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The multifrequency astrophysics of galaxy clusters

S. Colafrancesco *

INAF - Osservatorio Astronomico di Roma, Monteporzio (Roma) I-00040, Italy

Abstract We discuss the evidence and the physical relevance of the astrophysical phenomena (of thermal and non-thermal origin) occurring in galaxy clusters as obtained from multi-frequency observations, from radio to gamma-rays.

Key words: Cosmology — Galaxies: clusters

1 GALAXY CLUSTERS ACROSS THE E.M. SPECTRUM

Clusters of galaxies are the largest gravitationally bound structures in the universe and, according to the viable cosmological scenario for structure formation, they are also the youngest structures in the universe. These cosmic structures are the largest containers of cosmic material: (*i*) they contain baryonic matter in condensed (stars, galaxies with a mass fraction $M_\star/M \sim 0.013$) and diffuse (hot and warm intra-cluster medium - hereafter ICM - with a mass fraction $M_{\rm ICM}/M \sim 0.13$) forms as probed by optical and X-ray emission, respectively; (*ii*) the vast majority ($\sim 90\%$) of their matter content is constituted by Dark Matter (DM) which forms their gravitational potential wells probed by the gravitationally distorted images of lensed background galaxies; (*iii*) a third component of the cluster atmospheres is constituted by a population of relativistic (or slightly sub-relativistic) particles with a non-thermal energy distribution whose presence is mainly probed by the diffuse synchrotron emission.

The various emission phenomena induced by the presence and interaction of the constituents of the cluster atmospheres are observed over the whole electromagnetic (e.m.) spectrum, from the radio to the gamma-ray frequencies.

At radio frequencies, galaxy clusters show diffuse synchrotron emission (radio halos and relics) in the frequency range ~ 10 MHz to ~ 10 GHz (see Fig.1).

To emit synchrotron radiation at these frequencies in a intra-cluster (IC) magnetic field of order $B_\mu \equiv (B/\mu{\rm G}) \sim 1$, the electrons must have energies $E_e = 16.4$ GeV $(\nu/{\rm GHz})^{1/2} B_\mu^{-1/2}$ which fall in the range $\sim 2-50$ GeV. The notable precision of the radio-halo spectra data, usually fitted by a power-law $F_\nu \sim \nu^{-\alpha_r}$, allows to constrain the shape of the relativistic electron equilibrium spectrum $n_{\rm rel} \sim E_e^{-x}$ since the radio-halo spectral index α_r is directly related to the electron spectrum index x by $\alpha_r = (x-1)/2$ (e.g., Longair 1993). The observed values are in the range $\alpha_r \approx 1-1.5$ which yield $x \approx 3-4$. Synchrotron emission from radio halos yields also a direct indication of the existence of a tangled IC magnetic field filling the cluster atmospheres. The IC magnetic field B is expected to have a radial profile (with a central concentration) after the

* E-mail: cola@mporzio.astro.it

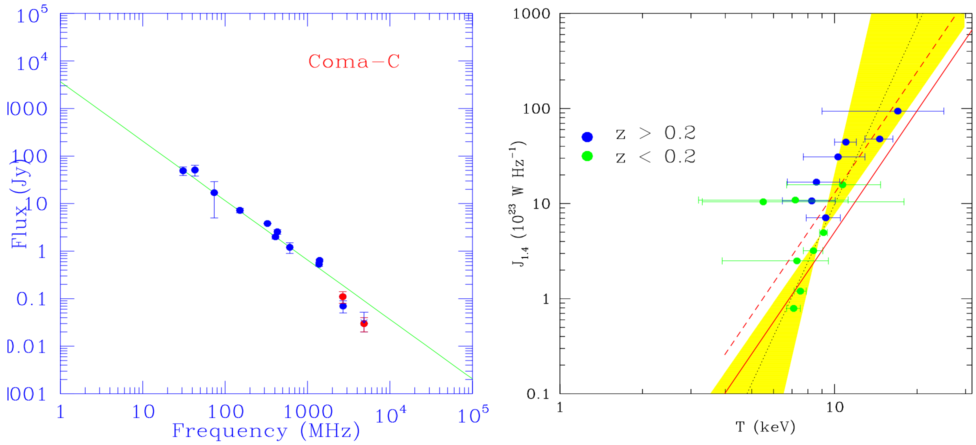

Fig. 1 **Left.** The Coma radio-halo spectrum. The power-law fit to the data at $\nu \leq 1.4$ GHz corresponds to an electron spectral index $x = 3.5$. Data compilation is taken from Thiearbach et al. 2002. **Right.** The Radio luminosity $J_{1.4}$ – IC temperature T correlation for nearby radio-halo clusters (from Colafrancesco 1999, Colafrancesco & Mele 2001). We show the best fit and 1σ uncertainty region and the predictions of secondary models at $z < 0.2$ (solid line) and $z > 0.2$ (dashed line).

cluster reaches its virial equilibrium (e.g., Dolag et al. 2001). A decreasing radial profile is also expected based on the correlation of the value of B with the IC gas density (Dolag et al. 2001). Estimates of its amplitude are quite uncertain and depend on the considered observational method (Carilli & Taylor 2002). Faraday Rotation measures local (central) line of sight values with amplitude $B_0 \sim 5 - 75$ μG (Eilek 1999) while the combination of synchrotron and Inverse Compton Scattering (ICS) interpretation prefer lower values $\langle B_\mu \rangle \sim 0.1 - 1$ of a *uniform* field. We observe today more than 50 galaxy clusters with radio halos whose spatial extension varies from a few hundreds kpcs to a few Mpcs (Giovannini et al. 2000, Kempner & Sarazin 2001). The large linear size of radio halos ($\sim$Mpc) compared to the short paths traveled by high-E electrons - which rapidly loose their energy due to Compton and synchrotron losses (Longair 1993) - require either an efficient and isotropic re-acceleration mechanism or an *in-situ*, stationary production. The spatial distribution of radio-halo brightness seem to resemble the spatial distribution of the cluster X-ray brightness (Govoni et al. 2001) indicating a connection between non-thermal and thermal phenomena. However, the best indication of the connection between non-thermal and thermal phenomena in clusters is provided by the radio-halo luminosity J_ν – IC temperature T correlation (Colafrancesco 1999, Liang et al. 2000, Colafrancesco & Mele 2001; see Fig.1).

At sub-mm frequencies, galaxy clusters are detectable as sources of Compton scattering of the CMB photons (the SZ effect; Sunyaev & Zel'dovich 1972, Birkinshaw 1999) which produces a systematic increase of CMB photon frequencies. As a consequence of the SZ effect, clusters appear as regions of temperature (brightness) decrement with respect to the CMB at $\nu \lesssim 218$ GHz, and as regions of temperature (brightness) increment at $\nu > 218$ GHz (the exact location of the frequency of null variation depends on the entity of the relativistic corrections to the thermal SZ effect, see Birkinshaw 1999, Colafrancesco et al. 2003). The SZ induced brightness (temperature) change is given by $\Delta I/I \propto \Delta T/T \propto y \cdot g(x)$ where $y = \sigma_T \int d\ell n_e \frac{kT_e}{m_e c^2}$ and $g(x)$ contains the spectral dependence of the SZ effect (see Fig.2). Since the SZ effect is redshift independent (there is no z-dependence in the expression of $\Delta T/T$), it is a powerful tool

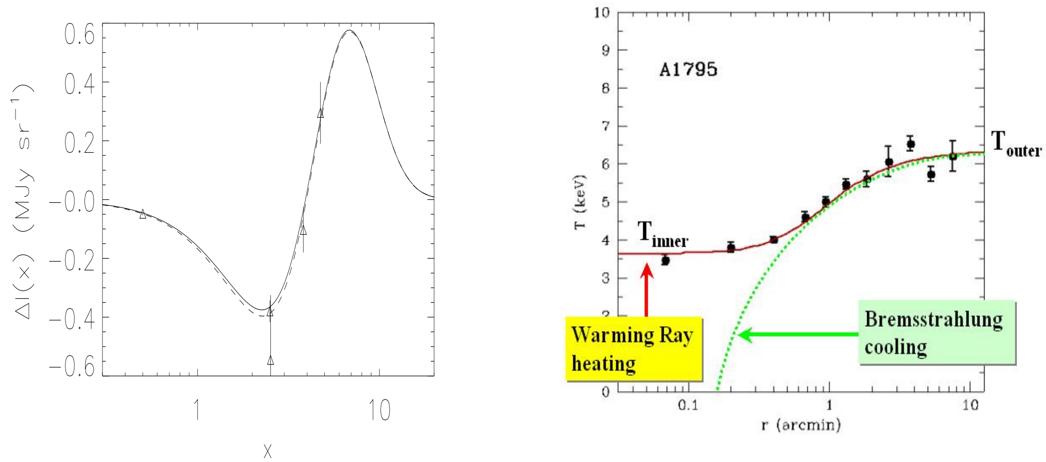

Fig. 2 **Left.** Theoretical expectations for the spectrum of the SZ effect in A2163. We show the fit to the available data yielded by a thermal population (solid curve) and the expectations obtained from a combination of thermal and non-thermal populations with a value of the pressure ratio $P_{\rm rel}/P_{\rm thermal} = 0.29$ (dashed curve), which provides the best fit. **Right.** The radial temperature distribution of the cluster A1795 as fitted by the *warming rays* model (see Colafrancesco et al. 2004 for details). The schematic representation of the T distribution due to bremsstrahlung cooling is shown as the dotted curve.

for searching and studying the physics of high-z clusters. As such, it can be efficiently used to probe the cosmological scenario of structure formation (Carlstrom et al. 2002).

There are a few evidence of IR emission from galaxy clusters and most of it seems to be associated with the IR emission of cluster galaxies.

The cluster galaxies are best studied in the visible part of the e.m. spectrum. This frequency range gives the opportunity to study both the dynamics and the overall population evolution of the galactic component of the cluster. Moreover, weak and strong lensing of background galaxies produced by the intervening cluster mass distribution provide a unique tool to probe the details of the cluster gravitational well and of the spatial distribution of the DM (Bartelmann & Schneider 2001). Preliminary evidence of diffuse IC light is also emerging (Feldmeier et al. 2002) and provides a possibly important tool to probe cluster galaxy evolution and the effects of their inner material ejection.

Optical studies on the cluster dynamics and of their DM content are complemented by X-ray studies in the $\sim 1 - 10$ keV energy range which make use of the emission properties of the hot ($T_e \sim 10^8$ K), optically thin ($\tau \sim 10^{-3}$ with IC density $n_e \sim 10^{-3}$ cm^{-3} and linear size $\ell \sim 1\ h_{100}^{-1}$Mpc) IC plasma in hydrostatic equilibrium with the overall gravitational potential well of the cluster (e.g., Sarazin 1988). Studies of the cluster X-ray thermal bremsstrahlung emissivity, $\varepsilon_X \propto n_e^2 T_e^{1/2}$, and temperature T_e allow to determine the physical properties of the IC gas and its evolution over a large part of the cosmic history. Deep observations of nearby and distant X-ray clusters have also offered the possibility to probe both the matter (baryons and DM) distribution on the large scales of the universe, and to set constraints to the fundamental cosmological parameters.

However, the advent of high-sensitivity, high-spatial resolution X-ray telescopes like Chandra and XMM has also pointed out the existence of more detailed physical processes in the IC medium which demands a more refined physical description of its origin and evolution. Cluster cores definitely show a much more complicated interplay between the central (active) galaxies, the relativistic fluid, the magnetic field and the surrounding IC medium. As a matter of fact, the IC gas doesn't cool efficiently into the cluster cores - as was expected on the basis of the simple physical description - but settles into a high-density, thermal equilibrium phase at an inner temperature $T_{\rm inner} \sim T_{\rm outer}/2$ (Peterson et al. 2002), which requires the onset of a non-gravitational source of heating. Possible heating mechanisms which alleviate the problem involve thermal conduction, heating by radio/active galaxy jets, and heating by cosmic-ray (CR) electrons. The solution to the cooling-flow problem requires, however, an energy deposition more intense and more distributed than in conventional CR models. In the alternative model recently proposed by Colafrancesco et al. 2004, the X-ray energy emitted by clusters is supplied, in a quasi-steady state, by the hadronic CRs, which act as *warming rays*. The temperature distribution in the IC space is successfully predicted from the measured plasma-density distribution (see Fig.2). The presence of cavities and bubbles filled with relativistic gas and magnetic field floating in the IC medium (McNamara 2003) provide further evidence for the interplay between thermal and non-thermal plasmas. The high metal abundances in cluster cores (Kaastra et al. 2003) set also contraints to the mixing efficiency of the IC material.

In the cluster environment another unforeseen event seems to takes place. Warm gas with $T_e \sim 10^5 - 10^6$ K is observed in the soft X-ray and extreme UV (EUV) ranges. In fact, several galaxy clusters show an emission of extreme UV (Lieu et al. 1996, Durret et al. 2002) and soft X-ray (Bonamente et al. 2002, Kaastra et al. 2003) radiation in excess to the extrapolation of thermal bremsstrahlung emission produced by the hot, thermal electron population. For example, the Coma EUV flux observed in the $65 - 245$ eV band is $\sim 36\%$ above the expected flux from the thermal bremnsstrahlung emission of the $k_B T \approx 8.2$ keV IC gas (Ensslin & Biermann 1998) and it can be modeled with a power-law spectrum with a slope , $\alpha_{EUV} \approx 1.75$. This EUV emission excess can be consistent with both ICS of CMB photons off a non-thermal electron population (see, e.g., Lieu et al. 1999, Bowyer 2000) with $E_e = 608.5$ MeV $(h\nu/\mathrm{keV})^{1/2} \gtrsim 149$ MeV for $h\nu \gtrsim 60$ eV, and with thermal emission from a warm gas at $k_B T_e \lesssim 1$ keV (Bonamente et al. 2002). In the ICS origin, the EUV excess requires a relativistic electron spectrum with a slope $x \approx 2.5$, which is much flatter than the value $x \approx 3.5$ required by the radio halo spectrum.

At energies $\gtrsim 20$ keV another emission excess over the thermal bremsstrahlung emission from the hot thermal IC plasma emerges from the analysis of several nearby, bright clusters (Nevalainen et al. 2004). The shape of the hard X-ray (HXR) emission observed towards the direction of the Coma cluster with the BeppoSAX-PDS (Fusco-Femiano et al. 1999) is still consistent with ICS of CMB photons off a non-thermal electron population with energies $E_e \gtrsim 3.3$ GeV for $h\nu \gtrsim 30$ keV whose spectrum should have a slope $x \sim 3.5 - 4$. It is difficult, however, to assess the role of contamination of the HXR excess by other hard X-ray sources in the direction of the cluster, like heavily absorbed Seyfert-II galaxies in the wide field of view of the PDS instrument (Nevalainen et al. 2004). Such possible contamination thus allows to get only upper limits to the density of relativistic electrons estimated in the ICS interpretation. Alternative explanations of the HXR excess in terms of a suprathermal electron population in Coma (Ensslin et al. 1999) seems to be excluded due to large energy injection required by the associated non-thermal bremsstrahlung emission (Petrosian 2001). A model in which the HXR emission in Coma is provided by synchrotron emission of high energy electrons produced in the interaction of very high-E gamma-rays (Timokhin et al. 2003) relies on the (unclear) possibility to have a specific source of very high-E gamma-rays in clusters. The HXR emission

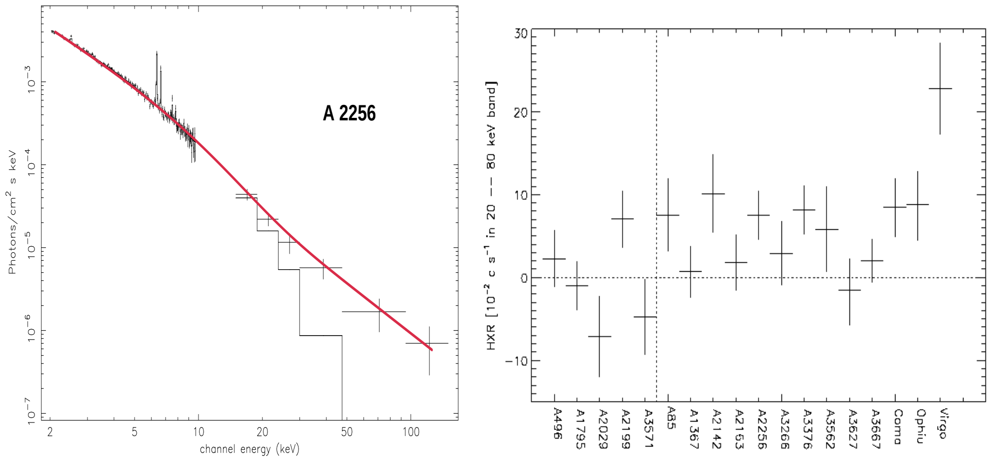

Fig. 3 **Left.** The HXR emission from the cluster A2256 (data from Fusco-Femiano et al. 2000) together with the fit provided by the CR model of Colafrancesco et al. 2004 (thick-red curve). **Right.** The 20-80 keV luminosity of the clusters which show evidence of HXR emission (from Nevalainen et al. 2004).

from clusters can indeed be fitted by a model in which cosmic rays are injected in the IC plasma by GRBs-cannonballs acting in the many cluster galaxies (Colafrancesco et al. 2004). In this model, the electrons knocked-on by the cannonball recoil with large kinetic energy and then, the scattered electrons cool and thermalize mainly via bremsstrahlung at high-E and by Coulomb collision at low-E. This model provides a simple solution for warming up the cluster cores in cooling-flow clusters and for producing HXR tails in non cooling-flow clusters, as observed.

The extrapolation of the ICS spectrum which fits the HXR excess of Coma down to lower energies $\lesssim 0.25$ keV does not fit the EUV excess measured in Coma because it is too steep and yields too high flux compared to the measured flux by the EUV satellite in the $0.065-0.245$ keV band. Thus, under the assumption that the HXR of Coma is produced by ICS of CMB photons, the minimal requirement is that a break in the electron spectrum should be present in the range $0.3-2.8$ GeV in order to avoid an excessive EUV contribution by the relativistic electron ICS and to be consistent with both the radio halo spectrum and with the EUV excess of Coma. The ICS interpretation of the HXR excess in Coma also requires a quite large density of relativistic electrons, so large that the uniform IC magnetic field required to accomodate for the simultaneous synchrotron radio emission is $B \lesssim 0.2\ \mu$G, sensibly smaller than that implied by Faraday Rotation measures (see, Carilli & Taylor 2002). This discrepancy might be alleviated by considering cut-off in the electron energy spectrum, spatial profiles of the magnetic fields or a power spectrum analysis of the magnetic field (e.g., Colafrancesco 2004 for a recent review). However, such a low value of B contrasts also with the lower limit $B \gtrsim 0.4\ \mu$G derived from the EGRET gamma-ray upper limit on Coma (see, e.g., Sreekumar et al. 1996, Colafrancesco & Mele 2001).

There is not yet a definite detection of diffuse gamma-ray emission from galaxy clusters. While there is a preliminary evidence of gamma-ray emission from a dozen bright, radio-active clusters which host powerful radio galaxies and Blazars (see Fig.4) and are associated to unidentified EGRET sources (Colafrancesco 2002), many of the quiet, X-ray selected clusters only have upper limits for their emission at $E > 100$ MeV. The possibility of having spatial and spectral information on the diffuse gamma-ray emission from clusters is of great importance because it

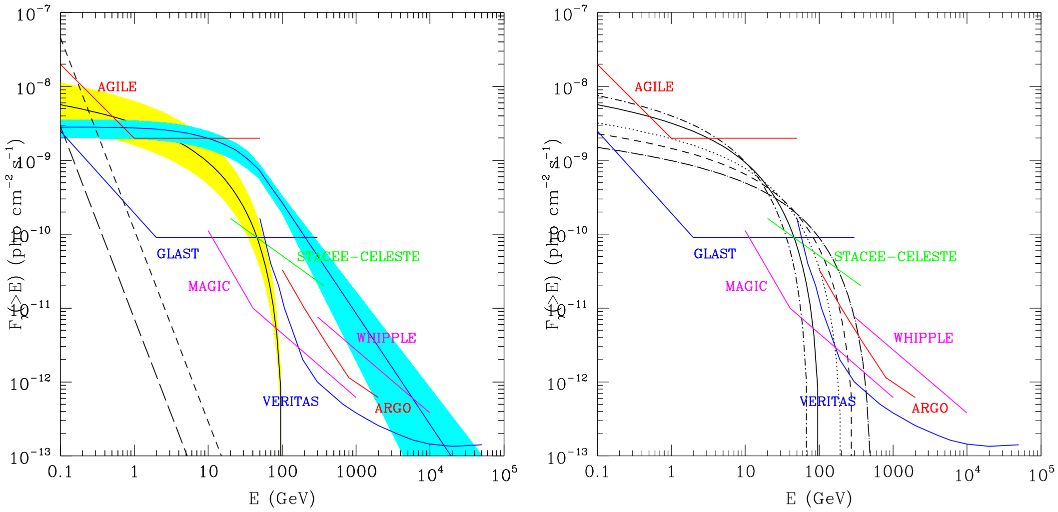

Fig. 4 **Left.** The prediction of the diffuse gamma-ray emission of Coma in different models for the CRs origin: bremsstrahlung for $B_\mu = 0.3$ (short dashes) and 1 (long dashes); neutralino annihilation for $M_\chi = 100$ GeV (yellow area) and p-p collision (blue area) (from Colafrancesco 2002). **Right.** The gamma-ray emission spectra expected from neutralino annihilation in galaxy clusters. Different curves are computed for increasing values of $M_\chi = 70, 100, 200, 300, 500$ GeV (from Colafrancesco & Mele 2001).

can yield direct information on the origin of the relativistic particles in the cluster atmosphere (see Fig.4). Gamma-rays are, in fact, expected to be emitted from clusters due to a variety of mechanisms: $\pi^0 \to \gamma + \gamma$ due to either proton-proton collisions or to DM particle (neutralino) annihilation; bremsstrahlung and ICS emission from both primary and secondary electrons accelerated and/or injected in the IC medium. Interestingly, the emission spectra of these models are quite different and this could allow to disentangle the CR origin in Large Scale Structures (see Colafrancesco 2004 for a review).

Cosmic rays (electrons and protons) are indeed expected to be produced or injected in the cluster atmospheres by the occurrence of different mechanisms. X-ray observations and N-body simulations (see Fig.5) indicate the existence of shocks in the IC medium. Internal shocks arising from substructure merging are typically small, fragmented and diffused in the cluster environment. External, accretion shocks are, on the contrary, large, coherent and localized (Ryu et al. 2003). Internal shocks have low Mach number and may provide $\sim 95\%$ of the gas thermalization efficiency as well as $\sim 90\%$ of the particle acceleration efficiency, reaching momentum values $p \gtrsim 10^2 m_e c$ (Ryu et al. 2003). External shocks are energetically less important but can, in principle, accelerate CRs to Ultra High Energies. Beyond shock acceleration, CRs can also be injected in the cluster atmosphere either by the energetic jets of active galaxies or by the GRBs-cannonballs developing inside many cluster galaxies (e.g., Colafrancesco et al. 2004). Finally, CRs with large enough energies (up to the DM particle mass) may also be produced as secondary decaying products in the annihilation of DM particles like neutralinos (e.g., Colafrancesco & Mele 2001).

To summarize, the full picture of the cluster emission properties across the e.m. spectrum spans over more than 16 orders of magnitude in energy (see Fig.6). The hot thermal electron

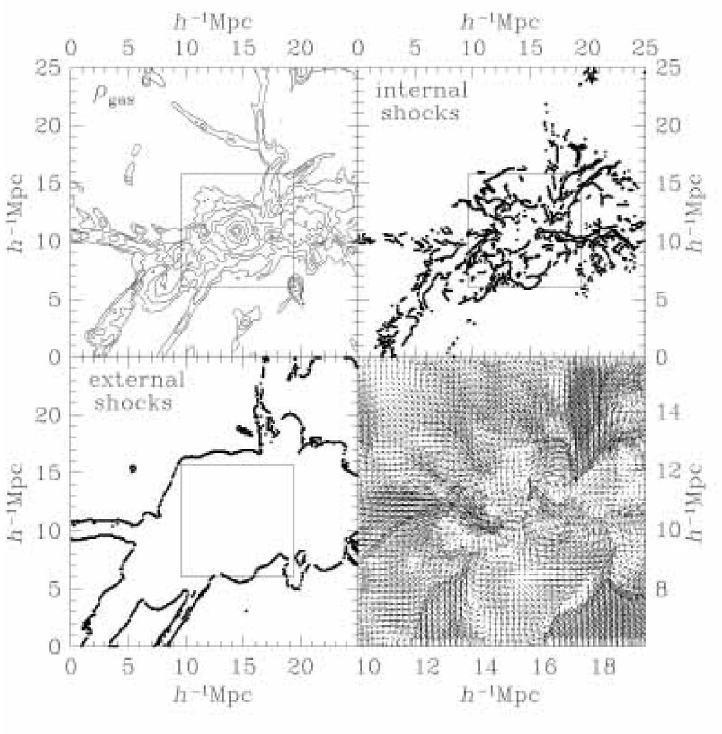

Fig. 5 The 2-D slice of $(25h^{-1}\ \mathrm{Mpc})^2$ around a simulated $T \sim 3.3$ keV cluster showing gas density, shock distribution and velocity field (from Ryu et al. 2003).

distribution with $T_e \sim 10^8$ K and $n_e \sim 10^{-3}$ cm^{-3} provides the bulk of the thermal X-ray emission. The preliminary evidence indicate also a possible warm component with temperature $T_{\rm warm} \sim 10^6$ K and much more uncertain density. A population of relativistic electrons (whose origin is still uncertain) is expected with a non-thermal spectrum in the energy range $\sim 0.2-30$ GeV and possibly extending to higher energies $\gtrsim 100$ GeV. The combination of these data provide overall constraints to the spectrum of the thermal (warm and hot) and relativistic particles (electrons and hadrons) which are present in the cluster atmospheres (see Fig.6).

2 THREE MORE WAYS TO STUDY CLUSTERS: A THEORETICIAN'S TALE

The available evidence suggests the simplified model for the cluster structure which is shown in Fig.7. According to this model, the properties of the cluster atmospheres can be studied from multi-frequency observations to derive some interesting constraints to the physics of the main cluster constituents. Let us briefly discuss three examples.

Dark Matter. Galaxy clusters can yield specific information on the presence and amount of DM from both the properties of the thermal IC medium (e.g., Sarazin 1988) and from the study of gravitational lensing (e.g., Bartelmann & Schneider 2001). These methods provide standard astrophysical probes for the presence, amount and spatial distribution of DM in galaxy clusters. However, such methods are not able to provide direct constrains on the nature and physical composition of the DM particles.

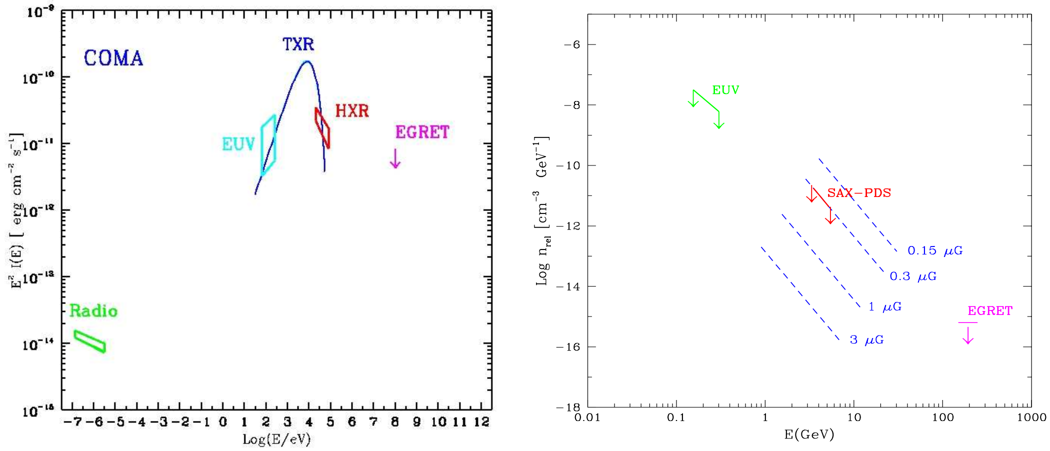

Fig. 6 **Left**. The overall observed spectrum of the Coma cluster from radio to gamma-ray frequencies (see labels). **Right**. The constraints to the spectrum of relativistic electrons in Coma as obtained from different observation (see labels): the radio halo data (blue dashed lines) for different values of the IC magnetic field; the HXR data (red solid line with arrows), the EUV data (green solid line with arrows) and the EGRET upper limit (magenta arrow) derived under the ICS interpretation of a single relativistic electron population which also produce the radio-halo emission. The arrows indicate that the spectra should be considered as upper limits (see text for details).

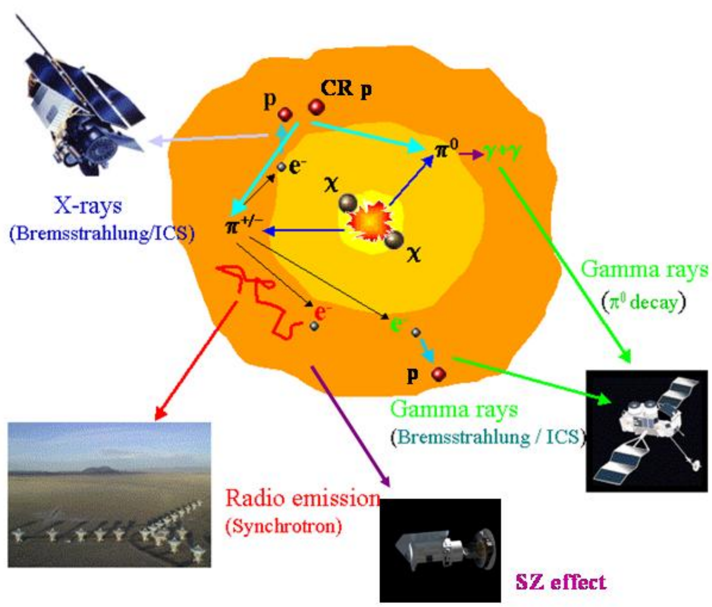

Fig. 7 We show a simplified cluster model which describes the role of thermal and non-thermal particles (see text for details).

It is nonetheless possible to obtain direct constrains on both the mass and physical composition of DM particles from the observational features of the associated non-thermal emission phenomena (see Colafrancesco & Mele 2001). Specifically, we pointed out that the observed features of radio halo and of the cluster gamma-ray emission (which will be observable with the next generation gamma-ray telescopes) can provide constraints on the mass and on the composition of the neutralinos χ, the lightest particle that is predicted in supersymmetric extensions of the Standard Model. In fact, we have shown that the highest observed frequency of the radio halo spectrum sets a lower limit to the neutralino mass $M_\chi \geq 70.5$ GeV $B_\mu^{-1/2}$ which is independent of the χ composition. In the same framework, the slope of the radio halo spectrum could also give an indication on the neutralino physical composition. The radio halo spectrum of the two clusters that we considered (e.g., Coma and 1E0657–56) are fitted by a model in which neutralinos behave like pure gauginos, and annihilate mainly into fermions (see Colafrancesco & Mele 2001 for details). Not only radio observations but also gamma-ray data can provide direct constrains on the neutralino physics. The next coming observations of nearby clusters in gamma-rays could, in fact, provide constraints on the neutralino mass from the observation of the cutoff in their gamma-ray spectra (see Colafrancesco 2004 for a review). It is reasonable, in conclusion, to expect - in the coming future - that the neutralino properties will be further constrained from an appropriate combination of astrophysical and accelerator data. It is appealing, in these respects, to expect that some astrophysical features of galaxy clusters might give information on the fundamental properties of the DM particles.

Probing the spectrum of high-E particles. The spectral energy distribution of cosmic rays in galaxy clusters can be studied from the combination of radio, HXR, EUV and gamma-ray observations. However, these emission features probe only separate energy regions of the CR spectrum. It has been recently proposed (Colafrancesco et al. 2003) to use the non-thermal SZ effect in clusters (i.e., the Compton scattering of CMB photons by high-E, non-thermal electrons), which depends on the total pressure of the electronic population, to set constraints on the overall spectrum of the clusters CRs. The data on the radio-halo cluster A2163 (for which wide frequency SZ observations are available) show that the relativistic particle pressure is $P_{\rm rel} \lesssim 0.3 P_{\rm thermal}$. As a consequence, the energy spectrum of the relativistic electrons should have a minimum-E break at ~ 50 MeV or flatten substantially at $E \lesssim 1$ GeV (see Colafrancesco et al. 2003 for details).

The Origin of high-E particles. Two distinct families of models for the CR origin in galaxy clusters have been proposed so far: *i*) the electronic and the *ii*) hadronic models. Electronic models deal with primarily accelerated electrons and rely on the existence of an efficient and *omnipresens* re-acceleration mechanism (merging shocks and IC turbulence are often invoked). These models also rely on low values of the uniform IC magnetic field $B_\mu \sim 0.2$, require a high CR injection to fit the available data and predict substantial amount of gamma-ray emission which is spatially concentrated around the shocks, and provide a modest amount of feedback on the IC gas. Hadronic models, on the contrary, deal with secondary electrons produced by the decay of collision/annihilation products (mainly $\pi^\pm \to e^\pm$) of p-p/χ-χ interactions. The secondary electrons are produced *in situ* (thus avoiding to invoke re-acceleration) and are consistent with values $B_\mu \sim 1 - 10$, found to be closer to Faraday rotation data. Moreover, these models require a substantial proton/electron ratio (like that observed in our Galaxy and in SNe remnants), predict a gamma-ray emission which is naturally spatially extended and provide a substantial feedback on the IC gas. The next generation gamma-ray observatories (GLAST, VERITAS, MAGIC) have the sensitivity and spectral resolution to disentangle, or at least constrain, the CR origin in galaxy clusters (see Fig.4). Gamma-ray observations offer, in fact, the most direct look at both the basic mechanism and at the site for the origin of CRs in large-scale structures.

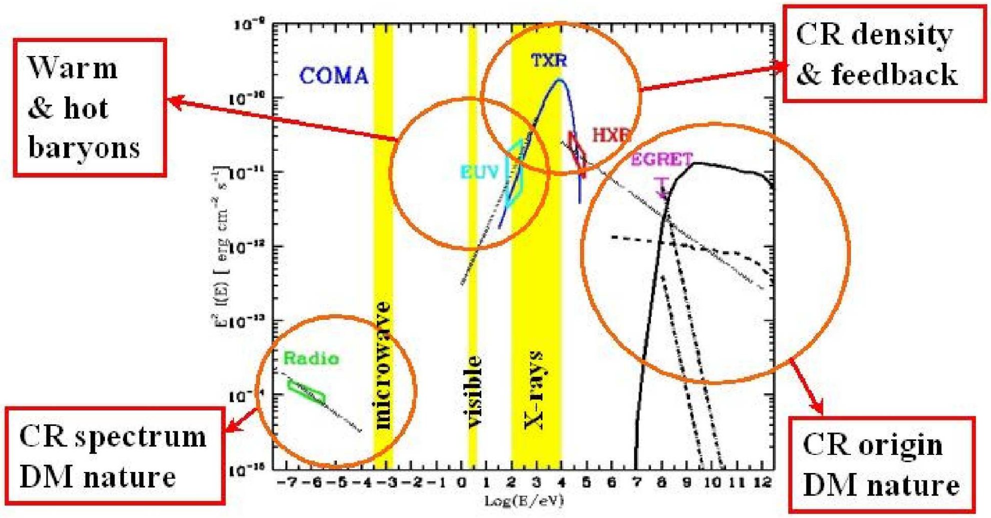

Fig. 8 The astrophysical study of galaxy clusters at different wavelengths can provide information on various physical phenomena, as labelled (see text for details).

In conclusion, we can state that multi-wavelength astrophysics is the key to piece together the puzzle offered by the various astrophysical phenomena occurring in galaxy clusters. Figure 8 shows the frequency regions where it will be possible to perform an optimal study of the various thermal and non-thermal phenomena occurring in clusters and to probe their astrophysical and cosmological relevance.

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