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**Memorie** della

# X–ray emission from clusters of galaxies

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**Abstract.** In the last eight years, the Chandra and XMM–Newton satellites changed significantly our view of X–ray clusters of galaxies. In particular, several complex phenomena have been directly observed: interactions between cluster galaxies and the Intra Cluster Medium (ICM), cold fronts in the ICM, hot bubbles due to relativistic jets from radio loud AGN, the lack of cold gas in "cool–cores", and non–thermal X–ray emission. Still, this increasing complexity does not prevent us from using X–ray clusters as a tool to constrain cosmological parameters. In addition, observations of clusters up to redshift ∼ 1.3, allowed us to trace the thermodynamical and chemical evolution of the ICM on a time interval as large as 8 Gyr. In this presentation, I will give a personal introduction to the most debated topics in this field, to end with some prospects for the next–generation X–ray satellites.

**Key words.** X–rays – Galaxy: Clusters – Cosmology: observations

## 1. Introduction

Clusters of galaxies are the largest virialized objects in the Universe. They form via gravitational instability from the initial perturbations in the matter density field. Clusters are made out of three main ingredients: non–collisional dark matter (∼ 80%), hot (and warm) diffuse baryons (∼ 17%), and cooled baryons (stars in galaxies or diffuse stars, ∼ 3%). The dark matter is dynamically dominant and form potential wells in which the baryons are trapped. The collapse leads to violent relaxation: dark matter and baryons rapidly adjust and reach a pressure balance with the gravitational forces. The velocities of particles inside the halos become randomised, and all the matter components share the same equilibrium within the virial radius.

The diffuse baryons are heated to temperatures between $T_X \sim 1$ keV and $T_X \sim 10$ keV (roughly corresponding to masses ranging from $10^{14}$ to $5 \times 10^{15} M_\odot$) and constitute the Intra Cluster Medium (from now on ICM). Thanks to the very low density of the electrons (typically $n_e \sim 10^{-3}$ cm$^{-3}$) the ICM is optically thin and it is in a state of collisional equilibrium established between the electrons and the heavy ions. The resulting emission from the ICM in the X–ray band is described by a continuum component due to thermal Bremsstrahlung (roughly scaling as $\propto T^{1/2} n_e^2$) plus line emission from K–shell and L–shell transitions of heavy ions (Iron being the most prominent). The collisional equilibrium allows one to derive directly from the X–ray spectrum of the ICM both the electron temperature and the abundances of heavy elements (see Kahn 2005).

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Since the discovery of the X–ray emission from clusters of galaxies by the Uhuru satellite, X–ray cluster samples have been considered one of the best tools for cosmology, thanks to the simple link between the X–ray spectral properties and the total dynamical mass (as a consequence of the virial theorem) and to the simple selection function depending only on the flux limit. Now that we are in the maturity of the Chandra/XMM–Newton era, we realize that clusters harbor an unexpected complexity, that demands a much deeper understanding of the thermodynamics of the ICM and its relation with the other mass components, such as member galaxies and dark matter. This is a well known effect: as soon as you look at Nature with better instruments, it reveals increasing complexity[1].

The present challenge is to update the models of the thermodynamics of the ICM, including several complex processes, in order to re-establish on a firmer basis the reputation of clusters as "laboratories for galaxy evolution" and "signposts for cosmology". In this perspective, I will briefly review what I consider the most relevant issues to address in order to better understand the ICM physics. These are:

- interactions between galaxies and ICM;
- the "cool–cores" problem;
- non thermal X–ray emission;
- chemistry and thermodynamics of the ICM at high redshifts.

Finally, I briefly discuss what we would like to do with the next generation of X–ray satellites.

## 2. Interactions between ICM, cluster galaxies and dark matter

As we said above, the naive picture of clusters of galaxies envisages the baryons as a thermal plasma smoothly sitting in the dark matter potential well, with the galaxies as test particles flying around without any relevant effect on the surrounding medium. We know now that galaxies do affect the ICM, not only because of their motion, but mostly because of energetic internal processes like star formation and nuclear activity.

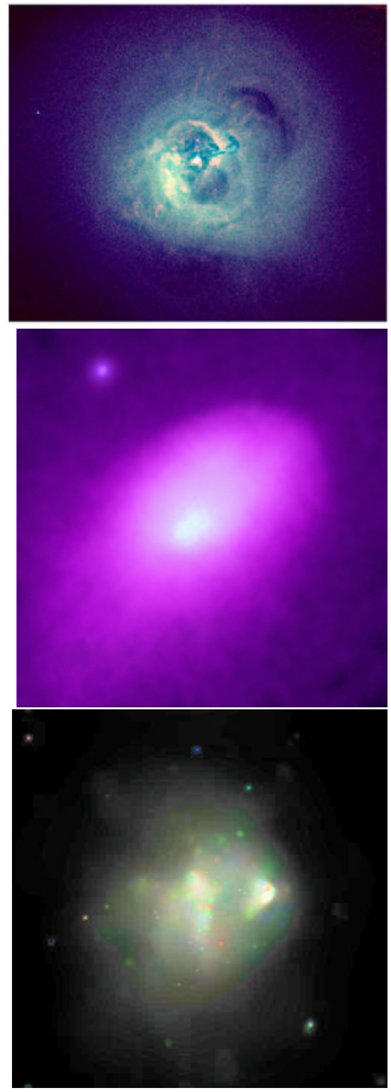

**Fig. 1.** A short gallery of Chandra images of X–ray clusters with ongoing interactions between ICM, galaxies and dark matter. From top to bottom: cavities in the ICM of the Perseus cluster due to the jets from the central radio loud AGN (Fabian et al. 2003); cold fronts in Abell 2142 (Markevitch et al. 2000); an ongoing massive merger in 1E0657–56, the *bullet cluster* (Markevitch et al. 2004).

[1] In better words: "There are more things in heaven and earth, Horatio, Than are dreamt of in your philosophy."

The most dramatic view of galaxy/ICM interactions is given by the gosthly surface brightness distribution of the Perseus cluster (Fabian et al. 2003), shown in the first panel of Figure 1. The radio loud AGN in the central galaxy is responsible for the two large simmetric cavities, originated by the relativistic electrons of the radio jet that pushed away the ICM. Other cavities in the ICM at larger distance from the center show that this episode is somehow recurrent. The mechanical energy associated to these events is huge, and may have a dominant role in giving energy to the ICM in excess with respect to that associated to virialization. However, it is not clear how this mechanical energy can be transformed into thermal energy of the ICM. The presence of an AGN in the central galaxy is also expected to be relevant for the solution of the cool–cores problem (see below), and more in general to raise the average entropy level of the ICM with respect to the self–similar scaling (Ponman et al. 2003).

The second panel of Figure 1 shows cold fronts visible as sharp discontinuities in the surface brightness distribution of Abell 2142. The presence of *cold fronts* has been discovered in Chandra images of bright nearby clusters (Markevitch et al. 2000; Mazzotta et al. 2001). Despite the jump in the electron density, the pressure gradient is constant across the front. The cold fronts are probably due to subsonic motion of colder, group sized clumps of gas. Maybe they are the final stages of a major merger before the onset of a new equilibrium configuration. These observations warn against the use of a simple beta model (Cavaliere & Fusco Femiano 1976) to describe the gas distribution and to derive the total mass of a cluster, as indicated also by significant differences between the X–ray and the lensing mass determinations found in some systems.

In some cases clusters show clear signs of ongoing massive mergers strongly affecting the dynamical equilibrium. A spectacular example is 1E0657–56, the *bullet cluster* (Markevitch et al. 2004), shown in the third panel of Figure 1. Comet–like structures such as the "bullet" are bow shocks associated to ultrasonic motions. In these non–equilibrium stages, the distribution of the diffuse, pressure–supported baryons can significantly differ from that of the dark matter, with significant implications on the nature of the dark matter itself (Douglas et al. 2006).

## 3. The cool–cores enigma

More than half of X–ray clusters of galaxies present central spikes in the surface brightness distribution. The temperature in these central regions is significantly lower than the average one. Due to the higher electron density, the cooling time is significantly lower than the dynamical time of the cluster. Therefore, it is reasonable to expect that the ICM is actually cooling at a rate directly related to the X–ray luminosity, as in the case of the isobaric cooling model. One of the prediction of the so called "cooling–flow" model, is that a wide range of temperatures must be present in the center of such clusters, down to the lowest temperatures detectable in the X–ray band (few tenths of keV). Due to the widespread presence of heavy elements in the ICM, the low temperature gas cools mainly through line emission.

It was a big surprise when the analysis of the high resolution X–ray spectra of the "cooling flows" (taken with the Reflection Grating Spectrometer onboard XMM–Newton) strongly contradicted this picture. It turned out that the emission lines associated to the coldest gas were missing, as shown in Figure 2 (Peterson & Fabian 2006). The lack of the emission lines implies the lack of cold gas. It is possible to estimate a lower limit to the temperature of the gas in the center of X–ray clusters, which always turns out to be about a third of the average (or virial) temperature. Since the gas is cooling but only down to a minimum temperature, these regions have been dubbed "cool–cores" as opposed to "cooling–flows". Istantaneously the nature of "cool–cores" became one of the most enigmatic issue in the field of X–ray clusters.

Which is the process that keep the temperature of the ICM above $1/3\ T_{vir}$? The presence of some extra–energy in the ICM was already known from the study of the scaling relations between X–ray observables like temperature

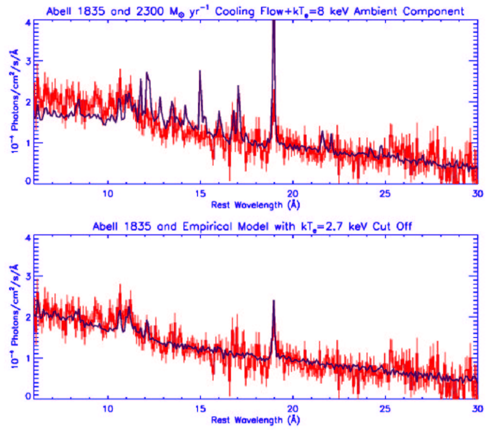


**Fig. 2.** The top panel shows the model (blue) and the data from the Reflection Grating Spectrometer of XMM–Newton for the cool–core cluster Abell 1835. In the bottom panel the gas colder than 2.7 keV has been removed in the model, which now shows a good agreement with the data (Peterson & Fabian 2006).

and luminosity. Gravitational processes (shock heating and virialization) predict a self–similar relation of the kind $L_X \propto T^2$, as confirmed by hydrodynamical N–body simulations. The observed $L_X \propto T^3$ relation, as well as the observation of an entropy excess in the ICM with respect to the self–similar scaling (Ponman et al. 1999), already demonstrated that the ICM can be well described with an extra heating of about 1 keV per particle in addition to the virial energy.

However, the modeling of non–gravitational heating is very difficult, since the cooling is a runaway process which depends on the square of the electron density, while many energetic process we may think of, scale linearly with the total mass density. We have two obvious candidates which can inject energy associated to non–gravitational processes: the prime candidate is feedback from star formation processes, whose effects on the ICM are clearly shown by the presence of heavy elements in the ICM. The ICM is polluted with SNe ejecta (in particular Iron, seen in the X-ray spectrum at 6.7-6.9 keV rest–frame) in an amount consistent with being produced by the massive ellitpicals observed within the virial radius (Matteucci & Vettolani 1988). However it is quite hard to predict the amount of energy dumped into the ICM by SNe explosions, since a large part of it can be radiated away, depending on the physical state of the insterstellar medium around star forming regions. N–body hydrodynamical simulations however, seem to indicate that star formation alone is not sufficient to raise the entropy of the ICM to the observed level (see Borgani et al. 2005).

The second, and most promising, candidate is recurrent feedback from nuclear activity in the cluster galaxies, as directly observed in some nearby bright objects (as in Perseus, shown in Figure 1). Relativistic jets from radio loud AGN may have the right amount of energy, but, once again, the mechanism of transfer of the mechanical energy into thermal energy of the ICM, and the duty cycle of this process, are still unclear.

The Occam's razor pushes us to think that the same process is responsible for both the break of self–similarity of X–ray scaling laws and the temperature floor in cool–cores. Not only, our love for simplicity suggests that also the processes regulating star formation in galactic halos have the same nature. It is well known, in fact, that in Cold Dark matter model, the process of galaxy formation from baryons cooling in dark matter potential wells would cause a "cooling catastrophe" without some sort of feedback which re–heats most of the baryons and stop star formation (see Muanwong et al. 2002). Once again, jets from radio loud AGN and SNe explosions are considered the main agents responsible for the self–regulation of star formation everywhere in the Universe.

To summarize, the evidences of non–gravitational heating of the ICM (feedback) are:

- observation of jets/ICM interactions (direct);
- emission lines of heavy elements in the X–ray spectra of the ICM (direct);
- temperature floor in cool–cores (indirect);
- breaking of self–similar scaling (indirect);

– the absence of catastrophic overcooling (indirect).

It is worth mentioning that the presence of the non–gravitational energy input does not hamper the use of clusters as a tool for cosmology. The relation between X–ray observables and the dynamical mass (which is crucial to link the distribution of clusters to cosmological parameters as briefly described below), is still valid, and maybe it is even tighter once we can provide a comprehensive model for the ICM thermodynamics. A recent example is the use of the parameter $T_X M_{gas}$ which appears to be tightly correlated to the dynamical mass (Kravtsov et al. 2006). Therefore, my feeling is that this increasing complexity is not an impediment, but, on the contrary, is giving us a more powerful tool to investigate at the same time many aspects of structure formation, from subgalactic to cluster scales. The price to pay is, of course, a bigger effort in describing the ICM physics.

## 4. Non–thermal X–ray emission

It is now recognized that non thermal components are relevant in the ICM. The clearest evidence of a relativistic component comes from the radio band. In particular, some clusters show a large scale radio halo, or radio relics, which are produced by a relativistic population of electrons emitting via synchrotron in the presence of a magnetic field. Such relativistic electrons may be associated to acceleration mechanisms occurring at the shocks during major mergers, or during diffuse turbulence.

The study of these components can strongly benefit by the combined observation of the radio and the X–ray emission. In fact, the relativistic electrons are expected to produce an hard tail in the X–ray spectrum of the ICM mainly due to inverse Compton. Hard tails have been observed in few nearby clusters (see Fusco Femiano et al. 2007), despite their existence is still controversial.

Even if the energy content of non–thermal components is limited to few percents, as commonly thought, its effects are relevant to understand the ICM physics. For example, the evaluation of the magnetic field is crucial to assess the role of thermal conduction, which, in turn, can affect the structure of cooling cores, where strong temperature gradients are present.

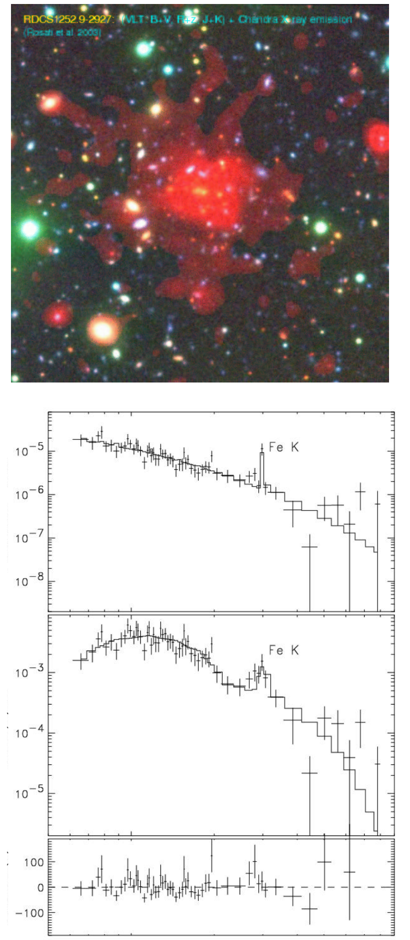


**Fig. 3.** The top panel shows the X–ray emission (in red) of the cluster RXJ1252 at $z = 1.235$ on top of the optical image. Lower panels show the X–ray spectrum of RXJ1252, where the Iron emission line is clearly visible (Rosati et al. 2004).

## 5. Clusters of galaxies up to $z \sim 1.3$

Chandra and XMM–Newton deep observations allowed to study the ICM of clusters at redshifts as high as $z \sim 1.3$. One of the best example is the Chandra observation of RXJ1252, where we clearly detected the Iron line in the X–ray spectrum (see Figure 3).

The presence of heavy elements in the ICM traces the distribution of SNe products into the diffuse hot baryons. Therefore, the evolution of heavy elements abundances with cosmic epoch is a crucial information concerning the interaction of the ICM with cluster galaxies. Precise measurements of the heavy elements content of clusters over large look–back times provide a useful fossil record for the past star formation history of cluster baryons. So far, only the abundance of Iron can be traced back to the highest redshifts where X–ray clusters are observed. Recently, Balestra et al. presented results from a sample of 56 clusters at redshifts $z > 0.4$ observed by *Chandra* and XMM-*Newton* Balestra et al. (2007). The average Iron abundance is already significant at $z \sim 1.3$, at a look-back time of $\sim 9$ Gyr, in line with the peak in star formation for proto–cluster regions occurring at redshift $z > 2$. In addition, an increase of the average Iron abundance with cosmic time below $z = 0.5$ has been observed in the central regions (see Figure 4). The evolution in $Z_{Fe}$ with $z$ can be parametrized by a power law of the form $\sim (1+z)^{-1.25}$. The observed evolution implies that the average Iron content in the inner regions (radii $R \leq 0.2 R_{vir}$) of the ICM at the present epoch is a factor of $\sim 2$ larger than at $z \simeq 1.3$. These data provide significant constraints on the time scales of the physical processes that drive the chemical enrichment of the ICM. For example, this evolution can be explained by the release of enriched gas into the ICM from disk galaxies transforming into S0 in the central regions of clusters (Calura et al. 2007). However, the mechanism responsible for the gradual transfer of the enriched gas from the cold, low entropy phase associated to galaxy or group–size halos to the ICM is still under investigation with hydrodynamical simulations (Cora et al. in preparation).

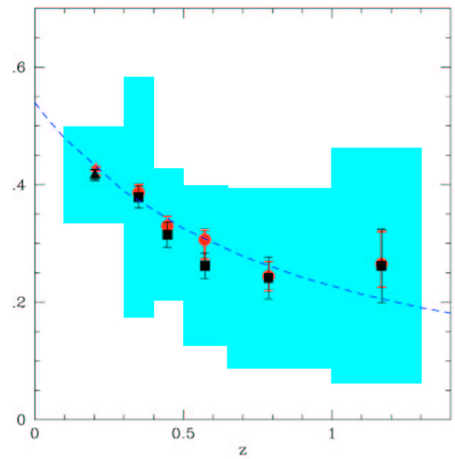


**Fig. 4.** Solid squares and circles show Iron abundance in the inner regions of hot clusters ($kT > 5$ keV) averaged over about 10 clusters in each bin (with two different combining methods), as a function of redshift (Balestra et al. 2007). The shaded area show the rms dispersion of the single measures, while the dashed line is a fit to the $Z_{Fe}$ evolution of the form $\sim (1+z)^{-1.25}$.

## 6. Cosmology with X–ray clusters

Clusters are ideal objects to trace the large scale structure of the Universe. In particular, their number density as a function of the mass scale and of the cosmic epoch strongly depend on cosmological parameters. The observation of clusters over a wide range of redshifts is therefore a valuable tool for cosmology. In Figure 5 we show the hierarchical evolution of hot ($kT > 3$ keV) clusters in different cosmologies, as it appears in N–body simulations. Given the same local abundance of clusters, in a flat ΛCDM Universe (first row) there are several hot massive clusters at redshift $z \sim 1.4$, as opposed to an high density Universe (second row). About fifteen years ago, before results from deep surveys with the ROSAT satellite had been published (Rosati et al. 1998), the presence of massive, hot clusters at redshift as low as $z \sim 0.2$ was strongly questioned. Now, the presence of massive clusters at redshift as large as $z \sim 1.3$ is firmly established, and this represents a strong hint in favour of a low density, $\Omega_0 \sim 0.3$, $\Lambda \sim 0.7$ CDM Universe. This

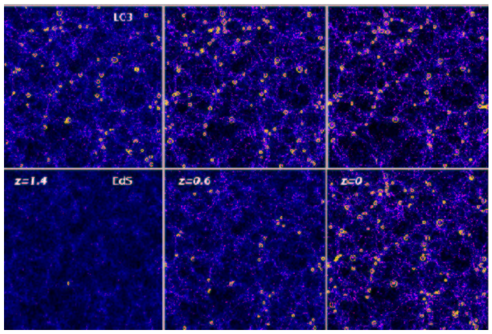


**Fig. 5.** A visual rendition of the hierarchical growth of clusters of galaxies in a ΛCDM (first row) and a critical (second row) Universe. Massive clusters, indicated with small circles, are abundant in a ΛCDM Universe even at redshift $z \sim 1.4$.

is in line with what has been found in several CMB experiments in recent years.

The distribution of clusters can be used to constrain cosmological parameters thanks to well established models for the mass function of virialized halos. The simple theory of linear evolution of the initial density-perturbations field plus the virial theorem applied to the non–linear overdensities, allows one to compute straight out the mass distribution of virialized halos as a function of cosmic epoch. The Press & Schechter theory (Press & Schechter 1974) and its extensions, have been widely tested with numerical simulations, and are now commonly used to predict the temperature and luminosity distribution of X–ray clusters. The main uncertainty is now due to the relation between the dynamical mass and the X–ray observables. As discussed above, this relation is not simple, but it is well established on an observational basis and on theoretical grounds. Quite clearly, the challenge now is to refine the modeling of the mass/X–ray observables relations and their intrinsic scatter, in order to perform the so called "precision cosmology" with clusters.

However, X–ray clusters always proved to be an excellent tool for cosmology. An example of their effectiveness is given by the constraints on the cosmological density parameter $\Omega_0$ and on the normalization of the linear spectrum of density fluctuations $\sigma_8$, derived using

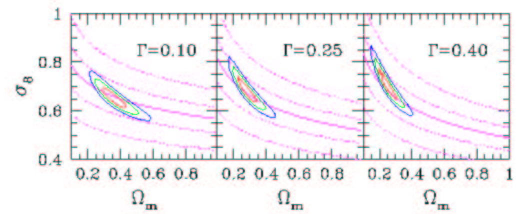


**Fig. 6.** Confidence levels in the $\sigma_8$–$\Omega_0$ plane from the X–ray luminosity function of distant clusters of galaxies observed with ROSAT (Borgani et al. 1999). Different panels correspond to different shapes of the linear power spectrum of density fluctuations.

ROSAT data, as shown in Figure 6. In particular, we would like to remark that the value of $\sigma_8 \sim 0.7$ found for clusters, initially at variance with the measure $\sigma_8 = 0.84 \pm 0.04$ in the first year of WMAP, is now in agreement with the new WMAP results (Spergel et al. 2007). Once again, this is a good example of the complementarity of X–ray clusters with respect to other geometrical cosmological tests, like high–z SNe and CMB experiments.

## 7. Great expectations

Next future X–ray clusters astronomy must face a double challenge: first, understanding the physics of the ICM, exploring in greater details the cool–cores but also the low surface brightness regions in the outskirts of clusters; second, finding more clusters and groups at high redshifts. It is a matter of fact that the large majority of high–z X–ray clusters, which are the targets of present–day Chandra and XMM–Newton deeper observations, have been discovered by ROSAT, while only and handful have been discovered in recent times.

In order to find more high–z clusters, how much wide and deep do we need to go? A step forward will be provided by missions like eRosita (PI G. Hasinger), which will provide a medium–deep, all–sky survey with medium spatial resolution. Another strategy is going deeper in a smaller solid angle with a wide field imager with good spatial resolution (few arcsec). This is one of the goal of EDGE, a medium size class mission, devoted to the study of diffuse baryons both in emission or in absorption against bright GRB (PI L. Piro). Deep pointings with EDGE of about 1 Ms will reach flux limits comparable to Chandra deep surveys but on a much larger solid angle. EDGE will allow one to detect groups out to $z > 1$ and clusters out to $z \geq 3$. In addition, another instrument onboard of EDGE, the Wide Field Spectrometer based on cryogenic microcalorimeters, with excellent energy resolution of about 3 eV will be able to provide direct velocity measurements in the cluster cores to study turbulence in the ICM and the cool–cores problem, as well as the faint outer regions of clusters.

## 8. Conclusions

The physics of the ICM is complex, and it must include the combined effects of star formation and nuclear activity in the cluster galaxies on the diffuse baryons. Understanding this complex interplay requires a comprehensive approach to galaxy formation, mass accretion processes onto Super Massive Black Holes, heavy elements production and diffusion, AGN jets–ICM Interactions, effects of the non–thermal components, and other phenomena, all at the same time. The good news is that understanding the ICM means also understanding galaxy formation, and being able to constrain cosmological parameters and the growth of the large scale structures across cosmic epochs.

To capitalize and extend what we have learned so far with Chandra and XMM–Newton, we must have soon both a wide area medium–deep survey as well as a mission devoted to the properties of the ICM. Looking further into the future, the next generation of X-ray telescopes must achieve a spatial resolution comparable to that of Chandra, which proved to be crucial to avoid confusion limit and to isolate genuine diffuse emission at very high redshifts.

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