Aspen DM 2011

Probing Dark Matter with Neutrinos from the Galactic Center

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Erkoca, Gelmini, Reno and Sarcevic, Phys. Rev D81 (2010)
Erkoca, Reno and Sarcevic, Phys. Rev. D 82 (2010)

Dark Matter Searches

- Direct searches:

  look for DM interactions with target nuclei (XENON, CDMS, DAMA,CoGeNT)

- Indirect searches:

  DM annihilation producing electrons, positrons, gamma-rays (PAMELA, ATIC, FERMI/LAT, HESS ...) and neutrinos (IceCube, Km3Net)

Neutrino Flux from DM Annihilation and from DM Decay in the Galactic Center

Erkoca, Gelmini, Reno and Sarcevic,
Phys. Rev. D81, 096007 (2010)

- **Model-independent DM signals with neutrino-induced upward and contained muons and cascades (showers)**

- **Signals for IceCube and Km3Net**

Neutrino Flux from Dark Matter

Neutrino flux from DM annihilations/decay:

$$\left(\frac{d\phi_\nu}{dE_\nu}\right) = R \times \sum_F B_F \left(\frac{dN_\nu}{dE_\nu}\right)_F$$

where R for DM annihilation is:

$$R = B\frac{<\sigma v>}{8\pi m_\chi^2}\int d\Omega \int_{l.o.s} \rho(l)^2 dl$$

and for DM decay:

$$R = \frac{1}{4\pi m_\chi \tau}\int d\Omega \int_{l.o.s} \rho(l) dl$$

Define $< J_n >_\Omega$ as:

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

$l(\theta)$ distance from us in the direction of the cone-half angle θ from the GC

$\rho(l)$ density distribution of dark mater halos

R_o distance of the solar system from the GC

ρ_o local dark matter density near the solar system

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

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

Neutrino Flux at the Production

Neutrinos can be produced directly or through decays of leptons, quarks and gauge bosons:

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

$$\to \tau^- \tau^+ \to (\nu_\tau l^- \bar{\nu}_l)\,(\bar{\nu}_\tau l^+ \nu_l)$$

$$\to W^+ W^- \to (l^+ \nu_l)\,(l^- \bar{\nu}_l)$$

$$\to b\bar{b} \to (c\,l^- \bar{\nu}_l)\,(\bar{c}\,l^+ \nu_l)$$

$$\to t\bar{t} \to bW^+ \bar{b}W^- \to (cl^- \bar{\nu}_l)(l^+ \nu_l)(\bar{c}l^+ \nu_l)(l^- \bar{\nu}_l)$$

- Detection: neutrinos interacting below detector or in the detector producing muons
- Signal: upward and contained muons
- Upward muons lose energy before reaching the detector
- Neutrinos interacting in the detector producing showers
- Signal: contained showers

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

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

- α : ionization energy loss $\alpha = 10^{-3}\mathrm{GeVcm^2/g}$.
- β : bremsstrahlung, pair production and photonuclear interactions $\beta = 10^{-6}\mathrm{cm^2/g}$.

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

Contained and Upward Muon Flux

Contained muon flux is given by

$$\frac{d\phi_\mu}{dE_\mu} = \int_{E_\mu}^{E_{max}} dE_\nu \left(\frac{d\phi_\nu}{dE_\nu}\right) N_A \rho \frac{d\sigma_\nu(E_\nu)}{dE_\mu}$$

Upward muon flux is given by

$$\frac{d\phi_\mu}{dE_\mu} = \int_0^{R_\mu(E_\mu^i, E_\mu)} e^{\beta\rho z} dz \int_{E_\mu^i}^{E_{max}} dE_\nu \left(\frac{d\phi_\nu}{dE_\nu}\right) N_A \rho P_{surv}(E_\mu^i, E_\mu) \frac{d\sigma_\nu(E_\nu)}{dE_\mu}$$

Hadronic Shower Flux

$$\frac{d\phi_{sh}}{dE_{sh}} = \int_{E_{sh}}^{E_{max}} dE_\nu \left(\frac{d\phi_\nu}{dE_\nu}\right) N_A \rho \frac{d\sigma_\nu(E_\nu, E_\nu - E_{sh})}{dE_{sh}}$$

Neutrino Energy Distribution

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

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

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

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

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

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

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

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

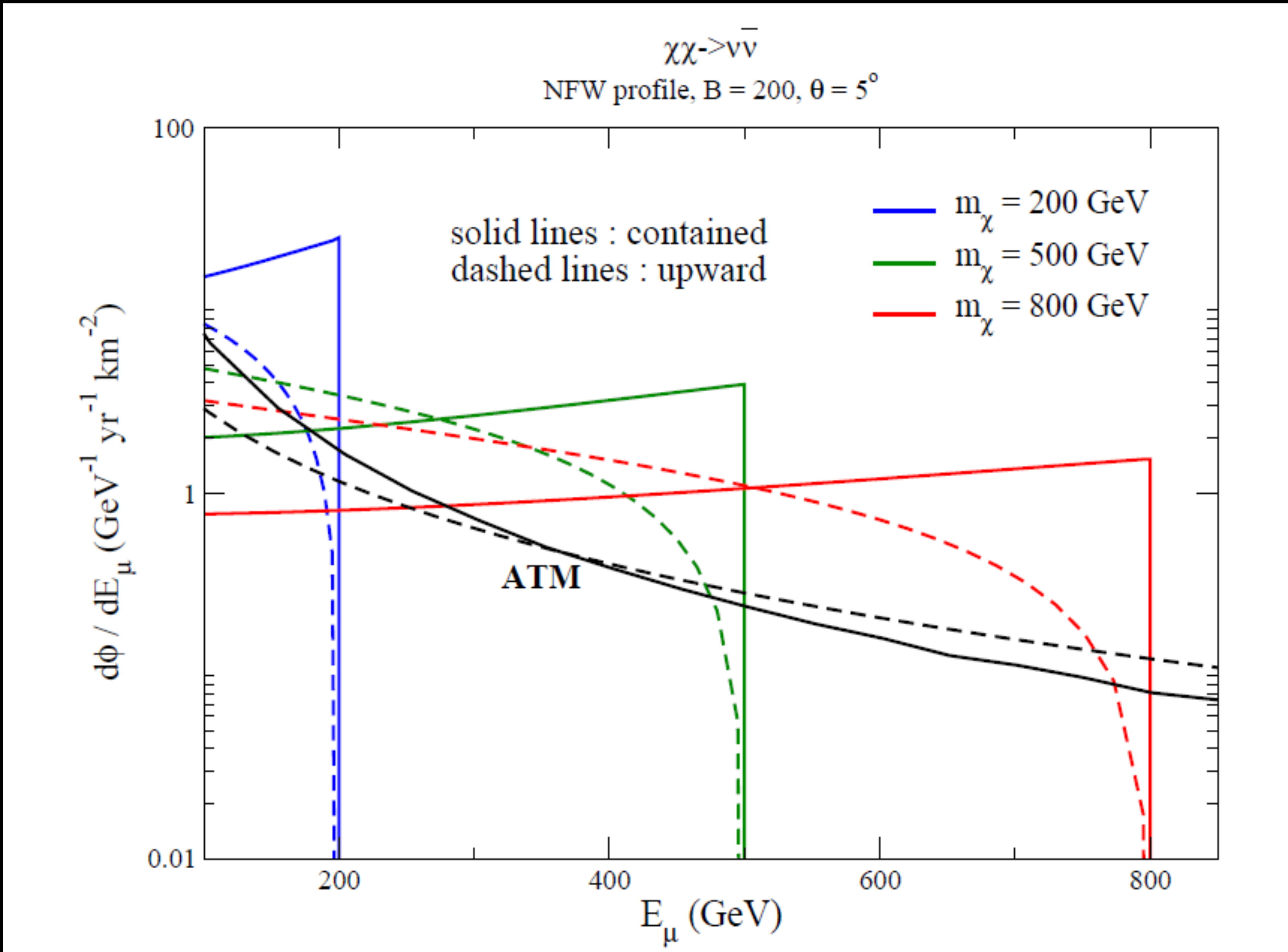
$$(n_f\,,\,B_f) = \begin{cases} (1\,,\,0.105) & W \text{ decay,} \\ (2\,,\,0.067) & Z \text{ decay.} \end{cases}$$

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

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

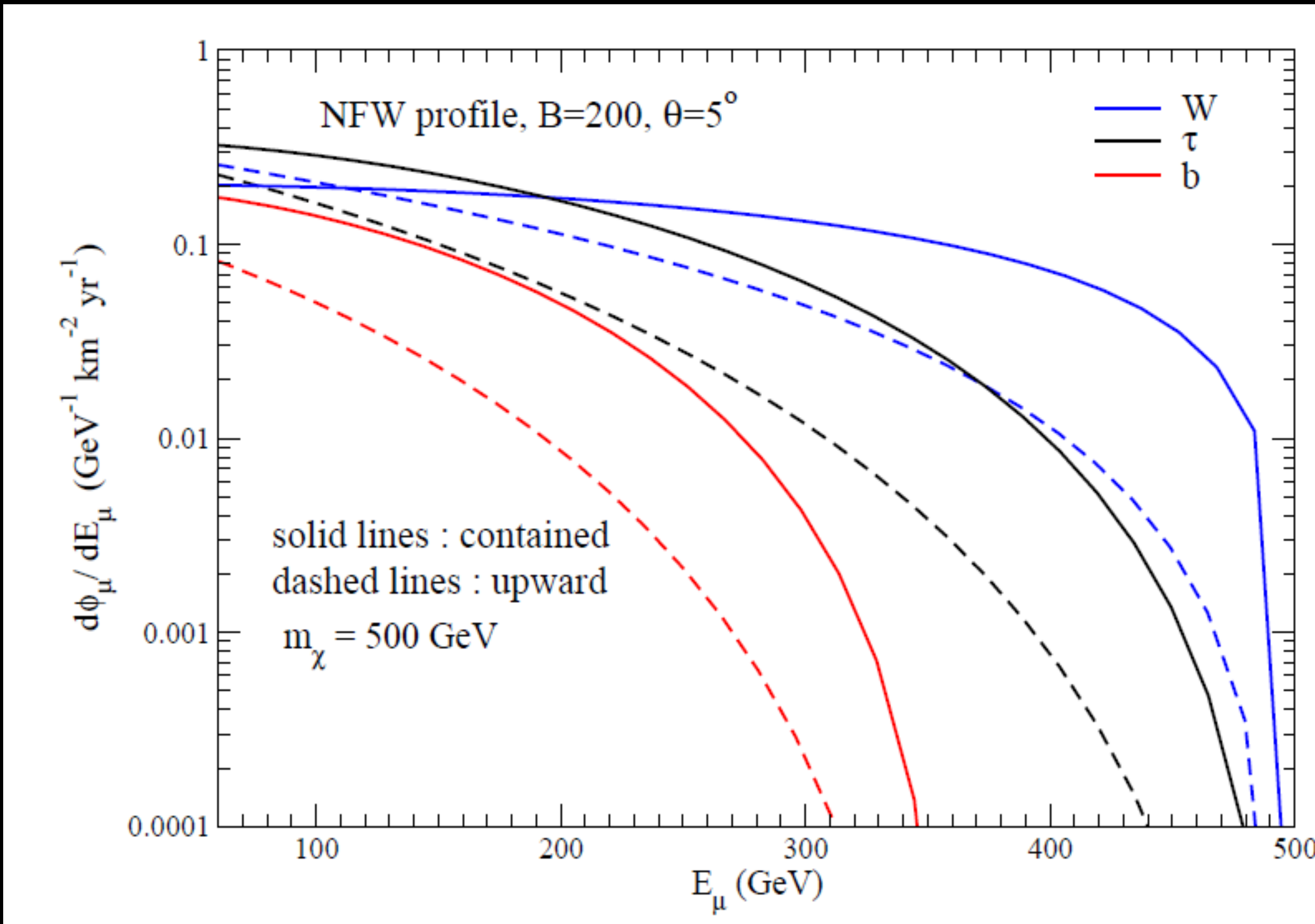
Boosting this expression yields the neutrino spectrum for top quarks moving with velocity β_t

Muon Flux

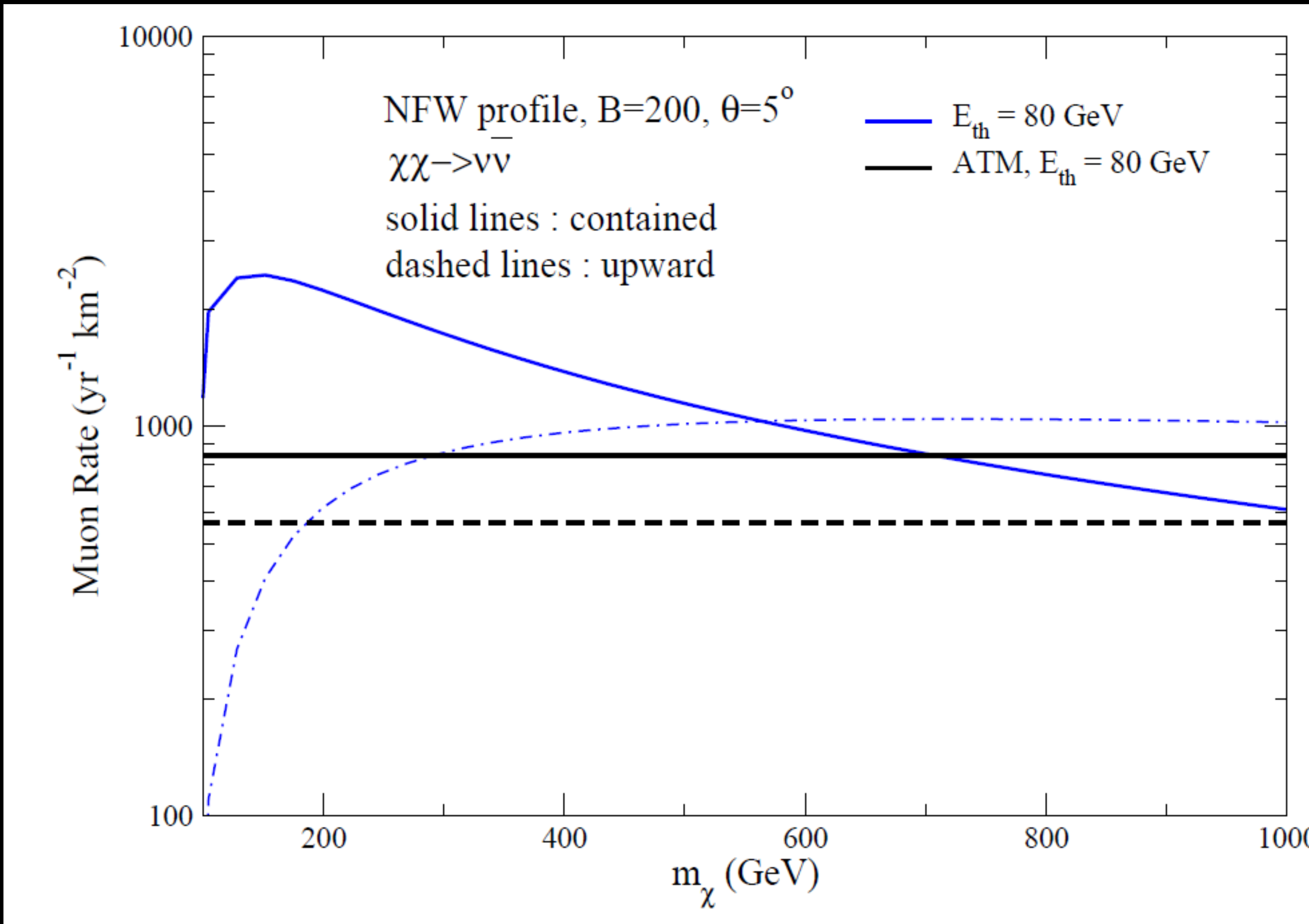


χχ->νν̄
NFW profile, B = 200, θ = 5°
solid lines : contained
dashed lines : upward
m_χ = 200 GeV
m_χ = 500 GeV
m_χ = 800 GeV
ATM
100
1
0.01
200
400
600
800
$d\phi / dE_\mu$ (GeV^{-1} yr^{-1} km^{-2})
E_μ (GeV)

Muon Flux for Different DM Annihilation Modes

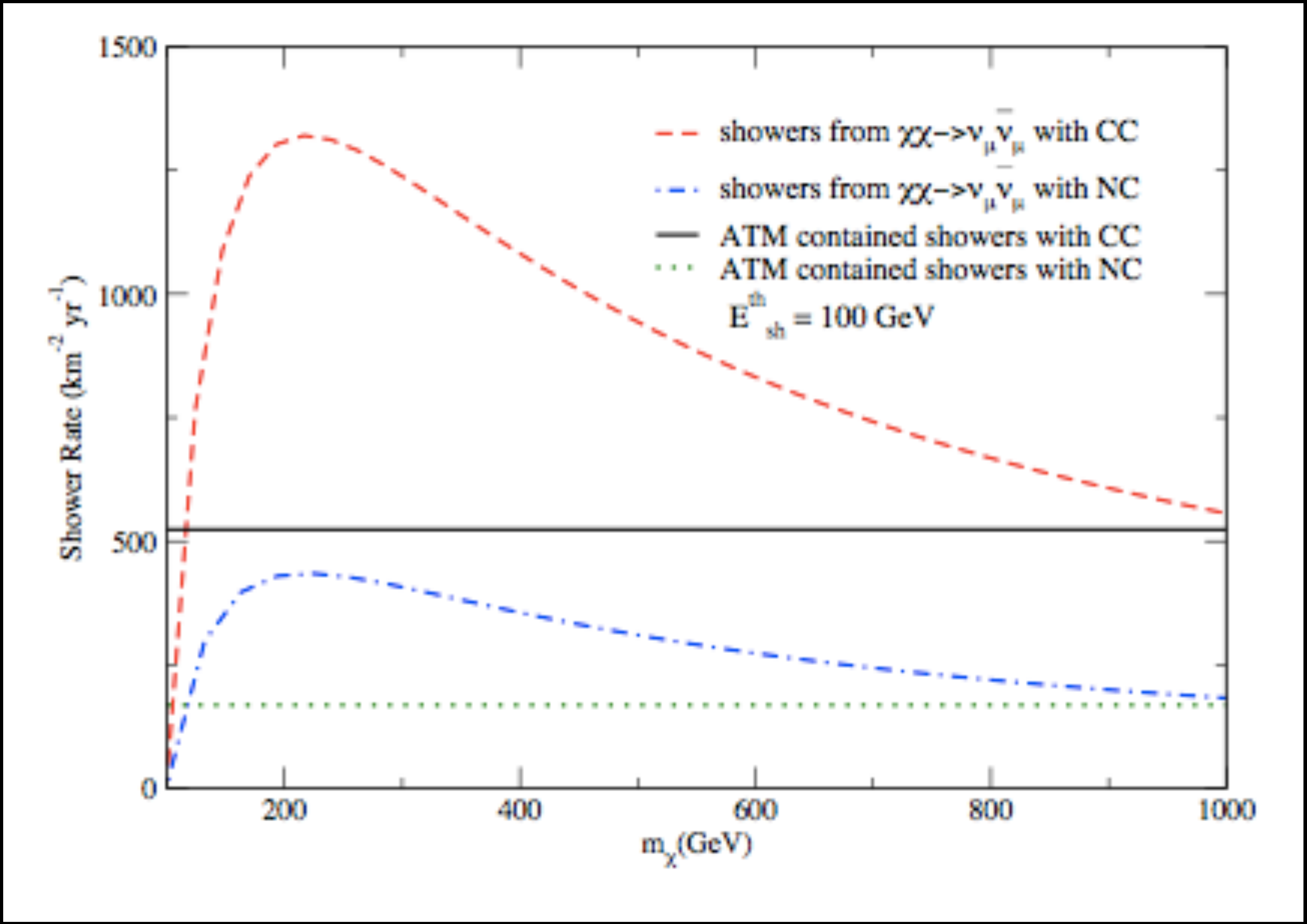


Muon Rates

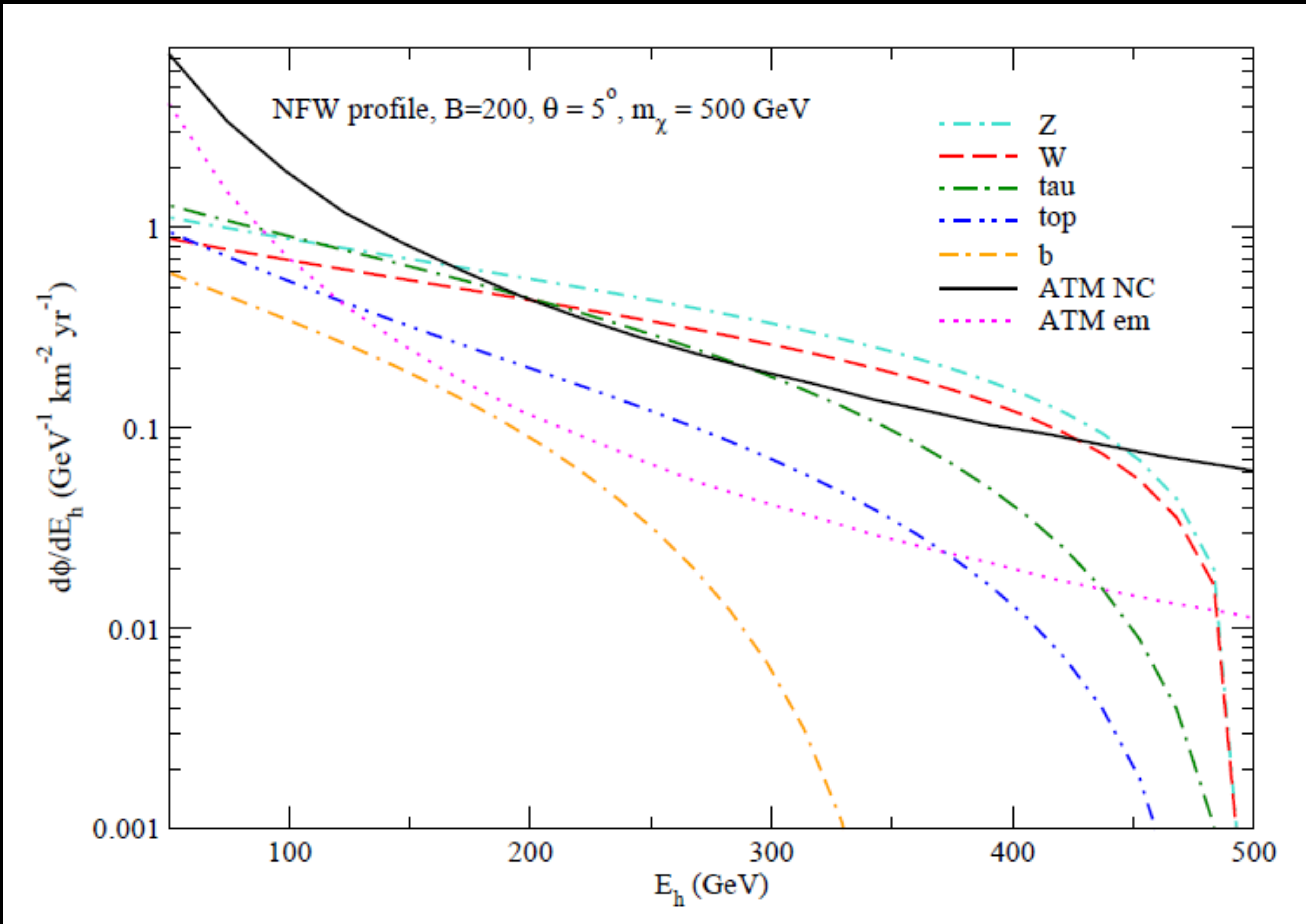


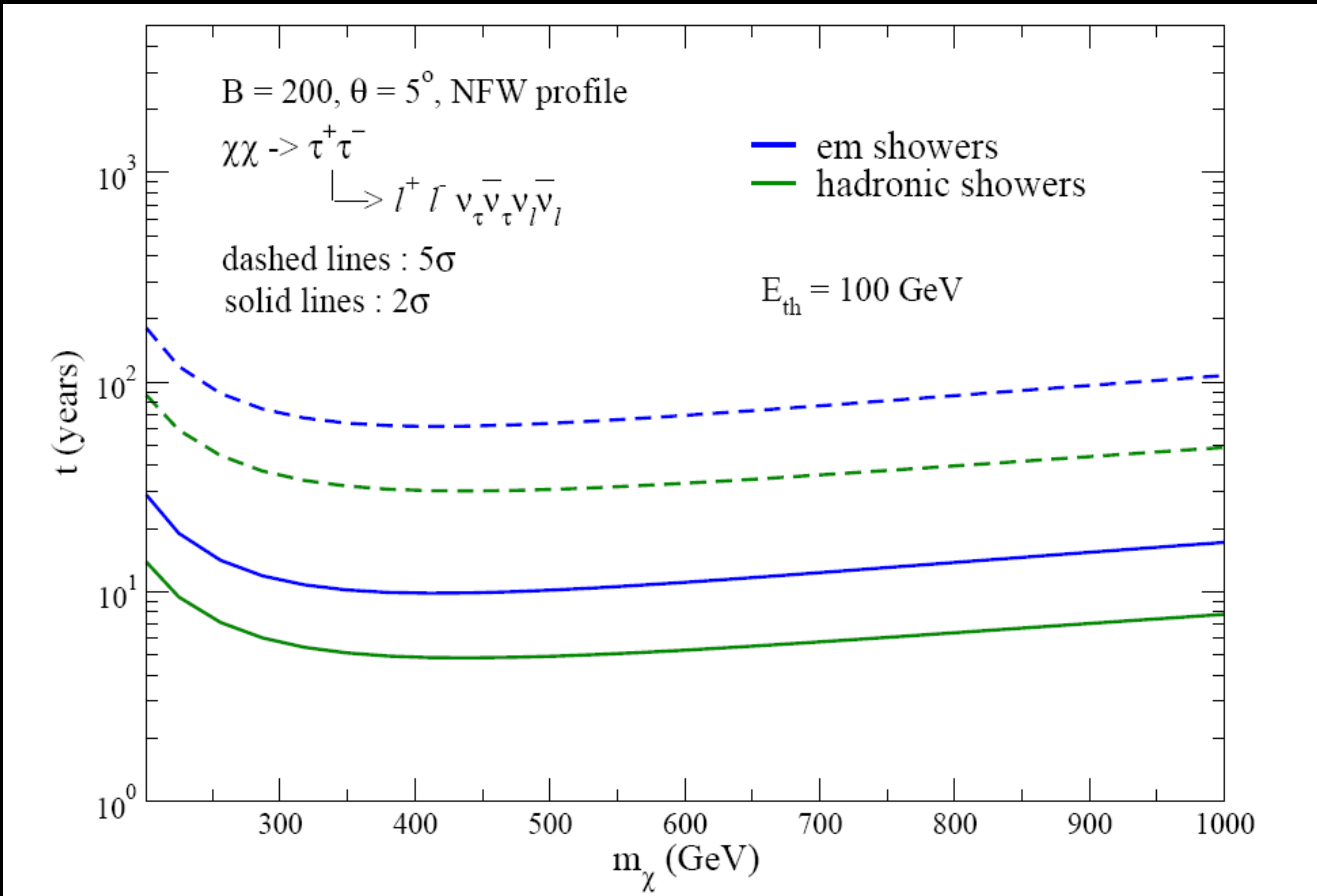
NFW profile, B=200, θ=5°
χχ−>νν̄
solid lines : contained
dashed lines : upward
E_th = 80 GeV
ATM, E_th = 80 GeV
Muon Rate (yr^-1 km^-2)
10000
1000
100
200
400
600
800
1000
m_χ (GeV)

Shower Rates



Hadronic Shower Spectra without track-like events





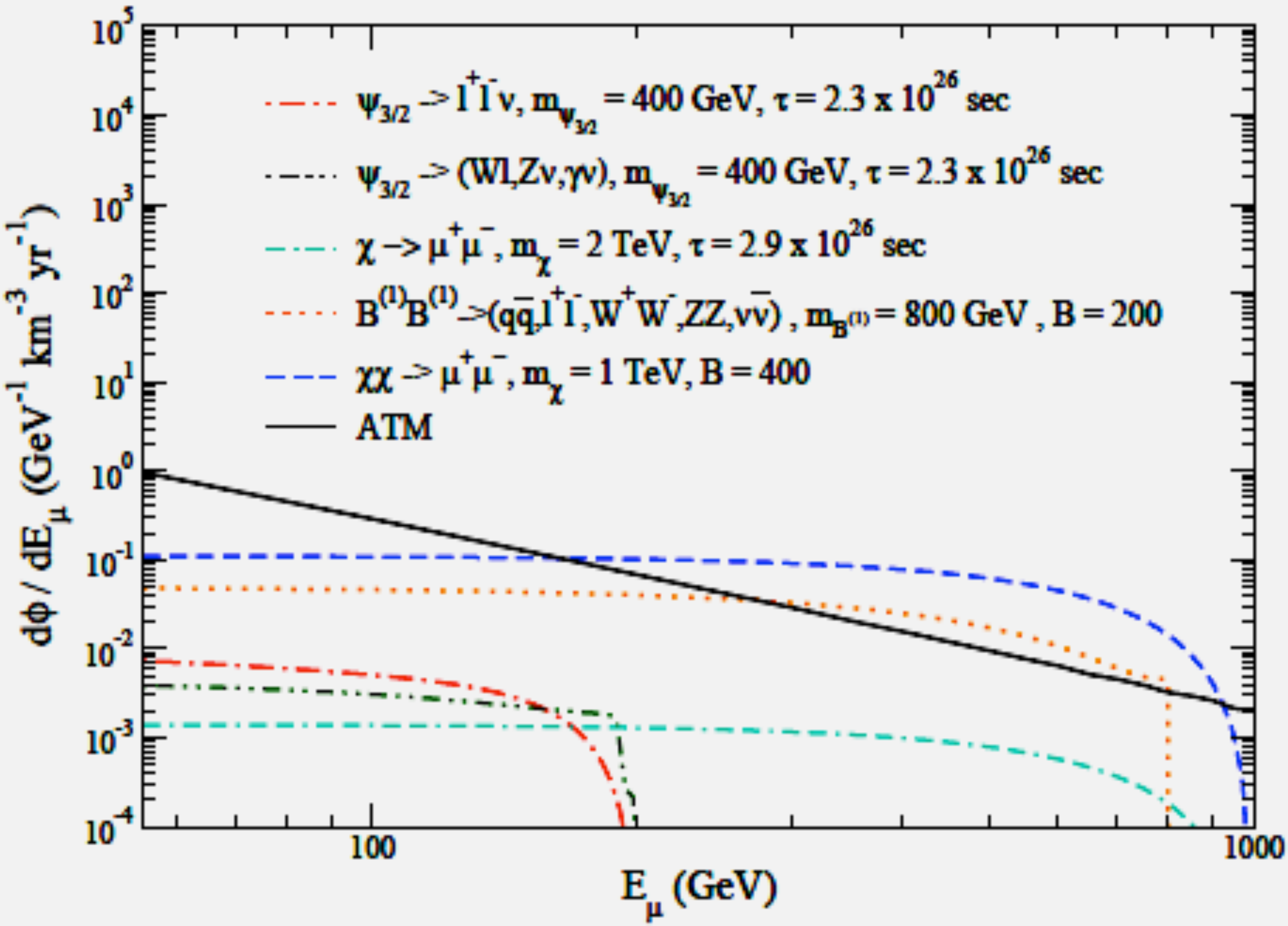
B = 200, θ = 5°, NFW profile
χχ -> τ⁺τ⁻
-> l⁺ l⁻ ν_τ ν̄_τ ν_l ν̄_l
dashed lines : 5σ
solid lines : 2σ
em showers
hadronic showers
E_th = 100 GeV
t (years)
m_χ (GeV)
10^0
10^1
10^2
10^3
300
400
500
600
700
800
900
1000

Probing the Nature of Dark Matter with Neutrinos

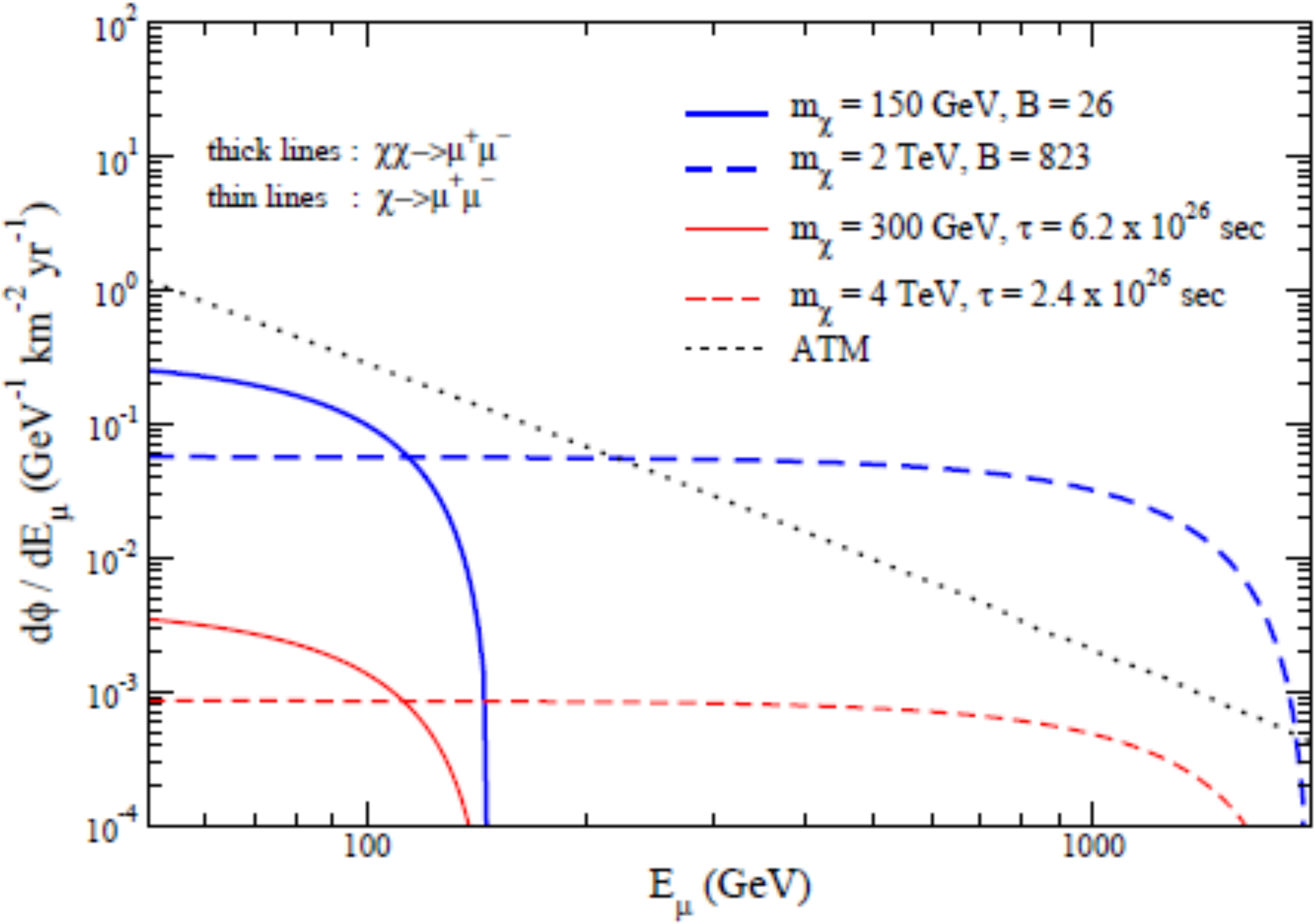
Erkoca, Reno and Sarcevic, Phys. Rev. D82, 113006 (2010)

- DM candidates: gravitino, Kaluza-Klein particle, a particle in leptophilic models.
- Dark matter signals: upward and contained muon flux and cascades (showers) from neutrino interactions
- Experimental signatures that would distinguish between different DM candidates

Contained Muon Flux



Contained Muon Flux



		m_χ (TeV)									
		0.2	0.4	0.6	0.8	1	2	4	6	8	10
$\psi_{3/2} \to l^+ l^- \nu$	$N_\mu^{ct}(50^\circ)$	4.94	11.15	13.8	15.3	16.2	18.1	19.0	19.3	19.5	19.6
$B_\tau = 2.3$	$N_\mu^{up}(50^\circ)$	8.68	59.5	120	180	239	503	912	1228	1485	1704
	$N_{sh}(50^\circ)$	4	11	13	15	16.3	19	21	22	22	22
	$t_\mu^{up}(10^\circ)$	1.3×10^4	277	69	30	17	4	1.2	0.7	0.5	0.4
	$t_\mu^{up}(50^\circ)$	3490	74	18	8	5	1	0.32	0.18	0.12	0.09
	$t_{sh}(50^\circ)$	196	23	16	12	10	7	6.3	5.8	5.8	5.8
$\psi_{3/2} \to (Wl, Z\nu, \gamma\nu)$	$N_\mu^{ct}(50^\circ)$	6.1	8.4	8.9	9.1	9.15	9.2	9.2	9.2	9.2	9.2
$B_\tau = 2.3$	$N_\mu^{up}(50^\circ)$	9.9	50.9	95.6	139	181	364	638	844	1010	1150
	$N_{sh}(50^\circ)$	3.6	7.66	9.6	10.74	11.5	13.17	14.12	14.46	14.64	14.74
	$t_\mu^{up}(10^\circ)$	1×10^4	378	107	51	30	7.5	2.5	1.4	1	0.8
	$t_\mu^{up}(50^\circ)$	2693	101	29	14	8	2	0.7	0.4	0.3	0.2
	$t_{sh}(50^\circ)$	210	47	30	24	21	16	14	13	13	13
$\chi \to \mu^+ \mu^-$	$N_\mu^{ct}(50^\circ)$	2.13	6.45	8.43	9.5	10.2	11.5	12.2	12.4	12.5	12.6
$B_\tau = 2.9$	$N_\mu^{up}(50^\circ)$	3.14	29	62.3	97	131	286	533	728	886	1022
	$N_{sh}(50^\circ)$	1.95	8.22	12.09	14.55	16.2	20.2	22.45	23.27	23.68	23.94
	$t_\mu^{up}(10^\circ)$	1×10^5	1×10^3	252	104	57	12	3.5	1.9	1.3	0.97
	$t_\mu^{up}(50^\circ)$	2.6×10^4	316	68	28	15	3.2	0.93	0.5	0.34	0.26
	$t_{sh}(50^\circ)$	709	40	19	13	11	6.9	5.5	5.2	5	4.8
$B^{(1)} B^{(1)} \to \ldots$	$N_\mu^{ct}(10^\circ)$	14.2	9.8	7.2	5.6	4.6	2.4	1.25	0.84	0.63	0.51
$B = 200$	$N_\mu^{up}(10^\circ)$	86.1	131	140	130	128	124	108	92	81	72
	$N_{sh}(10^\circ)$	11	9	7	5.7	4.8	2.6	1.4	0.9	0.7	0.6
	$t_\mu^{up}(1^\circ)$	1.27	0.63	0.54	0.65	0.66	0.7	0.87	1.14	1.42	1.72
	$t_\mu^{up}(10^\circ)$	1.55	0.68	0.57	0.71	0.72	0.76	1.0	1.36	1.76	2.2
	$t_\mu^{up}(50^\circ)$	5.1	2.2	1.84	2.29	2.3	2.44	3.2	4.5	5.8	7.2
	$t_{sh}(1^\circ)$	3.4	4.4	5.9	7.7	9.6	22	61	116	189	280
	$t_{sh}(10^\circ)$	1.3	1.9	2.9	4.3	5.8	18	64	136	237	364
	$t_{sh}(50^\circ)$	3.3	5	8	12	16.3	57	204	445	777	1202
$\chi\chi \to \mu^+ \mu^-$	$N_\mu^{ct}(10^\circ)$	40.19	29.58	22.01	17.39	14.3	7.59	3.90	2.63	1.98	1.59
$B = 400$	$N_\mu^{up}(10^\circ)$	144	241	273	283	320	266	221	190	167	151
	$N_{sh}(10^\circ)$	51.4	45.6	36.4	30	25	14	7.4	5	3.8	3
	$t_\mu^{ct}(1^\circ)$	1.11	1.68	2.55	3.61	4	13.64	44	92	156	238
	$t_\mu^{ct}(10^\circ)$	0.66	1.18	2.06	3.24	4.7	16.31	61	133	234	364
	$t_\mu^{ct}(50^\circ)$	1.93	3.55	6.38	10.2	15	53	201	444	781	1213
	$t_\mu^{up}(1^\circ)$	0.54	0.24	0.2	0.18	0.14	0.21	0.28	0.35	0.43	0.50
	$t_\mu^{up}(10^\circ)$	0.47	0.21	0.16	0.15	0.12	0.17	0.25	0.33	0.42	0.52
	$t_\mu^{up}(50^\circ)$	1.83	0.65	0.51	0.47	0.37	0.54	0.78	1.1	1.35	1.7
	$t_{sh}(1^\circ)$	0.63	0.72	0.91	1.12	1.37	2.58	5.5	9	13	18
	$t_{sh}(10^\circ)$	0.12	0.14	0.2	0.26	0.34	0.87	2.63	5.34	9	13.6
	$t_{sh}(50^\circ)$	0.18	0.22	0.33	0.48	0.7	2.1	7.2	15.5	27	42
Atmospheric	N_μ^{ct}	$2.28(1^\circ)$				$227.5(10^\circ)$			$5347(50^\circ)$		
	N_μ^{up}	$28(1^\circ)$				$2794(10^\circ)$			$65668(50^\circ)$		
	N_{sh}	$0.3(1^\circ)$				$28.8(10^\circ)$			$676(50^\circ)$		

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 to detect dark matter and to probe its physical origin
- Contained and upward muon flux is sensitive to the DM annihilation mode and to the mass of dark matter particle
- Combined measurements of cascade events and muons with IceCube+DeepCore and KM3Net look promising
- Neutrinos can probe DM candidates, such as gravitino, Kaluza-Klein DM, and a particle in leptophilic models