M87 - Feedback at Group Scales

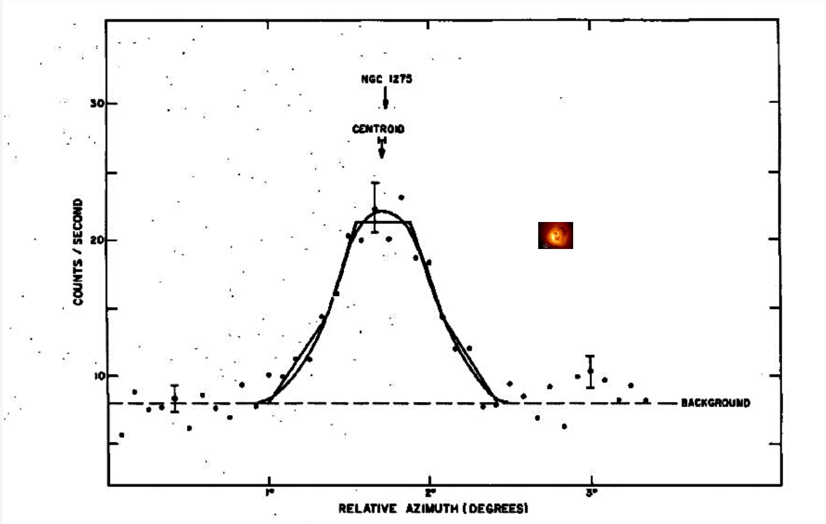
Bill Forman (SAO-CfA)

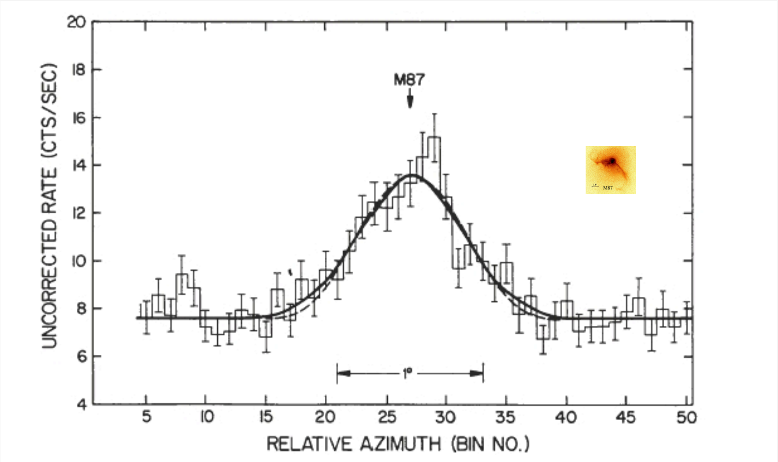
Collaborators: Eugene Churazov, Sebastian Heinz, Christine Jones, Akos Bogdan, Paul Nulsen, Ralph Kraft, Alexey Vikhlinin

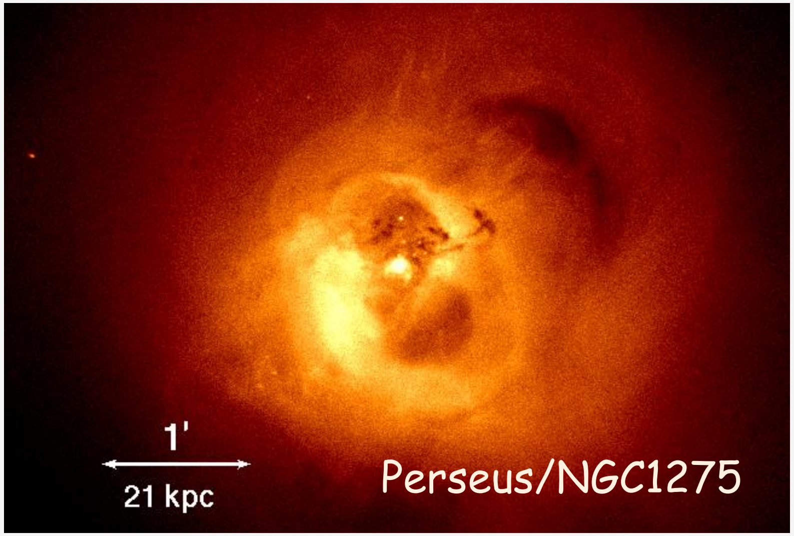
- Outburst up close (and personal)
- Classic shock
- Buoyant bubbles
- Energy partition and outburst duration
- **Early type galaxies with SMBH - feedback mode**
  - Feedback present in X-ray/optically luminous galaxies
  - Hot X-ray atmospheres - mechanism to capture SMBH energy
  - ADAF-like accretion

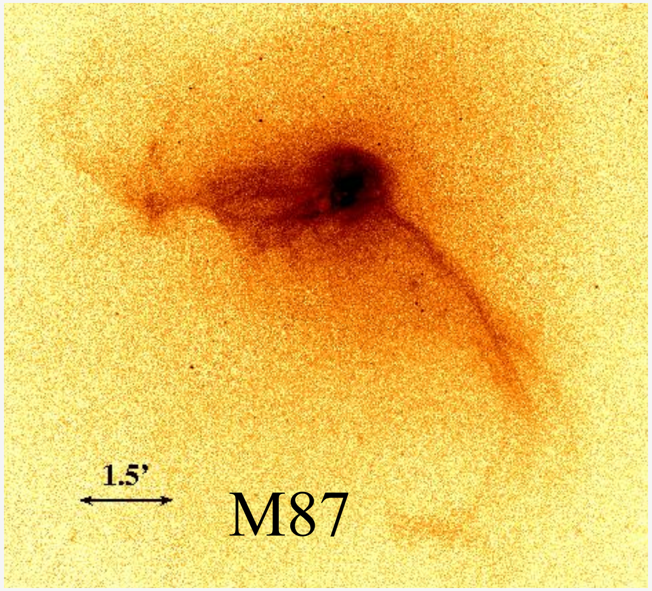
From UHURU (12 Dec 1970) to Chandra (1999)+11 years

from 1/2° to 1″



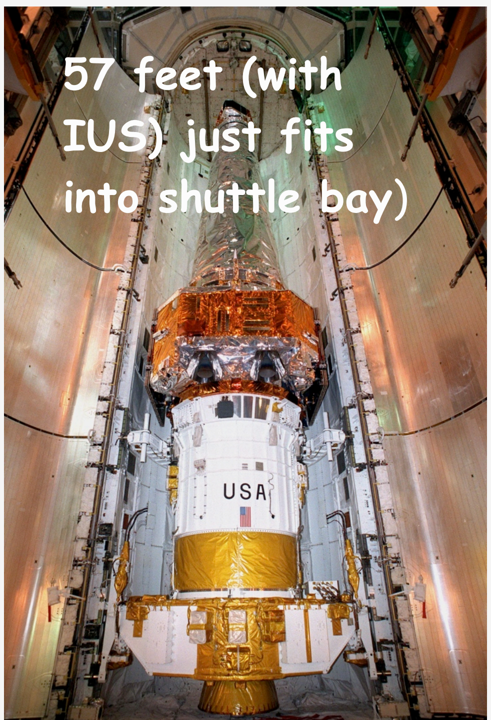






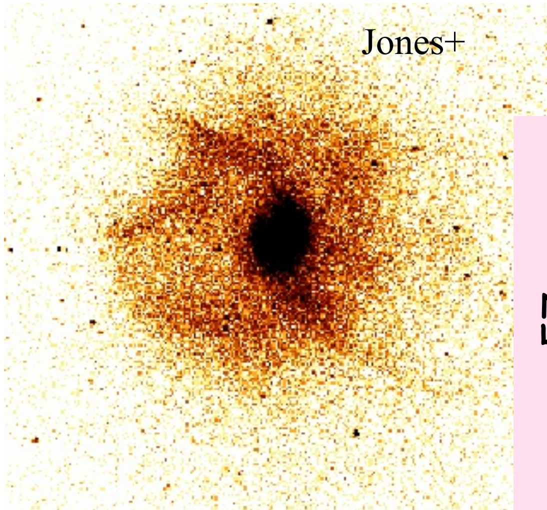
X-ray Astronomy - from Sco X-1 to Chandra

3 inch diameter solar X-ray telescope mirrors



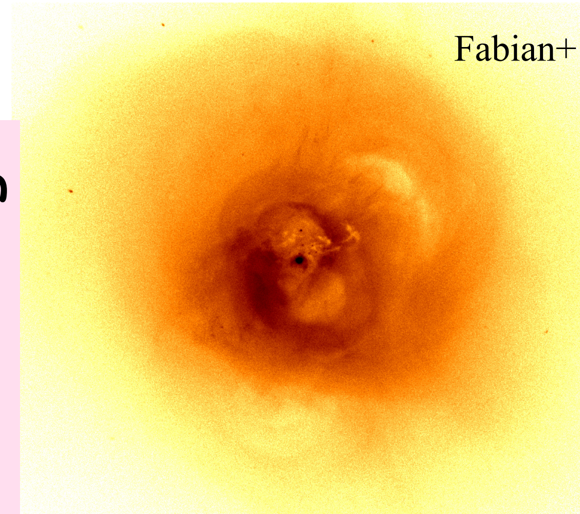
- 1962 - Detection of first non-solar X-ray source Sco X-1
- First imaging solar X-ray telescope (Giacconi 1963)
  - About the same diameter and length as Galileo's 1610 telescope
  - 380 years later, Hubble is 10^8 times more sensitive
- In 37 years X-ray astronomy achieved comparable increase in sensitivity with launch of Chandra
  - Largest/heaviest (22000 kg) payload launched by shuttle (Chandra+IUS)
  - Orbit goes 1/3 of distance to the moon (64 hour orbit)
  - Power 2300 watts = 1 hair dryer

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

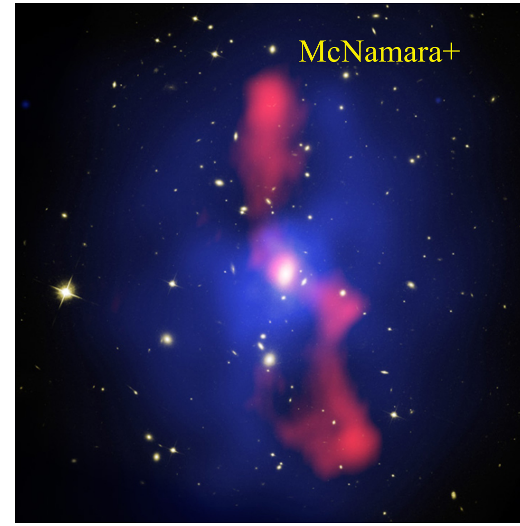


Galaxy
1 kpc
10^{56} ergs
10^{42} erg/s

M87 ~ 5×10^{57} ergs



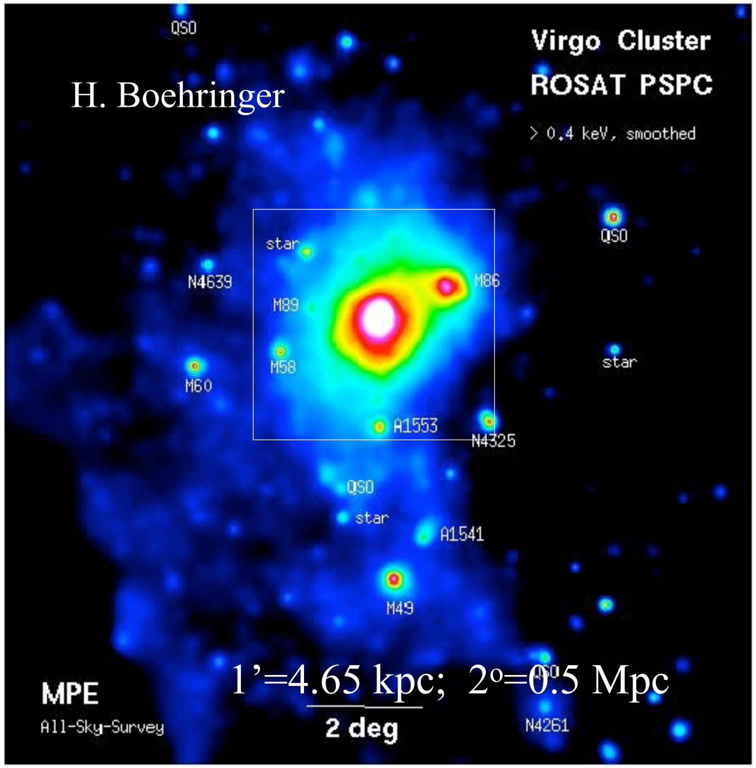
Group/Cluster Core
10 kpc
10^{59} ergs
10^{45} erg/s



Cluster (MS0735)
100 kpc
10^{62} ergs
10^{46} erg/s

Powerful outflows
Little radiation from black hole - not the familiar “AGN”
Gas cooling rates vary by > 100x
Span a wide range of dark matter halo mass
see Christine Jones for more on lower mass systems (Wednesday)

Virgo Cluster and M87



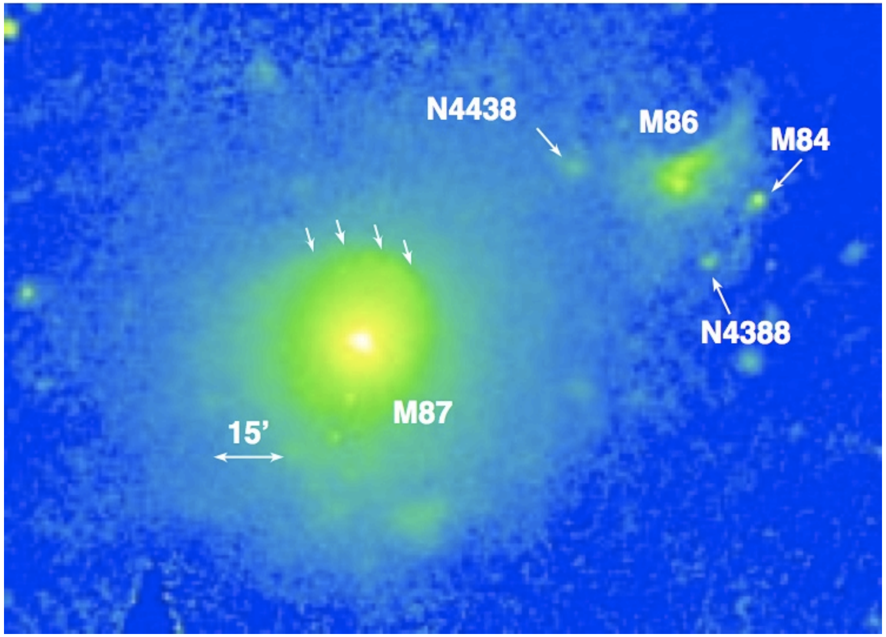
Optically luminous early-type galaxies are (hot) gas rich - up to 10^{10} M_{sun}

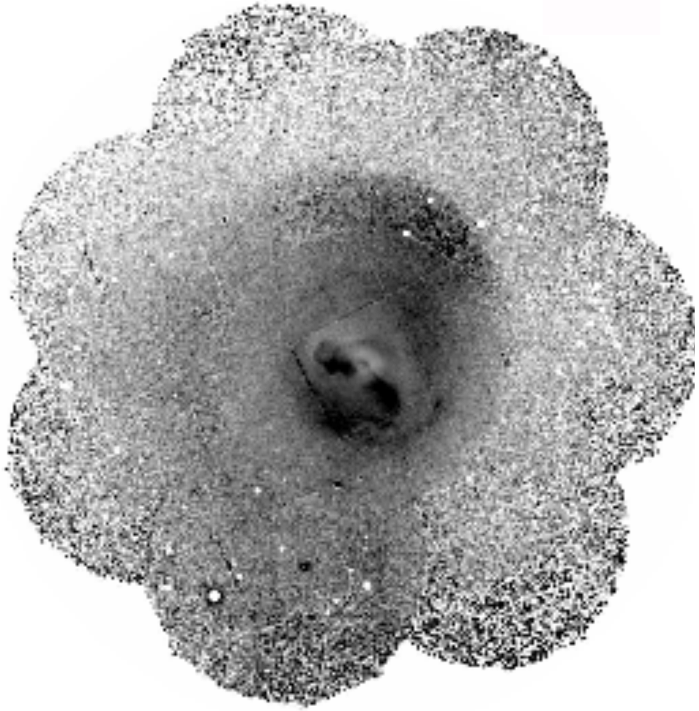
Virgo is dynamically young extensive merging, stripping

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 - **don't believe everything you "see"** (optically)
- M87 hosts $6\times10^{9}M_{sun}$ supermassive black hole and jet
- ***Classic cooling flow (24 M_{sun}/yr)***
- *Ideal system to study SMBH/gas interaction*

Gas Sloshing in M87 (XMM)





M87 shows gas "sloshing"

"Edge", contact discontinuity - cold front at ~100kpc

(Aurora Simionescu+10 from XMM-Newton)

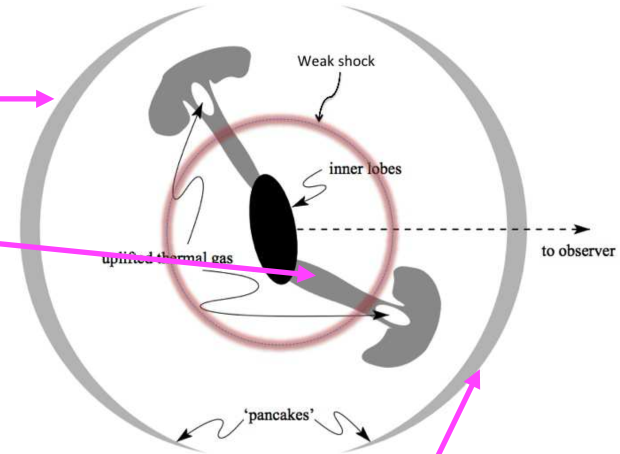
Very common (14/18) in "peaked" clusters (Markevitch+03)

see Markevitch & Vikhlinin 2007 for a review

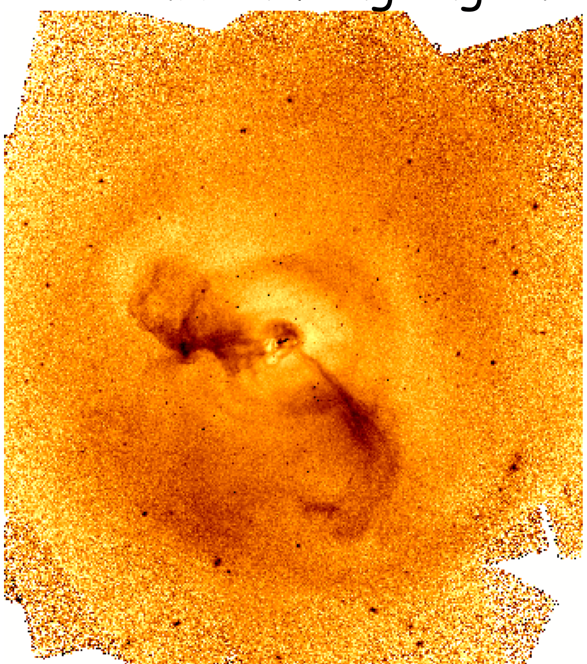
Driven by mergers

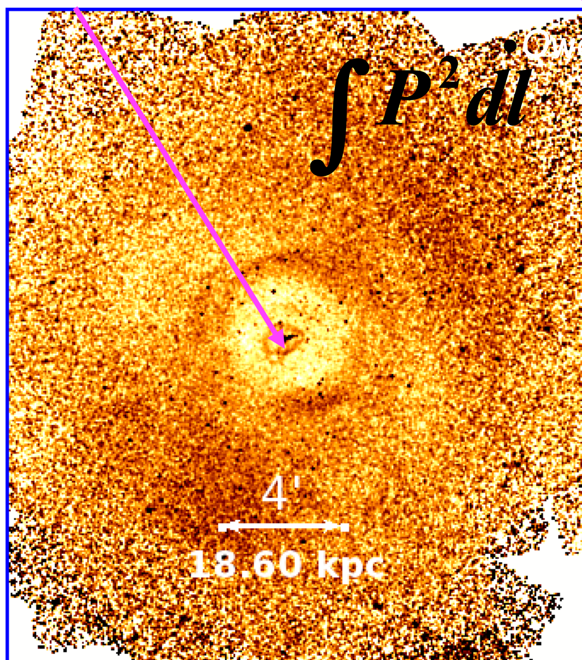
X-ray and Radio View of M87

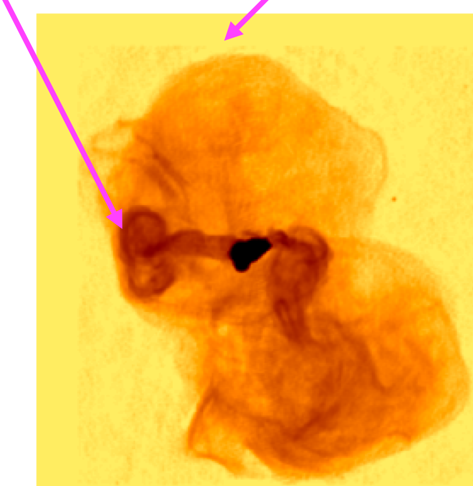
- At least four major SMBH outburst events
  - Large radio "bubbles" - also LOFAR (de Gasperin+12)
  - Radio/X-ray "arms" - produced/uplifted by buoyant radio bubbles - **pressure equilibrium**
    - **classic buoyant bubble** with torus i.e., "smoke ring" (Churazov et al 2001)
  - Shock at 12 kpc - initial inflation of bubble
  - Current/ongoing outburst



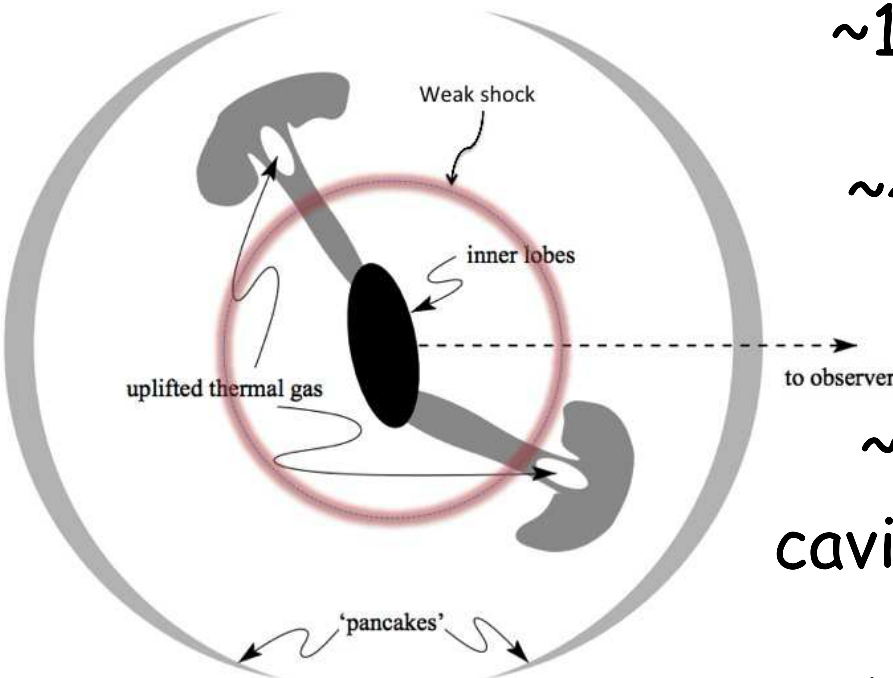
Old bubbles







- Owen+00 VLA
- Forman+05,+07
- Million+10, Werner+10



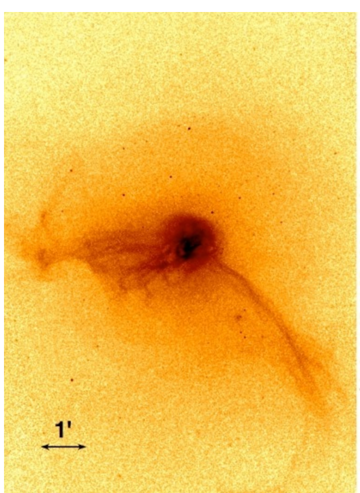
~100 Myr - old (radio) bubbles

~40 Myr - torus &
uplifted arms

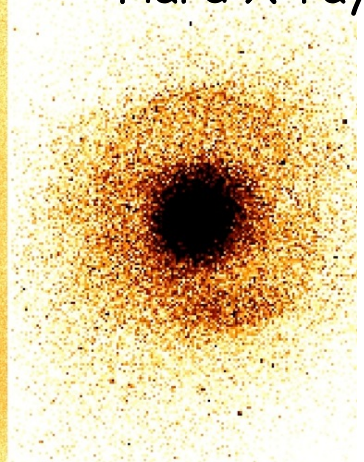
~12 Myr - shock & initial
cavity (still surrounds SMBH)

now - re-inflating cavity

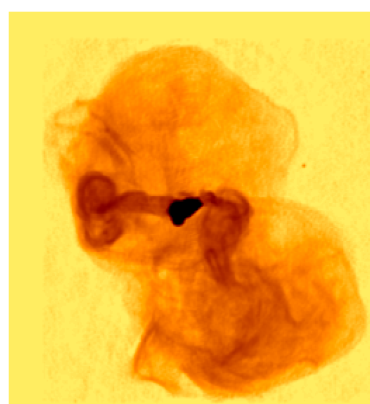
Soft band X-ray

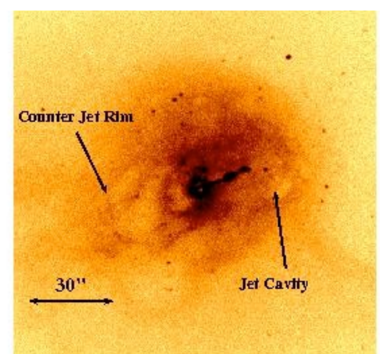


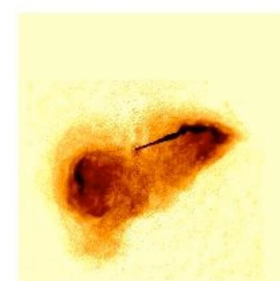
Hard X-ray

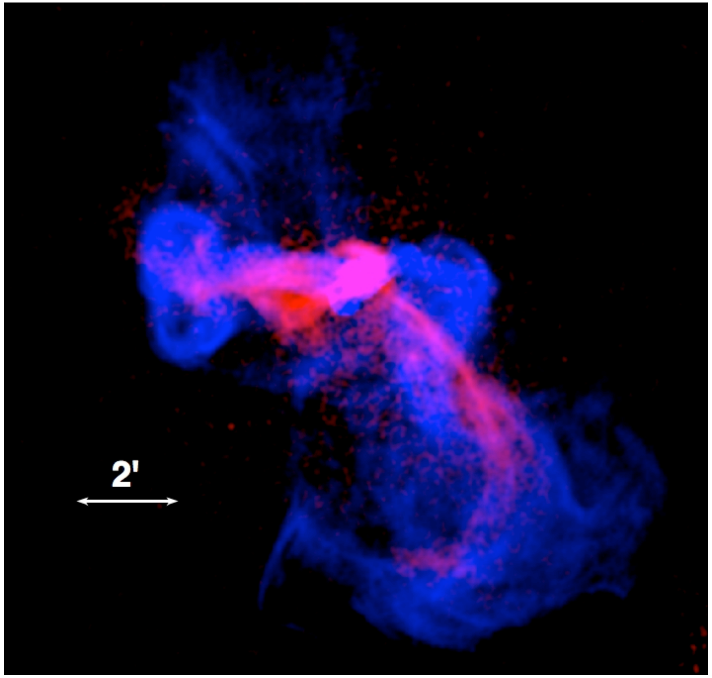


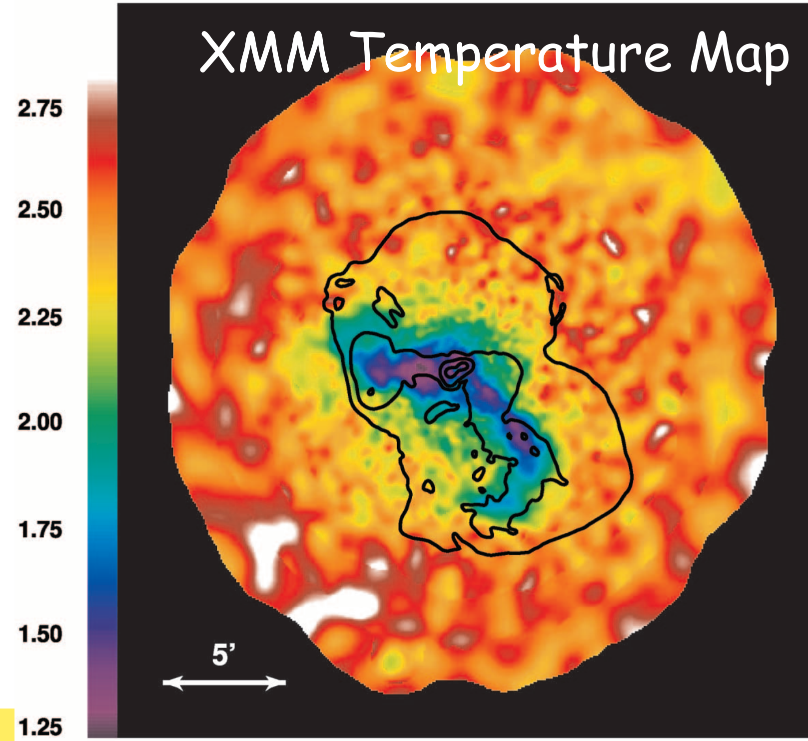
Radio

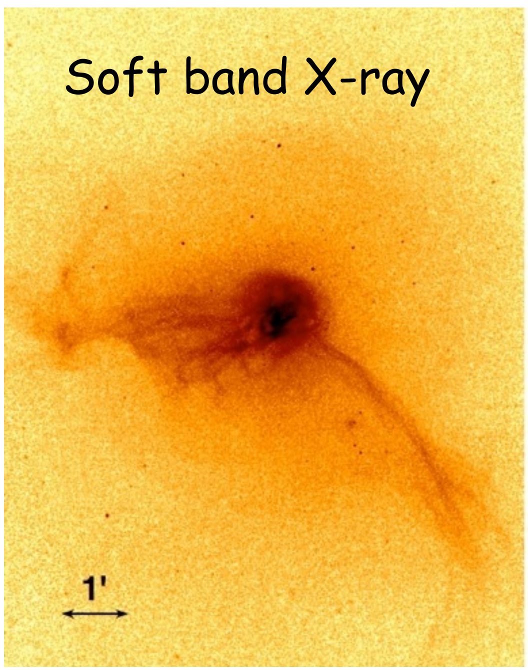


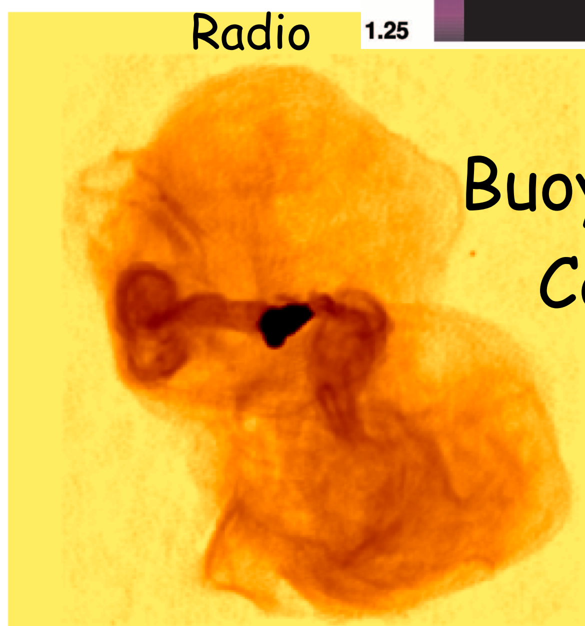








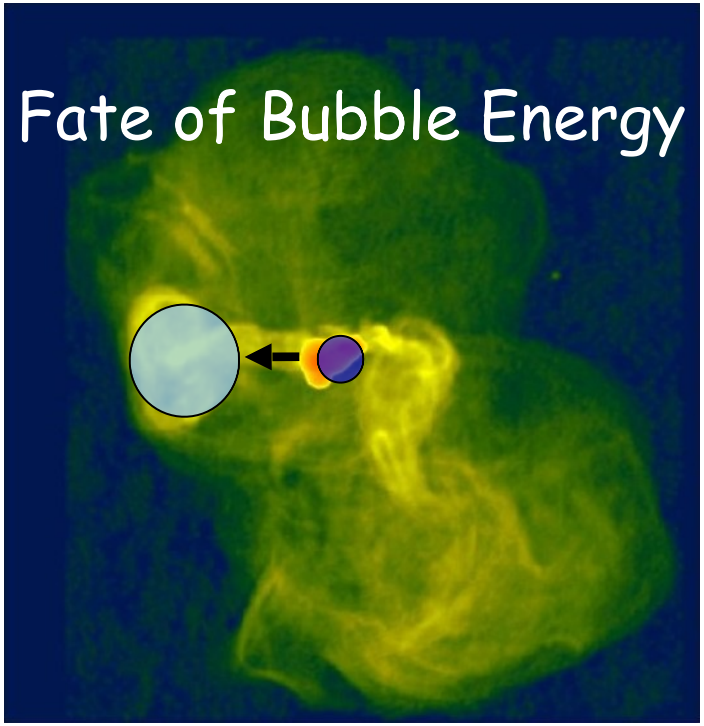




Buoyant (radio) bubbles

Cool, uplifted arms

Fate of Bubble Energy



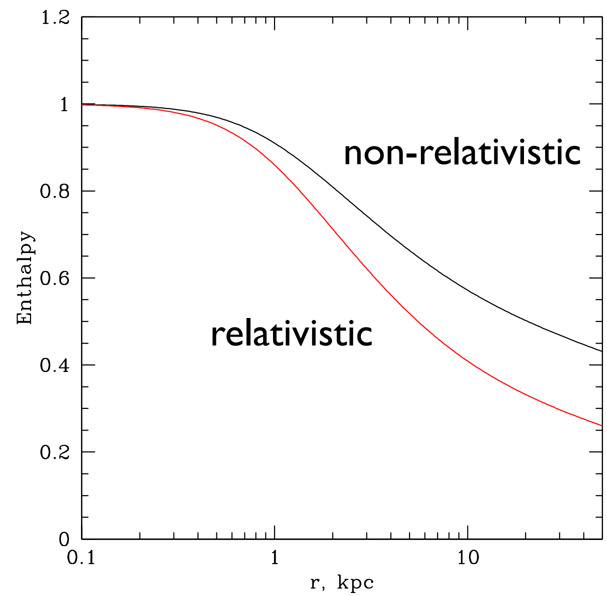
Rising bubble loses energy to surrounding gas

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

Generates gas motions in wake

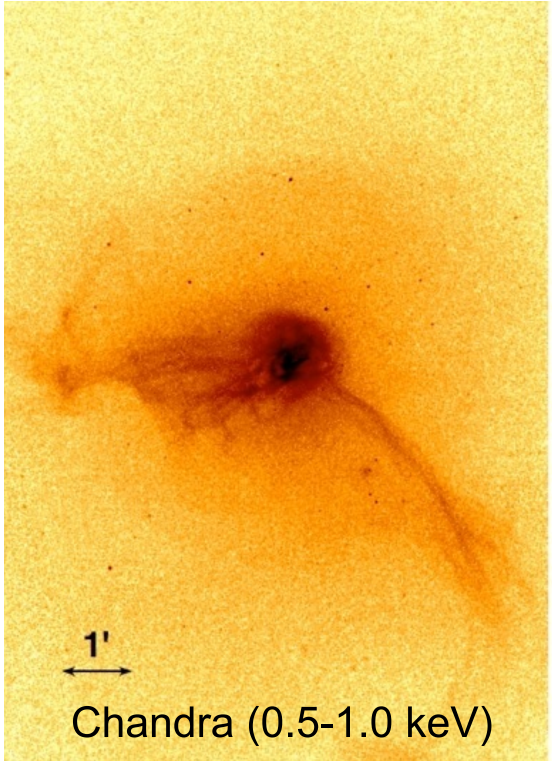
Kinetic energy (eventually) converted to thermal energy (via turbulence)

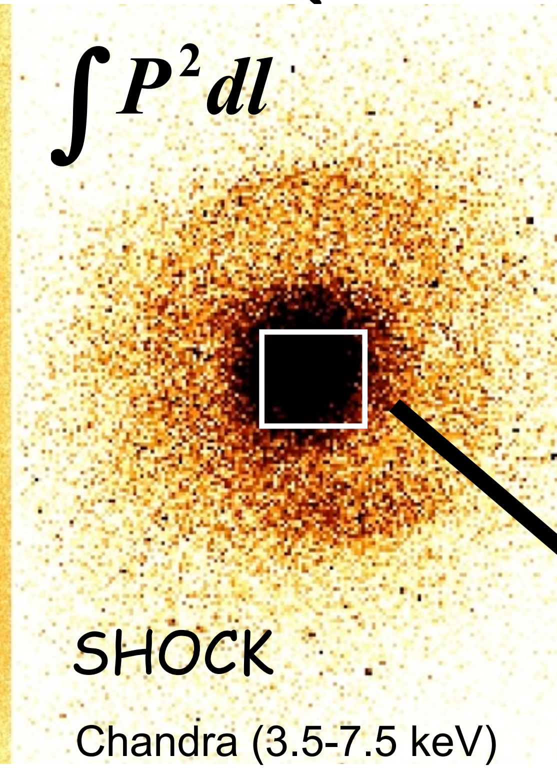
Bubble energy remaining vs. radius



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

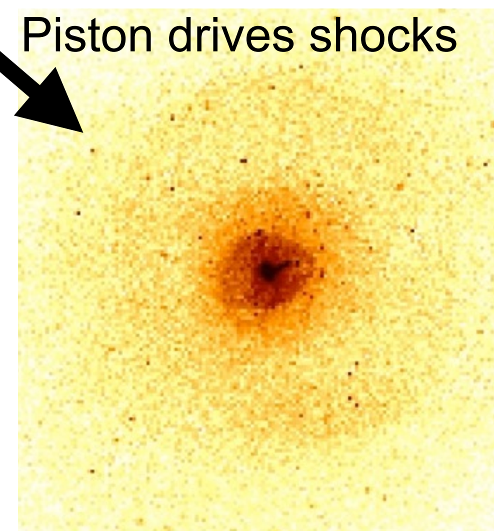
Shocks (and Bubbles)





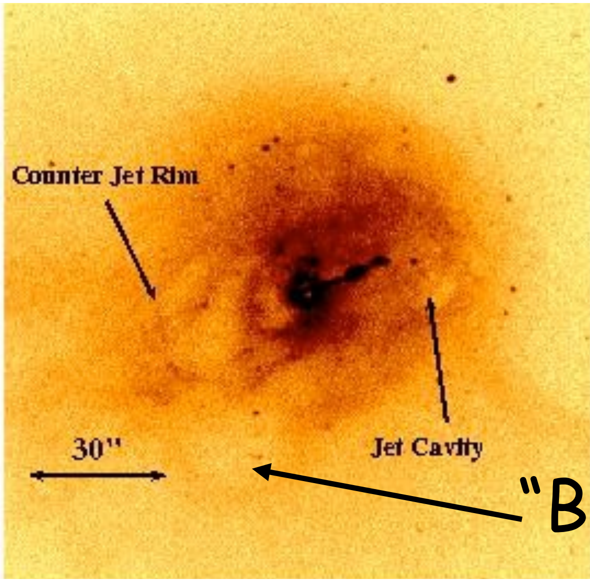
23 kpc (75 lyr)

Xarithmetic (Churazov et al. 2016)- choosing proper bands - isobaric arms (Arevalo et al. 2016)

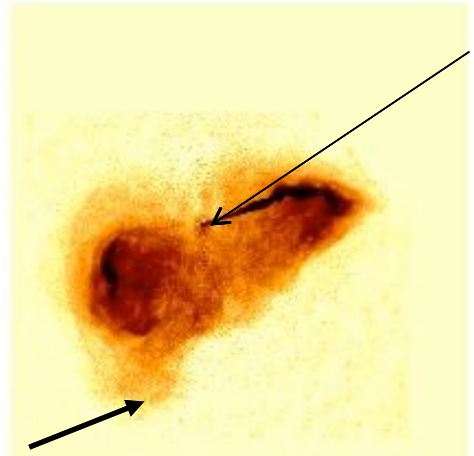


- Black hole = 6.6×10^9 solar masses (Gebhardt+11)
- SMBH drives jets and shocks
- Inflates "bubbles" of relativistic plasma
- Many small "bubbles"
- Heat surrounding gas
- **Model to derive detailed shock properties**

Central Region of M87 - the driving force



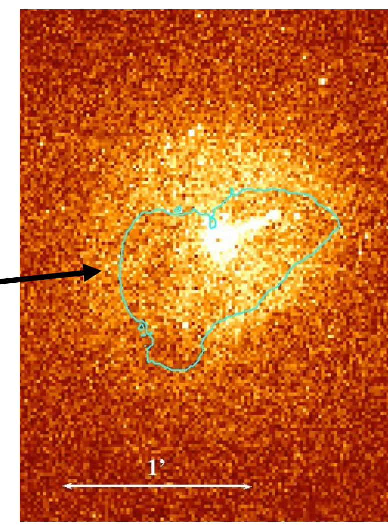
"Bud"



SMBH $3x10^9 M_{sun}$

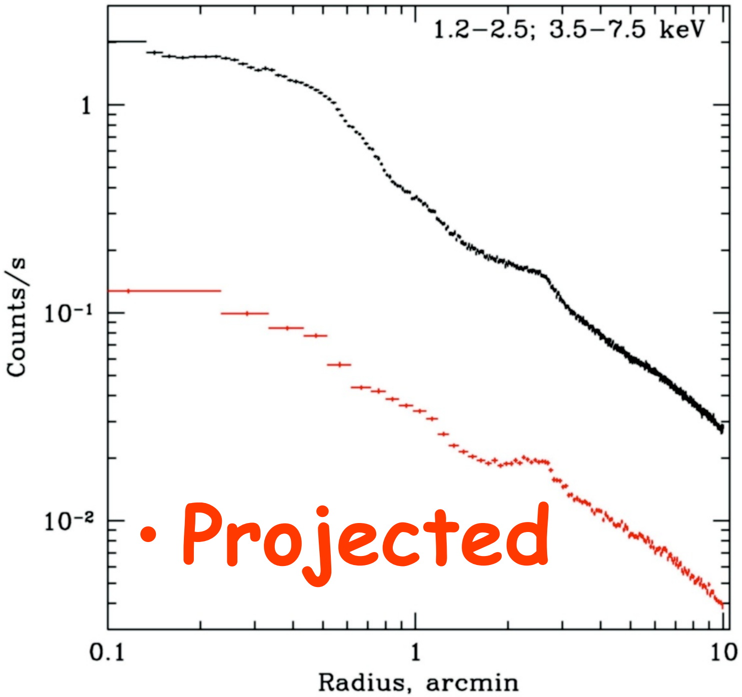
6cm radio

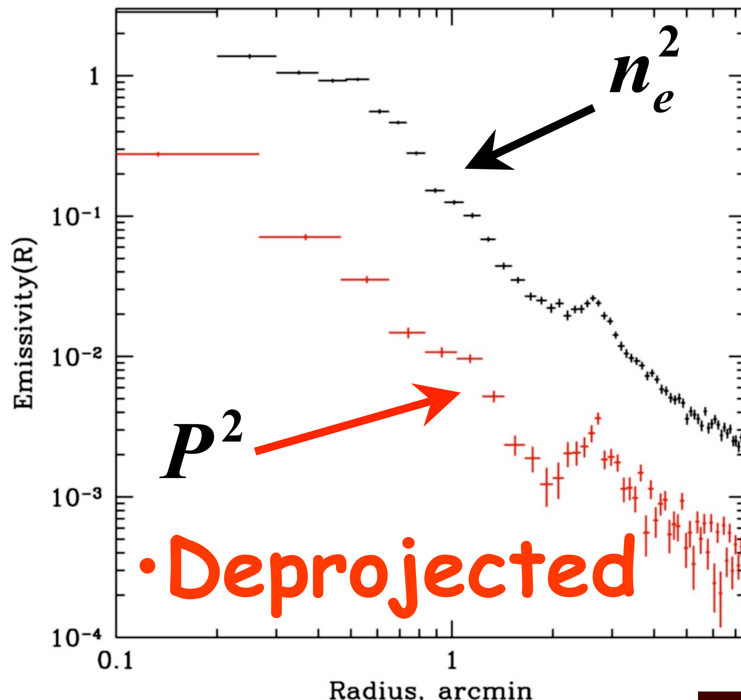
- Cavities surround the jet and (unseen) counterjet
- Bubble breaking from counter jet cavity
  - Perpendicular to jet axis;
  - Radius ~1kpc.
  - Formation time ~4 $x10^6$ years
- Piston driving shock
  - X-ray rim is low entropy gas uplifted/displaced by relativistic plasma

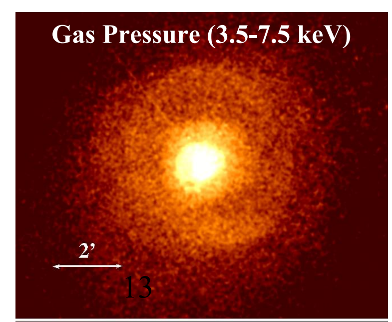


Shock Model - the data

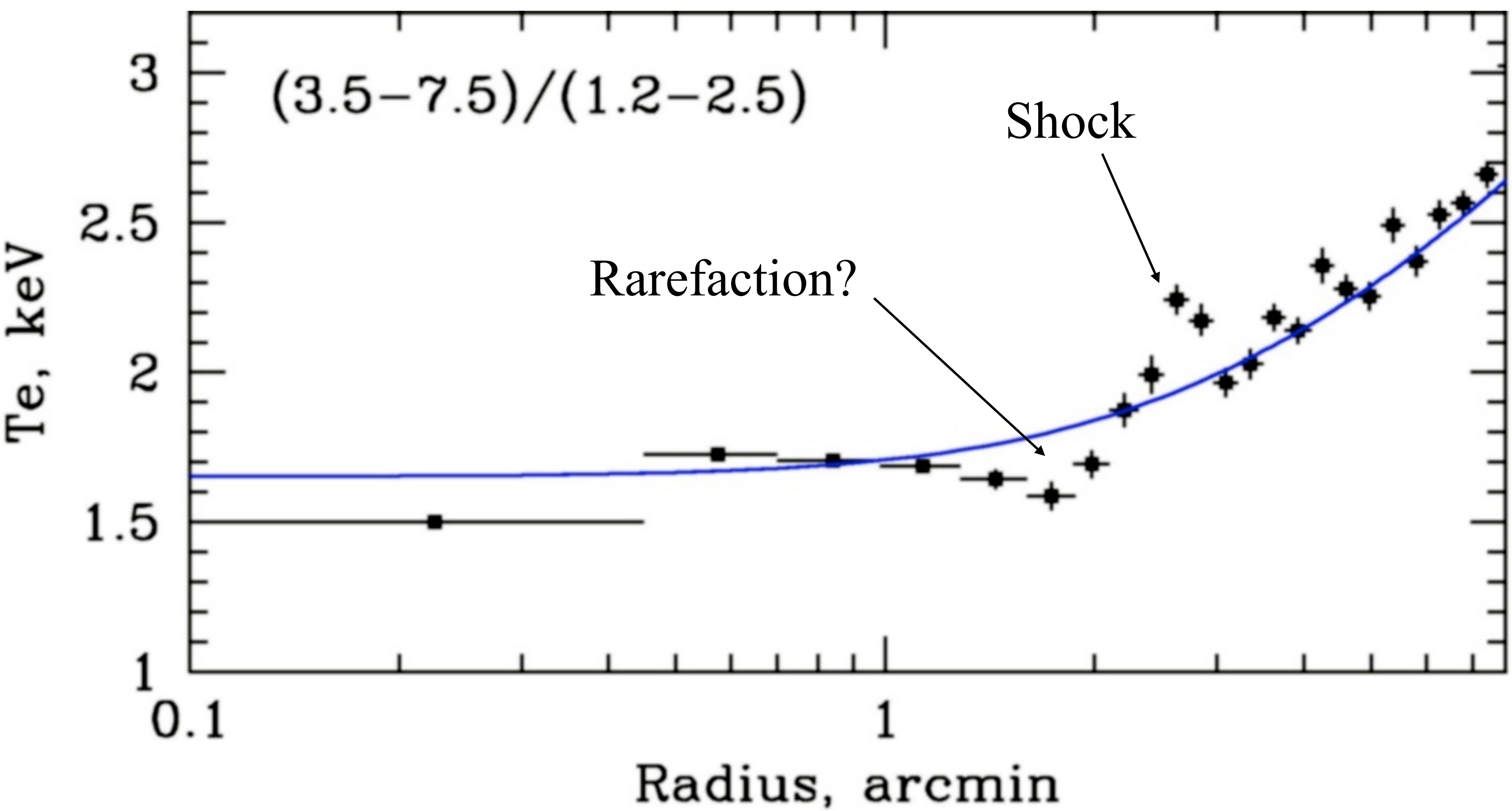
- Hard (3.5-7.5 keV) pressure
- soft (1.2-2.5 keV) density profiles







Deprojected Gas Temperature



Textbook Example of Shocks
Consistent density and temperature jumps

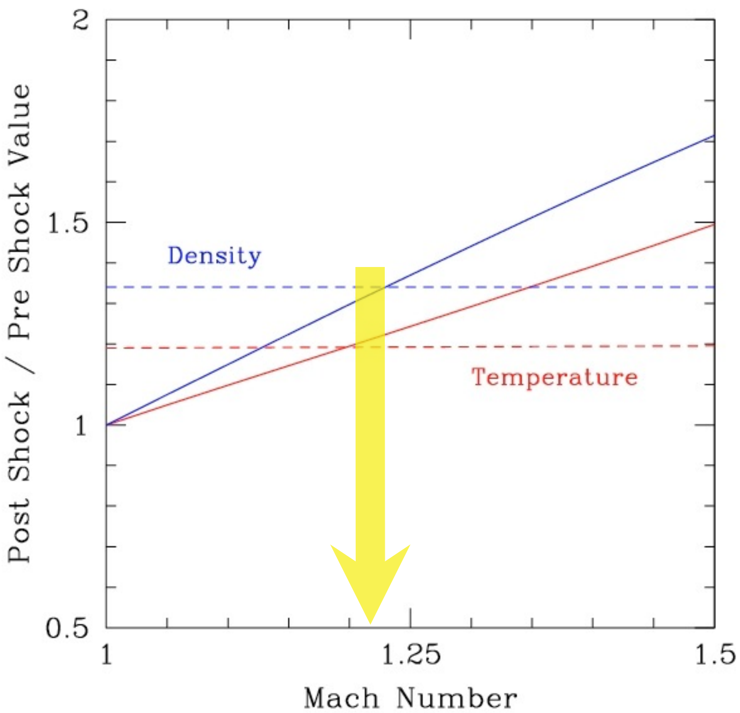
Rankine-Hugoniot Shock Jump Conditions

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

$$\rho_2/\rho_1 = 1.34$$

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

$$T_2/T_1 = 1.18$$



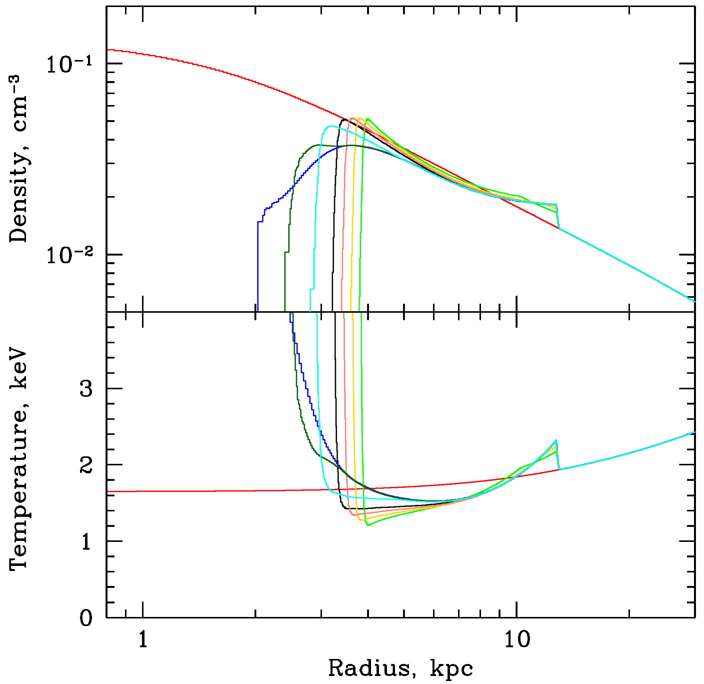
yield same Mach number:

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

M=1.2

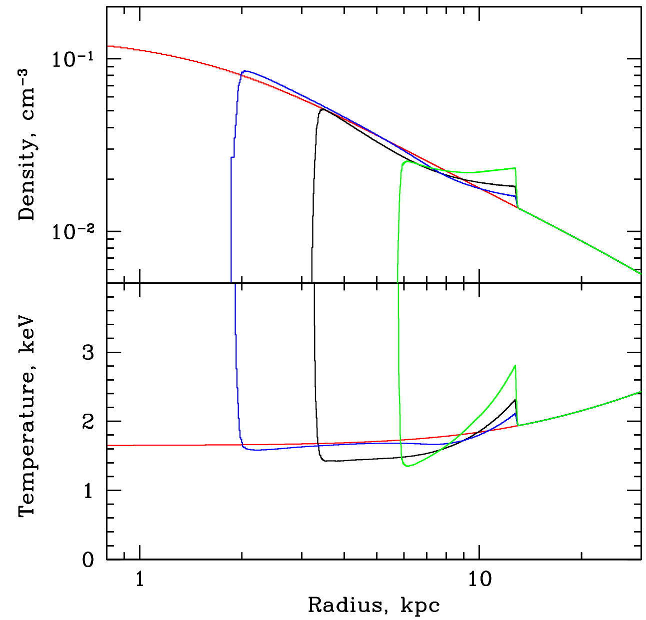
Outburst Model - grid in total energy and duration

Forman et al. 2016



E_{tot} = 5.5x10^{57} ergs, durations = 0.1, 1.1, 2.2, 3.1, 4.0, 4,4, 6.2 Myrs

Shock strength (nearly) governed by E_{tot}

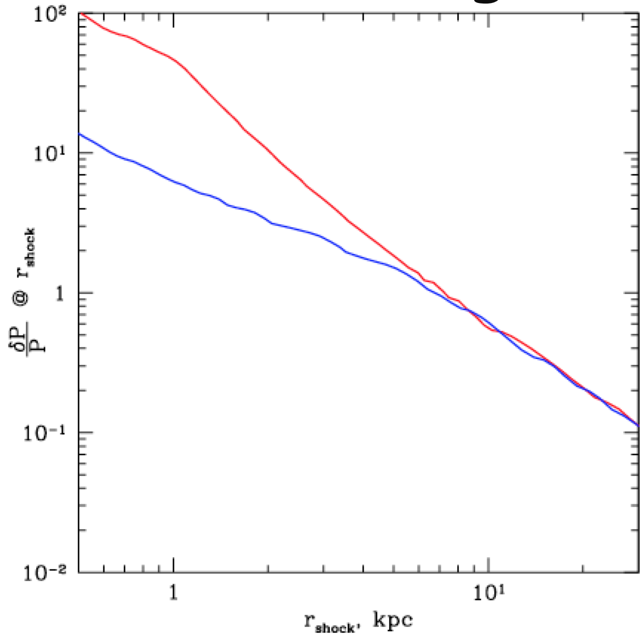


E_{tot} = 1.4, 5.5, 22x10^{57} ergs)
duration = 2.2 Myr

Central piston size drives duration

Match all constraints

Characterizing M87's outburst - Long vs. Short Durations

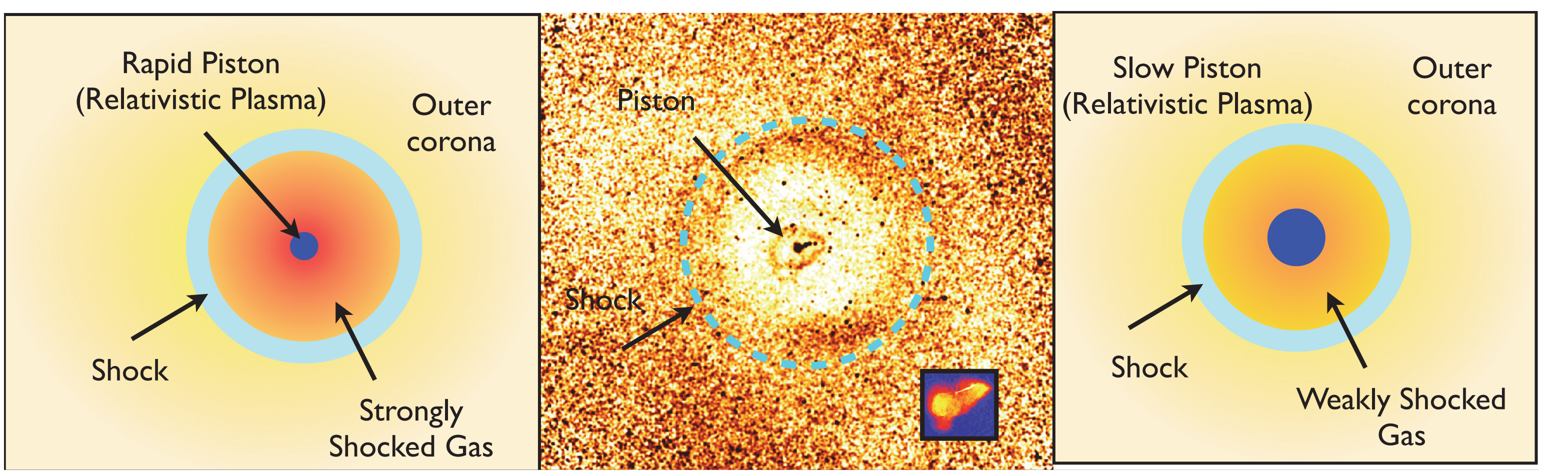


Forman et al. 2016

0.6 vs 2.2 Myr duration outbursts with $E_{outburst} = 5.5 \times 10^{57}$ ergs

Short outburst - leaves hot, shocked envelope outside the piston

NOT observed $\Rightarrow$ longer duration outburst required



M87 Outburst - superman or winnie?

Age ~ 12 Myr

Energy ~ 5x10^{57} erg

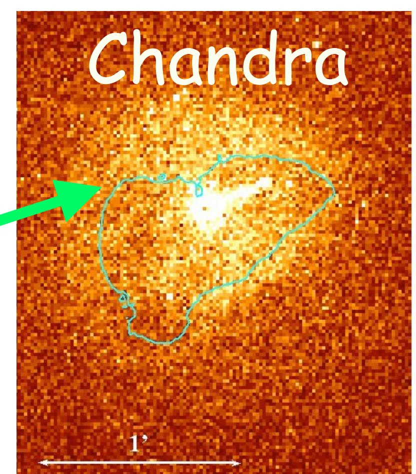
- **Bubble 50%**
- **Shocked gas 25% (25% carried away by weak wave)**

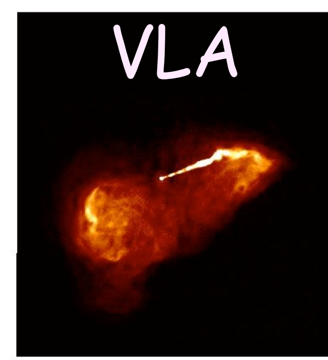
Outburst duration ~ 1 Myr

Outburst is “slow”

Fast - hot, low density shock heated region

Slow - dense, cool rim



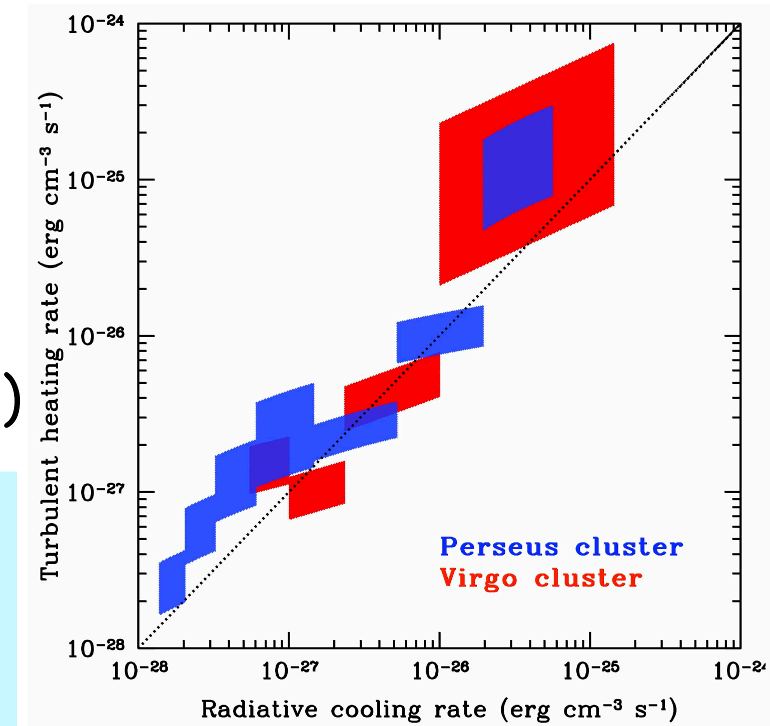


Zhuravleva+14 - Solving the "cooling flow" problem?

- 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+14b)

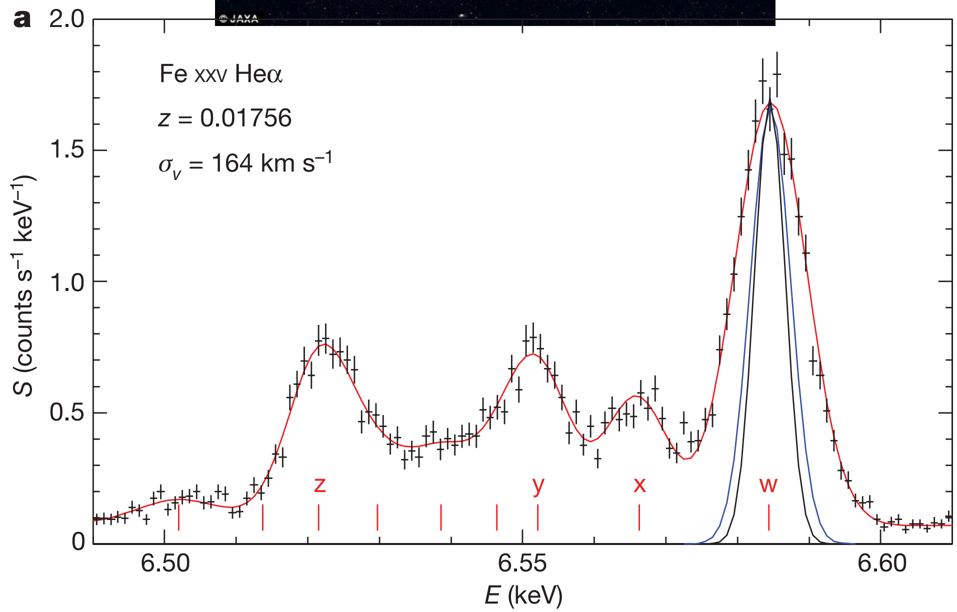
- Turbulent heating may be sufficient to offset radiative cooling
- Balances locally at each radius
- May be key to heating hot coronae from clusters to early type galaxies

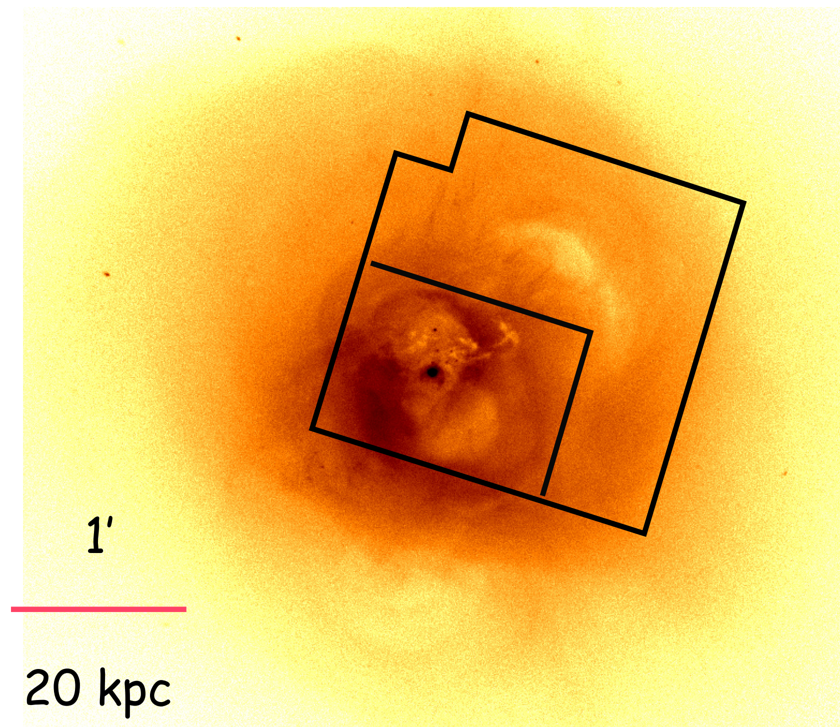


For M87 and Perseus

Hitomi - Feb 2016

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



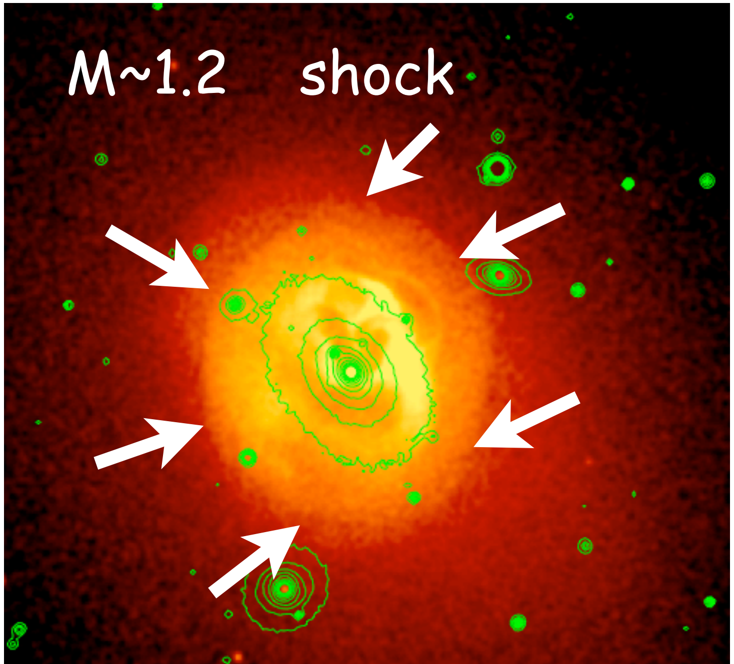


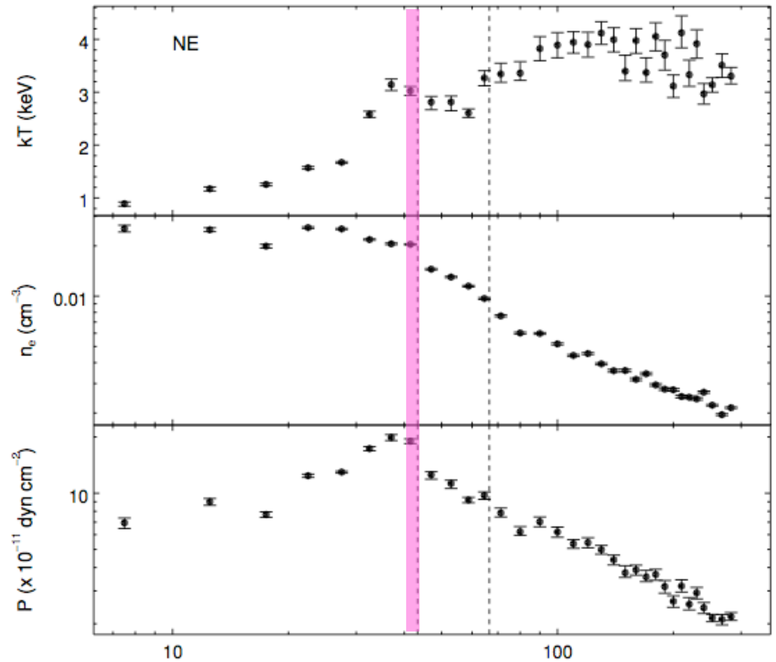
Lines are broadened - $\sigma = 165$ km s^{-1}

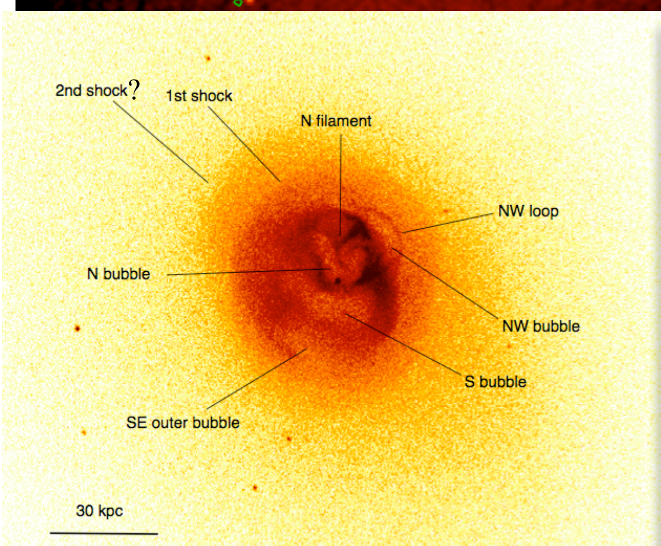
Sufficient to offset radiative cooling

Velocity equivalent to 4% of thermal pressure

Abell 2052 (650 ks) - Blanton+11



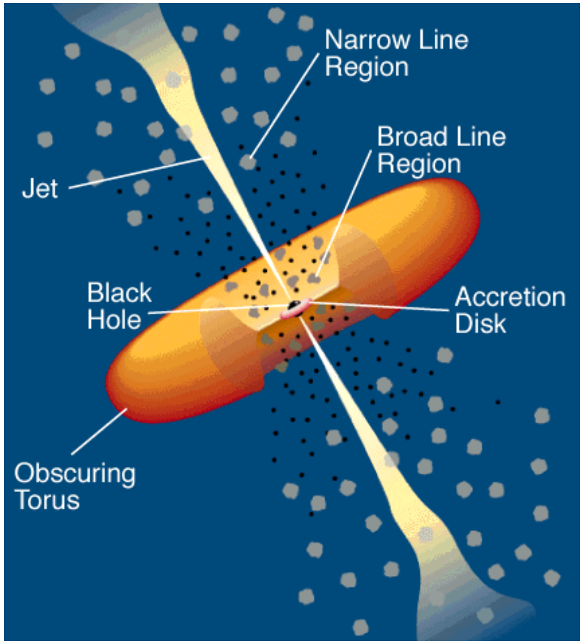




M~1.17 shock (at 31 kpc) nearly spherical

- density jump $\rho1/\rho2 = 1.25 \pm 0.02$ predicts T_{jump} measured at 2.1
- Hard to measure T_{jump} for weak shocks

Two Types of AGN accretion modes

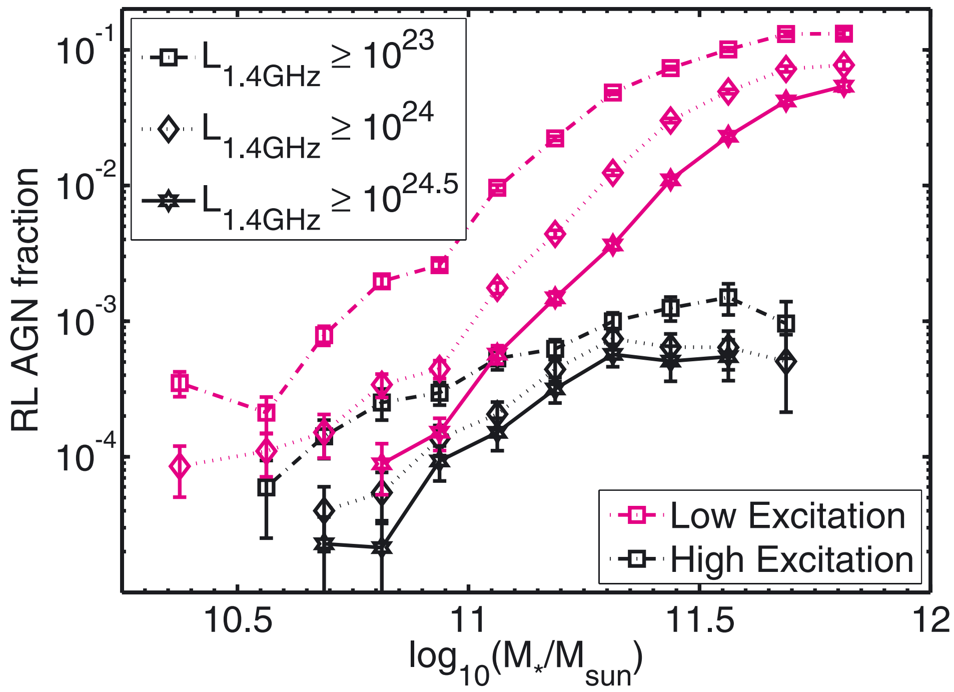


Croton +06
Churazov +05
Merloni & Heinz 08
Best +05, +06, +07, +12
...

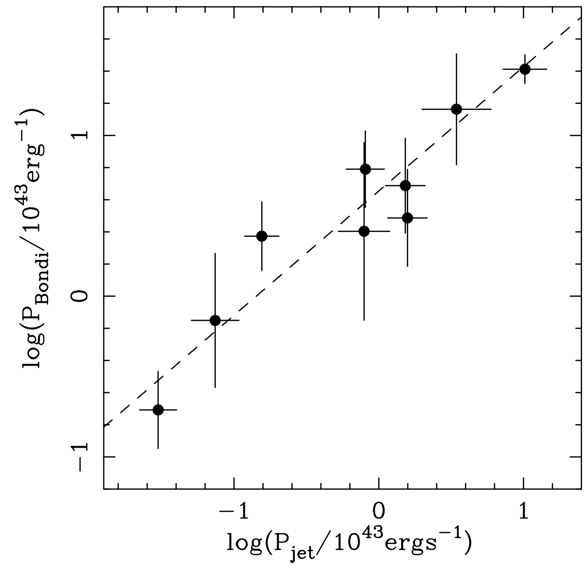
High excitation AGN
"standard" picture (called "quasar mode")

Low excitation AGN

- massive, red galaxies
- NO strong emission lines
- LACK accretion disk, broad line region, torus, ...
- Accrete cooling hot gas
- Advection-dominated accretion flows (ADAFs) - low Eddington ratio accretion
- show "radio-mode" feedback



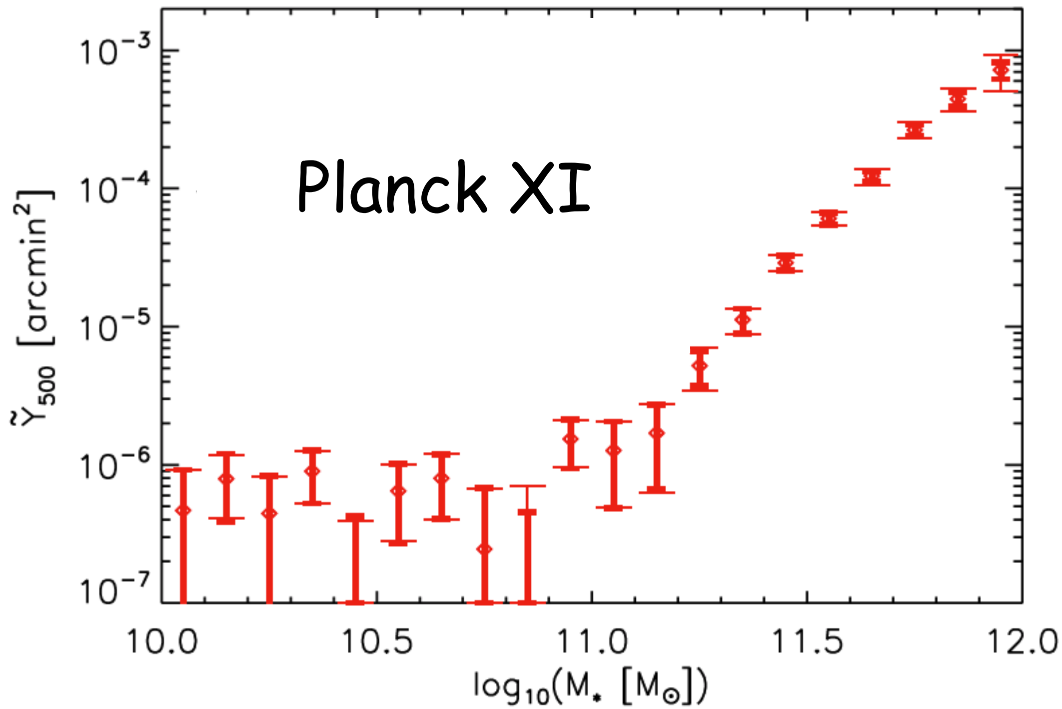
Janssen et al. 2013



Allen et al. 2006

Low excitation, massive, red galaxies

- accrete cooling hot gas (Bondi 1952 accretion)?
- have low Eddington accretion rates ($<10^{-5}$)
- show radio-mode feedback
  - $L_{radiated} \ll L_{total} \sim$ (up to a few percent of) $L_{Eddington}$



- Planck detects early type/BCG galaxy/group coronae in SZ stacks (to a few times 10^{11} M_{sun})
- 260,000 locally brightest galaxies from SDSS
- Probing wide range of halo mass to $M_{500} \sim 2 \times 10^{13}$ M_{sun}
- **Great promise with higher angular resolution (SPT/ACT)**
- **Will hot corona vanish at low mass (onset of winds)? Is there a qualitative change in radio jet/lobe properties vs. stellar/halo mass as hot coronae vanish?**

Feedback (black holes + hot gas) and Baseball

Early type (bulge) galaxies (and massive spirals - see Akos Bogdan's talk/poster)
- 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

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

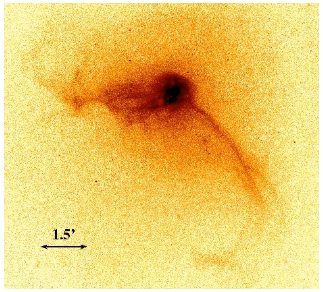
Bubble energy ~50% of total outburst energy

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



SMBHs in early type galaxies - radio/X-ray activity common

Key to providing outburst (accretion) energy

ADAF-like accretion ($L_{edd} < 10^{-5}$)

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

Finis!