Energy exchange mediated by radio galaxies: one size doesn't fit all

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Radio mode heating:

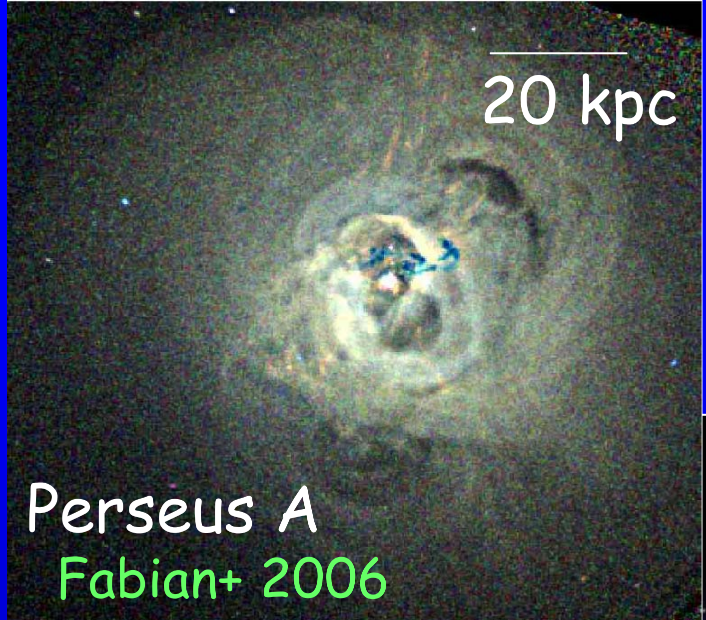
Ignoring the issue of AGN fuelling, we'd like a better observational understanding of which radio galaxies are engaged in heating and how the heating occurs.

- Long history to the recognition that radio sources inject energy into the surrounding ISM/IGM (e.g., Scheuer 1974), with jet kinetic powers exceeding radiative powers (e.g.,Willott+ 1999)
- Through cavity detections, Chandra has demonstrated this conclusively for radio sources in clusters and solved(?) the cooling-flow problem

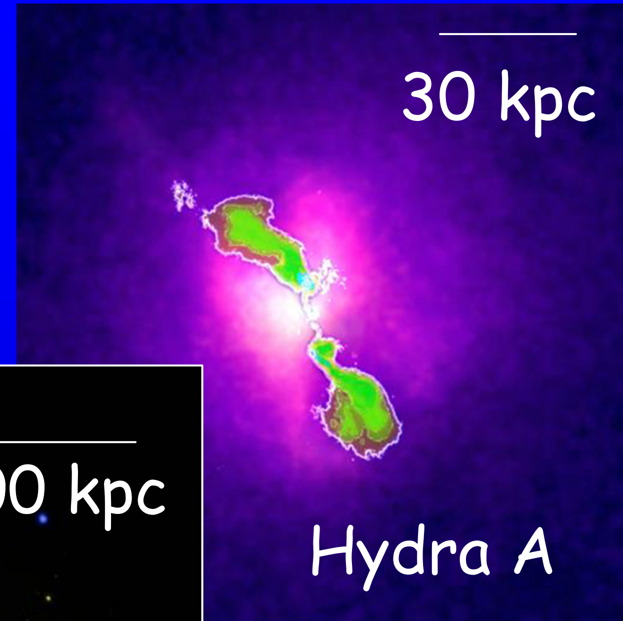
But,

Sources of a wide range of powers and sizes participate, with smaller sources showing (needing) multiple outbursts.

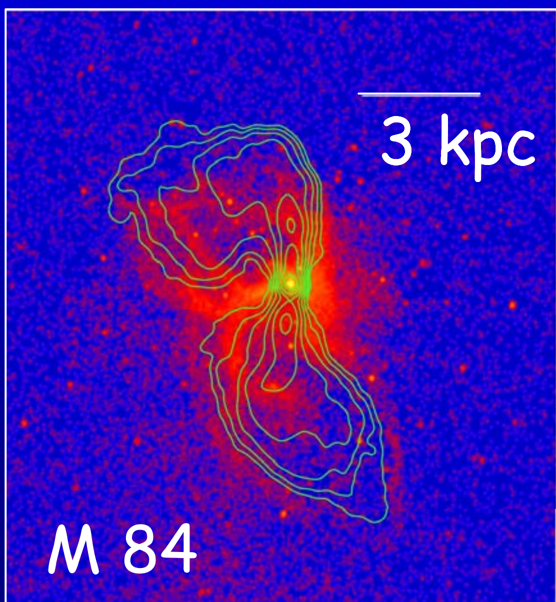
Complex selection effects in cavity population. Large range in size and power. Examples in order of increasing low frequency radio power →



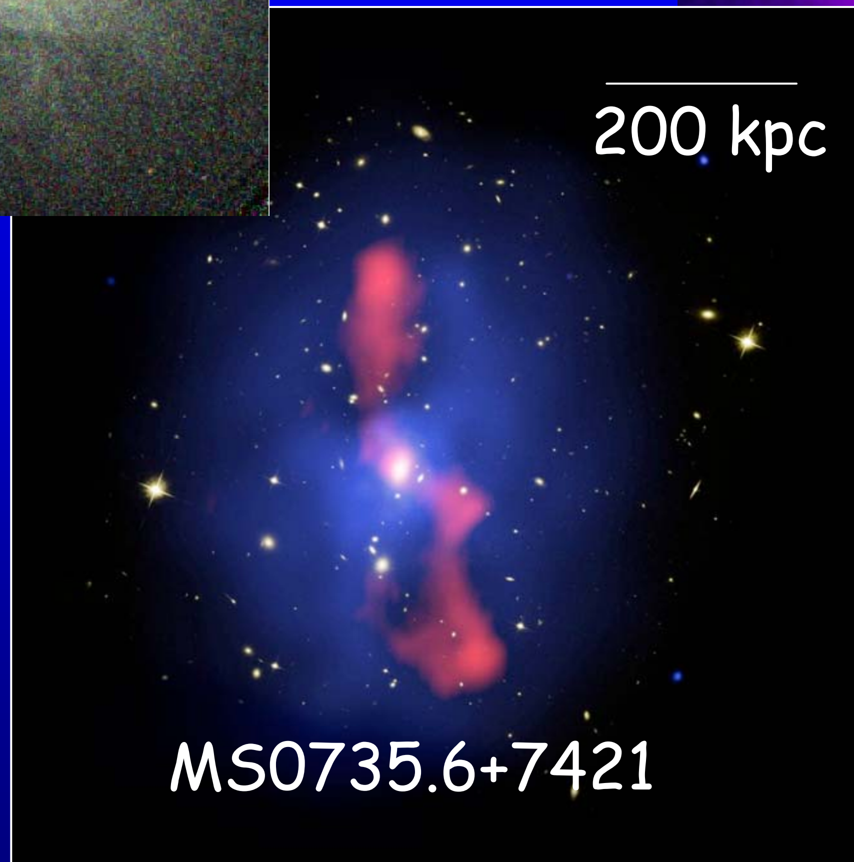
Fabian+ 2006



McNamara+ 2000



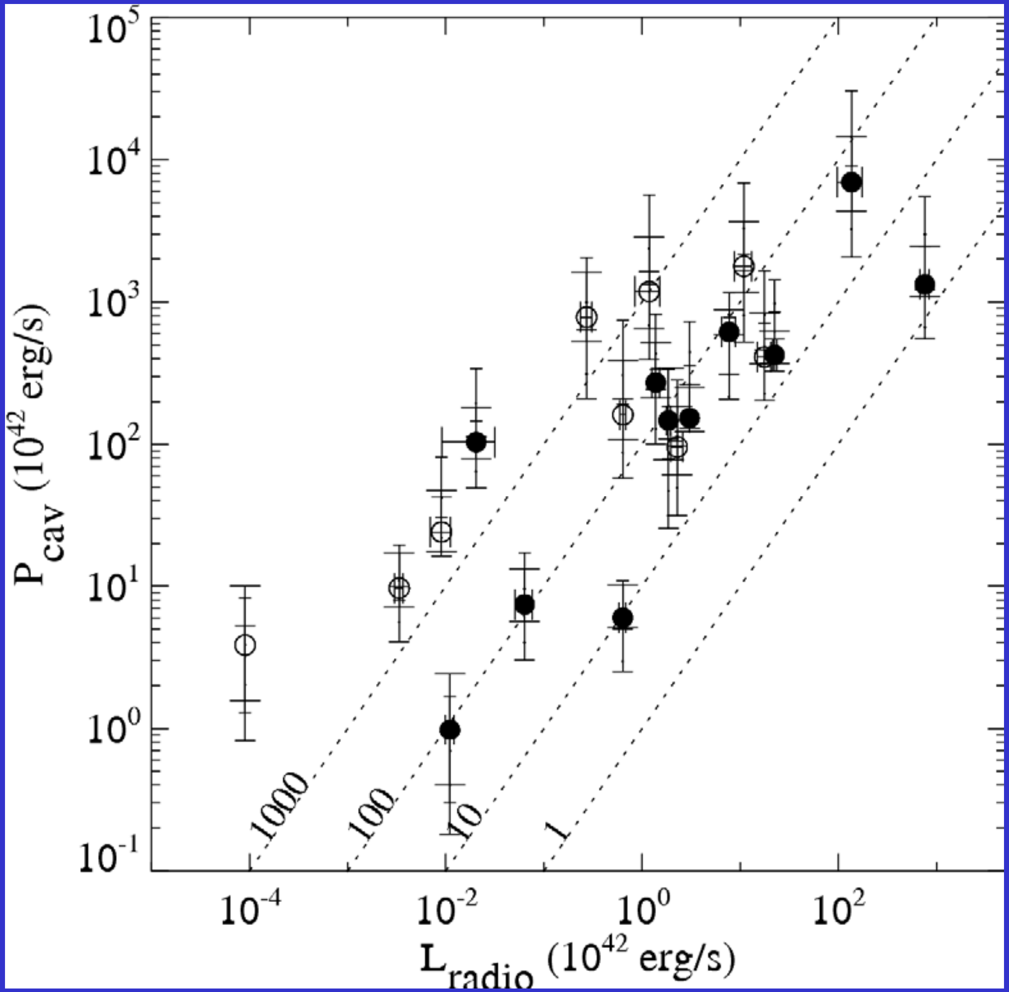
2010 Birkinshaw+
(Finoguenov+ 2008)



McNamara & Nulsen 2007
(McNamara+ 2005)

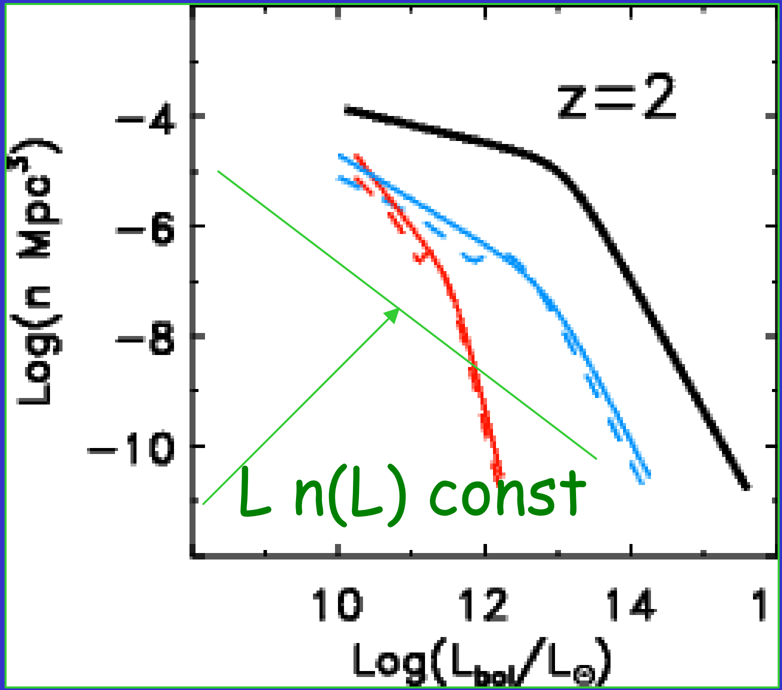
Which are the typical sources?

Cavity power v radio power



McNamara & Nulsen 2007

$L_{mechanical}$ $n(L)$ significant over a wide range of L. Peaks at low $L_{mechanical}$ based on cavity power, or close to FRI/FRII boundary based on min energy.



Cattaneo & Best 2009

How do we get distributed heating?

Paradigm is that distributed heating in the smaller, weaker cavity sources (e.g., M84, M87, Perseus A) occurs principally through multiple, small, buoyant cavities (motions in Swiss Cheese, gas mixing).

Need:

1) inflated lobes
2) jets changing direction
3) intermittency

What do we learn from other well-studied sources of L_{radio} within factor ~10 of Perseus A, typically in group environments?

Are inflated lobes common?

Well known that low-power radio galaxies are under-pressured relative to X-ray environments taking only the relativistic electrons and minimum syn energy (e.g., Morganti + 1988). Can fix by adding relativistic protons.

Simulations, starting at <0.1c, find fat cavities

- if jets stay light (e.g., Guo & Mathews 2010)

Or

- if large entrainment at the edge or through entruders, energy carrier must be wide (1/2 opening angle >30 degs) or jets precess (e.g., Sternberg & Soker 2009 for MS0735+7421)

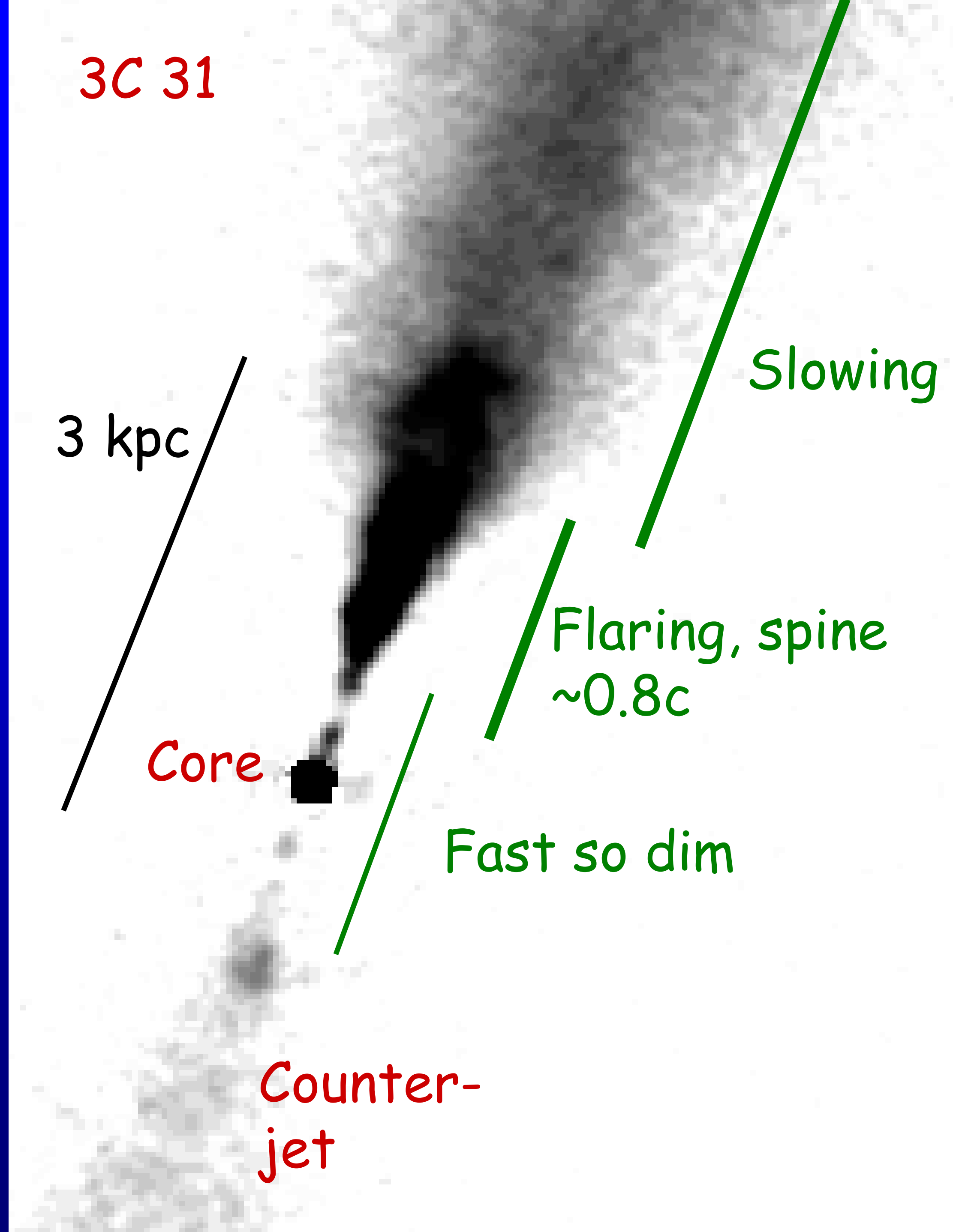
Do we see fat cavities (& fat or precessing energy flows)?

VLBI proves sources start out highly relativistic.

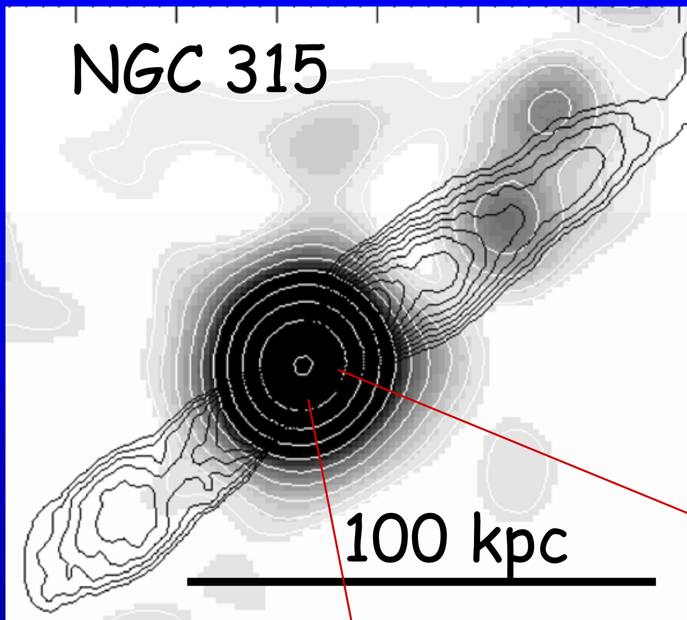
Kinematic modeling is possible in some 2-sided cases with good radio mapping and polarimetry.

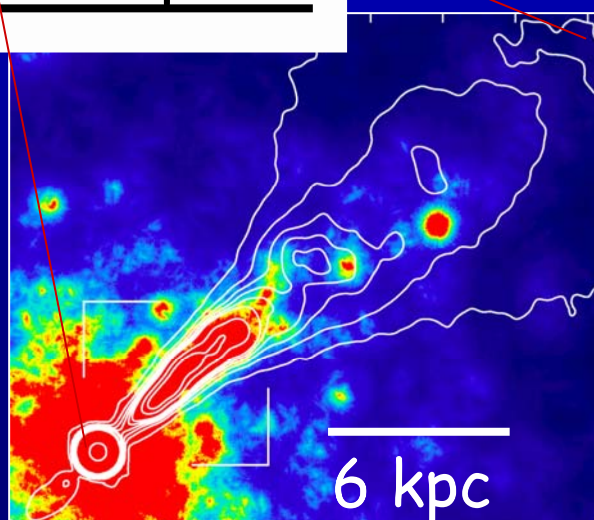
Success in dynamical modelling if narrow flow of energy carriers in contact with the ISM (e.g., Laing & Bridle 2002, for 3C 31)

Will be heat release in the inner many kpc



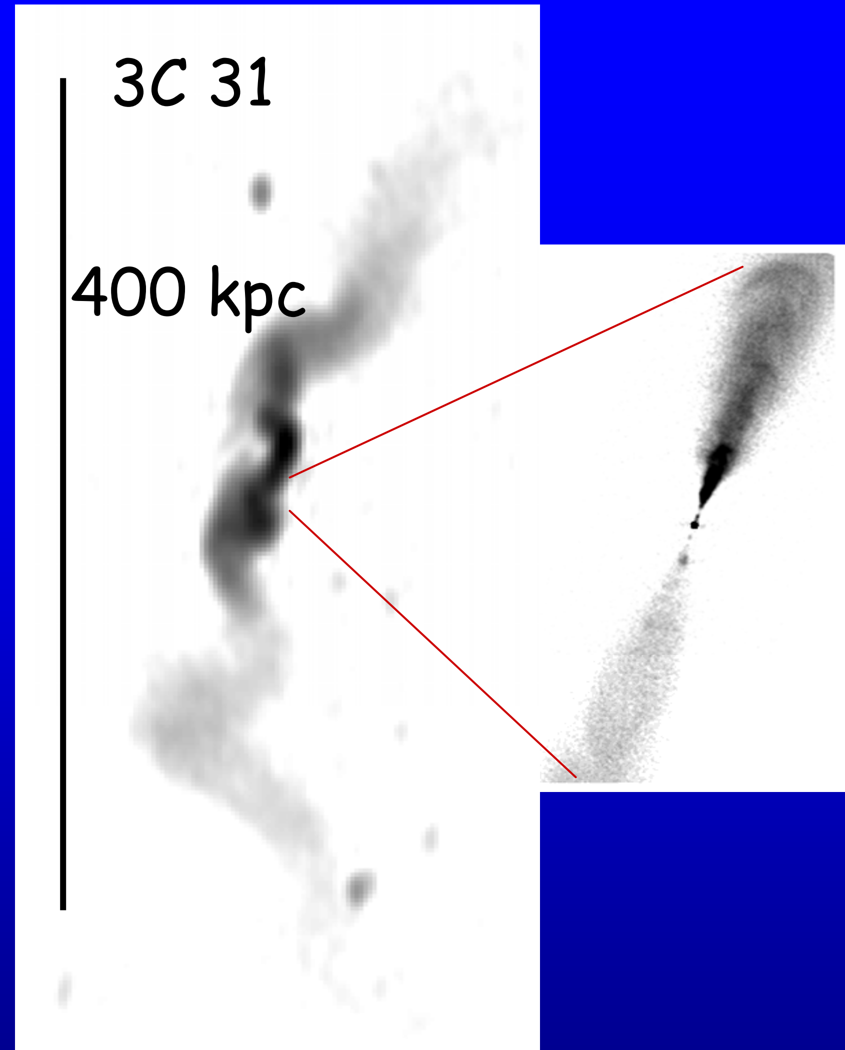
Many do not develop fat lobes in their galaxy or group atmospheres, e.g.,





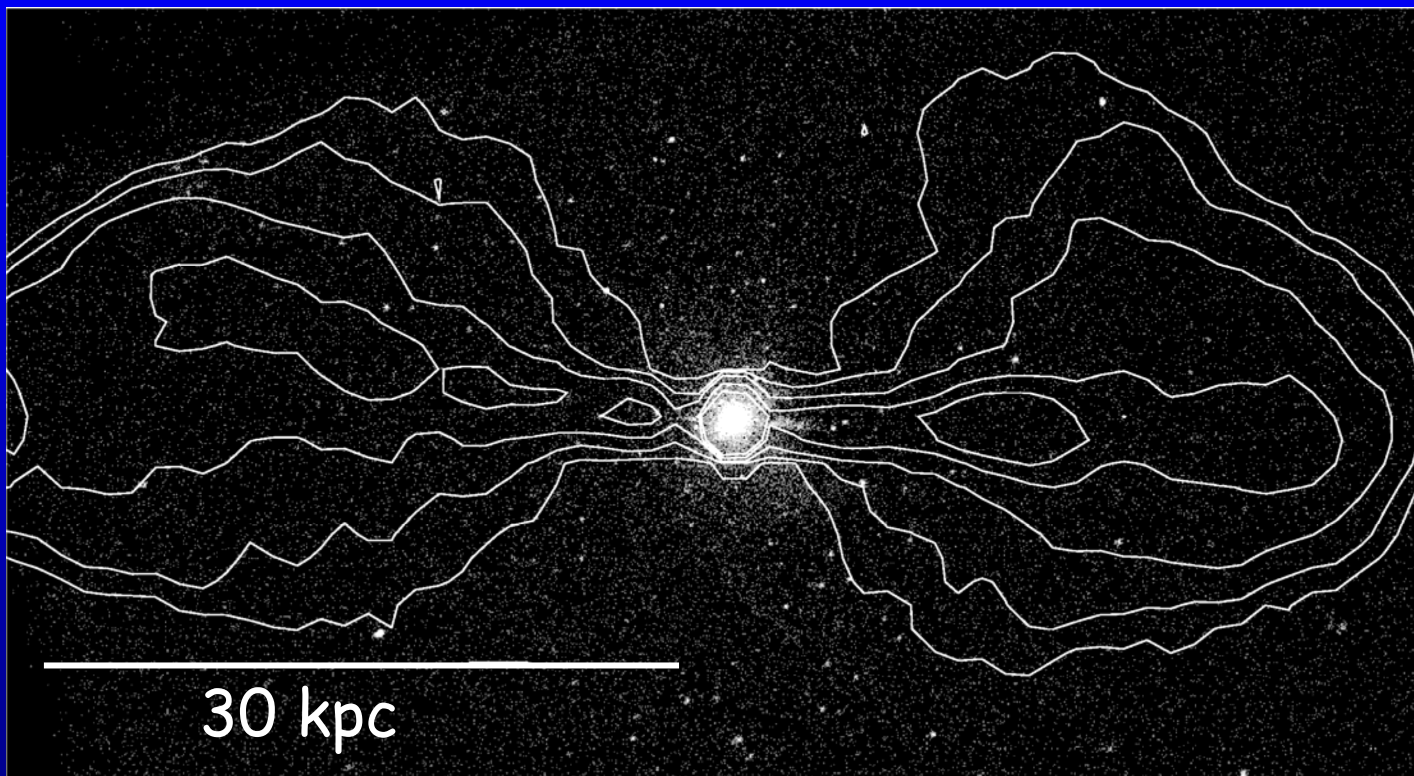
Worrall & Birkinshaw 2000, Worrall+ 2007

Radio contours on X-ray



Laing & Bridle 2002

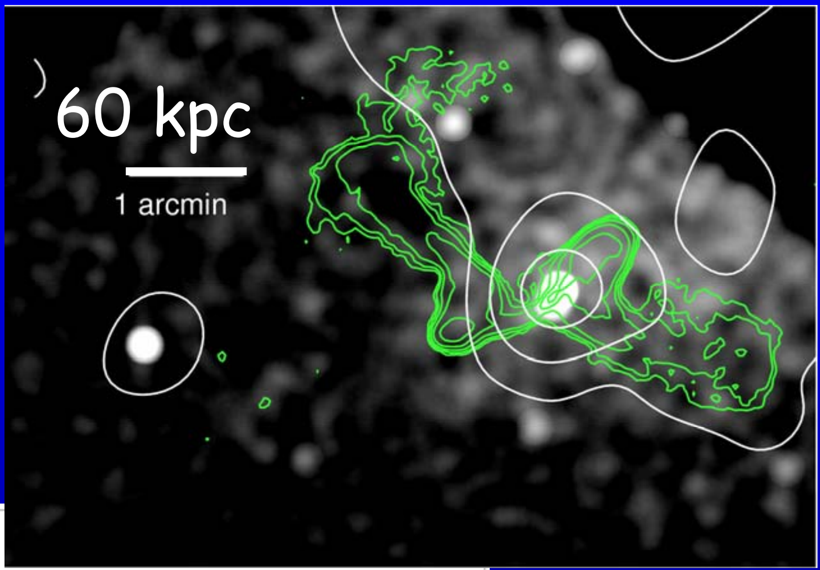
Others do – e.g., NGC 4261 which is bracketed in power by   NGC 315 and 3C 31.

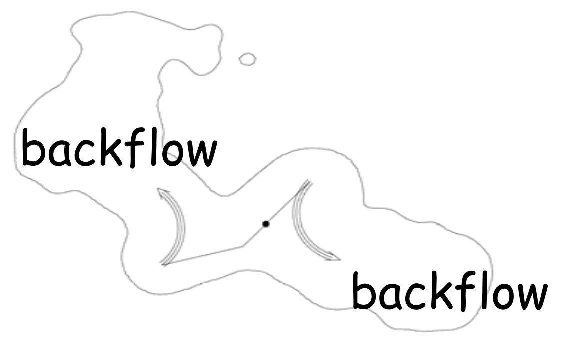


Statistical study using complete samples and X-ray atmospheres underway.

Do jets commonly make larges changes in direction?

No. But yes if companion galaxy or encounter.



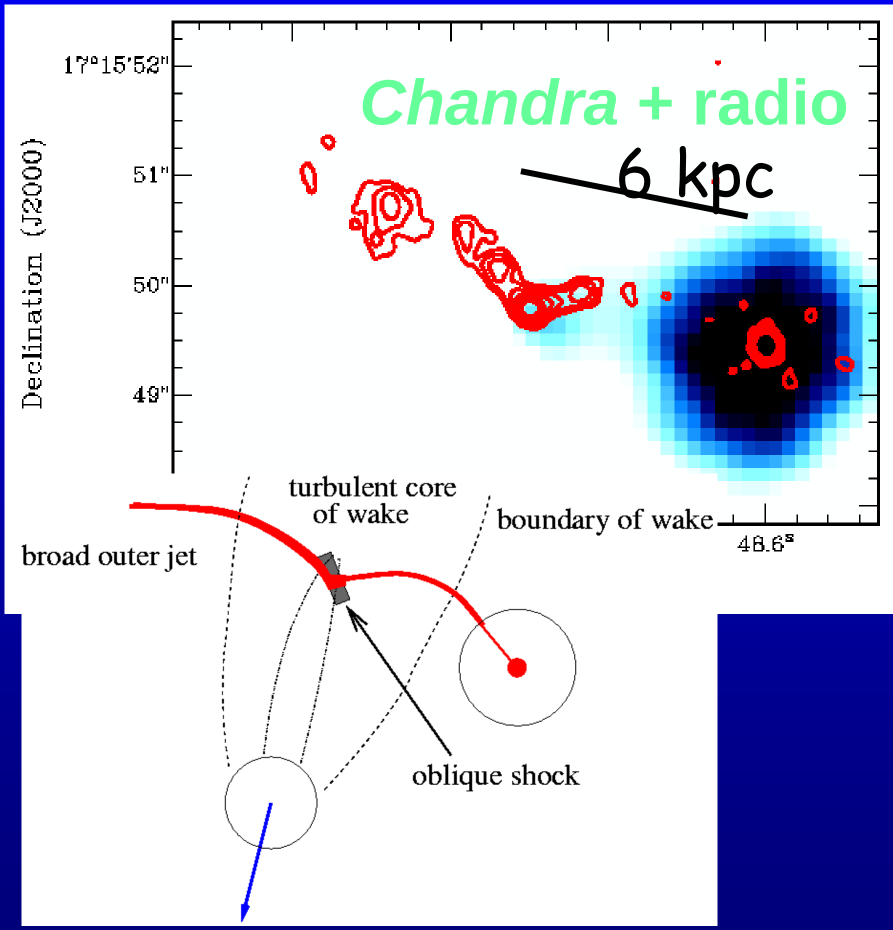


Worrall+ 1995,2010

Dumbbell
NGC 326

Buoyancy, not precession

3C 346

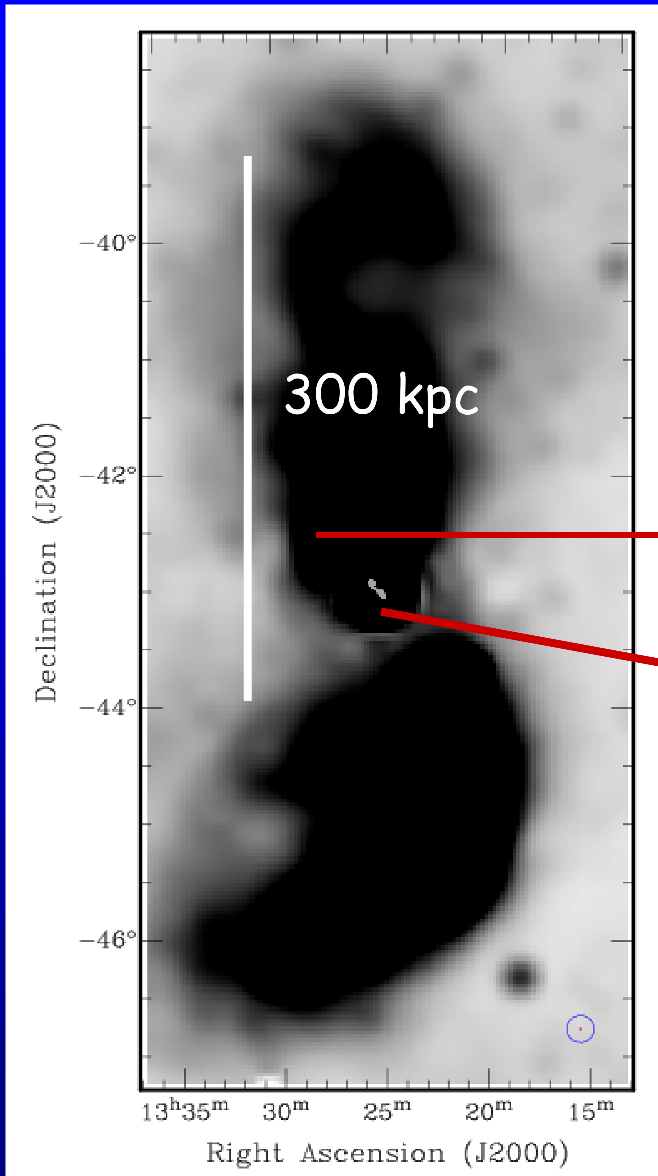


Worrall & Birkinshaw 2005

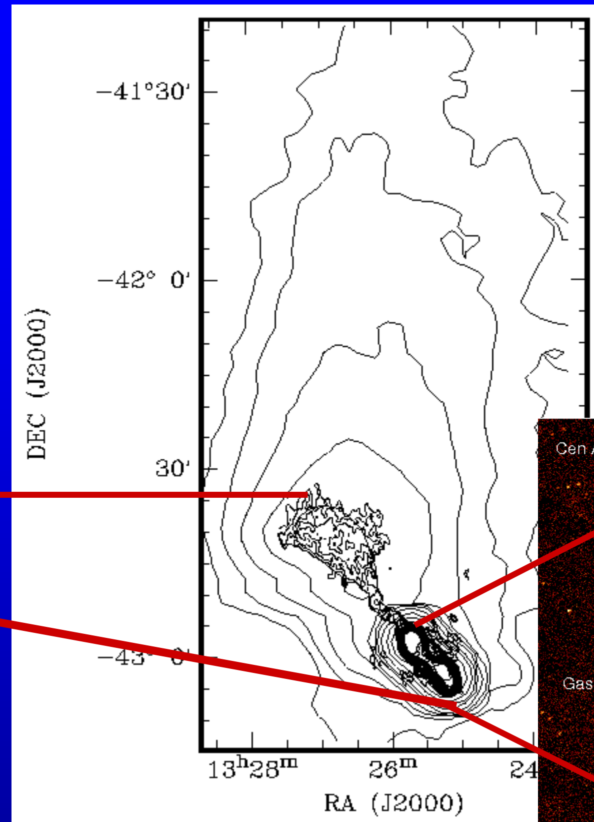
Is intermittency common?

Cen A

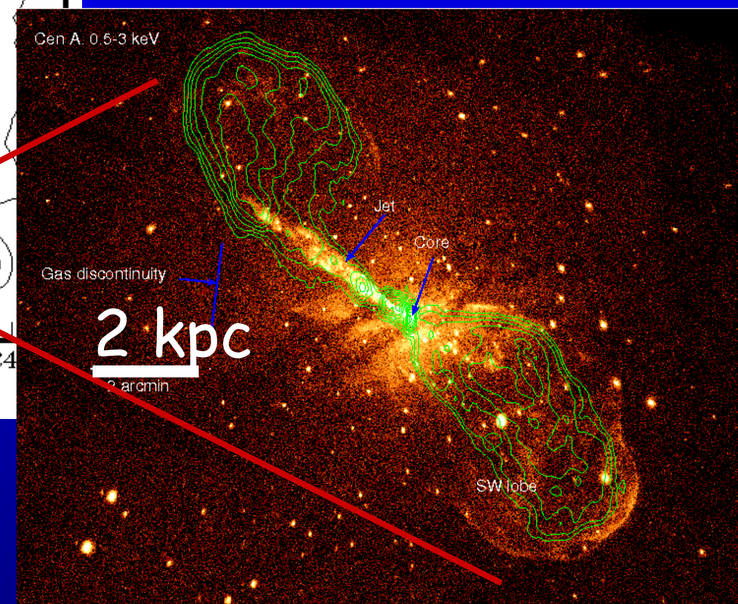
The closest radio galaxy → best linear resolution



Junkes/Klamer



Morganti+ 1999



Chandra VLP team 2008

Do many galaxies contain embedded highly-shocked cavities?

Mach numbers for observed cavity sources are so far low (e.g., M ~ 1.2—1.7). However, Cen A (L_{radio} between M84 and Perseus A) gives us the highest linear resolution and shows embedded M ~ 8 cavities.

Heat input scales roughly M^2/unit volume, so Cen A ~30 times more effective per unit volume for fixed external gas properties.

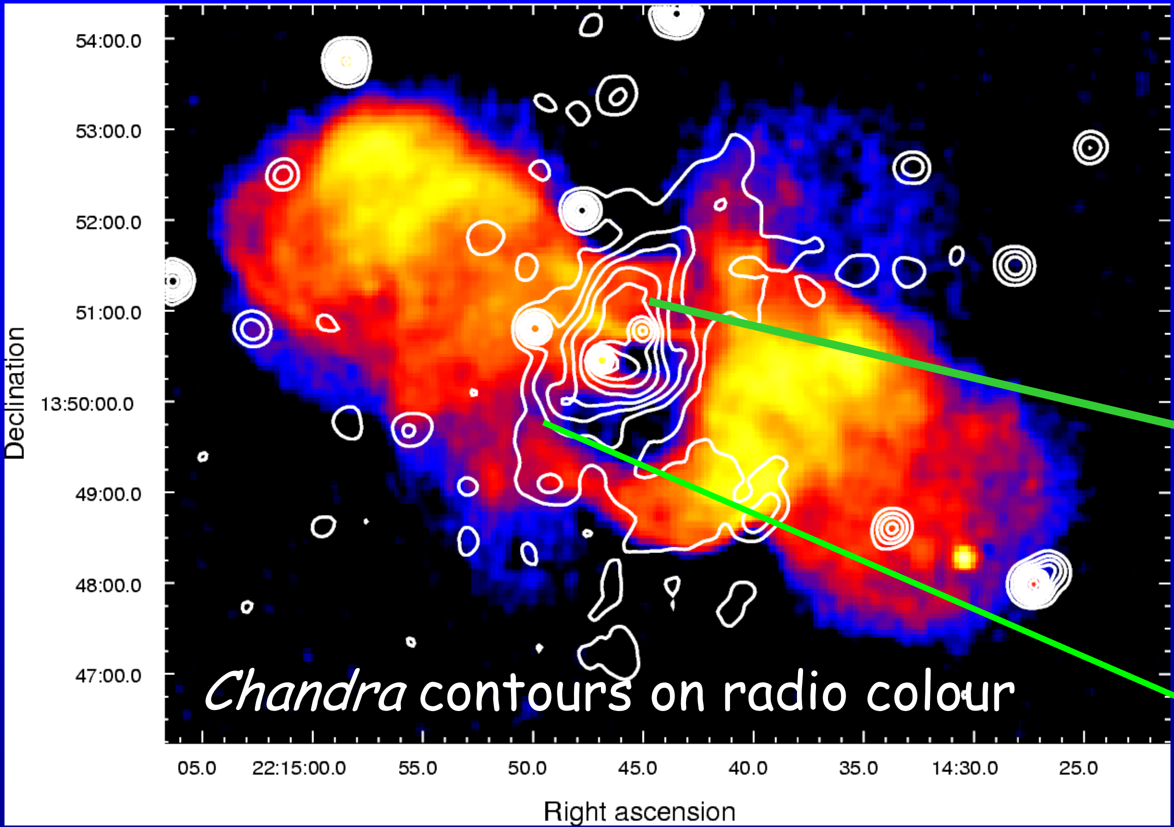
Observational limitations: very few of the brighter radio sources have kpc scales filling more than a few Chandra PSFs – insufficient resolution & sensitivity to measure heating.

Unless morphology clearly shows multiple outbursts, (as in Cen A) modest changes in jet power are hard to measure in the radio since particle lifetimes long.

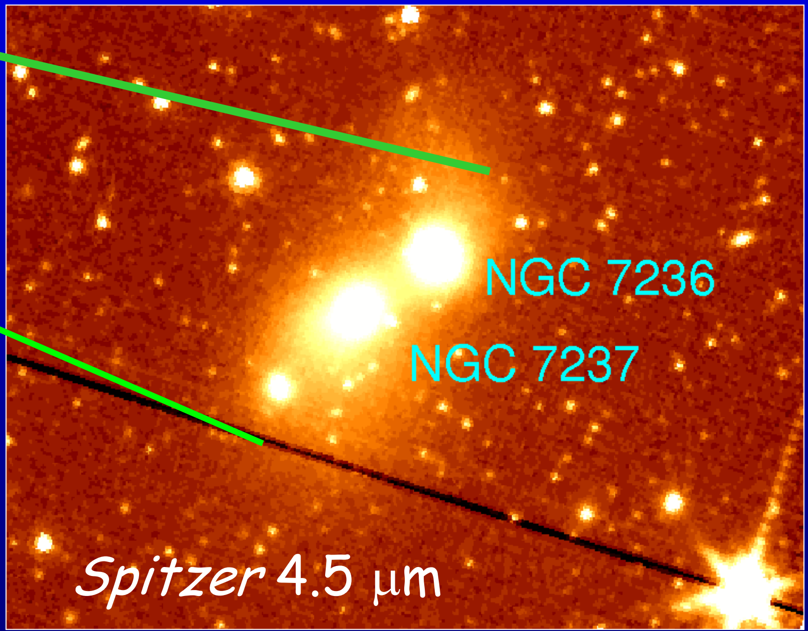
Novel method applied to twin jets in NGC 4261, based on the idea that jet X-ray emission is brighter during outburst, suggests source re-energized ~ 6 x 10^4 yrs ago -- well within its overall lifetime (Worrall+ 2010).

Close Encounters. e.g., 3C 442A

Energy exchange can reverse direction: *gas* → radio plasma



Merger gas causes old radio lobes to separate and energize



Worrall+ 2007

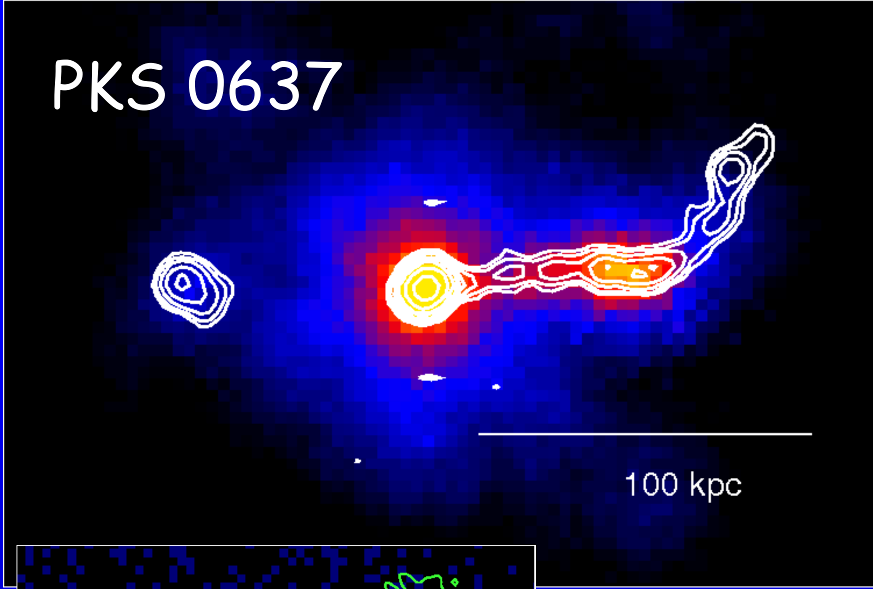
Study of more merger cases underway

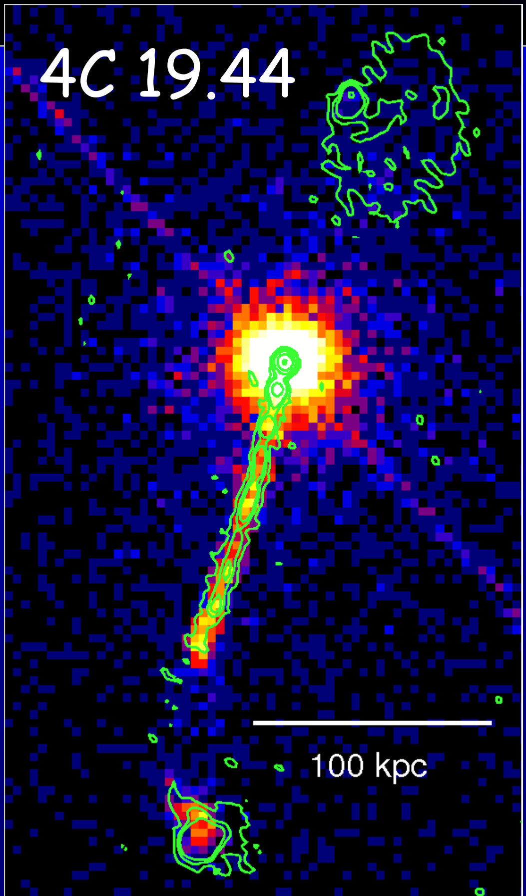
FRII jets have the highest powers.

They are highly relativistic, as deduced from their X-ray emission, typically live in significant clusters (e.g., Belsole+ 2008) but travel large distances.

They may be rare, but have large energy to dissipate, initially through shocking the gas.

Lobes of aged electrons may then become re-energized in cluster mergers (possible origin of radio relic sources, themselves relatively rare).





Radio contours Chandra images

Worrall 2009 (Schwartz + 2000, Harris+ 2010)

Conclusions

- Radio sources of typical radio output reside in typical gas environments (groups rather than clusters).
- Still work to be done to relate their diverse properties with their physical environments.
- The speed and composition of the energy carriers remain uncertain and plague simulations and modeling of data.
- Heating scenarios are plausible, but the mechanisms remain unclear. Much interesting work to be done.