Energy and momentum transfer by AGN jets as revealed in X-rays

Diana Worrall
University of Bristol

Galaxies near and far   Perugia, May 2011

Outline

1. Mechanical power of AGN jets
2. Work done on X-ray gas (or vice versa)
3. The problem of energy → heat
4. Importance of jets of intermediate power
5. Case studies
    1. 3C 346
    2. PKS B2152-699
6. Summary

1. Mechanical Power

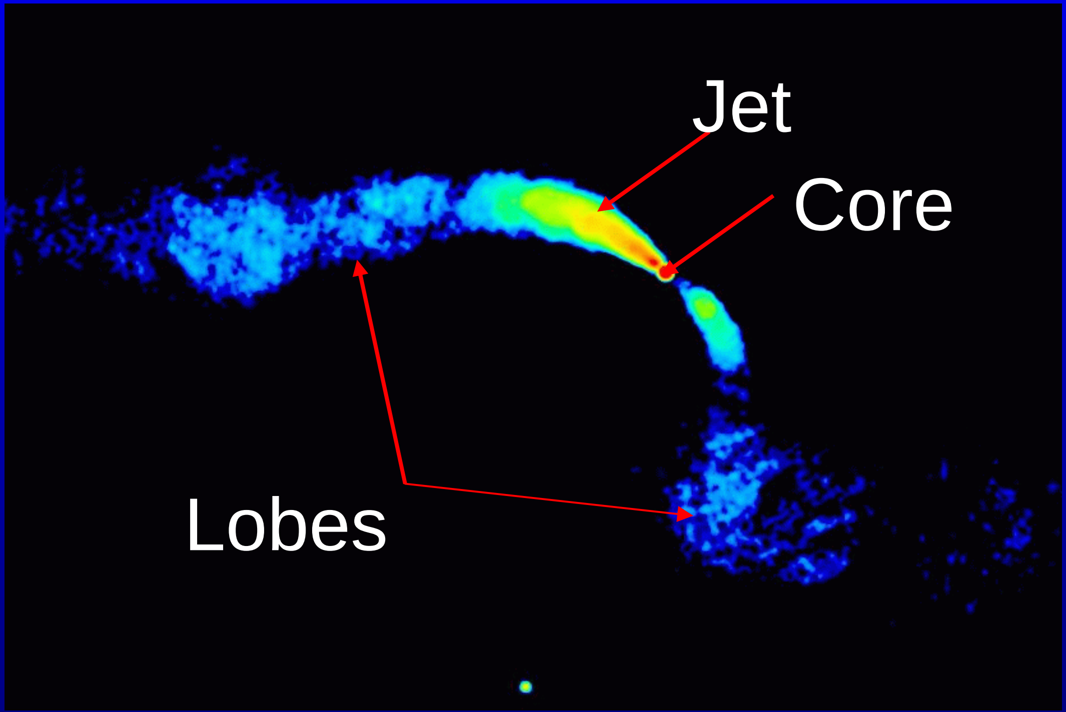
- Long history to the recognition that radio sources inject energy into the surrounding ISM/IGM (e.g., Scheuer 1974), with jet kinetic powers exceeding radiative powers (e.g.,Willott+ 1999)

- *Chandra* → Conclusive demonstrations.
  - dominant component of the baryonic medium
  - non-thermal jet emission:
    - Synchrotron from TeV electrons
    - iC on CMB (mandatory) but only strong if highly relativistic bulk flow and jet oriented towards the observer

Fanaroff & Riley (1974)

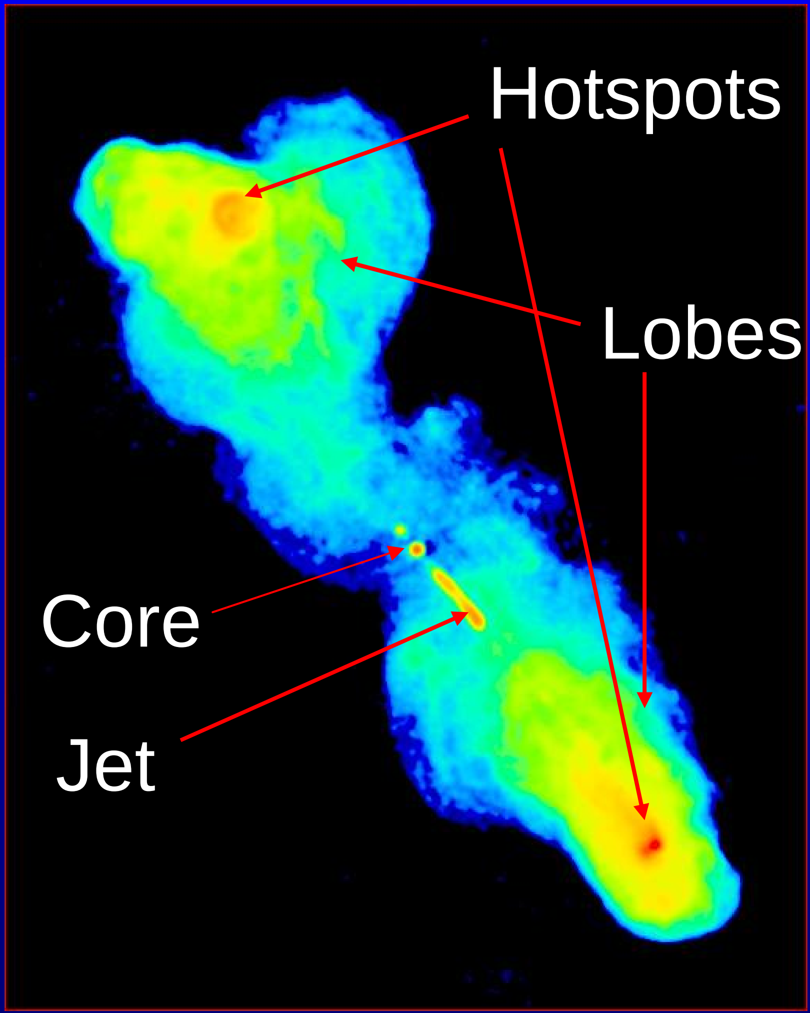
Low-power FRI

BL Lac if jet boosted in line of sight



High-power FRII

Quasar if jet boosted in line of sight



Mechanical Power

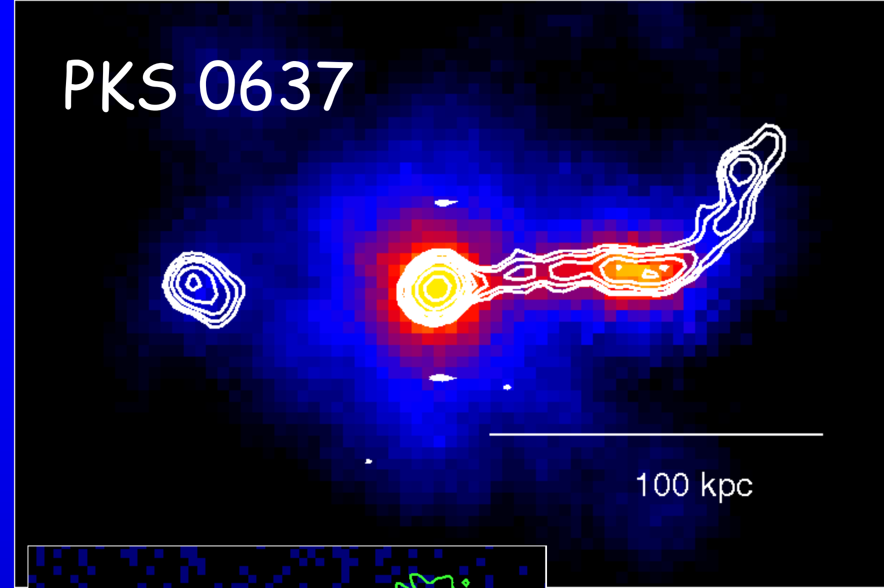
FRIIs

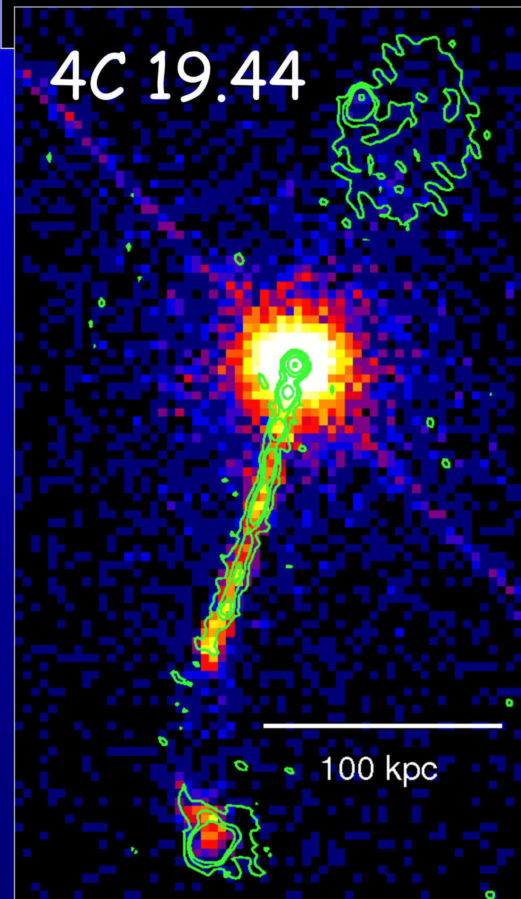
- Quasar jets detected. FRII radio-galaxy jets generally not.
- Jets of similar length in X-ray and radio.
- Must be iC-CMB. Jets must travel at ~c on huge scales for special relativity to assist.
- Much kinetic power (~10^{39} W)

(e.g. Schwartz + 2006)

FRIs

Power estimated from work done on the X-ray emitting gas





Radio contours Chandra images

Worrall 2009 (Schwartz+ 2000, Harris+ 2010)

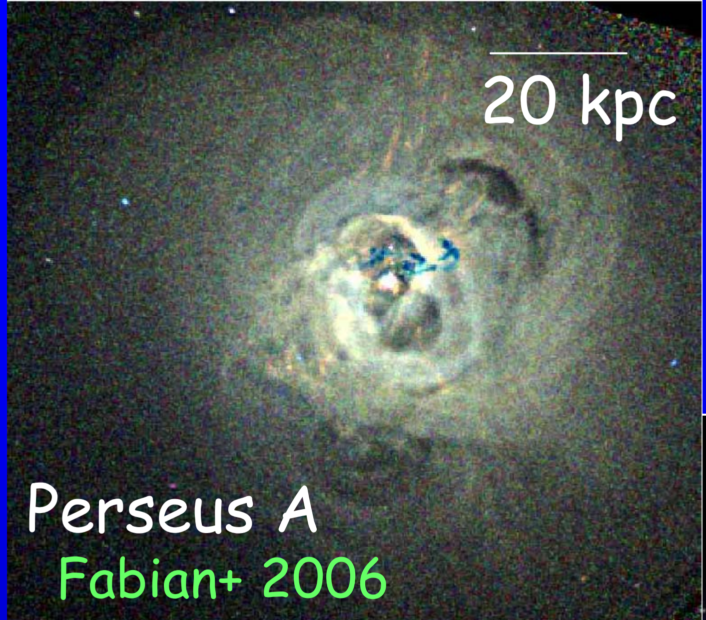
2. Work Done

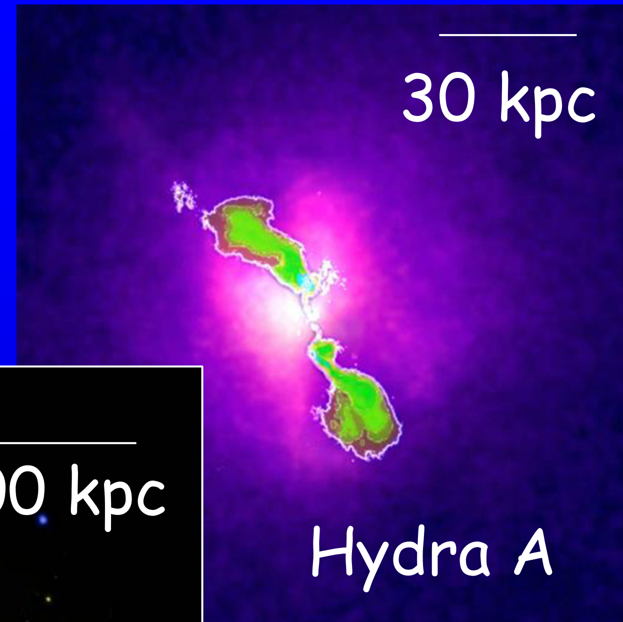
•FRIIs travel large distances, have large energy to dissipate, initially through shocking the gas. Rare.

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

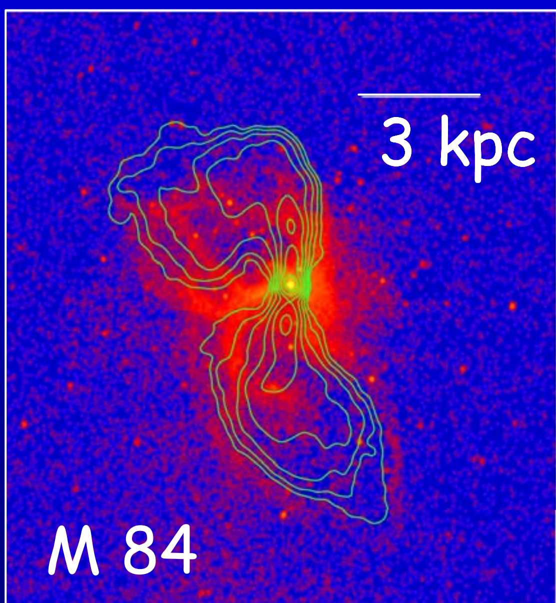
•FRIs (mostly, but large range in size and power): mechanical power measured through the work done in evacuating gas cavities.

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

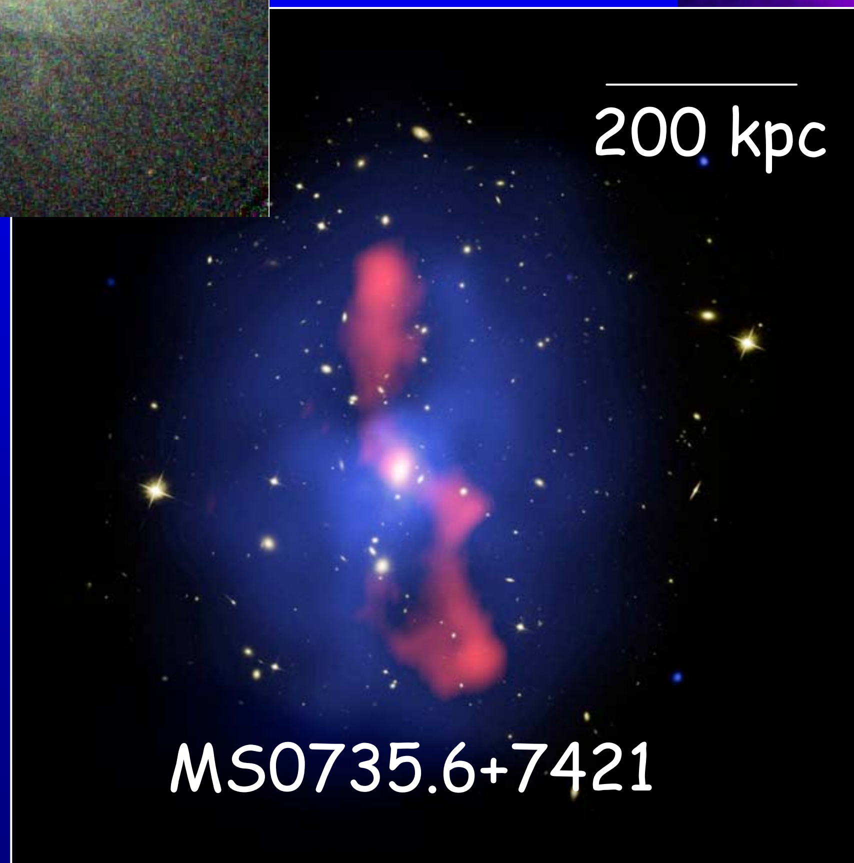




McNamara+ 2000



2010 Birkinshaw+
(Finoguenov+ 2008)

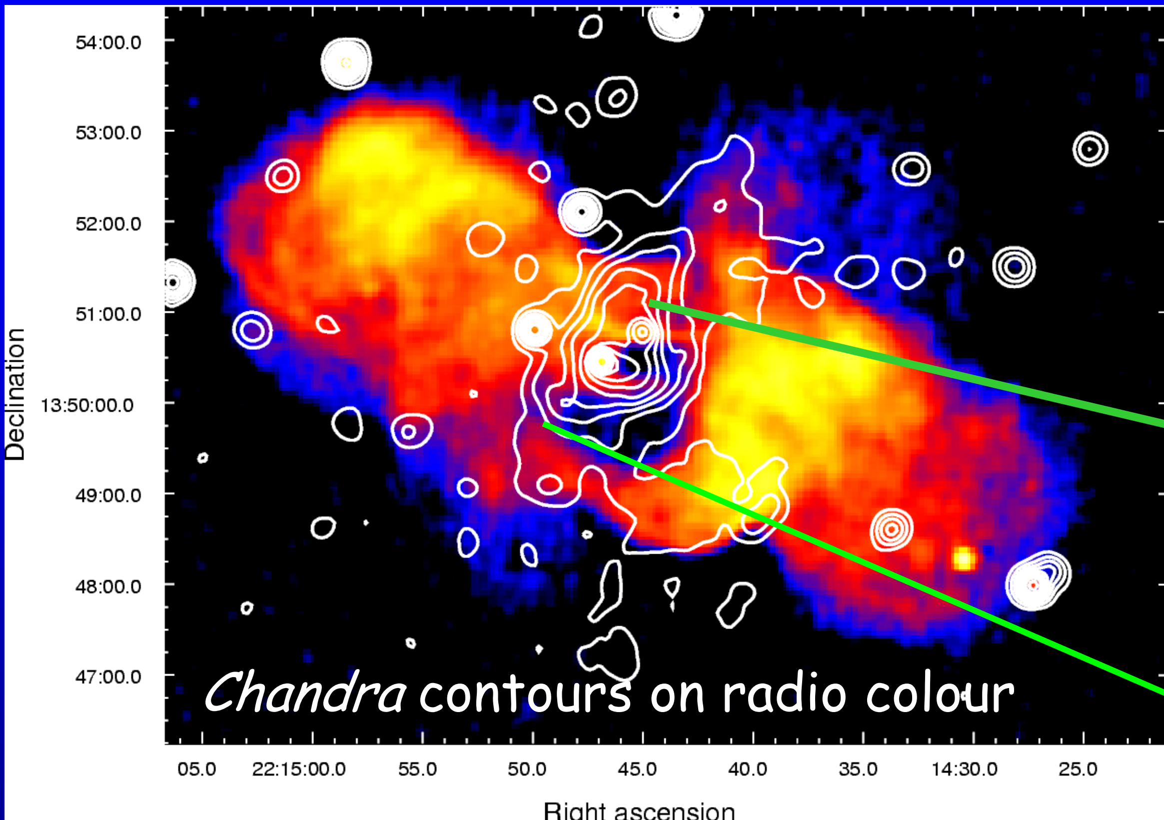


McNamara & Nulsen 2007
(McNamara+ 2005)

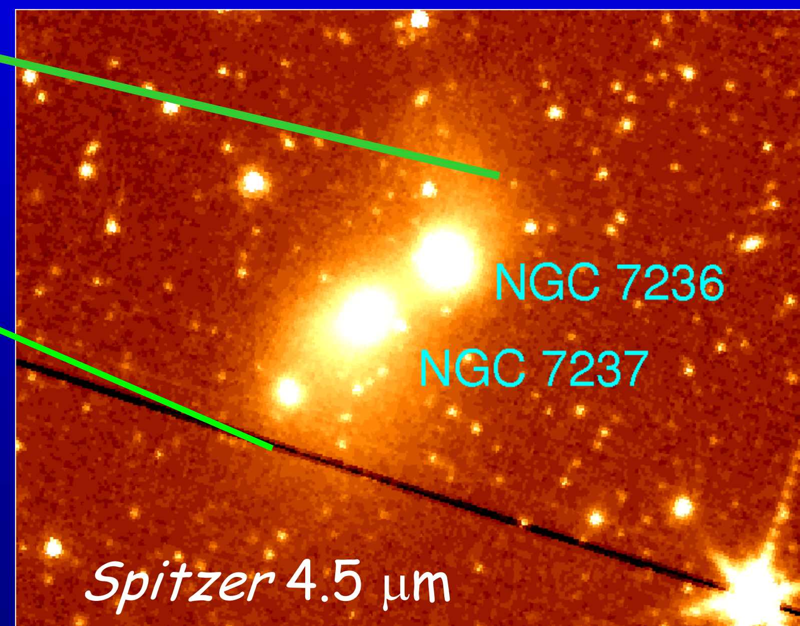
Work done

Energy exchange can reverse direction: gas → radio plasma

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



Merger gas causes old radio lobes to separate and energize



Worrall+ 2007

Study of more merger cases underway

3. Energy -> Heat

Important since many astronomers care!

Structure-formation simulations over-produce over-dense structures. Need injection of heat.

SMBH and galaxy bulge masses correlate. Need AGN feedback.

Two channels:

Quasar mode (nuclear winds) and Radio mode (this talk)

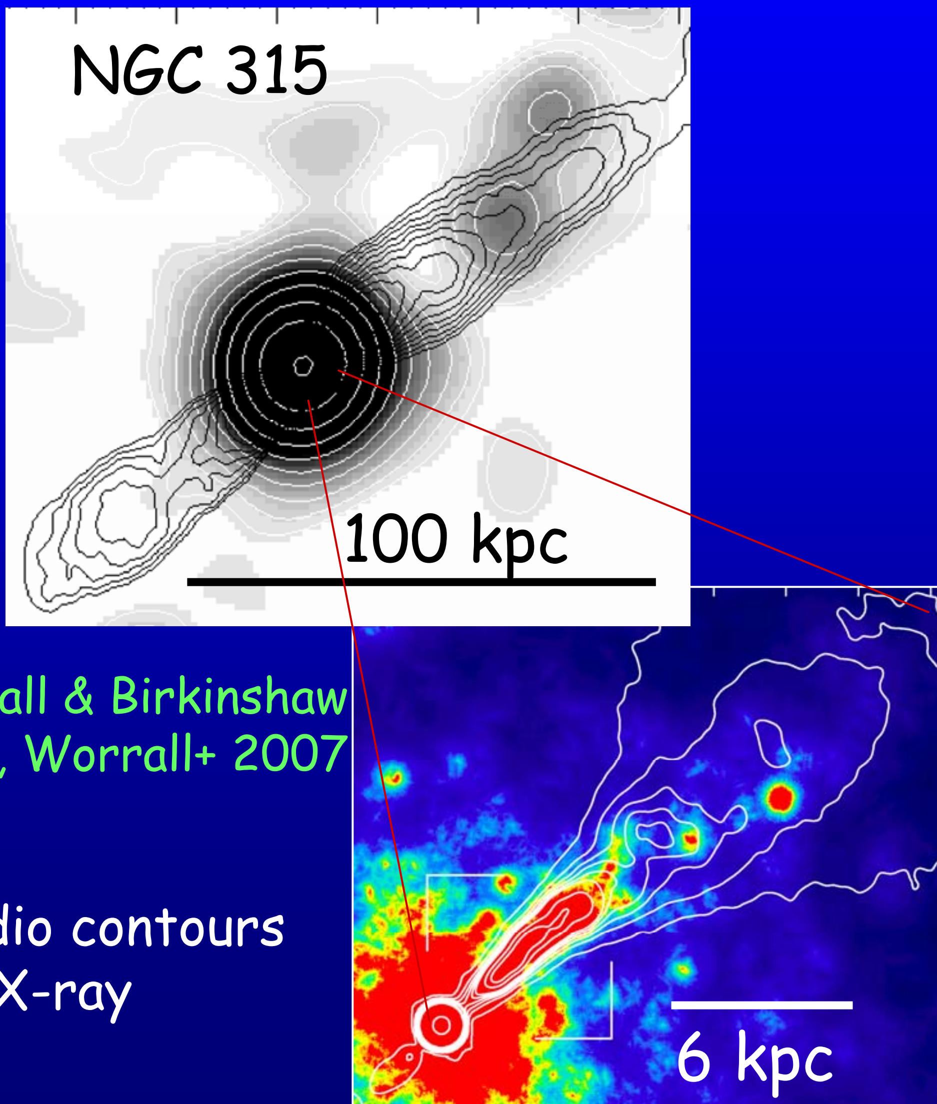
Energy-> Heat

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).

Problems:

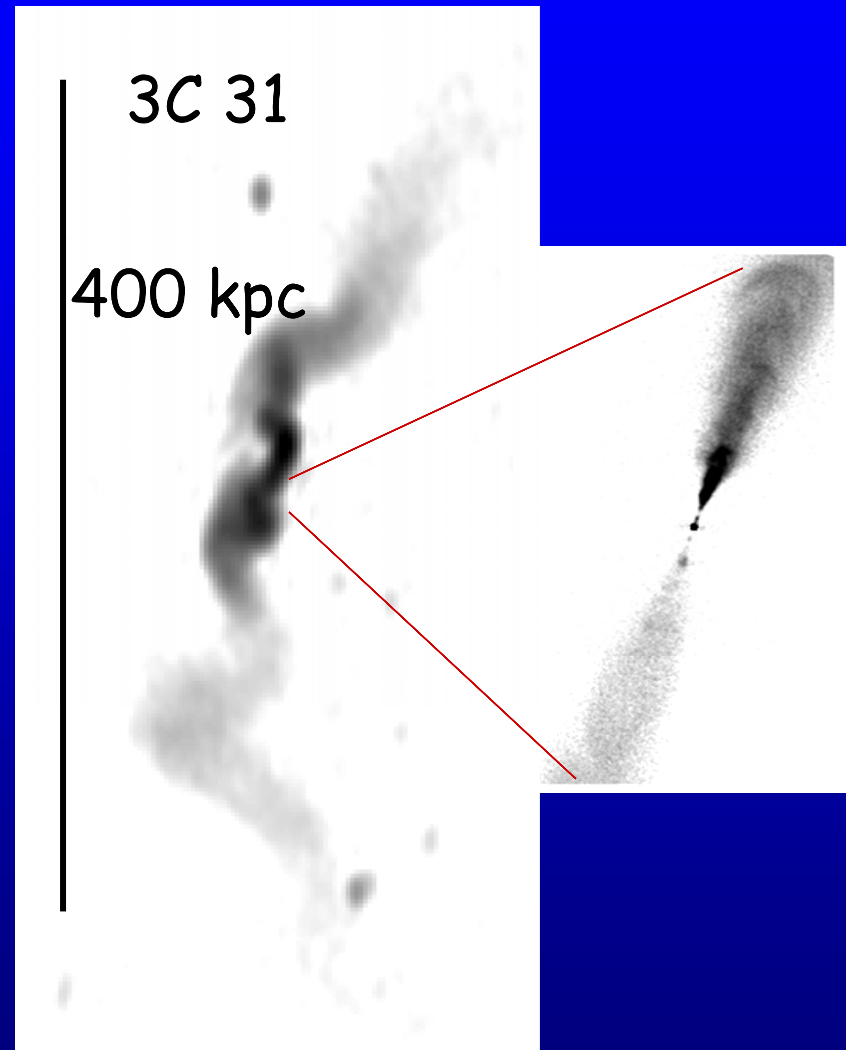
- Lifted gas needs to thermalize rather than gain bulk kinetic energy after bubbles burst.
- Individual sources may need only a fraction of the mechanical power to keep their atmospheres hot (e.g., O'Sullivan et al 2011). What causes regulation?
- Most jet-gas interactions are in relatively small volumes.
- Many jets don't inflate cavities. Many FRIIs and some FRIs travel far out of their group/cluster atmospheres.

Examples of FRIs that do not develop fat lobes in their galaxy or group atmospheres:



Worrall & Birkinshaw 2000, Worrall+ 2007

Radio contours on X-ray



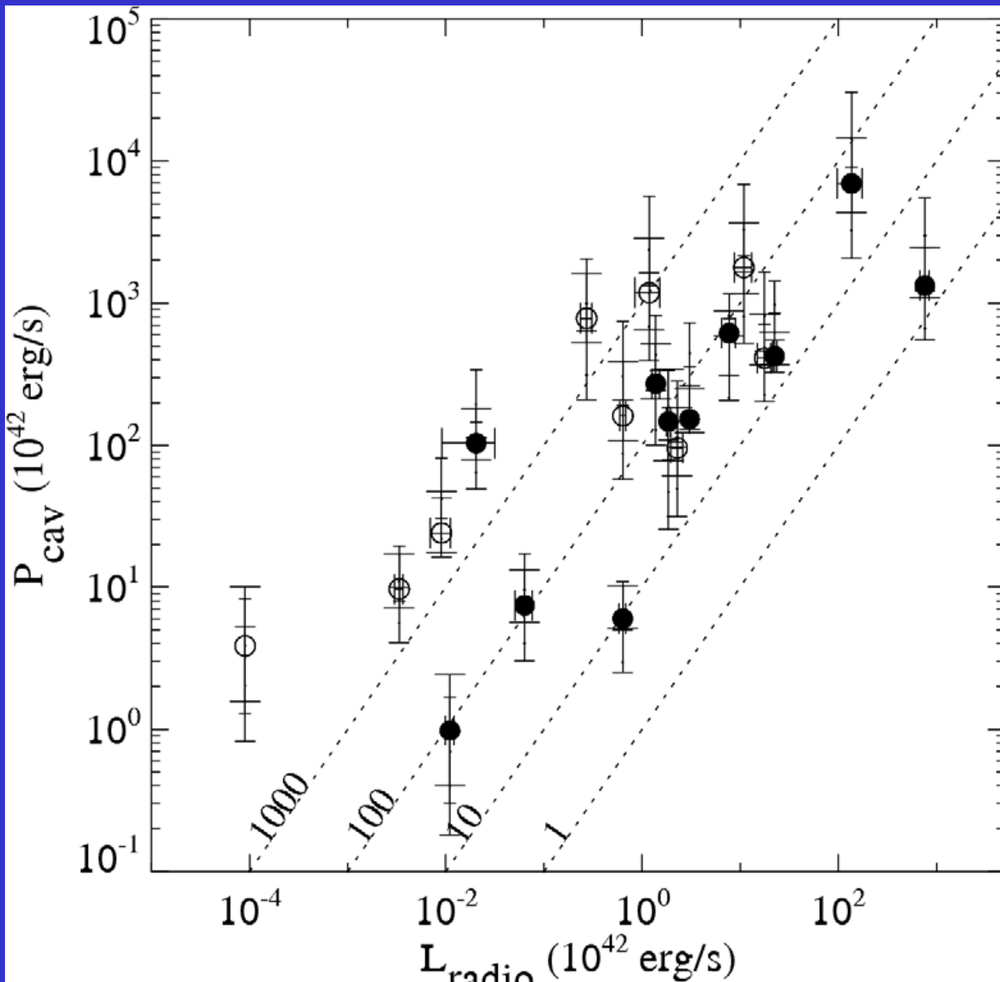
Laing & Bridle 2002

4. Jets of intermediate power

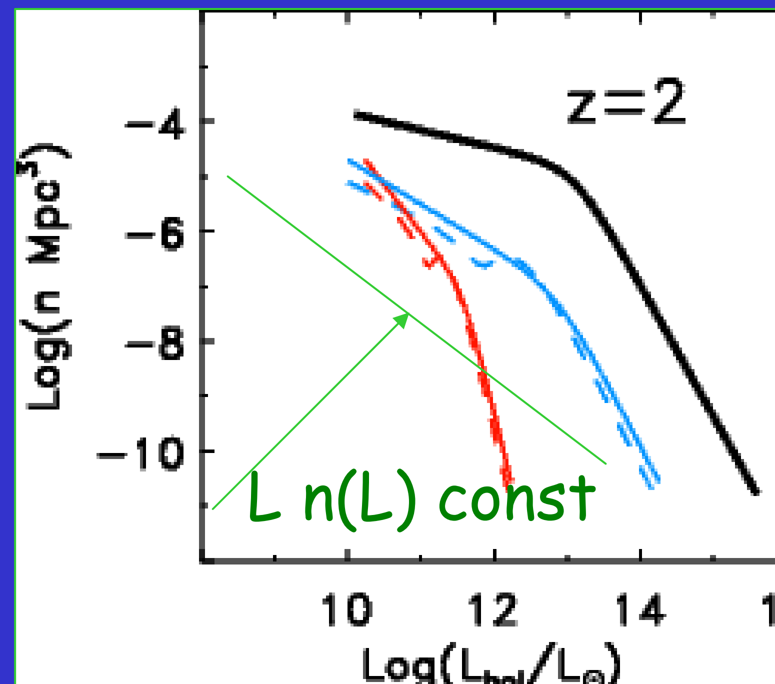
- These are the energetically dominant population of radio-loud AGN

$L_{mechanical}$ $n(L)$ significant over a wide range of L. Peaks at low $L_{mechanical}$ based on cavity power, but better correlations now place this close to the FRI/FRII boundary, agreeing with arguments based on min energy.

Cavity power v radio power



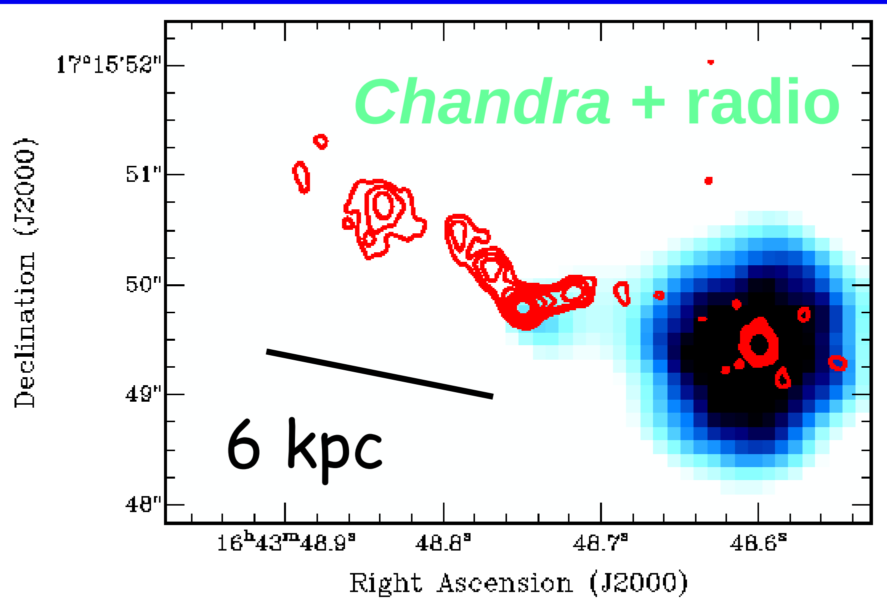
McNamara & Nulsen 2007

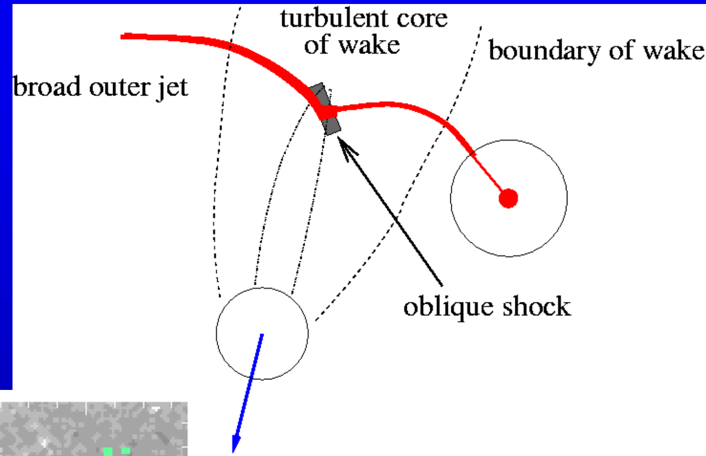


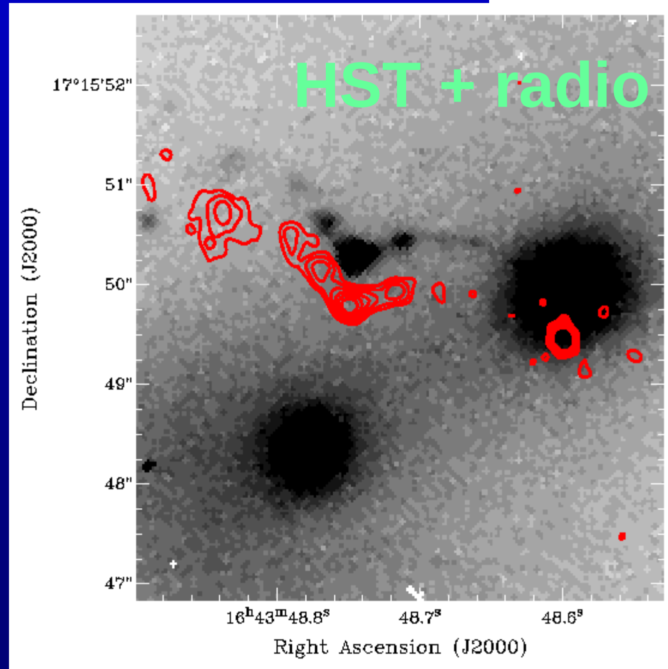
Cattaneo & Best 2009

5.1 Case Studies. 3C 346

Intermediate radio power. Hotspot in W lobe. Bent E jet with X-ray emission close to the bend.







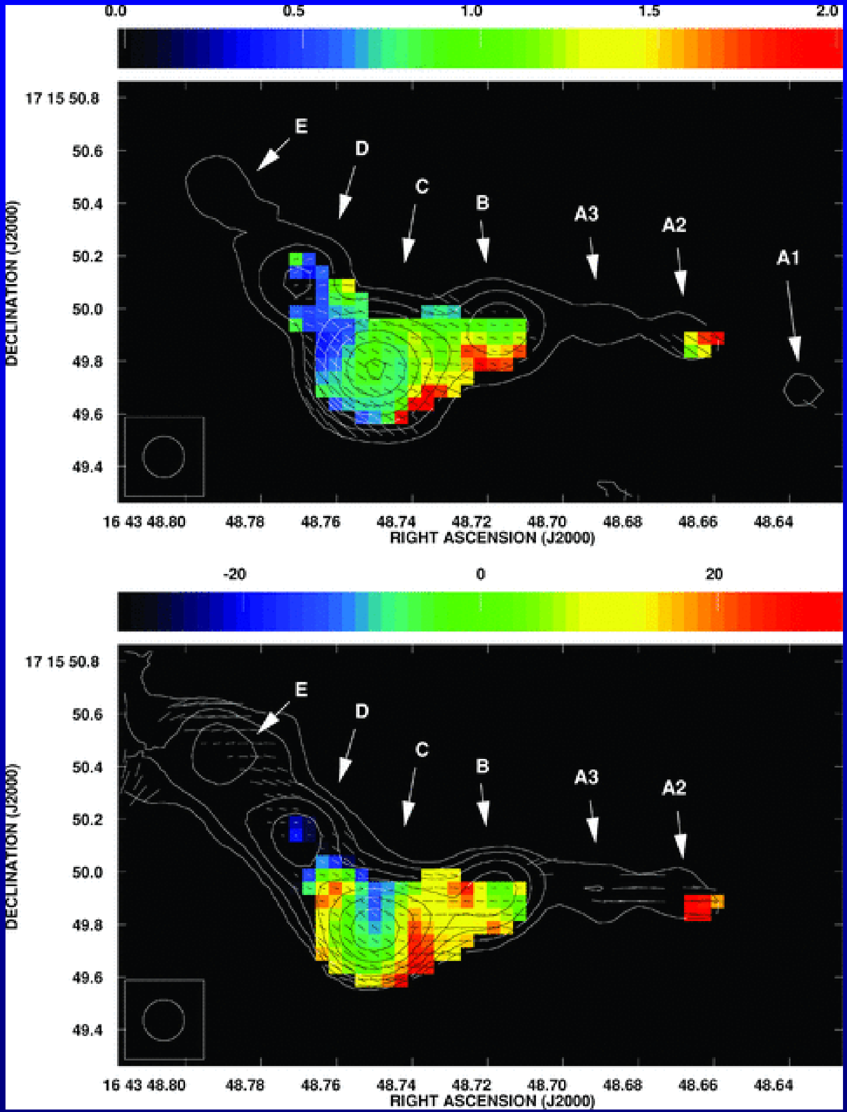
Worrall & Birkinshaw 2005

3C 346, optical/radio

3C 346 at 1.4 cm and 606 nm.

Comparison of radio polarimetry (bottom) and optical polarimetry (top).

E vectors (rotated 90° to show apparent magnetic field direction) differ – colour scales show ratio of percentage polarizations (top) and position angle difference (bottom).



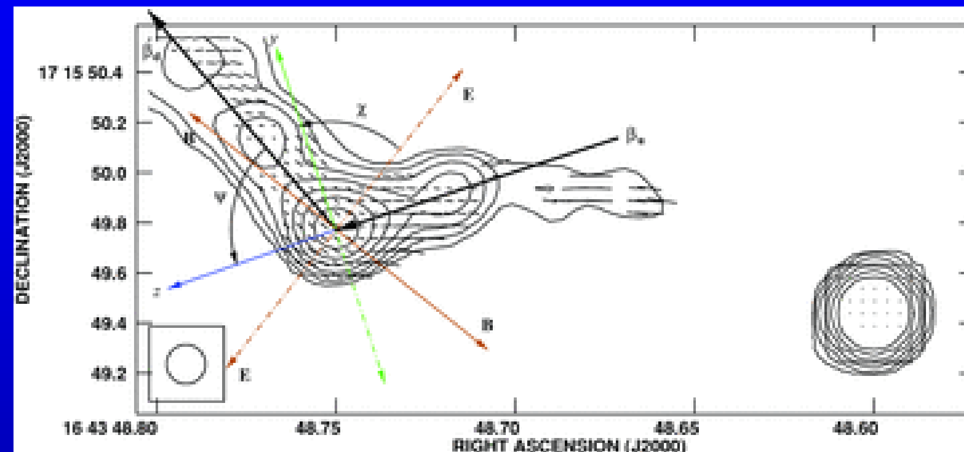
Dulwich 2008, Dulwich+ 2009

3C 346, optical/radio

3C 346 polarization (1.4 cm)

Can be interpreted as oblique shock, where the jet turns at a shock plane and the magnetic field changes character because of the compression, if $v \approx 0.9c$.

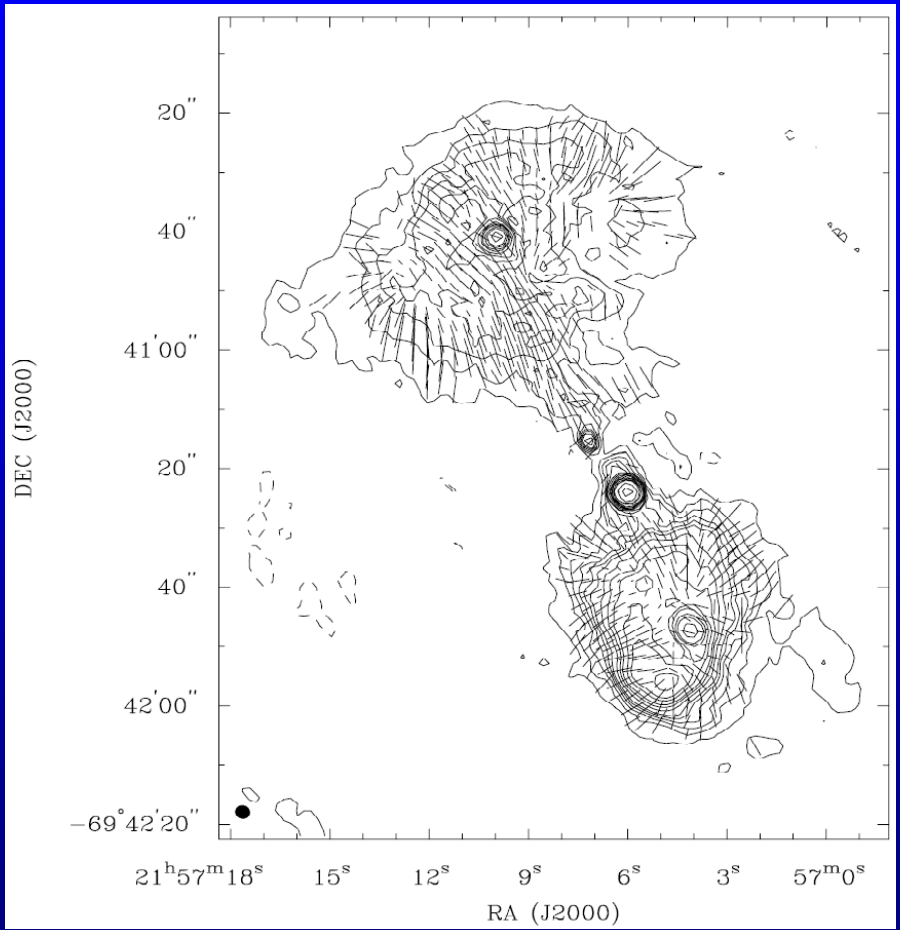
Apparent jet deflection of 70° is three times the true deflection because of projection effects (upstream jet at 15° to line of sight).



Dulwich 2008, Dulwich+ 2009

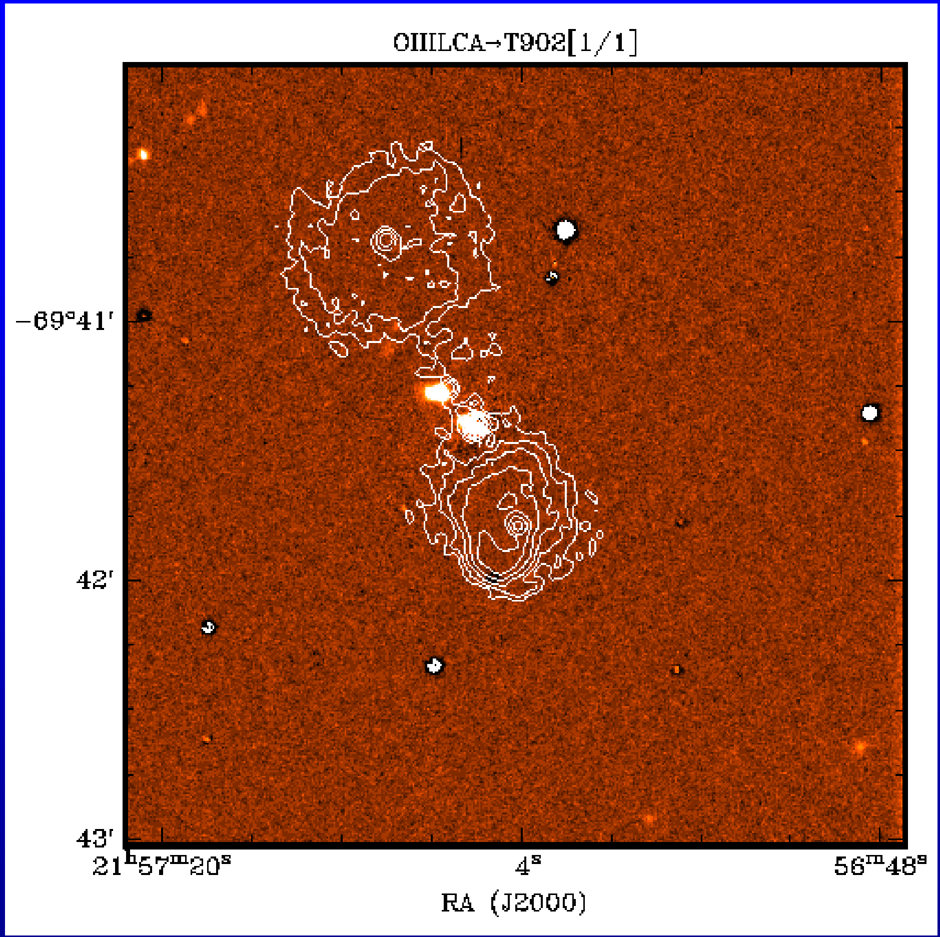
5.2 Case Studies. PKS B2152-699

Situation as of Dec 2003

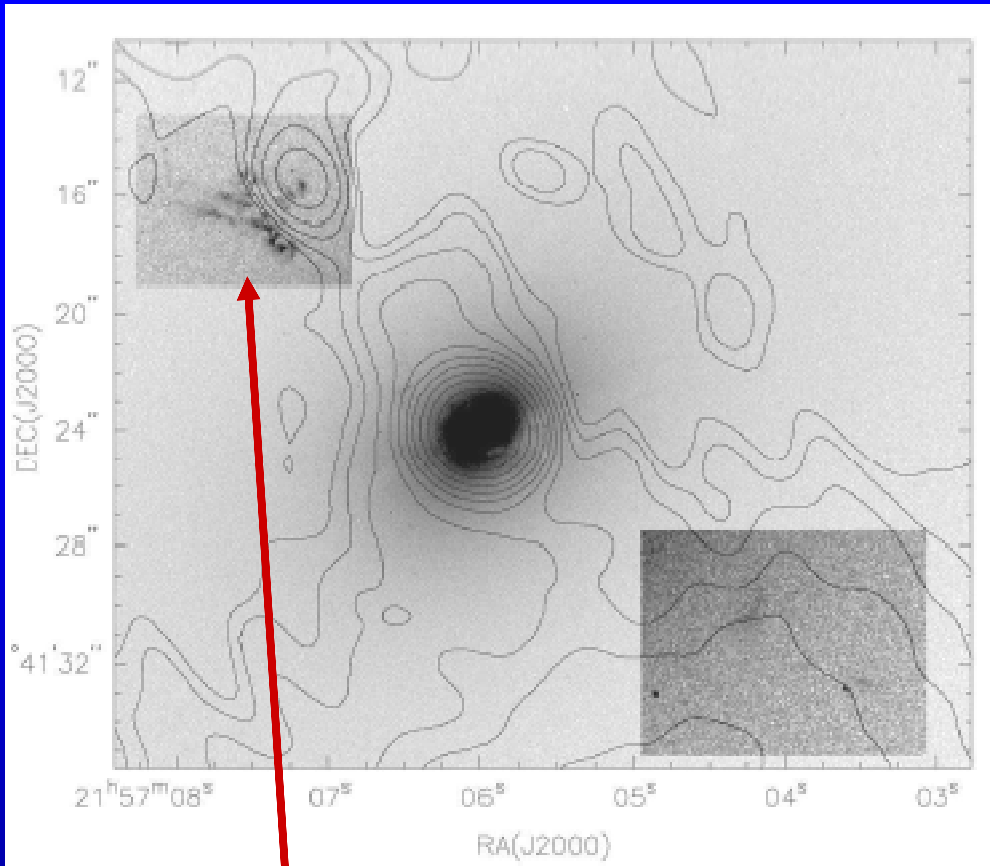


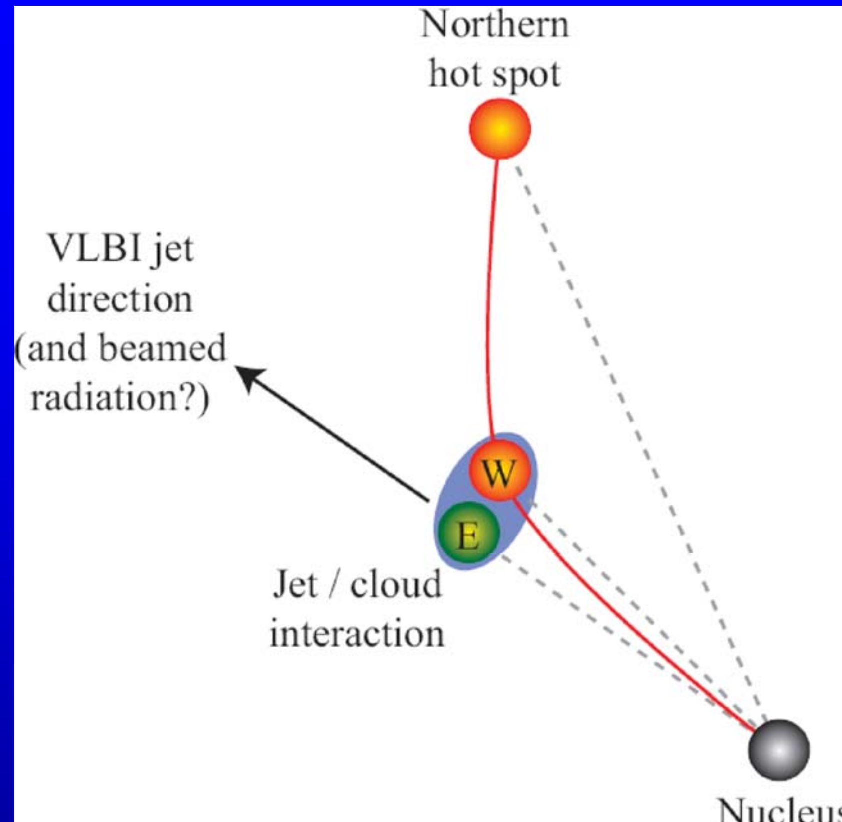
4.8 GHz ATCA

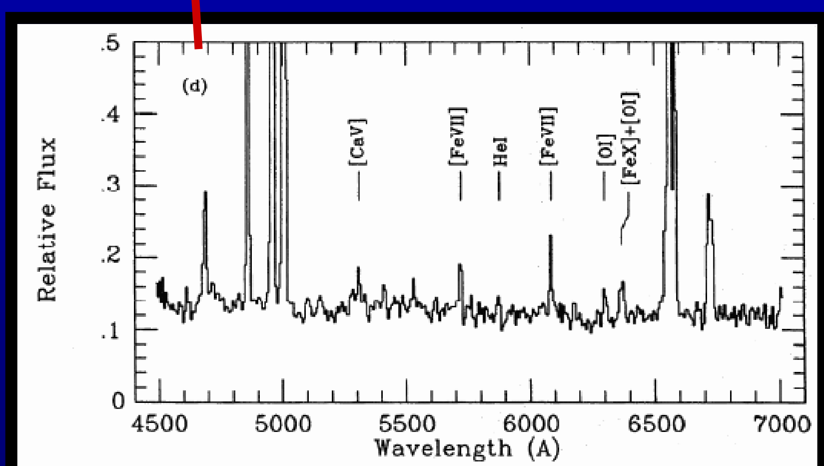
Fosbury + 1998



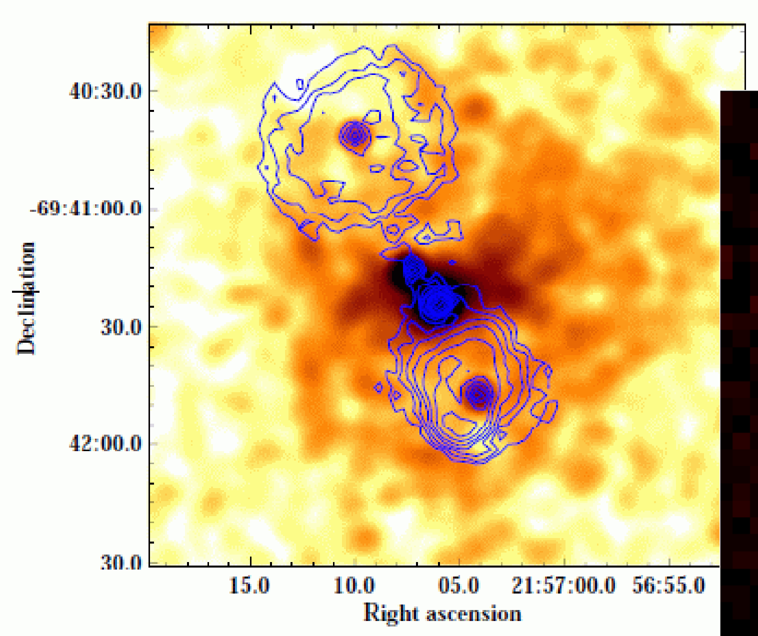
HIC + distant OII Emission clouds





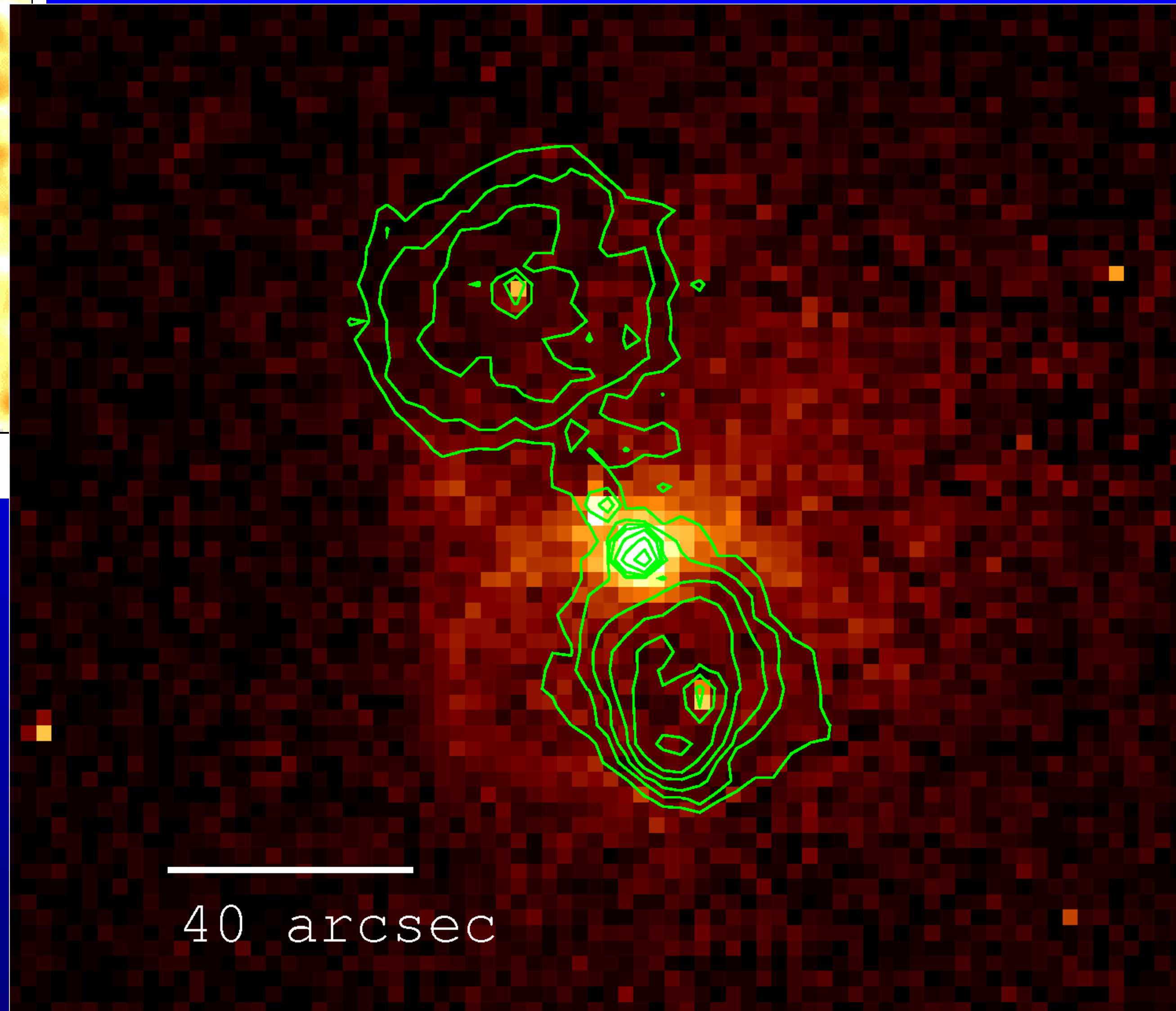


Now new work. Contributions from DMW, Andy Young, Mark Birkinshaw, Raffaella Morganti, and Bob Fosbury.

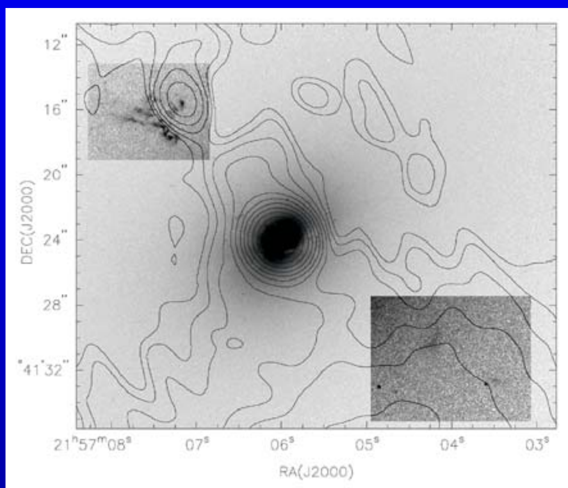


Young + 2005

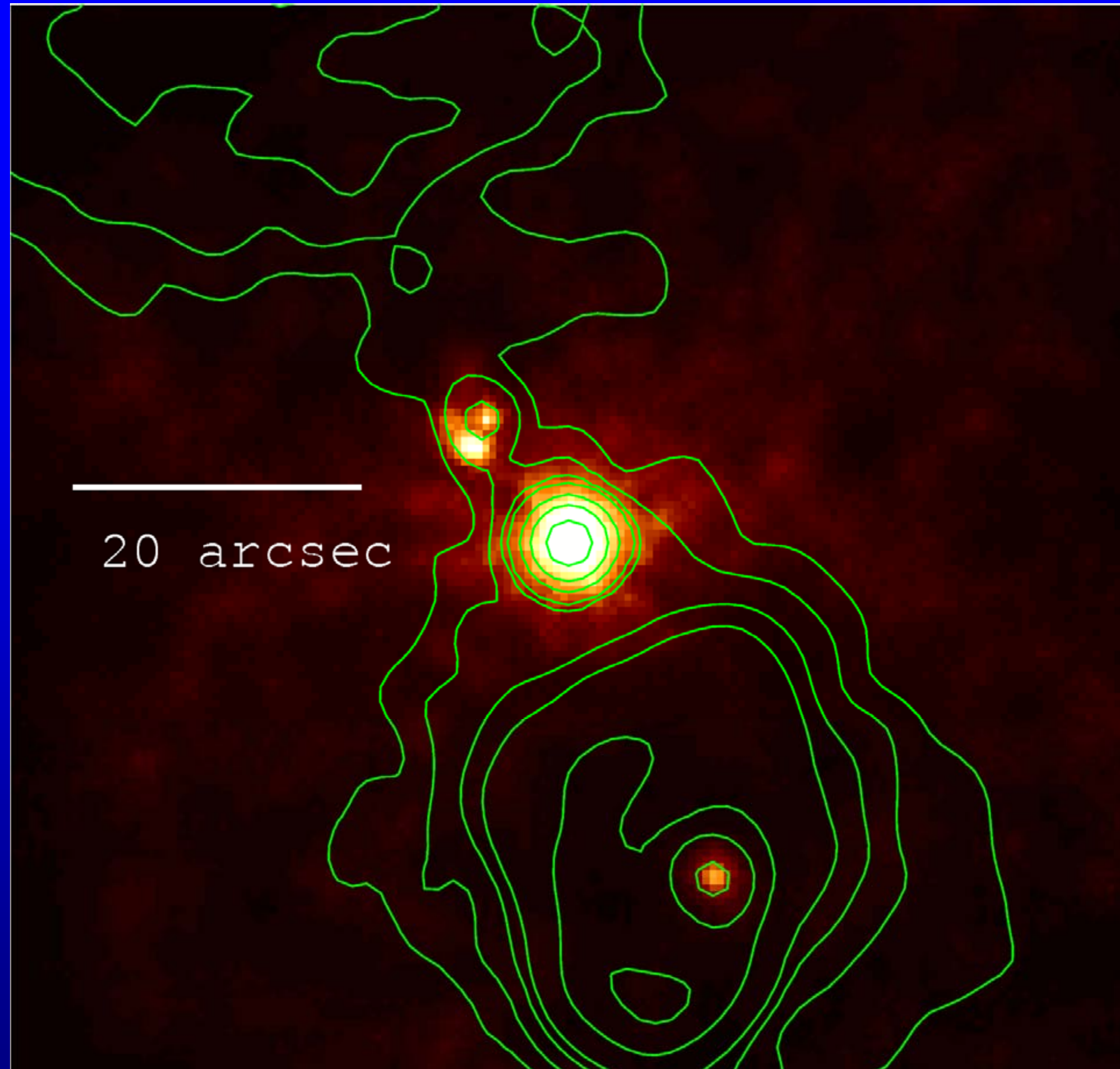
~12 ks *Chandra* exposure now aggregated to ~127 ks



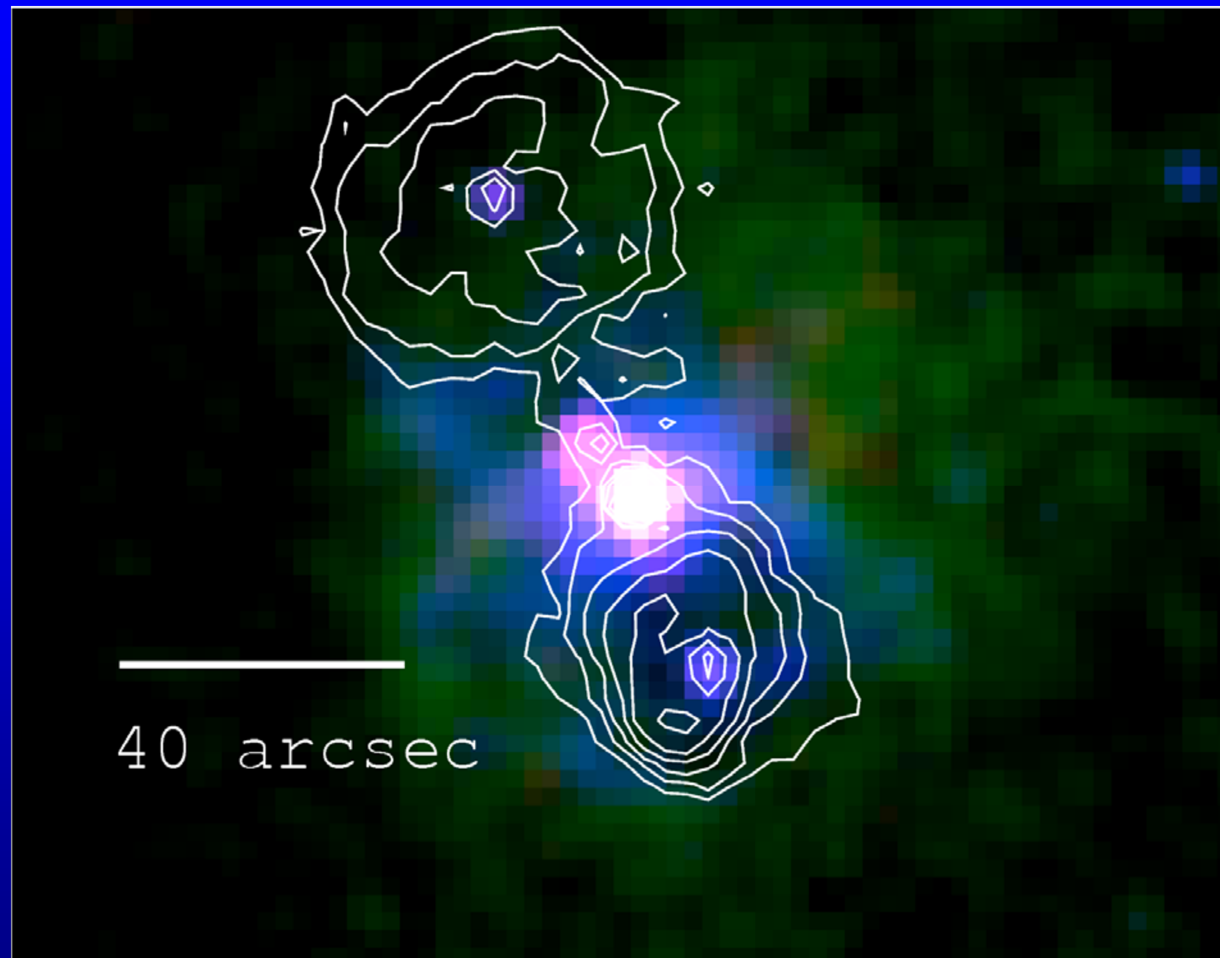
Chandra binned 2.5". Radio 2.4" beam

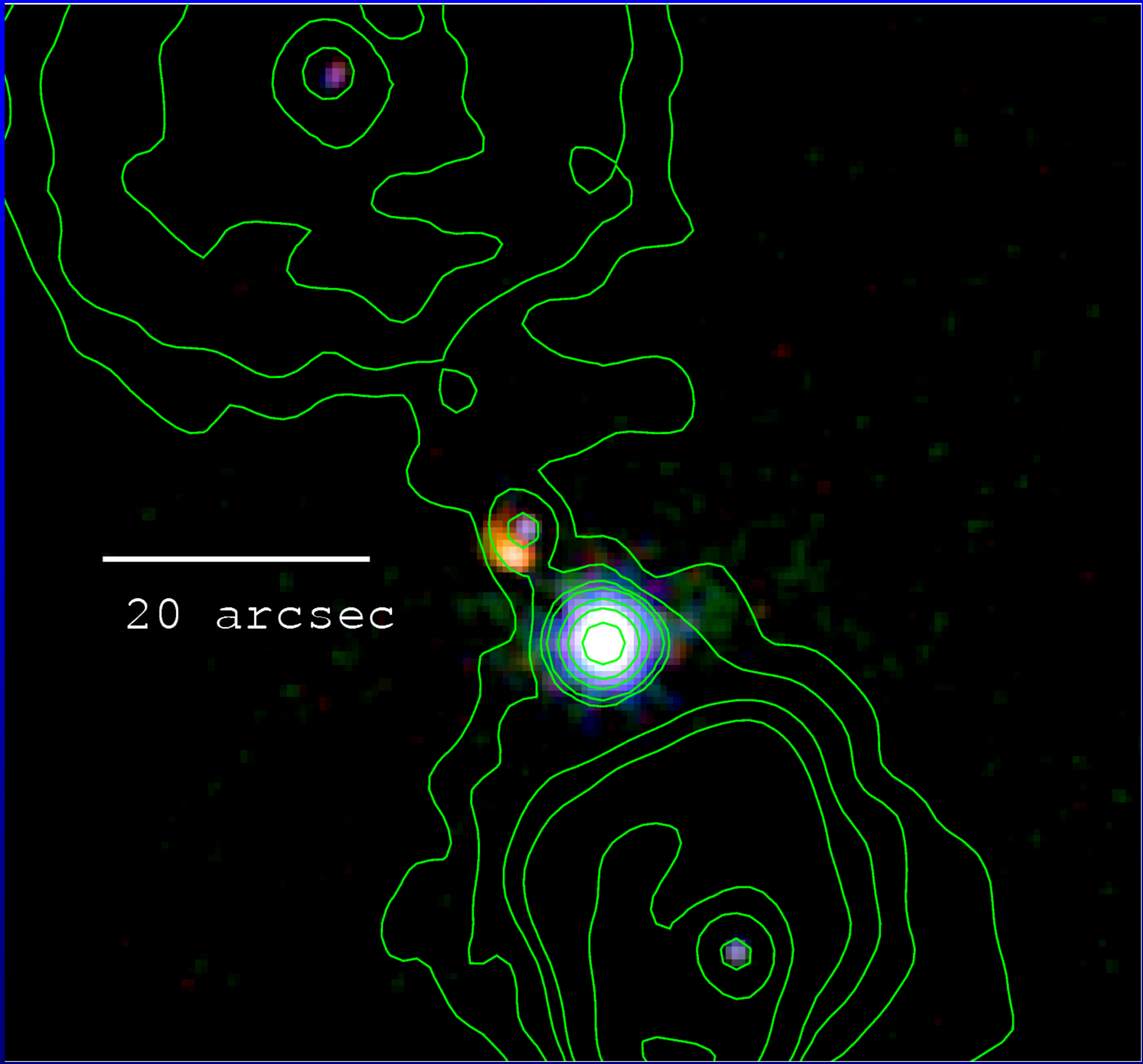


With old X-ray



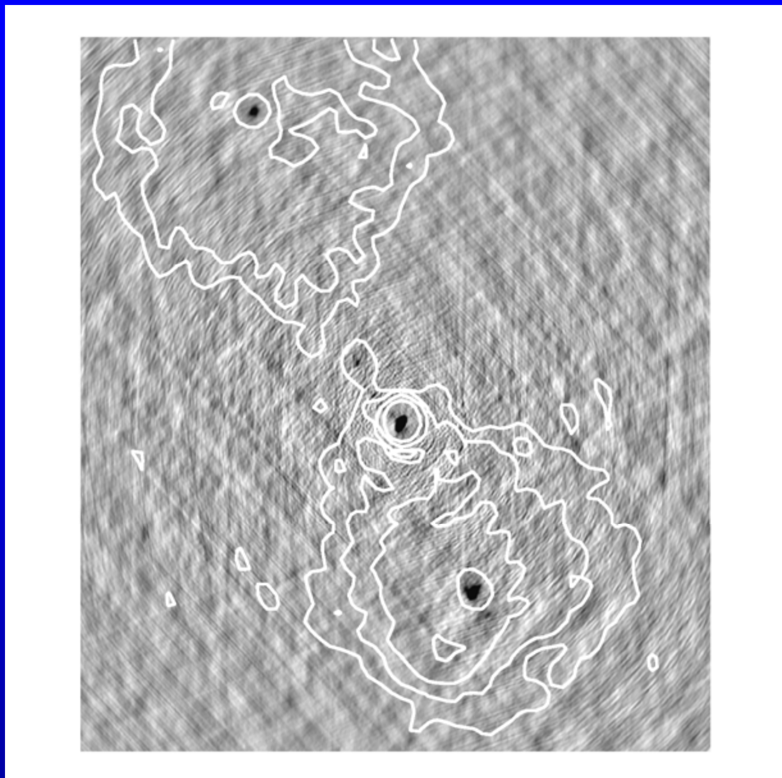
With new X-ray


40 arcsec

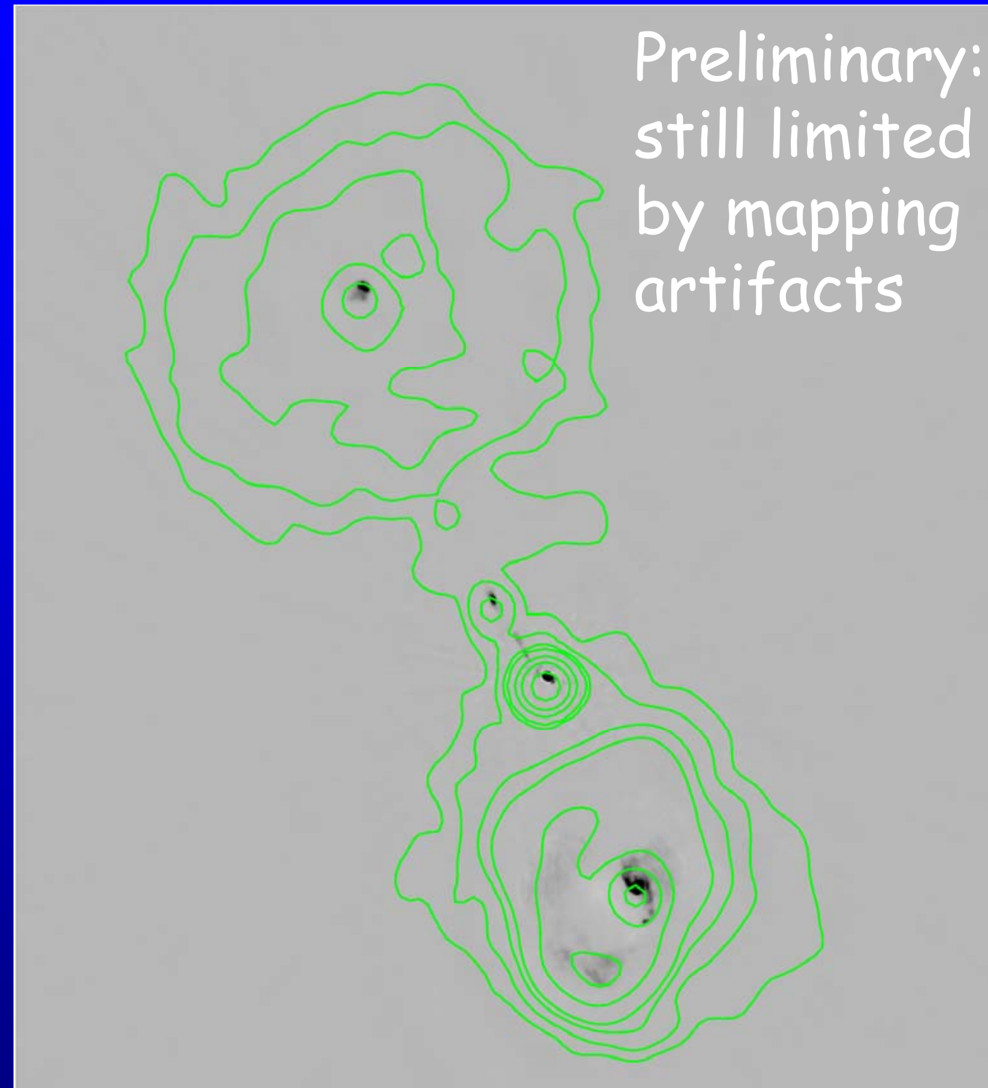

20 arcsec

12, 15 mm radio to match PSF of *Chandra*
20 GHz

17, 19 GHz



ATCA 1.5 hrs Feb 2008
(R Morganti)



ATCA CABB 12 hrs July 2009

2x128 MHz -> 4 GHz. 4096 spectral channels

July 15th 2010

July 16th 2010

Photos courtesy Andy Young

……….later July 16th 2010

Photos courtesy Andy Young

6. Summary

- Probing the energetics of jets needs to include the X-ray
- Jets of intermediate FRI/FRII radio power such as PKS B2152-699 are of key importance
- Uncertainties exist in where and how mechanical power is converted to heat
- Much work to be done by future generations of astronomers