Probing annihilations and decays of low-mass galactic dark matter by track and cascade events in IceCube DeepCore

Fei-Fan Lee (李非凡)
National Chiao-Tung U. Taiwan

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In collaboration with

Guey-Lin Lin

arXiv:1105.5719

Outline

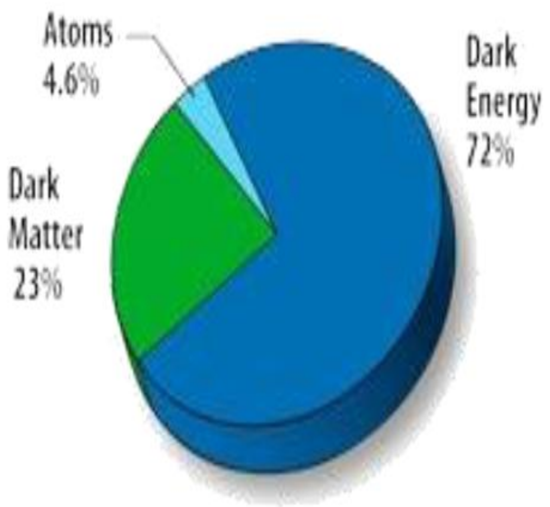
- Introduction
- Neutrino flux from annihilations and decays of dark matter in the galactic halo
- Atmospheric neutrino fluxes
- Detection sensitivity in IceCube+DeepCore
- Summary

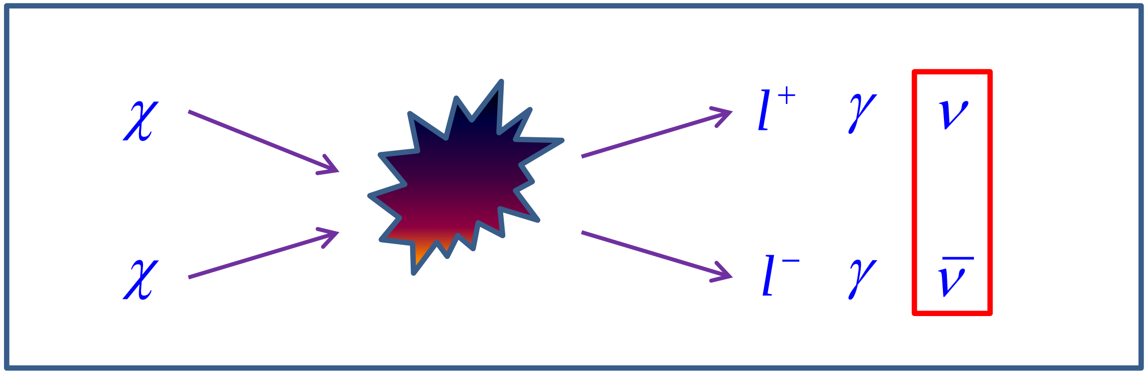
Dark Matter

- A unknown type of matter does neither emit nor reflect EM radiation.

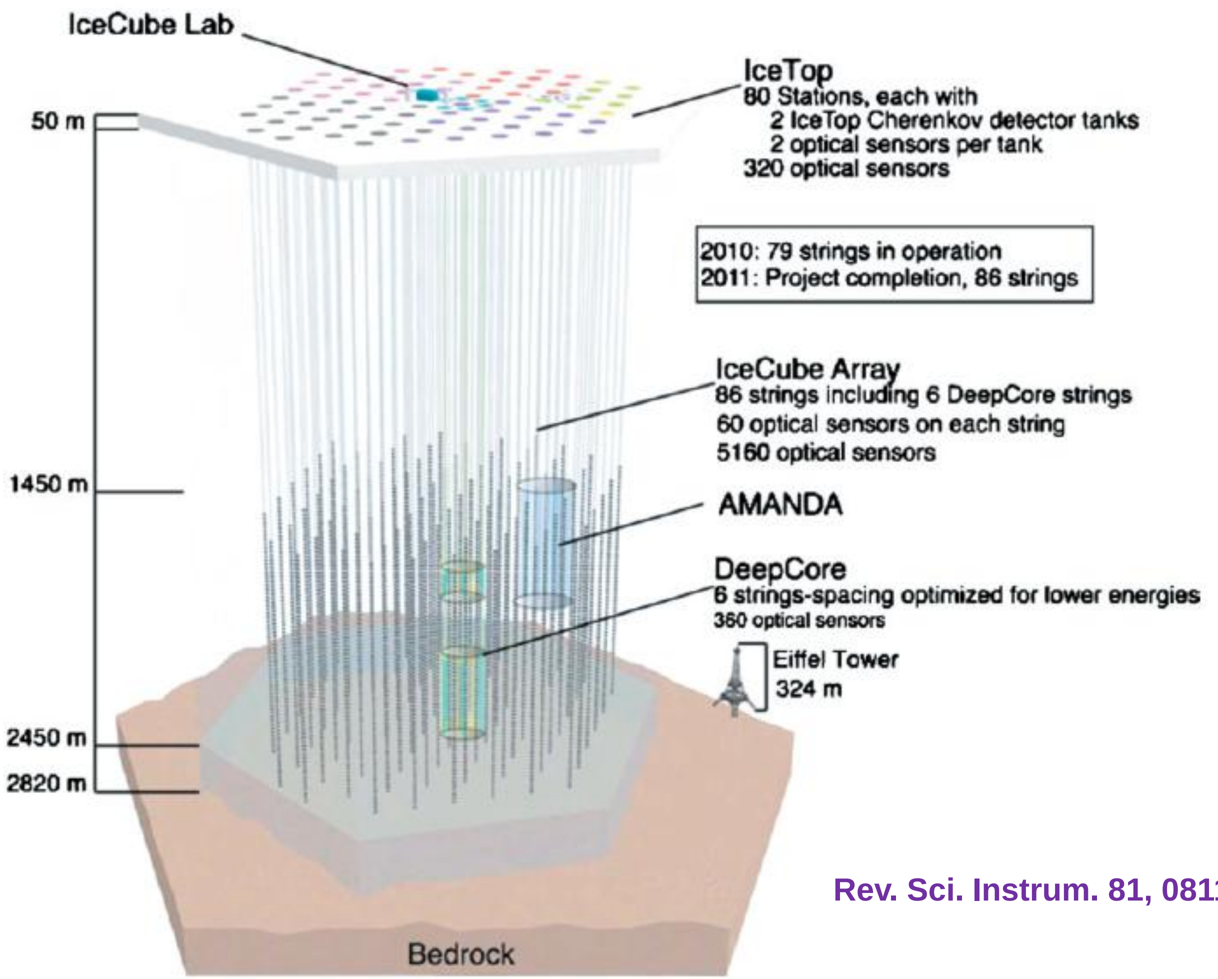
- Weakly Interacting Massive Particles (WIMPs) are one of the leading candidates for DM.

- WIMPs are theoretically well motivated and capable of producing the correct relic density.





IceCube Neutrino Observatory



Rev. Sci. Instrum. 81, 081101 (2010)

Detection threshold energy of **Iceube** > **100GeV**

Detection threshold energy of **Iceube + DeepCore** ~ **10GeV**

Track Events & Cascade Events

Track Events

$$\text{Charged-Current } \nu_\mu \text{ interaction}: \nu_\mu + N \rightarrow \mu^- + X$$

Cascade Events

$$\text{Neutral-Current } \nu_l \text{ interaction}: \nu_l + N \rightarrow \nu_l + X\,(\text{Hadronic})$$

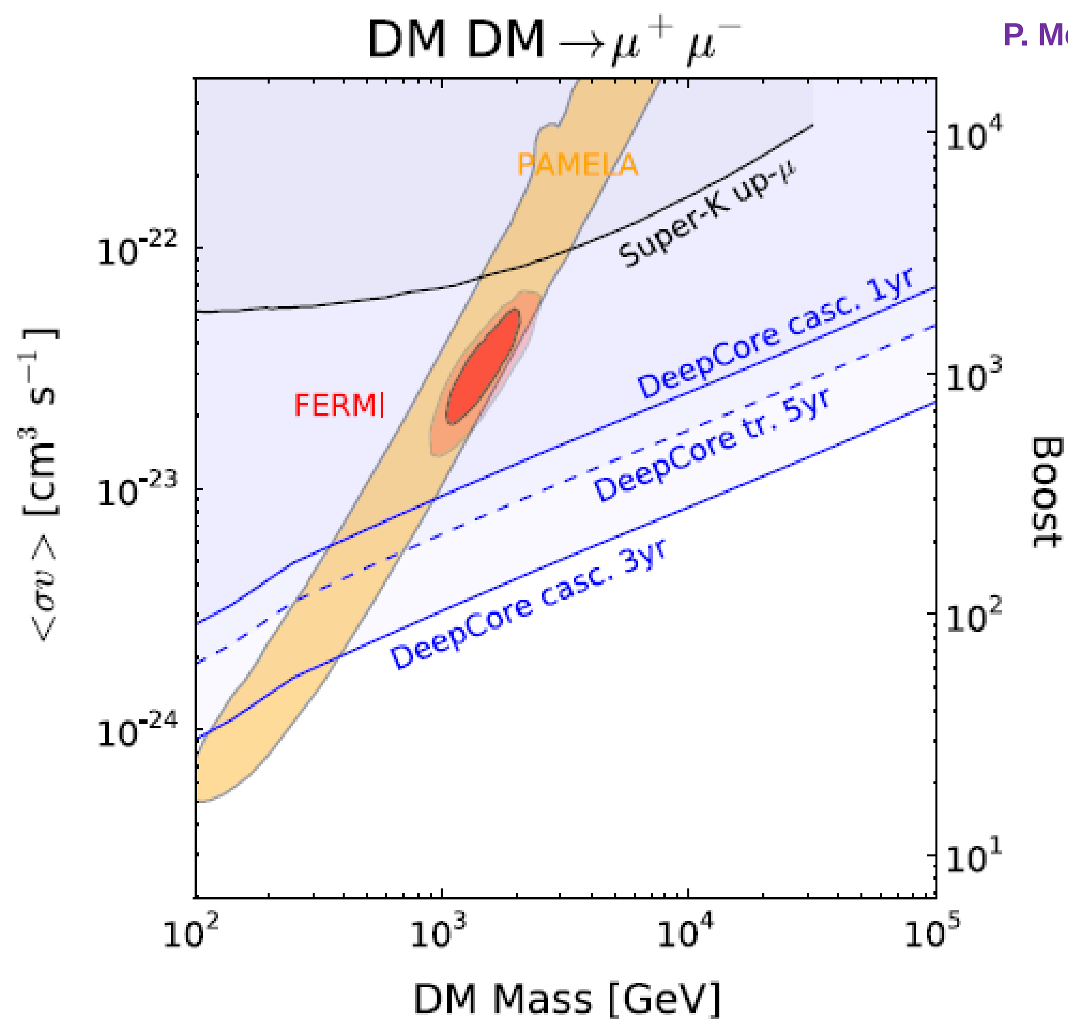
$$\text{Charged-Current } \nu_\mathrm{e} \text{ interaction}: \nu_\mathrm{e} + N \rightarrow e^-(\text{EM}) + X\,(\text{Hadronic})$$

$$\text{Charged-Current } \nu_\tau \text{ interaction}: \nu_\tau + N \rightarrow \tau^- + X$$

Constraints for annihilation to $\mu^+\mu^-$

S. K. Mandal et al. Phys. Rev. D81, 2010

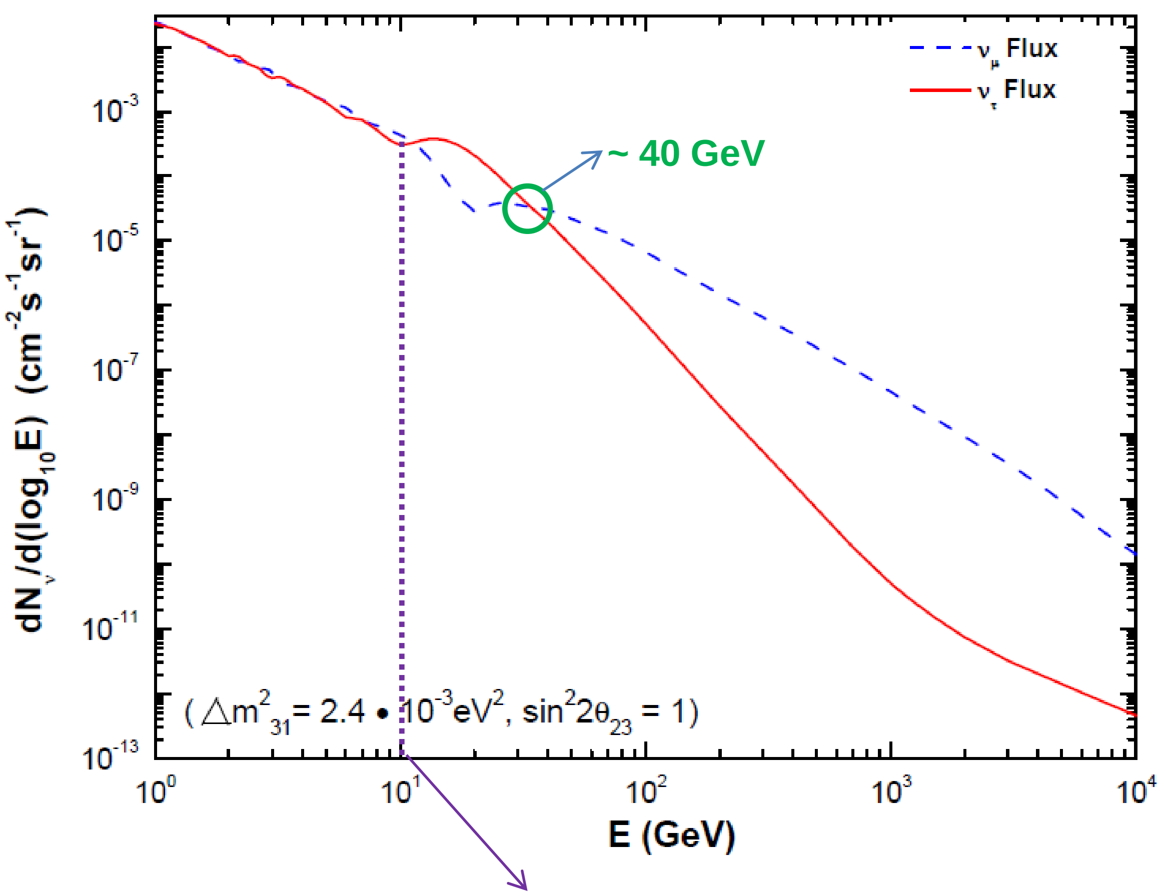
P. Meade et al. Nucl. Phys. B 831, 2010



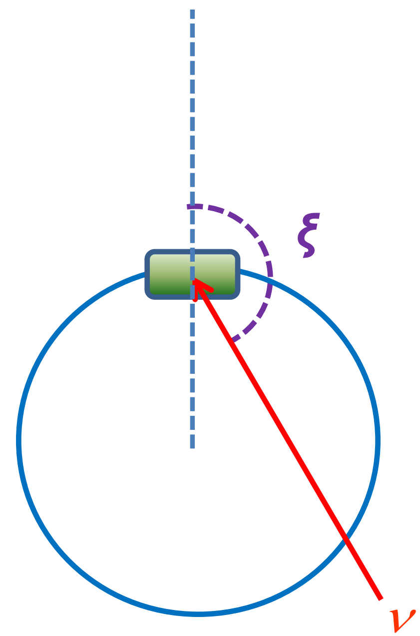
- In leptophilic DM model
- E^{th} =40 GeV

Atmospheric neutrino fluxes averaged for $-1 \leqq \cos\xi \leqq -0.4$

F. F. Lee, G. L. Lin, Astropart. Phys. 25, 2006



Detection threshold energy of **Iceube + DeepCore**



Neutrino flux from DM decay in the galactic halo

$$\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = \frac{\Delta\Omega}{4\pi}\frac{1}{m_\chi \tau_\chi}\left(\sum_F B_F \frac{dN^F_{\nu_i}}{dE}\right) R_\oplus \rho_\oplus \times J_1(\Delta\Omega) \quad \propto \frac{\rho}{m_\chi \tau_\chi}$$

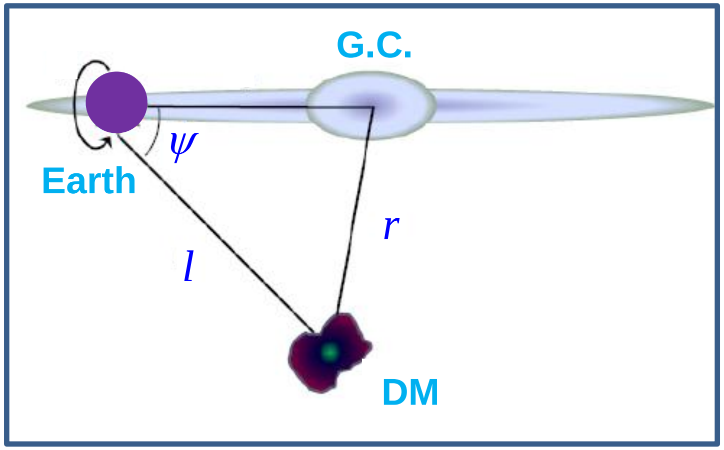
- $R_\oplus = 8.5\mathrm{kpc}$: distance from the galactic center to the solar system
  $\rho_\oplus = 0.3\,\mathrm{GeV/cm}^3$: DM density in the solar neighborhood
  $dN^F_{\nu_i}/dE$: neutrino spectrum per decay for a given decay channel F
  τ_χ: DM lifetime

- $J_1(\Delta\Omega)$ is the DM distribution integrated over the line-of-sight (l.o.s) for decay and averaged over a solid angle $\Delta\Omega = 2\pi(1 - \cos\psi_{max})$

$$J_1(\Delta\Omega) = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{l.o.s} \frac{dl}{R_\oplus}\left(\frac{\rho(r(l,\psi))}{\rho_\oplus}\right)^1$$

Navarro-Frenk-White (NFW) DM density profile

$$\rho(r) = \rho_s \left(\frac{R_s}{r}\right)\left(\frac{R_s}{R_s + r}\right)^2$$



Neutrino flux from DM annihilation in the galactic halo

$$\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = \frac{\Delta\Omega}{4\pi}\frac{\langle\sigma\upsilon\rangle}{2m_\chi^2}\left(\sum_F B_F \frac{dN_{\nu_i}^F}{dE}\right) R_\oplus \rho_\oplus^2 \times J_2(\Delta\Omega) \quad \propto \frac{\rho^2\langle\sigma\upsilon\rangle}{2m_\chi^2}$$

- $<\sigma v>$ is the thermally averaged annihilation cross section

$$\langle\sigma\upsilon\rangle = B\langle\sigma\upsilon\rangle_0$$

B : boost factor . $<\sigma v>_0 = 3 \times 10^{-26}$: typical cross section for DM relic density.

- $J_2(\Delta\Omega)$ is the line-of-sight (l.o.s) integral for annihilation

$$J_2(\Delta\Omega) = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{l.o.s} \frac{dl}{R_\oplus}\left(\frac{\rho(r(l,\psi))}{\rho_\oplus}\right)^2$$

Neutrino fluxes on Earth

$$\begin{pmatrix}\Phi_{\nu_e}\\ \Phi_{\nu_\mu}\\ \Phi_{\nu_\tau}\end{pmatrix} = \begin{pmatrix}P_{ee} & P_{e\mu} & P_{e\tau}\\ P_{\mu e} & P_{\mu\mu} & P_{\mu\tau}\\ P_{\tau e} & P_{\tau\mu} & P_{\tau\tau}\end{pmatrix}\begin{pmatrix}\Phi^0_{\nu_e}\\ \Phi^0_{\nu_\mu}\\ \Phi^0_{\nu_\tau}\end{pmatrix} = P\begin{pmatrix}\Phi^0_{\nu_e}\\ \Phi^0_{\nu_\mu}\\ \Phi^0_{\nu_\tau}\end{pmatrix}$$

J. G. Learned, Astropart. Phys. 3, 1995
H. Athar et al. Phys. Rev. D62, 2000
L. Bento et al. Phys. Lett. B476, 2000
K. C. Lai et al. Phys. Rev. D82, 2010

- $\Phi^0_{\nu_\alpha}$: neutrino flux measured on the Earth
- Φ_{ν_α} : neutrino flux at the astrophysical source
- $P_{\alpha\beta}$: probability of the oscillation $\nu_\beta \to \nu_\alpha$

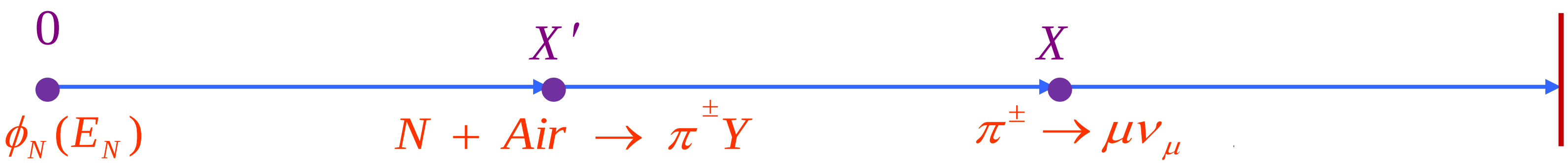
- In the tribimaximal limit of neutrino mixing angles: $\sin^2\theta_{23} = 1/2, \sin^2\theta_{12} = 1/3, \sin^2\theta_{13} = 0$

$$P = \begin{pmatrix}\frac{5}{9} & \frac{2}{9} & \frac{2}{9}\\ \frac{2}{9} & \frac{7}{18} & \frac{7}{18}\\ \frac{2}{9} & \frac{7}{18} & \frac{7}{18}\end{pmatrix} \Rightarrow \begin{cases}\Phi_{\nu_e} = \frac{5}{9}\Phi^0_{\nu_e} + \frac{2}{9}\Phi^0_{\nu_\mu} + \frac{2}{9}\Phi^0_{\nu_\tau}\\ \Phi_{\nu_\mu} = \Phi_{\nu_\tau} = \frac{2}{9}\Phi^0_{\nu_e} + \frac{7}{18}\Phi^0_{\nu_\mu} + \frac{7}{18}\Phi^0_{\nu_\tau}\end{cases}$$

Atmospheric neutrino fluxes

$E_\nu \geqq 10$ GeV

Intrinsic Atmospheric ν_μ Flux Due To π/k Decays



$$\frac{d^2 N^{\pi}_{\nu_\mu}(E,\xi,X)}{dE\,dX} = \int_E^\infty dE_N \int_E^{E_N} dE_\pi \frac{\Theta\left(E_\pi - \frac{E}{1-\gamma_\pi}\right) \times B(\pi \rightarrow \mu\nu_\mu)}{E_\pi(1-\gamma_\pi)} \frac{1}{d_\pi}$$

$$\times \int_0^X \frac{dX'}{\lambda_N} P_\pi(E_\pi, X, X') \times \frac{F_{N\pi}(E_\pi, E_N)}{E_\pi} \times \exp\left(-\frac{X'}{\Lambda_N}\right) \phi_N(E_N)$$

- E : neutrino energy。 d_π : pion decay length (in units of g/cm^2)。 $\gamma_\pi = m_\mu^2 / m_\pi^2$。
- ξ : the zenith angle in the direction of the incident cosmic-ray nucleons。
- Λ_N : the nucleon attenuation length。 λ_N : the nucleon interaction length。
- $F_{N\pi}(E_\pi, E_N)$: the normalized inclusive cross section for $N + air \rightarrow \pi^{\pm} + Y$。
- $P_\pi(E_\pi, X, X')$: the probaility that a charged pion produced at the slant depth X' (g/cm^2) survives to the depth X ($> X'$)。

Primary cosmic-ray spectrum

$$\phi_N(E_N) = \sum_A A\phi_A(E_N) \quad A: \text{atomic number}$$

$$\phi_A(E_N) = K \times \left(E_N + b\exp\left[-c\sqrt{E_N}\right]\right)^{-\alpha}$$

in the unit $cm^{-2}s^{-1}sr^{-1}GeV^{-1}$

parameter / component	α	K	b	c
Hydrogen (A = 1) ($\leq 10^2$ GeV)	2.74	14900	2.15	0.21
Hydrogen (A = 1) ($> 10^2$ GeV)	2.71	14900	2.15	0.21
He (A = 4)	2.64	600	1.25	0.14
CNO (A = 14)	2.60	33.2	0.97	0.01
Mg - Si (A = 25)	2.79	34.2	2.14	0.01
Iron (A = 56)	2.68	4.45	3.07	0.41

T. K. Gaisser and M. Honda, 2002
M. Honda et al. Phys. Rev. D70, 2004

Intrinsic Atmospheric ν_μ Flux Due To μ Decays

$$\pi^\pm \to \mu\nu_\mu \qquad \mu \to e\nu_e\nu_\mu$$

Atmospheric μ flux from π decays

$$\frac{\mathrm{d}N_\mu^\pi(E,\xi,X)}{\mathrm{d}E} = \int_{E'}^{\infty}\mathrm{d}E_N \int_{E'}^{E_N}\mathrm{d}E_\pi \int_0^X \mathrm{d}X''\, P_\mu(E,X,X'') \frac{\Theta(E_\pi - E')\Theta\left(\frac{E'}{\gamma_\pi} - E_\pi\right)B(\pi\to\mu\nu_\mu)}{E_\pi(1-\gamma_\pi)}\frac{1}{d_\pi}$$

$$\times\int_0^{X'}\frac{dX'}{\lambda_N}P_\pi(E_\pi,X'',X')\times\frac{F_{N\pi}(E_\pi,E_N)}{E_\pi}\times\exp\left(-\frac{X'}{\Lambda_N}\right)\phi_N(E_N)$$

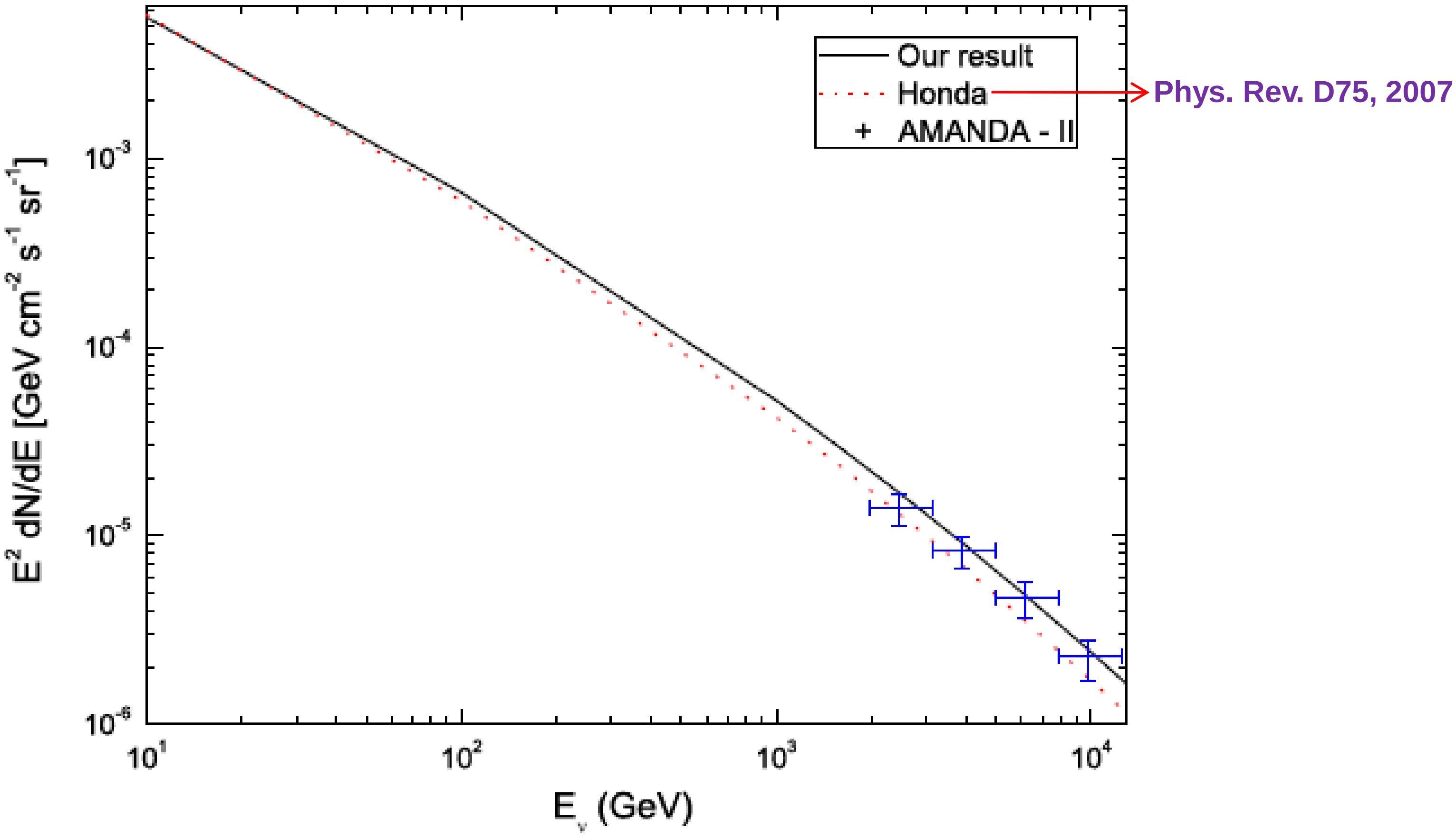
where E' and E are μ energies at X'' and X'. Then we multiply by $P_{\mu_s^\pm}^\pi$ (probabilities for the produced μ to be different helicities) to get the ν_μ flux arising from μ decays :

$$\frac{\mathrm{d}^2 N_{\nu_\mu}^{\mu^\pm}(E,\xi,X)}{\mathrm{d}E\mathrm{d}X} = \sum_{s=L,R}\int_E^\infty \mathrm{d}E_\mu \frac{F_{\mu_s^\pm\to\nu_\mu}(E/E_\mu)}{d_\mu(E_\mu,X)E_\mu}\cdot\frac{\mathrm{d}N_{\mu_s^\pm}(E_\mu,\xi,X)}{\mathrm{d}E_\mu} \quad ;$$

$$\frac{\mathrm{d}N_{\mu_s^\pm}^\pi(E_\mu,\xi,X)}{\mathrm{d}E_\mu} = \frac{\mathrm{d}N_\mu^\pi(E_\mu,\xi,X)}{\mathrm{d}E_\mu}\cdot P_{\mu_s^\pm}^\pi$$

Angle-averaged atmospheric muon neutrino flux for 0 ≦ cos*ξ* ≦ 1

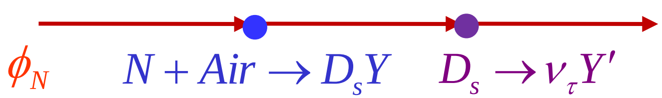
(without oscillations)



$$\frac{\mathrm{d}^2 N_{\nu_\mu}}{\mathrm{d}E\mathrm{d}X} = \frac{\mathrm{d}^2 N_{\nu_\mu}^{\pi}}{\mathrm{d}E\mathrm{d}X} + \frac{\mathrm{d}^2 N_{\nu_\mu}^{\mu^\pm}}{\mathrm{d}E\mathrm{d}X}$$

Intrinsic Atmospheric ν_τ Flux

Cascade equations



$$\begin{cases} \dfrac{\mathrm{d}\phi_N(E,X)}{\mathrm{d}X} = -\dfrac{\phi_N}{\lambda_N} + Z_{NN}\dfrac{\phi_N}{\lambda_N} \\ \dfrac{\mathrm{d}\phi_{D_s}(E,X)}{\mathrm{d}X} = -\dfrac{\phi_{D_s}}{\lambda_{D_s}} - \dfrac{\phi_{D_s}}{dD_s} + Z_{ND_s}\dfrac{\phi_N}{\lambda_N} + Z_{D_sD_s}\dfrac{\phi_{D_s}}{\lambda_{D_s}} \\ \dfrac{\mathrm{d}\phi_{\nu_\tau}(E,X)}{\mathrm{d}X} = Z_{D_s\nu_\tau}\dfrac{\phi_{D_s}}{dD_s} \end{cases}$$

- For $E_\nu < 10^6$ GeV

$$\frac{\mathrm{d}^2 N_{\nu_\tau}(E,X)}{\mathrm{d}E\,\mathrm{d}X} = \frac{Z_{ND_s} Z_{D_s\nu_\tau}}{1 - Z_{NN}(E)} \cdot \frac{\exp(-X/\Lambda_N)\,\phi_N(E_N)}{\Lambda_N}$$

Z moment : $Z_{ij}(E_j) \equiv \int_{E_j}^{\infty} dE_i \dfrac{\phi_i(E_i)}{\phi_i(E_j)} \dfrac{\lambda_i(E_j)}{\lambda_i(E_i)} \dfrac{dn_{iA\to jY}(E_i,E_j)}{dE_j}$

where $\mathrm{d}n_{iA\to jY}(E_i,E_\mathrm{j}) \equiv \mathrm{d}\sigma_{iA\to jY}(E_i,E_\mathrm{j}) / \sigma_{iA}(E_i)$.

Atmospheric Neutrino Flux With Oscillations

$$\frac{\mathrm{d}\bar{N}_{\nu_\mu}(E,\xi)}{\mathrm{d}E} = \int_0^{X_{\max}(\xi)} \mathrm{d}X \left[\frac{\mathrm{d}^2 N_{\nu_\tau}(E,\xi,X)}{\mathrm{d}E\,\mathrm{d}X} \cdot P_{\nu_\tau \to \nu_\mu}(E, L(X,\xi)) + \frac{\mathrm{d}^2 N_{\nu_\mu}(E,\xi,X)}{\mathrm{d}E\,\mathrm{d}X} \cdot \left(1 - P_{\nu_\mu \to \nu_\tau}(E, L(X,\xi))\right) \right]$$

$$\frac{\mathrm{d}\bar{N}_{\nu_\tau}(E,\xi)}{\mathrm{d}E} = \int_0^{X_{\max}(\xi)} \mathrm{d}X \left[\frac{\mathrm{d}^2 N_{\nu_\mu}(E,\xi,X)}{\mathrm{d}E\,\mathrm{d}X} \cdot P_{\nu_\mu \to \nu_\tau}(E, L(X,\xi)) + \frac{\mathrm{d}^2 N_{\nu_\tau}(E,\xi,X)}{\mathrm{d}E\,\mathrm{d}X} \cdot \left(1 - P_{\nu_\tau \to \nu_\mu}(E, L(X,\xi))\right) \right]$$

$$P_{\nu_\mu \to \nu_\tau}(E, L(X,\xi)) = P_{\nu_\tau \to \nu_\mu}(E, L(X,\xi)) \equiv \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{1.27\Delta m_{31}^2 L}{E}\right)$$

$$\sin^2 2\theta_{23} = 1 \;;\; \Delta\mathrm{m}_{31}^2 = 2.47\times10^{-3}\,\mathrm{eV}^2$$

M. C. Gonzalez-Garcia et al. JHEP 1004, 2010

Event Rates

$$\Gamma_{\text{track}} = \int_{E_\mu^{\text{th}}}^{E_{\max}} \mathrm{d}E_\mu \int_{E_\mu}^{E_{\max}} \mathrm{d}E_{\nu_\mu} N_A \rho_{\text{ice}} V_{\text{tr}} \times \frac{\mathrm{d}\Phi_{\nu_\mu}}{\mathrm{d}E_{\nu_\mu}} \cdot \frac{\mathrm{d}\sigma^{CC}_{\nu_\mu N}\left(E_{\nu_\mu}, E_\mu\right)}{\mathrm{d}E_\mu} + \left(\nu \to \overline{\nu}\right)$$

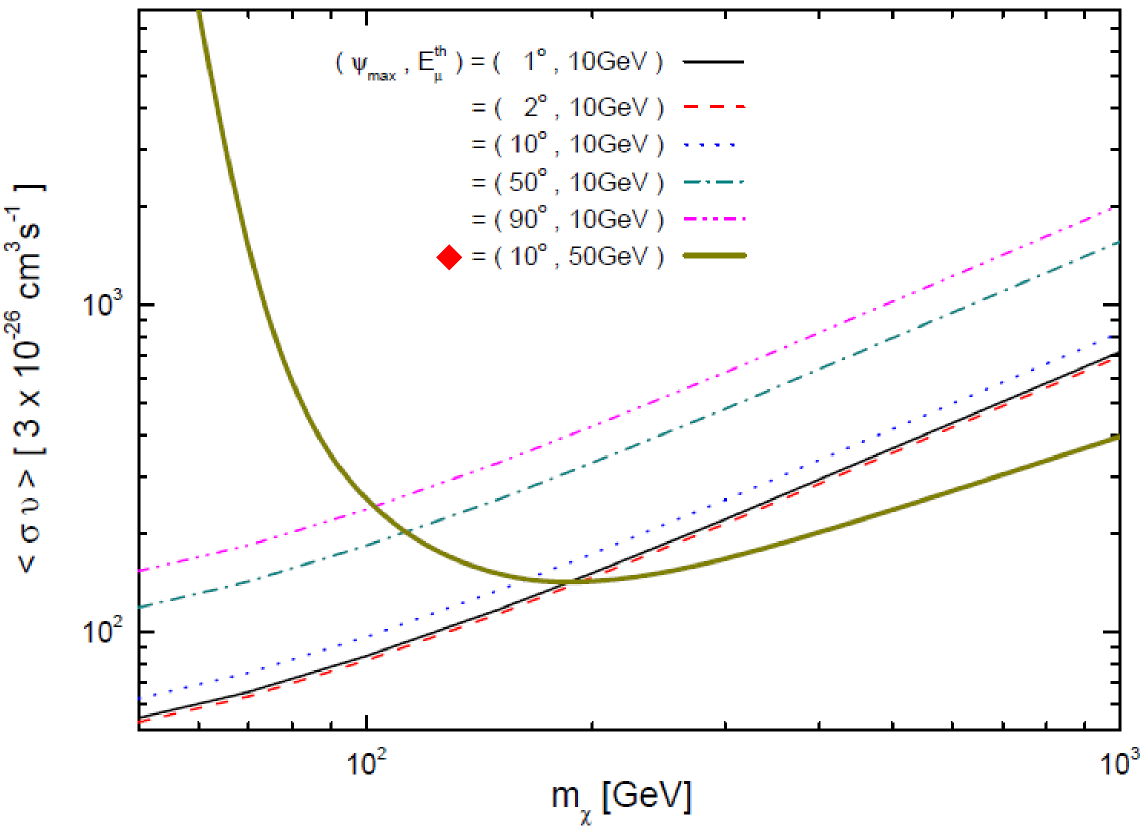
$$\Gamma_{\text{cascade}} = \int_{E_{\text{shower}}^{\text{th}}}^{E_{\max}} \mathrm{d}E_{\text{shower}} \int_{E_{\text{Shower}}}^{E_{\max}} \mathrm{d}E_\nu N_A \rho_{\text{ice}} V_{\text{casc}} \times \frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} \cdot \frac{\mathrm{d}\sigma_{\nu N}\left(E_\nu, E_{\text{shower}}\right)}{\mathrm{d}E_{\text{shower}}} + \left(\nu \to \overline{\nu}\right)$$

→ $(\nu_e N)_{\text{CC}}$, $(\nu_e N)_{\text{NC}}$, $(\nu_\mu N)_{\text{NC}}$, $(\nu_\tau N)_{\text{CC}}$, $(\nu_\tau N)_{\text{NC}}$

- $\rho_{\text{ice}} = 0.9\ \text{g cm}^{-3}$ is the density of ice ; $N_A = 6.022 \times 10^{23}\ \text{g}^{-1}$ is Avogadro's number
- $V_{\text{tr}} \approx 0.04\ \text{km}^3$ is the effective volume of IceCube DeepCore array for muon track events
  $V_{\text{casc}} \approx 0.02\ \text{km}^3$ is the effective volume of IceCube DeepCore array for cascade events
- $E_{\max}$ is taken as m_χ for DM annihilation ; $E_{\max}$ is taken as $\frac{m_\chi}{2}$ for DM decay
- $\frac{\mathrm{d}\Phi_{\nu_e}}{\mathrm{d}E_{\nu_e}}$ is taken from **M. Honda et al. Phys. Rev. D75, 2007**

Constraints for DM annihilation $\chi\chi \to \mu^+\mu^-$ (track events)

Leptophilic DM model for illustration



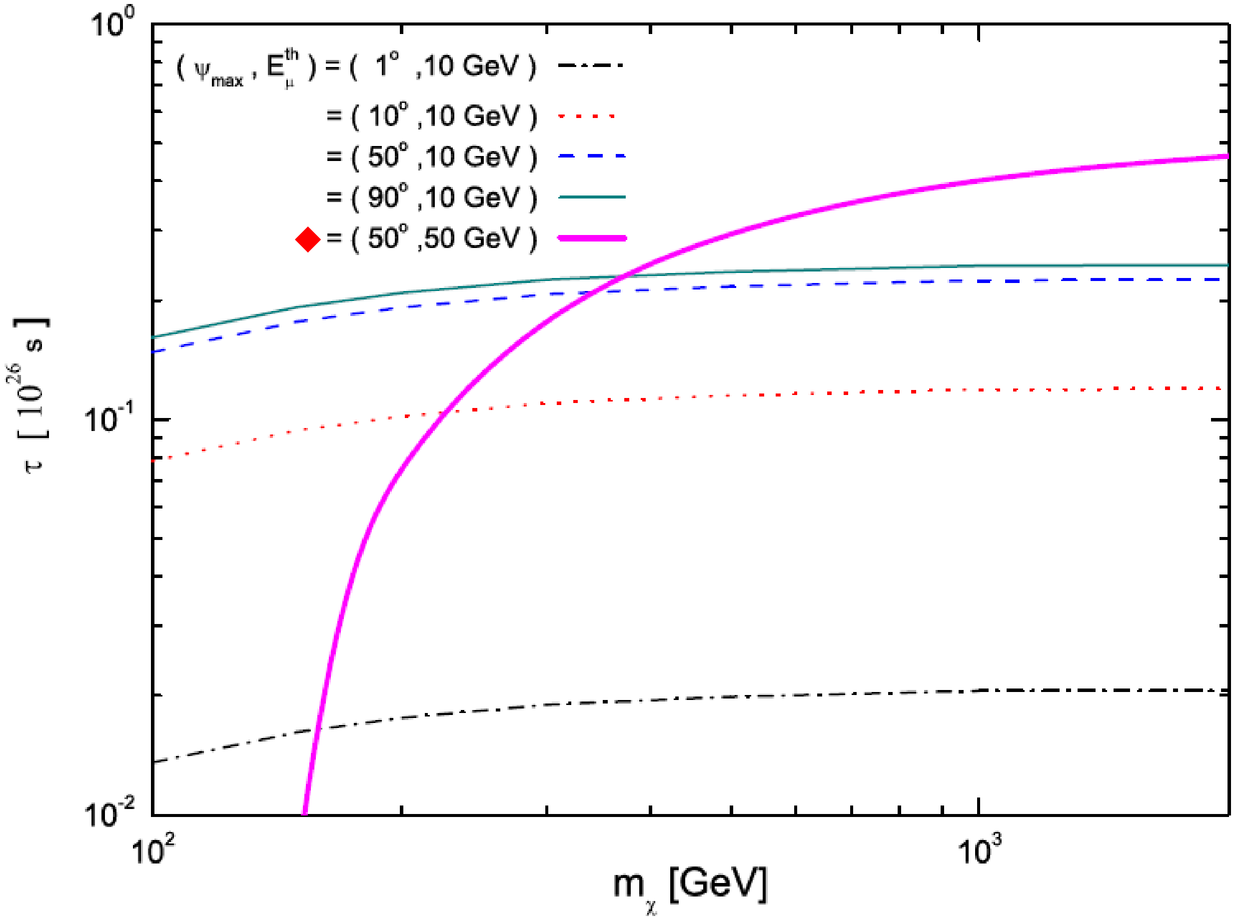
Event rates per year

(ψ_{max}, E_μ^{th})	ATM	Signal
2^o, 10GeV	47.8	6.6
10^o, 10GeV	1.2×10^3	31.4
90^o, 10GeV	7.5×10^4	244.9
10^o, 50GeV	222	13.7

- DM annihilation cross section required for a 2σ neutrino detection significance in 5 years for different DM masses

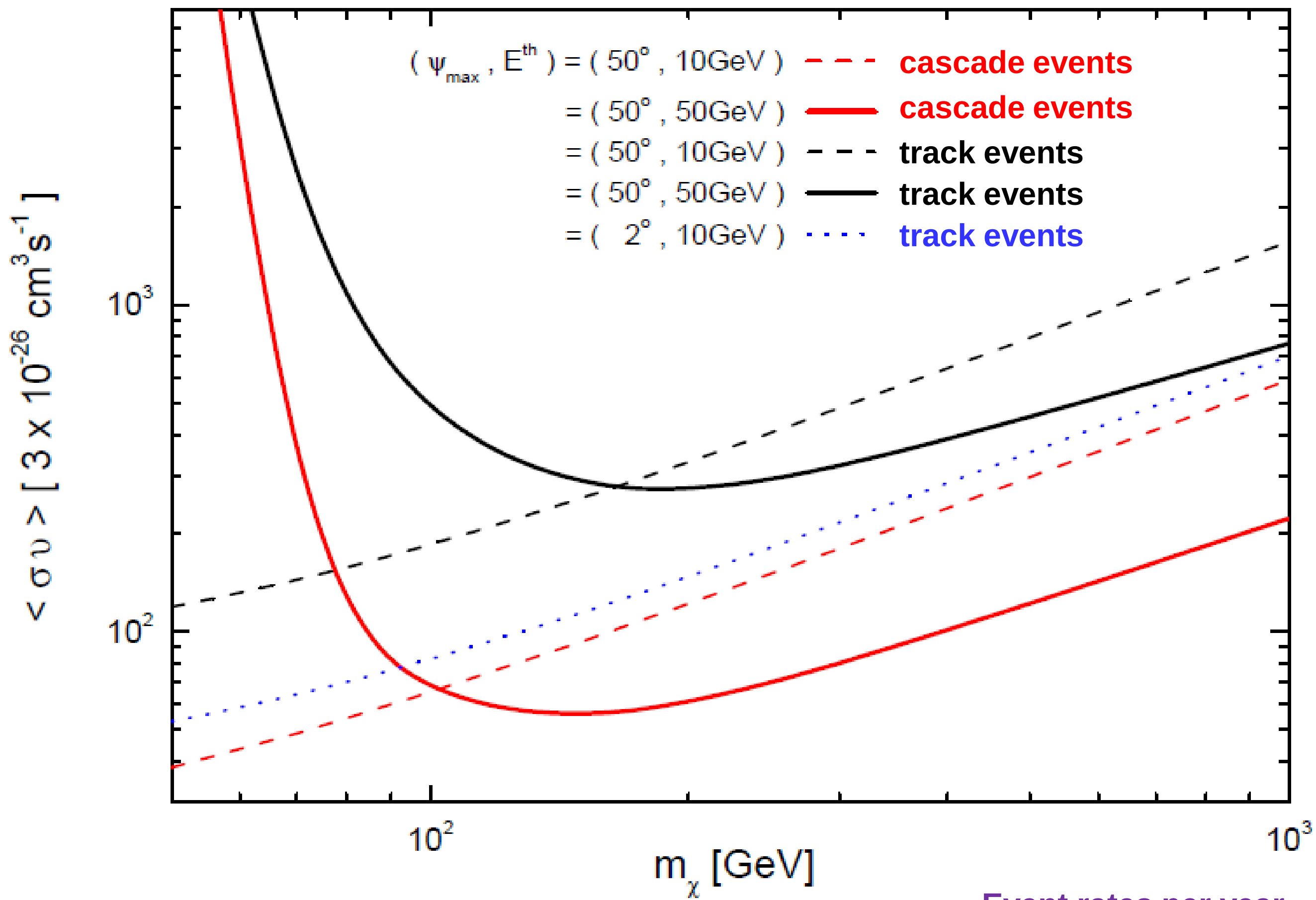
◆ **A. E. Erkoca, M. H. Reno, I. Sarcevic, Phys. Rev. D82, 2010 :**
$\psi_{max} = 10^o$ is the most optimal cone half-angle for constraining DM annihilation cross section at $E_\mu^{th} = 50\,\text{GeV}$

Constraints for DM decay $\chi \to \mu^+ \mu^-$ (track events)



◆ A. E. Erkoca, M. H. Reno, I. Sarcevic, Phys. Rev. D82, 2010

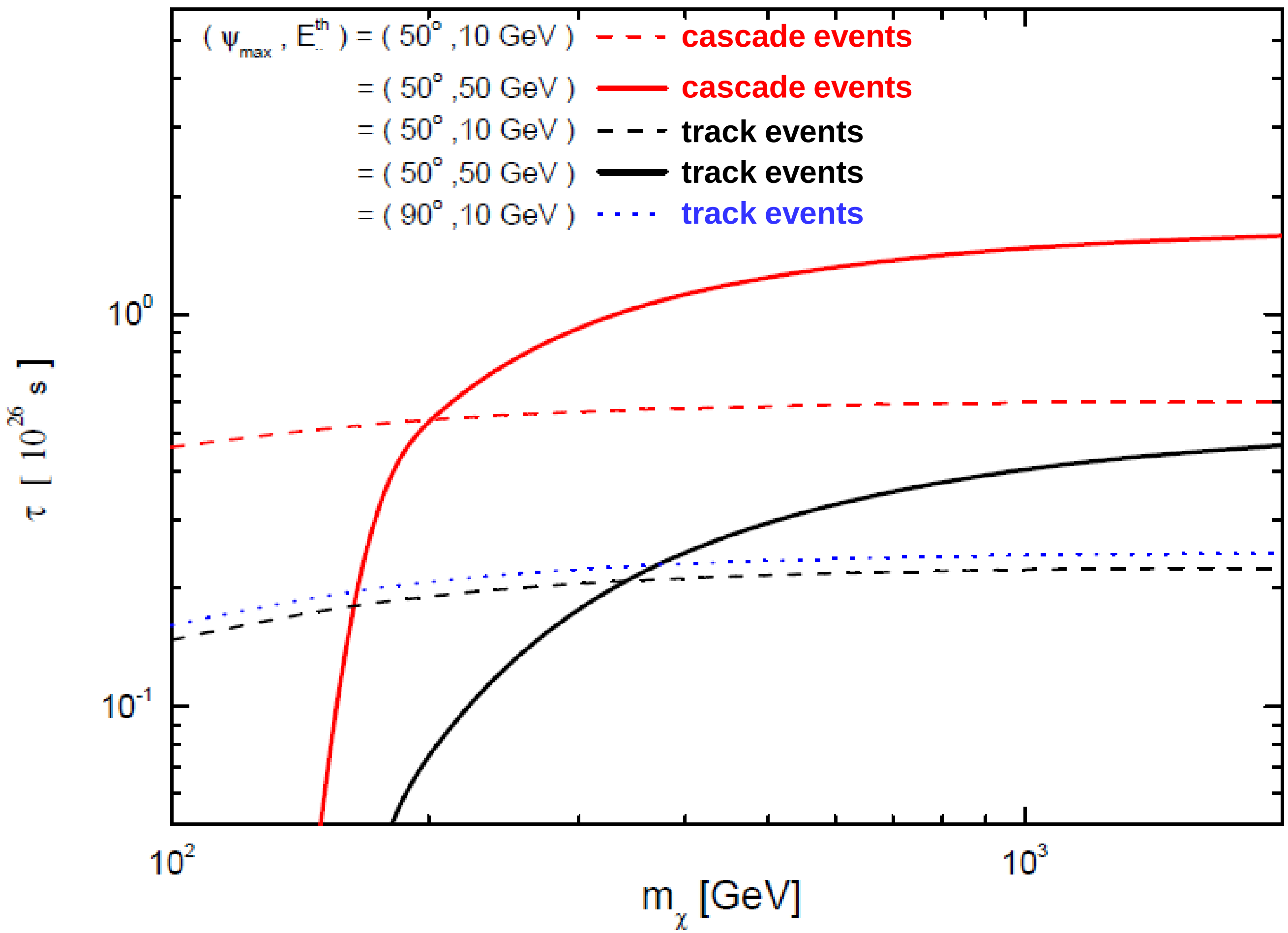
Constraints for DM annihilation $\chi\chi \to \mu^+ \mu^-$ (track & cascade)



Event rates per year

	(ψ_{max}, E^{th})	ATM	Signal
cascade	50^o, 10GeV	1.2×10^4	97
track	50^o, 10GeV	3×10^4	157.3
track	2^o, 10GeV	47.8	6.6

Constraints for DM decay $\chi \rightarrow \mu^+ \mu^-$ (track & cascade)



Summary

- We employ NFW DM profile and leptophilic DM model to calculate the track and cascade event rates in IceCube DeepCore due to neutrino fluxes from DM annihilations and decays in the galactic halo.

- We take into account neutrino oscillations and calculate the event rates due to atmospheric neutrino background.

- For track events, we compare our calculated sensitivity based upon E^{th} = 10 GeV with those obtained by taking E^{th} = 50 GeV and conclude that our choice of E^{th} = 10 GeV significantly improves the sensitivity to DM signature for m_χ < 100 GeV in the annihilation channel and m_χ < 300 GeV in the decay channel.

- Cascade events provide stronger constraints on DM annihilation cross section and DM decay time than the corresponding constraints provided by track events with the same threshold energy.

- For DM annihilation, the sensitivity of track events for sufficient small cone half-angle would be comparable to the sensitivity of cascade events.