Jet-gas interactions at the crucial jet power for feedback

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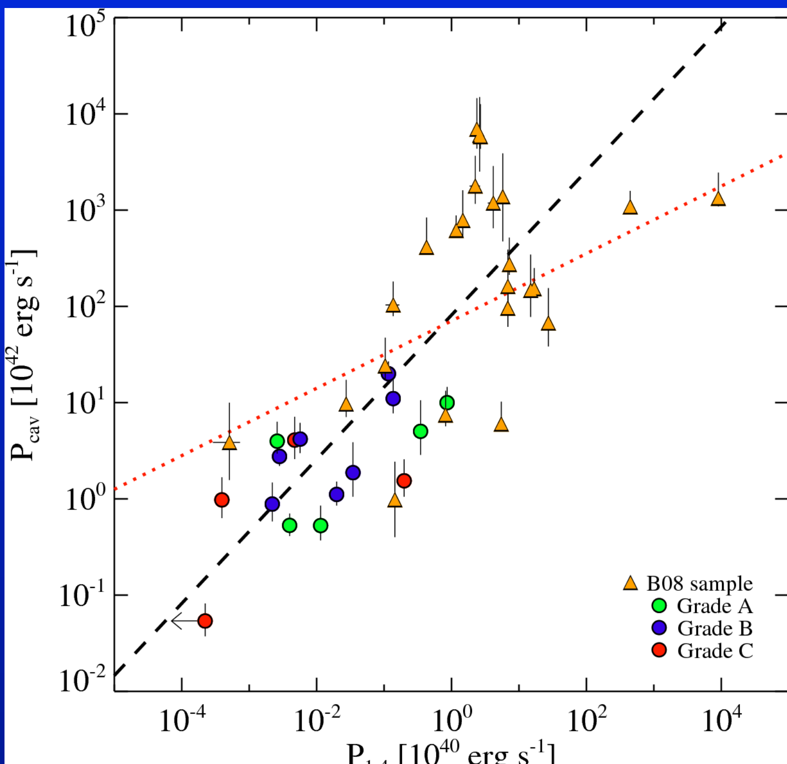
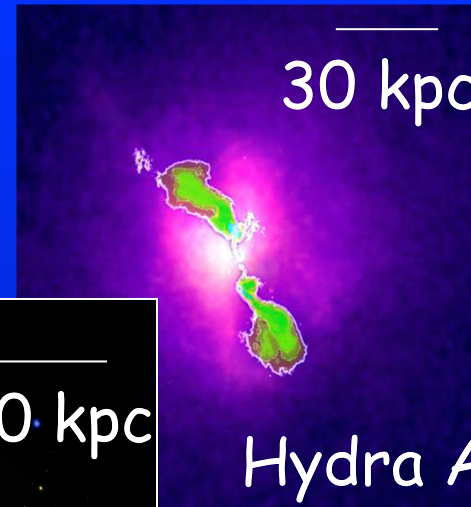
Chandra: radio sources bore cavities in range of atmospheres – ISM to ICM.
Correlations between radio power and cavity power.

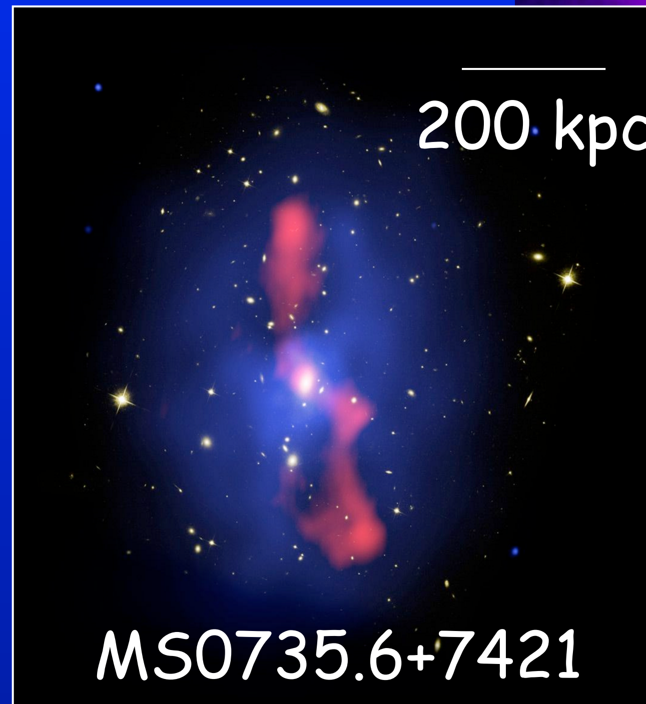
e.g.,



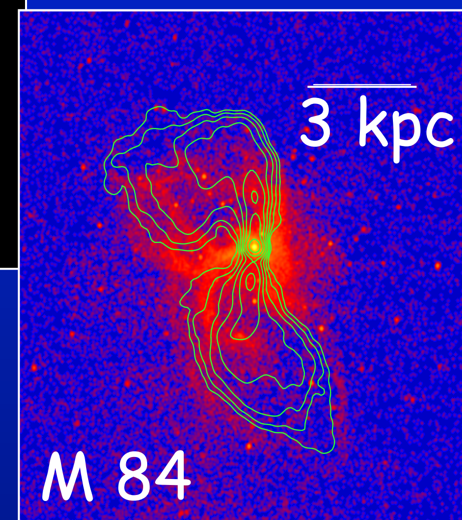
Cavagnolo+ 2010



McNamara+ 2000

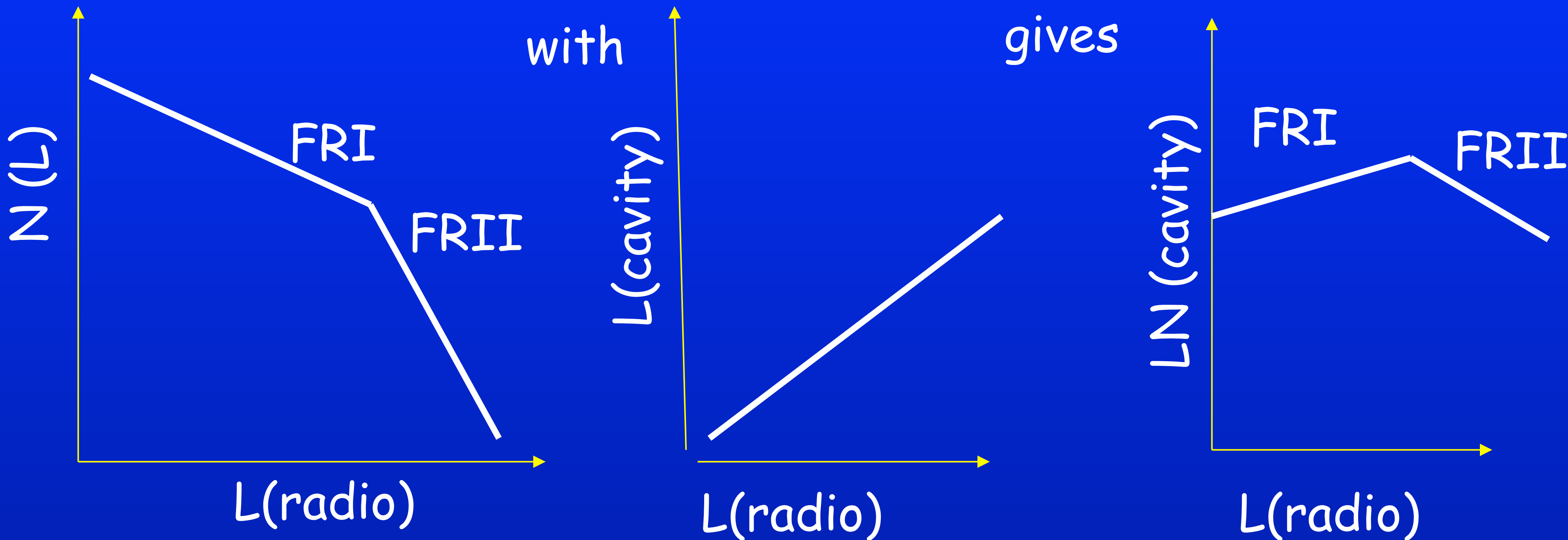


McNamara+ 2005



Finoguenov+ 2008

FRI/FRII border



Radio luminosity function
e.g., Best+ 2005

Correlation
e.g. Cavagnolo+ 2010

Half of the heating in the local Universe should arise from sources with powers 0.3 – 3 of the FRI/ FRII transition power.

16 FRI/II transition sources in 3CRR, 15 of which are at $z < 0.1$ and all have good *Chandra* observations (median exposure ~43 ks). Unbiased in atmosphere.

A number of published papers on these 15, most relevant for gas interactions/heating:

Sun+ 2005 ApJ
Hardcastle+ 2005, 2012 MNRAS; 2007, ApJ
Hodges-Kluck+ 2010 ApJ
Kraft+ 2012 ApJ
Mannering 2013+ MNRAS

Range of properties:

- X-rays from cores, hotspots, jets, lobe inverse Compton, of varying strength
- The environments, and level of interaction between radio plasma and gas, vary

Giants which no longer have a rich atmosphere to heat

Trail sources shaped by rich atmospheres and ram pressure, and other sources with localized gas interactions

Belted sources, where radio plasma driven by gas arising from mergers or fossil groups – probably little current heating of large-scale X-ray gas, but ongoing local interactions - common

Sources where strong shocks are inferred:

Mach 2 shock into 0.4 keV gas – Hardcastle+ 2012 MNRAS

Mach 1.7 shock into 2 keV gas. Cavity. – Kraft+ 2012 ApJ

Beamed cores/BLRGs – cores and hotspots (bright cores make shocked gas difficult to detect)

These (small number) statistics suggest <~20% chance a given source is widely heating its ISM/ICM. In some cases heating may be complete. Local heating rather common.

For mechanisms, important to target interesting FRI/II transition sources for deep observation.

2 examples here:

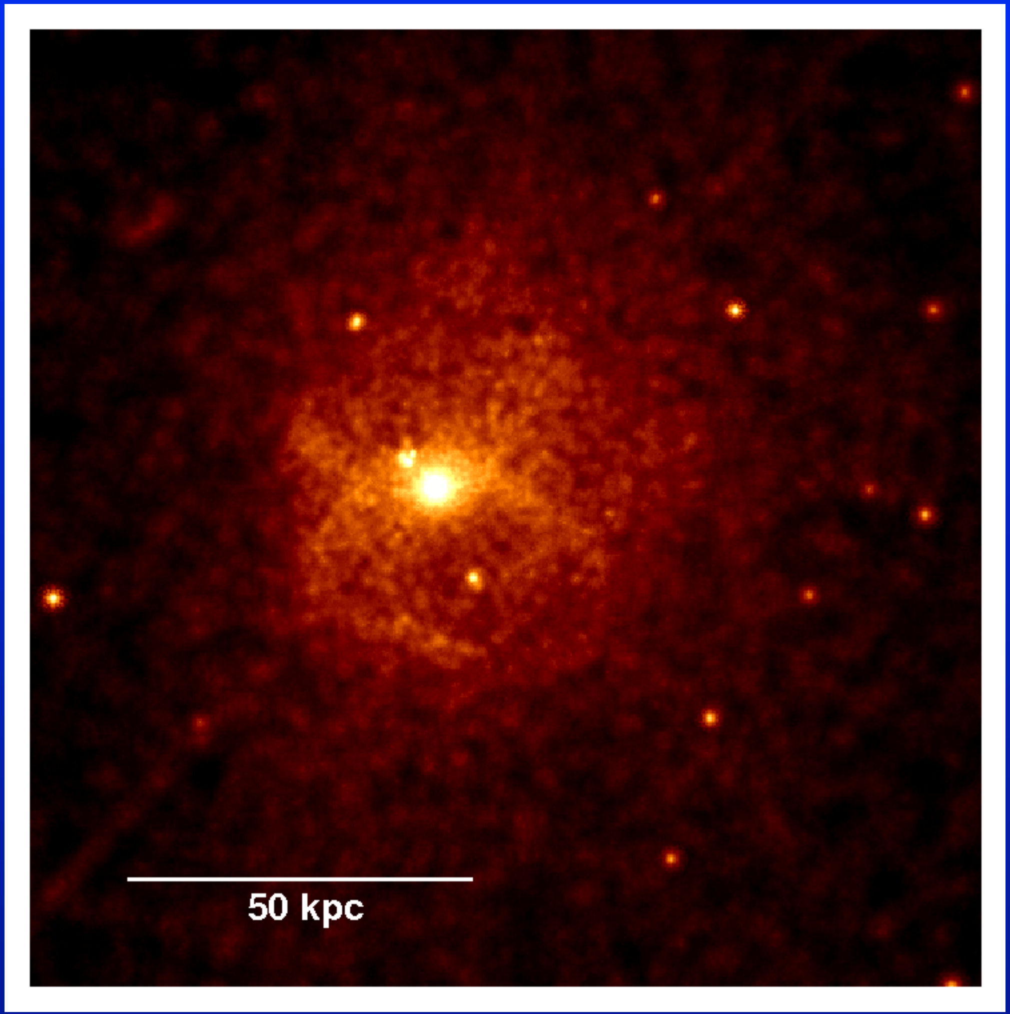
First - one of the brightest radio sources in the S hemisphere (3CRR equivalent)

PKS B2152-699

z=0.0282

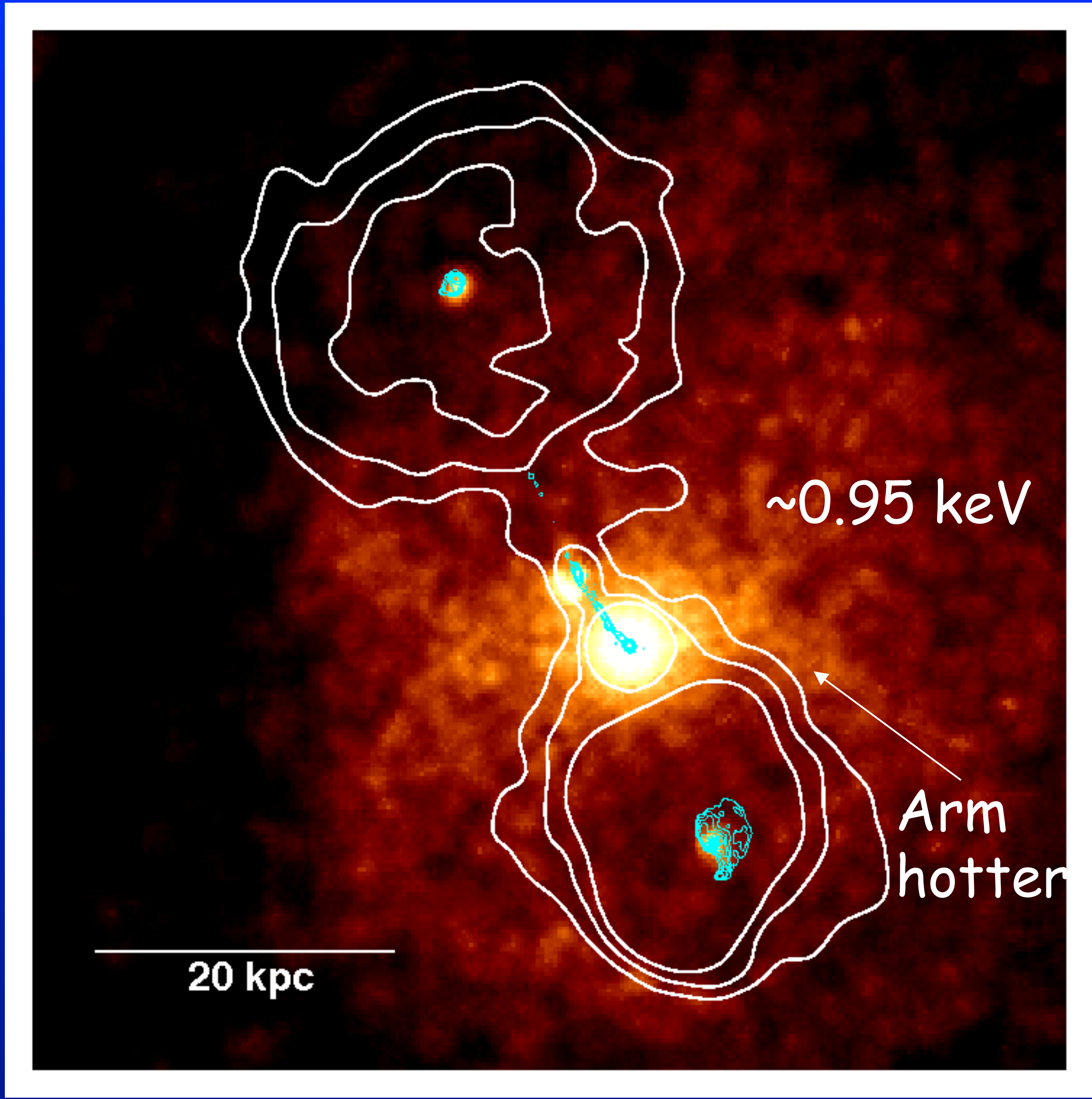
Structured group atmosphere

Bright core.
Borderline NLRG/ BLRG



Basic properties already in Worrall+ 2012 MNRAS

- Gas cavities
- Lobe inverse-Compton measures lobe energetics (don't need
- to trust minimum energy)
- Strong shocks: Mach ~2.7
- X-rays from jet knots and hotspots. 10^0 viewing angle. $\delta \sim 6$.



Energy budget (Worrall+ 2012 MNRAS)

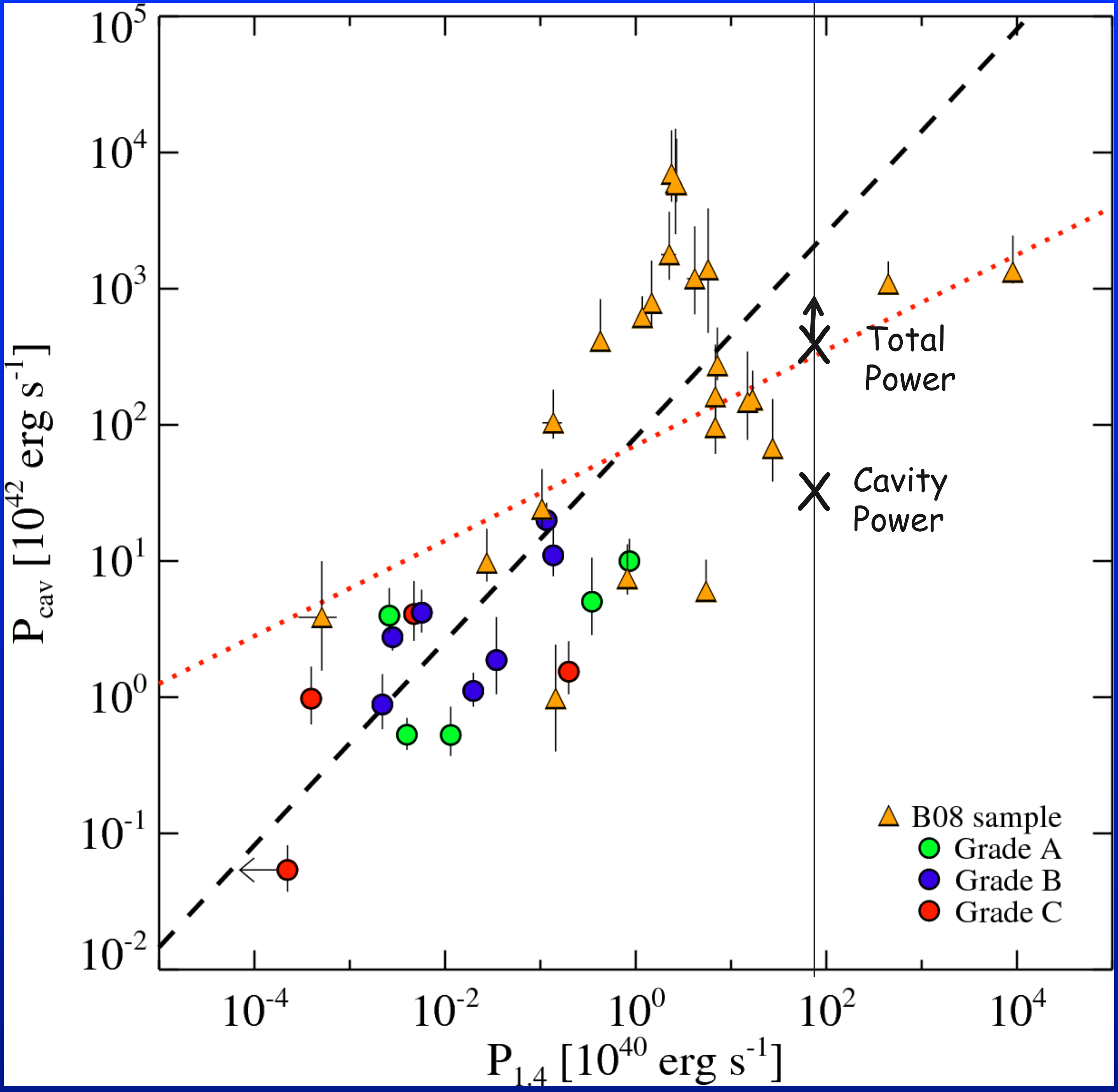
P_{cavity} only ~3 x 10^{43} erg s^{-1} (even reducing time 1/3 for Mach ~3 shock)

Kinetic power to shock the gas ~ 24 x 10^{43} erg s^{-1}

Heating of shocked gas > 7 x10^{43}erg s^{-1} (underestimated due to cool gas in line of sight)

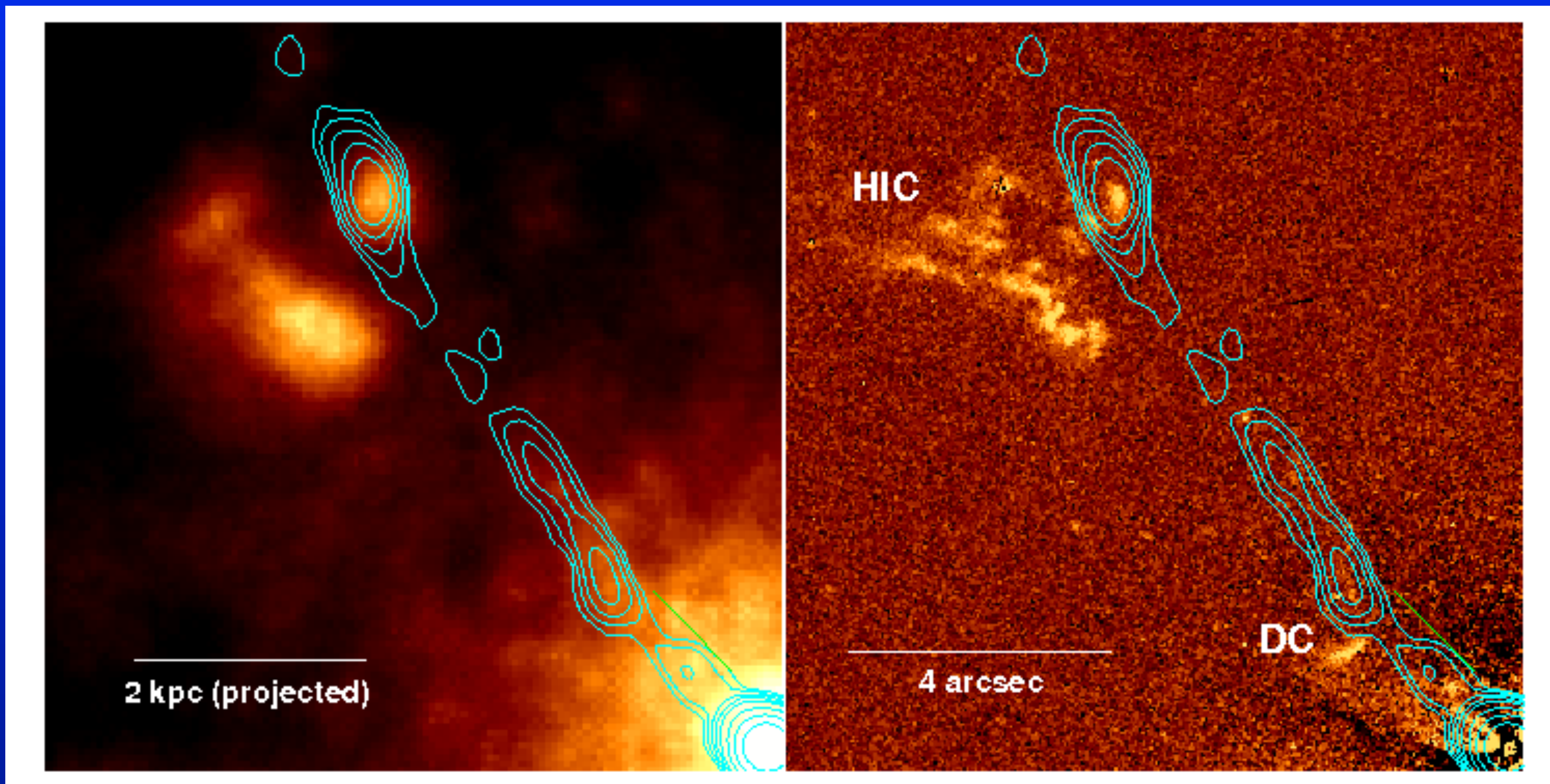
P_{total} (>~ 4 x 10^{44} erg/s) >> P_{cavity} (~ 3 x 10^{43} erg/s)

Total power (not cavity power) sits reasonably well on correlation with radio power



Cavagnolo+ 2010

Localized heating also at a High Ionization Cloud (HIC) - also possible at an inner deflection cloud



radio contours with

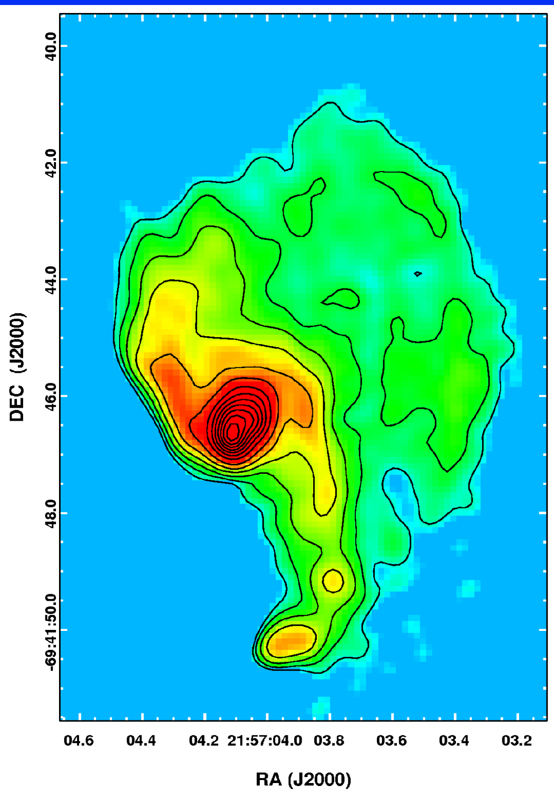
Chandra *HST*

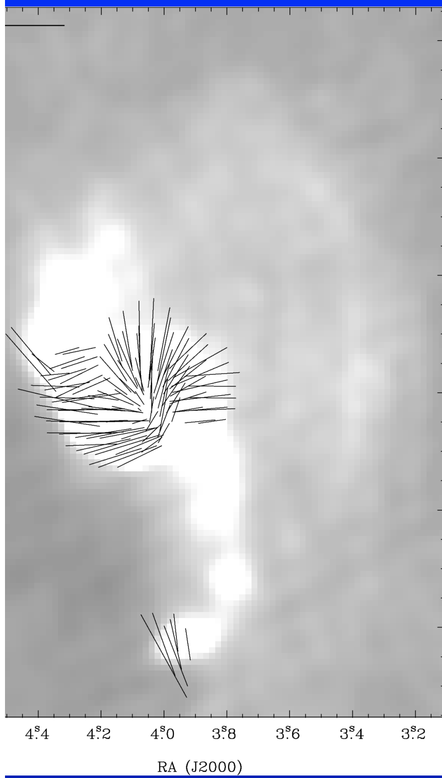
IFU data mapping the cloud

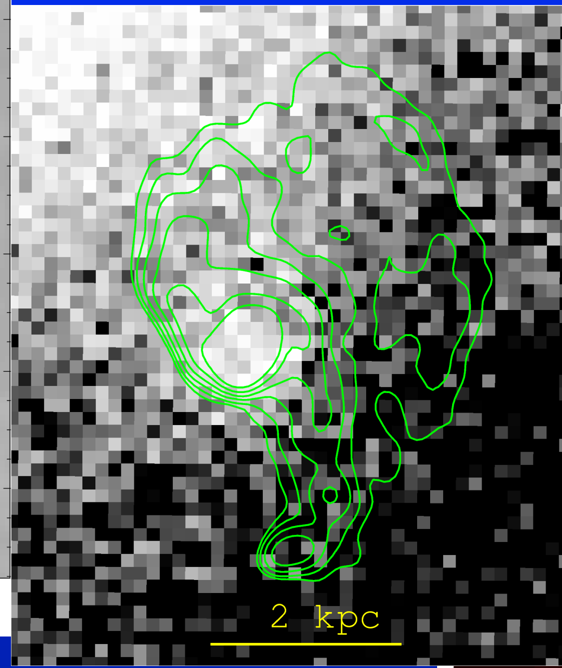
Velocity structure with distance from jet confirms interaction. Energetics seem to work.

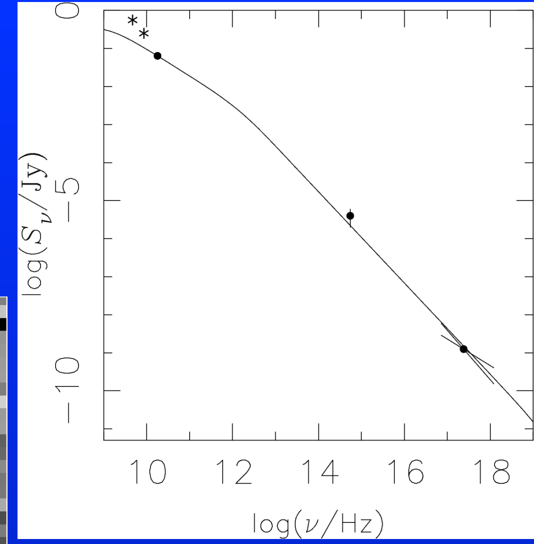
Duncan Smith+, in preparation

PKS B2152-699: S Hotspot



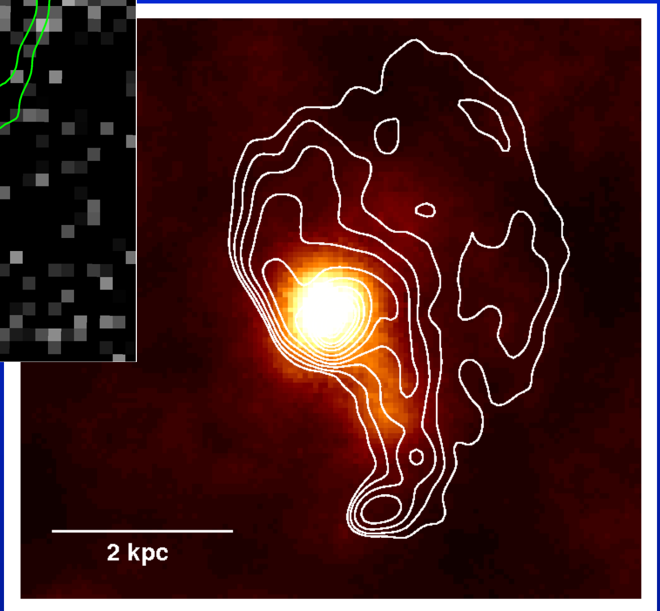






ATCA radio

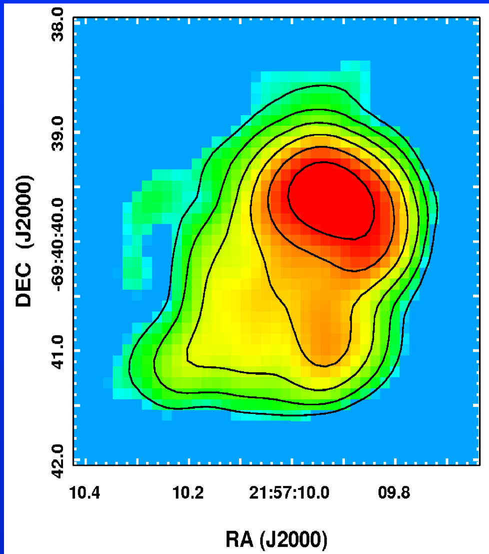
Optical
ESO 2.2m WFI

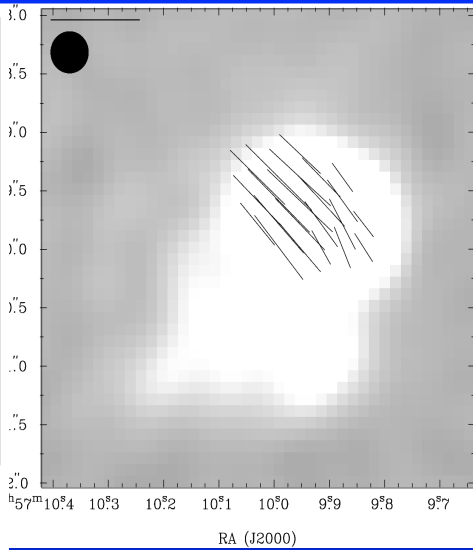


Chandra X-ray

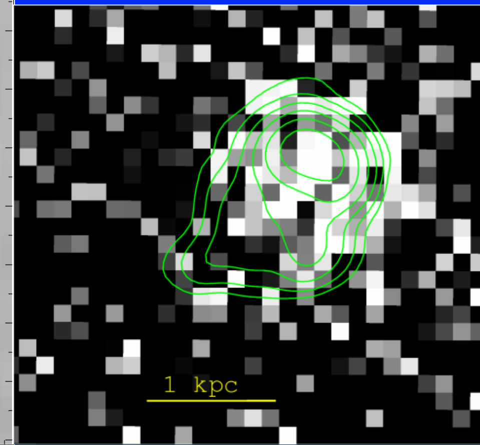
Peak hotspot emission
coincides at all wavelengths.
Synchrotron

PKS B2152-699: N Hotspot





ATCA radio



Optical
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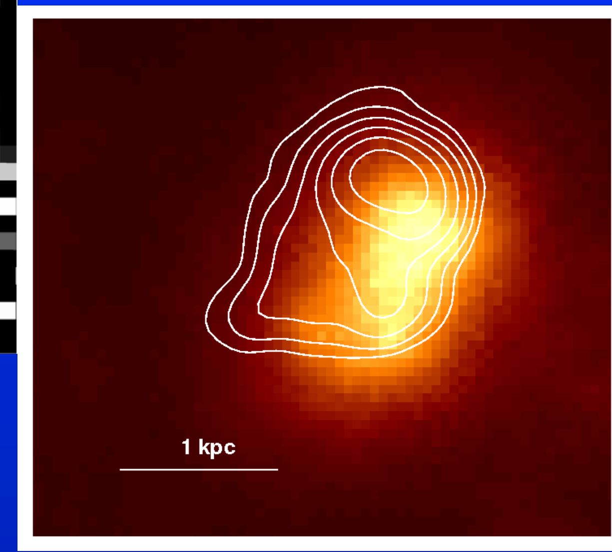


Chandra X-ray

δ~ 6, 10^0 viewing angle supported if offset X-ray emission is inverse Compton on CMB and hotspot synchrotron – being tested by new X-ray data.

A 3744. NGC 7016/7018 both FRI/II boundary sources

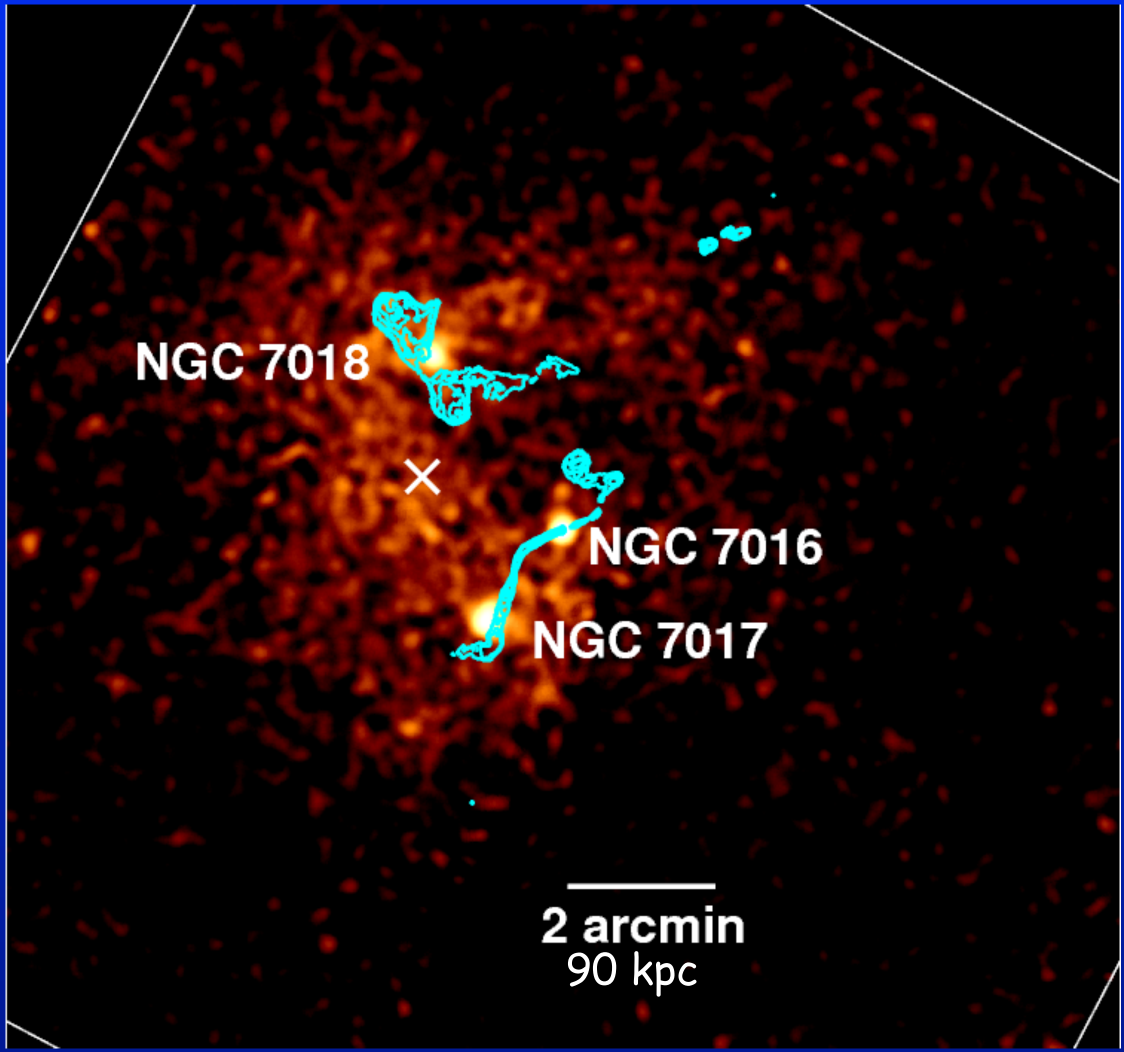
75 ks *Chandra*

z=0.038

Worrall+ 2014 ApJ

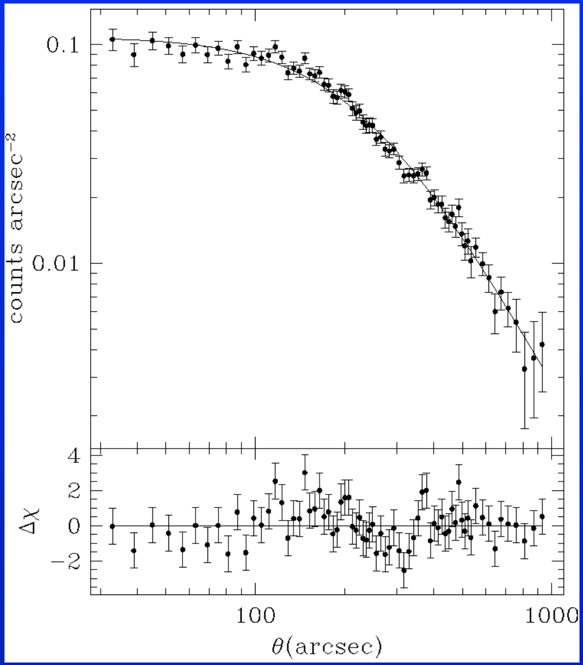
X-ray cavity

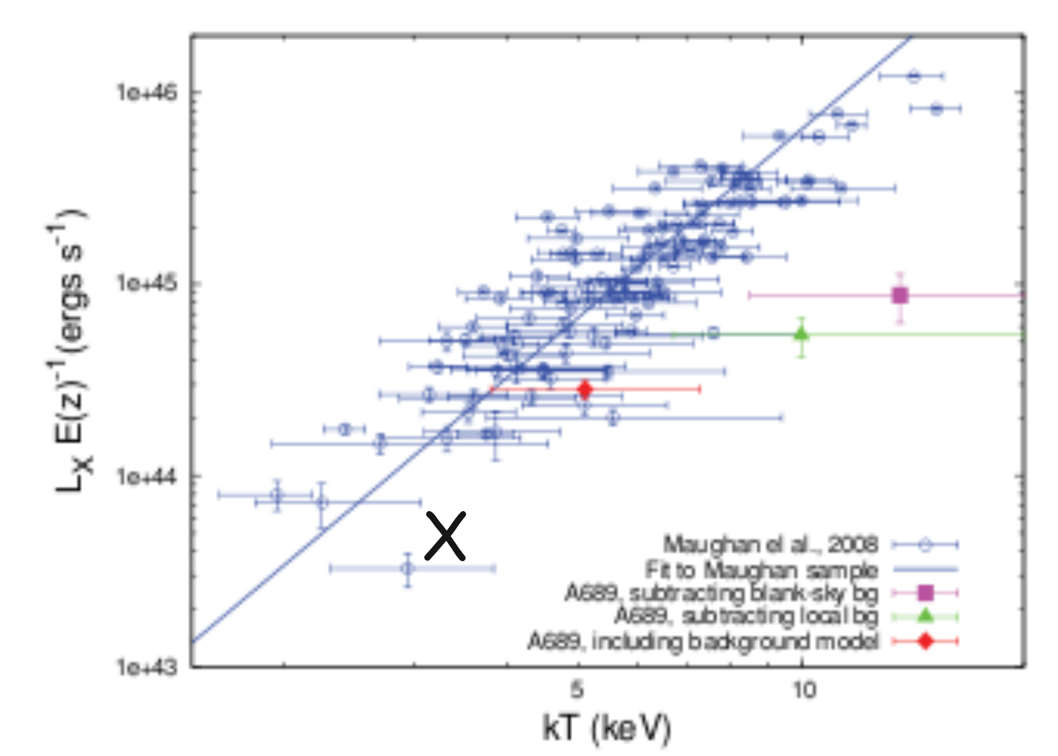
Non cool-core cluster



Cluster too hot for its luminosity: low gas-mass fraction

(~0.073) since M α T



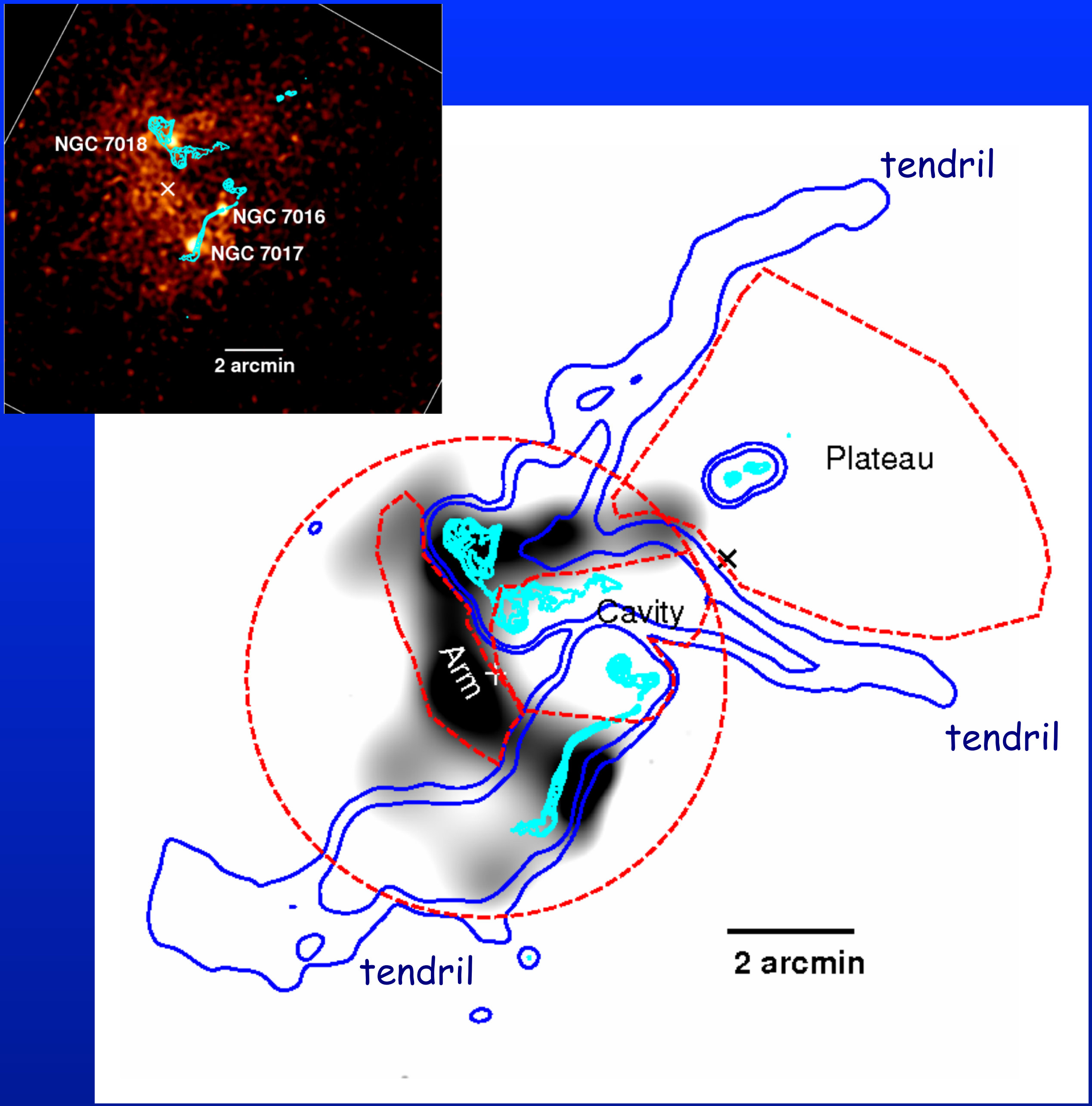


Giles+ 2012

L_{bol} =(3.2+/-0.2)x 10^{43} erg/s to r_{500} of 1200"

kT=3.5+/-0.15 keV

Too hot by 1.5 keV
➔ excess enthalpy
1.7x10^{62} ergs



Cavity enthalpy
2×10^{60} ergs

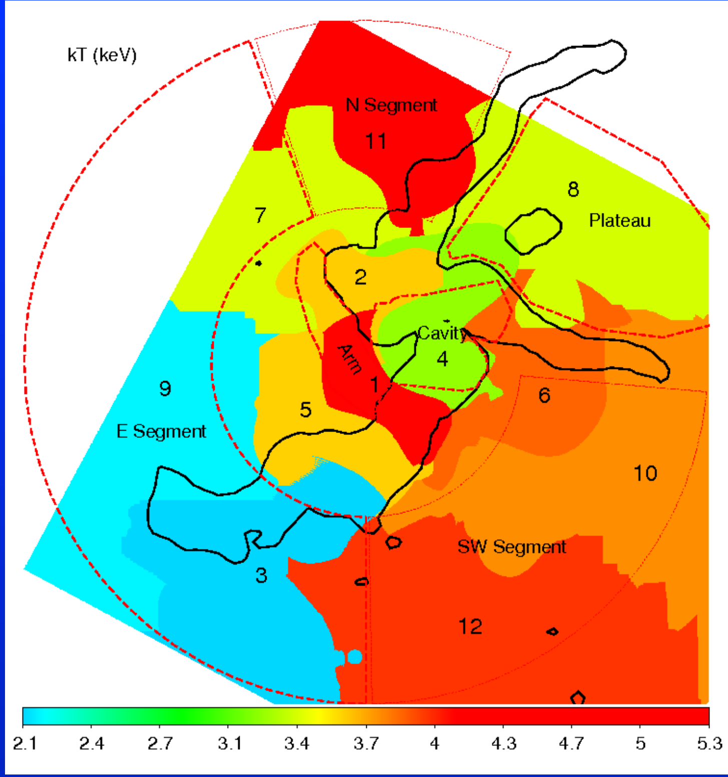
Energy from
85 cavities would be needed to explain excess temperature of cluster

Recent merger more likely. Candidate galaxies identified

Tendrils of note

Relativistic plasma shaping X-ray gas

CONTBIN (Sanders 2006) to define spectral regions from adaptively smoothed X-ray image.



Radio tendrils in NGC 7018 hug the plateau gas, with significantly hotter gas beyond. Similar thermal protection from tendril of NGC 7016.

Why?
Magnetized relativistic plasma acts as barrier to transport: -- smaller gyro-radius in radio plasma
- ordered field (from motions) reduces (perpendicular) thermal conductivity

Lubricating layer may help reduce viscosity between gas layers, helping to preserve post-merger flows

Summary

- Half of the heating in the Universe should arise from sources within 0.3 – 3 of FRI/FRII transition power.
- Statistics from 3CRR then suggest <~20% chance a given source is interacting/heating large-scale gas now. Local heating common.

Objects with deep data:

- 2152-699: P_{cavity} dominated by input of kinetic energy and heat to shocked gas – then fits P_{jet}/P_{rad} correlations
- Jet deflection at HIC – jet energy accelerating optical gas
- Cavity from pair in A3744 provides <2% of excess enthalpy needed to have heated the gas -> merger.
- Radio tendrils along temperature boundaries appear to lubricate gas flows and inhibit heat transfer.