Supermassive Black Holes (SMBH) at Work: Effects of SMBH Outbursts on Clusters, Groups and Galaxies

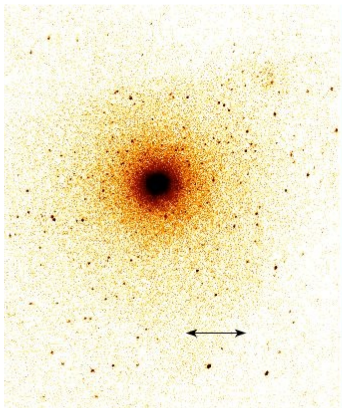
Bill Forman/Christine Jones/Eugene Churazov - SAO/CfA

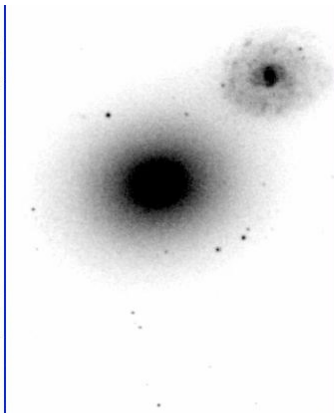
- Family of dark matter halos + hot gas
  - Galaxies, groups, clusters
- M87
  - Outburst up close
  - Classic shock
  - Buoyant bubbles
- Early type galaxies with SMBH
  - Feedback present in X-ray luminous systems
  - Hot X-ray coronae - mechanism to capture SMBH energy
  - Driver of galaxy evolution

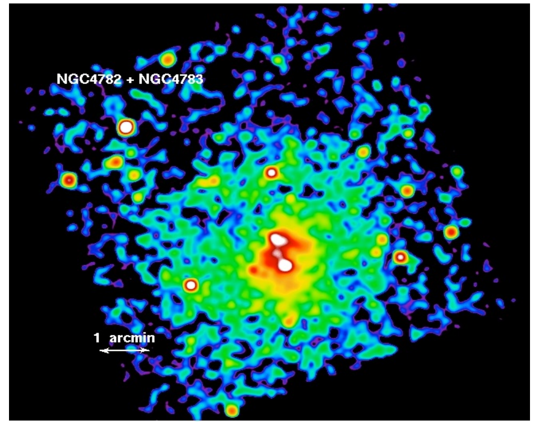
Collaborators: Scott Randall, Ralph Kraft, Paul Nulsen, Larry David, Jan Vrtilek, Simona Giacintucci, Marie Machacek, Ming Sun, Maxim Markevitch, Alexey Vikhlinin

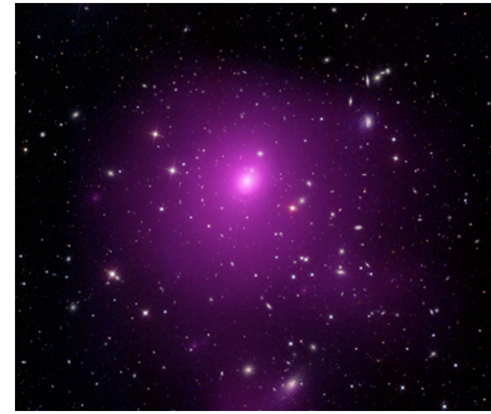
Setting the stage - Gas Rich Systems

Family of increasing mass, temperature, and luminosity









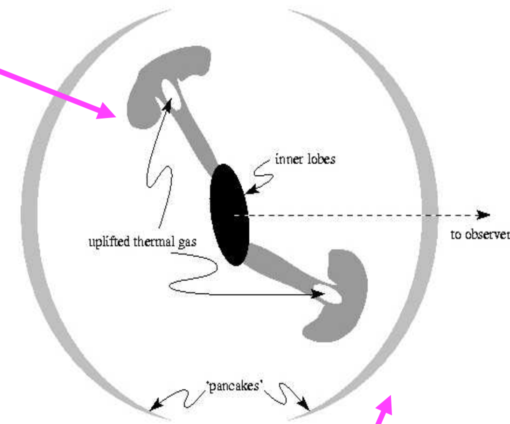
- Galaxy family discovered with Einstein (Forman +79, +85)
- Mini cooling flows described by Thomas et al. (1986)

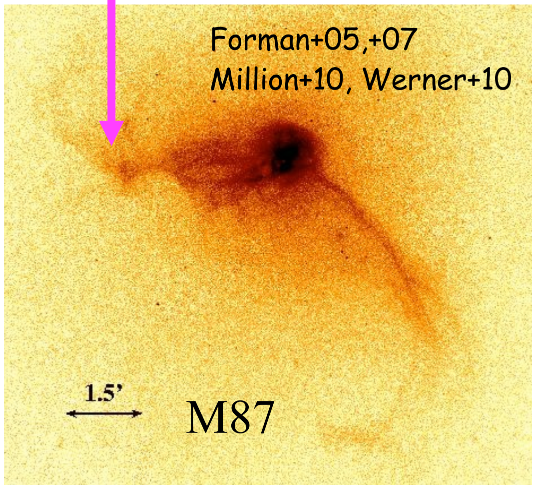
	E/S0 Galaxies	Groups	Clusters
L_x	10	10	10
Gas Temp	0.5-1.0 keV	1-3 keV	2-15 keV
M	0.02	1	5

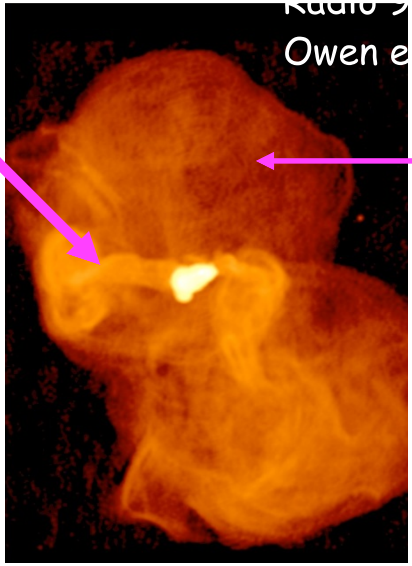
- Compared to groups/clusters, galaxy physical processes are identical
- Optically Luminous E/S0 Galaxies have as much gas as spirals - BUT kT ~ 1keV

X-ray and Radio View of M87

- Multiple - at least three - AGN 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)

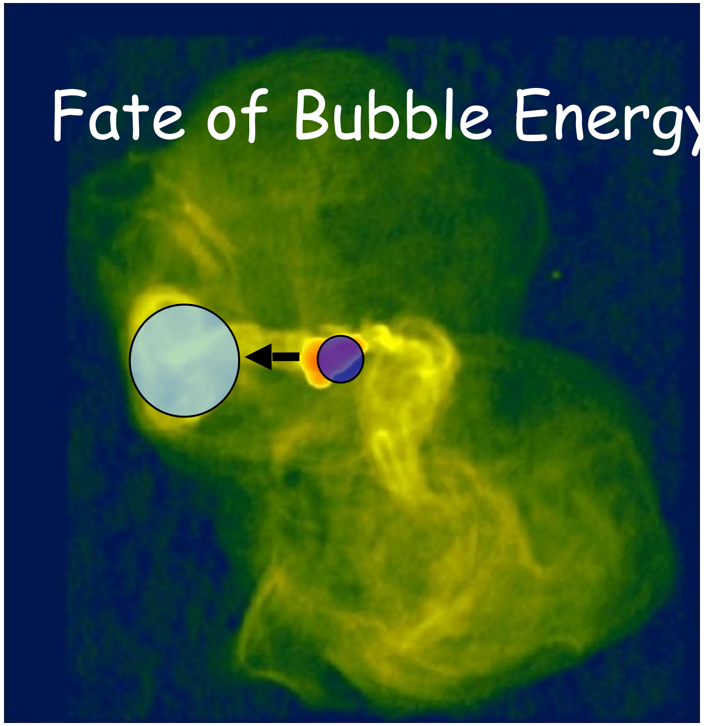






Old bubbles - no apparent spectral aging - still powered by AGN?

Fate of Bubble Energy



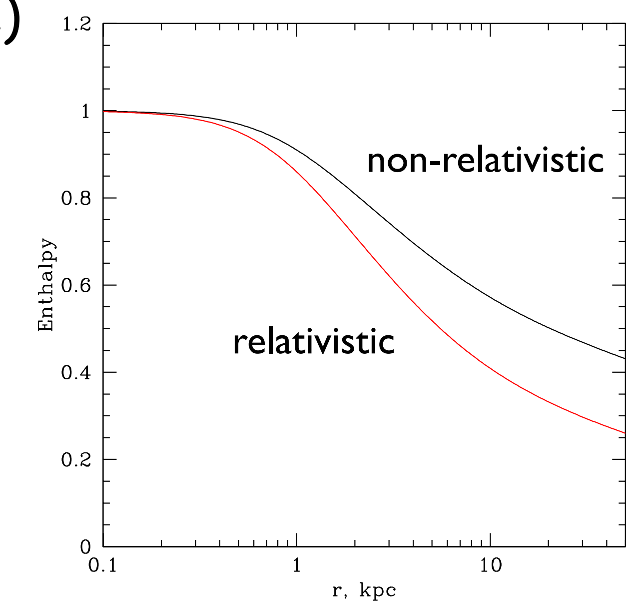
Rising bubble loses energy to surrounding gas

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

Generates gas motions in wake

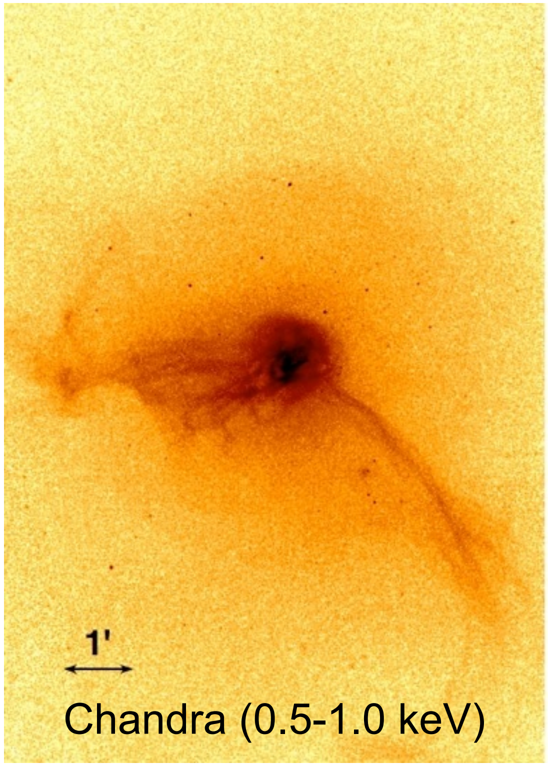
Kinetic energy (eventually) converted to thermal energy (via turbulence)

Bubble energy remaining vs. radius

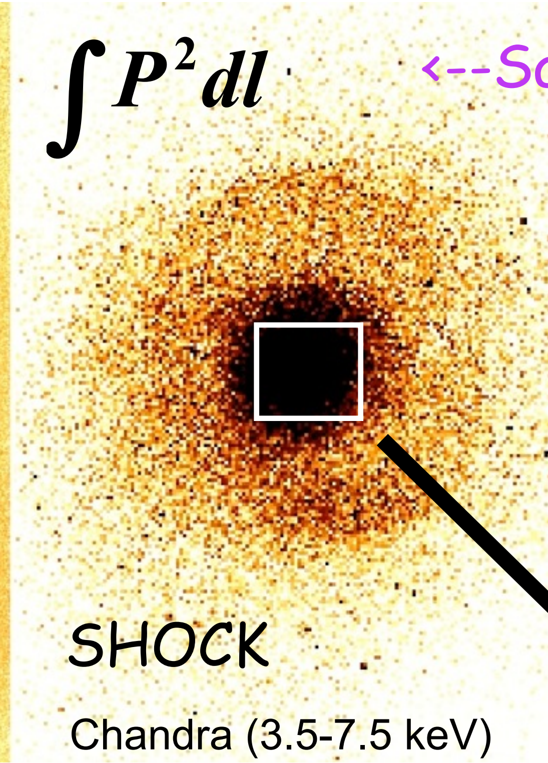


$$\Delta E_{gas} = -\Delta E_{Bubble} = -\Delta \frac{\gamma}{\gamma - 1} PV = E_0 \left[1 - \left(\frac{P}{P_0} \right)^{1-1/\gamma} \right]$$

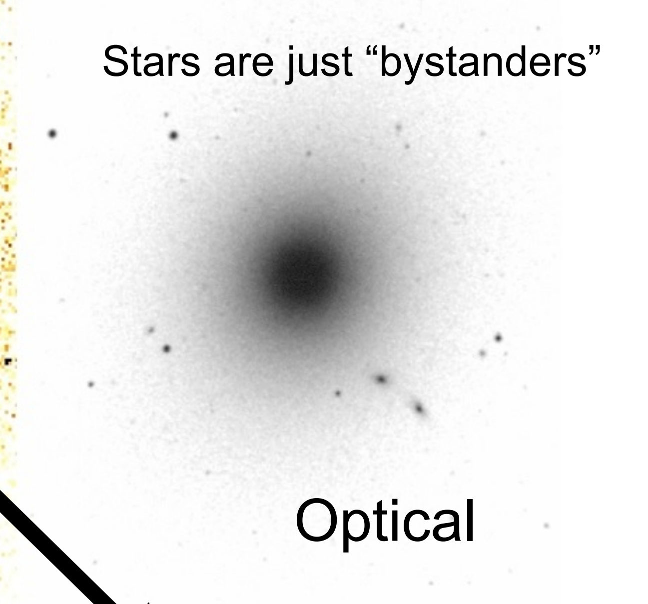
Classical Shock in M87

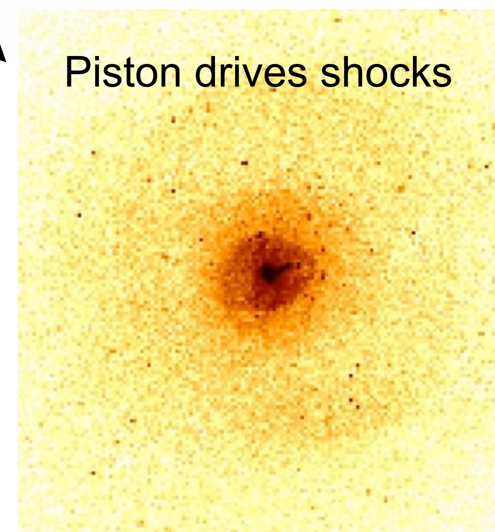


23 kpc (75 lyr)



<--Same Scales -->



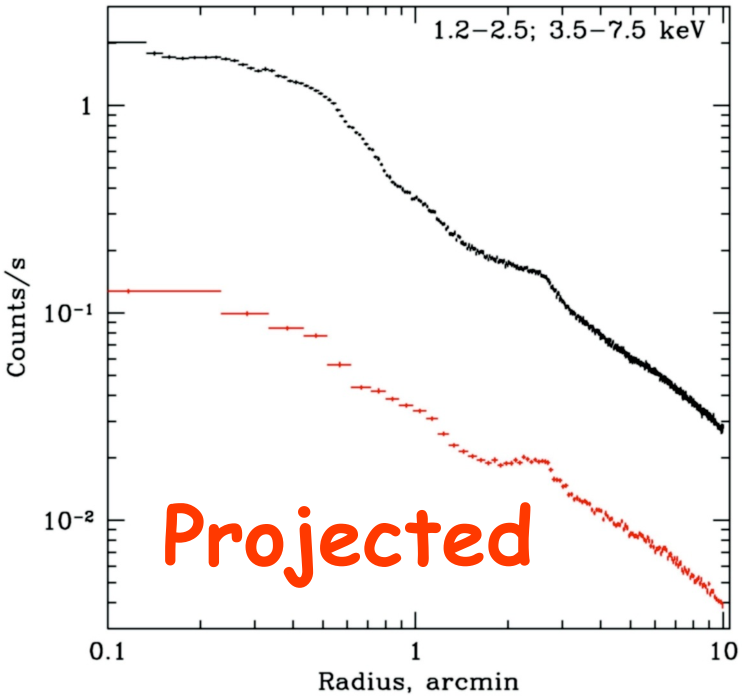


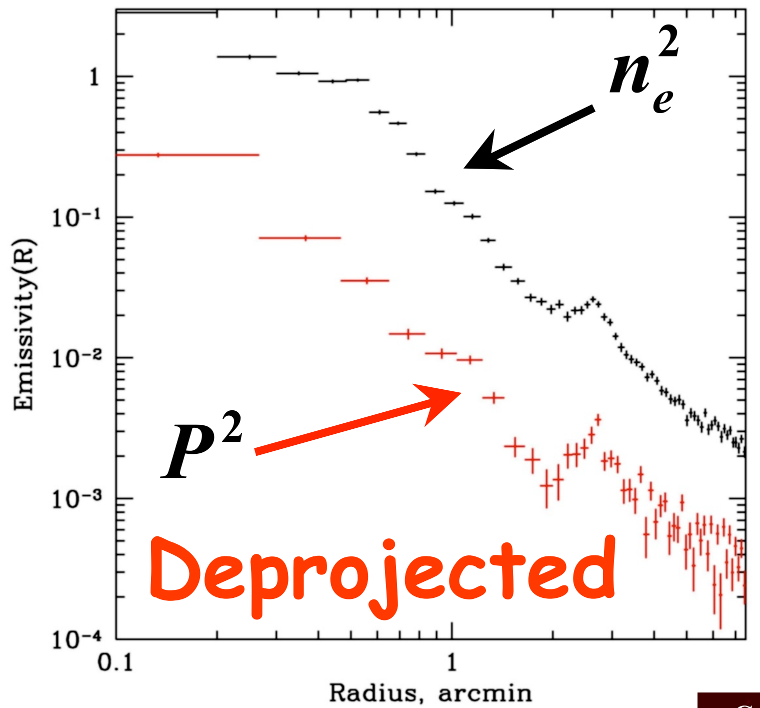
- Black hole = 6.6×10^9 solar masses (Gebhardt+11)
- SMBH drives jets and shocks
- Inflates “bubbles” of relativistic plasma
- Heats surrounding gas
- Model to derive detailed shock properties

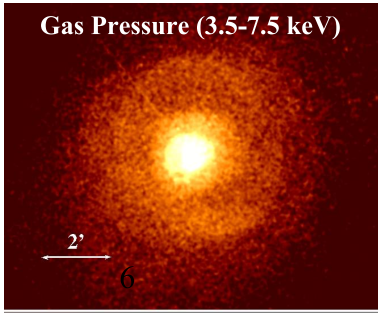
Shock Model - the data

Hard (3.5-7.5 keV) pressure

soft (1.2-2.5 keV) density profiles







Textbook Example of Shocks

Consistent density and temperature jumps

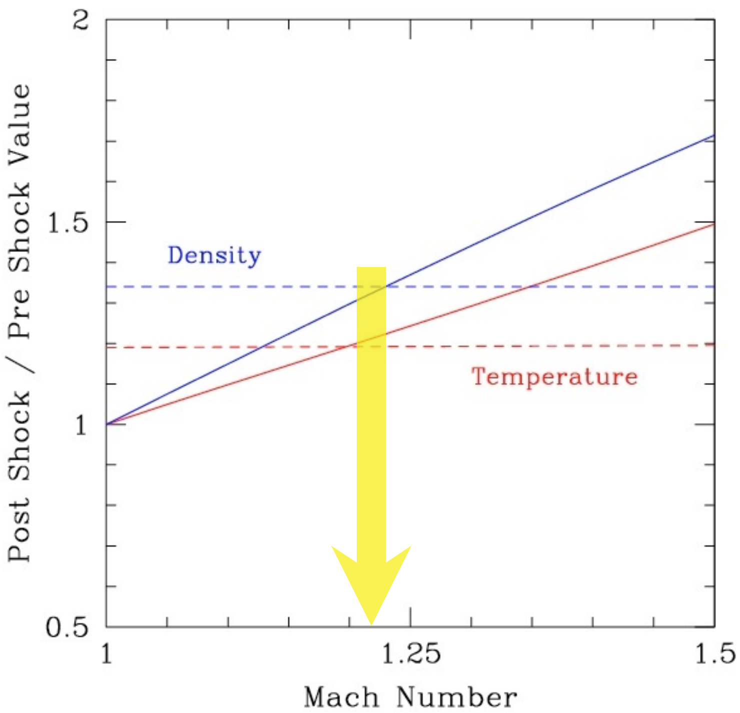
Rankine-Hugoniot Shock Jump Conditions

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

$$\boxed{\rho_2/\rho_1 = 1.34}$$

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

$$\boxed{T_2/T_1 = 1.18}$$



yield same Mach number:

($M_{T=}$1.24 M_{ρ}=1.18)

M=1.2

M87 Outburst Energy Partition

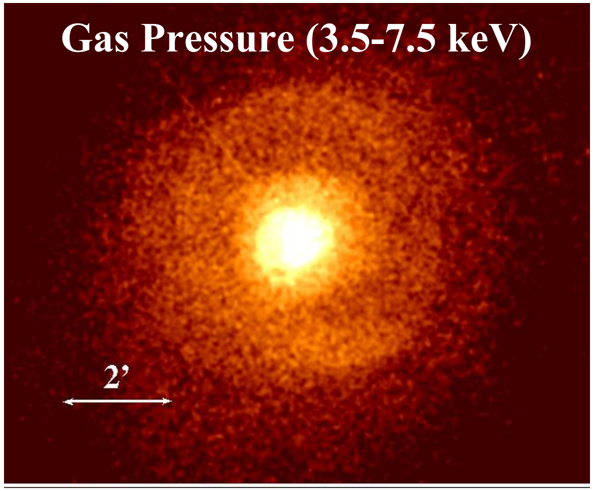
Detect shock (X-ray) and driving piston (radio)

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 50%

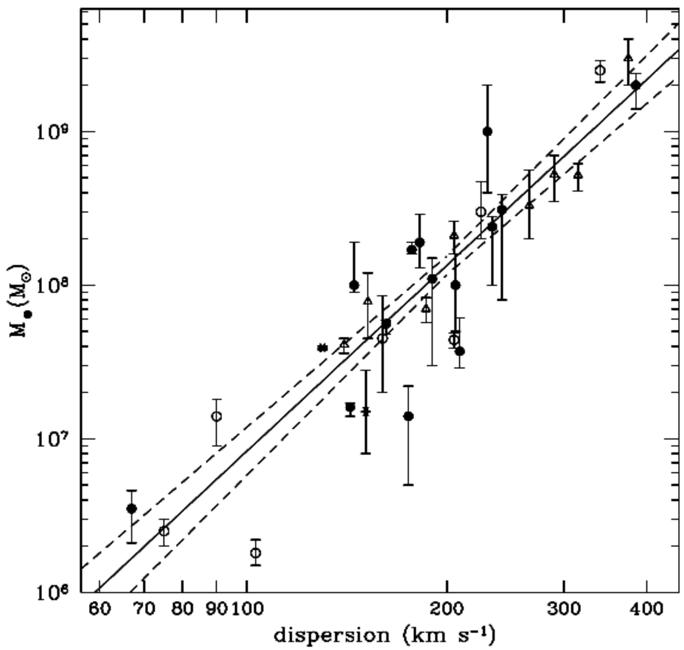
Shocked gas 25% (25% carried away by weak wave)

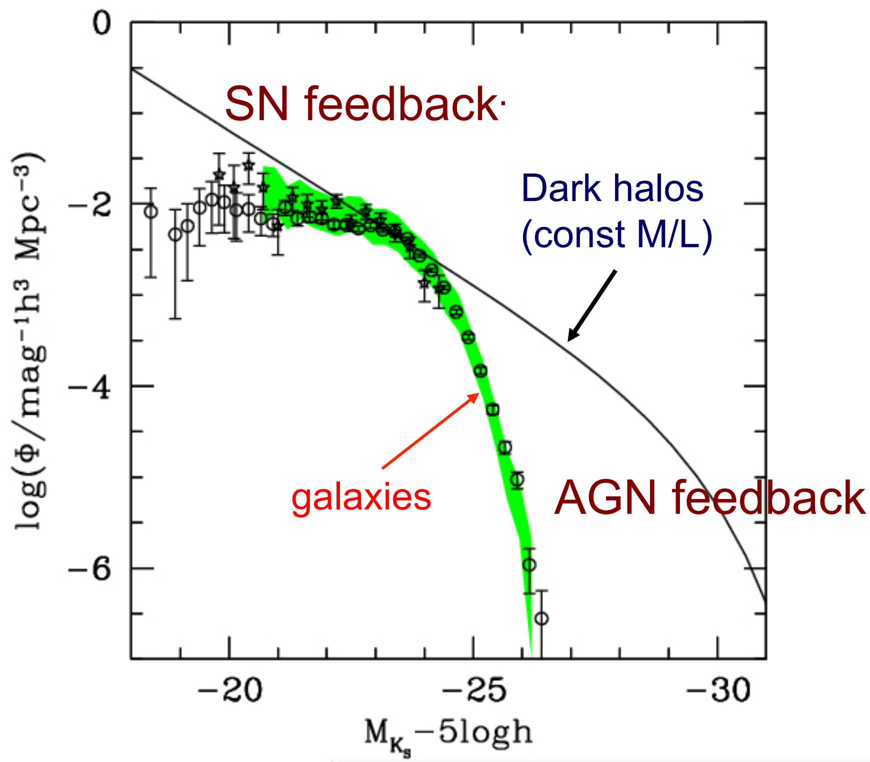
Outburst duration ~ 2 Myr

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

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

Feedback from Supermassive Black Holes key component in galaxy formation

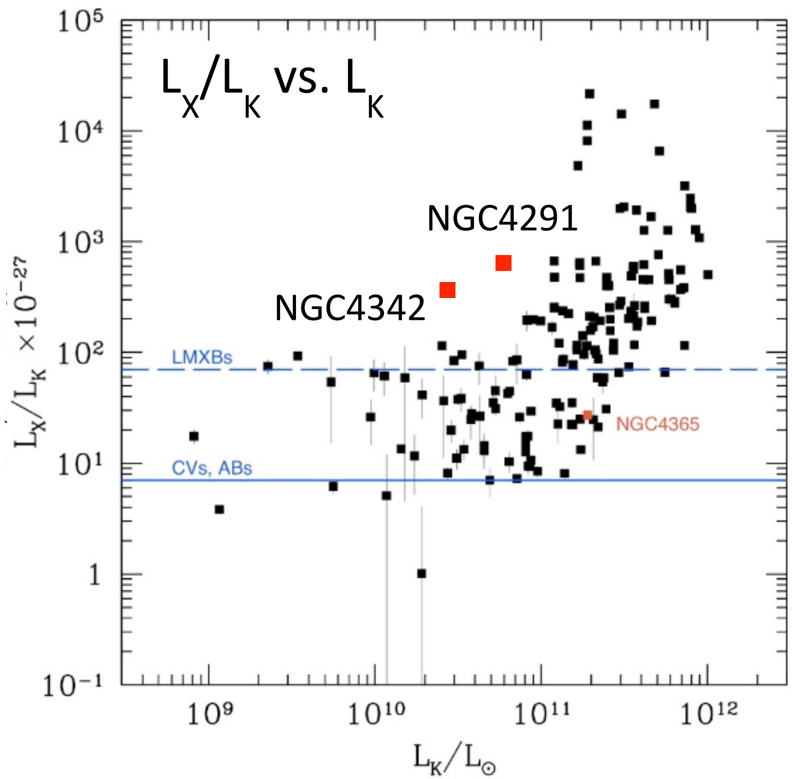




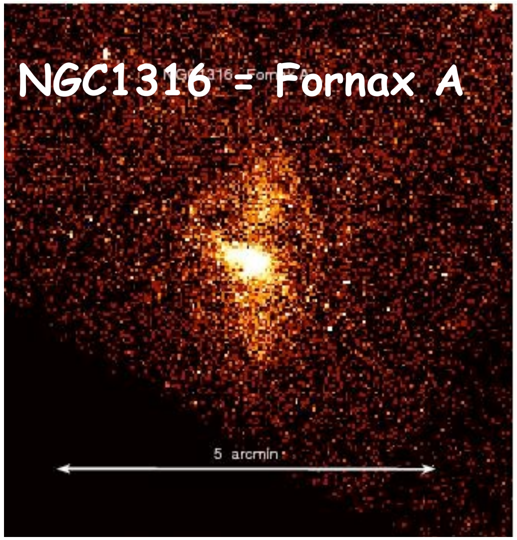
- Feedback - mass closely tied to mass of surrounding stars - $M_{SMBH} \approx 10^{-3} M_{bulge}$
- SMBH key to regulating star formation in evolutionary models at high mass end

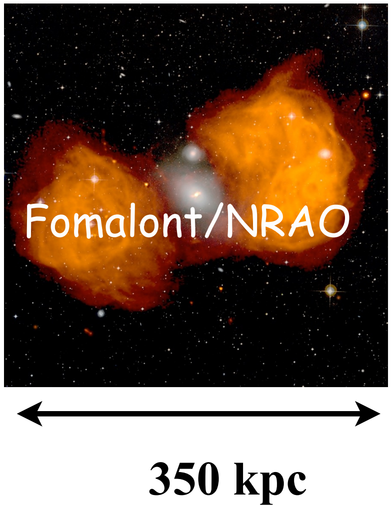
e.g. Croton+06, White & Frenk 91, Cole+92 Benson+'03 Best+06, Teyssier+11,

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



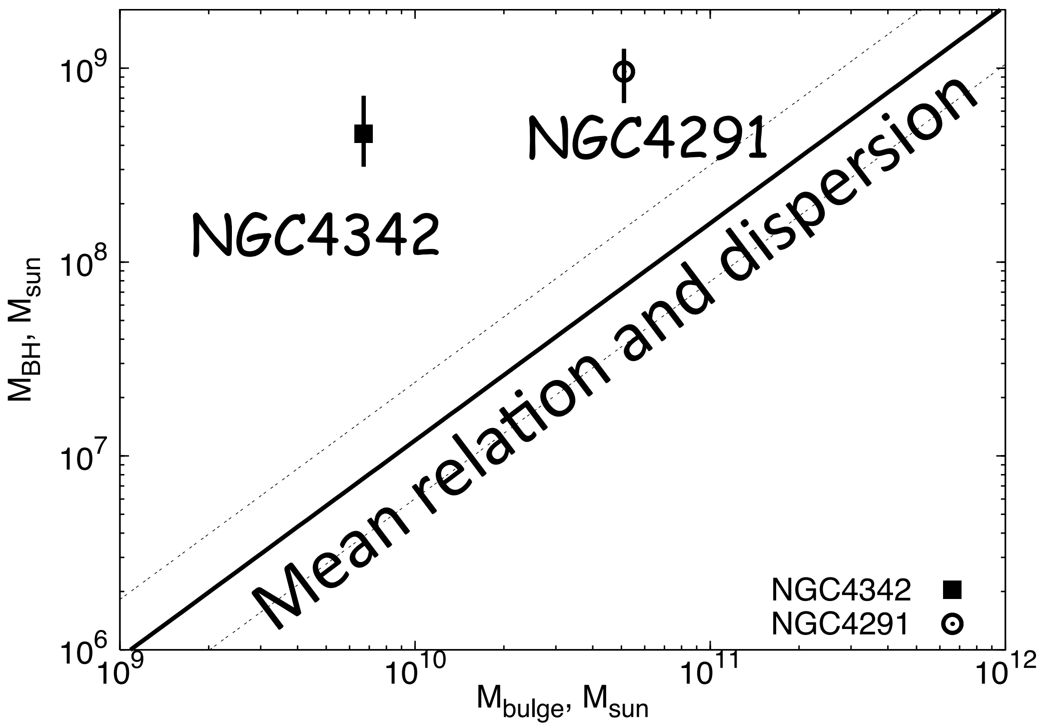
Scatter in L_X-opt mag relation is partly due to gas removal and partly due to environment (galaxies in the centers of "groups")





- Outskirts of Fornax cluster (>1.4 Mpc from NGC1399)
- L_{nuc}~2×10^{42} erg/s
- Likely merger driven outburst (e.g., Mackie/ Fabbiano98)
- **Massive SMBH is willing and able to disrupt atmosphere given sufficient fuel**; outburst power ~ 5×10^{58} ergs (Lanz+10)
- **Such outbursts at early epochs could disrupt star formation**

Massive Black Holes - two outliers



NGC4342 ~ 4.6 × 10^8 $M_\odot$

NGC4291 ~ 9.6 × 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 dark matter halos

- •measured using X-ray gas (hydrostatic equil)
- • 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 expected**

NGC4342 and NGC4291 - star formation disrupted at early times - see Akos Bogdan poster

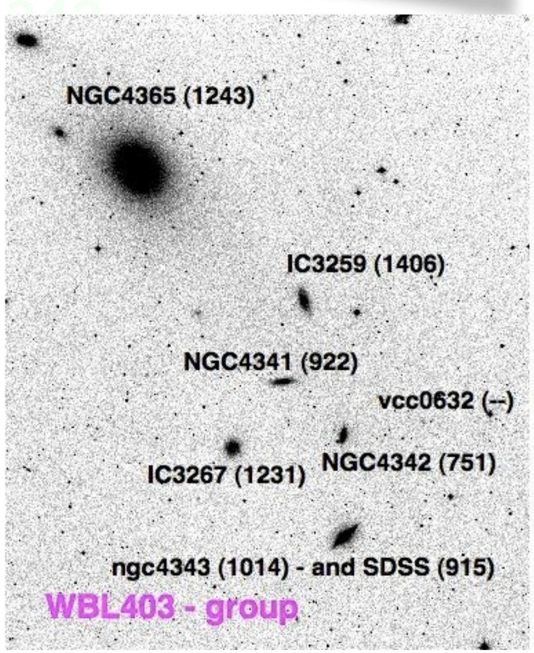
Extra energetic SMBH terminates star formation at early times (e.g. Fornax A - like outburst)

(Bogdan et al. 2012a, b)

- Evolutionary scenario for NGC4342 and NGC4291

  Star formation suppressed: black hole grew faster than stars

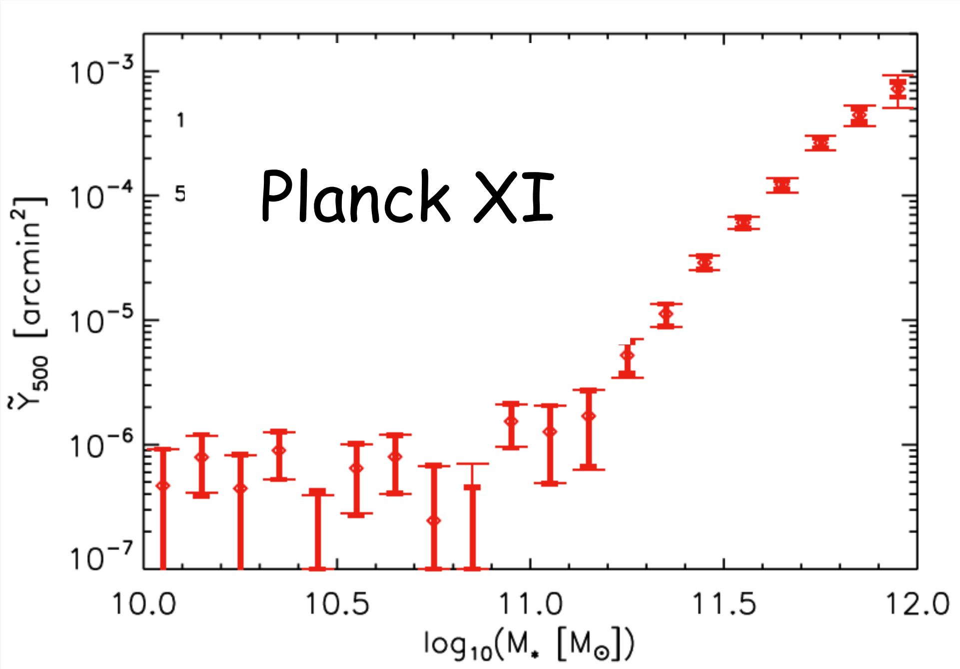
  Recall early SMBH growth (see REFERENCE??)



eRosita will inventory massive halos

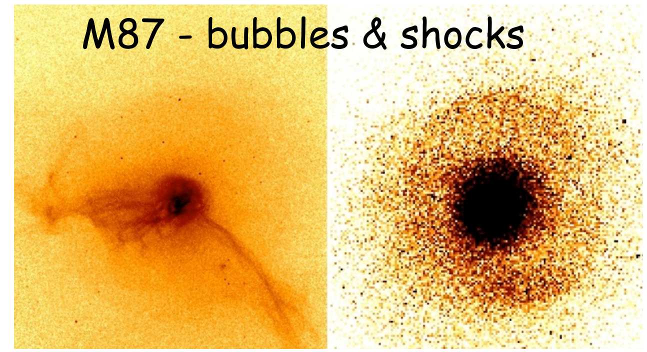
SZ Detections of hot gaseous galaxy coronae

- already see 25% of baryons in local Universe in SZ (Planck XI)
- Detect lower mass early type galaxies
- Detect onset of winds
  - decrease in SZ signal
- Detect hot halos of spirals!! *see Andersen+11;Bogdan+13a,13b (NGC1961, NGC6751)*

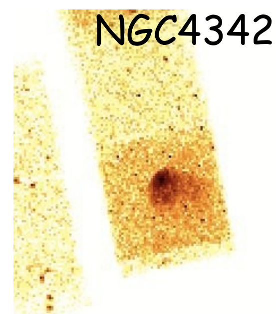


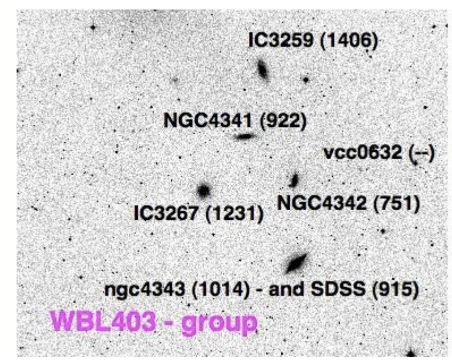
Conclusions

- Cavities (and shocks) - BEST way to measure black hole outburst history
  - Measure energy, age, duration
- SMBH governs correlation with bulge/halo
  - SMBH can disrupt star formation at early times (e .g., NGC4342 - see Bogdan poster)
  - Can break "tight" correlation of M_{SMBH} with M_{bulge}



X-ray (soft & hard)

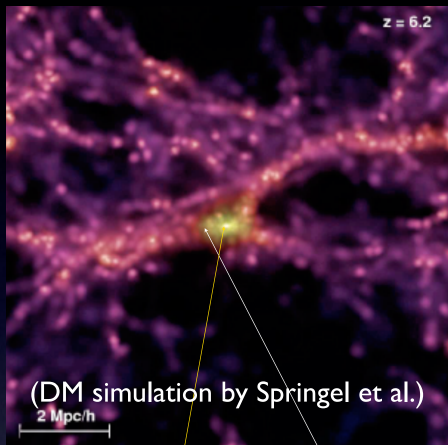


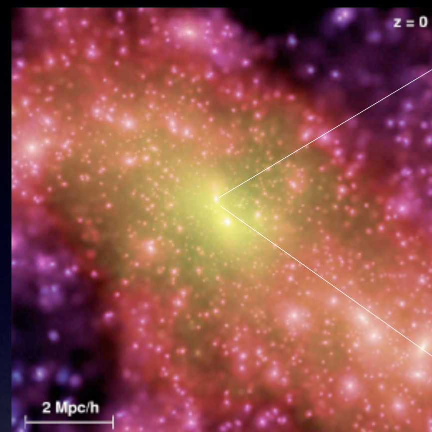


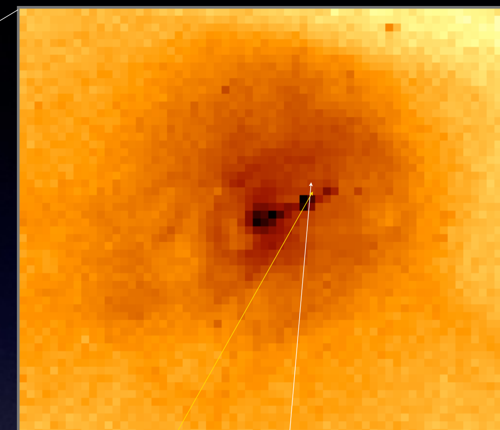
SMART-X (1” 30 x Chandra): Growth of galaxy groups and 10^9 $M_\odot$ black holes from z = 6 to the present

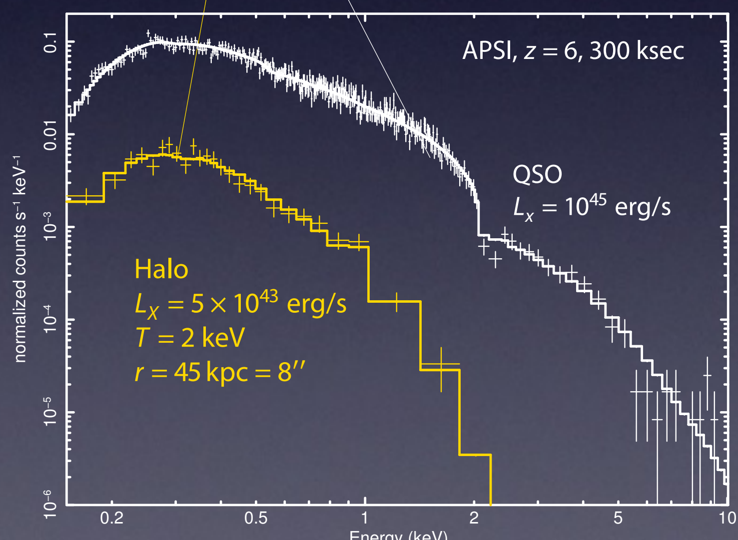
Sloan quasar at z=6 ⟶ “nursing home” at z=0

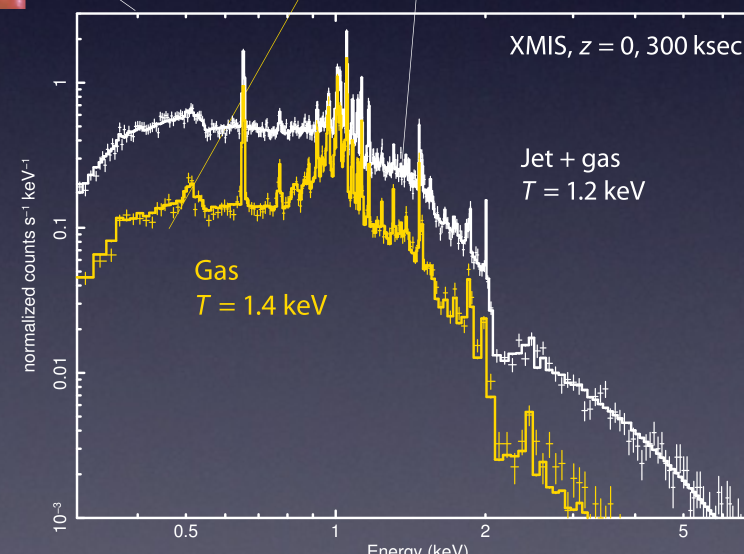
M87, *Chandra*, 1″ pixels











√ ***Sensitivity + angular resolution — detect and resolve quasar host halos and galaxy groups at z=6***

√ ***High-res spectroscopy on 1″ scales — feedback and physics in clusters, galaxies, SNRs***

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