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Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

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Probing dark matter with neutrinos

Ina SARCEVIC

University of Arizona
USA

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

NUSKY 2011

Probing Dark Matter with Neutrinos from the Galactic Center

Ina Sarcevic

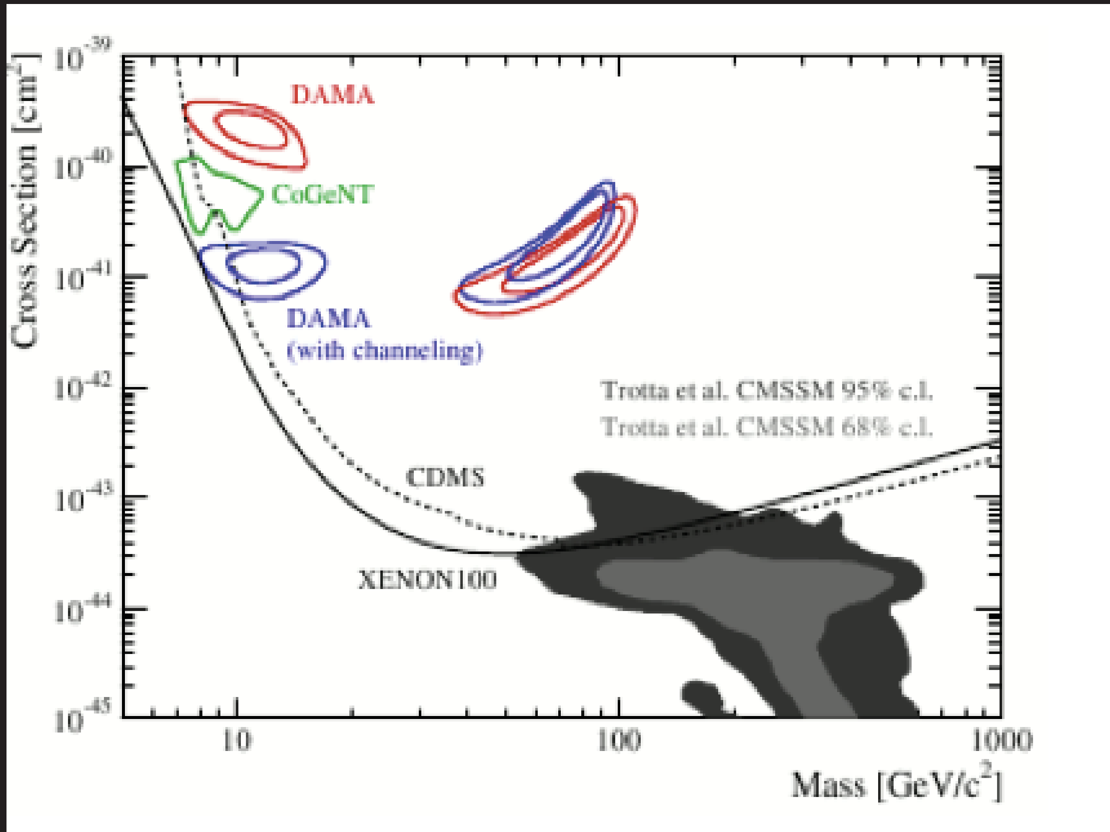
Erkoca, Gelmini, Reno and Sarcevic, Phys. Rev D 81 (2010)
Erkoca, Reno and Sarcevic, Phys. Rev. D 82 (2010)
Erkoca, Reno and Sarcevic, Phys. Rev. D 80 (2009)

- Indirect evidence for dark matter comes from observations of galaxy and group of galaxies rotating as if they contain far more matter than observed
- Dark matter is about 23% of the total density of the Universe, while baryonic matter is only 4%
- Dark matter particle with mass of ~100GeV - few TeV can account for dark matter density
- No viable candidate for dark matter in the Standard Model

Dark Matter Searches

- Direct searches:

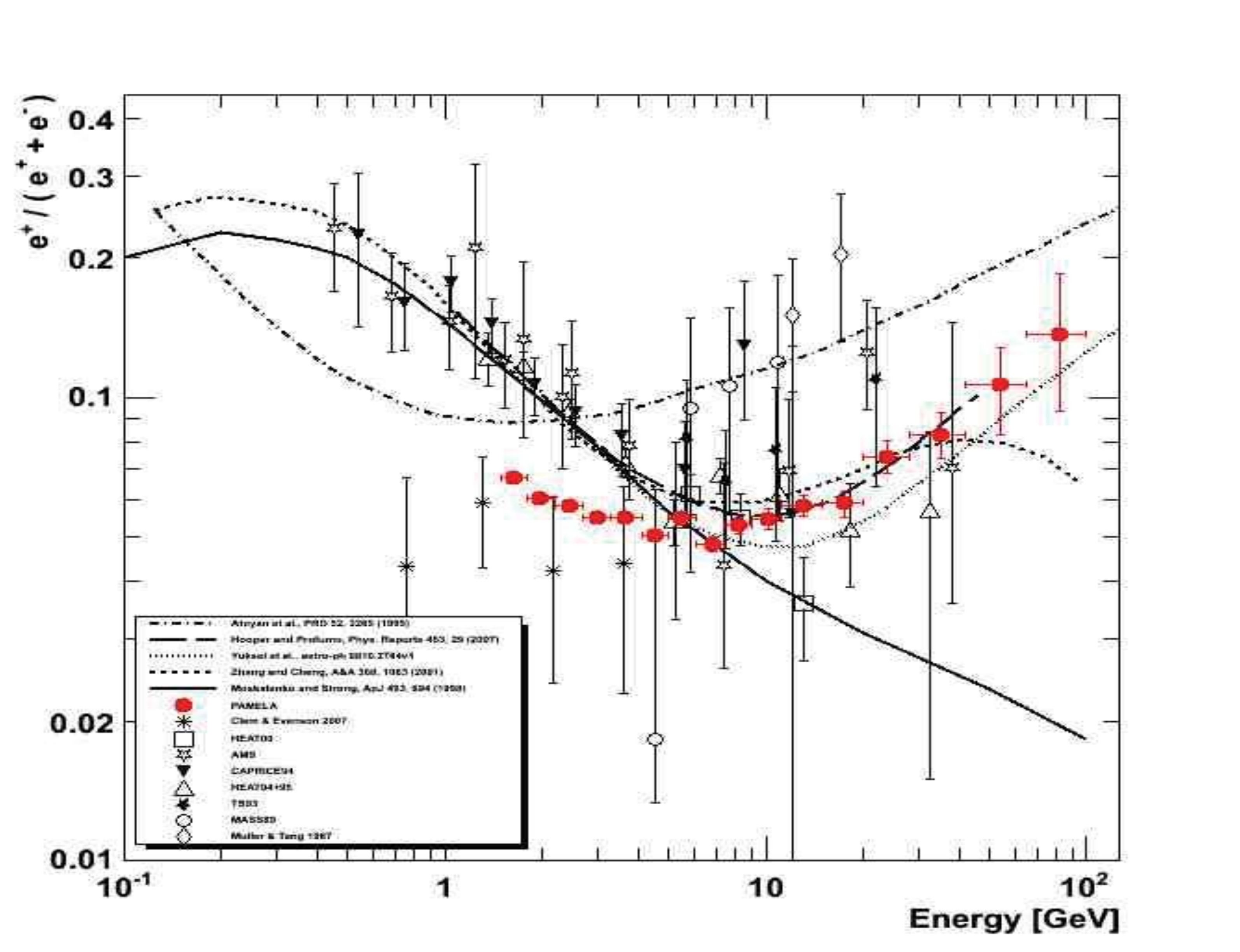
look for DM interactions with target nuclei (XENON, CDMS, DAMA …)



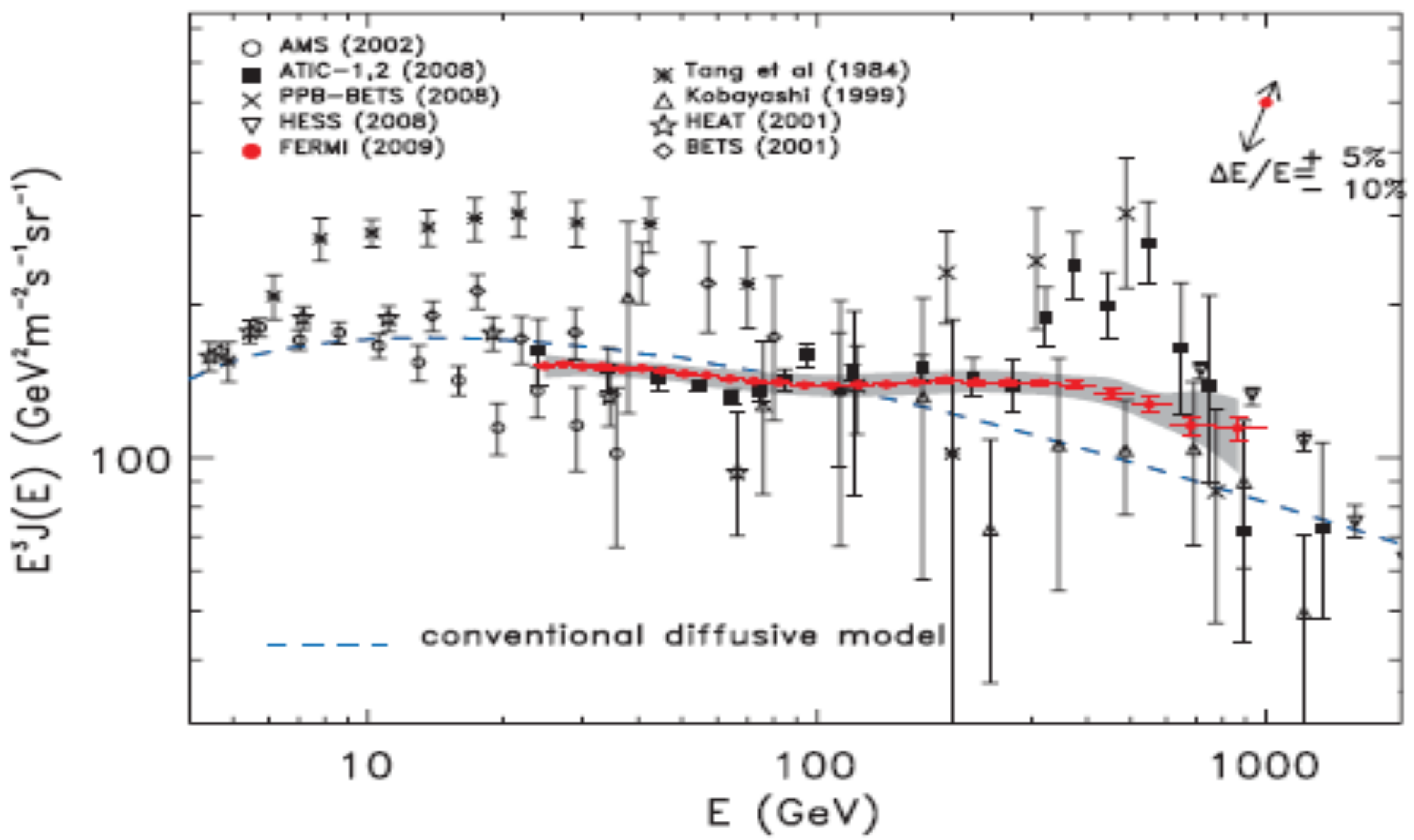
- Indirect searches:

  DM annihilation producing electrons, positrons, gamma-rays (PAMELA, ATIC, FERMI/LAT, HESS, Veritas …) and neutrinos (IceCube, KM3Net…)

PAMELA Positron Fraction



FERMI Cosmic Ray Electron Spectrum



Neutrino Flux from DM Annihilation in the Galactic Center

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

- Model independent DM signals: neutrino-induced upward and contained muons and cascades (showers)
- For dark matter density, we use different DM density profiles (Navarro-Frenk-White, isothermal, etc)
- Predictions for IceCube and Km3Net

Neutrino Flux from Dark Matter

Neutrino flux from DM annihilation/decay:

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

here 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 (dN_ν/dE_ν) at the Production

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

$$\chi\chi \rightarrow \nu_i\overline{\nu_i}$$

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

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

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

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

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

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

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

- α : ionization energy loss $\alpha = 10^{-3}\,\mathrm{GeV cm^2/g}$.
- β : bremsstrahlung, pair production and photonuclear interactions $\beta = 10^{-6}\,\mathrm{cm^2/g}$.
- Relation between the initial and the final muon energy:

$$E_\mu^i(z) = e^{\beta\rho z} E_\mu^f + (e^{\beta\rho z} - 1)\frac{\alpha}{\beta}$$

Muon range:

$$R_\mu \equiv z = \frac{1}{\beta\rho} log\left(\frac{\alpha + \beta E_\mu^i}{\alpha + \beta E_\mu^f}\right)$$

Contained and Upward Muon Flux

Contained muon flux is given by

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

Upward muon flux is given by

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

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

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

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

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

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

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

- $\chi\chi \to W^+W^-, ZZ$ 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)

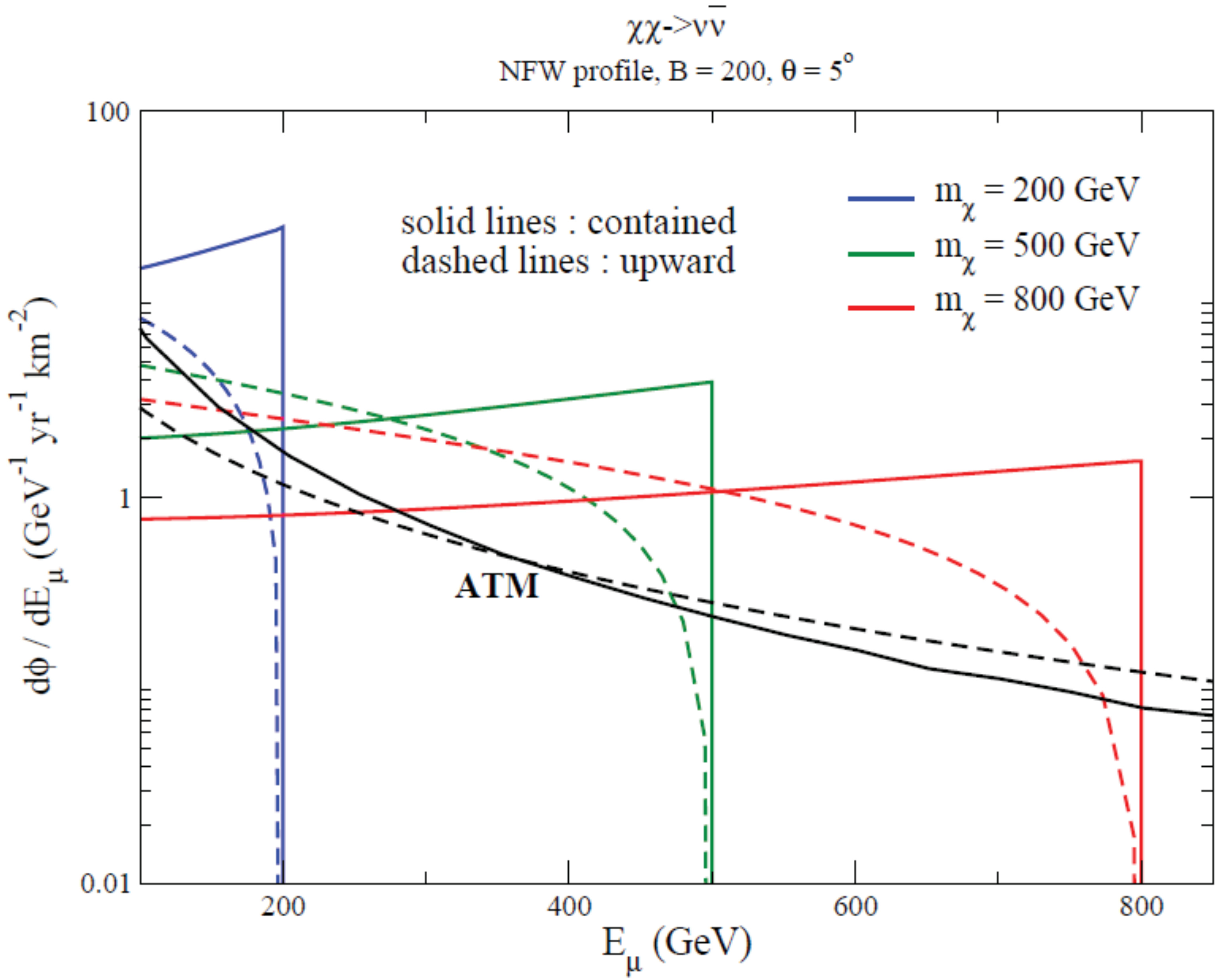
$$(n_f\,,\,B_f) = \begin{cases} (1\,,\,0.105) & W \text{ decay,} \\ (2\,,\,0.067) & Z \text{ decay.} \end{cases}$$

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

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

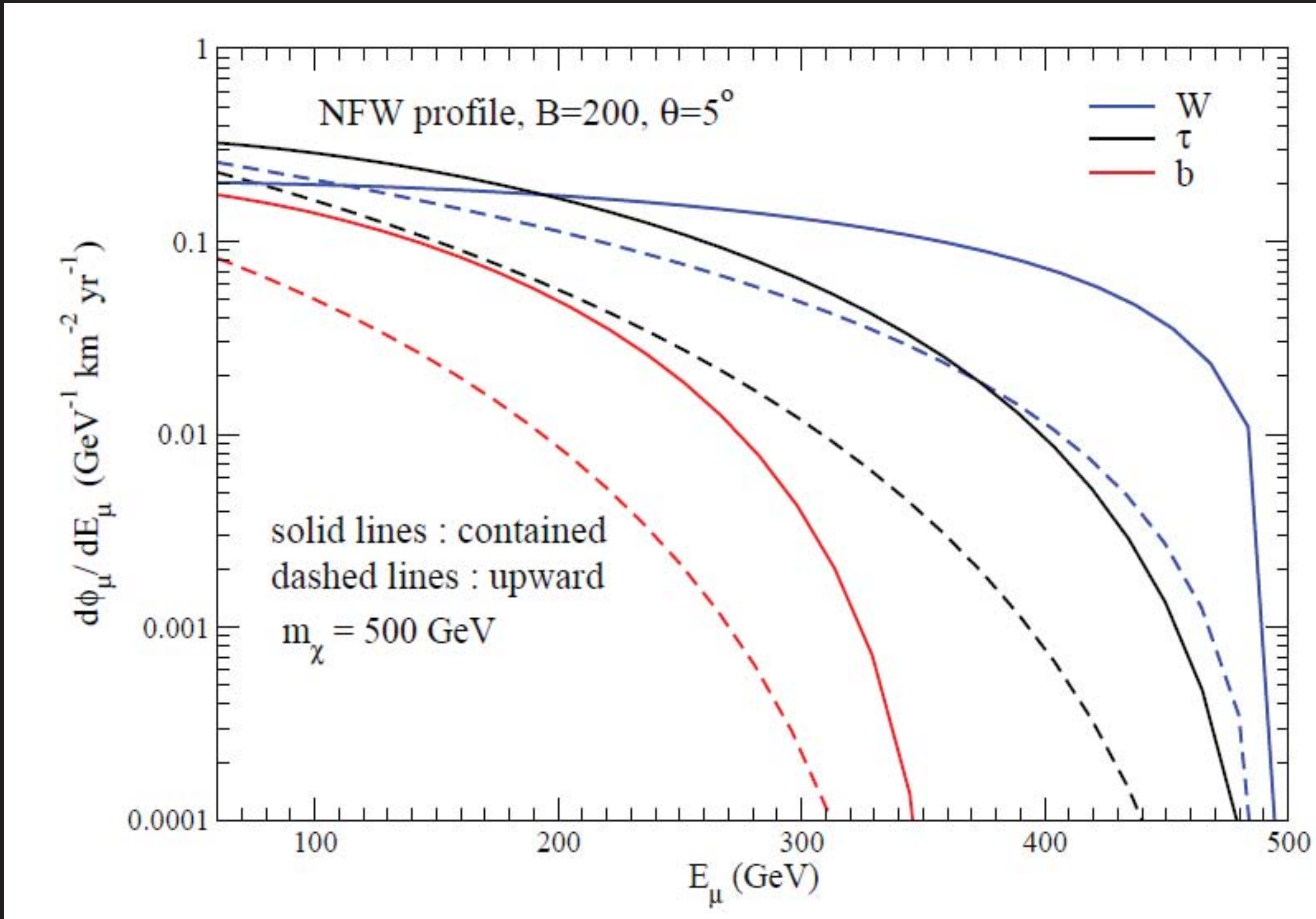
Boosting this expression yields the neutrino spectrum for top quarks moving with velocity β_t

Muon Flux

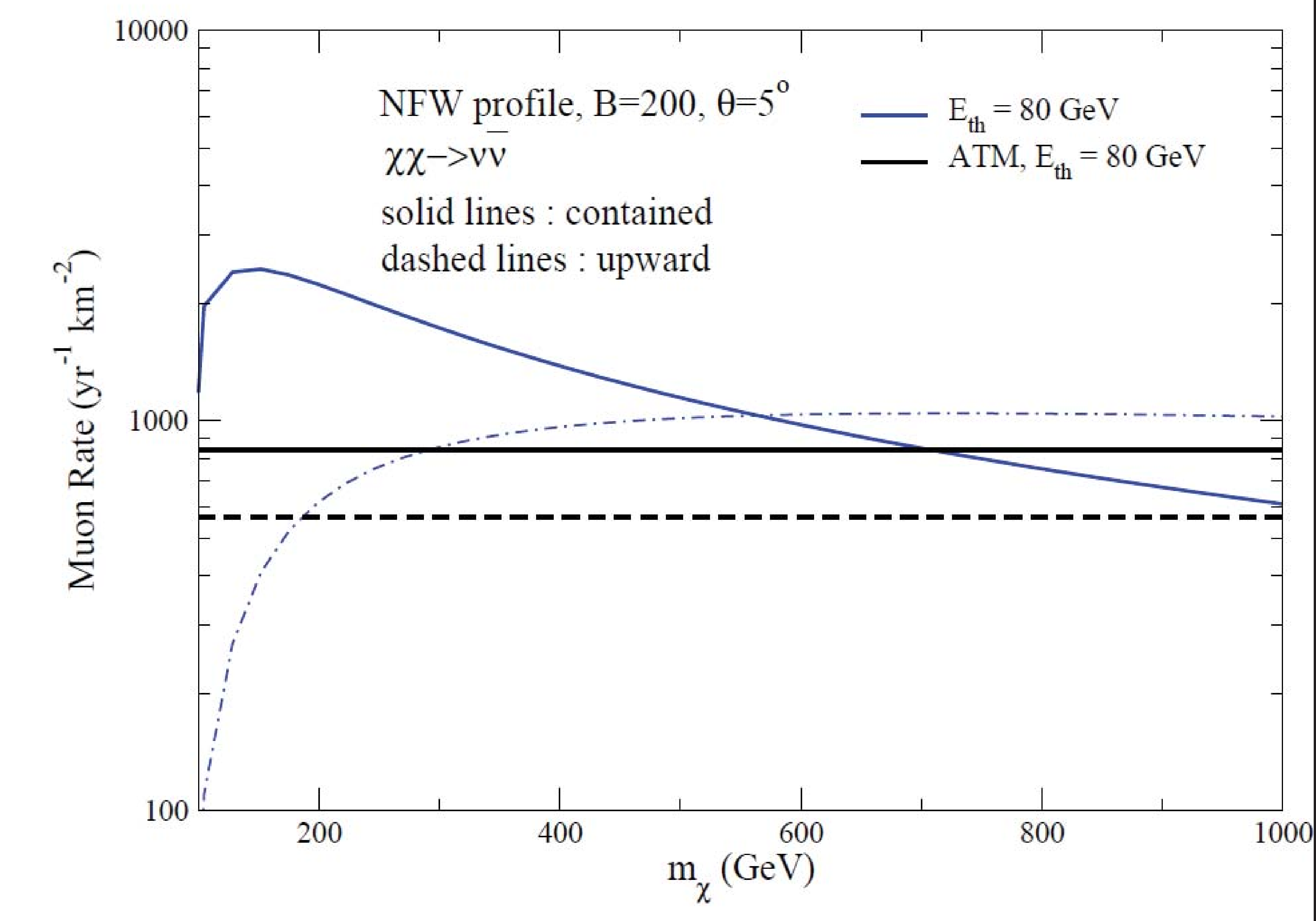


χχ->νν̄
NFW profile, B = 200, θ = 5°
solid lines : contained
dashed lines : upward
m_χ = 200 GeV
m_χ = 500 GeV
m_χ = 800 GeV
ATM
dφ / dE_μ (GeV^-1 yr^-1 km^-2)
E_μ (GeV)
100
1
0.01
200
400
600
800

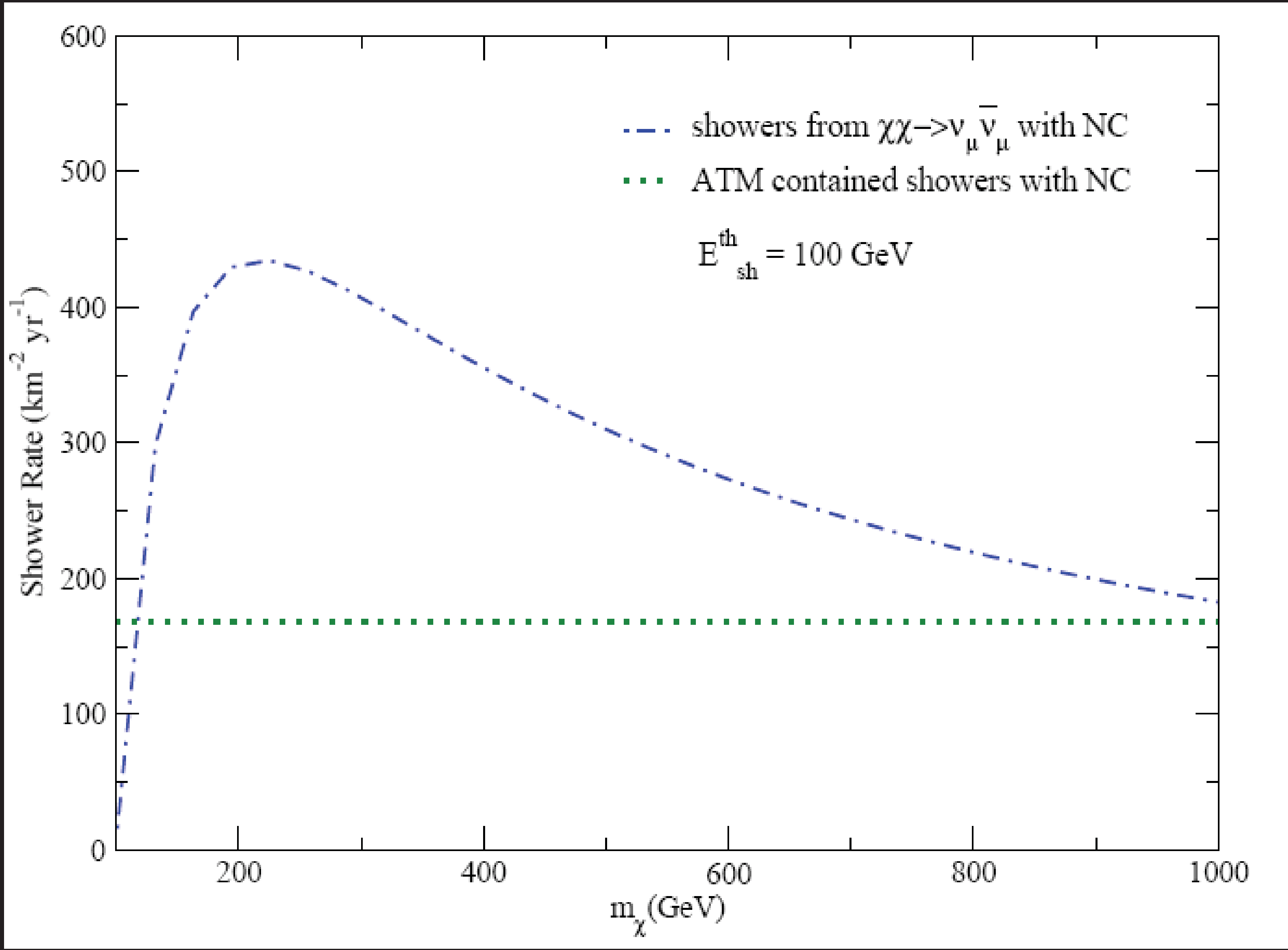
Muon Flux for Different DM Annihilation Modes



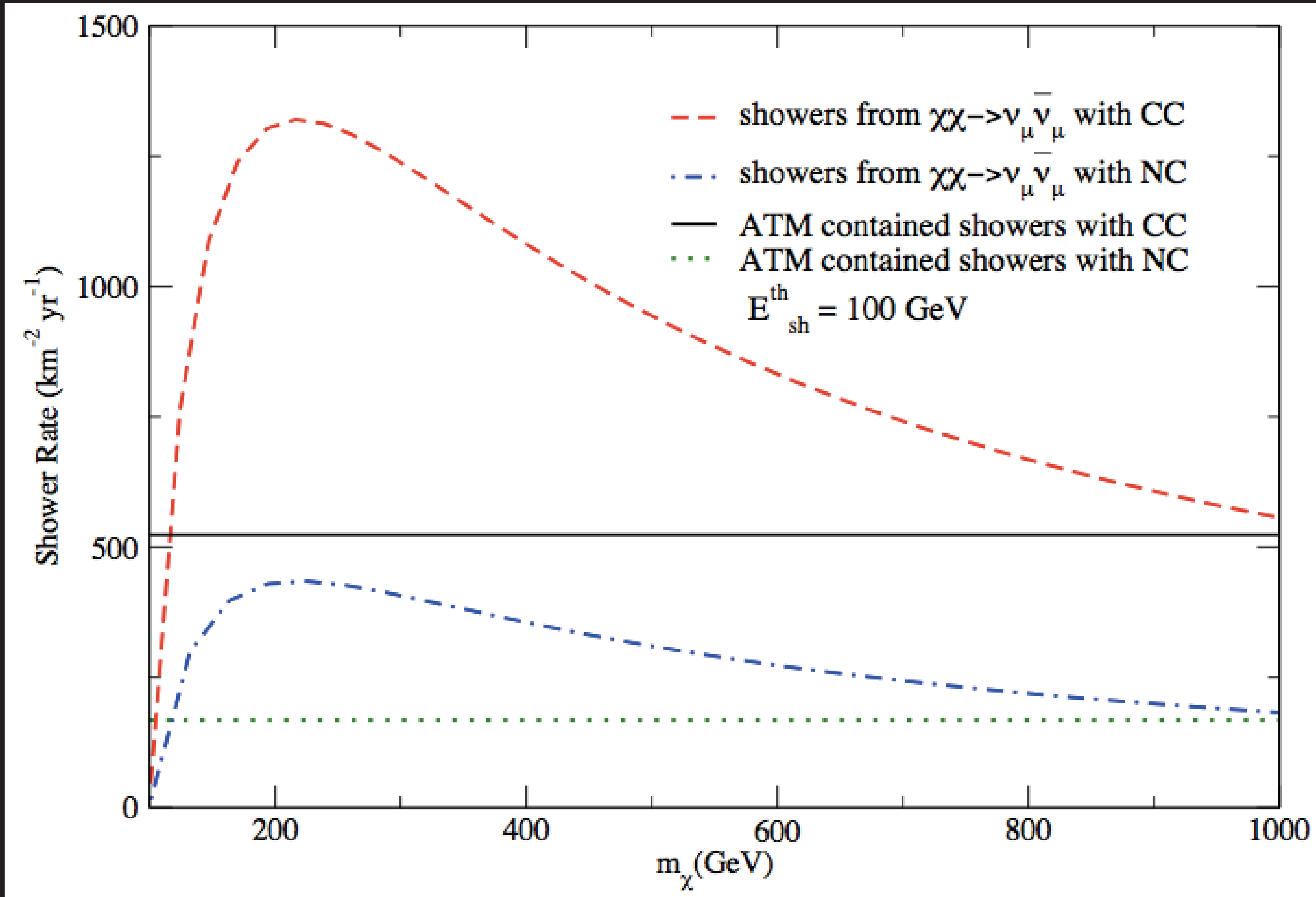
Muon Rates



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)

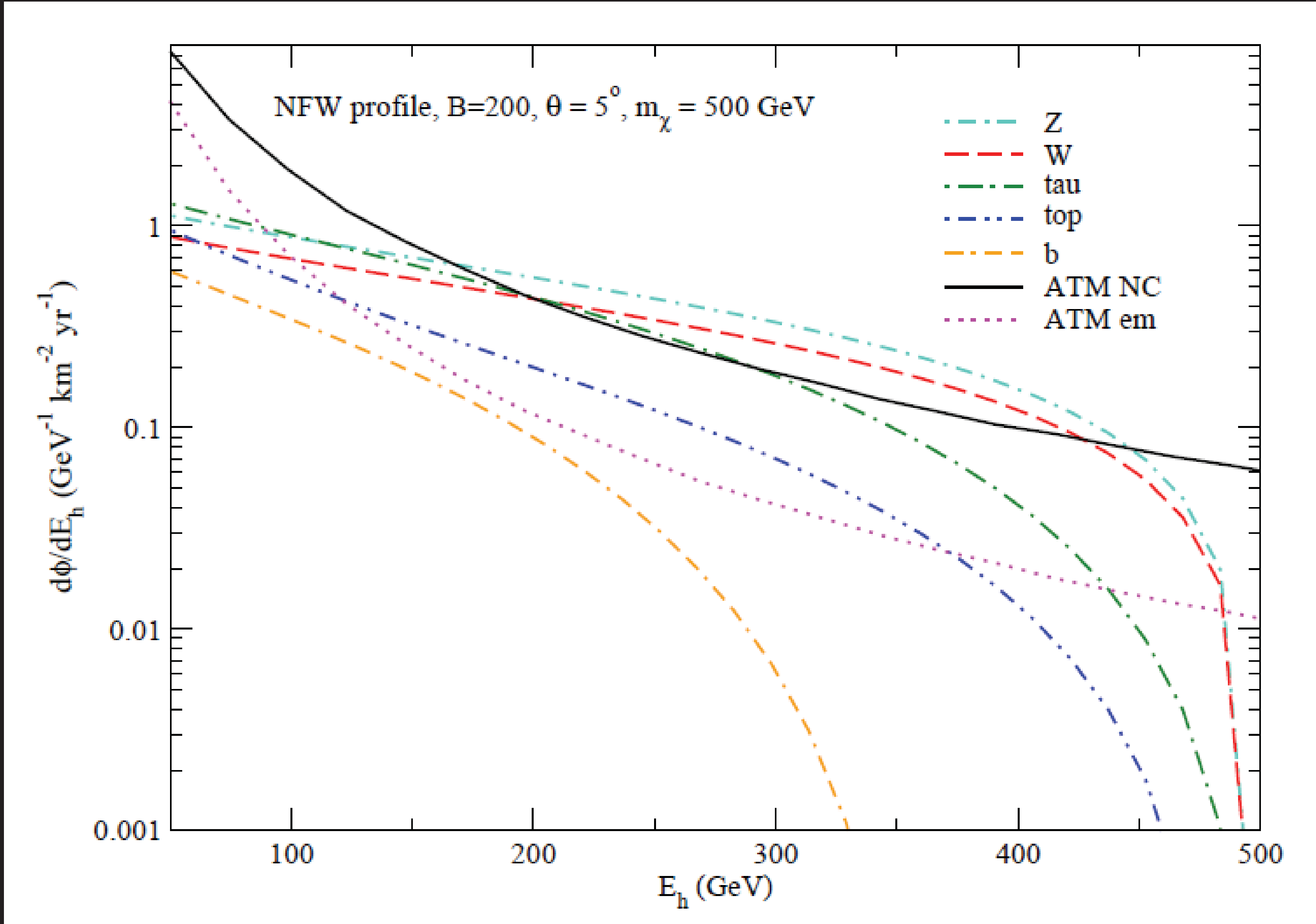


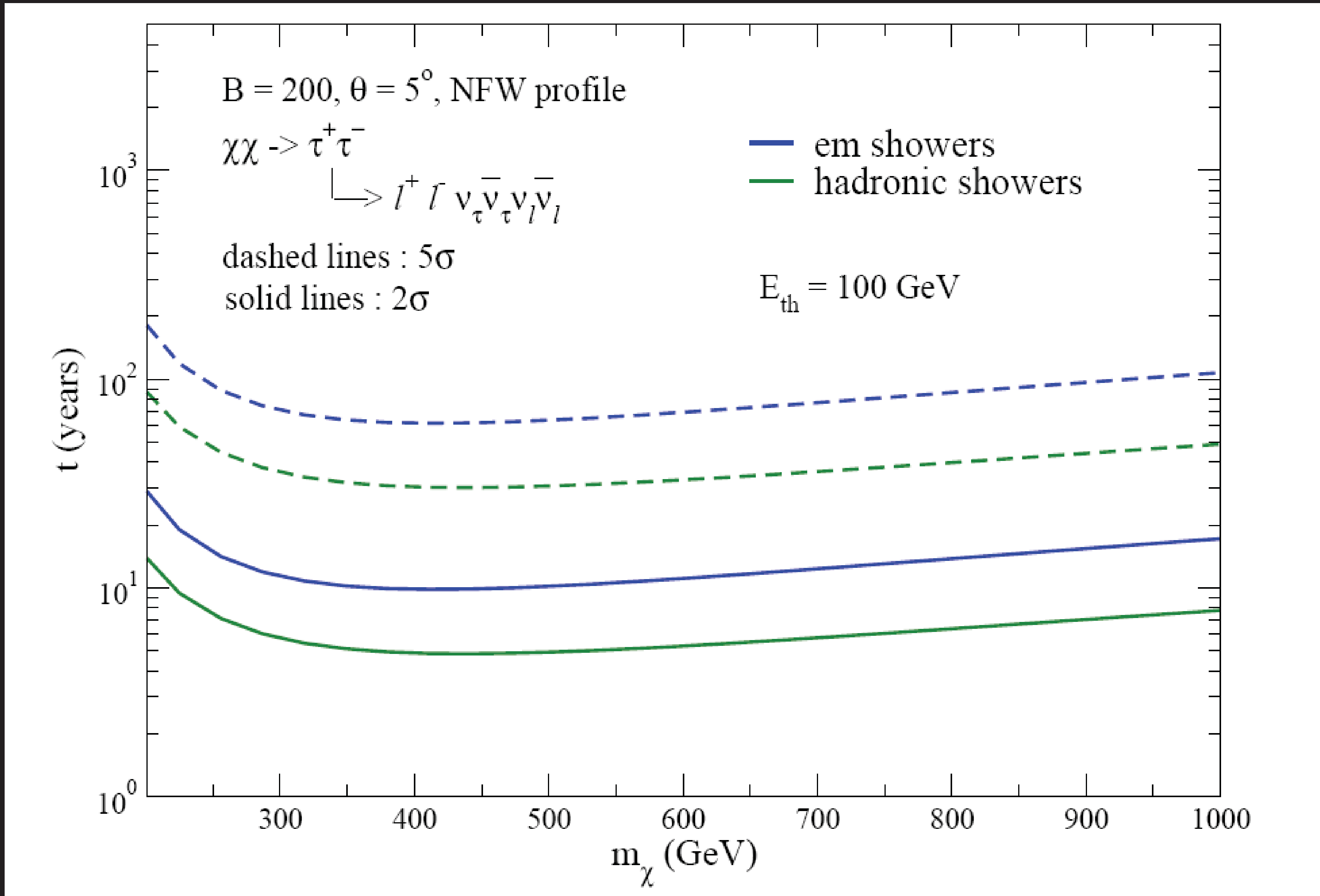
showers from χχ−>$\nu_\mu \bar{\nu}_\mu$ with NC
ATM contained showers with NC
E^{th}_{sh} = 100 GeV
Shower Rate (km^{-2} yr^{-1})
m_χ(GeV)
0
100
200
300
400
500
600
200
400
600
800
1000



showers from χχ->$\nu_\mu\bar{\nu}_\mu$ with CC
showers from χχ->$\nu_\mu\bar{\nu}_\mu$ with NC
ATM contained showers with CC
ATM contained showers with NC
E^{th}_{sh} = 100 GeV
Shower Rate (km^{-2} yr^{-1})
1500
1000
500
0
200
400
600
800
1000
m_χ(GeV)

Hadronic Shower Spectra without track-like events





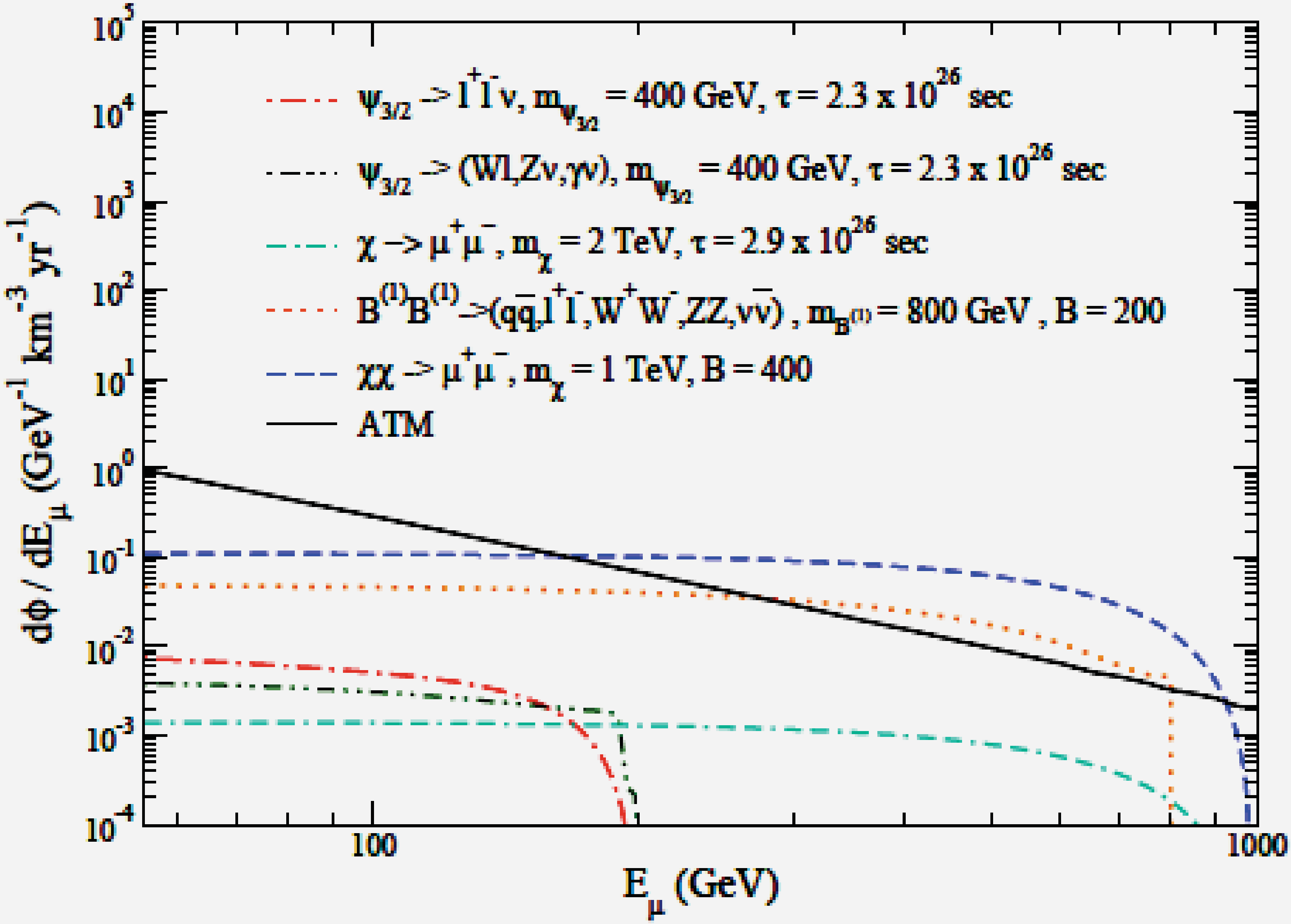
B = 200, θ = 5°, NFW profile
χχ -> τ⁺τ⁻
-> l⁺ l⁻ ν_τ ν̄_τ ν_l ν̄_l
dashed lines : 5σ
solid lines : 2σ
em showers
hadronic showers
E_th = 100 GeV
t (years)
m_χ (GeV)
10^0
10^1
10^2
10^3
300
400
500
600
700
800
900
1000

Probing the Nature of Dark Matter with Neutrinos

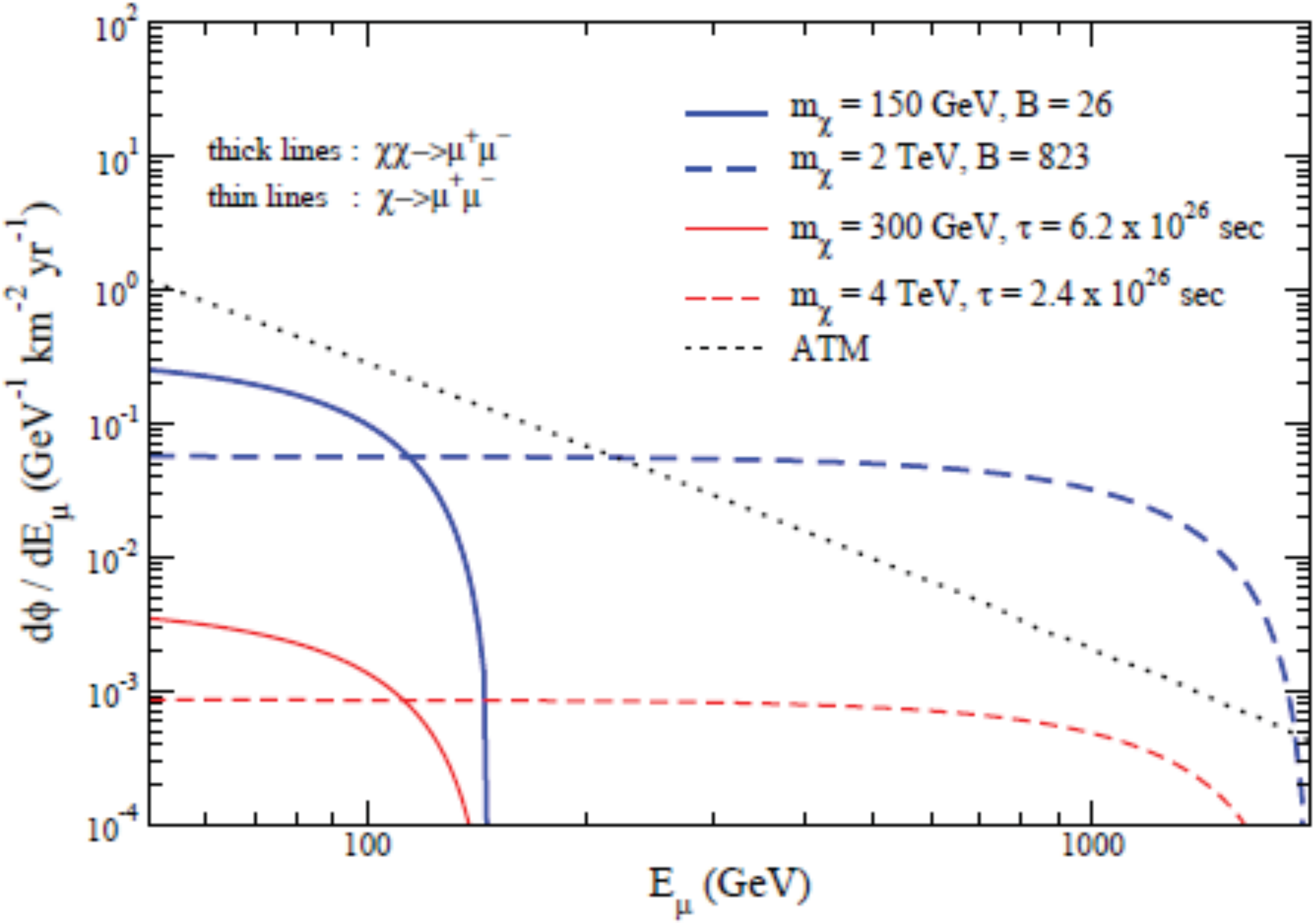
Erkoca, Reno and Sarcevic, Phys. Rev. D82, 113006 (2010)

- 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
- We include neutrino oscillations
- 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
$B^{(1)}B^{(1)} \to ...$	$N_\mu^{ct}(10^\circ)$	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°)			227.5(10°)				5347(50°)	
	N_μ^{up}		28(1°)			2794(10°)				65668(50°)	
	N_{sh}		0.3(1°)			28.8(10°)				676(50°)	

DM Detection with Neutrino Telescopes

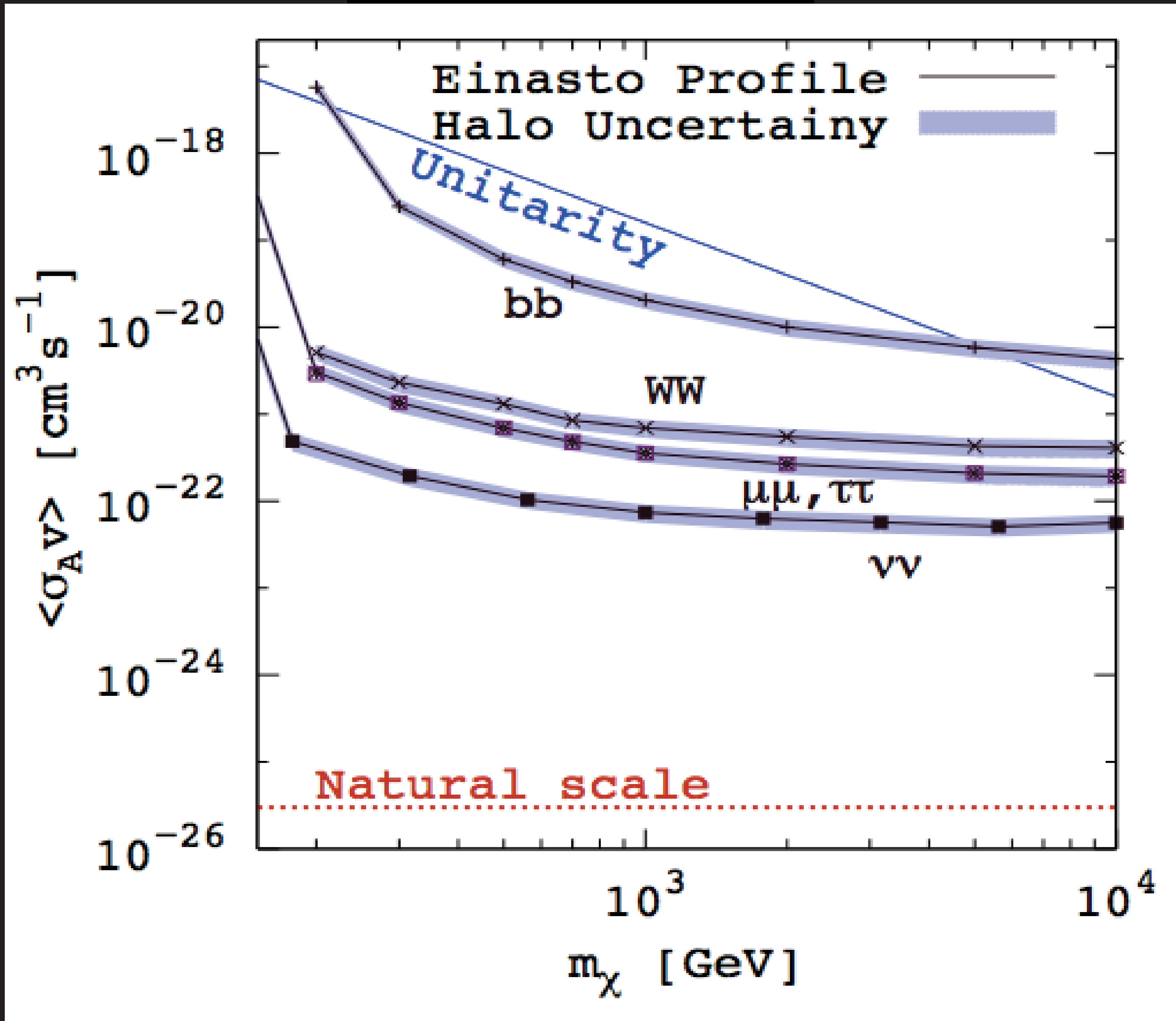
IceCUBE : 1 km^3 neutrino detector at South Pole

- 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

IceCube DM search from the Galactic Hallo (arXiv:1101.3349)



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