3rd International Workshop on
Dark Matter, Dark Energy and
Matter-Antimatter Asymmetry

Dark Matter Induced Neutrino Signature in IceCube and KM3NeT

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F.-F. Lee and G.-L. Lin, Phys. Rev. D85, 023529 (2012)
F.-F. Lee, G.-L. Lin and Sming Tsai, Phys. Rev. D (2013)

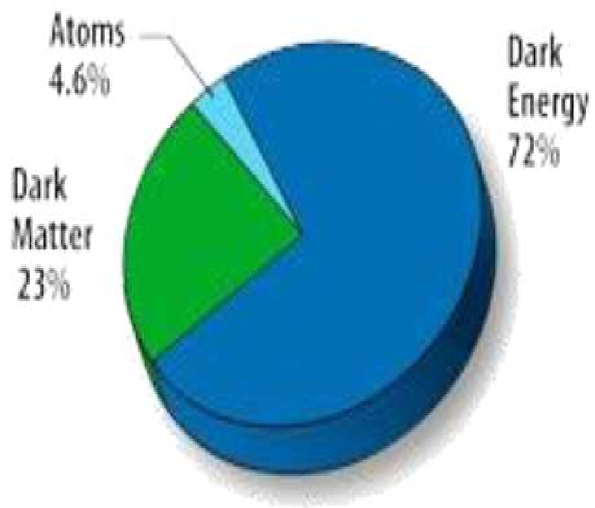
Outline

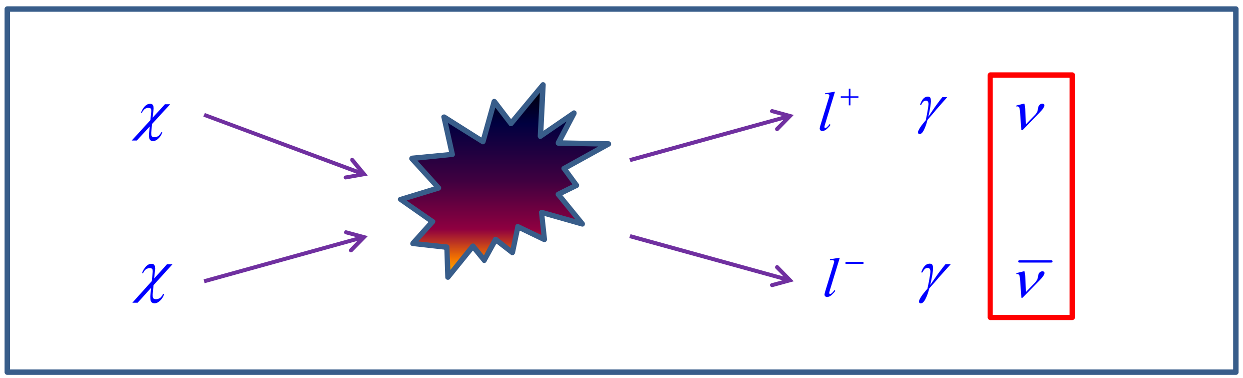
- **Introduction**
- **IceCube 22-string search for galactic dark matter**
- **Detection sensitivity in IceCube+DeepCore—phenomenological analysis**
- **Constraints from gamma ray observations**

Prospects of detection in IceCube DeepCore and KM3NeT

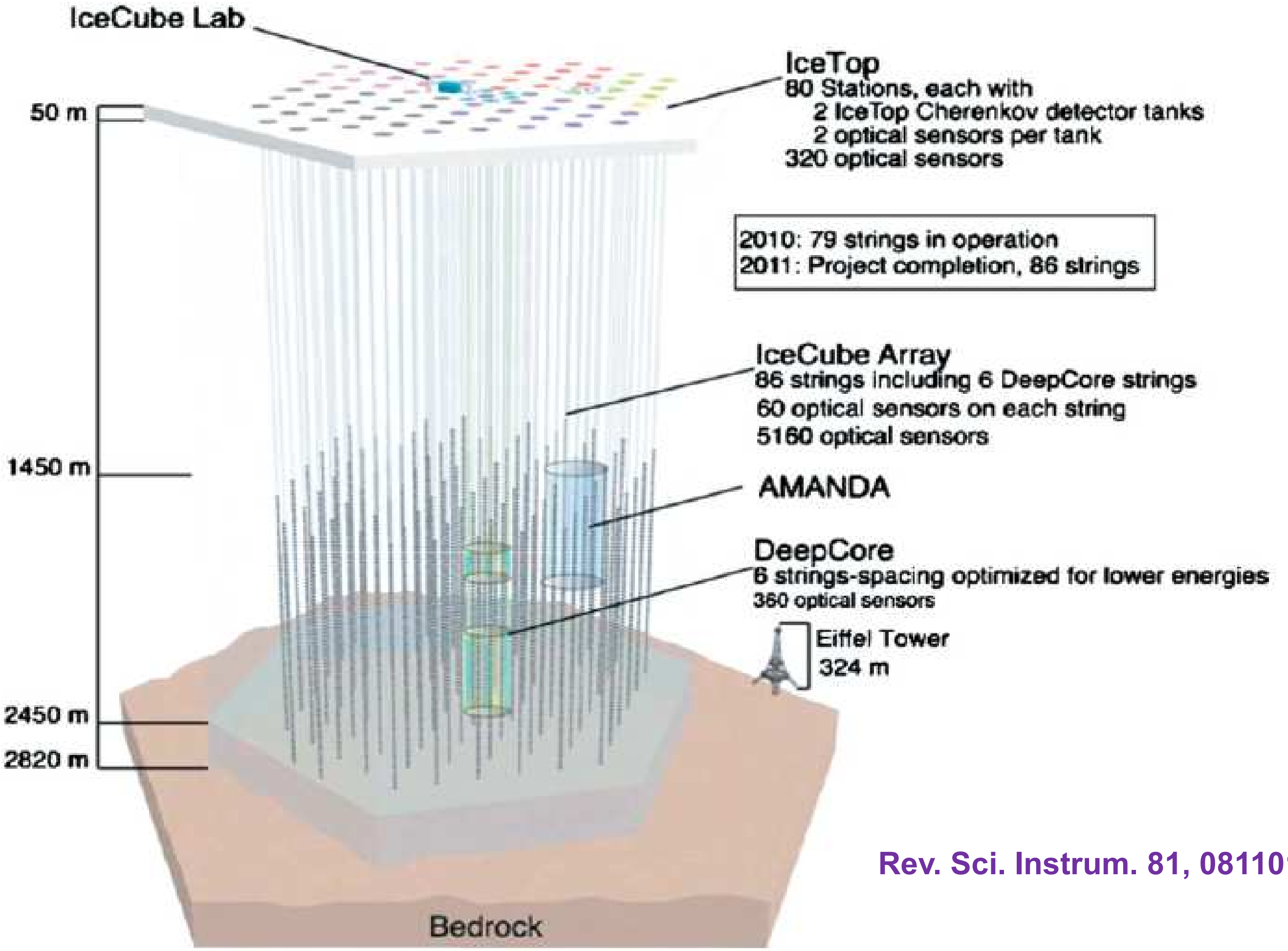
Dark Matter

- An 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

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

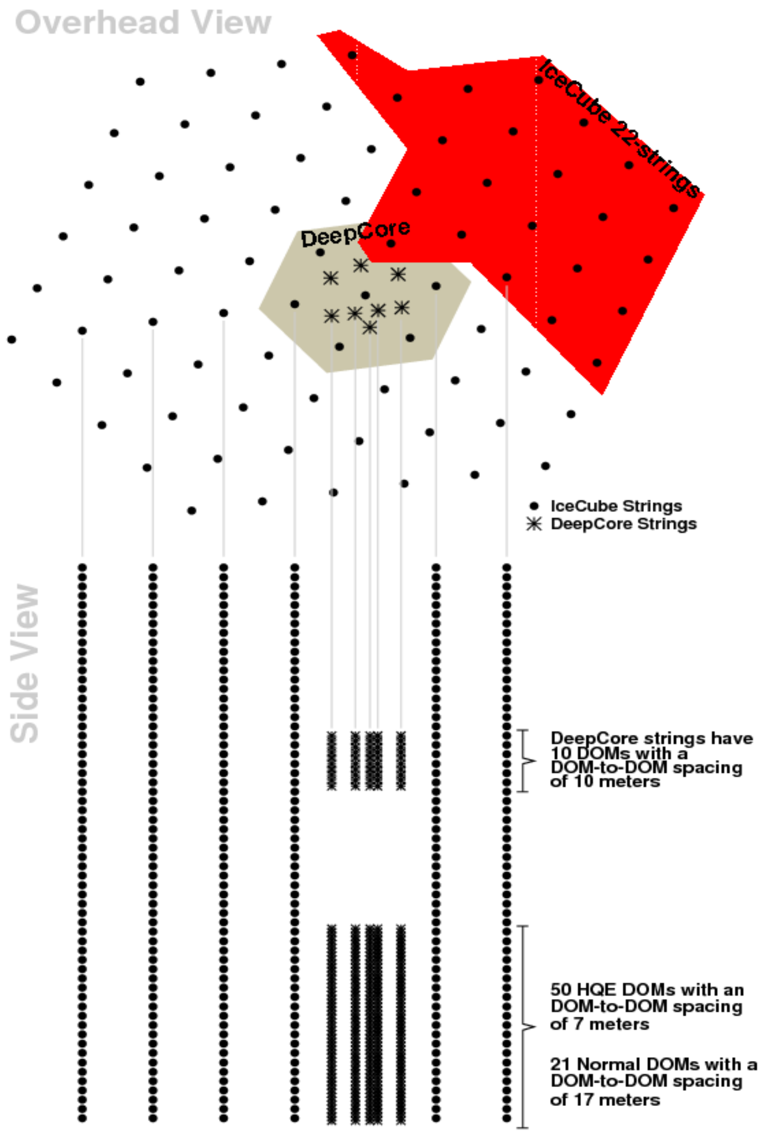
Cascade Events

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

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

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

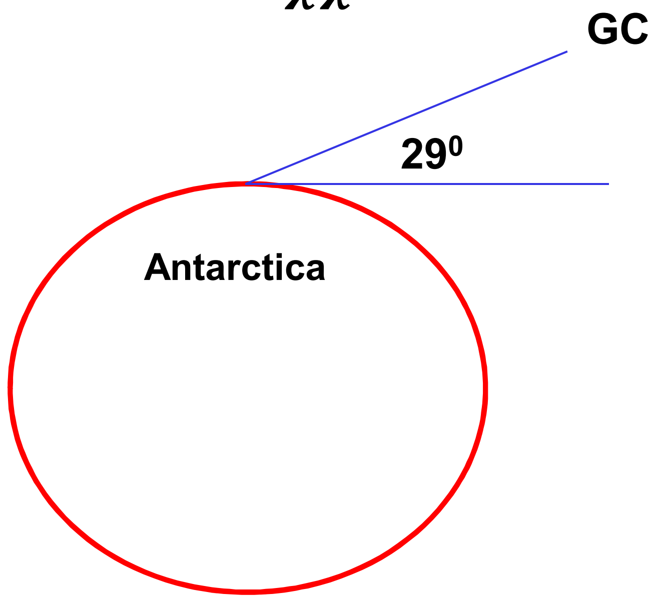
IceCube 22 String Result

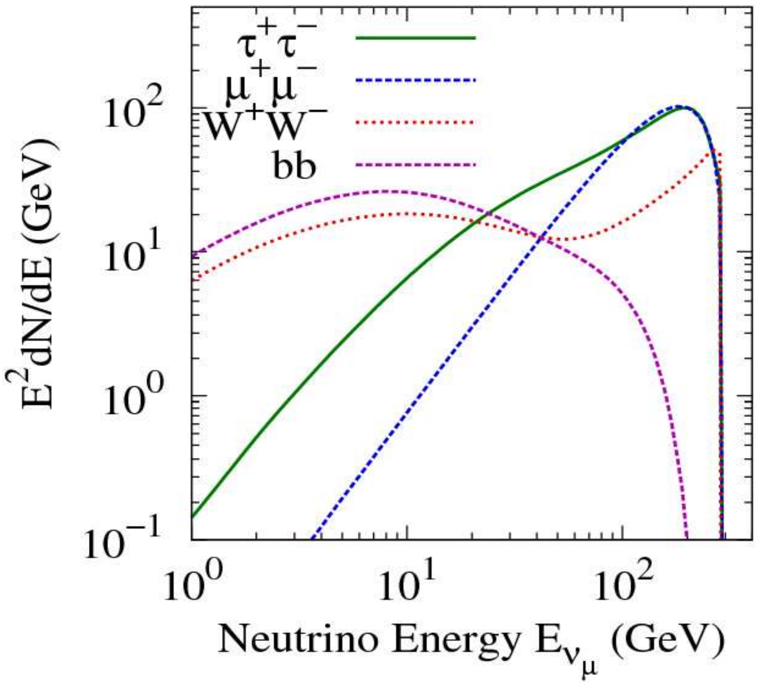


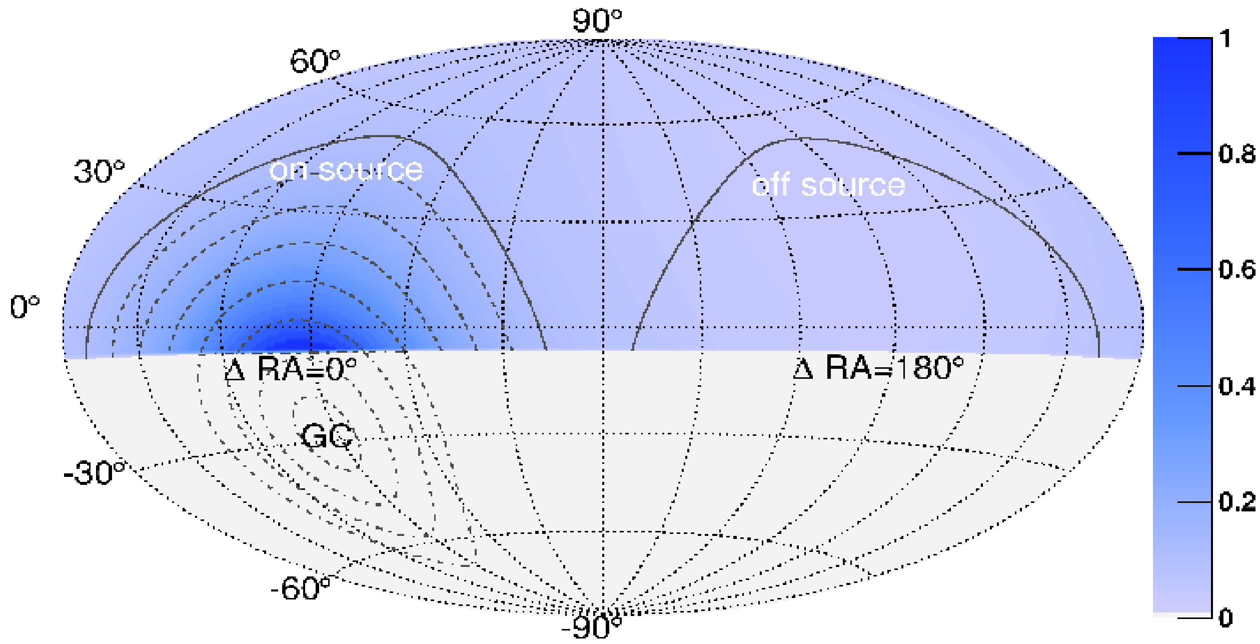
Phys. Rev. D 84, 022004 (2011)
2007~2008, 276 days of data

Search for muon neutrino induced by DM annihilation in galactic halo

Also includes $\chi\chi \rightarrow \nu\bar{\nu}$

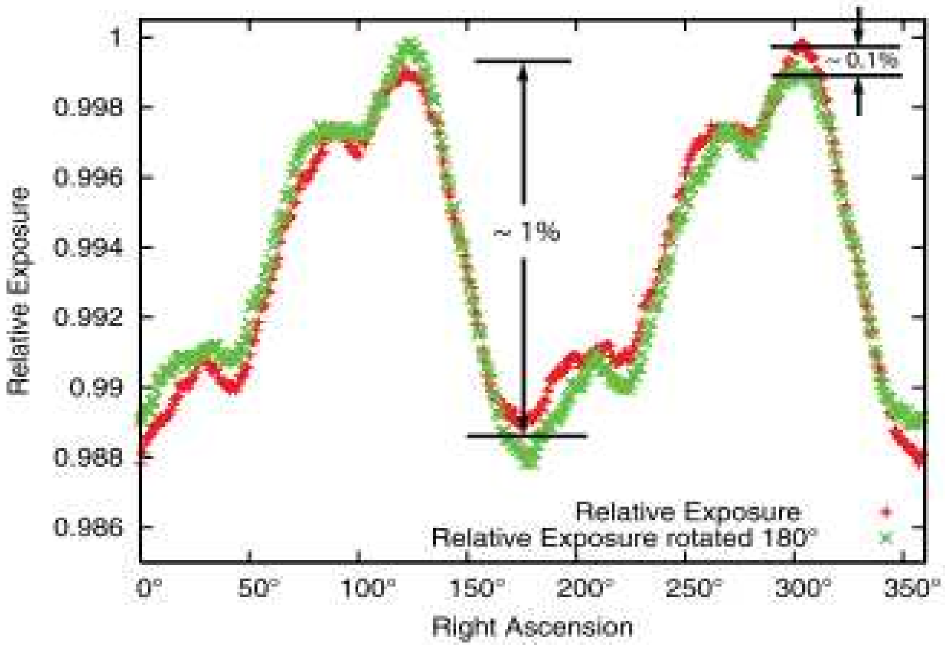






GC is located at
266° right ascension (RA)
And -29^0 declination.

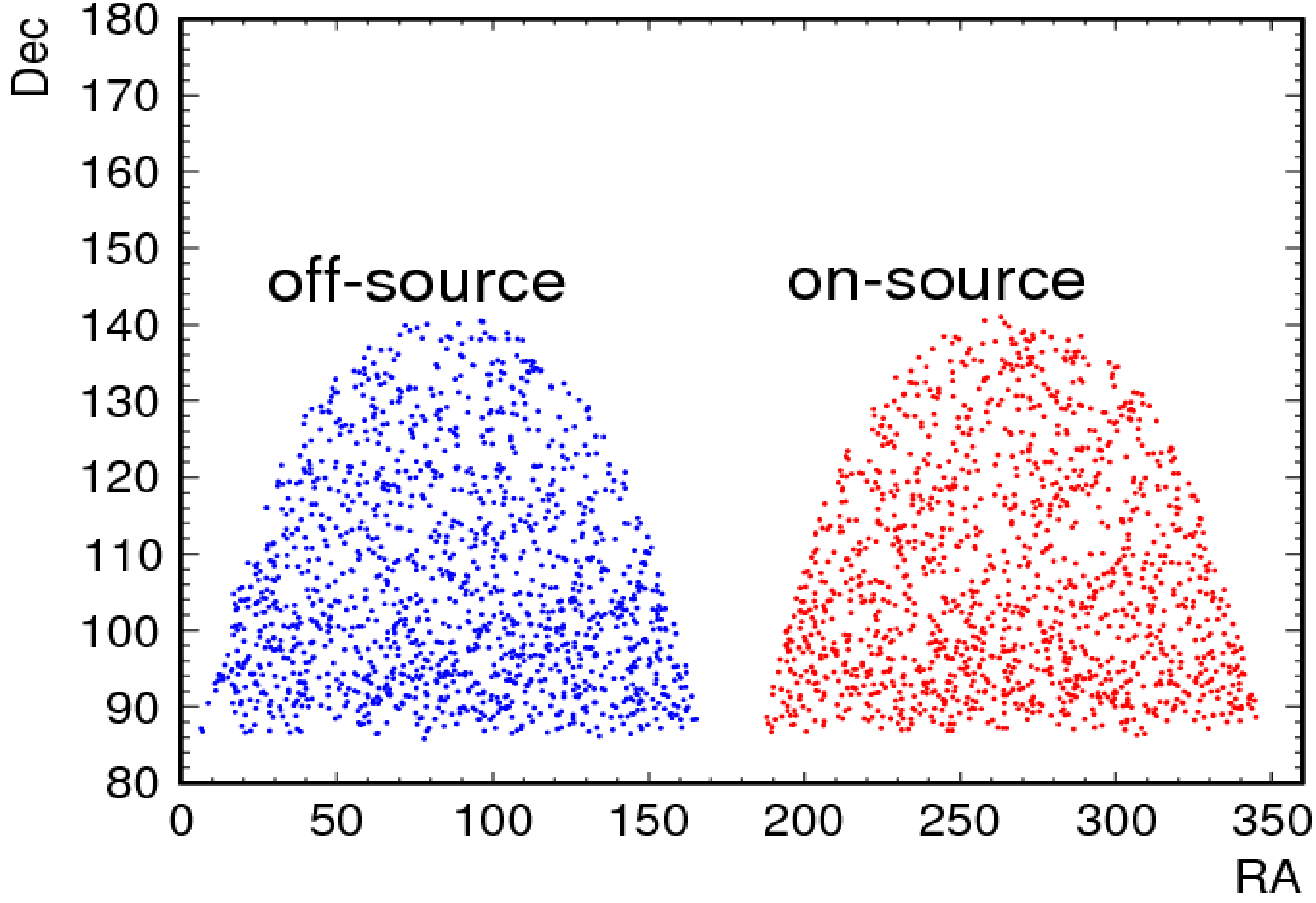
Select muon track events from -5^0 to 85^0 in declination.

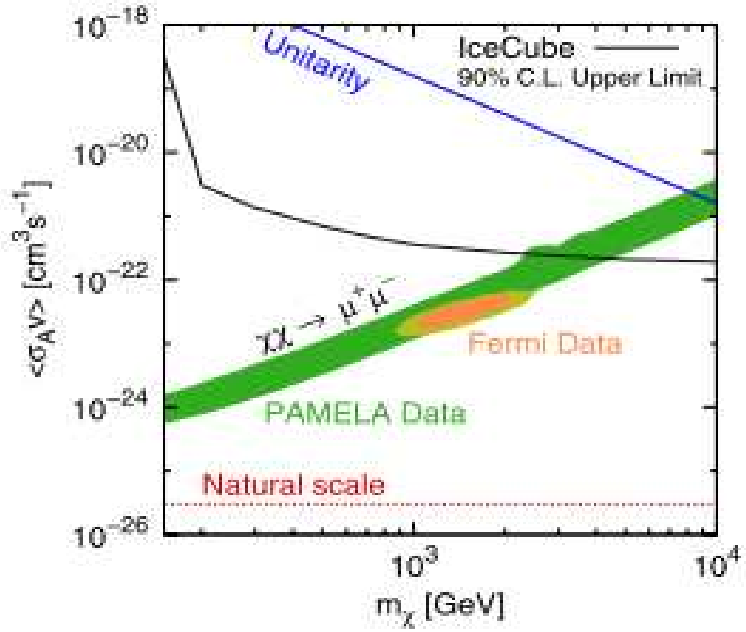


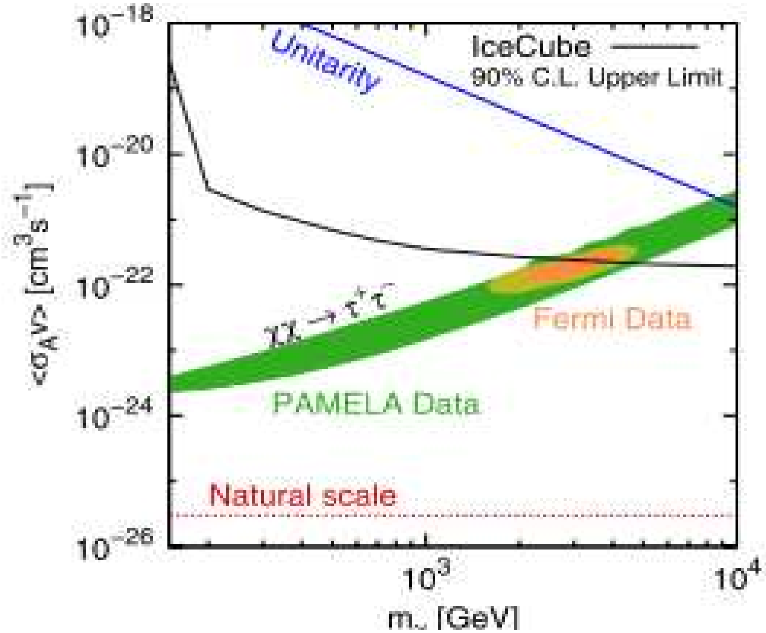
Measure $\Delta N = (N^{bkg}_{on} + N^{sig}_{on}) - (N^{bkg}_{off} + N^{sig}_{off})$

$\approx \Delta N^{sig}$

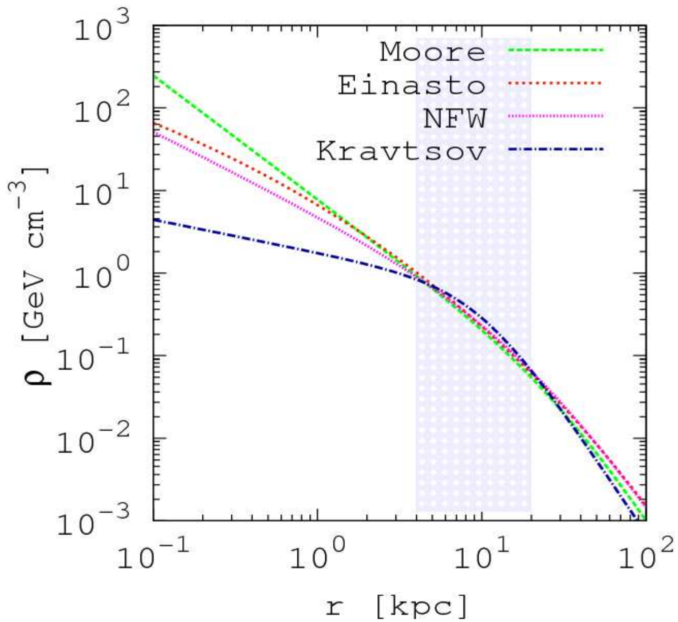
Search results



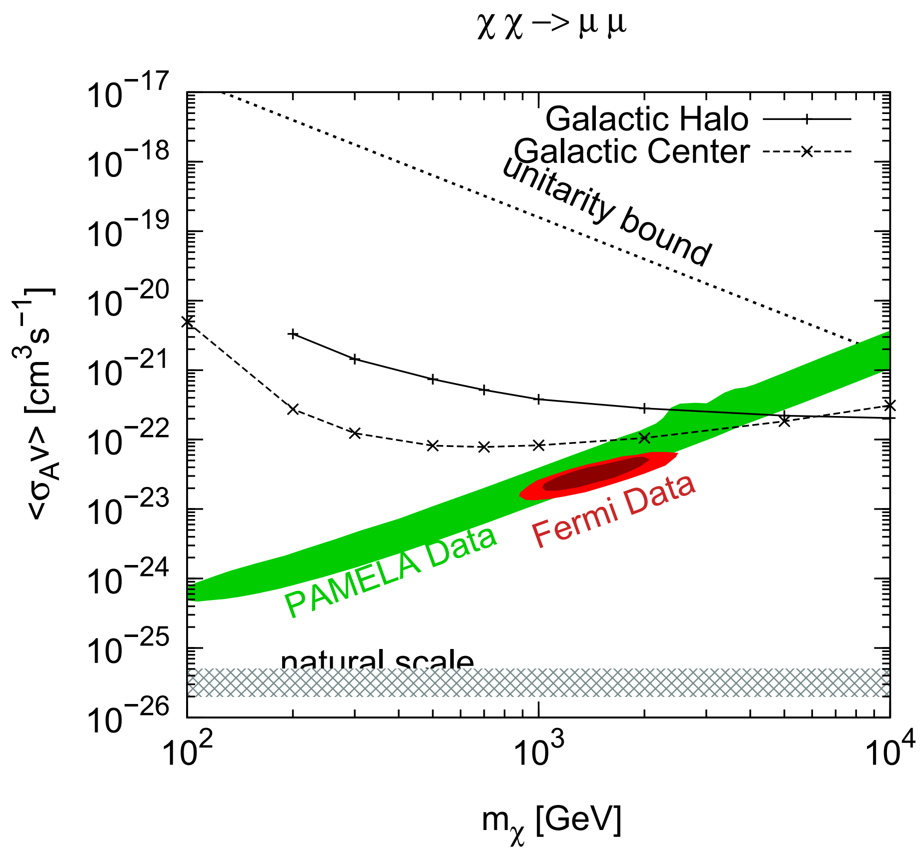


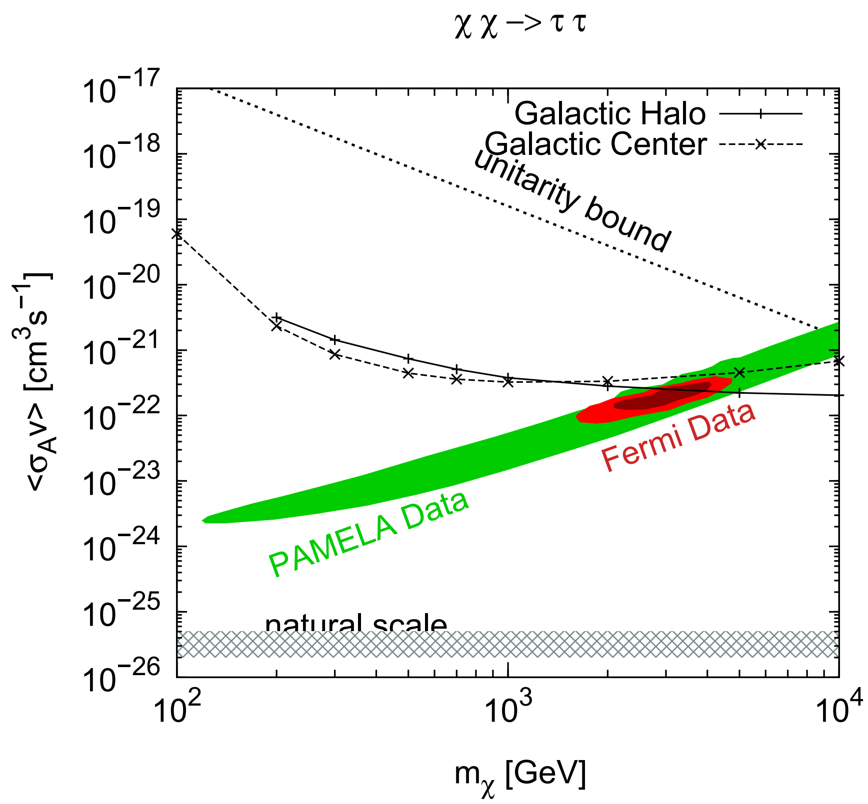


This result is almost independent of galactic halo model



PAMELA: GeV positron excess
Fermi: electron spectra





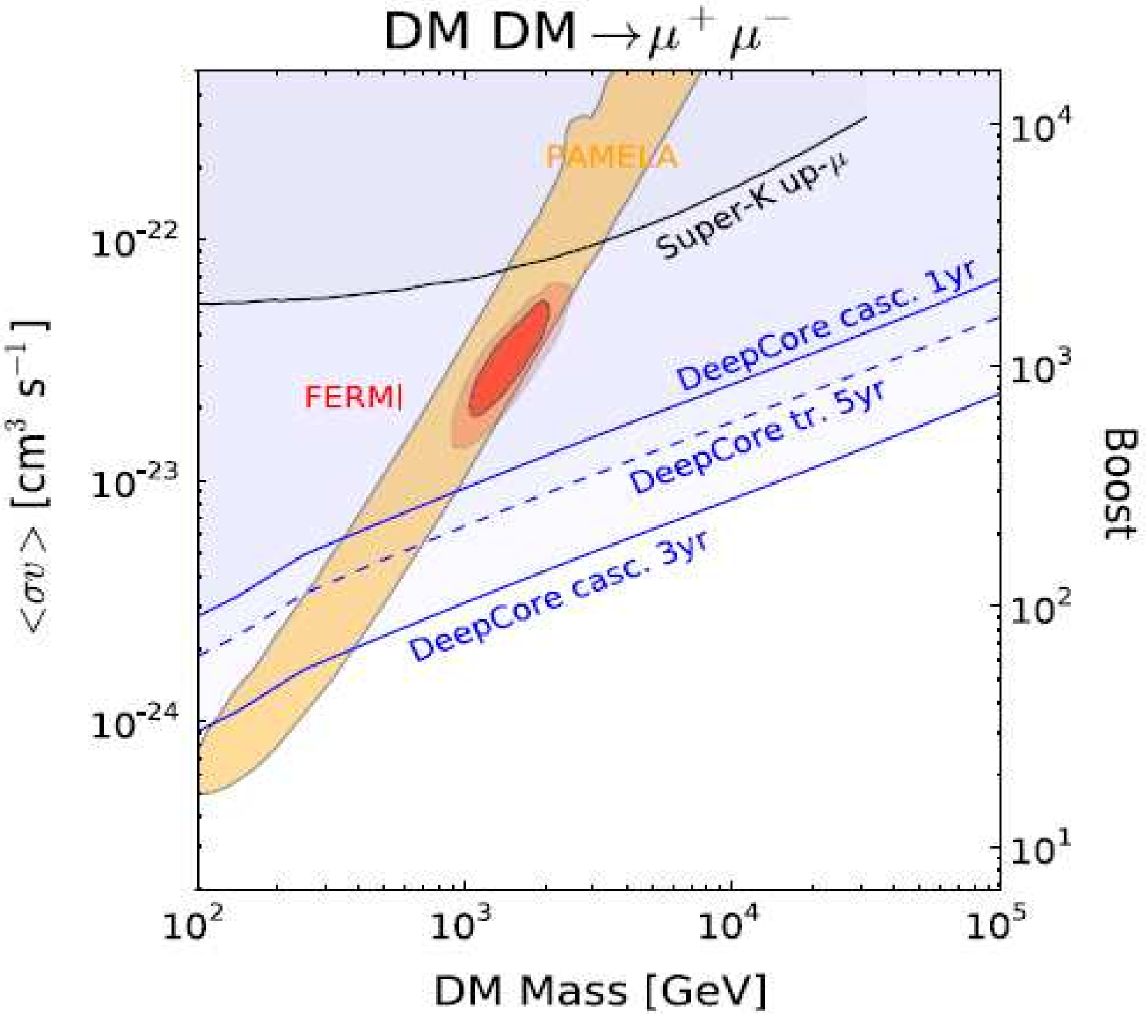
IceCube 40 string result

arxiv: 1210.3557

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

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

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

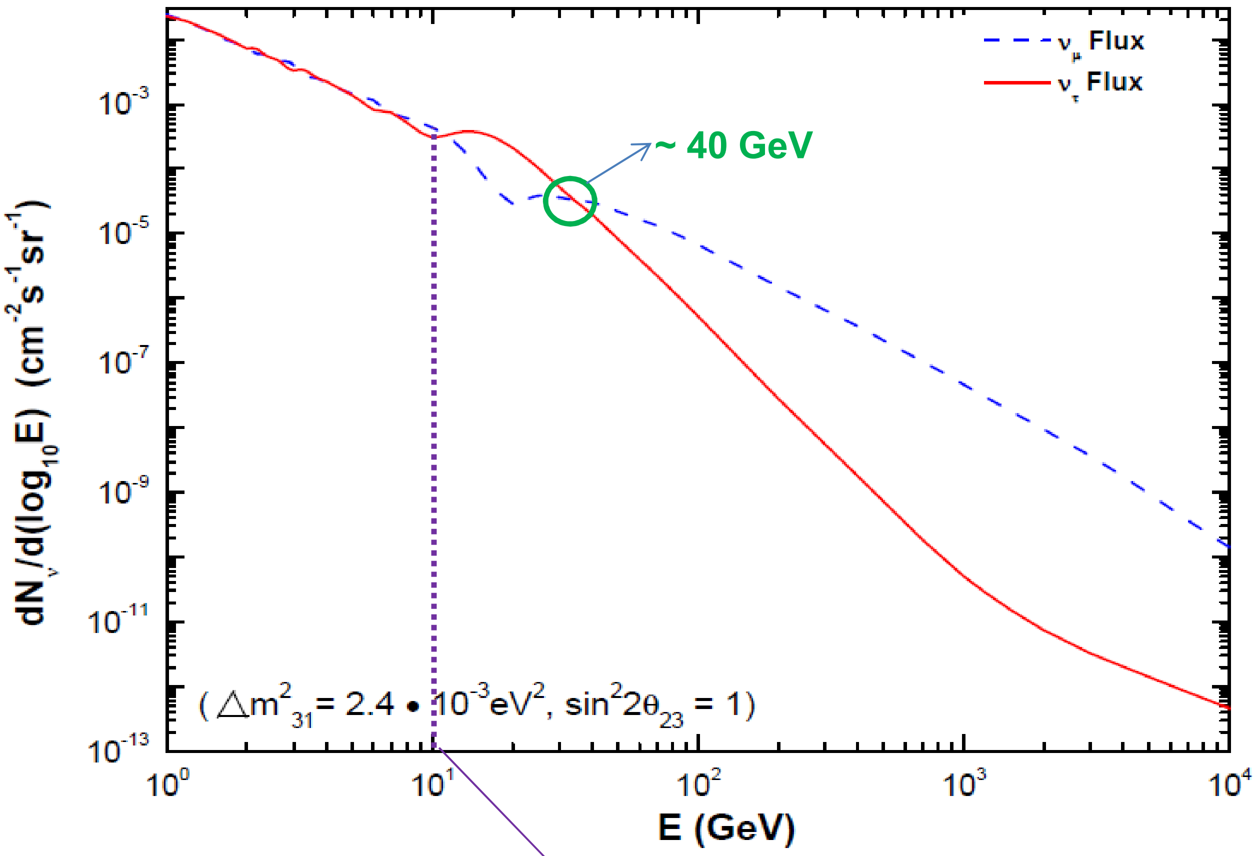


- Constraints are expected to Improve with DeepCore data
- Look for downward going neutrinos from GC, in additional to upward going events
  - E^{th} =40 GeV

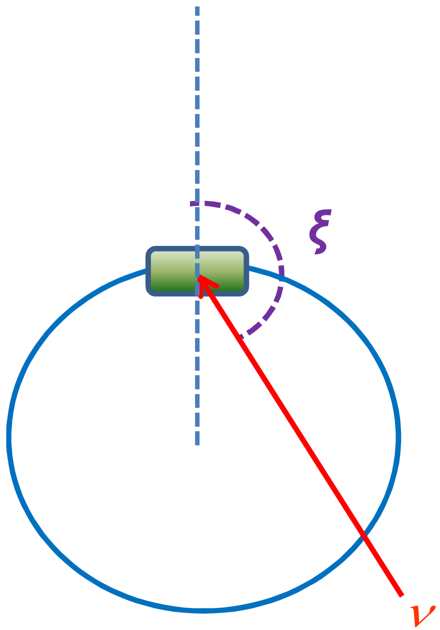
We are interested in low DM mass case
Consider 10 GeV energy threshold for track and shower

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

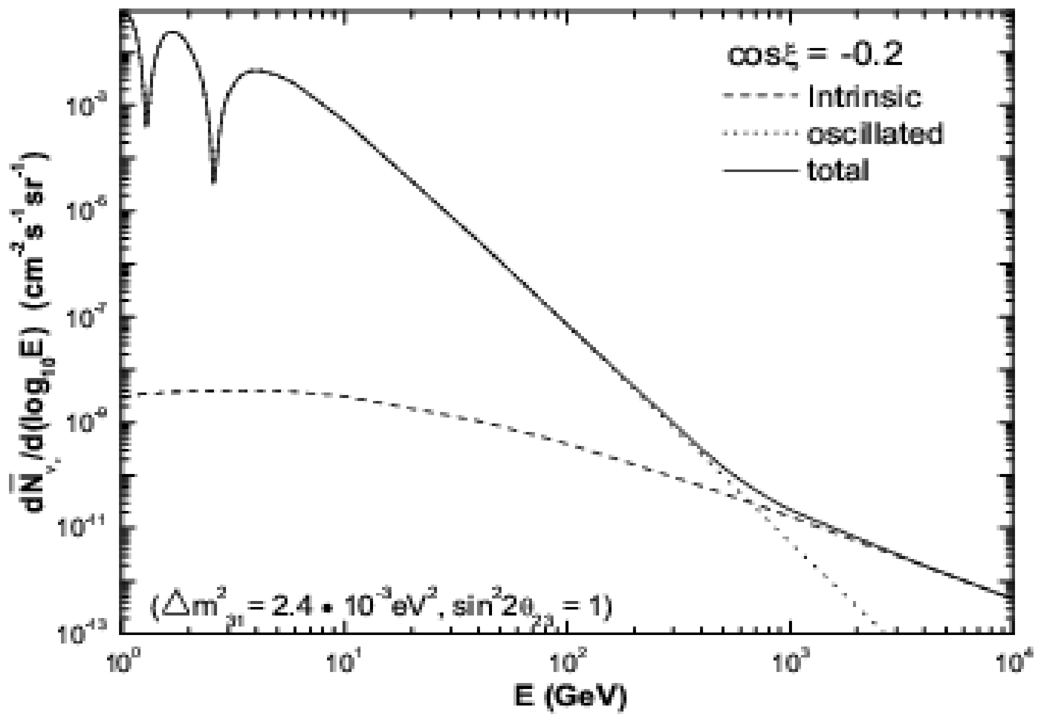
F. F. Lee, G. L. Lin, Astropart. Phys. 25, 2006



Detection threshold energy of Iceube + DeepCore

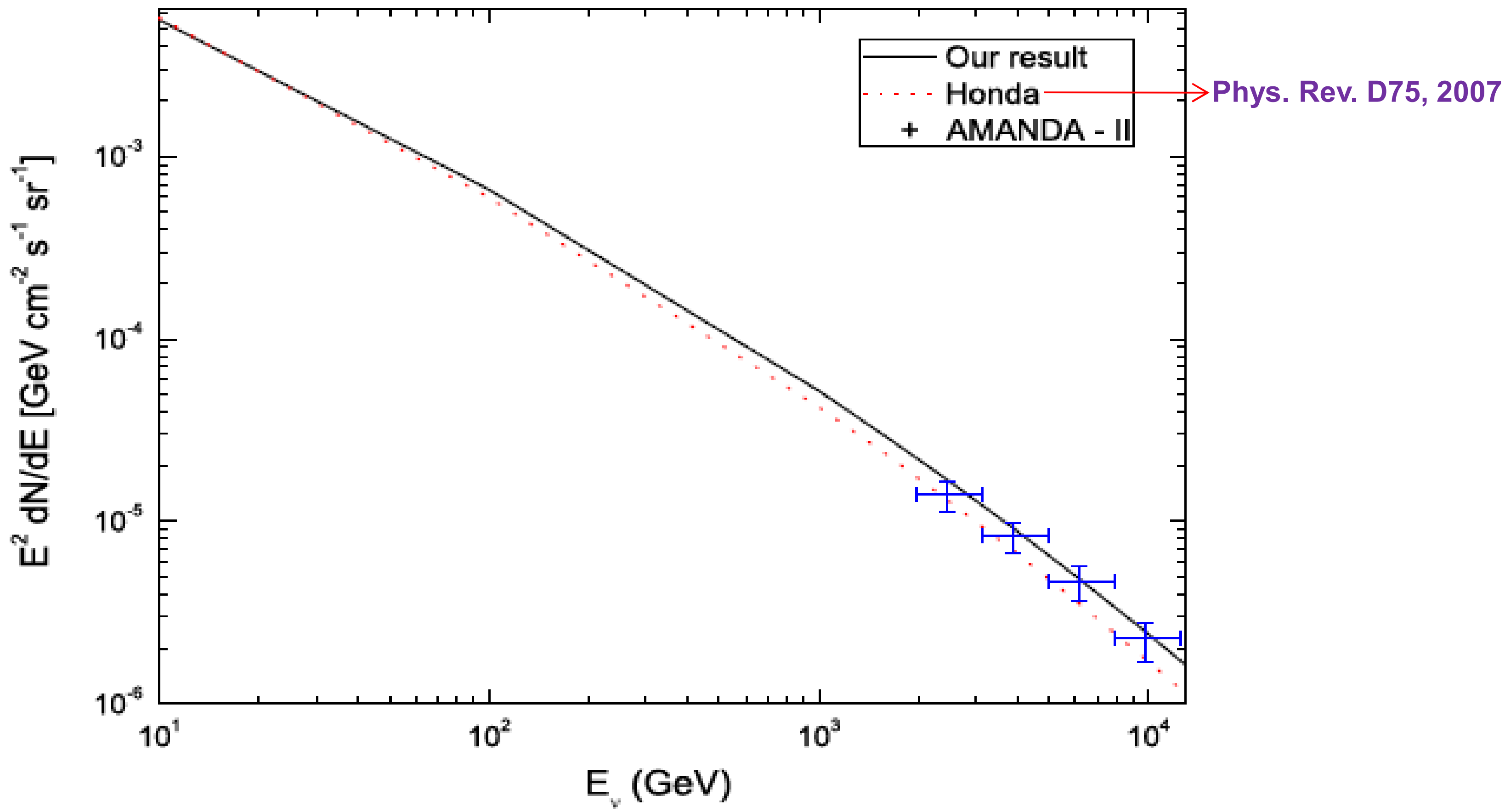


ν_τ flux $\cos\xi = -0.2$



Angle-averaged atmospheric muon neutrino flux for 0 ≦ cosξ ≦ 1

(without oscillations)



Comparison with Honda flux and AMANDA-II measurement

Neutrino flux from DM decay in the galactic halo

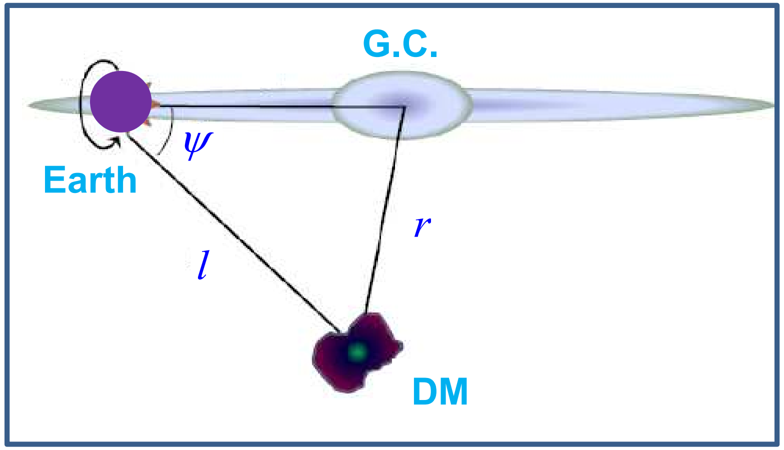
$$\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = \frac{\Delta\Omega}{4\pi}\frac{1}{m_\chi \tau_\chi}\left(\sum_F B_F \frac{dN_{\nu_i}^F}{dE}\right) R_\oplus \rho_\oplus \times J_1(\Delta\Omega) \quad \propto \frac{\rho}{m_\chi \tau_\chi}$$

- $R_\oplus = 8.5\text{kpc}$: distance from the galactic center to the solar system
  $\rho_\oplus = 0.3\,\text{GeV/cm}^3$: DM density in the solar neighborhood
  $dN_{\nu_i}^F / dE$: 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

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

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

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

B : boost factor . $<\sigma v>_0 = 3 \times 10^{-26}\ cm^3 s^{-1}$: 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 at the astrophysical source
- Φ_{ν_α} : neutrino flux measured on the Earth
- $P_{\alpha\beta}$: probability of the oscillation $\nu_\beta \rightarrow \nu_\alpha$

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

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

- with recently measured θ_{13} value: $\sin^2 2\theta_{13} = 0.092$

Dayabay best fit, PRL108, 171803(2012)

See also

Double Chooz, PRL108, 131801 (2011)

RENO arXiv:1204.0626

$$P = \begin{pmatrix} 0.53 & 0.26 & 0.21 \\ 0.26 & 0.37 & 0.37 \\ 0.21 & 0.37 & 0.42 \end{pmatrix}$$

Event Rates

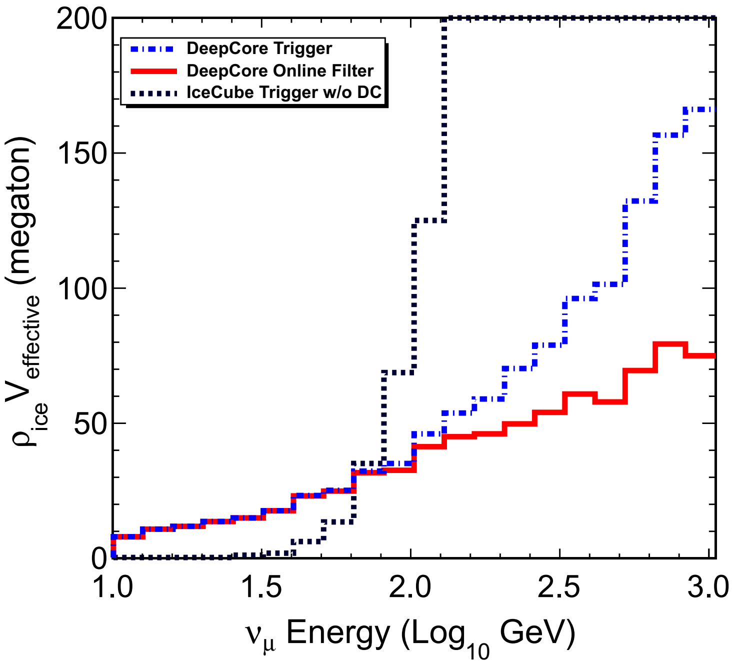
$$\Gamma_{\rm track} = \int_{E_\mu^{\rm th}}^{E_{\max}} {\rm d}E_\mu \int_{E_\mu}^{E_{\max}} {\rm d}E_{\nu_\mu} N_A \rho_{\rm ice} V_{\rm tr} \times \frac{{\rm d}\Phi_{\nu_\mu}}{{\rm d}E_{\nu_\mu}} \cdot \frac{{\rm d}\sigma^{CC}_{\nu_\mu N}\left(E_{\nu_\mu}, E_\mu\right)}{{\rm d}E_\mu} + \left(\nu \to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

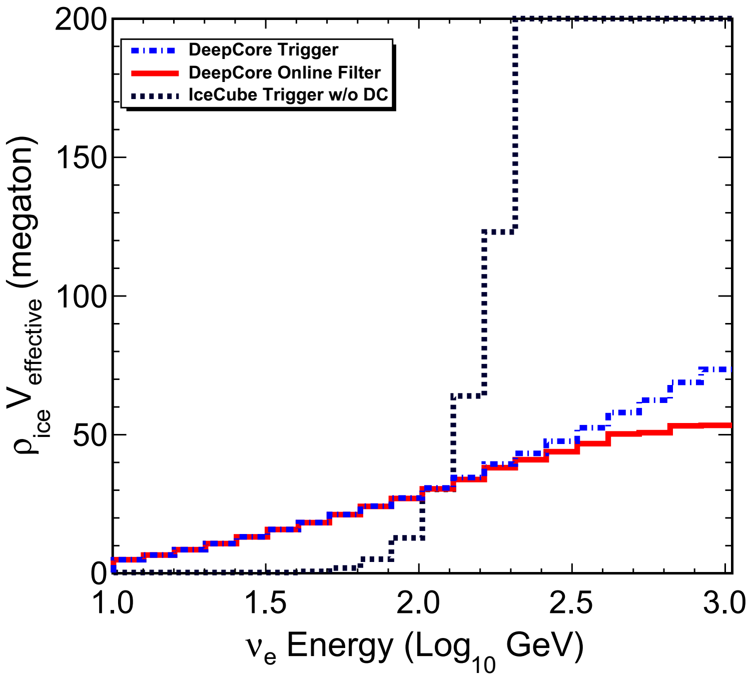
$$\Gamma_{\rm cascade} = \int_{E_{\rm shower}^{\rm th}}^{E_{\max}} {\rm d}E_{\rm shower} \int_{E_{\rm Shower}}^{E_{\max}} {\rm d}E_\nu N_A \rho_{\rm ice} V_{\rm casc} \times \frac{{\rm d}\Phi_\nu}{{\rm d}E_\nu} \cdot \frac{{\rm d}\sigma_{\nu N}\left(E_\nu, E_{\rm shower}\right)}{{\rm d}E_{\rm shower}}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

$\to$ $(\nu_e N)_{\rm CC}$, $(\nu_e N)_{\rm NC}$, $(\nu_\mu N)_{\rm NC}$, $(\nu_\tau N)_{\rm CC}$, $(\nu_\tau N)_{\rm NC}$

- $\rho_{\rm ice} = 0.9\ {\rm g\ cm^{-3}}$ is the density of ice ; $N_A = 6.022 \times 10^{23}\ {\rm g^{-1}}$ is Avogadro's number
- $V_{\rm tr} \approx 0.04\ {\rm km}^3$ is the effective volume of IceCube DeepCore array for muon track events

  $V_{\rm casc} \approx 0.02\ {\rm km}^3$ 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
- $\frac{{\rm d}\Phi_{\nu_e}}{{\rm d}E_{\nu_e}}$ is taken from **M. Honda et al. Phys. Rev. D75, 2007**

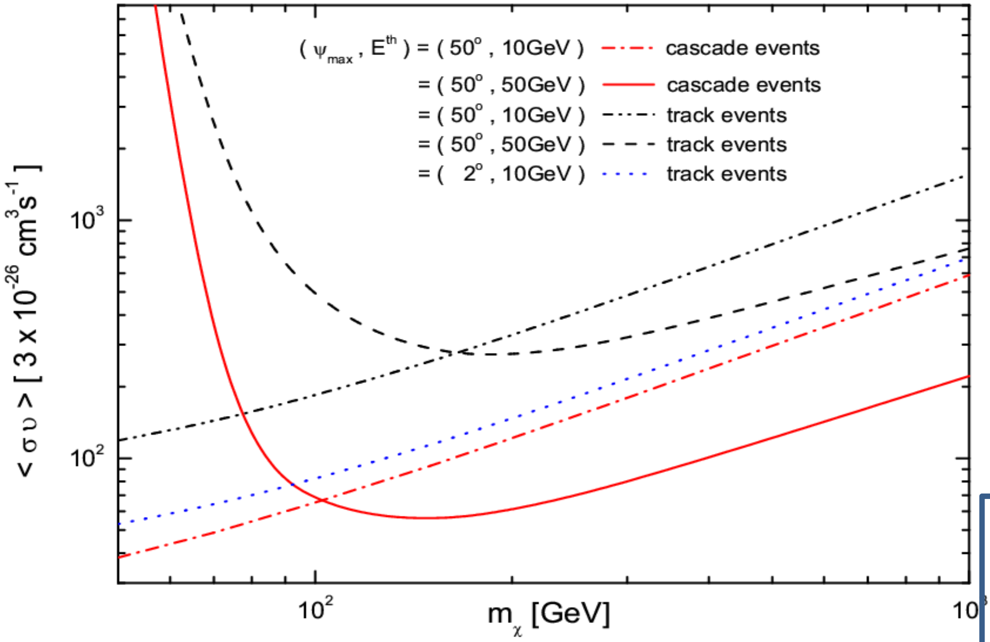




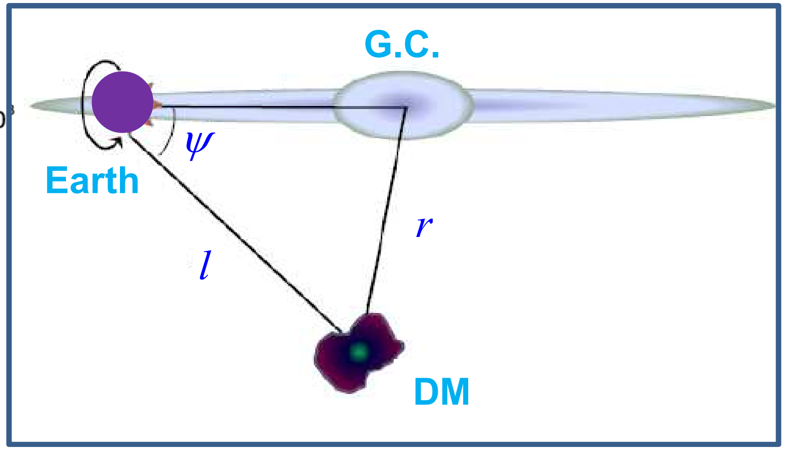
Precise effective volumes for IceCube DeepCore for muon and electron neutrinos

Astroparticle Physics 35 (2012) 615-624

Sensitivities in probing DM annihilation cross section

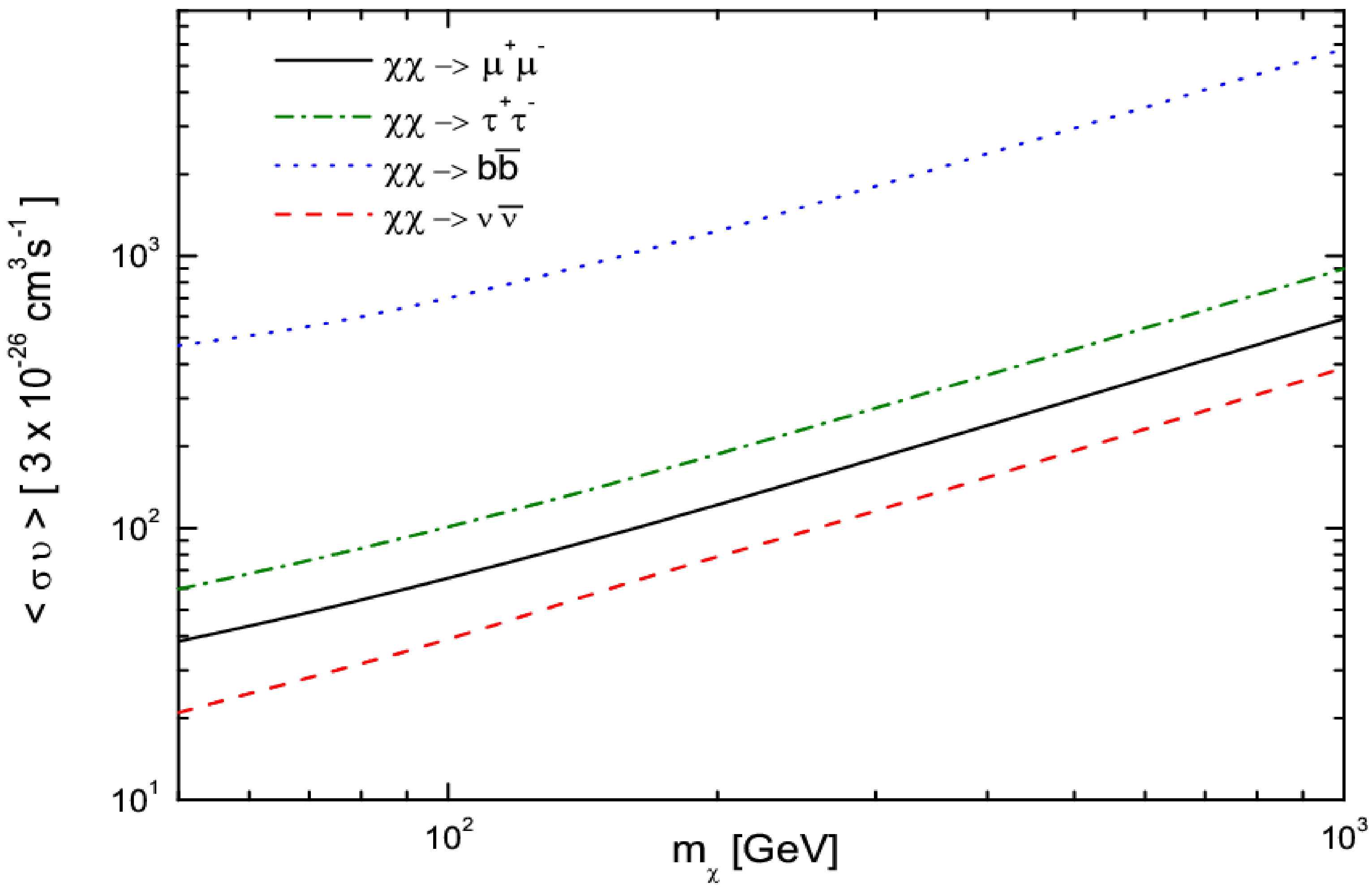


2σ in 5 years



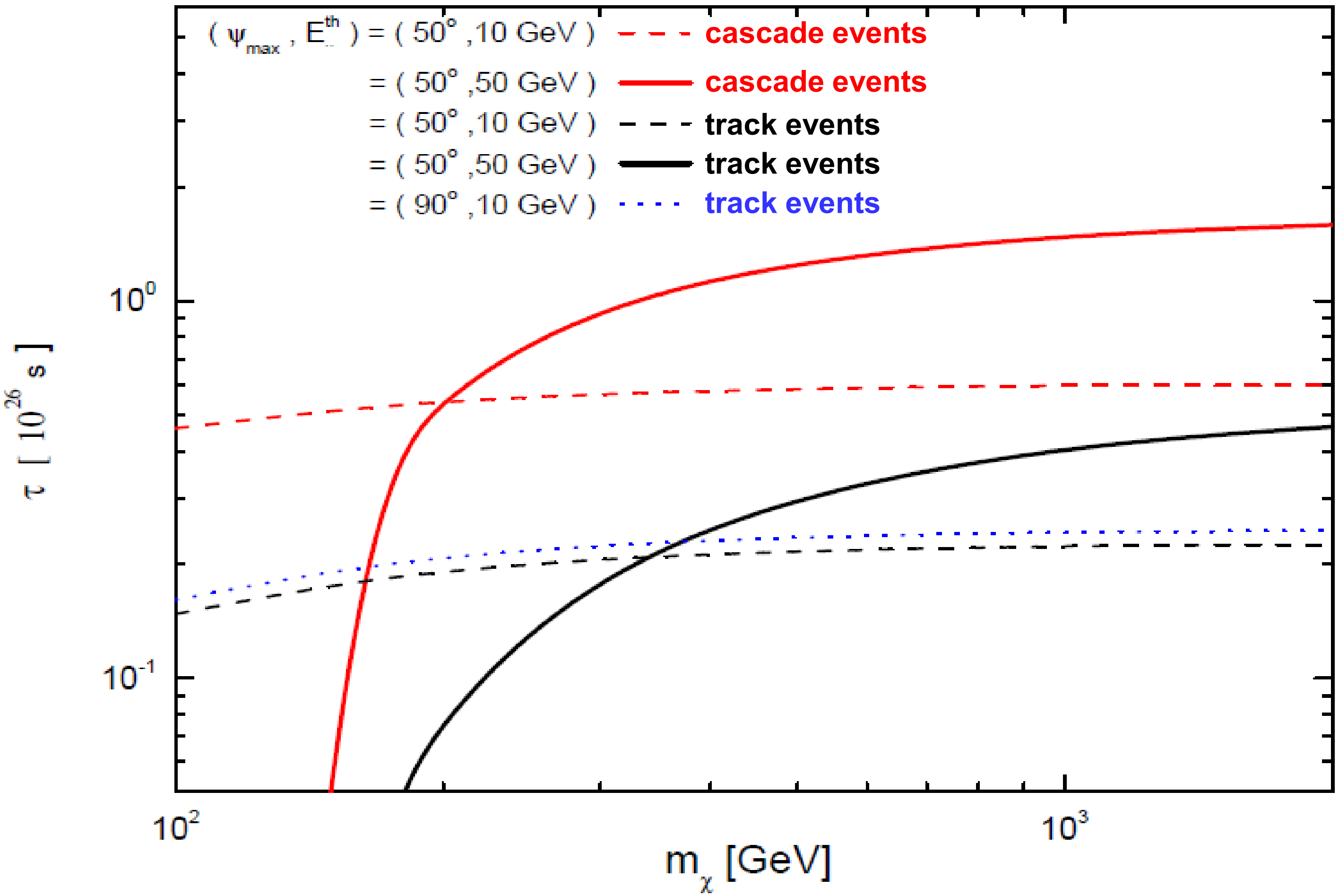
$\chi\chi \to \mu^+\mu^-$

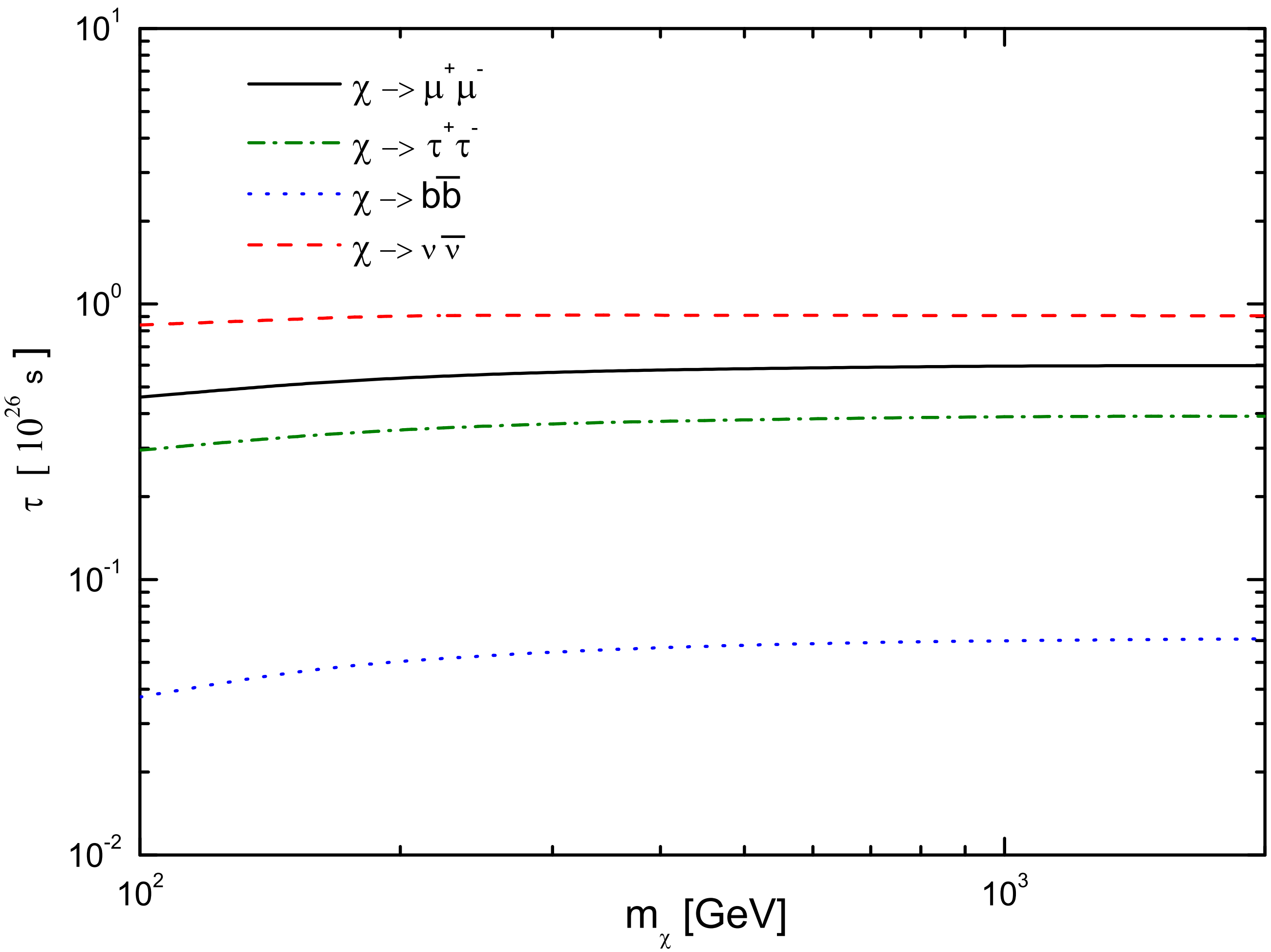
50 GeV threshold from A. E. Erkoca, M. H. Reno, I. Sarcevic, Phys. Rev. D82, 2010



Constraints on various modes

Sensitivity on $\chi \longrightarrow \mu\mu$



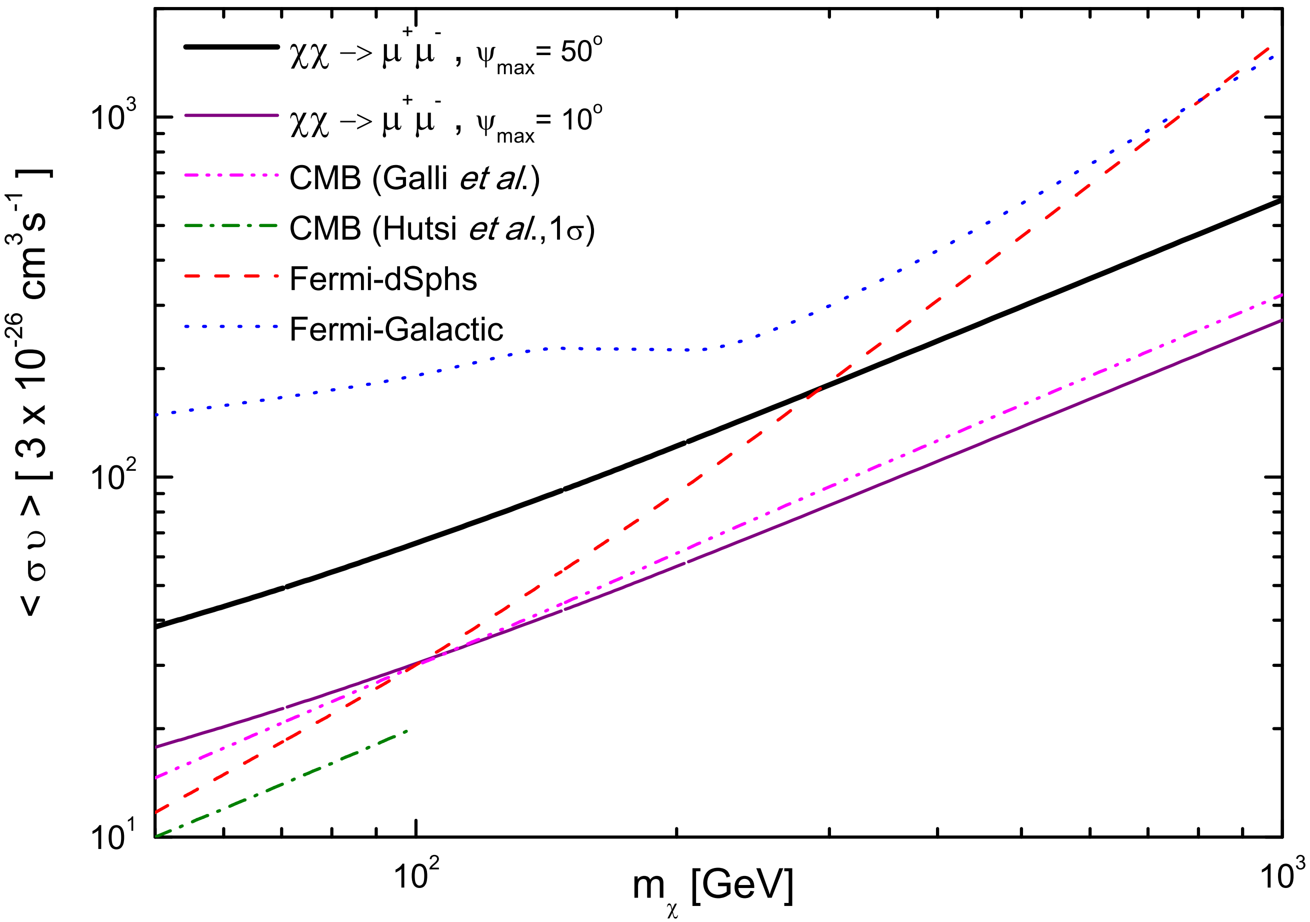


Constraints on DM decay time for various modes

95% C.L. dSphs M. Ackermann et al. Phys. Rev. Lett. 107, 241302 (2012)

Fermi |b|>10 degree & 20 deg. by 20 deg. centered at GC

NFW



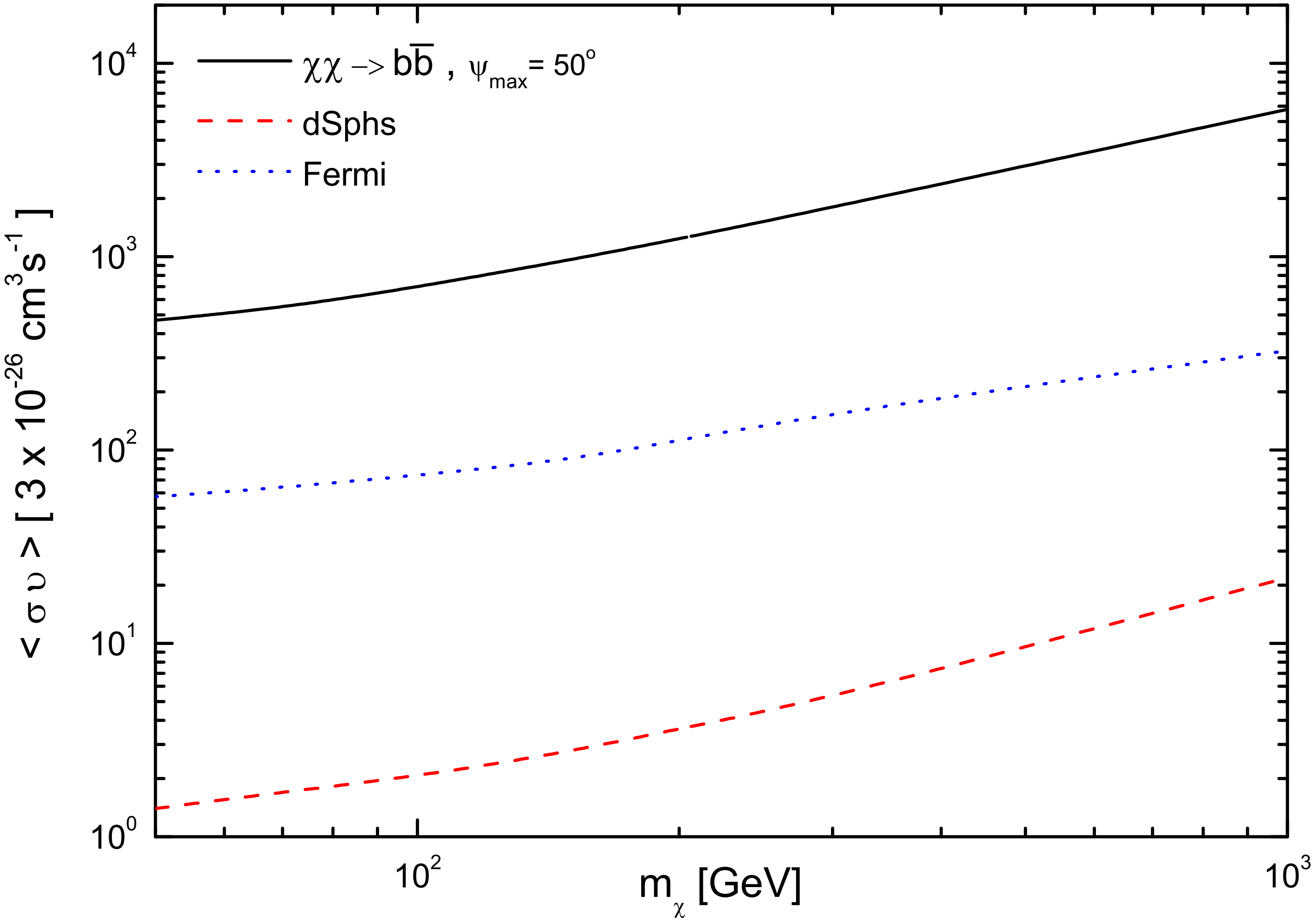
CMB WMAP7+ACT 95% C.L.

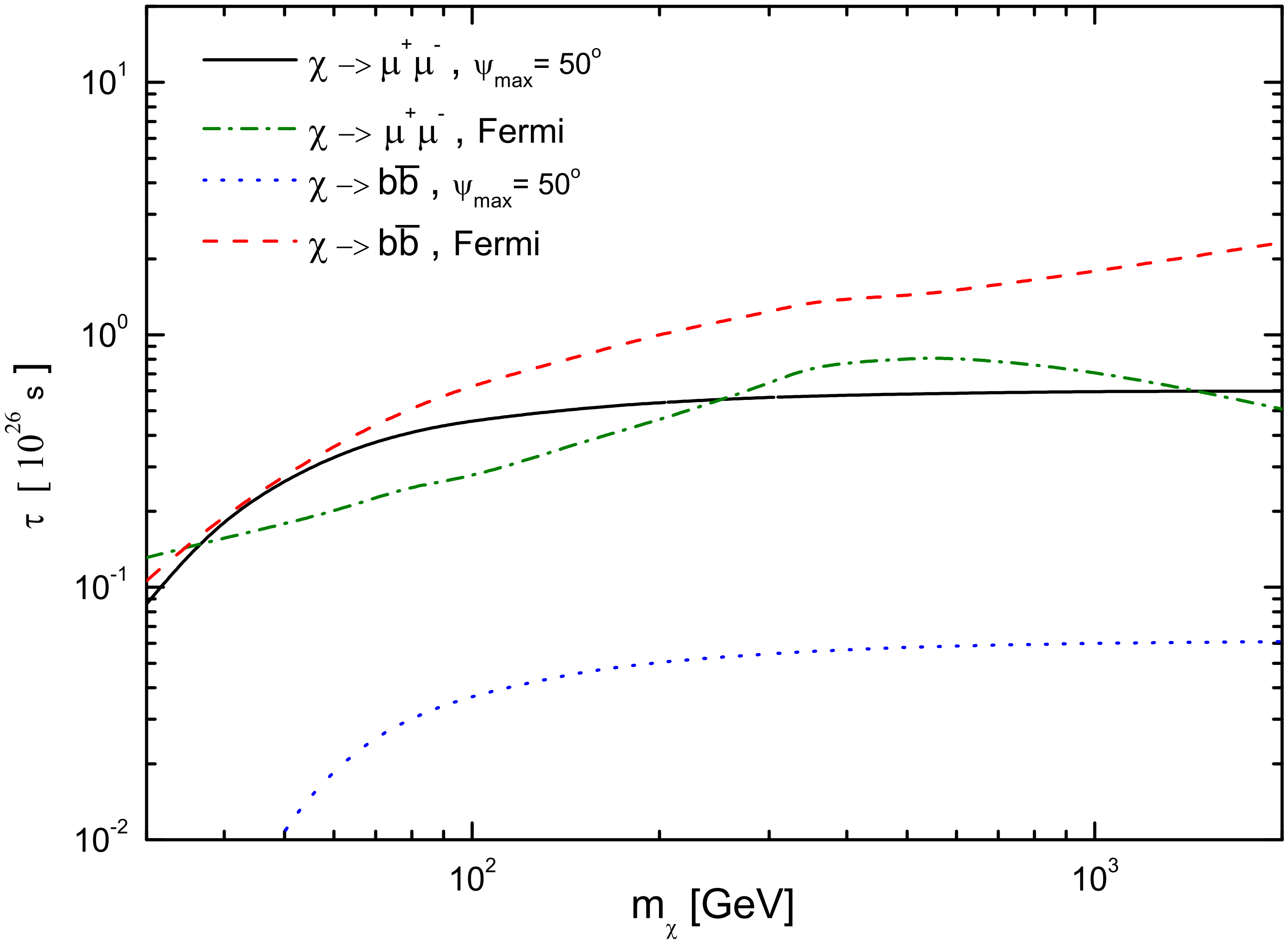
S. Galli et al. Phys. Rev. D 84, 027302 (2012)

Poor neutrino sensitivity in hadronic mode

Gamma ray is more easily produced by hadronic mode

Neutrino is more easily produced by leptonic mode





Compare with gamma ray constraints

DM annihilation and decay are in general tightly constrained by gamma ray data.
It is challenging to observe DM signature (galactic halo) in IceCube/DeepCore.

However, monochromatic neutrino production modes are not constrained.

$\chi\chi$—>$\nu\nu$, χ—>$\nu\nu$ could be dominant modes in some models:

R. Allahverdi et al. Phys. Rev. D 80, 055026 (2009)
A. Falkowski, J. Juknevich and J. Shelton, arXiv: 09081790

$U(1)_{B-L}$ extension of MSSM
RH sneutrino+RH sneutrino-->RH neutrino+RH neutrino
RH neutrino-->LH neutrino+neutral Higgs

Current IceCube limit (22 string) on $\chi\chi \longrightarrow \nu\nu$

$<\sigma\upsilon> \sim 5\times10^{-22}\ cm^3\ s^{-1}$

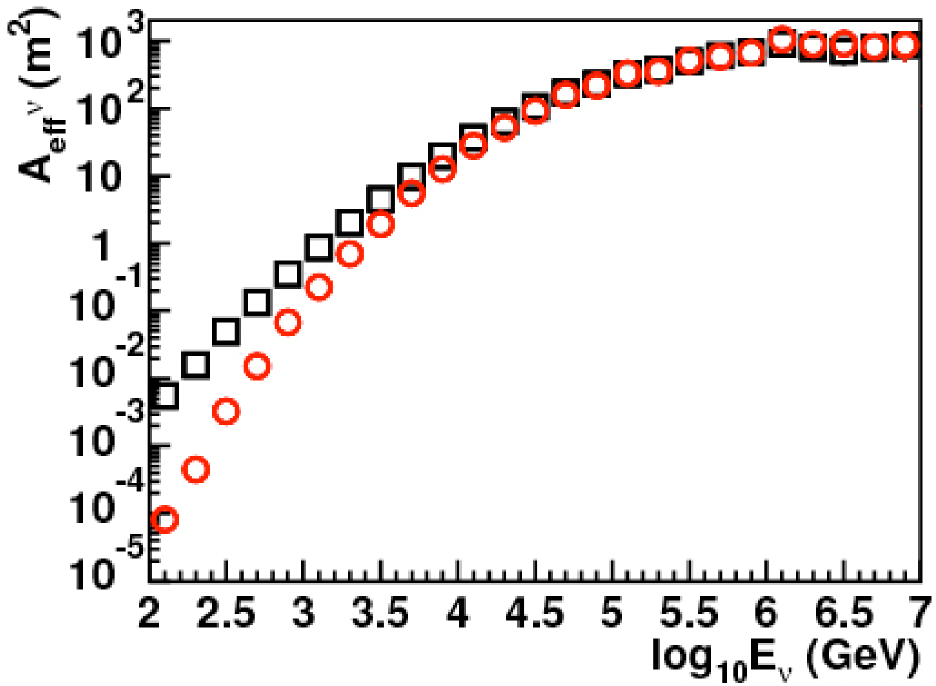
at M_χ = 200 GeV

The sensitivity will be improved by two orders of magnitude for the same DM mass. The improvement is less for heavier DM.

IceCube 40 string gives a factor of 5 improvement.

KM3NeT

Deep Sea Neutrino Telescope in Mediterranean Ocean
with Instrumented Volume Larger Than IceCube

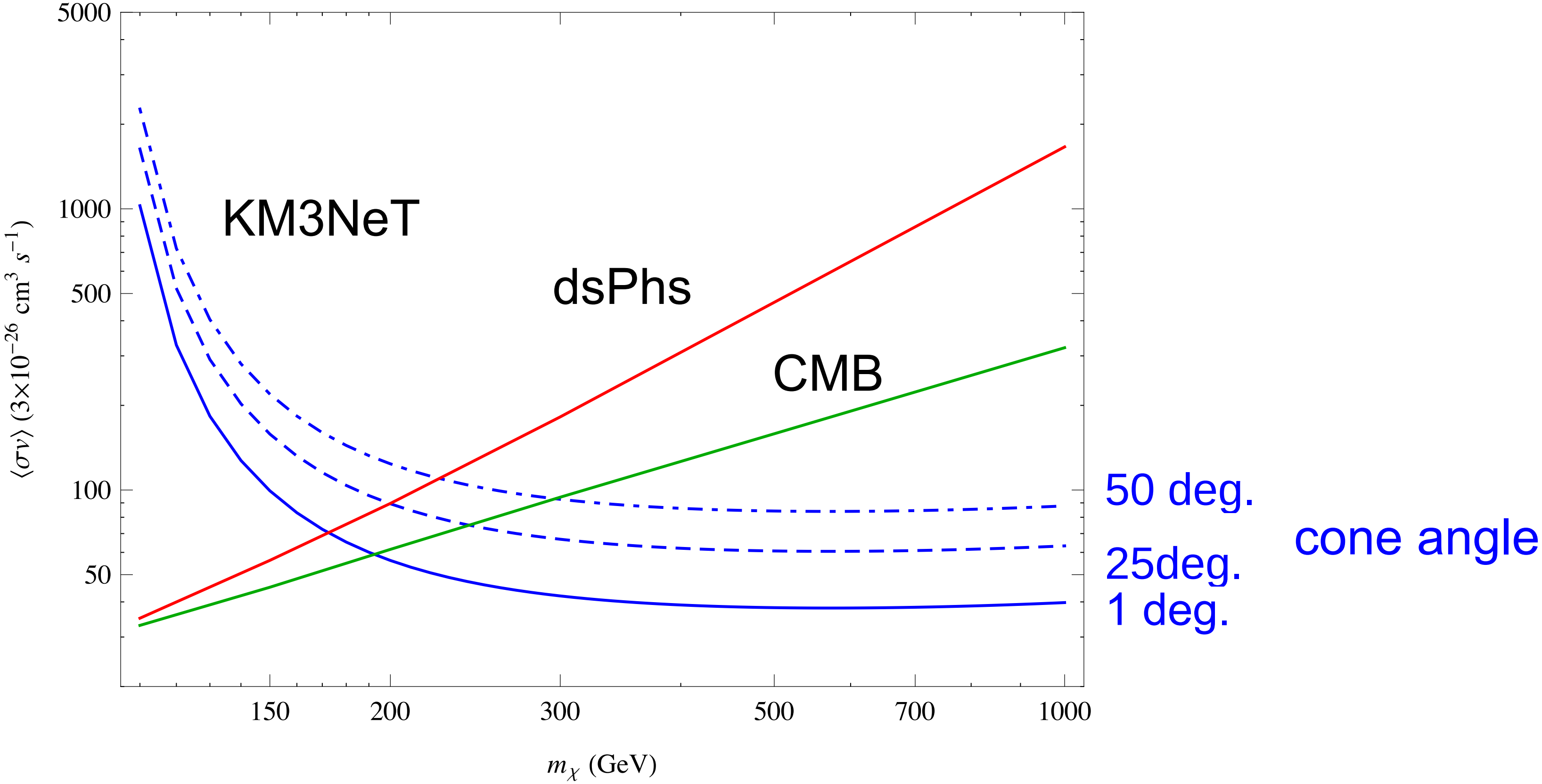


effective area for upper going muons

http://www.km3net.org/TDR/TDRKM3NeT.pdf

$$N_s = \iint A_{eff}^{\nu}(E_\nu, \theta_\nu) \frac{d\Phi_\nu}{dE_\nu d\theta_\nu} \, dE_\nu \, d\theta_\nu$$

χχ-->μμ   Preliminary



upward muon events for KM3NeT

Summary

(1) We employ NFW DM profile to calculate the track and cascade event rates in IceCube DeepCore due to neutrino fluxes from WIMP annihilations and decays in the galactic halo.

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

(3) 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.

(4) Fermi_LAT gamma ray constraints are generally more stringent than those expected at IceCube DeepCore. On the other hand, DM annihilating directly into neutrino pair is not constrained by gamma ray. DeepCore sensitivity will however improve significantly if angular resolution of cascade events can be improved.

Summary

(5) KM3NeT situated in northern hemisphere has a comparable sensitivity to IceCube DeepCore with good angular resolution for DM mass greater than 200 GeV.