AGN feedback and galaxy evolution in nearby galaxy groups with *CLoGS*: The Complete Local-Volume Groups Survey

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More than 50% of galaxies and most of the baryonic matter in local Universe reside in groups **(Eke et al., 2004).** Many of them host radiative cooling gas halos, which can fuel a central SMBH, thus groups are probably the key environment for the study of AGN/hot gas interactions. The CLoGS sample consists of 53 candidate groups in the local Universe (<80 Mpc), with optical data already available (from eg, LEDA), X-ray data from the Chandra and XMM-Newton X-ray observatories and low-frequency radio data from the Giant Metrewave Radio Telescope. By focusing on low-frequency radio emission from GMRT (240 MHz and 610 MHz), past as well as current AGN activity can be identified by taking advantage of the combination of good spatial resolution at 610 MHz and the sensitivity to older electron populations at 240 MHz. Radio morphology, radio spectral indices and radiative ages provide insights of the properties of radio emission. The combination then of radio with optical and X-ray bands reveals the complex interactions with their environment and the physical processes that govern galaxy evolution. All very important processes for the investigation of the link between IGM and AGN and the understanding of the physical mechanisms of the energy injection (AGN feedback). Unfortunately, the study of AGN feedback in groups is currently hindered by an important obstacle: The lack of a statistically complete radio/X-ray sample of nearby groups.

The CLoGS project is the first statistically complete survey of galaxy groups observed in the X-ray, optical and radio wavebands. Selecting a representative group sample is not easy. Available representative X-ray selected samples of galaxy clusters with high-quality X-ray data are non-statistical collections of systems known to be biased towards systems with cool cores, which produce an easily-detected central surface brightness peak (eg., Eckert et al. 2011). In galaxy groups, their small number of member galaxies mean that opticaly-selected catalogs are usually contaminated by uncollapsed systems and chance superpositions.

Main science goals include:

- Determining the basic physical properties of a representative sample of groups for the first time
- Examining the temperature and density structure of the gaseous halos of groups, ability of groups to retain gas, and the fraction of systems with central cooling cores
- Characterization of the AGN population in groups, and examination of their impact on the intra-group gas and member galaxies
- Identification of new groups and new classes of groups
- Study of the galaxy population of groups, and the relationships between galaxies, their environment star formation and nuclear activity

CLoGS Sample

**Defined as richness parameter R the number of galaxies with $L_B > 3\times10^{10}\ L_\odot$ within 1 Mpc and 3σ in velocity dispersion range of the BGE*

LGG	BGE	D (Mpc)	R	sigma (km/s)	X-ray	Radio	LGG	BGE	D (Mpc)	R	sigma (km/s)	X-ray	Radio
High-Richness Subsample													
072	NGC 1060	76	8	496	X,C	610,235	473	NGC 7619	54	8	466	X,C	610,235
009	NGC 193	74	7	493	C	610,235	031	NGC 677	78	7	249	X	610,235
066	NGC 978	69	7	209	X	610,235	278	NGC 4261	32	7	743	X,C	610,235
351	NGC 5153	60	7	251	C	610,235	363	NGC 5353	35	7	240	X,C	610,235
018	NGC 410	77	6	393	X,C	610,235	158	NGC 2563	65	6	379	X,C	610,235
185	NGC 3078	34	6	1013	C	610,235	042	NGC 777	73	5	291	X,C	610,235
338	NGC 5044	38	5	336	X,C	610,235	393	NGC 5846	26	5	717	X,C	610,235
027	NGC 584	25	4	160	C	610,235	058	NGC 940	74	4	229	X	610,235
061	NGC 924	64	4	126	X	610,235	080	NGC 1167	72	4	94	X	610,235
103	NGC 1453	63	4	537	X	610,235	117	NGC 1587	51	4	126	C	610,235
262	NGC 4008	54	4	230	X	610,235	276	NGC 4169	45	4	93	X	610,235
310	ESO 507-25	45	4	557	C	610,235	345	NGC 5084	23	4	680	C	610,235
402	NGC 5982	44	4	230	X,C	610,235	421	NGC 6658	63	4	241	X	610,235
Low-Richness Subsample													
006	NGC 128	60	3	669	X,C	610,235	012	NGC 252	72	3	675	X	610,235
078	NGC 1106	64	3	776	X	610,235	097	NGC 1395	21	3	168	X,C	610,235
126	NGC 1779	45	3	443	X	610,235	138	NGC 2292	30	3	325	X	610,235
177	NGC 2911	45	3	288	X	610,235	205	NGC 3325	80	3	463	X	610,235
232	NGC 3613	32	3	442	X,C	610,235	314	NGC 4697	18	3	1022	X,C	610,235
341	NGC 5061	28	3	423	X	610,235	370	NGC 5444	60	3	316	X	610,235
398	NGC 5903	36	3	421	X,C	610,235	014	NGC 315	73	2	846	X,C	610,235
023	NGC 524	34	2	216	X,C	610,235	100	NGC 1407	23	2	368	X,C	610,235
113	NGC 1550	53	2	576	X,C	610,235	167	NGC 2768	23	2	706	X,C	610,235
236	NGC 3665	32	2	91	X,C	610,235	255	NGC 3923	20	2	207	X,C	610,235
329	NGC 4956	71	2	88	X	610,235	350	NGC 5127	72	2	794	X	610,235
360	NGC 5322	29	2	254	X,C	610,235	376	NGC 5490	71	2	303	X,C	610,235
383	NGC 5629	67	2	267	X	610,235	457	NGC 7252	66	2	397	X,C	610,235
463	NGC 7377	46	2	120	X	610,235							

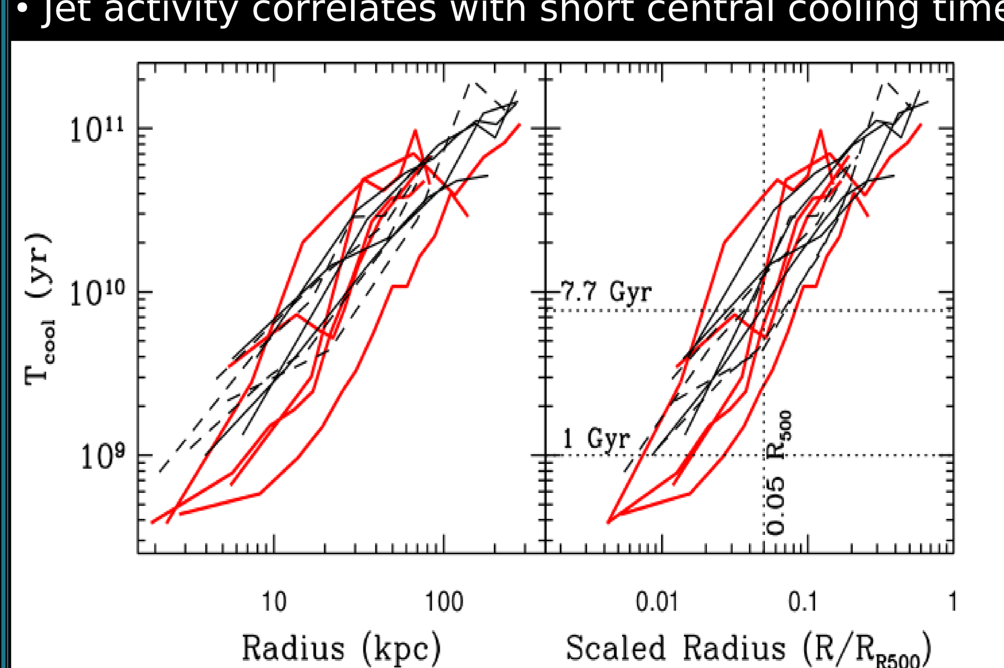
C and X indicate Chandra and XMM-Newton data respectively. Values in the Radio column indicate whether GMRT 610 or 235 MHz data are available; in some cases 327 and 150 MHz data are also in the archive. **Bold** entries indicate data awarded to our proposals for this project.

Group selection: Groups are chosen from the Lyon Galaxy Group catalogue (Garcia 1993), and are required to contain ≥4 galaxies, of which ≥1 must be early-type, with $L_B>3\times10^{10}\ L_\odot$. Groups containing early-type galaxies are more likely to possess a detecteable Intra-group medium (Mulchaey et al. 2003) and have evidently undergone some galaxy evolution. Groups are also required to have Dec>30° to ensure coverage by the VLA and GMRT observatories.

Radio and X-ray results in the High-Richness sample

Groups been categorised as *X-ray faint (<65 kpc)* and *X-ray bright (>65 kpc)*

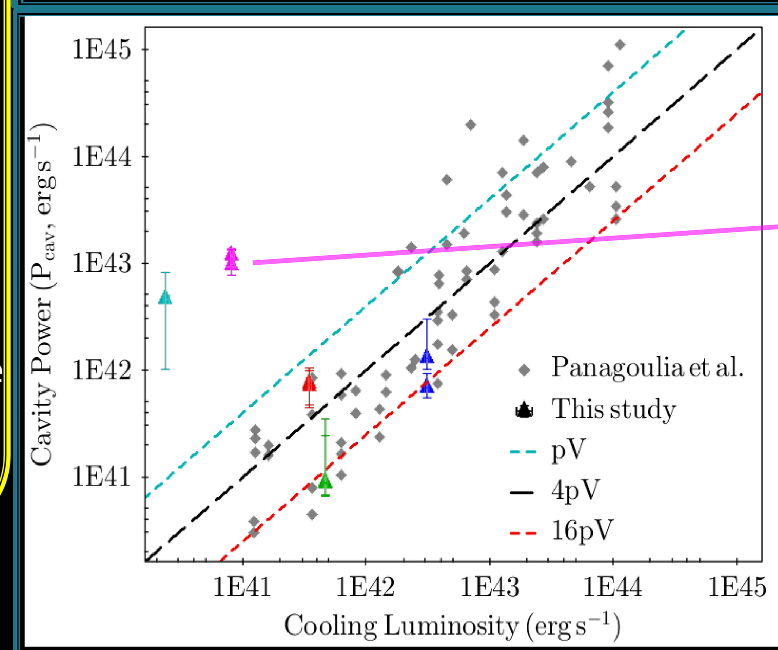
- 55% of groups present a full scale IGM (14/26)
- 3/14 ***X-ray bright*** groups were unknown/misidentified as single galaxies prior our observations
- ~20% of ***X-ray bright*** groups might be unknown in the local Universe
- 5/14 (~36%) of ***X-ray bright*** groups host jet systems → AGN duty cycle for CLoGS of ~1/3
- All jet systems are found in systems that possess cool cores
- Jet activity correlates with short central cooling times rather than low central entropies

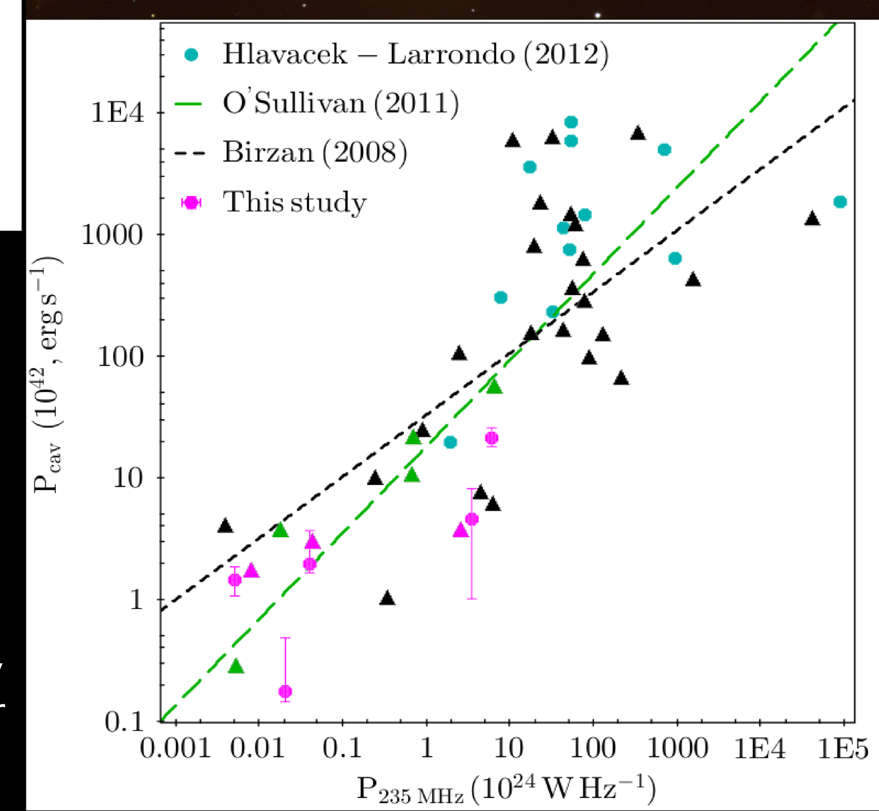


- 92% (24/26) of BGEs in high-richness sample are detected at any radio frequency
- Confirmation of trend of a high radio detection rate of BGEs in the local Universe (eg., Dunn et al. 2010)
- Majority of radio detections at GMRT 235/610 MHz are of pointlike morphology
- All radio non-detections are found in ***X-ray faint*** groups

X-ray CLoGS: O' Sullivan E., Ponman T., Kolokythas K. et al., 2017, MNRAS, 472, 1482 (Paper I)
Radio CLoGS: Kolokythas K., O' Sullivan E. et al., 2018, MNRAS, 481, 1550 (Follow up Paper II)

Jets and Energetics in High-Richness sample: Heating vs Cooling





- Mechanical power values in the range 10^{41} — 10^{43} erg s^{-1}, typical for groups
- CLoGS groups fall lower in comparison to cluster samples
- Small-scale & remnant jet systems are found in approximate thermal balance
- The 2 large-scale jet systems NGC 193 & NGC 4261 are found to be significantly **overpowered** exceeding over 100x their environment's X-ray cooling luminosity
- ***AGN feedback in groups can manifest as relatively gentle near-continuous thermal regulation, but also as extreme outbursts, which could potentially shut down cooling for long periods***

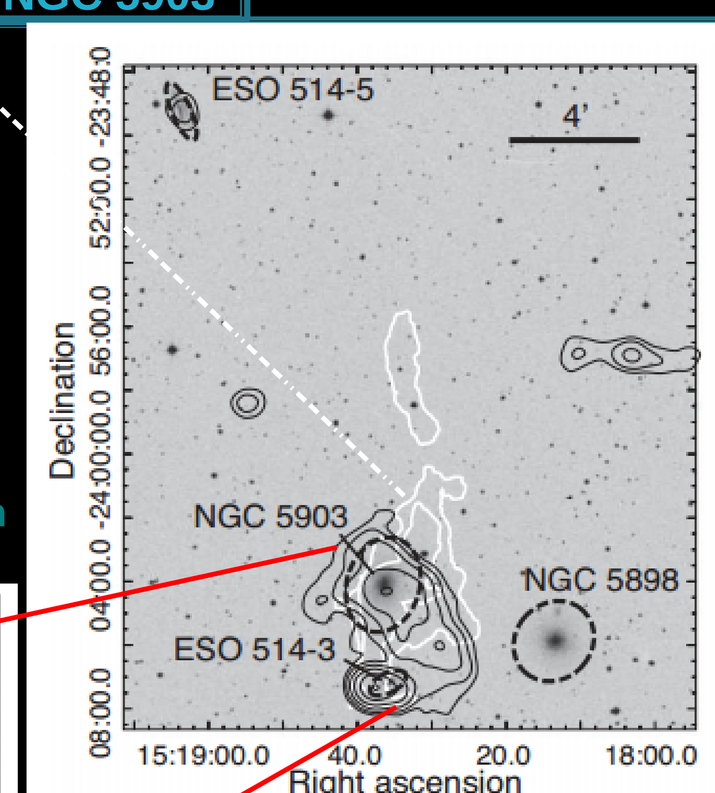
Radio CLoGS: Kolokythas K., O' Sullivan E., Raychaudhury S. et al., 2018, MNRAS, 481, 1550

Interaction history in groups: The case of NGC 5903

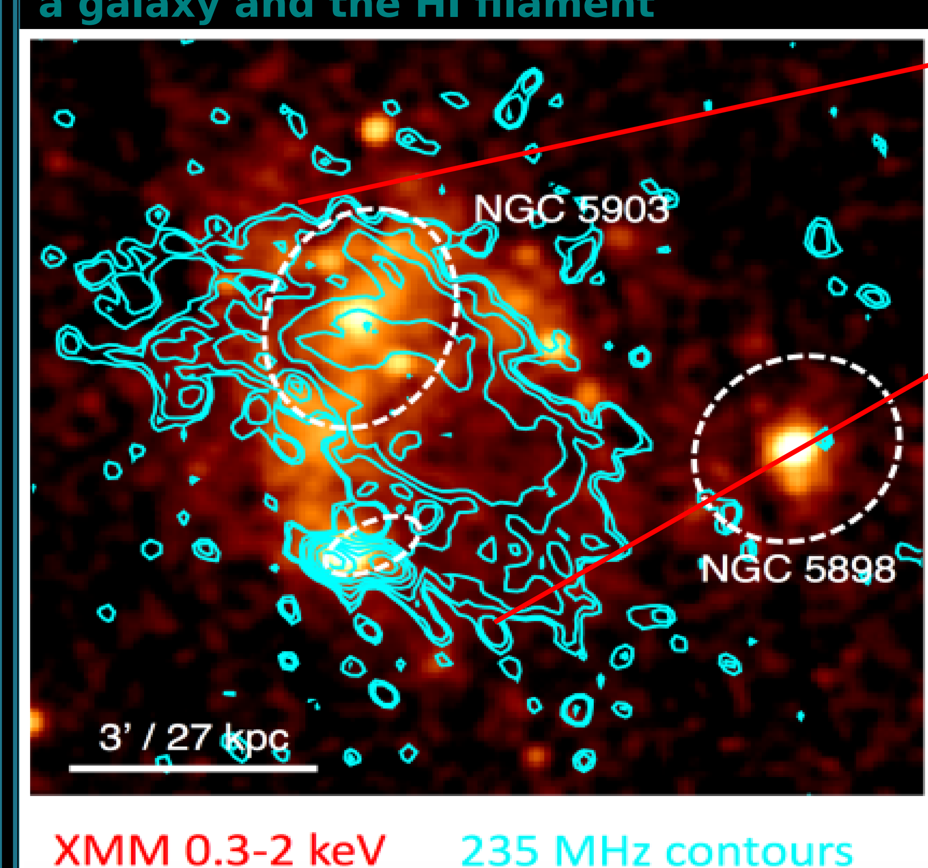
- ~110 kpc HI filament through NGC 5903 (Appleton1990)
- ~75 kpc diffuse steep-spectrum radio source
- Detection of a previously unknown extended (~145 kpc), X-ray bright hot IGM of ~0.65 KeV

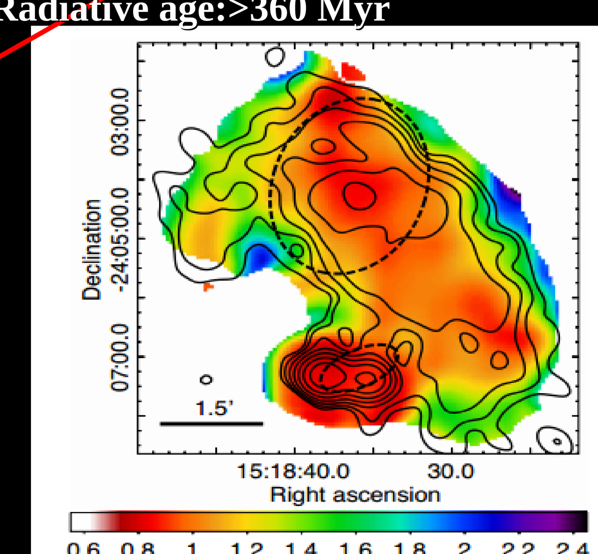
Origin of diffuse radio emission:
Through an interaction-triggered AGN outburst with jet power 8 × 10^40 erg/s

***And* via a high-velocity collision between a galaxy and the HI filament**



Spectral index 150-610 MHz range: ~1.03
Radiative age:>360 Myr

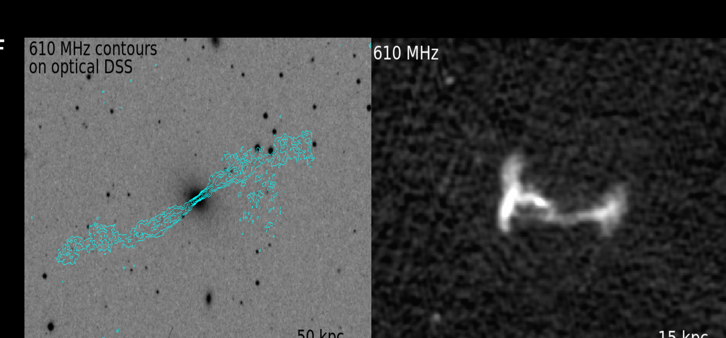




O' Sullivan E., Kolokythas K., Kantharia N. et al., 2018, MNRAS, 473, 5248

Statistics and first results from total CLoGS sample in radio

- We find a high detection rate of **87% (46/53)** of dominant galaxies hosting radio sources
- Wide range of radio power, 10^20 – 10^25 W/Hz
- **53%** present point-like radio emission, followed by **19%** having jets and non-detections at **13%**
- Mean spectral index in 235-610 MHz range is ~0.68 with *3.8% presenting ultra-steep spectrum*
- *Point-like* systems reside in dynamically young groups with *jet* systems having no environmental preference to their near environment
- M_{BH} of BGEs ranges between 2-50 x10^8 $M_\odot$
- A certain M_{BH} of host BGEs is essential, but does not play a definitive role for the jet emanation in CLoGS groups



Radio Morphology	Low–richness	High–richness	CLoGS total
Point-like	52% (14/27)	54% (14/26)	53% (28/53)
Non-detection	19% (5/27)	8% (2/26)	13% (7/53)
Large-scale jet	15% (4/27)	8% (2/26)	11% (6/53)
Diffuse emission	4% (1/27)	14% (4/26)	9% (5/53)
Small-scale jet	7% (2/27)	8% (2/26)	8% (4/53)
Remnant jet	4% (1/27)	8% (2/26)	6% (3/53)
Overall	82% (22/27)	92% (24/26)	87% (46/53)

Radio CLoGS II: Kolokythas K., O' Sullivan E., Intema H. et al., 2019, in prep. (Paper III)

Collaborators

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More info at: http://www.sr.bham.ac.uk/~ejos/CLoGS.html