Muon Fluxes From Dark Matter Annihilation [a]

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- The muon neutrino flux from WIMP annihilation → detectable muons, model-independent calculation.

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[a] A.E. Erkoca, M.H. Reno and I. Sarcevic, hep-ph/0906.4364 **(2009)**

OUTLINE

- Introduction
- Dark Matter Capture in the cores of the astrophysical objects
- Muon Flux
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Introduction

- Several different observations imply the existence of cold (non-relativistic) dark matter $\sim 23\%$, and only 4% of the total density of the Universe can be attributed to the baryonic matter ⇒ new physics explanations are required.
- Some candidates : WIMPs, axions, solitons, ...
- a WIMP of mass ∼ 100 GeV can account for the observed density of dark matter.

$$\Omega_X h^2 = 0.1 \left(\frac{< \sigma v >_{f.o}}{3 \times 10^{-26} cm^3/s} \right)^{-1}$$

Collider experiments (e.g. LHC) will explore the new scale physics in the near future ⇒ possible to detect dark matter particles, however, not possible to determine the stability or abundance.

- independent and complementary searches : direct and indirect experiments.
  - ⋆ Direct Searches : They look for energy deposition via nuclear recoils from WIMP scattering by using different target nuclei and detection strategies, try to observe the same WIMP mass and couplings, provide upper bounds on spin-independent $\sim 10^{-7}$ pb (XENON,CDMS) and spin-dependent $\sim 0.01 - 1.0$ pb (XENON,Super-K, KIMS, COUPP, NAIAD) WIMP-nucleon cross sections. only positive signal → DAMA modulation signal.
  - ⋆ Indirect Searches : They look for positron, antiproton, γ ray and neutrino signals from dark matter annihilation process. In recent years, an excess in the positron fraction (HEAT, PAMELA, ATIC, PPB-BETS), in the flux of 1-10 GeV diffuse (extra-)galactic γ rays (EGRET), very bright emission of 511 keV photons (INTEGRAL), ... were observed → may all have dark matter origin.

IceCUBE : 1 km^3 neutrino detector being built at the South Pole [a]

- detects Cherenkov radiation from the charged particles produced in neutrino interactions and has 4800 optical sensors attached to 80 vertical strings which are deployed in a hexagonal array.
- has a very good timing resolution $\Rightarrow$ to be able to find the vertices of the contained events.
- will be able to distinguish different neutrino flavors.

KM3Net : a future deep-sea research infrastructure which hosts a neutrino telescope with a volume $\sim$ 1 km^3 [b]

- an angular resolution better than 0.1 degree for $E_\nu \geq 10$ TeV
- sensitive to neutrino flavors and to neutral current interactions
- will be unique in the world in its physics sensitivity.

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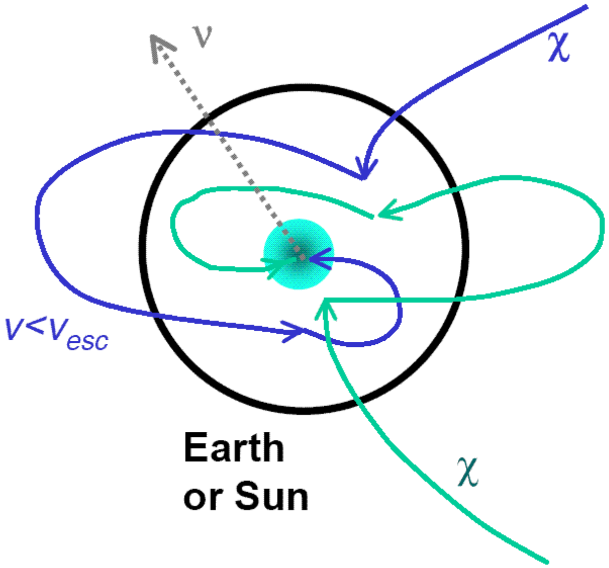
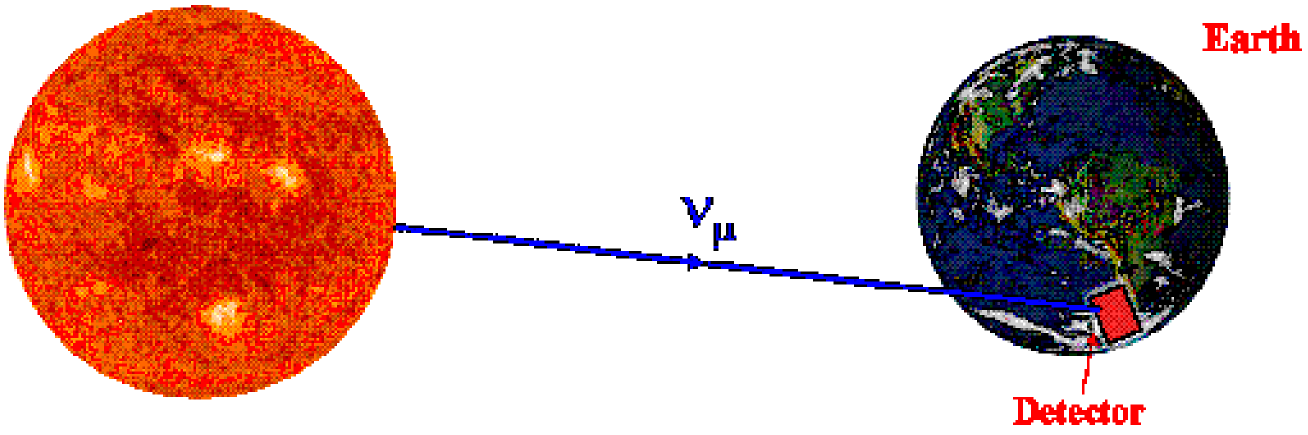
[a] http://www.icecube.wisc.edu/

[b] http://www.km3net.org/

Dark Matter Capture [a]





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[a] home.fnal.gov/ dhooper/mit.ppt

Dark Matter Capture

- Capture Rate [a] :

$$C = c\frac{\rho_{0.3}^{\chi}}{(m_\chi/GeV)\overline{v}_{270}}\sum_i F_i(m_\chi)\, f_i\, \phi_i\, S(m_\chi/m_{N_i}) \times \frac{\sigma_0^i}{10^{-8}pb}\frac{1GeV}{m_{N_i}},$$

$$c = \begin{cases} 4.8 \times 10^{11}\mathrm{s}^{-1} & \text{Earth,} \\ 4.8 \times 10^{20}\mathrm{s}^{-1} & \text{Sun.} \end{cases}$$

- $S(m_\chi/m_{N_i})$: kinematic suppression; $S \to 1$ when $m_\chi \to m_{N_i}$.
- ϕ_i : velocity distribution function $< v_i^2 > / < v_{esc}^2 >$
- f_i : mass fraction in the astrophysical object

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[a] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. **267**, 195 (1996); A. Gould, Astrophys. J. **321**, 571 (1987).

- $F_i(m_\chi)$: form factor suppression; due to the finite size of the nucleus, disrupts the coherence in the scattering process, a negligible effect for WIMPs scattering off of the H and He nuclei. If the momentum transfer in the interaction is not small compared to the inverse of the nuclear radius, the WIMP does not 'see' the entire nucleus. If so, the cross section is form-factor suppressed. oxygen 1% , silicon 6% , iron 28% effect.

- Annihilation Rate : $\chi\chi \rightarrow \cdots$

  $$\Gamma_A = \frac{C}{2} \tanh^2(t_0\sqrt{CC_A})$$

  where

  $$C_A = \frac{< \sigma v >}{V_{eff}}$$

  and V_{eff} is the effective volume of the core of the Earth or Sun, while t_0 is the age of the solar system.

- Equilibrium condition : $\Gamma_A = \frac{C}{2}$, if $t_0\sqrt{CC_A} \gg 1$.

Muon Flux

- The probability of the conversion of a neutrino into a muon over a distance dr via CC interactions :

$$dP_{CC} = dr\, dE_\mu \left(\rho_p \frac{d\sigma_\nu^p(E_\nu, E_\mu)}{dE_\mu} + (p \to n) \right) \; . \tag{1}$$

  where the weak scattering cross sections are [a] :

$$\frac{d\sigma_\nu^{p,n}}{dE_\mu} = \frac{2 m_p G_F^2}{\pi} \left(a_\nu^{p,n} + b_\nu^{p,n} \frac{E_\mu^2}{E_\nu^2} \right) \tag{2}$$

- The muons can be created in the detector (contained events) or in the rock below the detector (upward events).

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[a] V. Barger, W. Keung, G. Shaughnessy and A. Tregre, Phys. Rev. D **76**, 095008 (2007).

Contained Events

- The contained event rate, for a detector with size l :

$$\begin{aligned} \frac{d\phi_\mu}{dE_\mu} &= \int_R^{R+\ell} dr \int_{E_\mu}^{m_\chi} dE_\nu \frac{dP_{CC}}{dr\, dE_\mu} \frac{d\phi_\nu}{dE_\nu}(E_\nu, R) \\ &+ (\nu \to \bar{\nu}) \end{aligned} \tag{3}$$

- Neutrino Flux :

$$\frac{d\phi_\nu}{dE_\nu}(E_\nu, R) = \frac{\Gamma_A}{4\pi R^2} \sum_F B_F \left(\frac{dN_\nu}{dE_\nu} \right)_{F,\mu} . \tag{4}$$

- $R \simeq R_E = 6400$ km (Earth) or $R \simeq R_{SE} = 150$ Mkm (Sun).

Neutrino Energy Distribution [a] :

- $\chi\chi \longrightarrow \nu\overline{\nu}$ channel :

$$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi) \tag{5}$$

- $\chi\chi \longrightarrow \tau^+\tau^-, b\overline{b}, c\overline{c}$ channels :

$$\frac{dN_\nu}{dE_\nu} = \frac{2B_f}{E_{in}}(1 - 3x^2 + 2x^3), \quad \text{where} \quad x = \frac{E_\nu}{E_{in}} \leq 1. \tag{6}$$

where

$$(E_{in}\ ,\ B_f) = \begin{cases} (m_\chi\ ,\ 0.18) & \tau \ \text{decay}, \\ (0.73m_\chi\ ,\ 0.103) & b \ \text{decay}, \\ (0.58m_\chi\ ,\ 0.13) & c \ \text{decay}. \end{cases}$$

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[a] G. Jungman and M. Kamionkowski, Phys. Rev. D **51**, 328 (1995)

- $\chi\chi \rightarrow W^+W^-, ZZ$ channels :

$$\frac{dN_\nu}{dE_\nu} = n_f \frac{B_f}{m_\chi \beta} \quad \text{if} \quad \frac{m_\chi}{2}(1-\beta) < E_\nu < \frac{m_\chi}{2}(1+\beta) \qquad (7)$$

where β is the velocity of the decaying particle(W or Z),

$$(n_f \ , \ B_f) = \begin{cases} (1 \ , \ 0.105) & W \ \text{decay}, \\ (2 \ , \ 0.067) & Z \ \text{decay}. \end{cases}$$

- $\chi\chi \rightarrow t\bar{t}$ channel :

$$\left(\frac{dN_\nu}{dE_\nu}\right)^{rest}_{t\bar{t}} = \left(\frac{dN_\nu}{dE_\nu}\right)_{W^+W^-} + \left(\frac{dN_\nu}{dE_\nu}\right)_{b\bar{b}} \qquad (8)$$

Then, boosting this expression yields the neutrino spectrum from top quarks moving with velocity β_t,

$$\begin{aligned}\frac{dN_\nu}{dE_\nu} &= \frac{B_W}{2\gamma_t\beta_t E_W \beta_W} ln \frac{min(E_+, \epsilon_+)}{max(E_-, \epsilon_-)} \\ &\times\Theta(\gamma_t(1-\beta_t)\epsilon_- < E_\nu < \gamma_t(1+\beta_t)\epsilon_+) \\ &+\frac{B_b}{2\gamma_t\beta_t E_d} D_b[E_-/E_d, min(1, E_+/E_d)] \\ &\times\Theta(E_\nu < \gamma_t(1+\beta_t)E_d),\end{aligned} \qquad (9)$$

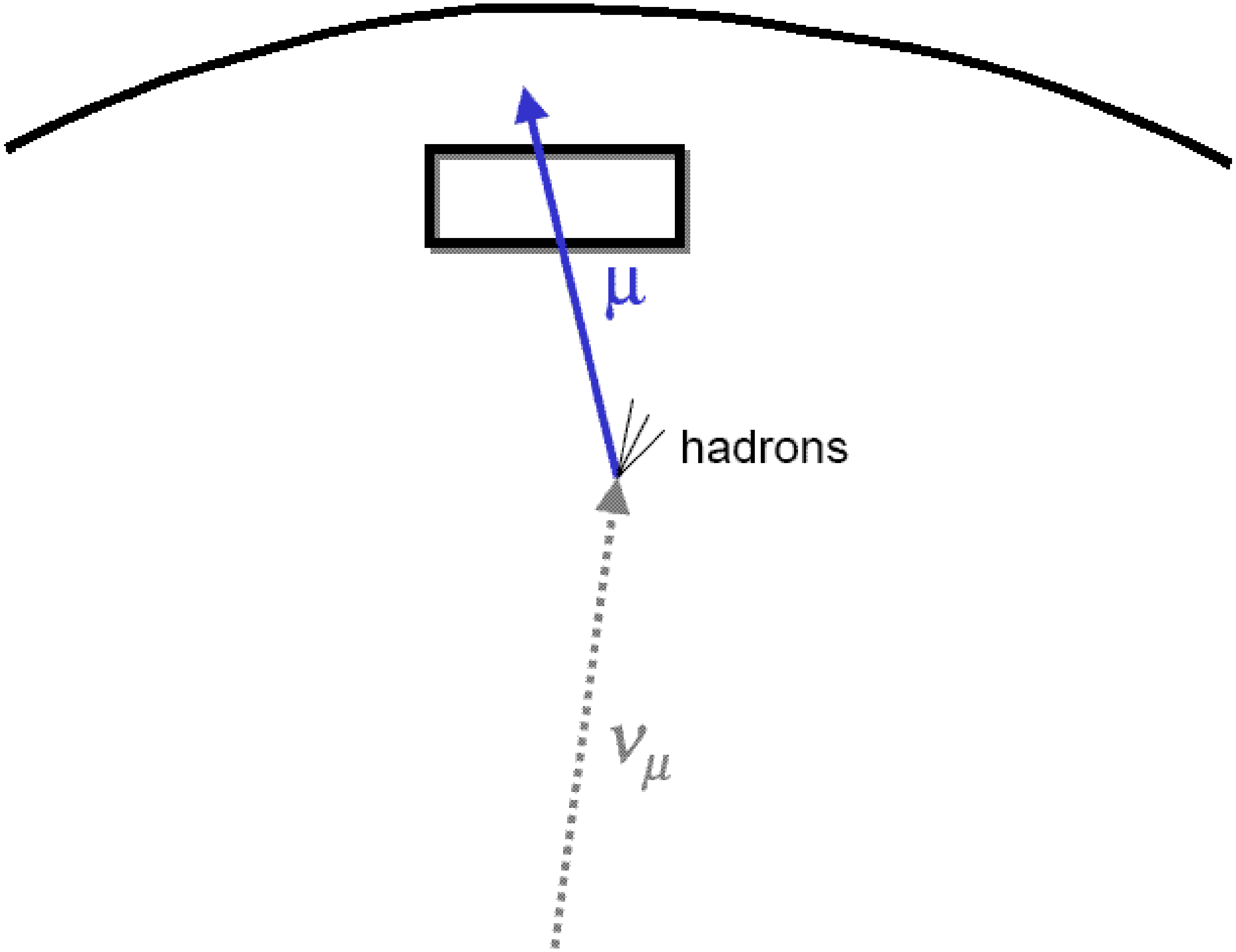
where $\epsilon\mp = E_W(1 \mp \beta_W)/2$ and $E_d = 0.73E_b$ with E_W, β_W and E_b equal to their values in the top-quark rest frame, i.e,

$$\begin{aligned}E_b &= \frac{m_t^2 - m_W^2}{2m_t} \\ E_W &= \frac{m_t^2 + m_W^2}{2m_t} \\ \beta_W &= \frac{E_b}{E_W}.\end{aligned} \qquad (10)$$

In addition, $E_{\mp} = E_{\nu}\gamma_t^{-1}(1 \pm \beta_t)^{-1}$, where $\gamma_t = m_{\chi}/m_t$, and $\Theta(x) = 1$ if x is true and $\Theta(x) = 0$ otherwise. The function D_b is given by

$$D_b[x, y] = \frac{1}{3}[9(x^2 - y^2) - 4(x^3 - y^3) + 6ln\frac{y}{x}]$$

Upward Events



Upward Events

- Energy loss of the muons over a distance dz :

$$\frac{dE}{dz} = -(\alpha + \beta E)\rho, \tag{11}$$

- α : ionization energy loss $\simeq 2 \times 10^{-3}$ GeV cm^2/g ,
- β : bremsstrahlung, pair production and photonuclear interactions $\simeq 3.0 \times 10^{-6}$ cm^2/g .
- Then, what is the relation between the initial and final muon energies?

$$E^i_\mu(z) = e^{\beta\rho z} E^f_\mu + (e^{\beta\rho z} - 1)\frac{\alpha}{\beta}. \tag{12}$$

$$R_\mu(E^i_\mu, E^f_\mu) \equiv z = \frac{1}{\beta\rho} log\left(\frac{\alpha + \beta E^i_\mu}{\alpha + \beta E^f_\mu}\right)$$ "muon range"

- Muons with energies of a few 100 GeV are stopped (Sd : stopping distance) in the rock ($\rho \simeq 2.6 \text{ g/cm}^3$) before they decay ($Dl$: Decay length $= \gamma c \tau$). Examples :
  - ⋆ $Dl =$ 3000 km , $Sd =$ 1 km (for 500 GeV muons)
  - ⋆ $Dl =$ 300 km , $Sd =$ 100 m (for 50 GeV muons)

- However, decay length information → Survival Probability :

$$P_{\text{surv}}(E_\mu^i, E_\mu^f) = \left(\frac{E_\mu^f}{E_\mu^i}\right)^\Gamma \left(\frac{\alpha + \beta E_\mu^i}{\alpha + \beta E_\mu^f}\right)^\Gamma \tag{13}$$

  where $\Gamma \equiv m_\mu/(c\tau\alpha\rho)$.

- Here,

$$P_{\text{surv}}(E_\mu^i, E_\mu^f) \simeq 1$$

  for the energies considered.

- Then, the upward muon flux :

$$\begin{aligned} \frac{d\phi_\mu}{dE_\mu} &= \int_{R_{min}}^{R} dr \int_{E_\nu^{min}}^{m_\chi} dE_\nu \frac{dP_{CC}}{dr\, dE_\mu^i} \\ &\times \frac{d\phi_\nu}{dE_\nu} P_{\mathrm{surv}}(E_\mu^i, E_\mu) \frac{dE_\mu^i}{dE_\mu} \\ &+ (\nu \longrightarrow \bar{\nu}) \ . \end{aligned} \tag{14}$$

where $E_\mu \equiv E_\mu^f$ and with a change of variable; $z = R - r$:

$$\begin{aligned} \frac{d\phi_\mu}{dE_\mu} &= \frac{\Gamma_A}{4\pi R_E^2} \int_0^{R_\mu(m_\chi, E_\mu)} dz e^{\beta\rho z} \int_{E_\mu^i}^{m_\chi} dE_\nu \left(\frac{dN_\nu}{dE_\nu}\right)_{F,\mu} \\ &\times \left(\frac{E_\mu}{E_\mu^i} \frac{\alpha + \beta E_\mu^i}{\alpha + \beta E_\mu}\right)^{\Gamma} \times \left\{ \frac{d\sigma_\nu^p}{dE_\mu^i} \rho_p + (p \longrightarrow n) \right\} \\ &+ (\nu \longrightarrow \bar{\nu}). \end{aligned} \tag{15}$$

Attenuation of the Neutrino Flux in the Sun

- Similarly, muon flux from dark matter annihilation in the Sun is given by

$$
\begin{aligned}
\frac{d\phi_\mu}{dE_\mu} &= \frac{\Gamma_A}{4\pi R_{SE}^2}\int_0^{R_\mu(m_\chi,E_\mu)} dz e^{\beta\rho z}\int_{E_\mu^i}^{m_\chi} dE_\nu \left(\frac{dN_\nu}{dE_\nu}\right)_{F\mu} \\
&\times \left(\frac{E_\mu}{E_\mu^i}\frac{\alpha+\beta E_\mu^i}{\alpha+\beta E_\mu}\right)^\Gamma \times \left\{\frac{d\sigma_\nu^p}{dE_\mu^i}\rho_p + (p\longrightarrow n)\right\} \\
&\times \prod_{\delta r'} exp(-\rho(r')\sigma_{CC}\delta r'/m_H) \qquad (16) \\
&+ (\nu \longrightarrow \bar{\nu}).
\end{aligned}
$$

- The muon flux decreases by a factor of
  - ⋆ 3, 10, 100 for m_χ = 250 GeV, 500 GeV, 1 TeV .

Atmospheric Background

- Parametrization for the flux of atmospheric ν_μ and $\overline{\nu}_\mu$ (in units of $GeV^{-1}km^{-2}yr^{-1}sr^{-1}$) [a] :

$$\frac{d\phi_\nu}{dE_\nu d\Omega} = N_0 E_\nu{}^{-\gamma-1} \times \left(\frac{a}{1+bE_\nu cos\theta} + \frac{c}{1+eE_\nu cos\theta} \right) . \tag{17}$$

γ	1.74
a	0.018
b	0.024 GeV^{-1}
c	0.0069
e	0.00139 GeV^{-1}
N_0	1.95×10^{17} for ν
	1.35×10^{17} for $\overline{\nu}$

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[a] M.Honda *et al.*, Phys.Rev.D **75**,043006 (2007).

Results 1

- Assumptions :
  - ⋆ WIMP-nucleon cross section, $\sigma_0 = 10^{-8}$ pb and $\sigma_0^i \simeq \sigma_0 N_i^4$,
  - ⋆ Capture Rate - Annihilation Rate Equilibrium : $\Gamma_A = \frac{C}{2}$,
  - ⋆ Branching Fractions : $B_F = 1$,
  - ⋆ cone of half angle, $\theta = 1$ deg.
- compare with the expression for the muon flux, widely used in the literature :

$$\begin{aligned} \frac{d\phi_\mu}{dE_\mu} &= \frac{\Gamma_A}{4\pi R^2} \int_{E_\mu}^{m_\chi} dE_\nu \left(\frac{dN_\nu}{dE_\nu}\right)_{F,\mu} R_\mu(E_\mu, E_{th}) \\ &\times \left\{ \frac{d\sigma_\nu^p}{dE_\mu} \rho_p + (p \to n) \right\} + (\nu \to \overline{\nu}), \end{aligned} \tag{18}$$

- also compare with the parametrization [a] .

$$\frac{d\phi_\mu}{dE_\mu} = B_F \Gamma_A \frac{p_1 m_\chi e^{-p_7 E_\mu}(1 - e^{-p_5 m_\chi})}{1 + e^\psi} \tag{19}$$

where

$$\psi = \frac{E_\mu - m_\chi(p_6 + p_2 exp(-p_3 m_\chi))}{p_4 m_\chi}$$

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[a] J. Edsjö PhD Thesis; J. Edsjö, Nucl. Phys. Proc. Suppl. **43**, 265 (1995).

WIMP Capture in the Earth

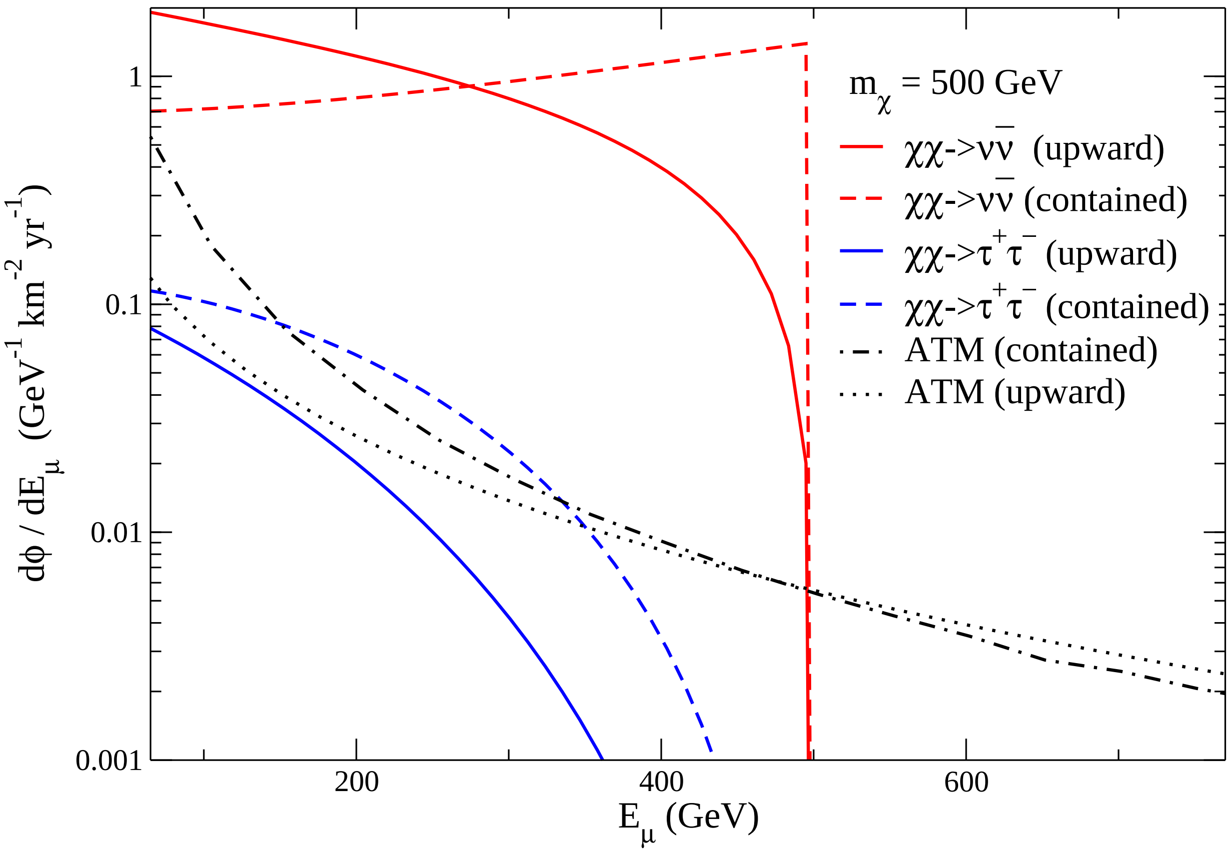

Figure 1: muon fluxes from upward and contained events.

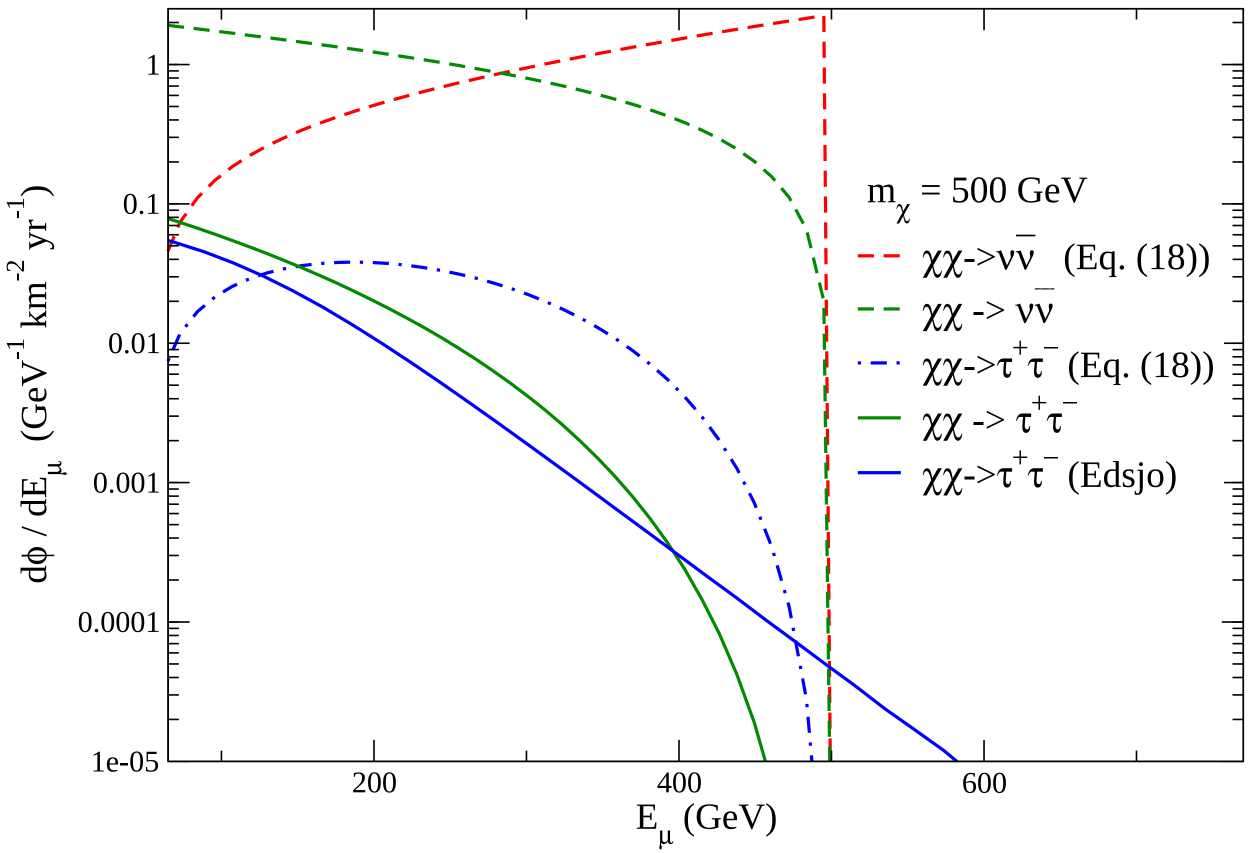

Figure 2: comparison of the muon fluxes from the upward events.

Notice how different the shapes of the muon flux distributions are for both $\chi\chi \rightarrow \nu\overline{\nu}$ and $\chi\chi \rightarrow \tau^+\tau^-$ channels.

WIMP Capture in the Sun

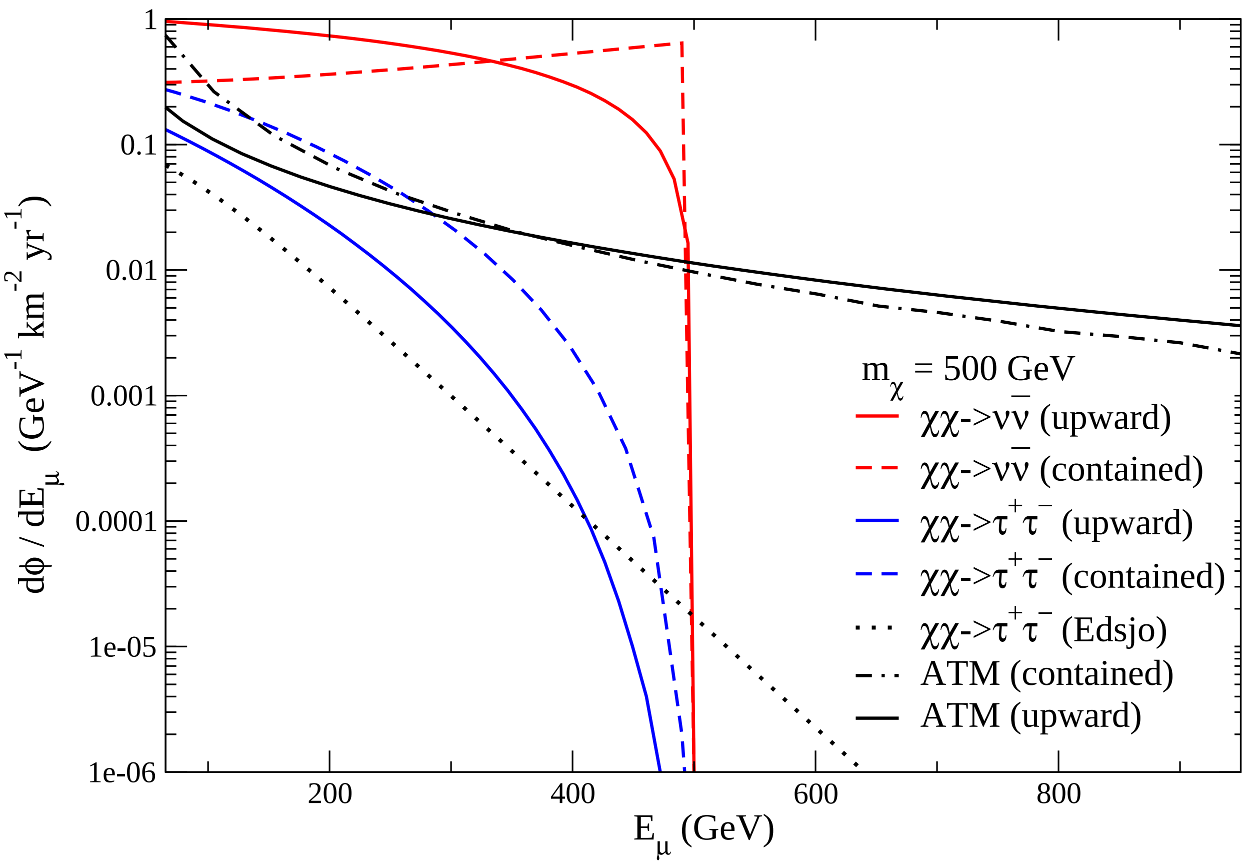

Figure 3: upward and contained events from $\chi\chi \to \nu\overline{\nu}$ and $\chi\chi \to \tau^+\tau^-$ channels.

Cosmic Diffuse Neutrino Flux [a]

- Relic dark matter can also annihilate in the halos → cosmic diffuse neutrino flux
  - ⋆ evolution with redshift
  - ⋆ the radial density profiles
  - ⋆ the number density of halos of a given mass at a given redshift
- cosmic diffuse neutrinos from the channel $\chi\chi \rightarrow \nu\overline{\nu}$ can be described by a power law function :

$$\left(\frac{d\phi_\nu}{dE_\nu\, d\Omega}\right)_{\nu_\mu+\overline{\nu}_\mu} \simeq A\frac{(E_\nu/GeV)^{0.5}}{(m_\chi/GeV)^{3.5}} \qquad E_\nu \leq m_\chi \ . \tag{20}$$

- The overall normalization A is determined by requiring

$$\int_{\frac{m_\chi}{\sqrt{10}}}^{m_\chi} dE_\nu A\frac{(E_\nu/GeV)^{0.5}}{(m_\chi/GeV)^{3.5}} = \int_{\frac{m_\chi}{\sqrt{10}}}^{m_\chi} dE_\nu \left(\frac{d\phi_\nu}{dE_\nu d\Omega}\right)_{av} \tag{21}$$

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[a] J.F. Beacom, N.F. Bell and G.D. Mack, Phys.Rev.Lett.**99**, 231301 (2007).

Results 2

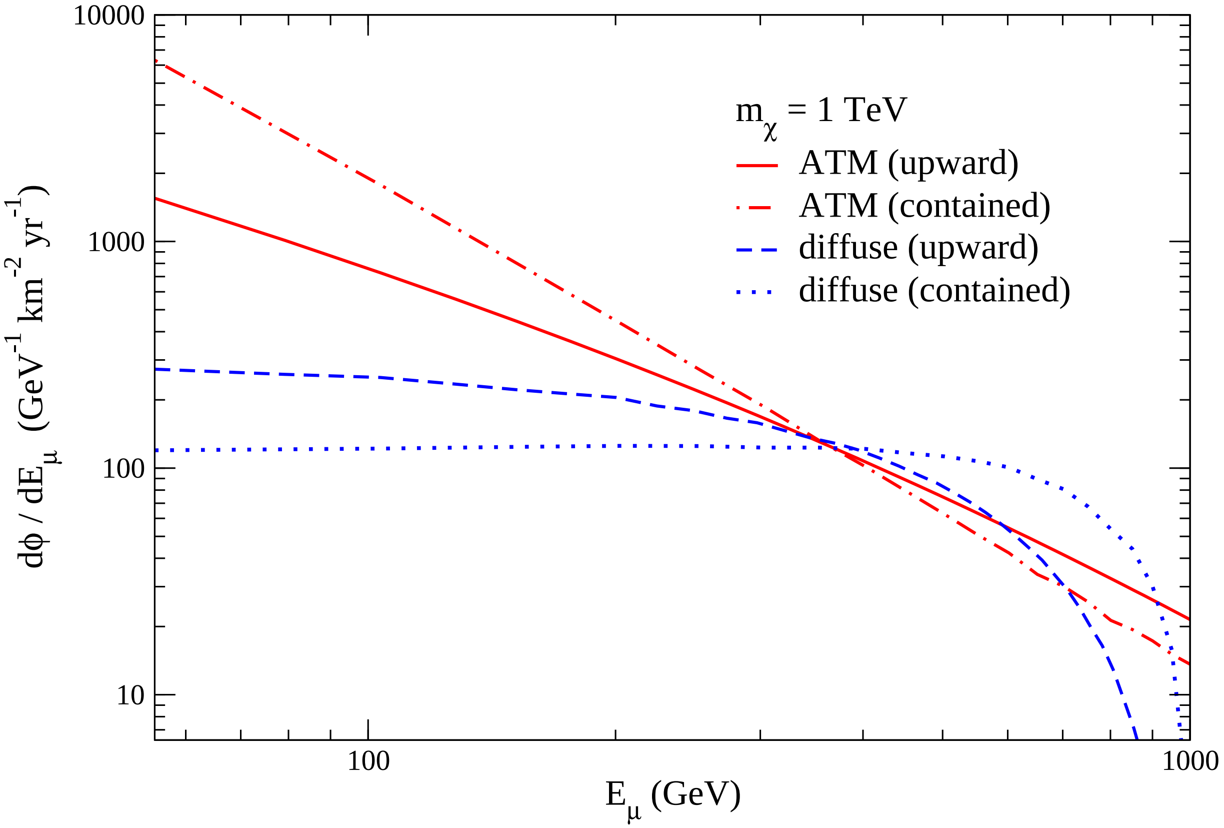

Figure 4: contained and upward events due to the cosmic diffuse neutrino signal compared to the atmospheric background.

Discussion and Conclusion

In this study, we have

- presented a systematic way of calculating muon fluxes at neutrino telescopes from WIMP annihilations in the core of the astrophysical objects and from the WIMP annihilations in the galactic halos.
- considered $\chi\chi \to \nu\overline{\nu}$ and $\chi\chi \to \tau^+\tau^-$ followed by $\tau \to \nu_\tau \mu \overline{\nu}_\mu$ channels as representatives of direct and secondary ν production.
- shown that our results exhibit a very different energy dependence than those obtained from Eq.(18) that is widely used in the literature. It is clear that with the use of Eq.(18) one can not obtain the required energy distribution of the muons to be detected in the detector, but rather a quantity related to the muon flux far from the detector $\Rightarrow$explains the similarity with the fluxes due to the contained events.

Coming Soon :

- model dependent calculation : with the exact branching fractions of the decay channels for a given model. Muon flux for a specific dark matter model can be determined by summing up the contributions from all decay channels weighted with corresponding branching fractions.
- regeneration and MSW effects accompanied with NC and CC interactions and energy loss of the heavy hadrons in the Sun and vacuum oscillations If the injected spectra are uniformly populated among the neutrino flavors when they are first created, vacuum oscillations and MSW effects are expected to be almost negligible. However, sufficiently large WIMP mass may yield high energy tau neutrinos and makes CC interactions considerably large. Then, the tau regeneration becomes an important factor which introduces an asymmetry among the neutrino flavors !!!!

THANK YOU !

BACK-UP SLIDES

After multiplying with the energy dependent effective area [a]

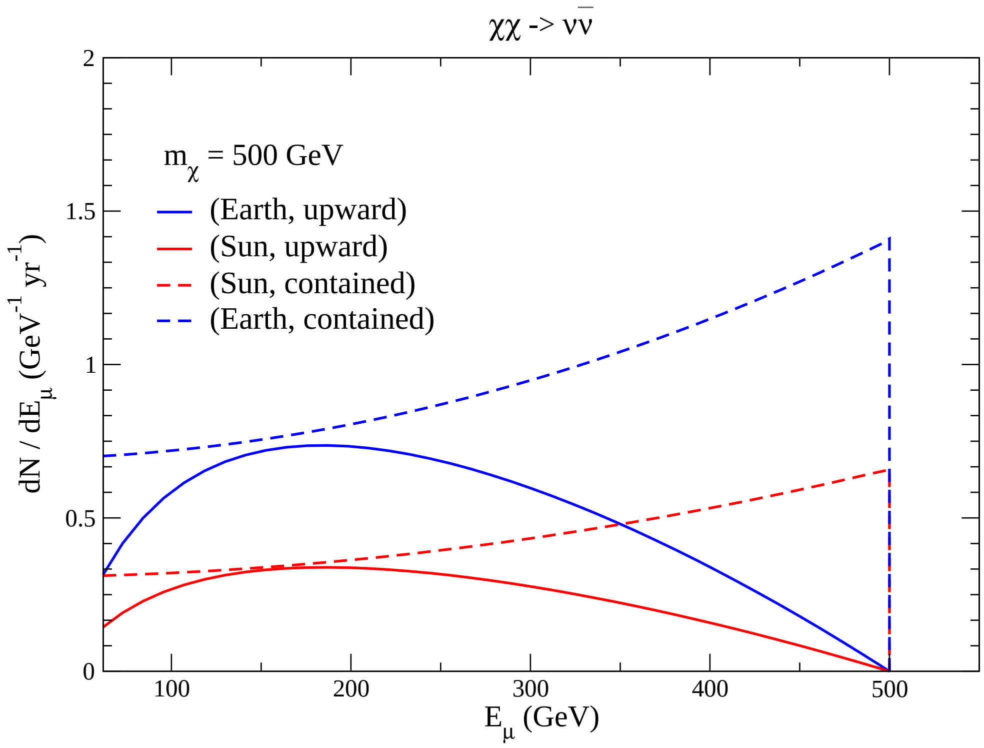

Figure 5: area-integrated muon flux from contained and upward events both for the Earth-born and the Sun-born neutrinos via $\chi\chi \rightarrow \nu\overline{\nu}$ channel.

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[a] M.C.Gonzalez-Garcia, F.Halzen, S.Mohapatra, astro-ph.HE/0902.1176.