The gamma ray background from large scale structure formation

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Abstract

Hierarchical clustering of dark matter halos is thought to describe well the large scale structure of the universe. The baryonic component of the halos is shock heated to the virial temperature while a small fraction of the energy flux through the shocks may be energized through the first order Fermi process to relativistic energy per particle. It has been proposed that the electrons accelerated in this way may upscatter the photons of the universal microwave background to gamma ray energies and indeed generate a diffuse background of gamma rays that compares well to the observations. In this paper we calculate the spectra of the particles accelerated at the merger shocks and re-evaluate the contribution of structure formation to the extragalactic diffuse gamma ray background (EDGRB), concluding that this contribution adds up to at most 10\% of the observed EDGRB.

Key words:

1 Introduction

EGRET observations [1] showed that the universe is permeated by a background of gamma radiation that seems to exceed the flux of gamma rays expected from cosmic ray interactions in our own Galaxy, as calculated using

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theoretical models of the origin and propagation of cosmic rays. This excess has long been considered of extragalactic origin, and innumerable attempts to explain it in terms of different kind of sources have been made. Whether this radiation is the result of discrete unresolved extragalactic sources or rather a truly diffuse background is still unknown, and is matter of investigation for future gamma ray telescopes such as GLAST.

It is somehow disturbing that the extragalactic origin for this background has been inferred from a combination of measurements and theoretical modelling of the diffuse galactic gamma radiation. In fact some authors [2] have proposed that observations can be also explained as a result of a population of galactic relativistic electrons upscattering the microwave and starlight radiations to gamma ray energies through inverse Compton scattering (ICS). These electrons would not be correctly accounted for in standard models of cosmic ray propagation in the Galaxy.

If this radiation is in fact mainly extragalactic, its source or sources need to be found. While it is believed that blazars may contribute a large fraction of the extragalactic diffuse gamma ray background [4,5,3,6] (EDGRB), it is not yet clear whether they can saturate it (see, for example [7,8]). Around 1 GeV a non negligible contribution to the diffuse background might also come from normal galaxies [9].

In the last few years, clusters of galaxies have been proposed as sources of high energy gamma rays and in fact even as sources of the EDGRB. The first paper to propose this possibility is Ref. [10]. Some problems were identified in these calculations and discussed in Refs. [11,12]. A detailed calculation of the EDGRB due to clusters of galaxies was carried out in [13], where the authors concluded that not more than a few percent of the observed background of gamma rays could be accounted for in terms of hadronic interactions in clusters of galaxies.

More recently, the authors in Ref. [14,15] have reproposed a connection between the EDGRB and clusters of galaxies. More correctly the connection should exist between the EDGRB and the process of hierarchical large scale structure formation. The claim is that the whole EDGRB can be explained in terms of ICS of electrons accelerated at shocks during structure formation up to ultrarelativistic energies. Shocks form naturally during the merger of two halos that generate a new bigger structure.

In a recent paper [16] we have studied in detail the process of acceleration and reacceleration of particles at shocks during mergers of clusters of galaxies, and we have proposed a semi-analytical method to evaluate in a self-consistent manner the Mach numbers of the shocks developed at each merger event. The Mach numbers are related in a unique way to the strength of the shocks.
and therefore to their ability to accelerate particles. We adopt here the same method introduced there and apply it to the calculation of the contribution of structure formation to the EDGRB.

Our conclusion is that at most 10% of the observed EDGRB can be explained by invoking the process described above. We discuss in detail the reasons for the difference between our results and those in [14,15].

The paper is planned as follows: in §2 we describe the basics of hierarchical clustering and the formation of shock surfaces during structure formation. In §3 we summarize the physics of shock acceleration and specialize the discussion to the case of merger shocks. In §4 we illustrate our calculations of the diffuse gamma ray background from structure formation. We conclude in §5.

2 Structure formation and related shocks

The standard theory of structure formation predicts that larger structures result from the mergers of smaller structures, which on average are formed at earlier times. Press and Shechter [17] (hereafter PS) were the first to propose an efficient analytical description of the hierarchical clustering. It represents an extremely powerful tool that allows one to reconstruct realizations of the merger history of a cluster with fixed mass at the present time. There are now different flavors of these analytical methods with different levels of sophistication [18,19].

In [16] we described in detail the procedure adopted to simulate the merger history of a cluster. We summarize here the basic points involved in this procedure.

In the PS formalism, the differential comoving number density of clusters with mass $M$ at cosmic time $t$ can be written as:

$$\frac{dn(M,t)}{dM} = \sqrt{\frac{2}{\pi}} \frac{\rho}{M^2} \frac{\delta_c(t)}{\sigma(M)} \left| \frac{d}{dM} \ln \sigma(M) \right| \exp \left[ -\frac{\delta_c^2(t)}{2\sigma^2(M)} \right].$$

The rate at which clusters of mass $M$ merge at a given time $t$ is written as a function of $t$ and of the final mass $M'$ [20]:

$$\mathcal{R}(M, M', t)dM' =$$

$$\sqrt{\frac{2}{\pi}} \left| \frac{d\delta_c(t)}{dt} \right| \frac{1}{\sigma^2(M')} \left| \frac{d\sigma(M')}{dM'} \right| \left( 1 - \frac{\sigma^2(M')}{\sigma^2(M)} \right)^{-3/2}$$
\[ \exp \left[ -\frac{\delta^2_c(t)}{2} \left( \frac{1}{\sigma^2(M')} - \frac{1}{\sigma^2(M)} \right) \right] \, \mathrm{d}M', \]  

where \( \varrho \) is the present mean density of the universe, \( \delta_c(t) \) is the critical density contrast linearly extrapolated to the present time for a region that collapses at time \( t \), and \( \sigma(M) \) is the current rms density fluctuation smoothed over the mass scale \( M \). For \( \sigma(M) \) we use an approximate formula proposed in [21], normalized by assuming a bias parameter \( b = 0.9 \). We adopt the expression of \( \delta_c(t) \) given in [22]. In this respect our approach is similar to that adopted in [23].

In fig. 1 we plot a possible realization of the merger tree for a cluster with present mass of \( 10^{15} M_\odot \). The history has been followed back in time up to redshift \( z = 3 \). The big jumps in the cluster mass correspond to merger events, while smaller jumps correspond to what in the literature are known as accretion events. During the merger of two clusters of galaxies, the baryonic

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Fig. 1. Merger history of a cluster with present mass \( 10^{15} \) solar masses. The mass (y-axis) suffers major jumps in big merger events. Time is on the x-axis.
component, feeling the gravitational potential created mainly by the dark matter in the two cluster, is forced to move supersonically and shock waves are generated in the intracluster medium.

In order to properly describe the physical properties of these shocks, we use here the approach introduced in [24,16]. We assume to have two dark matter halos, as completely virialized structures, at temperatures $T_1$ and $T_2$, and with masses $M_1$ and $M_2$ (here the masses are the total masses, dominated by the dark matter components). The virial radius of each cluster can be written as follows

$$r_{\text{vir},i} = \left( \frac{3M_i}{4\pi \Delta_c \Omega_m \rho_{\text{cr}} (1 + z_{f,i})^3} \right)^{\frac{1}{3}} = \left( \frac{GM_i}{100 \Omega_m H_0^2 (1 + z_{f,i})^3} \right)^{\frac{1}{3}},$$

(3)

where $i = 1, 2$, $\rho_{\text{cr}} = 1.88 \times 10^{-29} h^2 \text{g cm}^{-3}$ is the current value of the critical density of the universe, $z_{f,i}$ is the redshift of formation of the halo $i$, $\Delta_c = 200$ is the density contrast for the formation of the halo and $\Omega_m$ is the matter density fraction. In the right hand side of the equation we used the fact that $\rho_{\text{cr}} = 3H_0^2/8\pi G$, where $H_0$ is the Hubble constant. The formation redshift $z_f$ is on average a decreasing function of the mass, meaning that smaller structures form at larger redshifts, consistently with the hierarchical scenario of structure formation. There are intrinsic fluctuations in the value of $z_f$ at fixed mass, due to the stochastic nature of the merger tree. The formation redshift $z_f$ is calculated here following [20] \(^3\).

The relative velocity of the two merging structures, $V_r$, can be easily calculated from energy conservation:

$$-\frac{GM_1 M_2}{r_{\text{vir},1} + r_{\text{vir},2}} + \frac{1}{2} M_r V_r^2 = -\frac{GM_1 M_2}{2R_{12}},$$

(4)

where $M_r = M_1 M_2 / (M_1 + M_2)$ is the reduced mass and $R_{12}$ is the turnaround radius of the system, where the two subhalos are supposed to have zero relative velocity. In fact the final value of the relative velocity at the merger is quite insensitive to the exact initial condition of the two subclusters. In an Einstein-De Sitter cosmology this spatial scale equals twice the virial radius of the system. Therefore, using eq. (3), we get:

$$R_{12} = 2 \left( \frac{M_1 + M_2}{M_1} \right)^{1/3} \frac{1}{1 + z_{f,1}} r_{\text{vir},1}. $$

(5)

\(^3\) We adopt here as formation redshift the peak value of the distribution given in [20].
where \(z_f\) is the formation redshift of the halo with mass \(M_1 + M_2\). This expression remains valid in approximate way also for other cosmological models [25]. The sound speed of the halo \(i\) is given by

\[
c_{s,i}^2 = \gamma_g (\gamma_g - 1) \frac{GM_i}{2r_{\text{vir},i}},
\]

where we used the virial theorem to relate the gas temperature to the mass and virial radius. The adiabatic index of the gas is \(\gamma_g = 5/3\). The Mach number of each cluster while moving in the potential of both clusters can be written as follows:

\[
M_1^2 = \frac{4(1 + \eta)}{\gamma(\gamma - 1)} \left[ \frac{1}{1 + \frac{1+z_{f,1}}{1+z_{f,2}} \eta^{1/3}} - \frac{1}{4(1+z_{f,1})^{1/3}(1+\eta)^{1/3}} \right],
\]

\[
M_2^2 = \eta^{-2/3} \frac{1 + z_{f,1}}{1 + z_{f,2}} M_1^2,
\]

where \(\eta = M_2/M_1 < 1\). The procedure illustrated above can be applied to a generic couple of merging halos, and in particular it can be applied to a generic merger event in the history of a cluster with fixed mass at the present time.

The results of our calculations of 500 realizations of the merger history produce the Mach numbers plotted in fig. 2. The striking feature of this plot is that for major mergers, involving clusters with comparable masses (\(\eta \sim 1\)), the Mach numbers of the shocks are of order unity. In other words the shocks are only moderately supersonic. In order to achieve Mach numbers of order of \(3 - 4\) it is needed to consider mergers between clusters with very different masses (\(\eta \sim 0.05\)). These events are the only ones that produce strong shocks, and this is of crucial importance for the acceleration of suprathermal particles, and, as discussed below, for the calculation of the spectrum of the diffuse gamma rays generated by the accelerated particles.

Each merger here is assumed to be a two body event, namely the potential well is assumed to be dominated by the two merging structures. It may be argued that the merger between two objects may occur in the deeper gravitational potential created by nearby structures. In this case, the relative velocity between the two clusters, and also the related shock Mach numbers may be larger (or smaller) than those estimated above. Following [16] we briefly discuss here a simple argument that suggests that this problem should not be relevant for our purposes. We assume that the two clusters, with mass \(M_1\) and \(M_2\), are merging in a volume of average size \(R_{sm}\) where the smoothed overdensity is \(1 + \delta\) (\(\delta = 0\) corresponds to matter density equal to the mean value). Clearly the overdense region must contain more mass than that associated with the
Fig. 2. Distribution of the Mach numbers of merger related shocks as a function of the mass ratio of the merging subclusters. The upper strip is the distribution of Mach numbers in the smaller cluster, while the lower strip refers to the bigger cluster.

two halos, therefore for a top-hat overdensity at \( z = 0 \) we can write:

\[
\frac{4}{3} \pi R_{sm}^3 \rho_{cr} \Omega_m (1 + \delta) = \xi (M_1 + M_2),
\]

where \( \xi > 1 \) is a measure of the mass in the overdense region in excess of \( M_1 + M_2 \). In numbers, using \( \Omega_m = 0.3 \), this condition becomes:

\[
(1 + \delta) = 2\xi M_{15} R_{10}^{-3},
\]

where \( M_{15} \) is \( M_1 + M_2 \) in units of \( 10^{15} \) solar masses and \( R_{sm} = 10 \) Mpc \( R_{10} h^{-1} \).

If the clusters are affected by the potential well of an overdense region with total mass \( M_{tot} \), the maximum relative speed that they can acquire is \( v_{max} \approx 2\sqrt{GM_{tot}/R_{sm}} \). Note that this would be the relative speed of the two clusters if
they merged at the center of the overdense region and with a head-on collision, therefore any other (more likely) configuration would imply a relative velocity smaller than $v_{\text{max}}$. In particular, the presence of the local overdensity might even cause the two merging clusters to slow down, rather than a larger relative velocity. In numbers

$$v_{\text{max}} = 1.1 \times 10^8 \xi^{1/2} M_{15}^{1/2} R_{10}^{-1/2} \text{cm/s}.$$ 

Using the usual expression for the sound speed in a cluster with mass $M_i$ we also get

$$c_s = 8.8 \times 10^7 M_{i,15}^{1/3} \text{cm/s}.$$ 

Therefore the maximum Mach number that can be achieved in the i-th cluster is

$$M_{i,\text{max}} = 1.25 \xi^{1/2} R_{10}^{-1/2} M_{i,15}^{1/2} M_{15}^{-1/3}. \quad (9)$$

As stressed in the previous sections, the Mach numbers which may be relevant for particle acceleration are $M > 3$, which implies the following condition on $\xi$:

$$\xi > 5.8 M_{i,15}^{-1} M_{15}^{2/3} R_{10}, \quad (10)$$

that, when introduced in eq. (8) gives:

$$(1 + \delta) > 11.6 R_{10}^{-2} M_{i,15}^{2/3}. \quad (11)$$

Similar results may be obtained using the velocity distribution of dark matter halos as calculated in semi-analytical models [26] and transforming this distribution into a pairwise velocity distribution, by adopting a suitable recipe.

The probability to have an overdensity $1 + \delta$ in a region of size $R_{sm}$ has the functional shape of a log-normal distribution, as calculated in [27]. Eq. (11) gives the overdensity $1 + \delta$ necessary for a cluster of mass $M_i$ to achieve a Mach number at least 3 in the collision with another cluster in the same overdense region. The probabilities $P(\delta)$ as a function of the mass of the cluster $M_i$ were estimated in [16]. For rich clusters, with masses larger than $5 \times 10^{14} M_\odot$ (corresponding to X-ray luminosities $L_X > 4 \times 10^{44} \text{erg/s}$) the probability that the presence of a local overdensity may generate Mach numbers larger than 3 has been estimated to be less than $10^{-3}$, suggesting that our two body approximation is reasonable, in particular for the massive clusters that are typically observed to have nonthermal activity. For smaller clusters, the probabilities become higher, indicating that the distribution of Mach numbers might have a larger spread compared with that illustrated in fig. 2. Note however that for small clusters, even the two body approximation gives relatively high Mach
numbers, provided the merger occurs with a bigger cluster, simply as a result of a lower temperature and a correspondingly lower sound speed.

Motivated by these arguments, in the following we keep the assumption of binary mergers.

3 Shock acceleration during structure formation

Merger related shocks may serve as cosmic ray accelerators. In this section we estimate the maximum energy achievable in one of these shocks for acceleration of electrons. We aim at using the most optimistic situation, to achieve the highest maximum energy for the accelerated particles. For this reason, we adopt a Bohm diffusion coefficient

\[ D(E) = \frac{1}{3} r_L c = 3.3 \times 10^{22} E(\text{GeV}) B^{-1} \mu \text{cm}^2/\text{s}, \]

where \( E \) is the particle energy in GeV and \( B_\mu \) is the magnetic field at the shock in units of \( \mu \text{G} \). Other possible choices for the diffusion coefficient are discussed in [28,16].

The acceleration time is defined as follows:

\[ \tau_{\text{acc}} = \frac{3}{u_1 - u_2} \left[ \frac{D_1}{u_1} + \frac{D_2}{u_2} \right] \approx \frac{3D(E) r(r + 1)}{u_1^2} \frac{r}{r - 1}, \quad (12) \]

where in the last step we neglected the jump in the magnetic field at the shock, and we introduced the ratio \( r = u_1/u_2 \) of the two velocities upstream and downstream the shock. The compression ratio \( r \) is related to the Mach number of the shock through the relation

\[ r = \frac{8}{3} \mathcal{M}^2. \]

For relativistic electrons the main channel of energy losses is represented by ICS on the photons of the microwave background. The time scale for these losses is

\[ \tau_{\text{ICS}} \approx 4 \times 10^{16} E(\text{GeV})^{-1} \text{ s}. \]

Requiring that acceleration occurs faster than losses implies the following maximum energy

\[ E_{\text{max}} = 6.3 \times 10^4 B_\mu^{1/2} h(r)^{-1/2} u_8 \text{ GeV}, \quad (13) \]
where \( h(r) = r(r + 1)/(r - 1) \) and \( u_8 \) is the collision speed in units of \( 10^8 \) cm/s. It is worth stressing that larger diffusion coefficients would significantly reduce the value of the maximum energy compared to that given in Eq. (13). This effect is discussed in [28] and [16].

It is instructive to evaluate the energy of the photons radiated by electrons with energy \( E_{\text{max}} \) due to synchrotron emission and ICS respectively. The peak frequency for synchrotron emission is

\[
\nu_{\text{max}} = 1.4 \times 10^{16} B_\mu h(r)^{-1} u_8^2 \text{ Hz.}
\]

This corresponds to an energy

\[
h\nu_{\text{max}} \approx 58 B_\mu^2 h(r)^{-1} u_8^2 \text{ eV.}
\]

The peak energy for ICS off the microwave photons is

\[
\epsilon_{\text{ICS}} \approx 10 B_\mu h(r)^{-1} u_8^2 \text{ TeV.}
\]

The choice of a diffusion coefficient that is larger than the Bohm coefficient would considerably decrease the values of \( \nu_{\text{max}} \) and \( \epsilon_{\text{ICS}} \). The gamma ray production from ICS strongly relies upon the assumption of Bohm diffusion.

The spectrum of the accelerated electrons is provided by the standard theory of first order shock acceleration, and in the linear regime is uniquely determined by the compression factor (or equivalently the Mach number) of the shock. In fact the spectrum can be written as a power law \( E^{-\gamma} \) with \( \gamma = (r+2)/(r-1) \). The slope tends asymptotically to \( \gamma = 2 \) for strong shocks \((r \sim 4)\).

### 4 The diffuse gamma ray background from hierarchical clustering

Electrons accelerated at each merger event lose energy through ICS on the photons of the cosmic microwave background, that are upscattered to higher energies, up to gamma ray energies. At each merger, two main shock surfaces are generated [16], each one able to accelerate its own population of non thermal electrons. The balance between injection and energy losses drives the electrons toward their time independent equilibrium distribution, with a spectrum one power steeper than the injection spectrum. The rate of gamma ray production from each merger, \( Q_\gamma(E_\gamma, M_1, M_2) \) (see [28] for details of the calculation of \( Q_\gamma \) from the electron spectrum) is thus the sum of the contributions from the two shocks, which in general depends upon the masses \( M_1 \) and \( M_2 \) of the merging structures. Each shock generates a power law spectrum of gamma rays with two different slopes (determined by the compression factors at the shocks as explained in the previous section) and a cutoff determined by the
maximum energy of the accelerated electrons. The flux of gamma radiation (in units of phot cm$^{-2}$s$^{-1}$sr$^{-1}$GeV$^{-1}$) is then given by

$$I_\gamma(E_\gamma) = \frac{c}{4\pi H_0} \int_0^{z_{\text{max}}} \frac{dz}{S(z)} \int_0^\infty dM \ n(M, z) \times$$

$$\int_0^M dM' \ R(M, M + M', z) Q_\gamma(E_\gamma(1 + z), M, M') \Delta t_{\text{mer}}(M, M'),$$

(14)

where $S(z) = \sqrt{\Omega_m(1 + z)^3 + \Omega_\Lambda}$, $R(M, M + M', z)$ is the merger rate between clusters of masses $M$ and $M'$ at redshift $z$, and $\Delta t_{\text{mer}}(M, M')$ is the duration of the merger between two clusters with given masses $M$ and $M'$, as defined in [16].

In the literature the expression accretion events is often used [23,29] to describe the mergers of small subclusters with a large dark matter halo. This definition, implying an artificial separation between merger events and accretion, may be useful in other contexts, but here may be quite confusing. As discussed in §2, the so-called accretion events are the ones that generate high Mach numbers and therefore flat spectra of accelerated particles [16]. It would therefore be instructive but rather difficult to define the boundary between accretion and merger events. In the older literature, the concept of accretion onto a large scale structure was discussed in detail (see for instance [30]) but it had a rather different meaning: a small perturbation in the density field grows as a result of gravitational instability, so that more matter falls onto the potential well. There is a radius, the so-called turnaround radius at which the inflow velocity is balanced by the expansion of the universe. An accretion shock is formed at a position that depends on time in the same way as the turnaround radius and as the virial radius of the structure. The shock surface carries the information of the virialization of the inner region of the cluster. This type of accretion is also called secondary infall, meaning that matter accretes on a potential well which has already been formed. In the following, we adopt this simple approach and calculate the gamma ray production due to particle acceleration at the accretion shock, and compare it with the result of the gamma ray production from mergers.

For simplicity let us assume that the shock is located exactly at the virial radius $R_{\text{vir}}$. The total energy per unit time flowing across the shock is then:

$$L_{\text{tot}} = \frac{1}{2} \rho_{\text{cr}} \frac{\Omega_b}{\Omega_m}(1 + z)^3 v_{\text{ff}}^3 4\pi R_{\text{vir}}^2,$$

where $\rho_{\text{cr}} \Omega_m$ is the matter density of the universe, $\Omega_B$ is the baryon fraction and $v_{\text{ff}}$ is the free-fall velocity of the matter at the distance of the shock radius.
The secondary infall just described is a simplification of the mass flow through large scale shocks in the filamentary structures seen in N-body simulations. Although the geometry is different, the total energy crossing the shock per unit time and per unit surface should not be very different from the same quantity calculated for spherical inflow.

The accretion shock, by definition, propagates in a cold (non-virialized) medium, therefore its Mach number may be very high, although the typical speed of the shock is of the same order of magnitude as the merger speed of two clusters. The exact value of the Mach number depends on the temperature of the medium before entering the overdense virialized region. If we take for such temperature the range of values $T = 10^4 - 10^6$ K, and a typical shock speed of $\sim 10^8$ cm/s, the corresponding Mach numbers range between 10 and 100. These Mach numbers, being much larger than unity, correspond to spectra of accelerated particles which are $\sim E^{-2}$, with a cutoff at the maximum energy (Eq. 13). If the intergalactic medium were pre-heated before the gravitational collapse, these Mach numbers could be lower [31].

The rate of gamma ray production from the accelerated electrons, $Q_\gamma(E_\gamma, M, z)$, can be calculated in the usual way [28]. Given $Q_\gamma(E_\gamma, M, z)$ (in photons$^{-1}$ GeV$^{-1}$) in an accreting cluster of mass $M$ at redshift $z$, the diffuse flux is

$$I(E_\gamma) = \frac{c}{4\pi H_0} \int_0^{z_{\text{max}}} dz \frac{1}{S(z)} \int_0^\infty dM n(M, z) Q_\gamma(E_\gamma(1 + z), M, z).$$

The diffuse flux of gamma radiation from mergers (dashed line) and from accretion (dotted line) is plotted in Fig. 3, where an acceleration efficiency (for electrons) of 5% is assumed. The observed EDGRB is the shaded region [1]. In the same figure we plot for comparison the predictions of Ref. [14] (solid line), where our same acceleration efficiency was adopted. The meaning of the dash-dotted line will be explained below.

Three conclusions are evident:

1) the flux of gamma radiation from both mergers and accretion is a factor $\sim 10$ smaller than the observed EDGRB and smaller than the flux predicted in [14,15], by the same factor. An acceleration efficiency of the order of 50% should be adopted in order to reproduce observations. This would be unreasonable for electrons as accelerated particles, and would violate our initial assumption of shock acceleration in the linear regime (no backreaction of the accelerated particles on the shock);

2) the gamma ray diffuse flux from mergers is at the same level as that due to accretion (secondary infall);
Fig. 3. Diffuse gamma ray emission from structure formation. The shaded area is the result EGRET observations. The dashed line is the result of our calculations for mergers while the dotted line is the flux of gamma rays from accretion. The dash-dotted line assumes a minimum mass of the merging halos of $10^{13}M_\odot$.

3) all predicted spectra are approximately power laws with slopes between 2 and 2.1.

The flatness of the spectrum may give us the key to understand the differences between our result and that of [14,15]. The authors of Ref. [14,15] assume that all the shocks are strong, so that the spectrum of the accelerated particles is fixed to $E^{-2}$. In our approach the Mach numbers of the shocks, as well as the energy flux through each shock are calculated self-consistently, so that the spectrum of the diffuse radiation is the result of the superposition of spectra with different slopes. However, although major mergers are energetically very powerful, they generate steep spectra of accelerated particles [16]. Therefore the contribution of relativistic electrons from these mergers is small compared with that of smaller, less energetic mergers, which however produce flatter spectra. This is the reason why the gamma ray spectra resulting from mergers
have almost the same spectrum as that predicted in [14,15]. Our absolute normalization is however a factor $\sim 10$ lower, which may suggest that merger related shocks are not always strong, and in fact they are almost always weak, as illustrated in Fig. 2.

Our results can be better clarified by using Fig. 4. The upper panel shows the average normalized energy flux per unit time through the merger related shocks of a cluster with mass $10^{15} M_\odot$ (solid line), $10^{14} M_\odot$ (dotted line) and $10^{13} M_\odot$ (dashed line) at redshift $z = 0$, as a function of the mass of the merging subcluster (here $M'/M \leq 1$ is the ratio between the masses of the two subclusters). The curves represent the energy flux contributed by mergers with mass ratio larger than $M'/M$. The energy flux sums up to $\sim 70 - 80\%$ of the total for subcluster masses larger than $\sim 0.1M$. This implies that the energy flux that crosses the shocks formed during mergers of the cluster with mass $M$ and subclusters with masses smaller than $0.1M$ is small ($20 - 30\%$). In other words, the energy flux is dominated by major mergers.

In the second panel of Fig. 4 the energy flux is plotted for a cluster of fixed mass of $10^{14} M_\odot$ at three redshifts, $z = 0$ (solid line), $z = 0.5$ (dotted line) and $z = 1$ (dashed line). The same conclusions explained above hold here.

The third panel is the most interesting: it represents the normalized energy flux through the merger related shocks that contribute to the diffuse gamma ray background above 100 MeV, for clusters of masses as labelled in the upper panel, at $z = 0$. It is immediately clear that most of the contribution to the gamma ray emission is provided by mergers with small mass ratios, $M'/M \leq 10^{-2}$, namely the ones having the larger Mach numbers (see Fig. 2).

Summarizing, while most of the energy flows through shocks associated to major mergers, the energy flux that contributes to the gamma ray background is the one that crosses strong shocks, occurring when a large cluster encounters a subcluster with $\sim 0.01$ times the mass of the larger cluster. This may explain why the diffuse gamma ray background as derived in the present paper is substantially lower than that estimated in previous calculations [14,15]. In a recent paper [32], a reevaluation of the diffuse gamma ray background from large scale structure shocks was carried out and there seems to be there a closer agreement with the conclusions of our calculations. In [32] many issues were discussed as possible reasons for the discrepancy with the results of [14]: one of the points that the authors correctly find out is that simulations do suggest the formation of weak shocks, although difficult to identify. Another numerical calculation was also carried out in Ref. [33]. In [32] the authors emphasize the difficulties in the identification of shocks with Mach number below 10 (and the impossibility to detect shocks with Mach numbers below $\sim 3 - 4$). The Mach number distribution obtained in [32] presents an artificial peak at the threshold of detectability ($M \sim 4$). A peak is seen also in [34],
but it is argued that it is not an artifact of the numerical procedure. In our semi-analytical approach no peak is found at $\mathcal{M} \sim 4$, while the Mach number distribution seems peaked at $\sim 1.5$ [16].

Another ingredient introduced in our calculation (as well as in [32]) but not in [14] is the redshift dependence of the $\gamma$-ray emissivity. This also induces $\gamma$-ray diffuse fluxes smaller than those in [14], as also pointed out in [32].

![Graph](image.png)

**Fig. 4.** Upper panel: normalized energy flux per unit time through the merger related shocks of a cluster with mass $10^{15} M_\odot$ (solid line), $10^{14} M_\odot$ (dotted line) and $10^{13} M_\odot$ (dashed line) at redshift $z = 0$ with clusters with mass larger than $M'/M$. Middle panel: Same as above for a cluster of mass $10^{14} M_\odot$ at redshifts $z = 0$ (solid line), $z = 0.5$ (dotted line) and $z = 1$ (dashed line). Lower panel: normalized energy flux through the merger related shocks that contribute to the diffuse gamma ray background above 100 MeV, for the same halos as in the upper panel.

The flux of diffuse gamma rays due to accretion (secondary infall) has a spectrum which is exactly $E^{-2}$ because the Mach number of the accretion shock is always much larger than unity. It is somewhat surprising that the diffuse gamma ray background contributed by electrons accelerated at the accre-
tion shock is comparable with that produced in merger events (the latter, as stressed above, is dominated by mergers between clusters with \( M'/M \ll 1 \), that in some literature are indeed defined as accretion events). In this respect however some additional discussion is required: for a cluster with mass \( 10^{14} M_{\odot} \) a mass ratio \( M'/M \sim 10^{-2} \) corresponds to a substructure with mass \( 10^{12} M_{\odot} \), comparable with the mass of our galaxy. This clearly does not make physical sense. Galaxies move within the intracluster medium without their medium being shocked. It is more likely that a bow shock is formed in front of the galaxy, due to the internal pressure of the galactic medium [35]. Actually simulations show that large galaxies penetrating the intracluster medium of a rich cluster can even be completely stripped of their gas content [35]. This suggests that a low mass cutoff should be imposed in the calculation of the gamma ray diffuse background from cluster mergers. The dash-dotted line in Fig. 3 has been obtained by considering only structures with virial masses larger than \( 10^{13} M_{\odot} \), corresponding to galaxy groups. The diffuse background of gamma rays is a factor \( \sim 10 \) smaller in this case and is slightly steeper in spectrum. This happens because the main contribution comes from mergers between clusters with masses \( M_{\text{min}} = 10^{13} M_{\odot} \) and \( M = M_{\text{min}}/10^{-2} \approx 10^{15} M_{\odot} \). Clusters with masses as large as \( 10^{15} M_{\odot} \) are already on the tail of the Press-Schechter distribution even at \( z = 0 \), therefore the corresponding contribution to the diffuse background is suppressed. On this basis, the dash-dotted line in Fig. 3 is the most realistic estimate of merger shocks to the diffuse gamma ray background, amounting to \( \sim 1\% \) of the observed EDGRB (this result agrees with the estimate in [36]). On the other hand the strong shocks associated to accretion of matter onto a cluster may generate a gamma ray background as large as that plotted as a dotted line in Fig. 3, and this contribution remains at the level of \( \sim 10\% \) of the observed EDGRB. This may be considered as the most realistic prediction of the contribution of clusters of galaxies to the EDGRB.

Our results are in agreement with the recent estimate of the diffuse gamma ray flux from rich clusters carried out by cross correlating high galactic latitude EGRET data with the location of Abell clusters [37].

5 Conclusions

We calculated the contribution of structure formation to the EDGRB radiation. We find that this contribution is only \( 1 - 10\% \) of the observed flux of the alleged extragalactic radiation above 100 MeV as measured by EGRET. The calculation has been carried out in two different scenarios, one that relies upon the hierarchical scenario for structure formation, and the other that is based on the secondary infall (accretion) of matter onto a potential well which has already been formed.
In the hierarchical approach, large structures are formed by merging of smaller halos whose mass is dominated by dark matter. The baryon components of these halos, moving supersonically, develop shock surfaces that in principle can accelerate particles to relativistic energies. We evaluate the Mach numbers of these shocks following the recipe introduced in [16,24], that allows us to self-consistently calculate the spectra of accelerated particles at each merger event. This distinguishes our approach from previous calculations [14,15] where the shocks were all assumed strong (infinite Mach number), so that the spectra of accelerated particles were by definition $E^{-2}$. We find that this assumption may lead to incorrect conclusions, as evidenced by the comparison between our results and those in [15].

In [16] we investigated the role of protons first accelerated and then diffusively confined in large scale structures [12]. We find that the spectral shape of the protons is very steep and is unlikely to produce a relevant effect on high energy radiation generated by clusters of galaxies. This conclusion is mostly due to the fact that major mergers, that energetically dominate over smaller merger events, generate weak shocks and therefore steep particle spectra.

In the present paper we focused our attention on electrons as accelerated particles. Their ICS energy losses were in fact proposed [14,15] as responsible for upscattering the photons of the cosmic microwave background to gamma ray energies, therefore generating a diffuse background of gamma radiation accompanying the process of structure formation. While previous calculations suggest that the observed EDGRB may be saturated by the contribution of particles accelerated during structure formation, we find here that at most 10% of the observed background can in fact be explained in this way. More recent numerical calculations [32,33] seem to lower previous predictions.

Although structure formation is generally believed to follow the hierarchical picture outlined above, some secondary infall of matter onto forming structures must occur, and is in fact observed in numerical N-body simulations in the form of filamentary-like accretion flows. In order to account for this contribution we adopt a simple model, similar to that proposed in [30], in which an accretion shock is formed at approximately the virial radius of a structure that is accumulating matter from the expanding universe. This shock, as those formed in the filaments, propagates in the cold unshocked medium and may have very large Mach numbers, of order 10-100 (possibly lower if pre-heating occurs [31]). Particles accelerated at this type of shocks have the flattest spectrum allowed in the linear theory of shock acceleration, namely $E^{-2}$. The diffuse gamma ray background due to ICS of electrons accelerated at accretion shocks is also of order 10% of the observed EDGRB, and may be larger that that due to mergers. The reason for this result is the following: although the energy flux through merger shocks is larger than that crossing accretion shocks, the former is mainly converted into very steep spectra (due
to the weakness of the shocks), while the latter is more easily channelled into particles that may contribute to gamma rays with energy above $\sim 100$ MeV, because of the flatter spectra.

In the perspective of future work in this field, it seems to us that priority should be given to improve N-body simulations in order to have a better handling of the shocks with intermediate strength generated during structure formation. This will allow a self-consistent treatment of both the gas heating and the acceleration of particles at these shocks, and make a solid case in favor or against clusters of galaxies as sources of high energy gamma radiation.

The results presented in this paper suggest that clusters of galaxies, and more in general structure formation, do not contribute appreciably to the EDGRB. However, several clusters could be observed as single gamma ray sources by future experiments such as GLAST (Blasi and Gabici, in preparation) and provide useful information on the non thermal history of these large scale structures.

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