AGN feedback in galaxy groups using X-rays, Radio, CO and Hα observations

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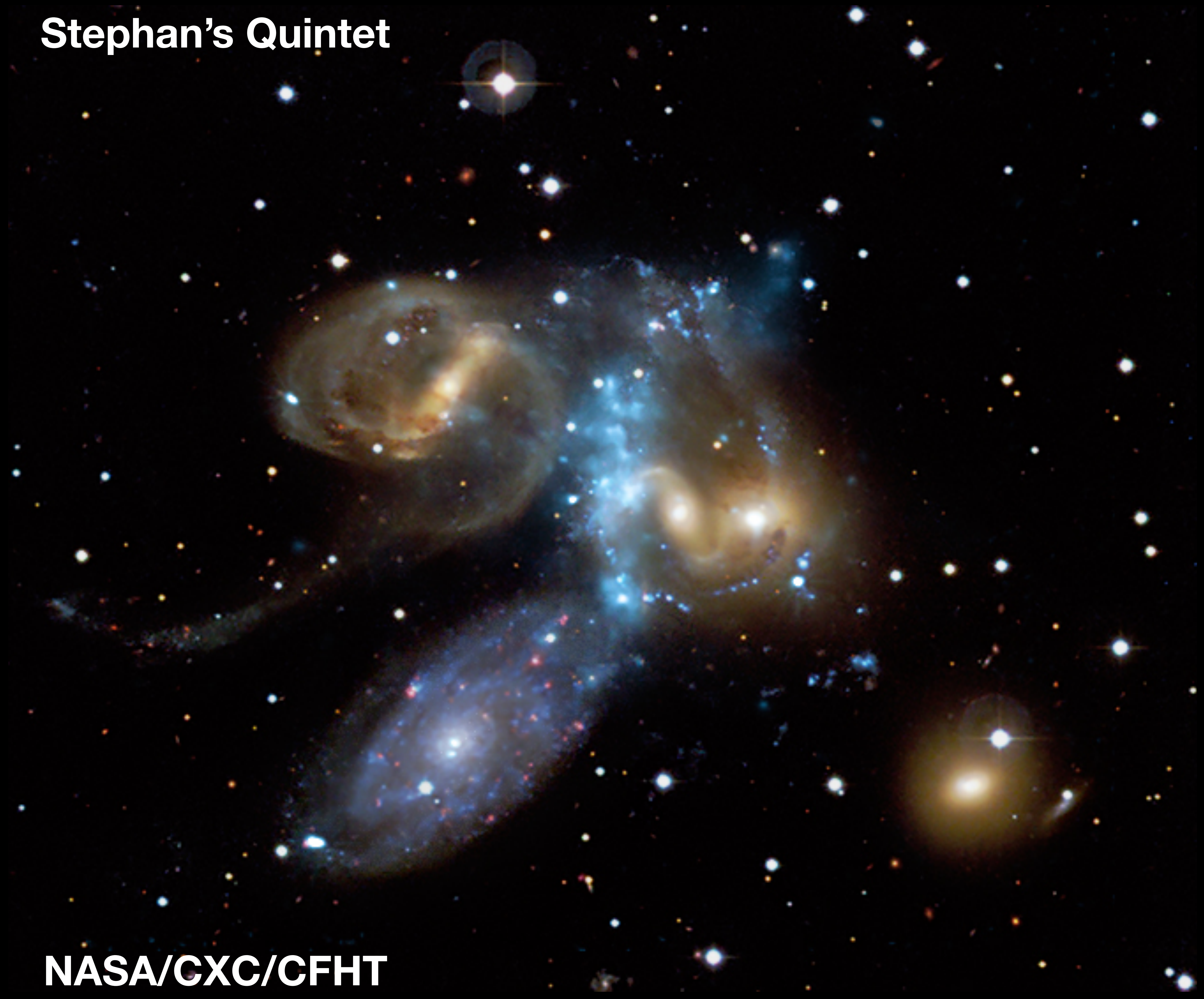
HARVARD & SMITHSONIAN

Galaxy groups

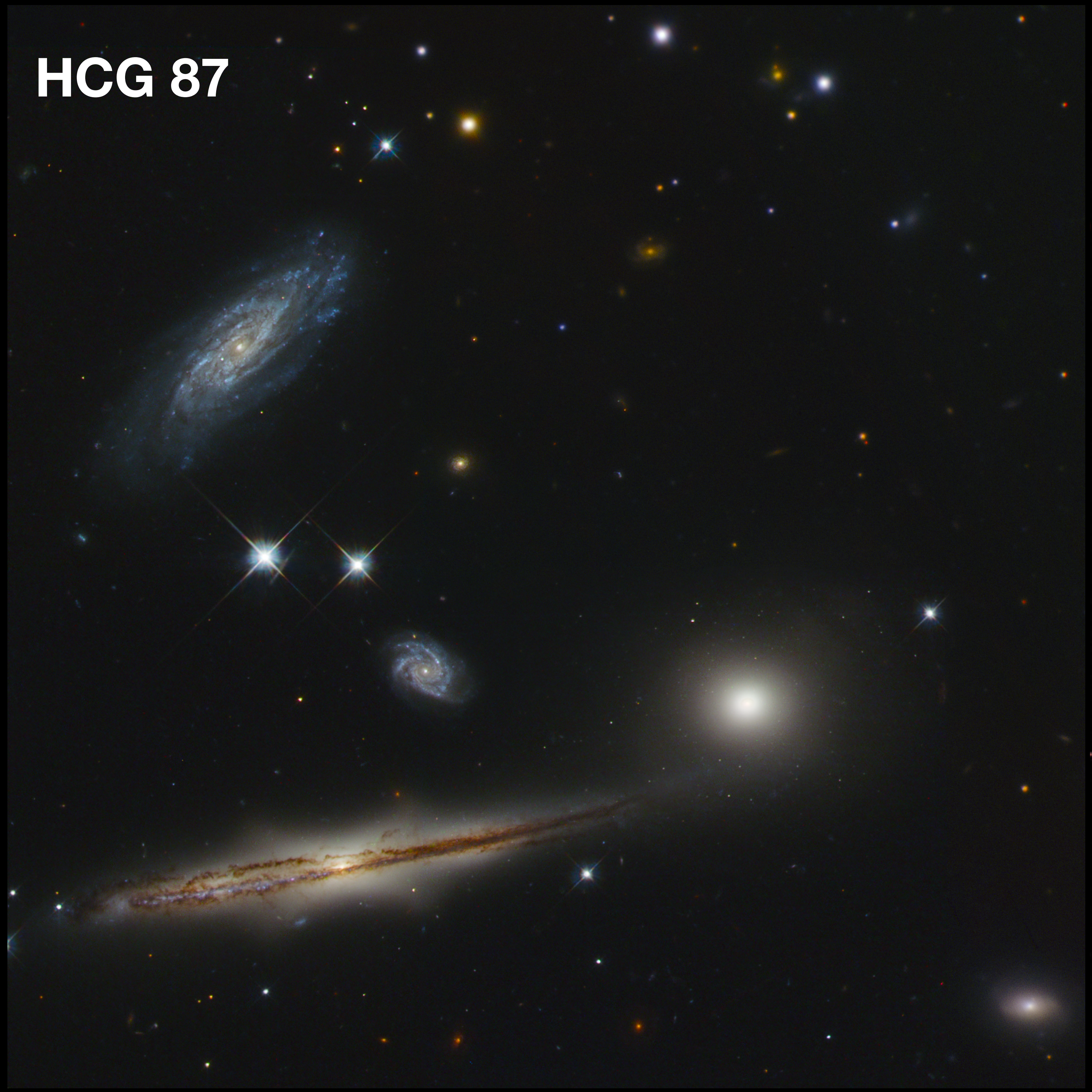


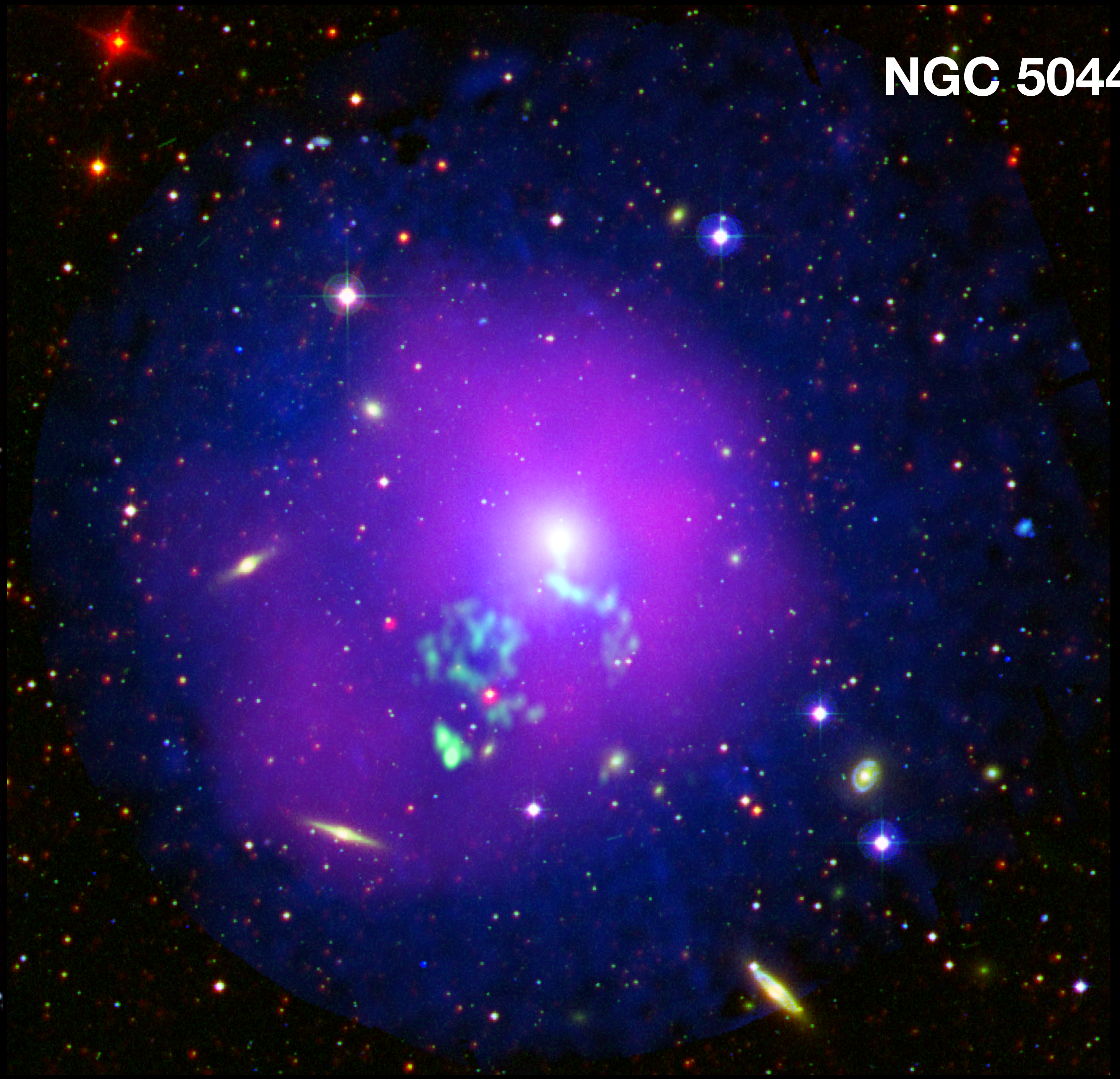
Most galaxies are located in groups

Environment drives interesting physics:

- Galaxy evolution
- Gas stripping and shock heating
- Formation of hot intra-group medium
- Shallow potential wells
  ➜ greater impact from AGN, mergers?

Galaxy groups: a diverse class

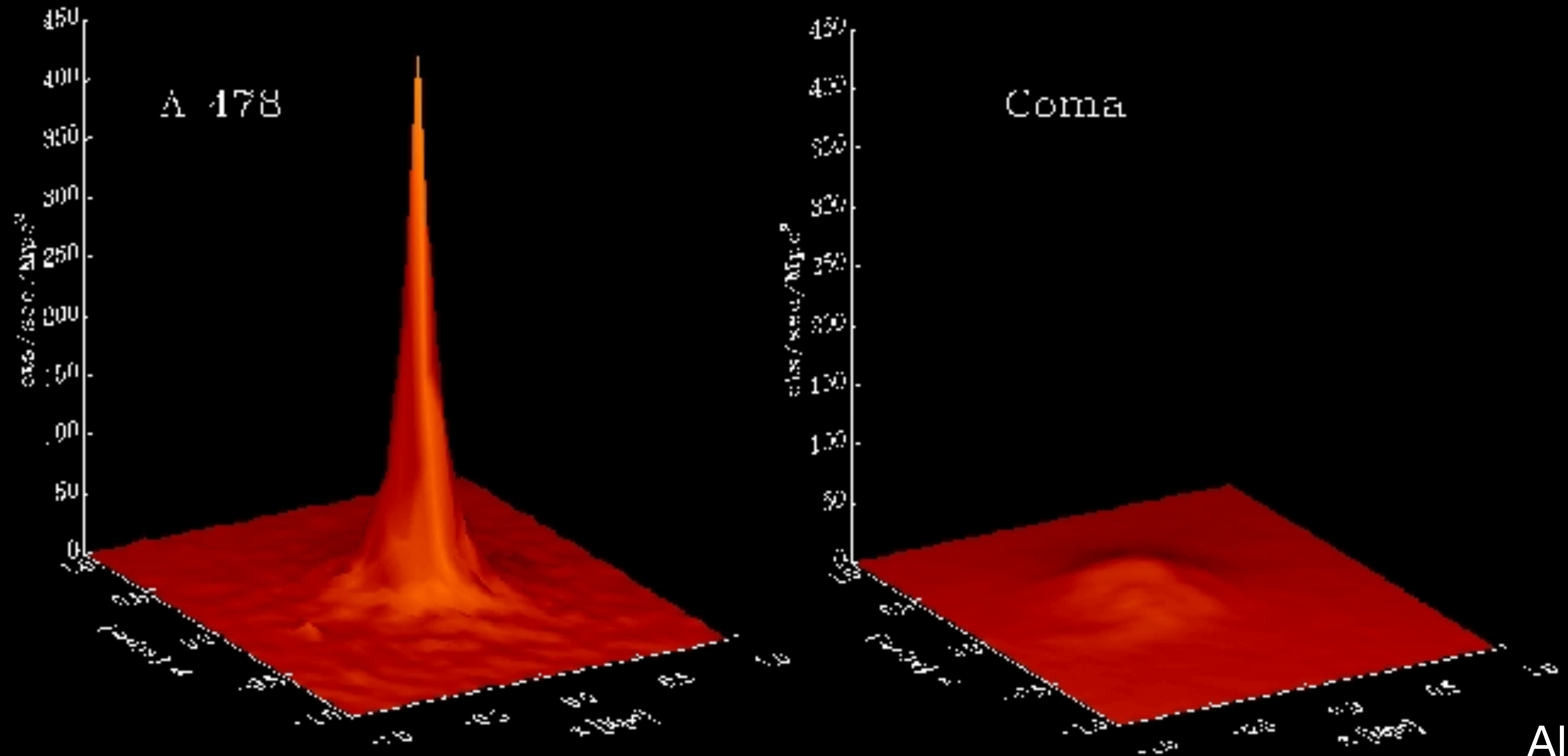




NASA/ESA/Gemini

X-ray and AGN feedback studies focus on X-ray bright, ~10^{13}-10^{14} $M_{\odot}$, ~0.5-2 keV systems

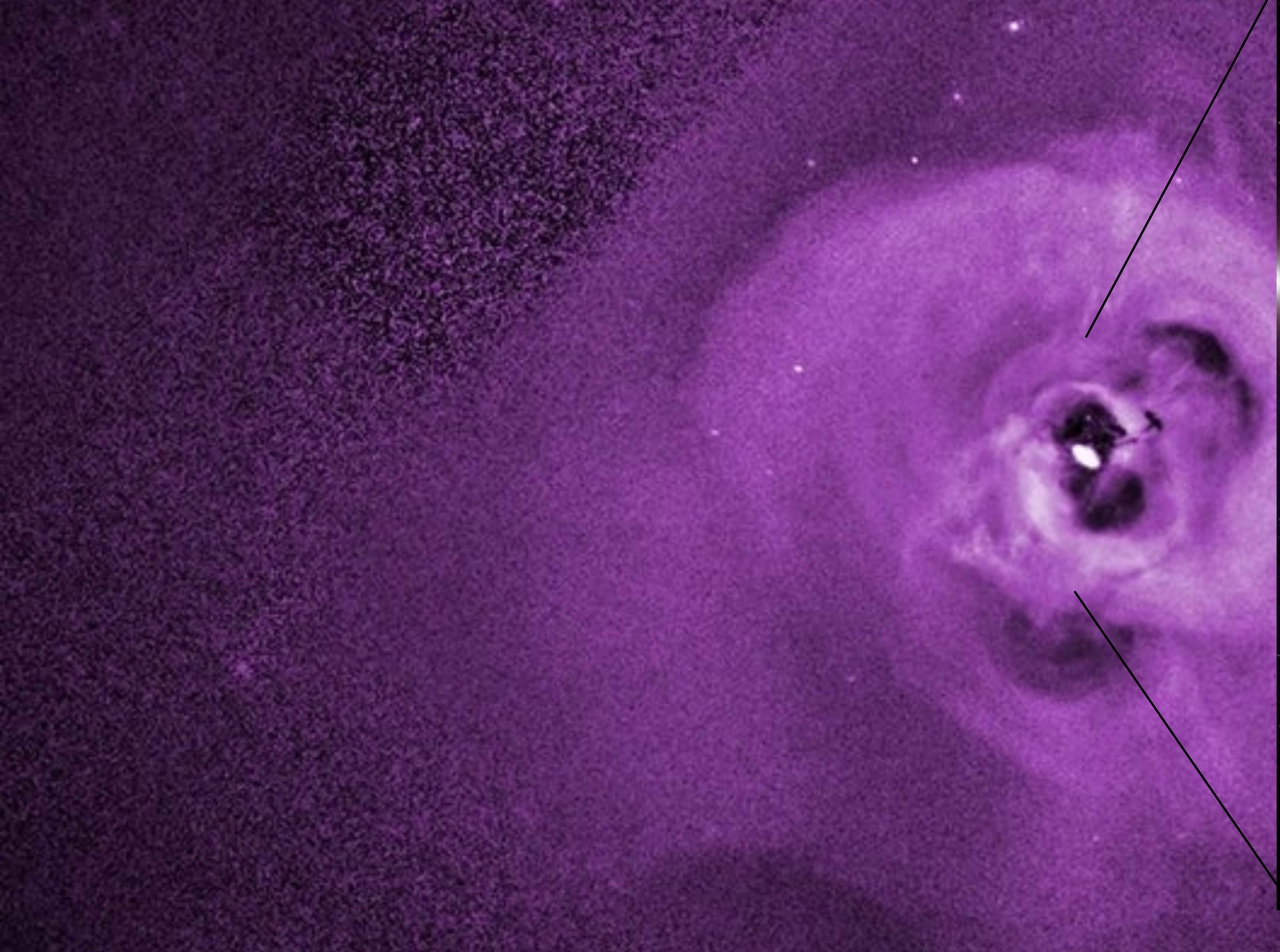
The cooling flow problem



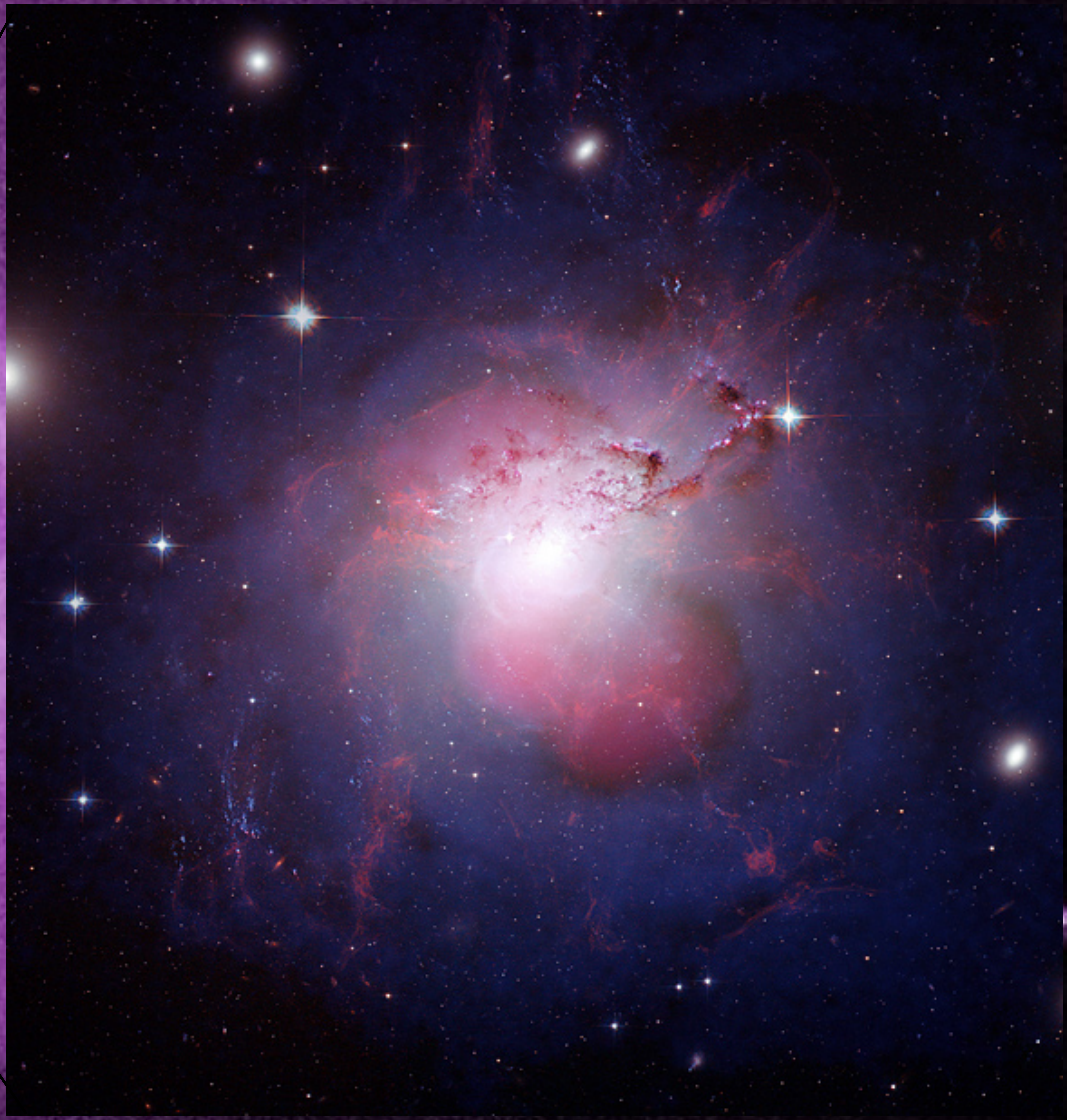
Allen & Fabian (1997)

- ICM X-ray emission proportional to n_e^2 ➜ rapid cooling in relaxed cluster cores
- Observed cooling rates (X-ray, cold gas, star formation) far lower than expected
- What suppresses cooling?

The Perseus cluster

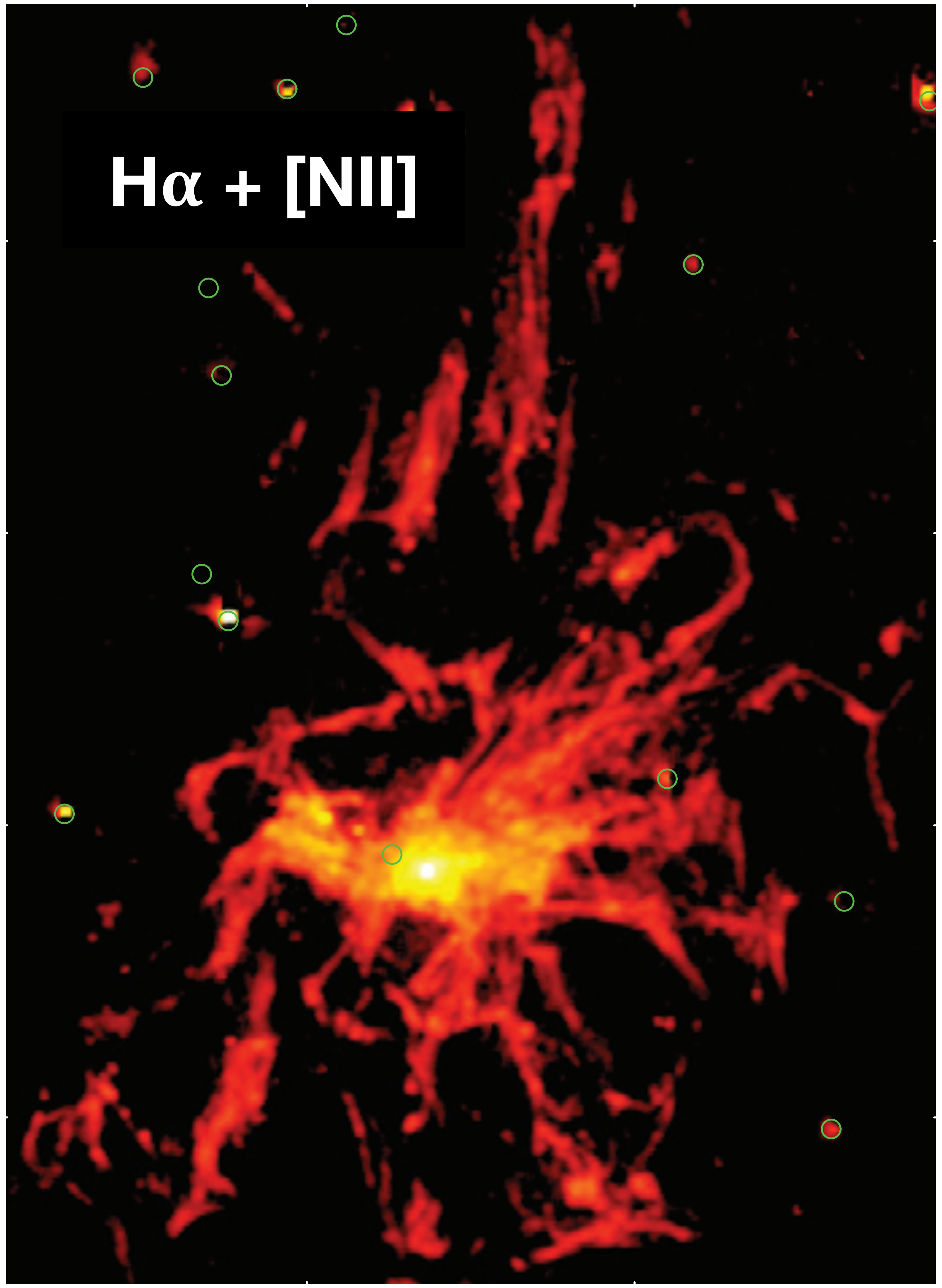


NASA/CXC/Stanford/I. Zhuravleva et al.

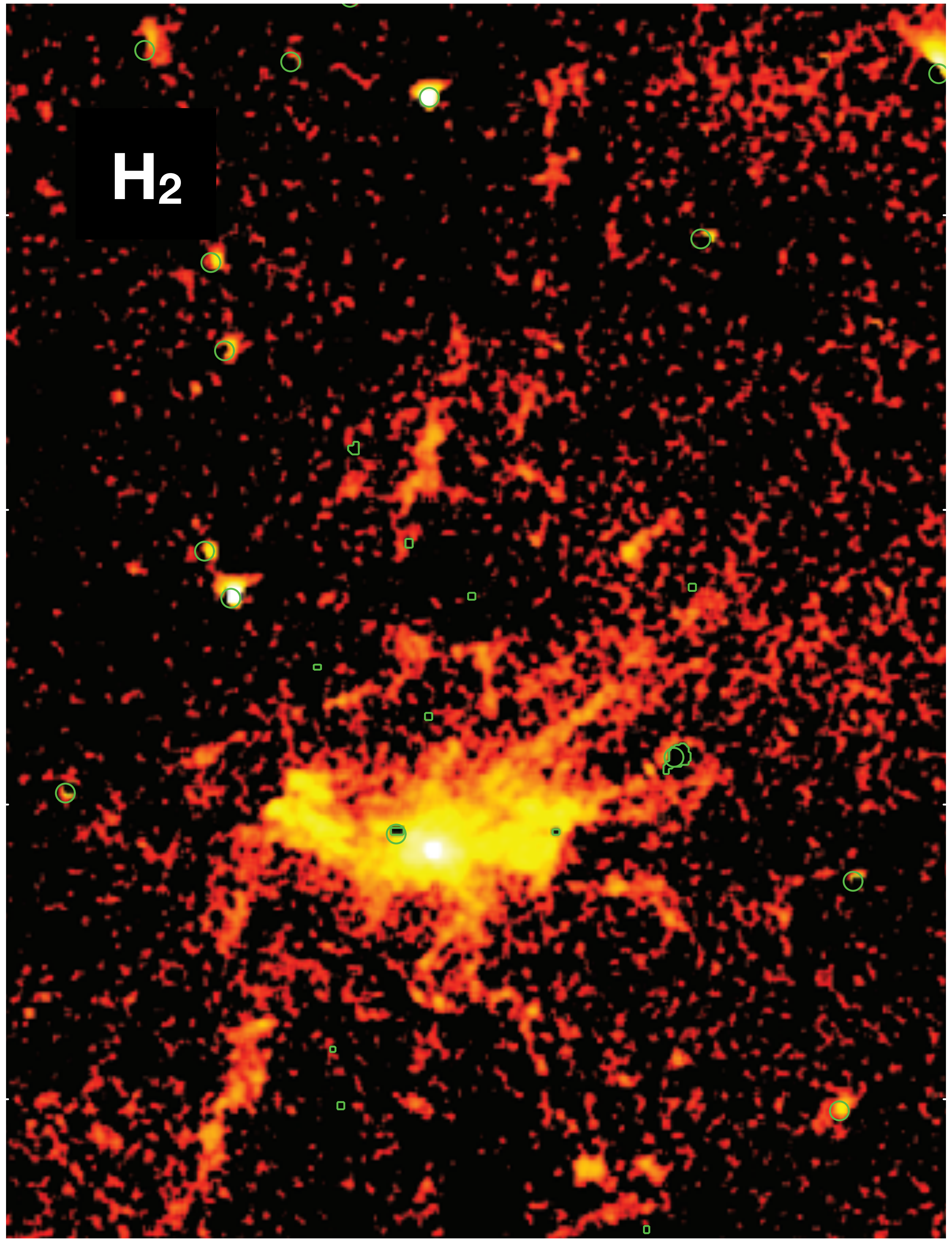


NASA/CXC/IoA/A.Fabian et al.; NRAO/VLA/G. Taylor; NASA/ESA/Hubble Heritage (STScI/AURA)

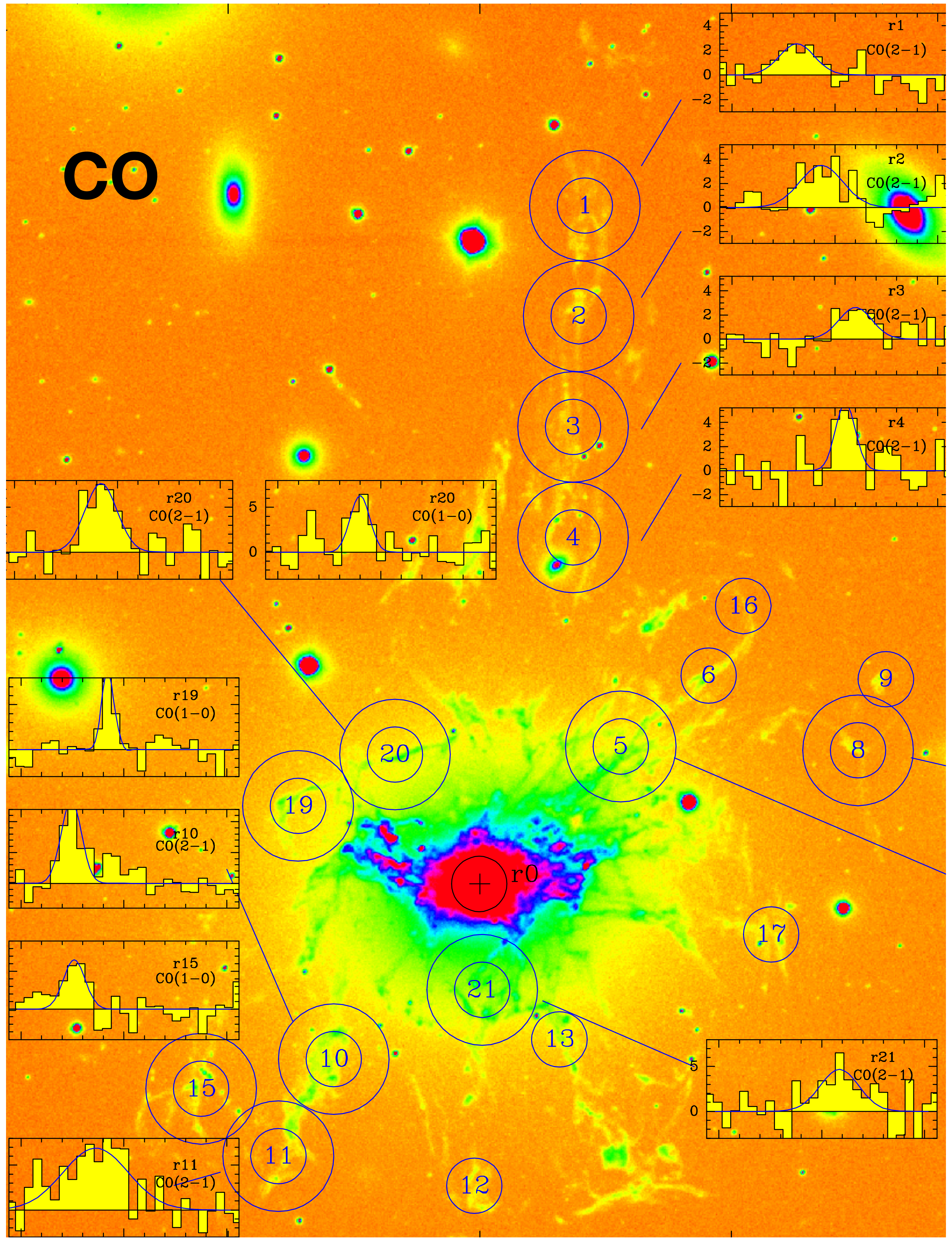
Perseus: Cooling gas



Conselice et al. (2001)



Lim et al. (2010)



Salomé et al (2011)

Filamentary nebula of gas with temperatures 10-10^5 K, but relatively little star formation

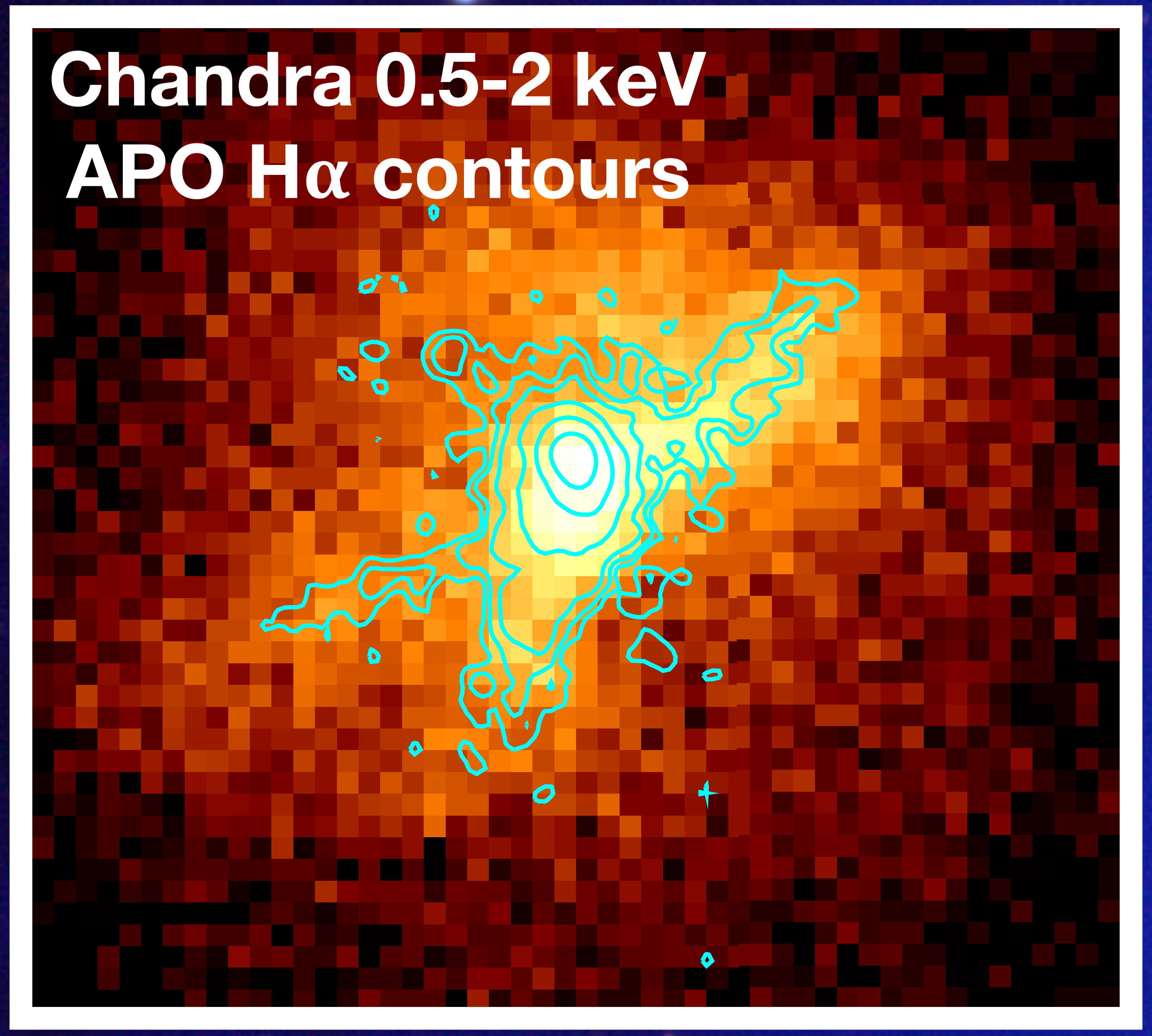
AGN feedback in NGC 6338

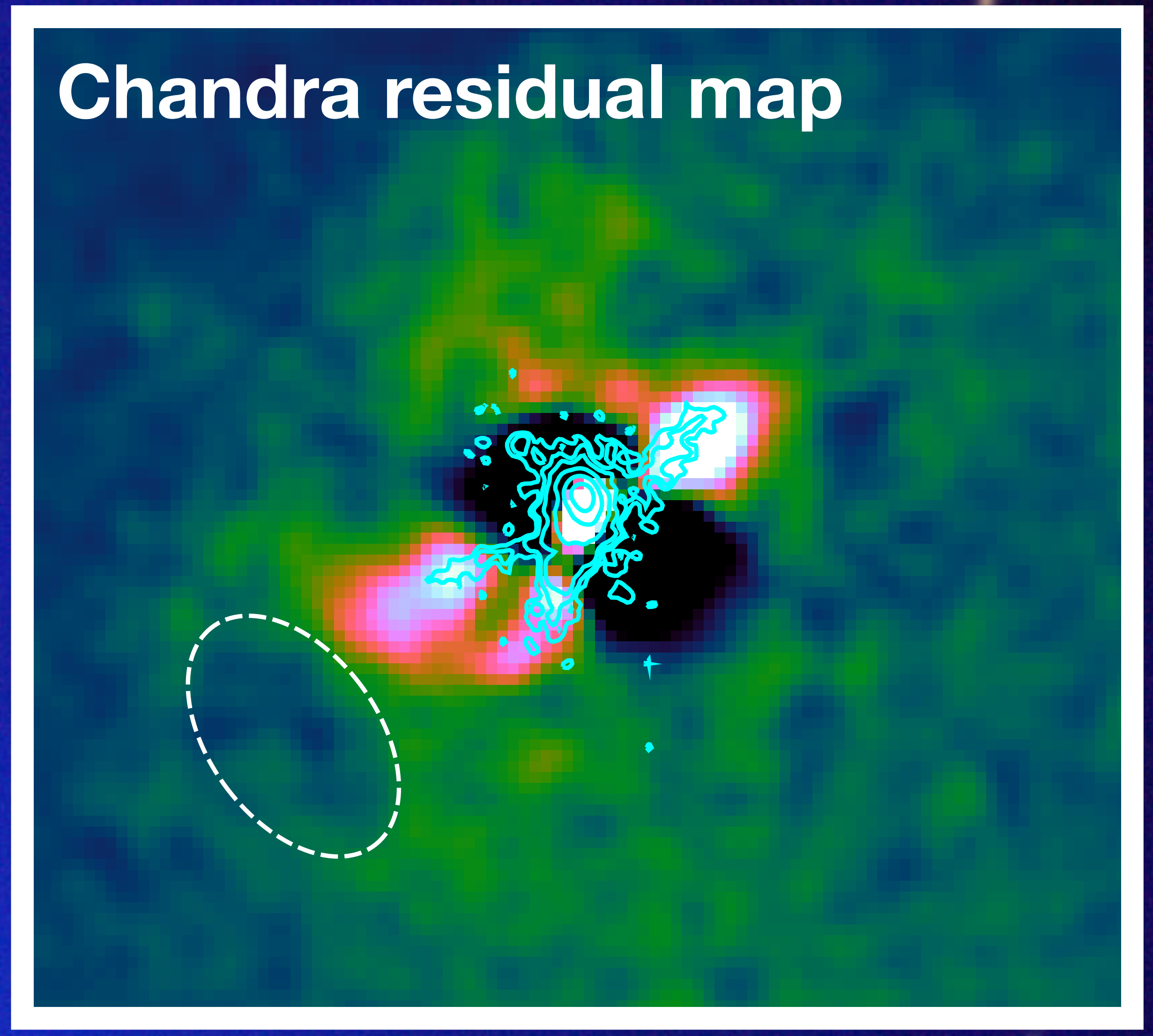
High mass merging group

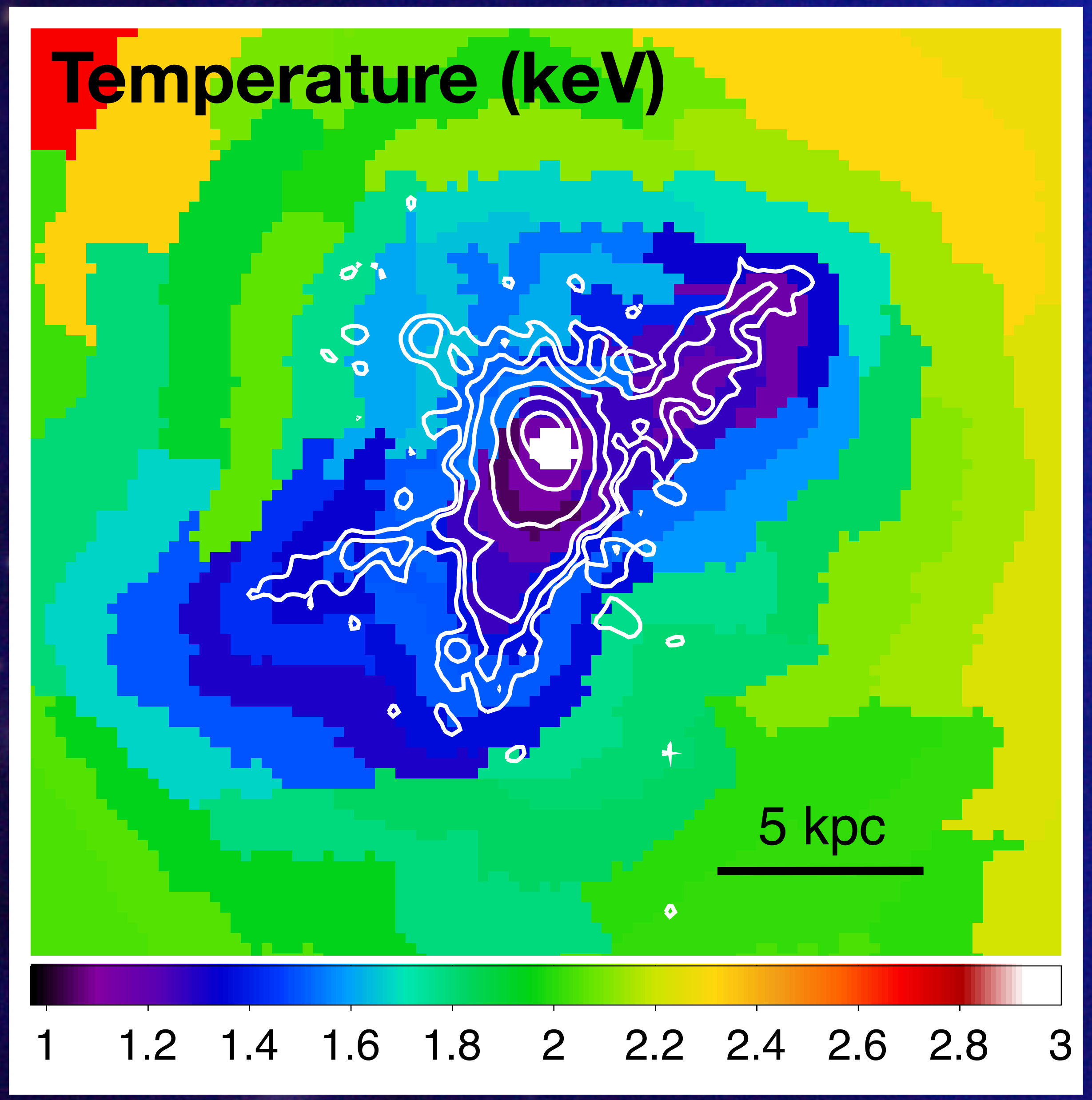
Both cores show evidence of cooling and feedback

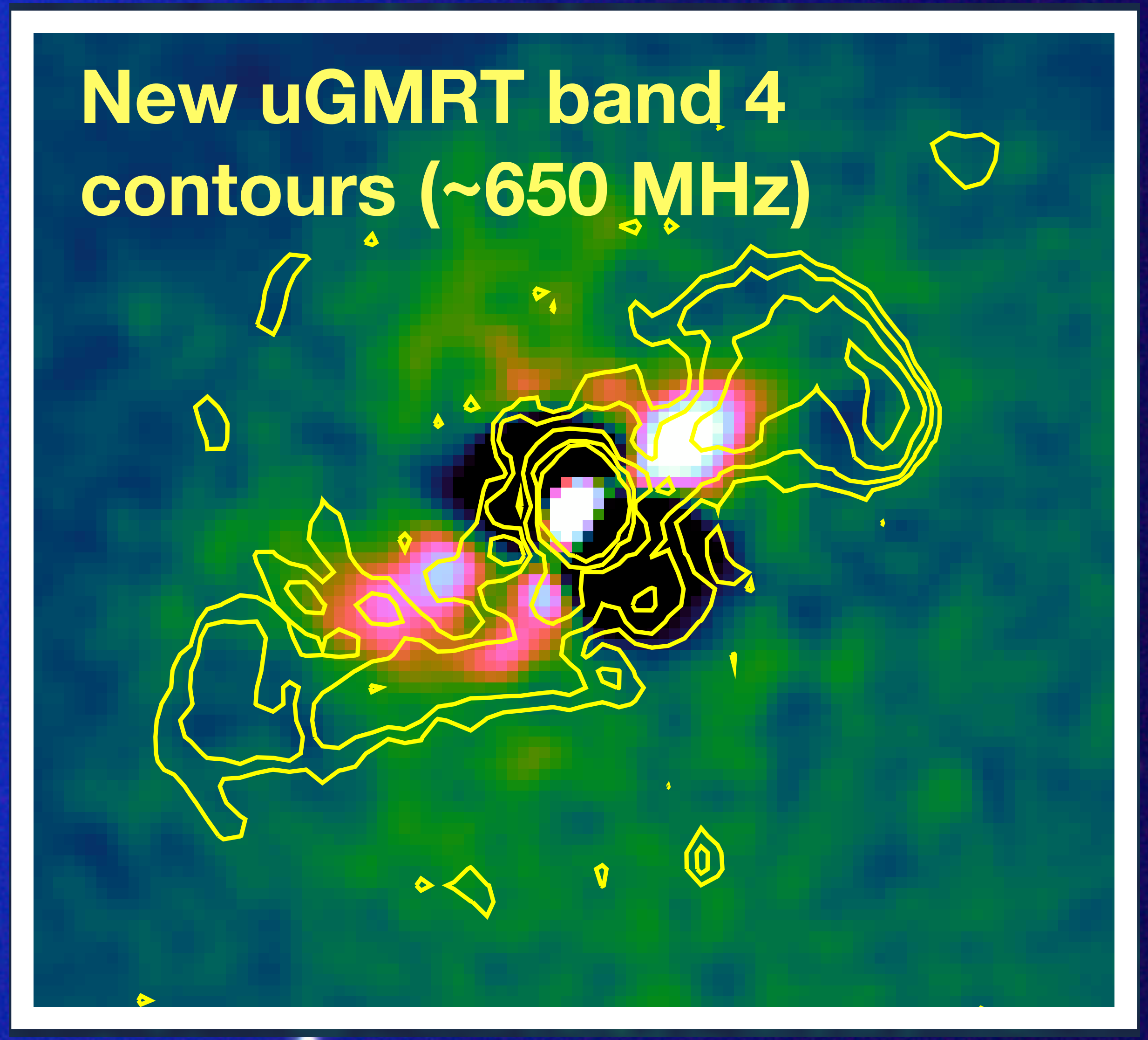
O'Sullivan et al. 2019
Pan et al. 2020

AGN feedback in NGC 6338



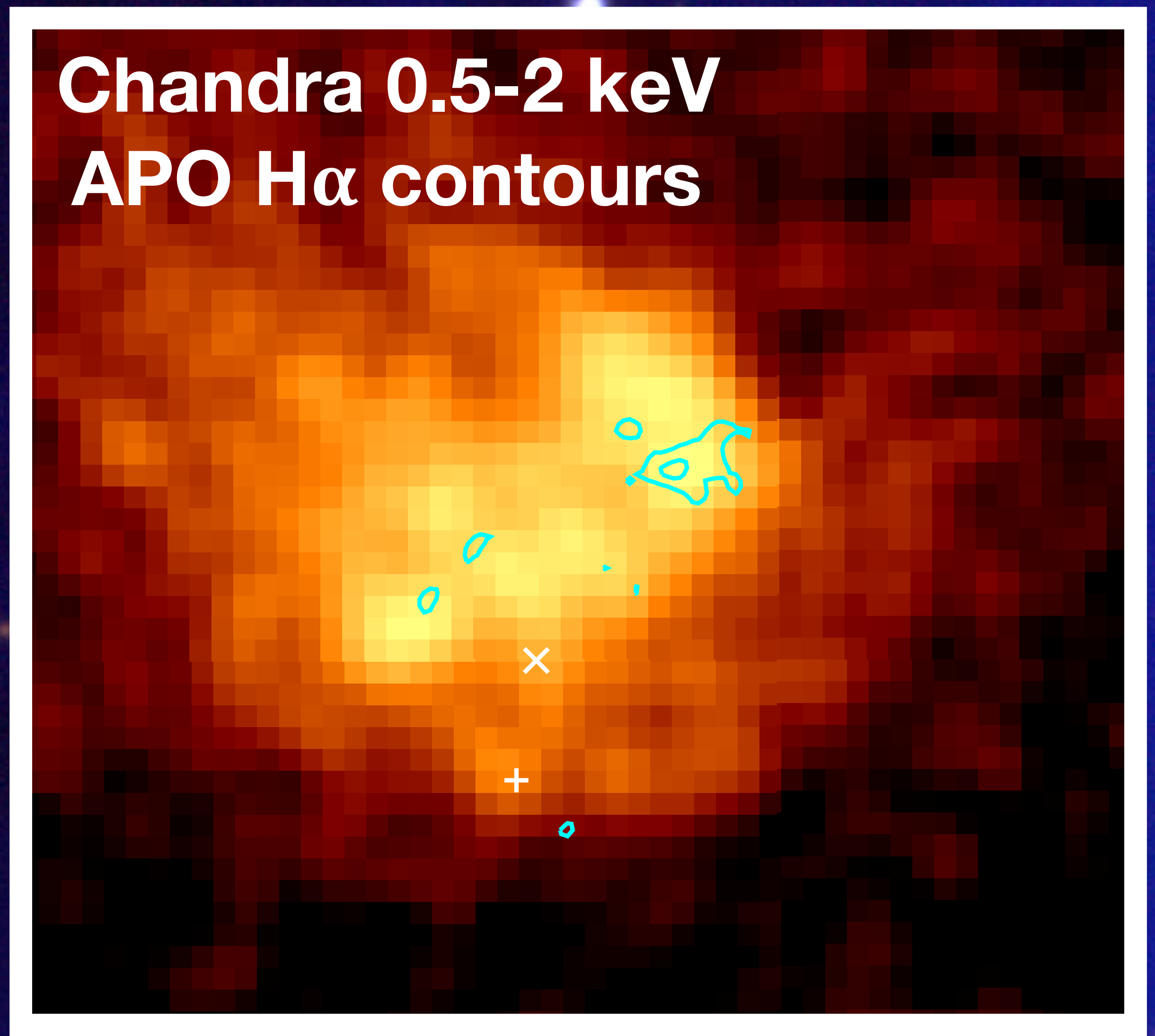


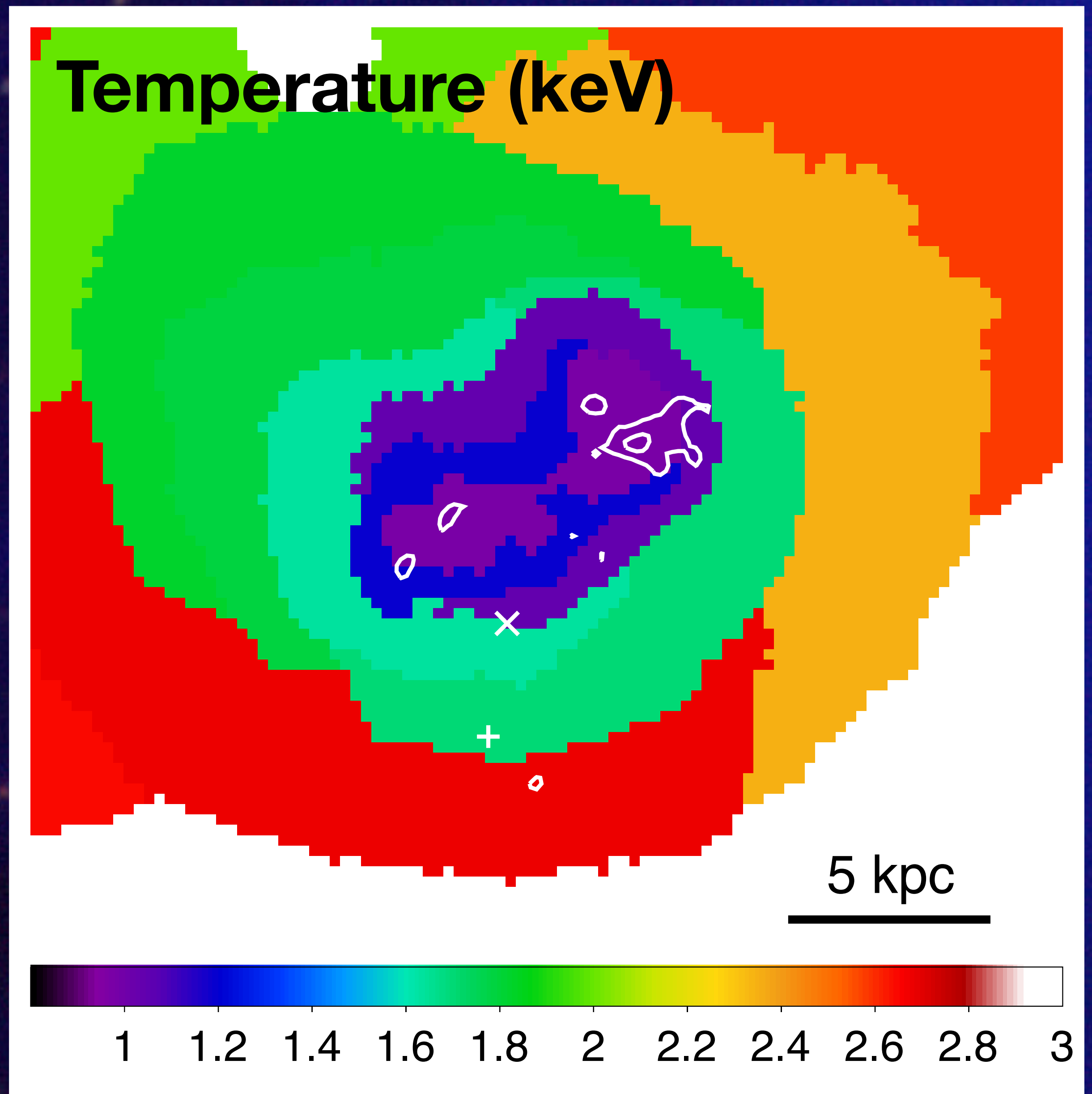


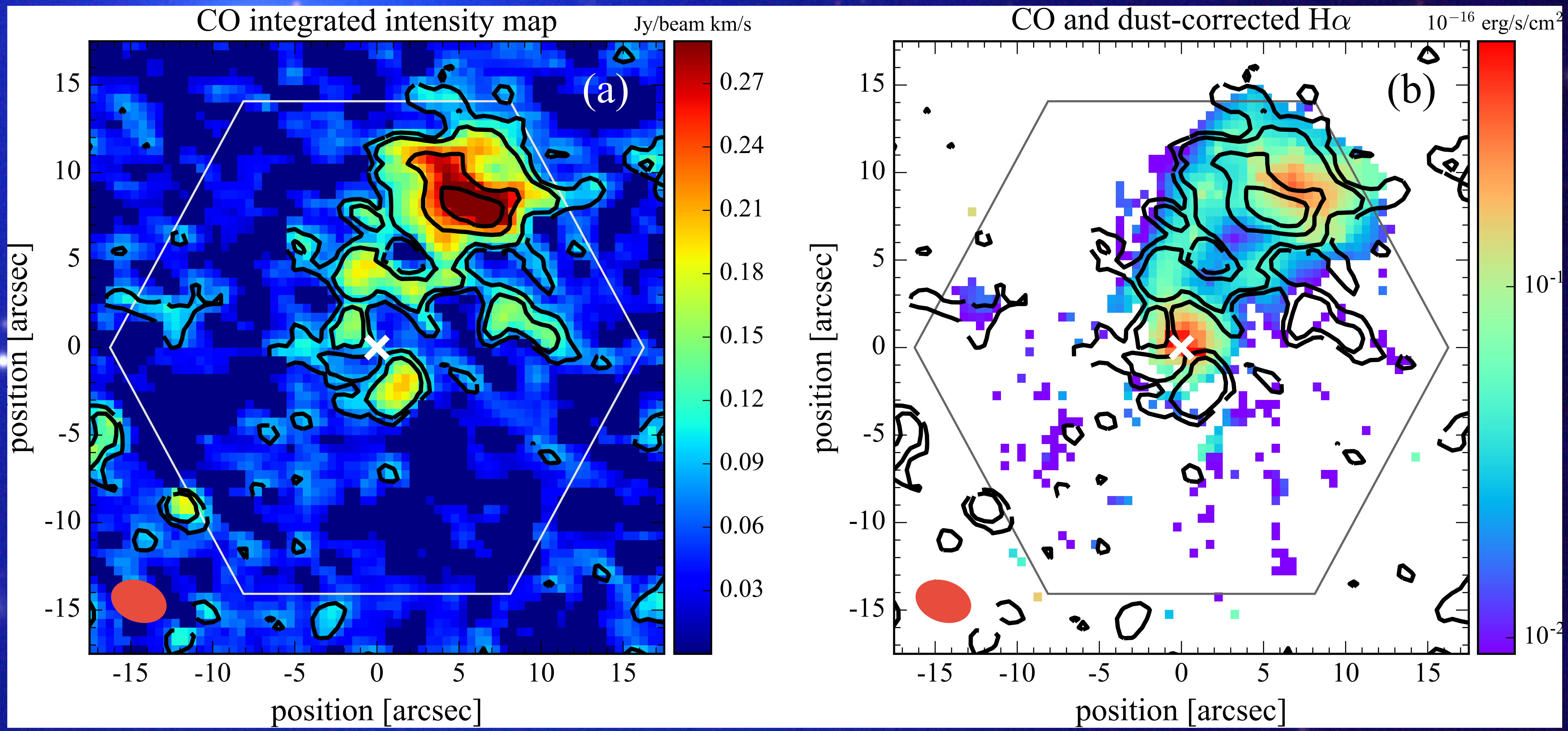


see also Birzan et al. (2020)

AGN feedback in NGC 6338





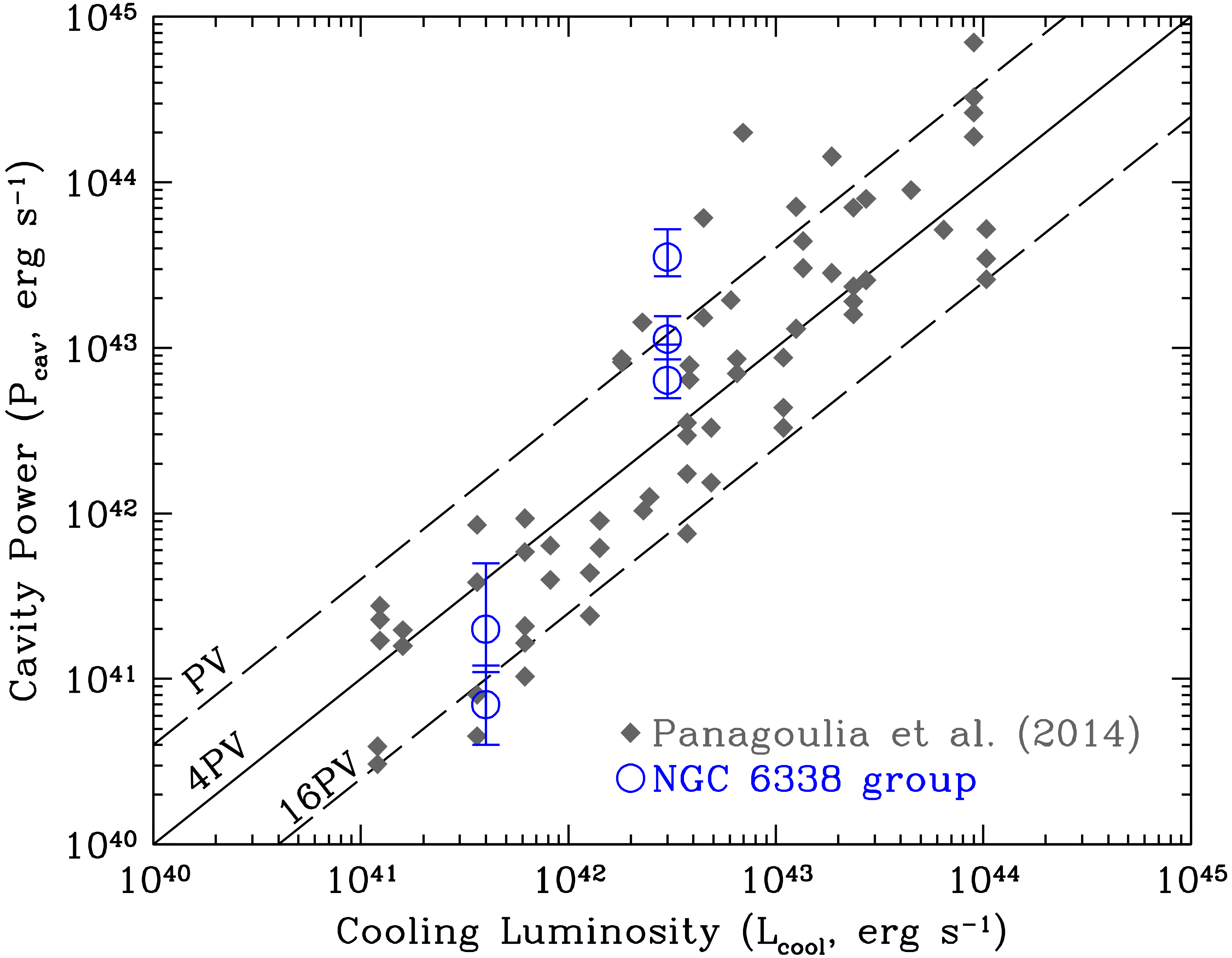


NOEMA CO(1-0), SDSS MaNGA Hα (Pan et al. 2020)

AGN feedback: thermal balance

- Energy input from AGN jets
  = cavity enthalpy
  = 4pV / t_{sonic}

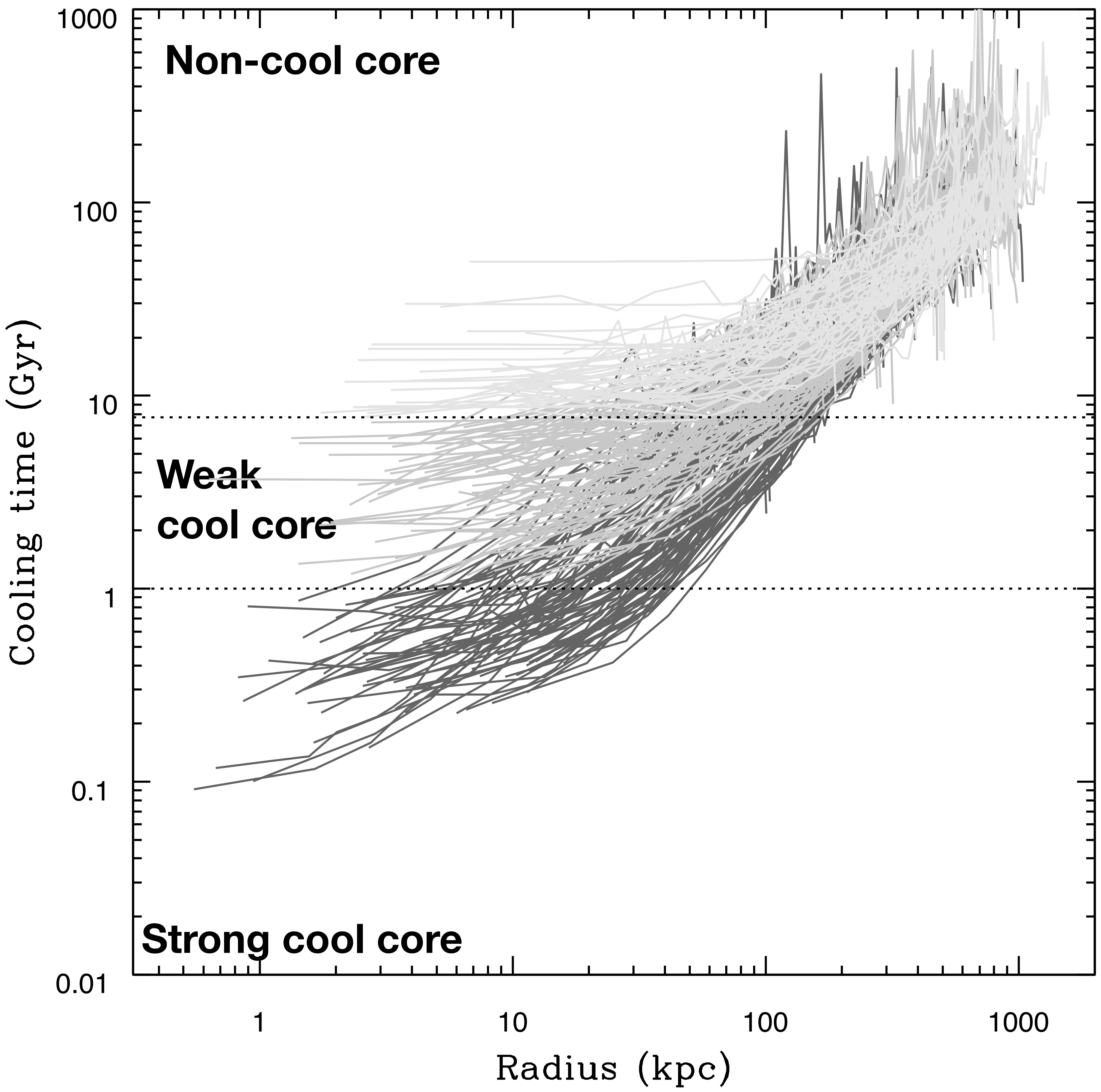
- Energy losses
  = X-ray luminosity of cooling region



Cooling and feedback: clusters

- Clusters can be divided into strong, weak and non-cool core systems

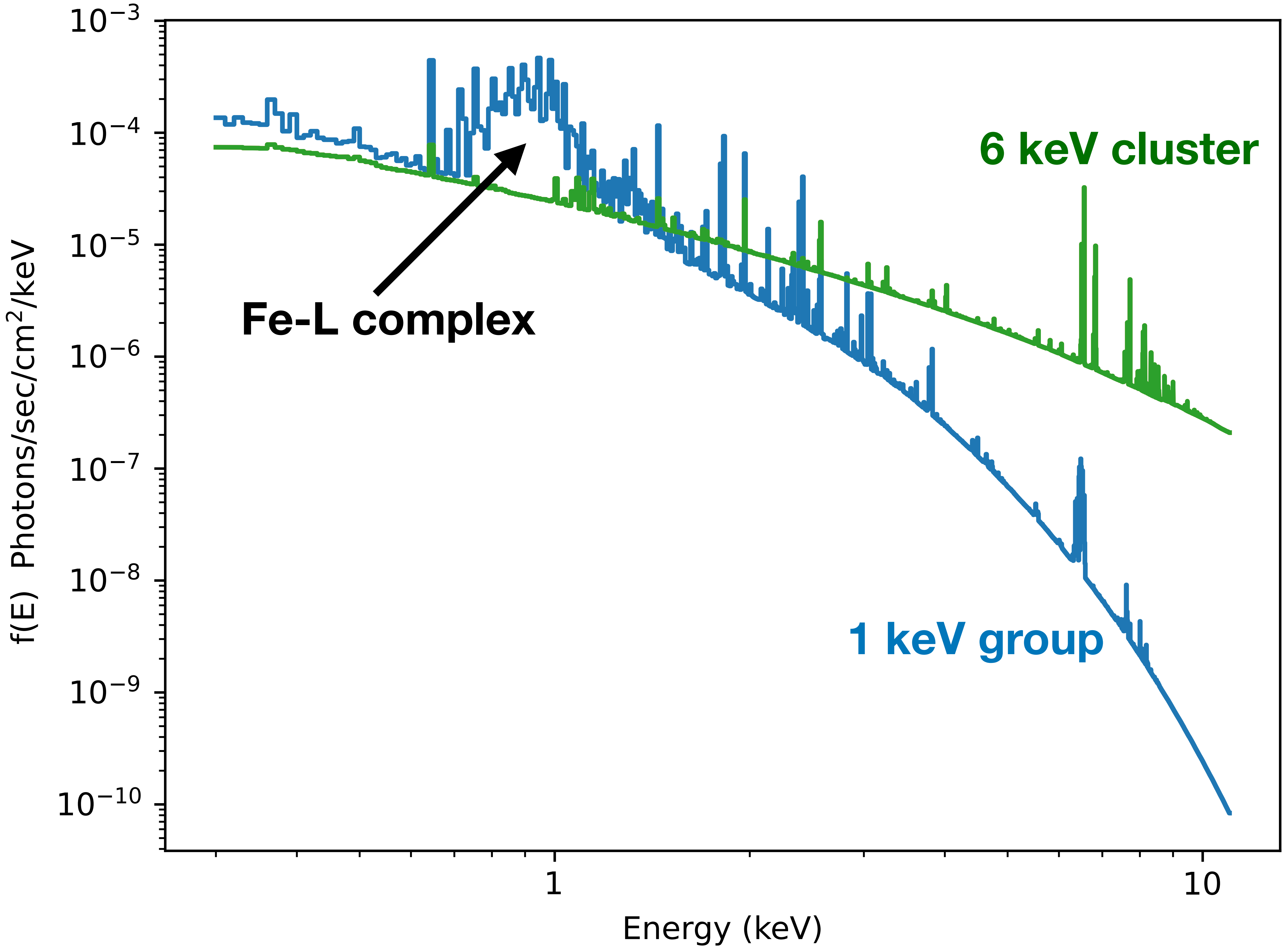
- Evidence of cooling (AGN jets, H**α**, CO, star formation) strongly correlated with T_{cool}

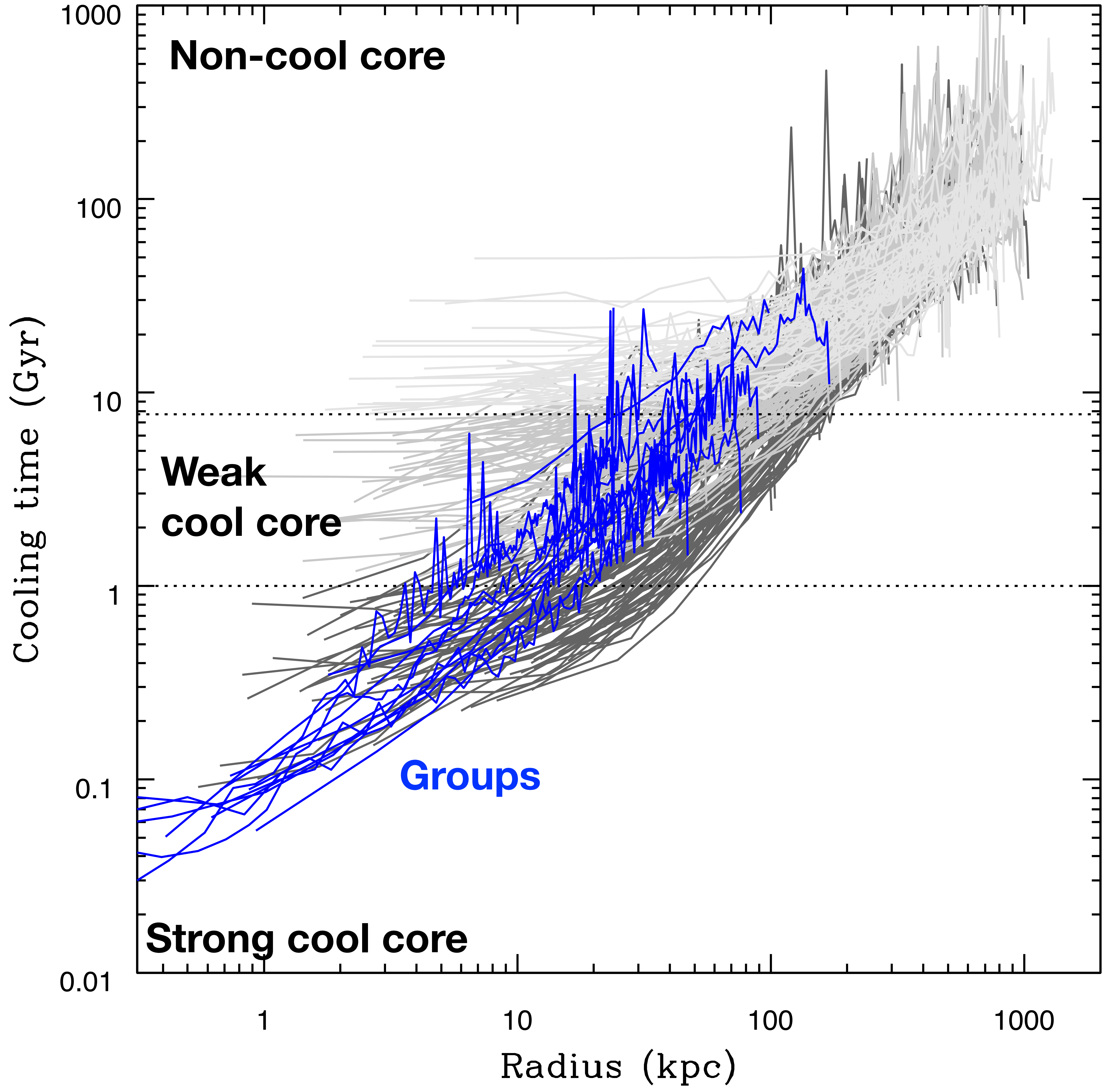


ACCEPT sample, Cavagnolo et al. (2010)

Cooling and feedback: clusters vs groups

- X-ray line emission means groups cool more rapidly than clusters
  ➜ almost all groups are strong CC

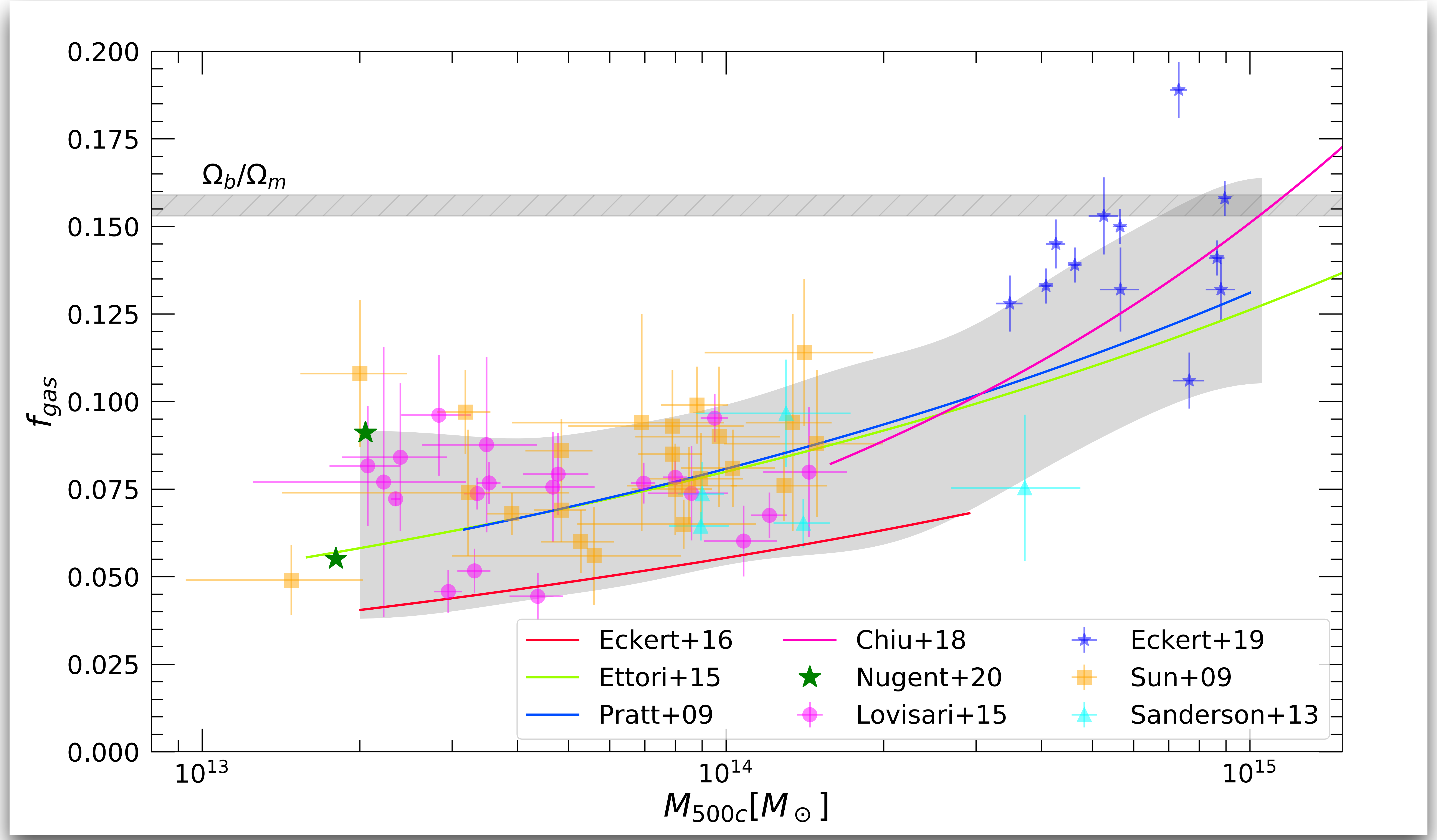




ACCEPT sample, Cavagnolo et al. (2010)

Cooling and feedback: clusters vs groups

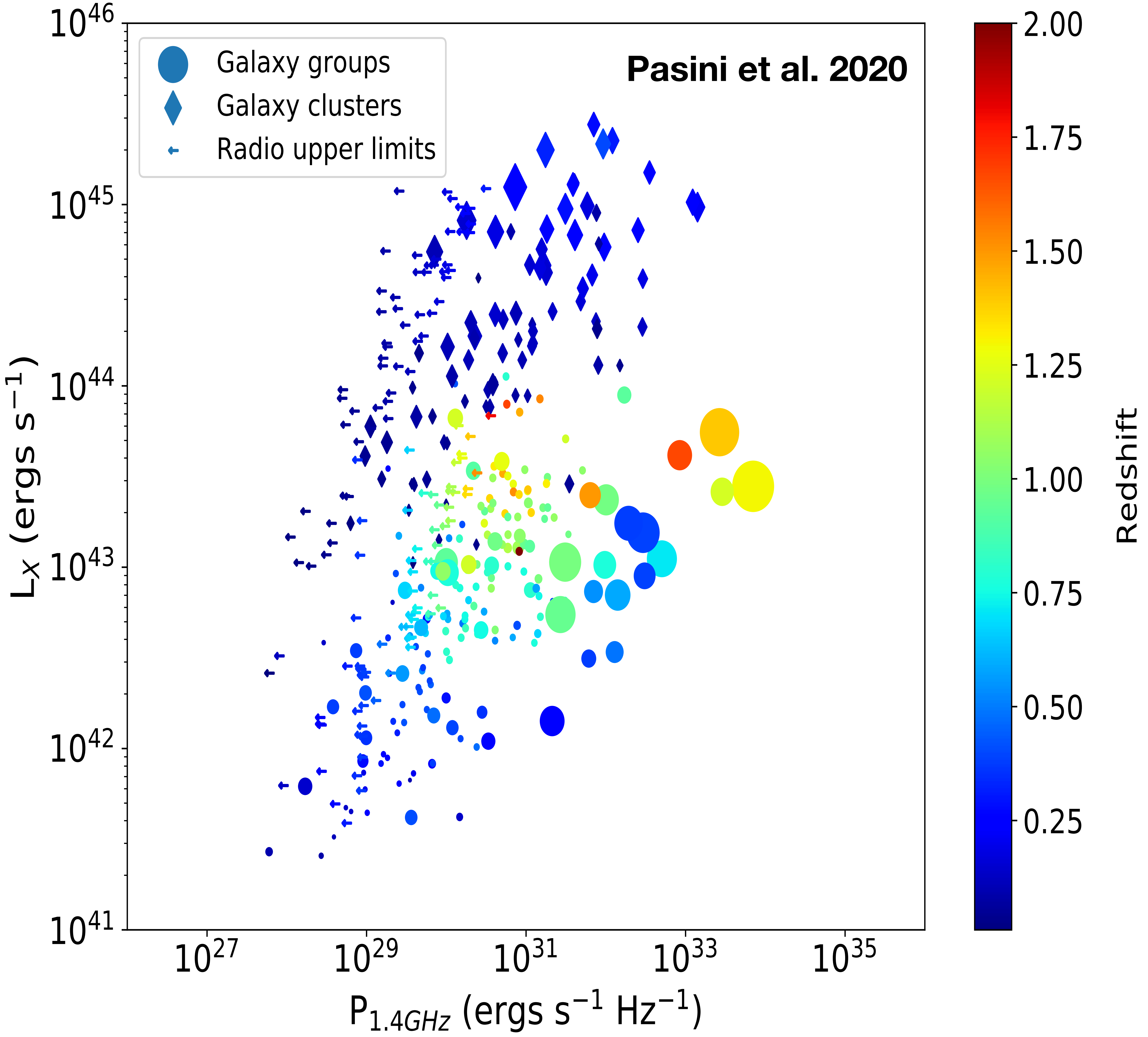
- Radio samples suggest efficiency of AGN jet heating decreases from clusters to groups (Best et al. 2007)
- If it does not, group AGN are powerful enough to unbind gas (Giodini et al. 2010)
- Gas mass fraction in group cores is lower than in cluster cores (e.g., Eckert et al. 2021, Laganá et al. 2013)



Cooling and feedback: clusters vs groups

- Proposed solution: “bubbling” feedback - group-central AGN have smaller outbursts more often
  (e.g., Gaspari et al . 2011, 2012)

- But observations show many large, powerful group-central radio galaxies
  (Pasini et al. 2020)



Galaxy groups: selection problems

Selecting representative, unbiased group samples is difficult

- X-ray selection:
  - RASS based surveys biased toward bright, concentrated groups (Eckert et al. 2011)
  - Deeper surveys mostly at moderate redshift
    ➜ difficult to resolve morphology, AGN, cool core status, interactions
  - *eROSITA* should determine population statistics but not detailed structure
- Optical selection:
  - tends to include false groups (chance associations, uncollapsed systems)
  - optical mass estimates unreliable for groups with $\lesssim$30 members (Pearson et al. 2015)

Complete Local-Volume Group Sample (CLoGS): Selection

485

Begin with Lyon Galaxy Group Sample (Garcia 1993)

all-sky, optically selected, cz<5500 km/s, D<80 Mpc

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Select groups with:

- ≥4 members
- ≥1 early-type member with $L_B \geq 3\times10^{10}\ L_\odot$
- Declination > -30° ➜ *visible from VLA, GMRT*

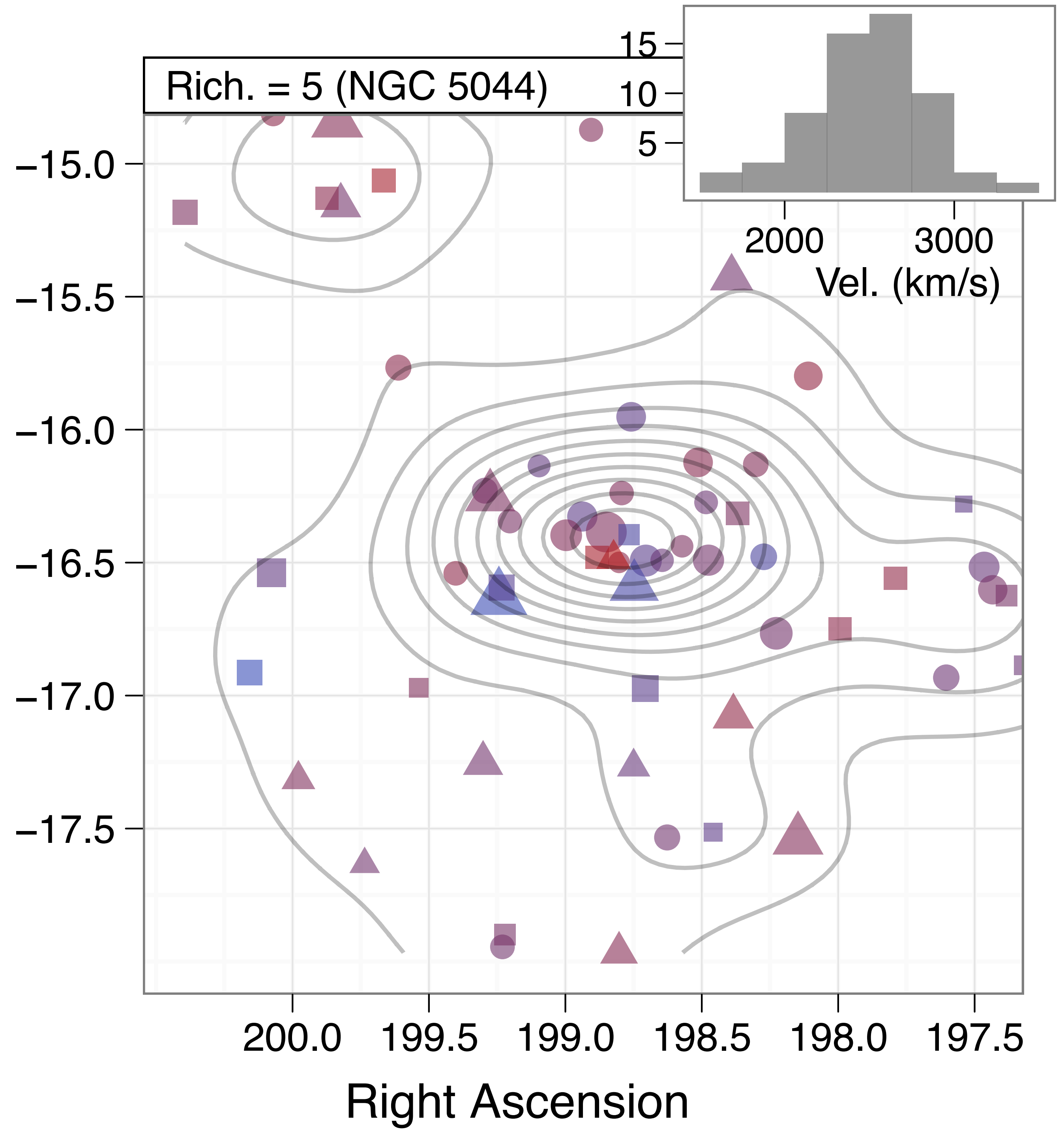
Expand and Refine membership

- Update membership from HyperLEDA
- Use isodensity maps to reject problem cases

53

Filter on Richness (*R* = N_{gal} *with* $LB \geq 1.6\times10^{10}\ L_\odot$)

- Exclude known clusters: R≥10
- Exclude groups too small to characterize: R=1

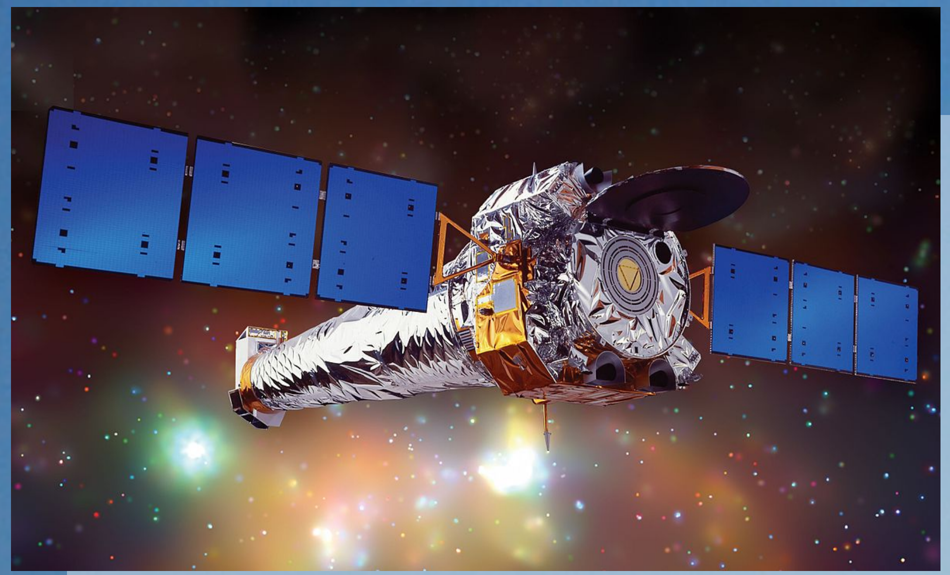


High-richness subsample:

R=4-8, 26 groups

Low richness subsample:

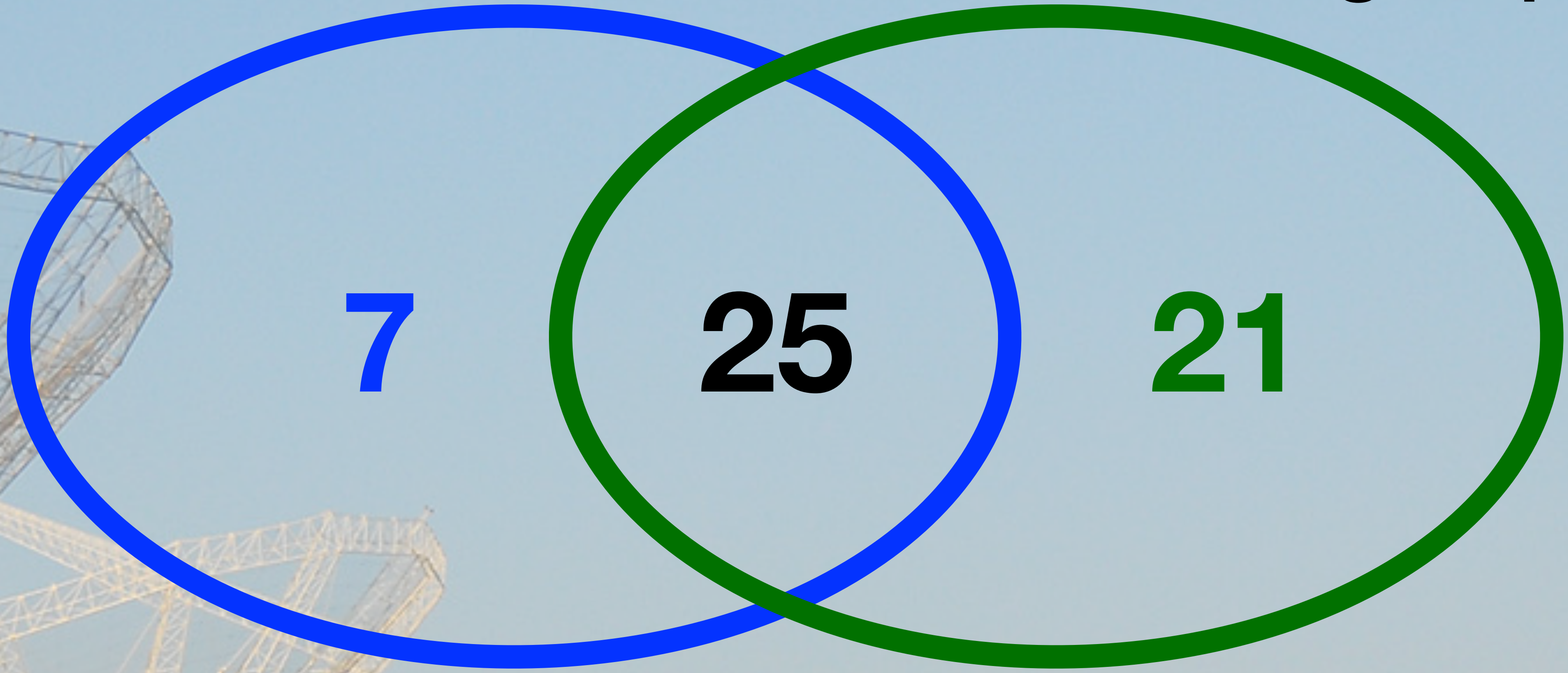
R=2-3, 27 groups



CLoGS: Observational data

- **X-ray:** (O'Sullivan et al. 2017)
  Chandra and/or XMM for all 53 groups

Chandra:
7 new observations (~360ks)
25 archive observations



XMM:
27 new observations (~800ks)
19 archive observations

- **Radio:** Kolokythas et al. 2018, 2019)
  GMRT 610 & 235 MHz for all groups (~4 hr/target, rms ~0.1mJy/b @610MHz, ~0.6mJy/b @235MHz)

- **CO:** (O'Sullivan et al. 2015, 2018)
  IRAM 30m or APEX for all dominant galaxies (1-2 hr/target, detecting $M_{H2} = 10^7 - 6x10^9 M_\odot$)

- **Hα:** (Olivares et al., in prep)
  MUSE IFU for 18 dominant galaxies in high-richness groups (1 hr/target, 1.5" seeing)

- + long-slit spectra, wide-field optical imaging, etc.

CLoGS: X-ray & radio results

Detection fraction

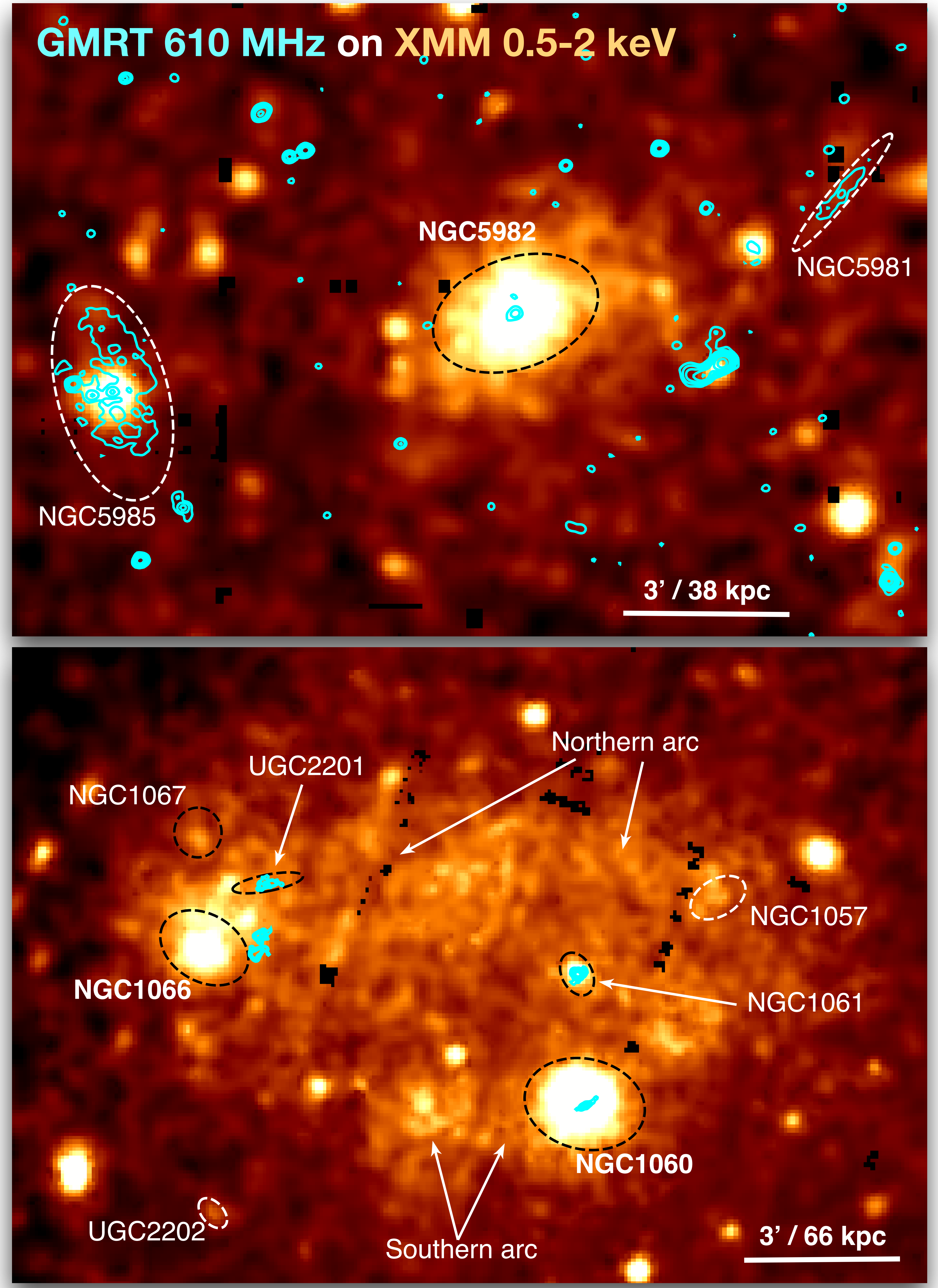
- ~50% (26) have group-scale halos (>65kpc, $L_X>10^{41}$ erg/s)
- ~30% (16) have galaxy-scale halos ($L_X=10^{40}$-10^{41} erg/s)
- ~20% have no detected diffuse X-ray emission

Temperature range: 0.4-1.5 keV

Mass range: 0.5-5 x 10^{13} $M_\odot$

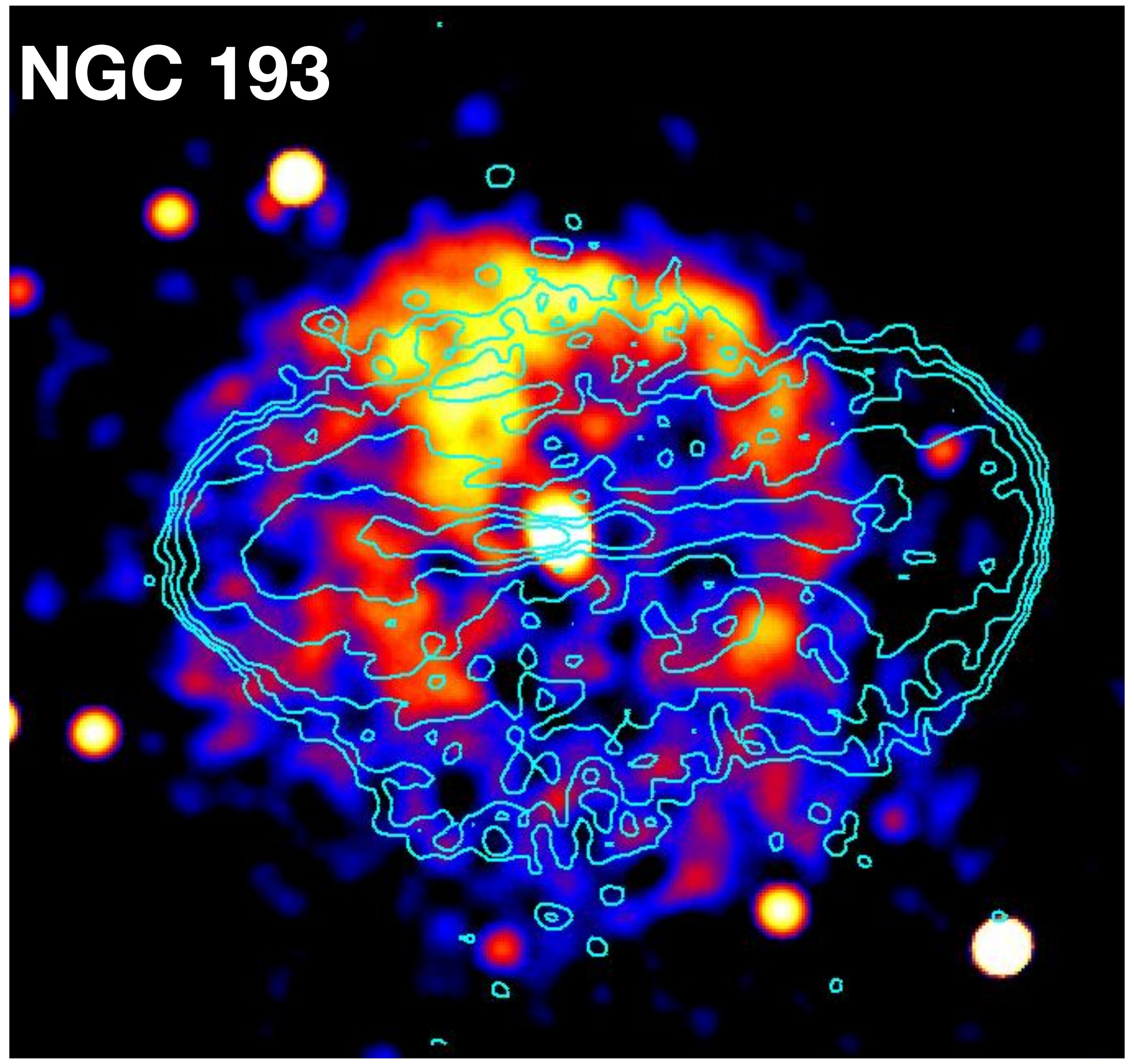
Of the group-scale halos:

- ~1/3 are dynamically active (mergers or sloshing)
- 11 (42%) host radio jet sources
- 12 of 26 not previously identified as X-ray bright groups of which 8 not detected by RASS
  ➜ >40% of nearby groups excluded from previous studies?

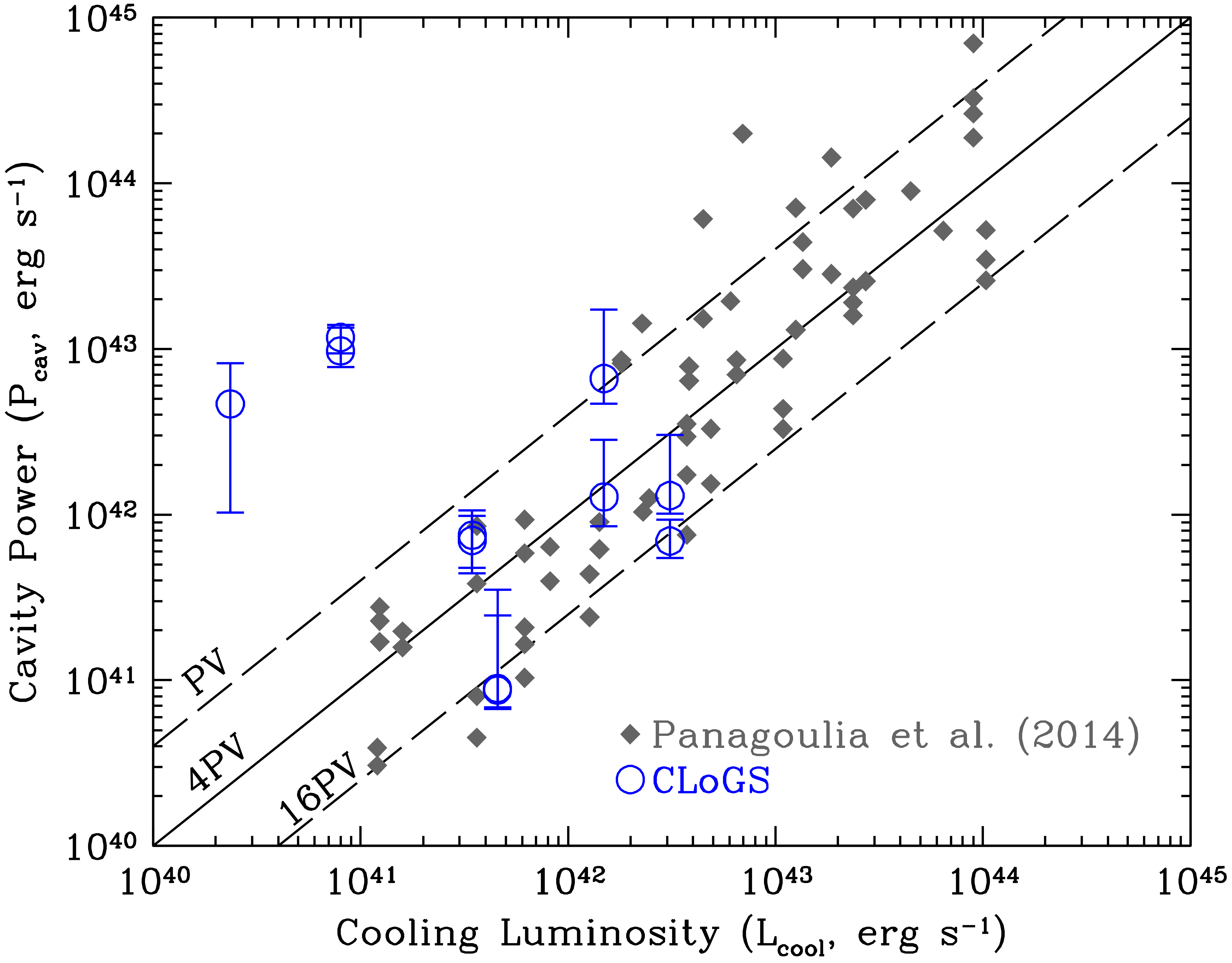


CLoGS: thermal balance in high-richness groups

XMM 0.5-2 keV / GMRT 235 MHz

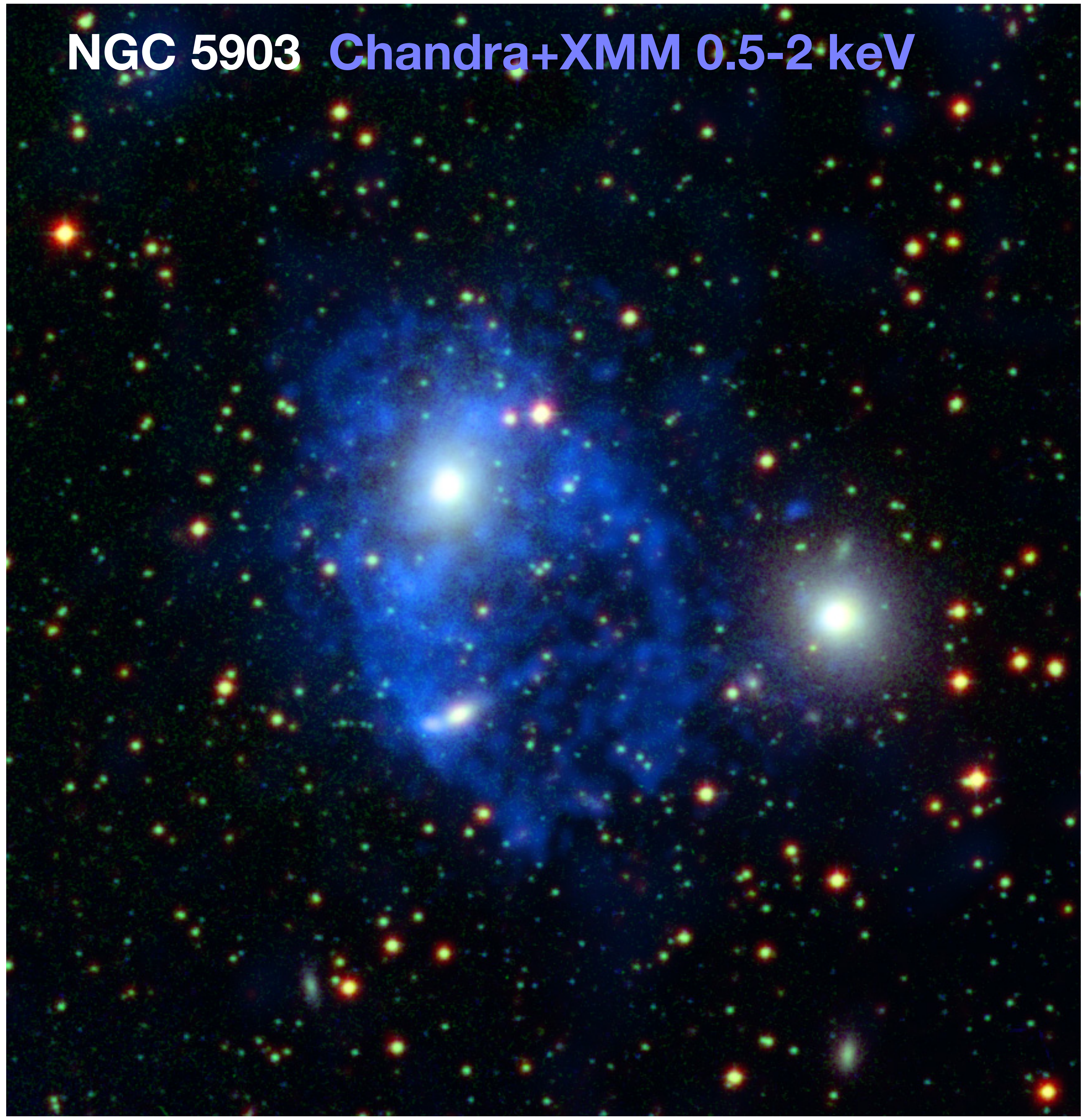


Chandra 0.3-2 keV / GMRT 235 MHz contours

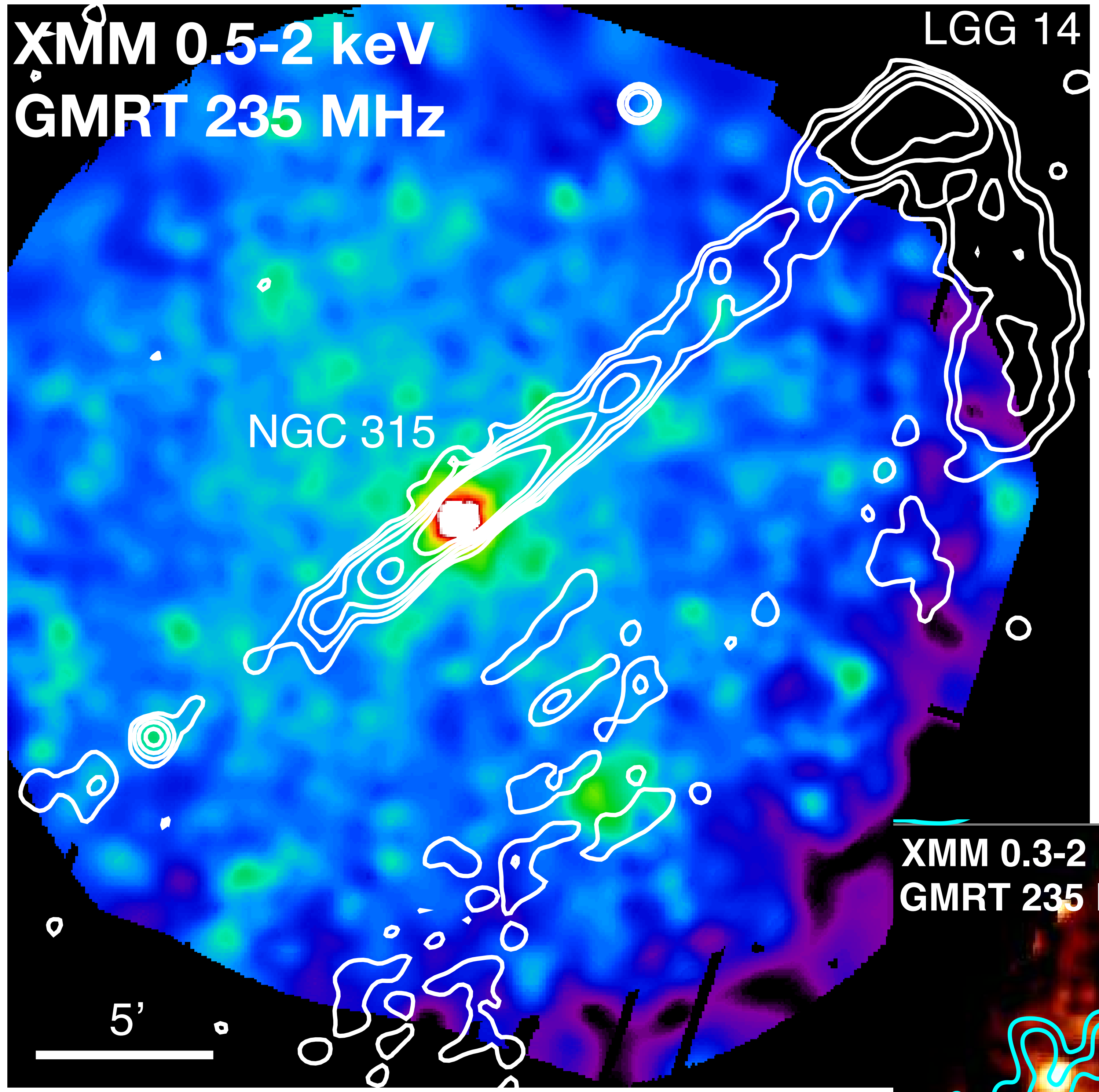


(Adapted from Kolokythas et al. 2018)

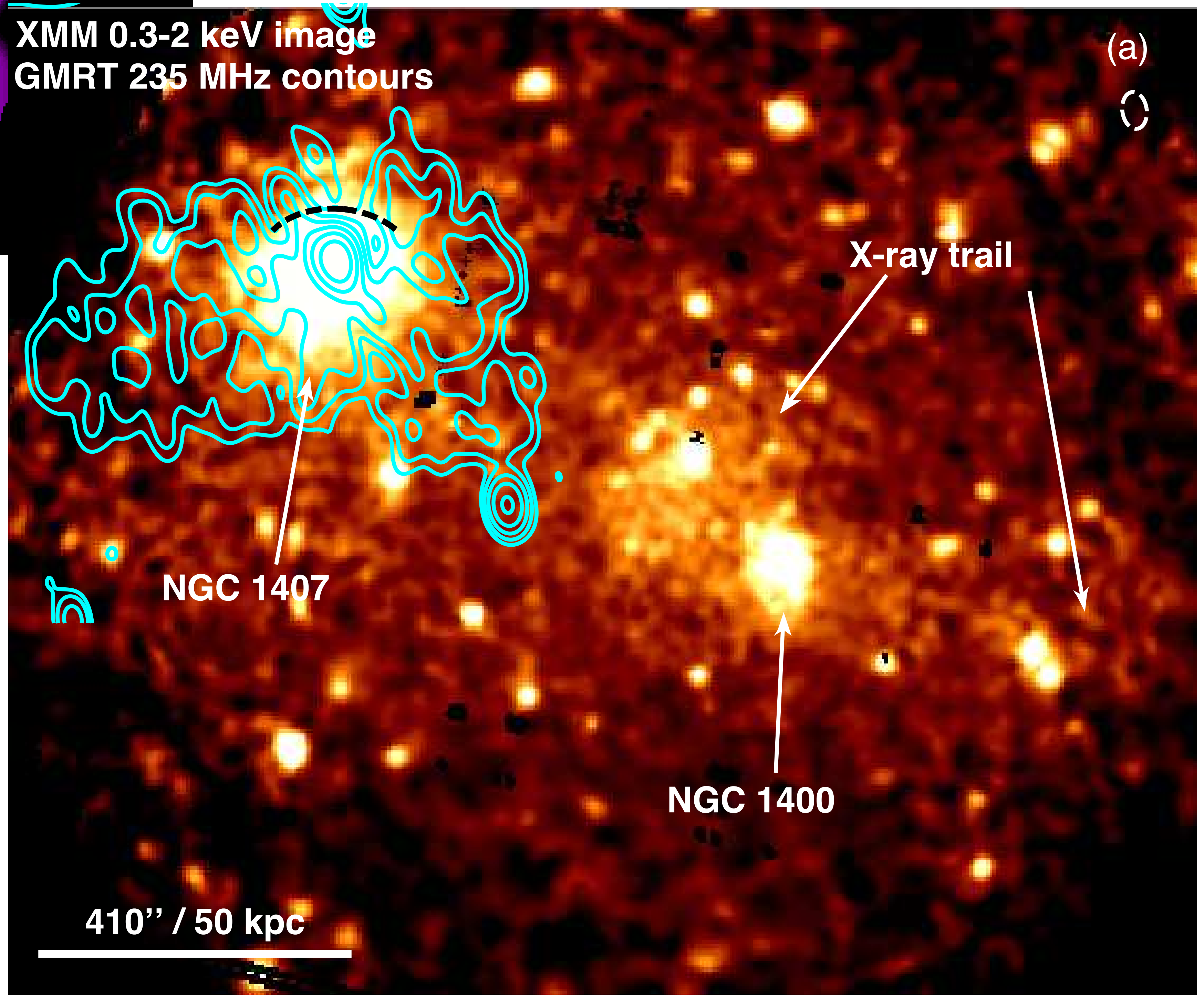
CLoGS: problem cases



NGC 5903
- 75 kpc single cavity / radio lobe
- P_{cav} ~100x L_{cool}
- central T_{cool}~7 Gyr ➜ disrupted cool core?



NGC 315
- Giant plumed FR-I
- No clear cavities
- jets depositing energy >100kpc from core?



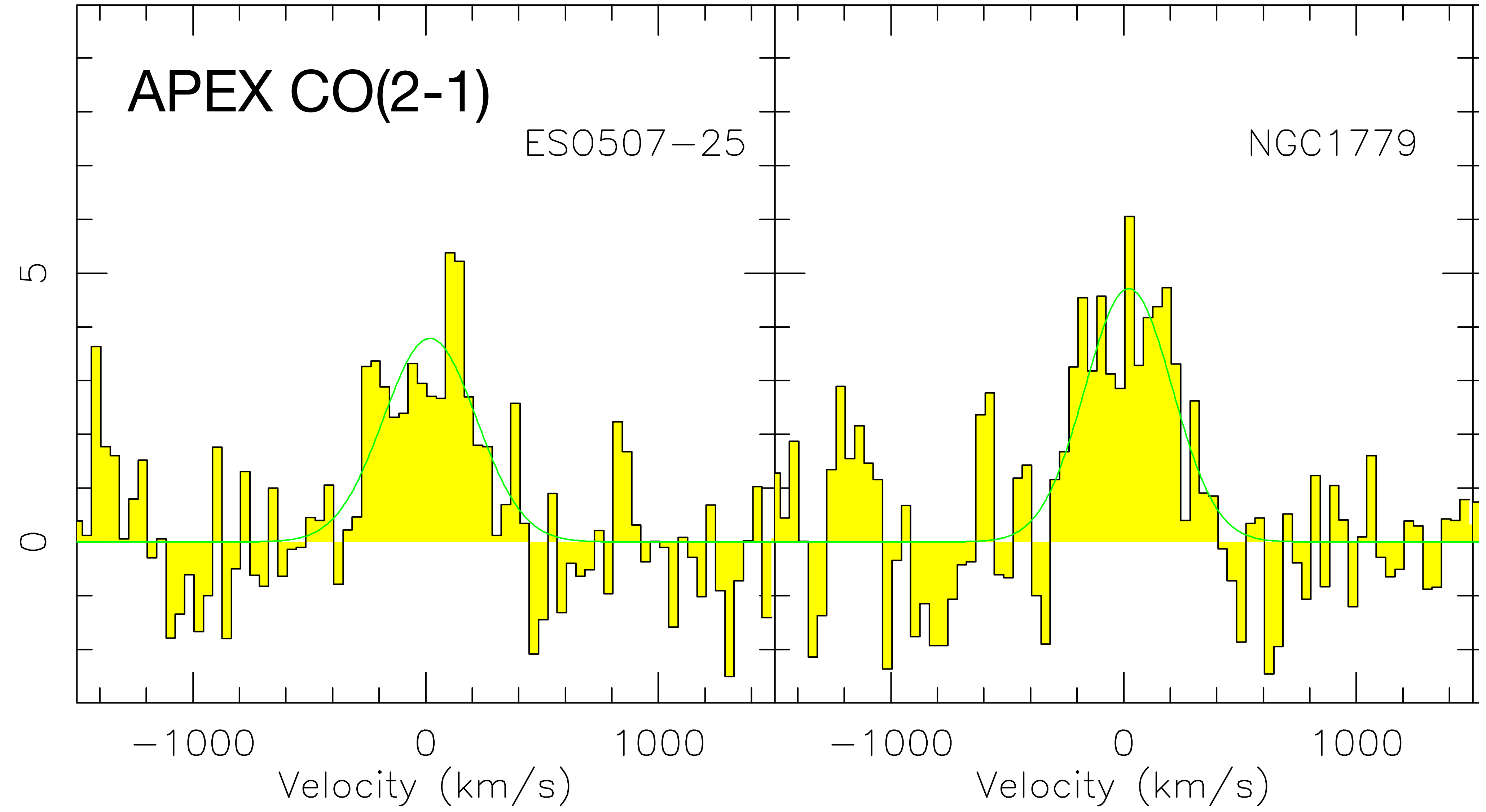
NGC 1407
- 80 kpc diffuse radio lobes
- No clear cavities

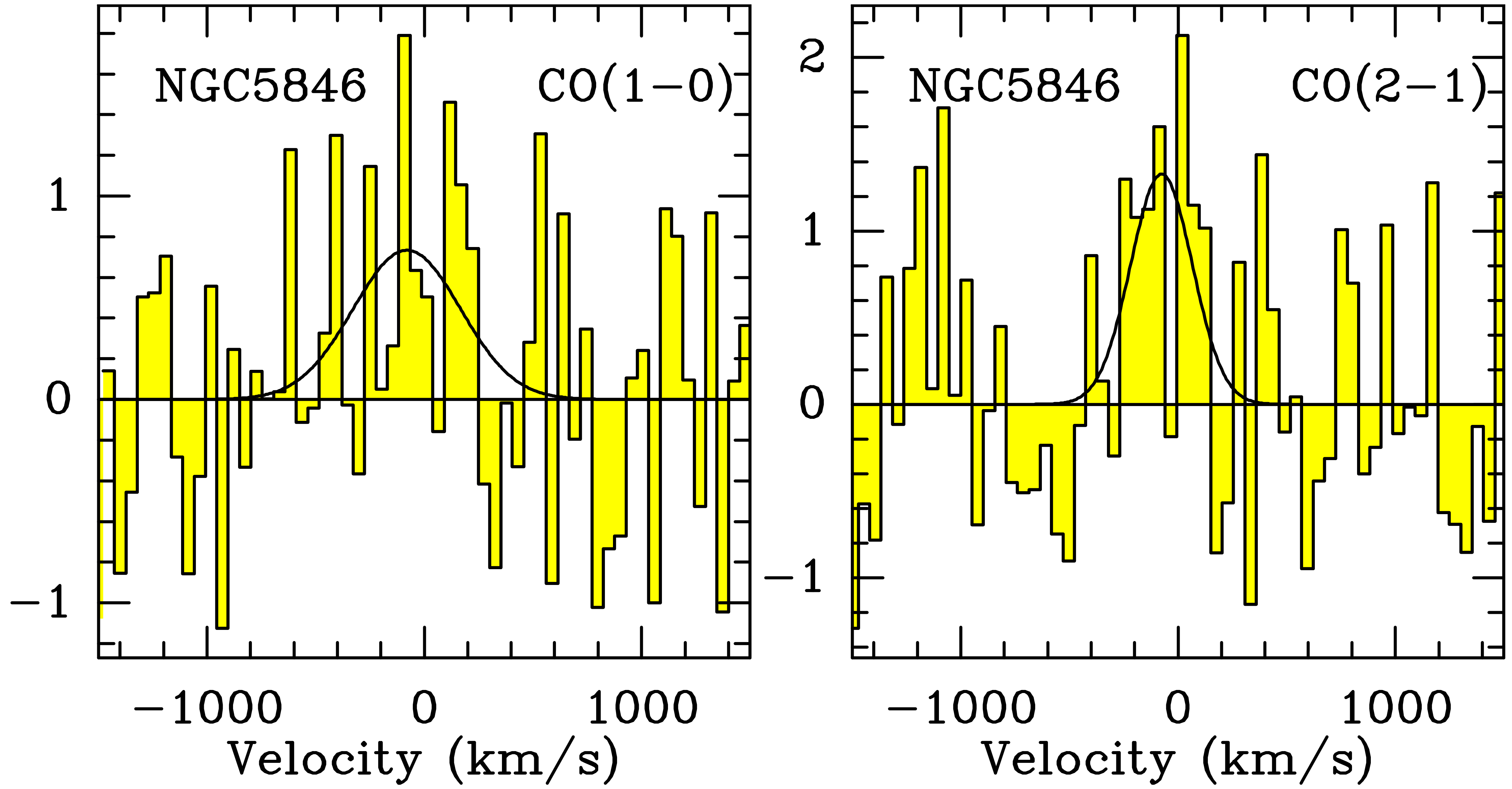
Giacintucci et al. (2012), O'Sullivan et al. (2018)

CLoGS: Cool gas

Group dominant galaxies surveyed with
IRAM 30m CO(1-0) and (2-1) or APEX CO (2-1)

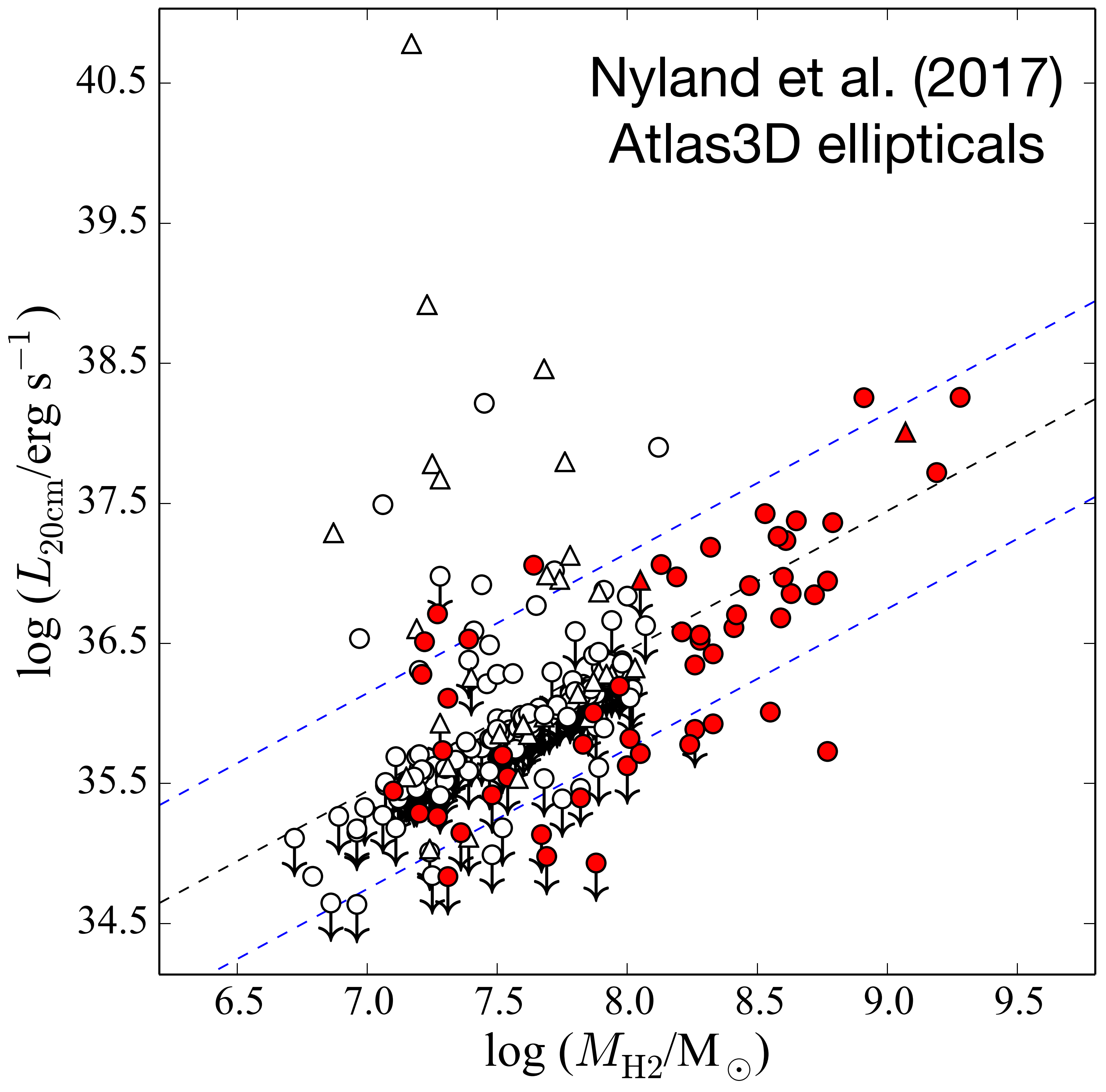
- CO detection fraction: 49%
- HI detection fraction (from literature): > 50%
- M_{H2} = 0.5-61 x10^8 $M_\odot$, SFR = ~0.01-1 $M_\odot$/yr
- Depletion time <1 Gyr ➜ rapid replenishment of gas reservoirs

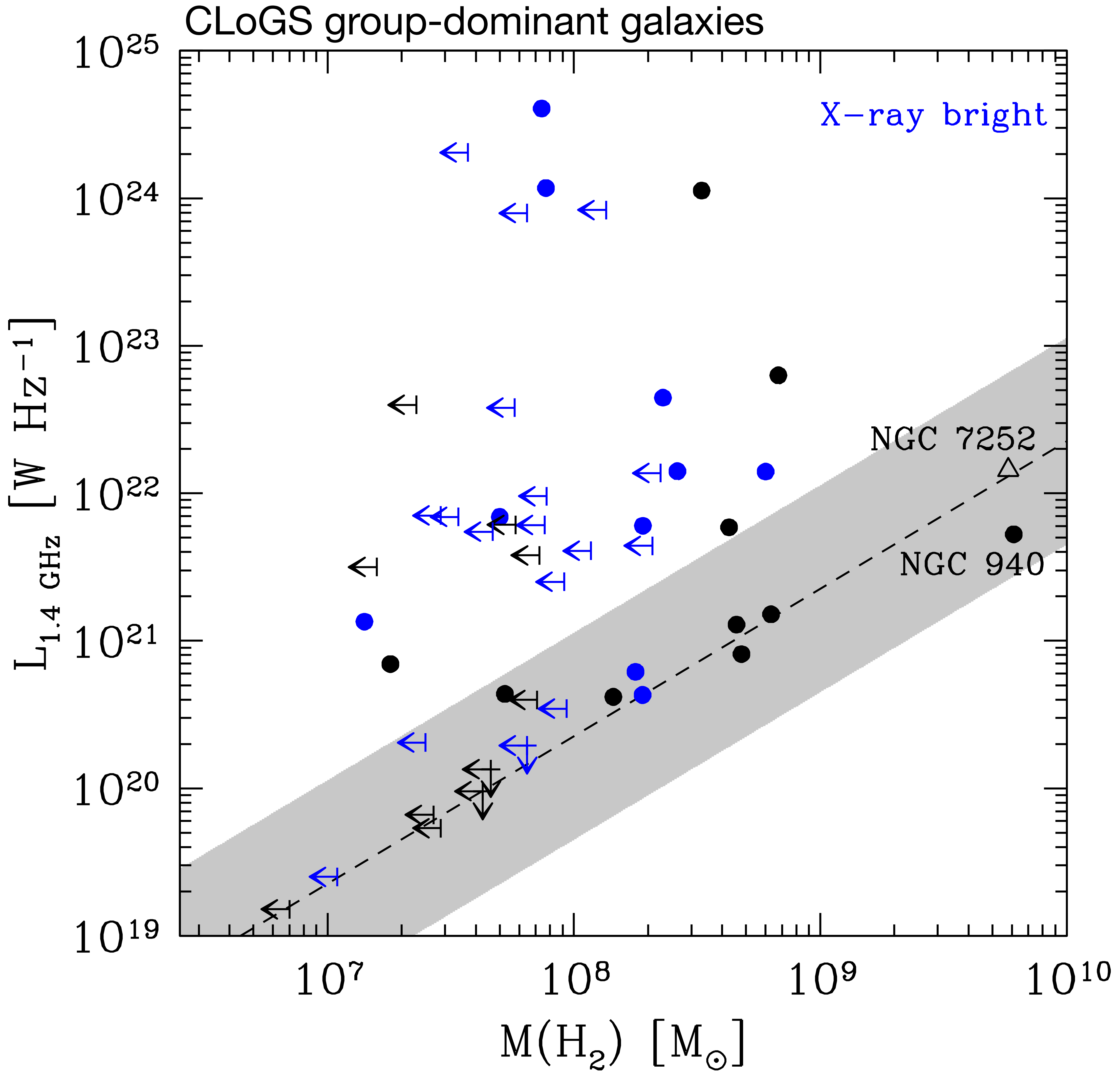




CLoGS: Cool gas

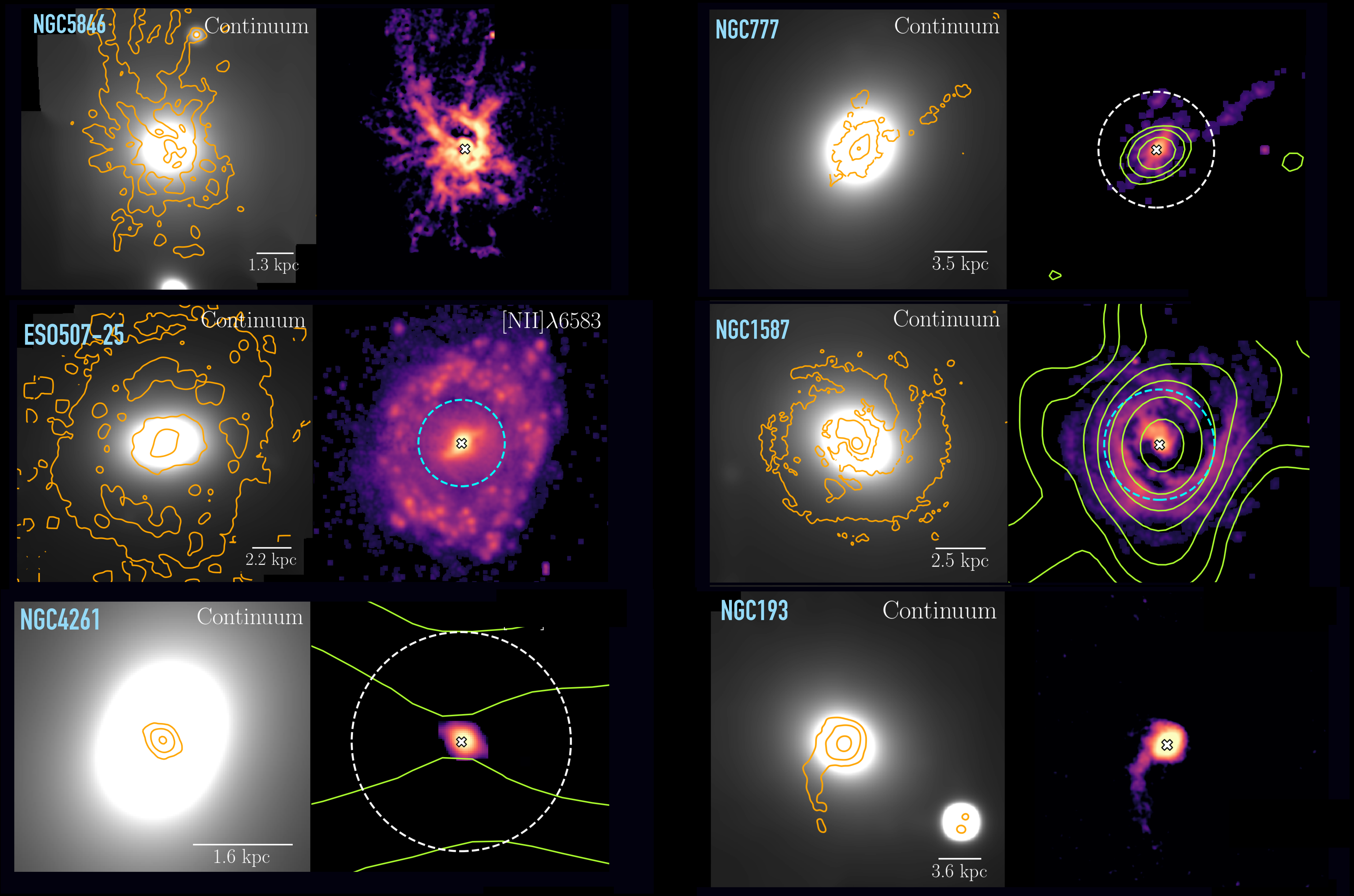
- CO detection fraction: 49±9%
- compare with 22±3% for Atlas3D ellipticals (similar survey depth)





- Large CO masses in X-ray bright and faint groups ➜ gas supplied by cooling and mergers?
- Large gas mass not required for AGN outburst

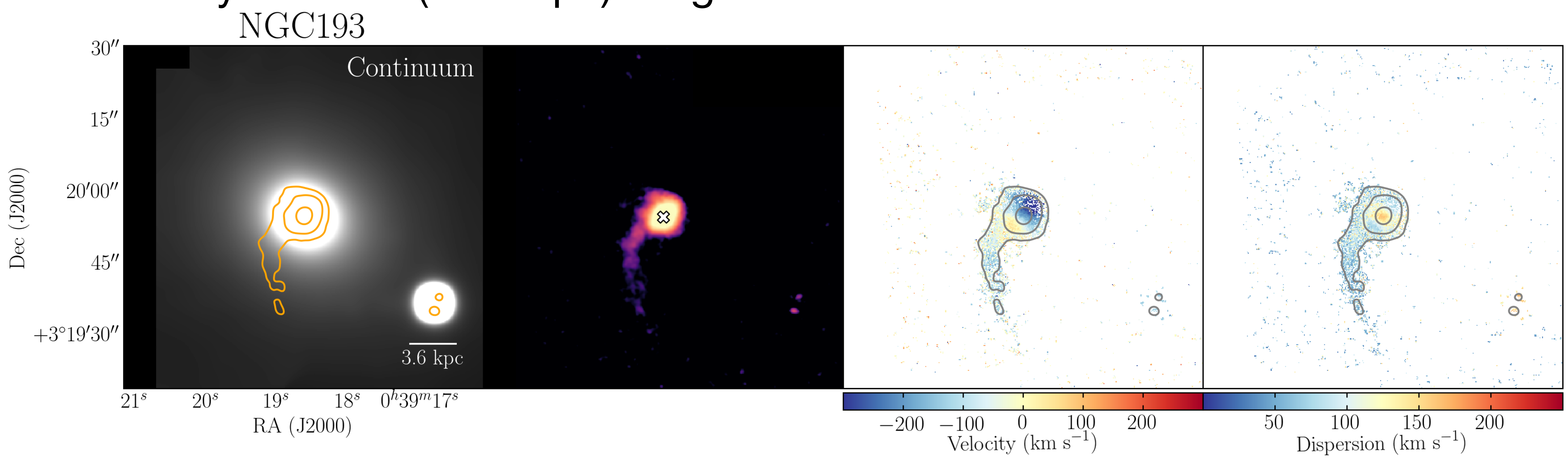
Warm gas morphology (Olivares et al., in prep.)



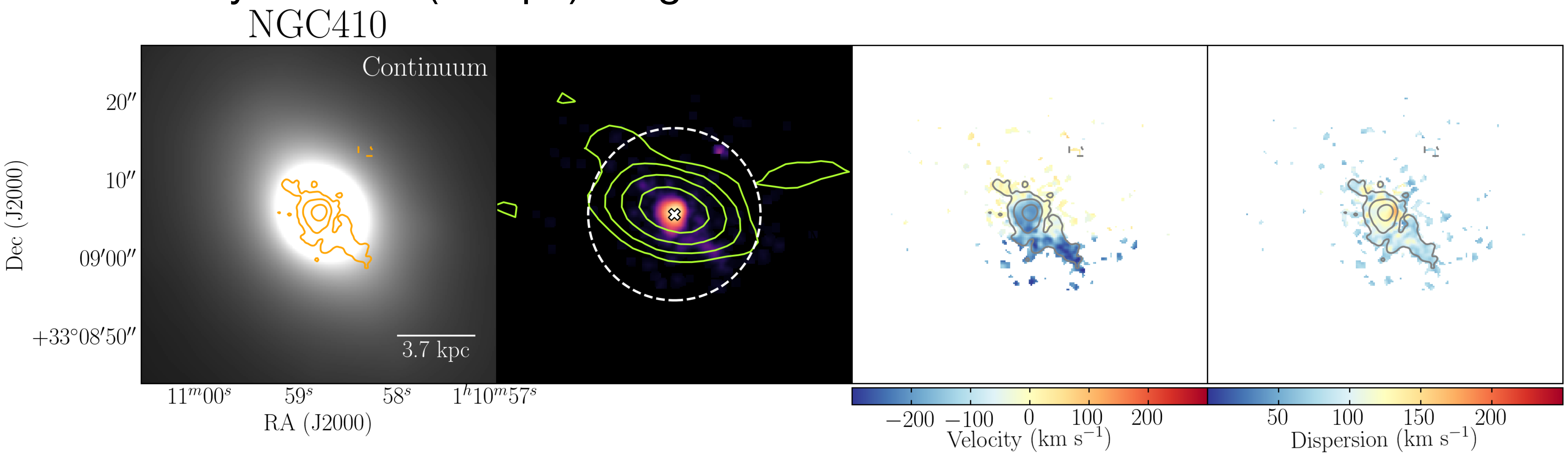
Orange contours:
MUSE Hα+[NII]
Green contours:
GMRT 610 MHz radio
Cyan circles:
IRAM 30m/APEX beam size

Warm gas kinematics (Olivares et al., in prep.)

Extended filamentary nebulae (5-12 kpc) - 6 galaxies

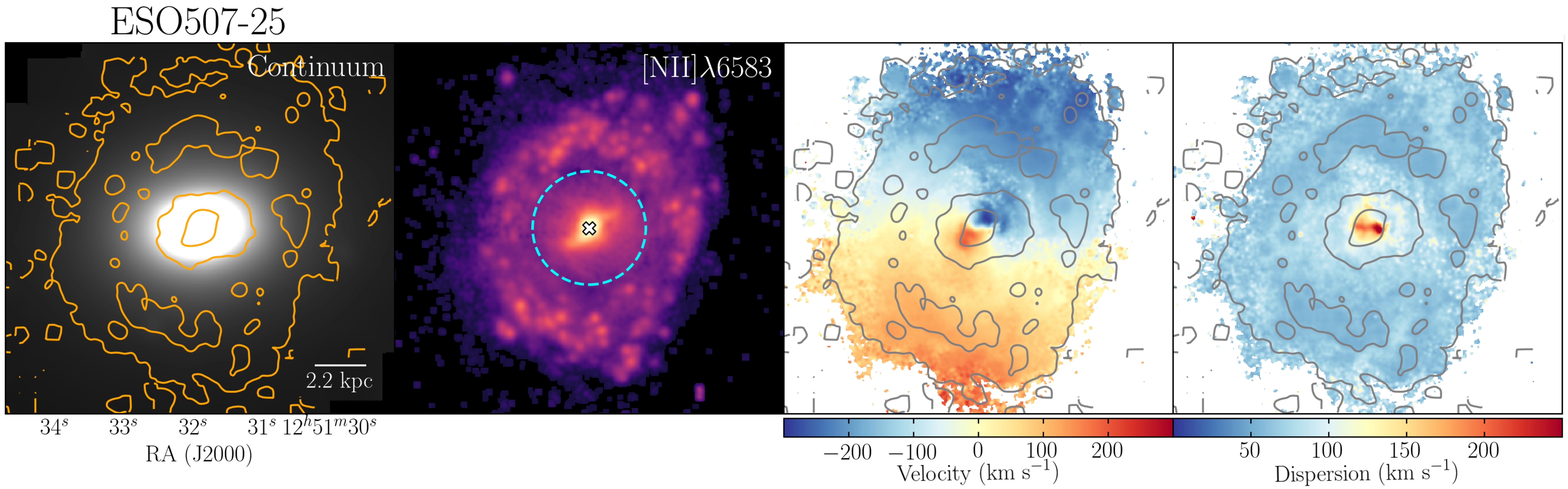


Compact filamentary nebulae (<5 kpc) - 4 galaxies

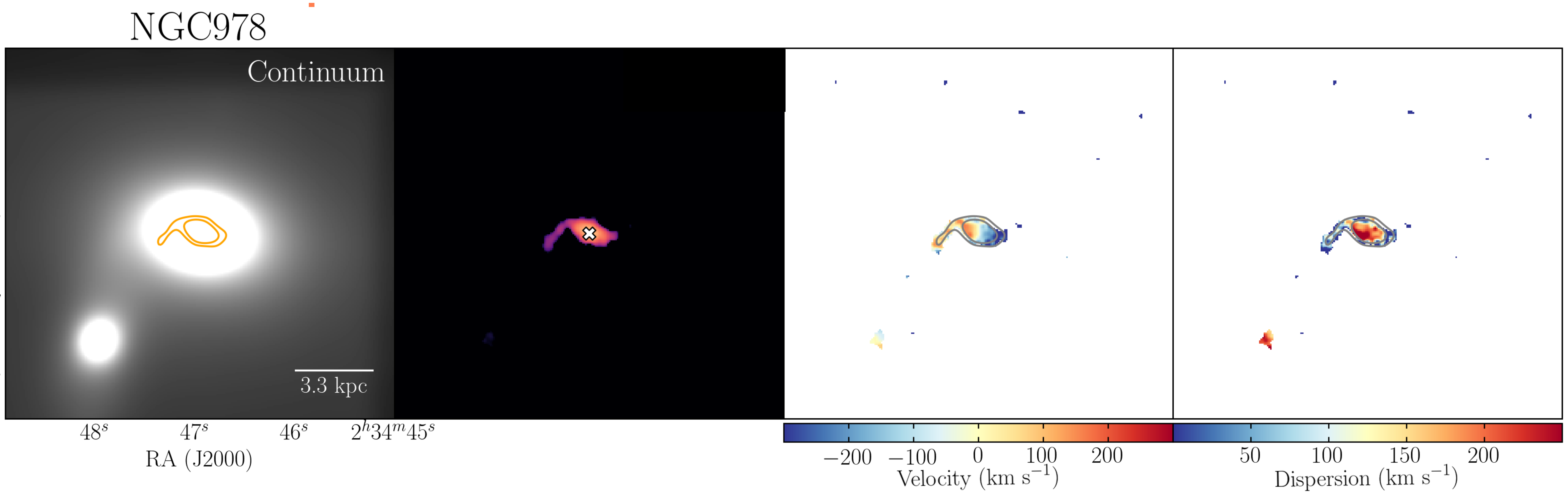


Warm gas kinematics (Olivares et al., in prep.)

Extended rotating disks (diameter 3-21 kpc) - 5 galaxies



Compact rotating disks (diameter 1-3 kpc) - 2 galaxies

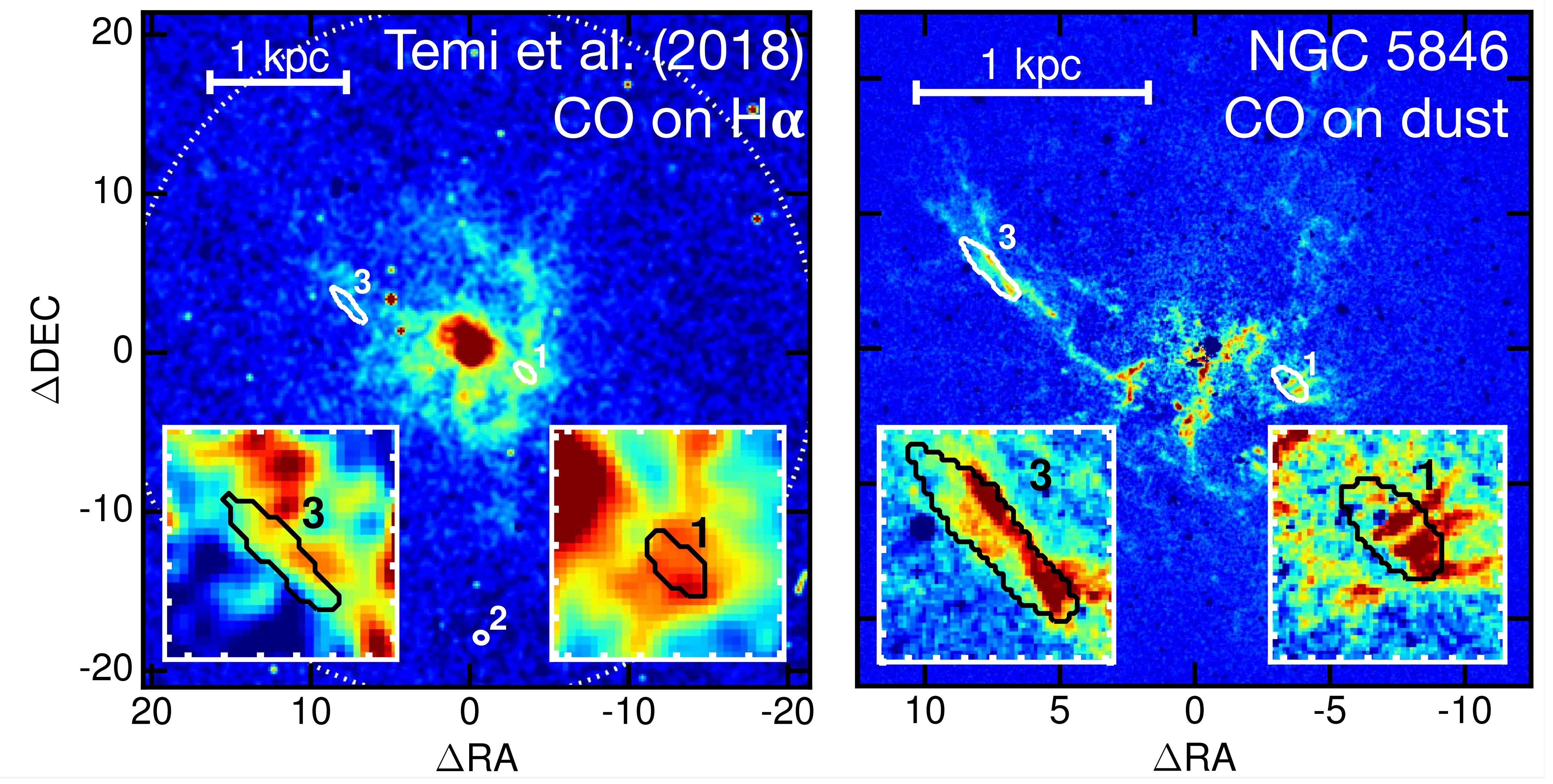


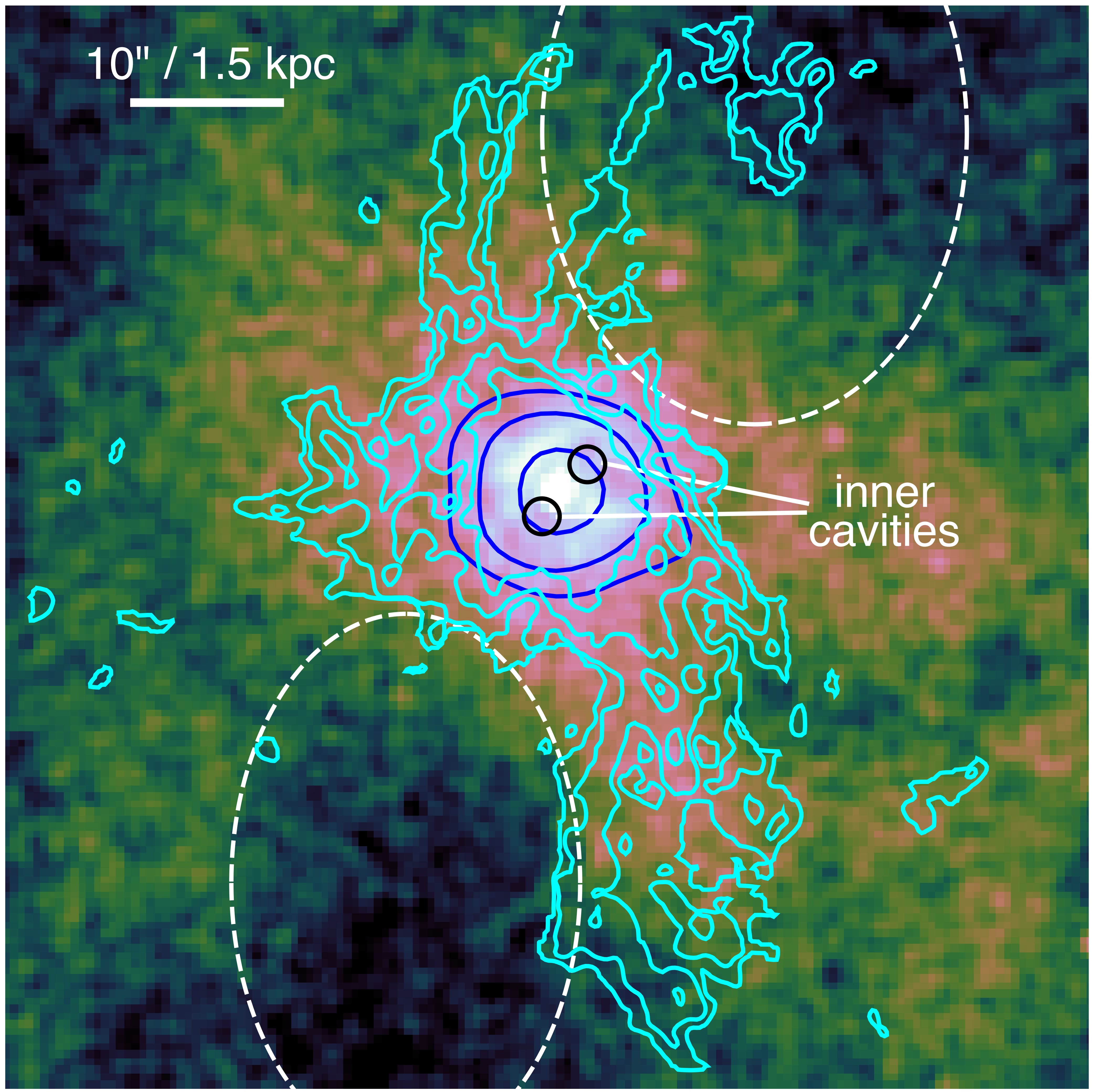
Cold gas: filaments

Few groups imaged with ALMA so far

High resolution: dense molecular clumps located in Hα/dusty filaments (David et al. 2014, 2017, Temi et al. 2018)

Low resolution: ACA captures majority of CO emission, correlated with Hα (Schellenberger et al. 2020)





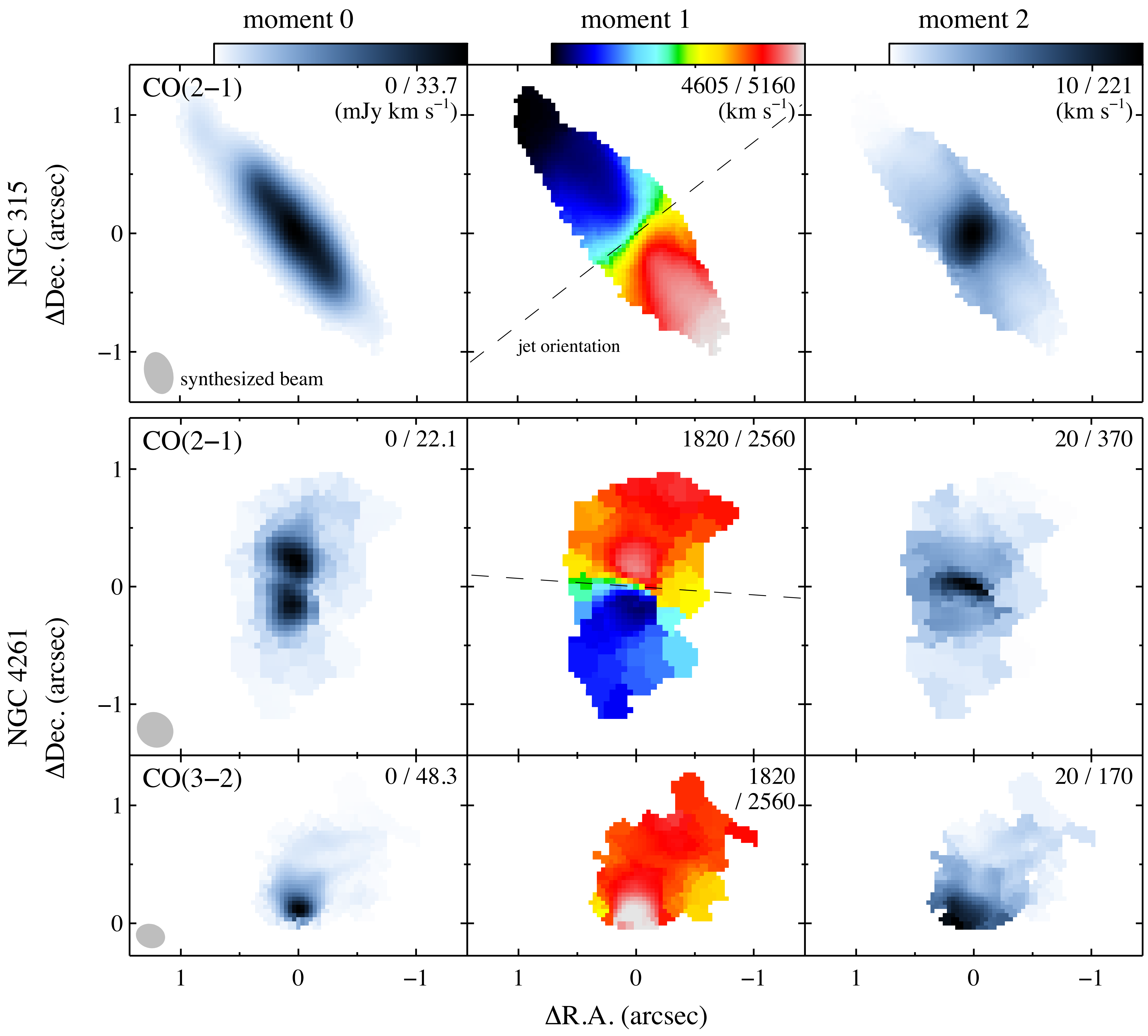
NGC 5044: Chandra 0.5-2 keV image with contours showing Hα (white) and diffuse CO (blue, Schellenberger et al. 2020)

Cold gas: disks

Boizelle et al. (2020):
ALMA observations of NGC 315 and NGC 4261 to determine black hole mass

300-800pc rotating disks

No filamentary nebula detected
➜ resolution issues?



Summary

Based on CLoGS, an optically-selected, statistically complete sample of nearby groups:

- A significant fraction (~40%) of X-ray bright galaxy groups in the local Universe were not identified in prior surveys. Typically disturbed, low luminosity systems.
- A subset of group-central AGN appear to be over-powered, with P_{cav}=100x L_{cool} and in some cases with jets extending beyond the cooling region.
- Cool gas (Hα, HI, CO) is detected in >50% of group-central galaxies. Some X-ray bright groups host filamentary nebulae (as seen in clusters) but some powerful radio galaxies are fueled by small rotating disks.
- Further work is needed to understand the cooling and feedback cycle in groups (MeerKAT, ALMA+ACA, MUSE, *Chandra*, *XMM-Newton*)
- eROSITA surveys will provide much improved population statistics, but more in-depth studies needed to understand feedback mechanisms