Feedback from Super-Massive Black Holes - M87

Bill Forman (SAO-CfA)

- Outburst up close (and personal)
- Classic shock
- Buoyant bubbles
- Energy partition and outburst duration

Collaborators: Eugene Churazov, Sebastian Heinz Christine Jones, Paul Nulsen, Ralph Kraft, Scott Randall, Alexey Vikhlinin

Churazov+01
Forman+05, 07, 17

Virgo Cluster and M87

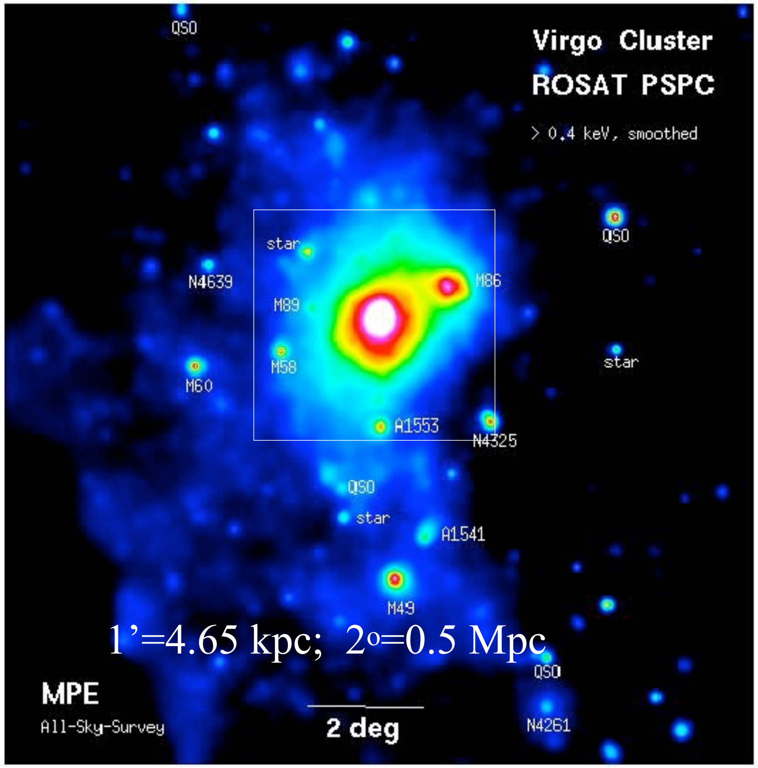
Old:

Messier, 1781 => Age > 200 yr

Mean stellar age ~ 10 Gyr

Popular:

~5800 papers (NASA ADS) => Most popular elliptical galaxy in the observable Universe with 360,000 citations



M87 is central dominant galaxy

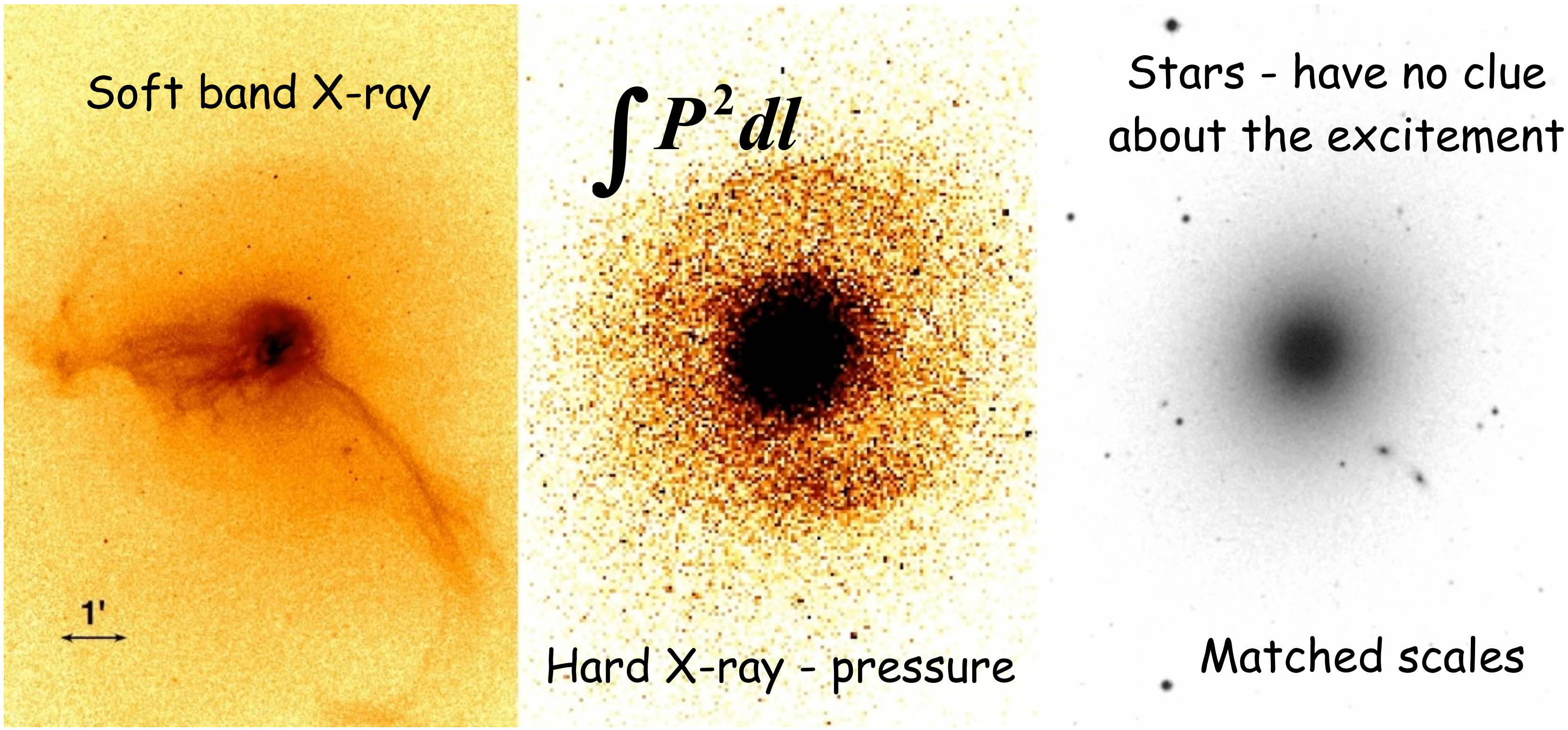
- hosts 3-6x$10^9 M_{sun}$ supermassive black hole and jet
- Classic cooling flow (24 M_{sun}/yr)
- Ideal system to study SMBH/gas interaction

Chandra view of M87

"Raw" images

Just select different energy bands

See the over-pressurized regions = shocks



Isobaric arms (Arevalo et al. 2016)

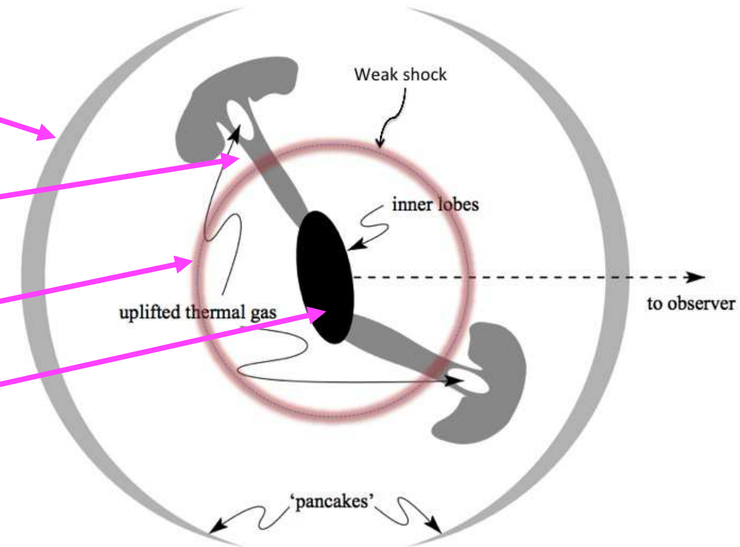
Xarithmetic (Churazov et al. 2016)

~100 Myr - old (radio) bubbles

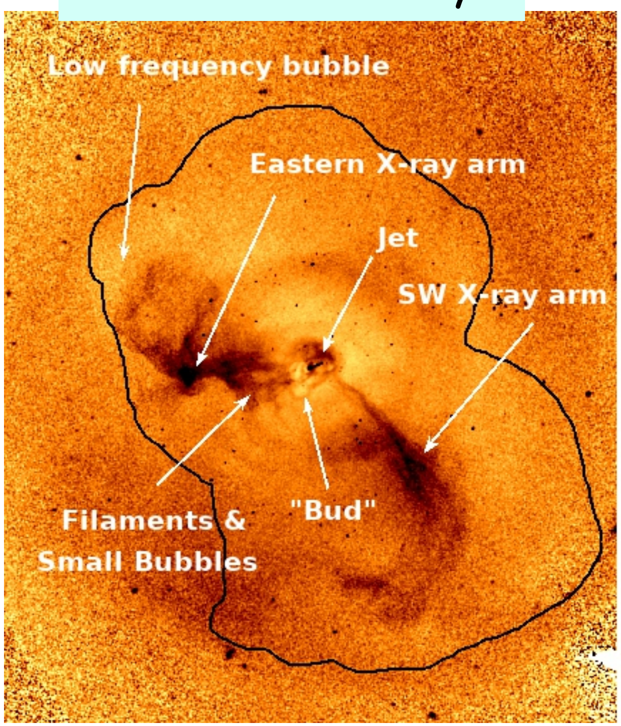
~40 Myr - torus & uplifted arms

~12 Myr (12 kpc) - shock

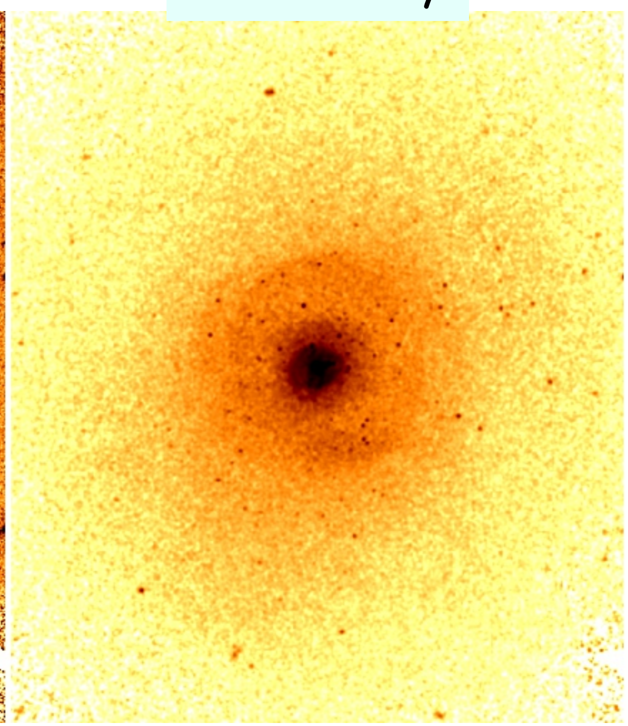
now - re-inflating cavity



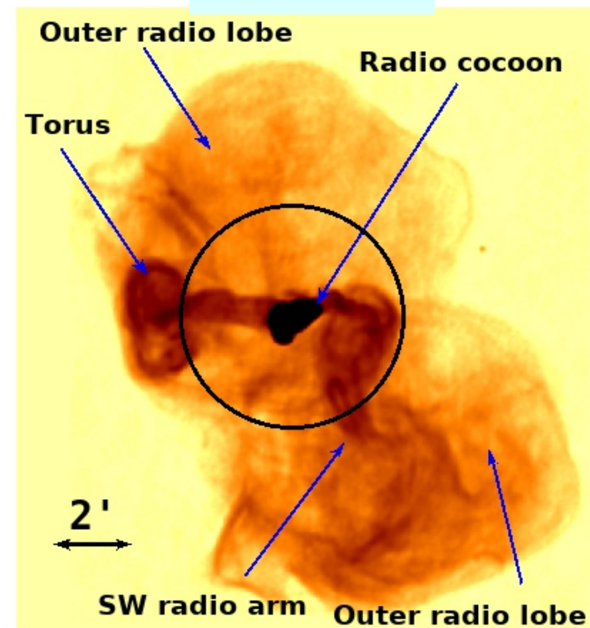
Soft band X-ray

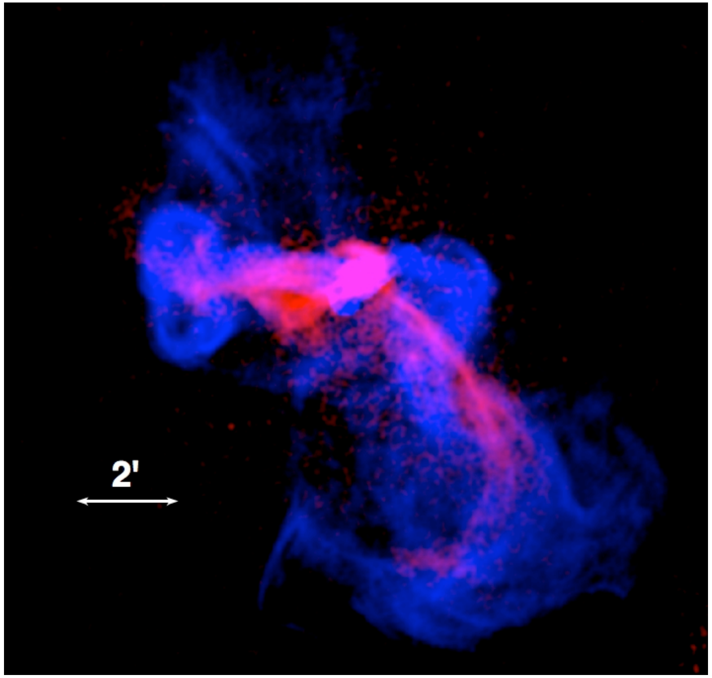


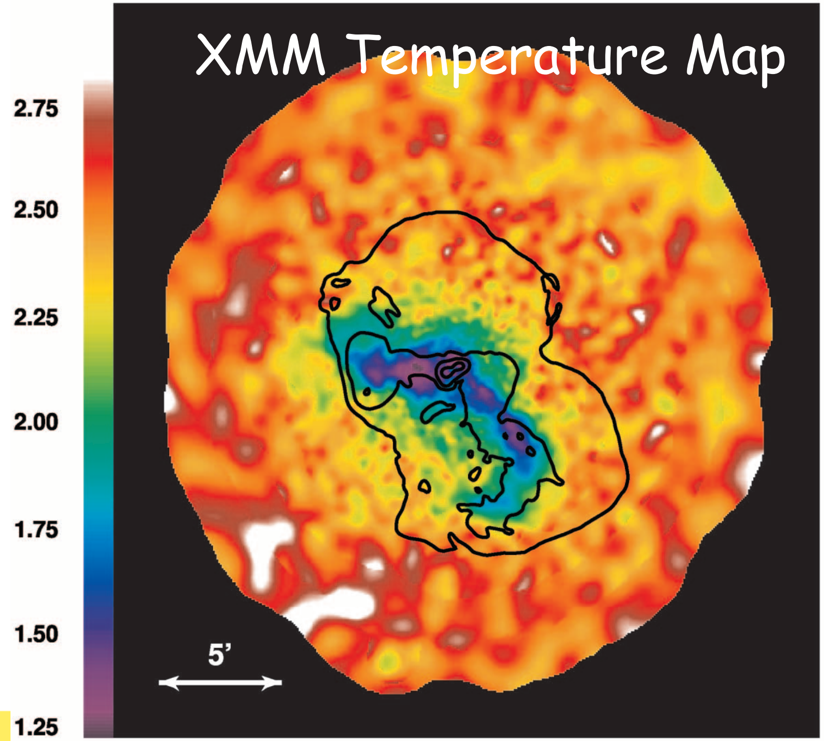
Hard X-ray

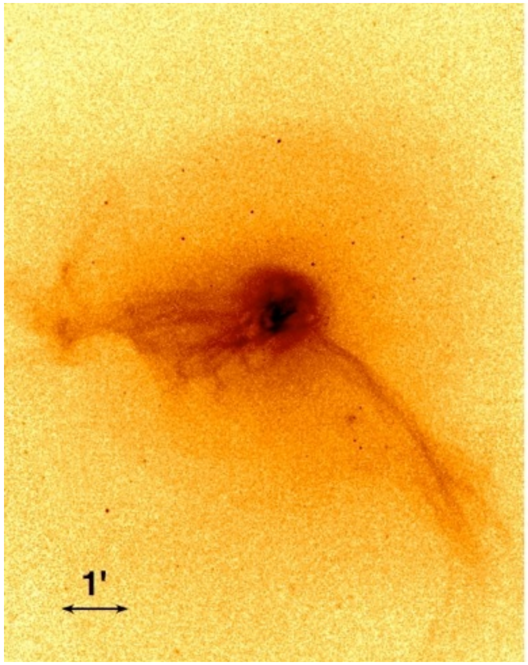


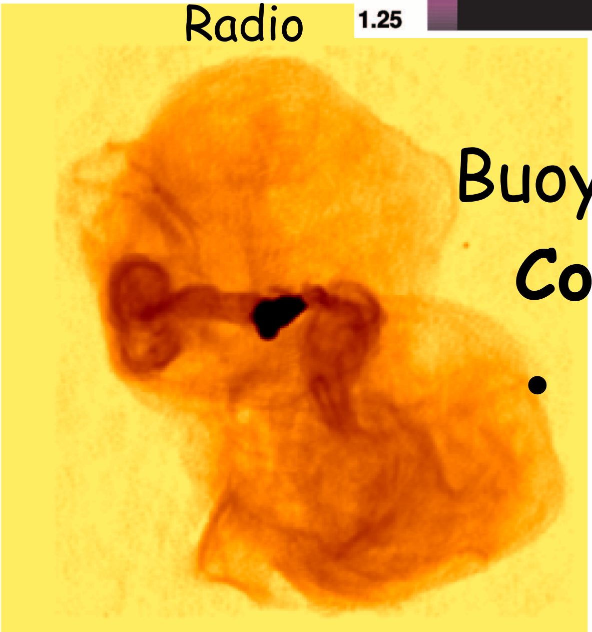
Radio









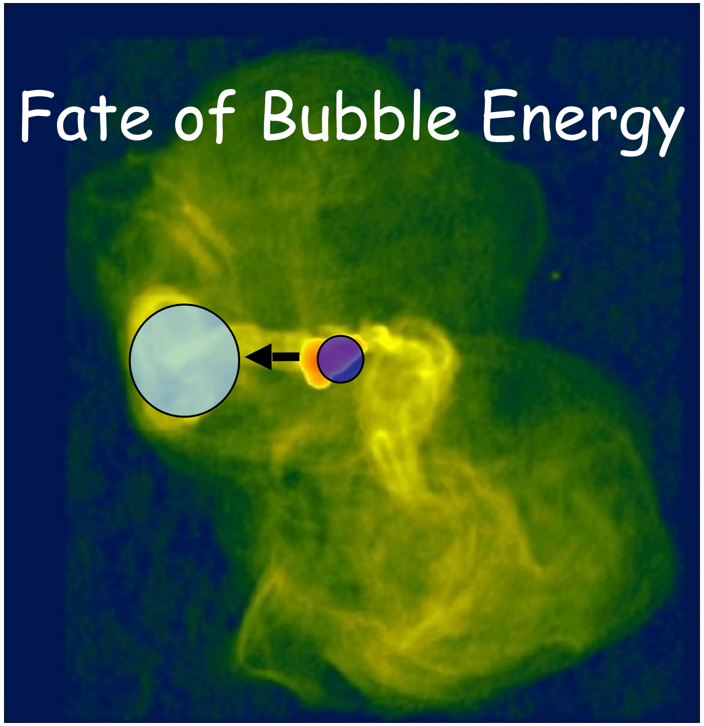


Buoyant (radio) bubbles

Cool, uplifted arms

- classic buoyant bubble with torus i.e., "smoke ring" (Churazov et al 2001)

Fate of Bubble Energy



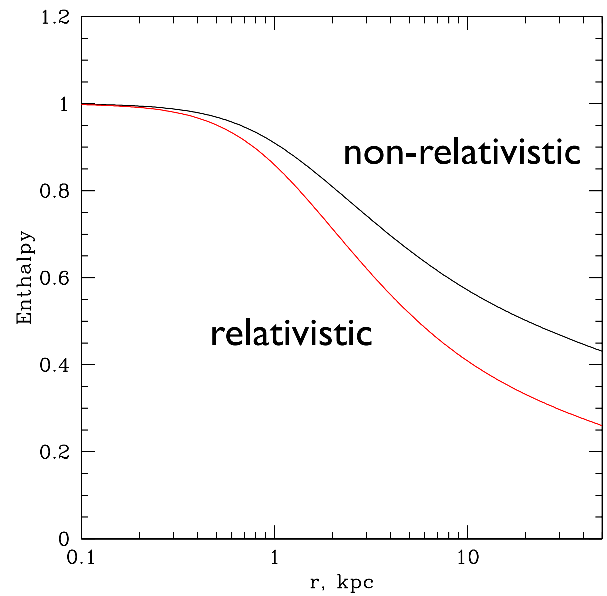
Rising bubble loses energy to surrounding gas

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

Generates gas motions in wake

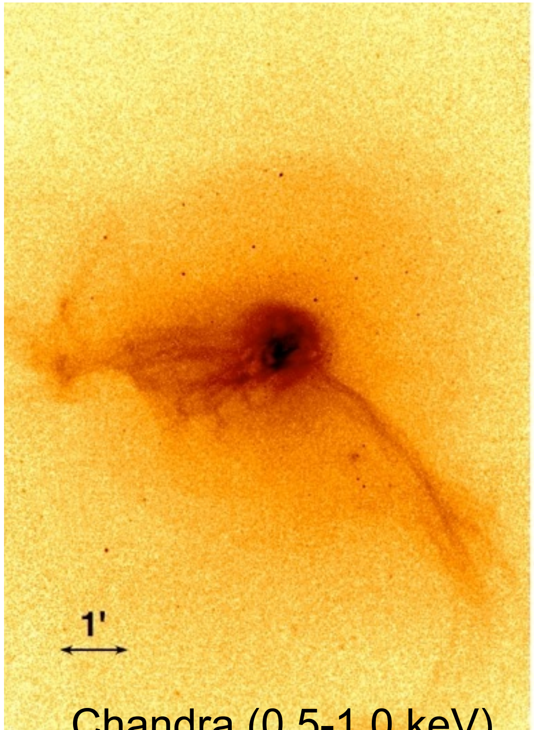
Kinetic energy (eventually) converted to thermal energy (via turbulence)

Bubble energy remaining vs. radius

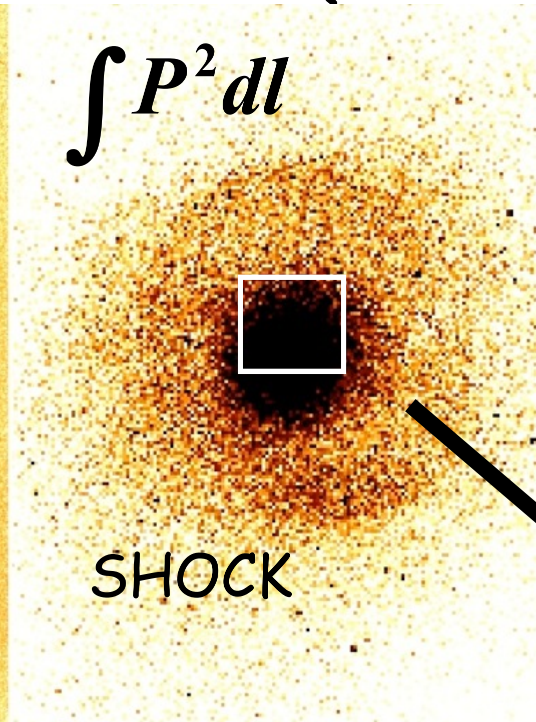


$$\Delta E_{gas} = -\Delta E_{Bubble} = -\Delta \frac{\gamma}{\gamma - 1} PV = E_0 \left[1 - \left(\frac{P}{P_0} \right)^{1-1/\gamma} \right]$$

Shocks (and Bubbles)



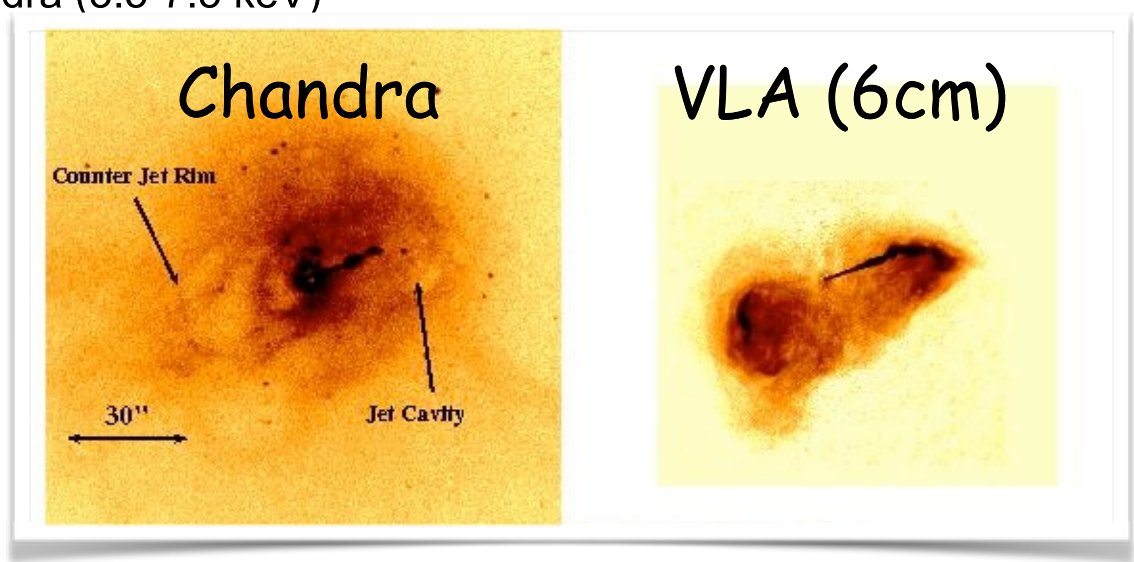
Chandra (0.5-1.0 keV)



Chandra (3.5-7.5 keV)

23 kpc (75 lyr)

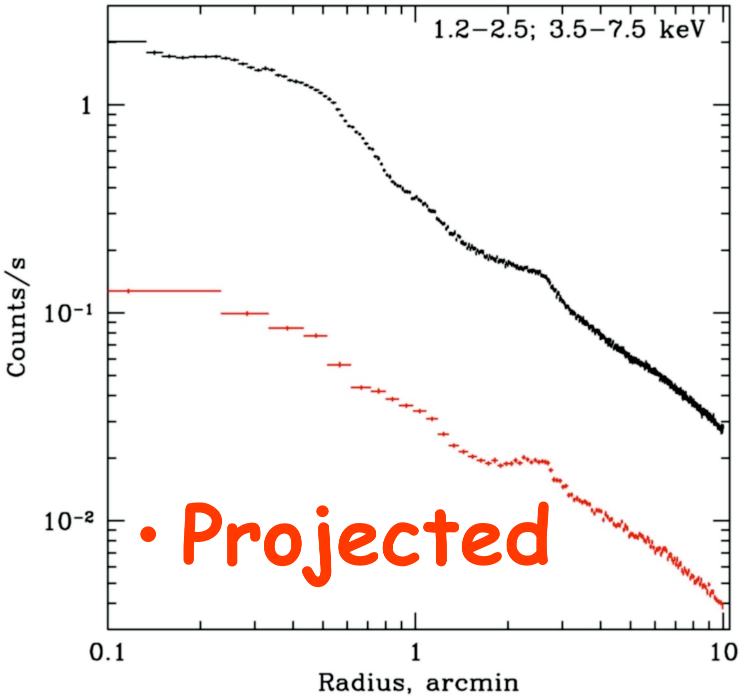
- SMBH drives jets and shocks
- Inflates "bubbles" of relativistic plasma
- **Model to derive detailed outburst properties**

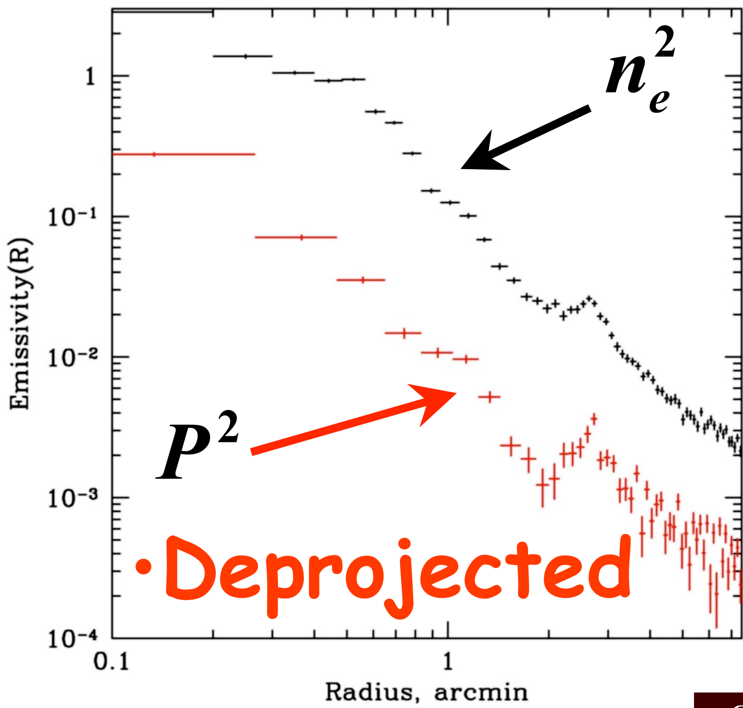


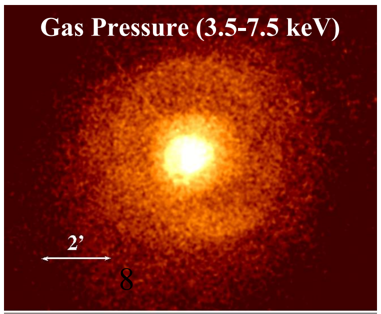
Central piston drives shock

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

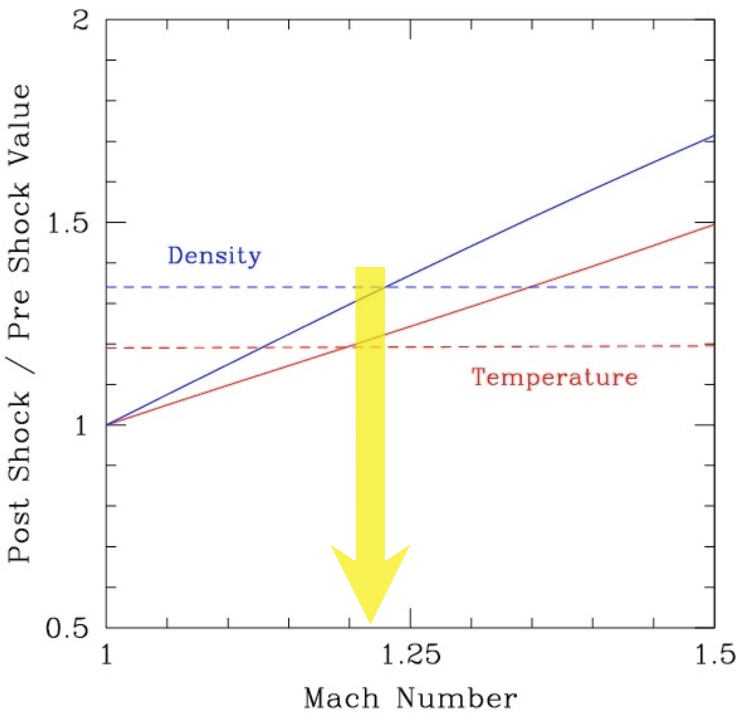
Rankine-Hugoniot Shock Jump Conditions

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

$$\rho_2/\rho_1 = 1.34$$

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

$$T_2/T_1 = 1.18$$

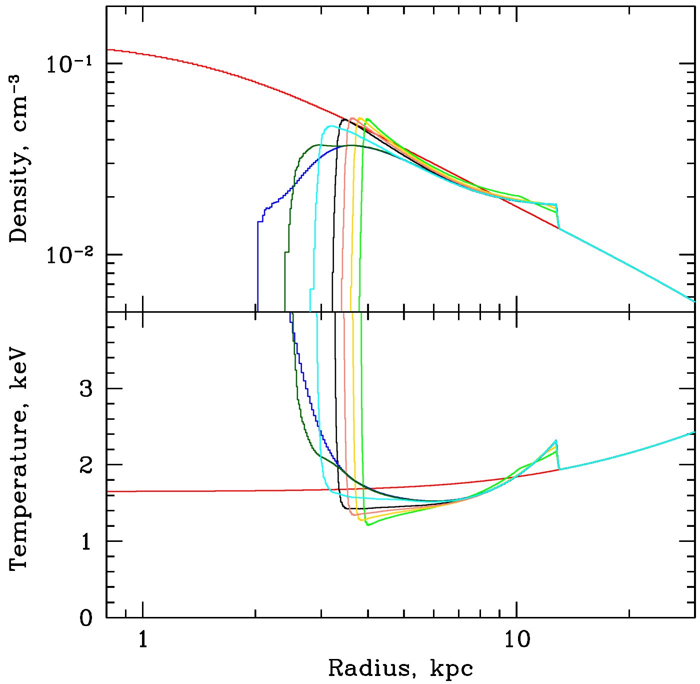


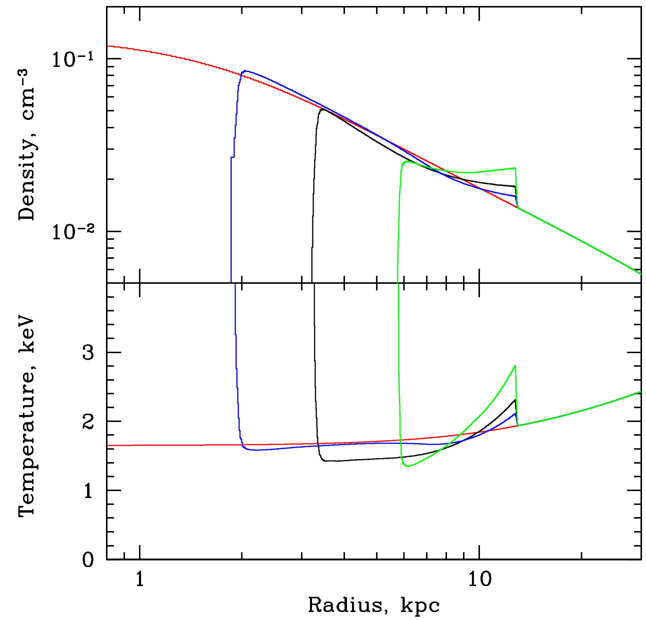
yield same Mach number:
($M_{T=}1.24$ $M_\rho=1.18$)

M=1.2

Outburst Model - grid in total energy and duration

Forman et al. 2017



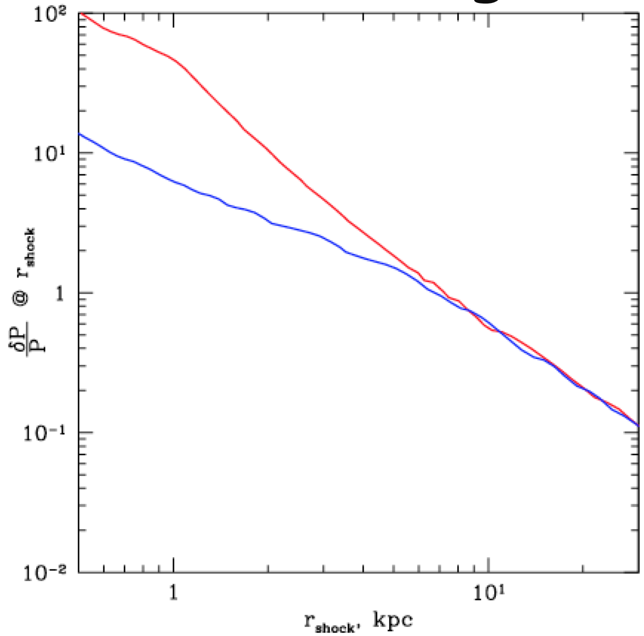


E_{tot} = 5.5x10^{57} ergs,
Different durations = 0.1, 1.1, 2.2, 3.1, 4.0, 4,4, 6.2 Myrs
Shock strength (nearly) governed by E_{tot}

Same duration = 2.2 Myr
Different E_{tot} = 1.4, 5.5, 22x10^{57} ergs)
Produces different central piston sizes (observable)

Match all constraints

Characterizing M87's outburst - Long vs. Short Durations

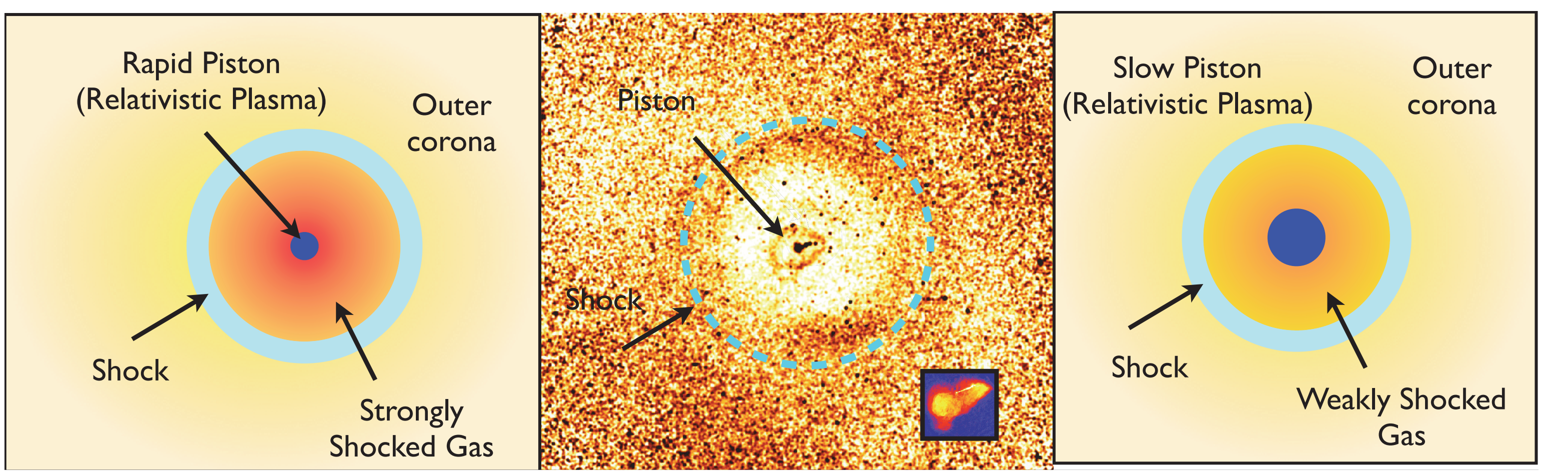


0.6 vs 2.2 Myr duration outbursts with $E_{outburst}$ = 5.5x10^{57} ergs

Short outburst - leaves hot, shocked envelope outside the piston

Not observed — longer duration outburst required

Size constrains outburst



M87 Outburst - superman or winnie?

Age ~ 12 Myr

Energy ~ 5x10^{57} erg

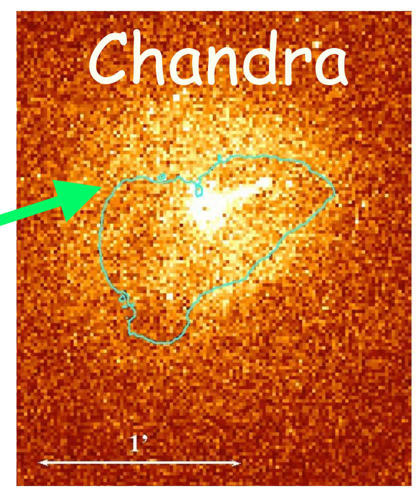
- **Bubble 50%**
- **Shocked gas 25% (25% carried away by weak wave)**

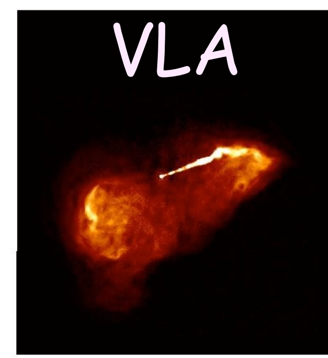
Outburst duration ~ 1 Myr

- Outburst is "slow"

Fast - hot, low density shock heated region

Slow - dense,cool rim



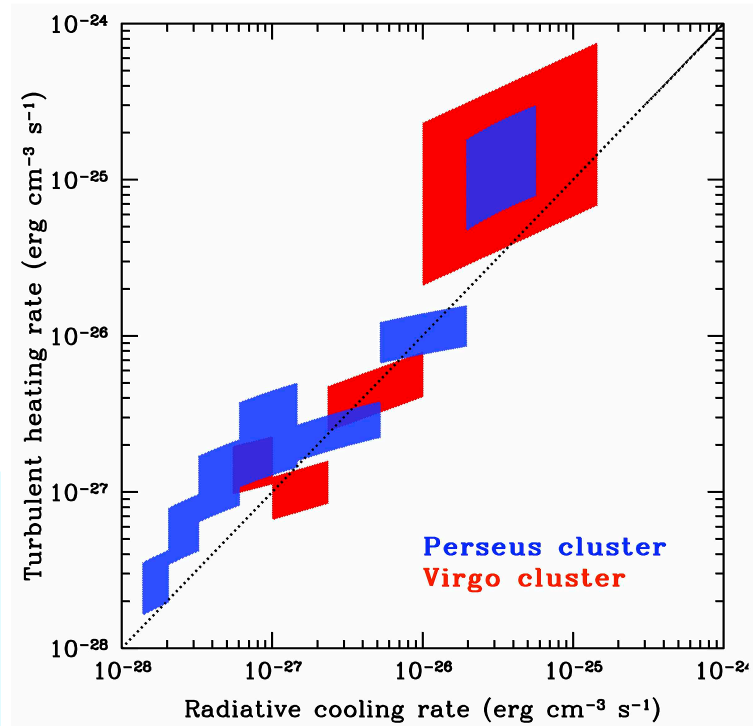


Zhuravleva+14 - Solving the “cooling flow” problem?

- for observed gas t_{cool} is < t_{age}
- More than enough energy from SMBH in buoyant bubbles & shocks
- Plus mergers and gas sloshing
- But how, exactly, does the energy transfer occur?

- Measure power spectrum of surface brightness fluctuations
- Deproject to get density fluctuations
- 1D gas velocity ∝ rms density fluctuations (see Irina Zhuravleva+14)

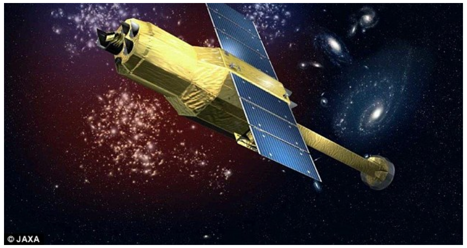
- Turbulent heating may be sufficient to offset radiative cooling
- Balances locally!!
- **May be key to heating hot coronae from clusters to early type galaxies**

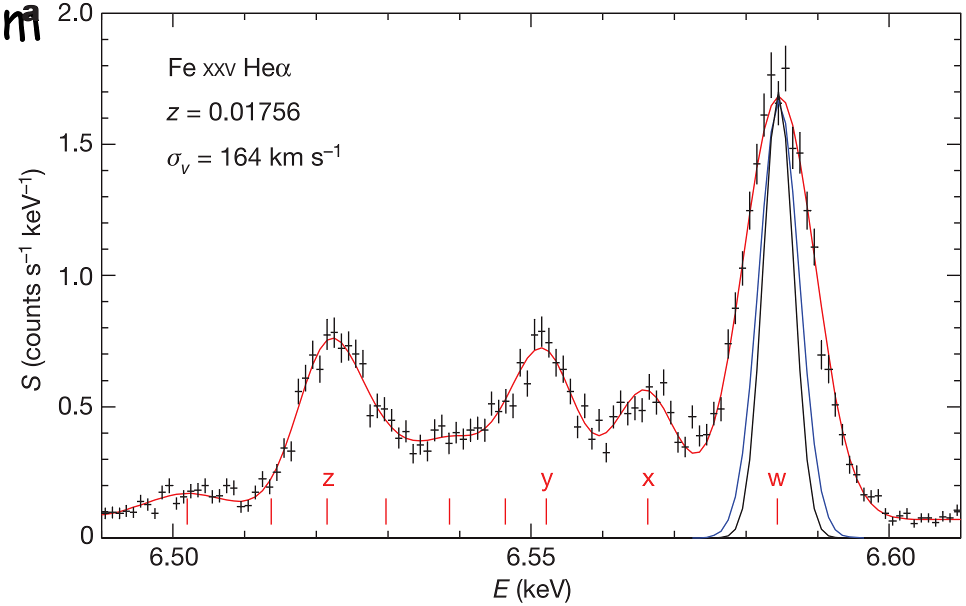


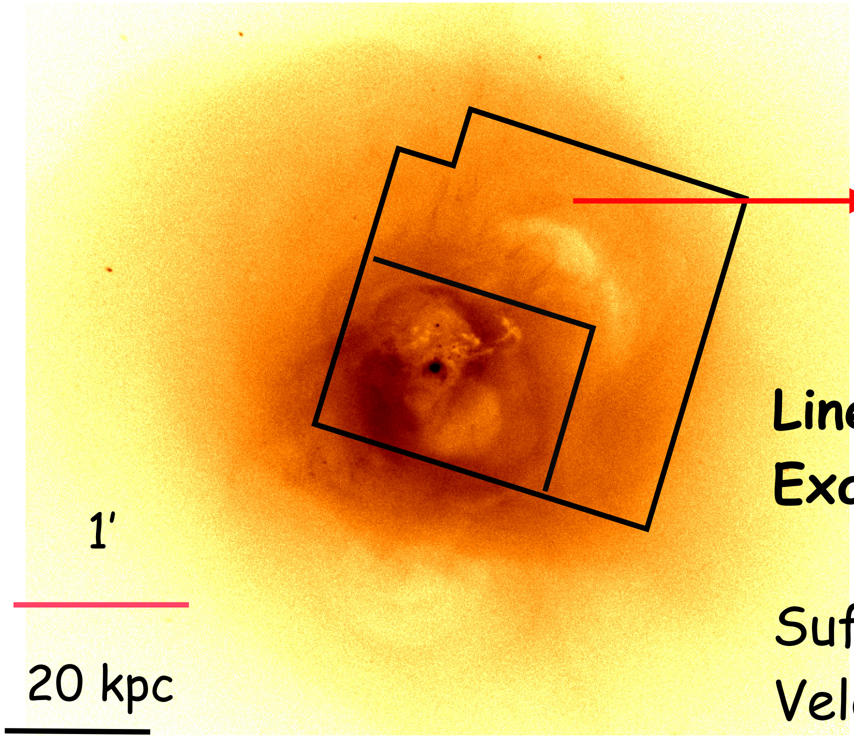
For M87 and Perseus

Hitomi - Feb 2016

- Microcalorimeter - first successful flight; 3 days of data
- Detector cooled to 0.05K yielded 5 eV energy resolution
- Sign error in maneuvering algorithm
  - Spun up and broke apart







Lines are broadened - σ = 165 km s^{-1}

Exactly as predicted from fluctuations

(but could also come from bulk flows)

Sufficient to offset radiative cooling

Velocity equivalent to 4% of thermal pressure

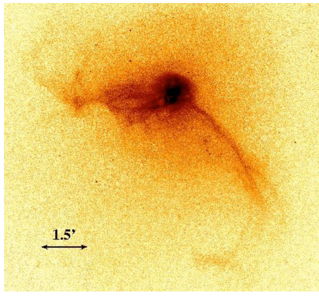
Supermassive Black Hole Outbursts M87 is the prototype

Massive (luminous) early type galaxies **ALL have hot atmospheres**:
Key to capturing feedback - **not perfect balance**

M87 shows details of shock/bubble energy partition
SMBH powers plasma outflow, drives shock, creates bubbles

Bubble energy ~50% of total outburst energy
Shock - 25% of energy captured
Outbursts are "long" duration (~1 Myr); weak shocks
Provide energy to radiatively cooling gas (5×10^{57} erg over 12 Myr)
Matches radiated X-ray emission

See the glimmer of unification of black holes, accretion modes, galaxy formation and SMBH co-evolution, dichotomy of spirals/ellipticals, ….

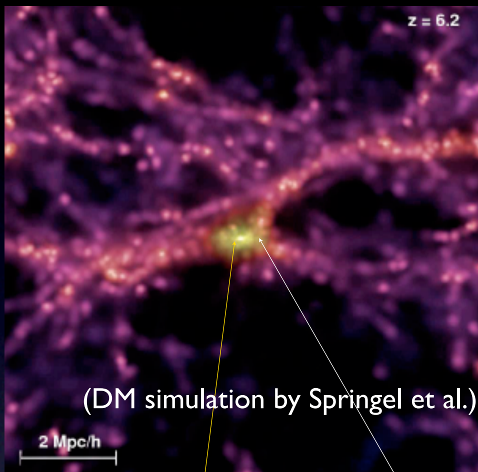


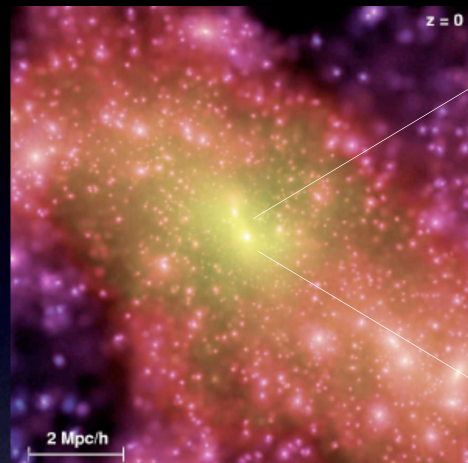
LYNX - 30 x Chandra's area with <1" angular resolution

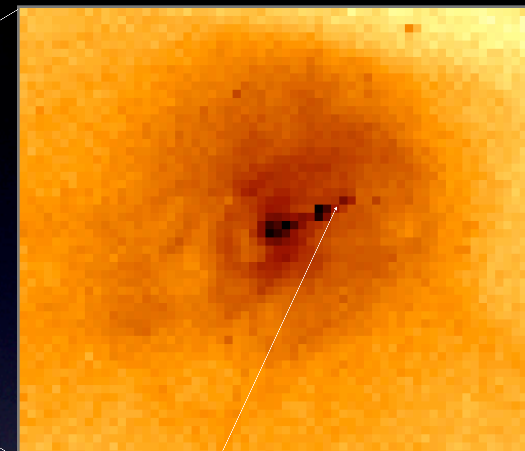
Growth of galaxy groups and $10^9 M_\odot$ black holes from z=6 to the present

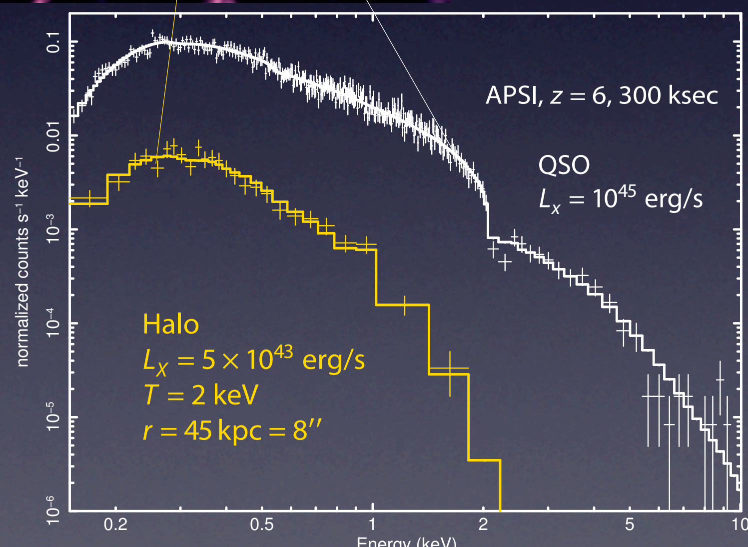
Sloan quasar at z=6 ⟶ "nursing home" at z=0

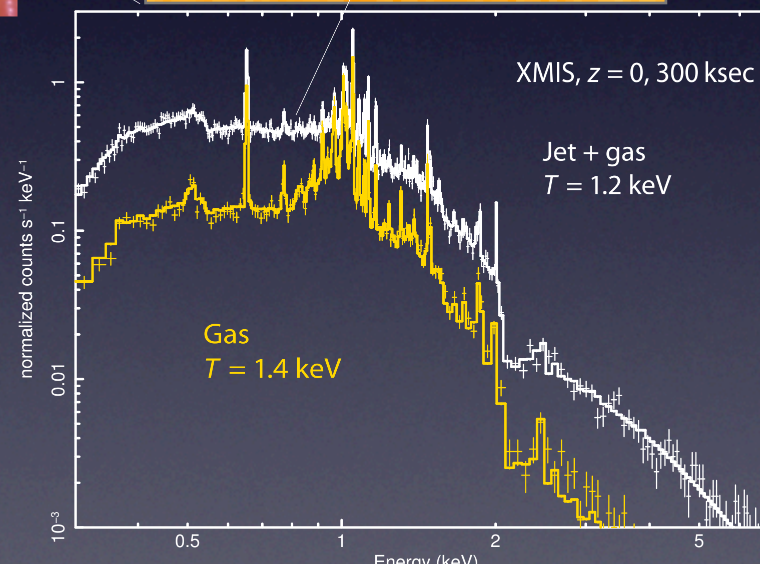
M87, *Chandra*, 1″ pixels











Sensitivity + angular resolution with wide-field imager — detect and resolve quasar host halos at z=6

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

Finis!