Hot gas and AGN Feedback in Nearby Groups and Galaxies

Part 1. Cool cores and outbursts from supermassive black holes in clusters, groups and "normal" galaxies

Part 2. Hot gas halos in faint ellipticals

Part 3. Gas stripping from galaxies and groups

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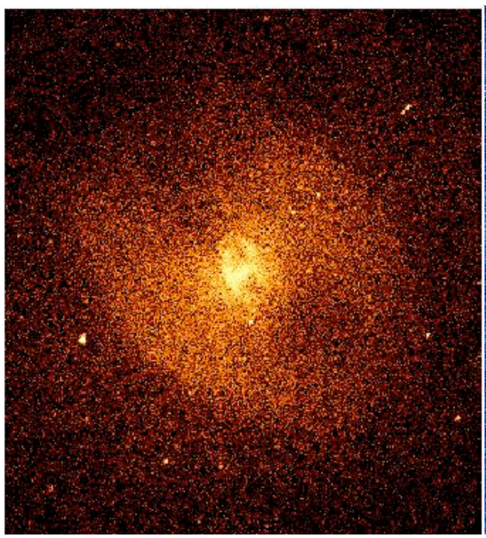
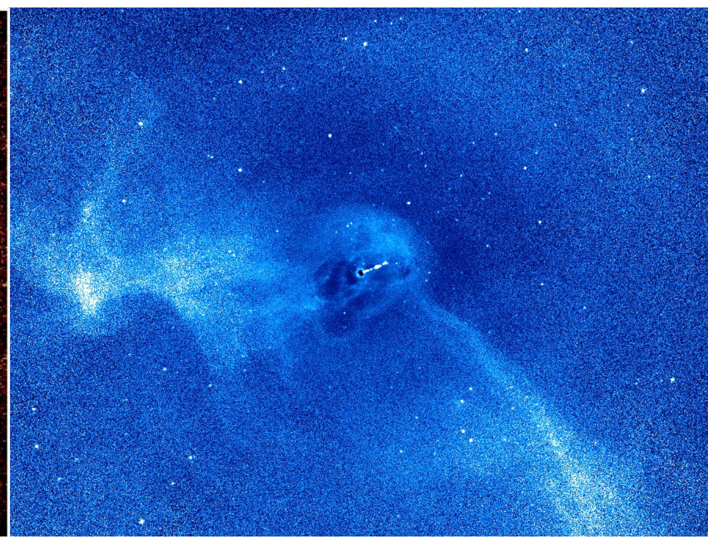
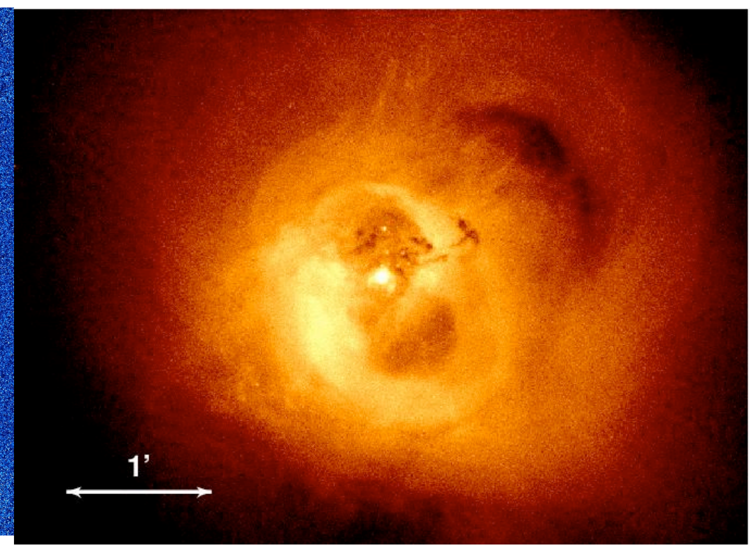


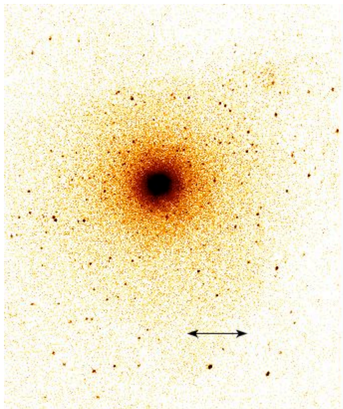
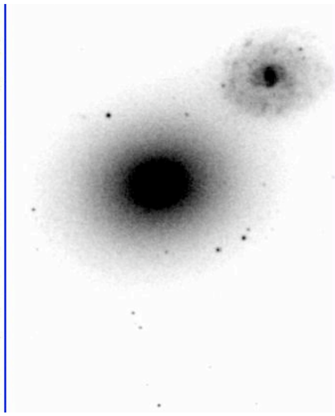
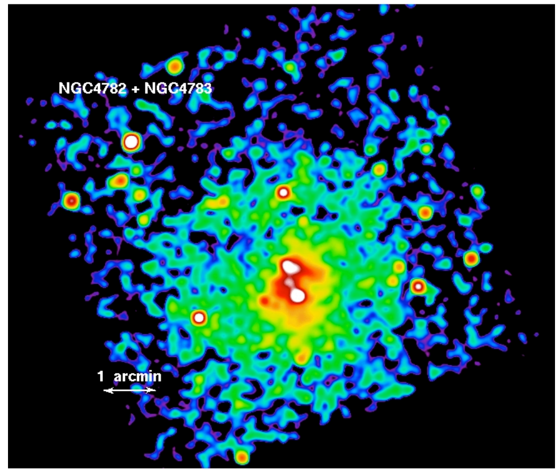




NGC5813 M87 Perseus

Setting the stage

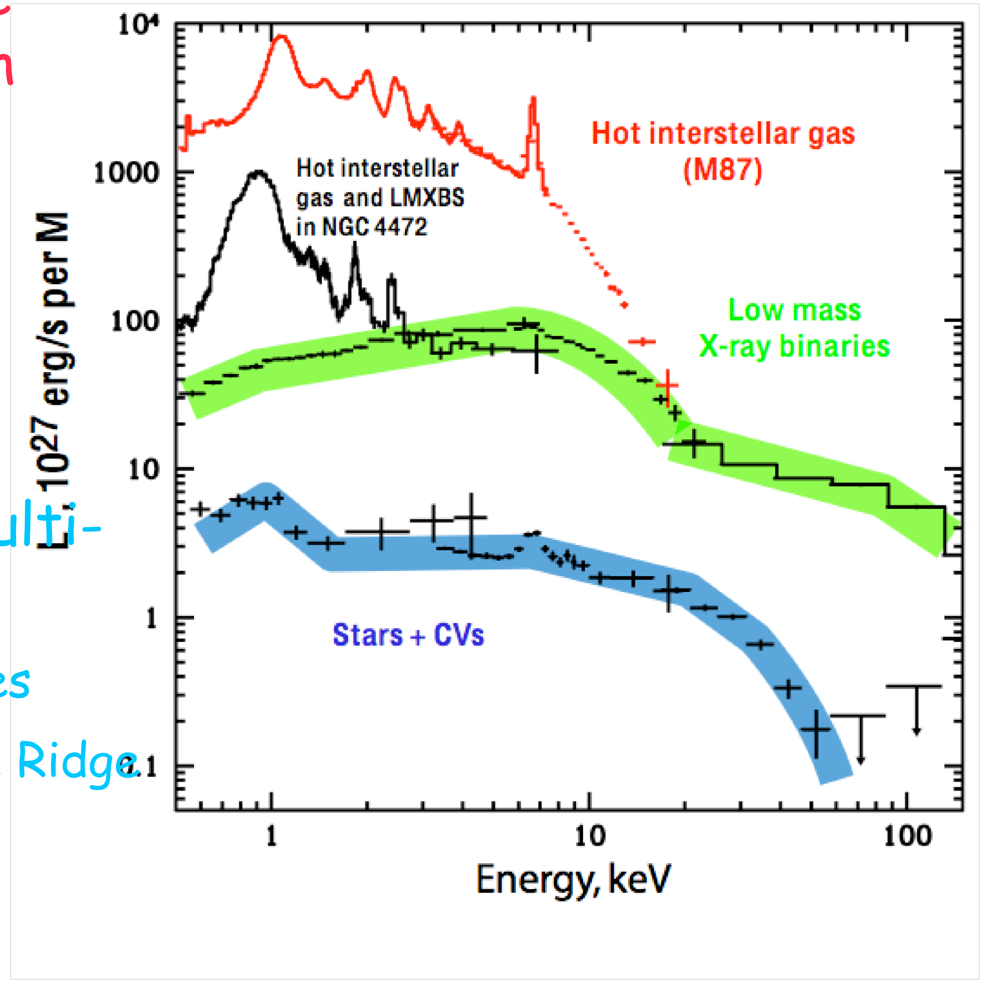
Family of increasing mass, temperature, and luminosity

	E/S0 Galaxies	Groups	Clusters
L_x (ergs/sec)	10^{40-42}	10^{42-43}	10^{43-46}
Gas Temp	0.5-1.0 keV	1-3 keV	2-15 keV
$M_{gas}/M_{stellar}$	0.02	1	5

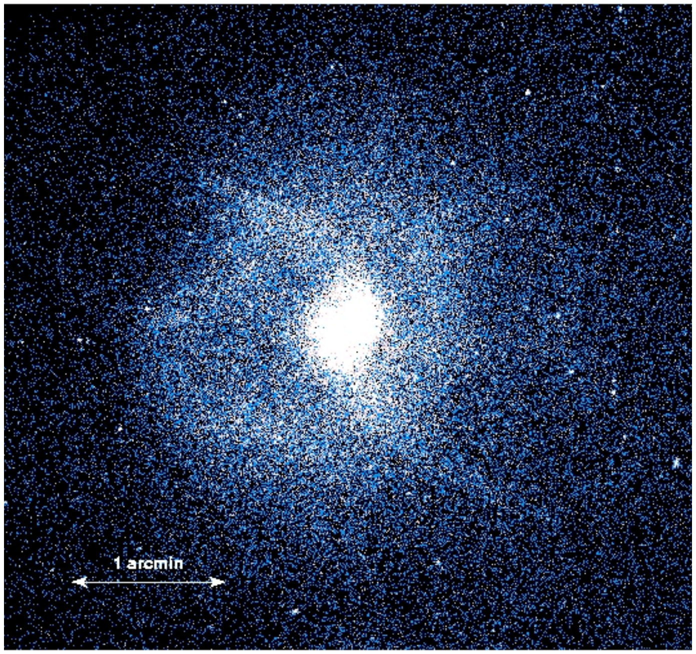
Components of X-ray emission in Galaxies

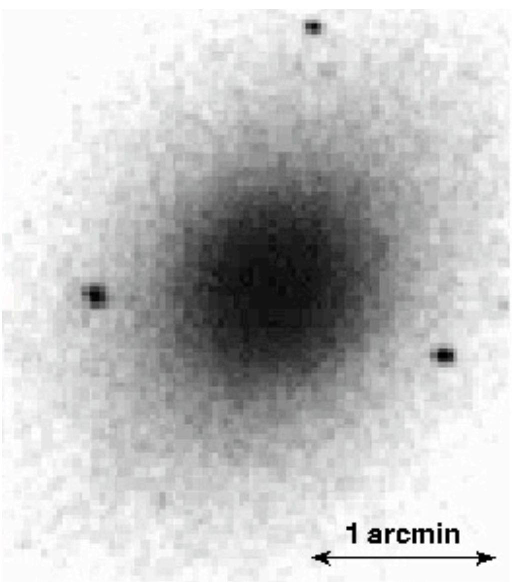
- Massive/luminous early type galaxies ($L_K > 10^{11}$ L_{sun}) - gas rich
  - M_{gas} up to 10^{10} M_{sun}
  - kT_{gas} ~10^7 K
  - Mergers not "dry"
- X-ray binaries & globular clusters
- X-rays from Stars +CV's (multi-component spectrum)
  - Detected in fainter, nearby galaxies
  - Resolved in the Milky Way Galactic Ridge (Revnivtsev et al 2008).
- Low luminosity AGN



Hot X-ray Gas in Galaxies and Clusters - fossil record of AGN activity

N4636





Hot X-ray emitting atmospheres provide "fossil record" of SMBH activity and often the primary evidence of AGN activity

- Observe outburst frequency - common
  >50% clusters (Dunn,Fabian)>30% galaxies
- Measure total power - mechanical (cavities and shocks) >> radiative
- Measure outburst duration and age

- Insight into high redshift universe
  - Growth/formation of galaxies
  - Growth of SMBH
  - Feedback from AGN

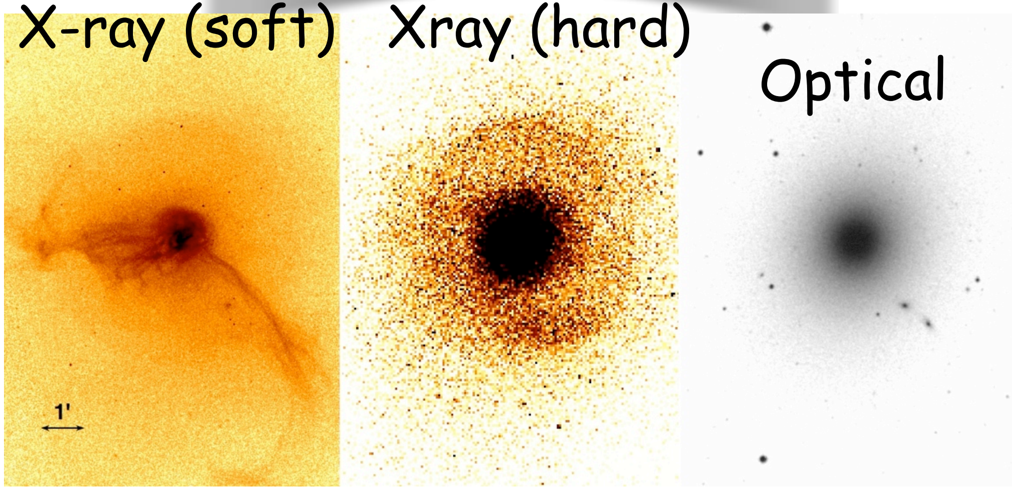
X-ray cluster/group/galaxy studies are key

Two puzzles

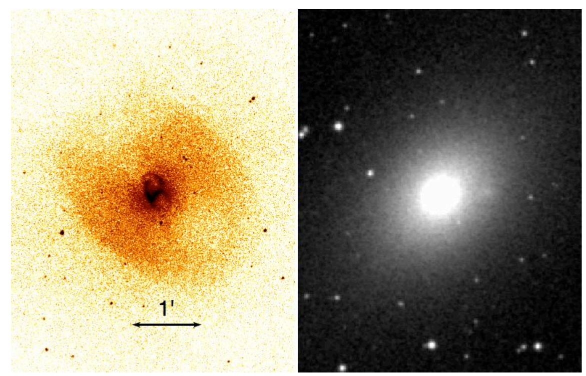
1) Why don't we see cool gas in the core as the X-ray emitting gas radiates in clusters and groups? – the "cooling flow" problem

2) How do red galaxies – ellipticals – prevent star formation? Why don't they form new stars from the mass lost by their own evolving stars?

Shocks and bubbles

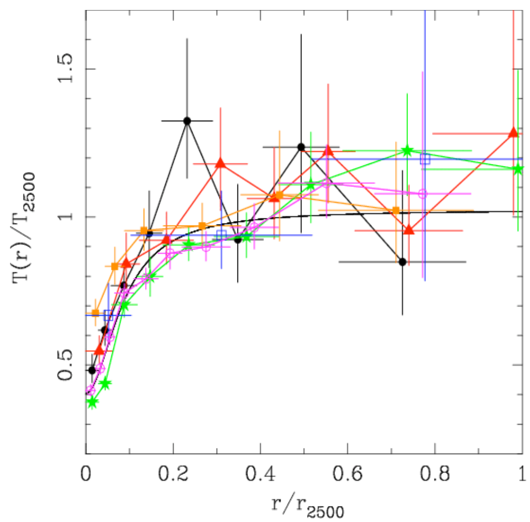


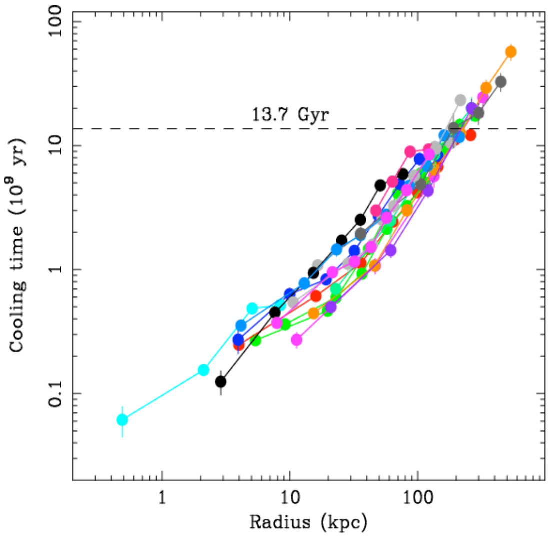
M87 $E_{outburst} \sim 5\times10^{57}$ ergs

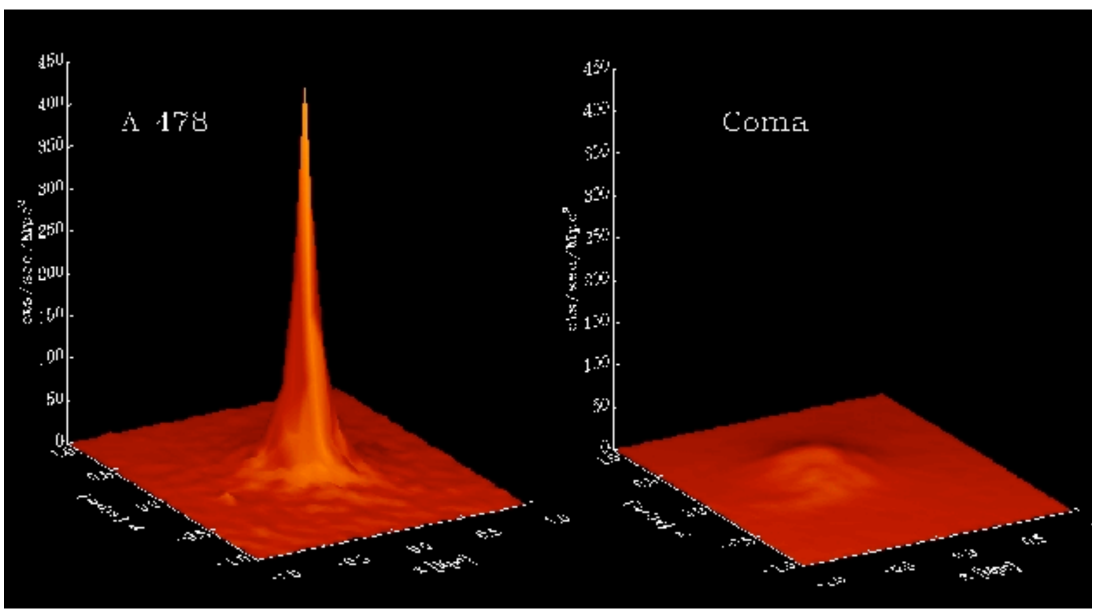


NGC5813 $E_{outburst} \sim 5\times10^{55}$ ergs

Puzzles that outbursts "solve"





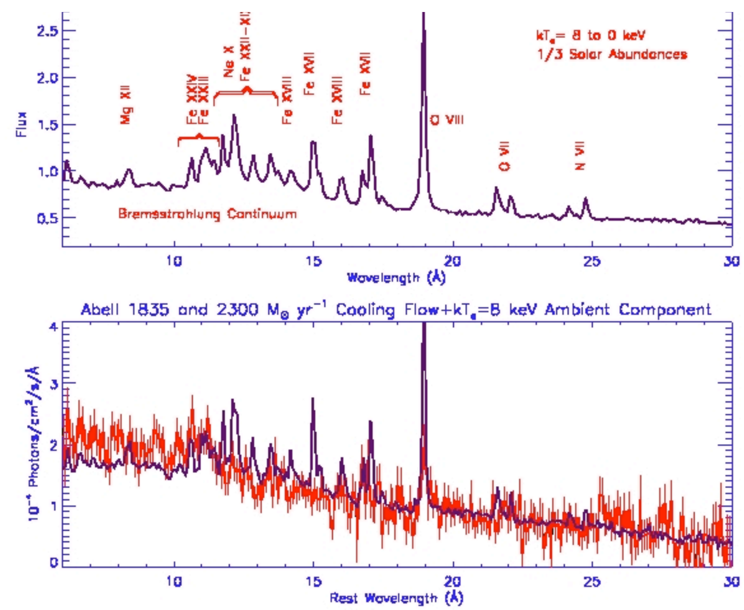


Cooling flow problem

Radiative cooling times are short in cluster cores

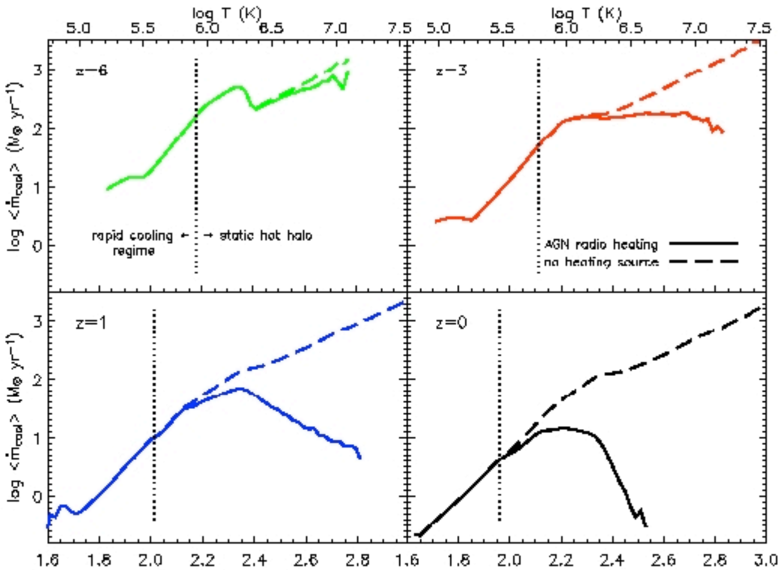
➢Large mass cooling rates, but large amounts of cool gas or SF not found.

AGN outbursts reheat cooling gas



Peterson et al. 2001.

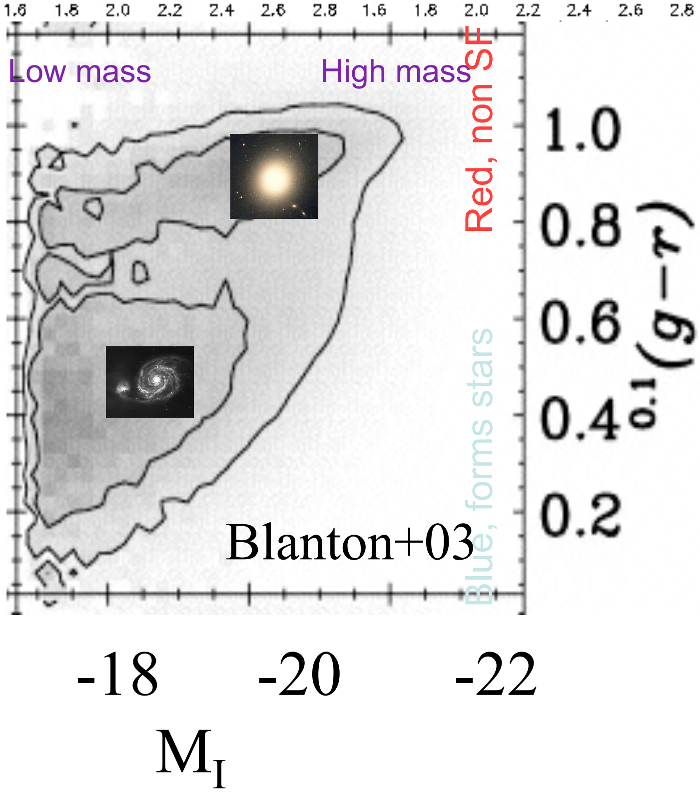
Puzzles that outbursts "solve"



No VERY massive galaxies observed

Simulations produce massive galaxies, unless AGN curtail star formation by heating gas.

Croton et al. 2006



Formation of Red sequence- **Blue Cloud**

Red galaxies have hot gas halos (re)heated by AGN feedback which reduces new star formation.

Red galaxies live in groups/clusters where hot IGM protects them from cold wet mergers.

All large bulge galaxies host a SMBH.

Feedback (black holes + hot gas) and Baseball

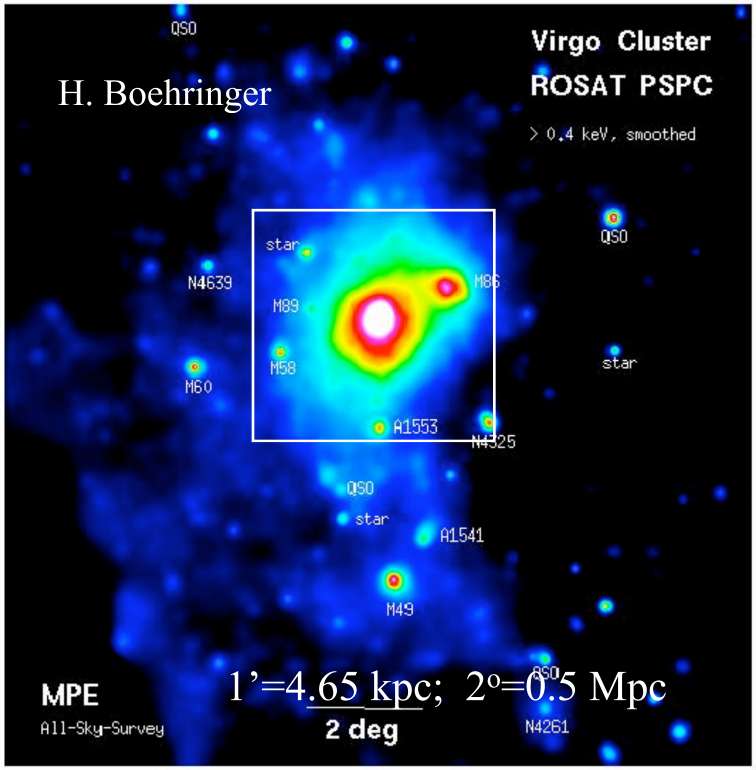
Early type (bulge) galaxy - like a baseball team
Batter = SMBH - sometimes hits the ball (outbursts)
 infrequent
 exact trigger unknown
 different sizes (singles, doubles…home runs, outs)
Pitcher = provides ball/fuel (cooling gas for accretion)
Hot X-ray emitting gas = fielders
 capture AGN output

Fielders are critical
No fielders (no gas)
==> No energy capture
==> No feedback

Hot Gas Provides archive of AGN activity

(from Bill Forman)

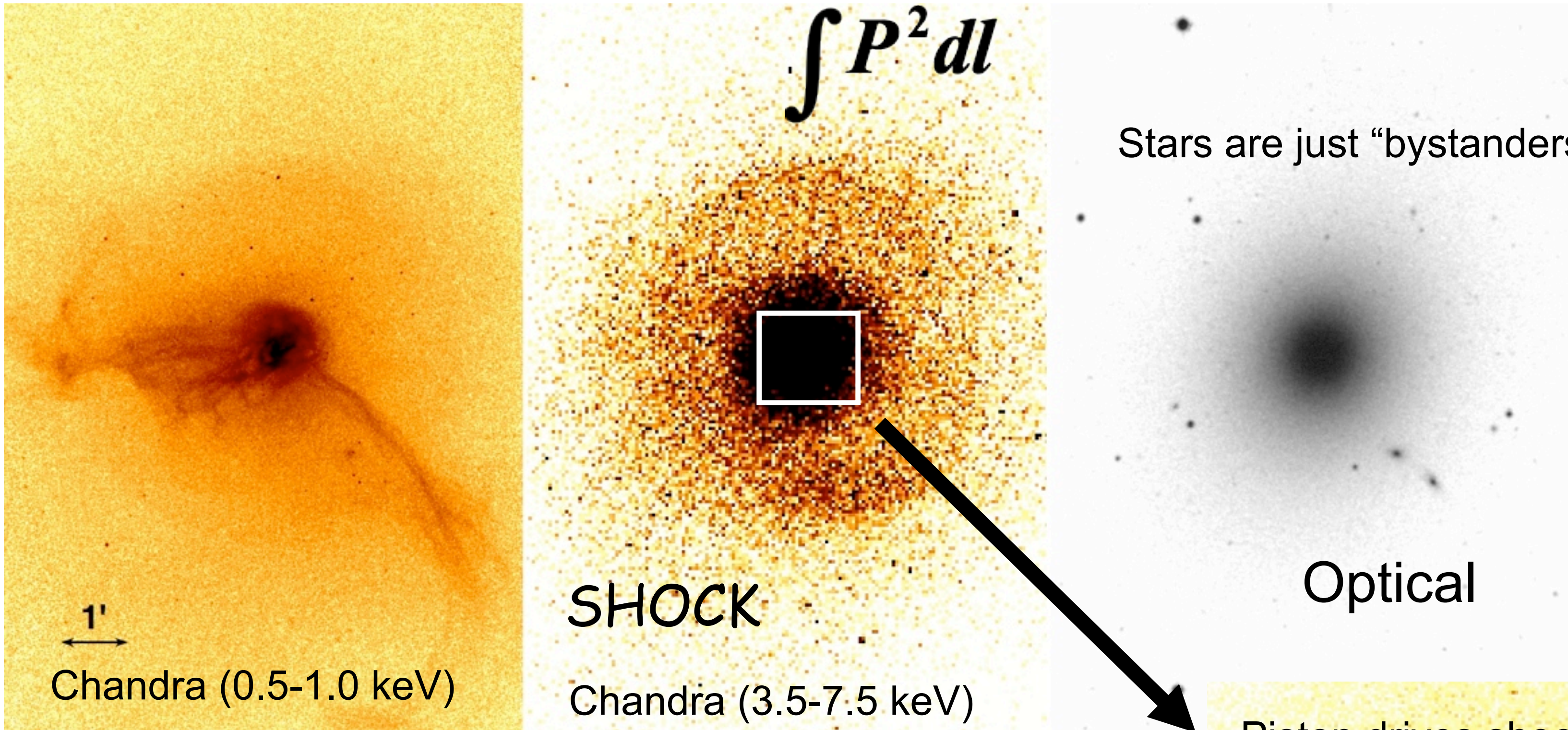
M87 - Virgo Cluster



M87 is central dominant galaxy

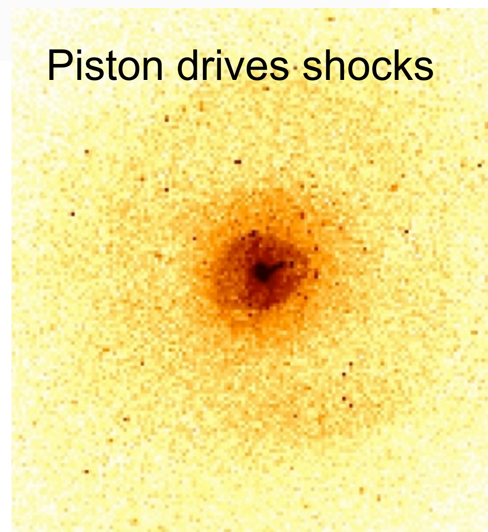
- M87 is 50 x more X-ray luminous than NGC4472
- NGC4472 (a bit) optically more luminous than M87
- M87 hosts $6 x 10^9 M_{sun}$ SMBH and jet
- Classic cooling flow (24 M_{sun}/yr)
- Ideal system to study SMBH/gas interaction

Classical Shock in M87



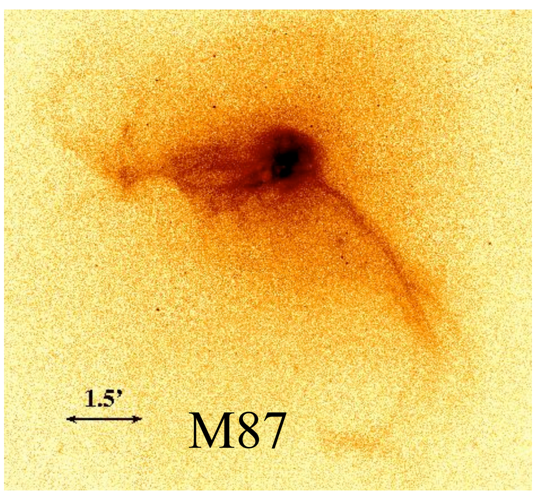
23 kpc (75 lyr)

- Black hole = 6.6x10^9 solar masses (Gebhardt+11)
- SMBH drives jets and shocks
- Inflates “bubbles” of relativistic plasma
- Heats surrounding gas
- Model to derive detailed shock properties

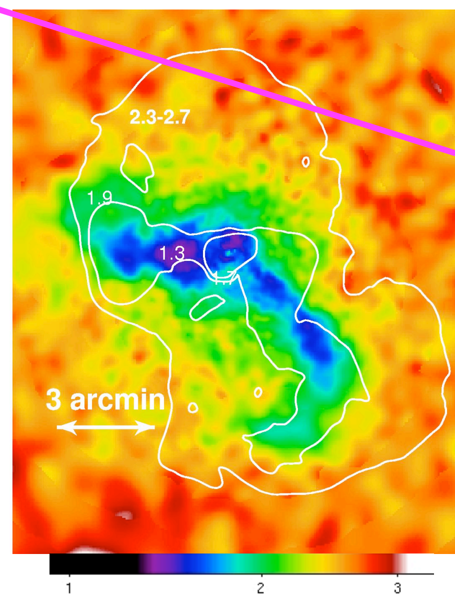


Chandra-XMM-VLA View

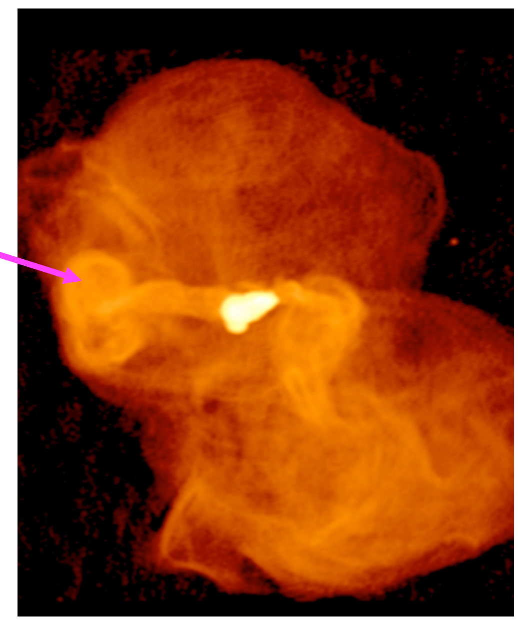
- Two X-ray "arms"
- X-ray (thermal gas) and radio (relativistic plasma) "related"
- Eastern arm - classic buoyant bubble with torus i.e., "mushroom cloud" (Churazov et al 2001)
  - XMM-Newton shows cool arms of uplifted gas (Belsole et al 2001; Molendi 2002)
  - CLASSIC BUBBLE
  - **With torus**



Chandra   Forman et al



XMM Belsole et al;Molendi

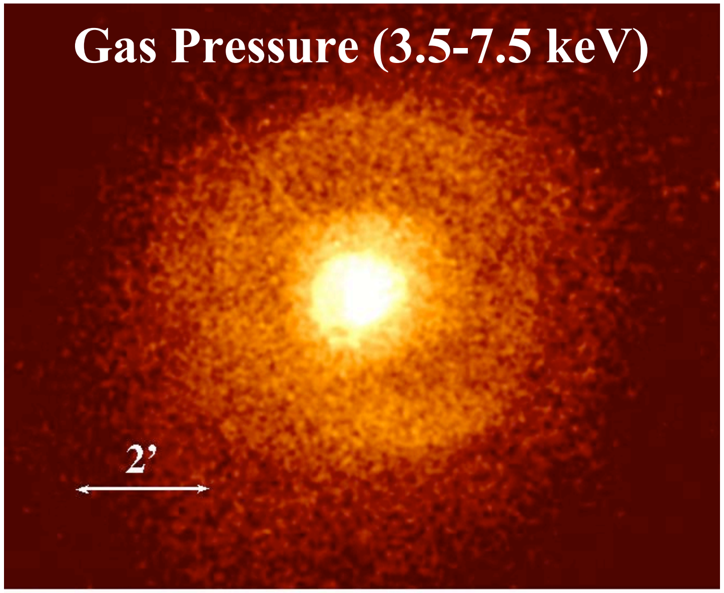


VLA Owen et al.

M87 Outburst Model

Detect shock (X-ray) and driving piston (radio)

Classical (textbook) shock M=1.2 (temperature and density independently)



Outburst Model

Age ~ 12 Myr (cavity rise times)

Energy ~ 5×10^{57} ergs

Bubbles 50%

Shocked gas 25%

(25% carried away by weak wave)

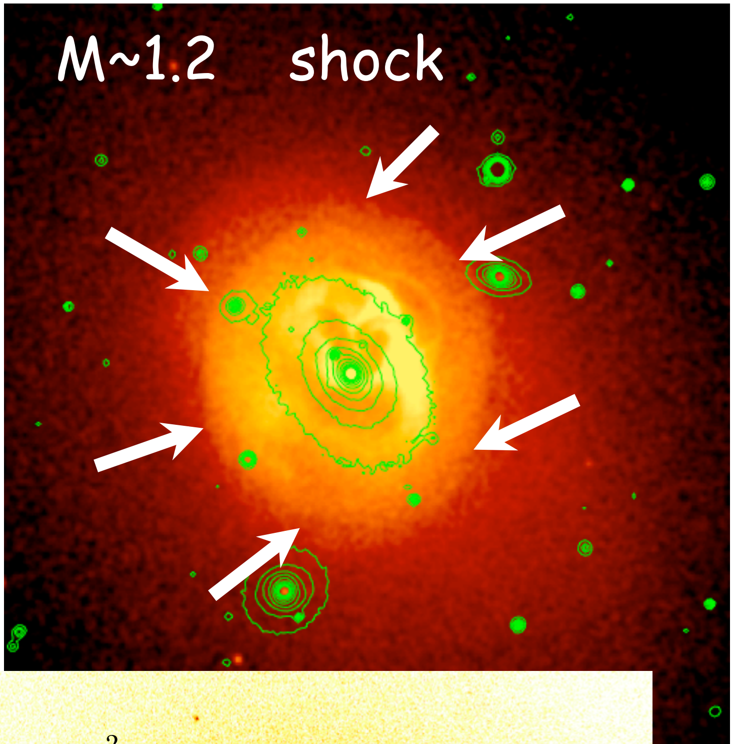
Outburst duration ~ 2-5 Myr

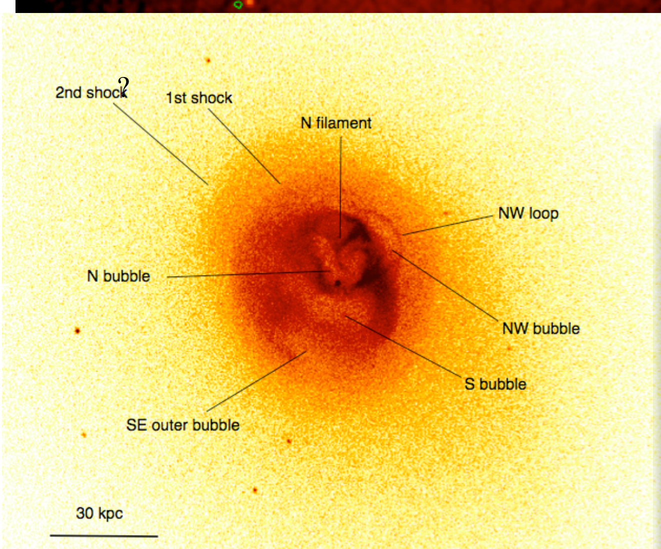
Outburst energy "balances" cooling (few 10^{43} erg/sec)

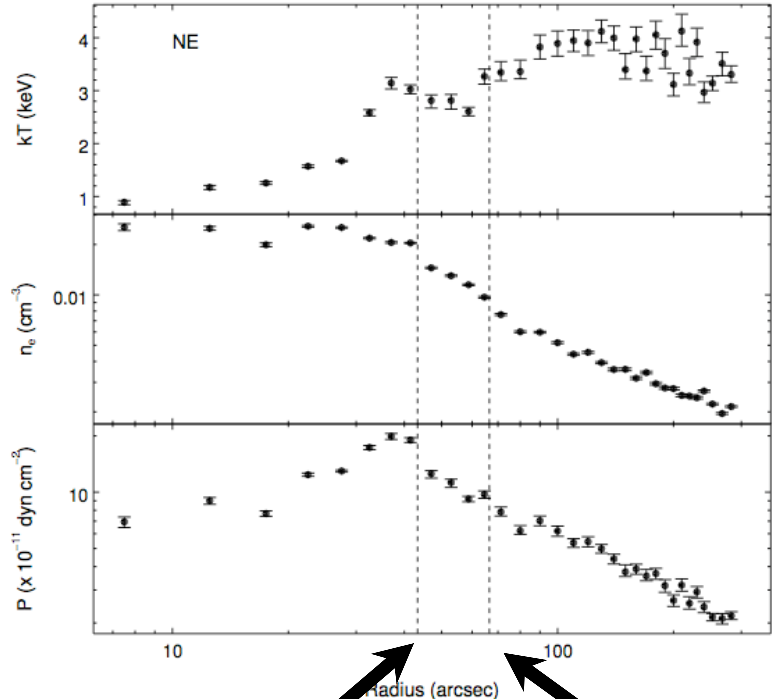
AGN outbursts - key to feedback in galaxy evolution, growth of SMBH

Forman et al 2007, 2012

Abell 2052 - Blanton+11



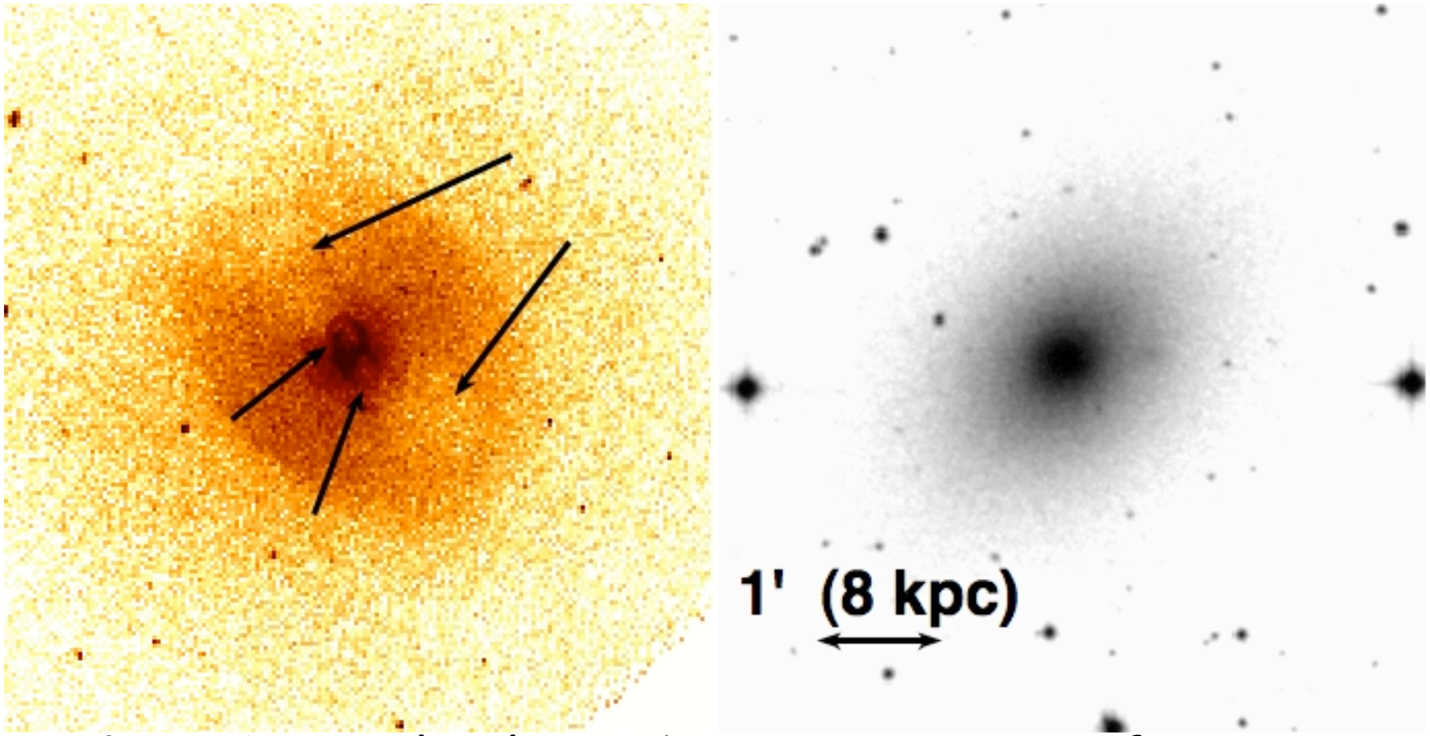




M~1.17 shock
nearly spherical
consistent density/
temperature jumps

Second
feature
likely cold
front

AGN Outbursts in Groups and Galaxies

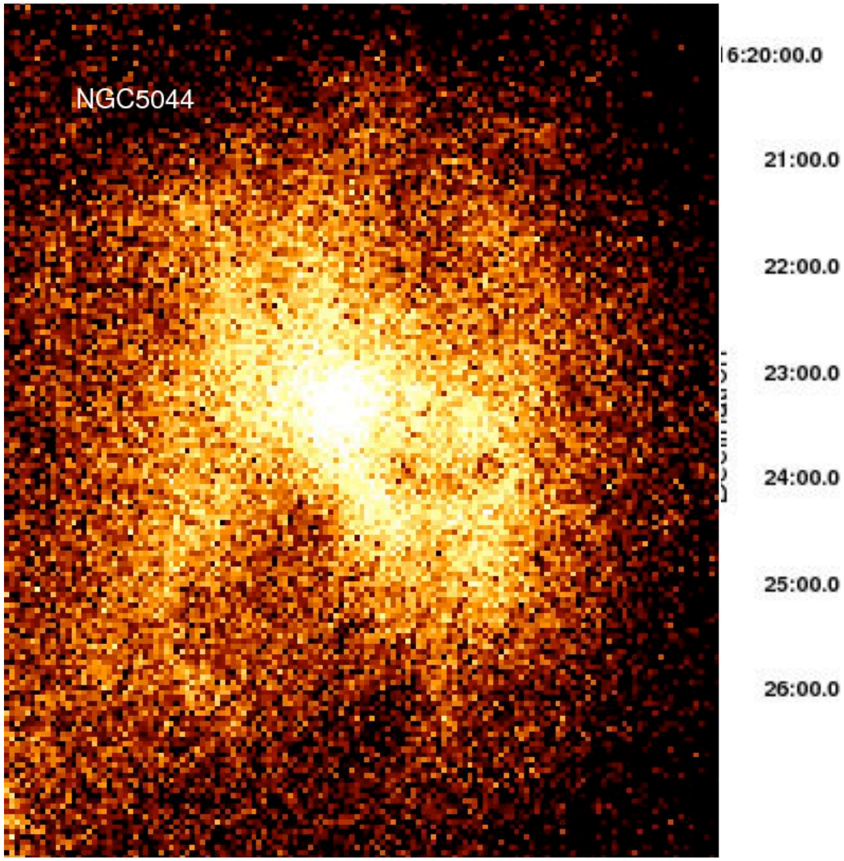


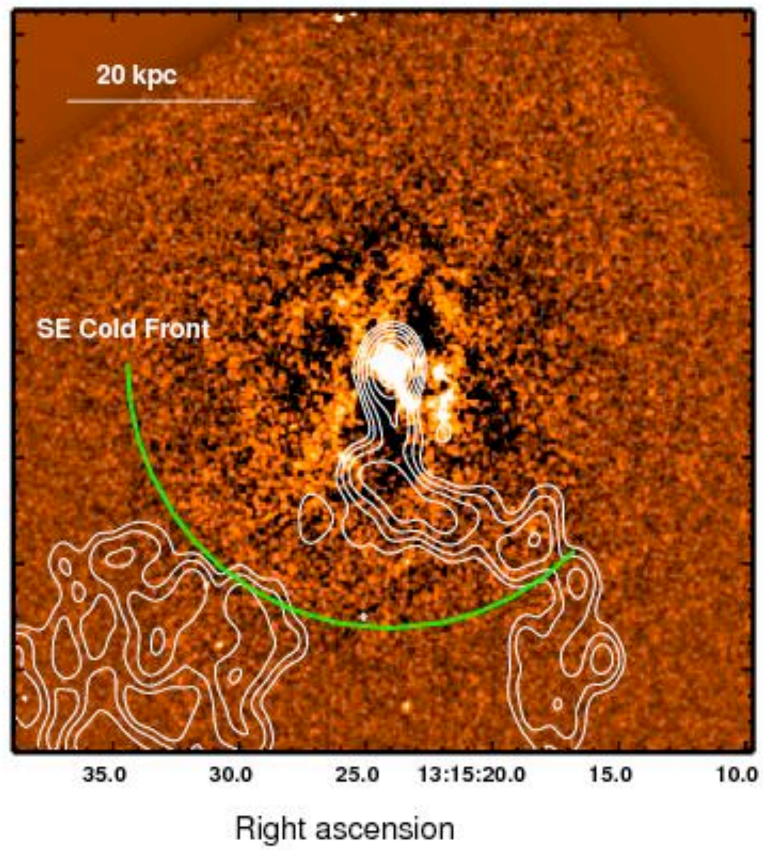
NGC5813 Multiple outbursts - 3 sets of cavities
plus sharp outer edges from shock (Randall et al 2011)

Shock velocities (M ~1.7 (inner) & 1.5 (middle)).
~10^{56} ergs to produce inner cavities, 4 10^{57} ergs middle cavities

Outburst ages 3, 20, 90 10^{6} yrs

NGC5044 -- several small cavities (David et al. 2009)



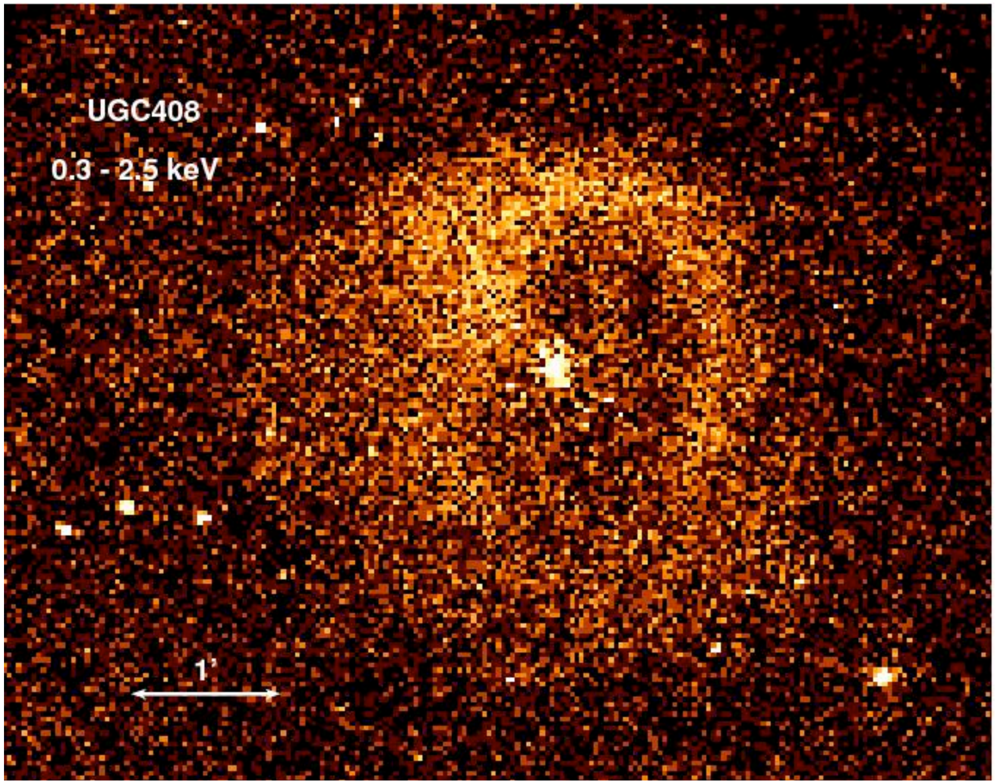


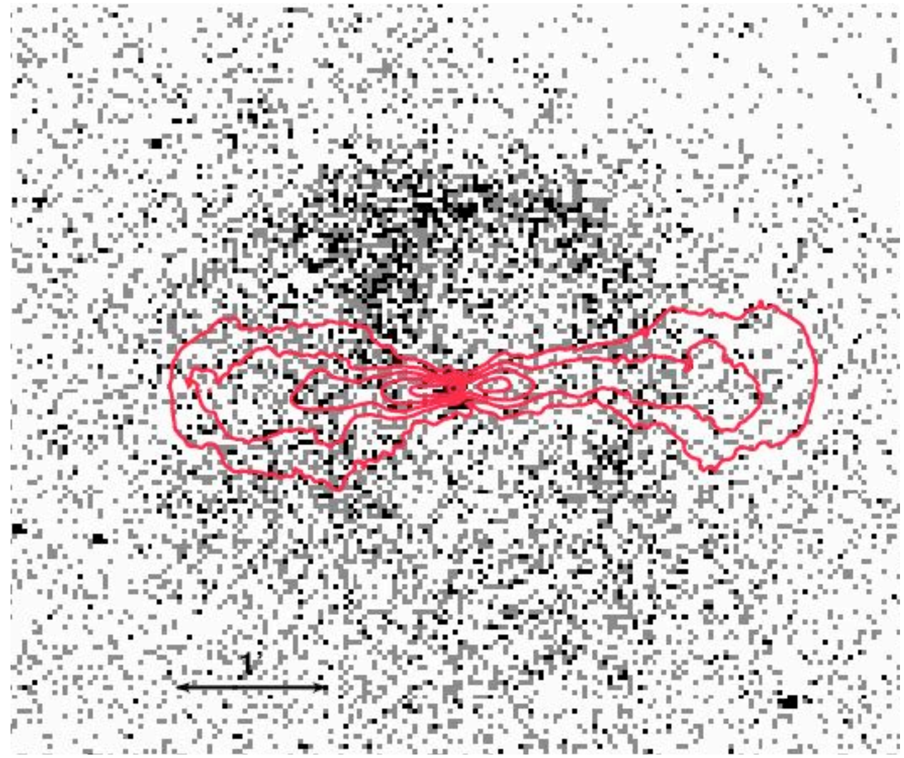
Mechanical power from largest cavity more than enough to balance radiative cooling

Chandra unsharp masking with GMRT contours. Small cavities are radio quiet.

Mechanical power from small cavities (few kpc in size) ~ half the total radiative cooling in 10 kpc

UGC408 (NGC193)



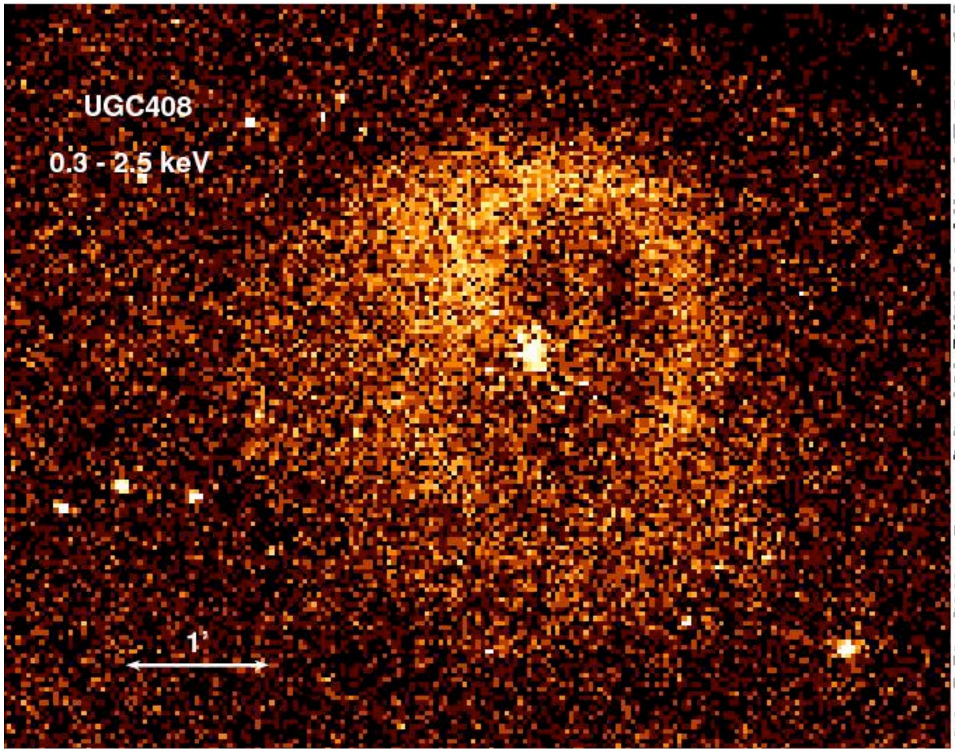


X-ray emission from nucleus and 20 kpc (radius) ring

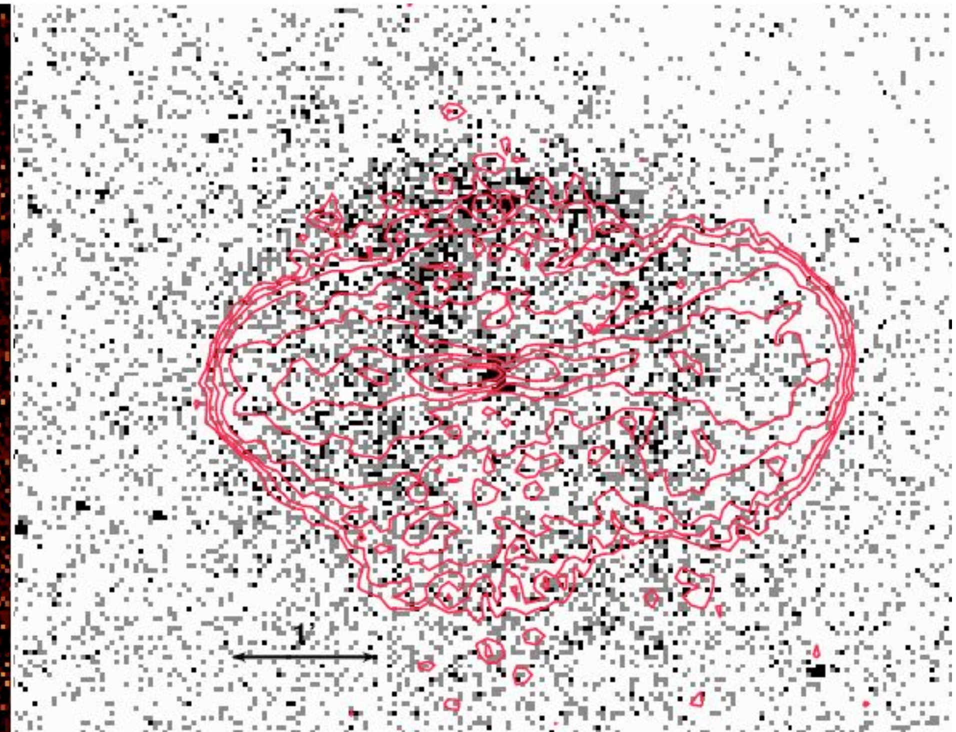
UGC408 Chandra with 1.4 GHZ VLA

Radio emission usually fills cavities???

UGC408 - two outbursts?

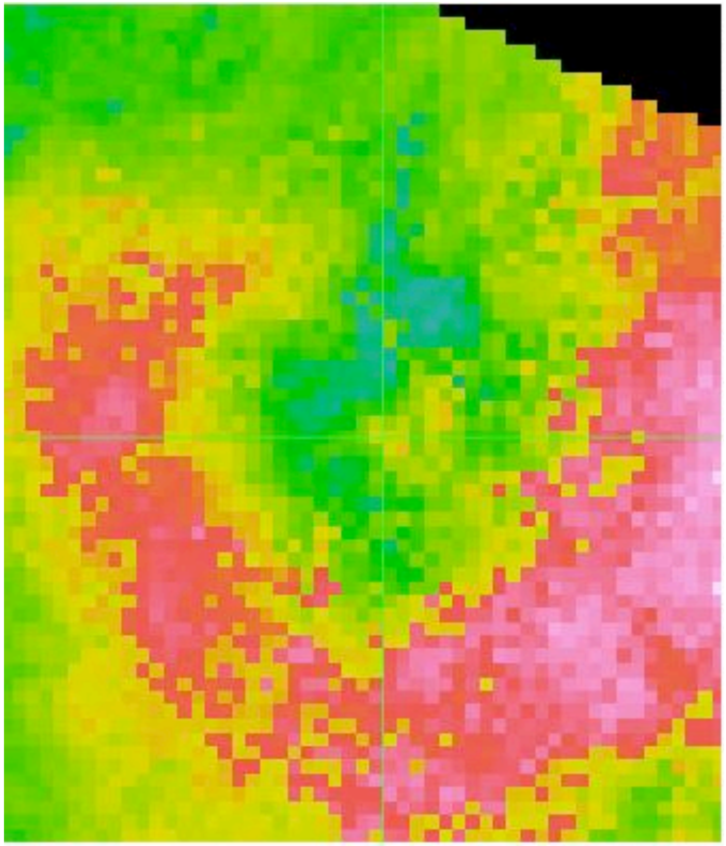


X-ray emission from nucleus and 20 kpc ring.

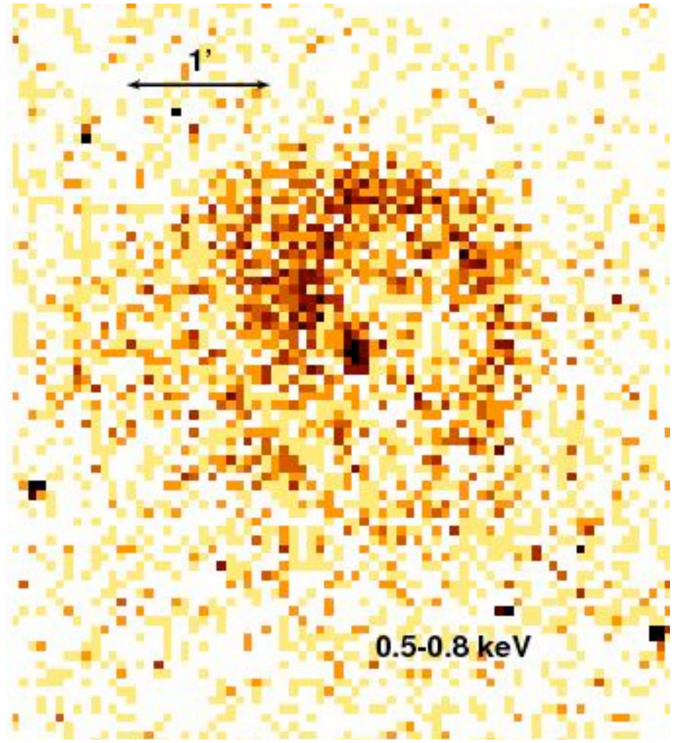


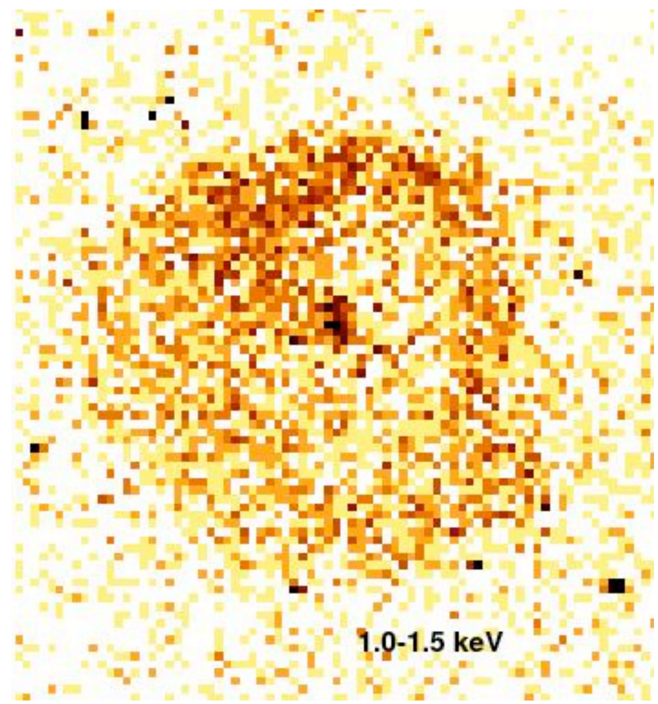
UGC408 Chandra with 610 MHZ GMRT (from S Giantucci) Probably two outbursts

UGC408 - two outbursts and a shock

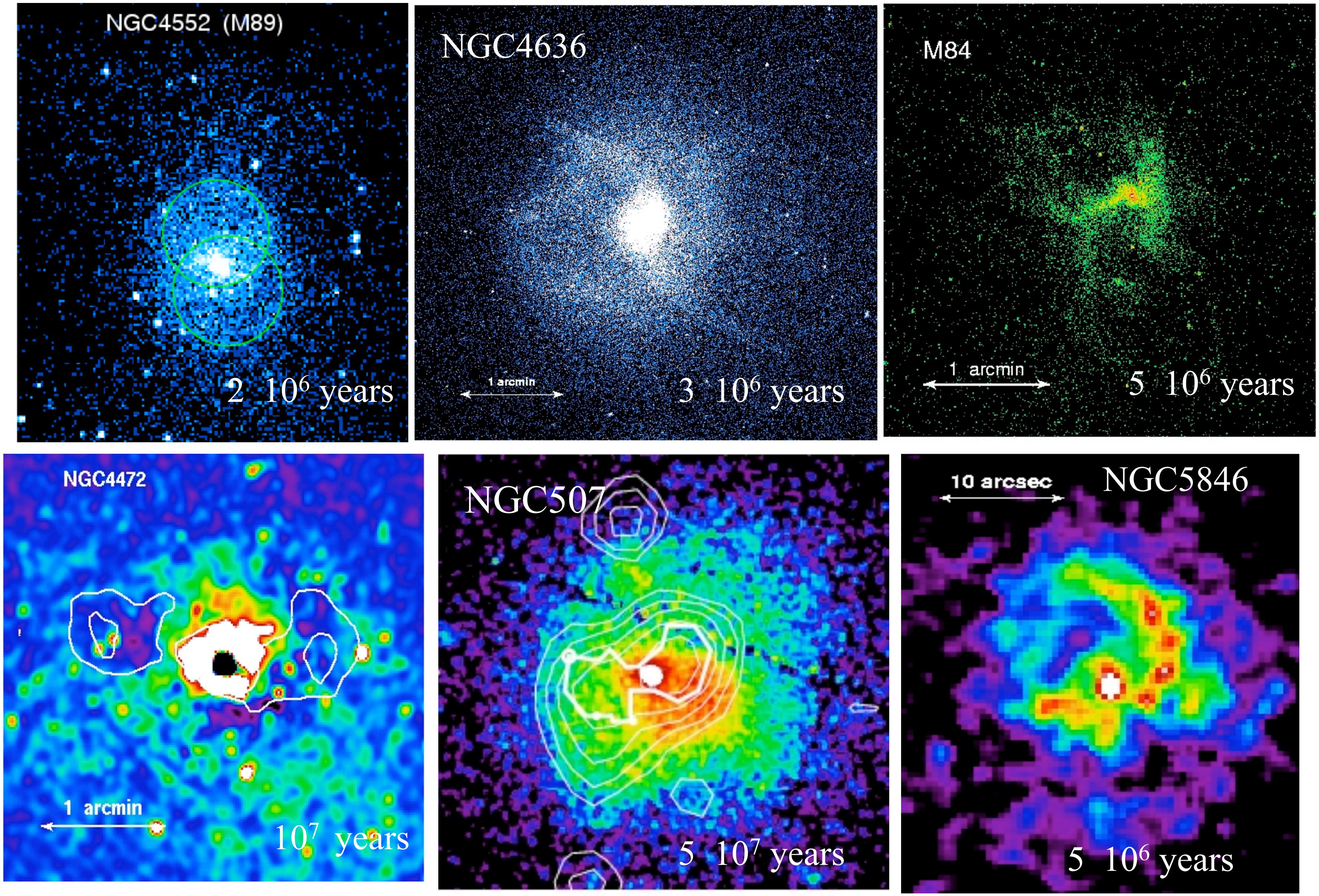


Hotter (1 keV red regions) in southern, fainter part of rim in soft X-rays, brighter in hard X-rays - heated by shock



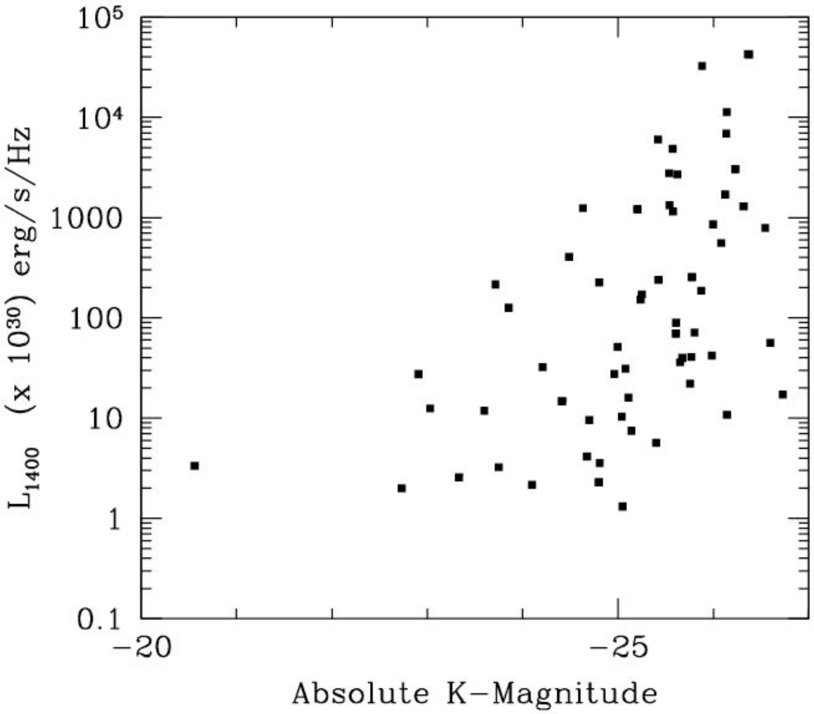


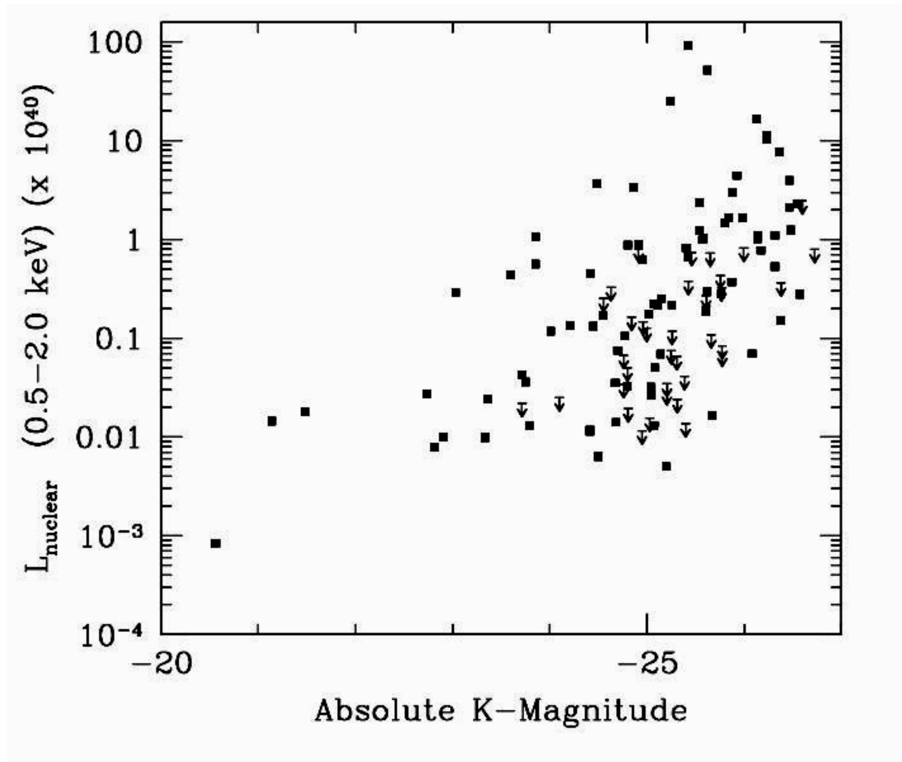
Normal massive Early-type galaxies – 30% have cavities



Outburst energy ~10^{55} - 10^{58} ergs age 2 x 10^6 - 10^8 years

SMBH X-ray and Radio Luminosities in normal Early type Galaxies

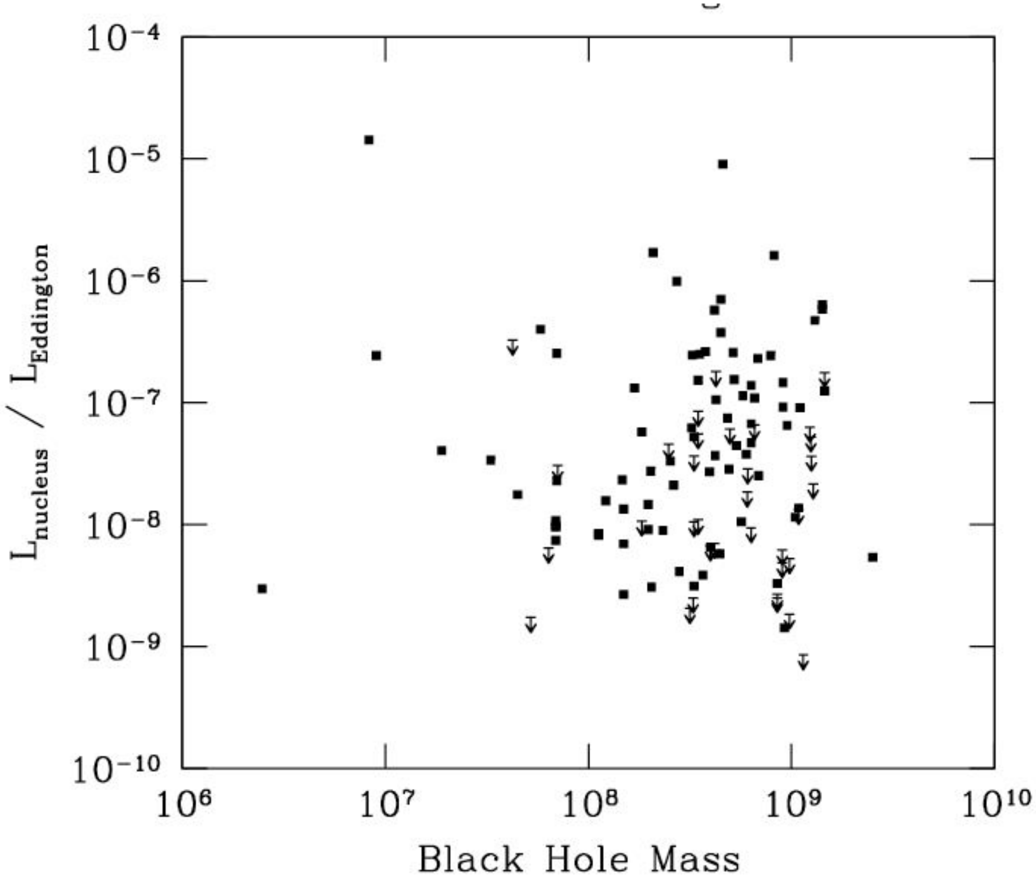




Nuclear X-ray emission detected in ~80% of SMBHs in galaxies with gas
Radio emission (1400 MHz) detected in ~80% of gas rich galaxies
(only three galaxies brighter than -25 not detected in radio (or X-ray)

See Sravani Vaddi's poster

Eddington ratios for nuclear X-ray emission in normal early type galaxies

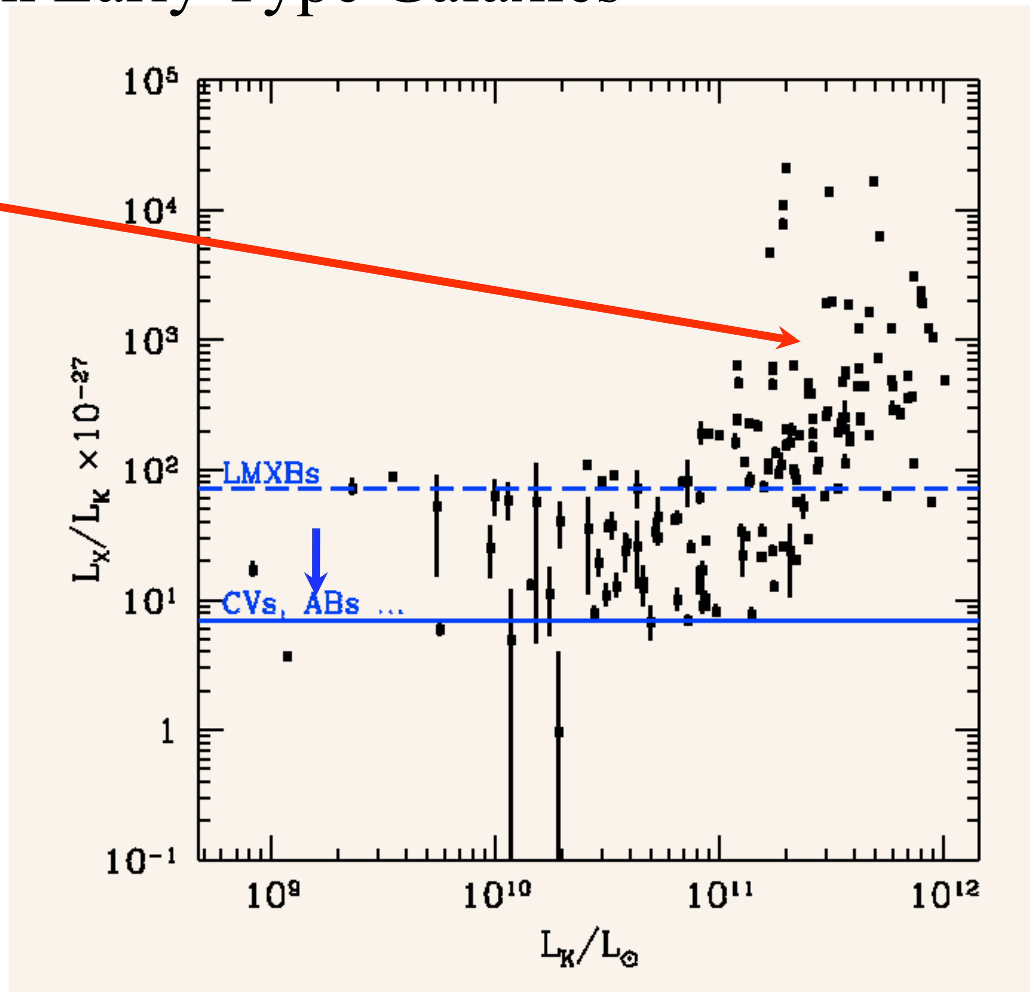


Eddington ratios ~10^{-5} to 10^{-9} in these low luminosity AGN

(for QSO's ~0.3) Energy is mechanical, not radiative for LLAGN

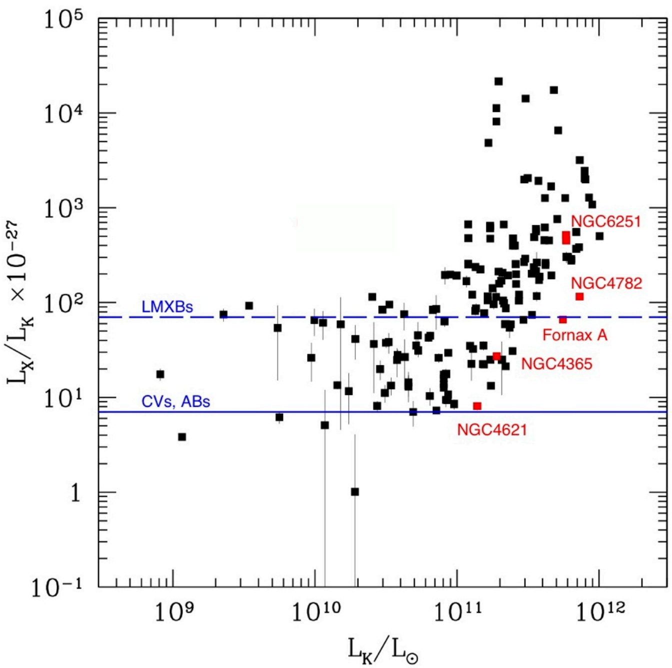
X-ray Emission in Early Type Galaxies

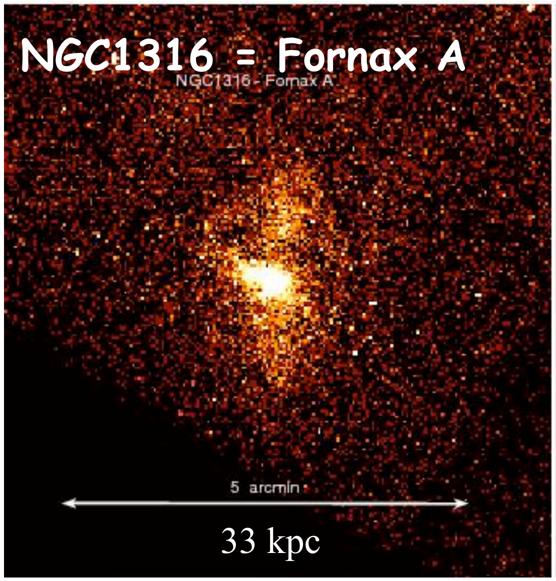
- Cavities
  - Common 30% of luminous galaxies; 50% in clusters with cooling cores)
  - power sufficient to balance cooling (Nulsen+09)
- AGN/SMBH
  - ~80% detected in radio/X-ray (see also Dunn+10 for clusters)
  - Radiatively weak - radiated power < 10^{-3} of mechanical power
- Wide range in L_X at fixed L_K - environment (group) or powerful outburst disrupting atmosphere (e.g., Fornax A)

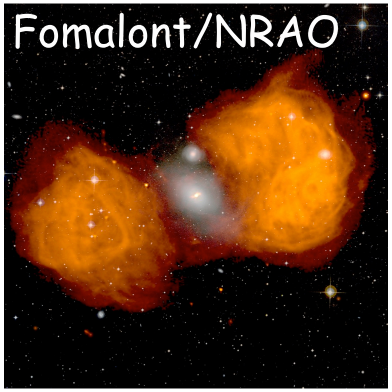


Jones+12 - 150+ galaxies

Massive SMBH, with enough fuel can disrupt galaxy atmospheres - e.g., Fornax A = NGC1316



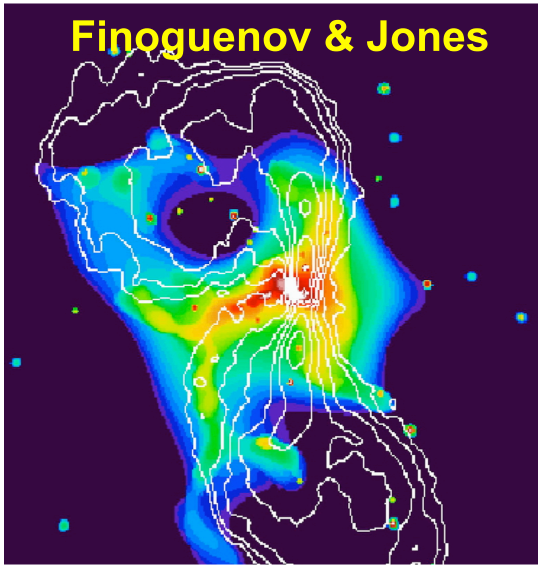


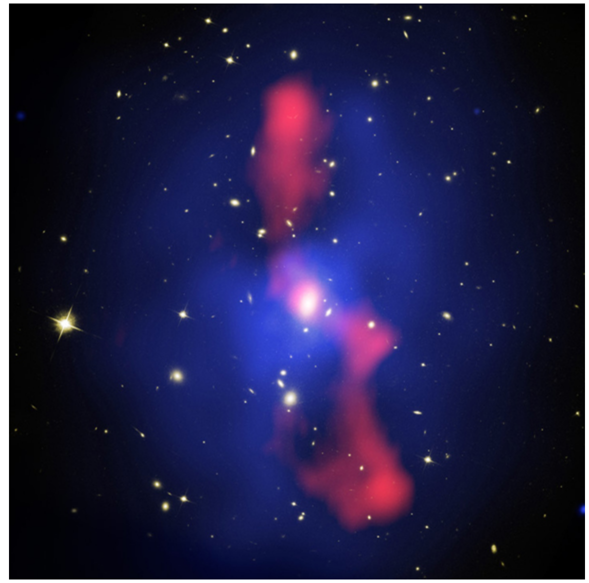


Scatter in L_X-opt mag relation is partly due to gas removal and partly due to environment (galaxies in the centers of "groups")

- Outskirts of Fornax cluster (>1.4 Mpc from NGC1399)
- L_{nuc}~$2x10^{42}$ erg/s
- Gas/dust/disturbed optical morphology (e.g., Schweizer81, Mackie/Fabbiano98)
- likely merger driven outburst
- Massive SMBH is willing and able to disrupt atmosphere given sufficient fuel; outburst power ~ $5x10^{58}$ ergs (Lanz+10)

M84 galaxy | Perseus cluster | MS0735 cluster





M84 galaxy	Perseus cluster	MS0735 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

Very powerful outflows,
very little radiation from the AGN

Churazov et al. 2005 MNRAS …switching from very bright to very dim

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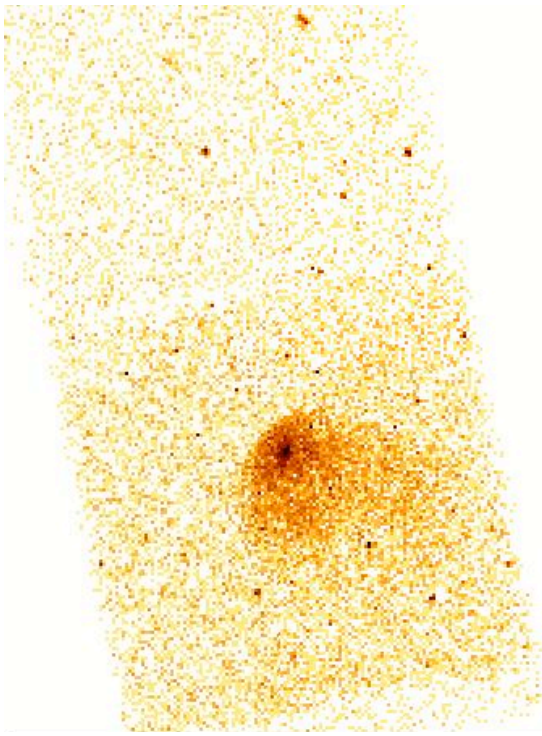
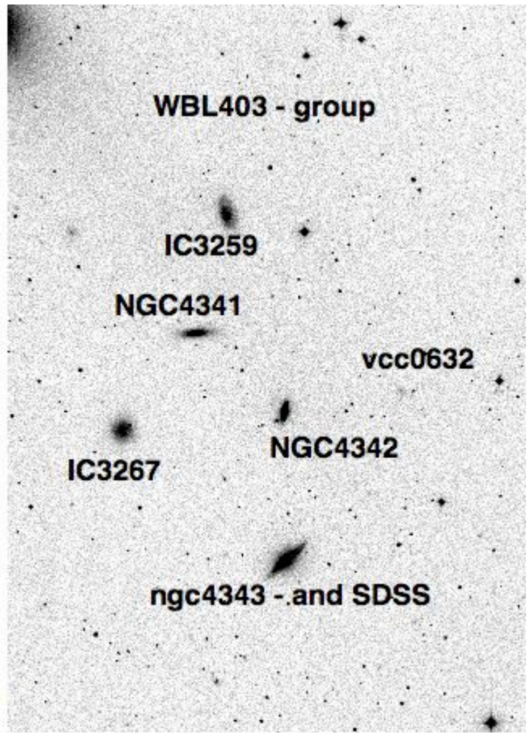
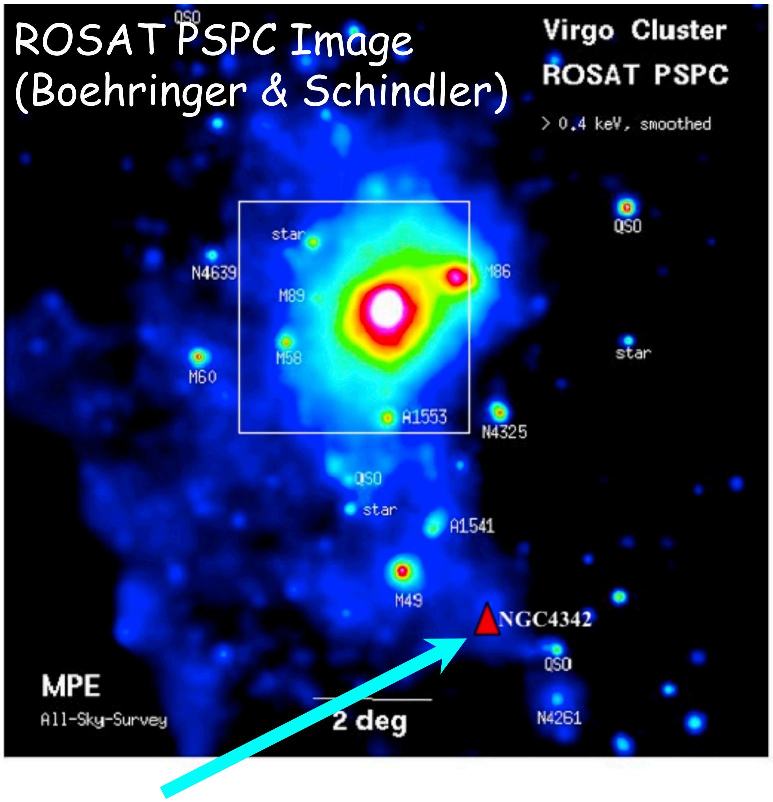


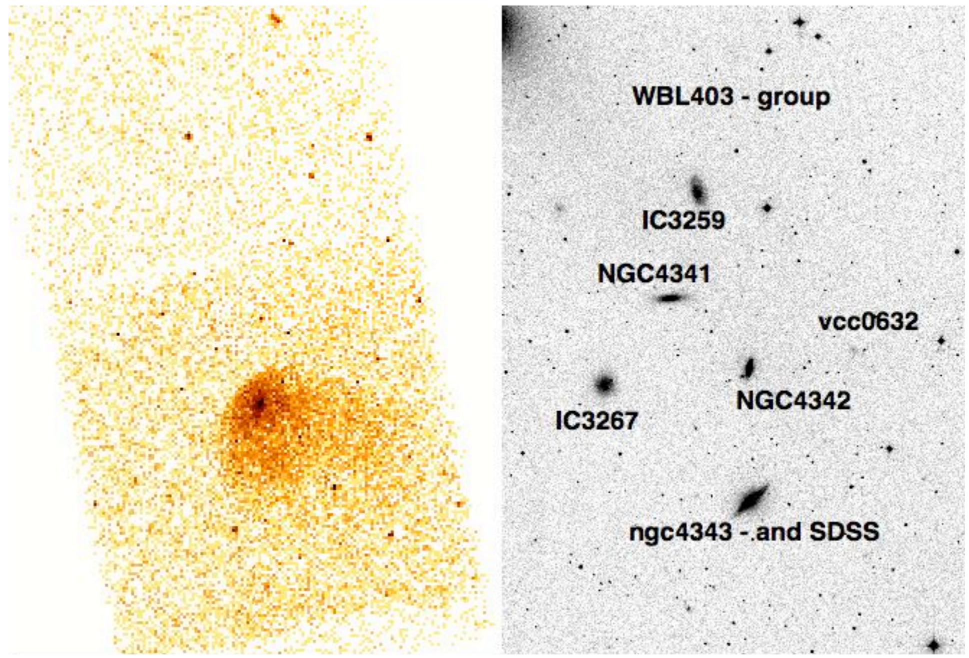


NGC4342

Optically faint, gas rich galaxies - NGC4342



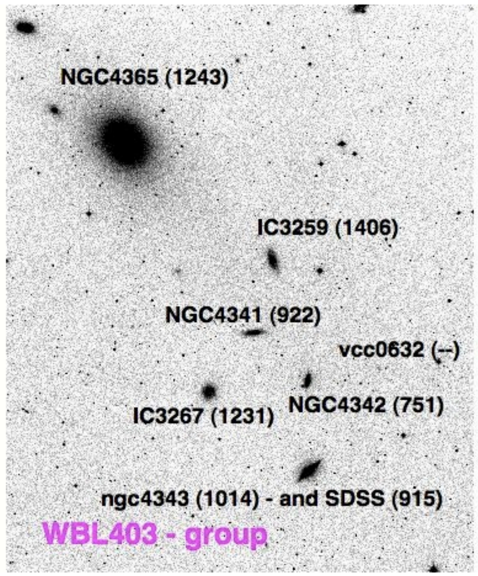
NGC4342 beyond r_{200} from M87
Only ~0.5 Mpc from NGC4472 (M49)
Virgo gas distribution - elongated N-S

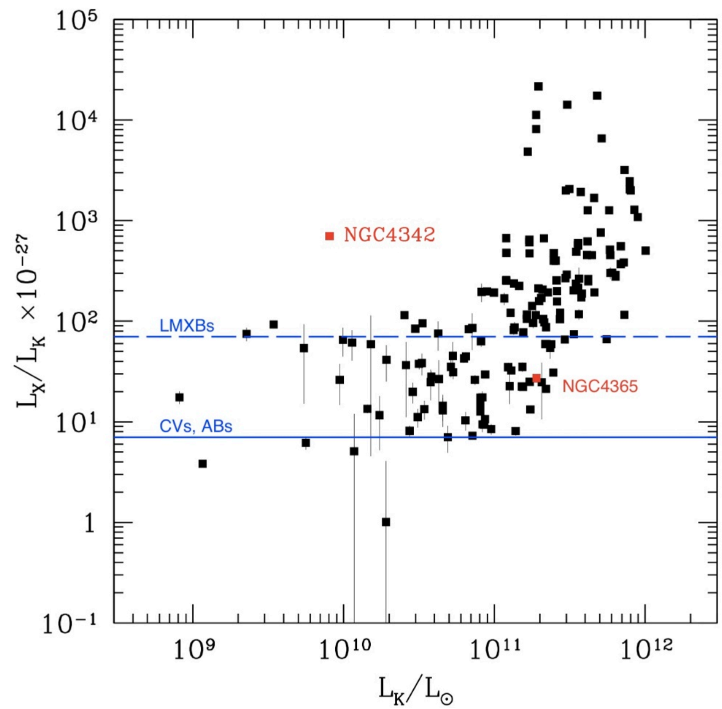


Gaseous filament in Virgo outskirts?
Falling into NGC4365 halo (23 Mpc)

Ram pressure stripping

Optically faint, gas rich galaxies - NGC4342





- S0/E7 galaxy
- 5.25 deg from M87
- 1.46 Mpc in projection
- r_{200} = 1.3 Mpc for M87
- cz=751 km/s
- M_{BH} ~ 3×10^8 M_{sun} (Cretton & van den Bosch 1997)
- high velocity dispersion 252 km/s

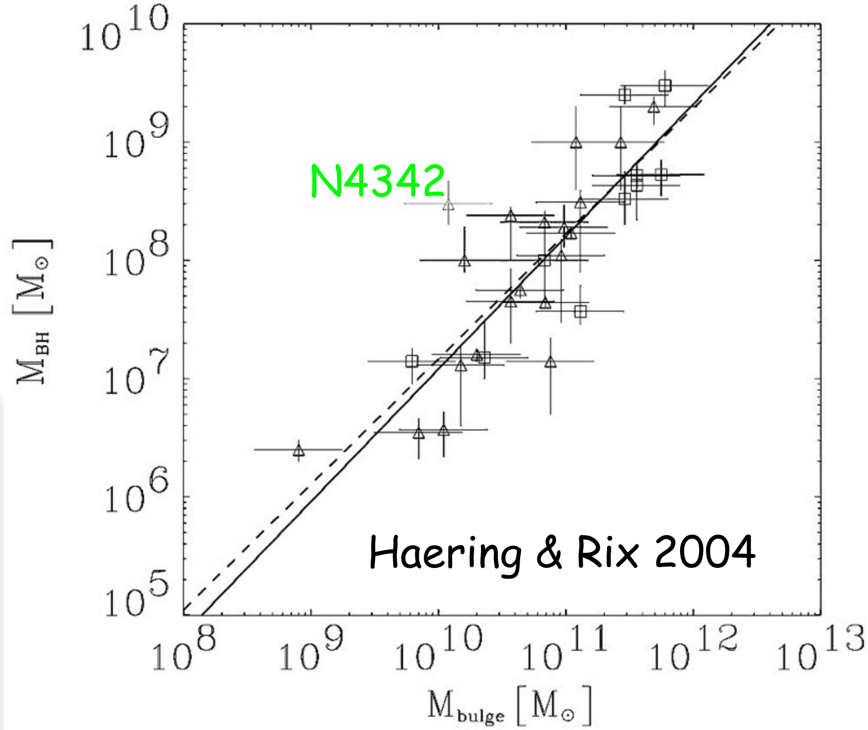
- Thermal emission
  - kT=0.58±0.02 keV
  - M_{gas} ~ 5×10^7 M_{sun}
- Mach ~ 1.5 (from X-ray analysis)
- External medium detected
  - kT=1.1-1.2 keV

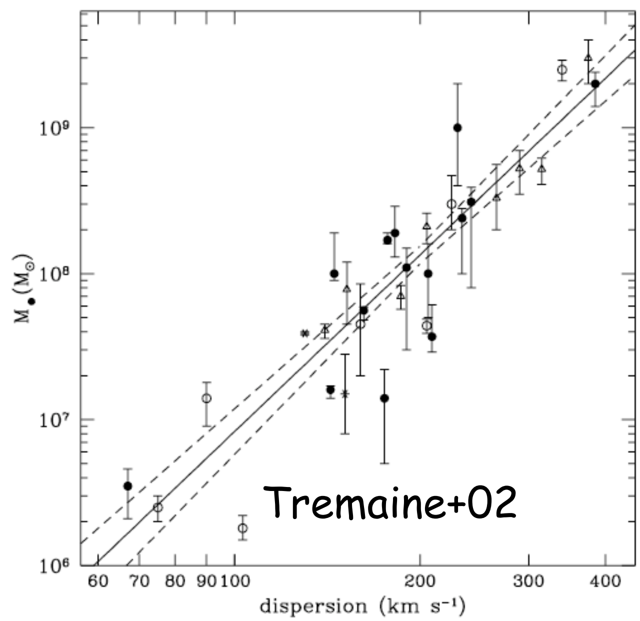
A. Bogdan et al. (2012)

M_{bulge} is too small (or M_{BH} is too large)

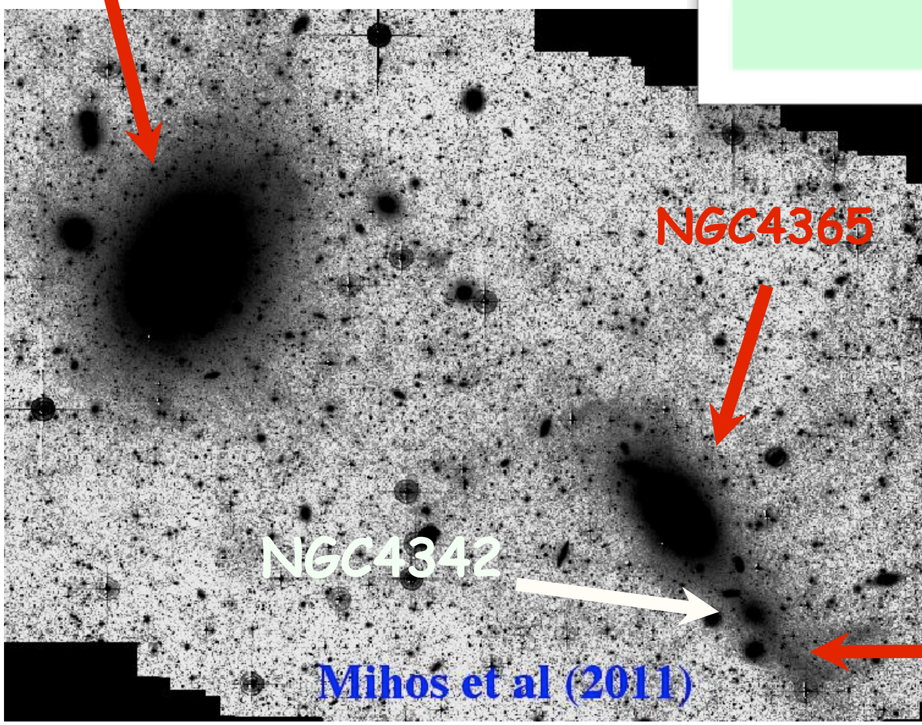
But M_{BH} - velocity dispersion is "normal" suggests that it is the stellar mass that is a problem

M_{halo} is likely large as expected for a galaxy with a large velocity dispersion AND from presence of external gas



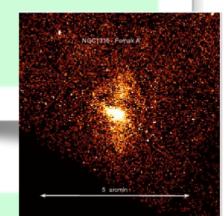


WHAT IS NGC4342?



- Detect hot corona around NGC4365
- NGC4342 is entering the NGC4365 group for the first time
- NGC4342 has a massive dark matter halo to hold hot gas

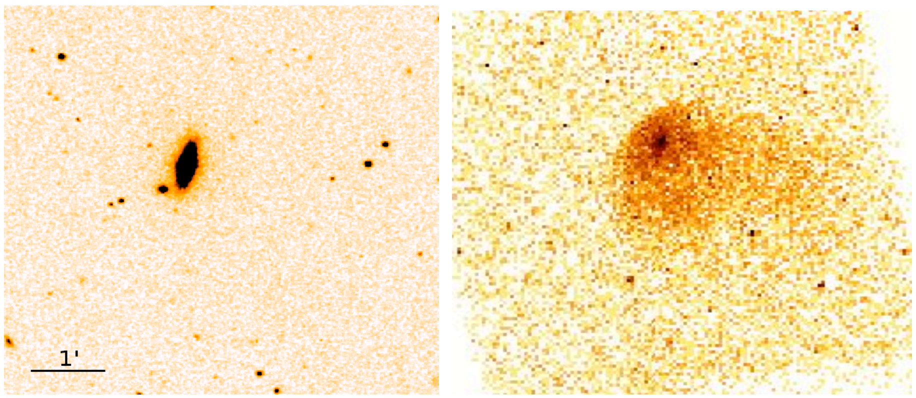
Extra energetic SMBH terminates star formation (recall Fornax A)



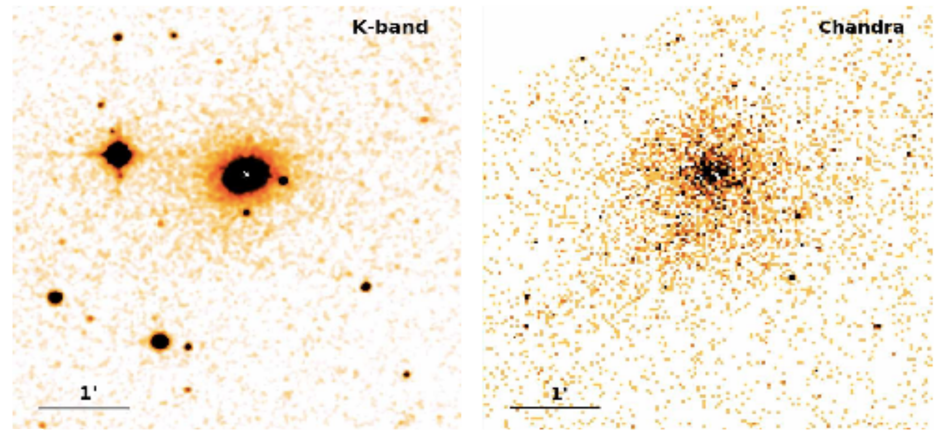
SMBH can grow BEFORE stellar bulge

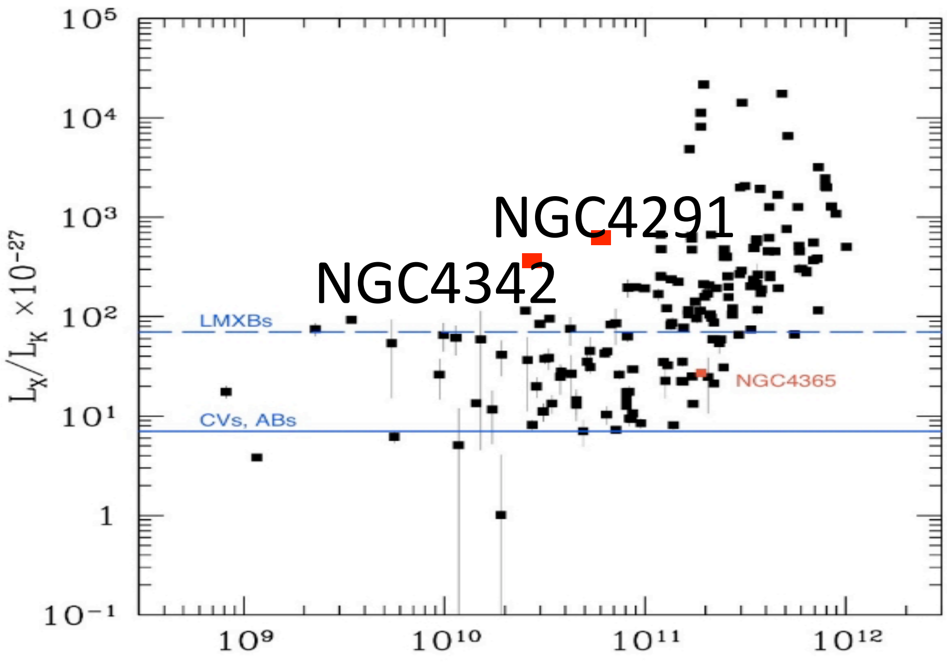
Hot Gas Halos in Optically Faint Galaxies

N4342 - Chandra

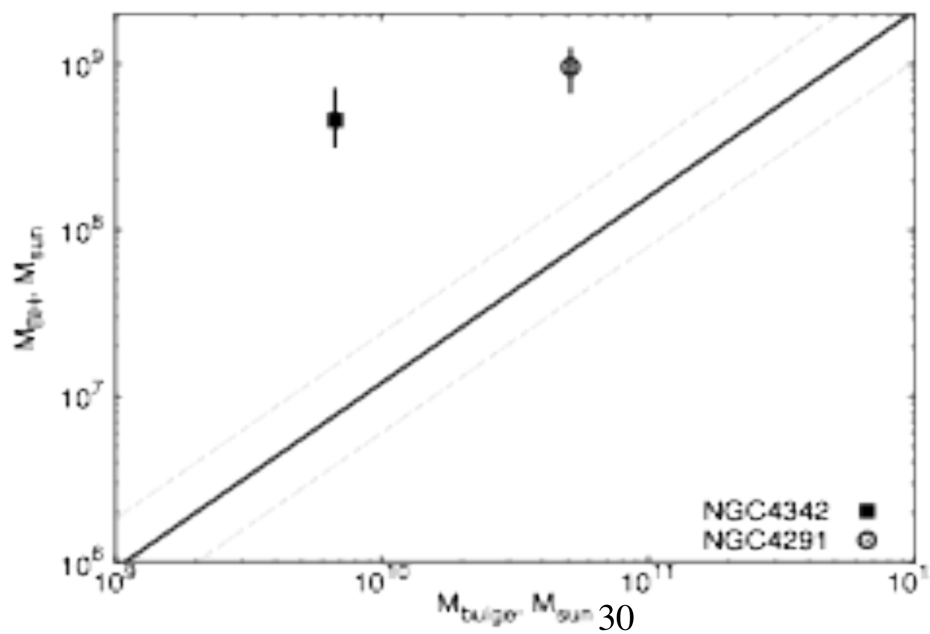


N4291 - Chandra





L_X/L_K vs. L_K

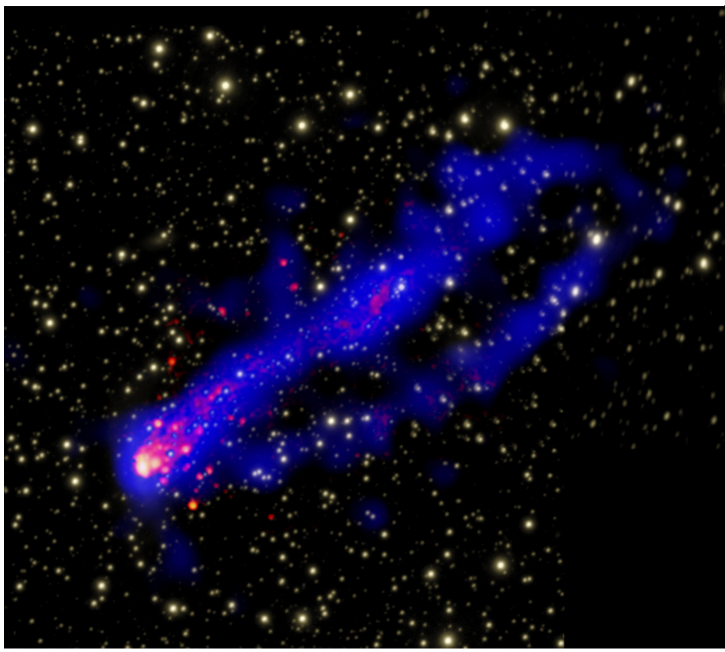


Bogdan et al. (2012)

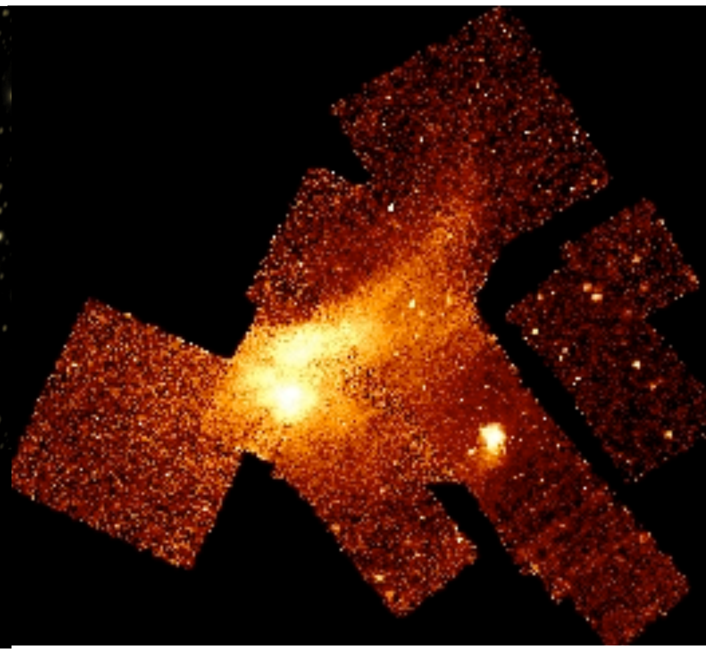
Part 1. Cool cores and outbursts from supermassive black holes in clusters, groups and "normal" galaxies

Part 2. Hot gas halos in faint ellipticals

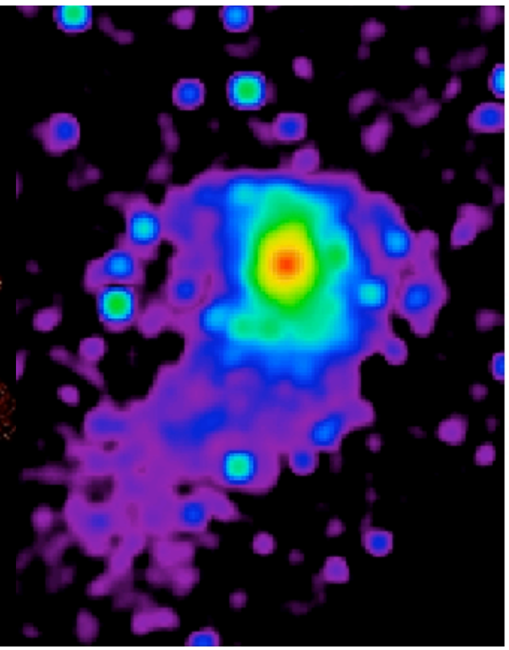
Part 3. Gas stripping from galaxies and groups



ESO137-002 in A3627

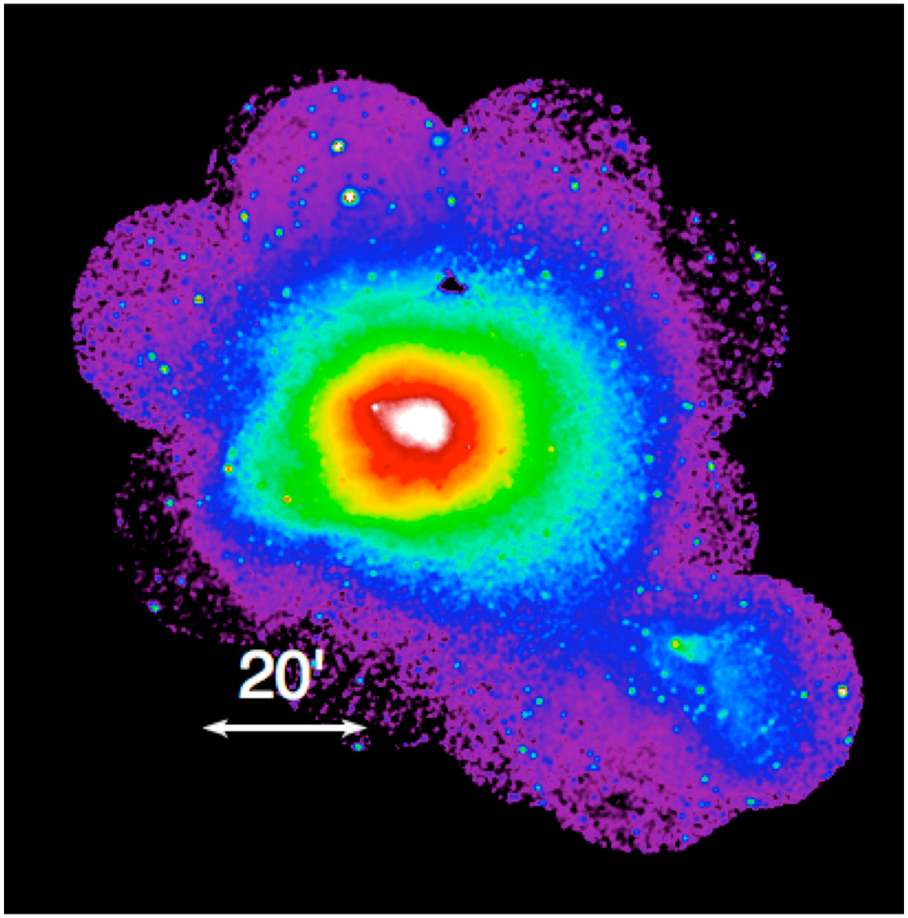


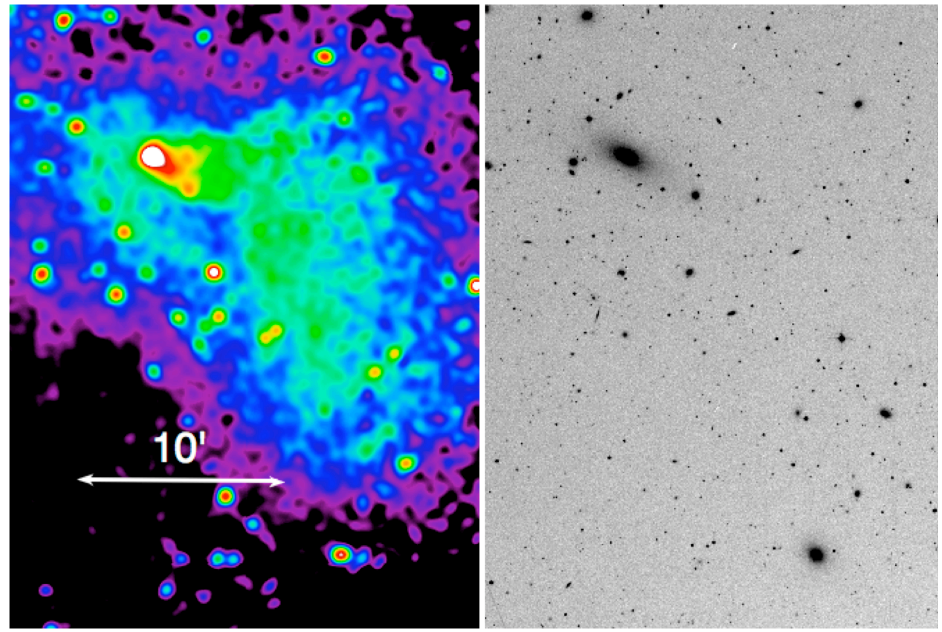
M86 & M84



NGC4552

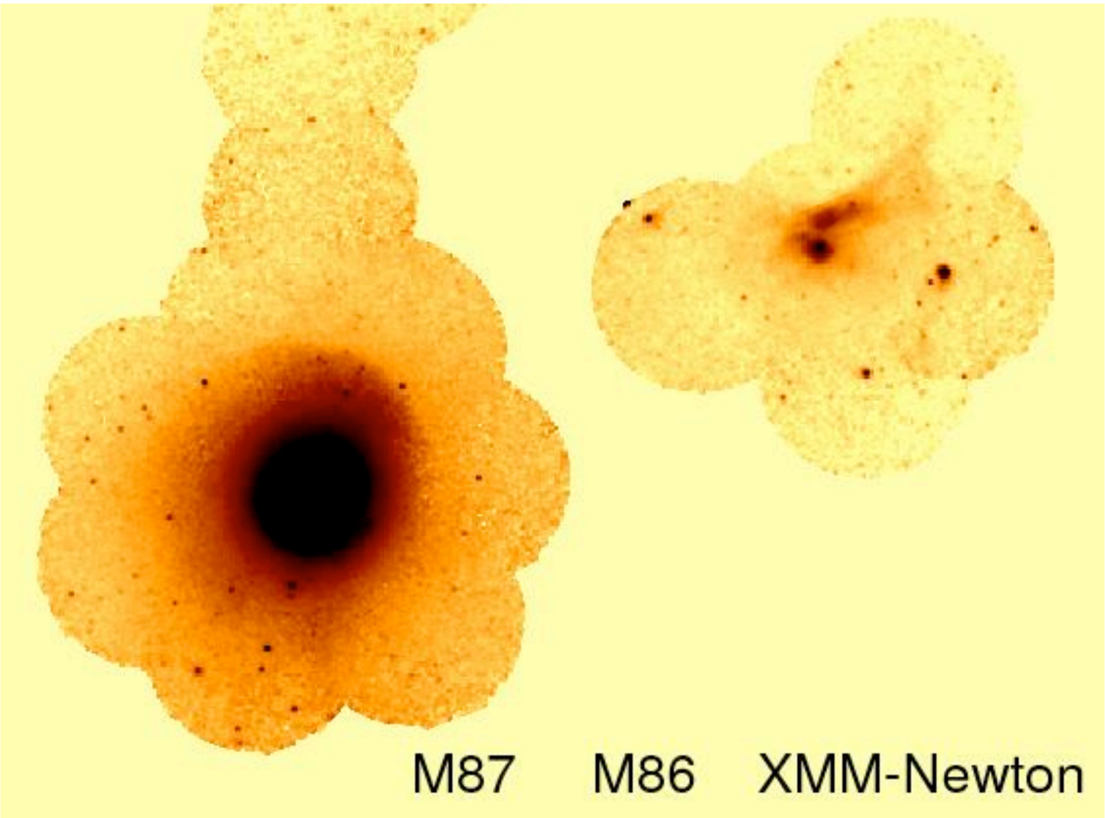
COMA Cluster

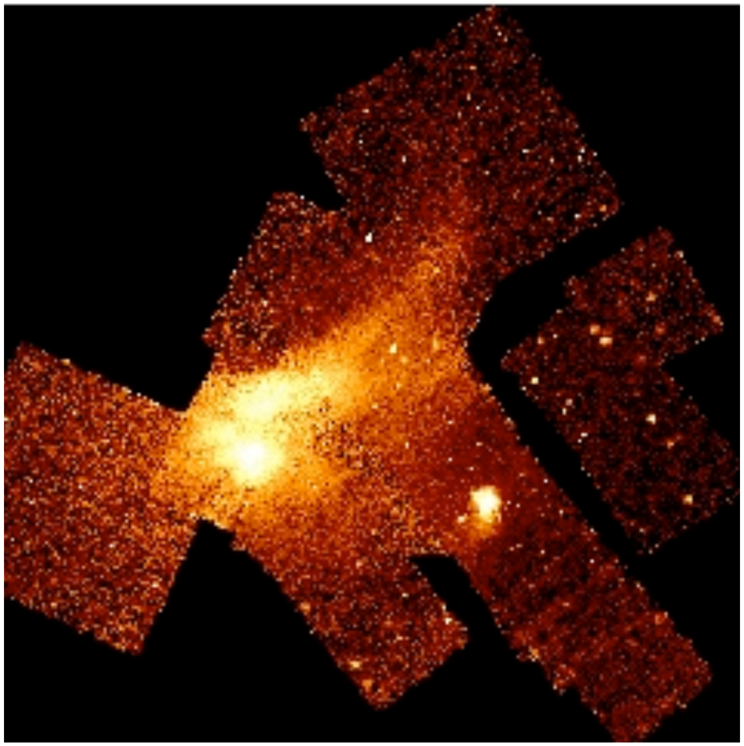




Infall of NGC4839 group into the Coma cluster
(XMM-Newton - Forman et al 2012)

Ellipticals in the Virgo cluster -- M84 & M86





Chandra

M86 falling into Virgo core with supersonic velocity.

125 kpc tail -- projected on sky (~380 kpc tail) Randall et al 2008

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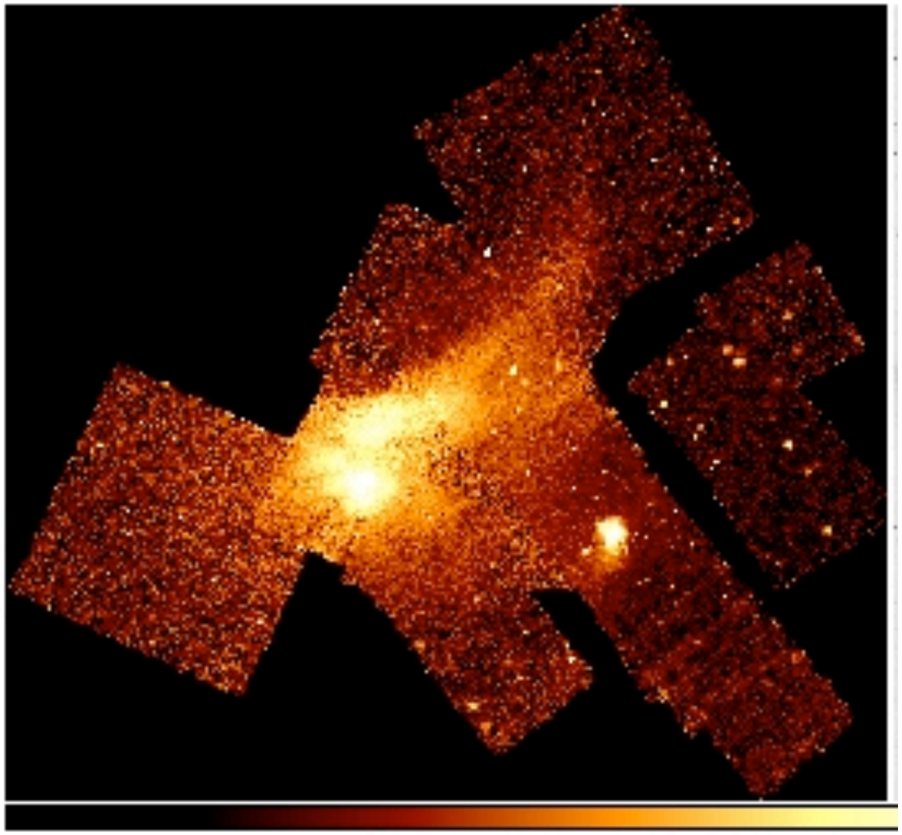
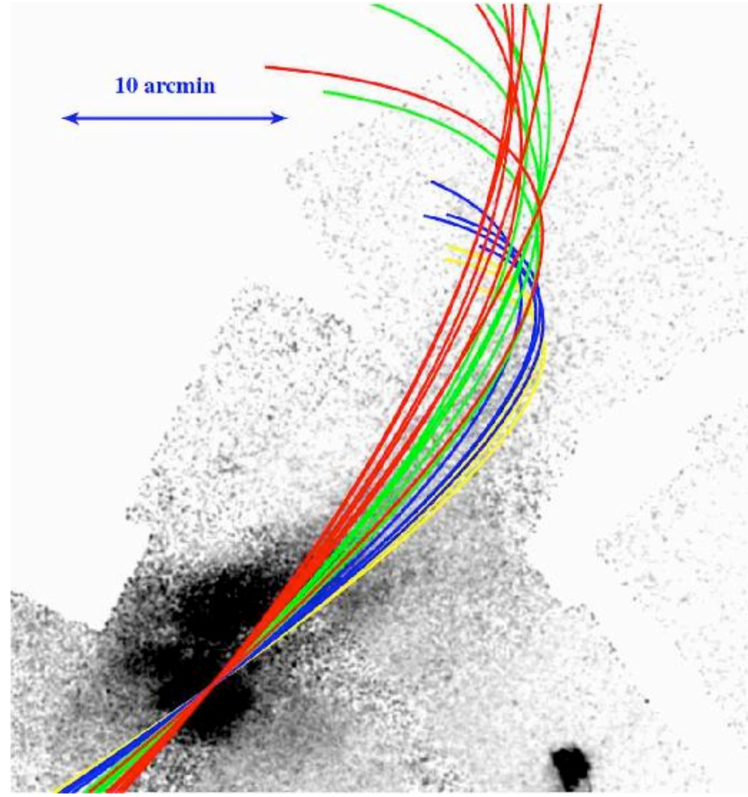
M84 small gas coronae -- outburst and X-ray tail

Ellipticals in the Virgo cluster – M86





M86 falling into Virgo core with supersonic velocity.

Constrain infall parameters   Randall et al 2008

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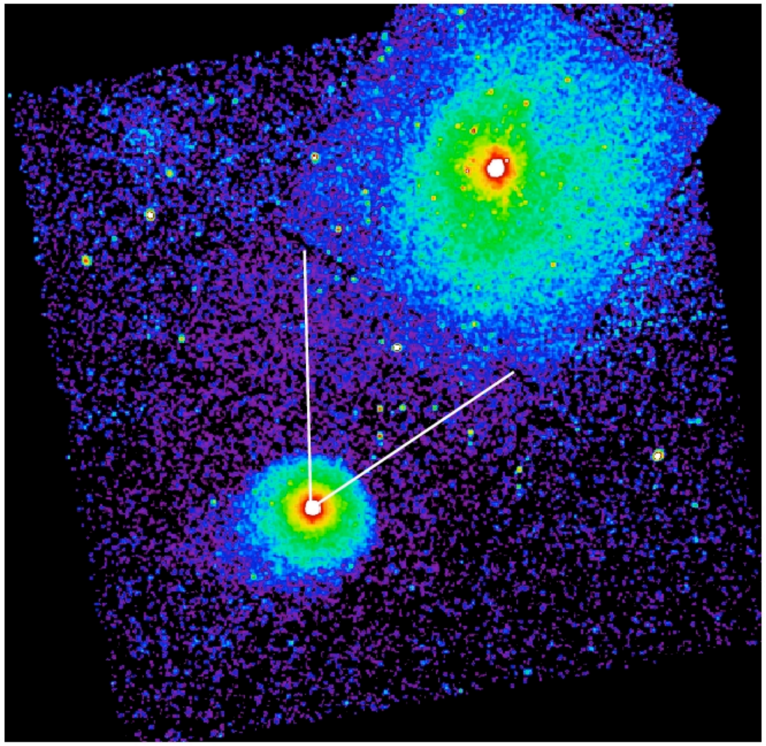
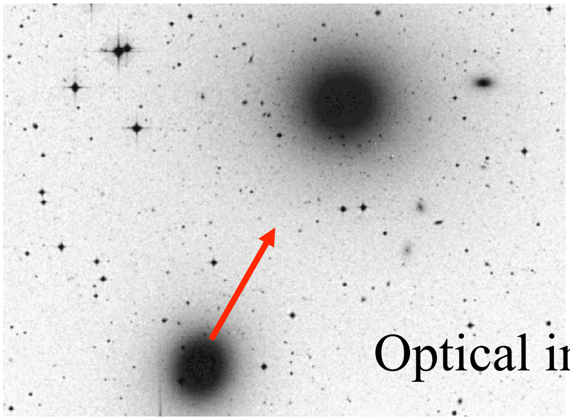
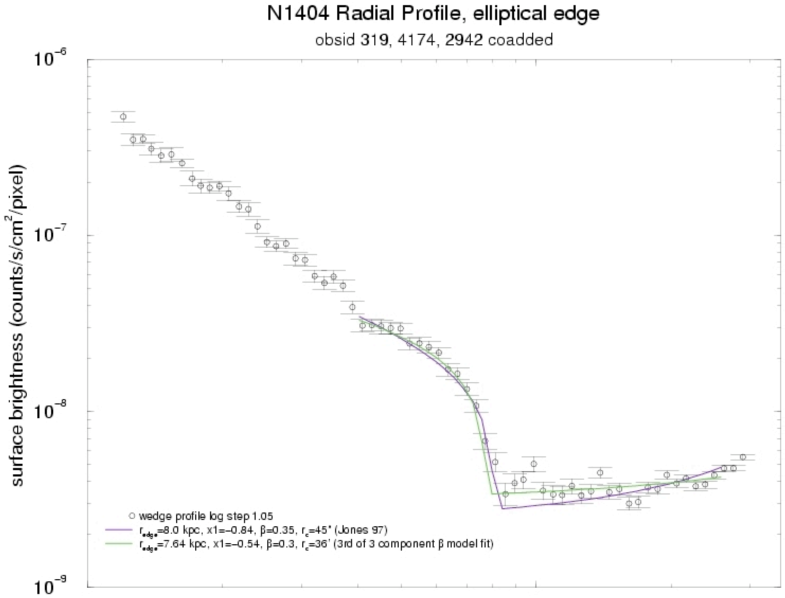
Galaxy Cold Fronts – Fornax Cluster





Optical image

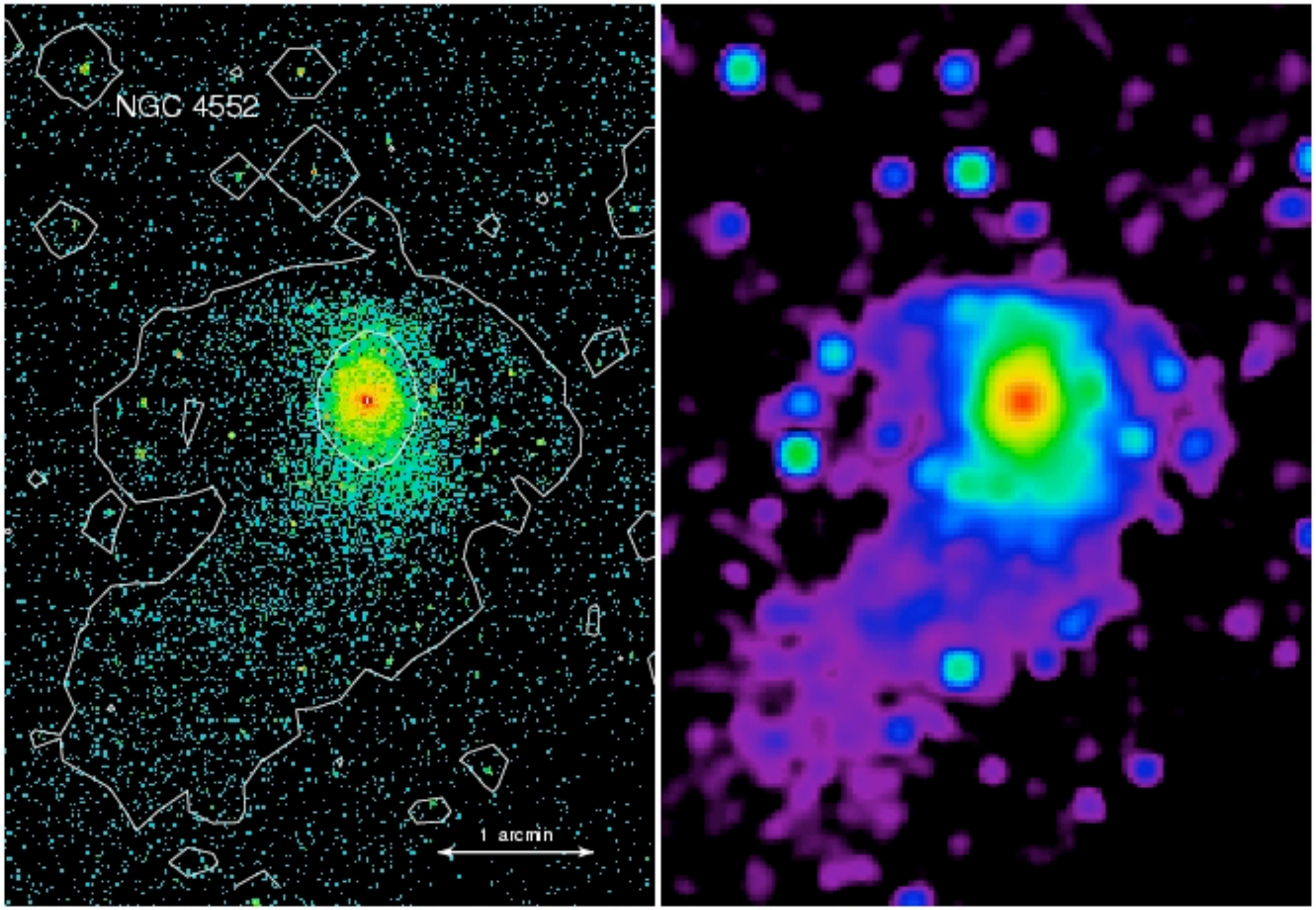
- Clearly infall of NGC1404 into cluster center - NGC1399
- z=0.00475; 1 arcmin = 8.2 kpc



Can measure full velocity of infall

Scharf et al 2004
Machacek et al 2004

NGC4552 - M89

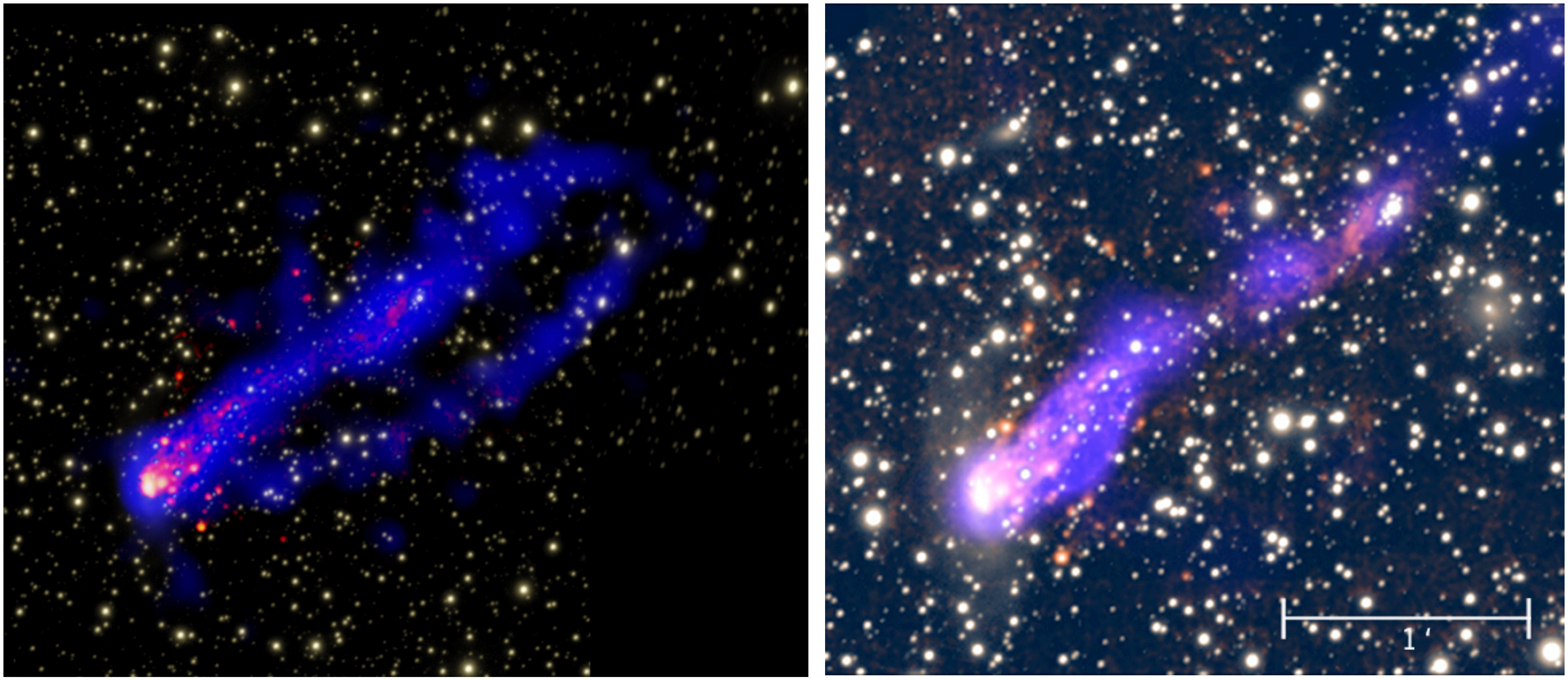


Chandra   Chandra smoothed image

From optical spectroscopy, NGC4552's los velocity 340 km/sec -- M87's 1300 km/sec
From X-ray NGC4552's total velocity is ~1680 km/s (Mach 2); ~35 deg toward us

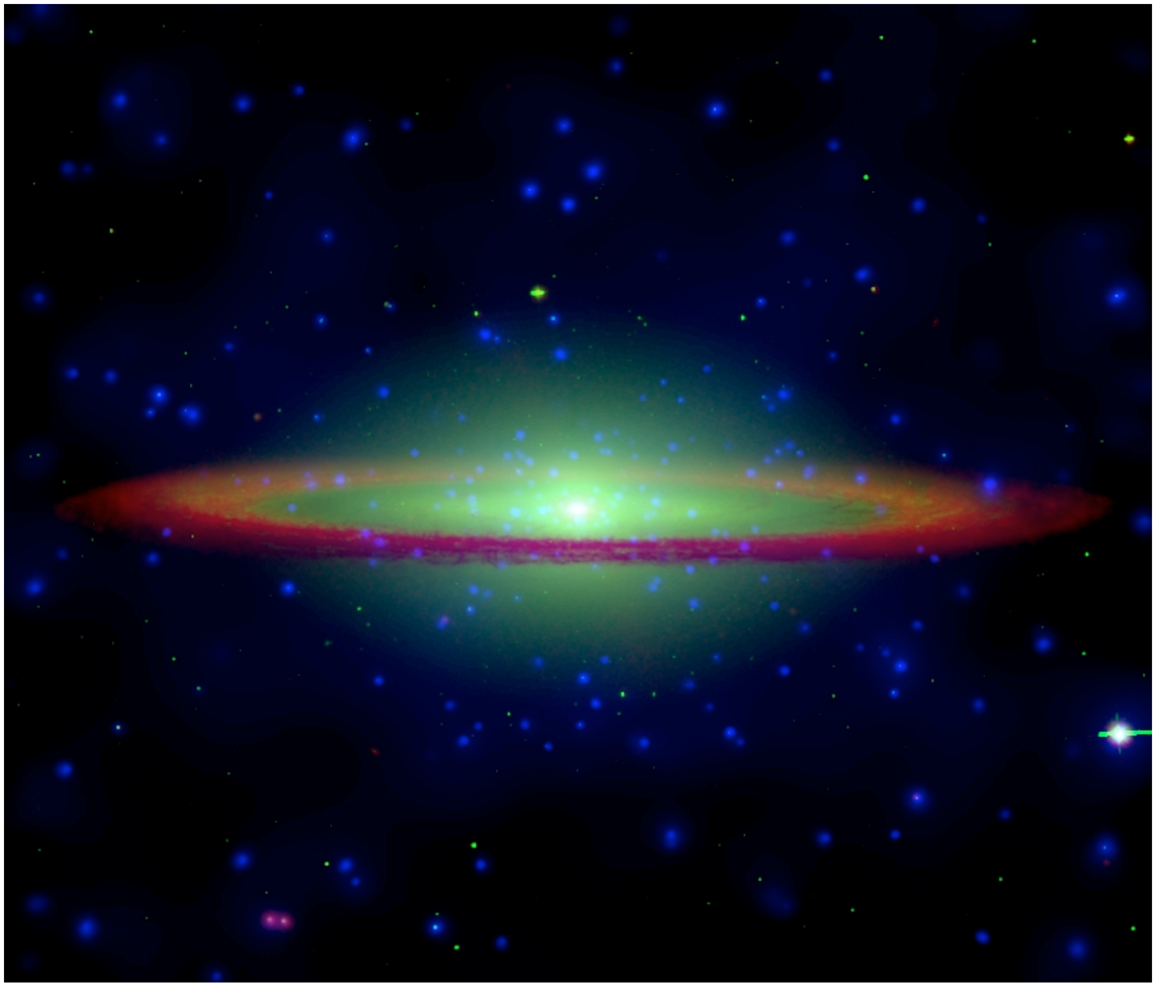
Machacek et al. 2006 ApJ 644, 155

Hot gas tails in spiral galaxies

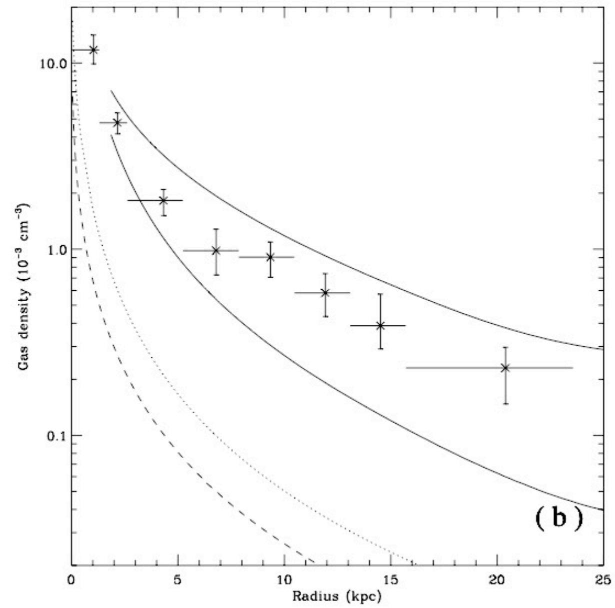


X-ray (blue) tails in ESO137-002 (left) and ESO137-001(right) show shock heated gas as galaxies fall into A3627 (Sun et al. 2007, 2010)

The Sombrero Galaxy Hot Gas Halo



Blue – X-ray; red – IR; white-optical



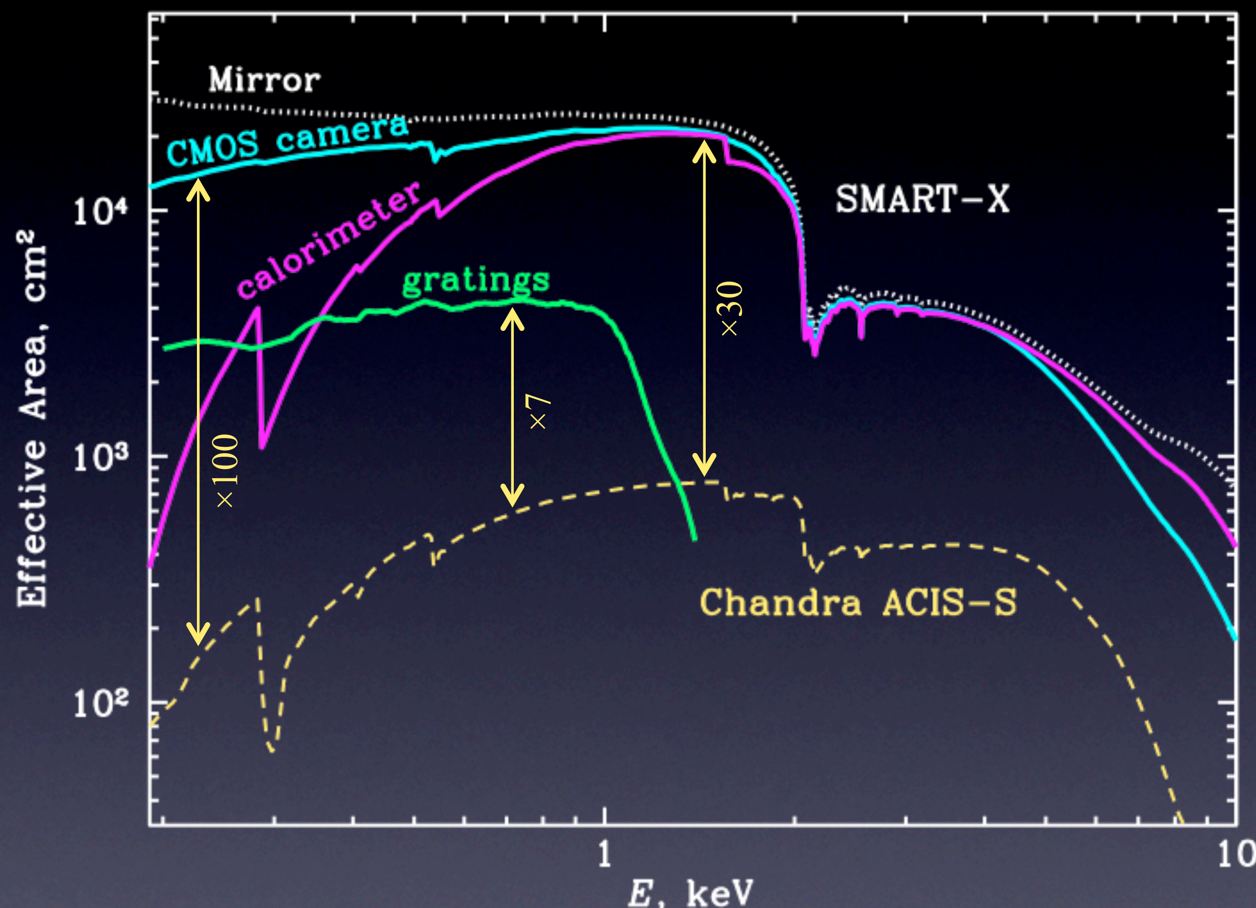
X-ray surface brightness flatter than stellar

Halo gas mass (3 10^8 M_{sun}) < expected from stellar mass loss

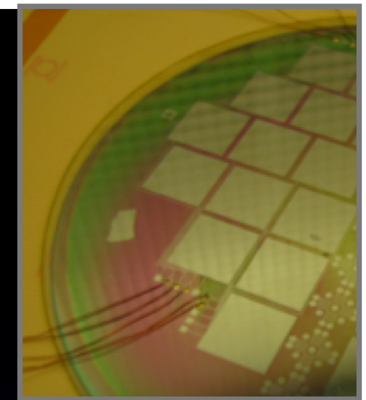
Subsonic wind

(Z. Li et al. 2010)

Possible Future SMART-X capability

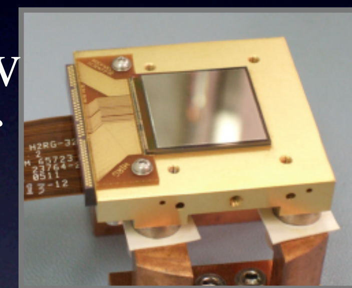


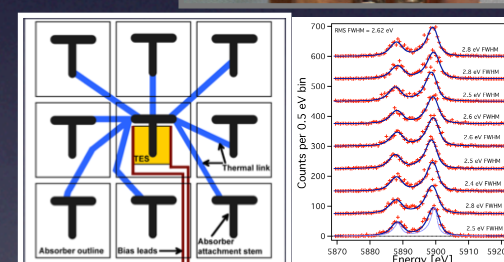
- Capability far exceeds *Chandra* (Chandra angular resolution, ×30 effective area, high-res spectroscopy for point and extended sources)
- Excellent match to JWST, ALMA, LSST, eVLA



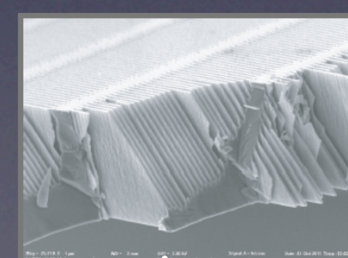
Adjustible optics

w
f
i



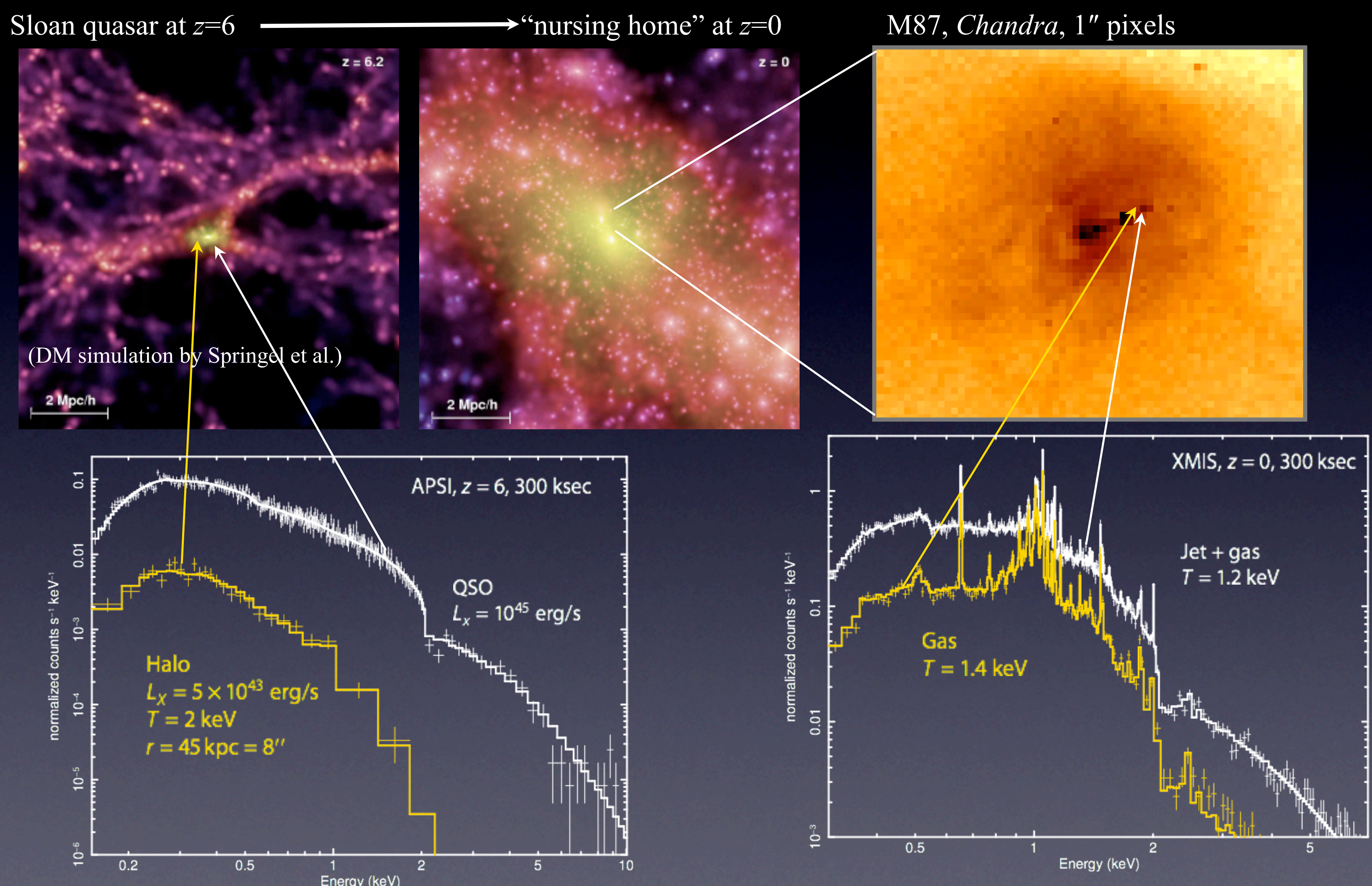


calorimeter



gratings

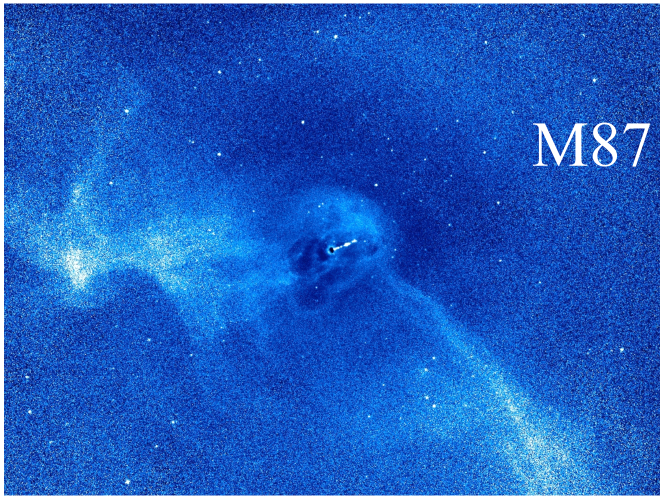
Tracing growth of supermassive black holes and their environment from z=6 to the present with *SMART-X*



- ✓ ***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***

Hot Gas and AGN outbursts in Galaxies, Groups & Clusters

- Outbursts from galaxies to clusters 10^{55}-10^{62} ergs
  - Accretion can grow the SMBH
  - Outbursts reheat cooling gas through shocks/buoyant bubbles in all gas rich systems
  - Key to galaxy evolution - truncate star formation
  - Hot coronae central to AGN feedback



Hot & Dark Halos around faint galaxies (SMBH)

Gas stripping from elliptical and spiral galaxies and groups – determine total infall velocity, metal enrichment to ICM.

Future - an X-ray mission for ~2025 (large light weight mirrors, sub-arcsecond resolutions – needs technology support)

THANKS

PV work balances cooling for galaxies with cavities

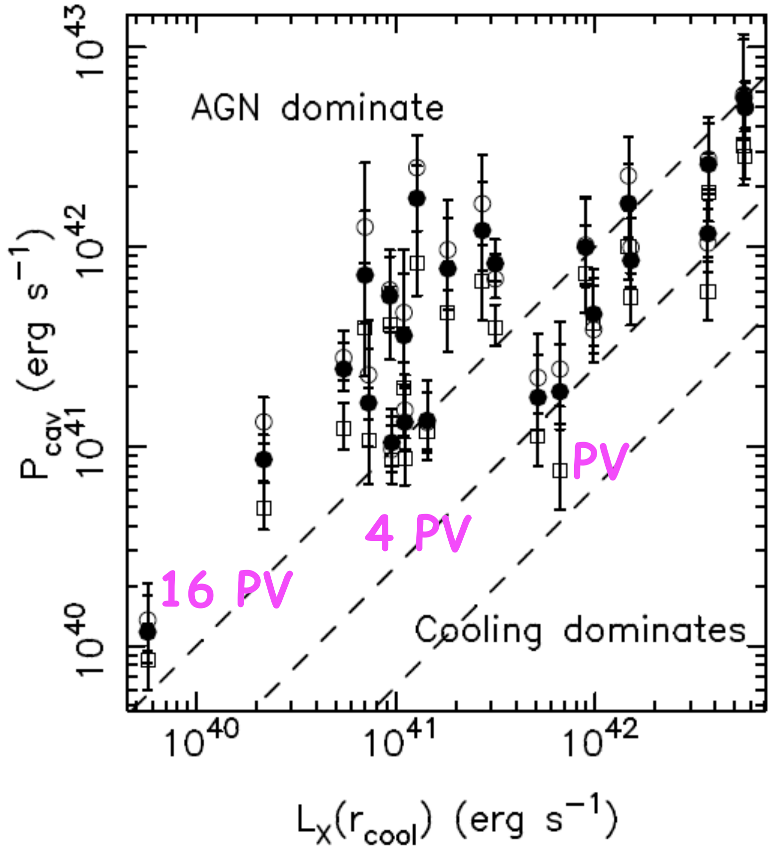
Power of AGN estimated from ages and outburst energies

- three estimates of age
    - sound crossing time
    - refill time (of displaced volume)
    - buoyancy time

•For 4PV, AGN power exceeds L_{rad} for all the galaxies (assuming an age given by the sound crossing time).

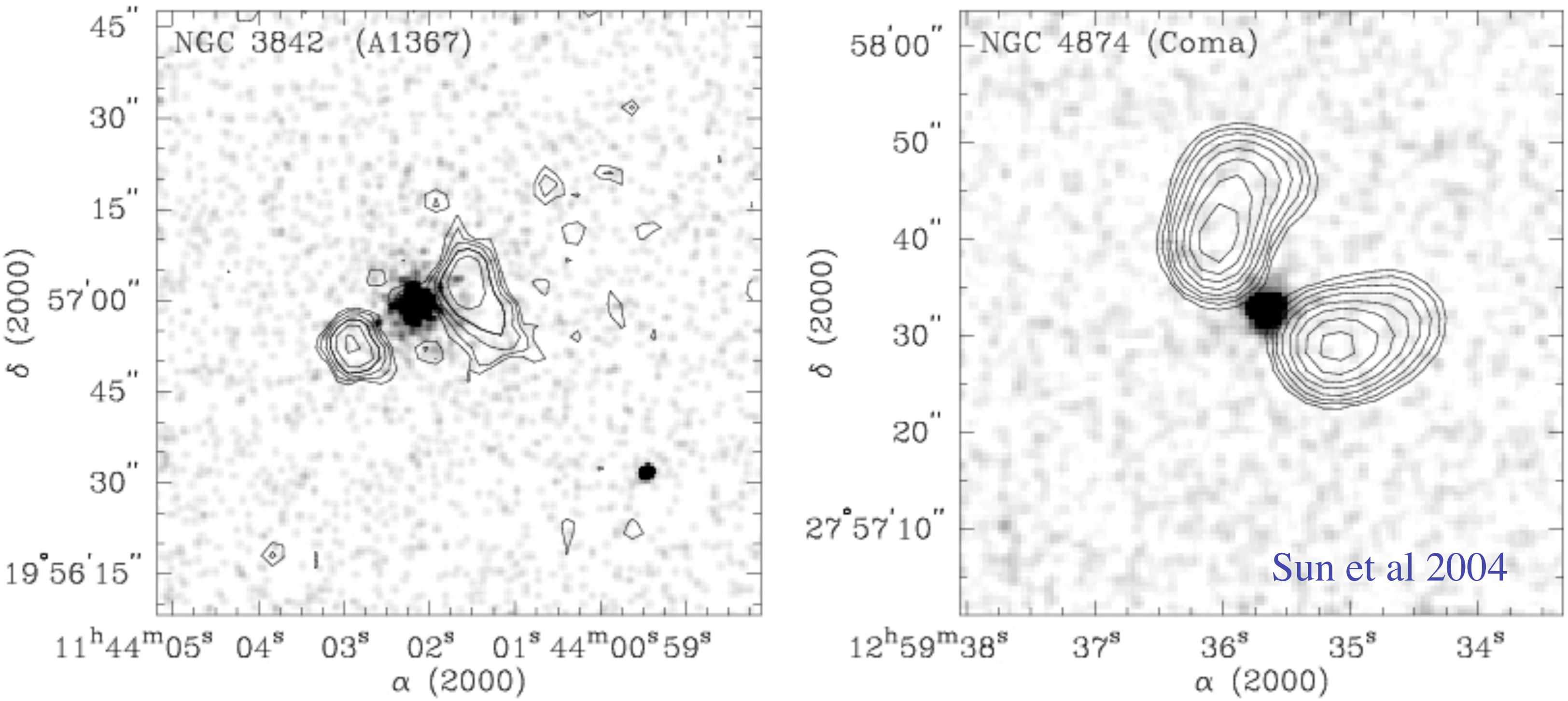
Nulsen+09

(similar results for clusters e.g. Dunn/Fabian



H = γPV/(γ-1) where γ=4/3 for relativistic plasma

Small Cool Compressed Coronae in Hot Clusters



First found by Vikhlinin et al. in Coma - Extensive survey of cDs by Sun et al.

Require: Suppression of thermal conduction to survive

Radio sources must deposit energy outside region coronae

If AGN mechanical power deposited within, coronae would be disrupted

For M87 - Outburst Energy measured directly from gas density and temperature

Series of models with varying initial outburst energies - 2, 5, 10, 20 x 10^{57} ergs

Match to data

- E = 5 x 10^{57} ergs
- Determined by jumps
- Independent of duration