Probing cosmology and astro-particle physics with the SZ effect

© S. Colafrancesco [1,2]

[1] ASI-ASDC c/o ESRIN, Via G. Galilei, 00040 Frascati -Italy
[2] Email: colafrancesco@asdc.asi.it ; cola@mporzio.astro.it

Abstract: The SZ effect is a unique tool to study the complex physics of cluster atmospheres because it is sensitive to the specific features of the spectra of the various electronic populations. Multi-frequency (X-ray, optical and radio) observations of galaxy clusters indicate, in fact, that the atmospheres of these cosmic structures consist of a complex structure of thermal (hot and warm) and non-thermal (with different origin and spectra) distribution of electrons (and protons) which is, therefore, far from its modelling as a single, thermal electronic plasma. This evidence requires to go beyond the simple, standard lore of the SZ effect.
Such a task is challenging for both the theoretical aspects of their modelling and for the experimental goals to be achieved, but it will return a large amount of physical information by using the SZ effect as a unique tool for astro-particle and cosmology. In such a context, the coming SZ experiments from space (like OLIMPO and SAGACE) will open a new path in the exploration of the SZ effect as a probe for Cosmology and Astro-Particle Physics.

1. The SZ effect: the standard lore

The Sunyaev-Zel'dovich effect (hereafter SZE, Zel'dovich & Sunyaev 1969, Sunyaev & Zel'dovich 1972, 1980) produces distortions of the CMB spectrum by means of the Compton scattering of CMB photons off the energetic electrons which are present in the atmosphere of cosmic structures, like clusters of galaxies and galaxies (see Rephaeli 1995, Birkinshaw 1999, Colafrancesco 2007 for reviews).
Such a scattering is proportional to the energy density of the electron population and produces a systematic shift of the CMB photons from the Rayleigh-Jeans (RJ) to the Wien side of the spectrum. In this respect, it is a powerful probe of the physical conditions of electronic plasmas in astrophysical and cosmological context.
The standard description of the non-coherent Compton scattering of an isotropic Planckian radiation field by a non-relativistic Maxwellian electron population - like the one constituting the hot (with temperature Te ~ 10^7-10^8 K), optically thin (with density $n_e \sim 10^{-3}$-10^{-2} cm $^{-3}$, and size R ~ Mpc) intracluster (IC) medium - can be obtained by means of the solution of the Kompaneets (1957) equation.
As such, the origin of the SZE can be considered as a fall-out effect of the cold war: in fact, the Compton scattering Fokker-Planck equation for a population of scattered photons was first derived by A.S. Kompaneets in the early 1950 and then remained classified due to nuclear bomb research until 1956 (see, e.g., Goncharov 1996); it was finally published in 1957 (Kompaneets 1957).
In 1969, Ya.B. Zel'dovich and R. Sunyaev (1969) derived the SZ effect applying the Kompaneets equation to the case of the Compton scattering of CMB photons off the thermal population of electrons confined in the potential wells of galaxy clusters, i.e. the intra-cluster medium (ICM).
The change in the spectral intensity of the CMB seen in the direction of a galaxy cluster as due to the scattering of CMB photons by a *thermal* electron distribution can be written as

$$\Delta I_{th} = 2\frac{(k_B T_0)^3}{(hc)^2} y_{th} g(x) \ , \qquad (1)$$

where $x = h\nu / k_B T_0$ is the a-dimensional frequency and the spectral features of the effect are contained in the function $g(x)$ which reads as

$$g_{non-rel}(x) = \frac{x^4 e^x}{(e^x - 1)^2}\left[x\frac{e^x+1}{e^x-1} - 4\right] \qquad (2)$$

in the non-relativistic limit. This function (see Fig.1) is zero at the frequency x_0=3.83 (or ν = 217 GHz for a value of the CMB temperature T_0 = 2.726 K), negative at $x < x_0$ (in the RJ side) and positive at $x > x_0$ (in the Wien side).
The Comptonization parameter y_{th} due to the thermal SZE reads as

$$y_{th} = \frac{\sigma_T}{m_e c^2} \int d\ell \; P_{th} \; , \qquad (3)$$

wl n density and temperature of the IC gas, respectively, σ_T is the Thomson cross se T_0, k_B is the Boltzmann constant and $m_e c^2$ is the rest mass energy of the electron. The Comptonization parameter y_{th} is proportional to the integral along the line of sight l of the kinetic energy density of the IC gas, $\varepsilon_{th} \approx n_e k_B T_e$, or equivalently the kinetic pressure, that we define here as $P_{th} = n_e k_B T_e$.

Since the previous description of the thermal SZE is obtained under the Kompaneets approximation and in the single scattering regime of the photon frequency redistribution function, it only provides an approximation of the SZE for low electronic temperatures ($k_B T_e \le 3$ keV) and low values of the optical depth

$$\tau = \sigma_T \int d\ell n_e \; , \qquad (4)$$

which is usually $\sim 10^{-3}$ in galaxy clusters.

The existence of many high-temperature X-ray clusters (see Arnaud 2005 for a review) with $k_B T_e$ up to ~ 17 keV (see, e.g., Tucker et al. 1998, Liang et al. 2000) which correspond to $k_B T_e / m_e c^2 \approx 3.3 \; 10^{-2}$, requires to take into account the appropriate relativistic corrections in the calculation of their thermal SZE (see Rephaeli 1995, Birkinshaw 1999 and references therein).

Analytical and numerical expressions for the SZE in the relativistic case have been considered by various authors using both analytical and Monte Carlo techniques (see, e.g., Stebbins 1997; Itoh et al. 1998; Challinor & Lasenby 1998; see also Birkinshaw 1999 and references therein). Some of these calculations (out of the Monte Carlo simulations) are still approximate since they have been carried out in the limits of:

i) single scattering of CMB photons against the IC gas electrons;

ii) diffusion limit in which the use of the Kompaneets equation is justified.

The results of Itoh et al. (1998) based on a generalised Kompaneets equation and by direct integration of the Boltzmann collision term, can be regarded as exact in the framework of the single scattering approximation.

Analytical fitting formulae of such derivation are available (Nozawa et al. 2000; Itoh et al. 2002) and offer a detailed description of the thermal SZE for $k_B T_e \le 15$ keV, while Monte Carlo simulations describe more correctly the thermal SZE even for $k_B T_e \ge 20$ keV (see, e.g., Challinor & Lasenby 1998). Numerical solutions for the thermal SZE which are valid for generic values of τ and T_e have been given by Dolgov et al. (2001) based on an analytical reduction of the collision integral which is contained in the Boltzmann-like collision equation.

Sazonov & Sunyaev (2000) presented a derivation of the monochromatic redistribution function in the mildly relativistic limit which considers also quantum effects and the use of the Klein-Nishina cross-section which reproduces, in the limit $h\nu \ll k_B T_e$, the results of Fargion et al. (1997). However, they still consider only the single Compton scattering limit and the relativistic corrections up to some intermediate order due to low-energy photons and relativistic electrons. Itoh et al. (2001) also presented a calculation of the thermal SZE which considers the contribution from multiple scattering in the relativistic limit, and Colafrancesco et al. (2003) derived a general form of the SZE valid in the full relativistic regime, for generic values of τ and T_e and for multiple scattering regimes.

Another general assumption which is made in the calculation of the SZE is the use of a single population of thermal electrons (i.e., the hot ICM). This assumption is based on the evidence that the ICM is mainly constituted by thermal electrons (and protons) which are responsible for the thermal bremsstrahlung X-ray emission observed in clusters (see Sarazin 1988 for a review). A further assumption is to use the electronic temperature T_e as a measure of the average energy per particle, a condition which is not ensured in plasma undergoing fast, non-equilibrium processes which may yield $T_e \neq T_p$.

The study of the thermal SZE, caused by the random scatterings of the thermal (isotropically distributed) electrons, is complemented in the standard description by a kinematic (Doppler) SZE, SZ_{kin} which appears when the cluster has a whole has a finite (peculiar) velocity V_r in the CMB frame. The expressions for the intensity and temperature changes due to the SZ_{kin} can be obtained, assuming that the SZ_{th} and SZ_{kin} are separable, by a simple relativistic transformation (see, e.g., Rephaeli 1995 for a review) which yields

$$\Delta I_{kin}(x) = -2 \frac{k_B T_{CMB})^3}{(hc)^2} \frac{V_r}{c} \tau \frac{x^4 e^x}{(e^x - 1)^2} \; , \qquad (5)$$

where the line-of-sight peculiar velocity V_r is positive (negative) for a receding (approaching) cluster.

At variance with the temperature change due to the thermal SZE (see Eqs. 1 and 2), the kinetic SZE temperature change ΔT_{kin}= - T_0 (V_r/c) τ is independent of frequency.

1.1 The standard lore of the SZE: simple physics and cosmology

Simple astrophysical and cosmological results can be obtained from the study of the standard (both thermal and kinematic) SZE (see Birkinshaw 2003).

As for cluster physics, the SZE can be used to study:
- the integrated SZE, which provides information on the total thermal energy content and the total electron content;
- the spatial SZ structures: these are not as sensitive as the available X-ray data, and also need for IC gas temperature estimates;
- the mass structures and their relationship to gravitational lensing derived structures;
- the radial peculiar velocity of galaxy clusters via the SZ_{kin} .

As for cosmology, the SZE can provide information on:
- cosmological parameters, like the cluster-based Hubble diagram or the distribution of the cluster counts vs. redshift, which can be used to probe Щ$_M$, with a minor sensitivity to Щ$_\Lambda$ (see Carlstrom et al. 2002);
- cluster evolution physics, i.e. the evolution of cluster atmospheres, the evolution of their radial velocity distributions and the evolution of their baryon fraction;
- the evolution of T_0 with redshift (see, e.g., Battistelli et al. 2002).

We must keep in mind, however, that two basic working approximations are assumed in such use of the standard SZE:
i) the diffusion limit (i.e., the single scattering approximation valid for $\tau \ll 1$);
ii) a single electron population (i.e., the population of thermal hot electrons which is confined in the cluster atmosphere and emits in the X-rays by bremsstrahlung.
There are several pieces of evidence and physical arguments that require to go beyond this standard lore of the SZE.

2. The SZE: more than basics.

The electronic distribution of the atmospheres of galaxy clusters is neither simple nor unique. There are, in fact, three matter components in clusters that can provide different sources of electrons: baryons, Dark Matter, relativistic plasmas.

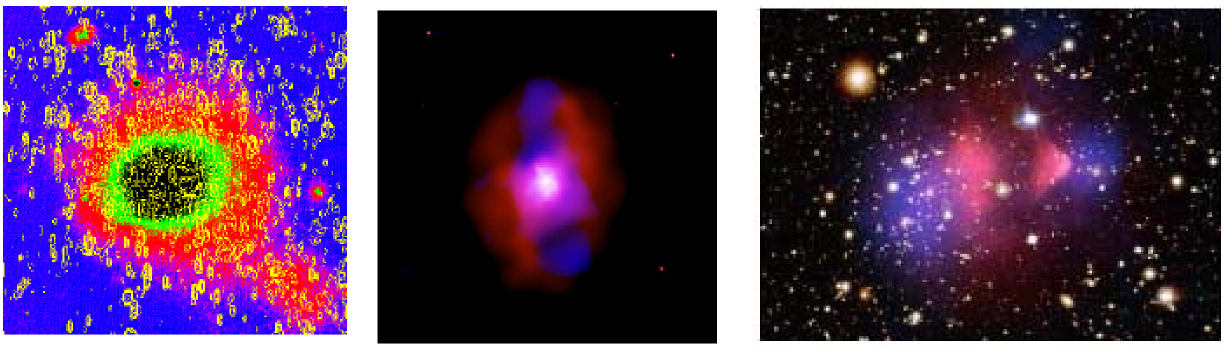


Fig.1.We show the images of three clusters which have atmospheres with complex electron distributions: Coma with its co-spatial X-ray (colours) and radio-halo (contours) emission (left, Feretti 2003), MS0735+7421 with two large cavities filled with relativistic plasma (blue) embedded in its thermal (red) IC gas (center, McNamara et al. 2005; http://chandra.harvard.edu/photo/2005/ms0735/), 1ES0657-556 with two DM clumps (blue) offset w.r.t. the ICM X-ray (pink) emission (right, Clowe et al. 2006 http://hubblesite.org/newscenter/newsdesk/archive/releases/2006/39/image/a).

While the SZE from the baryonic, hot plasma component has been described in the Sect.1, we will provide here the basic information on other non-thermal electronic components residing in cluster atmospheres.
Many galaxy clusters contain - in addition to the thermal IC gas - a population of relativistic electrons which produce a diffuse radio emission (radio halos and/or relics) via synchrotron radiation in a magnetized ICM (see, e.g., Govoni & Feretti 2004 for a review). The electrons which are responsible for the radio halo emission have energies $E_e \sim 16$ GeV $B_\mu^{-1/2}$ $(\nu$ / GHz$)^{1/2} \geq$ a few GeV to radiate at frequencies $\nu \geq 30$ MHz in a $\sim$ μG magnetic field ($B_\mu \sim 1$) in order to reproduce the main properties of the observed radio halos (see, e.g., Blasi & Colafrancesco 1999; Colafrancesco & Mele 2001, Colafrancesco et al. 2006 and references therein). The origin of such relativistic electrons is not certain and models of bottom-up production (i.e., re-accelerated by IC turbulence, see e.g. Brunetti 2003 for a review) or top-down origin (i.e., secondarily produced by Dark Matter WIMP annihilation, see e.g. Colafrancesco et al. 2006, 2007) can fit the observed radio-halo features.
The presence of Extreme UV/soft X-ray excesses (Lieu et al. 1996, Kaastra et al. 2002; Bowyer 2000) and of an hard X-ray excess (Fusco-Femiano 2004; Rephaeli 2004; Kaastra et al. 1999) in a few nearby clusters indicate the presence of an additional population of secondary relativistic electrons (see Bowyer et al. 2004, Marchegiani, Perola & Colafrancesco 2007) or a combination of warm (reproducing the EUV excess, Lieu et al. 2000) and (quasi-)thermal (reproducing the hard X-ray excess by bremsstrahlung, see Wolfe & Melia 2006, Dogiel et al. 2007) populations of distinct origins.
The further evidence for new physical phenomena occurring in the cluster atmospheres -- e.g., non-thermal heating in the cluster cores (see, e.g., Colafrancesco, Dar & DeRujula 2004, Colafrancesco & Marchegiani 2008 and references therein), AGN and radio-galaxy feedback (Siemiginowska et al. 2005), intra-cluster cavities (McNamara et al. 2005) and radio bubbles (Birzan et al. 2004) filled with relativistic non-thermal electrons, multi-scale magnetic fields (see, e.g., Govoni & Feretti 2004) - imply the presence of additional electronic components with peculiar spectral and spatial characteristics (see Fig.1).
Finally, there are strong physical arguments indicating that viable Dark Matter candidate annihilation can produce copious amounts of secondary electrons with a spatial distribution which, in massive clusters like Coma, is strictly related to that of the original DM (see Colafrancesco et al. 2007). It is interesting to note, in this context, that the spectral distribution of DM-produced secondary electrons carries information on the mass and the physical composition of the original DM particles.
In conclusion, the cluster electronic atmosphere is a complex combination of thermal (hot and warm) and non-thermal (quasi-thermal due to stochastic acceleration, relativistic due to DM annihilation and/or to AGN injection) distributions with different energy spectra and spatial distributions (see, e.g., Colafrancesco 2007 for a review). Each one of the electron populations which reside in the cluster atmosphere inevitably produces a distinct SZE with peculiar spectral and spatial features.
The description of the non-thermal SZE produced by a single electron population with a non-thermal spectrum has been attempted by various authors (McKinnon et al. 1991; Birkinshaw 1999; Ensslin & Kaiser 2000). Several limits to the non-thermal SZE are available in the literature (see, e.g., Birkinshaw 1999 for a review) from observations of galaxy clusters which contain powerful radio halo sources (such as Coma and A2163) or radio galaxies (such as A426), but only a few detailed analysis of the results (in terms of putting limits to the non-thermal SZE) have been possible so far (see Colafrancesco et al. 2003, Colafrancesco 2004a).
The problem of detecting the non-thermal SZE in radio-halo clusters is likely to be severe because of the associated synchrotron radio emission, which could contaminate at low radio frequencies the small negative signal produced by the SZE. At higher frequencies there is in principle more chance to detect the non-thermal SZE, but even here there are likely to be difficulties in separating the SZE from the flat-spectrum component of the synchrotron emission (see Birkinshaw 1999). In addition, Colafrancesco (2004a) noticed that dust obscuration does not allow any detection of the SZ signal from clusters at frequencies ≥ 600 GHz.
From the theoretical point of view, preliminary calculations (Birkinshaw 1999, Ensslin & Kaiser 2000) of the non-thermal SZE have been carried out in the diffusion approximation ($\tau \ll 1$), in the limit of single scattering and for a single non-thermal population of electrons.
Matters are significantly more complicated if the full relativistic formalism is used. However, this is necessary, since many galaxy clusters show extended radio halos and the electrons which produce the diffuse synchrotron radio emission are certainly highly relativistic so that the use of the Kompaneets approximation is invalid. Moreover, the co-spatial presence of thermal and non-thermal electrons renders the single scattering approximation and the single population approach unreasonable, so that the treatment of multiple scattering among different electronic populations coexisting in the same cluster atmosphere is necessary to describe correctly the overall SZE.

In this context, a complete and general derivation of the SZE produced by a generic distribution of non-thermal electrons in the full-relativistic description, with multiple scatterings and also with different electron families co-spatially distributed has been provided by Colafrancesco et al. (2003). We will refer to this approach in our discussion aimed to probe the origin of every particle family using a single technique: the SZE.

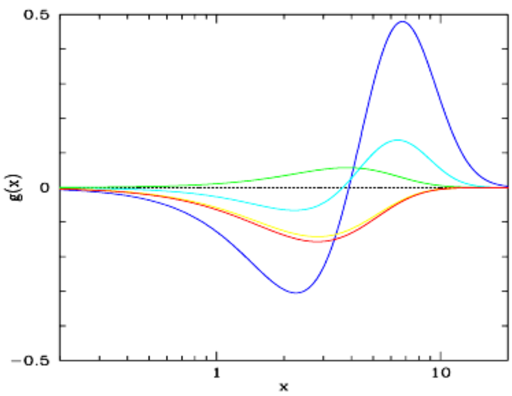


Fig.2. The function g(x) is shown as a function of the adimensional frequency x for different electronic populations residing in the cluster atmosphere: thermal with $k_B T_e = 8.2$ keV (blue); warm with $k_B T_e = 1$ keV (cyan); secondary electrons from DM annihilation with $M_\chi = 20$ GeV (red); relativistic electrons which fit the Coma radio halo integrated spectrum (yellow). The kinematic SZE with a negative peculiar velocity (green) is shown for comparison. The amplitudes of the various curves have been artificially renormalized to highlight their frequency dependence.

3. The SZE: a generalized description

The generalized expression for the SZE which is valid in the Thomson limit ($\gamma h \nu << m_e c^2$ in the electron rest frame) for a generic electron population, in the full relativistic treatment and includes also the effects of multiple scatterings and the combination with other electron populations has been derived by Colafrancesco et al. (2003) and we will refer to this paper for technical details (see also Colafrancesco 2007 for a review).
Such derivation is has the advantage to describe both thermal and non-thermal SZE using a unique formalism in terms of a generalized Compton parameter y and of a spectral function g(x).According to these results, the spectral distortion observable in the direction of a galaxy cluster can be written as

$$\Delta I(x) = 2\frac{(k_B T_{CMB})^3}{(hc)^2} y \, \tilde{g}(x) \ , \tag{6}$$

where the generalized Comptonization parameter y is given by

$$y = \frac{\sigma_T}{m_e c^2} \int P_e d\ell \ , \tag{7}$$

in terms of the pressure P_e contributed by the specific electron distribution within the cluster.
The function g(x) for the considered electron population can be written, in its most general form, as

$$\tilde{g}(x) = \frac{m_e c^2}{\langle k_B T_e \rangle} \left\{ \frac{1}{\tau} \left[\int_{-\infty}^{+\infty} i_0(x e^{-s}) P(s) ds - i_0(x) \right] \right\} \ , \tag{8}$$

in terms of the photon redistribution function P(s) and of the undistorted CMB spectrum
$i_0(x) = [2 (k_B T_{CMB})^3/(h c)^2] \cdot x^3/(e^x - 1)$. The quantity

$$\langle k_B T_e \rangle \equiv \frac{\sigma_T}{\tau} \int P_e d\ell = \int_0^\infty dp f_e(p) \frac{1}{3} p v(p) m_e c \tag{9}$$

(see Colafrancesco et al. 2003) is the analogous of the average temperature for a thermal electron population (in this case $< k_B T_e > = k_B T_e$ obtains, in fact).
The photon redistribution function $P(s) = \int dp\, f_e(p)\, P_s(s; p)$ with $s = \ln(\nu'/\nu)$, in terms of the CMB photon frequency increase factor ν'/ν, contains the crucial dependence on the electron momentum distribution $f_e(p)$, where p is normalized to $m_e c$. Here $P_s(s; p)$ is the mono-energetic frequency redistribution function (see Colafrancesco et al. 2003 for details).
The spectral function of the SZE evaluated for various electron spectra is shown in Fig.2. It is clear that the different nature of the electron distribution reflects directly in the different spectral shape of the relative SZE.

Thus, the SZE is a powerful probe of the energy spectrum of the various electronic populations residing in the atmospheres of cosmic structures.
We will describe in the following the relevance of the SZE as a tool to study several different aspects of the astro-particle physics of cosmic structures in the universe (see also Colafrancesco 2007 for a review).

3.1 The SZE and cosmic rays in galaxy clusters

We know that high-energy and relativistic particles exist in galaxy clusters through their diffuse radio-halo emission and their hard X-ray emission, but we do not know yet their origin. There are three viable scenarios for the production of high-energy particles in the atmospheres of galaxy clusters: i) direct acceleration or stochastic re-acceleration; ii) injection by AGNs or other compact objects; iii) Dark Matter annihilation.

Testing the acceleration history of cosmic rays.

One of the most favourite scenarios is that high-energy particles (cosmic rays) are energized by stochastic acceleration due to e.g., cluster turbulence, merging shocks or other injection/acceleration mechanisms acting coherently on the large (~Mpc) scale of the cluster atmospheres. Specific models of turbulent re-acceleration producing a high-energy tail up to relativistic energies (e.g., Brunetti et al. 2003) and stochastic acceleration of thermal particles producing a quasi-thermal tail (Dogiel et al. 2006) have been worked out.
Whatever the mechanism that accelerate particles is, thus producing non-thermal or quasi-thermal spectral tails, it should be extremely efficient to beat the competing thermalization process for such high-energy particles (see, Wolfe & Melia 2006, see also Dogiel et al. 2007). As a result, the viable models produce rather different non-thermal or quasi-thermal electron spectra whose nature can be constrained by studying the associated SZE (see Fig.3).
If the acceleration is so efficient to produce a high-E power-law tail, the SZE attributed to the relativistic electrons that produce the cluster radio-halo spectra is expected to be completely negative at all the frequencies relevant for the SZ experiments ($\nu \sim 20$ - 350 GHz) and with an amplitude of a few % of the thermal SZE in the cluster which renders its detection quite challenging.
On the other hand, the SZE effect produced by quasi-thermal electrons stochastically accelerated in the cluster environment is expected to produce a detectable CMB temperature decrement $\Delta T \sim 40$-50 μK at low frequencies (see Fig.3) that could prove or set relevant constraints to this scenario as well as to the efficiency of thermalisation and acceleration processes.
In the case of inefficient shock acceleration, an increase of the average plasma temperature is provided by the thermalization of high-energy particle which, in turn, yields a SZE with thermal features (Fig.3).

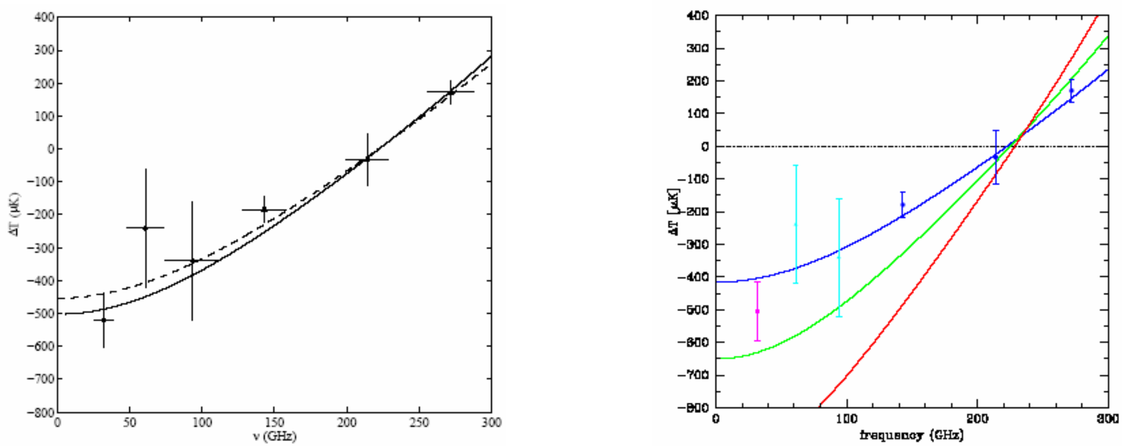


Fig.3. The SZE from the quasi-thermal particle distribution that fits the Hard X-Ray emission of Coma in a stochastic acceleration scenario (see Dogiel et al. 2007, left panel) and the SZE from inefficient shock acceleration (see Wolfe & Melia 2006, right panel).

Testing the content and the energetics of cluster cavities.

While the properties of cluster cavities and of the relativistic plasma they contain is usually studied by combining high-resolution X-ray and radio maps, we have proposed (Colafrancesco 2005), as an alternative strategy, to study the consequences of the Compton scattering between the high-energy electrons filling the cavities and the CMB photon field (i.e. the SZE) whose amplitude, spectral and spatial features depend on the overall pressure and energetics of the relativistic plasma in the cavities (see Colafrancesco 2005 for the specific case of the cluster MS0735+7421, see also Fig.4.).

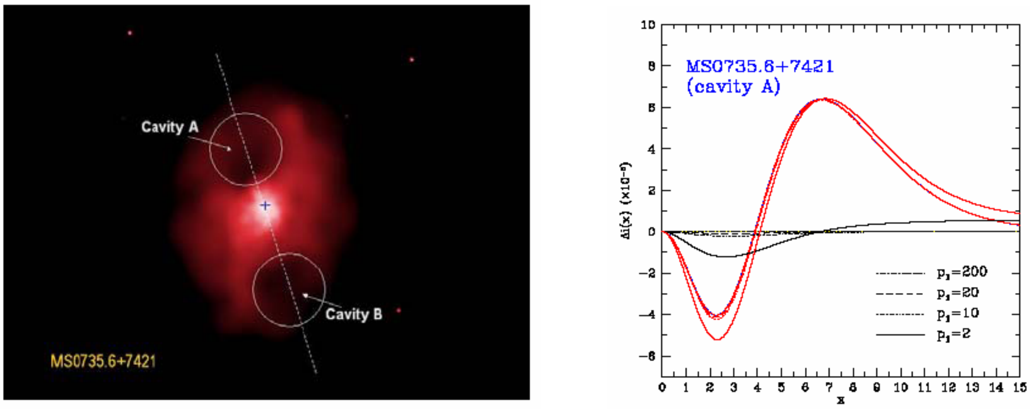


Fig.4.
Left. The geometry of the cavities in the cluster MS0735.6+7421 is shown. The two cavities have a radius ~100 kpc and are located at a distance of ~125 kpc and ~170 kpc from the central radio galaxy (whose position is indicated by a cross) along the axis represented in the picture.
Right. The spectrum of the overall SZE from the cluster MS0735.6+7421 has been computed at a projected radius of ~125 kpc from the cluster center where the los passes through the center of cavity A. We show the thermal SZE (blue), the non-thermal SZE from the cavity (black) and the total SZE (red).
The plotted curves are for different values of the lowest electron momentum: p_l= 200 (dot-dashes), p_l=20 (dashes), p_l=10 (dots) and p_l=2 (solid). The non-thermal SZE is normalized to the cavity pressure P=6 10^{-11} erg cm^{-3} and it must be considered as a lower limit of the true SZE coming from the cavity.

At frequencies x ~ 2.5 there is the maximum amplitude of the non-thermal SZE from the cavity (for a given electron spectrum and pressure). This produces a bump in the spatial distribution of the overall SZE at the cavity location with the addition of a negative SZE signal to the thermal SZE of the cluster.
At $x > x_{0,th}(P_{th})$ - where $x_{0,th}$ is the crossover frequency at which the thermal SZE is null - we have the opposite effect but with smaller amplitudes: a depression in the SZE at the cavity location caused by the addition of a negative SZE signal to the positive thermal SZE.
We emphasize that SZ observations at the frequency $x_{0,th}(P_{th})$ (which is ~ 3.87 for a $k_B T_e$=5 keV cluster) provide a unique way to probe the overall energetics, the pressure and the spatial extent of the non-thermal plasma contained in giant cavities, an observation which is rich in information and complementary to those obtained by X-ray and radio observations of cluster cavities. At this frequency, in fact, the overall SZE from the cluster reveals only the Compton scattering of the electrons
residing in the cavities without the presence of the intense thermal SZE from the cluster's thermal atmosphere observable at lower and higher frequencies. Hence, the SZE from a cluster containing cavities (like the case of MS0735.6+7421) shows up uncontaminated at frequencies ~ 220 GHz: it is less extended than the overall cluster SZE because it is only emerging from the cavity regions and it is also well separable because the cavities are well defined in both X-rays and SZ images.
We also emphasize that the observation of the zero and of the spectrum of the non-thermal SZE in the cavities provide a definite way to determine uniquely the total pressure and hence the nature of the electron population within the cavity, an evidence which adds crucial, complementary information to the X-ray and radio analysis.
Even though the determination of the crossover frequency $x_0(P_e)$ can be biased by possible sources of additional SZE (e.g., the kinematic SZE or the SZE coming from additional electron components), a full spectroscopic study of the SZE around the zero of the thermal SZE will provide unbiased information on the various electron populations in clusters (Colafrancesco, Prokhorov & Dogiel 2008). These studies will be also rele-

vant to determine the impact of specific events of the nature of cavities on the use of SZ and X-ray clusters as probes for cosmology and for the evolution of large scale structure of the universe.

Testing relativistic electrons in powerful radio-galaxy lobes

The SZE produced in the jets of isolated powerful radio-galaxies is, similarly to the case of cluster cavities, completely non-thermal and it is, contrary to the case of cluster cavities, not contaminated by the surrounding ICM. Colafrancesco (2008) showed that high-sensitivity and high-resolution SZE observations (like those achievable with ALMA) can also provide relevant information on the spectrum and on the pressure and energetic structure of the jets/lobes of powerful radio-galaxies.

3.2 SZE and the nature of Dark Matter.

Dark Matter annihilations in the halo of galaxies and galaxy clusters have relevant astrophysical implications, even for SZE observations. Colafrancesco (2004b) proposed to explore the consequences of the Compton scattering between the secondary electrons produced from the WIMP annihilation in massive DM halos (like galaxy clusters and dwarf galaxies) and the CMB photon field, i.e. the DM-induced SZE which has specific spectral and spatial features. This is an inevitable consequence of the presence and of the nature of DM in large-scale structures.

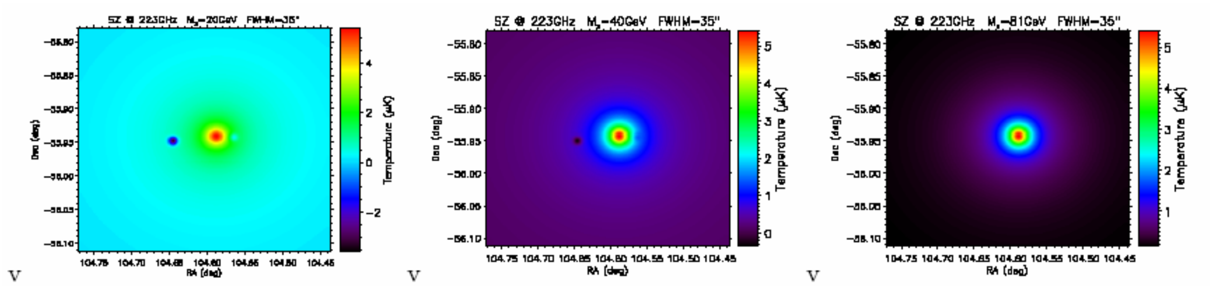


Fig.5. Simulated SZ maps of the cluster 1ES0657-556 as observable with the SPT at 223 GHz for three different neutralino masses: M_χ=20 GeV (left panel), 40 GeV (mid panel) and 81 GeV (right panel) (see Colafrancesco et al. 2007 for details).

The analysis of the DM induced SZE in galaxy clusters provides a probe for the presence and for the nature of DM in cosmic structures which is complementary to those obtainable through a multifrequency analysis (see Sect.2). The available SZ observations on the Coma cluster (see Colafrancesco 2004b) can already set a lower limit to the neutralino mass of $M_\chi \geq 17$ - 20 GeV ($M_\chi \geq 13$ GeV at 90 % c.l. with the adopted value of $<\sigma v> = 3\ 10^{-27}$ cm^{-3} s^{-1}/Щχ h^2 with Щχ $h^2 = 0.116$). The SZ_{DM} signal does not strongly depend on the assumed DM density profile at intermediate angular distances from the cluster center and on the DM clumpiness since $y_{DM} = (\sigma T/m_e c^2) \int dl\, P_{e,DM}$ is the integral of the secondary electron pressure $P_{e,DM}$ along the line of sight l.

The presence of a substantial SZ_{DM} effect is likely to dominate the overall SZ signal at frequencies $x \geq 3.8$-4.5 providing a negative total SZE (see Fig.2). Even though in such frequency range there are other possible contributions to the SZE, like the kinematic effect and the non-thermal SZE which could provide additional biases (see, e.g., Colafrancesco et al. 2003).

An appropriate spectroscopic analysis of the overall SZE is required, in principle, to separate the various SZ contributions and to provide an estimate of the DM induced SZE. A particularly good case in which the SZ_{DM} could be revealed is that of the cluster 1E0657-556 where the SZ_{DM} signal is peaked on the DM clumps, and is well separated (by several arcmin) from the thermal SZE concentrated on the X-ray emitting IC gas location and from the non-thermal SZE associated with the shock. In this case, the SZ_{DM} signal is the only one remaining at frequencies $x=x_{0,th}$ at the DM clump locations (see Fig.5, see Colafrancesco et al. 2007).

Future SZ experiment with ~μK sensitivity (and ≤ arcmin angular resolution) could be able to detect direct signals from DM annihilation in the most favourable supersymmetric scenarios.

3.3 SZE and magnetic fields.

There are also non-standard aspects of the widely-used thermal SZE that need to be carefully and specifically addressed. In particular, the presence of an intra-cluster magnetic field can produce relevant changes to the thermal SZE in galaxy clusters (Colafrancesco 2008, see also Colafrancesco 2007 for a review).
The presence of a wide-scale magnetic field implies modification on the thermal and density structure of the IC gas by acting on both the magnetic virial theorem (MVT) and the Hydrostatic Equilibrium (HE) condition (Colafrancesco & Giordano 2006, 2007). As a consequence, the cluster thermal SZE is influenced by the presence of an intracluster magnetic field, as shown in Fig.6. For idealized isothermal clusters, the magnetic SZE is reduced w.r.t. the unmagnetized case by two separate effects: the decrease in the cluster temperature for increasing values of B as derived by the MVT

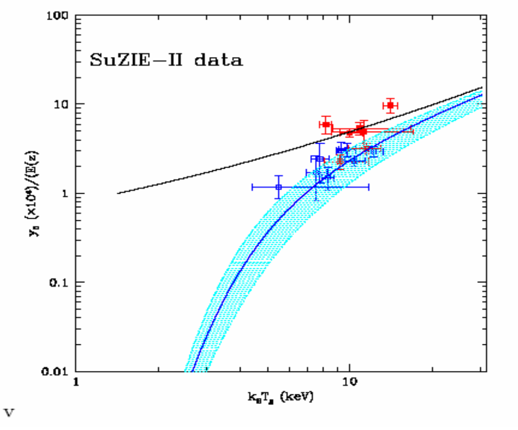
$$2K + 2U + U_B + W = 0. \tag{10}$$

where K is the DM kinetic energy, U is the gas kinetic energy, U_B is the magnetic field energy and W is the potential energy (see Colafrancesco & Giordano 2006, 2007), and the decrease of the central gas density profile for increasing values of B according to the HE condition

$$\frac{dP_g}{dr} + \frac{dP_B}{dr} = -\frac{GM(\leq r)}{r^2}\rho_g \tag{11}$$

The variations of the thermal SZE for magnetized clusters is larger for lower-mass systems because in these structures the pressure provided by the magnetic field is of larger relative importance w.r.t. to the thermal pressure of the IC gas settling in the potential wells provided by DM. This allows to reproduce the steepening of the y_0-T relation shown by the most recent data (see Fig.6).
The increasing observational evidence, the refinements of numerical simulations and the theoretical expectations for the presence of magnetic fields in galaxy clusters render a revision of the standard description of the thermal SZE necessary to describe both single SZ observations and SZ scaling-law analyses in a self-consistent astrophysical and cosmological framework (see discussion in Colafrancesco 2007).

Fig.6.
The $y_{th}(0)$-T_e relation for B=0 (black curve) is compared with that calculated assuming the scaling $B \propto T^{\eta}$ (cyan shaded area) which best fits the S-T and L_X-T relations for clusters (Colafrancesco & Giordano 2007). Data are from the SuZIE II experiment (Benson et al. 2004): filled squares refer to clusters with cool cores while open squares refer to clusters without cool cores. Figure from Colafrancesco 2008.



4. Theoretical and experimental outline

The most recent achievements in multi-frequency (radio through X-rays) precision observations of galaxies and galaxy clusters provided a wealth of detailed and, in some cases, unexpected physical information on the structure, physical state and composition of the atmospheres of these cosmic structures.
Radio-halo non-thermal emission, hard-X-ray quasi-thermal excess emission, cluster cavities and radio bubbles, absence of strong radiative cooling in cool-cores, AGN's feedback, Dark Matter distribution and dy-

namics, appear to be relevant ingredients for a detailed description of cluster structure and evolution: these processes put the standard description of the cluster atmosphere (as a single, thermal IC gas) to the ropes.
Therefore, the theoretical modelling of galaxy cluster atmospheres evolved in the last decade up to a level of high-detail, complex physical description that requires to take consistently into account several electronic components (of thermal, non-thermal and relativistic nature), the effects of magnetic field, the feedback (heating, particle injection, magnetic field compression, etc.) produced by AGNs, radio-galaxies and blazars, the evolution and the interaction of relativistic plasma bubbles, the complex interplay of cooling and (non-thermal) heating processes in cool cores, the effects of a possible Dark Matter annihilation, the non-trivial physical conditions of the IC gas at cluster boundaries and its transition into the cosmic-web IGM distribution on larger scales.
As a consequence, the standard lore of the SZE is no longer viable in cosmic structures on large scales, like galaxy clusters. The simple SZ physics is no longer representative of the actual observational status; in this sense, it cannot provide neither reliable cluster physics nor an adequate cosmological use.
It is therefore inevitable to go beyond the standard lore of the SZE. This provides, nonetheless, a way to use SZE as a single technique to efficiently study the leptonic structure of clusters/galaxy atmospheres and thus obtain information on the density, entropy, pressure and energetics of the electrons, the presence and the spectra of different electron populations, their (possible) equilibrium conditions.
The SZ signals expected from the non-thermal plasma, from DM annihilation and from cluster cavities and radio bubbles in addition to the thermal SZE and its modifications due to the inclusion of the intra-cluster magnetic field physics are usually in the range from a few μK to a few tens of μK. This is the reason why they have not yet clearly discovered in the past and ongoing SZ experiments.
These additional SZ components are however present in the overall SZ signal observable from many galaxy clusters, and therefore they enrich the available physical information contained in the SZE data. Such signals could be disentangled from the thermal SZE by the future experiments with order of μK sensitivity and sub-arcmin resolution. Nonetheless, they constitute a bias of complex spatial and spectral nature for those experiments with ≥ 10 μK sensitivity (like WMAP and PLANCK). In each case, their theoretical study and simulation analysis is mandatory for any astrophysical and cosmological use to be reliably carried on.
Such a program requires a definite technological effort which is directed towards high sensitivity (sub or ~μK level) and spatial resolution (~ arcsec to arcmin level) together with a wide-band continuum spectral coverage obtainable from space experiments like OLIMPO (see Masi et al. 2006) and SAGACE (see http://oberon.roma1.infn.it/sagace/).

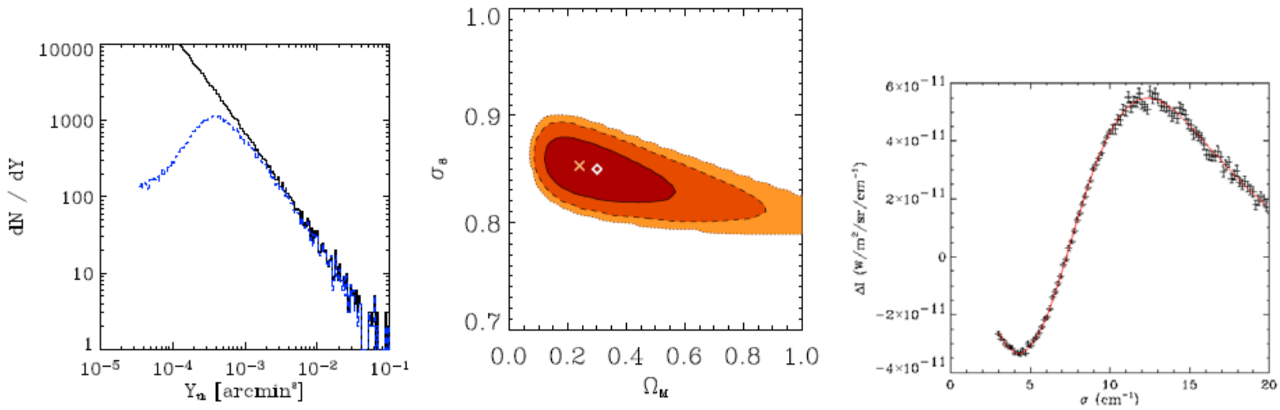


Fig.7.
Left: simulation of SZ cluster counts in a 400 deg^2 survey provided by OLIMPO: the black curve is the histogram of generated cluster flux, compared to the blue histogram of true cluster detection. Center: Expected constraints on σ_8 and Ω_M from an OLIMPO scientific flight, with full spectroscopic follow-up of the sources. Right: simulation of the SZ spectrum a galaxy cluster with y=10^{-4} observed with SAGACE in 600 s. The central region of the cluster is considered here.

This goal is definitely at the frontier of the present technology and is, therefore, a challenge for the future SZE experiments but it will be, nonetheless, able to open the door to the exploration of fundamental (astro-particle) issues like the nature of Dark Matter, the evolution of $T_{CMB}(z)$ and of scenarios of Dark Energy – Dark Matter interaction (Colafrancesco & Baryshev 2008), the origin and the distribution of cosmic rays and magnetic fields in large-scale structures, and other relevant questions which are on the discussion table of modern astrophysics and cosmology.

References

1.Arnaud, M. 2005, in Proc. of the Int. School of Physics Course CLIX, Eds. F. Melchiorri & Y. Rephaeli (astro-ph/0508159)
2.Battistelli, E. et al. 2002, ApJ, 580, L101
3. Belanger, G. et al. 2003 (astro-ph/0310037)
4. Birkinshaw, M. 1999, Phys.Rep., 310, 97
5. Birkinshaw, M. 2003, Review for Carnegie Observatories Centennial Symposium 3 (astro-ph/0307177)
6. Birzan, L. et al. 2004, ApJ, 607, 800
7. Blasi, P. & Colafrancesco, S. 1999, APh., 12, 169
8. Bowyer, S. 2000, AAS, 32, 1707
9. Bowyer, S. et al. 2004, ApJ, 605, 168
10. Brunetti, G. 2003, ASPC, 301, 349 (astro-ph/0208074)
11. Carilli, C.L. & Taylor, G.B. 2002, ARA&A, 40, 319
12. Carlstrom, J., Holder, G.P. & Reese, E.D. 2002, ARA&A, 40, 643
13. Challinor, A. & Lasenby, A. 1998, ApJ, 499, 1
15. Colafrancesco, S. 2004a, in ``Soft X-ray Emission from Clusters of Galaxies and Related Phenomena'' Eds. R. Lieu & J.Mittaz, Kluwer Academic Pub., Dordrecht, The Netherlands, p.137 and p.147
16. Colafrancesco, S. 2004b, A&A, 422, L23
17. Colafrancesco, S. 2005, A&A, 435, L9
18. Colafrancesco, S. 2007, New Astronomy Review, 51, 394
19. Colafrancesco, S. 2008, MNRAS, 371C
20. Colafrancesco, S. & Mele, B. 2001, ApJ, 562, 24
21.Colafrancesco, S., Dar, A. & De Rujula, A. 2004, A&A, 413, 441
22. Colafrancesco, S., Marchegiani, P. & Palladino, E. 2003, A&A, 397, 27
23. Colafrancesco, S., Marchegiani, P. & Perola, G.C. 2005, A&A, 443, 1
24. Colafrancesco, S., Profumo, S. & Ullio, P. 2006, A&A, 455, 21
25. Colafrancesco, S., Profumo, S. & Ullio, P. 2007, PRD, (astro-ph/0607073)
26. Colafrancesco, S. et al. 2007, A&A, 467, L1
27. Colafrancesco, S. & Giordano, F. 2006, A&A, 454, L131
28. Colafrancesco, S. & Giordano, F. 2007, A&A, 466, 421
29. Colafrancsco, S: & Marchigiani, P. 2008, A&A, in press (arXiv:0801.2737)
30. Colafrancesco, S. 2008, A&A, submitted
31. Colafrancesco, S. Prokhorov, D. & Dogiel, V. 2008, A&A, submitted
32. Colafrancesco & Baryshev 2008, in preparation
33. DePetris, M. et al. 2002, ApJ, 574, L119
34. Dogiel, V., Colafrancesco, S., Ko, C.M. et al. 2007, A&A, 461, 433 (astro-ph/0610120)
35. Dolgov, A.D. et al. 2001, ApJ, 554, 74 (astro-ph/0010412)
36. Ensslin, T. & Kaiser, C. 2000, A &A, 360, 417
37. Feretti, L. 2003, in ``Matter and Energy in Clusters of Galaxies'', ASP Conf. Series, Eds. S. Bowyer & C.-Y. Hwang (astro-ph/0301576)
38. Fusco-Femiano, R. 2004, Ap&SS, 294, 37
39. Goncharov, G.A. 1996, Physics Uspekhi, 39, 1033
40. Govoni, F. & Feretti, L. 2004, IJMPD, 13, 1549
41. Itoh, N., Kohyama, Y. & Nozawa, S. 1998, ApJ, 502, 7
42. Itoh, N. et al. 2001, MNRAS, 327, 567
43. Itoh, N. et al. 2002, A&A, 382, 722
44. Kaastra, J. et al. 1999, ApJ, 519, L119
45. Kaastra, J. et al. 2002, ApJ, 574, L1
46. Kompaneets, A.S. 1957, Soviet Phys. JETP, 4, 730
47. Liang, H. et al. 2000, ApJ, 544, 686
48. Lieu, R. et al. 1996, Science, 274, 1335
49. Marchegiani, P., Perola, G.C. & Colafrancesco, S. 2007, A&A, 465, 41
50. Masi, S. et al. 2006, ASI COFIS 2006, WP2420
51. McKinnon, M.M. et al. 1991, AJ, 101, 2026
52. McNamara, B.R., Nulsen, P.E.J., Wise, M.W. et al. 2005, Nature, 433, 45
53. Nozawa, S., Itoh, N., Kawana, Y. & Kohyama, Y. 2000, ApJ, 536, 31
54. Pfrommer, C., Ensslin, T. & Sarazin, C.L. 2005, A&A, 430, 799
55. Rephaeli, Y. 1995, ARA&A, 33, 541
56. Rephaeli, Y. 2004, 35th COSPAR Scientific Assembly, p.2380
57. Sarazin, C.L. 1988, ``X-ray emission from clusters of galaxies'', Cambridge University Press
58. Sazonov, S.Y. & Sunyaev, R.A. 2000, ApJ, 543, 28
59. Siemiginowska, A. et al. 2005 (astro-ph/0511464)

60. Shimon, M. & Rephaeli, Y. 2002, ApJ, 575, 12
61. Stebbins, A. 1997, in ``The Cosmic Microwave background'', Kluwer Acad. Press, p.241 (astro-ph/9705178)
62. Sunyaev, R.A. & Zel'dovich, Ya.B. 1972, Comm. Astrophys. Space Sci., 4, 173
63. Sunyaev, R.A. & Zel'dovich, Ya.B. 1980, ARA&A, 18, 537
64. Tucker, W. et al. 1998, ApJ, 496, L5
65. Wolfe, B. & Melia, F. 2006, ApJ, 638, 125
66. Zel'dovich, Ya.B. & Sunyaev, R.A. 1969, Ap&SS, 4, 301