Closing the Window on Strongly Interacting Dark Matter with IceCube

Ivone F. M. Albuquerque[1,2] and Carlos Pérez de los Heros[3]

[1]*Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL, 60510. USA*
[2]*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
[3]*Department of Physics and Astronomy. Uppsala University. Uppsala. Sweden*

(Dated: February 16, 2010)

We use the recent results on dark matter searches of the 22-string IceCube detector to probe the remaining allowed window for strongly interacting dark matter in the mass range $10^4 < m_X < 10^{15}$ GeV. We calculate the expected signal in the 22-string IceCube detector from the annihilation of such particles captured in the Sun and compare it to the detected background. As a result, the remaining allowed region in the mass versus cross section parameter space is ruled out. We also show the expected sensitivity of the complete IceCube detector with 86 strings.

PACS numbers: 95.35.+d, 95.85.Ry
Keywords: Super-heavy dark matter, Simpzillas, IceCube

I. INTRODUCTION

The search for dark matter is currently one of the most active fields of research in experimental astroparticle physics. Common candidates are weakly interacting massive particles (WIMPs), with only weak and gravitational interactions with normal matter, and which encompass a variety of particle types in the mass range from a few tens of GeV to a few hundred TeV, where the upper limit is based on theoretical arguments to preserve unitarity [1]. Among WIMP candidates are the lightest neutralino arising in the Minimal Supersymmetric Extension of the Standard Model (MSSM), or the lightest Kaluza-Klein mode in models of Universal Extra Dimensions (UED) [2]. These candidates are thermal relics from the Big Bang, and since they are stable, assumed to be able to contribute to the dark matter content in the halos of galaxies.

In a different scenario, it has been shown that supermassive particles can be produced in the early Universe and account for dark matter, independently of their interaction strength with normal matter. In order to avoid the mass limit imposed by unitarity constraints, one can model non–thermal production of super-massive particles [3, 4]. The large mass will prevent the particle to ever get into thermal equilibrium with the primordial plasma. Super-massive dark matter candidates were coined wimpzillas [5] if assumed to interact weakly with matter and simpzillas [6] if the interaction is strong. The production mechanism discussed in [3, 4] favours particles with masses of the order of the inflaton mass ($\sim 10^{12}$ GeV), but particles of masses as low as a few hundred GeV can also be produced, normally denoted as strongly interacting massive particles (SIMPs). Although SIMPs are in general taken to be in the mass range $\sim 10^4 \lesssim m_X \lesssim 10^8$ GeV, and simpzillas, with masses $m_X > 10^8$ GeV, we will generically call them either simpzillas.

Searches for simpzillas have been carried out in a variety of ways in the past. Figure 1 shows the current exclusion region in the mass versus simpzilla–nucleon cross section parameter space. The "Mine/Space" region (blue square hatched) was ruled out by many different experiments underground or space-borne [7, 8] [1]. More recently, a search for simpzillas using results from direct detection experiments excluded most of the remaining parameter space for high masses (solid yellow, labeled "Direct") [9]. A recent analysis further constrained the allowed region by using the Earth heat flow to set constrains on the annihilation of captured dark matter in the Earth's center (green striped, labelled "Earth heat") [10]. The blank triangular regions in Figure 1 remained unprobed until this work.

Whether thermally produced or not, stable dark matter candidates can gravitationally accumulate as a halo in our galaxy, becoming bound in orbits in the solar system. Further energy losses can occur in elastic interactions with matter in large celestial bodies, like the Sun. If they lose enough energy they can fall below the escape velocity of the object, accumulating in its center and annihilating therein [11–13]. Neutrinos of energies $O(100$ GeV) can be produced from the decays of the annihilation products. This allows for an 'indirect search' for dark matter with neutrino telescopes, based on a search for an excess neutrino flux from the direction of the Sun over the known atmospheric neutrino background. Predictions of simpzilla event rates and neutrino telescopes sensitivity have been anticipated in [14].

In this paper we explore the capabilities of IceCube to detect high-energy neutrinos from simpzilla annihilations in the Sun. The baseline IceCube geometry consists of 80 strings with 60 digital optical modules each, instrumenting 1 km^3 of ice at depths between 1450 m–2450 m near the geographic South Pole [15]. Recently, an addition of six strings forming a denser core in the middle of the IceCube array has been proposed in order to lower the neutrino energy threshold of the detector to about 10 GeV, the so–called "DeepCore" array [16].

[1] Note that part of the exclusion region shown in [8] and reproduced in [10] was corrected in [7]

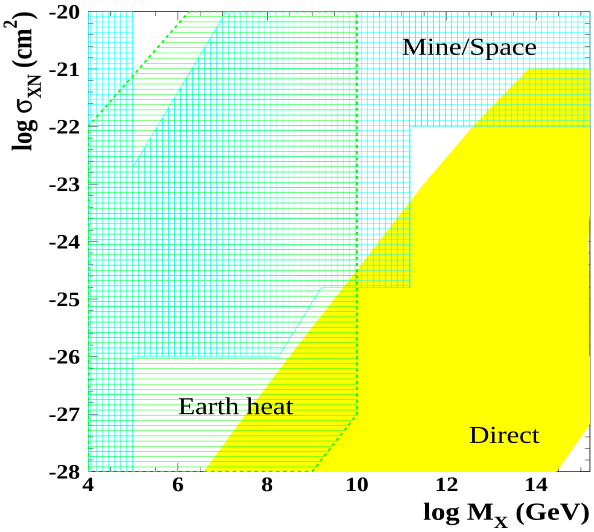

FIG. 1: Excluded region at 90% C.L. in the simpzilla mass versus cross section parameter space. The region labeled "Direct" (solid yellow region) was excluded based on direct dark matter detection [9]; the "Earth heat" region (green striped) is excluded based on the Earth's heat flow [10] and the blue square–hatched "Mine/Space" region is based on many experiments, underground and space-borne [7, 8].

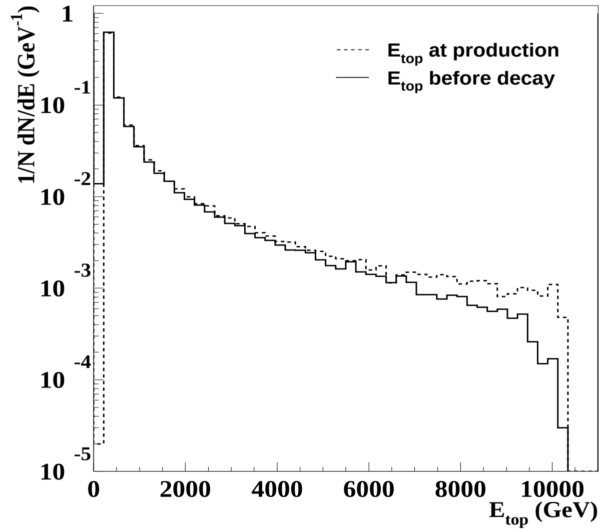

FIG. 2: Energy distribution of the top quarks produced in simpzilla annihilations at production point (dashed line) and before decaying (full line). The figure shows that initial-state gluon radiation does not play an important role in degrading the energy of the tops before they decay.

Although the IceCube geometry has been optimized to detect ultra-high energy (>TeV) neutrinos from potential cosmic sources with sub-degree angular resolution, its angular response is still adequate at O(100 GeV) to perform directional searches for dark matter. IceCube has recently published results on the searches for WIMPs arising in the MSSM [17] or the simplest UED model [18] using 22 strings deployed in the 2006/2007 Antarctic season. In this work we use this 22-string detector (hereafter referred to as IceCube-22) which took data during the 2007 austral winter. We set a limit in the simpzilla mass, m_X, versus simpzilla-nucleon cross section, σ_{XN}, phase space using the fact that IceCube-22 has not detected any neutrino excess from the direction of the Sun. We also estimate the sensitivity of the full IceCube detector in its expected final configuration with 86 strings (hereafter referred to as IceCube-86).

II. NEUTRINO SPECTRUM FROM SIMPZILLA ANNIHILATIONS

In order to estimate the neutrino rate from simpzilla annihilations in the Sun, we use the capture rate, as well as the full-flavour neutrino flux and energy spectrum at the core of the Sun as determined in [6]. We then simulate the neutrino propagation to the Earth, including energy losses and oscillation effects.

The capture rate, Γ_c, depends on the mass of the simpzilla, m_X, and the strength of the interaction of simpzillas with nucleons, σ_{XN}. The capture efficiency can be described by the parameter $q = \frac{m_X}{m_N\, n_N\, \sigma_{XN} R_\odot}$, where m_N is the average nucleon mass, n_N is the number density of nucleons in the Sun and $R_\odot$ is the radius of the Sun. For large cross sections, $q \leq 1$, and simpzillas lose enough energy in their passage through the Sun to be efficiently captured. The capture rate (in s^{-1}) is then given by

$$\Gamma_c = 10^{17}(1+y^2)\left(\frac{10^{12}\,\mathrm{GeV}}{m_X}\right)\times \times\left(\frac{u_{th}}{240\,\mathrm{km\,s^{-1}}}\right)\left(\frac{R_\odot}{7\times10^{10}\mathrm{cm}}\right)^2 \quad (1)$$

On the other hand, if q>1, capture is determined by the relative velocity, and only low velocity simpzillas are trapped. In such case, the capture rate is

$$\Gamma_c = 10^{17}[1+y^2-e^{-x^2}(1+y^2+x^2)]\left(\frac{10^{12}\,\mathrm{GeV}}{m_X}\right)\times \times\left(\frac{u_{th}}{240\,\mathrm{km\,s^{-1}}}\right)\left(\frac{R_\odot}{7\times10^{10}\mathrm{cm}}\right)^2 \quad (2)$$

where in the above expressions

$$y = 2.5\left(\frac{v_\odot}{600\,\mathrm{km\,s^{-1}}}\right)\left(\frac{u_{th}}{240\,\mathrm{km\,s^{-1}}}\right)^{-1} \text{ and } x = \frac{y}{\sqrt{q-1}} \quad (3)$$

and u_{th} is the speed of the Sun in the galaxy and $v_\odot$ is the Sun escape velocity. Note that if σ_{XN} goes to zero, then the capture rate goes to zero through its dependency on x, as it is expected.

The simpzilla capture rate is large enough to reach equilibrium with the annihilation rate, Γ_A, in the lifetime of the solar system, and therefore we can assume $\Gamma_A = \Gamma_c/2$.

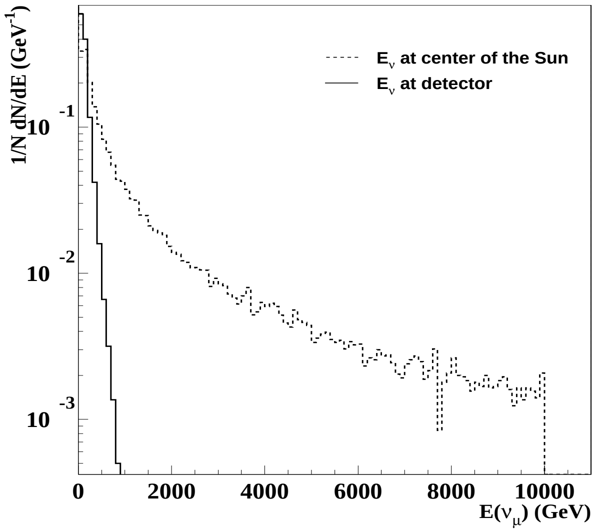

FIG. 3: Muon-neutrino energy distribution from top decays at the center of the Sun (dashed) and at the IceCube location (full line), after energy losses and oscillations have been taken into account.

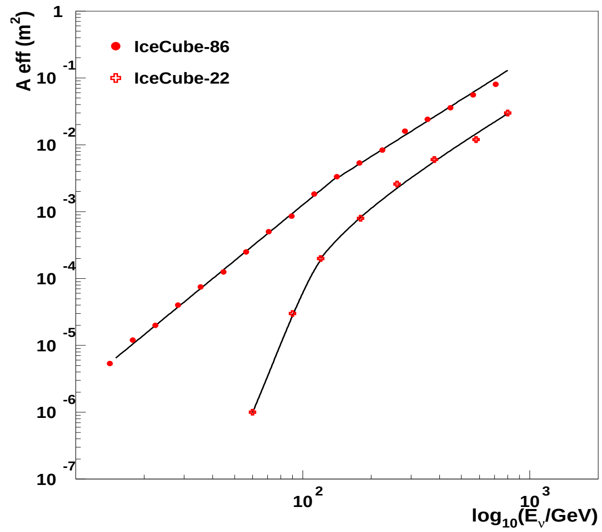

FIG. 4: Neutrino effective area of IceCube, both the 22-string detector and an estimation for the planned 86-string final configuration, as a function of neutrino energy.

The neutrino spectrum from simpzilla annihilations is modeled as producing a pair of quarks or gluons, which will fragment into high multiplicity hadronic jets. Long-lived light and charmed hadrons will lose energy through interactions in the dense solar interior before decaying, producing low energy neutrinos. On the other hand, due to its short lifetime, $\sim 10^{-25}$ s, the top quark will not have time to hadronize or lose energy through interaction in the medium before decaying into Wb. The W then decays into $l\nu_l$, with similar probability into each flavour $l = e, \mu, \tau$. Annihilations into top quarks is therefore a promising channel to produce high energetic neutrinos detectable by neutrino telescopes. Bottom quarks are also a potential source of high energy neutrinos [6]. However in this work we only consider neutrinos produced from the top decay chain, which makes our results conservative. Note that although the initially available energy for each top is very high (the mass $\mathrm{m_X}$ of the simpzilla), the available phase space is shared among many produced particles ($2.8\times10^5\sqrt{m_{\mathrm{X}/12}}$ tops are produced per annihilation [6], where $m_{\mathrm{X}/12}$ is the mass of the simpzilla in units of 10^{12} GeV), so the average energy per produced particle is of O (TeV). The main consequence of this is that initial-state gluon radiation can be neglected, not playing an important role in further degrading the energy of the tops before they decay. This is illustrated in Figure 2, which shows the energy distribution of the tops at the production point (dashed line) and just before decaying (full line), obtained with a full `PYTHIA` [19] simulation.

Taking into account the above considerations, the energy distribution of the neutrinos produced from top decays at the center of the Sun can be parametrized as

$$\frac{dN}{dE_\nu} \propto \frac{E_\nu + \mathrm{m_W}}{\sqrt{(E_\nu + \mathrm{m}_t)[(E_\nu + \mathrm{m}_t)^2 - \mathrm{m}_t^2][(E_\nu + \mathrm{m_W})^2 - \mathrm{m_W^2}]}} \tag{4}$$

where $\mathrm{m_W}$ and m_t are the W boson and top quark masses respectively, and we have omitted a constant normalization factor.

The energy dependence of the neutrino flux at the detector (Earth) will be modified by neutrino energy losses in their way out of the Sun and by oscillations. In order to include these effects we use the publicly available Wimpsim code [20], which we have modified so it takes the neutrino spectrum from equation (4). We use as input the three flavours with their correct relative intensity from the top decay chain. Figure 3 shows the injection spectrum of muon neutrinos at the Sun from simpzilla annihilations according to equation (4) (dashed line), and the resulting spectrum at the Earth (full line). The injection spectrum has been truncated at 10 TeV for display purposes. As mentioned earlier, the initial energy available in the annihilation is shared among an enormous amount of annihilation products and, furthermore, the energy of the resulting neutrinos is further reduced by energy losses in the Sun. The spectrum at the detector is therefore not very different from those of lighter dark matter candidates, like MSSM neutralinos or Kaluza-Klein modes. This allows us to use IceCube-22 background determination found in both WIMP and Kaluza-Klein dark matter analysis [17, 18]. Since IceCube is mainly sensitive to muon neutrinos through the detection of muon tracks, we only use the muon-neutrino flux at the detector for our calculations in what follows.

III. RESULTS FROM ICECUBE-22

The number of signal events, N_s, from simpzilla annihilations in the Sun predicted in a neutrino telescope of effective area A_{eff} during an exposure time T, is given by

$$N_s(m_X, \sigma_{XN}) = N_t \cdot BR_W \cdot \Gamma_A(m_X, \sigma_{XN}) \cdot T \cdot \int \frac{dN_\nu}{dE} A_{eff}\, dE \quad (5)$$

where dN_ν/dE is the muon neutrino flux at the detector, N_t is the number of tops per annihilation, BR_W is the branching ratio of W decaying into neutrinos (0.326) and Γ_A is the annihilation rate in the center of the Sun. The effective area is a measure of the efficiency of the detector and includes the neutrino-nucleon interaction probability, the energy loss of the produced muon from the interaction point to the detector and the detector trigger and analysis efficiency.

In order to compare our expected signal with IceCube-22 observations, we use the neutrino effective area of IceCube-22 published in [18], and shown in Figure 4. In 104.3 days of live time IceCube-22 has detected 13 events from the direction of the Sun, while the expected number of atmospheric neutrinos is 18.5 [18]. The expected signal strength for the given live time is shown in Figure 5. We have assumed a 15% uncertainty in the expectation of the atmospheric neutrino flux at the relevant energies ($E_\nu \geq$50 GeV) in order to calculate the 90% CL upper limit on a possible signal, μ_s^{90}, following the prescription in [21]. We obtain $\mu_s^{90} = 3.1$. A scan in the (m_X, σ_{XN}) parameter space, selecting models that predict less events than μ_s^{90} leads to the 90% CL exclusion region shown in Figure 6 (read cross–hatched area). The results disfavour a large region of the parameter space, and we discuss their significance in section V.

IV. SENSITIVITY OF THE COMPLETED ICECUBE-86 DETECTOR

The sensitivity of the completed IceCube detector can be estimated from the expected number of background events (due to atmospheric neutrinos) and the detector effective area. An estimation of the expected effective area of IceCube-86 at trigger level has been given in [16]. Previous analyses of IceCube and AMANDA show that the effective area is reduced between a factor of 5 to 10 between trigger level and the final analysis level, due to the cuts that are applied to clean the data sets and select high quality tracks. We have taken a conservative approach here and we have reduced the trigger effective area given in [16] by a factor between 15 for low energies down to 5 at the higher energies, and used that as our estimate of where the effective area of IceCube-86 at a final analysis level might be. The curve used is shown as the upper curve in Figure 4.

We have calculated the number of atmospheric neutrino events in IceCube using the measured atmospheric neutrino flux by AMANDA [22]. We parametrized the curve in Figure 10 in [22] as $dN_\nu^{atm}/dEd\Omega$ = A $E^{-\gamma}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}, with A=0.11407 and $\gamma = 3.142$. The expected number of atmospheric neutrino events in IceCube-86 from the direction of the Sun in a exposure time T is then given by $N_\nu = T \cdot \int dN_\nu^{atm}/dEd\Omega\, A_{eff}\, dE\, d\Omega$, where the angular integration is performed over the 0.5° that the Sun subtends in the sky. We have assumed no contamination of misreconstructed atmospheric muons in the final sample, and therefore we use only the 3.4 atmospheric neutrino events from the direction of the Sun predicted by the integral above in 365 days live time. As in the previous section, we have used a 15% uncertainty on the overall normalization of the atmospheric neutrino flux, as also indicated by the AMANDA measurement, and calculated the sensitivity including this uncertainty. The 90% CL exclusion region from IceCube-86 is shown in Figure 6 as the black line. It agrees well with the predictions made in [14].

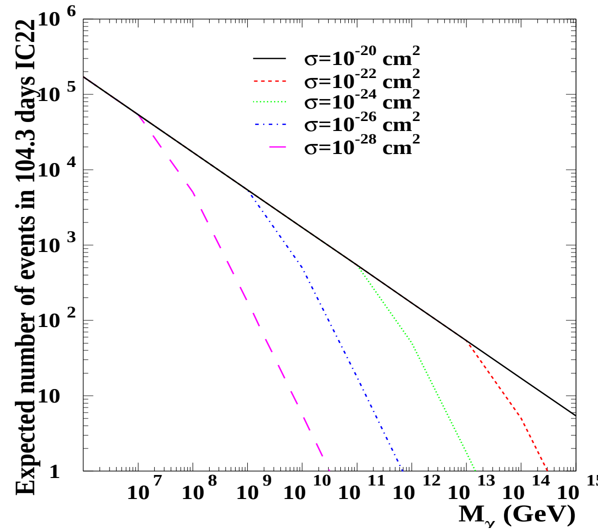

FIG. 5: Expected number of events in the IceCube-22 detector, in 104.3 days of lifetime. The rate is determined by our simulations and is shown for five different values of the cross section as labeled.

V. CONCLUSIONS

We have used recently published results from the 22-string IceCube detector on WIMP dark matter searches [17, 18] to extend the search to strongly interacting dark matter candidates in the mass range $\sim 10^4 \lesssim m_X \lesssim 10^{15}$ GeV. The fact that the IceCube results are compatible with the expected atmospheric neutrino background allows us to set restrictive limits on the mass versus nucleon cross section parameter space.

A note on the complementarity of direct and indirect

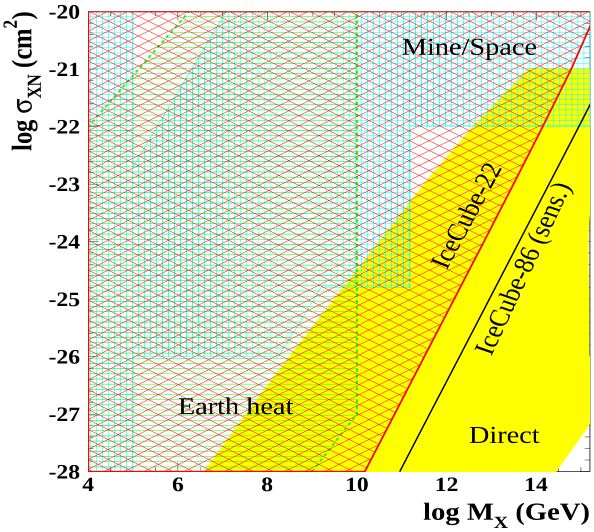

FIG. 6: Disfavoured region in the (m_X, σ_{XN}) parameter space at 90% confidence level from IceCube-22 (red cross–hatched area), overlayed with results from previous experiments: direct searches [9] (solid yellow area), space-borne detectors [7] (blue square–hatched area) and Earth heat flow analysis [10] (green striped area). The black line represents the 1 year expected sensitivity of the completed IceCube detector.

searches is due at this point. Generally, the total cross section with nucleons, σ_{XN}, can have at least two contributions, a spin-independent (or scalar) component and a spin-dependent (or axial-vector) component, the relative strength of each depending on the exact assumptions made on the structure and interaction of the simpzilla. There is no detailed modelling in the literature of the way that simpzillas interact with matter, other than the interaction is assumed to be "strong", as opposed to weak as in the case of WIMPs. However for experimental searches such distinction is important because different experiments probe different components of the cross section. The results from the experiments shown in Figure 1 refer mainly to the spin-independent component of the simpzilla-nucleon cross section, due to the nature of the targets involved or, in the case of the Earth heat flow analysis, due to the fact that the capture of dark matter candidates in the Earth proceeds mainly through scattering on spinless nuclei (Fe, Si, O, Mg). On the other hand the IceCube results are sensitive to the spin-dependent cross section since the Sun is the target for capture, which is essentially a proton target.

In view of the previous considerations, the current results from IceCube provide the most restrictive limits so far on the spin-dependent cross section of simpzillas. The fact that they overlap in the (m_X, σ_{XN}) parameter space with previous exclusion regions from experiments which probe mainly the spin-independent cross section, practically rules out simpzillas as dark matter. It would require an unreasonably narrow fine tuning of the mass and the structure of the cross section to propose a viable candidate that would evade all the current limits.

In conclusion, strongly interacting heavy relics from the early Universe can only account for the dark matter if they have masses above 10^{15} GeV. As these ultra heavy masses are not currently favored by any model, the window for simpzillas as the only component of dark matter can be considered closed.

Acknowledgments: We thank T. Sjöstrand for his kind help with `Pythia`. IA was partially funded by the U.S. Department of Energy under contract number DE-AC02-07CH11359 and the Brazilian National Counsel for Scientific Research (CNPq)

[1] K. Griest and M. Kamionkowski. Phys. Rev. Lett. **64**, 615 (1990).
[2] D. Hooper and S. Profumo. Phys. Rep. **453**, 29 (2007).
[3] D. J. H Chung, E. W. Kolb and A. Riotto. Phys. Rev. **D59**, 023501 (1998).
[4] D. J. H Chung, E. W. Kolb and A. Riotto. Phys. Rev. **D60**, 063504 (1999).
[5] D. J. H Chung, E. W. Kolb and A. Riotto. Phys. Rev. Lett. **81**, 4048 (1998).
[6] I. F. M. Albuquerque, L. Hui and E. W. Kolb. Phys. Rev. **D64**, 083504 (2001).
[7] P. C. McGuire and P. J. Steinhardt. Proceedings of the 27th International Cosmic Ray Conferences (ICRC 2001), Hamburg, Germany, Aug 2001. `astro-ph/0105567`.
[8] G. D. Starkman, A. Gould, R. Esmailzadeh and S. Dimopoulos, Phys. Rev. D **41**, 3594 (1990).
[9] I. F. M. Albuquerque and L. Baudis, Phys. Rev. Lett. **90**, 221301 (2003).
[10] G. D. Mack, J. F. Beacom and G. Bertone, Phys. Rev. **D76**, 043523 (2007).
[11] W. H. Press and D. N. Spergel. Astrophys. J. **296**, 769 (1985);
[12] T. K. Gaisser, G. Steigman and S. Tilav. Phys. Rev. **D34**, 2206 (1986).
[13] A. Gould. Ap. J. **328**, 919 (1988).
[14] I. F. M. Albuquerque, J. Lamoureux and G. F. Smoot, Phys. Rev. **D66**, 125006 (2002).
[15] J. Ahrens *et al.* Astropart. Phys.**20**, 507, (2004)
[16] C. Wiebusch *et al.* Proceedings of the 31st International Cosmic Ray Conferences (ICRC 2009), Lodz, Poland, July 2009. `arXiv:0907.2263`.
[17] R. Abassi *et al.* Phys. Rev. Lett. **102**, 201302 (2009).
[18] R. Abassi *et al.* arXiv:0910.4480.
[19] T. Sjöstrand, S. Mrenna and P. Skands, JHEP05, 025, (2006) http://home.thep.lu.se/~torbjorn/Pythia.html.
[20] J. Edsjö, WimpSim Neutrino Monte Carlo, http://www.physto.se/~edsjo/wimpsim/
[21] W. A. Rolke, A M. López and J. Conrad. Nucl. Instrum. Meth. **A551**, 493-503 (2005).
[22] R. Abassi *et al.* Phys. Rev. **D79**,102005 (2009).