GALAXY CLUSTERS IN GAMMA-RAYS: AN ASSESSMENT FROM OBSERVATIONS

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ABSTRACT

Clusters of galaxies are believed to constitute a population of astrophysical objects potentially able to emit electromagnetic radiation up to gamma-ray energies. Evidence of the existence of non–thermal radiation processes in galaxy clusters is indicated from observations of diffuse radio halos, hard X-ray and EUV excess emission. The presence of cosmic ray acceleration processes and its confinement on cosmological timescales nearly inevitably yields in predicting energetic gamma-ray emission, either directly deduceably from a cluster's multifreqency emission characteristics or indirectly during large–scale cosmological structure formation processes. This theoretical reasoning suggests several scenarios to actually detect galaxy clusters at gamma-ray wavelengths: Either resolved as individual sources of point-like or extended gamma-ray emission, by investigating spatial-statistical correlations with unidentified gamma-ray sources or, if unresolved, through their contribution to the extragalactic diffuse gamma-ray background. In the following I review the situation concerning the proposed relation between galaxy clusters and high-energy gamma-ray observations from an observational point-of-view.

Key words : clusters of galaxies – gamma-rays: observations

I. INTRODUCTION

Clusters of galaxies as the largest gravitationally bound objects in the universe, thus prime representatives for large scale formation and the evolution of cosmic structure. It has been found that the mass of the intracluster medium (ICM) dominates the luminous mass in comparison to the stars of the clusters constituent galaxies. A major fraction of the baryonic dark matter is believed to be located within the ICM. Typical temperatures up to several keV give rise to our understanding that the ICM contains presumably the same or even more kinetic and thermal energy as the constituent galaxies. Whereas galaxy clusters have been long known to be sources of thermal X-ray emission, growing evidence for the existence of a non–thermal emission component has been accumulated over the last years. Indications for a non–thermal particle population have been found at three regimes of the electromagnetic spectrum: At radio wavelengths through the existence of diffuse radio halos or radio relicts; at the extreme ultraviolet (EUV) through the still controversially discussed observations of excess emission on top of the expected free–free radiation in hot plasmas; and at hard X-ray wavelengths the existence of a distinct non–thermal emission component. Indication of an excess of observed against predicted emission has been recently reported from soft X-ray observations using ROSAT and XMM-Newton also.

Different scenarios have been suggested to connect and explain the physical links between observations.

Whereas the diffuse radio emission is clearly synchrotron radiation by highly relativistic electrons, the EUV excess emission was first attributed to a second but cooler thermal component. A more plausible explanation is Inverse Compton scattering of Cosmic Microwave Background (CMB) radiation by a non–thermal electron population (Enßlin & Biermann 1998, Blasi & Colafrancesco 1999, Völk & Atoyan 1999). The hard X-ray excess can be produced by Inverse Compton scattering of the same electron distribution generating the non–thermal radio emission (Giovannini et al. 1993, Sarazin 1999). To avoid the problem of the rather low magnetic field strength in such a scenario, non–thermal bremsstrahlung has been proposed as an alternative emission process (Enßlin et al. 1999, Sarazin & Kempner 2000). As pointed out by Petrosian (2001), the non–thermal bremsstrahlung cannot be persistently produced on account of the low radiation efficiency of electrons in the 100 keV range. Non–thermal bremsstrahlung scenarios still might be applicable if in-situ acceleration of thermal electrons through turbulence is favored against acceleration in external sites (Liang et al. 2002).

Hadronic particle populations were considered to produce gamma-rays via pp–interactions of high-energy cosmic rays with the intracluster medium (Jaffe 1977, Rephaeli 1977, Völk et al. 1996, Berezinsky et al. 1997), or as originating from a secondary population of relativistic electrons (Dennison 1980, Atoyan & Völk 2000, Miniati et al. 2001a). Cluster merger systems might offer sufficient cosmic ray injection rates in conjunction with a mechanism for heating the ICM to the observed cluster temperatures (Takizawa & Naito 2000,
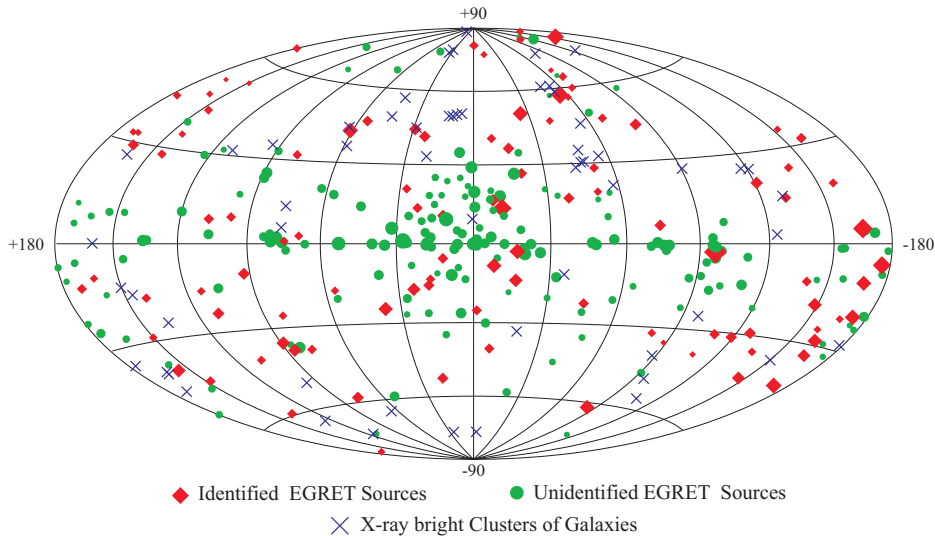
Fig. 1.— Positions of 58 nearby X-ray bright galaxy clusters and 3EG catalog gamma-ray sources, in galactic coordinates. This cluster sample has been studied by Reimer et al. (2003), individually as well as in superposition.

Blasi 2001). However, efficient particle acceleration occurs mainly in minor merger shocks (Fujita & Sarazin 2001, Gabici & Blasi 2003a, Kuo et al. 2003, Berrington & Dermer 2003) - major merger shocks are on average too weak and too rare. Also, diffuse radio halos and radio relics does have different observational signatures - whereas the radio halo is morphological similar to the diffuse X-ray emission and coincident with the cluster mass distribution, radio relics are filamented and indicate the presence of merger shock fronts, not necessarily correlated with the diffuse halo features of a cluster (Buote 2001, Miniati 2001b, Liang et al. 2002, Enßlin et al. 2002). Cluster mergers might generate sufficient turbulence (Ohno et al. 2002, Fujita et al. 2003) to effectively accelerate particles, which might explain the variety in observational features from galaxy clusters.

High-energy gamma radiation is also expected as a result of large scale cosmological structure formation (Dar & Shaviv 1995, Colafrancesco & Blasi 1998, Loeb & Waxman 2000, Totani & Kitayama 2000, Miniati 2002, Keshet et al. 2003). The standard scenario declares that larger structures evolve from mergers of adjacent but smaller structures. In such hierarchical merging scenarios baryonic matter condenses in form of galaxy clusters. Cluster merger events are basically interactions between dark matter halos of galaxy clusters. As a result of the merger process particle acceleration (1st order Fermi and/or plasma turbulence) takes place at the shock front between interacting cluster halos. The involved hadronic particle population (Miniati et al. 2001b) could account for a substantial fraction of the total pressure in the ICM when considered on the relevant timescales of cosmological structure formation.

Large scale structure formation scenarios also predict a contribution from galaxy clusters to the extragalactic diffuse gamma-ray background (EDGB). Apart from the general prediction of such a contribution, quantitative estimates range between 'dominant part of

the already observed extragalactic diffuse background by EGRET' (Dar & Shaviv 1995) to 'magnitudes below the detection threshold of the current gamma-ray instrumentation' (Blasi & Colafrancesco 1999, Keshet et al. 2003, Berrington & Dermer 2003, Gabici & Blasi 2003b, Miniati 2003) - a range of predictions substantially more uncertain than those for the contribution of unresolved AGN to the EDGB (see i.e. Mücke & Pohl (2000) and references therein). The benefit of dealing with a class of astronomical objects already detected at gamma-ray wavelengths is not granted for the galaxy clusters: In contrast to the blazar population detected by EGRET, no galaxy cluster has been unambiguously identified at gamma-ray wavelengths to date.

Consequently, three kinds of a connection between unidentified gamma-ray sources and galaxy clusters needs to be discussed:

- (i) unambiguous identification of a formerly unidentified gamma-ray source with a galaxy cluster
- (ii) spatial-statistical correlation between the population of unidentified gamma-ray sources and galaxy lusters
- (iii) detection of a galaxy clusters contribution to the EGDB equivalent to the identification of galaxy clusters as gamma-ray emitters

II. OBSERVATIONS TOWARDS INDIVIDUAL GALAXY CLUSTERS

The most direct way to connect gamma-ray sources and clusters of galaxies is the unambiguous identification of an gamma-ray source with a galaxy cluster, thereby establishing a second population of extragalactic astronomical objects able to emit persistent high energy gamma radiation. The identification sequence would follow the multifrequency observation approach:

One might look for a galaxy cluster in close vicinity of the source location of an unidentified source, whose spatial location should be well defined and characterized by absence of any other interesting counterpart at radio, optical and X-ray frequencies. The counterpart survey should be sufficient deep at the considered wavebands. In terms of its gamma-ray properties it should be a non-variable gamma-ray emitter, in particular cases supported also by an indication of being an extended source. Specific prediction for the flux of a few individual galaxy clusters at the high-energy gamma-rays exist in the literature: For the Perseus cluster (A426), the Coma cluster (A1656) and the Virgo cluster (M87) Dar & Shaviv (1995) predicted gamma-ray fluxes of the order of several 10^{-8} up to a few 10^{-7} cm^{-2} s^{-1}, similar to the prediction of Dermer & Rephaeli (1988) made for M87 under consideration of various magnetic field strengths. Enßlin et al. 1997 came to a similar result for A426 but predicted significant less gamma-ray flux for M87. Also, they gave a prediction in the order of 10^{-7} for the Ophiuchus cluster. These predictions, however, are made under the assumption of a specific cosmic ray electron to proton ratio, which may or may not be correct for the individual cluster. The given predictions can be confronted with actual experimental data: McGlynn et al. 1994 determined preliminary upper limits on the basis of the early EGRET observations, with follow-up observations using OSSE data by Rephaeli et al. 1994 for Coma and EGRET data by Sreekumar et al. 1996 for Coma and M87. The latest assessment of individual galaxy clusters has been made by Reimer et al. (2003), where the EGRET data have been analyzed at the position of 58 individual galaxy clusters (Fig.1) throughout the EGRET mission under consideration of the final instrumental efficiency corrections. The upper limit for the gamma-ray emission above 100 MeV for the Coma cluster and for M87, determined at the position of the X-ray emission maximum, is 3.8×10^{-8} cm^{-2} s^{-1}, and 2.2×10^{-8} cm^{-2} s^{-1}, respectively. With the apparent conflict between early model predictions and the given upper limits for a few individual galaxy clusters, such models are disfavored against models which predict gamma-ray emission below the sensitivity of the EGRET instrument like inverse Compton scenarios from cosmic ray electrons accelerated at accretion shocks by Colafrancesco & Blasi (1998) and Miniati (2002), or the assumption made of the cosmic ray proton (CRp) scaling parameter is too optimistic. Upper limits can be used to obtain upper bounds on the cosmic ray proton (CRp) scaling parameter $X_{crp} = \varepsilon_{crp}(\vec{r})/\varepsilon_{\text{th}}(\vec{r})$. Pfrommer & Enßlin (2004) concluded, that the most constraining observations consists in the case of Perseus and Virgo, which lie in the range $X_{crp} \in [0.08, 0.18]$ for different choices of the *crp* spectral index $\alpha_p \in [2.1, 2.7]$.

Thus, our present situation is to be characterized by the fact that no individual galaxy cluster has been conclusively related to an unidentified gamma-ray source yet.
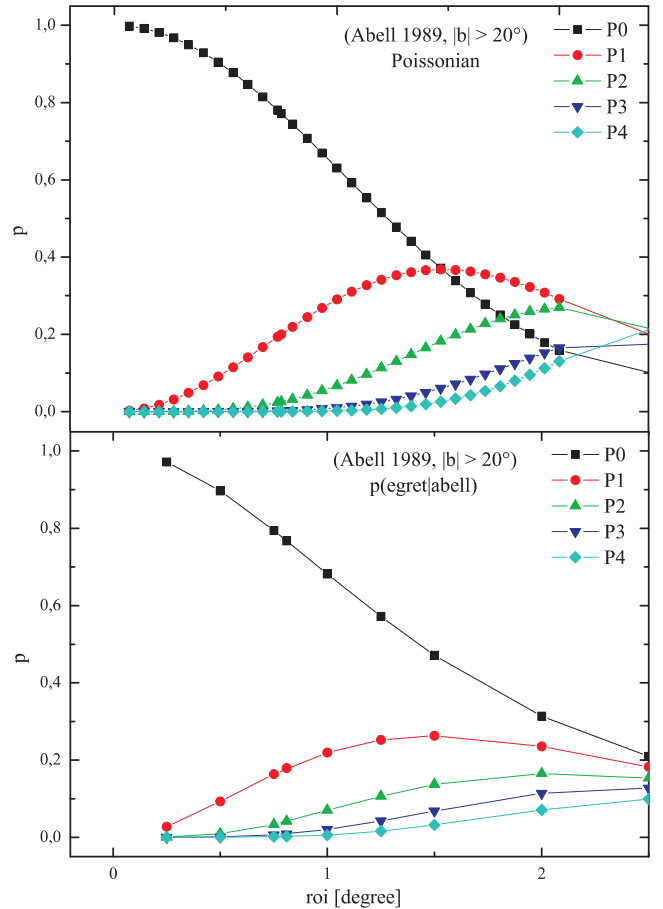

Fig. 2.— Poissonian statistics and modified statistics for cluster–cluster–autocorrelation for Abell clusters at $|b| > 20°$. P0, P1, P2 etc. are the probabilities for none, single, double coincidences between an arbitrary source and the Abell cluster sample for different source separations.

Experimental data provided only upper limits, which can be used to constrain parameters in multifrequency modeling of prominent galaxy clusters, most effectively in prominent cases like Perseus, Coma and Virgo.

III. SPATIAL-STATISTICAL CORRELATION STUDIES

Spatial-statistical correlation studies investigate global properties of an unknown source population, here the unidentified gamma-ray sources, and compare them to the spatial properties of a candidate source population, here clusters of galaxies. If spatial associations are found, an assessment is necessary in order to conclude on the statistical significance, and thus the validity of such a correlation.

Spatial-statistical correlations between galaxy clusters and unidentified gamma-ray sources have been suggested in several studies already: Totani & Kitayama (2000) proposed dynamically forming clusters of galaxies, hardly to be detected at optical or X-ray

wavelengths, but able to account for a significant fraction of the EGDB as well as "a few tens" of the unidentified EGRET sources. Although such populations do not have truly testable predictions at other than the proposed GeV waveband (Totani & Inoue 2002), this scenario has been used by Kawasaki & Totani (2002) to support a spatial-statistical correlation between a subset of the unidentified EGRET sources and possibly merging clusters of galaxies. The steady unidentified EGRET sources (Gehrels et al. 2000) at high-galactic latitude, a sample of 7 gamma-ray sources in total, have been proposed to correlate with pairs/groups of galaxy cluster candidates from the APM catalog data (http://www.ast.cam.ac.uk/apmcat/). Although the presence of cluster merger processes has not been conclusively established, the considered possibly merging cluster candidates correlate at the $3\,\sigma$ level with the seven steady unidentified EGRET sources. These cluster candidates are not necessarily established in existing cluster catalogs yet, so their classification remains to be confirmed. Because of the small size of the sample and consequently uncertainty in the statistical assessment of such a correlation, the tentative character of the suggested identifications as possibly merging cluster pairs, and the problematic discrepancy in the application of predictions from Totani & Kitayama (2000) to observational results as presented by Kawasaki & Totani (2002) will require individual multifrequency follow-up campaigns to conclude on the validity of the proposed cluster pair/unidentified gamma-ray source correlation.

At about the same time preliminary evidence for a large scale correlation between Abell clusters and unidentified EGRET sources has been given by Colafrancesco (2001, 2002). In a comparison of 3979 cataloged galaxy clusters from Abell et al. (1989) with 128 gamma-ray sources outside the galactic plane from Hartman et al. (1999) a spatial-statistical correlation between 24 Abell clusters and 18 unidentified EGRET sources has been suggested, accompanied with a detailed characterization of the individual cluster/gamma-ray source associations from archival X-ray and radio data. According to Colafrancesco (2002) the significance level of such associations is about $2.5\,\sigma$. Further support has been claimed from a correlation of the gamma-ray source flux with the radio flux at 1.4 GHz of the clusters brightest source and the clusters X-ray luminosity, respectively. Although this association is below also below $3\,\sigma$ statistical significance, further systematic biases are need to be addressed in order to quantify the suggested spatial-statistical association. First, the spatial distribution of EGRET source detections depends heavily on the uneven sky coverage (exposure) of the EGRET instrument and the reduced source detectability in the galactic plane due to pronounced diffuse gamma-ray emission. Also, the 3EG catalog of gamma-ray source has been constructed by applying two different detection thresholds, and even the individual source detections have

been determined from either individual viewing periods, combination of viewing periods or the full 4 year sky coverage of EGRET observations. As a result, the cataloged EGRET sources represent an inhomogeneous statistical sample, compiled without a consistent spatial detection probability - and source correlation studies need to account for this. The large sample size of ~ 4000 Abell cluster in a correlation study with unidentified gamma-ray sources invokes an additional problem: The average EGRET source location uncertainty contour includes an area of up to a few square degrees at the sky, and several Abell clusters may correlate with an individual unidentified gamma-ray source. Thus, we expect autocorrelation in the Abell cluster sample when comparing it with unidentified gamma-ray sources. Reimer et al. (2003) have determined the chance probability for an association between an arbitrary source and one of the Abell clusters as a function of their distance, corresponding to the maximum separation where both sources can be considered as associated. Referring to the suggested association between 24 Abell clusters and 18 unidentified EGRET sources, one expects 10.6 single, 2.5 double, and 0.2 triple associations by chance only (Fig.2). Hence, the pure chance coincidences amount to ~ 18 Abell cluster and ~ 14 EGRET sources, corresponding to a statistical significance of only $1\,\sigma$ in terms of the cumulative Poisson probability.

The topic of expected cluster associations have been recently theoretically addressed by Miniati (2002), Gabici & Blasi (2003a), Berrington & Dermer (2003), all arguing that more than a few of the isotropically distributed unidentified EGRET sources at high-galactic latitudes are unlikely attributed to radiation from non–thermal particles produced by cluster merger shocks. Especially the discrepancy between non–thermal activity in galaxy clusters and the relative ineffectiveness of major shocks to energize the underlying particle population has been emphasized.

In conclusion, we still have to await the determination of more precise gamma-ray source locations in order to establish the existence of a spatial correlation between Abell clusters and unidentified gamma-ray sources using population studies. The new generation of imaging atmospheric Cherenkov telescopes and the Gamma-ray Large Area Space Telescope GLAST-LAT will certainly contribute here decisively.

IV.   CONTRIBUTION OF UNRESOLVED GALAXY CLUSTERS TO THE EGDB

The least direct attempt to identify a new class of astronomical objects emitting high-energetic gamma radiation is by considering their contribution to the diffuse galactic or extragalactic gamma-ray background. This requires a profound understanding of the determination and theoretical modeling of the galactic diffuse emission and the extragalactic diffuse gamma-ray back-
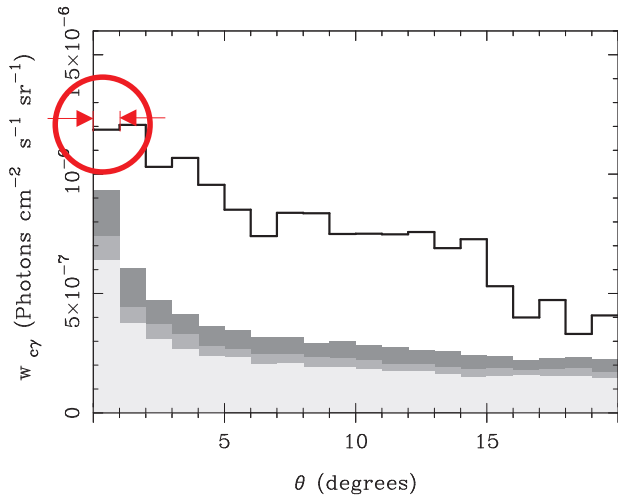
Fig. 3.— Cross-correlation or mean excess surrounding the stacked positions of the 447 richest Abell clusters ($E > 100$ MeV), in radial bins of 1° width (solid line), compared with a Monte Carlo result for a realization an the basis of such cluster sample but randomized gamma-ray data. The result of a cluster contribution is taken from the innermost 1° bin and corresponds to 1.19×10^{-6} ph s^{-1} cm^{-2} sr^{-1}. Adapted from Scharf & Mukherjee (2002).

Fig. 4.— Likelihood test statistics map (corresponding σ^2) for the combined cluster data set by Reimer et al. (2003) as observed by EGRET ($E > 100$ MeV). The region of interest is indicated by the 5° circle. Maps are shown in a cluster–centered coordinate system.

ground (EGDB), including the involved statistical and systematical uncertainties and residual contaminations. In case of an already detected source class like BL Lacs and FSRQs, such contributions can be quantitatively determined on the basis of their luminosity function or logN–logS source statistics from actual observations. For other source classes like the radio galaxies or nearby normal galaxies we still fail to benefit from a reasonably sized observational sample at gamma-ray wavelengths to carry out such a determination, thus different methods are required. Investigations of candidate source populations in the observational data by statistical superposition may be carried out, either in case of existing but numerically limited source detections as in the case of radio galaxies (Cillis et al. 2004) or predicted but not yet individually detected candidate sources as the galaxy clusters. In case of the galaxy clusters, two studies on the basis of gamma-ray observations have been made, both investigating a physical motivated selection of galaxy clusters.

Scharf & Mukherjee (2002) initially investigated 2469 cataloged Abell clusters at $|b| > 45°$, but considered also a subset of the 447 optically richest (R ≥ 2) clusters among those. Data taken from an EGRET all–sky intensity map have been utilized up to a radius of 20° off the location of the individual galaxy cluster. In order to account for the diffuse galactic emission, the diffuse emission model by Hunter et al. (1997) has been subtracted from the EGRET intensity data. Finally, the data have been stacked in radial annuli centered on the Abell clusters. The obtained results have been compared with Monte Carlo tests of scrambled gamma-ray data as well as a synthetically generated cluster catalog (randomized cluster positions). Fig.3 gives the main
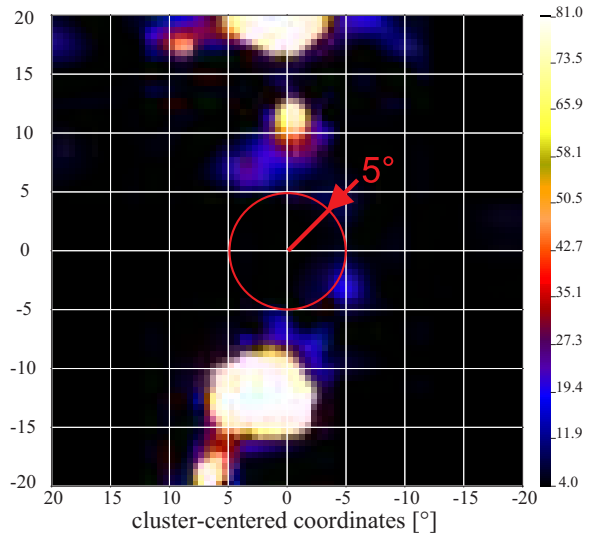
result from Scharf & Mukherjee (2002), indicating an excess in the stacked gamma-ray data at the positions of the considered Abell clusters in comparison with randomized gamma-ray data at the position of the Abell clusters. According to Scharf & Mukherjee (2002) this indicates a statistical detection of Abell clusters, in particular those of high optical richness, spatially co-incident with unresolved gamma-ray sources at the 3σ level. The given mean cluster flux has been determined to $\sim 1.14 \times 10^{-9}$ cm^{-2} s^{-1} at E > 100 MeV in a 1° radius aperture, corresponding to a 68% flux enclosure of the EGRET point-spread function. However, Reimer et al. (2003) noted, that the energy–averaged EGRET flux enclosure at E > 100 MeV in a 1° aperture, assuming a source spectrum with a power-law index of -2.0, is lower, namely 24.1%. The 68% flux enclosure is reached at a radius of 3.1°. Therefore the flux for the innermost (1°) radial bin from Scharf & Mukherjee (2002) corresponds to 4.7×10^{-9} cm^{-2} s^{-1}.

Reimer et al. (2003) expanded an earlier study of 58 nearby X-ray bright galaxy clusters (Reimer 1999, Reimer & Sreekumar 2001) by considering all relevant EGRET observations between 1991 and 2000. Using the finalized EGRET data, which incorporate the latest instrumental efficiency normalization, data at $E > 100$ MeV have been analyzed with the likelihood technique. Subsequently, the gamma-ray data from individual galaxy clusters have been co–added in cluster–centered coordinates. The co–added images were again analyzed using the likelihood technique, however in conjunction with an adequately adapted diffuse gamma-ray foreground model. Fig.4 gives the final result of the stacked cluster population. Of interest is the map center only, corresponding to the emis-

sion maximum of the considered galaxy clusters at X-rays. No significant gamma-ray emission excess has been found within a radius of $5°$ of the origin in the cluster-centered image. With a cumulative exposure of 3.4×10^{10} cm^2 s for E > 100 MeV the corresponding upper limit is 5.9×10^{-9} cm^{-2} s^{-1} for the average galaxy cluster in the sample. This result, which benefits from the application of the likelihood analysis technique in conjunction with an adapted diffuse emission model, appears to be inconsistent with Scharf & Mukherjee (2002). Apparently, studying a significantly larger sample by annuli binning of the EGRET intensity data at the cluster positions (Scharf & Mukherjee 2002) reaches a comparable sensitivity like investigating a comparatively small sample with the maximum-likelihood technique in conjunction with a customized diffuse galactic emission model (Reimer et al. 2003). In a $2°$ aperture, corresponding to the second inner-most bin of $\sim 1.2 \times 10^{-6}$ ph s^{-1} cm^{-2} sr^{-1} in Scharf & Mukherjee 2002, the corresponding mean cluster flux is 9.6×10^{-9} cm^{-2} s^{-1}, the somewhat surprising result that the statistical significance as well as the average cluster flux increases by going to larger radii from the cluster center. Thus we're confronted with the rather unsatisfactory discrepancy between the report of a statistical detection in the EGRET intensity data using a large cluster sample but rather crude analysis method of annuli binning and an observational upper limit at the reported average cluster flux using a smaller and differently motivated cluster selection, however analyzed by applying the maximum-likelihood technique well-proven in the many EGRET source detections and catalog compilations. Future observations will certainly clarify this situation. When the first galaxy cluster will be directly detected at high-energy gamma-rays, more precise and perhaps revised predictions of a cluster contribution to the EGDB will be possible. Recent theoretical modeling indicates already that more realistic estimates of a EGDB contribution from cluster merger shocks amount to only $\sim 10\%$ (Gabici & Blasi 2003b, Berrington & Dermer 2003).

In conclusion, we still have to await the first observational evidence for the high-energy gamma-ray emission of galaxy clusters, either from individual detections or as a collective. The last generation of gamma-ray telescopes aboard CGRO was not able to resolve an individual galaxy cluster nor the nearby, X-ray brightest clusters of galaxies as a population. Until the next generation of gamma-ray instruments will challenge this important scientific topic, progress is expected at other wavelengths: from GHz-frequency radio observations of radio halos, from studies of soft and hard X-ray excess features with sufficient statistical significance, and perhaps from measurements of the new generation of imaging atmospheric Cherenkov telescopes. While multi-GeV gamma-ray emission will almost certainly be generated by hadronic interactions, the lower energy gamma rays in the sub-GeV range can be generated by several processes related to electrons.
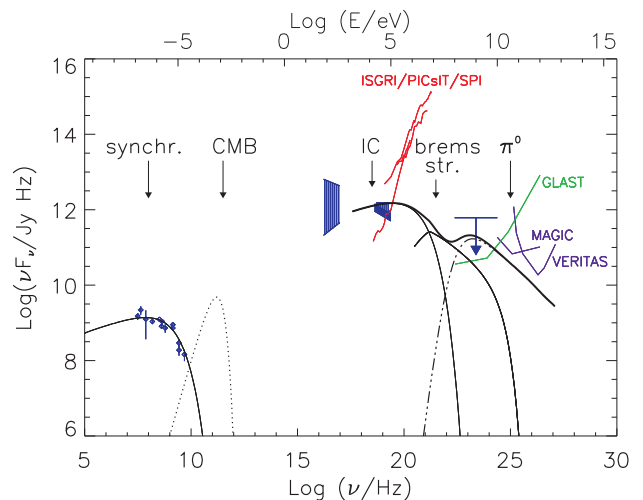

Fig. 5.— Broad band continuum spectrum of Coma. The radio continuum data together with the best-fit function are taken from Thierbach et al. (2003). The synchrotron spectrum has been corrected for self-absorption. The dotted line (left curve) represents the 2.73 K cosmic background radiation field corrected for the thermal Sunyaev-Zeldovich effect using a y-parameter of $0.75 \cdot 10^{-4}$ (see Enßlin 2002 and references therein). The inverse Compton and non–thermal bremsstrahlung fluxes are calculated for an exponential electron spectrum with volume-averaged magnetic field strengths of 0.1 μG with adjusted normalization and maximum electron momentum to fit the radio data, and using a gas density $n_i = 10^{-3}$cm^{-3}. They are extended to lower energies assuming the synchrotron spectrum follows a power law down to at least 10^{-9} eV. The hatched regions in the EUV and HXR domain correspond to the pulished data from PDS/BeppoSAX, PCA/RXTE, and EUV. The π^0-decay γ-ray spectrum (dotted line, most right curve) is calculated here only exemplary for a $\alpha_p = 2.5$ proton spectrum and the normalization of the particle spectra are adjusted to avoid violating the EGRET upper limit as well as the integral fluxes in the HXR and radio domain for a volume-averaged field strength of 0.1μG. The corresponding Inverse Compton and synchrotron flux, corrected for synchrotron self-absorption, are shown as dotted line. All γ-ray spectra are also corrected for absorption in the cosmic background radiation field using the background models in Aharonian (2001). Adapted from Reimer et al. 2004

Fig.9 describes the broad band continuum spectrum of Coma by modeling the various emission component and indicates relevant instrumental sensitivities. GLAST as the EGRET-successor and upcoming major astrophysics mission in the GeV-band will have the distinct chance to probe the parameter space among the various models found in the literature and directly detect the gamma-ray emission from Galaxy clusters. Subsequently, the estimates of a cluster contribution to the EDGB may be substantcially refined on available cluster detections at high-energy gamma-ray. The wealth of expected source detections in conjunction with more precise gamma-ray source locations and extended spectral coverage will also be essential for its usage in correlation studies, investigating the remaining unidentified gamma-ray sources from the EGRET-era and anticipated unidentified gamma-ray sources from GLAST

observations itself.

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