Outbursts from Supermassive Black Holes and their Impacts on the Hot Gas in Galaxies and Clusters

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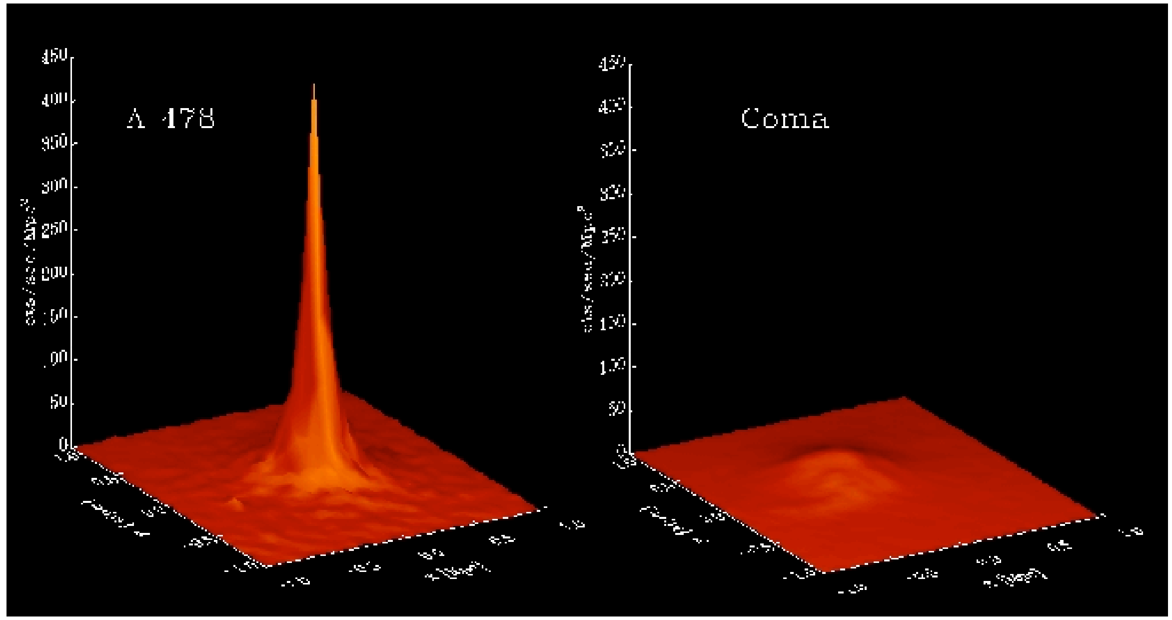
entire Chandra team

- Outbursts in clusters -- Perseus, M87, Hydra A, MSO735 & Hercules A
    - -- where did the gas in cooling flows go?
  - Spectacular Shocks
  - Plasma bubbles interacting with hot gas
- Outbursts in elliptical galaxies
  - Centaurus A -- the jet, counterjet and radio lobes
    - Interaction of the jet with the ISM
  - Other "normal" exploding galaxies in Virgo - NGC4636, M84, NGC4552
  - An Chandra survey of ellipticals
    - The X-ray luminosity of SMBH in "normal" galaxies
- Reflections of outbursts in surrounding gas show the history of AGN outbursts

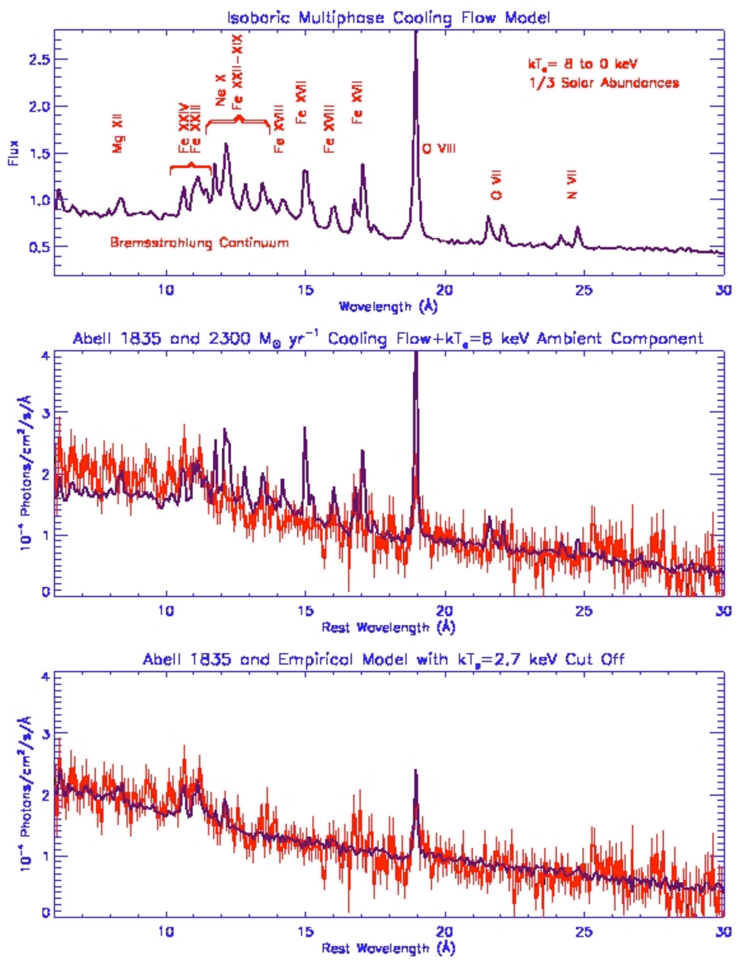
Cluster Cooling Flows



Allen/Fabian

- **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 cools unless reheated
- ROSAT, Einstein and ASCA showed cooler gas in cores
- Have central dominant galaxy - 80% have radio emission
- But large amounts of cool gas were not detected
- True test for cool gas would come from X-ray spectroscopy

Standard CF model predicts Large Amounts of Cold Gas



"Standard" Model

Gas Cools and settles over wide range of radii

Mass Deposition rates are large (1000 M/yr)

BUT

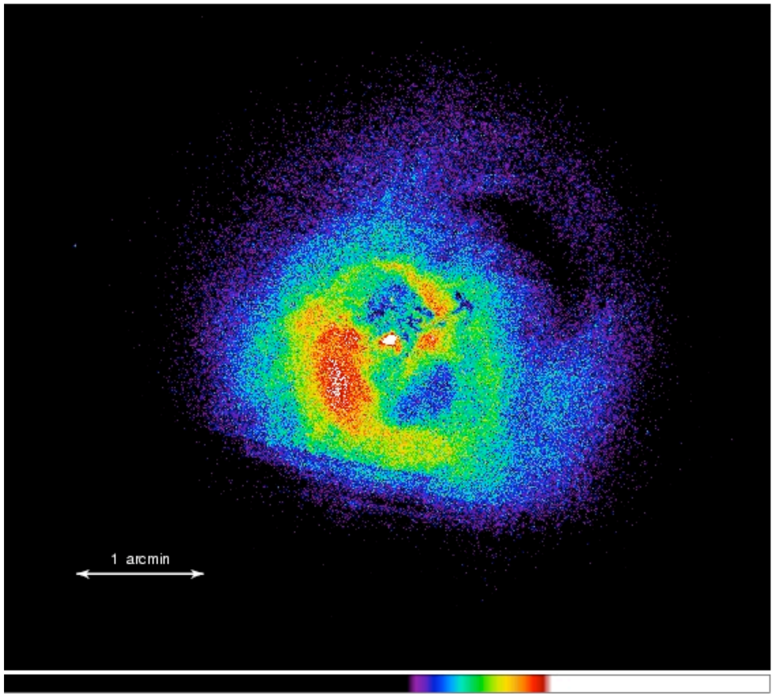
NOT SEEN BY XMM-NEWTON OGS

(cool gas only 10-20% of prediction)

(e.g., Peterson et al. 2001, 2002)

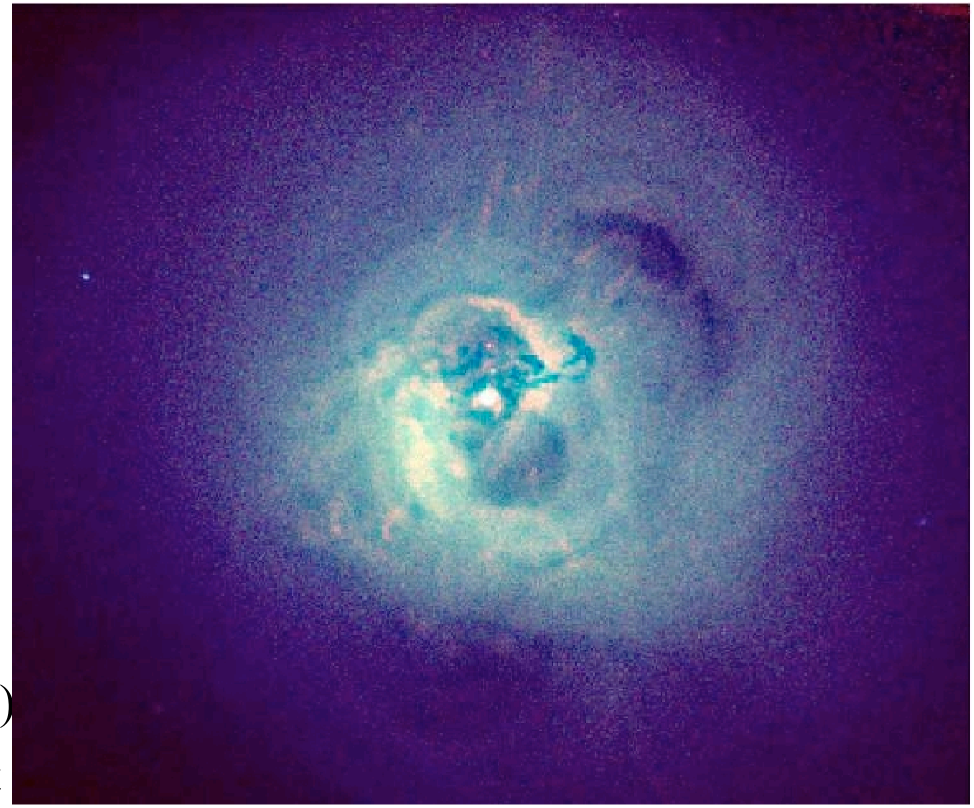
Gas Heating Mechanisms

- Cluster-subcluster mergers – plenty of energy (10^{64} ergs), but not dependable (plus cooling flow clusters appear relaxed)
- Thermal Conduction – from hot outer cluster gas to cool centers; see Tucker & Rosner 1983, Bertschinger & Meiksin 1986, Geatz 1989, Narayan and collaborators, probably not effective at center
- Energy from AGN Rosner & Tucker 1989, Böhringer & Morfill 1989, Binney & Tabor 1995, David & Tucker 1997, Churazov et al. 2001, Markevitch 2003
  - Bubbles
  - Shocks



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

- 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, τ=9.6x10^6 yr
  - Dissipate energy (high ion viscosity) over a distance < 100 kpc (Lamb 1879)
- Energy of bubbles/shocks is sufficient to balance cooling.



See Fabian et al. 2005

Color image (0.3-1.5 keV = red, 1.5-3.5 keV = green,), 3.5-7.0 keV= blue)

"sound wave pitch is B flat, 57 octaves below middle-C. much too deep to be heard (10^{15} times below limit of human ear)."

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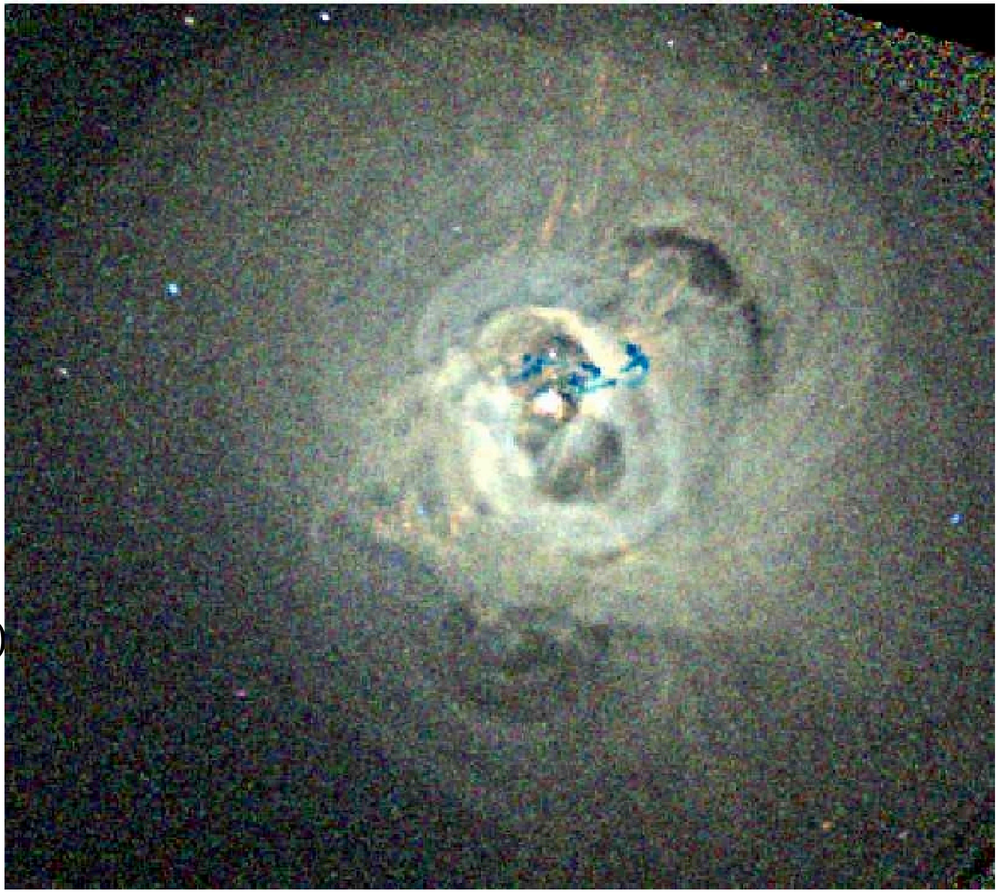
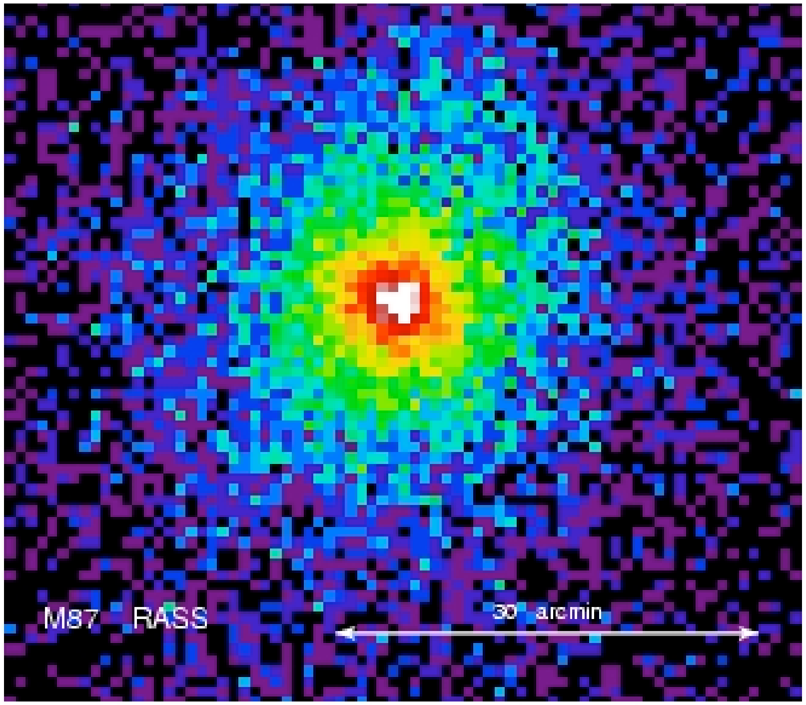
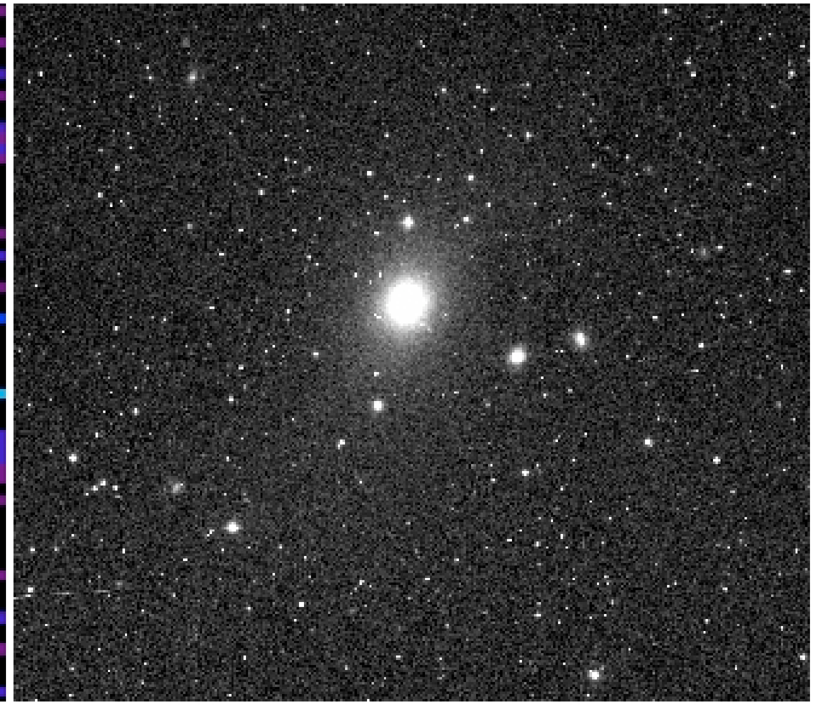


See Fabian et al. 2005

M87 Central Elliptical in Virgo (16 Mpc)

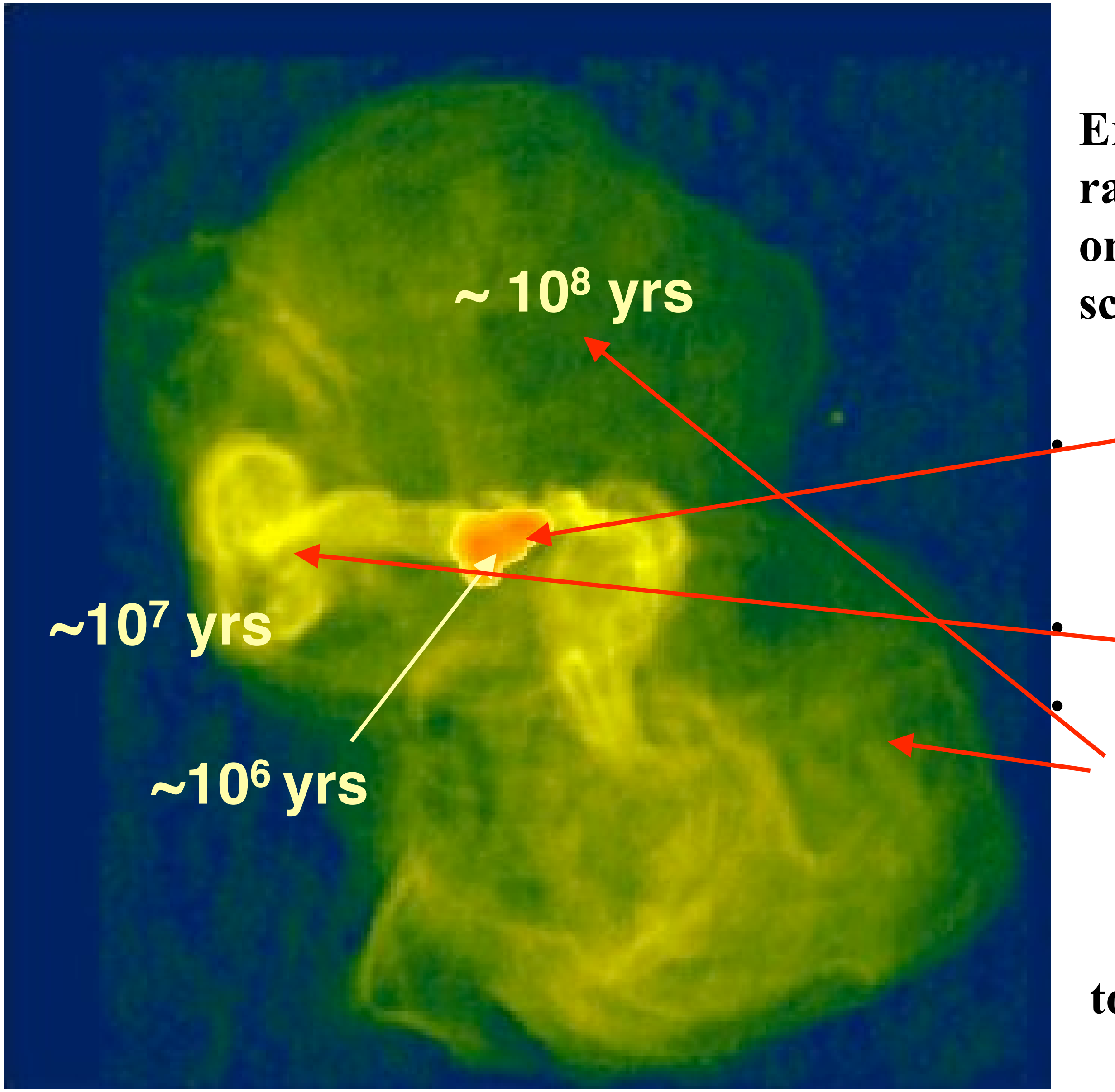




M87 with its proximity, active nucleus, jet and radio lobes is an ideal system to study the energy input from the AGN into the cooling gas with Chandra, XMM-Newton and the VLA.

Repetitive Radio Outbursts in M87

(Owen et al. 2000)

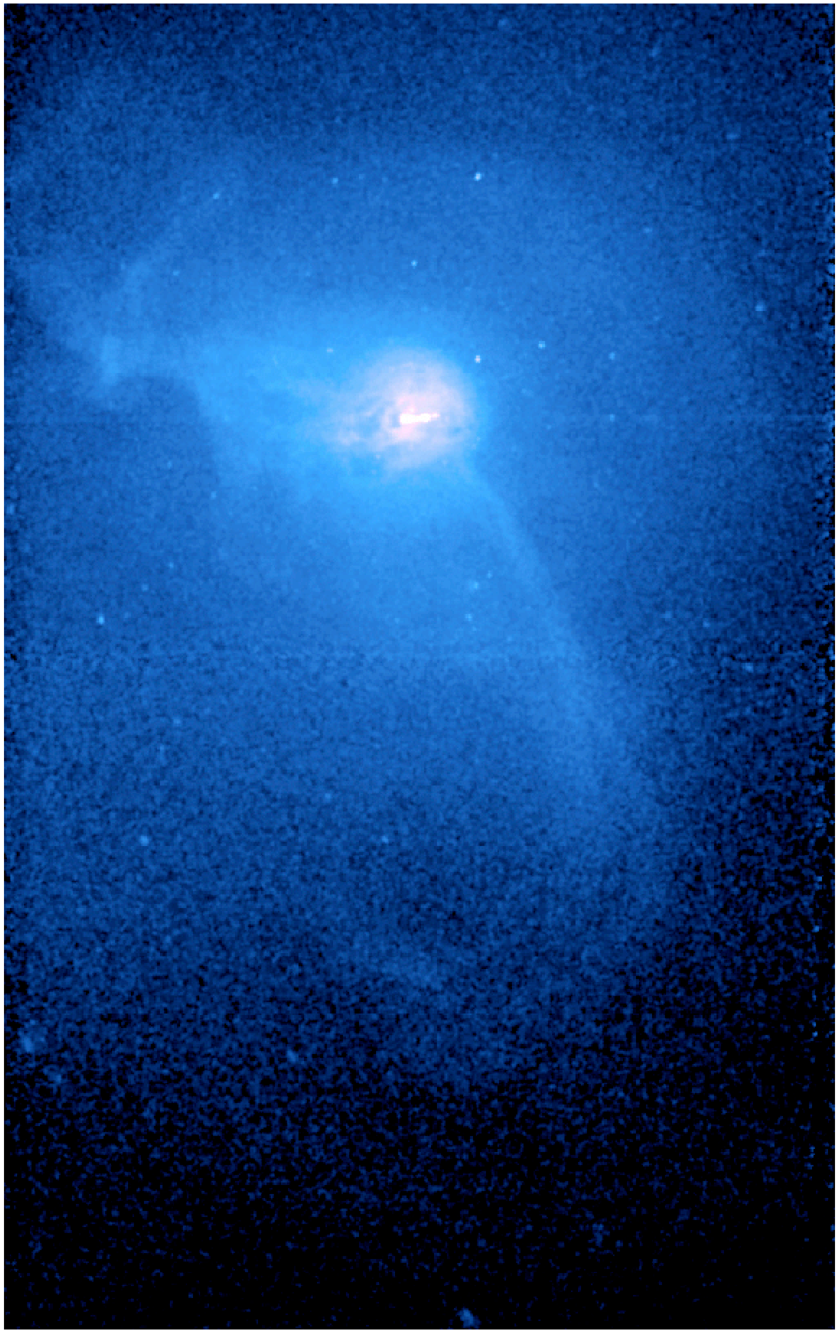


Energy input into the radio halo around M87 on three different time scales

- Inner jets 10^6 yr (Bicknell & Begelman 1996)
- Eastern arm 10^7 yr
- Outer pancakes 10^8 yr (Owen et al. 2000)

within ~ 40 kpc

total energy ~ 3 10^{59} ergs

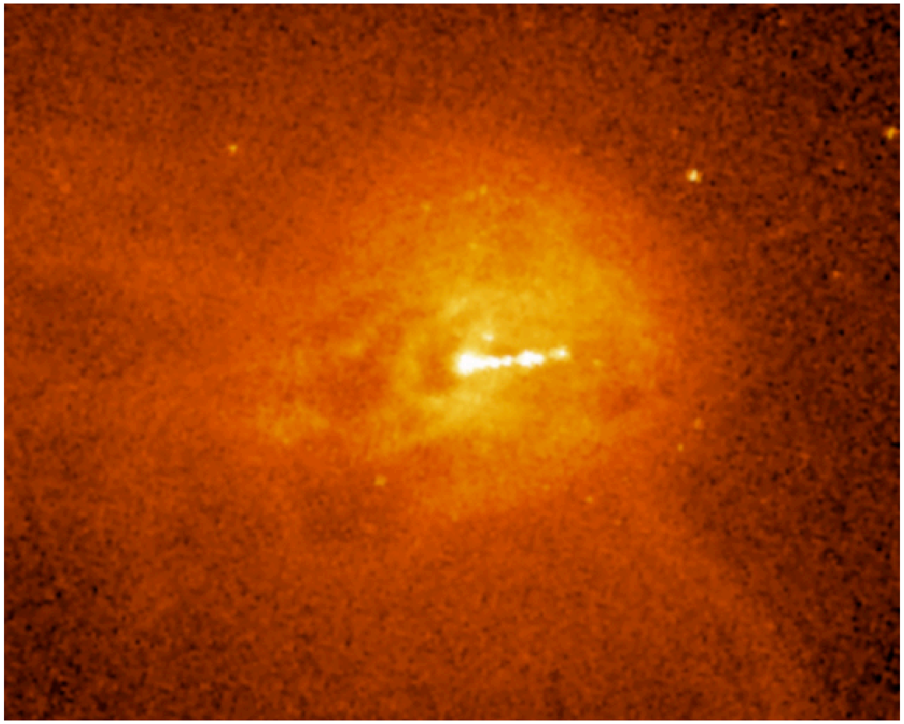


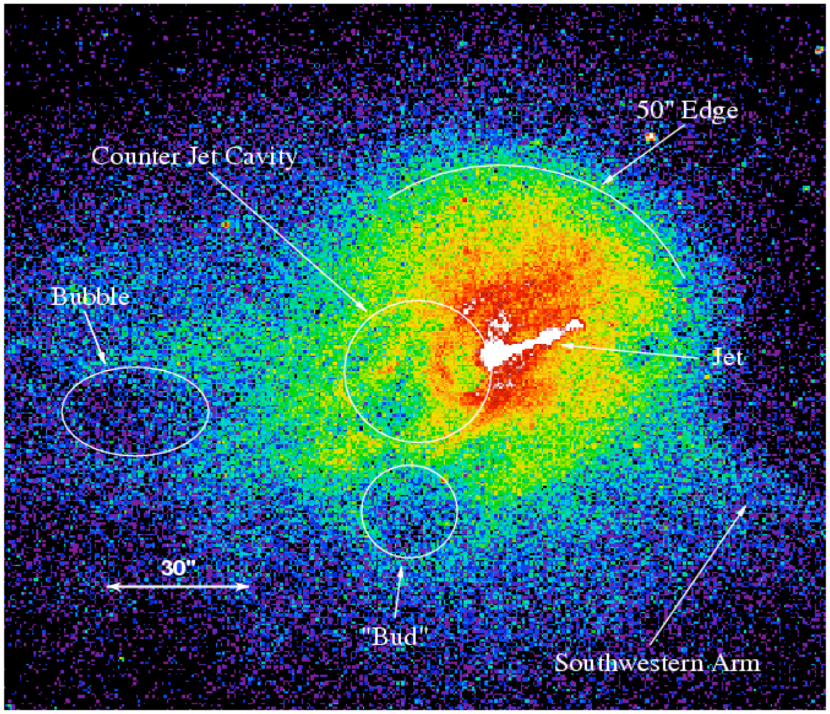
M87 with Chandra

- ACIS observations
  - •37 ksec in July 2000
  - •100 ksec in July 2002
- •Bright central region
- •X-ray-Radio arms
- •Shocks

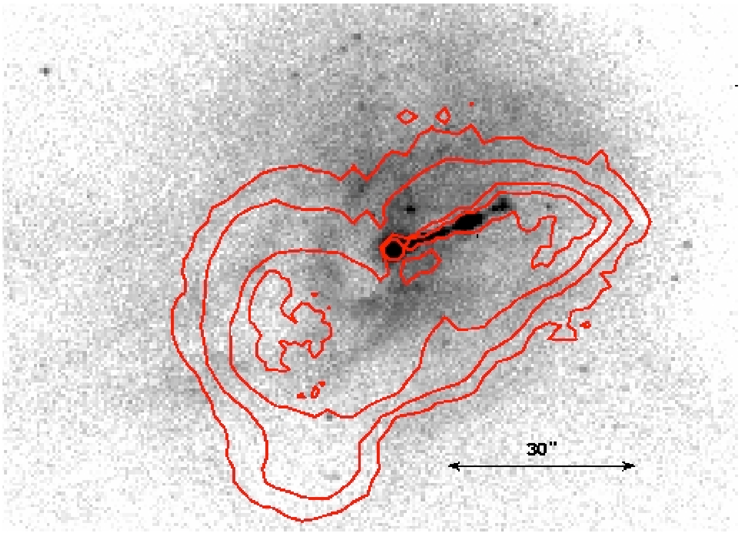
Forman et al. Ap J

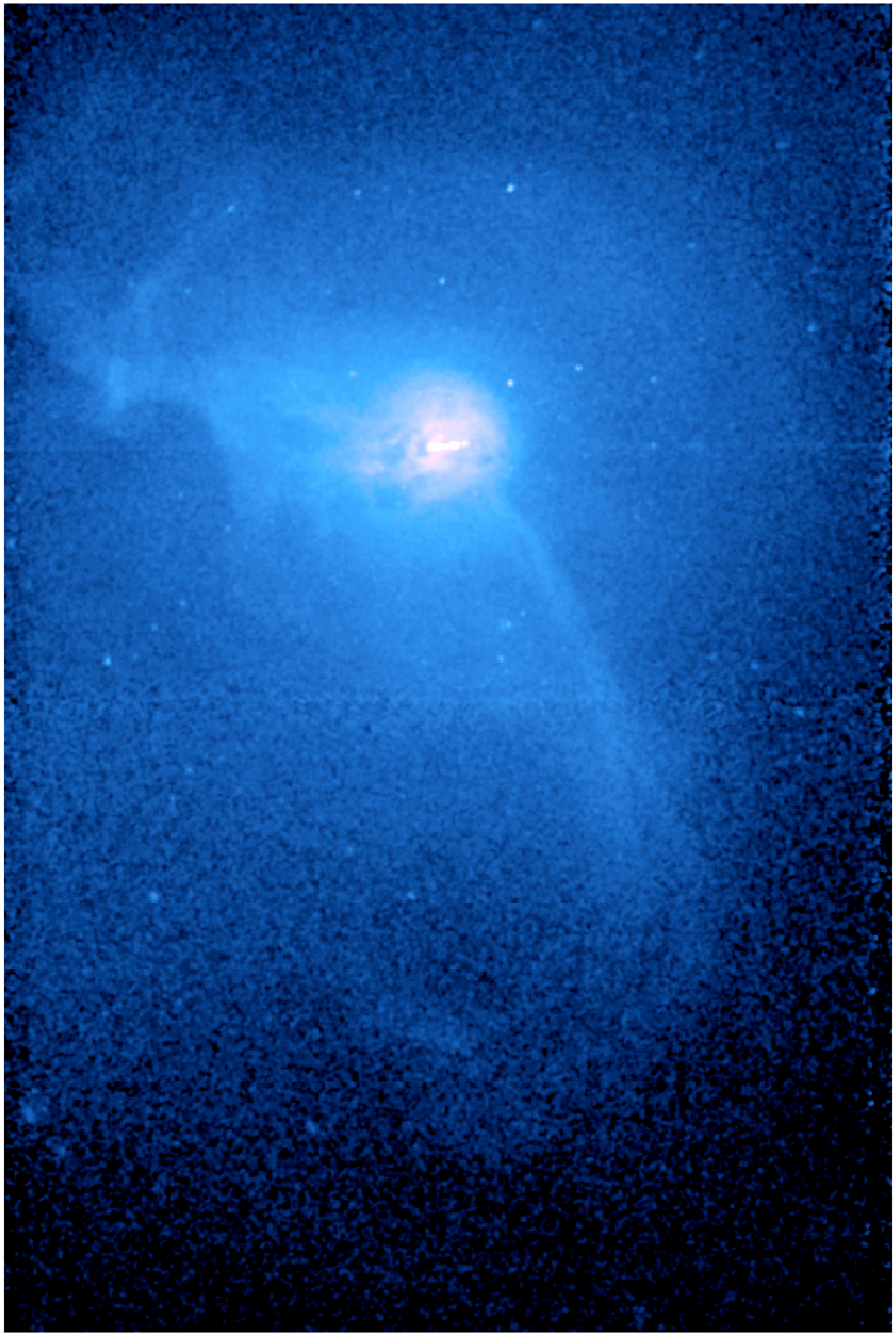
X-ray Features in the Central Region of M87





- The X-ray jet.
- X-ray cavities surrounding the jet and the (unseen) counterjet.
- X-ray cavity associated with the 'budding' bubble to the S/SW.
- X-ray bright core region.
- Cavities/bubbles in the eastern arm





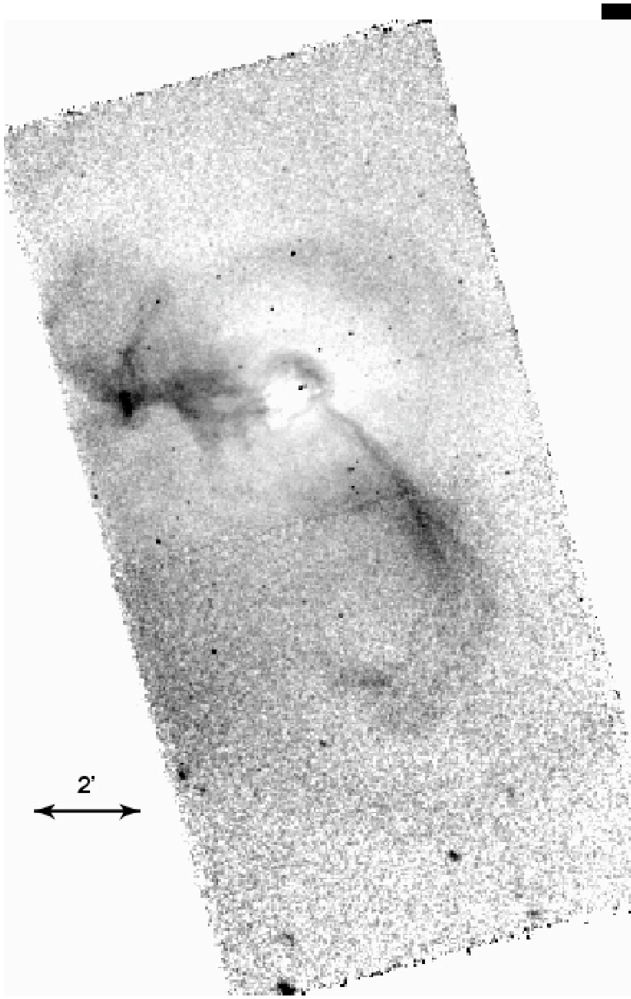
M87 arms & arcs

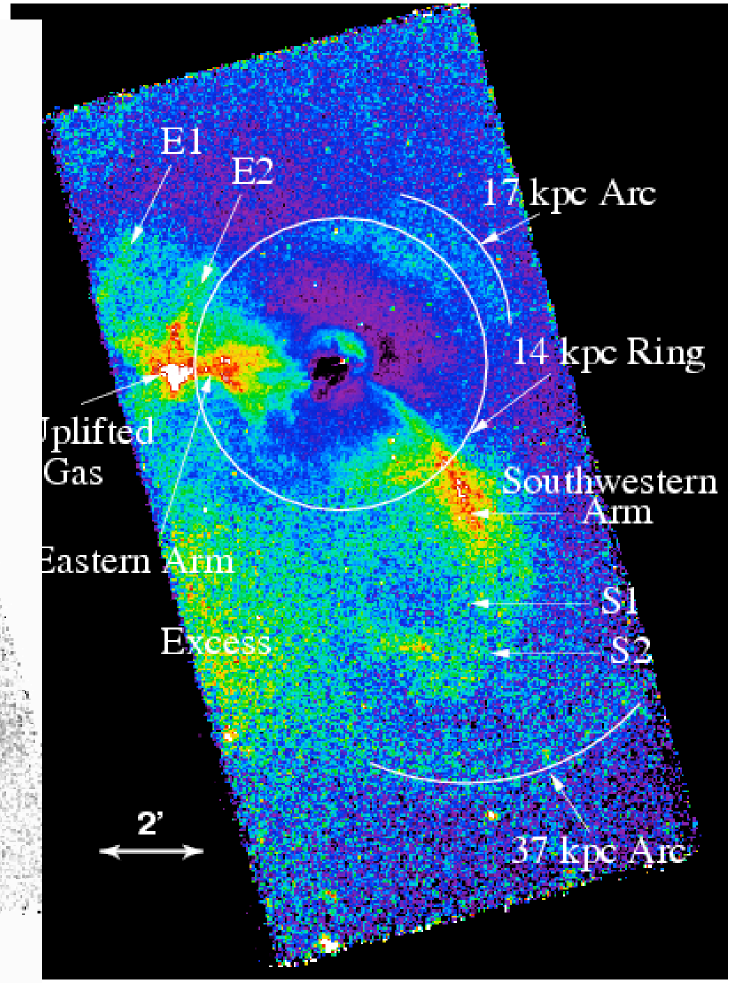
14 kpc ring and 17 kpc arc
-- two shocks

•Arms brighten at shock, then divide.

•Southwest arm (30 kpc), smooth, regular “plume”

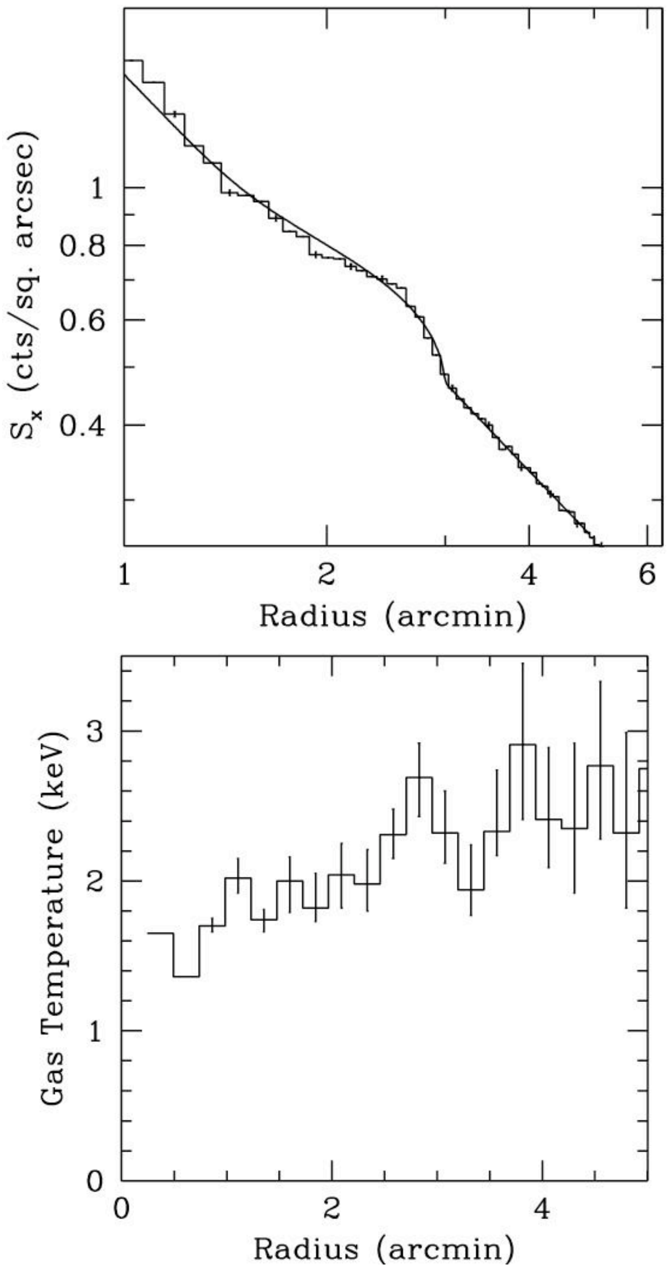
M87 Large Scale structures– azimuthally symmetric emission subtracted





We model the azimuthal rings as surface brightness discontinuities due to shock waves.
The shock model that matches the observed 14 kpc features is characterized by an explosion of $8x10^{57}$ ergs about 10^7 years ago.
The shock is mildly supersonic (M=1.2, v=950 km/s).

The 17 kpc ring was created by an outburst ~ $4x10^6$ yrs before the one that created the 14 kpc ring.



Surface brightness and temperature profiles

The 14 kpc Ring

- •Shocks driven by rapid expansion of inner radio lobes
- •Model SB and temperature - requires energy input of 8 10^{57} ergs, ~10^7 years ago
- •Shock is mildly supersonic M~1.2 (vel ~ 950 km s^{-1})
- •17 kpc arc - similar amplitude, so similar energy. ~ 4 10^6 years earlier.

Many X-ray features are a direct result of repetitive AGN outbursts.

Shocks are probably most significant channel for AGN energy into cooling gas.

For M87, energy in shock ($\sim 8\ \ 10^{57}$ ergs) greater than enthalpy in the cavities ($\sim 2\ \ 10^{57}$ ergs)

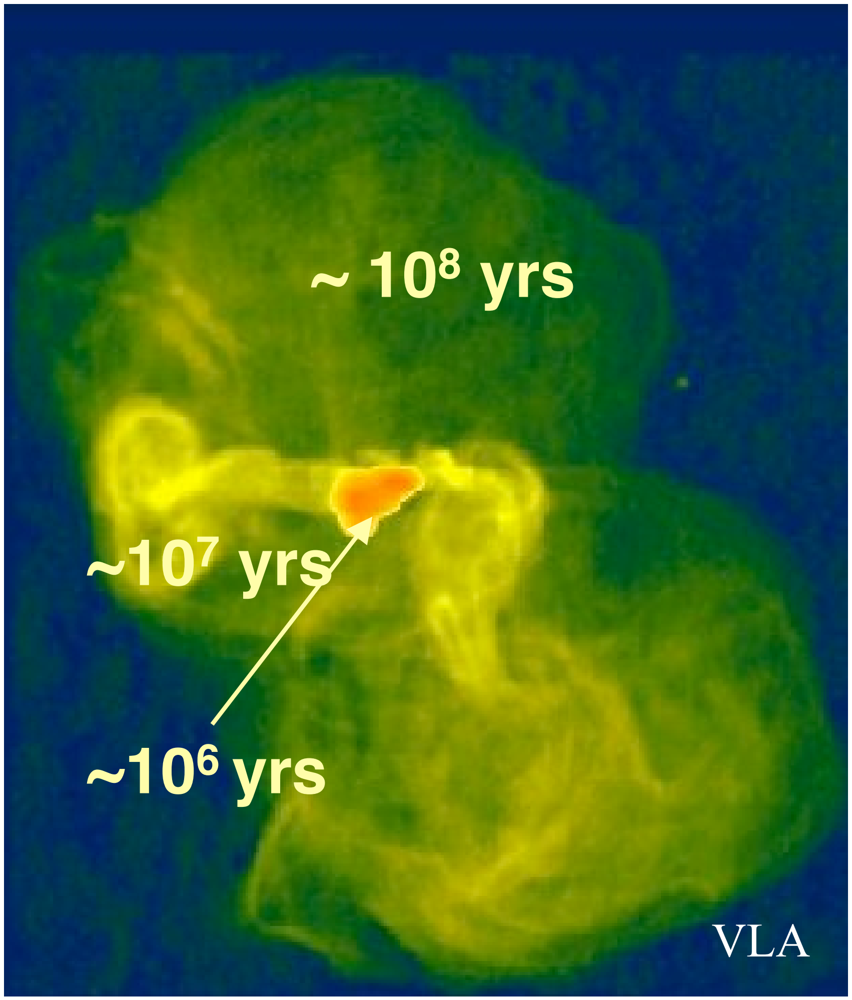
- Radiative loss from a cooling flow (within 70 kpc) is $\sim 10^{43}$ ergs s^{-1}. Outbursts every few 10^7 years are enough to reheat the gas.

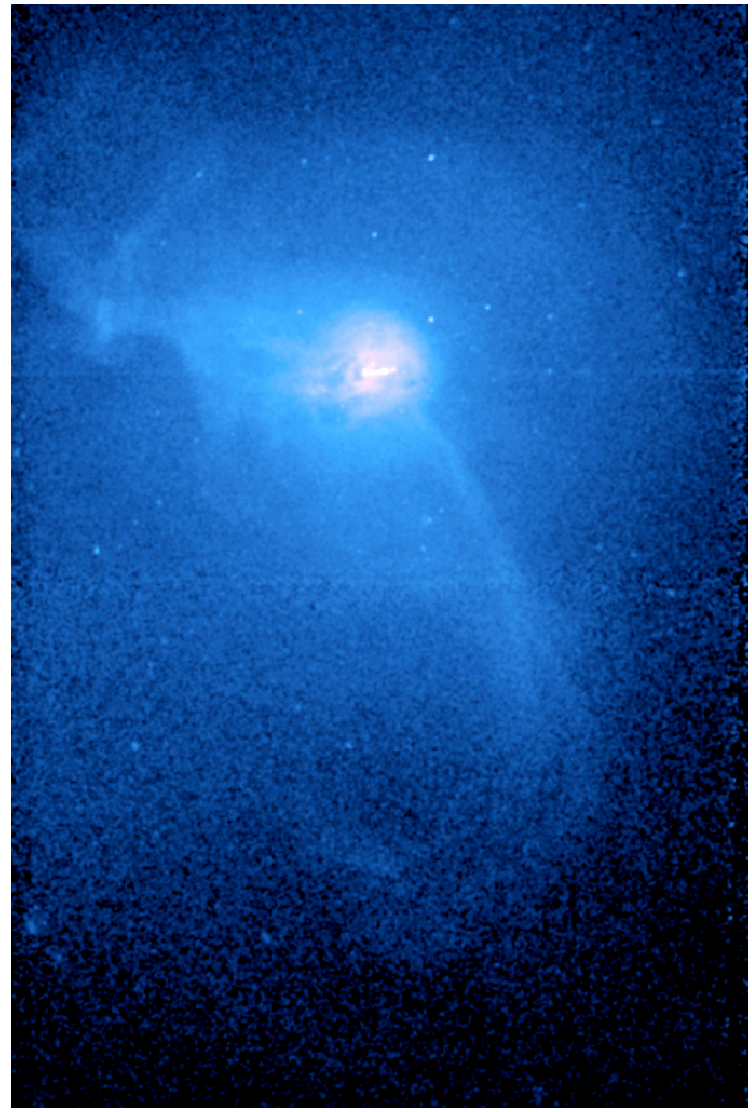
But shocks may not be the whole story.

Buoyant bubbles and arms in M87

Arms may provide a second mechanism for uplifting cool gas from the core.

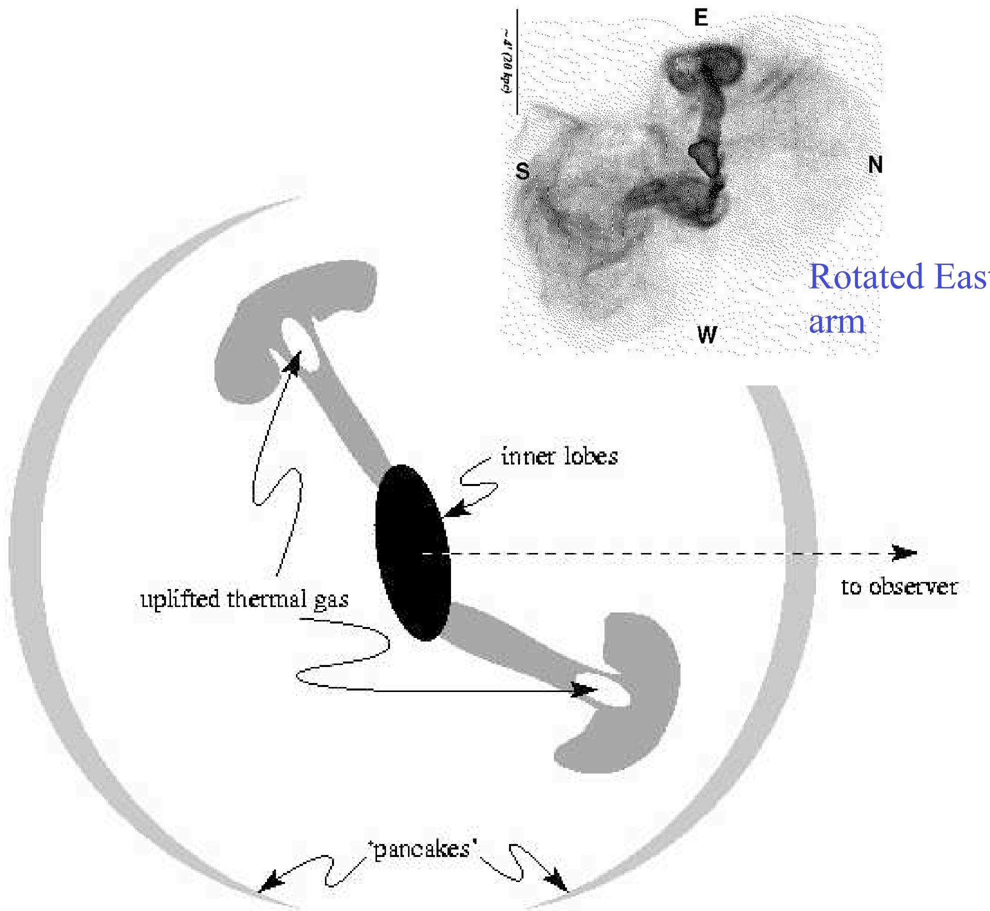
For Churazov et al. model rotate East arm





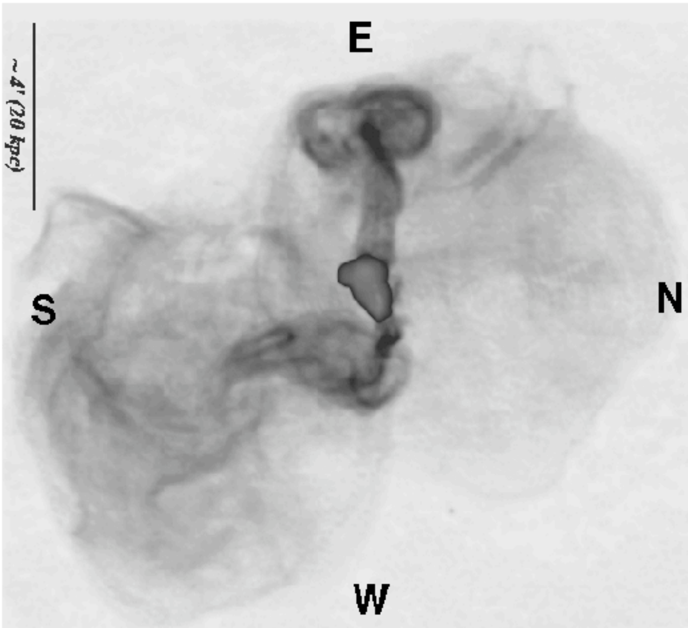
M87 – multiple bubbles

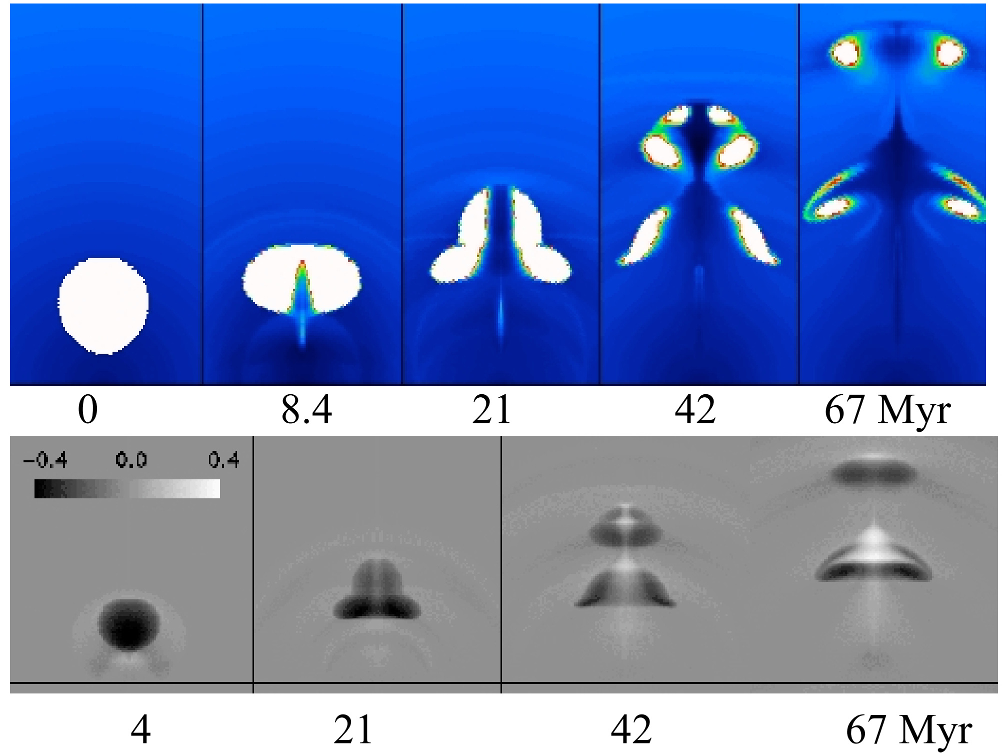
- •Three sets of bubbles
  - •Inner lobes (youngest)
  - •Rising mushrooms (arms)
  - •Pancakes (oldest)
- • Radio bubbles lose > 50% of the internal relativistic energy by adiabatic expansion
- • Further energy loss by uplifting ambient material
- •Bubbles rise rapidly
  - •400-700 km/sec



Churazov et al. 2001

Bubbles – The Model (Churazov et al.)





•AGN inflates buoyant plasma bubble (20 x 40 and 40 x 40 kpc boxes) which rises and entrains gas

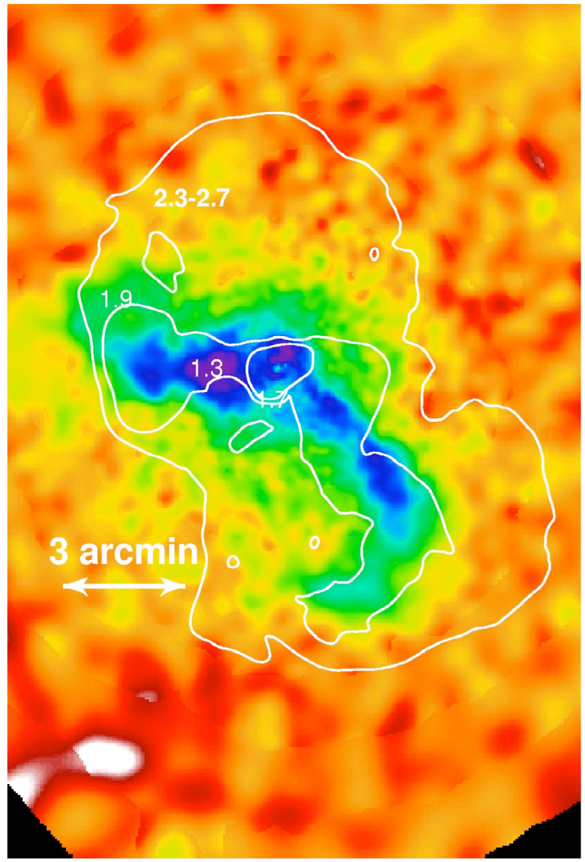
•Gas from lower in atmosphere rises, expands, cools gives rise to correlated radio/X-ray emission

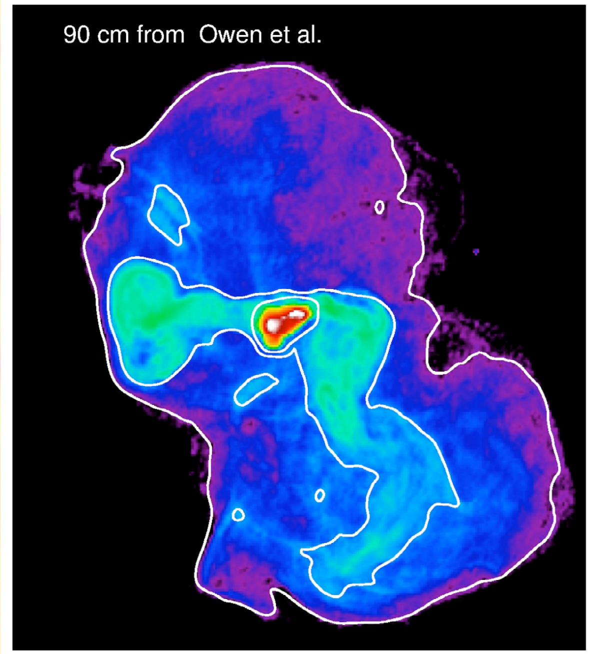
•1-10 M_{sun} uplifted by factor of 2 in radius, if bubbles launched every 10^7 yrs – comparable to mass in cooling flow

•See also Brüggen & Kaiser 2001, 2002, Brüggen et al. 2002

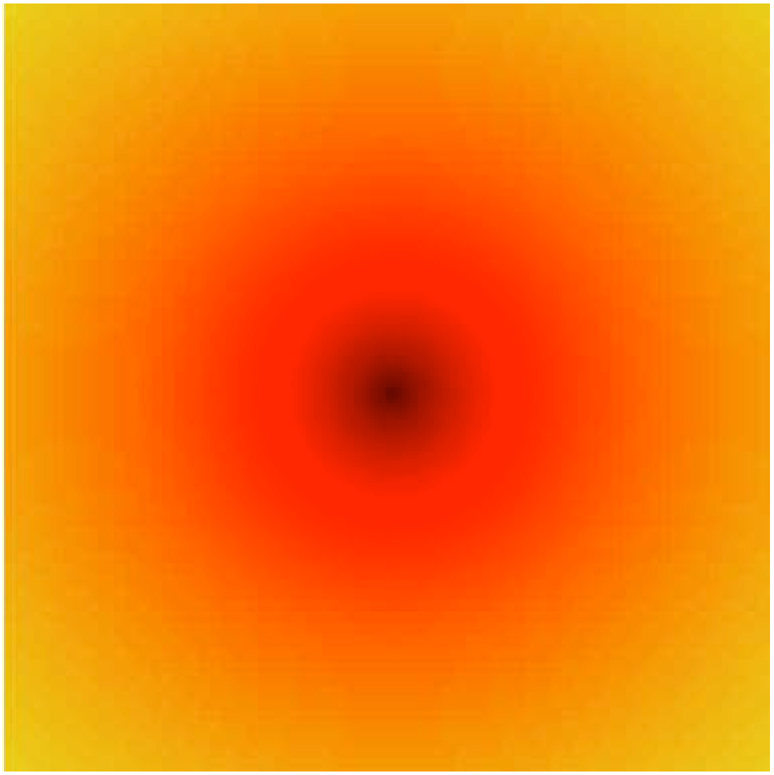
Cool gas in X-ray and radio arms

- XMM-Newton temperature map shows arms are cool (Belsole et al 2001; Molendi 2002)
- Temperature structure of arms is like rising torus (Churazov et al 2001) -- largest concentration of coolest gas midway in arm and cool gas column narrows at radio edge
- No shock heating in arms



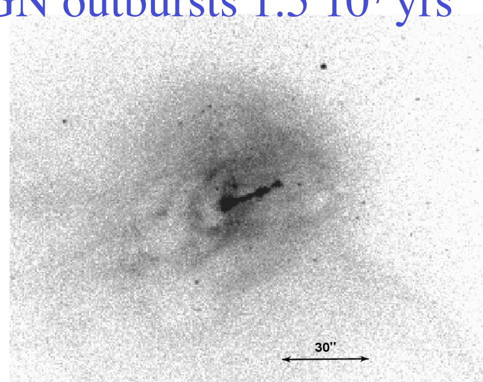


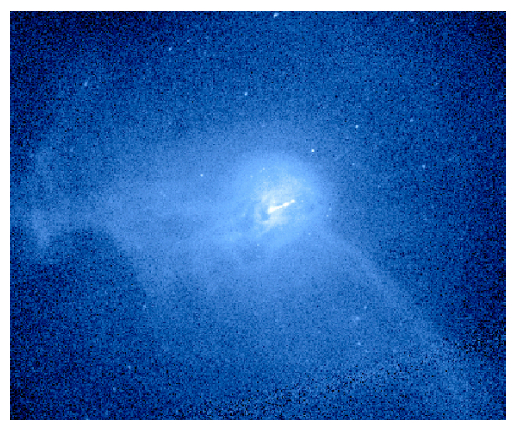
Simulations of Bubbles (Ruszkowski & Begelman)
Viscous dissipation of AGN induced gas motions



Repeated AGN outbursts 1.5 10^7 yrs

Energy dissipated in gas; no strong shocks





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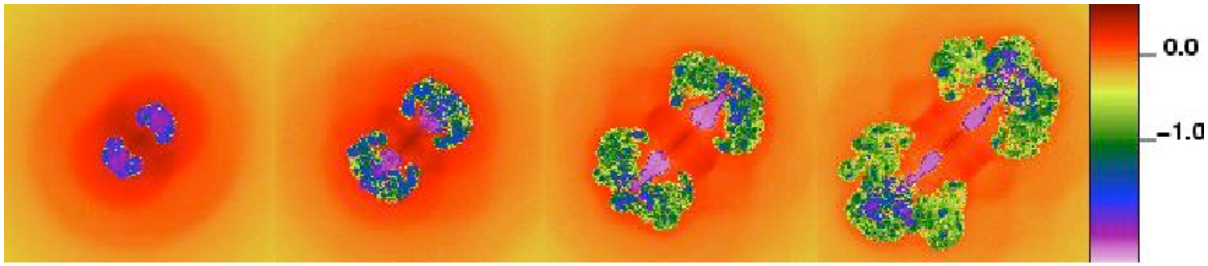

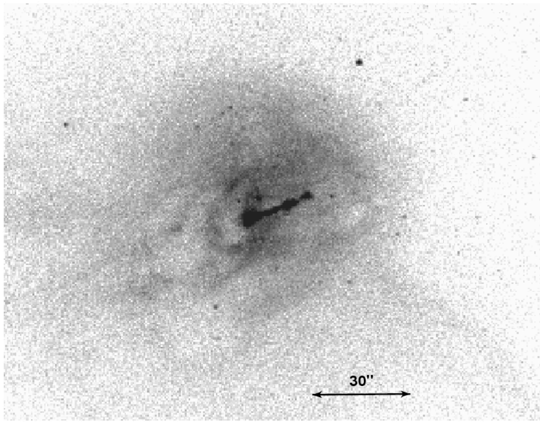

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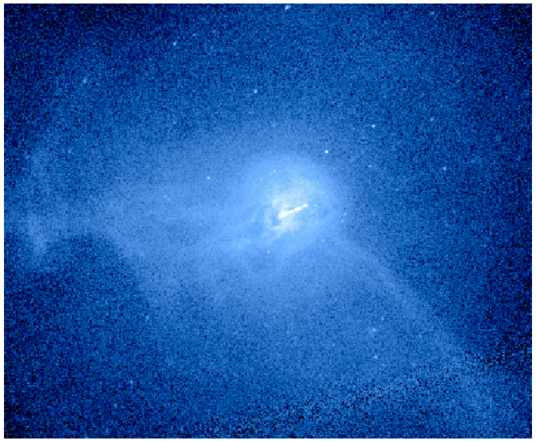

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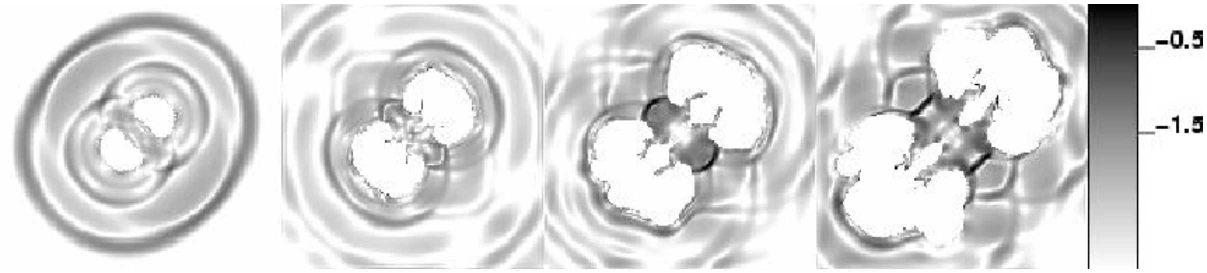
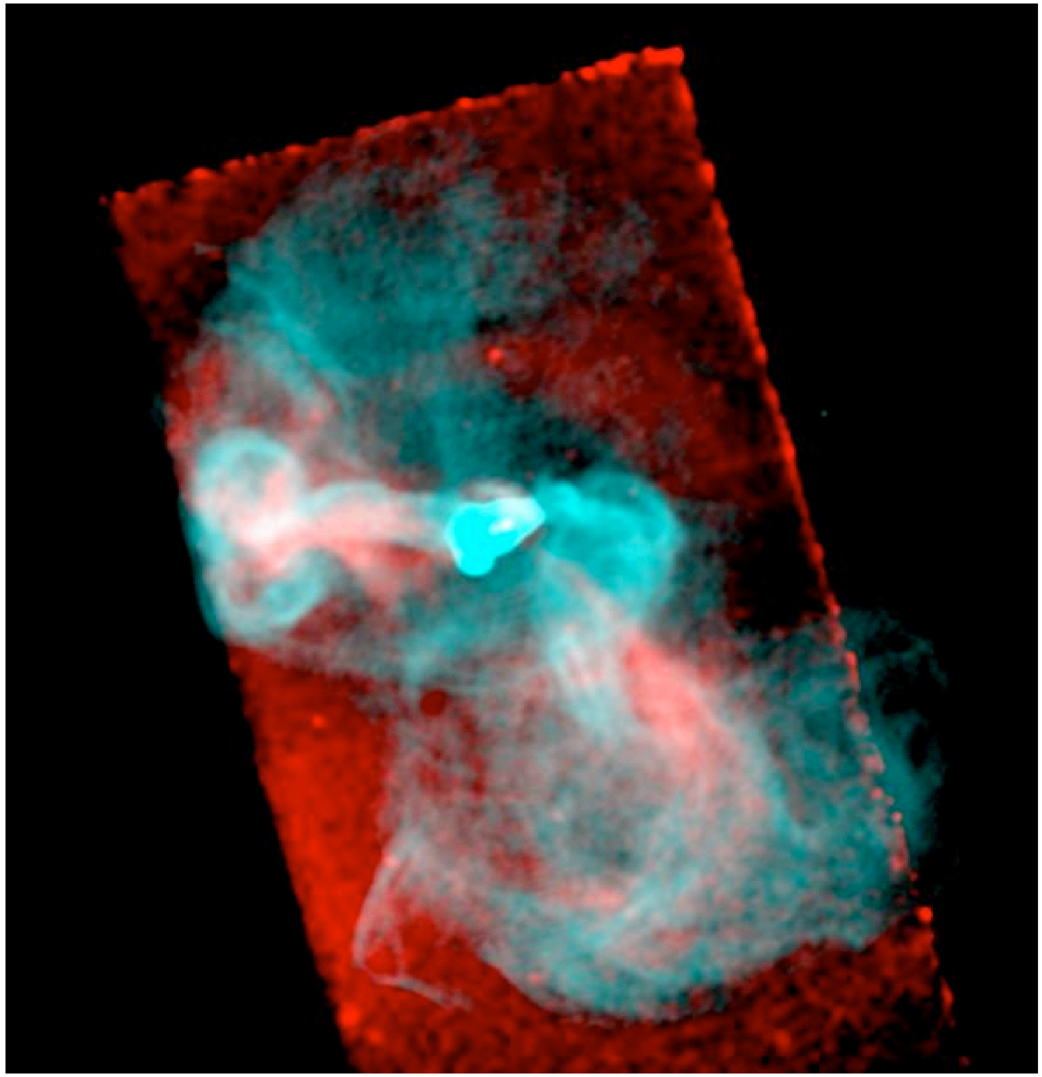


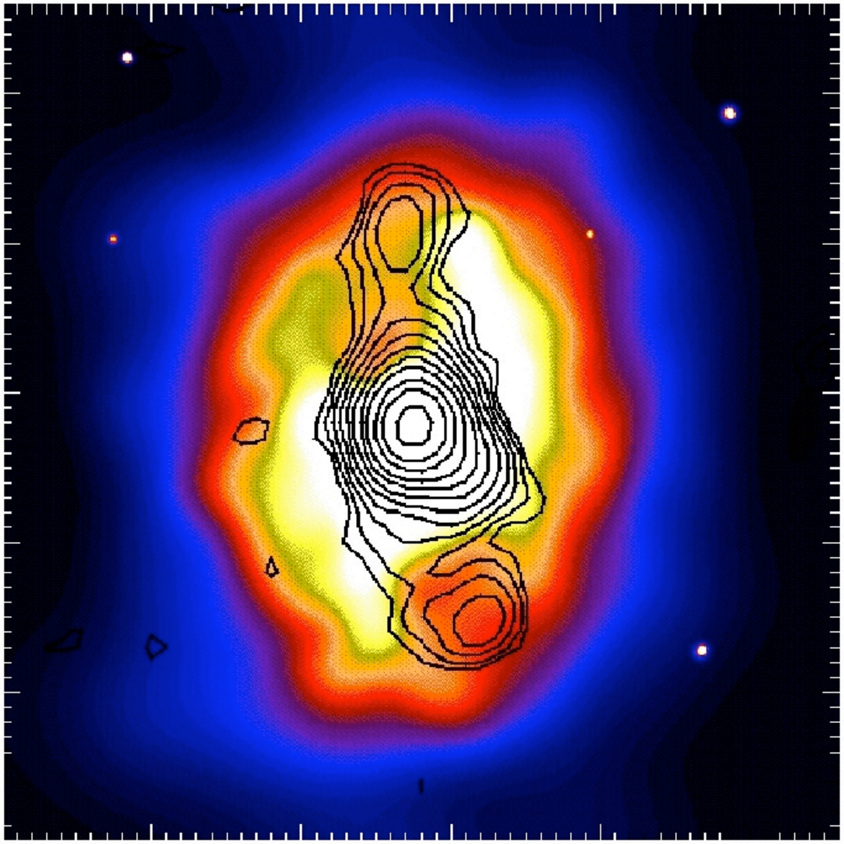
M87 – Chandra and VLA

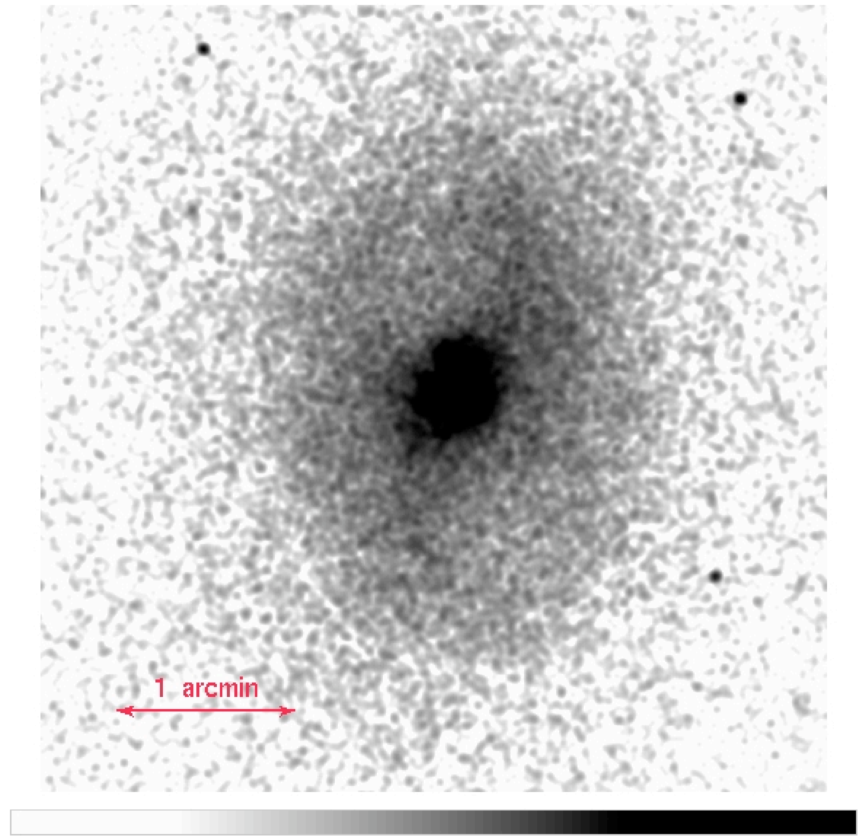


Radio (blue) and Chandra X-ray (red)

Most Energetic Outburst Yet Found

MSO735.6+7421   6 X 10^{61} ergs driving shock
(McNamara et al 2005)





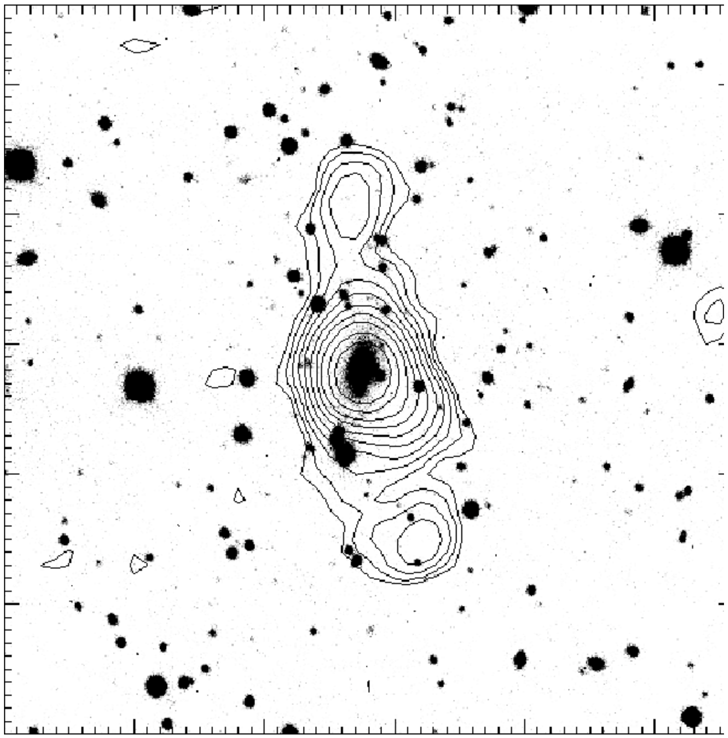
Radio lobes fill cavities (200 kpc diam) - displace and compress X-ray gas

Work to inflate each cavity ~10^{61} ergs

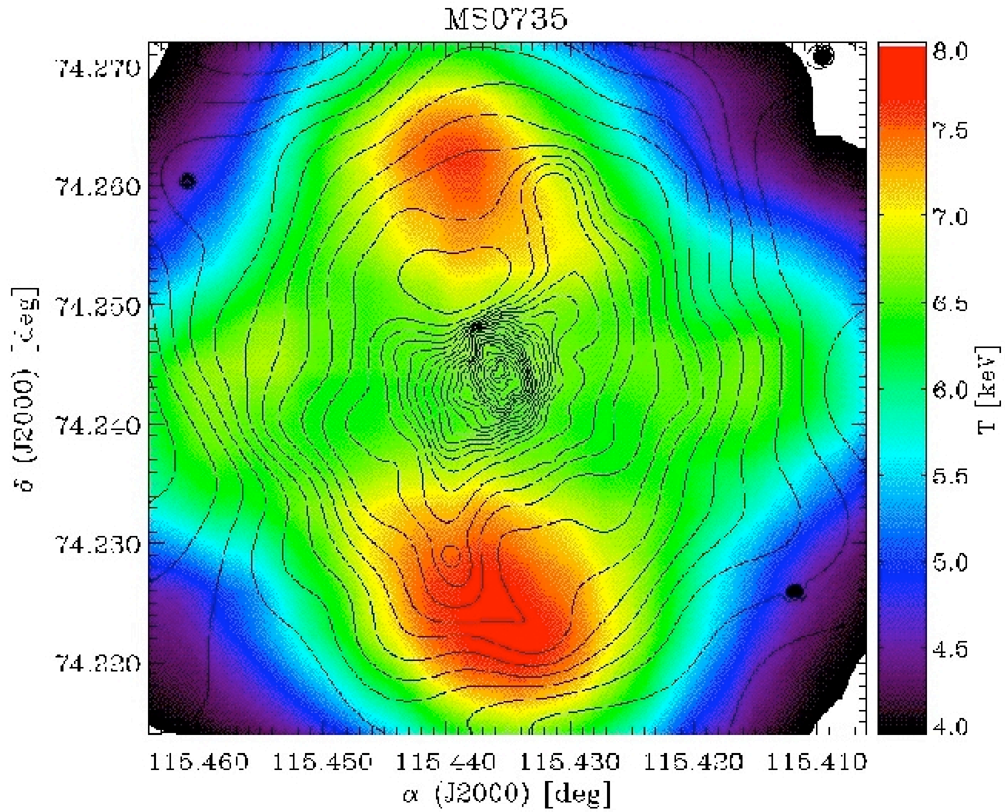
Time since outburst ~ 10^8 years -> average power of 1.7 X 10^{46} ergs s^{-1}

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

MSO735.6+7421 (McNamara et al 2005)



Radio contours on optical

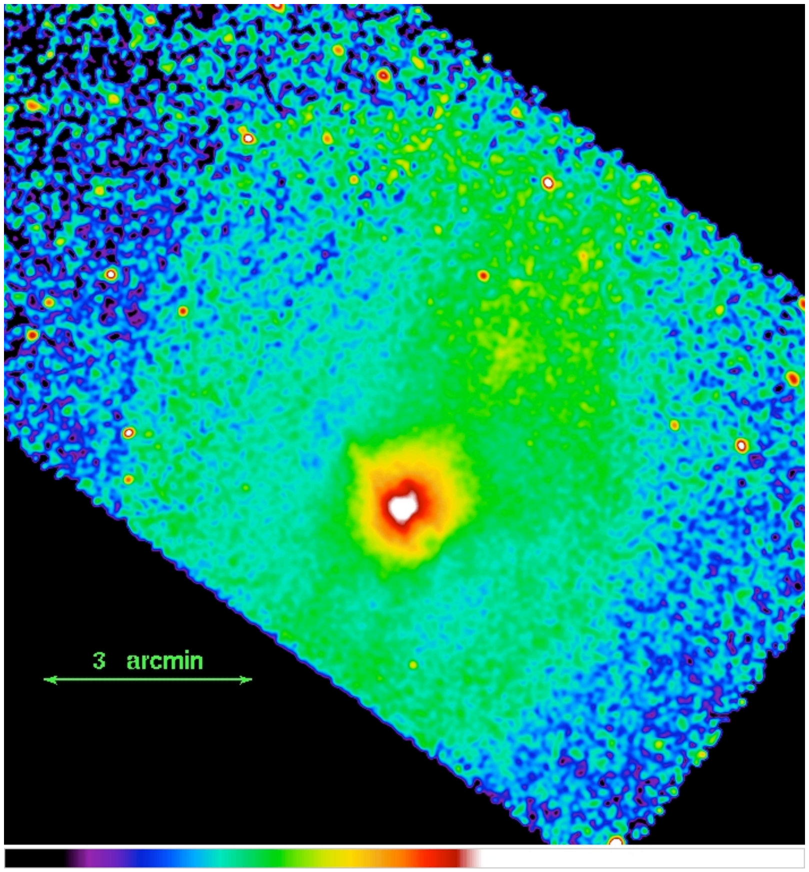


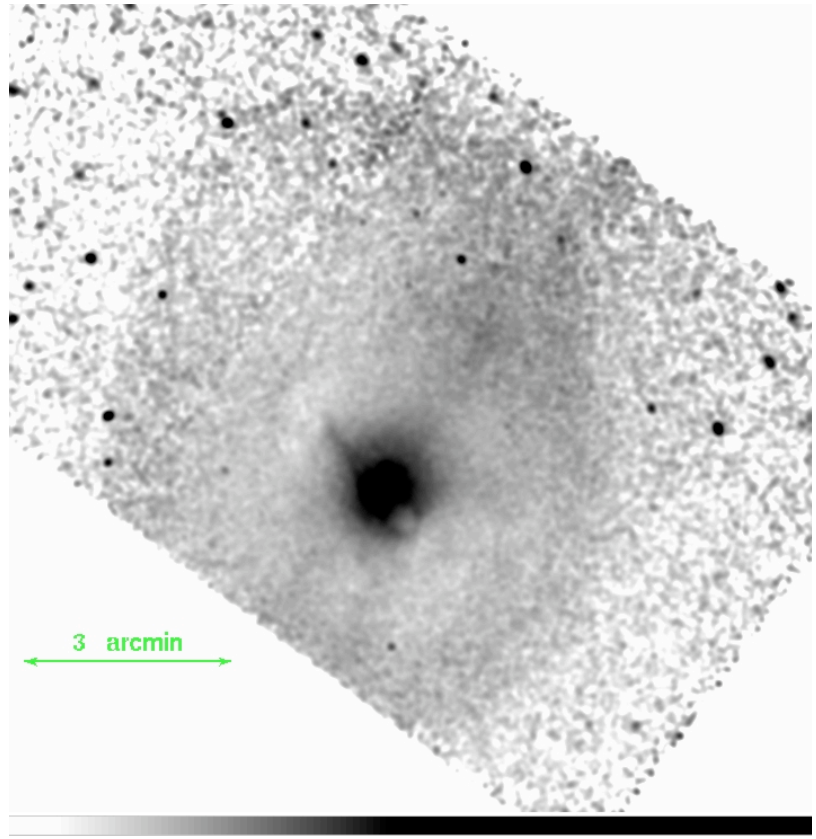
Gas Temperature Map

Hot cavities - heated by shock or IC emission?

Shock energy 6 X 10^{61} ergs from accretion ($0.1MC^2$) needs 3 X $10^8 M_{sun}$

Hydra A (Nulsen et al 2005)





Small cavities, medium cavities and a shock

Shock front 200-300 kpc from AGN

Shock energy 10^{61} ergs -- 1.4 X 10^{8} years since outburst

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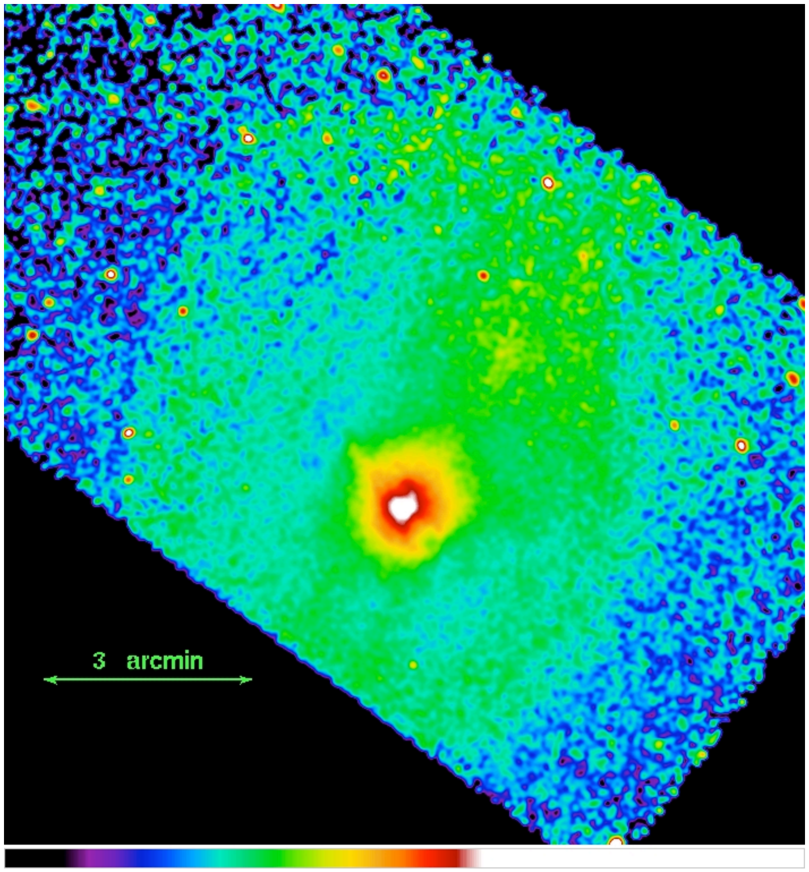

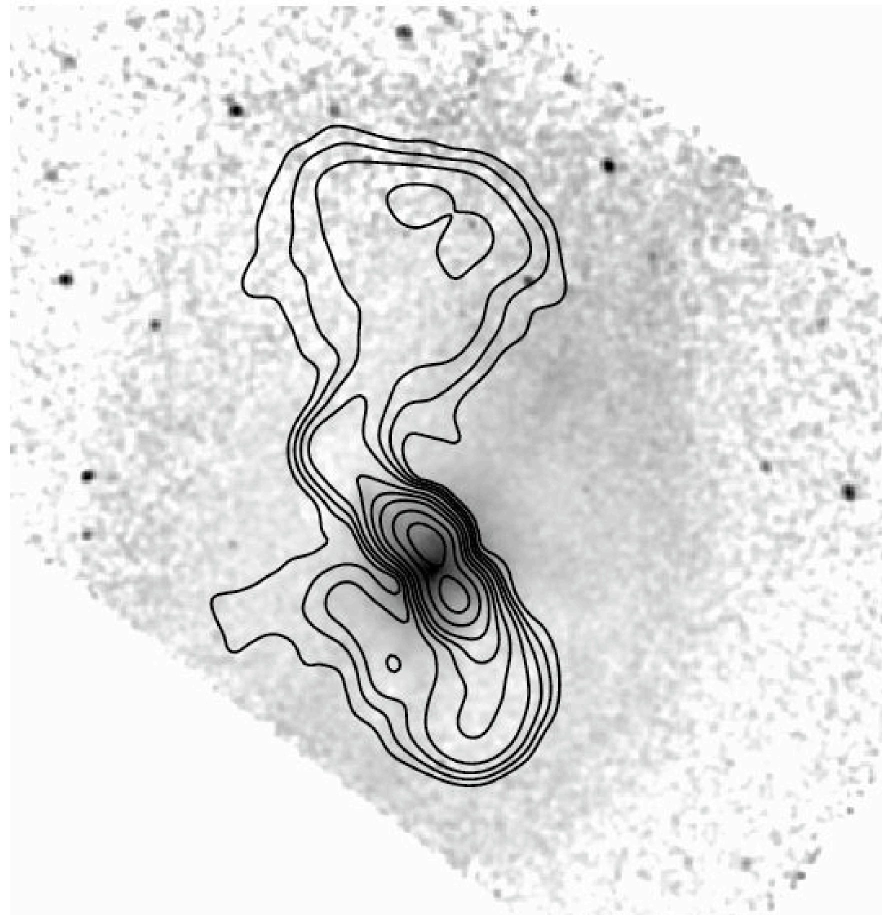

Small cavities, medium cavities and a shock

Shock front 200-300 kpc from AGN

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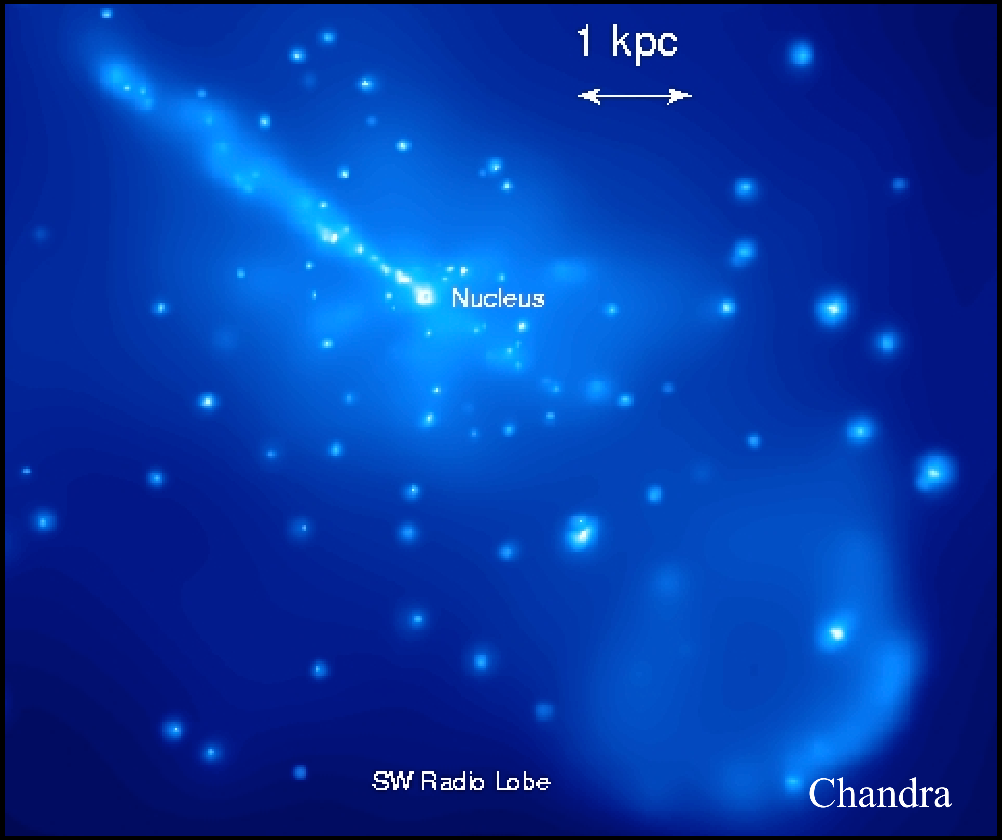
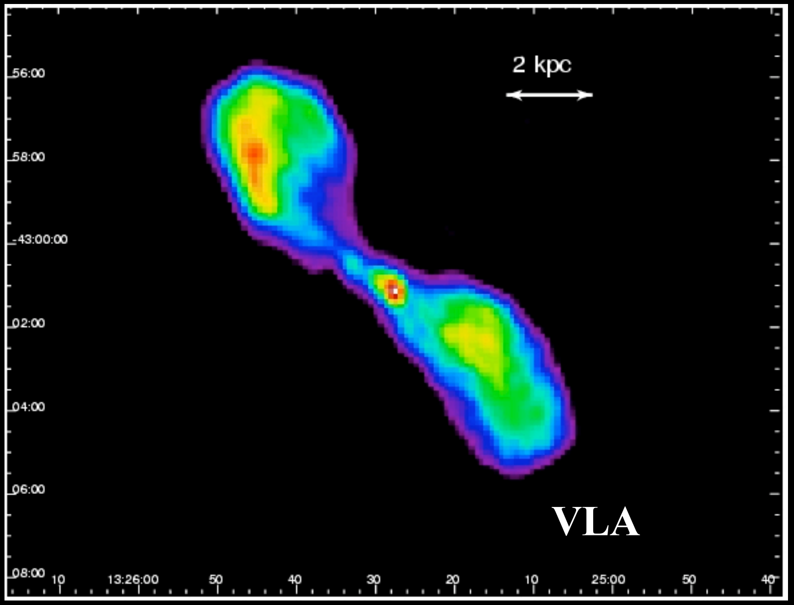
Centaurus A – the Nearest Radio Galaxy



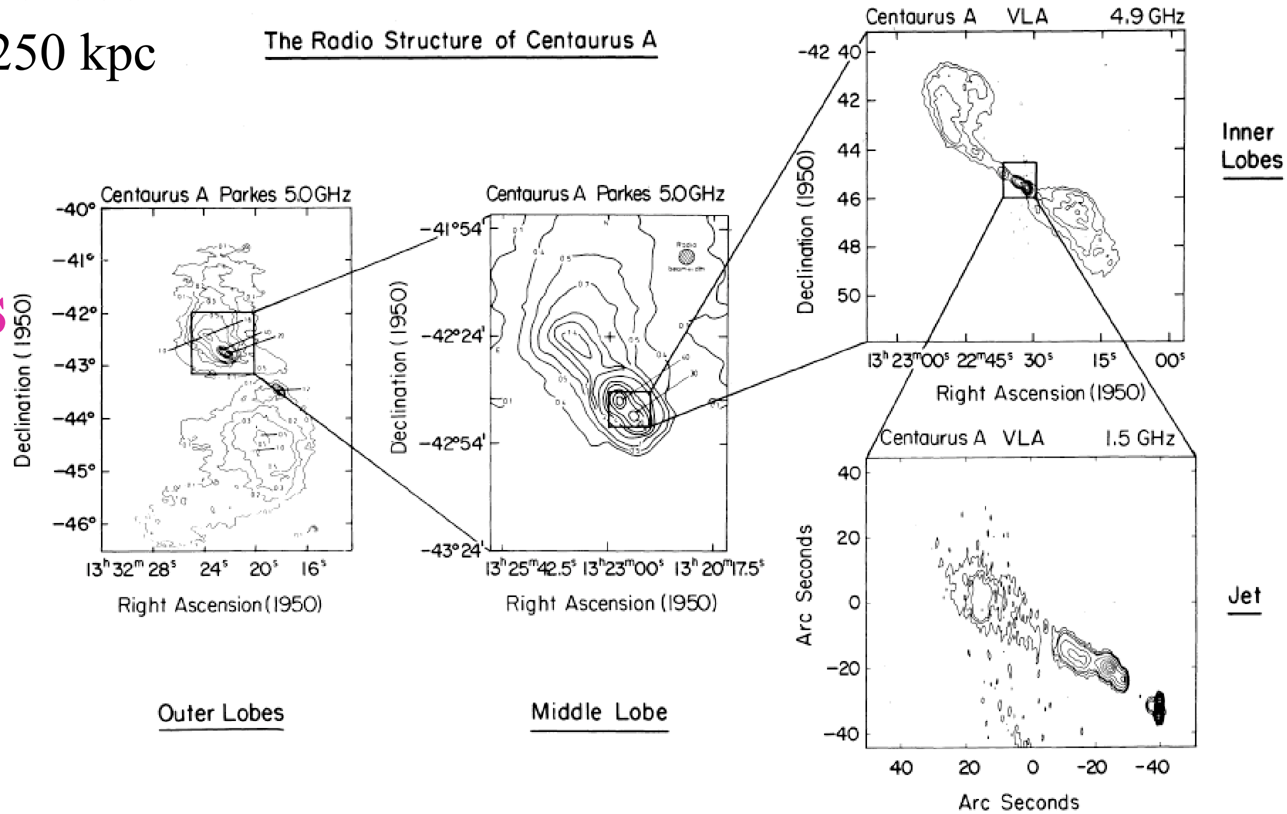


Kraft et al. 2000,2001,2003

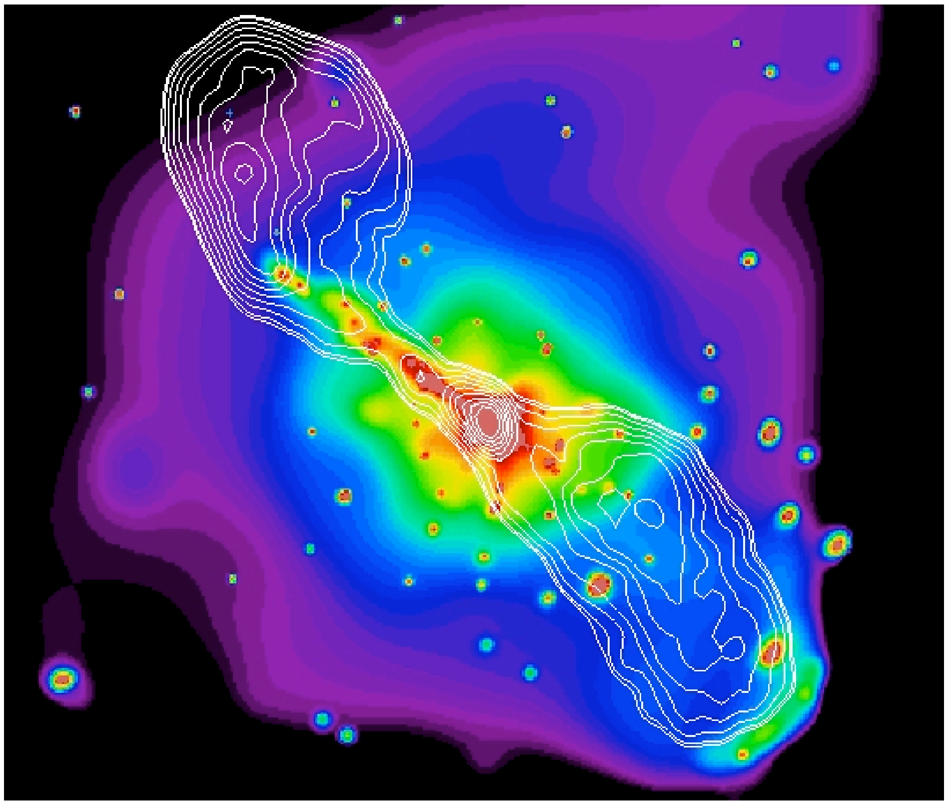
Multiple Outbursts in Cen A

- Series of outbursts seen in radio (Ekers/Burns)
- Nuclear jet 65 masec (5-10 yrs)
- Inner lobe $\tau = 6x10^8$ yrs
- Northern middle lobe
- Linear size to 250 kpc

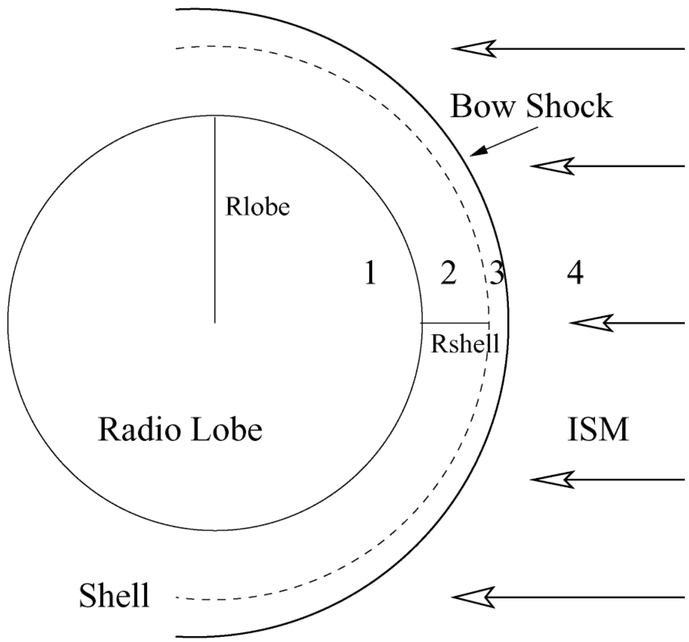
Repeated outbursts spanning 10^9 yrs

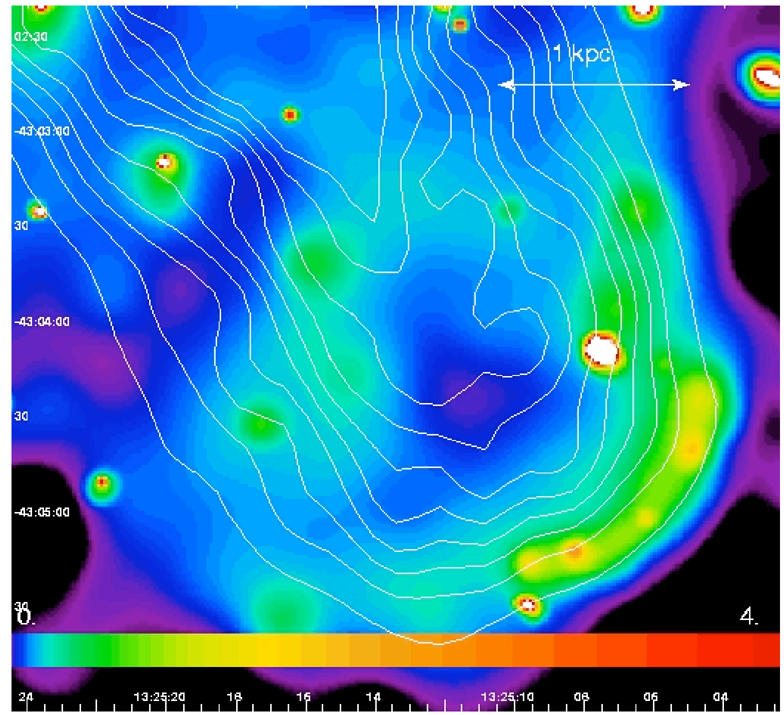


Chandra images of SW lobe with radio contours



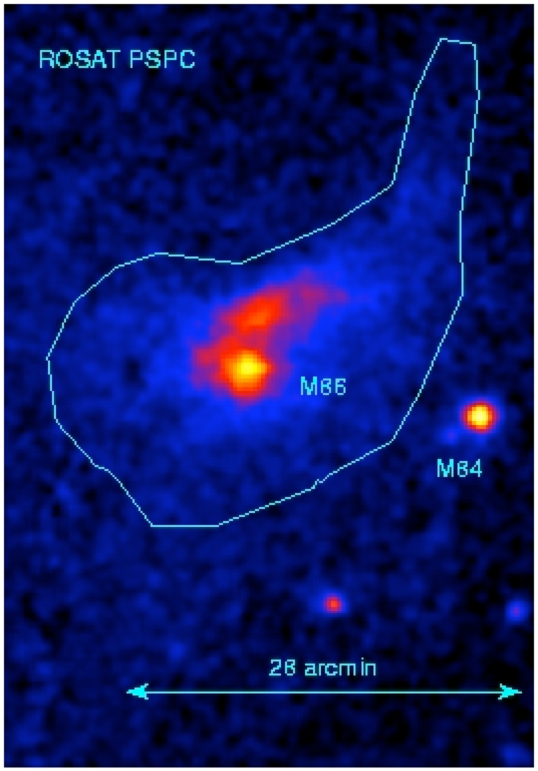
Centaurus A - Southwest Radio Lobe

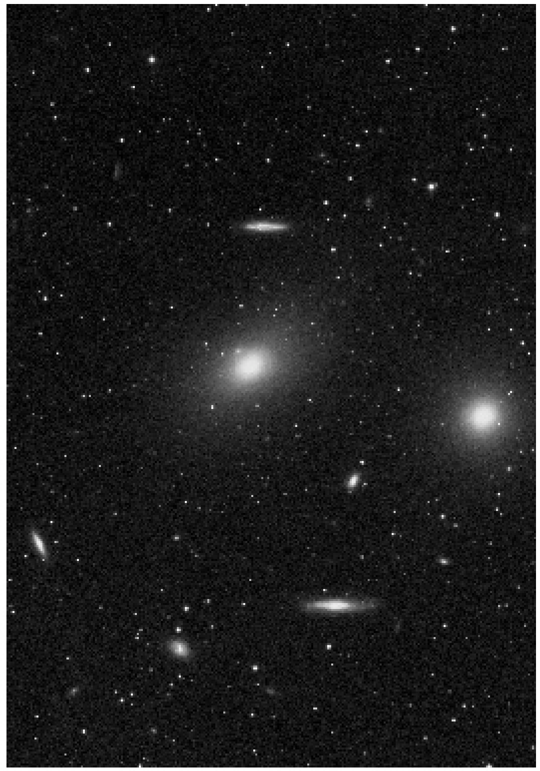




- Model X-ray bubble as driven by expansion of radio plasma
- Gas temperature in lobe ~2.9 keV (in ISM kT = 0.3 keV)
- Enhancement width ~ 15”
- Shell gas density $2\ 10^{-2}$ cm^{-3} (In ISM ~ $2\ 10^{-3}$ cm^{-3})
- Shell overpressured ($2\ 10^{-10}$ dyn cm^{-2}; in ISM ~10^{-12}, in lobe ~10^{-11})
- Bubble expanding supersonically at Mach 8.5 (2400 km/sec)
- Thermal energy in shell is $4\ 10^{55}$ ergs + kinetic energy (6.5 times greater) + internal bubble energy (Thermal energy of gas within 15 kpc is $2\ 10^{56}$ ergs)
- Strong source of energy input to galaxy corona.

Ellipticals in Virgo -- M84 & M86





ROSAT X-Ray

Optical

M86 falling into Virgo core with supersonic velocity.
125 kpc tail

M84 small gas coronae

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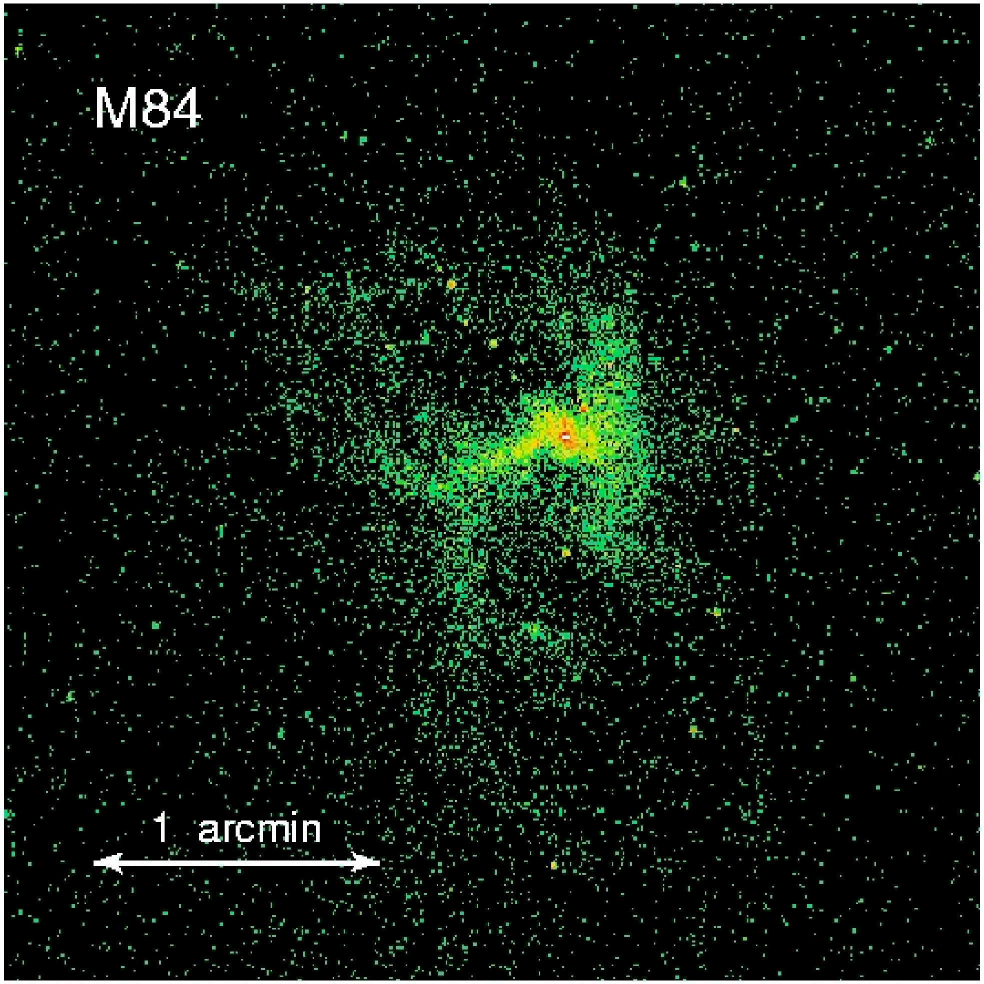


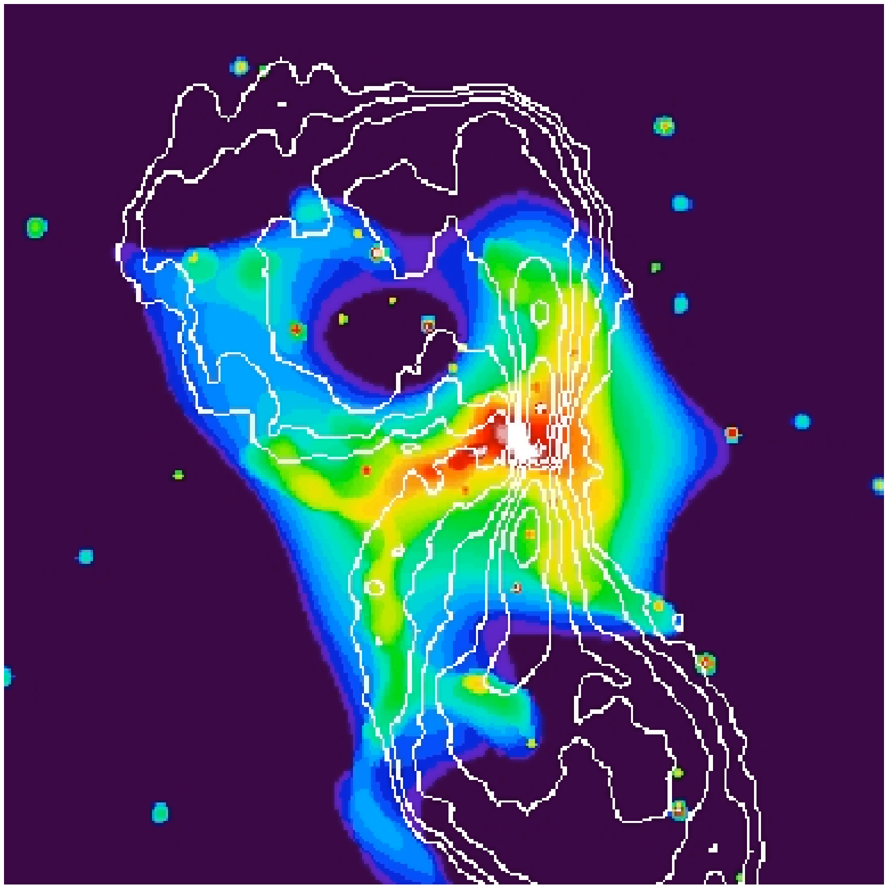
Finoguenov & Jones 2000,2001

Chandra image shows nucleus, bar and filaments.

Lobes ~ 4 kpc diameter - outburst ~ 4 - 6 10^6 yrs ago

Interaction with radio lobes of 3C272.1

Bubbles in a galaxy -- M84



X-ray image; radio contours

Scale 20” across bar of H

For Perseus, M87, M84, and for almost all others

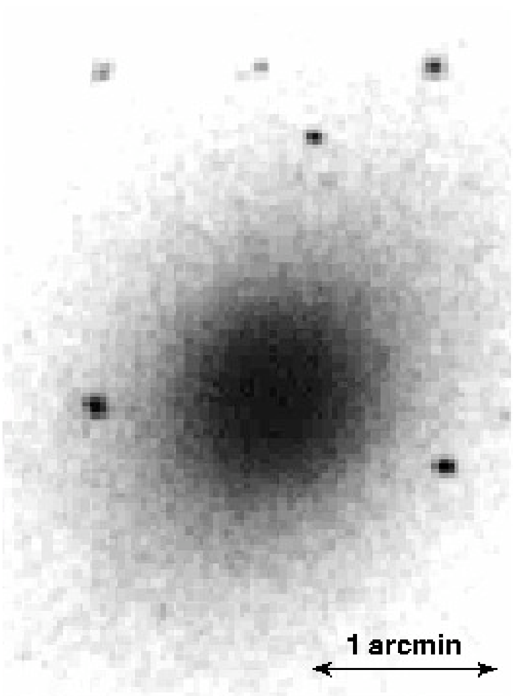
gas surrounding bubble is cool

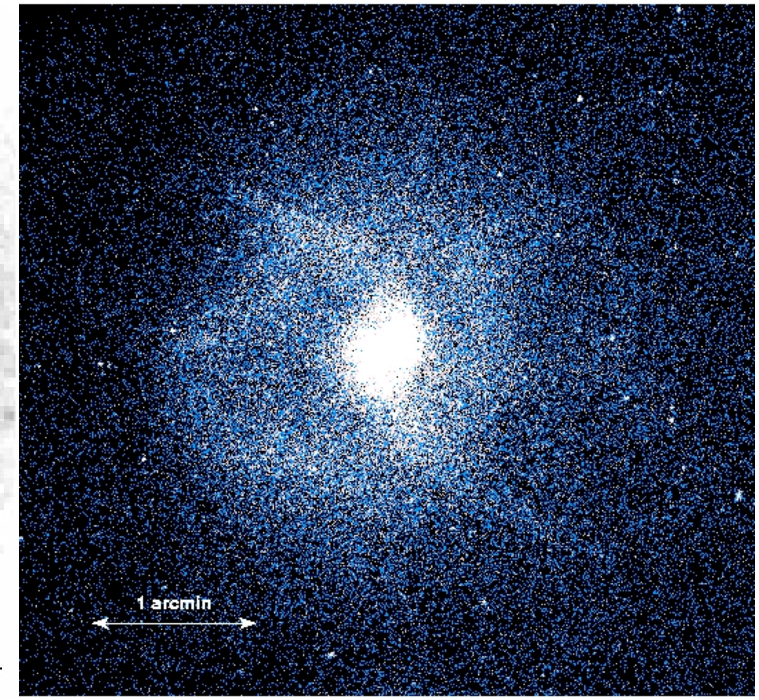
No shock heating in lobe

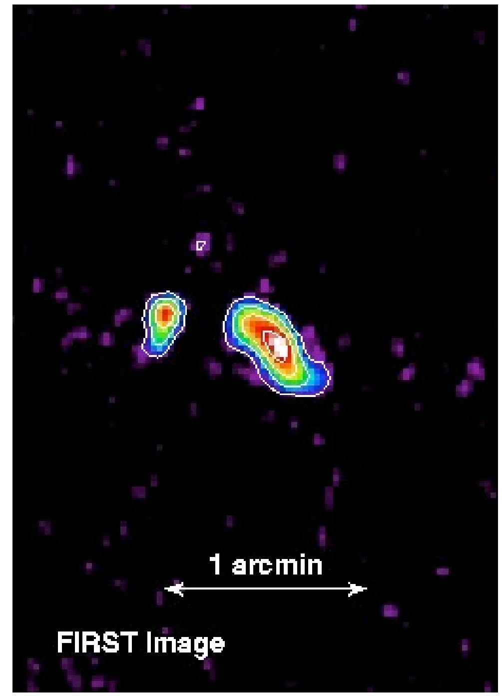
H-shaped gas has kT~ 0.6 keV

Ambient gas temperature increases from 0.6 to 0.8 keV with increasing radius

Another Exploding Elliptical -NGC4636







Jones et al 2001

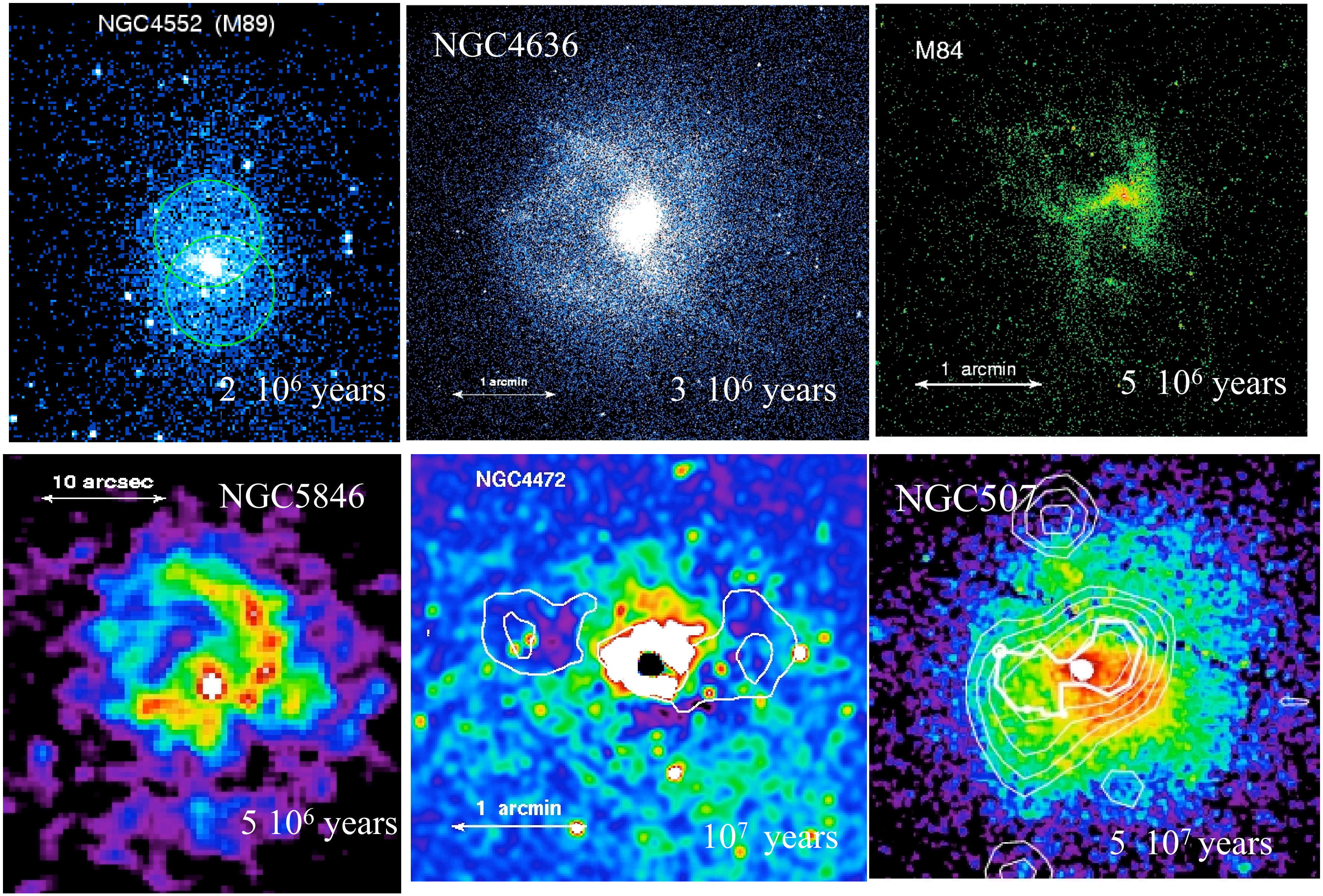
- **Strange X-ray structure in an otherwise normal Virgo elliptical galaxy**
- **Double pin wheel-like structure in X-rays!   X-ray arms ~8 kpc long.**
- **Nuclear outburst 3 X 10^6 years ago with energy 6 X 10^{56} ergs**
    - But small weak radio source

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
Hydra A	210	0.9	136	0.2	0.5
M87	14	0.0008	11	0.0024	0.0005
NGC4636	5	0.00006	3	0.0007	0.00003

Clusters to galaxies (gas kT = 5, 2.5, 0.7 keV)
Late growth of SMBH in "old" stellar population systems

Recent Nuclear Outbursts – powered by cooling flows?



A Chandra Survey of Ellipticals

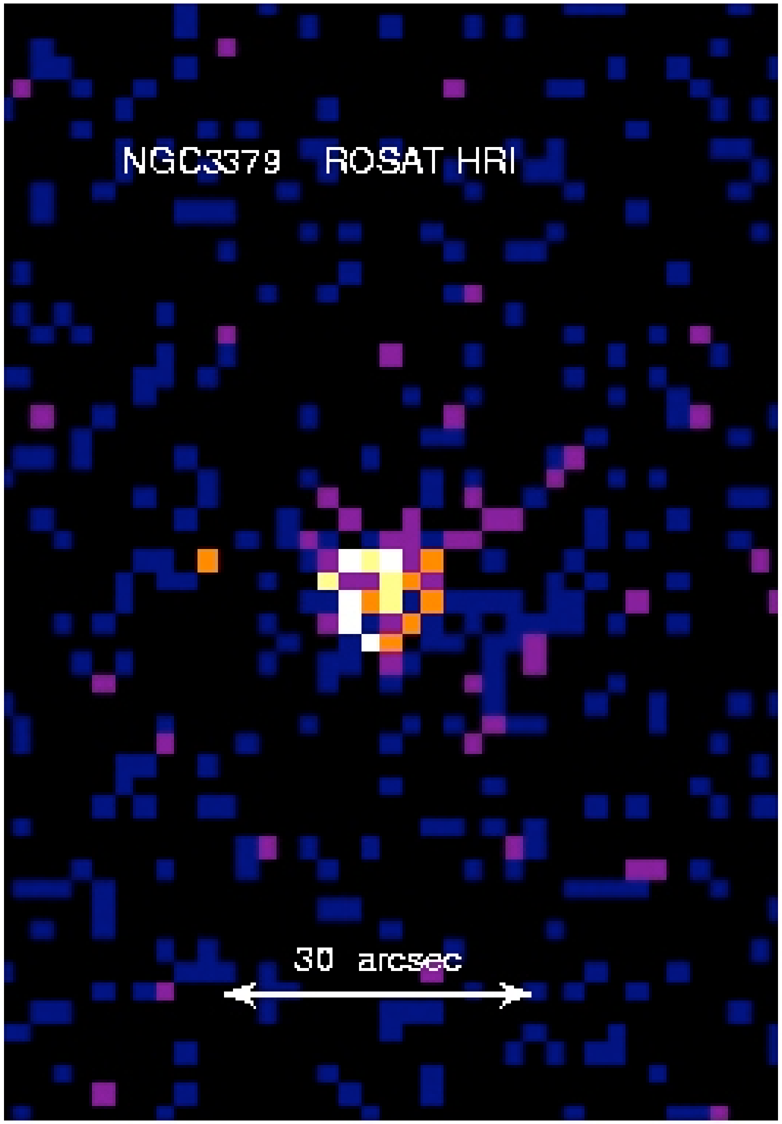
Two ROSAT surveys of early-type galaxies -- Beuing et al. 1999 used RASS to measure X-ray emission for 293 galaxies with B_T <13.5
O'Sullivan et al 2002 extended catalog to 401 galaxies.

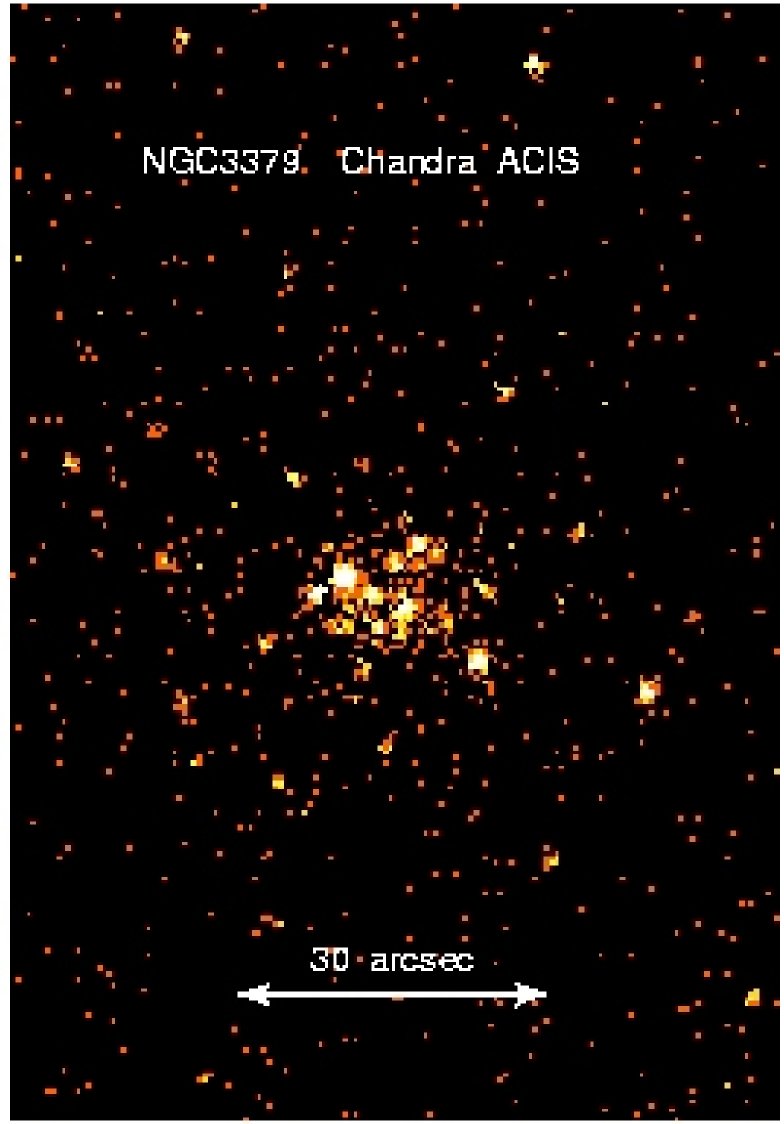
~160 galaxies observed by Chandra
X-ray flux from SMBH (requires Chandra resolution).

First result --
X-ray emission detected from nuclei in most galaxies

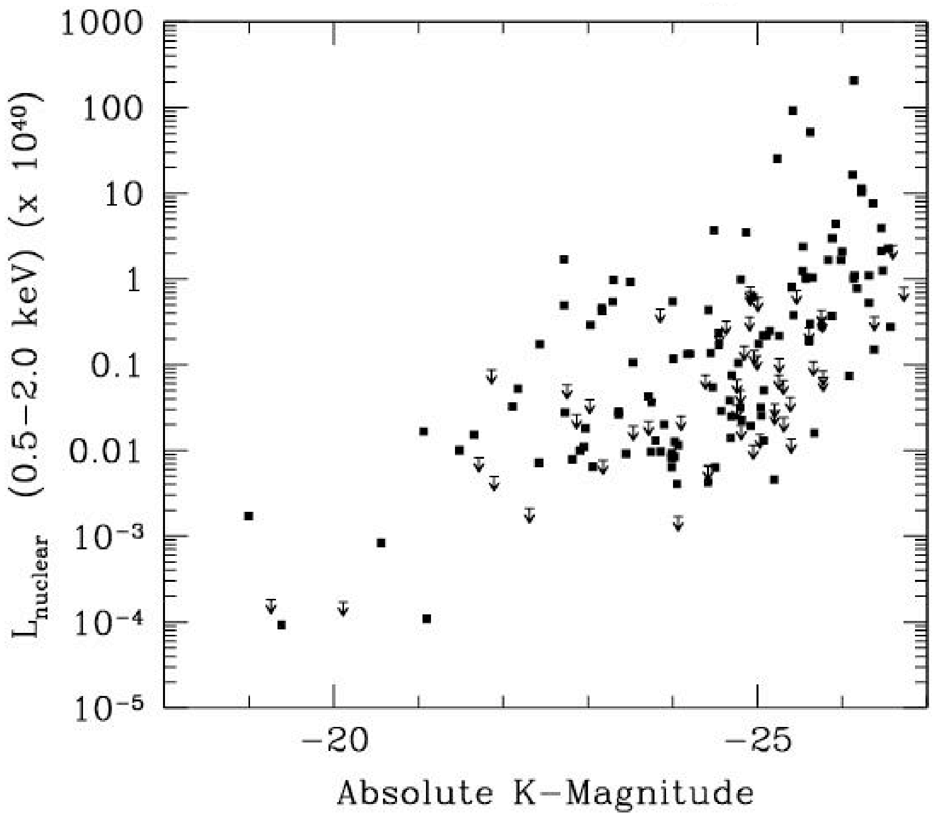
Second result --
26 galaxies show X-ray cavities/jets -- 15% of sample

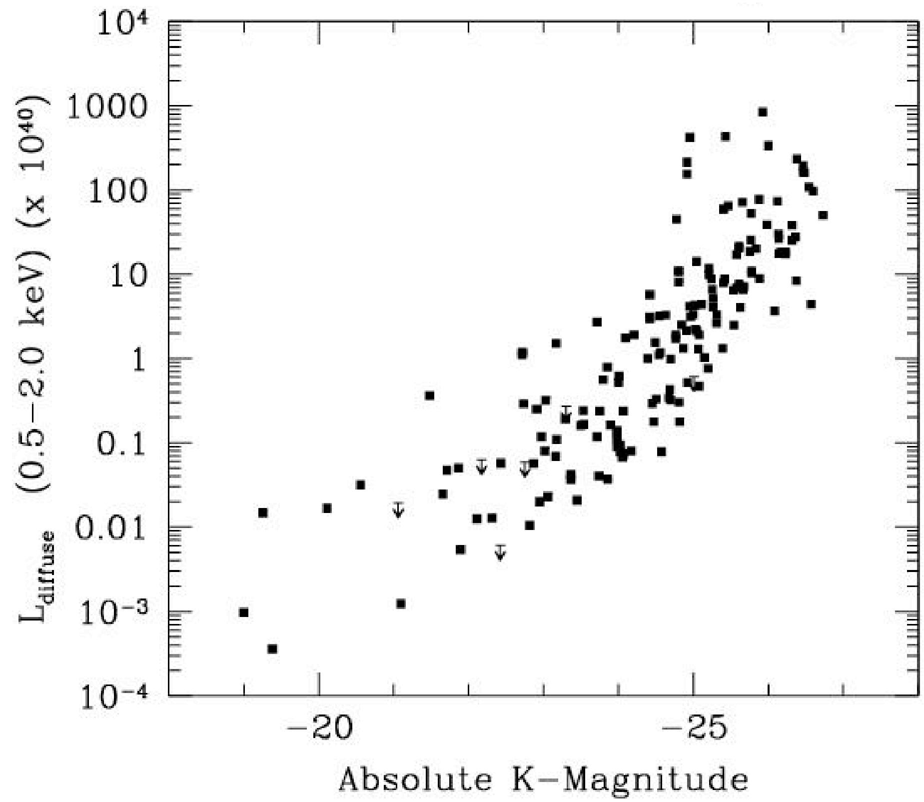
Chandra resolution required!





SMBHs & hot gas in "normal" early-type galaxies

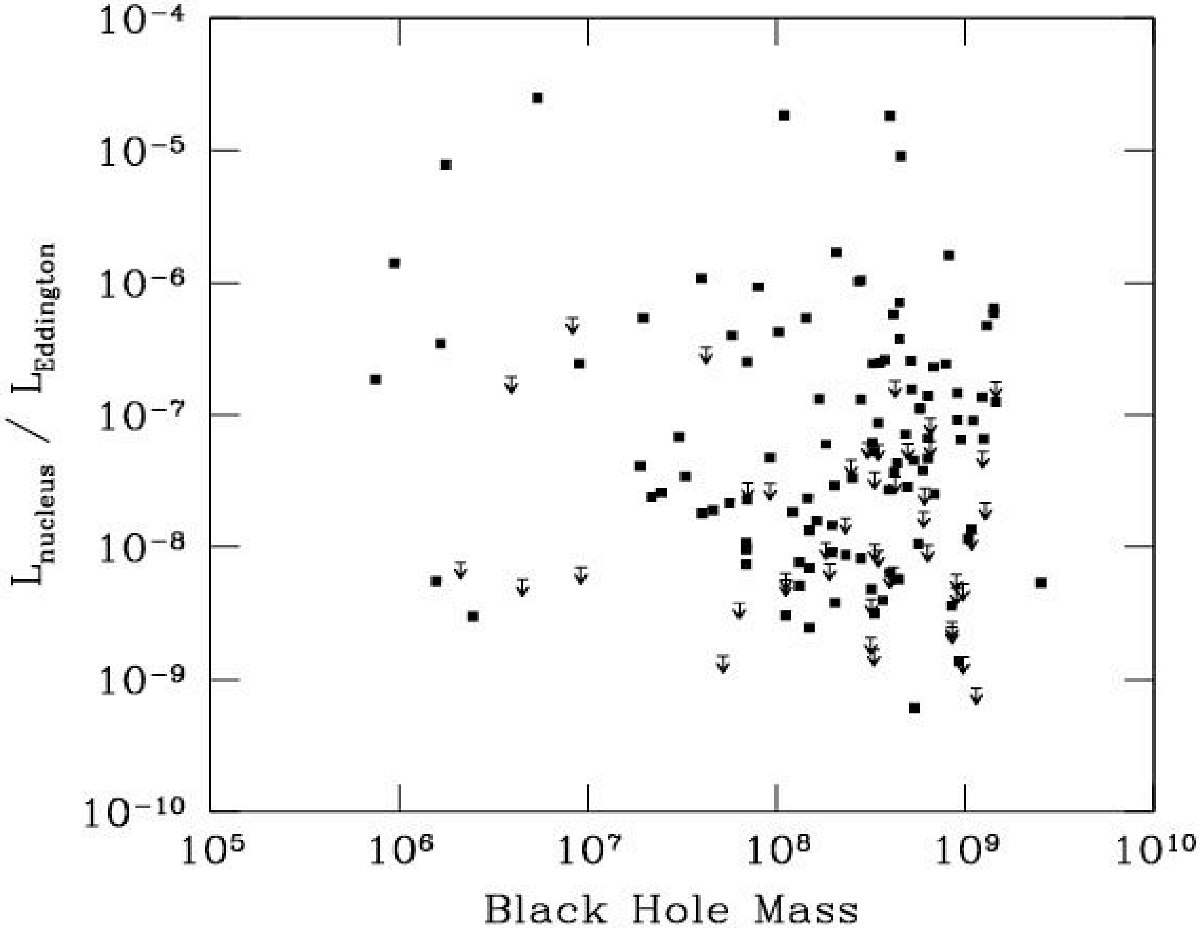




Correlation of ISM X-ray luminosity with K-mag is fairly tight

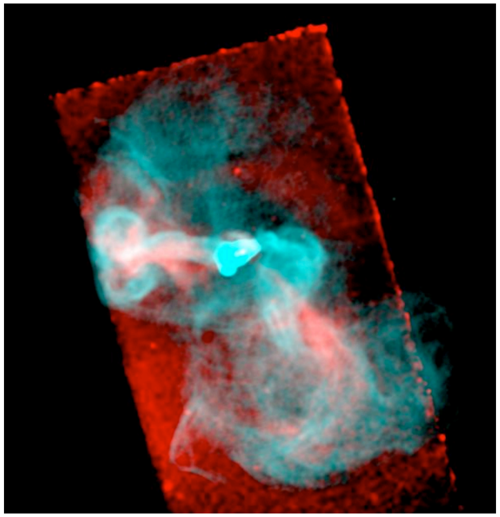
Correlation of nuclear L_X with K-mag is not

Eddington Ratio for "normal" early-type galaxies



Typical Eddington ratios for quasars are 0.1 – 1.
Kollmeier et al. (2005) finds 0.3
"Normal" galaxies are 10 million times smaller.

Impact of AGN outbursts on hot gas



M87

Beginning to understand the recent outburst history of AGN, and the energy transfer mechanisms between the SMBH and the hot gas.

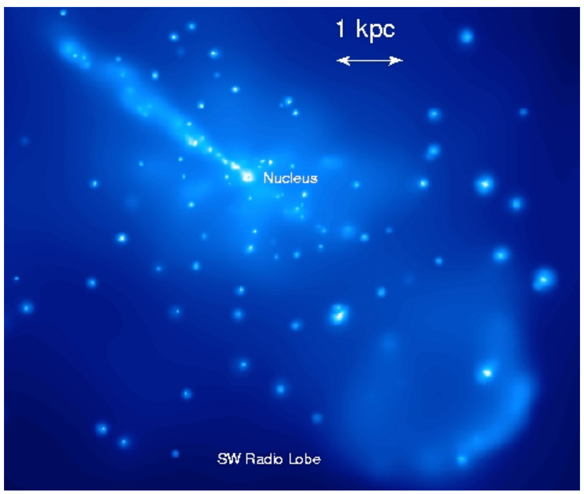
Shocks from multiple nuclear outbursts in Perseus and M87 (Fabian et al. 2003, 2005, Forman et al. 2005)

Powerful outbursts (10^{61} ergs) in MSO735, Hydra A, Her A (McNamara et al. 2005, Nulsen et al. 2005a,b)

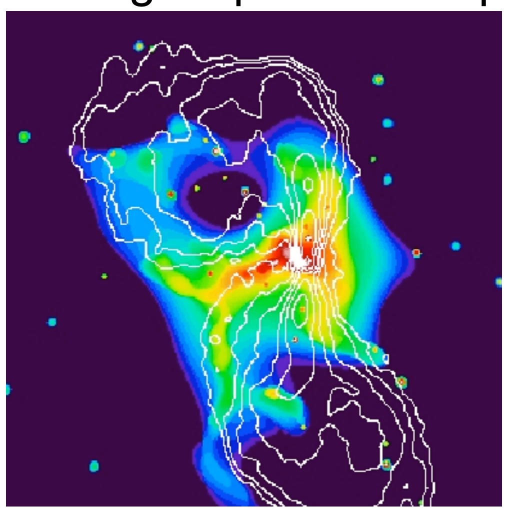
Cooling gas in galaxy/cluster cores can be reheated by AGN (through shocks) or transported by bubbles.

Complex interactions of radio plasma and ISM- M87 arms

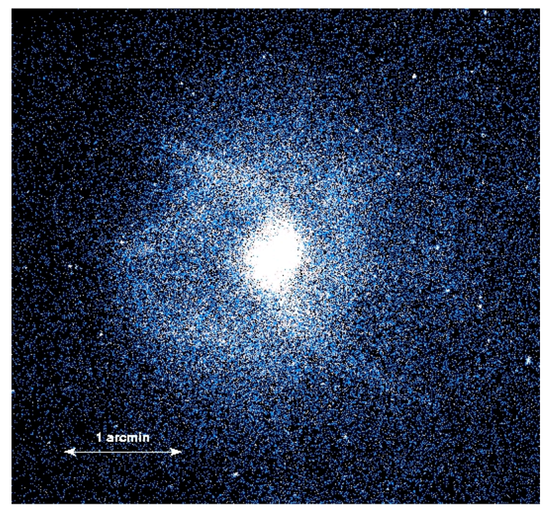
Effects in galaxies even more dramatic than in clusters -- e.g. supersonic expansion of lobe in Cen A.



Centaurus A



M84



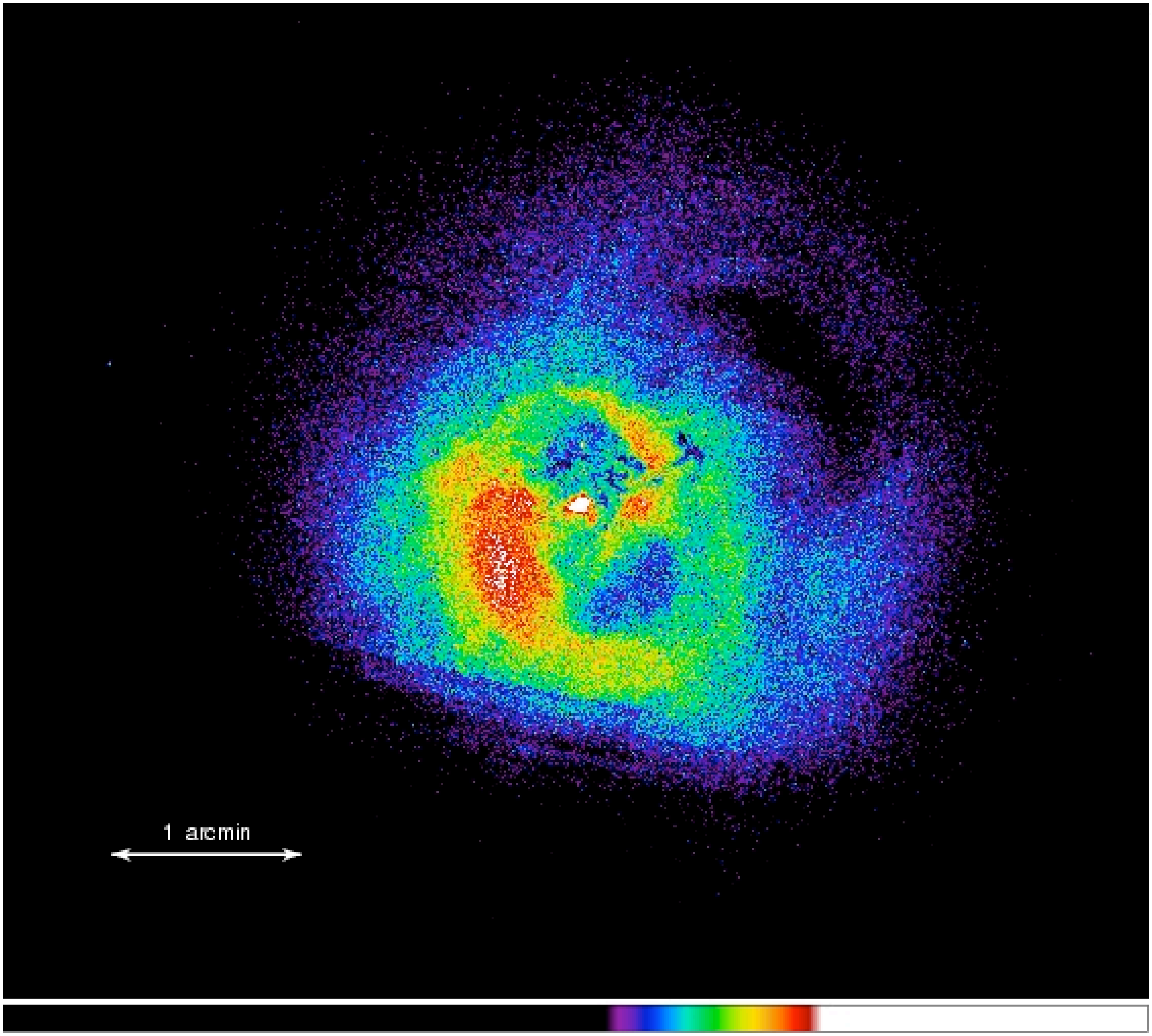
NGC4636

X-ray and radio observations allow us to probe the interactions between the central AGN, the relativistic plasma and the X-ray gas.

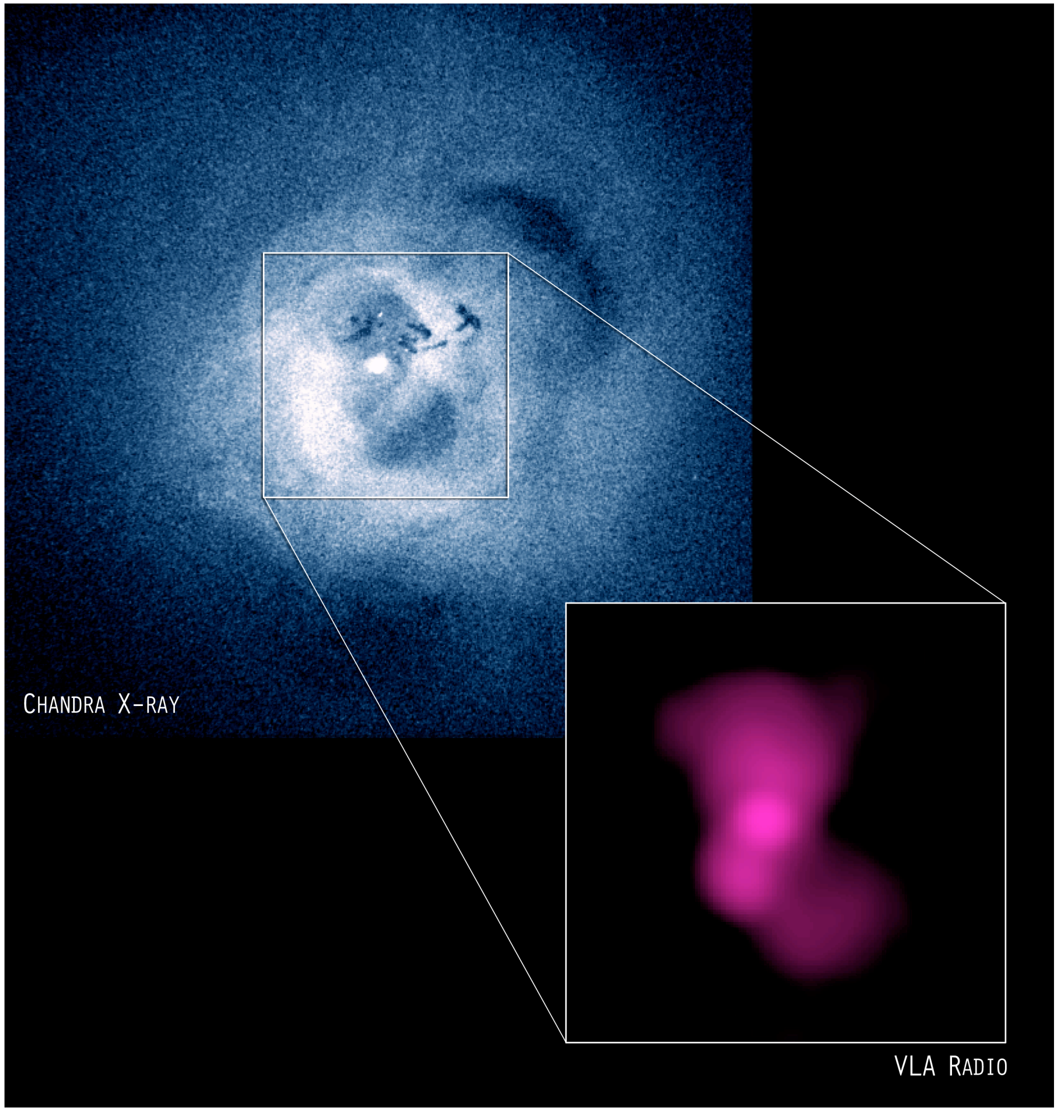
In M87, Perseus, & Hydra A, energy transfer mechanisms between the SMBH and the gas include

Uplifting material in buoyant bubbles
Entraining gas along sides of bubbles

Driving shocks which dissipate energy


1 arcmin

Perseus Cluster – bubbles, shocks & ripples (Fabian et al 2003, 2005)



Scientific Motivation - AGN and Their Environments

- What is the relationship between ISM/ICM cooling and AGN outbursts?
  - **Reminder**
    - **all E/SO galaxies are gas rich - up to 10^{10} solar masses of gas**
    - **In groups/clusters, hot gas is 1-5 times optical baryonic component**
  - Hot gaseous atmospheres in E/S0 galaxies, groups, clusters radiate and cool
  - Expect mass deposition from 1 to many 100's M_{sun}/yr (without reheating)
  - XMM gratings show actual rates are 5-10 times smaller than standard model

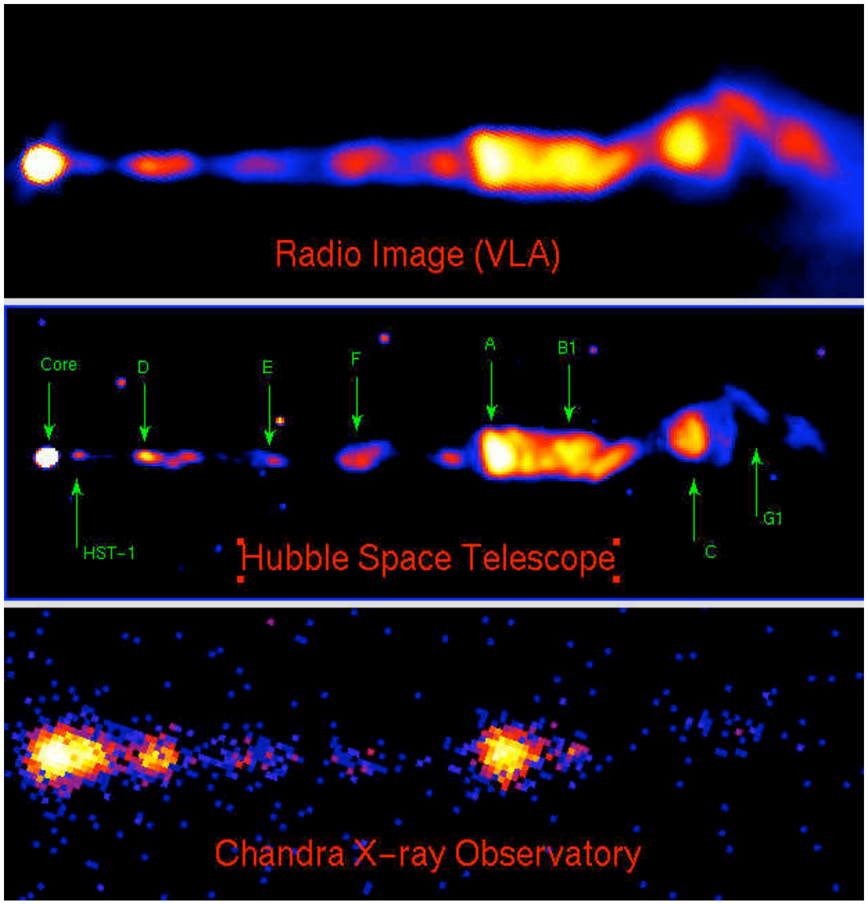
- Can jet outflows (mechanical power) suppress cooling?

- How do AGN jets affect gaseous coronae, ICM in groups/clusters?

- Do AGN outflows affect the mixing/distribution of heavy elements in the ISM/ICM?

- Can repeated nuclear activity explain the large variance in the observed X-ray luminosity of early galaxies for a given optical luminosity

M87 Nucleus & Jet

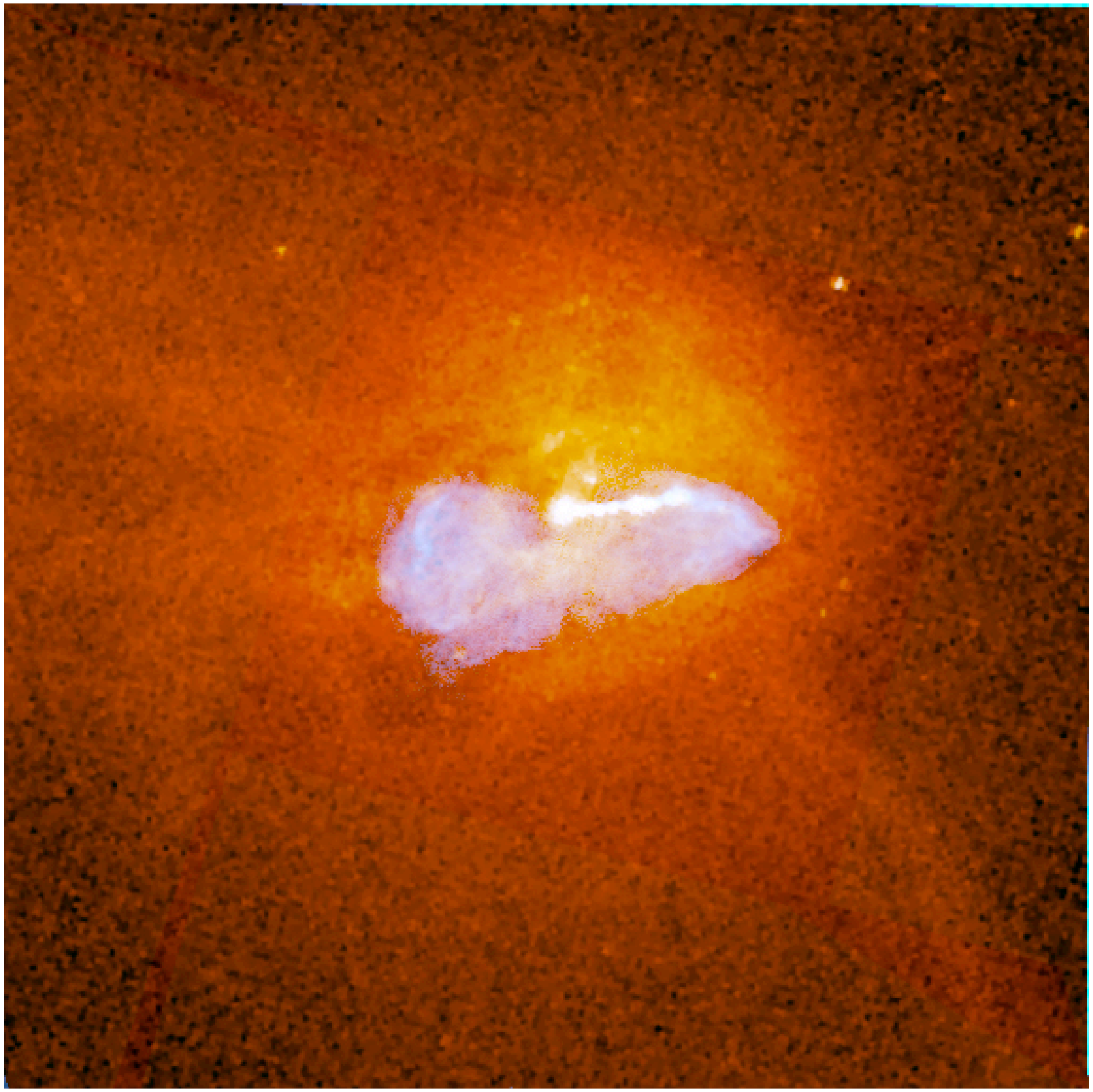


- Radio, optical & X-ray jet
- 20" X-ray jet has 7 knots

(Marshall et al 2002, Harris et al 2003)

- Jet path close to line of sight
- Nucleus with $3x10^9$ M_{sun} black hole

M87 Core - X-ray and Radio
Impact of current outburst



X-ray cavities created by expansion of radio lobes.
X-ray bright core around radio lobes.

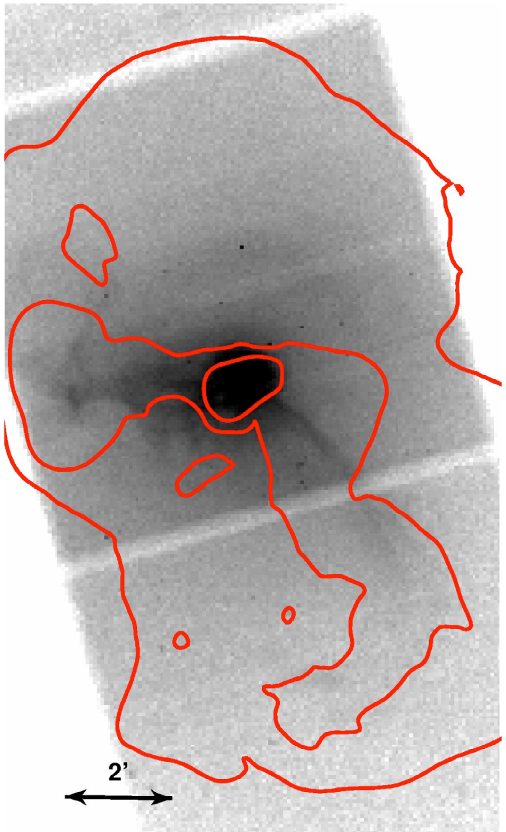
-Based on size and temperature of counterjet cavity, assuming subsonic expansion,

age > $1.7 \quad 10^{6}$ years

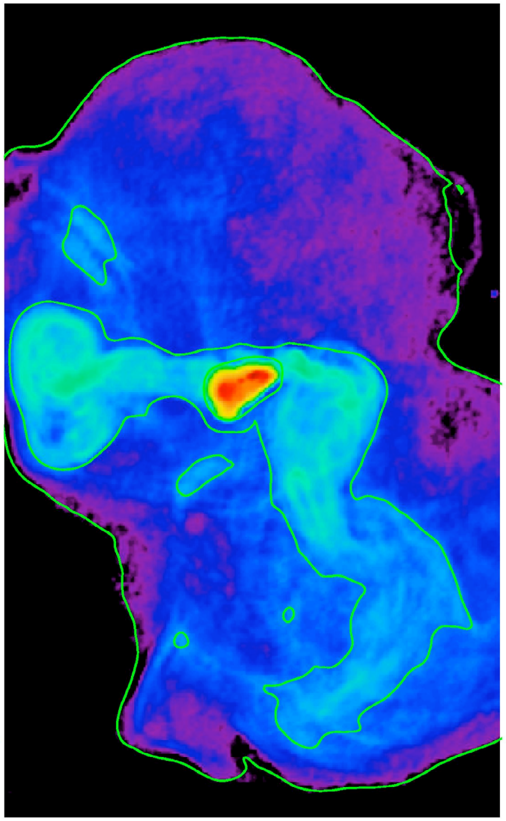
pV = $1.3 \quad 10^{56}$ ergs

Eastern Arm

- Radio ear at end of eastern arm falls between 14 kpc and 17 kpc shocks.
- Strong vorticity (ring-like structure) can be induced by a shock passing through a bubble of relativistic plasma, embedded in cooler material (Ensslin & Bruggen 2002)

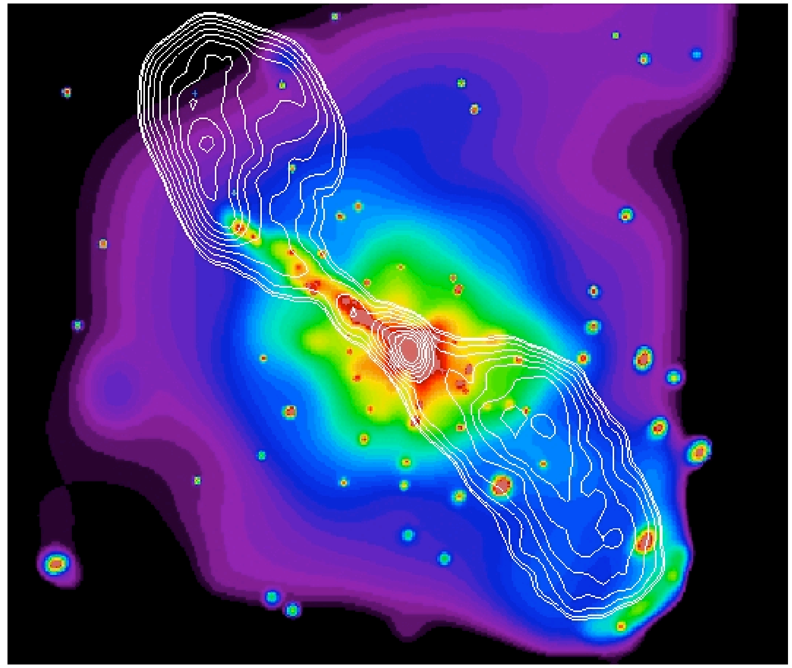


Chandra



Radio

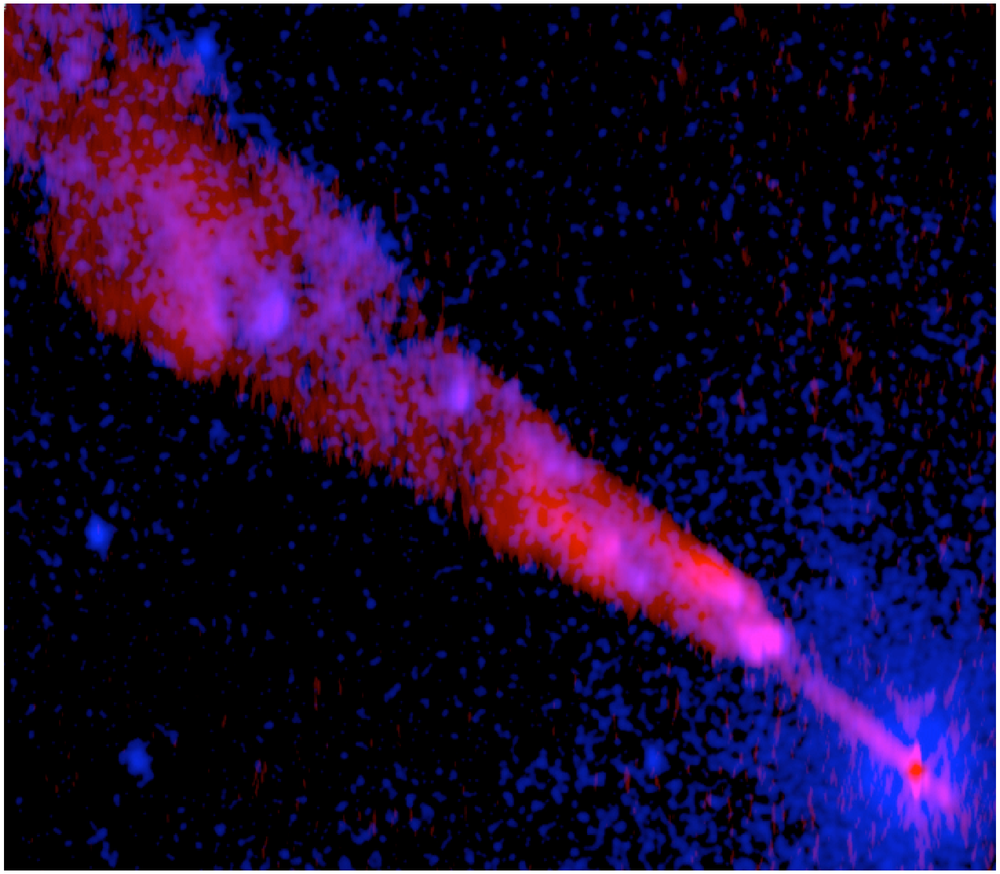
Centaurus A – Bubbles and Jets



Bubble diameter 3 kpc

- •Nearest active galaxy (3.4 Mpc; 1''=17pc); Merger with gas rich galaxy
- •250 X-ray point sources + nucleus + jet + knots
- •Spectacular view of an X-ray jet with opposing bubble; Chandra's resolution comparable to energy-loss travel distance of X-ray emitting photons (assuming moderately relativistic bulk motions)
- •Diffuse emission – kT=0.3 keV – typical for "faint"galaxy
- •Radio contours show interaction of radio plasma and origin of bubble

The Jet in Centaurus A

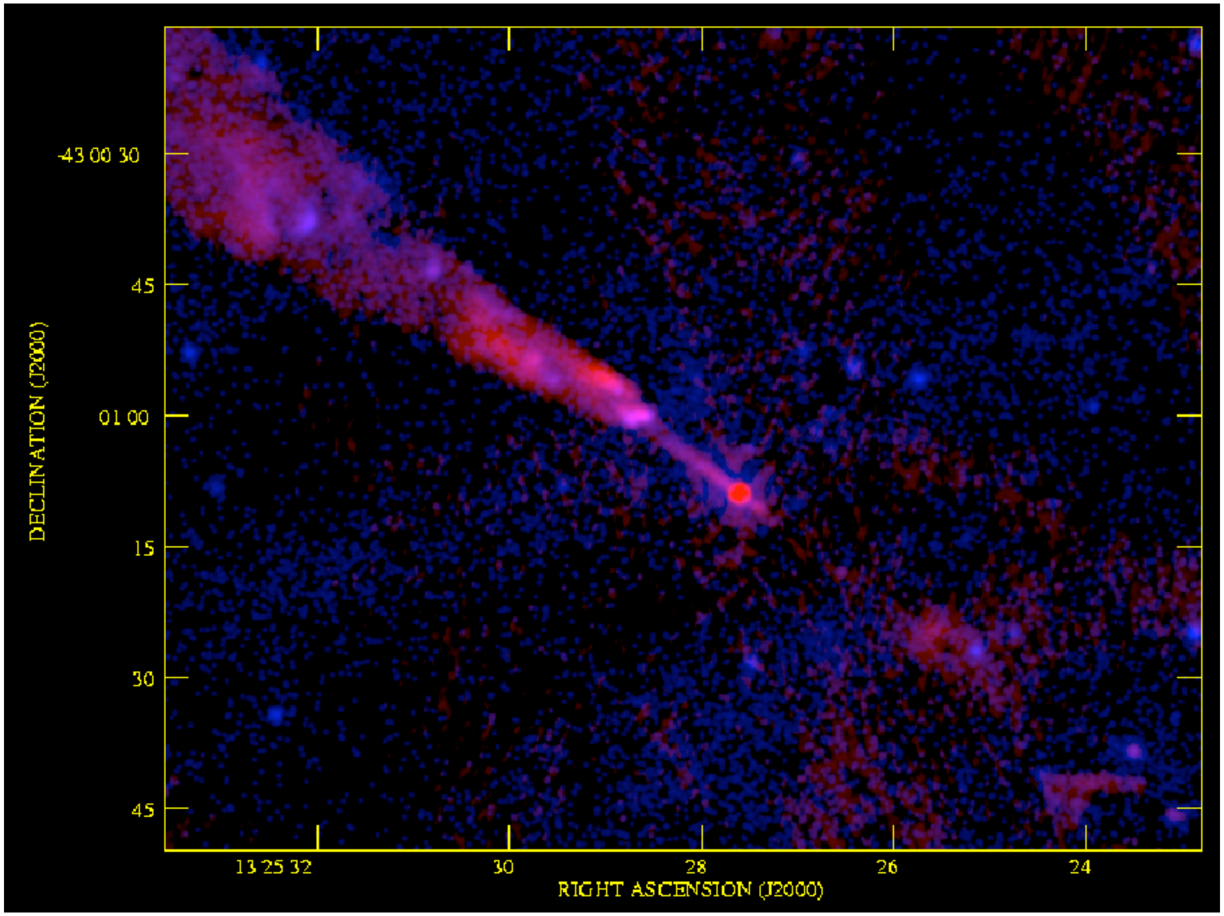


•Chandra (blue) and VLA (red 8.4 GHz) observations (Hardcastle et al 2003)

•Jet is synchrotron emission from relativistic electrons (Feigelson et al. 1980)

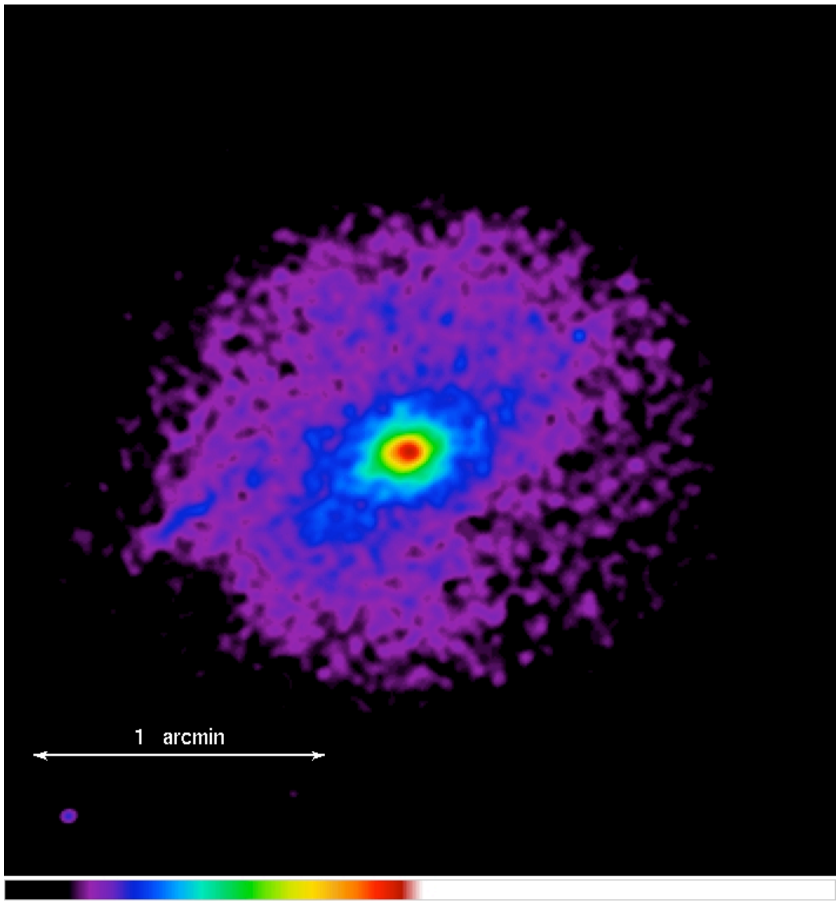
•Faint, well-collimated inner jet region detected. In standard FRI sources, this region is where efficient, supersonic flow transports energy up to where jet flares and becomes turbulent. Could have in situ particle acceleration here.

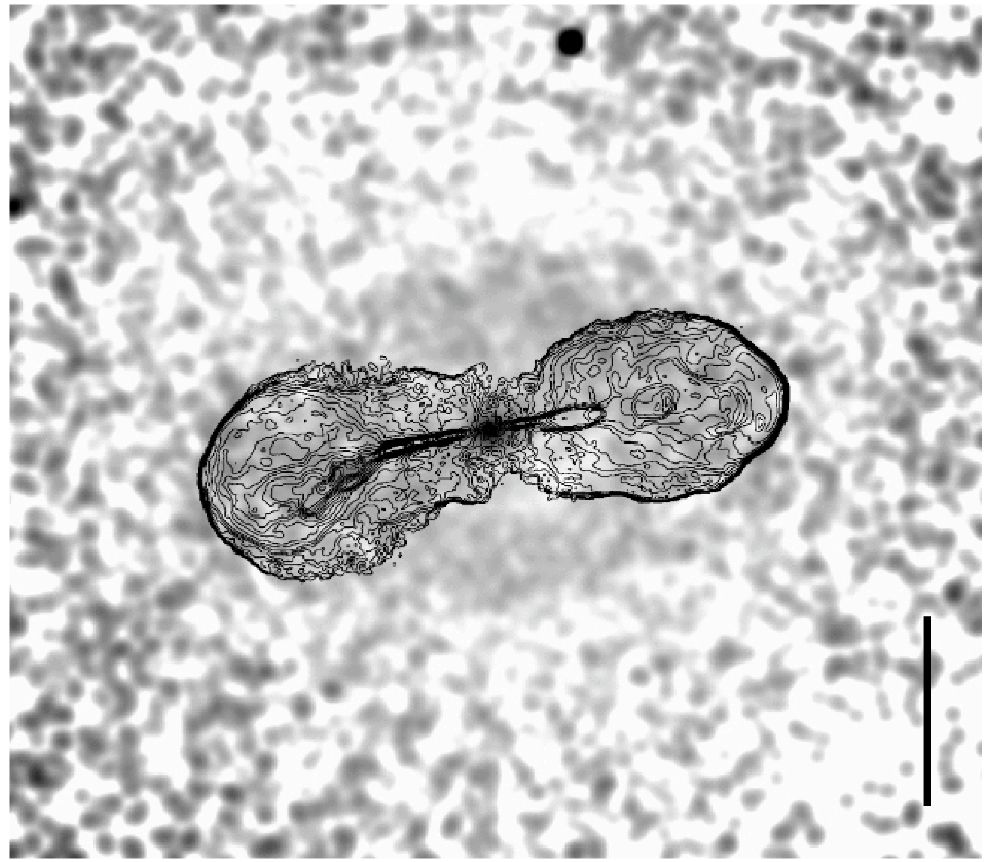
The Jet in Centaurus A



- Many of the X-ray knots correspond to radio knots -- in three, X-ray peaks lie closer to the nucleus than radio peaks.
- Ratio of X-ray to radio emission varies by more than order of magnitude
- Counter-jet - two X-ray knots correspond to radio knots
- What are knots – possibly gas clouds in ISM?

Hercules A (Nulsen et al 2005)



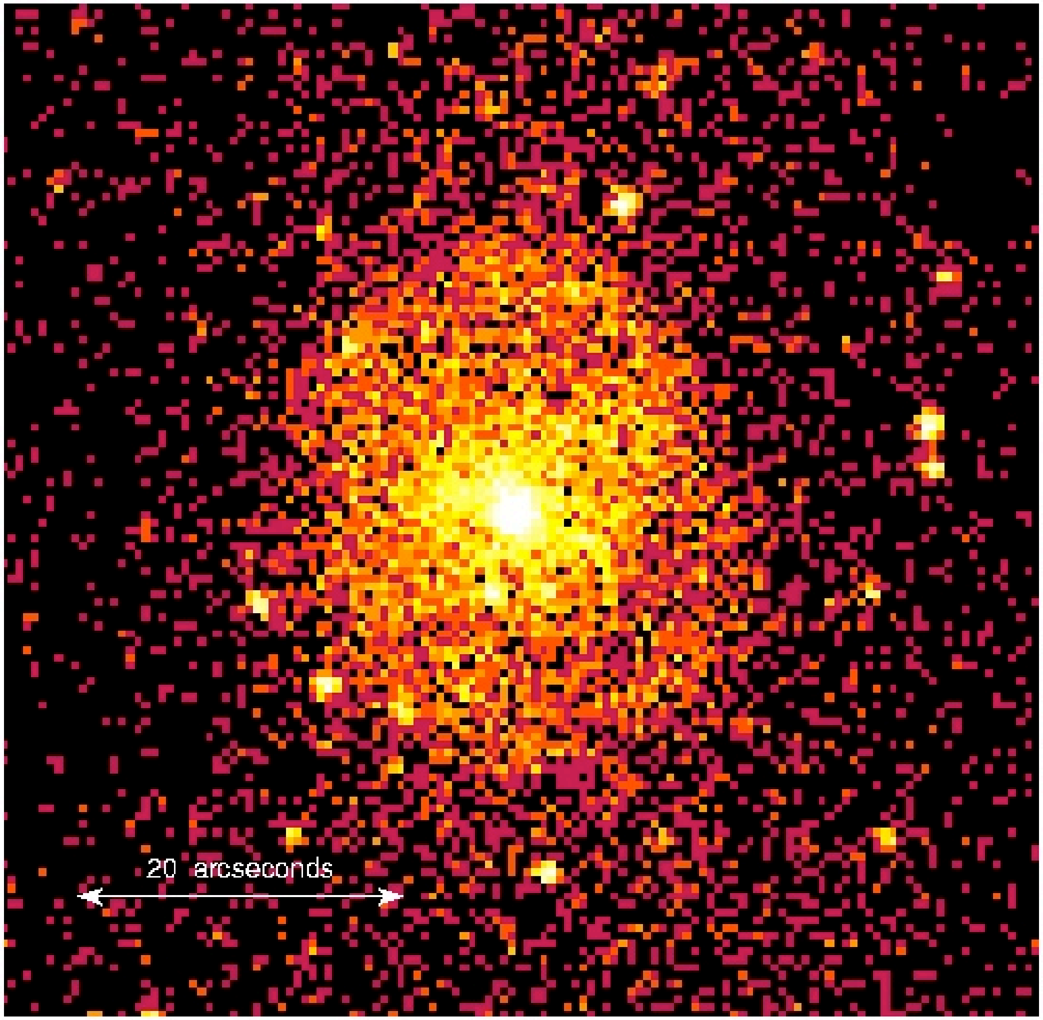


A jet, cavities and a shock

Shock front 160 kpc from AGN

Shock energy 3 X 10^{61} ergs -- 6 X 10^{7} years since outburst

Still Another Exploding Elliptical in Virgo



Chandra ACIS observation

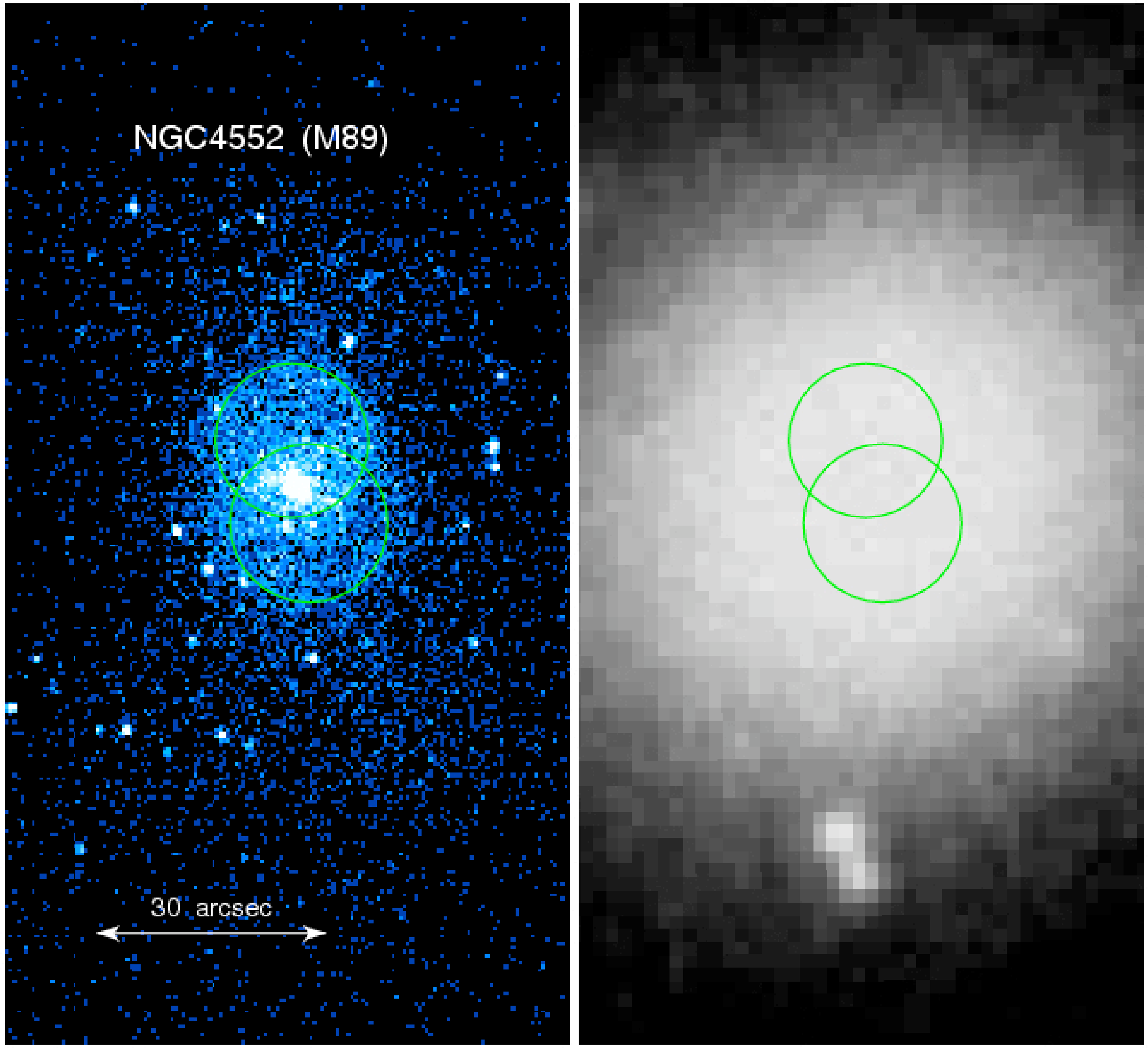
M89 – NGC4552

Bright X-ray nucleus

•Small lobes - 1 kpc
Outburst 1 - 2 10^6 yrs ago

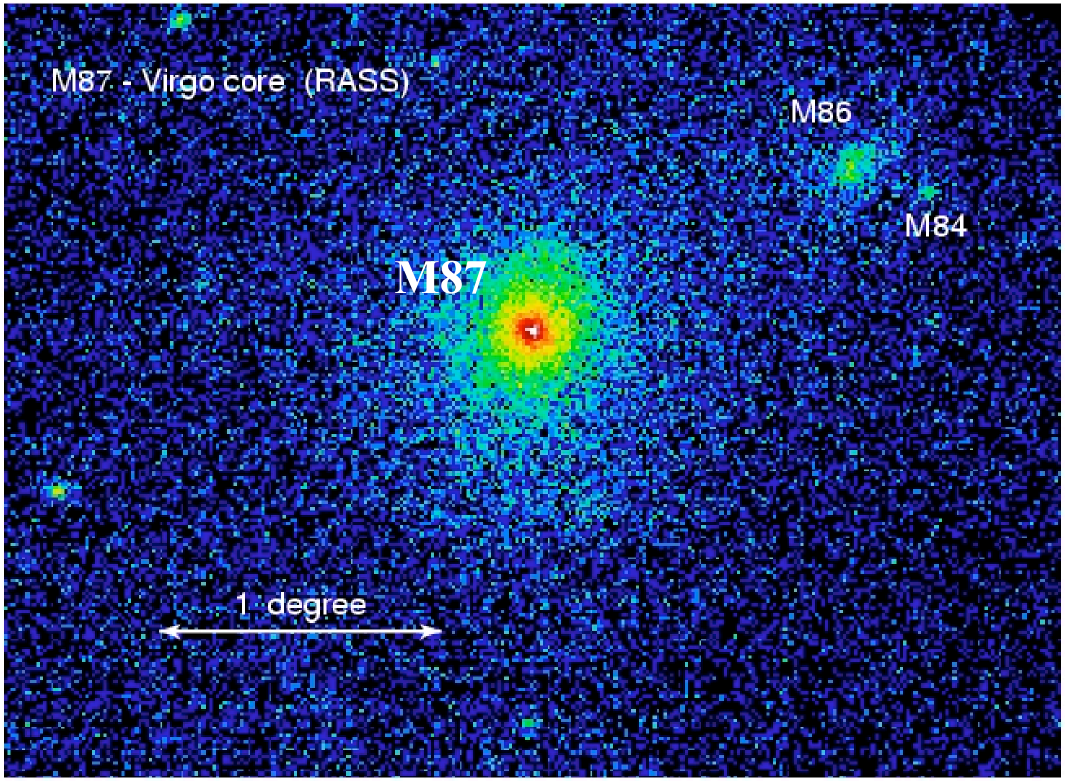
•Core radio source --
92 mJy (2380 MHz)

NGC4552 - M89



Chandra Optical (DSS)

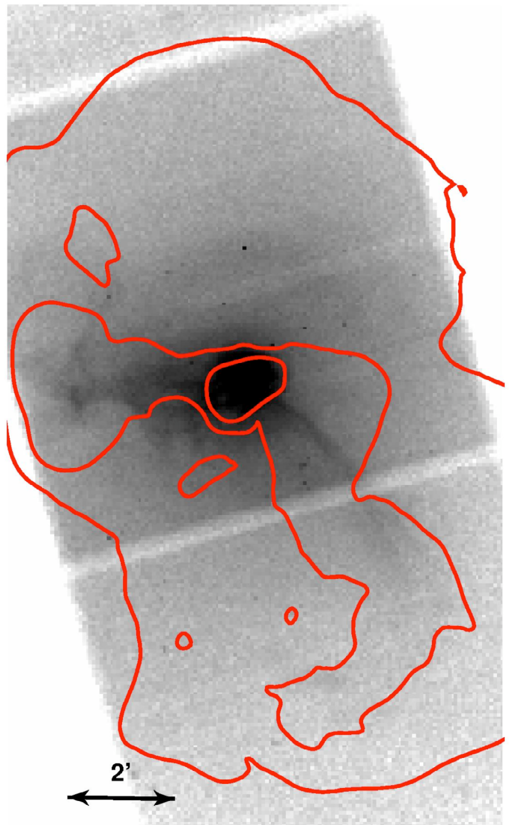
M87's Hot Atmosphere



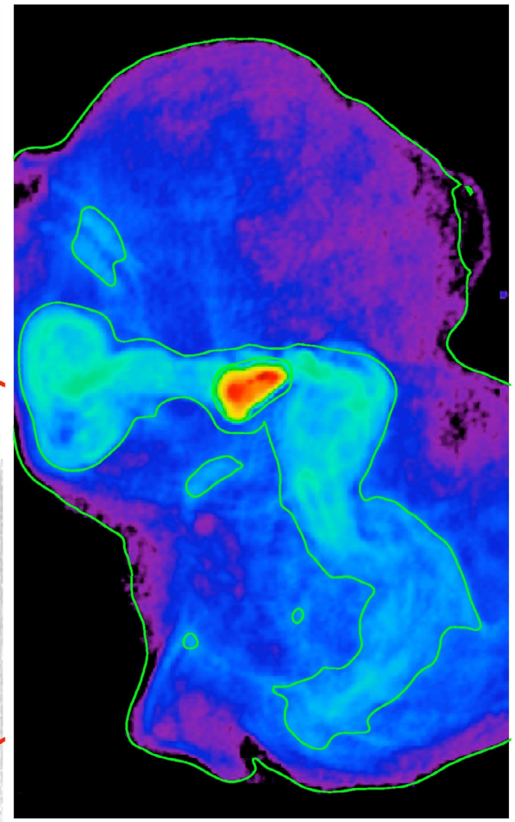
- Extensive gaseous atmosphere - 2 - 2.5 keV
- First example of total mass measurement in halo of elliptical using gas temperature and density (Fabricant, Gorenstein & Lecar 1979)
- Classic example of a "cooling flow" system

Southwestern Arm

- Southwestern arm begins differently, exits core as narrow (10'' – 0.8 kpc) filament.
- Inner southwestern X-ray arm seems uncorrelated with radio. Radio appears to spiral around X-ray filament (possible magnetic tension confining X-ray gas?).



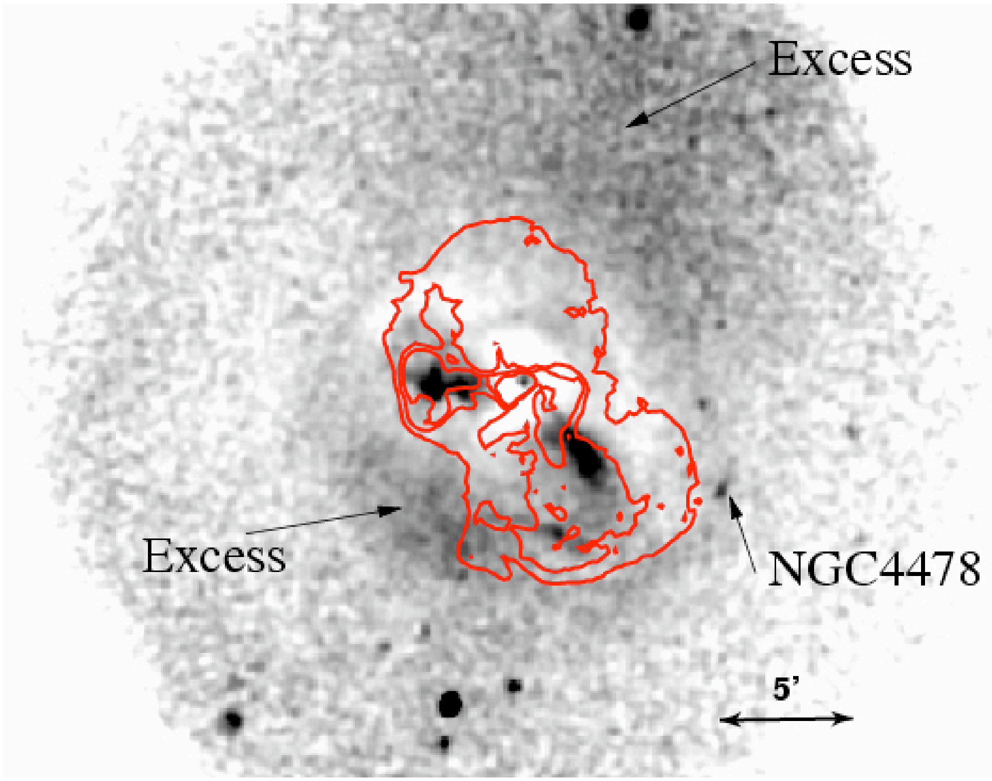
Chandra



Radio

M87 on Large Scales

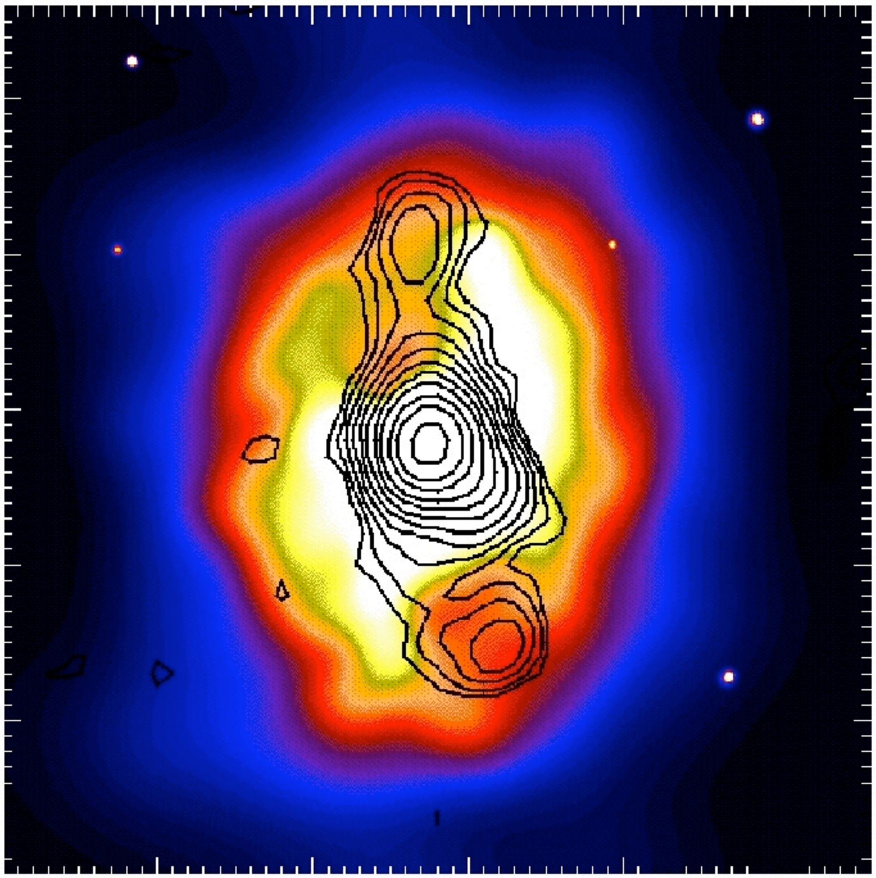
- X-ray enhancement at 37 kpc, on rim of southern radio lobe. Gas has high abundance (solar) but kT=2.5.
- On largest scales XMM-Newton and ROSAT show enhancements and depressions, perhaps from earlier AGN outbursts.

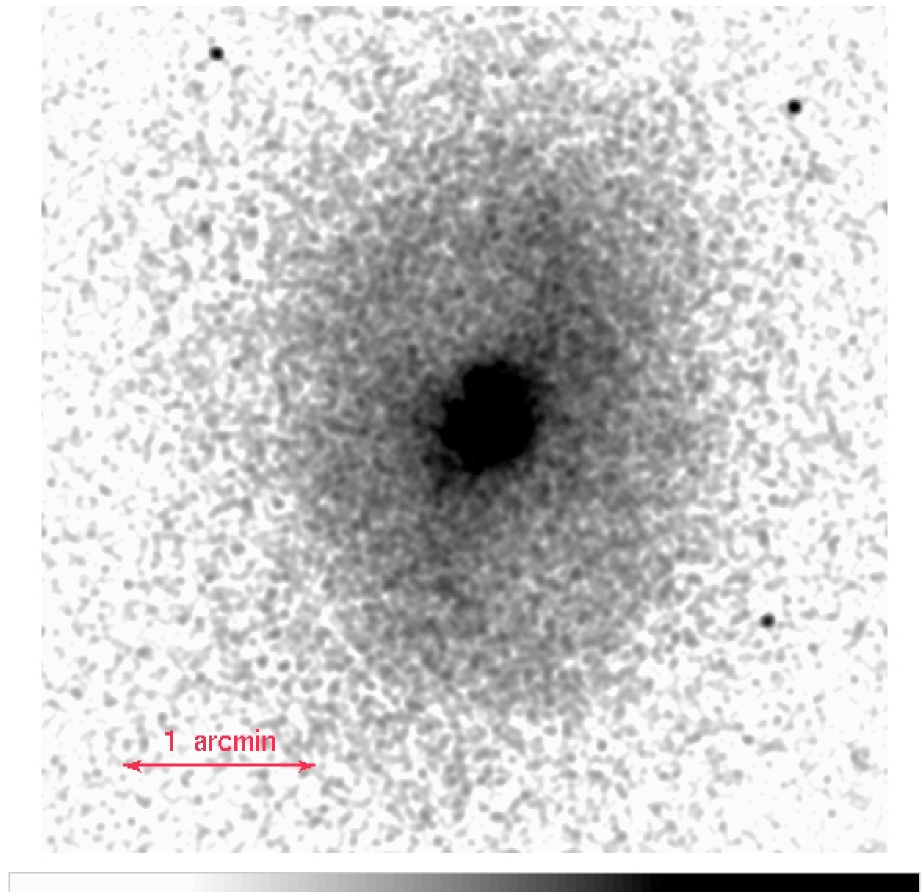


ROSAT HRI

MSO735.6+7421 - McNamara et al 2005

Cavities ~ 200 kpc diameter



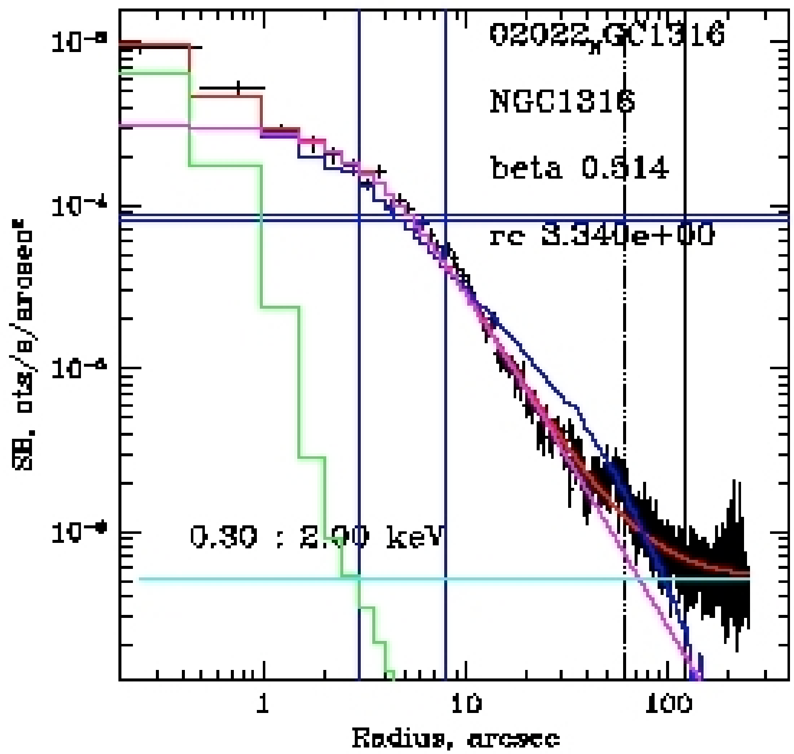


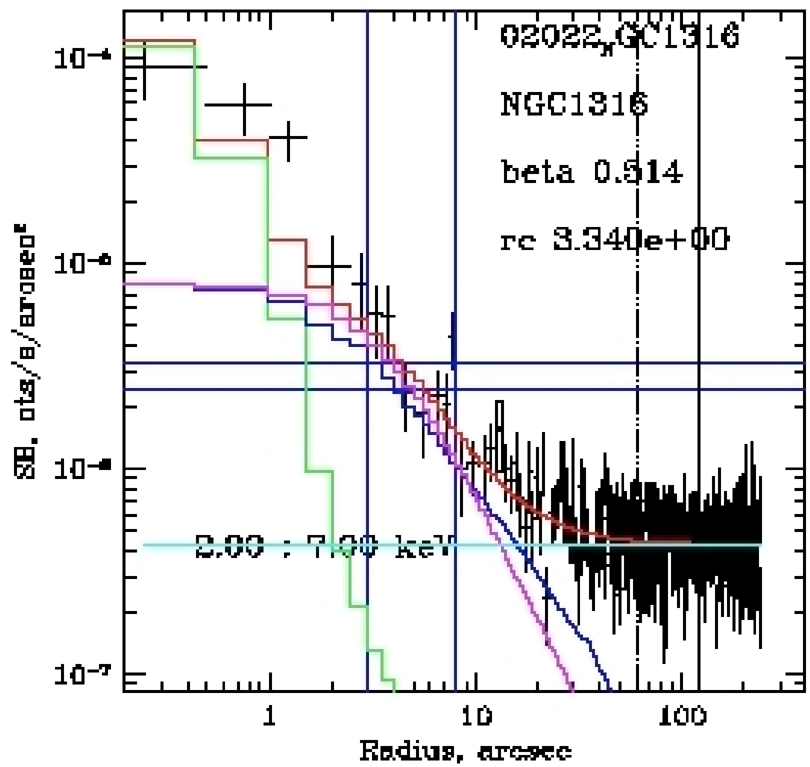
Energy Driving Shock 6 x 10^{61} ergs

Age of shock 1 X 10^8 years

Average power 1.7 X 10^{46} ergs/sec (weak radio, X-ray, opt nucleus)

Measuring nuclear emission in X-rays





Fit diffuse ISM + point source in 0.3-2 keV (where ~1 keV ISM is bright)

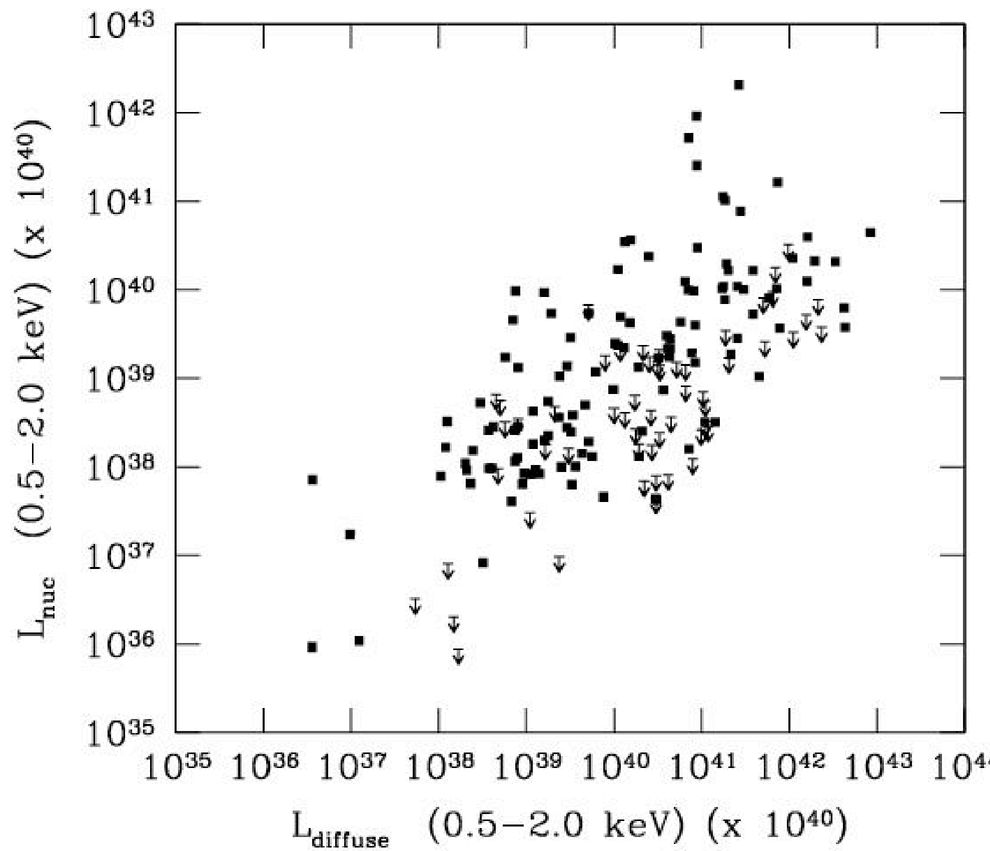
Use 0.3-2 keV fit of ISM to measure hard emission (2-7 keV) from nucleus

X-ray Nuclear Luminosity and ISM Luminosity

In "normal" early-type galaxies -

•X-ray emission detected from the nucleus for most early-type galaxies

•Large dispersion in L_x

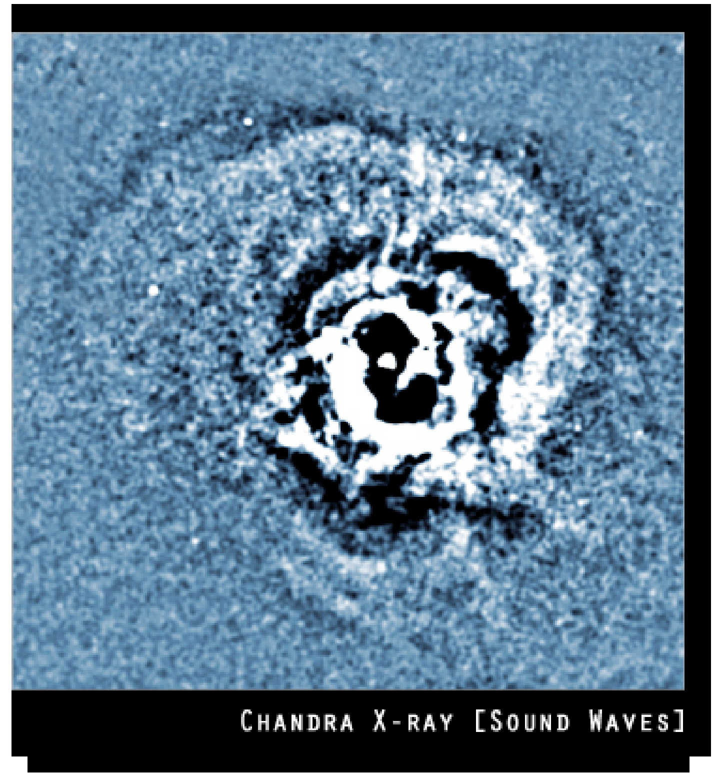


$L_{nuclear}/L_{Eddington}$

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

- 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, τ=9.6x10^6 yr
  - Dissipate energy (high ion viscosity) over a distance < 100 kpc (Lamb 1879)
- Energy of bubbles/shocks is sufficient to balance cooling.

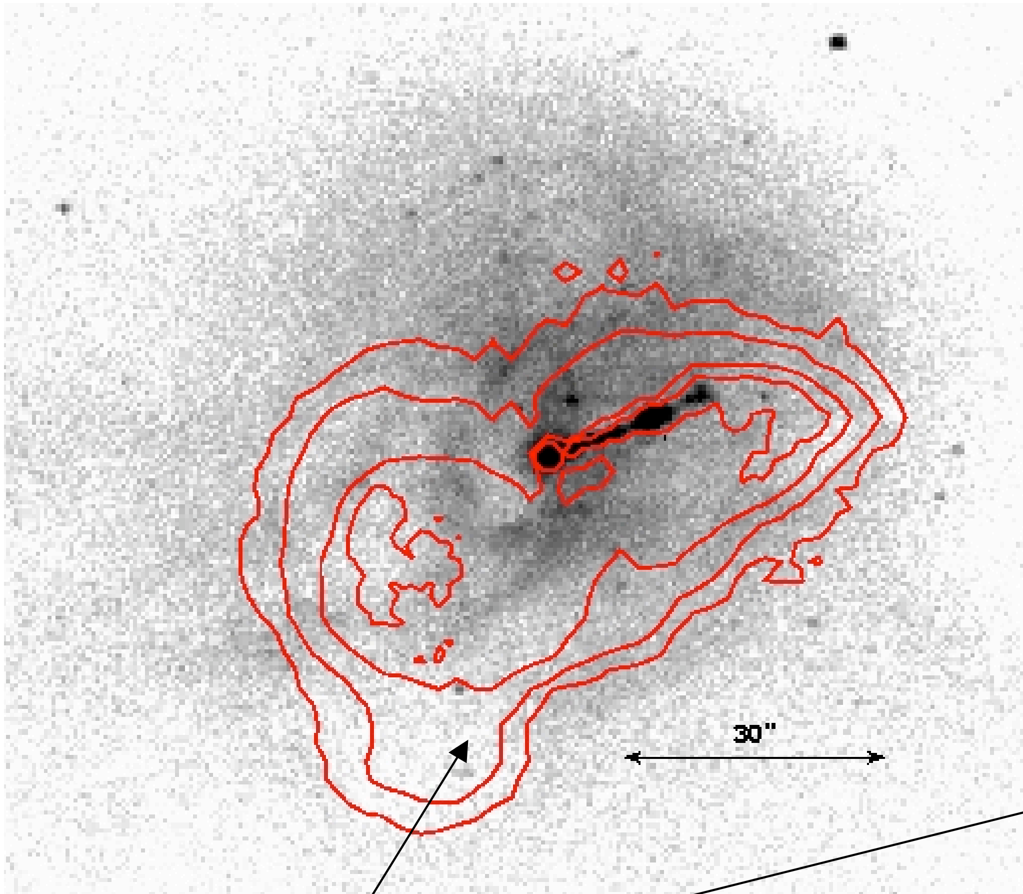
"sound wave pitch is B flat, 57 octaves below middle-C. much too deep to be heard (10^{15} times below limit of human ear)."



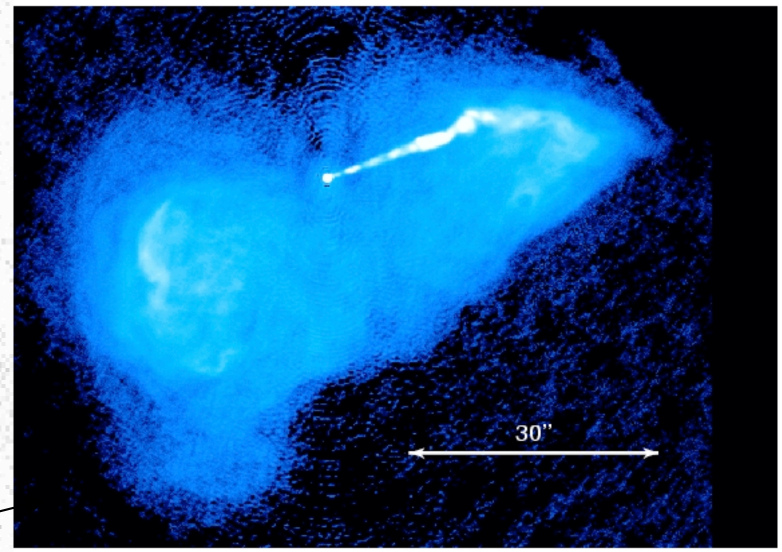
See Fabian et al. 2003 and Chandra www page

Color image (0.3-1.5 keV = red, 1.5-3.5 keV = green,), 3.5-7.0 keV= blue)

M87 Core - X-ray and Radio "Budding Bubble"

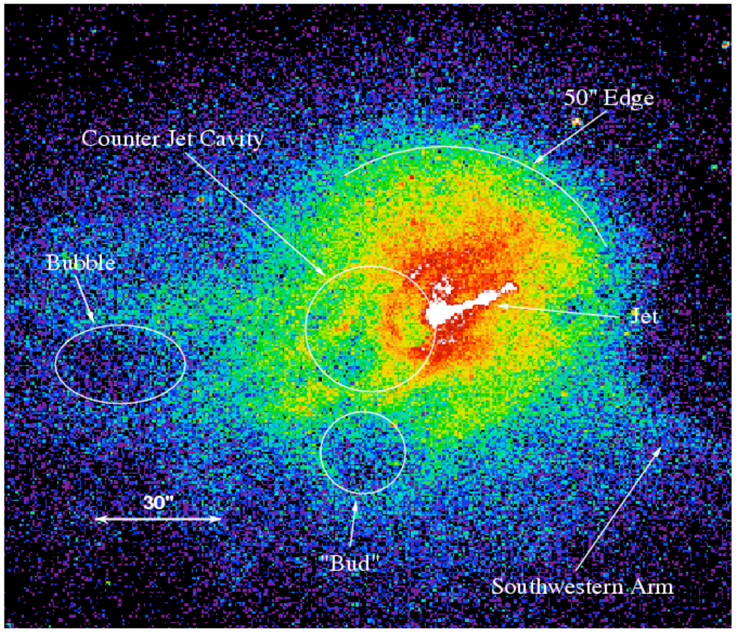


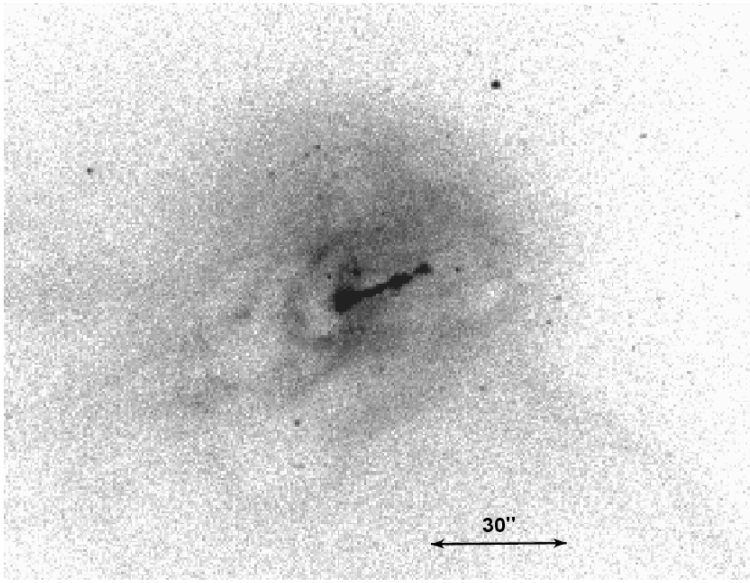
Radio emission

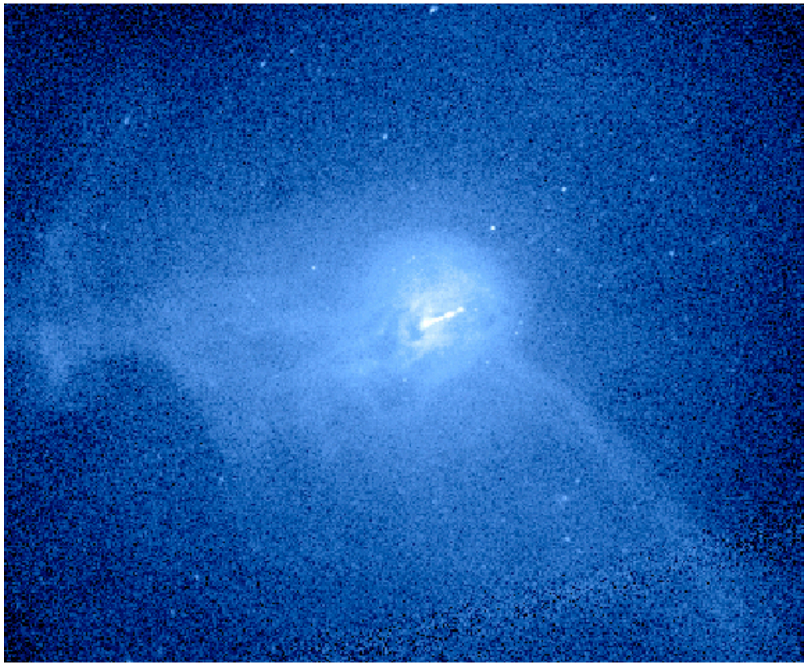


Budding bubble breaking from cocoon?
Not aligned with jet. Radius ~1kpc.
Formation time ~4 10^6 years.

Bubbles at base of Eastern Arm



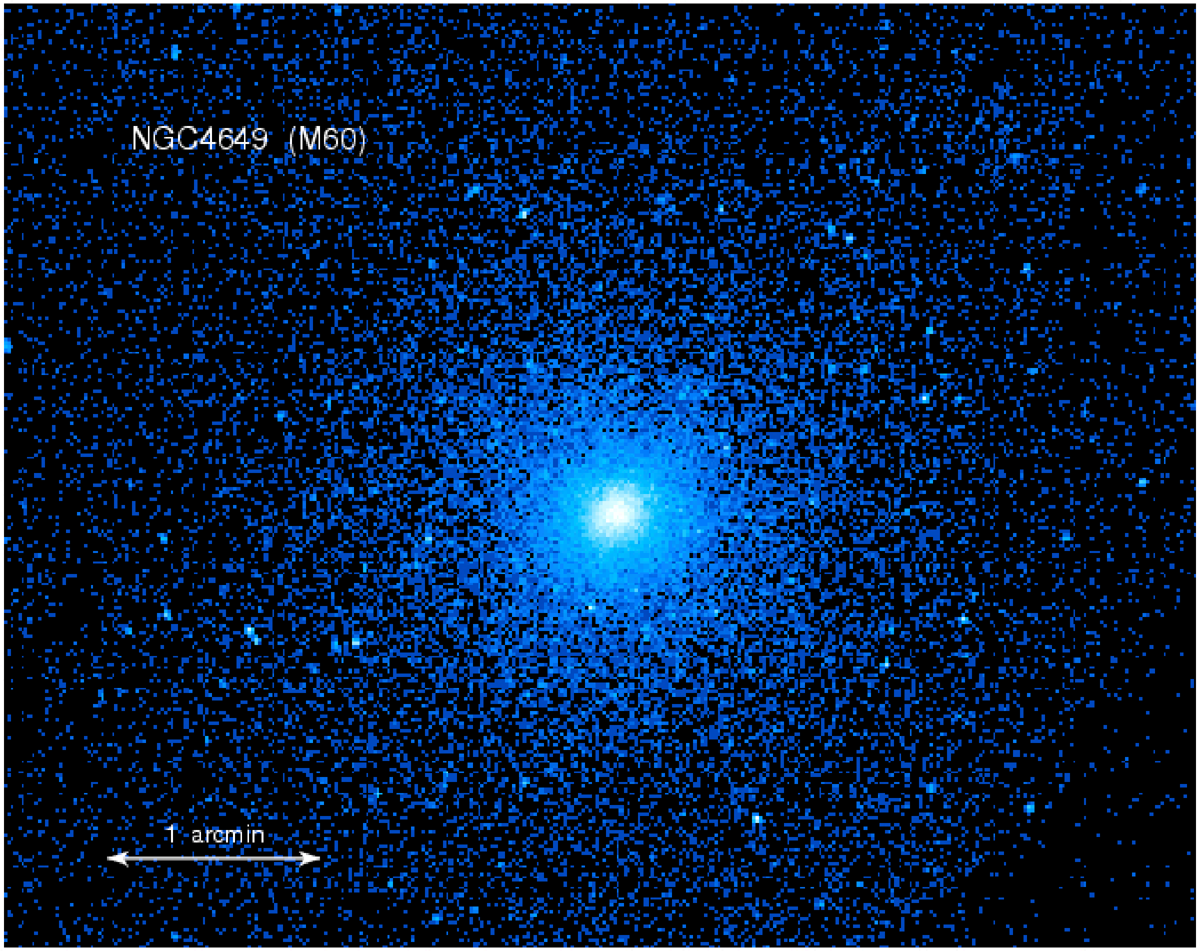




Bubbles seen at base of arm --

Bubble sizes 10” radius (0.8 kpc)

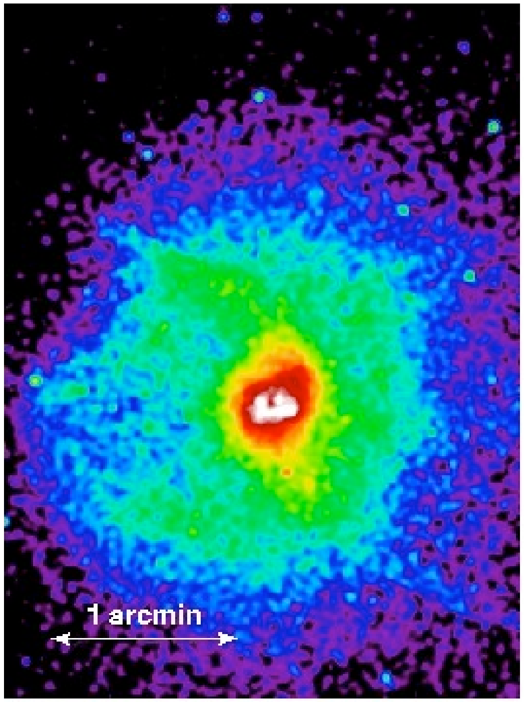
NGC4649 A normal elliptical in Virgo

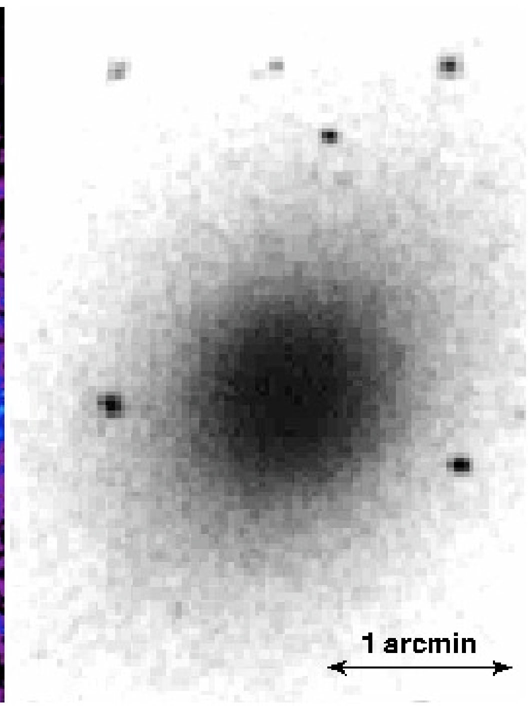


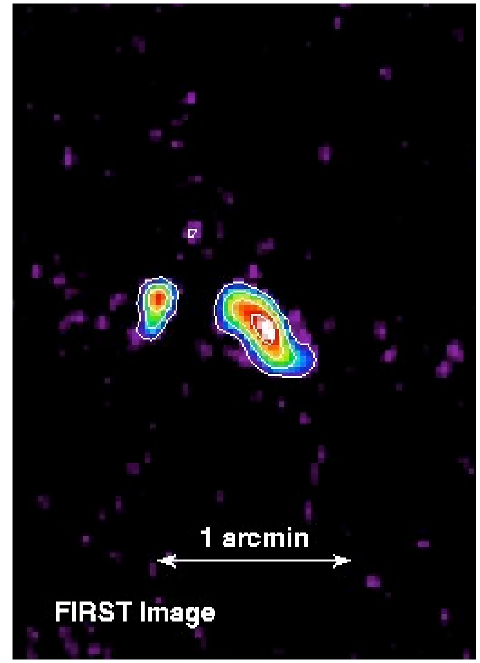
Chandra ACIS-S

As expected -- Hot ISM
and binary X-ray sources

NGC4636







- **Small, weak radio source of about 1.4x10^{38} erg/sec in core**
- **Energy injection (from nucleus) in regions east and west of galaxy center**
- **Shock travels more rapidly into lower density and forms “pin wheels”**
- **The energy in the outburst is 6 10^{56} ergs; occurred 3 10^{6} years ago**