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# Neutrino Signatures of Dark Matter

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# What do we know about dark matter?

- Indirect evidence for dark matter comes from observation of galaxy and group of galaxies rotating as if they contained far more matter than observed
- Direct searches: look for DM interactions with target nuclei (XENON, CDMS, DAMA ..)
- Indirect search: DM annihilation producing electrons, positrons, $\gamma$-rays, neutrinos (PAMELA, ATIC, FERMI, HESS, IceCube ..)

# Neutrinos Signatures of Dark Matter

**Erkoca, Reno and Sarcevic, PRD 80, 043514 (2009)**

- Neutrino flux from DM annihilation in the core of the Sun/Earth, produced directly or from particles that decay into neutrinos (taus, W's, b's)
- Neutrinos interacting below the detector or in the detector producing muons ⇒ upward and contained muon flux

# Neutrinos from DM annihilations

Neutrinos produced directly or through decays:

$$\chi\chi \to \nu_i \overline{\nu_i}$$

$$\to \tau^+\tau^- \to \nu_\tau l_i \nu_i$$

$$\to W^+W^- \to \nu_i l_i \nu_j l_j$$

Neutrino flux depends on annihilation rate, distance to source (Earth's core or Sun-Earth distance) and energy distribution of neutrinos, i.e.

$$\left(\frac{d\phi_\nu}{dE_\nu}\right)_i = \frac{\Gamma_A}{4\pi R^2} \sum_F B_F \left(\frac{dN}{dE_\nu}\right)_{F,i}$$

In equilibrium, annihilation rate and capture rate related: $\Gamma_A = C/2$

- Dark Matter Capture Rate [a] :

$$C = c\frac{\rho_{0.3}^{\chi}}{(m_{\chi}/GeV)}\sum_i F_i f_i \phi_i \frac{S_i}{(m_{N_i}/GeV)}\frac{\sigma_0^i}{10^{-8}pb}$$

$$c = 4.8\times 10^{11}\mathrm{s}^{-1}\ (\mathrm{Earth})\ ,\quad c = 4.8\times 10^{20}\mathrm{s}^{-1}\ (\mathrm{Sun})$$

- $\phi_i$ : velocity distribution function
- $f_i$ : 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)

- ★ Neutrinos from DM annihilation interact with matter → attenuation of the neutrino Flux in the Sun

- ★ Neutrinos also interact as they propagate through the Earth (upward muons) and in the detector (contained muons)

# Muon Flux

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

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

where the weak scattering cross section is :

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

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

# Contained and Upward Muon Flux

- The contained muon flux, for a detector with size *l*

$$\frac{d\phi_\mu}{dE_\mu} = \int_R^{R+l} dr \int_{E_\mu}^{m_\chi} dE_\nu \frac{dP_{CC}}{dr\,dE_\mu}\frac{d\phi_\nu}{dE_\nu}(E_\nu, R)$$

- The upward muon flux is given by

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

where the neutrino flux is

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

Muon survival probabilty is

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

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

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

# Neutrino Energy Distribution

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

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

- $\chi\chi \rightarrow \tau^+\tau^-, b\bar{b}, c\bar{c}$ channels :

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

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

- Energy loss of the muons over a distance *dz* :

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

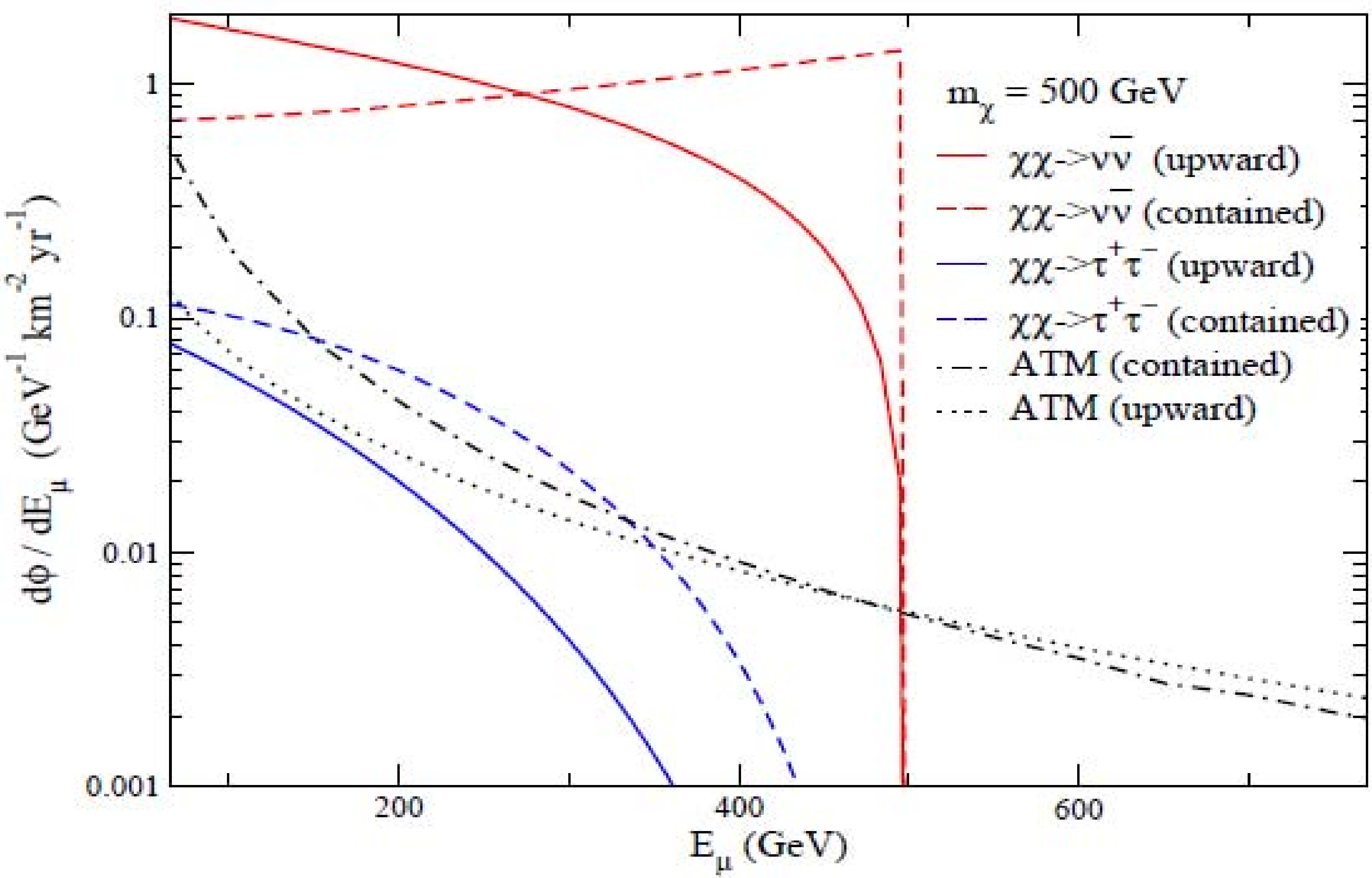
- $\alpha$ : ionization energy loss $\simeq 2\times10^{-3}\mathrm{GeV\,cm^2/g}$.
- $\beta$ : bremsstrahlung, pair production and photonuclear interactions $\simeq 3\times10^{-6}\mathrm{cm^2/g}$.
- Relation between the initial and the final muon energy:

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

**Muon range:**

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

# Upward and Contained Muon Flux from DM Annihilation in the Core of the Earth

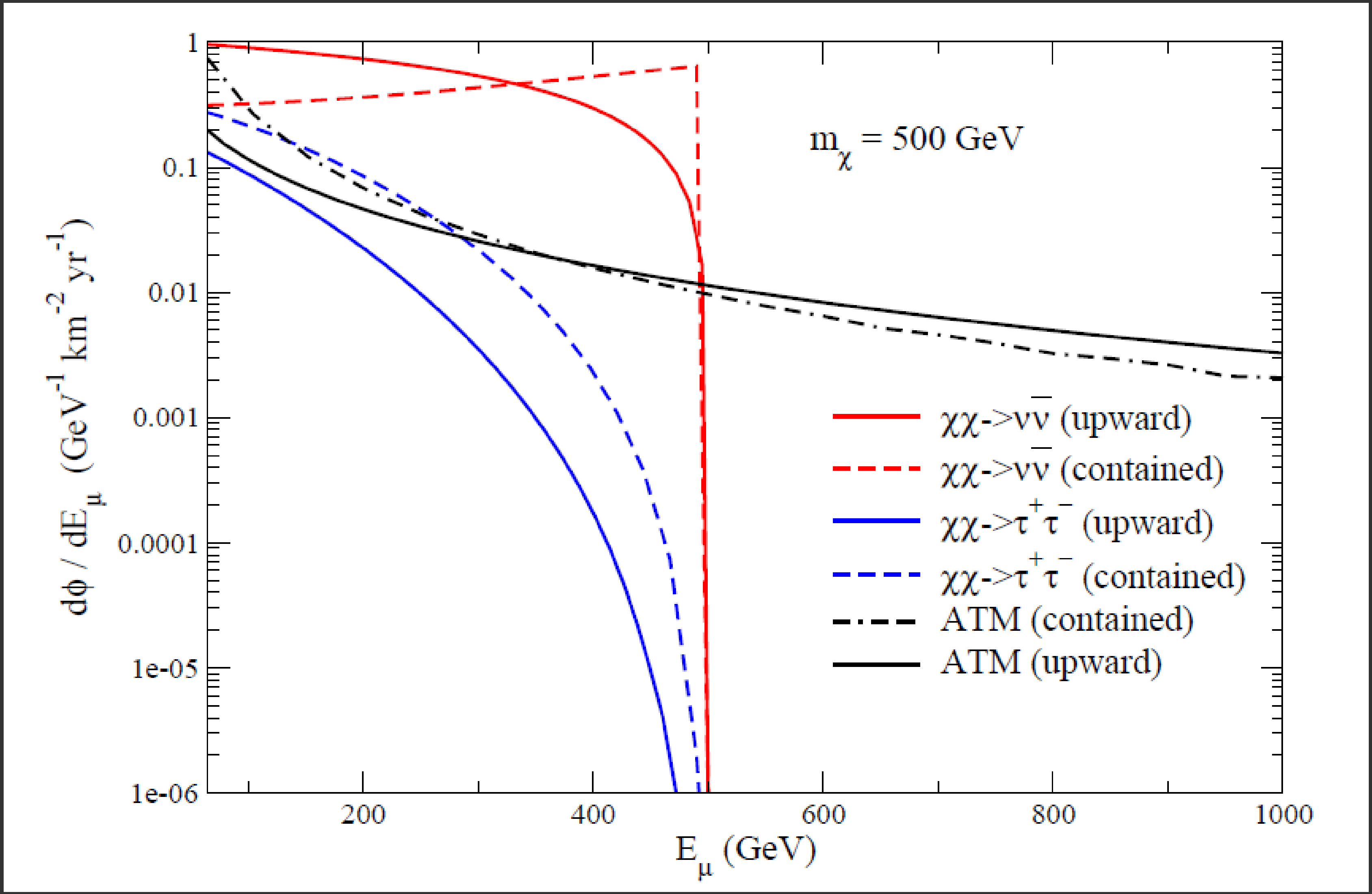


- Attenuation of the neutrino Flux in the Sun

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

- The muon flux decreases by a factor of 3, 10, 100 for $m_\chi$ = 250 GeV, 500 GeV, 1 TeV.

# Upward and contained muon flux from DM annihilation in the core of the Sun



# Neutrino Flux from the Galactic Center generated by DM annihilation

Erkoca, Gelmini, Reno and Sarcevic (2010)

- Dark matter halo density profiles given by Navarro-Frenk-White (NFW) and by isothermal form
- Upward and contained muon flux and showers from neutrino interactions
- Incorporate SuperK limits
- Predictions for IceCube and Km3Net

# Neutrino Flux from DM Annihilation

$$\left(\frac{d\phi}{dE_\nu}\right) = B\frac{<\sigma v>}{8\pi m_\chi^2}\sum_F B_F\left(\frac{dN}{dE_\nu}\right)_F\int_{l.o.s.}\rho(l)^2 dl(\theta)$$

where $\langle\sigma v\rangle$ is the DM annihilation cross section
and **B** is the boost factor

Define $< J_2 >_\Omega$ as:

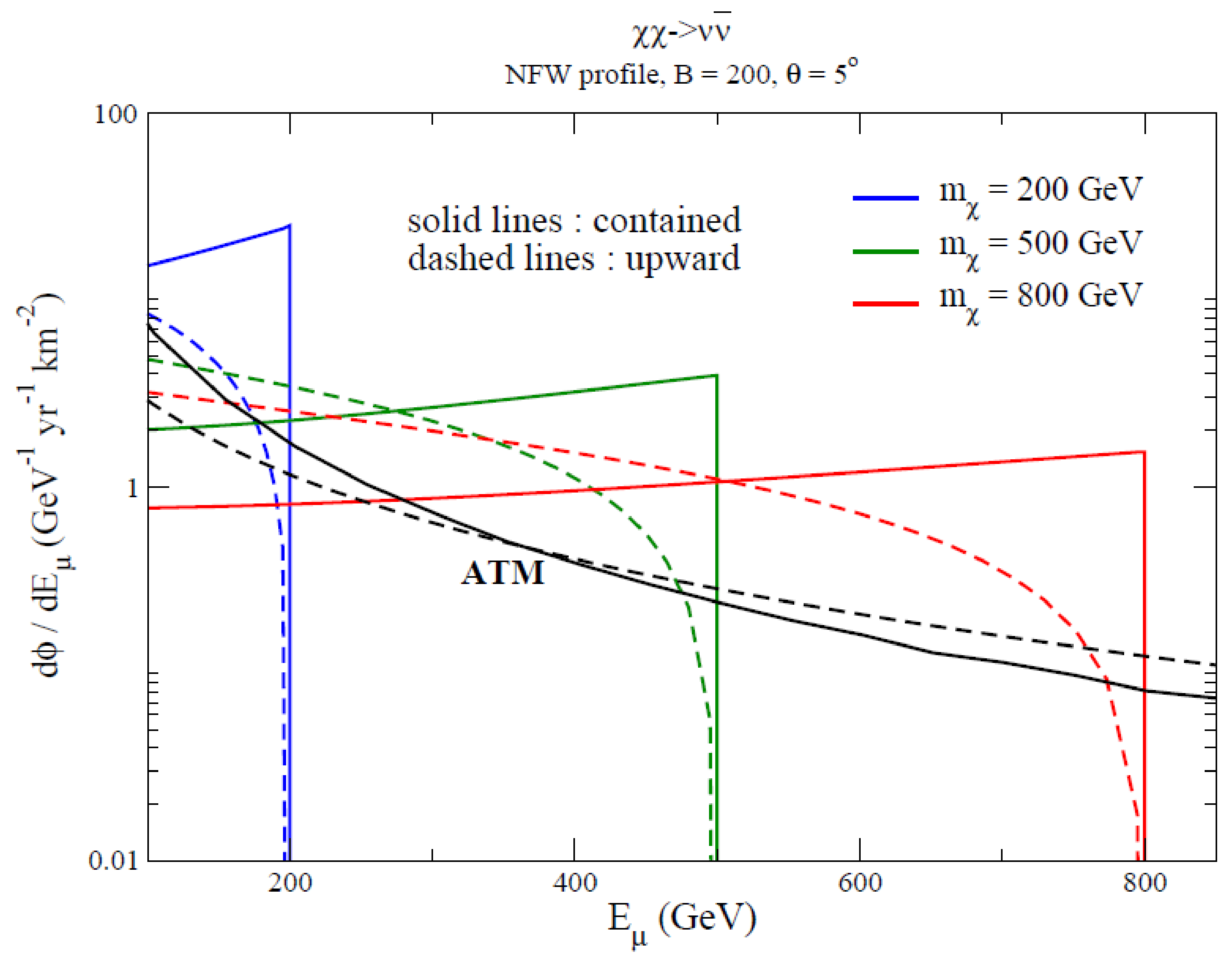
$$< J_2 >_\Omega = \int \frac{d\Omega}{\Delta\Omega} \int_{l.o.s.} \frac{dl(\theta)}{R_o} \left( \frac{\rho(l)}{\rho_o} \right)^2$$

where $l(\theta)$ is the distance from us in the direction of $\theta$ which is the cone-half angle from the Galactic Center and $\rho(l)$ is density distribution of dark mater halos, $R_o$ is the distance of the solar system from the GC and $\rho_o$ is the local dark matter density near the solar system

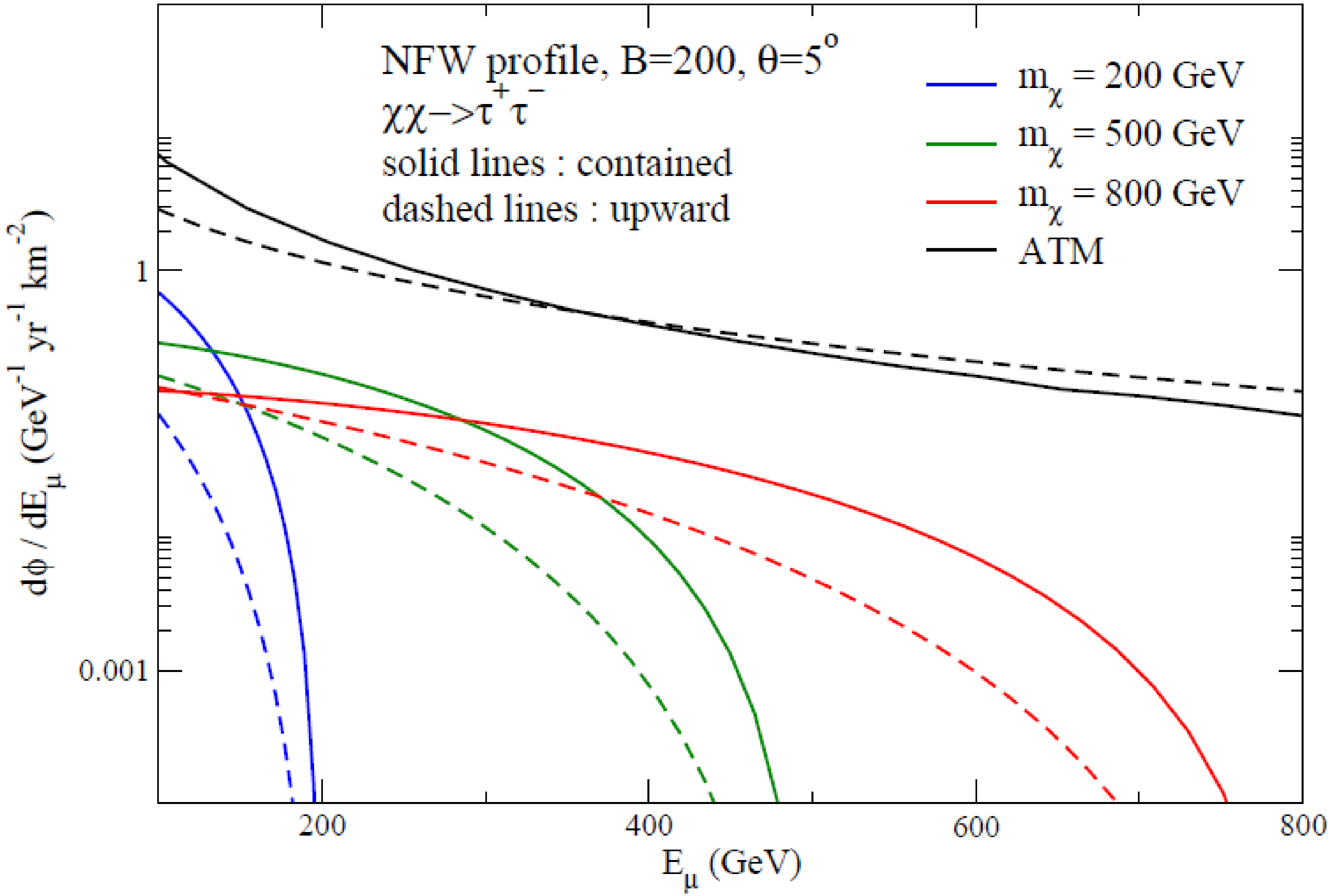
we take : $\langle \sigma v \rangle = 3 \times 10^{-26} cm^3 s^{-1}$

$R_o = 8.5 kpc \qquad \rho_o^2 = 0.3 GeV cm^{-3}$

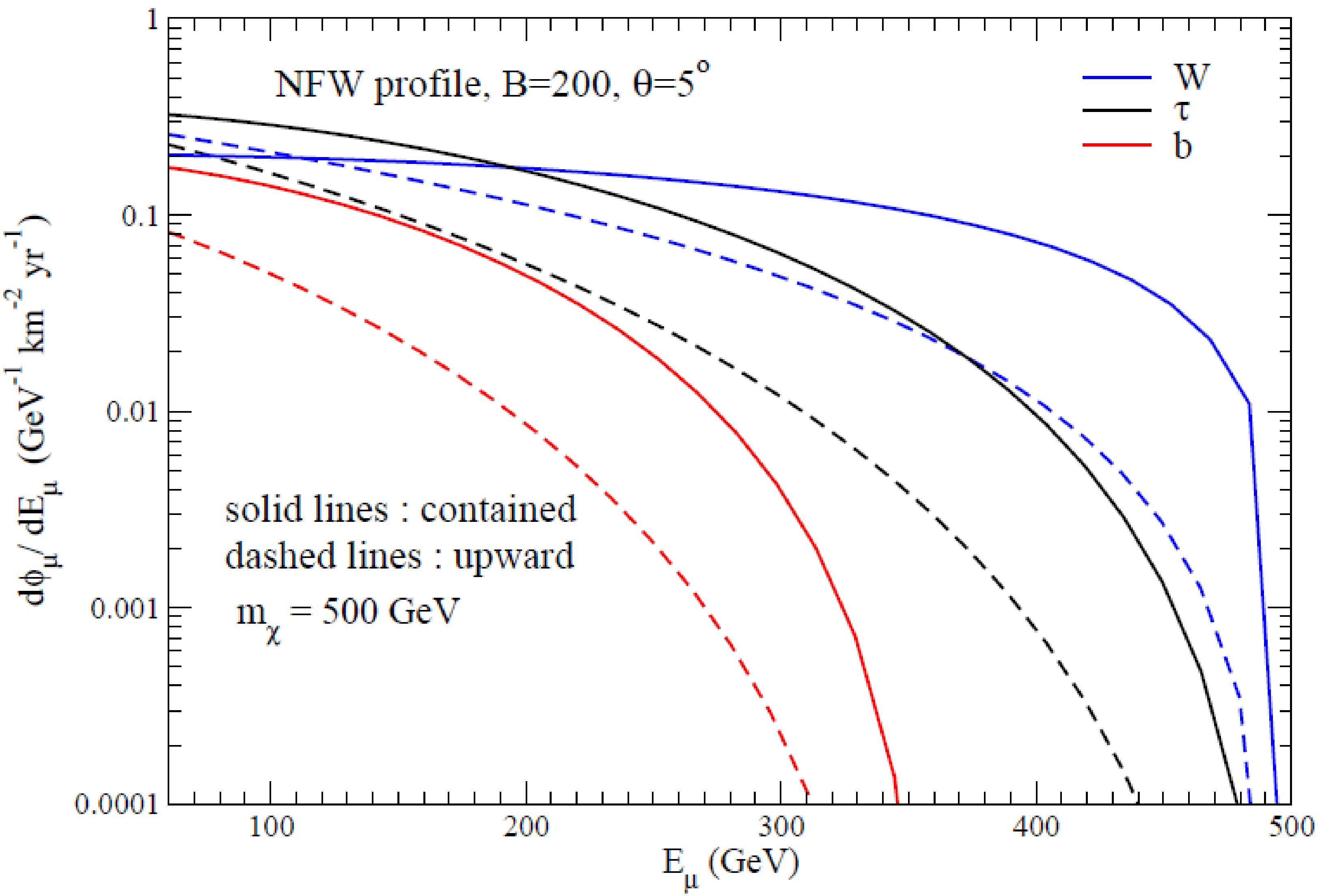
# Muon Flux


χχ->νν̄
NFW profile, B = 200, θ = 5°
solid lines : contained
dashed lines : upward
m_χ = 200 GeV
m_χ = 500 GeV
m_χ = 800 GeV
ATM
dφ / dE_μ (GeV^-1 yr^-1 km^-2)
E_μ (GeV)
100
1
0.01
200
400
600
800

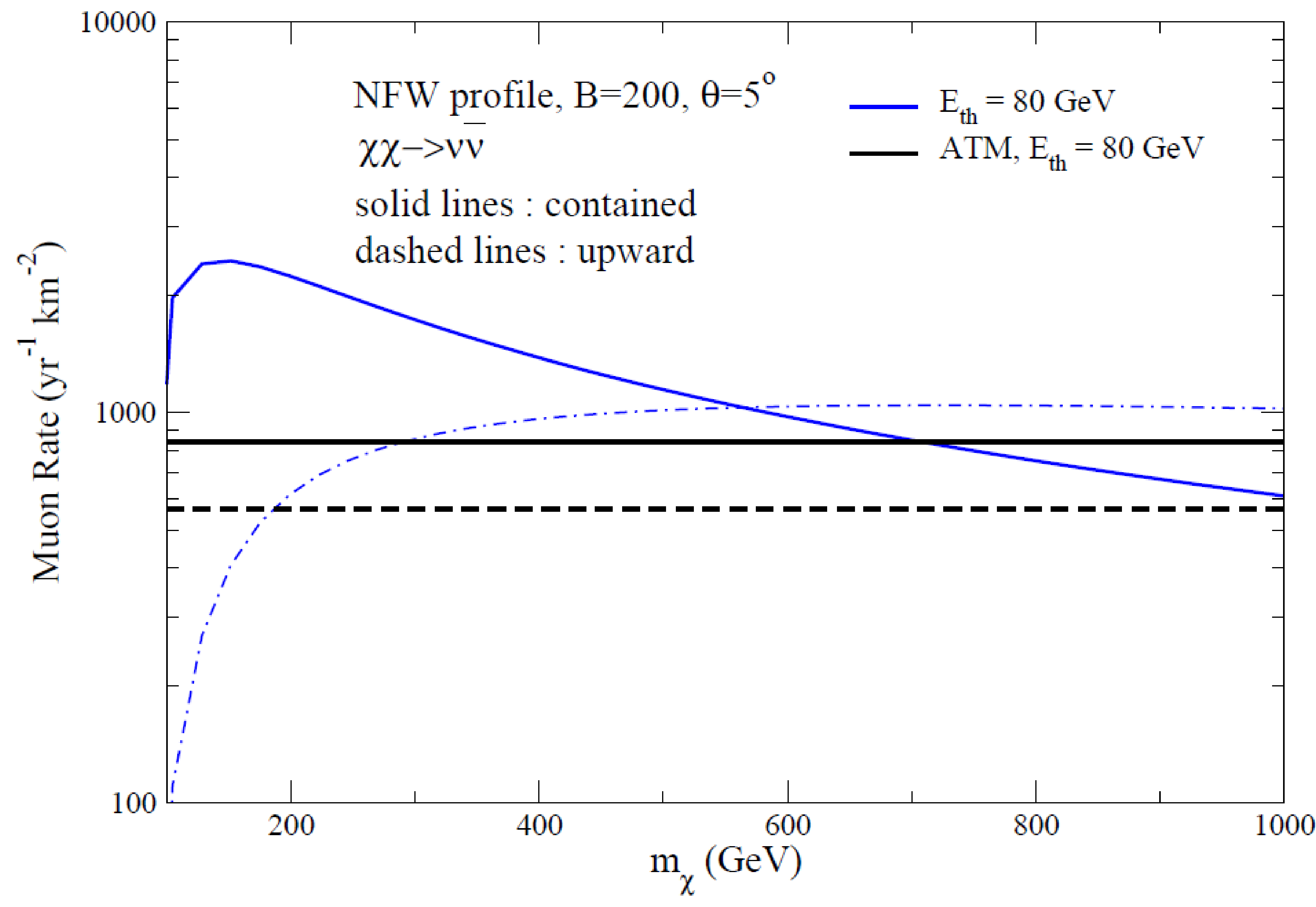
# Muon Flux for Secondary Neutrino Production



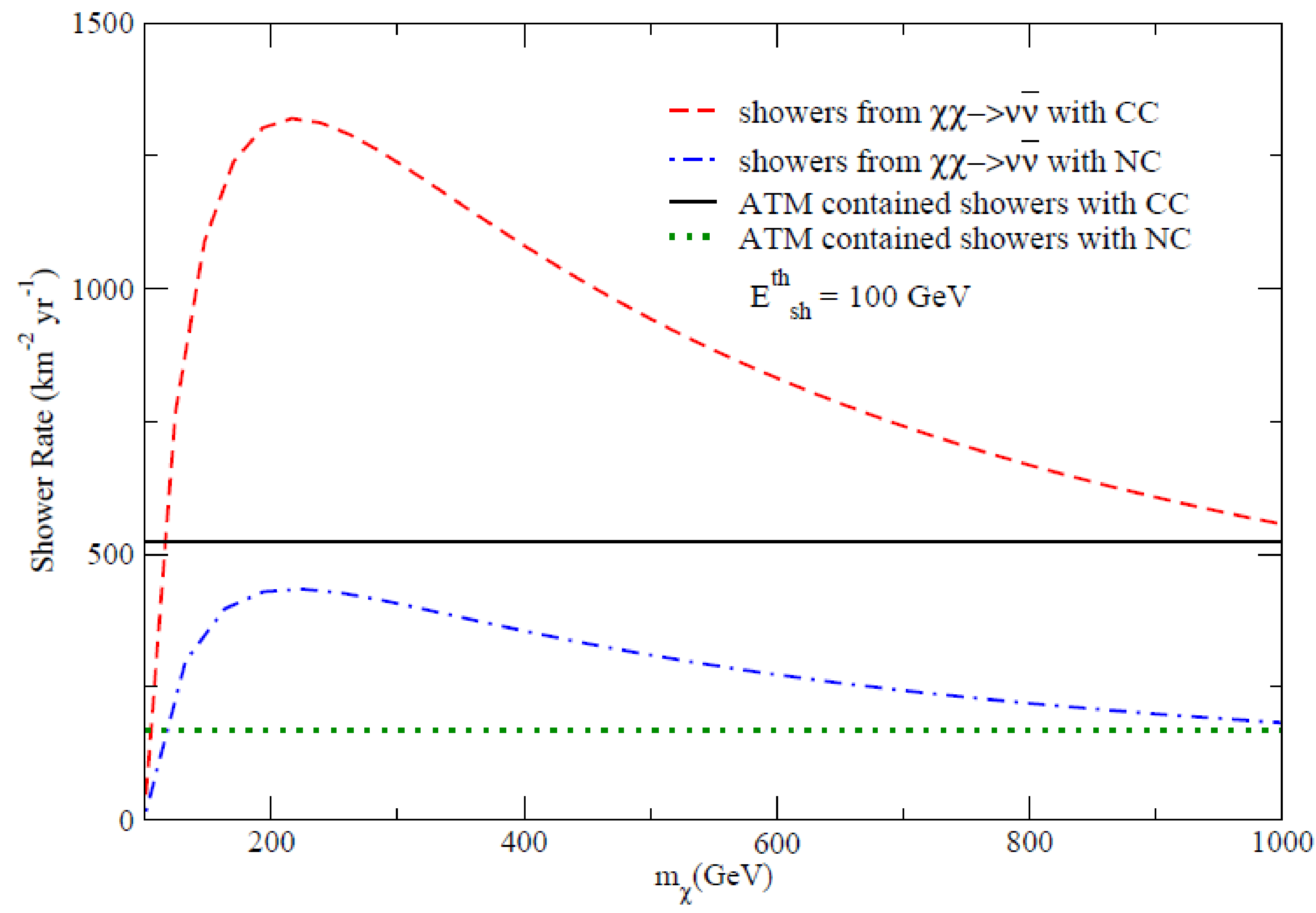
# Muon Flux for Different DM Annihilation Modes



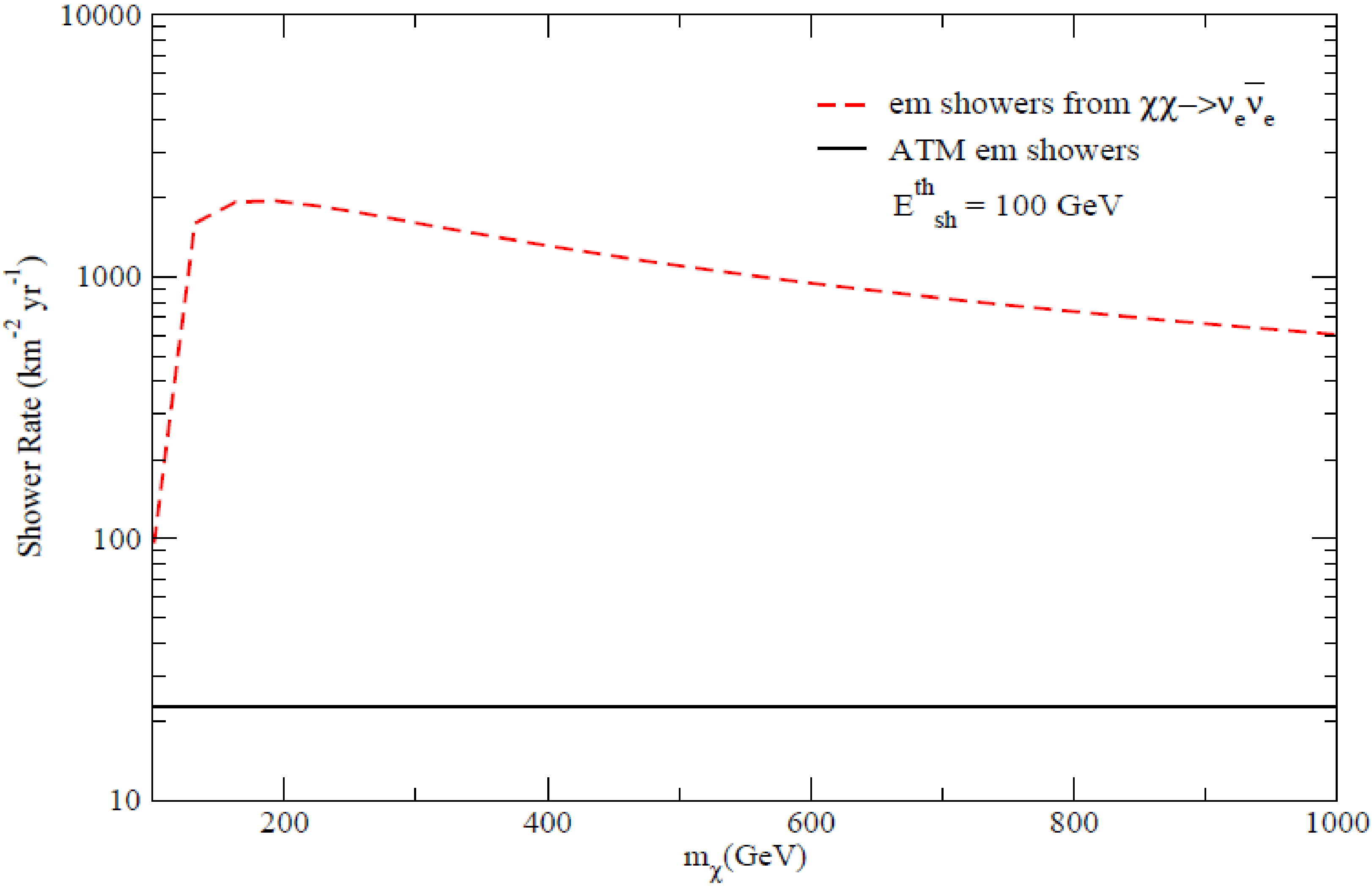
# Muon Rates


NFW profile, B=200, θ=5°
χχ−>νν̄
solid lines : contained
dashed lines : upward
E_th = 80 GeV
ATM, E_th = 80 GeV
Muon Rate (yr^-1 km^-2)
10000
1000
100
200
400
600
800
1000
m_χ (GeV)

# Hadronic Shower Rates



# EM Shower Rates



# DM Detection with Neutrino Telescopes

IceCUBE : 1 km$^3$ neutrino detector at South Pole

- detects Cherenkov radiation from the charged particles produced in neutrino interactions
- contained and upward muon events and showers
- contained muons from GC
- showers from GC with IceCUBE+DeepCore

KM3Net : a future deep-sea neutrino telescope

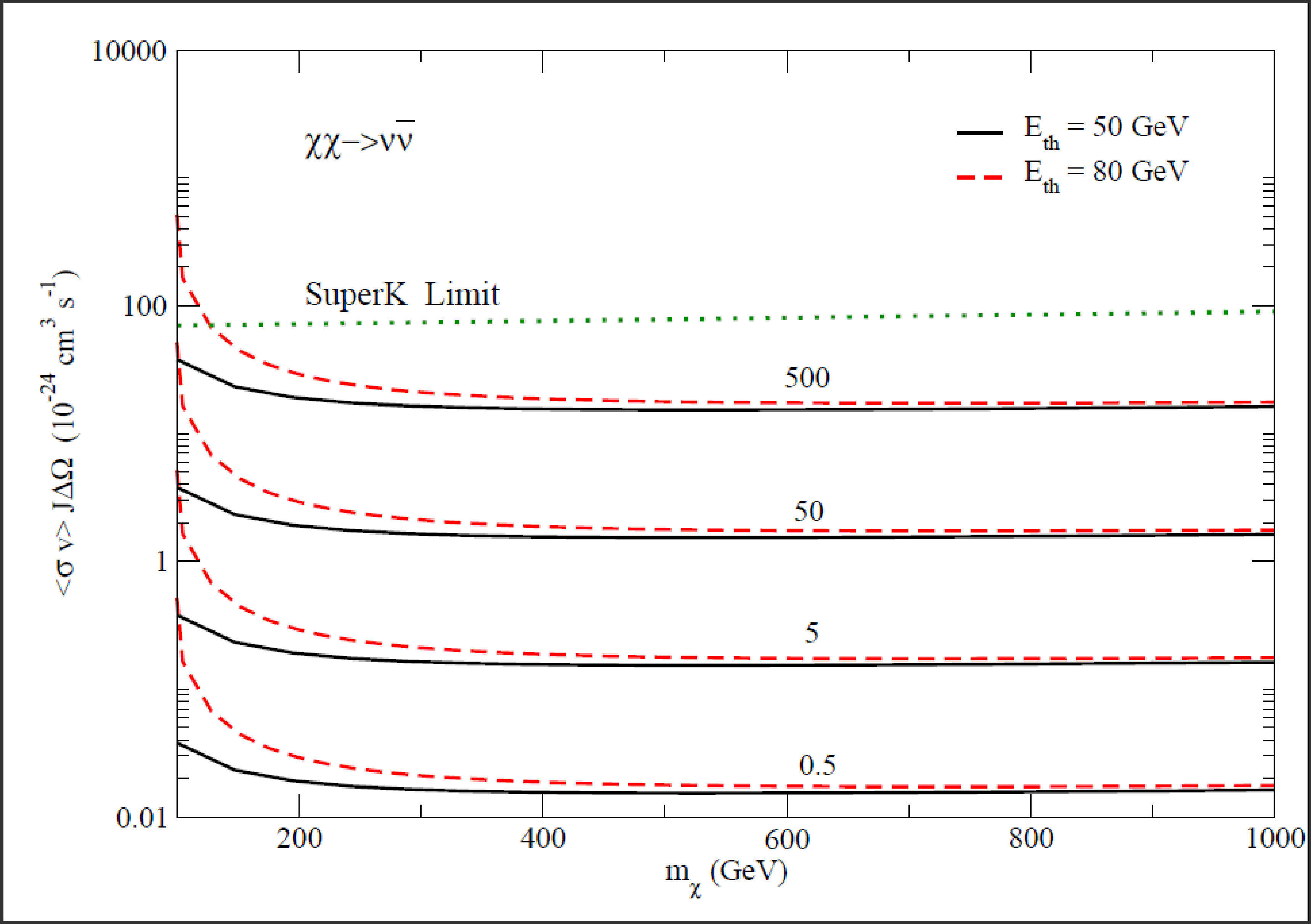
- contained and upward muon events and showers
- upward muons from GC

# Summary

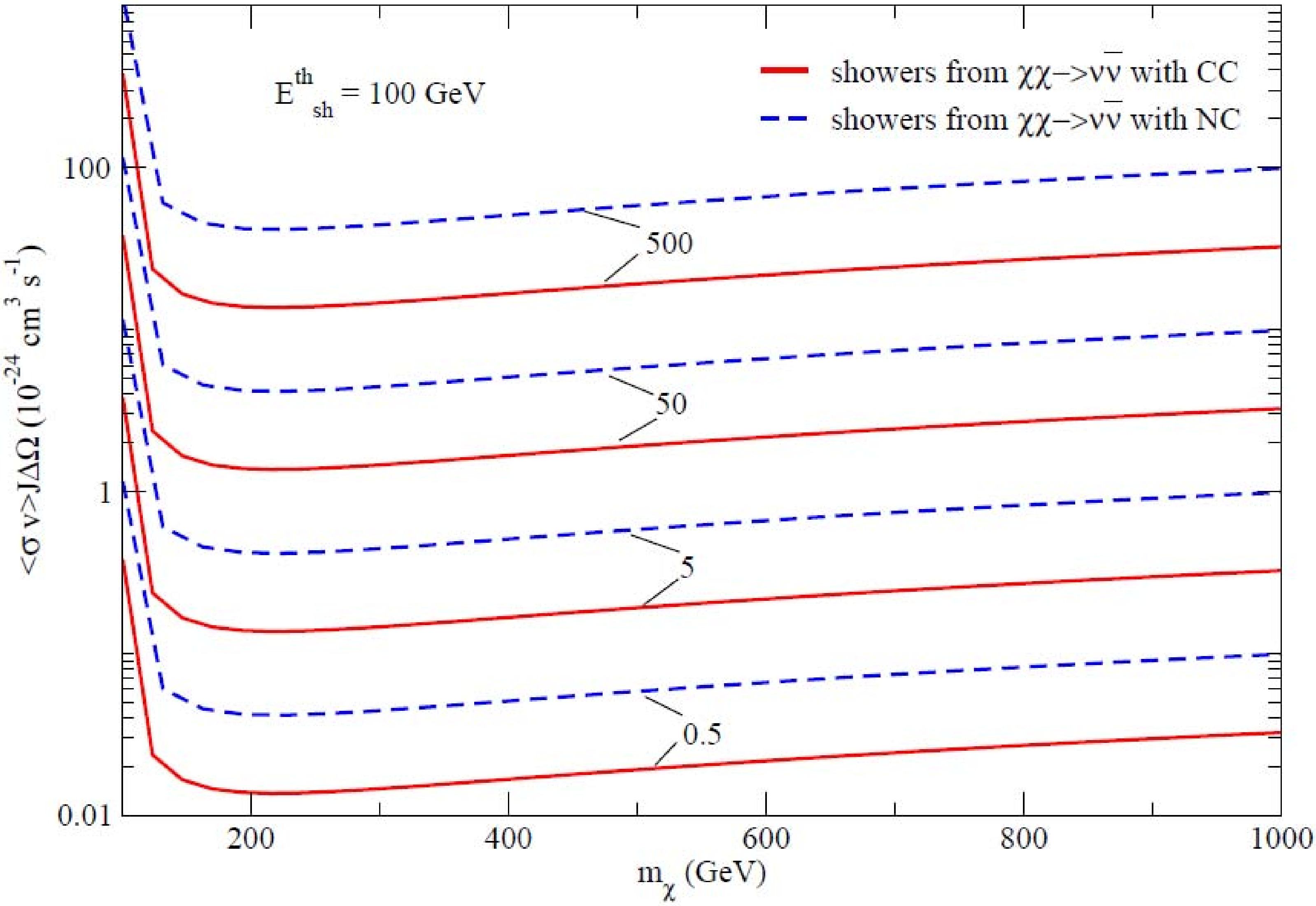
- Neutrinos could be used as signatures of dark matter and to probe its origin
- Contained and upward muon flux is sensitive to the DM annihilation mode and to the mass of dark matter particle providing unique signature of dark matter
- Combined measurements of showers and muons from neutrino interactions when neutrinos are produced in DM annihilation in the Galactic Center with IceCube+DeepCore and KM3Net look promising

# Back-up Slides

# Sensitivity of Upward Muon Rates



# Sensitivity of Hadronic Showers



# Sensitivity of EM Showers