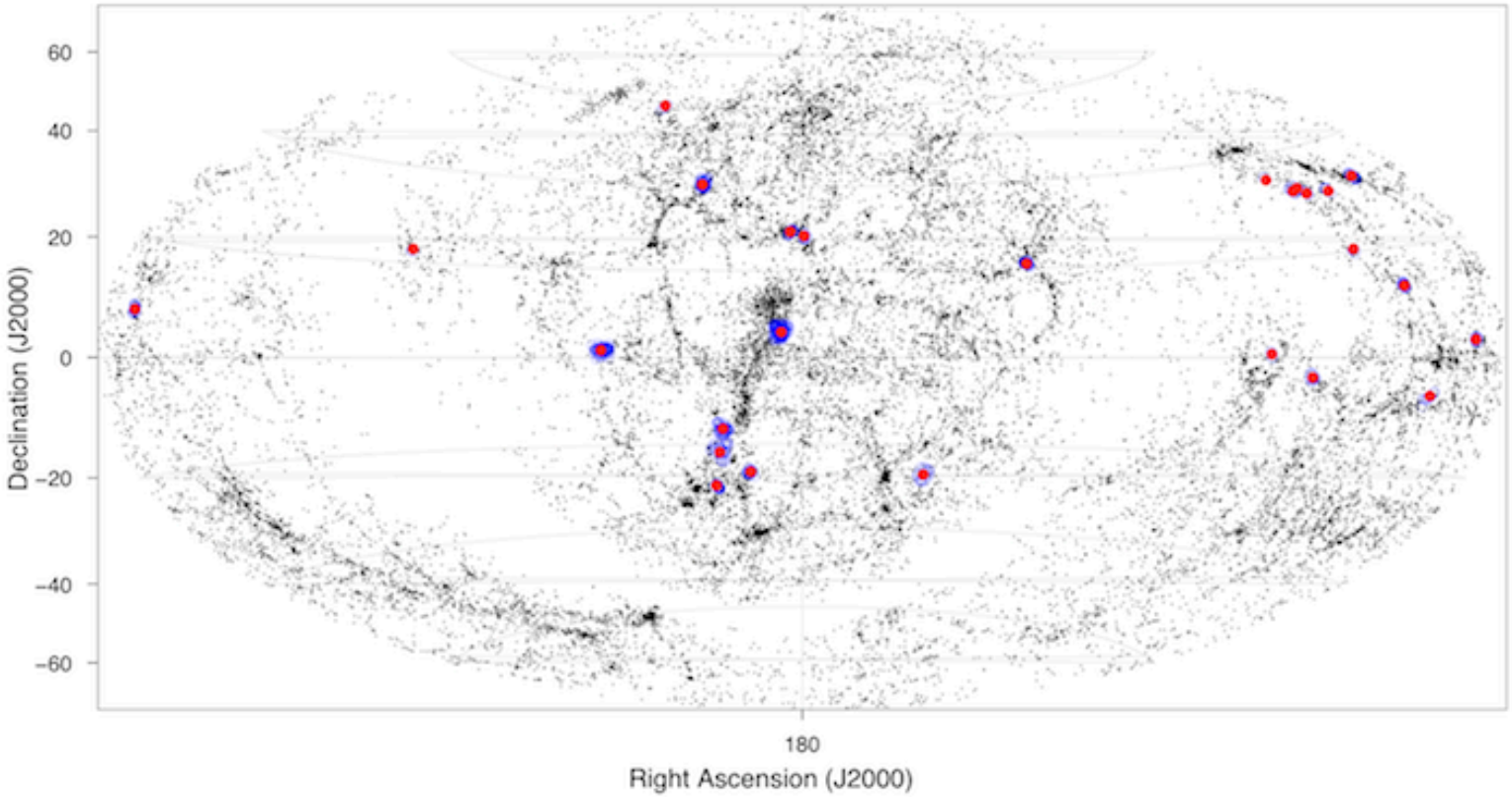
The Complete Local-Volume Groups Sample (CLoGS): progress in the unbiased assessment of galaxy group physics and evolution



Jan Vrtilek, Ewan O'Sullivan, Konstantinos Kolokythas, Laurence P. David, Simona Giacintucci, Somak Raychaudhury

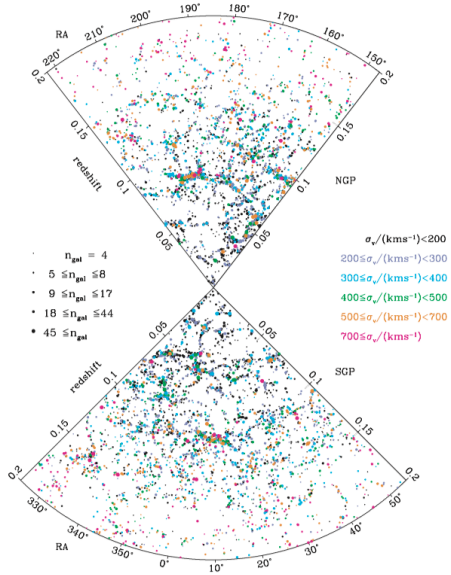
The CLoGS collaboration

SAO: **E. O'Sullivan**, J. Vrtilek, L. David, C. Jones, W. Forman, S. Murray
U. of Birmingham, UK: T. Ponman, K. Kolokythas, M. Gillone
Presidency U. & U. of Birmingham: S. Raychaudhury
NCRA-TIFR: N. Kantharia
U. Maryland: S. Giacintucci
U. de Chile: C. Haines
INAF-O.A. Bologna: M. Gitti
U. of Victoria: A. Babul
Observatoire de Paris: F. Combes, P. Salome, S. Hamer

Survey design: E. O'Sullivan
X-ray analysis: E. O'Sullivan
Radio analysis: K. Kolokythas, S. Giacintucci

Why focus on groups?

- Groups contain about *50% of galaxies in the local volume*
  (as opposed to clusters, which only contain ~2-5%),
  hence a highly significant environment for baryonic evolution.
  Rich clusters are rare. Groups are common.
  - Geller & Huchra 1983: CfA Redshift Survey; density contrast ≥ 20
  - Nolthenius & White 1987: comparison with numerical models
  - Tully 1987: analysis of redshifts
  - Eke et al. 2004 (2dFGRS)



2dFGRS Percolation-Inferred Galaxy Groups (2PIGGs) (Eke+04)

- *Galaxy / gas evolution.*
  Groups favor galaxy interactions. Small groups are rich in cold gas (HI), massive groups in hot gas (10^7K) How does this happen?
- Prerequisite for understanding *formation of structure*:
  galaxy => group => cluster hierarchy

Why yet another sample?
--- what problem does CLoGS address?

- We lack representative, unbiased samples…
  - *Optically-selected* catalogs include some false groups (chance associations, uncollapsed groups)
  - *X-ray selection* guarantees valid groups but:
    - Misses X-ray faint groups
    - Strongly favors cool core systems (Are there X-ray bright but non-cool-core groups to be discovered? -- *hint: yes, a few*)

- The CLoGS selection process is intended to overcome these limitations…

Why yet another sample?
--- the goals of CLoGS

- Physical properties of the nearby group population:
  - What fraction of optically-selected groups contain a hot IGM?
  - What is their range of mass, temperature, metal abundance, etc?
  - What fraction have cool cores?
    (Roughly 50% of clusters are CC, but non-statistical samples of groups have up to 85% CCs: e.g., Dong et al 2010, based on Chandra archive.)

Why yet another sample?
--- the goals of CLoGS

- Physical properties of the nearby group population:
  - What fraction of optically-selected groups contain a hot IGM?
  - What is their range of mass, temperature, metal abundance, etc?
  - What fraction have cool cores?
    (Roughly 50% of clusters are CC, but non-statistical samples of groups have up to 85% CCs: e.g., Dong et al 2010, based on Chandra archive.)

- Central AGN as a group-scale feedback mechanism:
  - Do group-central AGN balance cooling? What is duty cycle, power
  - How are central AGN affected by environment? Cool cores, entropy?

Why yet another sample?
--- the goals of CLoGS

- Physical properties of the nearby group population:
  - What fraction of optically-selected groups contain a hot IGM?
  - What is their range of mass, temperature, metal abundance, etc?
  - What fraction have cool cores?
    (Roughly 50% of clusters are CC, but non-statistical samples of groups have up to 85% CCs: e.g., Dong et al 2010, based on Chandra archive.)

- Central AGN as a group-scale feedback mechanism:
  - Do group-central AGN balance cooling? What is duty cycle, power
  - How are central AGN affected by environment? Cool cores, entropy?

- Impact of group environment on member galaxies:
  - Is star formation rate affected by group environment?
  - What fraction of member galaxies host AGN? Radio, X-ray, optical?

Selecting the sample (part 1)

Begin with LGG (Garcia 1993)

- *All-sky* catalog of groups
- *Shallow/local*: cz<5500 km s^{-1} (D<80Mpc)
- *Optically-selected*:

  combine friends-of-friends and hierarchical approaches

485 groups

Selecting the sample (part 1)

Begin with LGG (Garcia 1993)

- *All-sky* catalog of groups
- *Shallow/local*: cz<5500 km s^{-1} (D<80Mpc)
- *Optically-selected*:

  combine friends-of-friends and hierarchical approaches

485 groups

Select from LGG list: systems with

- ≥4 members
- ≥1 early-type member with $L_B \geq 3\times10^{10} L_\odot$

  spiral-only groups almost never have IGM detectable in X-rays
- Declination >-30° visible from VLA and GMRT

~70 groups

Selecting the sample (part 1)

Begin with LGG (Garcia 1993)

- *All-sky* catalog of groups
- *Shallow/local*: cz<5500 km s^{-1} (D<80Mpc)
- *Optically-selected*:
  combine friends-of-friends and hierarchical approaches

485 groups

Select from LGG list: systems with

- ≥4 members
- ≥1 early-type member with $L_B \geq 3\times10^{10} L_\odot$
  spiral-only groups almost never have IGM detectable in X-rays
- Declination >-30° visible from VLA and GMRT

~70 groups

Expand and characterize membership

- Find additional group members in LEDA archive within 1 Mpc and 2000 km s^{-1} of BGE
- Compute velocity dispersion
  Keep members within 3σ: iterate to stable membership

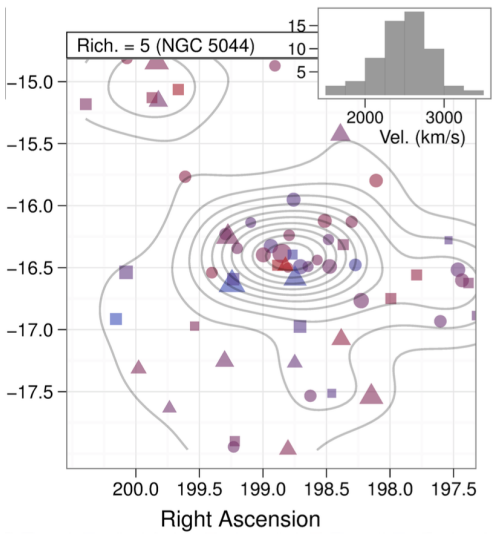
~70 groups

Selecting the sample (part 2)

Filter on *spatial distribution:*

- Make isodensity maps and reject cases
  - Without central peak
  - Substructures of known clusters

67 groups

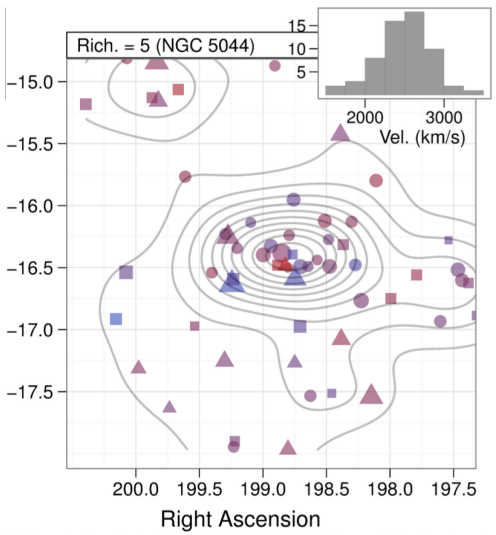


Selecting the sample (part 2)

Filter on *spatial distribution:*

- Make isodensity maps and reject cases
  - Without central peak
  - Substructures of known clusters

67 groups



Filter on *richness*

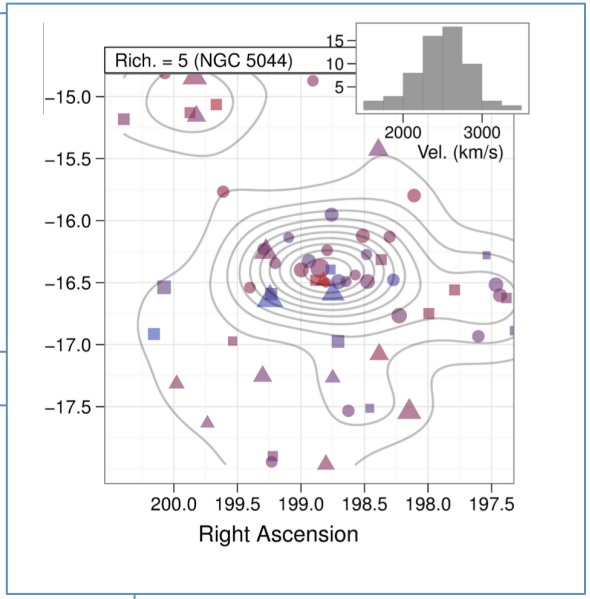
- R = number of galaxies with $L_B \geq 1.6 \times 10^{10} L_\odot$
  - Exclude known clusters: R≥10
  - Exclude groups too small to characterize: R=1

Selecting the sample (part 2)

Filter on *spatial distribution:*

- Make isodensity maps and reject cases
  - Without central peak
  - Substructures of known clusters

67 groups



Filter on *richness*

- R = number of galaxies with $L_B \geq 1.6 \times 10^{10}\ L_\odot$
  - Exclude known clusters: R≥10
  - Exclude groups too small to characterize: R=1

53 groups

26 groups
High-richness subsample (R=4-8)

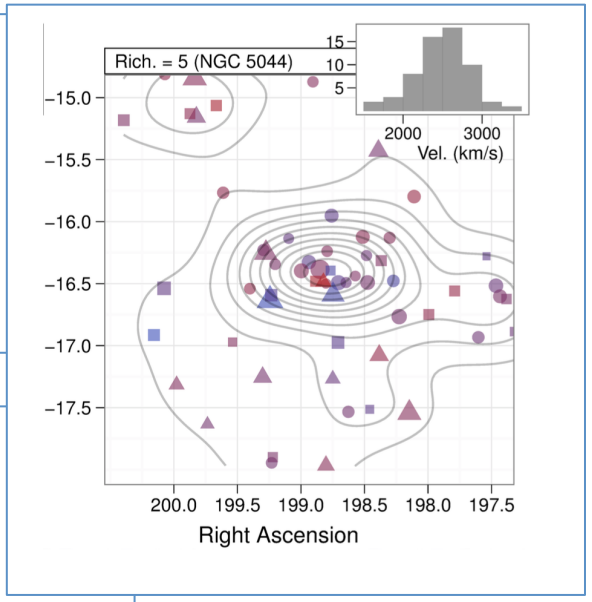
27 groups
Low-richness subsample (R=2-3)

Selecting the sample (part 2)

Filter on *spatial distribution:*

- Make isodensity maps and reject cases
  - Without central peak
  - Substructures of known clusters

67 groups



Filter on *richness*

- R = number of galaxies with $L_B \geq 1.6 \times 10^{10} L_\odot$
  - Exclude known clusters: R≥10
  - Exclude groups too small to characterize: R=1

53 groups

26 groups
High-richness subsample (R=4-8)

27 groups
Low-richness subsample (R=2-3)

CLoGS data: status of X-ray observations

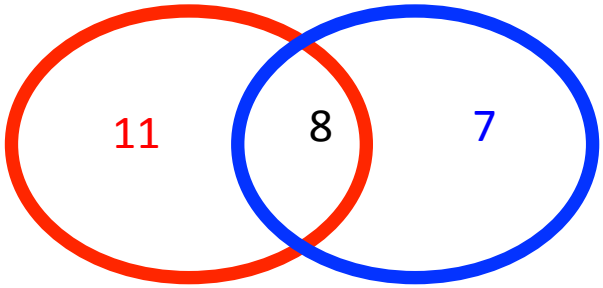
X-ray observations are complete for the full high-richness subsample (26 groups).

- New data: ~300ks XMM plus ~50ks Chandra obtained for this program
- Archival data added as available
- Limiting sensitivity:

  $L_x \geq 1.2\times10^{42}$ erg s^{-1} within $R<R_{500}$

  $L_x \geq 3.9\times10^{42}$ erg s^{-1} within R<65 kpc

XMM:
9 new observations
10 archive observations



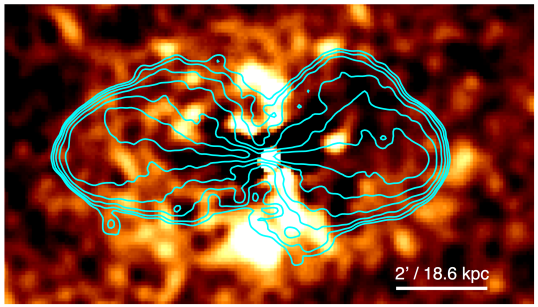
Chandra:
4 new observations
11 archive observations

(Low-richness subsample: 12 of 27 groups observed. 72% of *entire* sample has X-ray observations.)

CLoGS data overview: status of radio and other observations

- **Radio:**
  - *Full sample complete at 235 and 610 MHz*
  - ~200 hrs GMRT dual-freq. + archival data (Giacintucci et al. 2011)
  - ~4hrs/target, rms ~0.1mJy/b @610 MHz, ~0.6mJy/b @ 235 MHz.
  - GMRT Field of view well suited to groups, diameters >1°.
  - Data for high-richness sample fully reduced.

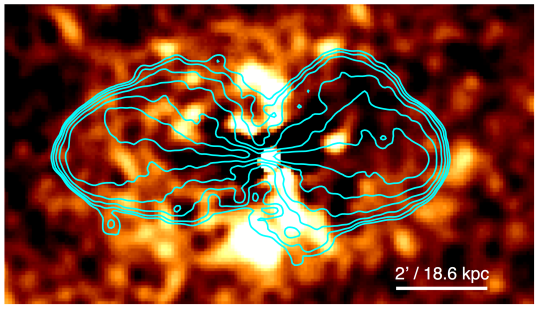
NGC 4261 (LGG 278)



CLoGS data overview: status of radio and other observations

- **Radio:**
  - *Full sample complete at 235 and 610 MHz*
  - ~200 hrs GMRT dual-freq. + archival data (Giacintucci et al. 2011)
  - ~4hrs/target, rms ~0.1mJy/b @610 MHz, ~0.6mJy/b @ 235 MHz.
  - GMRT Field of view well suited to groups, diameters >1°.
  - Data for high-richness sample fully reduced.

NGC 4261 (LGG 278)

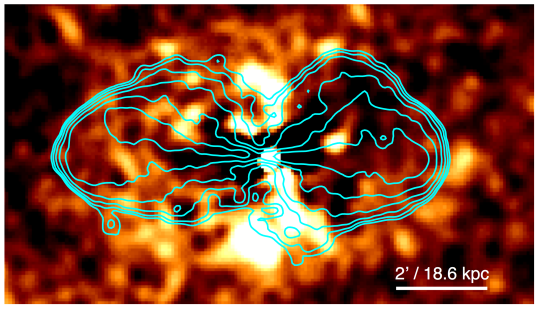


- **Hα:**
  - CHANGES
    Complete H-Alpha imaging of Nearby Group Environments
    PI: Chris Haynes
  - wide-field Hα and optical imaging
  - Steward Observatory 2.3m Bok telescope and the WIYN 0.9m telescope
  - Survey ~1/2 complete

CLoGS data overview: status of radio and other observations

- **Radio:**
  - *Full sample complete at 235 and 610 MHz*
  - ~200 hrs GMRT dual-freq. + archival data (Giacintucci et al. 2011)
  - ~4hrs/target, rms ~0.1mJy/b @610 MHz, ~0.6mJy/b @ 235 MHz.
  - GMRT Field of view well suited to groups, diameters >1°.
  - Data for high-richness sample fully reduced.

NGC 4261 (LGG 278)

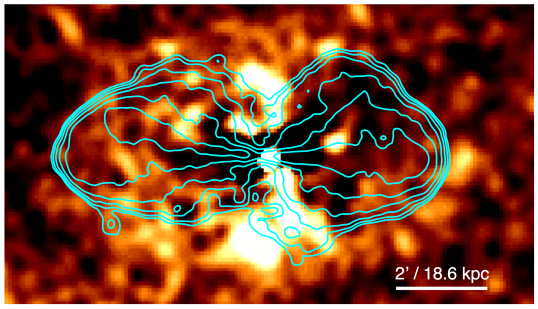


- **Hα:**
  - CHANGES
    Complete H-Alpha imaging of Nearby Group Environments
    PI: Chris Haynes
  - wide-field Hα and optical imaging
  - Steward Observatory 2.3m Bok telescope and the WIYN 0.9m telescope
  - Survey ~1/2 complete
- **CO:**
  - High richness subsample in progress (begin with x-ray bright groups with IRAS detections)
  - IRAM 30-m (a few target groups are too far south)

CLoGS data overview: status of radio and other observations

- **Radio:**
  - *Full sample complete at 235 and 610 MHz*
  - ~200 hrs GMRT dual-freq. + archival data (Giacintucci et al. 2011)
  - ~4hrs/target, rms ~0.1mJy/b @610 MHz, ~0.6mJy/b @ 235 MHz.
  - GMRT Field of view well suited to groups, diameters >1°.
  - Data for high-richness sample fully reduced.

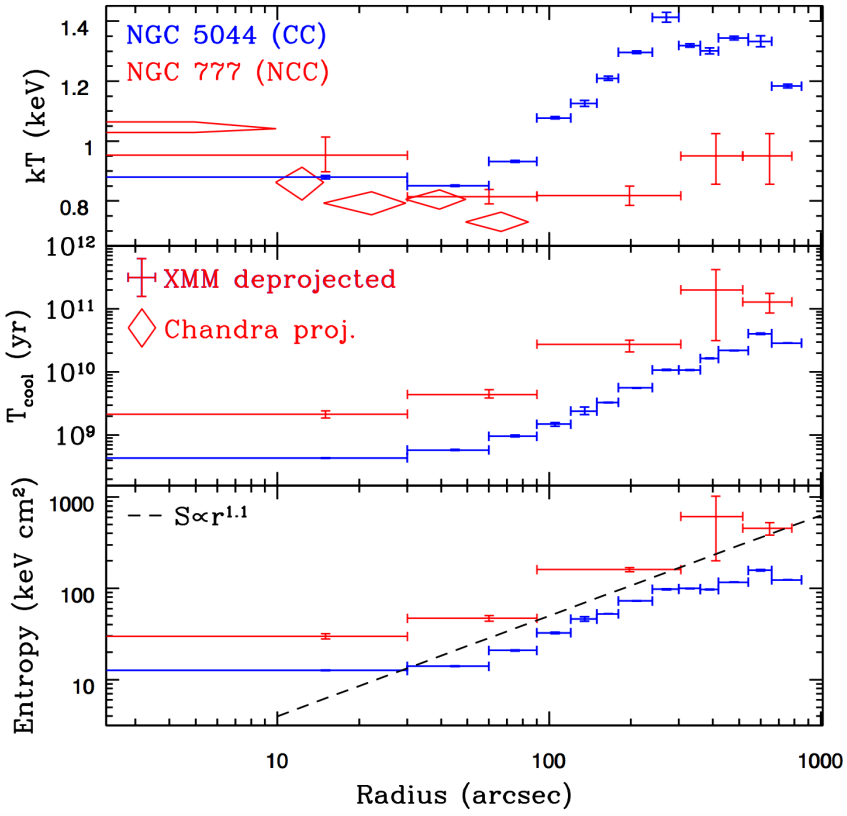
NGC 4261 (LGG 278)



- **Hα:**
  - CHANGES
    Complete H-Alpha imaging of Nearby Group Environments
    PI: Chris Haynes
  - wide-field Hα and optical imaging
  - Steward Observatory 2.3m Bok telescope and the WIYN 0.9m telescope
  - Survey ~1/2 complete
- **CO:**
  - High richness subsample in progress (begin with x-ray bright groups with IRAS detections)
  - IRAM 30-m (a few target groups are too far south)
- **HI:**
  - A few objects under study; mostly archival data
  - New data for NGC 5903 (GMRT)

CLoGS: X-ray overview

- Of the 26 groups in the high-richness subsample:
  - 14 (55%) are X-ray bright (with an extent >65kpc)
  - 7 have galaxy-scale emission
  - 5 show only point sources
- Dynamically-active groups:
  - 2/14 are group-group mergers
  - 2/14 "sloshing"
- Typical kT ≈ 0.5-1.6 keV ➔ $M_{500} \approx 8\times10^{12} - 6\times10^{13}\ M_{\odot}$
- Fraction of Cool Cores = 65%
  - 9/14 have declining central kT
  - Compare to ~50% in clusters.



CLoGS: radio overview (part 1: galaxy detections)

Central galaxies

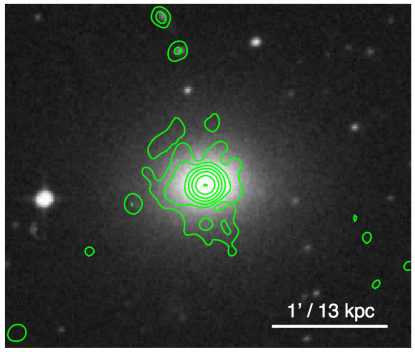
For the 26 groups in the high-richness subsample:

- 25 of the 26 group-central galaxies are detected at 610 or 235 MHz
- 3 are *diffuse*
- 15 are *unresolved*
- 7 host *jet sources*

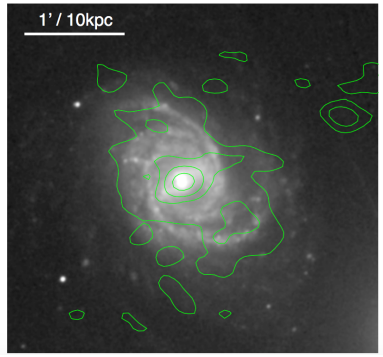
Non-central galaxies

For 18 groups processed to date:

- 72 of 170 galaxies detected (42%)
- *Late-type:* 43 of 62 detected (69%)
- *Non-central early-type:* 12 of 45 detected (27%)
- *Dwarfs/irregulars:* 17 of 63 detected (27%)



← ESO507-25: Diffuse source 610 MHz contours at (0.4,0.8,1.6,… mJy/b)



NGC 5350 → AGN+SF disk 235 MHz contours at (0.9,1.8,3.6,… mJy/b)

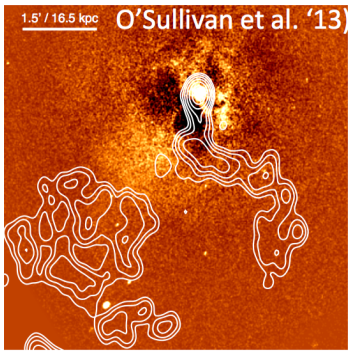
CLoGS: radio overview (part 2: jets)

Central AGN jets

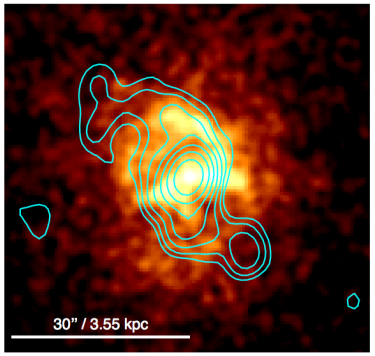
Of the 14 X-ray confirmed groups in the high-richness subsample:

- 6 host radio jets
- Large variety of morphologies
- Estimated ages 1 – 100 Myr
- Large range of enthalpies: 10^{55} – 10^{59} erg

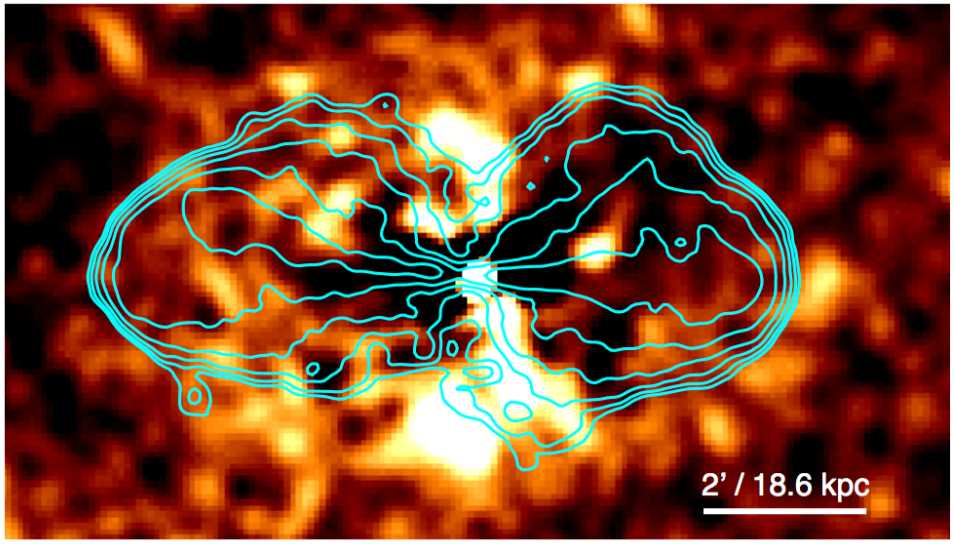
NGC 5044 (David et al. '09,'11 O'Sullivan et al. '13)



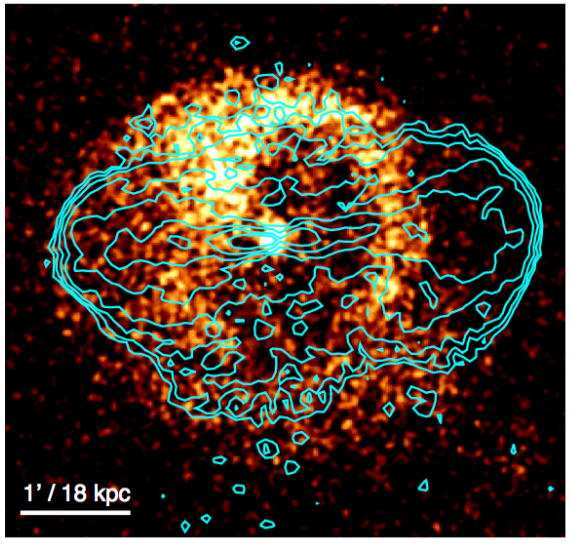
NGC 5846 (Machacek et al. '12)



NGC 4261 / 3C270 (O'Sullivan et al. '11



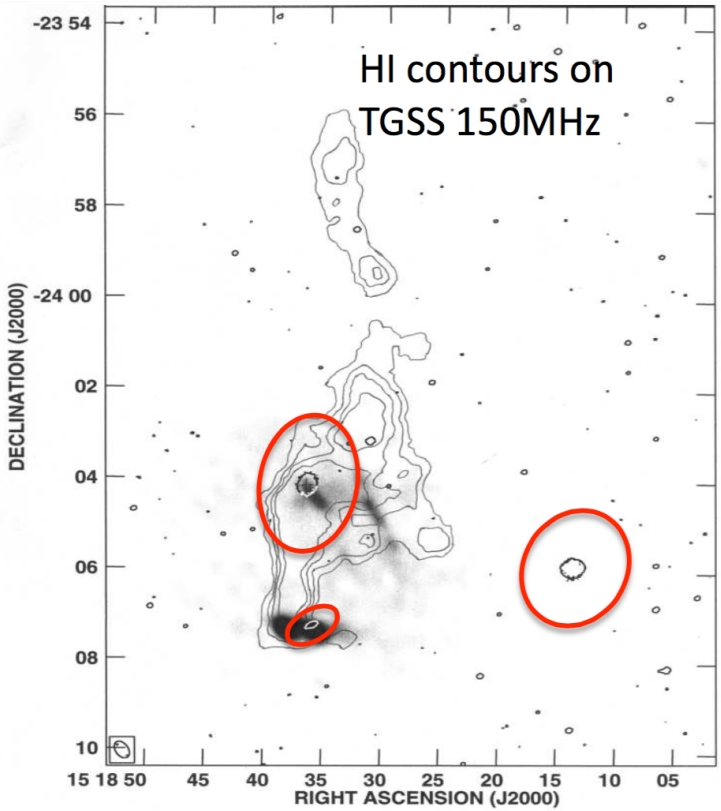
NGC 193 / 4C+03.01

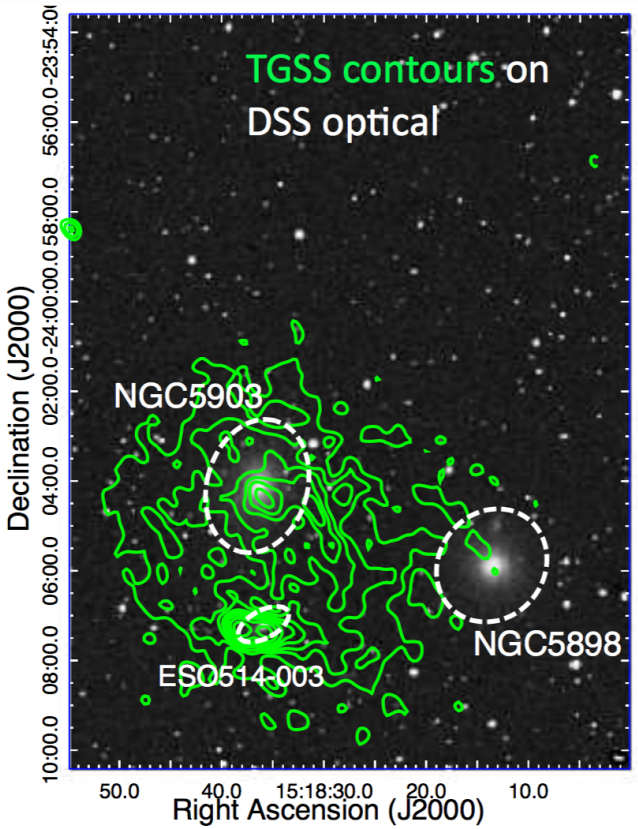


CLoGS: NGC 5903

… an example of a CloGS groups of individual interest:
HI-rich, with diffuse radio emission (cf. Gopal-Krishna+12).

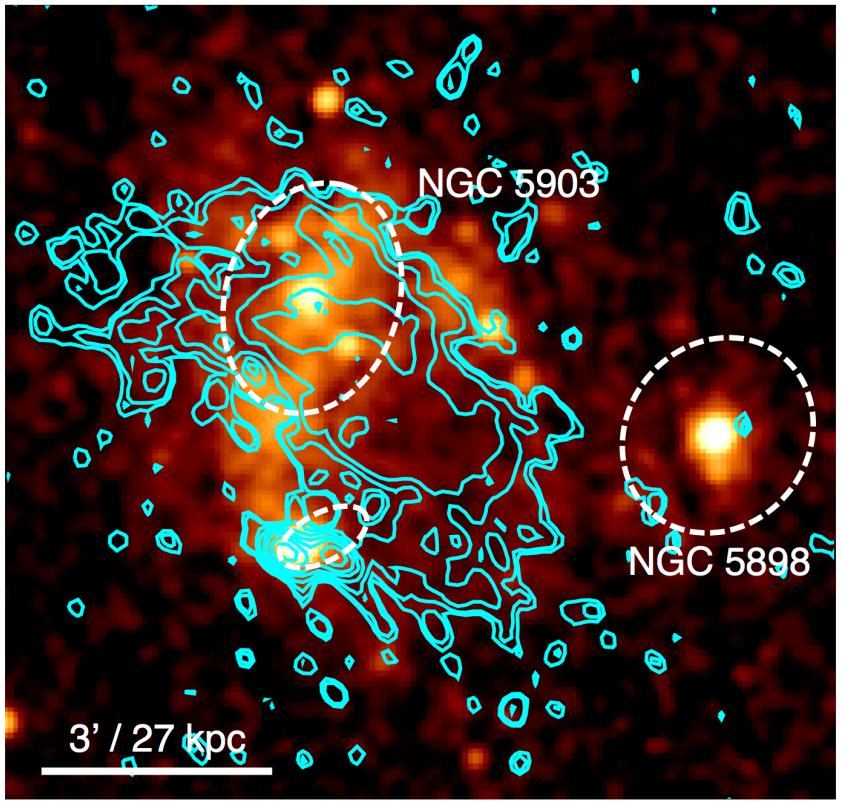
$3\times10^9\ M_\odot$ of HI in 100 kpc filament extending across NGC 5903 (Appleton+90)
TGSS confirms ~7 Jy diffuse structure around NGC 5903, $\alpha=1.5\pm0.08$





CLoGS: NGC 5903 --- a collision shock?

- X-ray data:
  ~40 ks XMM (low-level flaring throughout)
- Disturbed 0.7 keV IGM correlated with HI
- Hot gas mass ≈ HI deficit (3×10^{10} $M_\odot$)
  Similar to collision shock in Stephan's Quintet?



XMM 0.3-2 keV 235 MHz contours

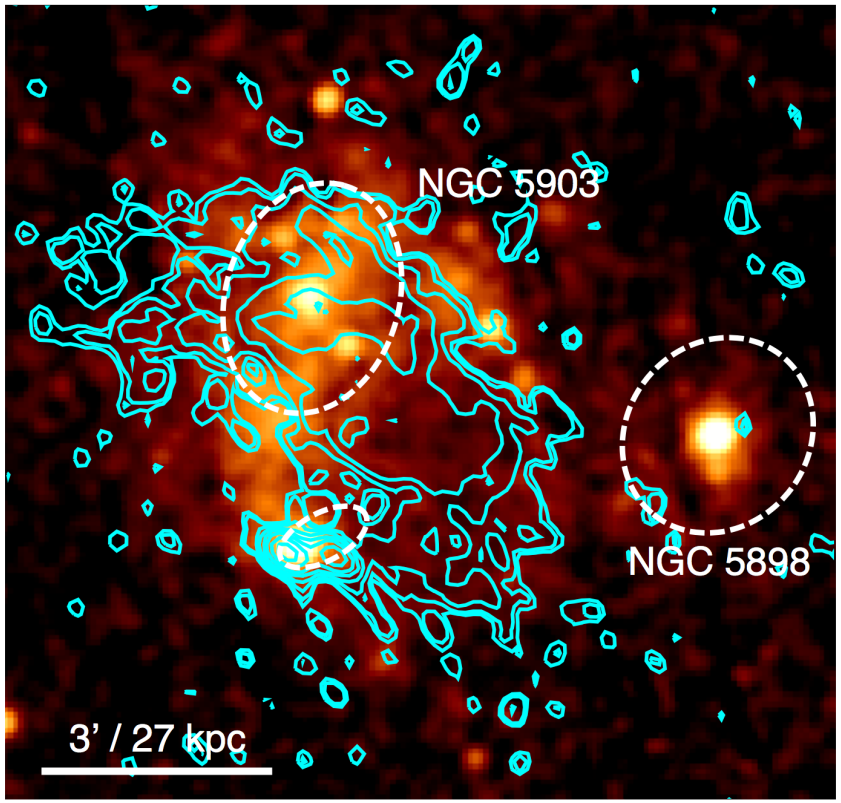
CLoGS: NGC 5903 --- a collision shock?

- X-ray data:
  ~40 ks XMM (low-level flaring throughout)
- Disturbed 0.7 keV IGM correlated with HI
- Hot gas mass ≈ HI deficit (3×10^{10} $M_\odot$)
  Similar to collision shock in Stephan's Quintet?

But…

- No clear high-velocity intruder galaxy.
- In SQ radio correlated with HI and X-ray. Here we only see a hint of this in NW ridge – age?

New HI observations (GMRT) have been obtained to get high-res.
velocity maps: reduction is pending.

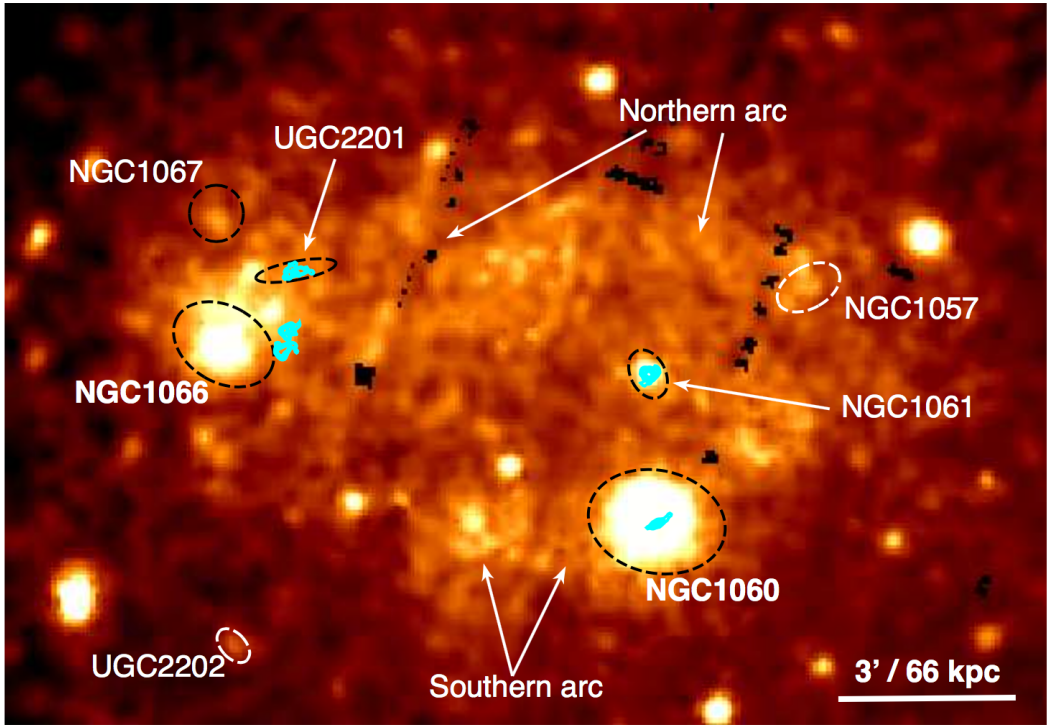


XMM 0.3-2 keV 235 MHz contours

CLoGS: …more interesting groups…

LGG 72

- Centered on ellipticals NGC 1060 and NGC 1066
- LOS velocities differ by 800 km s^{-1} (~Mach 2)
- Diffuse X-ray emission, elevated T: shock heating?
- Most energetic group merger in local Universe?
  120ks Chandra observation approved for cycle 17



XMM
0.3-2 keV

Summary

CLoGS: Complete Local-Volume Groups Sample

An optically-selected, statistically-complete sample of 53 groups within 80 Mpc, observed in radio and X-ray.

- High-richness subsample of 26 groups complete in X-ray.
- Full sample completely observed at 610 and 235 MHz.
- 14/26 groups confirmed as gravitationally bound with X-ray bright IGM, typical kT = 0.5-1.6 keV.
- 6/14 have central jet sources, enthalpies = 10^{55}-10^{59} erg, source ages ~1-100 Myr.
- Cool-core fraction ~65%, only CC groups host jet sources.
- Sample contains individual sources that merit followup. NGC 5903 may be a second Stephan's Quintet-like collision shock.
- Followup in Hα, CO, and (for selected objects) HI in progress