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Cosmic rays and diffuse non-thermal emission in galaxy clusters: an introduction

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Abstract. Recent multifrequency observations contribute to derive a comprehensive picture of the origin and evolution of relativistic particles in galaxy clusters. In this review I briefly discuss theoretical aspects and open problems of this picture.

Key words. Galaxies: clusters: general – Cosmic rays – Turbulence – Shock waves

1. Introduction

Radio observations prove the existence of non-thermal components, magnetic fields and relativistic particles, mixed with the hot Inter-Galactic-Medium (IGM). The mystery of their origin rises new questions on the physics of the IGM. Non-thermal components contribute to the energy of the IGM and drive physical processes that have the potential to modify our present view of the IGM (*e.g.,* Schekochihin et al. 2005; Subramanian et al. 2006; Brunetti & Lazarian 2011a).

Clusters host several sources of cosmic rays (CR). CR protons are predicted to be the dominant non-thermal particles component in the IGM (Sect. 2). Limits on their energy content are derived from γ–rays and radio observations (Sect. 3).

The acceleration of relativistic electrons in the IGM is directly probed by radio observations of diffuse (Mpc scale) synchrotron radio emission, *radio halos* and *relics* (*e.g.,* Venturi, this conference). In the last years large observational projects lead to significant steps in the knowledge of clusters radio properties. The GMRT Radio Halo Survey and its combination with the NVSS and WENSS surveys allow a statistical exploration of radio halos discovering a bimodality of the clusters's radio properties, with Mpc-scale radio sources found only in a fraction of massive clusters (Venturi, this conference). These surveys and their follow up in the X-rays demonstrated a tight connection between cluster mergers and radio halos (*e.g.,* Cassano et al 2010a and ref therein). It suggests that a fraction of the gravitational energy that is dissipated during cluster mergers is channelled into the acceleration of relativistic particles. Two models that connect the origin of radio halos and relics with mergers became popular, turbulent and shock acceleration respectively (Sect. 4), although the contribution to the non-thermal emission from secondary particles due to proton-proton collisions in the IGM is still debated (Sects. 3-4).

2. CR in galaxy clusters

Particle acceleration in the IGM occurs in several places, from ordinary galaxies to active

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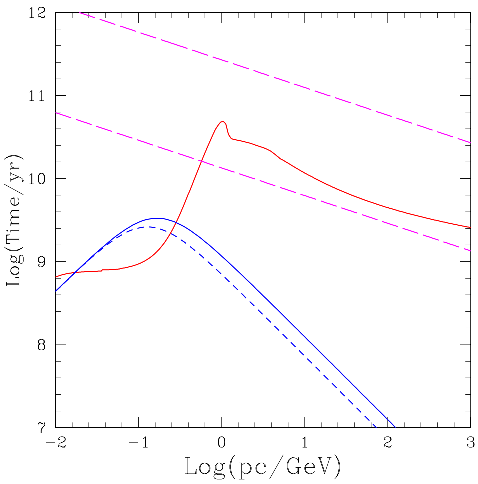

Fig. 1. Time scale for energy losses of protons (middle) and electrons (bottom). Calculations assume $z = 0.1$, $n_{th} = 10^{-3}\mathrm{cm}^{-3}$, $B = 1$ (dashed) and 3μG (solid). Long–dashed lines show diffusion times assuming a Kolmogorov spectrum of magnetic fluctuations, with $L_{30} = 1$, $B = 1.5\mu$G and $\xi = 1$ (upper) and 0.05 (lower).

galaxies (AGN) (*e.g.,* Blasi et al. 2007). Nowadays, it is believed that particle acceleration at cosmological shocks contributes the most to the energetics of non-thermal particles in galaxy clusters, with a total luminosity in CR protons $\sim$ few $\times 10^{42}$erg s^{-1} (*e.g.,* Pfrommer et al. 2006; Skillman et al. 2008; Vazza et al. 2009).

The evolution and propagation of CR injected in the IGM is determined by diffusion, convection and energy losses.

A optimistic estimate of the spatial diffusion coefficient of CR is obtained assuming a Kolmogorov spectrum $P(k) \propto k^{-5/3}$ of magnetic fluctuations (*e.g.,* Blasi et al. 2007):

$$D(E) \approx 3 \times 10^{29} E_{\rm GeV}^{1/3} \xi^{-1} B_{\mu}^{-1/3} L_{30}^{2/3} \ \mathrm{cm}^2\mathrm{s}^{-1}, \quad (1)$$

where ξ is the fraction of the cluster magnetic field energy in the turbulent field and L_{30} is the largest scale of magnetic fluctuations (in units of 30 kpc). The corresponding time-scale to diffuse on scale $L_D = 1$ Mpc, $\tau_D \approx L_D^2 D^{-1}$, is reported in Fig. 1. Even in the case of weakly turbulent field, $\xi = 0.05$, diffusion occurs in cosmological time-scales. Faraday rotation measures (RM) suggest that a sizeable fraction of the magnetic field is turbulent (Murgia, this conference), which readily implies an efficient confinement of CR in galaxy clusters (Voelk et al. 1996; Berezinsky et al. 1997; Enßlin et al. 1997).

Figure 1 also shows the time-scales for energy losses of protons and electrons. Electrons in the IGM are short–living particles, due to Coulomb and radiative losses. The typical lifetime is few Gyr for electrons with $E \approx 100$ MeV but it is much shorter, about 10^8 yr, for electrons with $E \approx$ few GeV, that are those emitting synchrotron radiation in the radio band. Because the diffusion time on halo scales (Mpc) of GeV electrons is much longer than their radiative life-time (Fig.1), mechanisms of in-situ (spatially distributed) acceleration/injection of electrons are necessary to explain radio halos (Jaffe 1977).

Contrary to electrons, CR protons are long–living particles that can be accumulated in the cluster volume (Fig. 1). This leads to the conclusion that protons should be the dominant non-thermal particles component in the IGM, with their properties tracing the history of the complex interplay between particle acceleration and advection processes that take place in clusters from their formation epoch (e.g. Blasi et al. (2007) and ref. therein).

The energy content of CR in galaxy clusters is uncertain. Modern numerical simulations explore CR acceleration at cosmological shocks with unprecedented details, still estimates of $E_{CR}/E_{IGM} \approx 0.03 - 0.5$ unavoidably reflect the uncertainties in the assumptions of the acceleration efficiency in these environments (*e.g.,* Ryu et al. 2003; Pfrommer et al. 2006).

3. Limits on CR protons from recent observations

The most direct approach to constrain the energy content of CR protons in galaxy clusters consists in the observation of γ-ray emission from the decay of the neutral pions due to pp collisions in the IGM.

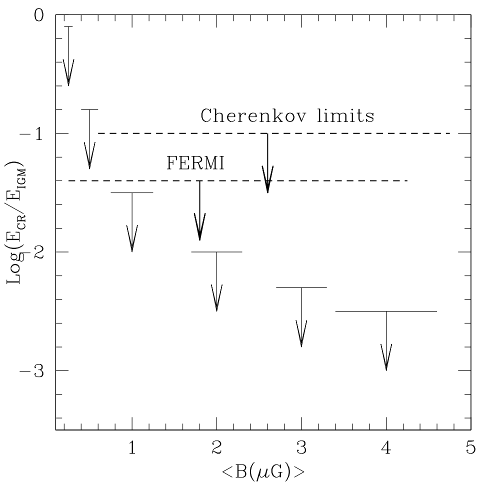

Fig. 2. Limits to E_{CR}/E_{IGM} from Cherenkov and FERMI observations (thick–dashed upper limit) and from radio observations (solid upper limits) (see text). Limits are obtained assuming $N(p) \propto p^{-\delta}$, with $\delta = 2.2$, and that CR follow the spatial distribution of thermal medium.

Gamma ray upper limits from EGRET observations allow to put limits $E_{CR}/E_{IGM} < 0.3$ in several nearby galaxy clusters (Reimer et al. 2003). More stringent limits are derived from deep pointed observations at energies >100 GeV with Cherenkov telescopes. These limits depend on the (unknown) spectral shape of the proton-energy distribution. In the relevant case $\delta = 2$ ($N_{CR}(p) \propto p^{-\delta}$) $E_{CR}/E_{IGM} < 0.1$ are obtained (Aharonian et al. 2009a,b; Aleksic et al. 2010), constraints being less stringent for steeper spectra. FERMI greatly improved the sensitivity of observations at MeV/GeV energies allowing a significant step. After 18 months of observations upper limits to the γ-ray emission of nearby clusters allow to derive $E_{CR}/E_{IGM} < 0.05$ (Ackermann et al. 2010; Jeltema & Profumo 2011), with a poor dependence on δ.

Also radio observations of galaxy clusters can be used to put limits on E_{CR}/E_{IGM} (Reimer et al. 2004; Brunetti et al. 2008). Limits to the presence of diffuse Mpc-scale radio emission in clusters can be used to constrain secondary electrons and thus the energy density of the primary CR protons (Brunetti et al. 2007). Limits from radio observations depend also on the cluster magnetic field strength and are complementary to those obtained from γ-rays.

Gamma and radio limits are reported in Fig. 2. Assuming a average (Mpc-scale) magnetic field $< B > \geq$ few μG, radio observations of clusters with no Mpc-scale radio emission provide the most stringent limits, $E_{CR}/E_{IGM} \leq$ few$\times 10^{-3}$. If the magnetic field is smaller, the CR energy content is mainly constrained by FERMI. RM provide independent constraints on the magnetic fields of clusters suggesting that (i) $< B > \approx 1 - 2\mu$G and that (ii) clusters with and without radio halos have similar fields (*e.g.,* Bonafede et al. 2011, Murgia, this conference). In this case both radio and γ-rays imply $E_{CR}/E_{IGM} \leq$ few$\times 10^{-2}$.

Constraints in Fig. 2 refer mainly to the innermost (~Mpc) regions of clusters where both the number density of thermal protons (target for π^o production) and the magnetic field are larger. It should be mentioned that no tight constraints are available for the clusters outskirts where the CR contribution might be larger.

4. A theoretical picture

The observed connection between mergers and cluster-scale radio emission guides models for the origin of CR in galaxy clusters.

Cluster mergers drive shocks in the IGM that can accelerate CR (protons and electrons). Protons can be advected in the cluster central regions where they generate secondary particles trough pp collisions. During cluster mergers large-scale turbulence is generated, it decays at smaller scales and can reaccelerate primary and secondary particles. According to the confinement of CR, protons smoothly diffuse on Mpc scale on clusters life-times, and guarantee a continuous source of secondary electrons independently of cluster dynamics. The interplay of all these mechanisms implies a complex mixture of primary and secondary CR; galaxies and AGN shall further contribute to the injection of primary CR in the IGM.

Radio halos and relics probe relevant aspects of this complex picture. In the most popular (yet simplified) view halos are connected with cluster-turbulence (via turbulent acceleration) and relics to cluster-shocks (via shock acceleration). A spatial coincidence of merger shocks with edges of radio halos (or with radio relics at the edges of halos) is now observed in many cases Markevitch (2010) suggesting that, although distinct phenomena, relics and halos can be connected with the same merger.

Hadronic models are also proposed for the origin of radio halos (*e.g.,* Blasi& Colafrancesco 1999; Pfrommer & Ensslin 2004; Keshet & Loeb 2010): extended and fairly regular radio emission from Mpc-scale is naturally expected when the radiating electrons are secondaries because the parent CR protons can diffuse on fairly large scales. Still several arguments may suggest that the observed giant halos cannot be explained by considering ("only") hadronic collisions, e.g. :

- Radio halos are very extended and most of them have radio brightness profiles much broader than those predicted by hadronic models (Dolag & Ensslin 2000; Brunetti 2004; Murgia et al. 2009; Donnert et al. 2010a; Brown & Rudnick 2011). The number density of thermal protons (targets for pp collisions) is indeed very small far from the cluster center implying a strong suppression of the radio brightness. It follows that a challenging, very large, energy budget of CR must be postulated in this model to explain the extension of giant halos, at least when constraints on B from RM are taken into account (see Donnert et al 2010a,b). Future RM studies (e.g. eVLA) will be important.
- Giant radio halos with very steep spectrum (USSRH), $\alpha > 1.5 - 1.6$ (with $F(\nu) \propto \nu^{-\alpha}$), exist (*e.g.,* Brunetti et al. 2008; Brentjens 2008; Dallacasa et al. 2009; Macario et al. 2010), questioning the "classical" idea that halos have a typical spectrum $\alpha \sim 1.2$ (see also Venturi 2011, this conference). Energy arguments can be used to rule out a hadronic origin of USSRH (*e.g.,* Brunetti 2004; Pfrommer & Ensslin 2004; Brunetti et al. 2008). Future LOFAR observations will be *crucial* to test if these USSRH contribute to a relevant fraction of the halos.
- Gamma ray emission from galaxy clusters is unavoidably predicted by hadronic models (*e.g.,* Blasi et al. 2007). Present FERMI upper limits significantly constrain the role of secondary electrons (Ackermann et al. 2010), challenging a hadronic origin of several clusters-radio halos (*e.g.,* Jeltema & Profumo (2011), see Sect. 4.3). The improvement in sensitivity that will be achieved by FERMI in next years will allow improving these constraints.

4.1. Shock acceleration in galaxy clusters and radio relics

The morphology and polarization of radio relics suggest that their origin is connected with shock waves (*e.g.,* Enßlin et al. 1998). The possibility to detect relics far from cluster cores makes them potential probes of the process of matter accretion in clusters.

The acceleration of CR at shocks is customarily described according to the diffusive shock acceleration (DSA) theory (*e.g.,* Blandford & Eichler 1987) that applies when particles can be described by a diffusion–convection equation across the shock. For strong shocks a substantial fraction of the energy flux goes into CR which in turn back react modifying the structure of shocks themselves (non linear shock acceleration theory, Malkov (1997); Blasi (2002); Kang & Jones (2005)). The most relevant theoretical uncertainty is the injection model, i.e. the probablity that supra-thermal particles at a given velocity can leak upstream across the subshock and get injected in the CR population. An other major hidden ingredient is the amplification of the magnetic field (perpendicular component) downstream due to CR driven instabilities and adiabatic compression, as this magnetic field self–regulates the diffusion process of supra–thermal particles and also affects the injection process (Ryu, Kang, this conference).

The energetics and spectrum of the accelerated CR depend on the shock Mach-number. There is consensus on the fact that most of the energy in clusters is dissipated at weak shocks, with Mach numbers 2–4 (Ryu et al. (2003); Pfrommer et al. (2006); Skillman et al. (2008); Vazza et al. (2009) see Vazza, Burns, Hoeft, this conference). This however raises several problems :

- The efficiency of CR acceleration at these weak shocks is very low and uncertain.
- The acceleration of CR electrons, that is relevant for radio relics, is still poorly understood.

Only a handful of merger shocks have been discovered using X-ray observations, with Mach numbers $M \approx 1.5 - 3$ (Markevitch & Vikhlinin 2001). Most of these shocks coincide with radio relics or with sharp edges of radio halos indicating that they must have something to do with producing the observed radio emission. Since weak shocks must be inefficient accelerators of CR, these observations may suggest that re-acceleration of relativistic (seeds) electrons is an important process in these environments (Kang, this conference).

4.2. Turbulent acceleration & Radio Halos

Acceleration of relativistic electrons by merger-turbulence is proposed for the origin of giant radio halos (*e.g.,* Brunetti et al. 2001; Petrosian 2001; Fujita et al. 2003). The "hystorical" motivation is that the particle acceleration mechanisms in radio halos are poorly efficient as demonstrated by the steepening observed (at $\geq$ 1 GHz) in the spectrum of the Coma halo (Schlickeiser et al. 1987). A more recent argument in favour of turbulent acceleration for the origin of halos comes from the discovery of USSRH (*e.g.,* Brunetti et al. 2008) that are interpreted as halos with a spectrum that steepens at even lower radio frequencies, favouring acceleration mechanisms poorly efficient.

Turbulence can be generated during cluster mergers on large scales, $L_o \sim 100 - 400$ kpc, with typical turbulent velocities $V_o \sim 300 - 700$ km/s. Numerical simulations provide an unprecedented view of this process (see Vazza, Iapichino, Jones, Paul, this conference). Large-scale turbulence in the IGM is sub–sonic, with $M_s = V_o/c_s \approx 0.25 - 0.6$, but strongly super-Alfvénic (hydrodynamics), with $M_A = V_o/v_A \approx 5 - 10$. At smaller scales, $l < l_A \sim L_o M_A^{-3}$, turbulence gets sub-Alfvénic (MHD) and three types of modes exist : Alfvén, slow and fast modes (Lazarian, this conference).

Turbulence can accelerate particles trough resonant and non-resonant mechanisms. A large part of turbulence at scales $l \geq l_A$ could be in the form of compressible motions and Transit-Time-Damping is the most relevant mechanism (*e.g.,* Brunetti & Lazarian 2011b).

At smaller scales, $l \leq l_A$, most of turbulence is probably in the form of Alfvén and slow modes whose contribution to particle acceleration via resonant (gyro-resonant) interaction is potentially strong but more uncertain due to the anisotropy that develops when these modes cascade from larger to smaller scales (*e.g.,* Yan & Lazarian 2004). Consequently Alfvénic models must postulate the injection of Alfvén modes "directly" at small scales. This may occur trough several processes in the IGM (Lazarian, this conference) although self-consistent calculations are not yet available.

Several open questions exist in turbulent acceleration models, e.g. :

- The efficiency of turbulent acceleration in the IGM is still poorly constrained, due to the fact that a self-consistent model of the multi-scale turbulence in galaxy clusters is still missing (Brunetti & Lazarian (2011a) for recent attempts).
- Theoretically this model provides a "unique" avenue to explain the *large spatial extent of giant radio halos* and the *variety of the observed spectral properties of halos*. However this has not be proved yet by detailed numerical simulations (see however first efforts in this direction, Donnert, ZuHone, this conference).

Although the uncertainties in the details of this complex model, future observations will allow clear tests. The model predicts the existence of USSRH (*e.g.,* Cassano et al. 2006). This is the consequence of the fact that spectral steepening occurs at lower frequencies in

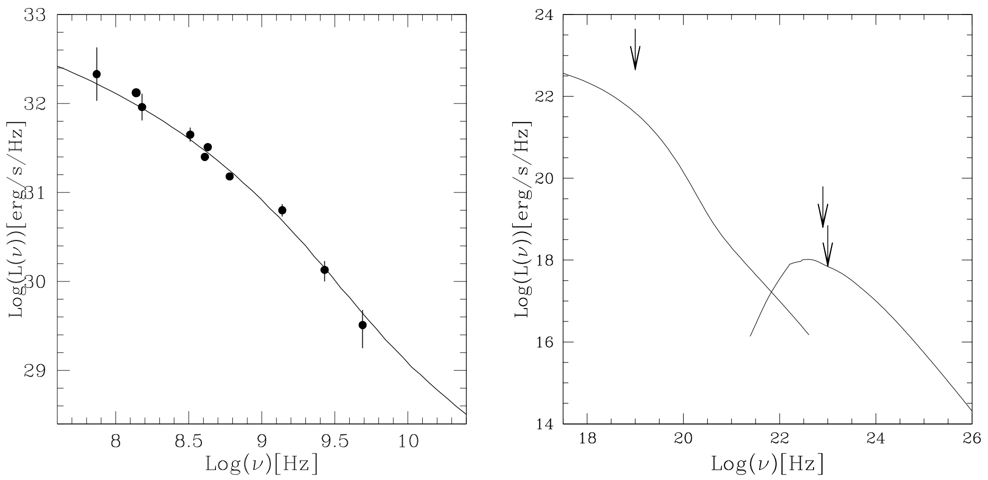

Fig. 3. Radio and γ-ray (IC and π^o) emitted spectrum of the Coma clusters obtained from hybrid models (readopted from Brunetti & Lazarian (2011b)).

those halos that are generated in less energetic merger events (see Cassano, this conference). Radio halos with very–steep spectrum must be common in this scenario and LOFAR surveys can test this (Cassano et al. 2010b).

4.3. *"Hybrid" models and constraints from γ-ray limits*

Acceleration of electrons from the thermal pool to relativistic energies by MHD turbulence in the IGM faces serious problems due to energy arguments (*e.g.,* Petrosian & East 2008). Consequently, turbulent acceleration models assume a pre-existing population of relativistic particles that provides the seeds to "reaccelerate" during mergers.

In "hybrid" models *seeds are secondary electrons* (Brunetti & Blasi 2005). Recent calculations have demonstrated that reacceleration of CR and their secondaries may be sufficient to generate the observed radio halos in merging clusters, including their *observed brightness profiles and spectra*, provided that the spatial distribution of the primary CR is relatively flat (Brunetti & Lazarian 2011b). Expectations are consistent with present upper limits (FERMI) provided that the magnetic field in clusters is in agreement with that derived from RM (Fig. 4).

Having in hands a complete treatment of primary and secondary particles in the IGM, "hybrid" calculations emulate hadronic models in the case we assume "no" (or negligible) turbulence. In this case the energy of CR that is necessary to reproduce the radio luminosity and the observed brightness profile of radio halos is much larger than that in the case of turbulent reacceleration; e.g. for Coma it is about 10 times larger than that in Fig. 4 ($E_{CR}/E_{IGM} \approx 0.3$, for $\delta = 2.6$, considering the magnetic field from Bonafede et al. (2010)). The consequence, *in addition to the well known difficulty to reproduce the radio spectrum*, is a γ-ray flux that becomes inconsistent with the present FERMI limit (Fig. 5), unless B is 2 times larger than that from RM.

5. Evolution of radio halos

It was quickly realised that radio halos are not common (Giovannini et al. 1999) and that this is a challenge for a hadronic models which predict long-living halos in all clusters (Hwang 2004). Recent surveys, such as the GMRT Radio Halo Survey (RHS, Venturi

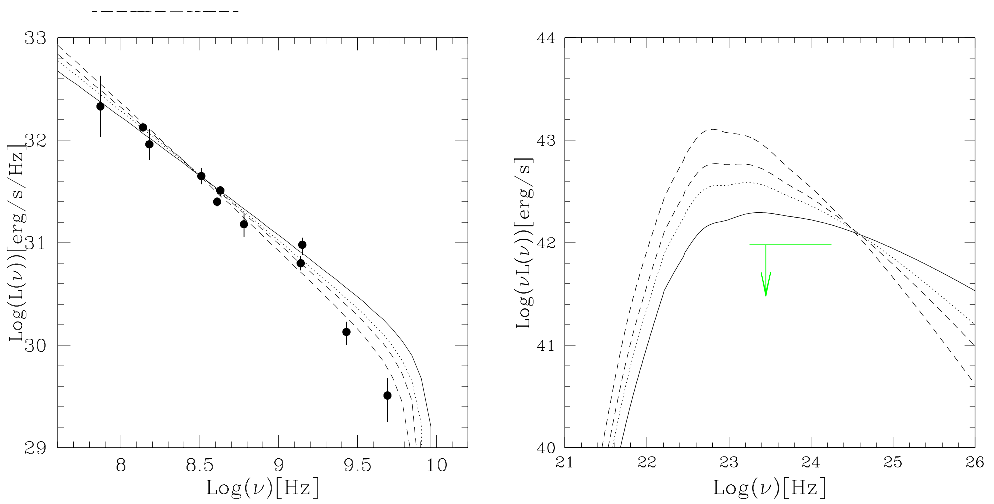

Fig. 4. Radio (including SZ decrement) and γ-ray (π^o) spectrum of the Coma clusters from secondary models assuming a magnetic field from Bonafede et al. (2010) and the observed brightness profile from Govoni et al. (2001). Different models assume δ = 2.6 ..3.2.

et al. (2008)), start the study of the occurrence of halos in clusters and their evolution with cosmic time. The RHS allows the discovery of a bimodal behaviour of galaxy clusters : in a $P_{1.4}$–L_X diagram "radio quiet" clusters are well separated from giant radio halos (Fig. 5). When combined with the radio halo – merger connection, the bimodality suggests that (i) relativistic particles are accelerated in mergers and cool when systems becomes more relaxed (Brunetti et al. 2007, 2009), or (ii) that the magnetic field is amplified during mergers and dissipated in relaxed clusters (Kushnir et al. 2009; Keshet & Loeb 2010). Present analysis of RM in clusters' radio sources do not find a difference between the magnetic properties of clusters with and without halos, supporting the scenario where the radio bimodality is due to merger-induced acceleration mechanisms (Bonafede et al. (2011) and ref. therein).

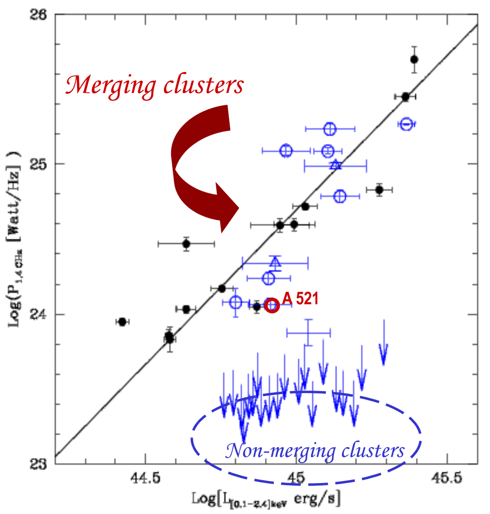

Fig. 5. Distribution of galaxy clusters in the $P_{1.4} - L_X$ diagram (readapted from Brunetti et al. (2009)).

It has been claimed that if CR propagate at super-Alfvénic speeds in (less turbulent) clusters, propagation of CR can also induce radio bimodality (Enßlin et al. 2011). The difficulty to maintain super-Alfvénic propagation of CR is however that it would get quenched by the scattering by the MHD waves that are generated by CR streaming itself (Schlickeiser (2002) for a modern review including high beta plasmas, such as the IGM).

6. Conclusions

Recent observations lead to a substantial progress in constraining the energy content of CR in clusters and the properties of Mpc-scale radio sources associated with a fraction of merging clusters. Present view of the non-thermal particle components in the IGM is very complex with several main players, shocks, turbulence and hadronic collisions. It is believed that radio halos and relics probe CR in turbulent and shocked regions, although the details of the mechanisms responsible for their origin are still unclear and observations with future radiotelescopes, such as LOFAR, will be crucial to test present models.

Although radio observations, and their follow up in the X-rays, contribute the most to our understanding of non-thermal phenomena in galaxy clusters, an important contribution is now coming from γ-ray observations. They put stringent limits on the energy content of CR in clusters and also provide new challenges for a "pure" hadronic origin of radio halos when combined with independent information on clusters magnetic fields.

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