Indirect Detection of Neutralino Dark Matter with Neutrino Telescopes

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Abstract

Principle of neutralino dark matter detection with neutrino telescopes and predictions are reviewed. The future Antares detector is described. Prospection in the CMSSM is exposed including comparison with experiment sensitivities of both neutrino indirect detection and direct detection experiments. Results in other frameworks are shortly surveyed. Models with a non negligible neutralino higgsino fraction are promising for neutrino telescopes detection.

1 Neutralino Dark matter in neutrino telescopes

Today, both theory and experimental data in cosmology suggest and focus on a ΛCDM flat and black universe with the amounts of dark energy and cold dark matter: $\Omega_\Lambda \sim 0.7$, $\Omega_{CDM} \sim 0.3$. Dark matter would be a bath of Weakly Interacting (to fulfil a relic density of order 1) Massive Particles: WIMPs which are non relativistic since their decoupling. In the MSSM framework, assuming R-parity conservation, the Lightest Supersymmetric Particle (LSP) is stable and is the lightest neutralino ($\equiv$ *the* neutralino(s) χ) in most regions of the parameter space. If present in galactic halos, relic neutralinos must accumulate in astrophysical bodies (of mass M_b) like the Sun or the Earth (see [1] for a review). The capture rate C depends on the neutralino-quark elastic cross section: $\sigma_{\chi-q}$. Neutralinos being Majorana particles, their vectorial interaction vanishes and the allowed interactions are scalar (via $\chi q \xrightarrow{H,h} \chi q$ in t channel and $\chi q \xrightarrow{\tilde{q}} \chi q$ in s channel) and axial (via $\chi q \xrightarrow{Z} \chi q$ in t channel and $\chi q \xrightarrow{\tilde{q}} \chi q$ in s channel). Depending on the spin content of the nuclei N present in the body, scalar and/or axial interactions are involved. Roughly, $C \sim \frac{\rho_\chi}{v_\chi} \sum_N M_b f_N \frac{\sigma_N}{m_\chi m_N} < v_{esc}^2 >_N F(v_\chi, v_{esc}, m_\chi, m_N)$, where ρ_χ, v_χ are the local neutralino density and velocity, f_N is the density of nucleus N in the body, σ_N the nucleus-neutralino elastic cross section, v_{esc} the escape velocity and F a suppression factor depending on masses and velocity mismatching. Considering that the population of captured neutralinos has a velocity lower than the escape velocity, and therefore neglecting evaporation, the number N_χ of neutralinos in the centre of a massive astrophysical object depends on the balance between capture and annihilation rates: $\dot{N}_\chi = C - C_A N_\chi^2$, where C_A is the total annihilation cross section $\sigma_{\chi-\chi}^A$ times the relative velocity per volume. The annihilation rate at a given time t is then:

$$\Gamma_A = \frac{1}{2} C_A N_\chi^2 = \frac{C}{2} \tanh^2 \sqrt{CC_A} t \tag{1}$$

with $\Gamma_A \approx \frac{C}{2} = cste$ when the neutralino population has reached equilibrium, and $\Gamma_A \approx \frac{1}{2} C^2 C_A t^2$ in the initial collection period (relevant in the Earth). So, when accretion is efficient,
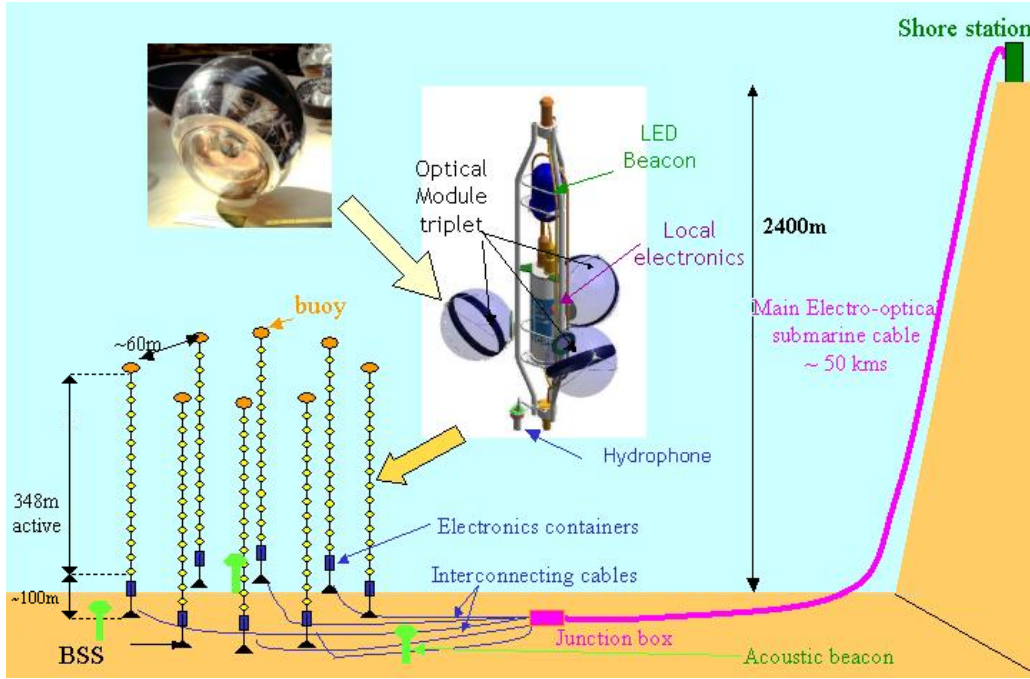
Figure 1: Schematic overview of the Antares detector showing the dimensions and separations of the elements and the structure of the triplets of optical modules at each storey of the detector.

the annihilation rate does not depend on annihilation processes but follows the capture rate C and thus the neutralino-quark elastic cross section.

The neutrino differential flux resulting of $\chi\chi$ annihilation is given by:

$$\frac{d\Phi}{dE} = \frac{\Gamma_A}{4\pi R^2} \sum_F B_F \left(\frac{dN}{dE}\right)_F \tag{2}$$

where R is the distance between the source and the detector, B_F is the branching ratio of annihilation chanel F and $(dN/dE)_F$ its differential neutrino spectrum. As $\chi\chi \to \nu\bar{\nu}$ is strongly suppressed by the tiny neutrino mass, neutrino fluxes come from decays of primary annihilation products, with a mean energy $E_\nu \sim \frac{m_\chi}{2}$ to $\frac{m_\chi}{3}$. The most energetic spectra, called "hard" come from neutralino annihilations into WW, ZZ and the less energetic, "soft", ones comes from $b\bar{b}$. Muon neutrinos give rise to muon fluxes by charged-current interactions in the Earth. As both the ν charged-current cross section on nuclei and the produced muon range are proportional to E_ν, high energy neutrinos are easier to detect.

As we will compare neutrino telescope and direct detection experiment sensitivities, we can notice here that the elastic cross section of a neutralino on a nucleus also depends on $\sigma_{\chi-q}$, the nucleus mass number A and its spin content. Depending on the chosen nuclei target, the detection rate of a direct detection experiment will be determined by those parameters.

Neutrino telescope principle : the Antares detector

Those kind of detection use the Earth as a target to convert neutrino fluxes into muons by charged current interactions. The muons produced emit Čerenkov light when travelling through deep water or ice. Then the detection principle is to have a 3-dimensional array of photomultipliers collecting muon Čerenkov light from which direction and energy of the muons(neutrinos)

can be reconstructed. The international Antares collaboration is constructing such a 0.1 km^2 telescope in Mediterranean sea at a depth of 2.4 km down south of Toulon (France). It will consists of 12 independent lines. Each line supports 90 optical modules which are water pressure resistant glass sphere including the photomultiplier tubes and the associated electronic material (see figure 1). The Antares sensitivity to CDM neutralino annihilation in a punctual source (Sun, Galactic Center) is obtained by requiring at least 2 lines hitted by Čerenkov light. The atmospheric neutrino background is suppressed by looking in an optimised angular cone (2-3 degrees) in the source direction. The neutrino spectrum shape is calculated following [2] for the background (this gives around 1-2 events in the cone per year) and assuming a "hard" spectrum for the signal. Results on the Antares sensitivity on muon fluxes coming from neutralino annihilation coming from the Sun are shown on figure 7a).
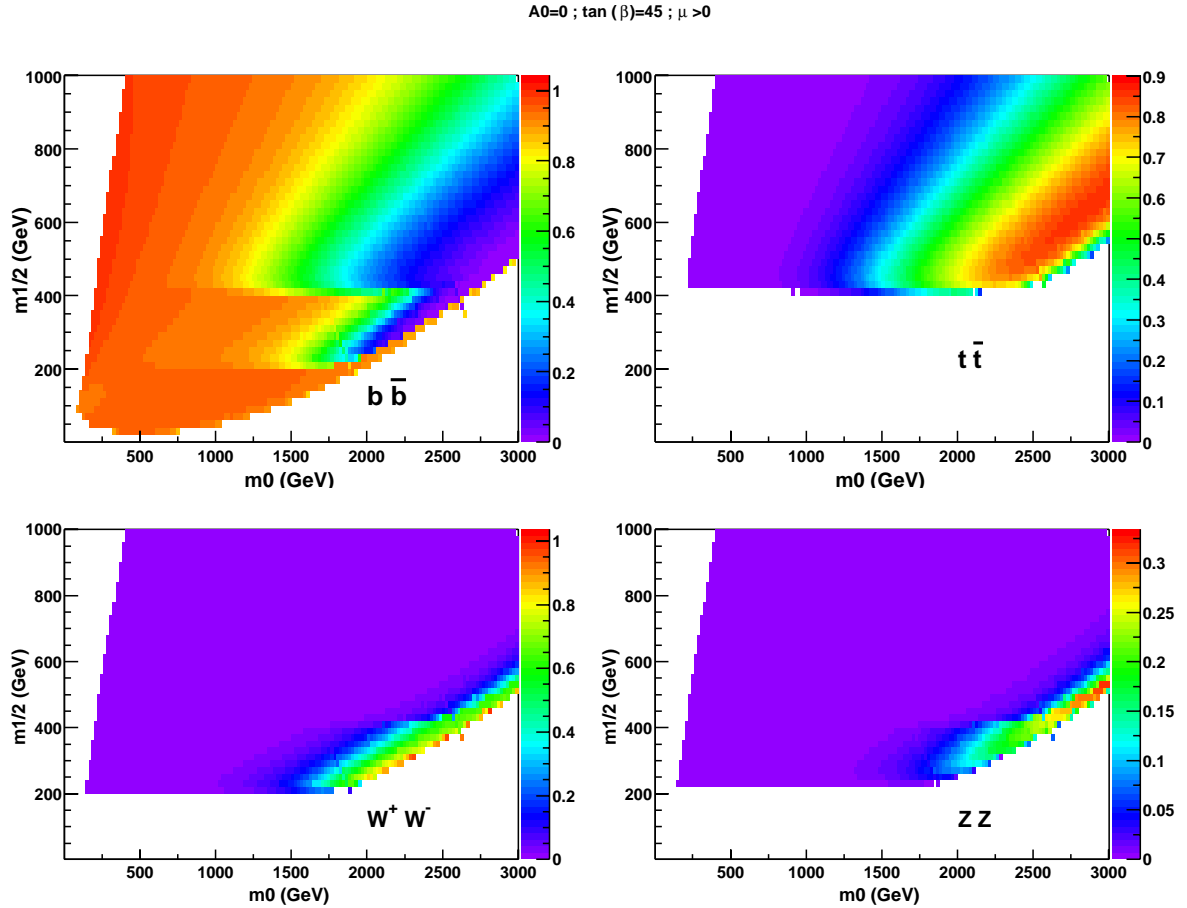
2 Prospection in CMSSM/mSugra

Figure 2: Dominant branching of the neutralino annihilation in the $(m_0, m_{1/2})$ plane.

Recent studies in this framework can be found in [3, 4, 5]. Those models, inspired by gravity-mediated supersymmetry breaking in supergravity [6], assume Grand Unification of soft terms at $E_{GUT} \sim 2.10^{16}$ GeV parameterized by m_0 (common scalar mass), $m_{1/2}$ (common gaugino mass), A_0 (common trilinear term), B_0 (common bilinear term), and the Higgs mass parameter

μ_0. Requiring radiative electroweak symmetry breaking

$$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2|_{Q_{EWSB}} - m_{H_u}^2|_{Q_{EWSB}} \tan^2\beta}{\tan^2\beta - 1} - \mu^2|_{Q_{EWSB}} \underset{\tan\beta \gtrsim 5}{\sim} - m_{H_u}^2|_{Q_{EWSB}} - \mu^2|_{Q_{EWSB}} , \quad (3)$$

the usual input parameters of a constraint MSSM or mSugra model [7, 8, 9] are

$$m_0, \ m_{1/2}, \ A_0, \ \tan\beta, \ sgn(\mu).$$

In those models the neutralino can exhibit two different natures, depending on the input parameter values :

- an almost pure bino-like neutralino for low m_0, as the RGE drive
  $M_1|_{Q_{EWSB}} \simeq 0.41 M_1|_{GUT} = 0.41 m_{1/2} << |\mu|_{Q_{EWSB}}$ and
  $M_2|_{Q_{EWSB}} \simeq 0.83 M_1|_{GUT} = 0.83 m_{1/2} << |\mu|_{Q_{EWSB}}$;

- for $m_0 \gtrsim 1000$ GeV, the neutralino picks up some higgsino mixing for $\tan\beta \gtrsim 5$ as the increase of m_0 drives $m_{H_u}^2$ to less negative values so that both $|m_{H_u}^2|$ and $|\mu|$ (via eq. 3) decrease [10, 3]. One can then have $|\mu|_{Q_{EWSB}} \lesssim M_1|_{Q_{EWSB}}$ depending on $m_{1/2}$. When $|\mu|$ is too small, EWSB cannot be achieved.

Neutralino annihilation

In a $(m_0, \ m_{1/2})$ plane one has typically 4 dominant branching ratios for neutralino annihilation [5]. A wide region of annihilation into $b\bar{b}$ when the neutralino is bino like and when the higgsino component is not negligible annihilation into gauge bosons $W^+W^-(ZZ)$ if $m_\chi < m_t$ or into $t\bar{t}$ if $m_\chi > m_t$. This is shown on figure 2 for $A_0 = 0$ and $\tan\beta = 45$. Varying their value only change size and shape of the 4 regions (*e.g* lower value of $\tan\beta$ increase the pseudo-scalar mass m_A and reduce the $b\bar{b}$ region).

Capture and direct detection

For the Earth, scalar interactions dominate. By increasing m_0 from its low value region, sfermions and H exchanges first decrease, and the scalar neutralino-proton cross section rises again when approaching the mixed higgsino region (see figure 3a).

For the Sun, the spin of hydrogen allows for axial interaction, which are stronger due to the Z coupling. The latter depends strongly on the neutralino higgsino fraction and is independent of $\tan\beta$, so the spin dependent neutralino proton cross section follows the higgsino fraction isocurves along the "no EWSB" region (figure 3b).

Depending on the spin of the experiment nuclei target, direct detection rates follow scalar or spin dependent neutralino-proton cross section $\sigma_{\chi-p}^{scal/spin}$.

Neutrino fluxes

For the Sun (figure 4), neutralinos do not reach complete equilibrium in the whole $(m_0, m_{1/2})$ plane studied, actually when capture is low (see figure 3b)). For high m_0 or small $m_{1/2} < 600$ GeV values, as equilibrium is nevertheless reached, fluxes follow essentially the higgsino fraction and the spin dependent $\sigma_{\chi-p}^{spin}$ isocurves of figure 3b). For low m_0 however, the equilibrium fluxes would drop with m_0 and C, and Γ_A feels the annihilation cross section behaviour.
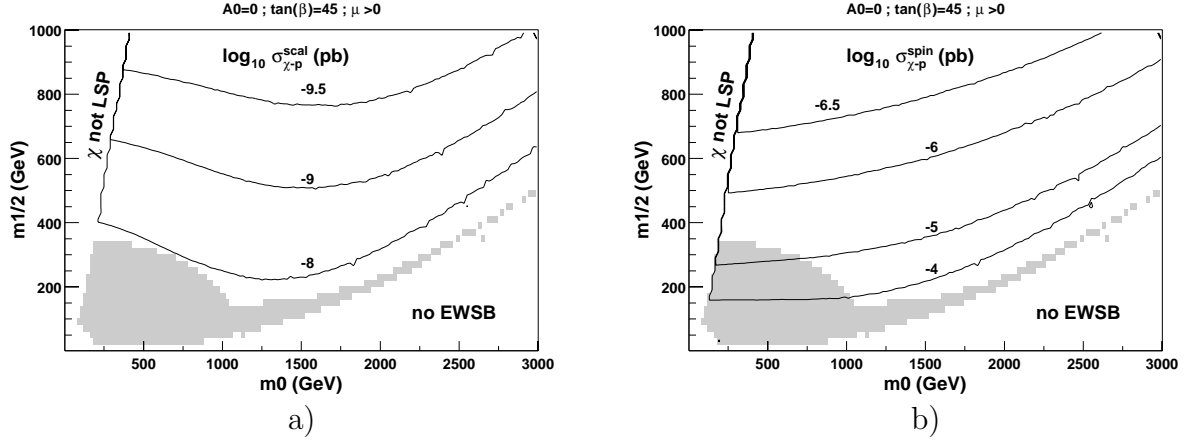
Figure 3: Scalar (a) and axial (b) cross sections for neutralino scattering on proton in pb. Grey region is excluded as explicited in [5] by experimental results (limits on SUSY masses, $m_h < 114$ GeV, branching ratio $b \to s + \gamma \notin [2.3 \times 10^{-4}; 5.3 \times 10^{-4}]$ and SUSY contribution to muon anomalous magnetic moment $a_\mu^{SUSY} \notin [-6 \times 10^{-10}; 58 \times 10^{-10}]$)
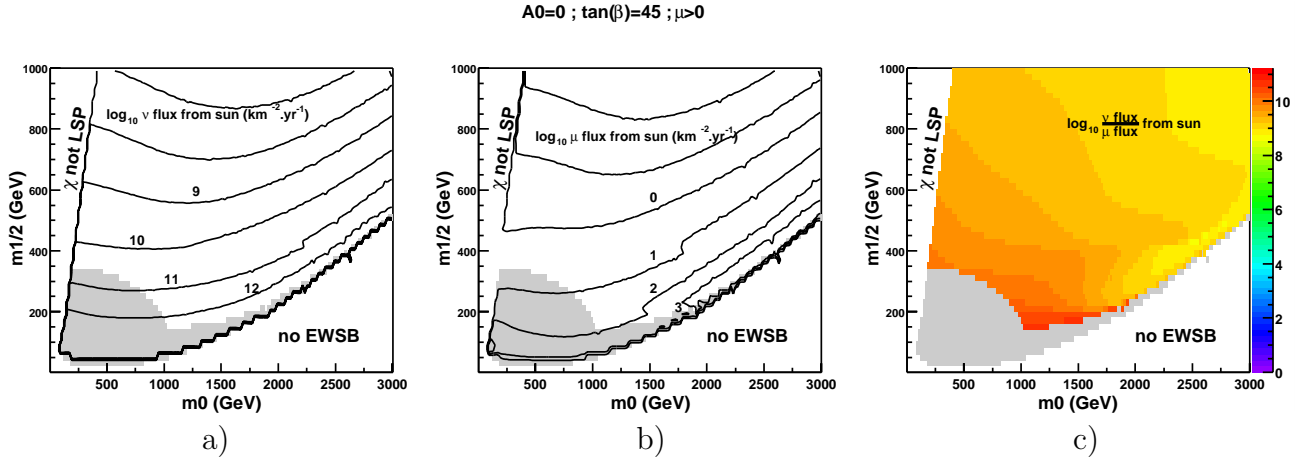

Figure 4: ν fluxes from the Sun (a), the corresponding μ fluxes with $E_\mu > 5$ GeV threshold (b) and their ratio (c).

This effect is stronger for high $m_{1/2}$ values where the neutralinos are heavier and more bino-like, and where capture is smaller. The effect is also larger when $\tan\beta$ (and thus $\sigma_{\chi-\chi}^A$) is low, as incomplete equilibrium makes $\nu(\mu)$ fluxes sensitive to $\sigma_{\chi-\chi}^A$, making the W and top thresholds more conspicuous.

For the Earth (figure 5), neutralinos are not in equilibrium. Neutrino fluxes depend both on C^2 and annihilation, giving an enhancement in the low and high m_0 regions where fluxes are boosted by annihilation (see figure 3 and 5). Since $M_\oplus < M_\odot$ and $\sigma_{\chi-p}^{scal} < \sigma_{\chi-p}^{spin}$, the capture rate and ν fluxes from the Earth are much smaller than from the Sun.

Comparing ν fluxes and μ fluxes, the $\nu \to \mu$ conversion factor increases with $m_{1/2}$ due to the increase of m_χ leading to more energetic neutrinos. This ratio also follows the annihilation final state regions described above. Indeed, spectra from WW, ZZ and $t\bar{t}$ are more energetic than $b\bar{b}$ spectra, so neutrino conversion into muon is more efficient in the mixed bino-higgsino
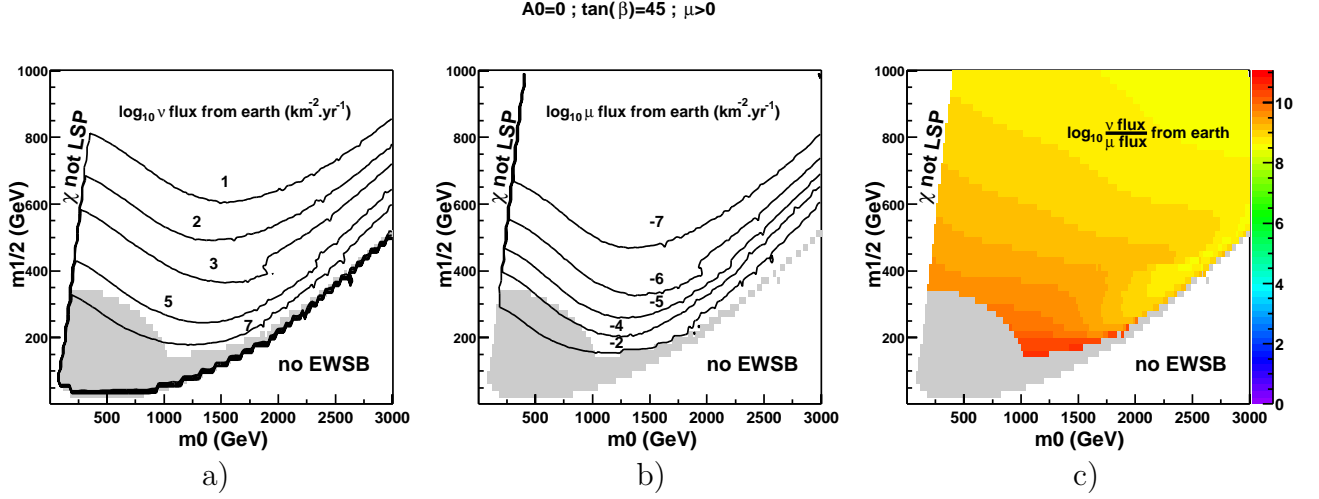
A0=0 ; tan(β)=45 ; μ>0

a)   b)   c)

Figure 5: ν fluxes from the Earth (a), the corresponding μ fluxes $E_\mu > 5$ GeV threshold (b) and their ratio (c).

region above W and top thresholds (see figure 4 and 5).

Comparison with Experimental sensitivities

Because of the very low value of $\nu(\mu)$ fluxes coming from neutralino annihilation in the Earth (figure 5), current and next generation experiments are not able to test the CMSSM on this signal. We can only compare current experiment sensitivities with the predictions for the Sun.
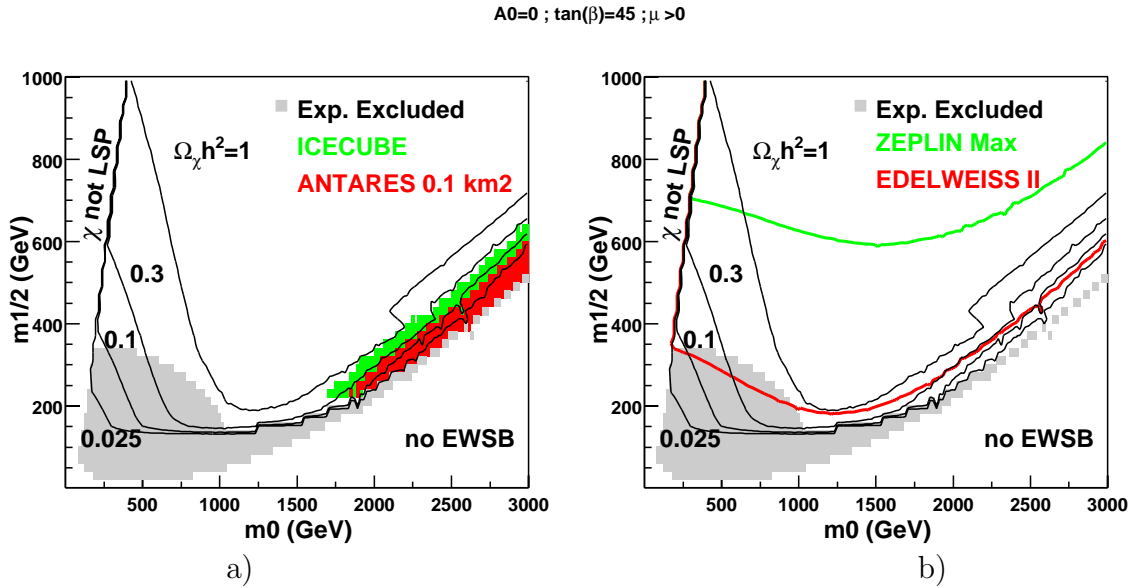
A0=0 ; tan(β)=45 ; μ >0

a)   b)

Figure 6: a) ν telescopes sensitivities on μ fluxes from the Sun and b) direct detection experiments sensitivities in the $(m_0, m_{1/2})$ plane.

mSugra with 5 GeV threshold vs neutrino Indirect Dection   **mSugra models vs Direct Detection**
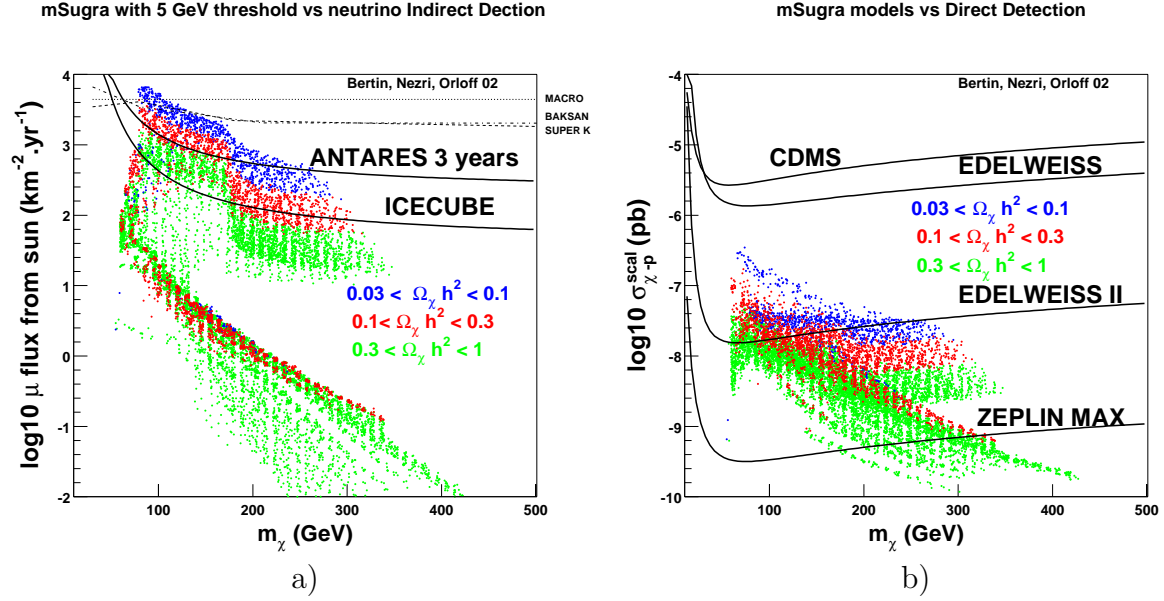

Figure 7: Neutrino indirect detection a) and direct detection b) sensitivities in the CMSSM.

Sensitivities of both neutrino indirect detection and direct detection experiments in the $(m_0, m_{1/2})$ plane are shown on figure 6 for $\tan\beta = 45$, $A_0 = 0$ and in the (signal; m_χ) plane on figure 7 for a wide sample of models. MSugra models predicting a good relic density of neutralinos give neutrino/muon fluxes which can be as high as the current experimental limits (Baksan [11], Macro [12], Super Kamiokande [13]). The 0.1 km^2 Antares detector will explore further the interesting parameter space [14]. Next generation neutrinos telescopes (Icecube, Antares km^3) will be much more efficient to test such models, $e.g$ Icecube expected sensitivity $\sim 10^2$ μ km^2 yr^{-1} from the Sun [15].

Indirect vs Direct detection (figures 6 and 7): a high neutralino-proton cross section is efficient in both direct and indirect detection (via capture). The large m_0 mixed higgsino-bino region pointed out in [3, 16] favours both direct and indirect detection due to the enhancement of $\sigma_{\chi-p}$ and $\sigma^A_{\chi-\chi}$. Both enter in the indirect detection which is moreover favoured by the production of more energetic neutrinos in WW, ZZ and $t\bar{t}$ decays, leading to better conversion into muons. This mixed region, which has a good relic density, is very attractive for neutrino indirect detection signal.

However, no current experiment is able to really test such models.

3   Short survey of other frameworks

Low energy MSSM

Severals studies [1, 17, 4] have been done in a low energy MSSM approach with more free parameters than in mSugra/CMSSM, especially m_A and μ, the latter leading more easily to an higgsino fraction as a dominant effect and high muon fluxes. This is shown on figure 8 extracted from [4]. It is clear that this kind of models exhibit less consistency and theoretical motivations but they allow to explore all phenomenologies that can not be tested with high energy models

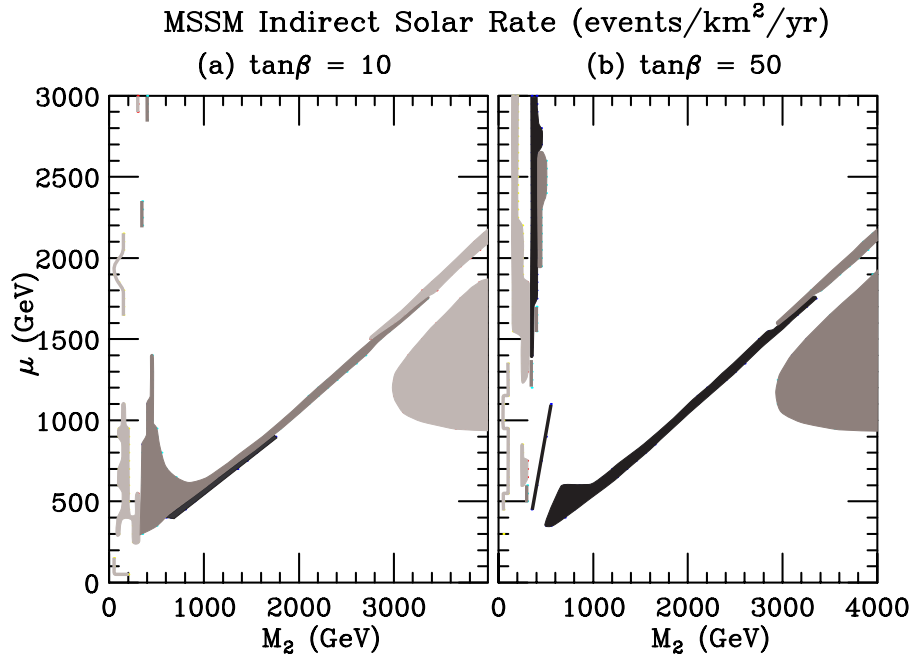because of the RGE evolution giving rise to a quite hierarchic SUSY spectrum.

MSSM Indirect Solar Rate (events/km^2/yr)

(a) tanβ = 10   **(b) tanβ = 50**

Figure 8: Low energy MSSM [4]: Regions of indirect detection rate of the neutralino dark matter in the (M_2, μ) plane with $M_{\text{SUSY}} = \text{MAX}(300 \text{ GeV}, 1.5 m_{\chi_1^0})$ for (a) $\tan\beta = 10$ and (b) $\tan\beta = 50$. The region with dark shading has $dN_{\text{ID}}/dA > 100$; the region with light shading has $dN_{\text{ID}}/dA < 10$; and the region with intermediate shading has $100 > dN_{\text{ID}}/dA > 10$ (event/km^2/year). The blank regions do not have a cosmologically interesting relic density $(0.05 \leq \Omega_{\chi_1^0} \leq 0.3)$ for the neutralino dark matter.

Non universality at GUT scale

An other possibility is to relax universality at high energy, keeping RGE treatment and radiative electroweak symmetry breaking [18].

This effect in the Higgs sector $(m_{H_1}^2|_{GUT} \neq m_{H_2}^2|_{GUT})$ has been studied in [19, 4, 20, 18] and allows lower values of μ and so higher muon fluxes more easily than in the universal case, but in a localised region. Typically in a $(m_0, m_{1/2})$ plane the region where radiative electroweak symmetry breaking *can not* be achieved is wider and the gradient of μ values along the boundary is more steeper than in mSugra/CMSSM.

Changing high energy gaugino mass relations can lead to more interesting effect, especially lowering $M_3|_{GUT}$ lead to wider region with cosmologically favoured neutralino relic density with strong enhancement of both direct and indirect detection rates [18].

4   Conclusion

Muon fluxes resulting from neutralino annihilations in the centre of the Earth are typically small. In RGE models, they are too low to be detected because of heavy scalars lowering capture rate $(\sigma_{\chi-p}^{scal})$, but the fluxes from this source can be enhanced in low energy models. The Sun

case can be interesting when the neutralino higgsino fraction lead to both a good relic density and high detection rates. This happens for heavy scalars along the radiative electroweak symmetry breaking boundary of the $(m_0, m_{1/2})$ plane in RGE models. Current neutrino indirect detection experiments are not sensitive enough to constrain RGE models, but future projects will be very efficient to test the Sun signal. This kind of information will be complementarity with accelerators since TeV's scalars are beyond reach of Tevatron or LHC. One also has to notice that RGE models giving high fluxes from the Sun have very small contribution to muon anomalous magnetic moment $g(-2)_\mu$ and would be ruled out in case of a real exclusion of $(g-2)_\mu^{SM}$. To finish a remark should be addressed on different predictions between authors mainly due to differences on the crucial μ parameter values due to differences between RGE codes in potential minimisation [21].

Acknowledgement

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