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A Novel Method to Extract Dark Matter Parameters from Neutrino Telescope Data

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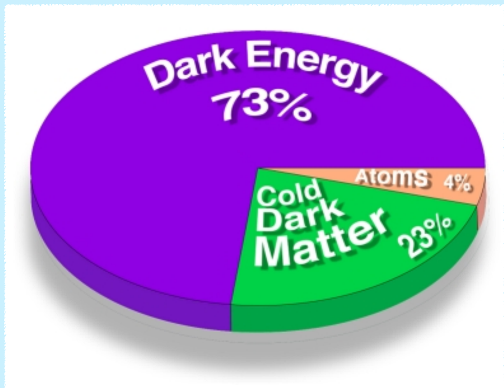
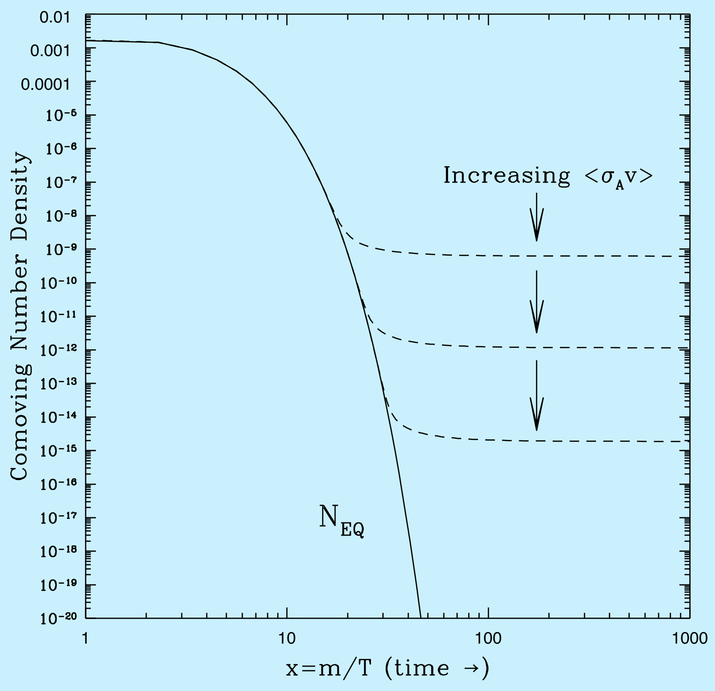
Introduction

Growing evidence from a wide range of cosmological and astrophysical observations shows that about 82 % of the matter content of the universe is composed of Dark Matter whose exact identity is yet unknown.

Among the various candidates, the Weakly Interacting Massive Particles (WIMPs) are arguably the most popular class of candidates. The reason of this popularity is the coincidence of the value of the annihilation cross section inferred from the present dark matter abundance with the generic value of the weak interaction annihilation cross section (the so-called WIMP miracle).





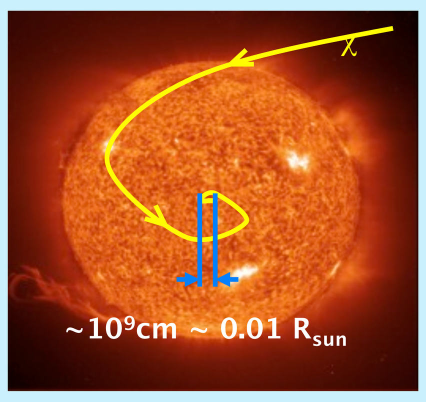
$$\Omega_X h^2 \approx 0.1 \left(\frac{x_{FO}}{20}\right)\left(\frac{g_*}{80}\right)^{-1/2}\left(\frac{a+3b/x_{FO}}{3\times 10^{-26}\mathrm{cm}^3/\mathrm{s}}\right)^{-1}$$

$\langle\sigma\rangle \sim$ pb

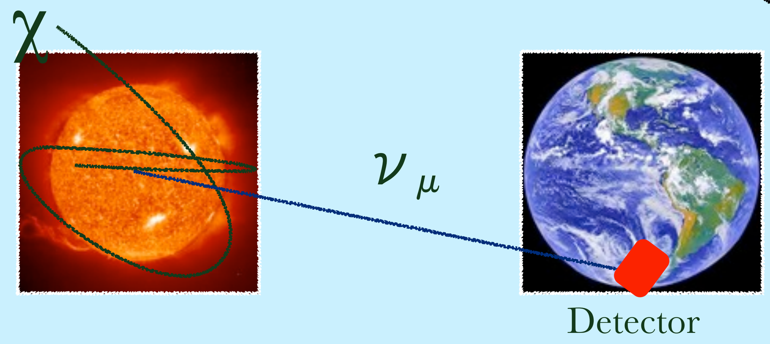
Generic weak interaction yields

$\langle\sigma\rangle \sim \alpha^2\,(100\ \mathrm{GeV})^{-2} \sim$ pb

Dark Matter Trapping and Annihilation inside the Sun



The WIMPs are expected to propagate in the space between the stars and planets. In time a considerable number of WIMPs will interact with the nuclei inside the Sun and lose energy. If the velocity drops below the escape velocity, the particle will be captured by the gravitational potential of the Sun. The DM particles will eventually thermalize inside the Sun and having a relatively large density inside the core, the DM particles will annihilate with each other.



$$\chi\chi \to \left\{ \begin{array}{c} q\bar{q} \\ \ell\bar{\ell} \\ Z, W^{\pm}, H \end{array} \right\} \to \nu_\alpha \bar{\nu}_\beta$$

$$C^{\odot} \approx 3.35\times 10^{20}\,\mathrm{sec}^{-1}\left(\frac{\rho_{\rm local}}{0.3\,\mathrm{GeV/cm^3}}\right)\left(\frac{270\,\mathrm{km/s}}{\bar{v}_{\rm local}}\right)^3\left(\frac{100\,\mathrm{GeV}}{m_X}\right)^2\left(\frac{\sigma_{X\mathrm{H,SD}}+\sigma_{X\mathrm{H,SI}}+0.07\,\sigma_{X\mathrm{He,SI}}+0.0005\,S(\frac{m_X}{m_{\rm O}})\,\sigma_{X\mathrm{O,SI}}}{10^{-6}\,\mathrm{pb}}\right)$$

$$\frac{t_\odot}{\tau_{eq}} = 10^3\left(\frac{\langle\sigma v\rangle_{ann}}{3\times 10^{-26}\mathrm{cm^3 s^{-1}}}\right)^{1/2}\left(\frac{7\times 10^8\mathrm{cm}}{r_{DM}}\right)^{3/2}$$

we consider the direct annihilation of DM particles to neutrinos

$$\chi\chi \to \nu\bar{\nu}$$

$$\boxed{F^0_{\nu_e} : F^0_{\nu_\mu} : F^0_{\nu_\tau} \neq 1:1:1}$$

The neutrinos are monochromatic (the average velocity of DM is $(3T_\odot/m_{DM})^{1/2}$=60 km/sec)

$$L_{osc} = \frac{4\pi E_\nu}{\Delta m^2_{12}} \sim 3\times 10^{11}\ \mathrm{cm}\left(\frac{E_\nu}{100\ \mathrm{GeV}}\right)\left(\frac{8\times 10^{-5}\ \mathrm{eV}^2}{\Delta m^2_{12}}\right)$$

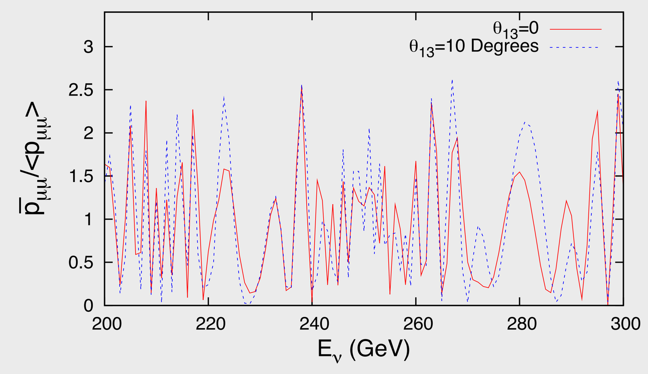
L_{osc} is of the order of the variation of Earth-Sun distance over a year

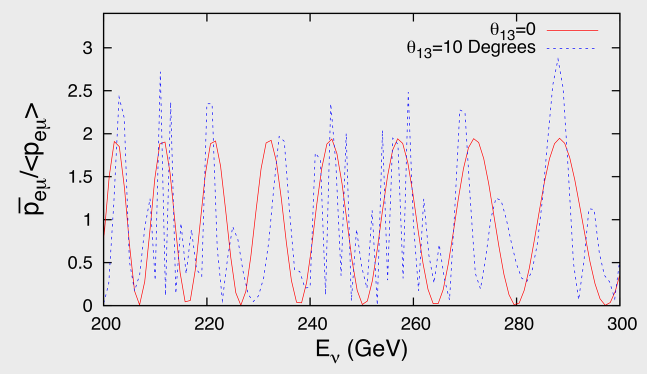
Seasonal variation of the flux of neutrinos should be seen ✔

Seasonal Variation

Does integration over the production region of the neutrinos, averages out the oscillatory terms ?

The graphs show the dependence of the ratios $P_{e\mu}/\langle P_{e\mu}\rangle$ and $P_{\mu\mu}/\langle P_{\mu\mu}\rangle$ on the energy of the produced neutrinos in the annihilation of the DM particles inside the Sun. $P_{\alpha\beta}$ is the oscillation probability $\nu_\alpha \to \nu_\beta$ obtained by integrating over the production point of neutrinos inside the Sun taking into account the oscillatory terms. We have taken the neutrino mass scheme to be normal hierarchical. The $\langle P_{\alpha\beta}\rangle$ is the same quantity without taking into account the oscillatory terms. Deviation of the ratio $P_{\alpha\beta}/\langle P_{\alpha\beta}\rangle$ from one is a measure of the significance of the oscillatory terms.

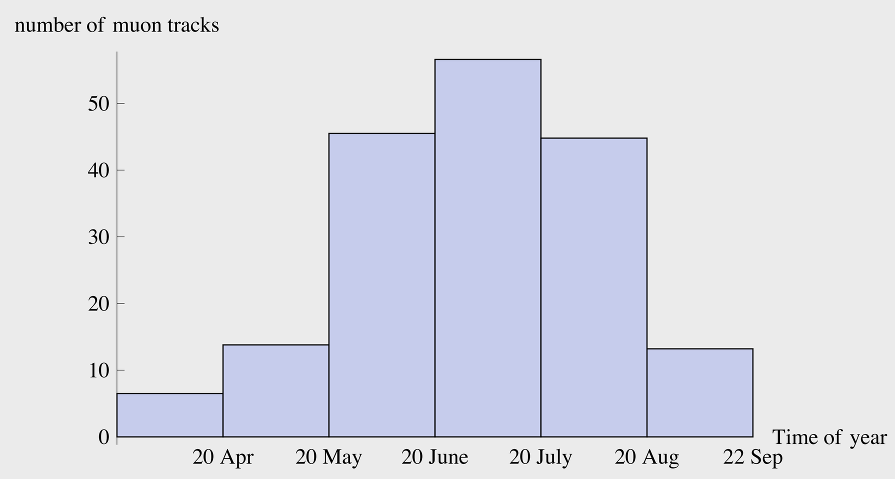




We define Δ as a measure of the existence or absence of the oscillatory terms

$$\Delta(t_1,\Delta t_1; t_2, \Delta t_2) \equiv \frac{\tilde{N}(t_1,\Delta t_1)-\tilde{N}(t_2,\Delta t_2)}{\tilde{N}(t_1,\Delta t_1)+\tilde{N}(t_2,\Delta t_2)}$$

$$\tilde{N}(t,\Delta t) \equiv \frac{\int_t^{t+\Delta t}(dN_\mu/dt)dt}{\int_t^{t+\Delta t}A_{eff}(\theta[t])L^{-2}(t)dt}$$



We calculate numerically the number of muon-tracks (both through-going events for the whole IceCube and the contained events in the DeepCore) for different periods of time during the year. For the propagation of the neutrinos inside the Sun, we consider the oscillation , absorption and ν_τ-regeneration in the matter density of Sun.

Through-going events for the whole IceCube

$$\frac{dN^{\rm IC}_\mu}{dt} = \int_{E_{\rm thr}}^{m_{DM}}\int_{E_{\rm thr}}^{E_{\nu_\mu}}\frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}}\left[\frac{d\sigma^{CC}_{\nu p}}{dE_\mu}(E_{\nu_\mu})\rho_p+\frac{d\sigma^{CC}_{\nu n}}{dE_\mu}(E_{\nu_\mu})\rho_n\right]$$

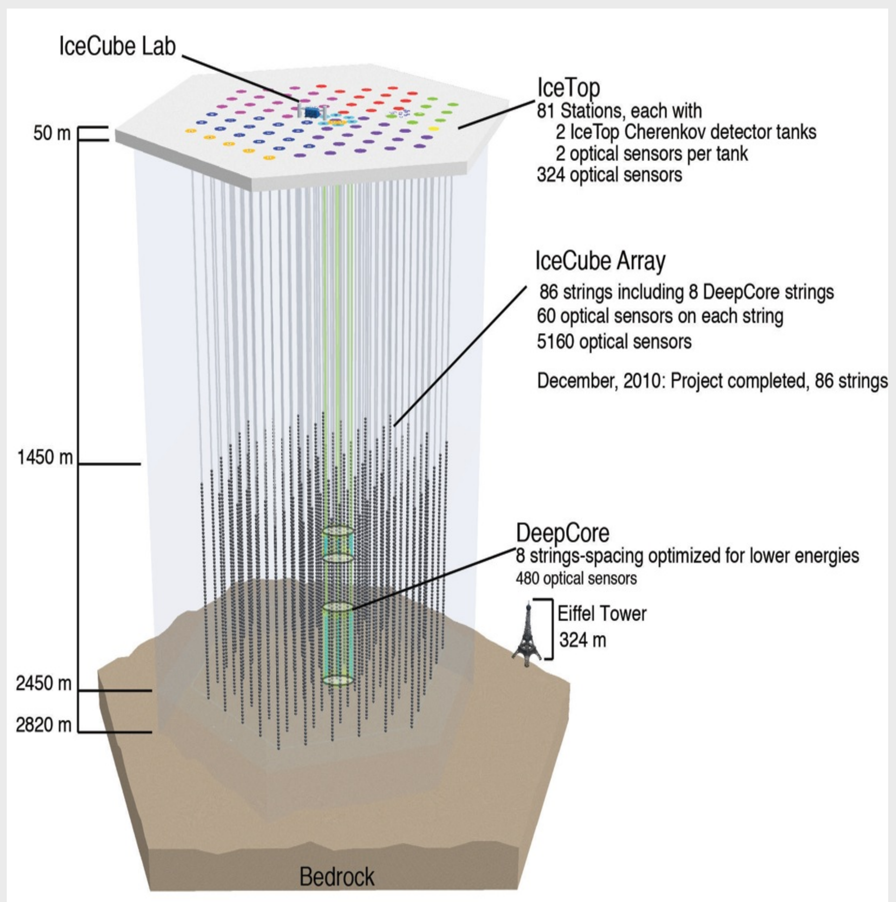
$$\times A_{eff}(E_\mu,\theta[t])\,(R_\mu(E_\mu,E_{\rm thr})+d)\,dE_\mu dE_{\nu_\mu}+(\nu_\mu\to\bar{\nu}_\mu)$$

DeepCore contained events

$$\frac{dN^{\rm DC}_\mu}{dt} = \int_{E_{\rm thr}}^{m_{DM}}\int_{E_{\rm thr}}^{E_{\nu_\mu}}\frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}}\left[\frac{d\sigma^{CC}_{\nu p}}{dE_\mu}(E_{\nu_\mu})\rho_p+\frac{d\sigma^{CC}_{\nu n}}{dE_\mu}(E_{\nu_\mu})\rho_n\right]$$

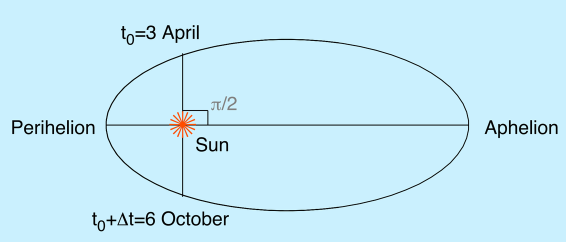
$$\times V^{\rm DC}_{eff}(E_\mu)\,dE_\mu\,dE_{\nu_\mu}+(\nu_\mu\to\bar{\nu}_\mu)$$

Number of the through-going μ-track events from the spring equinox (20 March) to autumn equinox (22 September) for θ_{13}=0. We assumed m_{DM}=270 GeV and DM+DM→$\nu_e\bar{\nu}_e$. Also, we took $C_\odot$=3.4 × 10^{22} s^{-1}.



Numerical Results

Seasonal variation for DM particles with mass m_{DM}=200 GeV and different annihilation modes. N/I indicates normal versus inverted neutrino mass scheme. Δ_{3Apr} is the seasonal variation between the two points shown in the figure, Δ_{3Apr}≡Δ(3 Apr,186 days,6 Oct,179 days).



Ann. channel	N/I	θ_{13}	δ	Δ^{IC}(3 Apr.)	Δ^{DC}(3 Apr.)
DM+DM→$\nu_e\nu_e$	N and I	0	0	0.5	0.5
DM+DM→$\nu_e\nu_e$	N	7°	0	0.5	0.4
DM+DM→$\nu_e\nu_e$	I	7°	0	0.4	0.4
DM+DM→$\nu_e\nu_e$	N	7°	π	0.4	0.4
DM+DM→$\nu_e\nu_e$	I	7°	π	0.4	0.4
DM+DM→$\nu_\mu\nu_\mu$	N	0	0	0.1	0.1
DM+DM→$\nu_\mu\nu_\mu$	N	7°	0	0.1	0.05
DM+DM→$\nu_\mu\nu_\mu$	I	7°	0	0.2	0.1
DM+DM→$\nu_\mu\nu_\mu$	N	7°	π	0.1	0.1
DM+DM→$\nu_\mu\nu_\mu$	I	7°	π	0.1	0.0
DM+DM→$\nu_\tau\nu_\tau$	N	0	0	0.1	0.0
DM+DM→$\nu_\tau\nu_\tau$	N	7°	0	0.1	0.0
DM+DM→$\nu_\tau\nu_\tau$	I	7°	0	0.0	0.0
DM+DM→$\nu_\tau\nu_\tau$	N	7°	π	0.0	0.0
DM+DM→$\nu_\tau\nu_\tau$	I	7°	π	0.1	0.0

Conclusion

In neutrino telescopes such as IceCube, the direction of μ-track can be reconstructed by amazing precision of ~1° which means neutrinos from the Sun can be singled out. Measurement of the spectrum of neutrinos is going to be challenging.

Two situations can be considered

- Spectrum can be constructed: $\boxed{\Delta \neq 0}$ ⇒ A sharp feature should be present in the spectrum of neutrinos
- Spectrum cannot be constructed: If a sharp line observed in the spectrum, but $\Delta = 0$ ⇒ $\boxed{F^0_{\nu_e} = F^0_{\nu_\mu} = F^0_{\nu_\tau}}$

Time variation of μ-track events contains valuable information on the nature of DM particles. By studying the μ-track events over different time intervals, the value of $\Delta m^2_{12}/m_{DM}$ can be extracted. Thus, by this method, m_{DM} can be checked against the value derived from studying the endpoint of the spectrum or from the accelerator experiments. To carry out this analysis, it will be enough to take data from 20th of March to 23rd of September when the neutrino from the Sun pass through the Earth to reach the detector and as a result the atmospheric muon background will not be a problem.

References

A. E. and Y. Farzan, ``A Novel Method to Extract Dark Matter Parameters from Neutrino Telescope Data,'' JCAP 1104 (2011) 007 [arXiv:1011.0500 [hep-ph]].

A. E. and Y. Farzan, ``On the Oscillation of Neutrinos Produced by the Annihilation of Dark Matter inside the Sun,'' Phys. Rev. D 81 (2010) 113010 [arXiv:0912.4033 [hep-ph]].