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Jet-gas interactions and feedback

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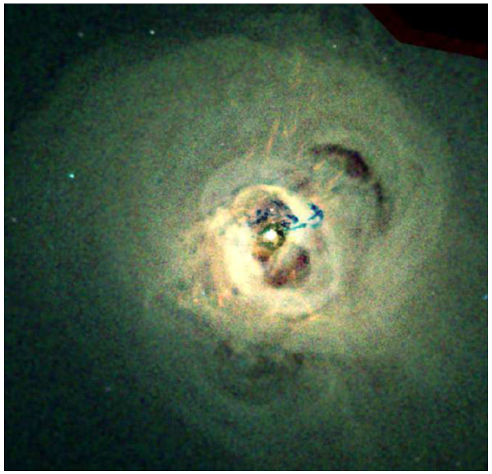
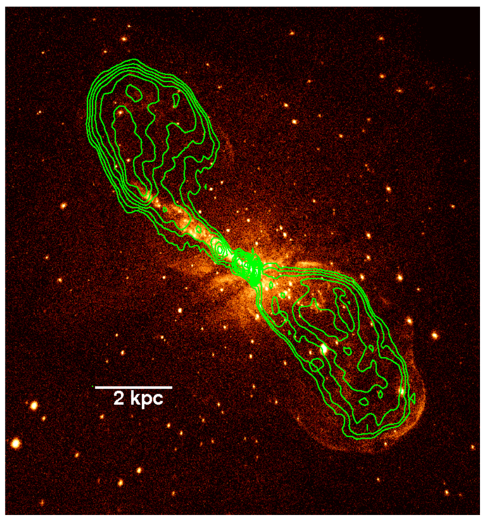
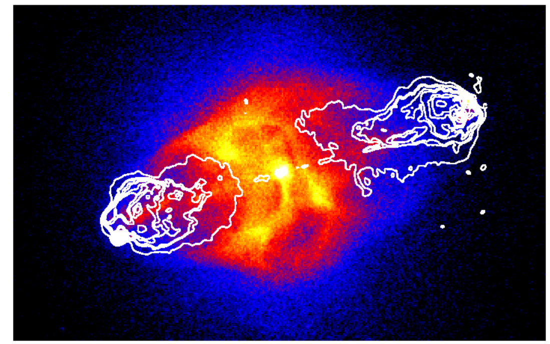
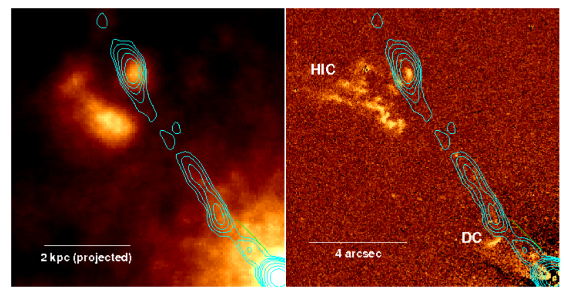








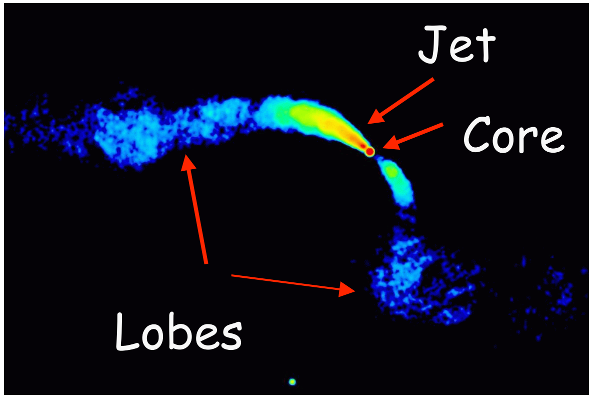
Radio-loud AGN. Consider Mpc (cluster) to kpc (galaxy) scales. Close to AGN?
Talk mostly restricted to interactions with largest gas-mass component (X-ray)

Outline

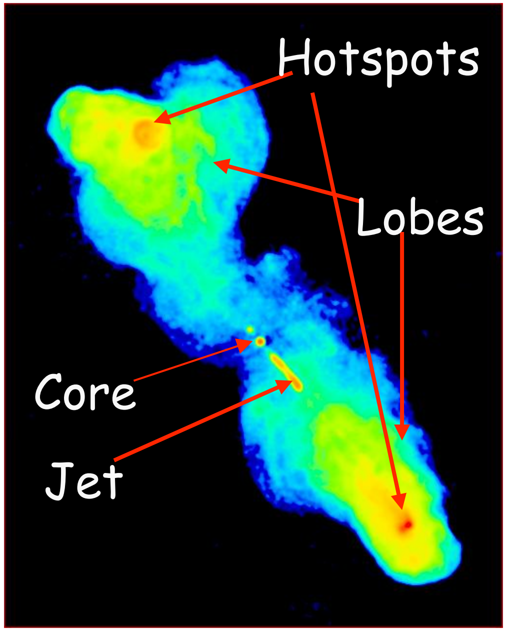
1. - Lobe and ghost cavities
2. - Source populations
3. - Strong shocks
4. - Jet bending at high ionization clouds (HICs)
5. - Gas belts
6. - Gas into the centre

Will mention Fanaroff & Riley class, so:

Lower-power FR I



Higher-power FR II



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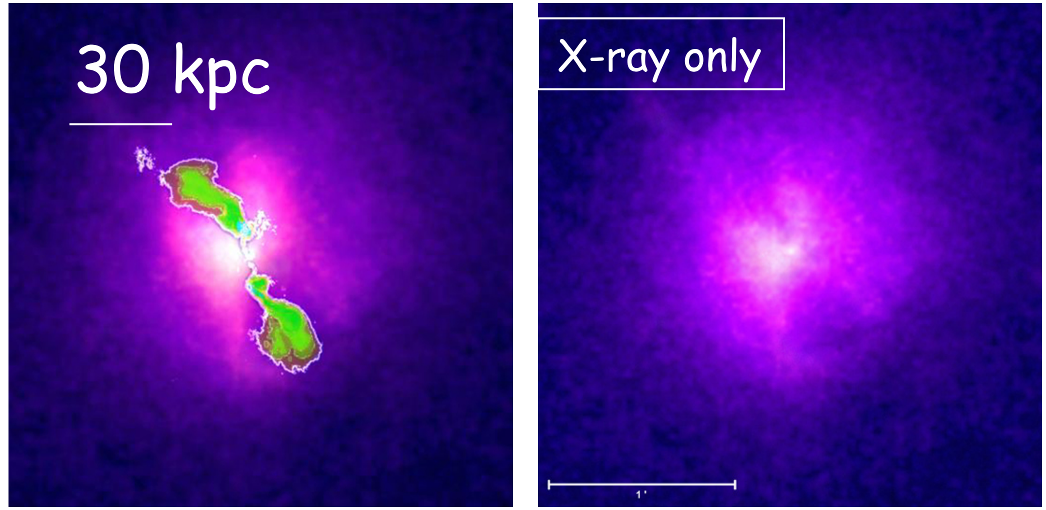
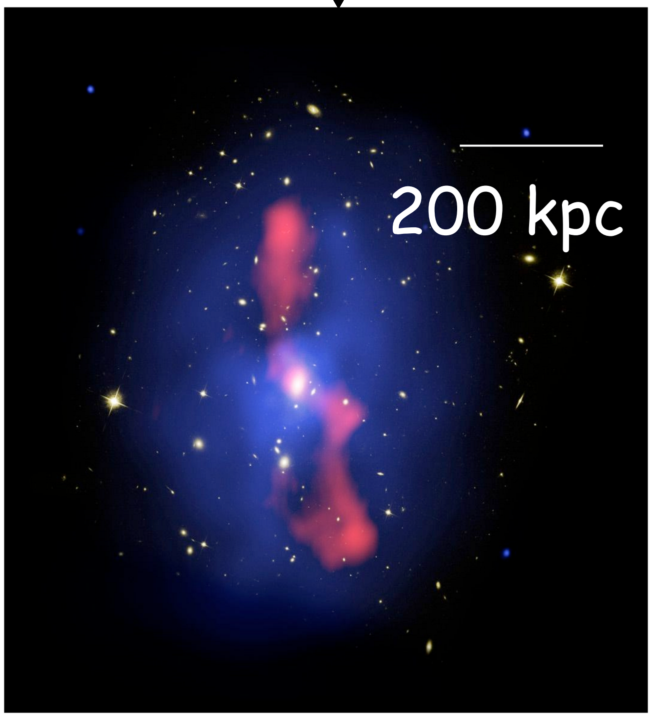
Lobe cavities: found commonly with *Chandra*

Hydra A

MS0735.6+7421



McNamara+ 2000



McNamara+ 2005

Cavity enthalpy (relativistic lobe plasma)

$4 P_{ext} V$

Estimate expansion time using size and c_s in external gas → cavity power (proxy for jet power)

Jet powers large and dominate radiative power: up to 10^{39} W

Lobe cavities: enough heat to stop cooling flows

Many cavity sources found in clusters with dense cores. Cooling time very fast, and once pressure support lost a cooling flow should result, but not seen. Dense cool cores persist.

Results suggested enough (time-averaged) cavity power to offset cooling e.g., Birzan+ 2004, Dunn+ 2005, Panagoulia+ 2014

Cavities in environments with wide range of kT e.g., Shin+ 2016

How is cavity power turned into heating?
- buoyant rise of cavities?
- subsonic inflation?
- sound waves?

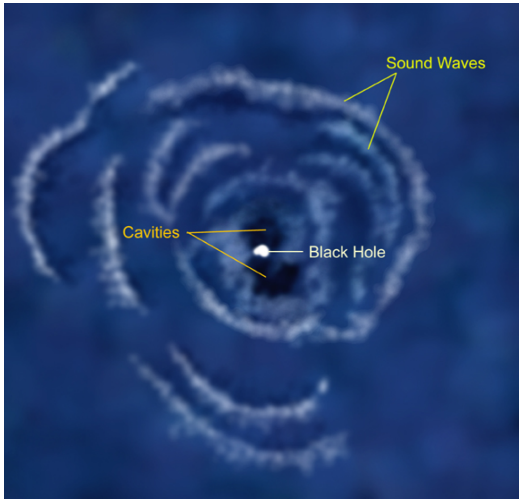
review by McNamara & Nulsen 2012 New J Phys

Lobe and ghost cavities: the iconic FRI Perseus A

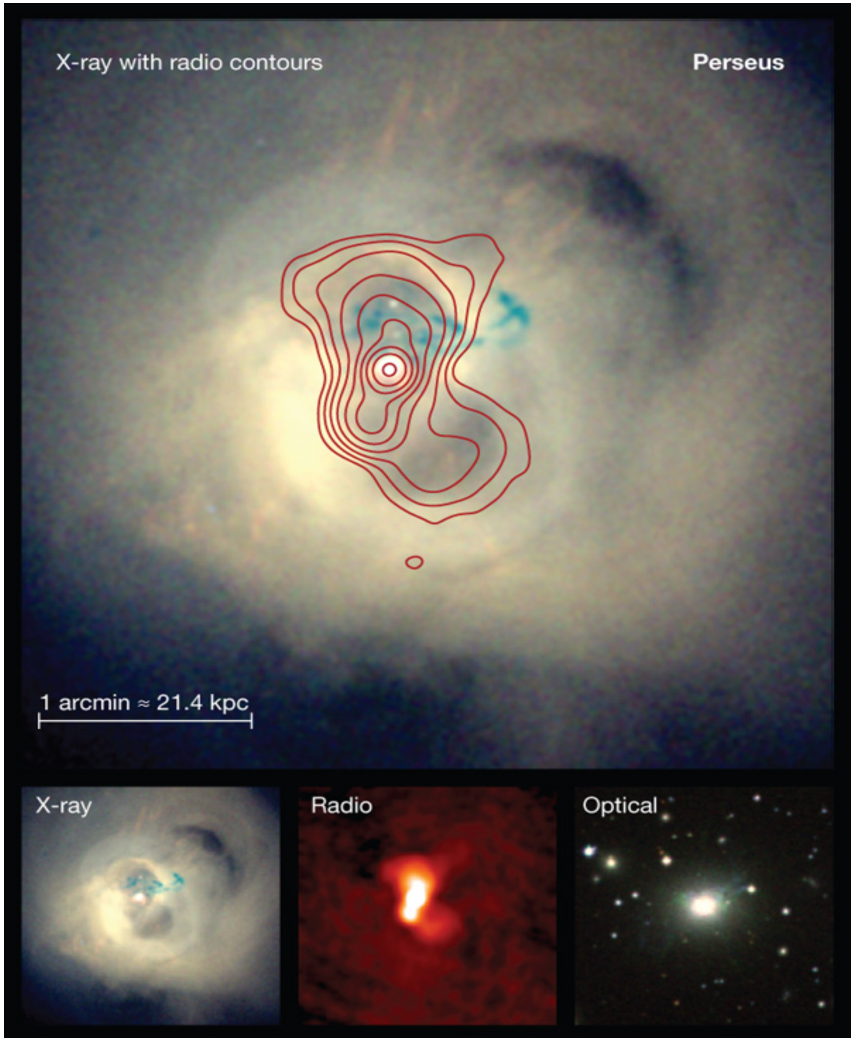
The only cavity source known before *Chandra*

With *Chandra*, much structure, ghost cavities

Sound waves (Fabian+ 2003)



NASA/NASA/CXC/M.Weiss



Cattaneo+ *Nature* **460**, 213 (2009)

Energy dissipation mechanism uncertain

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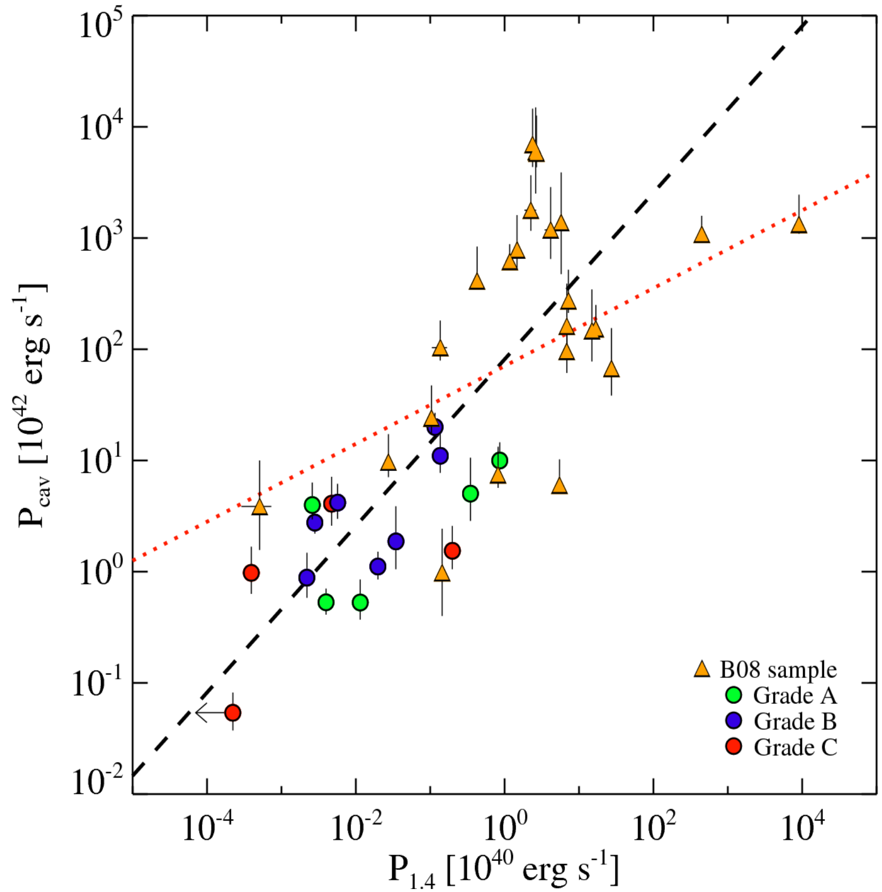
Lobe cavities: correlation P_j v P_r

Correlation of jet and radio powers. Initially flatter (Birzan+ 2008), steeper as data added.

Criticized by Godfrey & Shabala 2016, although for predominant subsample should be sound.



Cavagnolo+ 2010.
(See also O'Sullivan+ 2011)

Need to factor in population density to find where heating is dominant

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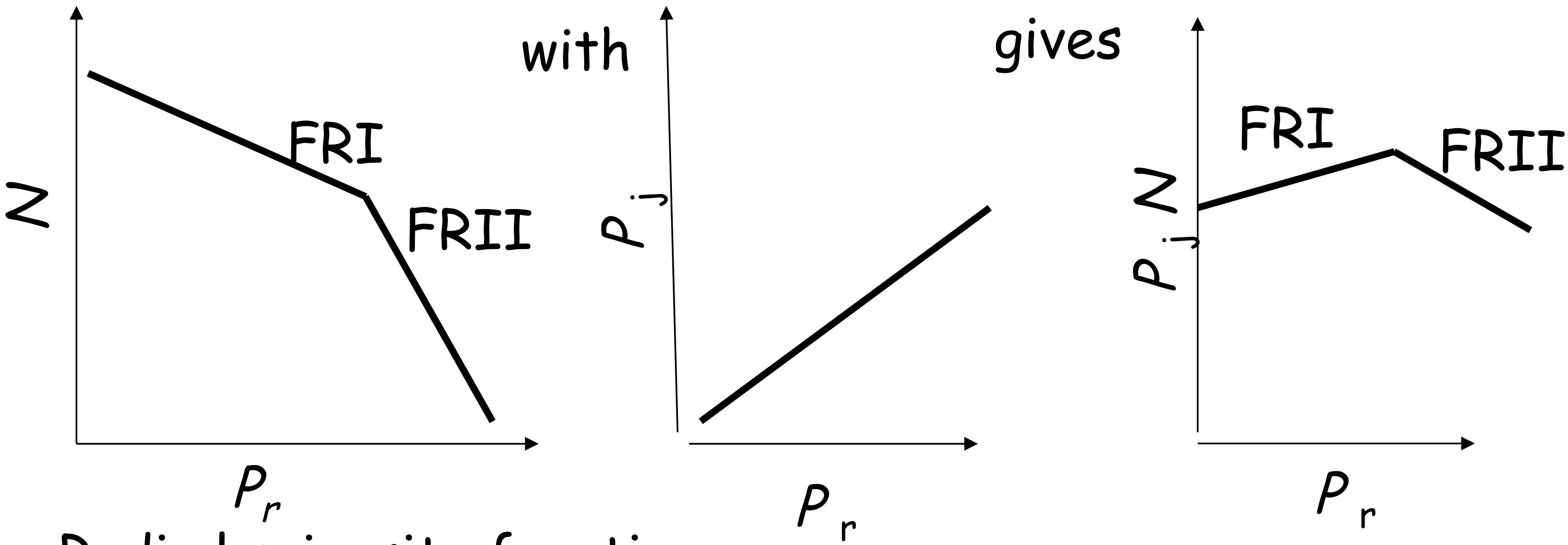
Populations: FR I/II boundary sources

Weight cavity power by source number density



Radio luminosity function
e.g., Best+ 2005

Correlation
e.g. Cavagnolo+ 2010

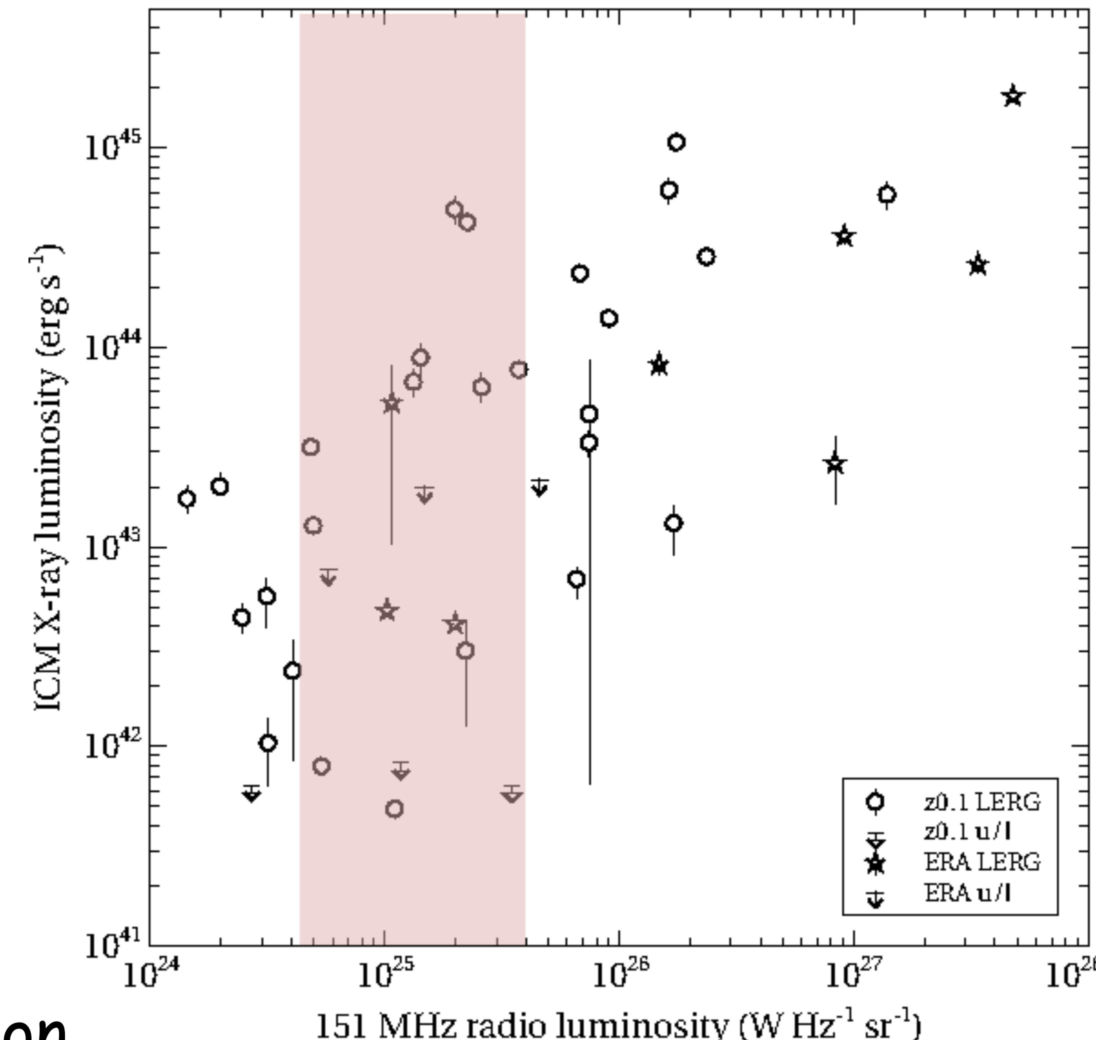
Half of all radio galaxy heating should be from sources within 0.3 – 3 of FRI/FRII transition. Comprises LERGS and HERGS. (low and high excitation lines in optical nucleus)

Populations: spread of atmospheres of FRI/IIs

Luminosity of atmosphere v radio power for LERGS
Ineson+ 2015

FRI/II's (pink band) span 3 orders of magnitude in X-ray luminosity of the environment.

Concentrate on $z < 0.1$ for best spatial resolution

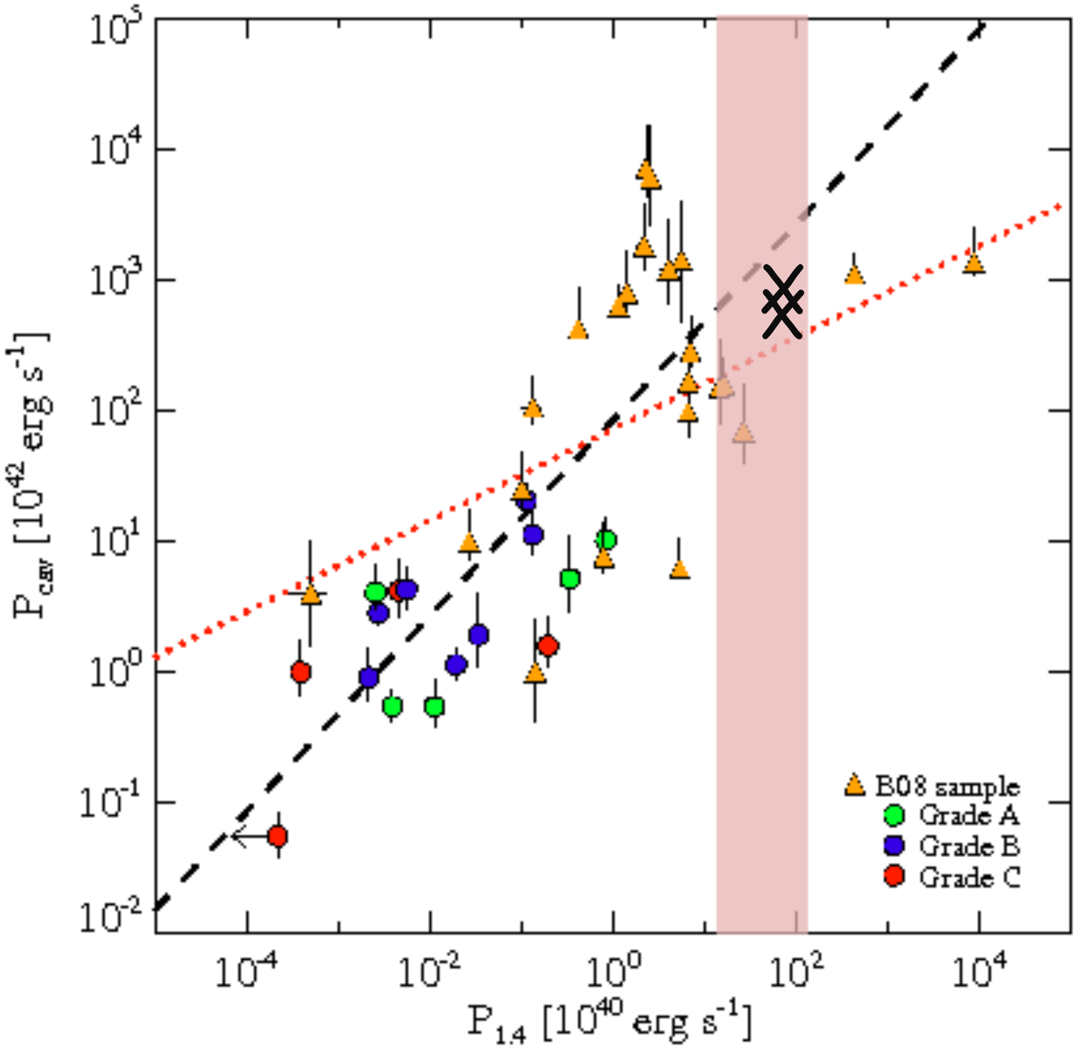


Populations: FRI/IIs on correlation P_j v P_r

Examples of sources with cavities:

PKS B1416-493 consistent using cavity power
DW & Birkinshaw 2016

PKS B2152-699 consistent with correlation taking into account kinetic and thermal energy of shocked gas.
DW+2012



FR I/II boundary source: PKS B1416-493

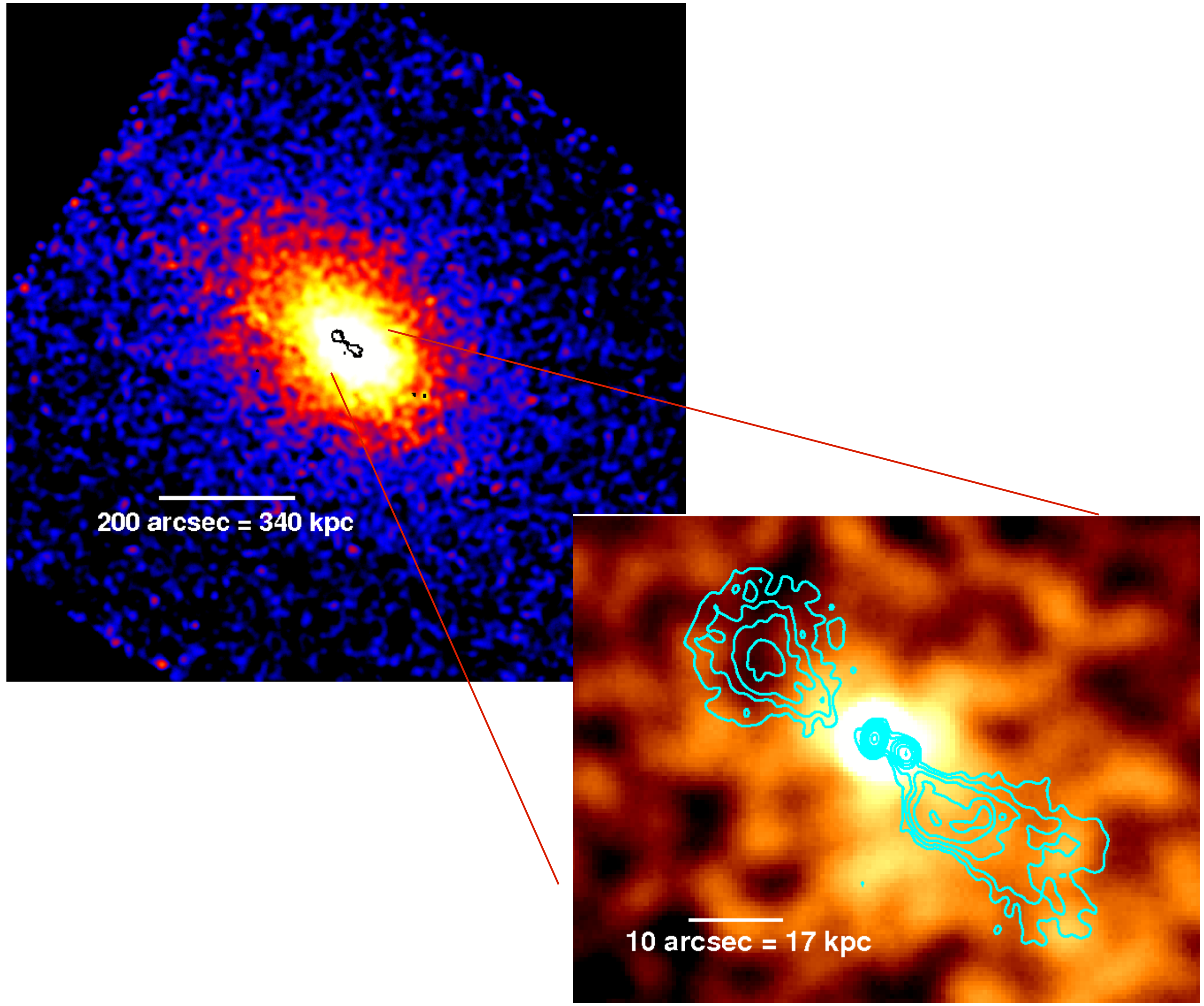
Environment is rich non cool-core 4.6-keV cluster

X-ray cavity at NE lobe

Lobe iC in SW lobe measures internal energetics

Cavity/radio powers lie on correlation

DW & Birkinshaw 2016



Chandra + radio contours

FR I/II boundary source: PKS B2152-699

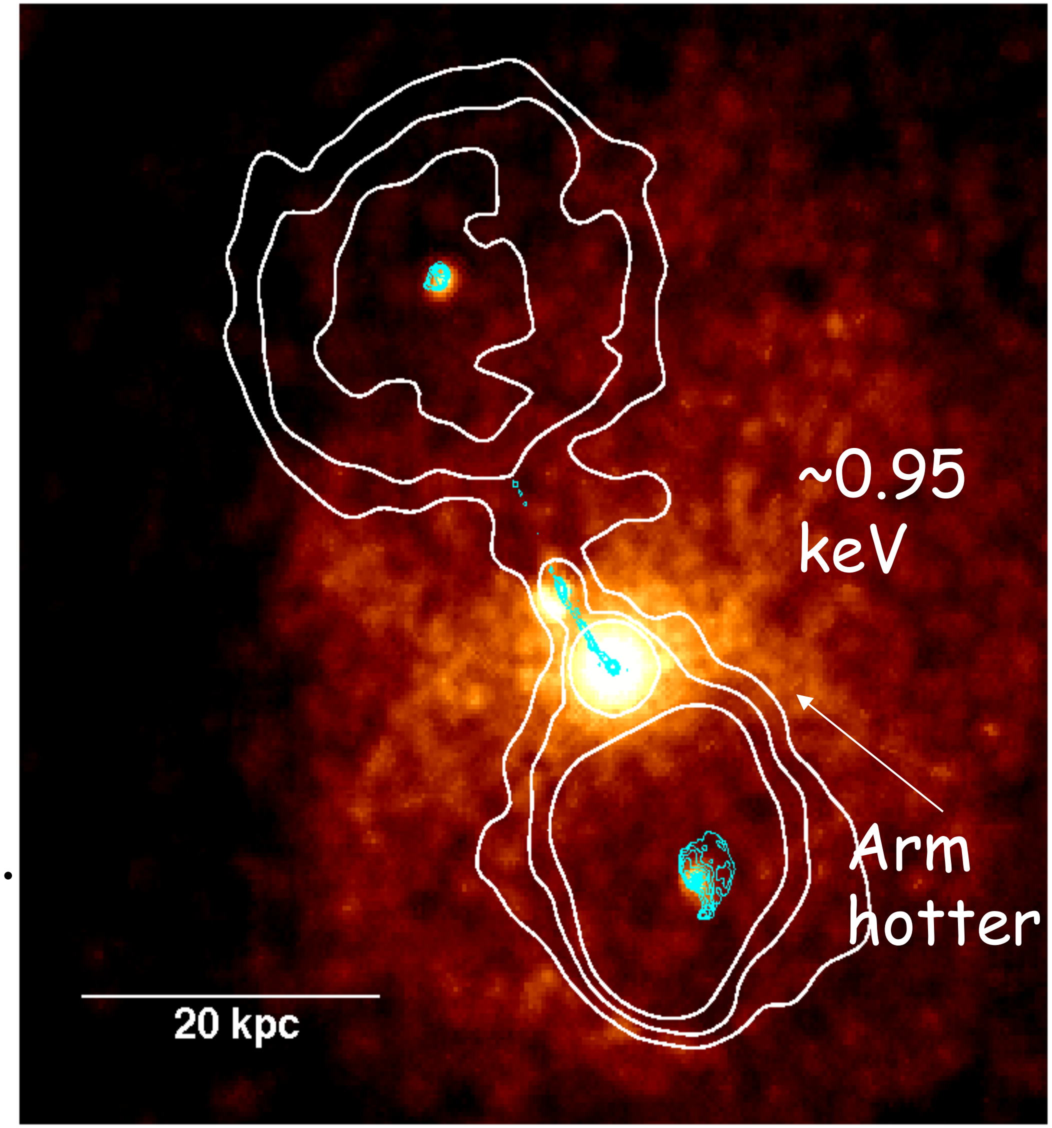
Environment is 1-keV group

X-ray cavities. Lobe iC measures internal energetics

X-rays from knots & hotspots. 10^0 viewing angle. $\delta \sim 6$.

Strong shocks: Mach ~2.7
Work in driving shocks dominates (x >10) cavity power.
Lies on P_j/P_r correlation when energy in
shocked gas included

DW+2012



Chandra + radio contours

Strong shocks: under-appreciated in earlier work

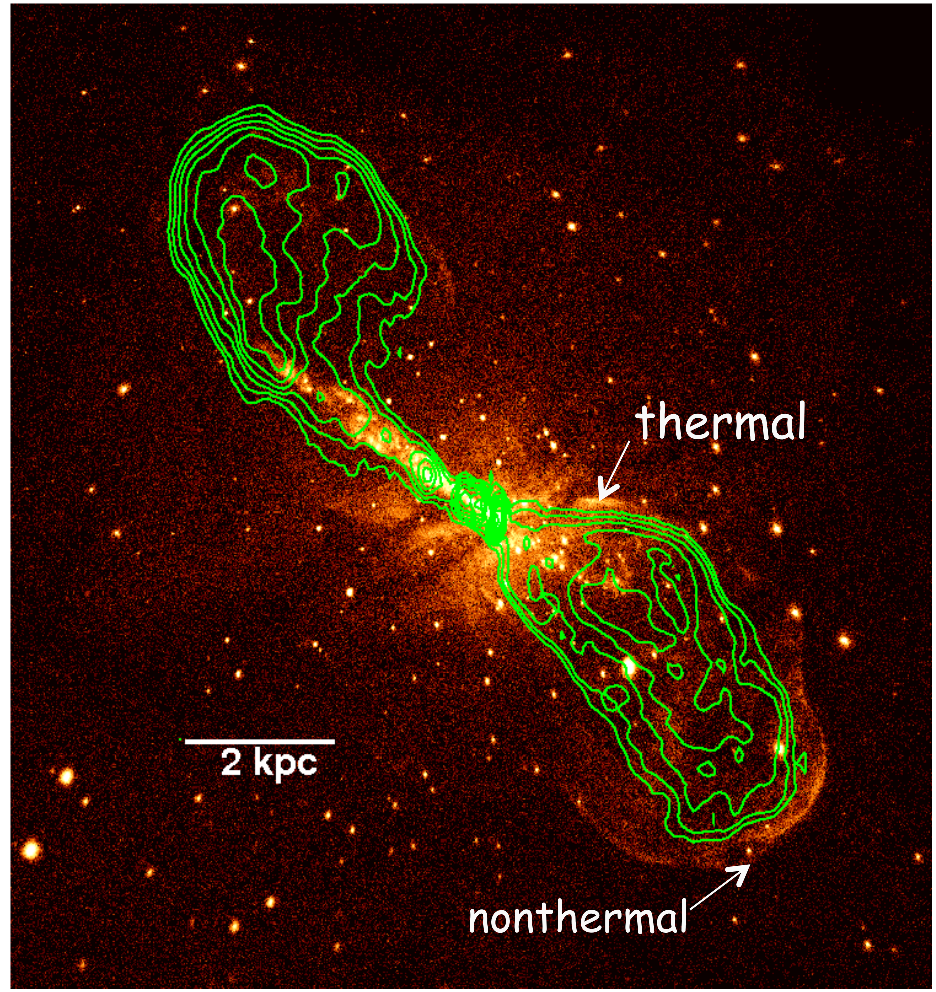
Earlier wisdom that shocks not generally important in dynamics & heat deposition (see McNamara & Nulsen 2007) but:

Inner lobes of the closest radio galaxy, the FR I Cen A

Temperature & density of both shocked and unshocked gas measure Mach number, $\mathcal{M}$ with redundancy to test model

$\mathcal{M} \sim 8$

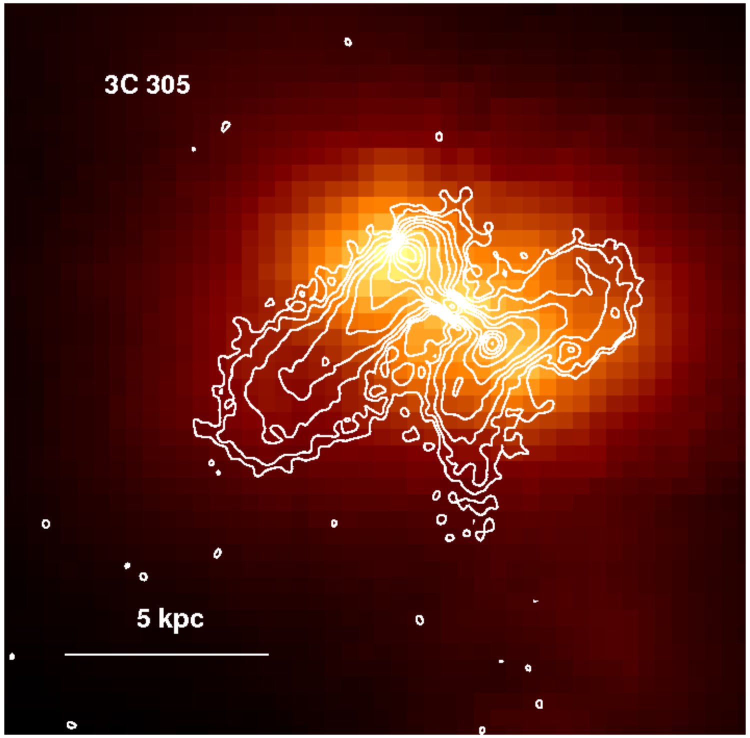
Kraft+ 2003, Croston+ 2009



Chandra + radio contours

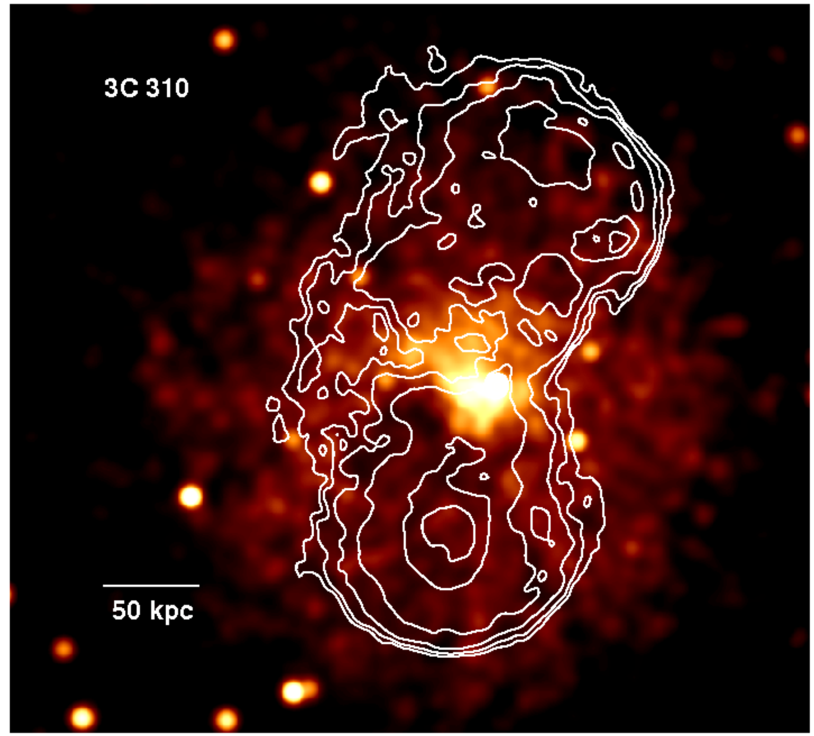
Moderate shocks: FRI/II transition sources

3C 305



$\mathcal{M} \sim 2$ shock, 0.4 keV gas
Hardcastle+ 2012

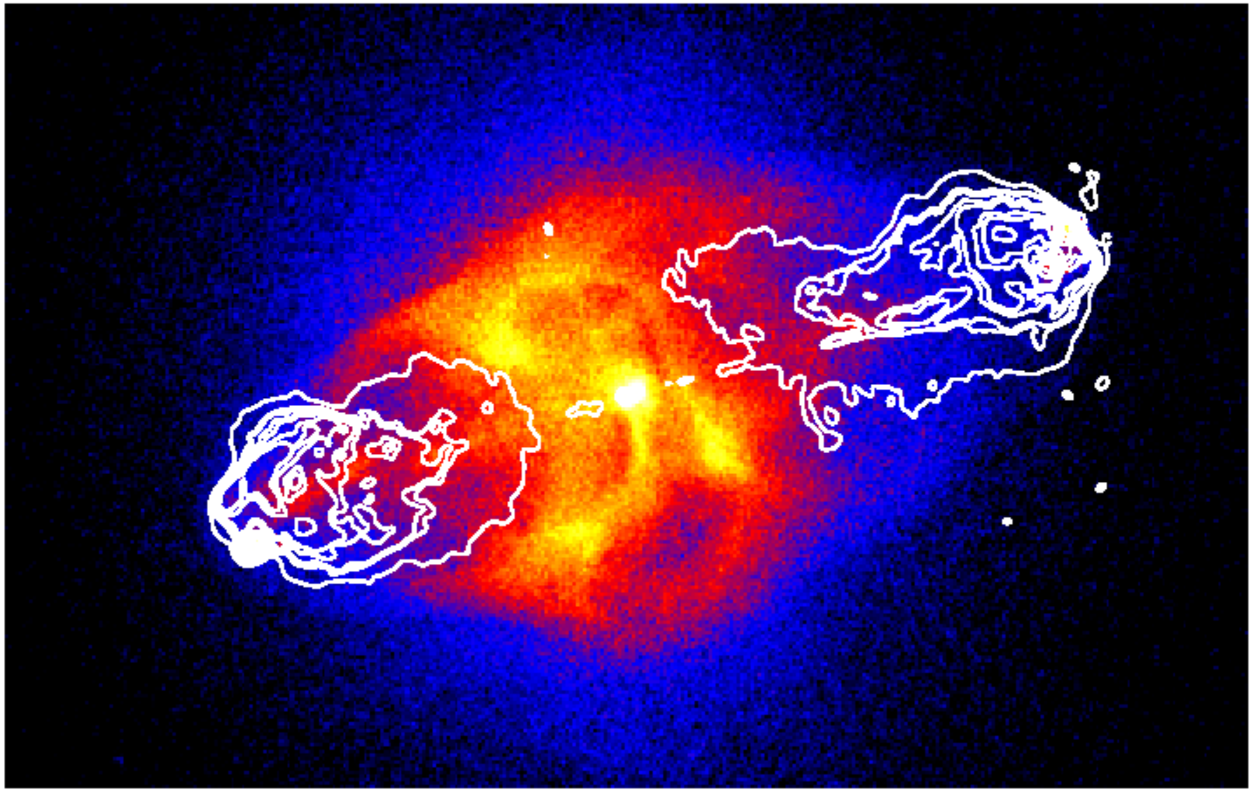
3C 310



$\mathcal{M} \sim 1.7$ shock, 2 keV gas.
Cavity Kraft+ 2012

Moderate shocks: the iconic FRII Cygnus A

Cocoon shock may only be $\mathcal{M} \sim 1.4$ Nulsen+ 2014



2 Ms (23 days) of Chandra data being accumulated. Watch this space!

Jet bending at High Ionization Clouds (HICs)

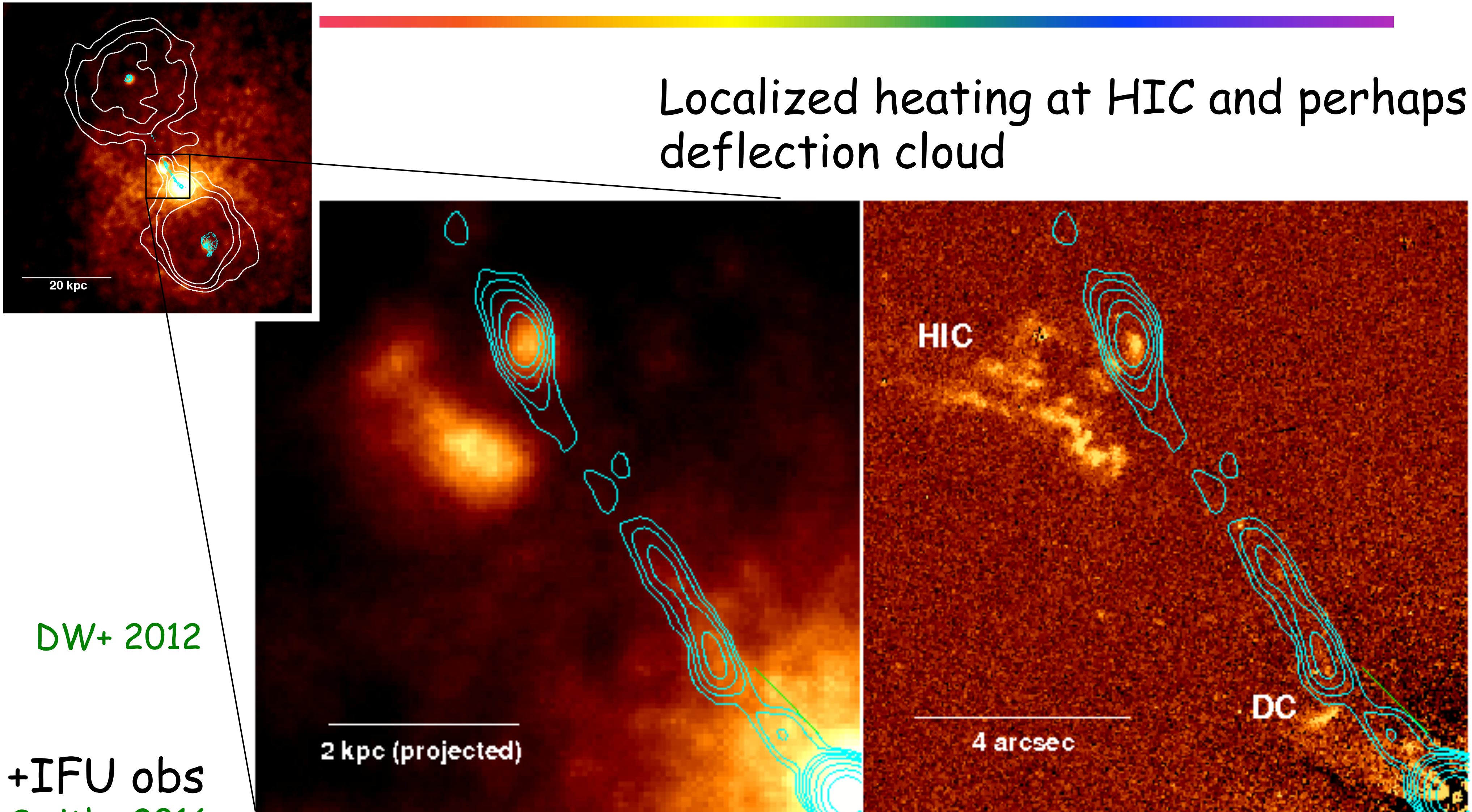
Jets can bend appreciably in interactions with localized gas – merger debris?

Jet energy heats gas to X-ray energies

Lifetimes ~10^7 years

Jet bending at HICs: PKS 2152-699

Localized heating at HIC and perhaps deflection cloud



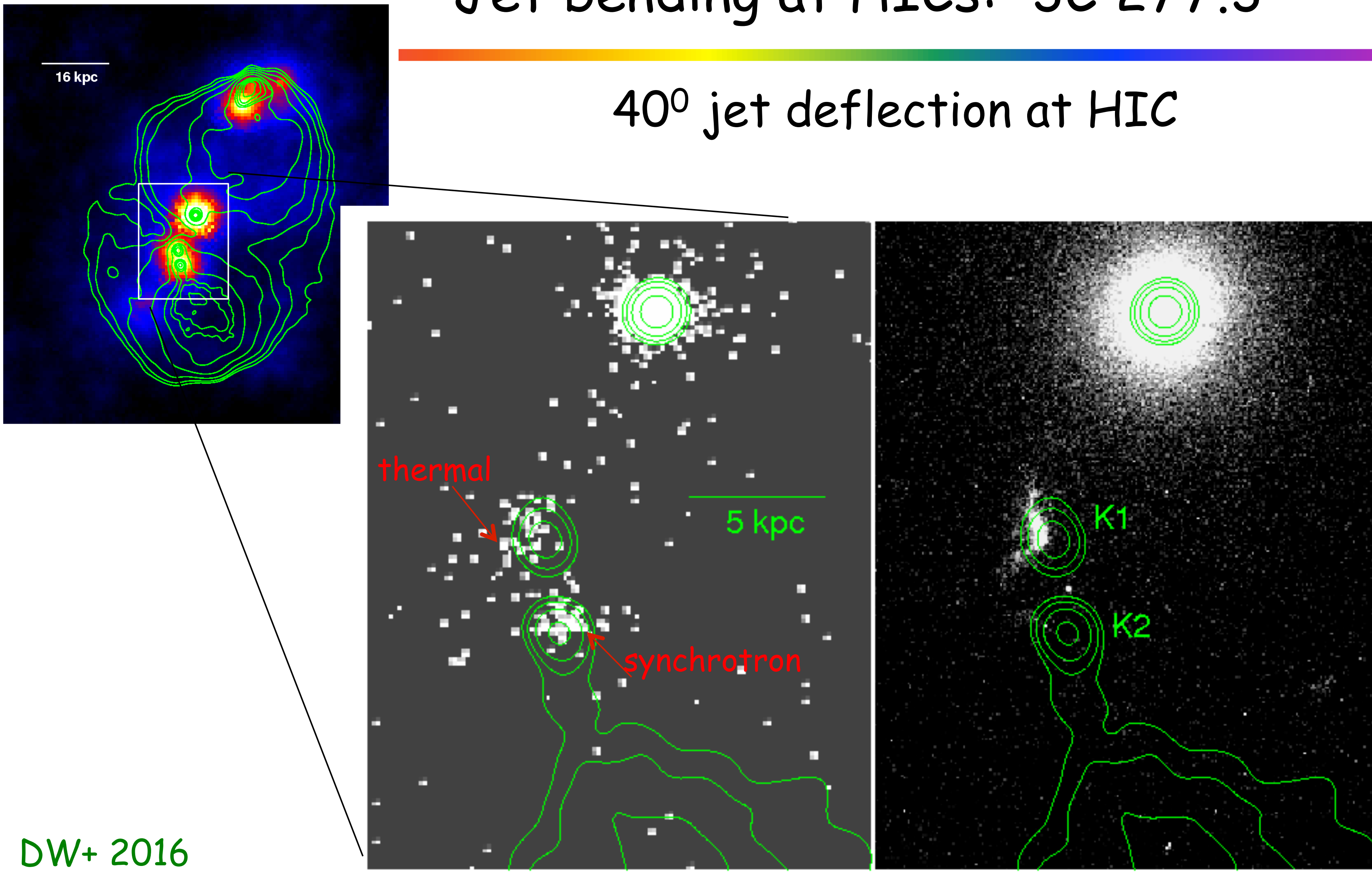
Chandra radio contours *HST*

DW+ 2012

+IFU obs
Smith+ 2016

Jet bending at HICs: 3C 277.3

40^0 jet deflection at HIC



DW+ 2016

Chandra radio contours *HST*

A simple stable feedback loop

Feedback needs a connection between large scale and AGN

more jet → less gas infall → less black hole growth and star formation
↓
less jet → more gas infall → more black hole growth and star formation
↑
more jet

But how does gas on jet/heating scale regulate sub-pc BH feeding scales?
Time scale of BH response short compared with heating times

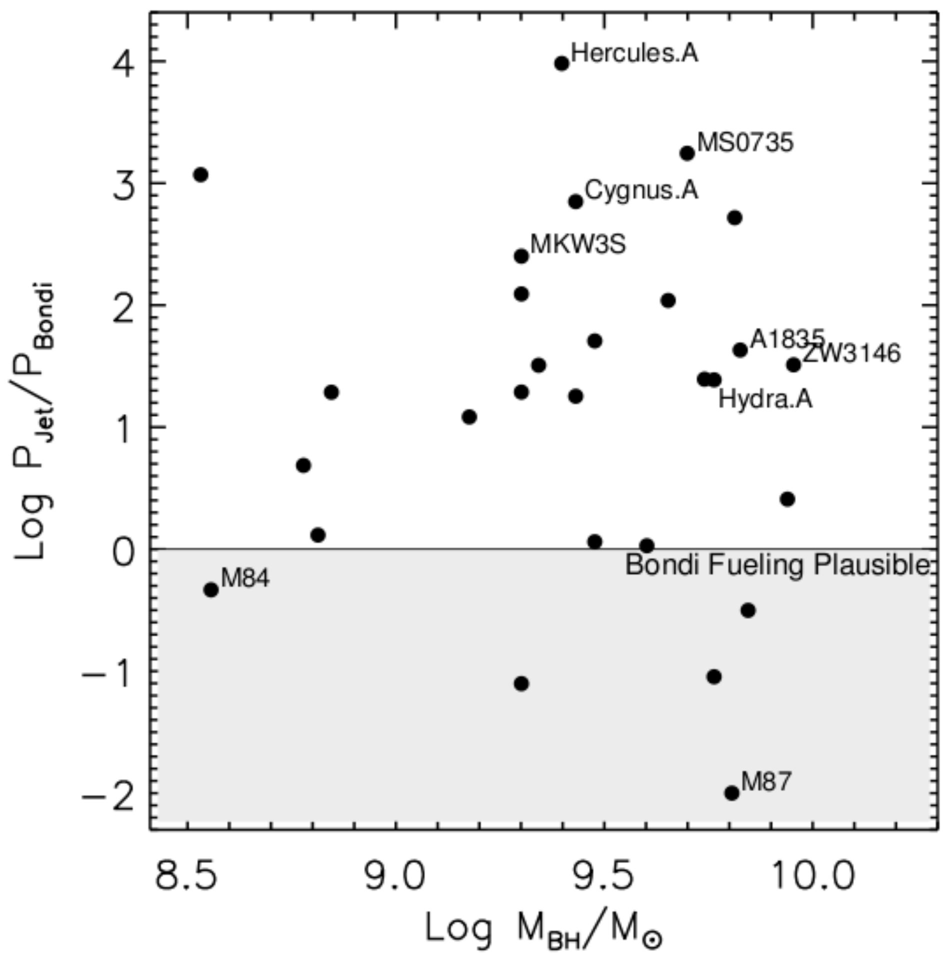
Galaxy-scale cool gas coronae unscathed by jet O'Sullivan+ 2011

Gas into the centre: mixture of processes

Most cavity sources have jets too powerful for Bondi accretion.

Trend for radio-brighter ellipticals to contain more molecular gas – much more than needed for fuelling
e.g. O'Sullivan+ 2015

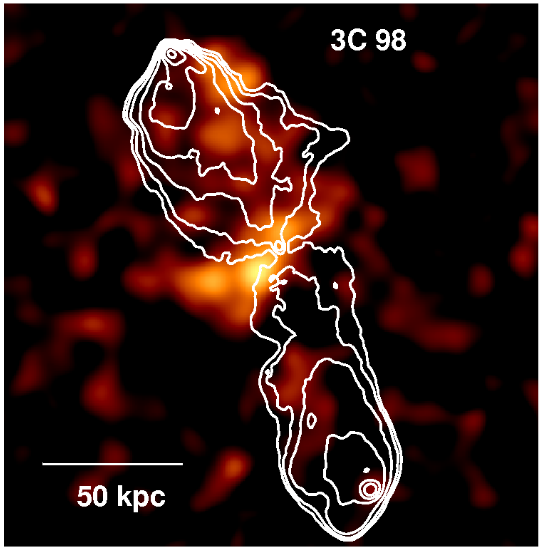
Does radio source have direct influence on gas compression?

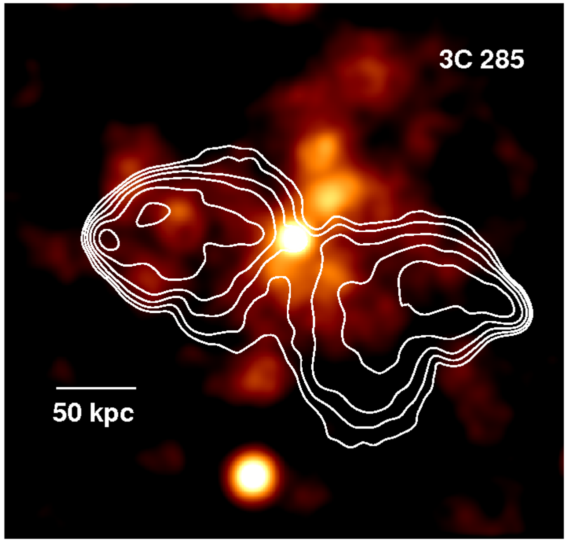


McNamara+ 2011

Gas into centre: Gas belts

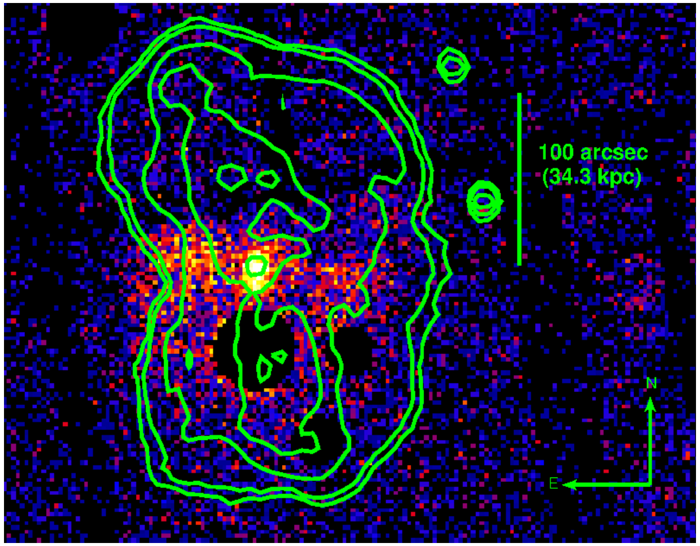
Radio galaxies commonly show belt-like gas structures between their lobes; 40% of $z < 0.1$ 3CRR Mannering 2013, Duffy+ 2016





Central gas perhaps from mergers or fossil groups

Temperature structure in 3C 386 suggests lobe-directed inflow towards relic core of group. Duffy+ 2016. Squeezing/compression?



Jet-gas interactions studied when most active. Dying radio sources?

Summary

- Half of the jet heating in the Universe should arise from sources within 0.3 – 3 of FR I/II transition power.
- Radio sources span large range of richness of environment
- Energy dissipation mechanisms still not well understood
- Kinetic and thermal energy of shocked gas can dominate cavity energy in FR I/II transition sources
- Local interactions with merger debris can bend jets
- Linking AGN fuelling with large-scale heating complex. Probably variety of processes. Gas that is initially cool needed. Gas belts may have dynamical role.
- Most work is for radio sources where time-averaged effects at a peak. Dying phase of jet?