Heating, Cooling and Polluting the Gas in Clusters of Galaxies

C. Jones, W. Forman, E. Churazov, A. Vikhlinin, M. Markevitch

Temperature structure and distribution of heavy elements in the ICM

OUTLINE

Basic cluster properties - baryons in clusters

How is the gas heated?

Cluster mergers -- cold fronts and shocks

How is the cooling gas in cluster cores reheated?

Outbursts from supermassive black holes

Is there non-thermal pressure support for the gas?

Is the gas turbulent?

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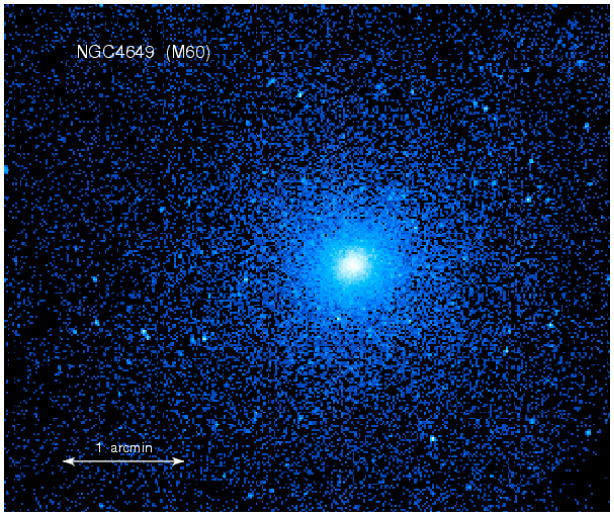
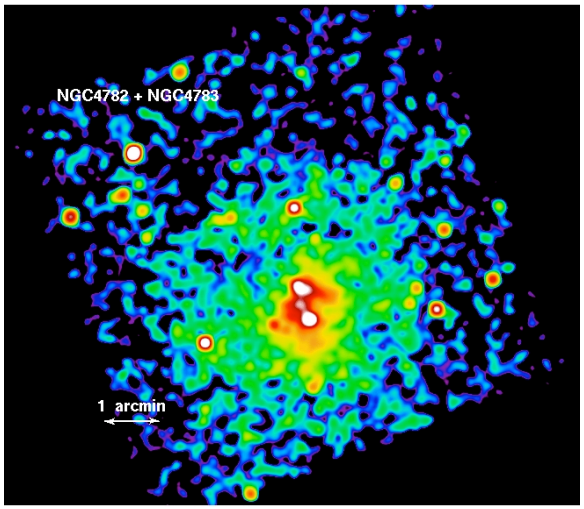
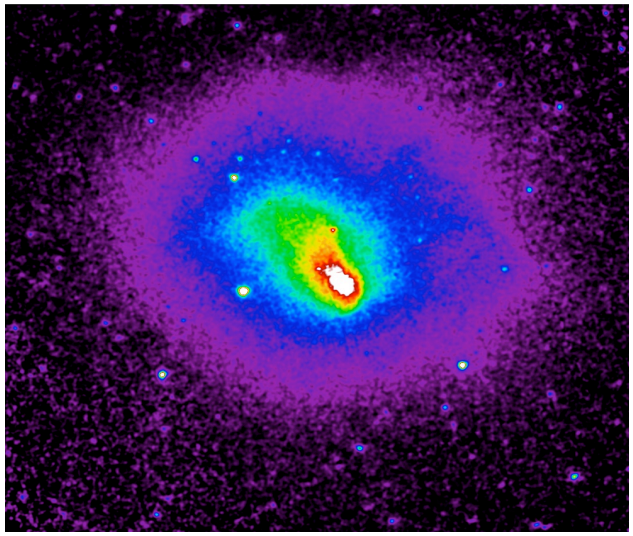
Family of increasing mass, temperature, and luminosity



Early type Galaxy



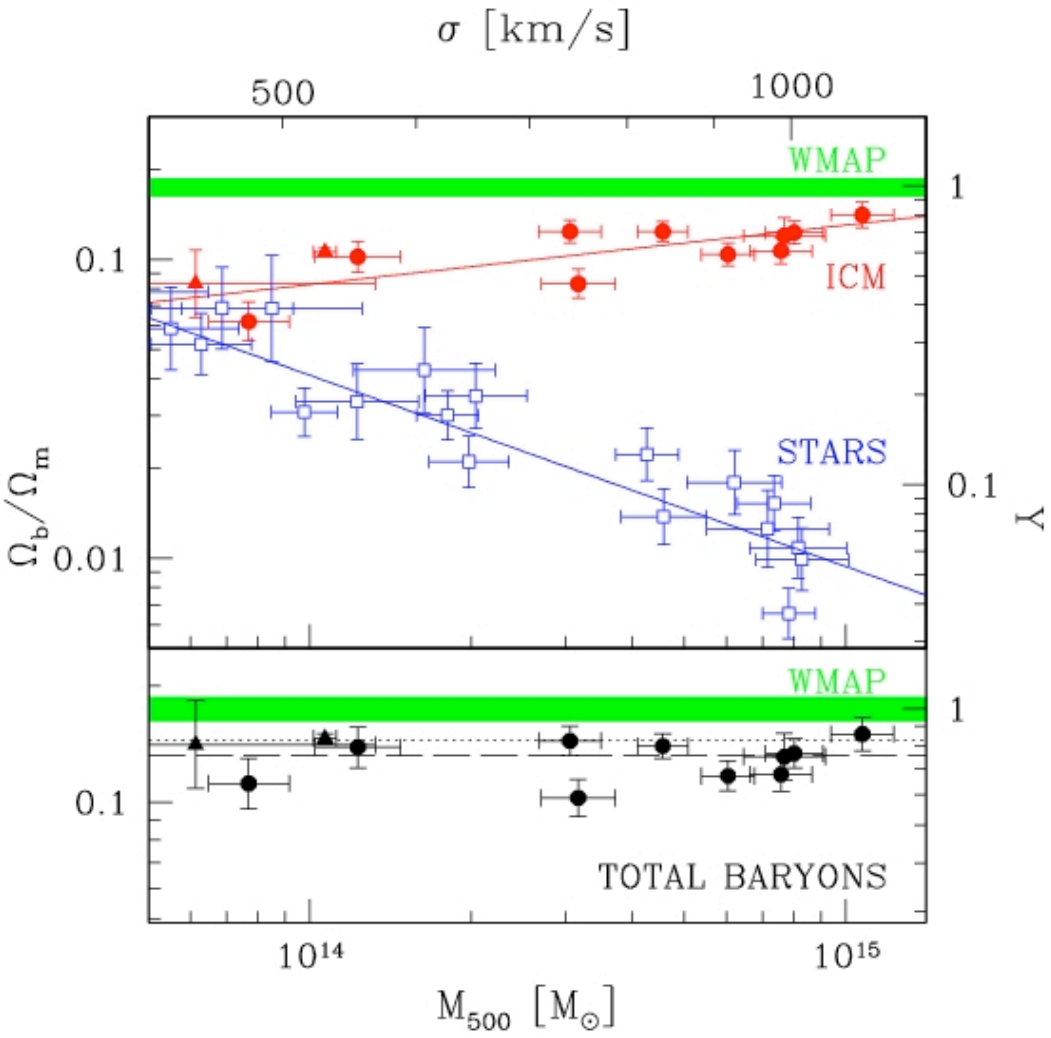
Group



Cluster

	E/S0 Galaxies	Groups	Clusters
L_x (ergs/sec)	$10^{40\text{-}42}$	$10^{42\text{-}43}$	$10^{43\text{-}46}$
Gas Temp	0.5-1.0 keV	1-2 keV	2-15 keV
$M_{gas}/M_{stellar}$	0.02	1	5

Census of Baryons in clusters and groups



From Gonzalez et al. 2007
arXiv 0705:1726

Clusters form from such large volumes that their baryonic mass to dark matter should be representative of the Universe.

Gonzalez et al include intracluster light as well as galaxies. Fraction of stars in ICL grows with decreasing cluster mass.

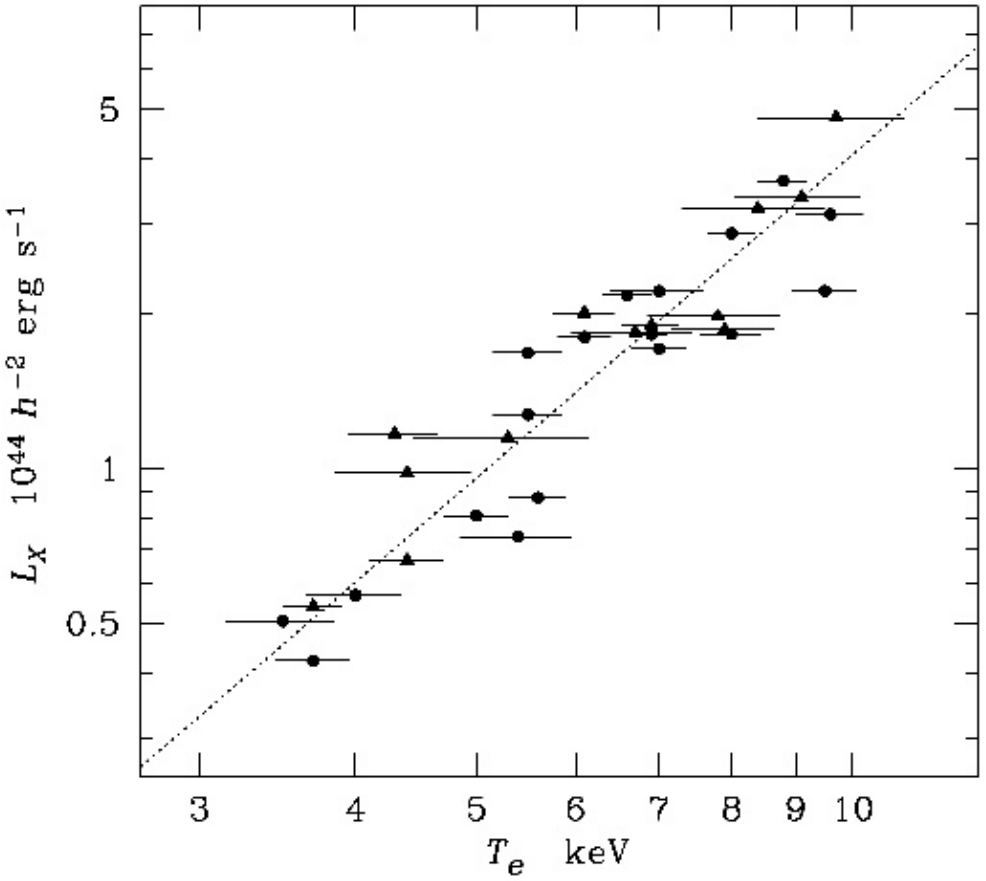
In massive clusters, most of the baryons are in the hot gas.

In poor clusters/groups, near equal amounts of baryons in stars and gas.

Decrease in star formation efficiency in more massive environments - hot cluster gas does not cool to form stars

Baryon fraction is constant and near WMAP value - no significant, undetected baryonic component

X-ray emission from clusters



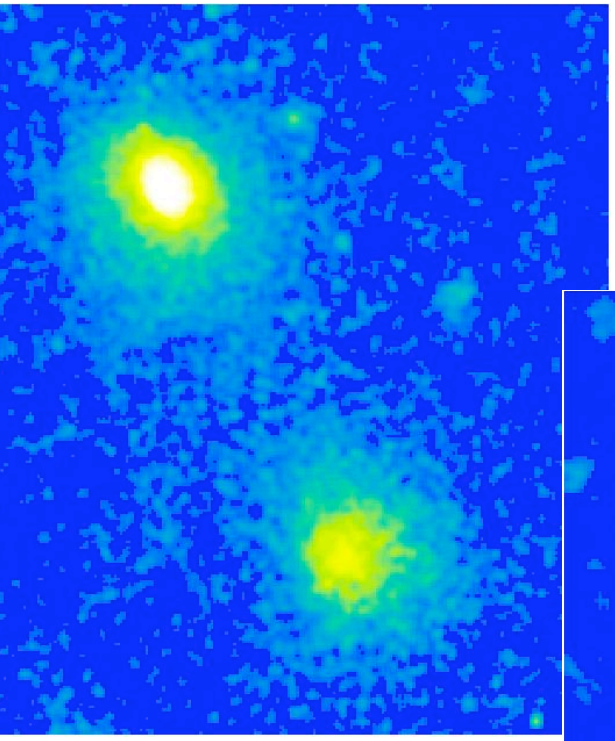
The hotter the cluster gas, the more X-ray luminous is the cluster.

Good correlation between gas temperature and cluster velocity dispersion (mass).

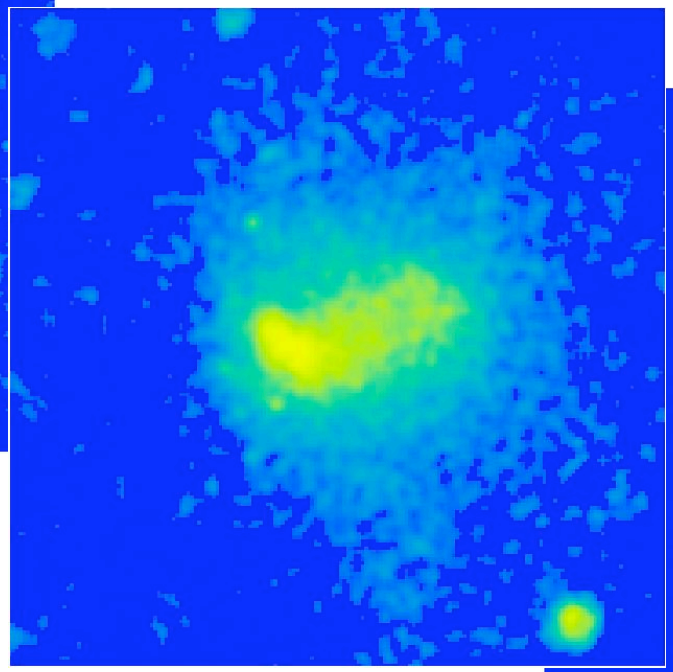
From Markevitch et al. 1998

Clusters grow hierachically through mergers

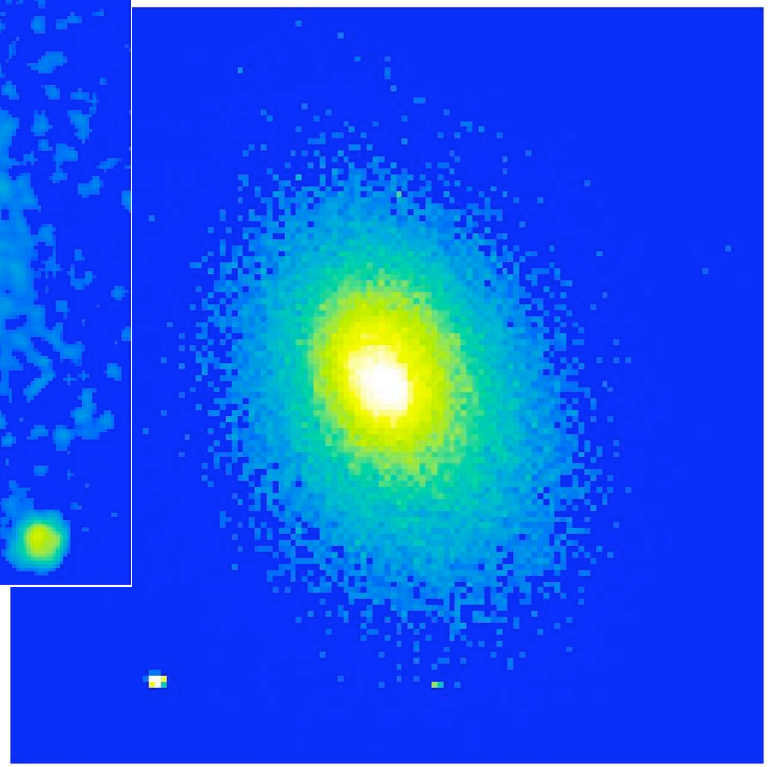
"relaxed" systems may be elliptical, but do not have significant structure in their X-ray surface brightness or temperature maps



A399 & A401



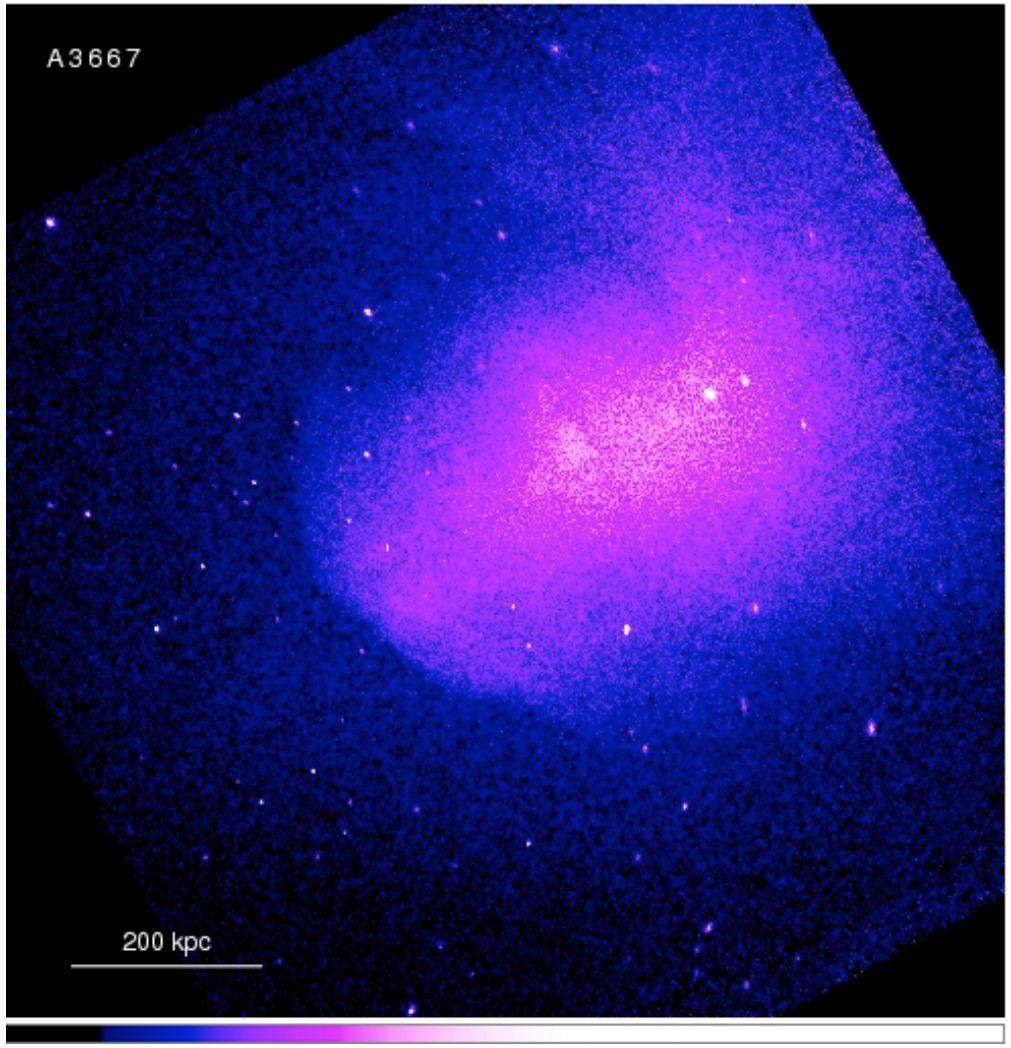
A754



A2029

Clusters grow through gravitational infall and mergers of smaller subclusters

A3667 -- mach = 1 merger - example of cold front



Cold fronts are sharp in terms of both their temperature and density jumps.

Measure pressure jump across edge to determine Mach number of cloud.

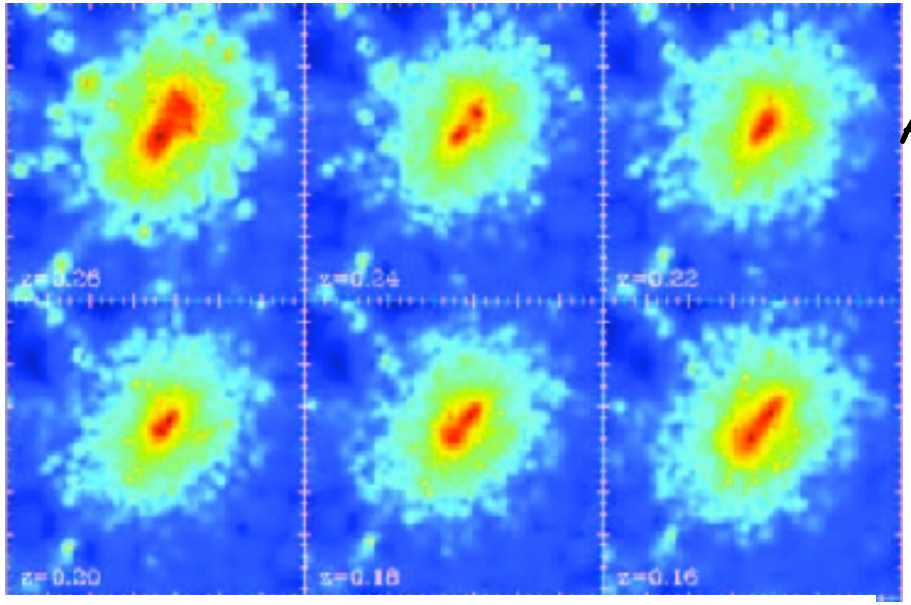
For A3667, Mach number is 1.0 (0.2) which is 1400 (300) km/s

Vikhlinin, Markevitch & Murray 2001a,b
Markevitch & Vikhlinin review arXiv 0701821

Cluster gas is heated through mergers

Mathis et al. 2005

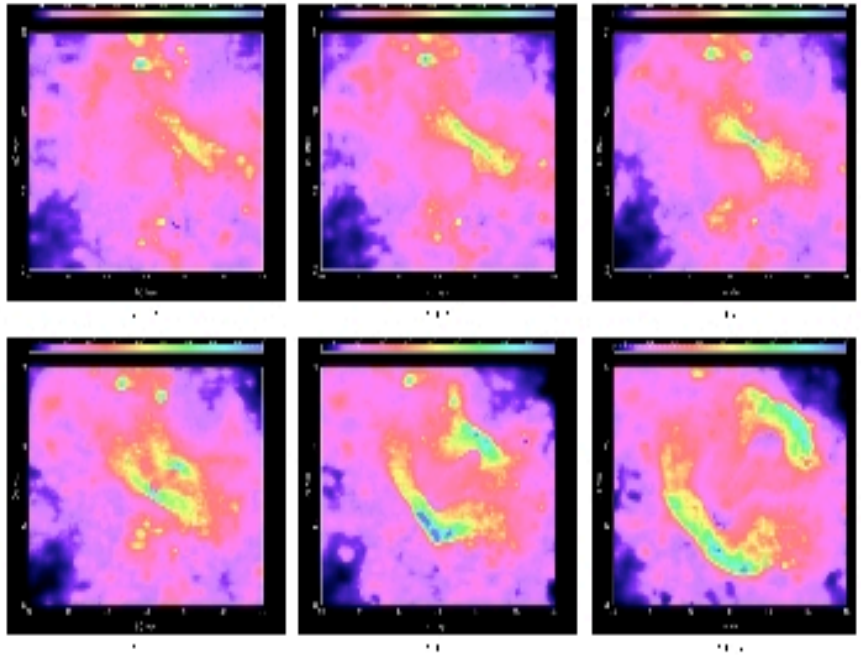
14 Mpc



Almost core passage

Dark matter

6 Mpc

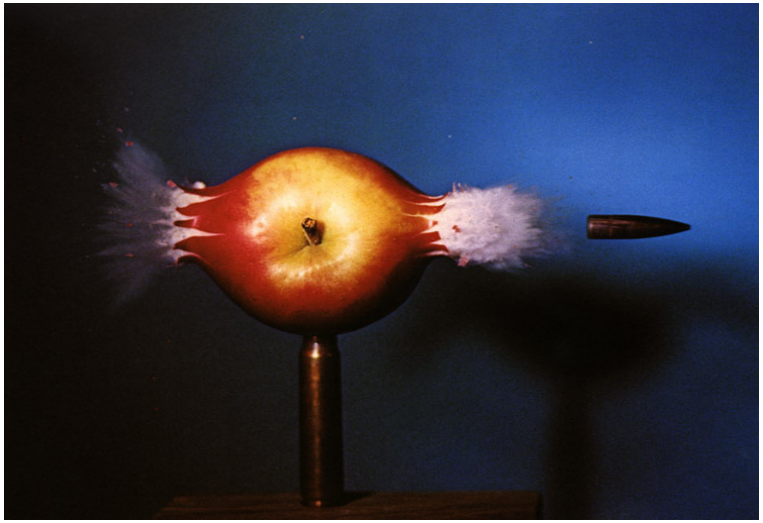


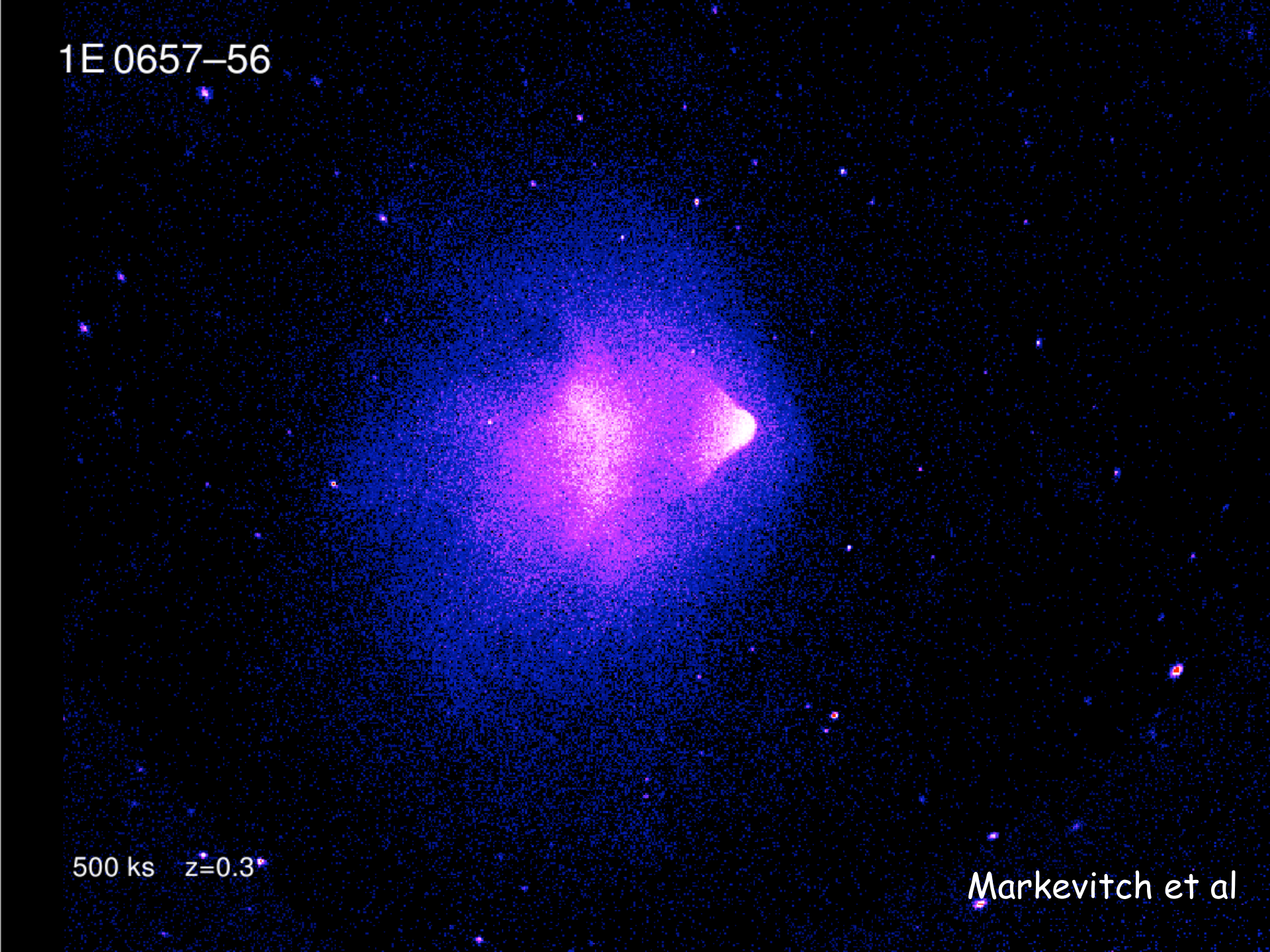
Compressed shock heated gas

GasTemperature

Cold fronts

The bullet cluster

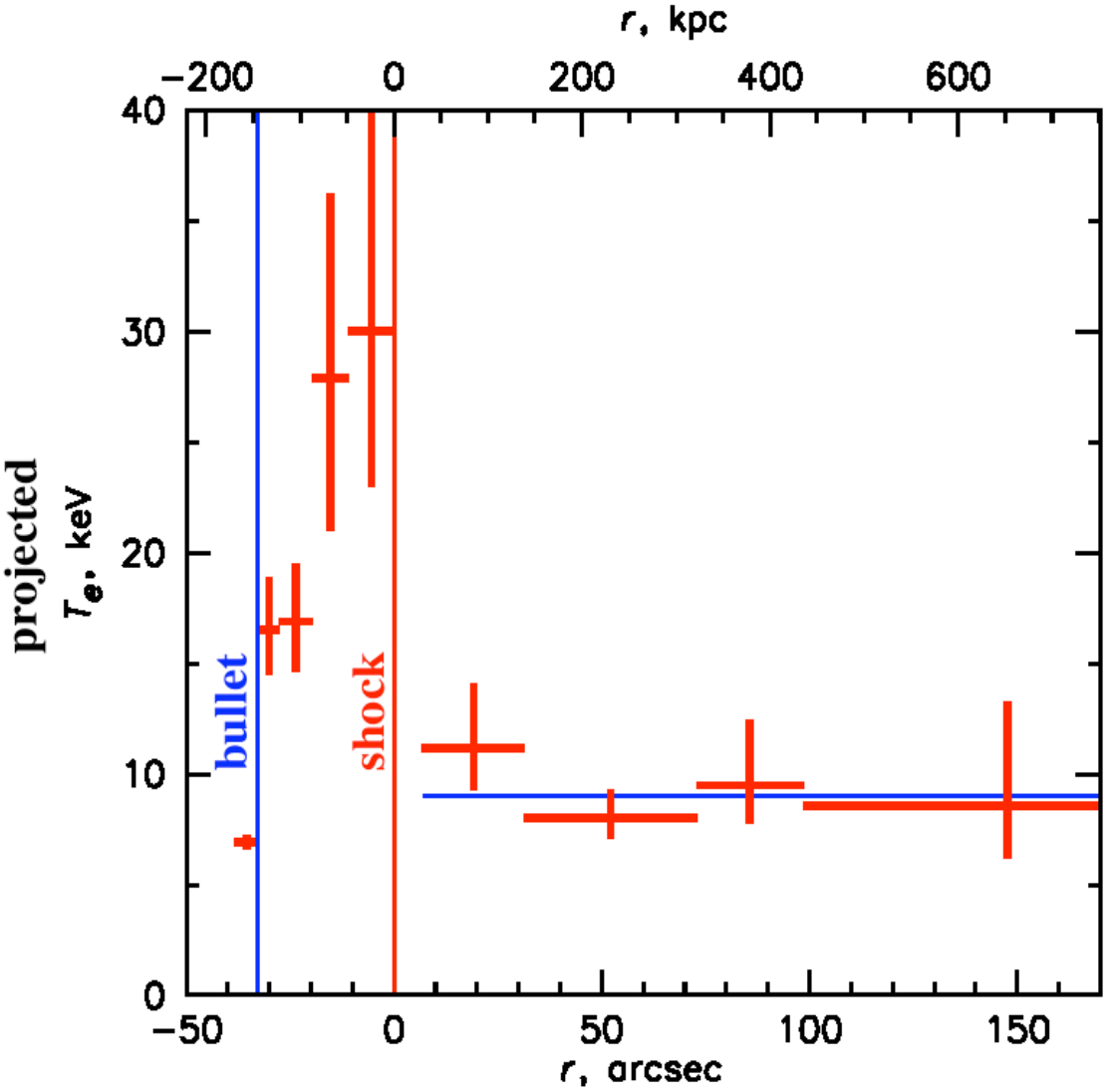



1E 0657–56
500 ks z=0.3
Markevitch et al

The temperature profile through the nose of the shock shows a strong shock and a cold front

X-RAY TEMPERATURE PROFILE FROM CHANDRA OBSERVATIONS

Markevitch et al. (2006)



Fitting the density jump in the X-ray surface brightness profile allows a measurement of the shock's Mach number

X-RAY SURFACE BRIGHTNESS PROFILE

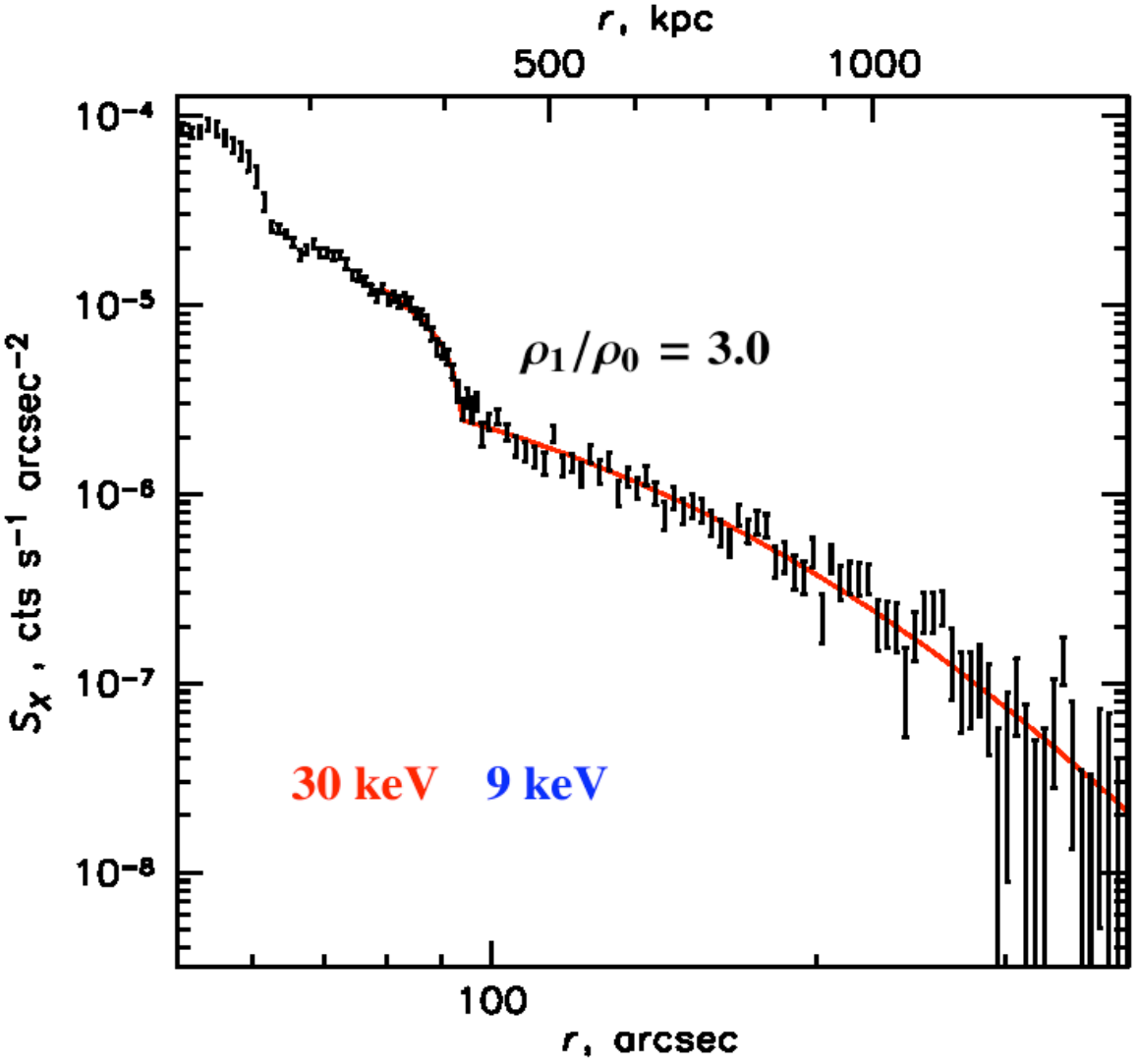
Markevitch et al. (2006)

shock strength:

M = 3.0 ± 0.4

shock velocity:

v_s = 4700 km/s

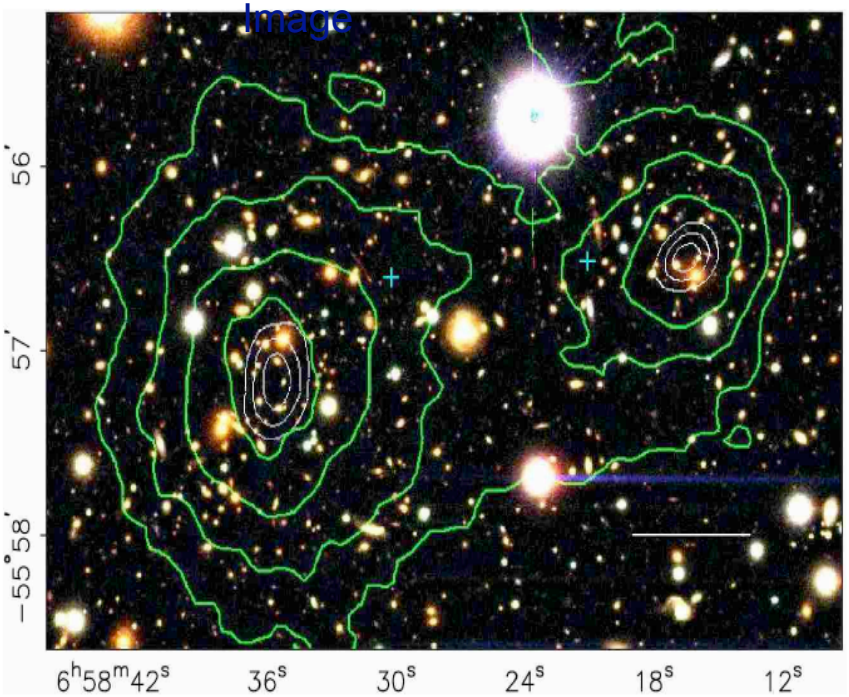


New weak lensing mass reconstructions have confirmed an offset between mass peaks and X-ray emission

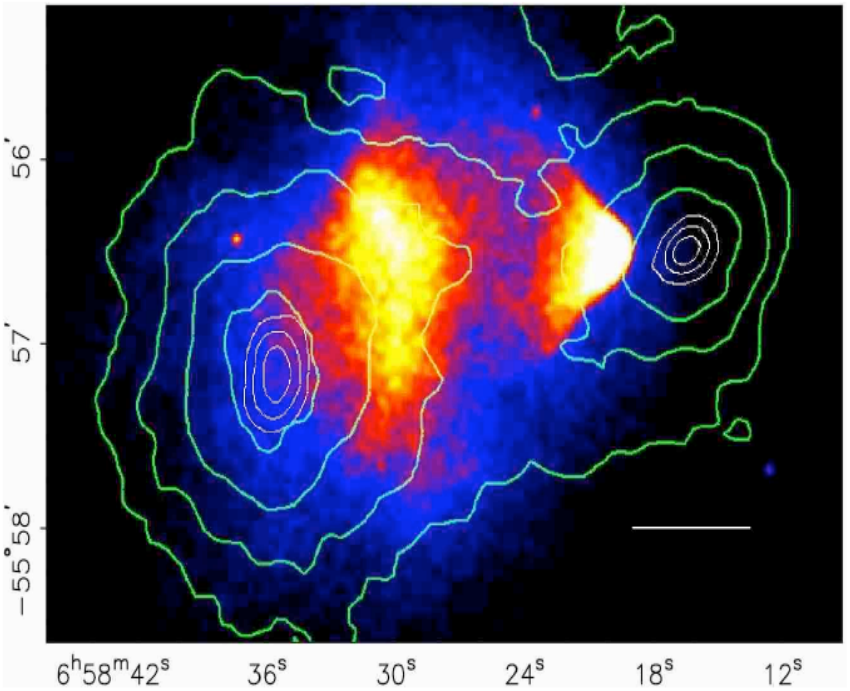
MASS CONTOURS FROM LENSING COMPARED TO X-RAY EMISSION

Clowe et al. (2006)

Magellan Optical Image



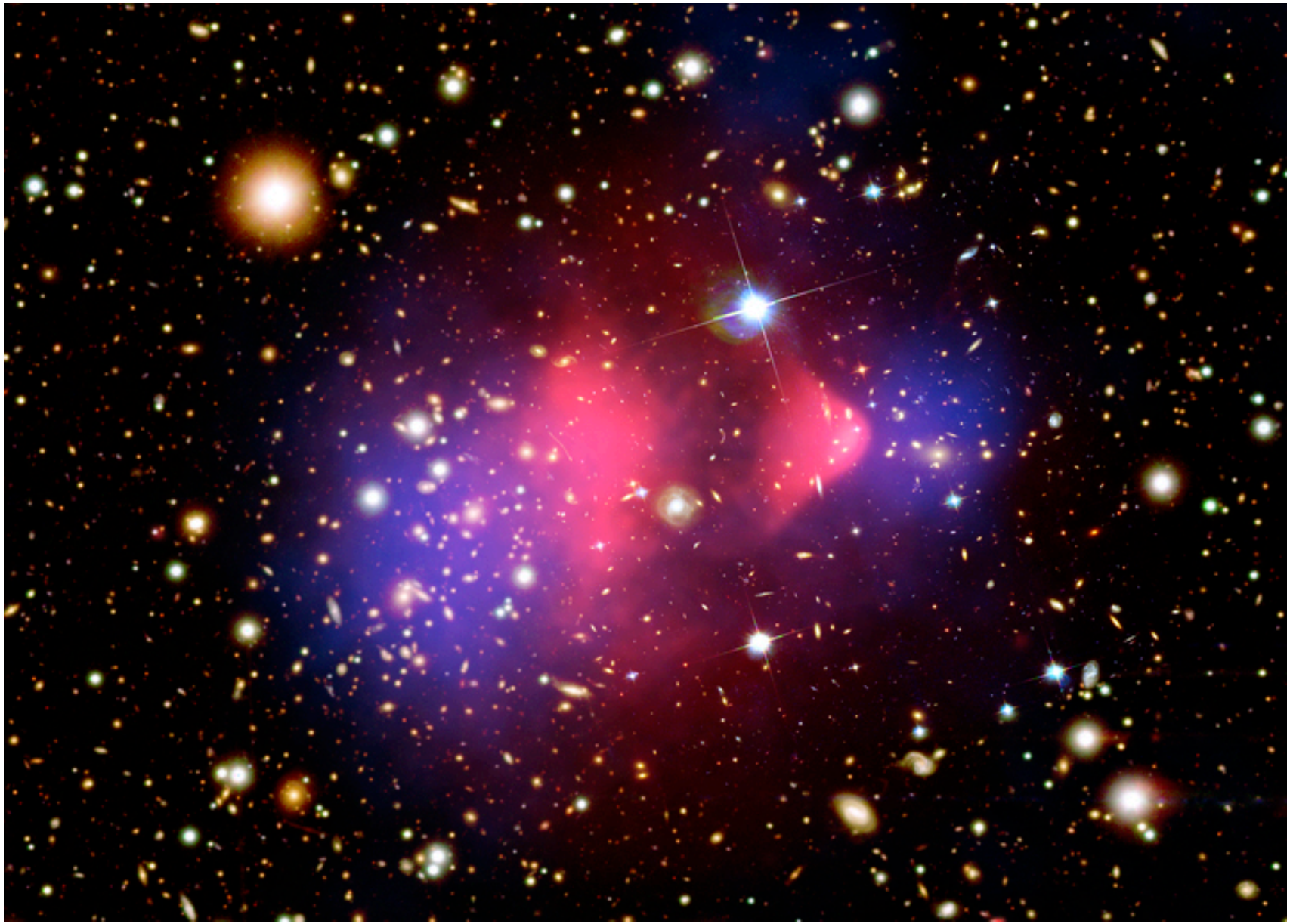
500 ksec Chandra exposure



weak lensing mass contours overlaid

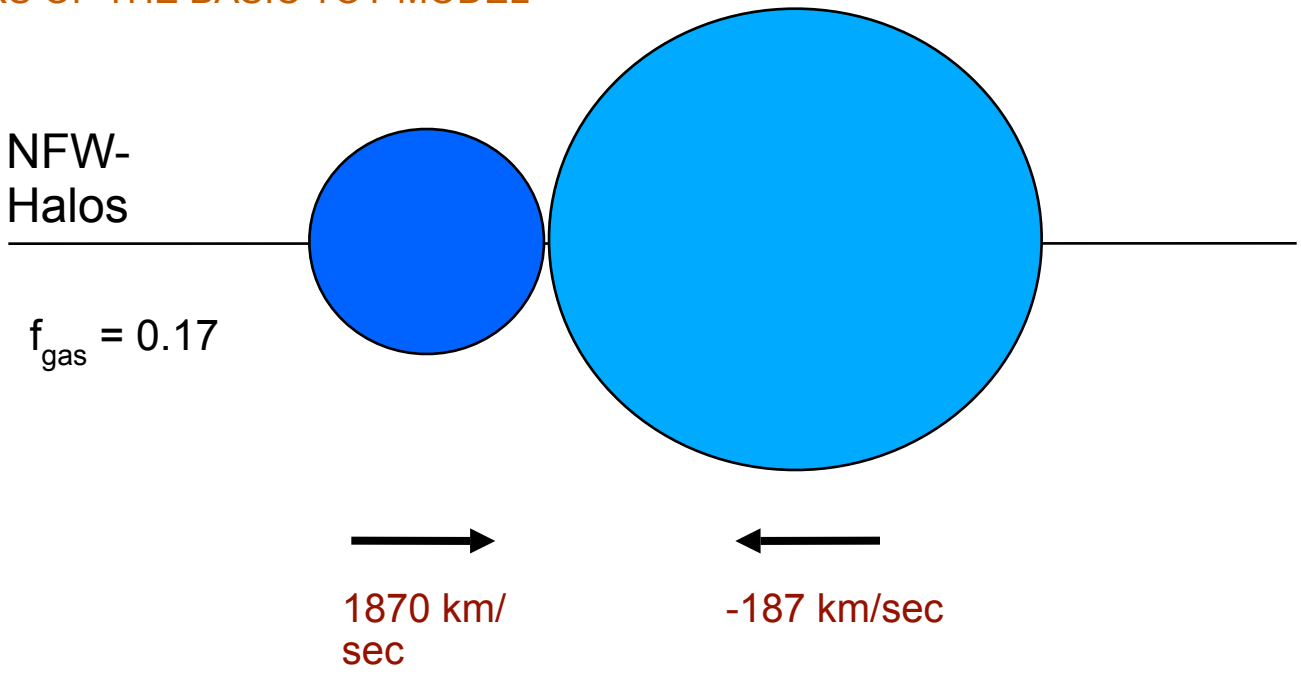
NASA Press Release Aug 21, 2006:

1E 0657-56: NASA Finds Direct Proof of Dark Matter



Volker Springel's simple toy merger model of two NFW halos on a zero-energy collision orbit

PARAMETERS OF THE BASIC TOY MODEL



Mass model from **Clowe et al. (2006):**

M_{200} = 1.5 x 10^{14} $M_\odot$

R_{200} = 1.1 Mpc
c = 7.2
V_{200} = 780 km/sec

M_{200} = 1.5 x 10^{15} $M_\odot$

R_{200} = 2.3 Mpc
c = 2.0
V_{200} = 1680 km/sec

VIDEO OF THE TIME EVOLUTION OF A SIMPLE BULLET CLUSTER MODEL - Volker Springel

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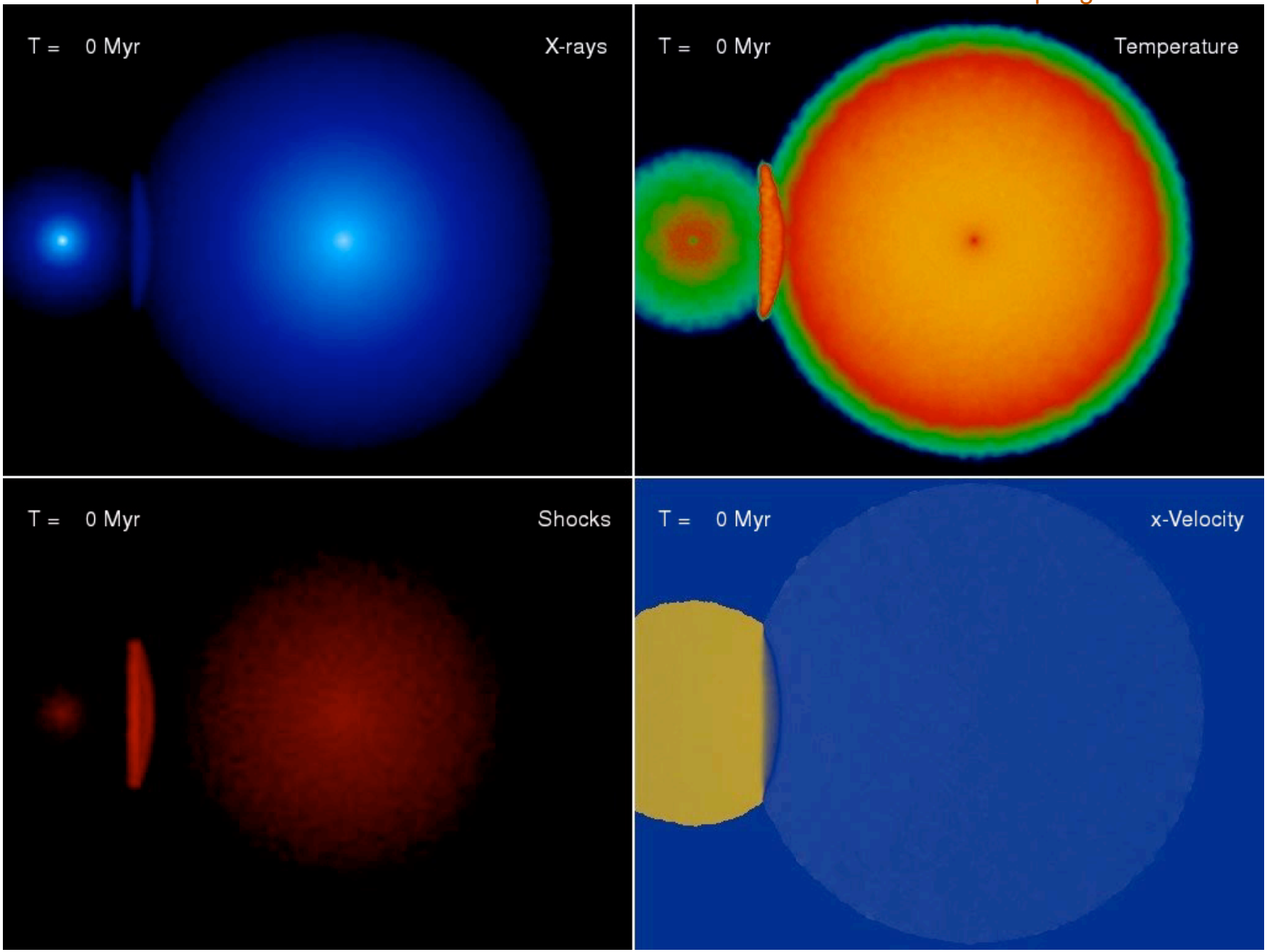
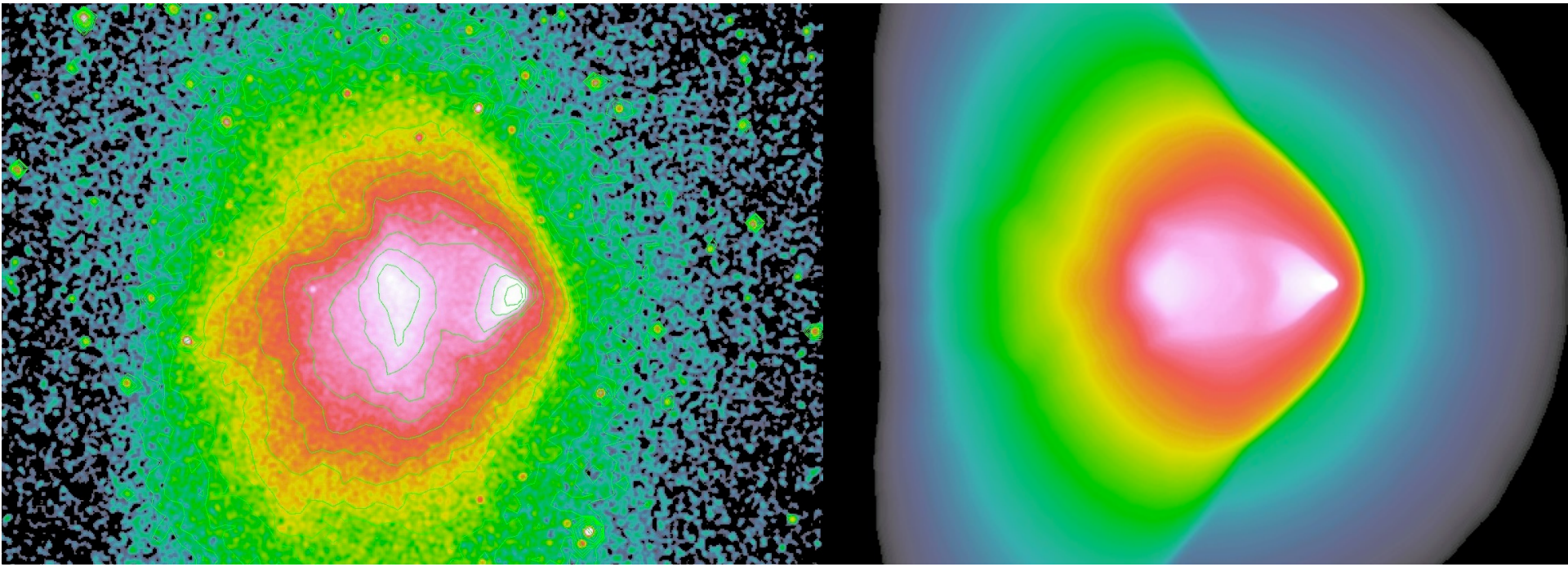


Drawing the observed X-ray map and the simulation images with the same color-scale simplifies the comparison

SPRINGEL SIMULATED X-RAY MAP COMPARED TO OBSERVATION

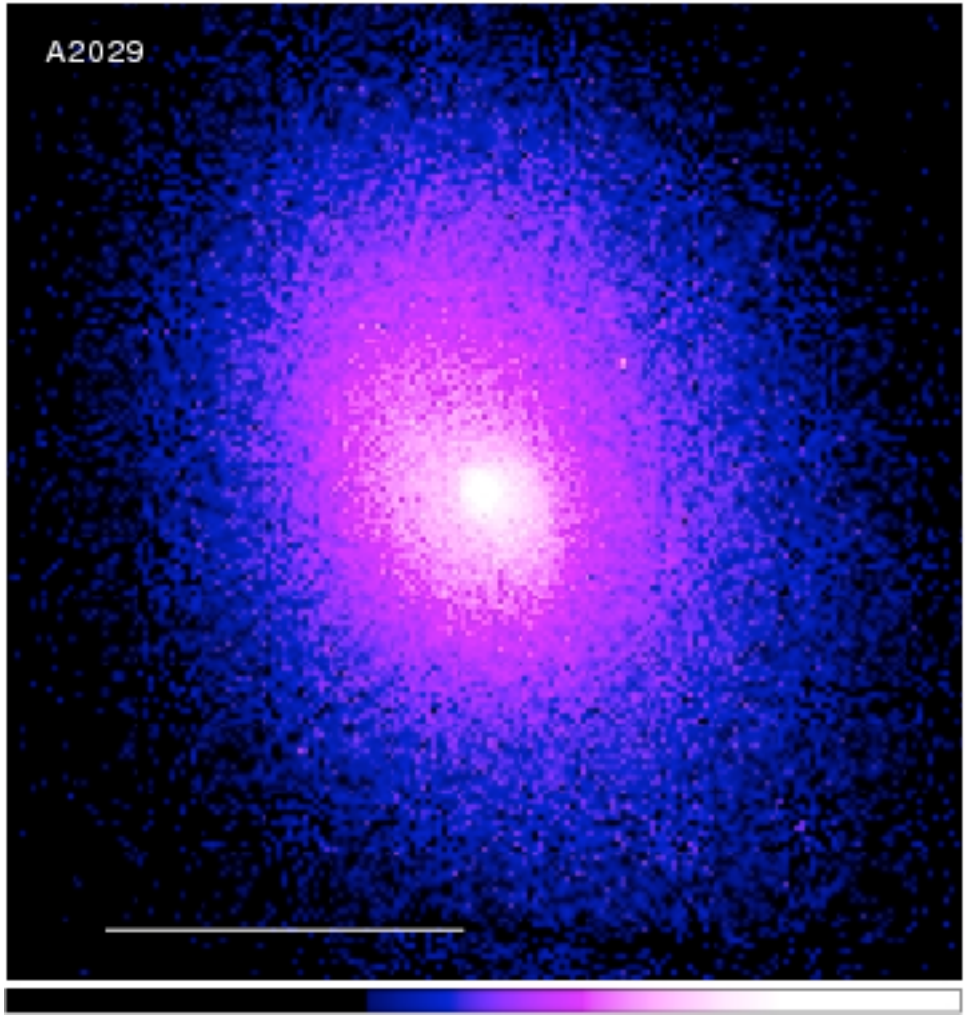
Chandra 500 ks image

bullet cluster simulation



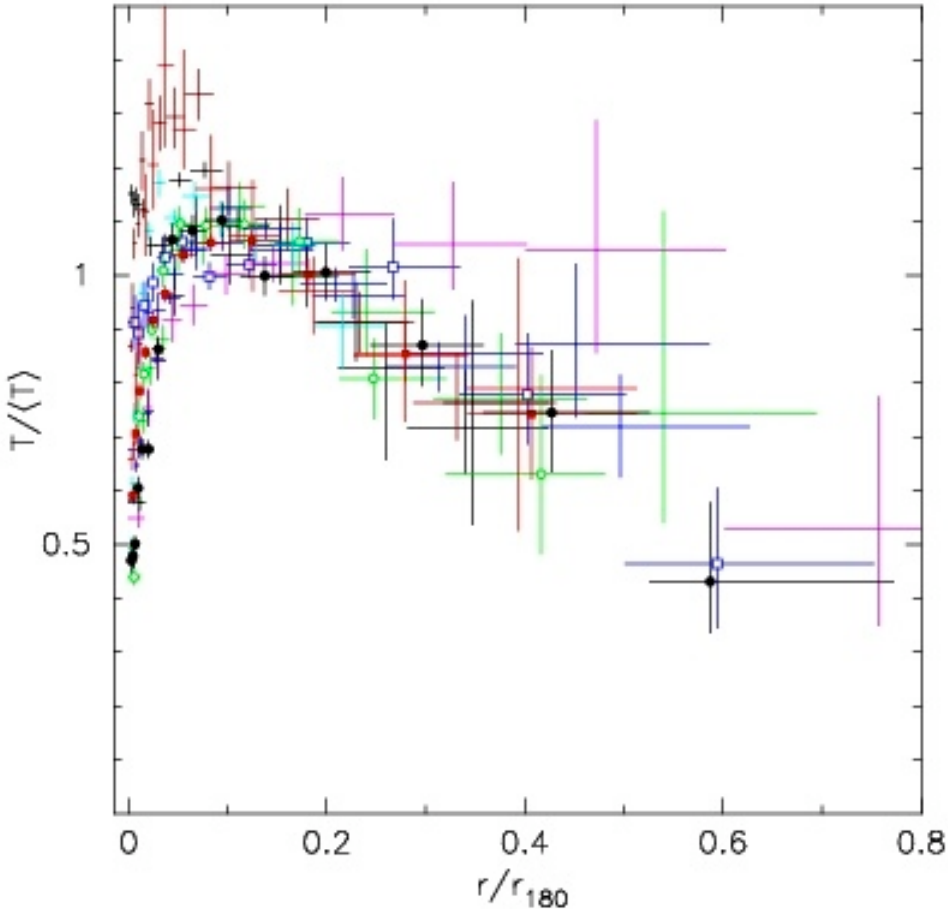
Relaxed Clusters

Temperatures and abundances -- radial profiles



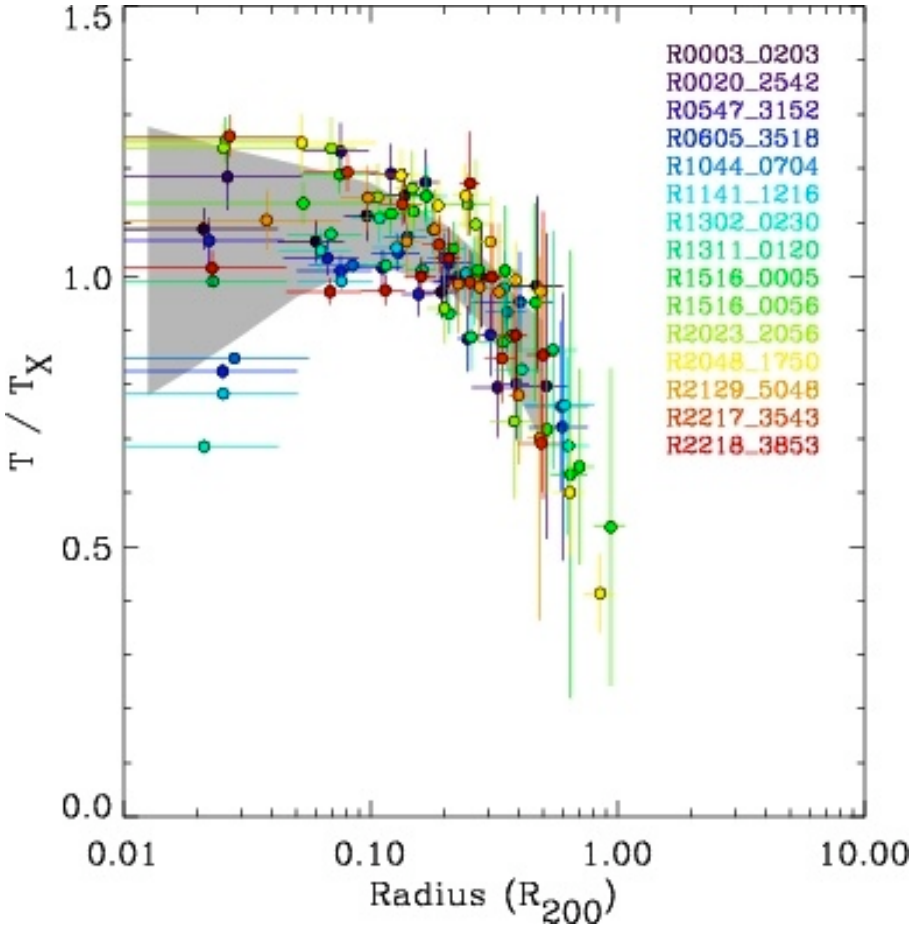
Cluster radial temperature profiles for "relaxed" systems

Chandra



Vikhlinin et al.

XMM-Newton

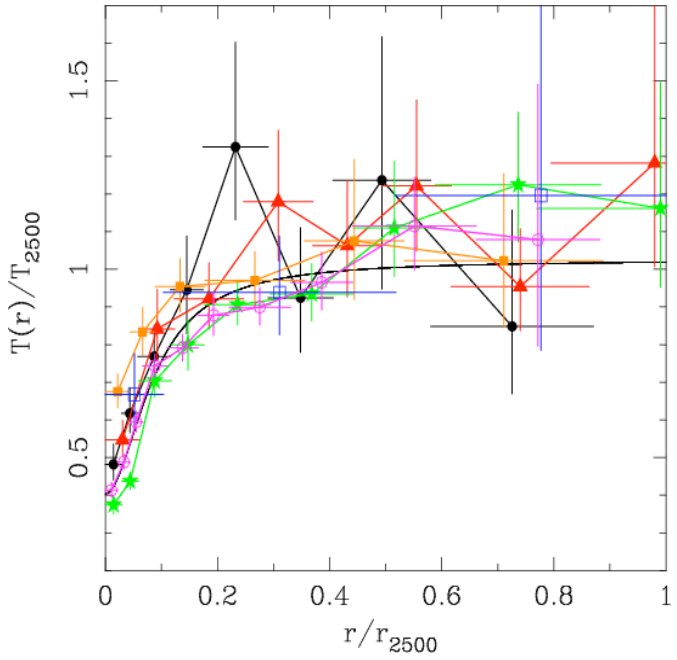


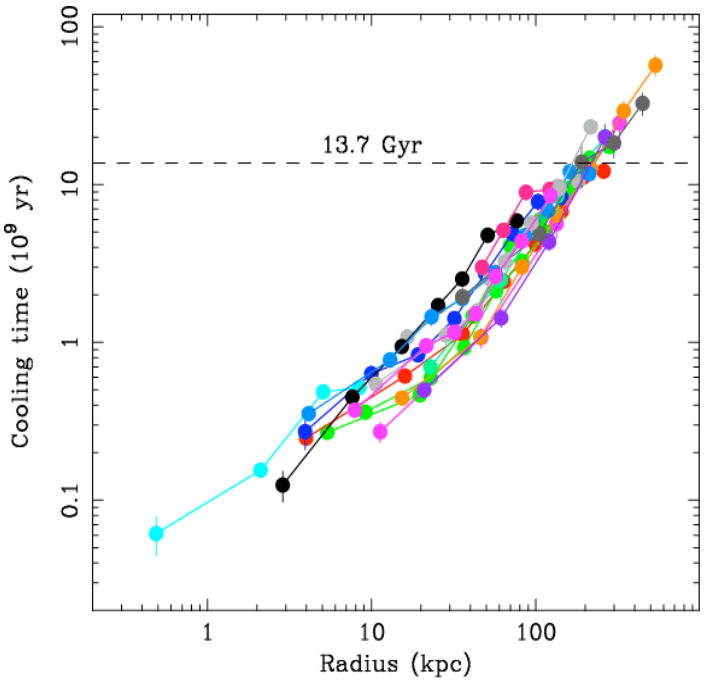
Pratt et al.

Cool cluster cores

- **Cool X-ray gas and short cooling times were found in cluster cores**
- **Estimated mass deposition rates were large (100 -1000 M/yr)**
- But large amounts of cool gas were not detected in HI, IR-optical-UV
- True test for cool gas came from X-ray spectroscopy showed little cool gas (Peterson et al. 2001)

Cool cluster cores





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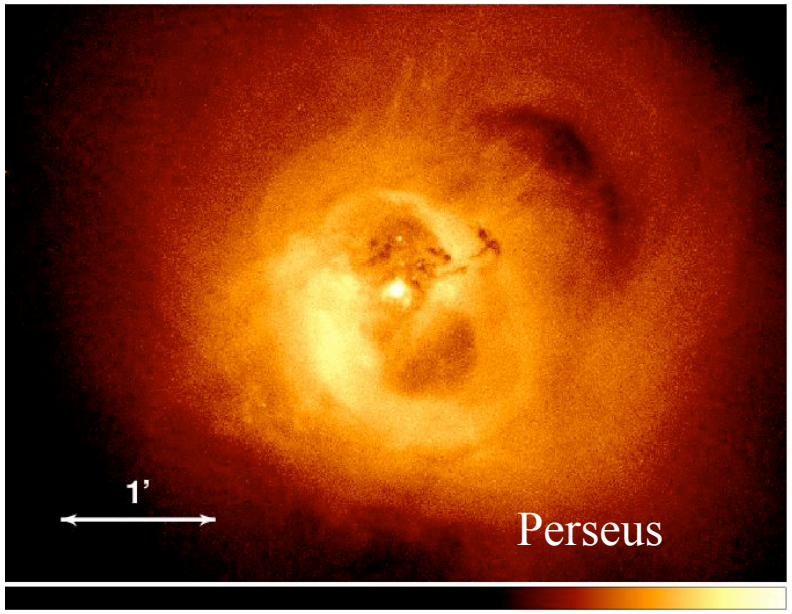
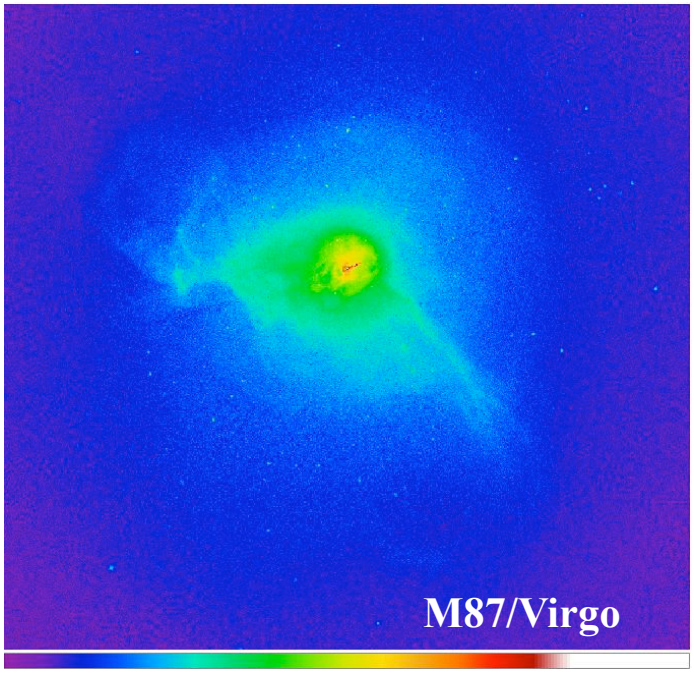
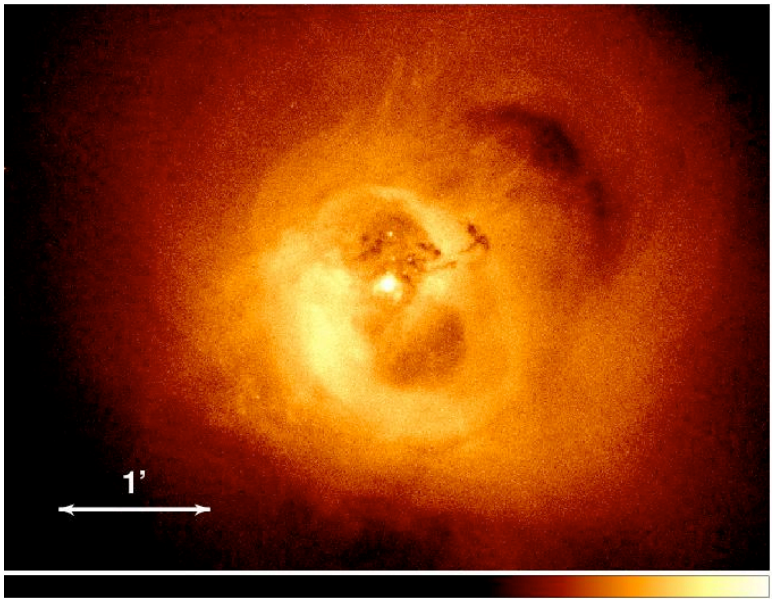
Gas Heating Mechanisms

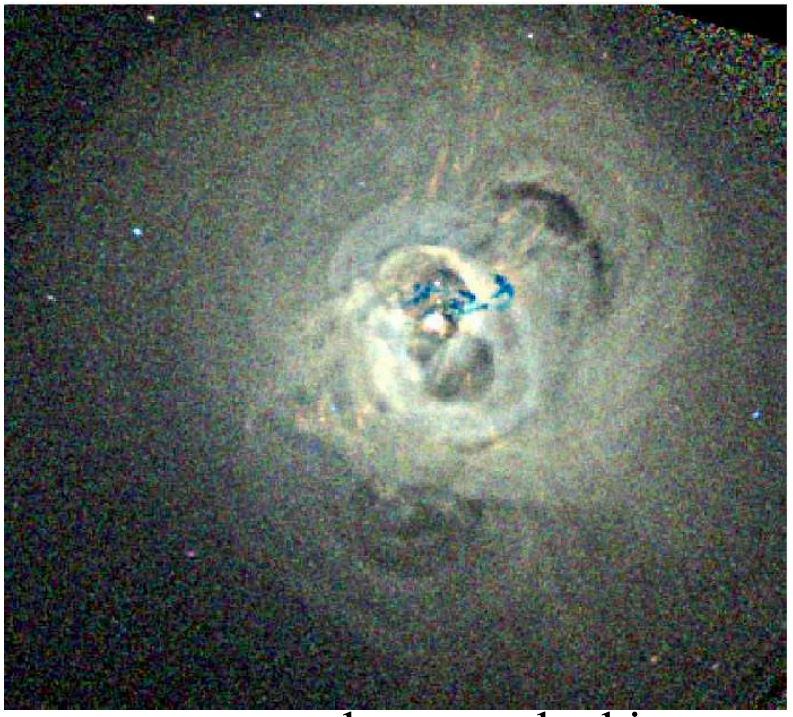
- Cluster-subcluster mergers – plenty of energy (10^{64} ergs), but not dependable (plus cooling flow clusters appear relaxed)
- "Sloshing" of gas in the core (Markevitch et al 2001)
- Thermal Conduction – from hot outer cluster gas to cool centers; see Tucker & Rosner 1983, Bertschinger & Meiksin 1986, Gaetz 1989, Narayan and collaborators, probably not effective at center
- Energy from AGN Rosner & Tucker 1989, Böhringer & Morfill 1989, Binney & Tabor 1995, David & Tucker 1997, Churazov et al. 2001
  - Bubbles
  - Shocks





Perseus Cluster - Shocks and Ripples (Fabian et al. 2002, 2003, 2005)





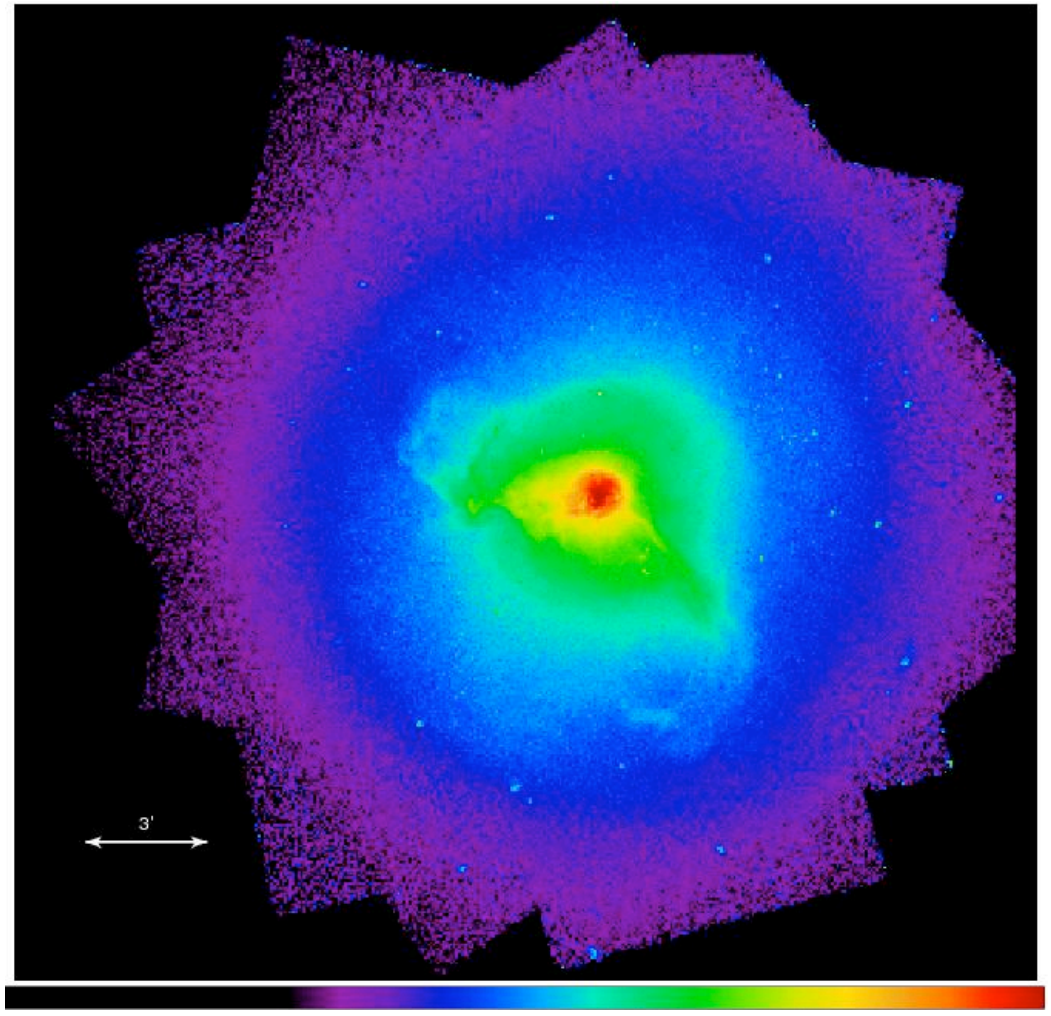
unsharp masked image

- Chandra image shows evidence for repeated outbursts
- Processed image (unsharp masking) shows faint ripples
- Sound waves (weak shocks) ? Driven by expansion of radio bubbles

  Sound speed =1170 km/sec, separation=11kpc, t=9.6x10^6 yr

  Dissipate energy (high ion viscosity) over a distance < 100 kpc
- Energy of bubbles/shocks balances cooling

M87 with Chandra

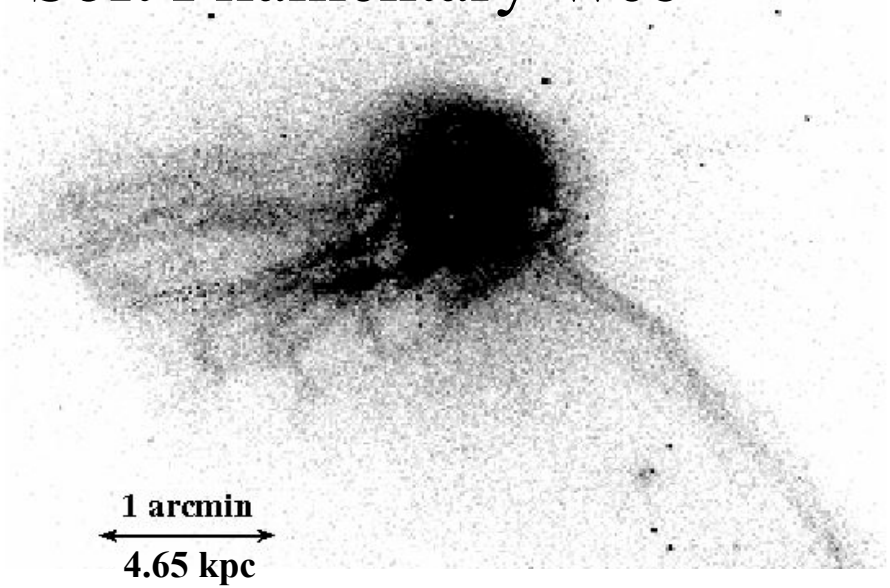


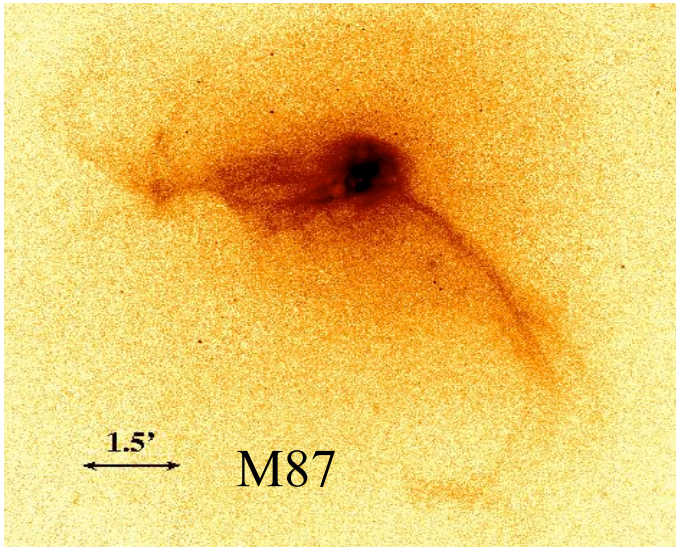
1'=4.5 kpc

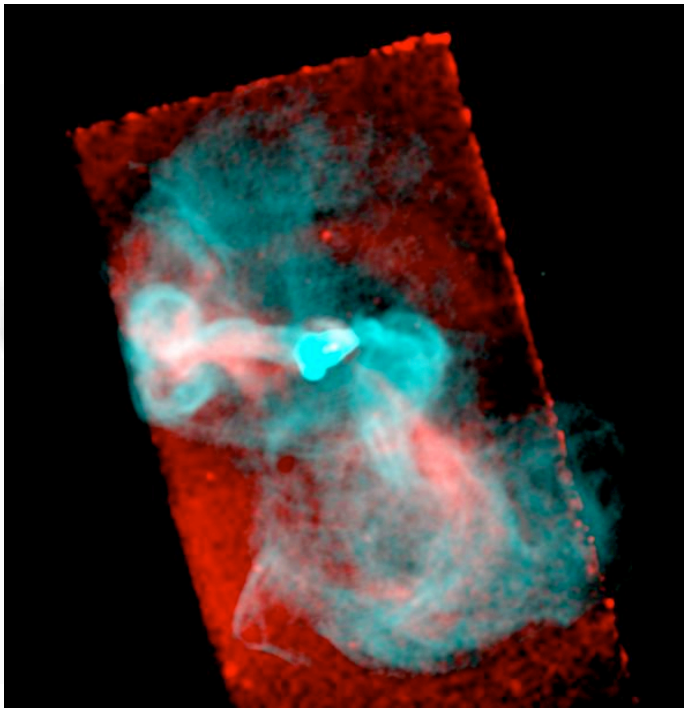
- ACIS observations
  - 100 ksec in 2002
  - 500 ksec in 2005
- Bright central region
- X-ray-Radio arms
- Shocks

- Forman et al. 2005, 2007

Soft Filamentary Web



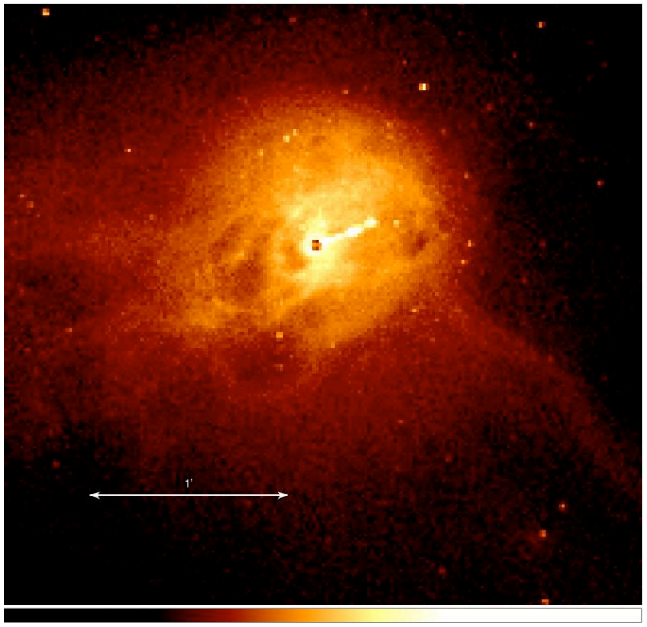


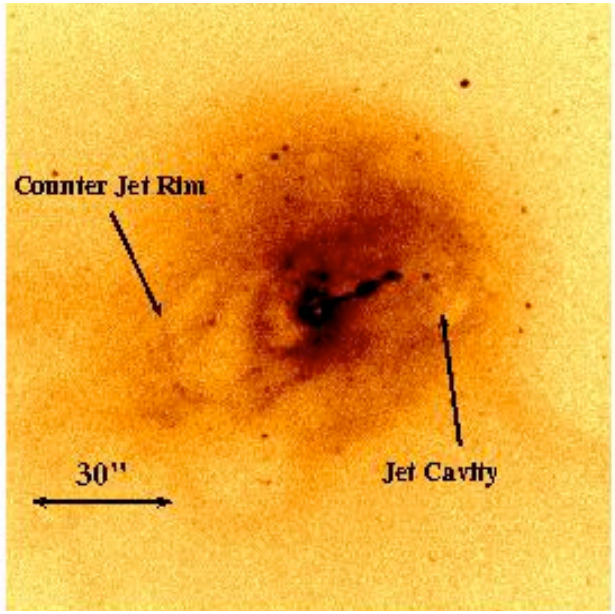


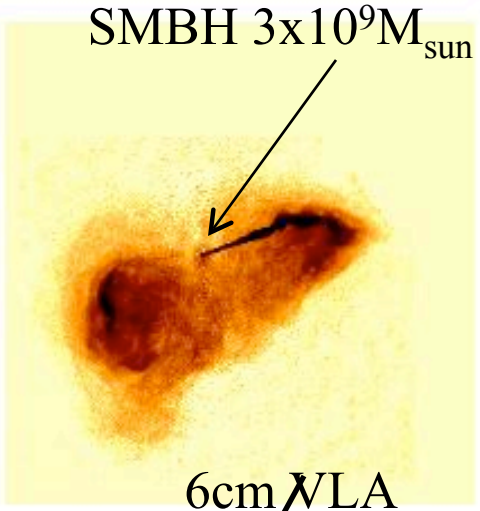
Eastern Arm - classical buoyant bubbles
Sequence of small buoyant bubbles
- PV ~ 10^{54} - 10^{55} ergs
- τ_{rise} ~ 10^{7} year

Southwestern arm - overpressured and "fine"
(~300pc, like bubble rims)

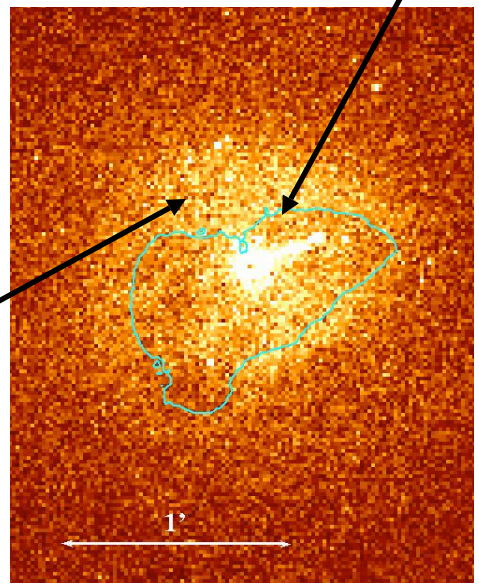
Central Region of M87 - the driving force

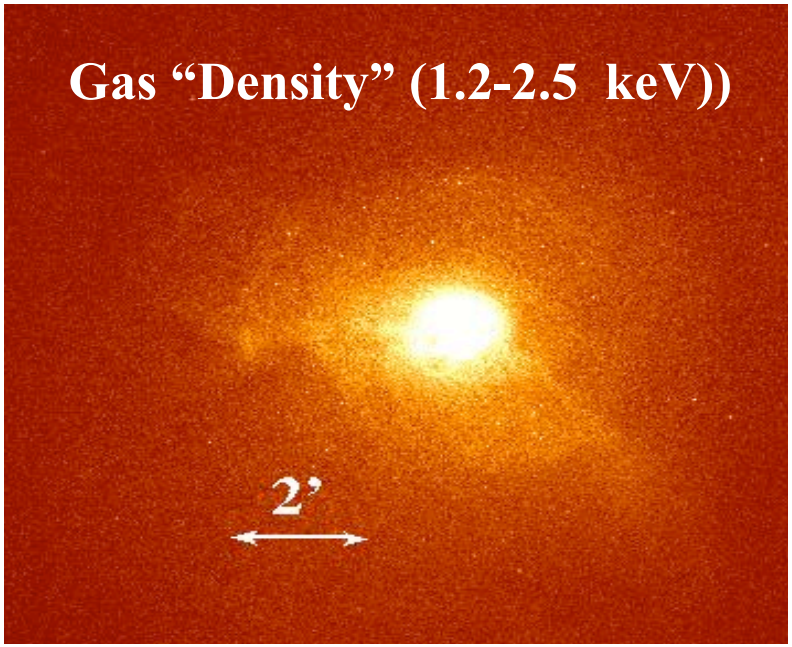


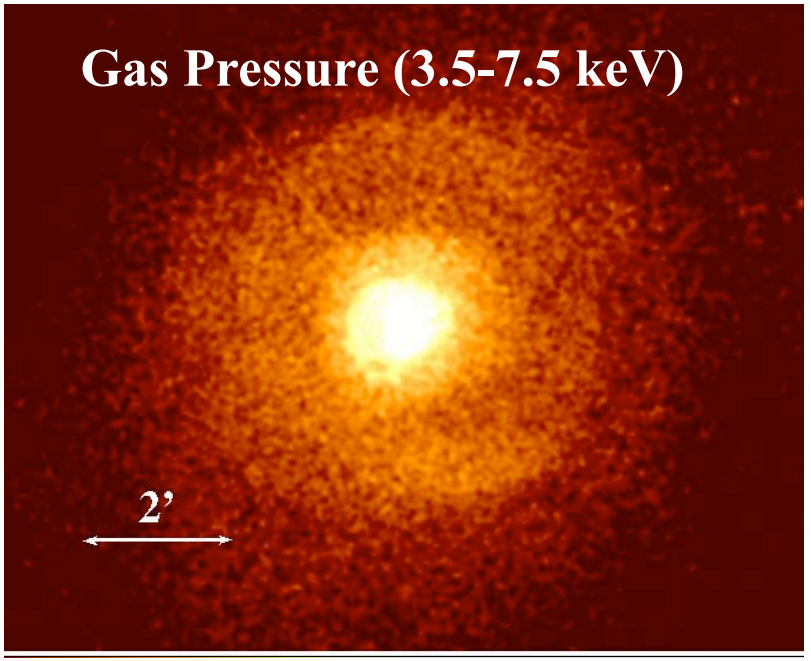


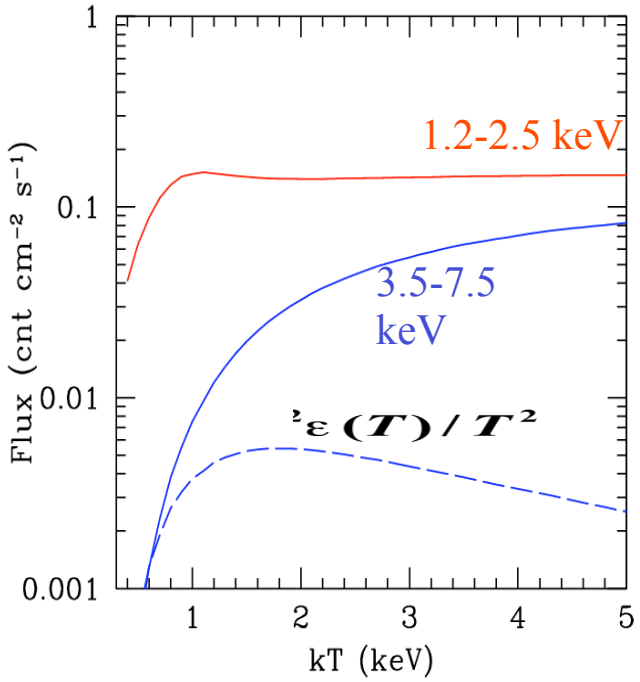


- Nucleus, jet (knots)
- Cavities surrounding the jet and the (unseen) counterjet
- Bubble breaking from counter jet cavity
  - Perpendicular to jet axis;
  - Radius ~1kpc.
  - Formation time ~4 x10^6 years
- **Piston driving shock**
  - X-ray rim is low entropy (cool) gas uplifted/ displaced by relativistic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









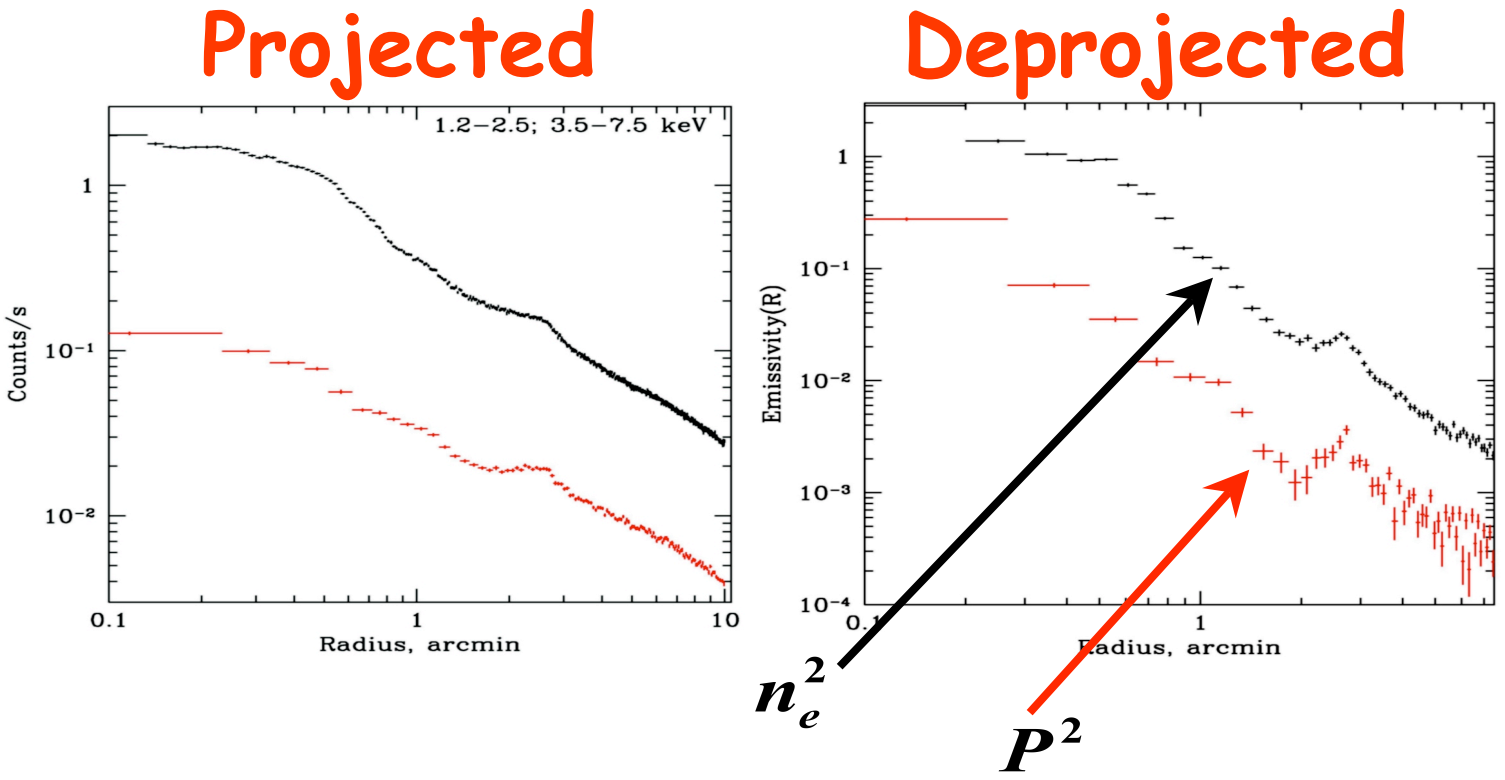
$$F = n^2 \varepsilon(T) = \left(\frac{P}{T}\right)^2 \varepsilon(T) = P^2 \varepsilon(T)/T^2 \approx C\,P^2$$

Central Piston
Shock
Filamentary arms

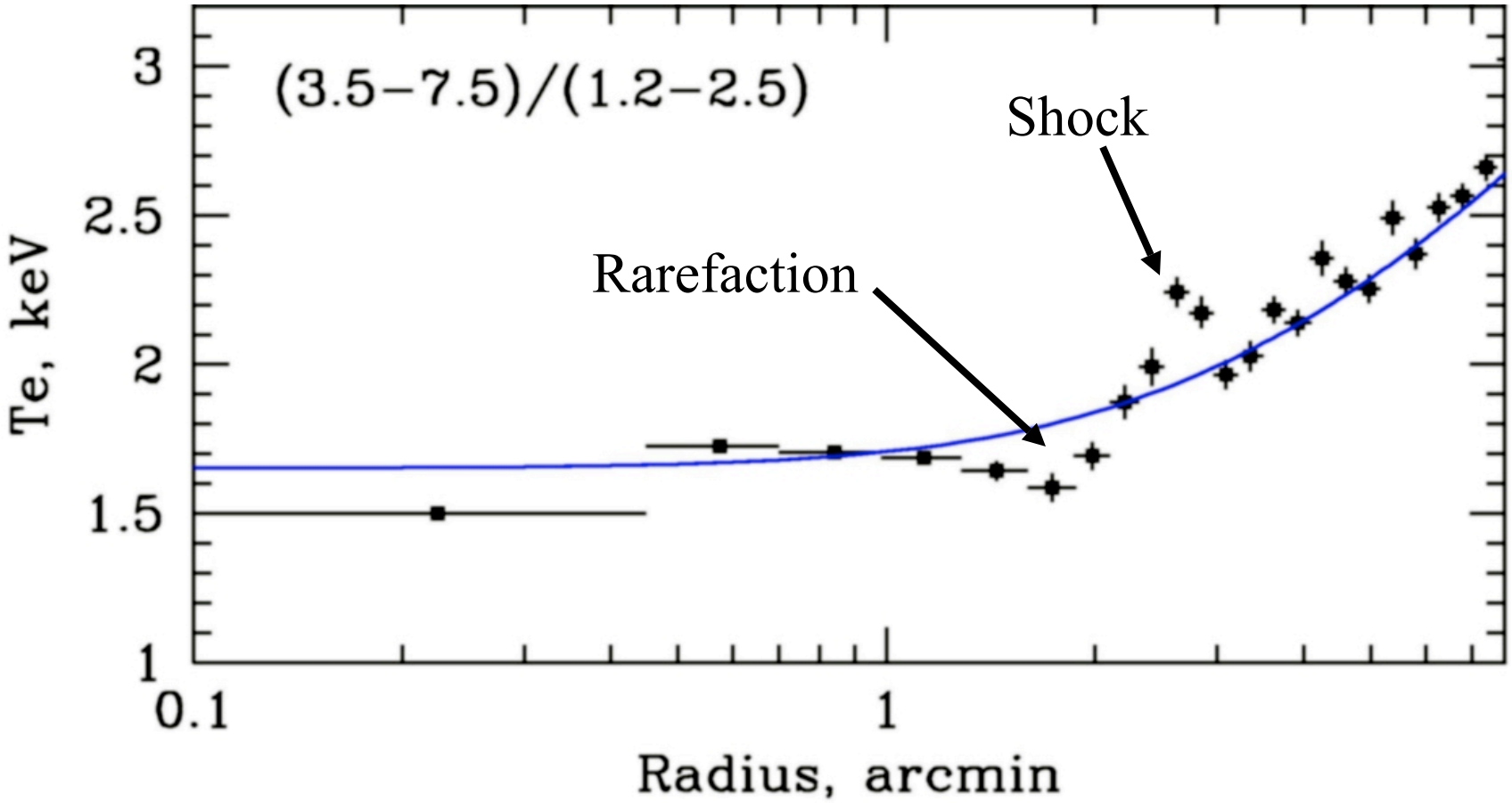
Measure temperature & pressure jumps across shock to determine shock speed

Shock Model - the M87 surface brightness profiles

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



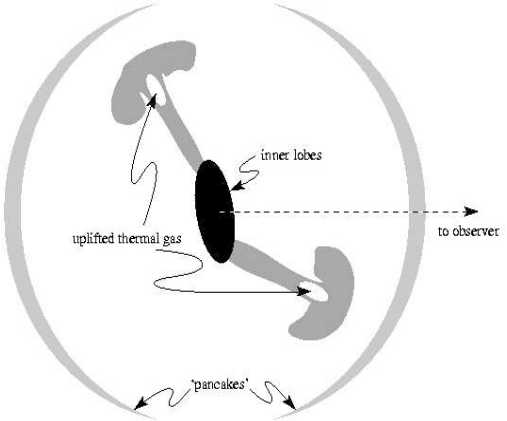
Deprojected M87 Gas Temperature

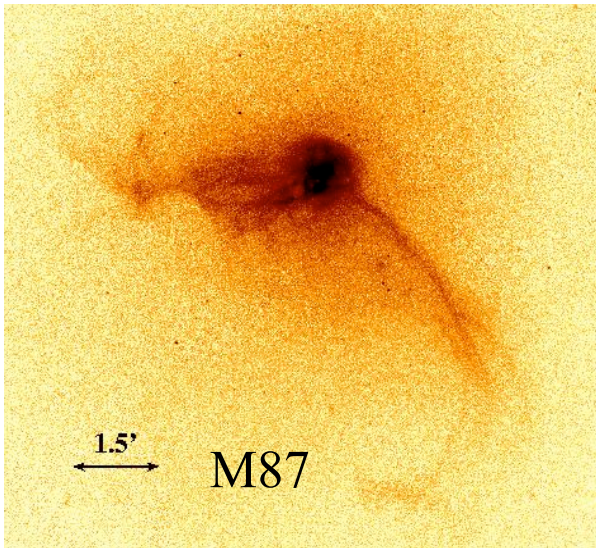


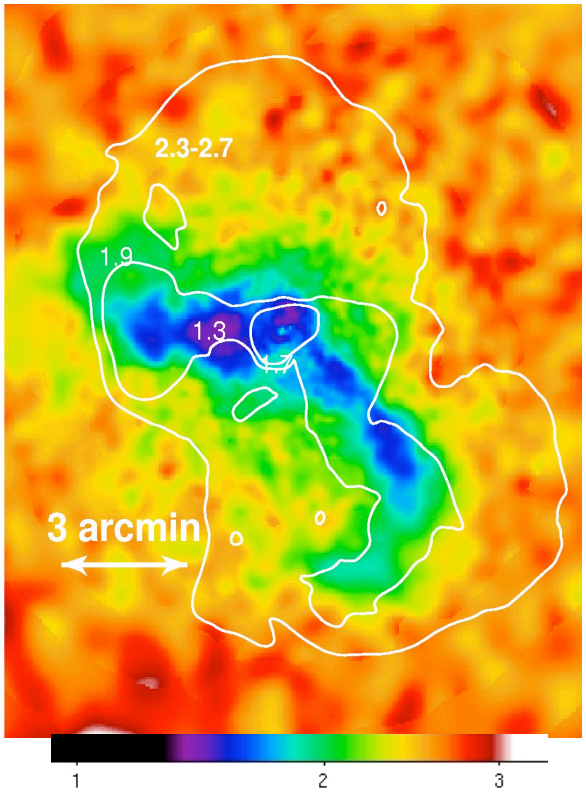
Mach 1.2 shock - transfers energy to cooling gas

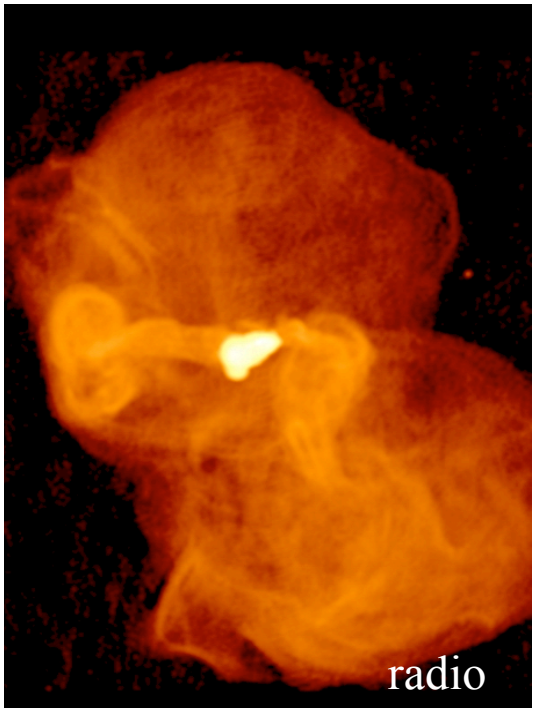
M87 “arms”

- Eastern arm - classical buoyant bubble; bubbles lose 50% of energy by adiabatic expension (Churazov et al 2001)
- XMM-Newton shows both arms are cool: uplifting cool gas from the core (Belsole et al 2001; Molendi 2002)



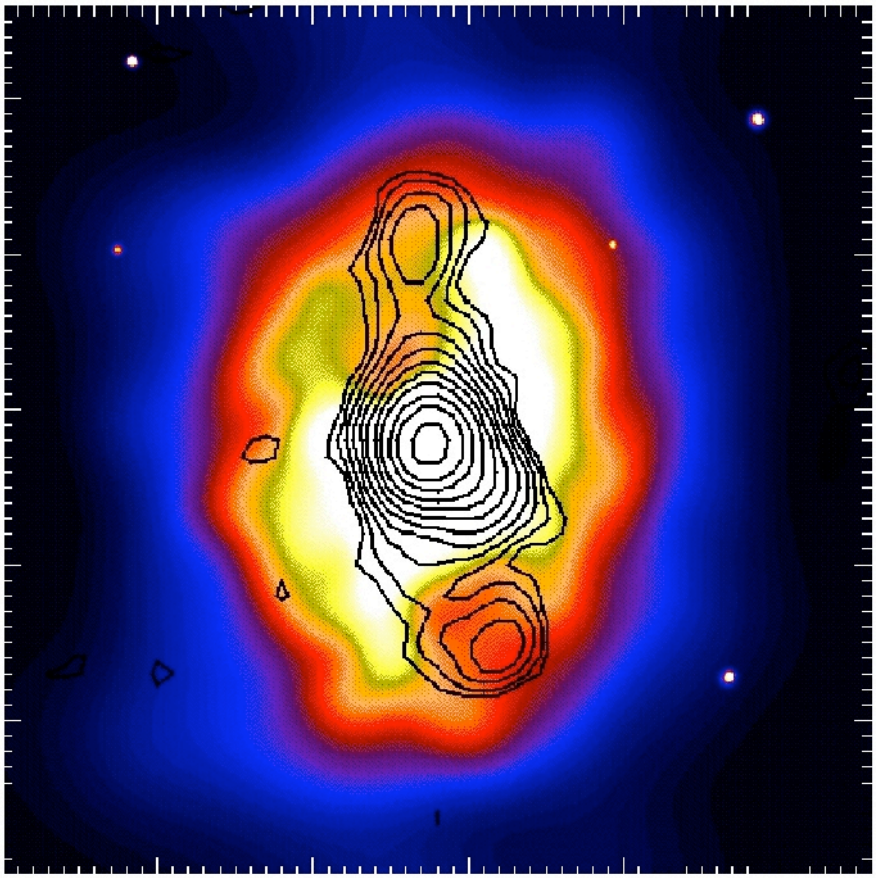


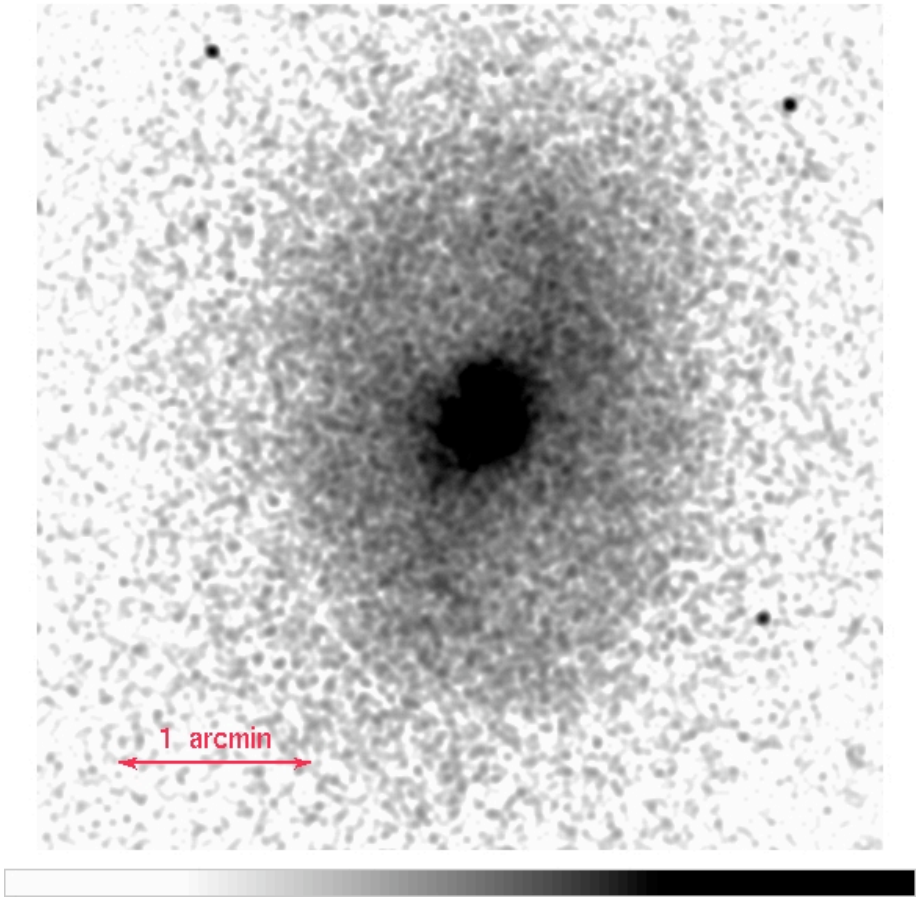




MSO735.6+7421 - McNamara et al 2005

Cavities filled by radio plasma ~ 200 kpc diameter PV work to create each 10^{61} ergs





Energy driving shock 6 x 10^{61} ergs (requires BH accretion 3 x 10^{8} m_{sun})

Age of shock 1 X 10^{8} years

Average power 1.7 X 10^{46} ergs/sec (weak radio, X-ray, opt nucleus)

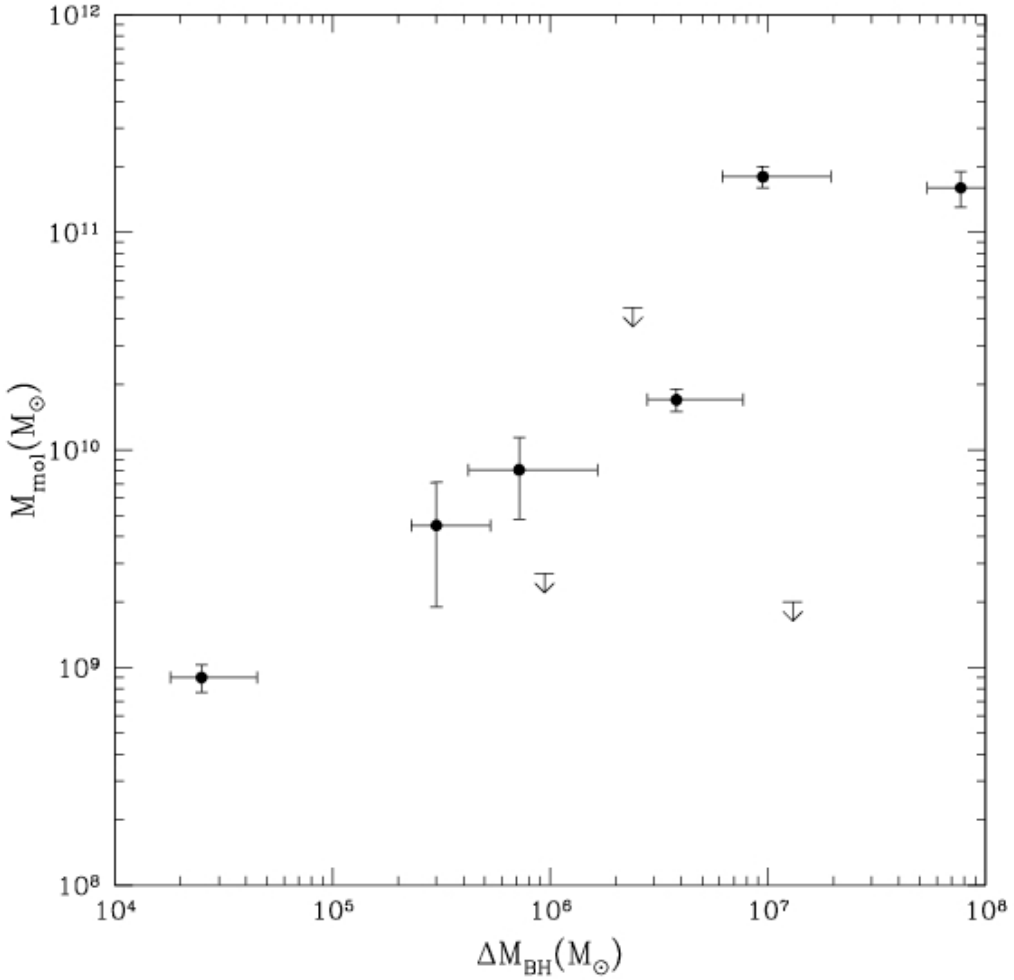
Outbursts from Clusters to Galaxies

SOURCE	SHOCK RADIUS (kpc)	ENERGY (10^{61} erg)	AGE (My)	MEAN POWER (10^{46} erg/s)	ΔM (10^8 M_{sun})
MS0735.6	230	5.7	104	1.7	3
HerculesA	160	3	59	1.6	1.7
Hydra A	210	0.9	136	0.2	0.5
M87	14	0.0008	11	0.0024	0.0005
NGC4636	5	0.00006	3	0.0007	0.00003

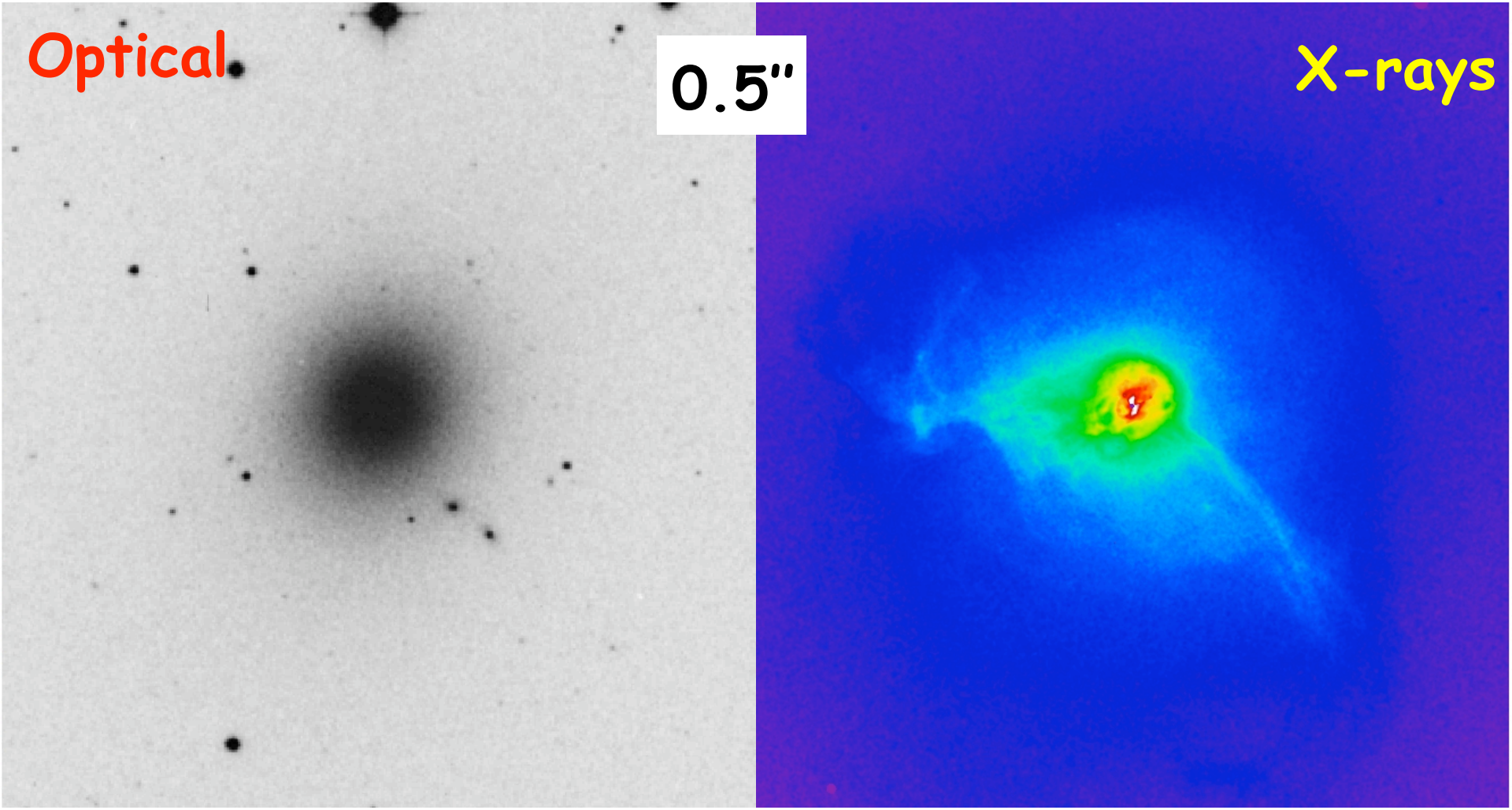
Clusters to galaxies (5, 2.5, 0.7 keV gas)
Late growth of SMBH by accretion in “old” stellar population systems
Grow stellar mass as well - see moderate star formation
AGN outbursts deposit energy into gas through shocks and bubbles

M_{mol} vs M_{dot} -- David & Nulsen (in prep)

Correlation of molecular mass in the cluster (Edge et al.) and



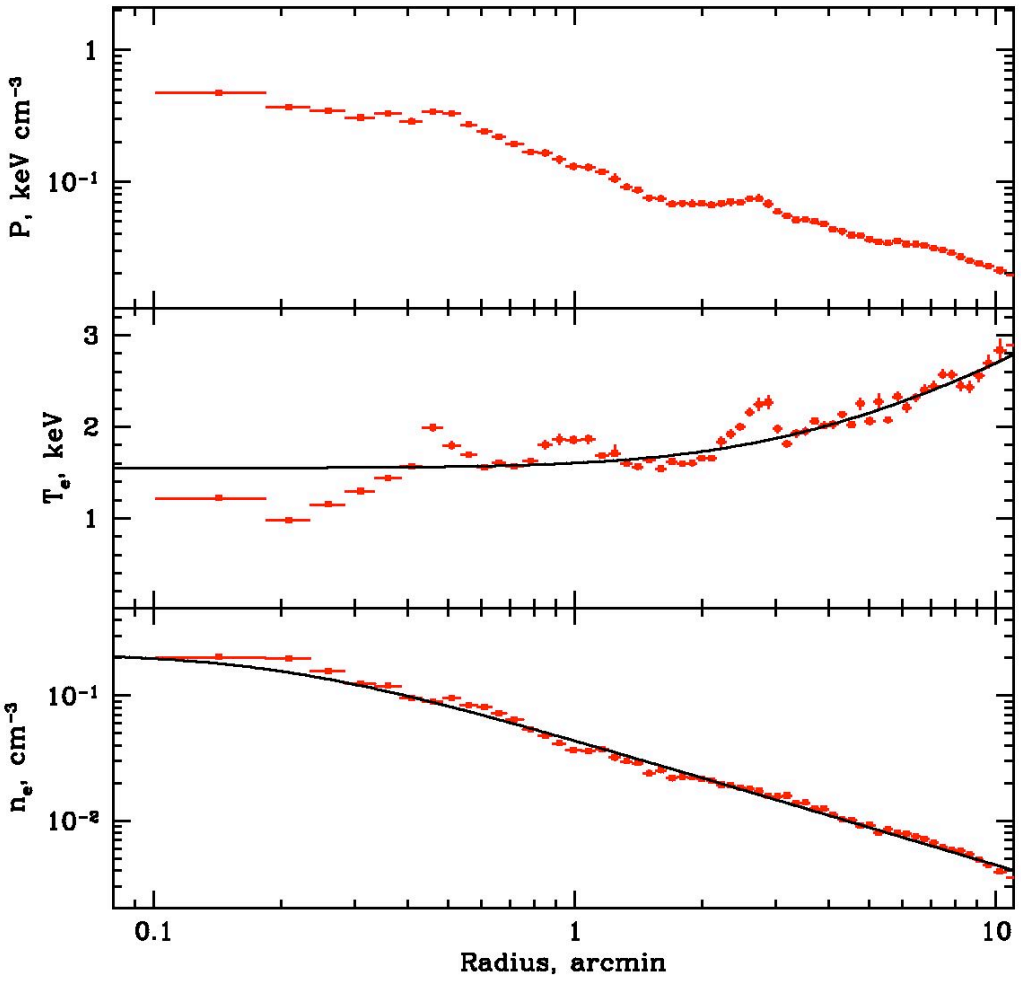
X-ray vs optical potential profiles (Churazov et al. arXiv0711.4686



Stars: gravity

Gas: gravity, cosmic rays, magnetic fields, turbulence

Deprojected X-ray data: gas temperature and density



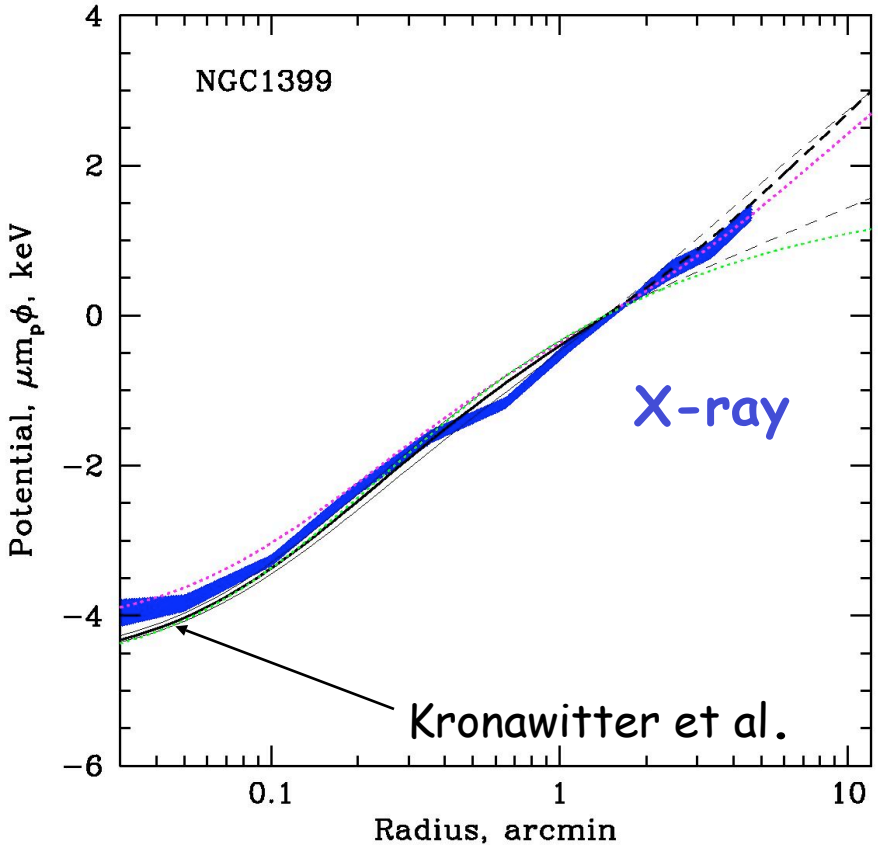
$$n_e(r), T_e(r) \quad P(r)$$

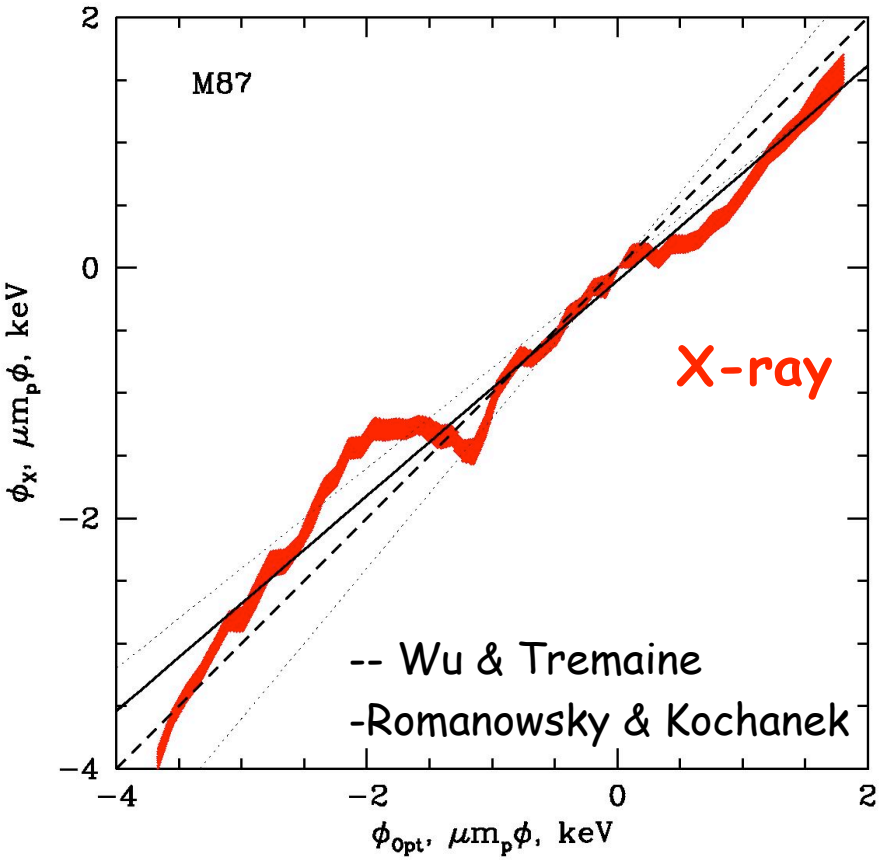
$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM}{r^2}$$

$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{d\varphi}{dr}$$

$$\varphi = -\frac{k}{\mu m_p}\left[\int T_e \frac{d\ln n_e}{dr}\,dr + T_e\right] + C$$

Gravitational potential depends only on measured quantities -- temperature & gas density And hydrostatic equilibrium!





N1399 $\varphi_X(r) \approx 0.93\varphi_{opt}(r)$

M87 $\varphi_X(r) \approx 0.85\varphi_{opt}(r)$

HEAVY ELEMENT ABUNDANCES IN THE ICM

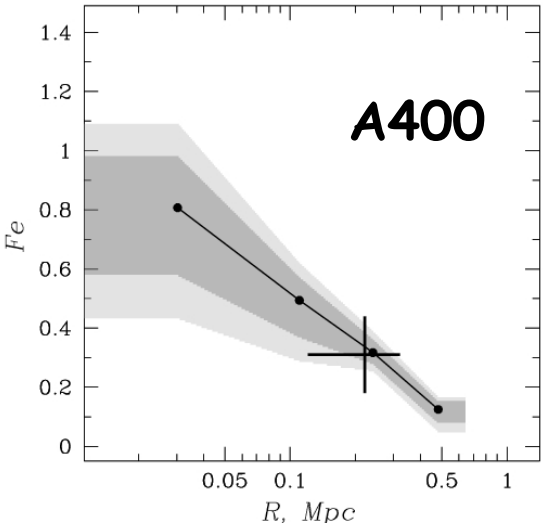
Historical note - Although even Uhuru observations with a scanning collimated (0.5 x 5 deg) proportional counter showed clusters were extended (Forman et al 1972, Kellogg et al 1972), Ariel 5 (Mitchell et al 1976) and OSO-8 (Serlemitsos et al. 1977) detected Fe-K emission showing X-ray emission from clusters was due to thermal gas.

More iron mass in the ICM than in all the cluster galaxies!
To produce this much iron required top heavy IMF at early epochs (Arnaud et al 1992, Elbas et al 1993) or higher rate of SNIa in the past (Rensini et al. 1993).

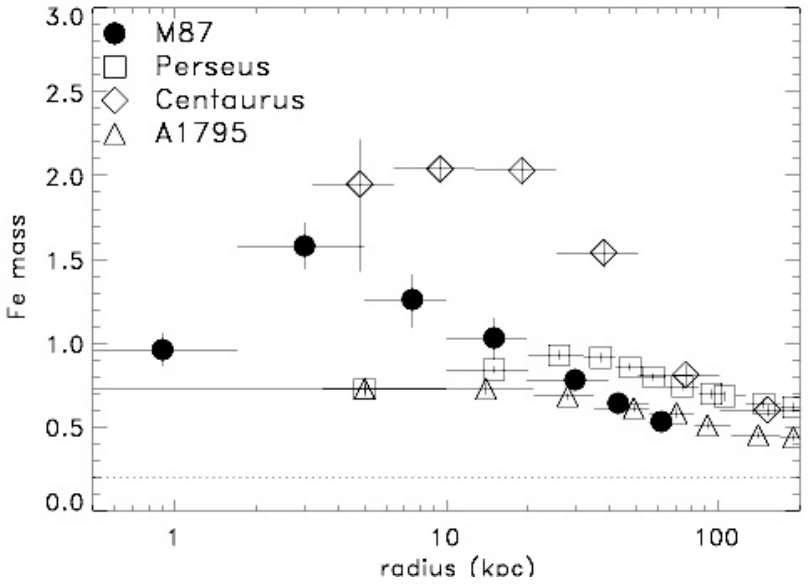
Outer cluster regions show iron-to-silicon typical of SN II.

Relaxed Clusters

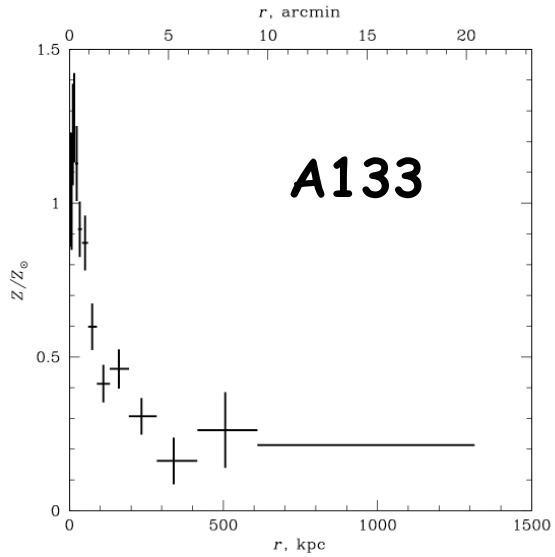
Heavy element abundances -- radial profiles - peaked around brightest cluster galaxy - excess Fe from SN Ia



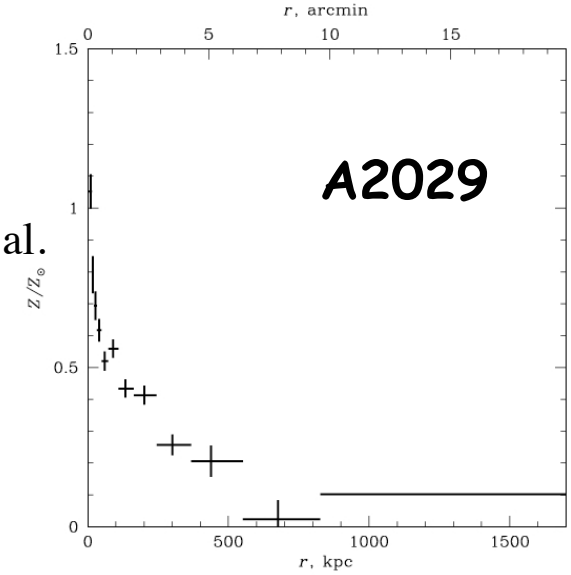
ASCA - Finoguenov et al.



XMM-Newton - Bohringer et al

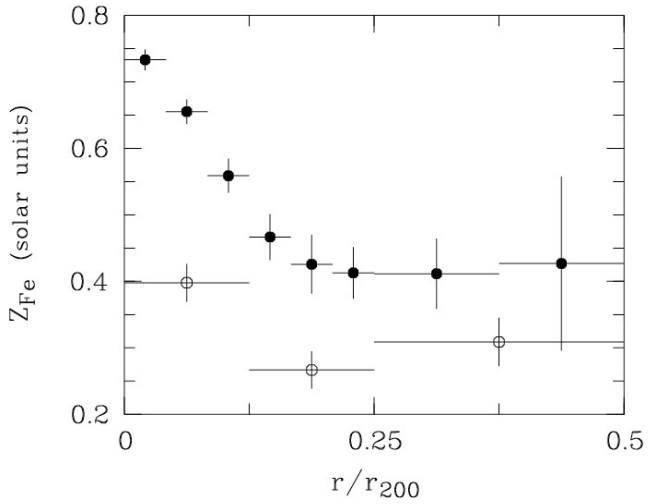


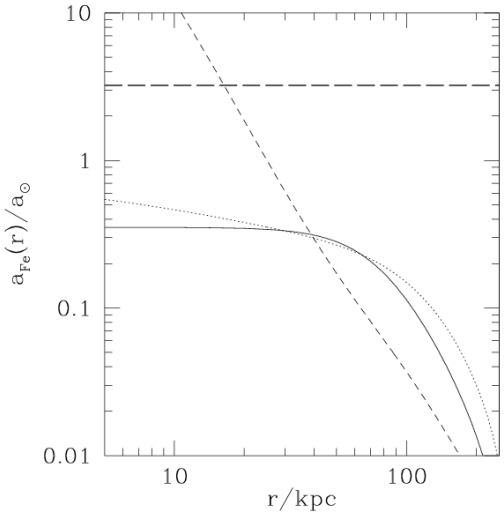
Chandra
Vikhlinin et al.

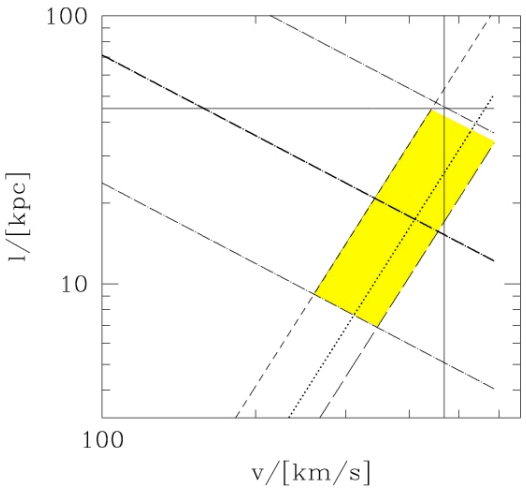


cD Abundance Peaks

Average abundance profiles
- Centered on cD
- Fe mass 1-20x10^{10} M_{sun}
- Long accumulation time (>5x10^9 yr)
- Excess Fe in center from cD
- Broader than cD stellar light
- BCG L_{opt} correlates with M_{Fe}







12 cD (CC) clusters
10 non CC clusters
De Grandi et al. 2004

For Perseus - from Rebusco et al. 2005

The important (cool) stuff --

--Clusters grow through mergers, the primary heating of the ICM is by shocks.

We can measure the space velocity of subclusters (or galaxies) by measuring temperature or pressure jumps across cold fronts; Dark Matter exists!

--Reheating of cool cores is by AGN outbursts, (+sloshing, mergers, conduction…)

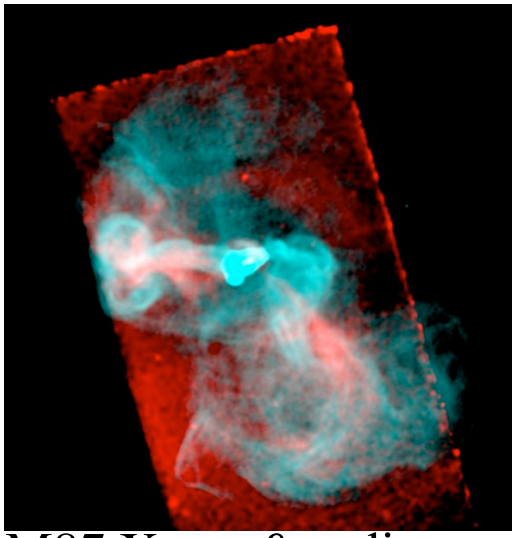
Observe past history of AGN activity and measure how much a black hole grows to produce the required energy to make shocks and cavities

--Gas temperature profiles are similar outside the core. Use measurements of the gas temperature and density to measure total cluster mass

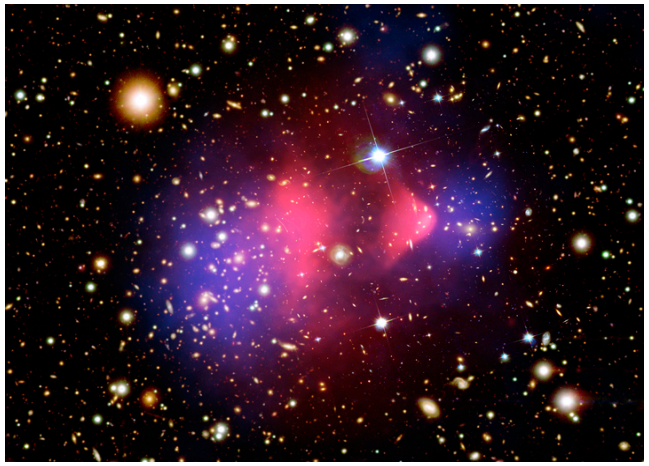
Compare X-ray and optical potential to determine non-thermal pressure support

--Measure element abundances in the ICM to determine mass & origin (SNII vs SNIa)

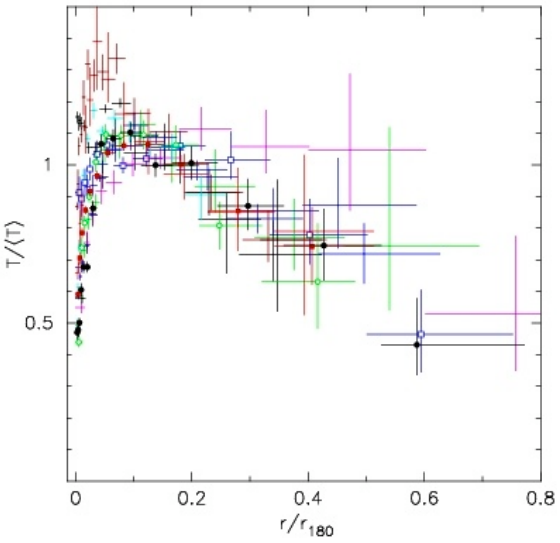
Compare Fe distribution to stars in the cD to search for gas turbulence



M87 X-ray & radio

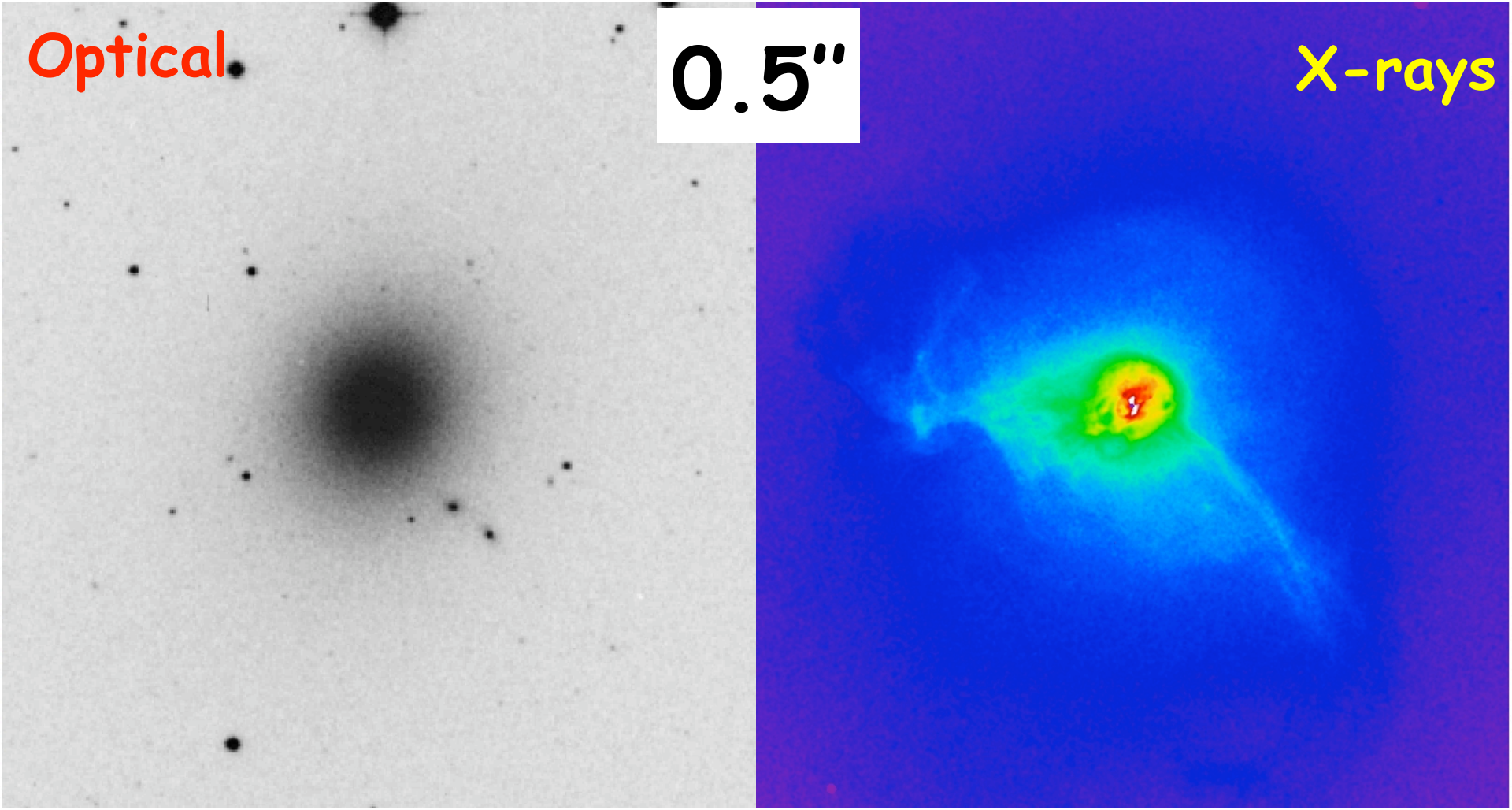


The Bullet cluster



Temperature profiles

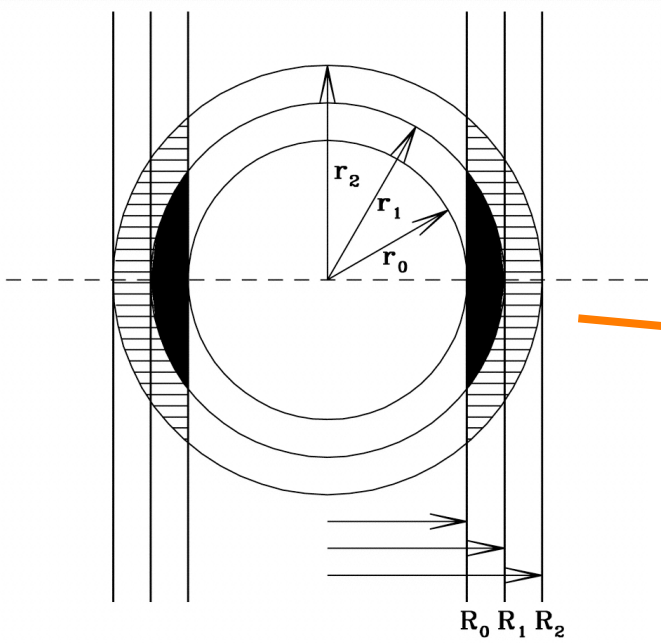
Confronting X-ray and Optical data: XO Project

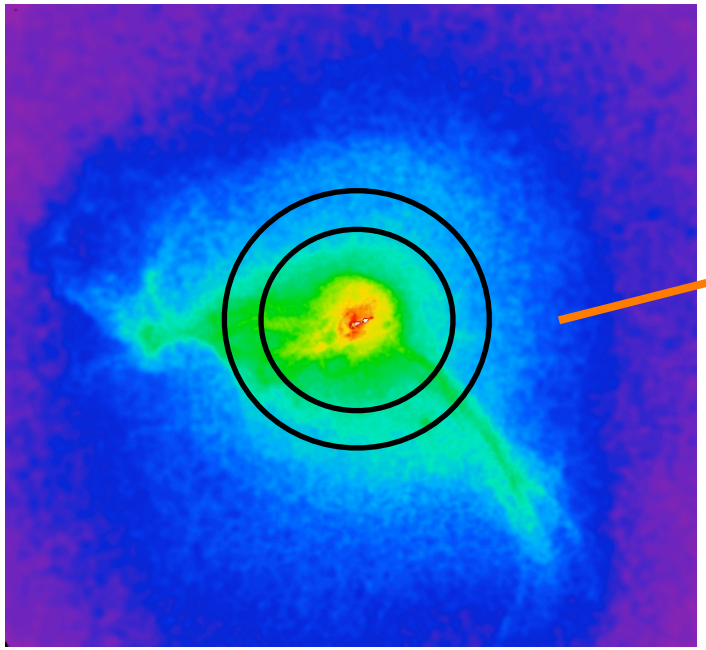


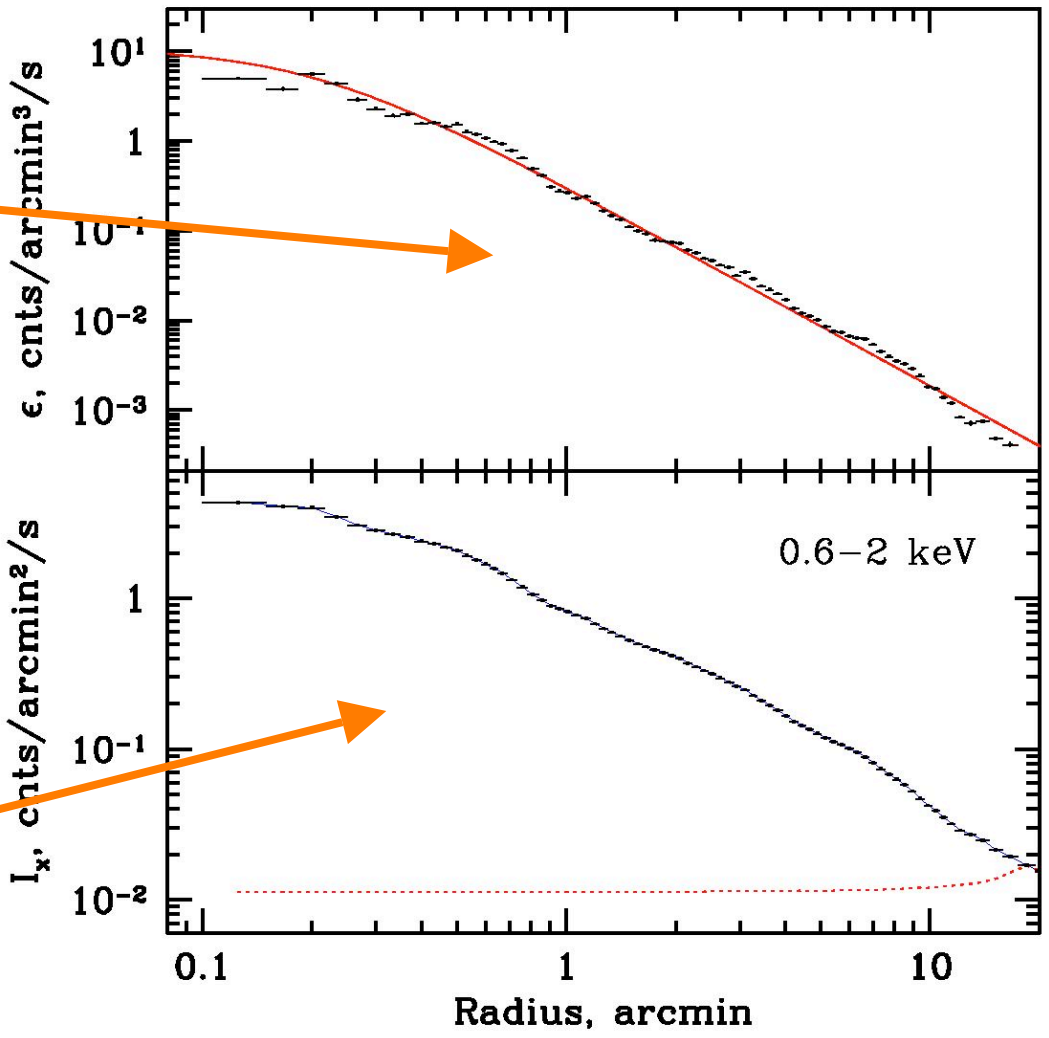
Stars: gravity

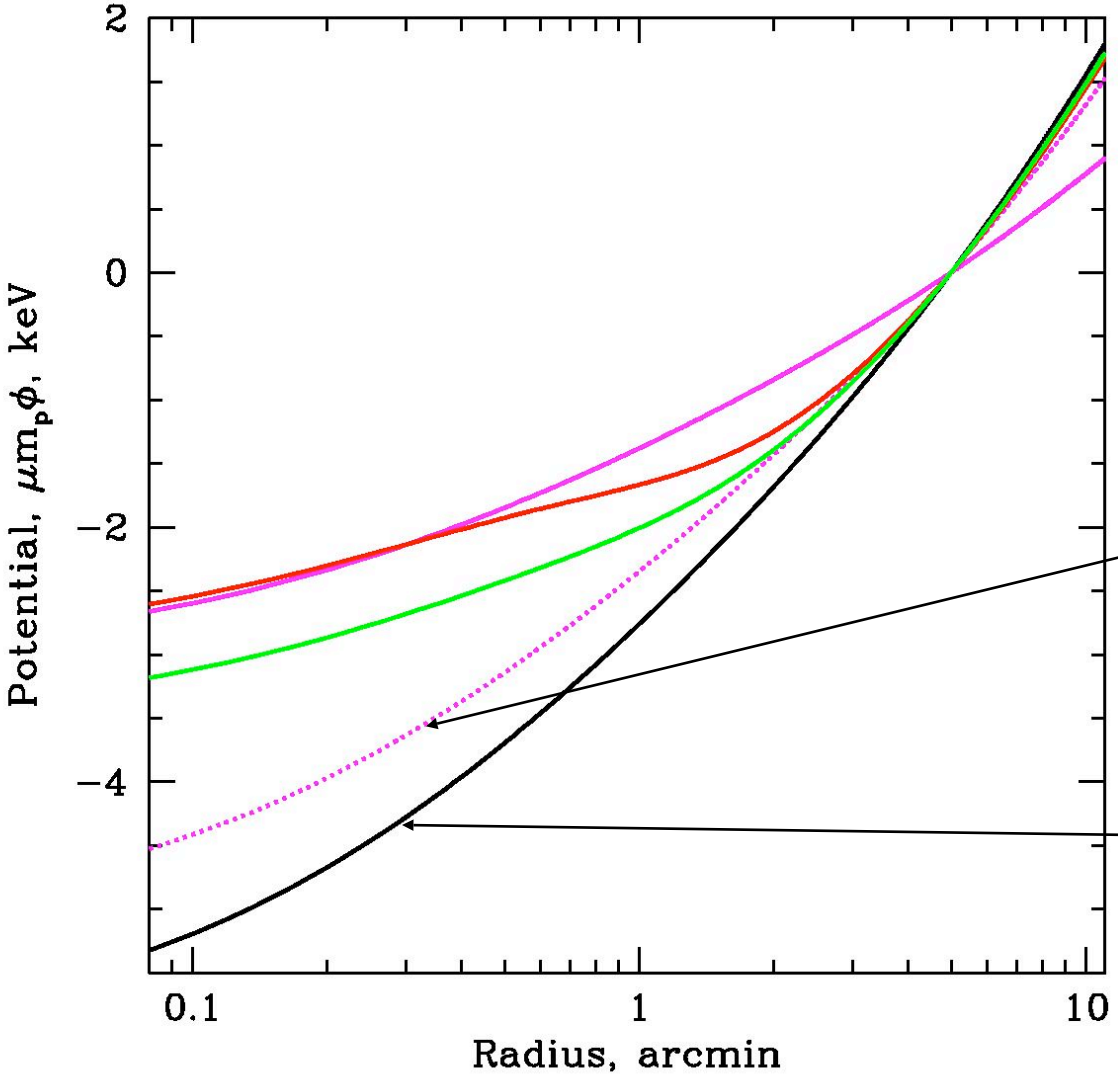
Gas: gravity, cosmic rays, magnetic fields, turbulence

Deprojection of X-ray data









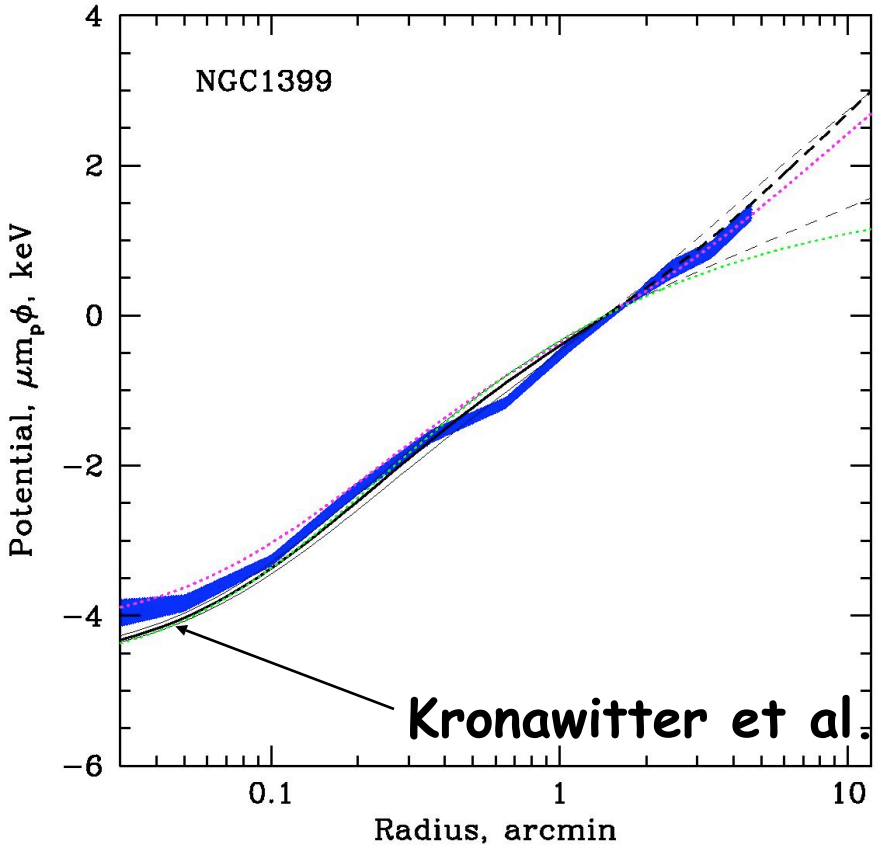
$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{d\varphi}{dr}$$

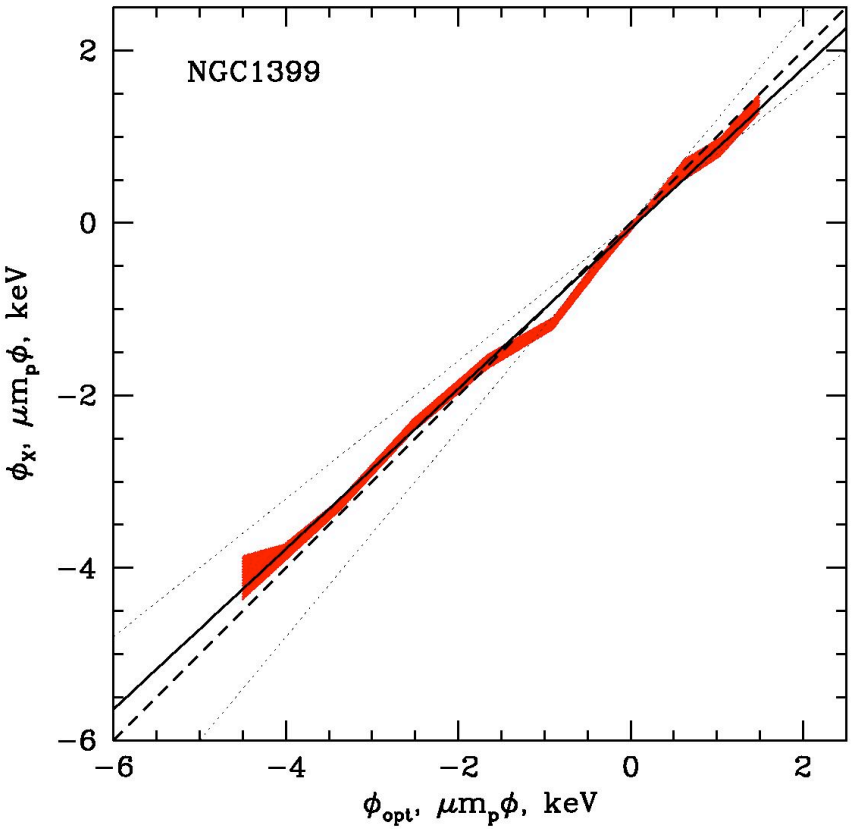
$$P_{true} = P_{gas} + \ldots.$$

Measured potential
25% in Cosmic Rays

True potential

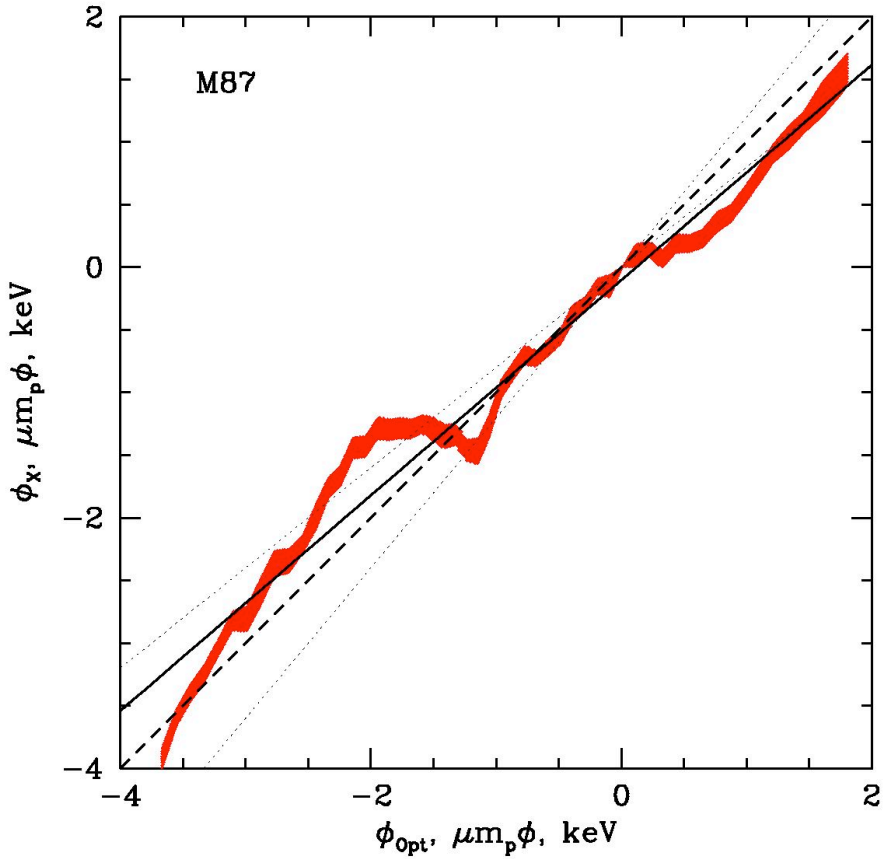
$$\varphi_X(r) \approx \alpha\,\varphi_{true}(r), \qquad \alpha \le 1$$





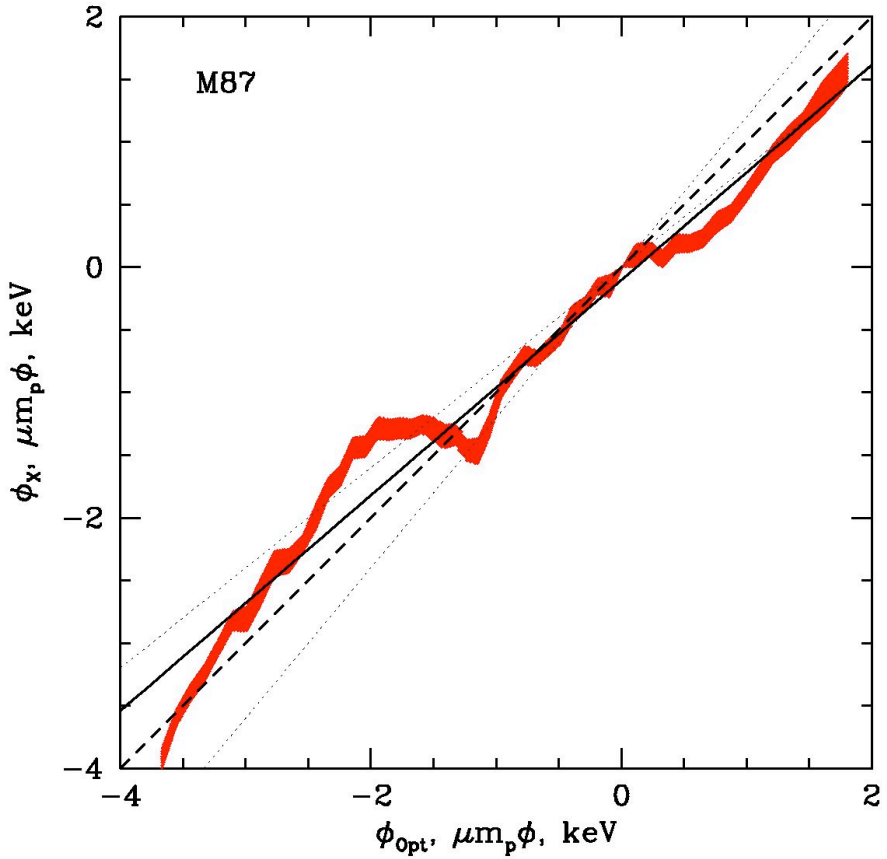
$$\varphi_X(r) \approx 0.93\varphi_{opt}(r) + C$$

$$U_{CR} + \frac{H^2}{8\pi} + U_{turb} = 0.07\,U_{thermal}$$



$$\varphi_X(r) \approx 0.85\varphi_{opt}(r)$$

$$U_{CR} + \frac{H^2}{8\pi} + U_{turb} = 0.15U_{thermal}$$



$$\varphi_X(r) \approx 0.85\varphi_{opt}(r)$$

$$U_{CR} + \frac{H^2}{8\pi} + U_{turb} = 0.15U_{thermal}$$

Cooling flow + AGN model: consistent!

measured $$U_{CR} + \frac{H^2}{8\pi} + U_{turb} = 0.07 - 0.15\, U_{thermal}$$

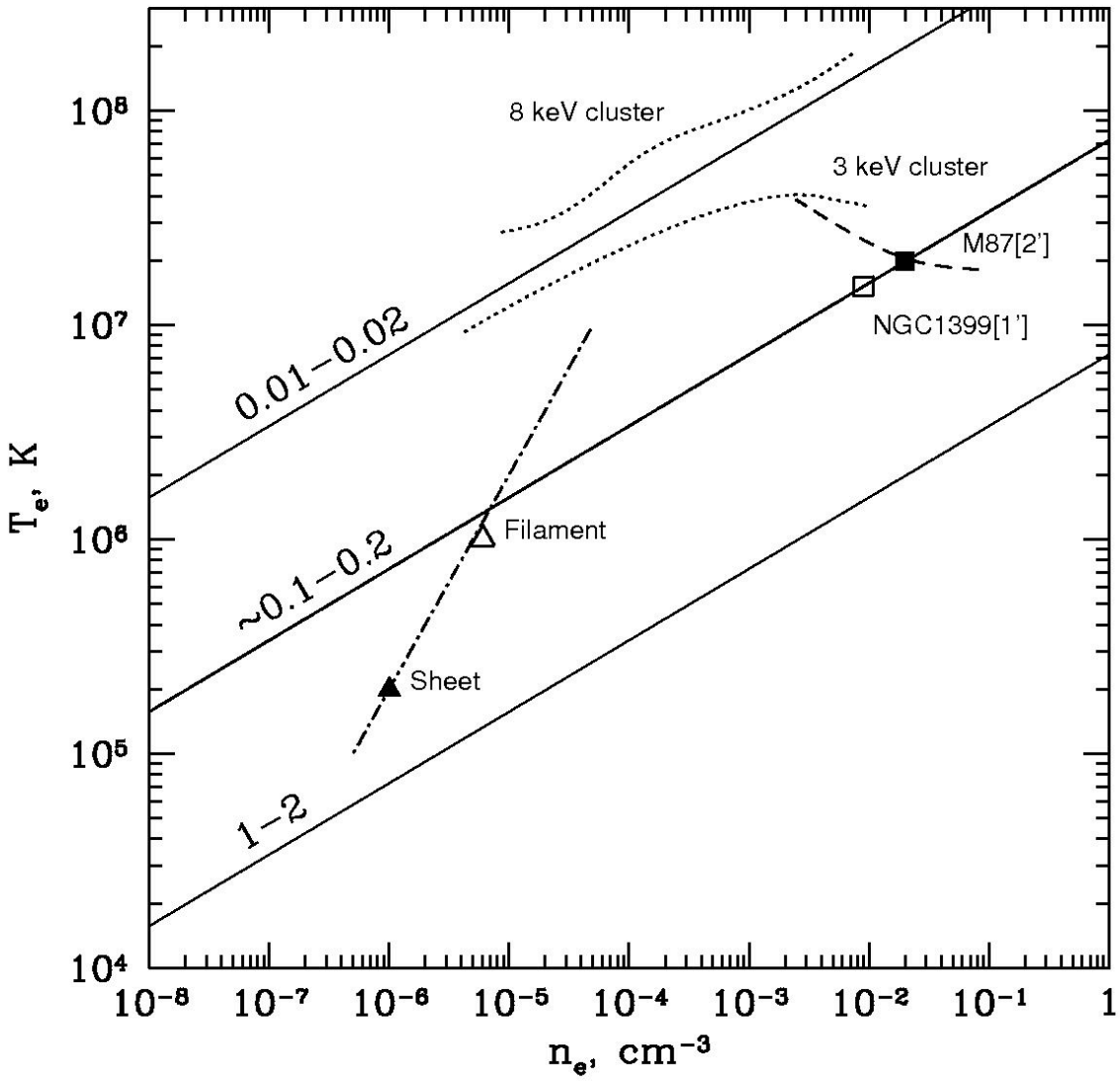
expected $$U_{CR} + \frac{H^2}{8\pi} + U_{turb} = 0.1 - 0.2\, U_{thermal}$$

AGN heating $$L_{heating} \approx L_{cooling}$$

$$\frac{U_{CR+}}{t_{cross}} \approx \frac{U_{thermal}}{t_{cool}}$$

$$t_{cross} \approx 0.1 - 0.2\, t_{cool}$$

Limits on the Cosmic Rays (protons) energy density in the past



Proton energy losses are small for γ>few

Proton do not diffuse

Adiabatic evolution of protons

If the (core) gas was shock heated => CR energy density < 0.01

How rare is the bullet cluster?

DISTRIBUTION OF VELOCITIES OF THE MOST MASSIVE SUBSTRUCTURE IN THE MILLENNIUM RUN

Hayashi & White (2006)

Adopted mass model from Clowe et al. (2004):

NFW-Halo with:

M_{200} = 2.96 x 10^{15} $M_\odot$
R_{200} = 2.25 Mpc

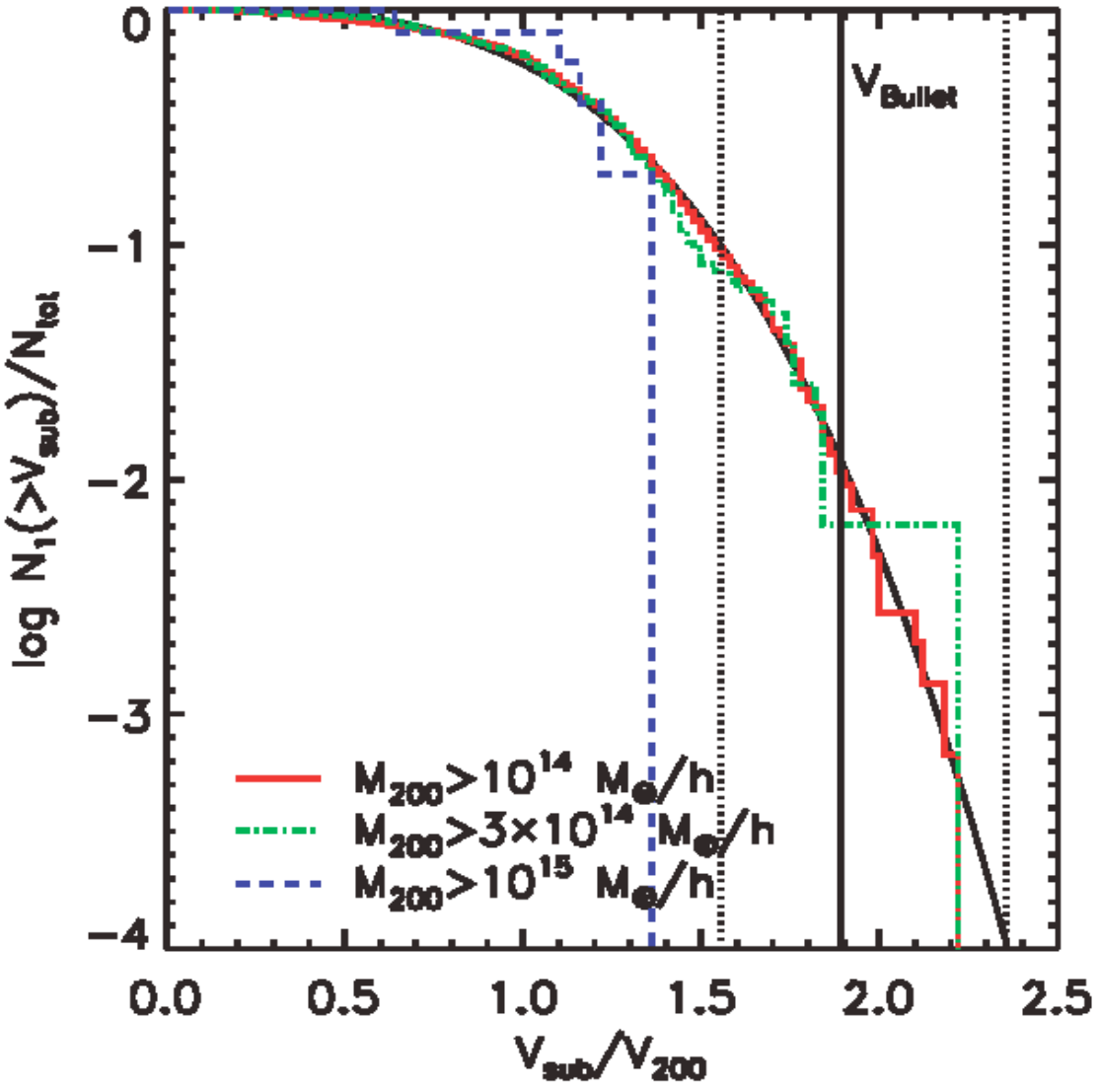
V_{200} = 2380 km/sec
V_{shock} = 4500 km/sec

But, revised data from Clowe et al. (2006) and Markevitch el al. (2006):

M_{200} = 1.5 x 10^{15} $M_\odot$

V_{200} = 1680 km/sec
V_{shock} = 4740 km/sec

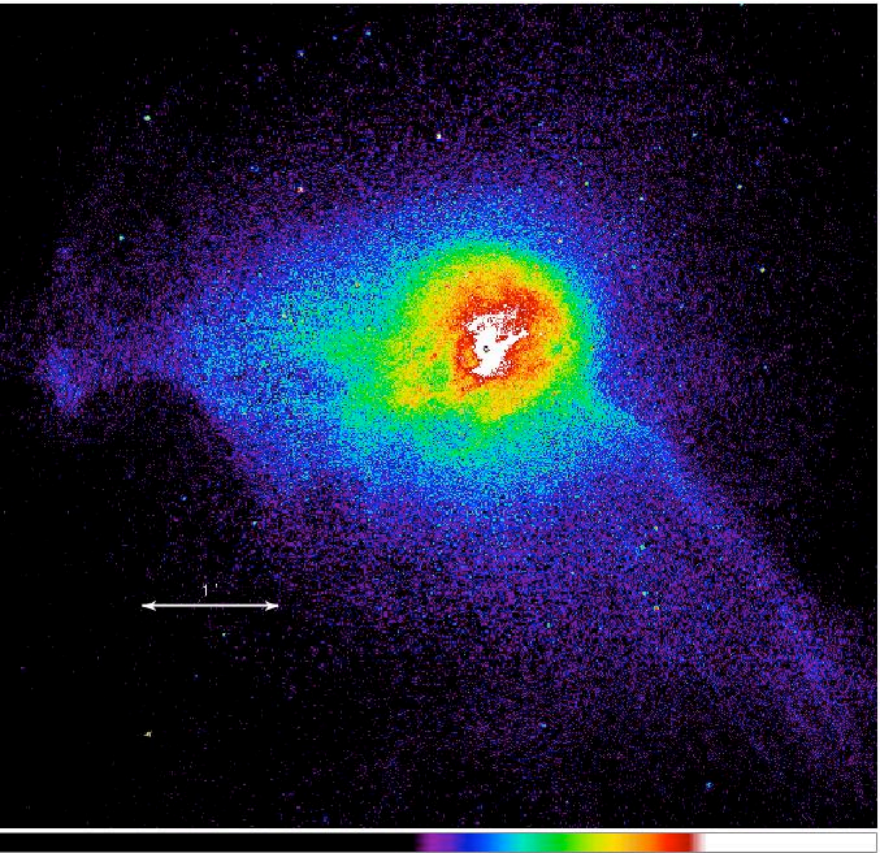
V_{sub}/V_{shock} = 2.8 chance: 10^{-7}

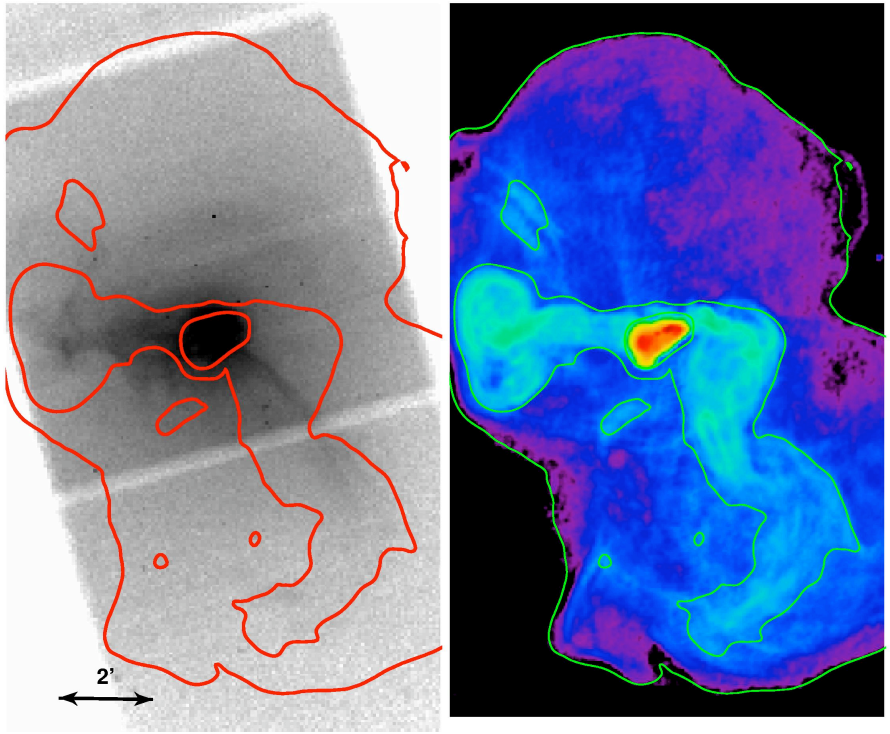


Southwestern Arm

Southwestern arm exits core as narrow (10” – 0.8 kpc) filament.

- Inner southwestern X-ray arm seems uncorrelated with radio. Radio appears to spiral around X-ray filament magnetic tension confining X-ray gas?).



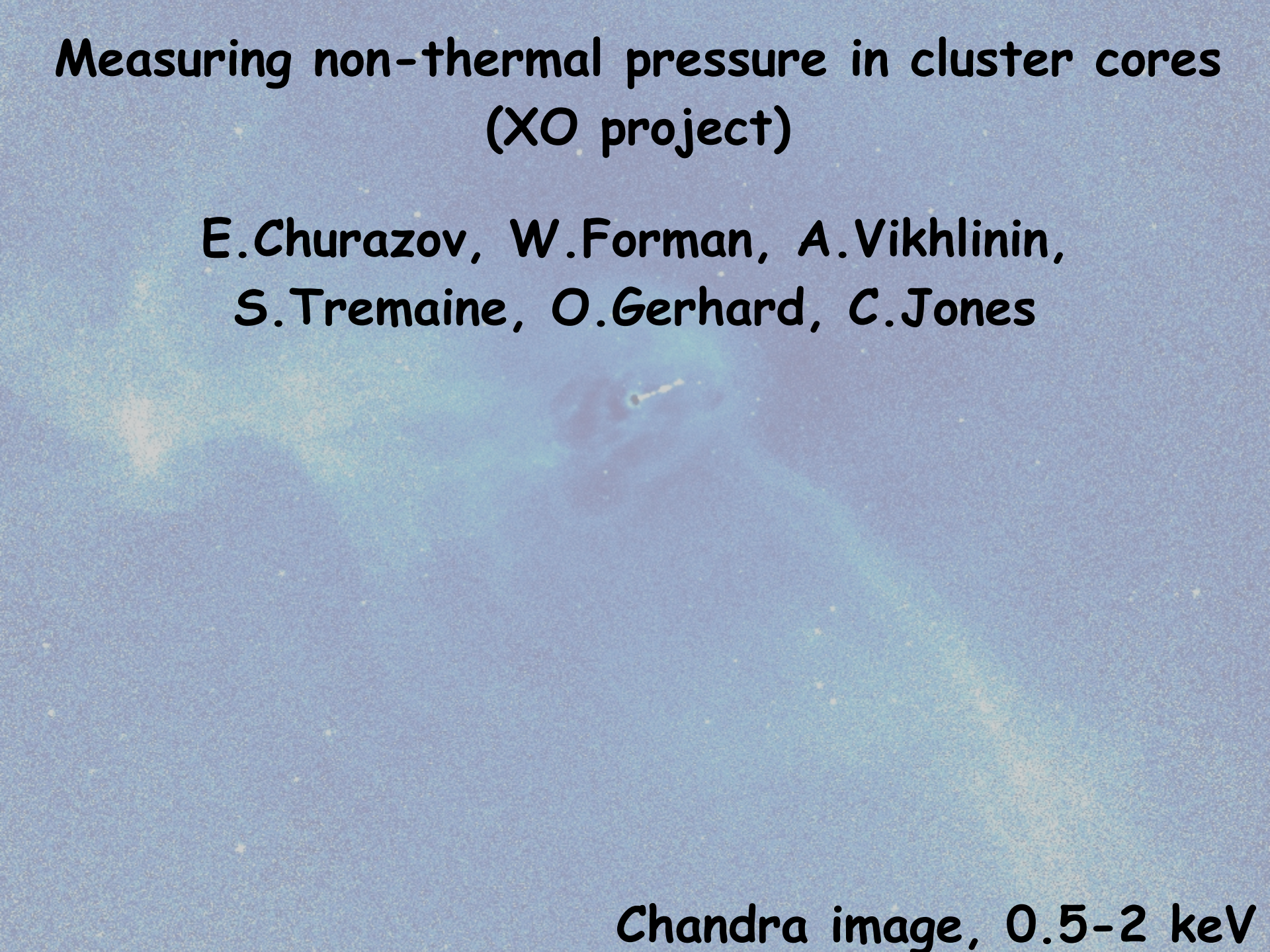


Chandra

Radio

Measuring non-thermal pressure in cluster cores (XO project)

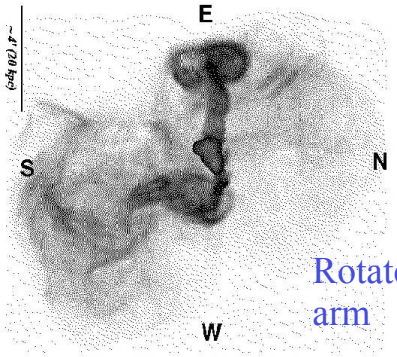
E.Churazov, W.Forman, A.Vikhlinin,
S.Tremaine, O.Gerhard, C.Jones



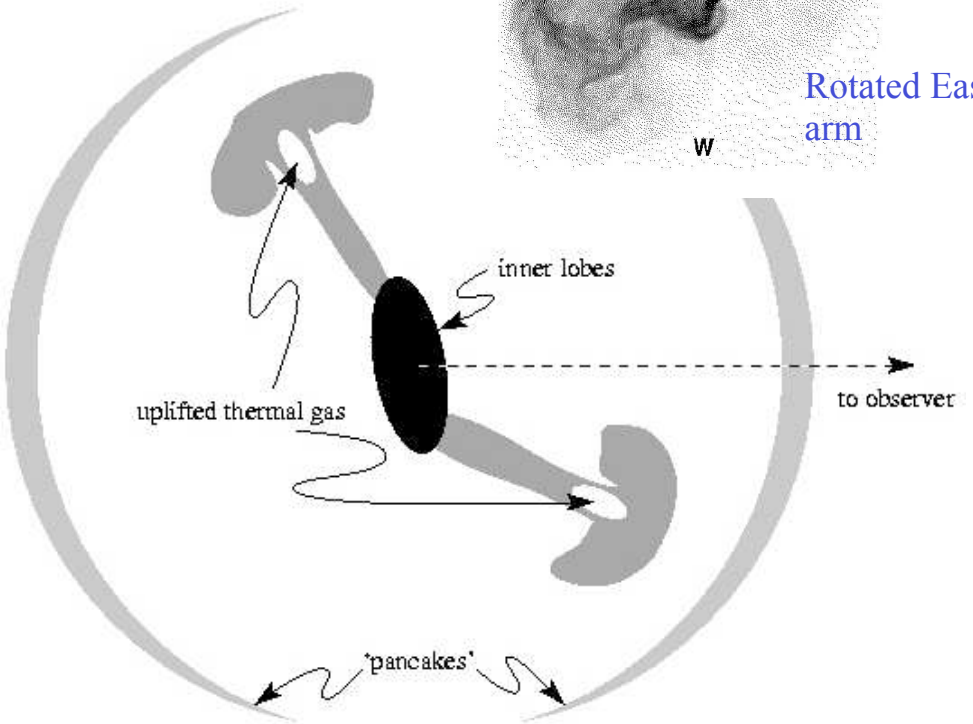
Chandra image, 0.5-2 keV

M87 – multiple radio/X-ray bubbles

- Three sets of bubbles
  - Inner lobes (youngest)
  - Rising mushrooms (arms)
  - Pancakes (oldest)
- Bubbles rise rapidly
  - ~400 km/sec
- Radio bubbles lose > 50% of the internal relativistic energy by adiabatic expansion
- Bubbles uplift ambient material from cool core

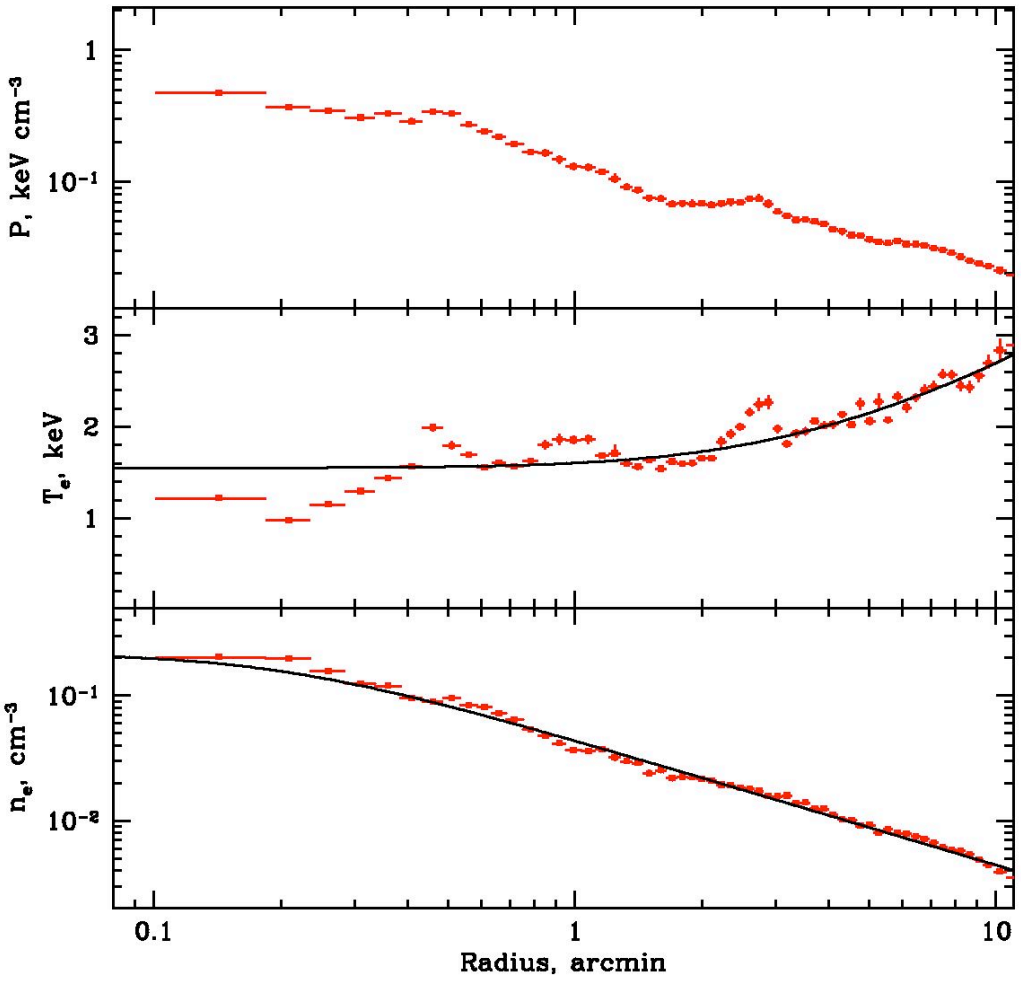


Rotated East arm



Churazov et al. 2001

Deprojected X-ray data: gas temperature and density



$$n_e(r), T_e(r) \quad P(r)$$

$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM}{r^2}$$

$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{d\varphi}{dr}$$

$$\varphi = -\frac{k}{\mu m_p}\left[\int T_e \frac{d\ln n_e}{dr}\,dr + T_e\right] + C$$

$$\varphi = -\frac{kT_e}{\mu m_p}\ln n_e + C$$