An X-ray View of the Nearby Clusters - Virgo, Fornax, and Coma

Bill Forman - SAO/CfA

- Coma
- Fornax
- Virgo - interactions galore; stripping at work, M87 outburst
- Galaxy Survey (not BCGs)
  - magnitude limited sample

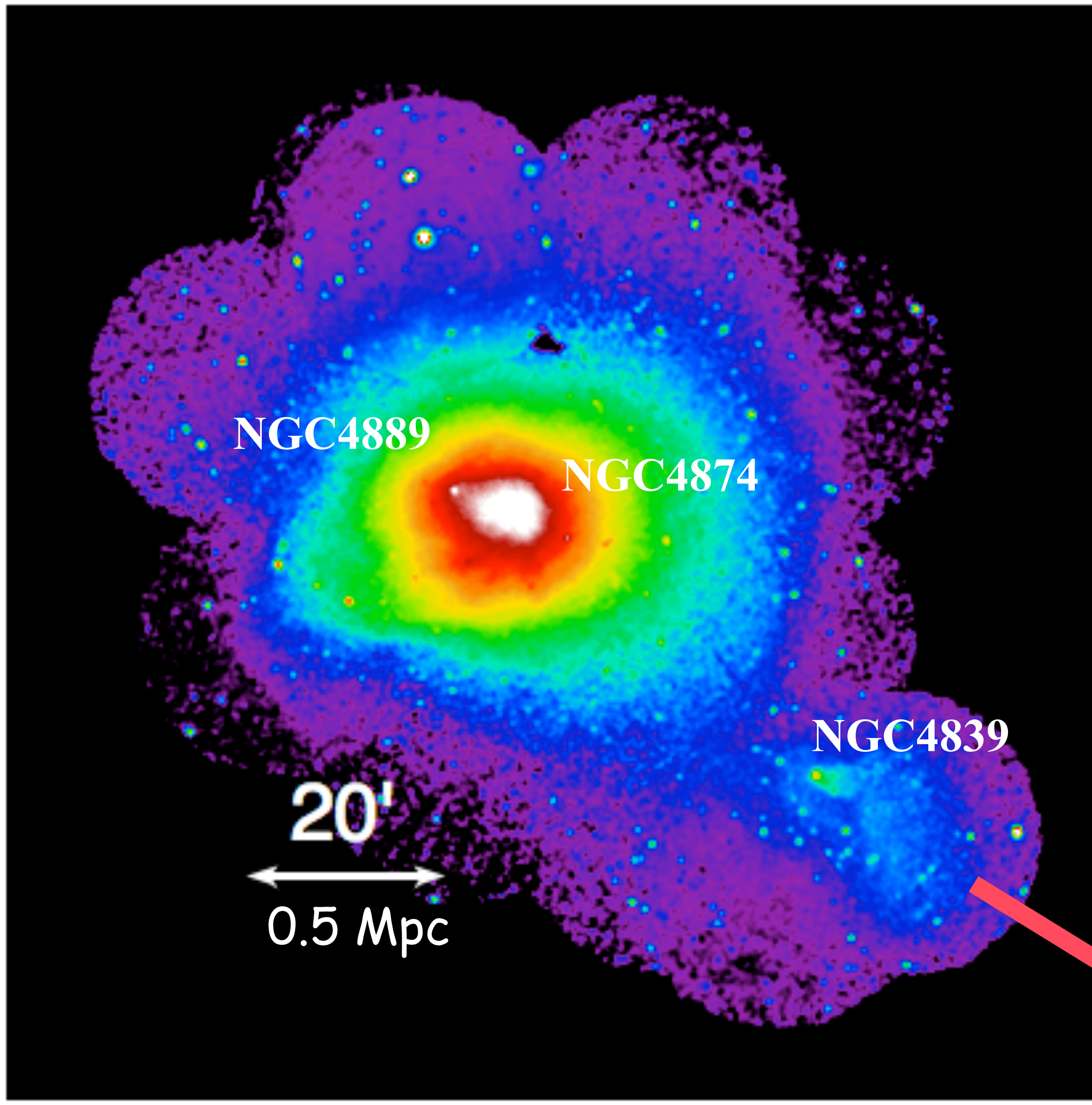
    AND
  - Chandra targeted galaxies

Collaborators

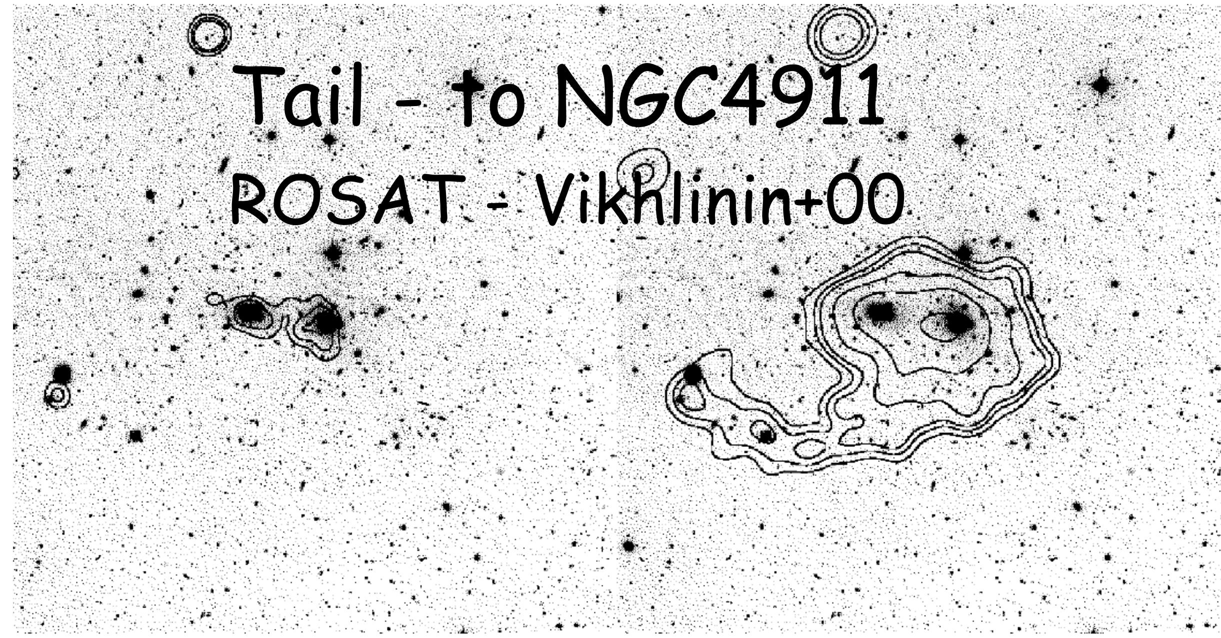
- Christine Jones, Eugene Churazov, Ralph Kraft, Paul Nulsen, Larry David, Jan Vrtilek, Simona Giacintucci, Marie Machacek, Ming Sun, Scott Randall, Maxim Markevitch, Alexey Vikhlinin

Optically luminous early type galaxies are - HOT GAS RICH - up to 10^{10} M_{sun}

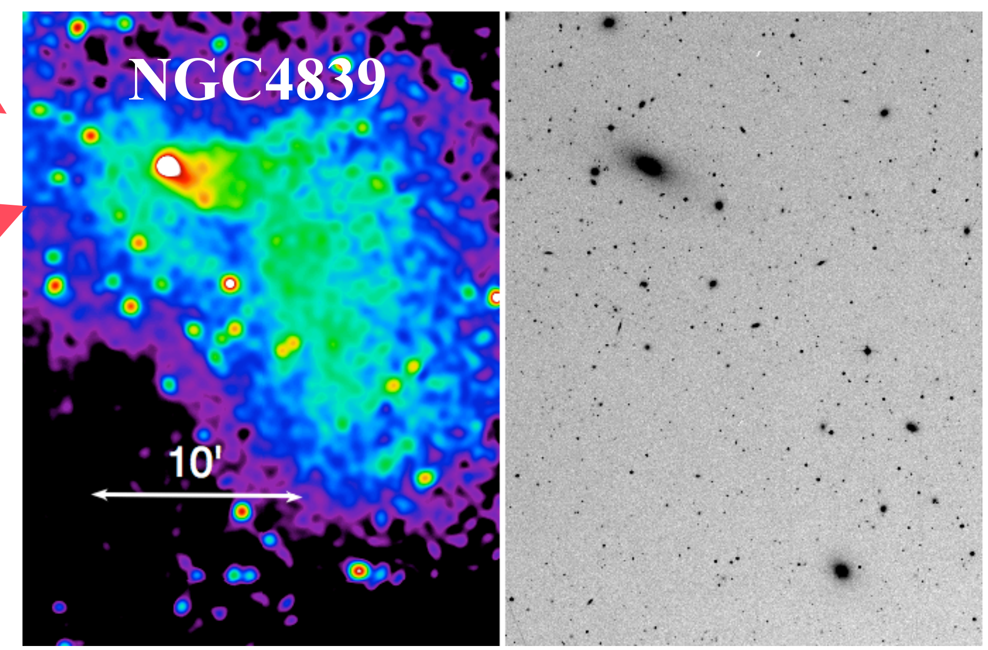
Coma - merging



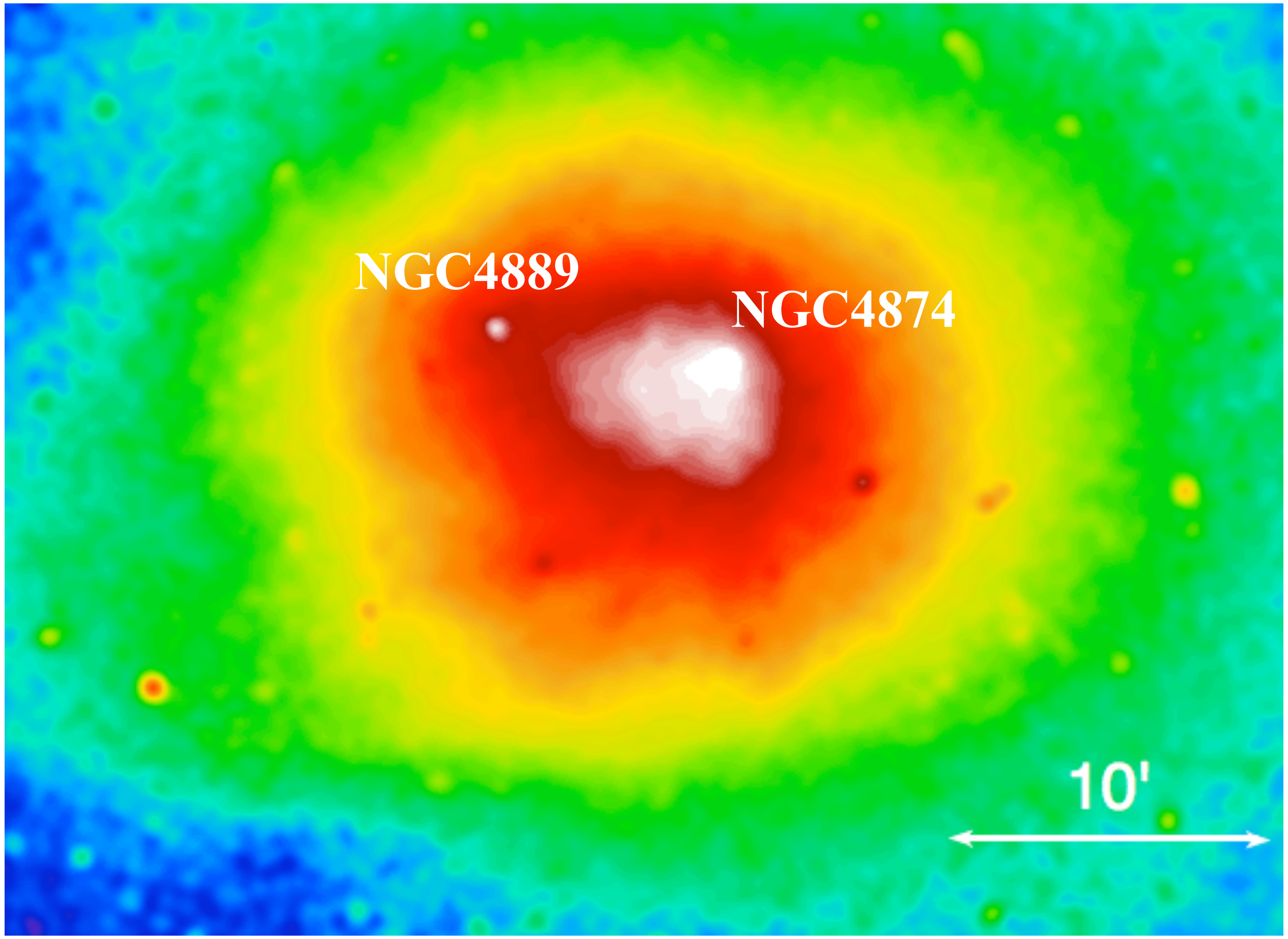
- Possible slightly supersonic merger
- Suggested by hot X-ray sheath ($kT \sim 6.2$-6.7 keV; $kT_{ambient} \sim 4.8$ keV
- $\Delta v \sim 1700$ km/s (Colless+07) ==> $M \sim 1.3$
- 400 kpc long tail
- $M_{group} > 10^{14}\ M_{sun}$



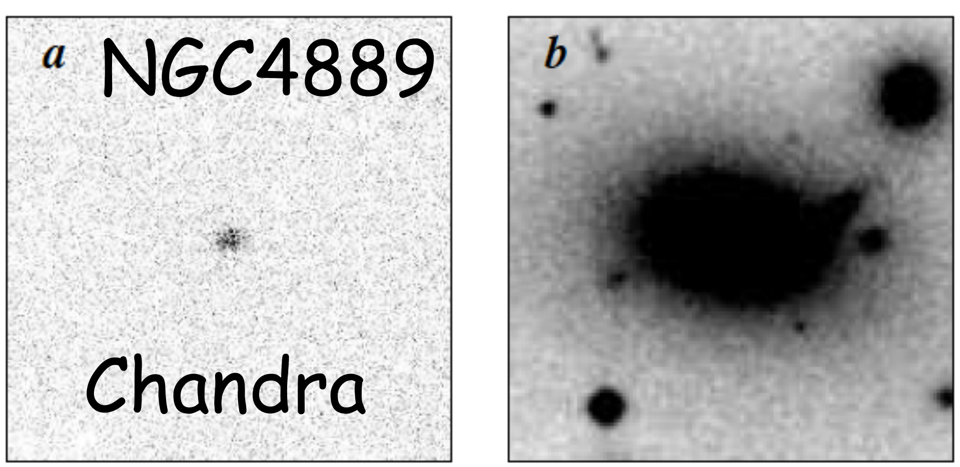
- $M_{gas} \sim 5 \times 10^{11}\ M_{sun}$; $kT \sim kT_{Coma}$
- Origin
  - Ram pressure stripped gas?
  - Cluster gas compressed in tidally stripped dark matter filament?

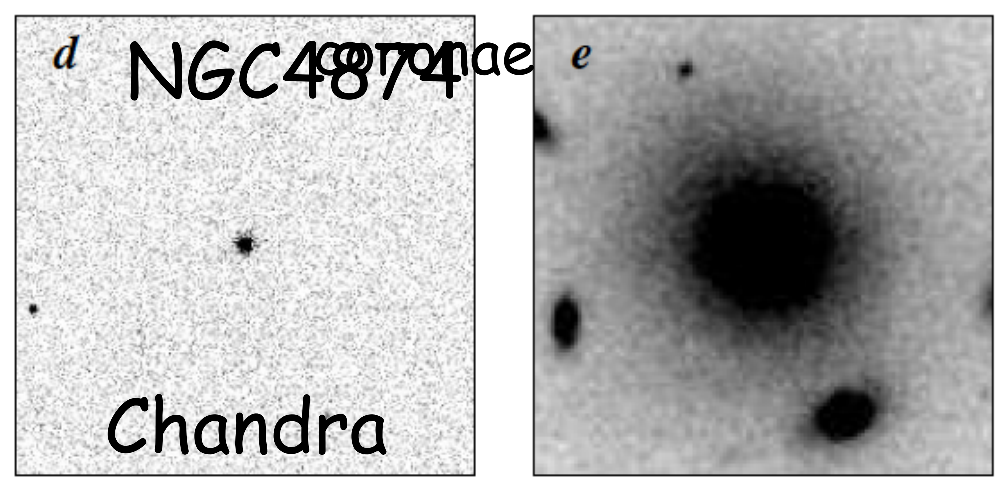


Coma - mini-coronae

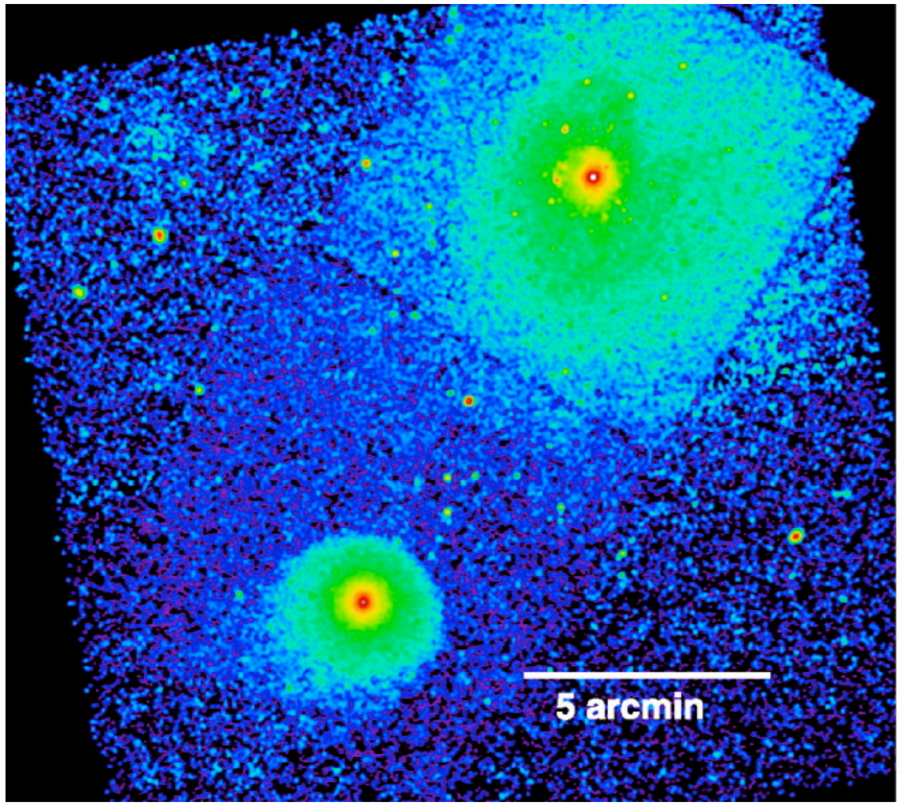


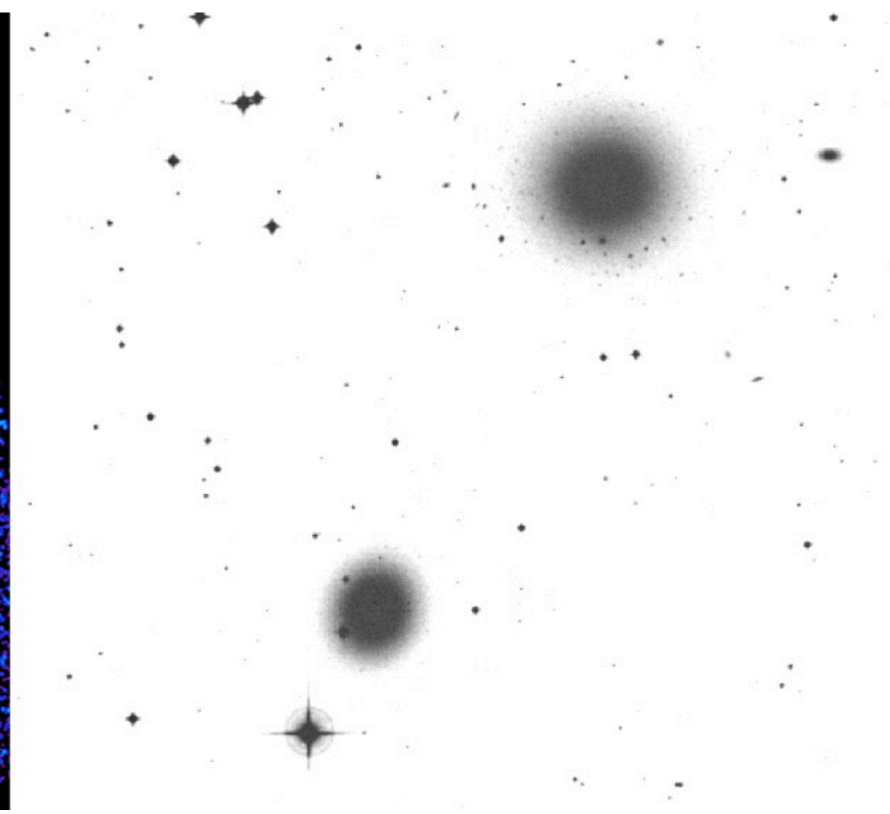
- Mini coronae around BOTH central cDs (Vikhlinin+01)
  - 3 kpc radius; 10^8 M_{sun} of gas; ~1 keV
  - pressure confined; thermal conduction suppressed by factor of 30-100
  - heated by conduction from hot Coma gas
- Sun+07 mini-corona survey
  - 25 hot (>3keV) clusters
  - 60% of >2L* galaxies (~100) have mini-coronae
  - X-ray fainter than "typical" coronae





Fornax/NGC1399





NGC1399 - kT ~ 1.5 keV (compare to Coma kT_{coma} ~ 9 keV)

Potential comparable to galaxies

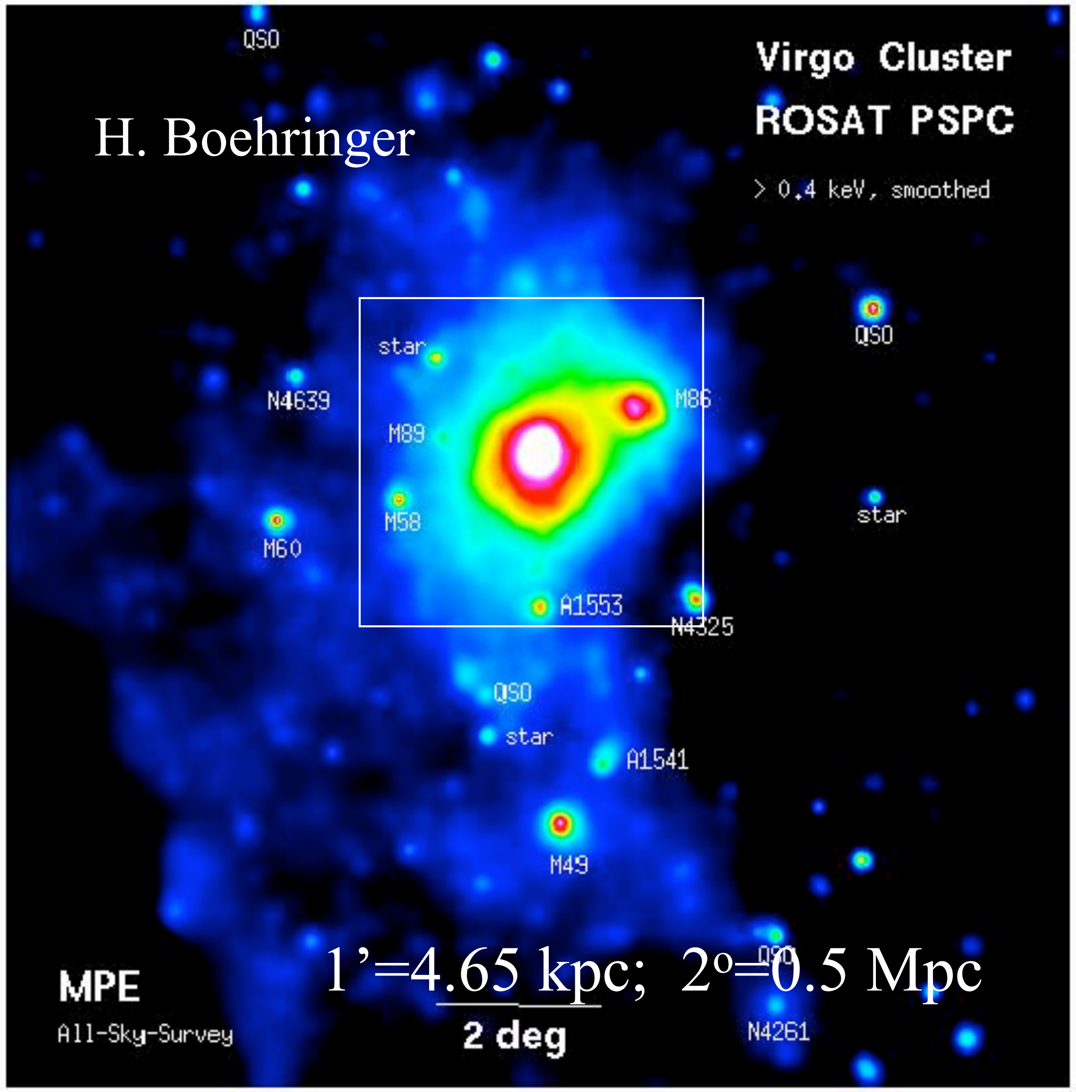
Shurkin, Dunn, Allen+08 - radio lobes and X-ray gas cavities

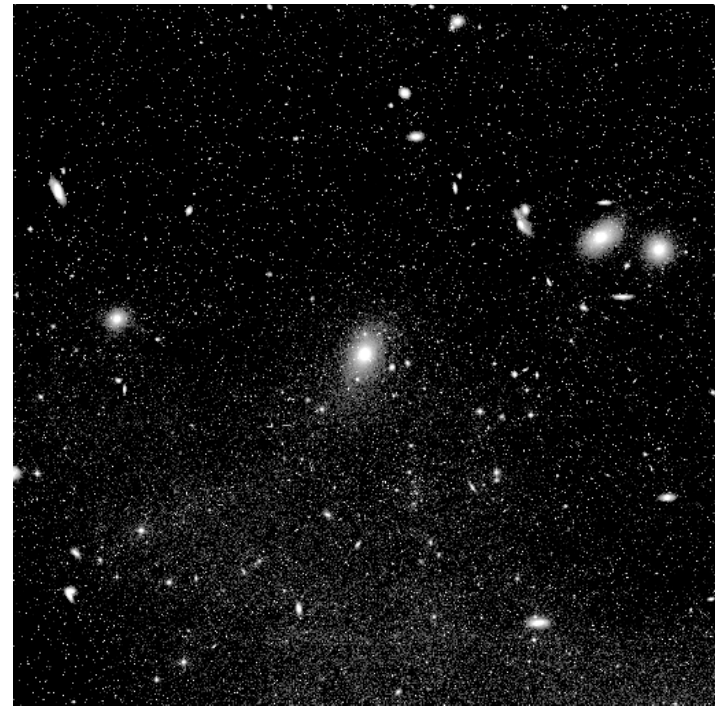
NGC1404 - Machacek+05 (see Scharf+05 for Fornax survey)

Spectacular example of “classical” cold front (see Markevitch & Vikhlinin07) and ram pressure stripped tail

Derive total velocity from pressure profile v = 530-660 km/s (M~0.8-1)

Virgo Cluster - X-ray/Optical





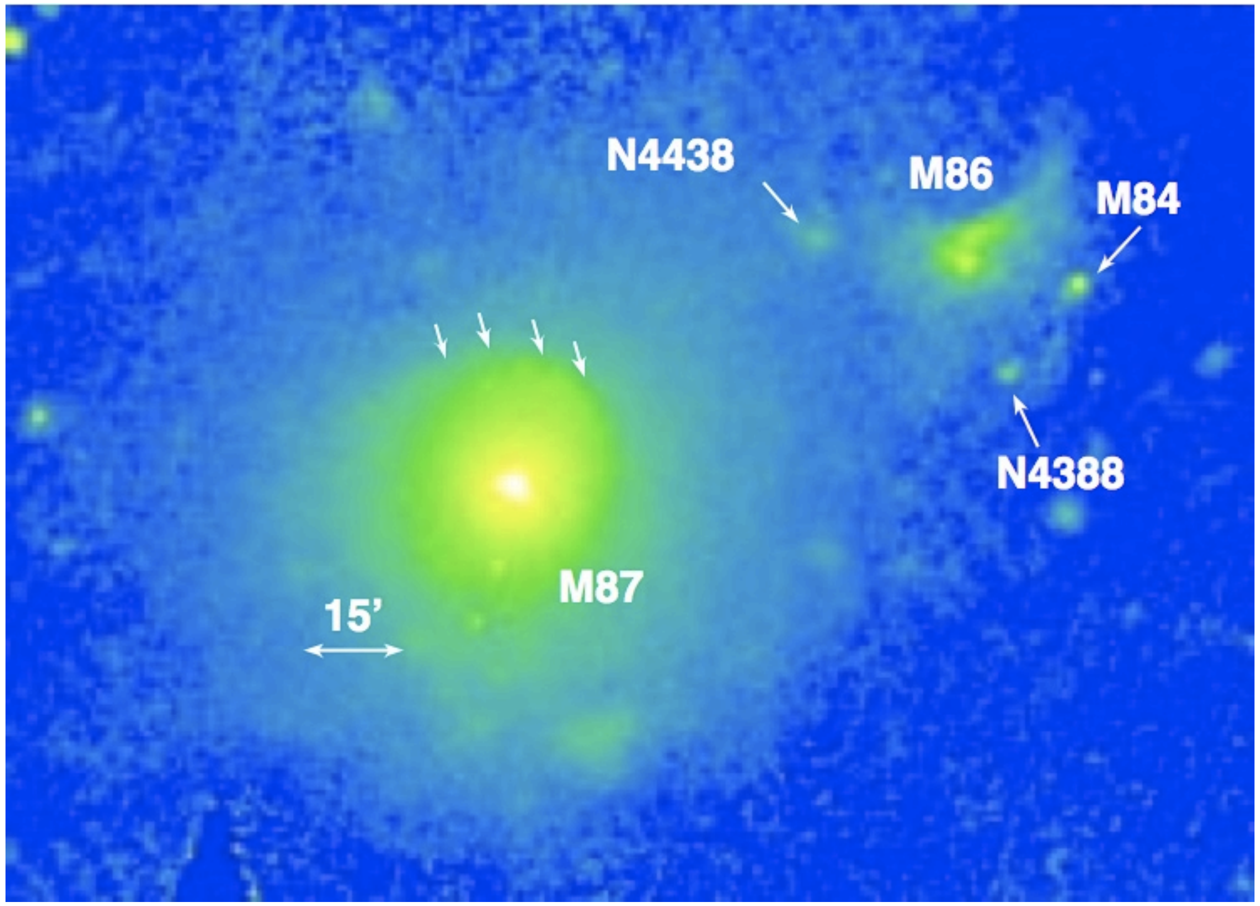
1) Optically luminous early-type galaxies are (hot) gas rich - up to 10^{10} M_{sun}

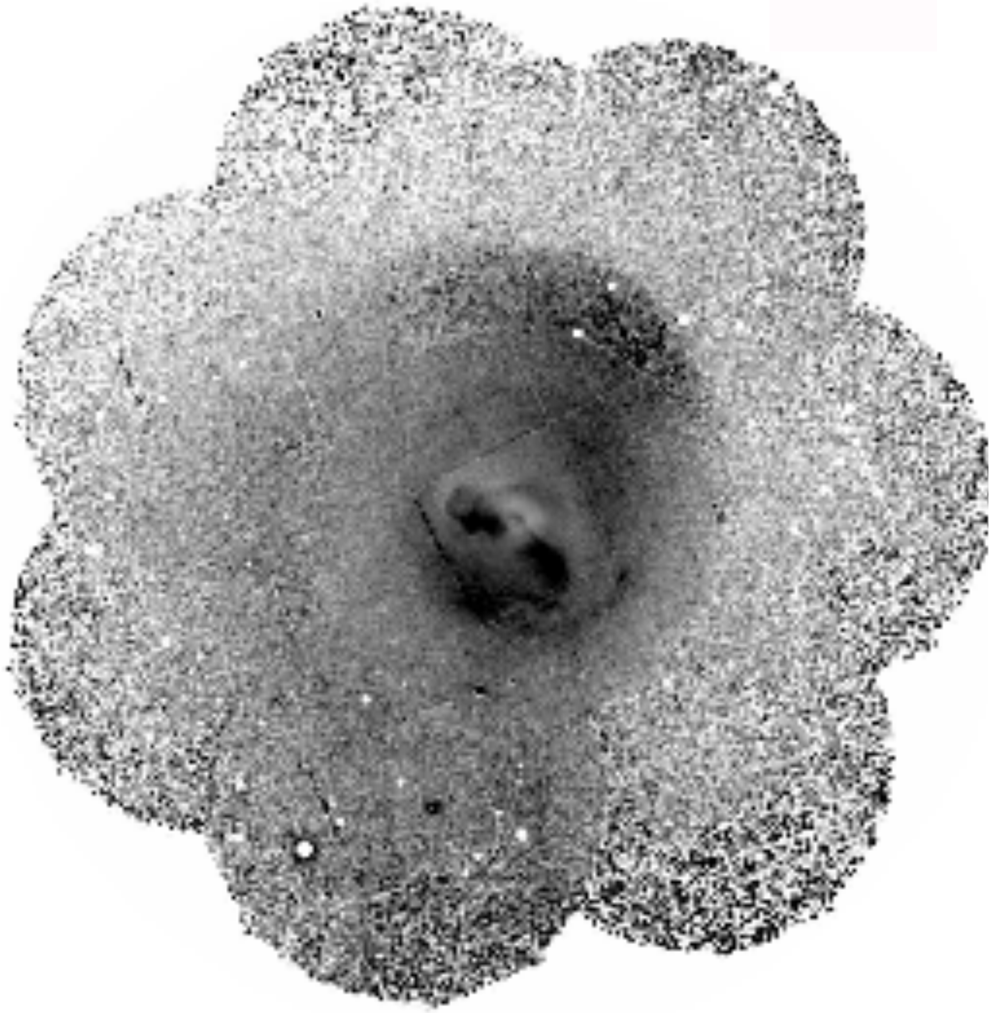
Virgo is dynamically young extensive merging, stripping

2) M87 is central dominant galaxy

- Clear from X-ray image
- M87 is 50 x more X-ray luminous than NGC4472
- NGC4472 (a bit) optically more luminous than M87
- M87 hosts $6x10^9 M_{sun}$ supermassive black hole and jet
- Classic cooling flow (24 M_{sun}/yr)
- Ideal system to study SMBH/gas interaction

Gas Sloshing in M87

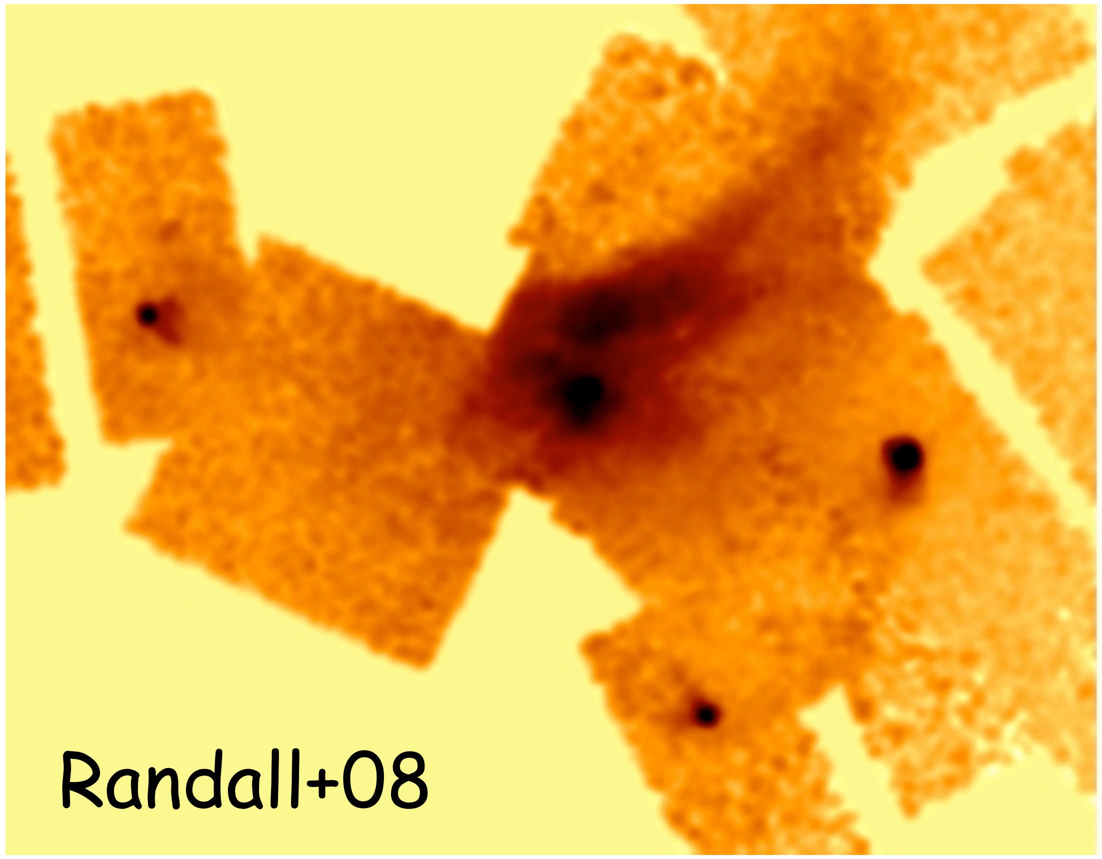


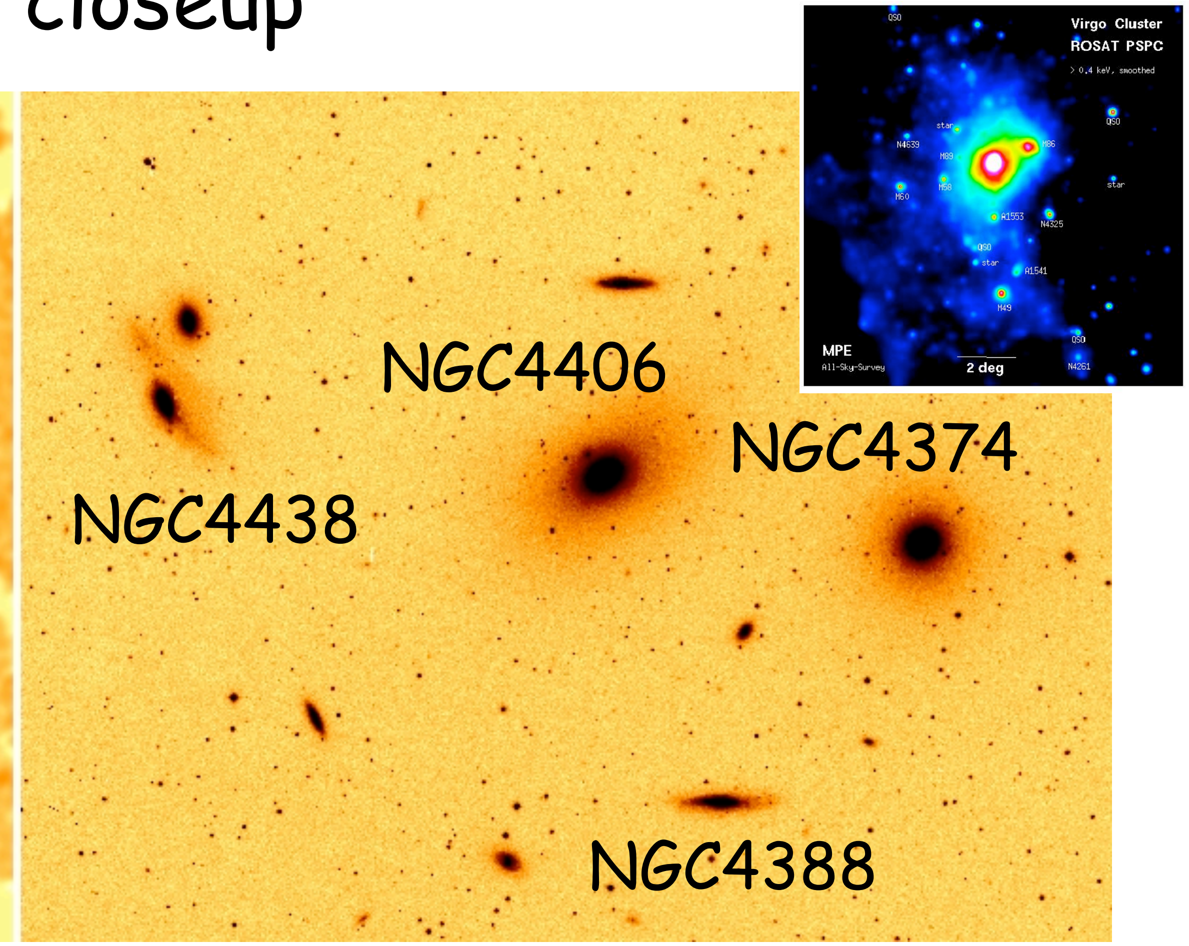


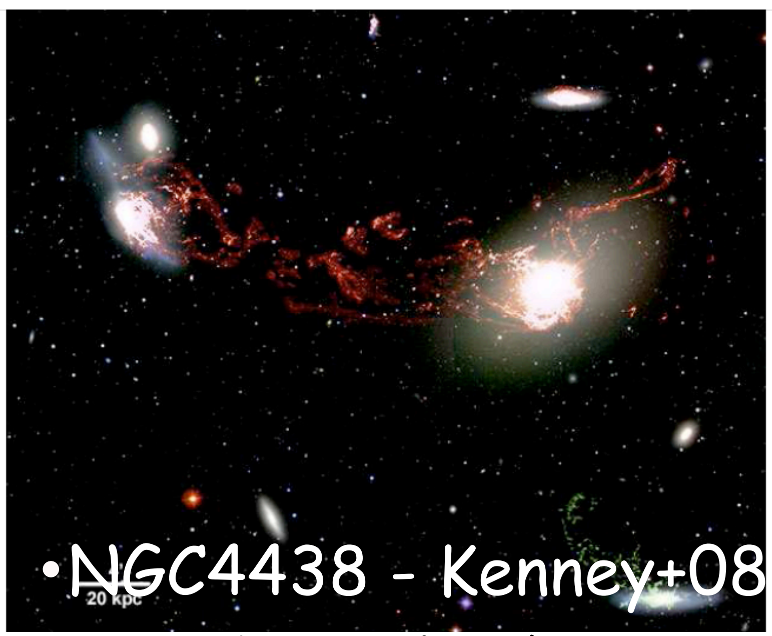
M87 shows gas "sloshing"

- "Edge", contact discontinuity - cold front at ~100kpc
  - (Simionescu+10 from XMM-Newton)
- Very common (14/18) in "peaked" clusters (Markevitch+03)
- see Markevitch & Vikhlinin 2007 for a review
  - & R. Johnson PhD 2011
- Driven by mergers

M86=NGC4406 closeup





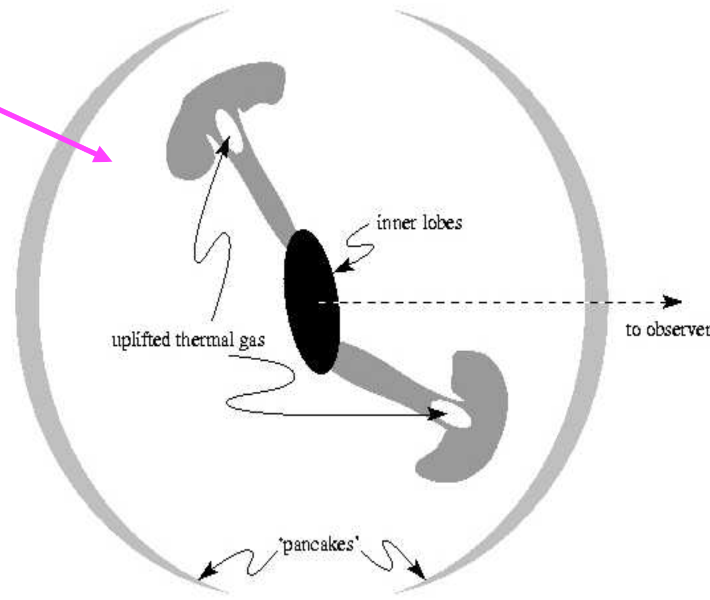


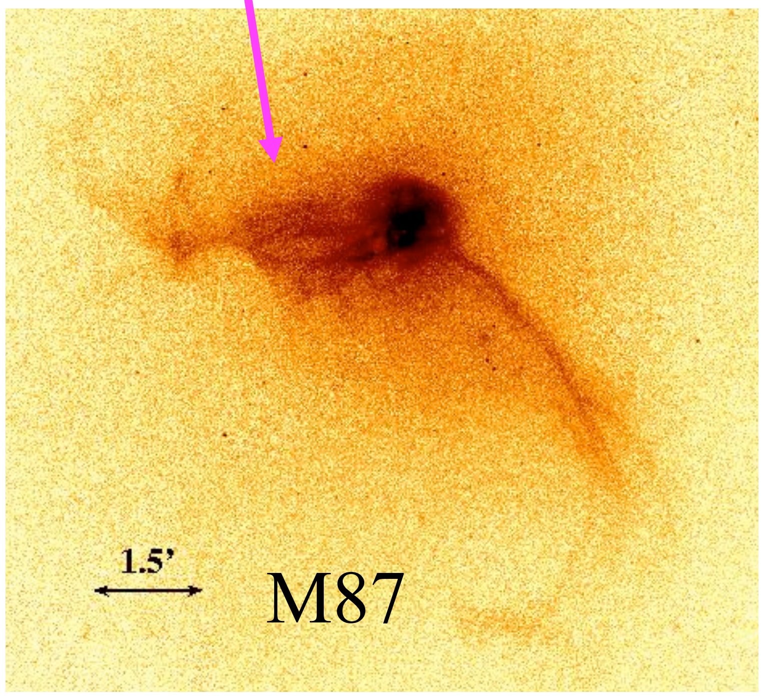
- NGC4438 - Kenney+08
  - red<500 km/s
  - green >2000 km/s

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

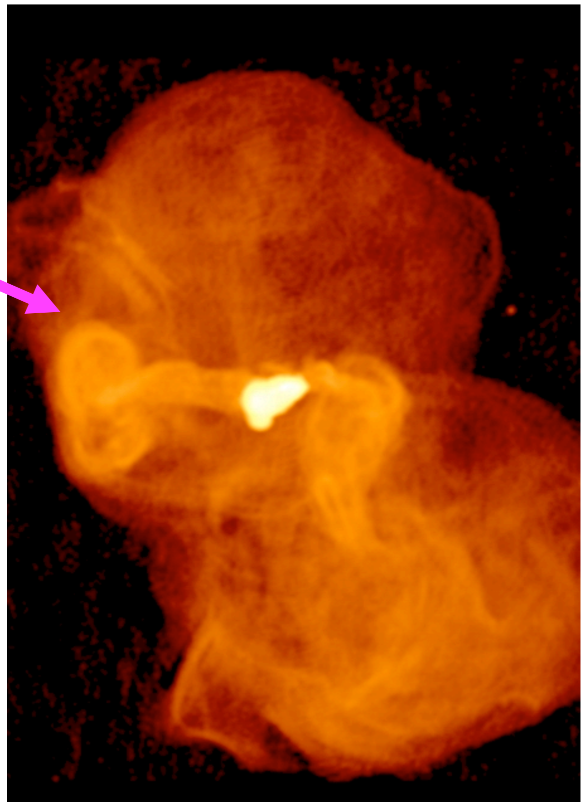
X-ray and Radio View of M87

- 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



Radio 90Mhz
Owen, Eilek, Kassim 2001

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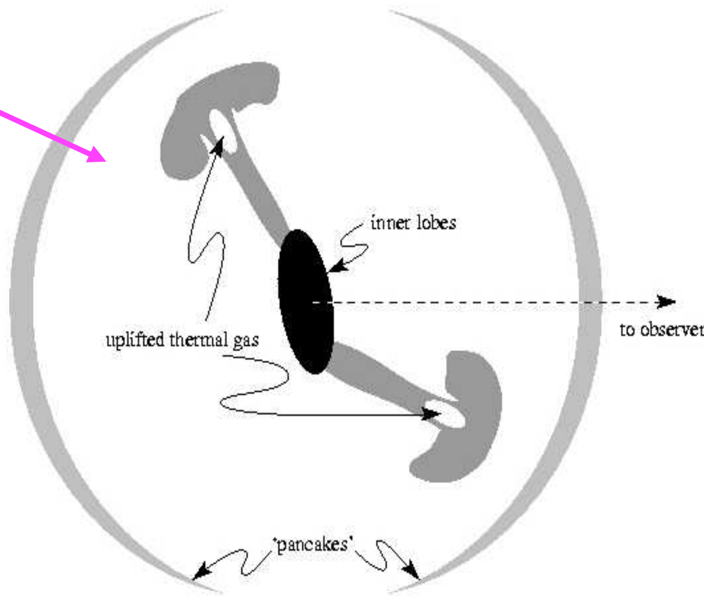

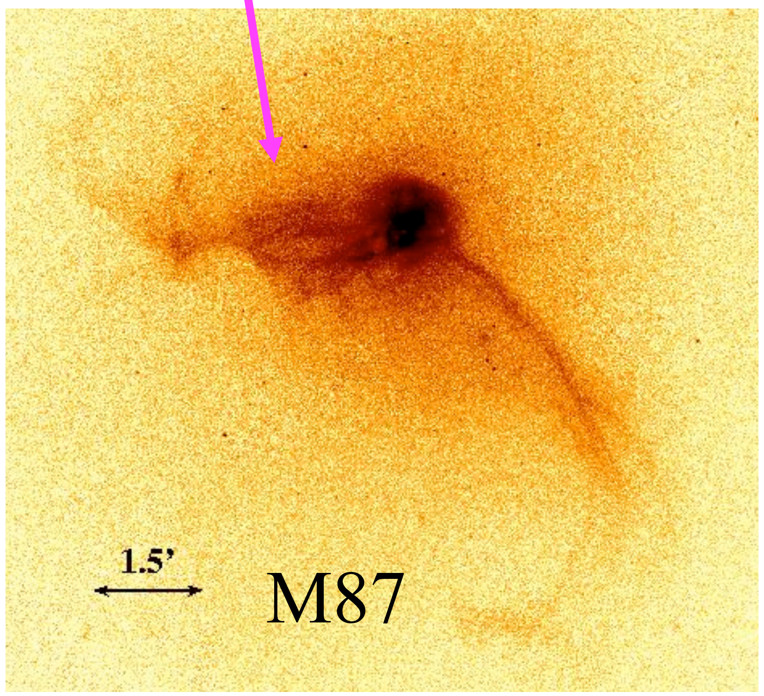

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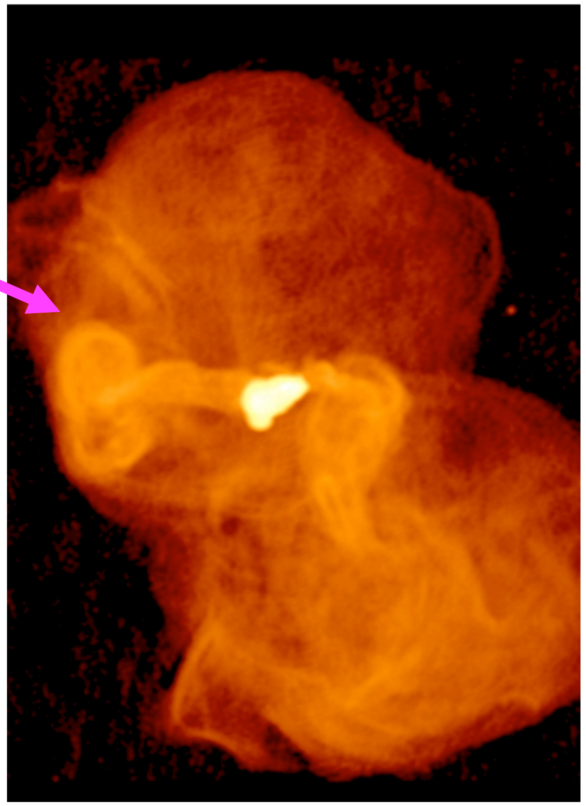

Radio 90Mhz
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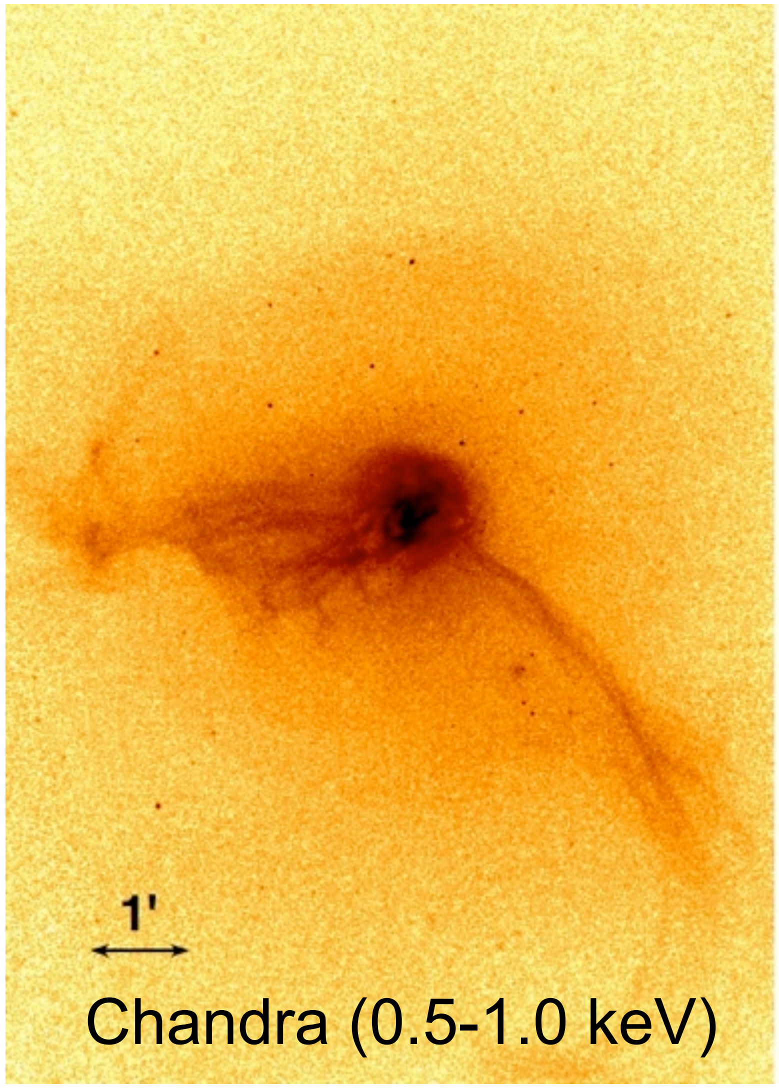
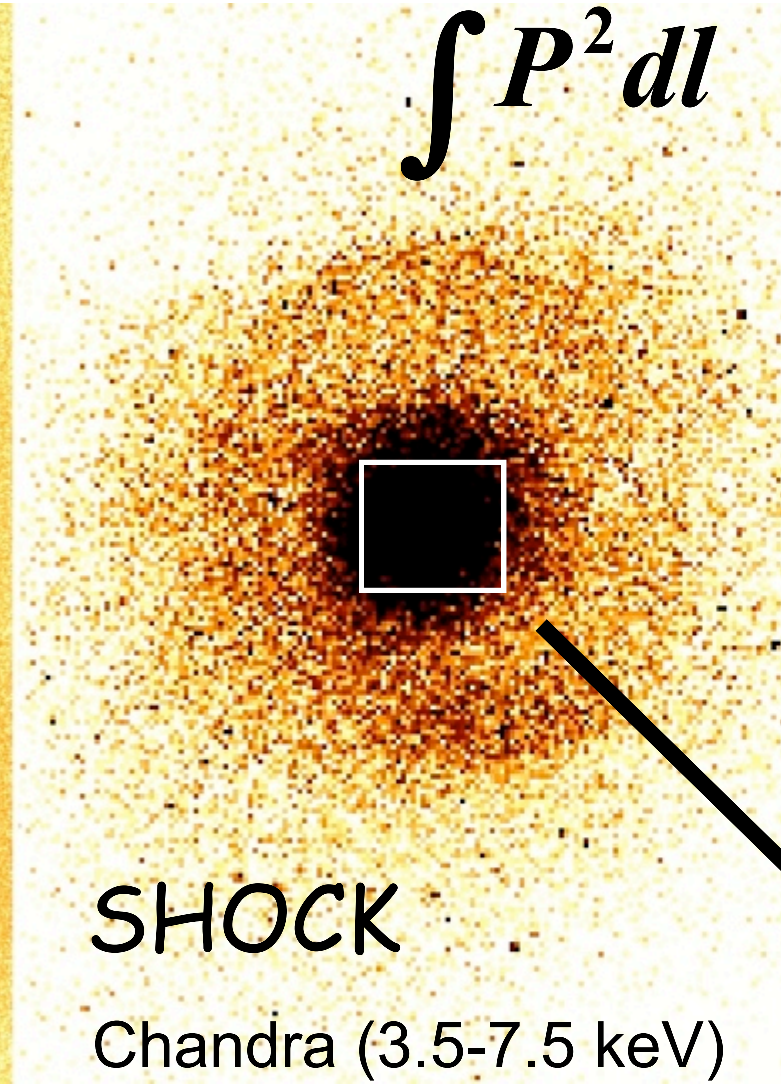
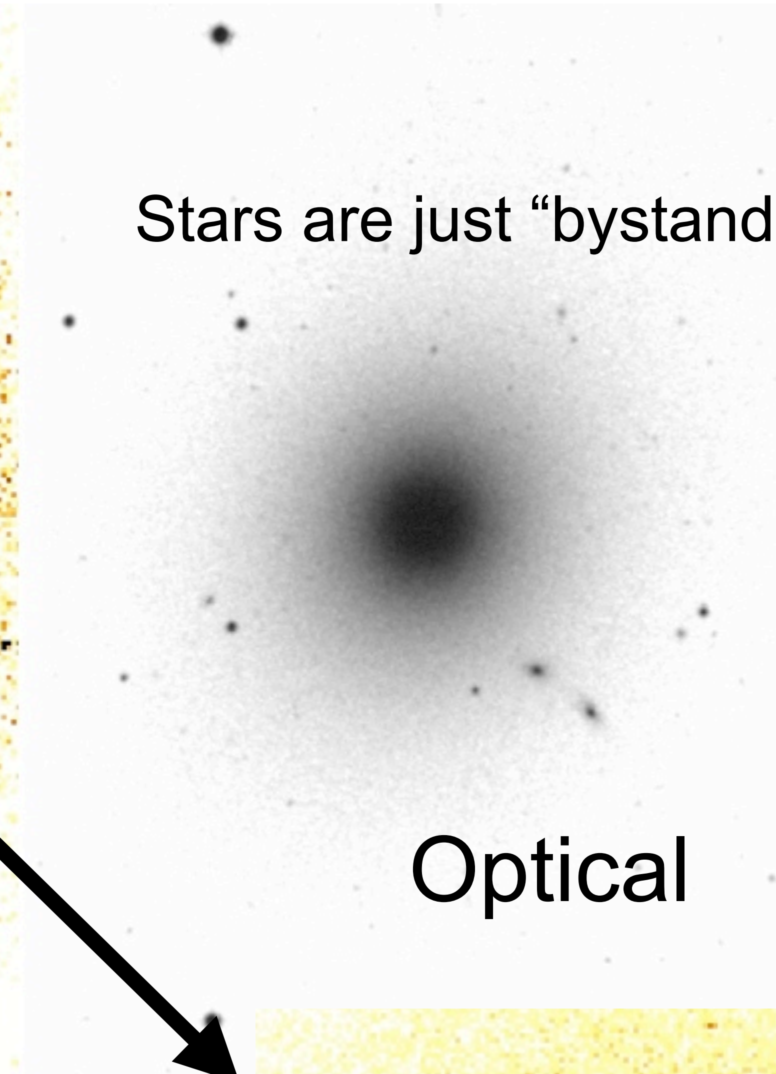
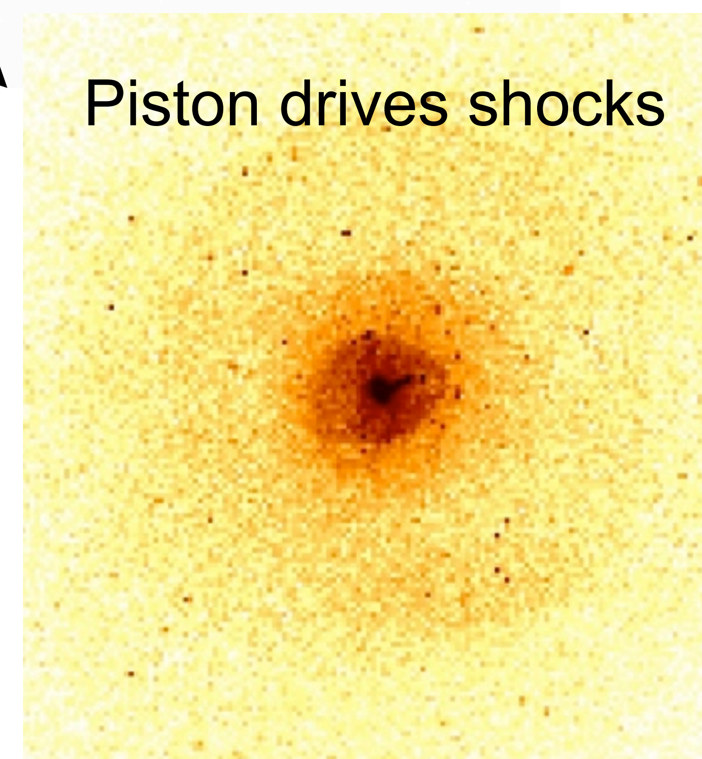
Feedback - M87







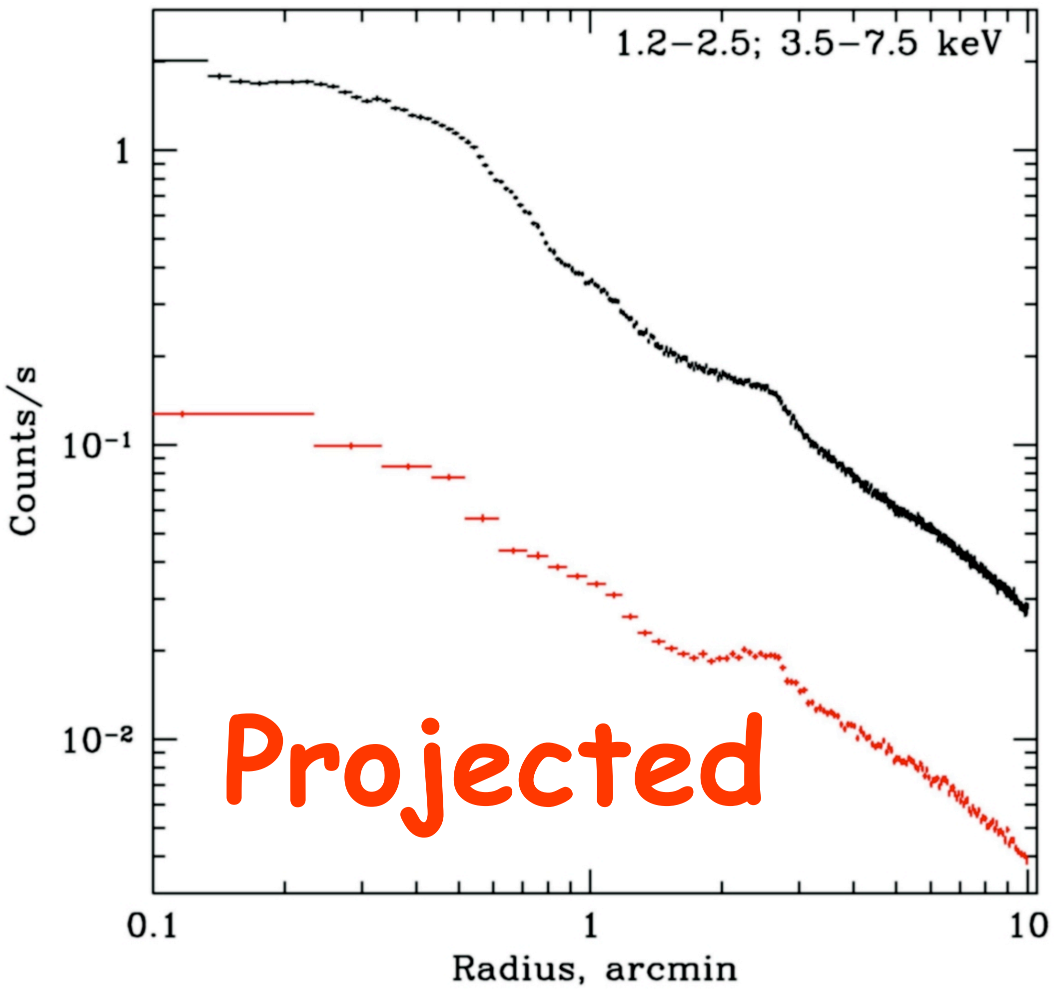


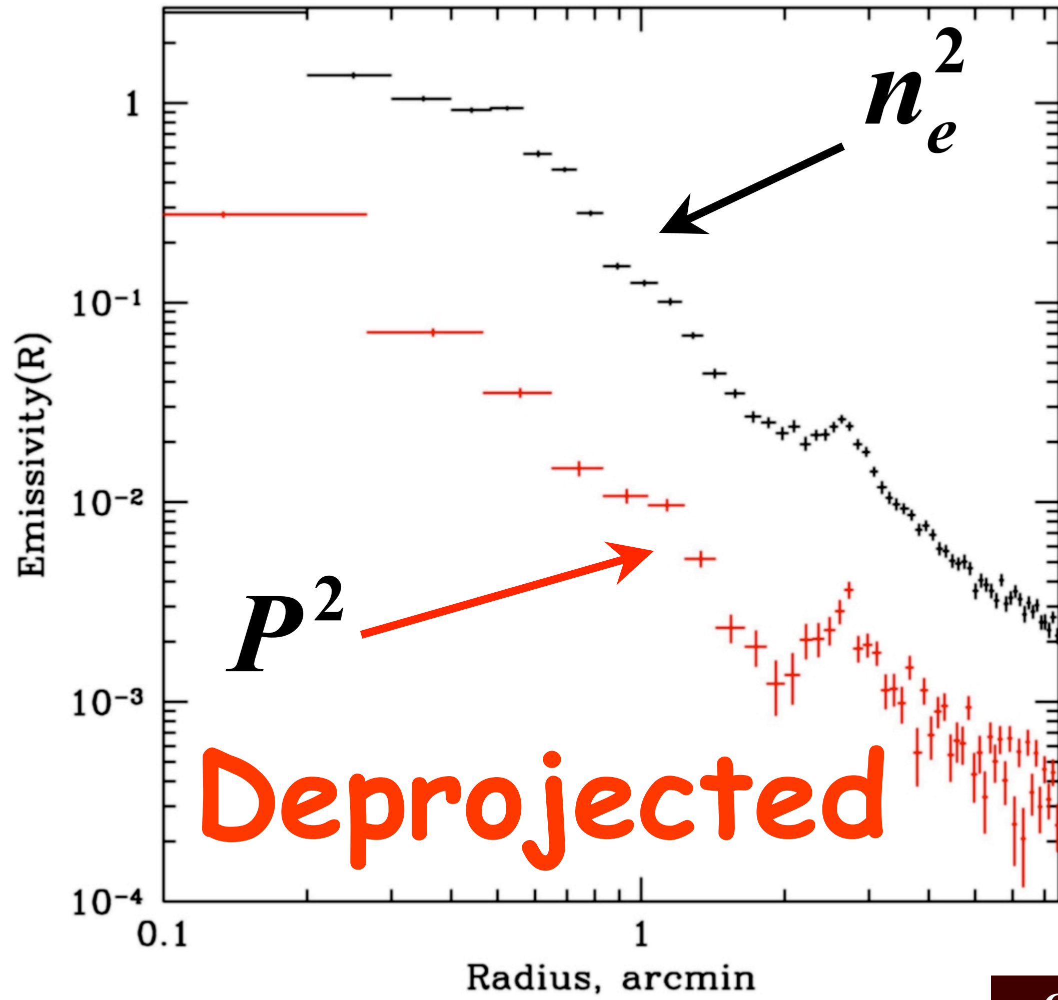
- Black hole = 6.6×10^9 solar masses (Gebhardt+11)
- SMBH drives jets and shocks
- Inflates "bubbles" of relativistic plasma
- Heats surrounding gas
- Model to derive detailed shock properties

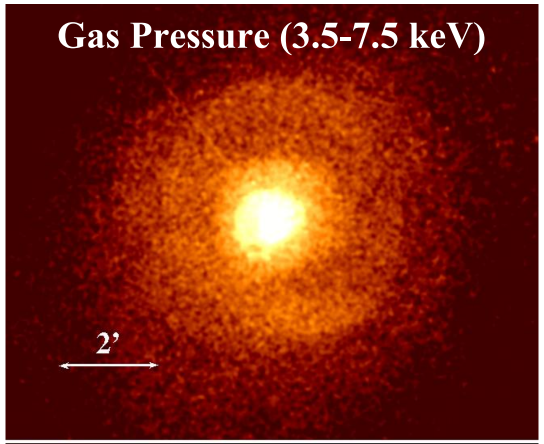
M87 Shock Model - the data

Hard (3.5-7.5 keV) pressure

soft (1.2-2.5 keV) density profiles







M87 - a Textbook Example of Shocks

Consistent density and temperature jumps

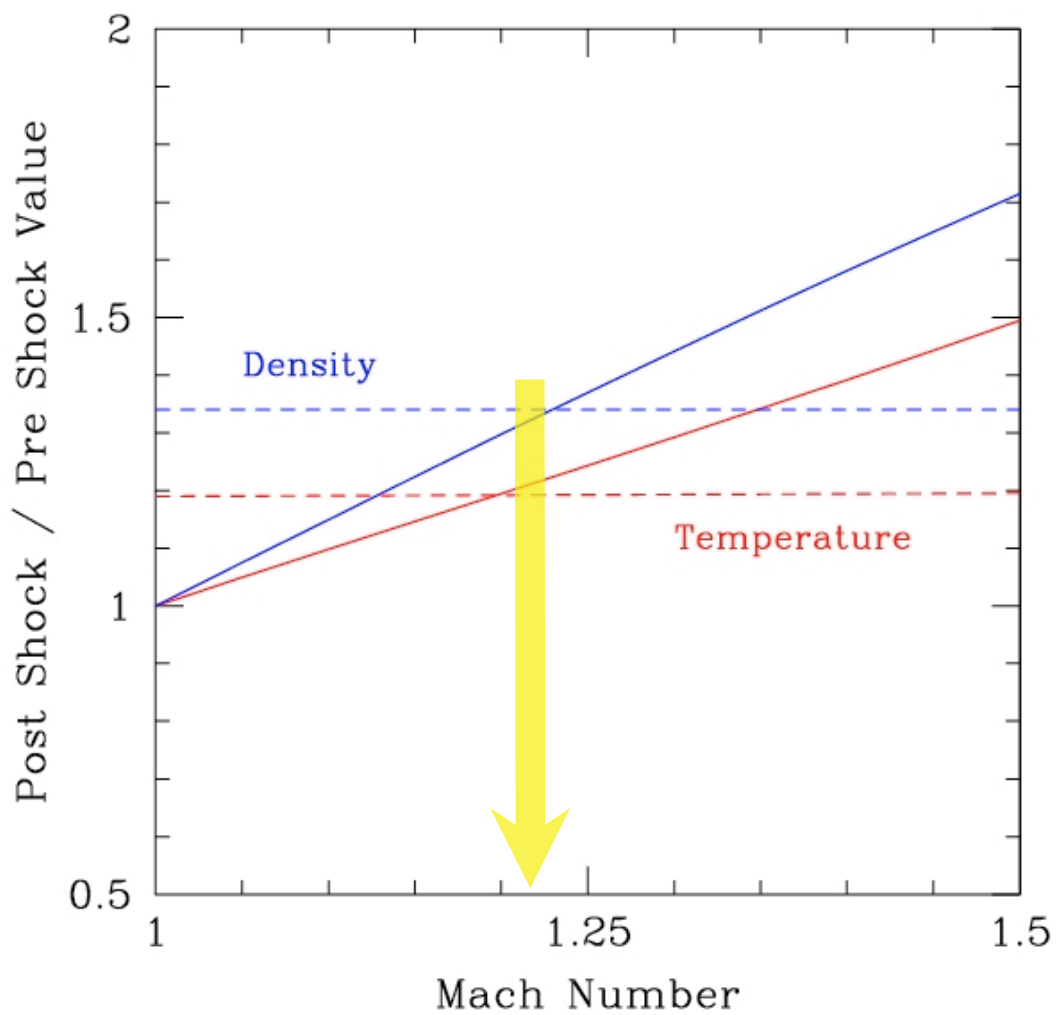
Rankine-Hugoniot Shock Jump Conditions

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

$$\rho_2/\rho_1 = 1.34$$

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

$$T_2/T_1 = 1.18$$



M=1.2

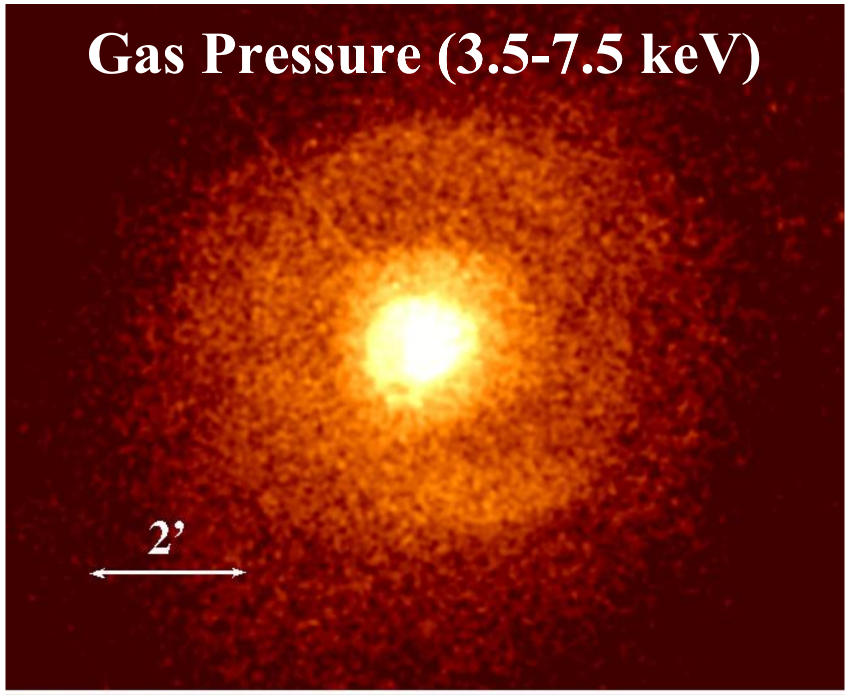
yield same Mach number:

($M_{T=}$1.24 M_ρ=1.18)

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)

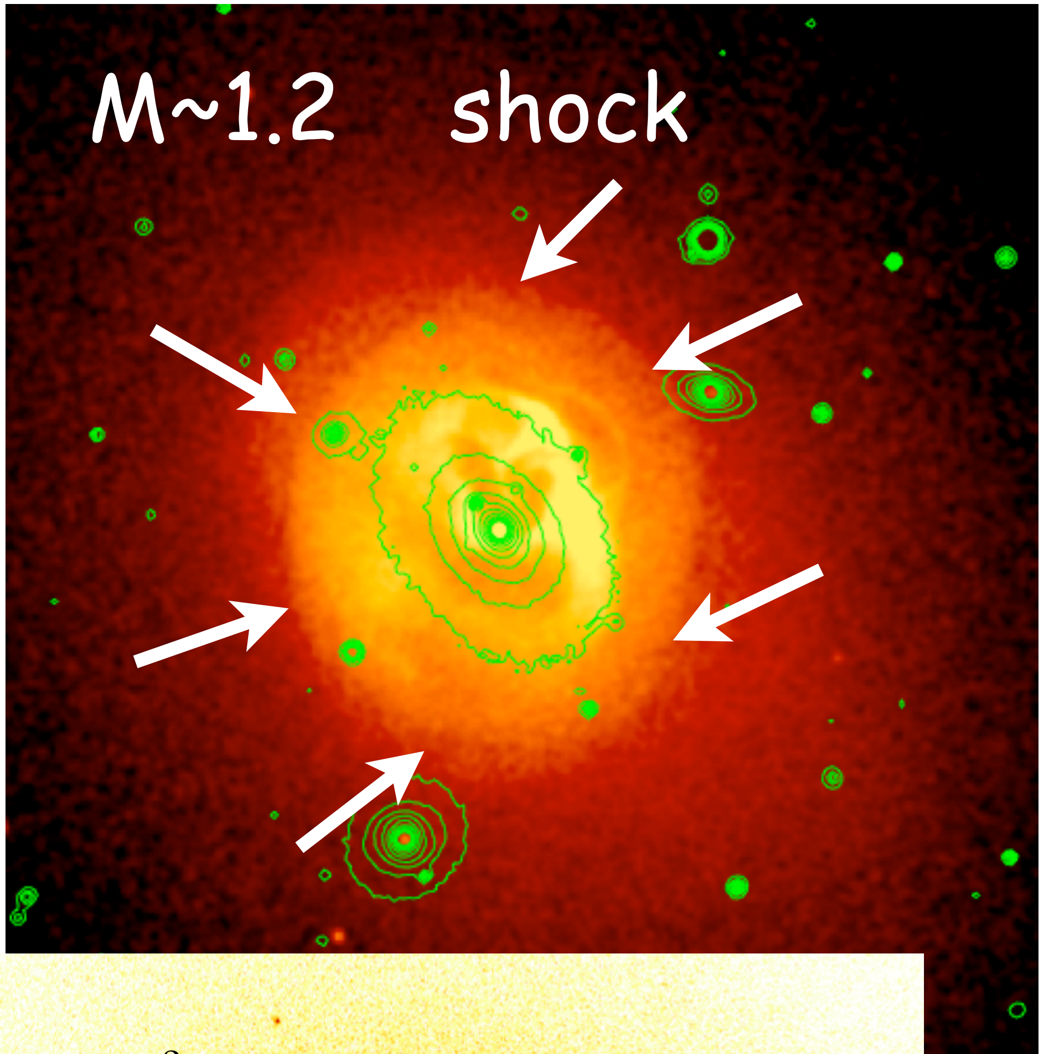


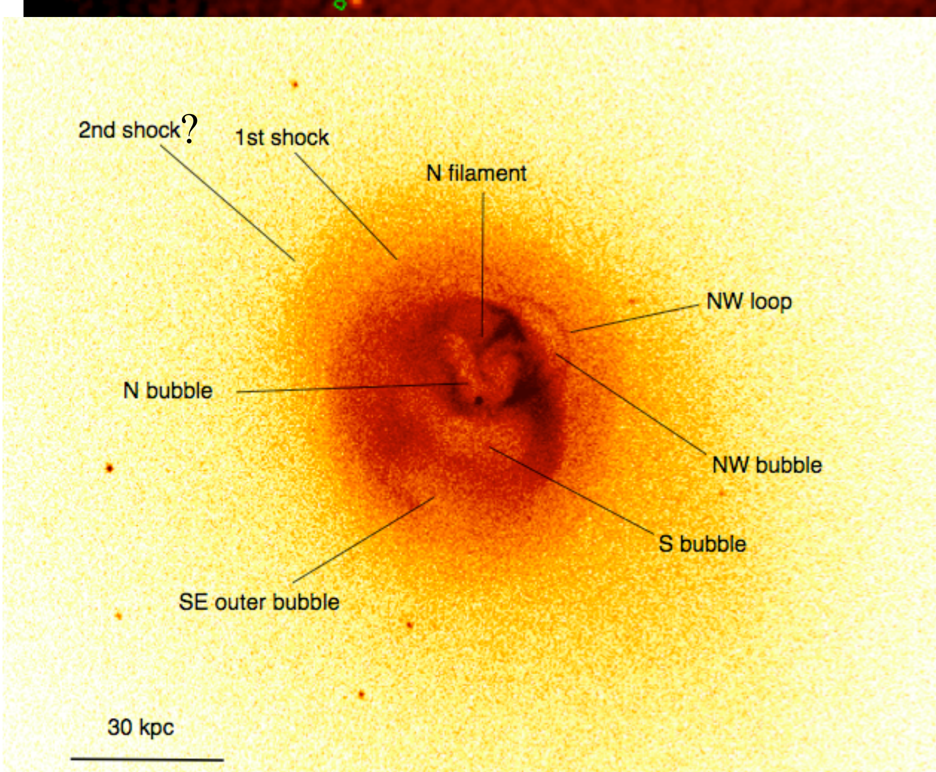
Outburst Model

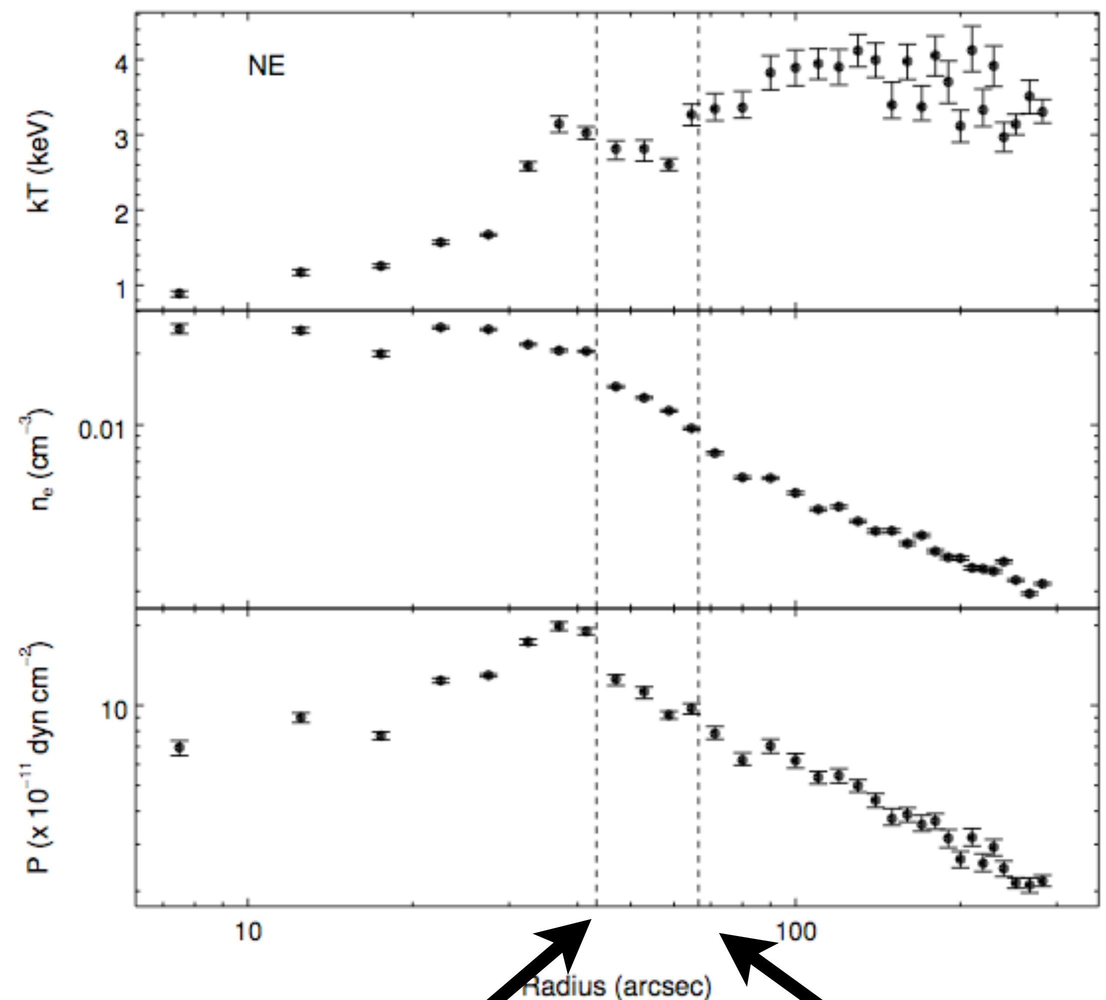
- Age ~ 12 Myr
- Energy ~ 5×10^{57} erg
  - Bubble 65%
  - Shocked gas 25% (25% carried away by weak wave)
- Outburst duration ~ 2-5 Myr

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

Abell 2052 - Blanton+11



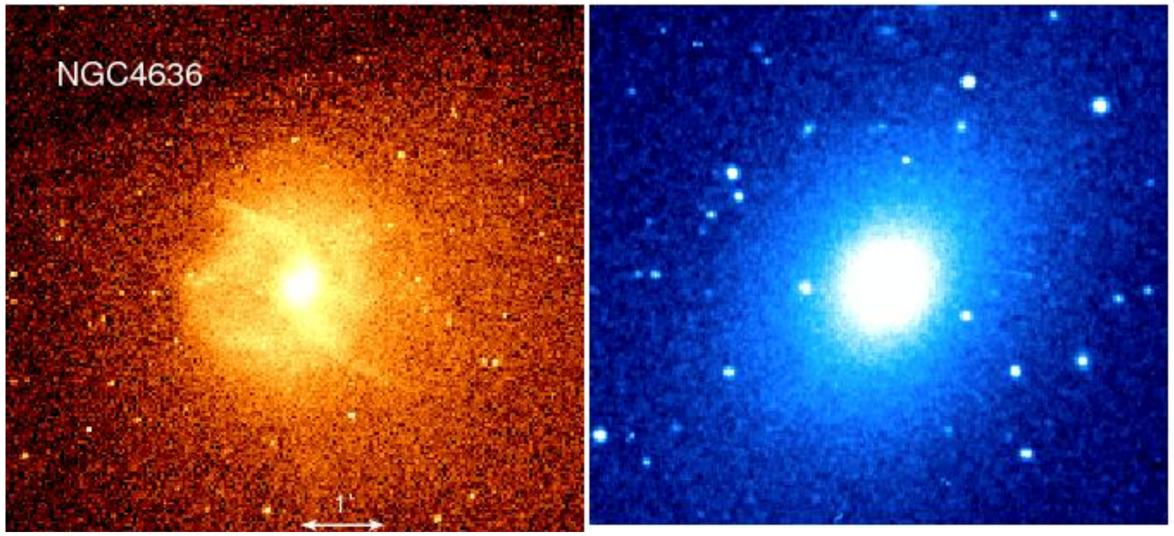


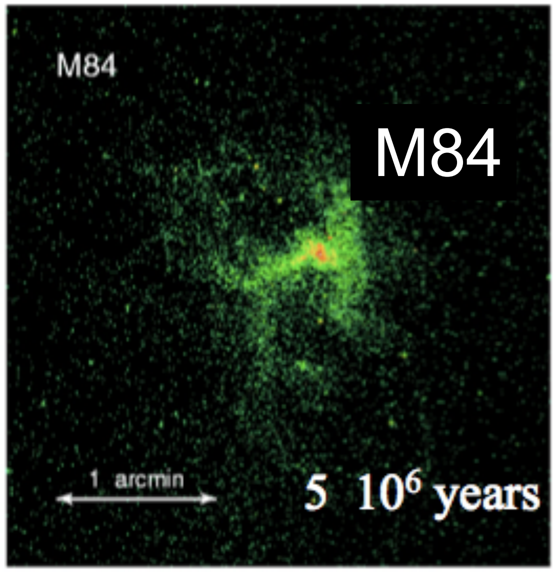


M~1.17 shock nearly spherical consistent density/ temperature jumps

Second feature shock or cold front?

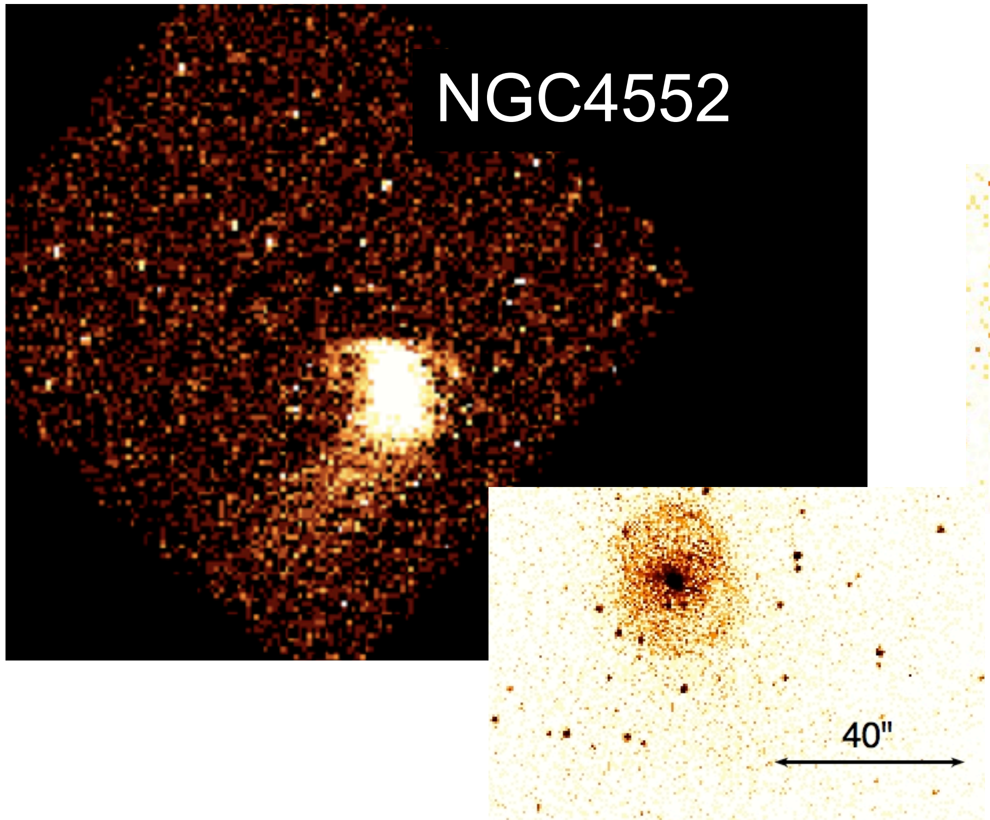
Gas Rich Early Type Galaxies

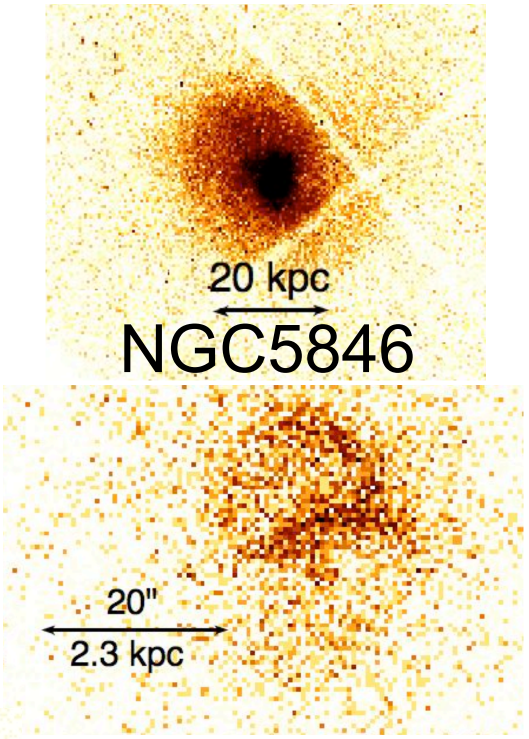




As a class, luminous early type galaxies ($L_K > 10^{11} L_{sun}$) have hot corona

- AGN outbursts, typical
- cavities common
- ram pressure stripping, common
- Complementary view from optical - see Ferrarese image this morning of NGC4552

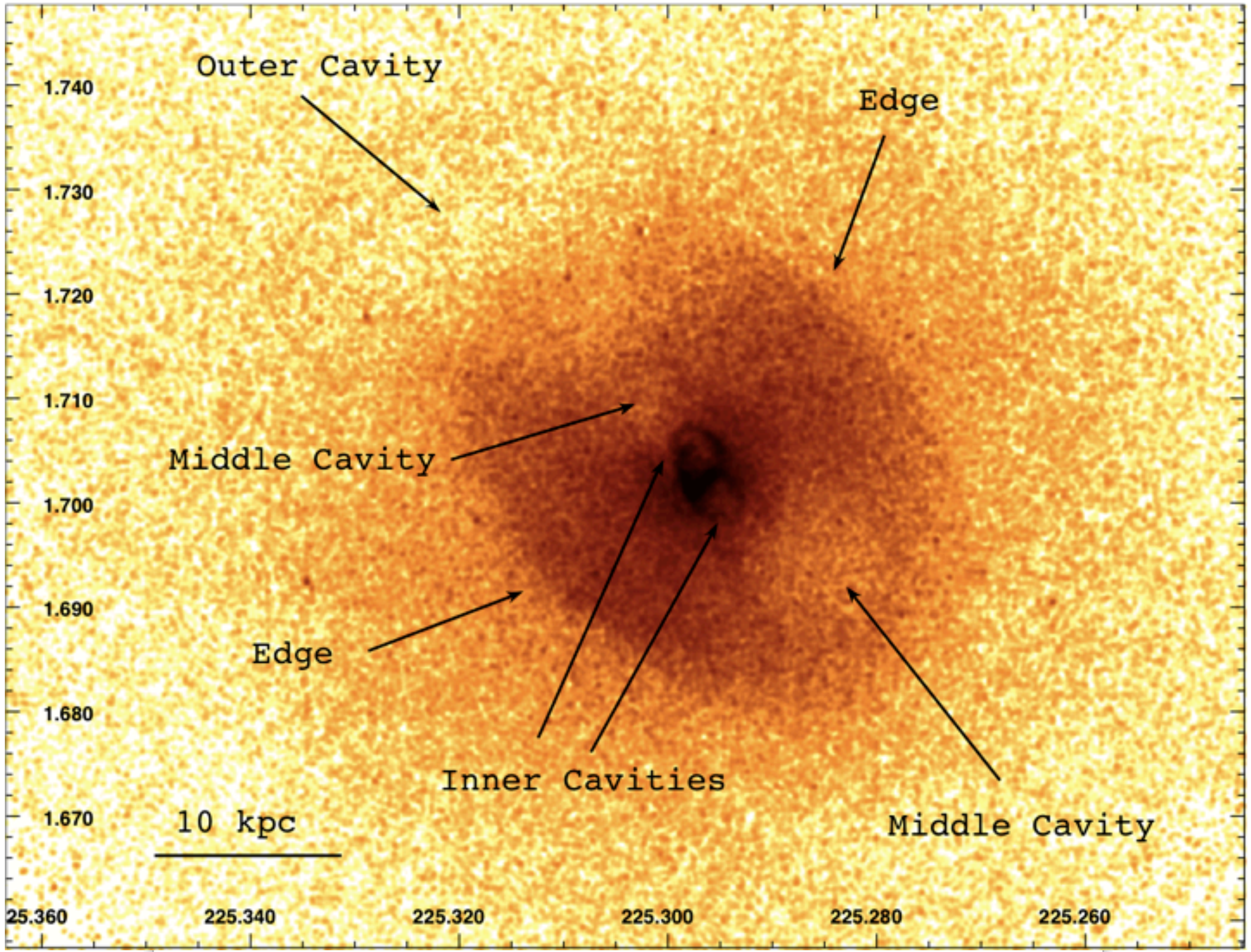




A "typical" galaxy

NGC5813 - multiple outbursts

S. Randall et al.



	inner	middle	
Ages	0.6	3	$\times 10^7$ yrs
Energies	1	10	$\times 10^{55}$ ergs
Mach	1.7	1.5	

$L_{nuc} \sim$ few $\times\ 10^{39}$ erg/s

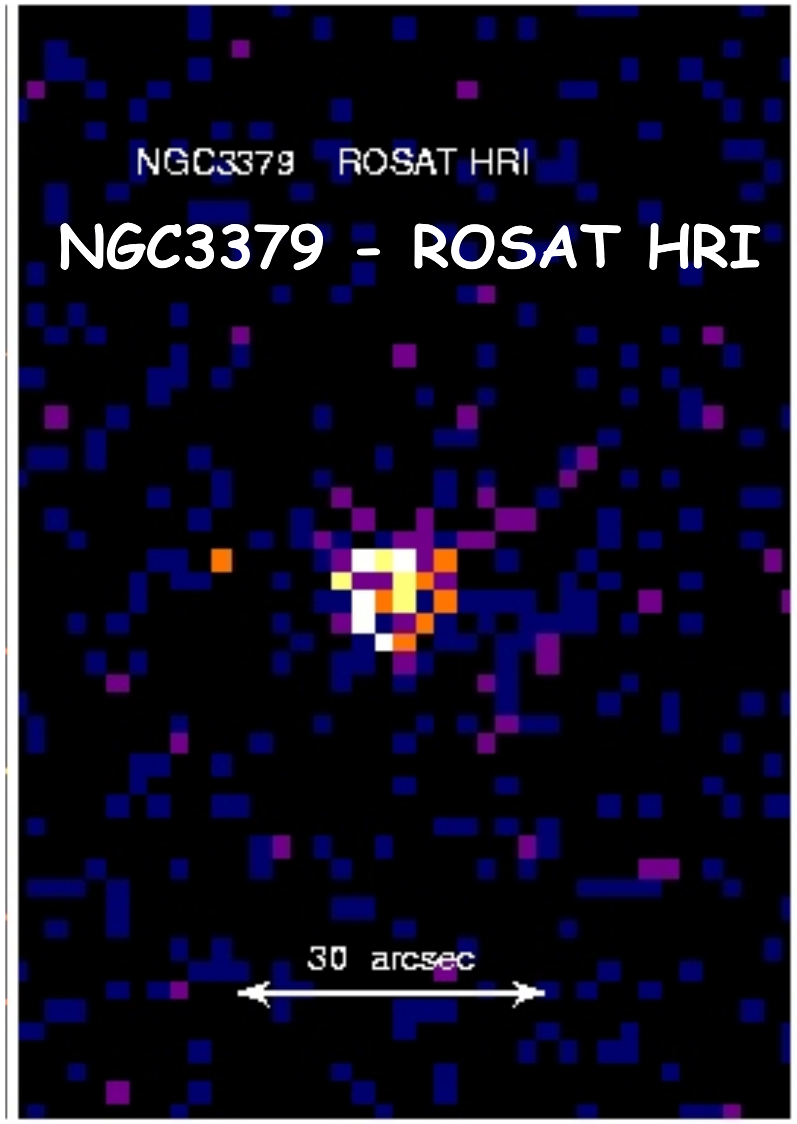
- Observed shock heating overcomes core cooling for NGC5813

- Galaxy Survey (not BCGs) ~ 150 galaxies (C. Jones+11)
    - magnitude limited sample (from Beuing+87 and O'Sullivan+01)

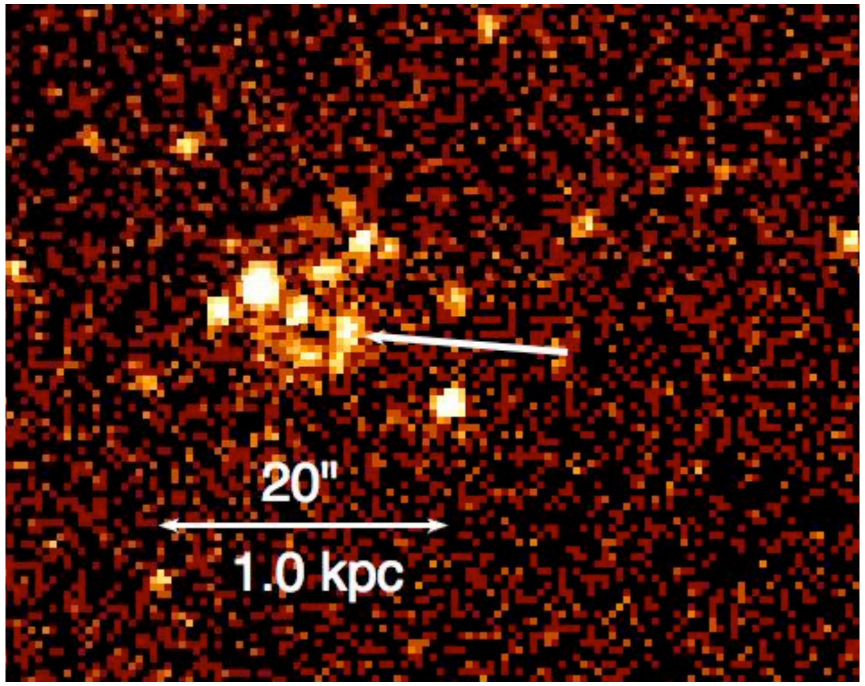
      AND

    - Chandra targeted galaxies
- working on more "complete" sample
- some galaxies are BGG's - brightest group galaxies
- not possible pre-Chandra
    - nuclei too faint
    - can't exclude bright low mass X-ray binaries

Chandra Angular Resolution Resolves Nuclear Regions



D=10.6 Mpc (51 pc/arcsec)



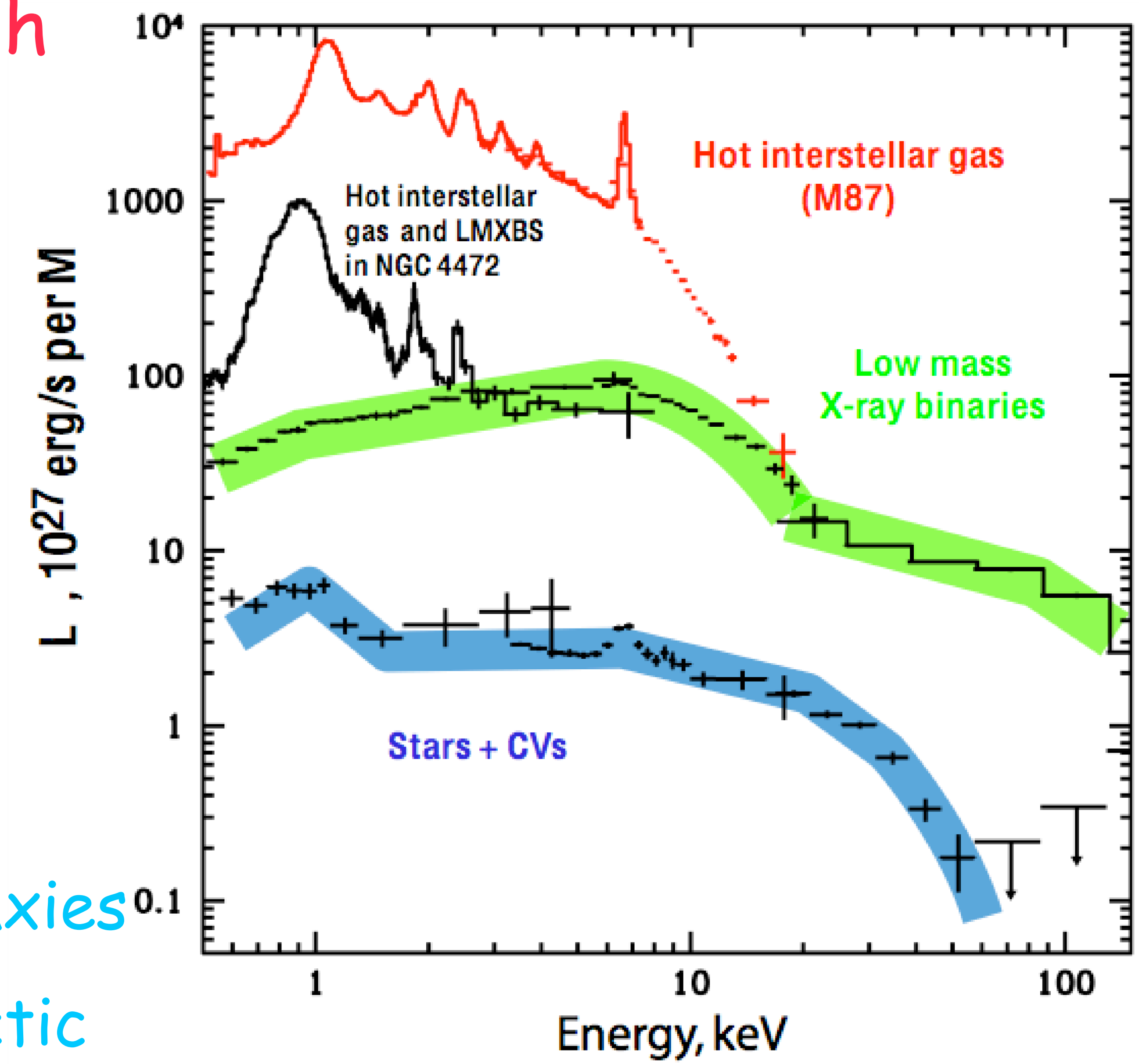
NGC3379
Chandra ACIS

Chandra's ~1" angular resolution

- detects/isolates faint nuclei
- removes LMXB's to detect faint diffuse emission
- L_{gas} ~ $2x10^{37}$ erg/s M_{gas} ~ $3x10^{5}$ M_{sun}
- hot gas likely in a wind (see Trinchieri +08; David+05)

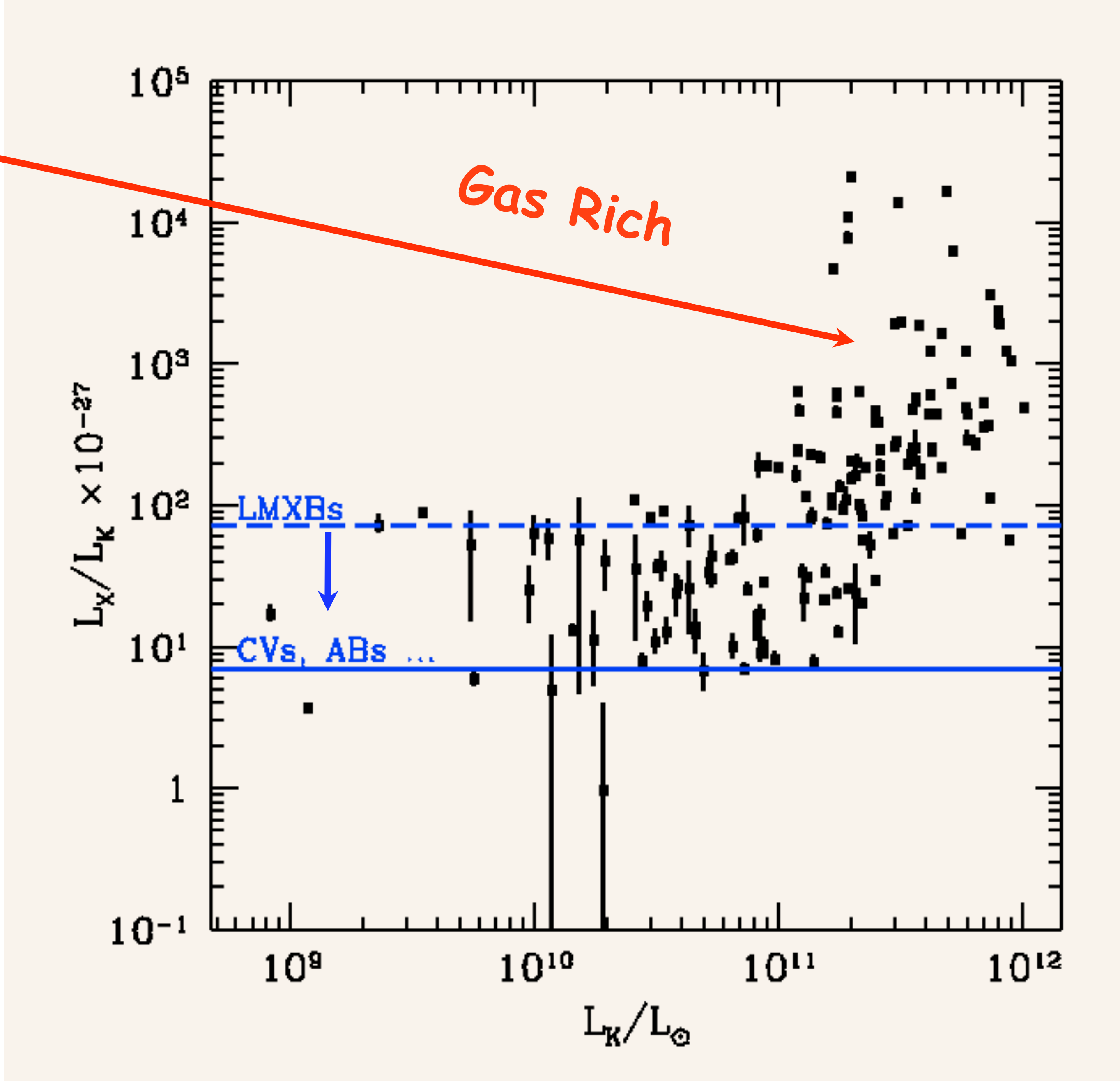
Components of X-ray emission in Galaxies

- 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 and globular clusters
- Stars +CV's (with a multi-component spectrum)
  - Detected in fainter, nearby galaxies
  - Resolved in the Milky Way Galactic Ridge (Revnivtsev et al 2008).
- Low luminosity AGN



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)
  - –Thermal gas kT~0.5-1 keV
- LMXBs - partially removed
- CVs, active binaries - always present and unresolved

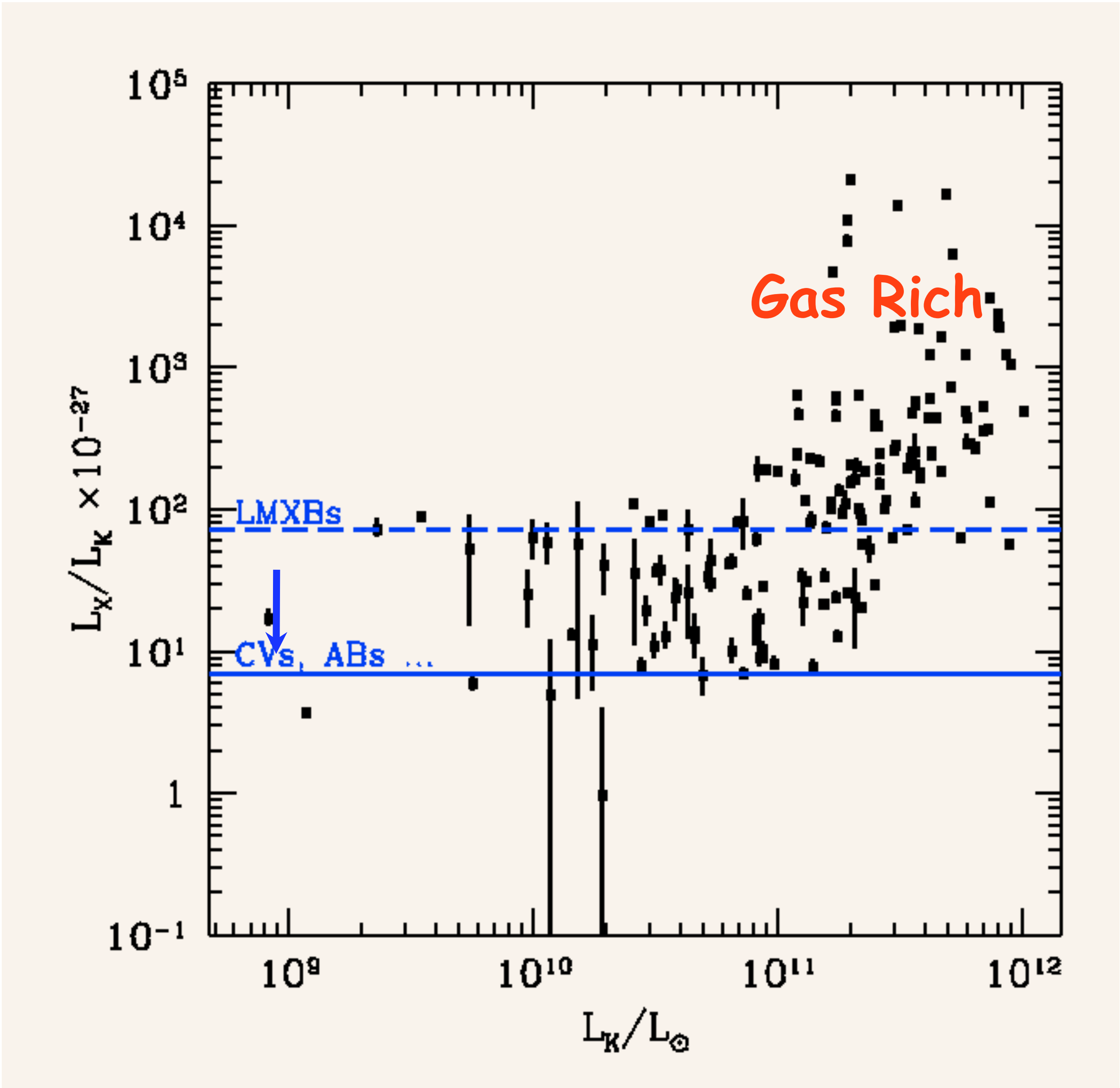


Jones+11 ~150 galaxies

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

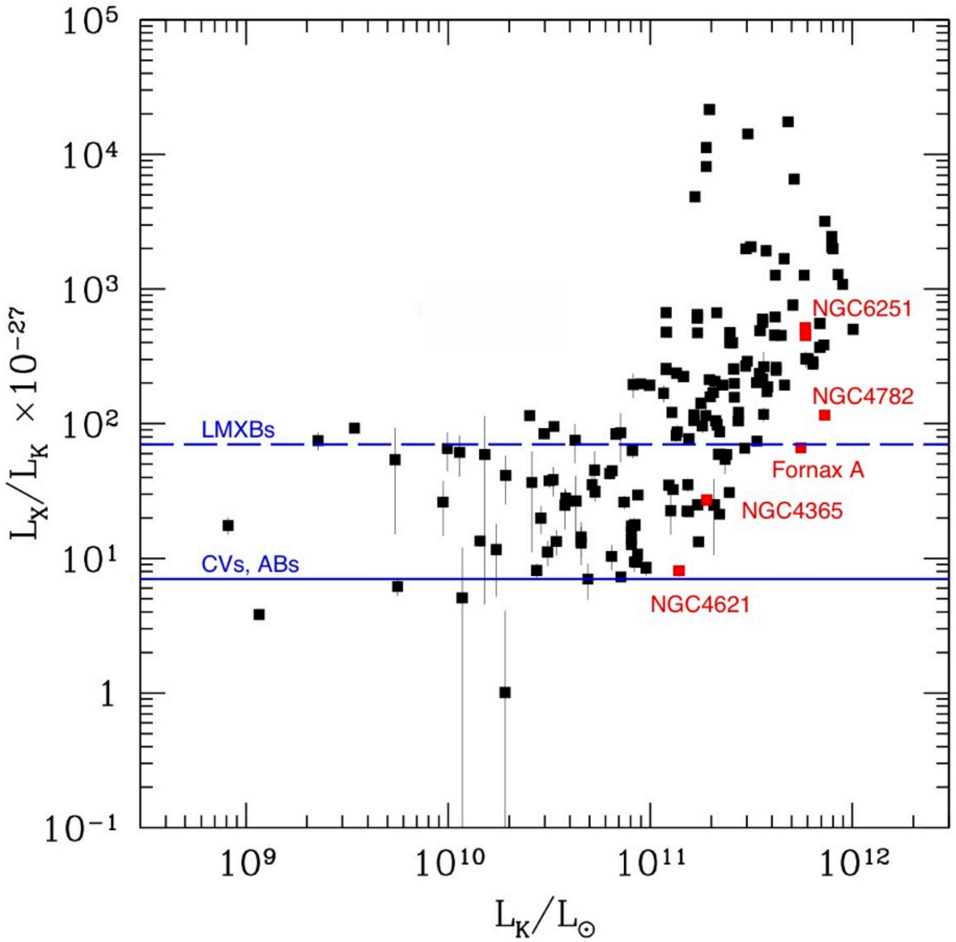
- Cavities
  - Common (30% in galaxies; 50% in clusters with cooling peaks)
  - Measure SMBH energy output
  - power sufficient to balance cooling (Nulsen+09)

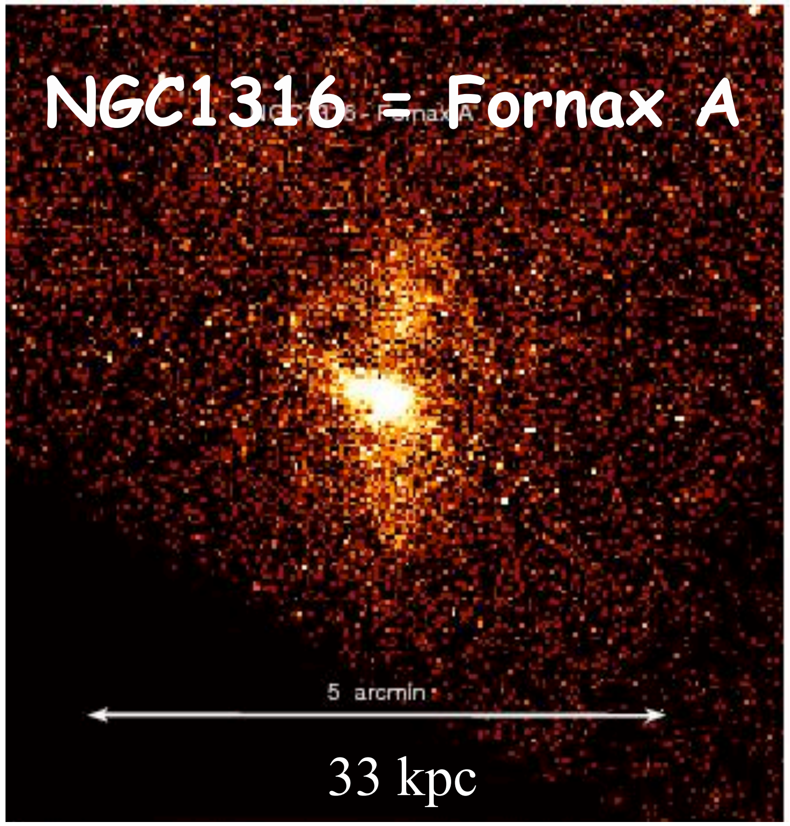
- AGN/SMBH
  - 70% detected in radio (see also Dunn+10 17/18 and 34/42)
  - Radiatively weak - radiated power < 10^{-3} mechanical power
- Wide range in L_X at fixed L_K - environment (group) or powerful outburst disrupting atmosphere (e.g., Fornax A)

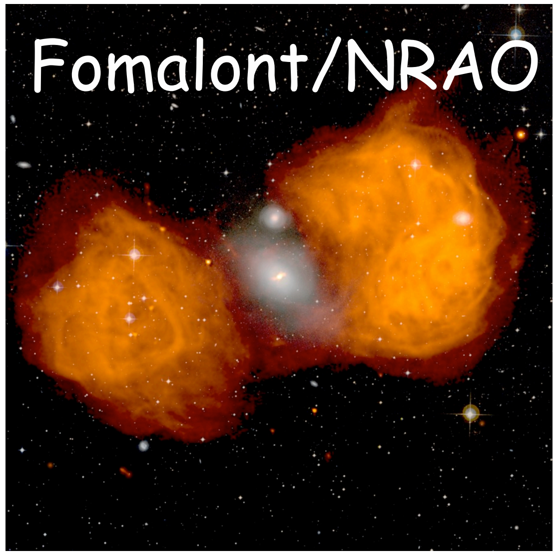


Jones+11 ~150 galaxies

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



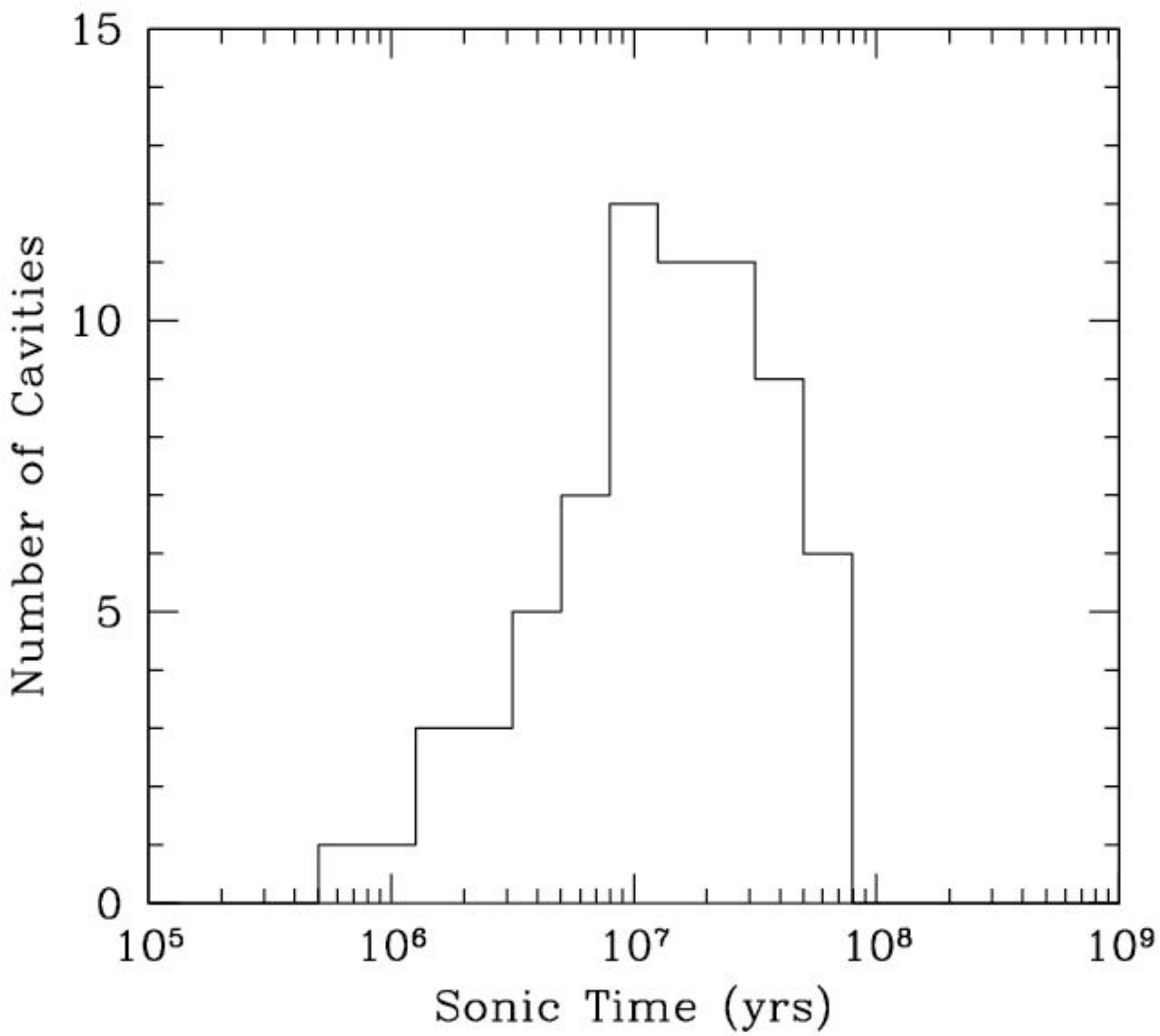


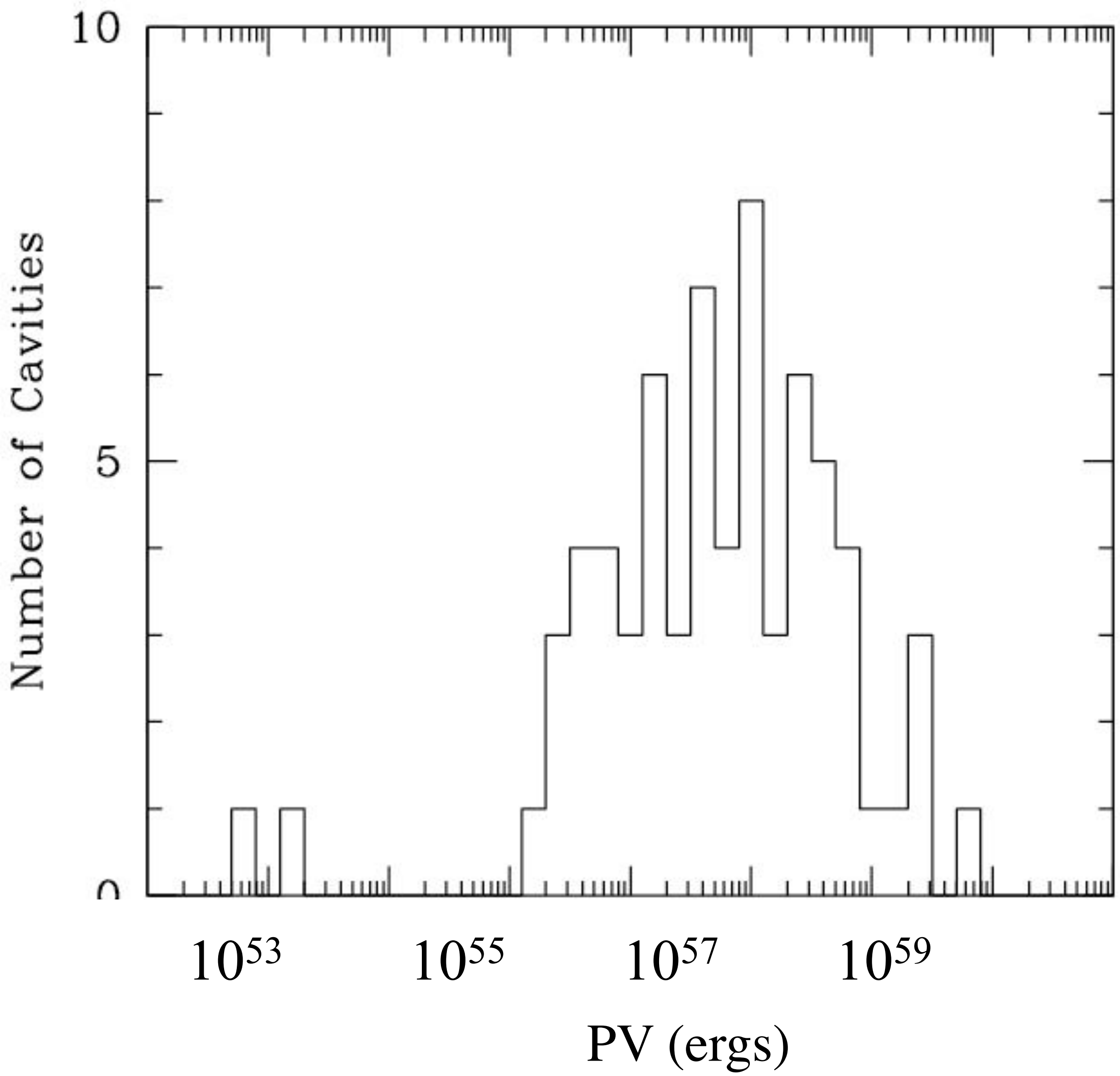


Scatter in L_X-opt mag relation is partly due to gas removal
and partly due to environment (galaxies in the centers of groups)

- 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)

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





Ages and outburst energies for galaxies with cavities (30% of optically luminous galaxies) - Nulsen, Jones, Forman, Churazov et al.)

Combine outburst energy and time scale - compare to radiated luminosity

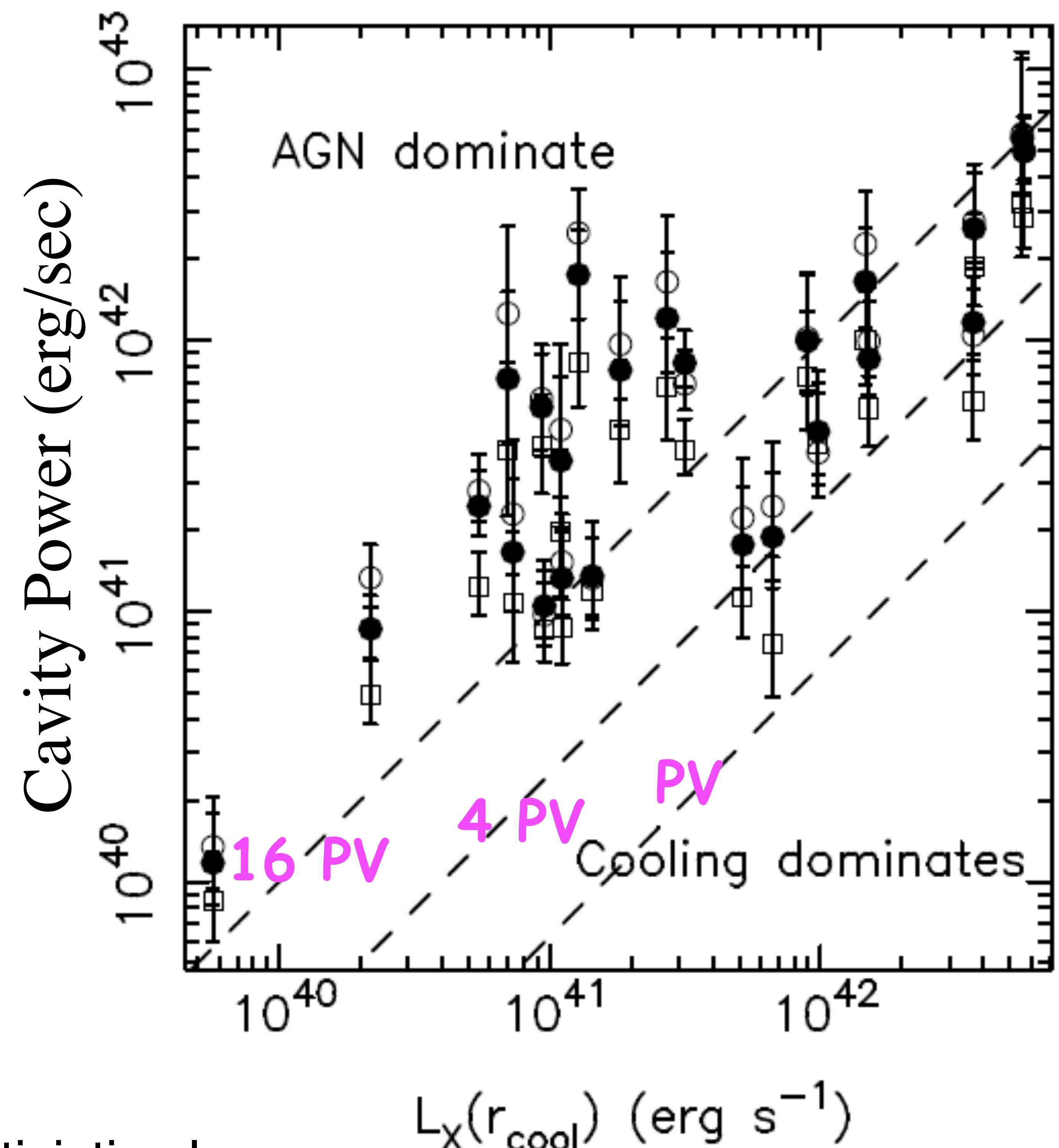
PV work balances cooling for galaxies with cavities

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).

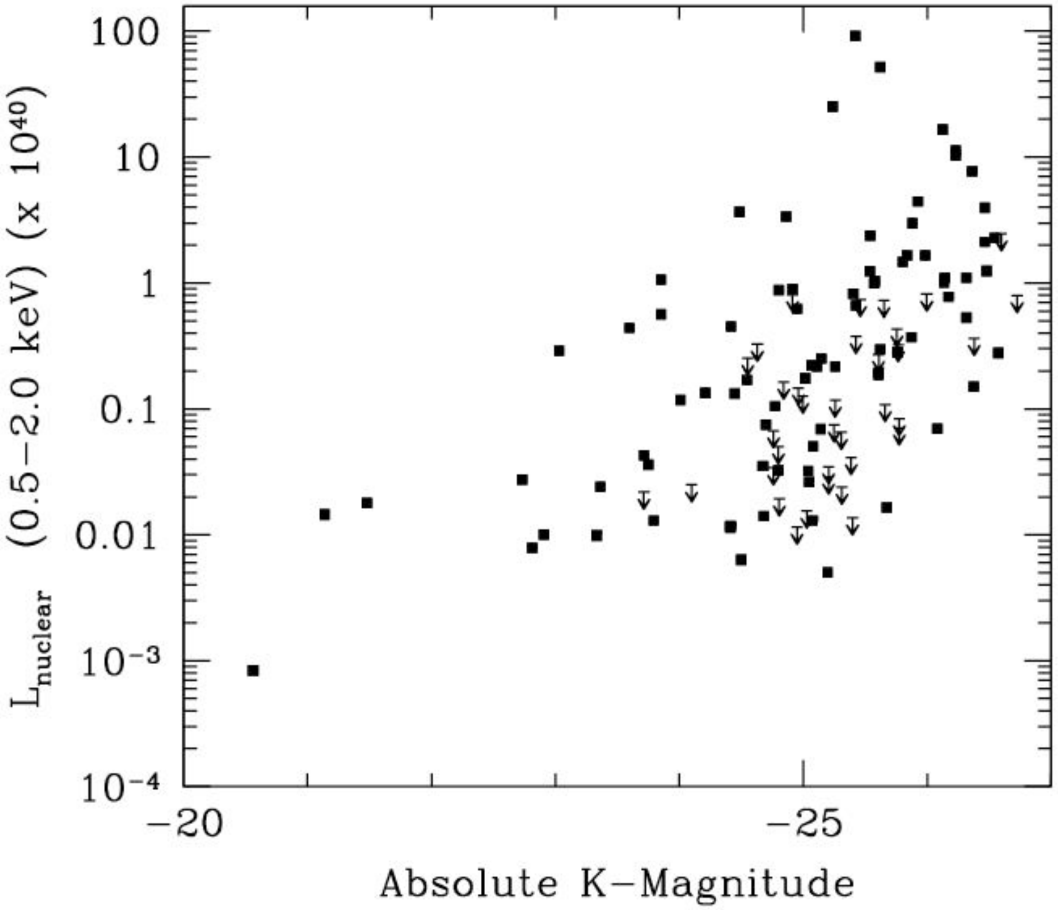
Nulsen+09

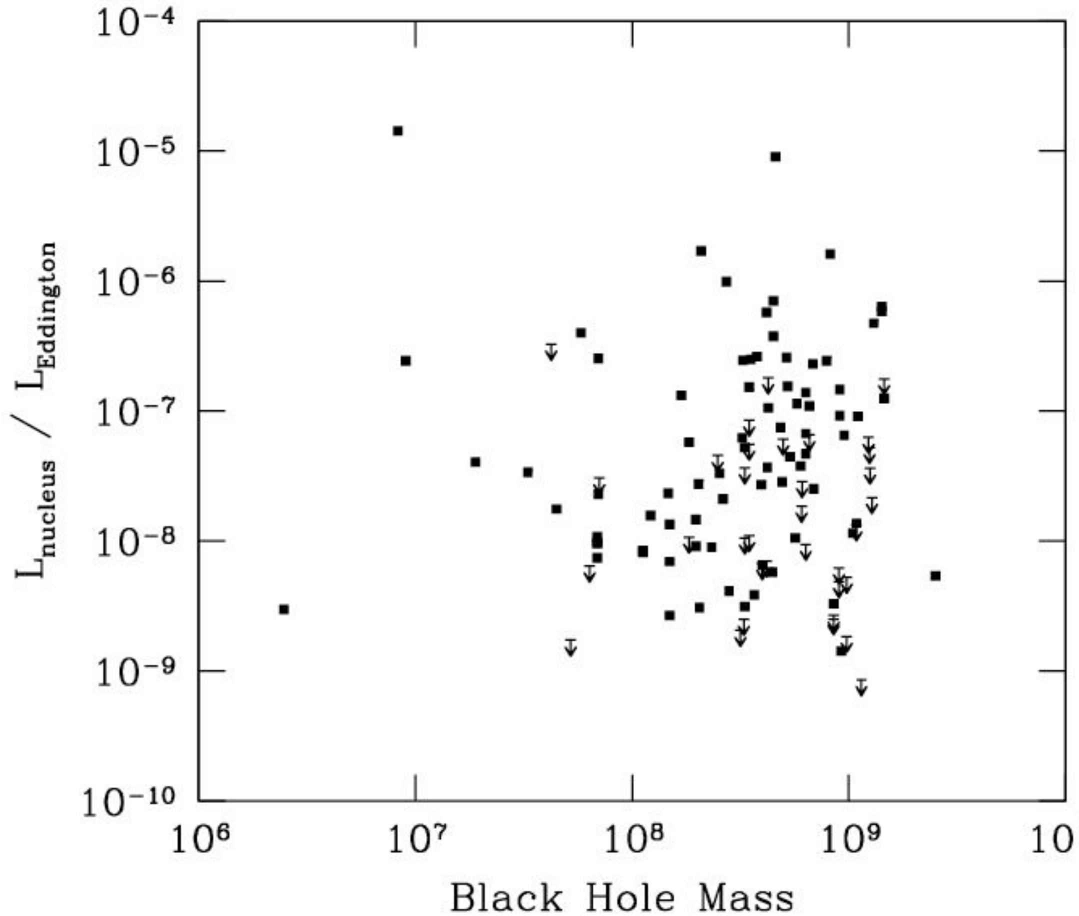
(recall Andy Fabian's figure for clusters)



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

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





Low luminosities : 70% have X-ray detected 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})

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 emitting gas = fielders

capture AGN output

Fielders are critical

No fielders (no gas)

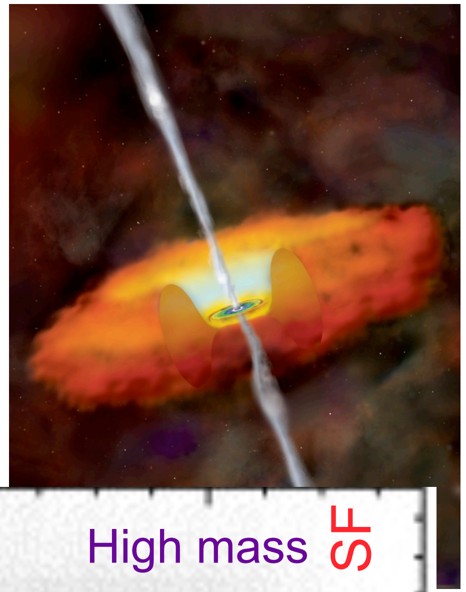
==> No energy capture

No feedback

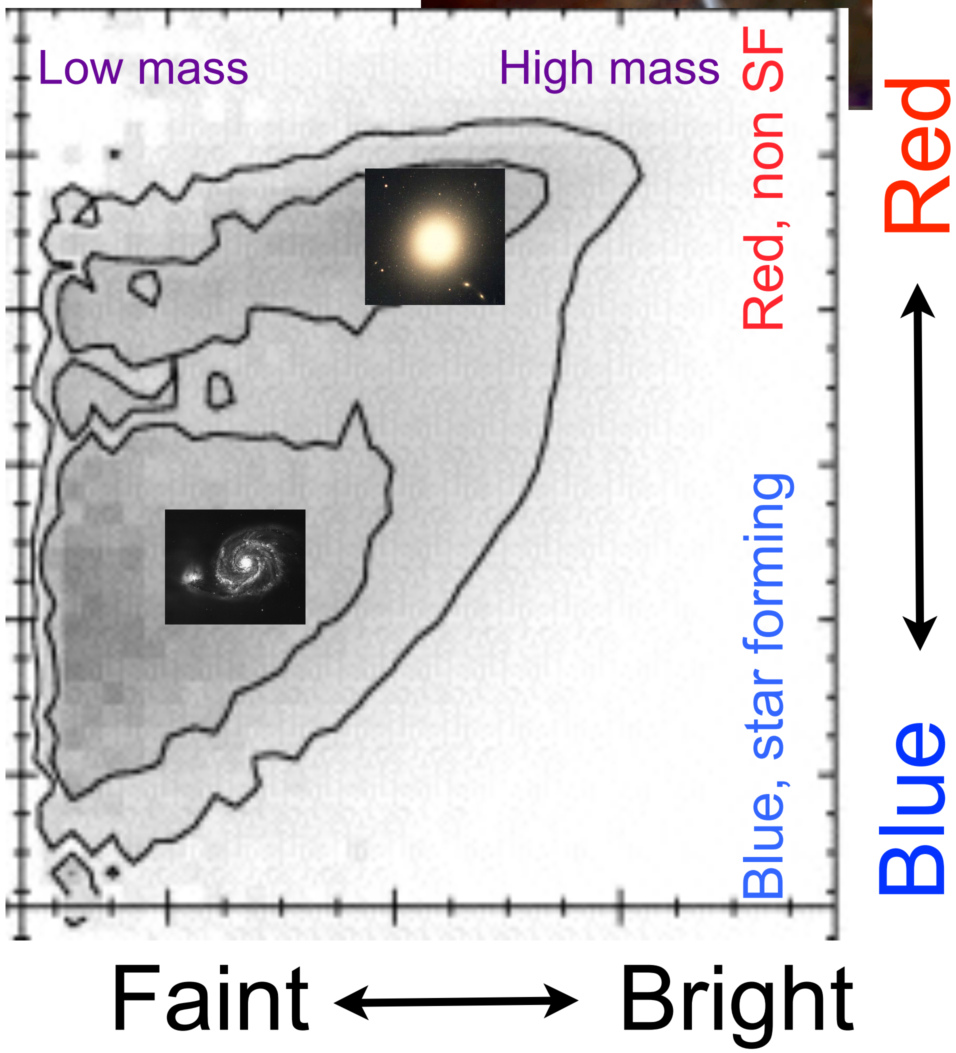
Unifies SMBH, AGN activity,
Galaxy properties (red/blue)
X-ray cooling flows

Gas Provides archive of AGN activity

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

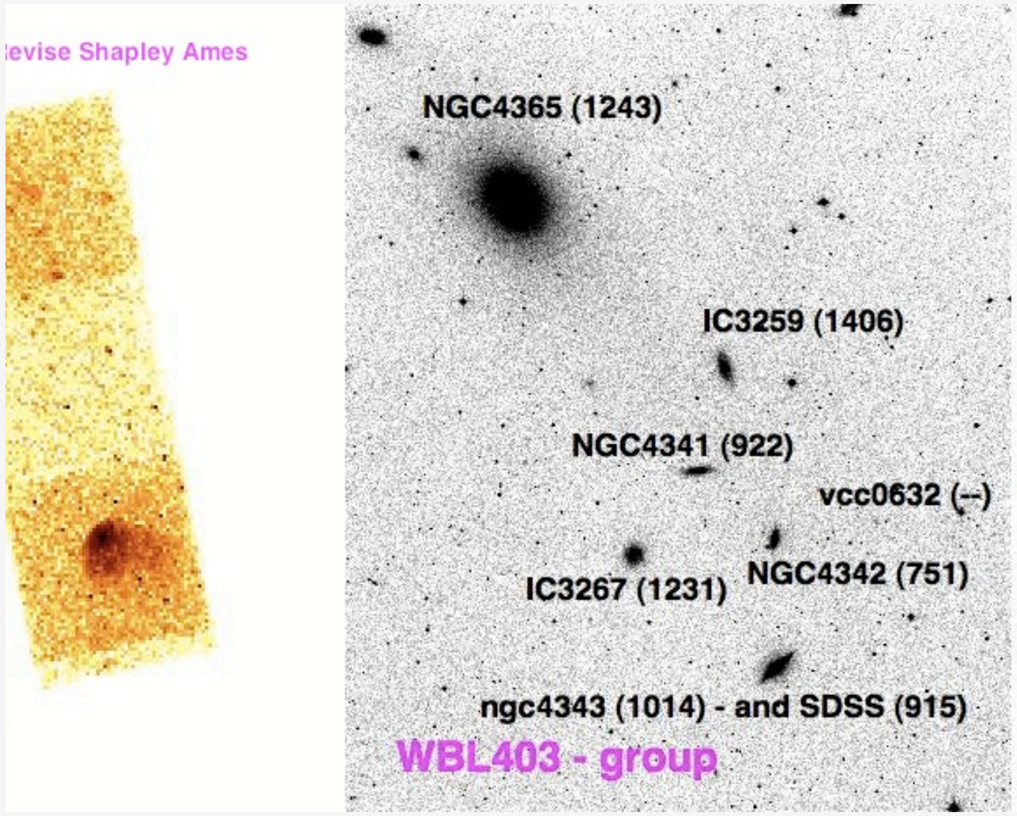


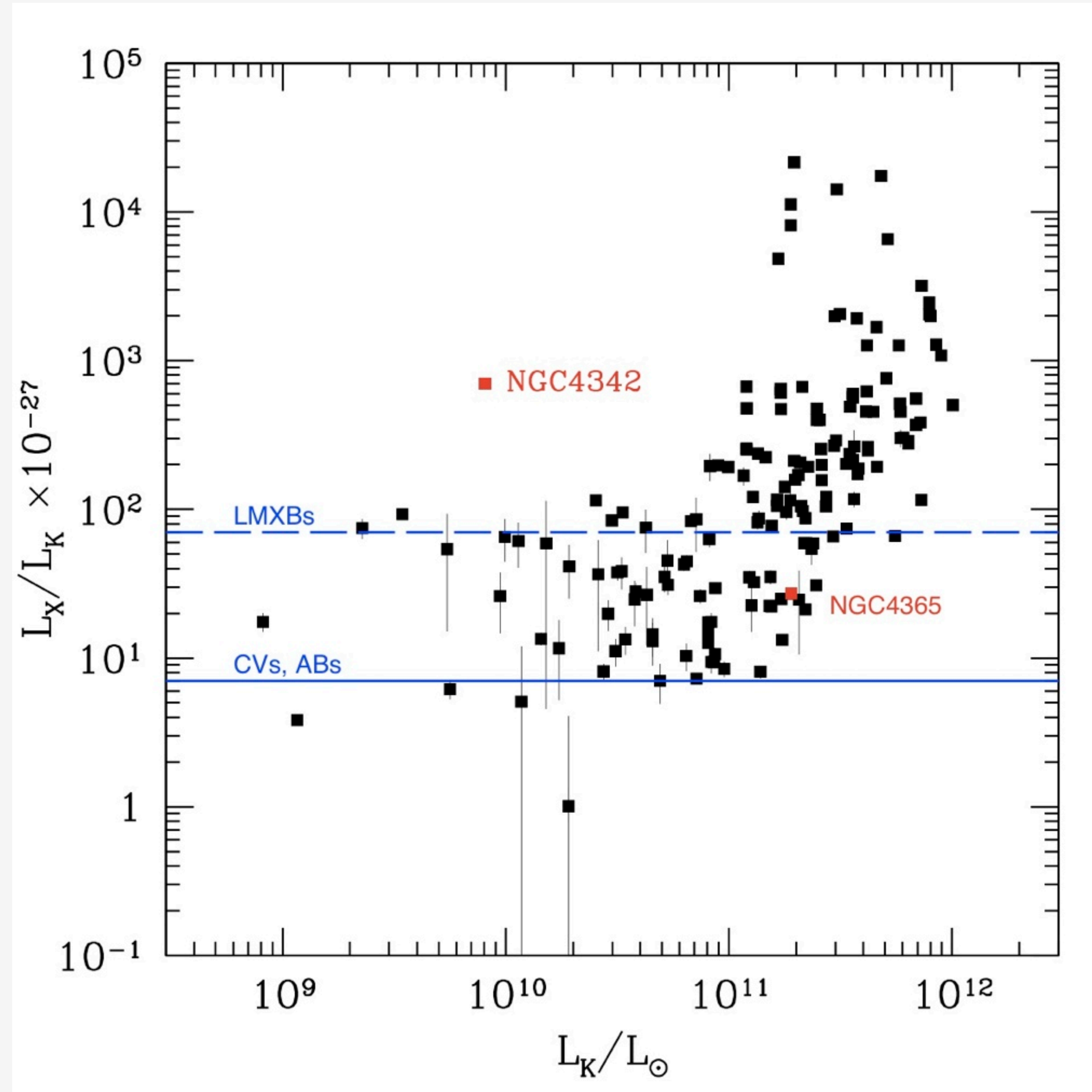
- Feedback
  - Supermassive Black Hole in galaxy nuclei
  - accretes matter
  - Black hole grows
  - Some energy returned (via jets) to control formation of new stars
  - red sequence/blue cloud (elliptical vs. spiral; old red, "dead" galaxies vs. blue/young ; hot gas rich vs. hot gas poor)
  - explains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



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

Optically faint, gas rich galaxies - NGC4342



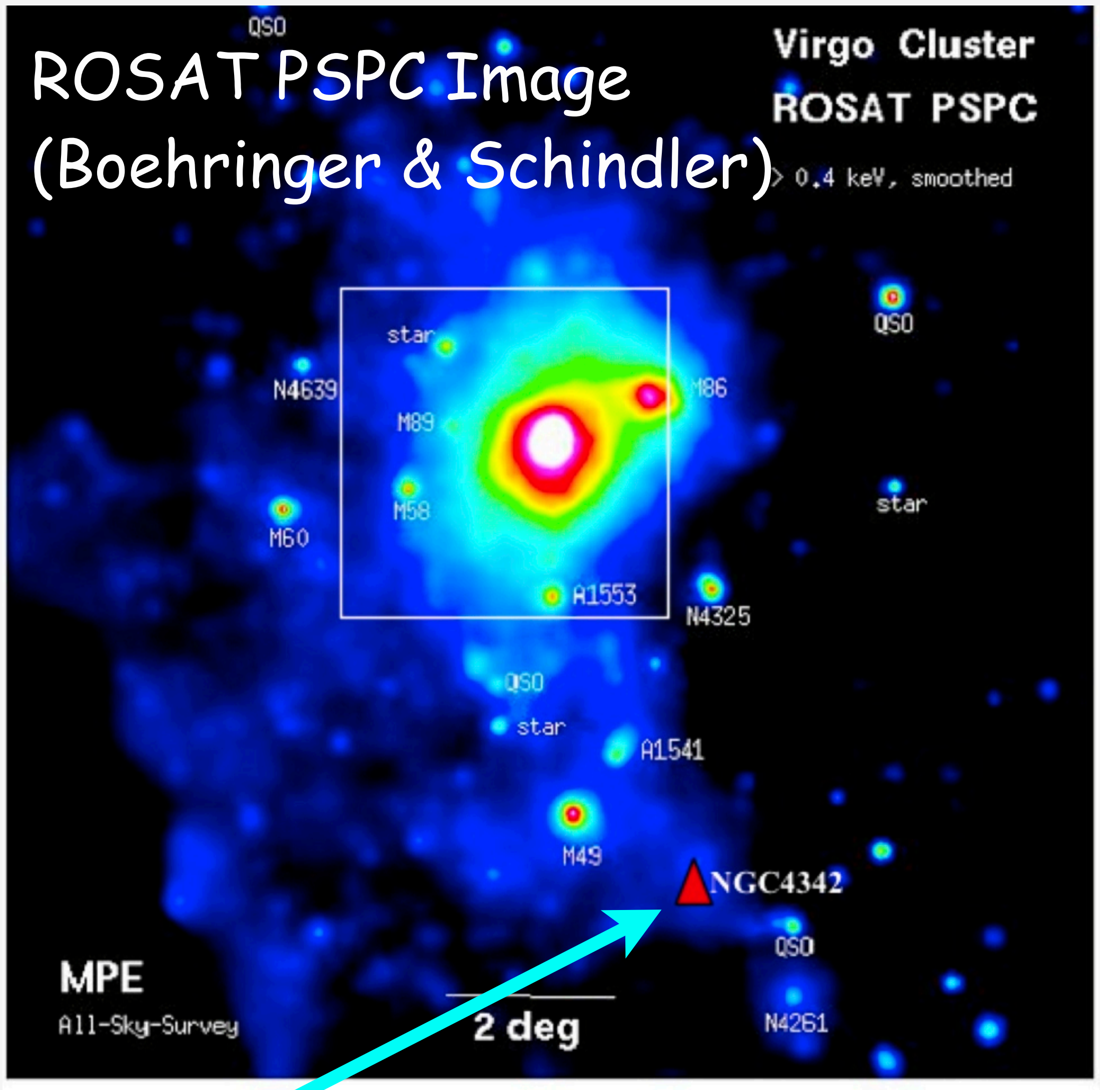


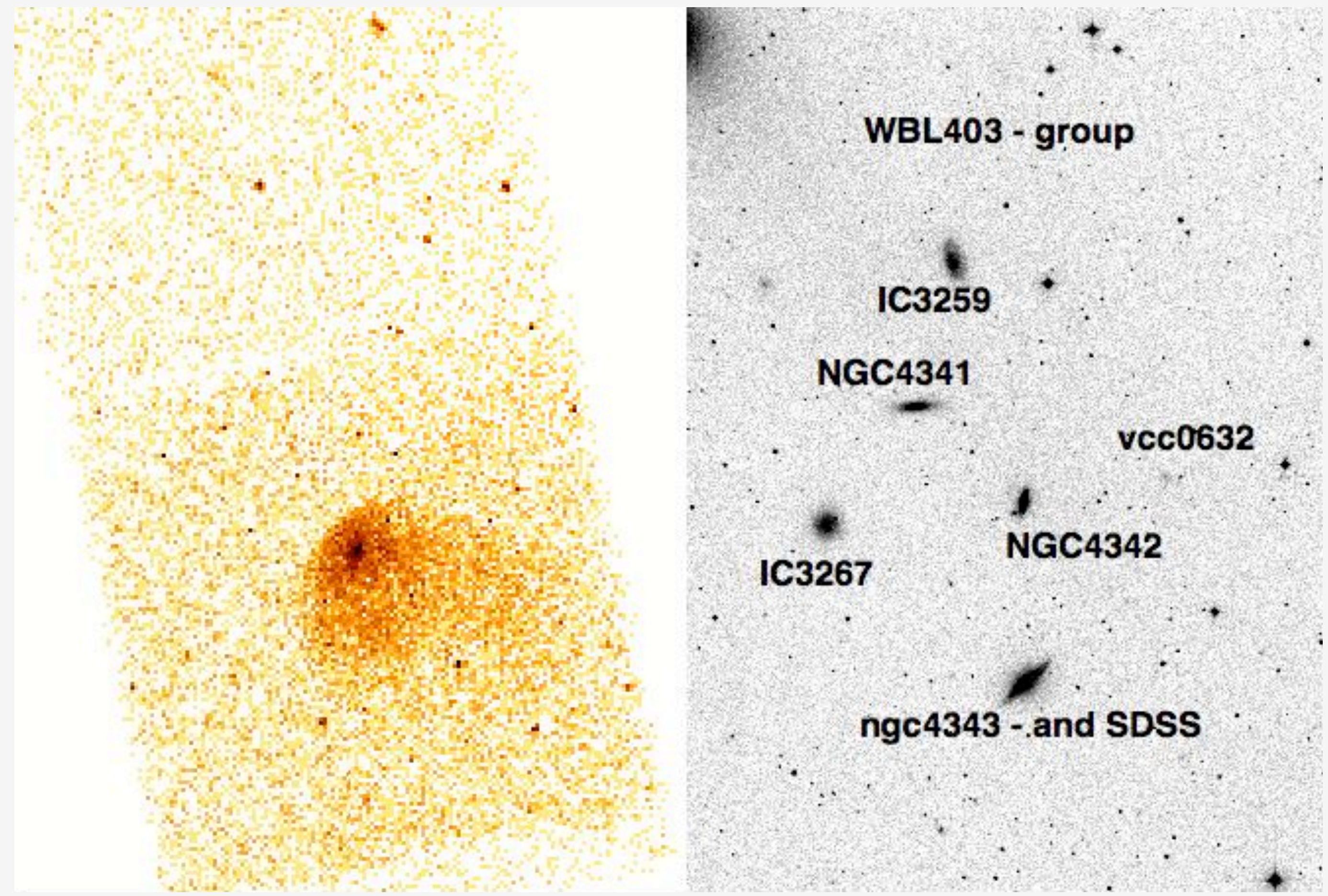
- S0/E7 galaxy
- 5.25 deg from M87
  - 1.46 Mpc in projection
  - r_{200} = 1.3 Mpc
- cz=751 km/s

A. Bogdan (2011, in preparation)

- Thermal emission
  - kT=0.58±0.02 keV
  - $M_{gas} \sim 10^7$ M_{sun}
- Mach ~ 1.5 (from X-ray analysis)

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

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)

Hot Gas and Galaxies in Virgo, Fornax, Coma

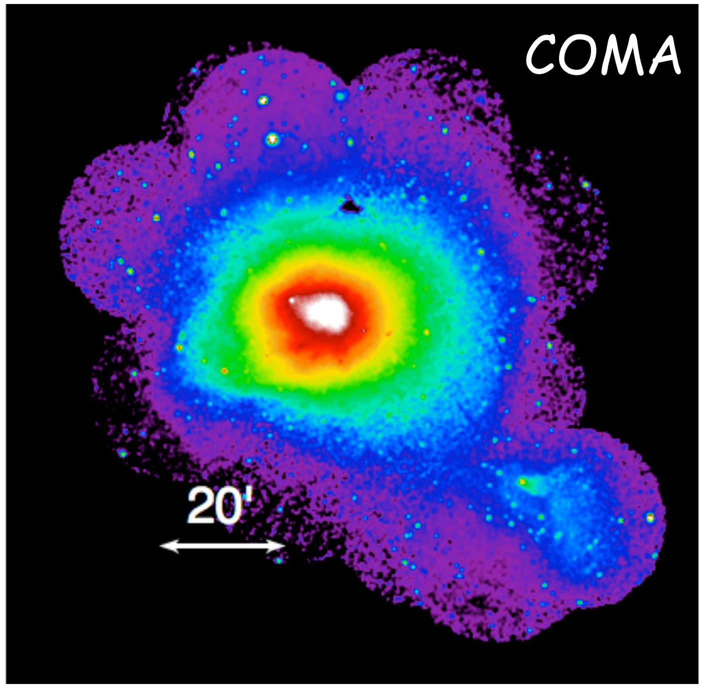
- Coma & Fornax - extensive merging with shocks and cold fronts
- Coma - mini-coronae; also seen in other hot clusters
- Hot atmospheres are key to capturing AGN mechanical energy

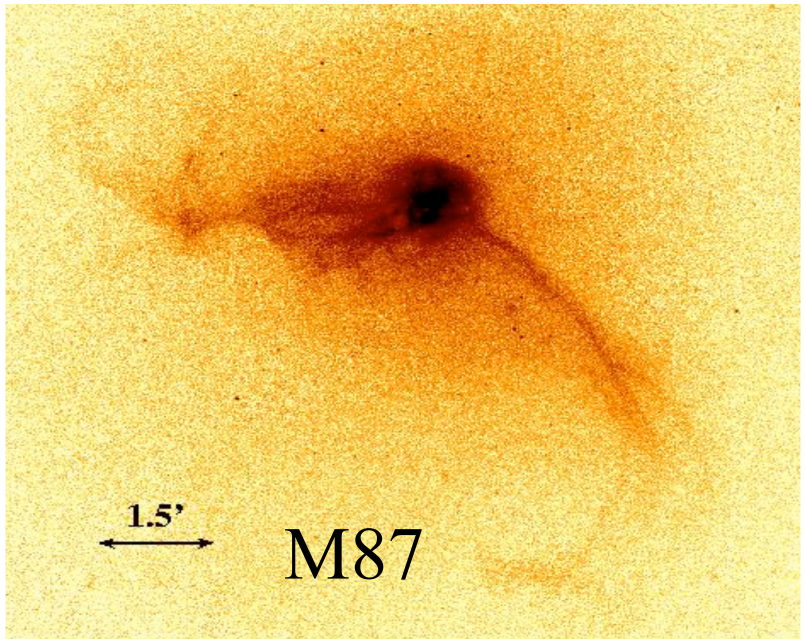
  Feedback on gas - prevents cooling in luminous early type galaxies

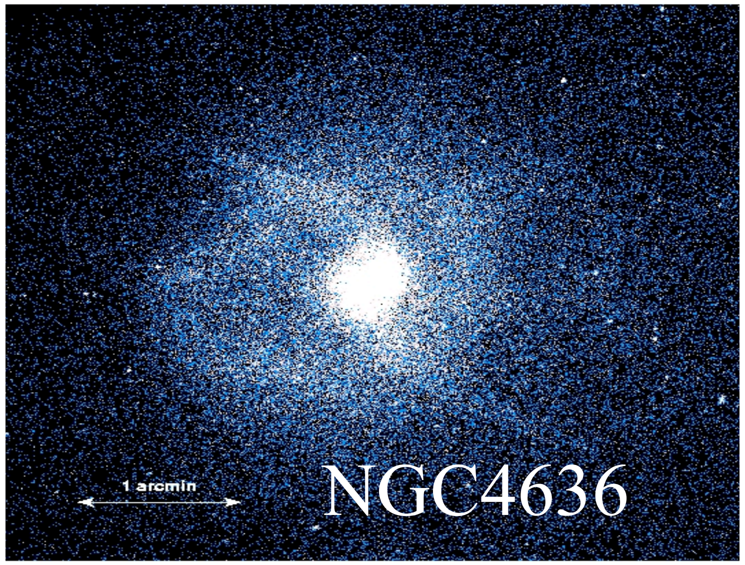
  - M87 - classical shock with buoyant radio lobes, X-ray filaments
    - energy output matches radiated luminosity
  - Galaxy AGN outbursts are common - 30% of early type galaxies show cavities;

    $\tau \sim 10^6$ - 10^8 yrs, $E \sim 10^{55}$-10^{58} erg - sufficient to balance cooling

X-ray/radio mini-AGN are common ~70% (10^{38}-10^{42} ergs s^{-1})







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