A Combined X-ray/Low-Frequency Radio View of AGN Feedback in Galaxy Groups

Ewan O'Sullivan

(University of Birmingham/SAO)

With thanks to: Simona Giacintucci,

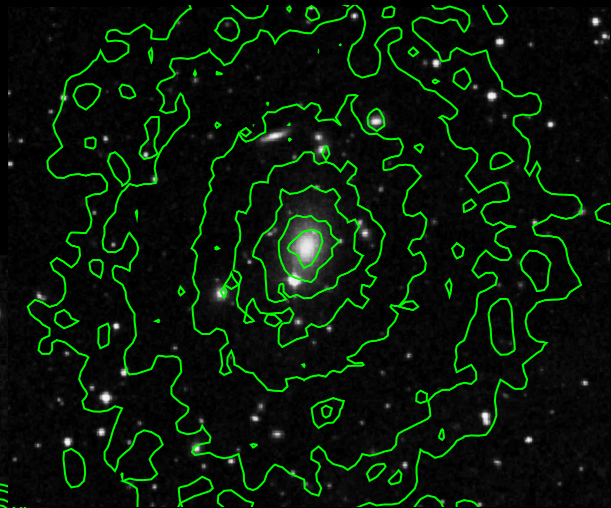
Larry David, Jan Vrtilek and Somak Raychaudhury

Overview

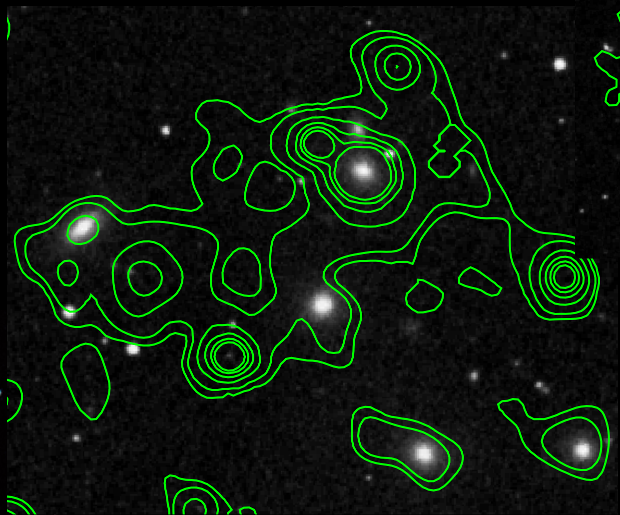
- Background
  - Why do we need feedback?
  - Why look at groups rather than clusters?
- The GMRT Groups Project
- Results
  - NGC 5044 - benefits of low-frequency observations
    - isotropic heating
  - AWM 4 - radio lobes without cavities?
    - the cool core and its effect on the AGN outburst
- Future Plans

Groups – A Diverse Class

Variation from low-mass, spiral-only, X-ray faint groups (e.g., local group) to massive, X-ray bright mini-clusters.



AWM4
Dominant gE + many smaller galaxies

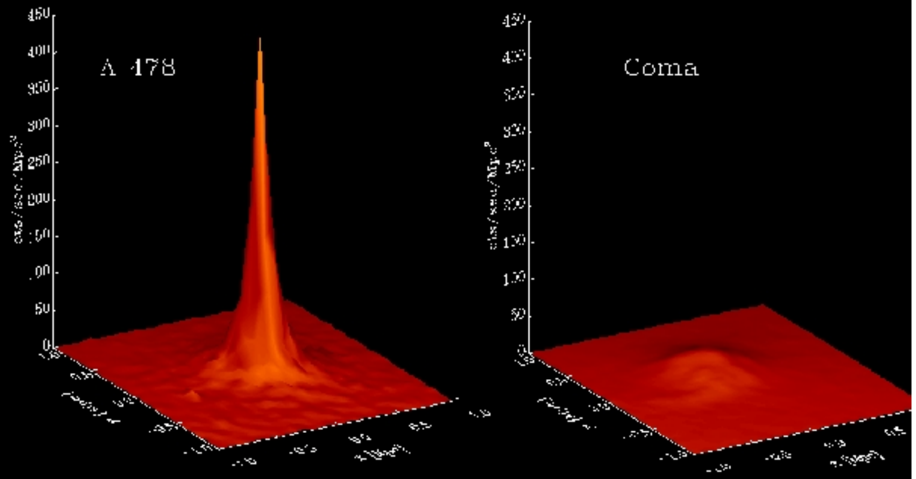


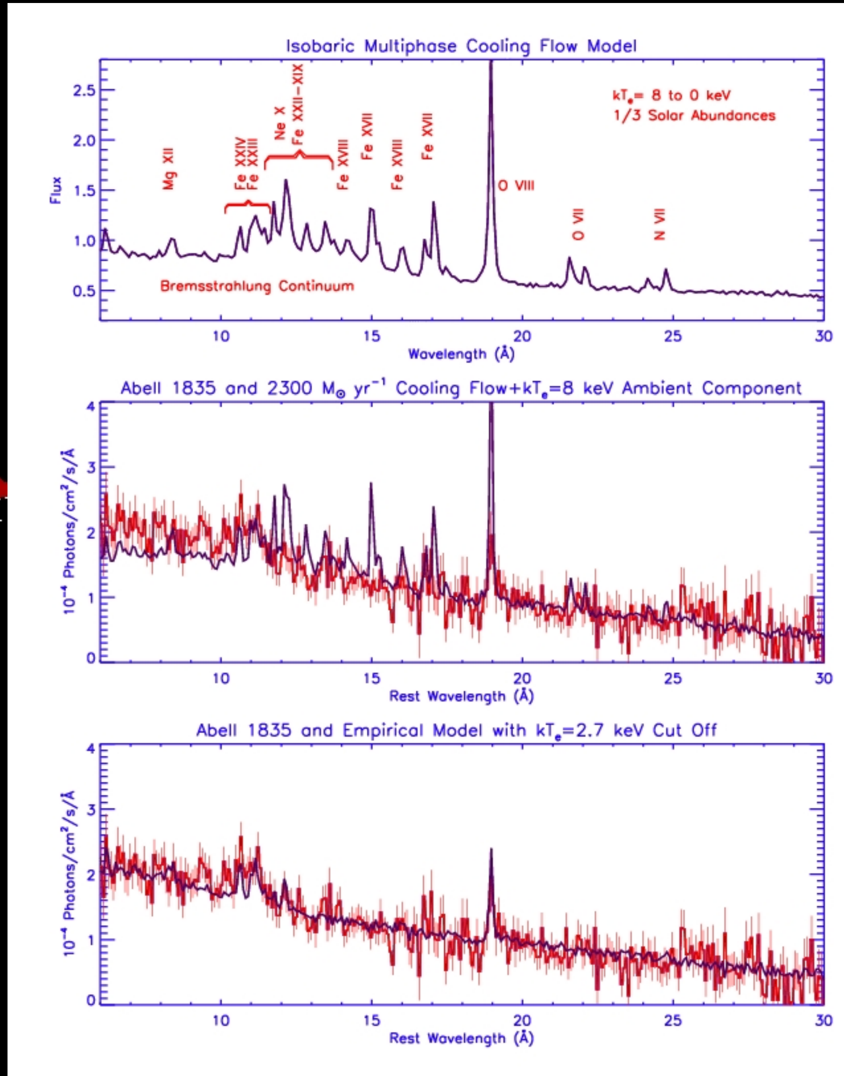
HCG 15
multiple E & S0s

Stephan's Quintet (HCG 92)
Spiral-rich
(O'Sullivan et al. 2009)

Why feedback is necessary - cooling flows

Fabian & Nulsen 1977

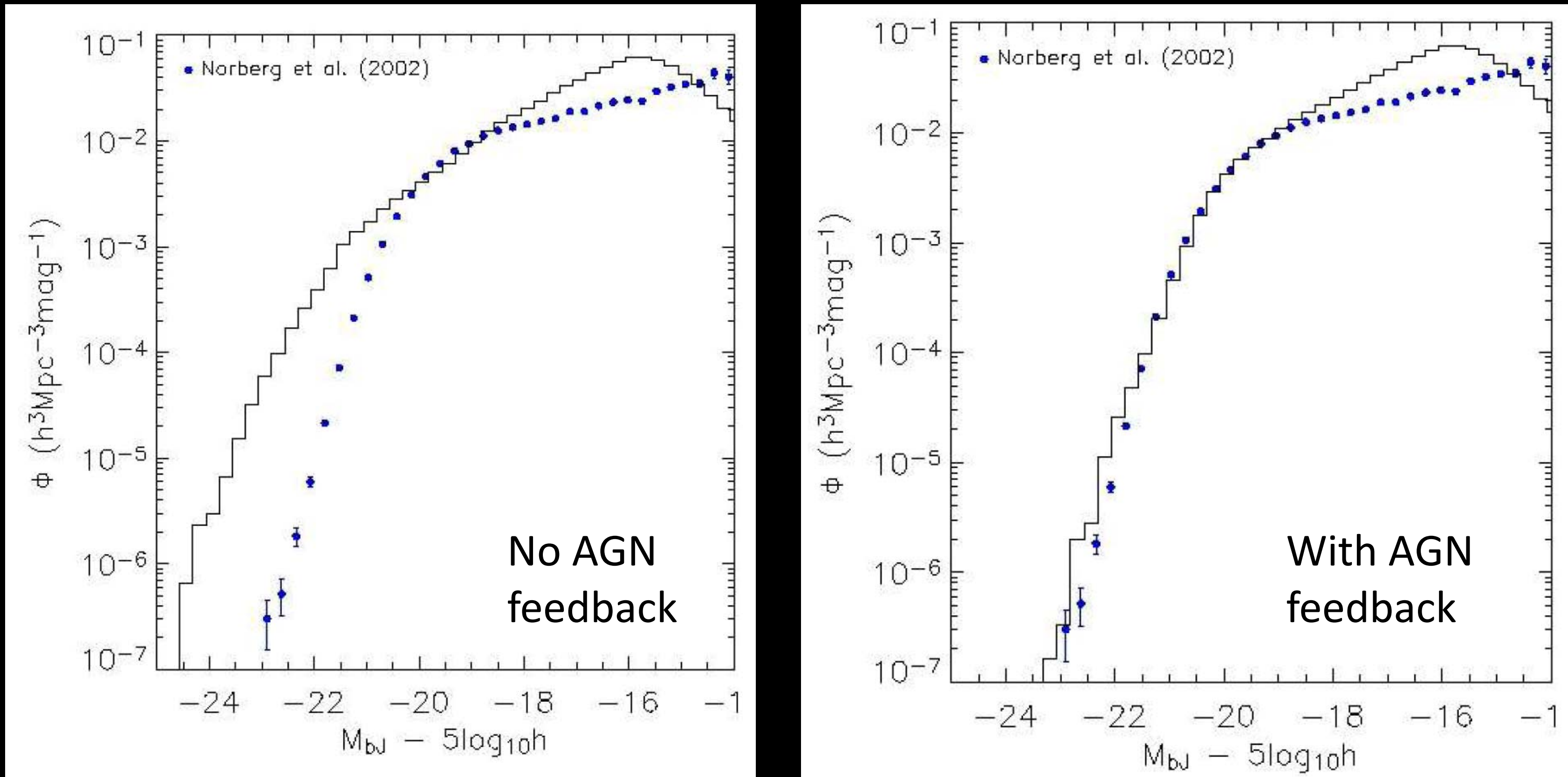




Peterson & Fabian 2006

- Relaxed clusters expected to have central cooling flows.
- XMM/Chandra show little gas cooler than $kT_{max}/3$.
- What suppresses cooling?

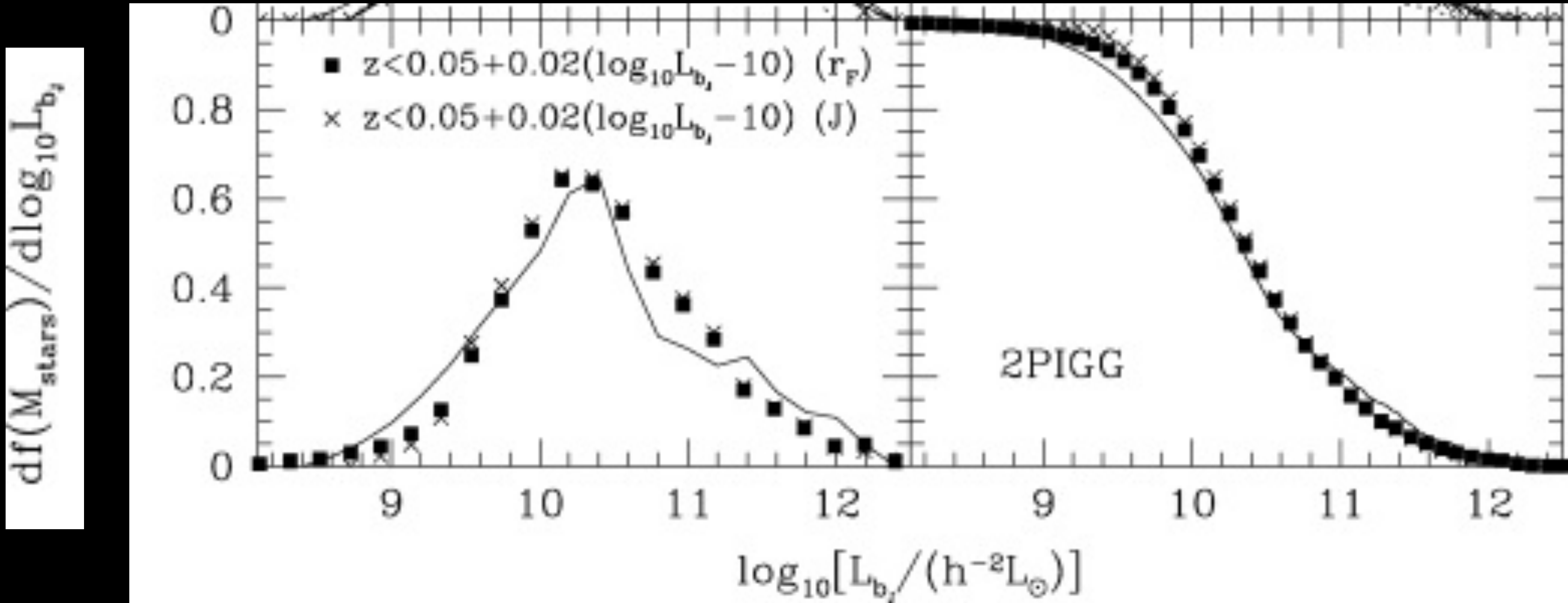
Why feedback is necessary - overcooling



Croton et al. 2004

Cosmological simulations without feedback produce too many stars and too many high-mass galaxies.

Why look at groups rather than clusters?

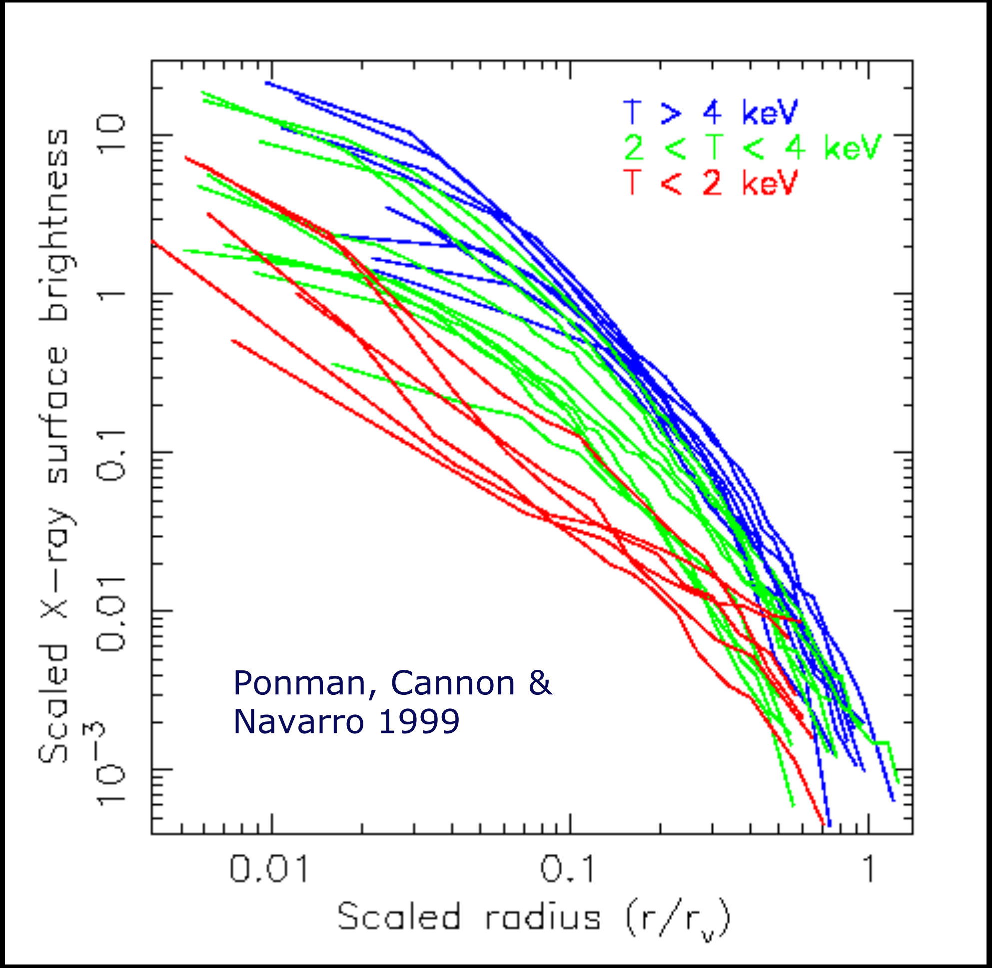


Eke et al. (2005) Log Stellar Mass 10, 11, 12 ≈ Log Total Mass 12, 13.6, 14.7

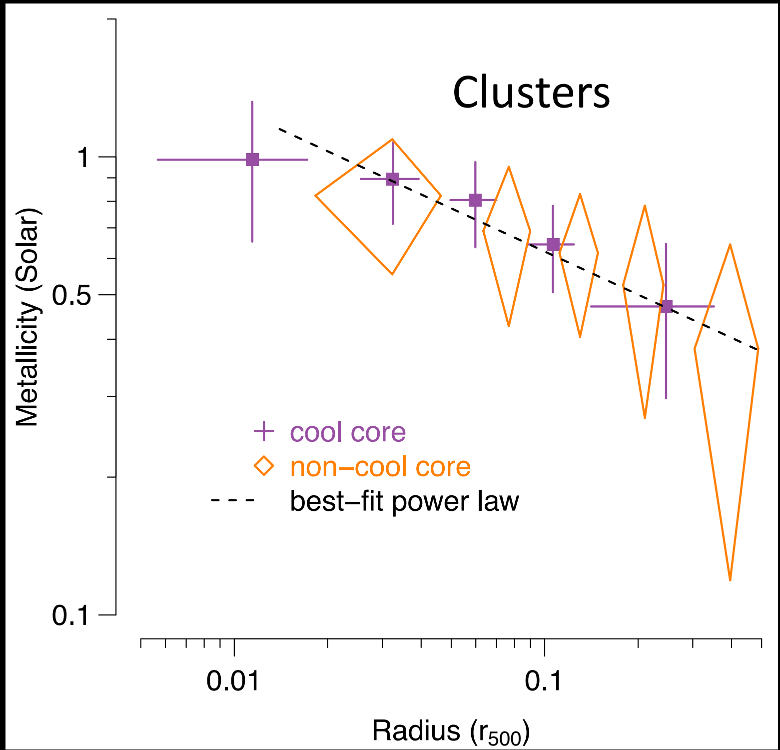
1. Only 2% of stars are found in clusters (log $L_B/L_\odot$ > 12)
   - Half of all stars in systems with log $L_B/L_\odot$ = 10-11 -- galaxies & small groups.
   - Massive groups (log $L_B/L_\odot$ ≈ 11) most typical environment of feedback.
2. Groups are locus of much galaxy evolution, so impact of feedback important
3. Lower mass and temperature mean feedback needed on short timescales and has potential to affect IGM more easily than in clusters.

Why look at groups? - Similarity breaking

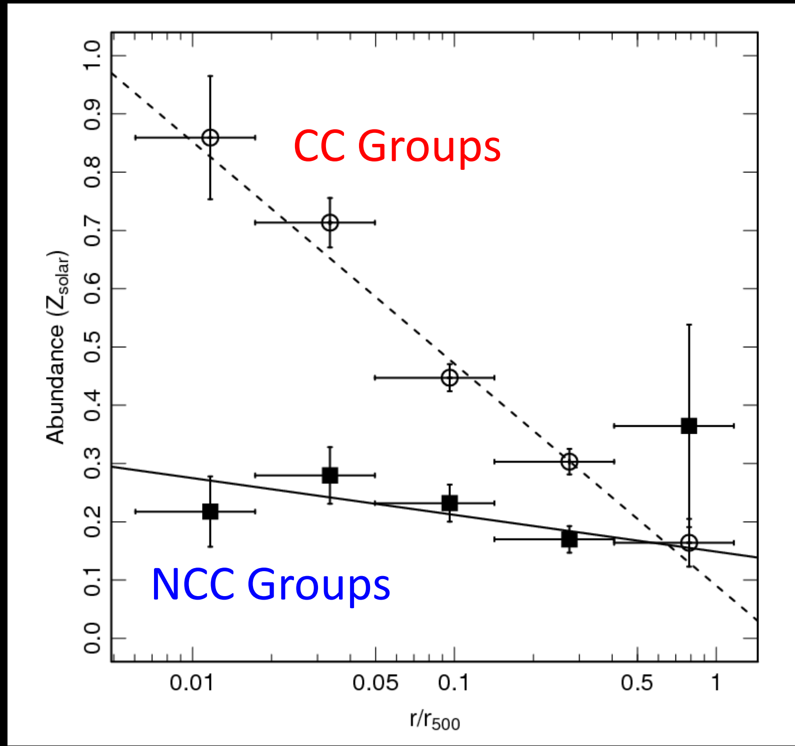
- Simplest models of clusters and groups are self-similar – everything scales simply with mass.
- Observations show similarity breaking.
- Cooler (less massive) systems have flatter emissivity and gas density profiles.



Why look at groups? - Abundance gradients



Sanderson, O'Sullivan & Ponman 2009



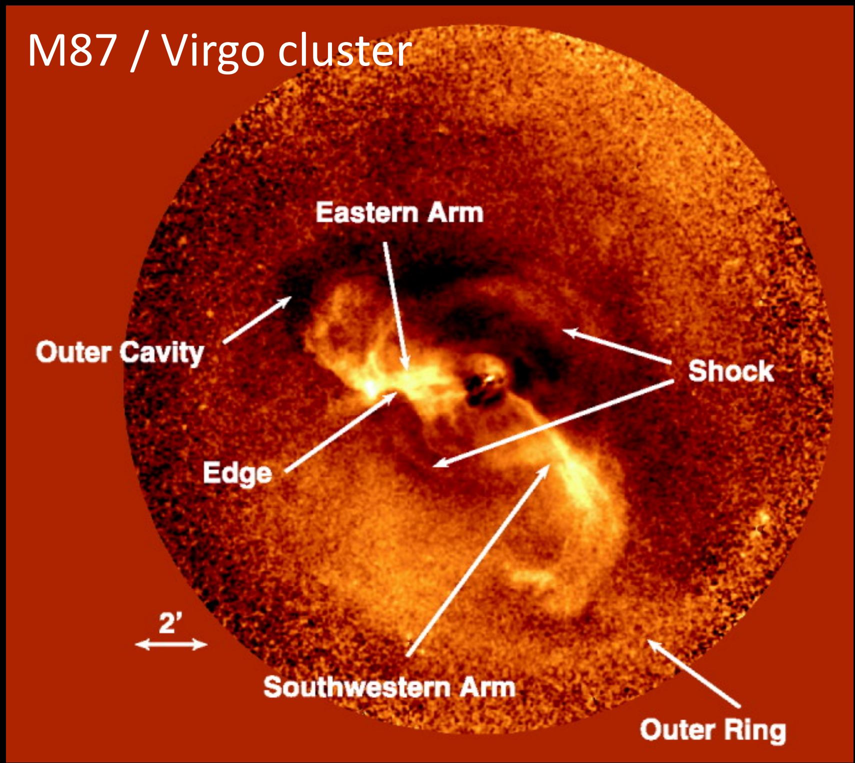
Johnson et al., MNRAS submitted

- Clusters have abundance gradient regardless of CC/NCC.
- NCC groups have much flatter abundance gradient than CC.
- Either CC and abundance peaks never form, or they are destroyed, probably by the same process ➔ gas mixing?

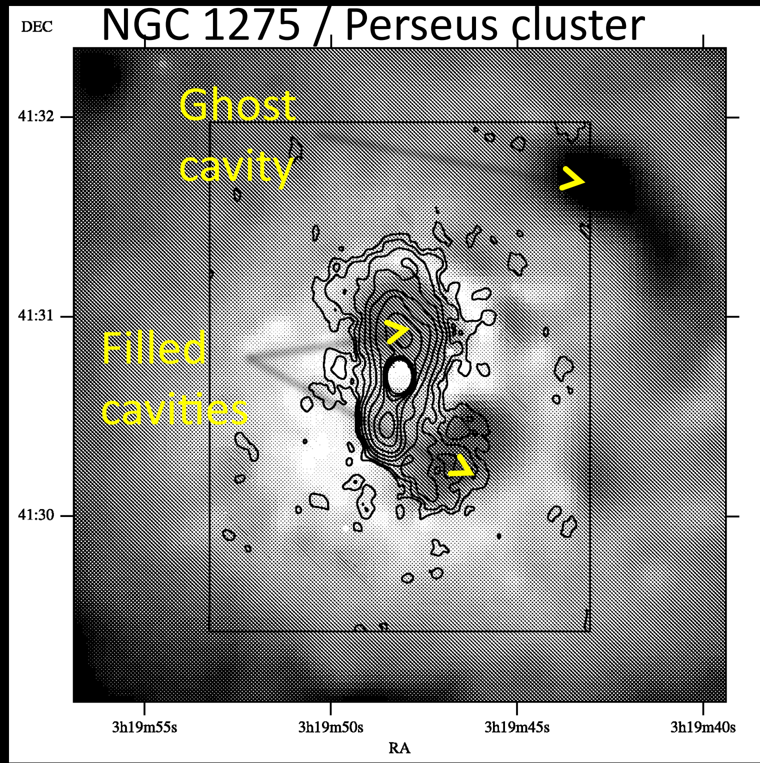
Potential sources of heating

1. Mergers
   - Large energy release, few 10^{63} erg. ✓
   - Only a few systems merging at any time. ✗
   - Do not break similarity. ✗
2. Supernovae
   - Inject ~1 keV/particle, OK for similarity breaking. ✓
   - Little star formation in X-ray bright group cores. ✗
   - More use in galaxies / small groups. ✓
3. Conduction
   - May stabilise NCC. ✓
   - Requires >Spitzer conductivity to heat cool cores. ✗
   - Magnetic suppression a serious problem. ✗
4. AGN
   - AGN common in CC systems. ✓
   - Feedback model ties heating to cooling. ✓
   - Heating occurs where most needed. ✓

AGN feedback as observed in clusters



Unsharp X-ray image (Forman et al. 2007)

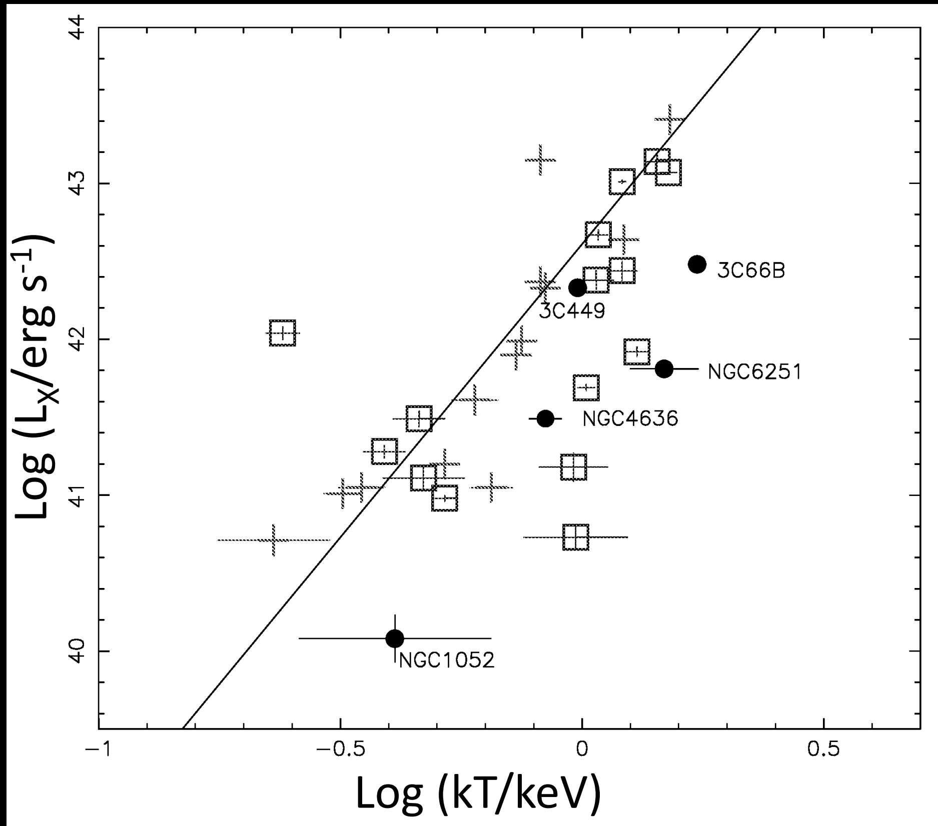


1.4 GHz on X-ray (Fabian et al. 2002)

- Radio galaxies in centers of 70-100% of CC clusters (Blanton et al. 2010)
- Cavities form in pairs, rise buoyantly, radio emission fades.
- Heating via shocks, PdV work done by expanding cavities, etc.

Evidence for AGN heating in groups

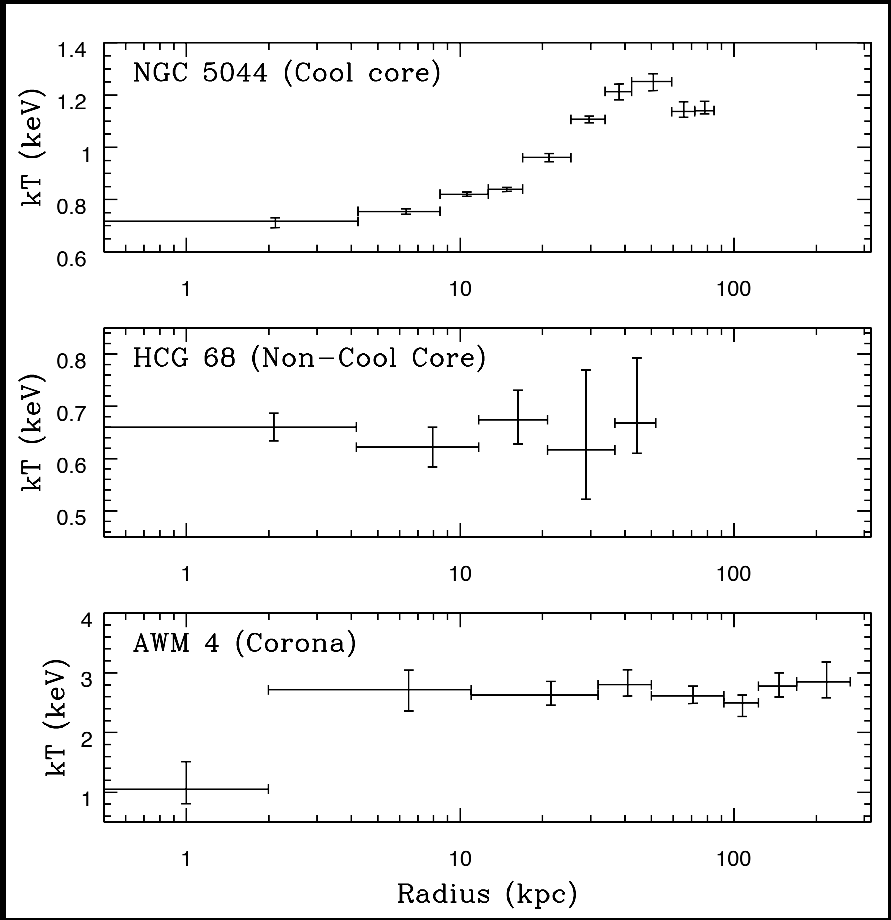
- Croston et al 2005: Radio-loud groups tend to have higher kT than expected.
- Dong et al. 2010: 26 of 51 nearby groups have definite or probable cavities.
- All 26 are CC systems. Only 4 NCC groups in sample, but none have cavities.
- AGN are capable of heating groups and are commonly seen to affect the IGM.



Croston, Hardcastle & Birkinshaw (2005)
+= radio quiet, ☐=radio loud

Groups & Clusters – Temperature Structure

- Usually classified as cool-core or non-cool-core.
- In clusters, CC/NCC split is roughly 50/50.
- Few NCC groups are observed but we have no statistical sample.
- New class – Galactic Coronae. Small cool cores only a few kpc across (Sun et al. 2007, 2009).
- kT, L_X, Abundance consistent with being gas from stellar mass loss, not intra-cluster medium.
- Strong kT jump at boundary➔ conduction suppressed by magnetic fields.

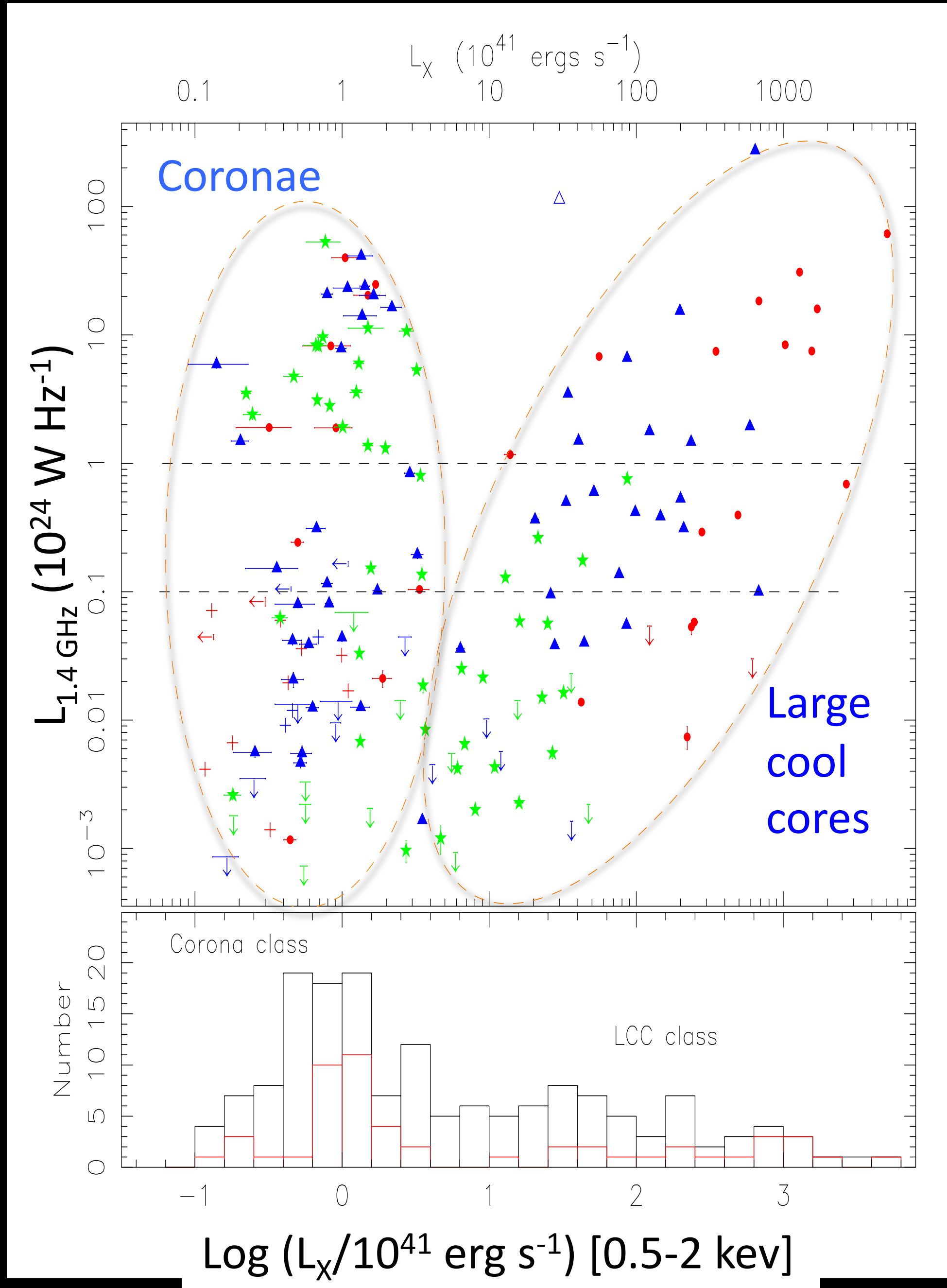


Coronae vs Large Cool Cores

Core L_X vs BCG L_{radio} (Sun 2009)

FR-I radio galaxies in BCGs all located in cool core of some kind.

Radio power not related to type of cool core – coronae can power strong AGN outbursts



Summary so far…

- Why do we need feedback?
  - As in clusters: to suppress cooling and star formation at high and low redshift.
  - To explain similarity breaking.
  - Specific to groups: to explain the flat abundance profiles of NCC groups?
- What form does feedback take?
  - AGN, fuelled by cooling gas, creating shocks and cavities.
  - Star-formation, mergers, conduction can help in some cases but are probably not the dominant process.
  - Evidence that AGN are common and effective in groups.

The GMRT Groups project

No statistical sample of nearby groups currently available!

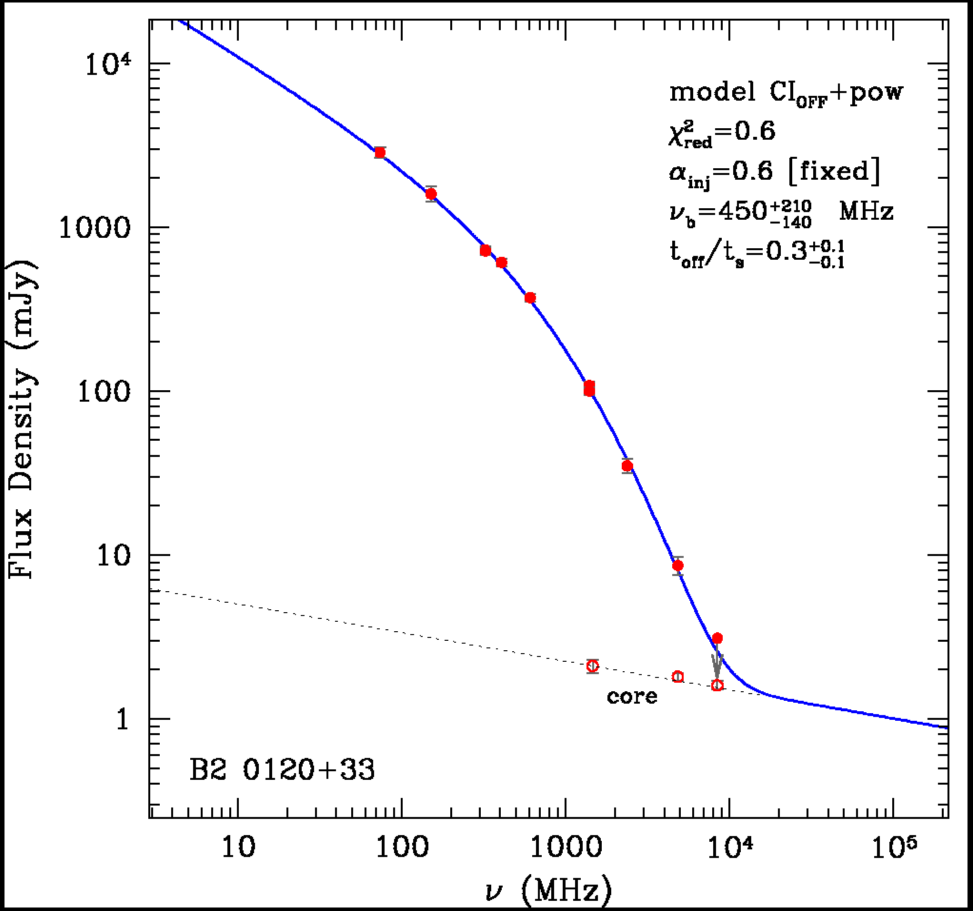
Our sample – 18 groups with Chandra/XMM X-ray data and GMRT low-frequency radio observations, covering a wide range of group and radio galaxy properties.

X-ray provides –
1) Location/properties of most baryons.
2) Estimation of energy in cavities, shocks, conduction & cooling rates.
3) Dynamical limits of age of structures.
4) Information on gas motions.

Radio provides –
1) Timescales via Synchrotron aging.
2) Constraints on source geometry.
3) Direct view of AGN/gas interactions.

Why low-frequency radio?

- As radio plasma ages, high-frequency declines fastest ➔ older structures easier to see at lower frequencies.
- Spectral index measured at high frequency steep, broader spectrum gives better estimate of total power.
- Break frequency allows age to be estimated.



NGC 507 (Murgia et al. in prep.)

GMRT sensitivity (for 2-3hr obs.):

rms ≈ 50-100 μJy/b @ 610 MHz

rms ≈ 300-500 μJy/b @ 235 MHz

Resolution: 5” at 610 MHz to 12” at 235 MHz (HPBW)

GMRT groups – project goals

1. How are X-ray and radio structures correlated?

   Do radio lobes always form cavities? How do AGN drive gas mixing?

2. What are the properties of group central radio galaxies?

   e.g., outburst timescale & energy, duty cycle, particle content of lobes, etc. Can AGN alone balance cooling in groups?

3. How are the effects of AGN related to their lifecycle and environment?

4. What are the mechanisms of energy injection?

   How is the jet energy distributed isotropically? Can we say whether shocks, cavities, or some other mechanism is dominant?

5. Is feedback in groups and clusters similar?

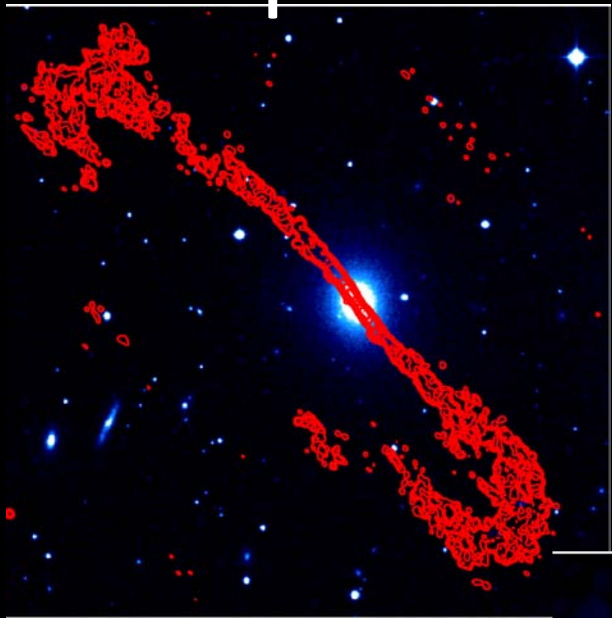
   Similarity breaking suggests groups have different history - is this related to feedback?

GMRT Groups sample

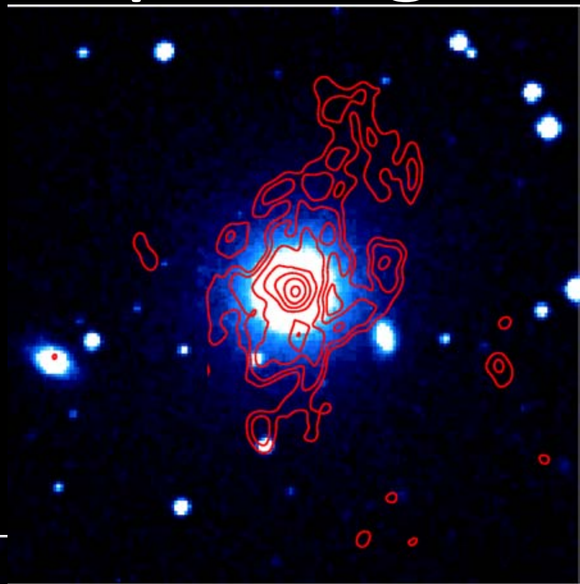
GROUP	z	Chandra	XMM	150 MHz	235 MHz	327 MHz	610MHz	Papers?
UGC 408	0.0147	✓		✔	✓		✓	CfA in prep…
NGC 315	0.0165	✓	✓		✓		✓	
NGC 383	0.0170	✓	✓		✓		✓	
NGC 507	0.0165	✓	✓		✓		✓	
NGC 741	0.0185	✓	✓		✓		✓	Jetha 08 +…
HCG 15	0.0208		✓		✓	✓	✓	
NGC 1407	0.0059	✓	✓		✓	✔	✓	
NGC 1587	0.0123	✓			✓		✓	
MKW 2	0.0368		✓		✓		✓	
NGC 3411	0.0153	✓	✓		✓		✓	O'S 07
NGC 4636	0.0031	✓	✓		✓		✓	O'S 05 + Baldi 09
HCG 62	0.0137	✓	✓		✓	✔	✓	Gitti (ApJ sub.)
NGC 5044	0.0090	✓	✓	✔	✓	✓	✓	David 09 +…
NGC 5813	0.0066	✓	✓	✔	✓			CfA in prep…
NGC 5846	0.0057	✓	✓				✓	
AWM4	0.0318	✓	✓		✓	✓	✓	SG 08+2xO'S 10
NGC 6269	0.0348	✓			✓		✓	Baldi 09
NGC 7626	0.0114	✓	✓	✔	✓		✓	Randall 09

GREEN = images/fluxes/spectra available RED = approved or unprocessed

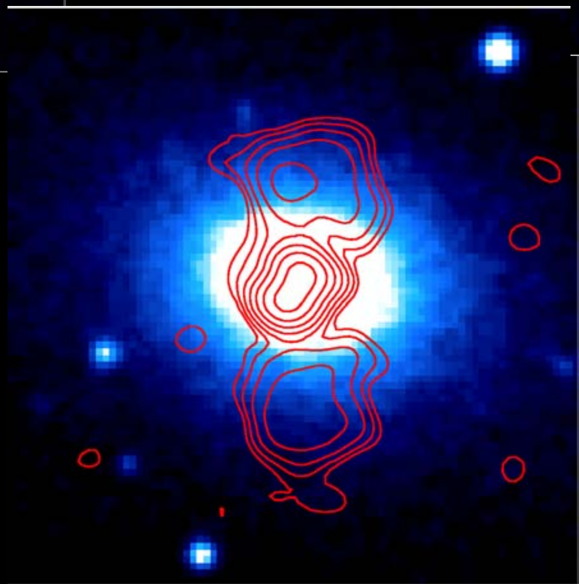
Groups - diverse radio morphologies



NGC 7626 - classic giant radio galaxy
610 MHz, res: 6”x5”
Major axis: 150 kpc



NGC 3411 - amorphous
610 MHz, res: 10”x7”
Major axis: 75 kpc

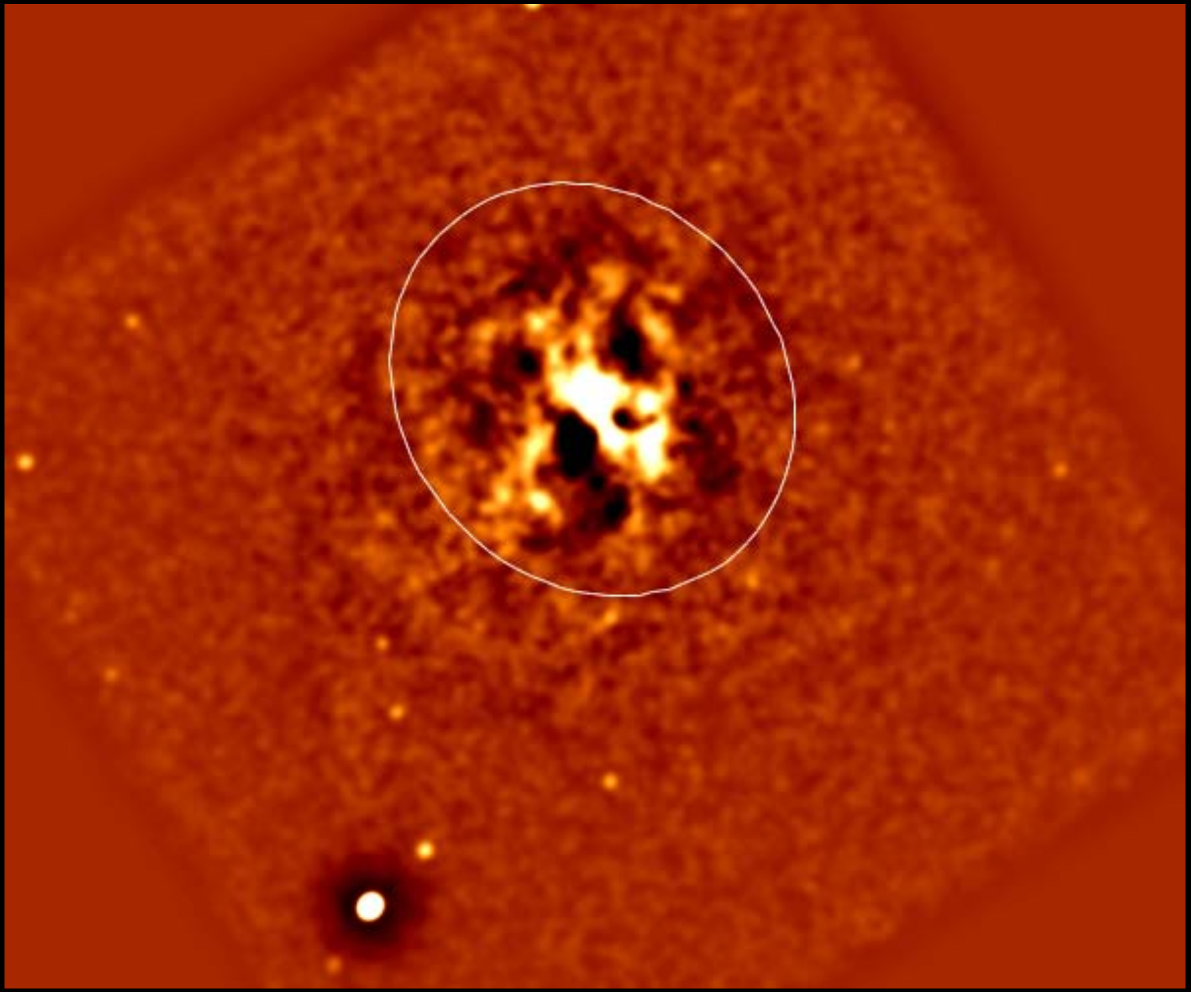


NGC 6269 - compact double-lobed source
610 MHz, res: 5”x4”
Major axis: 30 kpc

NGC 5044 – *Chandra* X-ray

- One of the brightest nearby galaxy groups (~10^{43} erg/s)
- Prior observations reveal some structure in X-ray
- X-ray image shows numerous cavities, filaments, fronts.
- Cavities are small but spread throughout the core, not just along main axis.
- At 1.4 GHz, only a central point source is detected.

David et al. 2009, ApJ, 705, 624

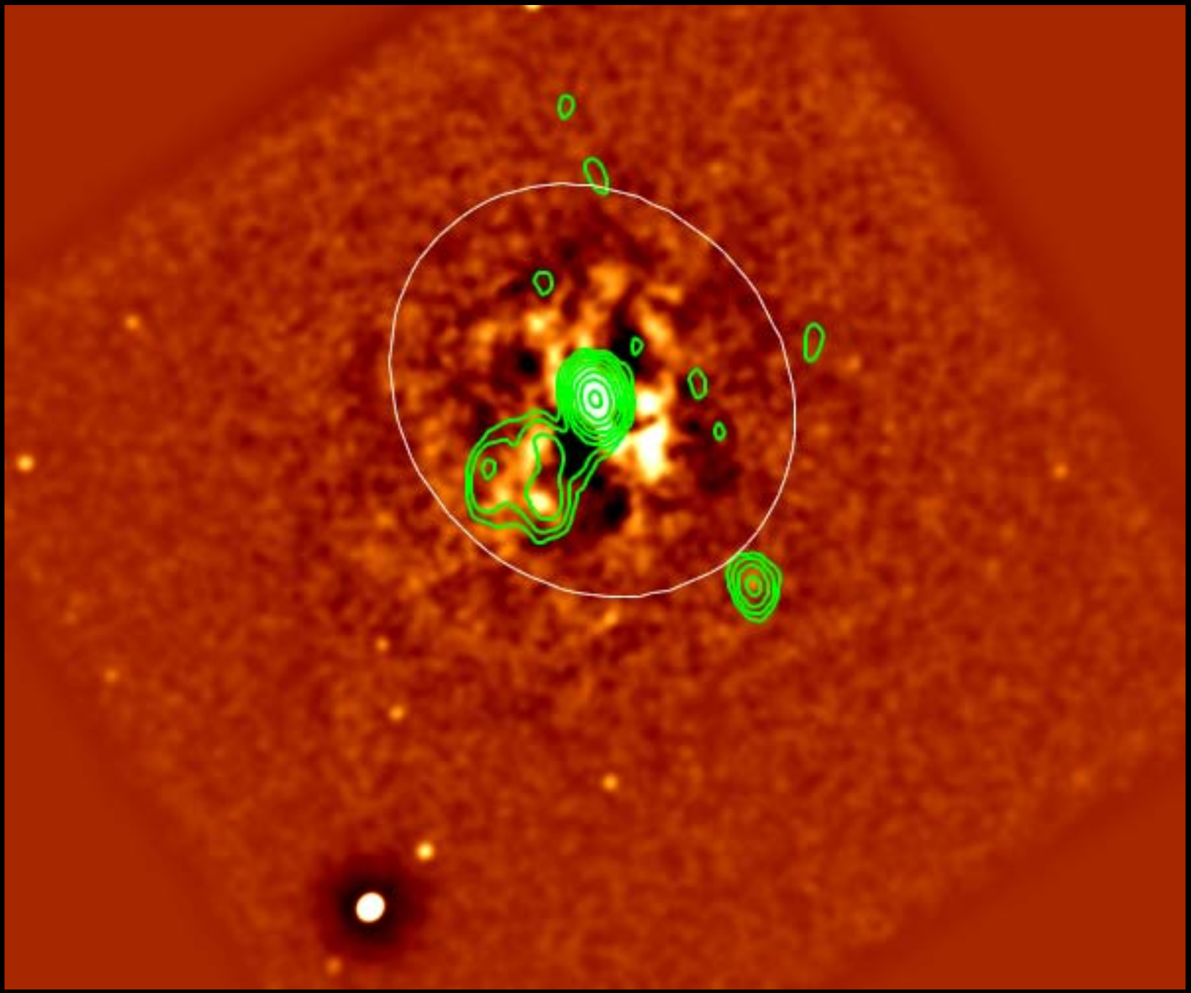


80ks 0.3-2 keV Chandra unsharp image, D_{25} ellipse overlaid

NGC 5044 – GMRT radio

At 610 Mhz:
Radio structure is extended – rising torus drawing out X-ray filament?

David et al. 2009, ApJ, 705, 624



0.3-2 keV Chandra unsharp image, D_{25} ellipse overlaid
GMRT 610 MHz contours

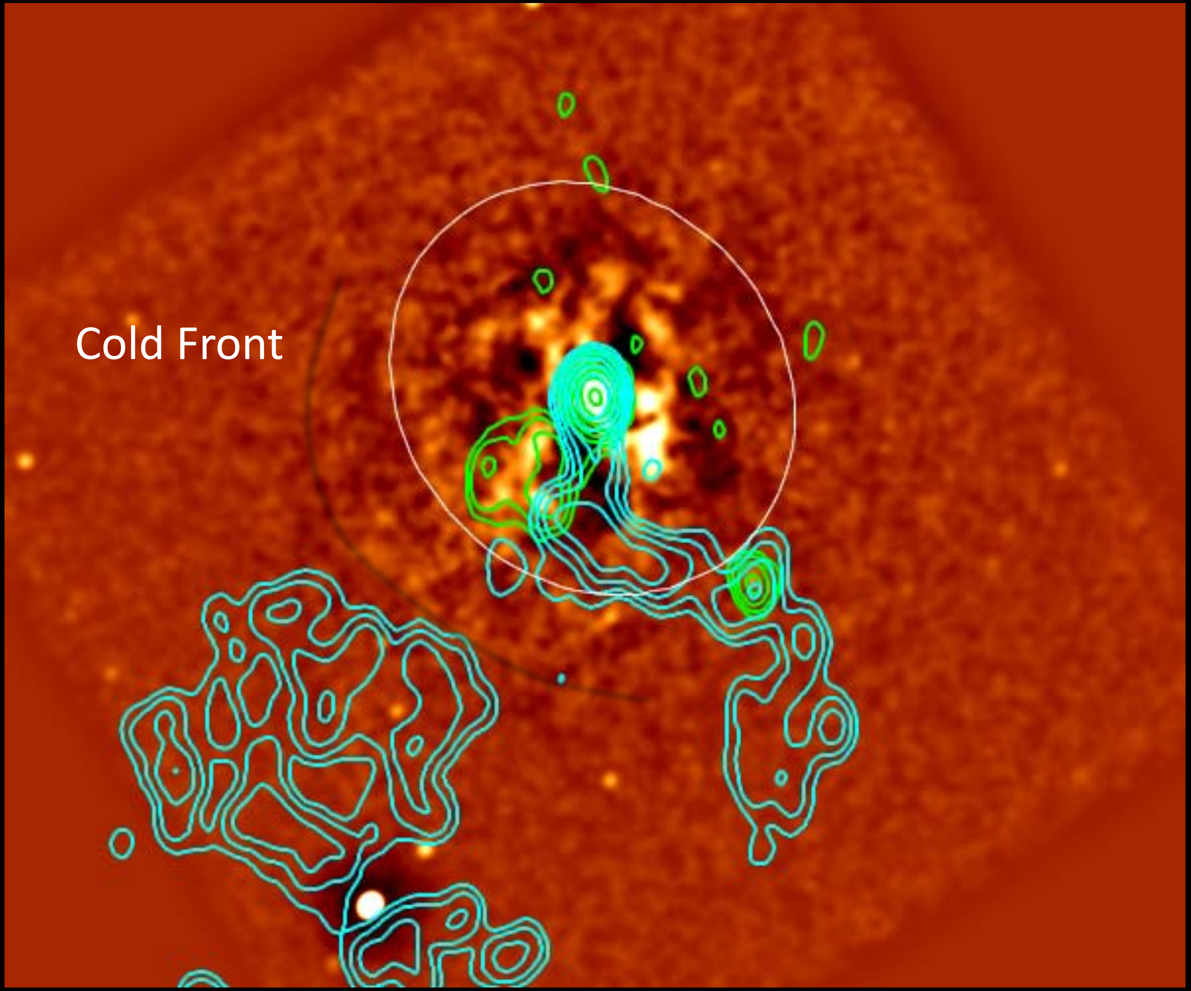
NGC 5044 – GMRT radio

At 235 MHz:

1. Detached radio lobe to the SE.
2. Filament following X-ray channel
3. Correlation between X-ray surface brightness front, filament and detached lobe.

We are seeing structures formed in two separate outbursts, and their interaction with the environment.

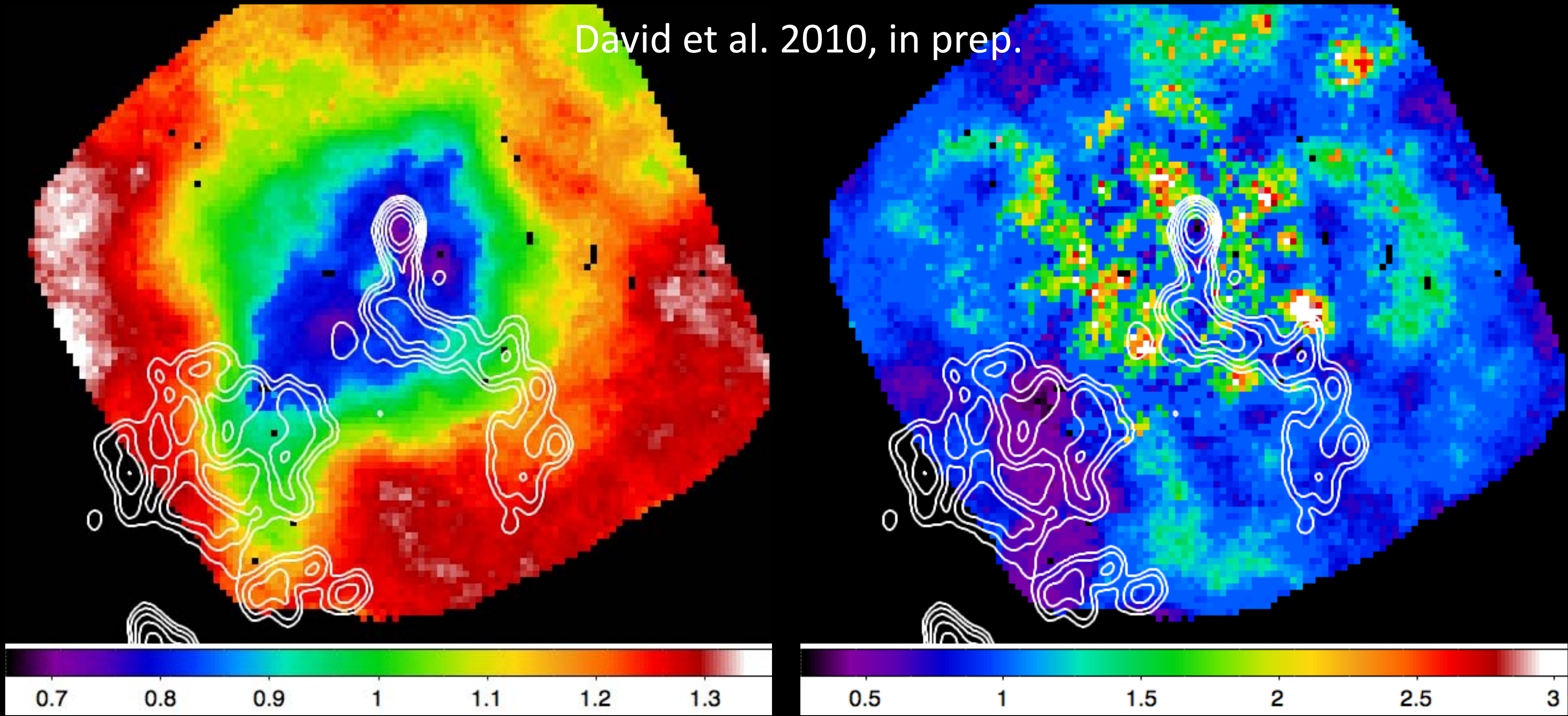
David et al. 2009, ApJ, 705, 624



0.3-2 keV Chandra unsharp image, D_{25} ellipse overlaid
GMRT 610 MHz contours   235 MHz contours

NGC 5044 – X-ray spectral maps

Temperature (keV) Abundance (solar)



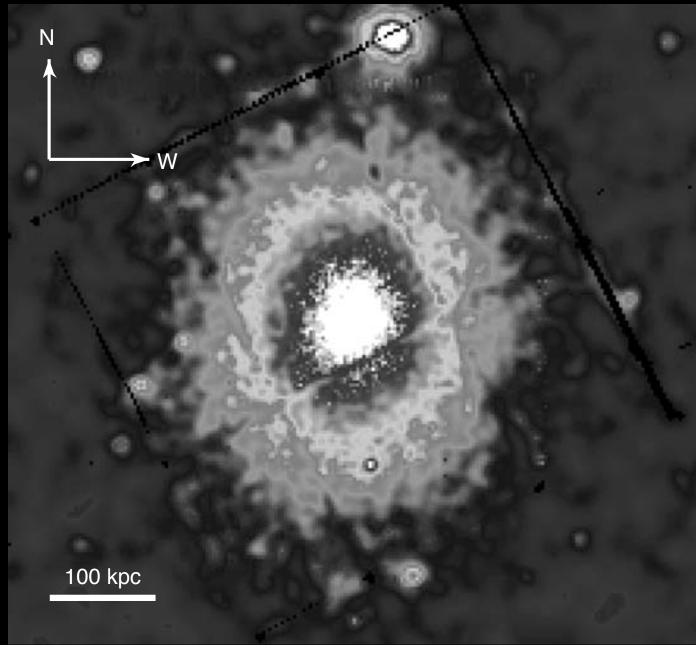
- Temperature drawn out to SE, following detached lobe → gas motion.
- High abundance features (2-3 solar!), low abundances regions correlate with cavities, radio structure →multiphase gas.
- Many small outbursts, cavities spread isotropically in core by gas motions.

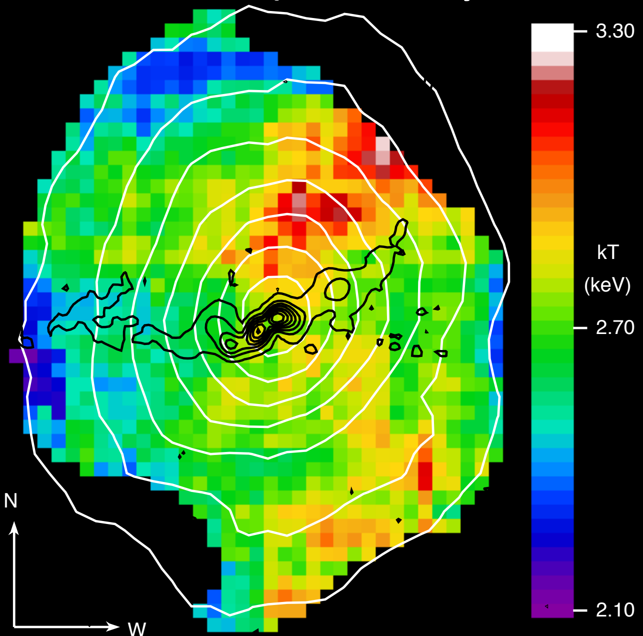
NGC 5044: Take-home points

- Low-frequency radio observations allow us to see evidence of multiple episodes of AGN jet activity
  ➔ direct measurement of the duty cycle.
  - Not unique, we see multiple episodes in other groups In our sample.
  - BUT in NGC 5044 we need deeper radio to measure the age and estimate the duty cycle.
- Many small cavities seen throughout the core
  ➔ mechanism for isotropic heating by jets & cavities.
  - Cavities probably moved by "weather", gas motions caused by movement of galaxy in group, effects of the AGN itself.
  - Gas motions lift cool gas out of group core, reducing its cooling rate.
  - Group core contains multiphase gas, implications for abundance measurements and pressure balance, mass measurements, etc.

AWM4: XMM-Newton data (O'Sullivan et al. 2005)

- ~2.6 keV poor cluster, relaxed morphology centred on BCG, no X-ray AGN
- No obvious substructure in galaxy population
- Fairly powerful central radio source 4C+24.36 (608 mJy @1.4 GHz)



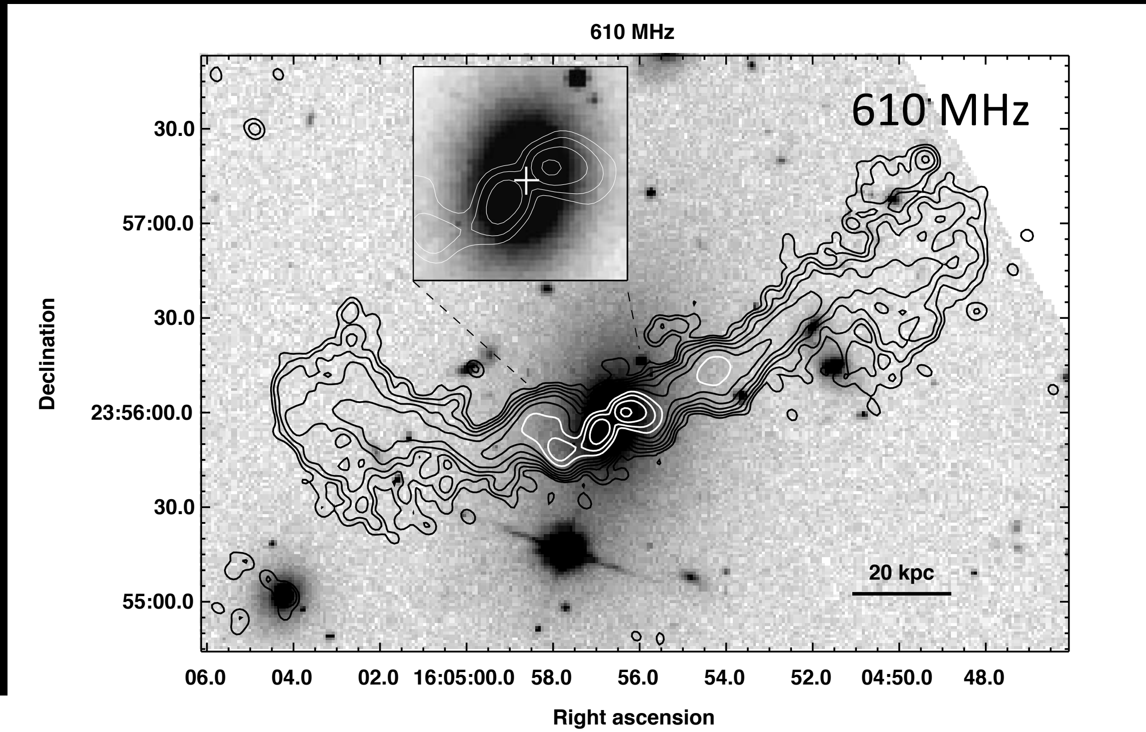


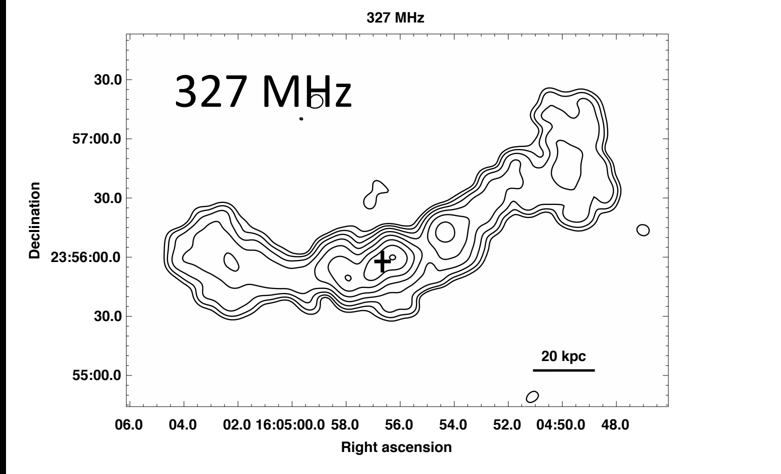
Surprises:

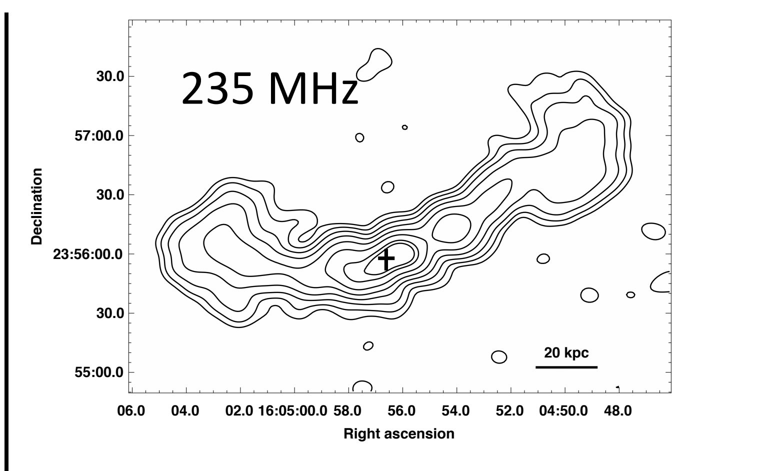
- **Isothermal – no cool core despite radio galaxy**
- **Lobes too small to heat system - ~9x10^{58} erg required**

AWM4: GMRT observations (Giacintucci et al. 2008)

- GMRT data to determine true extent of radio source, alignment, properties.
- 120min @ 610 MHz, 100@ 327 MHz, 160@ 235 MHz
- Large lobes detected
- 1.4 GHz obs only trace jets out to knots/bends
- Small scale jets <10° from plane of sky

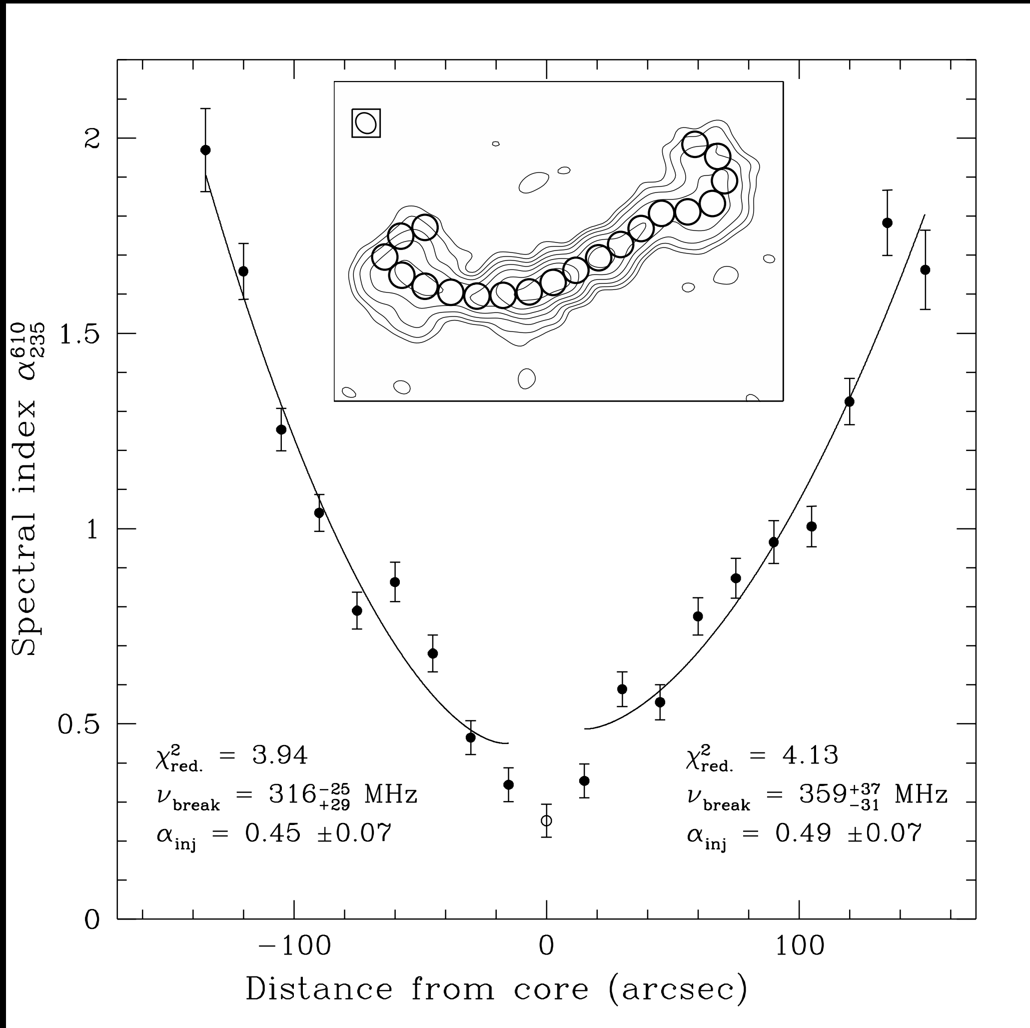






AWM4: radio source properties

- Model spectral index change along jets with Jaffe & Perola (1974) model
- Both jets give similar results
- Age ~170 Myr – very old (few 10s Myr typical)
- Pressure in lobes ~2.5x10^{-12} erg cm^{-3} -- factor ~15 lower than X-ray pressure, but this is common
- If lobes are empty, their enthalpy (4PV) might be enough to counter cooling, but no cavities detected by XMM.



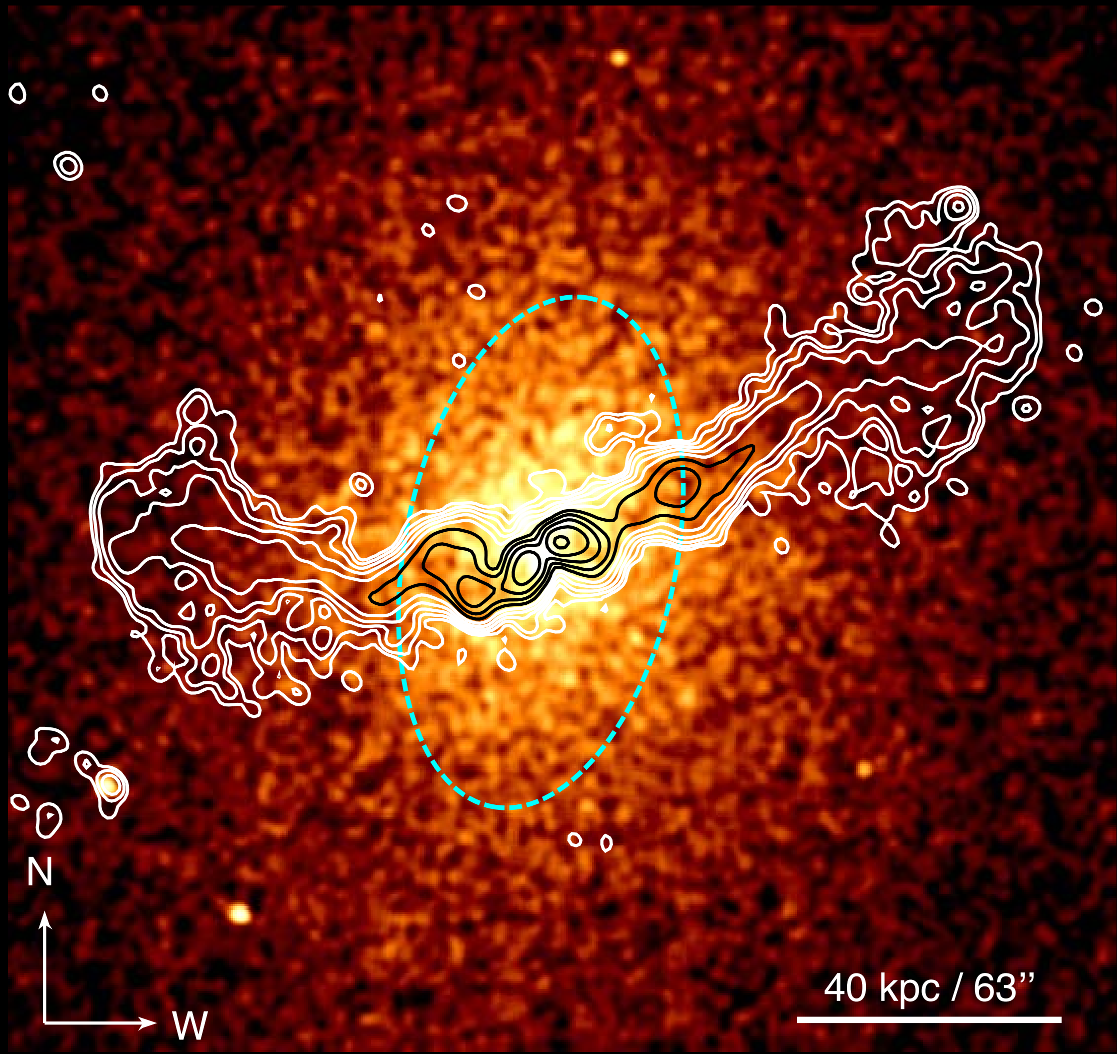
Giacintucci et al. 2008

AWM4: unresolved questions

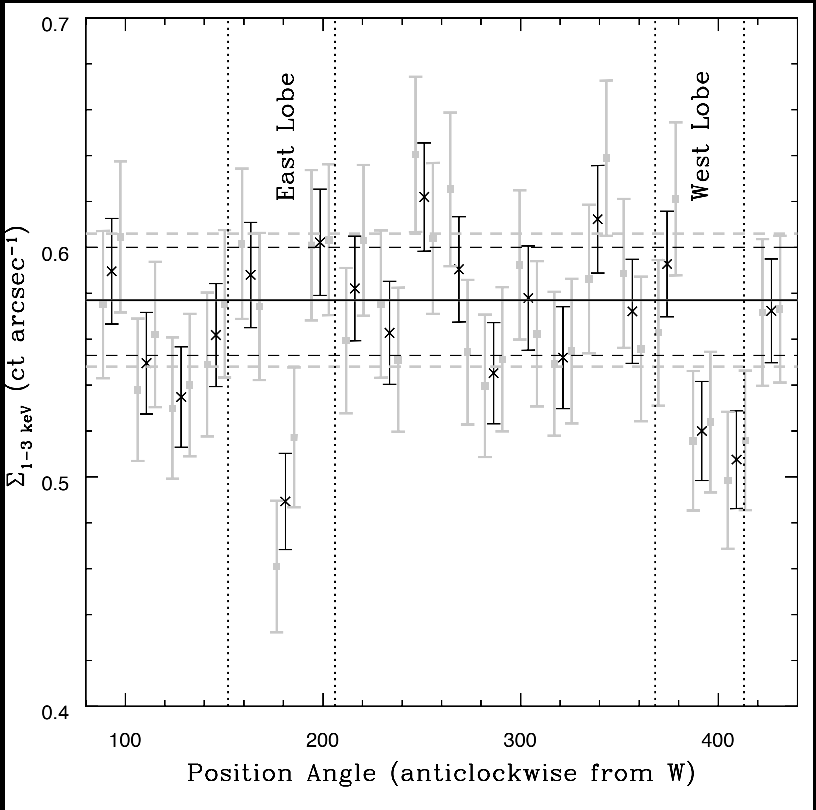
1. What fuels the AGN?
   - No cool core detected.
   - No indications of merger or cold gas in BCG.
2. Can the AGN balance cooling? How does it heat the gas?
   - Cavities associated with the lobes would be sufficient, but none detected by XMM.
   - No shocks detected – but XMM probably would not resolve them.
3. Why is the AGN so old?

AWM4: Chandra imaging

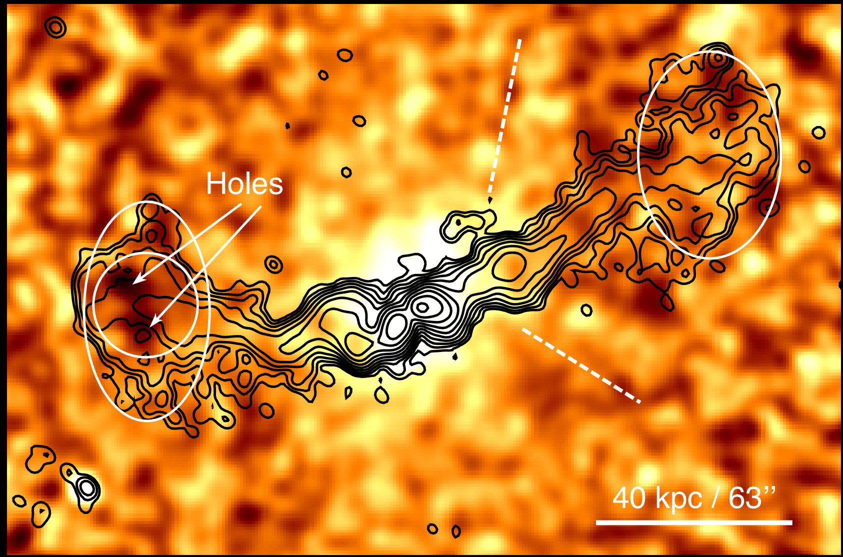
- ~80 ks exposure
- No shocks or fronts
- No clear cavities
- Slight offset of BCG to south of halo centroid – in motion as radio suggests?



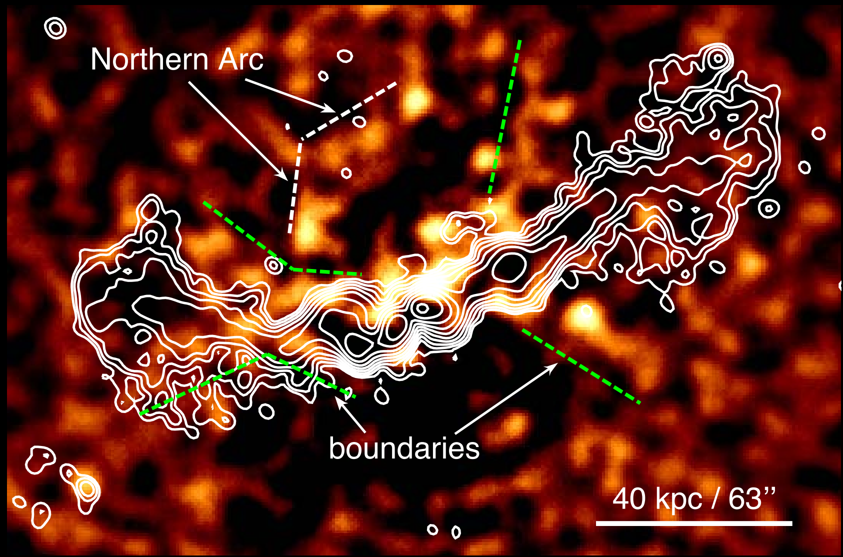
AWM4: Cavities?



- >3σ significant drop in surface X-ray brightness in E lobe, but smaller than the lobe – cavity?
- Broader, less significant western feature, weak filaments along jets?



1-3 keV unsharp masked image



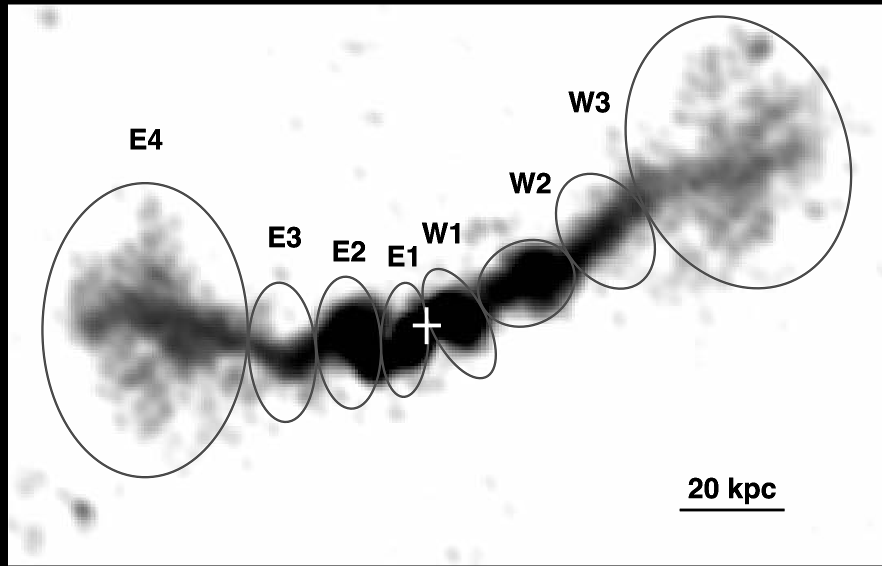
0.7-3 keV smoothed residual map

AWM4: Cavity Filling Factors

- We would expect to detect empty cavities for both lobes at 4-5σ significance ➔ somehow the cavities are "filled in".

Possibilities:

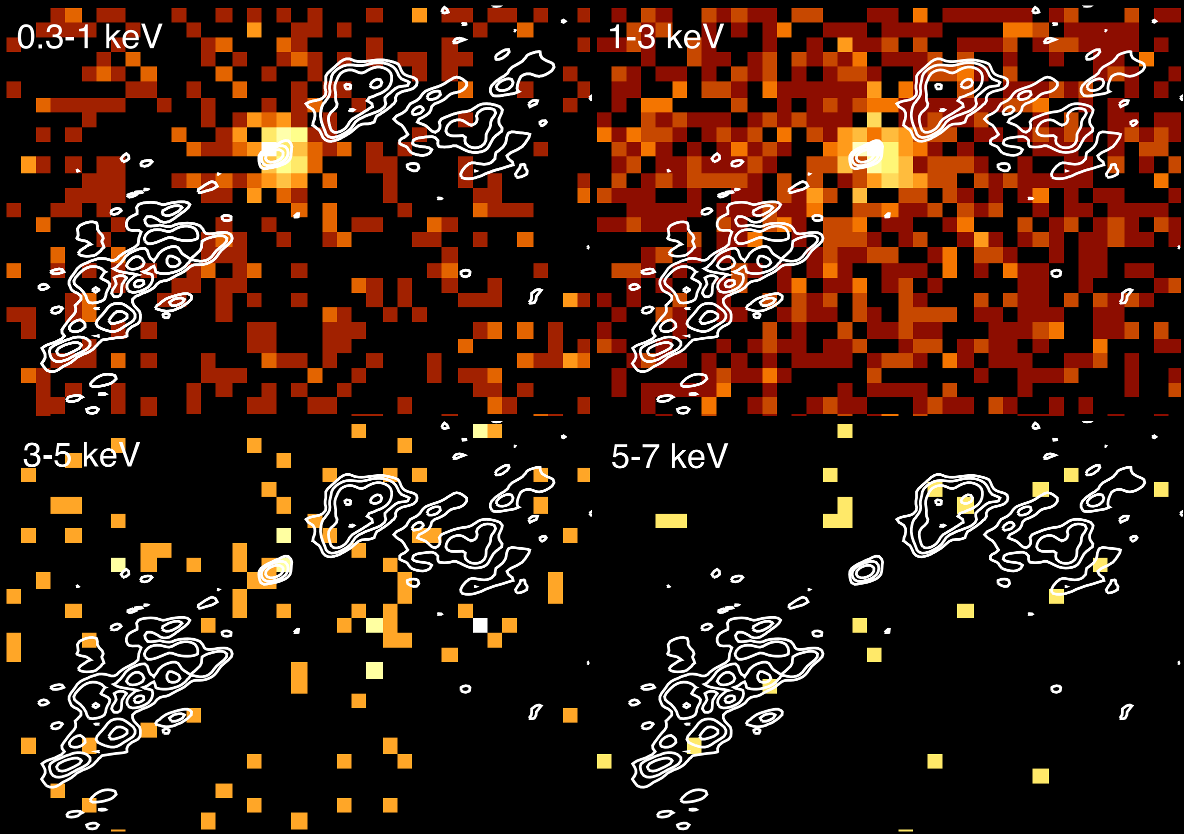
1. Expected Inverse-Compton flux from radio lobes a factor 10^{-4} too low.
2. Entrainment of ICM or stellar gas in the jets, without significant heating or mixing.
3. Mixing of the lobes with surrounding thermal plasma. Lobes possibly breaking up into clouds and filaments.



GMRT 610 MHz image (c/o Giacintucci)

Assuming lobes are mix of thermal and relativistic plasmas, the filling factors of radio-emitting component are:
Φ = 0.21 / 0.24 for east/west lobes
(3σ upper limits Φ<0.43 / 0.76)

AWM4: looking for a cool core



Raw Chandra images, 4.9 GHz VLA contours

- Small extended core source in soft bands (<3 keV), coincident with radio core.
- 3-5 keV counts consistent with LMXBs → AGN highly absorbed.
- Probable galactic corona – cool core made up of gas from the galaxy halo.

AWM4: the Corona

- 2-3 kpc radius, correlated with jet flare point
- ~1 keV compared to 2.6 keV ICM
- L_X~2x10^{40} erg/s
- t_{cool}=300 Myr, M_{cool}=0.067 Msol/yr
    - enough to fuel AGN given 0.1% efficiency
- Stellar mass losses in corona sufficient to replace gas lost through cooling.
- Spitzer conduction would heat in <20 Myr
- Jet would heat if interaction >0.4% efficient

  ➔ Magnetically isolated from AGN & ICM

  ➔ Breaks feedback cycle – the AGN does not reheat the gas which fuels is, so outburst is not self-limiting.

AWM4: Timescales and Energetics

Lobe	$t_{rad,total}$ $\gamma_{min}=100$ (Myr)	$t_{rad,total}$ $\gamma_{min}=10$ (Myr)	$t_{rad,lobe}$ $\gamma_{min}=100$ (Myr)	$t_{rad,lobe}$ $\gamma_{min}=10$ (Myr)	$t_{s,lobe}$ (Myr)	$t_{s,jet}$ (Myr)	t_{buoy} (Myr)	t_{refill} (Myr)
East	183^{+25}_{-24}	171^{+40}_{-15}	135^{+56}_{-66}	66^{+47}_{-41}	27.53	69.5	103.16	120.02
West	164^{+24}_{-23}	159^{+31}_{-22}	132^{+72}_{-52}	66^{+69}_{-48}	26.77	87.3	134.76	129.20

Dynamical age limits from X-ray & radiative age from radio. Two scenarios:

1. γmin=100, lobe has risen buoyantly to its position, slowing and either filling with entrained gas or beginning to break up.
   - Cavities/lobes main source of heating for ICM.
   - Jet power ~10^{43} erg/s, similar to L_X.

   ➔ Heating may only just balance cooling.
2. γmin=10, radiative age shorter than buoyant timescale, so jet expanded supersonically for some time.
   - Jet power doubles, additional heating from shocks.

   ➔ AGN could have reheated a large cool core.

AWM4: Take-home points

- The cavities in AWM4 are much weaker than expected. Are the lobes mixing with the ICM? Filled by entrained gas?
  - Plasmas still magnetically separated, little direct heating.
  - Outburst in AWM4 is unusually old, and we only see the lobes because we have low-frequency radio data. Do all lobes end up in this state?
  - Low filling factors mean less energy available to heat the ICM, but AGN power output still balances cooling.
- AWM4 hosts a corona of cool galactic gas, which can fuel the AGN indefinitely and is not heated by conduction or the jets. ➔ This breaks the AGN feedback loop.
  - May explain why outburst is so old, as feedback cannot stop it.
  - How did the corona form in the first place?