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The γ -ray line signature of the elusive neutrino

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Abstract

A heavy triplet neutrino may still solve the astronomical missing mass conundrum provided its mass lies in the range between 30 and 80 GeV. If present in the halo of our galaxy, this Majorana neutrino annihilates into monochromatic photons. We show that the resulting γ -ray line signal is well above the diffuse galactic background, due to a fairly large value of the relevant annihilation cross-section. A $1 \text{ m}^2 \text{ sr}$ effective area gamma-ray detector of the ASTROGAM caliber should accumulate ~ 35 high energy photons on a year period, to be compared with a background noise of 3 to 6 photons for a 5% energy resolution. We strongly urge high energy astrophysicists to explore the γ -ray sky up to energies $\sim 100 \text{ GeV}$. Should such an intense γ -ray line be discovered, the dark matter mystery would be unravelled.

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1 - Introduction.

A significant fraction of the mass of the Universe is invisible and its nature is still unsolved [1]. This dark matter may be made of brown dwarves or jupiters pervading the halos of galaxies. Observations of stellar micro-lensing events in the Large Magellanic Cloud [2] will test that hypothesis. Another fascinating option rests on the existence of exotic particles. Measurements of the total decay width of the Z^0 boson [3] point toward the existence of only three light neutrino families [4] so that the standard model looks distressingly valid. As a matter of fact, experiments at the Large Electron Positron storage ring, LEP, at CERN, supplemented by unavailing direct searches using germanium detectors [5] have excluded heavy Dirac or Majorana neutrinos of a hypothetical fourth generation as plausible dark matter candidates [6]. Finally, supersymmetry starts to be fairly contrived by the LEP bound on the chargino mass and the UA2 and CDF limits on the gluino mass [7] even if the lightest supersymmetric particle is still a viable dark matter candidate.

A heavy neutral species embedded inside a gauge triplet has recently been suggested [8] as a plausible dark matter candidate. Such a possibility implies the modest admixture to the standard model of an $SU(2) \times U(1)$ triplet of fermions, namely (E^+, N, E^-) , with hypercharge $Y_T = 0$. At the tree level, the neutral partner N couples only to its charged companion $E^\pm$ through W^{++} boson exchange. The species N cannot be produced directly in pairs by the decay of the Z^0 boson and is therefore invisible at LEP. The mass degeneracy between N and $E^\pm$, implied by gauge symmetry, may be lifted if an additional family of Higgs scalars with gauge triplet structure acquires a vacuum expectation value. It can be shown that the subsequent mass shift $Q_{EN} = m_E - m_N$ remains small. The behaviour of the elusive neutrino species N during the early stages of the Universe is cosmologically relevant. Should $E^\pm$ be slightly heavier than N , the latter would be stable and would provide a plausible solution to the long-standing dark matter conundrum, since its fossil abundance, $\Omega_N h^2$, would naturally be close to 1. The interesting mass range for m_N lies between 30 and 80 GeV. Below 30 GeV, $E^\pm$ should have been already detected at LEP. Above 80 GeV, N may directly annihilate into W^+W^- pairs so that the delicate interplay between N and $E^\pm$, which is the keystone of the cosmological behaviour of these species as explained in [8], does no longer take place.

If N cannot be directly detected at accelerators, its charged partner $E^\pm$ should not escape detection at LEP as soon as the beam energy is cranked up to ~ 100 GeV (LEP II). In this letter, we explore another potential signature of the triplet neutralino hypothesis. Should the species N pervade the galactic halo, its direct annihilation into two

photons, i.e., $NN \rightarrow \gamma\gamma$, [9, 10, 11] would be observable by the next generation of γ -ray observatories. Since the particles N are at rest with galactic velocity $v \sim 300$ km/s, the resulting photons are nearly monochromatic with energy $E_\gamma \simeq m_N$. The associated γ -ray line should be fairly narrow and therefore much easier to detect than a diffuse signal, provided that line is not swamped in the background. In Section 2, we derive the magnitude of the γ -ray line signal as a function of the annihilation cross-section $\sigma_{2,\gamma} v$. We also briefly discuss the background to the γ -ray line signal. Section 3 is devoted to an analysis of the annihilation process $NN \rightarrow \gamma\gamma$. Since gauge couplings are significantly larger for triplet species than for doublet particles, we find that the associated cross-section $\sigma_{2,\gamma} v$ is significantly larger than for standard neutrinos or photinos. We therefore conclude, in Section 4, that the resulting γ -ray line signal is well above background. We finally discuss the prospects for detecting such a line with the next generation of ASTROGAM caliber γ -ray telescopes.

2 - The annihilation γ -ray line signal and its background.

We assume that the dark matter halo of our Galaxy is nearly spherical and nearly isothermal. The dark matter density varies therefore with galacto-centric distance r as

$$\rho(r) = \rho_0 \frac{a^2 + r_0^2}{a^2 + r^2}, \quad (1)$$

where ρ_0 is the dark matter density in the solar neighbourhood and a is the core radius [12]. We consider the annihilation process $NN \rightarrow \gamma\gamma$, whose cross-section $\sigma_{2,\gamma} v$ will be computed in the next Section. The mass of the dark matter particles N ranges from ~ 30 GeV to 80 GeV, whereas their mean velocity in the halo is $v/c \sim 10^{-3}$. The energy E_γ of the outgoing γ 's is therefore practically equal to the particle mass m_N . The number of photons received at a detector in the solar system, from pair annihilations taking place at a distance R and in the direction defined by galactic latitude b and longitude l is [13]

$$F_N = \frac{\sigma_{2,\gamma} v}{4\pi} \int_0^\infty \left[\frac{\rho(R, b, l)}{m_N} \right]^2 dR \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (2)$$

when summed over the distance R . This expression may be computed analytically and at high galactic latitudes ($b \sim 90^\circ$) - for which the galactic diffuse background is expected to be the faintest - the flux reduces to

$$F_N \sim \frac{\sigma_{2,\gamma} v}{16} \left(\frac{\rho_0}{m_N} \right)^2 a \sqrt{1 + \Lambda^2}, \quad (3)$$

where A denotes the ratio r_0/a . As an illustration, we consider $\rho_0 = 0.45 \text{ GeV cm}^{-3}$ and $a \sim r_0 \sim 8 \text{ kpc}$ [12]. As shown hereafter, a mass $m_N = 30 \text{ GeV}$ implies a typical value of $\sigma_{\gamma\gamma} v \sim 2.3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ for the γ -ray pair annihilation cross-section. A detector of $1 \text{ m}^2 \text{ sr}$ effective area, such as ASTROGAM or IIR-GRAF [14], will therefore collect $N_{\text{line}} \simeq 35$ photons of energy $E_\gamma = 30 \text{ GeV}$ per year.

There is no measurement of γ -ray fluxes in the GeV-TeV energy range, so we must extrapolate from lower energy data. There are many different sources of background γ photons. The γ 's from the decay of π^0 's produced by collisions of cosmic ray protons with the interstellar medium are probably the dominant source of galactic background at energies larger than 1 GeV [15]. Bremsstrahlung γ 's from cosmic ray electrons should be negligible above 1 GeV as well as the inverse Compton emission resulting from the interaction between ultra-relativistic electrons and the electromagnetic field of the galaxy. From the known distribution of cosmic ray protons, one expects a flux [16]

$$\frac{dN_{\text{galactic}}}{dE_\gamma} \sim 8 \times 10^{-7} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-(1-2.7 \pm 0.3)} \quad (4)$$

at high galactic latitudes, and a correspondingly larger flux in the galactic plane.

The extra-galactic background is not well known, and different analyses do not agree on the extrapolation of COS-B and SAS-2 measurements to energies larger than 1 GeV [17]. Since it drops sharply above 1 GeV , we do not consider it any further [18].

Since N does not couple directly to the Z^0 boson, its direct annihilation into fermion-antifermion pairs is strongly suppressed. Such a process may still be mediated via a one-loop diagram involving W bosons, but the corresponding cross-section is small. Furthermore, the γ -rays which eventually arise from the subsequent $f\bar{f}$ decays and annihilations have an energy lower than m_N (for trivial kinematical reasons), and do not contribute to the line background. To summarize, we take Eq. 4 as representing the background.

3 - The $NN \rightarrow \gamma\gamma$ annihilation cross-section.

The gauge interactions of the neutral particle N and its charged partner E are described by the Lagrangian

$$\mathcal{L} = g \sin \alpha W_\mu^- \bar{E} \gamma^\mu N + h.c. - e A_\mu \bar{E} \gamma^\mu E - e \cot \theta_W Z_\mu^0 \bar{E} \gamma^\mu E. \quad (5)$$

Note that those gauge couplings are vector-like and conserve parity. Since they correspond to a gauge triplet with vanishing hypercharge, the neutral Majorana N does not couple to the Z^0 boson. Gauge symmetry implies that N and E have the same mass. In order

to lift that degeneracy, the triplet species may be mixed with a singlet fermion or with an additional triplet family. The corresponding mixing angle is generically denoted by α .

The leading diagram responsible for the annihilation reaction $NN \rightarrow \gamma\gamma$ is shown in Figure 1. Additional processes involving two or more W boson propagators as well as W - W - γ vertices will be hereafter disregarded. For $m_N < m_W$, those contributions have been shown to be negligible in the case of the two-photon annihilation of photino pairs [19], where scalar fermions play the role of the W . As long as the neutralino mass m_N does not exceed m_W , the entire series of box diagrams responsible for the two-photon annihilation reaction merely reduces to the loop process of Figure 1 where the W propagator has been pinched.

After the E and N fields are exchanged by Fiertz transformation, the two-photon annihilation amplitude reduces to ;

$$\mathcal{M}(NN \rightarrow \gamma\gamma) = e^2 g^2 \frac{\sin^2 \alpha}{m_W^2} \sum_i C_i J_T \mathcal{L}(\Gamma), \quad (6)$$

where the sum runs, a priori, over the scalar ($\Gamma = 1$), pseudoscalar ($\Gamma = \gamma_5$), vector ($\Gamma = \gamma^\mu$) and axial ($\Gamma = \gamma^\mu \gamma_5$) effective point-like couplings between the triplet fermions. As a result of the above-mentioned Fiertz transformation, the coefficients C_i may be expressed as

$$C_S : C_P : C_V : C_A = 1 : -1 : -1/2 : -1/2. \quad (7)$$

The Majorana current J_T is defined by

$$J_T = < 0 | \bar{N} T N | P_1, P_2 >, \quad (8)$$

where the initial state $|P_1, P_2 >$ refers to the momenta P_1 and P_2 of the annihilating particles N . Note that Majoranas do not have vector couplings, i.e., $\bar{N} \gamma^\mu N = 0$, so that J_V vanishes whilst, for the other currents, $J_T = 2 \bar{V}(2) \Gamma U(1)$. Since the W propagator is pinched, the box diagram of Figure 1 reduces to the one-loop process detailed in Figure 2 where the species E mediates the neutralino pair annihilation through its coupling Γ to the Majorana current J_T . Since E is charged, it also couples to photons so that the loops of Figure 2 contribute a factor

$$\mathcal{L}(\Gamma) = \mathcal{L}_{\mu\nu}(\Gamma) \epsilon_1^\mu \epsilon_2^\nu, \quad (9)$$

to the global amplitude, where the tensor

$$\mathcal{L}_{\mu\nu}(\Gamma) = \int \frac{d^4 q}{(2\pi)^4} \text{Tr} \left\{ \Gamma \frac{1}{\not{q} - \not{k}_2 - m_E} \gamma_\nu \frac{1}{\not{q} - m_E} \gamma_\mu \frac{1}{\not{q} + \not{k}_1 - m_E} \right\} + (k_1, \mu) \leftrightarrow (k_2, \nu) \quad (10)$$

is contracted with the polarizations ϵ_1^μ and ϵ_2^ν of the final photons. According to Furry's theorem, $\mathcal{L}(\gamma^\mu)$ vanishes whilst, for the other contributions, both loops in Figure 2 contribute equally

$$\begin{aligned}\mathcal{L}^{\mu\nu}(1) &= \frac{im_E}{2\pi^2} \{ \mathcal{D}_S g^{\mu\nu} + (I_{00} - 4I_{11}) k_2^\mu k_1^\nu + (4I_{00} - I_{00} - 4I_{11}) k_1^\mu k_2^\nu \} \\ \mathcal{L}^{\mu\nu}(\gamma_5) &= \frac{m_E}{2\pi^2} I_{00} \epsilon^{\alpha\beta\mu\nu} k_{1\alpha} k_{2\beta} \\ \mathcal{L}^{\mu\nu}(\gamma^\rho \gamma_5) &= \frac{1}{\pi^2} \{ \mathcal{D}_A \epsilon^{\alpha\nu\mu\rho} (k_1 - k_2)_\alpha \\ &\quad + k_{1\alpha} k_{2\beta} (I_{00} - I_{02}) (\epsilon^{\alpha\beta\mu\nu} k_1^\mu - \epsilon^{\alpha\beta\mu\nu} k_2^\mu) + k_{1\alpha} k_{2\beta} I_{11} (\epsilon^{\alpha\beta\mu\nu} k_2^\mu - \epsilon^{\alpha\beta\mu\nu} k_1^\mu) \}.\end{aligned}\quad (11)$$

The Feynman integral I_{ab} is defined as

$$I_{ab} = I_{ba} = \int_0^1 dx \int_0^{1-x} dy \frac{x^a y^b}{2xy k_1 \cdot k_2 - m_E^2}.\quad (12)$$

The divergent parts $\mathcal{D}_S$ and $\mathcal{D}_A$ are removed by imposing gauge invariance upon the global amplitude of the process

$$\sum_i G_i J_i \mathcal{L}_{\mu\nu}(\Gamma) k_1^\mu = \sum_i G_i J_i \mathcal{L}_{\mu\nu}(\Gamma) k_2^\nu = 0.\quad (13)$$

These coefficients may be expressed as a function of the photon momenta k_1 and k_2

$$\begin{aligned}\mathcal{D}_S &= (4I_{11} - I_{00}) (k_1 \cdot k_2) \\ \text{whilst} \\ \mathcal{D}_A &= I_{11} (k_1 \cdot k_2).\end{aligned}\quad (14)$$

The resulting expressions for $\mathcal{L}_{\mu\nu}(\Gamma)$ are in agreement with the corresponding formulae which Giudice and Griest [10] obtain in their appendix A5 except, however, for an overall factor of $-1/(k_1 \cdot k_2)$ in the case of the axial vector and pseudoscalar contributions.

The annihilation cross-section may be readily expressed as

$$\sigma_{2,\gamma} v = \frac{32}{\pi^3} \sin^4 \alpha G_F^2 \alpha_{em}^2 m_N^2 I^2 \left(\frac{m_E}{2m_N} \right),\quad (15)$$

where $\alpha_{em} = 1/137$ is the electromagnetic fine structure constant, G_F is the Fermi constant and the integral I is defined as

$$I(a) = \int_0^1 dx \int_0^{1-x} dy \frac{xy - a}{xy - a^2}.\quad (16)$$

The particles E and N are nearly degenerate in mass so that for $a \simeq 1/2$, the integral I boils down to $I(1/2) \simeq 1/2 + \pi^2/8$. Note that the two-photon annihilation cross-section increases with neutrino mass as m_N^2

$$\sigma_{2,\gamma} v \simeq 2.6 \times 10^{-31} \text{ cm}^3 \text{ s}^{-1} \sin^4 \alpha \left(\frac{m_N}{1 \text{ GeV}} \right)^2.\quad (17)$$

Comparison between doublet and triplet neutrinos illustrates how important gauge couplings may be, since the annihilation cross-section for N is $144 \times I^2(1/2) \simeq 400$ times larger than for the doublet species [11].

4 - Discussion.

The mass m_N of the zero-isospin neutrino N gracefully cancels out from expressions (3) and (17). The flux F_N of monochromatic photons with energy $E_\gamma = m_N$ due to neutrino N annihilation in the galactic halo does *not* depend therefore on the mass of the species. For galactocentric distance $r_\odot = 8.5$ kpc, core radius $a = 7$ kpc and dark matter density $\rho_\odot = 0.45 \text{ GeV cm}^{-3}$ in the solar vicinity, we infer a γ -ray line flux

$$F_N \simeq 1.1 \times 10^{-10} \sin^4 \alpha \text{ photons cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1},\quad (18)$$

independent of m_N .

The next generation of satellite- or space-station-borne γ -ray detectors [14] should have an effective aperture of $\sim 1 \text{ m}^2 \text{ sr}$ and should collect data for a year. Figure 3 displays the γ -ray spectrum obtained by such an instrument for $m_N = 50 \text{ GeV}$, $\sin \alpha = 1$ and a 5% energy resolution. With ~ 35 photons, the line clearly shows up with respect to the background. The latter merely provides ~ 16 photons in the same energy bin as the line which, therefore, is detectable at the 9σ level. Note that a good energy resolution is of paramount importance for the detection of the annihilation line. Should the energy resolution be 50% instead of 5%, the signal of Figure 3 would be visible at the 3σ level only.

In Figure 4, the expected signal S (solid), the corresponding background B (short dashed), i.e., the number of background photons collected in the same energy bin as the γ -ray line, and the background noise $\sqrt{B}$ (dotted - short dashed) are displayed as a function of the line energy $E_\gamma = m_N$, for $\sin \alpha = 1$. The signal only depends on the mixing angle α

$$S \simeq 35 \sin^4 \alpha \text{ photons},\quad (19)$$

whilst the corresponding background (or the noise) decreases as $E_\gamma^{-1.740.3}$ (or $E_\gamma^{-0.8840.15}$). As shown clearly in Figure 4, for a 5% energy resolution, the signal is always well above

background and detection of the annihilation γ -ray line should be achieved at the 6σ level for a 30 GeV neutralino, reaching up to the 12σ level for $m_{\tilde{N}} = 80$ GeV.

Note that $\sin\alpha$ may be less than 1. In order to lift the mass degeneracy between N and $\tilde{E}$, mixing between triplet species and, say, an additional singlet, may be required. Assuming the same mass for the triplet and singlet particles [8], the mass degeneracy between the neutral and charged species may be lifted if an additional family of Higgs bosons, embedded inside a gauge triplet, acquires a non-vanishing vacuum expectation value. The resulting off-diagonal term in the mass matrix implies full mixing between the triplet and singlet neutralinos, *i.e.*, the mixing angle $\alpha = \pi/4$, so that the magnitude of the γ -ray line is suppressed by a factor of 4.

More generally, the solid curve S of Figure 4 should be shifted downwards by a factor $\sin^4\alpha$ so that a better energy resolution must be achieved in order to disentangle the annihilation line from the background. A γ -ray telescope with energy resolution $\mathcal{R}$ should collect a signal with

$$\frac{\text{Signal}}{\text{Noise}} \simeq 4 \sin^4\alpha \left(\frac{E_{\text{line}}}{30 \text{ GeV}} \right)^{0.85 \pm 0.15} \left(\frac{10\%}{\mathcal{R}} \right)^{0.5} \quad (20)$$

The complete mixing between the triplet and singlet species of [8] implies that a 30 GeV neutralino is detectable at the 3σ level provided the energy resolution does not exceed 1% whilst, for a 80 GeV neutralino, 6% is enough. Finally, since the γ -ray detector should collect at the very least one signal photon, any mixing angle α for which $\sin\alpha < 0.4$ is unreachable with the next generation of γ -ray telescopes. As a matter of fact, since a 1% energy resolution is extremely hard to achieve, the lower bound on the mixing angle below which the annihilation line detection is no longer possible, is $\sin\alpha \sim 0.53$ (resp. 0.43) for a 30 GeV (resp. 80 GeV) neutralino.

The galactic halo has been assumed to be homogeneous. This uniformity of the dark matter distribution may be questioned. According to the CDM scenario of galaxy formation, if the density fluctuation spectrum $\delta\rho/\rho$ is almost flat on sub-galactic scales, it nevertheless departs from complete flatness so that small scales become non-linear before larger scales start to collapse. If these small clumps become self-gravitating much earlier than the entire galactic halo in which they are embedded, they are likely to survive tidal disruption. As suggested in [20], a fraction $f_{\text{clump}} \sim 1\%$ of the galactic halo should be condensed in clumps with typical mass $\sim 10^8 M_\odot$ and typical density $\rho_{\text{clump}} \sim 10^3 \rho_{\text{halo}}$. The annihilation γ -ray line produced in these substructures is, on average, $10^3 \times f_{\text{clump}} \sim 10$ times larger than the flux from the homogeneous component. If clumpiness holds, the line signal S is enhanced by an order of magnitude with respect to the predictions of Figure 4, whatever the direction of the line of sight.

Even more exciting is the possible presence of a clump near the solar system. If halo CDM clusters on a typical scale $M_{\text{clump}} \sim 10^8 M_\odot$, the probability for a clump to be at distance d from the earth is unity for

$$d \sim 10^4 \text{ pc} \left(\frac{M_{\text{clump}}}{10^8 M_\odot} \right)^{1/3} \left(\frac{0.01}{f_{\text{clump}}} \right)^{1/3} \quad (21)$$

Since their typical radius is

$$< r_{\text{clump}} > \sim 130 \text{ pc} \left(\frac{M_{\text{clump}}}{10^8 M_\odot} \right)^{1/3}, \quad (22)$$

the angular extension in the sky of nearby clumps is

$$\theta \sim 1.5^\circ \left(\frac{f_{\text{clump}}}{0.01} \right)^{1/3}, \quad (23)$$

independent of their mass. Subsequently, a typical $10^8 M_\odot$ clump in the solar neighbourhood subtending a $1^\circ \times 1^\circ$ solid angle, would contribute each year $\sim 10^5$ photons to the annihilation line signal collected by an ASTROGAM caliber instrument. A γ -ray telescope with a 1° angular resolution could therefore detect nearby clumps, even if they hide at fairly low galactic latitudes where the background is expected to increase significantly.

Should heavy triplet neutralinos pervade the galactic halo, they would not escape detection by the next generation of γ -ray telescopes. Direct annihilation of these neutralinos into photon pairs generates a strong line signal which stands well above background (see Figure 3). A variety of models may be explored down to a mixing angle $\sin\alpha \sim 0.4 - 0.5$. Finally, detection of strong γ -ray line sources at various galactic latitudes would be of considerable interest and would signal the presence of exotic matter concentrations inside the galactic halo.

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Figure captions

Figure 1 : Leading diagram for the annihilation $NN \rightarrow \gamma\gamma$. The generic mixing angle between the neutral N and charged E species of the gauge triplet, is denoted by α .

Figure 2 : When the W propagator is pinched, diagram 1 merely reduces, after a Fierz transformation upon E and N , to a set of loops which is denoted by $\mathcal{L}(\Gamma)$, where Γ is a Dirac matrix.

Figure 3 : After an entire year of observation, a $1 \text{ m}^2 \text{ sr}$ γ -ray telescope, with a 5% energy resolution, would collect this photon spectrum in the case of a 50 GeV neutrino N pervading the galactic halo. For $\sin\alpha = 1$, the annihilation line stands well above background. The galactocentric distance is set equal to $r_\odot = 8.5 \text{ kpc}$ whilst the dark matter halo has core radius $a = 7 \text{ kpc}$ and density $\rho_\odot = 0.45 \text{ GeV cm}^{-3}$ in the solar neighbourhood.

Figure 4 : Expected signal (S), background (B) and noise for non-energetic γ -rays due to pair annihilation of triplet neutrinos N in the halo of our galaxy. The full line displays the total number of annihilation γ 's received for an entire year of exposure on a detector with a $1 \text{ m}^2 \text{ sr}$ detector surface and a 5% energy resolution. The short dashed line corresponds to the number of background photons collected in the same energy bin as the annihilation line, while the dotted - short dashed curve indicates the background noise.

Fig. 1

Fig. 2

Figure 4

Figure 3