Indirect detection of unstable heavy dark matter

PAOLO GONDOLO

Department of Radiation Sciences, Uppsala University,
P.O. Box 535, 75121 Uppsala, Sweden

ABSTRACT

Unstable relics with lifetime longer than the age of the Universe could be the dark matter today. Electrons, photons and neutrinos are a natural outcome of their decay and could be searched for in cosmic rays and in γ-ray and neutrino detectors. I compare the sensitivities of these three types of searches to the mass and lifetime of a generic unstable particle. I show that if the relics constitute our galactic halo and their branching ratios into electron-positrons, photons and neutrinos are comparable, neutrino searches would probe the longest lifetimes for masses $\gtrsim 40$ TeV, while electron-positron searches would be better but more uncertain for lighter particles. If instead the relics are not clustered in our halo, neutrinos are more sensitive a probe than γ-rays for masses $\gtrsim 700$ GeV. A 1 km$^2$ neutrino telescope should be able to explore lifetimes up to $\sim 10^{30}$ s while searching for neutrinos from unstable particles above the atmospheric background.
1. Introduction

Popular elementary particle candidates for cold dark matter (e.g. neutrinos, cosmions and sneutrinos) have been ruled out or severely constrained by the SLC and LEP measurements of the $Z$ decay width combined with the non-observation of a signal in direct and indirect dark matter searches, in low-background germanium detectors and proton-decay experiments respectively (see e.g. ref. [1]).

It is so natural that alternative possibilities for non-baryonic cold dark matter are being (re)explored. Here I consider a class of unstable dark matter candidates that are heavy and long-lived, decaying on cosmological time scales. Many particles of this sort have been already proposed before the above-mentioned experimental results for various reasons.

Massive long-lived particles with a substantial relic density may arise in technicolor models, which are an interesting alternative to the standard Higgs mechanism for spontaneous $SU(2) \times U(1)$ symmetry breaking. It was pointed out in ref. [2] that the lightest technibaryon, which likely has mass $m \sim$ TeV and lifetime $10^{27-32}$ s could account for the missing mass if there is a technibaryon-antitechnibaryon asymmetry comparable to the baryon-antibaryon asymmetry. Non-perturbative fermion-number violating processes in the Standard Model could generate such an asymmetry in a natural way [3].

Motivated by a preliminary report of an anomalous high energy (> 10 GeV) positron component in cosmic rays which is unlikely to be generated by spallation processes, new massive long-lived particles have been proposed as dark matter candidates. It has been suggested that the excess positrons come from the decay of $\sim$ 30 GeV right-handed neutrinos with lifetime $\sim 10^{25}$ s [4] or from 1-3 TeV GUT particles with lifetime $\sim 10^{24}$ s [5].

The ‘lightest supersymmetric particle’ can be unstable and long-lived in supersymmetric models with very weak R-parity breaking. A decaying gravitino of mass $\sim$ 100 GeV [6] and a neutralino-neutrino mixed state of mass 10–50 GeV [7],
both with any lifetime longer than $\sim 10^{17}$ s, have been examined in a cosmological context.

As a final example, a simple solution via confinement [8] to the problem of fractional charges in models derived from the superstring [9] results in several integer-charged composite particles, named ‘cryptons’ [10], some of which could be long-lived with lifetimes as long as $10^{23}$ s and masses $\sim 10^{12}$ GeV and could, in principle, constitute the dark matter [11]. Their expected relic density is however very uncertain since it depends on the amount of entropy released in the decays of short-lived cryptons (and other particles) after the long-lived cryptons go out of chemical equilibrium.

It is therefore interesting to examine long-lived heavy particles, with masses $\gtrsim$ GeV and lifetimes $\gtrsim 10^{17}$ s, as dark matter candidates. At present, it seems appropriate to study such weakly unstable massive particles (WUMPs) in a model-independent way.

In general, a WUMP $x$ is characterized by its mass $m_x$, its lifetime $\tau_x$ and its branching fractions $b_y$ into different decay channels $y$. I focus here on WUMPs which constitute the dark matter today and I consider two classes of WUMP distributions: a uniform mass distribution throughout the Universe with critical value $\rho_c = 10.5$ keV cm$^{-3} h^2$ (unclustered WUMPs) and an inhomogeneous distribution with WUMPs clustered in our galactic halo with mass density $\rho_\odot = 0.3$ GeV cm$^{-3}$ in the solar neighborhood (clustered WUMPs). Other values of the relic WUMP density have been considered in refs. [11,12]. As usual, $h$ is the Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$.

Of the WUMP decay products, I consider here neutrinos, electrons and photons, which may give origin to diffuse extraterrestrial fluxes. In the following, I examine the range of WUMP masses and lifetimes that could be explored by background- and flux-limited detectors searching for such indirect signals from unstable dark matter particles.

* I adopt the terminology of ref. [4].
2. Diffuse photon, electron-positron and neutrino fluxes

Branching ratios and energies of the decay products, and even the nature of the decay products, depend of course on the particular model for the decaying dark matter. For the sake of definiteness, I imagine that WUMPs undergo 3-body decays, in which one (or more) decay product(s) is a photon, an electron, a positron or a neutrino, and acquires a typical energy $E_0 = m_x/3$. Furthermore, when comparing sensitivities to signals of different origin, I take all branching ratios $b_y$ to be equal, in particular I use $b_y = 1$ when stating limits on the lifetime $\tau_x$. All results can be trivially rescaled to the values appropriate to a specific model. More complicated generation scenarios, e.g. secondary products or jets, can also be easily incorporated by including the decay product multiplicity and possible continuous energy spectra in an energy dependent $b_y$.

The maximum WUMP lifetime explorable by background-limited detectors is obtain as a function of the WUMP mass by imposing that the electron-positron, photon and neutrino fluxes from WUMP decays be smaller than the respective backgrounds. I separately discuss now the three cases of decay photons, electron-positrons and neutrinos. I will use $t_0 = 10^{10}$ yr and $h = 1$.

2.1 Photons

The photon flux expected from uniformly distributed decaying dark matter is a superposition of the photon spectra generated in decays occurring at different times. The resulting present day flux $I_\gamma(E)$ can be written as an integral over the redshift $1 + z = E'/E$ of the photon spectrum per decaying particle $S_\gamma(E)$:

$$I_\gamma(E) = \frac{3}{8\pi} \frac{\rho c t_0}{m_x \tau_x} E^{1/2} \int_E^\infty \frac{dE'}{E'^{3/2}} S_\gamma(E').$$

(1)

(This equation is obtained for a matter-dominated universe and for $\tau_x \gg t_0$.)
For WUMPs clustered in the galactic halo no integration over redshift is necessary and the decay photon flux is given by

$$I_\gamma(E) = \frac{1}{4\pi} \frac{1}{m_x \tau_x} \int \frac{\rho_h(x)}{|x - x_\odot|^2} d^3x S_\gamma(E),$$

where $x_\odot$ denotes the position of the solar system and $\rho_h(x)$ is the WUMP distribution in the halo. If the dark matter distribution is taken to be

$$\rho_h(x) = \frac{2\rho_\odot}{1 + (r/a)^2},$$

the integral in eq. (2) evaluates to $31.0a\rho_\odot$ and for $\rho_\odot = 0.3$ GeV cm$^{-3}$ and $a_\odot = 8$ kpc, it is $\simeq 2.3\rho_c t_0$.

Two cases arise for the source function $S_\gamma(E)$ according to the energy of the primary decay photon $E_0$. If it is energetic enough to produce $e^+e^-$ pairs in collisions against the microwave photons, it can trigger electromagnetic cascades. Otherwise it is able to propagate to us without cascading. In the latter case, the source spectrum can be approximated by a line

$$S_\gamma(E) \simeq b_\gamma \delta(E - E_0).$$

The cascading case is more complicated. The electromagnetic cascade develops until the energies of the photons have fallen below the pair production threshold $E_{\text{max}}$. For a blackbody target this is given by [13]

$$E_{\text{max}} \simeq \frac{m_e^2}{20.4T \left[ 1 + \frac{1}{2} \ln \left( \frac{\eta}{7 \times 10^{-10}} \right)^2 + \frac{1}{2} \ln \left( \frac{E_{\text{max}}}{m_e} \right)^2 \right]},$$

where $m_e$ is the electron mass, $T$ is the blackbody temperature and $\eta$ is the baryon to photon ratio, which for simplicity I take to be just $7 \times 10^{-10}$. At the present epoch, $E_{\text{max}}(t_0) \simeq 3.4 \times 10^{12}$ eV and cascades can be generated if the WUMP
mass \( m_x \gtrsim m_{\text{crit}} \simeq 10^{13} \text{eV} \). The spectrum of the ‘breakout’ photons below the pair-production threshold falls as \( \sim E^{-1.5} \) until \( \sim 0.04E_{\text{max}} \) and then steepens to \( \sim E^{-1.8} \) before being cutoff at \( E_{\text{max}} \) \[14\]. With the normalization \( \int dE E S_\gamma(E) = E_0 \), the source spectrum per decaying WUMP with \( m_x \gtrsim 3E_{\text{max}} \) is

\[
S_\gamma(E) \sim \begin{cases} 
\frac{3}{4} b_\gamma E_0 E_{\text{max}}^{-1/2} E^{-3/2}, & \text{for } 0 \leq E \leq 0.04E_{\text{max}}, \\
\frac{3}{10} b_\gamma E_0 E_{\text{max}}^{-0.2} E^{-1.8}, & \text{for } 0.04E_{\text{max}} \leq E \leq E_{\text{max}}, \\
0, & \text{for } E \geq E_{\text{max}}.
\end{cases}
\]

The source functions (4) and (6) can then be inserted in eqs. (1) and (2) and the resulting photon fluxes can be compared with the diffuse background \( \gamma \) flux, which at \( E > 3 \text{ MeV} \) I approximate as (see ref. \[15\])

\[
I^\text{bkgd}_\gamma \lesssim 2 \times 10^{-3} \left( \frac{3 \text{ MeV}}{E} \right)^2 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{MeV}.
\]

I assume a detector with 10% energy resolution to smear the delta function occurring in the decay neutrino flux from non-cascading clustered WUMPs.

The maximum WUMP lifetimes accessible to \( \gamma \)-ray astronomy turn then out to be

\[
\tau_x \gtrsim \begin{cases} 
1.73 \times 10^{25} b_\gamma \text{ s}, & \text{for } m_x < m_{\text{crit}}, \\
1.46 \times 10^{24} b_\gamma \text{ s}, & \text{for } m_x > m_{\text{crit}},
\end{cases}
\]

for unclustered WUMPs and

\[
\tau_x \gtrsim \begin{cases} 
2.6 \times 10^{26} b_\gamma \text{ s}, & \text{for } m_x < m_{\text{crit}}, \\
6.0 \times 10^{26} b_\gamma \text{ s}, & \text{for } m_x > m_{\text{crit}},
\end{cases}
\]

for clustered WUMPs. These lifetimes (with \( b_\gamma = 1 \)) are shown in Fig. 1 as the solid lines labelled \( \gamma \). The different directions of the step at \( m_{\text{crit}} \simeq 10^{13} \text{eV} \) are due to the rapid falling of the background flux (7) with energy combined with the fact that the ratio between the WUMP-generated and the background fluxes is maximum at \( E = E_{\text{max}}(t_0) \) in the clustered case and at \( E \simeq 0.18E_{\text{max}}(t_0) \) in the unclustered one.
2.2 Electrons and positrons

If the decaying dark matter is clustered in the galactic halo, the galactic magnetic field is able to contain the decay electrons and positrons in the galaxy. The containment time is quite uncertain, typically thought to be of the order of \(10^{16}\) s for 1 GeV electrons, and possibly varying with energy. This is a source of uncertainty in the determination of the electron-positron fluxes from clustered WUMPs, and renders the corresponding bounds on the lifetimes less reliable than in the photon and neutrino cases.

For these reasons, it is therefore sufficient to describe the high energy \(e^\pm\) density \(n_e(E)\) using a leaky box model [16], with the \(e^\pm\) sources uniformly distributed over the halo,

\[
\frac{n_e(E)}{\tau_{\text{cont}}(E)} + \frac{d}{dE} [f(E)n_e(E)] = Q_e(E). \tag{10}
\]

Here \(f(E) = -\beta E^2\), with \(\beta \sim 3 \times 10^{-17}\) GeV\(^{-1}\) s\(^{-1}\), is the rate of energy loss of electrons and positrons due to synchrotron radiation and inverse-Compton scattering off microwave photons, \(Q_e(E)\) is the \(e^\pm\) source function, which I take to be

\[
Q_e(E) = b_e \frac{\rho_\odot}{m_x \tau_x} \delta(E - E_0), \tag{11}
\]

and \(\tau_{\text{cont}}(E)\) is the containment time in the halo. This can be estimated using a diffusion model [16] in which \(\tau_{\text{cont}}(E) \sim R_{\text{halo}}^2/D(E)\), taking for the halo size \(R_{\text{halo}} \sim 10\) kpc and for the diffusion coefficient \(D(E) \sim 10^{29} E_{\text{GeV}}^{1/3}\) cm\(^2\) s\(^{-1}\) [16]. The containment time results \(\tau_{\text{cont}}(E) \sim 10^{16}\) s \(E_{\text{GeV}}^{-1/3}\). The electron-positron flux is then obtained by solving eq. (10):

\[
I_{e^\pm}(E) = b_e \frac{1}{4\pi} \frac{\rho_\odot}{m_x \tau_x} \beta E^2 \exp \left[ \left( \frac{E_c}{E_0} \right)^{2/3} - \left( \frac{E_c}{E} \right)^{2/3} \right], \tag{12}
\]

with \(E_c = \left[ \frac{2}{3} \beta \tau_{\text{cont}}(1\ \text{GeV}) \right]^{-3/2} \sim 10\) GeV.
The combined cosmic-ray electron and positron flux has been measured up to about 2 TeV [17]. I adopt here the following parametrization for it (cfr. ref. [18]):

\[
I_{e^\pm}^{\text{bkgd}}(E) \simeq \begin{cases} 
4.4 \times 10^{-7} \left( \frac{E}{20\text{ GeV}} \right)^{-2.7} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}, & \text{for } E < 20 \text{ GeV}, \\
4.4 \times 10^{-7} \left( \frac{E}{20\text{ GeV}} \right)^{-3.5} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}, & \text{for } E > 20 \text{ GeV}.
\end{cases}
\] (13)

Comparing the decay and background fluxes (12) and (13), the maximum WUMP lifetime accessible to background-limited electron-positron searches is obtain as

\[
\tau_x \gtrsim \begin{cases} 
3.8 \times 10^{27} \beta_c m_x^{-0.3} \text{s}, & \text{for } m_x < 60 \text{ GeV}, \\
9.5 \times 10^{26} \beta_c m_x^{1/2} \text{s}, & \text{for } m_x > 60 \text{ GeV}.
\end{cases}
\] (14)

This is shown in Fig. 1 for \( \beta_c = 1 \) as the light line labelled \( e^\pm \). The dashed portion corresponds to the extrapolation of the background \( e^\pm \) flux (13) above the highest measured energies.

2.3 Neutrinos

The diffuse neutrino flux from decays of unclustered WUMPs is obtained by integration over redshift of a monochromatic decay spectrum with energy \( E_0 \). For lifetimes \( \tau_x \gg t_0 \), it is given by

\[
I_\nu(E) = b_\nu \frac{3}{8\pi} \frac{\rho_c}{m_x E_0} \frac{t_0}{\tau_x} \left( \frac{E}{E_0} \right)^{1/2}.
\] (15)

This equation applies separately to each neutrino and antineutrino flavor.

As a background to the decay neutrino flux I consider the \( \nu_\mu + \bar{\nu}_\mu \) atmospheric neutrinos produced in collisions of cosmic rays with nuclei of the upper atmosphere.
Their spectrum in the vertical direction has been estimated in ref. [19] as

\[ I_{\nu_{\mu} + \bar{\nu}_{\mu}}^{\text{bkgd}} \lesssim (4.4 E_{\text{GeV}}^{-3.69} + 2.4 \times 10^{-5} E_{\text{GeV}}^{-2.65}) \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}, \quad (16) \]

for \( E < 2.3 \times 10^6 \) GeV, and

\[ I_{\nu_{\mu} + \bar{\nu}_{\mu}}^{\text{bkgd}} \lesssim (4.4 E_{\text{GeV}}^{-3.69} + 3.9 \times 10^{-3} E_{\text{GeV}}^{-3}) \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}, \quad (17) \]

for \( E > 2.3 \times 10^6 \) GeV.

Comparison of the decay neutrino flux (15) with the atmospheric background at \( E = E_0 \) gives the maximum explorable lifetime for unclustered WUMPs

\[ \tau_x \gtrsim \begin{cases} 
1.4 \times 10^{22} \text{s} \frac{b_{\nu} m_{10}^{1.69}}{1 + 2 \times 10^{-5} m_{10}^{0.04}}, & \text{for } m_x < 6.9 \times 10^{15} \text{eV}, \\
1.4 \times 10^{22} \text{s} \frac{b_{\nu} m_{10}^{1.69}}{1 + 2 \times 10^{-3} m_{10}^{0.69}}, & \text{for } m_{10} > 0.6.9 \times 10^{15} \text{eV}.
\end{cases} \quad (18) \]

This lifetime is shown in Fig. 1 as the heavy solid line labelled \( \nu \), drawn for \( b_{\nu} = b_{\nu_{\mu}} + b_{\bar{\nu}_{\mu}} = 2 \).

For WUMPs clustered in our galactic halo, no integration over redshift needs to be performed and the decay neutrino flux is given by

\[ I_{\nu}(E) = b_{\nu} \frac{1}{4\pi} \frac{1}{m_x^2 \tau_x} \int \frac{\rho_h(x)}{|x - x_\odot|^2} d^3x \delta(E - E_0). \quad (19) \]

Assuming a detector with 10% energy resolution to smear the delta function the accessible lifetimes are a factor 15 larger than those for unclustered WUMPs. These lifetimes are shown in Fig. 1, again for \( b_{\nu} = 2 \), as the light solid line labelled \( \nu \).

Present neutrino detectors are already able to exclude a sizeable region of the WUMP mass-lifetime plane. The dotted line shows the lower bound on \( \tau_x \) obtained in ref. [12] using IMB and Fly’s Eye published data. Analogous calculations show that a future 1 km\(^2\) neutrino telescope would be able to explore the region limited by the dotted line labelled \( 10^6 \) at the flux level of 1 muon per year.
3. Conclusions

If the dark matter WUMPs are uniformly distributed in the universe, a background-limited neutrino detector would be able to explore longer lifetimes than those accessible to photon searches for any WUMP masses larger than $\sim 700 \text{ GeV}$.

If the WUMPs constitute the galactic halo, the longest lifetimes would be probed by electron-positron searches for $m_x \lesssim 10 \text{ TeV}$. This occurs because of the effective magnetic confinement of electrons and positrons in the galaxy. Unfortunately, the containment time is quite poorly known and the bounds so obtained would be subject to uncertainty. Searches for decay neutrinos seem again the most powerful for WUMP masses above $\sim 700 \text{ GeV}$.

In both cases, a $1 \text{ km}^2$ neutrino telescope might be able to reach lifetimes of order $10^{30} \text{ s}$ for masses $m_x \gtrsim 100 \text{ TeV}$. Such a detector would be quite a good probe of long-lived dark matter particles.

Acknowledgements

I would like to thank Subir Sarkar for valuable discussions.
REFERENCES

[1] K. Griest and J. Silk, Nature 343 (1990) 26;
    L. Krauss, Phys. Rev. Lett. 64 (1990) 999.

[2] S. Nussinov, Phys. Lett. B165 (1985) 55.

[3] S.M. Barr, R.S. Chivikula and E. Farhi, Phys. Lett. B241 (1990) 387.

[4] K.S. Babu, D. Eichler and R.N. Mohapatra, Phys. Lett. B226 (1989) 347.

[5] D. Eichler, Phys. Rev. Lett. 63 (1989) 2440.

[6] V. Berezinsky, Bartol preprint BA-90-87 (1990); Gran Sasso preprint LNSG-91-02 (1991).

[7] V. Berezinsky, A. Masiero and J.W.F. Valle, Phys. Lett. B266 (1991) 382.

[8] I. Antoniadis, J. Ellis, J. Hagelin and D.V. Nanopoulos, Phys. Lett. B231 (1989) 65.

[9] A.N. Schellekens, Phys. Lett. B237 (1990) 363.

[10] J. Ellis, J. Lopez and D.V. Nanopoulos, Phys. Lett. B247 (1990) 257.

[11] J. Ellis, G.B. Gelmini, J. Lopez, D.V. Nanopoulos and S. Sarkar, Nucl. Phys.
     B373 (1992) 399.

[12] P. Gondolo, G.B. Gelmini and S. Sarkar, UCLA preprint UCLA/91/TEP31.

[13] A. Zdiarski and R. Svensson, Astrophys. J. 344 (1989) 551.

[14] A. Zdiarski, Astrophys. J. 335 (1988) 786.

[15] M.D. Ressel and M.S. Turner, Comments Astrophys. 14 (1990) 323.

[16] V.S. Berezinsky, S.V. Bulanov, V.A. Dogiel, V.L. Ginzburg and V.S. Ptuskin,
    Astrophysics of Cosmic Rays (Elsevier, 1990).

[17] J. Nishimura et al., Astrophys. J. 238 (1980) 394.

[18] K.-K. Tang, Astrophys. J. 278 (1984) 881.

[19] L.V. Volkova, Sov. J. Nucl. Phys. 31 (1980) 784.
FIGURE CAPTIONS

Figure 1. Maximum accessible WUMP lifetime $\tau_x$ versus WUMP mass $m_x$ in electron-positron, photon and neutrino background-limited detectors. Light and heavy lines correspond to clustered and unclustered WUMP distributions respectively. The dotted lines indicate the present lower limits on $\tau_x$ imposed by the IMB and Fly’s Eye neutrino data and the region explorable by a neutrino telescope sensitive to 1 muon km$^{-2}$ yr$^{-1}$ (curve $10^6$).