'New' Physics

- The Cooling time ~τ~nkT/e ~8.5x10 ^{10}yrs$(n/10^{-3})^{-1}T_8^{1/2}$
- For bremmstrahlung but for line emission dominated plasmas it scales as $^1T_8^{-1/2}$;
- That is as the gas gets cooler it cools faster

Λ=cooling function

- $T_{cool}=5/2nkT/n^2\Lambda \sim t_{Hubble}T8\Lambda^{-1}_{-23}\ n_{-2}^{-1}$
- In central regions where the density (n) is large can cool in $t<10^9$ yrs
- 5/2 (the enthalpy) is used instead of 3/2 to take into the compression of as it cools (and remains in pressure equilibrium)

Cooling Cores

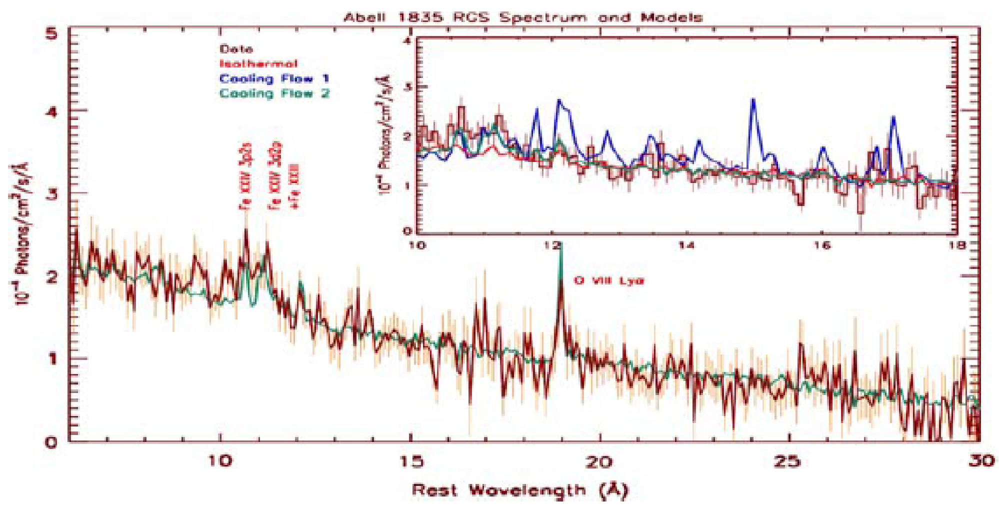
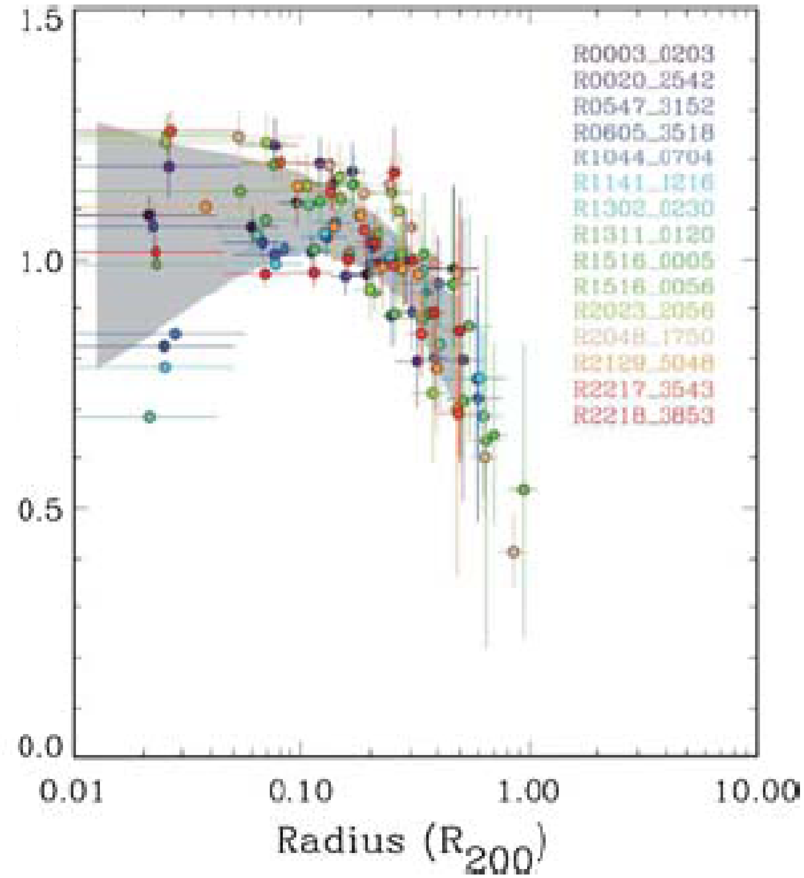
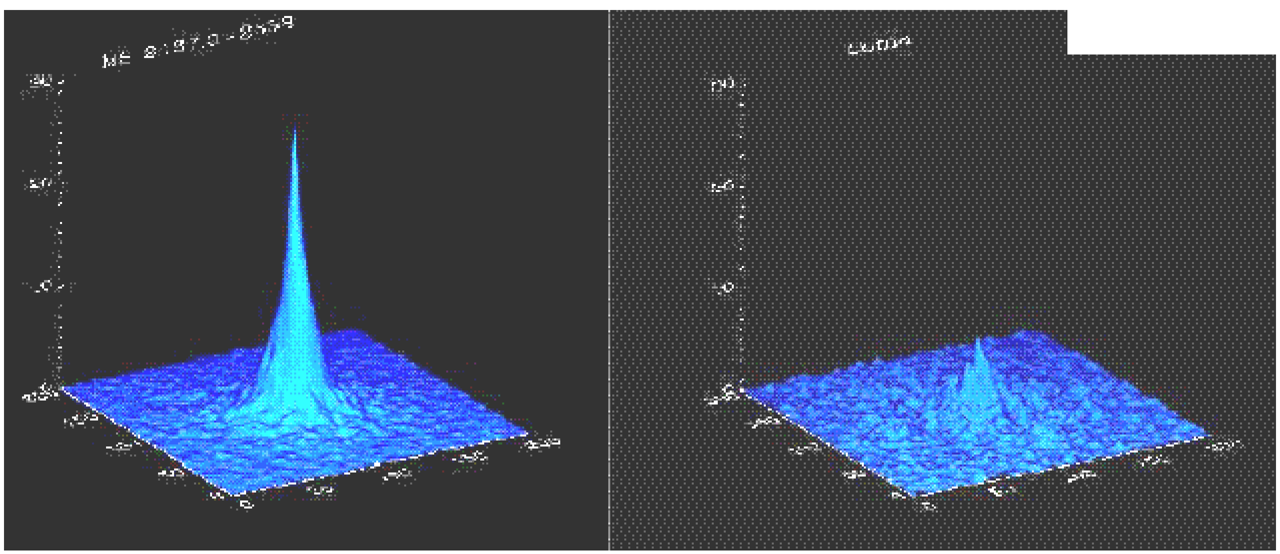


Fig. 22 *XMM-Newton* RGS spectrum of the central region of the prominent cool core cluster, A1835 com-

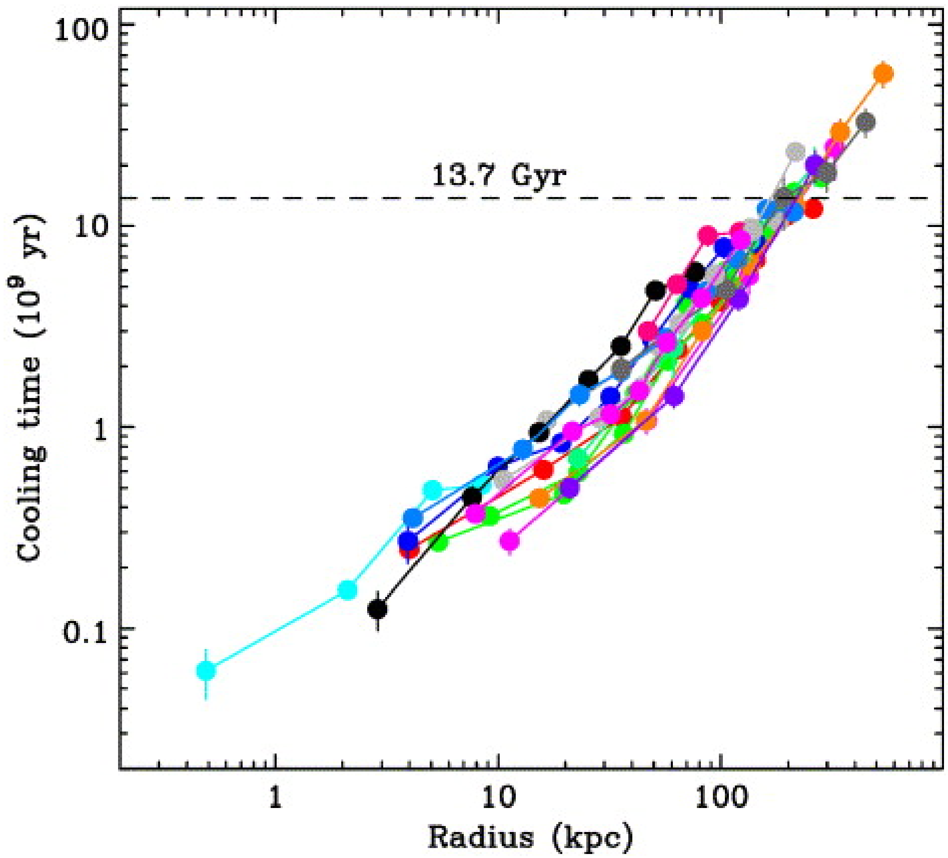
$$t_{cool} = 69\left(\frac{n_e}{10^{-3}\ \mathrm{cm}^{-3}}\right)^{-1}\left(\frac{T}{10^{8}\ \mathrm{K}}\right)^{1/2}\ \mathrm{Gyr}$$





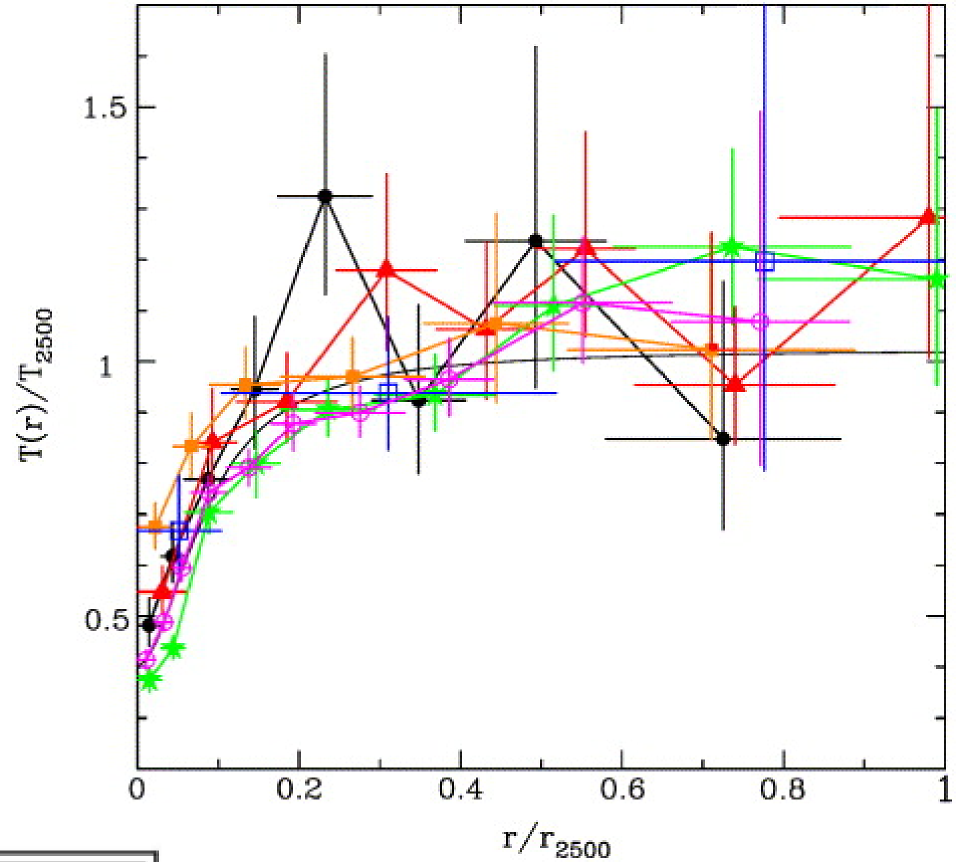
Notice that the central surface brightness of cool core clusters (left panel) is much higher than non-cooling core clusters

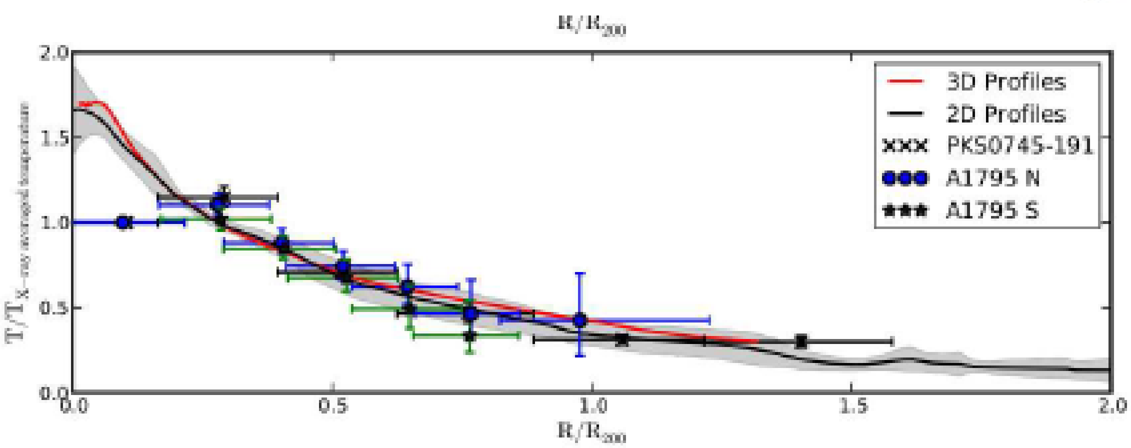
Cooling Time for a Sample of Clusters



Observed Temperature Profiles

- If the gas is in equilibrium with the potential (of the NFW form) it should be hotter in the center
- But in many clusters it is cooler

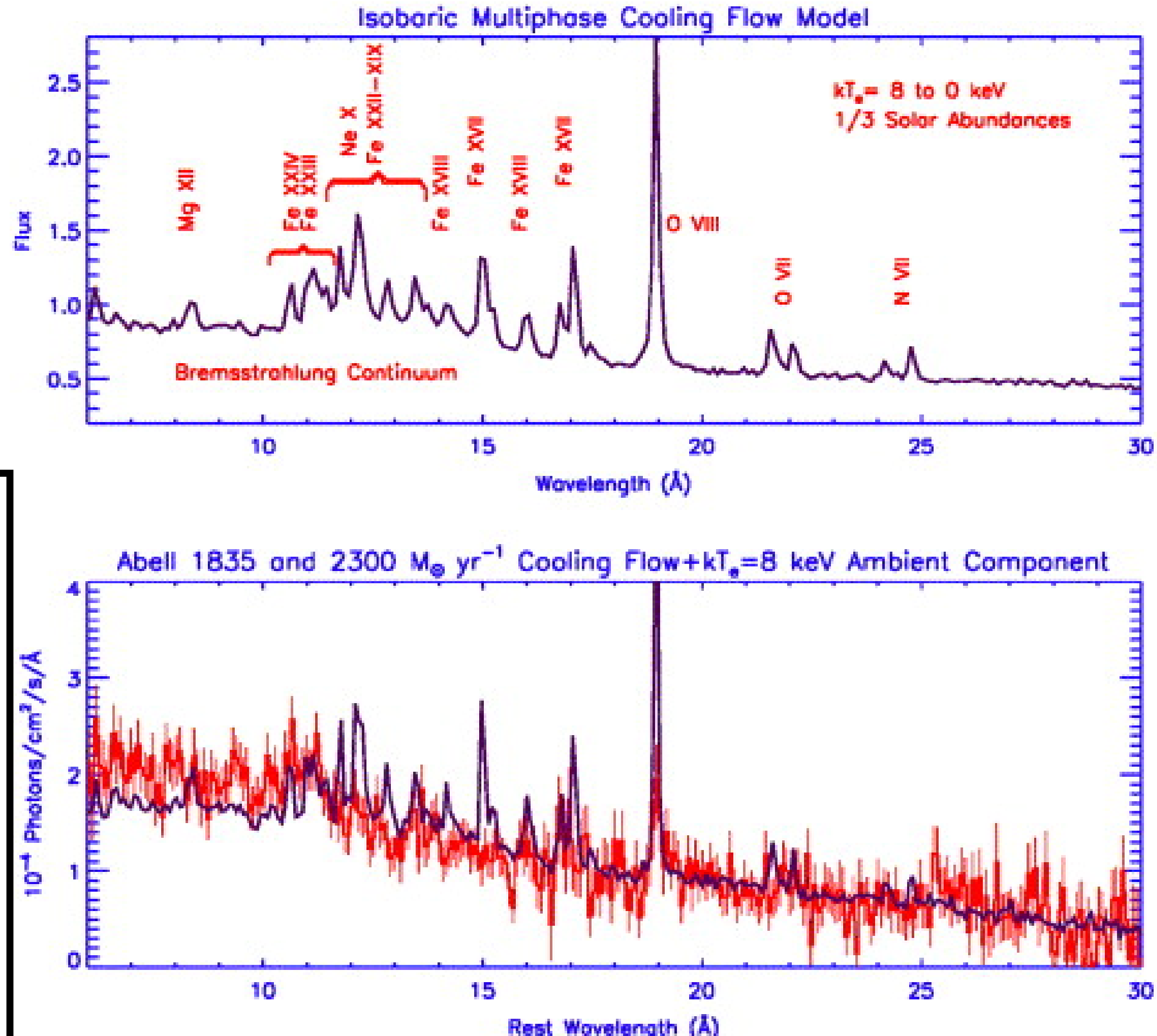




Left panel (from Burns et al 2010) shows the theoretical temperature profile if a NFW potential (in grey) compared to an set of actual cluster temperature profiles

Theoretical and Observed Spectrum of 'Cooling' Regions

- The theoretical models of cluster cooling predict strong lines from gas at $kT<10^7$k- these are not seen
- A major mystery



From Peterson and Fabian 2007- top panel shows the theoretical curve from a isobarically cooling cluster gas
The bottom panel shows the model (in blue) and real data in red. Notice the strong disagreemens near 15A (the location of a strong line from the L shell of Fe

How much Gas is at Each Temperature

- Theoretical cooling model predicts the flat line
- Data are in strong disagreement
- Something is wrong with the assumptions (gravity, cooling)
- Best idea is 'something else' is happening- input of energy from active galaxy in center

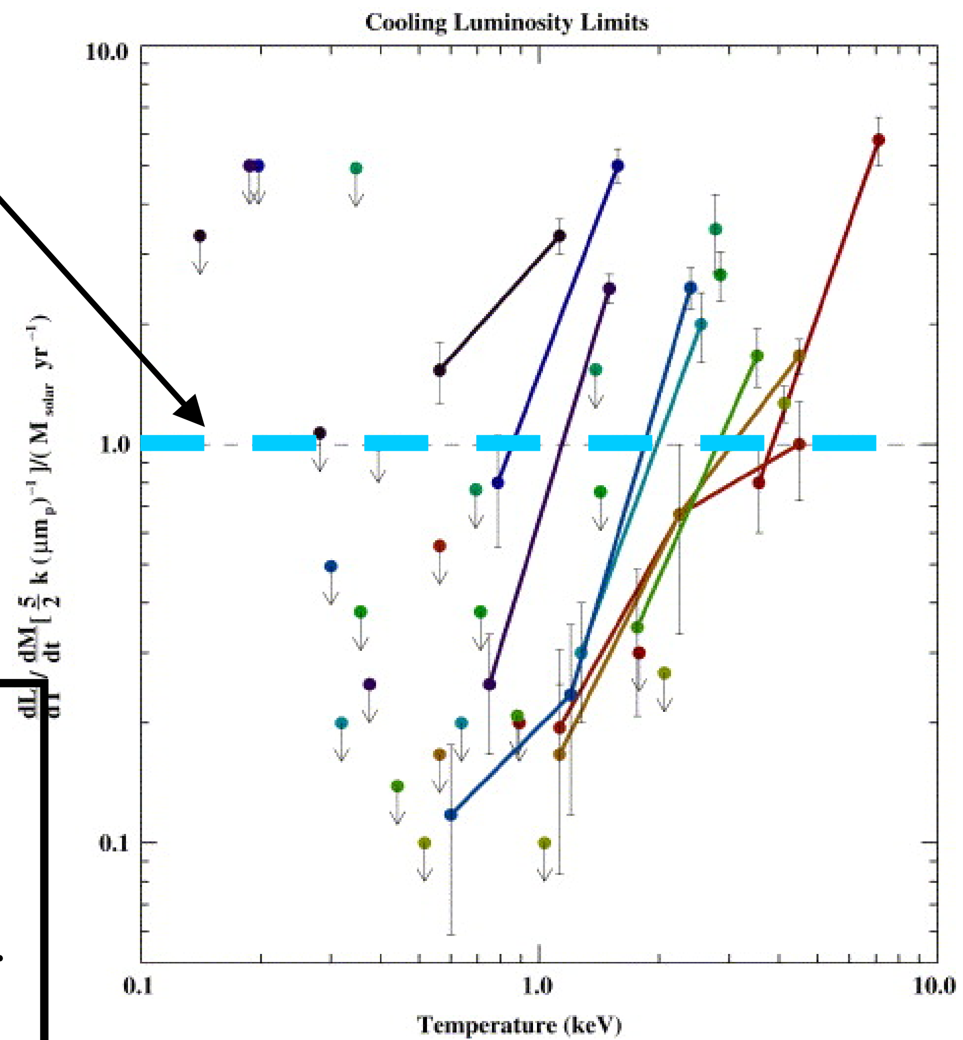
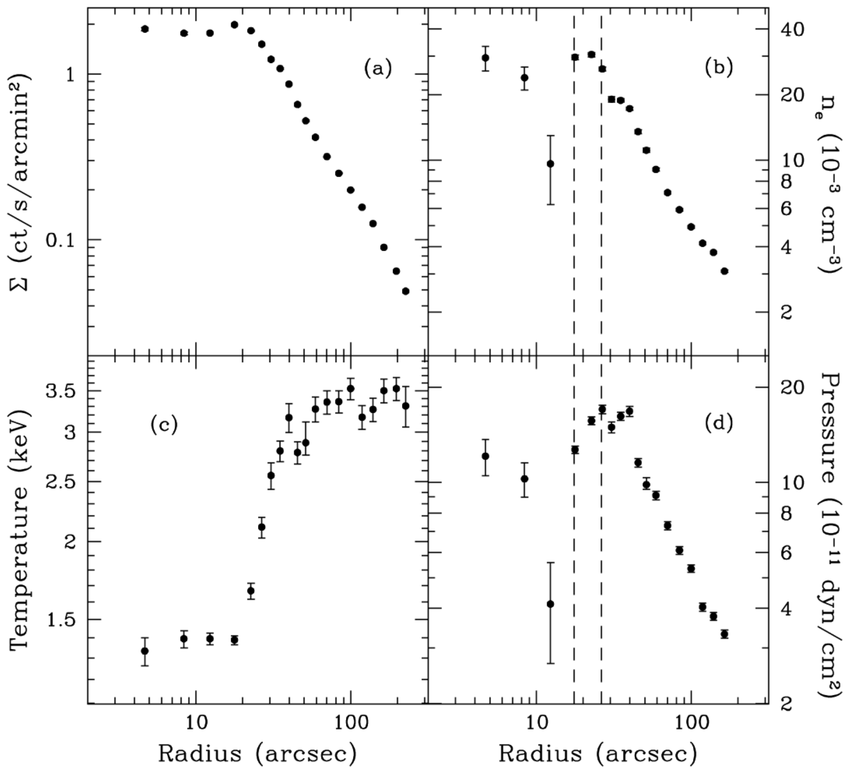


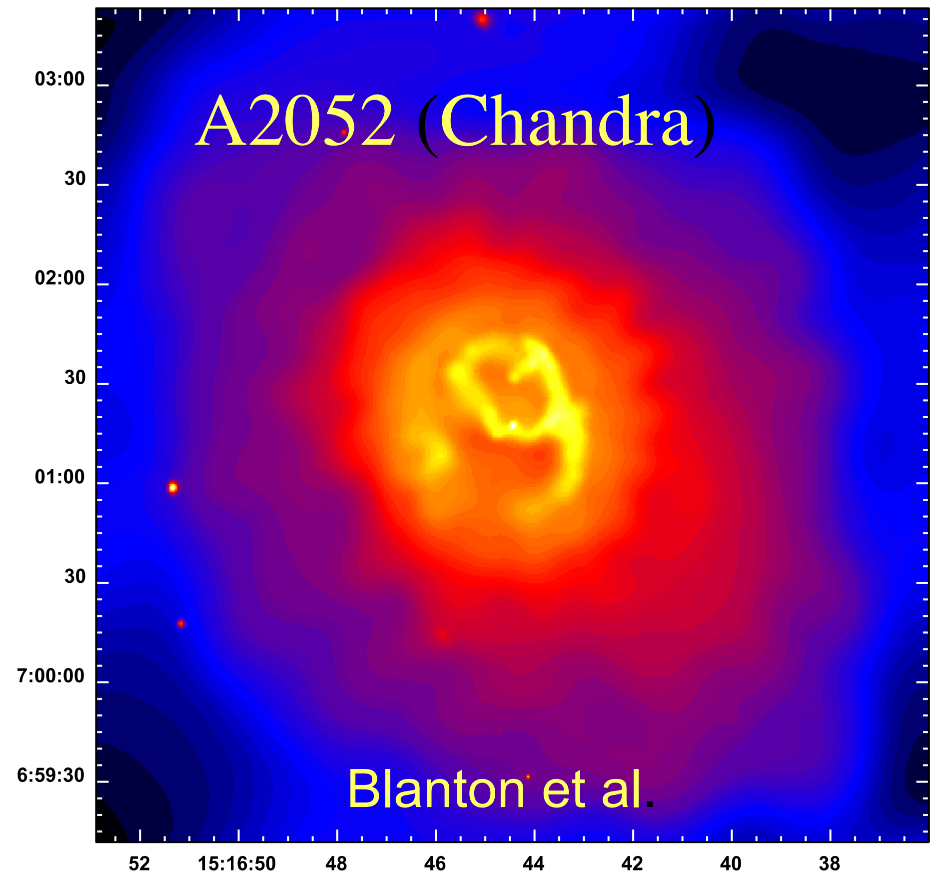
Figure from J. Sanders et al (2009) showing the amount of gas in the core region of a set of clusters as a function of temperature (each cluster is a different color)

Feedback

- There is evidence from cluster evolution, relation of temperature and luminosity, cutoff in galaxy star formation etc etc that additional physics beside gravity is needed to model structure formation- the is called 'feedback'

Effects of Feedback in Image and Temperature





AGN Feedback

- 'Color' Image of the Perseu Cluster

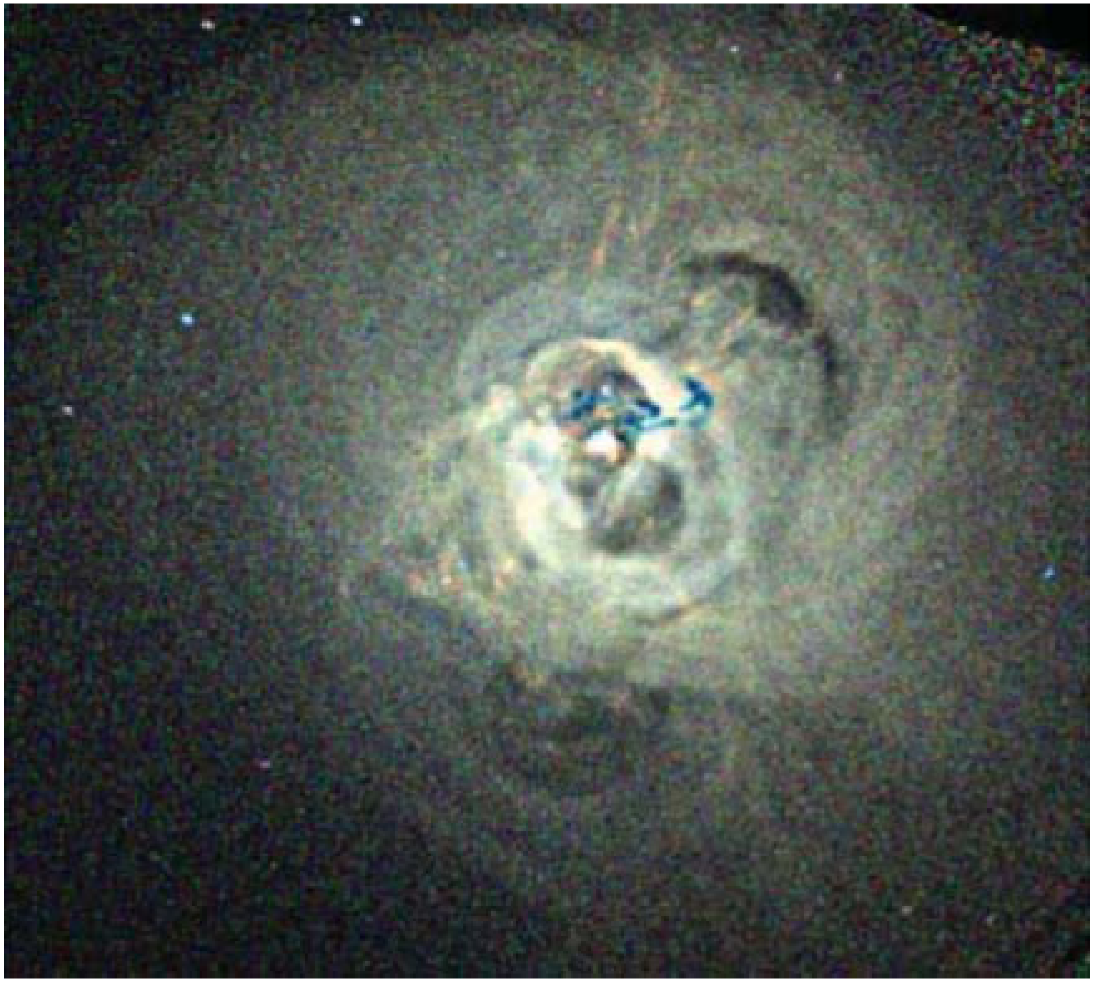
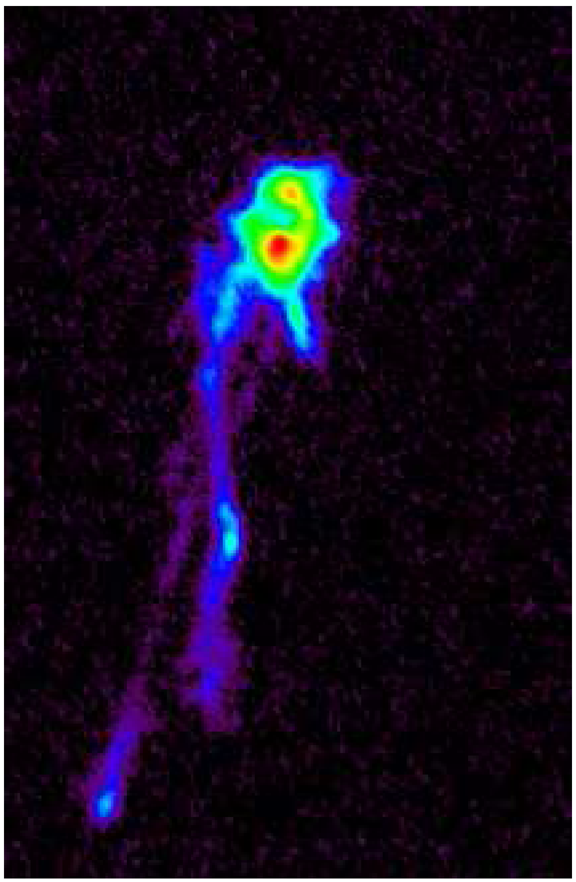


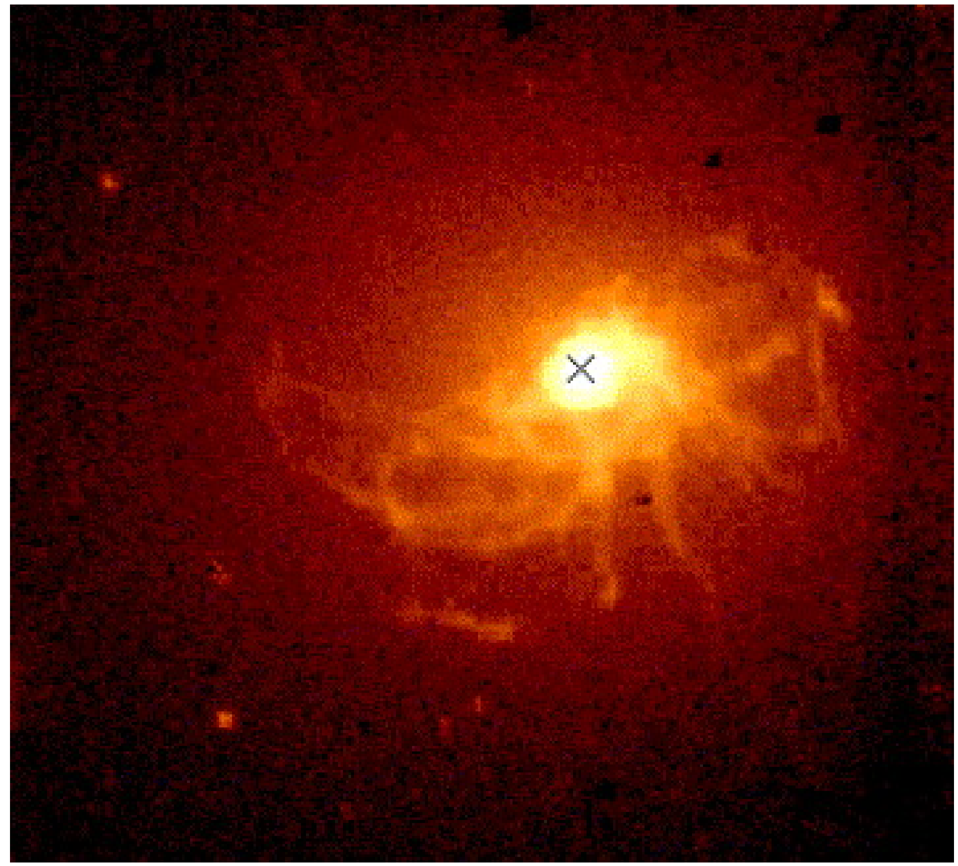
Fig. 25 False color image of the central region of the Perseus cluster produced from images in three energy bands 0.3–1.2, 1.2–2, and 2–7 keV. An image smoothed on a scale of 10 arcsec (with 80% normalization) has been subtracted from the image to highlight regions of strong density contrast. The image shows a series of nearly concentric "ripples" which are interpreted as sound waves or weak shock waves set off by the activity of the central AGN (Fabian et al. 2006)

Other Signs of Unexpected Activity

- Strong emission from Hα (gas at T~10^4 k) in centers of many cool core clusters

Sanders et al 20098

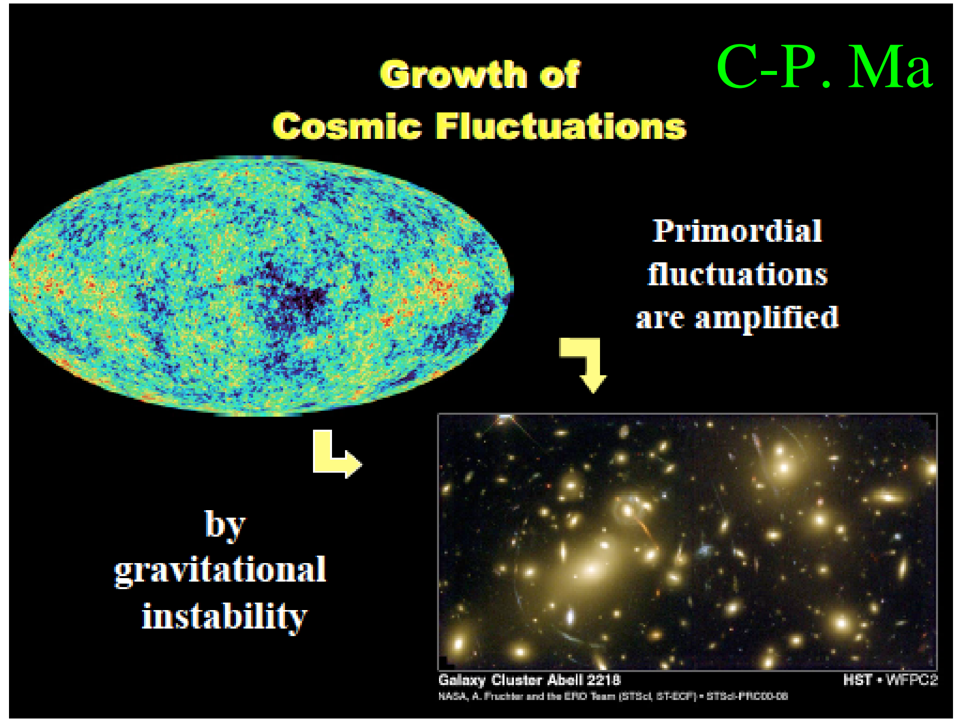


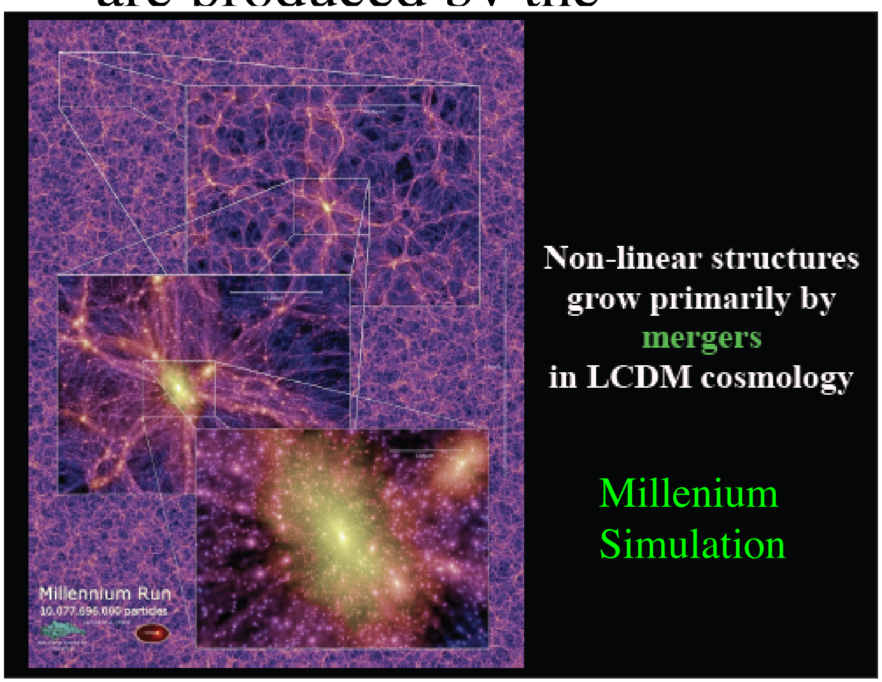


McDonald and Veilleux 2009

Formation

- Galaxy clusters form through gravitational collapse, driven by dark matter (~80% of their total mass)
- In the hierarchical scenario more massive objects form at later times: clusters of galaxies are produced by the





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How do Clusters Form- Mergers

- As time progresses more and more objects come together-merge

Now

10^{10} yrs ago

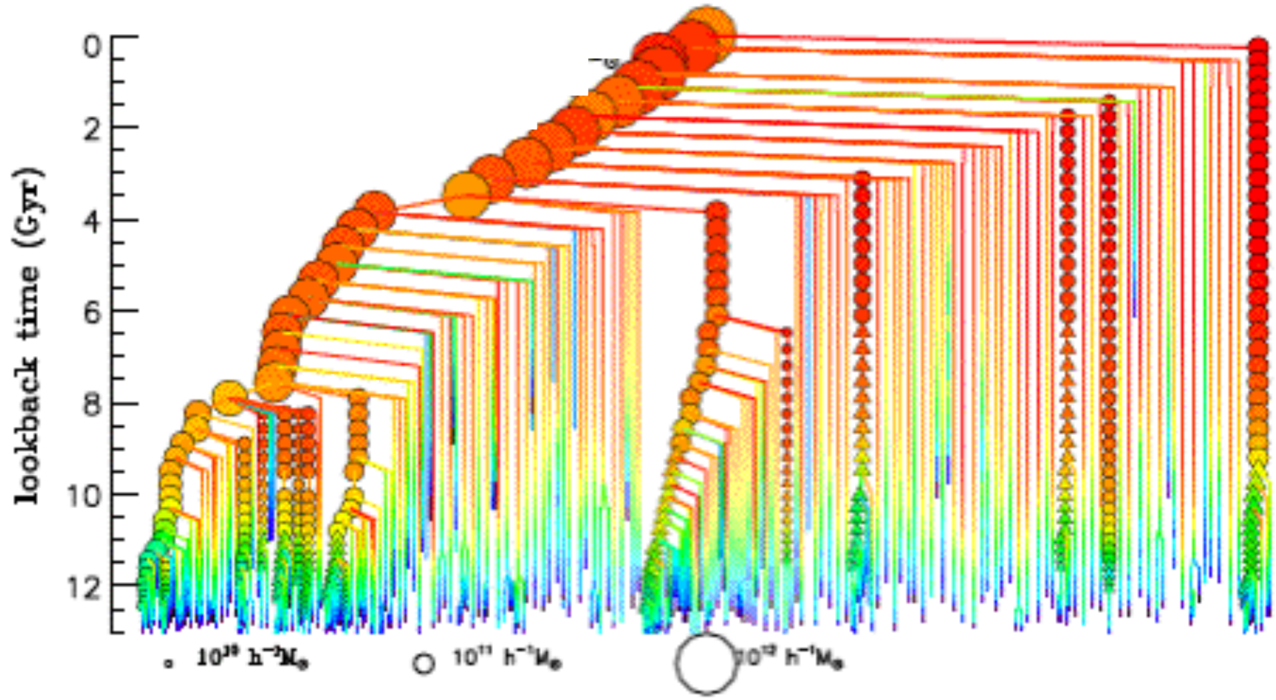
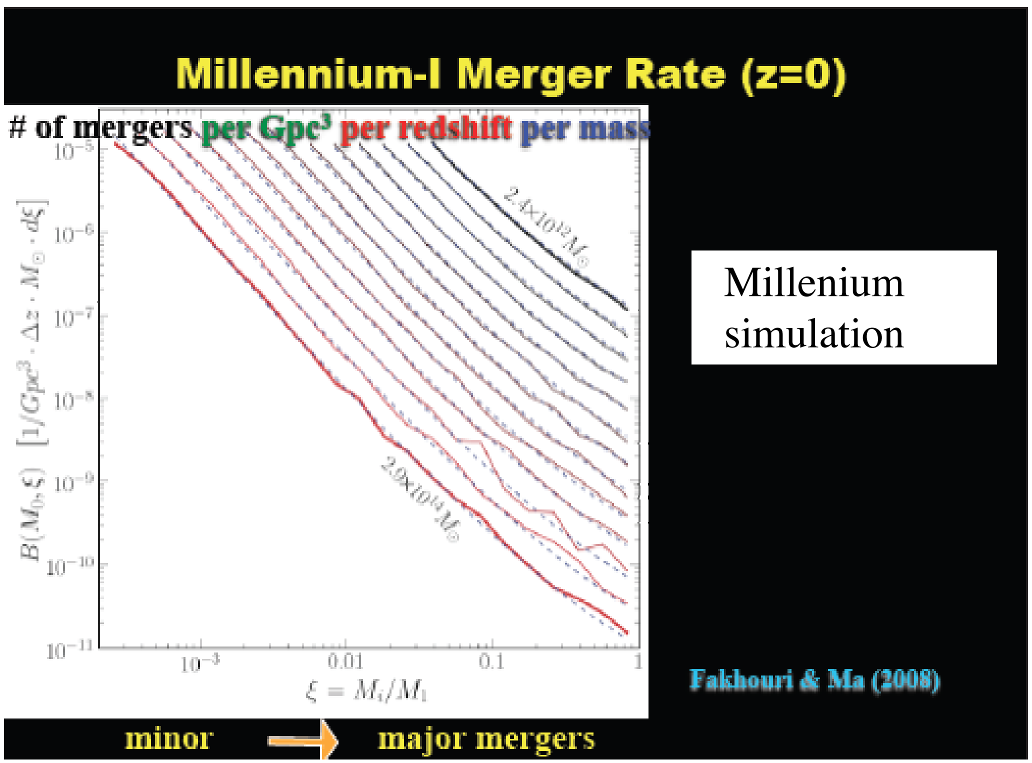
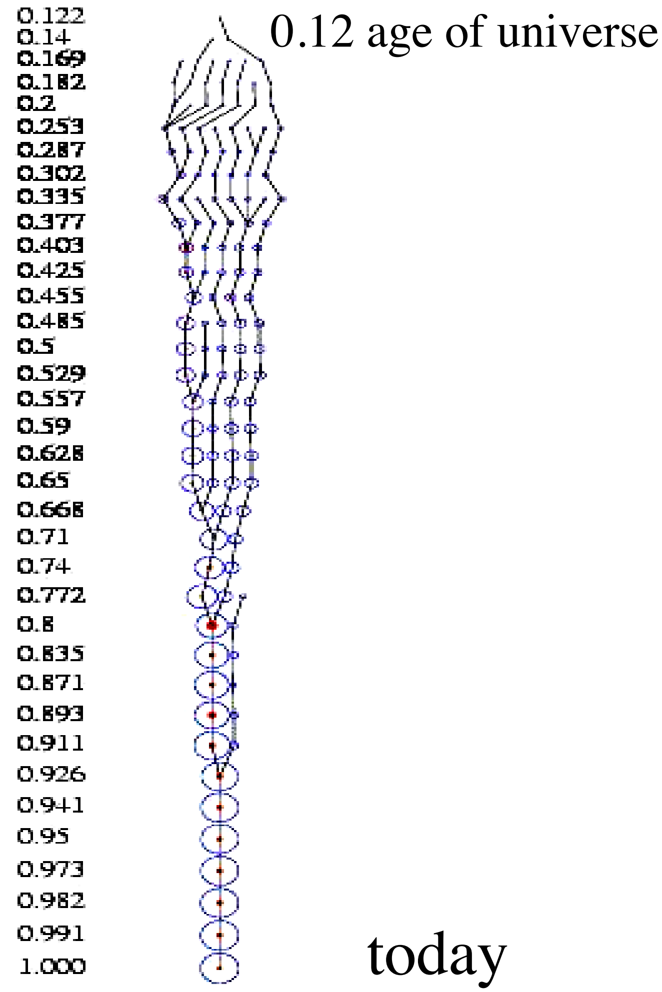


Figure 1. BCG merger tree. Symbols are colour–coded as a function of B - V colour and their area scales with the stellar mass. Only progenitors more massive than 10^{10} $M_\odot$ h^{-1} are shown with symbols. Circles are used for galaxies that reside in the FOF group inhabited by the main branch. Triangles show galaxies that have not yet joined this FOF group.

What is a Merger Tree

- In LCDM cosmology structure grows by the merging of bound systems + infall
- The fraction of contribution of each component depends on time and mass.





R. Wechsler

Mergers

- Can have strong spatial spectral structure in a merger

- Figure: temperature map (in color) and intensity map (contours) for a merging cluster (Abell 3921, Belsole et al 2005)

  notice the strong spectral features associated with the physics of the merger

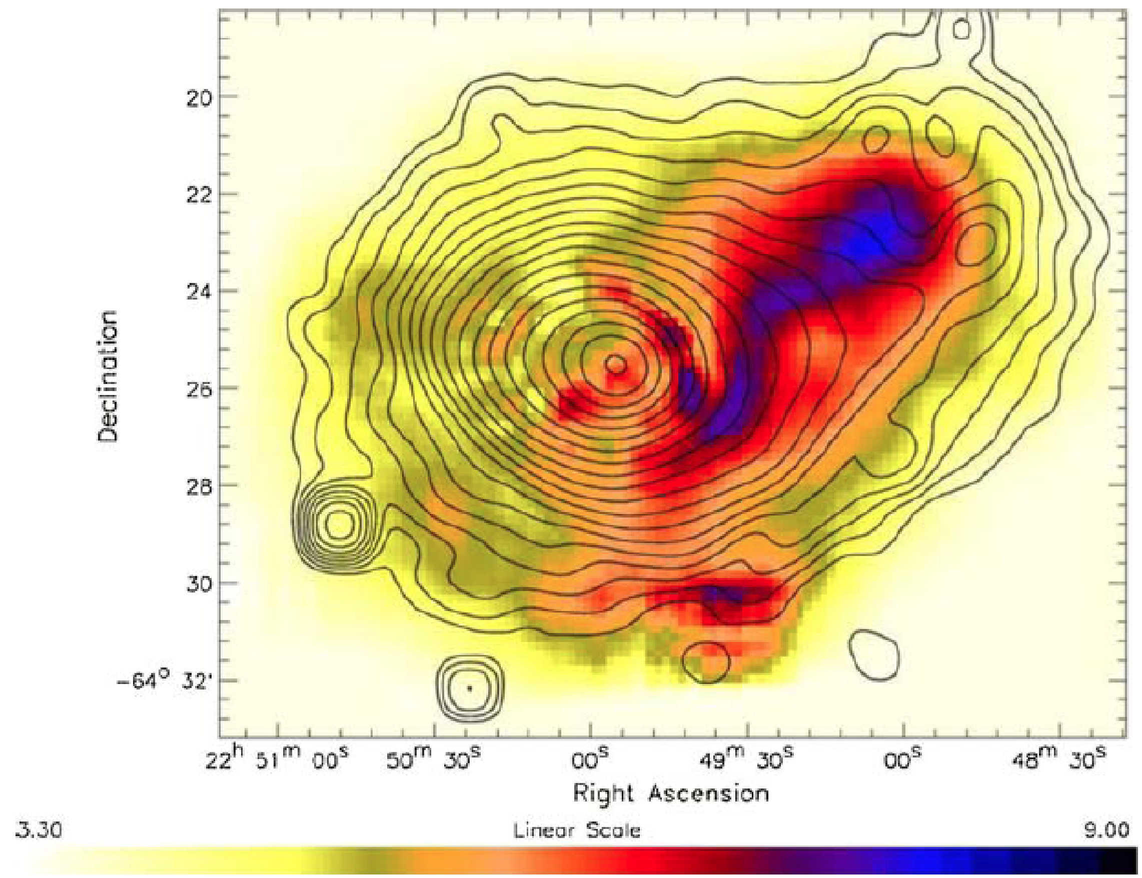


Fig. 15 Temperature map of the merging cluster A3921 by Belsole et al. (2005). The temperature map has

Extreme Merger

- Bullet cluster (1E0657)
- Allen and Million

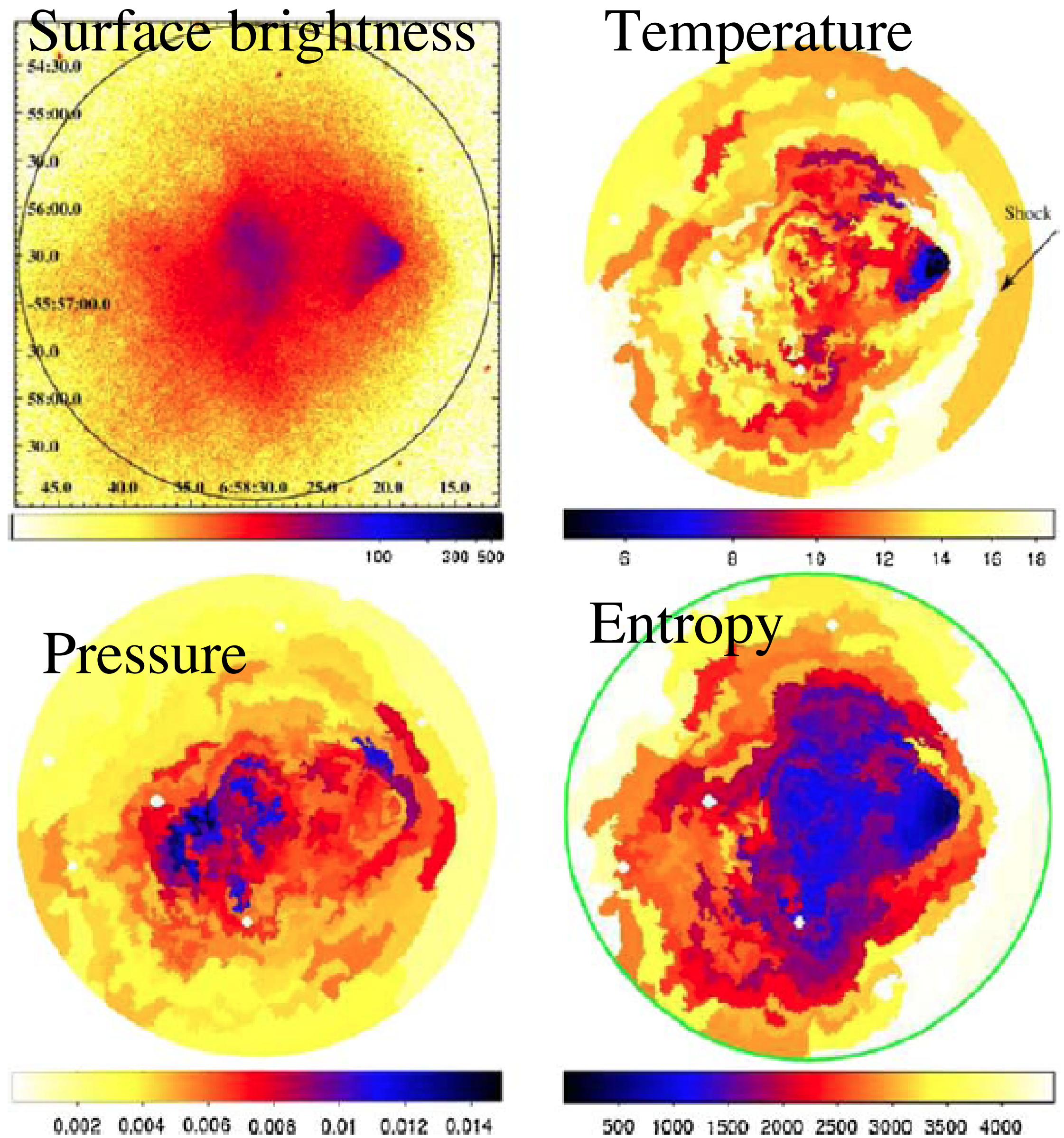
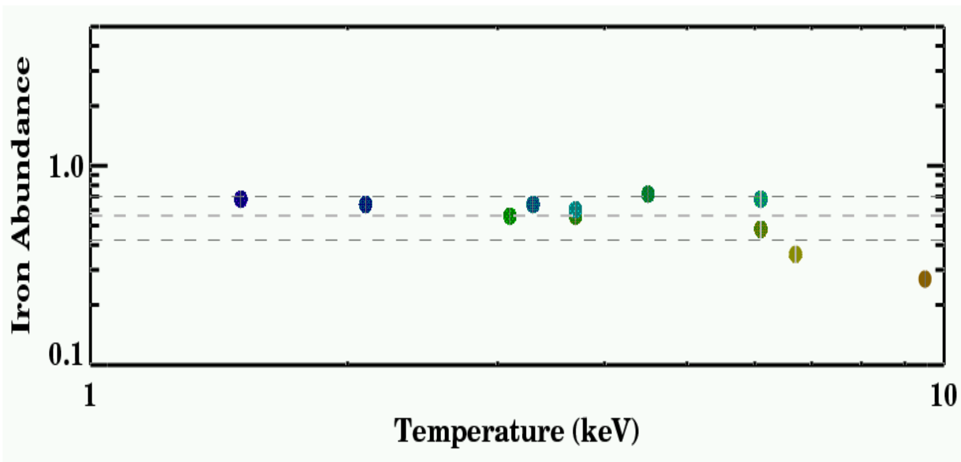


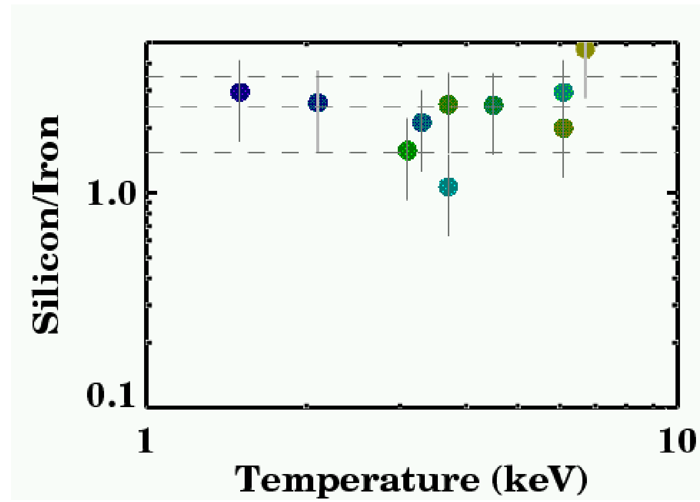
Fig. 16 Thermodynamic maps for the ICM of the "bullet cluster", 1E0657-56 (Million and Allen 2008)

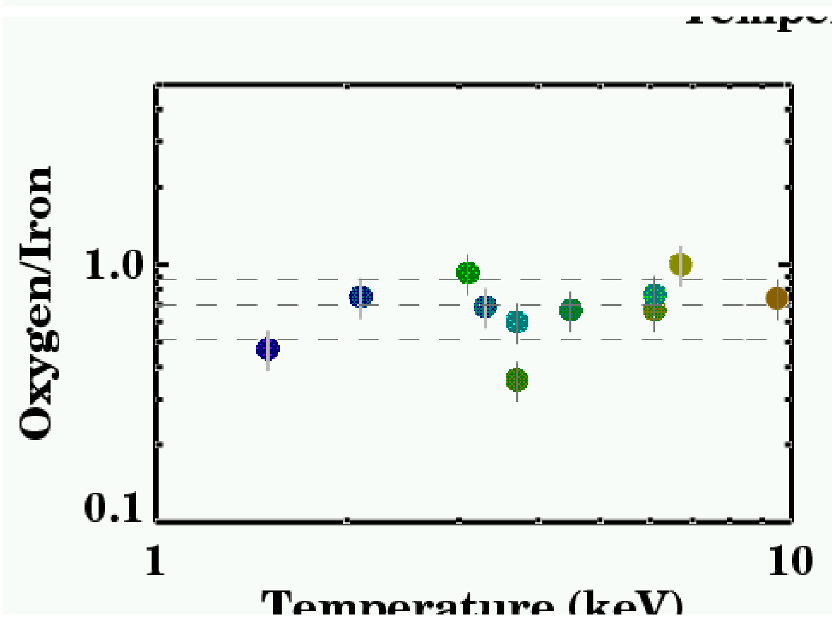
Virialized systems- Clusters, Groups and Big galaxies

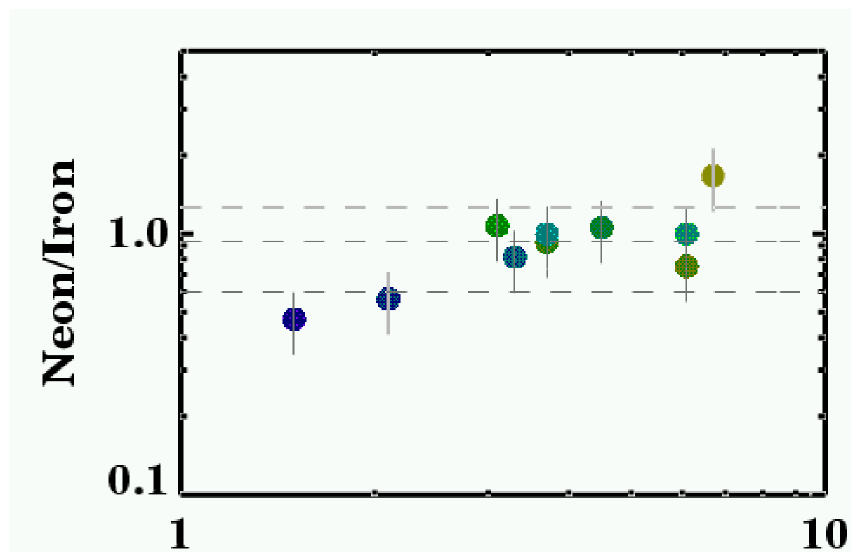
XMM Grating Results- J. Peterson et al

These data have less systematic errors than the CCD data but lower S/N









Chemical Abundances In Clusters

- Remember:
  - 80% of the baryons are in the gas
  - We detect line emission in the x-ray band from atomic transitions in H,He-like ions
  - Clusters are roughly big closed boxes
- Use these data to measure the chemical abundance of the gas
  - The strength of the lines depends on
    - Atomic physics
    - # of ions of a given species
    - Temperature
  - The number of protons (H atoms) depends on the strength of the bremmstrahlung continuum
  - The ratio of the number of ions to the number of protons is the abundance with respect to hydrogen

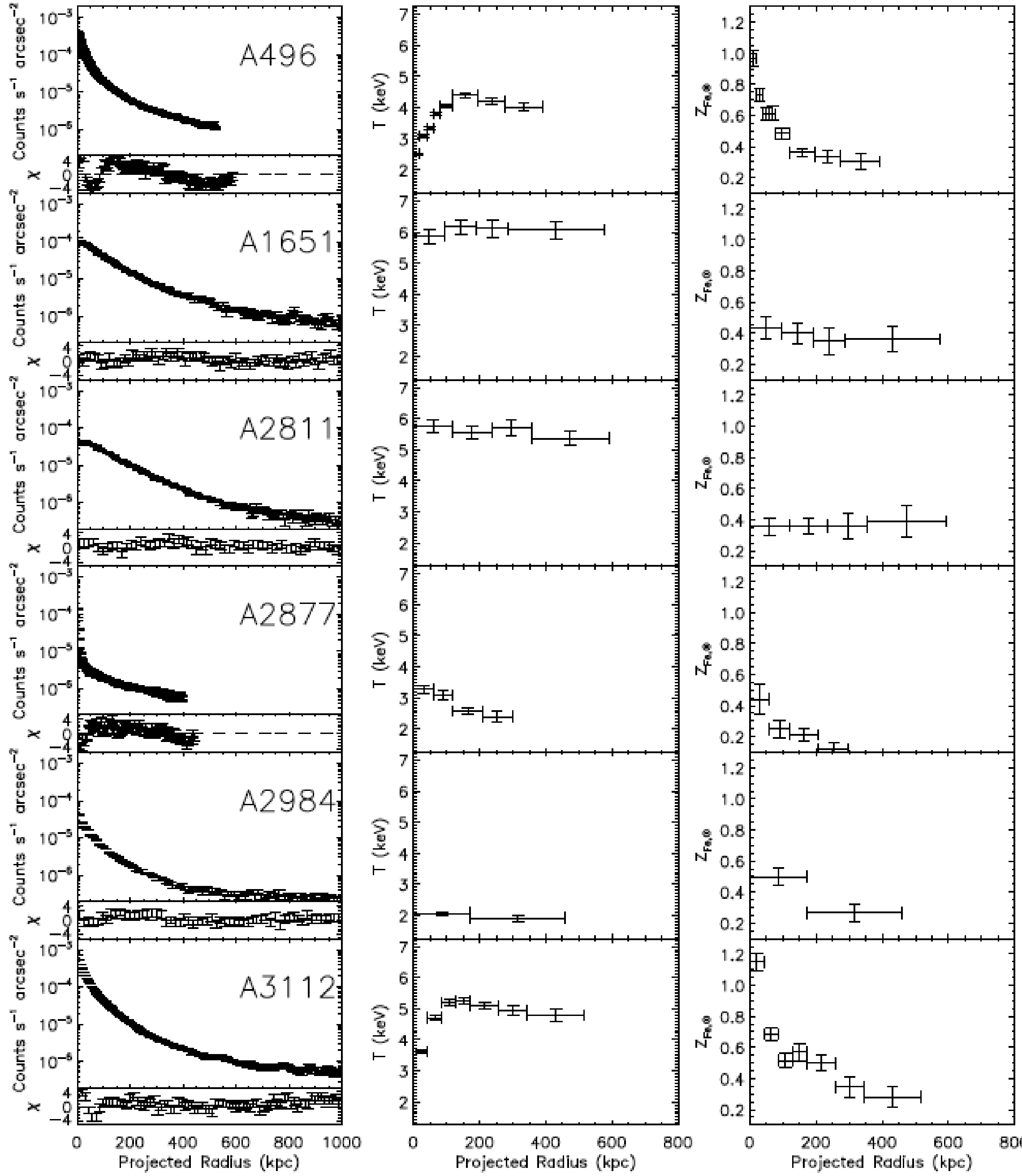
Origin of 'Metals'

- Metal production is dominated for (0…Ni) by supernova.
- Type II (core collapse) produce most of the O and Type I produce most of the Fe.
- The fraction of other elements (e.g. Si,S) that are produced by the SN depend on the IMF and the (poorly understood) yields of the SN.
- If the observed cluster galaxies are the source of the metals and 'standard' SN rates and IMF are assumed produces 1/3 of the the observed metals

Since most of the metals are in the gas>70% of the metals generated in galaxies has to be 'lost' from galaxies (where the stars live) to the ICM

Cluster Metallicity

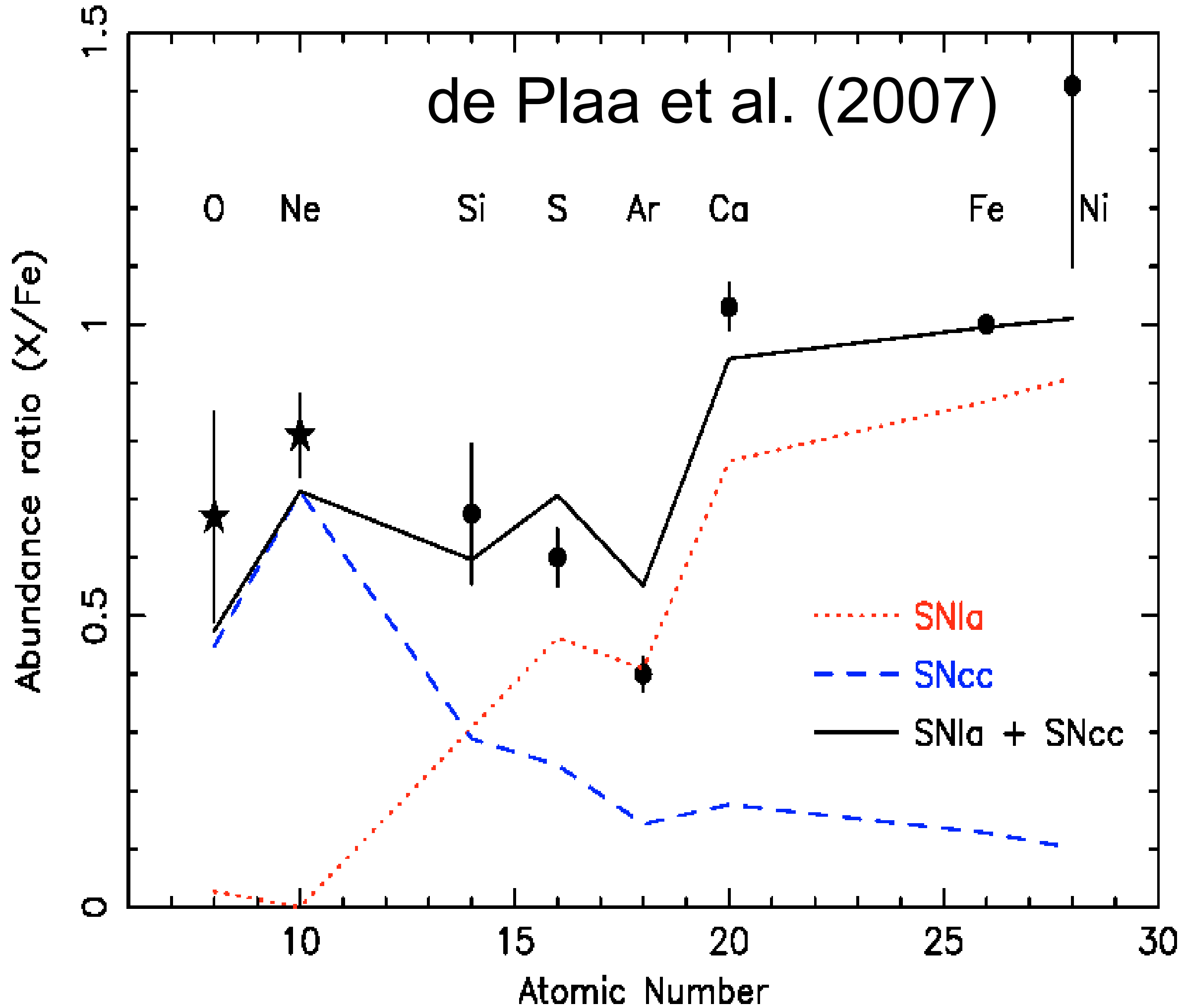
- The abunances are not uniform in the cluster but can be higher in the center

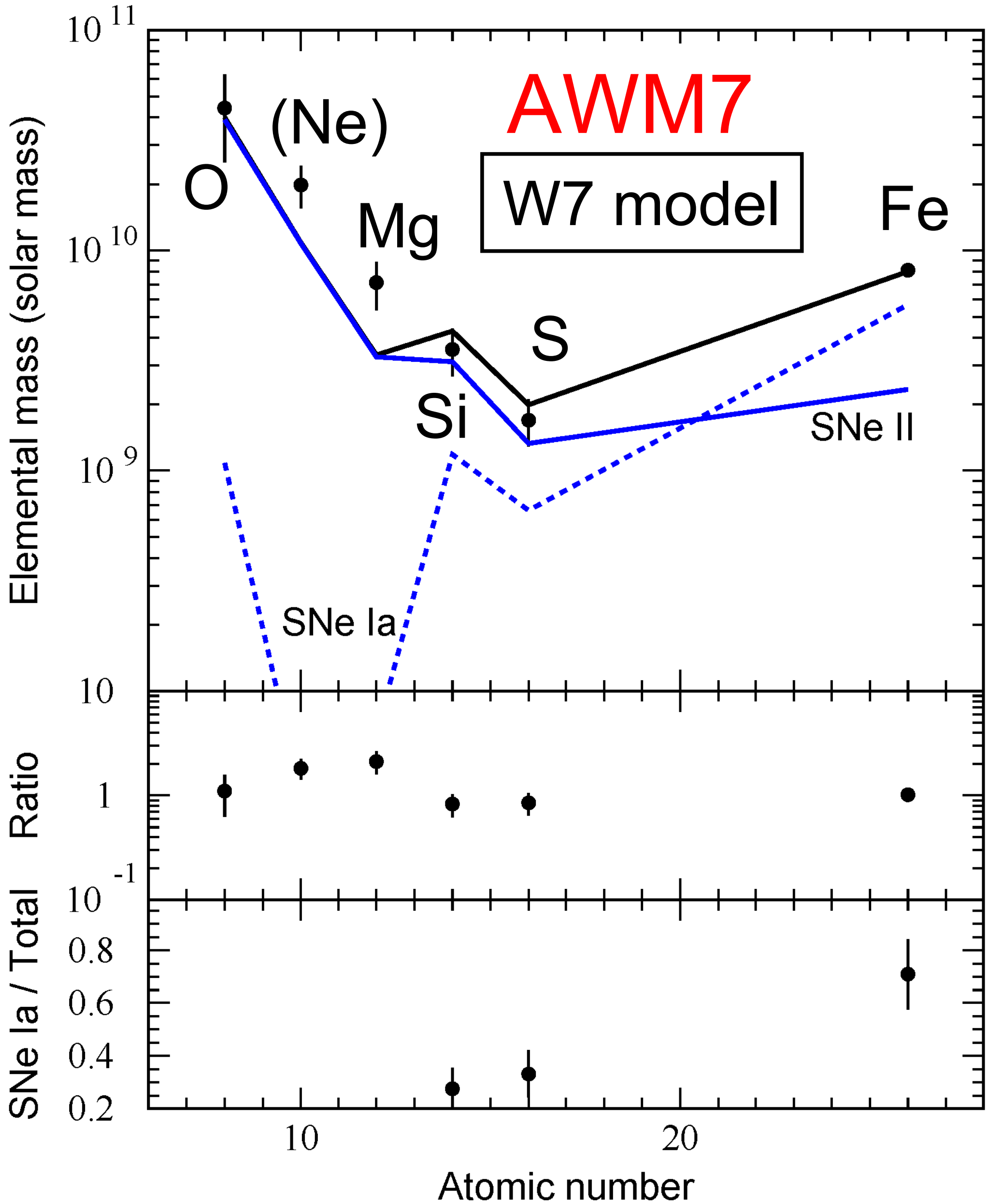


Temperature Abundance

Relative Abundance of Different Elements

- The relative abundance of differenet elements is related to the processes that produce them
- Fe and Ni are mostly made (we think) in type I supernova (the explosion of a white dwarf)
- Oxygen and Neon are made mostly in a type II SN- the explosion of a massive star
- The relative and



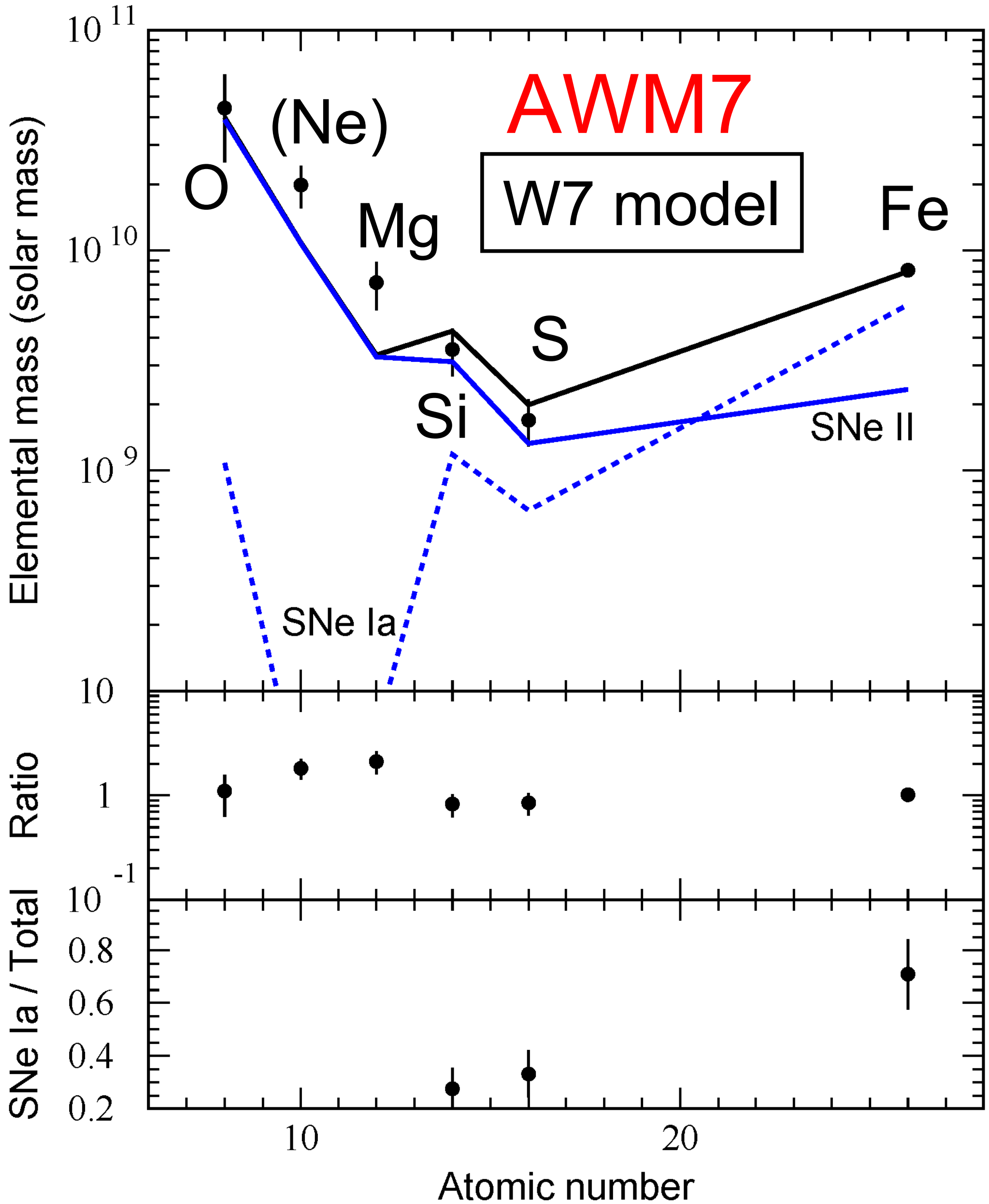


Ratio of the number of each type of SN

$N_{\mathrm{SNe\ II}} / N_{\mathrm{SNe\ Ia}} = 4.0 \pm 1.2$

- ~75% of Fe, ~40% of Si and S from SNe Ia

Sato et al

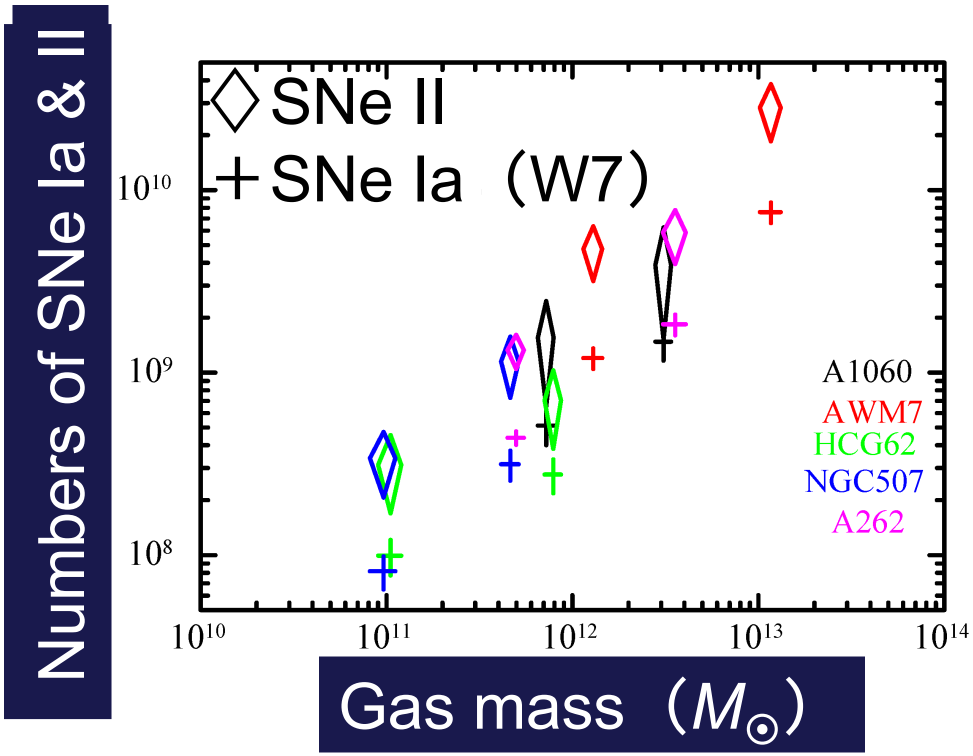


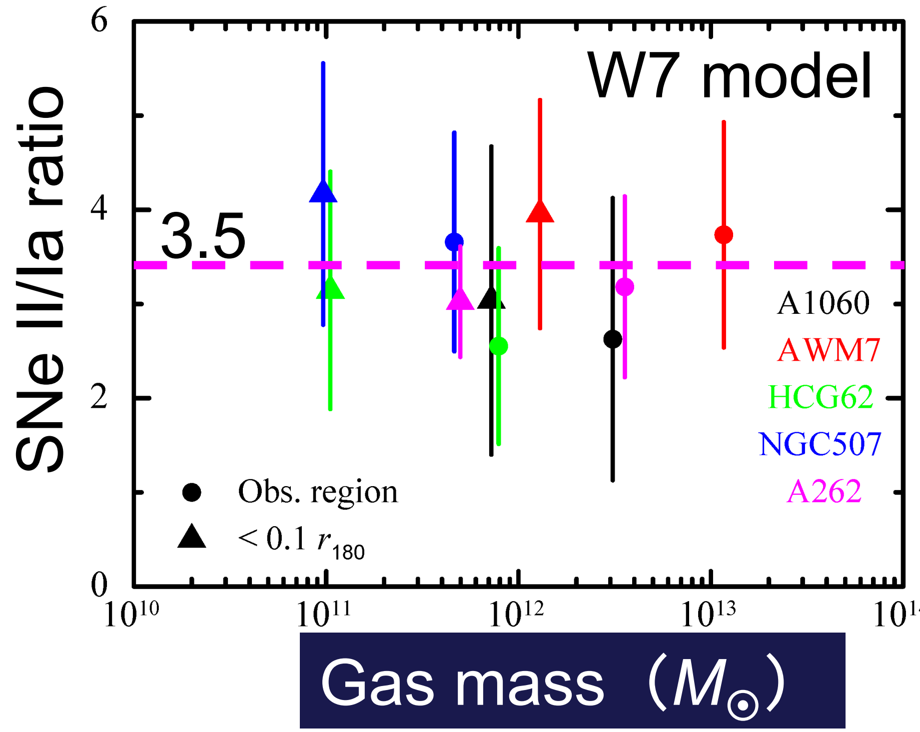
$N_{\mathrm{SNe\ II}} / N_{\mathrm{SNe\ Ia}}$
$= 4.0 \pm 1.2$

- ~75% of Fe, ~40% of Si and S from SNe Ia

Sato et al

Numbers and Ratio of SNe Ia &

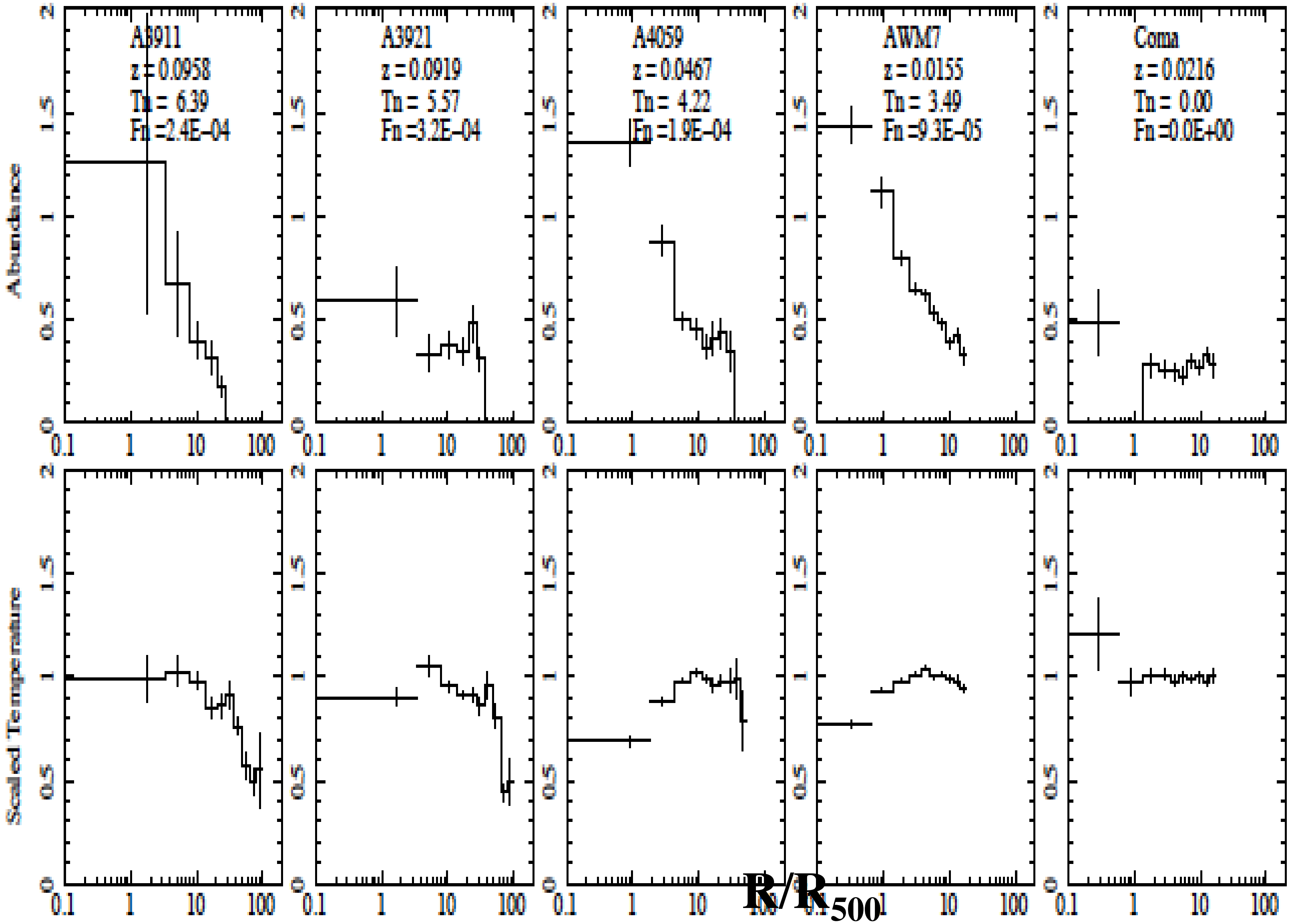




- Numbers of SNe Ia &
  SNe II/Ia Ratio: ~3.5 (W7 and WDD2), ~2.5 (WDD1)

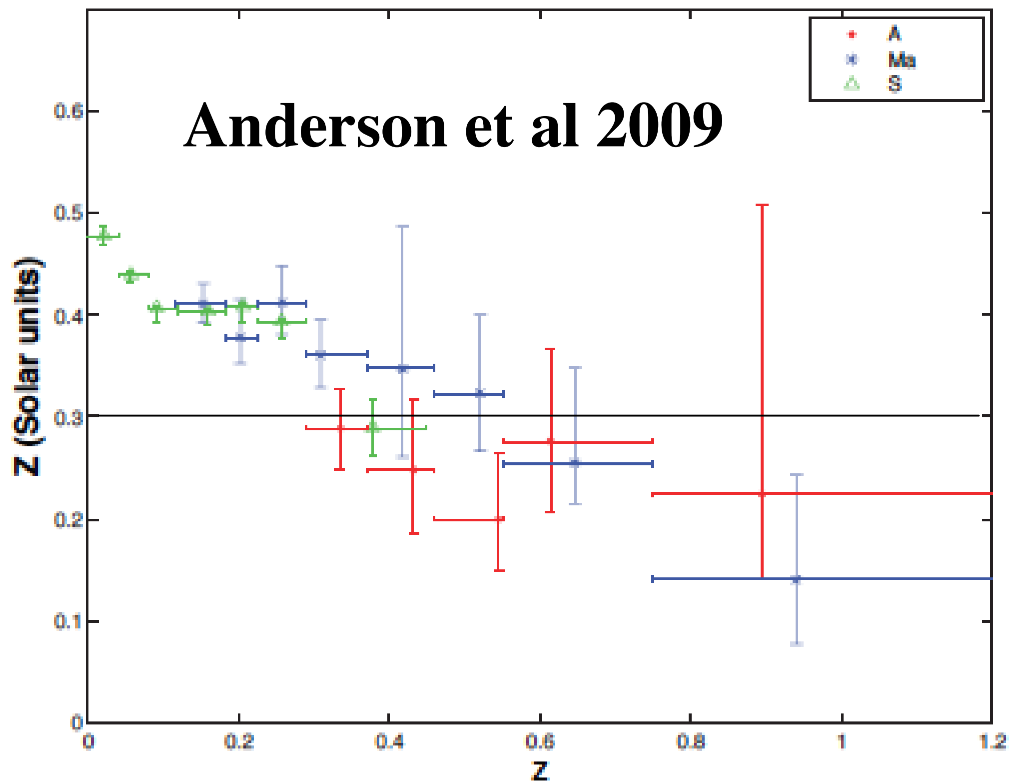
cf. Clusters (*XMM* ; de Plaa et al. 2007): ~3.5
Our Galaxy (Tsujimoto et al. 1995): ~6.7
LMC & SMC (Tsujimoto et al 1995): 3.3 – 5

Abundance Profiles



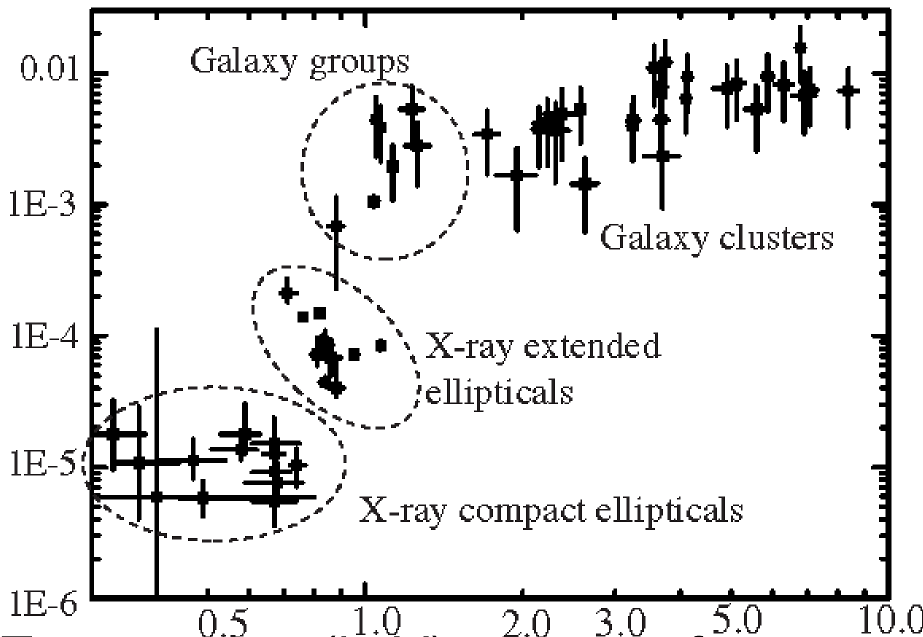
Metallicity Evolution

- There is weak evidence for cluster metallicity evolution- when and where the metals produced
- Most of the metals were in place at z~0.5 and maybe at z~1



Ehlert and Ulmer 2009- figure shows the cluster metallicity for3 samples as a function of redshift

Metals are synthesized in stars (galaxies):
Compare the mass of metals $M_{\mathrm{metal},\,<R}$ (in units of $\boldsymbol{M_\odot}$)
with B-band luminosity of stars
(similar to mass to light ratio)



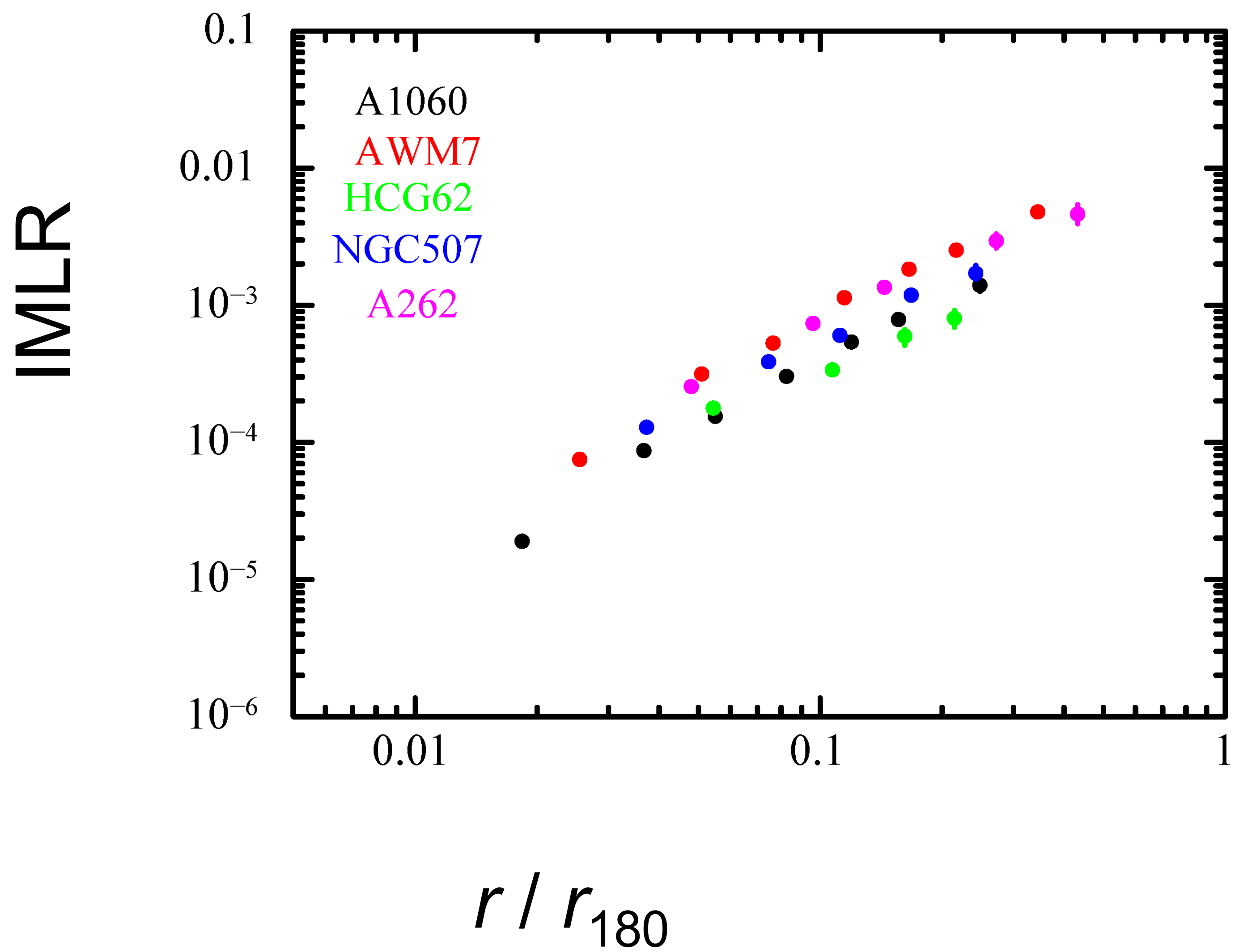
Temperature (keV) ∝mass of system

$$\mathbf{MLR} = \frac{M_{\mathrm{metal},\,<R}}{L_{\mathrm{B\ or\ K},\,<R}} \quad M_\odot$$

Makishima et al. (2001)

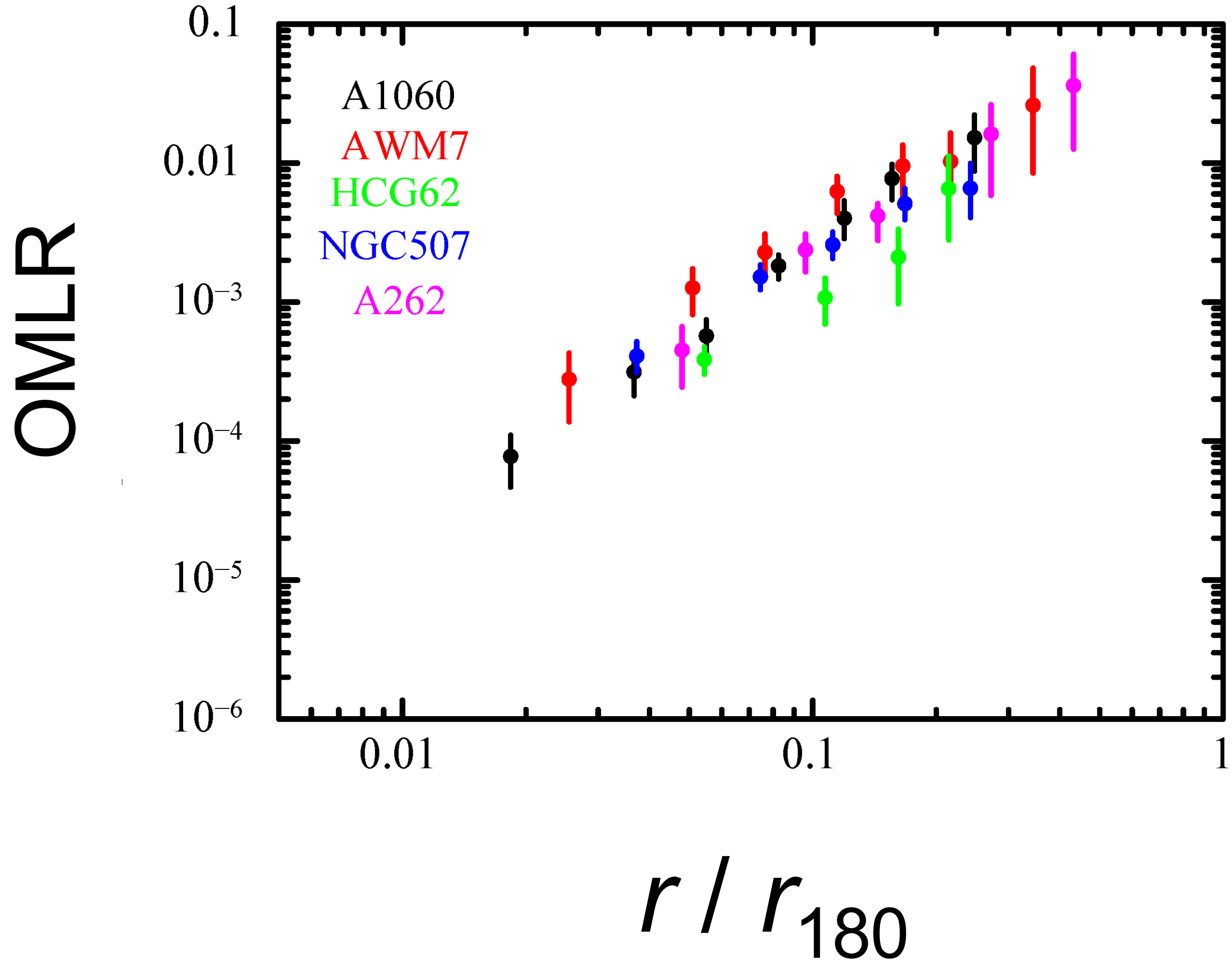
Oxygen Mass-to-Light Ratio: OMLR
Magnesium Mass-to-Light Ratio: MMLR
Iron Mass-to-Light Ratio: IMLR

Iron Mass to Light Ratio



K-band for optical light

Metal enrichment process in the ICM
- shows factor of several variation



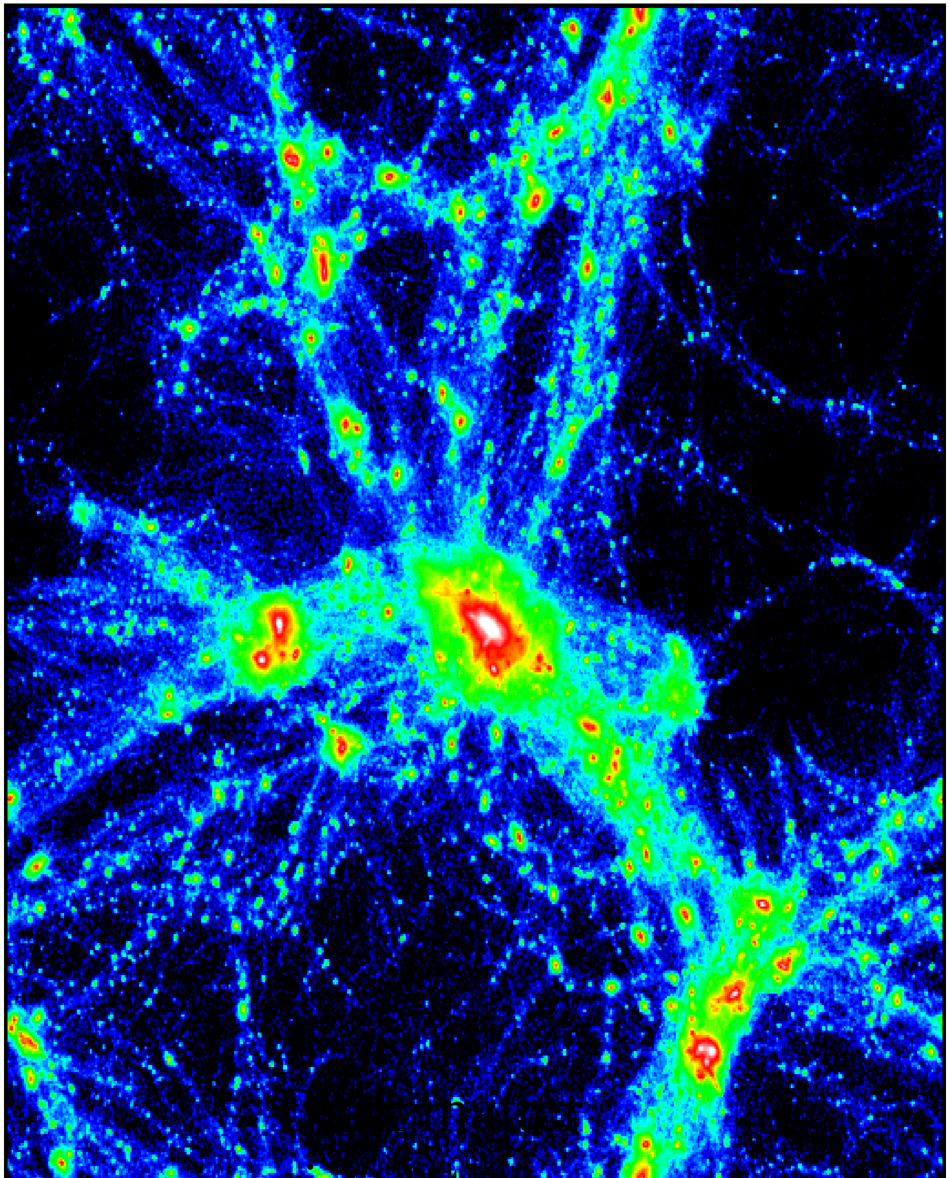
OMLR= oxygen mass to light ratio

Additional Material

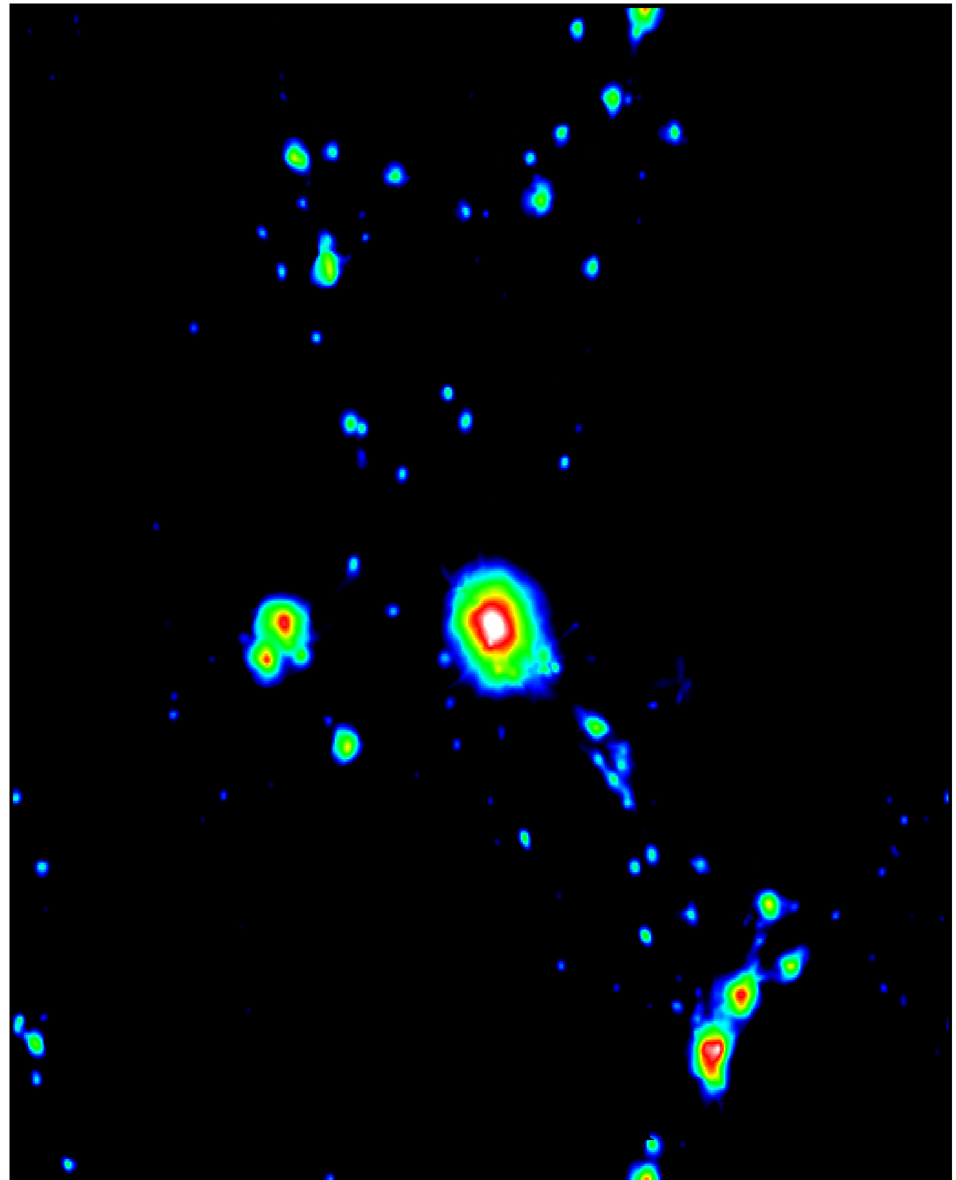
β model, hydrostatic equilibrium and cluster temperature profiles

Comparison of dark matter and x-ray cluster and group distribution

every bound system visible in the numerical simulation is detected in the x-ray band - bright regions are massive clusters, dimmer regions groups,



simulation



simulation

Sound Crossing Time

- Sound speed

$$c_s^2 = \gamma \frac{P}{\rho} = \frac{5}{3}\frac{P}{\rho}$$

$$c_s \approx 1500 \left(\frac{T}{10^8\,\mathrm{K}} \right)^{1/2} \mathrm{km/s}$$

- Sound crossing time

$$t_s \approx 6.6 \times 10^8 \left(\frac{T}{10^8\,\mathrm{K}} \right)^{-1/2} \left(\frac{D}{\mathrm{Mpc}} \right) \mathrm{yr}$$

Less than age _ unless something happens (merger, AGN, …),

gas should be nearly hydrostatic

Hydrostatic Equilibrium

$$\nabla P = -\rho \nabla \phi$$

$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{d\phi}{dr} = -\frac{GM(r)}{r^2} \quad \text{spherical}$$

Isothermal (T = constant)

$$\frac{1}{\rho}\nabla P = \frac{1}{\rho}\nabla\left(\frac{\rho kT}{\mu m_p}\right) = \left(\frac{kT}{\mu m_p}\right)\nabla \ln \rho = -\nabla \phi$$

$$\ln\left[\rho(r)/\rho_0\right] = \left(\frac{\mu m_p}{kT}\right)\left[\phi_0 - \phi(r)\right]$$

Beta Model

(Cavaliere & Fusco-Femiano 1976)

Assume King Model DM potential and tha the galaxies follow King Model, and have isotropic, constant velocity dispersion: then (Sarazin 2008)

$$\sigma_{gal}^2 \frac{d \ln \rho_{gal}}{dr} = -\frac{d\phi}{dr} = \left(\frac{kT}{\mu m_p}\right)\frac{d \ln \rho}{dr}$$

$$\rho_{gal}(r) = \frac{\rho_{gal,0}}{\left[1 + \left(\frac{r}{r_c}\right)^2\right]^{3/2}}$$

Beta Model (cont.)

$$\rho(r) = \frac{\rho_0}{\left[1 + \left(\frac{r}{r_c}\right)^2\right]^{3\beta/2}}$$

$$\beta \equiv \frac{\mu m_p \sigma_{gal}^2}{kT}$$ but treat as fitting parameter

$$I_X(r) \propto \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta+1/2}$$

Beta Model (cont.)

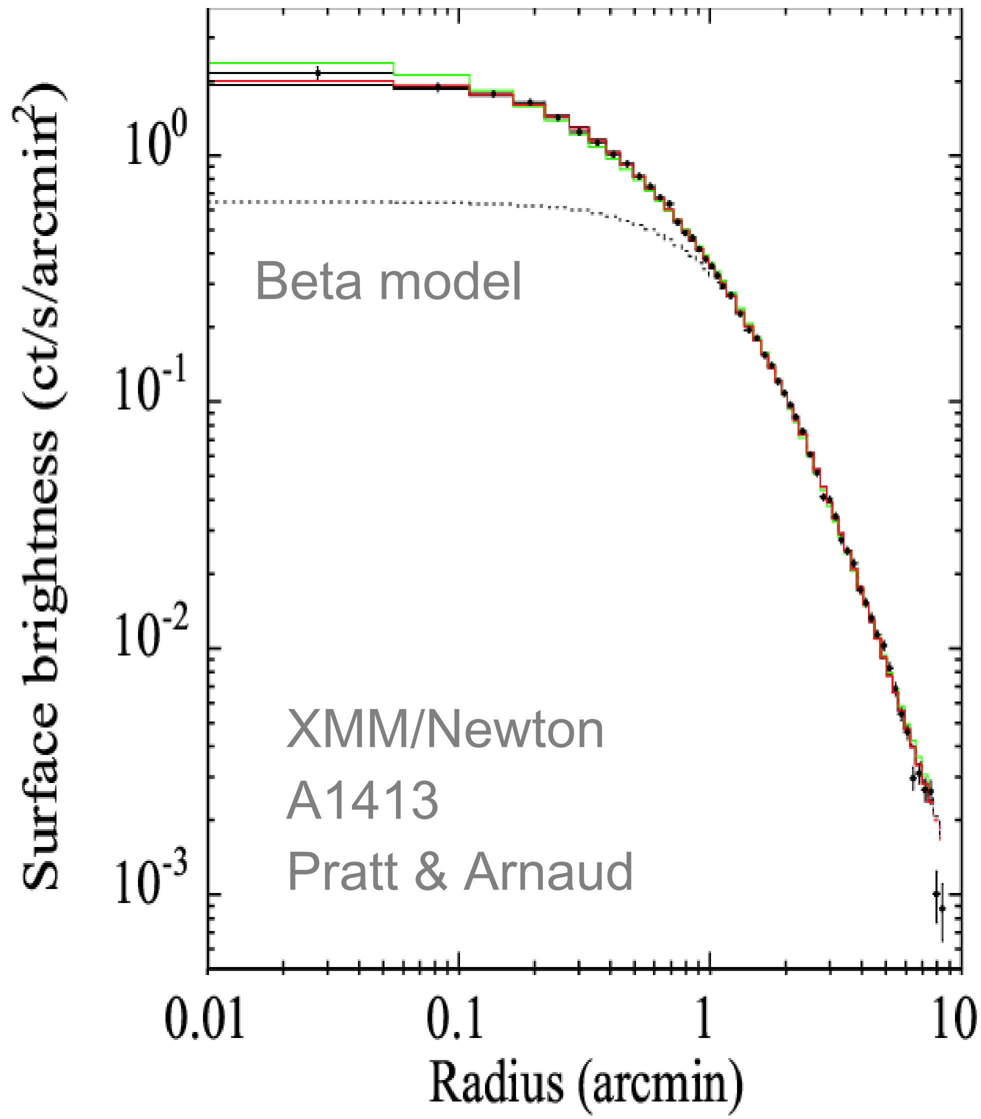
Fit outer parts of clusters

(Multiple beta models)

$\beta \approx 2/3$

ρ _ r^{-2}

I_X _ r^{-3}



Hydrostatic Equilibrium (cont.)

Adiabatic (Polytropic) Models

$$P \propto \rho^{\gamma} \text{ adiabatic if } \gamma = 5/3$$

$$\text{polytropic } 1 < \gamma \leq 5/3$$

$$\text{isothermal } \gamma \rightarrow 1$$

$$\frac{1}{\rho}\nabla P = \frac{\gamma}{\gamma - 1}\left(\frac{k}{\mu m_p}\right)\nabla T$$

$$\frac{T(r)}{T_0} = 1 + (\alpha - 1)\left[1 - \frac{\phi(r)}{\phi_0}\right], \quad \alpha \equiv \frac{T(\infty)}{T_0}$$

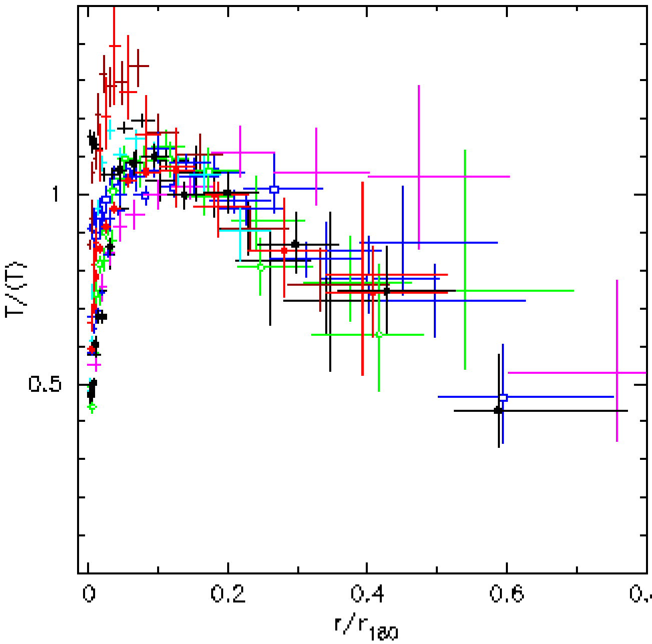
$$\frac{\rho(r)}{\rho_0} = \left[\frac{T(r)}{T_0}\right]^{1/(\gamma - 1)}$$

Cluster Temperature Profiles

- Rapid T rise with r at center (100 kpc, “cooling core”)
- T flat to 0.125 r_{vir}
- Slow T decline with r at large radii

  $\gamma \sim 1.2$

Chandra



(Vikhlinin et al 2005)