The Maximal Neutrino Flux from Neutralino Annihilation in the Galactic Center

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We discuss a robust and fairly model-independent upper bound on the possible neutrino flux produced by neutralino annihilation in the center of our galaxy, and show that its detection with present or future neutrino telescopes is highly improbable. This bound is obtained by relating the neutrino flux to the gamma flux that would be produced in the same annihilation processes, for which measurements do exist.

1 Introduction: Neutralino Dark Matter

A large number of cosmological observations on scales ranging from galactic or cluster sizes up to the cosmological horizon itself, clearly show that known matter (baryons) and radiation (photons, and neutrinos in a certain sense) gravitationally coupled by general relativity fail to provide a complete description of the observed Universe. In this scientifically challenging situation, some necessarily new ingredient is needed. Modifications of gravity have been proposed, that can reasonably cope with the galactic (newtonian) scales but require more work before being extended to the largest (relativistic) ones.

Another perhaps less drastic and more testable possibility, is to keep gravity intact and just imagine some new neutral (and thus dark) matter[1]. After all, the progresses of particle physics in the last fourty years have provided countless examples of new particles that could easily incarnate such new dark matter, except that their lifetimes are extremely short on a cosmological timescale. Another new particle χ is thus needed. It should be the least ad-hoc possible, and possess a cosmological lifetime. This requires an extremely small effective coupling $\alpha_\chi \doteq \Gamma_\chi/m_\chi < 2 \times 10^{-42}\mathrm{GeV}/m_\chi$. Since $n-$loop processes generically give much too large contributions of the order $\alpha^n_{QED,EW,QCD}$, a new symmetry is also needed to guarantee their vanishing. For these reasons, supersymmetry emerges together with R-parity to stabilize the lightest supersymmetric particle. The neutralino, a mixture of the SUSY partners of scalars and electroweak gauge bosons, is a well studied and fairly predictive dark matter candidate. Its relic density Ω_χ for instance, if determined from CMB measurements, fixes the annihilation cross-section $\sigma_{\chi\chi}^{ann} \sim \Omega_\chi^{-1}$ which in turn puts constraints on the particle physics model. This is because neutralinos once reached a status a thermodynamical equilibrium, which erased all memory of initial conditions. For the plots below[2], we considered CMSSM (a.k.a mSugra) models with the following parameters: 50GeV $< m_0 <$ 4TeV, 50GeV $< m_{1/2} <$ 2TeV, $A_0 = 0$, $\tan\beta = 5,\ 20,\ 35$. We also considered the deviations from gaugino universality at the Grand Unification scale $M_2|_{GUT} = 0.6 m_{1/2}$ or $M_3|_{GUT} = 0.6 m_{1/2}$ (instead of $1 m_{1/2}$), which have the most important effects on annihilation.

2 Indirect Detection: Uncertainties and Interest of the Galactic Centre

The indirect detection of dark matter is first a hunt for places where dark matter can be sufficiently concentrated to start its self-annihilation again. The annihilation products (gammas, neutrinos, antiparticles...) can then be looked for. Naively, one would guess that fixing the annihilation cross-section to comply with WMAP measurements, also fixes the indirect detection signal. This not quite so for three reasons.

First, the annihilations that occur at freeze-out involve higher kinetic energies than the later annihilations for indirect detection, which occur essentially at rest. Certain annihilation processes are then forbidden for symmetry reasons. The channel dominating the annihilation rate, and thus the controlling parameters, can be different.

Second, depending on the annihilation product looked for, and on the experimental sensitivity that can be achieved, different annihilation channels may become relevant[4]. For instance, in neutrino indirect detection, high energy neutrinos are both easier to detect and less numerous in the background. This makes the annihilation channels which proceed via a pair of gauge bosons (each of which can deposit half its energy in a neutrino) more relevant than channels proceeding through a pair of light quarks (which mostly fragment into hadronic cascades with little energy left for a neutrino).

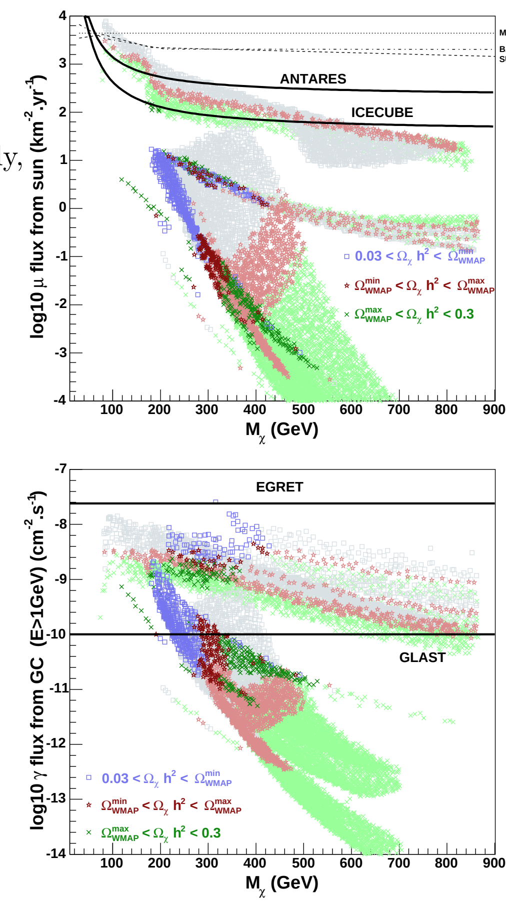

Figure 1: Indirect detection signals and experimental sensitivities: (top) neutrino-induced upgoing muon flux above 25 GeV from neutralinos annihilating in the Sun; (bottom) γ flux above 1 GeV from the GC, assuming a NFW profile with $J = 1300$; here and below, shades paler than in the legend denote models with a low, SM-like anomalous dipole moment of the muon $\delta_\mu^{susy} < 8.1\,10^{-10}$.

Finally, the flux of annihilation products goes like the square of the neutralino density. For neutralinos trapped in the gravitational wells of celestial bodies like the earth or the sun, this is fixed by how fast elastic collisions on the matter making these bodies can slow down neutralinos below the escape velocity. Although the cross section for elastic collision *on matter* is related to the cross section for annihilation *into matter* by crossing symmetry, the dominating amplitude and the relevant parameter may differ.

All these effects pile up to induce a large variability in indirect detection signals. This is illustrated on top Fig. 1 for the neutrino signal from annihilation of neutralinos captured inside the Sun: constraining the relic density within the 13% WMAP[3] uncertainties $\Omega_M h^2 = 0.135^{+0.008}_{-0.009}$ still leaves a 7 orders of magnitude room for the signal.

Our Galactic Center (GC) provides another, even deeper potential well than the sun, and thus possibly larger indirect detection fluxes. However, the variability in these signals resulting from the unknown dark matter density profile is even larger. Indeed this profile can only be inferred from the dynamics of sources orbiting our Galactic Center, which feel the total mass inside radius R: $M_\chi(R) = 4\pi \int^R dr\, r^2 \rho_\chi(r)$, where the small r contribution is strongly supressed. On the other hand, indirect detection signals are proportional to the squared density integrated along the line of sight in a direction ψ, often parametrized by $J(\psi) = (8.5\,\mathrm{kpc})^{-1}(0.3\mathrm{GeV/cm}^3)^{-2} \int_{l.o.s} ds\, \rho_\chi^2(r(s,\psi))$, which in the direction of the GC can vary from 30 (isothermal profile) to over 10^5 (Moore profile) or even more in the presence of an accretion spike on the GC Black-Hole. Even fixing this J factor to an intermediate NFW value of 1300 (as in bottom Fig. 1), the first two reasons above leave a three orders of magnitude range for the photon indirect detection signal from the GC. Larger values of J can bring certain particle models within the reach of EGRET. For the neutrino indirect detection signal from the GC, the situation is qualitatively the same, except that the larger gap between signal and experimental sensitivities requires larger values of J for observation. However such large values would imply a huge photon signal, that has not been seen.

3 A Model Independent Upper Bound

The observed photon flux from the GC clearly gives an upper bound on the photon flux from neutralino annihilation in the GC, which can be translated into an upper bound on the neutrino flux from the GC.[2] Indeed for a given dark matter candidate and particle physics contents, the ratio between the number of photons and the number of neutrinos emitted per annihilation is known. We can thus estimate the neutrino flux from the GC associated with a gamma-ray emission reproducing the EGRET data. Finally we can convert the flux of neutrinos into a flux of muons, produced by neutrinos interactions with the rock around detectors on Earth, in order to compare with experimental sensitivities.

The rescaled flux of muons $\phi_\mu^{\mathrm{norm}}(> E_{th})$ will thus be given by

$$\phi_\mu^{\mathrm{upper}}(> E_{th}) = \frac{\phi_\mu^{\mathrm{NFW}}(> E_{th})}{\phi_\gamma^{\mathrm{NFW}}(E_*)}\, \phi_\gamma^{\mathrm{EGRET}}(E_*) \qquad (1)$$

where the label NFW reminds that NFW profiles have been used to compute the (profile-independent) flux ratio, and E_* is the energy at which we decide to normalize the flux to the gamma-ray data (in our case $E_* = 2\mathrm{GeV}$). The results are shown in the left Fig.. 2. The ratio in (1) is by construction independent of J, but it also turns out to be rather model-independent: for a given neutralino mass, it spans less than a factor 10, which can be traced to the dominant annihilation channel. The comparison with Antares sensitivity shows that only the highest neutralino masses above 650 GeV can possibly be detected in the Galactic centre.

However, for such large masses, a higher choice of photon energy E_* would allow to tighten this upper bound. To crudely evaluate how much, we show in Fig. 2-right the photon flux above 60 GeV that should come together with the EGRET flux if it were 100% due to neutralino annihilation in the GC. The fact that HESS actually sees a smaller flux implies that at most 1% can be attributed to neutralinos above 650 GeV, which lowers the possible neutrino flux by as much for these masses. An update of Fig. 2-left including the most recent photon fluxes from the GC remains to be done, but the resulting neutrino upper bound should flatten out for neutralinos above 300 GeV, leaving little hope for neutrino telescopes.

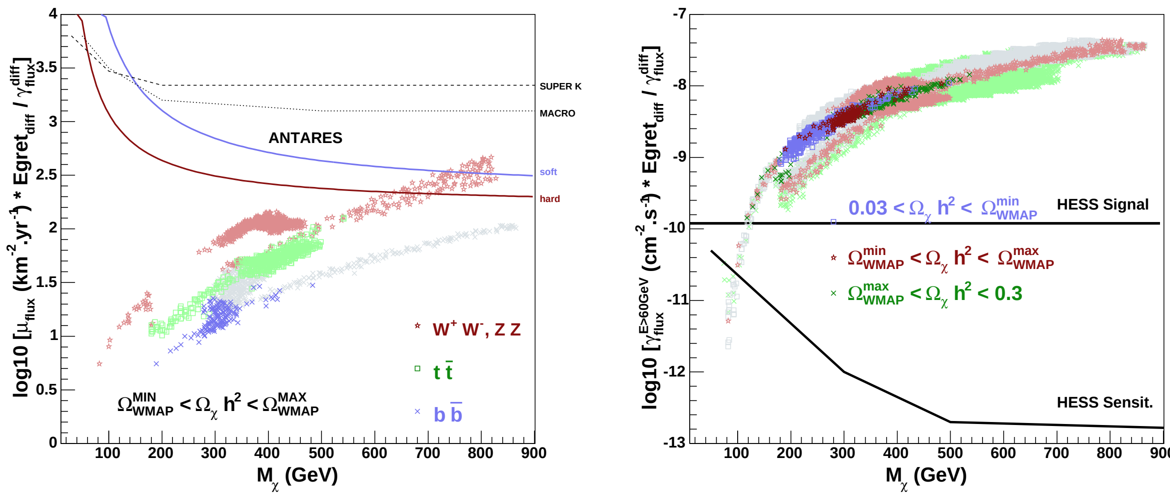

Figure 2: (left) Neutrino-induced muon flux from the Galactic centre normalized to EGRET, sorted by leading ($\equiv BR > 0.4$) annihilation channel for the preferred WMAP relic density; (right) the photon flux (above 60 GeV) normalized to EGRET, together with the planned HESS sensitivity above 60 GeV and the actual signal (with a higher threshold).

4 Discussion and loopholes

If neutrinos are nevertheless observed above the given fluxes, their interpretation as due to neutralino annihilation is problematic. The only possibility would then be to invoke selective absorption of the photons by electrons in the GC. However the photon mean free path being $\lambda_\gamma \approx 100\text{kpc}(E_\gamma/1\text{GeV})(10^5\text{cm}^{-3}/n_e)$, this would require huge electron densities.

Switching to other dark matter candidates, like Kaluza-Klein resonances[5], allows to increase the hard neutrino flux above the bound presented here. Indeed, neutralinos cannot annihilate into a hard neutrino anti-neutrino pair because of their Majorana nature. However, no natural candidate annihilates *only* into neutrinos, so that the present bound can only be relaxed by a factor $\approx 1/(1 - BR(\nu\bar{\nu}))$.

Finally, one may wonder if astrophysical sources other than dark matter annihilation could provide detectable neutrino fluxes, within the realm of the Standard Model. This question has recently been adressed[6] similarly using relations between the photon and neutrino fluxes, with a more positive conclusion.

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