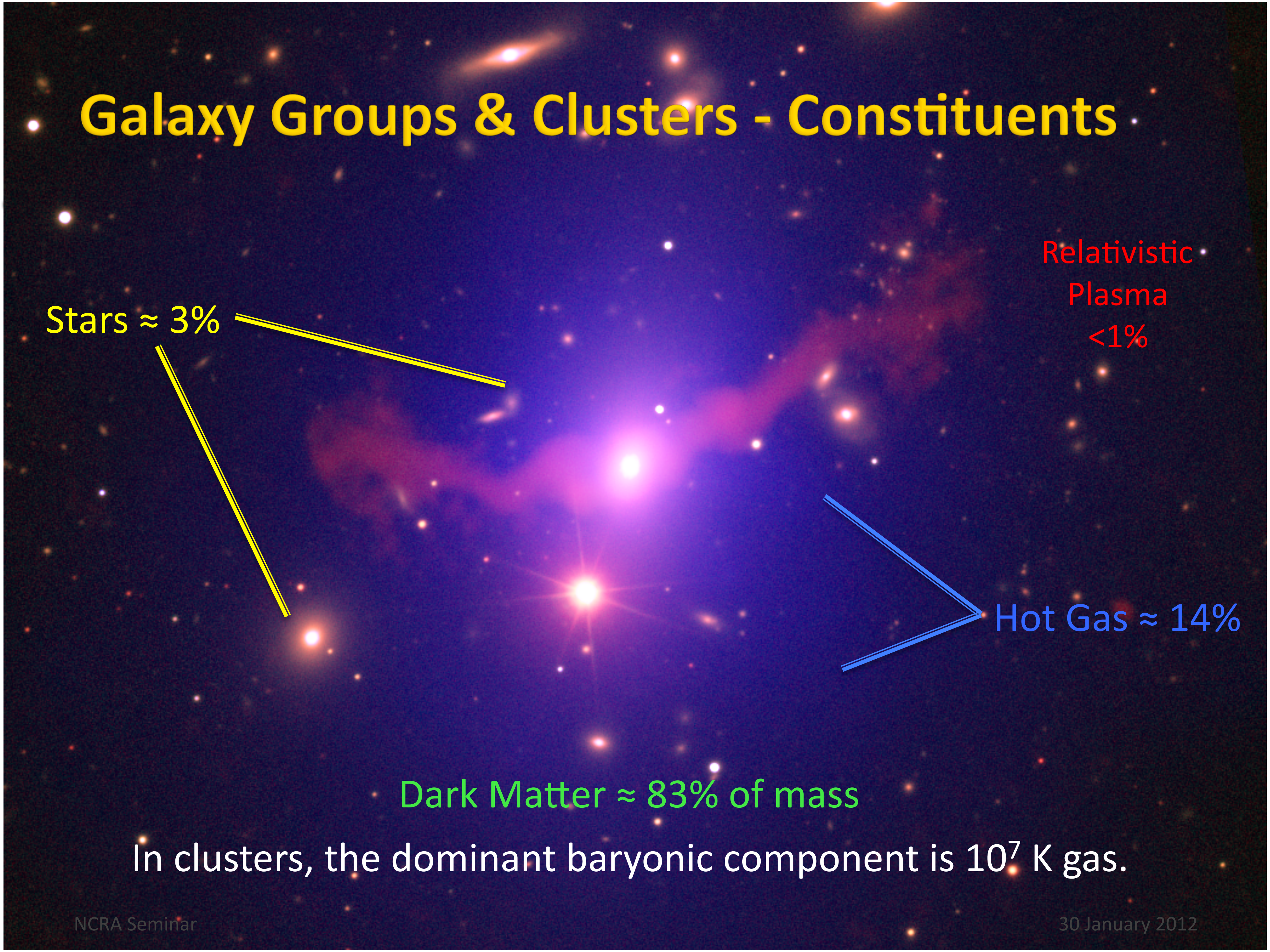
AGN feedback in galaxy groups

Ewan O'Sullivan (University of Birmingham/SAO)

With thanks to: S. Giacintucci (Maryland), M. Gitti (Bologna), S.Raychaudhury, K. Kolokythas & T.J. Ponman (Birmingham), C.H. Ishwara Chandra & N. Kantharia (NCRA), R. Athreya (IISER), L. David & J. Vrtilek (SAO)

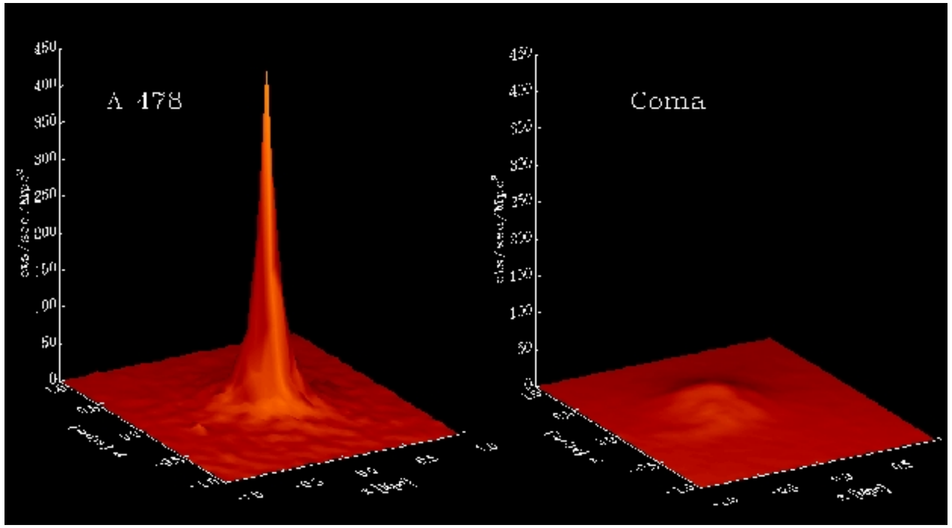
Overview

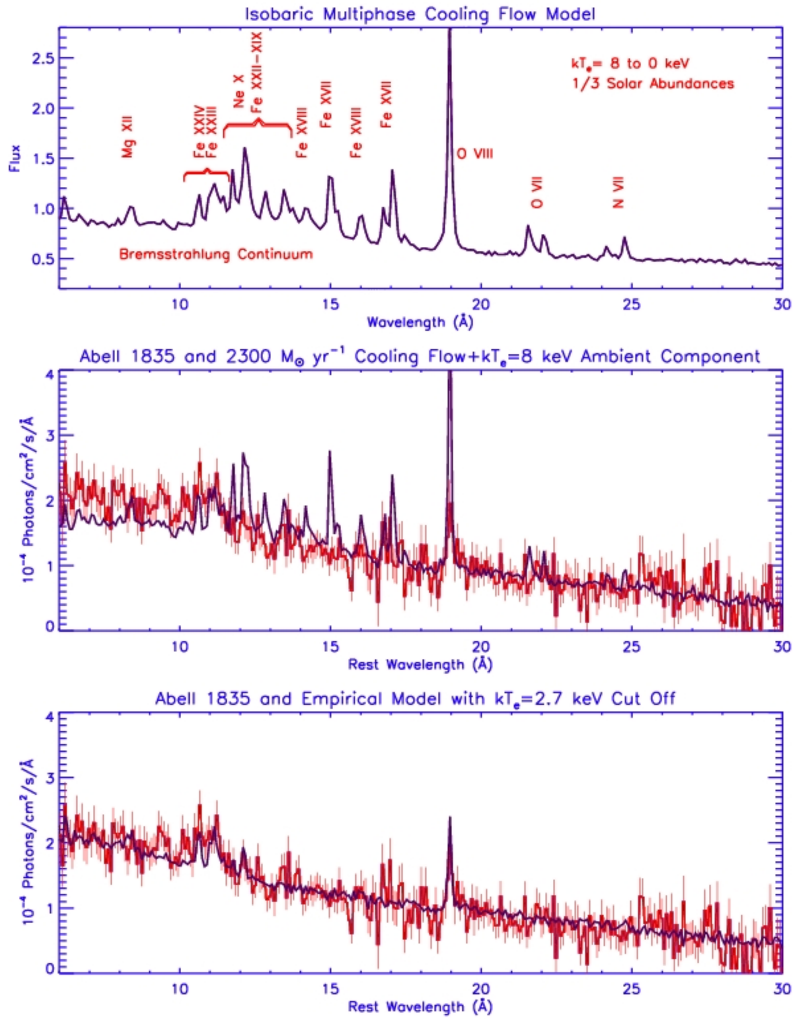
- Background
  - Why is feedback important?
  - Why look at groups rather than clusters?
- Sample
- Results
  - HCG 62, NGC 5813 & NGC 5044 - multiple AGN outbursts.
    - isotropic heating.
  - AWM 4 - radio lobes without cavities?
    - galactic coronae and the AGN duty cycle.
  - AGN Jets - Mechanical power vs. radio power.
- Future prospects: CLoGS


Galaxy Groups & Clusters - Constituents
Relativistic Plasma <1%
Stars ≈ 3%
Hot Gas ≈ 14%
Dark Matter ≈ 83% of mass
In clusters, the dominant baryonic component is 10^7 K gas.
NCRA Seminar
30 January 2012

Why feedback is necessary - cooling flows

Fabian & Nulsen 1977





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

Peterson & Fabian 2006

The AGN feedback cycle
(as observed in galaxy clusters)

Inflow stops, Jets switch off

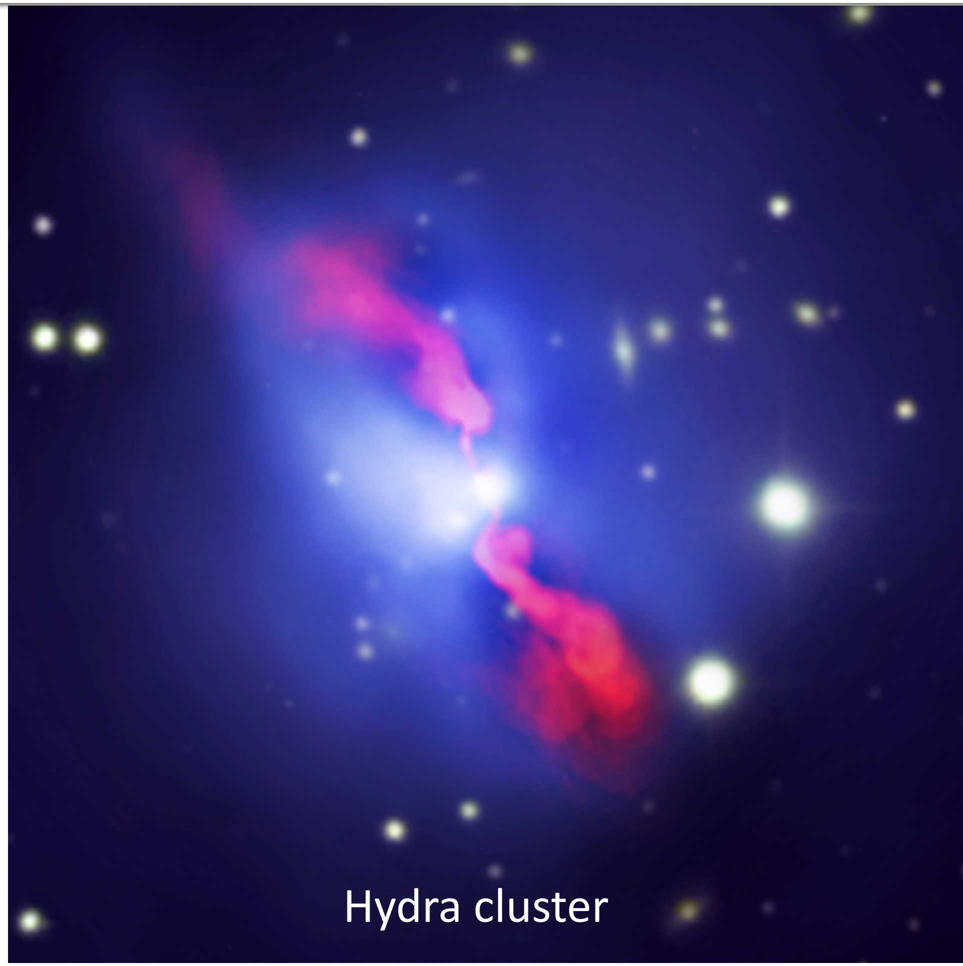
Gas Cools, flows in to SMBH

Accretion, Jets switch on

Jets heat gas via shocks, cavities

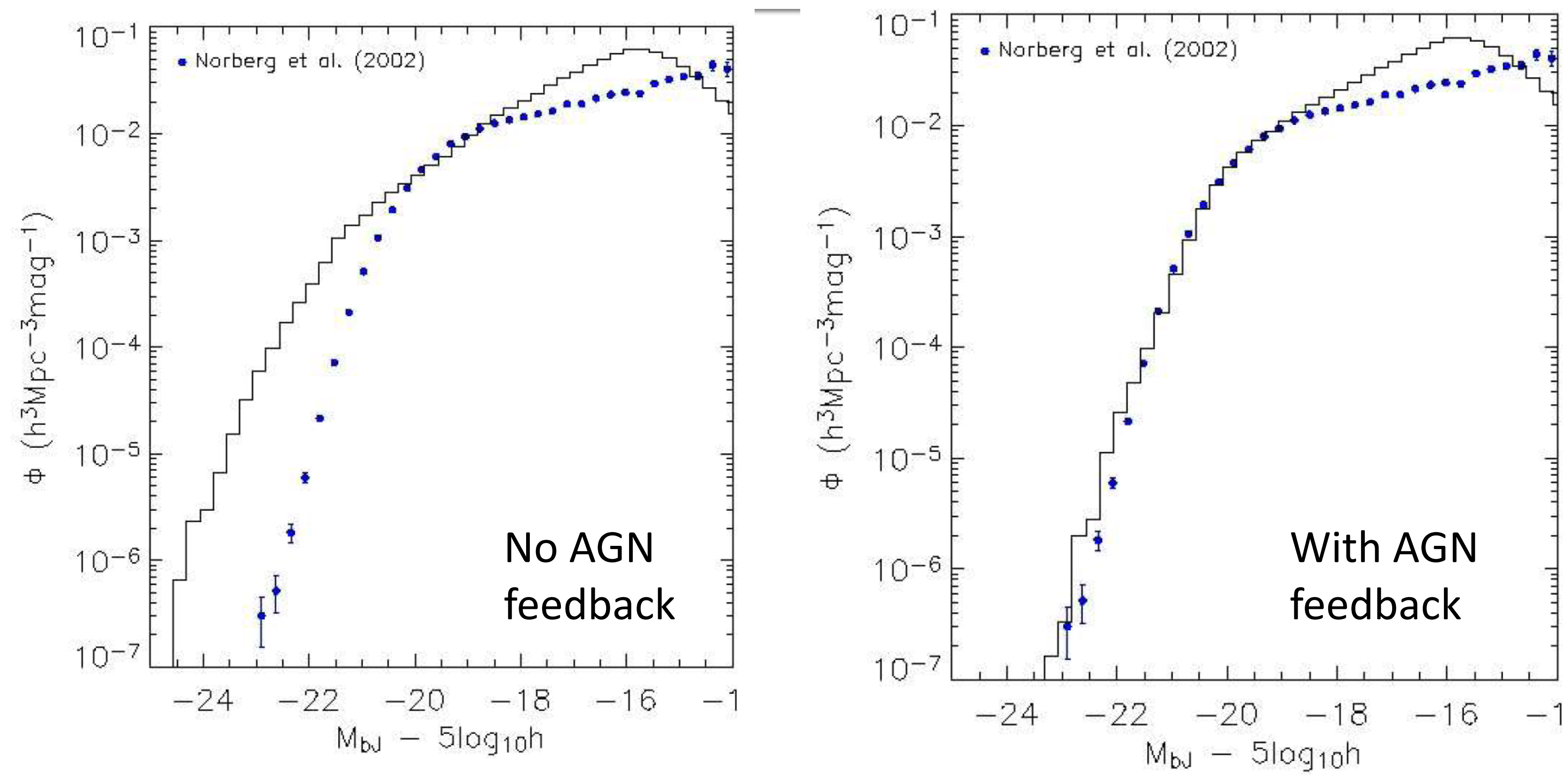
Repeat every ~10^8 years?

70-100% of CC clusters have central FR-I radio galaxies
(Blanton et al. 2010)



Chandra/VLA 1.4 GHz (Kirkpatrick et al. 2009)

Why feedback is necessary - overcooling

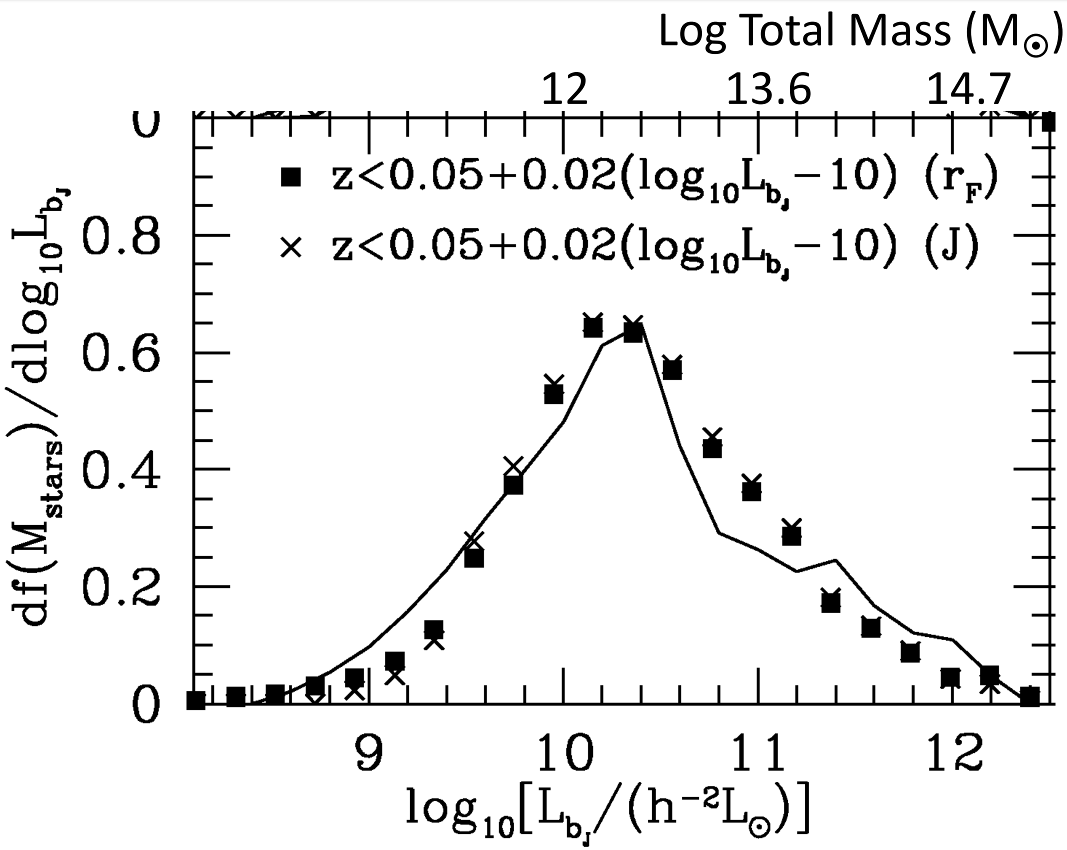


Croton et al. 2004

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

Why look at feedback in galaxy groups?

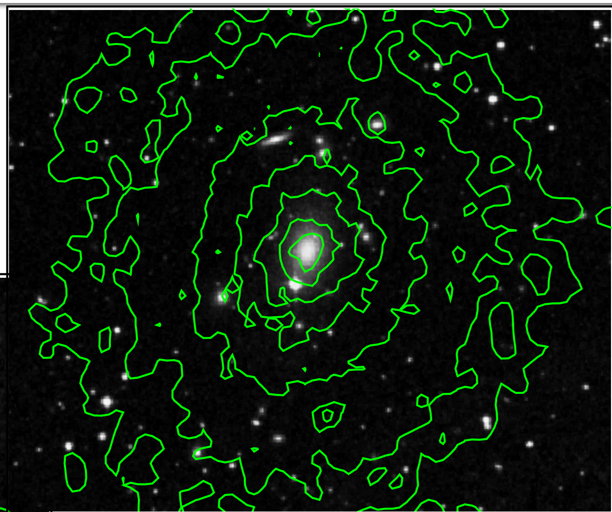
- Groups contain >50% of stars in the local Universe and most of the baryons.
- Group environment key to galaxy evolution, in which AGN play an important role.
- AGN Feedback in groups must be fine tuned. Outbursts should be weaker but occur more often (e.g., Gaspari et al. 2011)



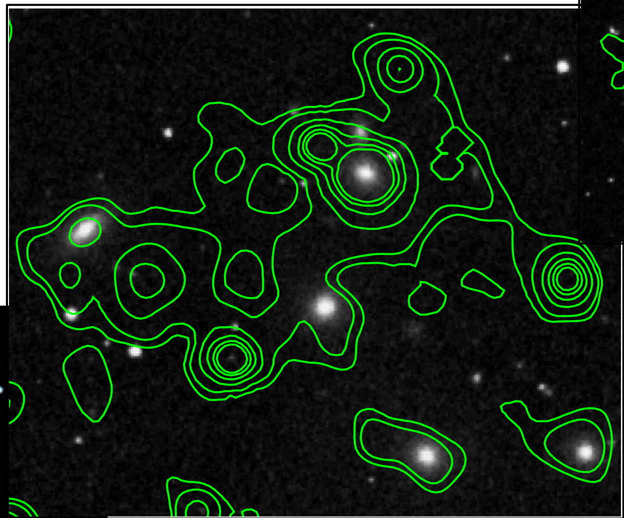
Eke et al. (2005)

Groups – A Diverse Class

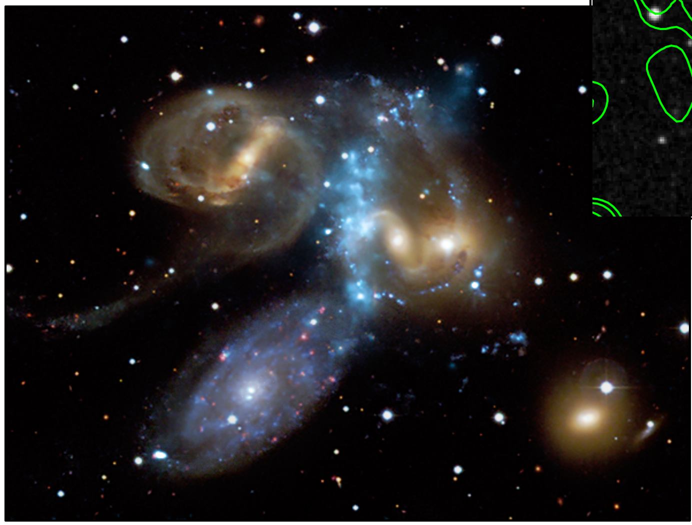
Variation from low-mass, spiral-only, X-ray faint groups (e.g., local group) to massive, X-ray bright mini-clusters.



AWM4
Dominant gE + many smaller galaxies



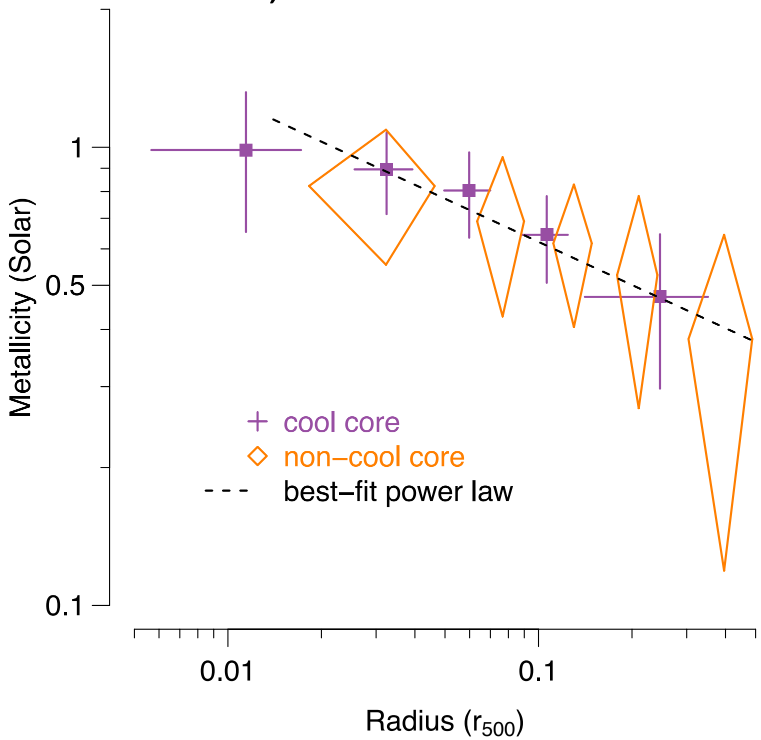
HCG 15
multiple E & S0s



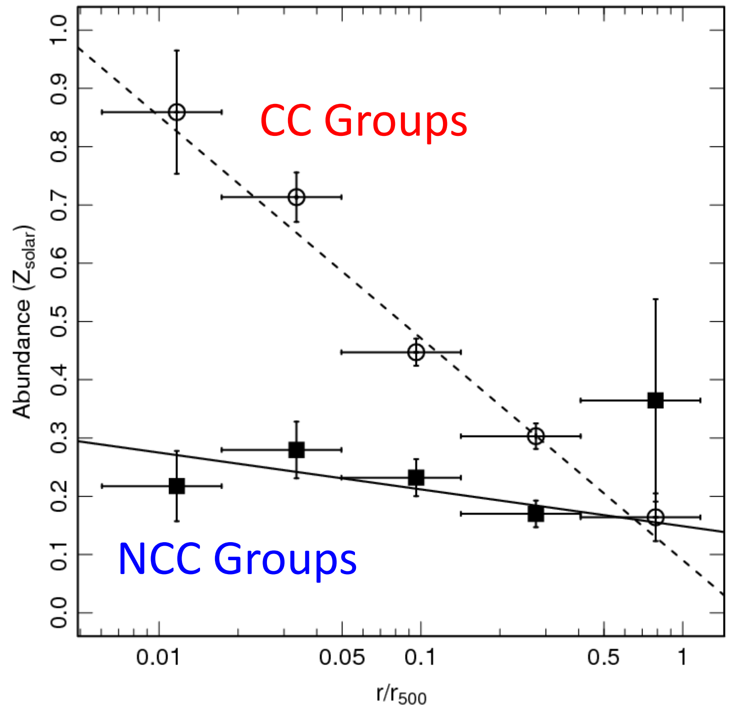
Stephan's Quintet (HCG 92)
Spiral-rich (O'Sullivan et al. 2009)

Why look at groups? - Abundance gradients

Sanderson, O'Sullivan & Ponman 2009



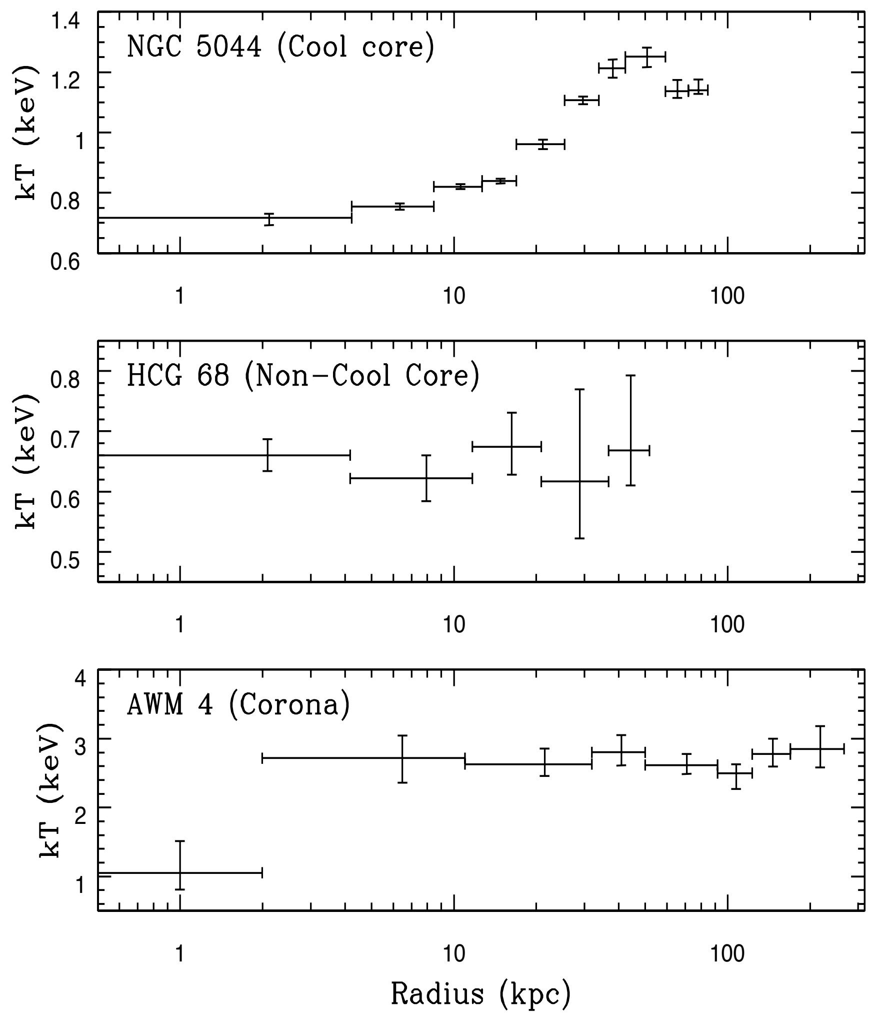
Johnson et al. 2011



- 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 ➔ AGN driven gas mixing?

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.

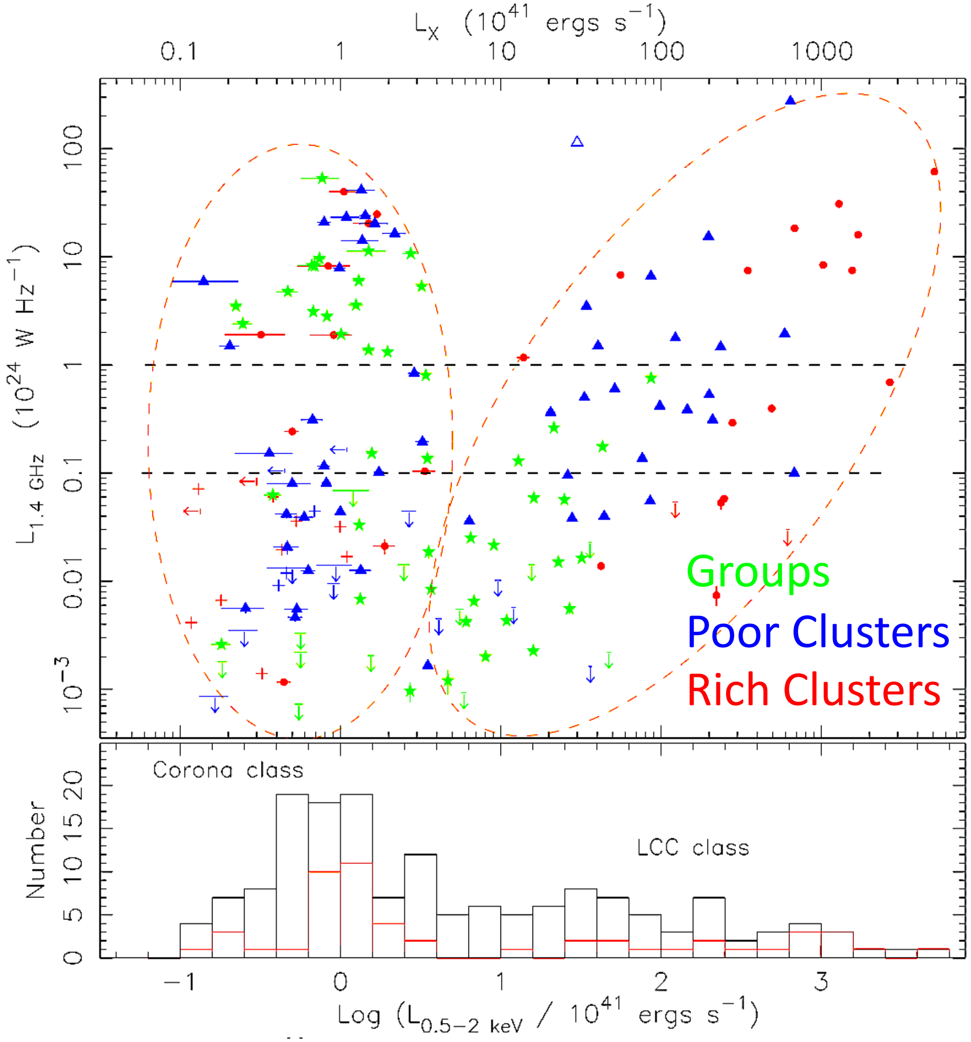


Coronae vs Large Cool Cores

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



The Sample

No statistical X-ray 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.

Groups sample: available data

GROUP	z	Chandra	XMM	150 MHz	235 MHz	327 MHz	610MHz	Papers?
UGC 408	0.0147	✓		✓ (red)	✓		✓	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	✓	✓		✓	✓	✓	SG in prep.
NGC 1587	0.0123	✓			✓		✓	
MKW 2	0.0368		✓		✓		✓	
NGC 3411	0.0153	✓	✓		✓		✓	O'S 07
NGC 4636	0.0031	✓	✓		✓		✓	Jones, O'S, Baldi
HCG 62	0.0137	✓	✓		✓	✓	✓	Gitti 10
NGC 5044	0.0090	✓	✓	✓ (red)	✓	✓	✓	David 09 & 11
NGC 5813	0.0066	✓	✓	✓ (red)	✓			Randall 11
NGC 5846	0.0057	✓	✓				✓	Machacek 11
AWM4	0.0318	✓	✓		✓	✓	✓	SG 08, O'S10&11
NGC 6269	0.0348	✓			✓		✓	Baldi 09
NGC 7626	0.0114	✓	✓	✓ (red)	✓		✓	Randall 09

GREEN = images/fluxes/spectra available RED = unprocessed

Why low-frequency radio?

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

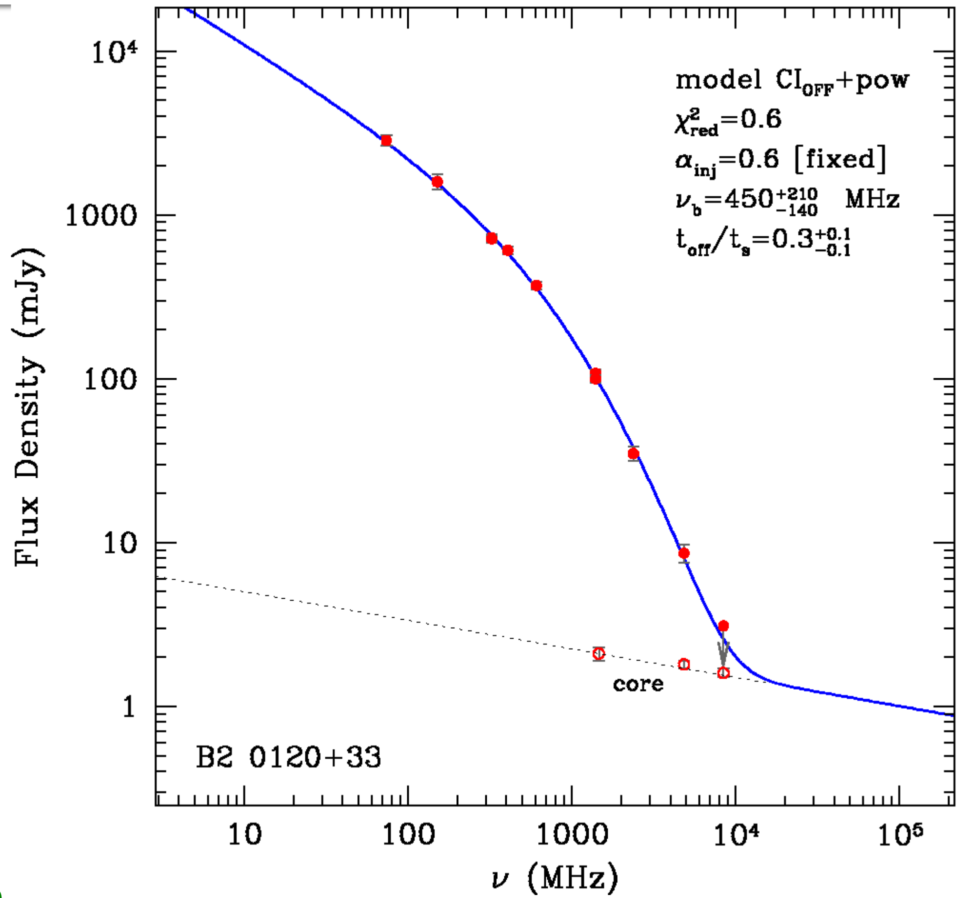
GMRT sensitivity (for 2-3hr obs.):

rms ≈ 50-100 μJy/b @ 610 MHz

rms ≈ 300-500 μJy/b @ 235 MHz

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

X-ray: 0.5” Chandra / 6” XMM (FWHM)

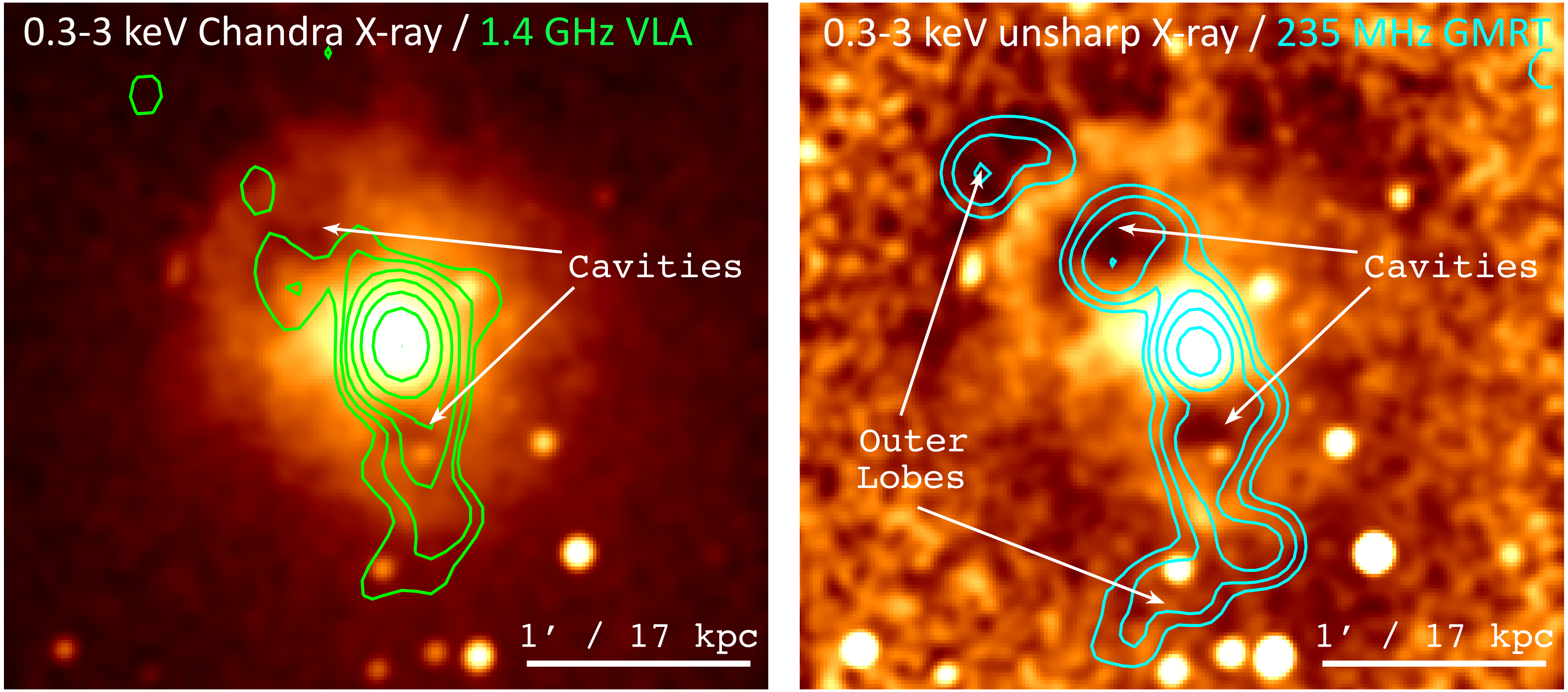


NGC 507 (Murgia et al. 2011)

Project goals

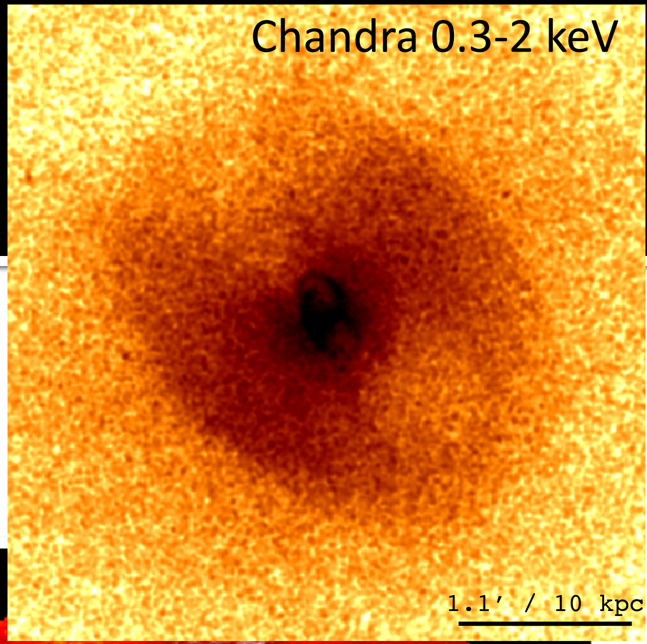
1. What are the properties of group-central AGN?
    - Power output, activity timescale, can they balance cooling?
2. What are the mechanisms of feedback heating?
    - Are shocks/cavities dominant? How is energy spread isotropically?
3. How are X-ray and radio structures correlated?
    - Do radio jets always inflate cavities? Do AGN drive gas mixing?
4. How are the effects of AGN related to their lifecycle and environment?
5. What is the relationship between radio luminosity and power output for AGN jets? How reliable is it?

Cavities in groups: HCG 62
(Gitti et al. 2010)



- Enthalpy of cavities = $4pV$ = 2.1×10^{57} erg. Power = 1.5×10^{43} erg/s
- Low-frequency radio sensitive to older electron population, reveals previously unknown outer lobes.

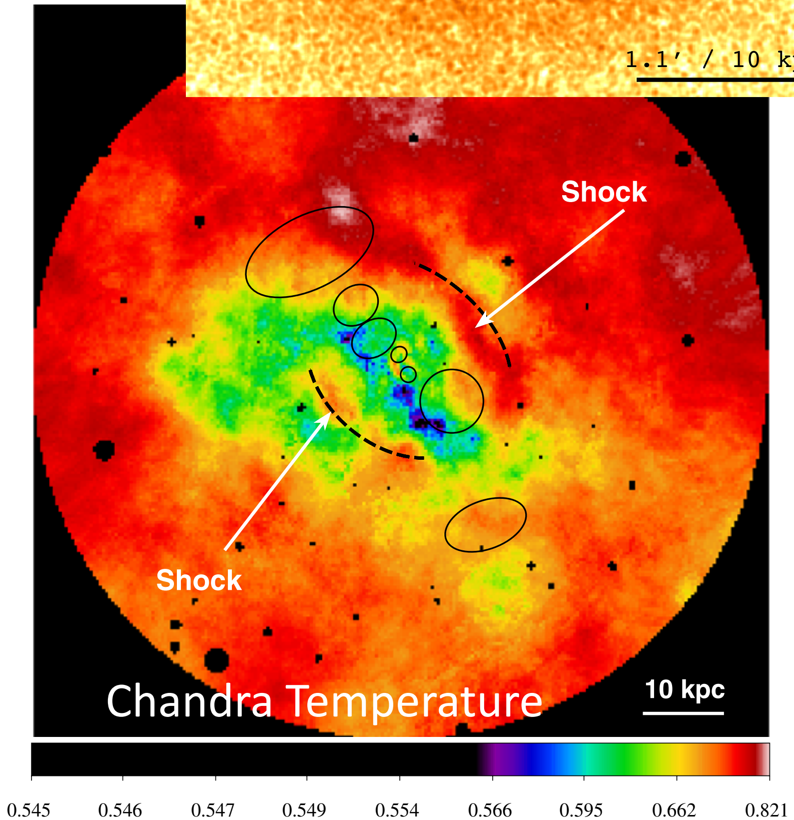
Shocks in NGC5813
(Randall et al. 2011)



- Difficult to observe – require high-quality Chandra data to measure temperature jump.
- Typically weak shocks (Mach < 2).

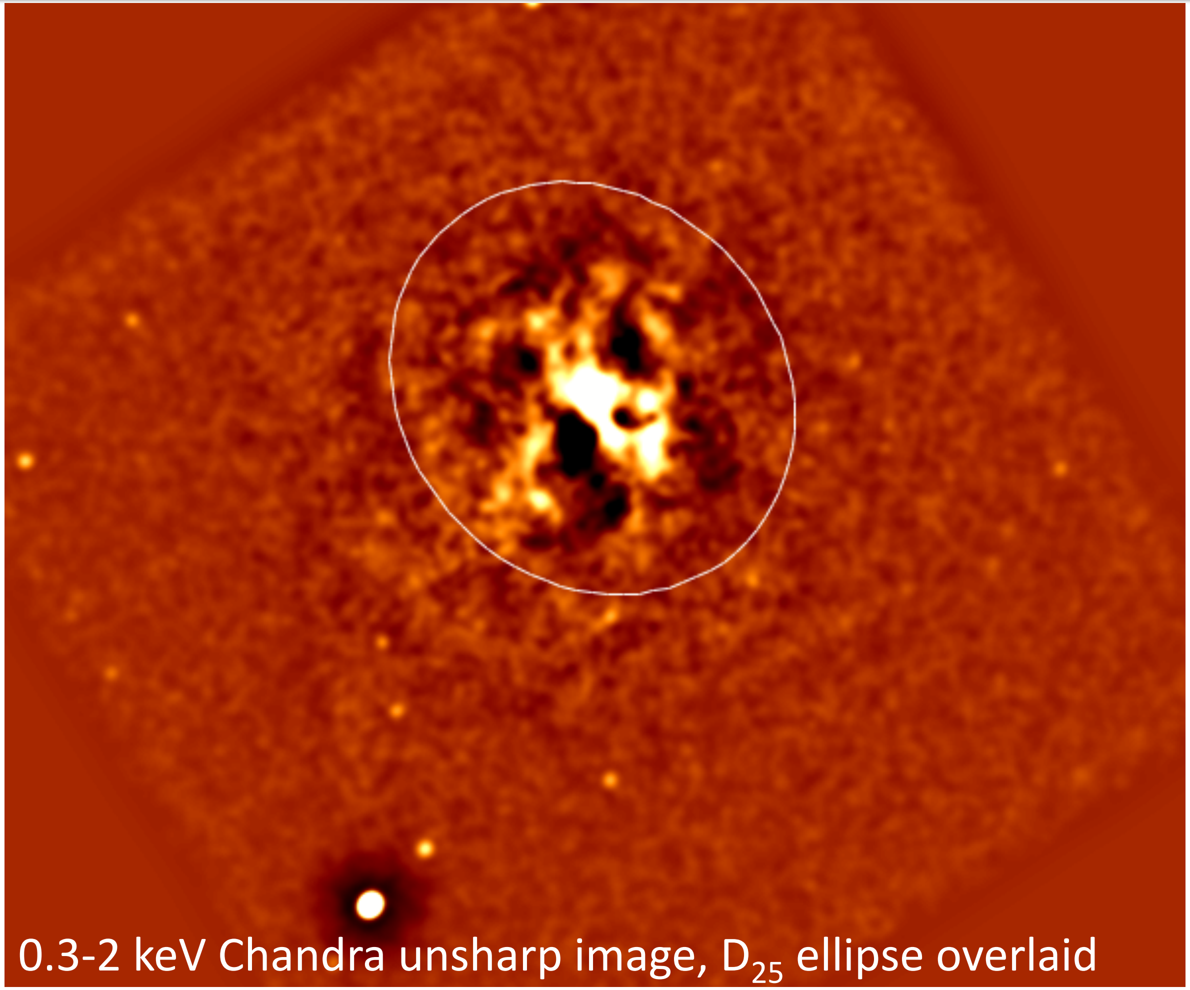
In NGC 5813:

- 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.



NGC 5044 – *Chandra* X-ray
(David et al. 2009)

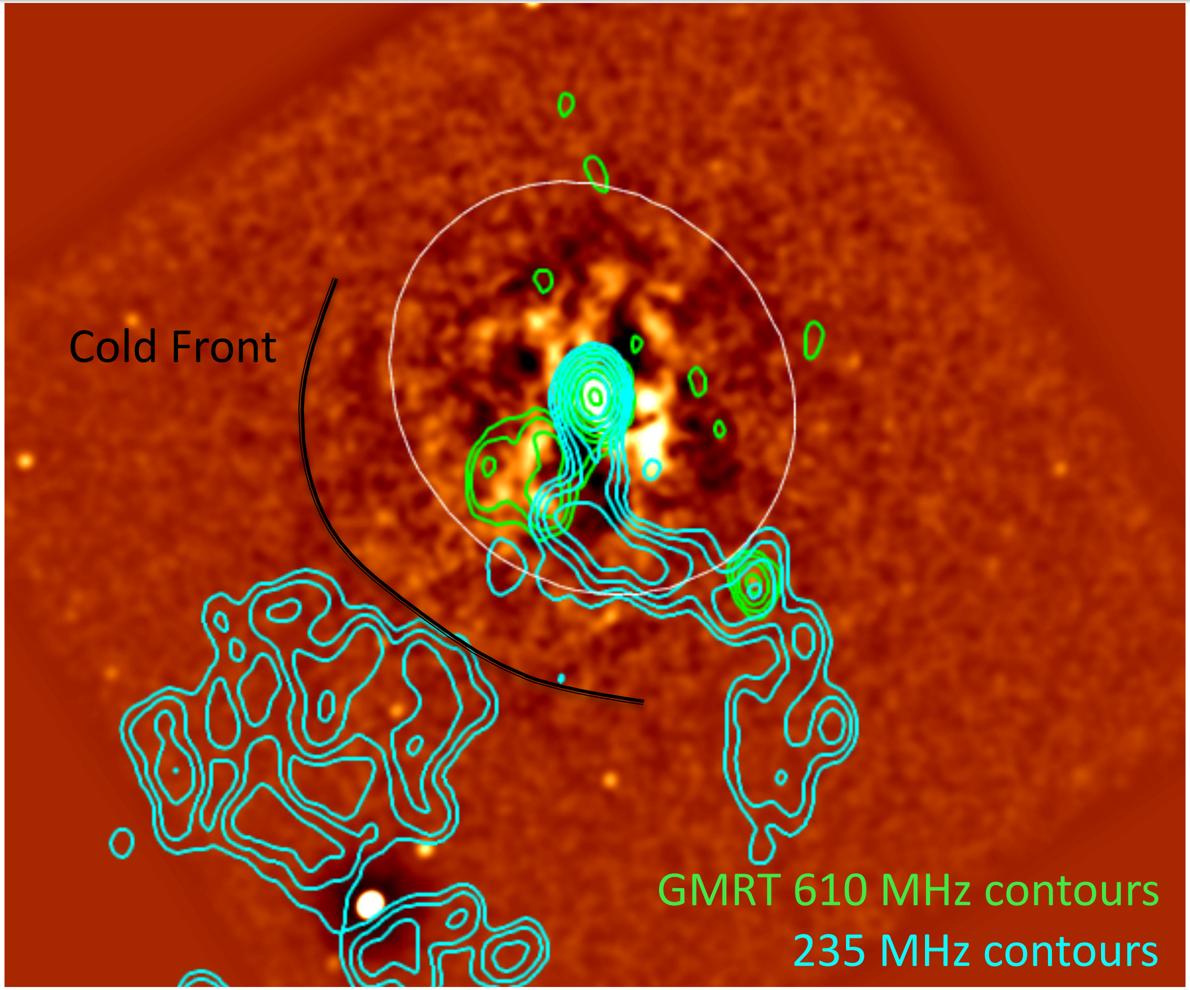
- One of the brightest nearby galaxy groups (~10^{43} erg/s)
- Prior observations reveal some structure in X-ray, radio point source
- X-ray image shows numerous cavities, filaments, fronts.
- Cavities are small but spread throughout the core, not just along main axis.
- At 1.4 GHz, only a central point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



NGC 5044 – GMRT radio
(David et al. 2009)

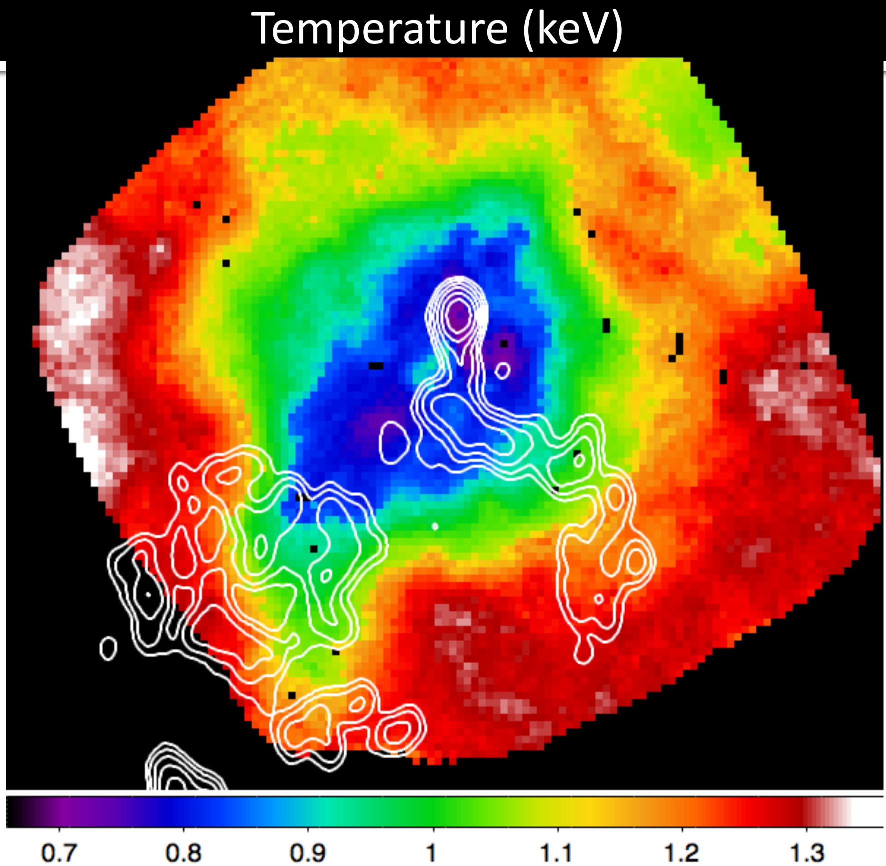
At 235 MHz:

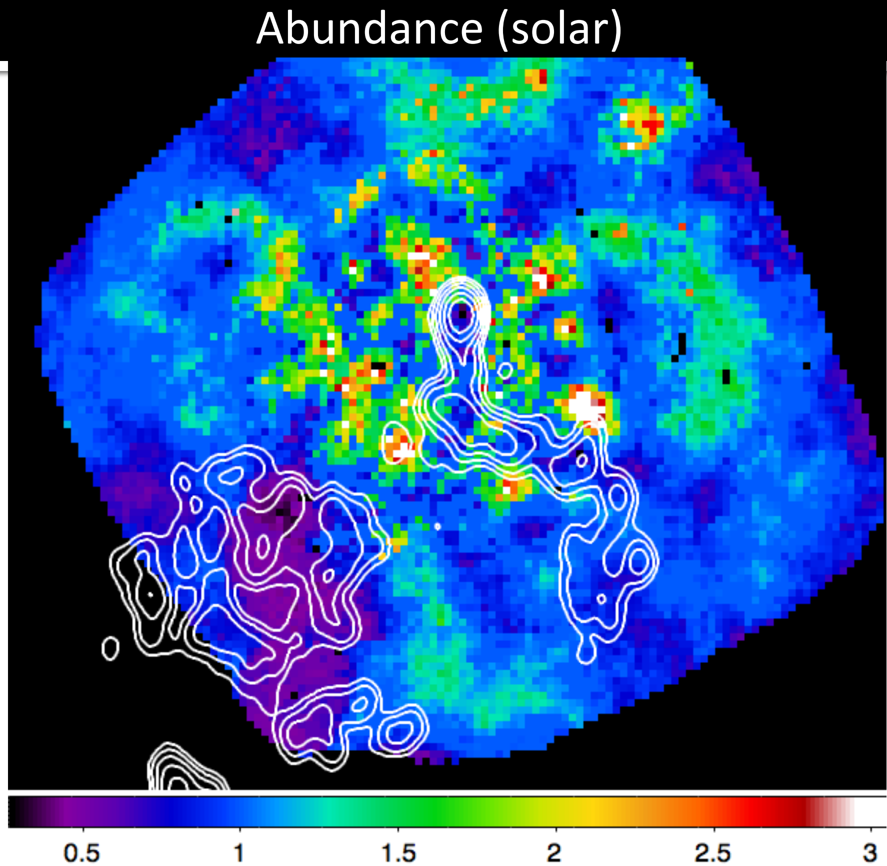
1. Detached radio lobe to the SE.
2. Filament following X-ray channel
3. Correlation between X-ray surface brightness front, filament and detached lobe



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

NGC 5044 – X-ray spectral maps (David et al. 2009, 2011)





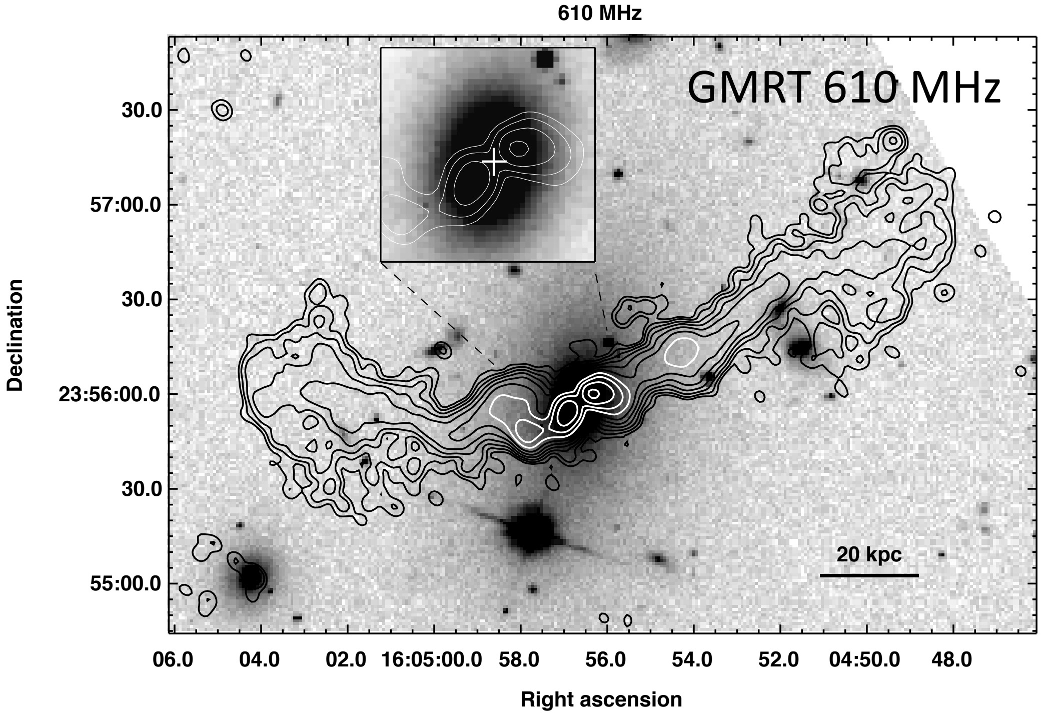
- Temperature drawn out to SE, following detached lobe ➔ gas motion.
- High abundance features (2-3 solar!), low abundances regions correlate with cavities, radio structure ➔ multiphase gas.
- Many small outbursts, cavities spread isotropically in core by gas motions.

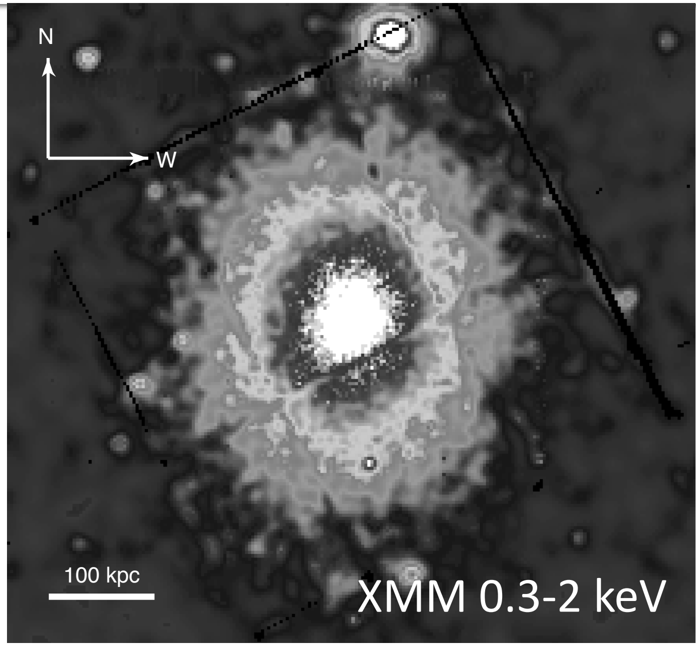
HCG 62, NGC 5813, NGC 5044: Take-home points

- 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.
- Evidence of multiple episodes of AGN jet activity → direct measurement of the duty cycle.
  - BUT gas motions make dynamical age estimates uncertain. New, deep radio data will allow comparison with radiative ages.
- Both shocks and cavities may contribute to heating.

AWM 4: Background
(O'Sullivan et al. 2005, Giacintucci et al. 2008)

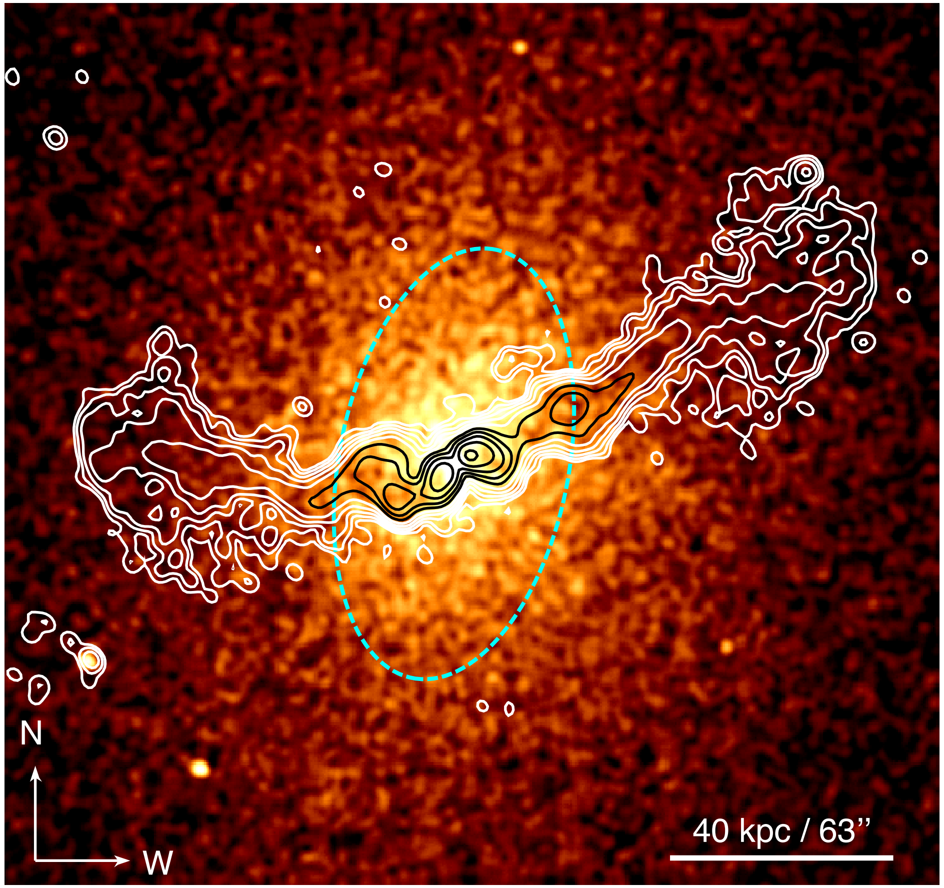
- ~2.6 keV relaxed poor cluster.
- 4C radio source (608 mJy @1.4 GHz).
- XMM finds no cool core or cavities.
- GMRT data shows radio source very old, ~170 Myr (few 10s Myr typical).





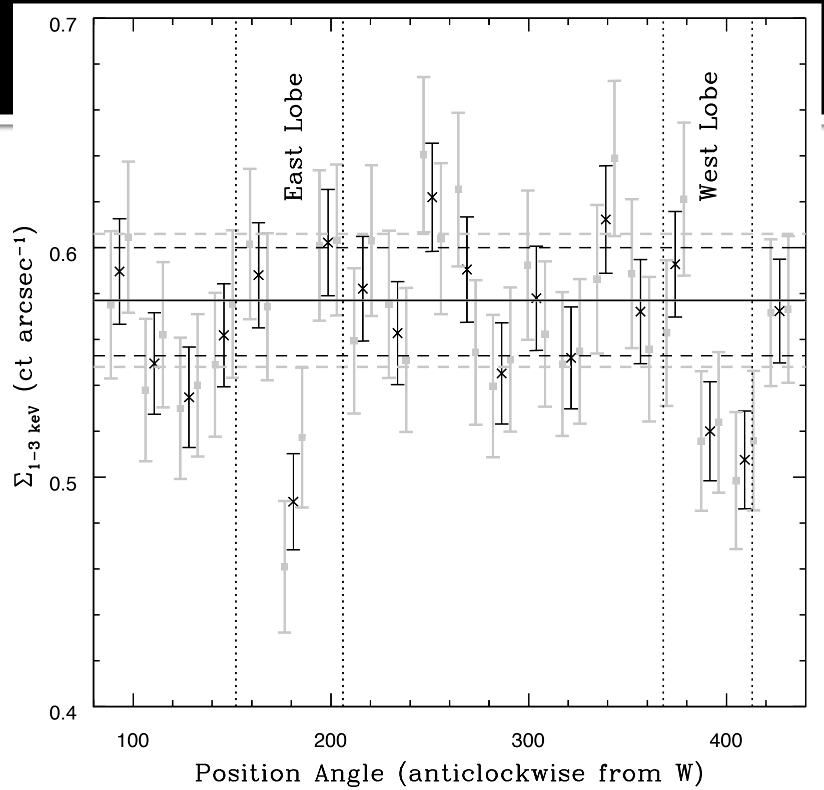
- Small-scale jets aligned <10° from sky.
- Lobe radio pressure lower than ICM thermal pressure by factor ~15 (as usual).

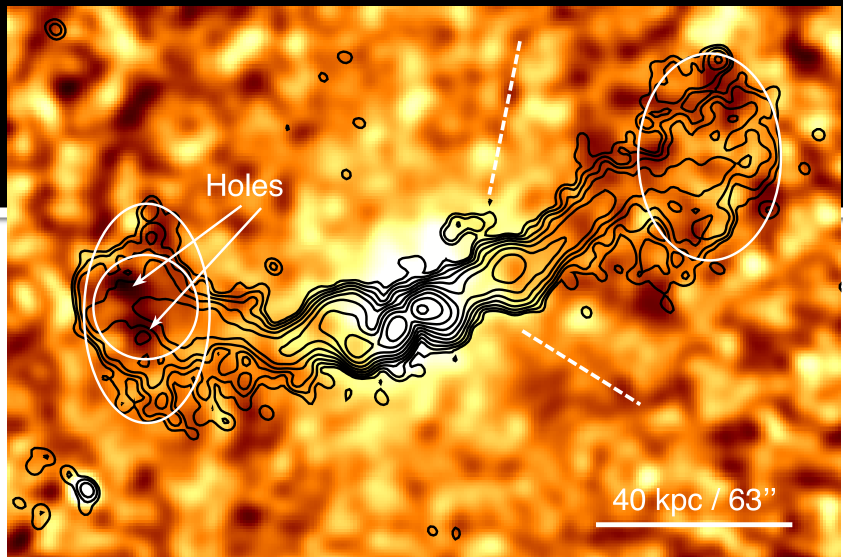
AWM4: Chandra observations
(O'Sullivan et al. 2010, 2011)



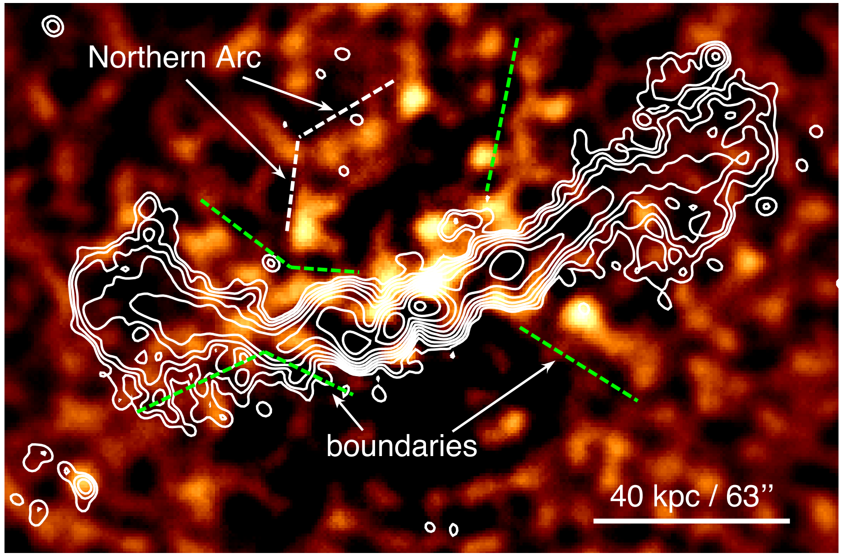
- ~80 ks exposure
- No shocks or fronts
- No clear cavities
- Slight offset of BCG to south of halo centroid – in motion as radio suggests?
- If lobes have formed cavities, Enthalpy ~10^{59} erg.

AWM4: Cavities?





1-3 keV unsharp masked image



0.7-3 keV smoothed residual map

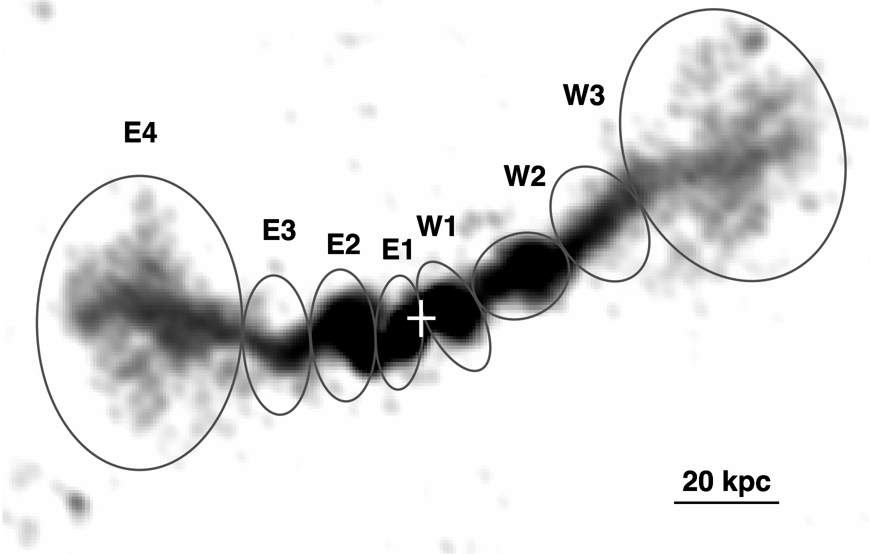
- >3σ significant drop in surface X-ray brightness in E lobe, but smaller than the lobe – cavity?
- Broader, less significant western feature, weak filaments along jets?

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:

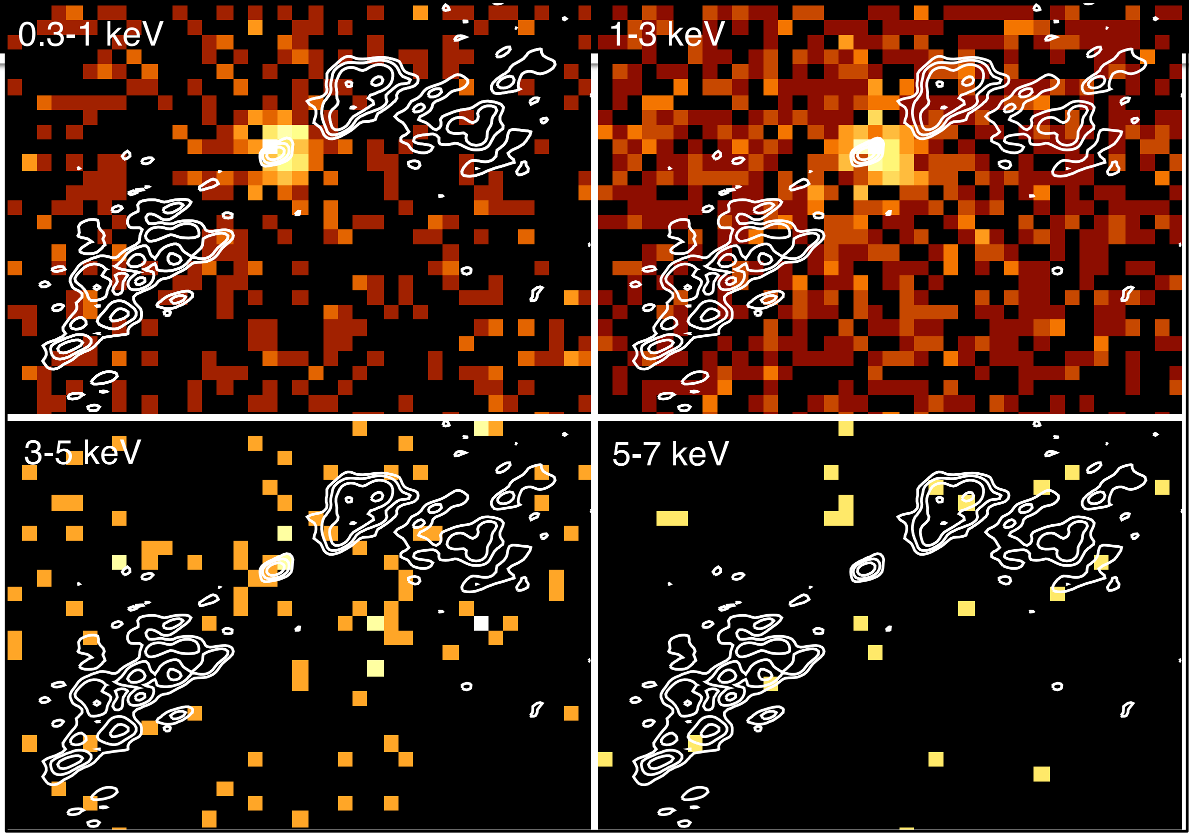
1. Expected Inverse-Compton flux from radio lobes a factor 10^{-4} too low.
2. Entrainment of ICM or stellar gas in the jets, without significant heating or mixing.
3. Mixing of the lobes with surrounding thermal plasma. Lobes possibly breaking up into clouds and filaments.



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 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.

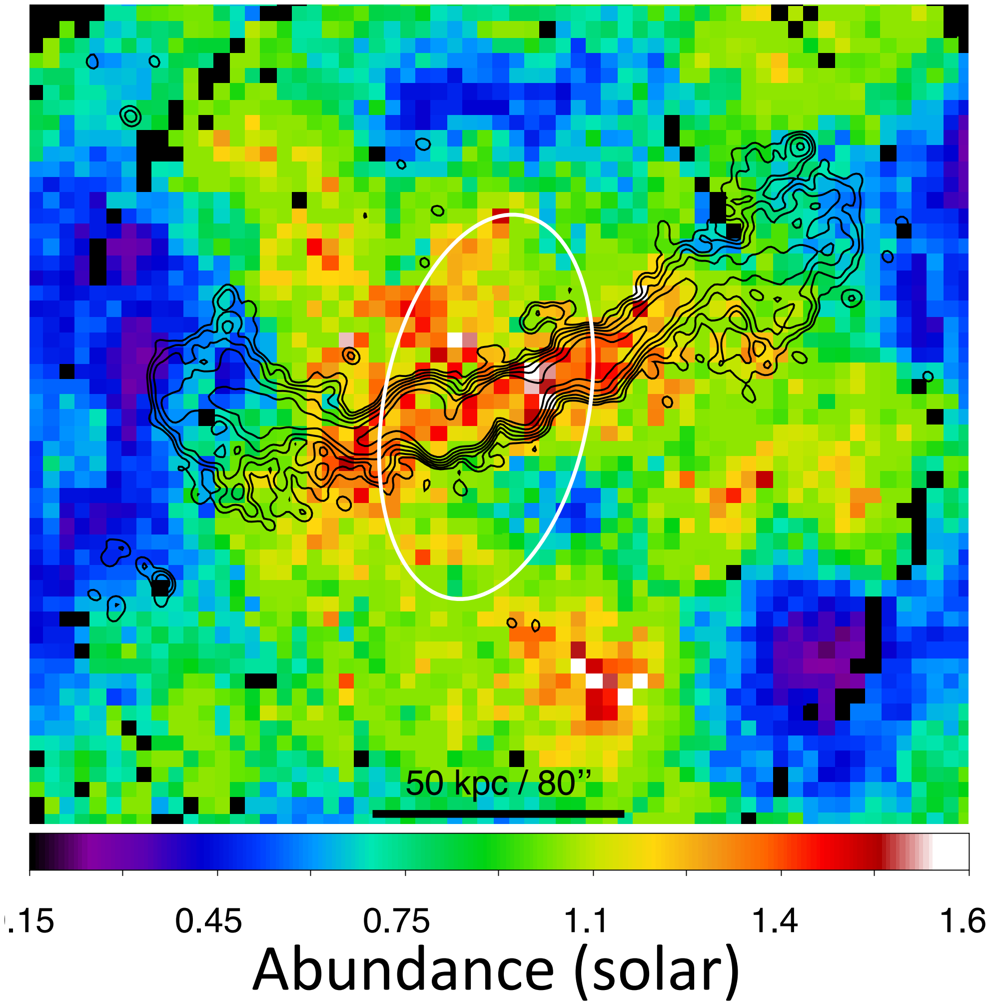
AWM4: the Corona

- 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.

AWM 4: metal enrichment and transport



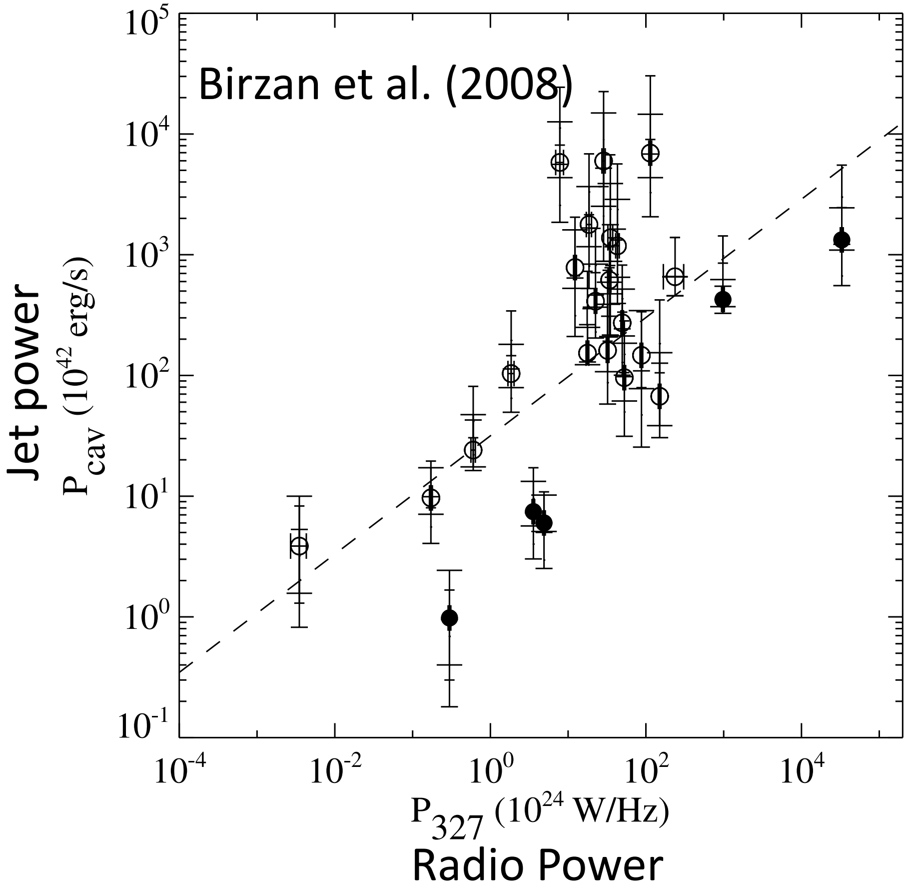
- Super-solar abundances extended along axis of radio jets.
- Unlikely to be formed *in situ.*
- ~10^9 $M_\odot$ gas entrained
- Requires ~1.6×10^{57} erg, significant fraction of total jet energy.

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?
  - 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.
  → Does this break the AGN feedback loop?
  - May explain age of outburst, as feedback may not be able to stop it.
  - Coronae are common – see also O'Sullivan et al. 2011c on NGC 4261.
- Jets uplift metals from BCG, enriching the intra-group medium.

AGN jets: mechanical power vs radio power

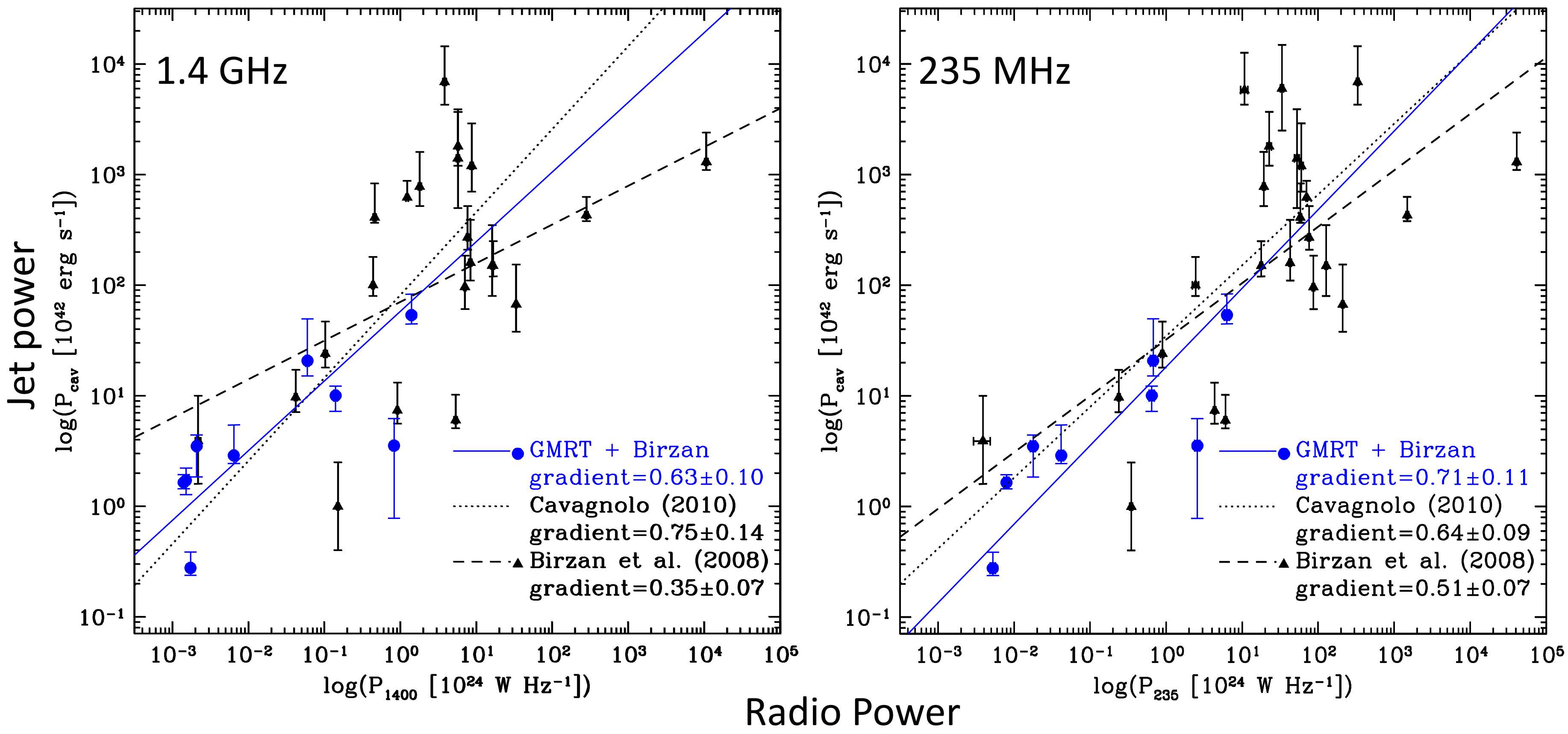
- In the local Universe, we can estimate P_{jet} from cavity enthalpy (E=4pV) and buoyancy time.
- Measuring the P_{jet}:P_{radio} relation allows us to estimate the amount of feedback from radio alone (e.g., at high redshift).
- Birzan et al (2004, 2008) used sample of ~25 clusters, VLA 1.4 GHz and 327 MHz data.
- Cavagnolo (2010) add 21 ellipticals, but with poor, low-resolution 200-400 MHz data.



- We add 9 groups, with high-quality GMRT 235 MHz data.

AGN jets: mechanical power vs radio power

(O'Sullivan et al. 2011)

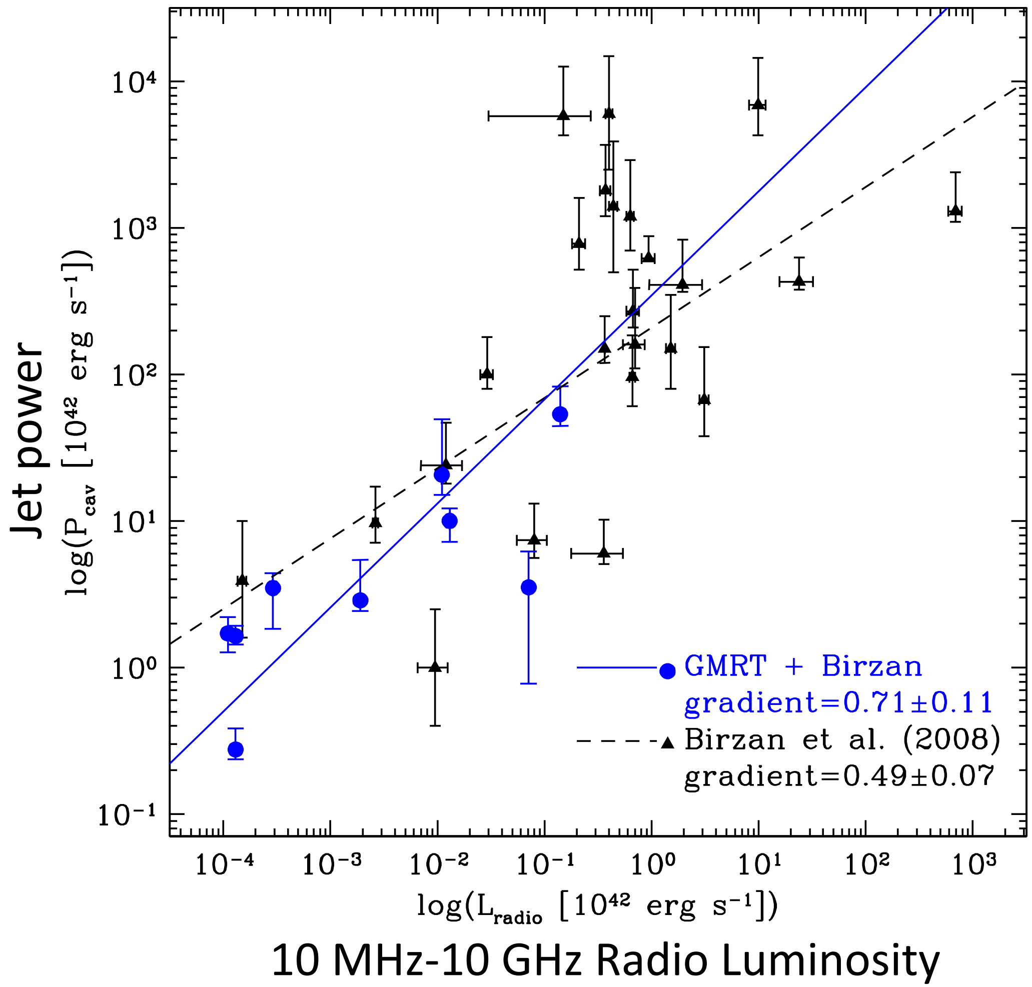


- Birzan et al used BCES Y|X fit, Cavagnolo and our fits use BCES orthogonal.

AGN jets: mechanical power vs radio power
(O'Sullivan et al. 2011)

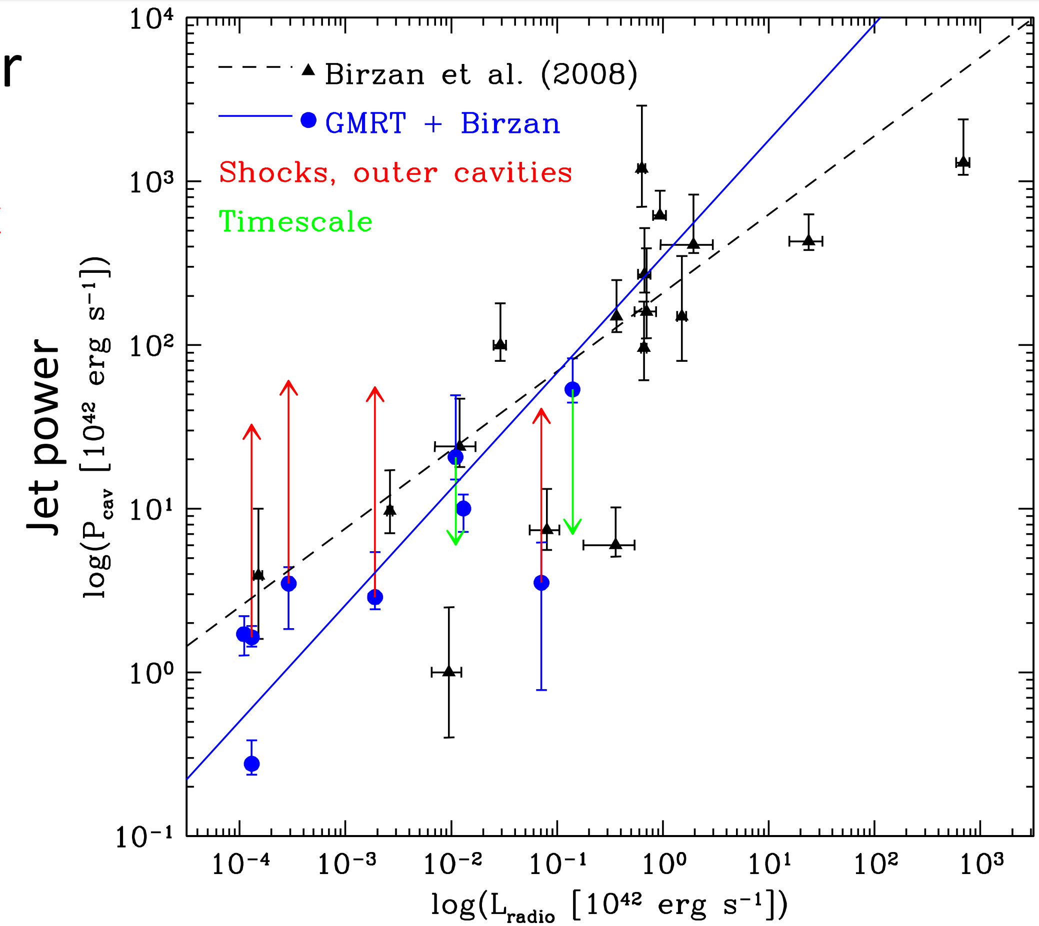
- Integrated radio power accounts for differences in spectral index ➔ superior estimator of jet power.
- Birzan again used BCES Y|X, but Orthogonal fit would give gradient = 0.78 ± 0.30 .

- Synchrotron theory predicts gradient = 0.86 (Willott etal. 99)
- BUT Willott assumes spectral index α=0.5 . For free spectral index, gradient will be 3/(α+3), e.g. gradient=0.76 for our typical α=0.95.



Mechanical power vs radio power: Caveats

- Cavity power may be a poor measure of jet power!
  - Energy in shocks can be 5-10x energy of cavities.
  - Buoyancy timescale is not always appropriate.
  - Young cavities likely to be missed. Detection of old cavities dependent on depth of data, radio freqs available.
  - Jet orientation.
  - AGN weather.
  - Filling factors <1 (c.f. AWM4).
- Correcting groups where possible flattens relation.



10 MHz-10 GHz Radio Luminosity

Mechanical Power vs Cooling

Power needed to balance cooling:

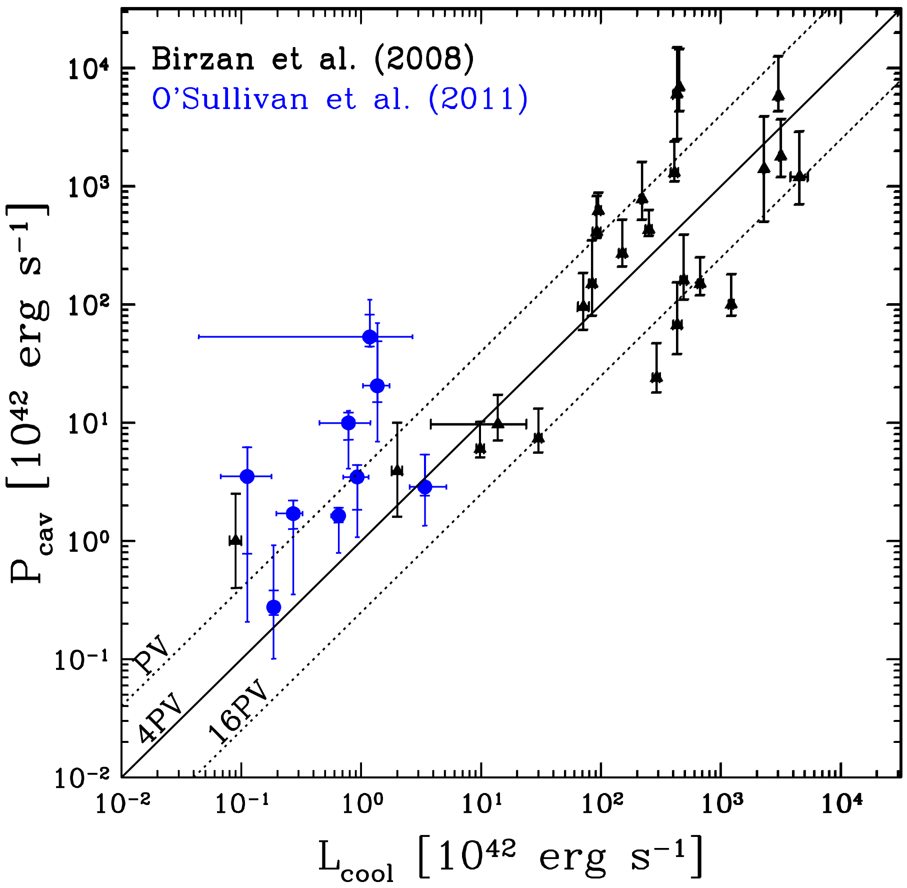
- In galaxy clusters ~4PV.
- In groups only ~1PV

(as for Ellipticals, Nulsen et al 2007).

- Scatter at least factor 4.

Factoring in shocks, AGN power output can reach $P_{jet} > 10\ L_{cool}$

- Most powerful outbursts in this sample still have cool cores.
- But sample is selected to have jet/gas interactions…



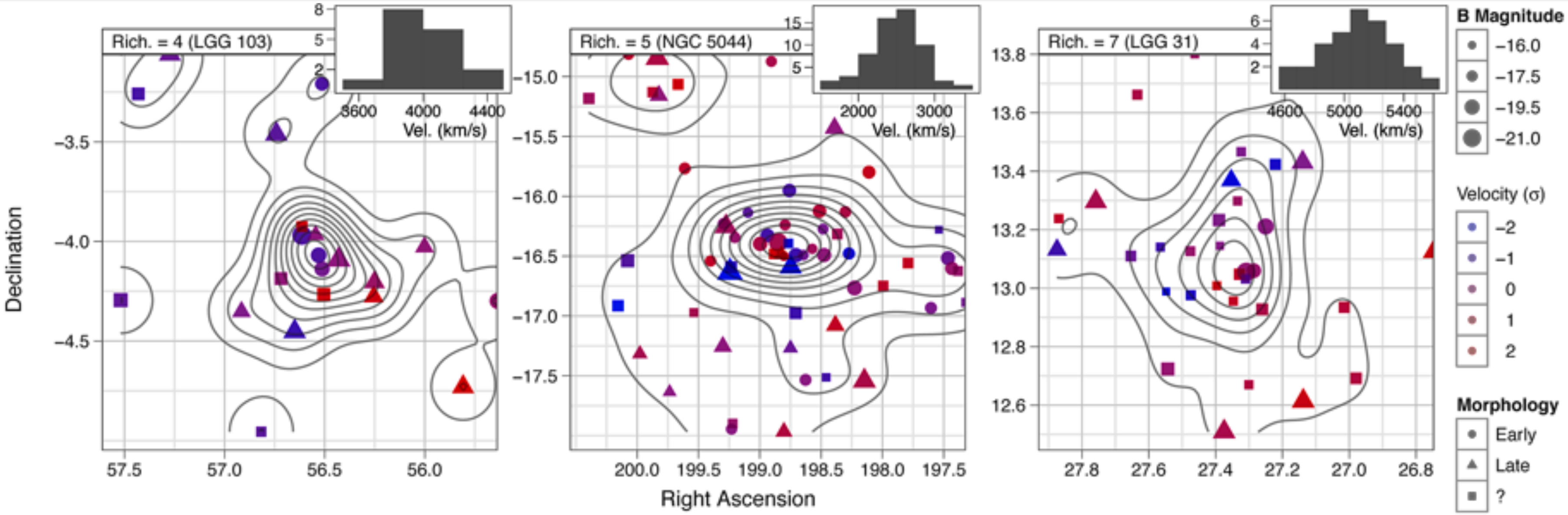
(Bolometric L_X for region $t_{cool} \leq 7.7$ Gyr)

Mechanical power vs radio power: Take-home points

- Low-frequency or integrated radio measurements are a more reliable predictor of jet power.
  - 1.4 GHz data, while readily available, produces less reliable relations because of the effects of spectral aging.
- Samples including groups (and ellipticals) provide better constraints on the P_{jet}:P_{radio} relations.
  - Our best fits give gradient ~0.7±0.1 with intrinsic scatter ~0.6 dex.
- Uncertainties on the mechanical power output of jets are large (factor of ~10).
  - ➔ further work needed to produce more reliable jet power estimates.

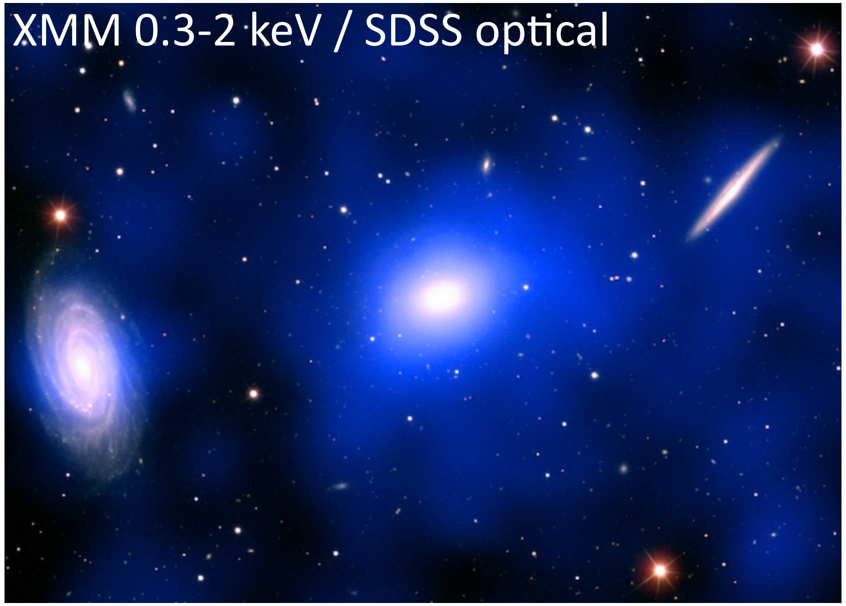
CLoGS: The Complete Local-Volume Groups Survey

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

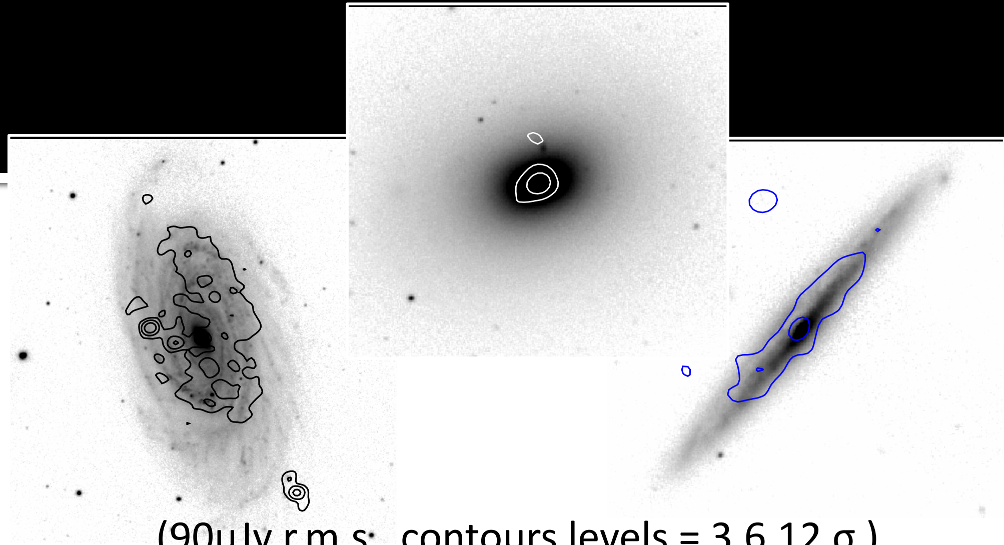


- Aims to be the first statistically complete sample of nearby, optically-selected groups with X-ray (XMM/Chandra) and radio (GMRT 235/610 MHz) coverage.
- 53 nearby groups, D<80 Mpc, excluding uncollapsed and false systems.
- So far 128 hrs GMRT, 50 ks Chandra GTO, 279 ks XMM-Newton approved.
- X-ray coverage of (statistically complete) richer half will be completed in 2012.
- Radio coverage of full sample hopefully complete as well…

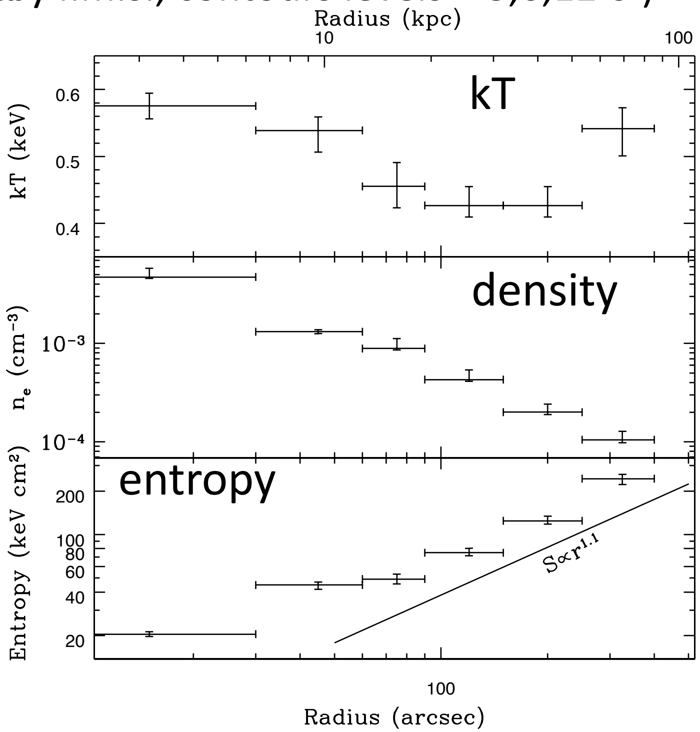
CLoGS: first results



GMRT 610 MHz contours / SDSS g'-band



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



- XMM detects 0.5 keV group halo to ~85 kpc.
- GMRT detects SF in spirals, AGN in all galaxies.
- Group is faint (L_X=2x10^{41}) but falls on scaling relations (L:T, σ:T, etc)
- No cool core (at resolution 6.4 kpc).