Supermassive Black Holes (SMBH) at Work: Effects of SMBH Outbursts
Driving Galaxy Evolution

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- **Family of dark matter halos + hot gas**
  - Galaxies, groups, clusters
- **M87**
  - Outburst up close
  - Classic shock
  - Buoyant bubbles
  - Energy partition and outburst duration
- **Early type galaxies with SMBH**
  - Feedback present in X-ray/optically luminous galaxies
  - Hot X-ray coronae - mechanism to capture SMBH energy
  - Driver of galaxy evolution

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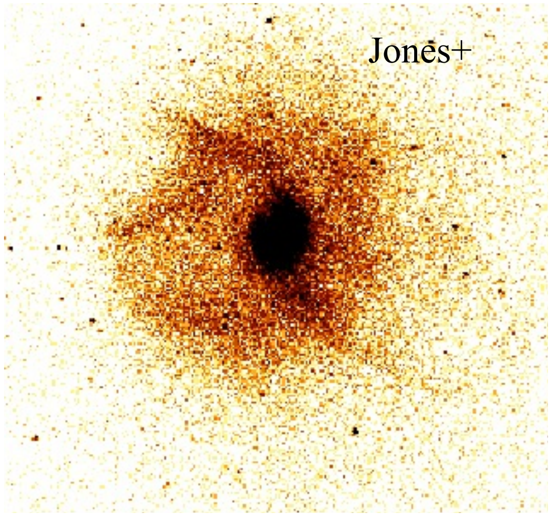
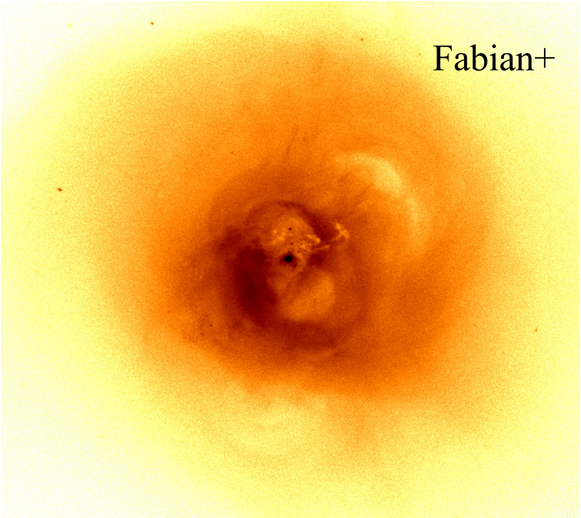
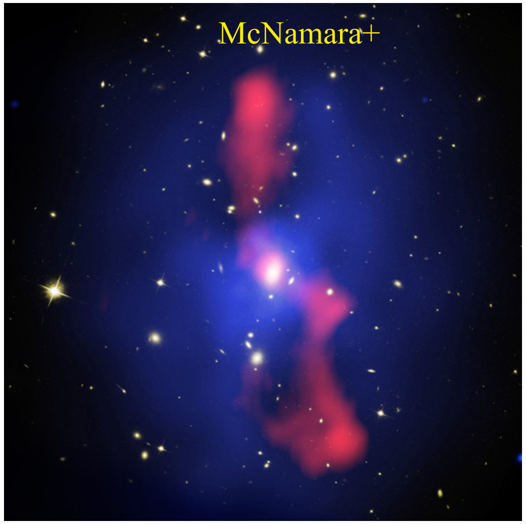
Supermassive Black Hole Outbursts in the Family of Early Type Galaxy Atmospheres





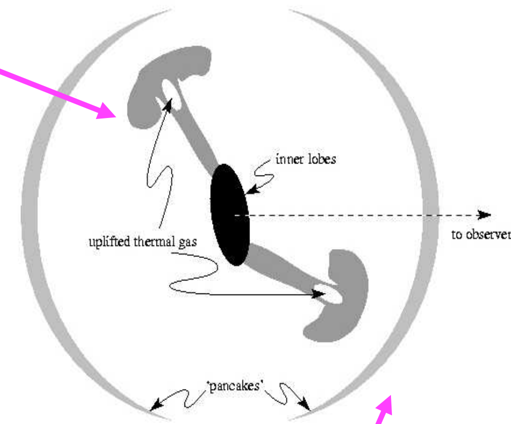


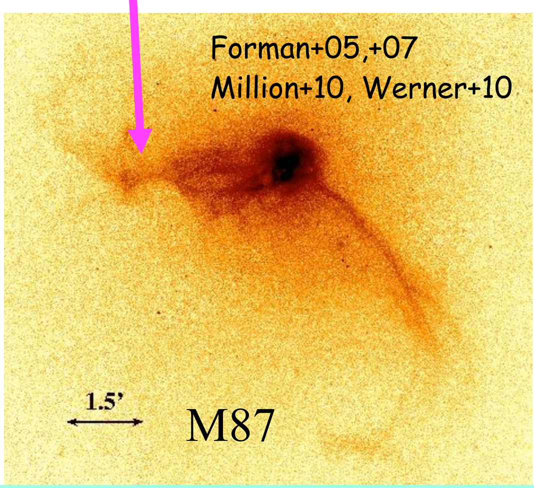
Galaxy	Group/Cluster Core	Cluster (MS0735)
1 kpc	10 kpc	100 kpc
10^{56} ergs	10^{59} ergs	10^{62} ergs
10^{42} erg/s	10^{45} erg/s	10^{46} erg/s

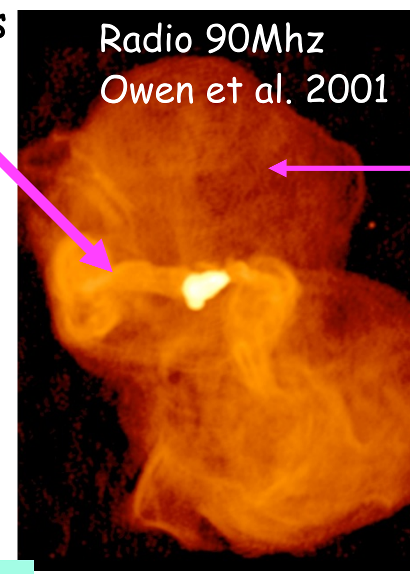
Very powerful outflows
Very little radiation from black hole
Predicted mass deposition rates vary by > 100x

X-ray and Radio View of M87

- Multiple - at least three - SMBH outbursts
- Two X-ray "arms" - produced/uplifted by buoyant radio bubbles
- Eastern arm - **classic buoyant bubble** with torus i.e., "smoke ring" (Churazov et al 2001)
  - XMM-Newton shows cool arms of uplifted gas (Belsole et al 2001; Molendi 2002)
  - Evidence for many small bubbles/filaments



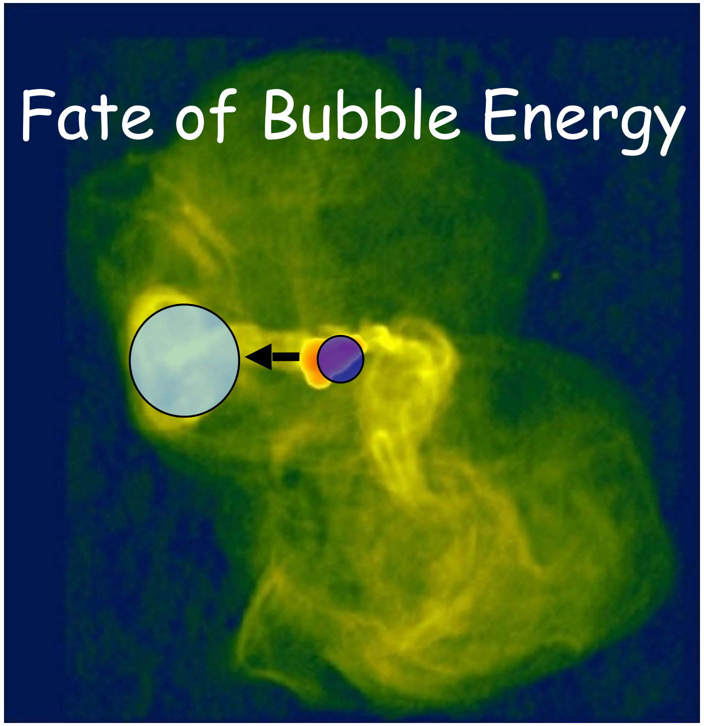




Fine, unperturbed X-ray filament
Radio plasma is "blowing in the wind

Old bubbles with no apparent spectral aging
- powered by AGN?
- Driven by turbulence?

Fate of Bubble Energy



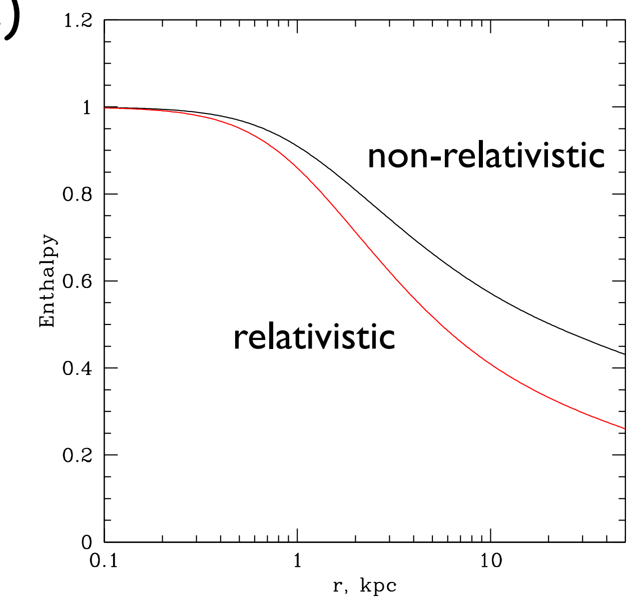
Rising bubble loses energy to surrounding gas

$$f = (p_1/p_0)^{(\gamma-1)/\gamma}$$

Generates gas motions in wake

Kinetic energy (eventually) converted to thermal energy (via turbulence)

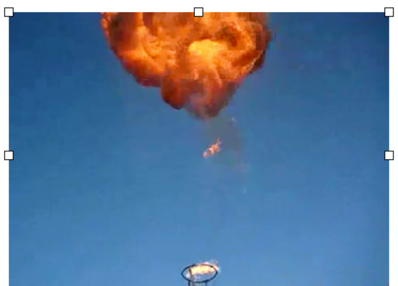
Bubble energy remaining vs. radius



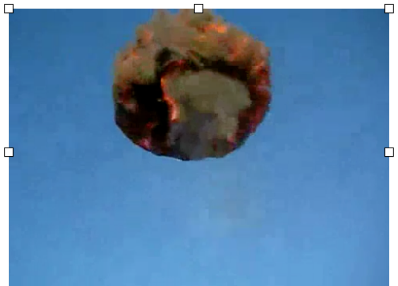
$$\Delta E_{gas} = -\Delta E_{Bubble} = -\Delta \frac{\gamma}{\gamma - 1} PV = E_0 \left[1 - \left(\frac{P}{P_0} \right)^{1-1/\gamma} \right]$$

Buoyant Bubble "Simulation" (from you tube)

t_0



t_1



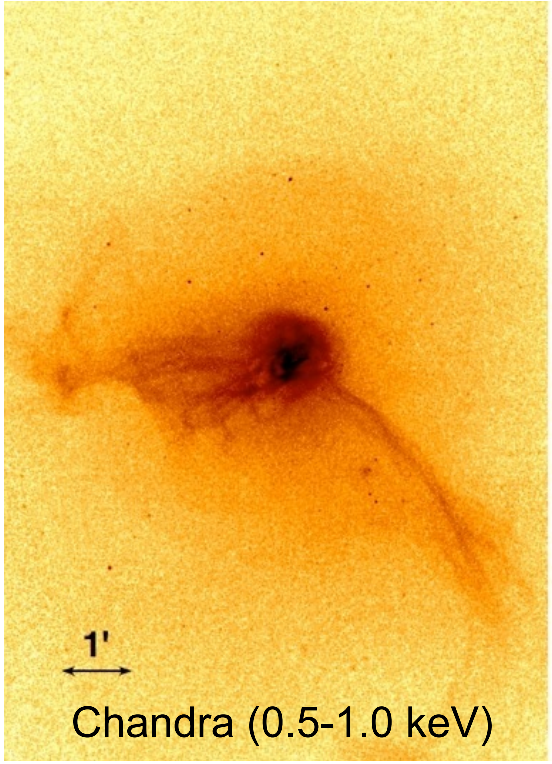
t_2

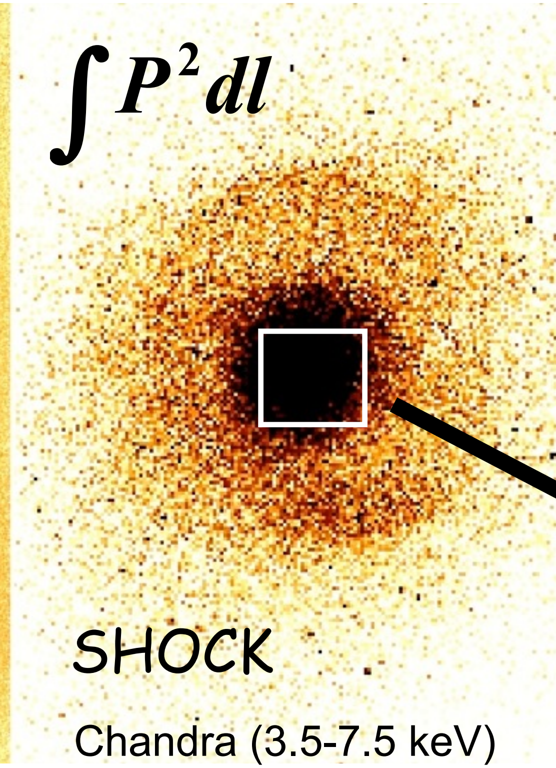
t_3

t_4

Rising bubble ----> torus

Classical Shock in M87

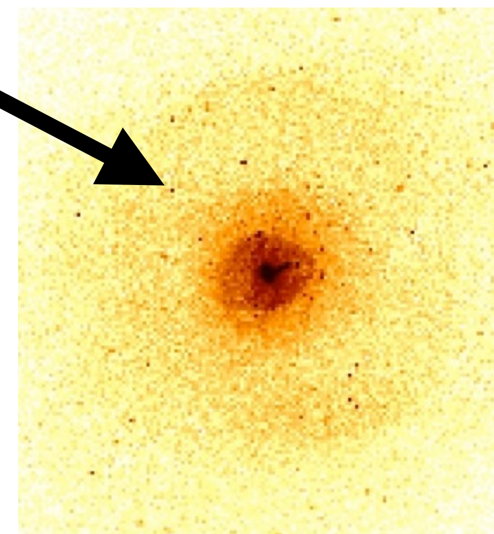




23 kpc (75 lyr)

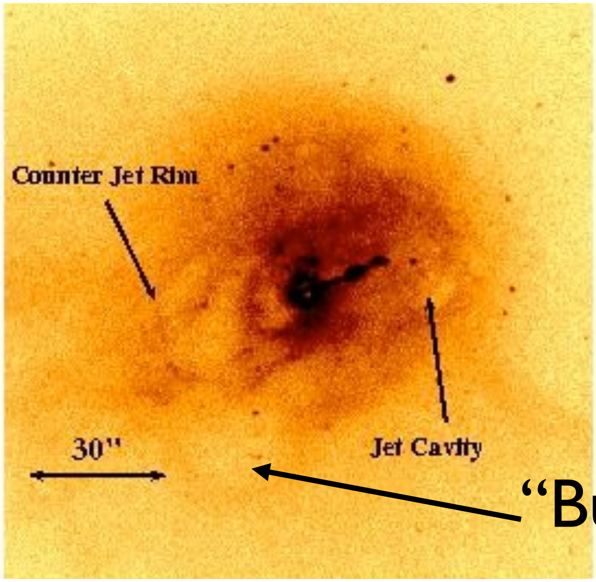
Xarithmetic (Churazov et al. 2015)- choosing proper band

Piston drives shocks

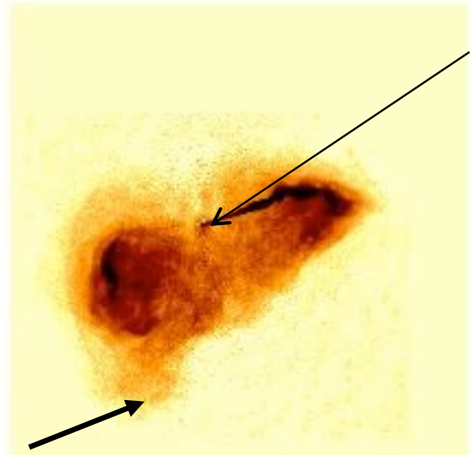


- Black hole = 6.6×10^9 solar masses (Gebhardt+11)
- SMBH drives jets and shocks
- Inflates “bubbles” of relativistic plasma
- Many small bubbles
- Heat surrounding gas
- **Model to derive detailed shock properties**

Central Region of M87 - the driving force



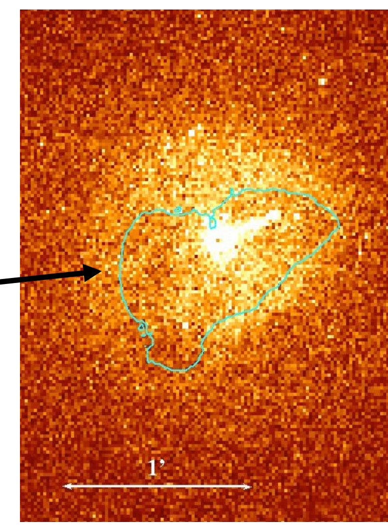
"Bud"



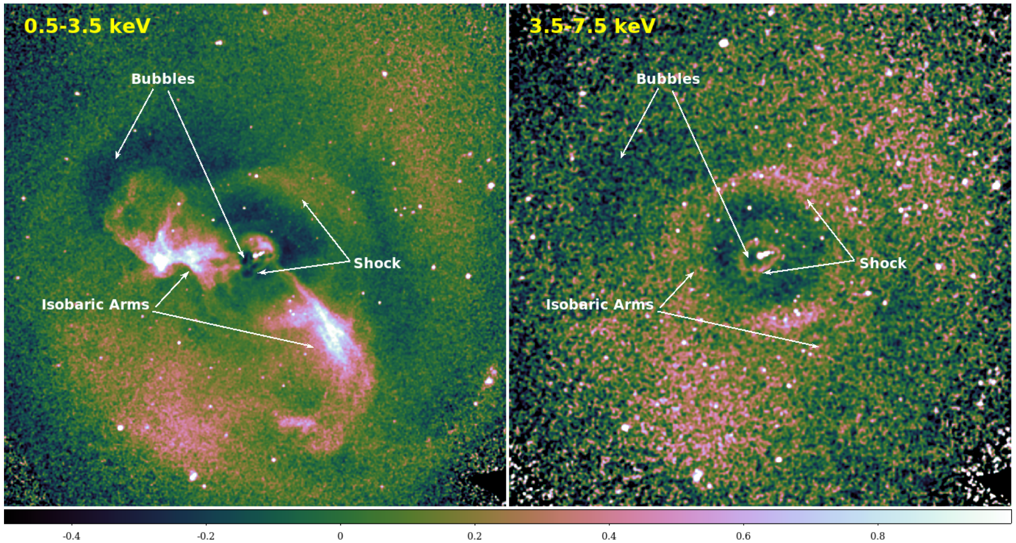
SMBH $3 \times 10^9 M_{sun}$

6cm radio

- Cavities surround the jet and (unseen) counterjet
- Bubble breaking from counter jet cavity
  - Perpendicular to jet axis;
  - Radius ~1kpc.
  - Formation time ~4 $\times 10^6$ years
- Piston driving shock
  - X-ray rim is low entropy gas uplifted/displaced by relativistic plasma



X-arithmetic - Churazov et al. 2015



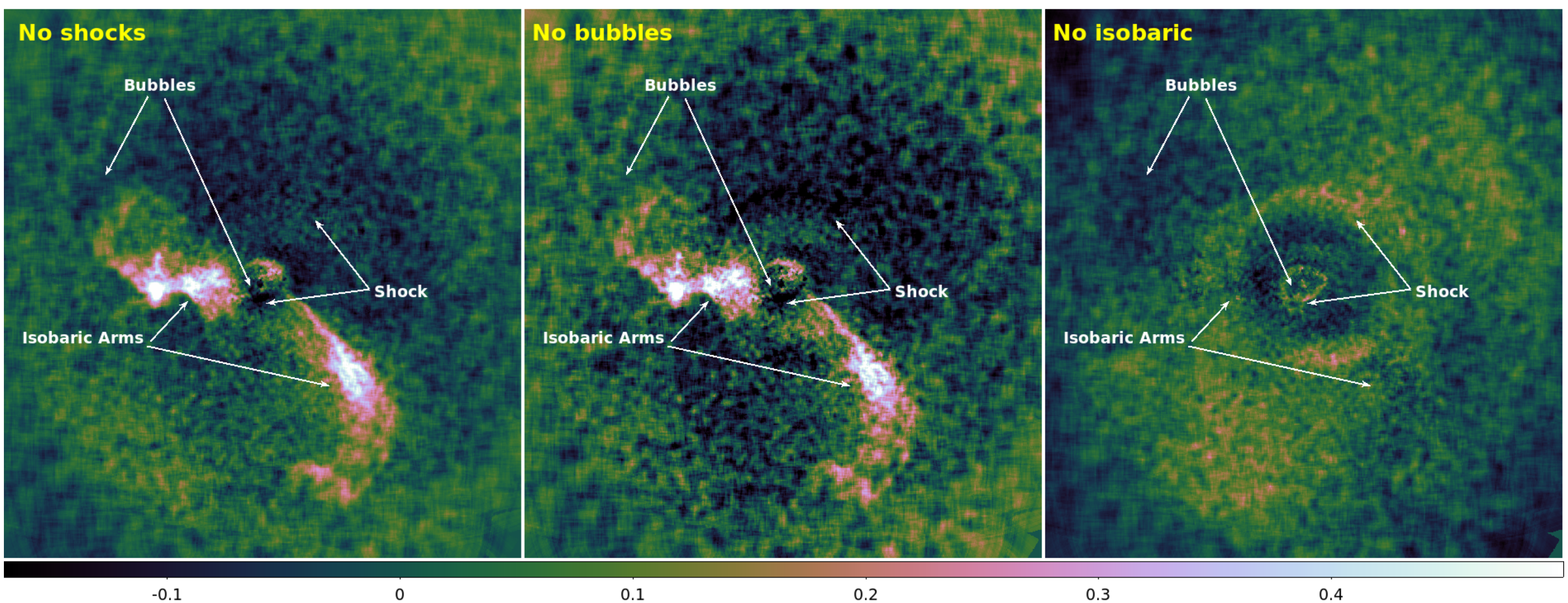
Isolate processes by manipulating energy bands:

$$\left(\frac{\delta T}{T}\right) \approx \left(\frac{\delta n}{n}\right)^{\gamma-1}$$

Churazov+2015

Arevalo+2015

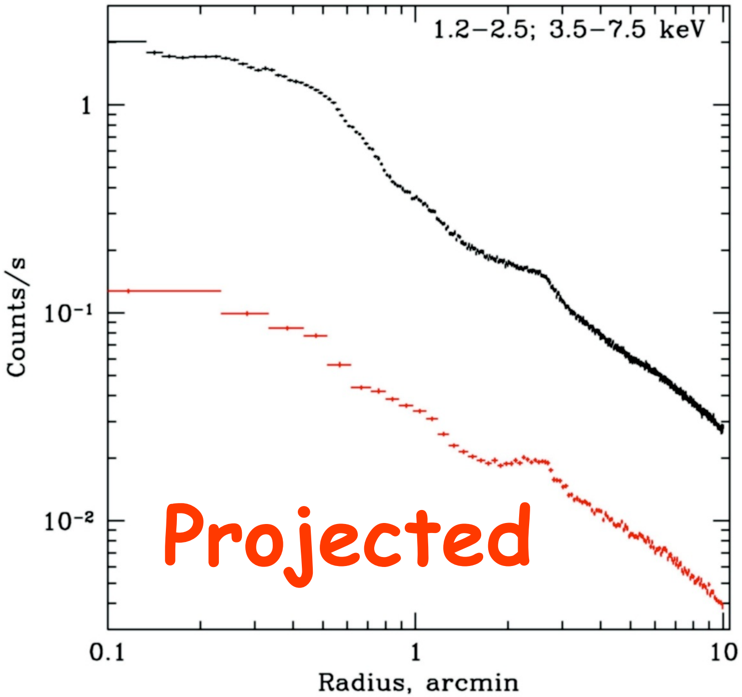
$$\gamma = 0(isobaric); 5/3(adiabatic); 1(isothermal)$$

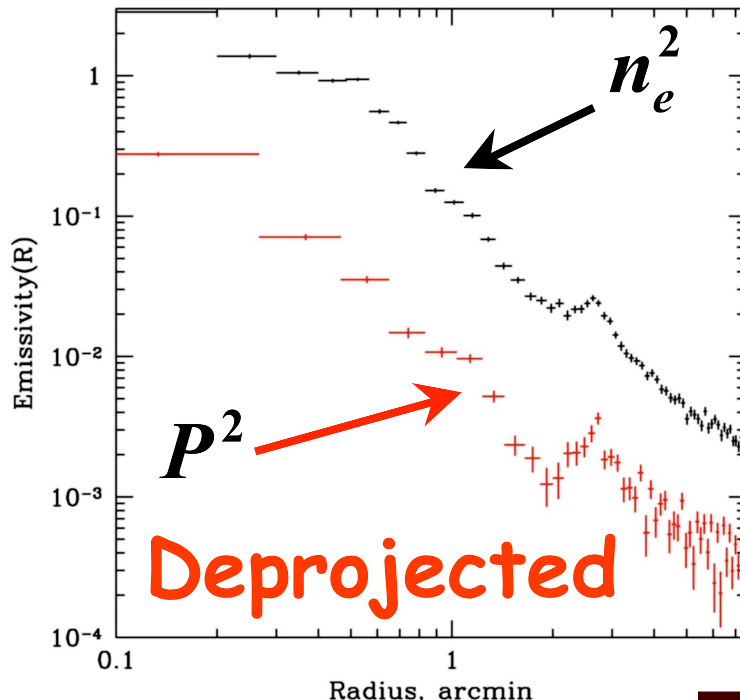


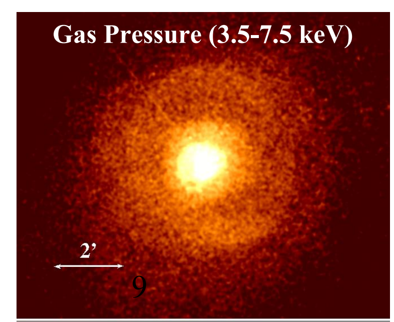
Shock Model - the data

Hard (3.5-7.5 keV) pressure

soft (1.2-2.5 keV) density profiles







Textbook Example of Shocks

Consistent density and temperature jumps

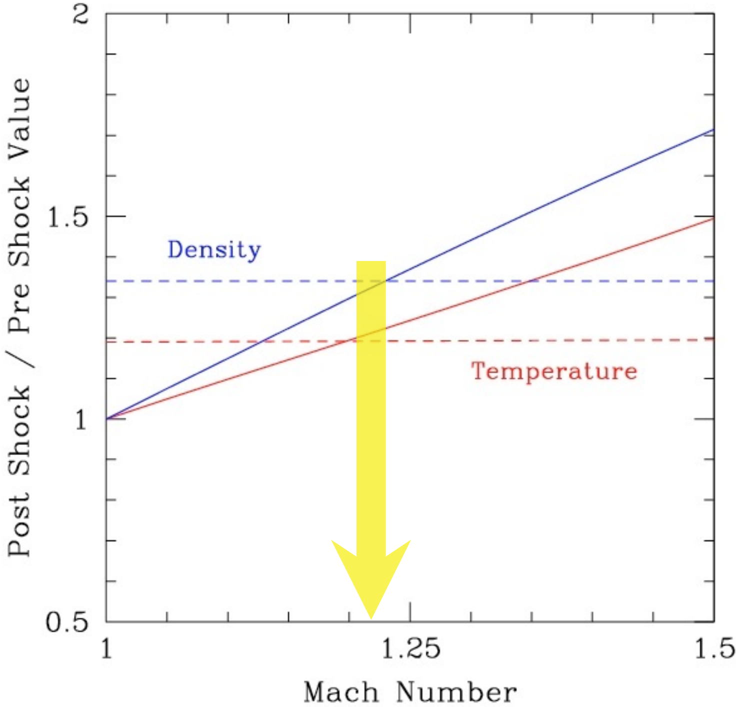
Rankine-Hugoniot Shock Jump Conditions

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

$$\rho_2/\rho_1 = 1.34$$

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

$$T_2/T_1 = 1.18$$

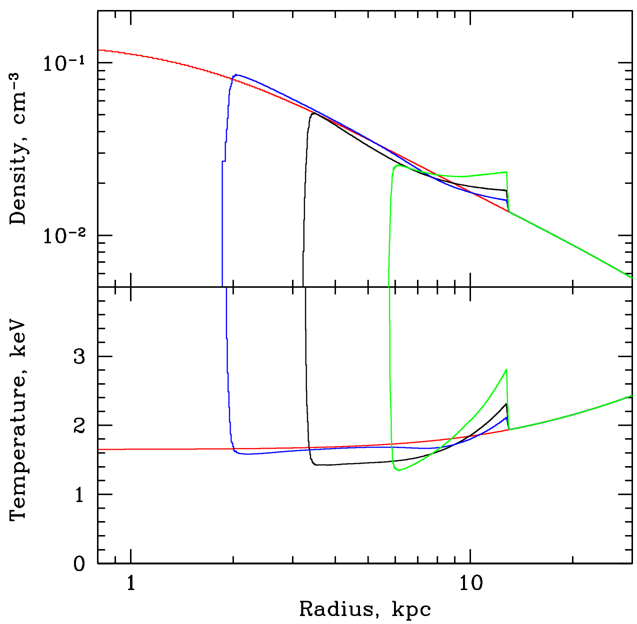


yield same Mach number:

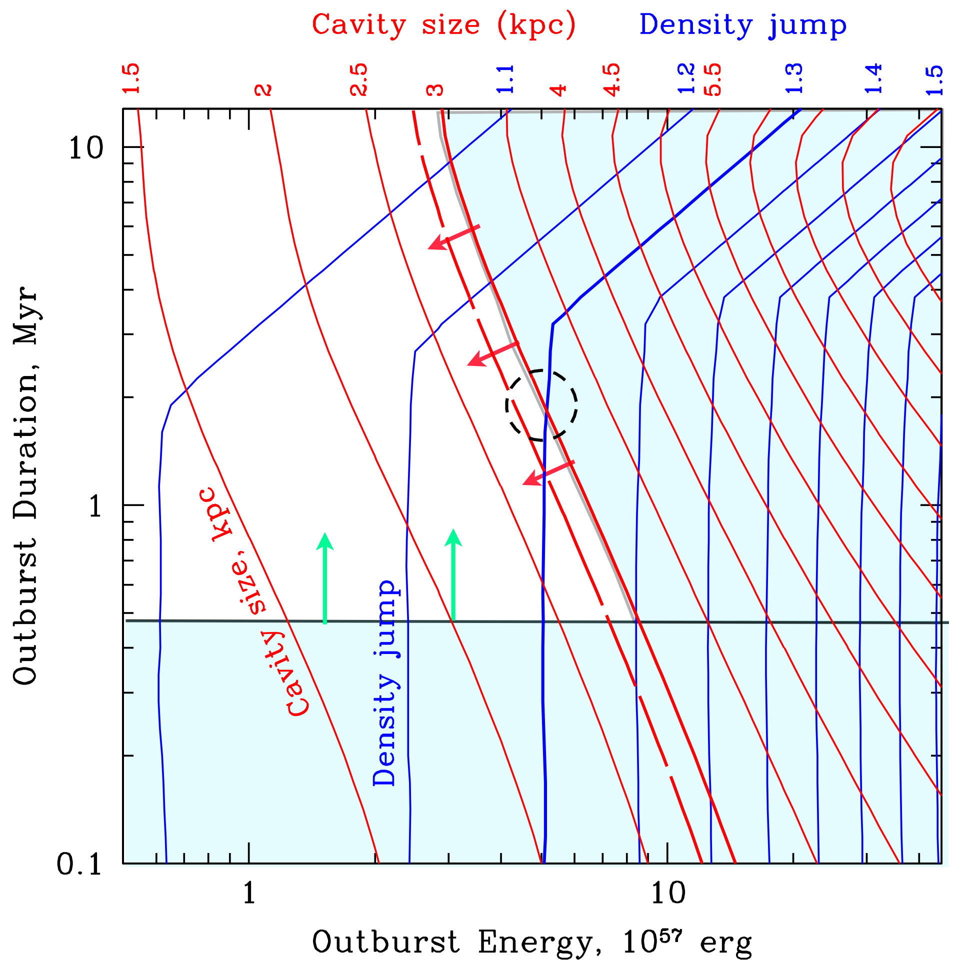
($M_{T=}1.24$ $M_\rho=1.18$)

M=1.2

Outburst Model

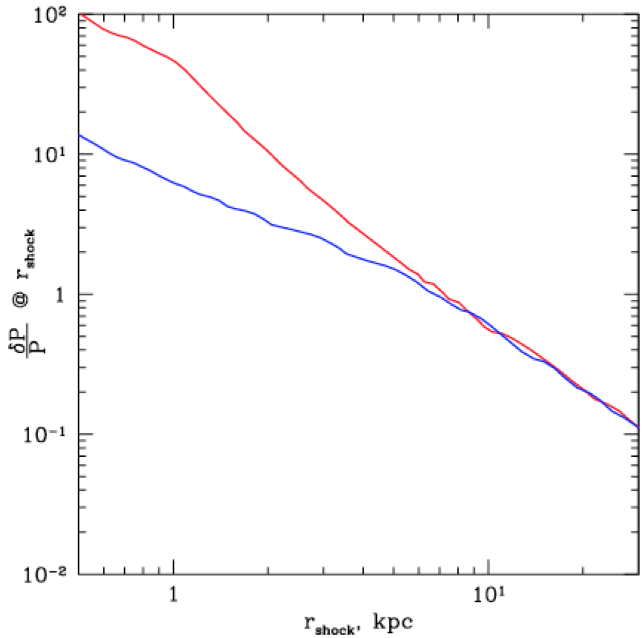


Series of outbursts of varying outburst energy (1.4, 5.5, 22×10^{57} ergs) with identical duration (2.2 yr) - energy determines shock amplitude



Energy vs. duration with cavity size and density jump constraints: duration ~ 2 Myr

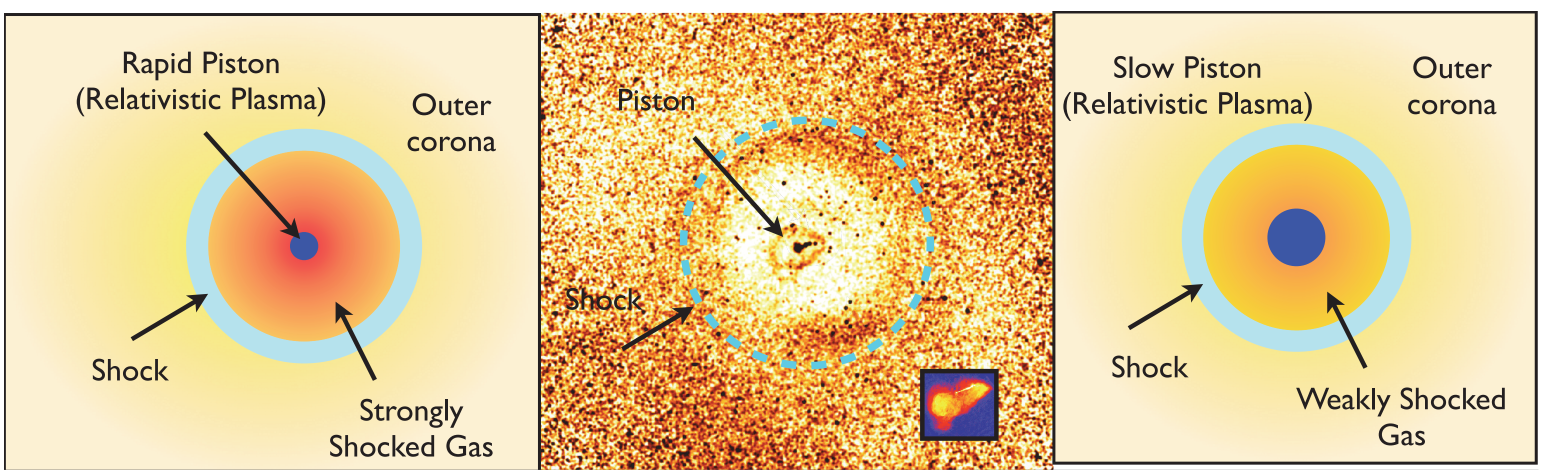
Long vs. Short Duration Outbursts



0.6 vs 2.2 Myr duration outbursts with $E_{outburst}$ = 5.5x10^{57} ergs

Short outburst - leaves hot, shocked envelope outside the piston

NOT observed ==> longer duration outburst required



M87 Outburst Energy Parameters

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)

Current shock radius

Outburst Model

Age ~ 12 Myr

Energy ~ 5×10^{57} erg

Bubble 50%

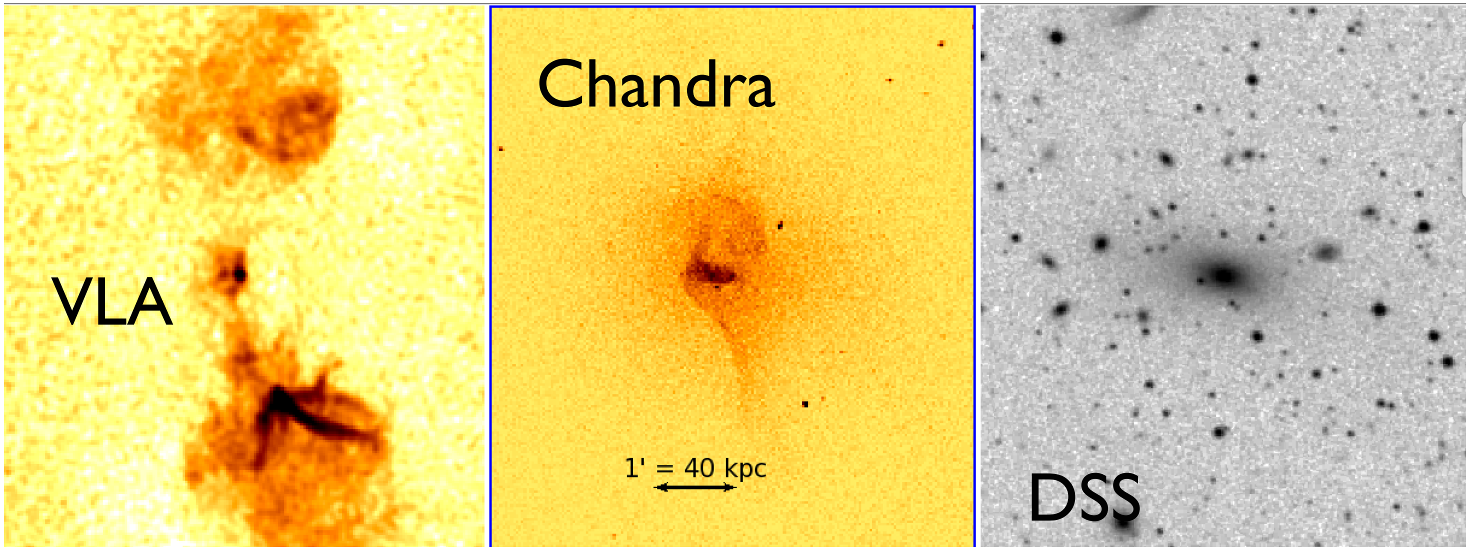
Shocked gas 25% (25% carried away by weak wave)

Outburst duration ~ 2 Myr

Outburst is not violent (not Sedov-like)

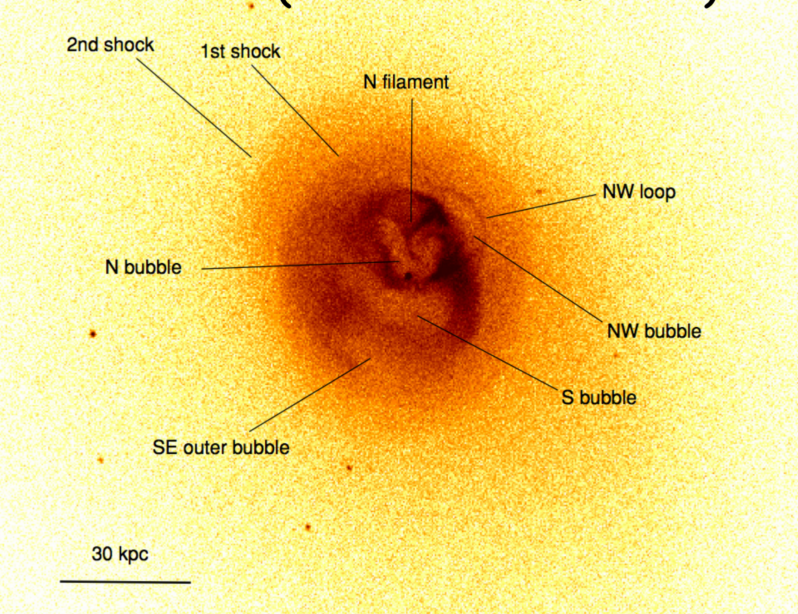
Outburst energy "balances" cooling (few 10^{43} erg/sec)

M87 is not alone - IC1262, A2052

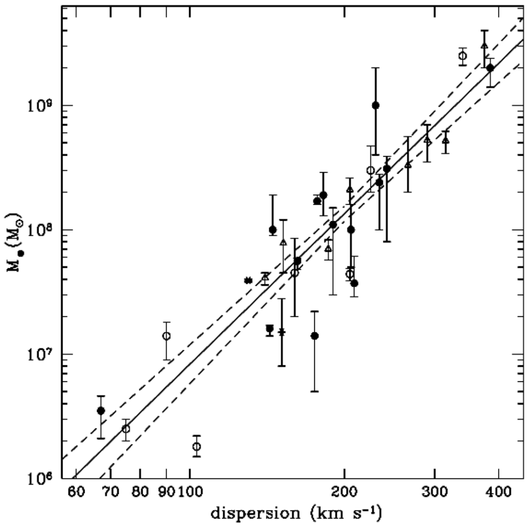


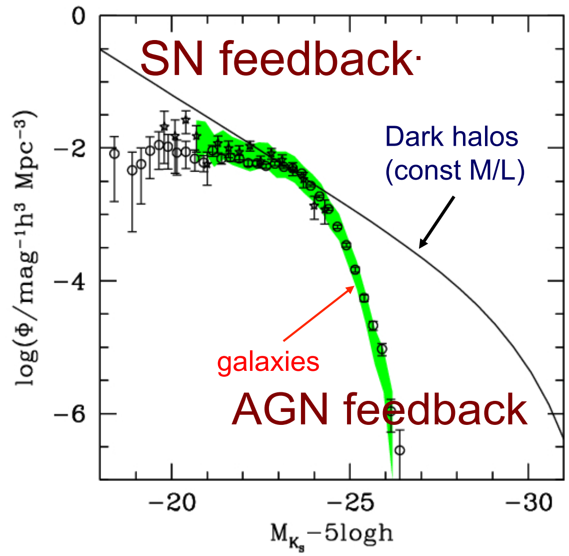
- IC1262 - slightly more luminous twin
  - Different orientation
  - Outbursts with a merger!
  - Core destroyed?

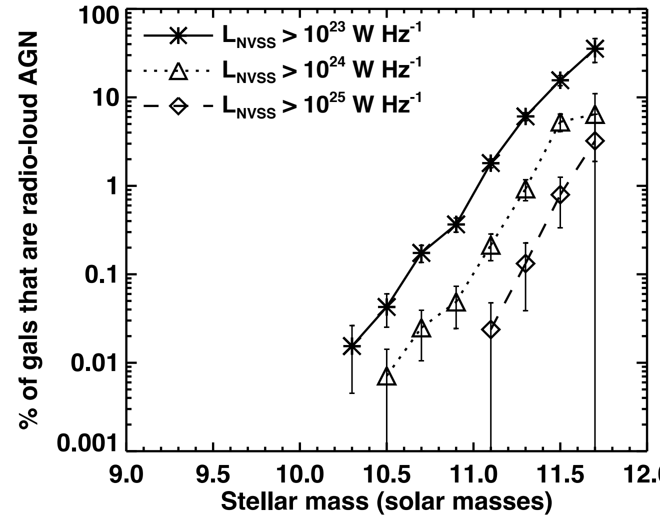
- A2052 (Blanton et al. 2011)



Feedback from Supermassive Black Holes key component in galaxy formation models



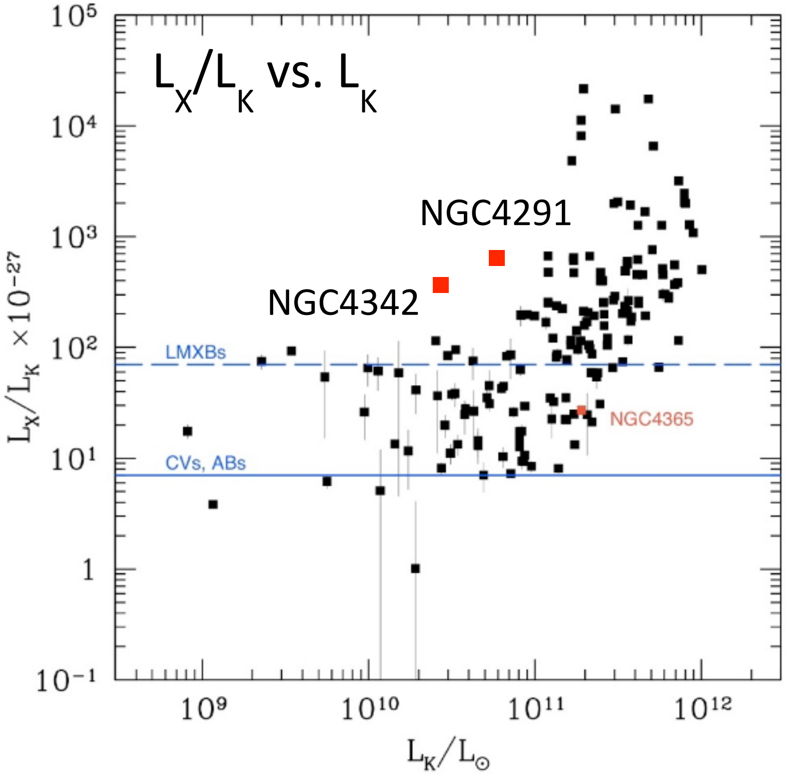


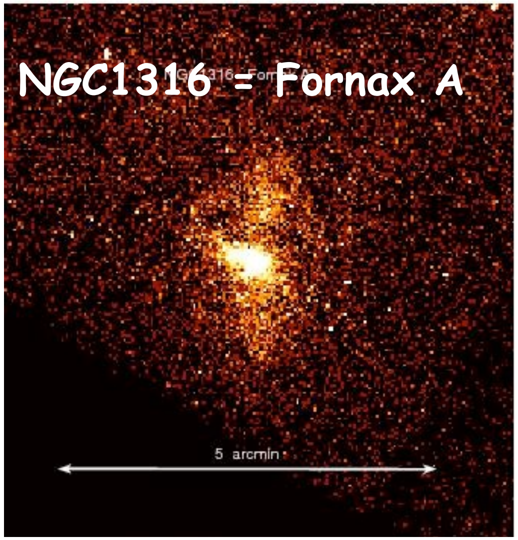


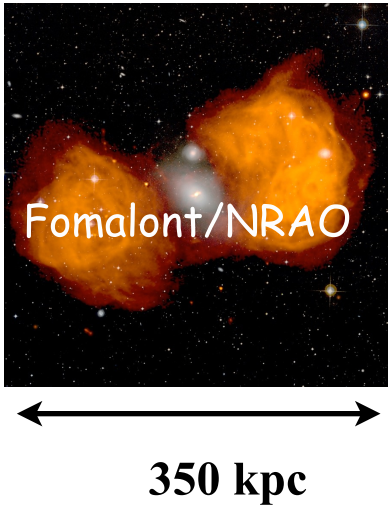
- Feedback - mass closely tied to mass of surrounding stars - $M_{SMBH} \approx 10^{-3} M_{bulge}$
- SMBH key to regulating star formation in evolutionary models at high mass end
- Radio loud AGN very common in massive galaxies

e.g. Croton+06, White & Frenk 91, Cole+92 Benson+'03 Best+06, Teyssier+11

Galaxy Sample from Jones et al. (Anderson, Churazov, Forman+)







- Cavities common > 30% in luminous systems
- SMBH detected 70% radio and 80% X-ray
- Winds at L^K < 10^{11}
- Scatter in L_X-opt partly environment/partly gas removal

•Outskirts of Fornax cluster (>1.4 Mpc from NGC1399)

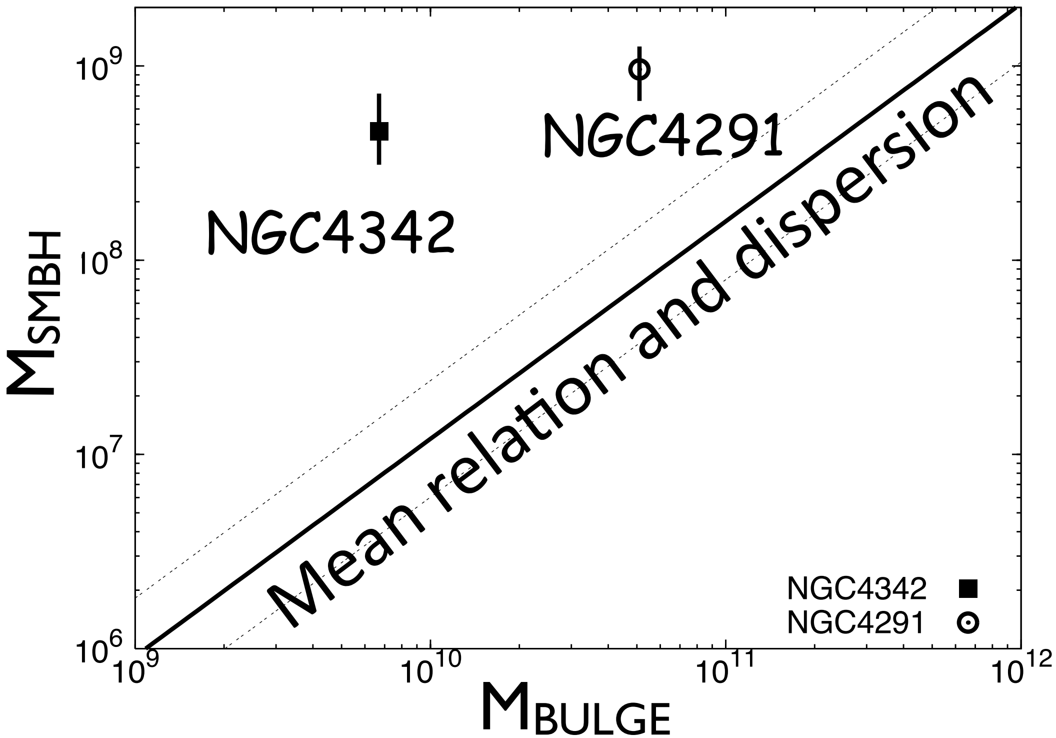
•L_{nuc}~$2x10^{42}$ erg/s

•**Massive SMBH is willing and able to disrupt atmosphere given sufficient fuel**; outburst power ~ $5x10^{58}$ ergs (Lanz+10)

•Likely merger (e.g., Schweizer 1980)

•**Gas rich mergers could drive such outbursts at early epochs and disrupt star formation**

Massive Black Holes (Bogdan et al. 2012) - two outliers



NGC4342 ~ $4.6 \times 10^8\ M_\odot$

NGC4291 ~ $9.6 \times 10^8\ M_\odot$

(Cretton & van den Bosch 1999; Haring & Rix 2004; Schultze & Gebhardt 2011)

- NGC4342 - an extreme outlier (5.1σ outlier)
- NGC4291 is less extreme (3.4σ outlier)

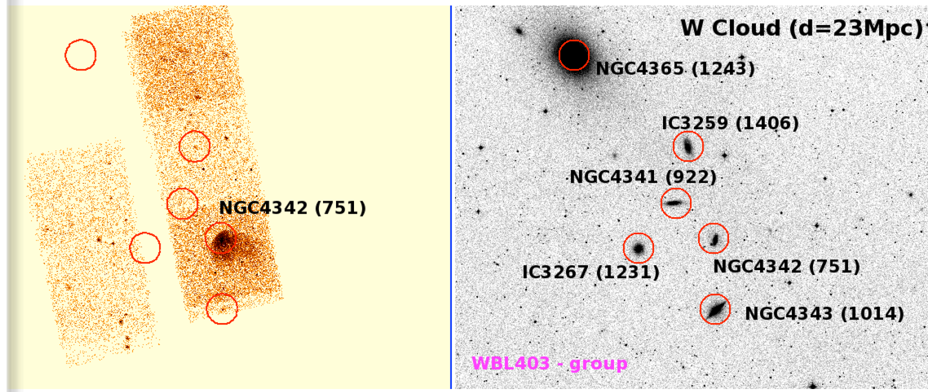
- NGC4342 and NGC4291 host massive dark matter halos sufficient to bind hot coronae
  - measured using X-ray gas (~hydrostatic equilibrium)
  - **Black holes are too massive for their bulges**
    - M_{BH}/M_{bulge} =0.069 for NGC4342 and 0.019 for NGC4391
    - **60x and 13x larger than "predicted"**

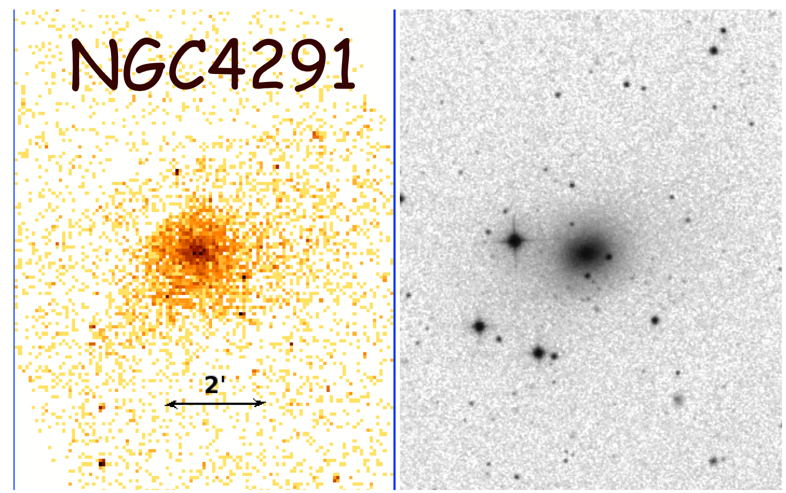
NGC4342 and NGC4291 - star formation disrupted at early times - Bogdan+2012

- Evolutionary scenario for NGC4342 and NGC4291
- Star formation suppressed by powerful SMBH outburst (e.g., like Fornax A driven by gas rich merger) at early epochs BEFORE all stars formed??
- SMBH growth precedes stellar component e.g., Sijacki+14

eRosita will inventory dark matter halos

NGC4342

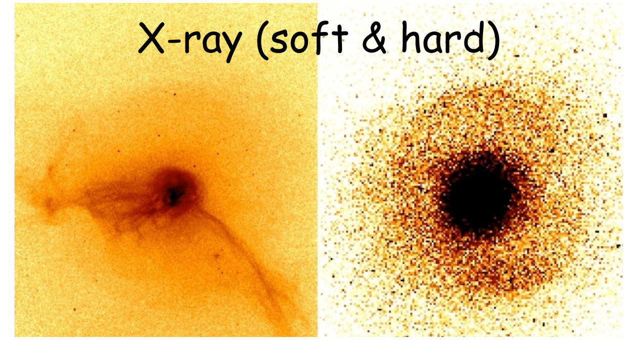


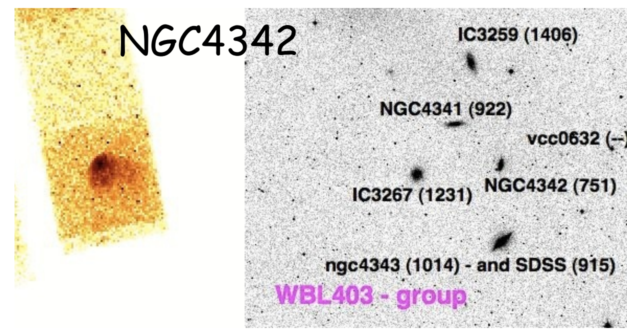


Conclusions

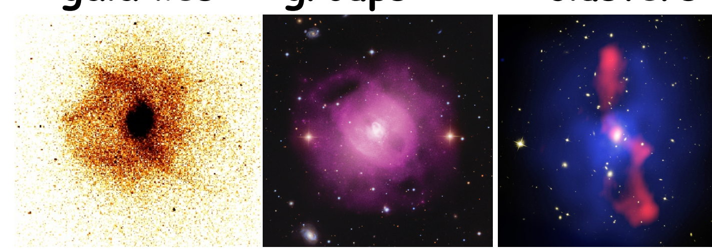
- M87 classic shock and bubbles
  - reveals detailed SMBH interaction
  - shocks are "weak"
  - outbursts are "long" (>Myr)
  - bubbles carry most of energy (>50%)
- AGN outbursts are common in all gas rich systems
  - bubbles/cavities everywhere!
  - more massive systems are more likely radio bright
- "cooling flows" from galaxies (~1 M_{sun}/yr) to clusters (~few 100 M_{sun}/yr) moderated by SMBH energy release
- SMBH's are willing and able to disrupt cooling atmospheres at low (and possibly high) redshifts (NGC4342/NGC4391 SMBH's are too massive for their stellar mass)
- **SMBH outbursts are a key phenomenon across a vast range of halo mass and cosmic time**

M87 - bubbles & shocks





galaxies groups clusters



$M_{halo} \sim 10^{12} \longrightarrow 10^{15}\ M_{sun}$

Finis