Characterizing the X-ray Emission of Galaxies in Groups

Christine Jones

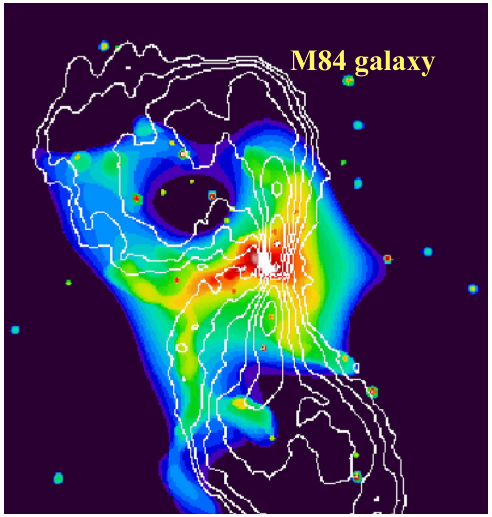
1) Interactions between Supermassive Black Holes and Hot Atmospheres in Groups of Galaxies (Hot X-ray atmospheres capture SMBH energy)

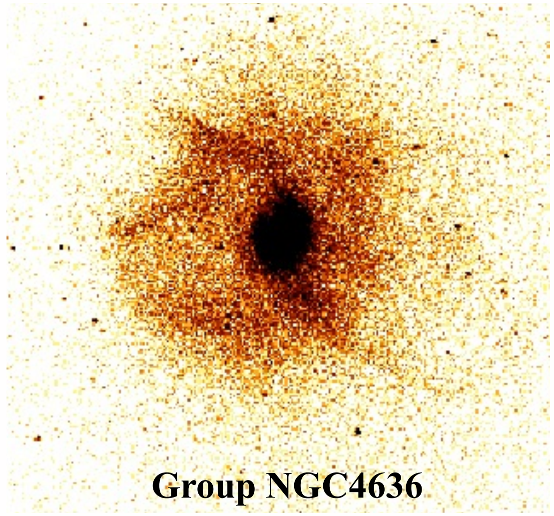
2) Galaxies/subclusters falling into clusters

3) X-ray "overluminous" galaxies

Collaborators: Bill Forman, Yuanyuan Su, Felipe Santos, Mike Anderson, Eugene Churazov, Paul Nulsen, Ralph Kraft, Marie Machacek, Alexey Vikhlinin, Akos Bogdan, Scott Randall

Hot Gas and Black Hole Outbursts in Early Type Galaxies, Groups, and Clusters



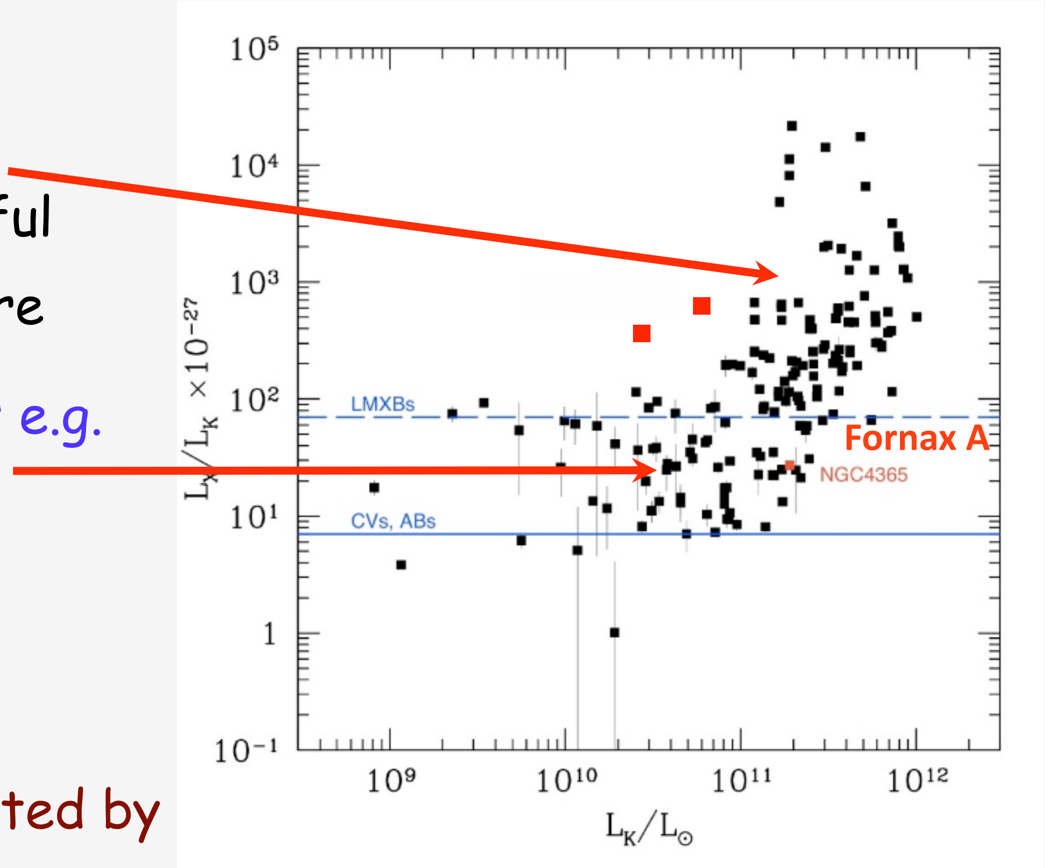


Measure energy released by AGN by measuring PV work associated with inflating X-ray cavities + energy in shocks. Assume X-ray cavities are in pressure balance with ICM, then can infer total energy in the cavities available for mechanical work (i.e. enthalpy) H = gamma/(gamma-1) PV. Measure outburst age, assuming that bubbles rise buoyantly.

Little radiation from black hole - mechanically powerful
Often radio emission filling the cavities (e.g. M84, Hydra A) or from the nucleus/SMBH

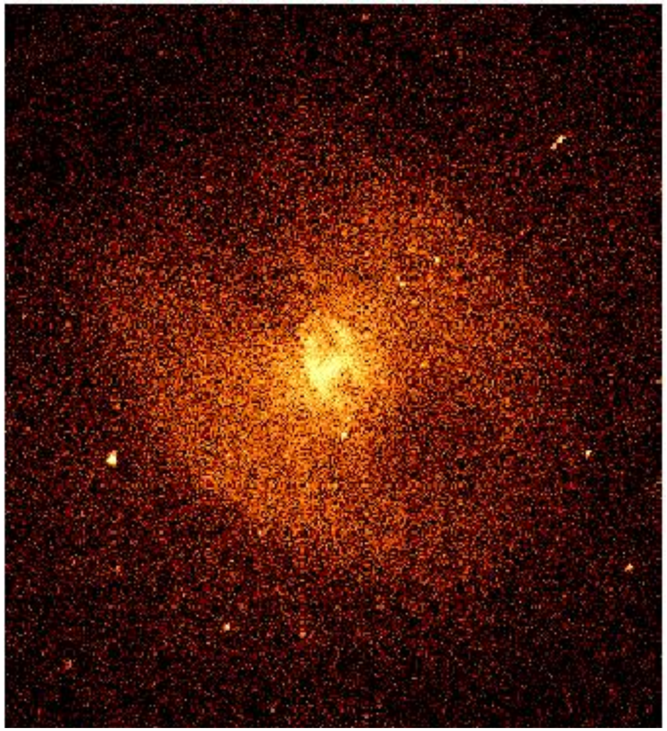
Gas Halos and cavities in Groups and Early Type Galaxies

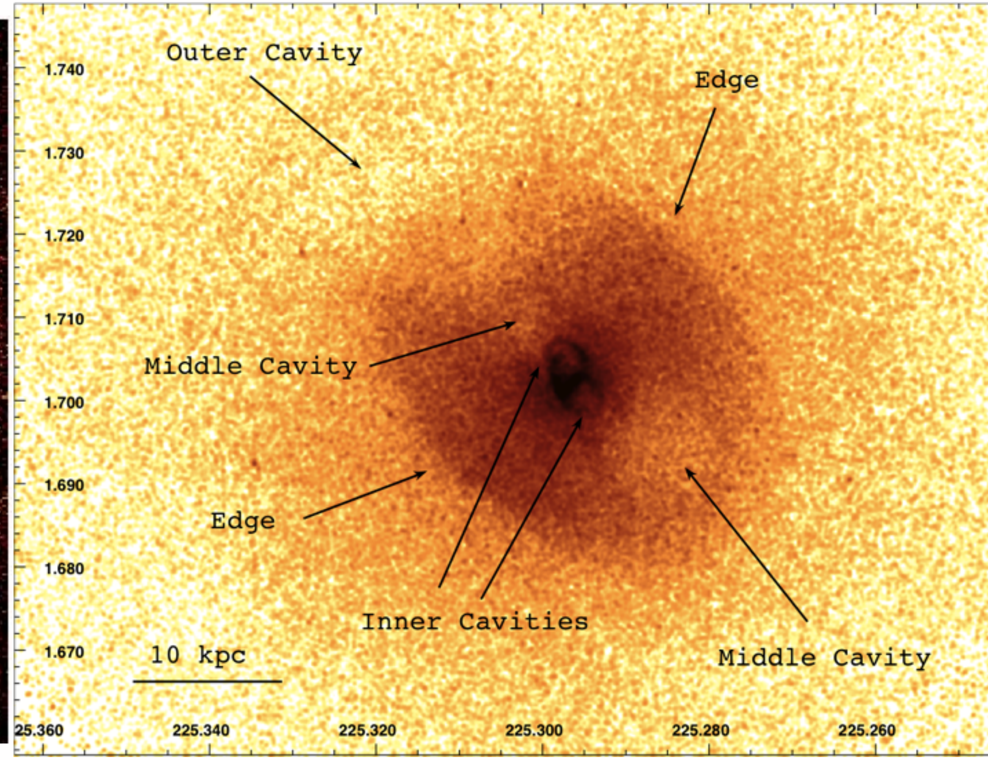
- Cavities - common ~30% of luminous galaxies
- Wide range in L_X at fixed L_K - environment (group) or powerful outburst disrupting atmosphere
- Low L_K - mostly galactic winds e.g. NGC4278 with bipolar gas distribution
- Hot gas in galaxies also detected by Planck through SZ effect



There are no dry mergers in massive galaxies

Three black hole outbursts in NGC5813 group show symmetric, alligned jet axis over 10^8 years (Randall+ 2011, 2015)



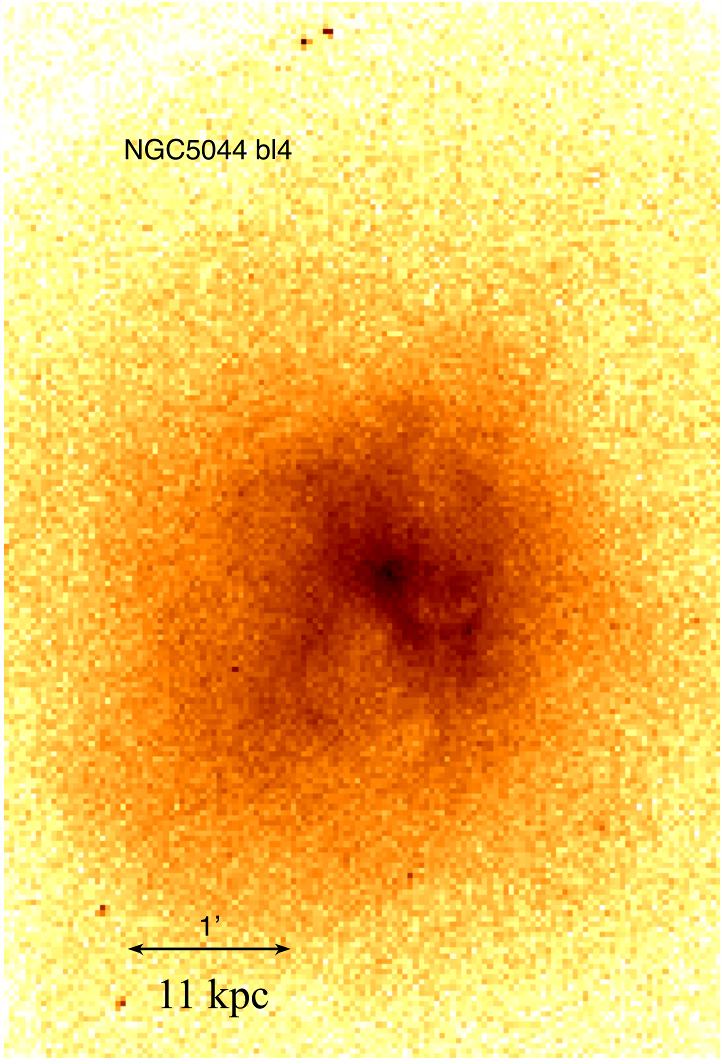


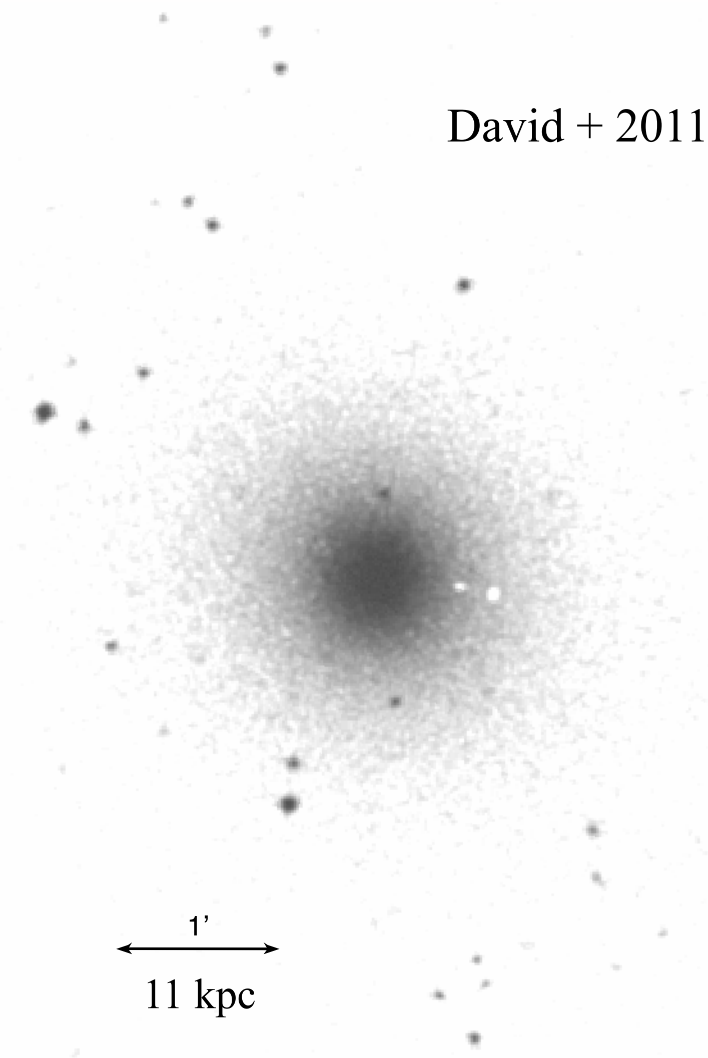
Three pairs of outbursts

Inner:	M = 1.7	Age 3×10^6 yr	P ~ 0.6×10^{42} ergs/s
Middle:	M = 1.5	Age 20×10^6 yr	P ~ 7×10^{42} ergs/s
Outer:	M = 1.4	Age 90×10^6 yr	P ~ 8×10^{42} ergs/s

Faint Nucleus $L_{nuc} = 2 \times 10^{39}$ ergs/s

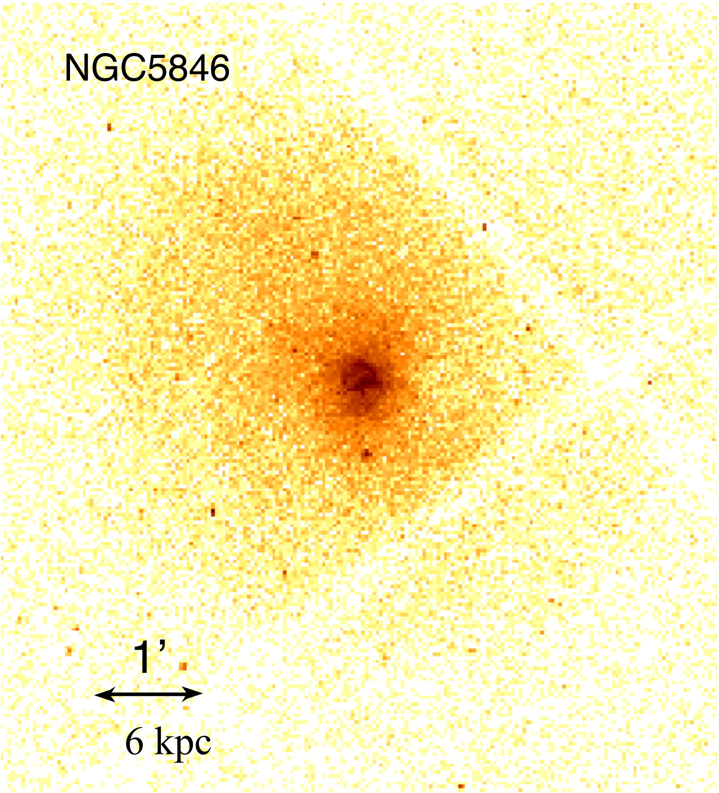
NGC 5044 group shows many small, not alligned bubbles

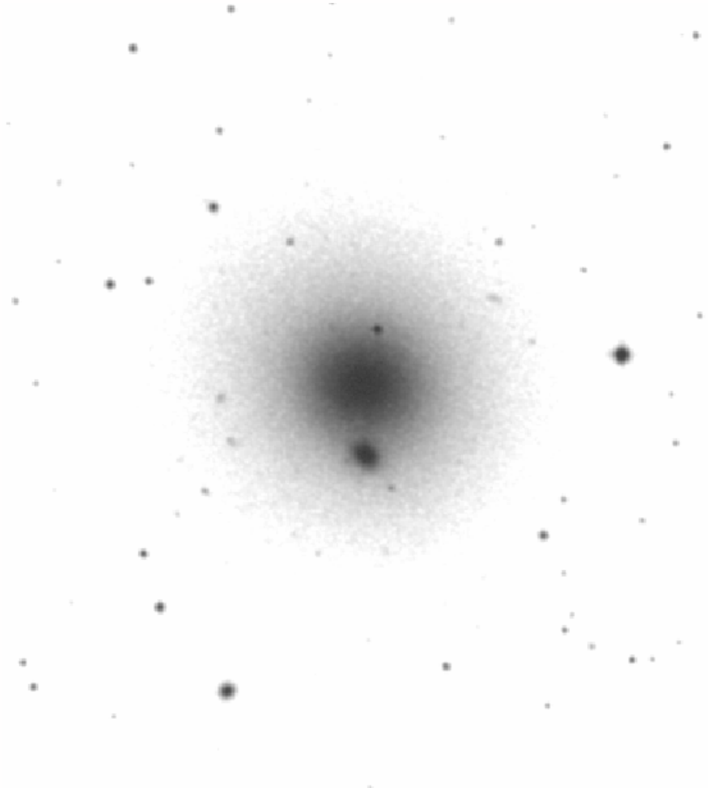




Why are NGC5044 and NGC5813 so different in bubble morphology? Strength of outbursts?

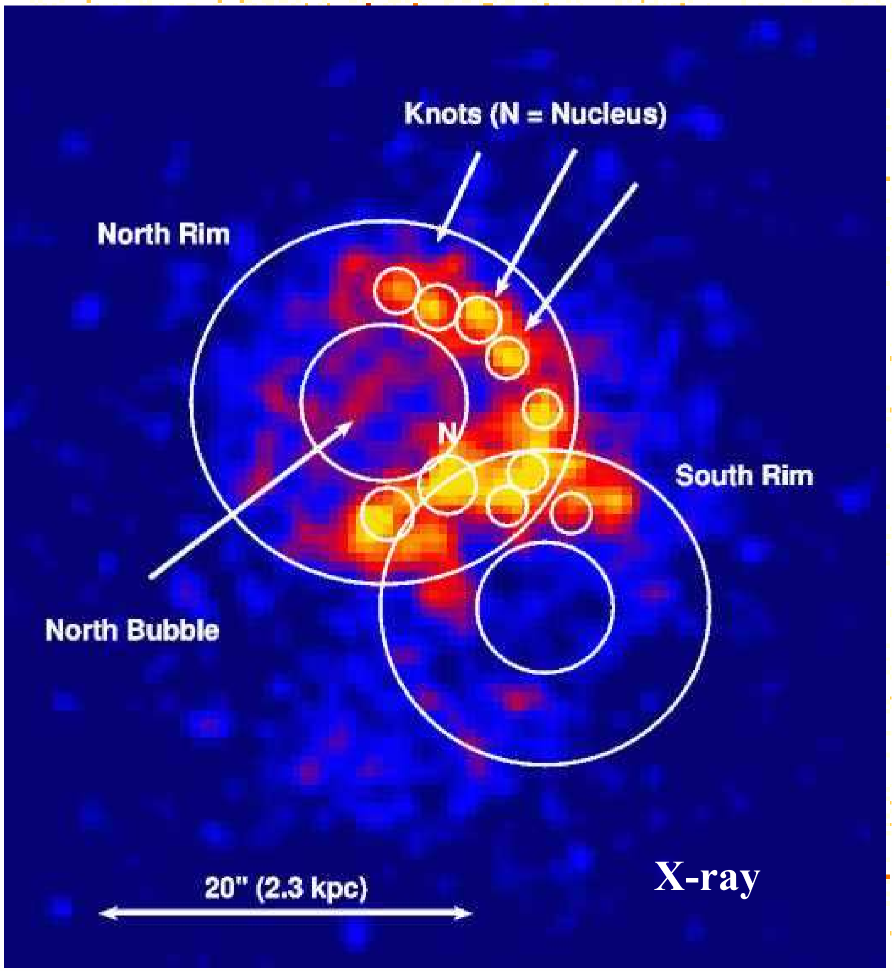
Hot gas and Black Hole Outbursts in the NGC5846 Group

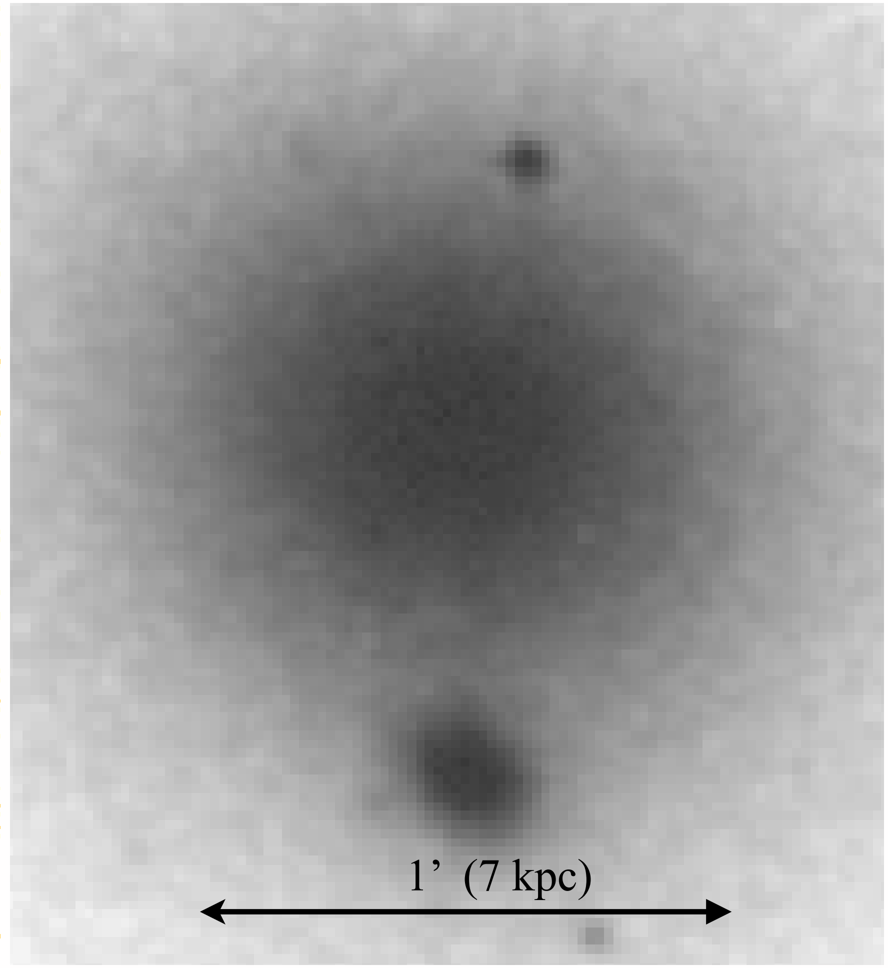




X-ray emission seen to 30 kpc (Machacek et al. 2011)
Gas sloshing and cavities.

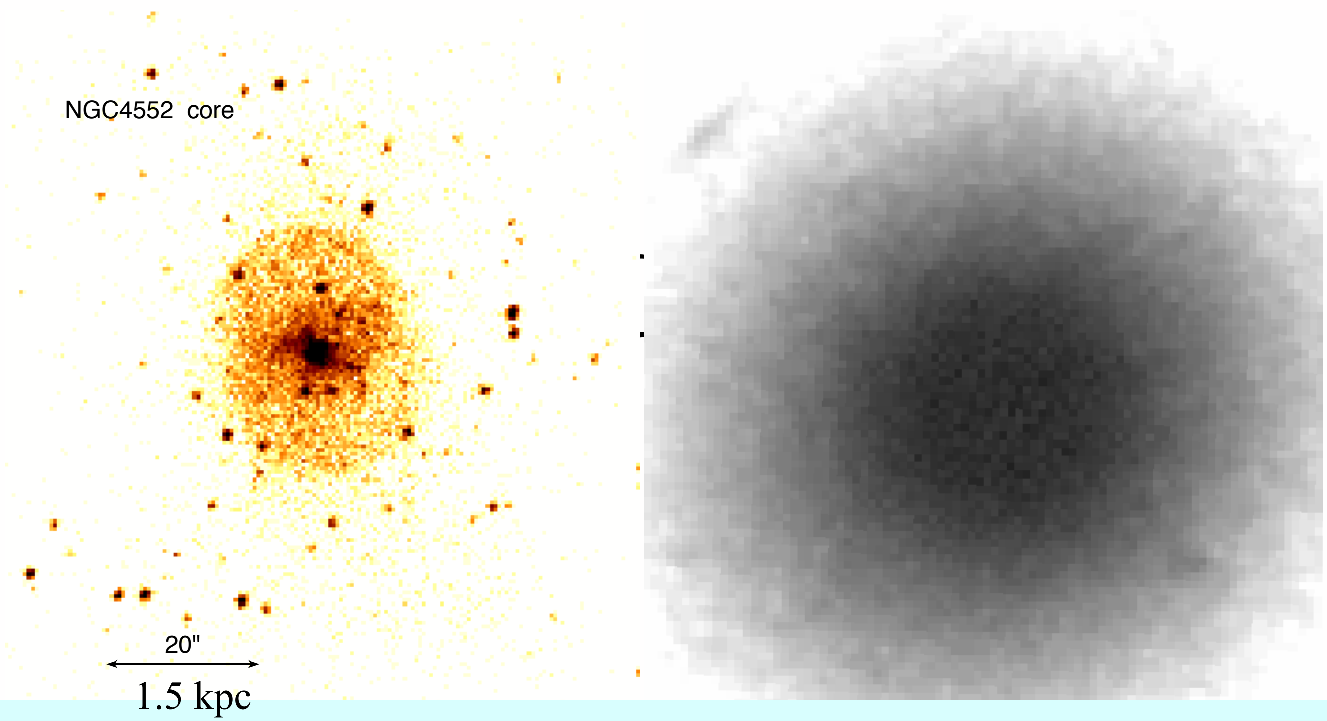
NGC5846 inner core shows ring of bright X-ray knots, possibly shock heated by AGN outburst (Machecek+2011).





Bipolar Nuclear Outflow Cavities in NGC4552 (M89)

Machacek + 2006



One outburst - one pair of bubbles

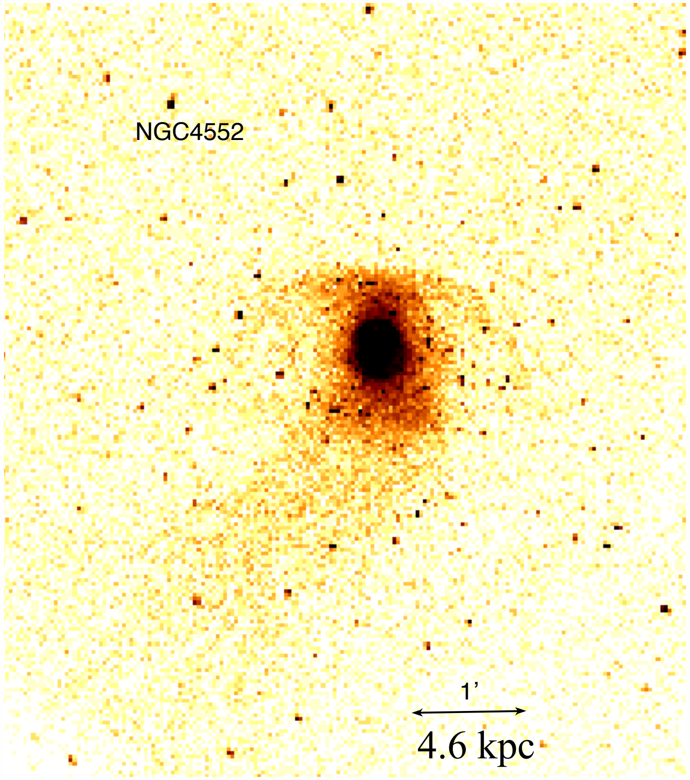
Mach 1.7 shock from 1.4 x 10^{55} ergs nuclear outburst

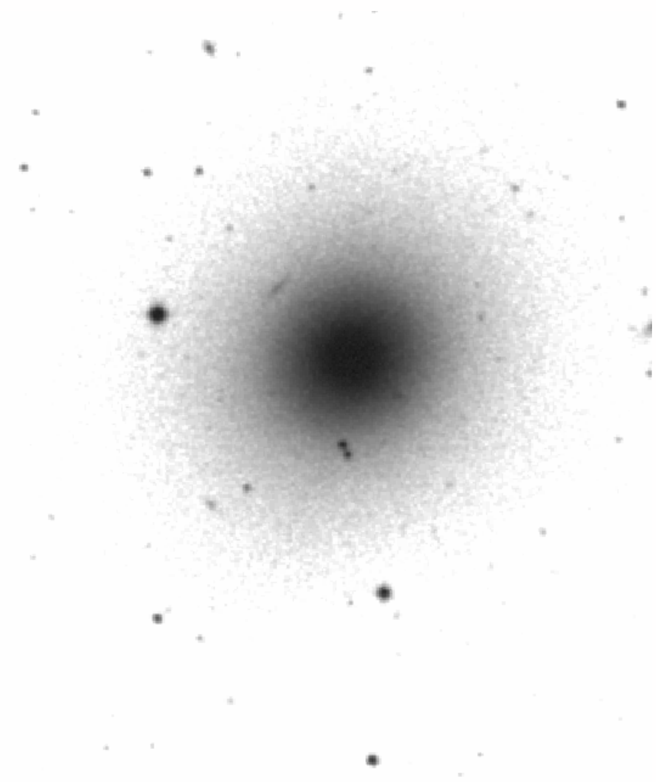
Outburst age ~1-2 10^{6} years

Higher gas temperature in galaxy core suggests directly observing reheating of ISM by nuclear outbursts

Beyond the Nuclear Outflow Cavities in NGC4552

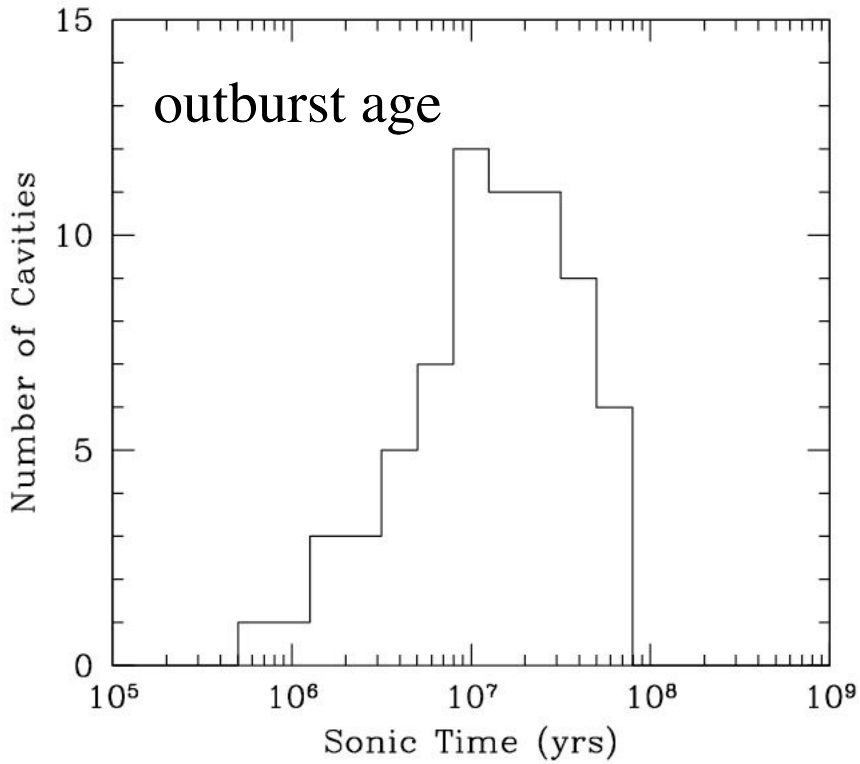
Machacek + 2006

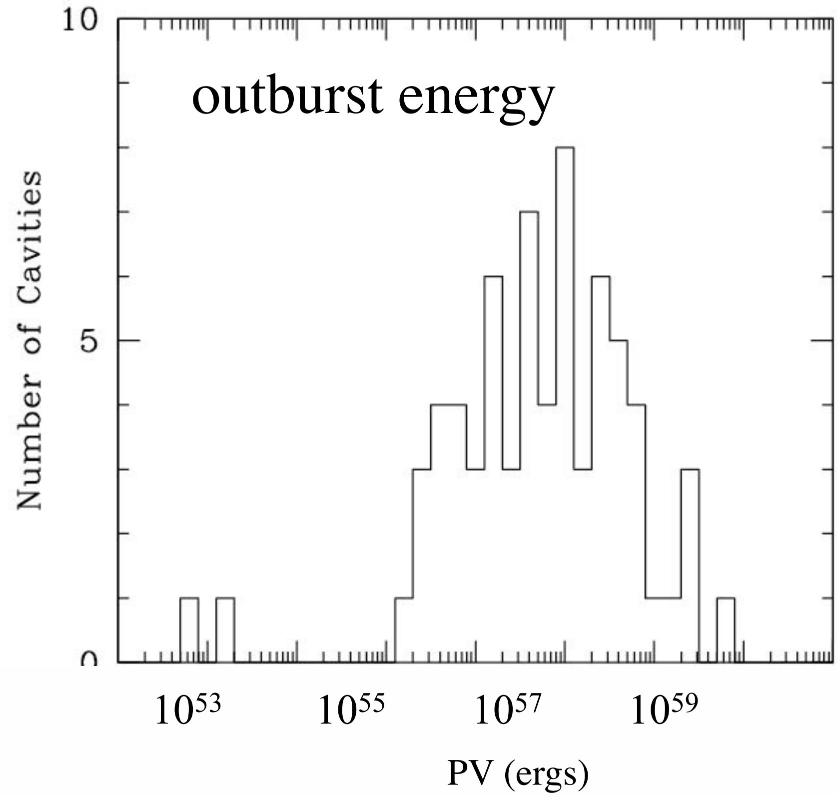




NGC4552 also has a stripped tail and “horns” !
Both an AGN outburst and gas stripping.

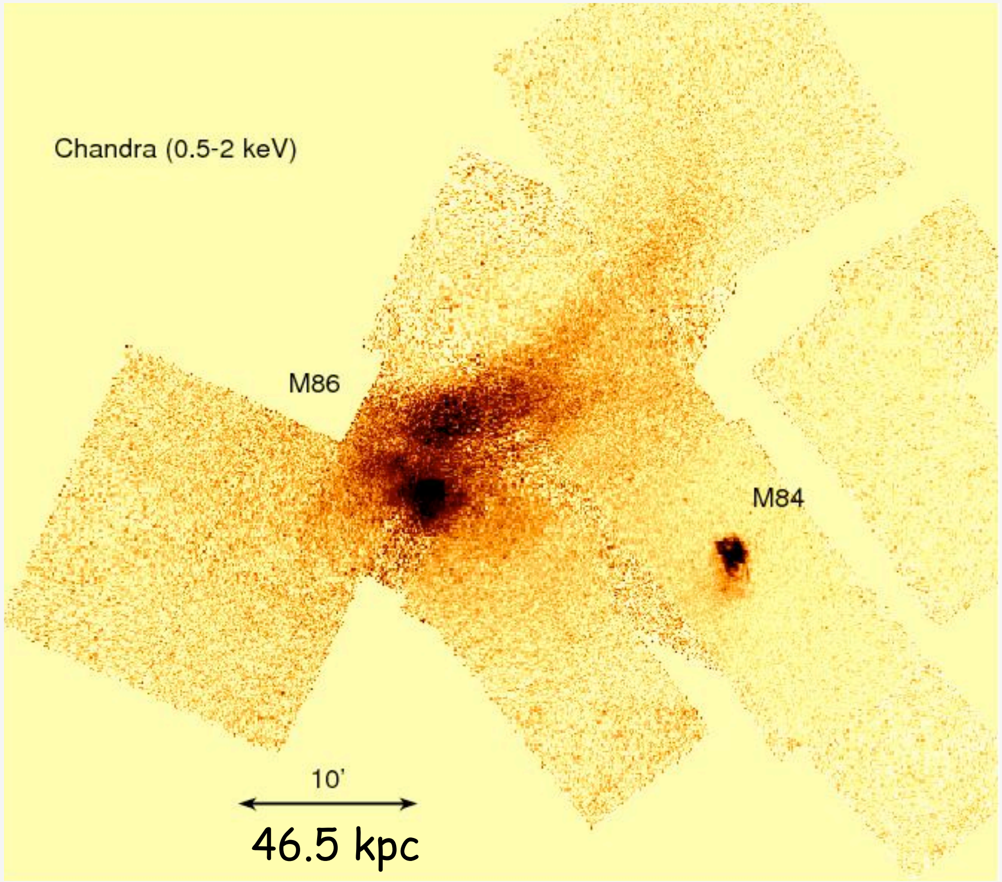
In galaxies and groups, detected gas cavities are young (10^6 - 10^8 years) => frequent outbursts





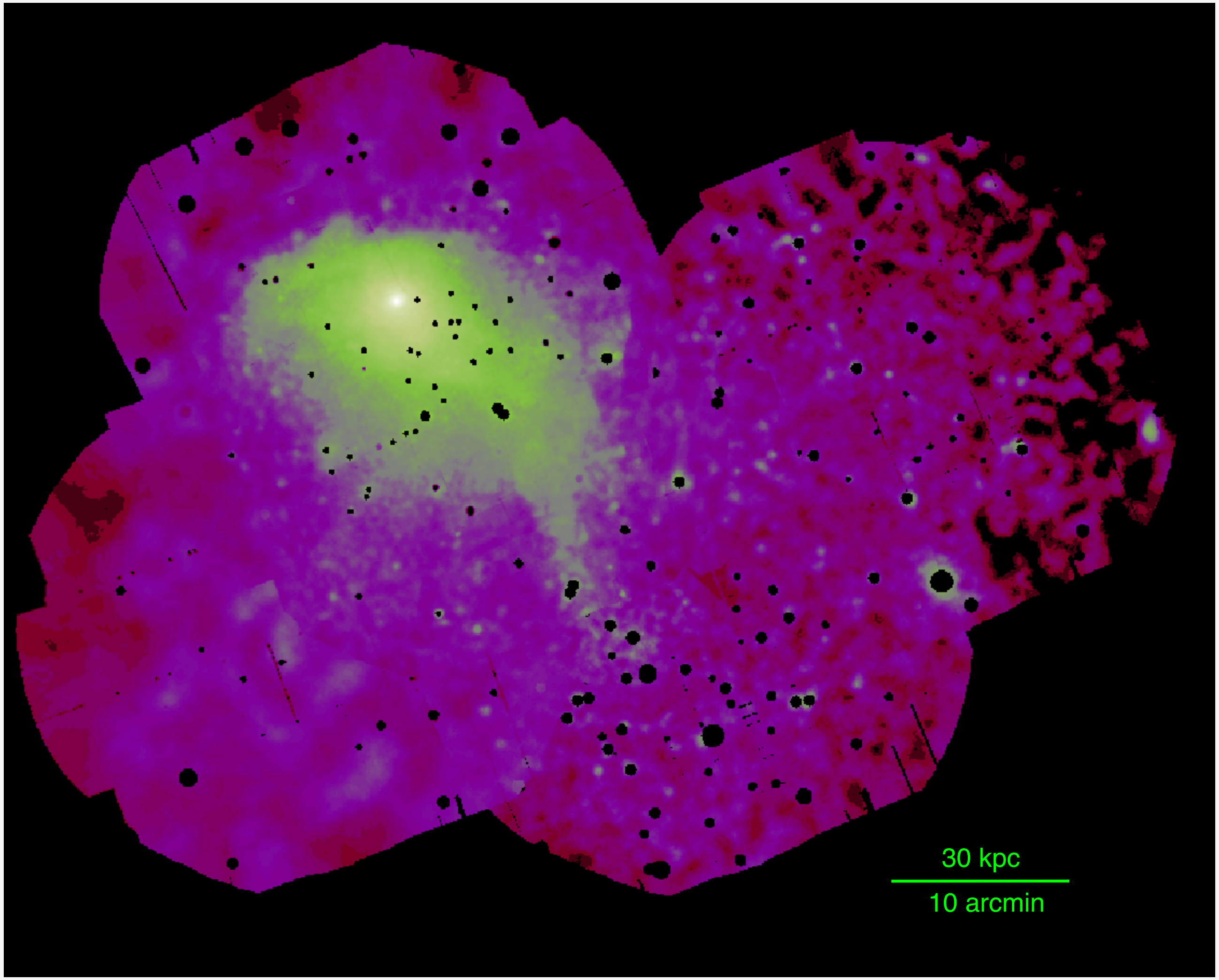
Ages and outburst energies for galaxies/groups with cavities (30% of optically luminous galaxies in the sample) - Nulsen, Jones, Forman, Churazov & friends)

2) Groups infalling into clusters (three examples - M86, NGC4472, NGC1404)

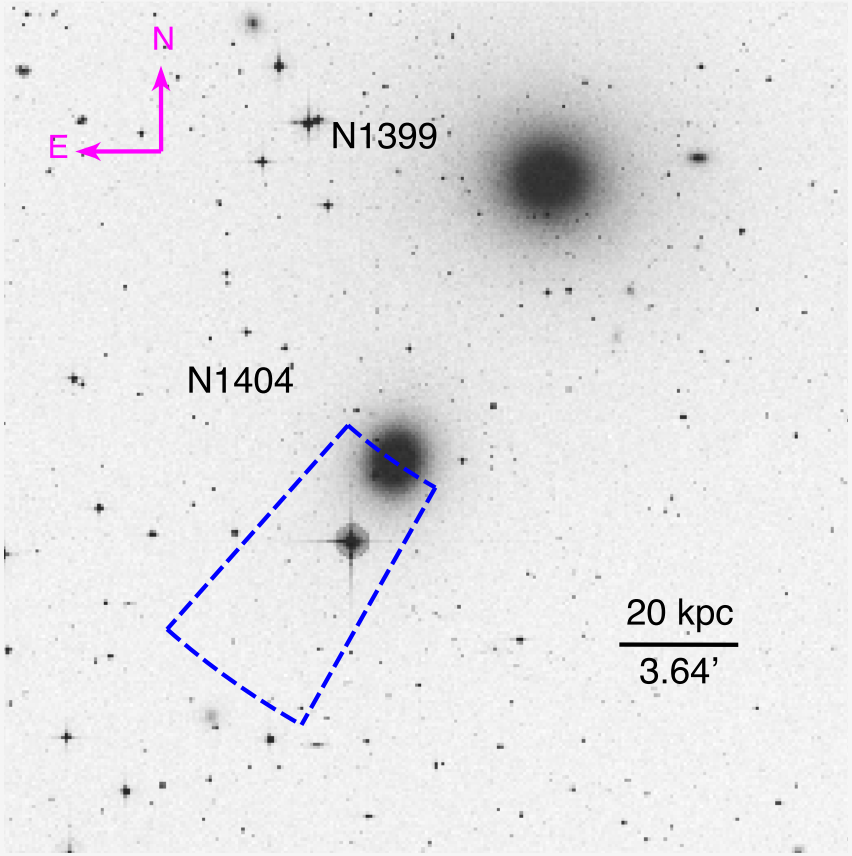


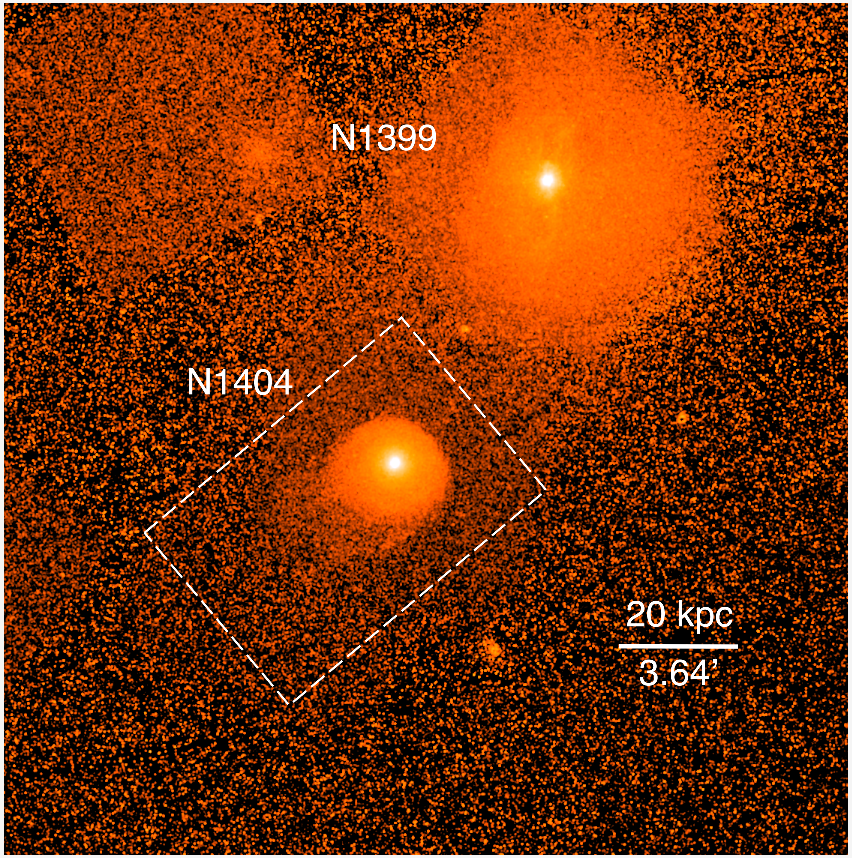
M86 group falling into Virgo. Ram pressure stripped gas. (Forman et al. Randall et al.)

Infall of the NGC4472 group toward M87
XMM-Newton (Su, Kraft et al. 2017)
Surface brightness edge to north and X-ray tail.



Infall of NGC1404 into Fornax cluster



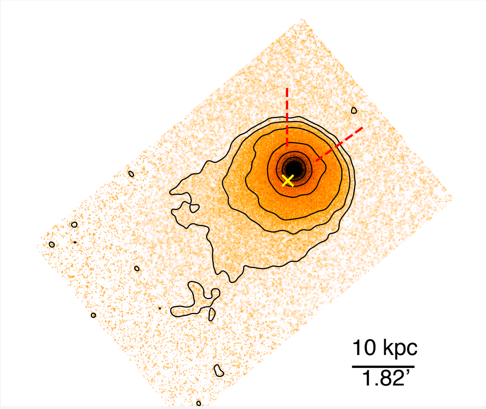


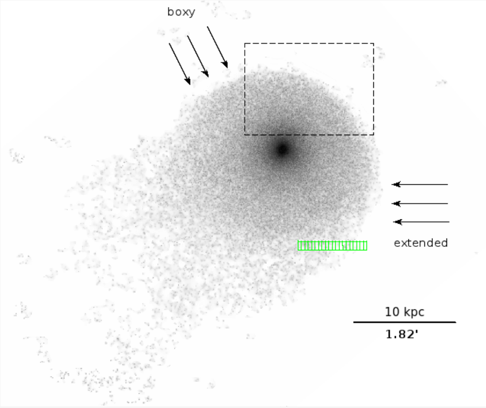
X-ray tail and cold front in NGC1404

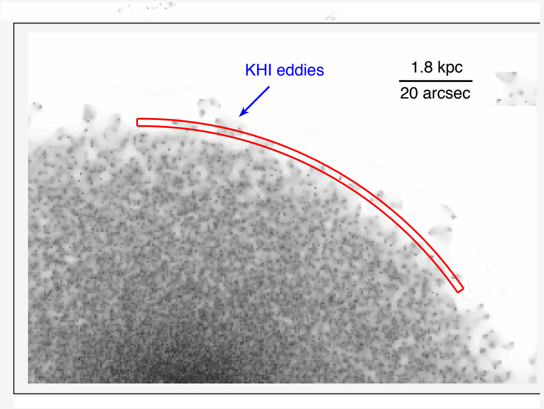
Su, Kraft et al. submitted

NGC1404 infalling into Fornax cluster - investigating the gas physics

Su, Kraft, Roedinger et al. submitted







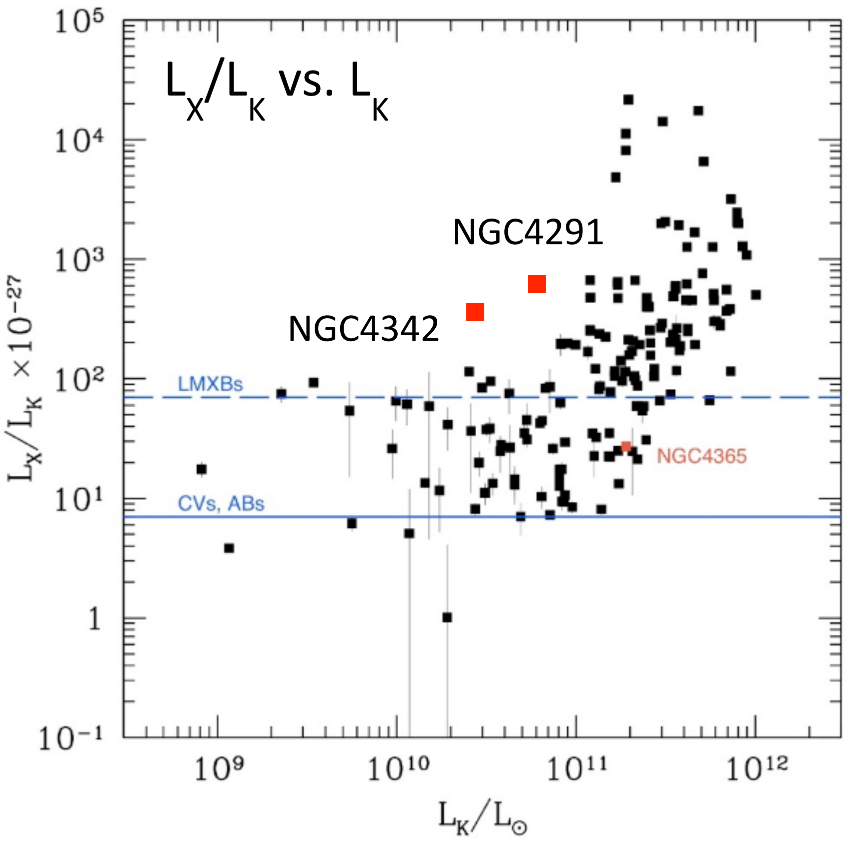
KH instabilities along cold front/contact discontinuity

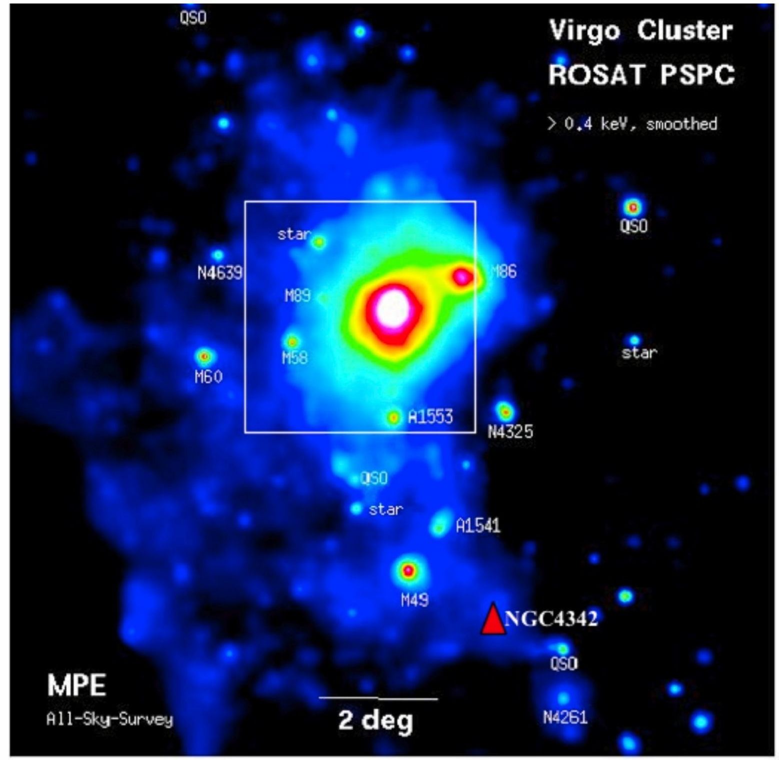
Isotropic viscosity of gas < 5% Spitzer.

Mixing of the hot cluster gas and the cooler galaxy gas in the downstream stripped tail provides further evidence of a low viscosity plasma.

Ordered magnetic fields in the ICM smaller than 5 microG to allow KHI.

3) NGC4342 + NGC4291- X-ray over-luminous Galaxies



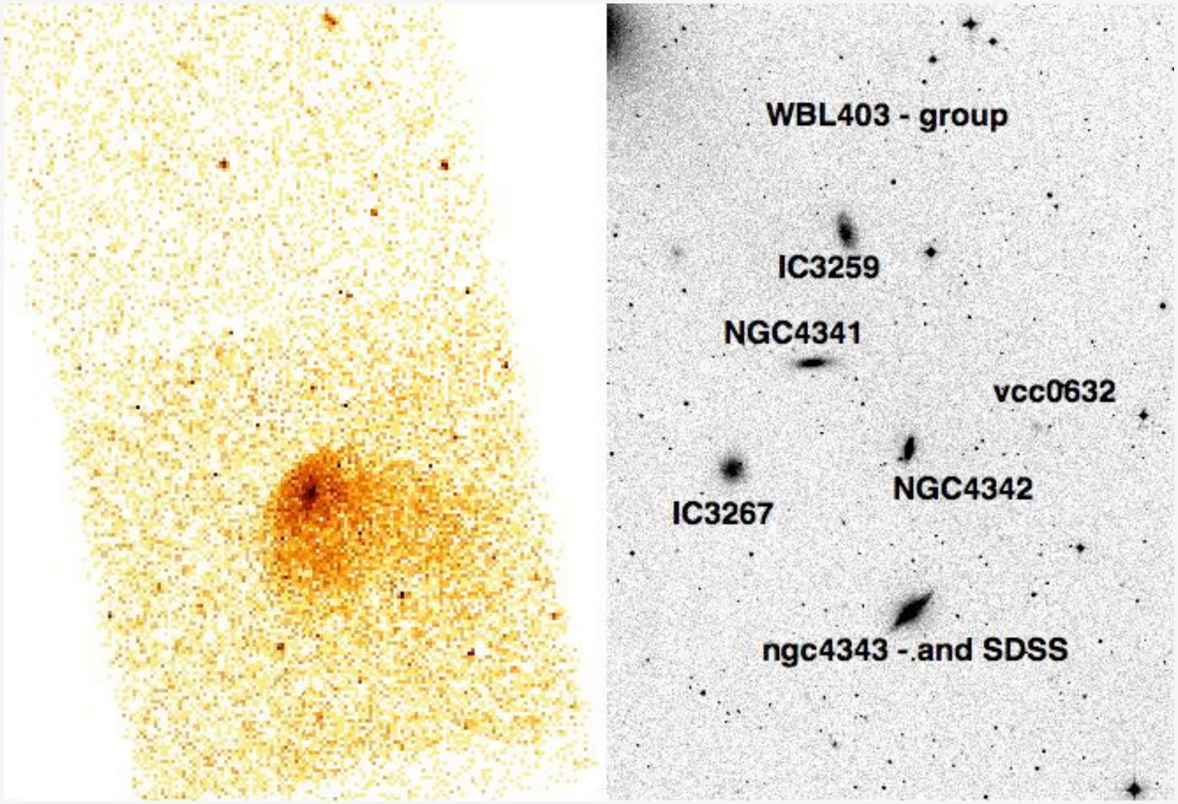


NGC4342 beyond Virgo core

Only ~0.5 Mpc from NGC4472 (M49)

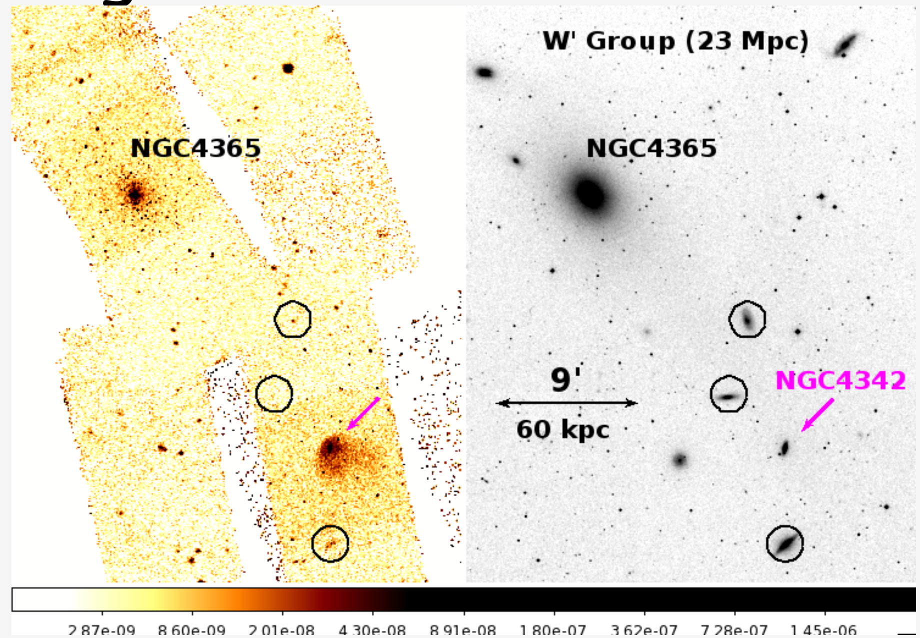
Virgo gas distribution - elongated N-S

NGC4342 (Bogdan + 2012)
another stripped galaxy in W' group



NGC4342 - low stellar mass,
large dark matter halo to bind hot gas
Ram pressure stripping underway.
What makes NGC4342 "special"?

Optically faint, gas rich galaxies - NGC4342



W' Group Centered on NGC4365 (projected on southern end of Virgo Cluster)
D ~ 21 Mpc

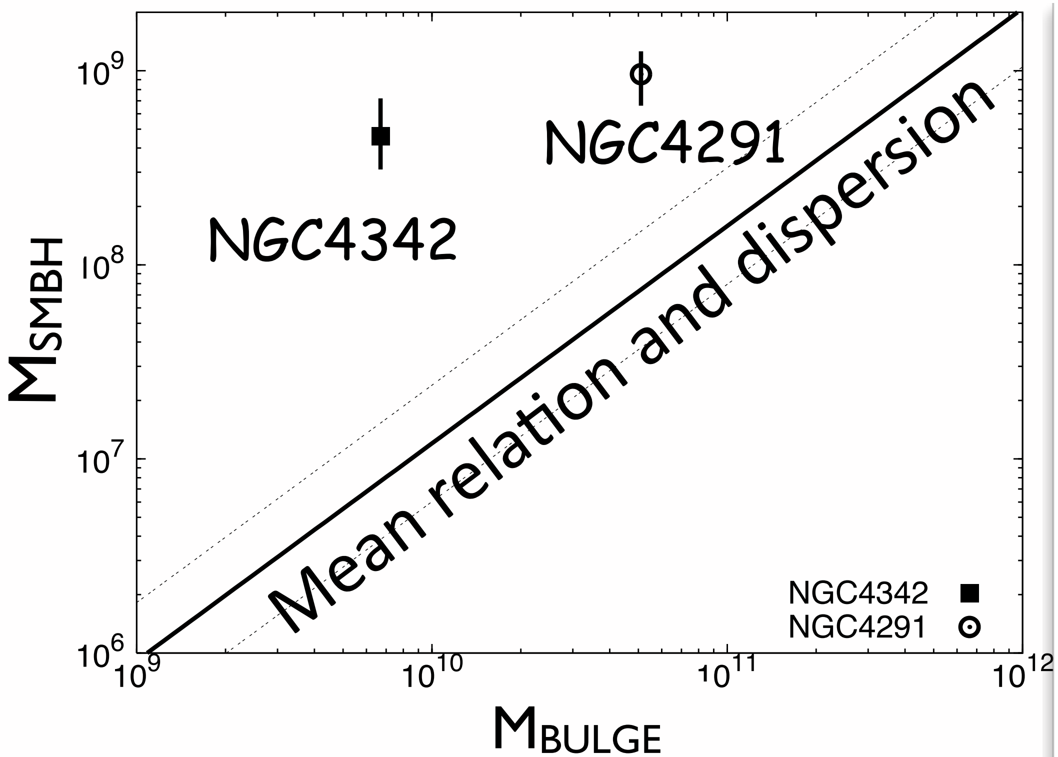
A lesson from Big Bird
One of these galaxies is NOT like the others

NGC4342 encounters external gas for the first time?
Ram pressure stripping underway

NGC4342 (& NGC4291)

- Dynamically measured SMBH
- Significant dark matter halos to bind hot coronae

Massive Black Holes (Bogdan et al. 2012) - two outliers



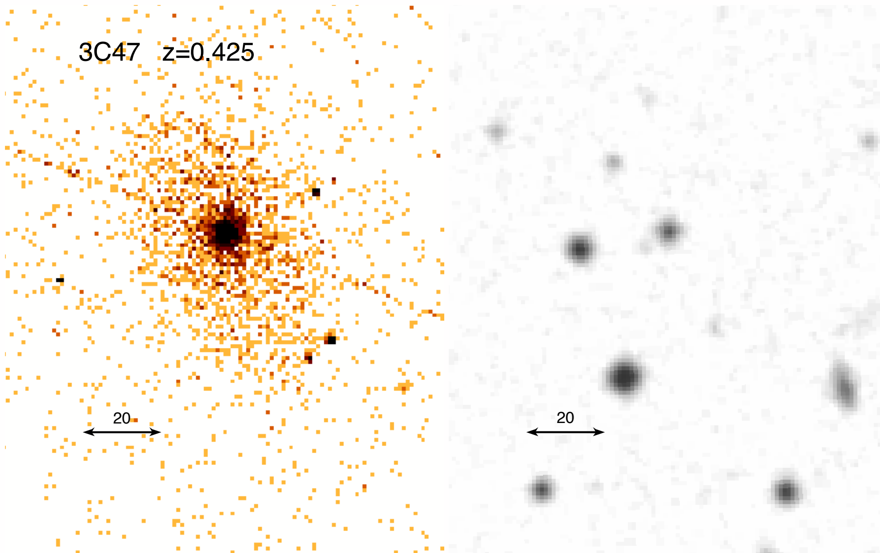
- Evolutionary scenario for NGC4342 and NGC4291
- Star formation suppressed by powerful SMBH outburst at early epochs BEFORE all stars formed
- SMBH growth precedes stellar component e.g., Sijacki+14
- eRosita will inventory dark matter halos

•NGC4342 and NGC4291 host massive dark matter halos sufficient to bind hot coronae

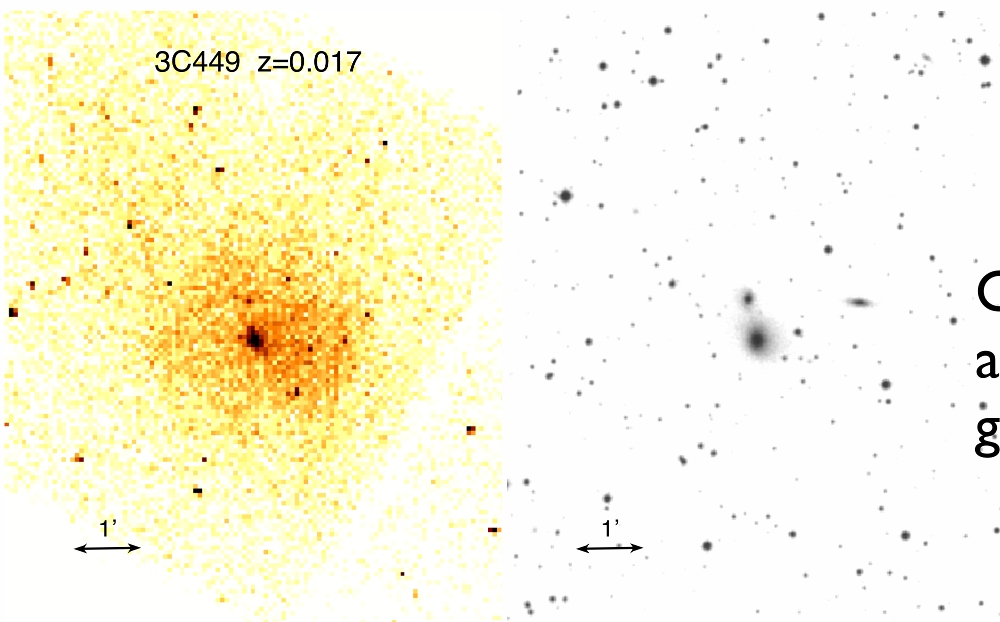
 •measured via hydrostatic equilibrium

• **Black holes are too massive for their stellar bulges (60x and 13x larger than "predicted")**

Hot Gas Halos around Radio bright Quasars



Growing observational evidence that radio-bright QSO's have group scale hot gas environments

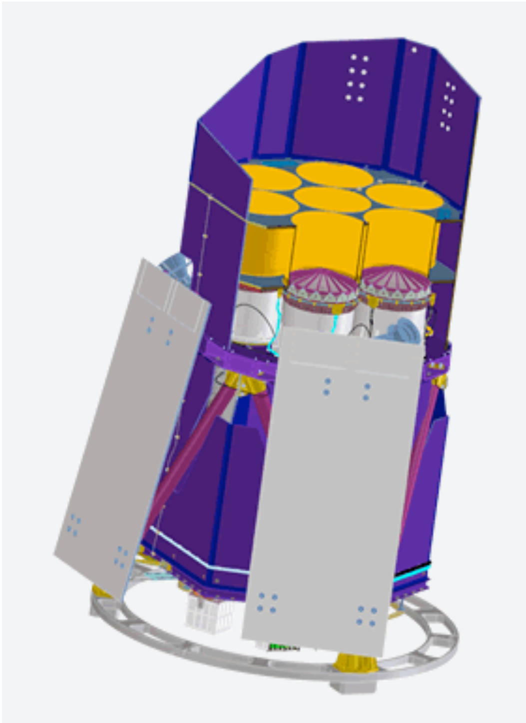


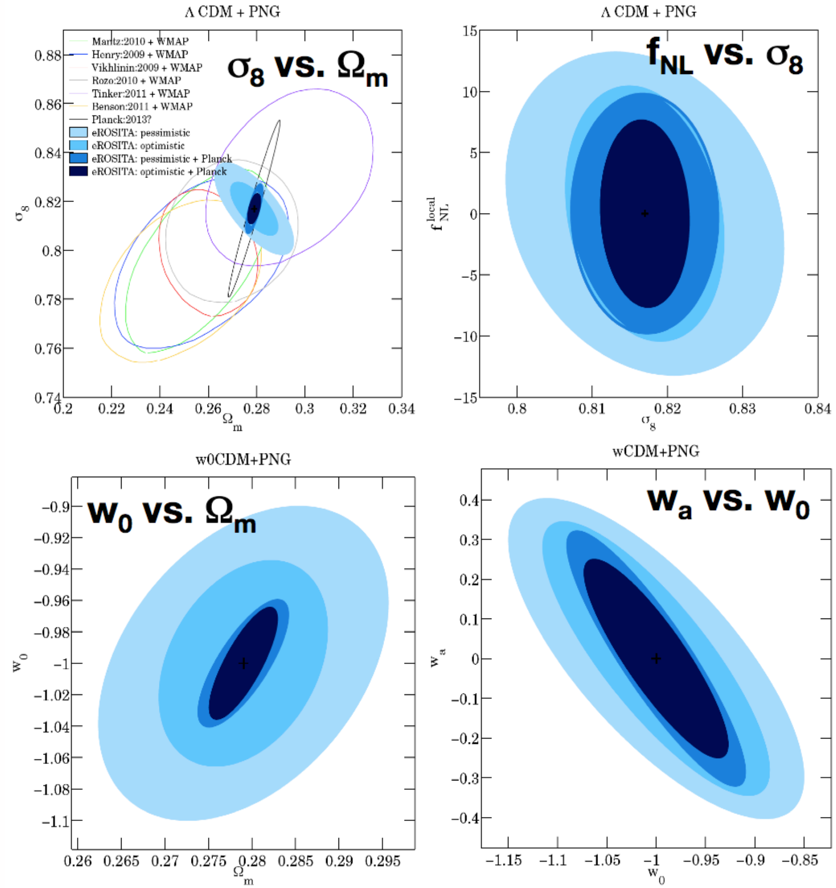
Chandra observations of 3C47 and 3C449 show surrounding gas halos (Calzadilla et al. 2016)

Summary - AGN Feedback and Gas Stripping

- Bubbles are common; shocks are rare. Most SMBH's are getting feedback "just right" (over some duty cycle), but there are very interesting "failures" in both directions.
- Too much feedback - NGC4342/NGC4291 - star formation likely terminated at early epochs by overly active SMBH
- Too little feedback - Phoenix Cluster (see McDonald+13) with 740 M_{sun}/yr of star formation
- eRosita - will provide wealth of new data yielding optically faint & X-ray bright (hot coronae) galaxies and galaxies with AGN suppressed star formation at early times

eROSITA/SXG





Primary Science Goals

- 30 X ROSAT sensitivity
- 0.2 - 10 keV
- 4 years all sky mapping, 3.5 years pointed observations

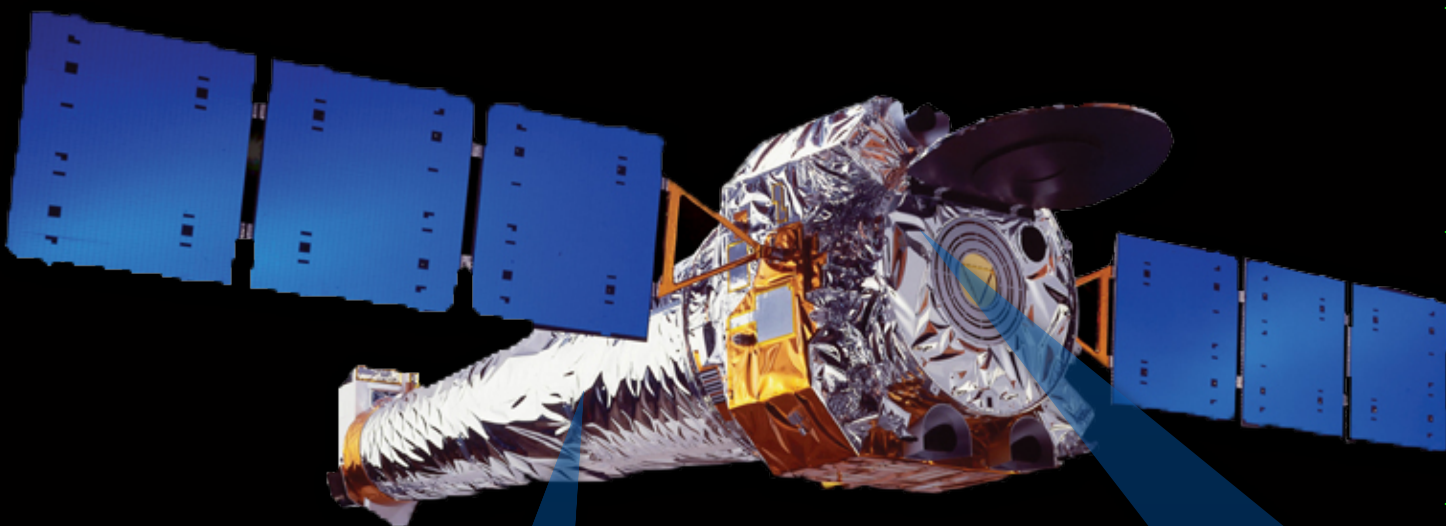
- Detect all massive (> 3 10^{14} M_{sun}) clusters (and groups to 200 Mpc)
-Refine scale relations and cosmological parameters
- Map LSS with groups within 200 Mpc and clusters to z~1.

- 2m effective area at 1 keV
- 5" angular resolution
- 0.3 - 12 keV
- Wide Field imager 40' FOV
- Calorimeter 5' FOV

Primary Cluster Science Goals

Trace the evolution of clusters and groups to z=1
Measure velocities, thermodynamics, chemical composition of hot gas to quantify non-gravitational heating and turbulence

X-ray Surveyor (aka LYNX) under study for the 2020 decadal



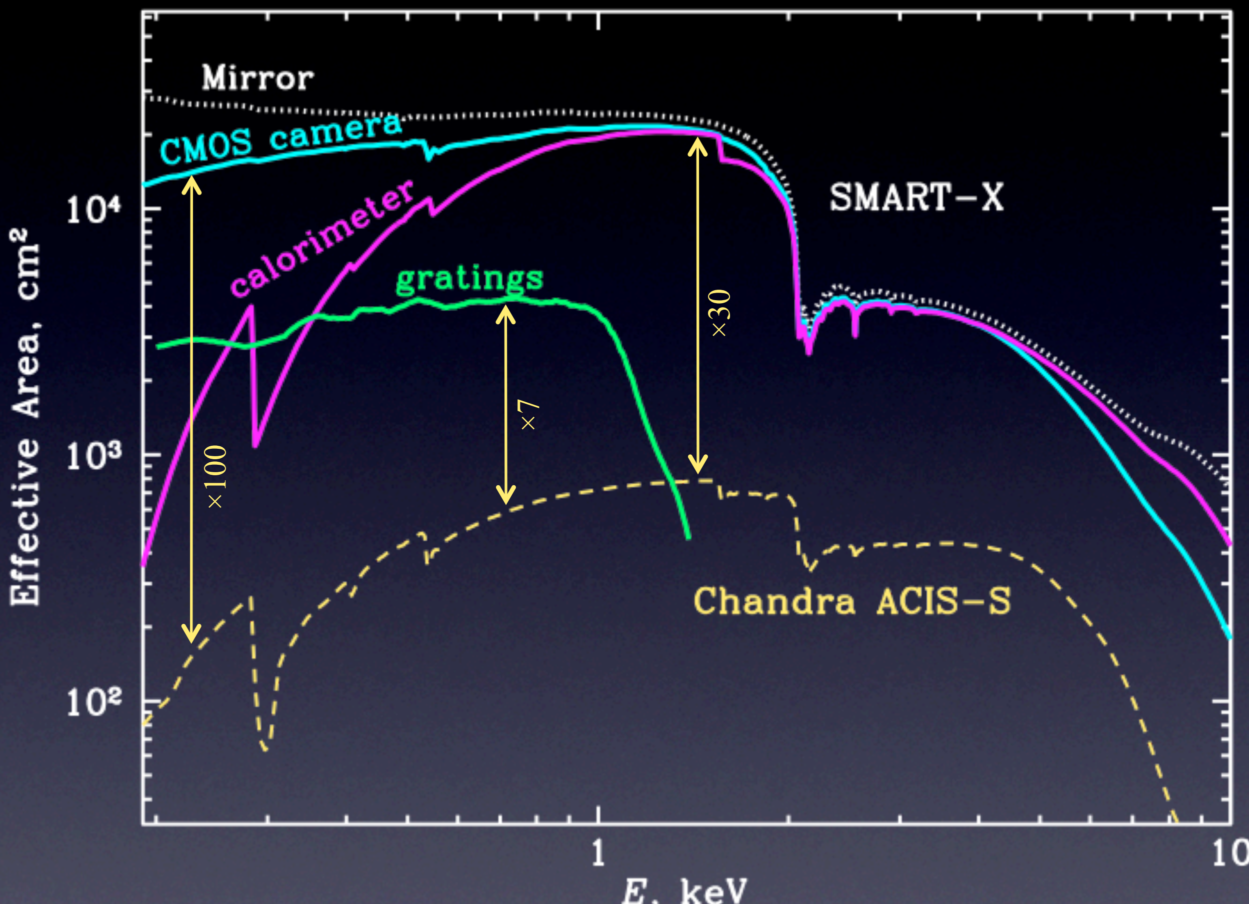
- ✓ **Technology incorporates IXO development and *Chandra* heritage**
- ✓ **No spacecraft requirements beyond those achieved for *Chandra***
- ✓ ***Chandra*-like cost**

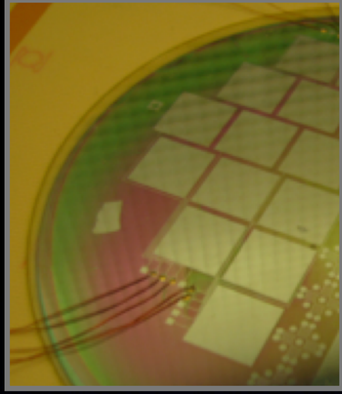
Next-generation science instruments, e.g.:

- 5×5′ microcalorimeter with 1″ pixels and high spectral resolution, 0.2–10 keV
- 22×22′ CMOS imager with 0.33″ pixels, 0.2–8 keV
- insertable gratings, R = 5000, 0.2–1.2 keV

"Smart" mirror system. Lower weight, same angular resolution, same focal length as *Chandra*'s. **A factor of 30 more effective area. Sub-arcsec imaging over 15×15′ field.**

Possible future X-ray Surveyor capability





Adjustible optics

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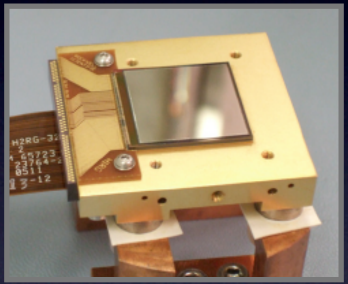
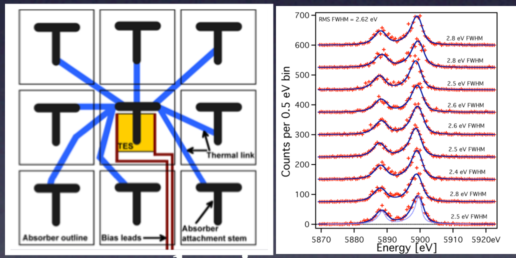
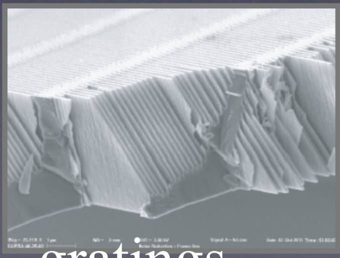




calorimeter



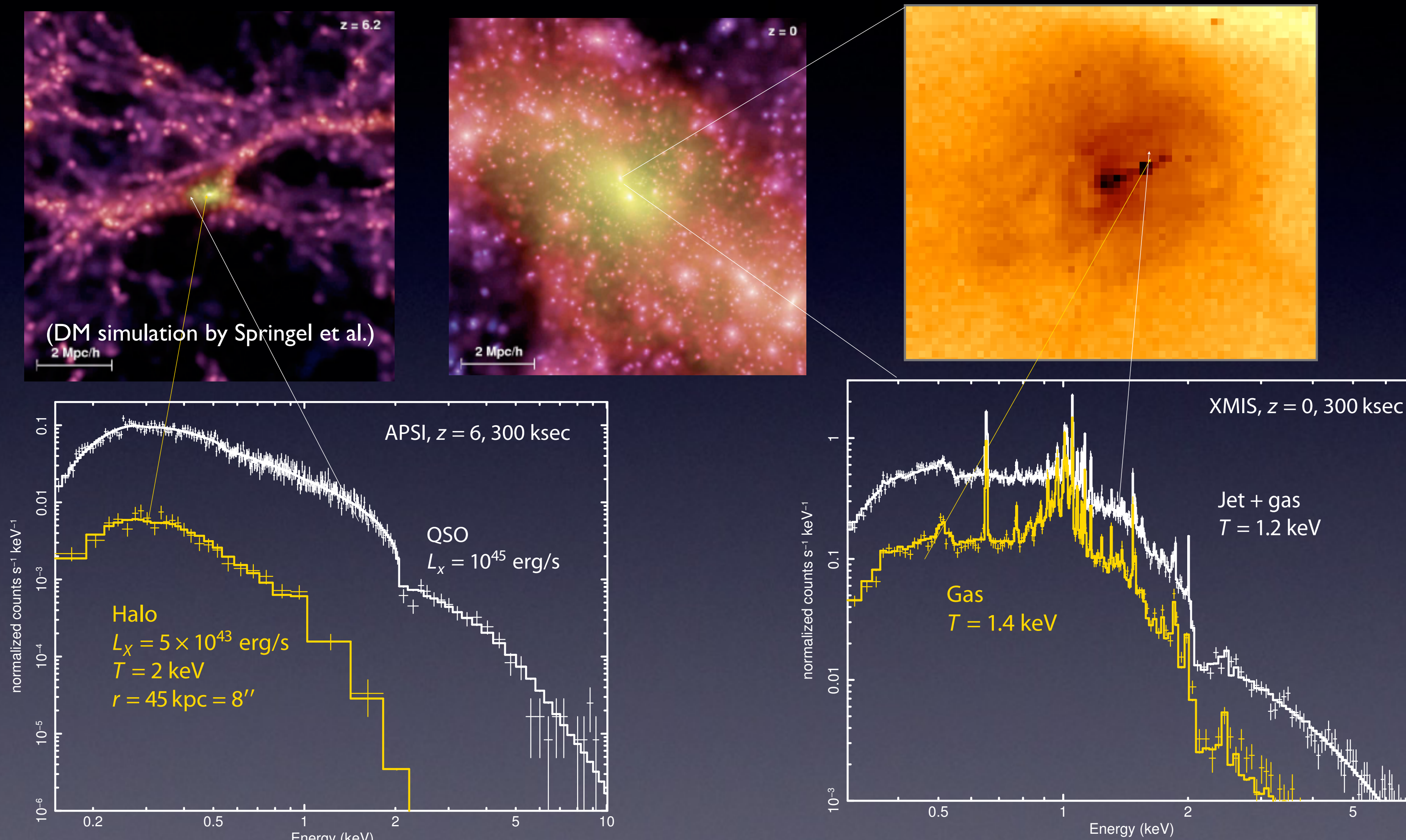
gratings

- Capability far exceeds *Chandra* (Chandra angular resolution, ×30 effective area, high-res spectroscopy for point and extended sources)
- Excellent match to JWST, ALMA, LSST, JVLA

Growth of galaxy groups and 10^9 $M_\odot$ black holes from z = 6 to the present

Sloan quasar at z=6 ⟶ "nursing home" at z=0

M87, *Chandra*, 1″ pixels

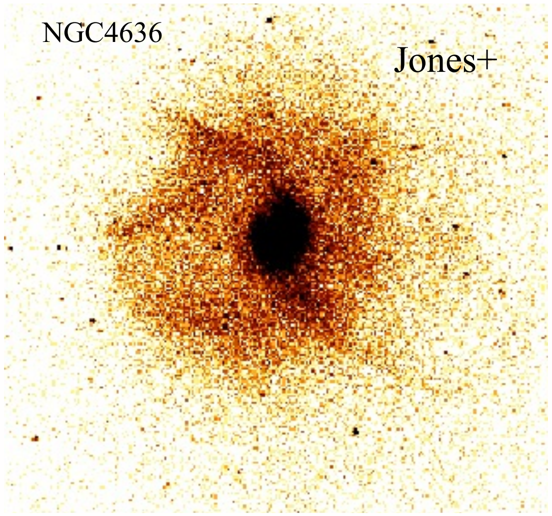


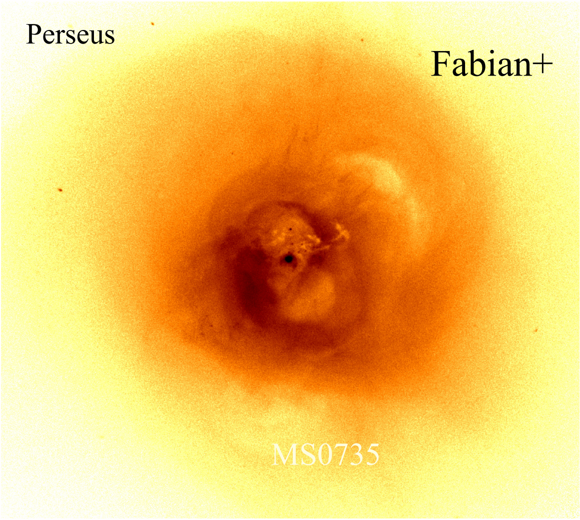
✓ ***Sensitivity + angular resolution — detect and resolve quasar host halos and galaxy groups at z=6***

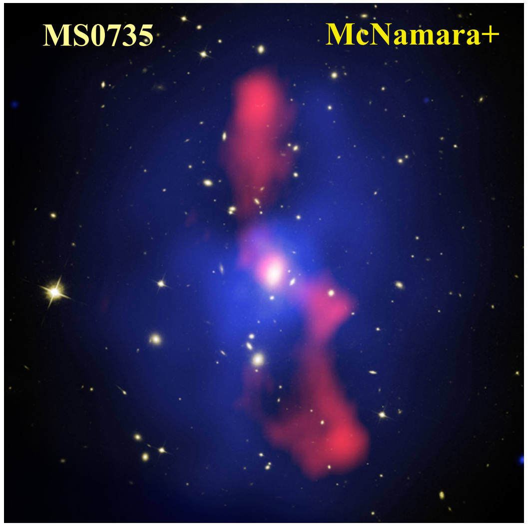
✓ ***High-res spectroscopy on 1″ scales — feedback and physics in clusters, galaxies, SNRs***

Thanks!

Supermassive Black Hole Outbursts in the Family of Early Type Galaxy Atmospheres



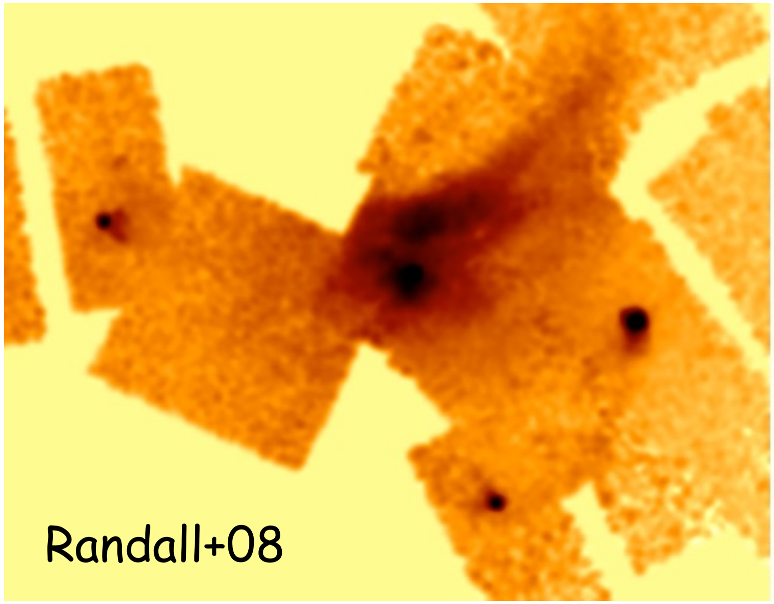


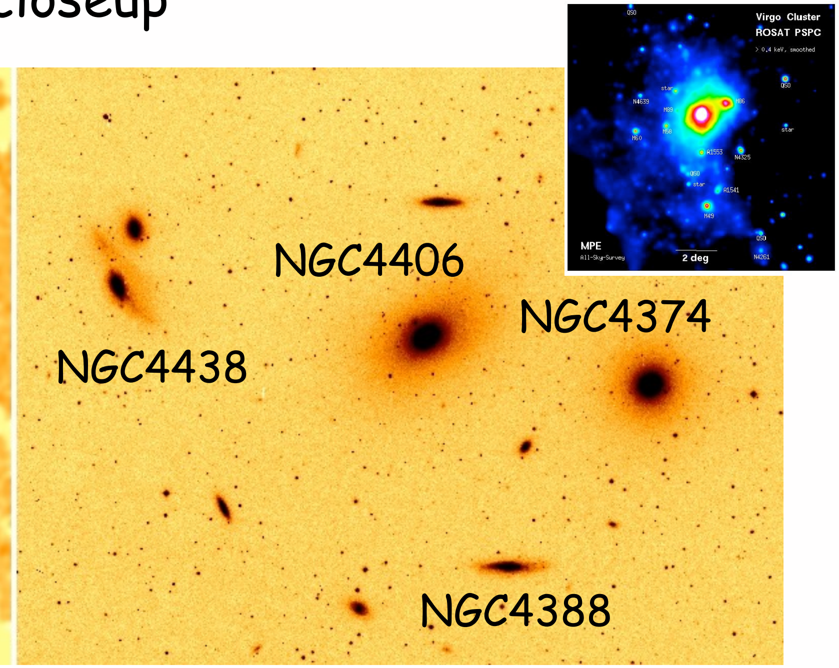


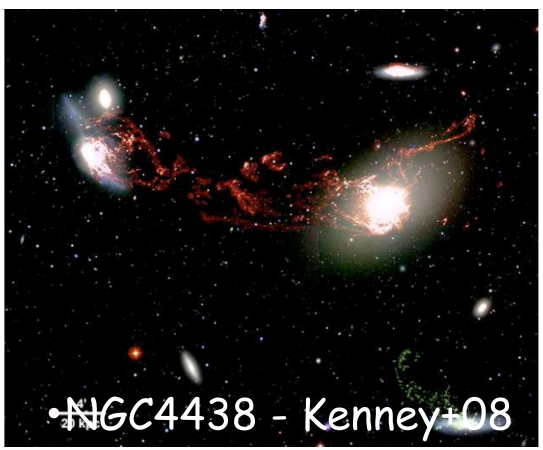
Galaxy/Group	Cluster Core	Massive Cluster
1 kpc	10 kpc	100 kpc
10^{56} ergs	10^{59} ergs	10^{62} ergs
10^{42} erg/s	10^{45} erg/s	10^{46} erg/s

Powerful outflows
Little radiation from SMBH (exception Phoenix cluster)
Gas cooling rates vary by > 100x
Span a wide range of dark matter halo mass

M86=NGC4406 closeup







•NGC4438 - Kenney+08

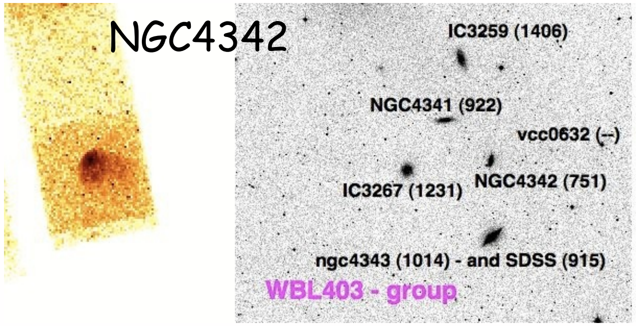
- red<500 km/s
- green >2000 km/s

- Ram pressure stripped tails everywhere
  - M86/NGC4406 (v=-244 km/s) Randall+08
  - M84/NGC4374 (v=1060 km/s) Jones/Finguenov02
  - NGC4438 (v=71 km/s) Machacek+04
  - NGC4388 (v=2524 km/s)
- Complex multi-component environment
  - Kenney+08 - Hα filaments
  - HI filament - Oosterloo & van Gorkom 05

Review

- M87 classic shock and bubbles
  - reveals detailed SMBH interaction
  - shocks are typically "weak"
  - outbursts are "long" (>Myr)
  - bubbles carry most of energy (>50%)
- *AGN outbursts are common in all gas rich systems*
  - bubbles/cavities everywhere!
  - more massive systems are more likely radio bright
- "cooling flows" from galaxies (~1 M_{sun}/yr) to clusters (~few 100 M_{sun}/yr) moderated by SMBH energy release
- SMBH's are willing and able to disrupt cooling atmospheres at low (and possibly high) redshifts (NGC4342/NGC4391 SMBH's are too massive for their stellar mass)
- **SMBH outbursts are a key phenomenon across a vast range of halo mass and cosmic time**

M87 - bubbles & shocks



galaxies groups clusters

$M_{halo} \sim 10^{12} \longrightarrow 10^{15}\ M_{sun}$