Outbursts from Supermassive Black Holes

Forman, Churazov, Jones,
Bohringer, Begelman, Owen, Eilek, Nulsen, Kraft

M87 interaction between a SMBH and gas rich atmosphere

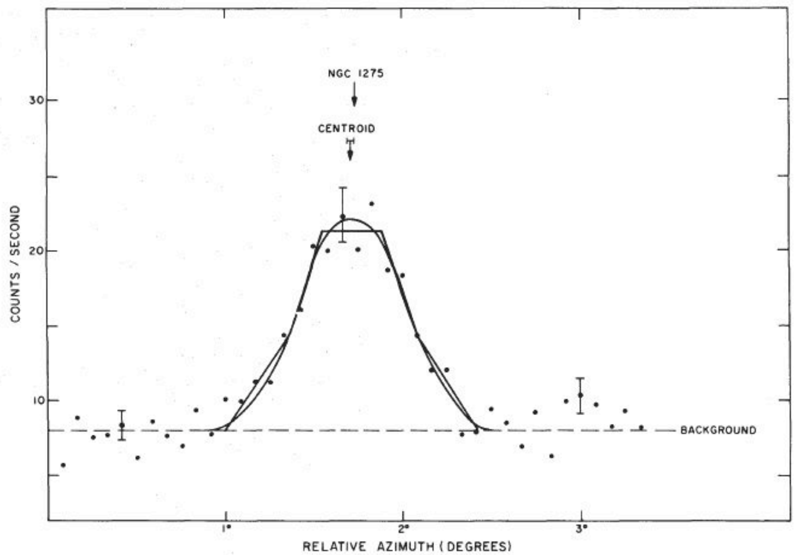
Shocks, Buoyant plasma bubbles, Jet, Cavities, Filaments

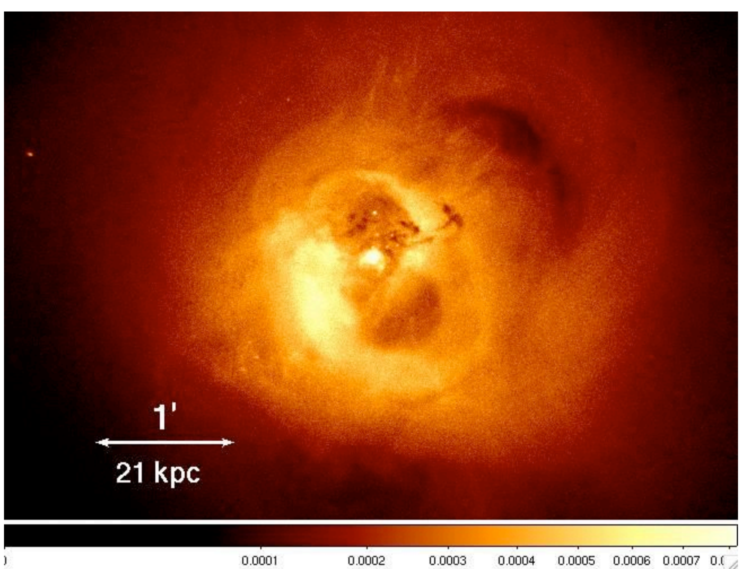
- **Outbursts from galaxies to (M87 to) rich clusters**
- Prevalence of bubbles/cavities in early type galaxies
- Outbursts range from $10^{55} < \Delta E < 10^{62}$ ergs
- See growth of SMBHs - $\Delta M_{SMBH} \propto \Delta E_{OUTBURST} / c^2$
- ΔM_{SMBH} up to 3×10^8 solar masses per outburst
- Understand "radio mode" and feedback from AGN during galaxy formation

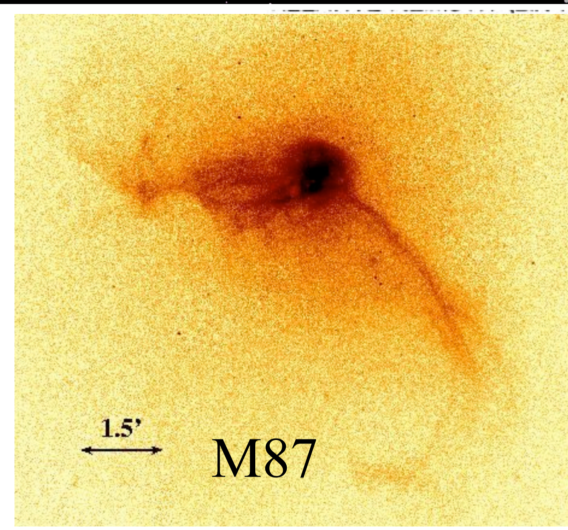
A look back to UHURU - a little history

Clusters from 1970 to Chandra

UHURU (1970) to Chandra (today) collimators to telescopes

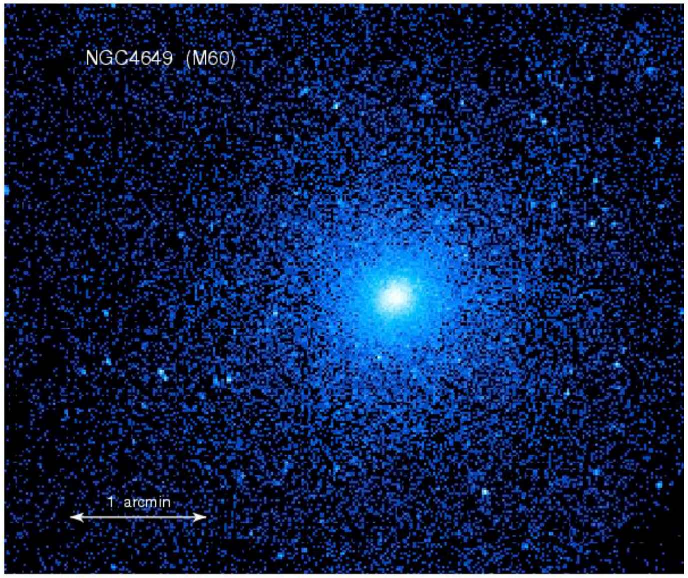


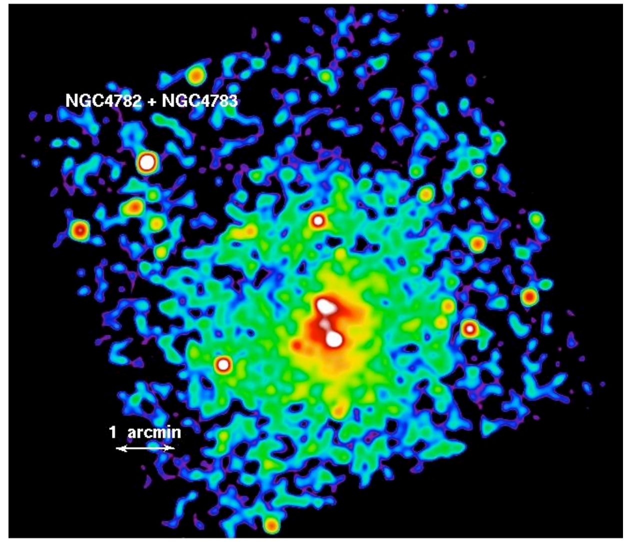


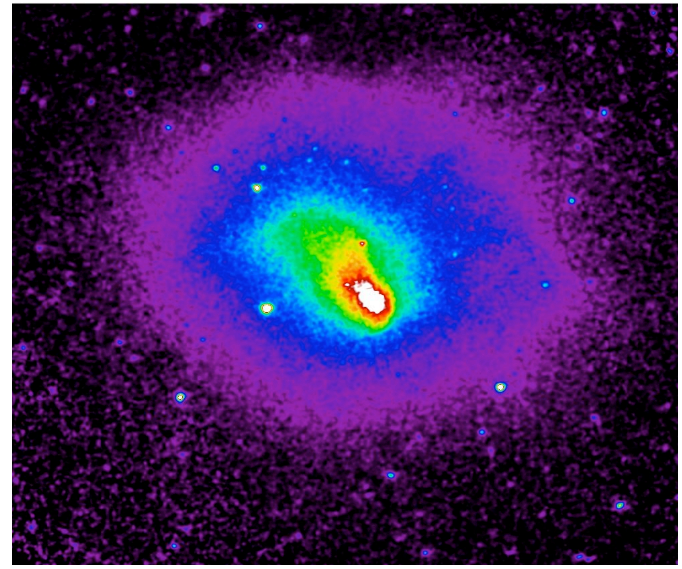


Setting the stage for cosmology

Family of increasing mass, temperature, and luminosity



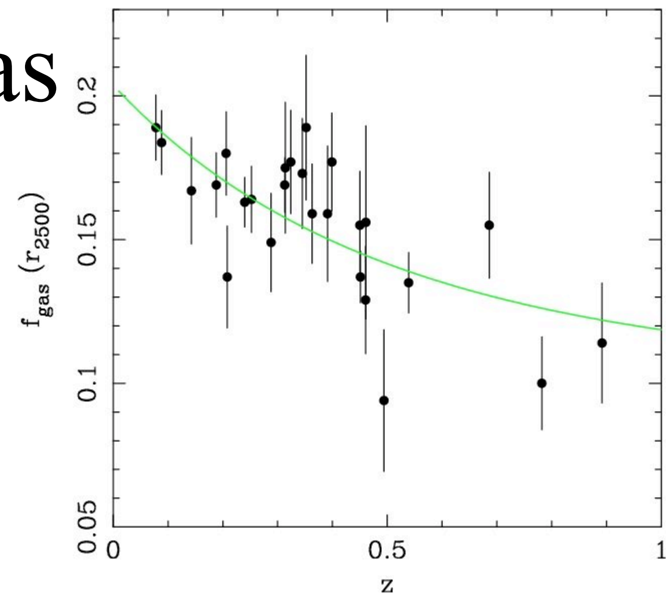




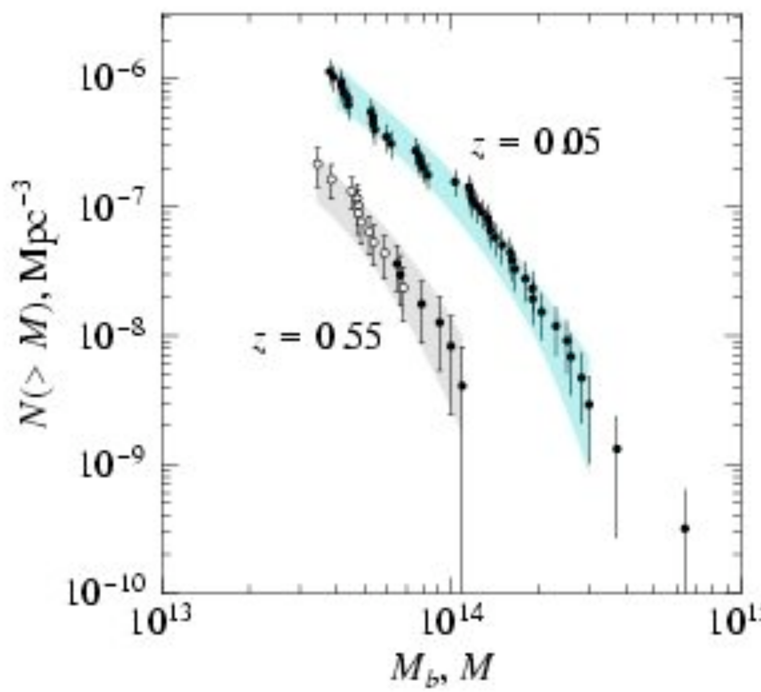
	E/S0 Galaxies	Groups	Clusters
L_x (ergs/sec)	10^{40-42}	10^{42-43}	10^{43-46}
Gas Temp	0.5-1.0 keV	1-3 keV	2-15 keV
$M_{gas}/M_{stellar}$	0.02	1	3-5 **

**Blumenthal, Faber, Primack, Rees 1983

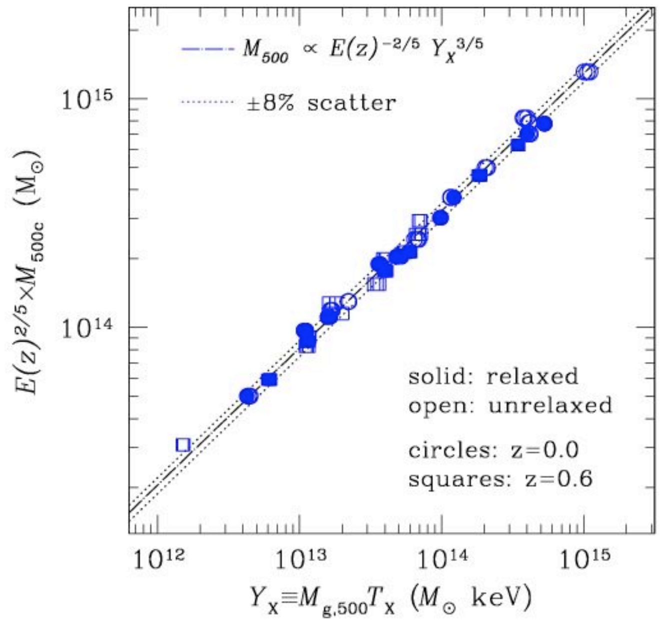
Large Mass of Hot Gas

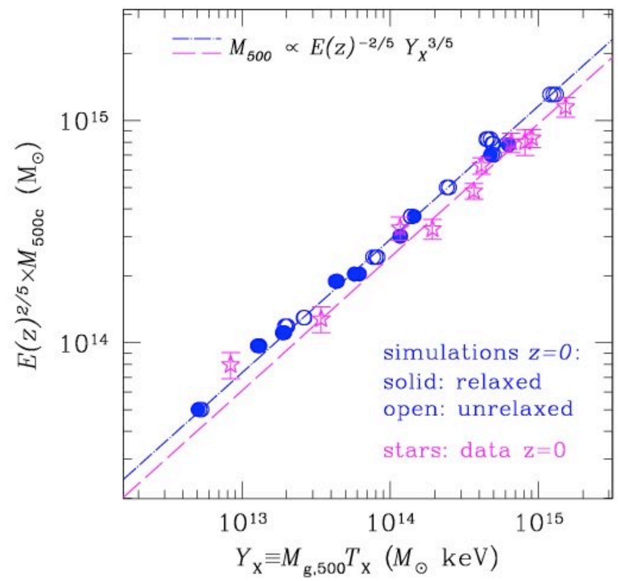


- SZ Effect
- Constant baryon fraction - assumes "fair sample"; use constancy of baryon fraction to derive cosmological parameters; Allen et al. (Sasaki 1996; Pen 1997)
  - Hard to measure (T at large radii)
- Gas mass as proxy for total mass (Vikhlinin et al.) uses simulations to predict growth of structure (Jenkins et al. 2001)



$Y_x = T\ M_{gas}$(Kravtsov/Vikhlinin/Nagai)

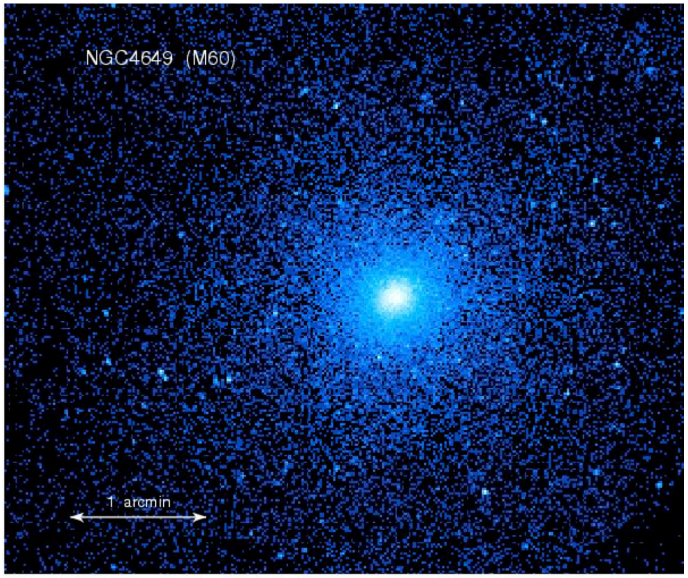


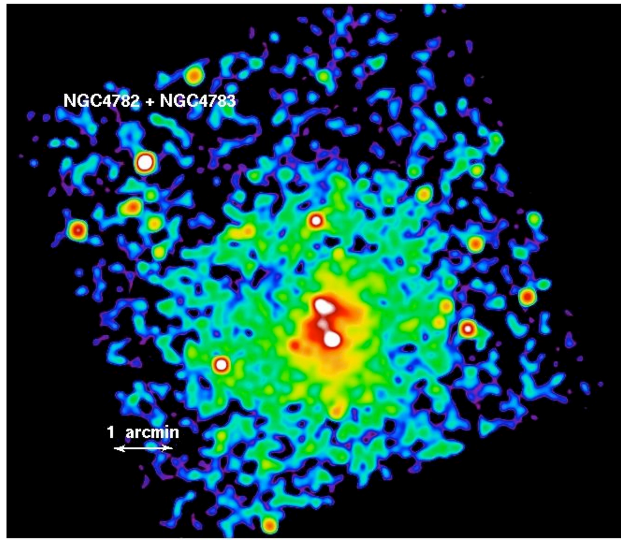


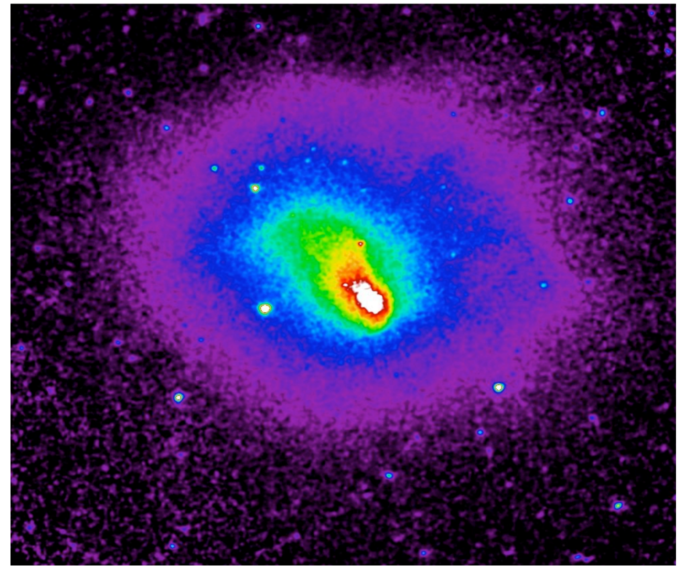
New technique with promise to reduce scatter
Simulations "realistic" - include needed physics

Setting the stage

Family of increasing mass, temperature, and luminosity



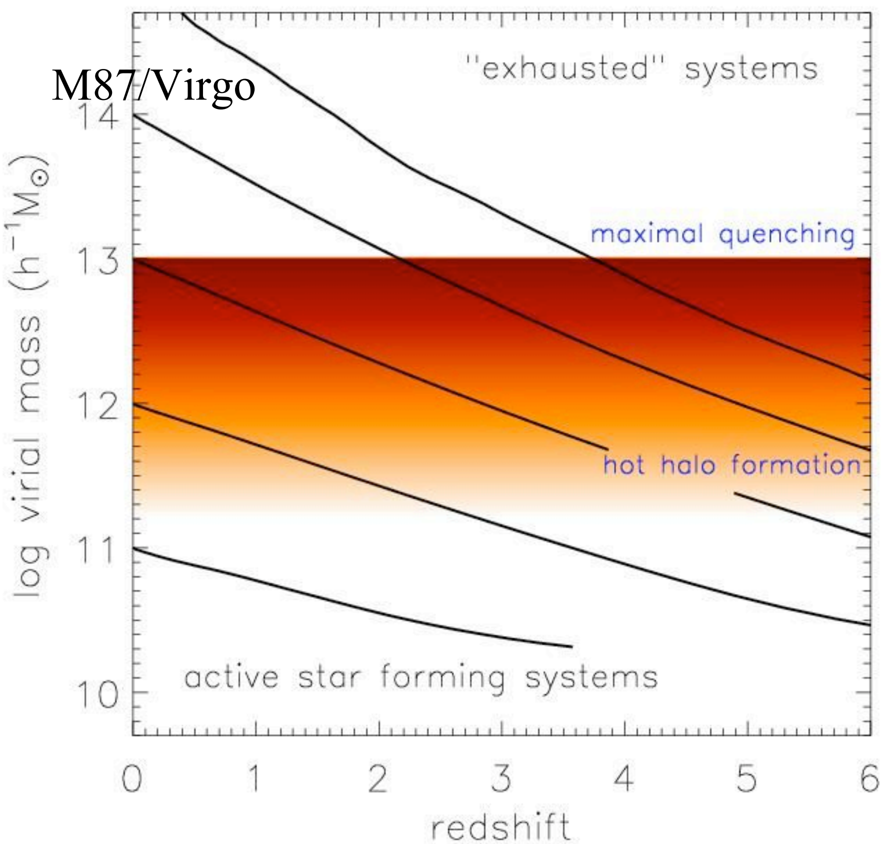




Hot gas provides a fossil record of mass ejections and energy outbursts

- Measure heavy element enrichment - history of star formation, winds, stripping
- Measure mechanical power over cosmic times
- Thermal Coronae - key to capturing AGN output in recent models
    - Radio mode - mechanical power dominates radiated luminosity

Hot Coronae - fossil record of AGN activity



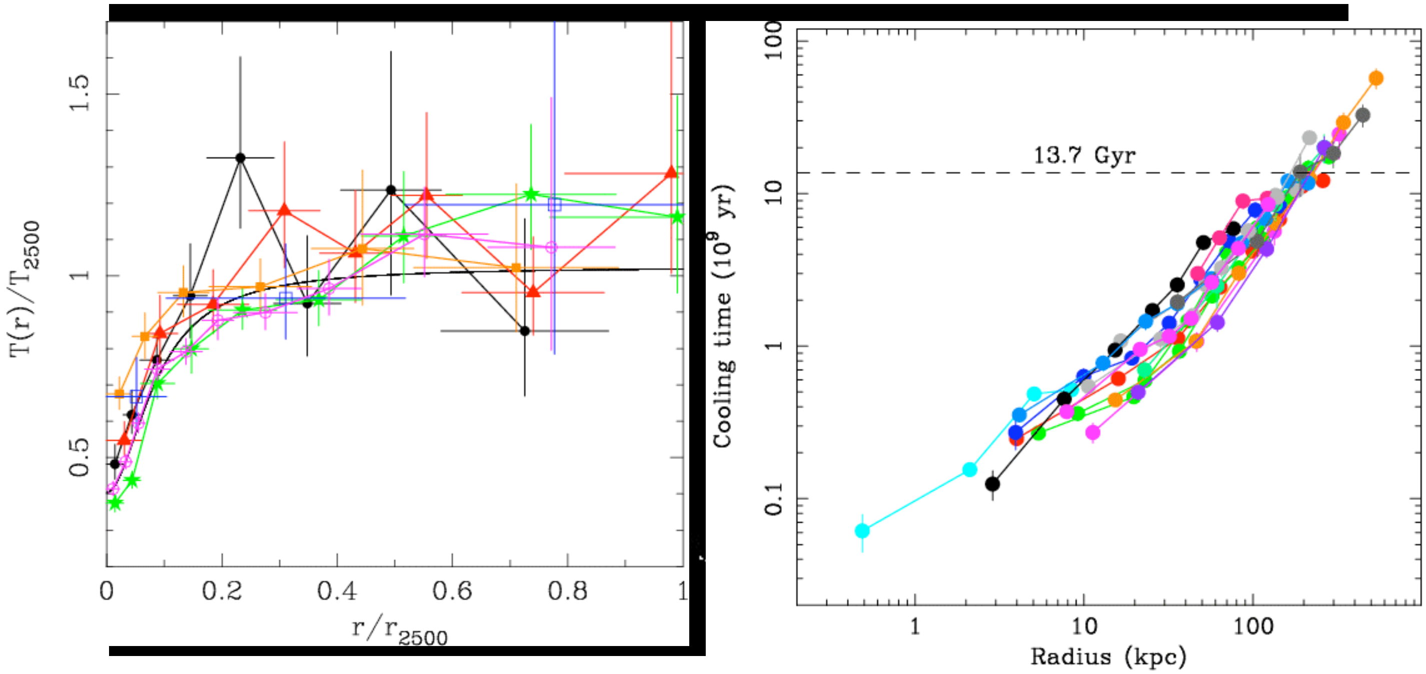
Hot X-ray emitting atmospheres provide "fossil record" of SMBH activity

- Observe outburst frequency
- Measure total power - mechanical vs. radiative (cavities)
- Understand interaction of outburst with surroundings
- Insight into high redshift universe
  - Growth/formation of galaxies
  - Growth of SMBH
  - M_{BH}-σ M_{BH}-M_{bulge} relations
  - Feedback from AGN

Millenium Simulation z=20 to z=0; star formation in most massive galaxies turned off by AGN feedback; continue to grow via mergers Croton et al. 2006

Ciotti & Ostriker (2007) model isolated elliptical - hot gas, SMBH outburst freq., growth, obscuration, star formation, galactic winds +

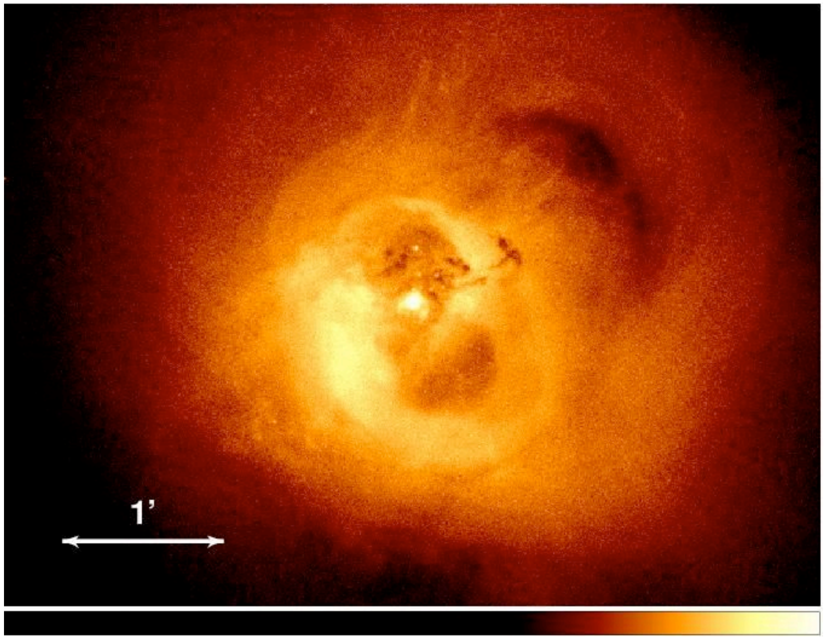
Cooling Flows



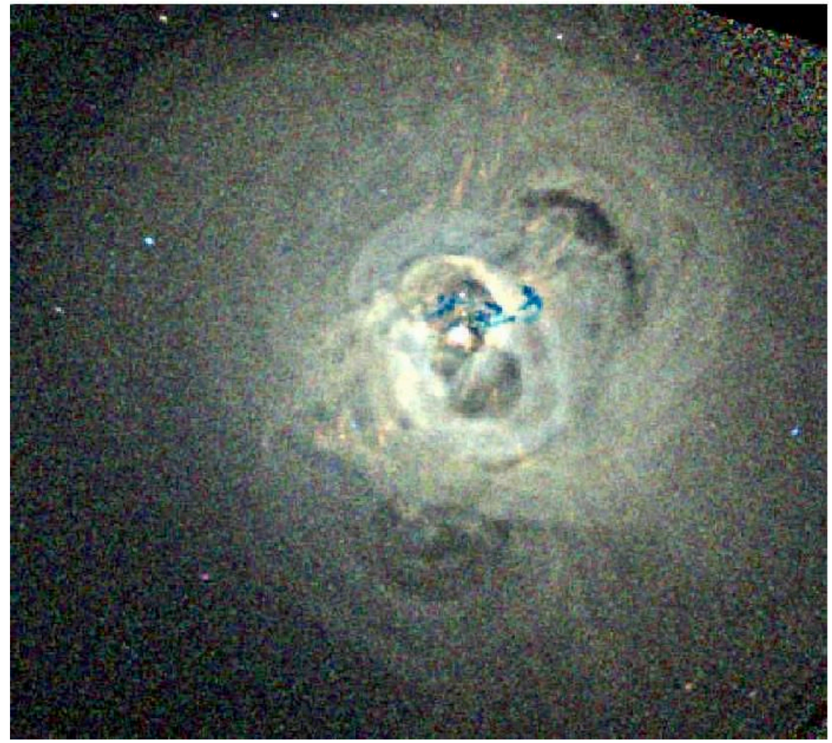
Allen/Fabian/Voigt

- **Cowie & Binney (1977) Fabian & Nulsen (1977) "Cooling gas in the cores of clusters can accrete at significant rates onto slow-moving central galaxies"**
- **Strong surface brightness peak → dense gas → short cooling time**
- Hot gas radiates – gas must cool unless reheated, then compressed by ICM
- **Mass Deposition rates are large (100 -1000 M/yr) - more than 50%**
- But large amounts of cool gas were not detected - must suppress cooling by factors of 5-10

Perseus Cluster - Shocks and Ripples (Fabian et al. 2002, 2003, 2005)



Fabian et al. 2005



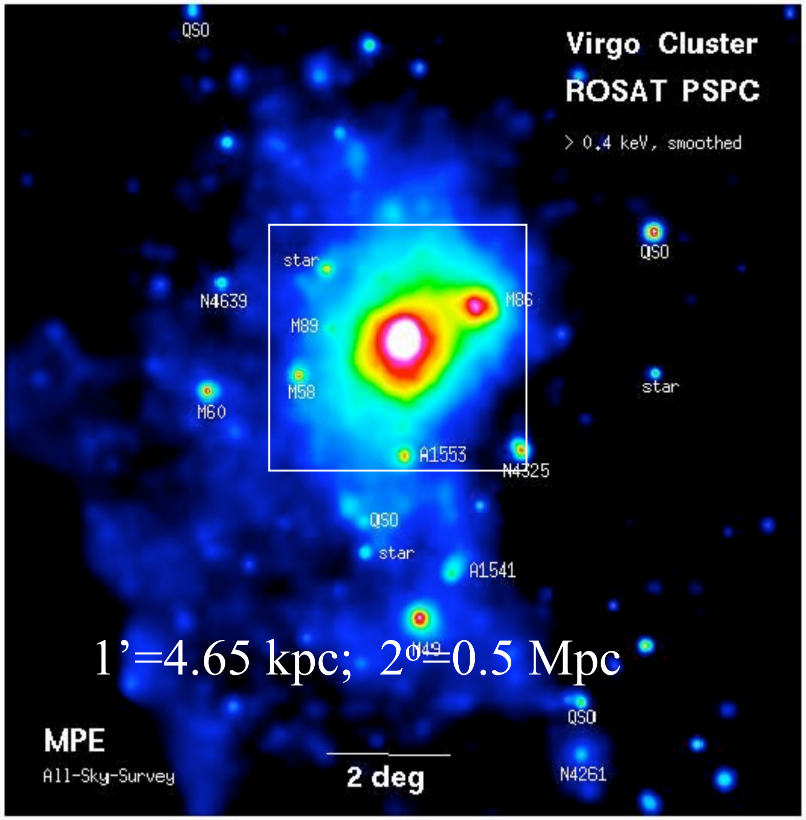
unsharp masked image

- Chandra image shows evidence for repeated outbursts
- Processed image (unsharp masking) shows faint ripples
- Sound waves (weak shocks) ? Driven by expansion of radio bubbles

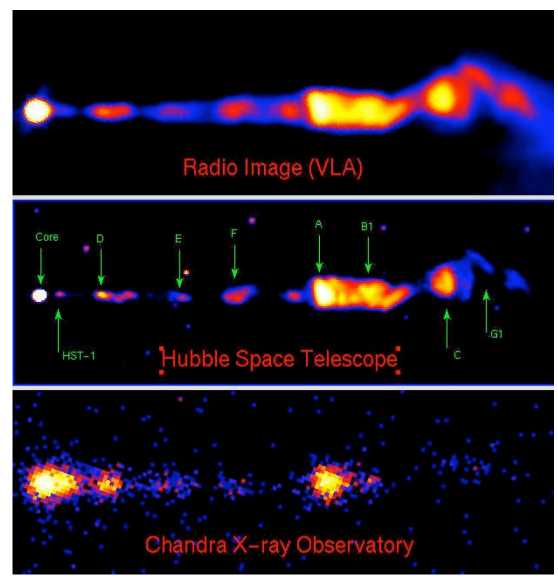
  Sound speed =1170 km/sec, separation=11kpc, t=9.6×10^{6} yr

  Dissipate energy (high ion viscosity) over a distance < 100 kpc
- Energy of bubbles/shocks balances cooling
- Hot cluster - difficult to measure small temperature rises from weak shocks (for Chandra)

Virgo Cluster - X-ray/Optical



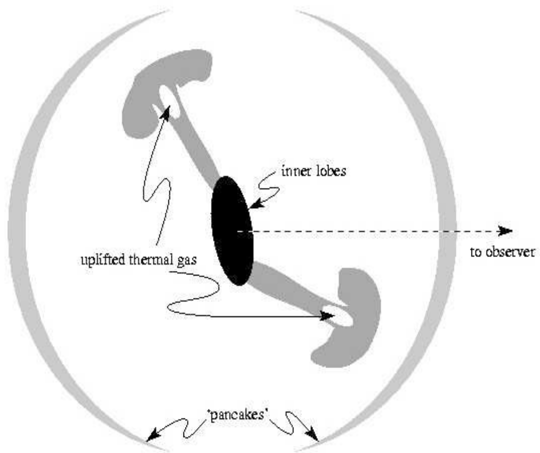
Central galaxy in Virgo cluster
D=16 Mpc

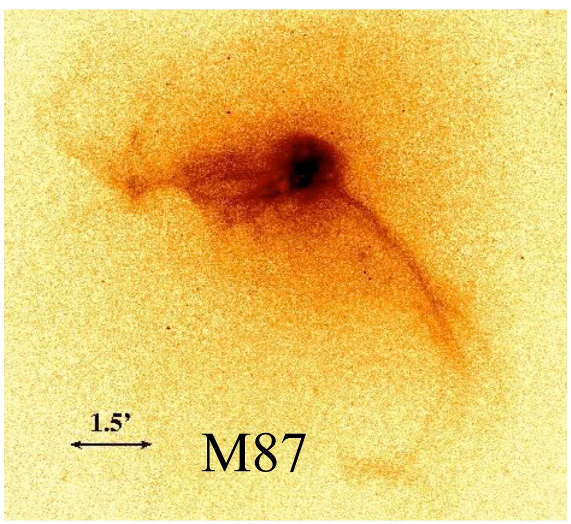


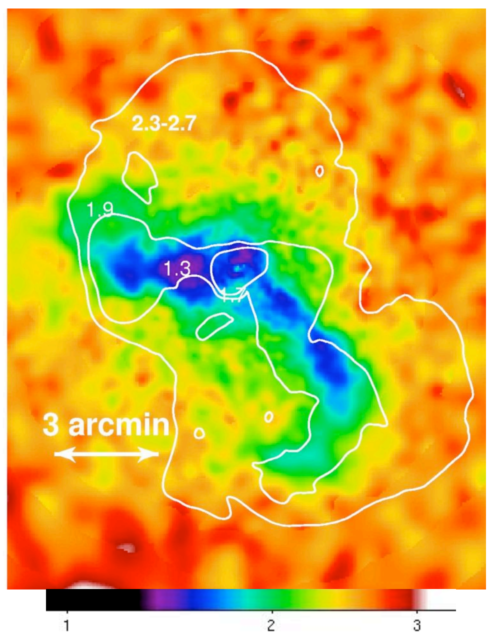
- **$3\times10^9 M_{sun}$ supermassive black hole**
- **Spectacular jet (e.g. Marshall et al.)**
- **Nearby (16 Mpc; 1'=4.5 kpc, 1"=75 pc)**
- **Classic cooling flow (24 M_{sun}/yr)**
- **Ideal system to study SMBH/gas interaction**

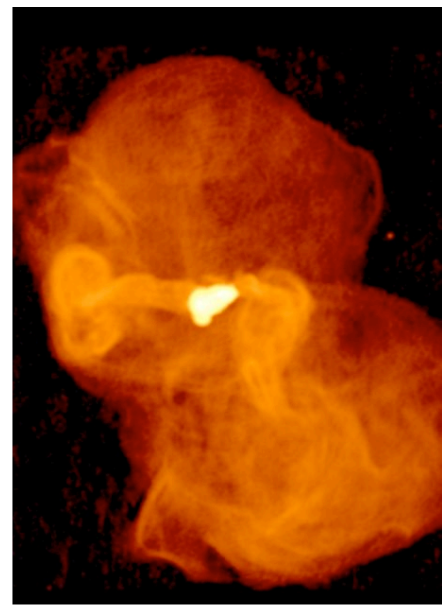
Chandra-XMM-VLA View

- 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)
- Southwestern arm - less direct relationship - radio envelops gas

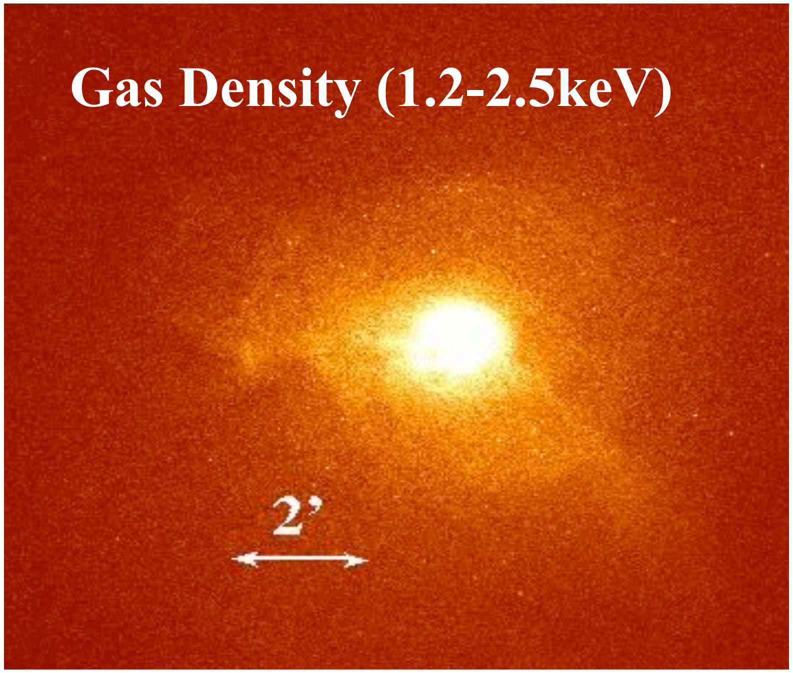


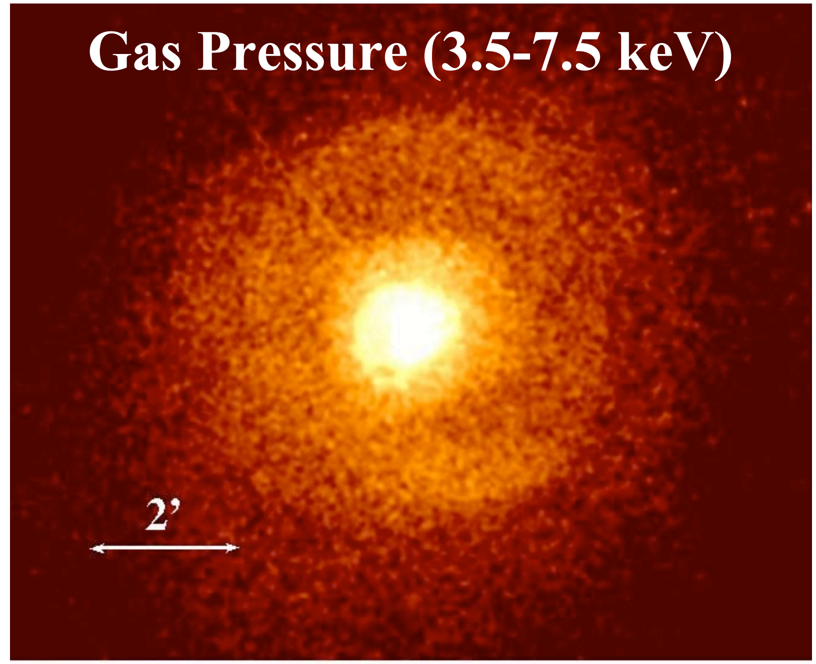


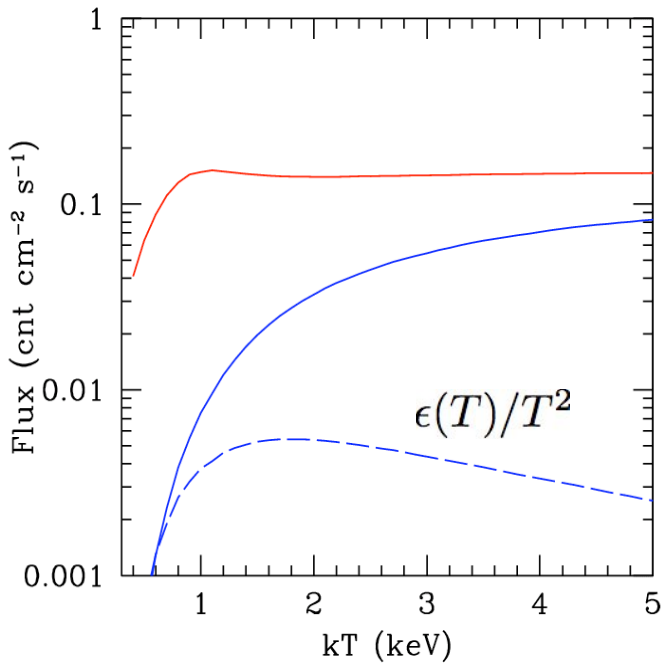




Owen et al.



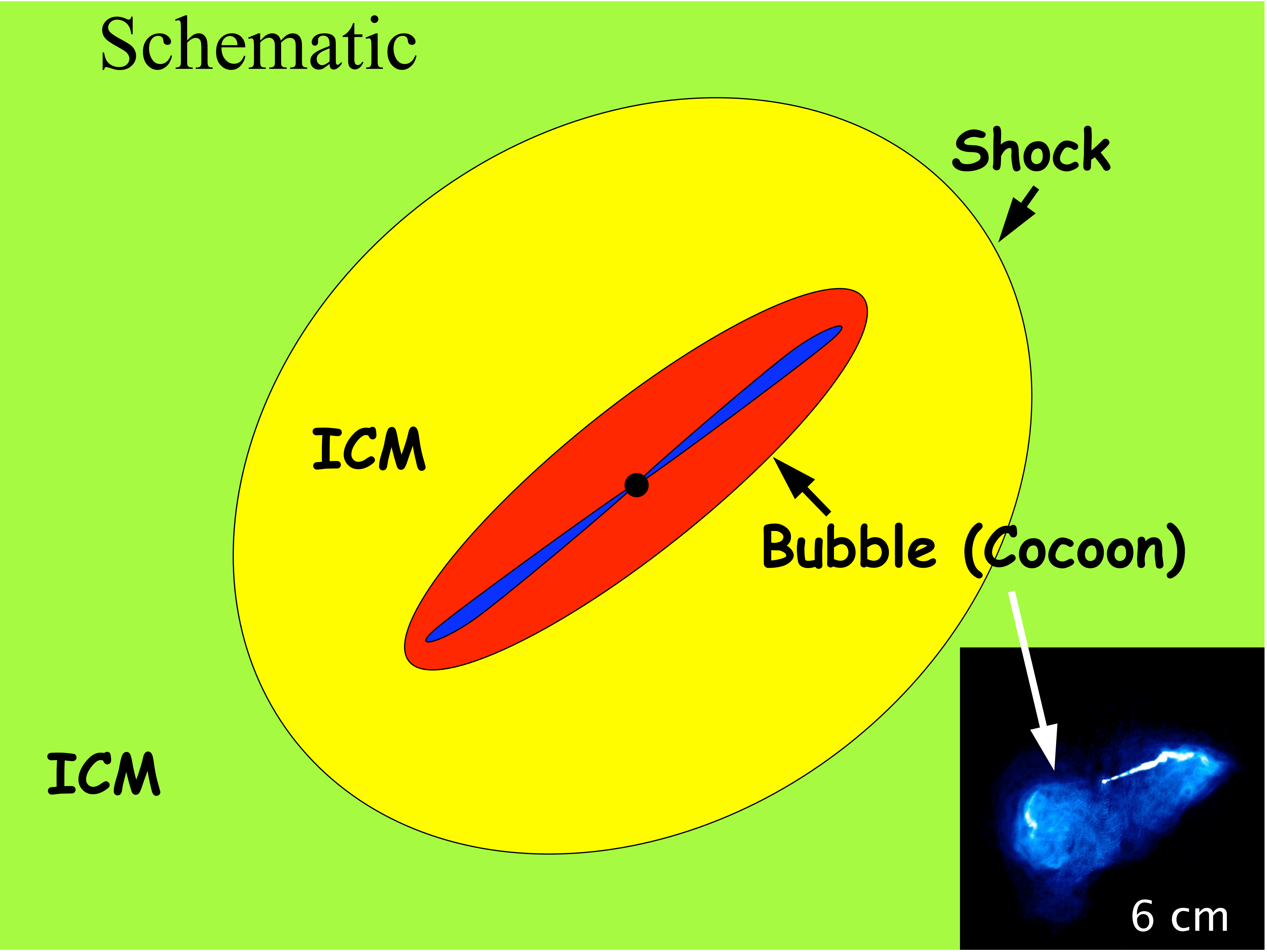




$$F = n^2 \varepsilon(T) = \left(\frac{P}{T}\right)^2 \varepsilon(T) = P^2 \varepsilon(T) / T^2 \approx C\, P^2$$

for 3.5-7.5 keV, brightness IS pressure

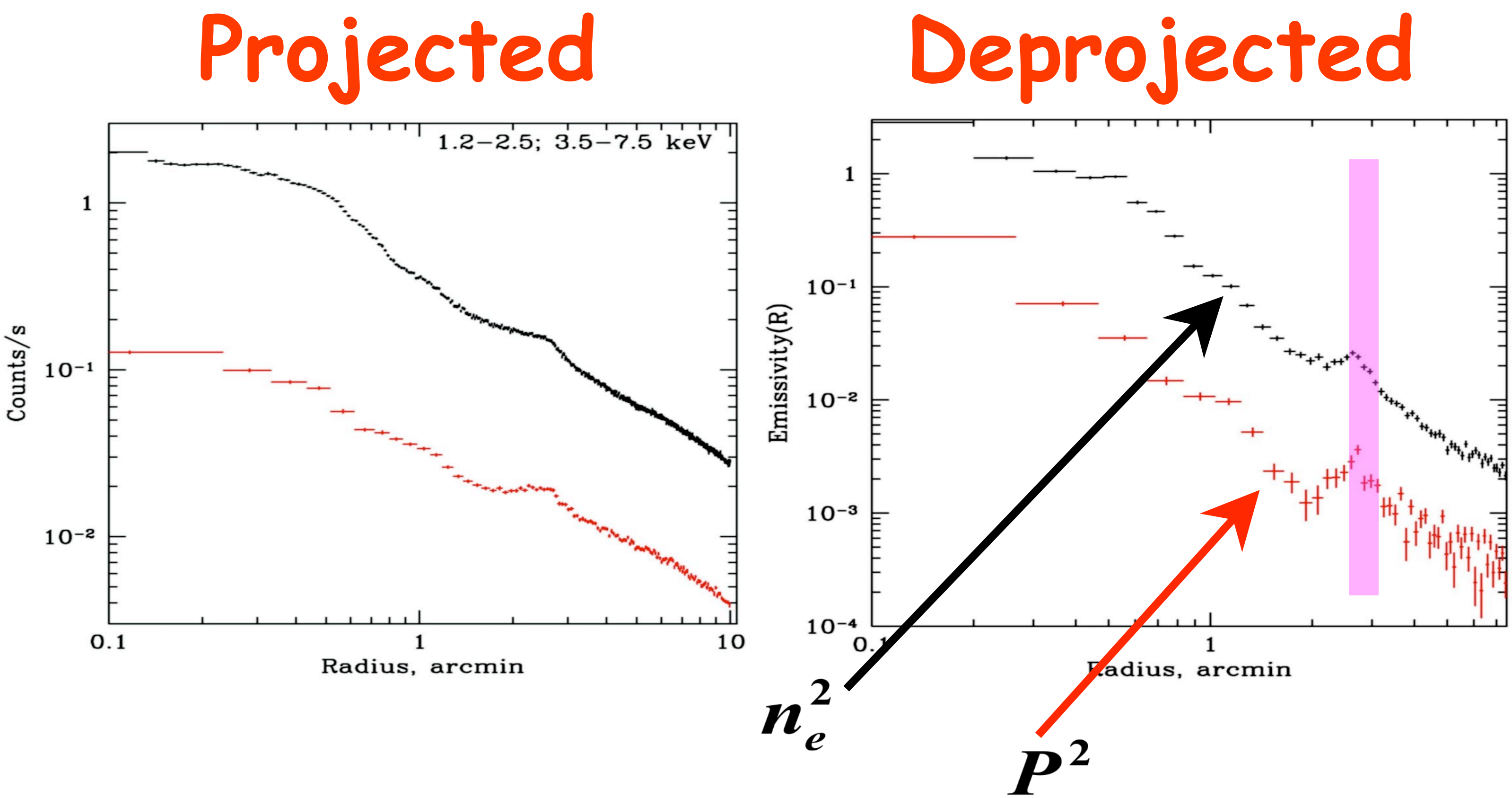
Central Piston = radio cocoon
Shock
Filamentary arms


Schematic
Shock
ICM
Bubble (Cocoon)
ICM
6 cm

Shock Model I - the data

Hard (3.5-7.5 keV) pressure

soft (1.2-2.5 keV) density profiles

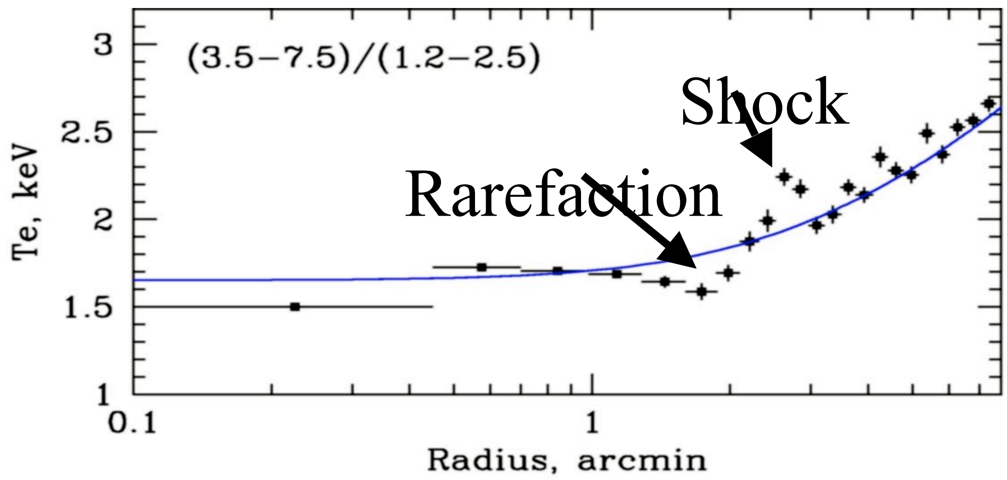


Radial profiles in soft (density) and hard (pressure) bands

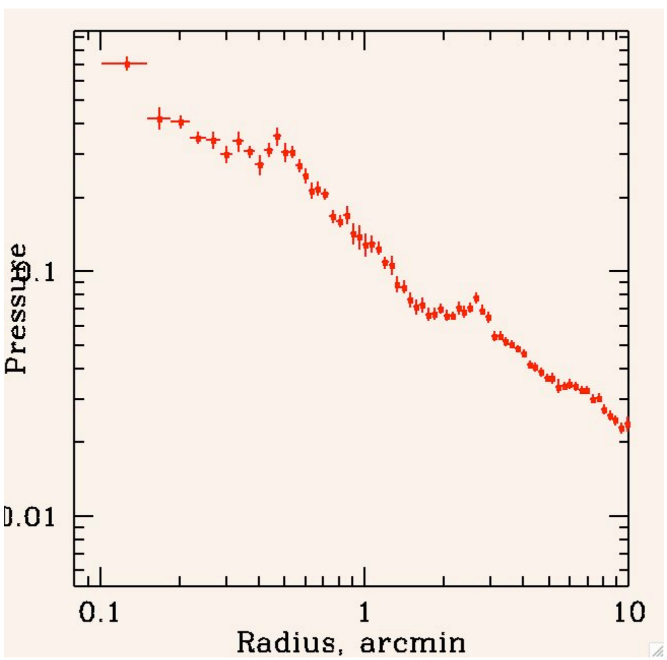
Both energy bands show shock

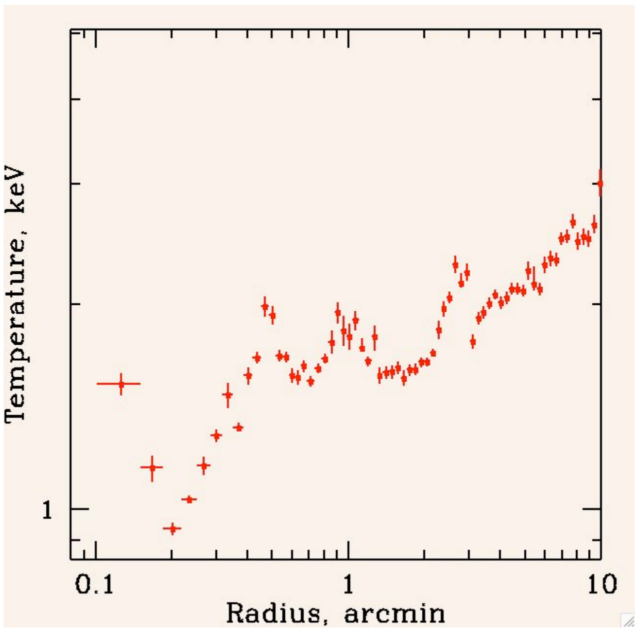
Deprojected Gas Temperature

Temperatures from Hardness ratios (hard/soft bands)



Complete spectral fits (temperature/abundance) with finer radial binning





Consistent **density** and **temperature** jumps

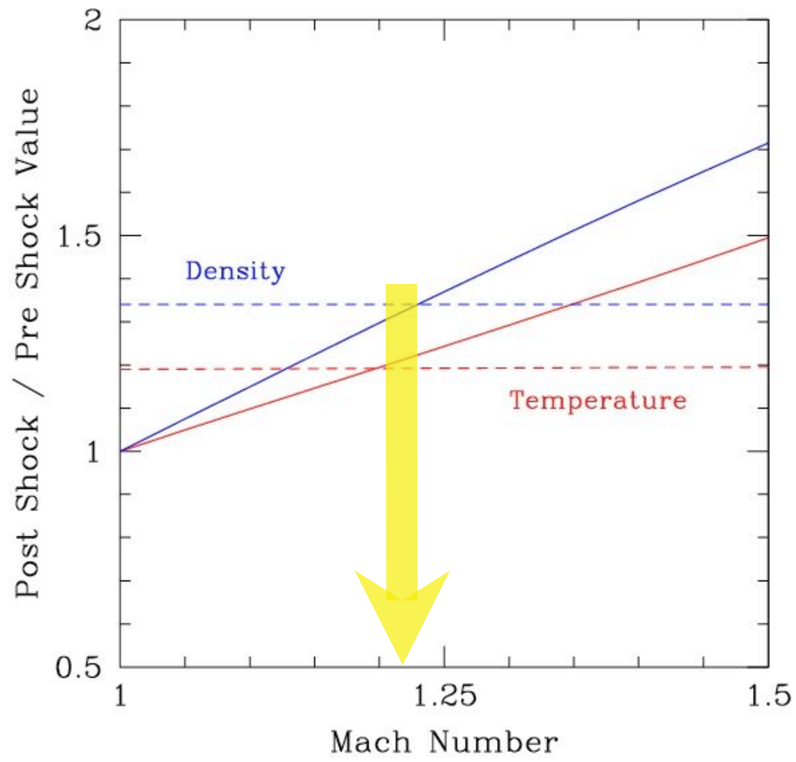
Rankine-Hugoniot Shock Jump Conditions

$$\rho_2/\rho_1 = \frac{(\gamma+1)M^2}{(\gamma+1)+(\gamma-1)(M^2-1)}$$

$$\rho_2/\rho_1 = 1.34$$

$$T_2/T_1 = \frac{\left[(\gamma+1)+2\gamma(M^2-1)\right]\left[(\gamma+1)+(\gamma-1)(M^2-1)\right]}{(\gamma+1)^2 M^2}$$

$$T_2/T_1 = 1.18$$

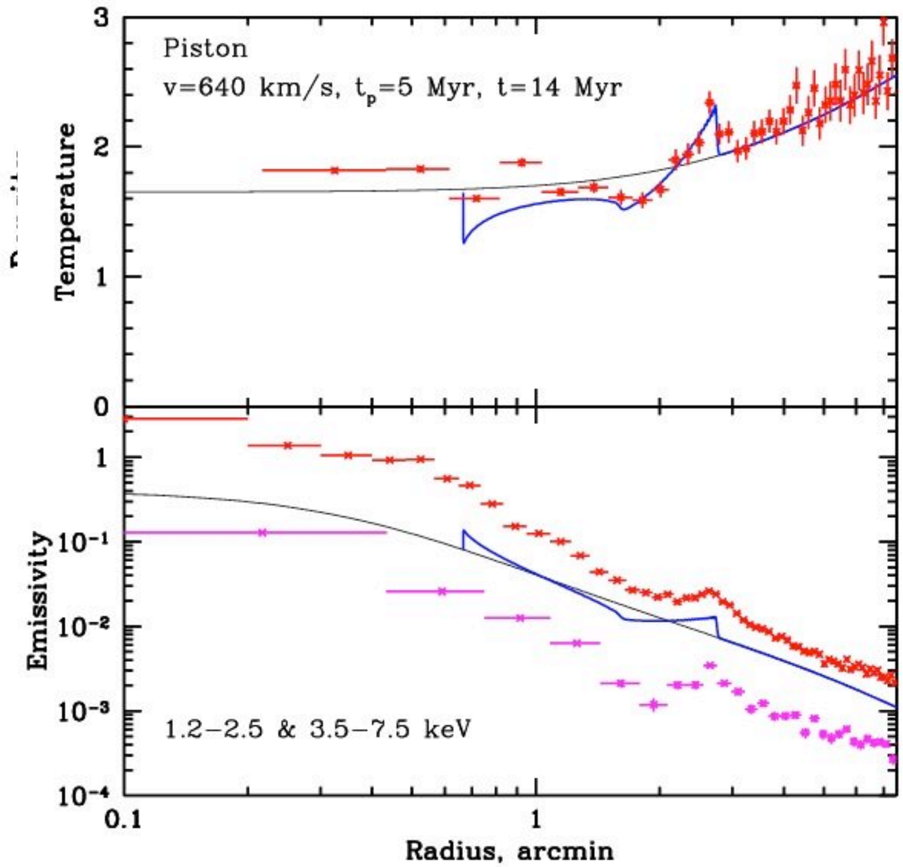


yield **same** Mach number:
($M_{T=}1.24$ $M_\rho=1.18$)

M=1.2

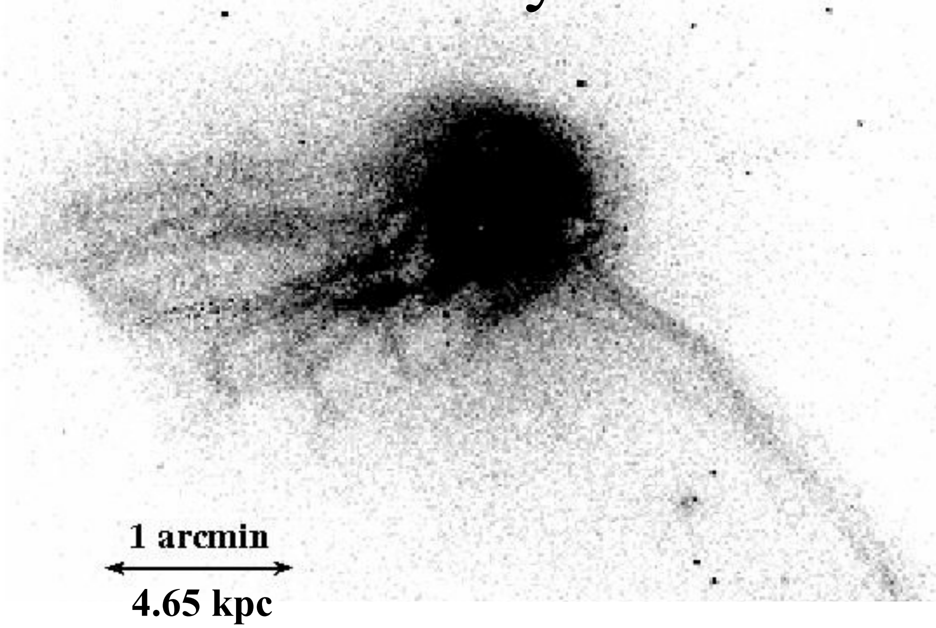
Outburst Energy

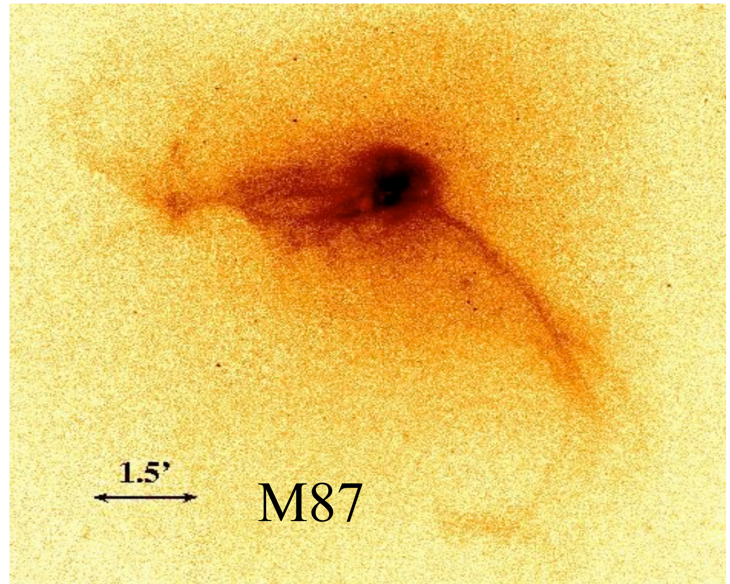
Series of models with varying
initial outburst energy
2, 5, 10, 20 x 10^{57} ergs
Match to data
E = 5 x 10 ^{57} ergs
Determined by jumps
Independent of duration

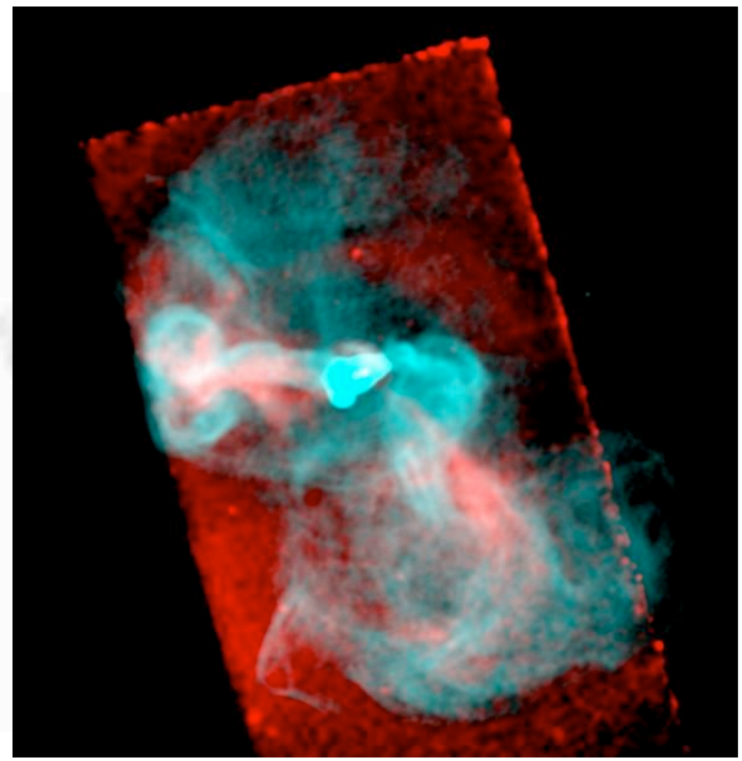


Absence of large shock heated region implies duration of outburst;
Cool material surrounds radio plasma cocoon
Timescale ~ 2 Myr
Energy balance from outburst:
25% in weak shock
25% shock heated gas
50% in buoyant bubble

Soft Filamentary Web







Sequence of buoyant bubbles

Many small bubbles (comparable to “bud”)

- PV $\sim 10^{54}$ - 10^{55} ergs
- $\tau_{rise} \sim 10^7$ years
- Arms - resolved
    - Eastern arm - classical buoyant bubble
    - Southwestern arm - overpressured and “fine’ (~100pc, like bubble rims)

M87 – Shocks and Bubbles Conclusions

Shocks and bubbles contribute to heating

Both naturally arise from AGN outbursts

Shock carries away ≤ 20-25% of energy

75% of outburst available to heat (bubble + shock heating)

Cool thermal rims of bubbles

Southwestern arm - interaction with radio plasma

Shock

Weak "classical" shock (M=1.2) - seen in T and density

R, jump in T or ρ => Total deposited energy 5×10^{57} erg

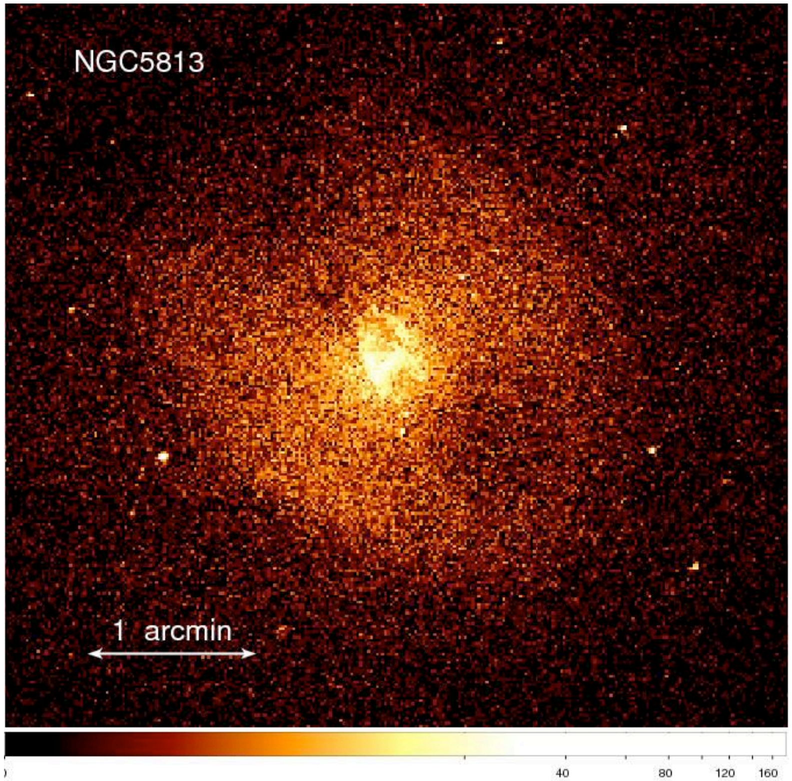
Cocoon and shock radius => Age ≈ 12×10^{6} yr

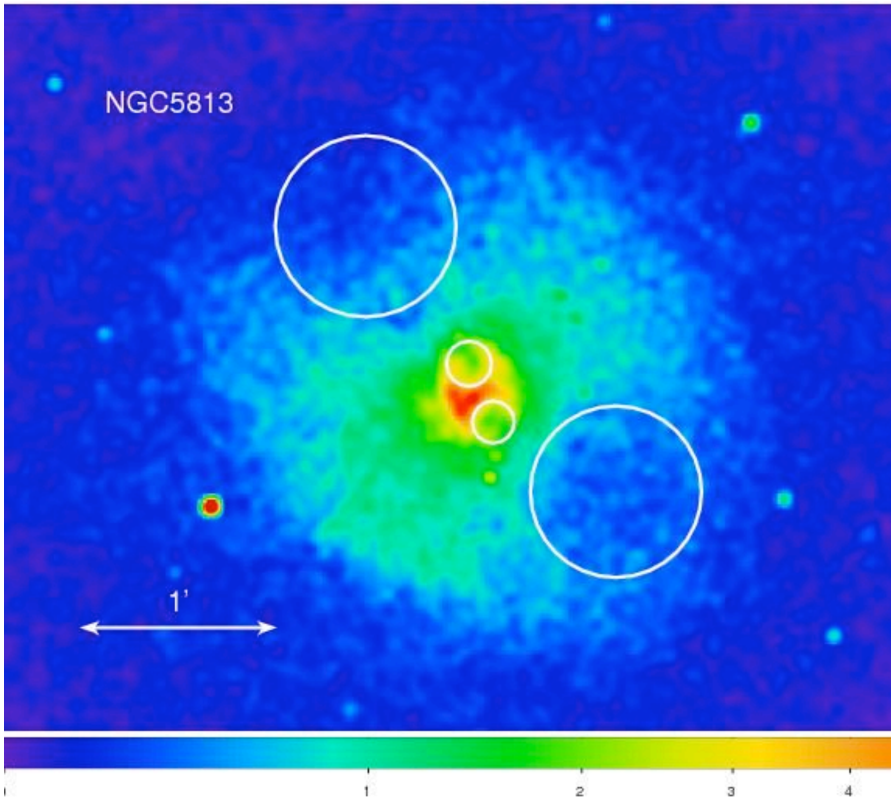
Cool/bright rims => "slow" energy deposition $2\text{-}5 \times 10^{6}$ years

Time averaged energy release:

few x 10^{43} erg/s ≈ Cooling losses in core

A Chandra survey of ~160 early type galaxies to measure outburst energy, age, frequency, plus diffuse/gas luminosity and nuclear emission (Jones et al.)





Pre Einstein - early type galaxies were assumed to be (cold) gas free

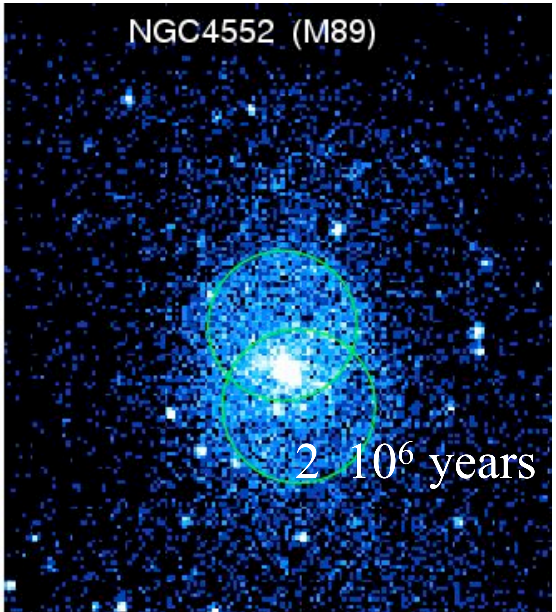
Contain as much hot as as spiral counterparts

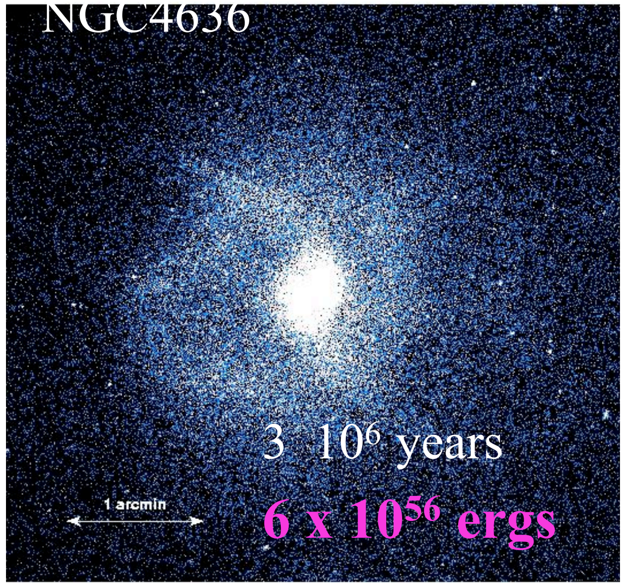
Study hot gas - as a function L_{opt}, velocity dispersion, ….

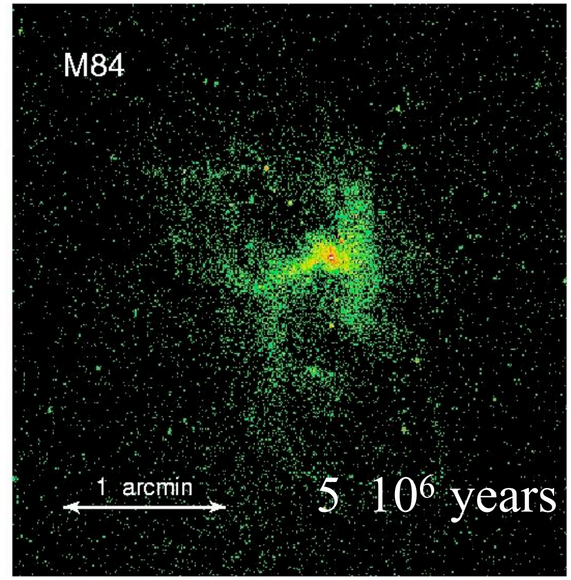
Measure cavities - determine outburst energies (PV) and timescales

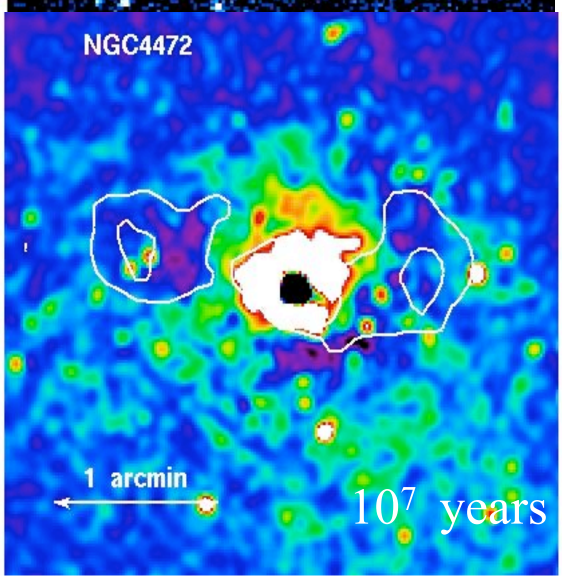
Derive nuclear luminosities - correlate with gas density

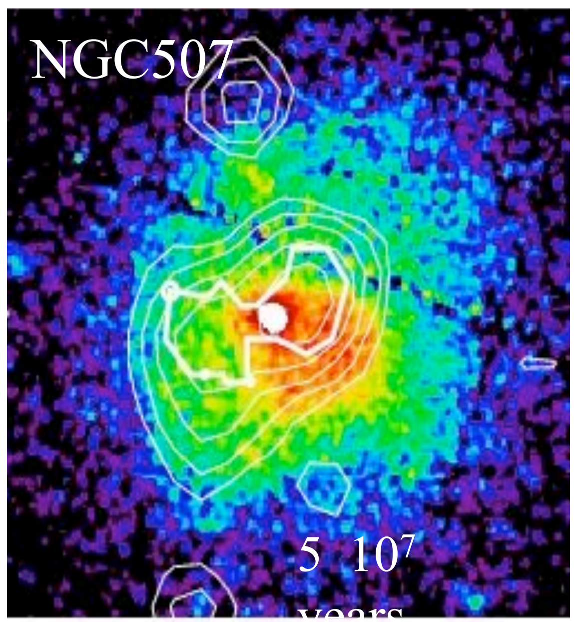
Galaxy rims are (generally) cool (like clusters) - weak shocks
Bubbles (seen as cavities) gently uplift and impart energy to the gas

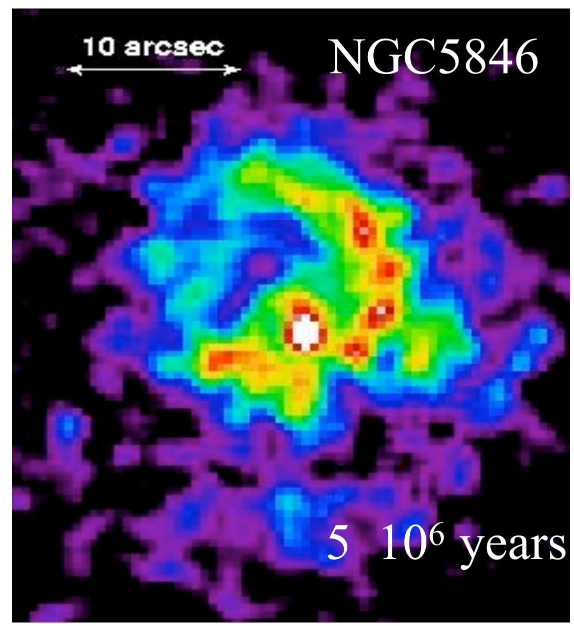








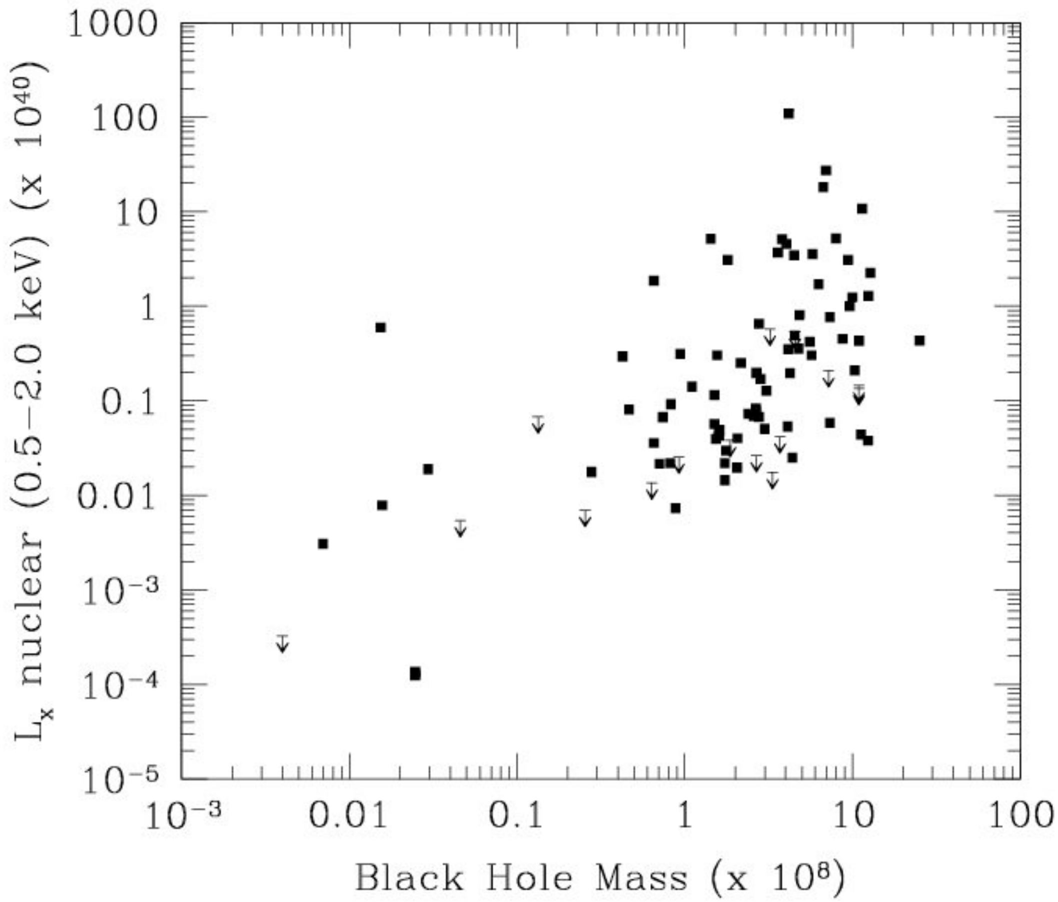




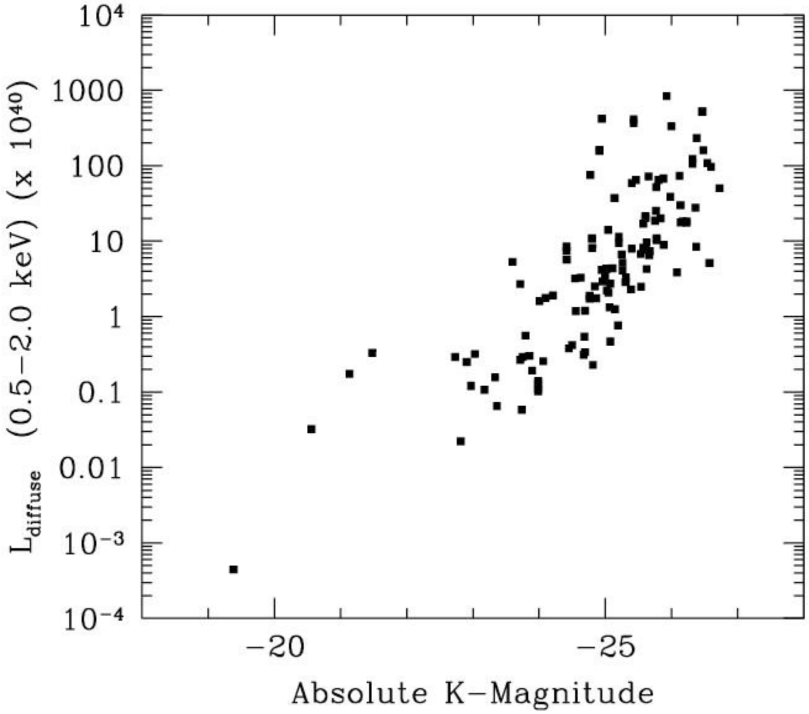
Nuclear activity - "AGN"
Determine fraction with nuclear X-ray emission

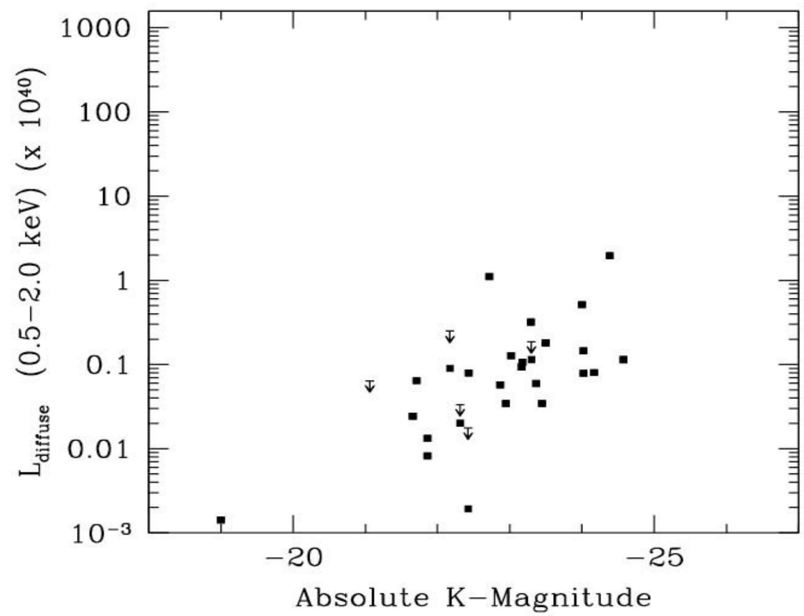
In "normal" early-type galaxies

•X-ray emission **detected** from the nucleus for ~80% of early-type galaxies



Luminous ellipticals - X-ray emission from hot gas
Fainter systems, emission from LMXBs dominates the “diffuse” emission





Gas dominates “diffuse” emission

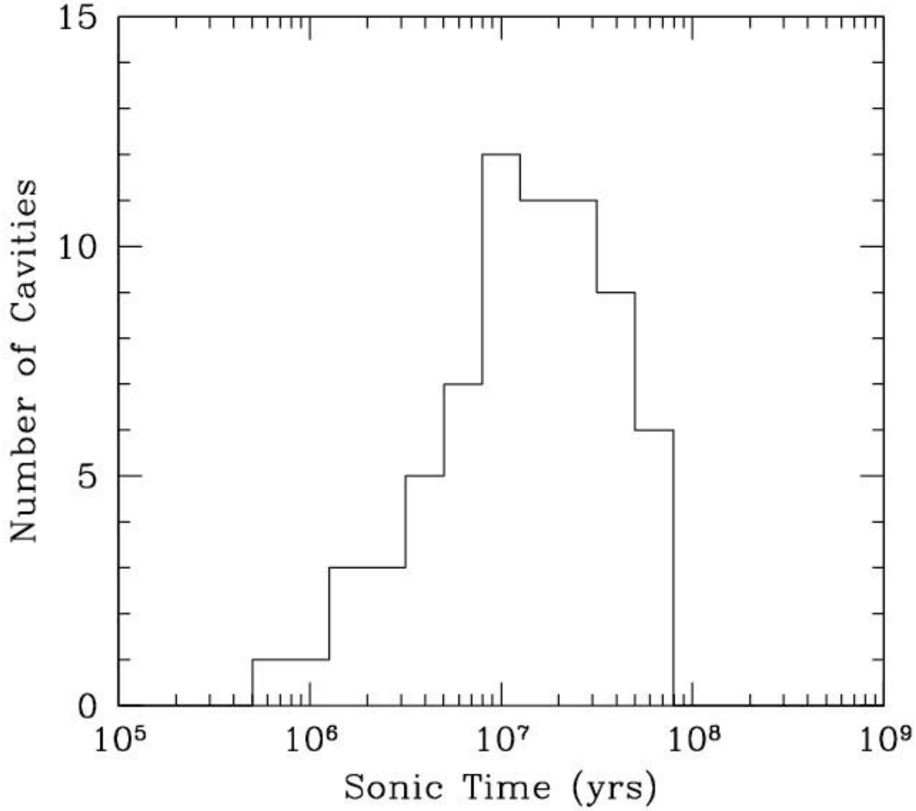
Correlation of L_x with $L_\star$ and $L_\bullet$ and σ

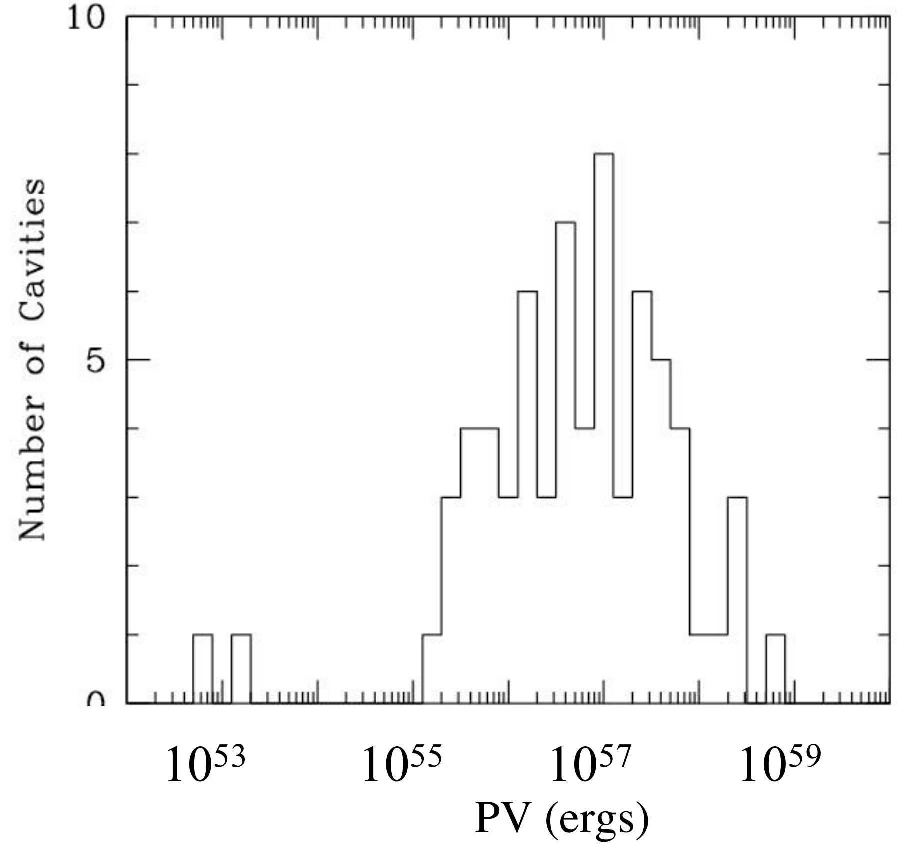
30% have cavities (mostly above K=-24)

Measure rise/buoyancy time and energy required to excavate cavities (PV)

Galaxies with little hot ISM Mostly unresolved LMXB’s (hard spectra) and some active stars/CV's (soft and hard component Revnivtsev et al.)

In galaxies, outbursts are recent (=> frequent) and impart significant energy to the ISM





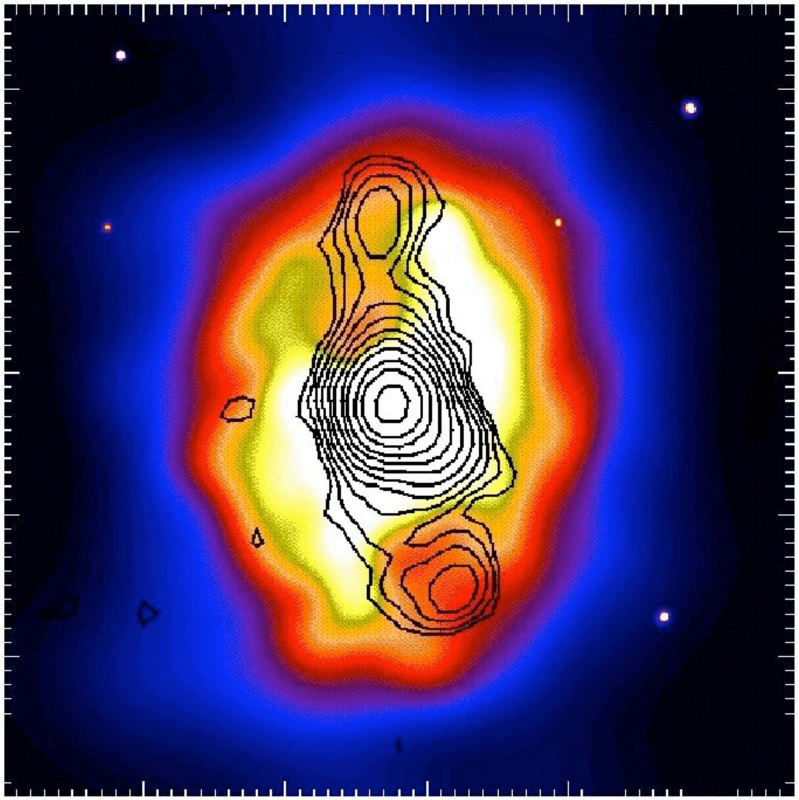
Ages and outburst energy for 27 systems with cavities

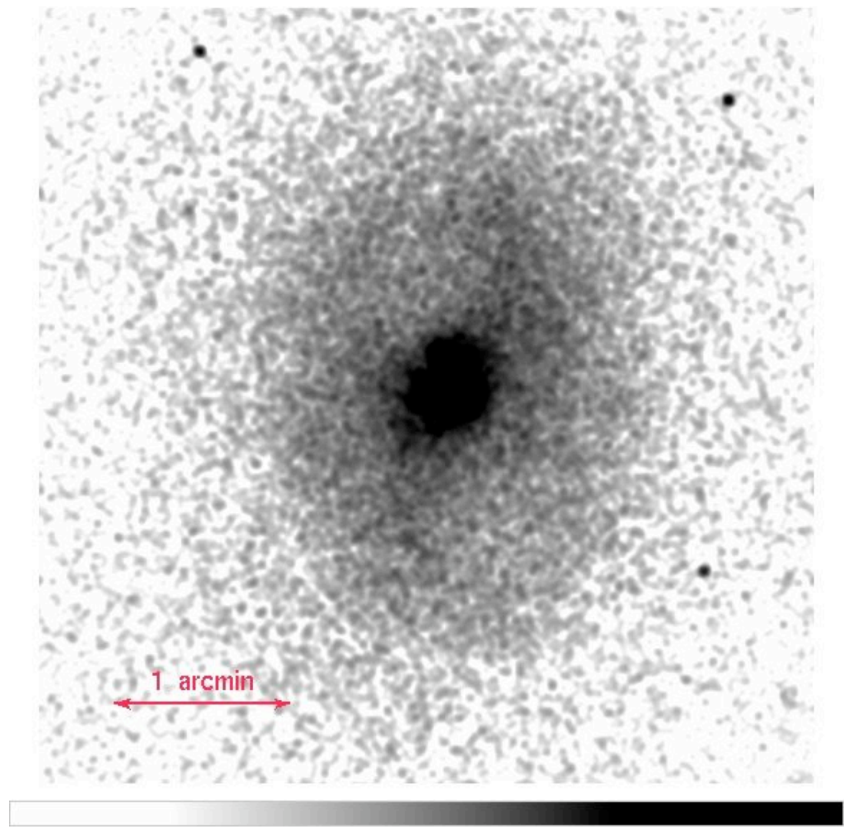
Note - hard to see (older) cavities at large radii - "contrast" is low

Cluster Scale Outbursts

MSO735.6+7421   6 X 10^{61} ergs driving shock

(McNamara et al 2005)





Cluster $L_x = 10^{45}$ ergs/sec   z=0.22

X-ray bright region - edge of radio cocoon lies at location of shock

Radio lobes fill cavities (200 kpc diam) - displace and compress X-ray gas

Work to inflate each cavity ~10^{61} ergs; age of shock 1 X 10^8 years

Average power 1.7 X 10^{46} ergs/sec (0.1 mc^2) needs 3 x $10^8 M_{sun}$ - one way to grow black holes!

Outbursts from Clusters to Galaxies

SOURCE	SHOCK RADIUS (kpc)	ENERGY (10^{61} erg)	AGE (My)	MEAN POWER (10^{46} erg/s)	ΔM (**10^8 M_{sun}**)
MS0735.6	230	5.7	104	1.7	3
Hercules A	160	3	59	1.6	1.7
Hydra A	210	0.9	136	0.2	0.5
M87	14	0.0005	14	0.0012	0.0003
NGC4636	5	0.00006	3	0.0007	0.00003

Growth of SMBH by accretion in "old" stellar population systems
(Rafferty et al. 2006 - $\dot{M}_{BH} \approx 0.1 - 1$ solar mass/yr)
with star formation to maintain M_{BH}-M_{bulge} relation
Mechanical power balances cooling in 50% of clusters
AGN outbursts deposit energy into gas through shocks and bubbles

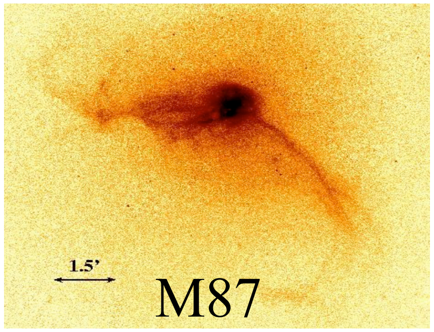
AGN outbursts and Coronae

•**M87 outburst $\tau \sim 15 \times 10^6$ years, $\Delta\tau \sim 2\text{-}5 \times 10^6$ years**

"classical shock - seen in density and temperature

Outburst energy matches cooling

Slow expansion of "piston" (no large shock heated region) - 50% of energy in bubbles

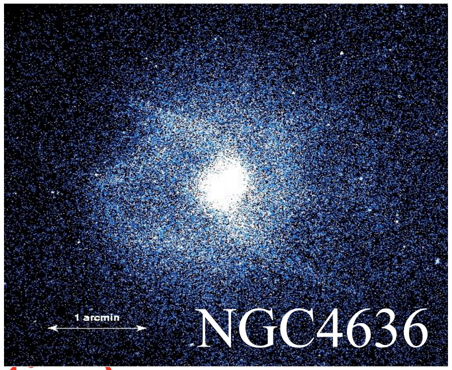


M87 arms from buoyant bubbles; soft filamentary web

Complex (magnetic field) interactions of radio plasma bubbles with ISM

•Galaxies

- **outbursts are common - 30% of early type galaxies show cavities; $\tau \sim 10^6$ - 10^8 yrs, $E \sim 10^{55}\text{-}10^{58}$ erg/sec**
- **"AGN" are common - 80%detected $L_{AGN} \sim 10^{38}\text{-}10^{41}$ erg/sec mini-AGN**



•Outbursts from galaxies to clusters $10^{55}\text{-}10^{62}$ ergs

- **Measure mechanical power (dominates SMBH radiation)**
- **grow SMBH (sometimes significantly)**
- **Reheat cooling gas through shocks/buoyant bubbles in all gas rich systems**