Evolution of clusters of galaxies and CR-induced γ-rays

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Abstract

The effect of merger history of clusters of galaxies on Intra-Cluster Cosmic Rays (ICCRs) is investigated. Though the effect of merger shock, which is responsible for (in-situ) acceleration of ICCRs, is ignored here, the effect of evolution is important for ICCRs and induced gamma-rays. Taking star formation history into account, we find 1) the gamma-ray flux from a cluster of galaxies is consistent with EGRET observation, and 2) the contribution of clusters of galaxies to the diffuse gamma-ray background is not so large, with reasonable parameter range.

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1. Introduction

Recently many authors have discussed about the relation between clusters of galaxies and cosmic rays(CRs) [1, 2, 3, 4, 5, 6, 7, 8]. The basic idea is: Clusters of Galaxies can confine CRs because of their strong and turbulent magnetic fields. The existence of turbulent magnetic fields in clusters of galaxies is observationally established based on the Faraday rotation.

Obviously the direct detection of CRs in clusters of galaxies is impossible. Gamma-rays can provide the evidence of existence for such powerful and non-thermal particles. γ-rays are produced via inelastic collision between CRs and intracluster gases ($pp \to \pi^0$+anything). When the amount of CRs is enough, clusters of galaxies should emit strong γ-rays and can be detected by γ-ray telescopes.

Early discussion is mainly based on energetics [1, 3]. The main assumption is that **the CR flux is almost universal**. This causes discrepancy with upper bound by EGRET[9].

Similar to our galaxy, the treatment of CR escape from clusters of galaxies is governed by the diffusion. The value of the diffusion efficient D is the problem. Berezinsky et al. [4] used $D \sim 10^{29}\mathrm{cm}^2/\mathrm{s}$ and concluded that the diffusion time exceeds the age of the Universe. Völk et al.[2] and Colafrancesco & Blasi[5] admitted $D \sim 10^{28}$ cm^2/s, this value is almost the same as that in our galaxy. The resonant diffusion, or the Bohm diffusion by intracluster magnetic field with the Kolmogorov spectrum, provides this value of D.

Tsubaki & Sato[6] used more realistic model for clusters of galaxies. The size of confinement region is assumed as the core region, not the whole cluster, because the outer region is not so dense. The diffusion time is enough smaller than the age of the Universe and expected γ-ray flux agrees with the observation.

Blasi[7] and Berrington & Dermer[8] take the acceleration by cluster merger shocks into account. The acceleration by merger shocks is used in the theory of radio emission by energetic electrons in clusters of galaxies.

This poster will provide new treatment of cluster merger tree in relation to intracluster CRs. The main usage of the merger tree is to evolve the mass of objects, not to accelerate chaged particles. The source of CRs is galaxies in clusters.

2. Method

2.1. Basic Equation

The basic equation is the diffusion equation:

$$\frac{dN(t)}{dt} = -\frac{N(t)}{\tau} + Q(t).$$

Assumptions for this basic equation are:

1. The chemical composition of CRs is ignored. CRs is composed of pure proton.
2. The deformation of spectrum is ignored. The CR spectrum is assumed as follows:

   $$j_p(E) = j_0\,(E + E_0)^{-\gamma}.$$

3. The diffusion time τ is determined as follows:

   $$\tau = \frac{R^2}{6D}, \quad D = \frac{1}{3}cl_{\rm MFP},$$

   where R is the size of an object and estimated by its virial radius, and the diffusion coefficient D is parameterized by the mean-free path (MFP)$l_{\rm MFP}$.
4. The source of CRs is galaxies. To evaluate the source function, the liniality in terms of mass is assumed:

   $$Q(M, z) = q_{\rm gal}{\rm SFR}(z)\left(\frac{M}{M_{\rm gal}}\right),$$

   where $q_{\rm gal}$ and $M_{\rm gal}$ is the CR emission rate and the mass of our galaxy, ${\rm SFR}(z)$ is the star formation rate (SFR), shown in the next section.

2.2. Evolution of CR Source

Porciani & Madau[11] provides the three types of SFRs ([$M_\odot {\rm yr}^{-1}{\rm Mpc}^{-3}$]):

$${\rm SFR}_1(z) = 0.3h_{65}\frac{\exp(3.4z)}{\exp(3.8z)+45}$$

$${\rm SFR}_2(z) = 0.15h_{65}\frac{\exp(3.4z)}{\exp(3.4z)+22}$$

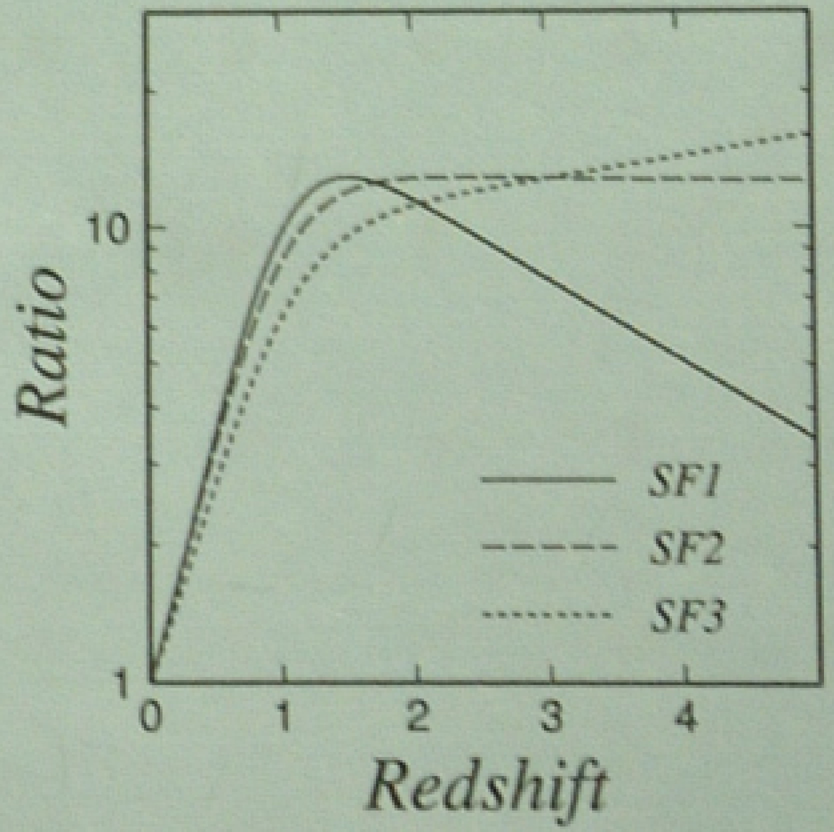
$${\rm SFR}_3(z) = 0.2h_{65}\frac{\exp(3.05z-0.4)}{\exp(2.93z)+15}$$

These three SFRs are plotted. The cosmological parameters are set as:

$$\Omega_0 = 0.3, \quad \lambda_0 = 0.7, \quad \sigma_8 = 1.0, \quad h = 0.7.$$

The rate is normalized by the current value:

$${\rm SFR}(z) = \frac{{\rm SFR}_i(z)}{{\rm SFR}_i(0)}.$$



Note that the CR emissivity of our galaxy is estimated as follows:

$$q_{\rm gal} = \frac{n_{\rm CR}V_{\rm gal}}{T_{\rm esc}} \sim 5.93 \times 10^{56}[\text{particles/Myrs}]$$

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2.3. Treatment of Cluster Merger

The number density of objects with mass M at time t is well described by the Press-Schechter Function[12]:

$$\frac{dn(M,t)}{dM} = \sqrt{\frac{2}{\pi}} \frac{\rho_0}{M} \frac{\delta_c(t)}{\sigma^2(M)} \left| \frac{d\sigma(M)}{dM} \right| \exp\left[-\frac{\delta_c^2(t)}{2\sigma^2(M)} \right].$$

By re-interpretation of this function as stochastic processes of merging, the merger probability can be obtained[13]:

$$\frac{dP_1(M_1,t_1|M_2,t_2)}{dM_1} = \frac{1}{\sqrt{2\pi}} \frac{\delta_{c1} - \delta_{c2}}{(\sigma_1^2 - \sigma_2^2)^{3/2}} \left| \frac{d\sigma^2}{dM_1} \right| \exp\left[-\frac{(\sigma_{c1} - \sigma_{c2})^2}{2(\sigma_1^2 - \sigma_2^2)} \right].$$

This function represents the probability of making the object with mass M_2 at time t_2 from the object with mass $M_1 (< M_2)$ at time $t_1 (< t_2)$.

By using this probability dP/dM, the evolution of CRs can be calculated by following scheme:

1. At the initial redshift z_{ini}, all objects have no CR particles: $N(z_{\mathrm{ini}}) = 0$.
2. During a given interval $\Delta t = t_{\mathrm{dyn}}(z)$ (t_{dyn} is the dynamical time), CR particles will escape from objects. This process can be calculated by using the basic equation.
3. After leaking for Δt, all objects are mixing up. The mixing ratio is represented by the merging probability dP/dM:

$$N(M_2, t + \Delta t) = \int_{M_{\min}}^{M_2} N(M_1, t) \frac{dP(M_1, t|M_2, t + \Delta t)}{dM_1} dM_1$$

4. Step 2 and 3 will be repeated up to now ($z = 0$).

3. Results

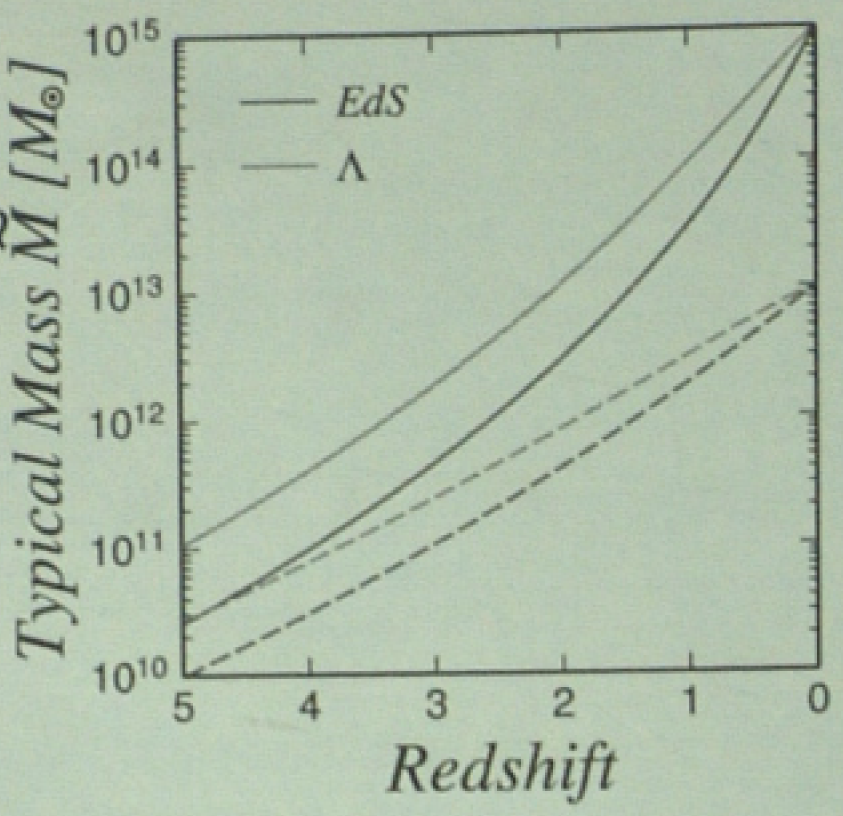
3.1. Typical Mass and Typical Density

The typical mass $\tilde{M}$ is defined as follows:

$$\tilde{M}(z) = \int M \frac{dP(M_0, z)}{dM} dM.$$

This typical mass is the "averaged" (or "expected") mass of an object with mass M_0 at present $z = 0$.
The typecal density $N/V(\tilde{M})$ can also be defined by using this typical mass $\tilde{M}$. This shows the "averaged" CR number density.

The right panel shows the evolution of the typical mass for $M_0 = 10^{13} M_\odot$ and $M_0 = 10^{15} M_\odot$. Obviously all objects should be small at high redshift (*i.e.* in the past).

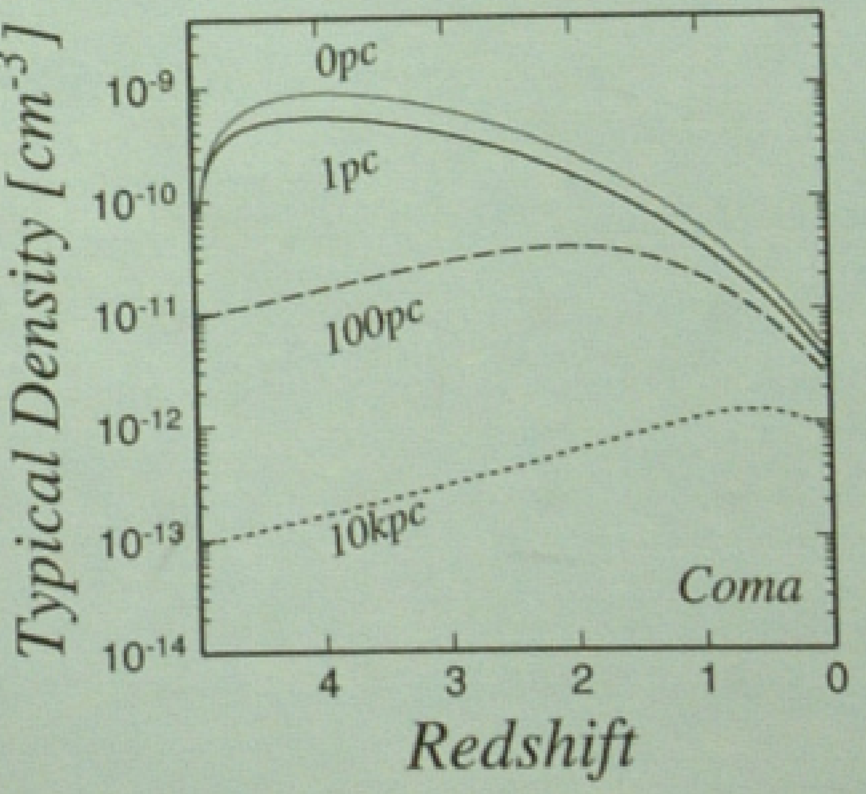


3.2. Effect of Diffusion

To check the effect of diffusion, here we set

$$SFR(z) = 1.$$

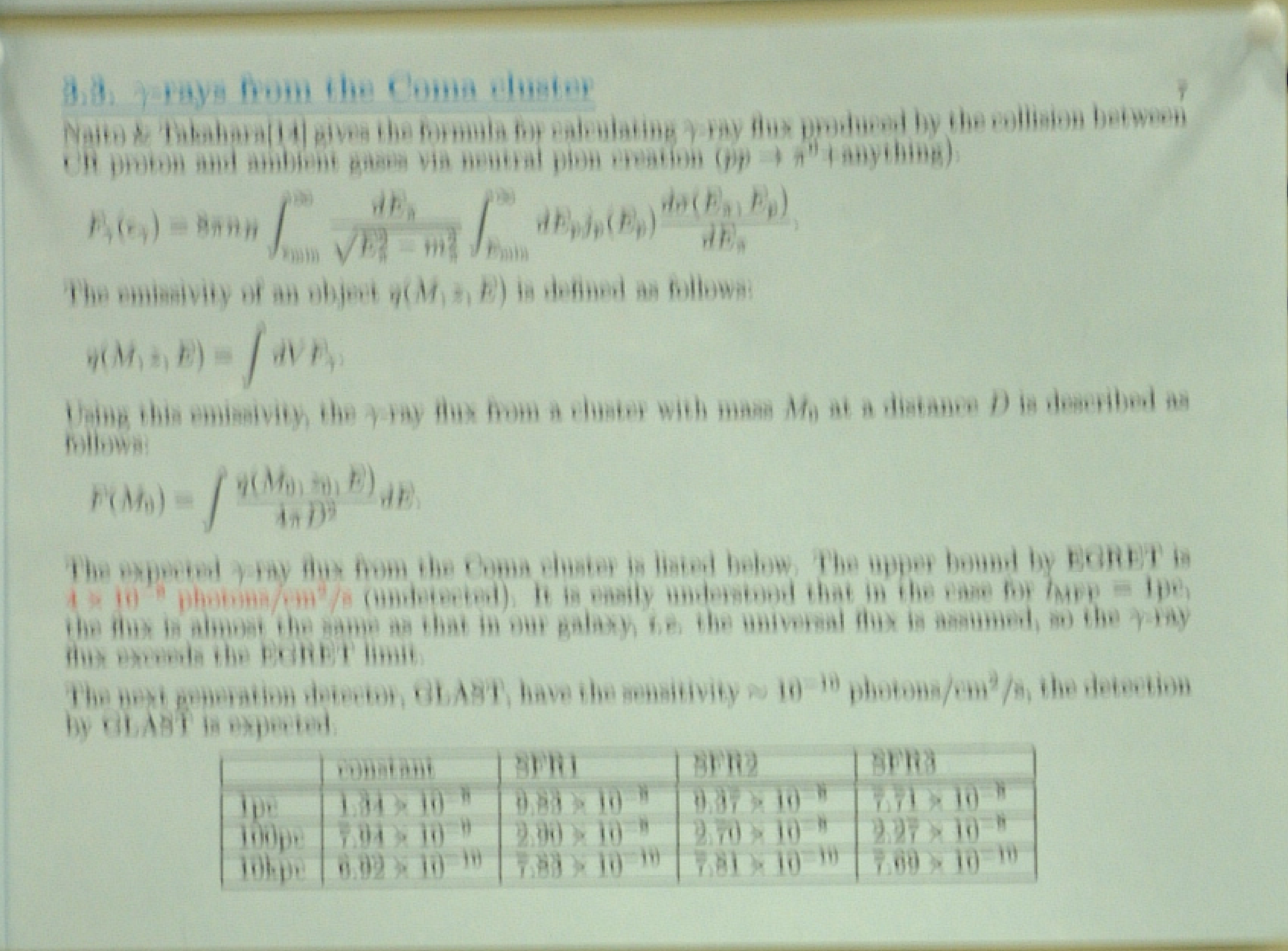
The result is shown in the right panel. The typical density is quickly dropping with the redshift $z = 0 \sim 1$. This cause is the quick evolution of typical mass $\tilde{M}$. This panel shows that at higher redshift, the effect of diffusion is stronger, because the size of object is enough small to diffuse CRs from the object. At lower redshift the size of the object is too big to diffuse and CRs are confined. The range of this confinement is $z < 1$. This range is less active of star formation. So the effect of SFR on γ-ray emission from a cluster is expected not to be so large.



This effect is more important for the contribution to the Diffuse Gamma-Ray Background.

3.3. γ-rays from the Coma cluster

Naito & Takahara[14] gives the formula for calculating γ-ray flux produced by the collision between



3.3. γ-rays from the Coma cluster

Naito & Takahara[14] gives the formula for calculating γ-ray flux produced by the collision between CR proton and ambient gases via neutral pion creation ($pp \to \pi^0$+anything):

$$F_\gamma(\epsilon_\gamma) = 8\pi n_H \int_{E_{\rm min}}^{\infty} \frac{dE_\pi}{\sqrt{E_\pi^2 - m_\pi^2}} \int_{E_{\rm min}}^{\infty} dE_p j_p(E_p) \frac{d\sigma(E_\pi, E_p)}{dE_\pi},$$

The emissivity of an object $\eta(M, z, E)$ is defined as follows:

$$\eta(M, z, E) = \int dV F_\gamma,$$

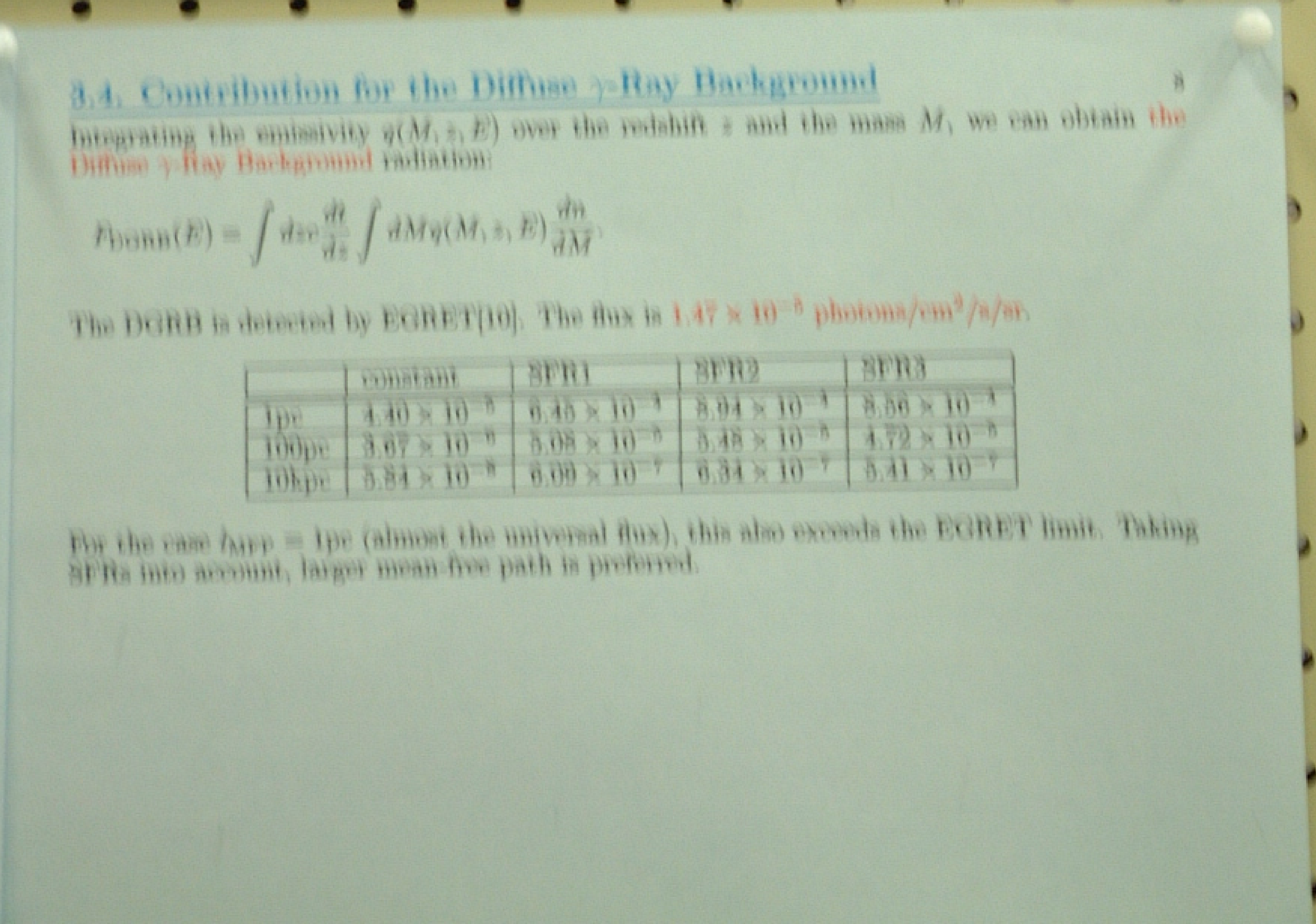
Using this emissivity, the γ-ray flux from a cluster with mass M_0 at a distance D is described as follows:

$$F(M_0) = \int \frac{\eta(M_0, z_0, E)}{4\pi D^2} dE,$$

The expected γ-ray flux from the Coma cluster is listed below. The upper bound by EGRET is 4×10^{-8} photons/cm^2/s (undetected). It is easily understood that in the case for $l_{\rm MFP}$ = 1pc, the flux is almost the same as that in our galaxy, *i.e.* the universal flux is assumed, so the γ-ray flux exceeds the EGRET limit.

The next generation detector, GLAST, have the sensitivity $\approx 10^{-10}$ photons/cm^2/s, the detection by GLAST is expected.

	constant	SFR1	SFR2	SFR3
1pc	1.34×10^{-8}	9.83×10^{-8}	9.37×10^{-8}	7.71×10^{-8}
100pc	7.94×10^{-9}	2.90×10^{-8}	2.70×10^{-8}	2.27×10^{-8}
10kpc	6.92×10^{-10}	7.83×10^{-10}	7.81×10^{-10}	7.69×10^{-10}



3.4. Contribution for the Diffuse γ-Ray Background

Integrating the emissivity $\eta(M, z, E)$ over the redshift z and the mass M, we can obtain the Diffuse γ-Ray Background radiation:

$$F_{\rm DGRB}(E) = \int dz c\frac{dt}{dz} \int dM \eta(M, z, E) \frac{dn}{dM},$$

The DGRB is detected by EGRET[10]. The flux is 1.47×10^{-5} photons/cm^2/s/sr.

	constant	SFR1	SFR2	SFR3
1pc	4.40×10^{-5}	6.45×10^{-4}	8.04×10^{-4}	8.56×10^{-4}
100pc	3.67×10^{-6}	5.08×10^{-5}	5.48×10^{-5}	4.72×10^{-5}
10kpc	5.84×10^{-8}	6.09×10^{-7}	6.34×10^{-7}	5.41×10^{-7}

For the case $l_{\rm MFP}$ = 1pc (almost the universal flux), this also exceeds the EGRET limit. Taking SFRs into account, larger mean-free path is preferred.

4. Conclusion

1. New treatment of cluster merger tree is introduced.
2. The evolution of a cluster is shown. This implies that the simple estimation of γ-rays from a cluster is imcomplete because such estimation assumes no evolution.
3. The source of CRs is assumed to be normal galaxies. Because any in-situ accerelations are ignored, this estimation gives lower bound for γ-rays from clusters of galaxies.
4. The diffusion has less effect on the γ-rays from a cluster, but affects to the DGRB.
5. The γ-ray from a cluster of galaxies is enough weak than the EGRET detection limit, and will be detected by the GLAST.
6. The contribution to the DGRB is $\sim 5\%$ (for $l_{\rm MFP} = 10$kpc).

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