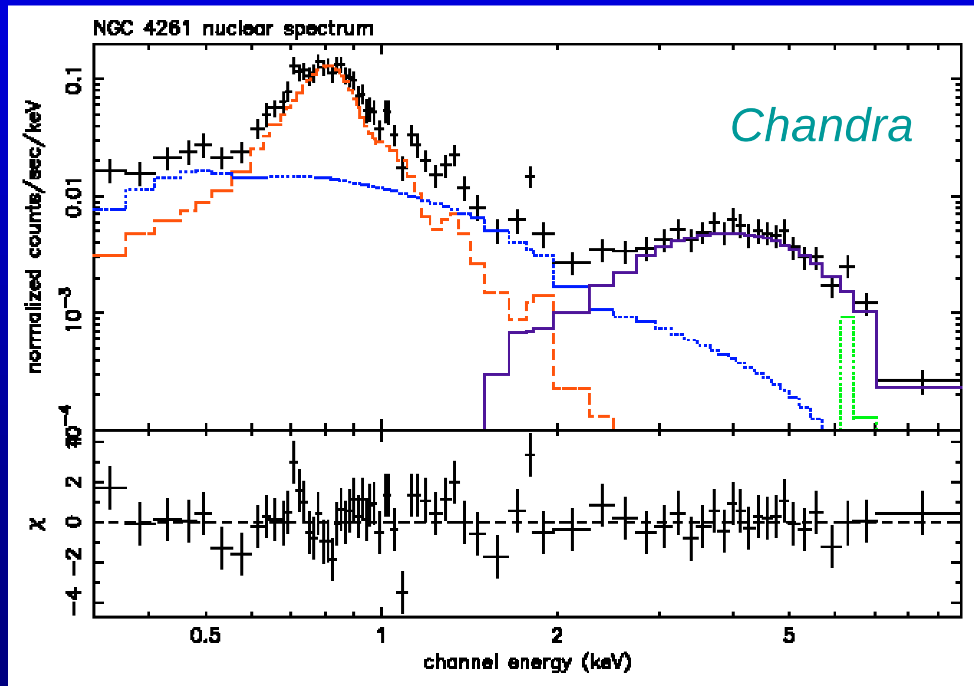
Low-power radio-galaxy cores interpreted either as SSC based on SEDs (e.g. Capetti et al. 2000) or thick/thin accretion disk based on variability or FeK emission (e.g. Gliozzi et al. 2003). Maybe both →

Cen A



Evans et al. (2004)

NGC 4261

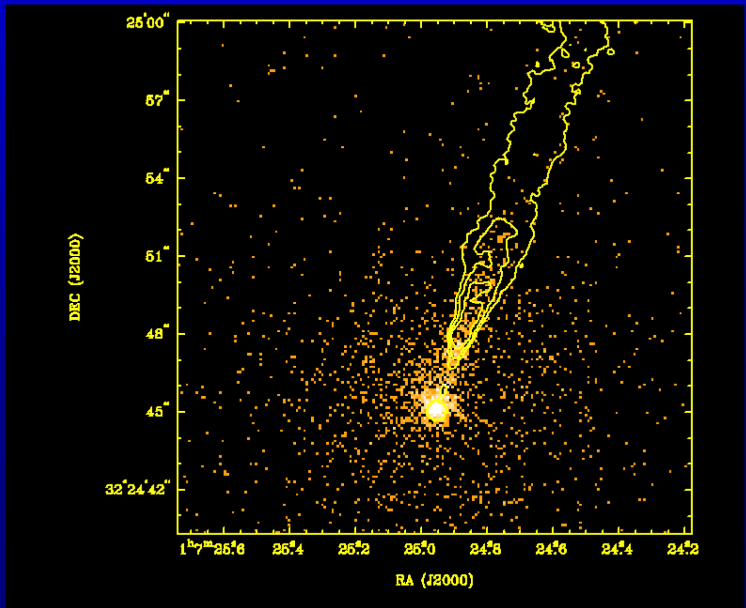


Zezas et al. (2004)

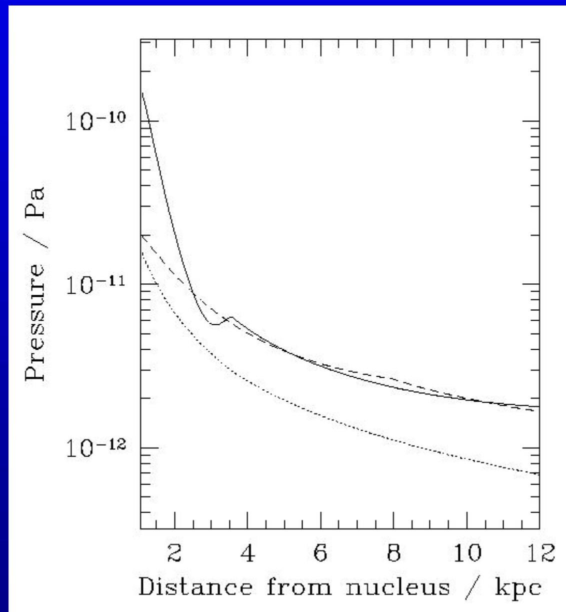
Interaction with X-ray-emitting medium, studied most, so far, in low-power sources

e.g., 3C 31

radio jet-sidedness → velocity → mass entrainment → density and pressure model (Laing and Bridle 2002) gives good match to X-ray pressure (Hardcastle et al. 2002).



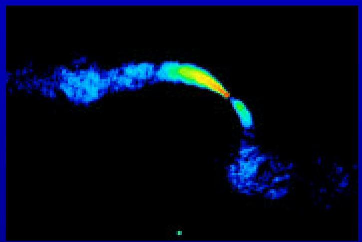
Chandra image with radio contours

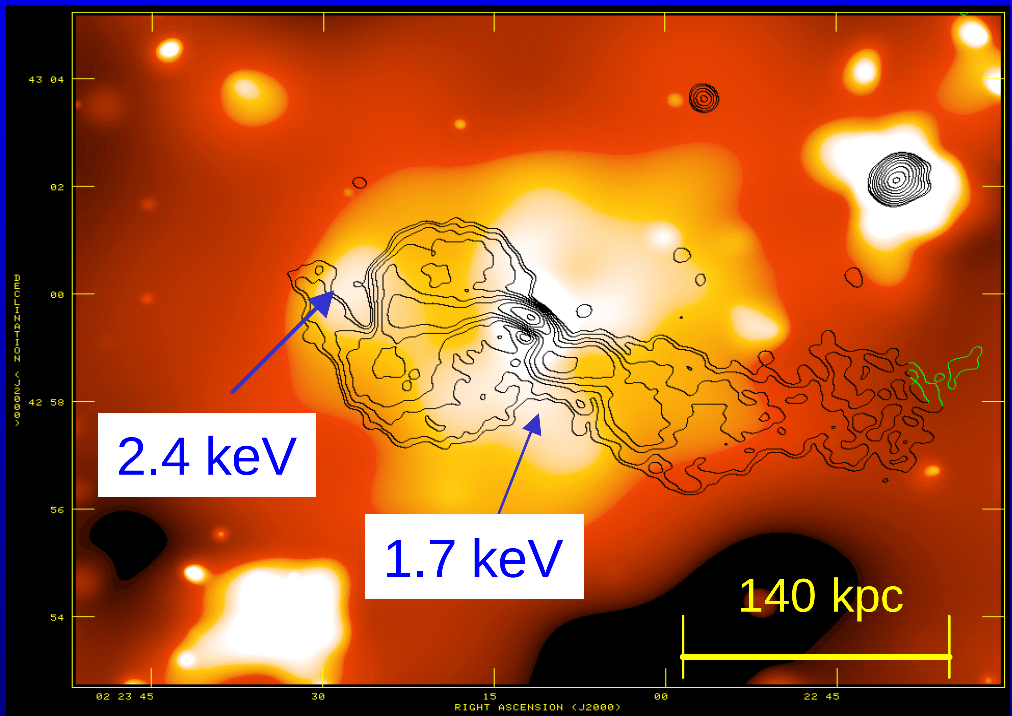


Solid line: pressure in radio source
Dashed line: pressure of external gas
Dotted line: synchrotron P_{min}

X-ray heating

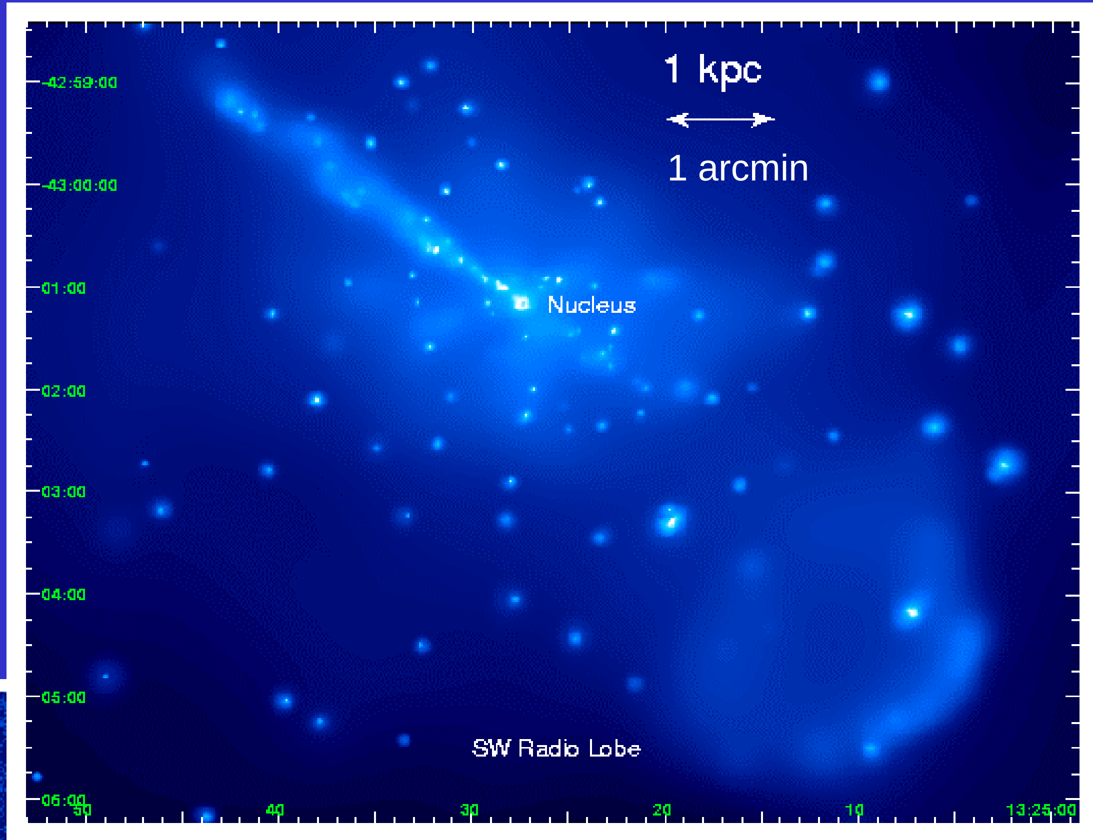
3C 66B, heating displaced gas (Croston et al. 2003).

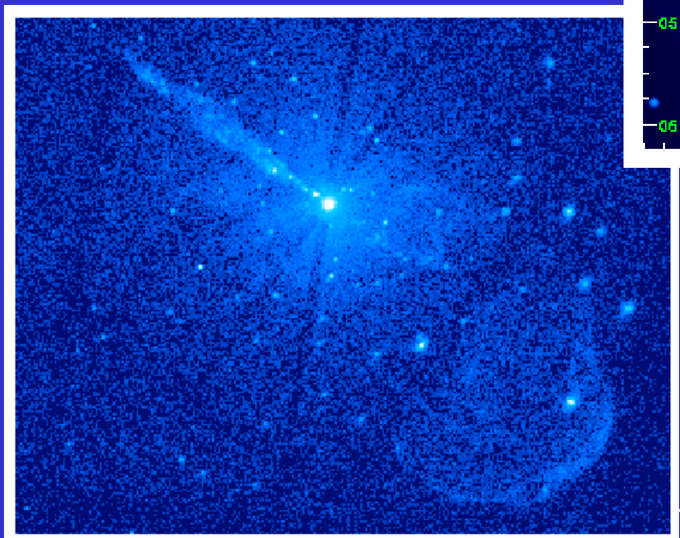




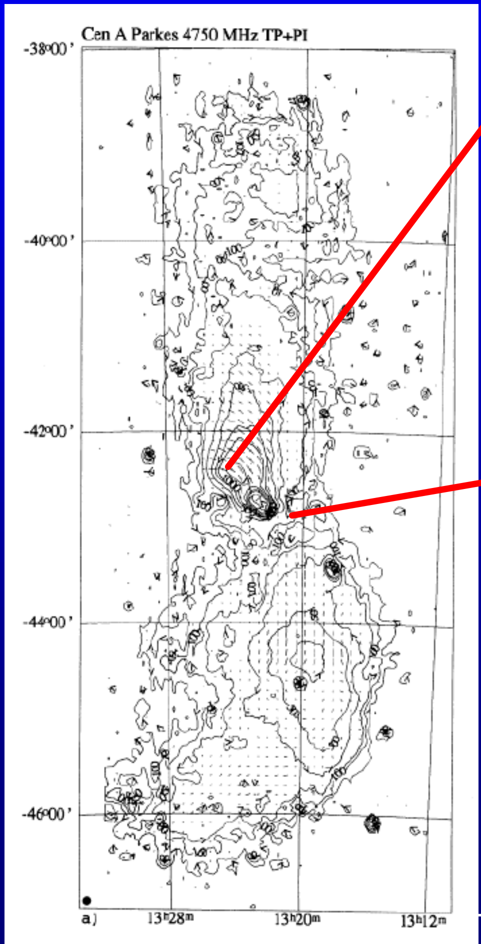
Radio contours on XMM-Newton

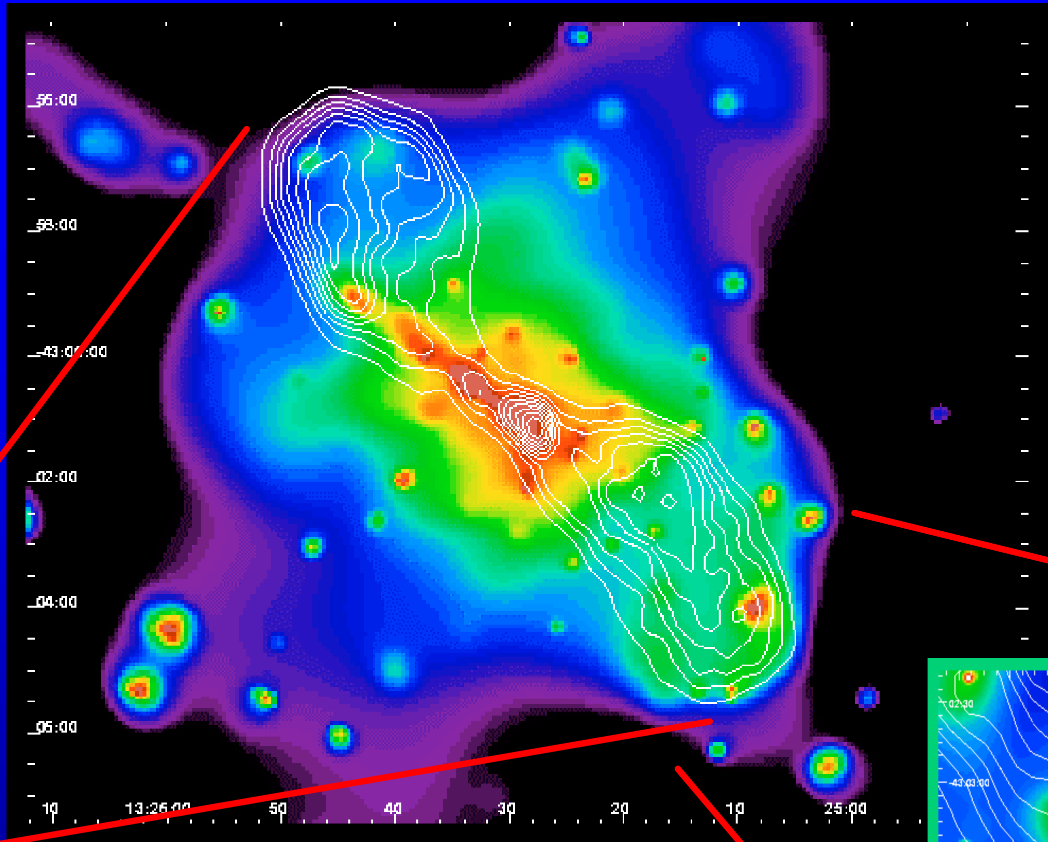
Supersonic X-ray-emitting shocked ISM in Centaurus A





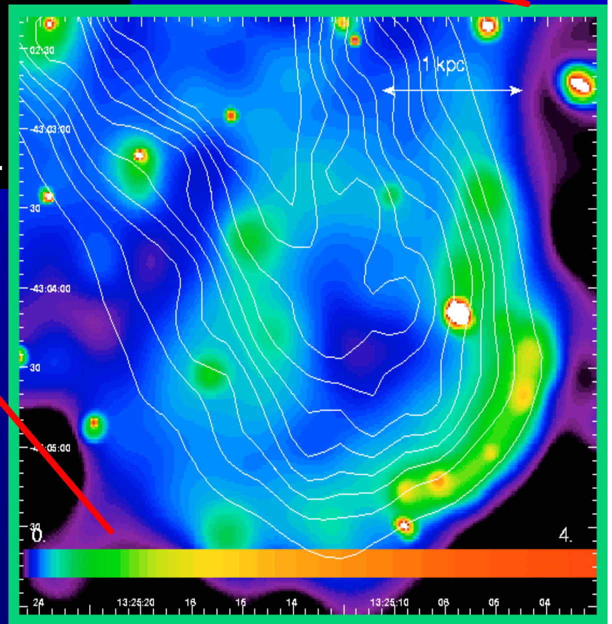
Chandra





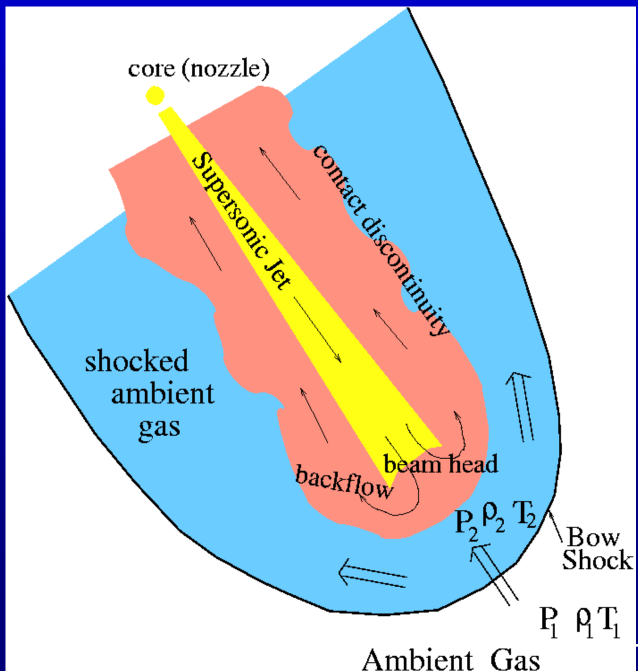
radio contours on XMM-Newton

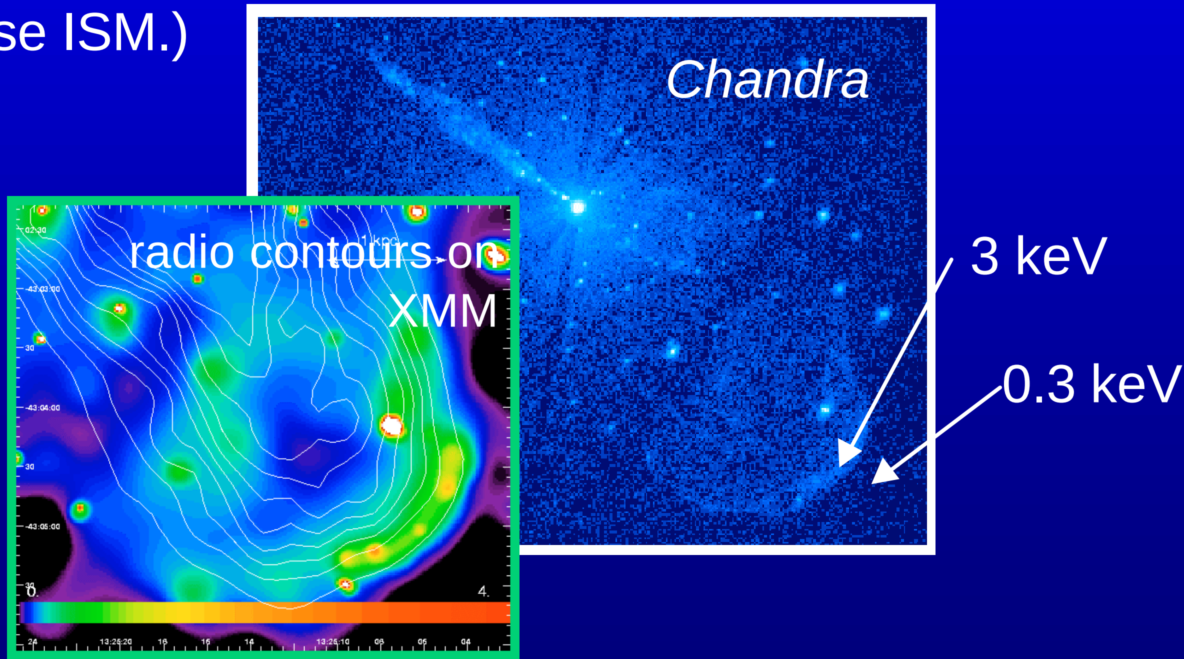
radio ~30'' resolution



The shell's density and temperature are wrong for gas in contact with the bow shock, but are correct for gas which has adiabatically cooled (e.g. Alexander 2002) in pressure balance with gas of $kT_2 \sim 6.8$ keV, where $v_{adv} \sim 2400$ km s^{-1}, $M \sim 8.5$.

(Emissivity of the 6.8 keV gas too low to separate its X-rays from those of the diffuse ISM.)





Broader interest from Cen A result:

The shell's kinetic energy is ~6.5 times its thermal energy, and exceeds the thermal energy of the ISM within 15 kpc of the center of the galaxy. As the shell dissipates, it will have a major effect on Cen A's ISM, providing distributed heating.

The tip of the iceberg:

Proposed new X-ray missions with high throughput and high-resolution spectroscopy could detect heated gas and measure the advance speed around many radio sources with jets.

Combine with Thrust Equation & Energy Equation

(based on internal energy)

→ v_{jet}, ρ_{jet}

Conclusions

High-energy observations of radio structures crucial for probing physical parameters. What we learn from resolved structures can be applied to the small scale.

Surprises:

- Synchrotron X-ray jets → intrinsic electron spectrum commonly continues to TeV energies
- Quasar iC X-ray jets → speeds close to *c* common out to Mpc distances

Successes:

- Agreement with hydrodynamical models for overall flow e.g. 3C 31

TBD:

- Unbiased samples of jet objects over broader *L-z* ranges
- Deep observations and refined theory of jet-lobe/ISM-ICM interactions
- Monitoring of X-ray/optical/radio knots, offsets, optical polarization, etc, to study acceleration sites and processes.