Dynamics of hot gas in Galaxies, Groups, & Clusters

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X-ray images of groups and clusters of galaxies

Conventional cooling flows

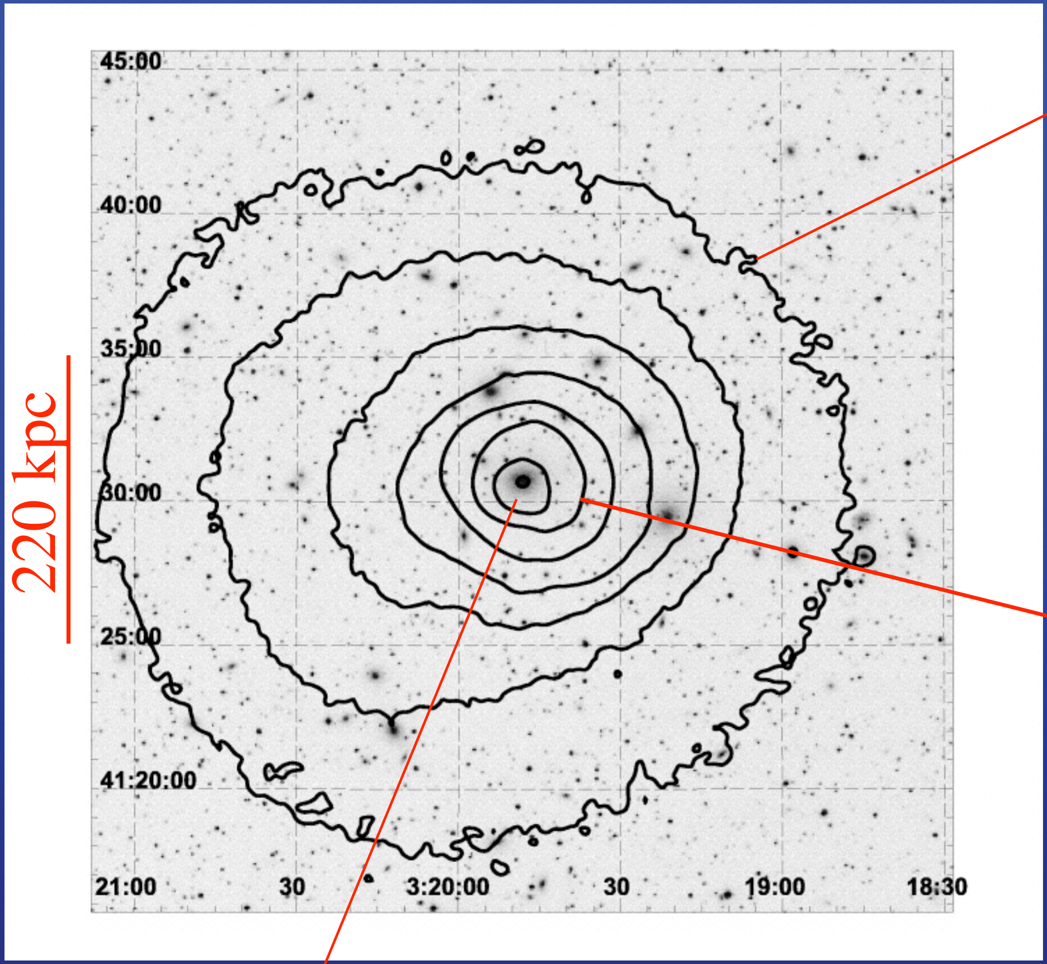
Evidence that cooling flows are not cooling as expected

Proposed explanations why cooling flows aren’t cooling
- Heating cluster gas with AGN energy
  - by dissipation of weak shock waves
  - by PdV work as X-ray cavities form
- Cosmic ray buoyancy and outward gas circulation

Typical Hot Gas Parameters

	E galaxies & groups	rich galaxy clusters	
Temperature	10^{7}	10^{8}	K
X-ray luminosity	10^{39-44}	10^{43-46}	erg/s
Fe abundance	0.4-1.0	0.4	solar
Total mass	10^{12-13}	10^{14-15}	M_{sun}
Baryon fraction	< 0.16	~0.16	

XMM Image of Perseus Cluster



X-ray contours

200ks Chandra image is here

Central active cD galaxy
NGC 1275

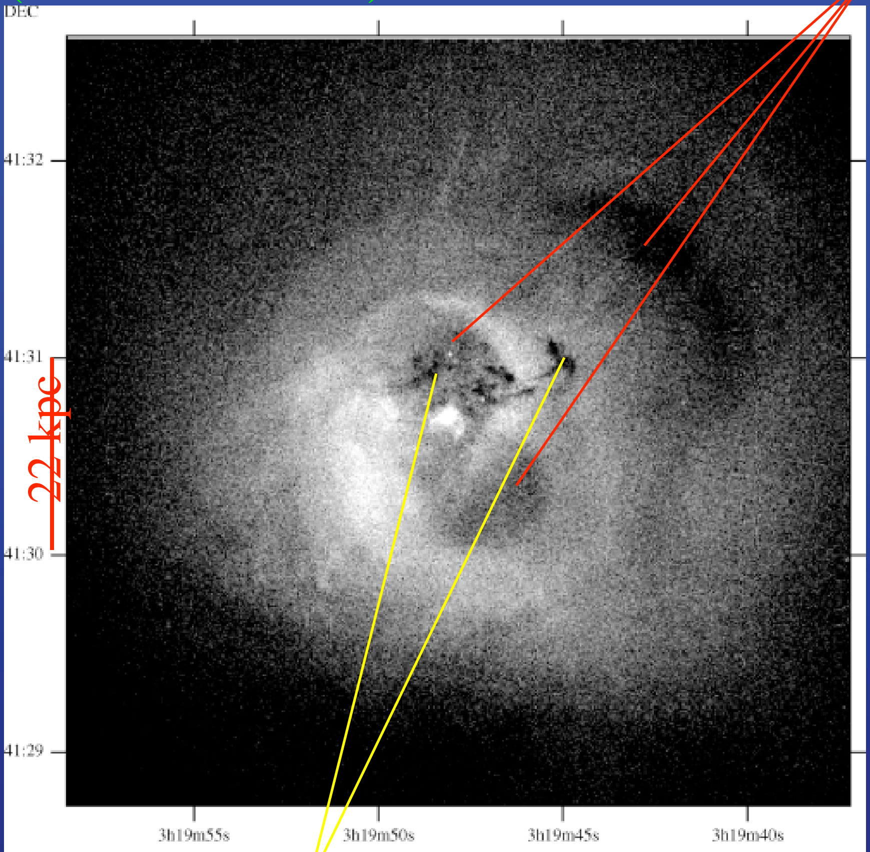
(Churazov et al. 2003)

virial mass: Mvir = $8.5\text{x}10^{14}$ M_{sun}

Deep 200ks Chandra Image of Perseus Cluster

(Fabian et al. 2003)

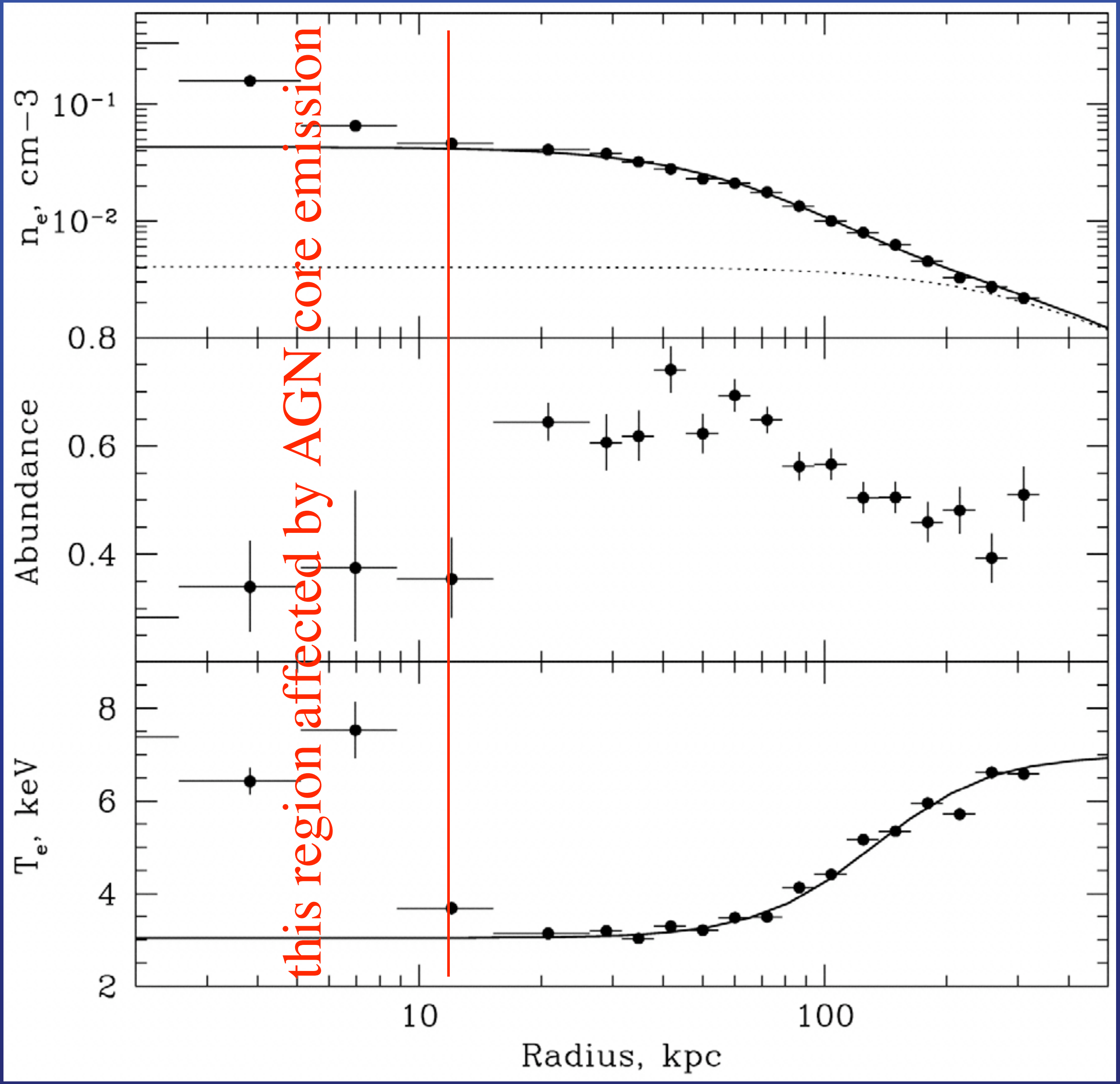
X-ray cavities -- bubbles



Absorption from foreground gas in merging galaxy

Distance	73 Mpc
L_x	10^{45} erg/s

Deprojected XMM Observations of Perseus Cluster

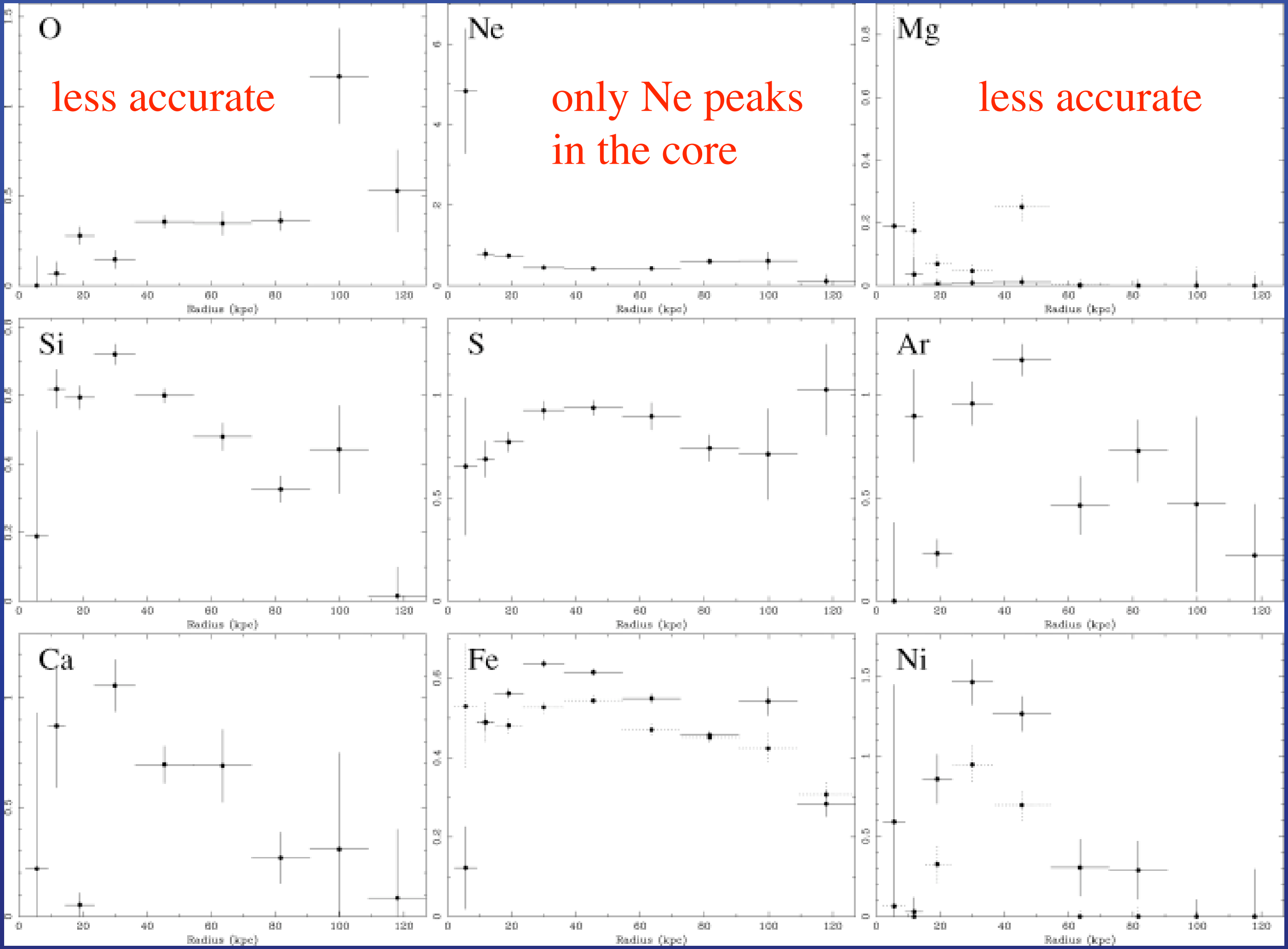


azimuthally averaged

(Churazov et al. 2003)

200ks Chandra Observations in Perseus

strange radial abundance gradients



less accurate

only Ne peaks in the core

less accurate

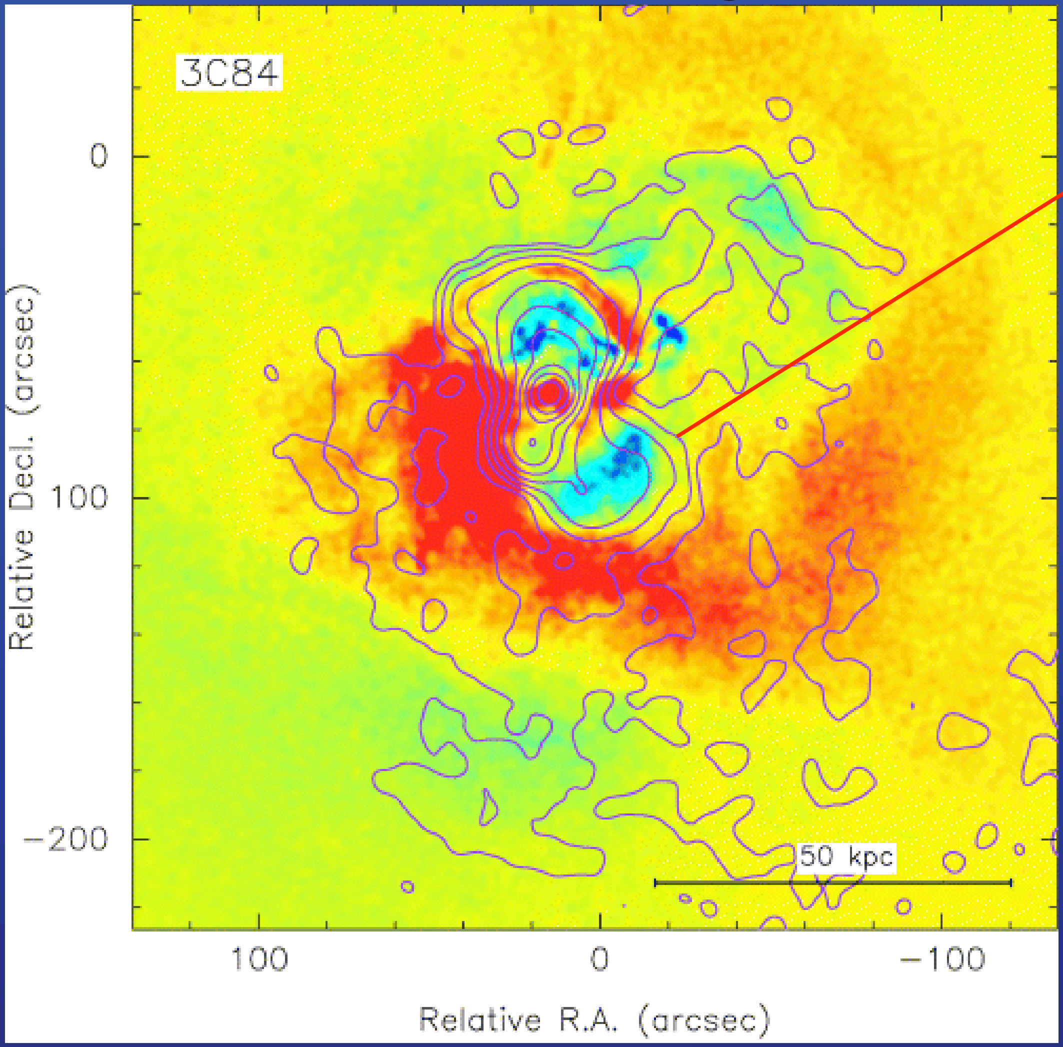
0 r (kpc) 120

(Sanders et al. 2004)

Many elements have strange off-center peaks

Abundance patterns are similar in Virgo (M87)

Chandra and Radio Images of Perseus

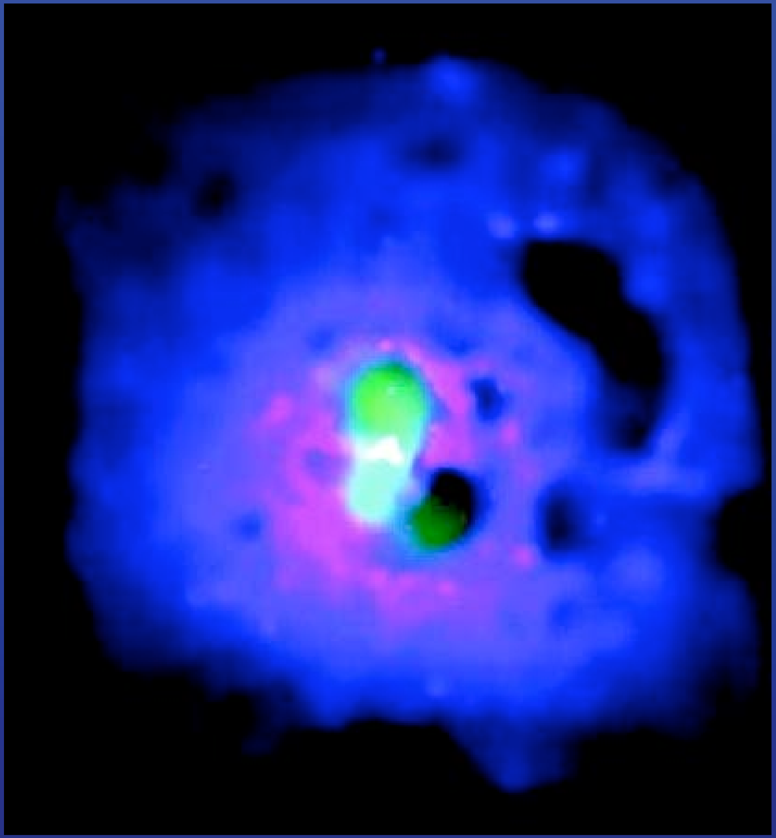


radio
contours

(Fabian et al. 2003)

non-thermal radio plasma fills the X-ray cavities

Perseus deep X-ray (red-blue) with 327 MHz radio (green)



(Birzan et al. 2008)

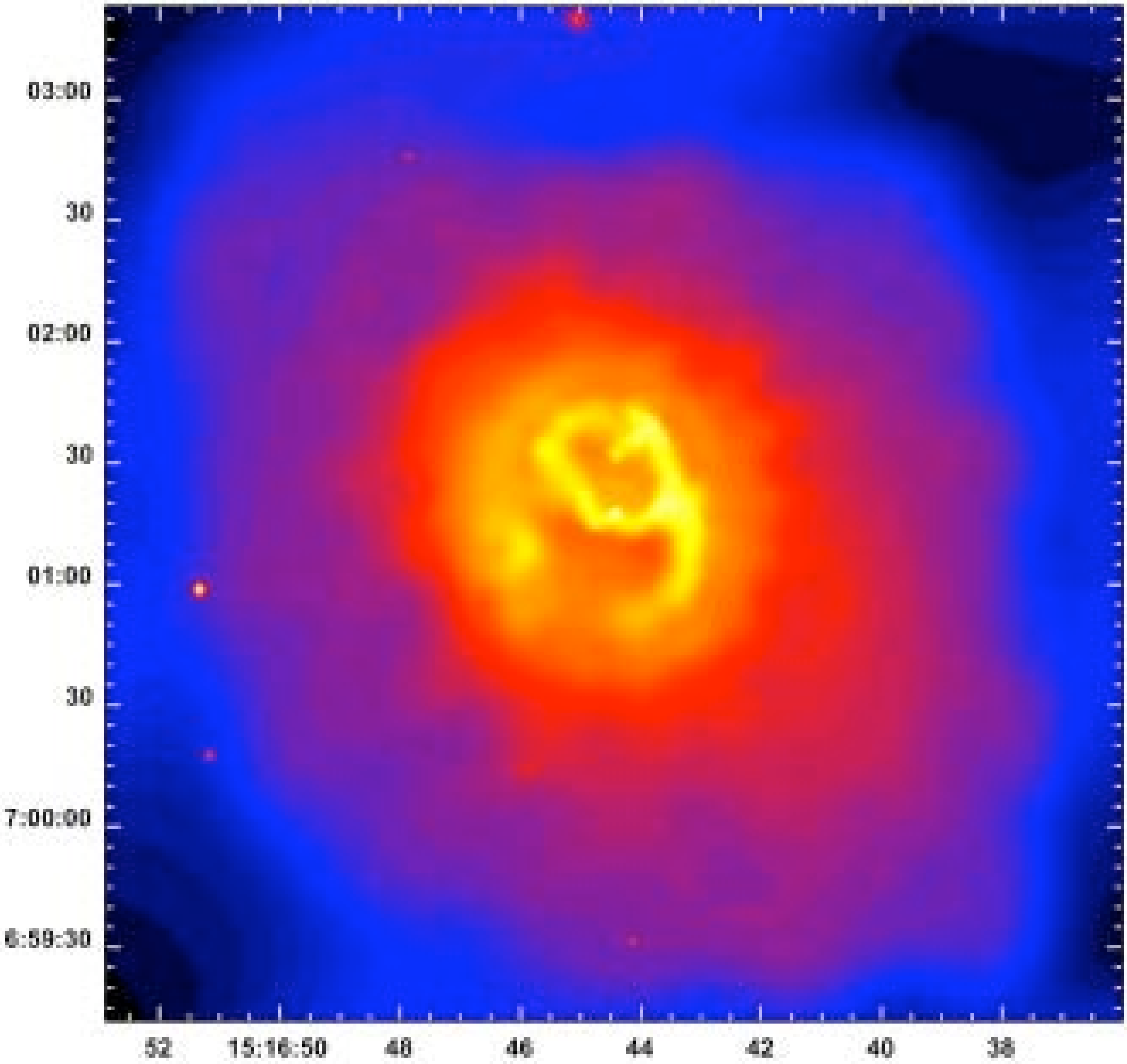
cavities produced in many directions
symmetric double cavities are rare

Chandra Image of Abell 2052

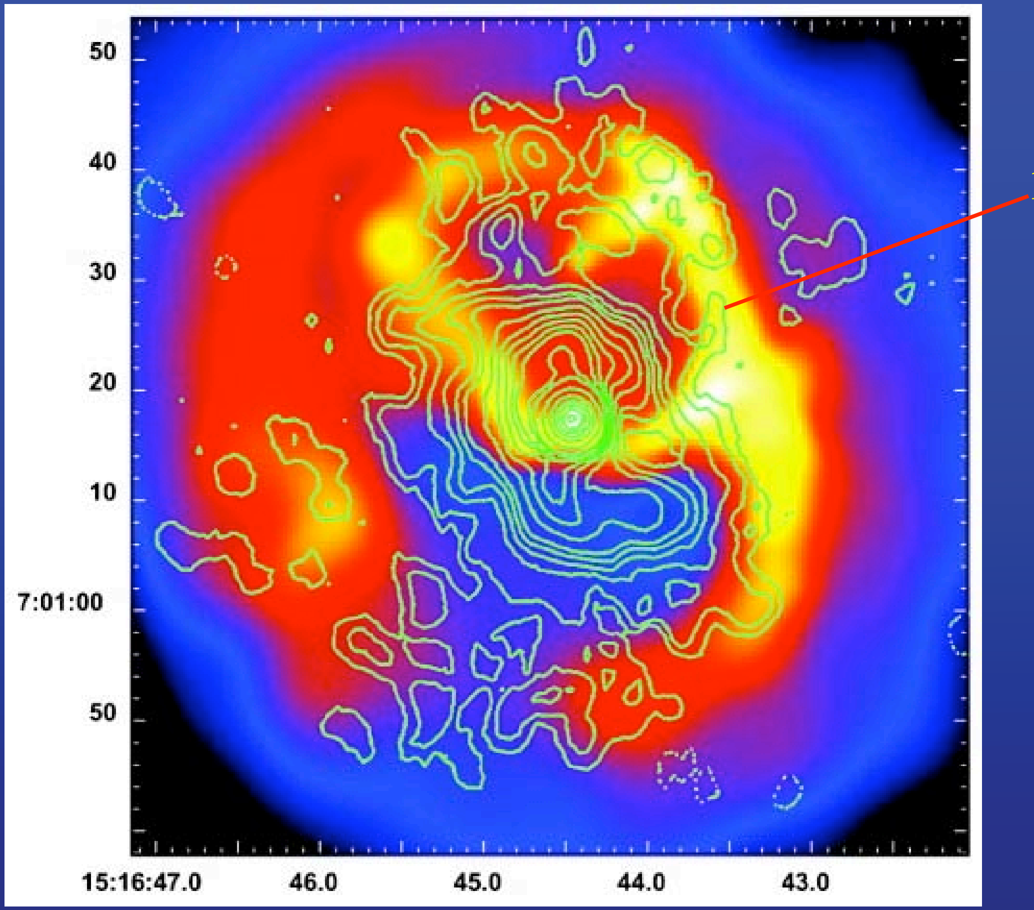
(Blanton et al. 2001)

T ~ 3 keV

1’ = 41 kpc



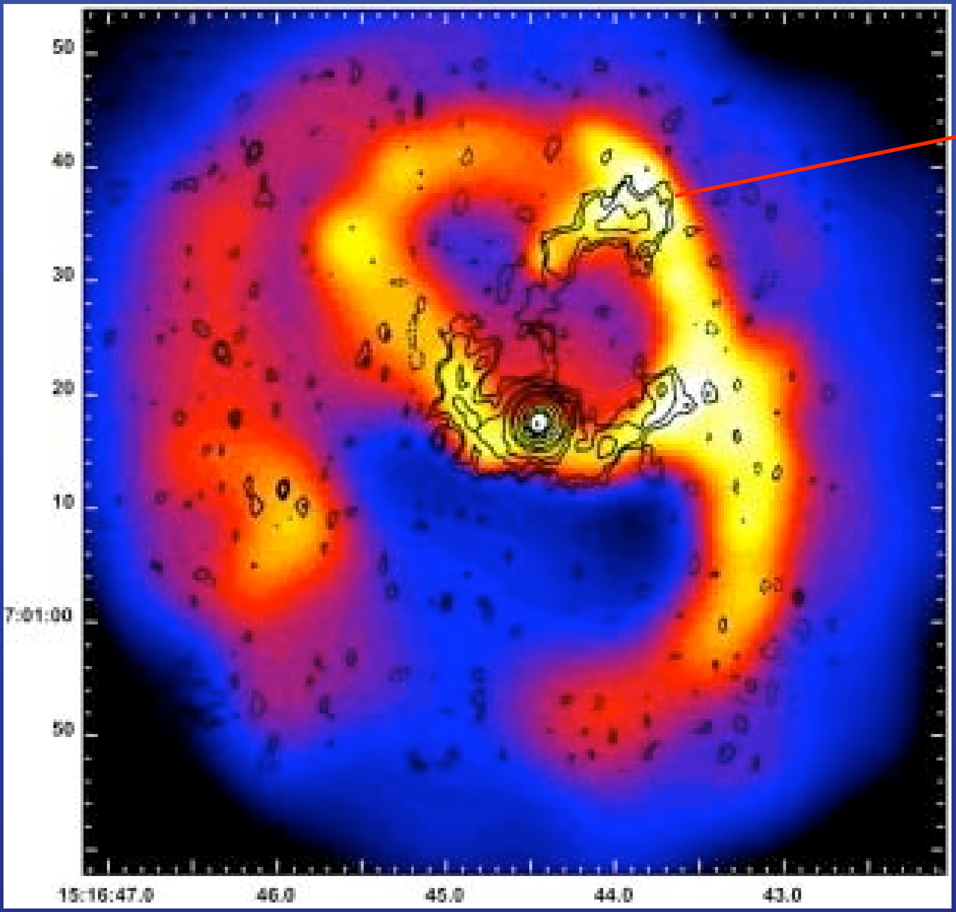
Chandra Image of Abell 2052



radio contours

(Blanton et al. 2001)

Chandra Image of Abell 2052



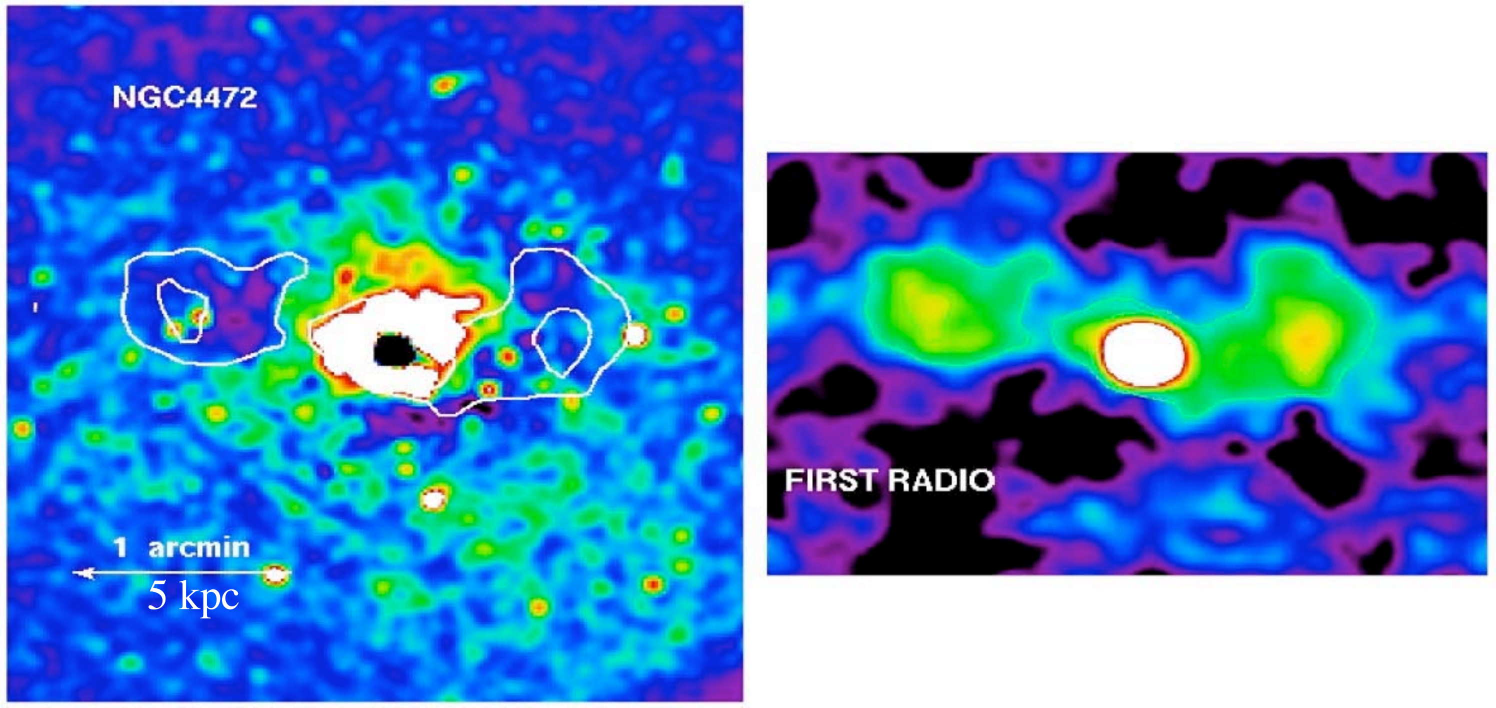
Contours show Hα emission

Gas near the rims of X-ray cavities typically has the lowest X-ray temperatures

(Blanton et al. 2001)

Chandra and Radio Image of core of E galaxy NGC 4472

$r_e = 1.7' = 8.6$ kpc

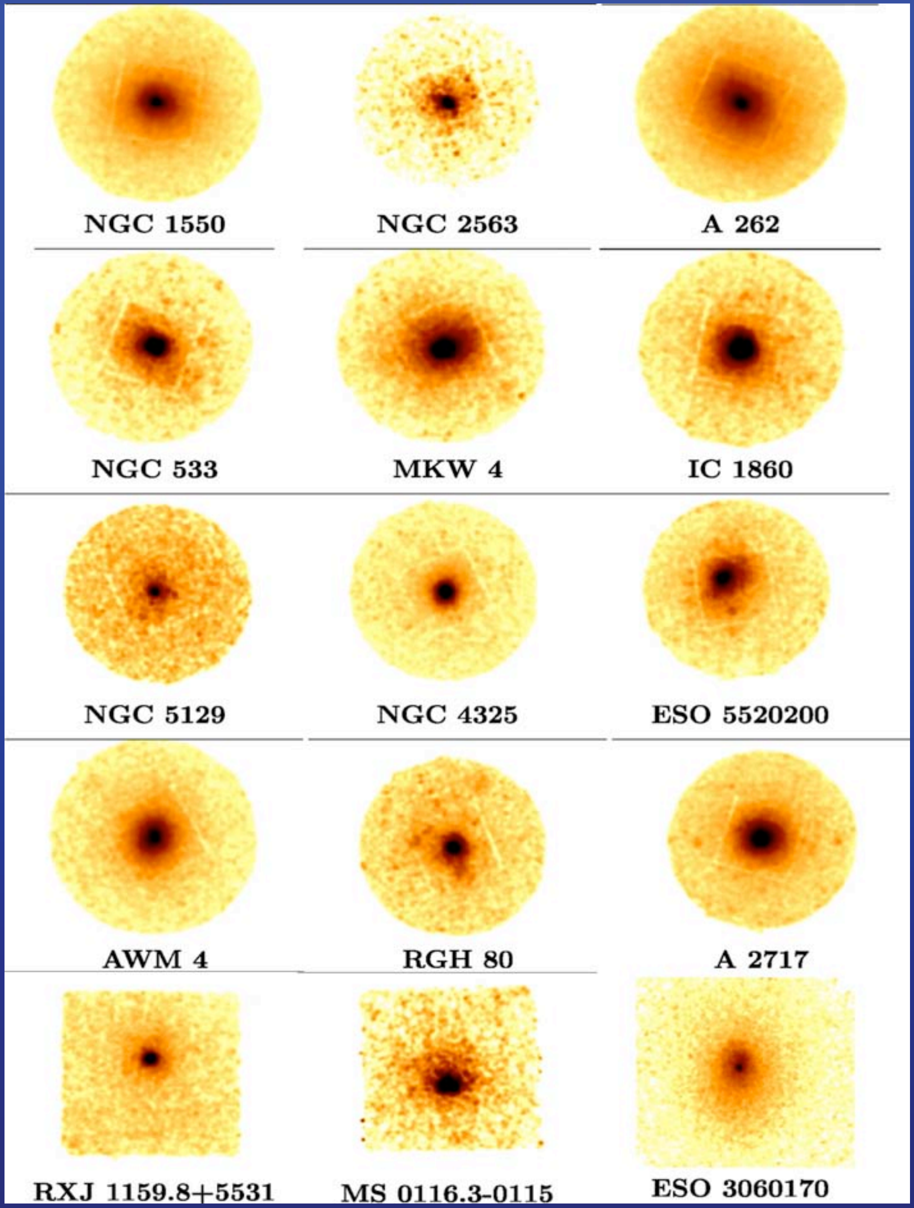


(Biller et al. 2004)

PV energy in radio lobes is ~ 10^{54} ergs

But keep in mind:

most (75%) groups and clusters have no cavities



Gastaldello et al. 2007

Standard Gas Dynamics Equations with Radiation Losses

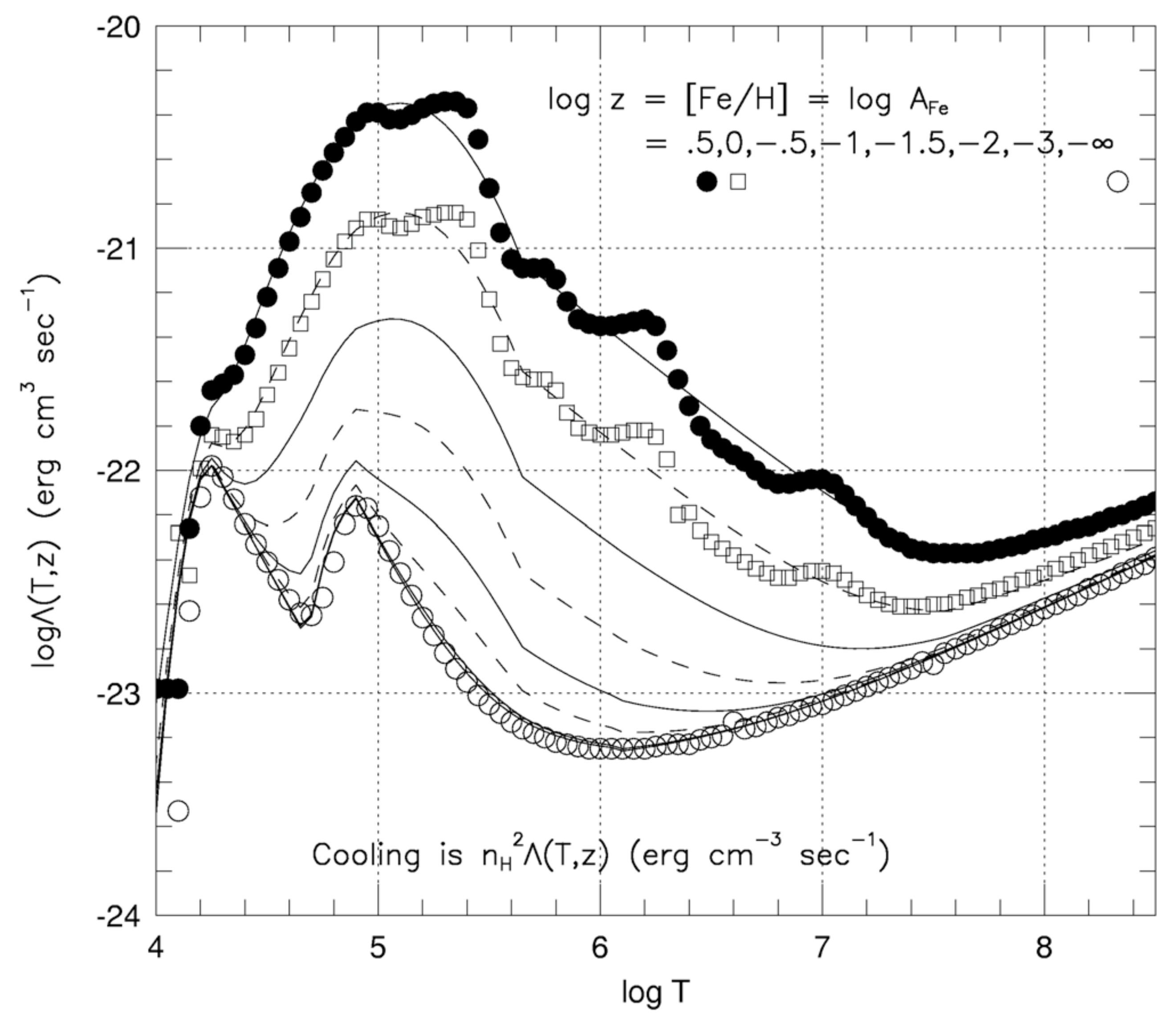
$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0$$

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} \right) = -\nabla P - \rho \mathbf{g}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \mathbf{u} e = -P(\nabla \cdot \mathbf{u}) - (\rho / m_p)^2 \Lambda(T, z)$$

$$P = (\gamma - 1)e$$

Optically thin Radiative Cooling Coefficient Λ(T,z)



(Sutherland & Dopita 1993)

$\Lambda = \Sigma_i < v_e\ \sigma_i\ \varepsilon_i >$ erg cm^3 /sec

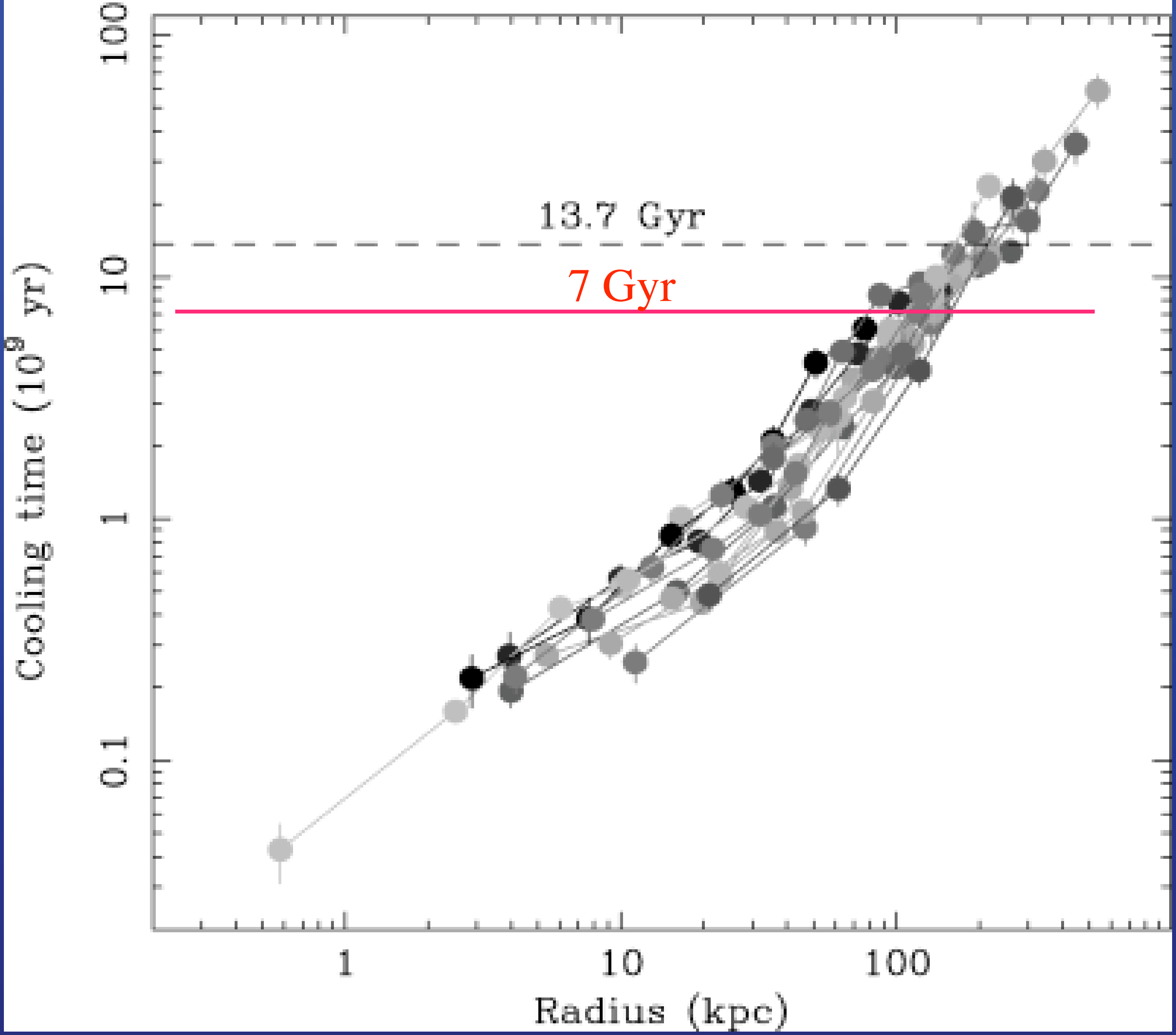
Radiative Cooling Times in Clusters

Isobaric cooling time

$$t_{cool} \gg t_{dy} \, ^{*}$$

$$t_{cool} = \frac{5}{2}\frac{m_p kT}{\mu \rho \Lambda}$$

$$t_{dy} \approx \left[\frac{r^3}{GM(r)}\right]^{1/2}$$



Voigt & Fabian (2004)

*a defining characteristic of cooling flows!

What is the expected cooling rate in the hot gas?

Hot gas is gravitationally bound to dark halos

When gas at radius r radiates, it loses energy
but does not cool at that radius --
instead it flows slowly inward and is heated
by PdV compression back to ~ T_{vir}

in this type of cooling flow,
the gas cools only near the center so that

$$L_x = (5/2)(kT/\mu\, m_p)\, \dot{M}_{cf} \quad \text{(isobaric cooling)}$$

or

$$\boxed{\dot{M}_{cf} = (2/5)\, (\mu\, m_p / kT)\, L_x}$$

~ 1- 10 M_{sun}/yr in E galaxies
~ 100- 1000 M_{sun}/yr in rich clusters

Evidence that cluster gas does not cool as originally expected

Star formation at $\dot{M}_{cf}$ with normal IMF is not observed in E galaxies, or central Es in groups & clusters

If only faint stars form, their mass would violate observed stellar M/L ratios in E galaxy cores

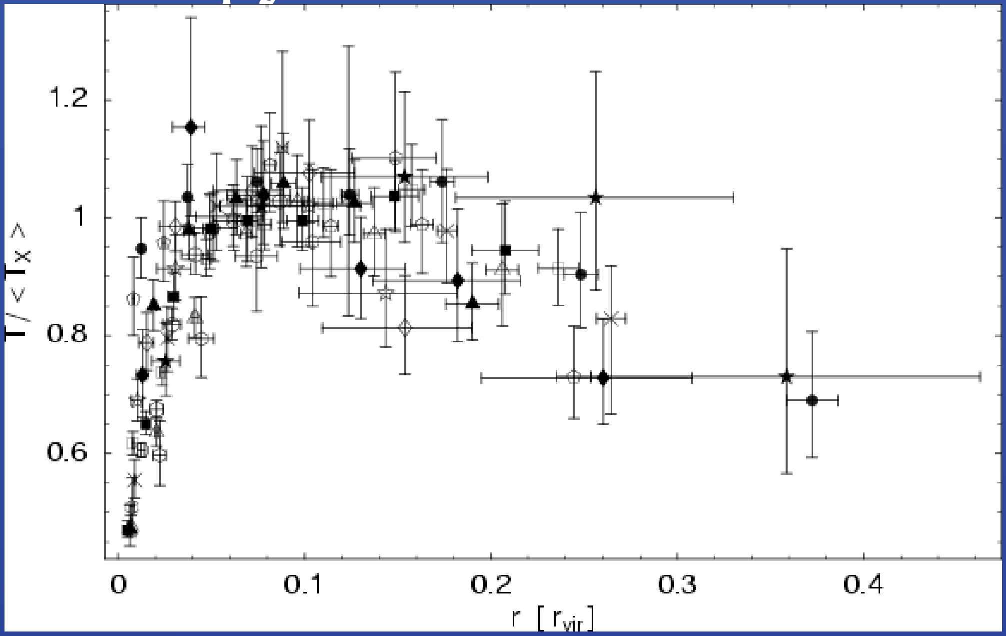
Steep L_x - <T> relation in groups and clusters

Enhanced gas entropy in group (and some cluster) cores

Absence of emission from cooling gas in X-ray spectra

Cluster Temperature and Entropy Profiles from XMM

Temperature structure in clusters looks like normal cooling flows

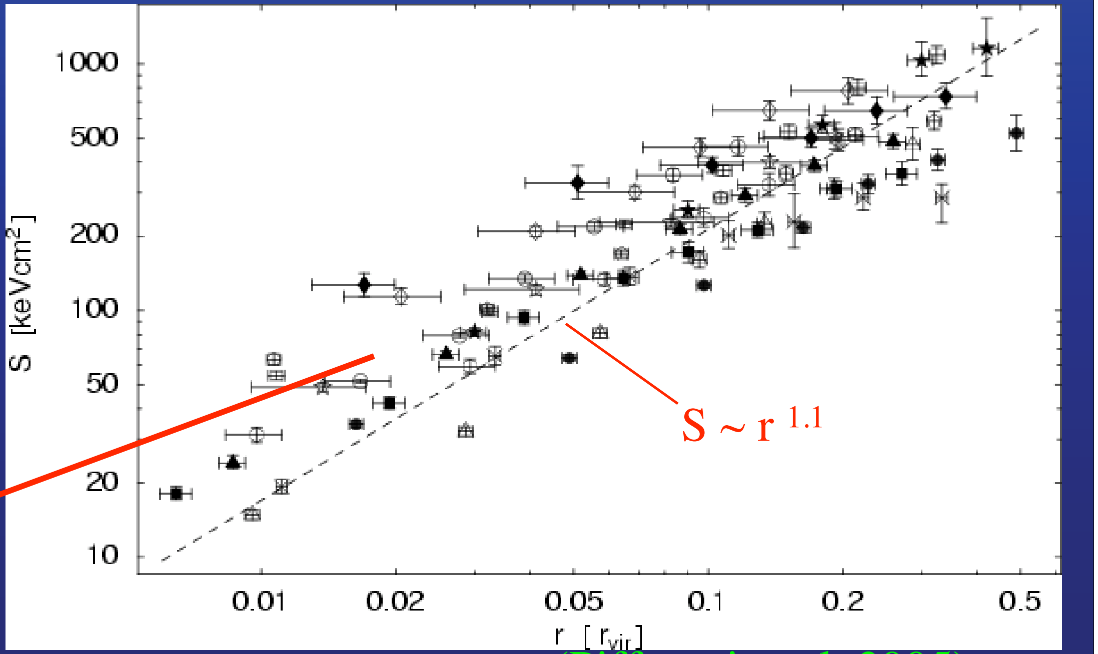


If the only source of heating is the accretion shock, the entropy is:

$$S = T/n_e^{2/3} \sim r^{1.1}$$

(Tozzi & Norman 2001)

High central entropy is evidence for “non-adiabatic” heating



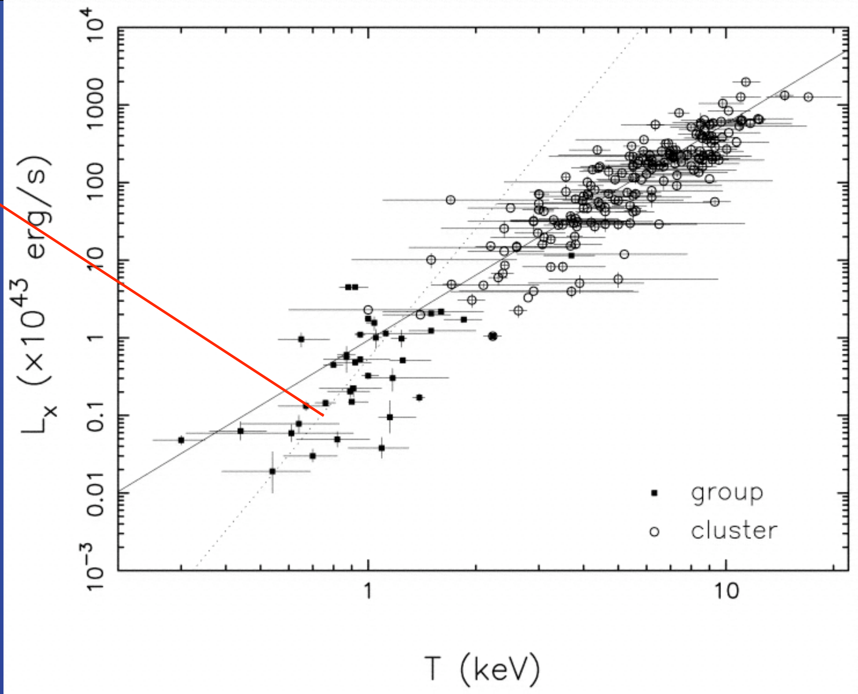
(Piffaretti et al. 2005)

Cluster L_x-T and T-σ Plots

“non-gravitational” heating

clusters: $L_x \sim \langle T \rangle^{2.9}$

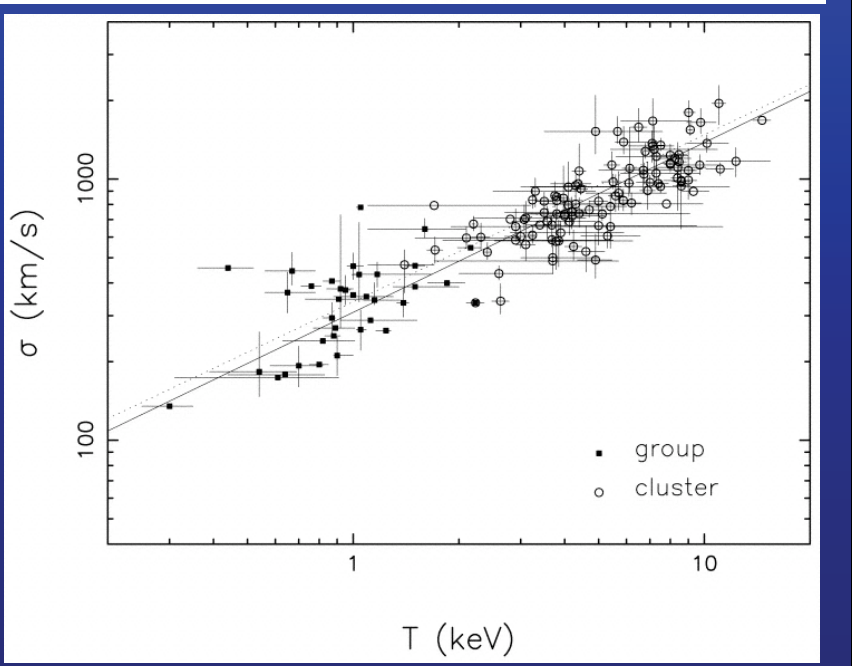
groups: $L_x \sim \langle T \rangle^{5.6}$



for both groups and clusters:

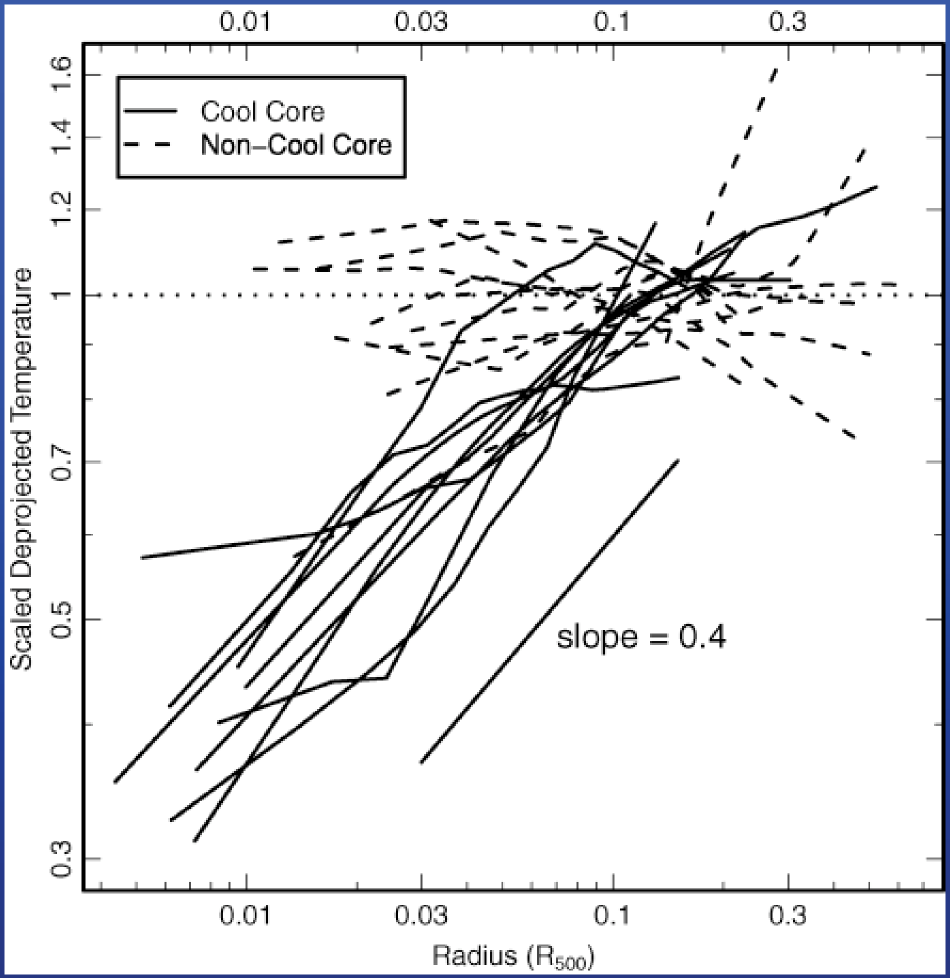
$\sigma_{gal} \sim \langle T \rangle^{0.64}$

expect: 0.5



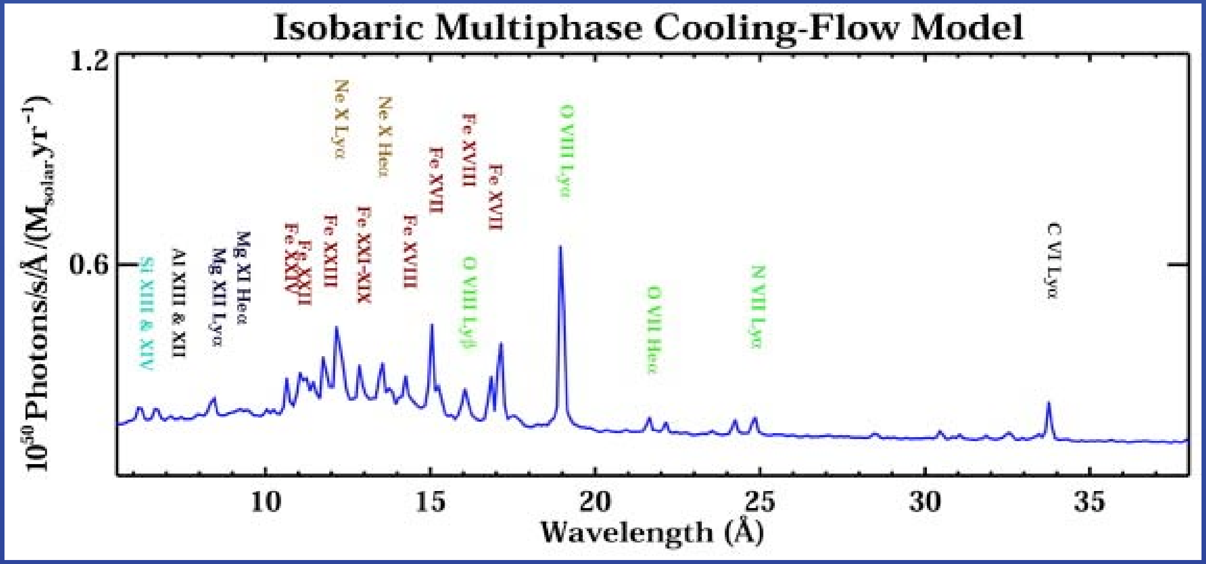
(Xue & Wu 2000)

T ~ r $^{0.4}$ in central ~100 kpc of cool-core clusters



(Sanderson et al. 2006)

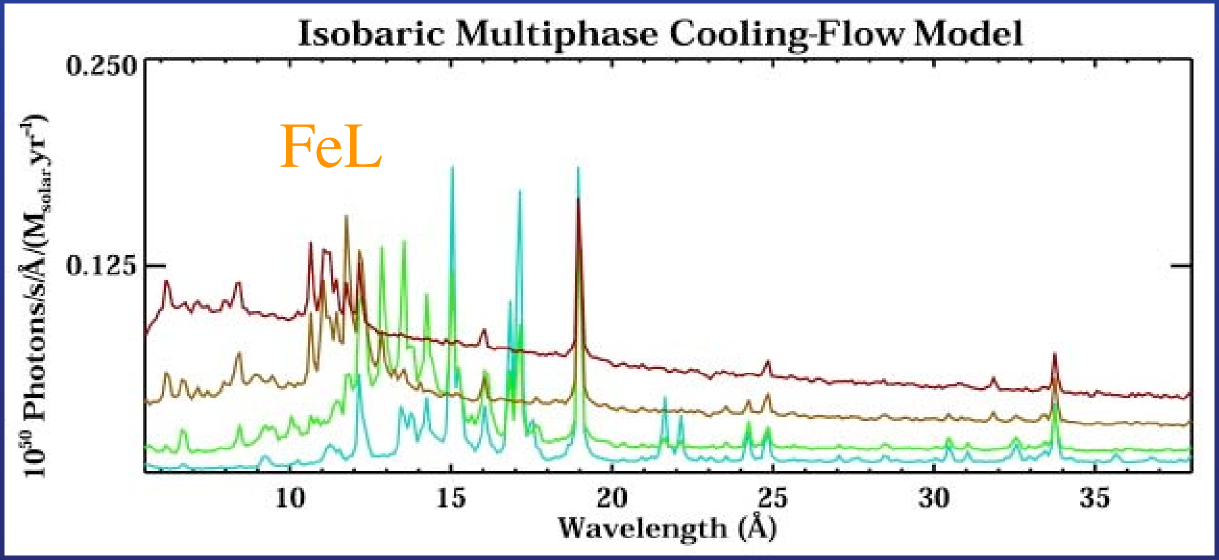
XMM X-ray Spectra of Cooling Gas



1 keV = 12.4 A

cooling spectra in
four temperature ranges:

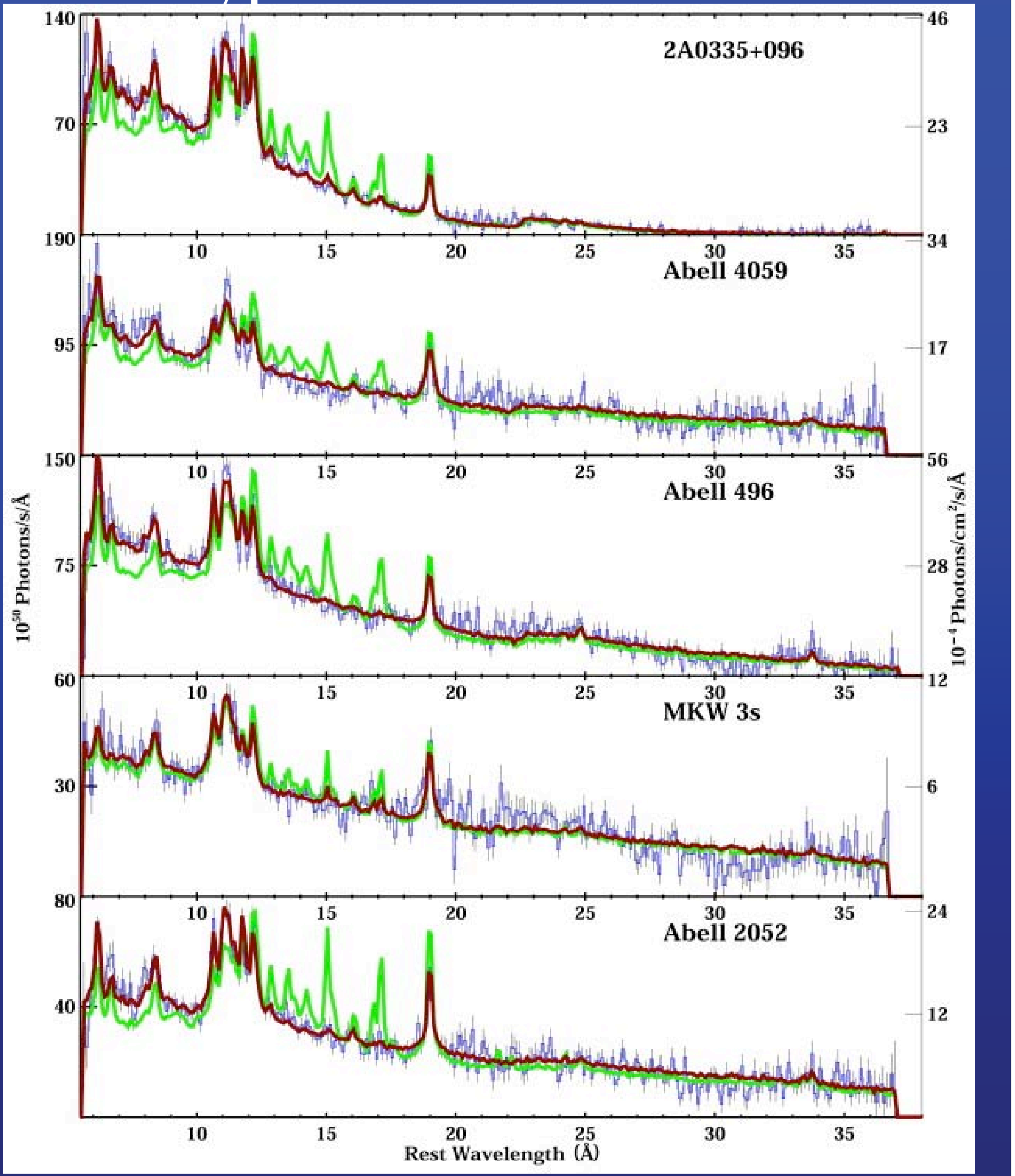
Dark brown: 6-3 keV
brown: 3-1.5 keV
green: 1.5-0.75 keV
blue: 0.75-0.38 keV



(Peterson et al. 2003)

XMM Spectra of Five Typical Clusters

blue: data
brown: T_{vir} <--> $T_{vir}/3$
(best fit model)
green: cooling flow



1 keV = 12.4 A

(Peterson et al. 2003)

No gas is observed with $T < 0.3\ T_{vir}$

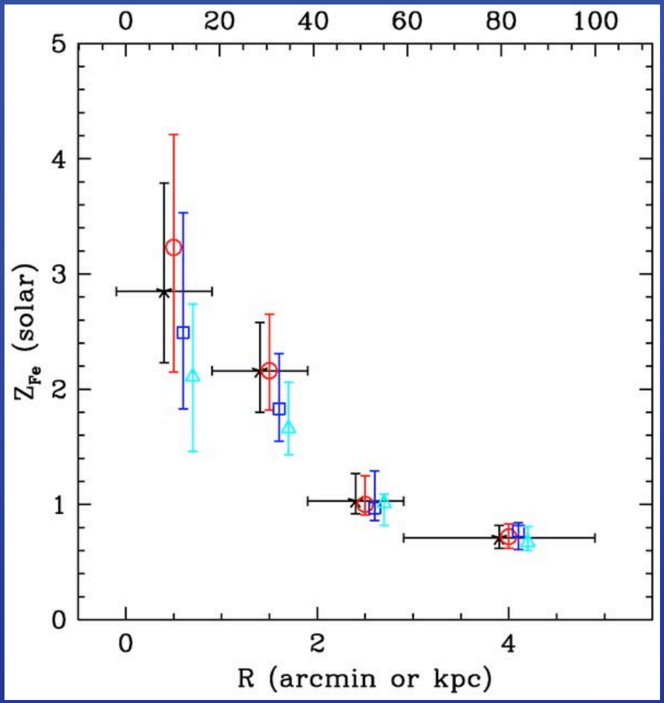
The cooling rate must be $< 0.1 - 0.2$ of the expected rate:

$$\dot{M}_{cf} = (2/5)\ (\mu\ m_p/\ kT)\ L_x$$

WHY?

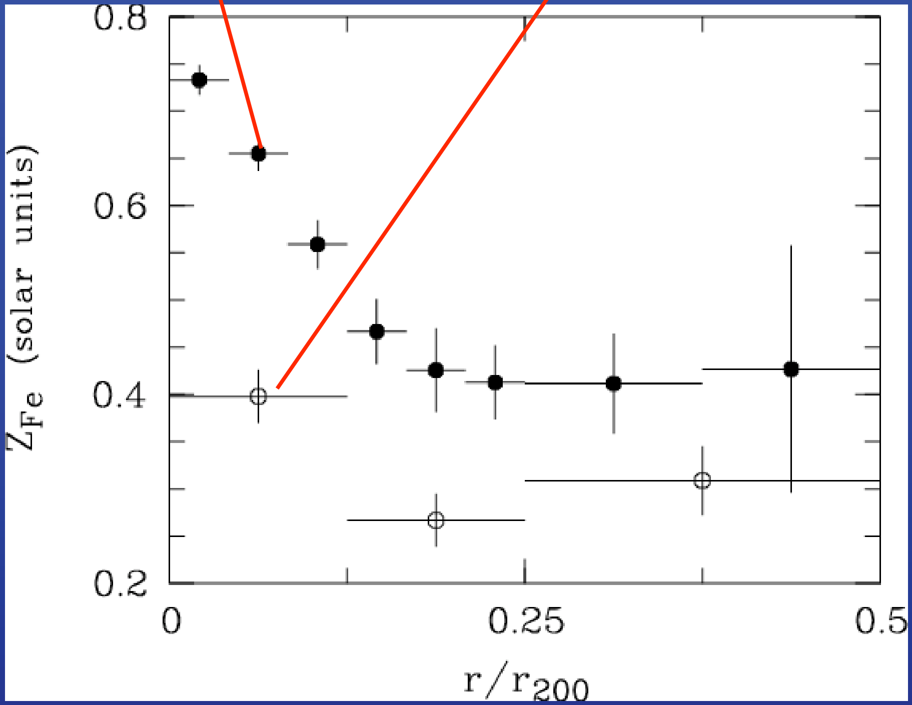
Central Iron Abundance Peaks are Common

in group NGC 507



Kim & Fabbiano 2004

in 12 CC and 10 non-CC clusters



De Grandi et al. 2004

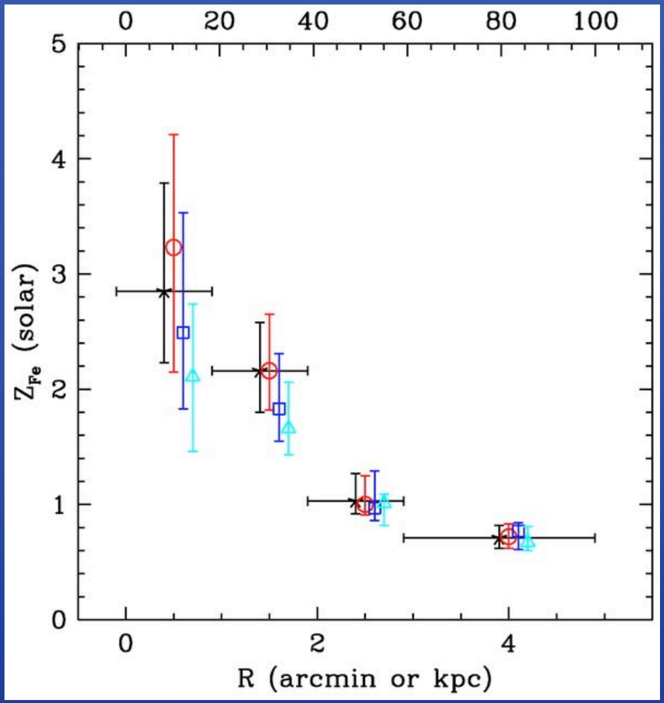
About 70-80 % of iron enrichment is from SNIa

Total iron mass in r < 100 kpc is $M_{Fe} \sim 10^8$-10^9 M_{sun}

Emission-weighted mean iron abundance = 0.4 solar

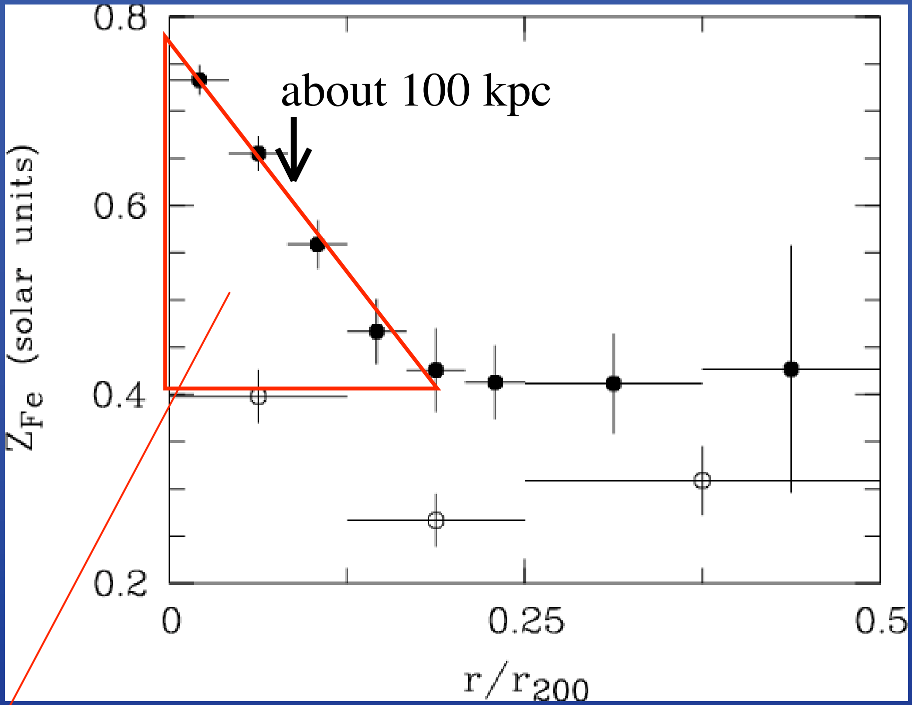
Central Iron Abundance Peaks are Common

in group NGC 507



Kim & Fabbiano 2004

in 12 CF and 10 non-CF clusters



De Grandi et al. 2004

“excess” iron mass in CF clusters correlates with L_B of central E galaxy

excess iron mass is mostly from SNIae in central E

Requirements for a Successful Theory

The cooling rate must be no more than ~ 0.1 $(dM/dt)_{cf}$

The gas temperature must increase to r ~ 0.3 r_{vir}

- i.e. T(r) must look like a conventional cooling flow
- central AGN is surrounded by the coolest gas!

The iron abundance profile

- must have a broad peak within r ~ 100 kpc
- must be ~ 0.4 solar on average

How Can Cooling Flows be Heated?

Accretion onto central massive black hole creates plenty of energy

Mass of black holes is related to total stellar mass M_{*t}:

$M_{bh} = 1.6\text{x}10^8\ (M_{*t}\ /\ 10^{11}M_{sun})^{1.12}\ M_{sun}$ (Haring & Rix 2000)

X-ray luminosity from standard cooling flow:

$L_x \sim (5/2)\ (dM/dt)_{cf}\ (kT\ /\ \mu m_p) \sim\ (dM/dt)_{cf}\ c_s^{\ 2}$

Accretion luminosity onto the black hole:

$L_{acc} \sim \varepsilon\ (dM/dt)_{acc}\ c^2$ where $\varepsilon \sim 0.1$

a tiny accretion can heat the entire flow:

set $L_{acc} \sim L_x$ then

$(dM/dt)_{acc}/(dM/dt)_{cf} \sim (0.1/\varepsilon)(c_s/c)^2 \sim 10^{-4}\ (0.1/\varepsilon)$

Some Popular (but largely unsuccessful) AGN Heating Mechanisms:

Radio Jets

Shock Waves

PV heating by inflating or dissipating X-ray cavities

turbulent heating, thermal conduction, supernovae,

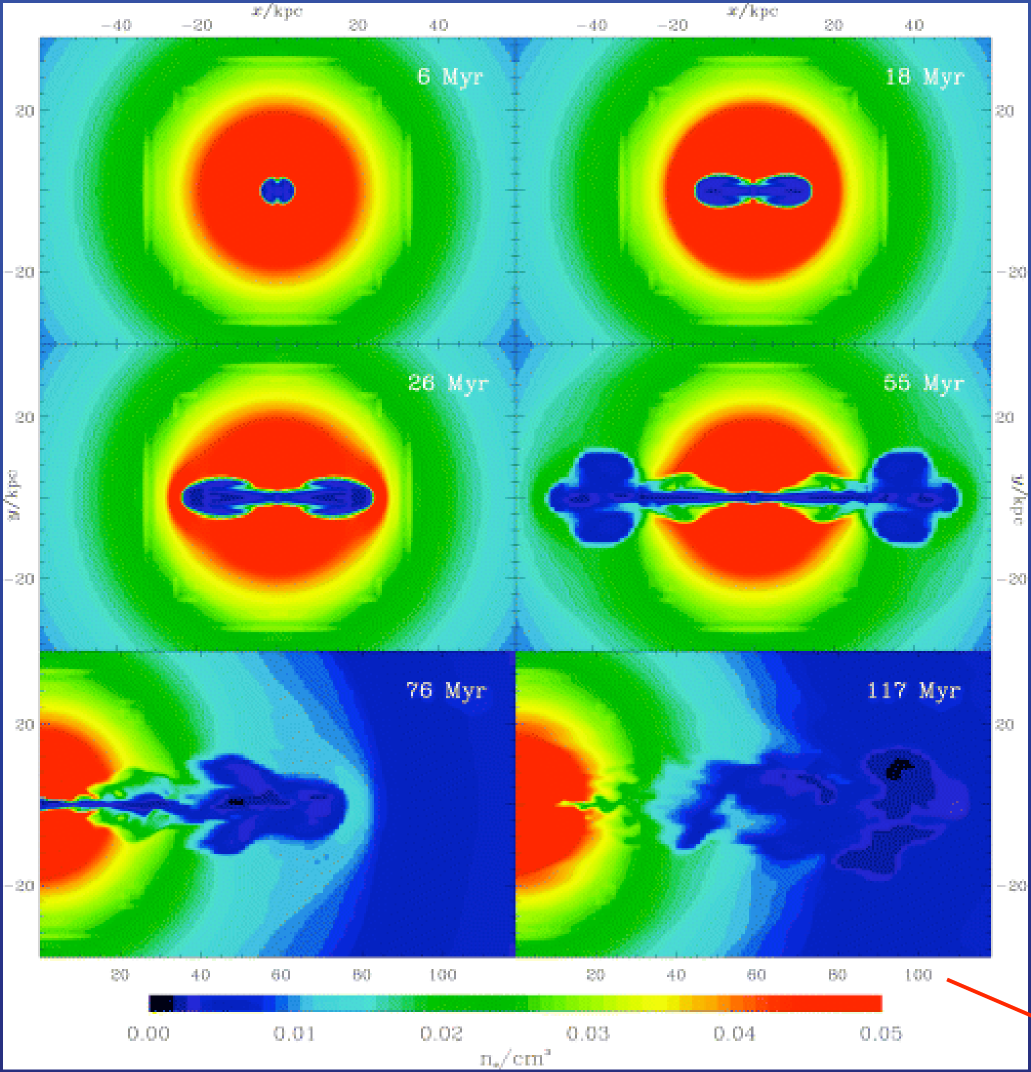
viscous dissipation, inverse Compton, etc

Heating Cooling Flows with Powerful Radio Jets

density contours
3D calculation

these cavities expand
out much more
rapidly than
bouyant bubbles

This does not look like
observed bubbles



100 kpc

(Omma, Binney, Bryan, Slyz 2004)

Intermittent heating by jets requires very powerful jets to balance L_x in massive clusters; little jet energy goes into gas perpendicular to jet near r~0 which then cools.

Injecting hot gas

2D calculation
continuous injection of hot gas into 1kpc sphere

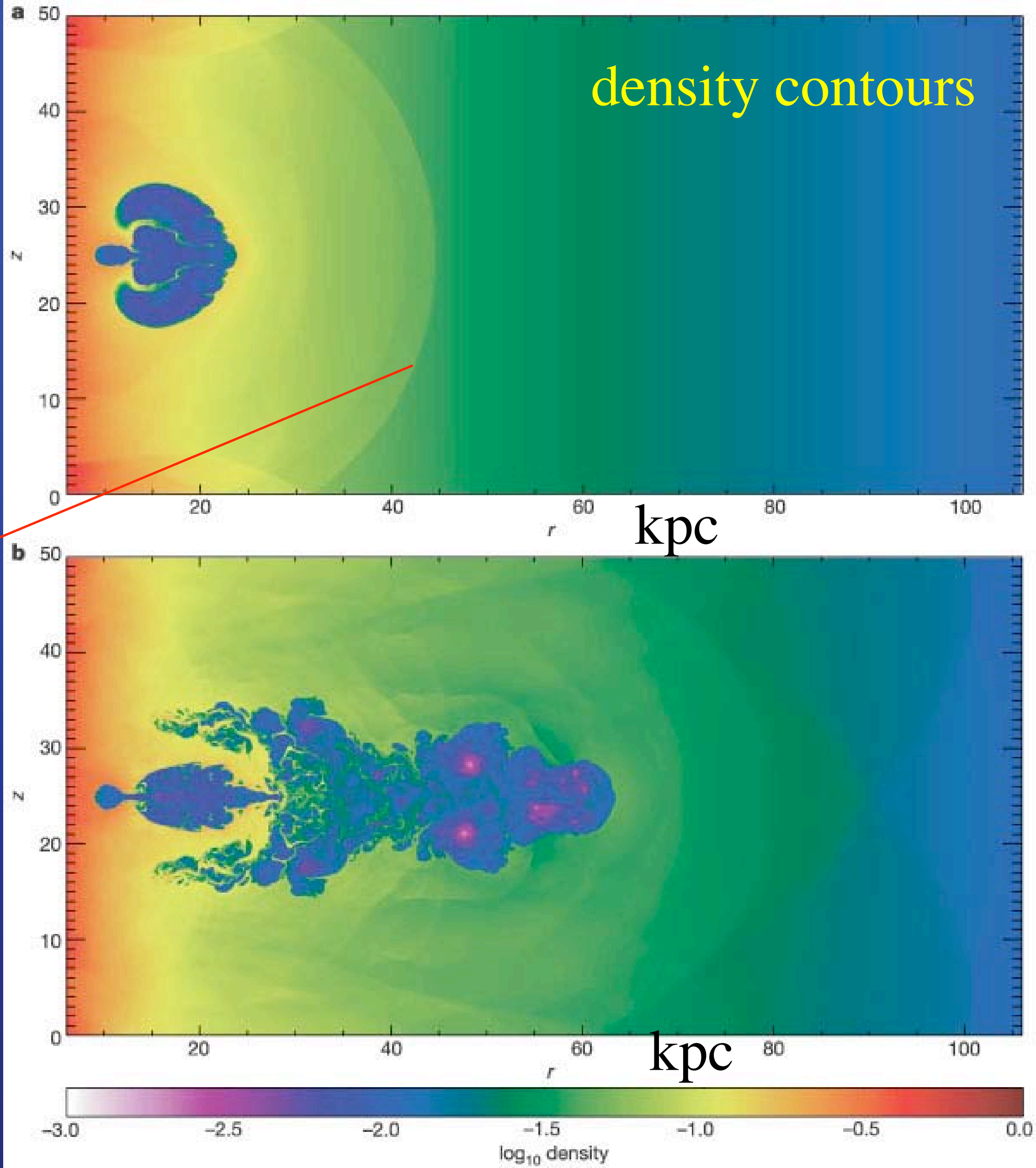
6 x 10^7 yrs

can weak shocks heat distant gas?

radiative cooling is ignored

12 x 10^7 yrs

does not look like observed cavities!

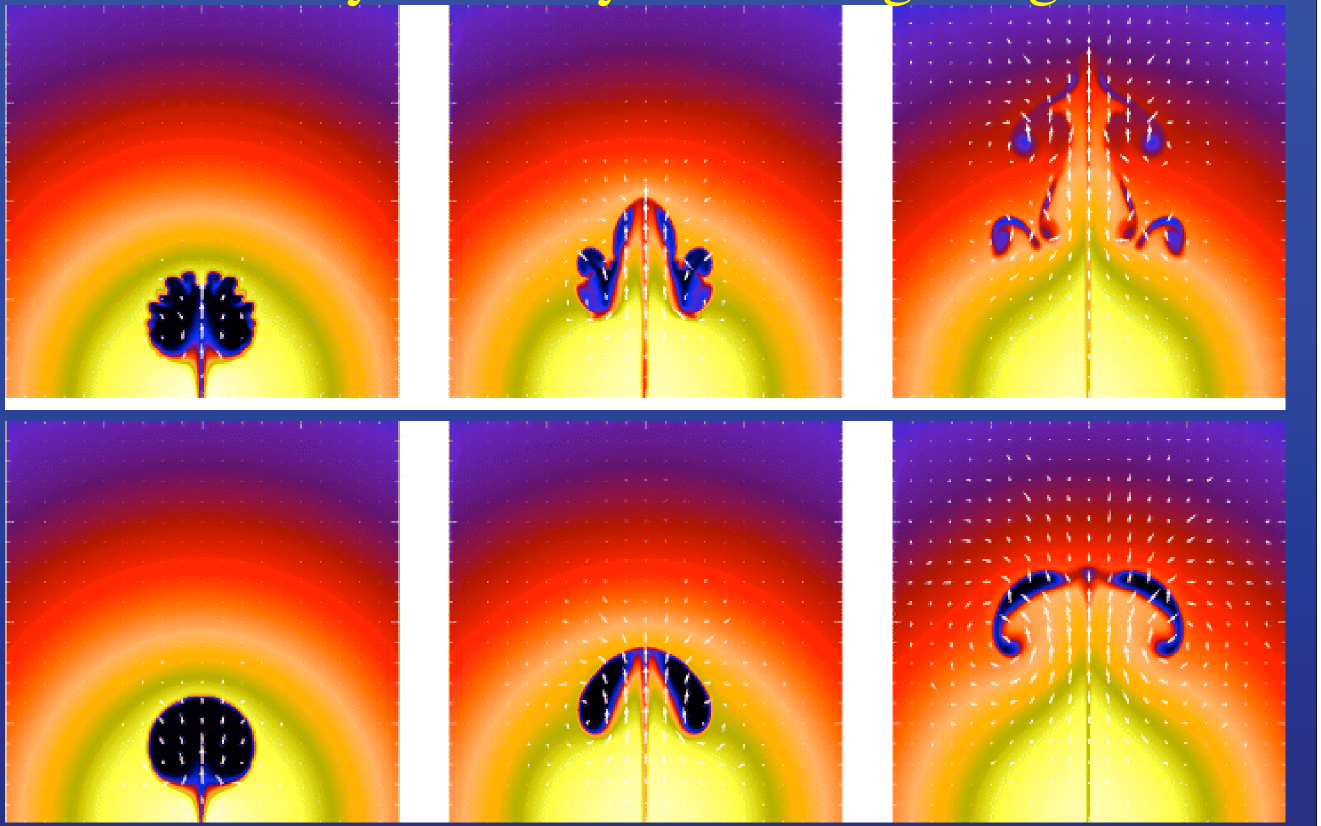


density contours

(Bruggen & Kaiser 2002)

Can Viscosity Preserve Coherence of Cavities?

3D calculations of a buoyant cavity containing hot gas:



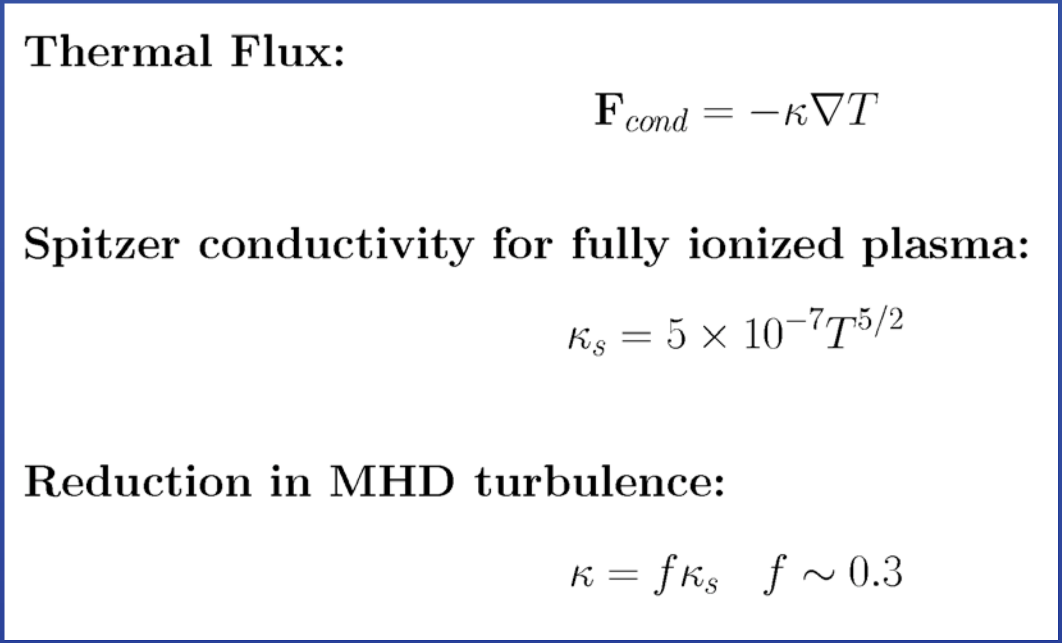
No viscosity

more coherence
with
0.25 Spitzer’s
viscosity

(Reynolds et al. 2005)
(Jones & De Young 2005)

But what is the source of viscosity?

Heating with thermal conduction:



Thermal Flux:

$$\mathbf{F}_{cond} = -\kappa \nabla T$$

Spitzer conductivity for fully ionized plasma:

$$\kappa_s = 5 \times 10^{-7} T^{5/2}$$

Reduction in MHD turbulence:

$$\kappa = f \kappa_s \quad f \sim 0.3$$

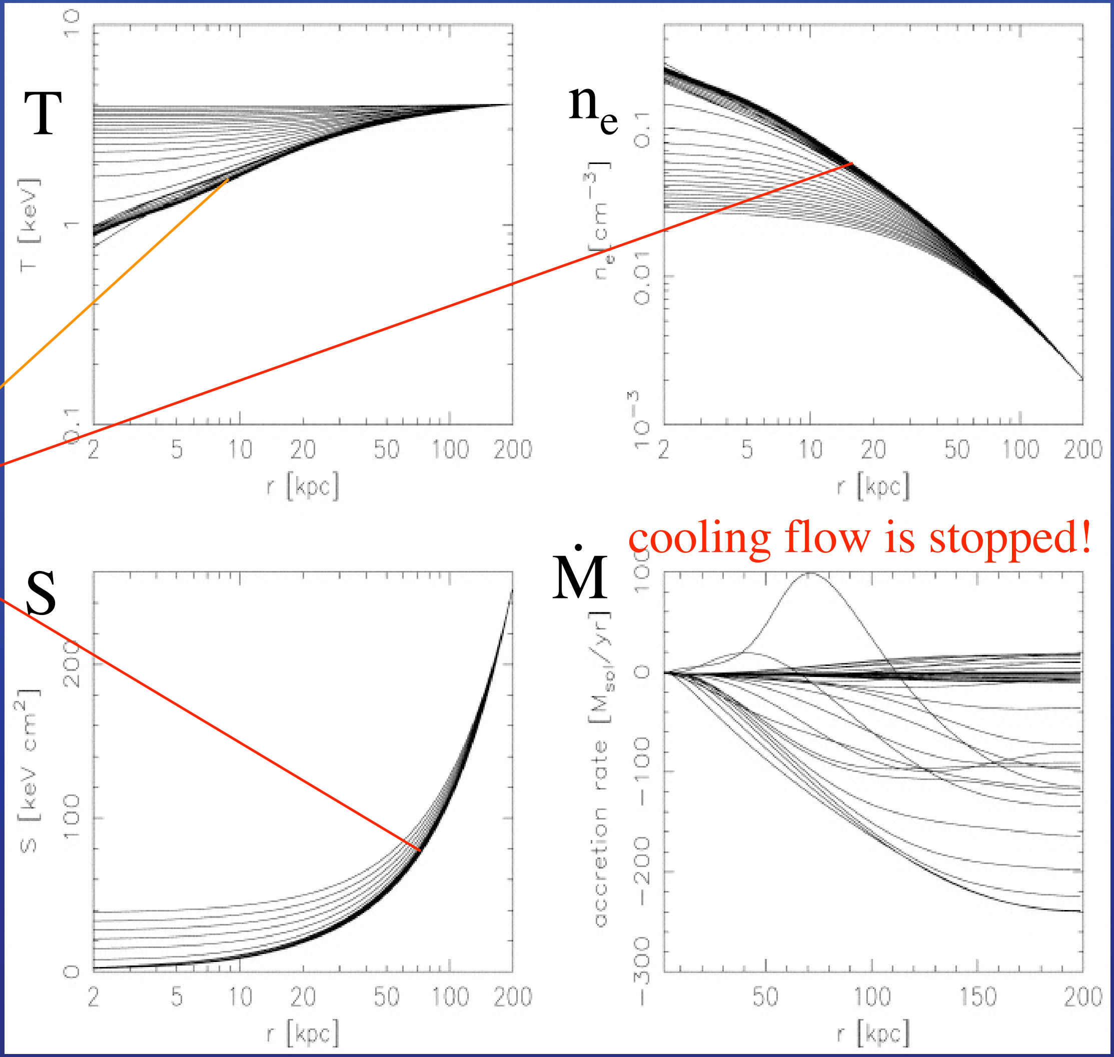
(Narayan & Medvedev 2001)

But conduction cannot provide enough heating
to balance radiation in all clusters (Voigt et al. 2004)
And cannot stop cooling in groups having lower
Temperature gas T ~ 1 keV (Brighenti & Mathews 2003)
Survival of ~1keV gas in cluster E galaxies
suggests f < ~0.02 (Brighenti & Mathews 2002; Sun et al. 2004)

AGN Heating from Inside, Conductive Heating from Outside

1D iterative calculation,
instantaneous
AGN heating from inside;
plus heating by thermal
conduction from large r

final steady profiles



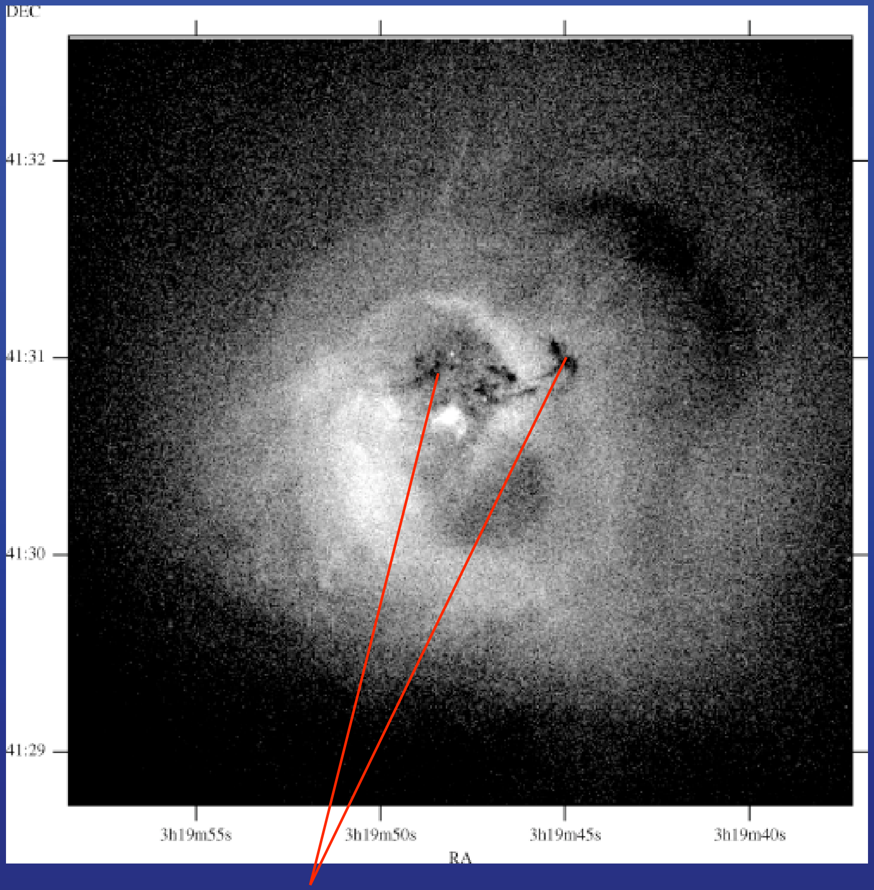
cooling flow is stopped!

Conduction: $\kappa = 0.23\ \kappa_s$

(Ruszkowski & Begelman 2002)

Has correct dT/dr
But does not work on E galaxy scales (Brighenti & Mathews 2003)

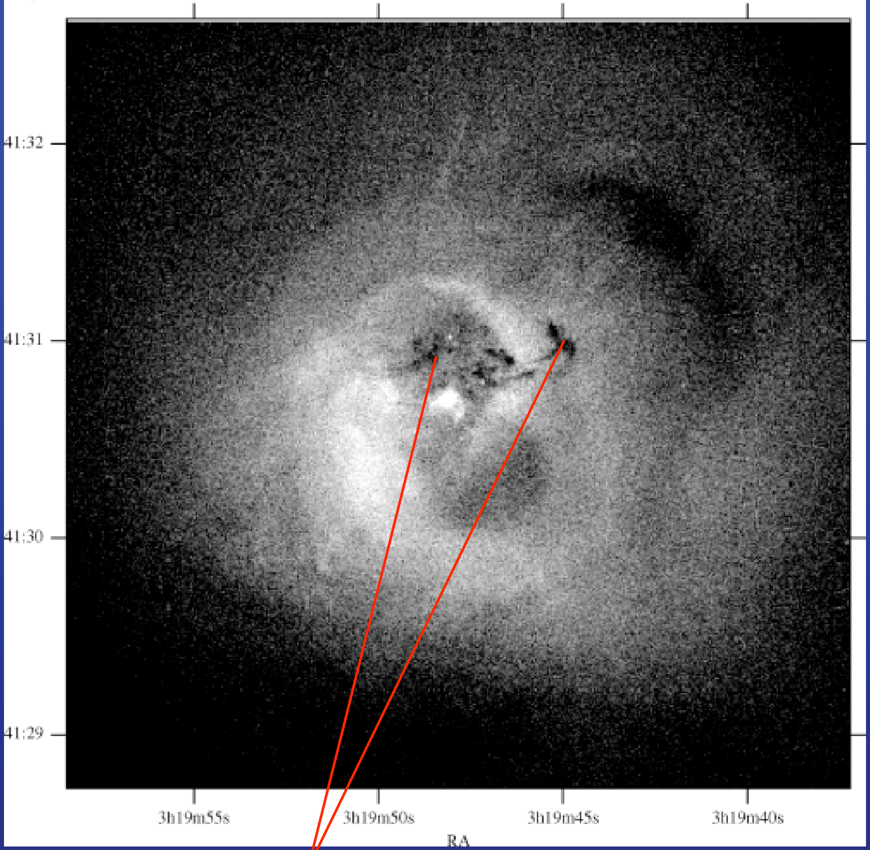
200ks Chandra Image of Perseus Cluster



absorption is from foreground dusty gas in merging galaxies

(Fabian et al. 2003)

200ks Chandra Image of Perseus Cluster

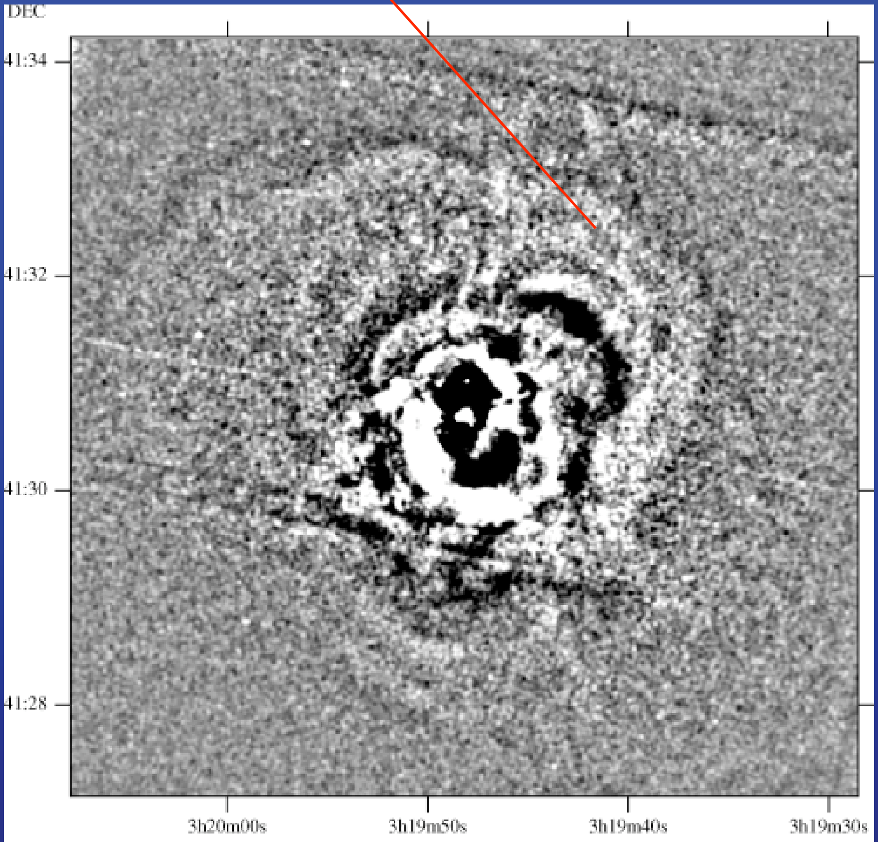


Absorption from foreground gas in merging galaxies

Ripples

wavelength λ ~ 10 kpc => ~10^7 yrs

(Fabian et al. 2003)



Unsharp-masking: smooth image with 10” gaussian, subtract original image, then smooth with 1” gaussian

Can Heating With Ripple-Shocks solve the Cooling Flow Problem?

Some Recent Quotes:

Ripple-shocks “provide a splendid way for the energy produced by accretion onto the central black hole to be dissipated in a general, isotropic manner in the surrounding hot gas.” (Fabian 2004)

“These shocks distribute energy which may be sufficient to balance the effects of radiative cooling in the cluster cores.” (Fabian 2005)

let’s test this idea by generating waves in Perseus

first step is to set up a traditional cooling flow …

Gravitational potential in Perseus Cluster

begin by constructing a mass model:

Assume hot gas is in hydrostatic equilibrium:

$$\frac{dP}{dr} = \frac{k}{\mu m_p}\frac{d(\rho T)}{dr} = -\rho g \quad => \quad g_{nT}(r) = \frac{kT}{\mu m_p}\left(\frac{1}{n_e}\frac{dn_e}{dr} + \frac{1}{T}\frac{dT}{dr}\right)$$

NFW dark halo

$M_{vir} = 8.5 \text{x} 10^{14}\ M_{sun}$

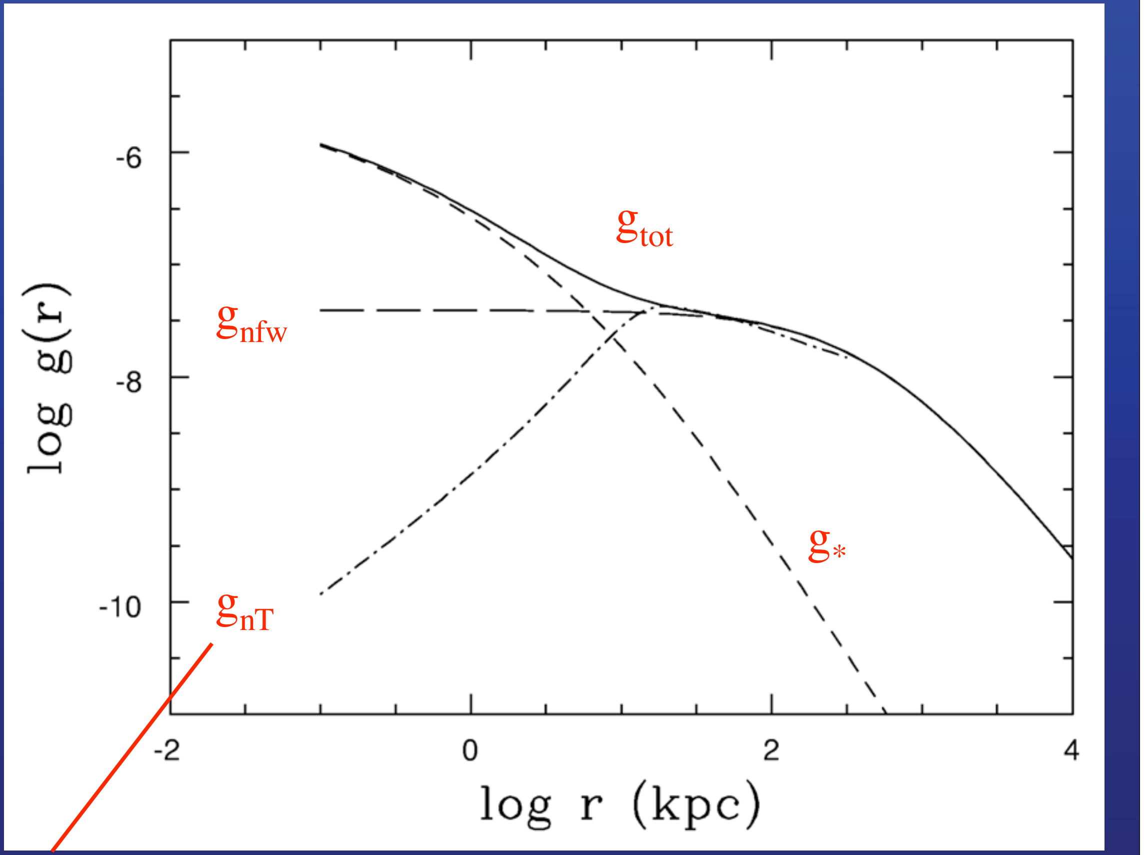
$c = 6.8$

de Vaucouleurs

stellar mass distribution

$M_* = 2.5 \text{x} 10^{11}\ M_{sun}$

this simple model ignores adiabatic contraction of dark matter by baryons

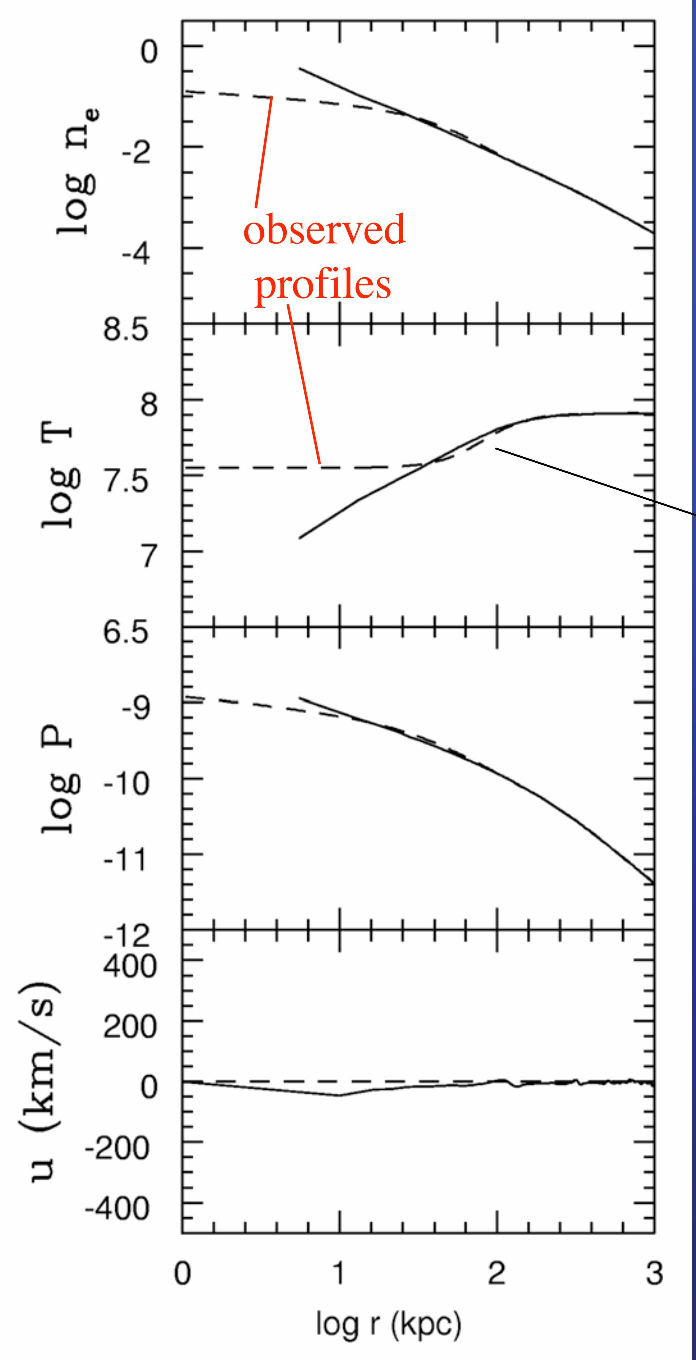


Observations fail at r < 10 kpc

(Mathews et al. 2005)

next compute
a pure cooling flow
in Perseus
for $4x10^9$ yrs
with fixed spherical
barrier at r_{p0} = 1kpc

Gas that cools
near r_{p0}
is removed from
the calculation



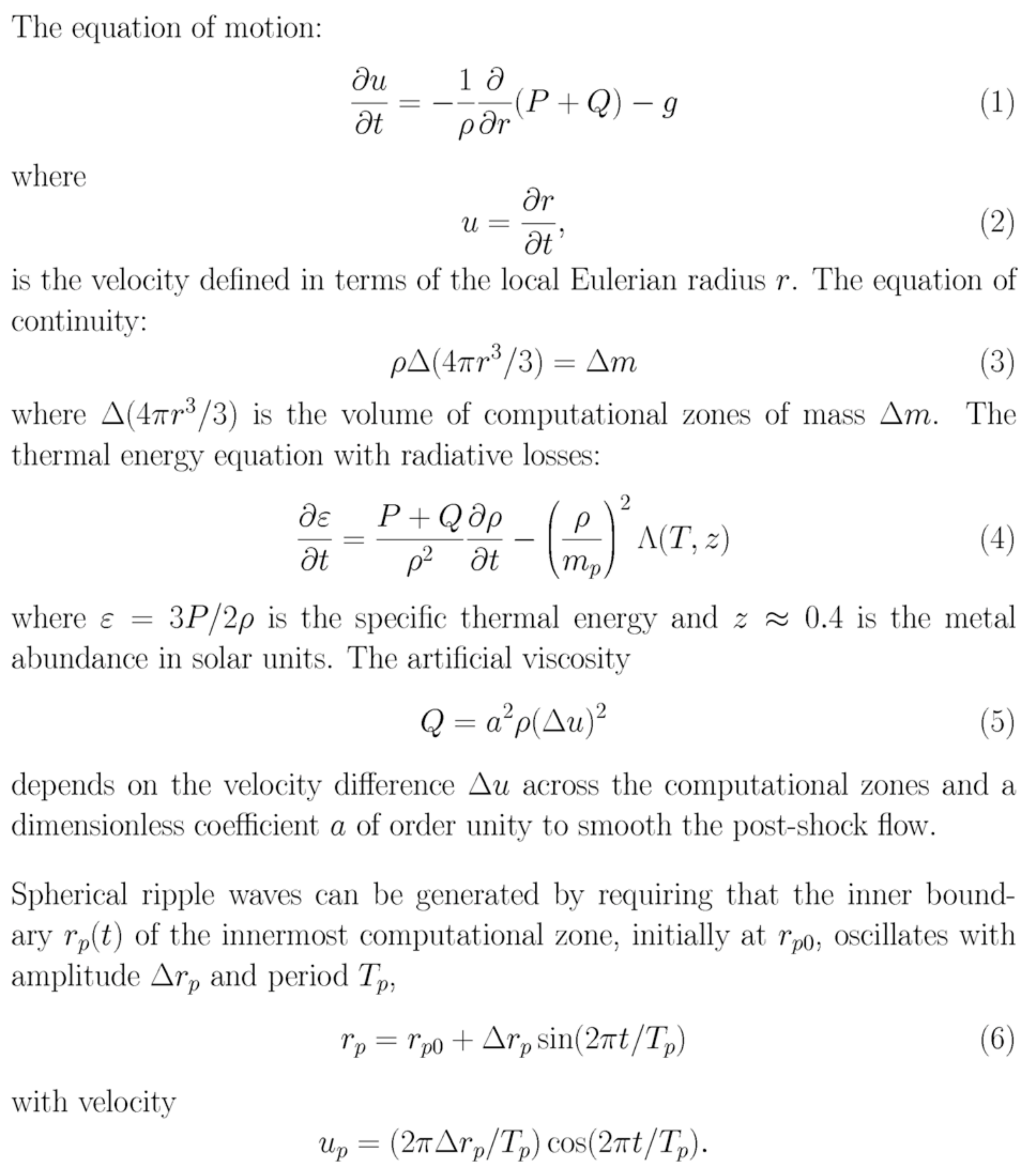
observed profiles

Cooling flows
(solid lines)
have central
density peaks

temperature
profile is correct
=> without
using thermal
conduction
Perseus looks
like a cooling flow

The cooling rate is
~250 M_{sun}/yr
(too large to fit
X-ray spectrum!)

Now heat the Perseus Cluster with a Lagrangian Wave Machine



The equation of motion:

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial r}(P+Q) - g \tag{1}$$

where

$$u = \frac{\partial r}{\partial t}, \tag{2}$$

is the velocity defined in terms of the local Eulerian radius r. The equation of continuity:

$$\rho\Delta(4\pi r^3/3) = \Delta m \tag{3}$$

where $\Delta(4\pi r^3/3)$ is the volume of computational zones of mass Δm. The thermal energy equation with radiative losses:

$$\frac{\partial \varepsilon}{\partial t} = \frac{P+Q}{\rho^2}\frac{\partial \rho}{\partial t} - \left(\frac{\rho}{m_p}\right)^2 \Lambda(T,z) \tag{4}$$

where $\varepsilon = 3P/2\rho$ is the specific thermal energy and $z \approx 0.4$ is the metal abundance in solar units. The artificial viscosity

$$Q = a^2\rho(\Delta u)^2 \tag{5}$$

depends on the velocity difference Δu across the computational zones and a dimensionless coefficient a of order unity to smooth the post-shock flow.

Spherical ripple waves can be generated by requiring that the inner boundary $r_p(t)$ of the innermost computational zone, initially at r_{p0}, oscillates with amplitude Δr_p and period T_p,

$$r_p = r_{p0} + \Delta r_p \sin(2\pi t/T_p) \tag{6}$$

with velocity

$$u_p = (2\pi\Delta r_p/T_p)\cos(2\pi t/T_p).$$

Heating the Perseus Cluster with waves

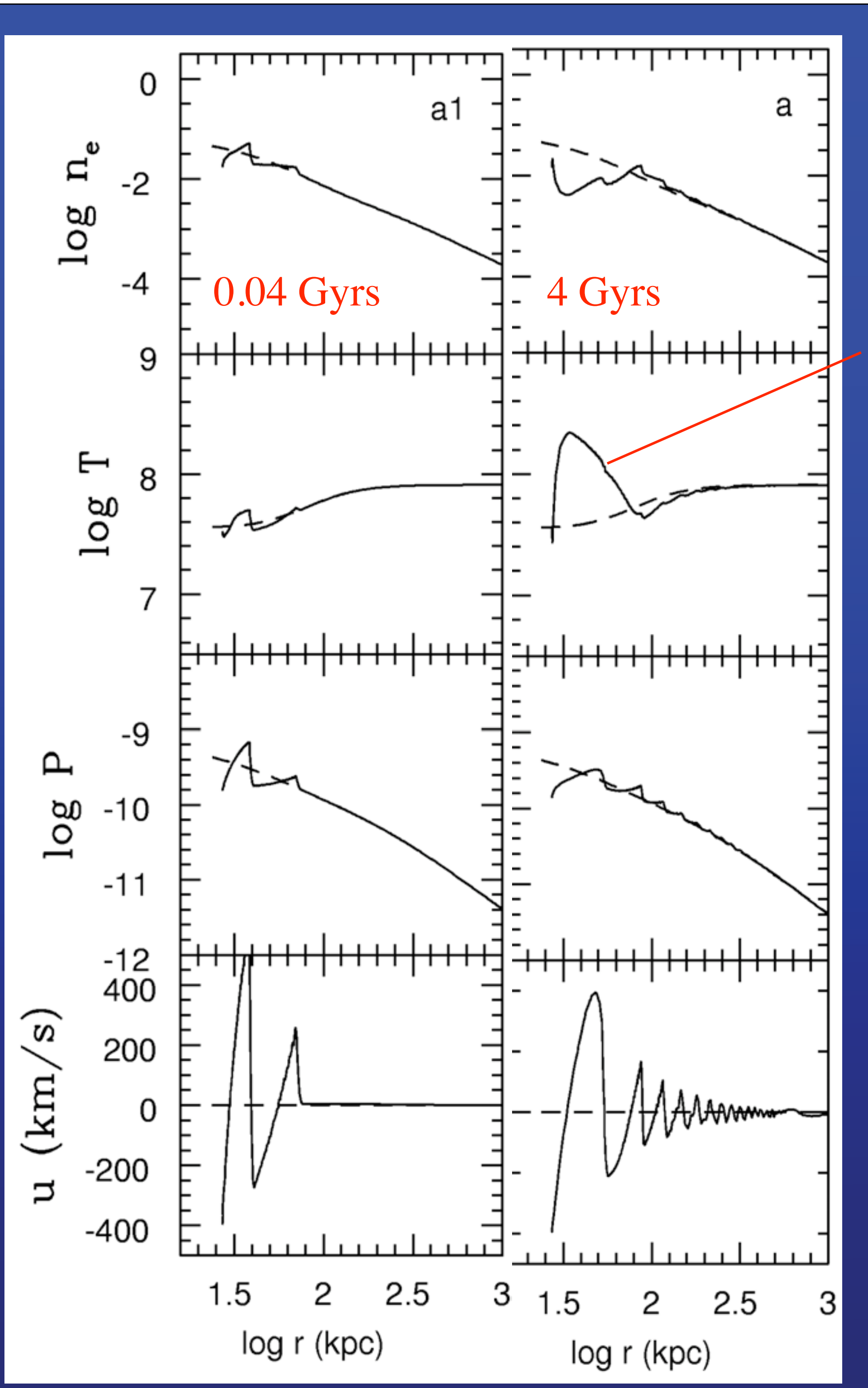
piston parameters

$r_{p0} = 24$ kpc

$\Delta r_p = 4$ kpc

$T_p = 3 \times 10^7$ yrs

$L_{mech} \sim L_x$



very little gas cools but the temperature profile is <u>incorrect</u>

Since gas density decreases slower than $\sim r^{-2}$, most of the wave dissipation occurs near the origin.

weak shock waves are not the dominant process that prevents cooling

(Mathews et al. 2005)

heating cluster gas with shock (or other) waves
depends on the density profile

if the density is constant, a point explosion results
in a temperature peak (Sedov solution)

if the density drops faster than r^{-2}, heating increases
with cluster radius

clusters density typically varies as r^{-1} - $r^{-1.5}$
so shock heating is centrally-concentrated

Heating with X-ray cavities:

it has long been recognized that cluster gas
can be shock-heated by as young cavities expand,
but this heating can be << PV if cavities form slowly

it is also thought that moving cavities can also heat
the cluster gas:

> "… the bubbles … will expand as they rise, doing PdV
> work on their surroundings. The expansion, of course,
> converts internal energy to kinetic form [which]
> is quickly converted to heat."

(Begelman 2001; Ruszkowski & Begelman 2002)

this is incorrect.

a currently favored mechanism is to heat cluster gas
by dissipating the energy $H = PV^*\gamma/(\gamma-1)$
as gas flows around a buoyant cavity (Churazov et al. 2002)

as gas flows around cavity, potential energy is turned
into kinetic energy which is dissipated beneath
the cavity (McNamara &Nulsen 2007)

NOTE: This idea does not account for the energy required
to compress the gas to the higher pressure
under the cavity -- nor does it consider thermal jets!

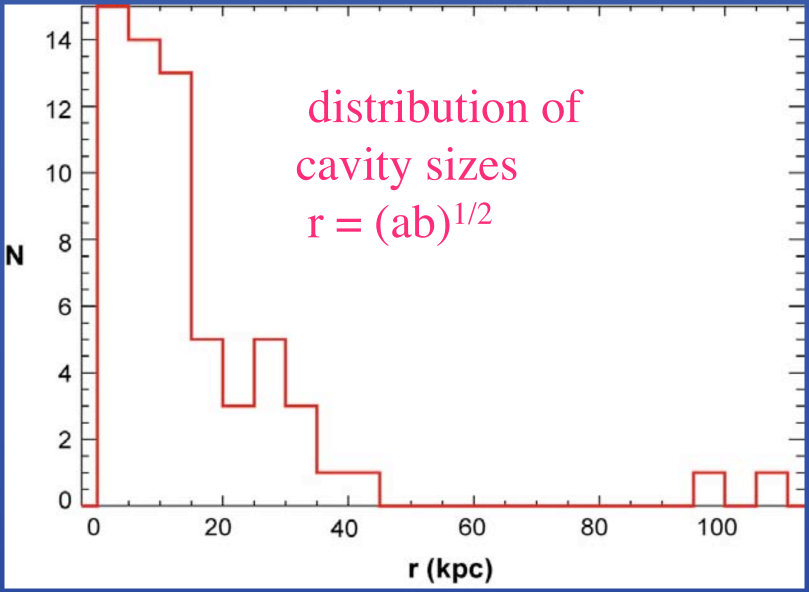
for a relativistic gas $\gamma = 4/3$ and $H = 4PV$
so the total heating rate in the wakes
of all buoyant cavities in a cluster is

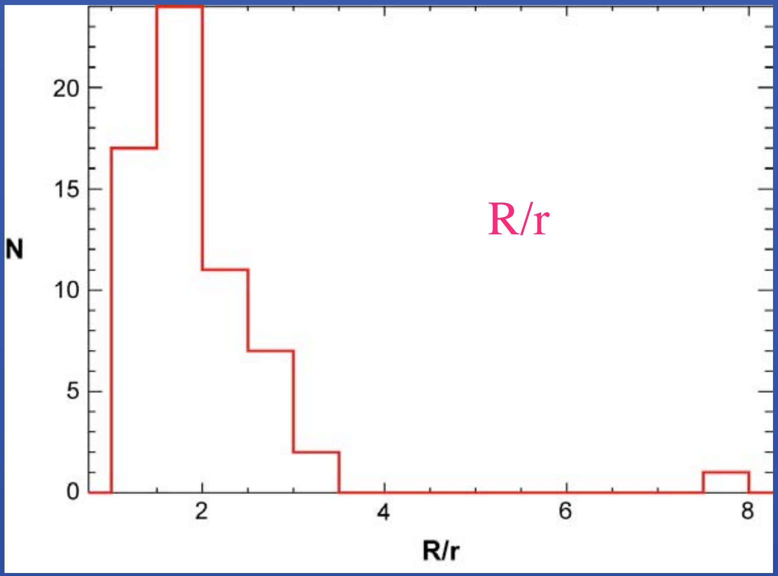
$$P_{cav} = \Sigma\, 4(PV)_i \,/\, t_{buoy}$$

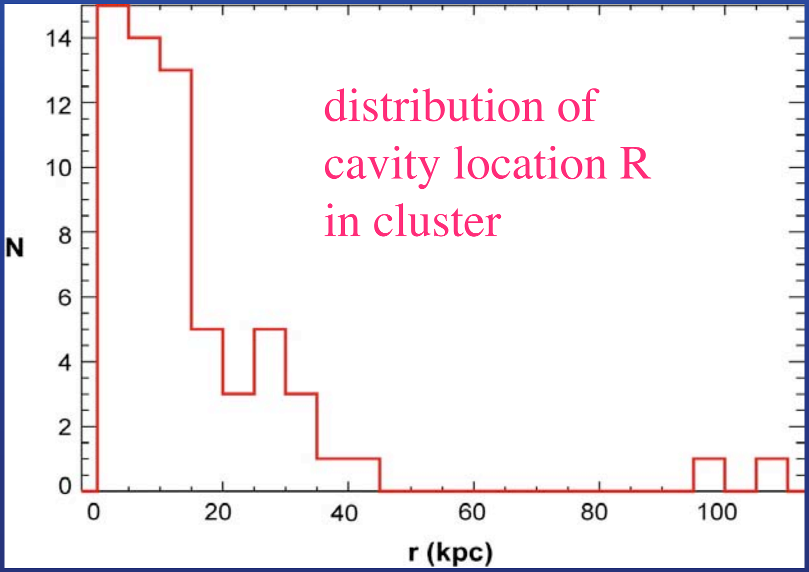
where the (subsonic) buoyant rise time is t_{buoy}
(Birzan et al. 2004, 2008)

Observations of cluster cavities

(McNamara & Nulsen 2007)

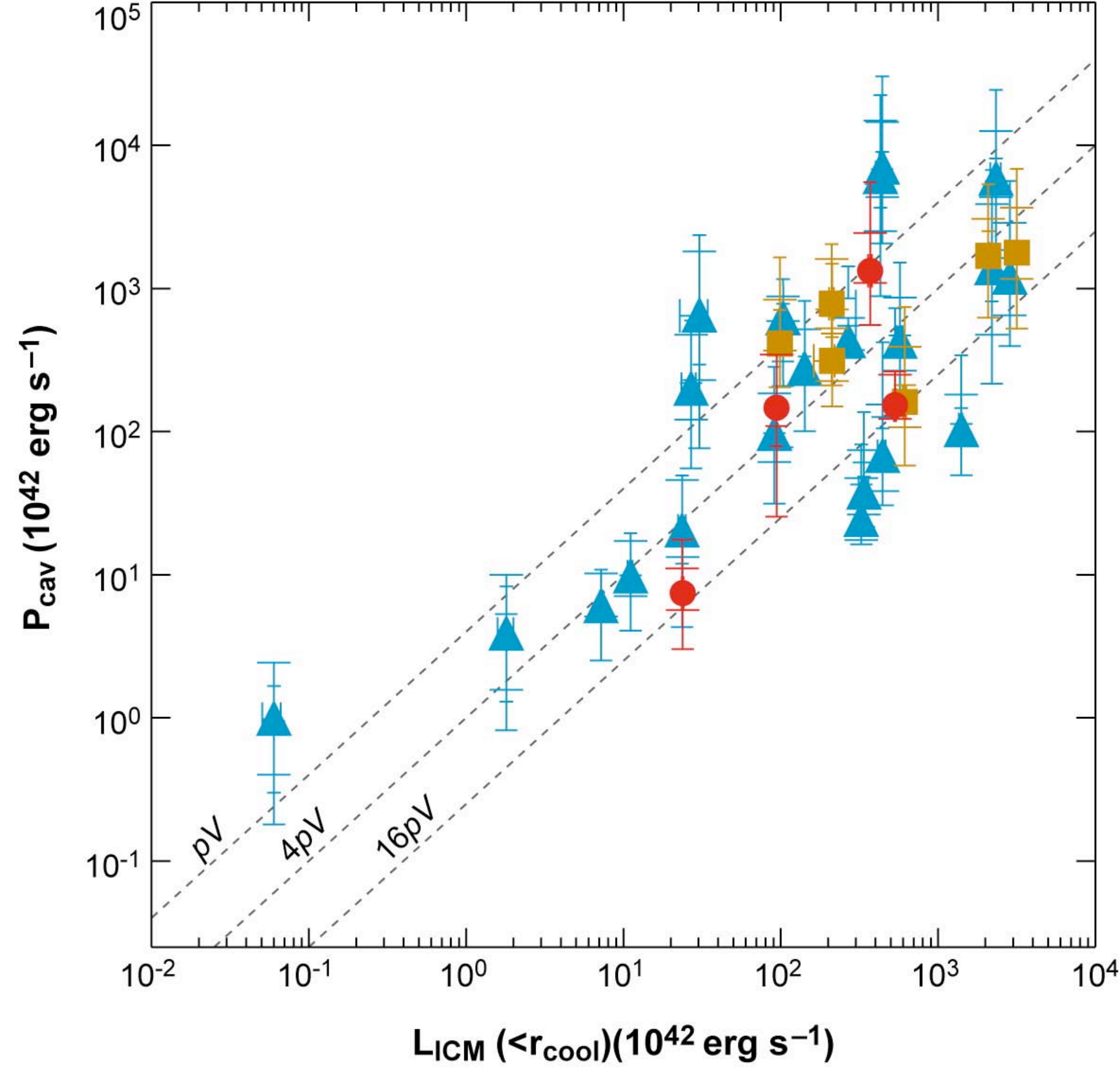

distribution of cavity sizes $r = (ab)^{1/2}$


R/r


distribution of cavity location R in cluster

many clusters need more than 4PV ergs per cavity!

$\Sigma 4(PV)_i / t_{buoy}$



X-ray luminosity within cluster radius that cools in 7 Gyrs

Blue and Red:
well-defined cavities

Yellow: poorly
defined cavities

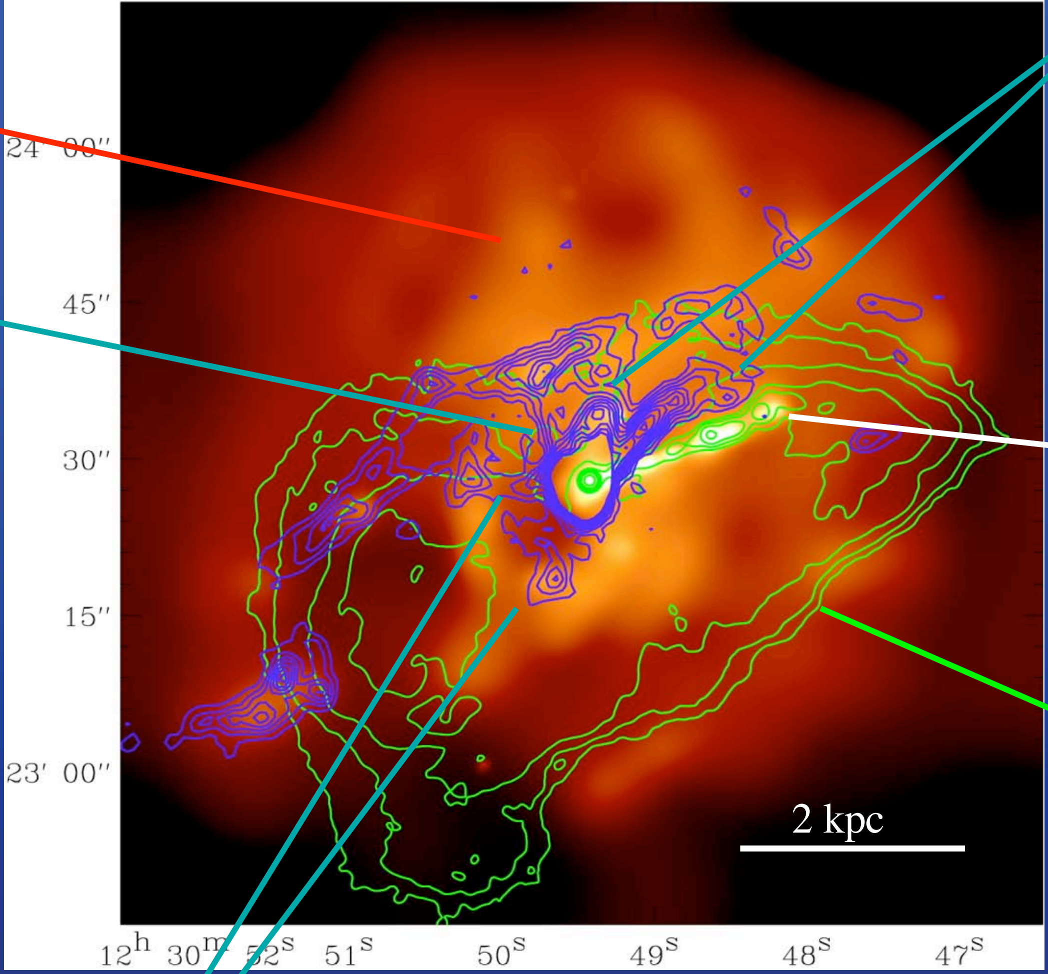
(McNamara
& Nulsen 2007)

instead of heating the cluster gas,
consider the buoyancy due to cosmic rays

can gas near cluster centers flow out before it cools?

for this calculation let’s consider the Virgo cluster …

Core of M87/Virgo has many jets and plumes



Chandra
X-ray image

warm plume
Hα + [NII]

warm plumes

non-thermal
2-kpc jet

90 cm radio
contours

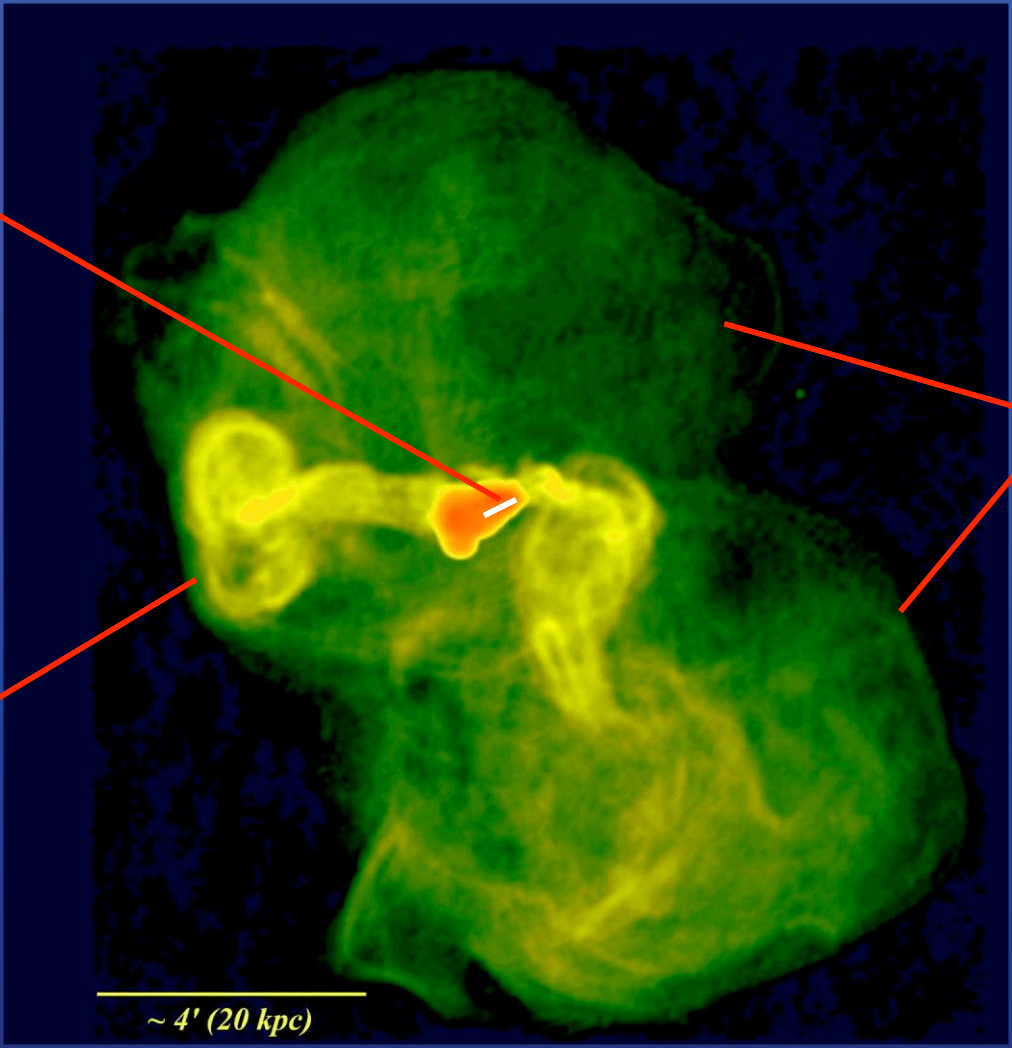
warm plumes

(Young, Wilson, Mundell 2002)

The warm plumes contain dust and some are blue-shifted

(Sparks, Ford, Kinney 1993)

On larger scales: A radio image of M87/Virgo at 90cm



2 kpc
M87 jet

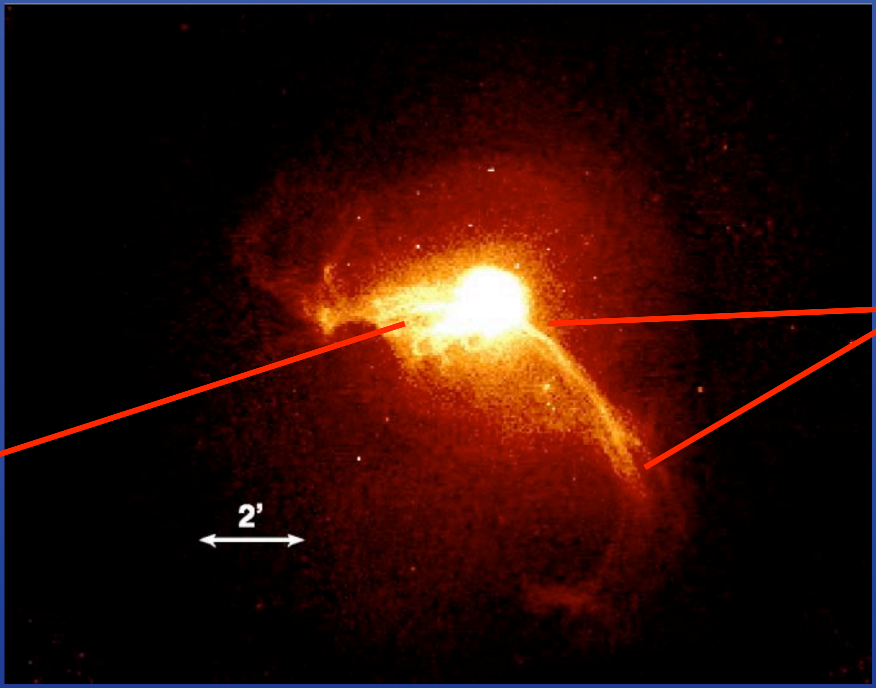
outer radio
lobes

synchrotron
age is ~10^8 yrs

buoyant
mushroom

(Owen, Eilek,Kassim 2000)

Extended features in soft Chandra X-ray image of M87/Virgo (0.5 - 1 keV)

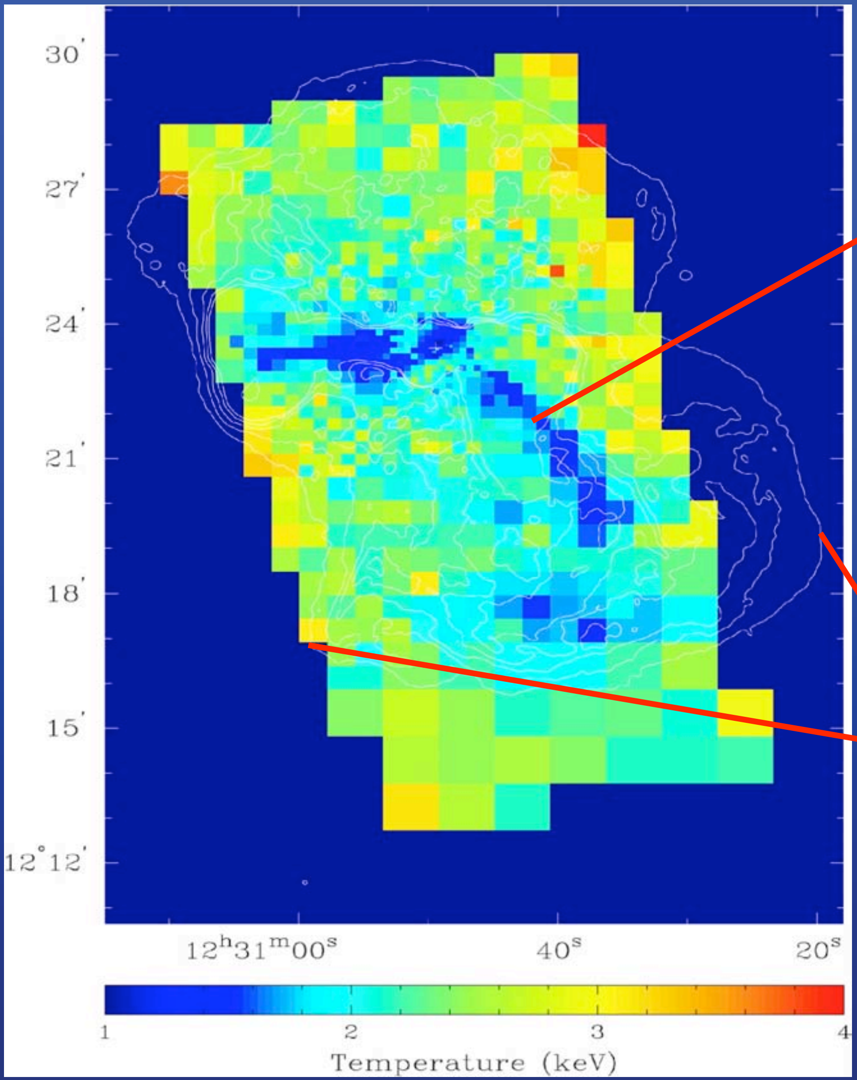


buoyant mushroom

~30 kpc long radial thermal filament along axis of old radio lobe

(Forman et al. 2006)

Radial X-ray filament and 90cm radio-sync emission in M87/Virgo



(Young, Wilson, Mundell 2002)

colder X-ray filament*

outer radio lobe*

*both can be made in 10^8 yrs with CR+hydro

Energy is ejected in many directions -- which is the BH spin axis?

Gas Dynamics Equations
with Diffusing-Advecting Cosmic Rays

cosmic rays
push on the gas via
weak magnetic fields

cosmic rays can
create cavities,
then diffuse through
cavity walls to
become radio lobes

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0$$

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} \right) = -\nabla(P + P_c) - \rho \mathbf{g}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \mathbf{u} e = -P(\nabla \cdot \mathbf{u}) - (\rho/m_p)^2 \Lambda(T,z)$$

$$\frac{\partial e_c}{\partial t} + \nabla \cdot \mathbf{u} e_c = -P_c(\nabla \cdot \mathbf{u}) + \nabla \cdot (\kappa \nabla e_c) + \dot{S}_c$$

$$P = (\gamma - 1)e \quad \text{and} \quad P_c = (\gamma_c - 1)e_c$$

$$\kappa = \begin{cases} 10^{30}\ \mathrm{cm}^2\mathrm{s}^{-1} & : \quad n_e \le n_{e0}\ \mathrm{cm}^{-3} \\ 10^{30}(n_{e0}/n_e)\ \mathrm{cm}^2\mathrm{s}^{-1} & : \quad n_e > n_{e0}\ \mathrm{cm}^{-3} \end{cases}$$

$$n_{e0} = 6 \times 10^{-3} \quad \text{and} \quad 6 \times 10^{-6}\mathrm{cm}^{-3}$$

the relativistic cosmic ray energy density e_c can be protons, e^+ or e^-

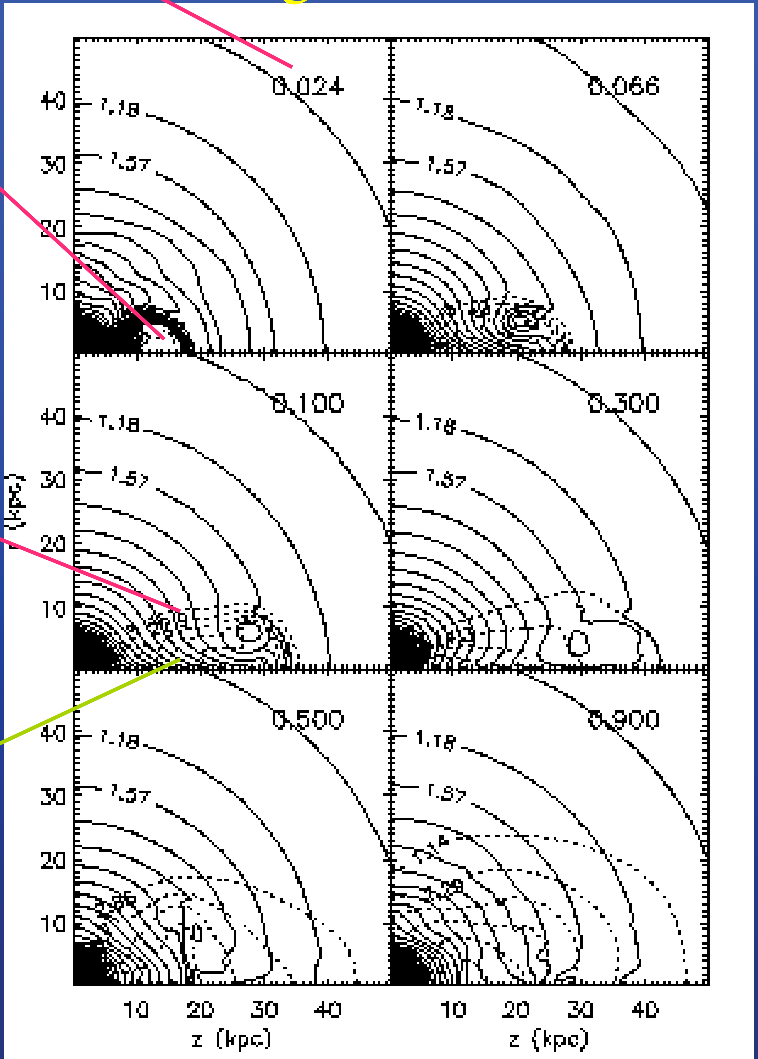
first study the energetics of cosmic ray-cavities

without radiative losses …

Co-evolution of X-ray Cavities and Radio Lobes

inject $E_{cr} = 10^{58}$ ergs in 2×10^{7} yrs at 10 kpc on z-axis

high diffusion



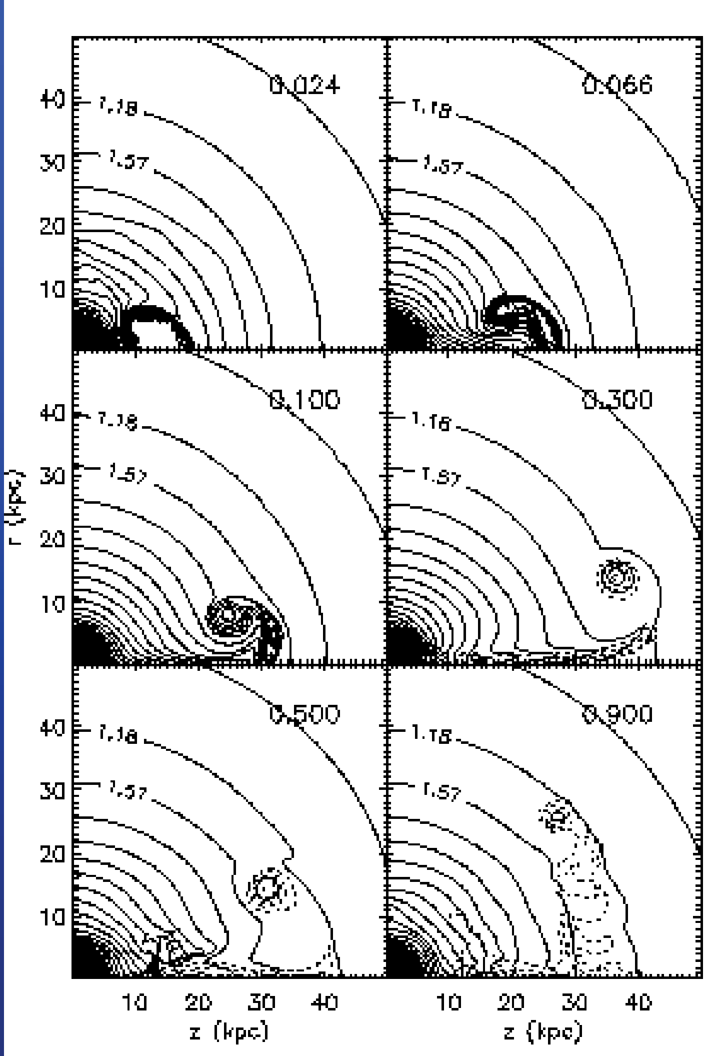
t_{Gyr}

X-ray cavity

$e_c(R,z)$ radio lobe

X-ray filament $\rho(R,z)$

low diffusion



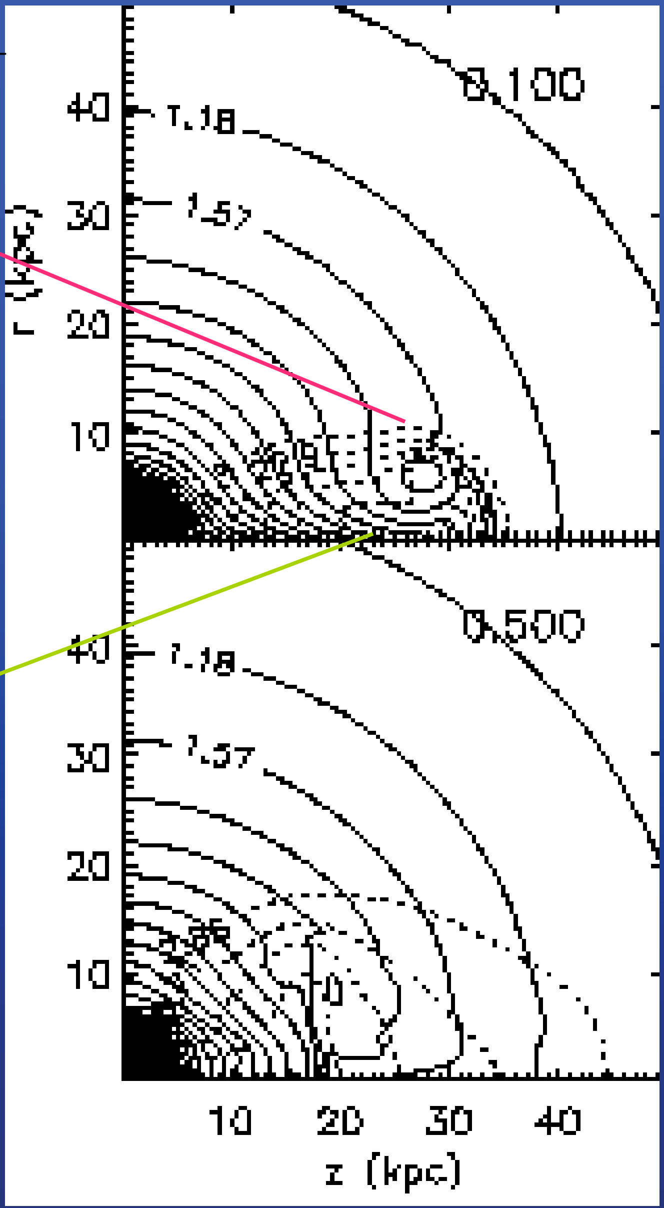
(Mathews & Brighenti 2008)

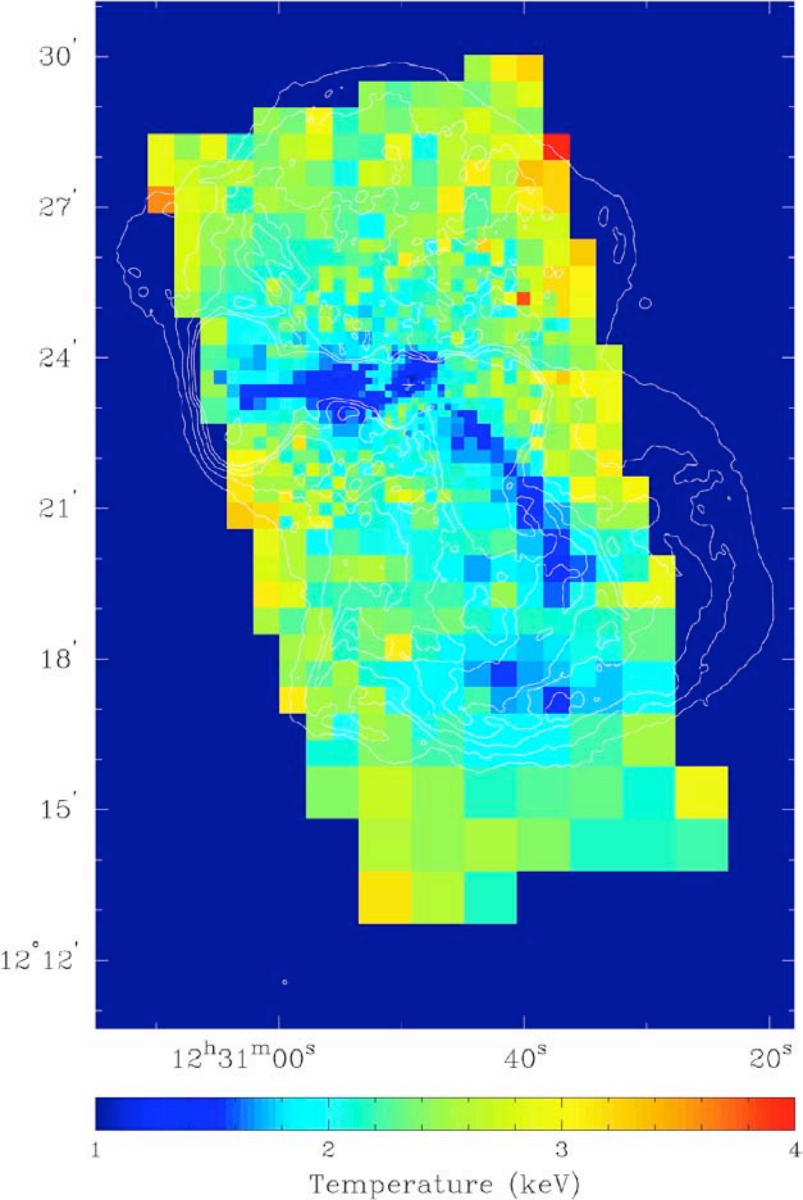
Closeup of post-cavity flow at 1 and 5x10^8 yrs

$e_c(R,z)$ radio lobe

X-ray filament

$\rho(R,z)$

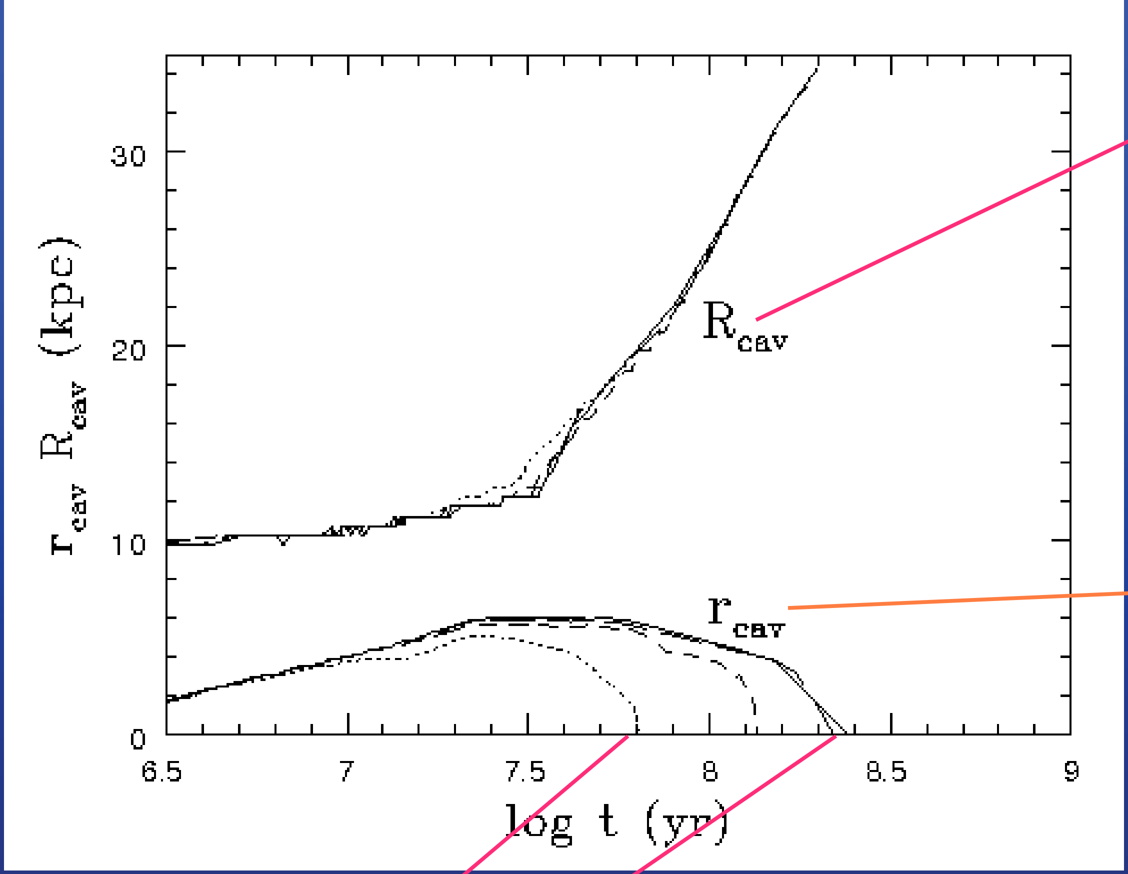




high diffusion (Mathews & Brighenti 2008)

Explanation of thermal jet-filaments:

cosmic ray cavities are long-lived



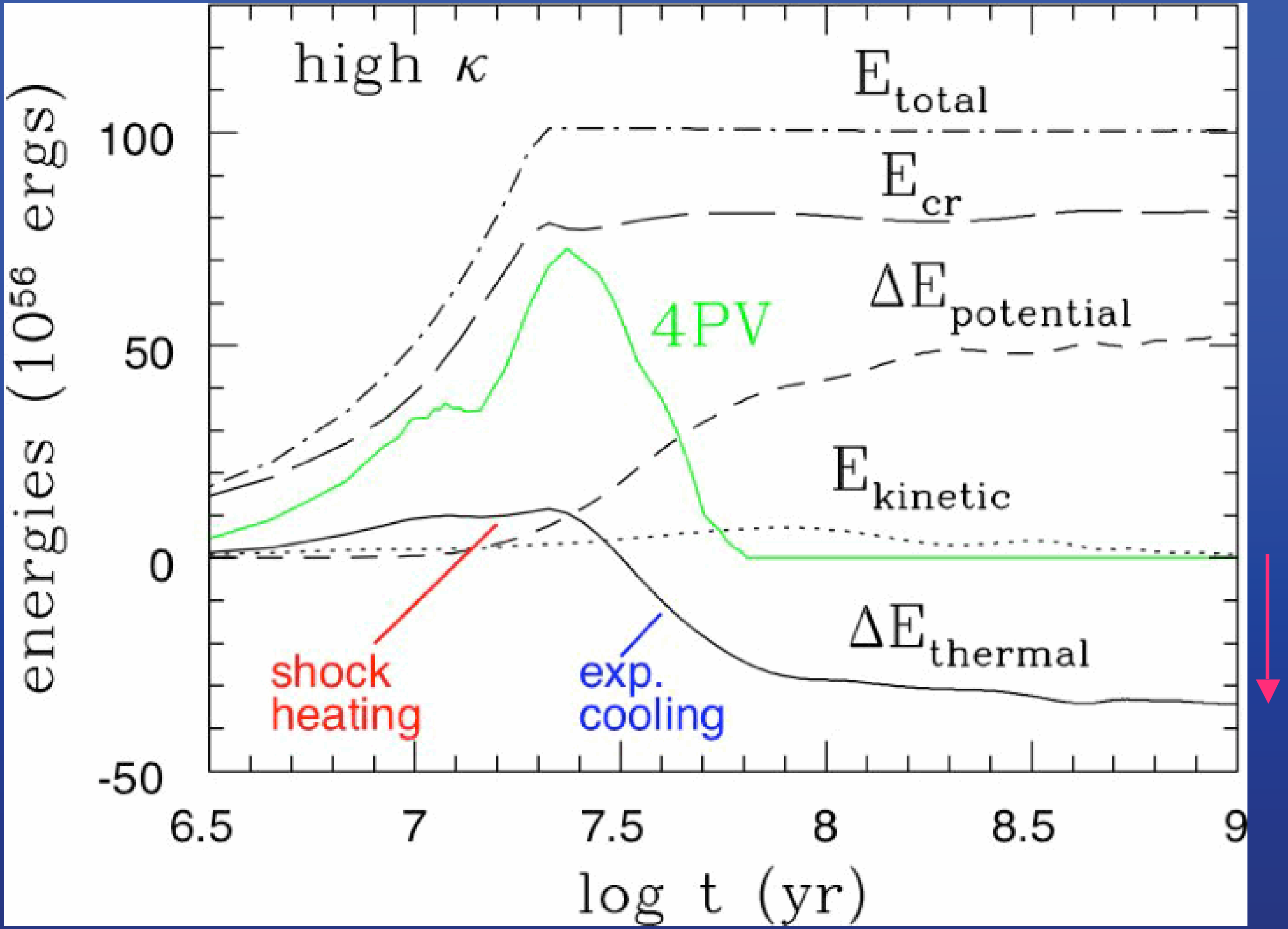
cavity position in cluster

cavity radius
(assumed spherical)

high & low diffusion

(Mathews & Brighenti 2008)

cluster gas is cooled, not heated, by X-ray cavities!

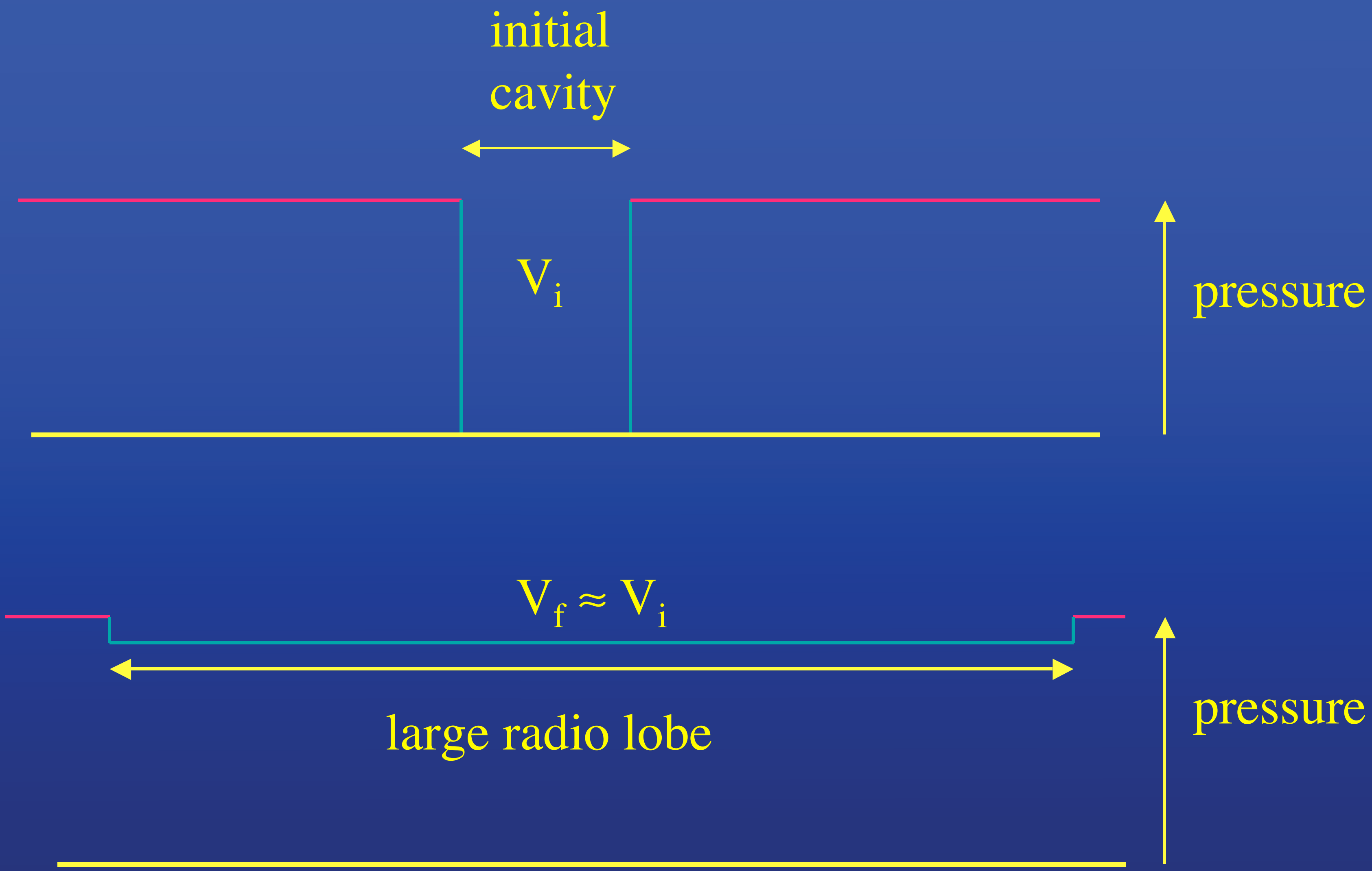


Cooling!

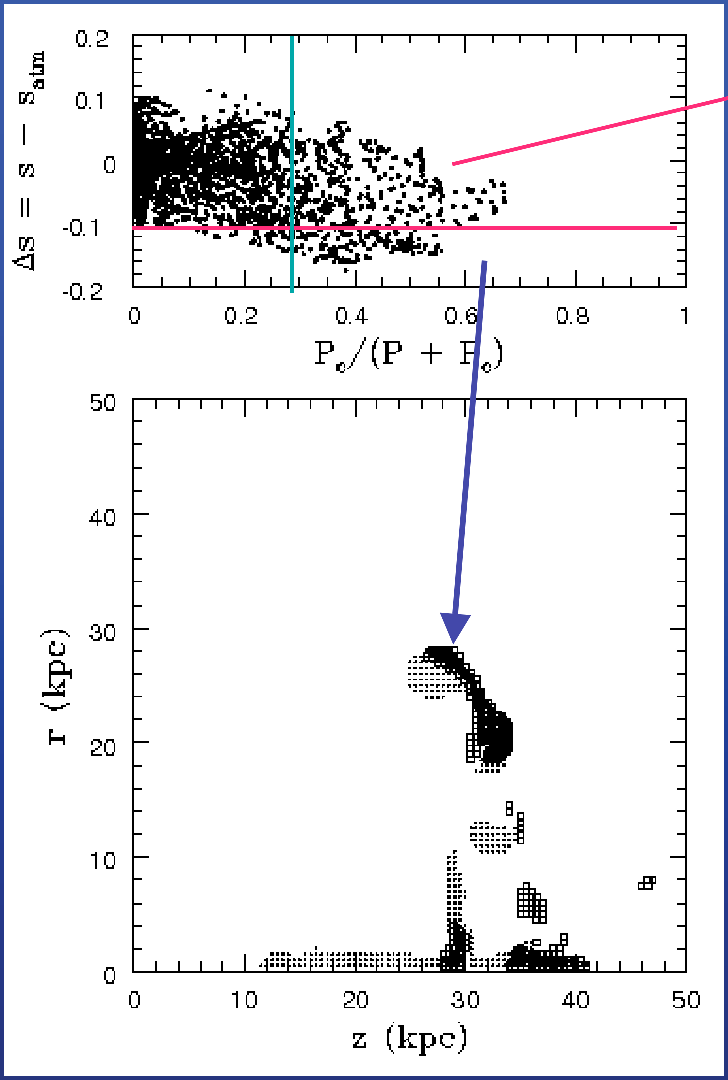
(Mathews & Brighenti 2008)

E_{kin} from cavity is small -- even when all E_{kin} is dissipated,
it is unable to heat the cluster gas --- 4PV varies with time

volume displaced to form cavity is approximately conserved after cosmic rays diffuse through cavity walls



after 0.9 Gyrs low-entropy gas has moved far out in cluster



each computational zone is plotted

low diffusion

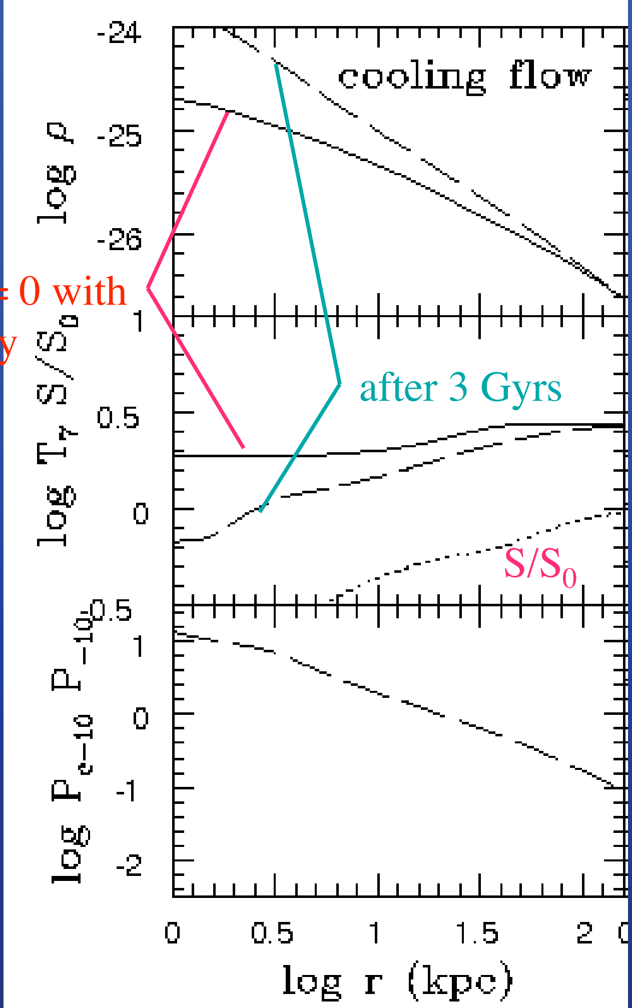
(Mathews & Brighenti 2008)

now add radiative losses

and explore the possibility that many successive cavites
can remove gas from the cluster core before it cools

Stopping Virgo Cooling Flow with Cosmic Rays

first set up a normal cooling flow without cosmic rays:



start at t = 0 with observed density & temperature

after 3 Gyrs

S/S_0

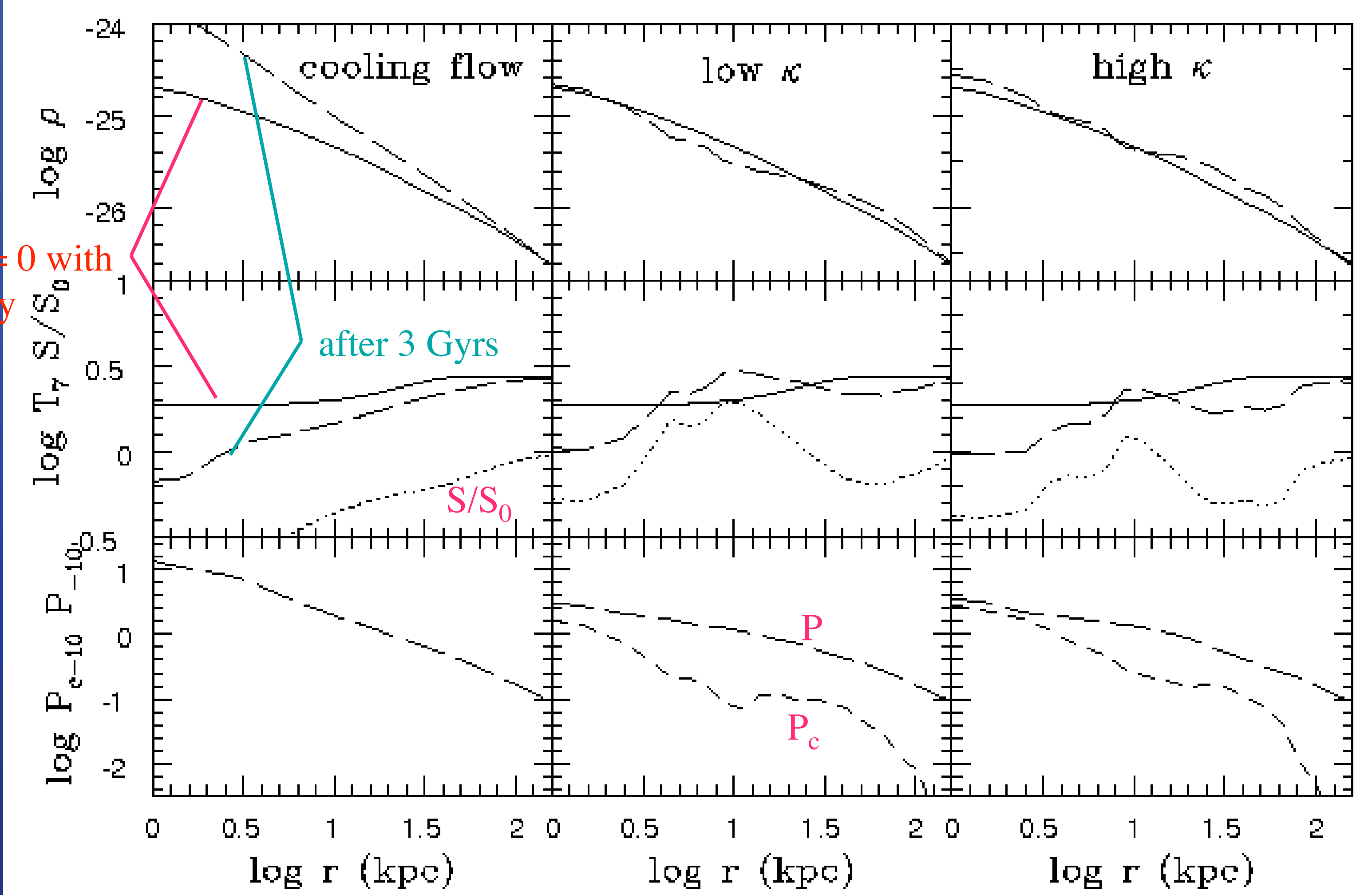
after 3 Gyrs: $\dot{M}$ = 85 M_{sun}/yr

(Mathews 2009)

Stopping Virgo Cooling Flow with Cosmic Rays

cavities every 200 Myrs at 10 kpc with $E_{cr} = 8\text{x}10^{58}$ ergs in 20 Myrs

L_{cr} = $3\text{x}10^{43}$ erg/s



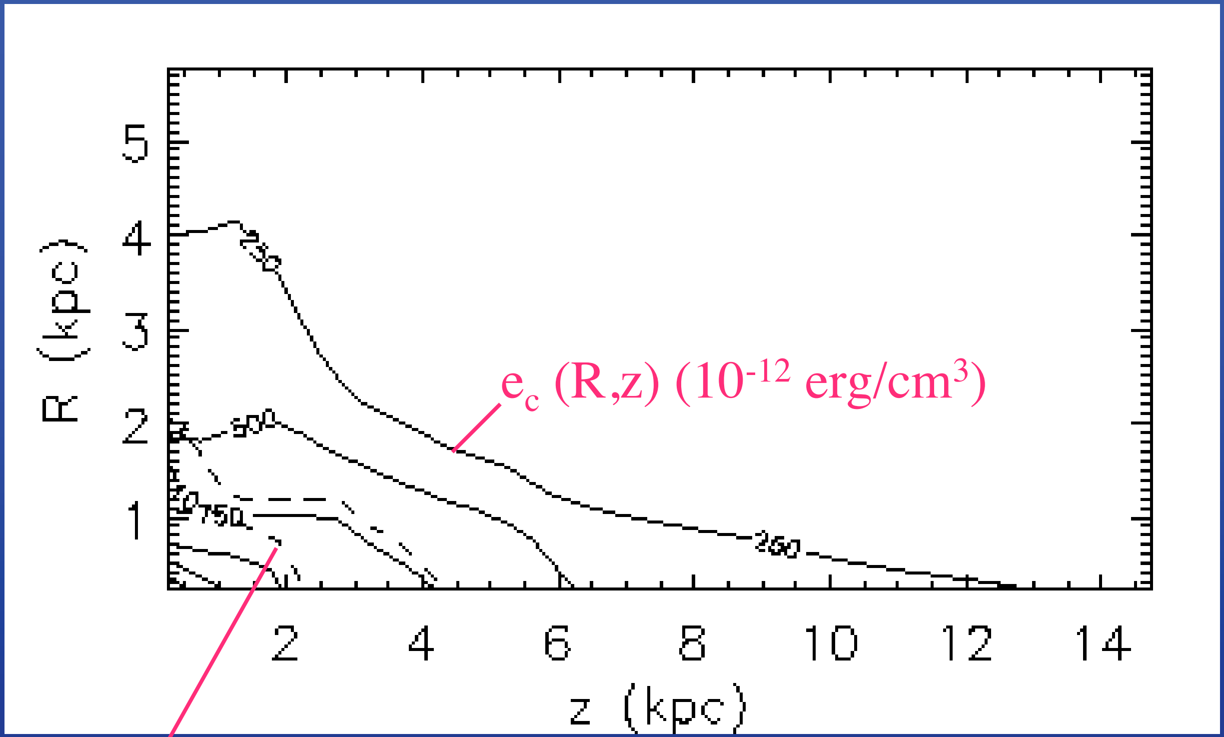
start at t = 0 with observed density & temperature

after 3 Gyrs

(Mathews 2009)

after 3 Gyrs: $\dot{M}$ = 85 0.1 1 M_{sun}/yr

distribution of cosmic rays and cooled gas after 3 Gyrs



e_c (R,z) (10^{-12} erg/cm^3)

cooled gas (10^8 M_{sun})

(Mathews 2009)

need cosmic rays to excite H_2 in cooled filament gas

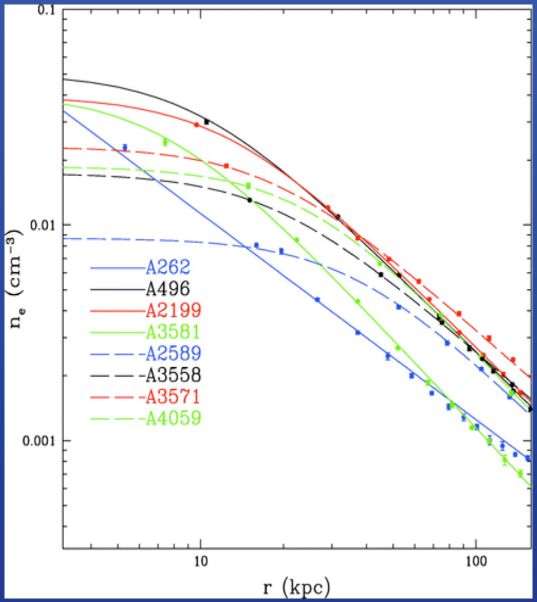
(Ferland etal 2008)

cosmic rays can also carry SNIa iron out to ~100 kpc

can SNIa iron be buoyantly transported to 50-100 kpc with heated regions rather than cosmic rays?

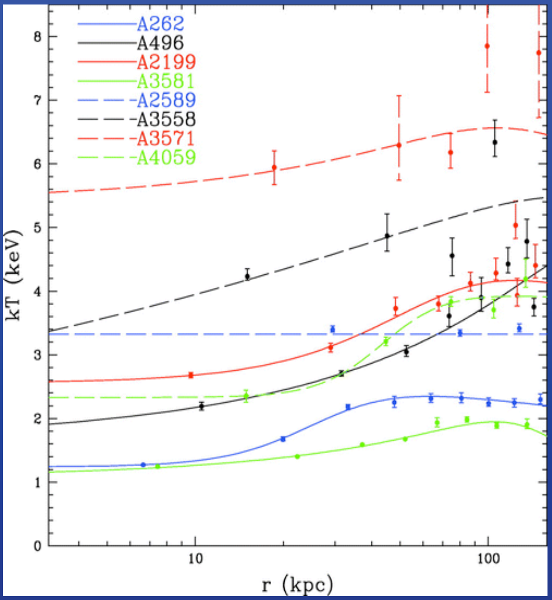
David & Nulsen: there is enough AGN energy to heat the gas and lift all the cluster iron out to ~100 kpc

cluster gas density



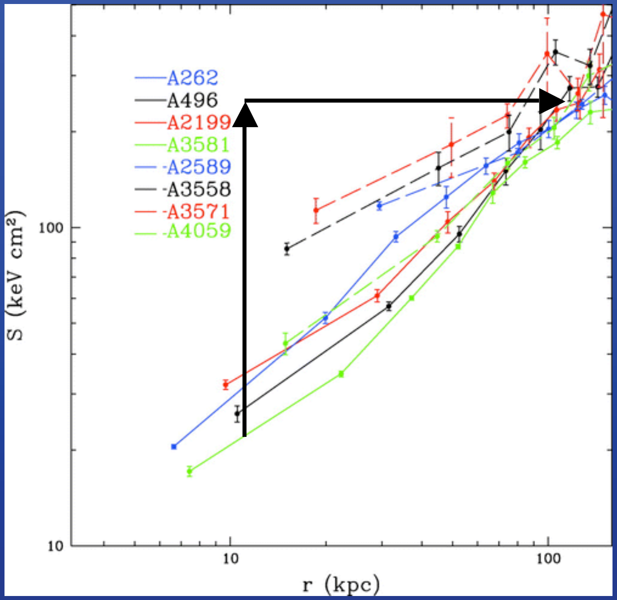
$n \sim r^{-1}$

temperature



T is nearly constant!

entropy ~ $T/\rho^{2/3}$



(David & Nulsen 2008)

entropy of gas at 10 kpc must increase by ~12
heated gas must not mix as it moves out!

suppose cluster gas is heated in cavities at 10 kpc and buoyantly flows out to 100 kpc

the gas T doesn't change much, so $S \sim Tn^{-2/3} \sim n^{-2/3}$
entropy S increases by about 12 from 10 to 100 kpc
and the density drops by $n \sim S^{-3/2} = 12^{-3/2} = 0.024$
typical density at r = 10 kpc is $n_{10} = 0.02$ cm^{-3} or $\rho_{10} = 1.14 * m_p * n_{10}$

suppose all cavities formed at r = 10 kpc have radii a = r
the mass of hot gas in each heated cavity is
$M_{cav} = (4/3)*pi*(0.024*\rho_{10})*a^3 = 5 \times 10^7 \ M_{sun}$
if clusters are 7 Gyrs old and produce cavities every 10^8 yrs, 70 cavities are made so
$M_{cav,tot} = 70 \ M_{cav} = 3.5 \times 10^9 \ M_{sun}$
since iron is fairly evenly distributed out to ~ 100 kpc,
the total mass of gas that needs to move out is comparable to total mass within 100 kpc!

typical cluster density varies as $\rho = \rho_{10} \ (r/10kpc)^{-1}$
so the total gas mass within 100 kpc is
$M_{gas,tot} = \int rho \ 4*pi*r^2*dr = 3 \times 10^{13} \ M_{sun}$

but only ~ 10^{-4} of this mass can be transported to 100 kpc by heated cavities!

regardless of the AGN energy,
heated cavities are too small and infrequent to transport iron

Conclusions:

- failure of preferred cluster heating mechanisms
  - jets
  - thermal conduction
  - heating by ~PV as cavities form or move out
  - shocks (produced by expanding cavities)

- cosmic ray buoyancy
  - a promising new way to preserve observed temperature and density in clusters
  - can be combined with additional sources of heating if necessary