A Shock Model for the the Outburst from the Supermassive Black Hole in M87

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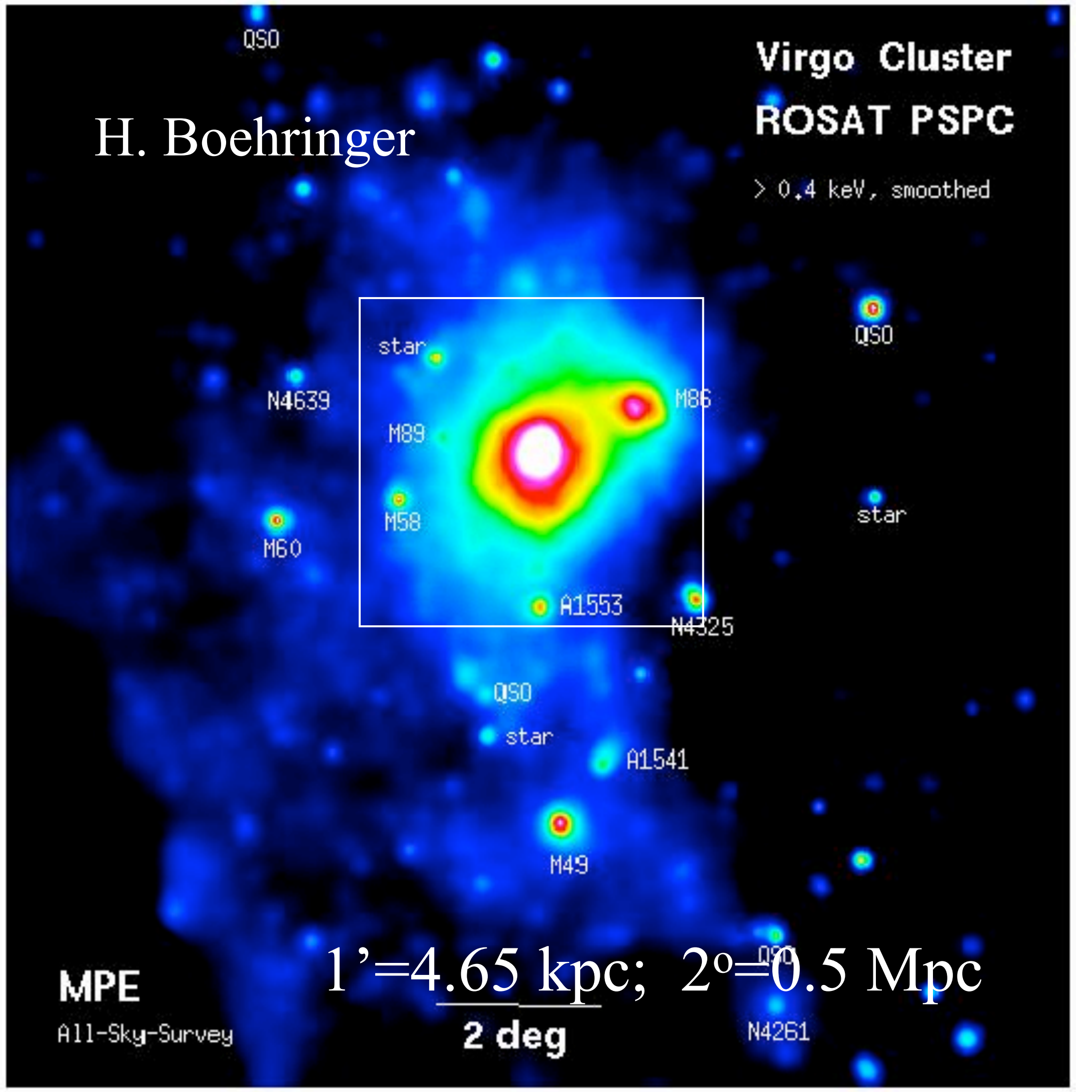
- M87
  - interactions galore; stripping at work, M87 outburst
  - Low Eddington ratio accretion (like other "normal" galaxies)
    - Not unique
- IC1262
  - Outbursts
  - Sloshing

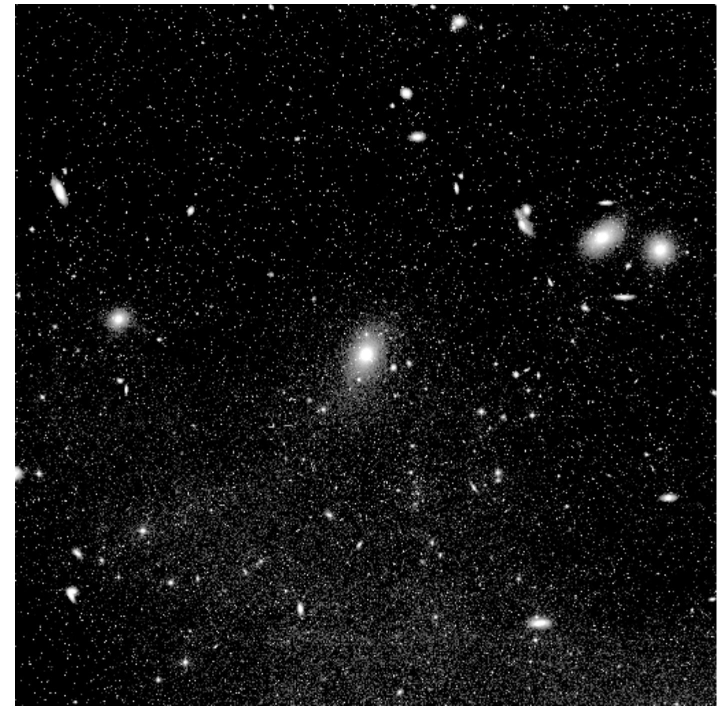
Collaborators

- Christine Jones, Eugene Churazov, Ralph Kraft, Paul Nulsen, Larry David, Jan Vrtilek, Simona Giacintucci, Marie Machacek, Ming Sun, Scott Randall, Maxim Markevitch, Alexey Vikhlinin

M87 - multiple outburts, gas sloshing; not unique
IC1262 - a different view of a near twin

Virgo Cluster - X-ray/Optical





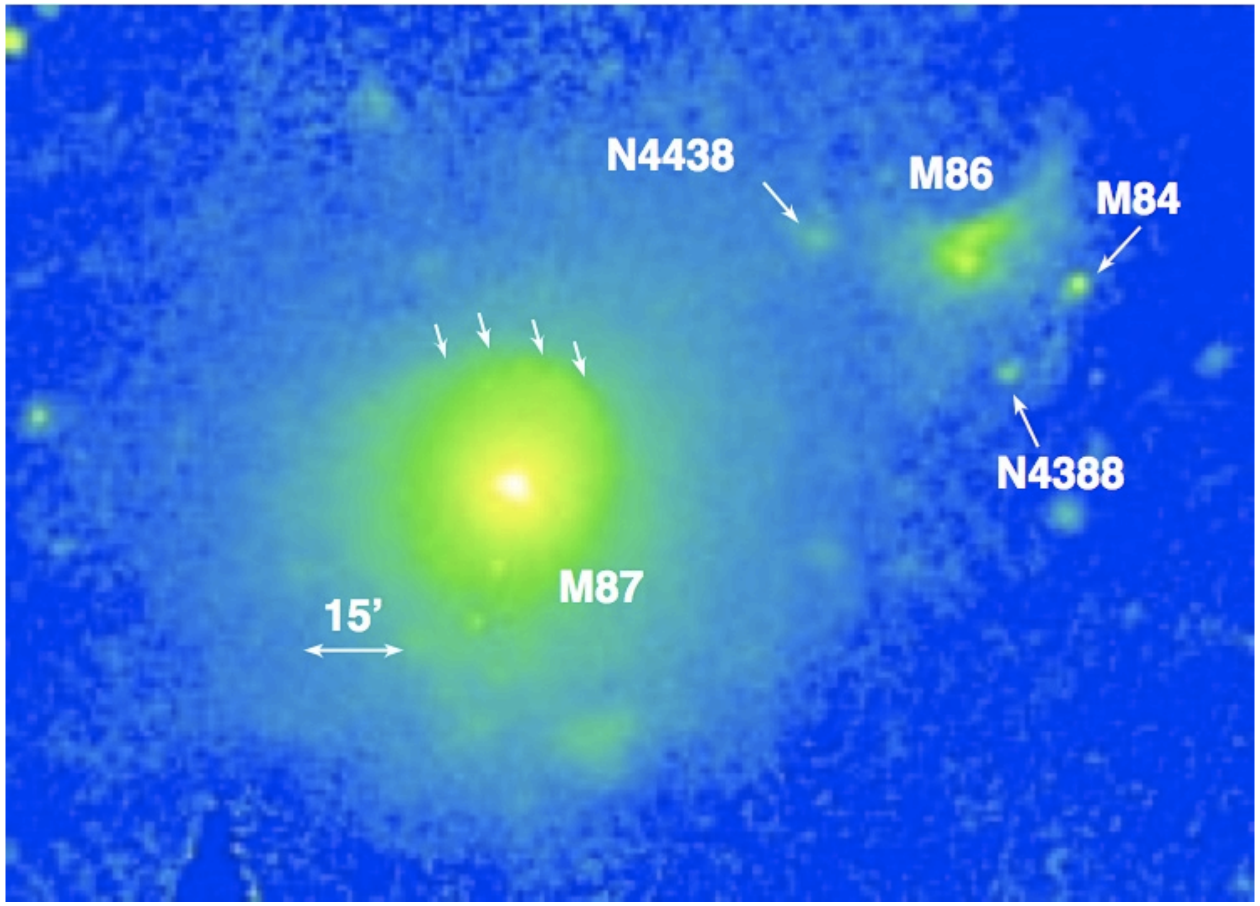
1) Optically luminous early-type galaxies are (hot) gas rich - up to 10^{10} M_{sun}

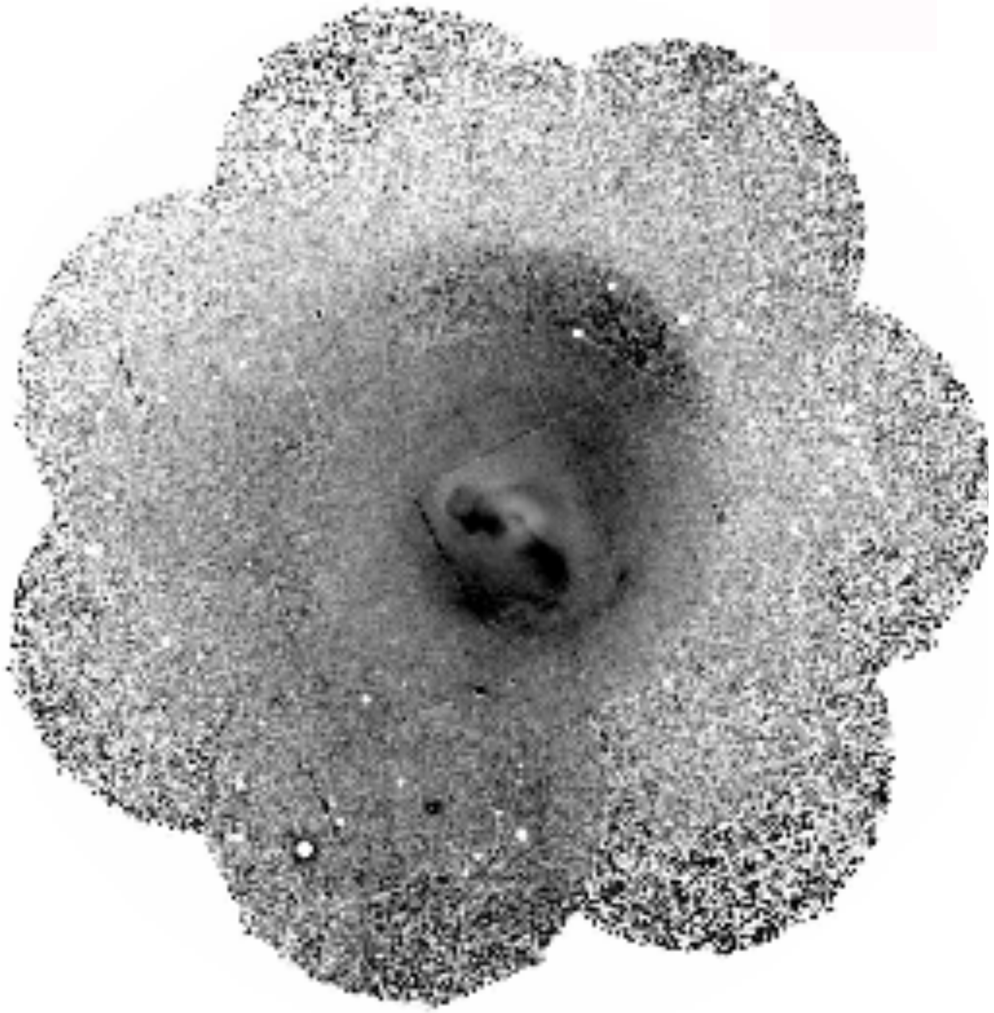
Virgo is dynamically young extensive merging, stripping

2) 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
- •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





M87 shows gas "sloshing"

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

(Simionescu+10 from XMM-Newton)

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

see Markevitch & Vikhlinin 2007 for a review

& R. Johnson PhD 2011 (see talk)

Driven by mergers

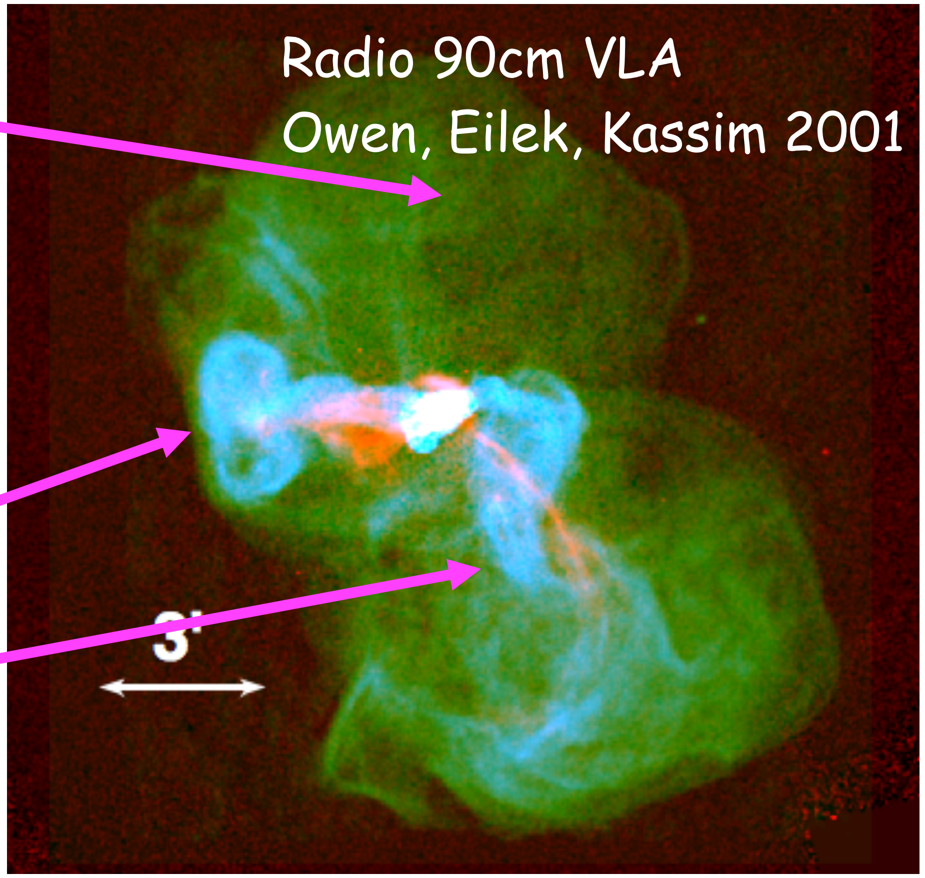
X-ray and Radio View of M87 - multiple outbursts

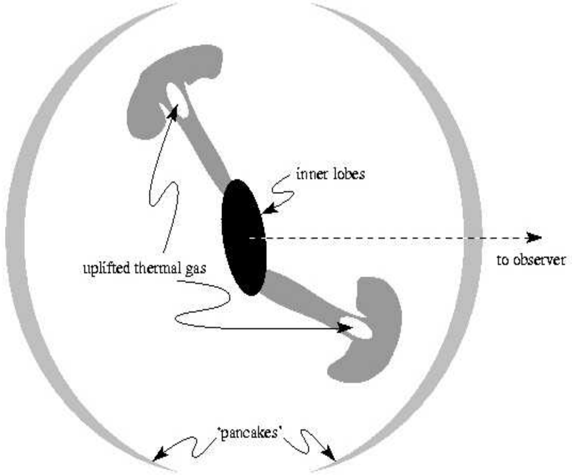
1 - Large "old" (100-150 Myr) lobes

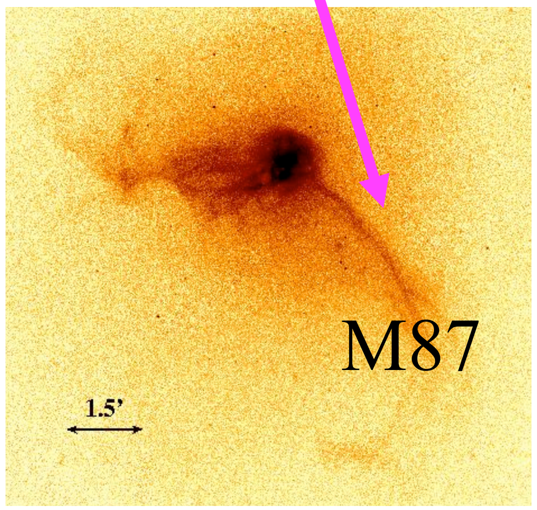
flattened pancakes

2 - Radio arms (buoyant bubbles)

- age $\gtrsim 3 \times 10^7$ yrs (buoyancy time)
- Classic torus to the east
- Southwest disrupted
- X-ray "arms" - produced by buoyant radio bubbles







Forman+05,+07
Million+10, Werner+10

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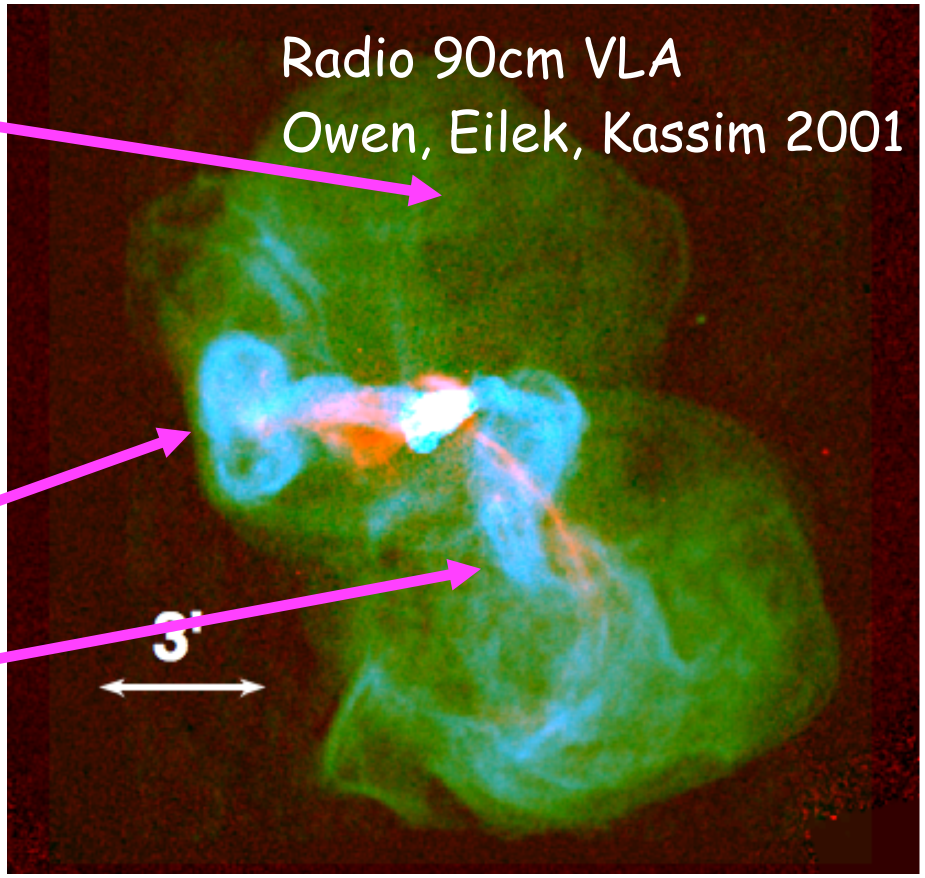
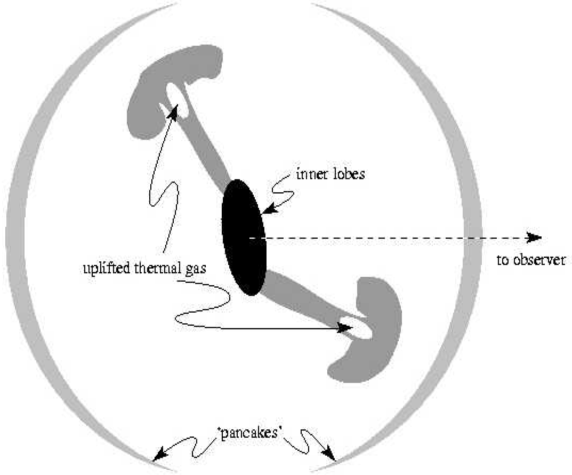
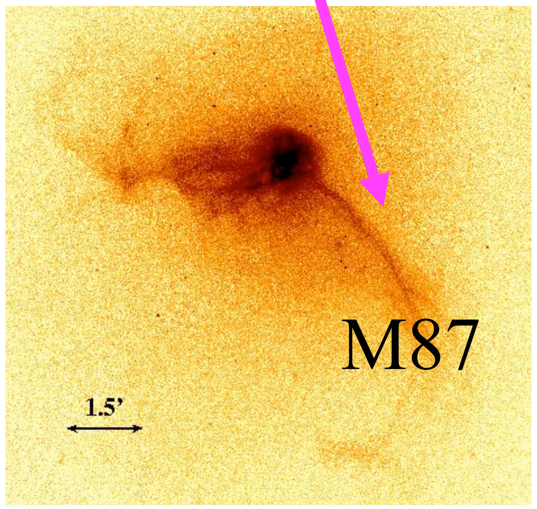






Forman+05,+07
Million+10, Werner+10

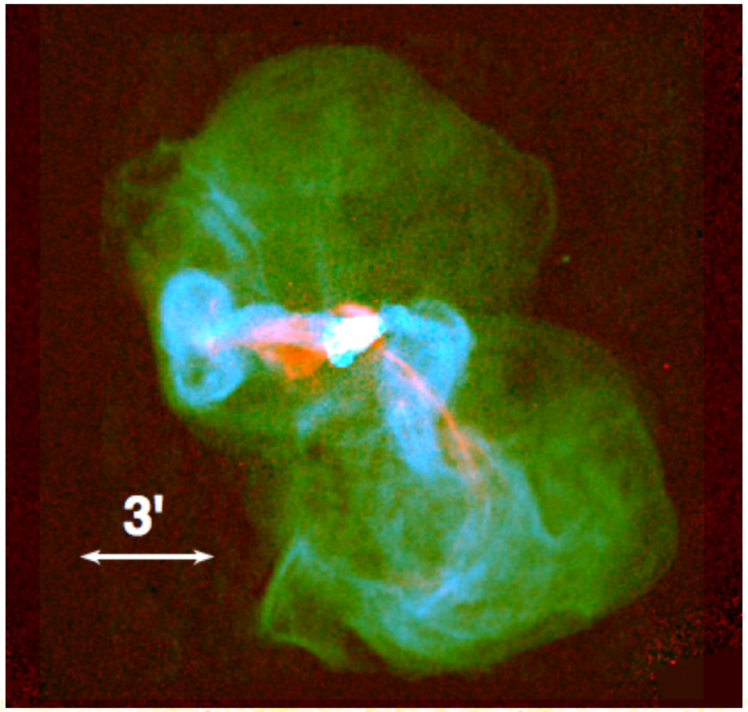
X-ray and Radio View of M87 - multiple outbursts

1 - Large "old" (100-150 Myr) lobes

flattened pancakes

2 - Radio arms - ≳ 3 x 10^7 yrs (buoyancy time)

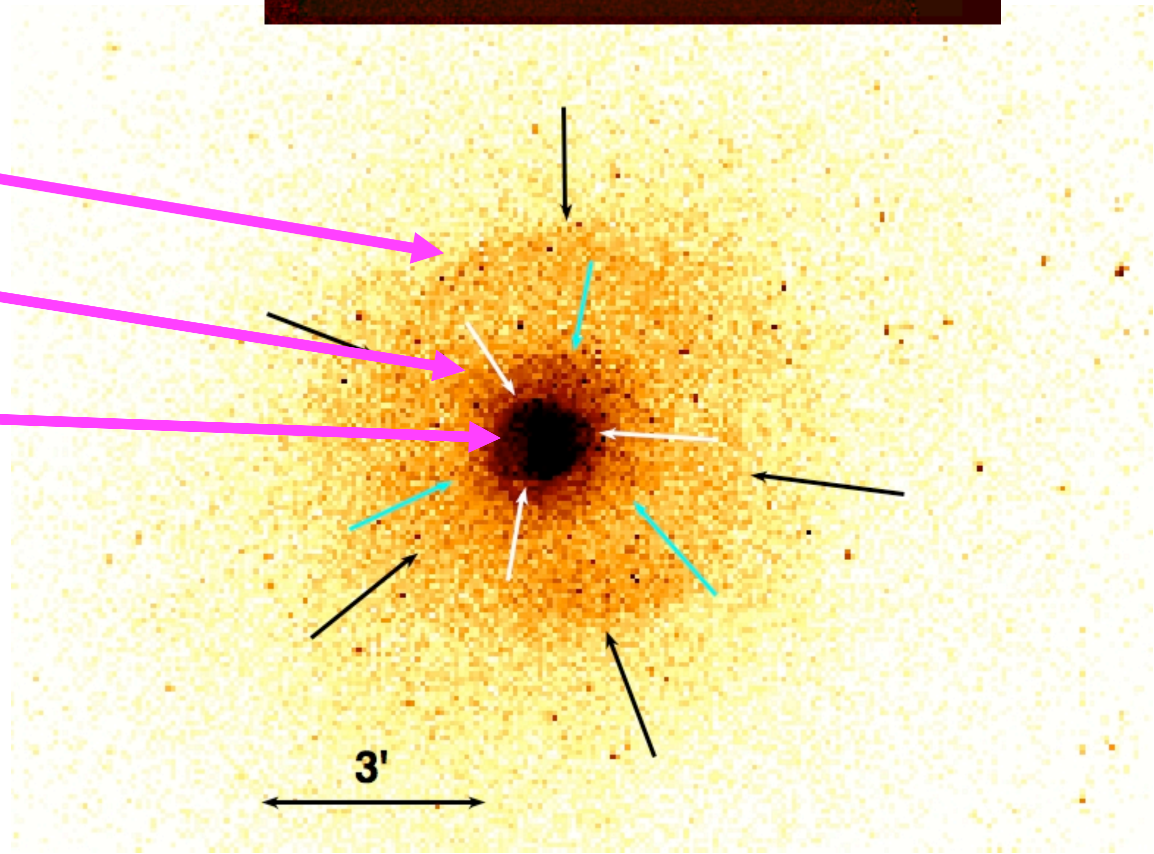
- Classic torus to the east
- Southwest disrupted
- Two X-ray "arms" - produced by buoyant radio bubbles



3 - 13 kpc (2.8') main shock (12 Myr)

4 - 5 kpc (1') weak "shock" (5.4 Myr)

5 - Central lobes/jet (ongoing)

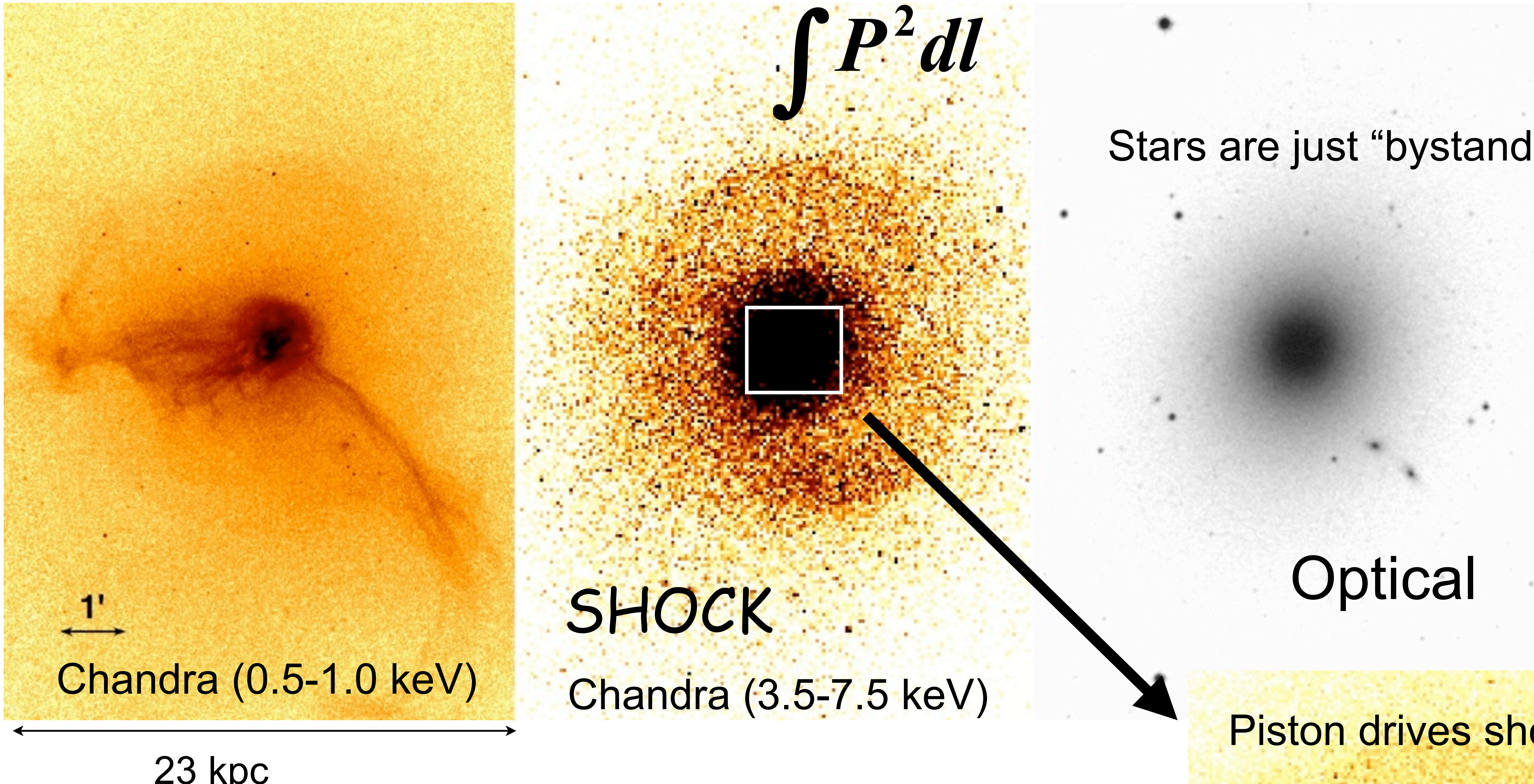


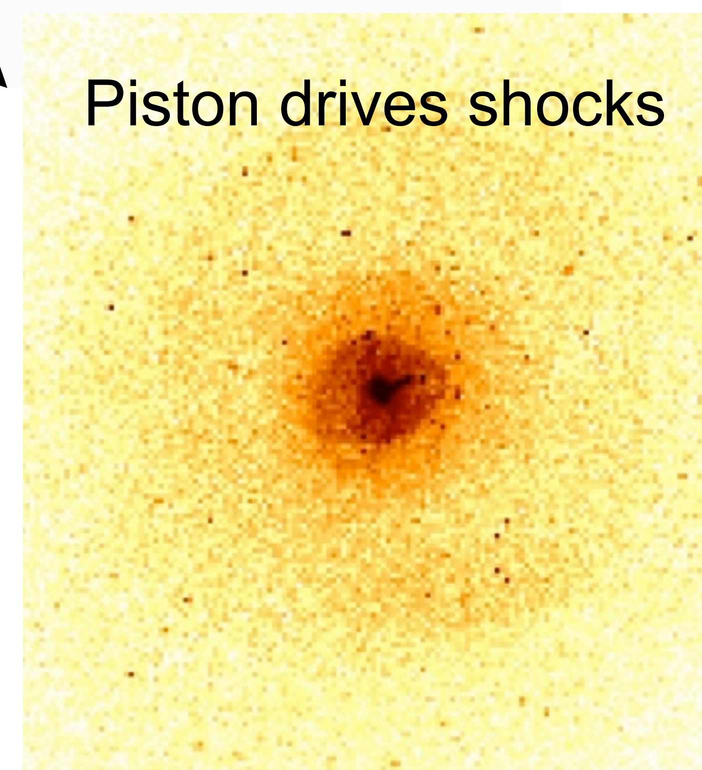
Central cavity plays special role - mediates outbursts

Forman+05,+07
Million+10, Werner+10

Radio 90 cm
Owen, Eilek, Kassim 2001

Feedback - M87





- Black hole = 6.6x10^9 solar masses (Gebhardt+11)
- SMBH drives jets and shocks
- Inflates "bubbles" of relativistic plasma
- Heats surrounding gas
- Model to derive detailed shock properties

M87 - a Textbook Example of Shocks

Consistent density and temperature jumps

Rankine-Hugoniot Shock Jump Conditions
(Rankine 1880, Hugoniot 1887)

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

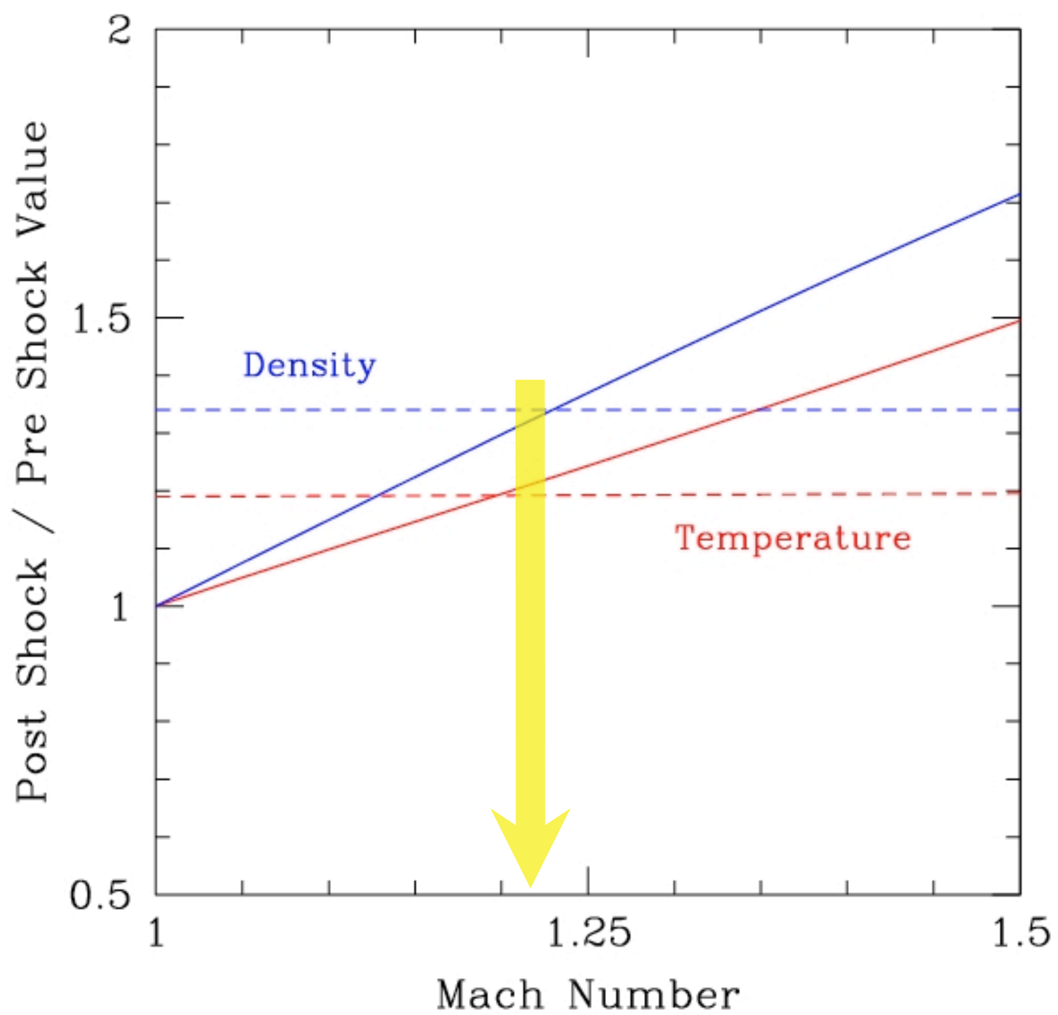
$$\rho_2/\rho_1 = 1.34$$

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

$$T_2/T_1 = 1.18$$

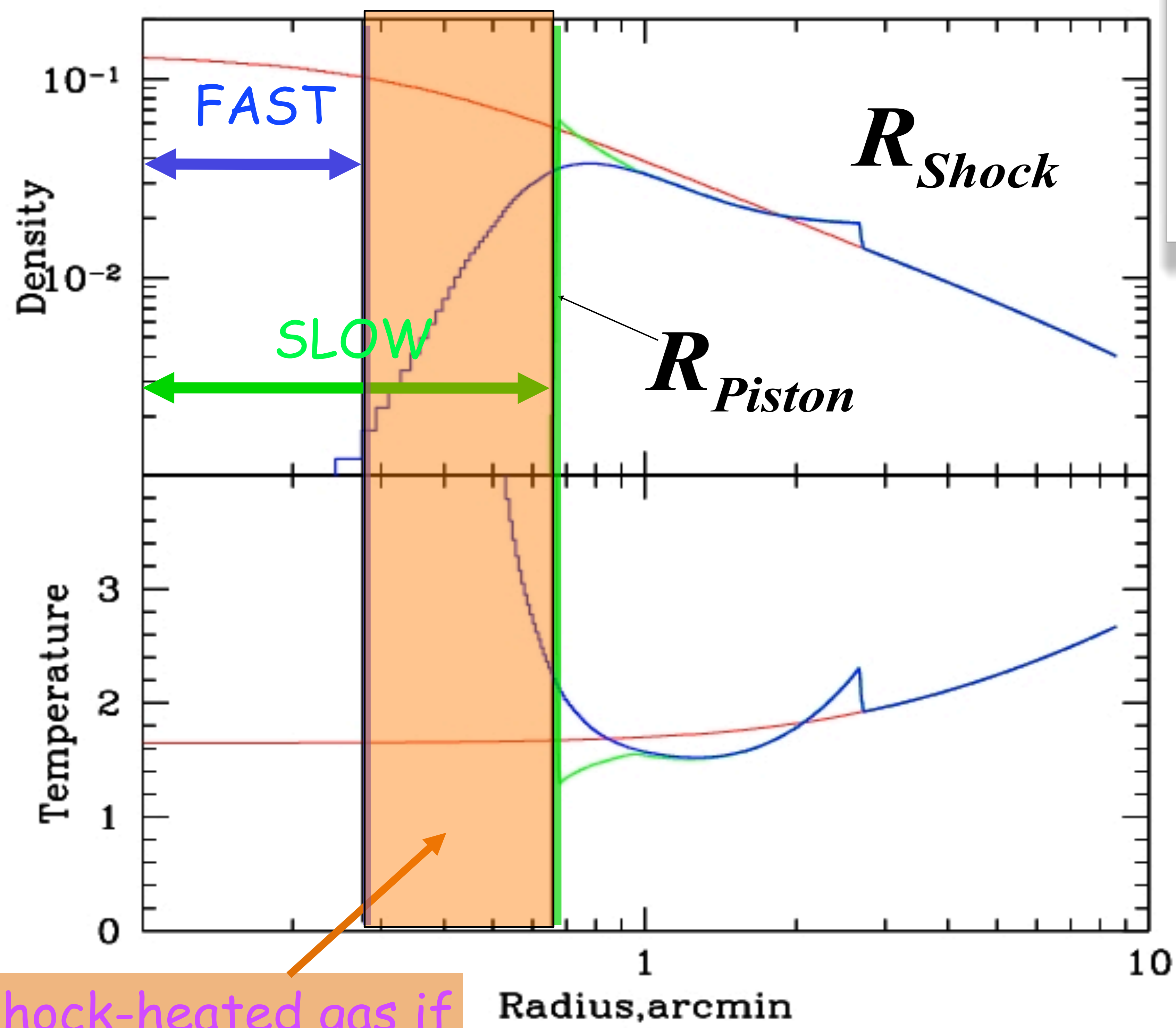
yield same Mach number:

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



M=1.2

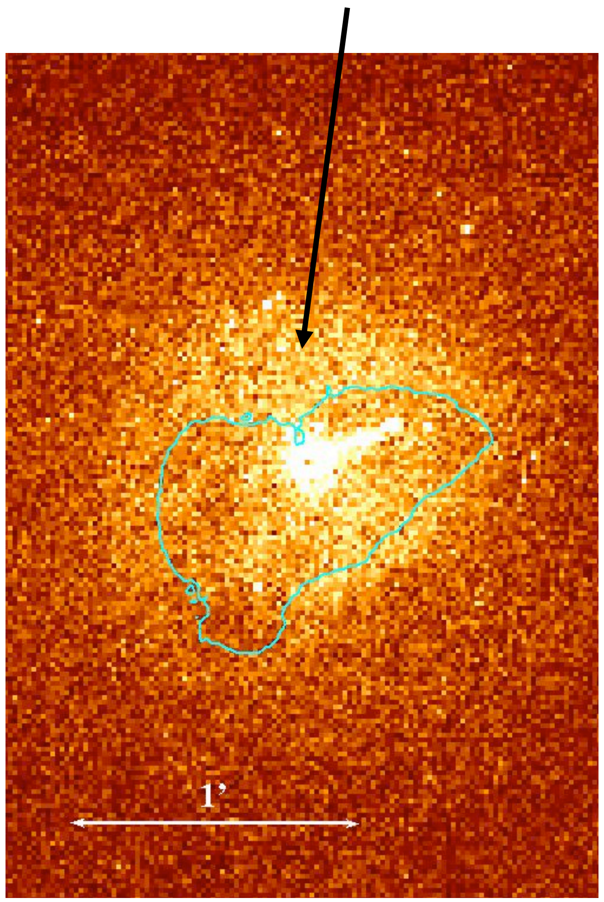
Derive outburst timescale



Shock-heated gas if $T_{outburst}$ is too short

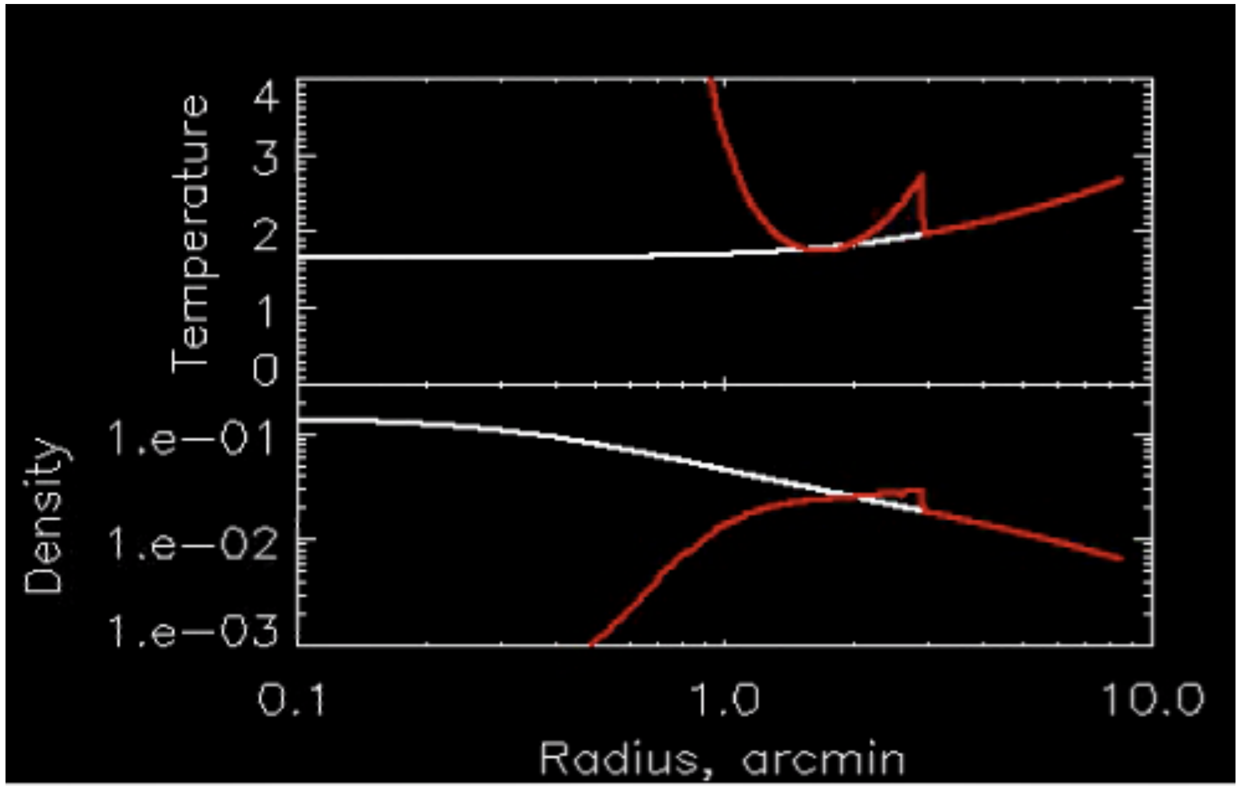
Fast - large shock heated region

Slow - cool rim



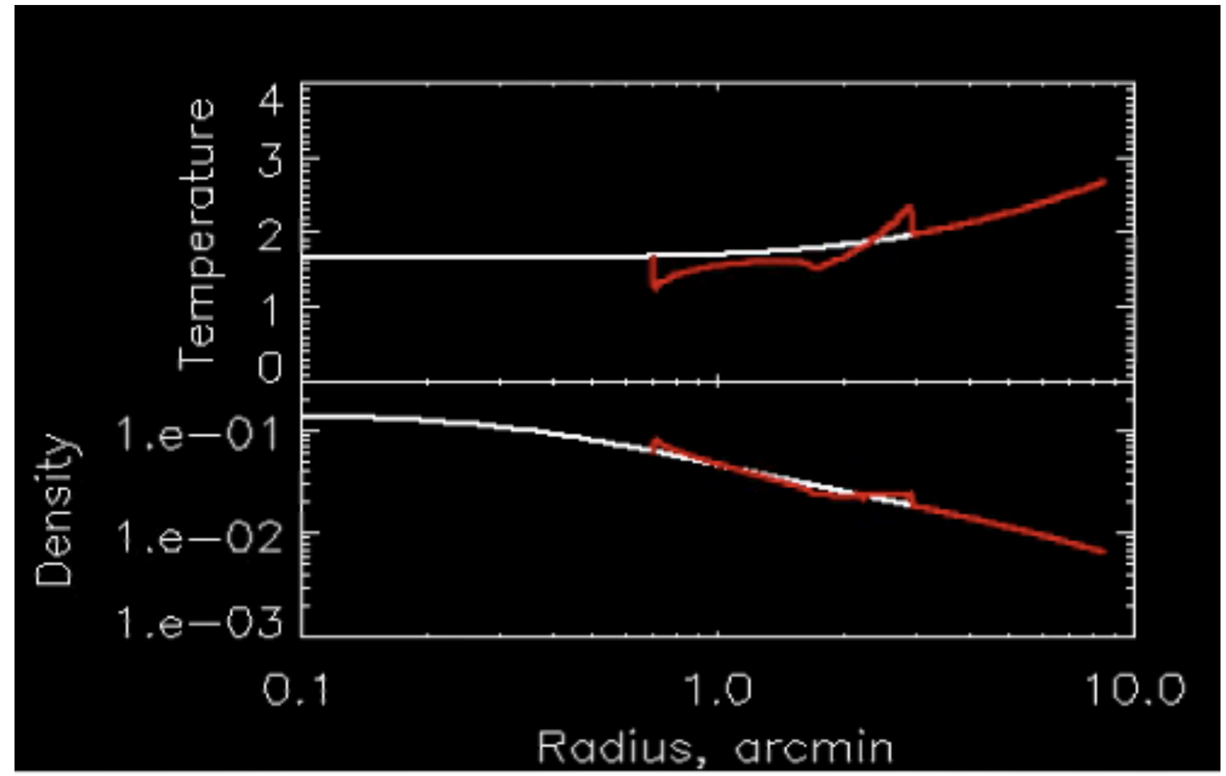
Absence of hot region constrains duration of outburst

Instantaneous energy release (Sedov-Taylor)



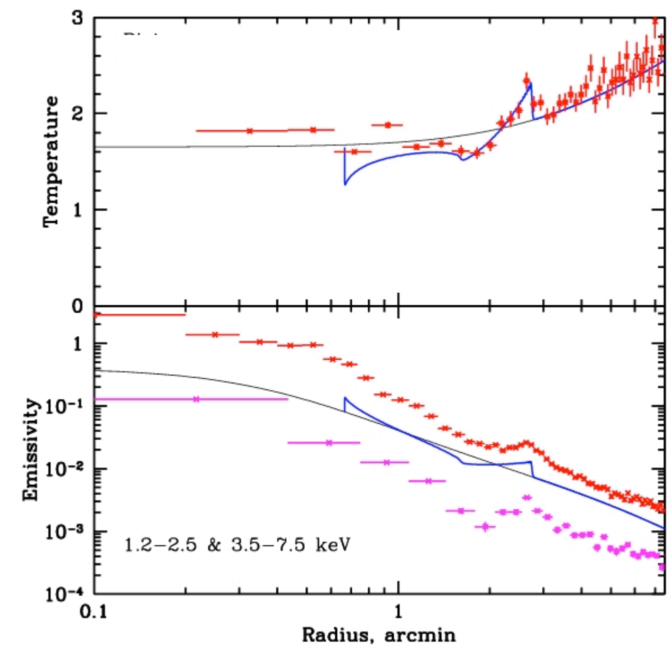
Hot, low density gas interior

Piston - gradual energy release



Cool, dense shell

- Absence of hot shocked region
  => gradual energy release
- Run grid of models to constrain:
  - Outburst duration
  - Outburst energy



Outburst Energy vs. Duration

Temperature Jump

$T_2/T_1=1.21\pm0.05$

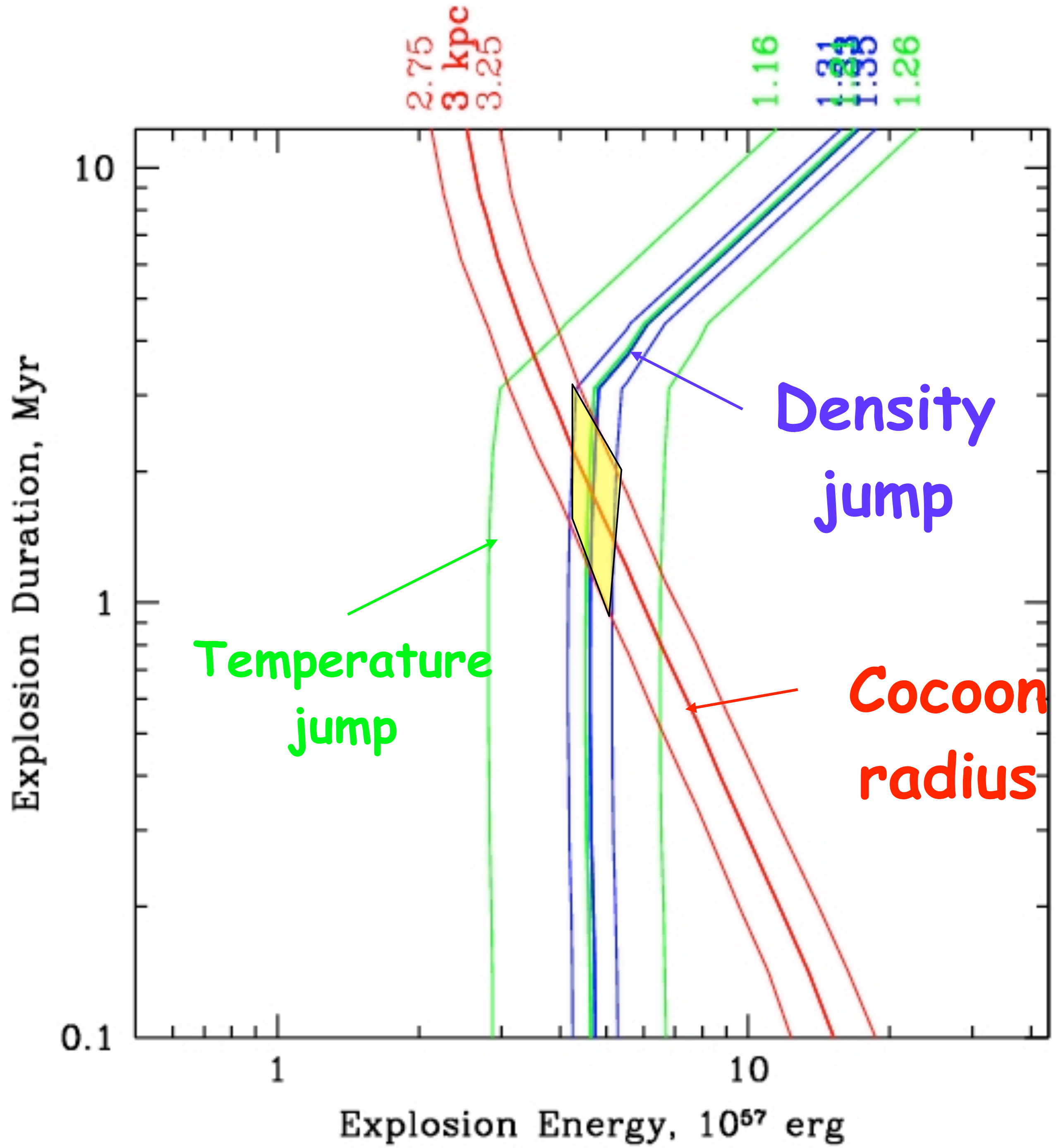
Density jump

$\rho_2/\rho_1=1.33\pm0.02$

M=1.2 for both

Cocoon radius

$R_{piston}= 3\pm0.25$ kpc

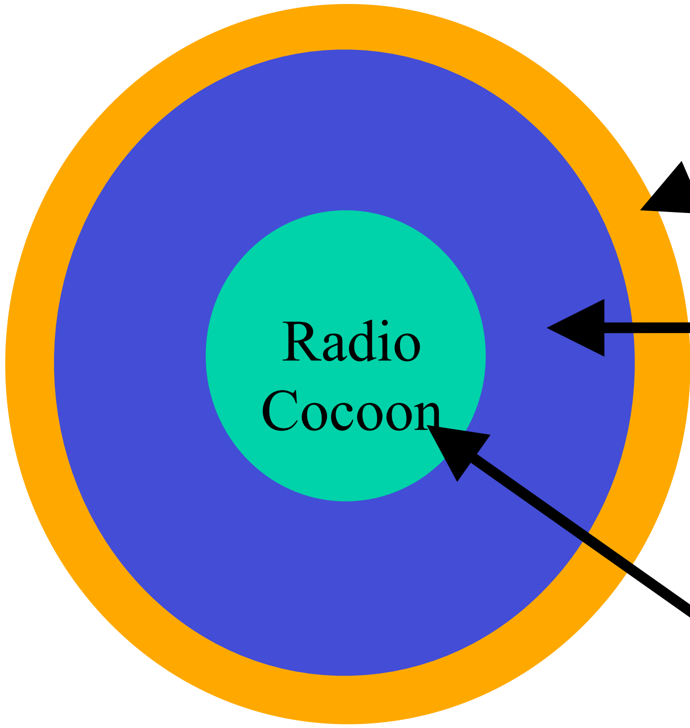


Duration = 1-3 Myr

Energy = 4-6 x 10^{57} ergs

Age = 12 Myr

Outburst Balances Radiation



Weak Shock: 25% E_0

(Slightly) Shocked gas
25% E_0

Radio Cocoon=young bubble
50% E_0

Solution to "cooling flow problem"

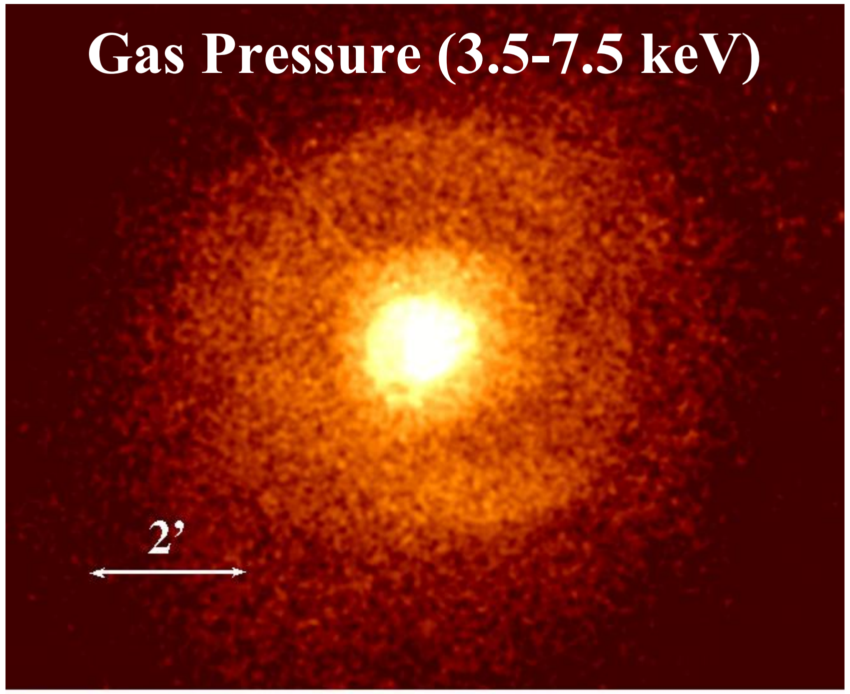
L_{rad} (10^{43} erg/s ≈ $L_{outburst}$ (E_0/age=10^{43}erg/s)

Best Model: $E_0=5\times10^{57}$ ergs; Age~12 Myr Δt~2Myr

M87 Outburst Model

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)

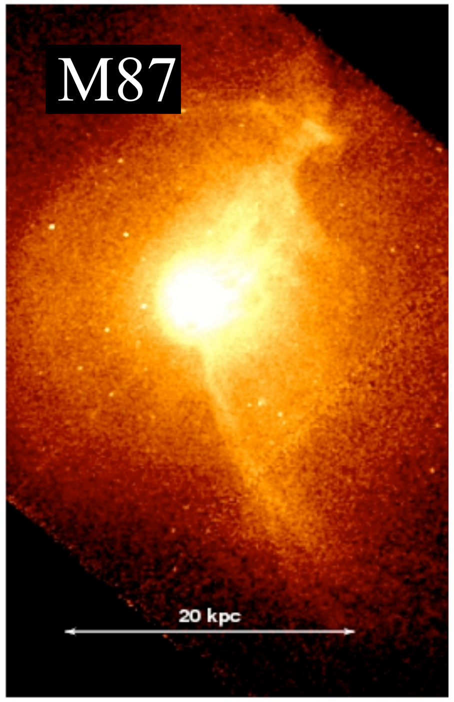


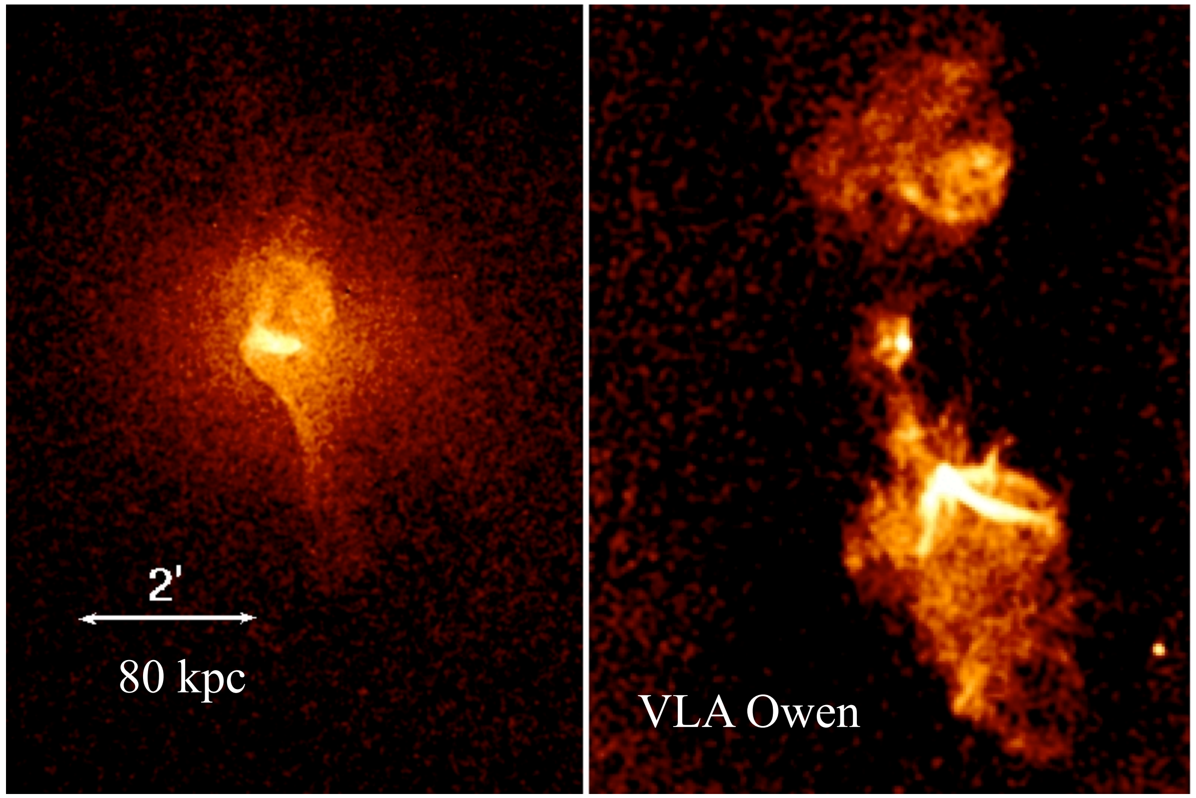
Outburst Model

- Age ~ 12 Myr
- Energy ~ 5×10^{57} erg
  - Bubble 50%
  - Shocked gas 25% (25% carried away by weak wave)
- Outburst duration ~ 1-3 Myr

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

IC1262: another M87? (Forman+11)





Cool (~ 1 keV) arms uplifted by buoyant (radio emitting) bubbles/ lobes

- Scale 8 times larger than M87
    - Arms ±80 kpc; Radio lobes ±160 kpc
    - Age $(D/c_s) > 2\times10^8$ yr

cD	IC1262	M87
Lx	2×10^{43}	3×10^{43} ergs/sec
kT	2 keV	2.5 keV
"Arms"	±20 kpc	±80 kpc
Radio Lobes	yes	yes
Shock	Maybe	M=1.2 (classical)

See also Hudson+03; Trinchieri+07,

- $4PV = 1.2\times10^{59}$ erg (outburst energy)
    - -Power ~ 2×10^{43} erg/s
    - -Very similar to M87

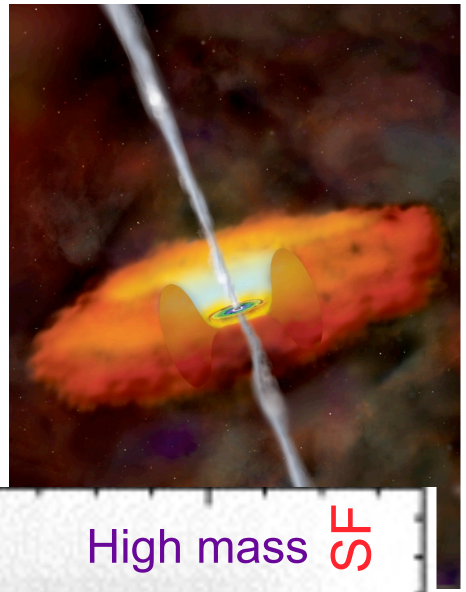
Gas Bar/Disrupted Core

$M_{gas} \sim 5\times10^8\ M_\odot$

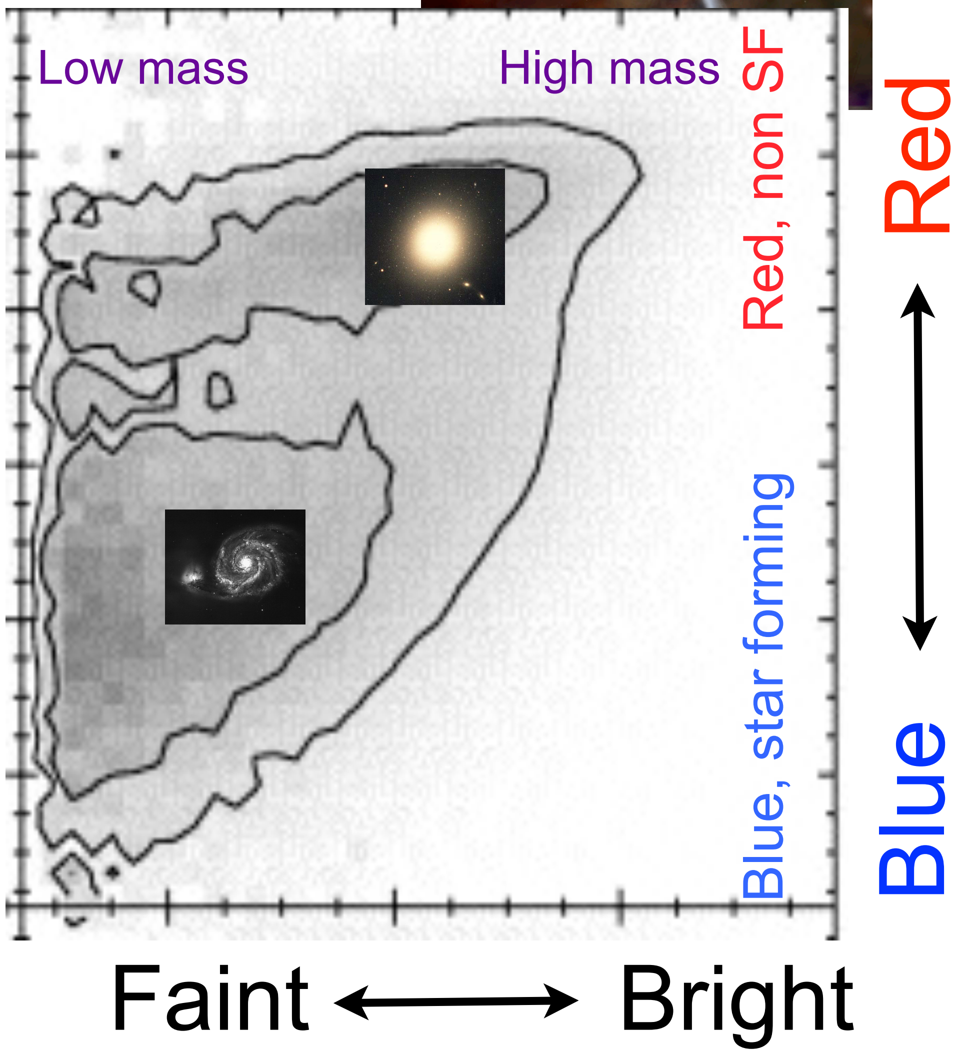
Outbursts from Clusters to Galaxies

	MS0735 McNamara+05	Hydra A Nulsen+05	M87 Forman+07	NGC4636 Jones+02
SHOCK RADIUS (kpc)	230	210	13	5
ENERGY (10^{61} erg)	5.7	0.9	0.0005	0.00006
AGE (My)	104	136	12	3
MEAN POWER (10^{46} erg/s)	1.7	0.2	0.0012	0.0007
ΔM (10^8 M_{sun})	3	0.5	0.0003	0.00003
$L_X/L_{EDDINGTON}$	0.03	0.003	1.8×10^{-5}	1.0×10^{-5}

Feedback from Supermassive Black Holes Explains Basic "Fact" of Astronomy - two kinds of galaxies



- Feedback
  - Supermassive Black Hole in galaxy nuclei
  - accretes matter
  - Black hole grows
  - Some energy returned (via jets) to control formation of new stars
  - red sequence/blue cloud (elliptical vs. spiral; old red, "dead" galaxies vs. blue/ young ; hot gas rich vs. hot gas poor)
  - explains galaxy luminosity function
- Key component of galaxy evolution

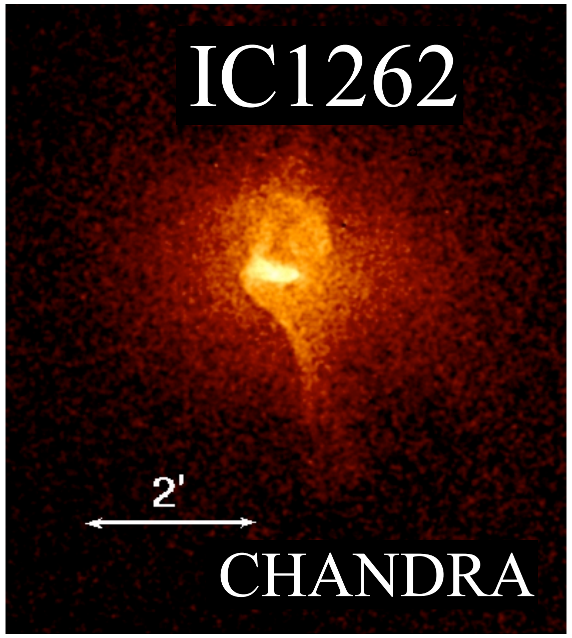


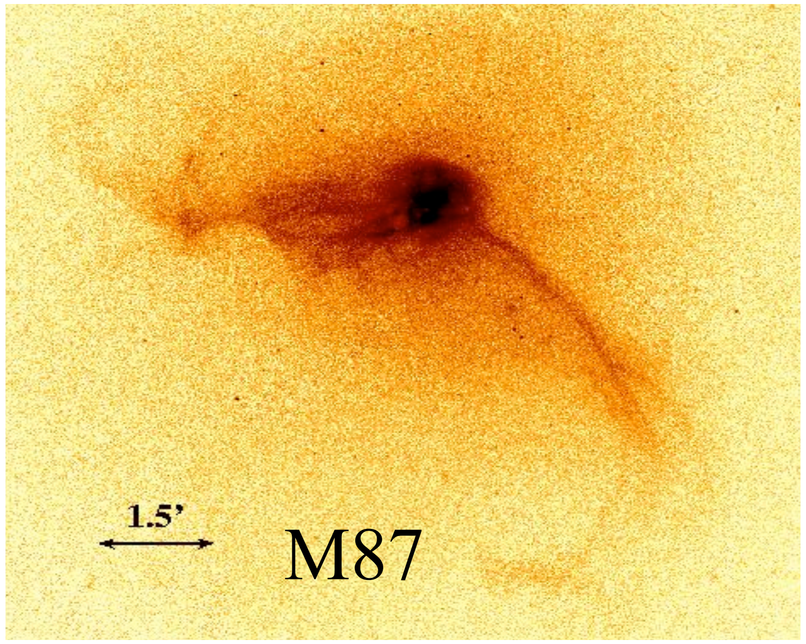
e.g. Croton+06, Best+06, Teyssier+11

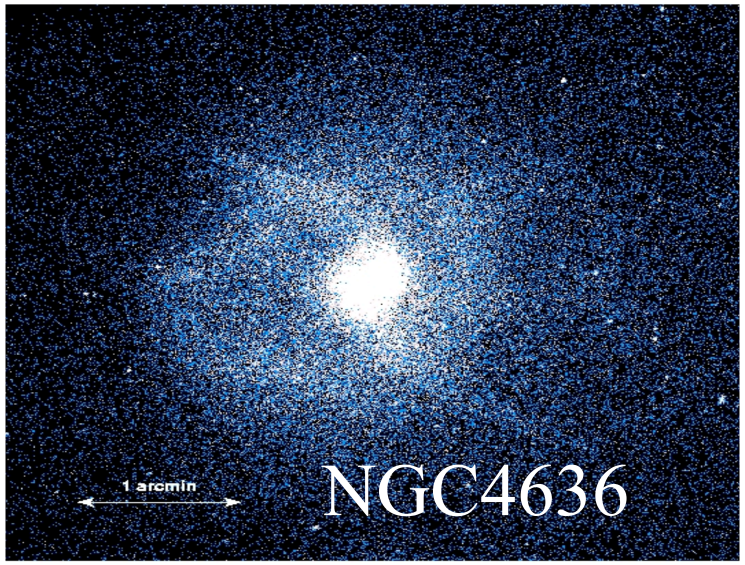
Hot atmospheres are key to capturing AGN mechanical energy

Prevents cooling in luminous/gas rich early type galaxies like M87

- M87 - classical shock with buoyant radio lobes, X-ray filaments
  - Energy output matches radiated luminosity
  - Predominant heating from bubble/lobe enthalpy
  - L_x/L_{edd} small (10^{-5} for M87) - ADAF mode - radiatively inefficient
  - Like other early type galaxies $\tau \sim 10^6$ - 10^8 yrs, $E \sim 10^{55}$-10^{58} erg
  - Sufficient to balance cooling
  - Key component of galaxy evolution i.e., "red and dead" vs. actively star forming galaxies







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