Cooling Cores, AGN, and Feedback

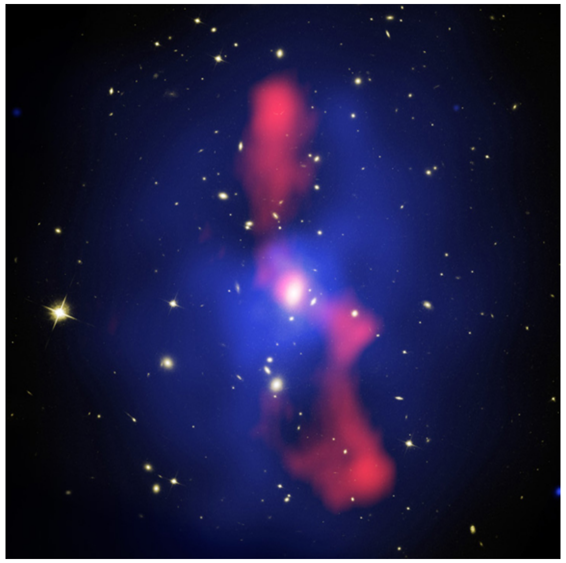
Bill Forman

- Why we need feedback
- Why you should care
- AGN - effective in all gas rich systems from clusters to groups to galaxies
- A detailed look at feedback at work - M87
- Feedback in "normal" galaxies

Collaborators

- Christine Jones, Ralph Kraft, Paul Nulsen, Larry David, Jan Vrtilek, Simona Giacintucci, Marie Machacek, Ming Sun, Scott Randall, Maxim Markevitch, Eugene Churazov, Alexey Vikhlinin

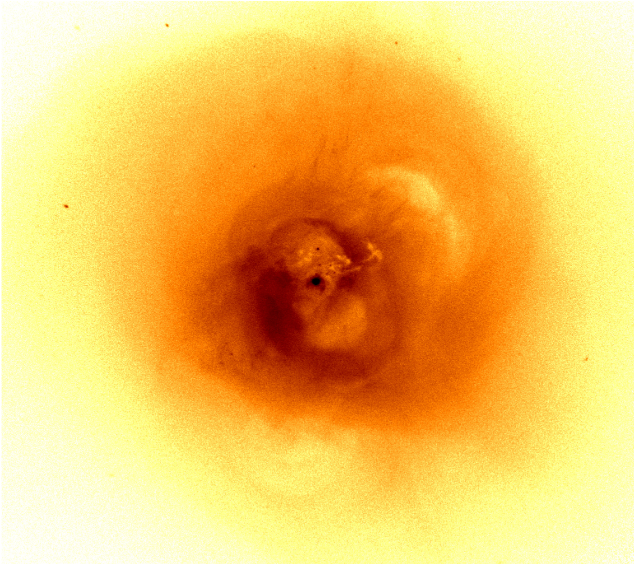
- X-rays "see" the bulk of the normal matter in the Universe when it falls into massive clusters (5x more gas than stars)
  - Heated to 10-100 million degrees
  - Extended, bright X-ray objects
    - Resolved to large distances
    - Trace Total Mass



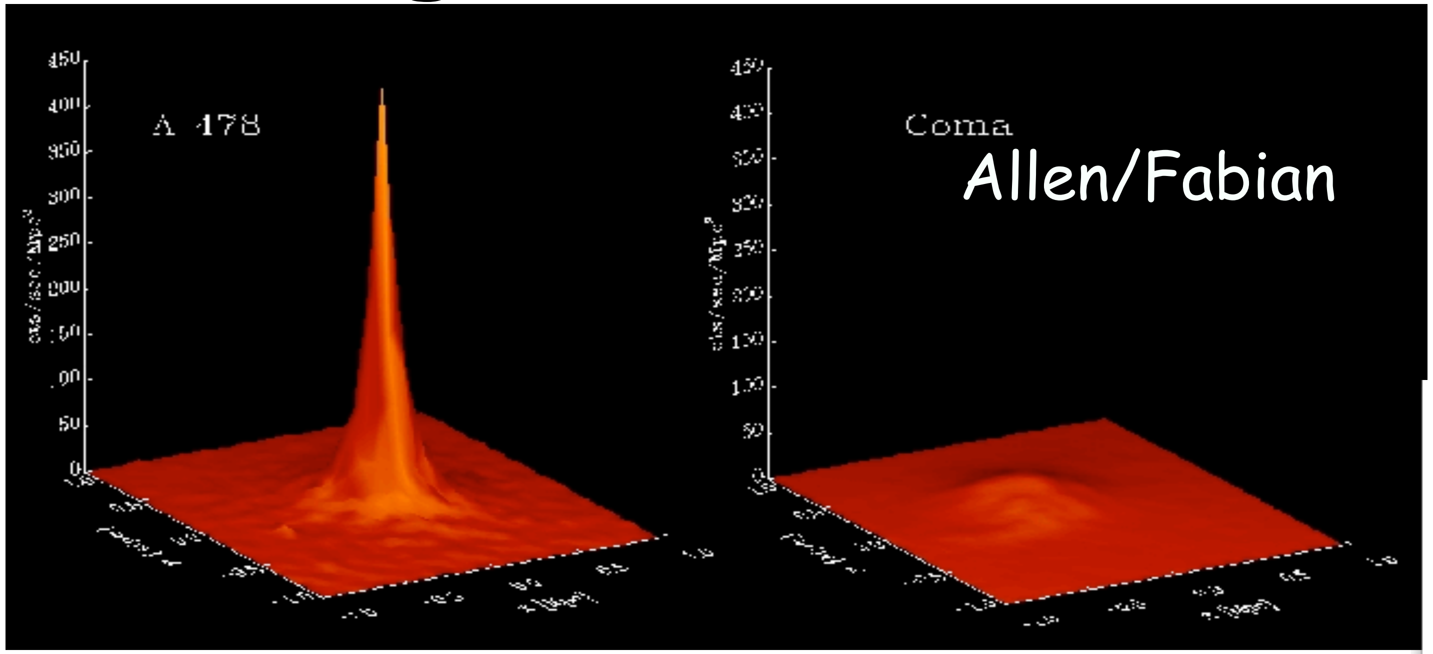
- Hot gas "captures" energy outbursts from supermassive black holes (SMBH) as they accrete and grow (up to a few 10^9 M_{sun})

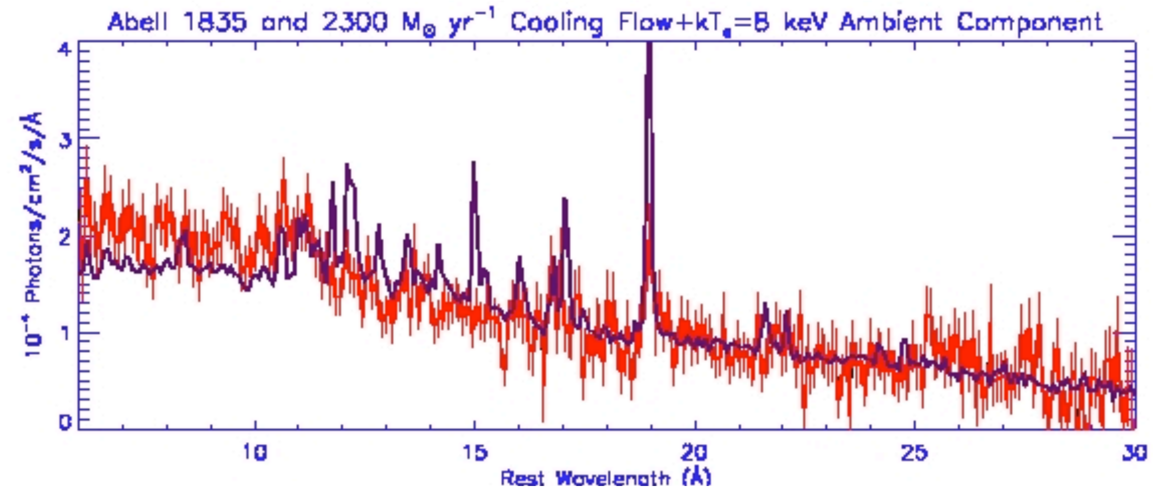
SMBH outbursts "control" galaxy evolution

- Best seen in X-rays
- Enables "feedback" studies from the SMBH



Cooling Flow Problem





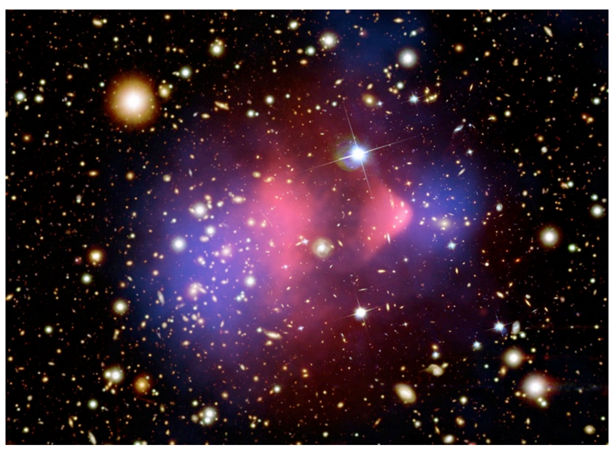
Lines from cooling gas weaker than predicted - Peterson+01,+05 (XMM) & L. David+01 from Chandra

- "Cooling gas in the cores of clusters can accrete at significant rates onto slow-moving central galaxies" Cowie & Binney (1977) Fabian & Nulsen (1977)
- Strong surface brightness peak --> dense gas --> short cooling time
- Hot gas radiates – gas must cool unless reheated in all systems with early type galaxies - galaxies, groups, clusters
- But large amounts of cool gas were never detected and red galaxies are (mostly) dead galaxies with little star formation
- Chandra & XMM changed a decades' old paradigm

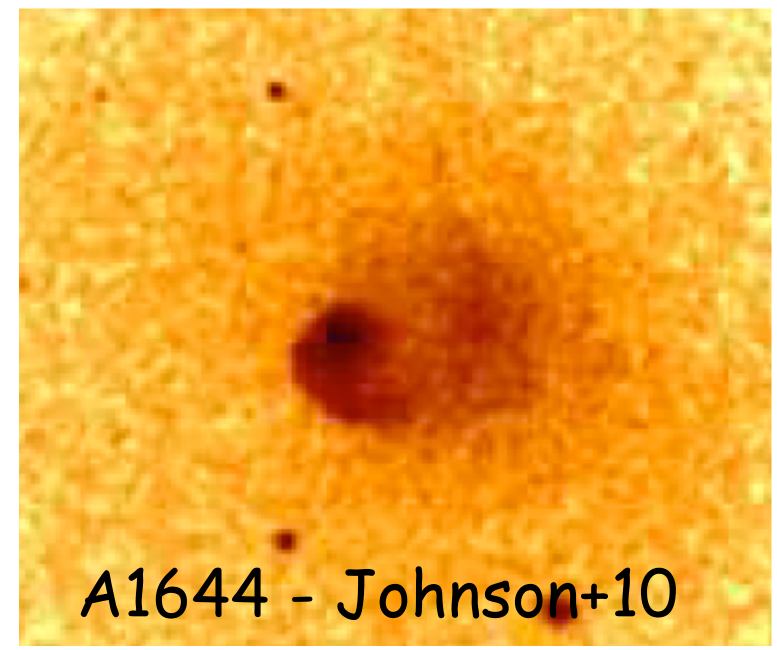
Solving the Cooling flow problem: Gas Heating and Feedback

Mergers and merger-driven sloshing – plenty of energy (up to 10^{64} ergs), but not "regular" (plus peaked clusters appear "relaxed")

Merger driven sloshing is very common (2/3 of cool core clusters; Markevitch+03, Johnson11)

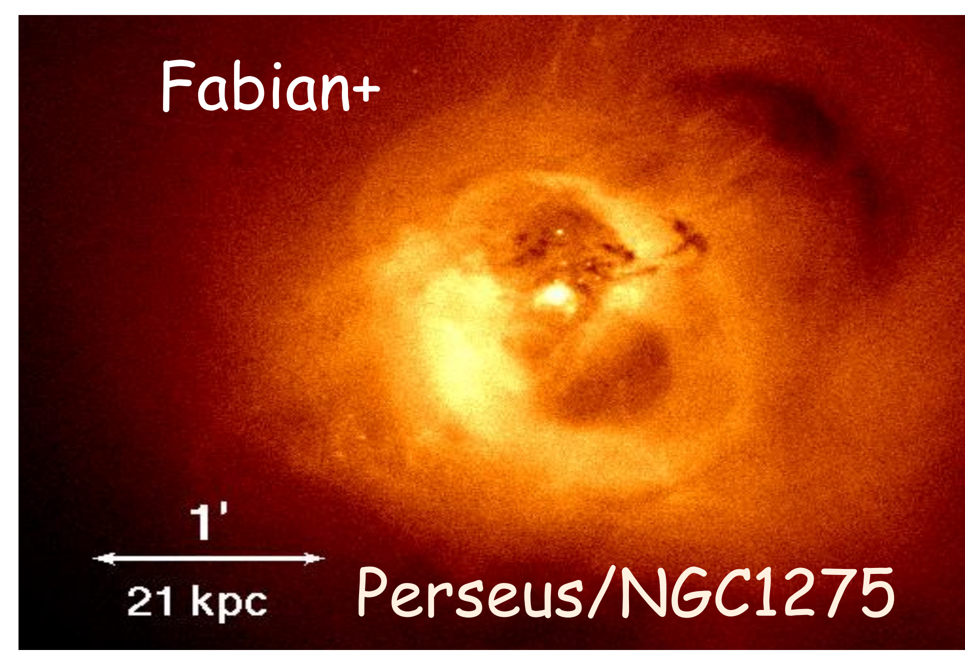


Sloshing- Markevitch & Vikhlinin

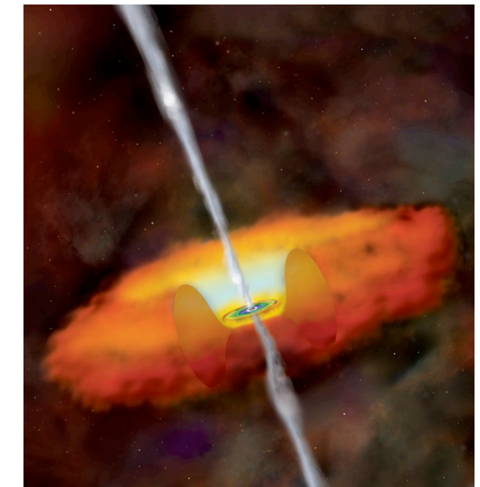


Energy from AGN

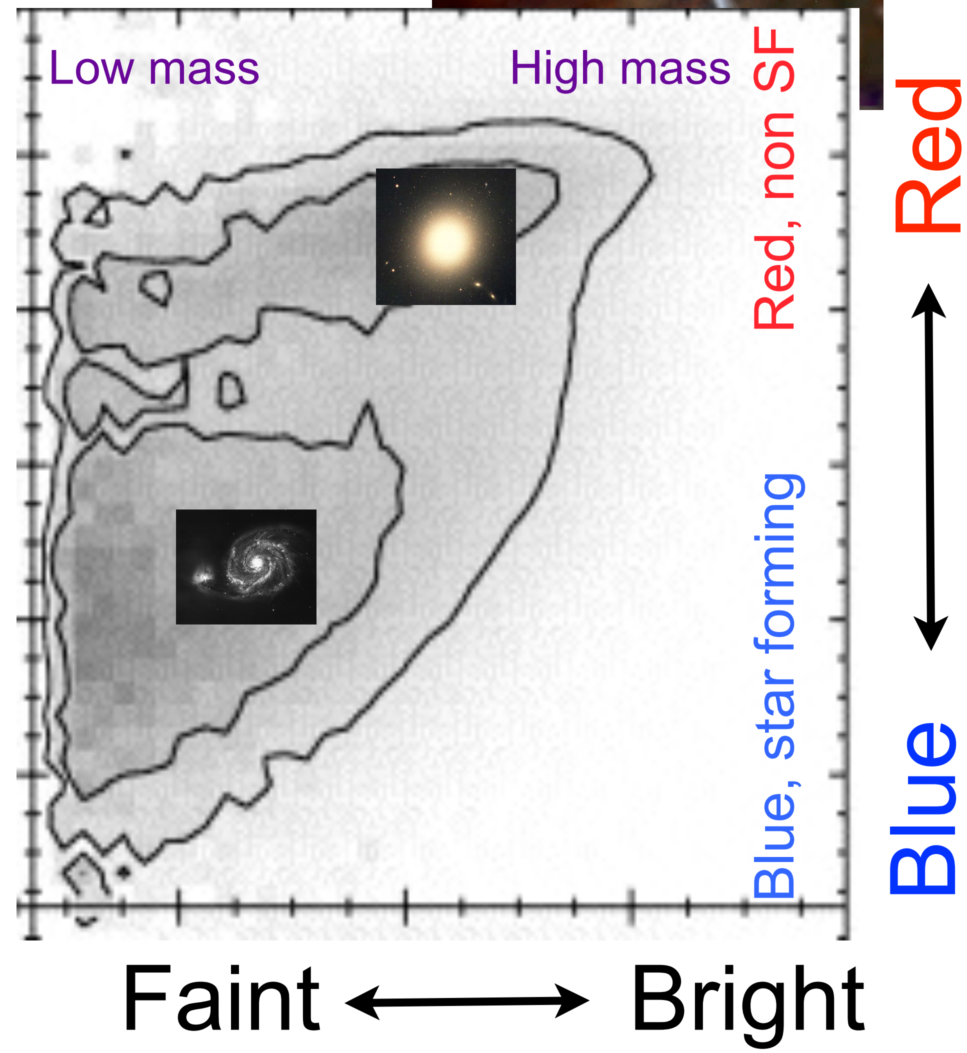
- X-ray cavities, plasma Bubbles/radio lobes, jets, ghost cavities, shocks
- Shocks
- works from galaxies to clusters
- "understands" or amenable to feedback



Feedback from Supermassive Black Holes Explains Basic "Fact" of Astronomy - two kinds of galaxies



- Feedback
  - Supermassive Black Hole in galaxy nuclei
  - accretes matter
  - Black hole grows
  - Some energy returned (via jets) to control formation of new stars
  - red sequence/blue cloud (elliptical vs. spiral; old red, "dead" galaxies vs. blue/young ; hot gas rich vs. hot gas poor)
  - explains galaxy luminosity function
- Key component of galaxy evolution

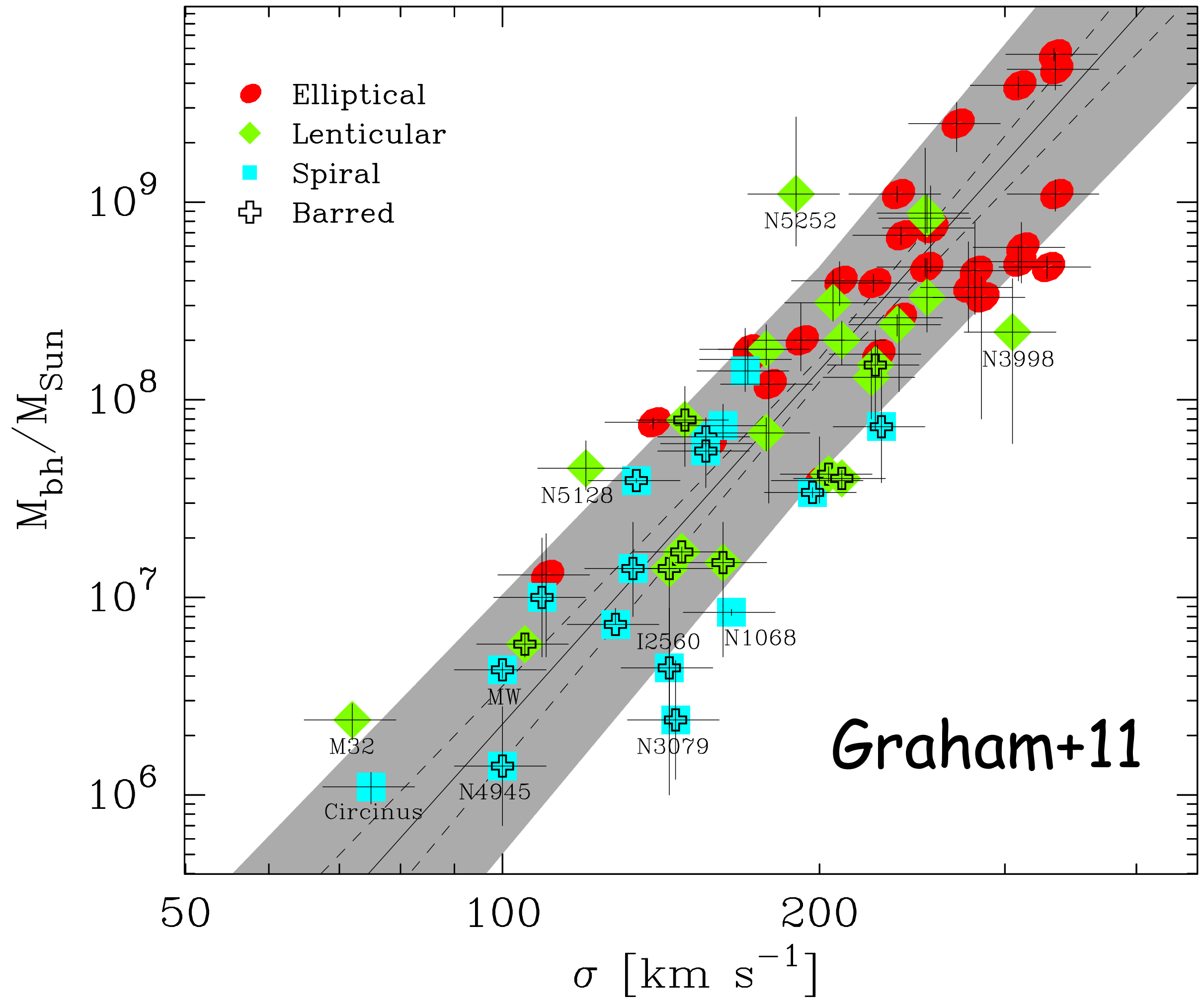


e.g. Croton+06, Best+06, Teyssier+11

All (red/old) bulges have SMBH

- efficient source of energy
- "ready and able" to balance gas cooling

- SMBH mass closely tied to bulge velocity dispersion (bulge stellar mass)
    - $M_{SMBH} \approx 10^{-3} M_{bulge}$



Feedback (black holes + hot gas) and Baseball

Early type (bulge) galaxies - like a baseball team

Batter = SMBH - sometimes hits the ball (outbursts)

- infrequent
- exact trigger unknown
- different sizes (walks, singles, ... home runs)

Pitcher = provides ball/fuel (cooling gas for accretion)

Hot X-ray emiiting gas = fielders

- capture AGN output

Fielders are critical

No fielders (no gas)

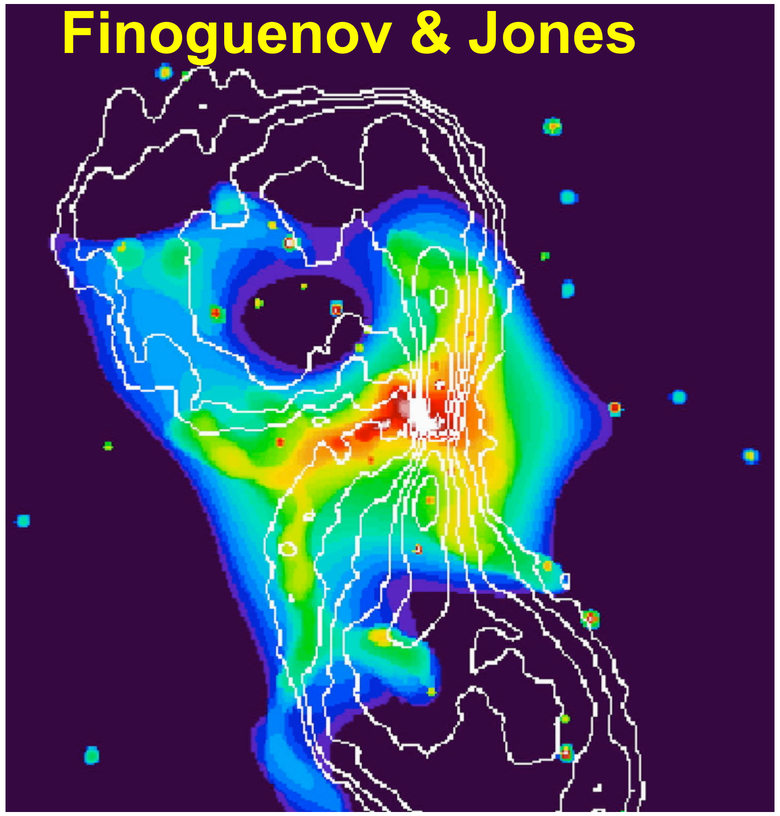
==> No energy capture

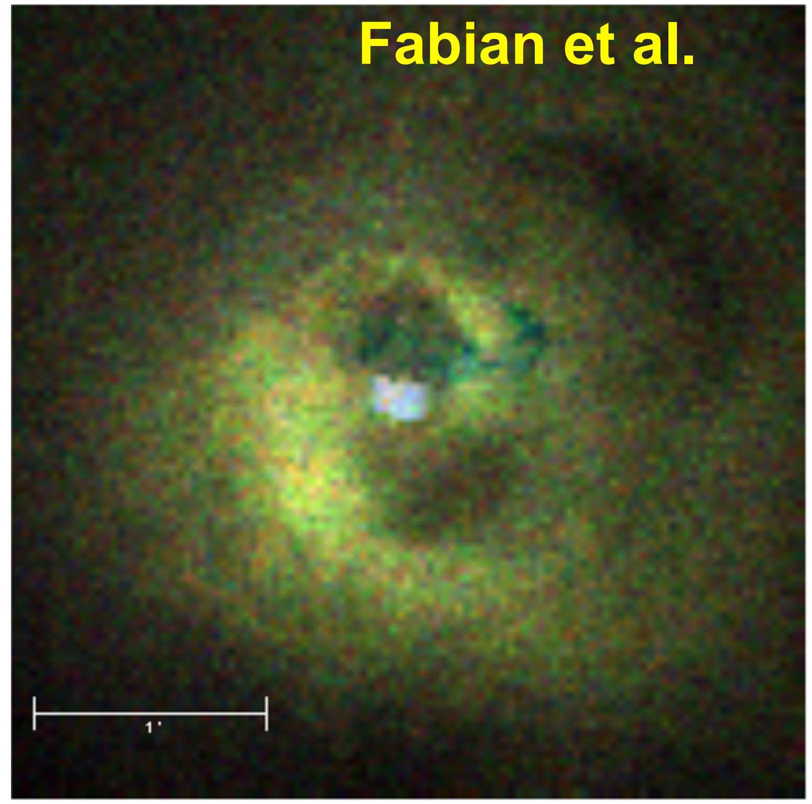
No feedback

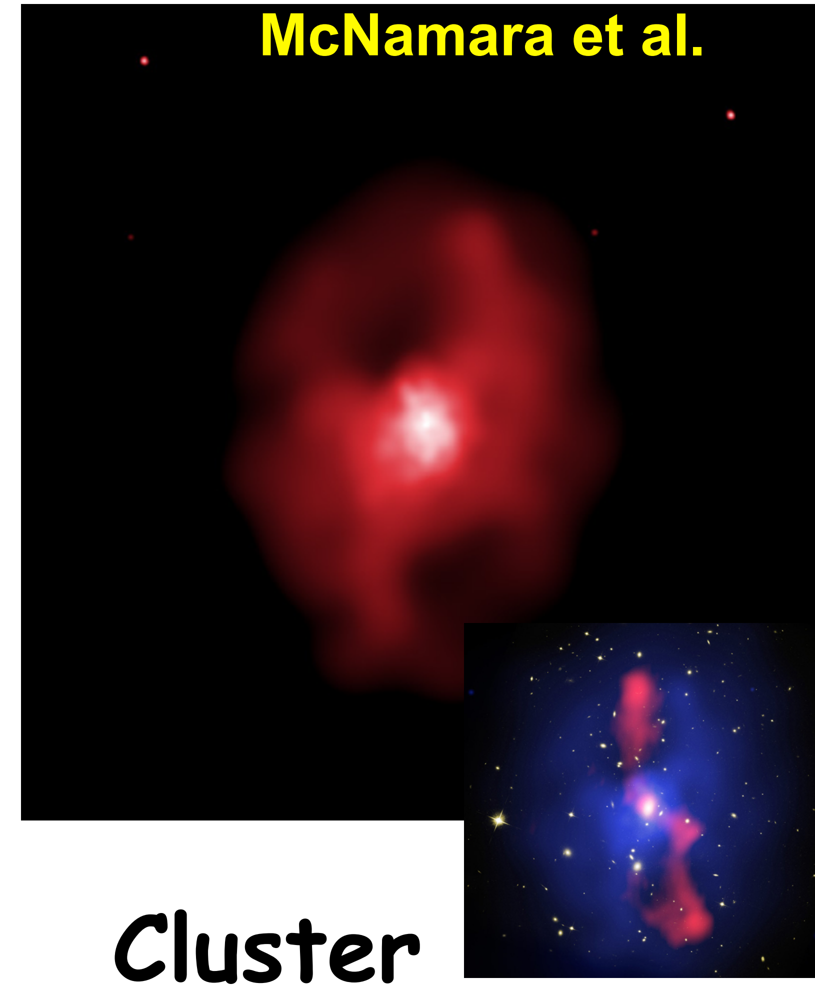
Unifies SMBH, AGN activity,
Galaxy properties (red/blue)
X-ray cooling flows

Gas Provides archive of AGN activity

Outburst Scales







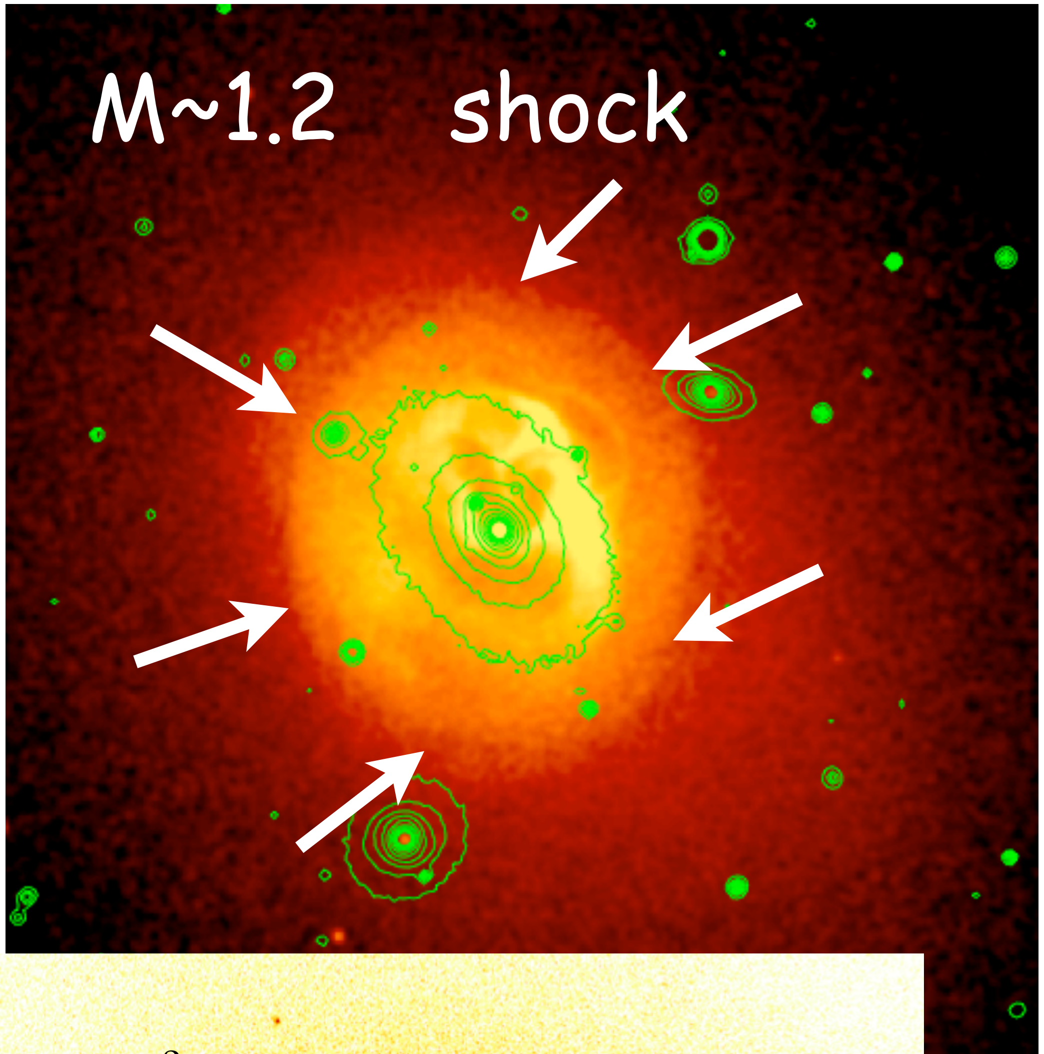
Galaxy
1 kpc
10^{56} ergs
10^{42} erg/s

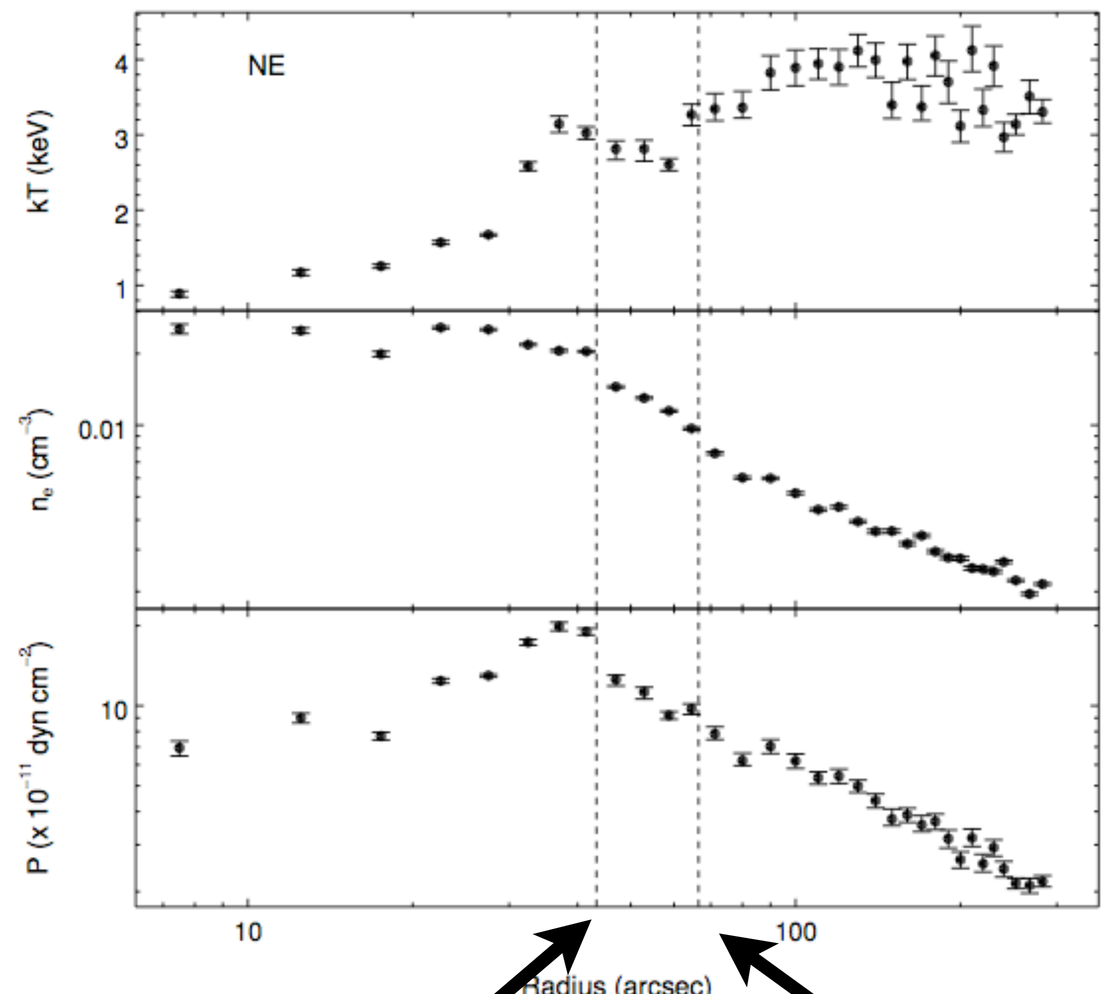
Group/Cluster Core
10 kpc
10^{59} ergs
10^{45} erg/s

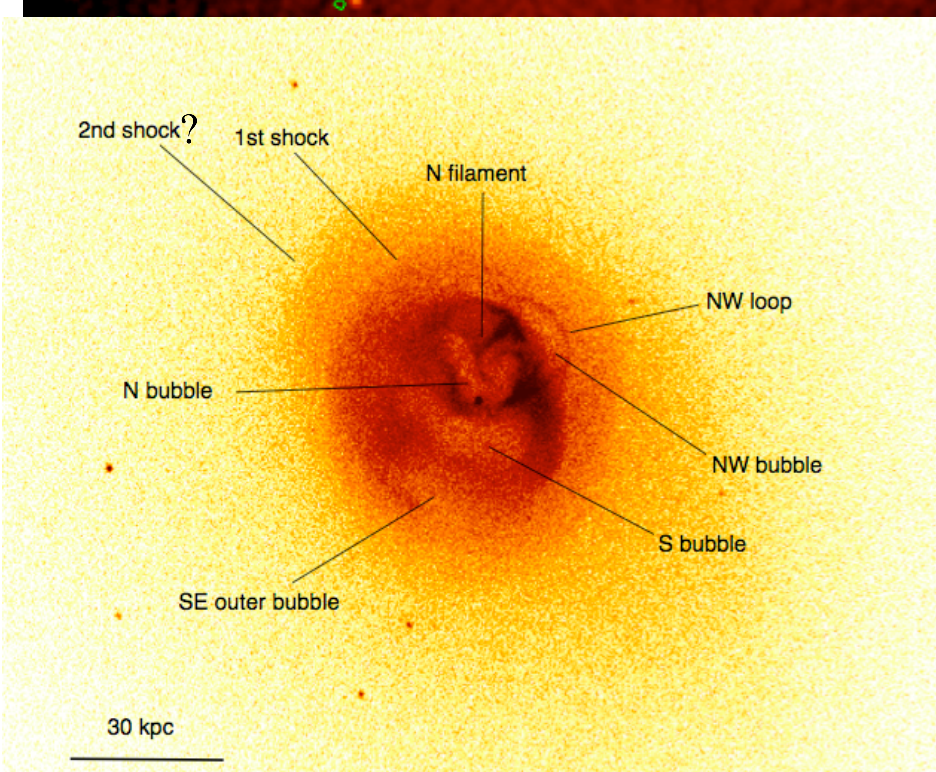
Cluster
100 kpc
10^{62} ergs
10^{46} erg/s

Very powerful outflows
Very little (nuclear) radiation

Abell 2052 - Blanton+11



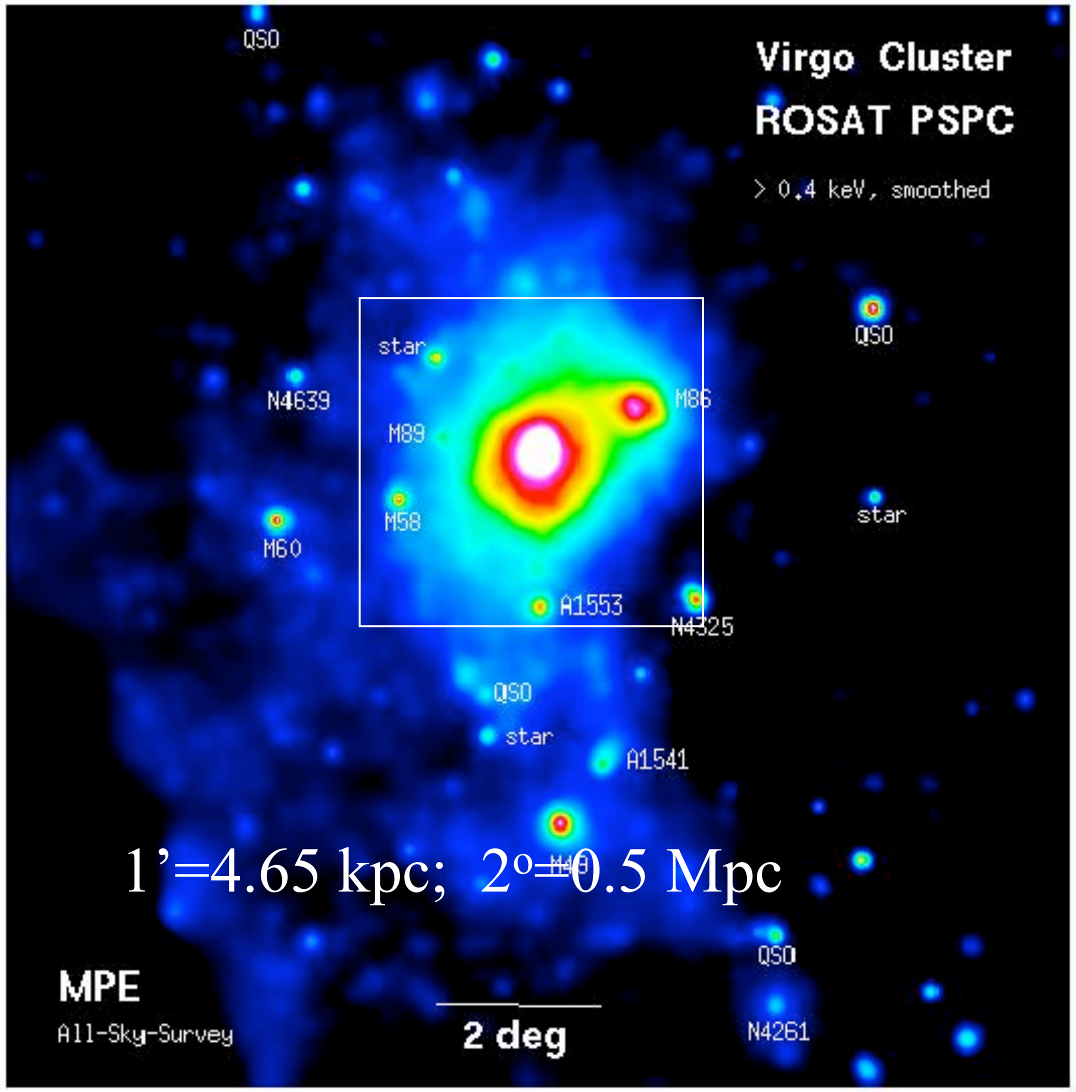


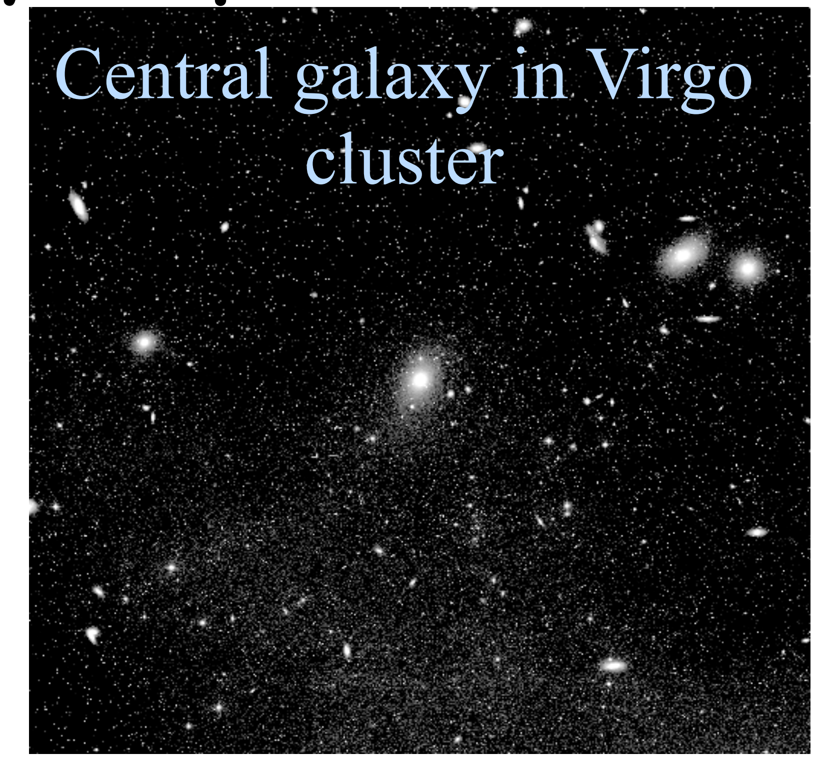


M~1.17 shock
nearly spherical
consistent density/
temperature jumps

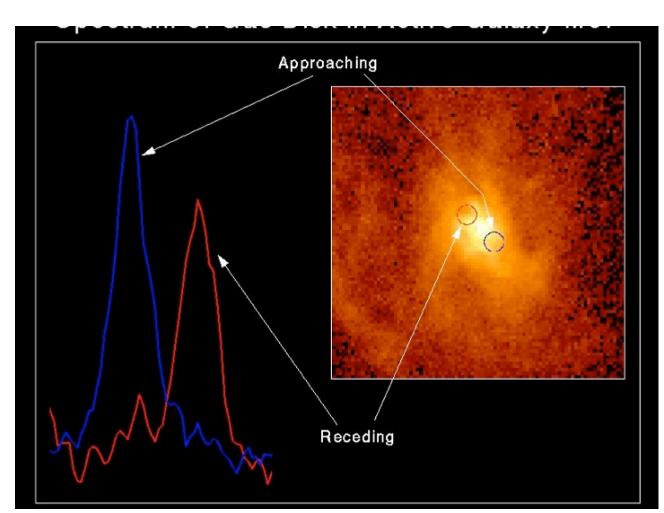
Second
feature
shock?

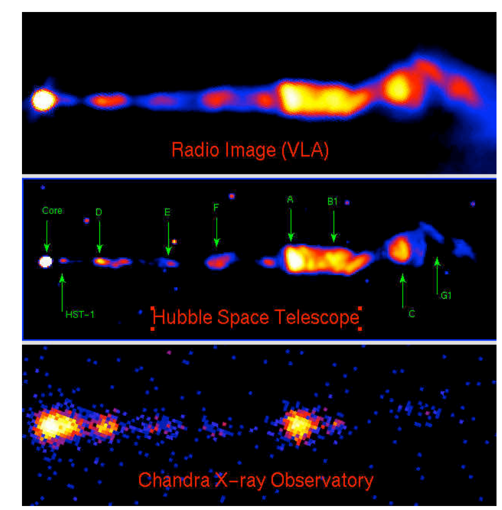
Virgo Cluster - X-ray/Optical





Key unit pc=3x10^{18} cm

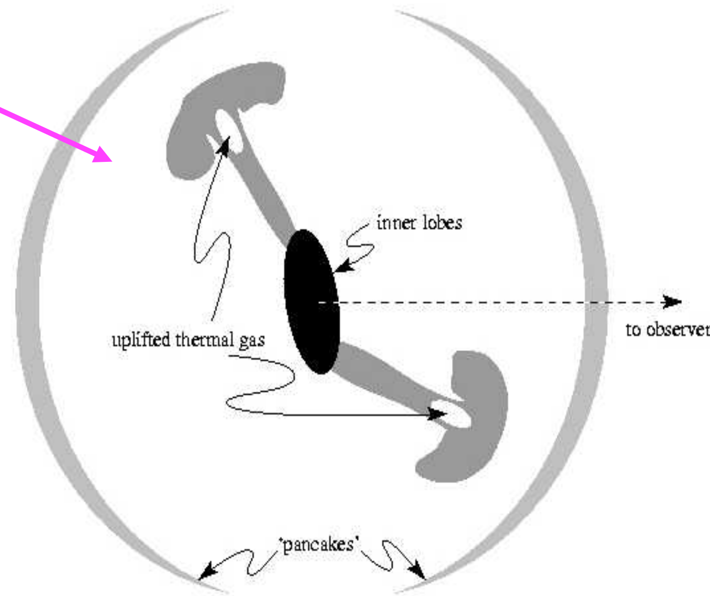


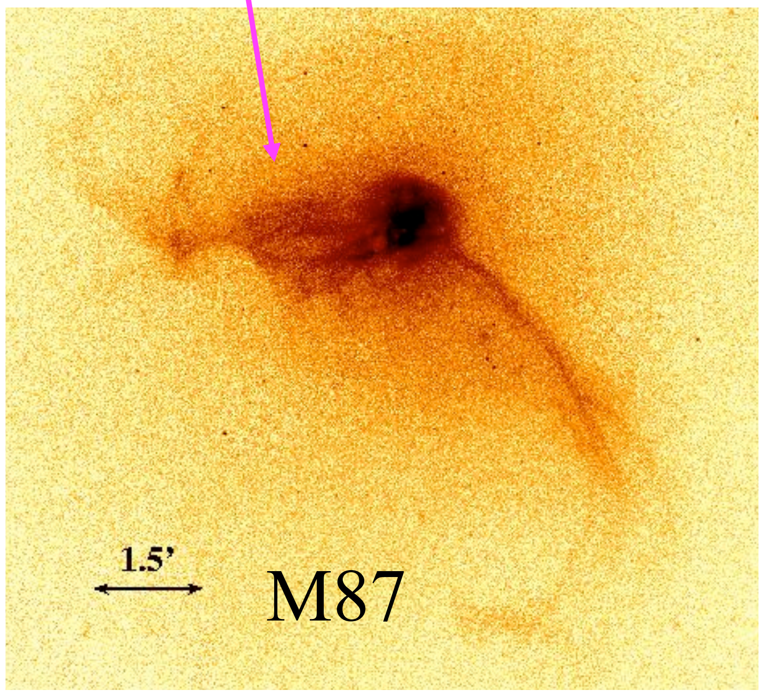


- $6\times10^9 M_{sun}$ supermassive black hole
- Spectacular jet (e.g. Marshall et al.)
- Classic cooling flow (24 M_{sun}/yr)
- Ideal system to study SMBH/gas interaction

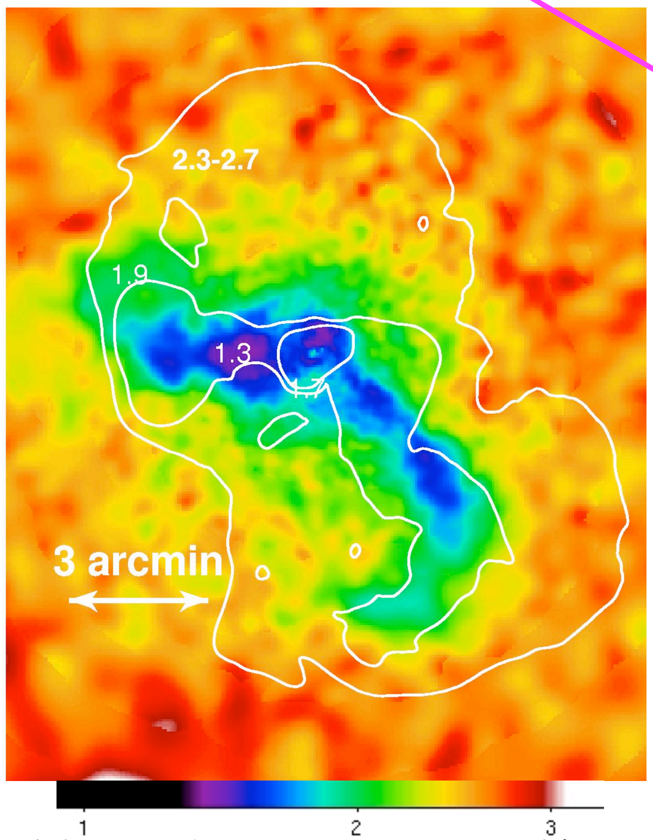
X-ray and Radio View of M87

- Multiple - at least three - AGN outbursts
- Two X-ray "arms" - produced by buoyant radio bubbles
- 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)

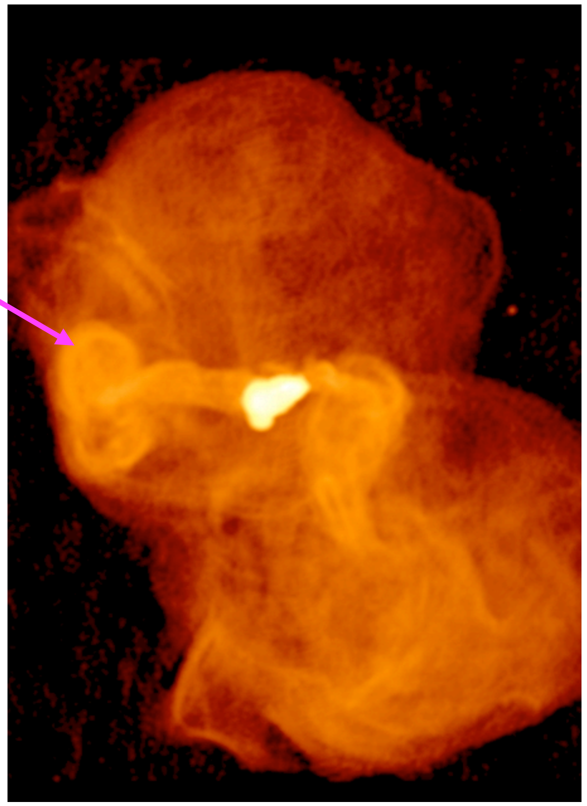




Forman+05,+07
Million+10, Werner+10

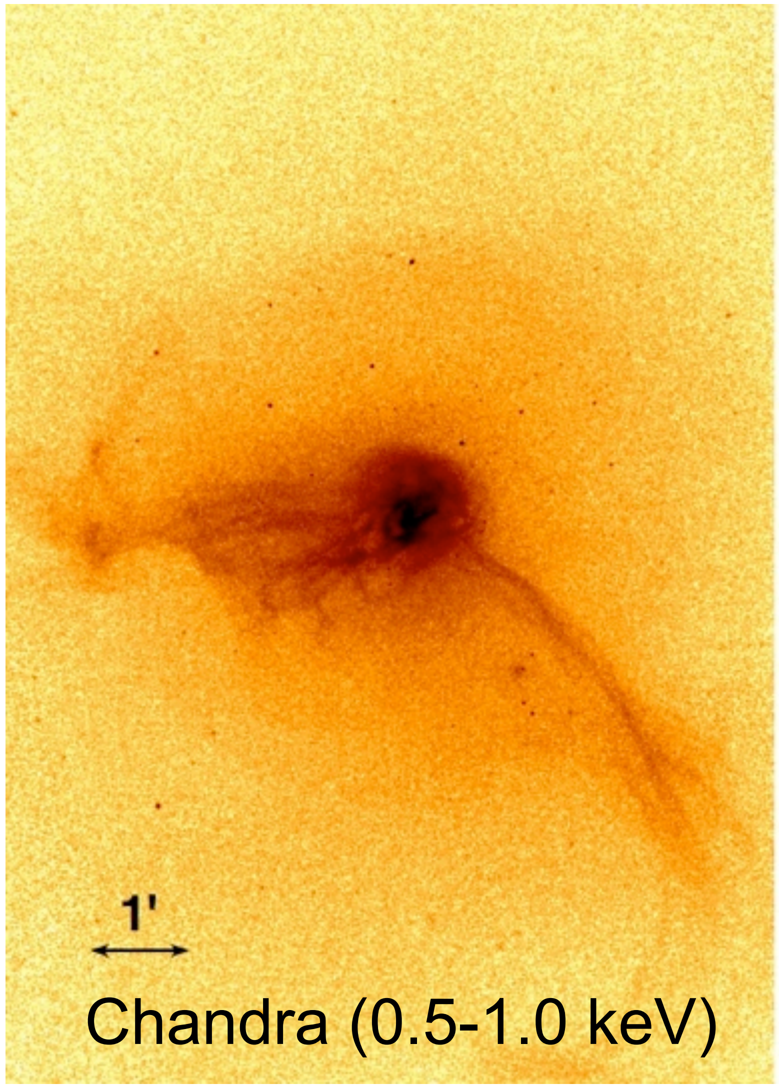


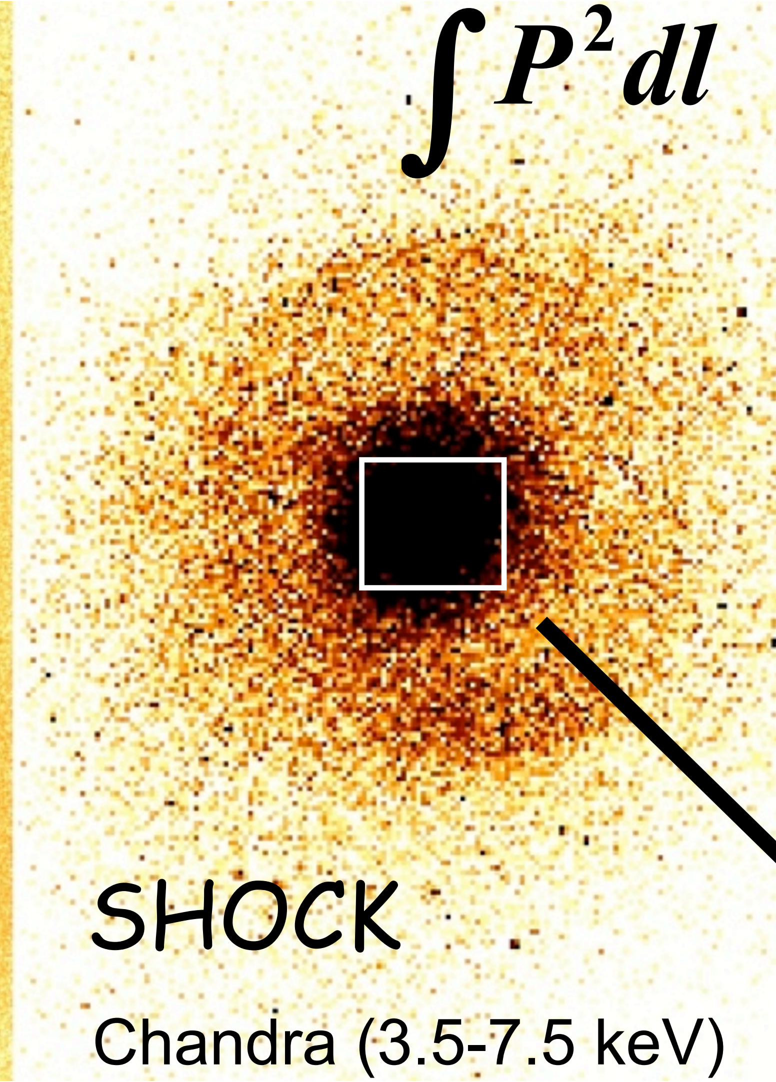
X-ray Temperature Map

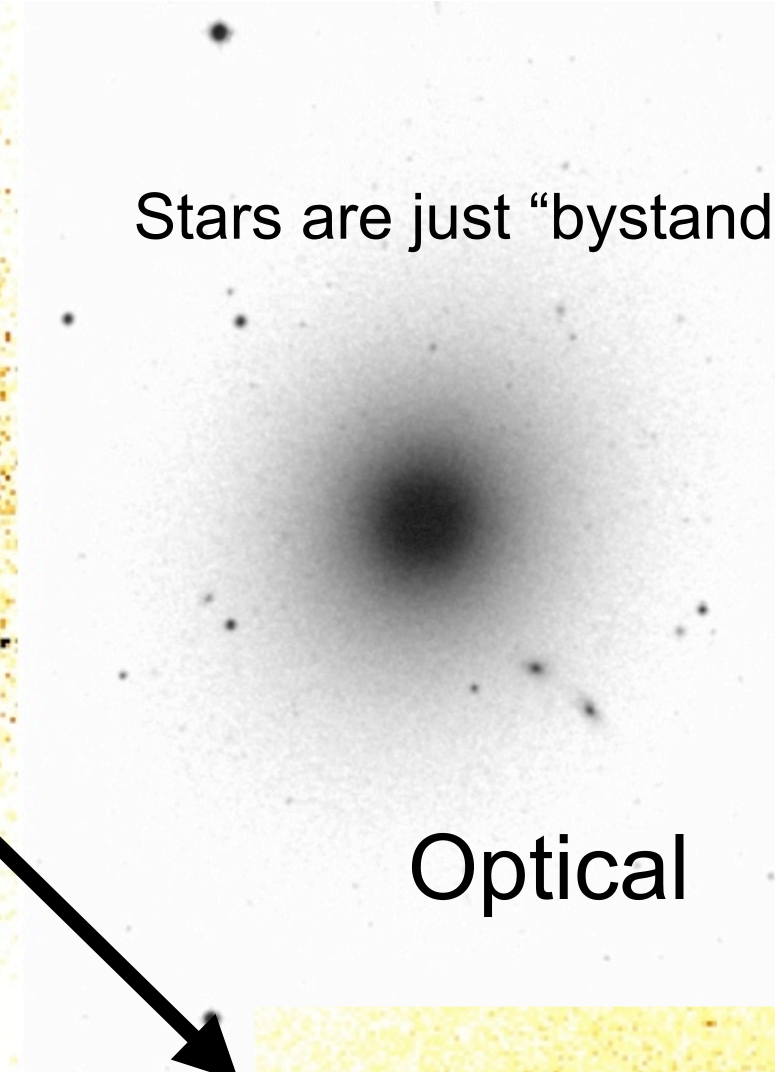


Radio 90Mhz
Owen, Eilek, Kassim 2001

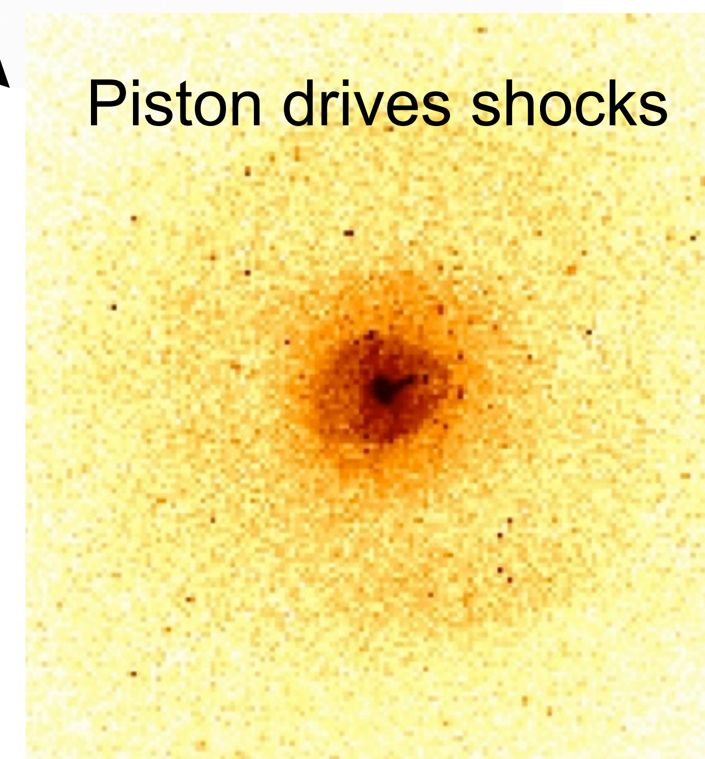
Feedback - M87







23 kpc (75 lyr)

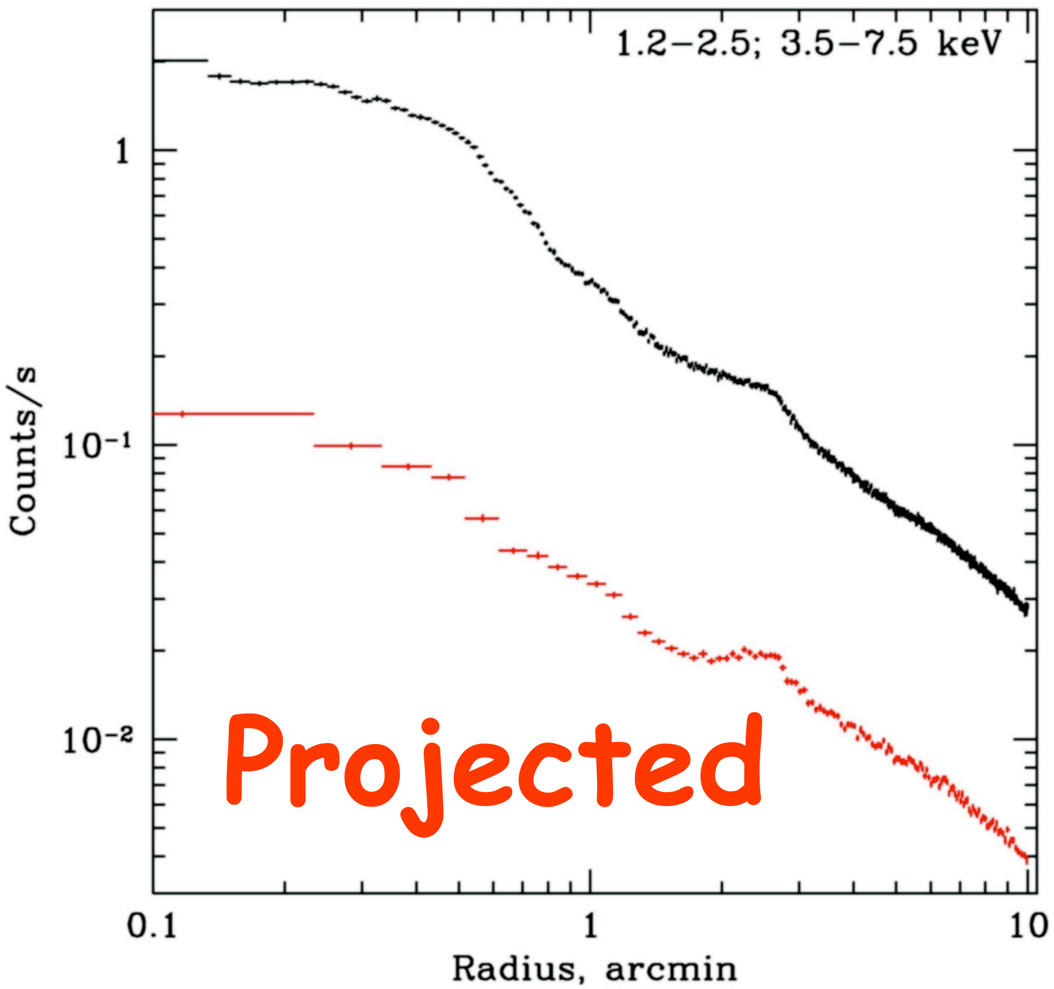


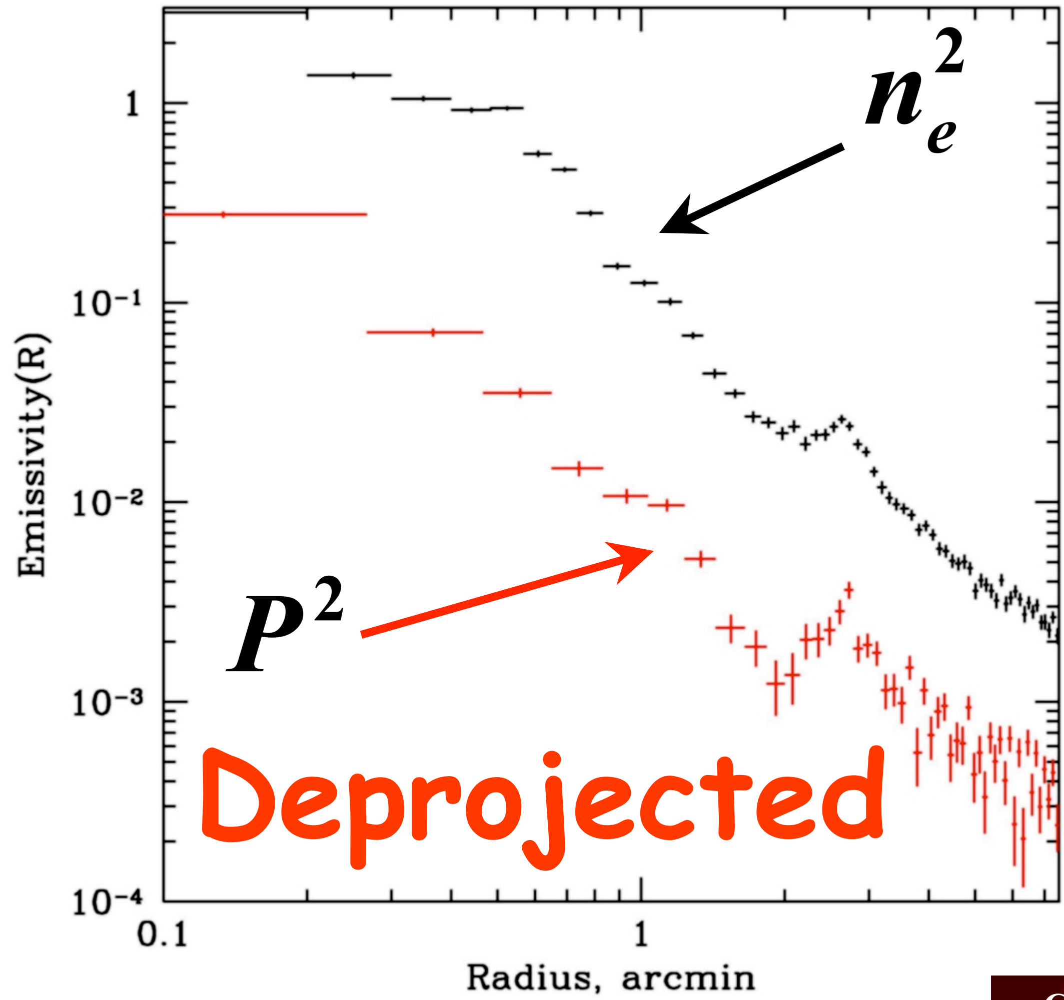
- Black hole = 6.6×10^9 solar masses (Gebhardt+11
- SMBH drives jets and shocks
- Inflates "bubbles" of relativistic plasma
- Heats surrounding gas
- Model to derive detailed shock properties

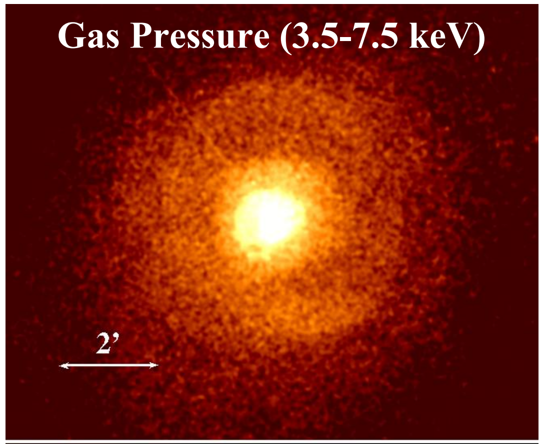
Shock Model - the data

Hard (3.5-7.5 keV) pressure

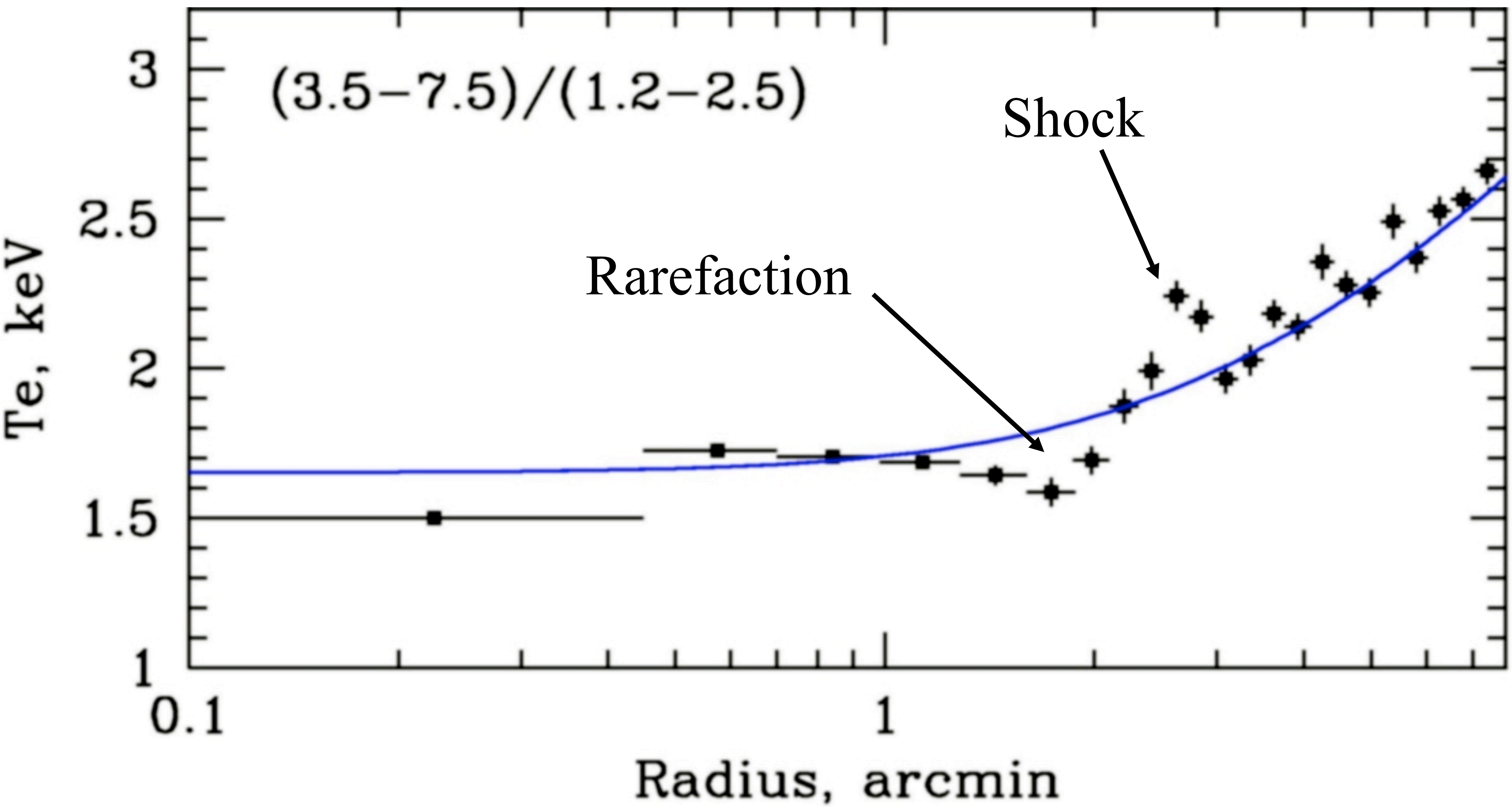
soft (1.2-2.5 keV) density profiles







Deprojected Gas Temperature



Textbook Example of Shocks

Consistent density and temperature jumps

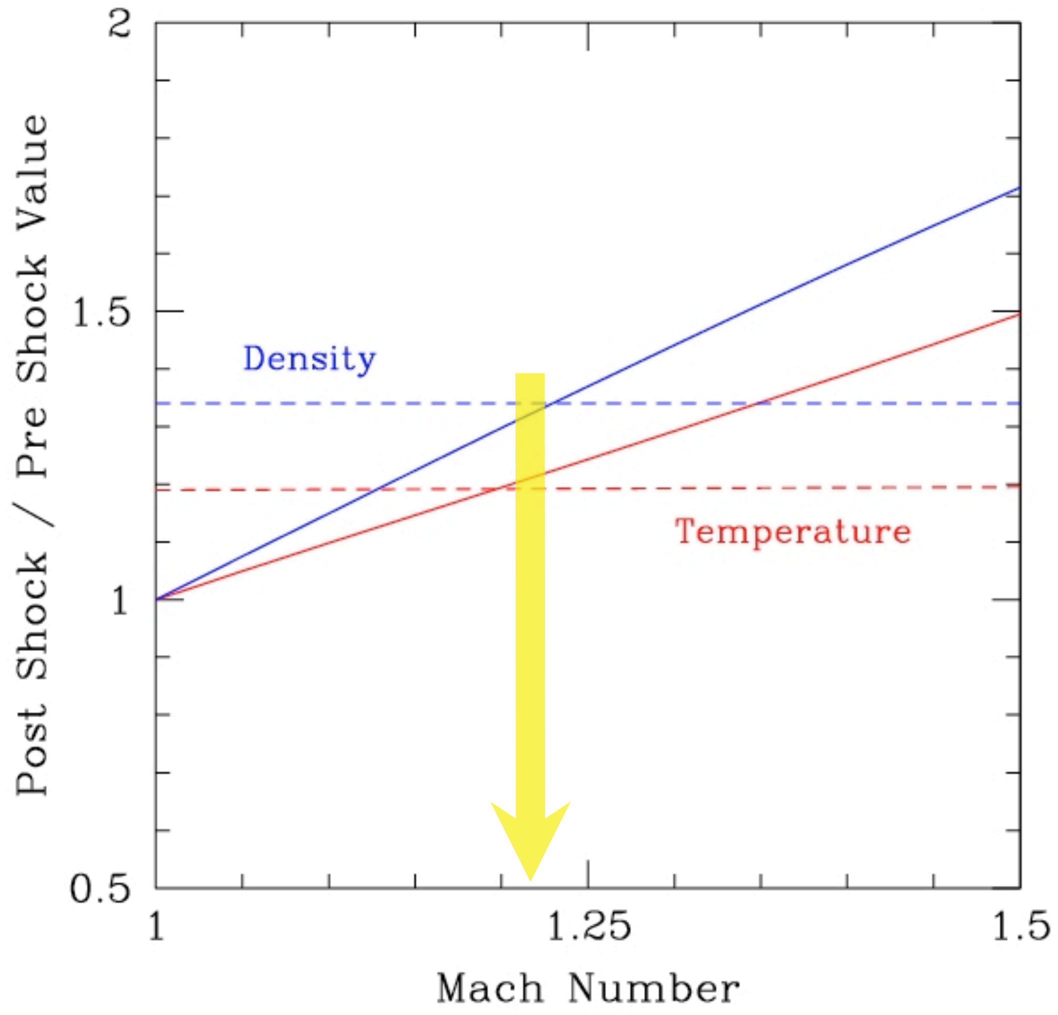
Rankine-Hugoniot Shock Jump Conditions

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

$$\rho_2/\rho_1 = 1.34$$

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

$$T_2/T_1 = 1.18$$

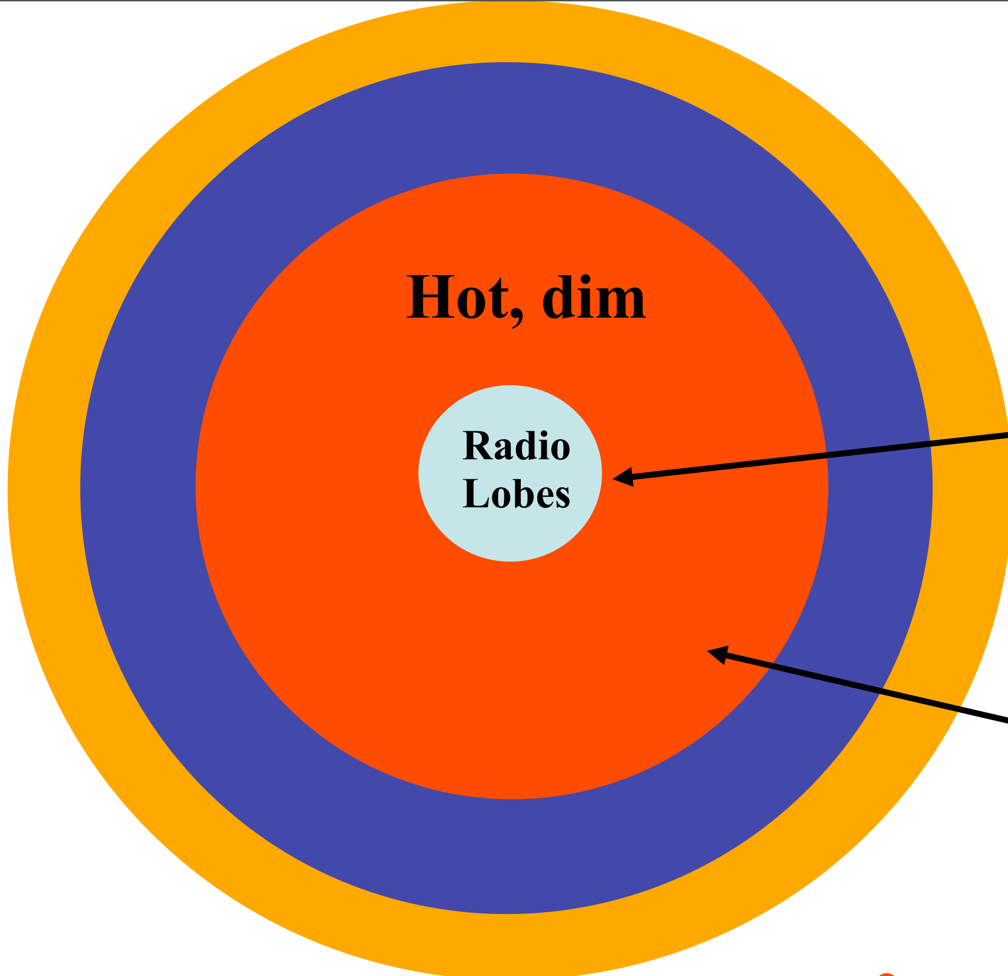


M=1.2

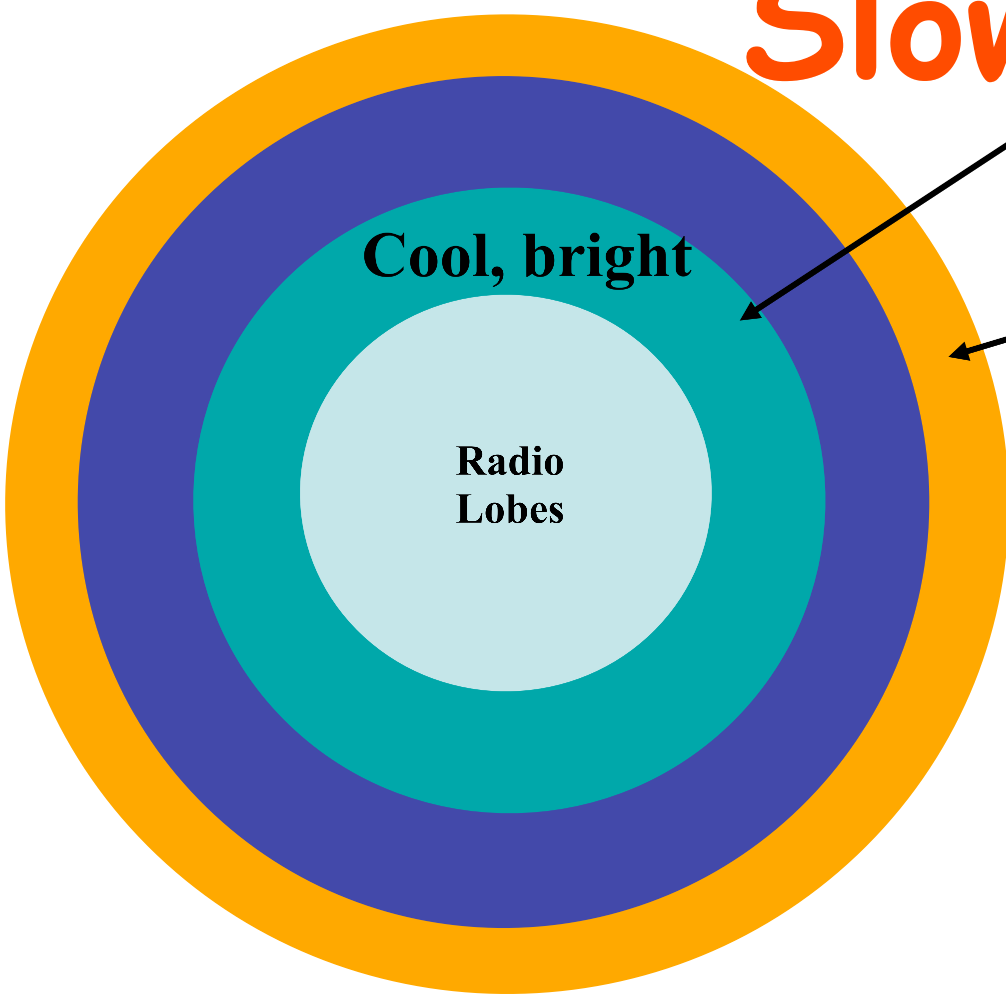
yield same Mach number:

($M_{T=}1.24$ $M_{\rho}=1.18$)

Fast



Slow



	Fast	Slow
Radio Lobes Radio bright X-ray dim	Small	Large
Shock heated gas Radio dim X-ray dim	Yes	**No**
Cool rims	No	**Yes**
Rarefaction region	Yes	Yes
Outer shock	Yes	Yes

"Slow" fits M87 shock
outburst duration = 2-5 Myr

Shock kinetic energy 10%
Energy carried away by weak shock 25%
Central bubble enthalpy ~65%
Energy available for heating ~75%

M87 Outburst Model

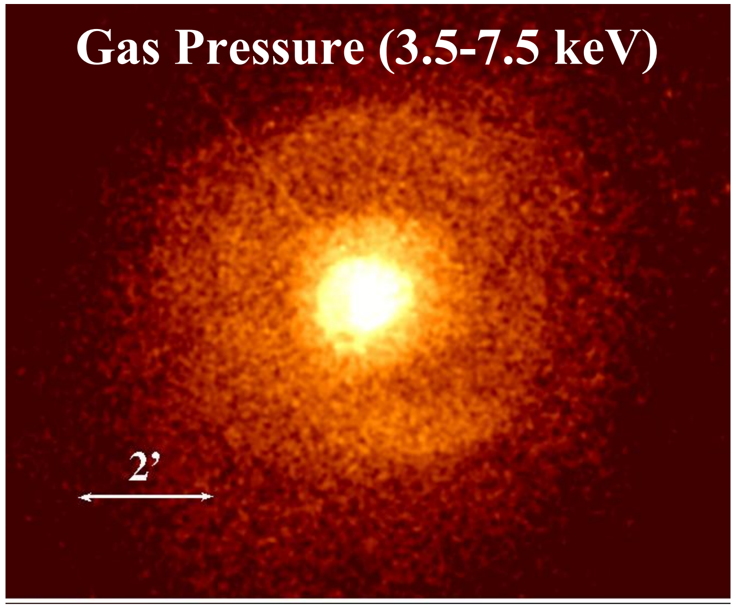
Detect shock (X-ray) and driving piston (radio)

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

Outburst constrained by:

Size of driving piston (radius of cocoon)

Measured T_2/T_1, ρ_2/ρ_1 (p_2/p_1)



Outburst Model

Age ~ 12 Myr

Energy ~ 5×10^{57} erg

Bubble 65%

Shocked gas 25% (25% carried away by weak wave)

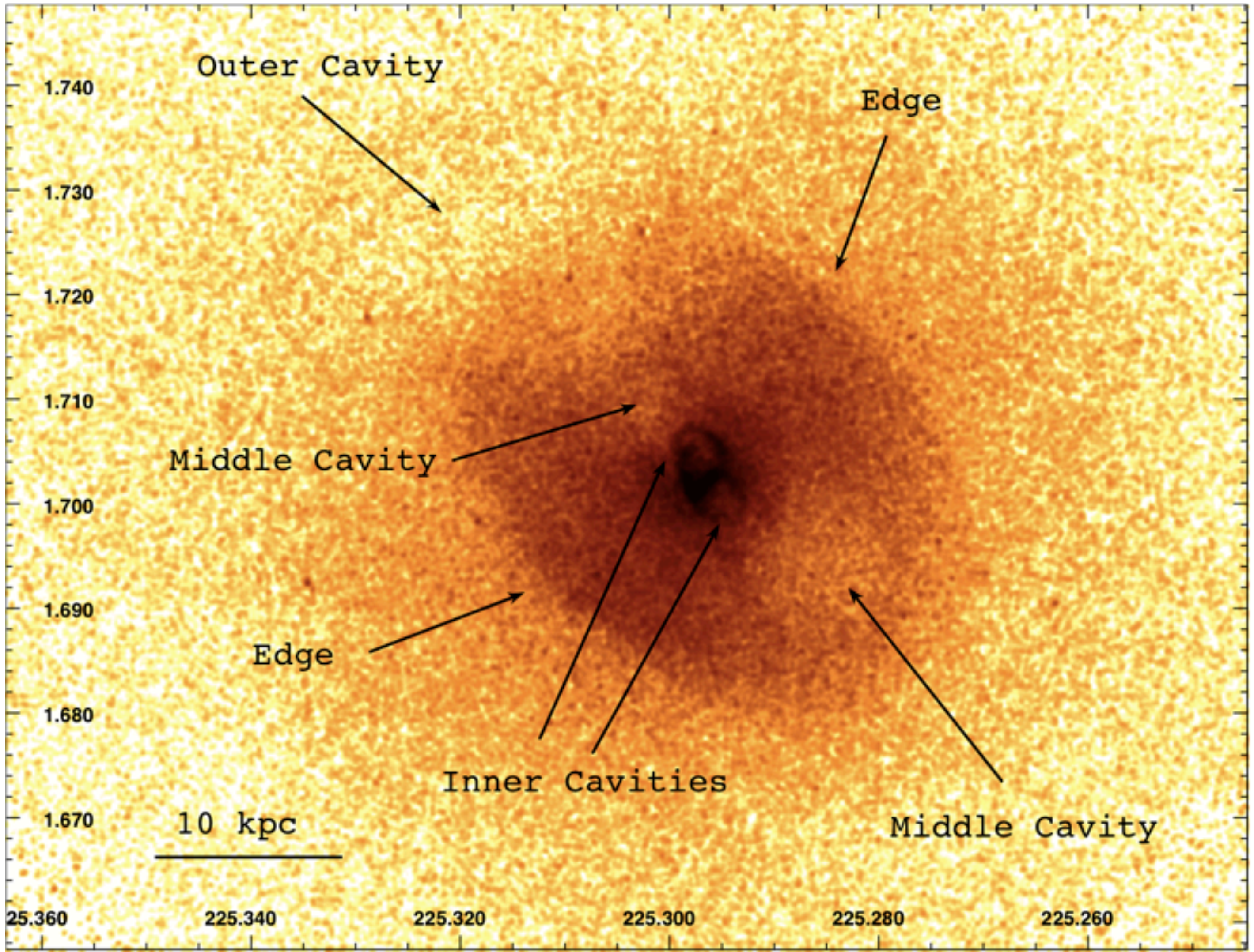
Outburst duration ~ 2-5 Myr

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

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

NGC5813 - multiple outbursts

Randall et al.



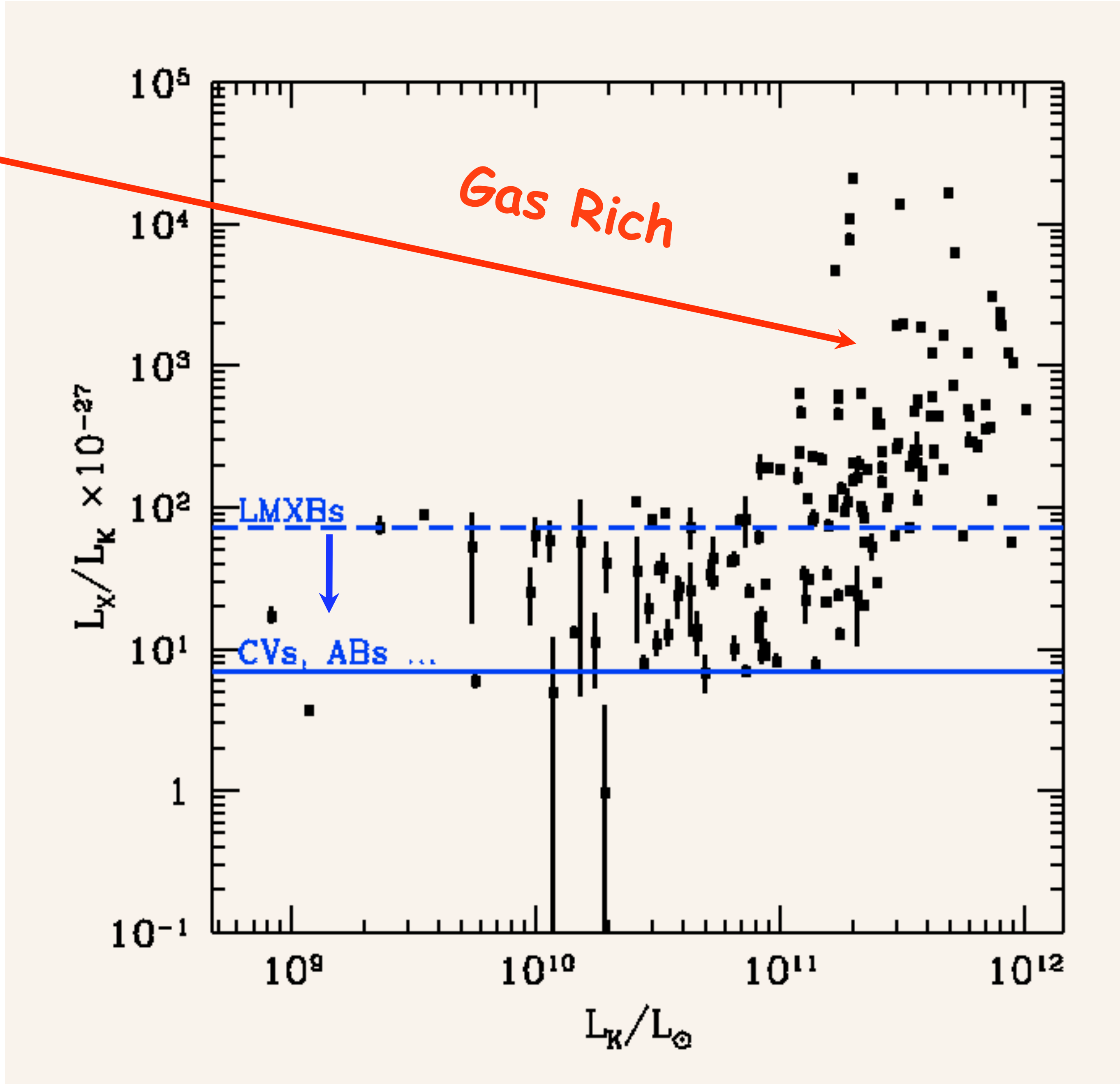
L_{nuc} ~ few x 10^{39} erg/s

	inner	outer	
Ages	0.6	3	x10^7 yrs
Energies	1	10	x10^{55} ergs
Mach	1.7	1.5	

- Cavities - Common (30% in galaxies; 50% in clusters with cooling peaks)
  - Measure SMBH energy output
- Active nuclei - 70% seen as radio
- Radiatively weak - radiated power < 10^{-3} mechanical power
- Measure power from cavity and shocks
- Observed shock heating overcomes core cooling

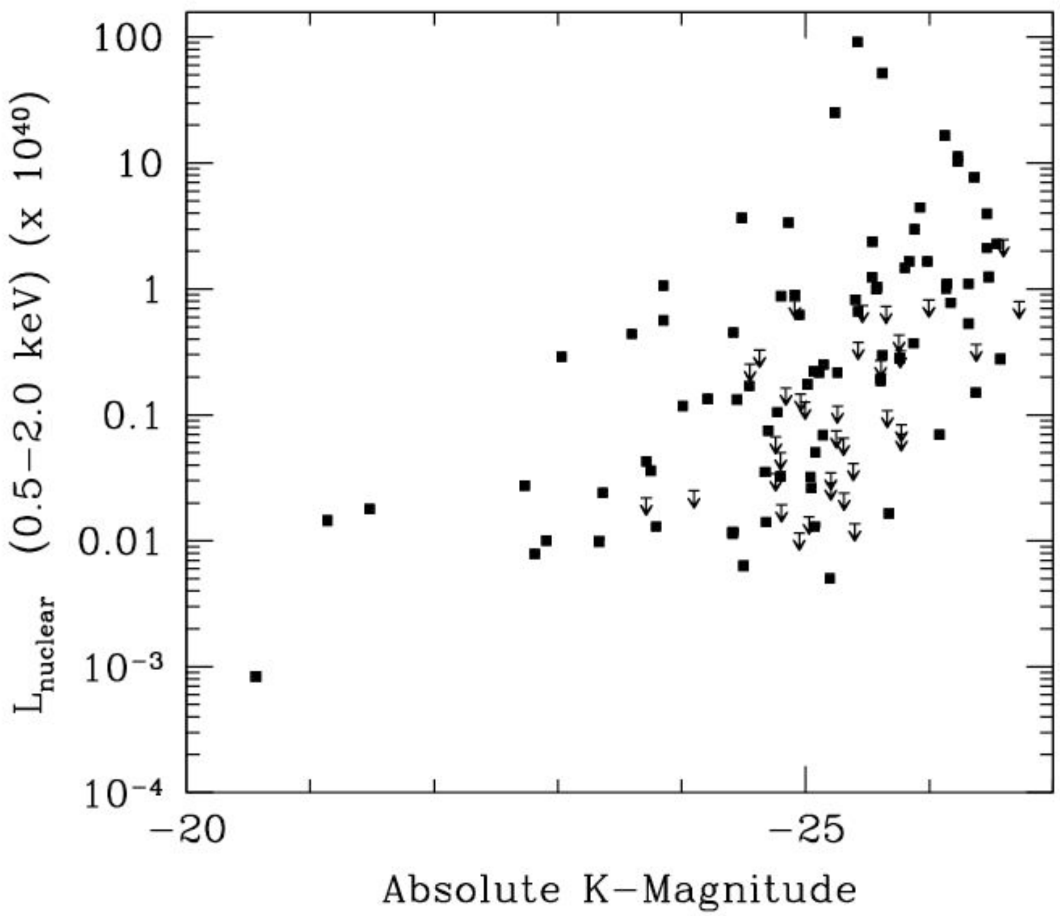
X-ray Emission in Early Type Galaxies - Jones+11

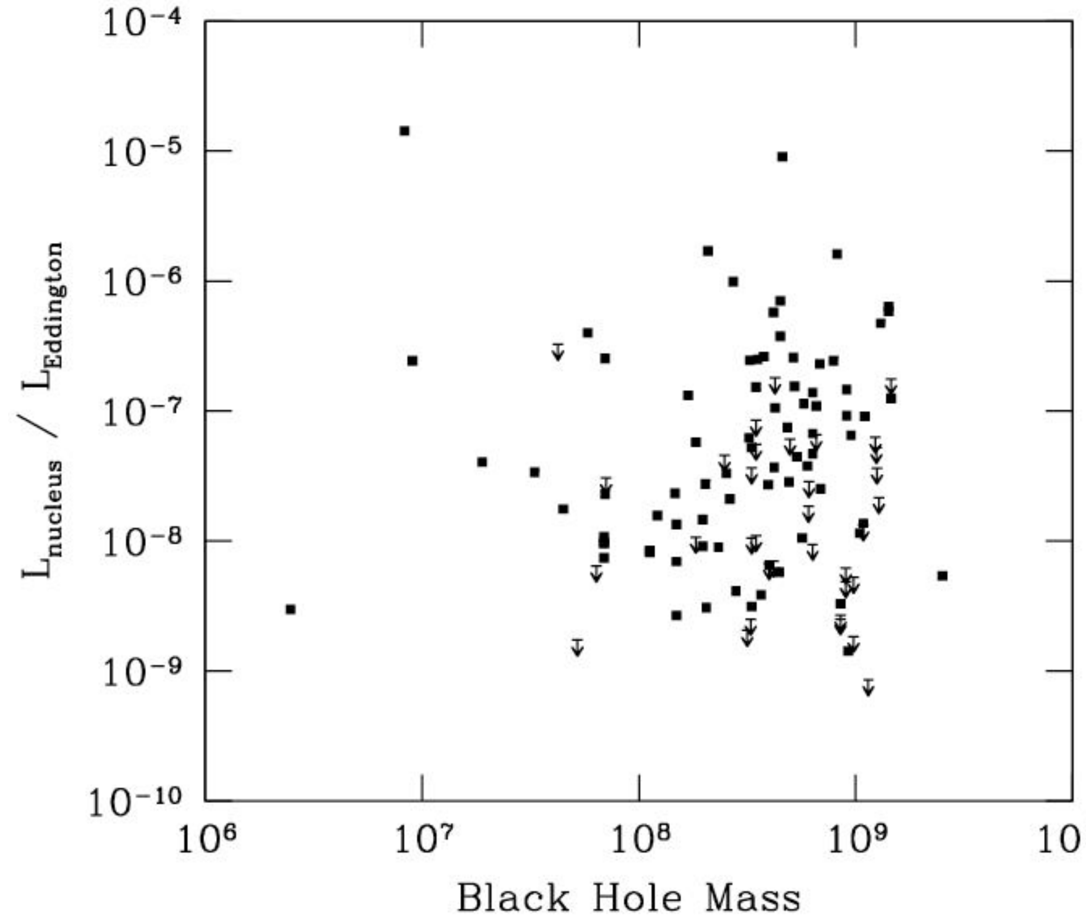
- Luminous early type galaxies have hot gaseous coronae (BCGs excluded from sample)
  - –Result from Einstein (see Forman, Jones, Tucker 1985
- LMXBs - partially removed
- CVs, ABs - always present
- 30% of luminous galaxies show cavities - power sufficient to overcome cooling (Nulsen+09)
- Wide range in L_X at fixed L_K - environment (group) or powerful outburst disrupting atmosphere (e.g., Fornax A)



Wednesday, May 25, 2011

SMBH X-ray Luminosities and Eddington Ratios in Normal Early type Galaxies





Low luminosities : 70% have AGN

luminosities range from ~10^{38} - 10^{42} erg s^{-1}

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

(for QSO's ~0.3) (Eddington ratio for Sag A = 10^{-9})

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	McNamara+05
Hercules A	160	3	59	1.6	1.7	Nulsen+05
Hydra A	210	0.9	136	0.2	0.5	Nulsen+05
M87	14	0.0005	14	0.0012	0.0003	Forman+07
NGC4636	5	0.00006	3	0.0007	0.00003	Jones+02

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

(Rafferty+06,Dunn&Fabian 06

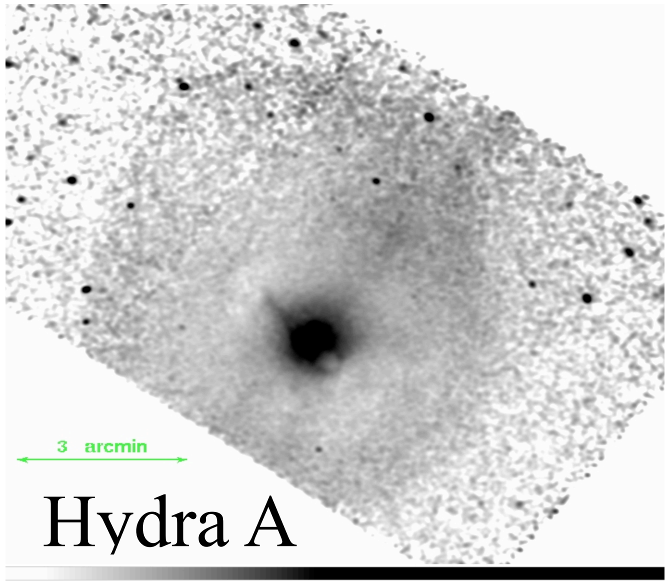
Impact of AGN outbursts on hot gas

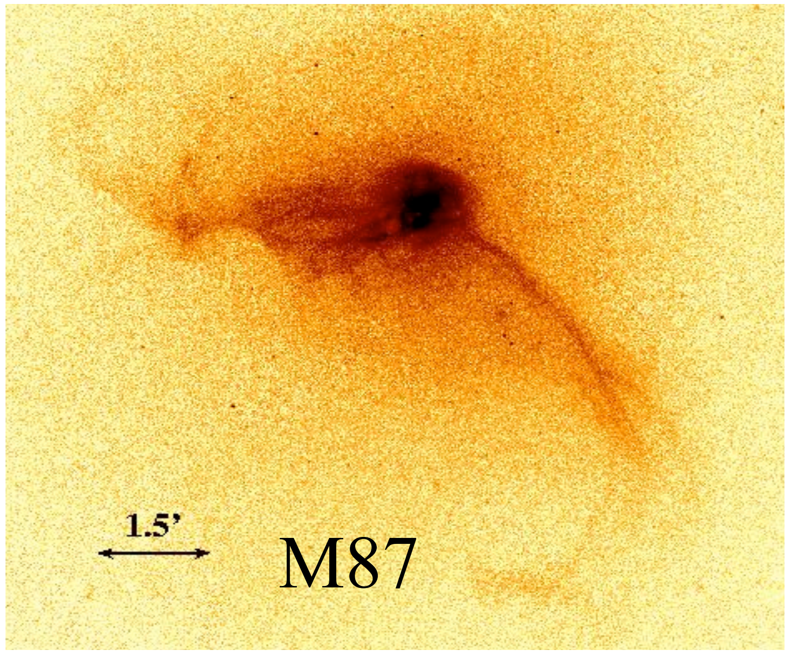
- **Hot atmospheres are key to capturing AGN mechanical energy**
- Feedback on gas - prevents cooling
- Controls galaxy evolution

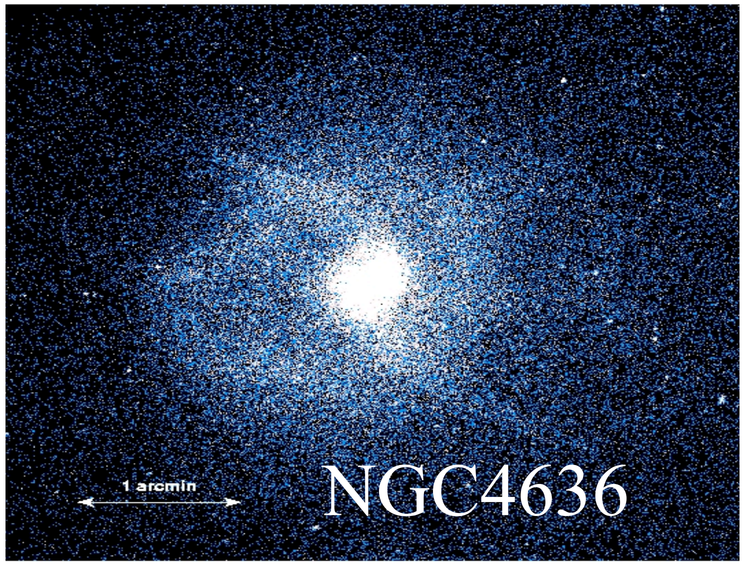
  Maintains dichotomy of red and blue galaxies
- Galaxy outbursts are common - 30% of early type galaxies show cavities;

  $\tau \sim 10^6$ - 10^8 yrs, E~10^{55}-10^{58} erg/sec - sufficient to balance cooling
- Galaxy X-ray nuclei, mini-AGN, are common - 70% (10^{38}-10^{42} ergs s^{-1})
- Cluster outbursts up to 10^{62} ergs reheat cooling gas through shocks/ buoyant bubbles

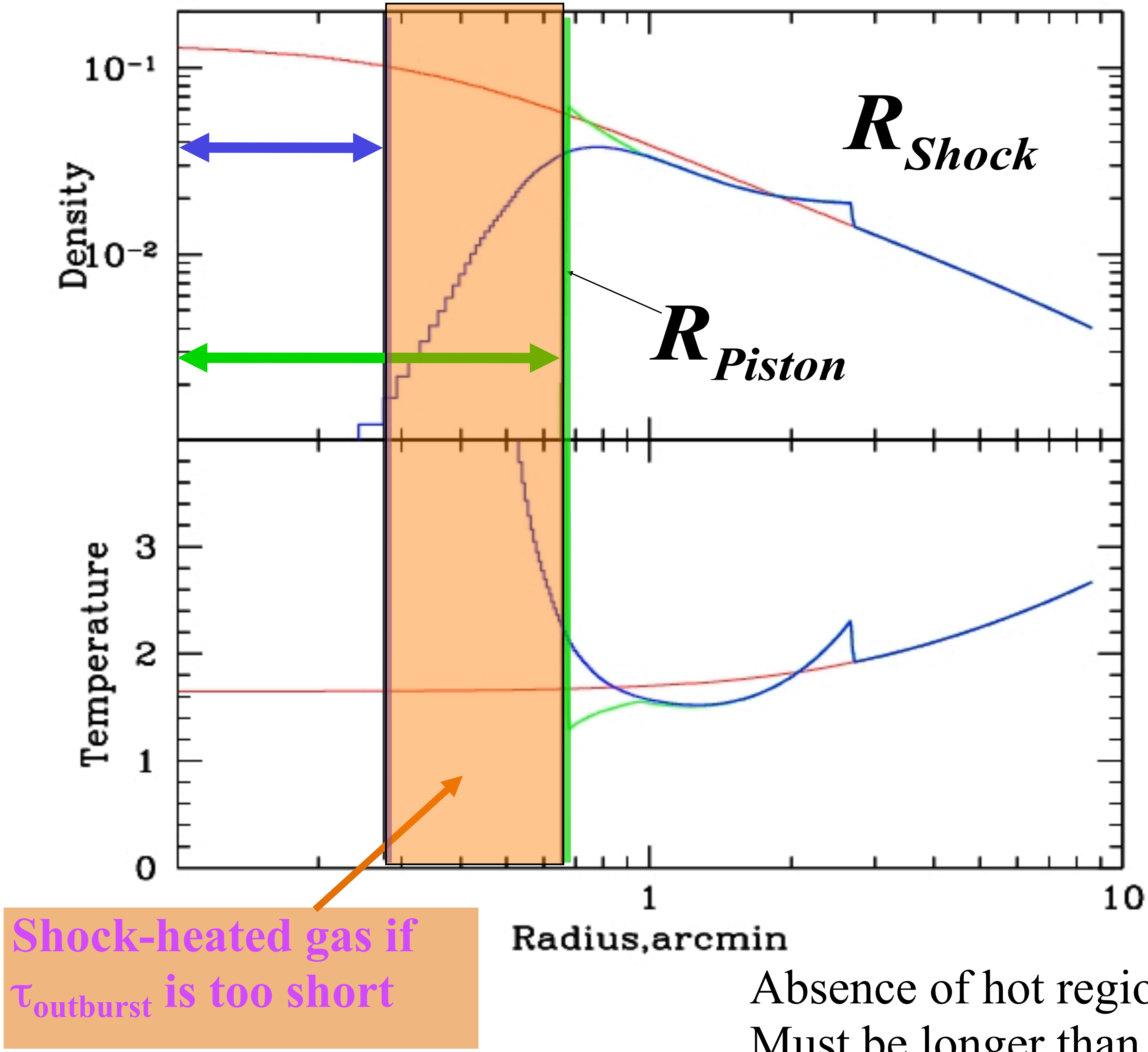
Stay tuned - new, deep Chandra observations coming







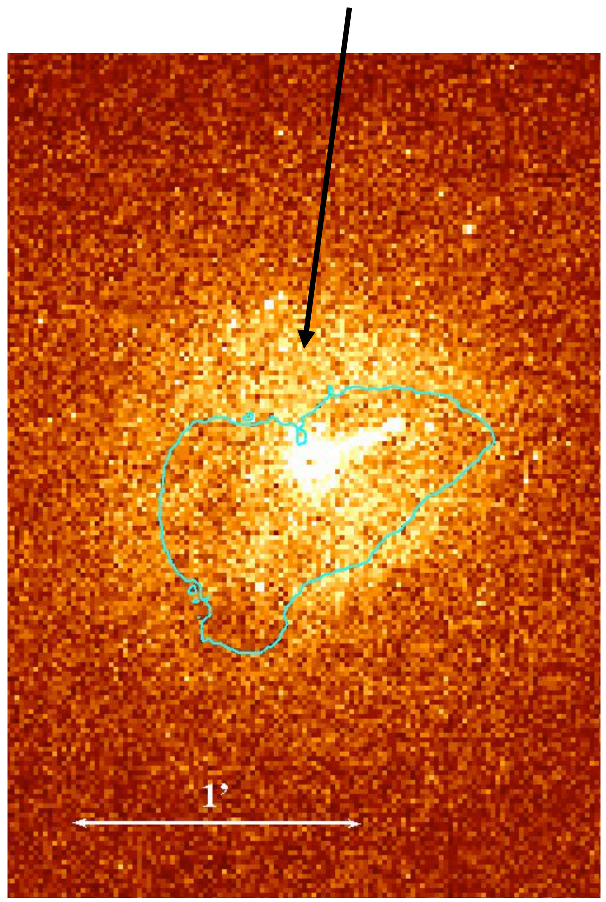
Estimate outburst timescale



Fast - large shock heated region

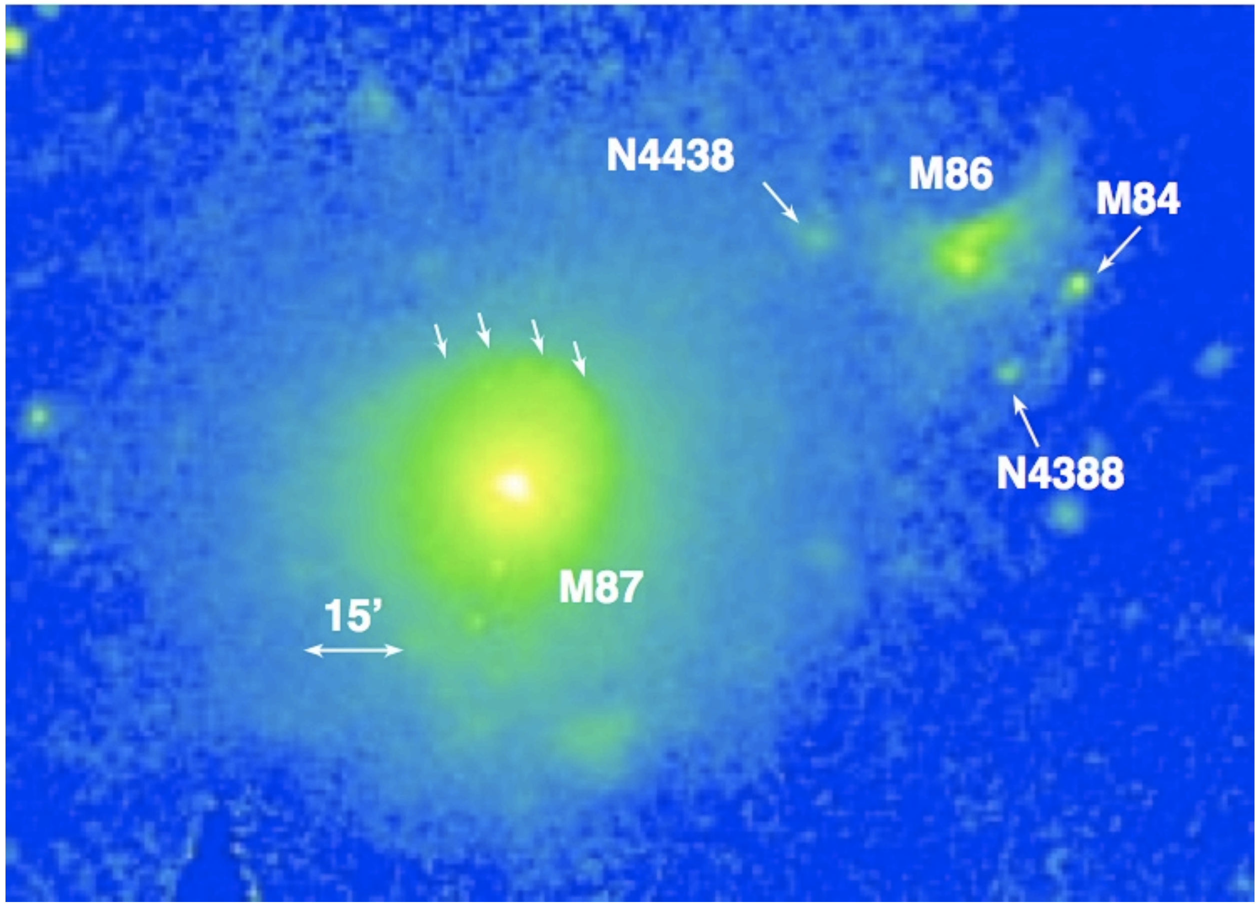
Absence sets outburst duration 2-5 million yrs

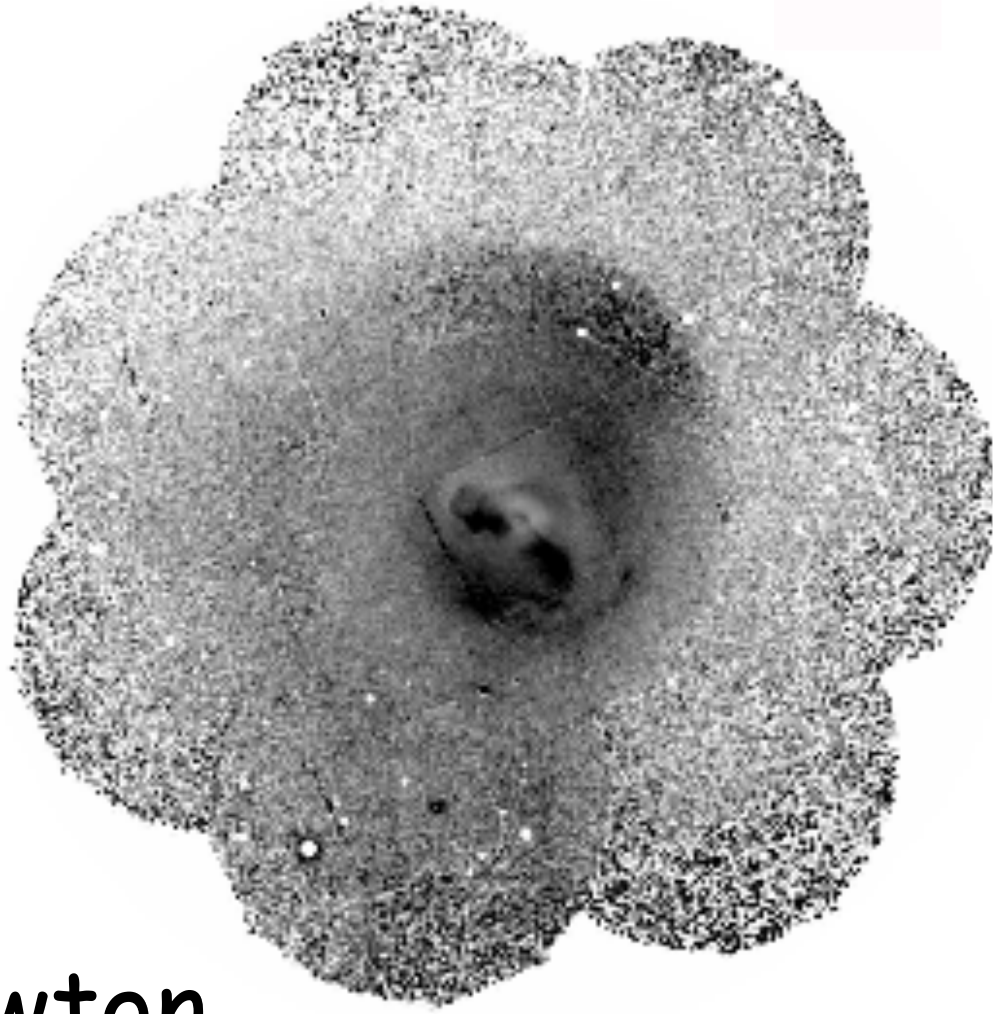
Slow - cool rim



Absence of hot region limits duration of outburst
Must be longer than 2 million years

Gas Sloshing in M87





Simionescu+10 from XMM-Newton

- Gas sloshing at ~100kpc
- Abundance edges
- Peaked abundance distributions dispersed by gas motions

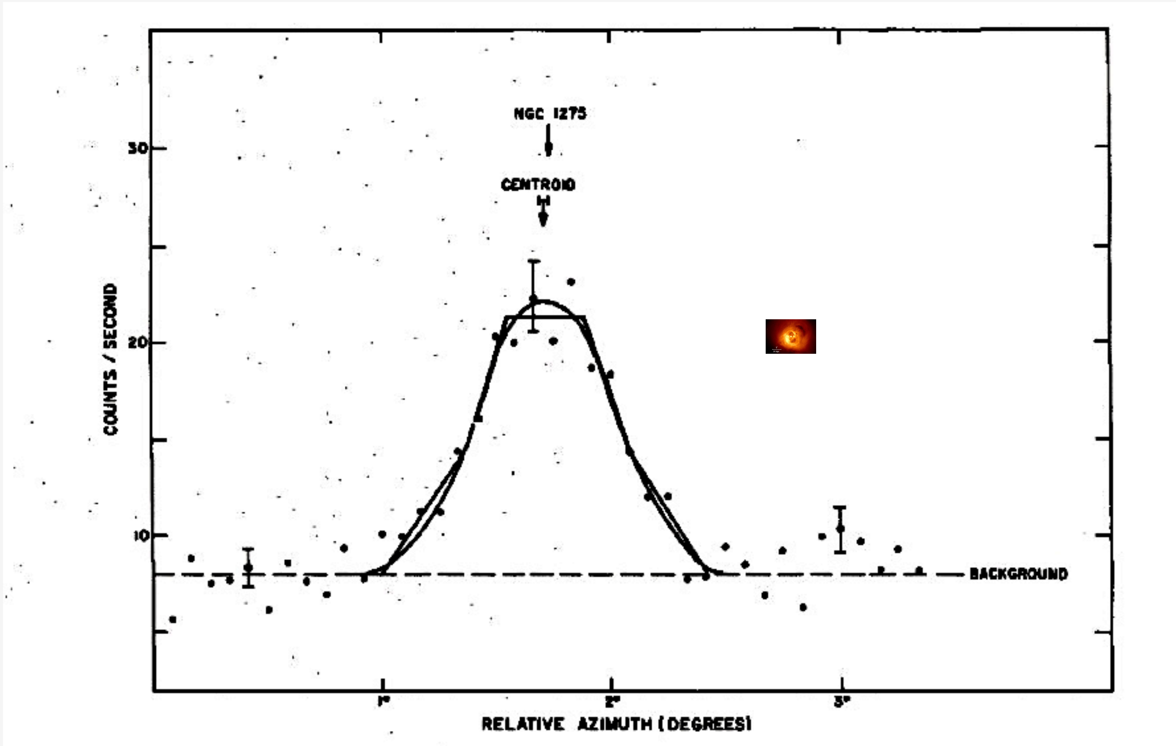
Cooling Cores, AGN, and the Mechanisms of Feedback

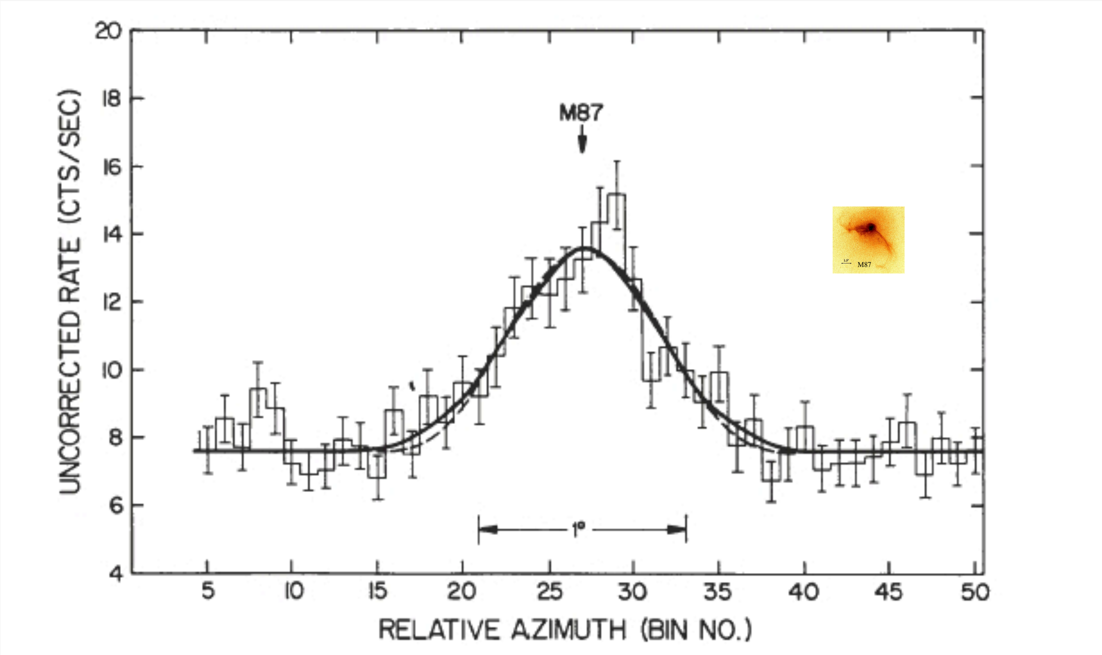
Wednesday, May 25, 2011, 2:00 PM - 2:30 PM

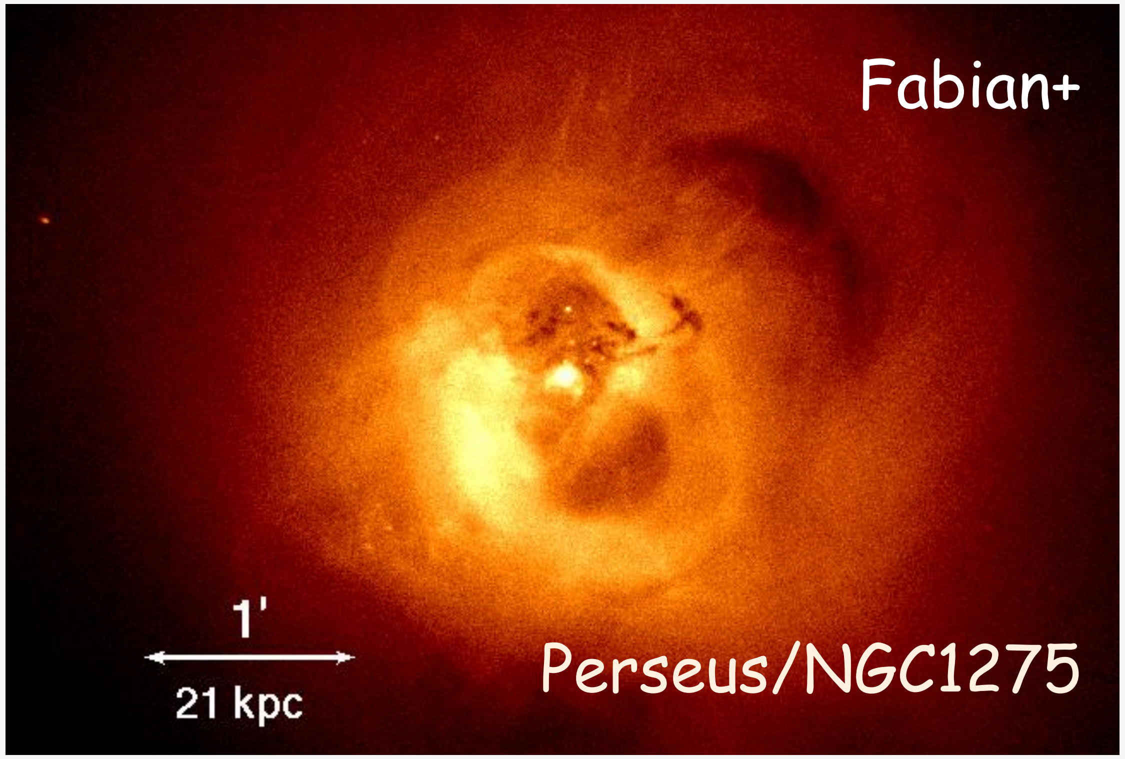
- Feedback between a central supermassive black hole (SMBH) and its host galaxy plays a key role in driving galaxy evolution and maintaining the dichotomy between red (and dead) galaxies and actively star-forming, blue galaxies. The improving angular resolution in X-ray astronomy, culminating with Chandra, has provided new insights into this feedback process in those systems with hot atmospheres including elliptical galaxies, groups and clusters. We discuss the details of the feedback process with specific examples including M87, NGC5813, and a sample of normal elliptical galaxies. Using the normal galaxy sample, we discuss the frequency of "active" galaxies, the radiative luminosity, outburst mechanical power, and Eddington ratio of the SMBHs in these galaxies. Finally, we discuss models of the outbursts that allow us to measure the outburst durations and the balance between shock heating and "cavity" heating.

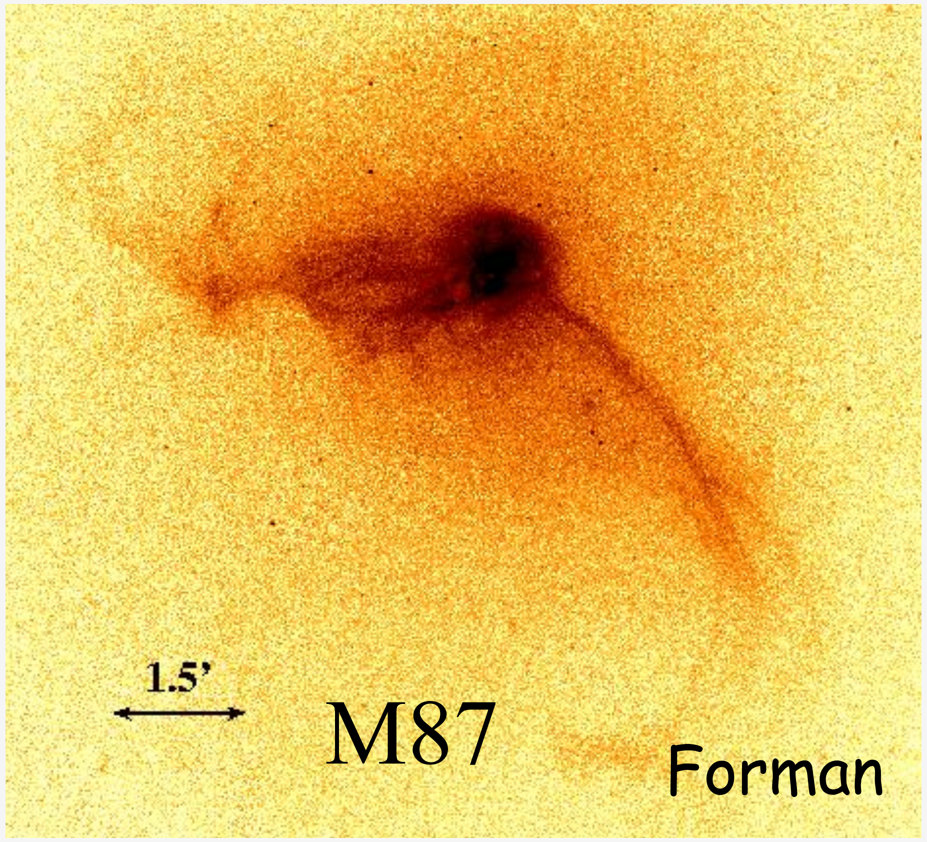
From UHURU (1970) to Chandra (1999)+12 years

from 1/2° to 1″









read hydra a and ms0735

- look at corsica for something new - esp better explanations

- should i try to fit in components - of early type - 1 slide? with n4472
- look at Proga and Kallman 2004 for outflows from agn and their citations this is the reference in the Athena presentation

- both for buoyant torus and filament comment that not much turbulence - at least in some systems - although there is sloshing. ASK EUGENE IF BUBBLES BUT NO TURBULENCE DOES THAT IMPY HIGH VISCOSiTY??

  – Gr¨utzbauch et al. 2010a,band consliece 2007
  – look at mcnamara papers for anything new/interesting
  – look at nulsen papers as well
  – look at ponman papers
  – fine somthing that shows cooling times in cores of ellipticals or groups maybe a ponman or maybe a steve allen