Gamma-ray Signatures of Dark Matter Particles

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Abstract

Indirect detection methods of dark matter particles are discussed. In particular, detection of supersymmetric dark matter through annihilation into gamma-rays is described. Aspects of the density structure of dark matter halos, important for estimating the chances of detection, are discussed. A new class of dark matter candidates, related to non-vanishing neutrinos masses and seemingly only detectable in gamma-rays, is described.

1. Introduction

Since Big Bang nucleosynthesis (BBN) puts an upper limit to the baryonic contribution Ω_b to Ω_M of [1]

$$\Omega_b h^2 \leq 0.022, \tag{1}$$

non-baryonic dark matter is required beyond any doubt also in the ΛCDM model, which has $\Omega_M \sim 0.3$. In fact, is has yet turned out to be impossible to explain the CMBR data and the large scale distribution of galaxies in models with only baryons.

The non-baryonic dark matter candidates we will discuss here, in particular weakly interacting particles (WIMPs) such as neutralinos, have the virtue of lending themselves to experimental investigations at a level that is already starting to probe relevant regions of the parameter space which defines the particle physics properties of such models.

However, there are still large uncertainties related to the way the dark matter is distributed in present-day galactic halos. On large scales like that of clusters of galaxies, gravitational lensing indicates that the dark matter is smoothly distributed, on the average. When it comes to the question of how the dark matter is distributed on the smallest, galactic and sub-galactic, scales the situation is much less clear, however (for a review, see, e.g., [2]). After being subject to an extensive debate, with both theoretical and observational controversies, it seems

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that the Cold Dark Matter model, with dark matter made of, e.g., weakly interacting massive particles, is in fair agreement with current observations, so that drastic modifications like strong self-interaction are not urgently called for (see, e.g., [3]).

2. Dark Matter Candidates

In principle, one could imagine having a sterile neutrino as dark matter, if it is non-thermally produced, e.g., generated through mixing with the active neutrinos. Generally, this candidate will have a mass in the keV to MeV range and would act as something inbetween cold and hot dark matter (sometimes named "wark dark matter", WDM). An unpleasant feature of these models is a necessary, delicate finetuning of the mixing angle versus mass to get the right abundance, but models of this kind have been constructed which so far evade experimental constraints [4], [5].

The right-handed neutrino, needed to give mass to the three known neutrino species, is in most models in the GUT mass range and cannot have been produced by thermal processes. Non-thermal production is again possible, but involves elements of fine-tuning. Recently, a version of the Zee model has been proposed [6], where a right-handed Majorana neutrino N_R has a TeV-scale mass. As we will see, this would be a favourable candidate for detection in gamma-rays.

One of the prime candidates for the non-baryonic component is otherwise provided by the lightest supersymmetric particle, plausibly the lightest neutralino χ.

If the scale of supersymmetry breaking is related to that of electroweak breaking, Ω_χ comes out in the right order of magnitude to explain the non-baryonic dark matter. This may be a numerical coincidence, or a sign of a deep connection between dark matter and whatever causes the breaking of electroweak symmetry.

The lightest neutralino χ is a mixture of the supersymmetric partners of the photon, the Z and the two neutral CP-even Higgs bosons present in the minimal extension of the supersymmetric standard model (for reviews see, e.g., [7], [8]). The attractiveness of this dark matter candidate stems from the fact that its generic couplings and mass range naturally gives a relic density in the required range to explain halo dark matter. Besides, its motivation from particle physics, which was originally based on solving the so-called hierarchy problem (the puzzling discrepancy between the mass scales of electroweak interactions and gravity), has become stronger due to the apparent need for 100 GeV - 10 TeV scale supersymmetry to achieve unification of the gauge couplings in view of

LEP results [9], and the prediction that the lightest Higgs boson should be below 135 GeV, as seems also favoured by LEP data [10].

Supersymmetry is a mathematically beautiful theory, and would give rise to a very predictive scenario, if it were not broken in an unknown way which unfortunately introduces a large number of unknown parameters.

When using the minimal supersymmetric standard model in calculations of relic dark matter density, one should make sure that all accelerator constraints on supersymmetric particles and couplings are imposed. In addition to significant restrictions on parameters given by LEP [11], the measurement of the $\mathrm{b} \to \mathrm{s}\gamma$ process is providing important bounds.

Recently, there has been much discussion (see, e.g., [12]) about the constraints on the MSSM which follow from the measurements of $(g-2)_\mu$, the anomalous magnetic moment of the muon [13]. The first set of data indicated a large discrepancy with theoretical calculations within the standard (non-supersymmetric) model. The requirement that the discrepancy be explained by MSSM contributions led to the identification of a region in supersymmetric parameter space where neutralinos couple relatively strongly to ordinary matter and therefore have large cross section for various detection methods [12]. However, it has subsequently appeared [14] that the original calculations of the standard model constributions contained errors. On the other hand, the new set of data which has recently been released still shows a discrepancy at the $2-3$ σ level, which can in principle be due to supersymmetry [15]. However, the case is not compelling due to the large uncertainties in the calculation of the hadronic part of the standard model contribution.

The relic density calculation in the MSSM for a given set of parameters is nowadays accurate to 10 % or so. A recent important improvement is the inclusion of coannihilations, which can change the relic abundance by a large factor in some instances [16]. Much of the effort that has gone into this field has resulted in publicly available computer program packages, for instance DarkSUSY [17], which is used in the examples below.

For detection of gamma-rays in Air Cherenkov Telescopes, it is important to note that there are supersymmetric models with masses up to 10 TeV (or even higher, if coannihilations are considered) which give the correct relic density and satisfy all other experimental constraints. For these high masses, it may be that ACTs are the only instruments capable of detecting a signal from dark matter annihilation. This occurs through the annihilation process when two neutralinos meet in the galactic halo. (The neutralino is a Majorana fermion and therefore its own antiparticle.) We now discuss this process in some detail.

3. Indirect detection through gamma-rays

When neutralinos collide and annihilates, the primary annihilation products are fermion-antifermion pairs (quark and leptons), or W^+W^-, ZZ, WH, ZH, or HH states. (Which states are kinematically allowed depends only on the mass of the neutralino, since galactic velocities $v/c \sim 10^{-3}$ means that the annihilations take place essentially at rest.) The gamma ray spectrum arising from the fragmentation of fermion and gauge boson final states is quite featureless and gives the bulk of the gammas at low energy where the cosmic gamma ray background is severe. However, the signal should be correlated with the mass distribution of the dark matter, which may be used to discriminate against more diffusely distributed backgrounds. In particular, there should be a noticeable enhancement towards the galactic center, as the annihilation rate grows with the square of the dark matter number density distribution (squared because two particles have to be at the same place for the annihilations to take place).

Since annihilations take place almost at rest, sharp (almost monoenergetic) high-energy gamma rays may result from the loop-induced annihilations $\chi\chi \to \gamma\gamma$ [18] or $\chi\chi \to Z\gamma$ [19].

The rates of these processes are difficult to estimate because of uncertainties in the supersymmetric parameters, cross sections and halo density profile. However, in contrast to other proposed detection methods they have the virtue of giving very distinct, "smoking gun" signals: monoenergetic photons with $E_\gamma = m_\chi$ or $E_\gamma = m_\chi(1 - m_Z^2/4m_\chi^2)$ from the halo.

Unfortunately, it is difficult to give reliable quantitative estimates of the line rates expexted from these processes, since the detection probability of the gamma line signal depends, as does the continuum signal, on the very poorly known density profile of the dark matter halo.

To illustrate this point, let us consider the characteristic angular dependence of the gamma-ray intensity from neutralino annihilation in the galactic halo. Annihilation of neutralinos in an isothermal halo leads to a gamma-ray flux of

$$\frac{d\mathcal{F}}{d\Omega} \simeq (2 \times 10^{-15}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}) \times \frac{(\sigma_{\gamma\gamma}v)_{29}(\rho_\chi^{0.3})^2}{(m_\chi/\,1\,\mathrm{TeV})^2}\left(\frac{R}{8.5\ \mathrm{kpc}}\right)J(\Psi) \tag{2}$$

where $(\sigma_{\gamma\gamma}v)_{29}$ is the annihilation rate in units of $10^{-29}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$, $\rho_\chi^{0.3}$ is the local neutralino halo density in units of 0.3 GeV cm^{-3} and R is the distance to the galactic center. The integral $J(\Psi)$ is given by

$$J(\Psi) = \frac{1}{R\rho_0^2}\int_{\mathrm{line-of-sight}} \rho^2(\ell)d\ell(\Psi), \tag{3}$$

and is evidently very sensitive to local density variations along the line-of-sight path of integration.

We remind of the fact that since the neutralino velocities in the halo are of the order of 10^{-3} of the velocity of light, the annihilation can be considered to be at rest. The resulting gamma ray spectrum is a line at $E_\gamma = m_\chi$ of relative linewidth 10^{-3} which in favourable cases will stand out against background. The process $\chi\chi \rightarrow Z\gamma$ is treated analogously and has a similar rate [19].

To compute $J(\Psi)$, a model of the dark matter halo has to be chosen. Recently, N-body simulations have given a clue to the final halo profile obtained by hierarchical clustering in a CDM scenario [20]. It turns out that the universal halo profile found in these simulations has a rather significant enhancement $\propto 1/r$ near the halo centre. If applicable to the Milky Way, this would lead to a much enhanced annihilation rate towards the galactic centre, and also to a very characteristic angular dependence of the line signal. This would be very beneficial when discriminating against the galactic and extragalactic γ ray background, and Air Cherenkov Telescopes (ACTs) would be eminently suited to look for these signals, if the energy resolution is at the $10-20$ % level. However, both the N-body simulations and the observations of rotation curves of galaxies are controversial at the present time [3], so it is not possible to give solid predictions for the expected fluxes. Besides the steep profiles, or “cusps”, seen in the N-body simulations, there is also a noticeable tendency for substructure (dark matter “clumps”) to be formed. This would of course increase the expected signals even further, but again an exact quantitative treatment is lacking at present.

In Fig. 1., we show the gamma ray line flux given in a scan of supersymmetric models consistent with all experimental bounds, assuming an effective value of 10^3 for the average of $J(\Psi)$ over the 10^{-3} steradians that typically an Air Cherenkov Telescope (ACT) would cover.

It can be seen that the models which give the highest rates should be within reach of the new generation of ACTs presently being constructed. These will have an effective area of almost 10^5 m^2, a threshold of some tens of GeV and an energy resolution around 10 %. For low-mass models, the space-borne telescope GLAST may have a better sensitivity. (See [21] for details.)

Another possibility to detect dark matter in gamma-rays has recently been investigated [22], [23]. If N-body simulations of structure formation are taken seriously, it appears that the average enhancement of the integrated signal from all cosmic structure in the Universe would be several orders of magnitude compared to the case when the dark matter density only scales with the cosmic dilution factor $(1+z)^3$. The signature would be a continuum from neutralino annihilations plus a characteristic redshift-smeared line with a very rapid fall-off beyond the energy corresponding to the neutralino mass. As an example, in Fig. 2. from

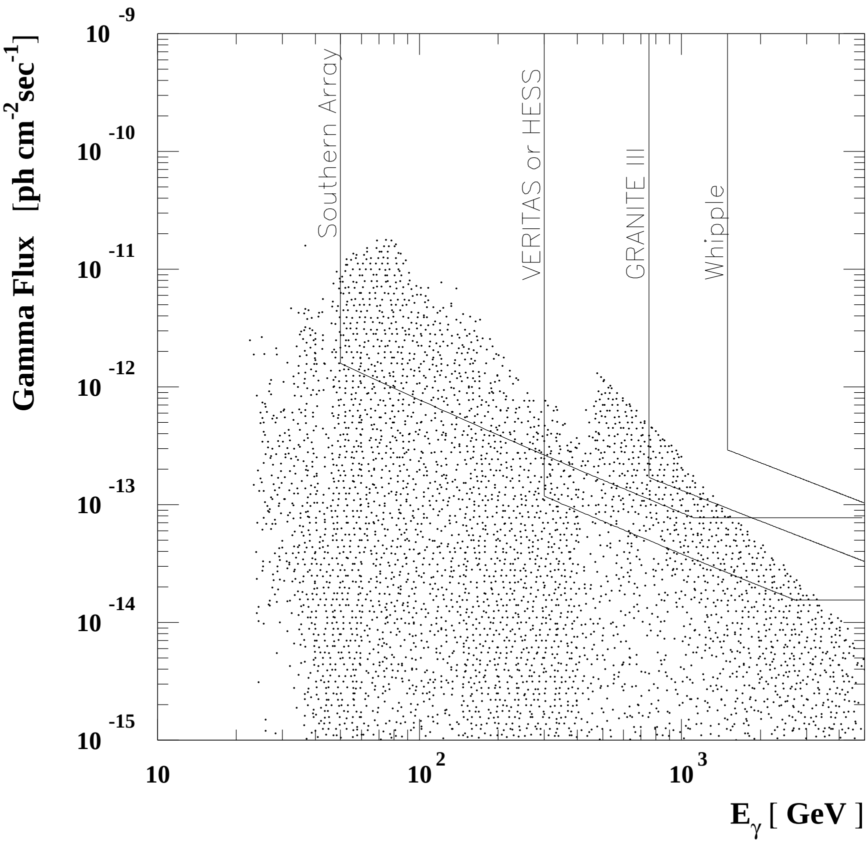

Fig. 1. Results for the gamma ray line flux in an extensive scan of supersymmetric parameter space in the MSSM [21]. Shown is the number of events versus photon energy in an Air Cherenkov Telescope of area $5 \cdot 10^4$ m^2 viewing the galactic centre for one year. The halo profile of [20] for the dark matter has been assumed.

[23], the expected diffuse gamma-ray signal predicted for GLAST in a couple of the high-rate MSSM models is shown.

Of course, the detection method we have been focusing on here, indirect detection through annihilation into gamma-rays, is only one of a number of different possibilities. The most convincing method would of course be the detection of a dark matter particle (e.g., the neutralino) in an accelerator experiment. One may also hope to detect dark matter particles directly as they scatter in terrestrial detectors. Recently, such detectors have reached a sensitivity where they start to skim the high-rate boundary of supersymmetric parameter space, and

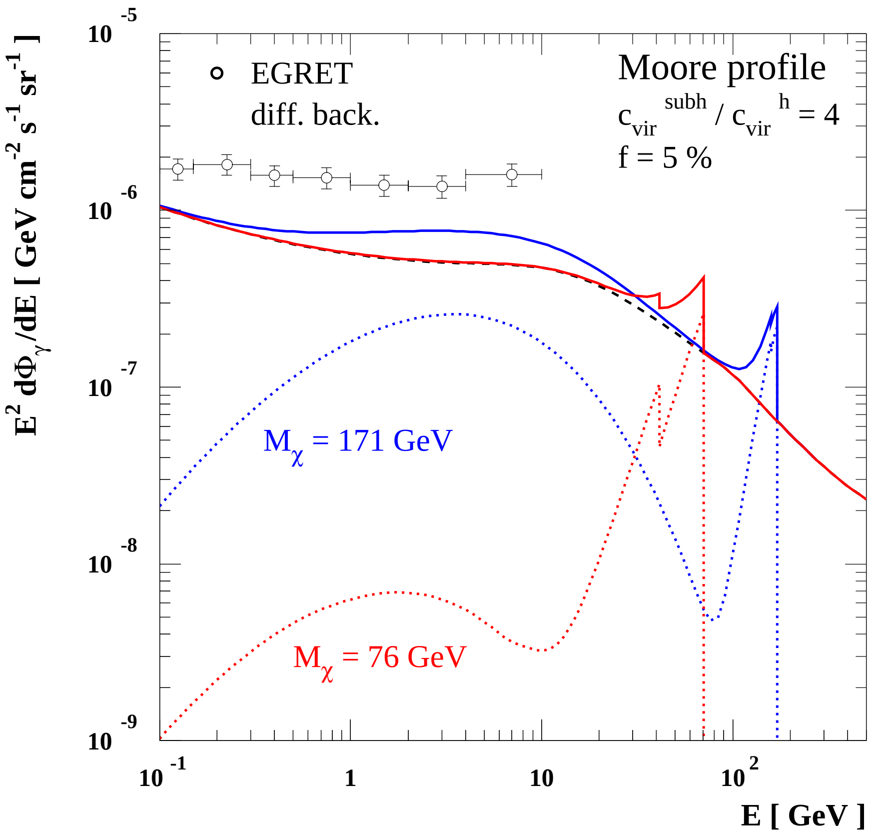

Fig. 2. Extragalactic gamma-ray flux (multiplied by E^2) for two sample thermal relic neutralinos in the MSSM (dotted curves), summed to the blazar background expected for GLAST (dashed curve). See [23] for details.

new detectors are being built which may push these limits a couple of magnitudes further.

If the scattering rate on heavy nuclei is large enough, dark matter particles may also be gravitationally trapped in the interior of the Sun or Earth, where they may annihilate into neutrinos which would be detectable in large neutrino telescopes.

Also, annihilation in the the halo giving antiprotons or positrons may yield a signature if the rate is above that expected from other sources, such as cosmic ray collisions with interstellar material.

Generally, all these rates depend in different ways on the supersymmetric parameters, so the best strategy seems to be to probe them all, with the hope that at least one method may eventually give a signal. Despite some preliminary indications of possible signals in some experiments, there is not yet consensus of any detection.

4. Non-supersymmetric candidates

The phenomenology of supersymmetric dark matter (neutralinos) may be very similar for other types of weakly interacting massive particles (WIMPs). However, one can also imagine models where the WIMP only couples to leptons. These leptonic WIMPs, or LIMPs, may at first seem essentially undetectable in present-day experiments. It may be shown, however, that in most cases they necessarily give energetic gamma rays in their annihilations, due to higher-order processes [24].

In Fig. 3. (a) we show the flux predicted for the continuum and line gamma-ray fluxes together with the estimated background towards the galactic center for a 100 GeV LIMP, and 110 GeV charged scalar S_2, Navarro-Frenk-White profile and angular acceptance $\Delta\Omega = 10^{-3}$, in the model explained in [6], [24]. For this energy range, we have used an energy resolution of 3% (GLAST). It may be difficult to push the N_R mass much below 100 GeV without fine tuning the parameters of this model (and the S_2 mass is also bounded by LEP results to be larger than around 100 GeV).

The natural mass range for the LIMP is around 1 - 10 TeV, where GLAST runs out of sensitivity but where ground-based arrays of Air Čerenkov Telescopes with large collecting area can detect a signal. Indeed, as we have heard at this Symposium, there are such arrays of telescopes planned or in operation such as CANGAROO, HESS, VERITAS and MAGIC. In particular, CANGAROO and HESS are well located to observe the galactic center for a sizable fraction of their observing time. As can be seen from the figure, the signal with these assumptions would stand out from the gamma-ray background. (We do not enter here into the more technical issue of rejecting other types of background, such as from hadrons and electrons, where there is a steady improvement in the techniques employed.)

In Fig. 3. (b) results are shown for a LIMP of mass $m_N = 8$ TeV and $m_{S_2} = 8.8$ TeV. These should be clearly observable with a very conspicuous "bump" in the spectrum, for the halo parameters chosen. We note with interest that preliminary results from the CANGAROO collaboration indeed show an excess flux of TeV gamma-rays from the galactic center [25]. The absolute flux level for this possible signal seems higher than that predicted here, so an enhancement beyond that provided by the NFW profile would then be indicated.

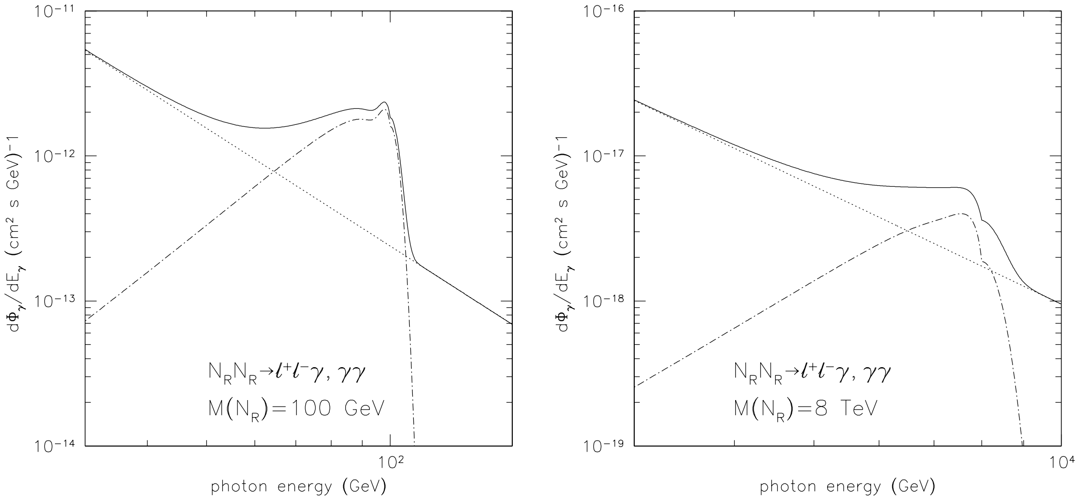

Fig. 3. (a) The total gamma-ray flux expected from a $\Delta\Omega = 10^{-3}$ sr cone around the galactic center (solid line). The flux is composed by a power-law background extrapolated from EGRET data (dotted line) and a 100 GeV LIMP annihilating with a cusped (NFW) density profile through a 110 GeV scalar S_2, giving both a continuous spectrum and a 2γ line. An energy resolution of 3% has been assumed for the line signal. (b) Same as (a) for an 8 TeV LIMP, $m_{S_2} = 8.8$ TeV. Here the line has been smeared by an assumed energy resolution of 5%.

5. Conclusions

To conclude, non-baryonic dark matter seems to be needed more than ever to explain new cosmological data, in particular the recent high-precision measurements of the microwave background. The fact that the favoured value of Ω_M has gone down from near 1 to around 0.3 is good news for detection, since larger cross sections generally means lower relic density. In particular this is true for the main particle physics candidate, the neutralino, which we have presented in some detail here. Indirect detection methods have the potential to be very useful complements to direct detection of supersymmetric dark matter candidates. In particular, new gamma-ray telescopes may have the sensitivity to rule out or confirm the supersymmetry solution of the dark matter problem. If the dark matter particle is leptonic in nature, gamma-rays may provide the only window of opportunity for detecting them.

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