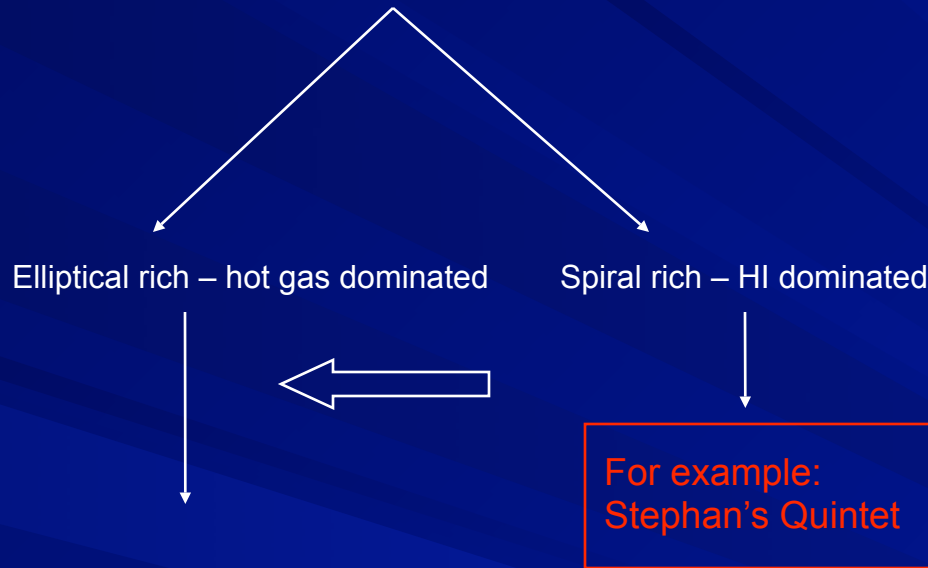


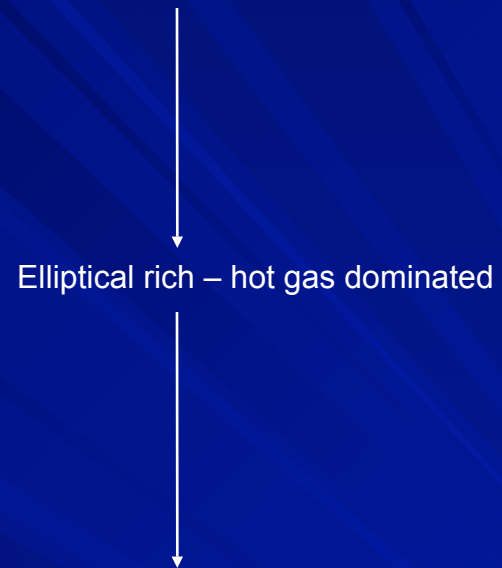
The AGN-Cooling Flow Connection in Groups of Galaxies

- Basic properties of groups and clusters of galaxies
- A GMRT sample of X-ray selected groups
- NGC 5044 – The X-ray brightest group of galaxies

Groups of Galaxies



Clusters of Galaxies



Basic Properties:

$$kT = 1-2 \text{ keV}$$

$$L_x = 10^{41}-10^{43} \text{ erg s}^{-1}$$

$$r_{200} = 1-1.5 \text{ Mpc}$$

$$M_{\text{gas}}/M_{\text{stars}} = 1$$

$$\text{Abund} = 50\%$$



+
gas

Basic Properties:

$$kT > 2 \text{ keV}$$

$$L_x > 10^{43} \text{ erg s}^{-1}$$

$$r_{200} = 1.5-3 \text{ Mpc}$$

$$M_{\text{gas}}/M_{\text{stars}} = 5-7$$

$$\text{Abund} = 20-30\%$$

Most of the gas is primordial

Gas is more extended than the dark matter

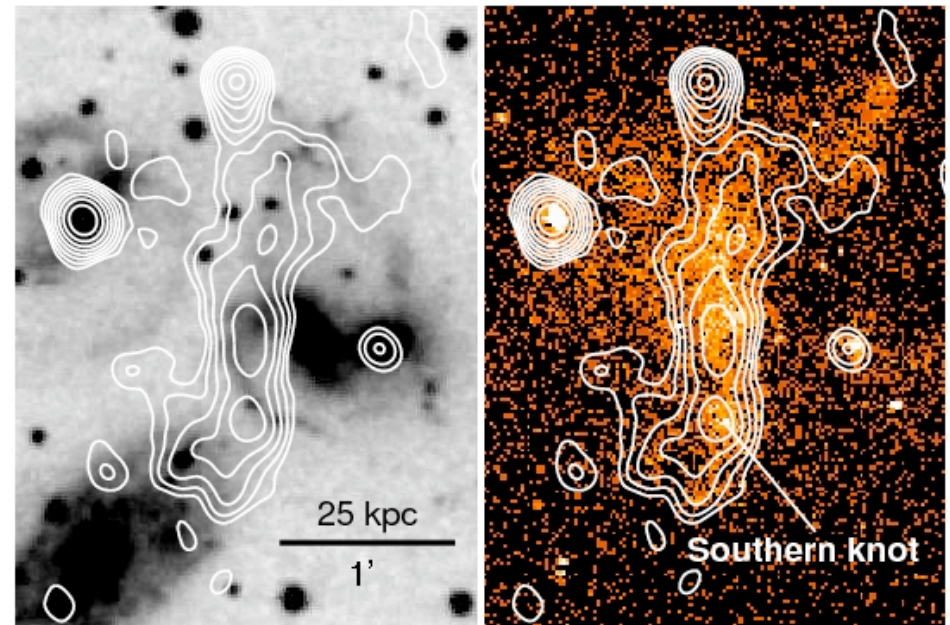
Most of the heavy elements reside in the ICM

Stephan's Quintet

610 MHz GMRT radio contours

Optical

Chandra



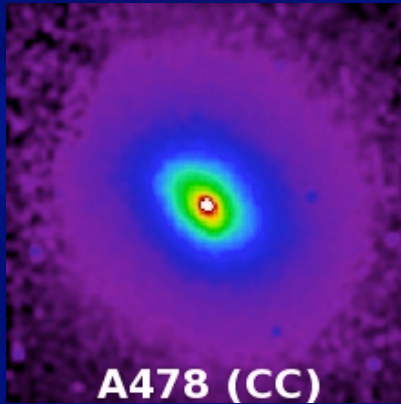
- Mass of hot gas \sim HI deficit
- Radio emission consistent with expected synchrotron emission from SNRs
- Possible shocks in the hot gas, but the hard component in the ACIS spectrum is consistent with emission from HMXBs

O'Sullivan et al. (2009)

Hot Gas Dominated Groups and Clusters

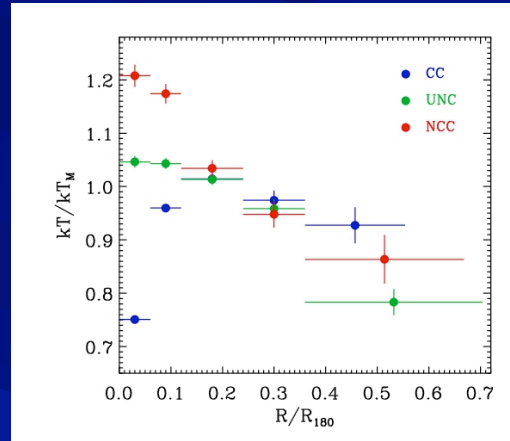
Leccardi & Molendi (2008)

Cool-Core
(Cooling Flow)

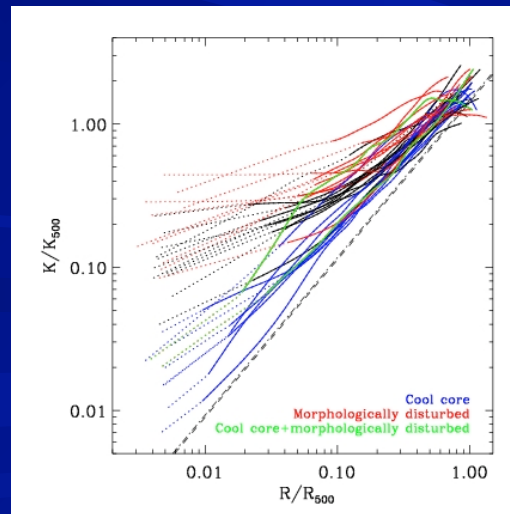


Henning et al. (2009)

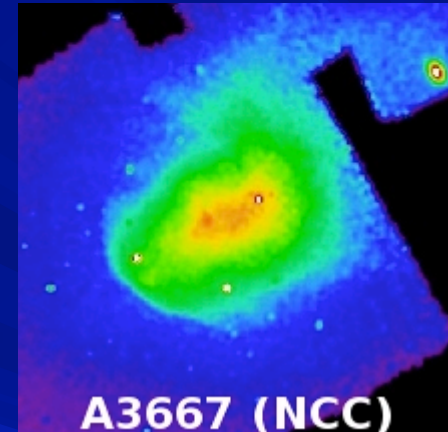
$$M_{\text{gas}}/t_{\text{cool}} = 100-1000 \text{ Mo yr}^{-1}$$



Pratt et al. (2009)



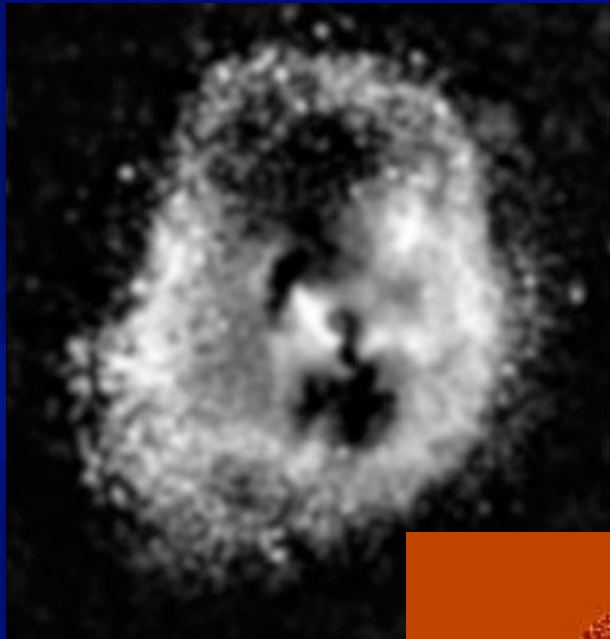
Non Cool-Core
(recent major merger)



Henning et al. (2009)

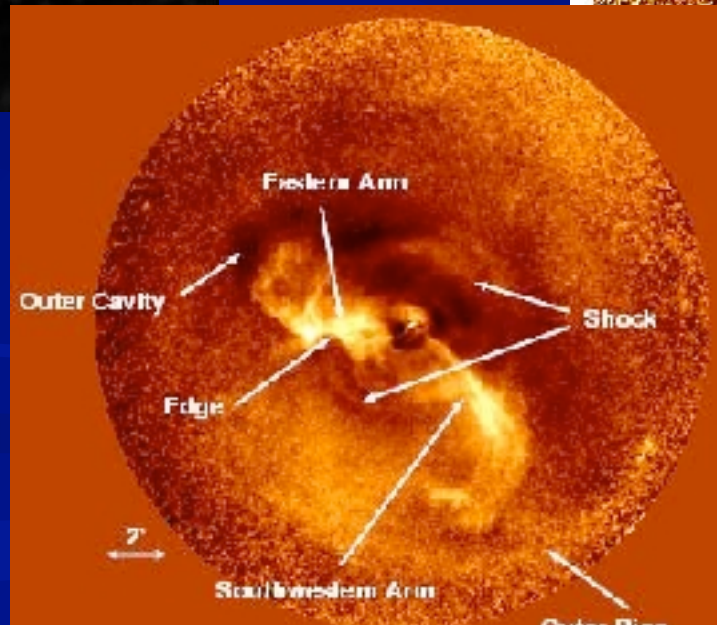
Cooling Flow Groups and Clusters

Hydra A

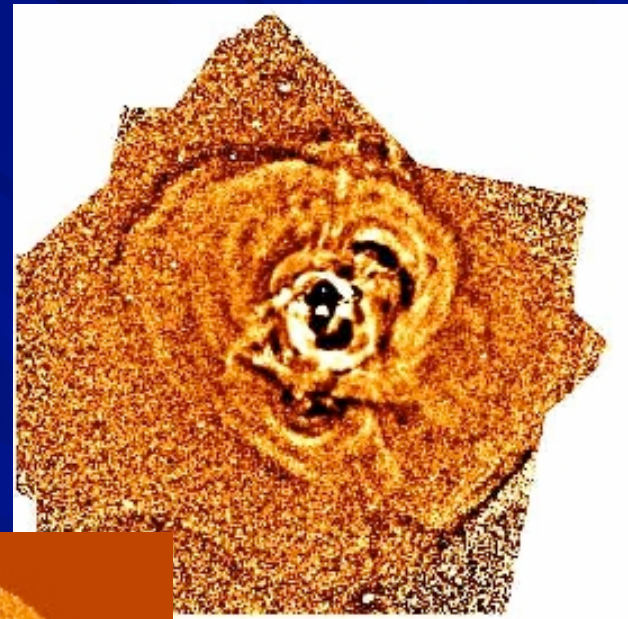


McNamara et al. (2000)
Kirpatrick et al. (2009)

M87



Perseus



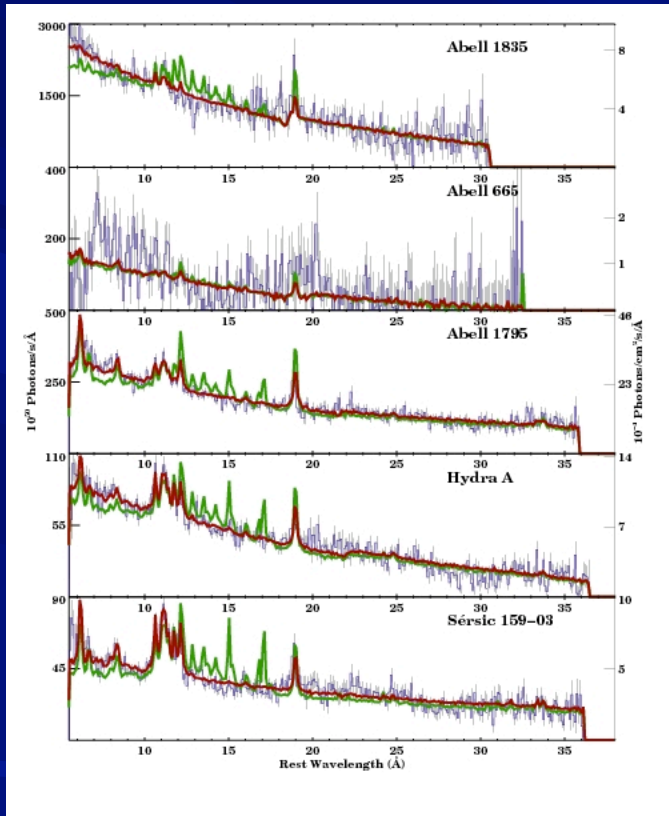
Fabian et al. (2006)

Forman et al. (2007)

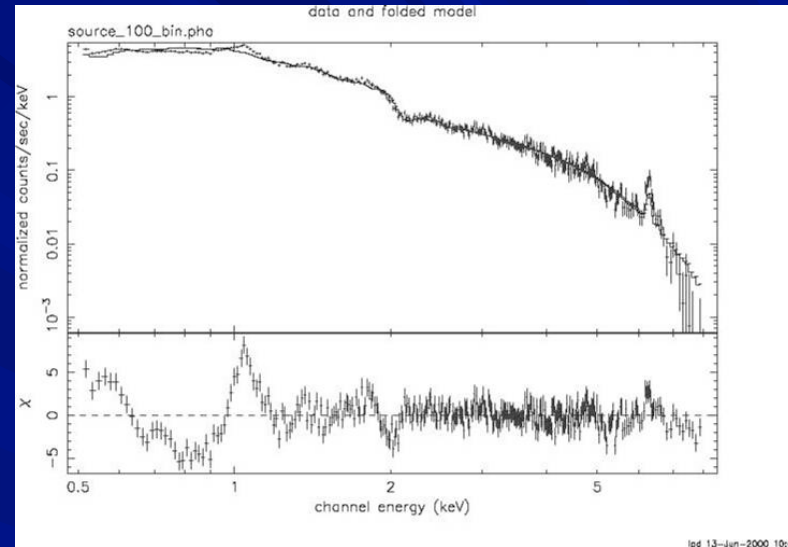
Cooling Flow Groups and Clusters

Chandra ACIS spectrum of Hydra A

XMM-Newton RGS spectra



Peterson et al. (2003)



David et al. (2001)

Stellar color gradients

Rafferty et al. (2008)



GMRT Observations of a Sample of X-ray Selected Groups

S. Giacintucci, E. O'Sullivan, J. Vrtilik, S. Raychadhury, T. Venturi, R. Athreya, T. Clarke, M. Murgia, P. Mazzotta, M. Gitti, T. Ponman, C. Ishwara-Chandra, C. Jones, W. Forman

Class 1 – Small radio sources with jet/lobe structures confined to the group core.

Class 2 – Large radio sources with jet/lobe structures extending beyond the group core.

Class 3 - Amorphous/diffuse radio sources.

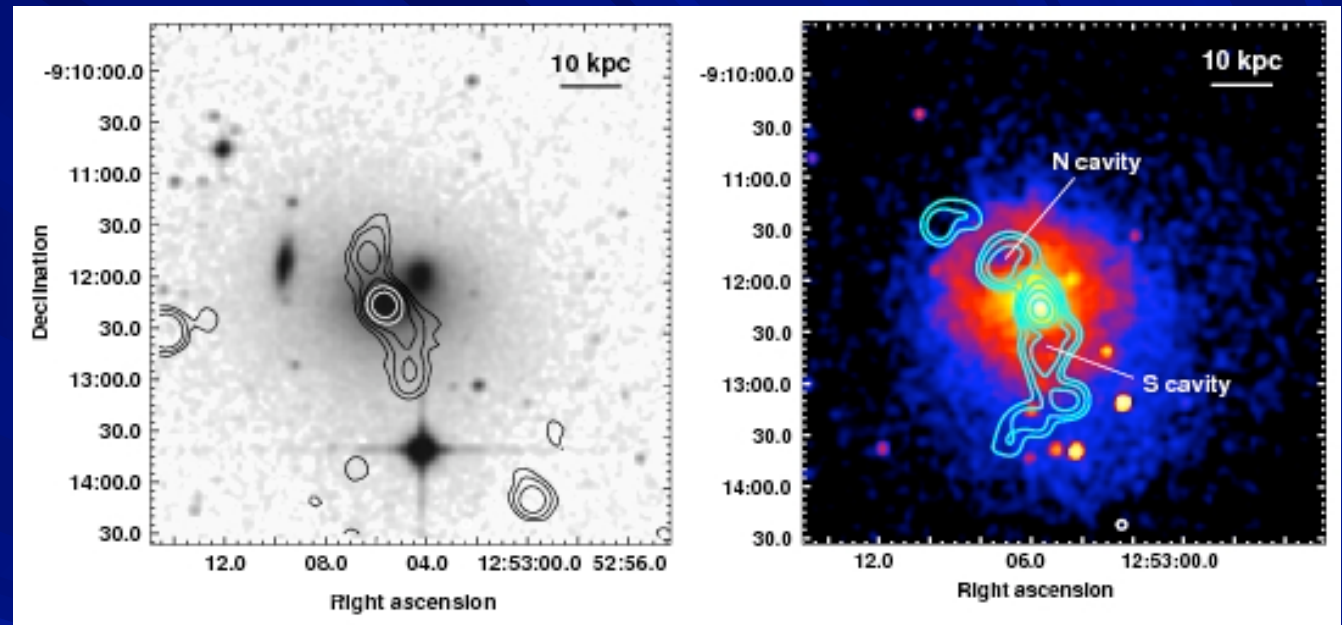
Table 1. Radio and X-ray properties of the groups

Source	$\log P_{235\text{ MHz}}$ (W Hz^{-1})	LLS ^a (kpc)	Radio morphology	$\log L_X$ (erg s^{-1})	X-ray cavities ^b	Class ^c
UGC 408	24.41	80	double + diffuse cocoon	41.40 ^d	–	1
NGC 315	24.98	1160	giant double with distorted tails	41.57	–	2
NGC 383	25.06	900	giant double with distorted tails	42.72	–	2
NGC 507	23.83	70	asymmetric double	42.95	1 (filled) ^e	1
NGC 741	24.65	210	complex	42.14	1 (ghost) ^f	1, 2
HCG 15	–	150 ^g	point source + diffuse emission	41.72	–	3
NGC 1407	23.06	80	double + diffuse emission	41.23	1 (filled) ^h	1, 3
NGC 1587	23.35	22 ^g	point source + diffuse emission	40.92	–	3
MKW 2	24.79	670	lobe-dominated double	42.32	–	2
NGC 3411	23.47	80	point source + diffuse emission	42.45 ⁱ	–	3
NGC 4636	21.72	10	asymmetric double	41.88	multiple (filled and ghost) ^j	1
HCG 62	22.25	33	asymmetric double	42.69	2 (filled) ^k	1
NGC 5044	22.62	63	complex	42.81	multiple (filled and ghost) ^l	1
NGC 5813	21.90	22	double-double	42.00 ^m	multiple (filled and ghost) ⁿ	1
NGC 5846	–	12 ^o	point source + extension	41.71	2 (filled) ^p	1
AWM4	24.80	160	WAT	43.64 ^q	1 (filled) ^r	1, 2
NGC 6269	23.81	36	double	43.20	2 (filled) ^s	1
NGC 7626	24.00	185	double with distorted tails	42.05	–	2

HCG 62

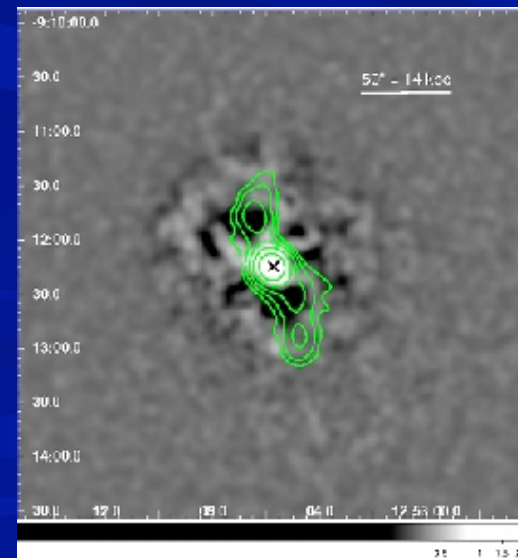
610 MHz contours

235 MHz contours and Chandra image



Chandra unsharp masked image

- Class 1 radio source
- A pair of radio filled x-ray cavities
- Emission is more extended at 235 MHz suggesting a previous outburst
- Gitti et al. (2009)

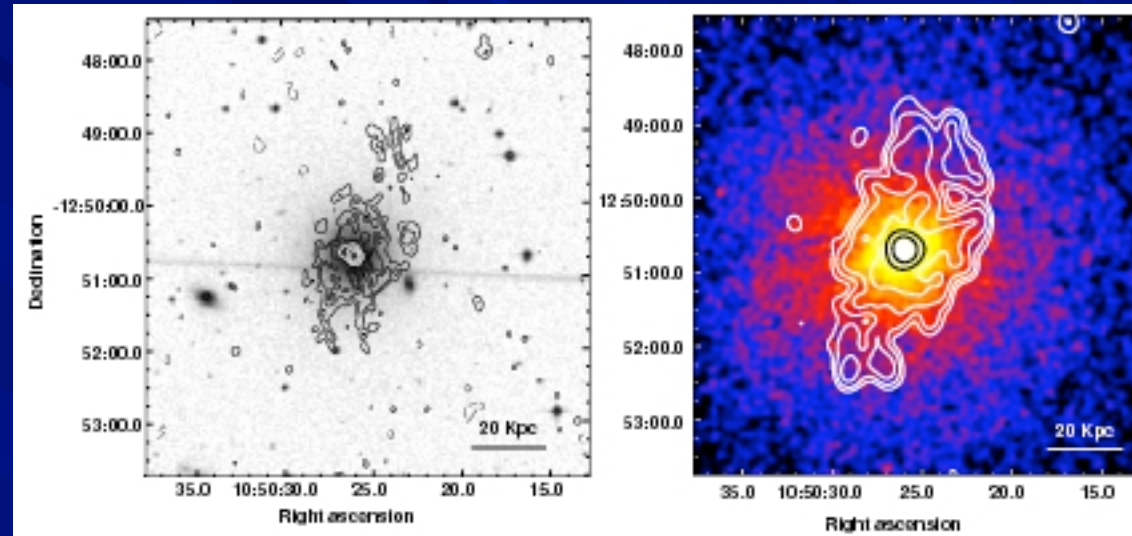
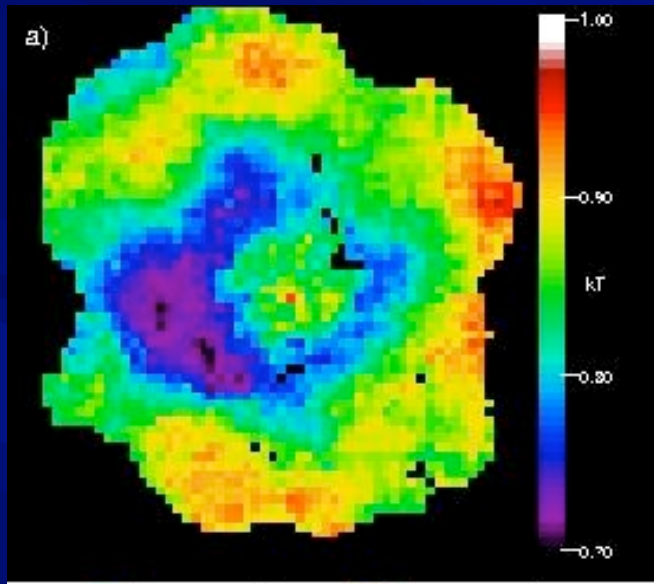


NGC 3411

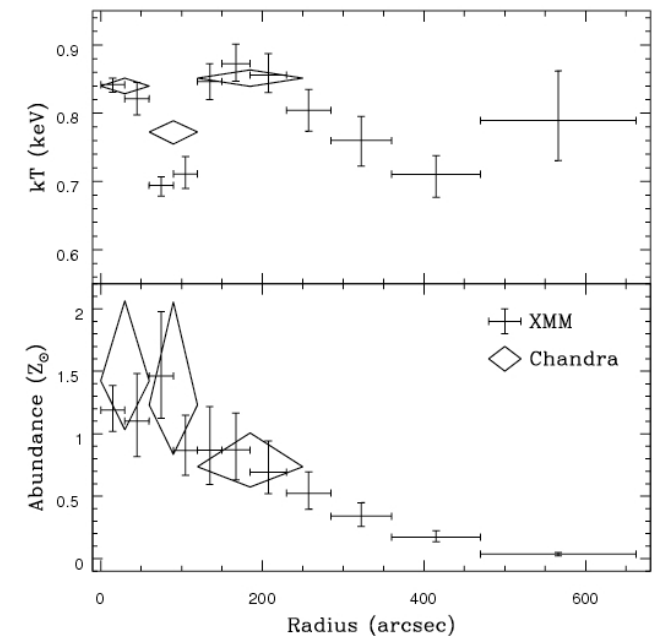
610 MHz contours

235 MHz contours

Gas temperature map

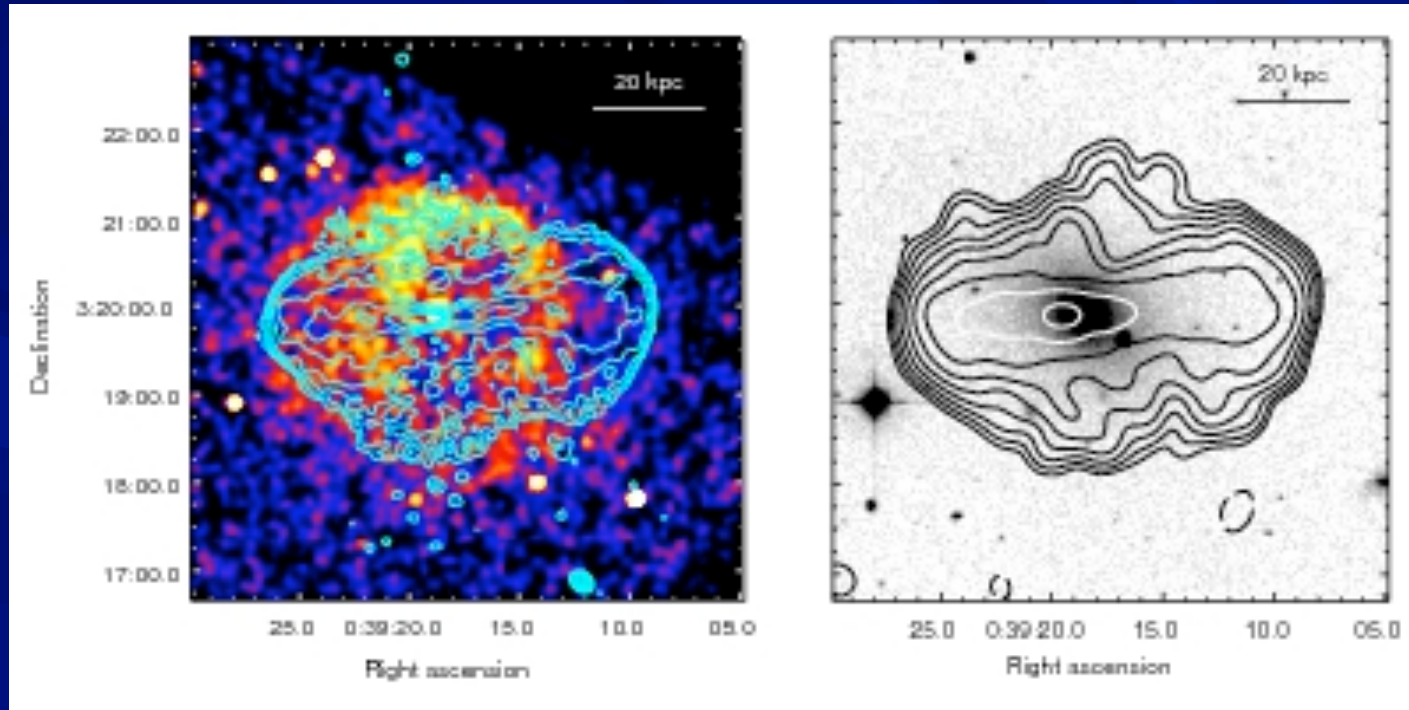


- Class 3 radio source
- No x-ray cavities
- Small hot region within a cool core possibly heated by the AGN outburst
- O'Sullivan et al. (2007)



UCG 408 (NGC 193)

610 MHz contours and 0.3-2.0 keV Chandra image

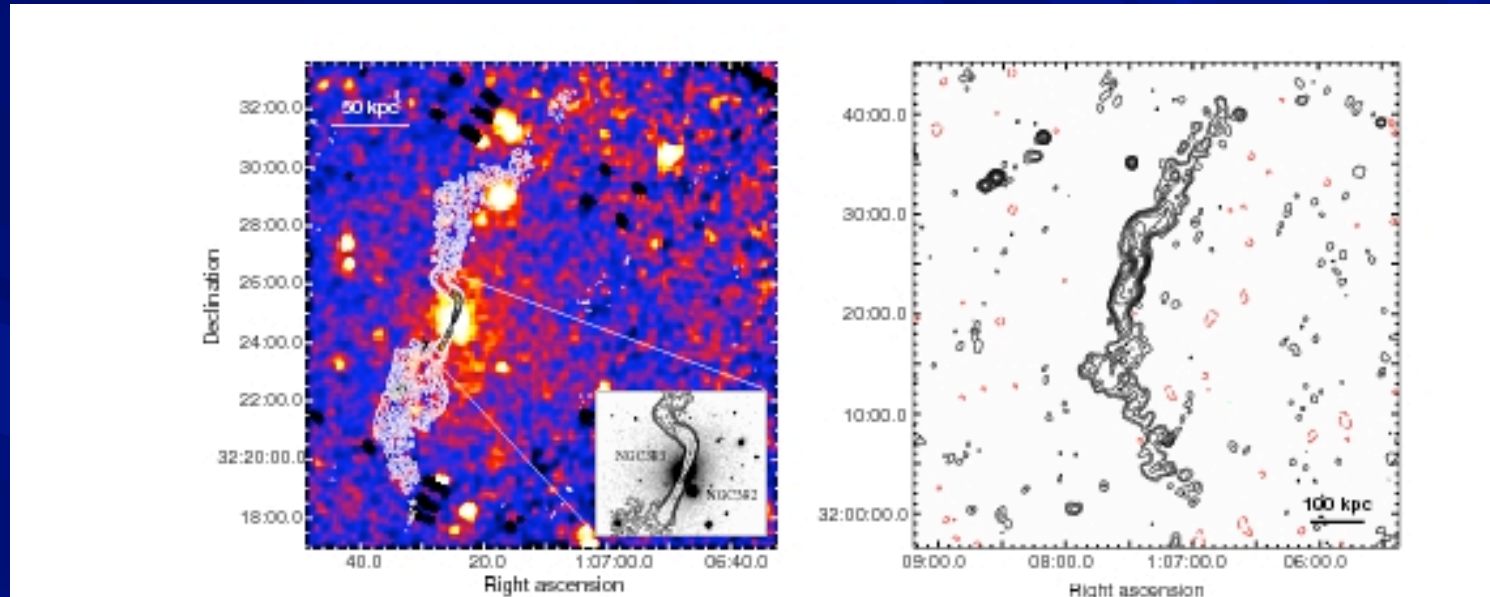


- Class 1 radio source
- Eastern jet is significantly brighter than the western jet
- 1 large or 2 smaller x-ray cavities seen in projection
- Lobes trace the rim of the cavities toward the N and S but are more extended than the cavities toward the E and W

NGC 383

610 MHz contours and XMM-Newton image

235 MHz contours

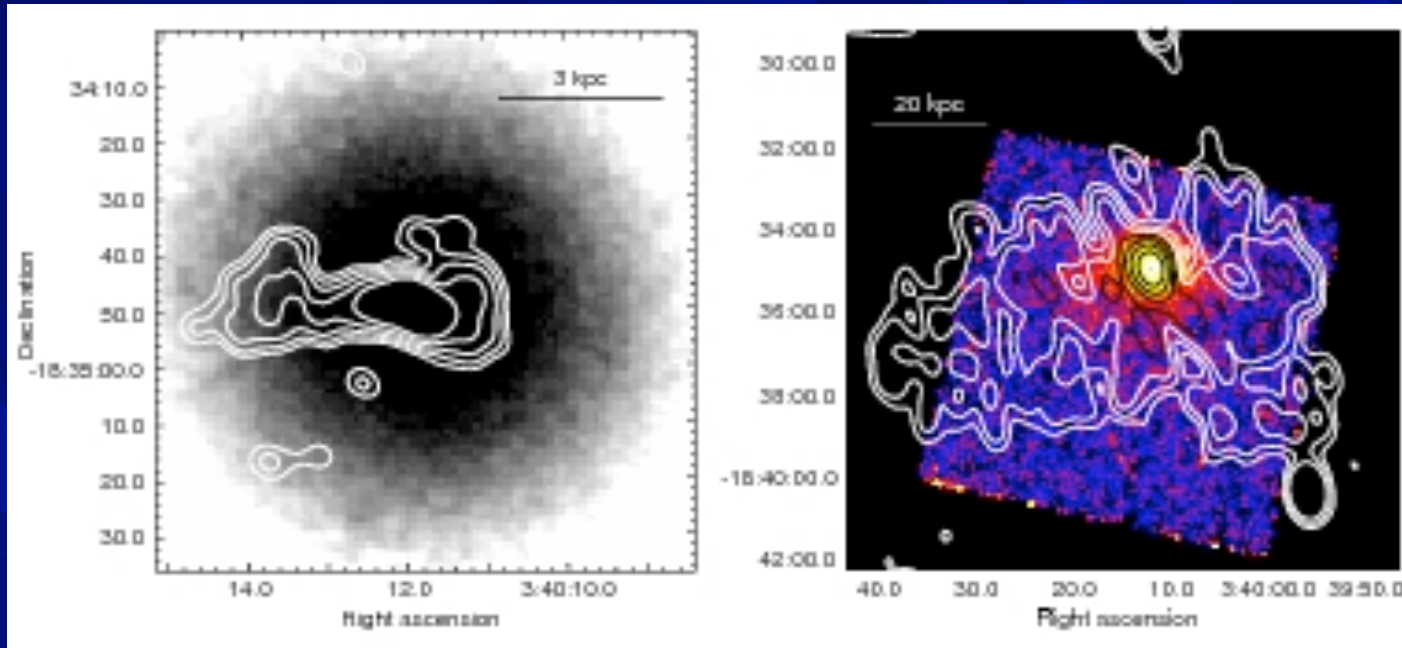


- Class 2 radio source
- Most luminous radio galaxy in our sample
- No detected x-ray cavities
- Typical x-ray luminosity and gas temperature – thermal pressure is similar to other groups

NGC 1407

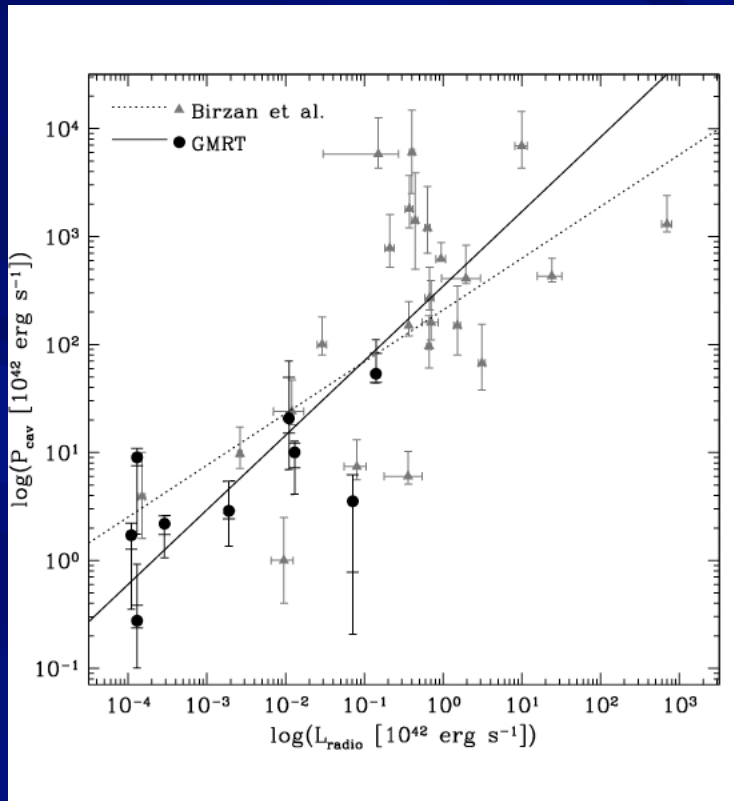
610 MHz contours

235 MHz contours and Chandra image



- Class 1 radio source at 610 MHz and Class 3 at 235 MHz
- 235 MHz emission is 10 times larger and displaced toward the S compared to the 610 emission – possibly due to motion of the galaxy toward the north
- Very steep spectral index ($\alpha > 2$) – probably two separate outbursts

Correlation between radio power and cavity power



O'Sullivan et al. (2011)

$$P_c = H/t_s \text{ where } H = \gamma PV/(\gamma-1)$$

where $\gamma = 5/3$ or $4/3$

and t_s is :

sound crossing time

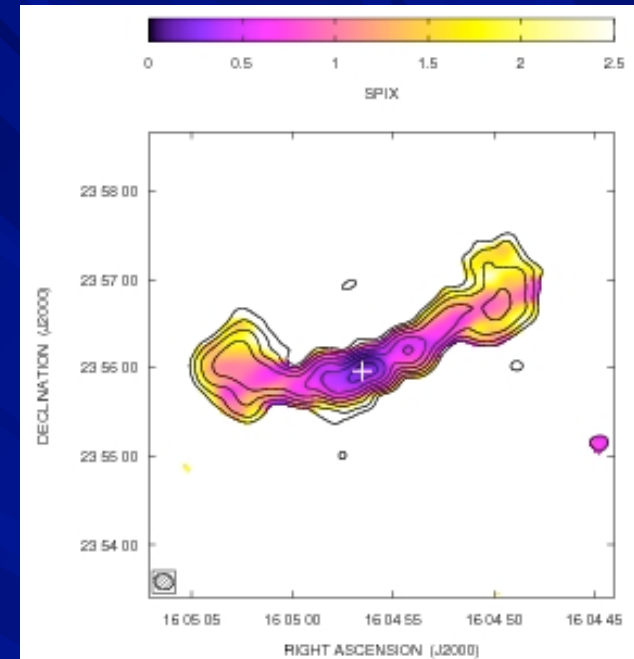
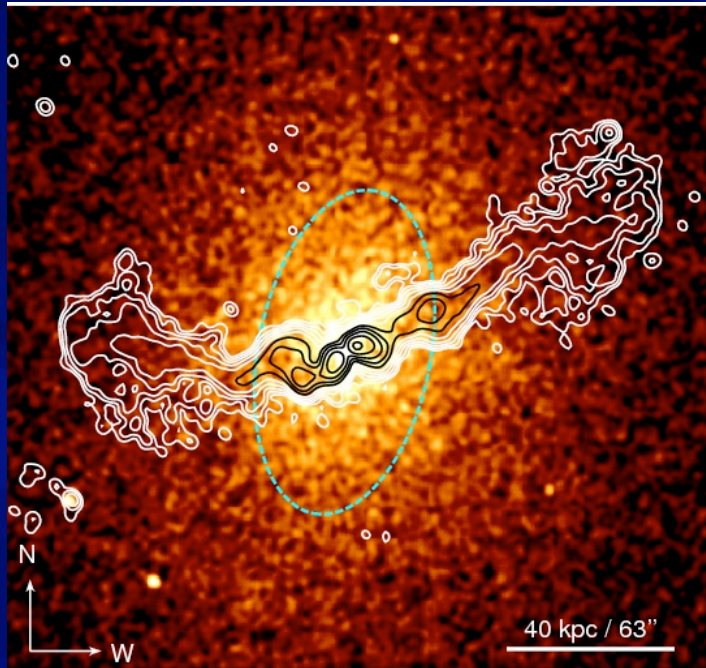
buoyancy rise time

refill time

$P_{\text{cav}}/P_{\text{radio}} \sim 10^4$ for weak radio sources

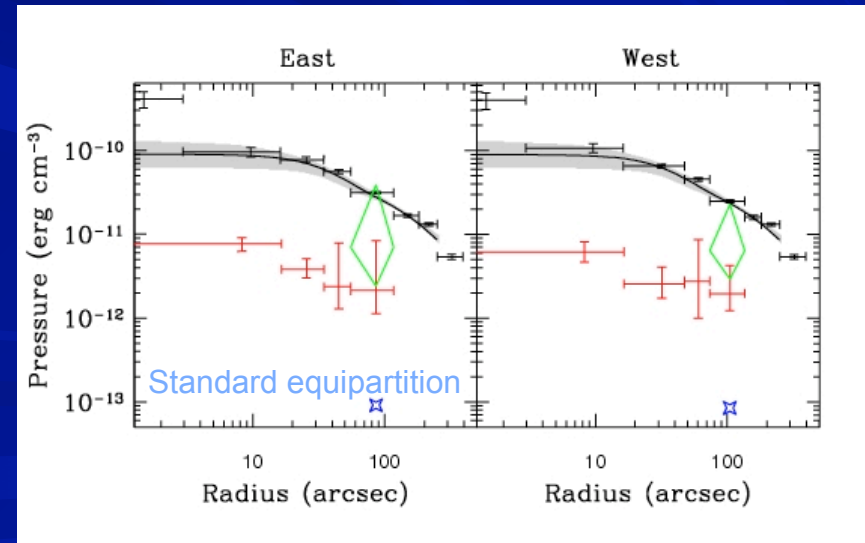
$P_{\text{cav}}/P_{\text{radio}} \sim 100$ for strong radio sources

610 MHz contours and Chandra image



Revised equipartition ($\gamma_{\min}=100$) ($\gamma_{\min}=10$)

- Class 2 radio source
- FR I - FR II WAT transition object
- Slight x-ray depression in the eastern lobe

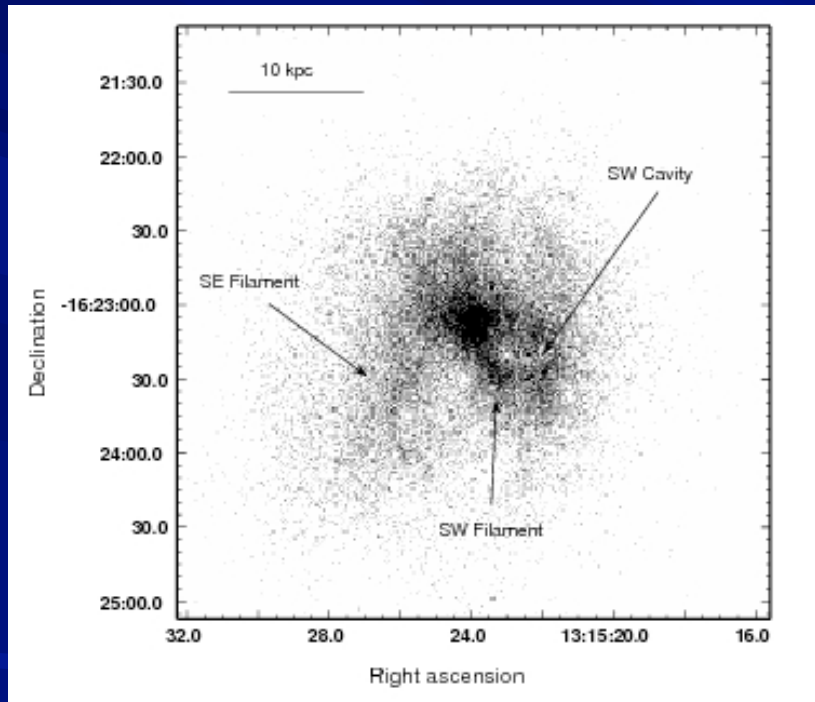


The NGC 5044 Group of Galaxies

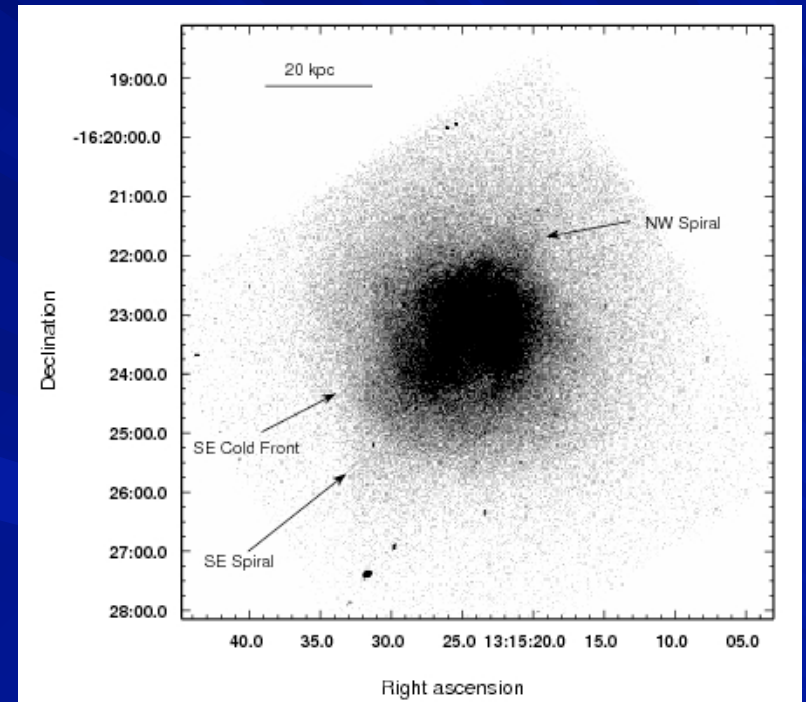
X-ray brightest group of galaxies in the sky

$M_B = -11.6$ E0 galaxy $D_L = 39$ Mpc

Chandra ACIS 0.5-2.0 keV images



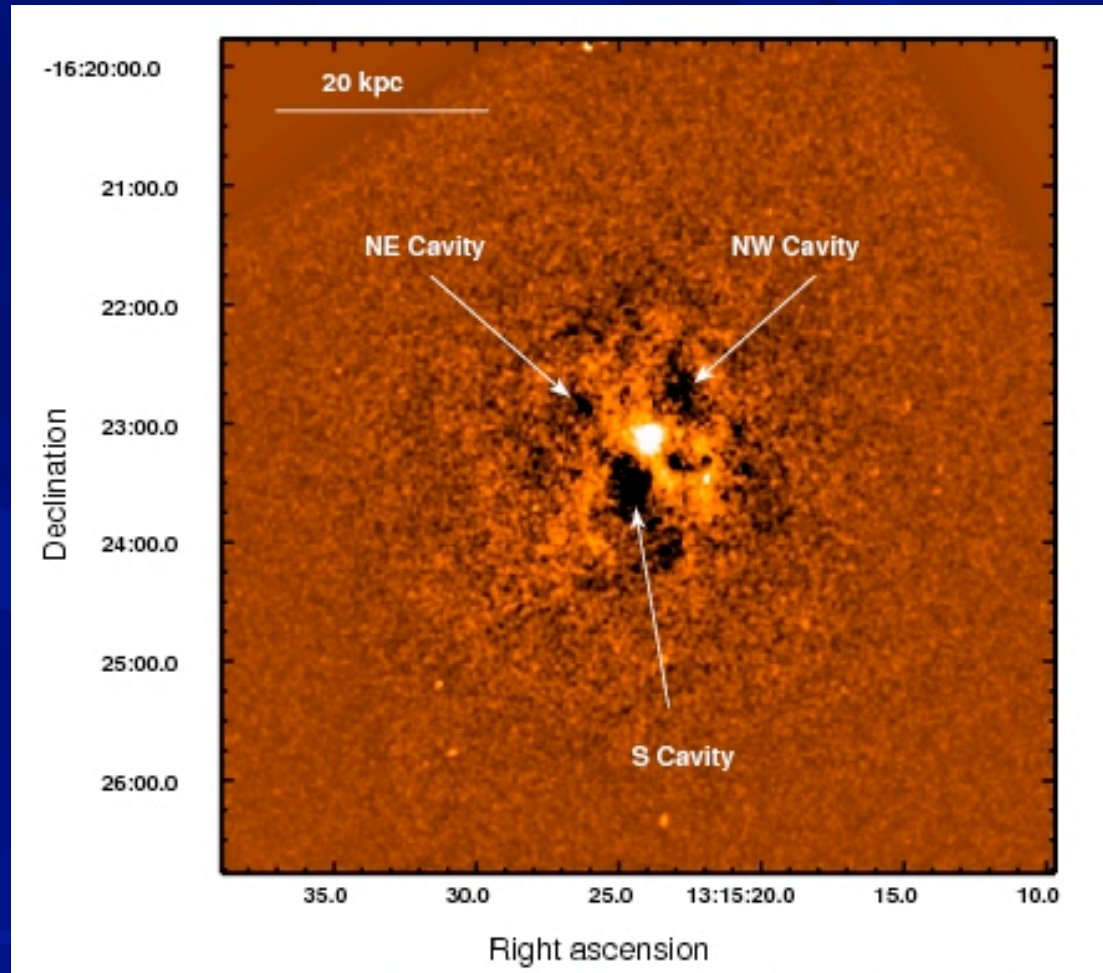
AGN-induced features



Merging-induced (sloshing) features

David et al. (2009)

NGC 5044



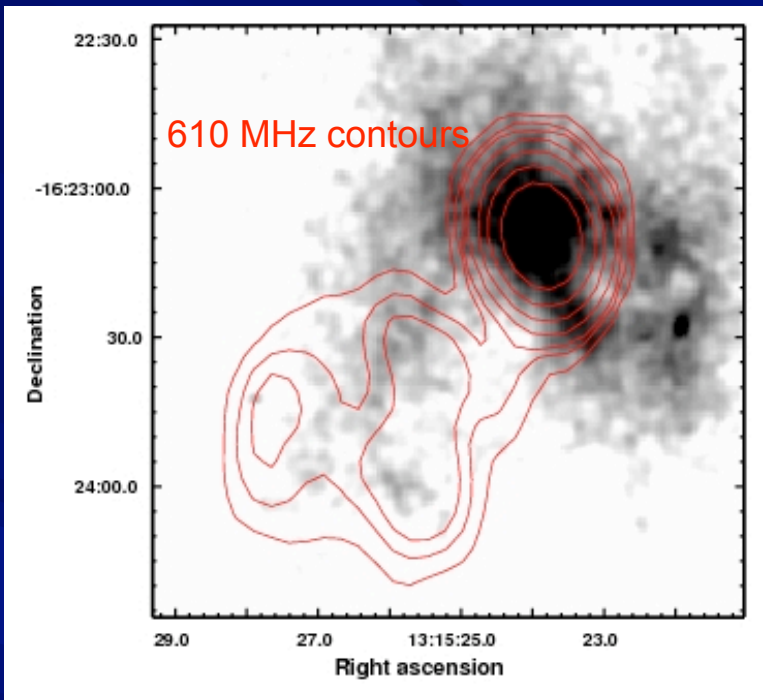
Chandra
unsharp
masked
image

Many small X-ray cavities and possibly some ripples similar to those observed in Perseus

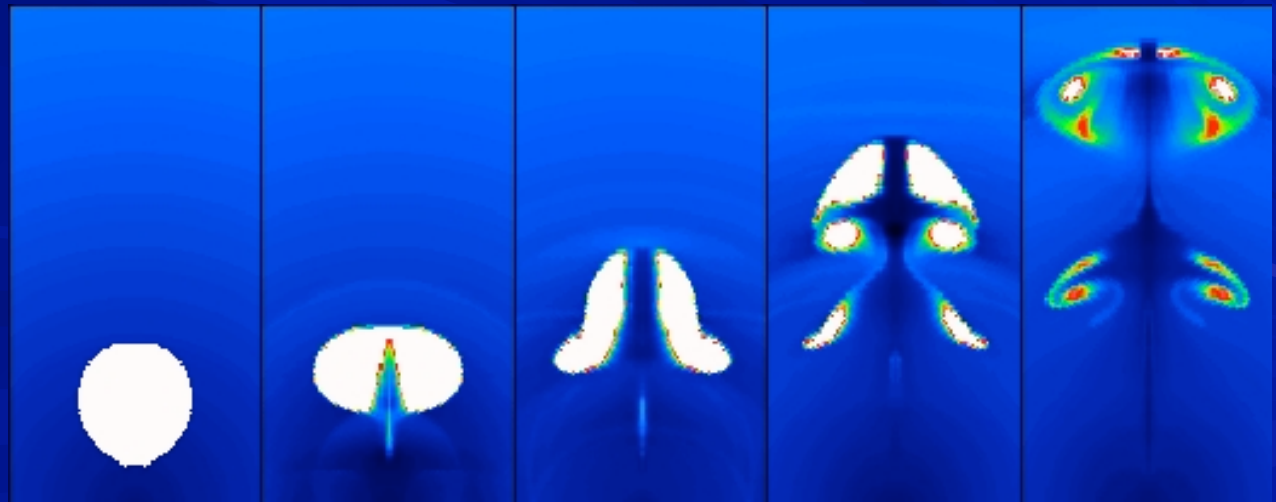
NGC 5044

Smoothed Chandra image and 610 MHz radio contours from a GMRT observation

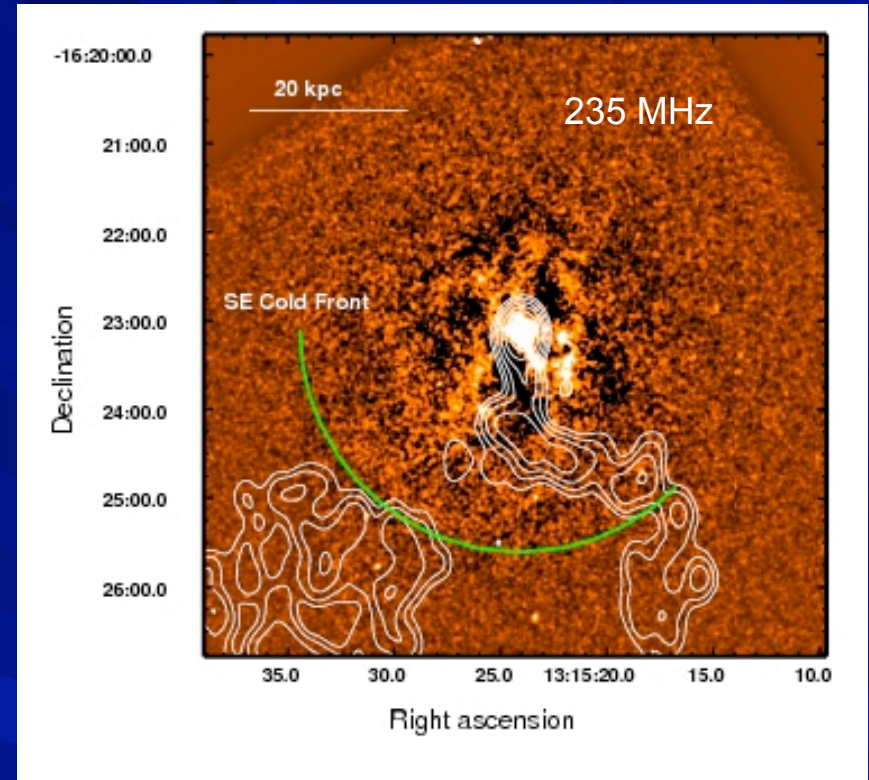
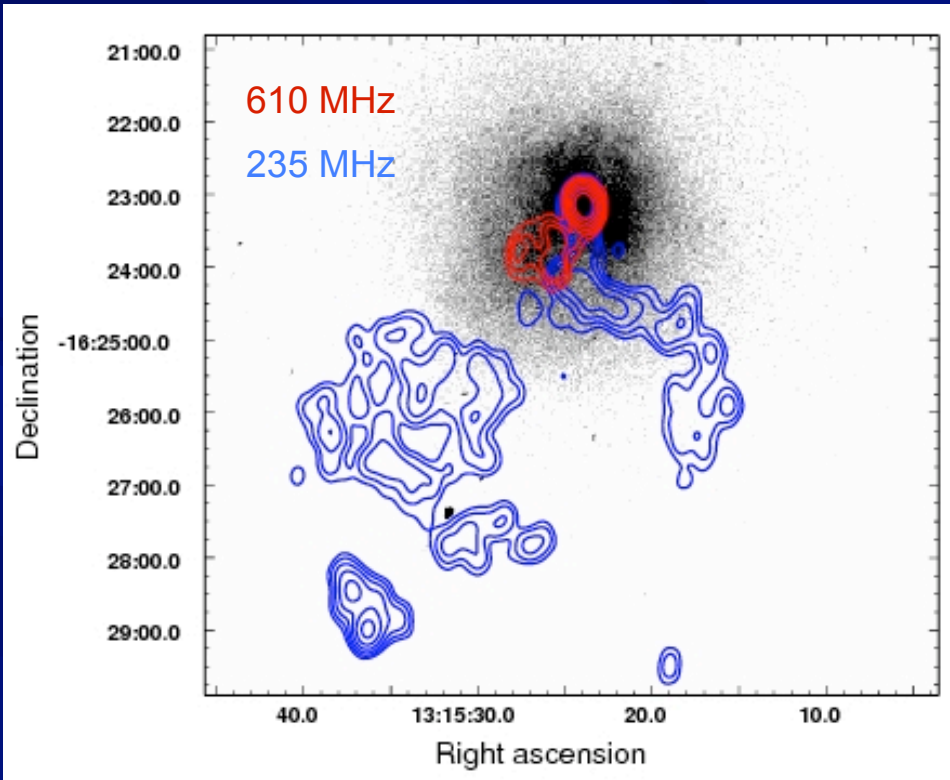
Uplifting of chemically enriched, low entropy gas from the center of the cluster.



Simulation of an AGN-inflated buoyant bubble from Churazov et al. (2001)



NGC 5044



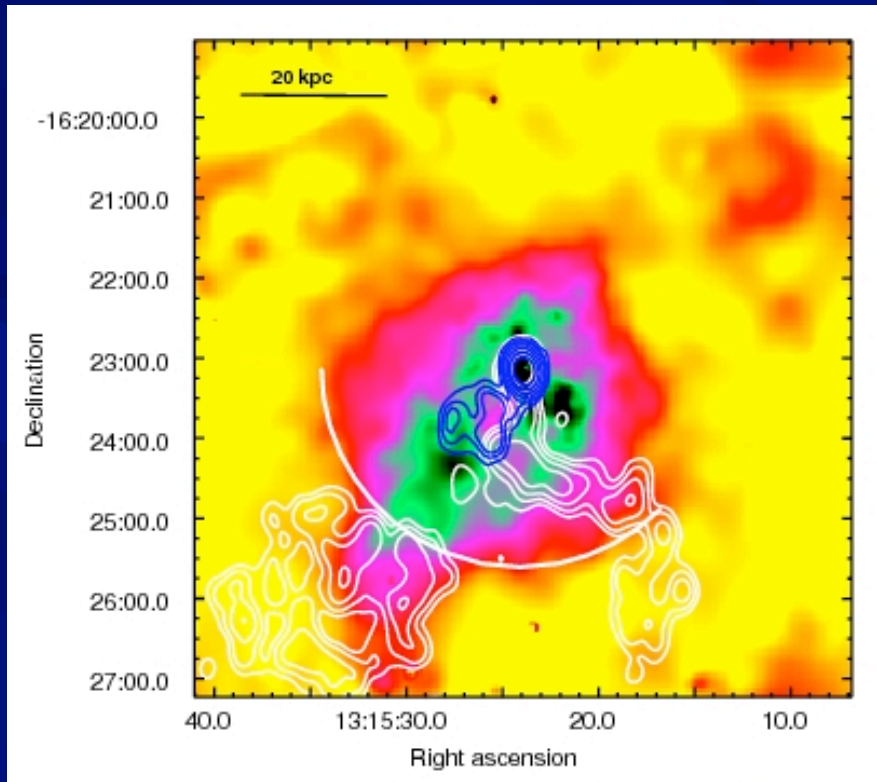
Three separate radio outbursts over the past 100 Myr

- Detached steep-spectrum 235 MHz feature
- Extended steep-spectrum 235 MHz feature toward the south
- Small flat-spectrum 610 MHz extended emission

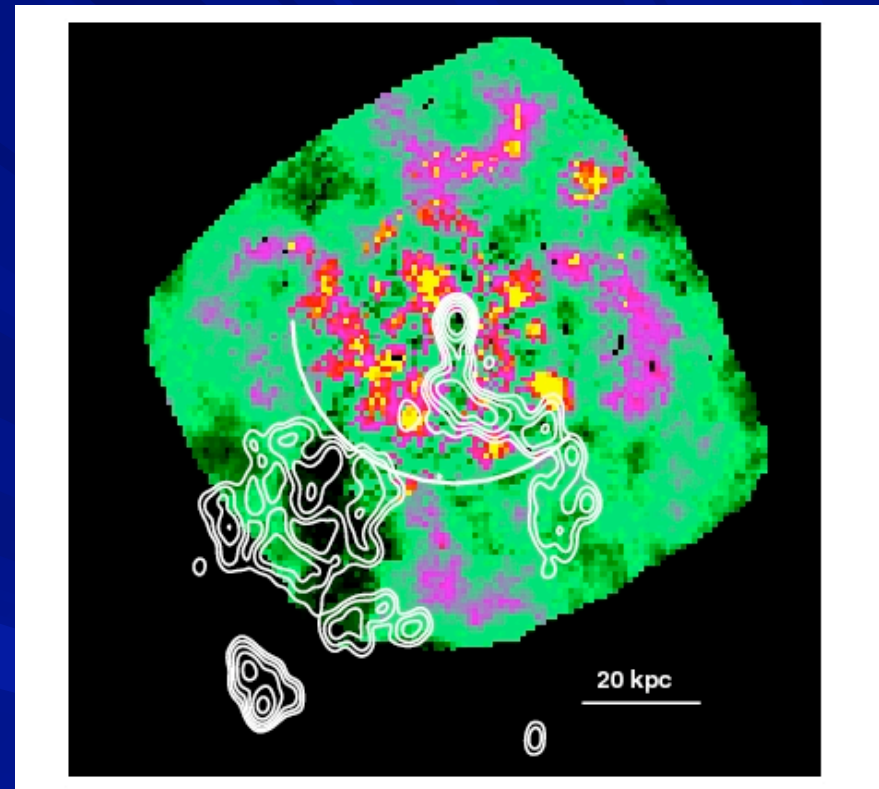
Most X-ray cavities are undetected at both radio frequencies

NGC 5044

Gas temperature map



Abundance map

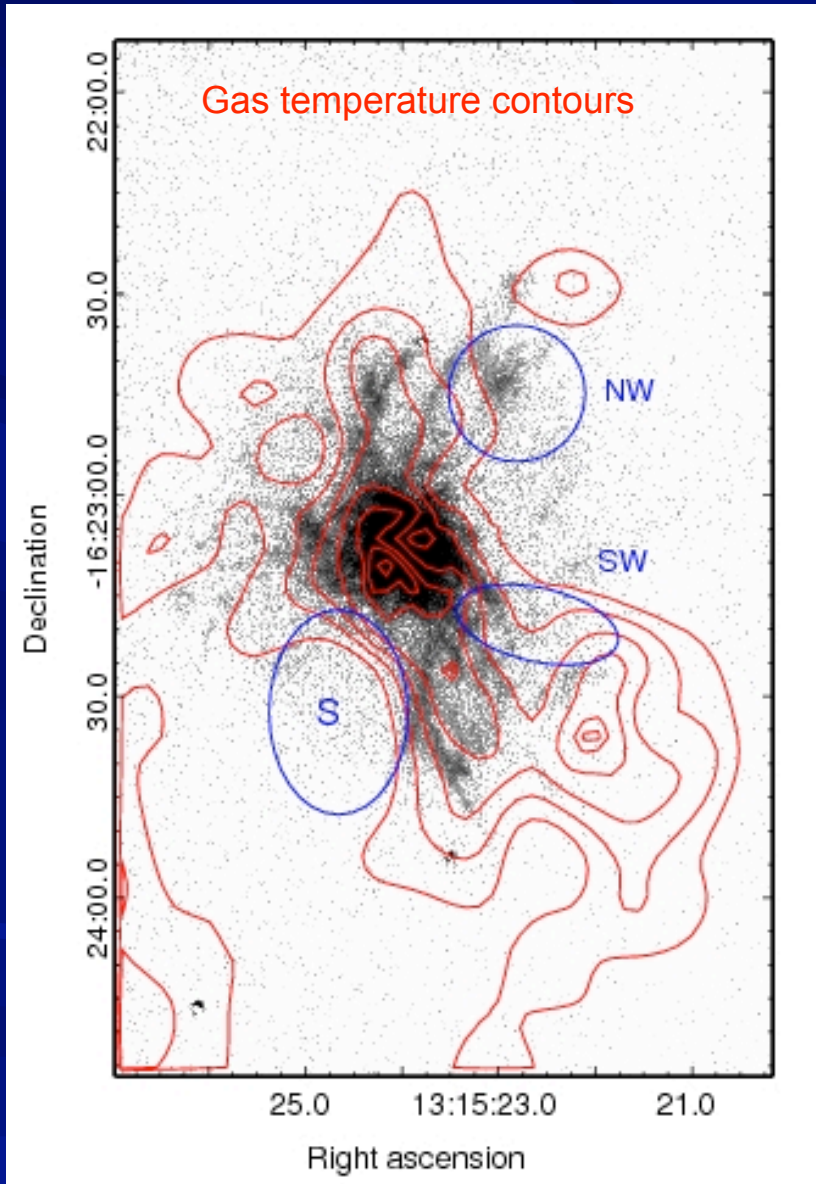


The cool spiral arm feature may be due to dredge-up by the detached 235 MHz radio lobe or merger-induced sloshing .

The gas near the detached 235 MHz radio lobe appears to have the lowest abundance gas – probably due to mixing of different temperature gas or the entrainment of gas in the radio lobe

H α image

NGC 5044



The H α filaments have the same spatial distribution as the coolest x-ray emitting gas

$$M_{\text{gas}}(\text{H}\alpha) = 8.5 \times 10^5 M_{\odot}$$

$$\dot{M}_{*} = 0.012 M_{\odot} \text{ yr}^{-1}$$

$$\dot{M}_{\text{c}} = 0.9 M_{\odot} \text{ yr}^{-1}$$

Gas cooling from the inner 2 kpc will dominate the supply of H α gas even if only 2% of the hot gas is able to fully cool.

Thanks to Ming Sun

NGC 5044

Effects of turbulence

Assume the dissipation of turbulent kinetic energy locally balances radiative losses

$$\Gamma_{diss} = \Delta L_{bol}$$

$$\Gamma_{diss} \propto \rho_g u^2 / t_{eddy} \propto \rho_g l^2 / t_{eddy}^3$$

$$l = \alpha r$$

$$t_{eddy} \propto \left(\frac{\alpha^2 r^2 \rho_g}{\Delta L_{bol}} \right)^{1/3}$$

$$\alpha = 0.1 \text{ and } 0.3$$

Effects of heat conduction

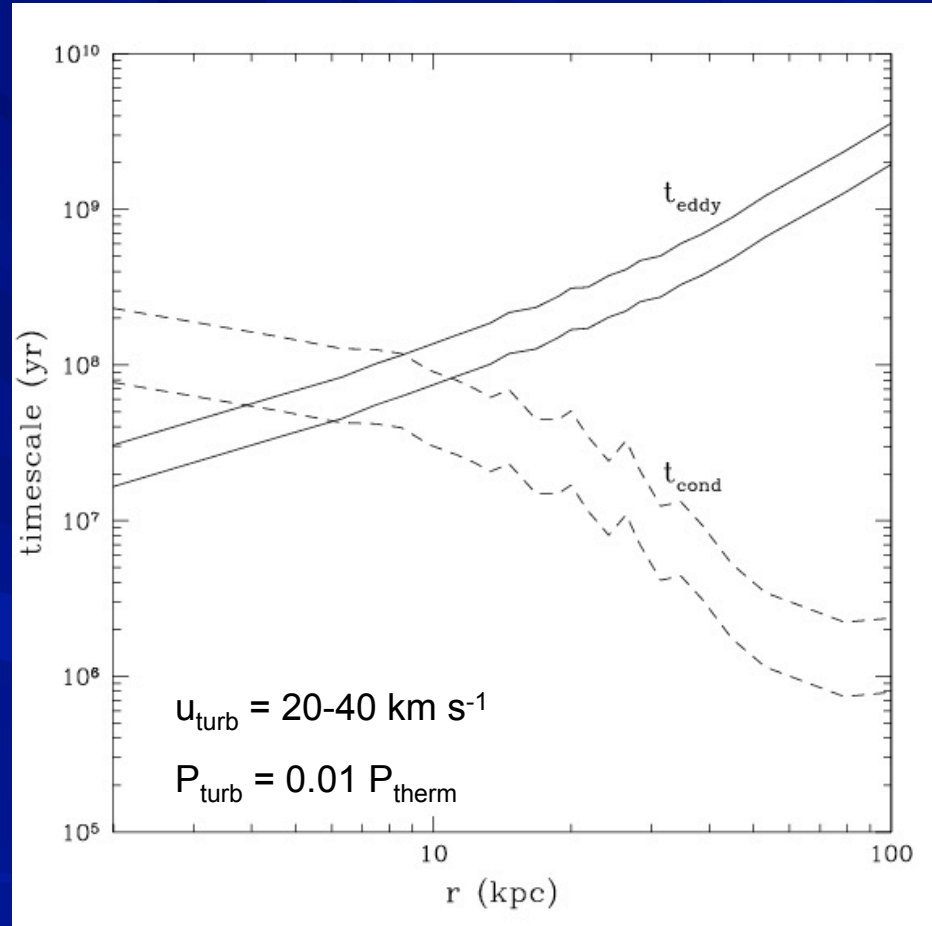
Evaporation of cool cloud

$$t_{cond} = \frac{\Delta H}{f_s F_c A}$$

$$\vec{F}_c \propto -T^{5/2} \vec{\nabla} T$$

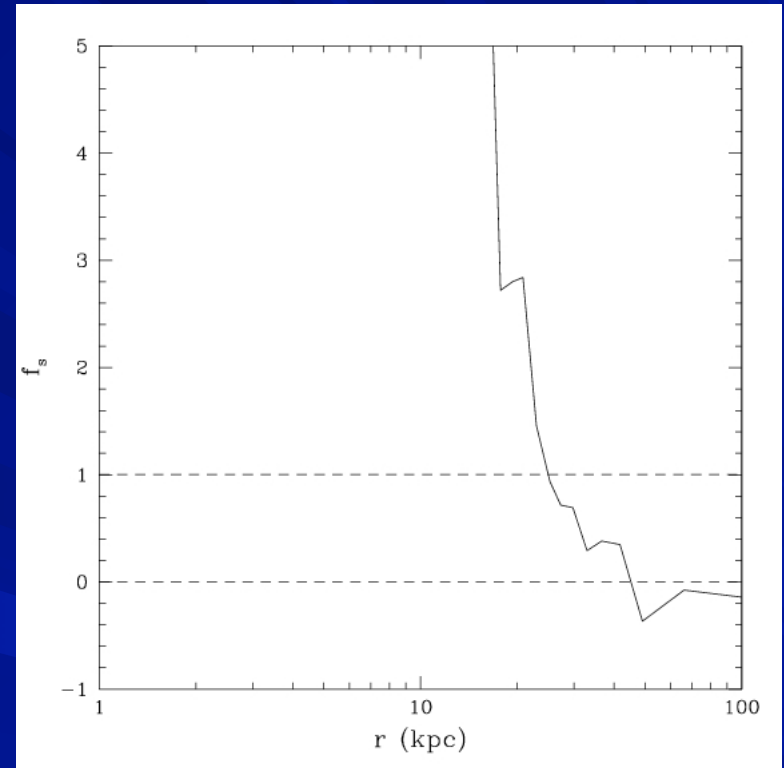
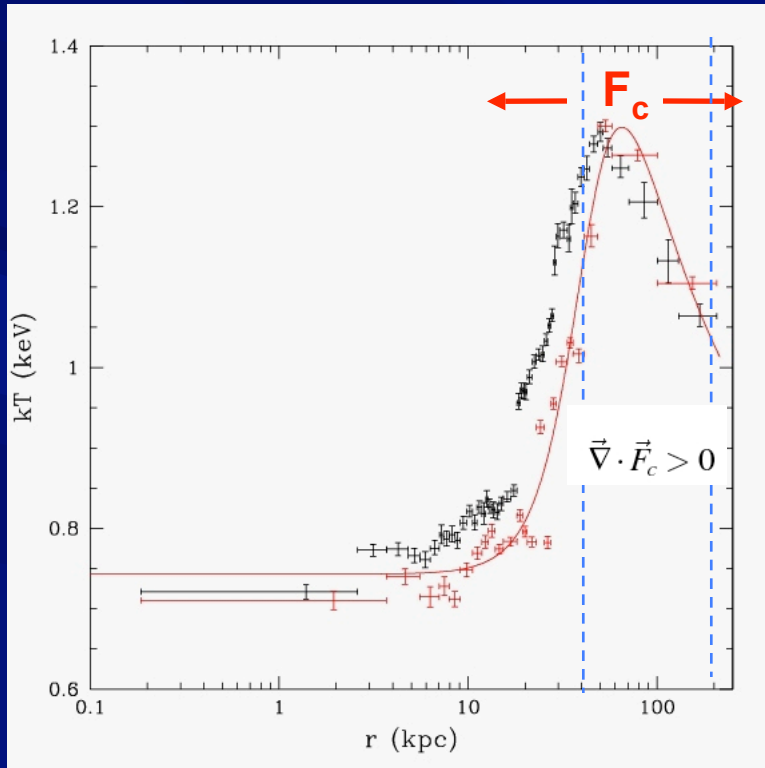
$$f_s = 0.1 \text{ and } 0.3, R_c = 1 \text{ kpc}$$

$$\Delta T = 20\%$$



NGC 5044

Global effects of heat conduction



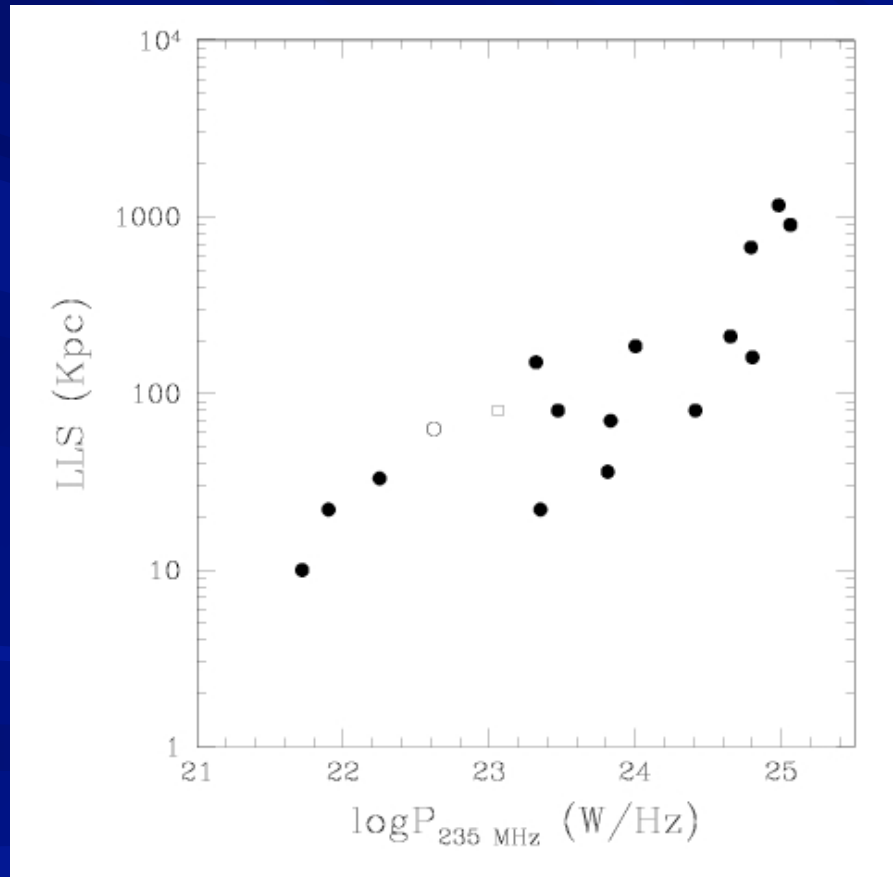
- Within 25 kpc, $f_s > 1$ is required to suppress radiative cooling
- Between 40–130 kpc – conduction helps cool the gas
- Conduction may only be important between 25–40 kpc

Conclusions

- X-ray cavities are most commonly detected in groups with less powerful (smaller), but collimated radio sources.
- More powerful (larger) radio sources probably produce x-ray cavities but the sensitivity of the x-ray observations beyond the core region of groups is insufficient to detect the x-ray cavities
- Amorphous radio systems may or may not produce detectable x-ray cavities. When cavities are detected, they tend to be more isotropically distributed.
- The cumulative effect of many weak radio outbursts which produce weather-driven AGN-inflated cavities may be the dominant mechanism leading to the suppression of star formation and the uplifting of metals in the cool cores of groups.
- The ASTROSAT UV telescope will be a very useful tool to study star formation in cooling flow clusters.

Correlation between radio power and linear size

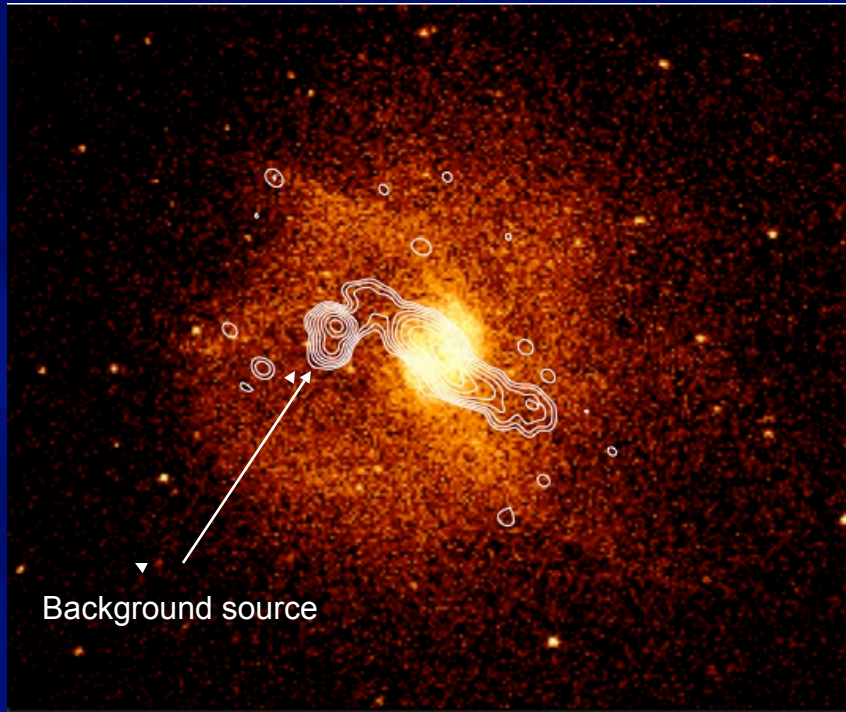
Ledlow et al. (2002) found that the correlation between linear size radio luminosity of FRI radio sources is the same for galaxies inside and outside of clusters



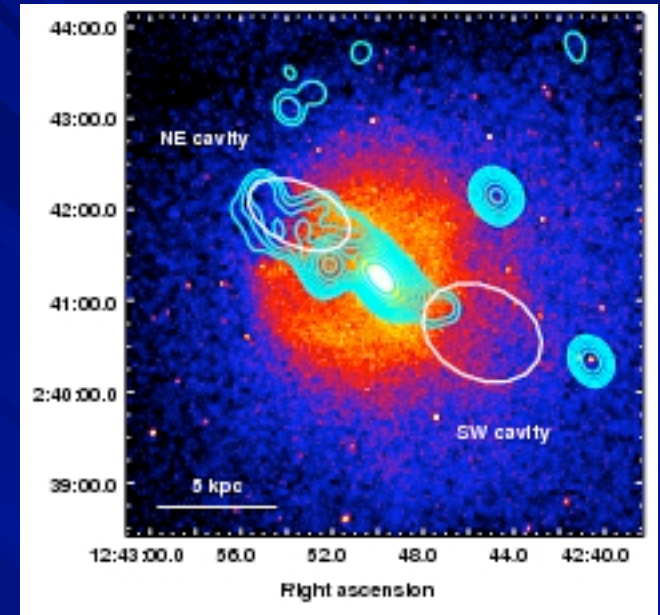
Giacintucci et al. (2011)

NGC 4636

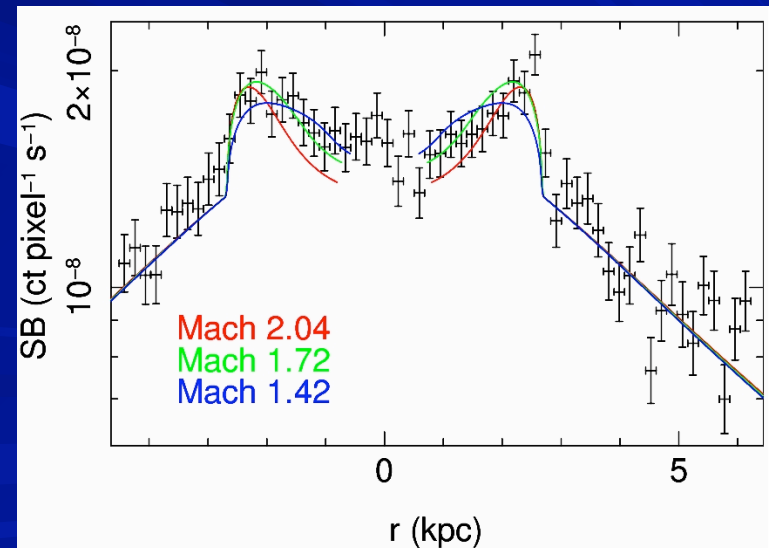
610 MHz GMRT contours and Chandra image



235 MHz contours



Surface brightness profile and shock models



- Class 1 radio source
- Multiple sets of x-ray cavities – some are radio filled
- Strong AGN-induced shock
- Jones et al. (2002) and Baldi et al. (2009)