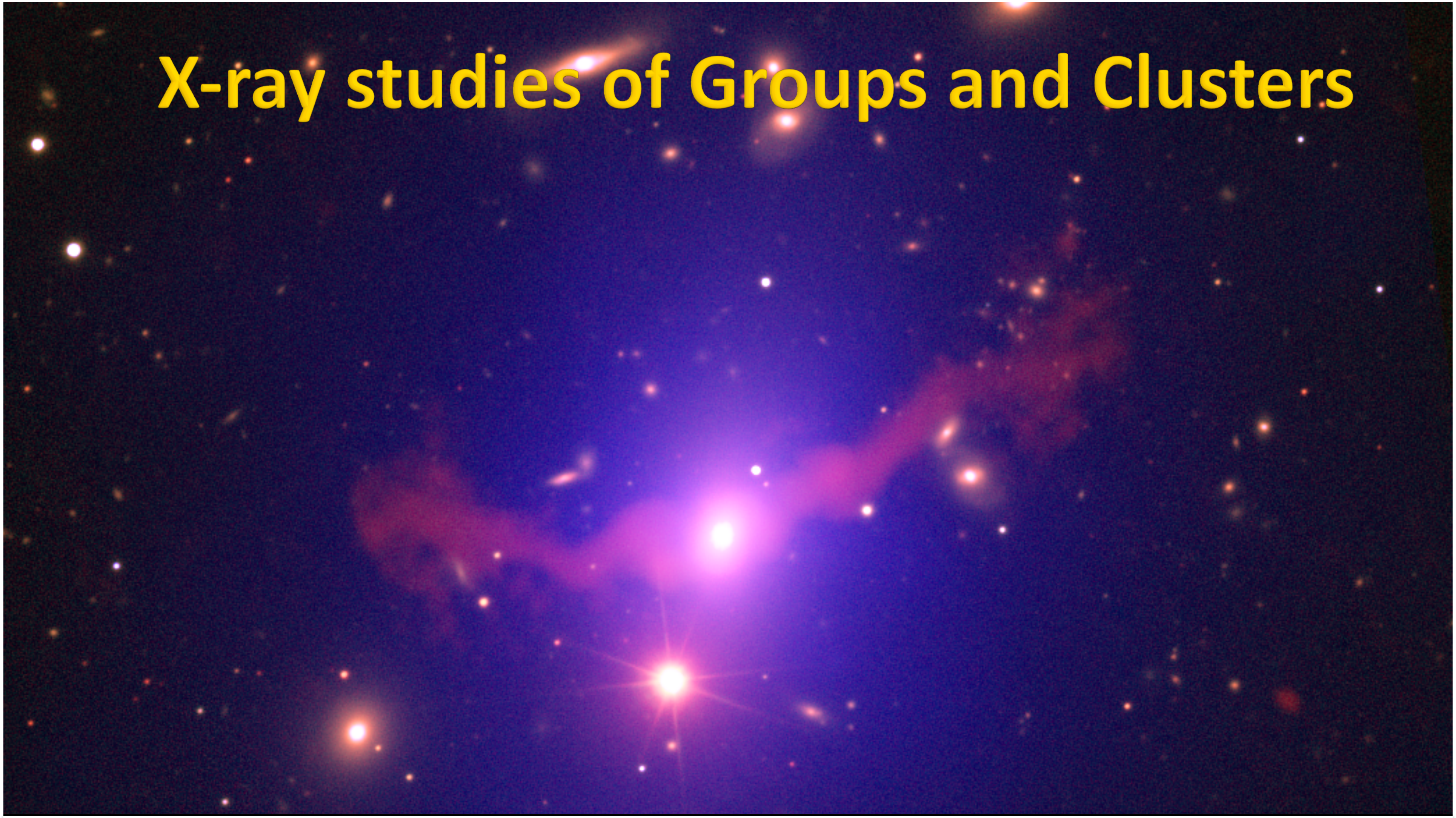
X-ray studies of Groups and Clusters



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S. Raychaudhury & T.J. Ponman (Birmingham), S. Giacintucci (Maryland), L. David & J. Vrtilek (SAO), M. Gitti (Bologna)

Outline

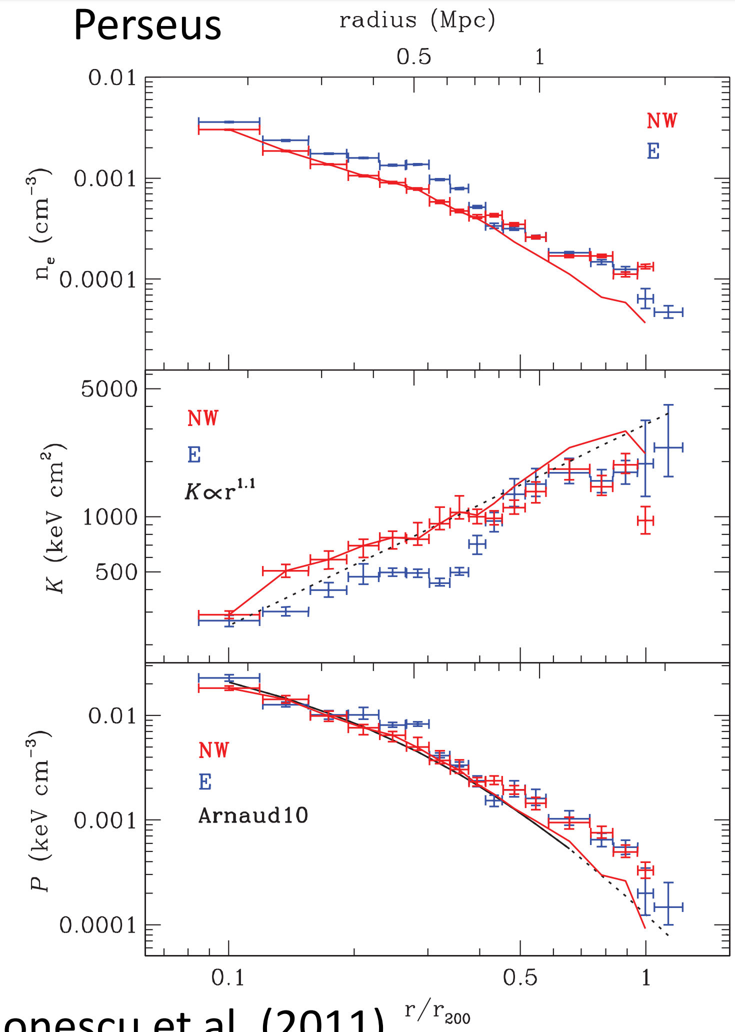
I will talk about:

- The outskirts of groups & clusters
- Gas motions & metallicity
- AGN heating (radio jets)
  - How do AGN heat the hot gas in groups/clusters?
  - How much power is available?
  - Over what timescales?
- Galactic coronae

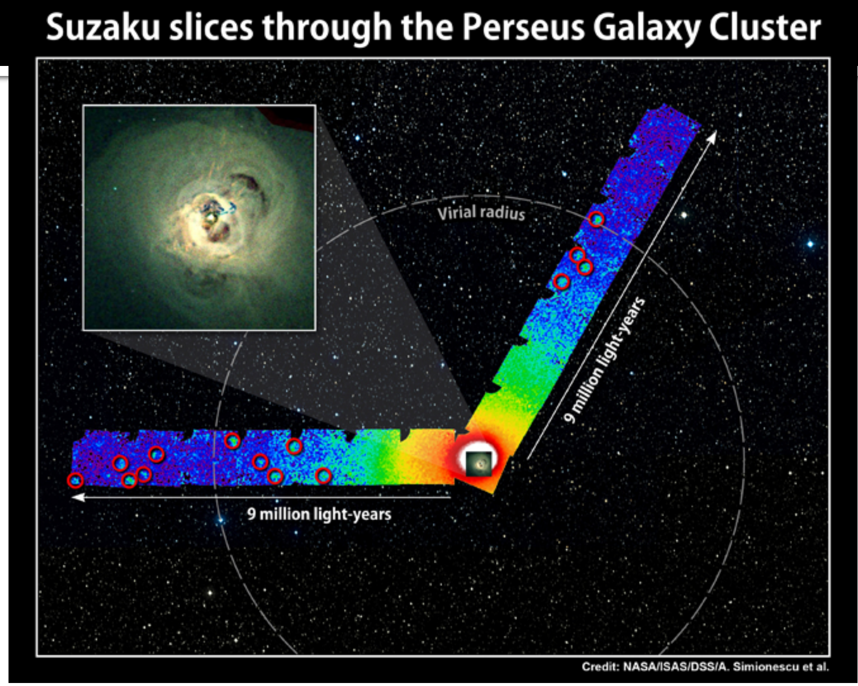
Important issues I won't talk about:

- Turbulence & magnetic fields
- Groups & clusters at moderate redshift.
- Low-mass groups / formation of IGrM.

Outskirts of Clusters and Groups



Simionescu et al. (2011)



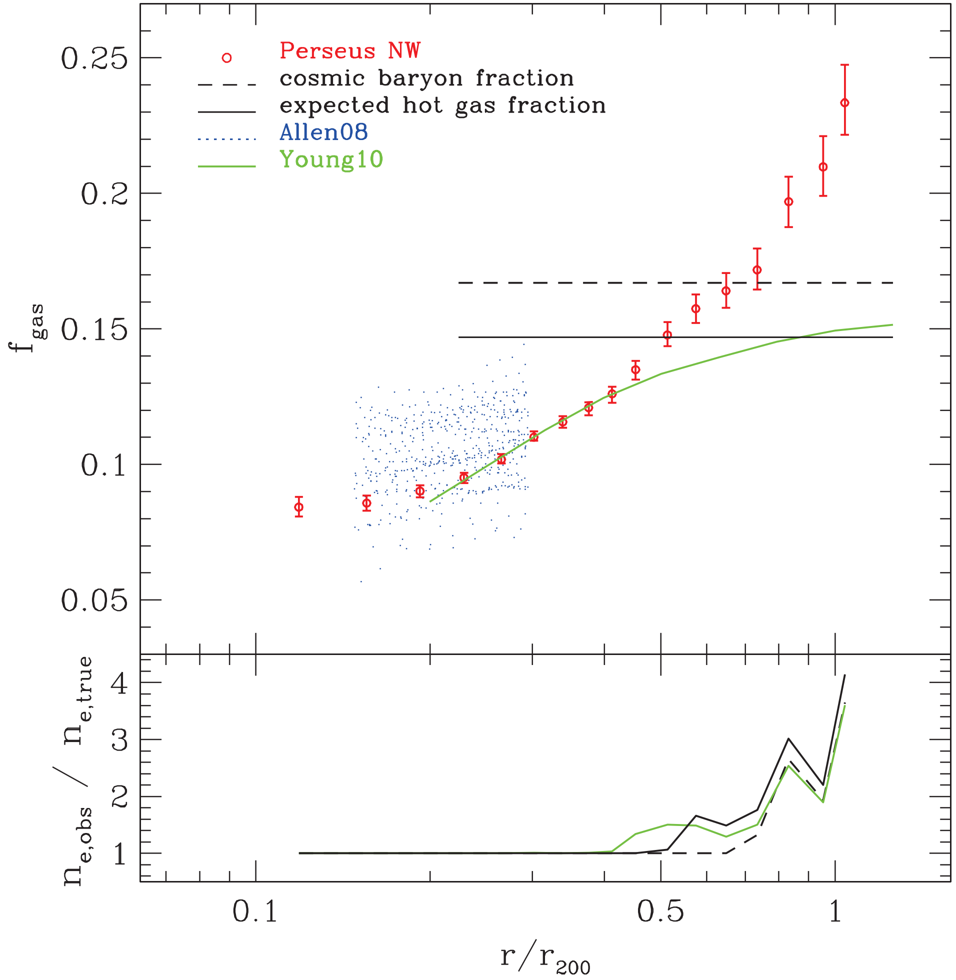
- Tracing Perseus and Virgo to virial radius (Simionescu et al. 2011; Urban et al. 2011).
- Deviations from expected radial profiles, to lower temperatures, higher densities.

Clumping in Perseus and Virgo

- Taken at face value, spectra indicate f_{gas}> universal f_{baryon}, and deviation of entropy from $r^{1.1}$ scaling.

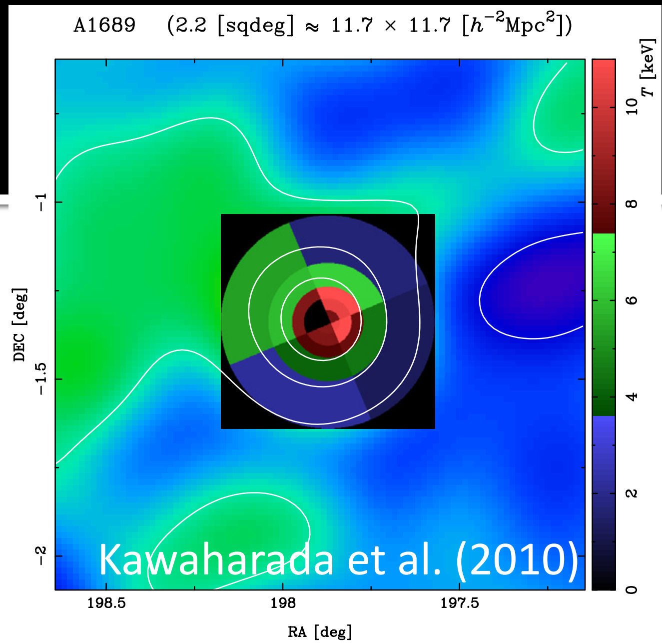
Explanations:

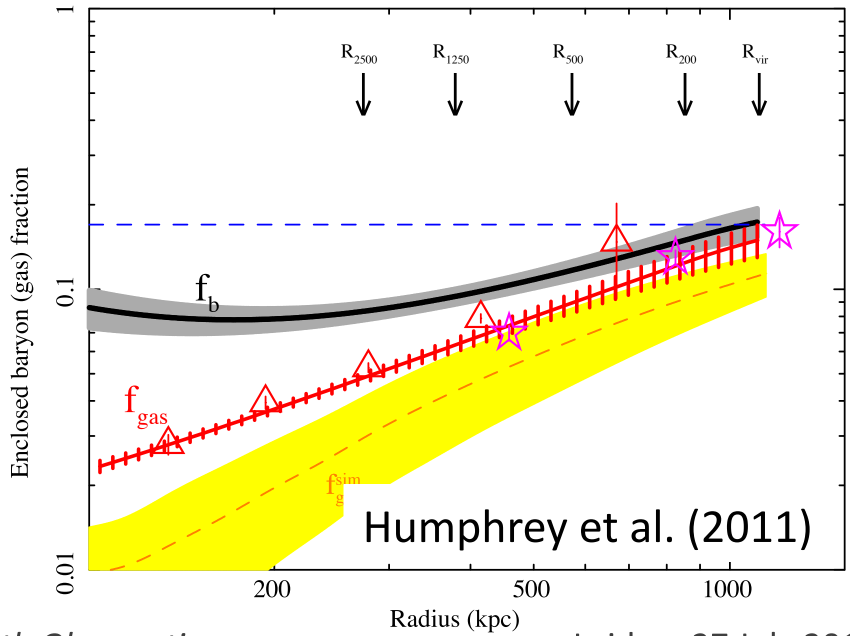
1. Electron-Ion equilibration issues (Akamatsu 2011, Kawaharada 2010)
   - Can explain low kT but not high densities?
2. Clumping: Outside R_{500} ICM contains small clumps of cool gas which dominate X-ray emission (Simionescu et al 2011; Urban et al. 2011)



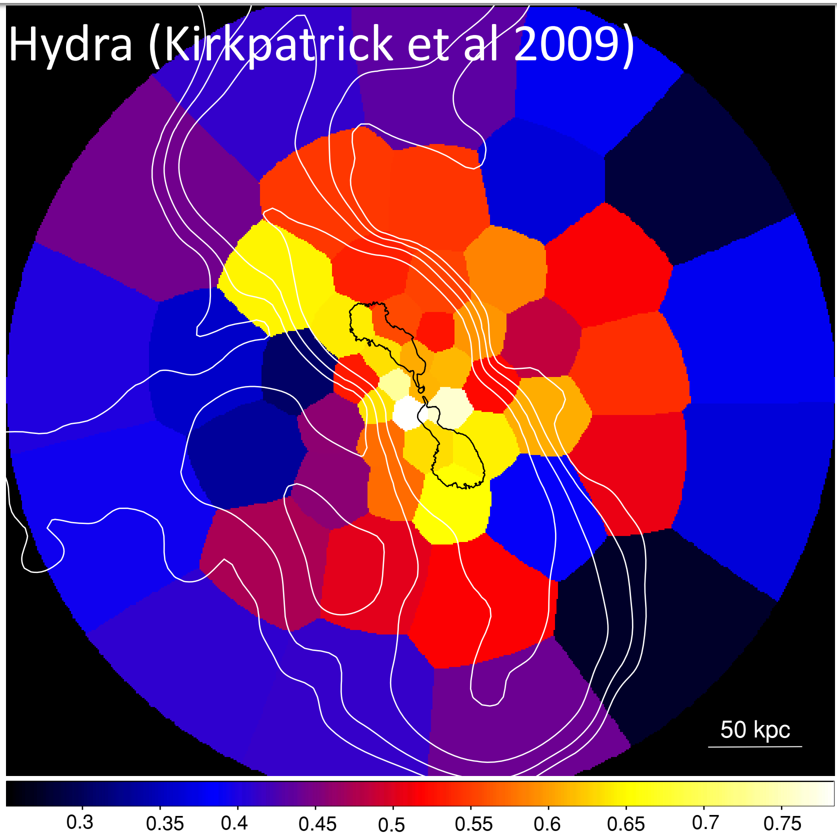
Clumping: problems to be resolved

1. Do we see clumping in all clusters & groups?
   - Vikhlinin: Yes in A133
   - E. Miller: No (one cluster, eight more TBD).
   - Kawaharada: Yes in A1689, but not in one quadrant.
   - Humphrey: No in fossil group RXJ 1159+5531
2. How big are the clumps?
   - Simionescu: 5kpc
   - Vikhlinin: 50-100 kpc
3. What is their origin?

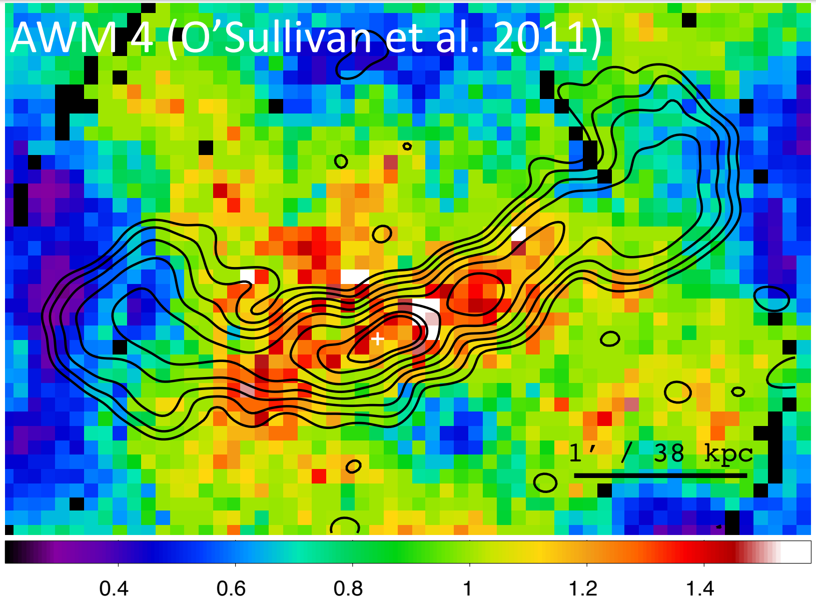




Gas motions & metallicity: AGN outflows



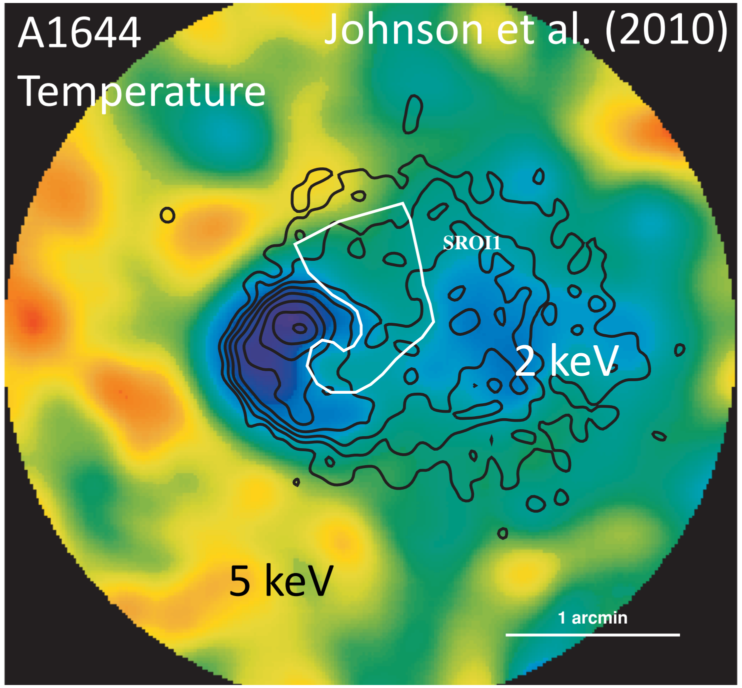
3.3 keV cluster, outburst energy=10^{61} erg
Outflow extent 120 kpc, M_{Fe} 2-7x10^7 $M_\odot$
5% of outburst energy needed to lift gas



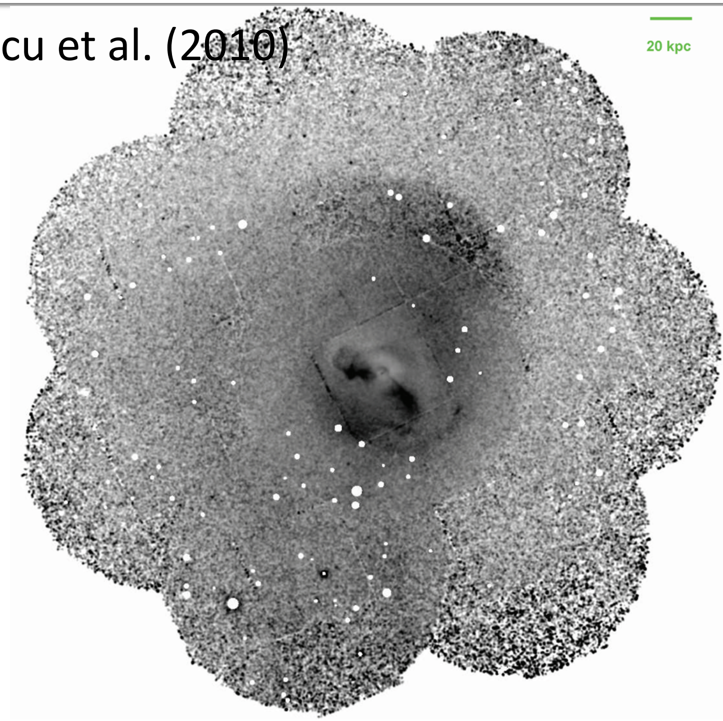
2.4 keV cluster, outburst energy = ~5x10^{58} erg
Extent of outflow = 35 kpc
Fe mass uplifted = 1.4x10^6 $M_\odot$
~10% of outburst energy required for uplift.

>10 examples known (Kirkpatrick et al. 2011)
Outflow radius R_{fe} α $P_{jet}^{0.42}$

Gas motions & metallicity: sloshing



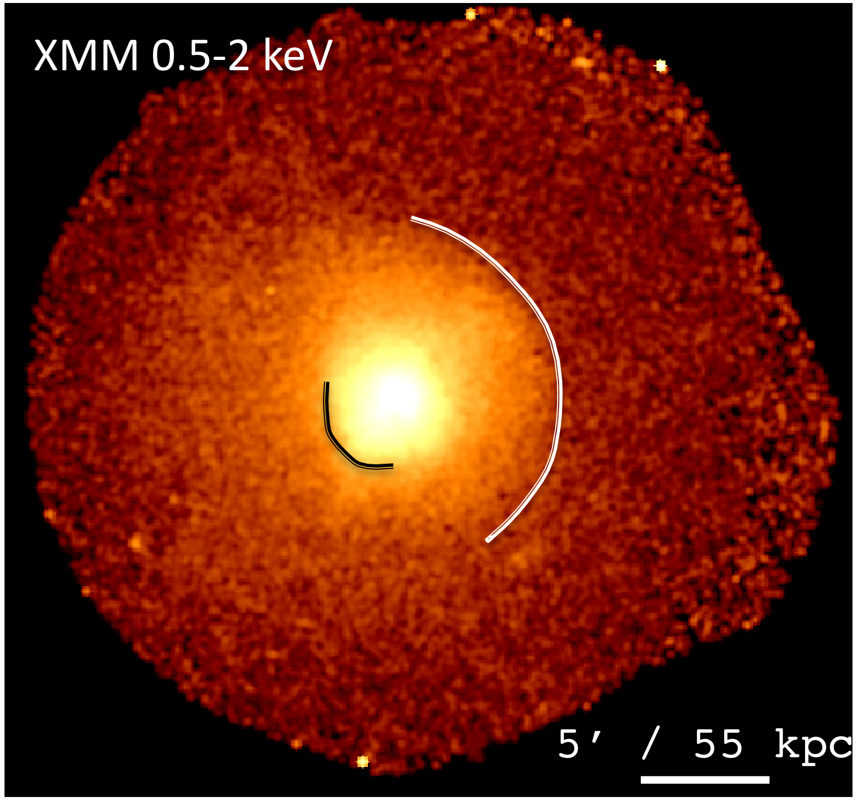
Simionescu et al. (2010)
Virgo

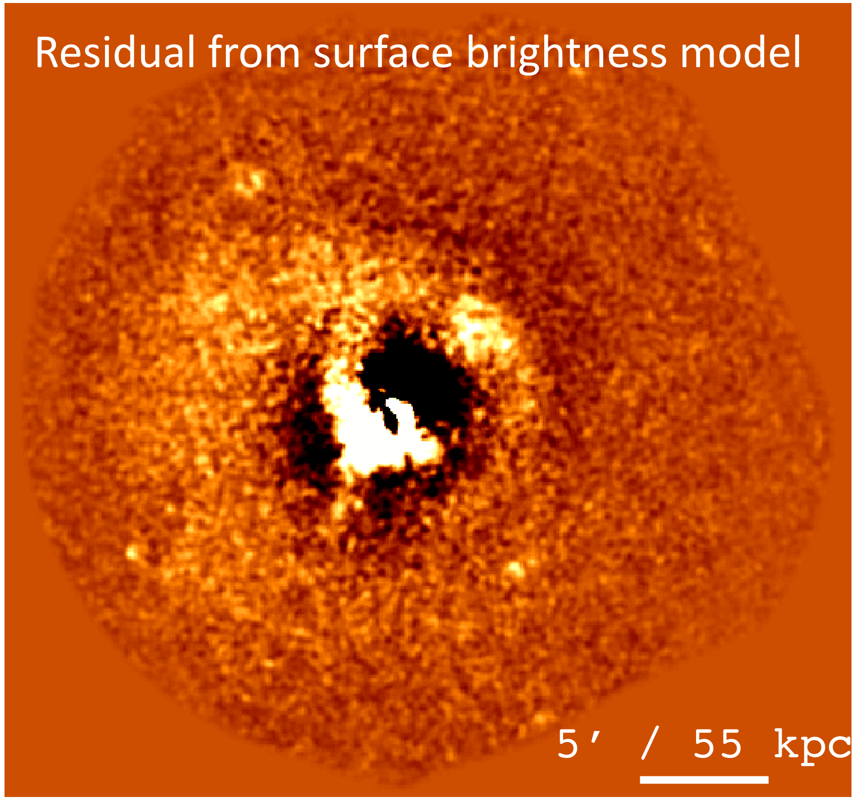


>60% of CC clusters show evidence of sloshing (Johnson et al., in prep.)

- Mixing: High metallicity gas pushed outward, high entropy gas drawn into core.
  In Virgo, ~8% of metals uplifted by sloshing, 2% by AGN (Simionescu et al. 2010)
- Magnetic fields: Sharp edges of cold fronts indicate suppressed conduction.

Sloshing also affects groups: NGC 5044





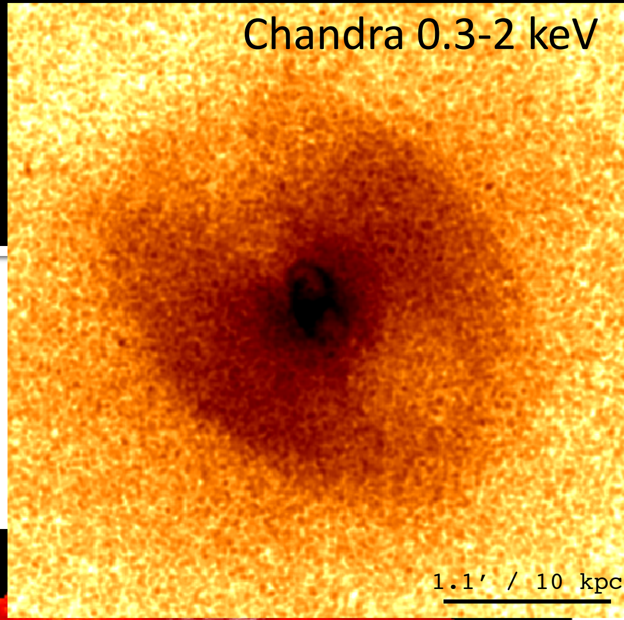
- Paired cold fronts (Gastaldello et al. 2009).
- BGG offset from group mean velocity by 150 km/s (Mendel et al. 2008).
- Also seen in IC 1860 (Gastaldello et al., in prep.), NGC 5098 (Randall et al. 2009)

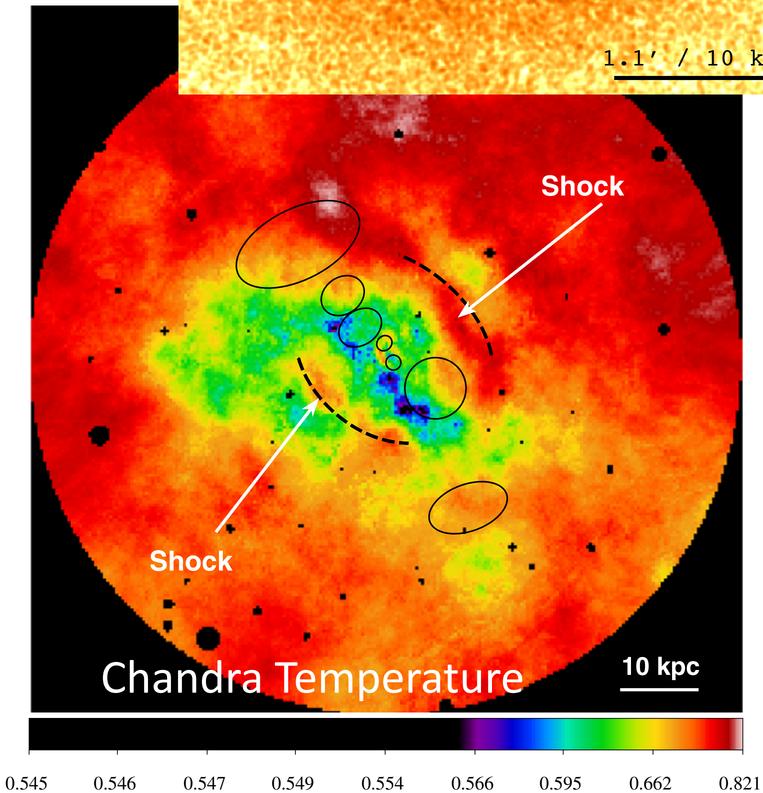
How do AGN heat gas? I. Shocks

- Best understood method of heating, probably occur in most systems, but difficult to observe.
- Typically weak shocks (Mach < 2).

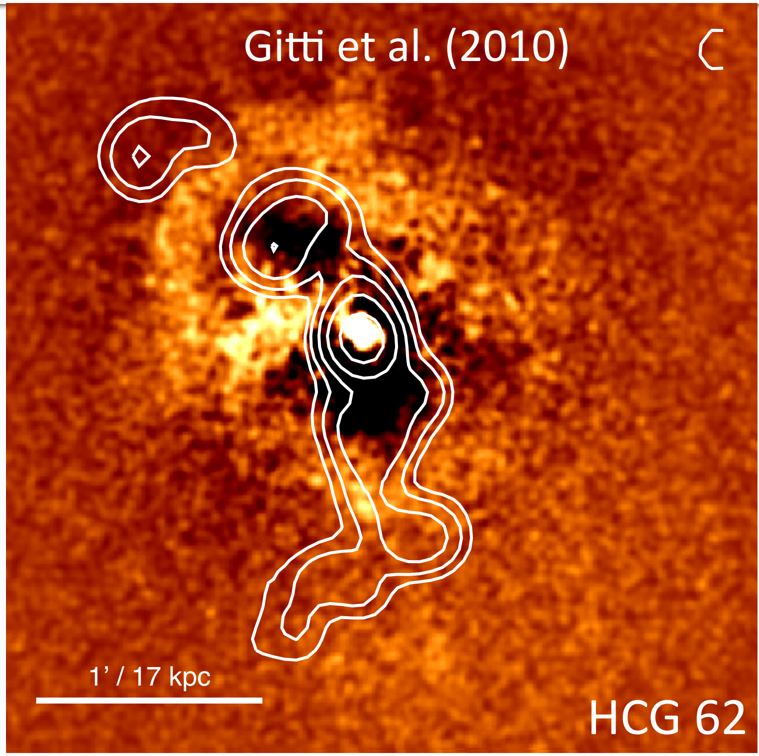
Example: NGC 5813 (Randall et al. 2011)

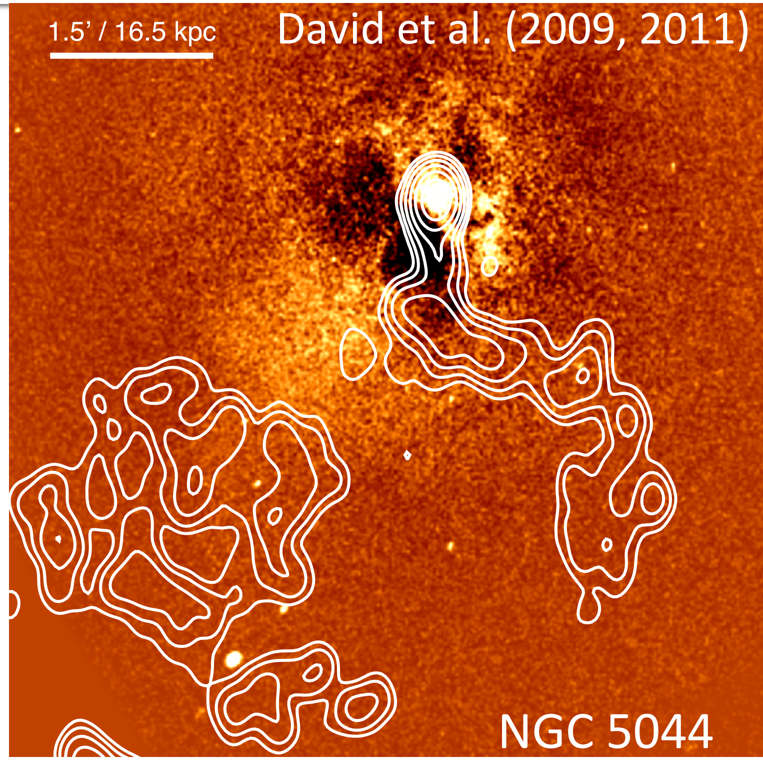
- Two shocks and three pairs of cavities
- Outburst power varies by factor ≥6.
- Energy in shocks: 0.2-3x10^{57} erg (40-80% of total outburst energy).
- Sufficient heating from shocks to balance cooling in central 10 kpc (assuming 10% efficiency) without cavity contribution.





How do AGN heat gas? II. Cavities

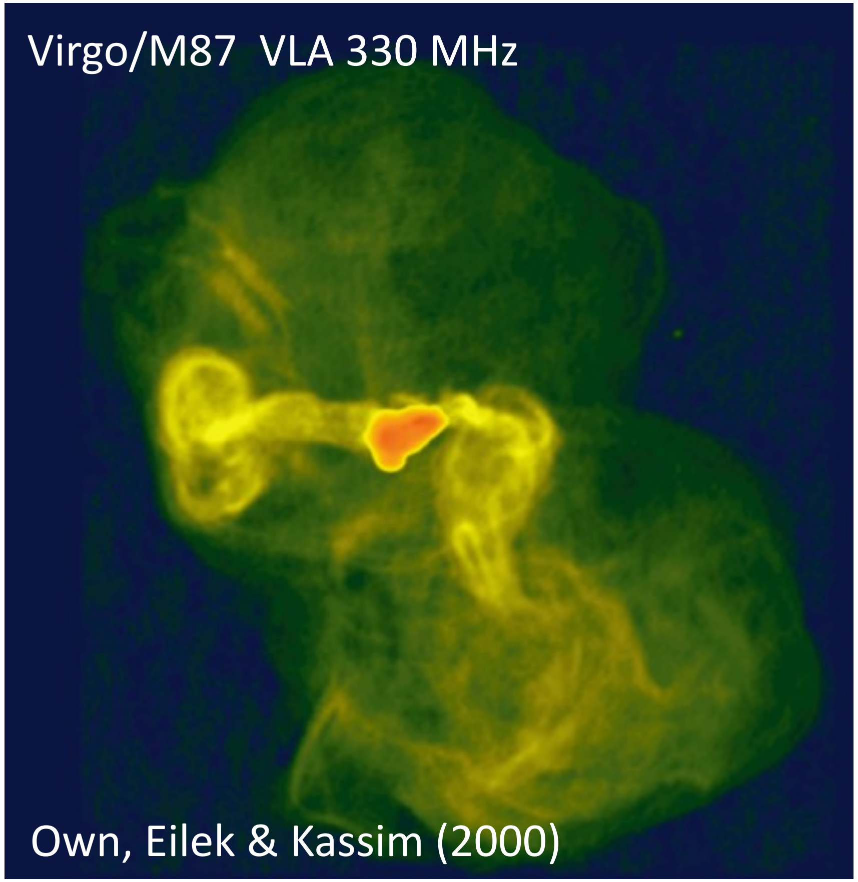




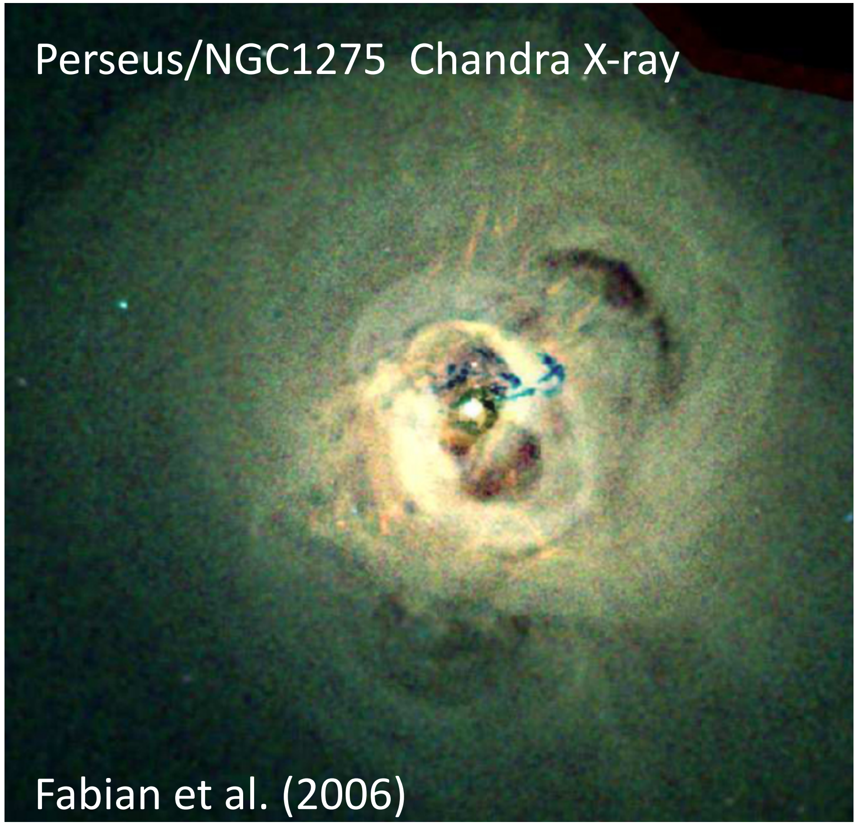
Smoothed Chandra 0.3-2 keV residual images 235 MHz GMRT contours

- Cavities inject pV energy via expansion, turbulence in wake
- HCG62 cavities are paired, NGC5044 cavities isotropically distributed by gas motions.
- Low-frequency radio reveals outer lobes, unclear from X-ray or high-freq. radio

What happens to old radio lobes? (How do we get the other 3pV energy out?)



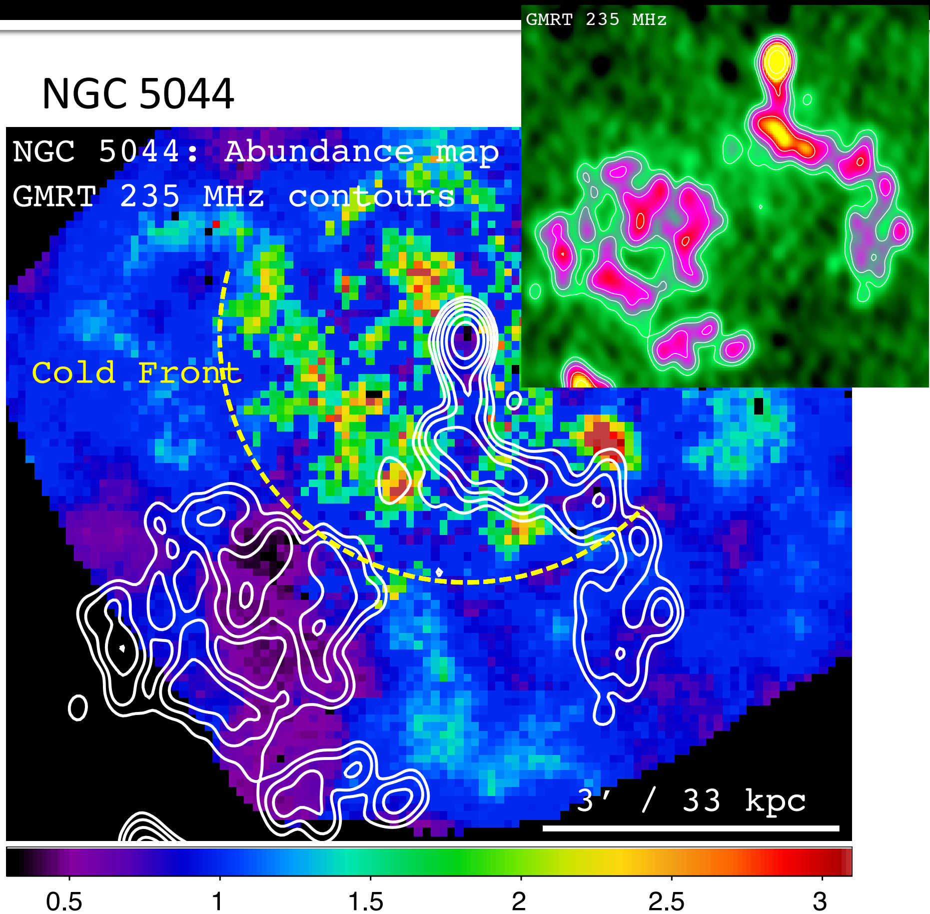
Age of outer “mushroom” lobes: few x10^7 – 10^8 yr.



Age of pancaked cavities: 7-8 x10^7 yr.

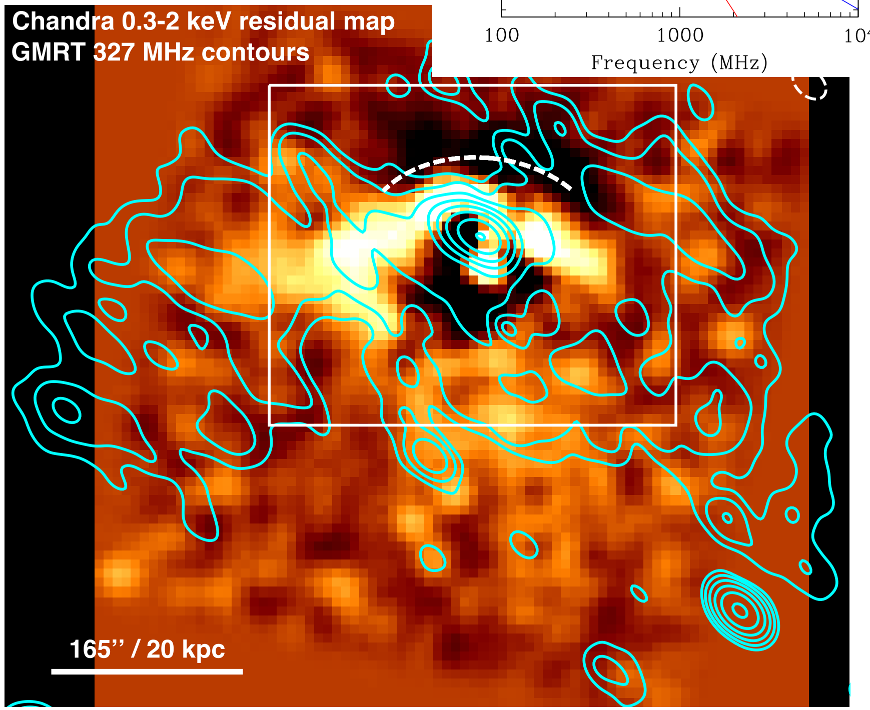
What happens to old radio lobes? (mixing with the IGM?)

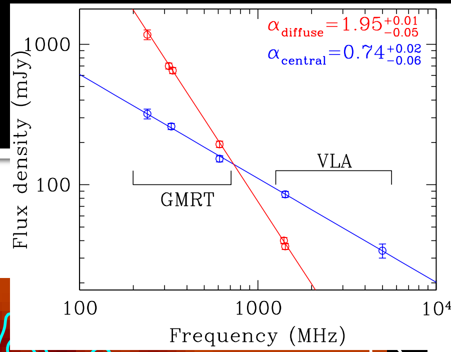
NGC 5044



Buoyancy age of outer lobe 4.5x10[7] yr
Morphology/abundance indicate mixing?

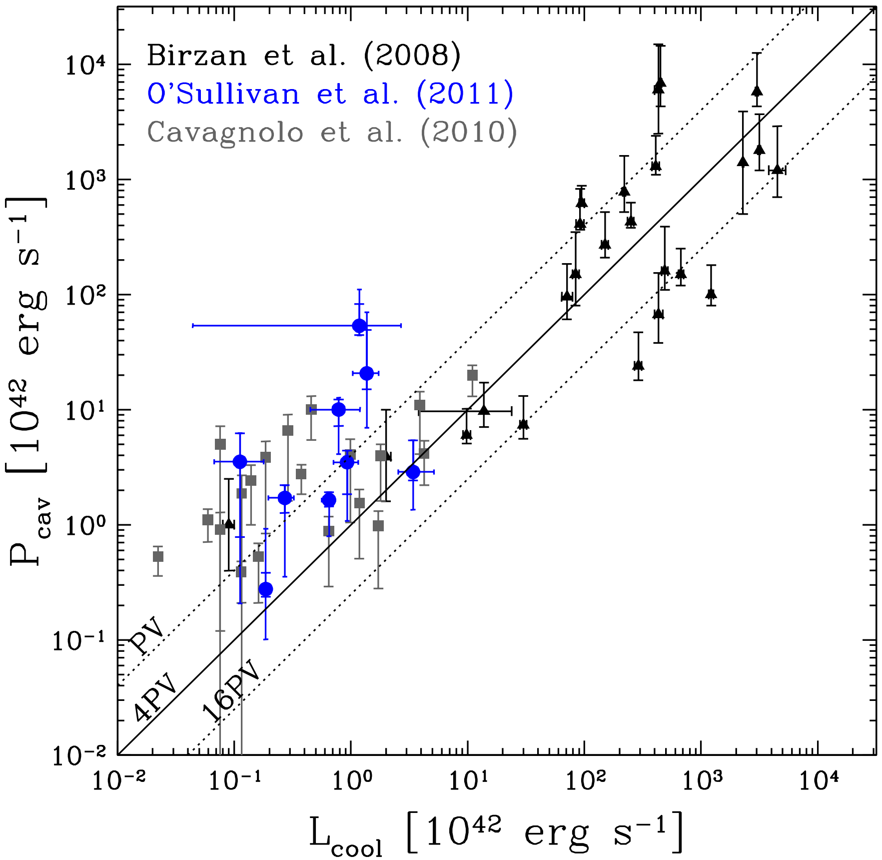
NGC 1407





Old radio lobes? No apparent cavities.
Synchrotron age estimate: >170 Myr
Buoyancy age estimate: <40 Myr
Could lobes be mixed with IGM?

Is there enough power to balance cooling?



(Bolometric L_X for region $t_{cool} \leq 7.7$ Gyr)

See also Rafferty et al. (2006), Nulsen et al. (2007)

$Pcav = 4pV/t_{buoy}$

Power needed to balance cooling:

- In clusters: 4PV
- In groups/ellipticals: 1PV

Scatter at least a factor of 4

Uncertainties:

- Shocks – factor ~10?
- Buoyancy times – factor ~5?
- Viewing angle – factor 3 (Mendygral et al. 2011)
- Gas motions / AGN "weather"
- Old/young cavities undetected.

AGN outbursts: timescales

- What is the (radio) AGN duty cycle? 10^7 yr on in every 10^8?
- Systems with multiple shocks or cavity-pairs:

System	Feature	Interval (yr)	
NGC5813	Shocks	1 $\times10^7$	Randall et al. (2011)
HCG62	Lobes/cavities	5 $\times10^7$	
NGC5044	Lobes/cavities	3 $\times10^7$	
Perseus	Cavities	5-7 $\times10^7$	Dunn et al. (2006)
Hydra	Cavities	7-25 $\times10^7$	Wise et al. (2007)

→ Interval between outbursts varies by factor >10.

- Outburst duration can be comparable to this interval:
  AWM4 still active after 17×10^7 yr,
  NGC4261 still expanding near-sonically after ~6.5×10^7 yr.

Galactic Coronae
(Sun et al. 2007, Sun 2009)

• Small-scale cool cores (<10 kpc radius) in group/cluster dominant galaxies.

➔ Difficult to detect, especially at z>0.1

• Sharp temperature gradient

(e.g., 4 keV in < 2 kpc)

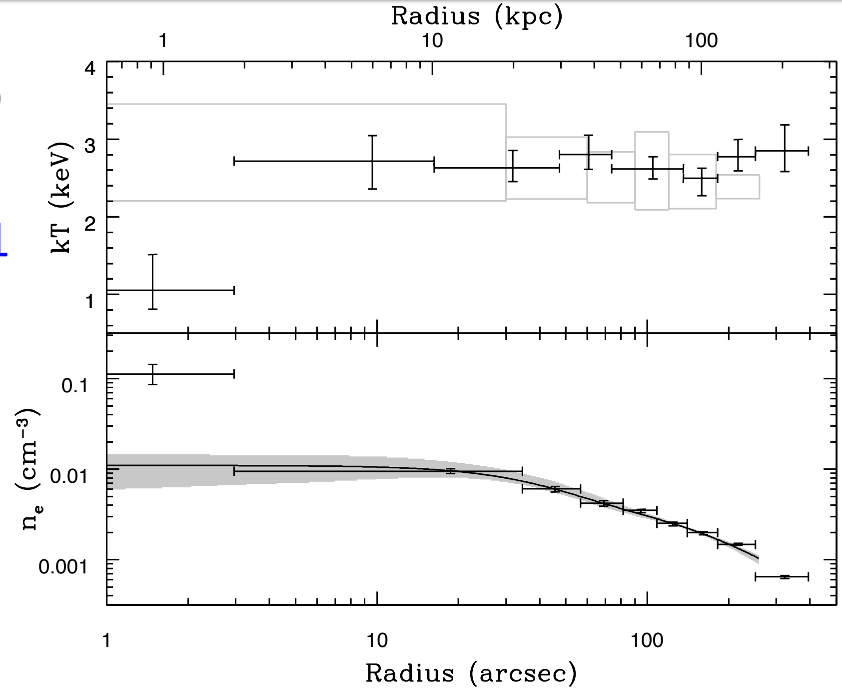
• Spitzer conduction would heat coronae on short timescales (<~10^7 yr).

➔ Magnetic isolation.

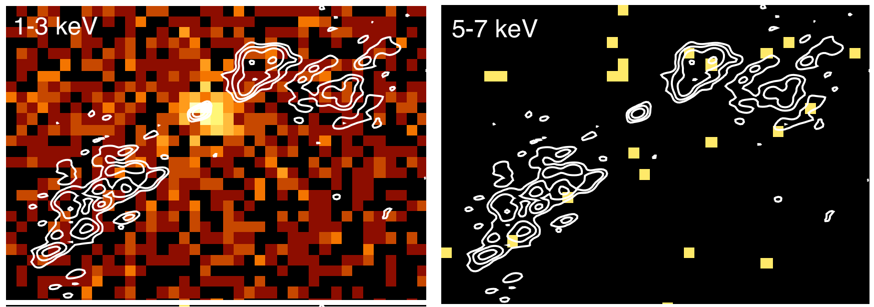
• Heating by AGN jets would destroy coronae if more than ~1% efficient.

➔Breaks AGN feedback cycle!

• Stellar mass loss in BCG ≈ cooling rate
➔ Self-sustaining?



AWM 4 (O'Sullivan et al. 2010)



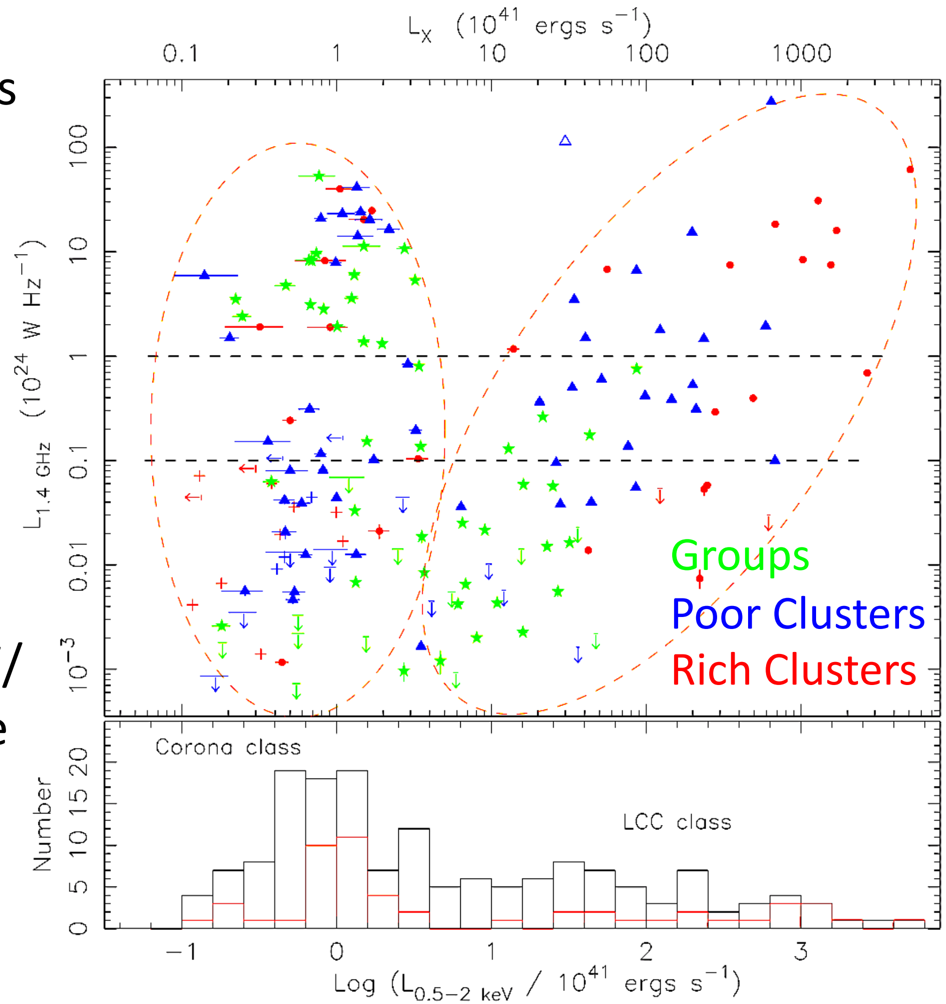
Coronae as radio galaxy hosts
(Sun 2009)

- Coronae and Large Cool Cores host equally powerful radio sources.

- In LCCs: $L_{radio} \propto L_{cool}$.
- In coronae:
  L_{radio} is independent of L_{cool}.

- In groups, the most powerful radio sources ($L_{1.4GHz}>10^{24}$ W/Hz) are only found in coronae

➔ corona radio sources effective in preventing formation of LCCs in groups?



Caveats affecting groups

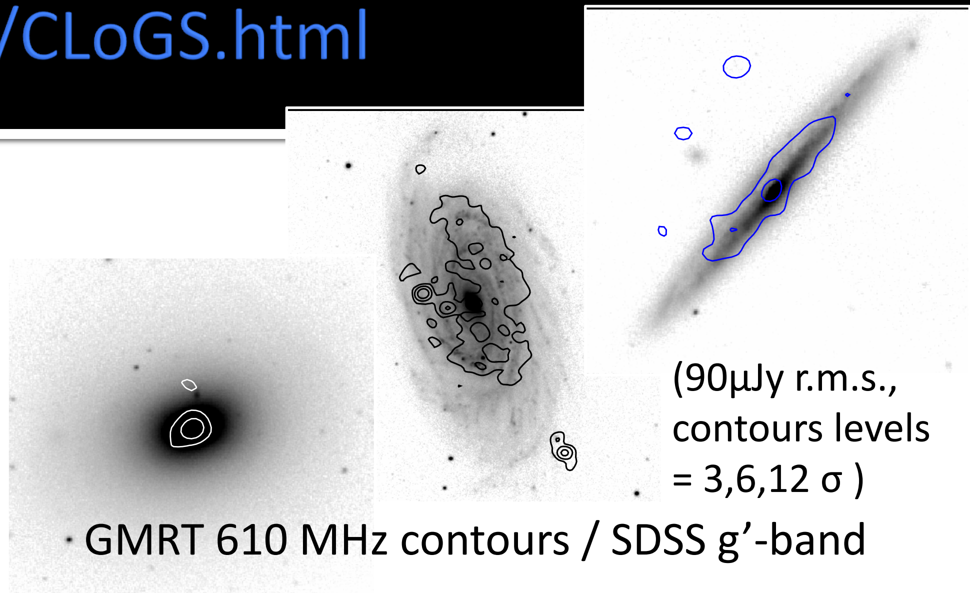
- In clusters we can easily select representative samples, examine both population properties and detailed physics.
- Very few representative group samples are available.
  - Optical selection very unreliable for small numbers of galaxies.
  - Nearby X-ray selected samples biased toward centrally peaked systems (Eckert et al. 2011), e.g., 85% of groups in Dong et al. (2010) are CC.
  - X-ray selection at moderate-*z* *may* be better, but groups are faint, so studies of detailed physics (cooling, mixing, feedback, etc.) are difficult.

➔ Detailed group studies focus on individual systems, or small non-statistical samples.

CLoGS: The Complete Local-Volume Groups Sample

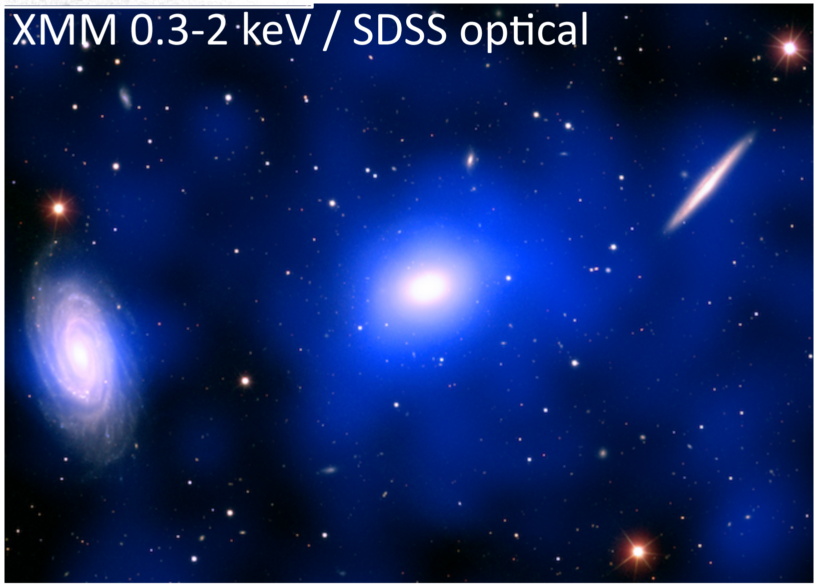
www.sr.bham.ac.uk/~ejos/CLoGS.html

- Complete, optically-selected sample of 53 groups:
  - 4+ galaxies, 1+ early-type
  - D<80 Mpc
  - Dec. > -30° (VLA & GMRT)
- Avoids bias toward cool-core systems in RASS-based X-ray samples (Eckert et al. 2011)
- Goal: complete coverage in X-ray (Chandra/XMM) and radio (GMRT 610 & 235 MHz).
- Richer half of will be almost complete by 2012.



(90µJy r.m.s., contours levels = 3,6,12 σ)

GMRT 610 MHz contours / SDSS g'-band



XMM 0.3-2 keV / SDSS optical

Open Questions

- For “jet-mode” feedback:
  - What happens to the extra energy available in groups?
  - How and where do we get the 3pV out of radio lobes? Mixing?
  - How is cavity/lobe energy isotropised? Gas motions?
  - Are galactic coronae doing something interesting?
- For “quasar-mode”: Can we observationally determine whether QSOs are heating their environment and if so, how?
- Gas motions: Uplift/sloshing impacts many systems, affects metals, AGN, etc. Could this be important for cosmological simulations?
- Clumping in cluster outskirts: What is the origin of the clumps? Do they exist in groups as well?
- We all agree (?) groups are important – how should we go about building representative, well-observed samples?