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NON-THERMAL EMISSION FROM GALAXY CLUSTERS AND FUTURE OBSERVATIONS WITH THE FERMI GAMMA-RAY TELESCOPE AND LOFAR

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RESUMEN

El observatorio FERMI (antes GLAST) y LOFAR pronto proporcionarán información crucial de los componentes no-térmicos (partículas relativistas y campo magnético) de cúmulos galácticos. Después de discutir hechos observacionales relevantes, que ya ponen algunas restricciones a las propiedades y origen de estos componentes no-térmicos, reportaré acerca del espectro de emisión esperado para los cúmulos galácticos, en el contexto de cálculos generales en los que las partículas relativistas (protones y electrones secundarios de colisiones protón-protón) interactúan con turbulencia MHD generada en el volumen del cúmulo durante la unión de cúmulos. En esta situación (conocida como re-aceleración) la radiación difusa en radio a escalas del tamaño de los cúmulos se produce en cúmulos masivos durante eventos de unión, mientras que la emisión de rayos gama, hasta cierto punto, se espera sea común en éstos. Algunas espectativas de interés para LOFAR y FERMI serán discutidas de forma breve.

ABSTRACT

FERMI (formely GLAST) and LOFAR will shortly provide crucial information on the non-thermal components (relativistic particles and magnetic field) in galaxy clusters. After discussing relevant observational facts that already put important constraints on the properties and origin of non-thermal components, I will report on the emission spectrum from galaxy clusters as expected in the context of general calculations in which relativistic particles (protons and secondary electrons due to proton-proton collisions) interact with MHD turbulence generated in the cluster volume during cluster-cluster mergers. In this scenario (known as re-acceleration scenario) diffuse cluster-scale radio emission is produced in massive clusters during merging events, while gamma ray emission, at some level, is expected to be common in clusters. Expectations of interest for LOFAR and FERMI are also briefly discussed.

Key Words: acceleration of particles — galaxies: clusters: general — radiation mechanisms: non-thermal — turbulence

1. INTRODUCTION

Clusters of galaxies are the largest gravitationally bound objects in the present universe, containing $\approx 10^{15}\ M_\odot$ of hot (10^8 K) gas, galaxies and dark matter. The thermal gas, that is the dominant component in the Inter-Galactic-Medium (IGM), is mixed with non-thermal components such as magnetic fields and relativistic particles, as proved by radio observations. Non-thermal components play key roles by controlling transport processes in the IGM (e.g. Narayan & Medvedev 2001; Lazarian 2006a) and are sources of additional pressure (e.g. Ryu et al. 2003), thus their origin and evolution are important ingredients to understand the physics of the IGM.

The bulk of present information on the non-thermal components comes from radio telescopes that discovered an increasing number of Mpc-sized diffuse radio sources in a fraction of galaxy clusters (e.g. Feretti 2003; Ferrari et al. 2008). Cluster mergers are the most energetic events in the universe and are believed to be the main responsible for the origin of the non-thermal components in galaxy clusters. A fraction of the energy dissipated during these mergers is expected to be channelled into the amplification of the magnetic fields (e.g. Dolag et al. 2002; Subramanian et al. 2006) and into the acceleration of particles via shocks and turbulence that lead to a complex population of primary electrons and protons in the IGM (e.g. Enßlin et al. 1998; Sarazin 1999; Blasi 2001; Brunetti et al. 2001, 2004; Petrosian 2001; Miniati et al. 2001; Ryu et al. 2003; Dolag 2006; Brunetti & Lazarian 2007; Pfrommer 2008). Theoretically relativistic protons are expected to be the dominant non-thermal particles component since they have long lifetimes and remain confined within galaxy clusters for a Hubble time (e.g. Blasi et al. 2007, and references therein).

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Confinement enhances the probability to have p-p collisions that in turns give gamma ray emission via decay of π° produced during these collisions and inject secondary particles that emit synchrotron and inverse Compton (IC) radiation whose intensity depends on the energy density of protons. Only upper limits to the gamma ray emission from galaxy clusters have been obtained so far (Reimer et al. 2003), however the FERMI Gamma-ray telescope[2] (formely GLAST) will shortly allow a step forward having a chance to obtain first detections of galaxy clusters or to put stringent constraints to the energy density of the relativistic protons.

The IGM is expected to be turbulent at some level and MHD turbulence may re-accelerate both primary and secondary particles during cluster mergers via second order Fermi mechanisms. Turbulence is naturally generated in cluster mergers (Roettiger et al. 1999; Ricker & Sarazin 2001; Dolag et al. 2005; Vazza et al. 2006; Iapichino & Niemeyer 2008) and the resulting particle re-acceleration process should enhance the synchrotron and IC emission by orders of magnitude (e.g. Brunetti 2004; Petrosian & Bykov 2008). In a few years the Low Frequency Array (LOFAR) and the Long Wavelength Array (LWA) will observe galaxy clusters at low radio frequencies (40–80 MHz and 120–240 MHz in the case of LOFAR[3] and 10–88 MHz in the case of LWA[4]) catching the bulk of their synchrotron cluster-scale emission and testing the different scenarios proposed for the origin of the non-thermal particles. Finally, the emerging pool of future hard X-ray telescopes (e.g. NuSTAR, Simbol-X, Next) should provide crucial constraints on the level of IC emission from clusters and on the strength of the magnetic field in the IGM.

Facts from radio observations suggest that MHD turbulence may play an important role in the acceleration of the electrons responsible for the cluster-scale radio emission. After briefly discussing observations (§ 2), in § 3 we will focus on re-acceleration models showing expectations from the radio band to the gamma rays.

2. GIANT RADIO HALOS

2.1. *Origin of the relativistic electrons in the IGM*

The most prominent examples of diffuse non-thermal sources in galaxy clusters are the giant Radio Halos. These are low surface brightness, Mpc-scale diffuse sources found at the centre of a fraction of massive and merging galaxy clusters and are due to synchrotron radiation from relativistic electrons diffusing in $\approx \mu$G magnetic fields frozen in the IGM (Feretti 2003; Ferrari et al. 2008). The origin of Radio Halos is still unclear, the starting point is that the timescale necessary for the emitting electrons to diffuse over Radio Halo sizescales, of the order of a Hubble time, is much longer than the electrons' radiative lifetime, $\approx 10^8$ years (Jaffe 1977). This implies the existence of mechanisms of either *in situ* particle acceleration or injection into the IGM. Understanding the physics of these mechanisms is crucial to model the non-thermal components in galaxy clusters and their evolution.

Two main possibilities have been proposed to explain Radio Halos: (i) the so-called *re-acceleration* models, whereby relativistic electrons injected in the IGM are re-energized *in situ* by various mechanisms associated with the turbulence in massive merger events (e.g. Brunetti et al. 2001; Petrosian 2001; Fujita et al. 2003), and (ii) the *secondary electron* models, whereby the relativistic electrons are secondary products of proton-proton collisions between relativistic and thermal protons in the IGM (e.g. Dennison 1980; Blasi & Colafrancesco 1999; Dolag & Enßlin 2000).

Extended and fairly regular radio emission is expected in the case of a secondary origin of the emitting electrons, since the parent primary protons can diffuse on large scales. Still several properties of Radio Halos cannot be simply reconciled with this scenario. Two *"historical"* points are:

- Since all clusters have suffered mergers (hierarchical scenario) and relativistic protons are mostly confined within clusters, extended radio emission should be basically observed in almost all clusters. On the other hand, Radio Halos are not common and, although a fairly large number of clusters has an adequate radio follow up, they are presently detected only in a fraction of massive and merging clusters (Giovannini et al. 1999; Buote 2001; Cassano et al. 2008; Venturi et al. 2008; § 2.2).

- Since the spectrum of relativistic protons (and of secondary electrons) is expected to be a simple power law over a large range of particle-momentum, the synchrotron spectrum of Radio Halos should be a power law. On the other hand (although the spectral shape of Radio Halos is still poorly known) the spectrum of the best studied Radio Halo, in the Coma cluster, shows a cut off at GHz frequencies implying a corresponding cut off in the spectrum of the emitting electrons at $\approx$ GeV energy that was interpreted

[2] http://fermi.gsfc.nasa.gov/.
[3] http://www.lofar.org/.
[4] http://lwa.nrl.navy.mil/.

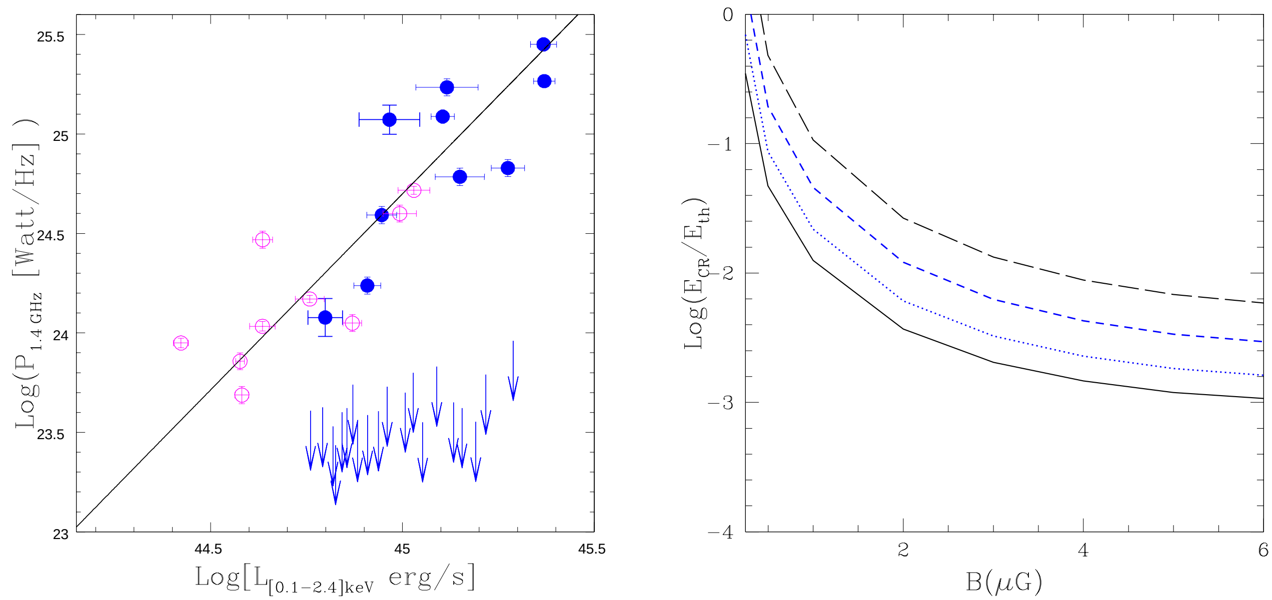

Fig. 1. Left Panel: distribution of galaxy clusters in the $P_{1.4} - L_x$ plane. Filled dots are galaxy clusters at z $\geq$ 0.2 (from GMRT-sample and from the literature), empty dots are clusters at lower redshift reported to highlight the $P_{1.4} - L_x$ correlation (solid line, from Cassano et al. 2006). Upper limits (represented by the arrows) are GMRT clusters with no hint of cluster-scale emission and their distribution should be compared with that of clusters at similar redshift (filled dots). Right Panel: upper limits (curves) to the ratio between the energy density of relativistic protons (p $\geq$ 0.01 mc) and that of the IGM calculated for δ =2.1, 2.3, 2.5, 2.7 (from bottom to top) assuming a proton spectrum $N(p) \propto p^{-\delta}$ (see Brunetti et al. 2007 for details).

in favour of *in situ* acceleration models (Schlickeiser et al. 1987; Thierbach et al. 2003).

2.2. *Inputs from new radio observations*

The two models in § 2.1 have different basic expectations in terms of statistical properties of Radio Halos and of their evolution. In particular, as already pointed out, in the context of *secondary electron* models, Radio Halos should be common and very long-living phenomena, on the other hand, in the context of *re-acceleration* models, due to the finite dissipation time-scale of the turbulence in the IGM, they should be *transient phenomena* with lifetime ≈1 Gyr (or less).

Radio pointed observations of a complete sample of about 50 X-ray luminous ($L_x \geq 5 \times 10^{44}$ erg s^{-1}) clusters at redshift $z = 0.2 - 0.4$ have been recently carried out at 610 MHz with the GMRT-*Giant Metrewave Radio Telescope* (Venturi et al. 2007, 2008). These observations were specifically designed to avoid problems in the detection of the cluster-scale emission due to the missing of short-baselines in the interferometric observations and to image, at the same time, both compact and extended sources in the selected clusters. Thus they allowed a fair analysis of the occurrence of Radio Halos in galaxy clusters. One of the most relevant findings of these GMRT observations is that only a fraction ($\leq 30\%$) of the X-ray luminous clusters hosts Radio Halos (Venturi et al. 2008); all Radio Halos being in merging-clusters. Remarkably, the fraction of clusters with Radio Halos is also found to depend on the cluster X-ray luminosity (and mass) decreasing at $\leq 10\%$ in the case of clusters at $z = 0.05 - 0.4$ with $L_X \approx 3 \cdot 10^{44} - 8 \cdot 10^{44}$ erg s^{-1} and suggesting the presence of some threshold in the mechanism for the generation of these sources (Cassano et al. 2008). Although these studies demonstrate that no cluster-scale emission is detected in the majority of cases, potentially synchrotron radio emission may be present in all clusters at a level just below the sensitivity of radio observations and this implies the importance to combine radio upper limits and detections. Figure 1 shows the distribution of GMRT clusters in the radio power ($P_{1.4}$)-cluster X-ray luminosity (L_x) plane. The important point is that clusters with similar L_x (and redshift) have a bimodal distribution, with the upper limits to the synchrotron luminosity of clusters with no hint of Radio Halos that lie about one order of magnitude below the region of the clusters with Radio Halos ($P_{1.4} - L_x$ correlation). It is probably useful to stress that these upper limits are solid (conservative) being evaluated through injection of fake Radio Halos into the observed datasets in order to account for the sensitivity of the different observations to the cluster-scale emission (Brunetti et al. 2007; Venturi et al. 2008).

Cluster bimodality and the connection of Radio Halos with cluster mergers, suggest that Halos are *transient phenomena* that develop in merging clusters. From the lack of clusters in the region between Radio Halos and upper limits, in the case that Halo-clusters evolve into radio-quiet clusters (and vice versa), the evolution should be fast, in a timescale of $\approx 0.1-0.2$ Gyr (Brunetti et al. 2007). This observational picture suggests that turbulent re-acceleration of relativistic electrons may trigger the formation of Radio Halos in merging clusters, in which case the acceleration timescale of the emitting electrons is indeed $\approx 0.1-0.2$ Gyr. On the other hand, unless we admit the possibility of *ad hoc* fast (on timescale of $\approx 0.1-0.2$ Gyr) dissipation of the magnetic field in clusters, the bimodal distribution in Figure 1 cannot be easily reconciled with *secondary* models. In this case –indeed– Radio Halos should be common and some general $P_{1.4}-L_x$ trend is predicted for all clusters (e.g. Miniati et al. 2001; Dolag 2006; Pfrommer 2008; see discussion in Brunetti et al. 2007 for more details).

2.3. *Limits on cosmic ray protons and future with the FERMI gamma-ray telescope*

Gamma ray observations with EGRET limit the energy of CR protons in a number of nearby clusters to $\leq 20\%$ of the energy of the IGM (Reimer et al. 2003; Pfrommer & Enßlin 2004).

The upper limits obtained for the clusters with no Radio Halos in Figure 1 imply that, regardless of the origin of the radio emission, the synchrotron emission from secondary electrons must be below the value of the upper limits. This allows to put a corresponding limit to the energy density of the primary protons from which secondaries are generated (Brunetti et al. 2007).

The limits are reported in Figure 1 (right) as a function of the magnetic field strength in the IGM and for different spectra of the primary protons. By assuming $> \mu$G field, the upper limits to the energy density of relativistic protons in the IGM are about one order of magnitude more stringent than those obtained from EGRET upper limits (at least for relatively flat proton spectra). As a matter of fact, under these assumptions, no more than 1% of the energy density of the IGM in X-ray luminous clusters can be in the form of relativistic protons; this would imply that even the FERMI Gamma-ray telescope might be not sensitive enough to detect the π° decay from these clusters. On the other hand, for steeper spectra of relativistic protons, or lower values of the field, the synchrotron constraints in Figure 1 (right) become gradually less stringent and the energy content of relativistic protons permitted by observations is larger. Since efficient particle acceleration mechanisms would naturally produce flat proton spectra, it is unlikely that a population of protons with steep spectrum stores a relevant fraction of the IGM energy and Figure 1 (right) reasonably implies that FERMI may detect the π° decay in a fairly large number of clusters provided that the IGM is magnetised at $\approx \mu$G level (or lower). In this case, since $E_{\rm CR}/E_{\rm th}$ (and also the spectrum of relativistic protons) can be constrained, the combination of gamma ray measurements with deep radio upper limits in clusters without Radio Halos will provide a novel tool to measure the magnetic field strength in galaxy clusters.

3. RE-ACCELERATION MODELS

3.1. *Basics*

The properties of the Mpc-scale radio emission in galaxy clusters suggest that turbulence, generated in cluster mergers, may play an important role in the acceleration of the emitting particles.

The physics of collisionless turbulence and of stochastic particle acceleration is complex and rather poorly understood, still several calculations from *first principles* have shown that there is room for efficient turbulent acceleration in the IGM.

One of the first points that have been realised is that turbulent re-acceleration is not efficient enough to extract electrons from the thermal IGM (e.g. Petrosian 2001) and thus a necessary assumption in the re-acceleration scenario is that seed particles, relativistic electrons with Lorentz factors $\gamma \sim 100-500$, are already present in the IGM. These seeds could be provided by the past activity of active galaxies in the IGM or by the past merger history of the cluster (e.g., Brunetti et al. 2001), alternatively they could be secondary electrons from p-p collisions (Brunetti & Blasi 2005).

Particle re-acceleration in the IGM may be due to small scale Alfvén modes (Ohno et al. 2002; Fujita et al. 2003; Brunetti et al. 2004) or due to compressible (magnetosonic) modes (Cassano & Brunetti 2005; Brunetti & Lazarian 2007). In the case of Alfvénic models, the acceleration of relativistic protons increases the damping of the modes and this severely limits the acceleration of relativistic electrons when the energy budget of relativistic protons is typically $\geq 5-7\%$ of that of the IGM (Brunetti et al. 2004). The injection process of Alfvén modes at small, resonant, scales in the IGM and the assumption of isotropy of these modes represent the most important sources of uncertainty in this class of models (see discussion in Brunetti 2006 and Lazarian 2006b). Alternatively, compressible (magnetosonic) modes might re-accelerate fast particles via resonant Transit Time Damping (TTD) and non-resonant turbulent compression (e.g., Cho et al. 2006; Brunetti & Lazarian 2007). The main source of uncertainty in this second class of re-acceleration models is our ignorance on the viscosity in the IGM. Viscosity could indeed severely damp compressible modes on large scales and inhibit particle acceleration, although the super-Alfvénic (and sub-sonic) nature of the turbulence in the IGM is expected to suppress viscous dissipation (see discussion in Brunetti & Lazarian 2007).

3.2. *The non-thermal spectrum of galaxy clusters*

The main goal of this Section is to suggest that the non-thermal emission from clusters is a mixture of two main spectral components: a long-living one that is emitted by secondary particles (and by π° decay) continuously generated during p-p collisions in the IGM, and a transient component that may be due to the re-acceleration of relativistic particles by MHD turbulence generated (and then dissipated) in cluster mergers. We model the re-acceleration of relativistic particles by MHD turbulence in the most simple situation in which only relativistic protons, accumulated during cluster lifetime, are initially present in a turbulent IGM. These protons generate secondary electrons via p-p collisions and in turns these secondaries (as well as protons) are re-accelerated by MHD turbulence. More specifically we adopt the Alfvenic model of Brunetti & Blasi (2005) and do not consider the possibility that *relic* primary electrons in the IGM can be re-accelerated. Also we do not consider the contribution to the cluster emission from fast electrons accelerated at shock waves that develop during cluster mergers and accretion of matter (see Enßlin 2009).

An example of the expected broad band emission is reported in Figure 2 for a Coma-like cluster (curves in figure are not fits to the data).

Upper panels show the non-thermal emission (synchrotron[5], IC, π° decay) generated during a cluster merger, while the spectra in lower panels are calculated after 1 Gyr from the time at which turbulence is dissipated, and thus they only rely with the long-living component of the non-thermal cluster emission. As a first approximation the non thermal emission in the lower panels does not depend on the dynamics of the clusters but only on the energy content (and spectrum) of relativistic protons in the IGM (and on the magnetic field in the case of the synchrotron radio emission). On the other hand, the comparison between the spectra in upper and lower panels highlights the transient emission that is generated in connection with the injection of turbulence during cluster mergers.

The results reported in Figure 2 have the potential to reproduce the radio bimodality observed in galaxy clusters (Figure 1): Radio Halos develop in connection with particle re-acceleration due to MHD turbulence in cluster mergers where the cluster-synchrotron emission is considerably boosted up (upper panel), while a fainter long-living radio emission from secondary electrons is expected to be common in clusters (lower panel); the level of this latter component must be consistent with the radio upper limits from radio observations (Figure 1, right).

An important point is that some level of gamma ray emission is expected. However, we do not expect a direct correlation between giant Radio Halos and the level of gamma ray emission from clusters, indeed this level only depends on the content of protons in the IGM (see Figure 2 caption). FERMI is expected to shortly obtain crucial information on that. By taking into account the constraints on the energy content of relativistic protons obtained from the radio upper limits of clusters without Radio Halos (§ 2.3, Figure 1) the gamma ray emission from a Coma-like cluster (assuming $E_{\rm CR} \propto E_{\rm th}$ and B$\approx \mu$G as in Figure 2) is expected $\approx 10-20$ times below present EGRET upper limits and no substantial amplification of this signal is expected in clusters with Radio Halo. On the other hand, in the case of smaller magnetic fields in the IGM, the gamma ray luminosity of clusters can be larger because a larger proton-content is permitted by radio upper limits (a more detailed discussion on the gamma ray properties of clusters in the re-acceleration scenario is given in Brunetti et al., in prep.).

Figure 2 shows that a direct correlation is expected between Radio Halos and IC emission in the hard X-rays since the two spectral components are emitted by (essentially) the same population of relativistic electrons. Because the ratio between IC and radio luminosity depends on the magnetic field in the

[5]SZ decrement at high frequencies is not taken into account.

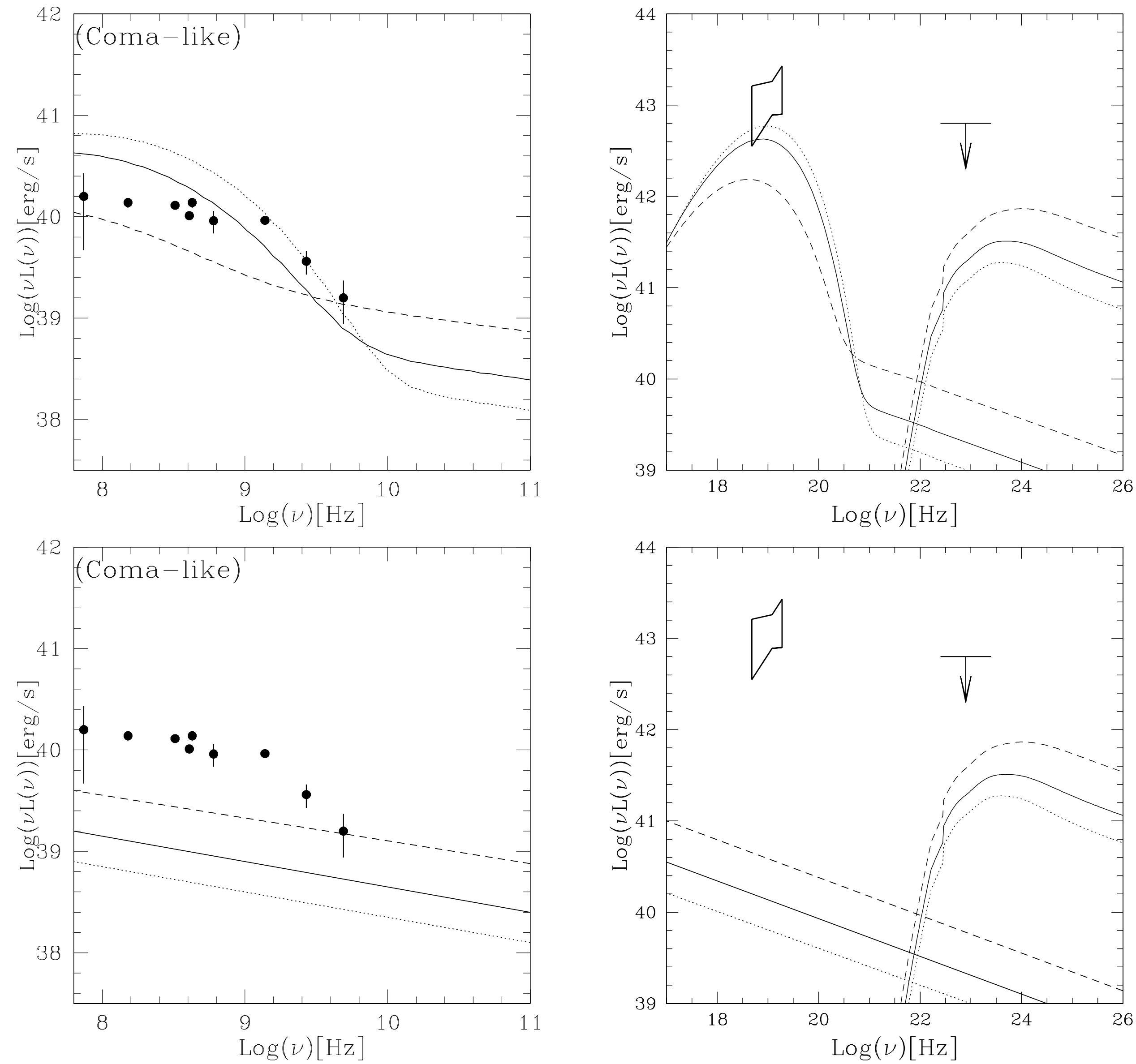

Fig. 2. Example of broad band spectrum for a Coma-like cluster. Upper panels: Synchrotron (left) and IC and π-o emission (right) calculated at t=0.75 Gyr from the injection of MHD turbulence in the IGM. Lower panels: Synchrotron (left) and IC and π-o emission (right) calculated at t=1.75 Gyr from the injection of MHD turbulence in the IGM; the energy density of turbulence is set =0 for t$\geq$0.8 Gyrs. In all panels calculations are shown assuming a ratio between the energy density of relativistic and thermal protons =3% (dashed lines), 1% (solid lines) and 0.5% (dotted lines) at t=0 (with proton spectrum $\delta = 2.2$), a central cluster-magnetic field $B_o = 1.5\ \mu$G, a scaling between field and thermal density $B(r) \propto n_{th}^{2/3}$, $E_{\rm CR} \propto E_{\rm th}$, and a beta-model profile of the Coma cluster. The energy density injected in Alfven modes between t=0–0.8 Gyr is $\approx 3\%$ of the thermal energy of the IGM. For the sake of completeness we show radio data, BeppoSAX data and EGRET upper limit for the Coma cluster, note –however– that model parameters are not chosen to fit the data (see e.g., Brunetti & Blasi 2005 for model fittings to the Coma data).

IGM, future hard X-ray telescopes (Simbol-X, NuSTAR and Next) are expected to detect a fairly large number of clusters with Radio Halos in the case that the IGM is magnetised at $\approx 1\ \mu$G level (or lower).

3.3. *Low frequency radio emission from galaxy clusters*

The maximum energy at which electrons can be re-accelerated by turbulence in the IGM, and ultimately the frequencies at which the spectra of Radio Halos cut off (e.g. Figure 2), depend on the acceleration efficiency that essentially increases with the level of turbulence in the IGM. The spectral cut off affects our ability to detect Radio Halos in the universe, introducing a strong bias against observing them at frequencies substantially larger than the cut off frequency. In the context of the re-acceleration scenario, presently known Radio Halos must result from the rare, most energetic merging events and therefore be hosted only in the most massive and hot clusters (Cassano & Brunetti 2005). On the other hand, it has been realised that a large number of Radio Halos should be formed during much more common but less energetic mergers and should be visible only at lower frequencies because of their ultra steep spectral slope (Figure 3). Thus the fraction of clusters with Radio Halos increases at lower observing frequencies and LOFAR and LWA, that will observe galaxy clusters with unprecedented sensitivity at low radio frequencies, have the potential to catch the bulk of these sources in the universe (Cassano et al. 2006).

This is a unique expectation of the re-acceleration scenario. In particular, following Cassano et al. (2008), it has been calculated that observations at 150 MHz have the potential to increase the number of giant Radio Halos observed in galaxy clusters with mass $M \leq 10^{15} M_{\odot}$ by almost one order of magnitude with respect to observations at 1.4 GHz, while this increase is expected to be smaller for clusters with larger mass.

4. SUMMARY

Recent observations show that Radio Halos are not common in galaxy clusters suggesting that they are transient sources in cluster mergers. These facts support the idea that MHD turbulence generated in cluster mergers may play an important role in the re-acceleration of particles in the IGM.

We have suggested that in the context of the re-acceleration scenario the non-thermal emission from galaxy clusters is a combination of two components : a long-living one that is emitted by secondary particles (and by π° decay) continuously generated during p-p collisions in the IGM, and a transient component due to the re-acceleration of relativistic particles by MHD turbulence generated (and then dissipated) in cluster mergers.

The latter component may naturally explain Radio Halos in merging and massive clusters and their statistical properties, on the other hand FERMI may detect the long-living gamma ray emission from clusters due to the decay of π° produced via collisions

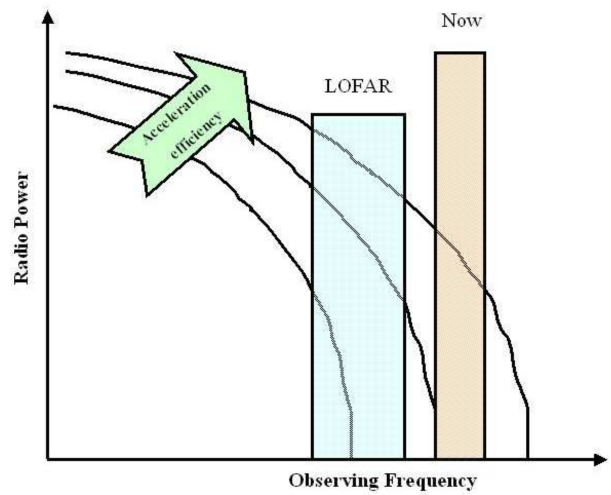

Fig. 3. Picture showing the connection between acceleration efficiency and spectrum of Radio Halos in the re-acceleration scenario. Boxes indicate the frequency range in which Radio Halos can be studied with present radio telescopes and with LOFAR.

between relativistic and thermal protons. In particular, given the constraints on the relativistic protons obtained from upper limits to the synchrotron emission due to secondaries in X-ray luminous clusters, we conclude that the detection of a fairly large number of clusters with FERMI would imply that the magnetic field in the IGM is at $\approx \mu$G level (or lower). In this case, the pool of future hard X-ray detectors (NuSTAR, Simbol-X and Next) should detect IC emission from a fairly large number of merging clusters with Radio Halos.

An important expectation of the re-acceleration scenario is the presence of a population of Radio Halos in the universe that should emerge only at low radio frequencies, and this can be easily tested in a few years with LOFAR and LWA. The detection of Radio Halos with ultra-steep spectral slope will thus provide compelling support to particle re-acceleration due to turbulence in the IGM.

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