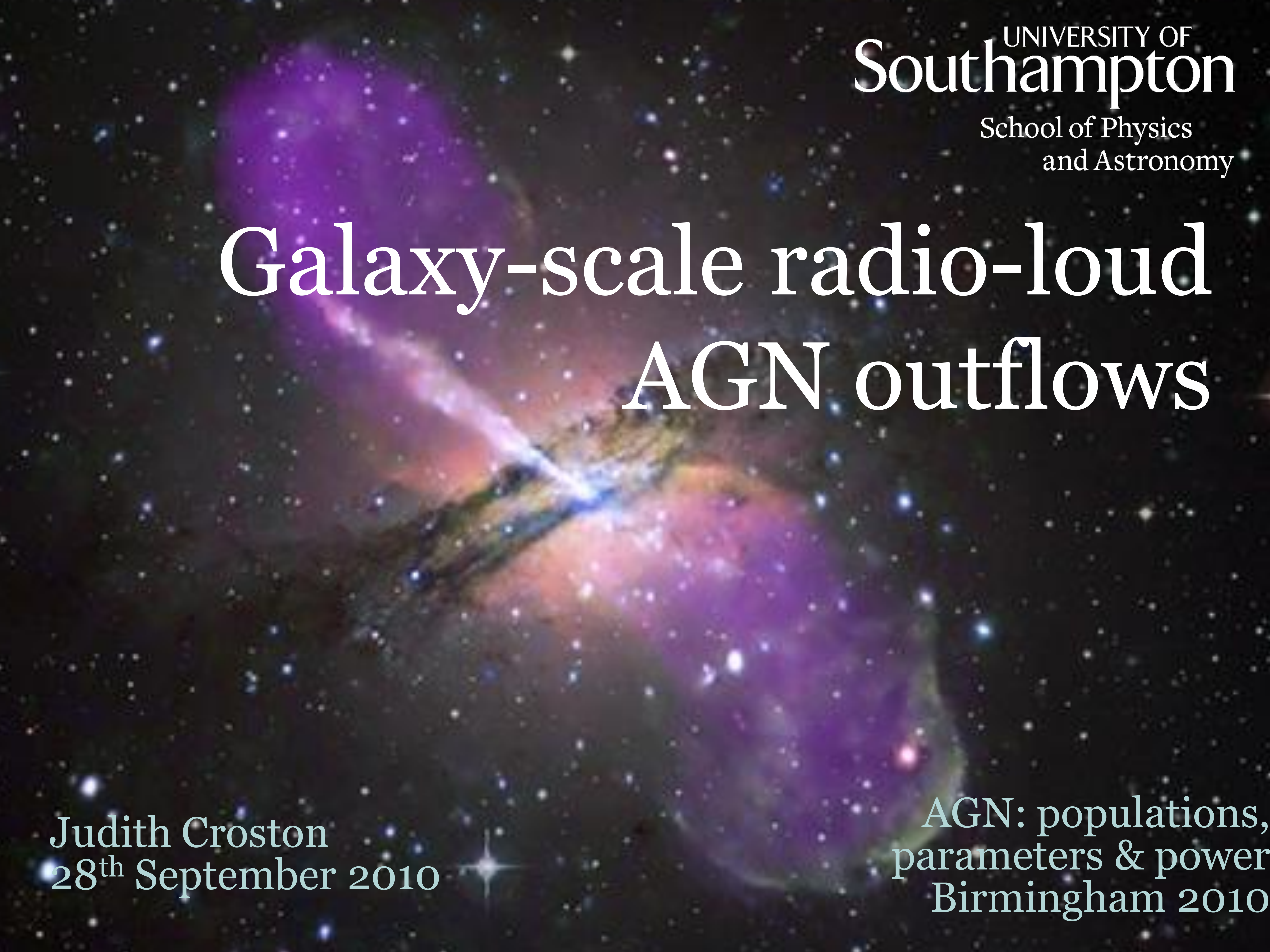

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Galaxy-scale radio-loud AGN outflows

Judith Croston
28th September 2010

AGN: populations, parameters & power
Birmingham 2010

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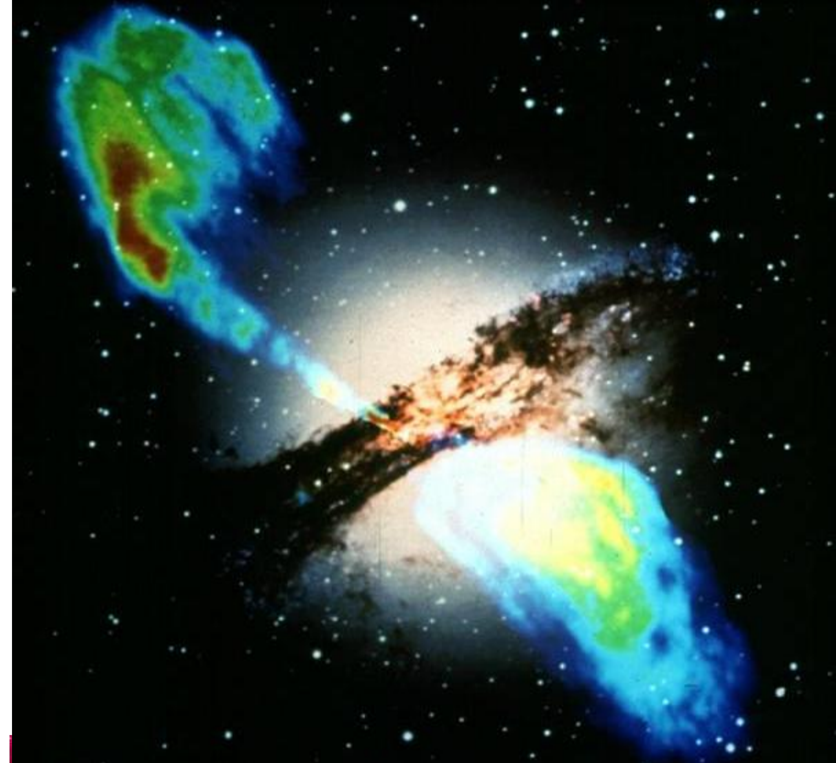
Thanks:

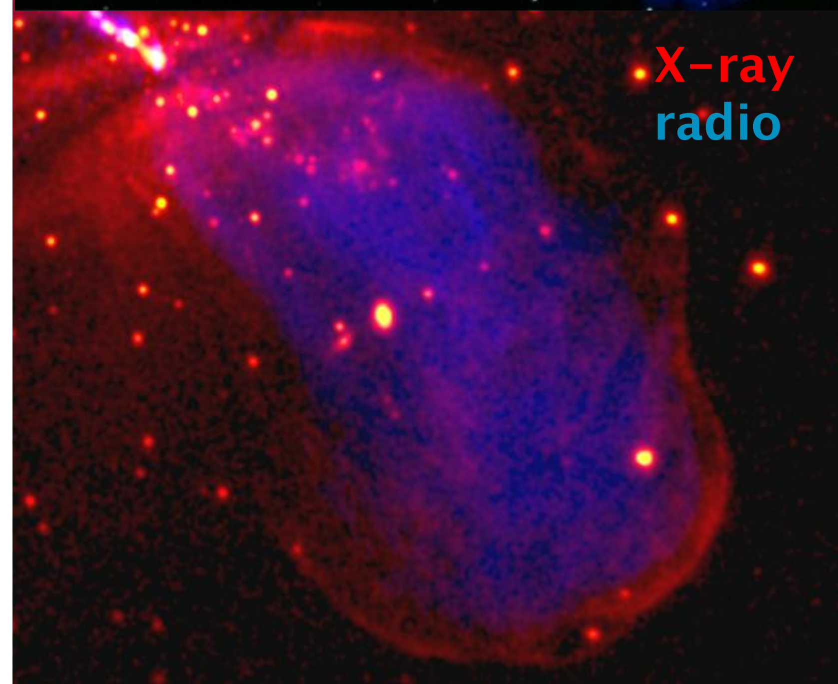
Ralph Kraft, Martin Hardcastle, Beatriz Mingo, Jamie Ownsworth, Preeti Kharb, Ananda Hota, Dan Evans & the Cen A VLP collaboration

SEPnet
South East Physics Network

What's special about galaxy-scale sources?

- Two types of galaxy-scale source:
  - early phase in the life of a full-sized radio galaxy
  - short-lived outbursts that never evolve to hundred-kpc scales
- Strong shocks **are** seen in a few nearby "galaxy-scale" sources (e.g. Kraft et al. 2003; Croston et al. 2007, 2009; Mingo et al. 2010)
- CSS samples dominated by FRIIs at high z (e.g. O'Dea 1998) => evidence that shocks are important in ionizing emission-line gas (e.g. Holt et al. 2008)





Shocks & radio source evolution

- All large radio galaxies must evolve through phase of supersonic expansion => shock heating of environment
- Signatures potentially visible in the X-ray (e.g. Heinz, Reynolds & Begelman 1998) => direct measurement of energy input to environment.
- Chandra has failed to find clear evidence for strong shocks around powerful RGs (though more examples of moderately strong shocks are emerging...)

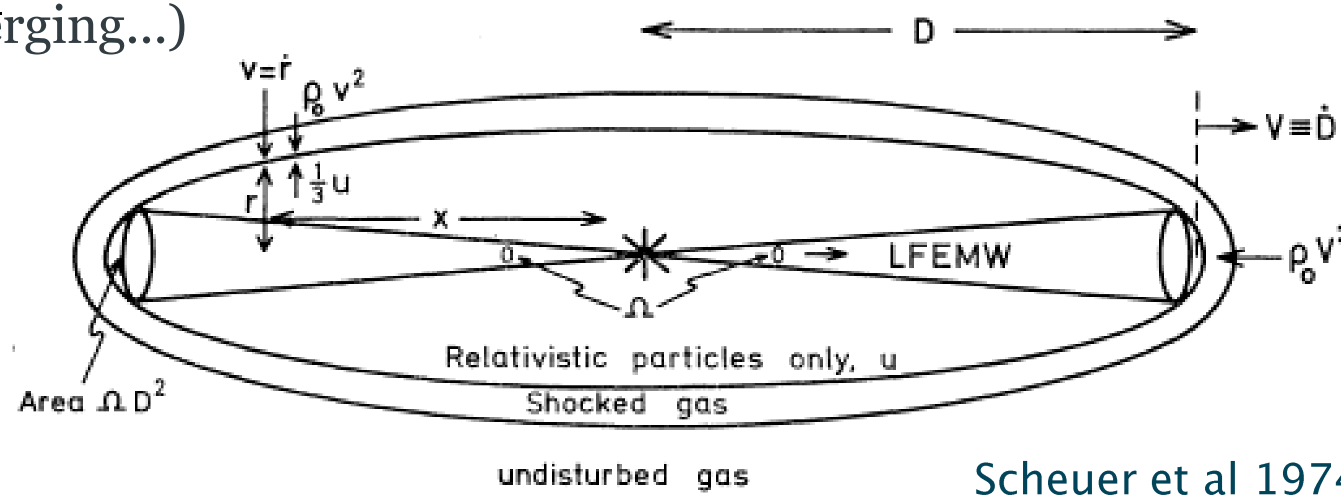


FIG. 1. *Model A.*

Scheuer et al 1974

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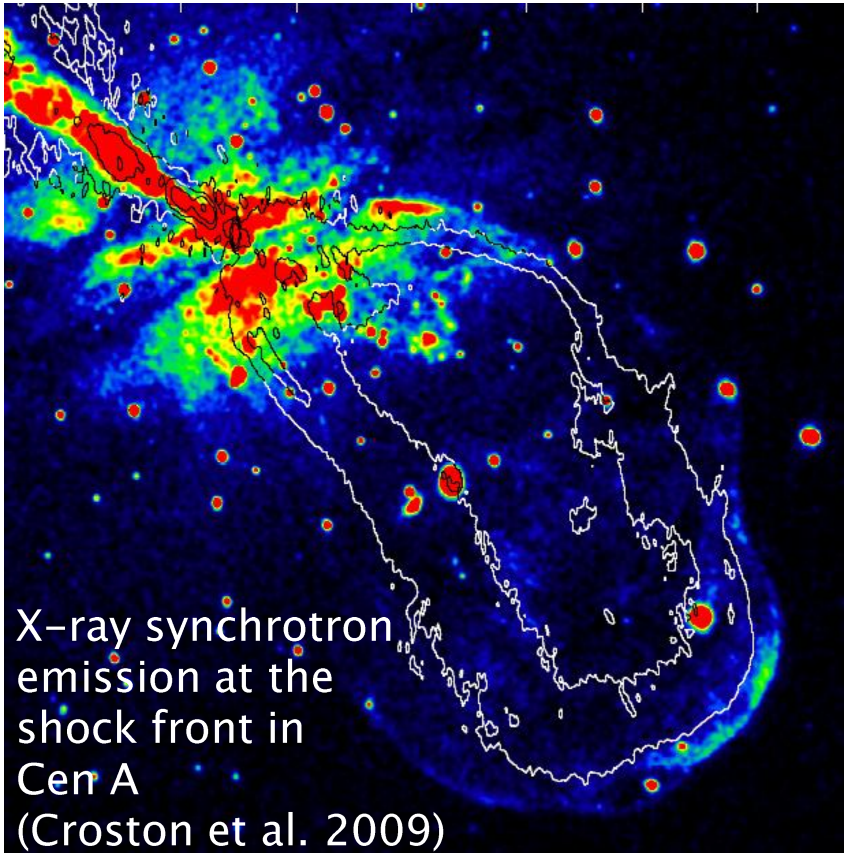
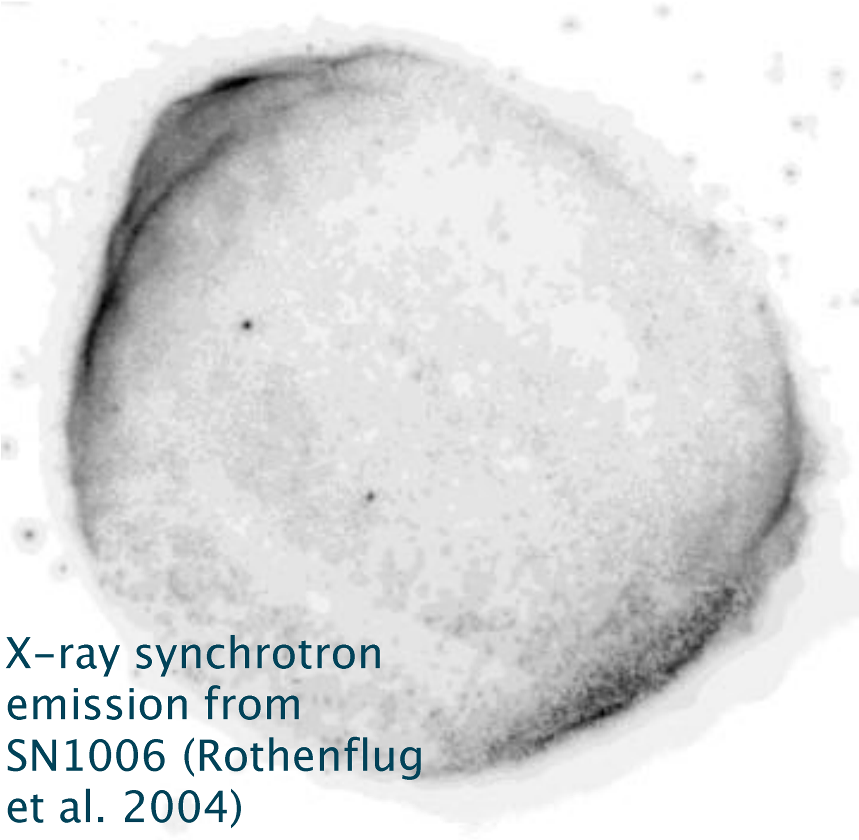
The impact of kpc-scale radio galaxies

High-energy particle acceleration



X-ray synchrotron emission at the shock front in Cen A (Croston et al. 2009)



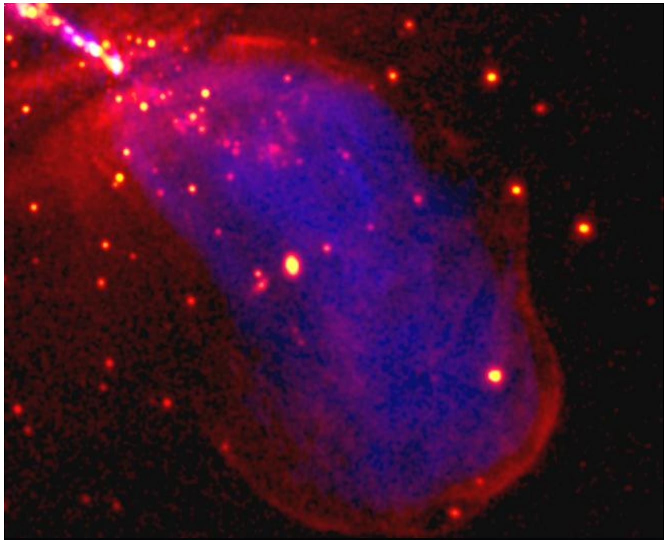
X-ray synchrotron emission from SN1006 (Rothenflug et al. 2004)

B field amplification?

- SNR shells inferred to have *B* fields >> simple compression of the ISM (e.g. Ellison & Vladimirov 2008, Reynolds 2008)

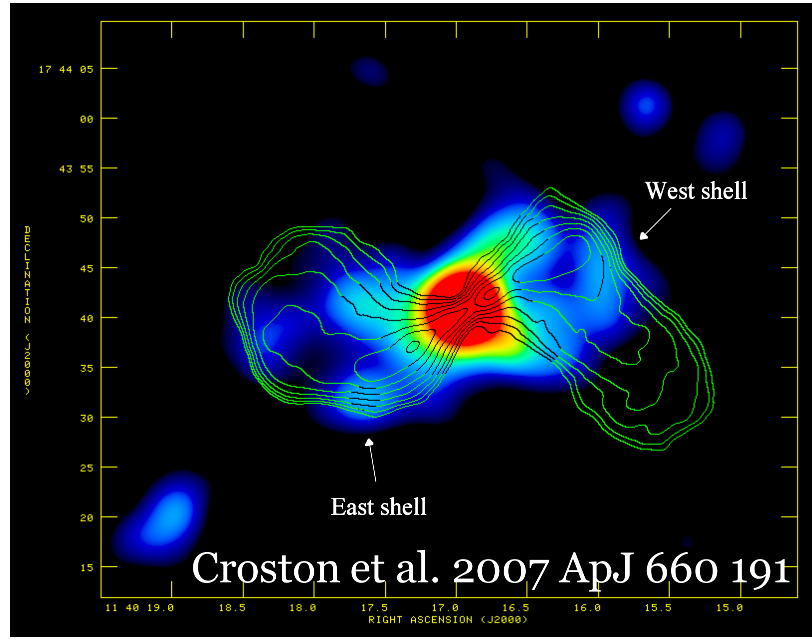
- Modelled as non-linear diffusive shock acceleration with *B* amplification (e.g. Bell & Lucek 2001).

- *B*-field amplification by factors of 10 – 100 plausible in Cen A (B_{eq} ~ 8 μG for κ=1 and ~30 μG for κ=100). HESS detection implies B > 7 μG.



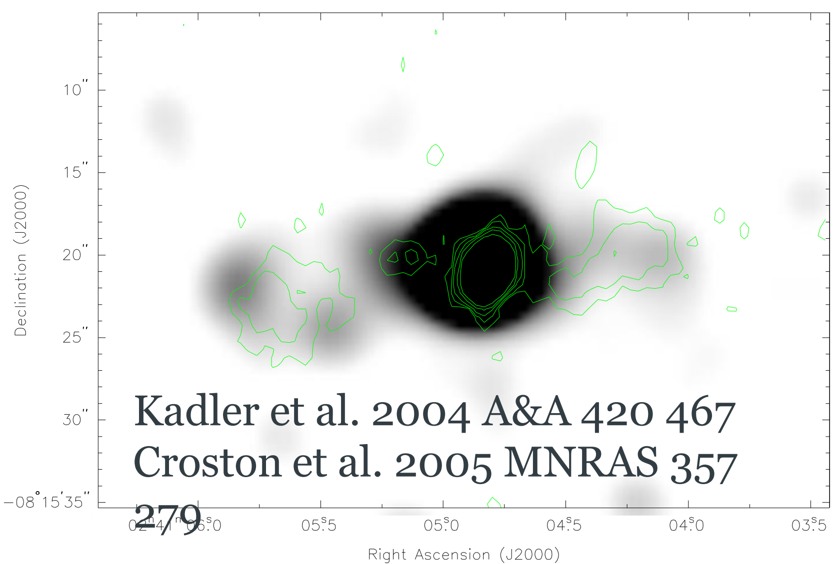
Shock heating of the ISM

- Non-thermal model ruled out (strong Fe L complex).
- $\mathcal{M} \sim 3 - 4$ & expansion speed comparable to inner region of Cen A where no particle acceleration seen.
- $E_{TOT} \sim 2 \times 10^{56}$ ergs, equiv. to thermal energy of ISM within 11 kpc – similar to Cen A energetics.

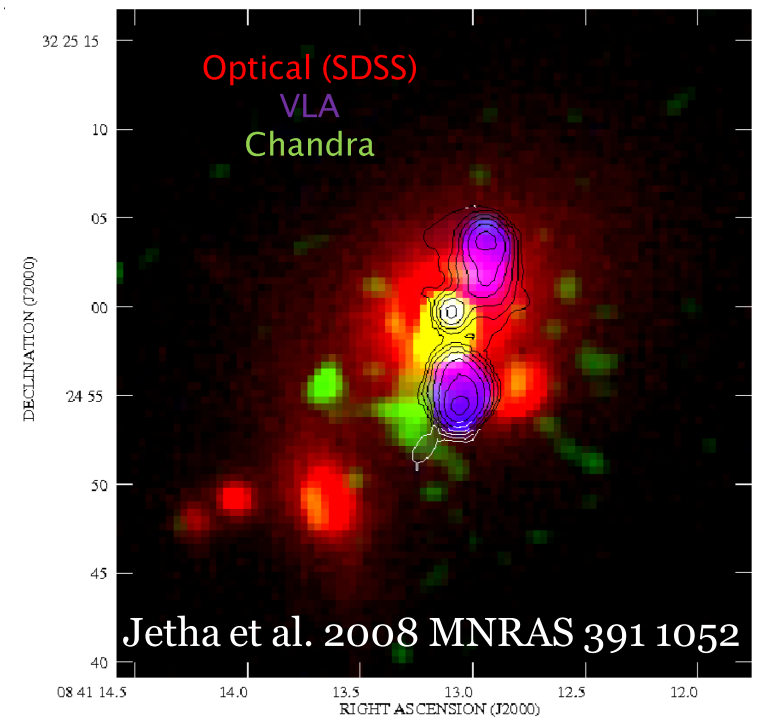


Croston et al. 2007 ApJ 660 191

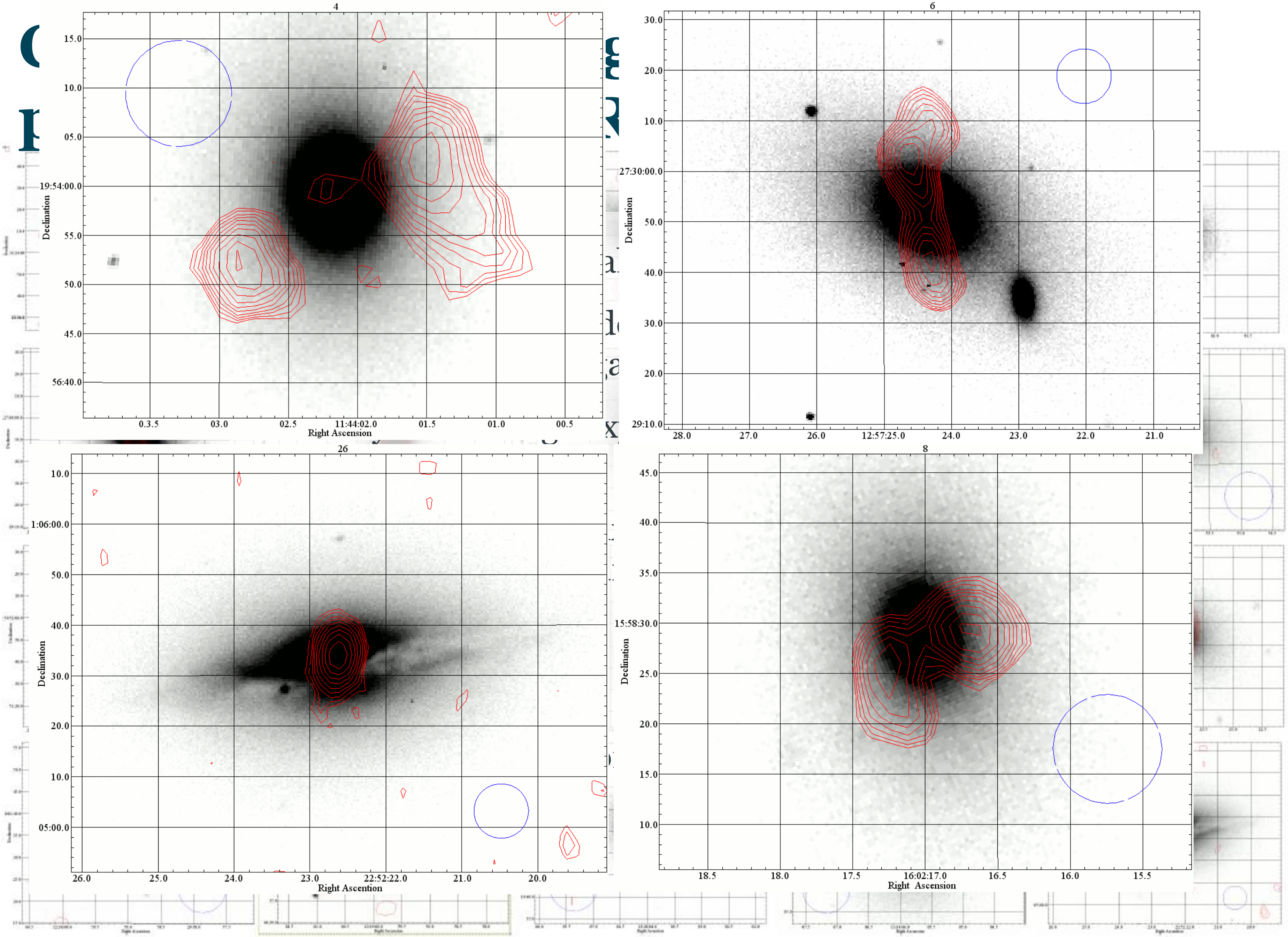
Some other examples: NGC 1052 (l) and B2 0838+32A (r)



Kadler et al. 2004 A&A 420 467
Croston et al. 2005 MNRAS 357 279



Jetha et al. 2008 MNRAS 391 1052



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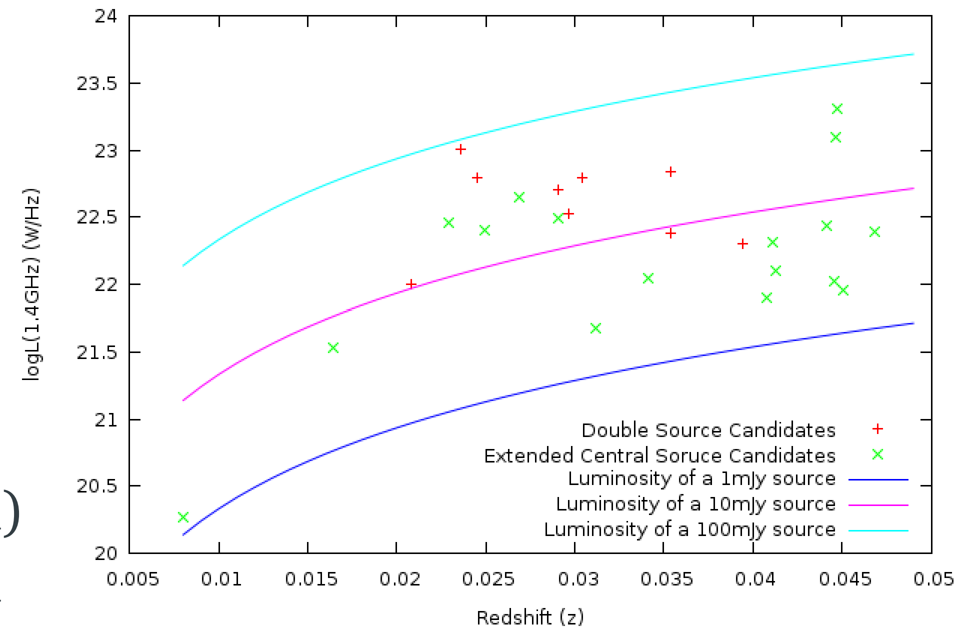
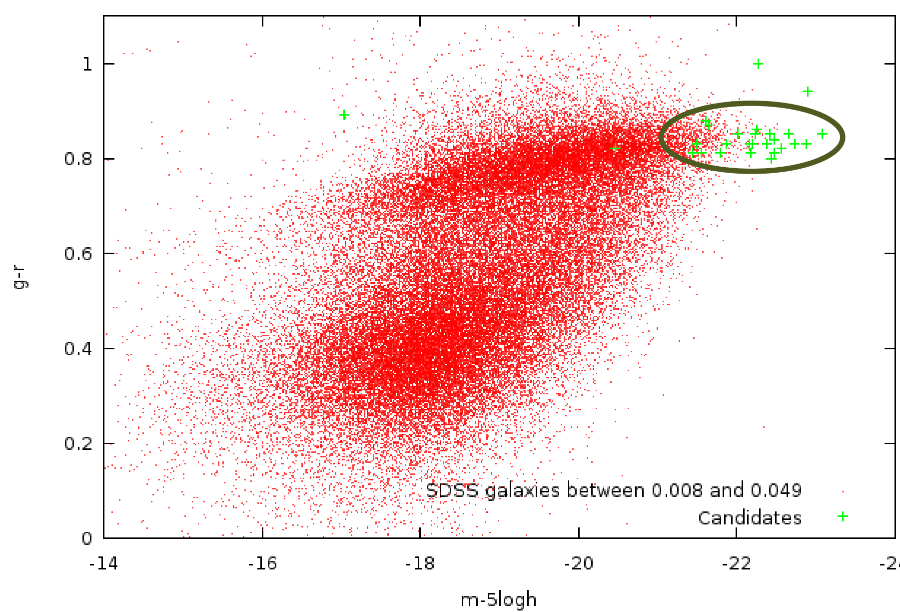
Preliminary statistics

- 25 galaxy-scale sources found from parent population of 103,000
- Luminosities of $10^{20} - 10^{23}$ W Hz^{-1}
- Mainly hosted by luminous, red galaxies
- 2/25 show visible merger signatures (comparable to normal E population)
- Environments appear systematically richer than parent population (work in progress)
- **Galaxy-scale sources are common in massive, red ellipticals (~1/200), but rare in galaxy population as a whole**





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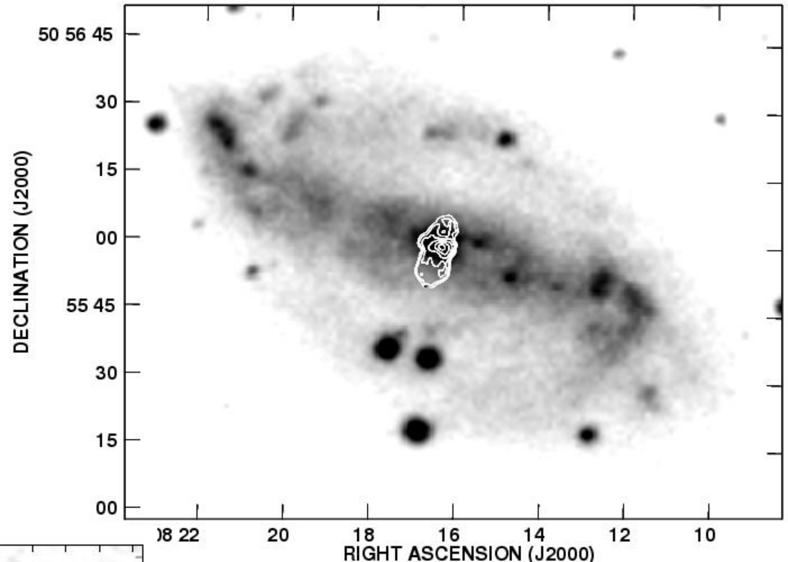
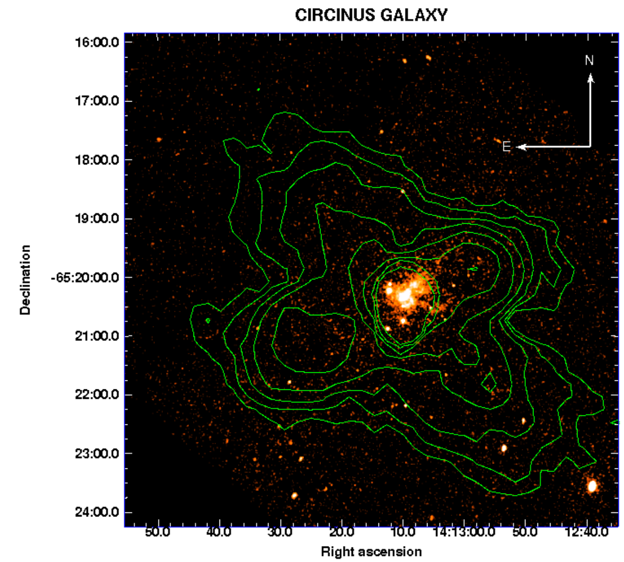
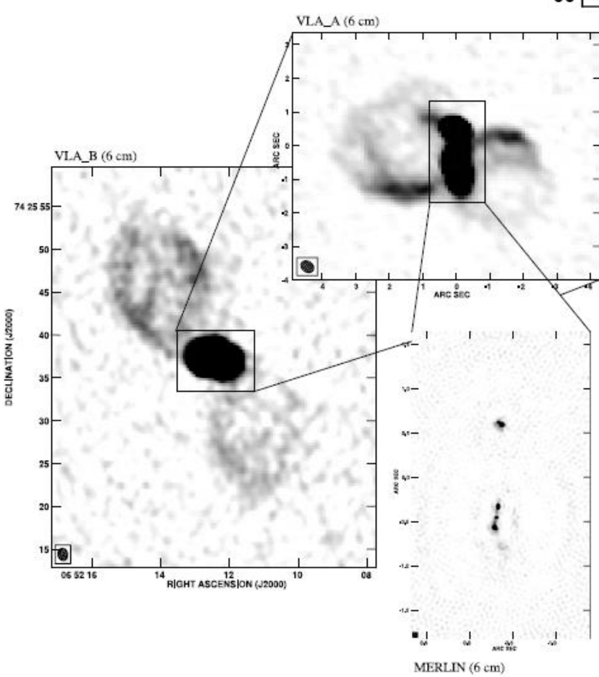
AGN-driven radio outflows in Seyferts

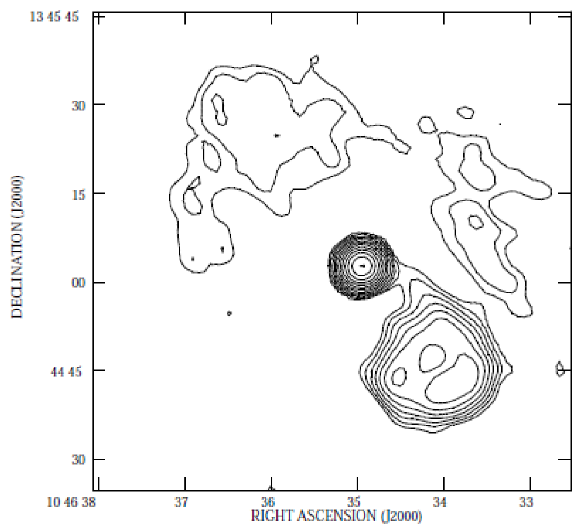
AGN-driven outflows in Seyferts

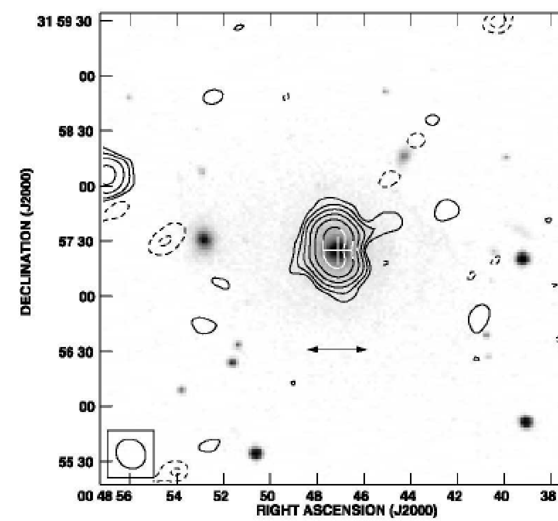
kpc-scale AGN-driven outflows are common in Seyferts (Gallimore et al. 2006)





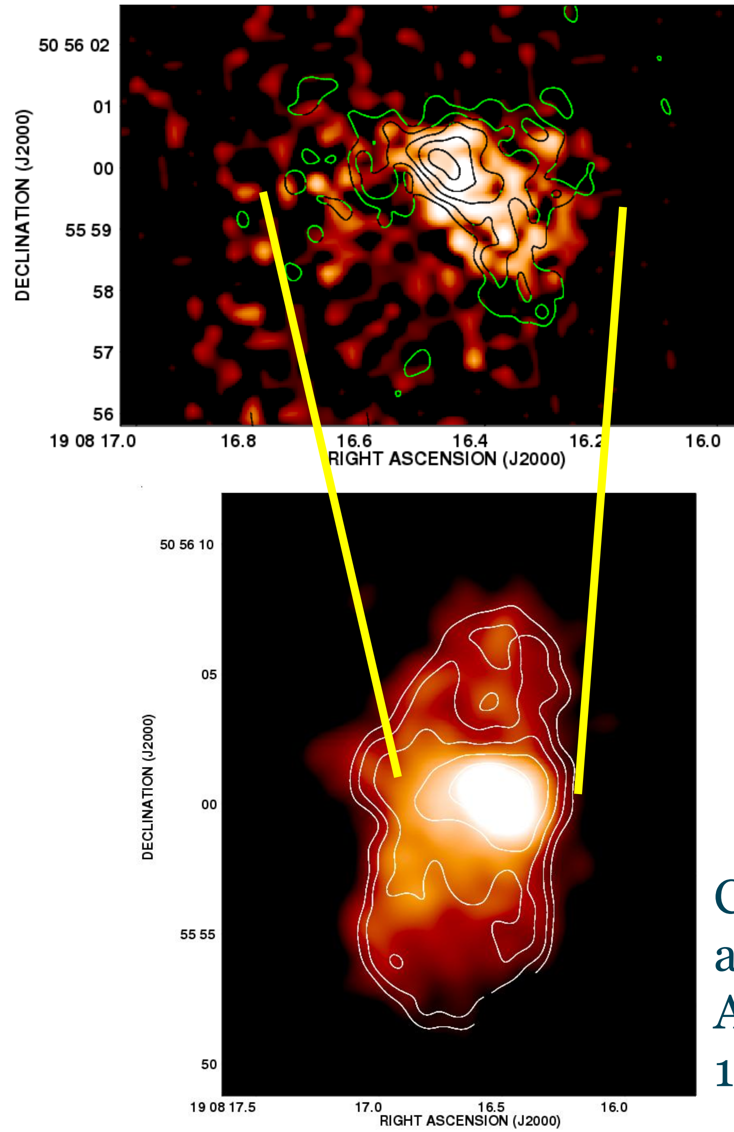


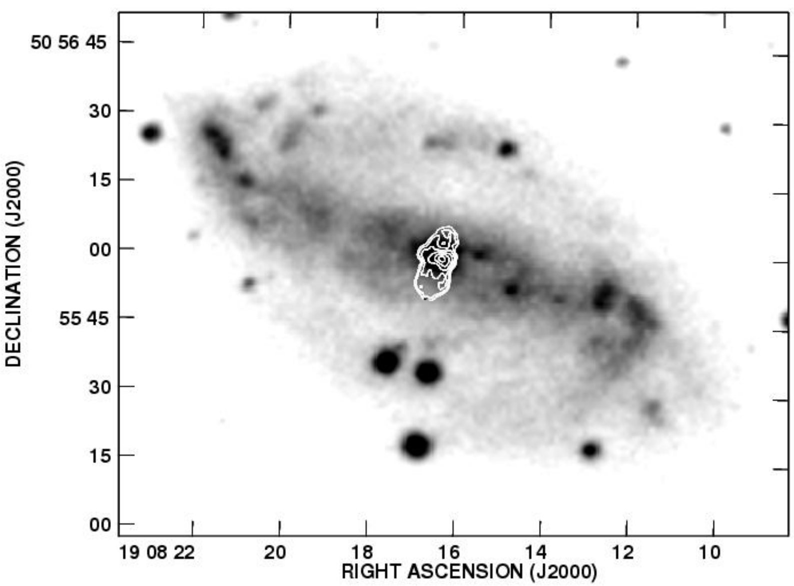




Disruption of weak jets in a dense environment

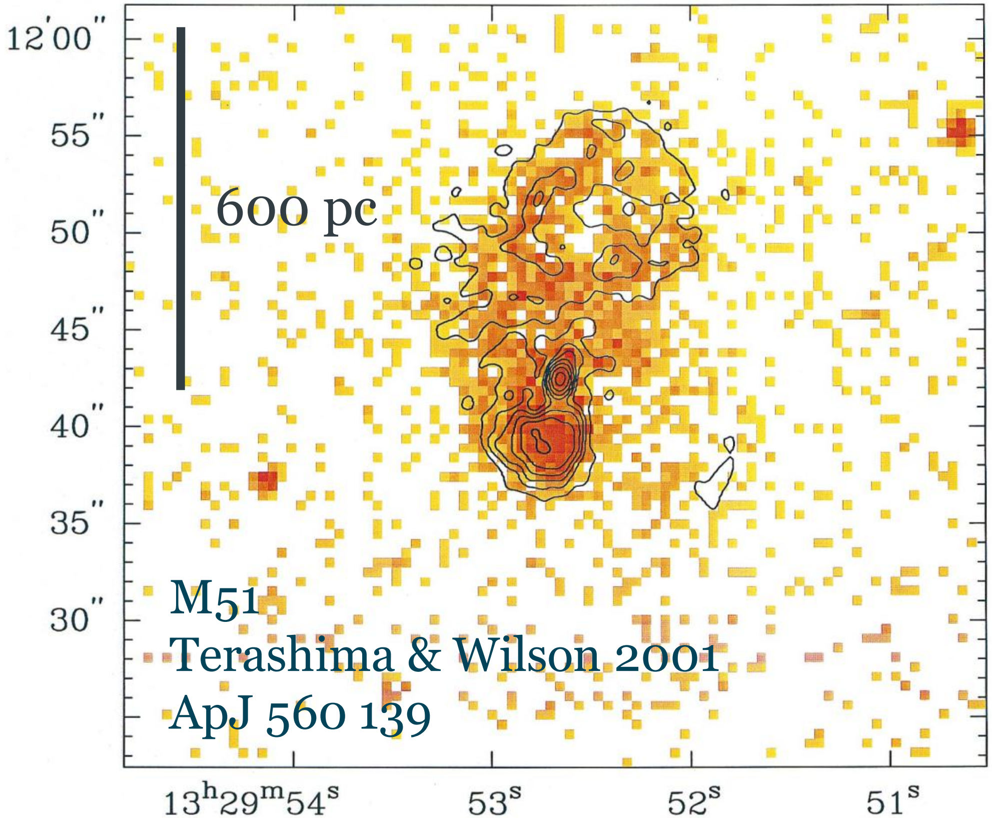
- Hot gas associated with the radio bubbles in NGC6764, with hottest region coincident with inner, bright collimated outflow.
- Shock signatures at outflow edge.
- Weak jet disrupted in galaxy bulge? (e.g. Sutherland & Bicknell 2007)

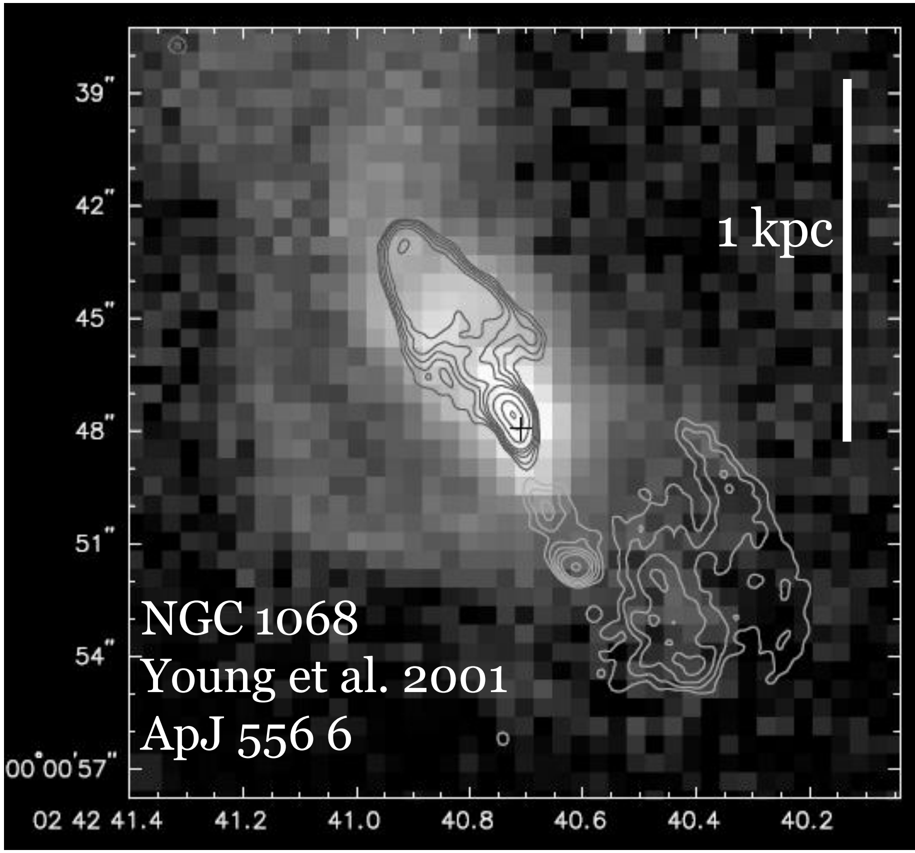




Croston et al. 2008, ApJ 688 190

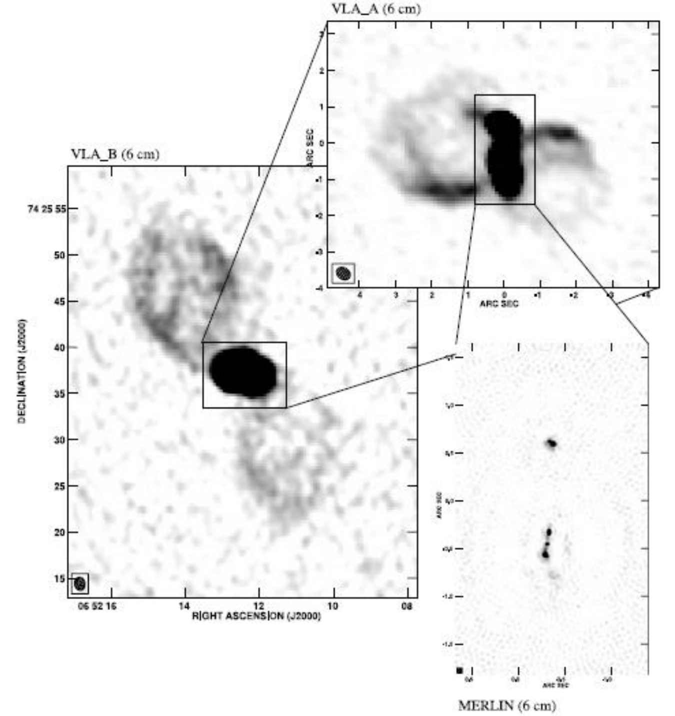
More shock heating in Seyfert radio outflows…

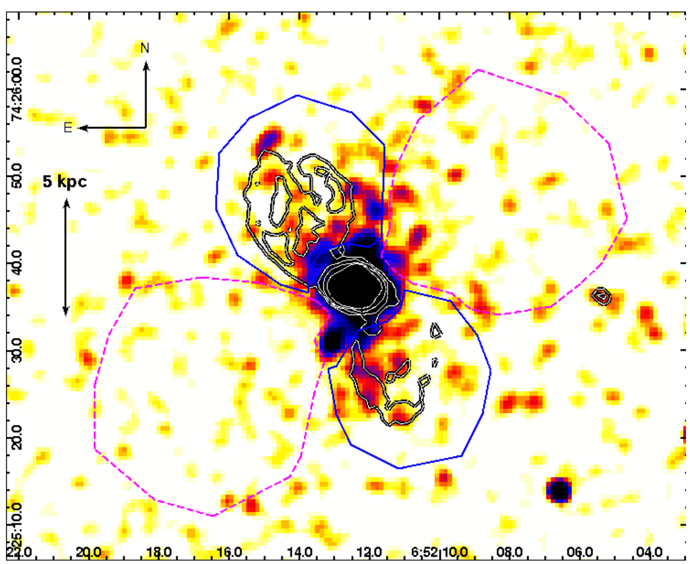




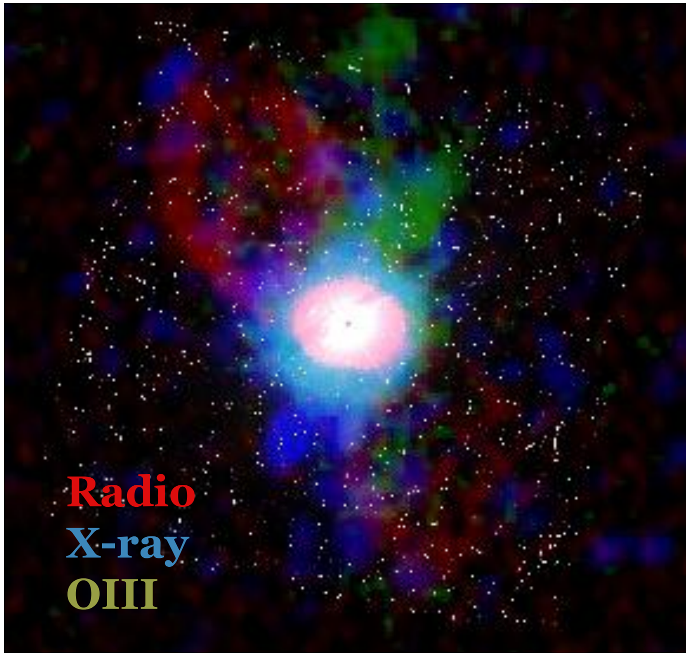
Shocked shells associated with a Seyfert outflow

- Shocked gas: $\mathcal{M}$ ~3.9, T ~0.9 keV, T_{ISM} ~0.2 keV
- Distributed round the edges of the bubbles (like NGC 3801 & Cen A) rather than inside (like the other Seyfert outflows).
- A more power radio outflow interacting with a less gas-rich host galaxy?





Markarian 6 (Mingo et al. 2010, submitted)



Conclusions

- Galaxy-scale radio-loud AGN have a dramatic effect on their host galaxies (not just coupling to group or cluster gas) :
  - shock heating of ISM at bow shock around supersonic radio lobes
  - high-energy particle acceleration at shock front
  - jet disruption, small-scale shocks and entrainment of hot gas
- Small (~1-10 kpc) radio galaxies are hosted by massive ellipticals: **probably not important for feedback on their own**, but provide clues to energy input during early stages of radio-galaxy evolution
- **"Kinetic" energy input in radio-quiet AGN could be significant:**
  - Seyfert jets and bubbles can inject considerable energy into ISM
  - Difficult to resolve and/or distinguish from SF
  - What about radio-quiet quasars?