Indirect Detection of Neutralino Dark Matter

Eva Dalberg
Department of Physics, Stockholm University

Since neutralinos are Majorana particles, they can annihilate pair-wise and form standard model matter. This can be done either in the dark matter halo itself or once the neutralinos have been gravitationally trapped and have accumulated in the center of the Sun or the Earth. The annihilation products can form detectable fluxes, for example in the form of anti-protons or neutrinos. Some characteristics of these signals will be reviewed. Examples of ongoing and future experimental efforts to detect them will be presented.

I. INTRODUCTION

There is strong evidence that a substantial fraction of the matter in the universe is "dark" and has only been seen by its gravitational effects. This is true not only in the Universe at large, but in our local galaxy. We are most probably surrounded by a dark matter halo formed by particles whose nature is unknown. From both particle physics and cosmology there are strong arguments favoring models where a substantial part of the dark matter is constituted by the lightest supersymmetric particle, the neutralino. In this talk, possibilities to indirectly detect this neutralino will be reviewed (see [1] for an extensive review of this field). These halo neutralinos would pair-wise annihilate and form standard model particles such as quarks, leptons and, if they are sufficiently massive, gauge-boson. Such particles, which would be seen as an extra component to the standard cosmic rays, can be detected with well-known techniques. In order not to be drowned by the background, it is necessary to look for species which are rare in cosmic rays from ordinary sources, such as positrons and anti-protons. We can also look for gamma-rays, which have the advantage of pointing back to their source.

Another possibility is to make use of the small elastic cross-section for neutralinos to scatter on nuclei while traversing objects like the Sun or the Earth. If their velocities after scattering fall below the escape velocity of the body, they will become gravitationally trapped and an accumulation will take place in the center of this body. In this high density region, annihilations will take place, and, as in the halo, standard model particles will be formed. In this case, the body will filter away most of the particles. The only component that can escape and be detected is the neutrinos. They will come either from direct decays of the annihilation products, or in meson or lepton decays in jets from the annihilation products. Thus we can look for a signal of high energy neutrinos from the center of the Earth or the Sun.

II. NEUTRALINO CHARACTERISTICS

Neutralinos are linear combinations of fermionic gauge- and higgs-boson superpartners [1]

$$\chi = Z_{11}\tilde{B} + Z_{12}\tilde{W}^3 + Z_{13}\tilde{H}_1^0 + Z_{14}\tilde{H}_2^0 \tag{1}$$

or

$$\chi = a_1\tilde{\gamma} + a_2\tilde{Z} + Z_{13}\tilde{H}_1^0 + Z_{14}\tilde{H}_2^0 \tag{2}$$

where

$$\tilde{\gamma} = cos\theta_W\,\tilde{B} + sin\theta_W\,\tilde{W}^3 \tag{3}$$

$$\tilde{Z} = -sin\theta_W\,\tilde{B} + cos\theta_W\,\tilde{W}^3 \tag{4}$$

It is common practice to characterize the composition of the neutralino with the help of

$$f = |Z_{11}|^2 + |Z_{12}|^2 \tag{5}$$

where a particle with $f \to 0$ is called higgsino and with $f \to 1$ gaugino.
Since the halo neutralinos were produced in the early universe, it is necessary that they are stable to be cosmologically interesting today. This condition is fulfilled if we have R-parity conservation and we chose the lightest of the possible linear combinations as our dark matter candidate. Many authors chose to work within the minimal supersymmetric model (MSSM), often constrained further by GUT-scale assumptions. The neutralino is a majorana particle and can annihilate pair-wise.
Neutralinos are part of the cold dark matter component in the universe. The density is about 0.3 GeV/cm^3 in our local neighborhood in the galaxy. This density is of course important for the predicted signal rates from annihilations in the halo or in the centers of heavy objects. However, not only is the total number of interest, but how this dark matter is distributed. It is possible that there is an enhancement of the halo dark matter density towards the galactic center, and/or that the distribution is clumpy rather than smooth. Since the annihilation rate is proportional to the square of the density, any density enhancements will strongly affect the experimental rates [2].
The allowed mass-range of the neutralino is from $\sim$ 30 GeV to a few TeV [3]. This range is, generally speaking, restricted from below by so far unsuccessful searches at accelerator experiments of neutralinos and charginos. The chargino can be used to restrict the neutralino mass, since its mass depends on the same parameters as the neutralino. From above, cosmological arguments constrains the allowed mass. The relic density is inversely proportional to $< \sigma v >$ and $< \sigma v > \propto m_\chi$ at those high masses. Because of this, Ω_χ put an upper bound on the possible mass, at least for a cosmologically interesting particle.

III. EXAMPLES OF SIGNALS

To be distinguishable, the fluxes of particles from neutralino annihilations need to be larger than the ordinary cosmic ray flux. Most promising is the cases where there is some special feature in the spectrum that is unique to this kind of signal, and can not be attributed to any other source than the neutralino annihilations. Otherwise, it requires a very good knowledge of the primary cosmic rays, in terms of composition, propagation, energy loss, solar modulation effects etc. to discern one flux from the other. Experiments often have to live with relatively poor statistics and systematic uncertainties, which reduces the restrictiveness of the measurements. Featureless spectra can then only be used to rule out models which would give very much too high fluxes than have been observed. There are cases, though, where the neutralino induced signals would be of a more special character. The absolute rates for these models will of course be affected by all astrophysical uncertainties listed above, but they have the advantage of giving a signal that leave a unique fingerprint. A few examples where this is the case will be given below.

A. Anti-protons

Anti-protons are rare in the cosmic rays, the $\bar{p}/p$-fraction is $\sim 10^{-5} - 10^{-4}$. Most cosmic ray anti-protons are produced in p-p interactions, $pp \to ppp\bar{p}$ [4]. The flux is expected to show a peak at a few GeV or so, because of the kinematics of the interaction and the shape of the proton flux. Neutralino annihilation production of anti-protons can be described as [5]

$$q_{\bar{p}}^{susy}(T_{\bar{p}}) = < \sigma_{ann} v > g(T_{\bar{p}}) \left(\frac{\rho_\chi(r,z)}{m_\chi} \right)^2 \tag{6}$$

where $T_{\bar{p}}$ is the kinetic energy of the anti-proton, $< \sigma_{ann} v >$ is the annihilation rate, $\rho_\chi(r,z)$ is the neutralino density at galactic coordinates r and z and m_χ is the neutralino mass. $g(T_{\bar{p}})$ is the differential spectrum of anti-protons produced in the annihilations, summed over all different annihilation channels, each with its own differential energy spectrum. This production mechanism will generate a spectrum that is rather flat, and which do not show the sharp cut-off at energies below a GeV, as expected from the background sources. This means that we have a window open at low energies where the neutralino produced anti-protons may give a larger flux than the cosmic ray induced ones.

Measurements of the anti-proton flux has so far been carried out by balloon-borne experiments, high up in the atmosphere (eg. BESS [6], IMAX [7] and CAPRICE [8]). This type of experiments is limited in size and exposure time, which has made the measurements suffer from low statistics, although the situation has been improved by the more recent experiments. Last year, a test flight with an experiment onboard the space-shuttle (AMS [9]) was carried out, and there is a number of space-based experiments in the pipe-line (for a review of the future of anti-matter experiments, see [10]).

The experimental situation is summarized in figure 1. The improved statistical situation achieved by the BESS experiment have been used to probe the supersymmetric parameter space [5] and it has been found that anti-protons mainly restrict relatively low mass gaugino or mixed neutralinos. It is however necessary to be cautious not to over-use the data since the accuracy of the models is limited. Changing the local neutralino density will drastically affect the rates, and there is a number of different models of how anti-protons will propagate and lose energy, including effects of the solar wind on these low energy anti-protons. Uncertainties both in measurements and predictions of the cosmic ray induced anti-protons makes it hard to restrict the supersymmetric parameter space with this channel. Even with an improved experimental situation there is not much room for a discovery, since neutralino induced spectrum will not give a very distinct spectrum (see figure 1) and most supersymmetric models give predictions that will drown in the background fluxes.

B. Positrons

Positrons are mainly produced in pion and kaon decays in hadron jets emerging from the pair of annihilating neutralinos. These processes will give continuous energy spectra with no prominent features. Positrons can also, with a very small branching ratio, be produced directly through [11]

$$\chi + \chi \rightarrow e^+ + e^- \tag{7}$$

where the positrons will show up as lines with the energy m_χ.

If the neutralino is heavy enough. $W^\pm$ and Z bosons will be produced with still small, but larger branching ratios than for direct positron production, and they will produce positrons in their decays [11] [12]

$$\chi + \chi \rightarrow W^+ + W^- \rightarrow e^+ + \nu_e + e^- + \bar{\nu_e} \tag{8}$$

and

$$\chi + \chi \rightarrow Z^0 + Z^0 \rightarrow 2e^+ + 2e^- \tag{9}$$

Here, the positron energy will be $\sim m_\chi/2$, but the flux will not be sharply peaked around this energy, but rather smeared as a soft "bump".

Pions from cosmic ray proton and nuclei interactions with the interstellar medium will produce positrons through their decays, $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$. The measured positron fraction is $e^+/(e^+ + e^-) \sim 0.1$ and $e^+/p \sim 10^{-3}$. The absolute flux has been measured by the balloon-borne High Energy Antimatter Telescope (HEAT) [13], as a recent example.

The expected fluxes of positrons from neutralino annihilations, using standard assumptions about how positrons propagate, are in general drowned by the cosmic ray positrons. Authors claim, however, that fluxes can be boosted many orders of magnitude if one takes into account dark matter density distribution uncertainties, or by allowing changes in the cosmic ray proton spectrum (for instance [11] [12]). It has been shown that there exist models where this type of boosts would not be in conflict with fluxes of other particle species, such as anti-protons [11]. This makes it possible to find models where neutralinos would annihilate into W-pairs and give rise to a clear structure in the positron spectrum, as described above, with a total flux that is well above the expected background.

The predicted fluxes in this channel are in general small compared to the background. A non-observation of a signal can because of this not be used to restrict the supersymmetric parameter space; the strength lies in the prospect of detecting the features in the spectrum which are possible for some supersymmetric models, especially higgsino like models with neutralino masses above the gauge boson masses.

C. Gamma-rays

The most promising way of detecting a gamma-ray signal from neutralino annihilations in the halo, is through their line-flux [14] [15]

$$\chi\chi \rightarrow \gamma\gamma \tag{10}$$

or [16]

$$\chi\chi \rightarrow Z^0\gamma \tag{11}$$

Since the neutralinos are non-relativistic they will give essentially mono-chromatic γ's,

$$E_\gamma = m_\chi \tag{12}$$

and

$$E_\gamma = m_\chi - \frac{M_Z^2}{4m_\chi} \tag{13}$$

respectively. There will be a continuous spectrum of photons produced besides these gamma lines, a spectrum that will be present also for neutralino models where the annihilation modes are not valid [17] [18]. These photons can in principle also be detected, but they are difficult to distinguish both from the galactic- and extragalactic backgrounds [19]. The line signal is expected to be very faint, but distinguishable with an instrument with good energy- and angular resolution [19] [20]. The planned GLAST satellite experiment will be able to probe this field [21]. The prospect of directly measure the neutralino mass from such a unique signal is most attractive.

D. Neutrinos

The flux of neutrinos from neutralino annihilation in the center of the Sun or the Earth is [22]

$$\frac{d\phi}{dE_\nu} = \frac{\Gamma_A}{4\pi R^2} \sum_F B_F \frac{dN}{dE_\nu} \tag{14}$$

where Γ_A is the annihilation rate, R is the distance from the source to the detector and F denotes the annihilation channel with branching ratio B_F and differential neutrino flux dN/dE_ν. The annihilation rate depends on the capture rate, the age of the capturing object, the annihilation cross-section and density-distribution inside the object. The capture rate depends on the elastic cross-section for neutralino scatterings on nuclei in the object, the escape velocity of the object, the local relic density of neutralinos as well as their velocity distributions. The heavier the neutralino is, the more concentrated to the very center of the object will the particles be [23]. This means that a heavier neutralino will have a more peaked angular neutrino spectrum than a lighter one. The branching ratios to different channels depends on the supersymmetric model. Gauge bosons will give harder neutrino spectra than quarks. The harder the spectrum is, the easier it is to measure. This is because neutrino experiments can only do this measurement indirectly, through the neutrino induced muons. Both the neutrino-nucleon interaction cross-section as well as the muon range is increasing with increasing energy. The effective volume of the detectors is thus increasing with energy. Typically, the muon energy will be $\sim \frac{1}{4}$ of the neutralino mass.

The neutralino neutrinos are easily distinguished from any other neutrino source since the angular spectra will show a narrow peak towards the center of the neutralino capturing object. The Sun will give larger fluxes than the Earth, but the duty cycle is lower for experiments looking at the Sun compared to the ones looking towards the center of the Earth. This is because even deep underground will the atmospheric muons far outnumber the neutrino induced one. This restricts the experiments to take data only at times when the Sun is below the horizon.

A number of underground neutrino experiments have put limits on the possible flux of neutrinos due to neutralino annihilations in the Sun and/or the Earth. The list includes Baksan [24], Kamiokande [25], IMB [26], MACRO [27] and the Baikal experiment [28]. The muon-track can, for example, be detected by scintillators as in the Baksan experiment, or through the emission of Cherenkov light in water (Kamiokande, Baikal). These experiment have, with the exception of the Baikal experiment, relatively low energy thresholds ($\sim$ 1 GeV) and have been primarily designed for the detection of other types of neutrinos (solar, atmospheric) or proton decays. A new generation of experiments, of which Baikal is one, is aiming at ultra-high neutrino energies, with the ultimate goal of detecting possible extra-terrestrial fluxes of neutrinos [29]. Apart from the Baikal experiment (in lake water), the AMANDA experiment (in ice) [30], is currently taking data. This experiment as well as the planned ANATARES detector (in the deep sea) [31] are aiming to reach an effective volume of $(1\text{km})^3$ within the next decade. As detectors grow their sensitivity to fainter and fainter fluxes increases, which makes this channel promising for the future. See figure 2 which shows the expected flux of neutrinos versus anti-protons for a selection of supersymmetric models. This figure illustrates that whereas the signal detection possibility for the anti-proton channel is limited by the background flux from ordinary cosmic ray sources, the usefulness of the neutrino channels is limited by the threshold and size of the neutrino experiments, since the signal is so unique. The sensitivity will be increased in the future as new detectors become functioning.

IV. CONCLUSIONS

As exemplified above, pair-annihilation of neutralinos in the halo or in the center of the Earth and the Sun can give unique signals in experiments measuring anti-protons, positrons, gamma-rays and neutrinos. For example, pairs of neutralinos can annihilate directly to gamma pairs, or to a gamma and a Z-boson, and an observation of such line-fluxes would be a direct measurement of the mass of the neutralino. Another clear signal is the neutrino signal. A measured point source of high-energy neutrinos from the center of the Earth or the Sun would be a very strong argument in favour of supersymmetry. The available supersymmetric parameter space can also be restricted if no signal is observed, at least for models predicting fluxes far above the measured ones. Unfortunately, the restrictive power is limited by a number of uncertainties. One important example is the local dark matter density, which usually is thought to be known at best within a factor of two. In some cases it is too poor knowledge about the background which is the limitation for improvements in the restrictive power of the experimental results on the available models. The field will benefit from many new or improved experiments in the near future. They will probe some of the models discussed above that give rise to very distinct signal characteristica. In other words, there is a very attractive potential for detection in this field, should it turn out to be that one of the largest mysteries in the universe has its solution in the form of supersymmetric dark matter.

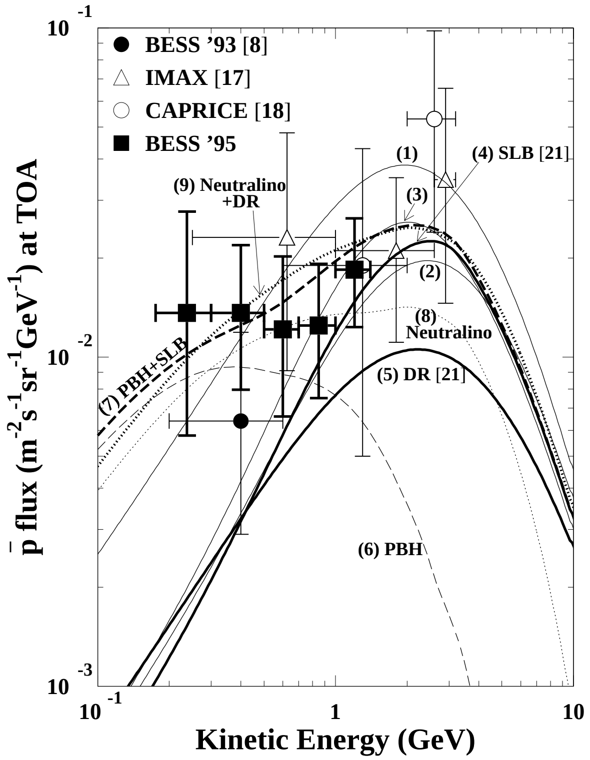

FIG. 1. Summary of measurements of anti-protons in the atmosphere, from [6]. The measurements are BESS93 [32], IMAX [7], CAPRICE [8] and BESS95 [6]. These measurements are compared with a number of calculations of the standard cosmic ray induced anti-proton flux (1)-(5) [33] [34] [35], with the flux of anti-protons from evaporating primordial black holes (6)-(7) and from neutralino annihilations (8) and this flux added to the background (model (5)). The neutralino mass in this model is 53.6 GeV and the supersymmetric model is of gaugino type [35].

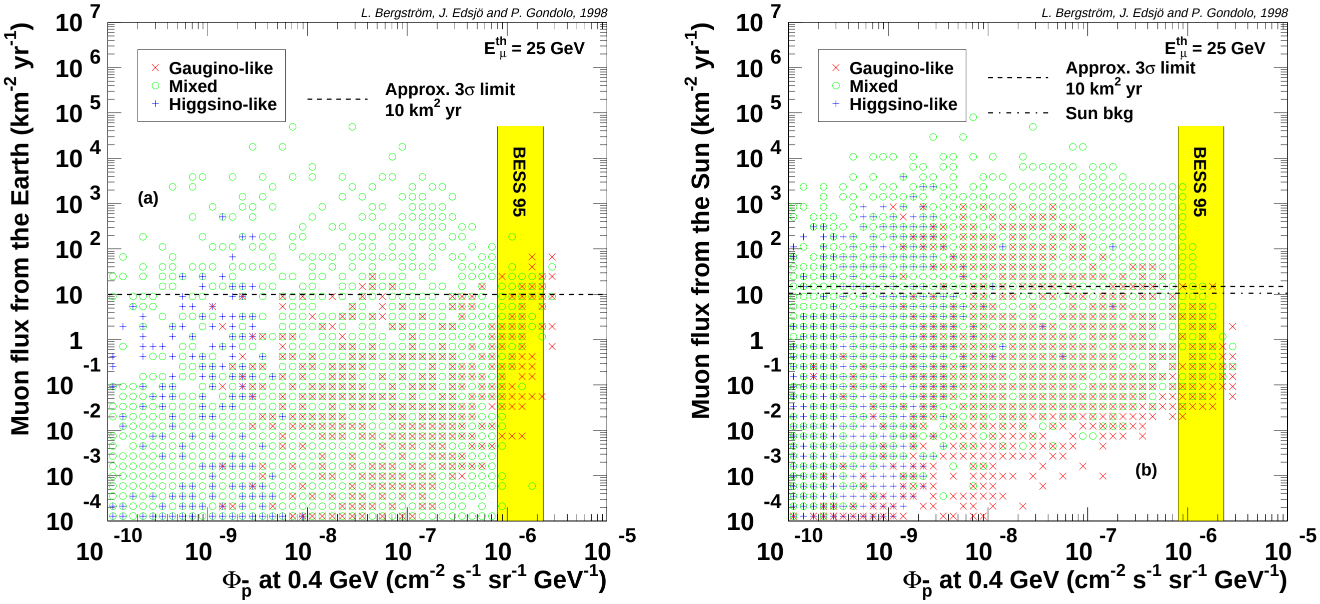

FIG. 2. Comparison of expected fluxes of neutrinos from neutralino annihilations in center of the Earth (left) or the Sun (right) versus the anti-proton flux from neutralino annihilations in the galactic dark matter halo, from [36]. The sensitivity of a possible future neutrino experiment with 10km^{2}yr exposure is marked by the dashed line. The anti-proton flux at 0.4 GeV as measured by BESS95 [6] is shown by the shaded region.

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