The Extra–galactic Gamma–Ray Signal of Supersymmetric Dark Matter

P. Salati[1], E.A. Baltz[2], C. Briot[1], R. Taillet[1], and J. Silk[3]
[1] *Laboratoire de Physique Théorique LAPTH, BP110, F-74941 Annecy-le-Vieux Cedex, France*
[2] *Department of Physics, University of California, Berkeley, CA 94720, USA*
[3] *Department of Astrophysics, Oxford University, Oxford OX1 3RH, United Kingdom*

Abstract

The giant elliptical galaxy M87, at the center of the Virgo Cluster, is known to contain ten times more dark matter than the Milky Way. X-ray observations of its ambient hot gas indicate that in the innermost 100 kpc the mass reaches $\sim 10^{13}\,\mathrm{M}_{\odot}$. If neutralinos such as supersymmetric species pervade the halo of M87, the gamma–ray signal resulting from their mutual annihilations should be ~ 100 times larger than for own galaxy. It should also spread over a few hundreds of square arcminutes. Cerenkov telescopes are appropriate for detecting such a hot spot insofar as they monitor small portions of the sky and benefit from large collecting areas. Below $\sim$ 70 GeV, the background is dominated by electron induced showers while above, misrecognized hadrons take over. Radial profiles of the gamma–ray emission of M87 are featured. We derive the domain of neutralino masses and gamma–ray production cross sections which the next generation of Cerenkov telescopes will explore.

1 Introduction:

One of the favourite candidates to the astronomical missing mass is a neutral weakly interacting particle. Such a species is predicted in particular by supersymmetry, a theory that is actively tested at accelerators. It is conceivable therefore that most of the dark matter in the halo of the Milky Way is made of such particles. The mutual annihilation of these so–called neutralinos would yield, among a few other indirect signatures, a flux of high–energy gamma–rays. The latter has been extensively studied in the literature (Bengtsson, Salati, & Silk, 1990; Berezinsky, et al., 1994; Jungman, Kamionkowski & Griest, 1996 and Refs. therein). It is unfortunately spoilt by the diffuse background produced by the spallation of cosmic–ray protons on the interstellar gas (Chardonnet, et al., 1995). The distribution of molecular hydrogen inside the galactic ridge is not sufficiently well known to ensure an accurate prediction of that diffuse emission. This may obliterate a reliable interpretation of any putative gamma–ray excess in terms of supersymmetric dark matter. We examine here the possibility to observe that kind of signal from extra–galactic systems that contain large amounts of unseen matter. The giant elliptical galaxy M87 provides an excellent illustration. It is known to contain ten times more mass than our own Milky Way. If neutralinos pervade its halo, a strong gamma–ray emission should be observed in the central region. Such a signal is well suited for atmospheric Cerenkov telescopes (ACT) which can only monitor small portions of the sky at the same time but have very large effective collecting areas. The distribution of matter inside M87 is modeled in Sect. **??** together with the radial profile of the neutralino induced gamma–ray emission. Various backgrounds to the signal are presented and the corresponding signal–to–noise ratio is inferred. In Sect. **??**, the supersymmetric parameter space is explored. We finally derive the sensitivity which an ACT of the HESS caliber may reach.

2 The gamma–ray signal from M87 and its backgrounds:

The properties of the hot X–ray gas in the vicinity of M87 were determined by Tsai (1993). The total mass distribution inside that system may be inferred from the electron density n_e and temperature T profiles

$$M(r) \; = \; - \frac{kT}{G \mu m_p} \left(\frac{d \log n_e}{d \log r} + \frac{d \log T}{d \log r} \right) \, r \quad , \tag{1}$$

assuming that the ambient gas is in hydrostatic equilibrium. Dark matter dominates over the distribution of stars and gas beyond a few kpc so that its radial distribution readily obtains from Eq. **??**. If it is made of neutralinos, we should expect an annihilation gamma–ray emission whose surface brightness may be expressed as

$$\Phi_\gamma \; = \; \frac{1}{4\pi} \, \langle \sigma v \rangle_{\rm cont} \, N_\gamma \int_{\rm los} n_\chi^2 \, ds \quad . \tag{2}$$

The astrophysical relevant quantity turns out to be the integral, along the line–of–sight, of the square of the dark matter density $\rho_\chi = n_\chi m_\chi$. On the other hand, the particle physics input corresponds to the effective gamma–ray production cross section $\langle \sigma v \rangle_{\rm cont} \, N_\gamma$ where a continuum of gamma–ray energies in excess of some threshold $E_\gamma^{\rm th}$ has been taken into account. The left pannel of Fig. **??** features the radial distribution of that annihilation signal (solid line) in the case of a 1 TeV neutralino with an effective gamma–ray production cross section of 10^{-25} cm^3 s^{-1}. The threshold has been set equal to 100 GeV. An ACT with an acceptance of 1 km^2 year has also been assumed. The signal may be swamped inside a variety of backgrounds corresponding to the dotted and dashed curves. High–energy electrons (a) generate showers at the top of the atmosphere

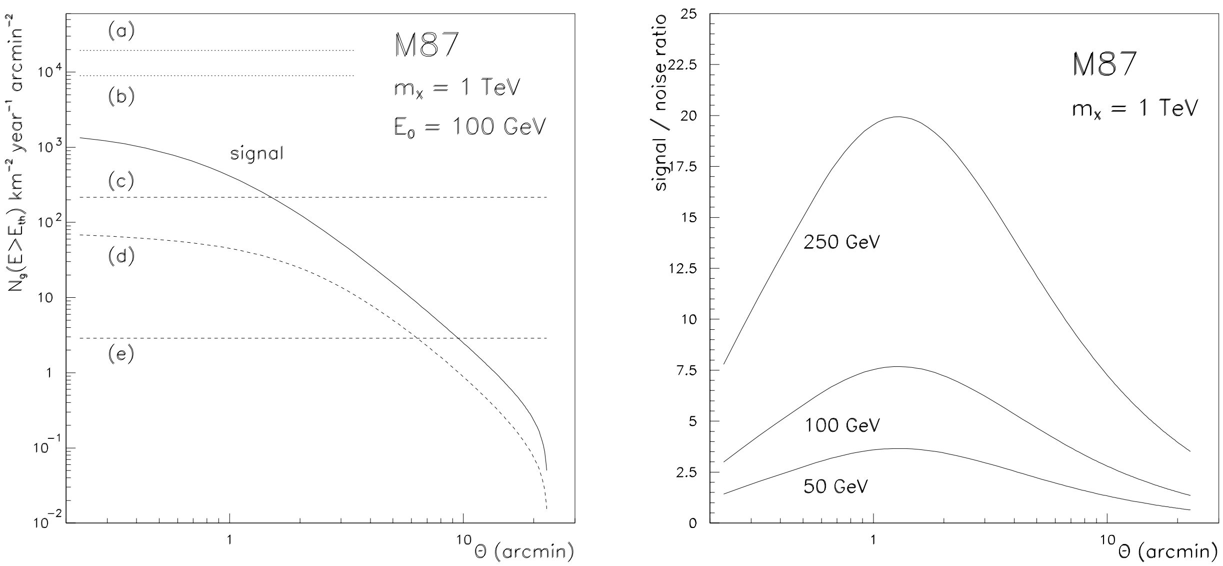

Figure 1: The radial profiles of the signal and its backgrounds are presented in the `left` pannel. A fiducial model for M87 with m_χ = 1 TeV and $\langle \sigma v \rangle_{\rm cont} \, N_\gamma = 10^{-25}$ cm^3 s^{-1} is considered while a threshold of 100 GeV is assumed. In the `right` pannel, the signal–to–noise ratio is featured as a function of threshold and beam size. An integration of 1 km^2 yr is assumed.

which cannot be distinguished from those induced by gamma–rays. They dominate over the other sources of background. Next come the misidentified cosmic–ray hadrons. Curve (b) corresponds to a rejection factor of 10^3, *i.e.*, we have assumed that one hadron over a sample of a thousand particles is mistaken for a gamma–ray. The background (c) is the extra–galactic emission. Finally, the diffuse emission from M87 itself as well as from the Milky Way are respectively featured by curves (d) and (e). An hydrogen column density of 1.7×10^{20} H cm^{-2} has been assumed when deriving (e) while the same cosmic–ray flux inside M87 as in our galaxy has been considered. In the right pannel of Fig. **??**, the gamma–ray flux has been integrated over the radial distance θ from the M87 center. The various backgrounds yield a total signal whose square root corresponds to our noise. At fixed value of $\langle \sigma v \rangle_{\rm cont} \, N_\gamma$, the signal–to–noise ratio increases with the gamma–ray energy threshold $E_\gamma^{\rm th}$ as a result of weaker backgrounds. The maximum is always reached for an angle of 1.4 arcminute.

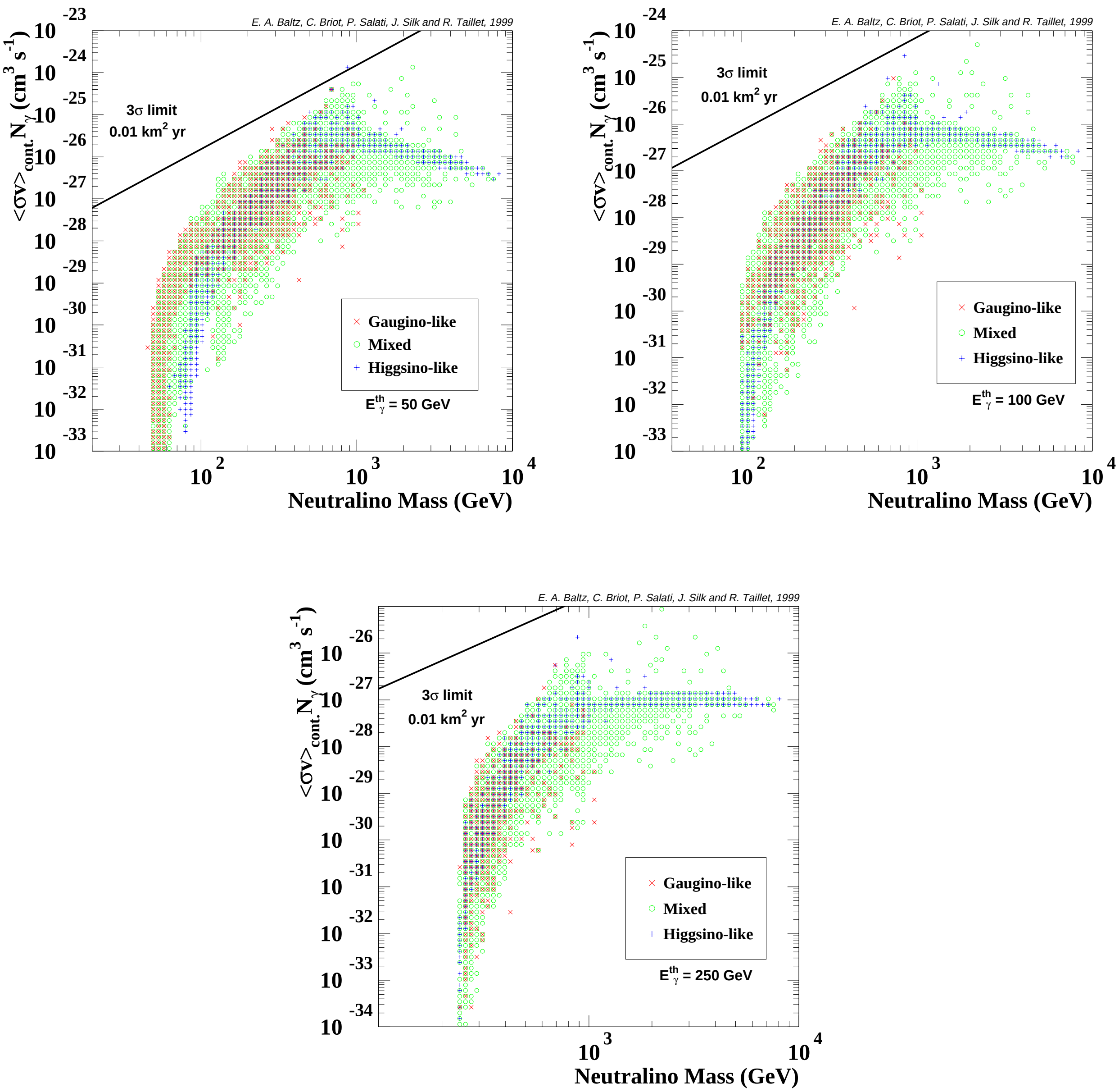

Figure 2: Annihilation rates in the continuum channels. Three thresholds are illustrated, $E_{\gamma}^{\rm th}$ = 50, 100 and 250 GeV. The 3σ detection limits for exposures of 0.01 km^2 yr are also presented.

3 Exploring the supersymmetric parameter space:

We have explored the Minimal Supersymmetric Standard Model (MSSM). This framework has many free parameters, but with reasonable assumptions the set of parameters is reduced to seven: the Higgsino mass parameter μ, the gaugino mass parameter M_2, the ratio of the Higgs vacuum expectation values $\tan\beta$, the mass of the CP–odd Higgs boson m_A, the scalar mass parameter m_0 and the trilinear soft SUSY–breaking parameters A_b and A_t for third generation squarks. For a more detailed description of these models, see Edsjö (1997) as well as Edsjö and Gondolo (1997). Present observations favor $h = 0.6 \pm 0.1$, and a total matter density $\Omega_M = 0.3 \pm 0.1$, of which baryons may contribute 0.02 to 0.08 (Schramm, & Turner, 1998). However, we have only required that $\Omega_\chi h^2 \leq 0.5$. We have also been interested in models where neutralinos are not the only component of dark matter. In models with $\Omega_\chi h^2 \leq 0.025$, we rescaled the relevant halo densities by a factor $\Omega_\chi h^2/0.025$ to account for the fact that a supplemental source of dark matter is required in such models.

Scans over the supersymmetric parameter space have been performed. Results are presented in the scatter plots of Fig. **??** where the continuum gamma–ray production rate $\langle \sigma v \rangle_{\rm cont} \, N_\gamma$ is featured as a function of neutralino mass m_χ, along with the 3σ detection limit for a typical exposure of 0.01 km^2 yr (heavy solid line). That acceptance is typical of the next generation of ACT's like HESS. The three pannels correspond to the gamma–ray thresholds $E_\gamma^{\rm th}$ = 50, 100 and 250 GeV. The HESS angular resolution of 0.1 degree has also been borrowed so that the signal–to–noise ratio for the M87 signal is not optimal. Low–energy gamma–rays are predominantly produced in neutralino annihilations. The lower the detection threshold, the better the sensitivity in spite of increasing backgrounds. A threshold of 50 GeV is nevertheless mandatory in order to graze the supersymmetric parameter space. Detection of a gamma–ray signal from neutralino annihilation in M87 is therefore marginally achievable by the next generation of Cerenkov detectors.

Notice however that we have so far assumed that the dark matter was uniformly distributed. Press–Schechter theory of structure formation predicts many dwarf systems with mass spectrum $dN/dM \propto M^{-2}$ in the tail of the distribution, to be compared to $dN/dL \propto L^{-1}$ observed in the luminosity function. Most of these structures are "failed" but the dark matter stays in bound clumps. So there might be many dark dwarfs floating around in the halo of M87 for every stellar cluster that is visible. If so, the clumpiness of the neutralino distribution would lead to a much larger signal than what has been derived here. The 3–σ boundary lines of Fig. **??** would be shifted accordingly downwards inside the supersymmetric parameter space.

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