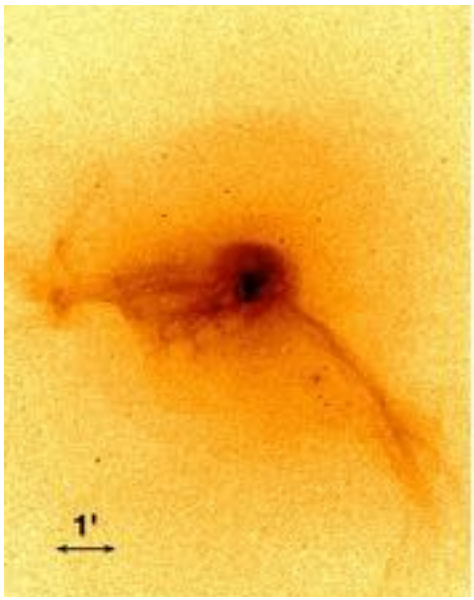
Characterizing the Outburst of the Super Massive Black Hole in M87

Bill Forman (SAO-CfA)

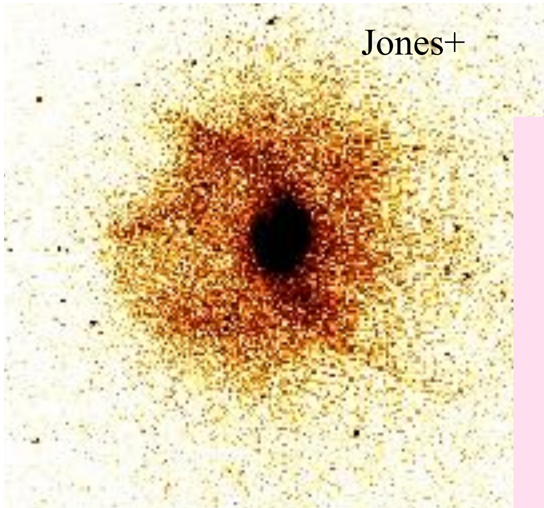
- Outburst up close
- Classic shock
- Buoyant bubbles and their filaments
- Energy partition and outburst duration
- Generally - weak shocks, buoyant bubbles



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

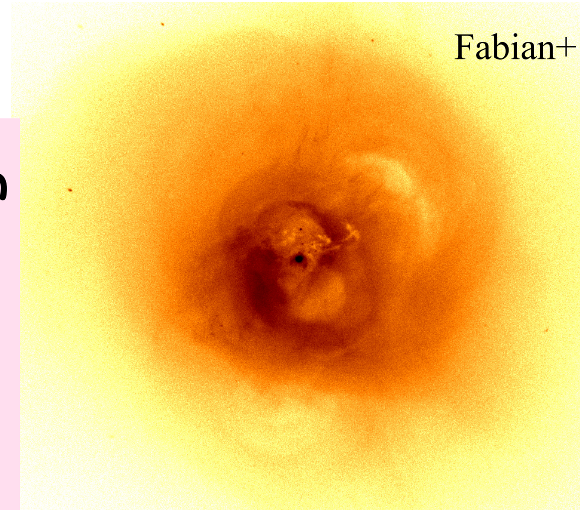
Churazov et al. 2001, ApJ, 554, 261
Forman et al. 2005, ApJ, 635, 894
Forman et al. 2007, ApJ, 665. 1057
Forman et al. 2017, ApJ, 844, 22

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

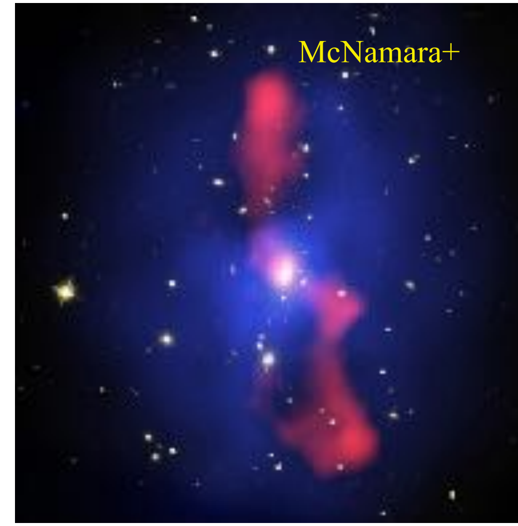


Galaxy
1 kpc
10^{56} ergs
10^{42} erg/s

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 - radiatively inefficient accretion
ADAF-like systems (see Yuan & Narayan 2014 for review)
Gas cooling rates vary by > 100x
Span a wide range of dark matter halo mass

Virgo Cluster and M87

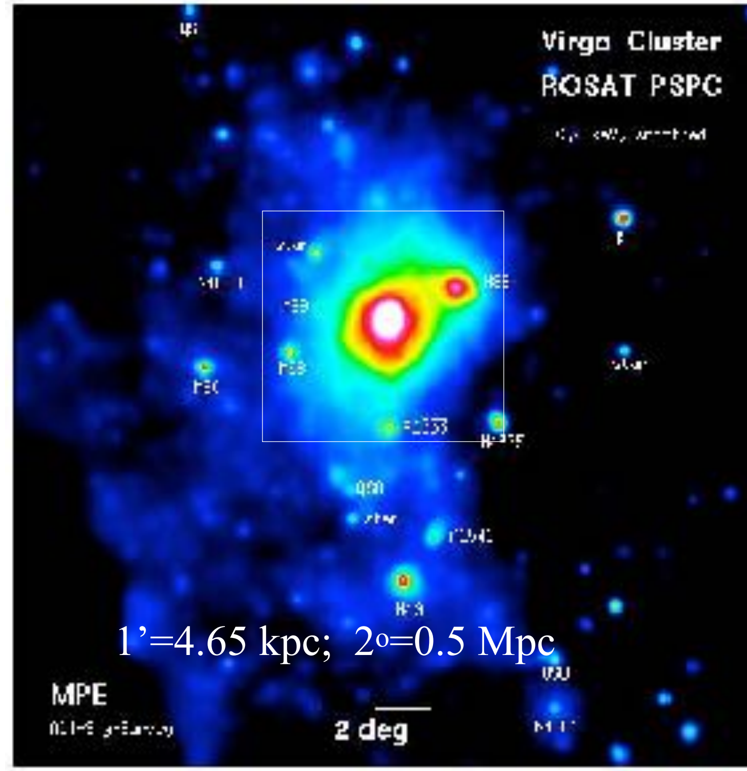
Old:

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

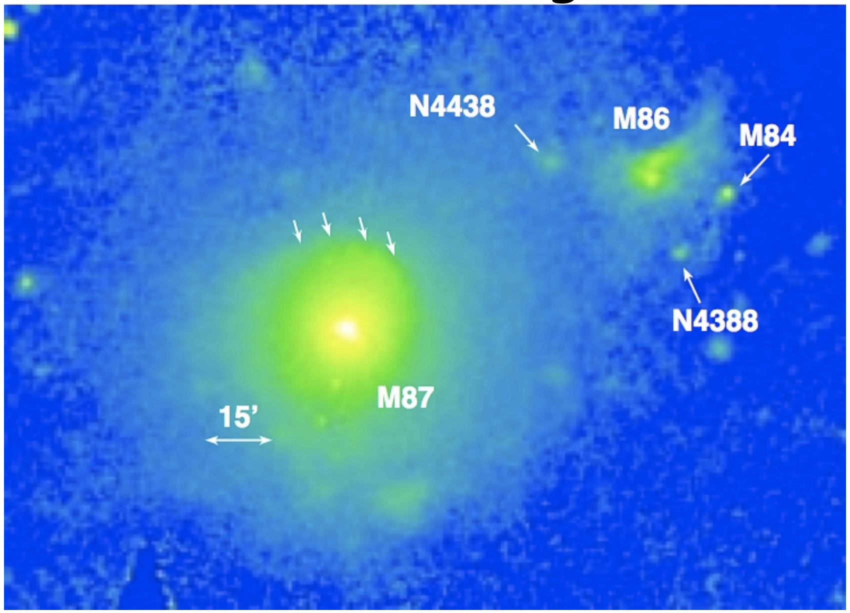


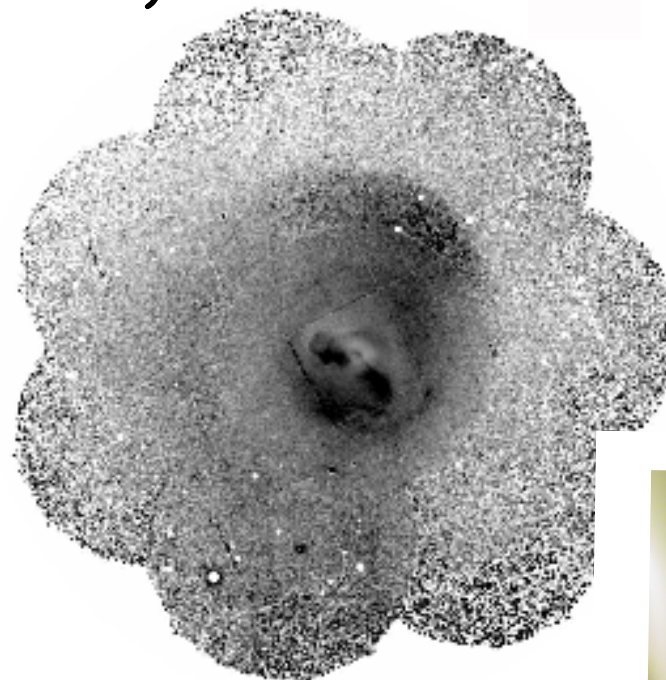
M87 - central dominant galaxy

- 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

4.65 kpc = 1′

Gas Sloshing in M87 (XMM)





M87 shows gas "sloshing"

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

(Simionescu+10 from XMM-Newton

Norbert Werner+16 argues for suppression of viscosity to less than 10% of Spitzer value

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

see Markevitch & Vikhlinin 2007; Bykov+15 for reviews

Driven by (minor) mergers

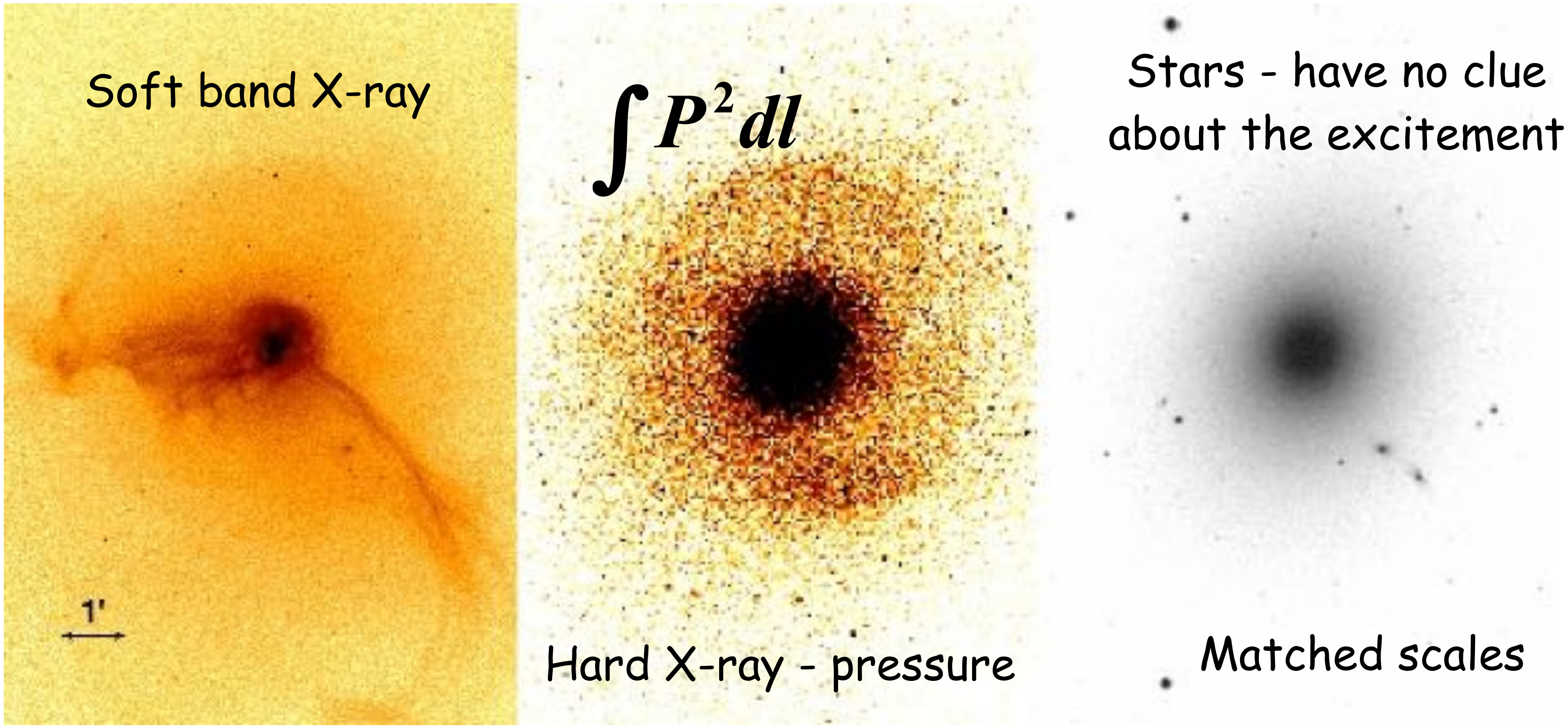
Mild compared to Perseus - M87 core is less disturbed

Chandra view of M87

"Raw" images

Just select different energy bands

See the over-pressurized regions = shocks



Isobaric arms (Arevalo et al. 2016)

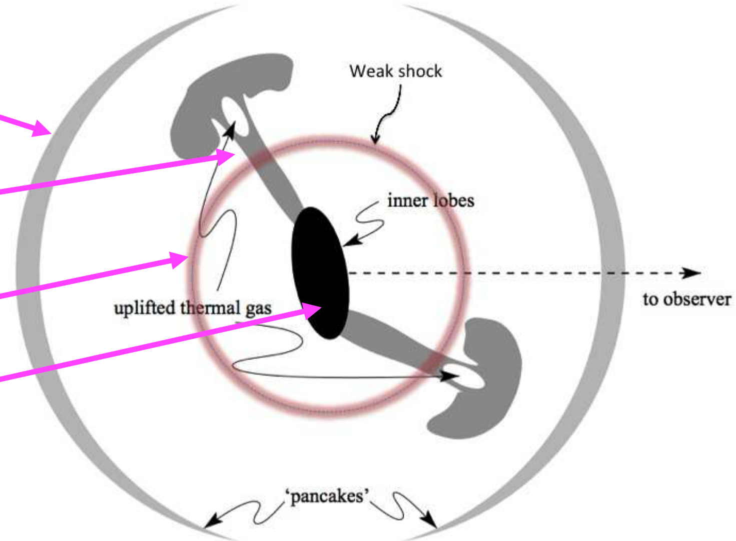
Xarithmetic (Churazov et al. 2016)

~100 Myr - old (radio) bubbles

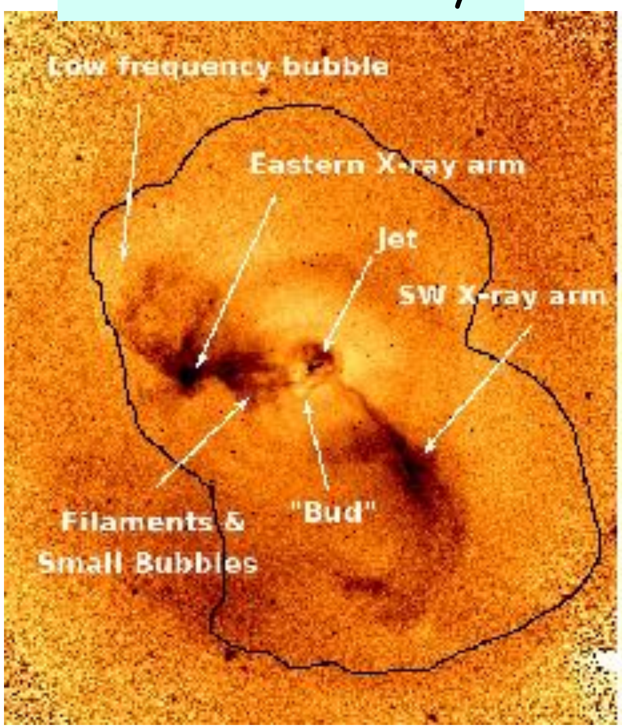
~40 Myr - torus & uplifted arms

~12 Myr (12 kpc) - shock

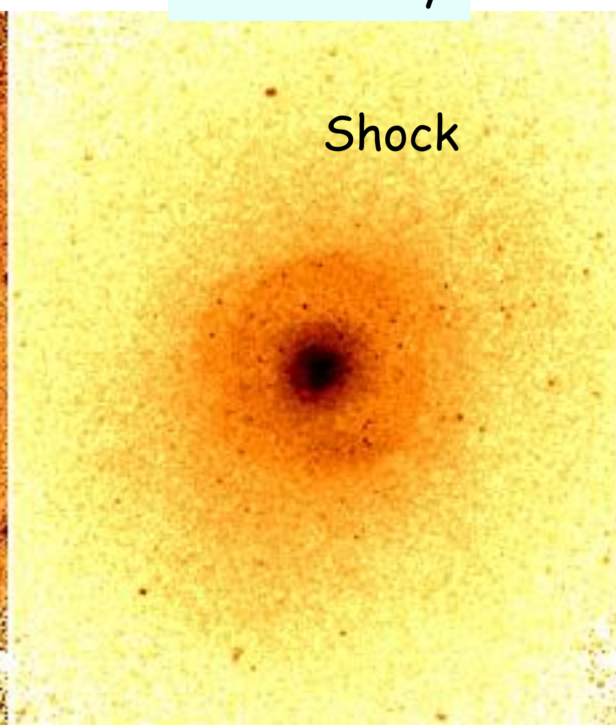
now - **re-inflating** cavity



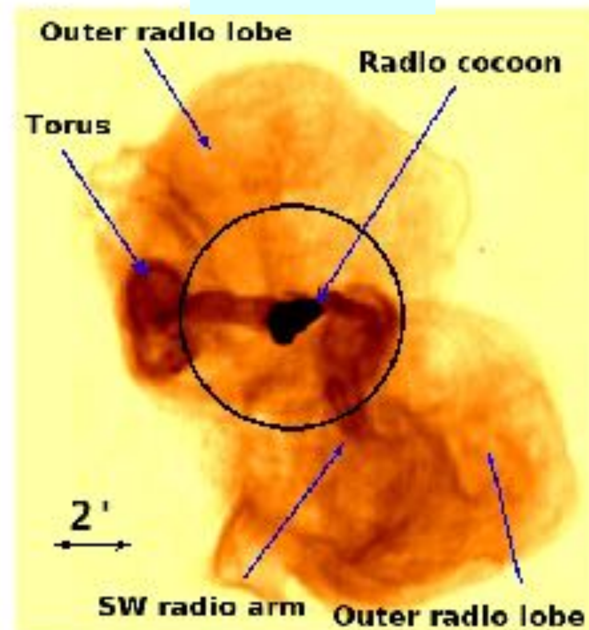
Soft band X-ray

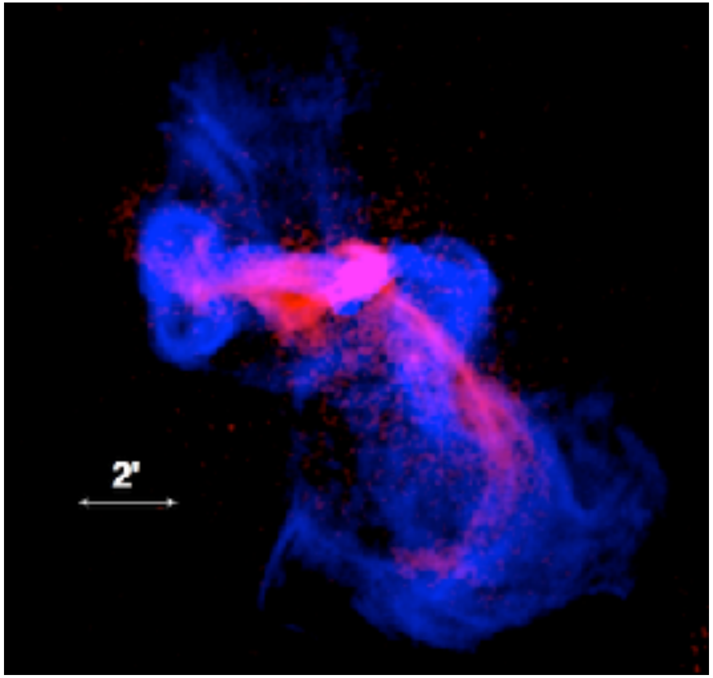


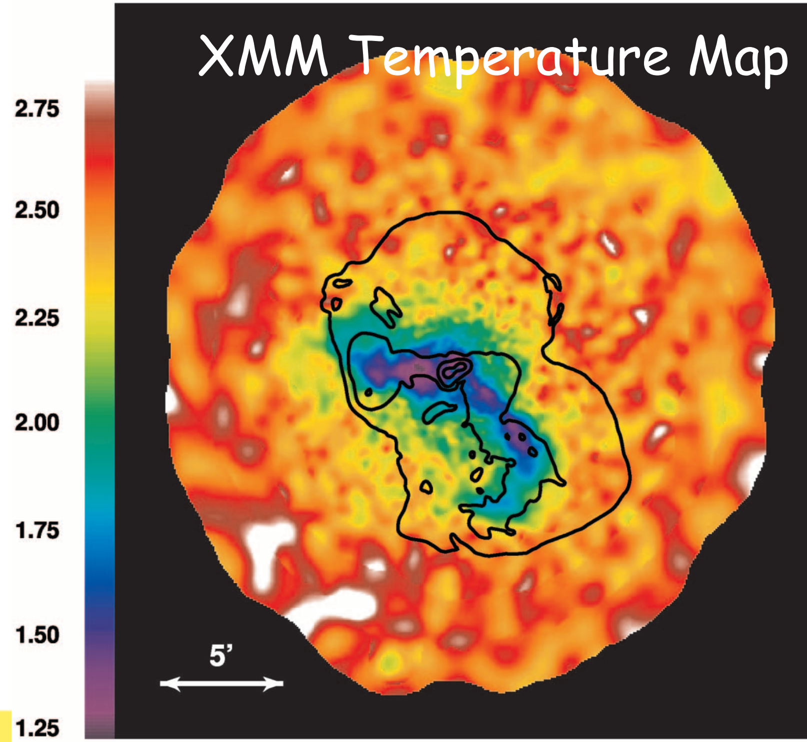
Hard X-ray

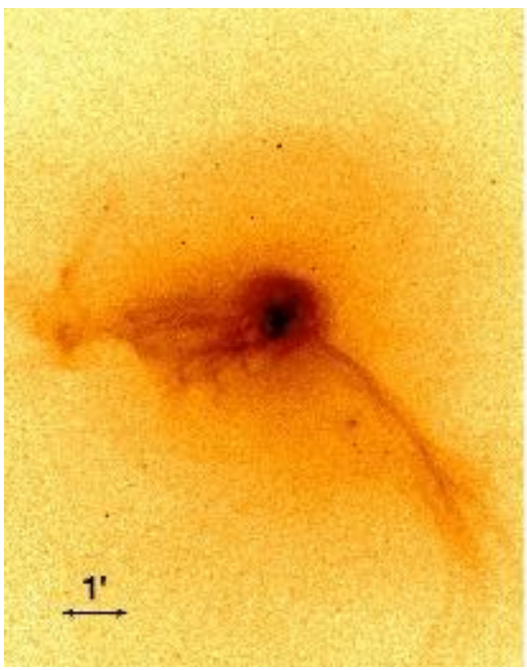


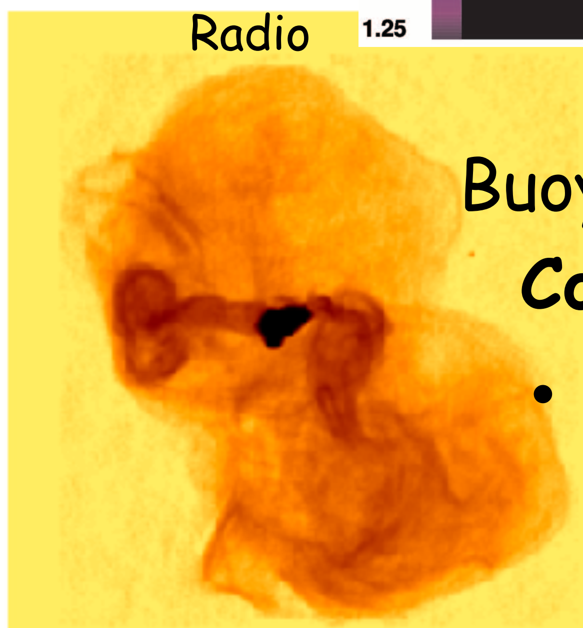
Radio









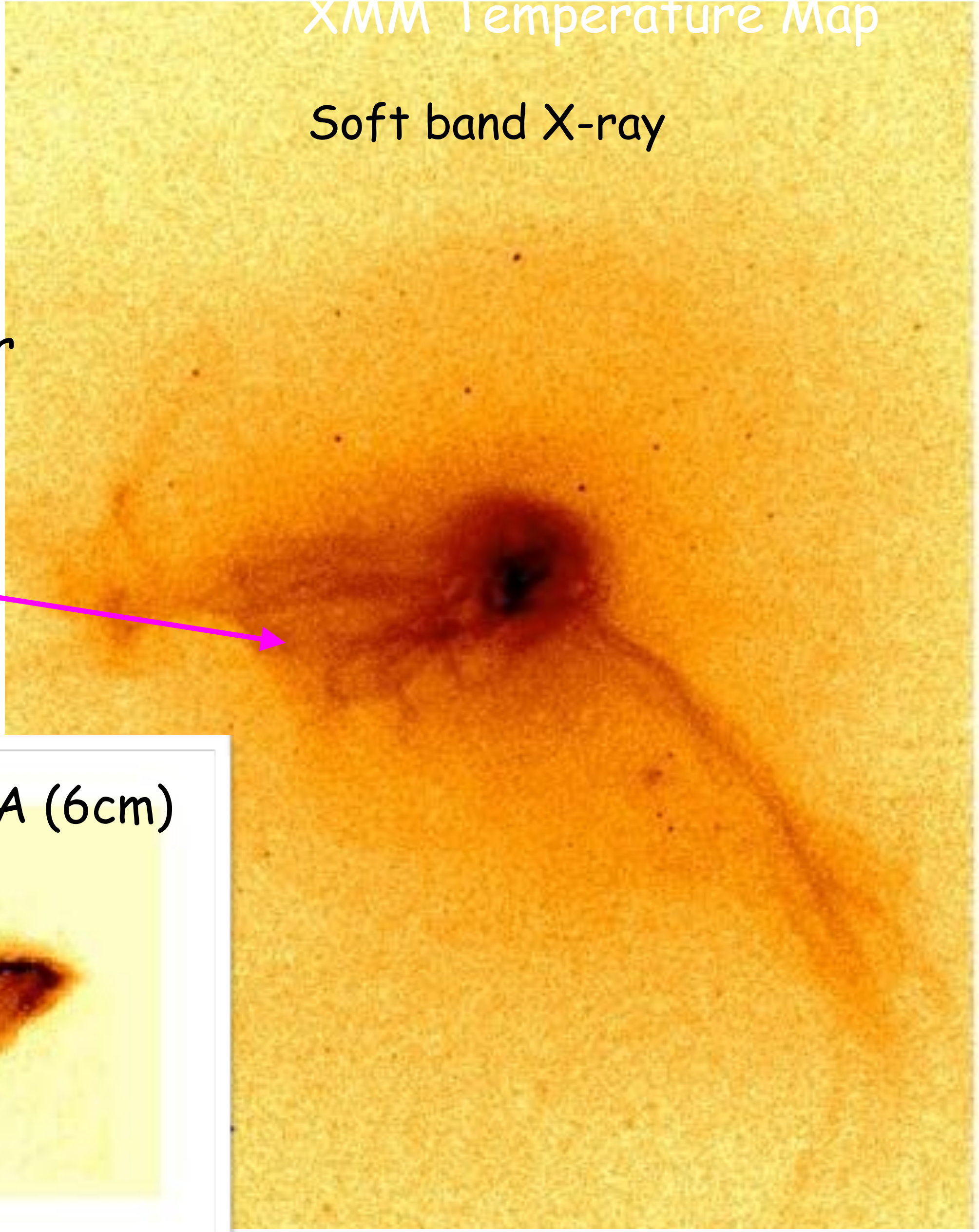


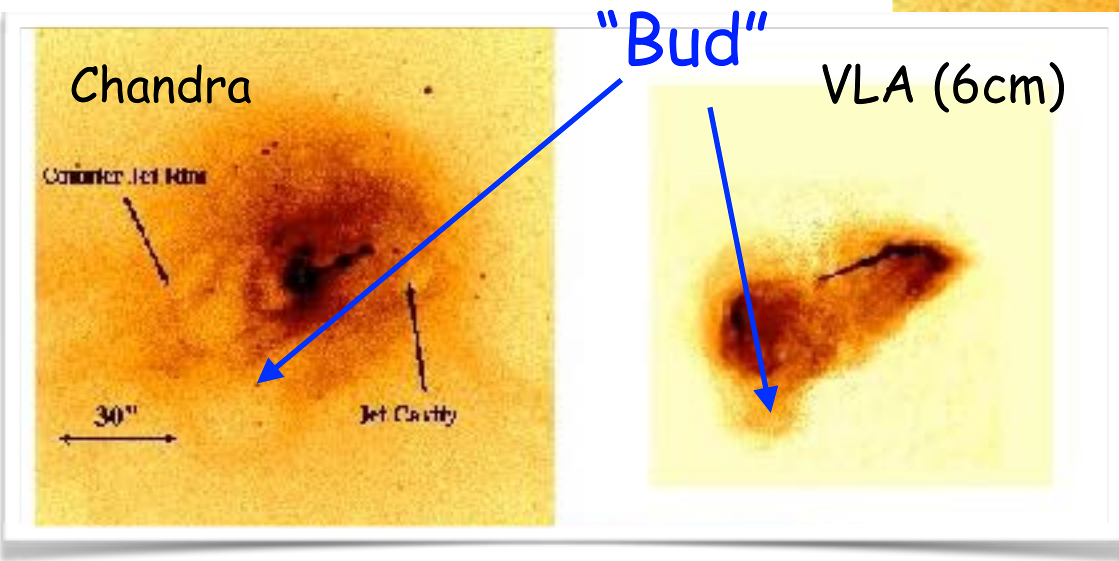
Buoyant (radio) bubbles

Cool, uplifted arms

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

- Current outburst
  - Re-inflating an existing bubble (that drove main shock)
  - Present cavity is an inclined (10-20 degree to LOS) cylinder
- Sequence of bubbles
  - Bud (few x 10^6 yrs; 10^{55} ergs
  - Series of "Bubbles" to SE
  - Radio torus farther east

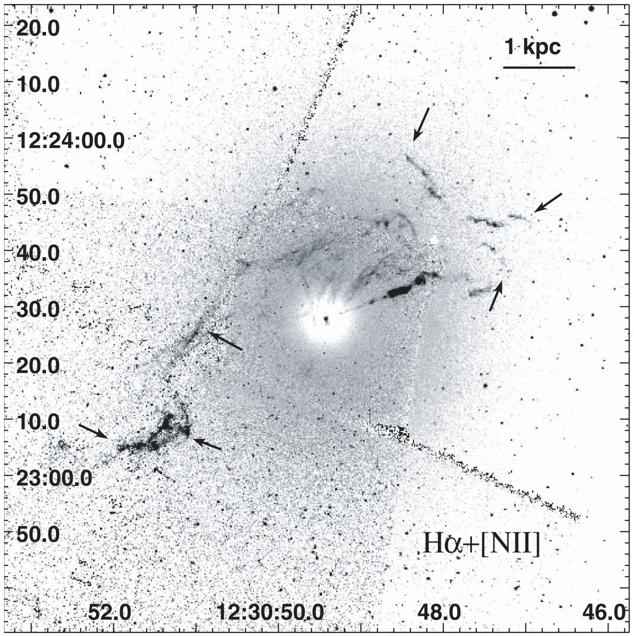


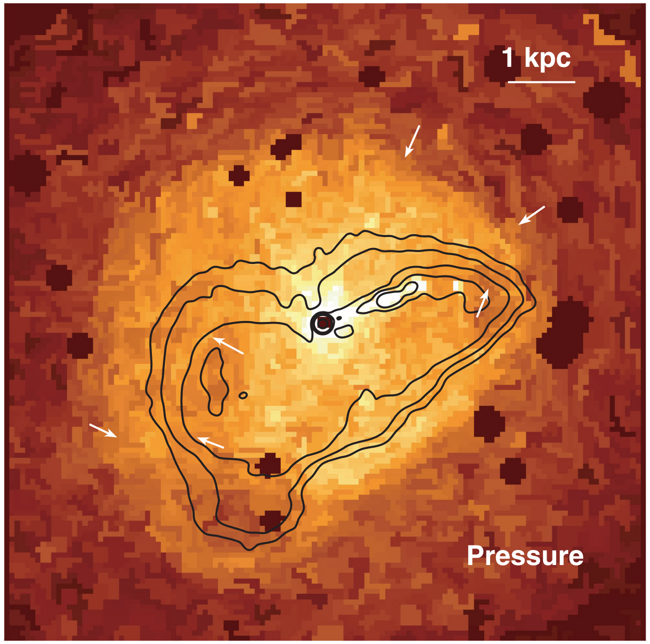


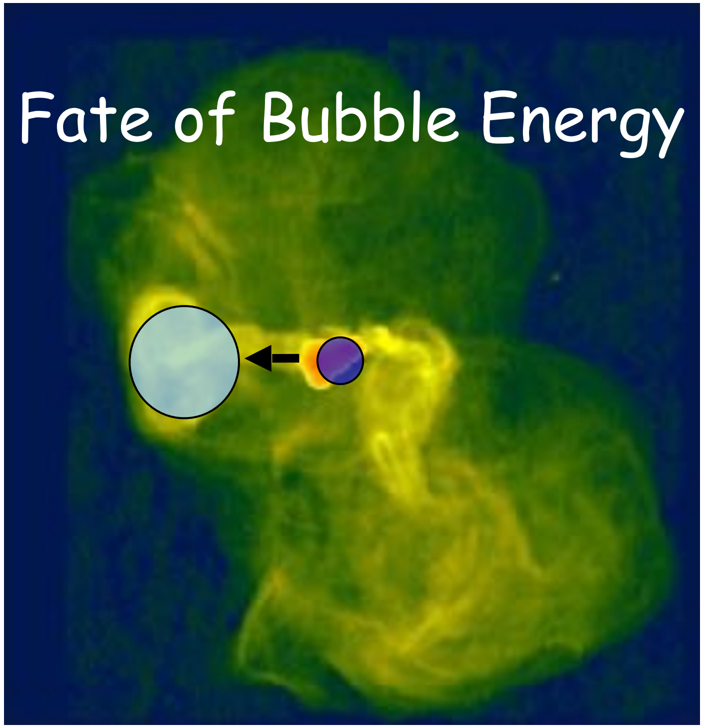
M87 - not rich in cold gas

- Reference: Cool X-ray gas mass in arms ~10^9 M_{sun}
- Cold gas image Ha + [NII] from Norbert Werner+10 (Fig. 5)
  - see also Sparks+93,+04
- Molecular gas mass < few 10^6 M_{sun} (Salome & Combes 2008)
  - in each of several pointings covering central region
- Ha mass 10^5-10^7 Msun (Sparks+93)
- CO detected with ALMA (Simionescu +18) in outer filament ($M(H_2)$ ~ 5×10^5 M_{sun})

Werner+10 (Fig. 5)







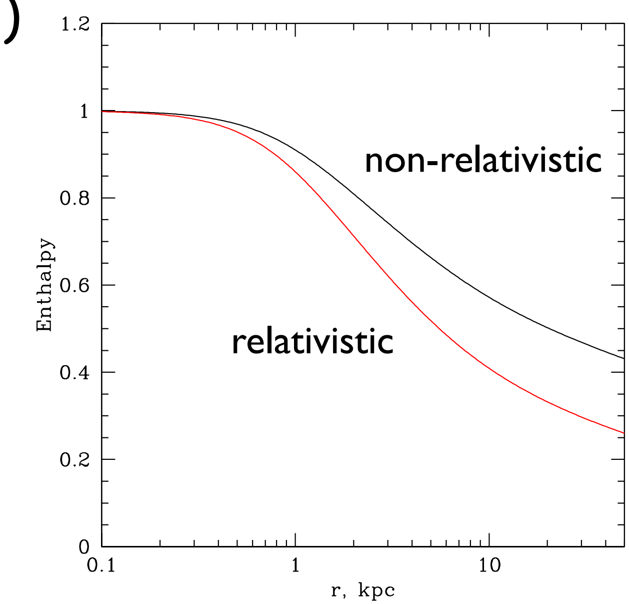
Rising bubble loses energy to surrounding gas

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

Generates gas motions in wake

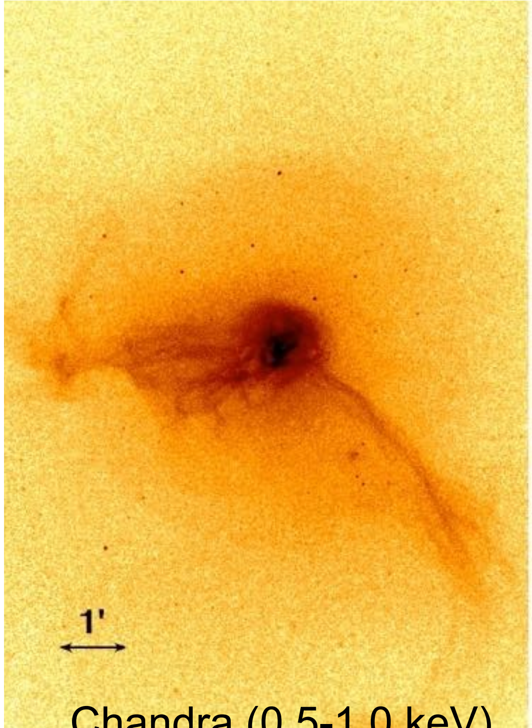
Kinetic energy (eventually) converted to thermal energy (via turbulence)

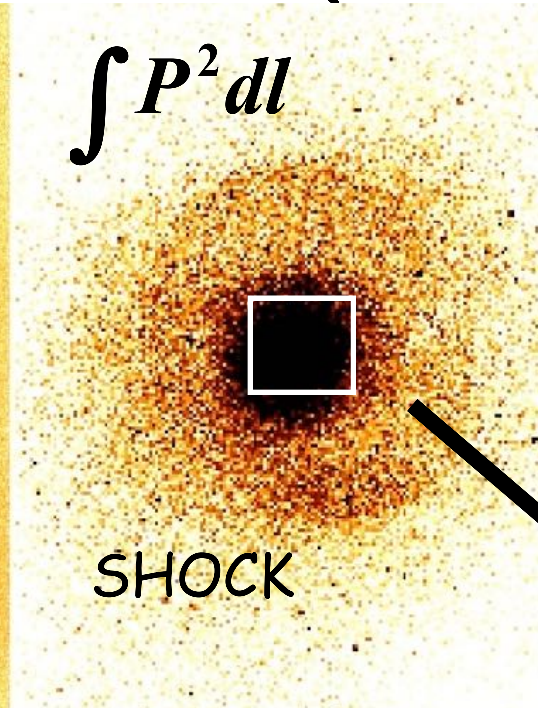
Bubble energy remaining vs. radius



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

Shocks (and Bubbles)



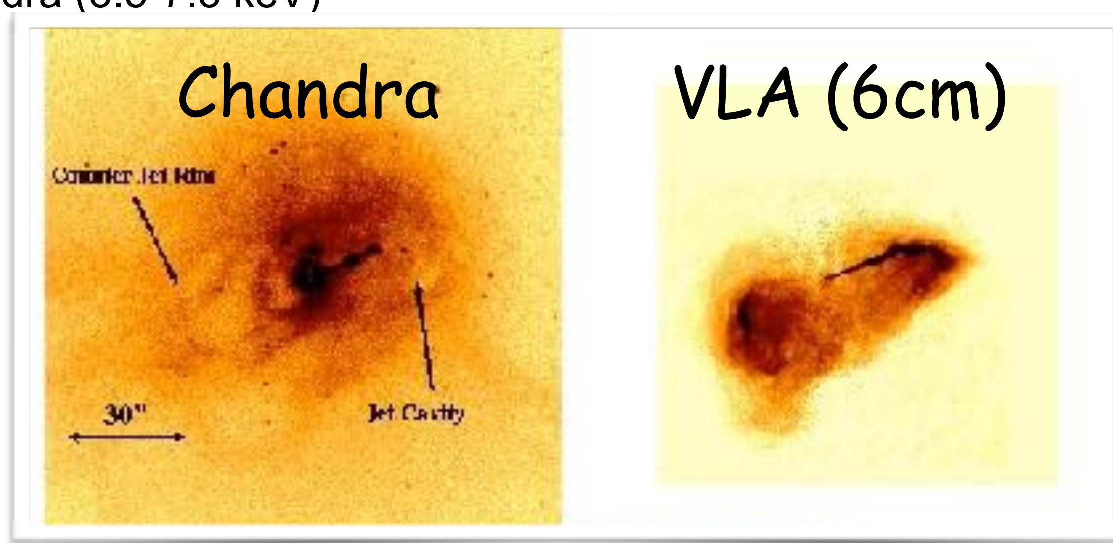


Chandra (3.5-7.5 keV)

23 kpc (75 lyr)

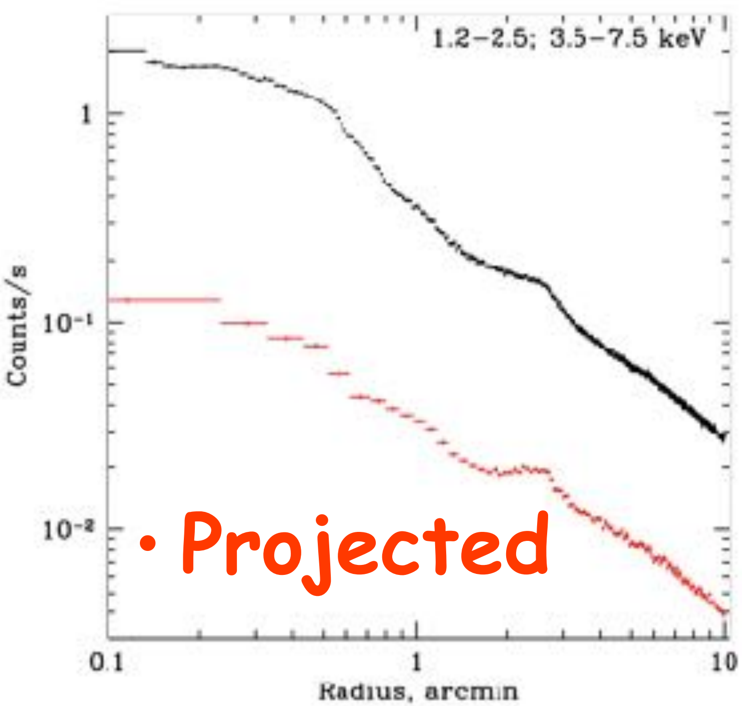
- SMBH powers jets
- Inflates "bubbles" of relativistic plasma
- **Model to derive detailed outburst properties**

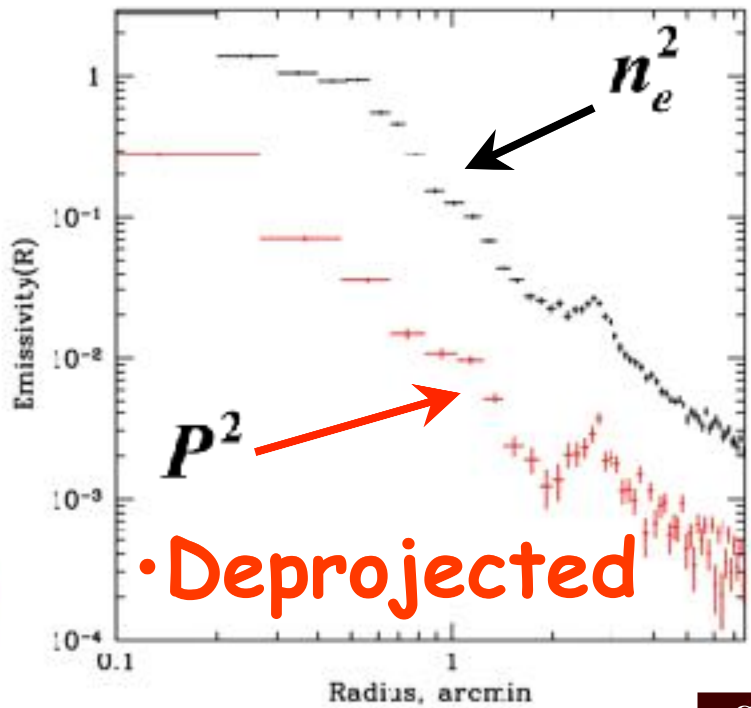
Central radio cocoon is piston Drives shock

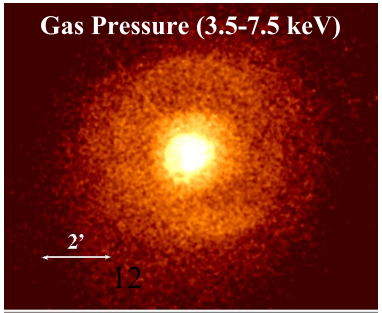


Shock Model - the data

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







Textbook Example of Shocks
Consistent density and temperature jumps

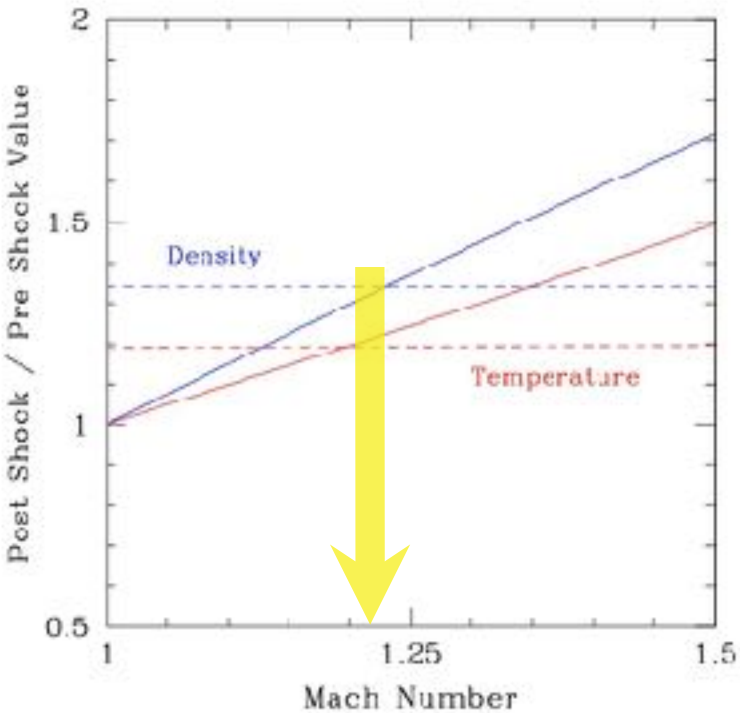
Rankine-Hugoniot Shock Jump Conditions

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

$$\rho_2/\rho_1 = 1.34$$

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

$$T_2/T_1 = 1.18$$

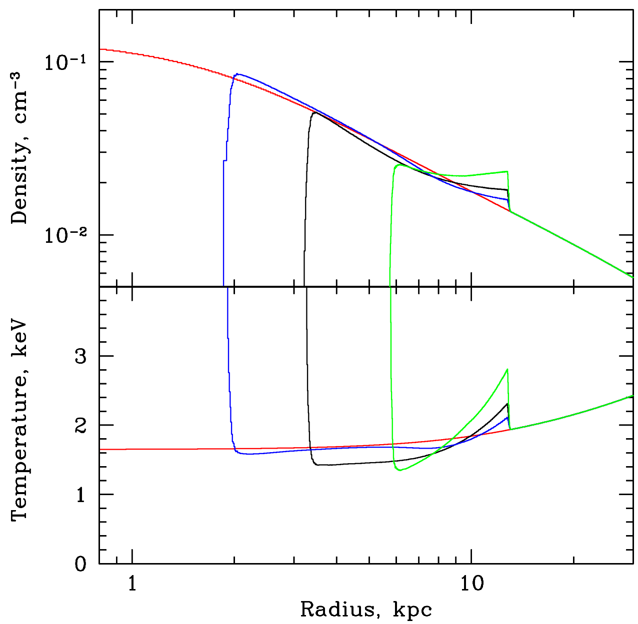


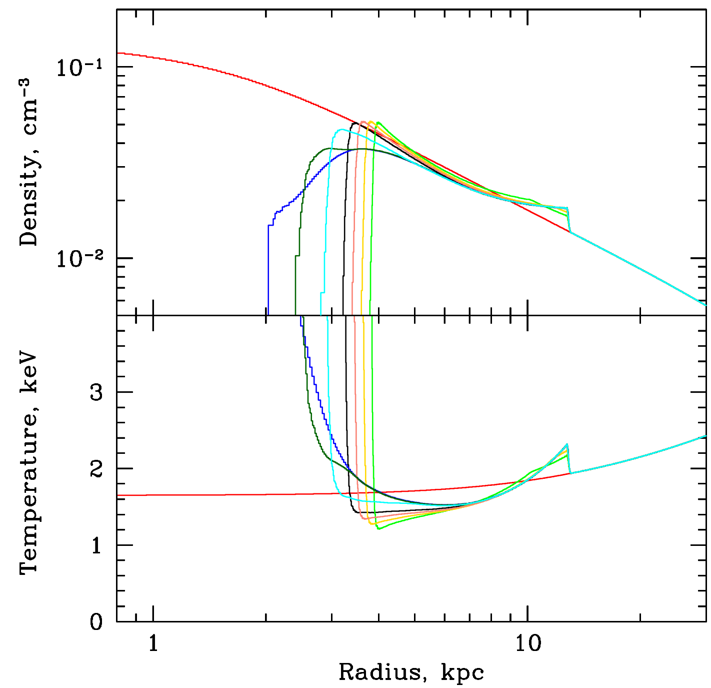
yield same Mach number:
($M_{T=}1.24$ $M_\rho=1.18$)

M=1.2

Outburst Model - grid in total energy and duration

Forman et al. 2017





Same duration = 2.2 Myr

Different E_{tot} = 1.4, 5.5, 22x10^{57} ergs)

Produces different central piston sizes (observable)

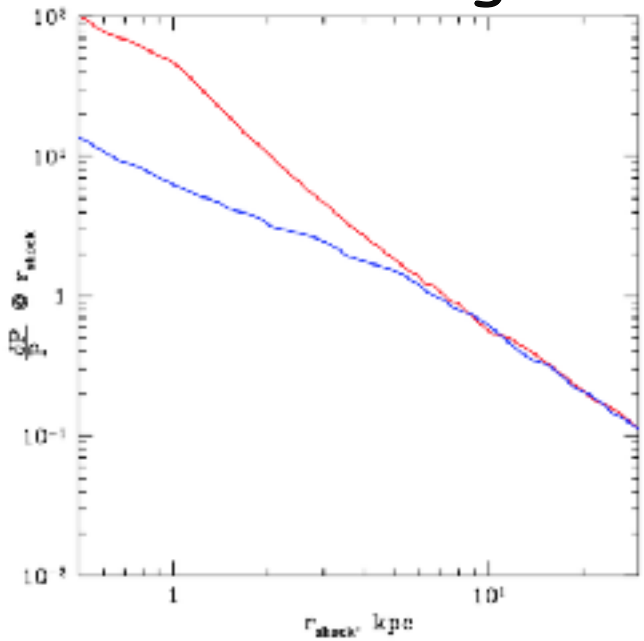
E_{tot} = 5.5x10^{57} ergs,

Different durations = 0.1, 1.1, 2.2, 3.1, 4.0, 4,4, 6.2 Myrs

Shock strength (nearly) governed by E_{tot}

Match all constraints

Characterizing M87's outburst - Long vs. Short Durations

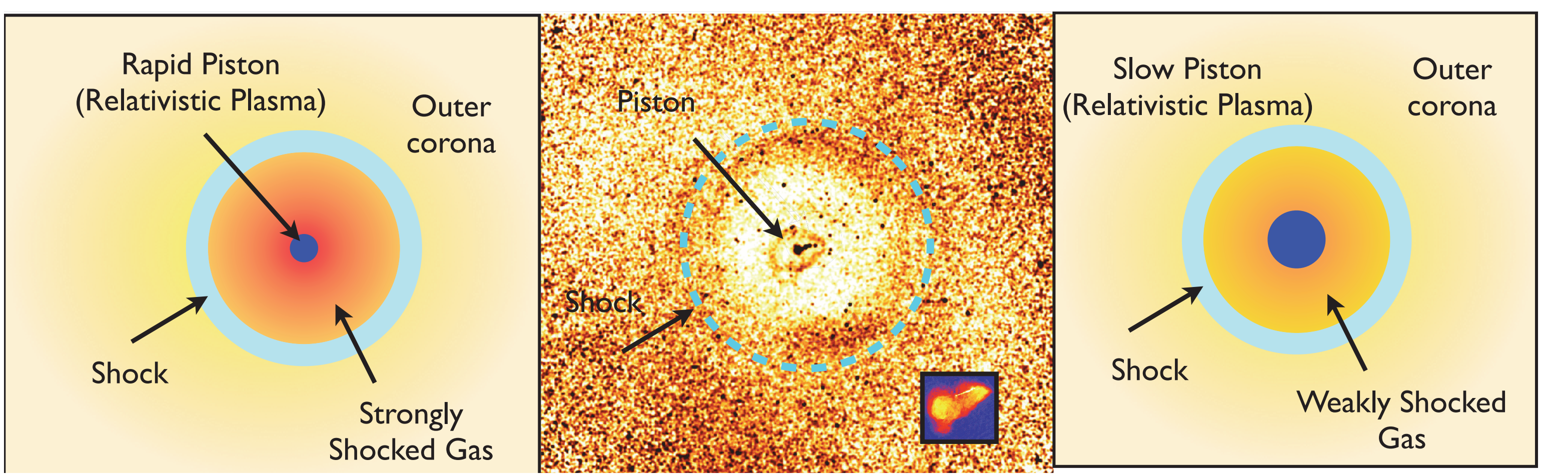


0.6 vs 2.2 Myr duration outbursts with $E_{outburst} = 5.5 \times 10^{57}$ ergs

Short outburst - leaves hot, shocked envelope outside the piston

Not observed — longer duration outburst required

Size constrains outburst



M87 Outburst - superman or winnie?

Age ~ 12 Myr

Energy ~ 5×10^{57} erg

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

Outburst duration ~ 1 Myr

Outburst is "slow"

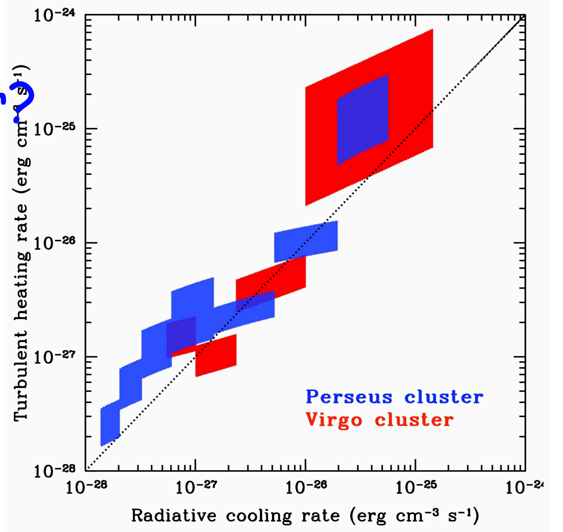
Fast - hot, low density shock heated region

Slow - dense,cool rim

- 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?

see Irina Zhuravleva+14 and Thursday talk

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



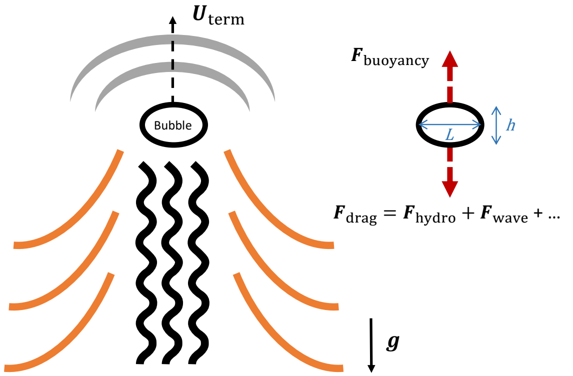
For M87 and Perseus

How is bubble energy distributed?

Generation of Internal Waves by Buoyant Bubbles in Galaxy Clusters and Heating of the Intracluster Medium

see Zhang+2018 and Thursday talk

- Other mechanisms may contribute e.g. cosmic ray heating (Svenja & Pfrommer 2017)



Family of dark matter halos from massive early type galaxies to clusters ALL have hot atmospheres:

Key to capturing feedback - **not perfect balance**

M87 is the prototype shows details of shock/bubble energy partition

SMBH powers plasma outflow, drives shocks, creates bubbles

Bubble energy ~50% of total outburst energy

Shock - 25% of energy directly heats core

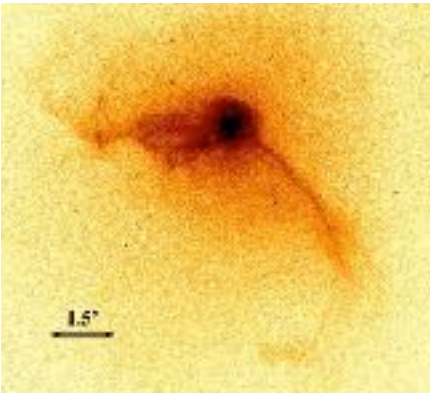
Outbursts are "long" duration (~1 Myr); weak shocks

Heat radiatively cooling gas (5x10^{57} erg over 12 Myr)

Roughly matches radiated X-ray emission

X-ray filaments are:

- **uplifted, cool plasma**
- **in pressure equilibrium**
- **structure "governed" by buoyant bubbles**

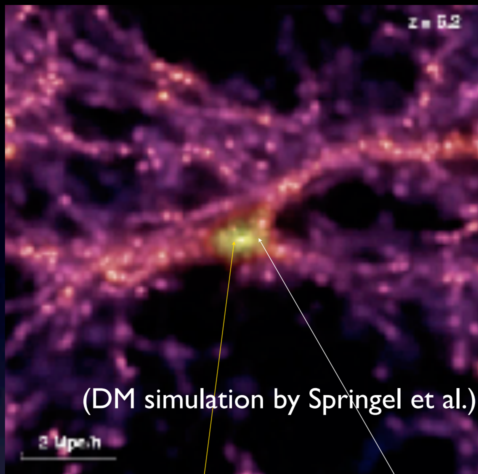


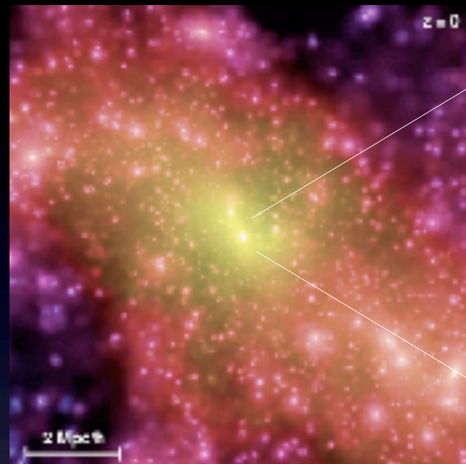
Glimmer of unification of black holes, accretion modes, galaxy formation and SMBH co-evolution …

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

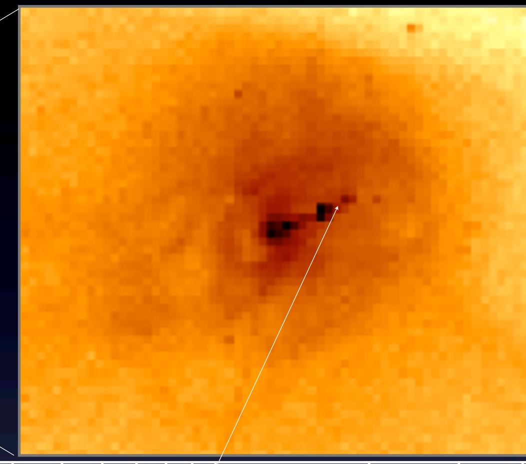
Growth of galaxy groups and $10^9\,M_\odot$ black holes from z=6 to the present

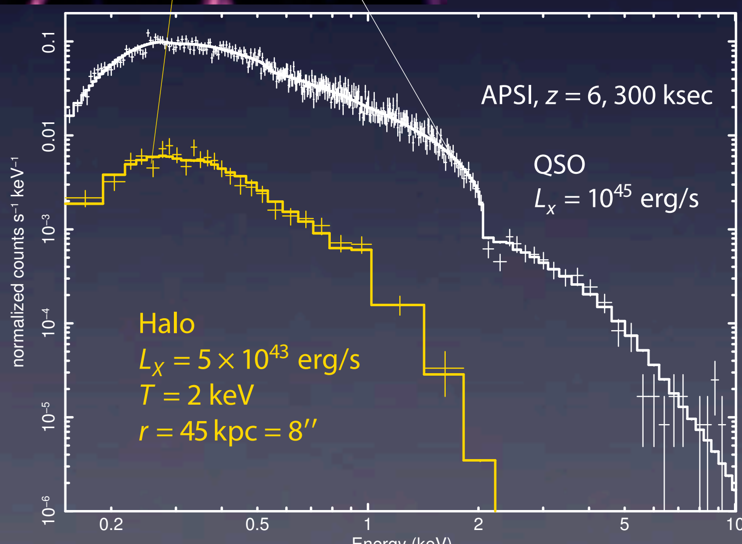
Sloan quasar at z=6 ⟶ "nursing home" at z=0

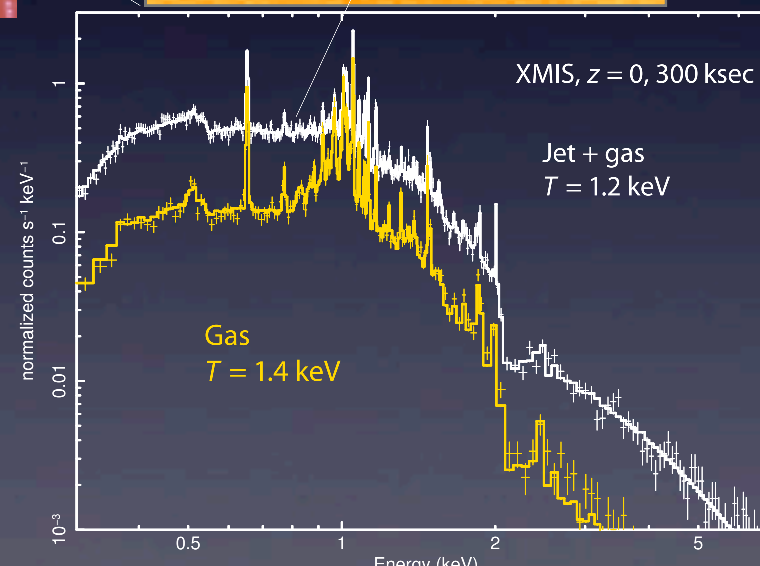




M87, *Chandra*, 1″ pixels



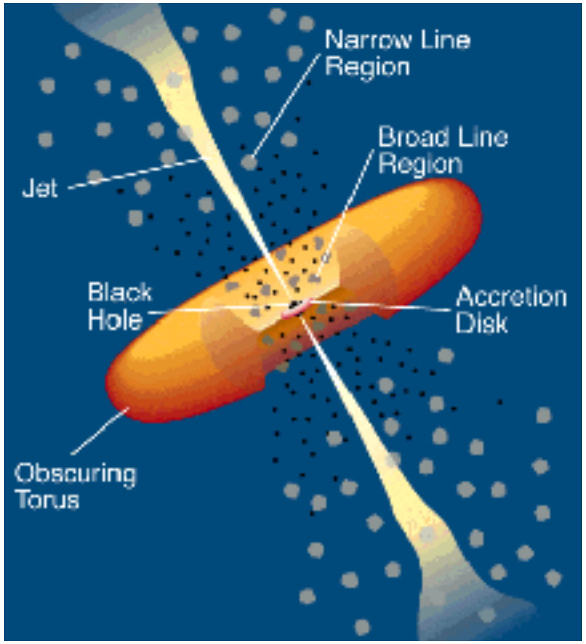




Sensitivity + angular resolution with wide-field imager — detect and resolve quasar host halos at z=6

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

Finis!



Two Types of AGN accretion modes

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

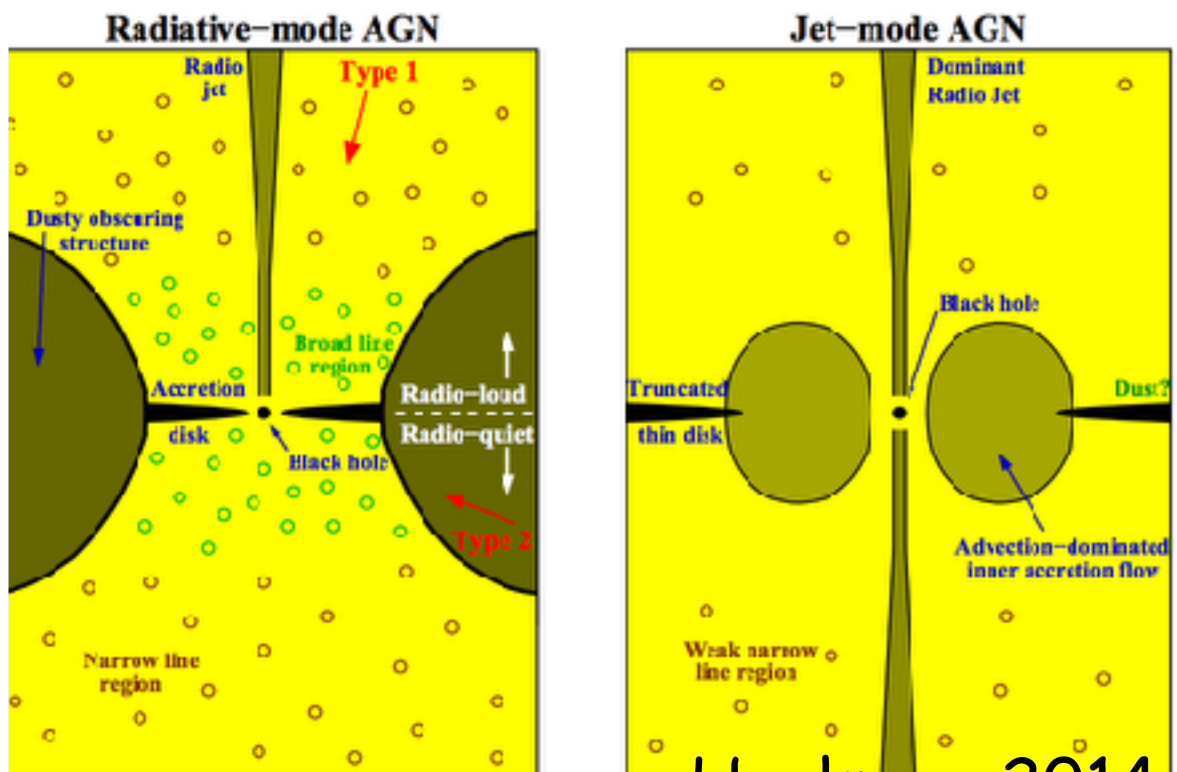
High excitation AGN
"standard" picture (called "quasar mode")

Low excitation AGN

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

Radiative/Quasar vs. Radio/Jet Mode

- Radiatively faint AGN
- Different structure to accretion disk at low accretion rates
- **accretion disk does not reach ISCO**
- radiatively inefficient but mechanically efficient
- accretion energy heats gas



Heckman 2014

- accretion energy advected into the back hole
- drives outflows/jets
- radio bright (but still low luminosity)
- see Yuan & Narayan 2013 for review

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 (good) hair dryer

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

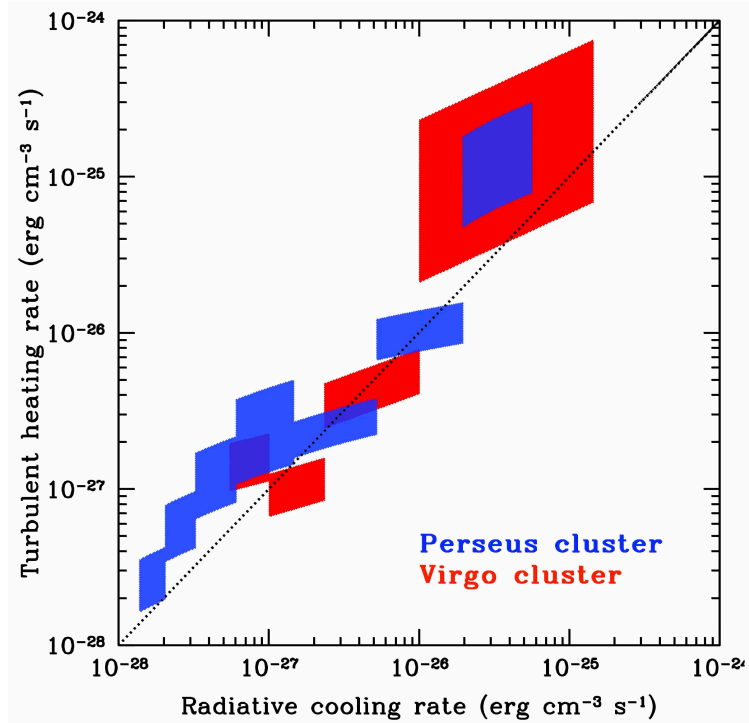
Gas Provides archive of AGN activity

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**



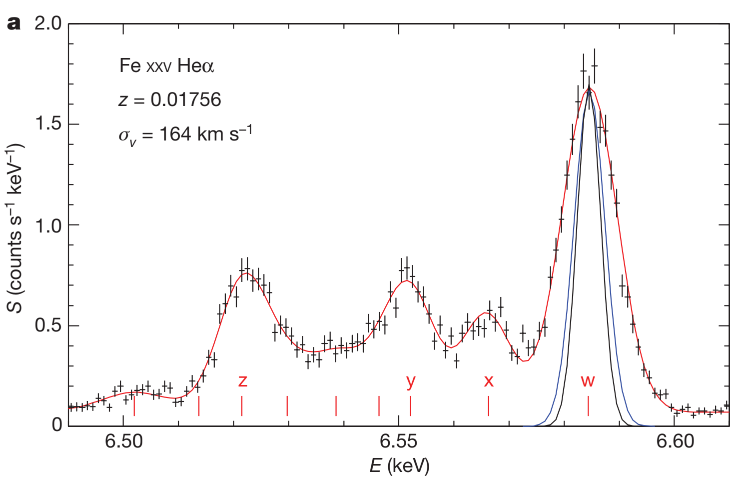
For M87 and Perseus

Hitomi - Feb 2016

Lines broadened - σ = 164 km s-1 As predicted from fluctuations

Broadening from bulk flows?

Not likely - resonant scattering results consistent with direct line broadening (see 1710.04648.pdf)



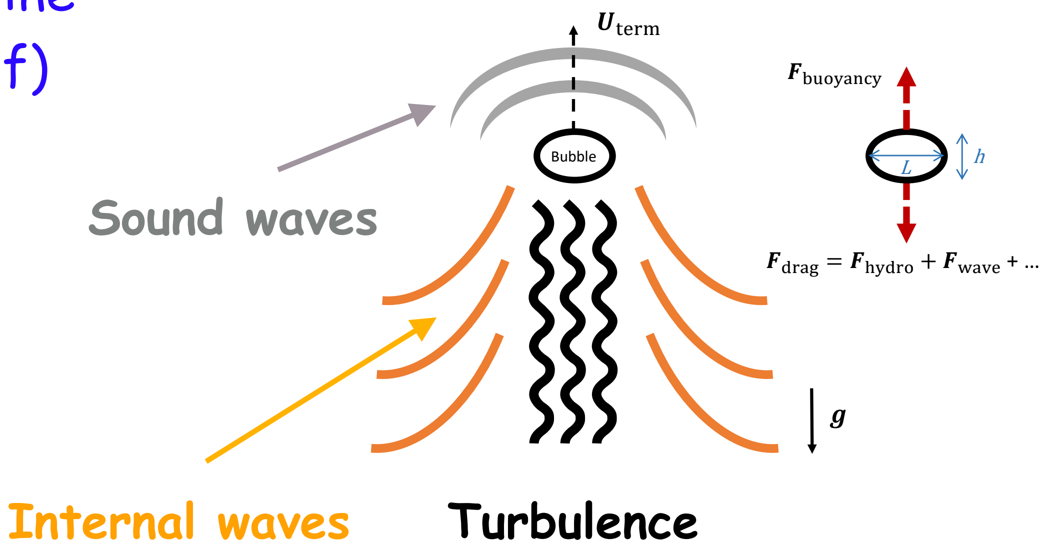
Bubble energy propagation?

Radially by bubble itself

Azimuthally by internal waves

Bubble in a stratified atmosphere

see Zhang+2018 and Thursday



Other mechanisms may contribute e.g. cosmic ray heating (Svenja & Pfrommer 2017)