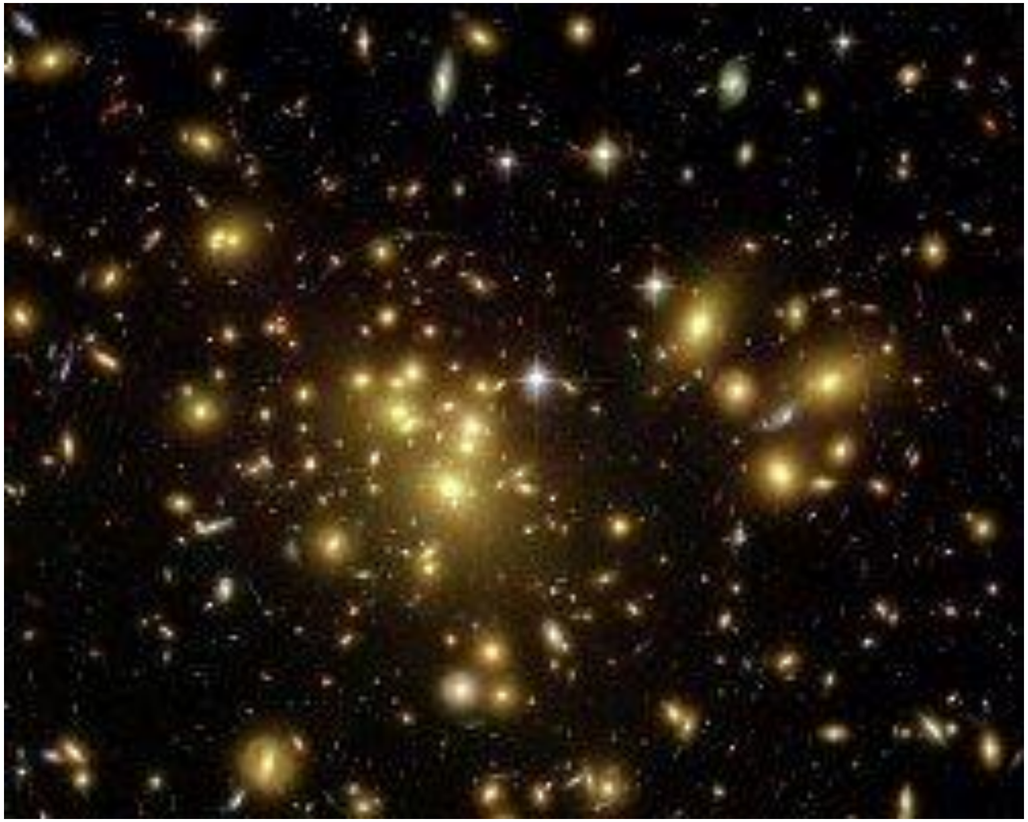
Clusters of Galaxies

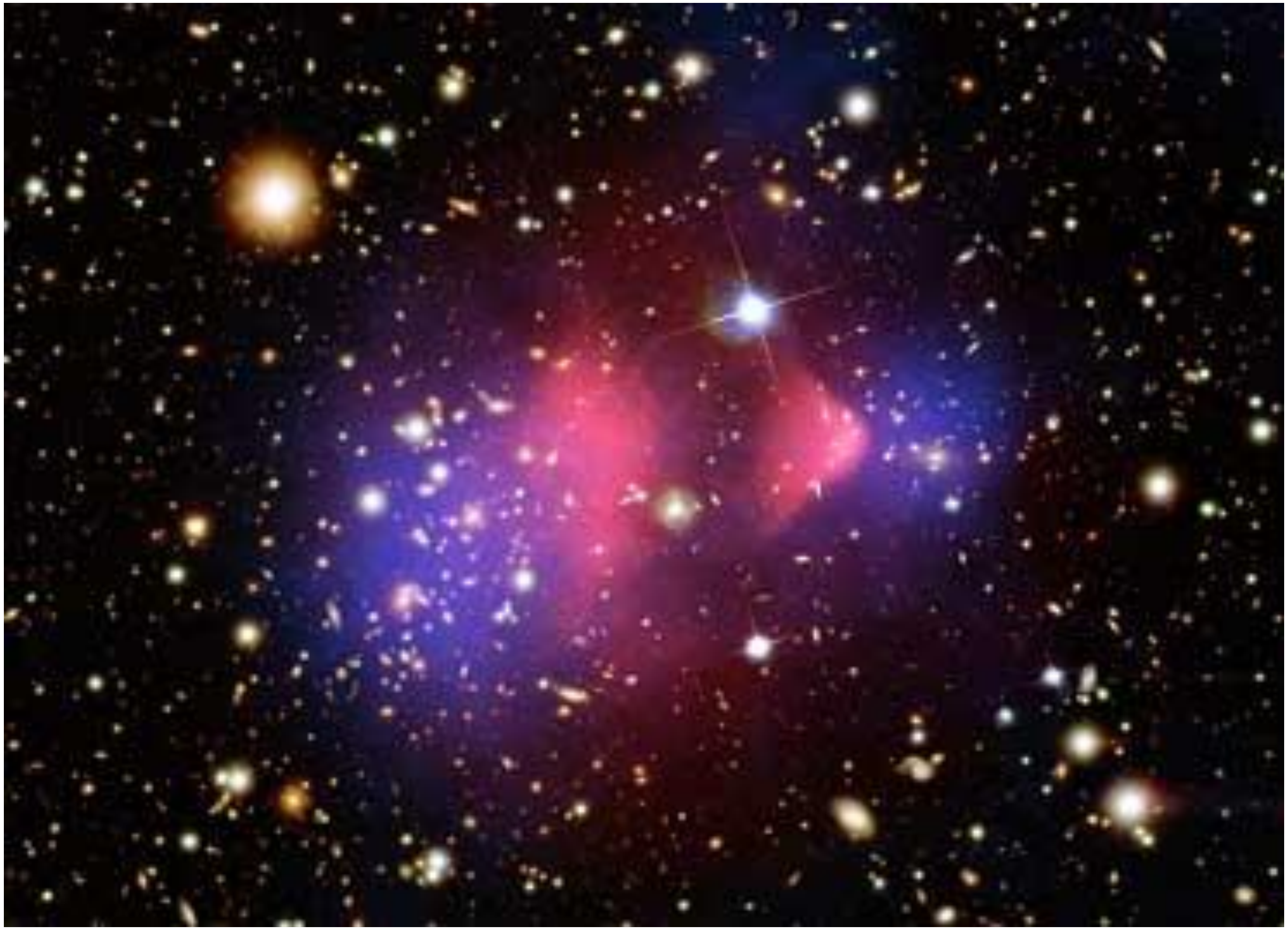
See Böhringer & Werner, 2010, A&A Rev., 18, 127

Introduction

- Typically contain 100s-1000s of galaxies
  - Radius ~ 3 Mpc
  - M > 5e14 M_{sun}
  - L_X ~ 10^{44}-10^{45} erg/s
- Clustering scales extend from:
  - Groups of ~10s of galaxies: R ~0.5 Mpc (e.g., Local Group)
  - Superclusters of ~100 clusters; R ~ several Mpc

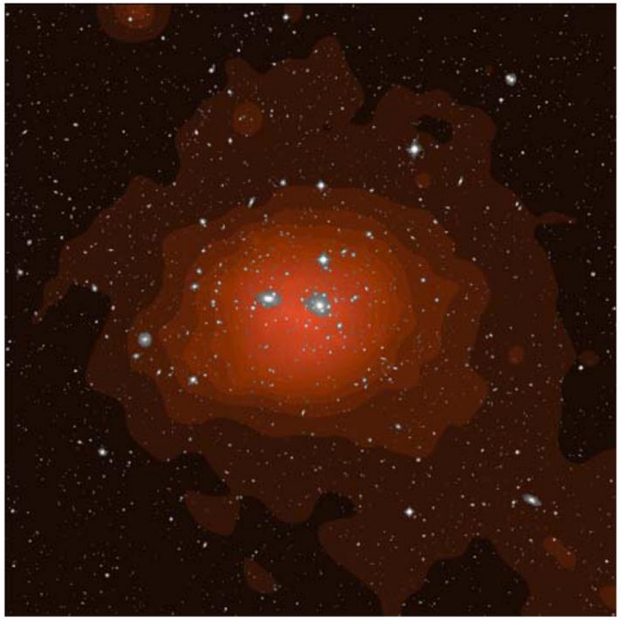


Most galaxies are found in clusters



- Clusters of galaxies are the largest structures that appear gravitationally bound
  - Dynamical timescale is so long that clusters retain an imprint of how they were formed
  - Can provide estimates of mass distribution over scales of several Mpc, particularly the amount of dark matter

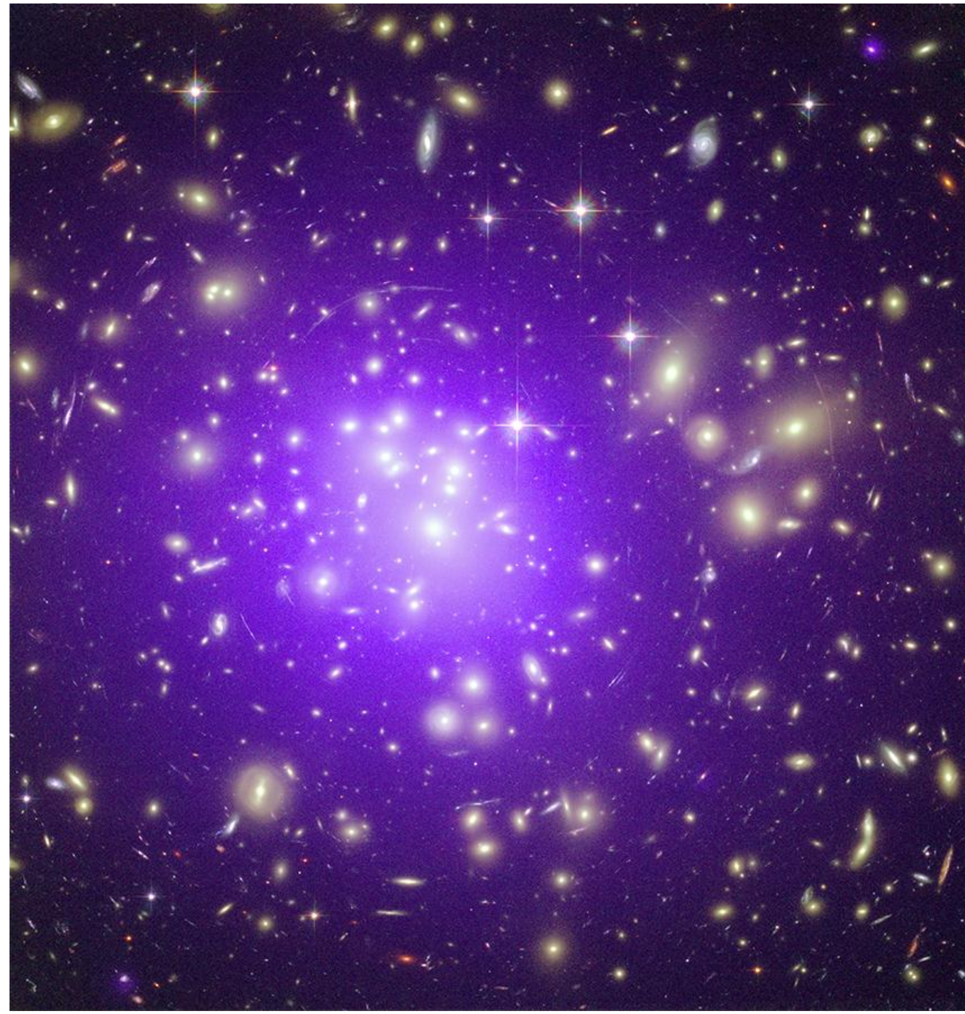
X-ray Observations of Clusters

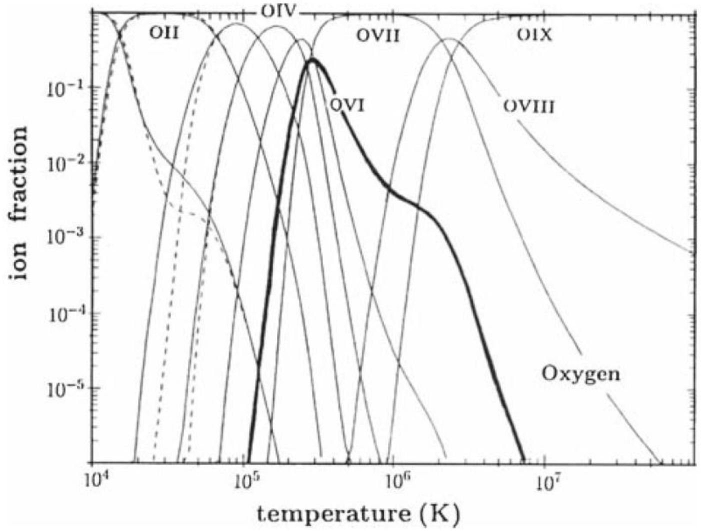


. 1 The Coma cluster of galaxies as seen in X-rays in the *ROSAT* All-Sky Survey (underlaying *red* or) and the optically visible galaxy distribution in the Palomar Sky Survey Image (galaxy and stellar ges from the digitized POSS plate superposed in *grey*)

- The dominant observed form of matter in clusters is the diffuse hot gas occupying the volume of space between the galaxies (the Intracluster Medium, or ICM)
  - Contains ~20% of the total cluster mass (c.f., ~3% for the visible galaxies)
- The X-ray emission from this hot gas is on average
  - Azimuthally symmetric
  - Centered on the bright dominant galaxy/galaxies
  - Spatially extended on scales >= 1 Mpc from cluster center
- Cluster ICMs show a wide range of properties and morphology

- The ICM is the hottest thermal equilibrium plasma that we can study in detail with temperatures ~100x that of the center of the Sun
- $T_X \sim 10^7 - 10^8$ K
- $n \sim 10^{-5} - 10^{-3}$ cm^{-3}
- `Collisionally' ionized plasma
  - Bremsstrahlung continuum
  - Recombination or bound-bound transitions of ionized heavy metals
  - Density low enough that 'forbidden' lines are commonly observed
  - No radiative transfer effects





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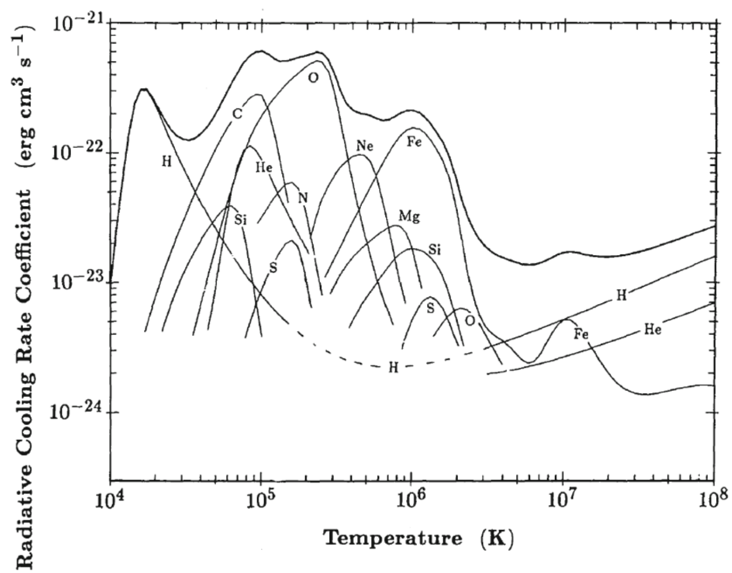


Fig. 5 Cooling rate of hot plasma as a function of the plasma temperature. The contribution to the cooling by the ions of different important abundant elements is indicated (Böhringer and Hensler 1989). Most of this contribution is in the form of line radiation, which is by far the dominant form of radiation in the temperature range from about 10^4 to 2×10^6 K. At higher temperatures over most of the regime of interest for the ICM the Bremsstrahlung contribution dominates

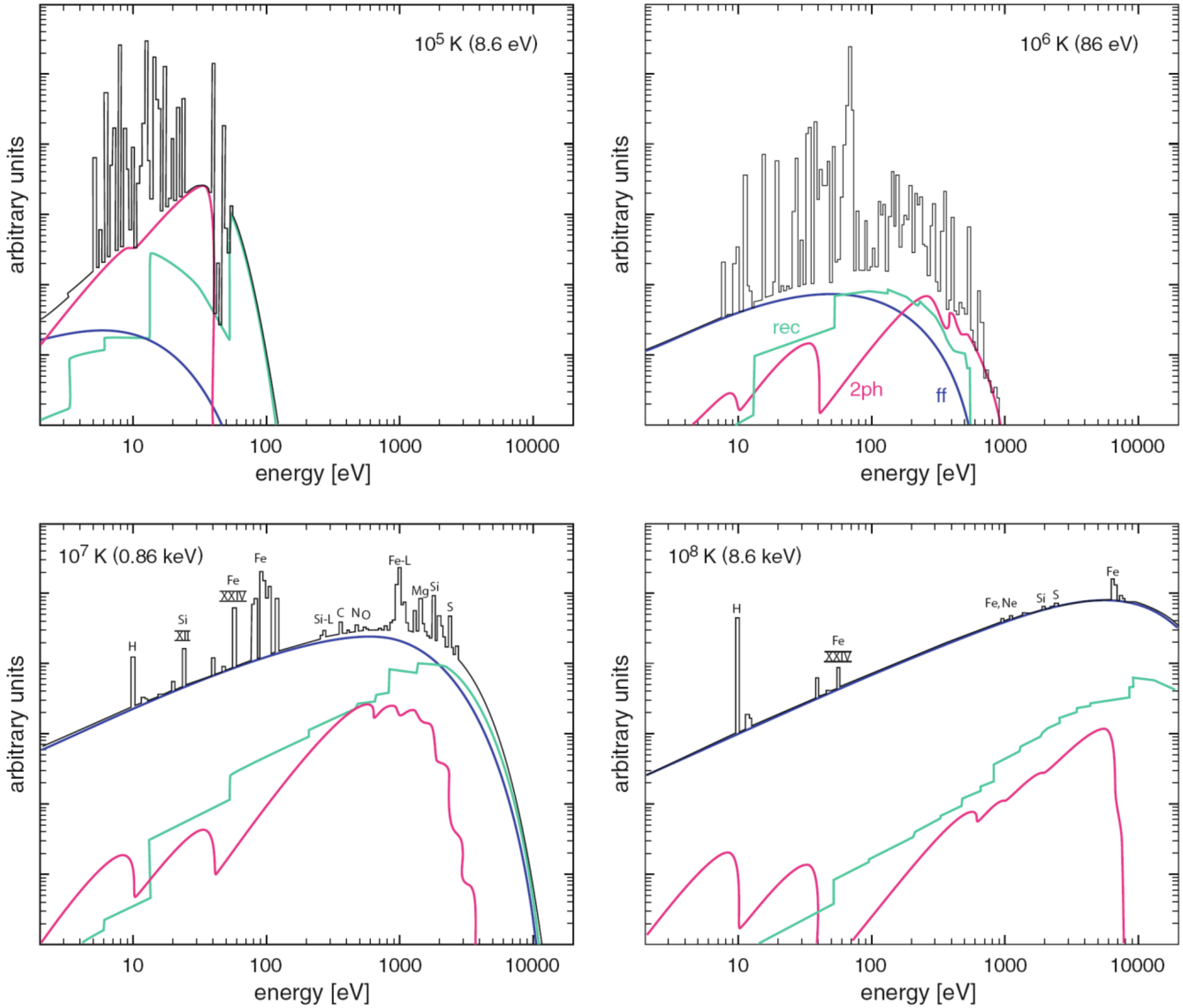
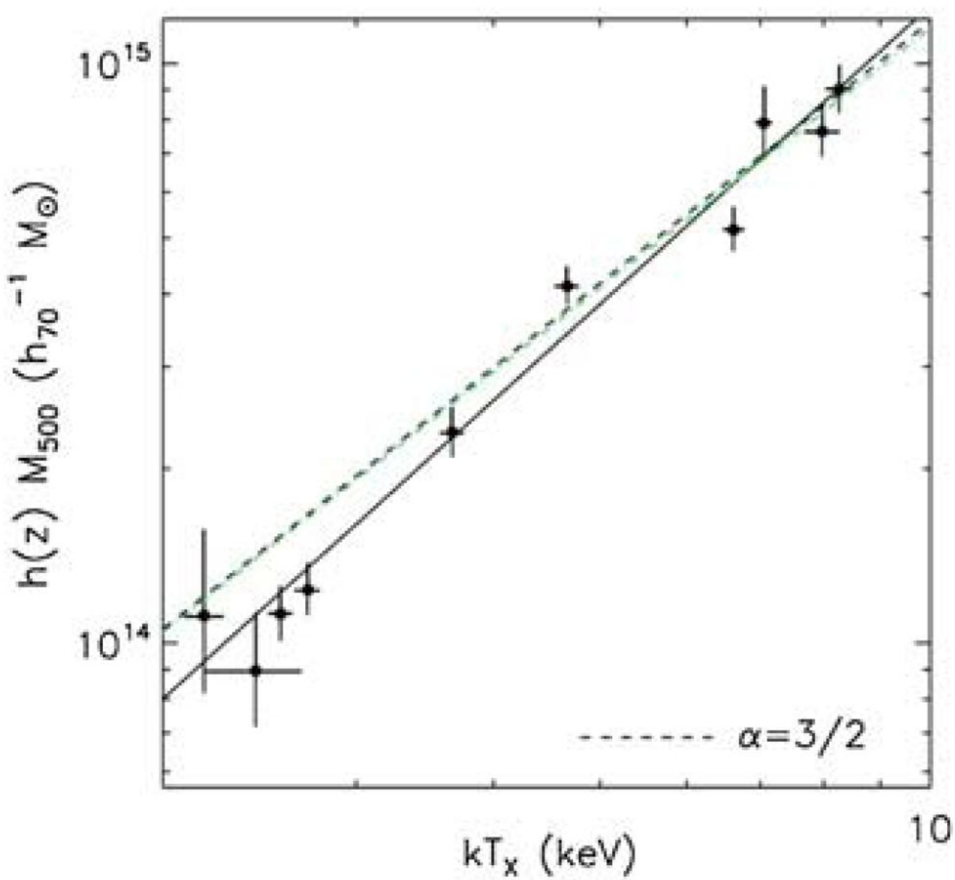


Fig. 6 X-ray spectra for solar abundance at different plasma temperatures. The continuum contributions from bremsstrahlung (*blue*), recombination radiation, characterized by the sharp ionization edges (*green*), and 2-photon radiation (*red*) are indicated. At the highest temperatures relevant for massive clusters of galaxies bremsstrahlung is the dominant radiation process (from the work described in Böhringer and Hensler 1989). The major emission lines in the panels for the higher temperatures relevant for galaxy clusters are designated by the elements from which they originate (The labels Fe-L ans Si-L refer to transitions into the L-shell in ions of Fe and Si, respectively, and two other lines with roman numbers carry the designation of the ions from which they originate involving transitions within the L-shells

- For relaxed, virialized clusters, T should be directly related to mass
  - Note that this is total mass (i.e., DM)
  - Slope is consistent with results from DM simulations that DM clusters should be self-similar
- T at a fiducal radius is now a standard measurement for cluster mass



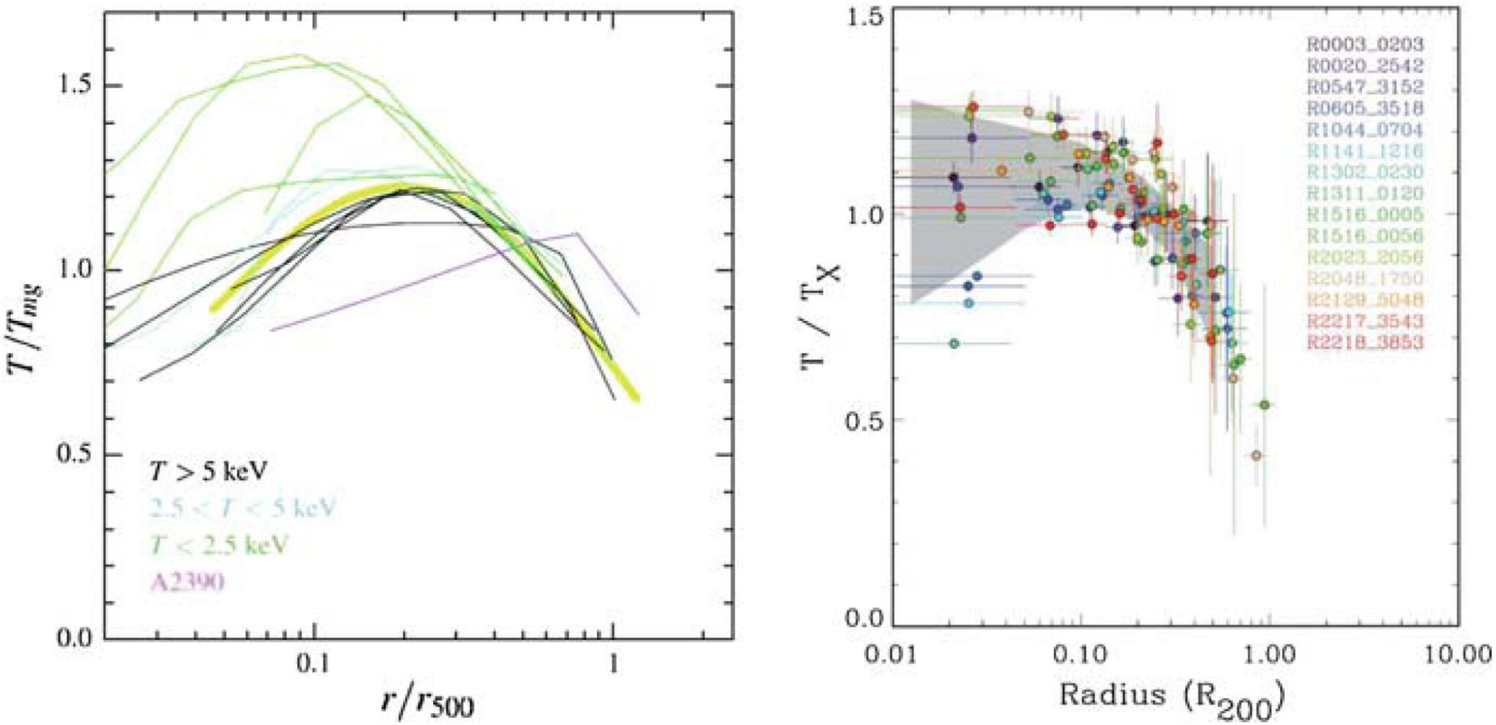
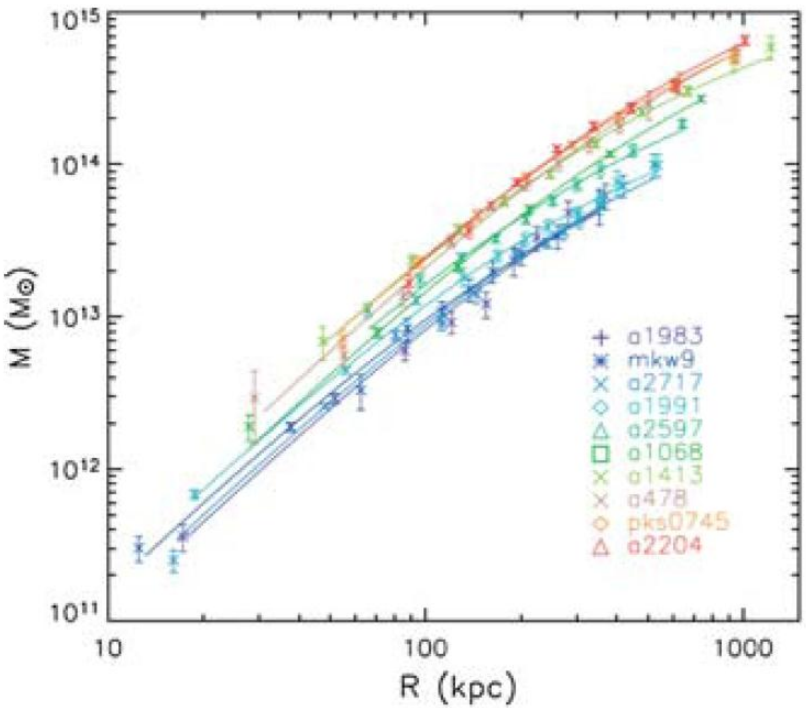
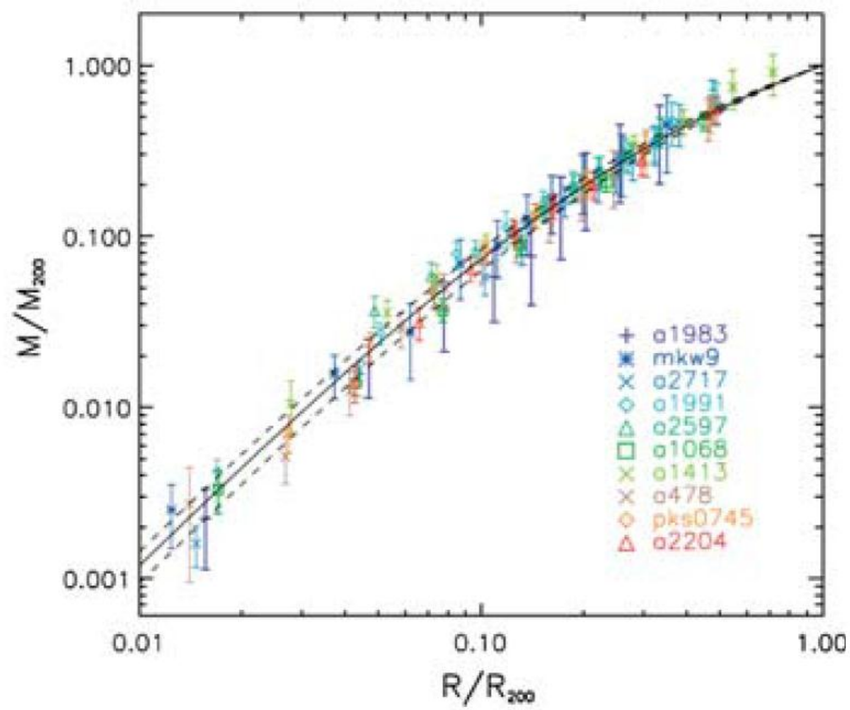


Fig. 10 Scaled temperature profiles of galaxy clusters derived from spectroscopic observations with the *Chandra* satellite (*left*, Vikhlinin et al. 2006) and results obtained for a sample of clusters observed with *XMM-Newton* (*right*, Pratt et al. 2007)

- Chandra & XMM-Newton allow for T to be measured as a function of radius.
- These are scaled to a certain overdensity radius
- Note that some clusters (the ones with the densest cores) have decreasing T as r gets small, and some remain flat or increase.

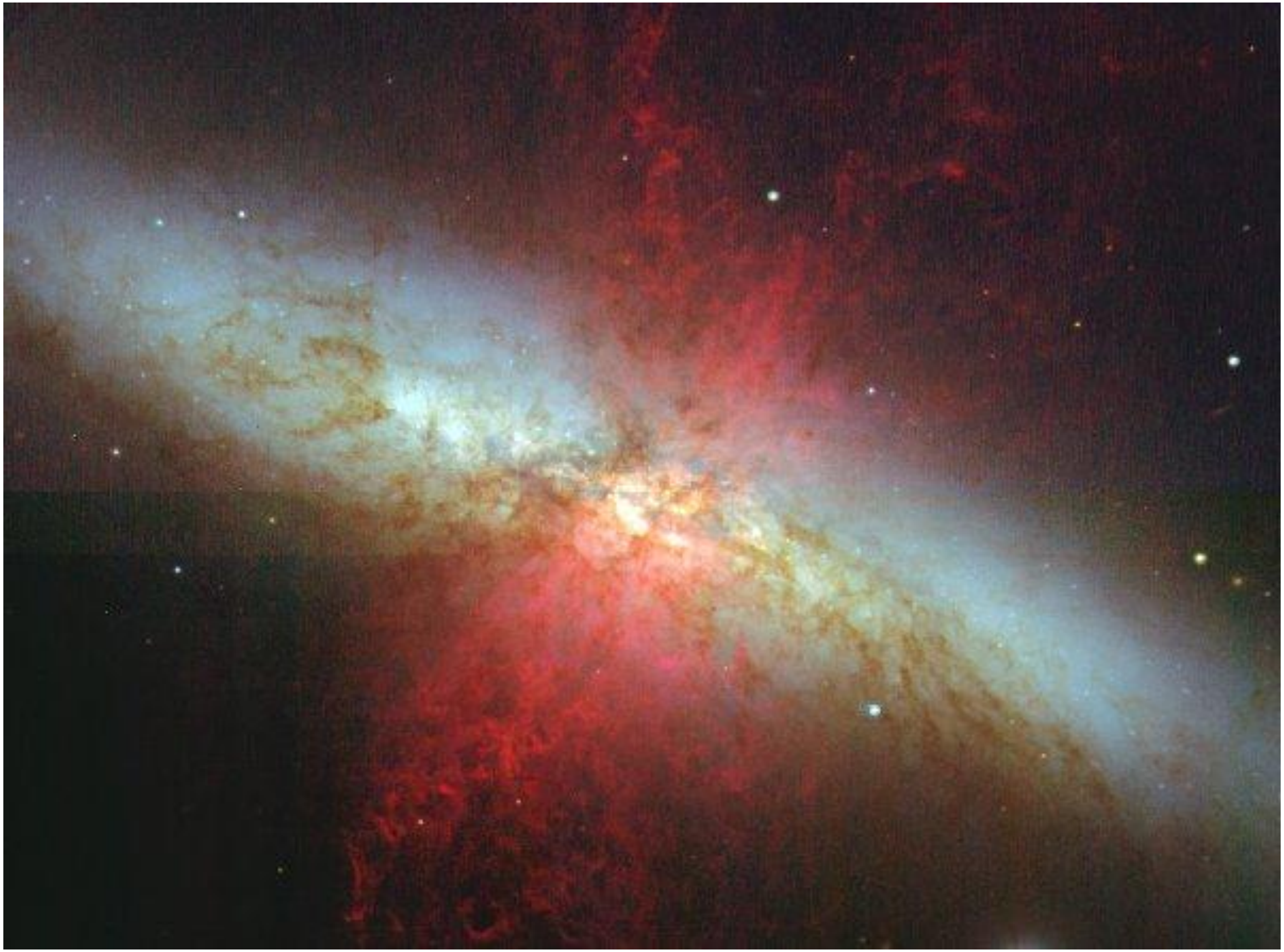




- With the T(r) and ρ(r) profiles, and assuming hydrostatic balance, can measure the total mass profile M(r)
- Well described the profile predicted by DM halo simulations

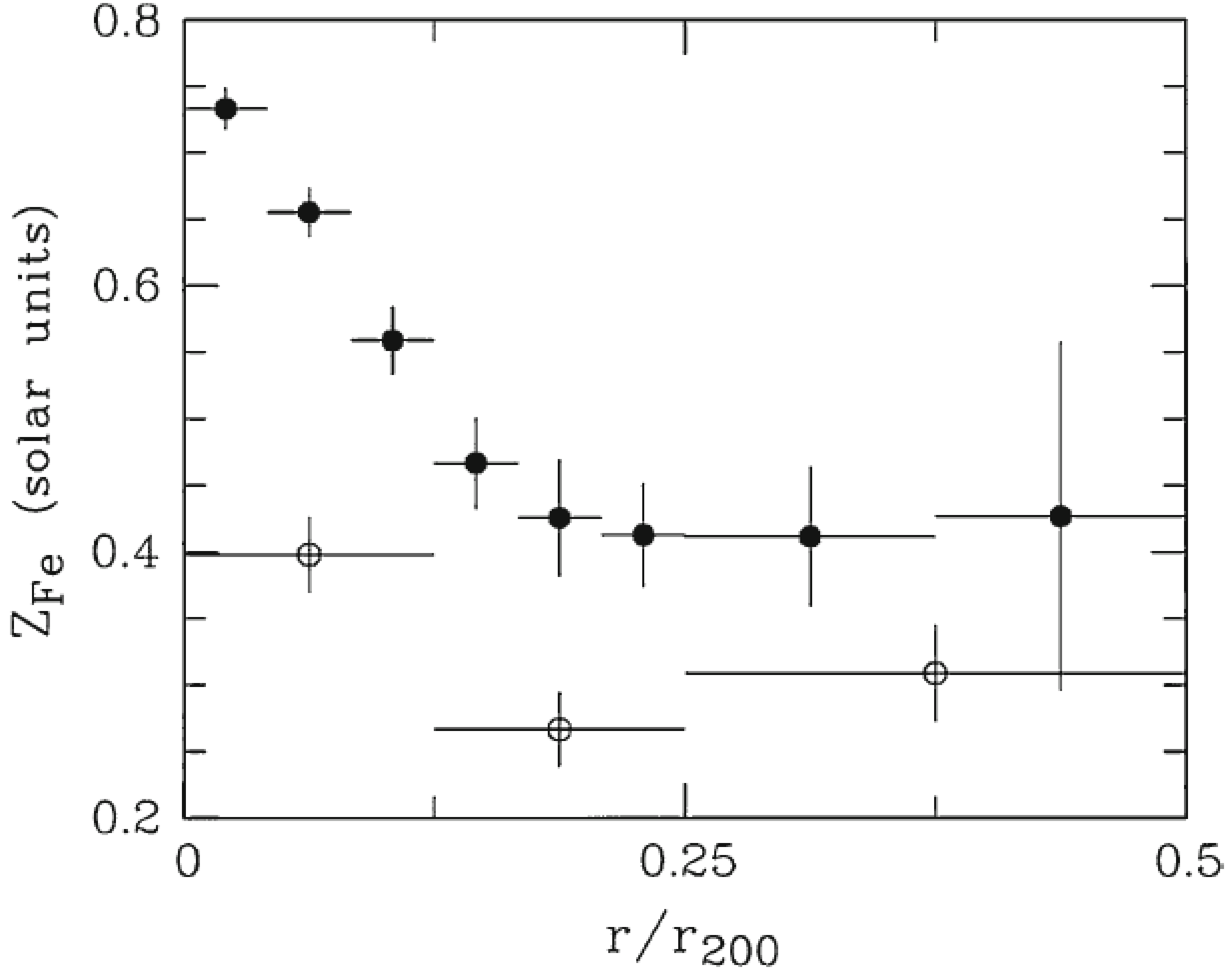
Metals in the ICM

- Emissions lines indicate gas is enriched at 0.3xSolar
- i.e., the ICM cannot just be due to primordial gas; must contain gas processed through stars and then removed from the galaxies
- Most likely mechanisms for injecting metals into the ICM are through:
  - Ramp pressure stripping of gas from galaxies by the ICM
  - Galactic winds



- M82

- But, current mass loss from cluster galaxies would only produce ~3% of the ICM in a Hubble time
  - Need a stage of early, rapid SF in elliptical galaxies
- Results in energetic SNe explosions that drive processed material from galaxies at early epochs of the cluster
- Measure relative abundances of Si, S, Fe etc.
  - Check if consistent with yields from Type II SN



- Abundance gradients observed in the metals
  - Especially prominent in clusters with dense cores/luminous central galaxies
  - Metals transported by winds/AGN interactions?

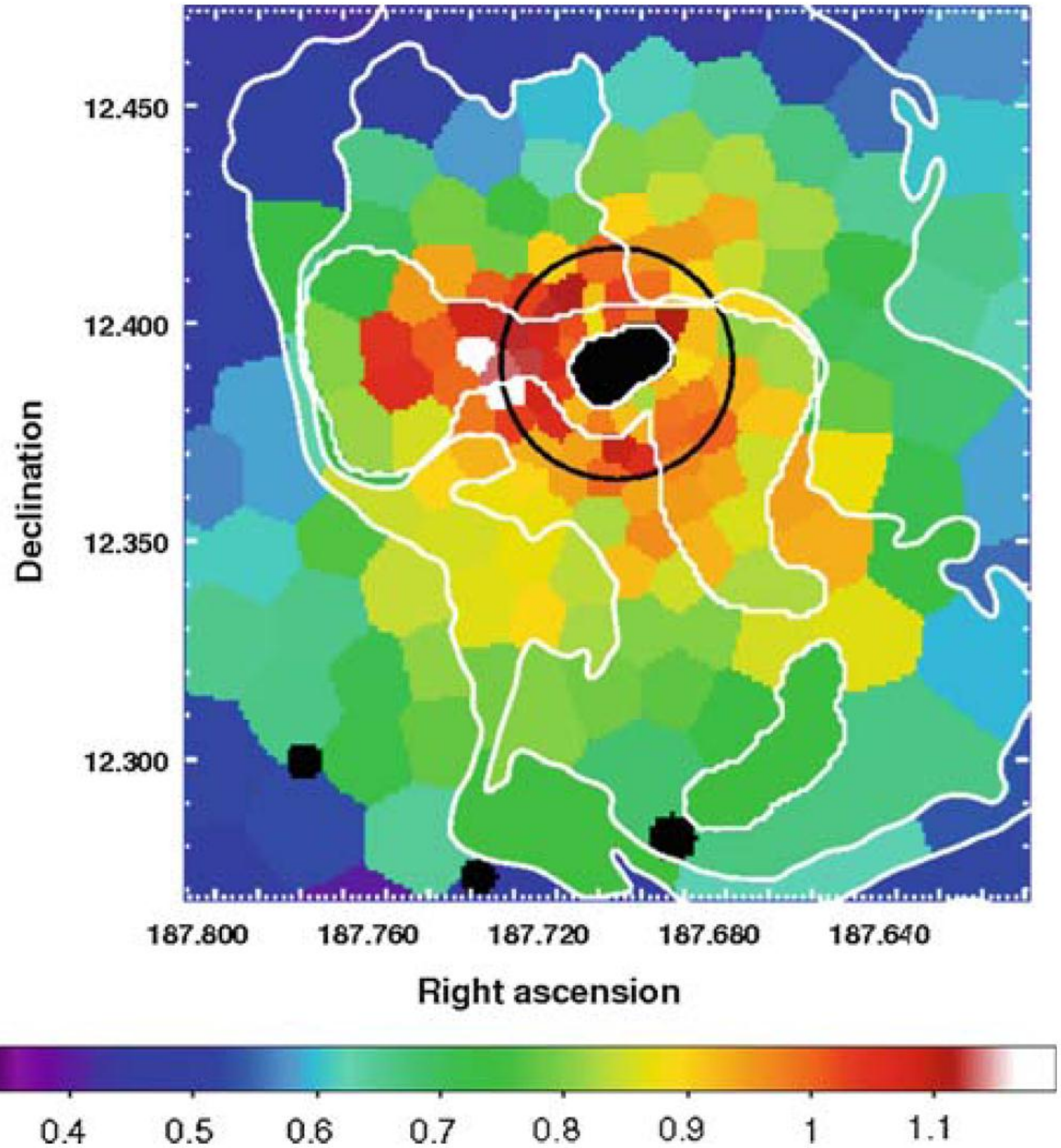


Fig. 34 Map of the Fe abundance in M 87 in Solar units indicated under the color bar. Contours of the 90 cm radio emission (Owen et al. 2000) are overplotted. Beyond the expected radial gradient, one clearly sees the enhanced Fe abundance in the radio arms, especially within the Eastern arm (from Simionescu et al. 2008)

Plasma Physics in Merging Clusters

- The merger of galaxy clusters produces the largest energy release in the Universe after the big bang with energies <~ 10^{63} ergs
- X-rays allow studies of the detailed physics of these slow-motion collisions

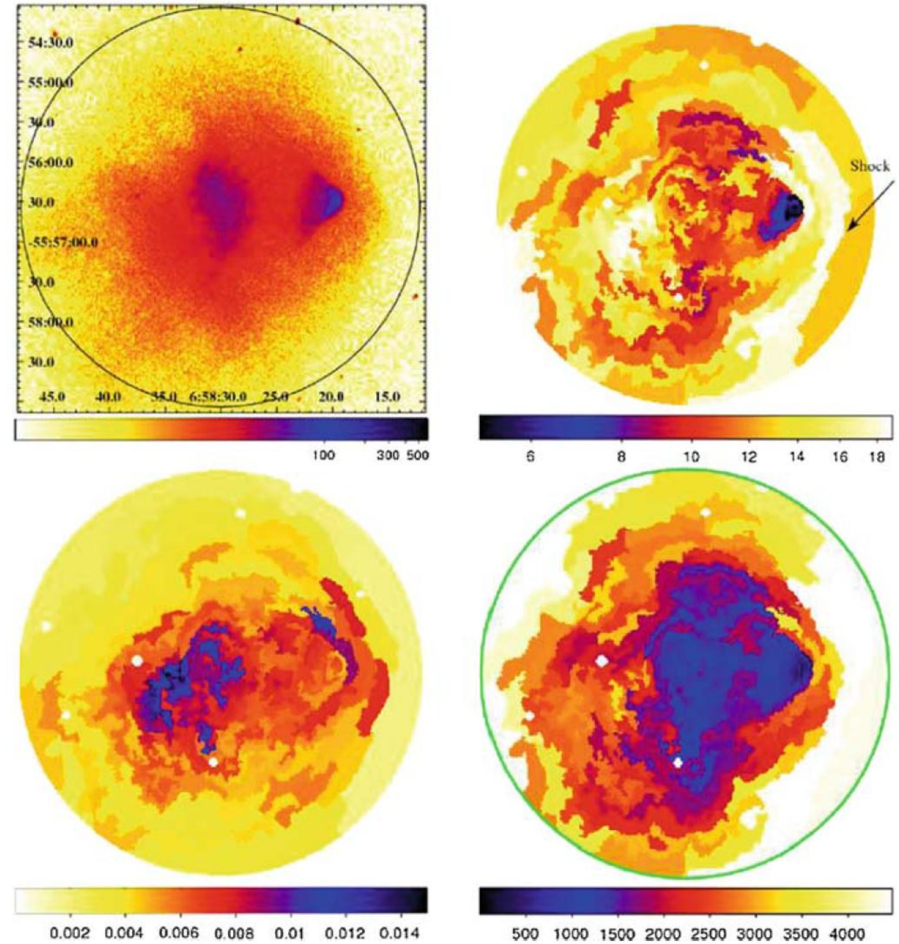
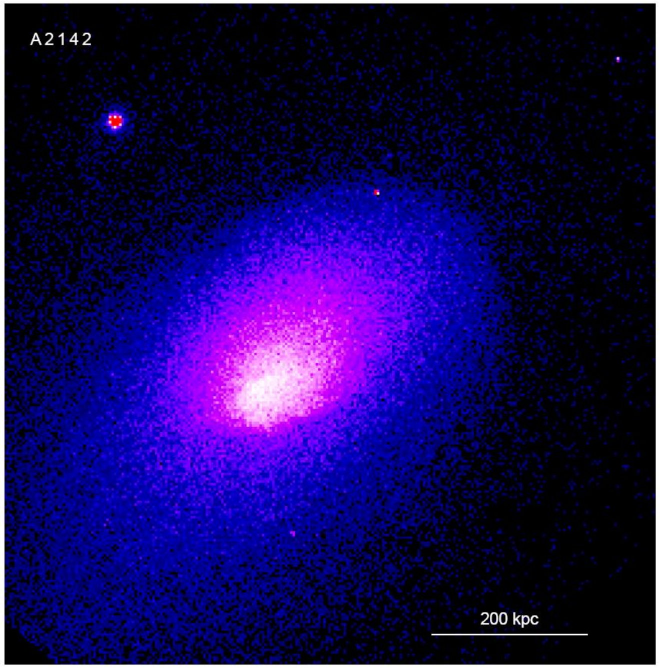
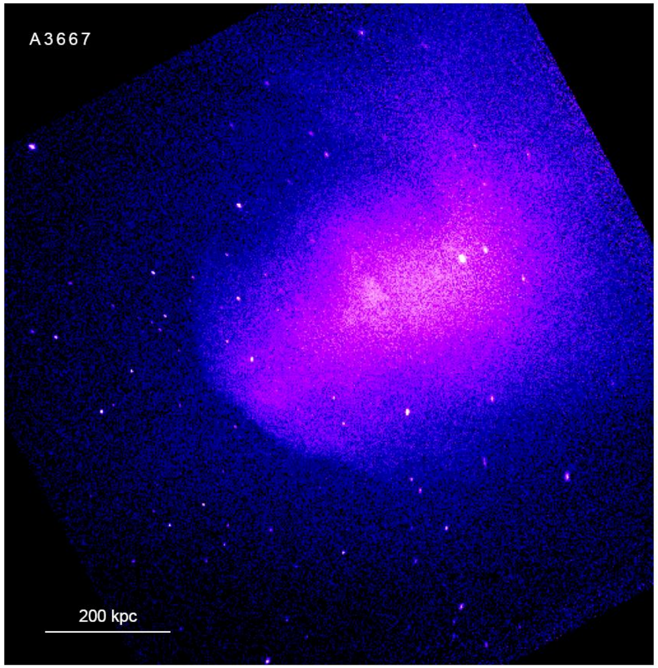


Fig. 16 Thermodynamic maps for the ICM of the "bullet cluster", 1E0657-56 (Million and Allen 2008) produced from a 500 ks observation of this cluster with *Chandra*. The panels show the X-ray surface brightness in the 0.8–7 keV band (*upper left*), the temperature, $k_B T$, in units of keV (*upper right*), the projected pressure in units of keV cm$^{-5/2}$ arcsec^{-1} (*lower left*) and projected entropy in units of keV cm$^{5/3}$ arcsec^{-1} (*lower right*). The shock front preceding the bullet is marked by an arrow in the temperature map

- Cold fronts
- Pressure is continuous across them, so not shocks
- Boundary between cold, denser gas and hot, tenous gas
- Sharpness and stability of these edges require an enormous suppression of conduction
- Argues for magnetic fields
- See astro-ph/0701821 for more





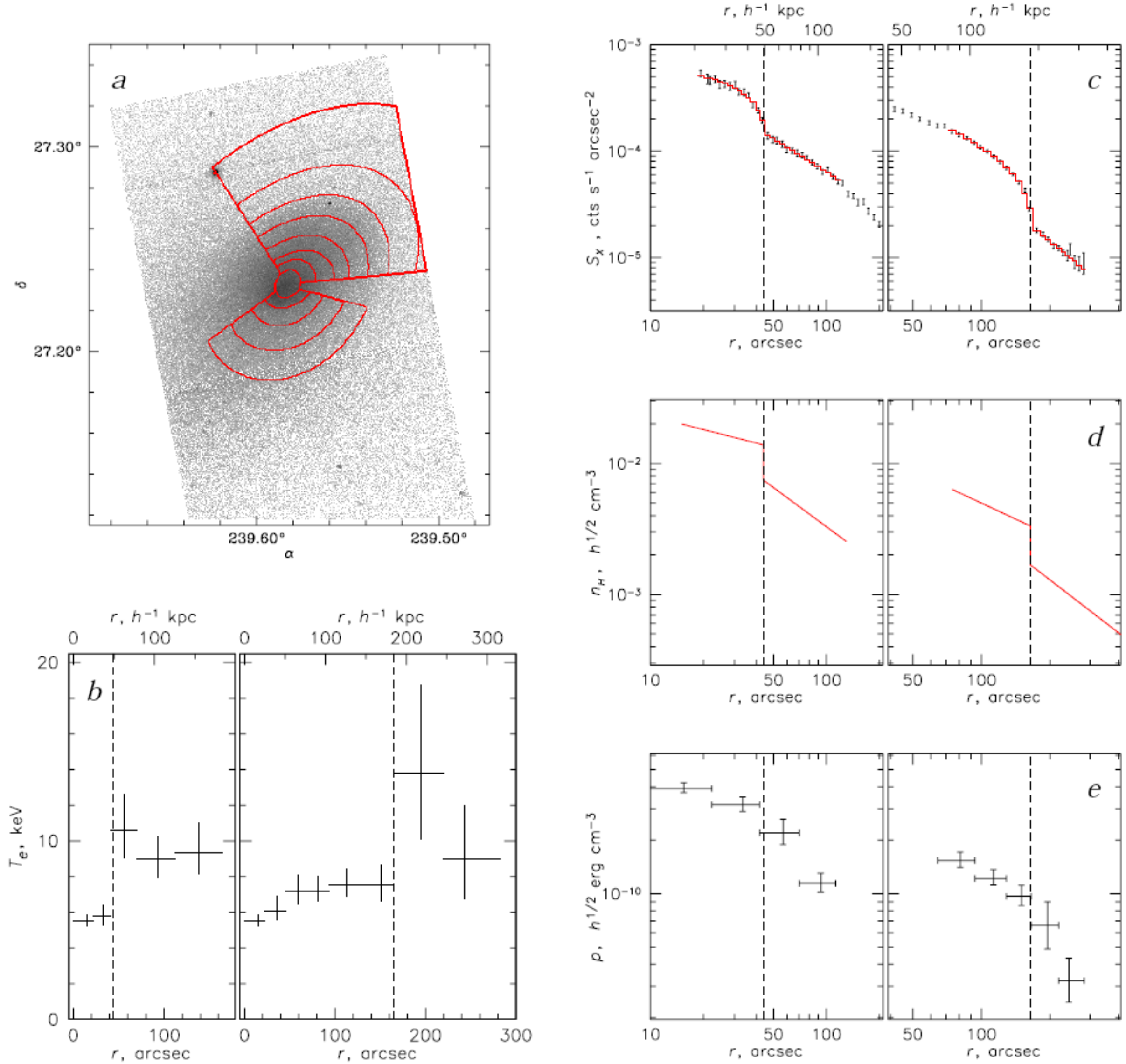


Fig. 4. Cold fronts in A2142 (reproduced from M00). (*a*) X-ray image with red overlays showing regions used for derivation of temperature profiles (panel *b*). In panels (*b*-*e*), the southern edge is shown in the left plot and the northwestern edge is in the right plot. Panel (*c*) shows X-ray brightness profiles across the edges in the same sectors. The red histogram is the brightness model that corresponds to the best-fit gas density model shown in panel (*d*). Panel (*e*) shows pressure profiles obtained from the temperature and density profiles. Error bars are 90%; vertical dashed lines show the positions of the density jumps.