NPAC Seminar
September 29,2011

Probing Dark Matter with Neutrinos

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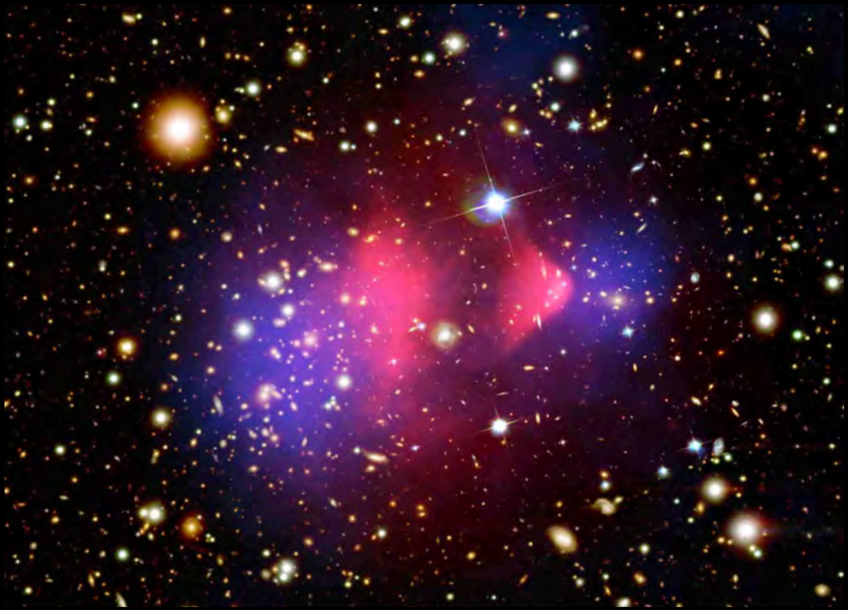
University of Arizona



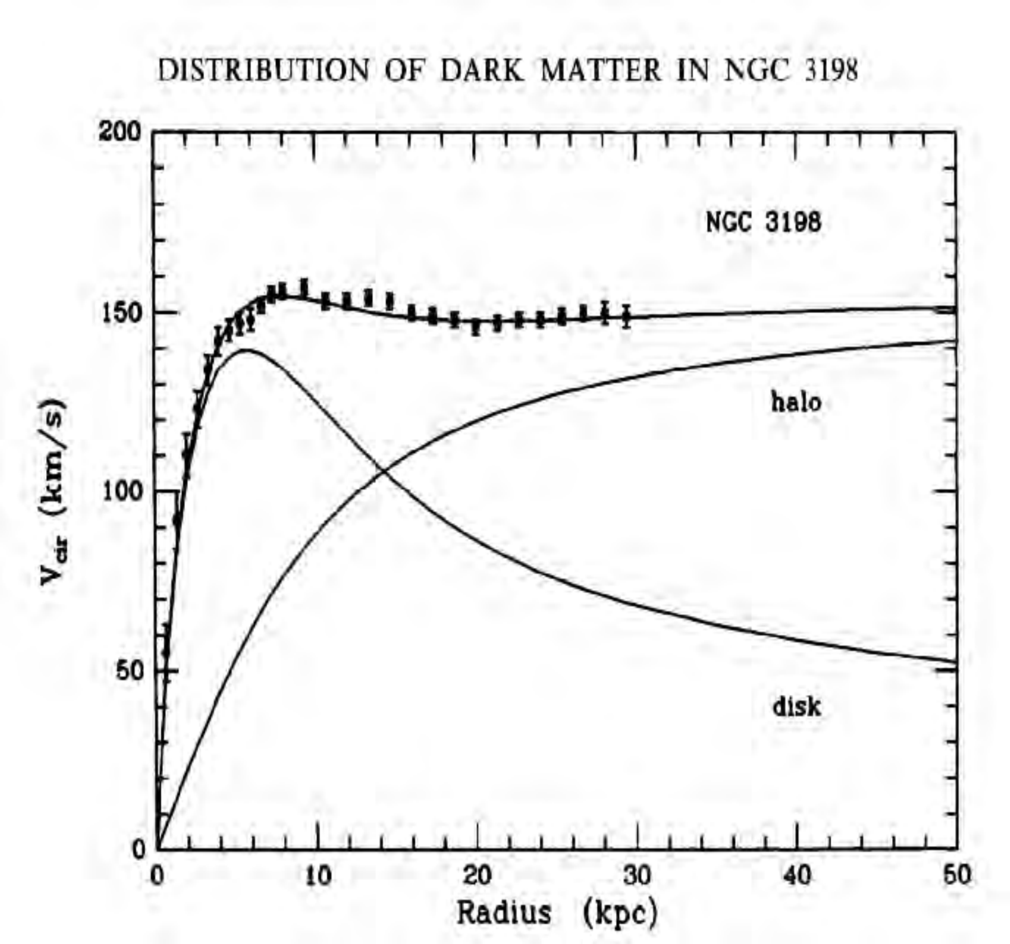
In collaboration with

Arif Erkoca, Graciela Gelmini
and Mary Hall Reno

EVIDENCE FOR DARK MATTER

In 1930's Zwicky observed the Coma cluster and found that galaxies were moving too fast to be contained by the visible matter.

In 1970's Vera Rubin and collaborators discovered that stars in galaxies were rotating too fast implying existance of invisible matter

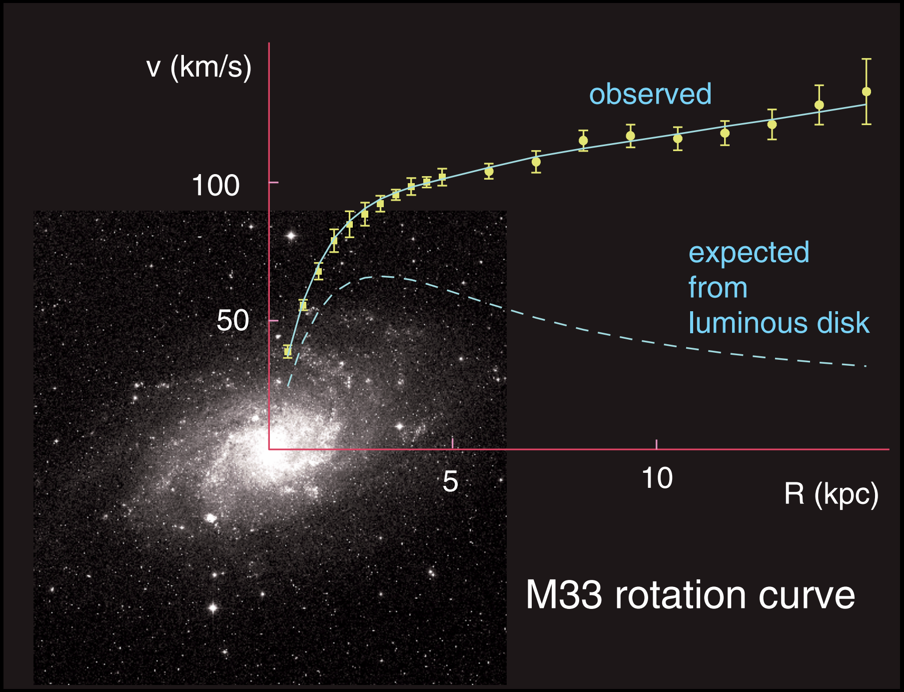


Observations indicate the existence of non-luminous matter with density profile at far distances in the form $\rho \sim \frac{1}{r^2}$

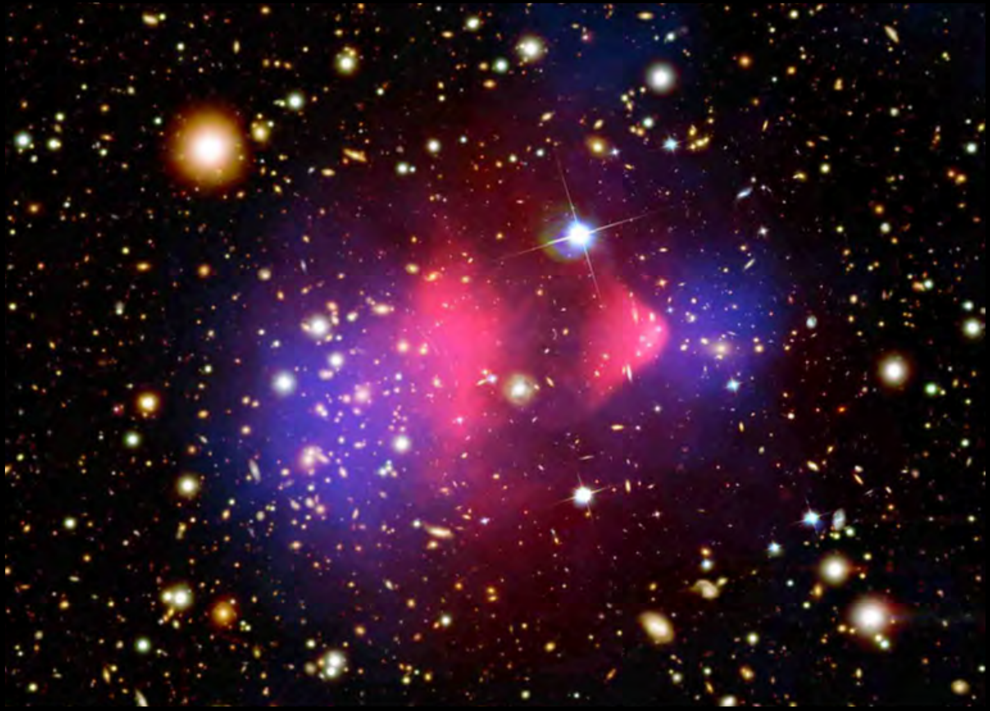
Non-baryonic Dark Matter

Many observations indicate presence of dark matter:
Galaxy rotation curves, galaxy clusters, BBN, CMB radiation, gravitational lensing, etc.

Bergstrom, Rep. Prog. Phys. 63, 793 (2000)

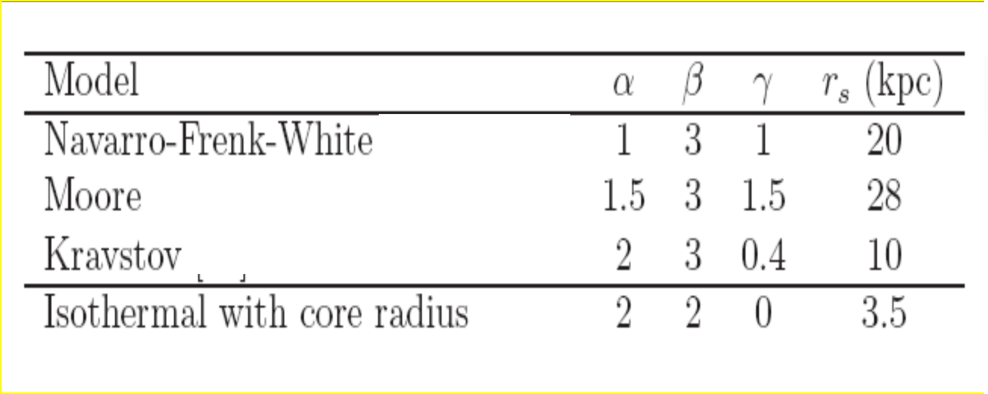


Bullet Cluster (IE0657-56)

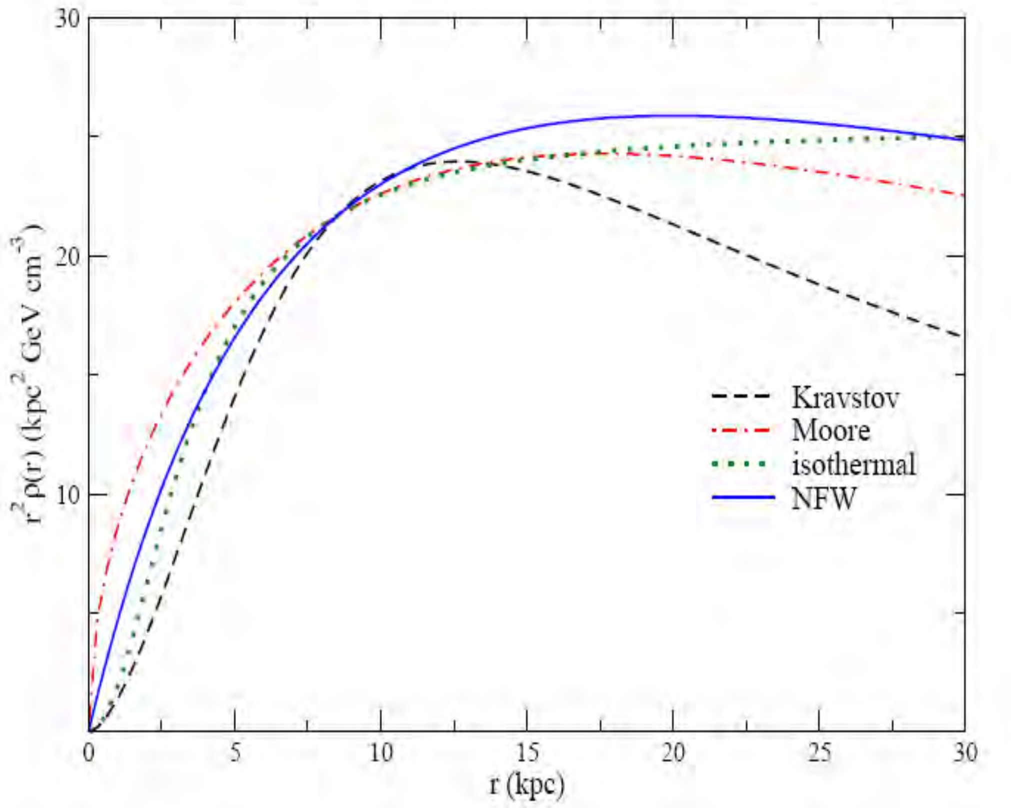


Dark Matter Density Profiles

$$\rho(r) = \frac{\rho_s}{(r/r_s)^{\gamma}[(1+r/r_s)^{\alpha}]^{(\beta-\gamma)/\alpha}}$$



Model	α	β	γ	r_s (kpc)
Navarro-Frenk-White	1	3	1	20
Moore	1.5	3	1.5	28
Kravstov	2	3	0.4	10
Isothermal with core radius	2	2	0	3.5



In the Milkyway, the rotation curves of the stars suggest that the dark matter density in the vicinity of our Solar System is:

$$\rho(r = 8.5kpc) = 0.3\,GeV\,/\,cm^3$$

Dark Matter –What do we know?

- Dark matter is about 23% of the total density of the Universe, while baryonic matter is only 4%

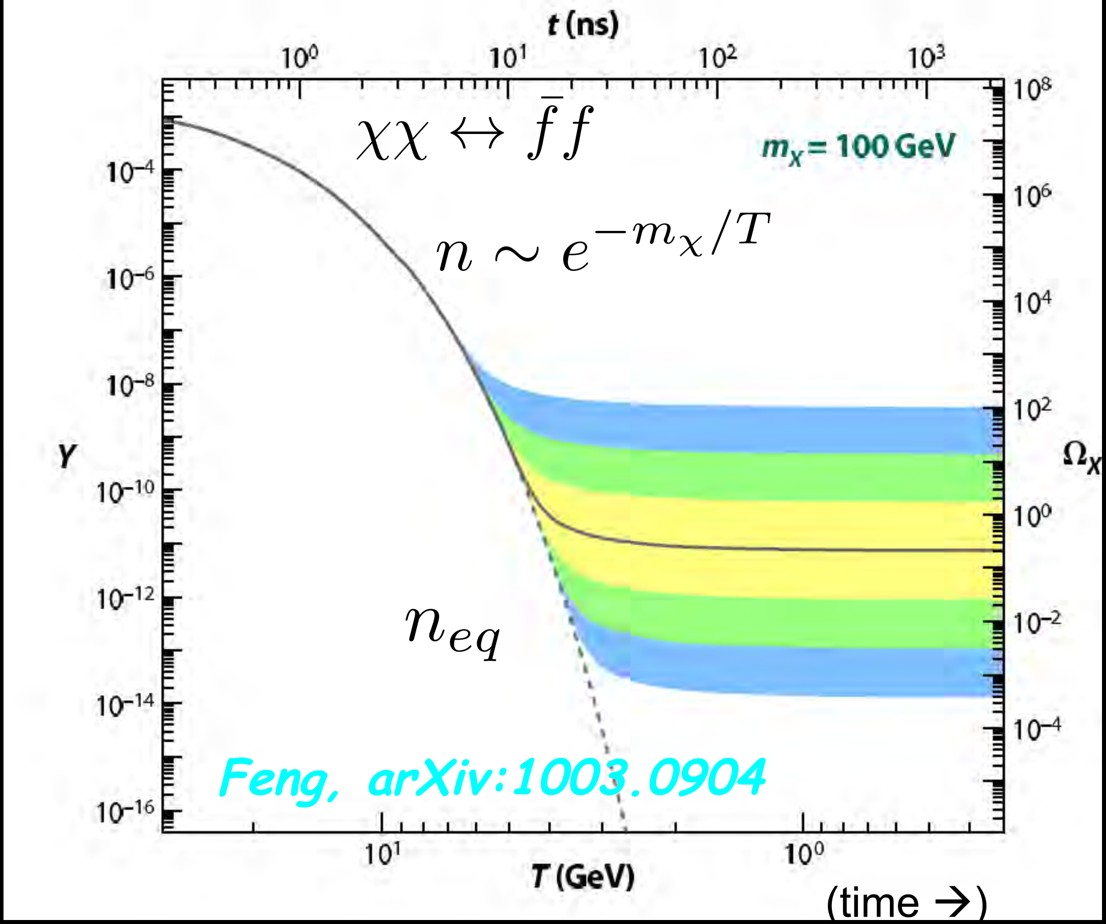
- Large-scale structure formation in the Universe imply that dark matter is “cold” (i.e. non-relativistic at freeze-out time)

Dark Matter as a Cold Relic

DM produced as a thermal relic of the Big Bang (Zeldovich,Steigman,Turner)

$$\frac{dn}{dt} = -3Hn - <\sigma v> (n^2 - n_{eq}^2)$$

Comoving number density Y



Feng, arXiv:1003.0904

(time →)

Initially DM is in thermal equilibrium

$$\chi\chi \leftrightarrow \bar{f}f$$

Universe cools

$$n \sim e^{-m_\chi/T}$$

Freese out time when

$$n < \sigma v >= H$$

Thermal relic density:

$$\Omega_\chi = 0.23 \left(\frac{< \sigma v >_{f.o.}}{3 \times 10^{-26} cm^3/s} \right)^{-1}$$

The current dark matter abundance in the Universe depends on the annihilation cross section at freeze-out.

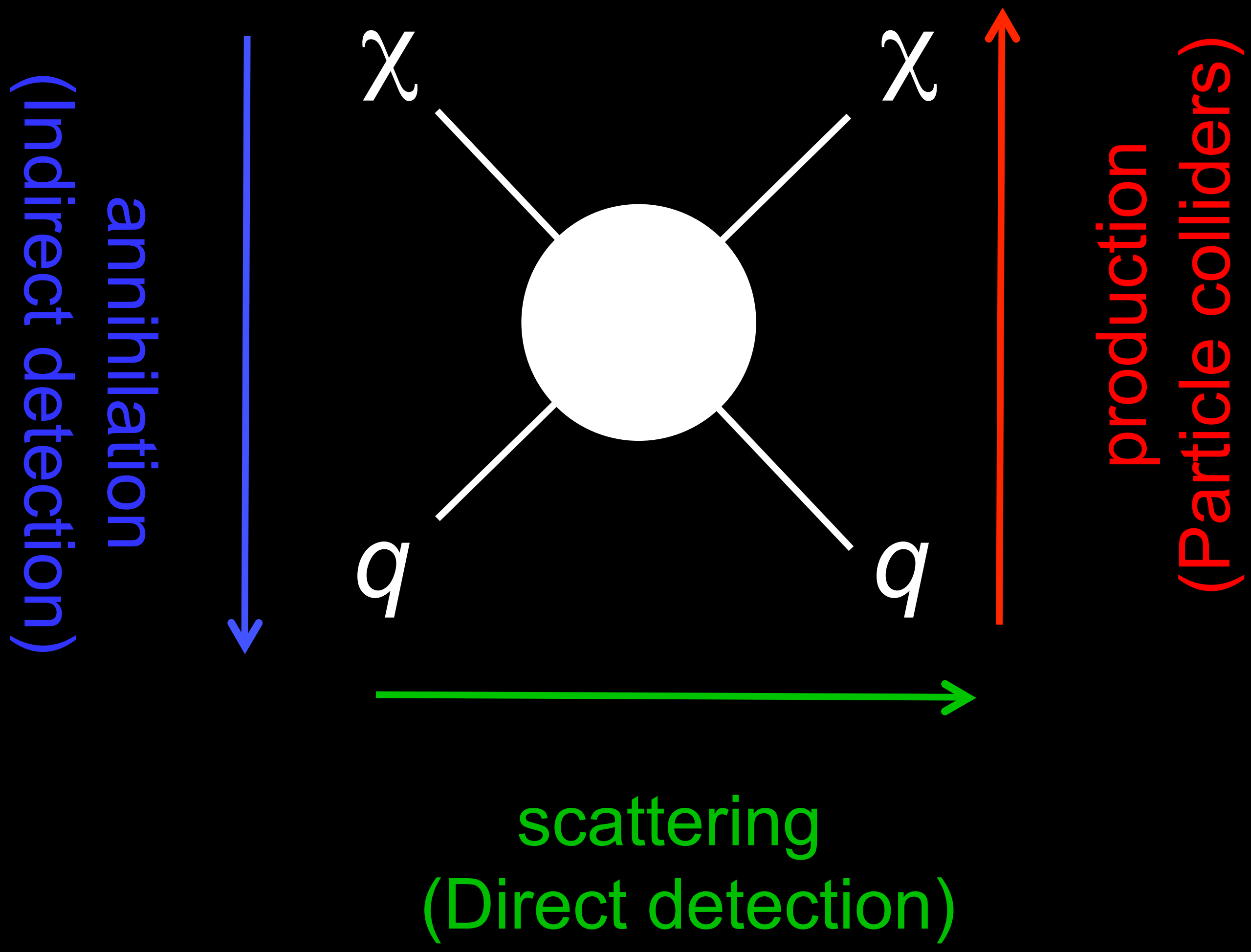
What is dark matter? The unknowns:

- Modification of the standard, Newtonian $1/r^2$ law, so that the observed effect is due to only baryonic matter is ruled out by Bullet Cluster observations

- Particle physics candidate for dark matter: weakly interacting particle which is non-relativistic at the time of freeze-out.

- No viable candidate for dark matter in the Standard Model

DARK MATTER DETECTION



annihilation
(Indirect detection)

production
(Particle colliders)

scattering
(Direct detection)

Dark Matter Detection

Direct Detection Experiments :

Look for energy deposition via nuclear recoils from dark matter scattering by using different target nuclei and detection strategies

DAMA, NAIAD, KIMS, CDMS, EDELWEISS, EURECA, ZEPLIN, XENON, WARP, LUX

Indirect Detection Experiments :

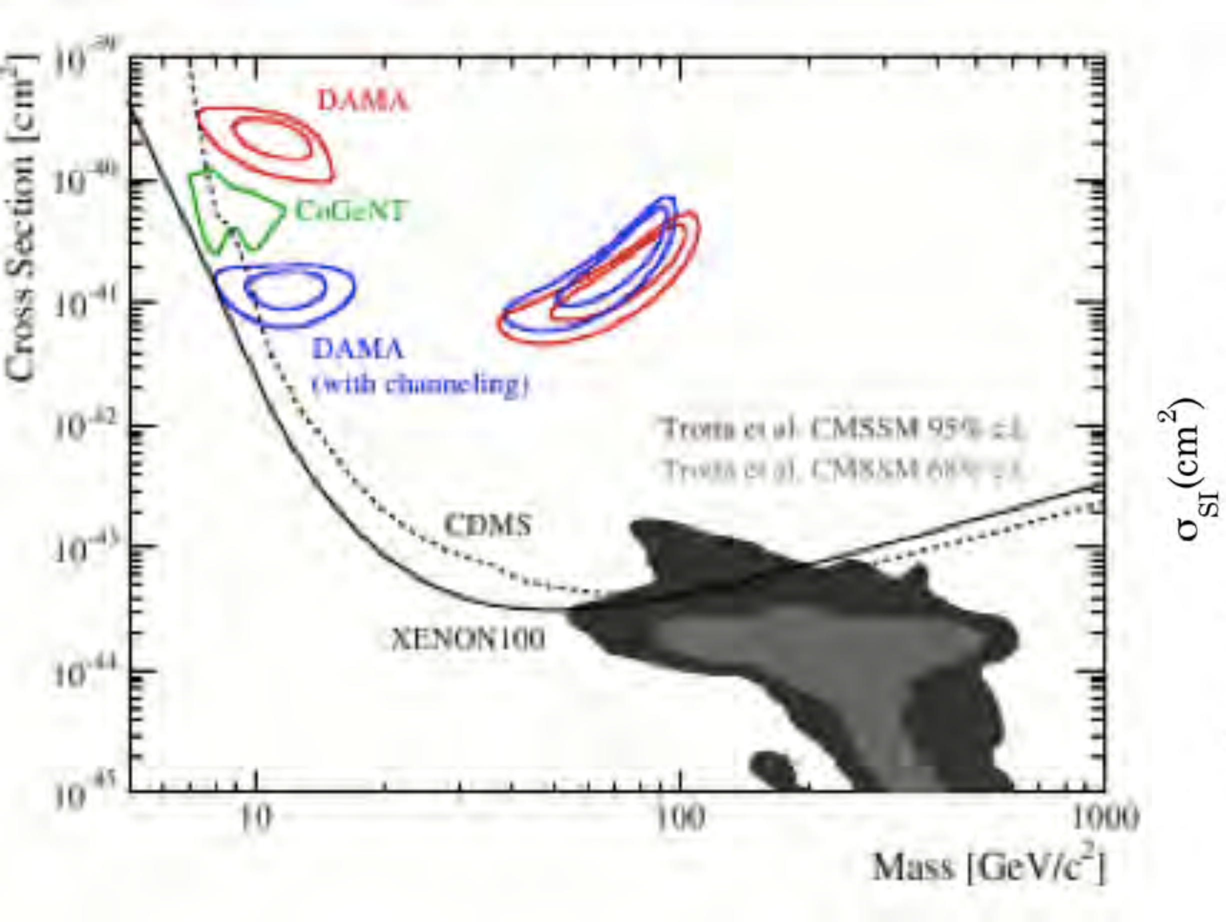
Look for annihilation products of dark matter *(Gamma-rays, positrons, electrons, neutrinos)*

HESS, MAGIC, VERITAS, CANGAROO-III, EGRET, Fermi/LAT, INTEGRAL, PAMELA, ATIC, AMS, HEAT, ICECUBE, KM3NET

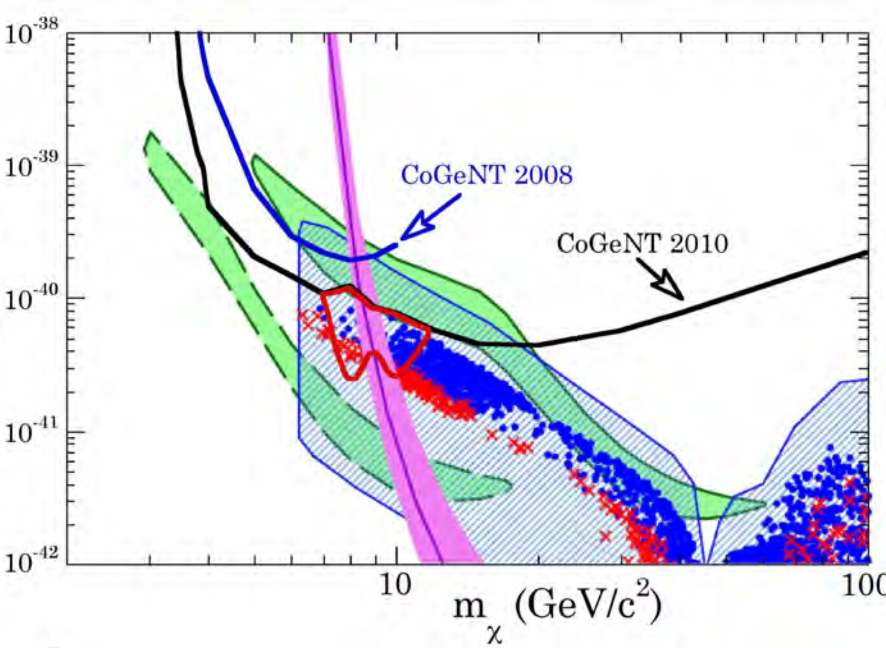
Dark Matter Searches

- Direct searches:

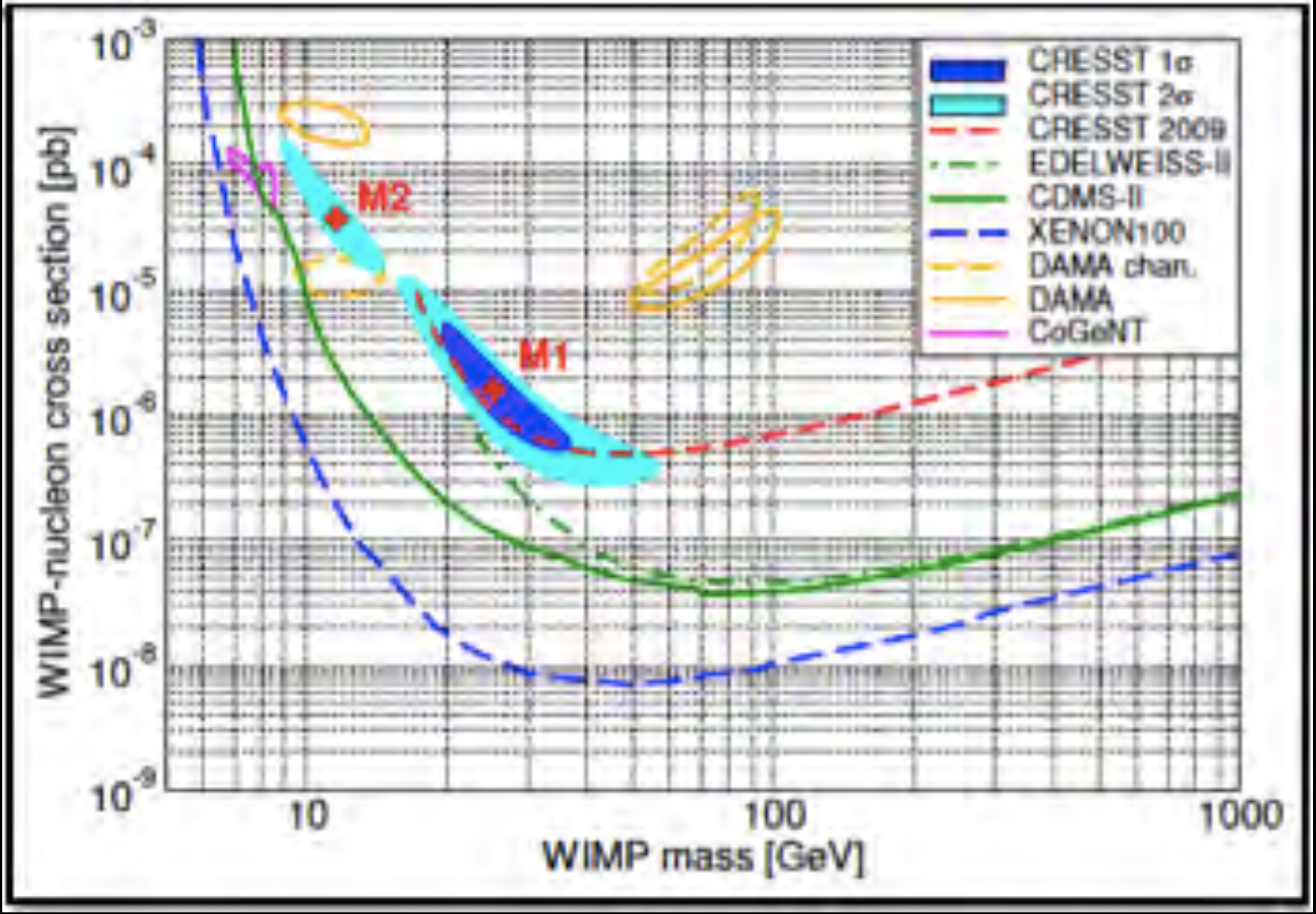
  look for DM interactions with target nuclei (XENON, CDMS, CoGeNT, DAMA, CRESST-II)



CoGeNT Collaboration: arXiv:1002.4703v2, PRL 106, 131301 (2011)



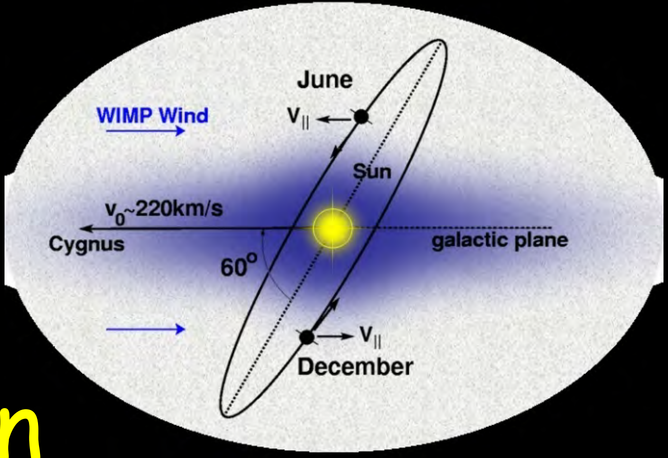
Recent CRESST-II data (4.7 σ)

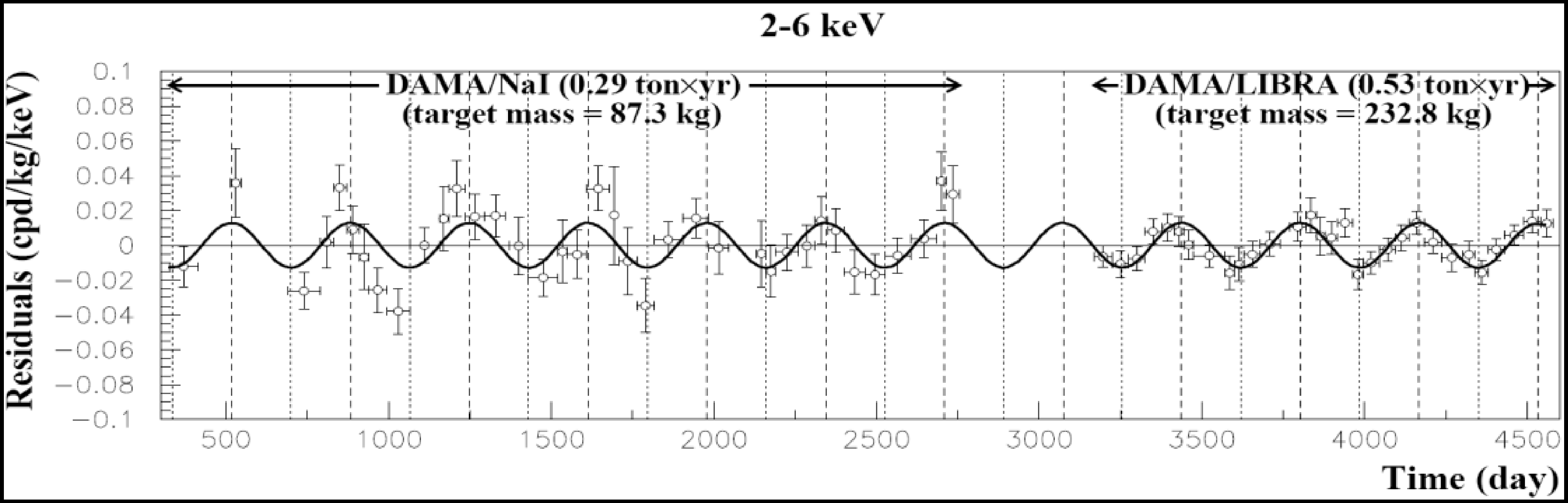


CRESST-II Collaboration:
arXiv:1109.0702

DAMA 8σ signal

Rate should change as Earth's velocity adds constructively/destructively to the Sun's -> annual modulation





DM-Ice Dark Matter Experiment at the South Pole will cross-check DAMA annual modulation observation

- Indirect DM searches:

  Detection of the products of DM annihilation (or decay) in the Galactic Center, Sun, Earth, DM halo, etc. producing electrons, positrons, gamma-rays (PAMELA, ATIC, FERMI/LAT, HESS, Veritas …) and neutrinos (IceCube, KM3Net…)

Indirect Dark Matter Detection

AMS

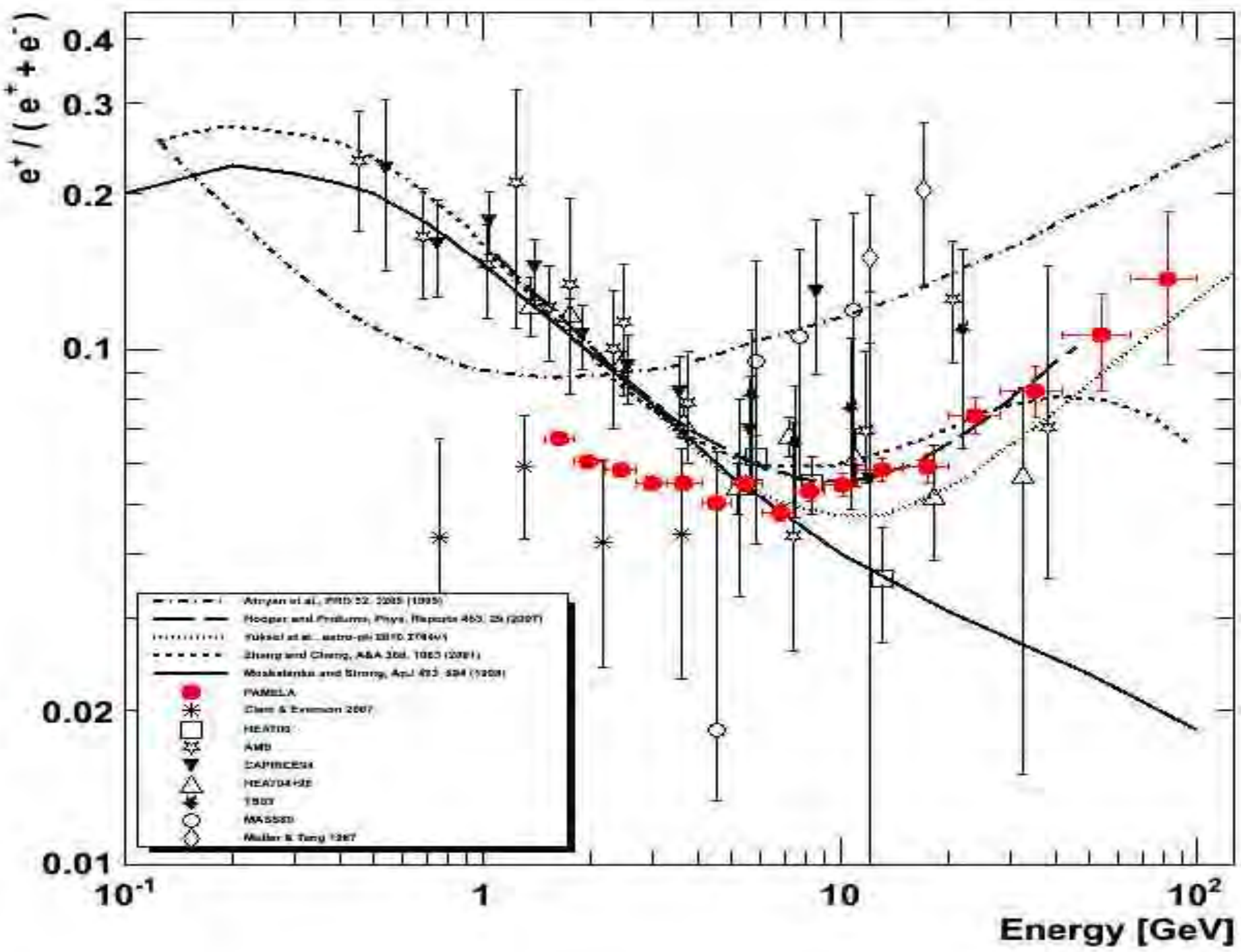
HESS

FERMI/LAT

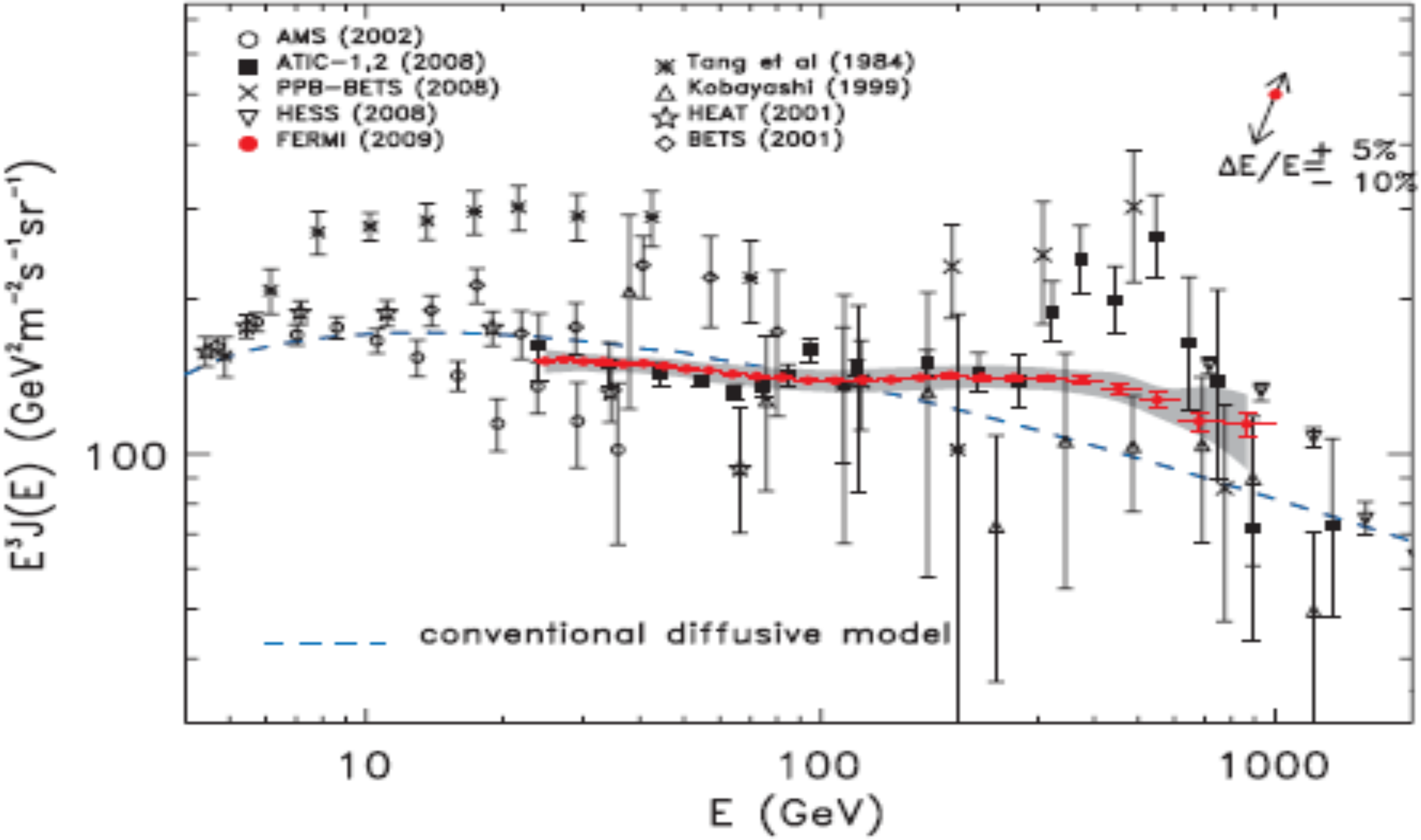
PAMELA

ATIC

PAMELA Positron Fraction



FERMI Cosmic Ray Electron Spectrum



If the observed anomalies are due to dark matter annihilation the annihilation cross sections must be **10-1000** times more than the thermal relic value of

$$<\sigma v> = 3 \times 10^{-26} cm^3/s$$

The required enhancement in the signal is quantified by the factor called the **“Boost Factor”** :

$$B = B_v \times B_\rho$$

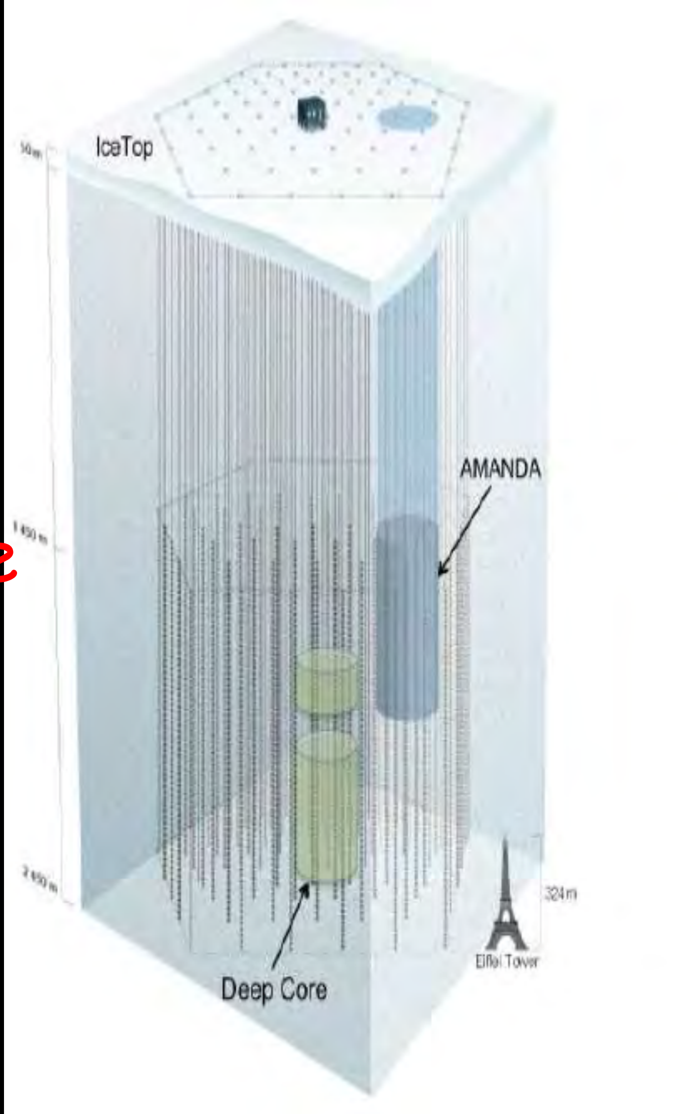
Low-velocity enhancement
(particle physics)

Sub-halo structures in the
Galaxy (astrophysics)

Dark Matter Signals in Neutrino Telescopes

Neutrinos are highly stable, neutral particles.
Detection of neutrinos depend on their interactions, i.e cross section.

IceCube



Annihilation of dark matter particles could produce neutrinos, directly or via decay of Standard Model particles

Neutrinos interacting with the matter,i.e nucleons, produce muons which leave charged tracks in the neutrino detector

- 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)

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

- Model-independent results for neutrino signal from DM annihilation in the Galactic Center

Erkoca, Gelimini, Reno and Sarcevic, PRD 81, 096007 (2010)

- Signals for dark matter when DM is gravitino, Kaluza-Klein particle or leptophilic DM.

Erkoca, Reno and Sarcevic, PRD 82, 113006 (2010)

Neutrinos from DM annihilations in the core of the Sun/Earth

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 :

$$C \sim \frac{\rho_{DM}}{m_\chi v_{DM}} \left(\frac{M}{m_p} \right) \sigma_{\chi N} < v_{esc}^2 >$$

$\rho_{DM} = 0.3 \ \text{GeV} \ \text{cm}^{-3}$ $v_{DM} \sim 270 \ \text{km} \ \text{s}^{-1}$

$v_{esc} = 1156 \ \text{km/s}$ for the Sun

$v_{esc} = 13.2 \ \text{km/s}$ for the Earth

M is the mass of the Sun/Earth

Capture rate in the Sun is about 10^9 times larger than capture rate in the Earth

For the Sun, annihilation rate = C/2

- ★ Neutrinos from DM annihilation interact with matter $\Longrightarrow$

attenuation of the neutrino Flux in the Sun is important effect

- ★ Neutrinos also interact as they propagate through the Earth producing muons below the detector

$$\nu_\mu + N \to \mu + X$$

$$\nu_e + N \to e + X$$

$$\nu_{\mu,e,\tau} + N \to \nu_{\mu,e,\tau} + X$$

Neutrino Detection

Neutrinos interact as they propagate through the Earth producing muons below the detector (upward muons) or in the detector (contained muons) or producing showers/cascades in the detector:

$$\nu_\mu + N \to \mu + X$$

$$\nu_{\mu,e,\tau} + N \to \nu_{\mu,e,\tau} + X$$

$$\nu_e + N \to e + X$$

Muon Flux

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

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

where the neutrino scattering cross section is:

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

- 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

$$P_{surv}(E^i_\mu, E^f_\mu) = \left(\frac{E^f_\mu}{E^i_\mu}\right)^\Gamma \left(\frac{\alpha + \beta E^i_\mu}{\alpha + \beta E^f_\mu}\right)^\Gamma$$

where $\Gamma = \mathrm{m}_\mu/(\mathrm{c}\rho\alpha\tau)$

R_E= 6400 km or

R_{SE}=150 Mkm (Sun-Earth distance)

Neutrinos from DM annihilations

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

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

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

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

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

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

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 :

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

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

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

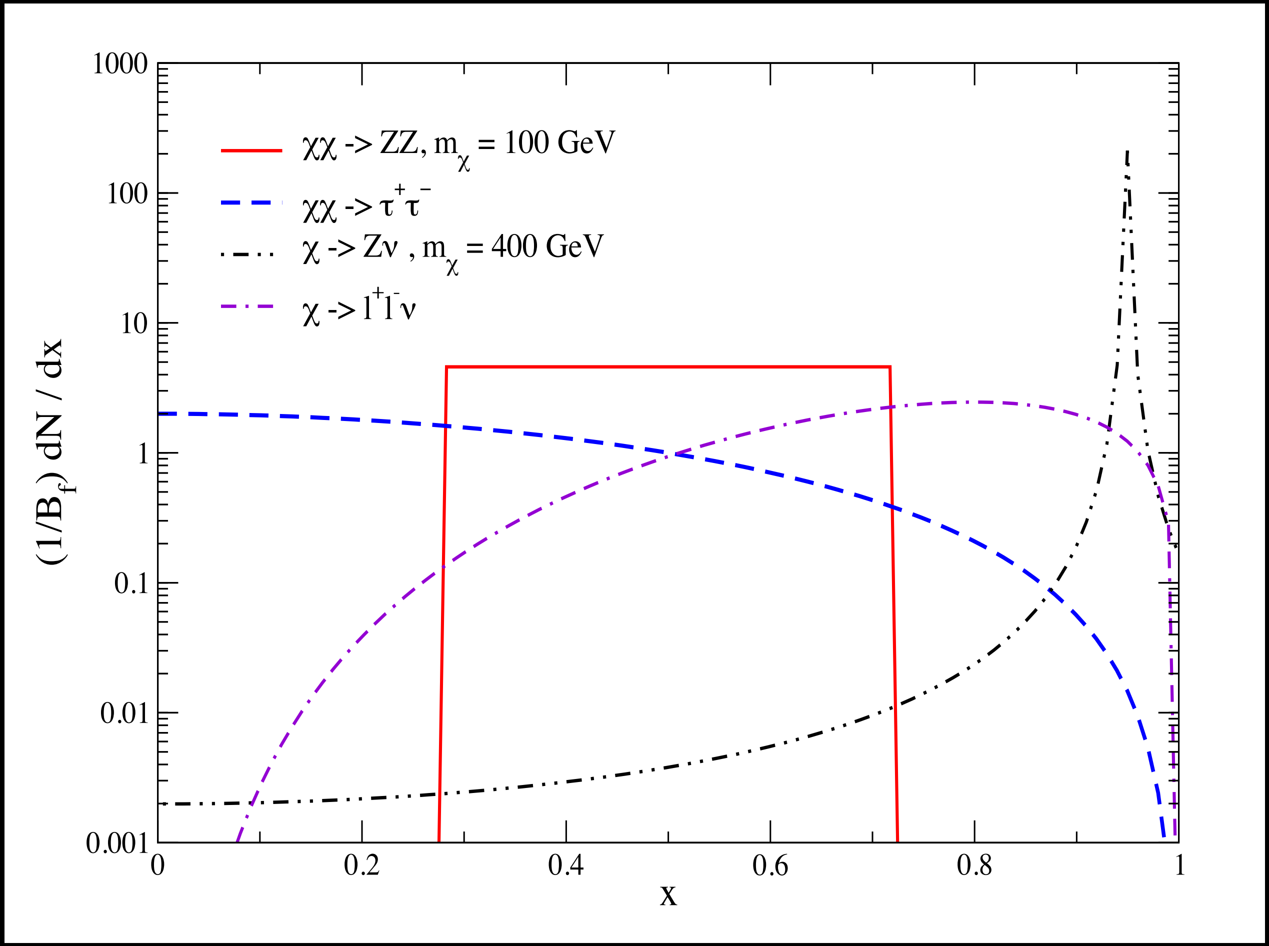
$$(n_f\,,\,B_f) = \begin{cases} (1\,,\,0.105) & W \text{ decay,} \\ (2\,,\,0.067) & Z \text{ decay.} \end{cases}$$

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

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

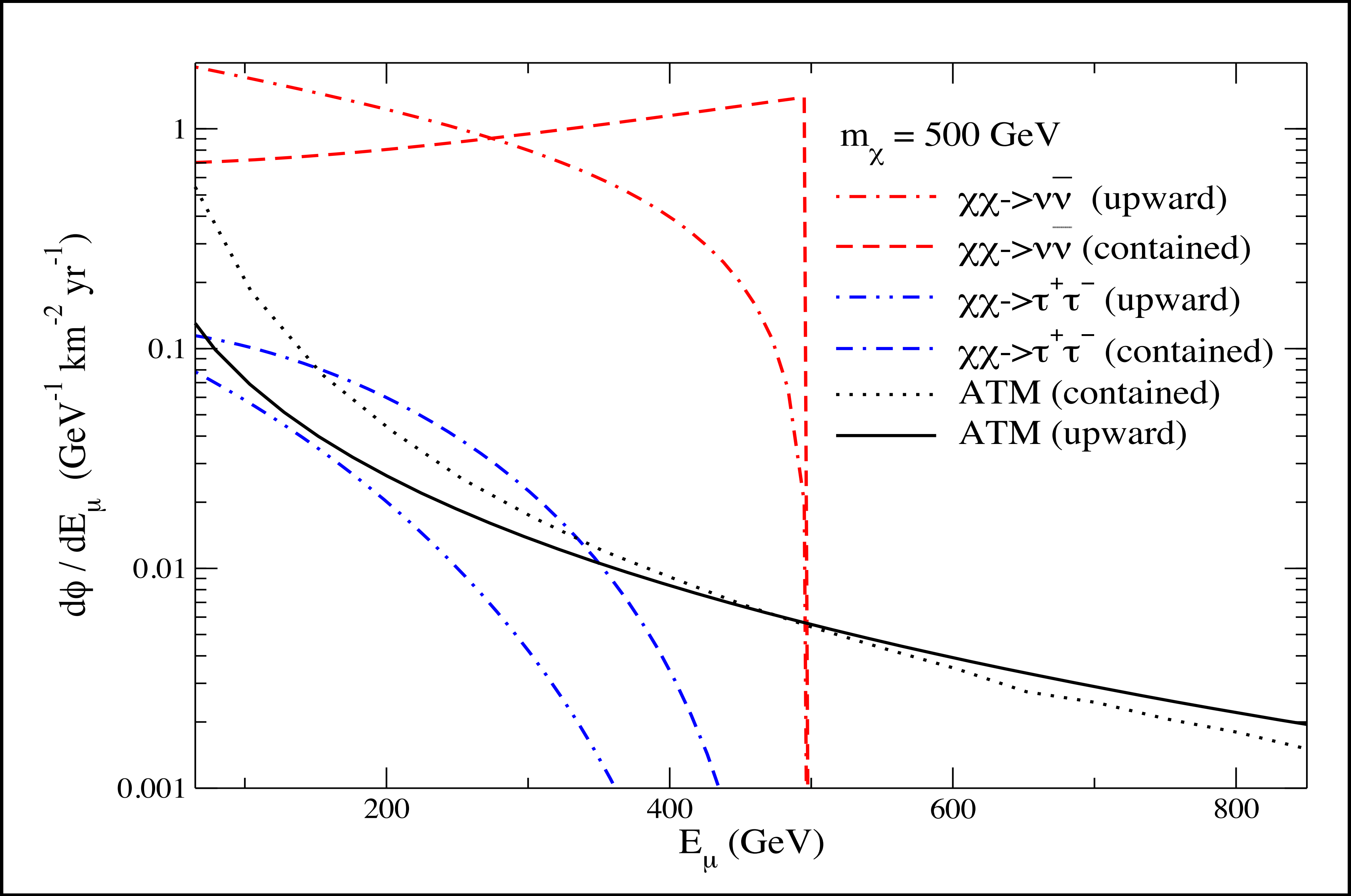
Boosting this expression yields the neutrino spectrum for top quarks moving with velocity β_t

Muon Neutrino Spectra



$$x = E_\nu / E_{\nu,max}$$

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

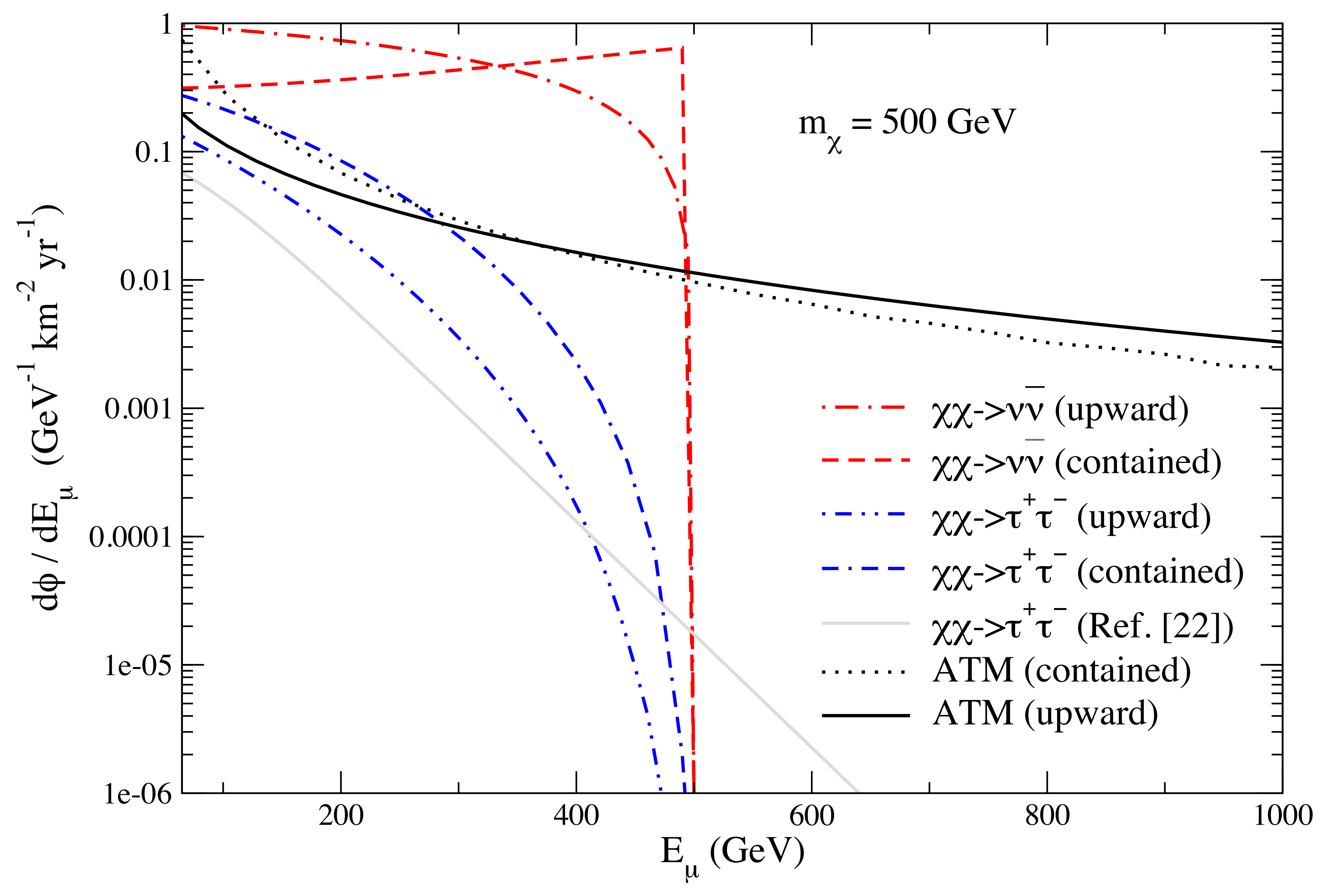


- Attenuation of the neutrino Flux in the Sun

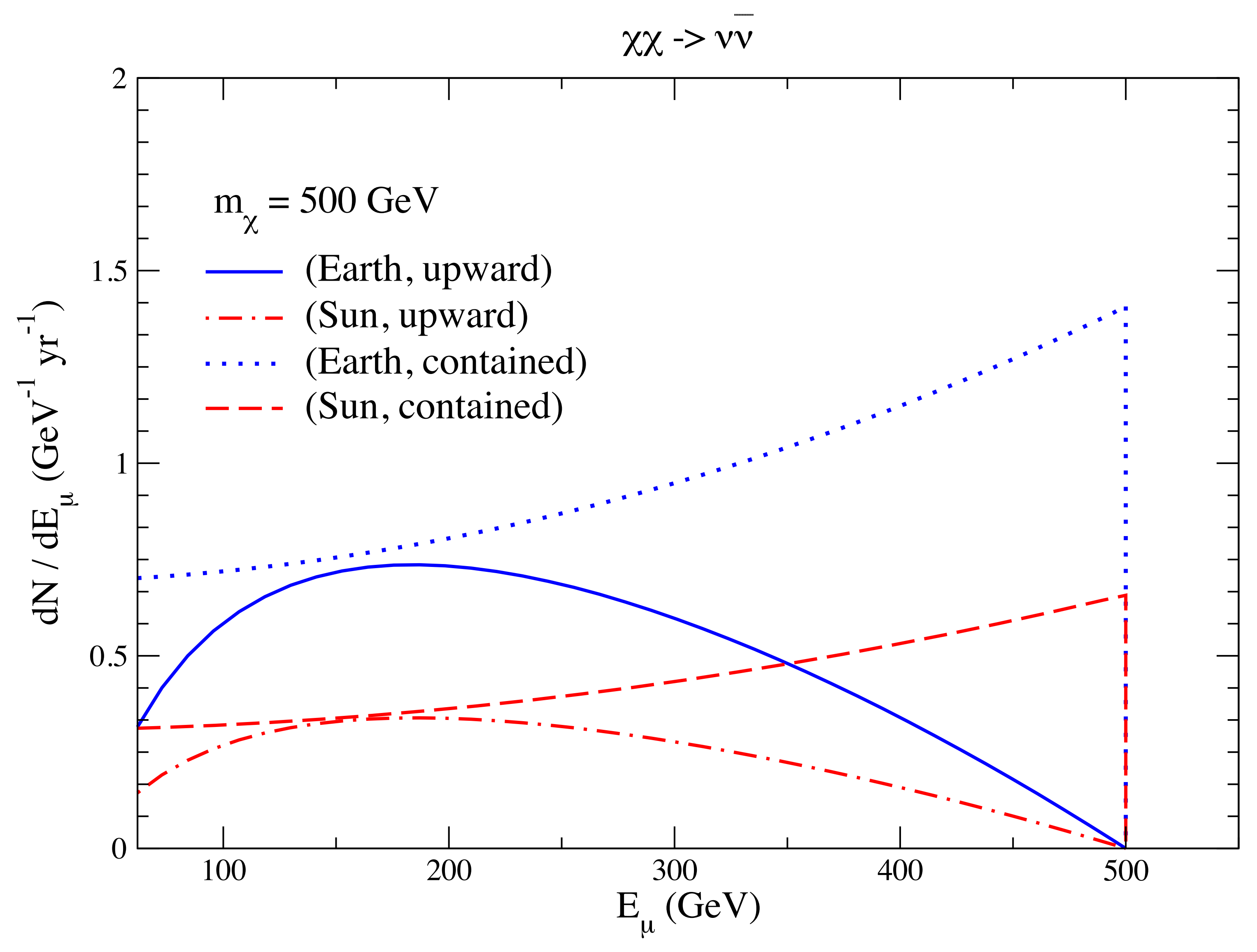
$$\begin{aligned}
\frac{d\phi_\mu}{dE_\mu} &= \frac{\Gamma_A}{4\pi R_{SE}^2}\int_0^{R_\mu(m_\chi,E_\mu)} dz e^{\beta\rho z}\int_{E_\mu^i}^{m_\chi} dE_\nu \left(\frac{dN_\nu}{dE_\nu}\right) \\
&\times \left(\frac{E_\mu}{E_\mu^i}\frac{\alpha+\beta E_\mu^i}{\alpha+\beta E_\mu}\right)^{\Gamma} \times \left(\frac{d\sigma_\nu^p}{dE_\mu^i}\rho_p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

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

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



Comparison of the signals from the core of the Sun and from the Earth



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

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

R_o is distance of the solar system from the GC

ρ_o is local dark matter density near the solar system

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

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

Dark Matter Density Profiles

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Model	α	β	γ	r_s (kpc)
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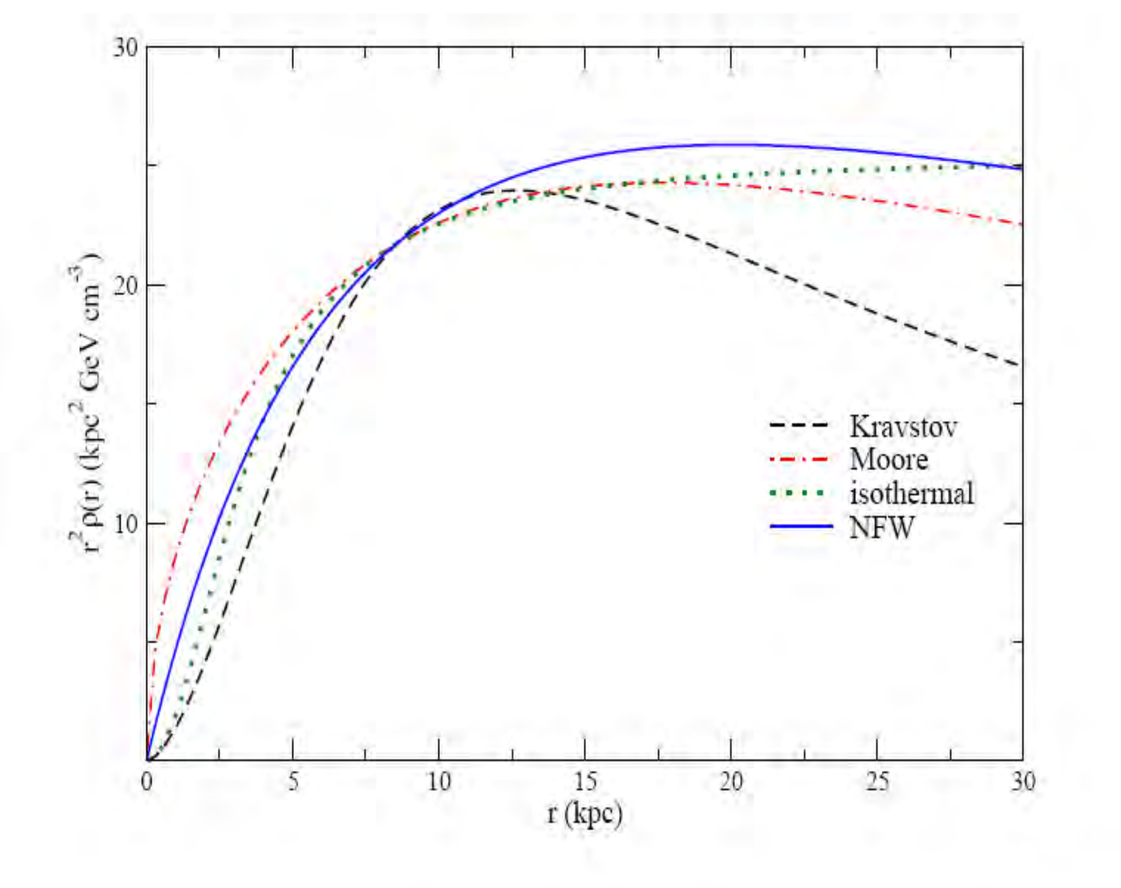


In the Milkyway, the rotation curves of the stars suggest that the dark matter density in the vicinity of our Solar System is:

$$\rho(r = 8.5 kpc) = 0.3\, GeV / cm^3$$

Neutrino Flux (dN_ν/dE_ν) at the Production

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

$$
\begin{aligned}
\chi\chi &\rightarrow \nu_i\overline{\nu_i} \\
&\rightarrow \tau^-\tau^+ \rightarrow (\nu_\tau l^- \bar{\nu}_l)\,(\bar{\nu}_\tau l^+ \nu_l) \\
&\rightarrow W^+W^- \rightarrow (l^+\nu_l)\,(l^-\bar{\nu}_l) \\
&\rightarrow b\bar{b} \rightarrow (c\,l^-\bar{\nu}_l)\,(\bar{c}\,l^+\nu_l) \\
&\rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow (cl^-\bar{\nu}_l)(l^+\nu_l)(\bar{c}l^+\nu_l)(l^-\bar{\nu}_l)
\end{aligned}
$$

- 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:

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

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

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

Upward muon flux is given by

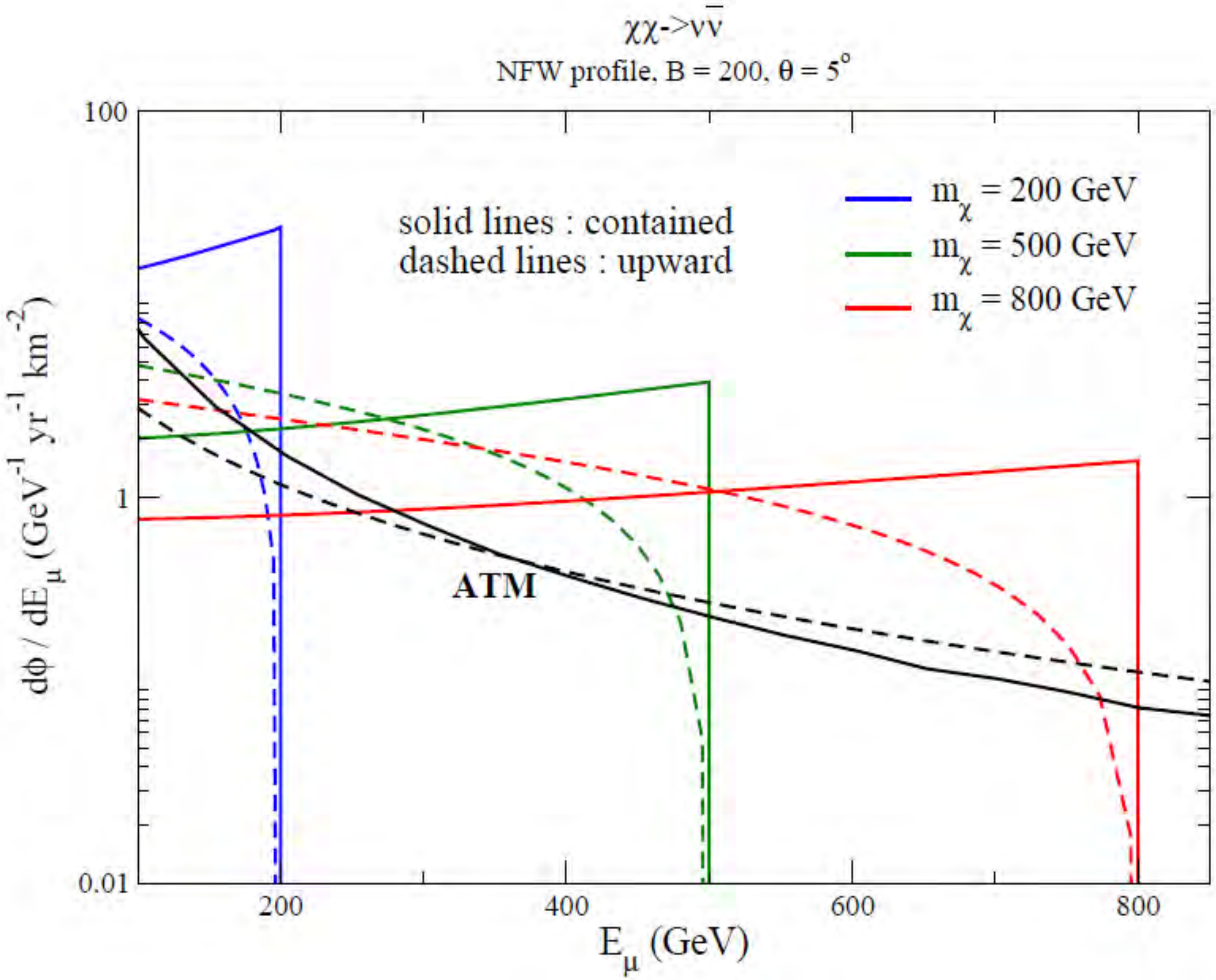
$$\frac{d\phi_\mu}{dE_\mu} = \int_0^{R_\mu(E_\mu^i, E_\mu)} e^{\beta\rho z} dz \int_{E_\mu^i}^{E_{max}} dE_\nu \left(\frac{dN}{dE_\nu}\right) N_A \rho$$

$$\times P_{surv}(E_\mu^i, E_\mu) \frac{d\sigma_\nu(E_\nu)}{dE_\mu}$$

Hadronic Shower Flux

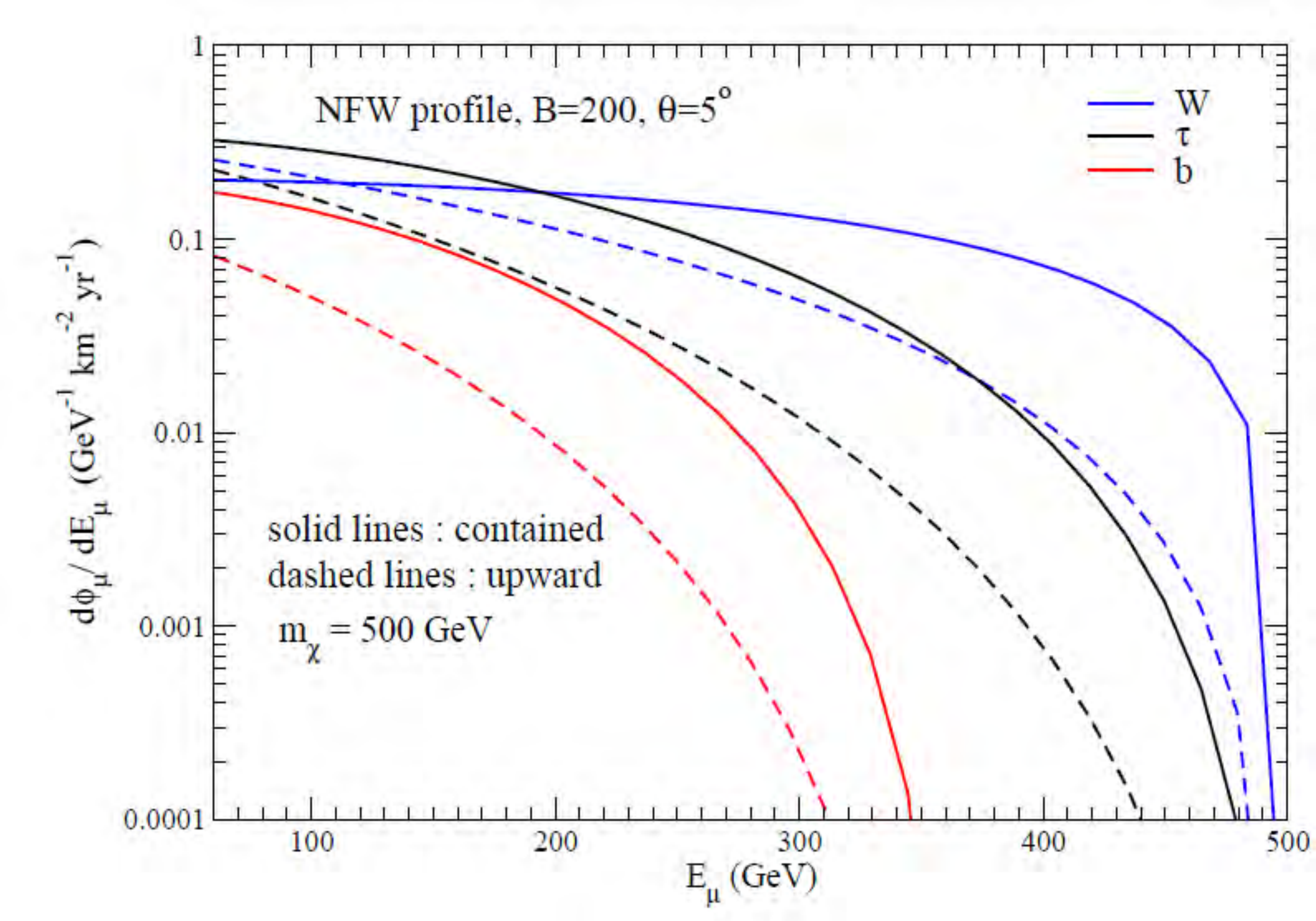
$$\frac{d\phi_{sh}}{dE_{sh}} = \int_{E_{sh}}^{E_{max}} dE_\nu \left(\frac{d\phi_\nu}{dE_\nu}\right) N_A \rho \frac{d\sigma_\nu(E_\nu, E_\nu - E_{sh})}{dE_{sh}}$$

Muon Flux

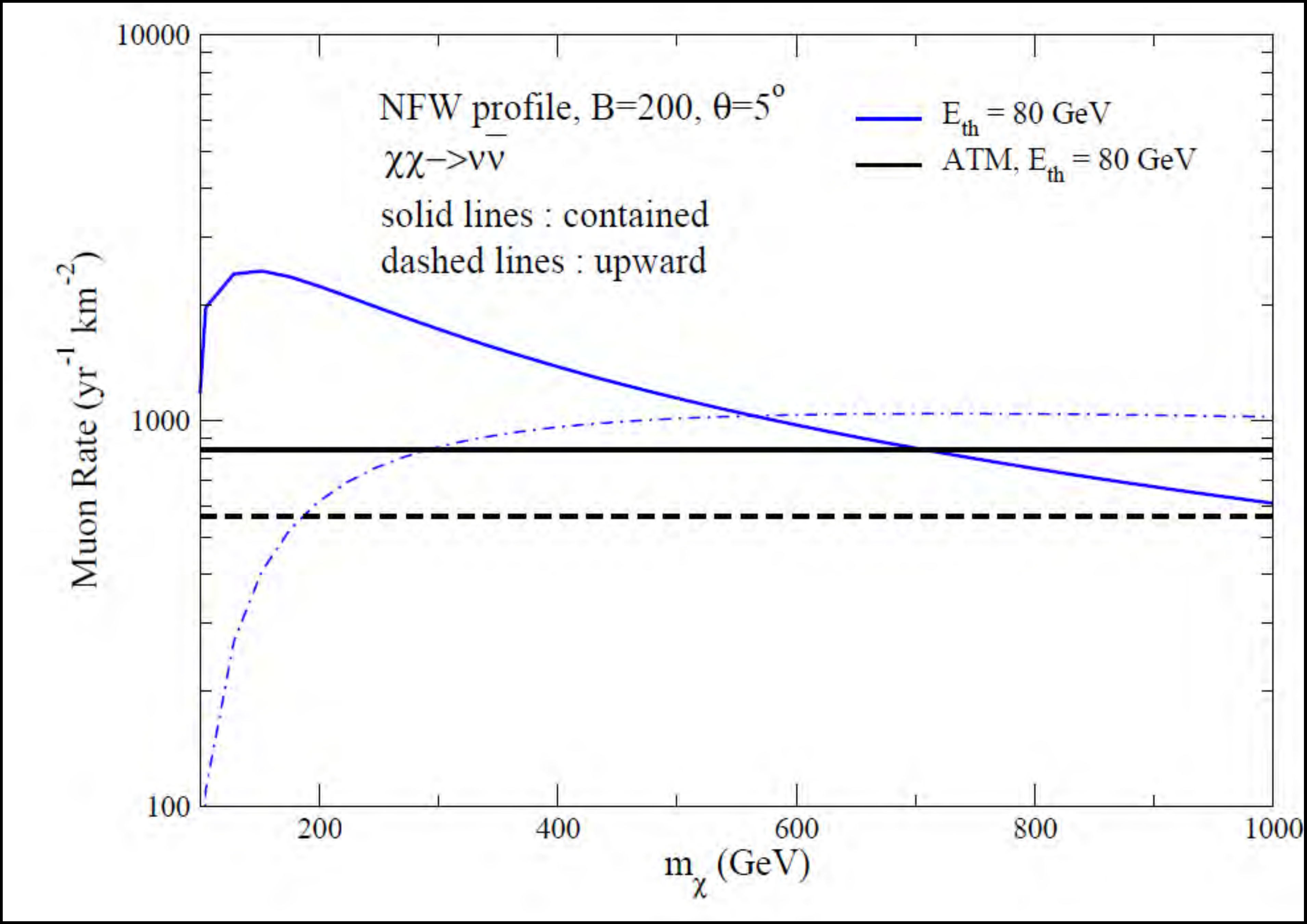


$\chi\chi \to \nu\bar{\nu}$
NFW profile, B = 200, θ = 5°
solid lines : contained
dashed lines : upward
m_χ = 200 GeV
m_χ = 500 GeV
m_χ = 800 GeV
ATM
$d\phi / dE_\mu$ (GeV^{-1} yr^{-1} km^{-2})
E_μ (GeV)
100
1
0.01
200
400
600
800

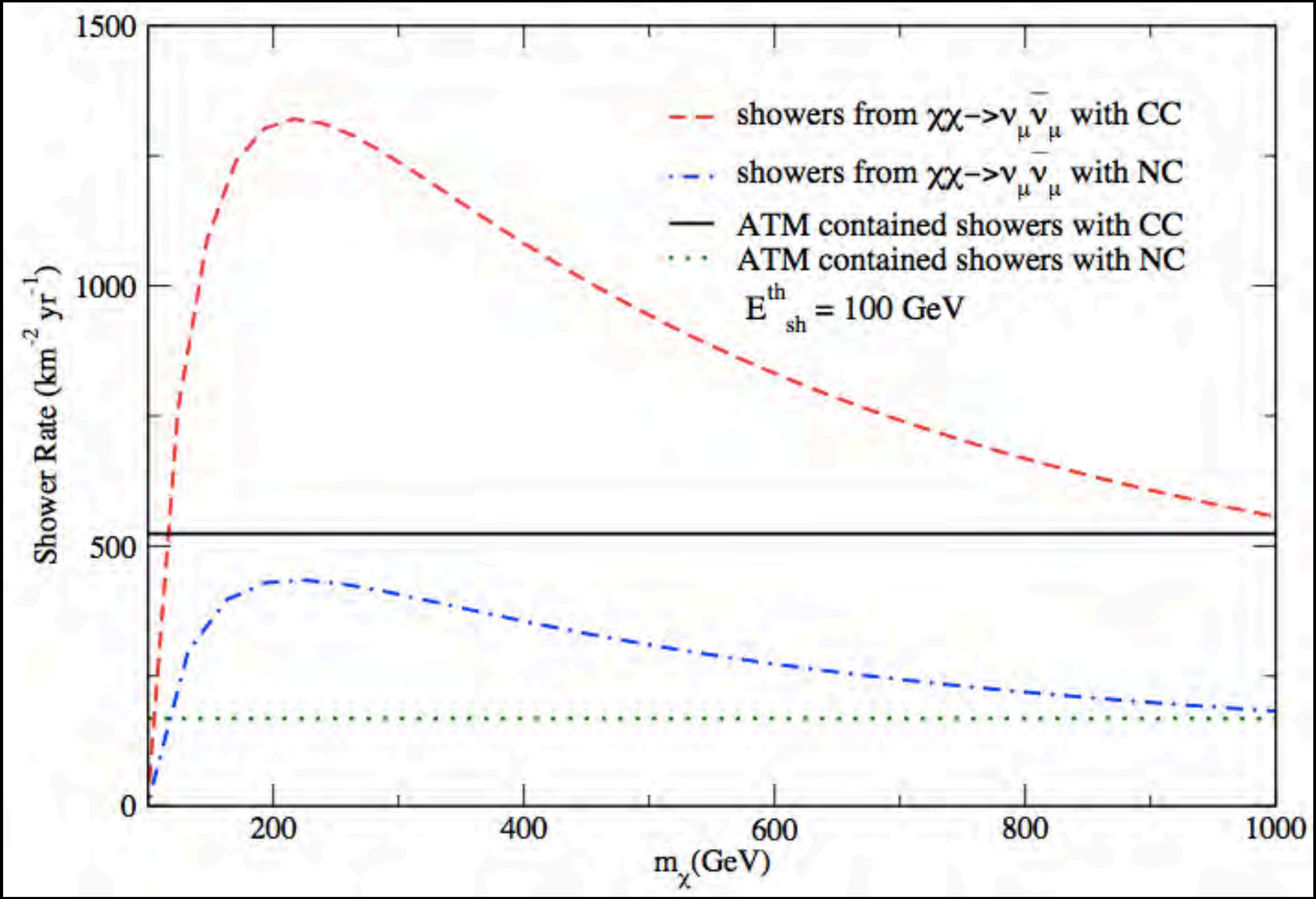
Muon Flux for Different DM Annihilation Modes



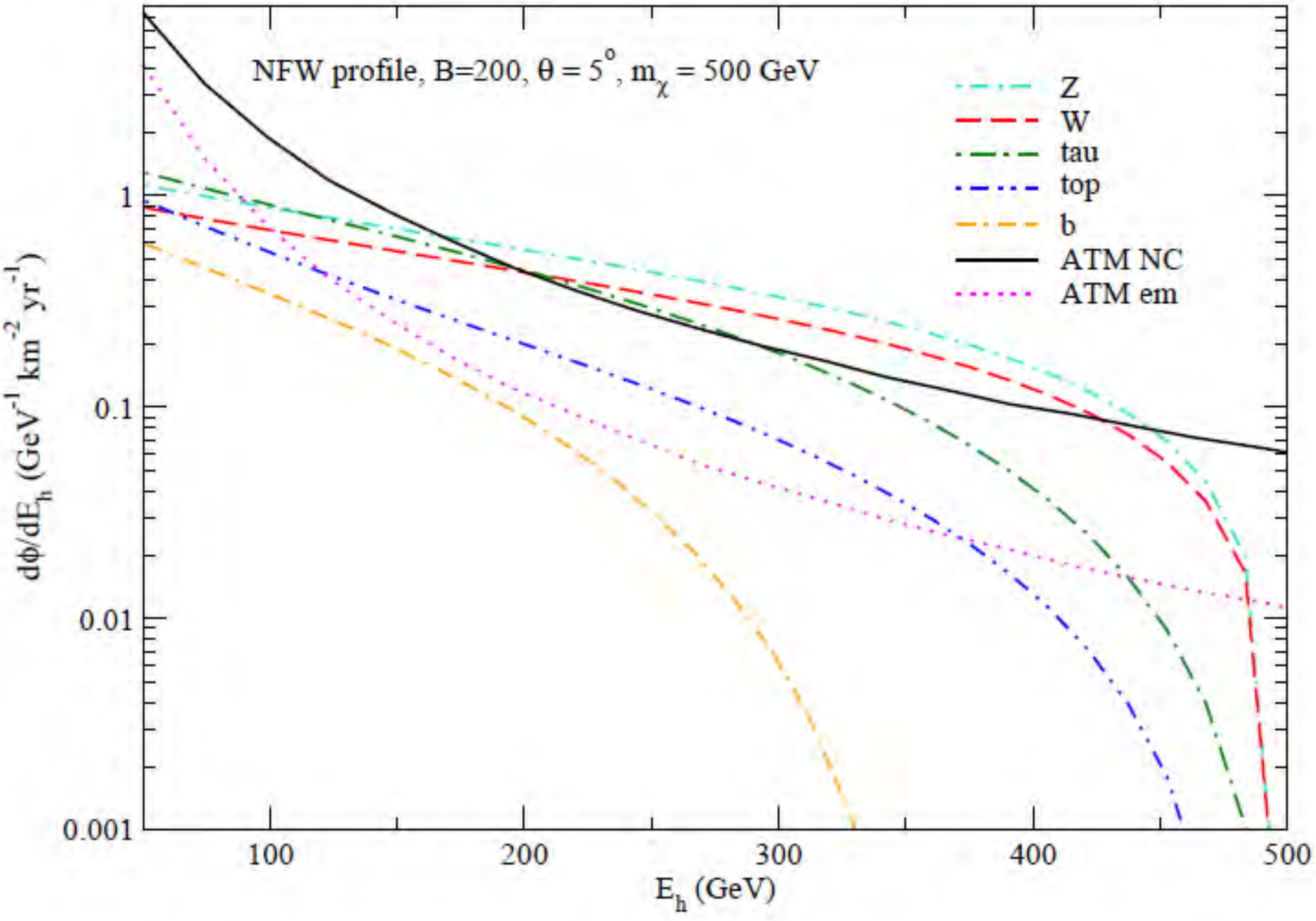
Muon Rates


NFW profile, B=200, θ=5°
$\chi\chi \rightarrow \nu\bar{\nu}$
solid lines : contained
dashed lines : upward
E_{th} = 80 GeV
ATM, E_{th} = 80 GeV
Muon Rate (yr^{-1} km^{-2})
m_χ (GeV)
10000
1000
100
200
400
600
800
1000

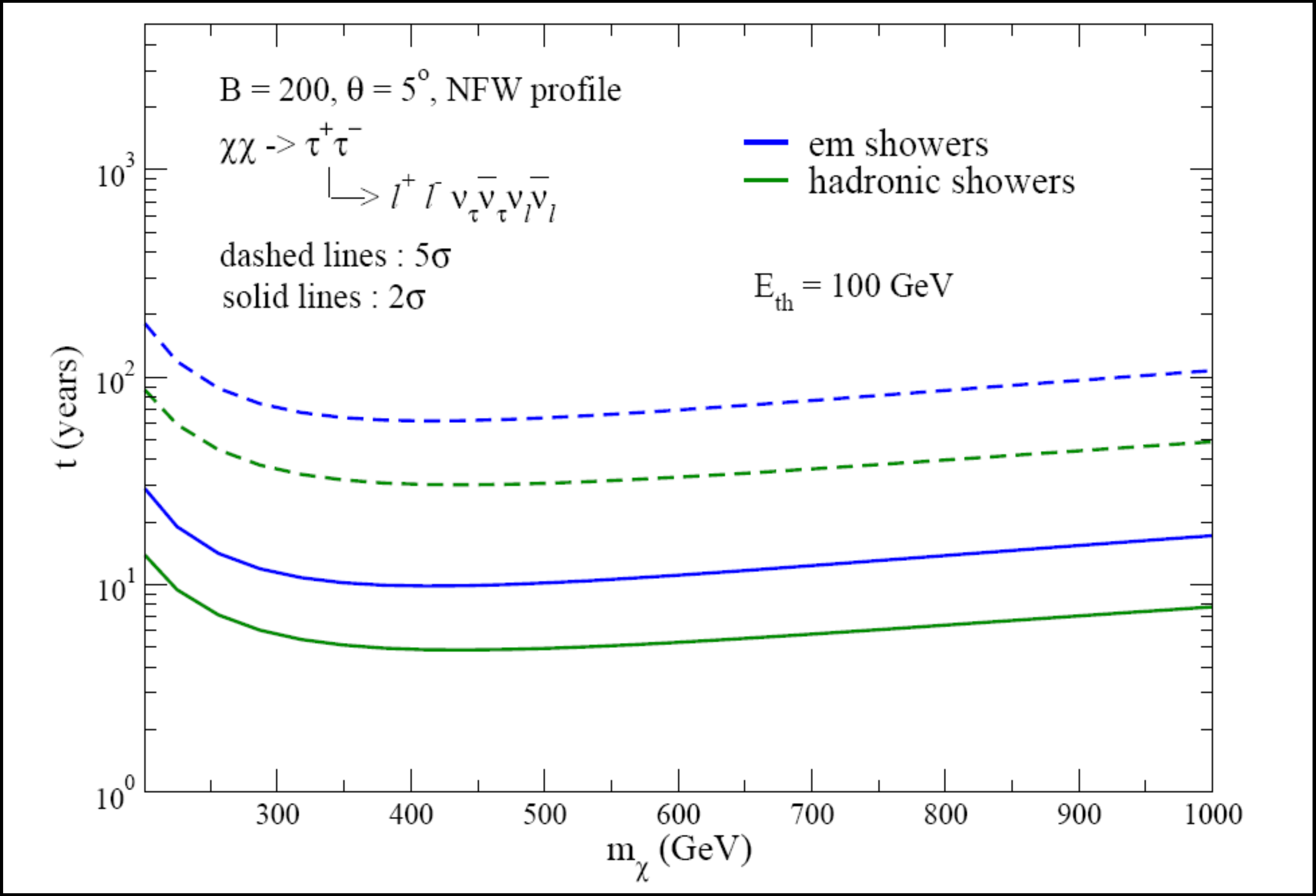
Shower Rates



Hadronic Shower Spectra without track-like events



Hadronic and EM Showers

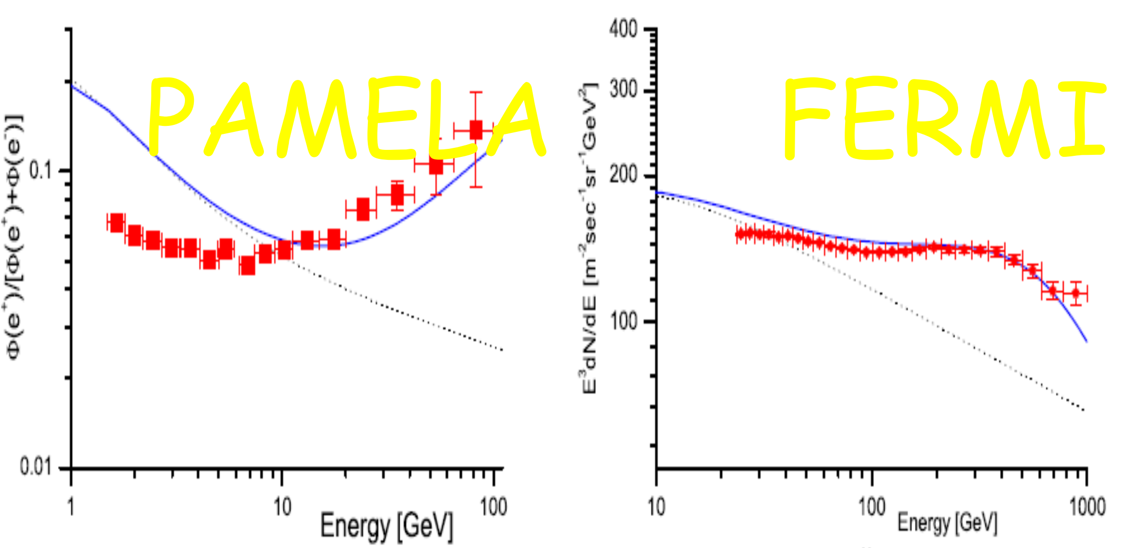


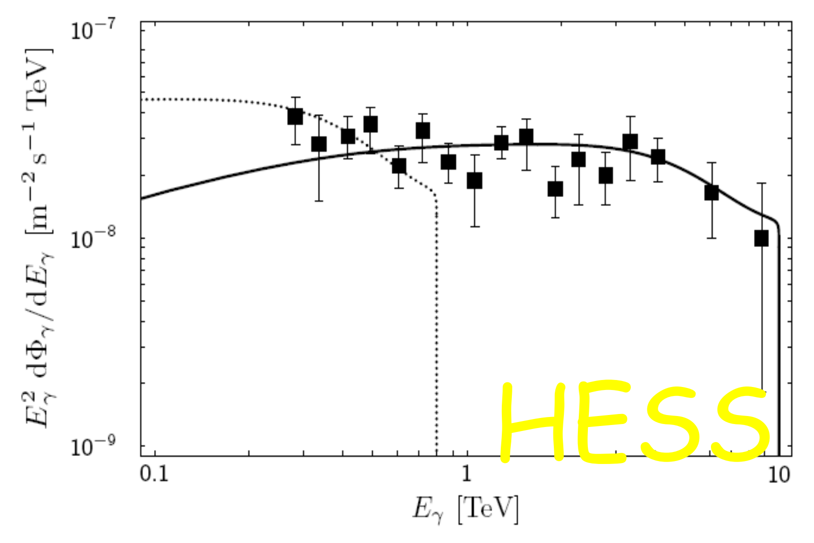
Probing the Nature of Dark Matter with Neutrinos

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

Probing Dark Matter Models with Neutrinos





Gravitino decay

$$\Psi \to l^+ l^- \nu$$

B. Bajc et al.
JHEP 1005 (2010) 048

KK Dark matter annihilation

$$B^{(1)}B^{(1)} \to l^+l^-, W^+W^-, ZZ, q\bar{q},$$

L. Bergstrom et al.
Phys.Rev.Let.94:131301,2005

$$B = 431 m_\chi - 38.9$$

$$\tau = \left(2.29 + \frac{1.182}{m_\chi}\right) \times 10^{26}\ \mathrm{sec} = B_\tau \times 10^{26}\ \mathrm{sec}$$

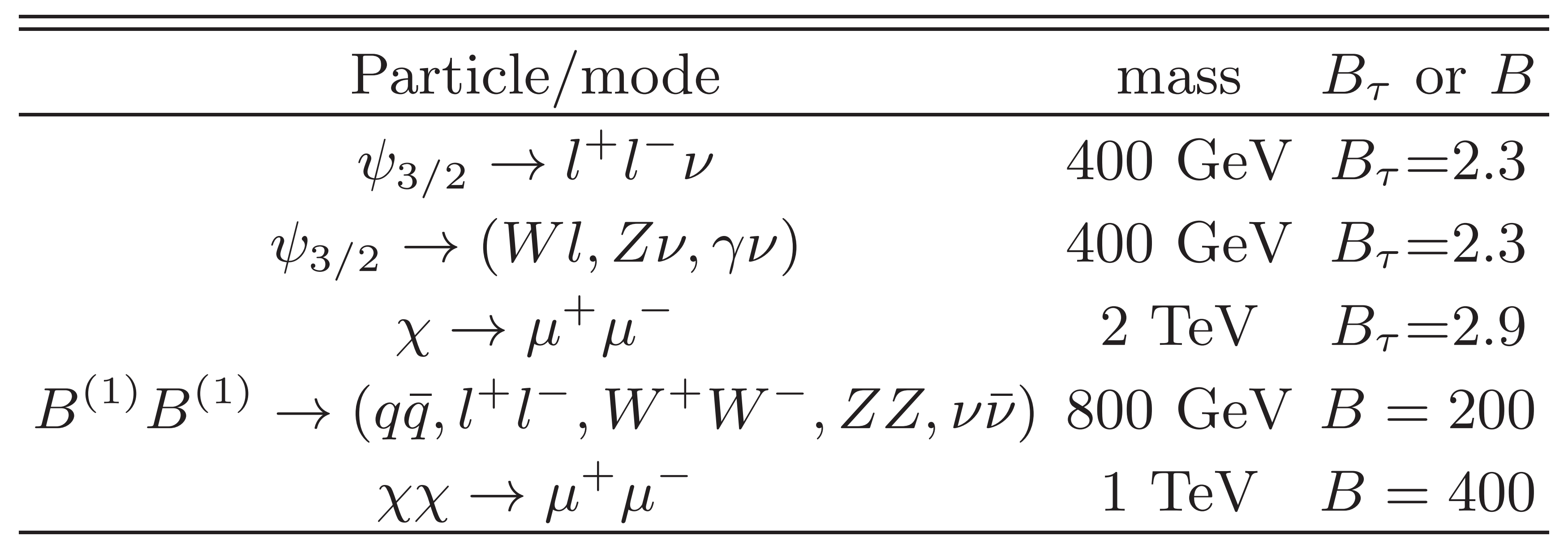
$$\chi\chi \to \mu^+ \mu^-$$

Leptophilic Dark Matter Annihilation/Decay

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

V. Barger et al.
hys. Lett. B678:283, 2009

Model parameters used to explain Fermi/LAT and PAMELA

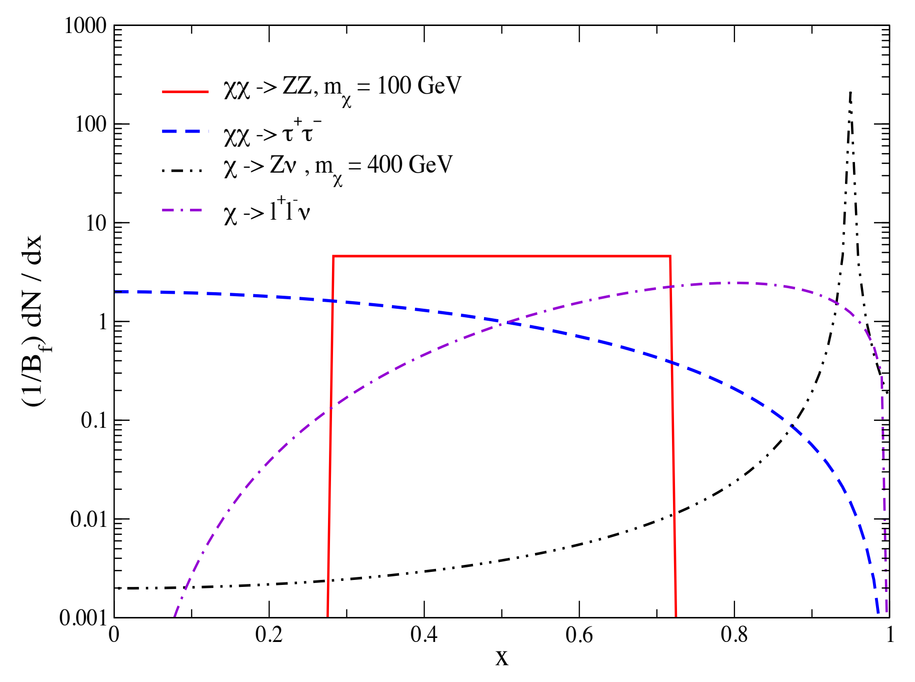


Particle/mode	mass	B_τ or B
$\psi_{3/2} \to l^+ l^- \nu$	400 GeV	B_τ=2.3
$\psi_{3/2} \to (Wl, Z\nu, \gamma\nu)$	400 GeV	B_τ=2.3
$\chi \to \mu^+ \mu^-$	2 TeV	B_τ=2.9
$B^{(1)} B^{(1)} \to (q\bar{q}, l^+ l^-, W^+ W^-, ZZ, \nu\bar{\nu})$	800 GeV	$B = 200$
$\chi\chi \to \mu^+ \mu^-$	1 TeV	$B = 400$

$\chi\chi \to \mu^+ \mu^-$ 1 TeV B

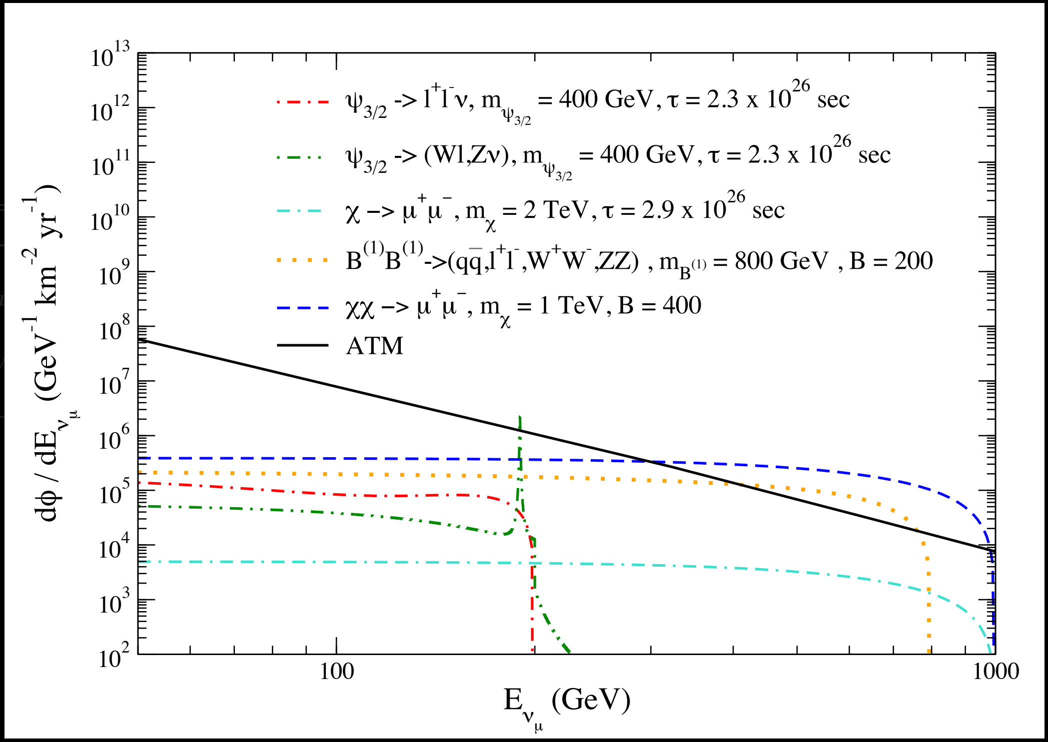
$$\tau = B_\tau \times 10^{26} s$$

Muon Neutrino Spectra

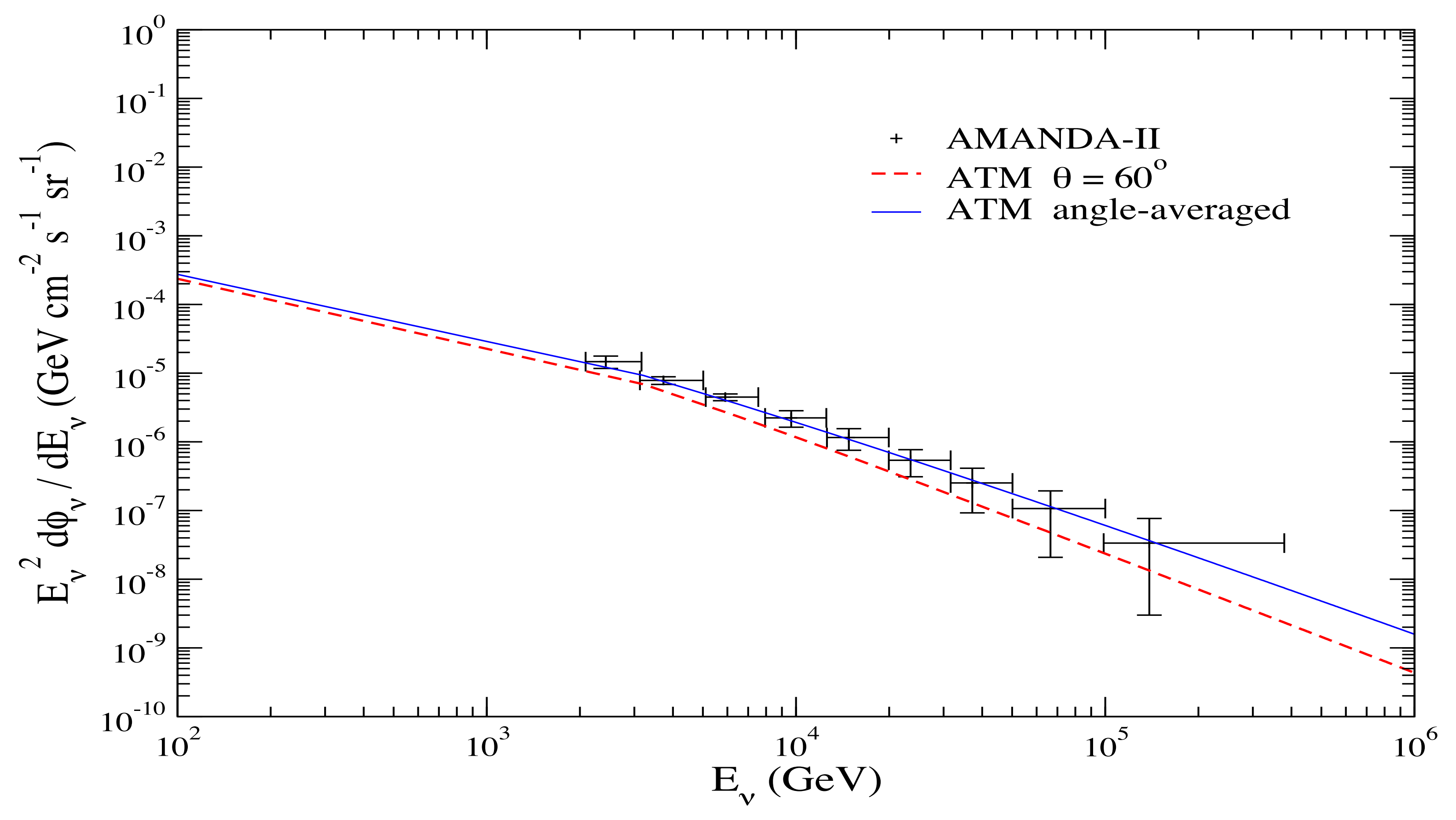


$$x = E_\nu / E_{\nu,max}$$

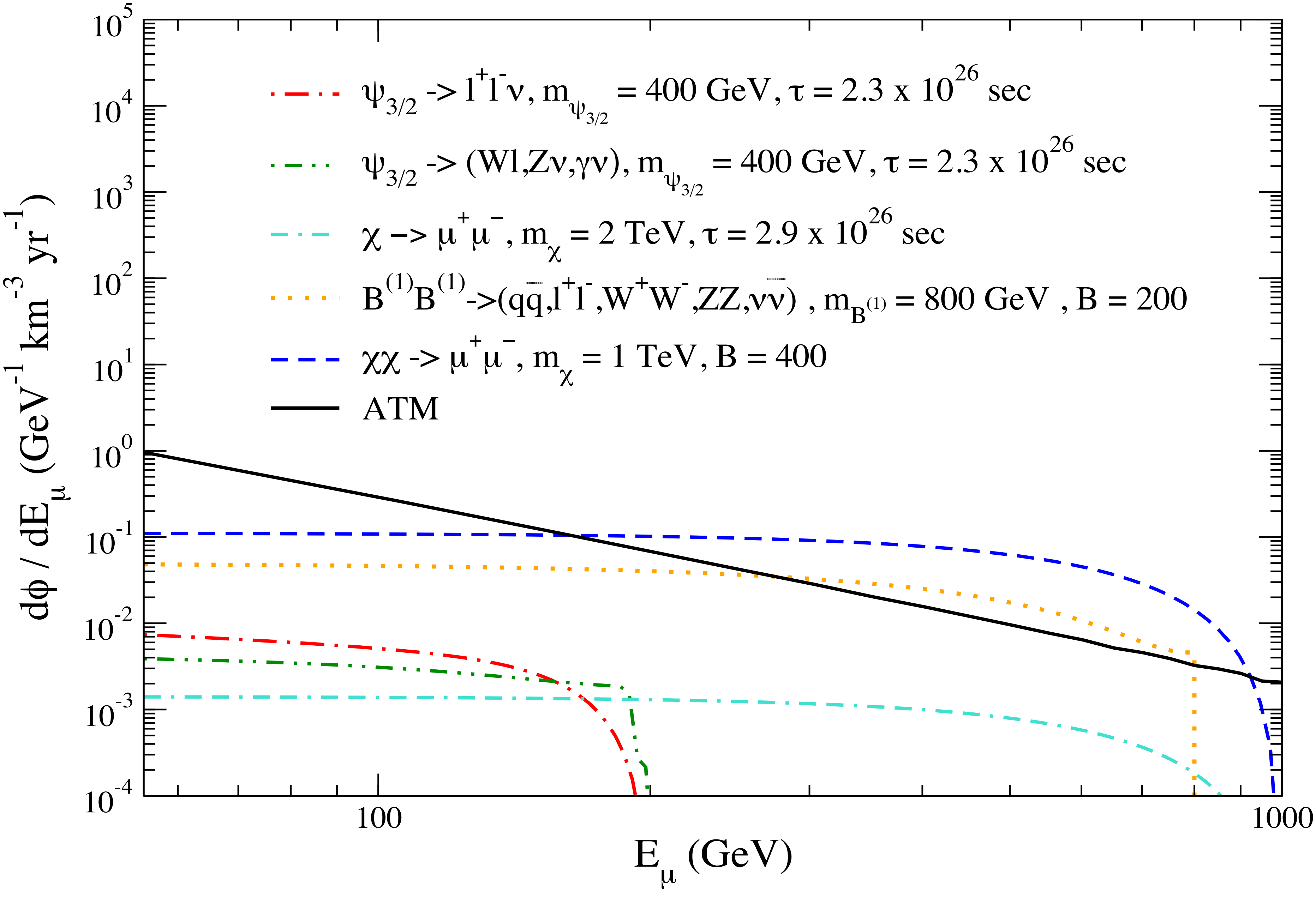
Muon Neutrino Fluxes



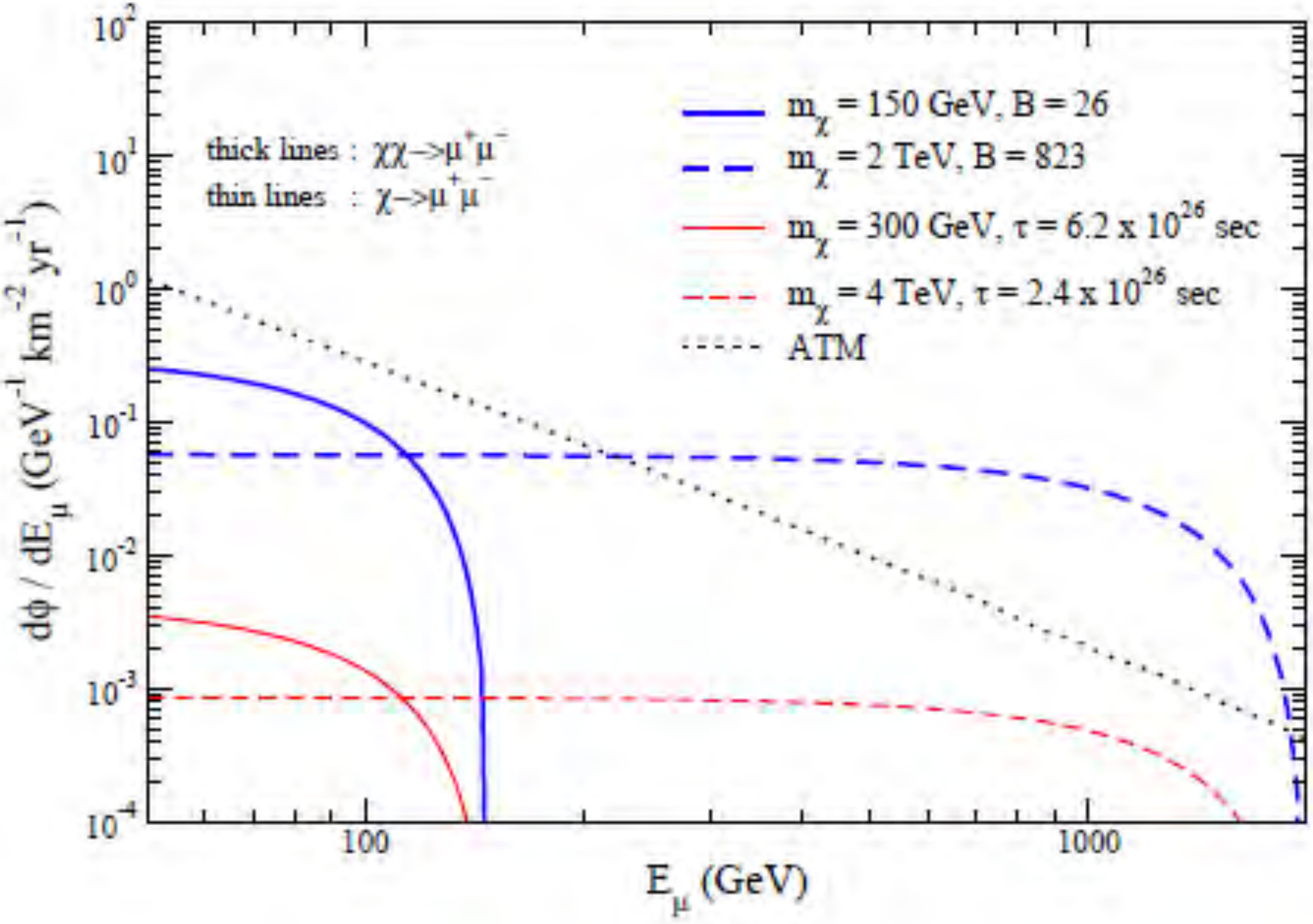
Atmospheric Muon Neutrino Flux



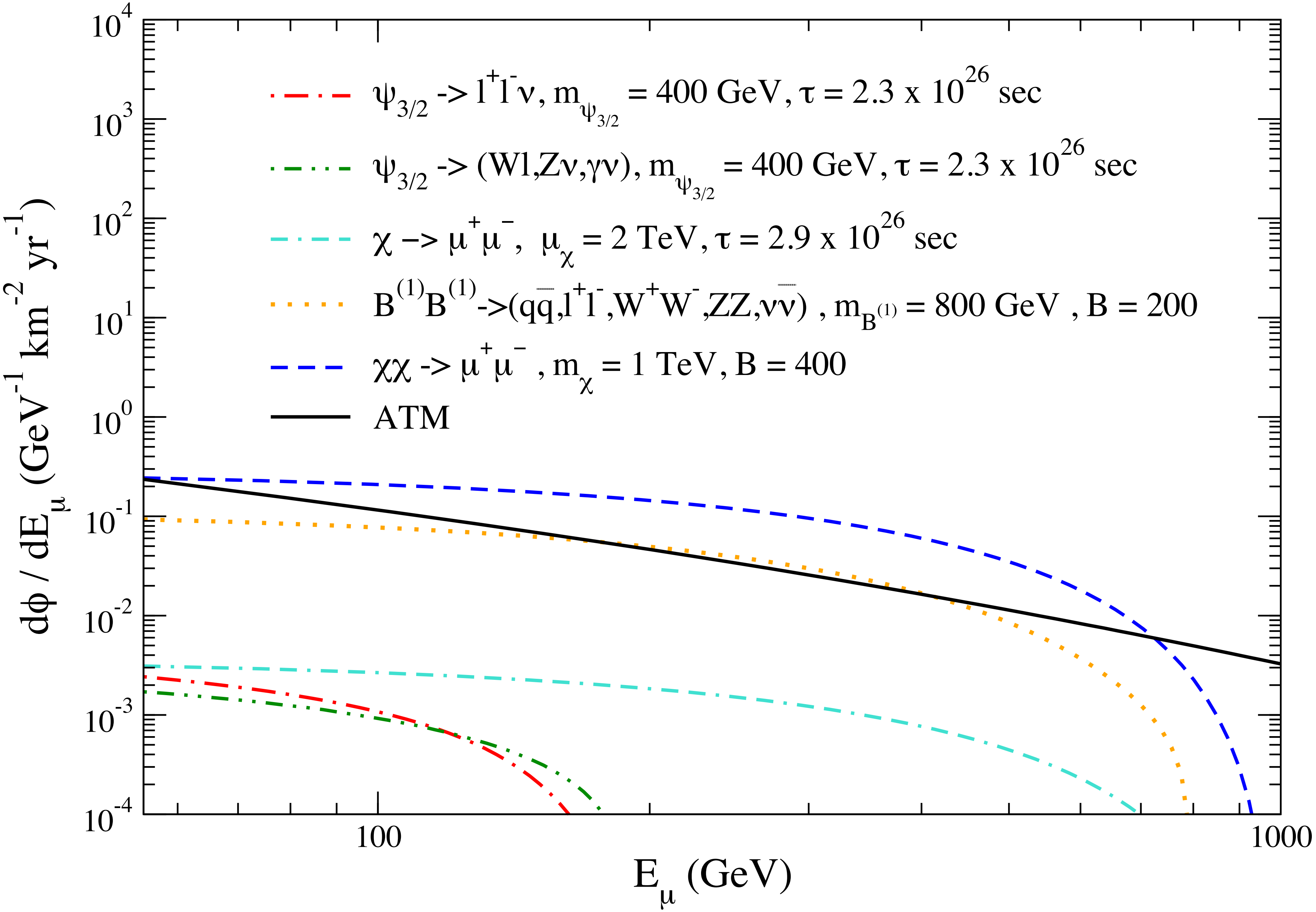
Contained Muon Flux



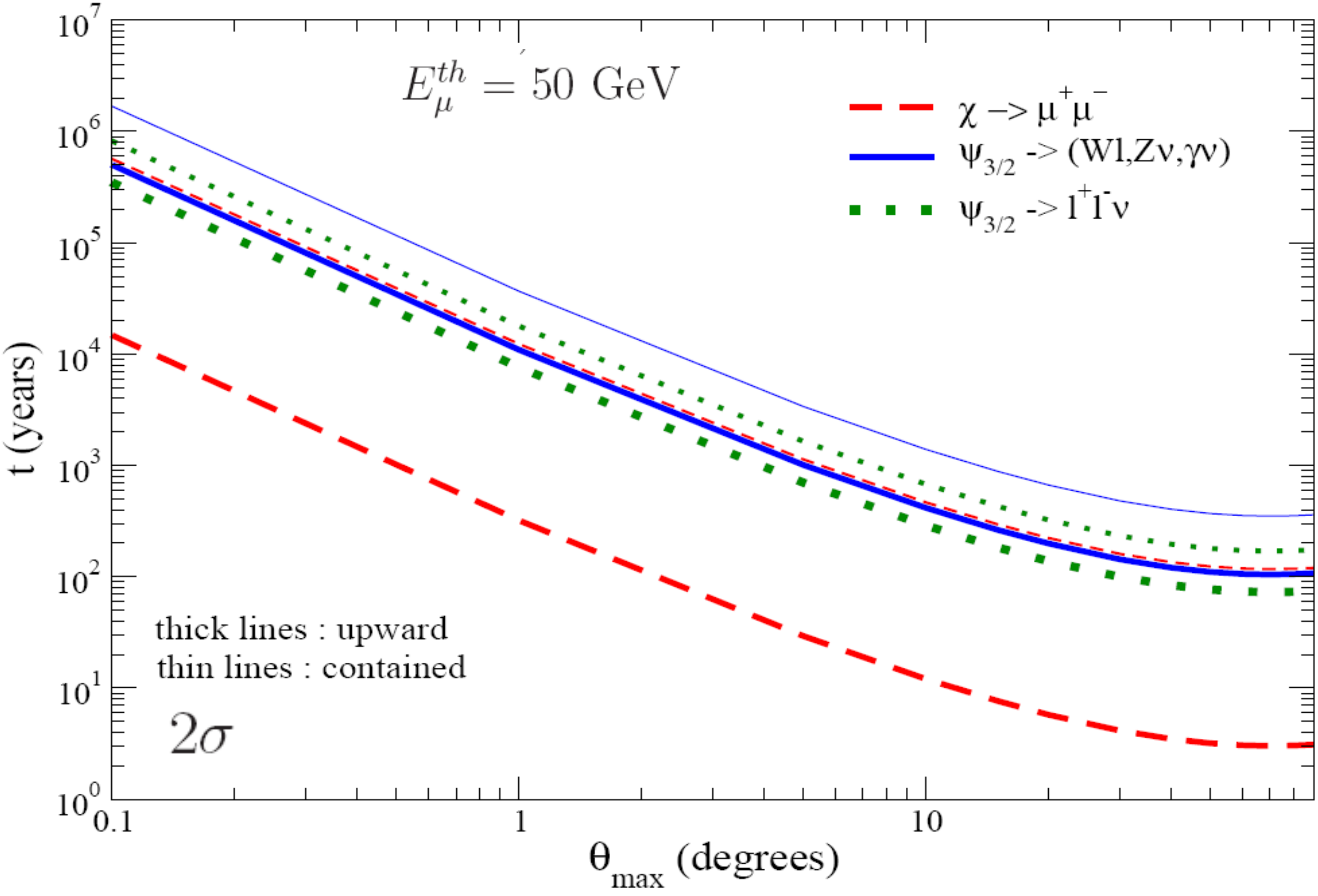
Contained Muon Flux for Leptophilic DM



Upward Muon Flux



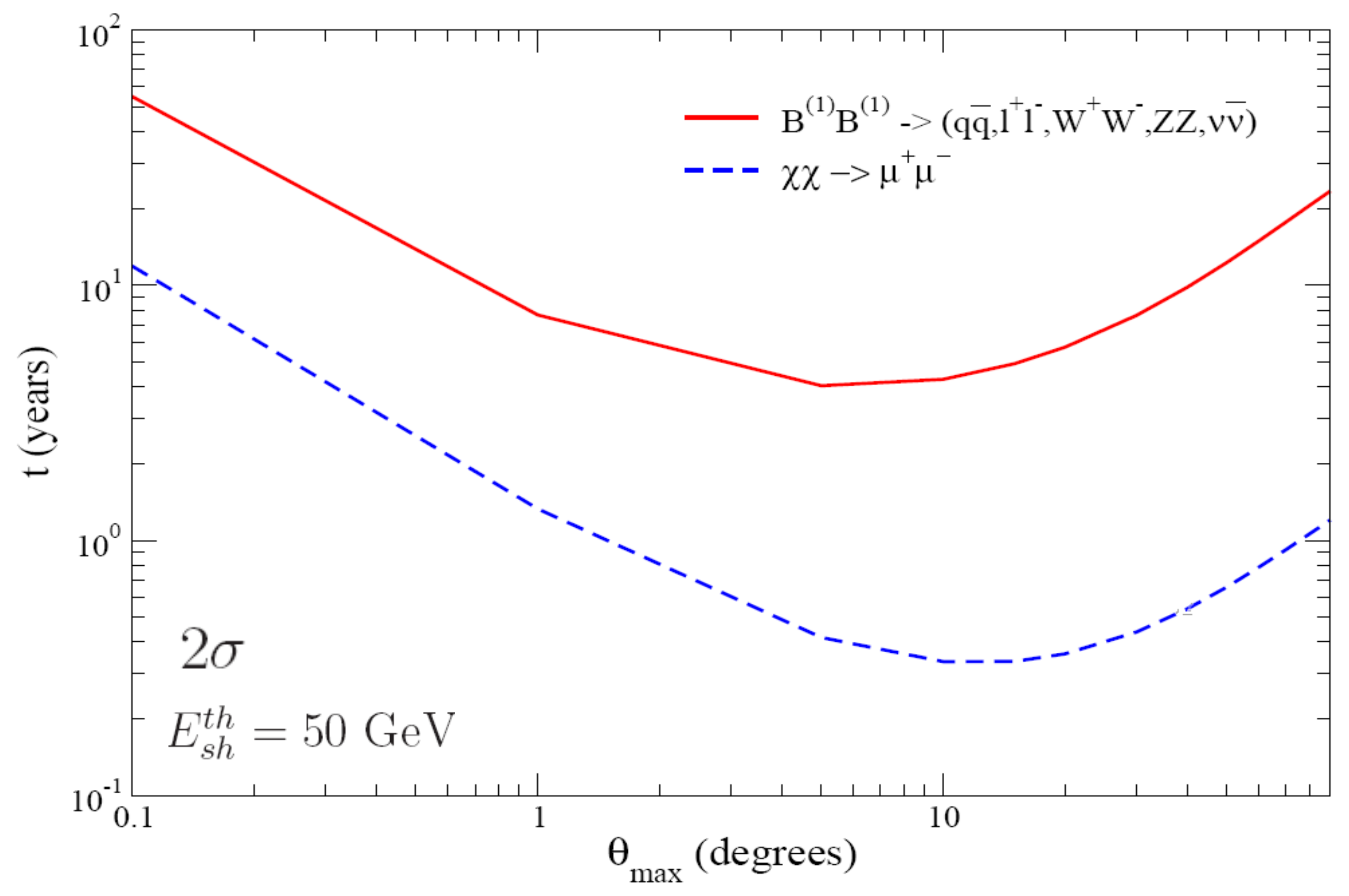
Decaying DM



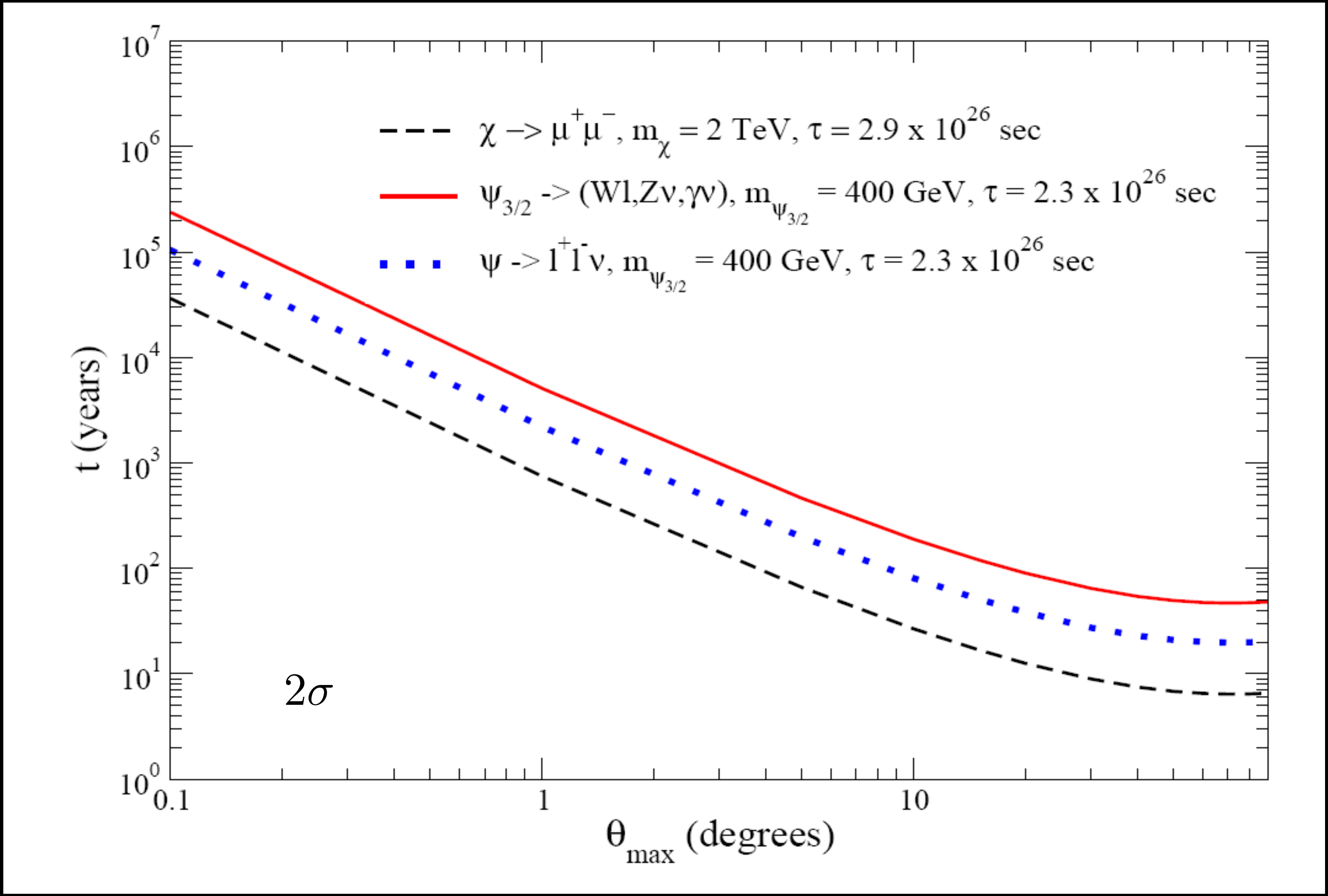
$E_\mu^{th} = 50$ GeV
$\chi \to \mu^+\mu^-$
$\psi_{3/2} \to (Wl, Z\nu, \gamma\nu)$
$\psi_{3/2} \to l^+l^-\nu$
thick lines : upward
thin lines : contained
2σ
t (years)
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
0.1
1
10
θ_{max} (degrees)

Shower Events in IceCube+DeepCore

Annihilating DM

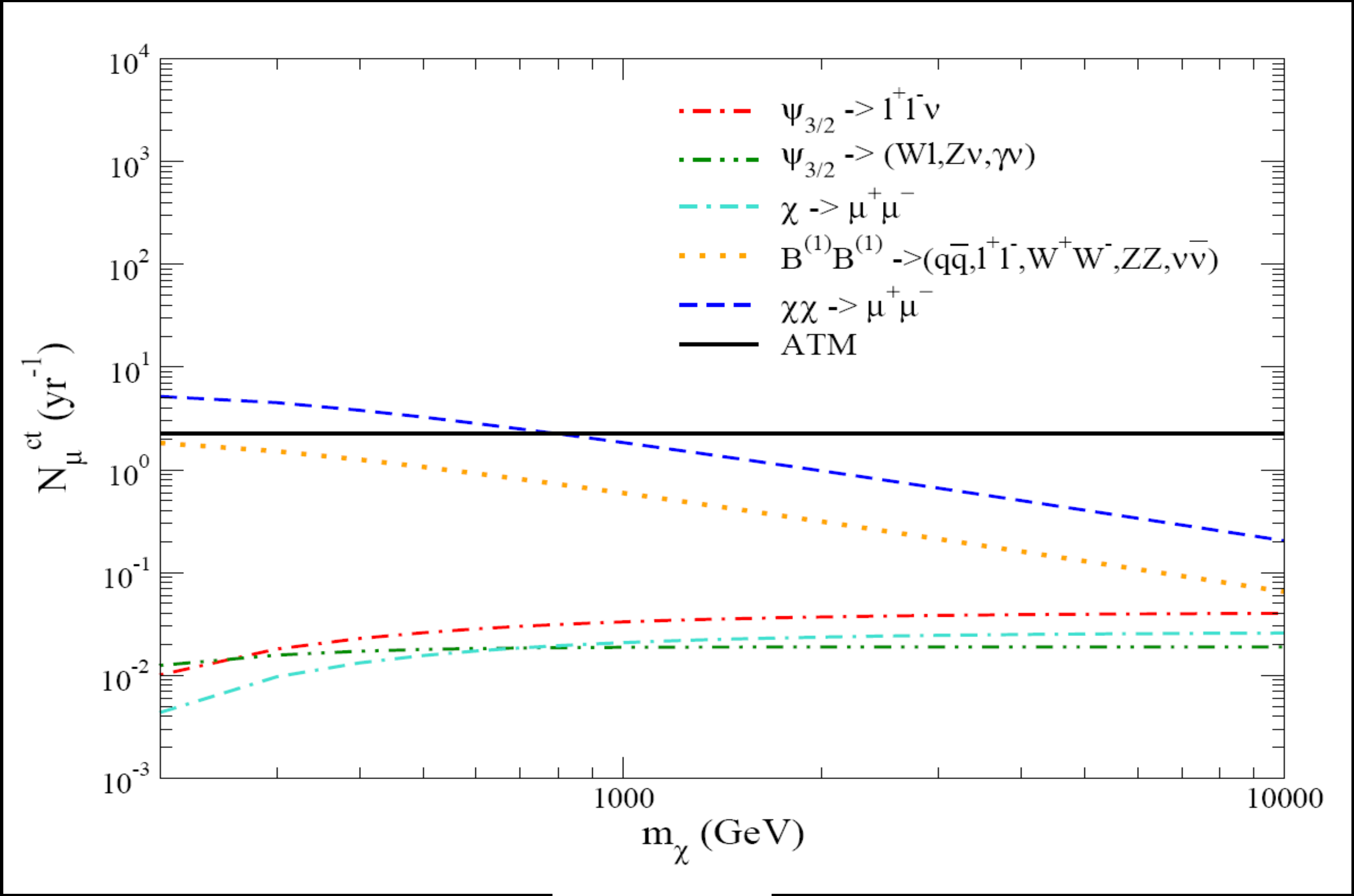


Decaying DM



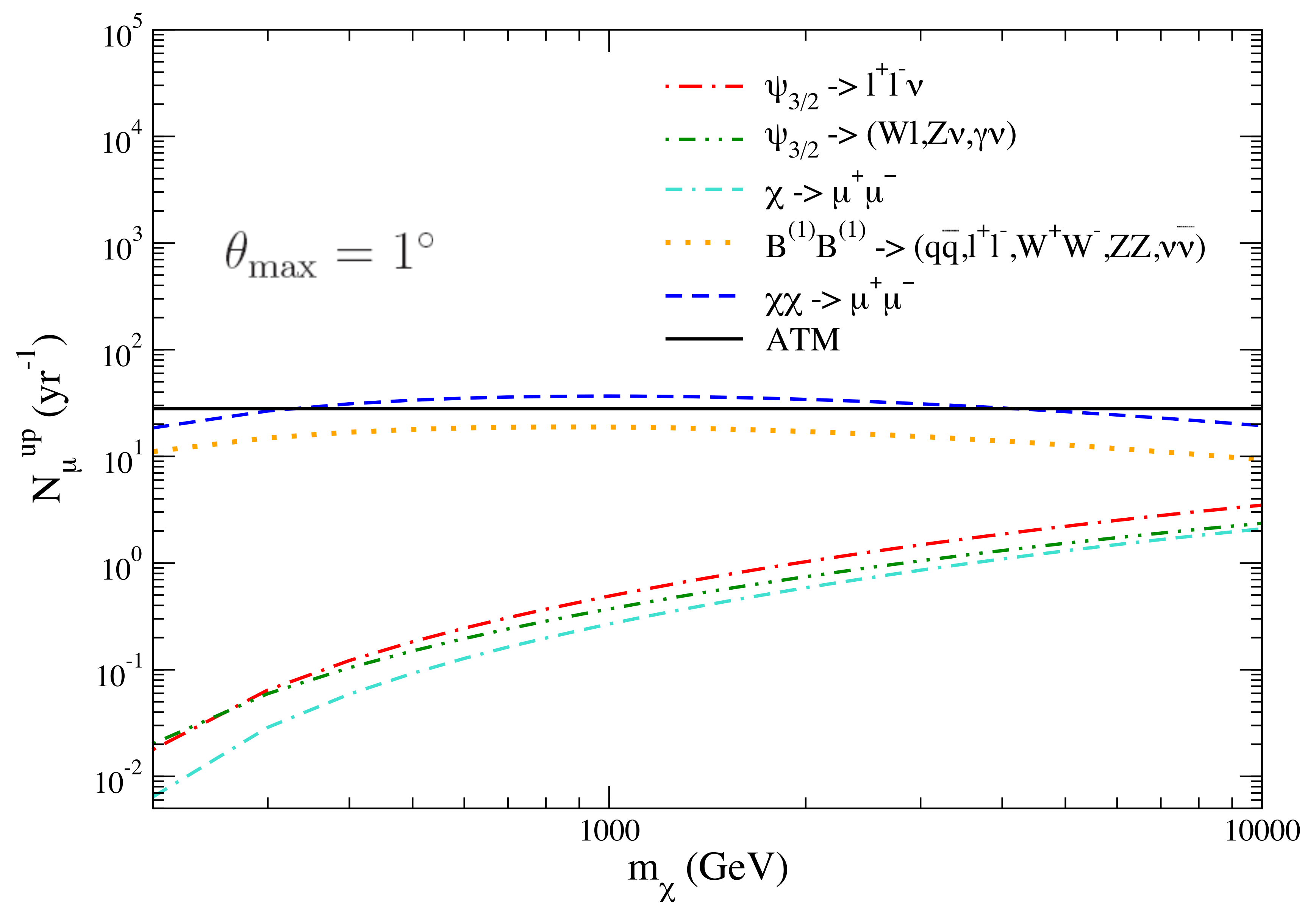
$E_{sh}^{th} = 50$ GeV

Contained Muon Events

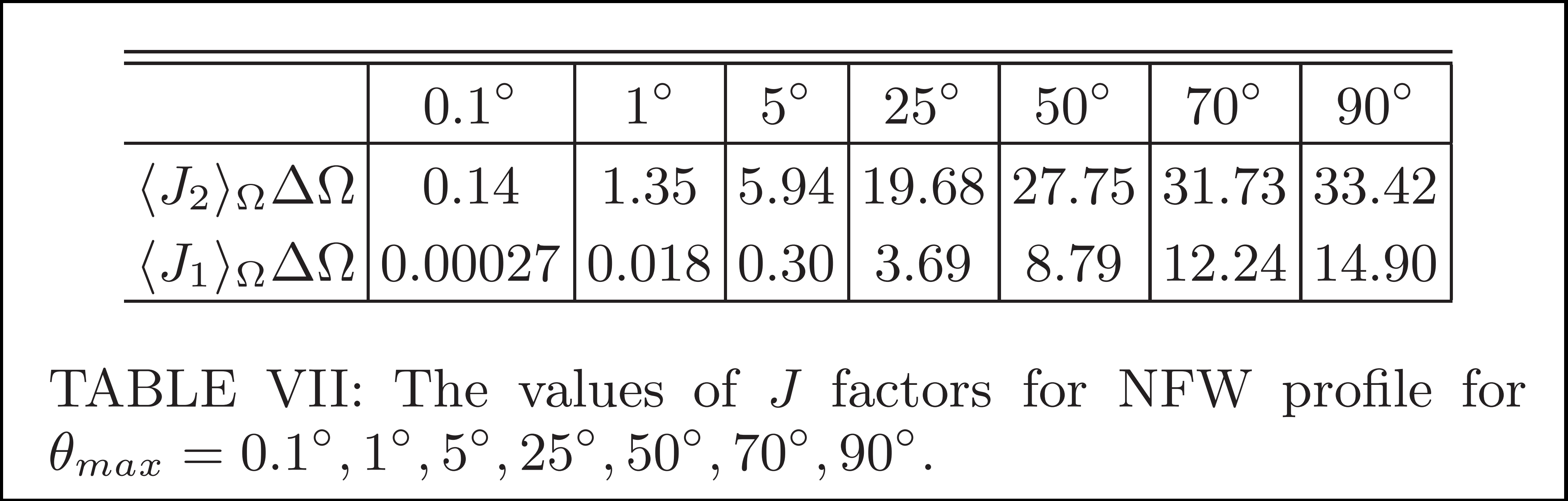


$$\theta_{\max} = 1^\circ$$

Upward Muon Events with $E_\mu^{th} = 50\mathrm{GeV}$



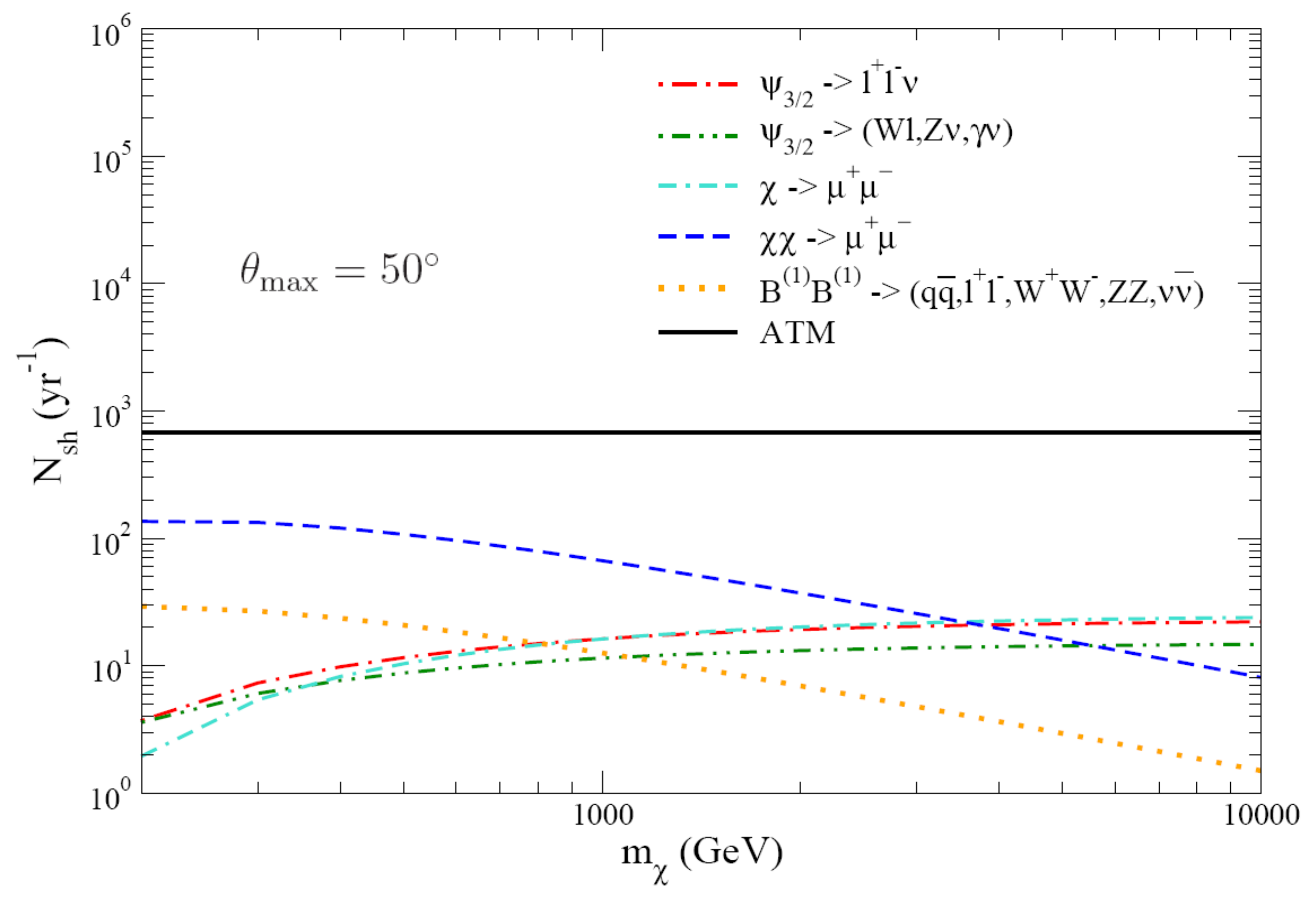
Event Rates Dependence on θ_{max}



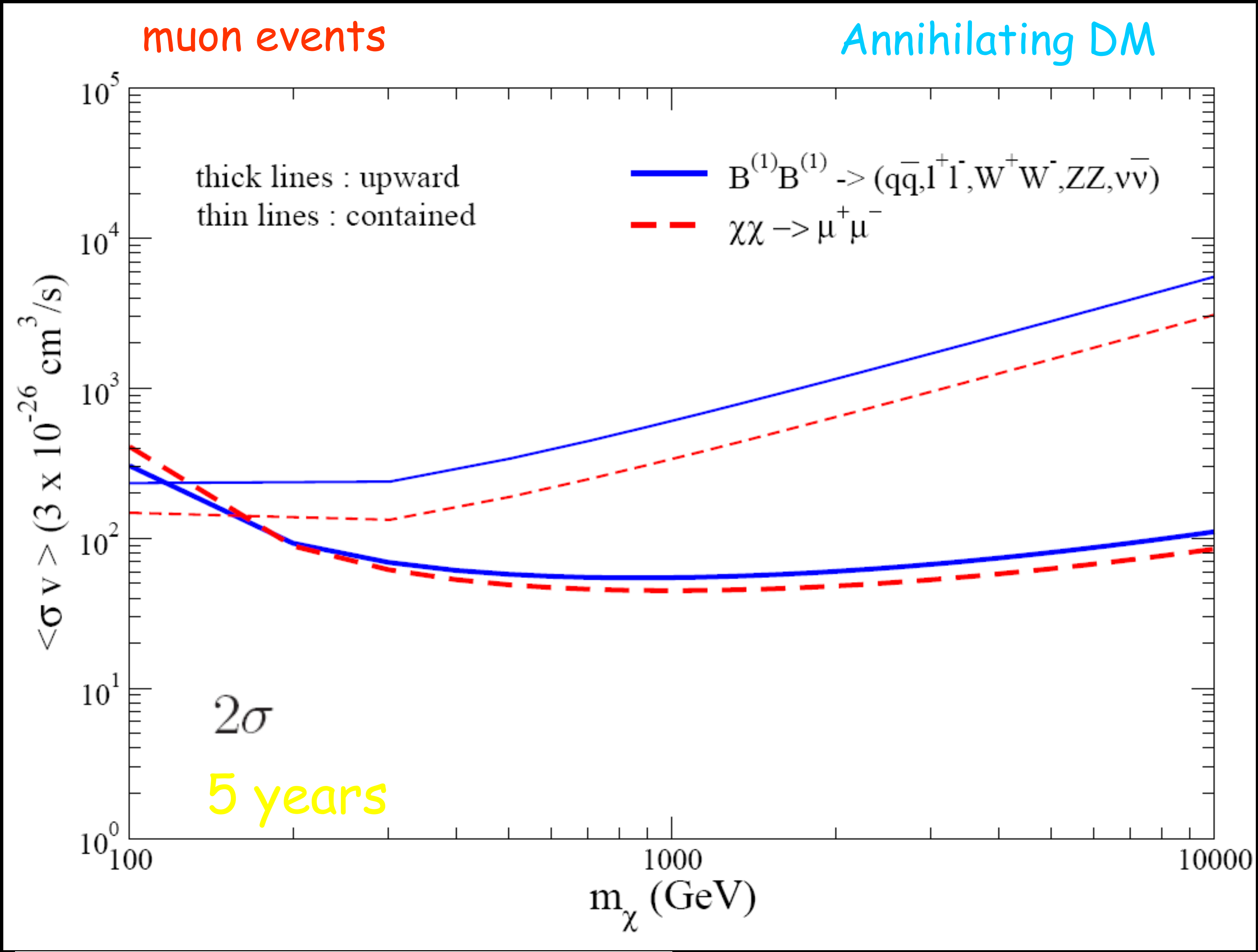
	0.1°	1°	5°	25°	50°	70°	90°
$\langle J_2 \rangle_\Omega \Delta\Omega$	0.14	1.35	5.94	19.68	27.75	31.73	33.42
$\langle J_1 \rangle_\Omega \Delta\Omega$	0.00027	0.018	0.30	3.69	8.79	12.24	14.90

TABLE VII: The values of J factors for NFW profile for $\theta_{max} = 0.1^\circ, 1^\circ, 5^\circ, 25^\circ, 50^\circ, 70^\circ, 90^\circ$.

Shower Events



Probing the Parameter Space



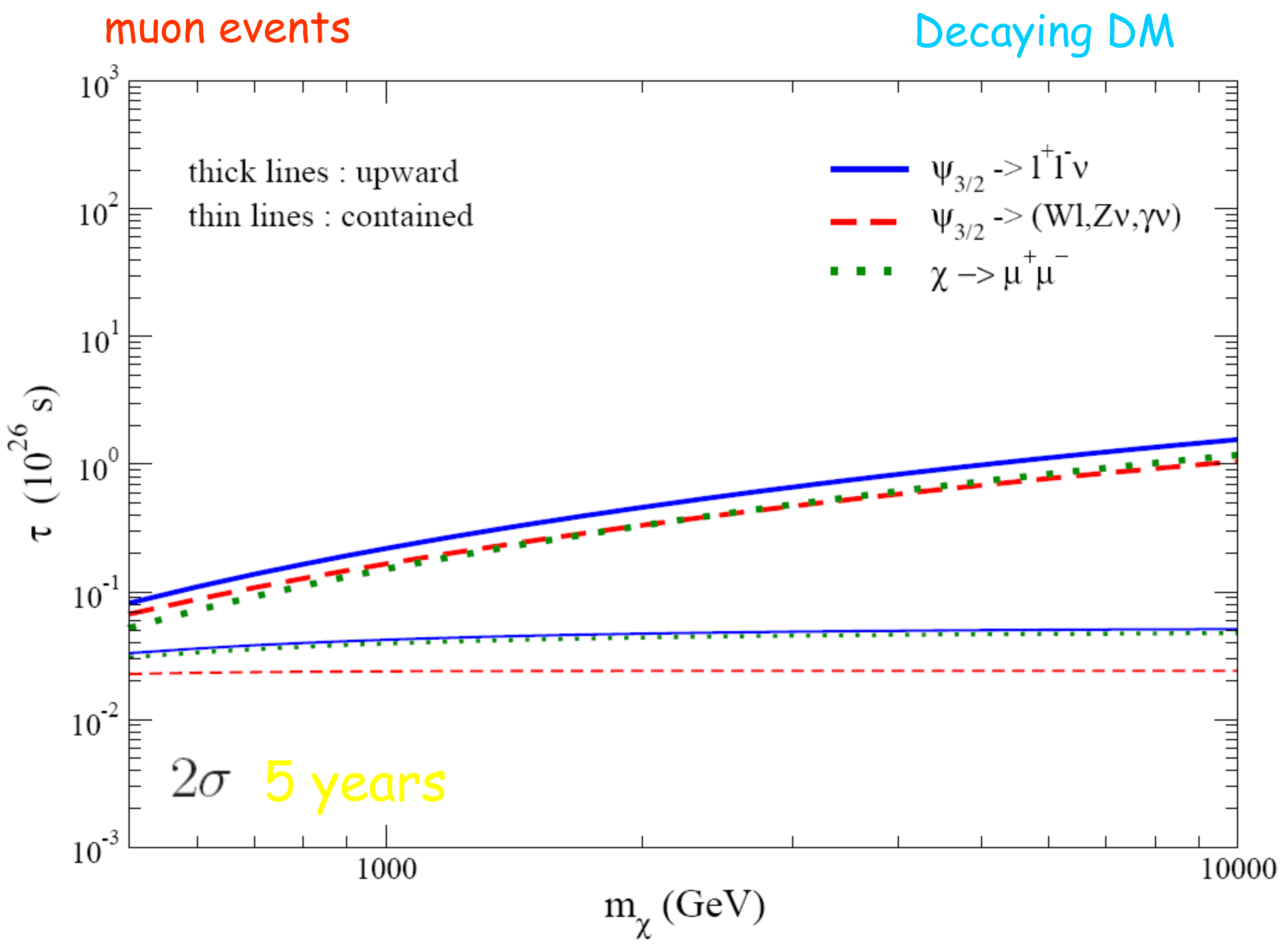
muon events

Annihilating DM

5 years

$$\theta_{\max} = 1^\circ \text{ and } E_\mu^{th} = 50 \text{ GeV}$$

Probing the Parameter Space



muon events

Decaying DM

5 years

$\theta_{\max} = 1^\circ$ and $E_\mu^{th} = 50$ GeV

		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}	$2.28(1^\circ)$			$227.5(10^\circ)$				$5347(50^\circ)$		
	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

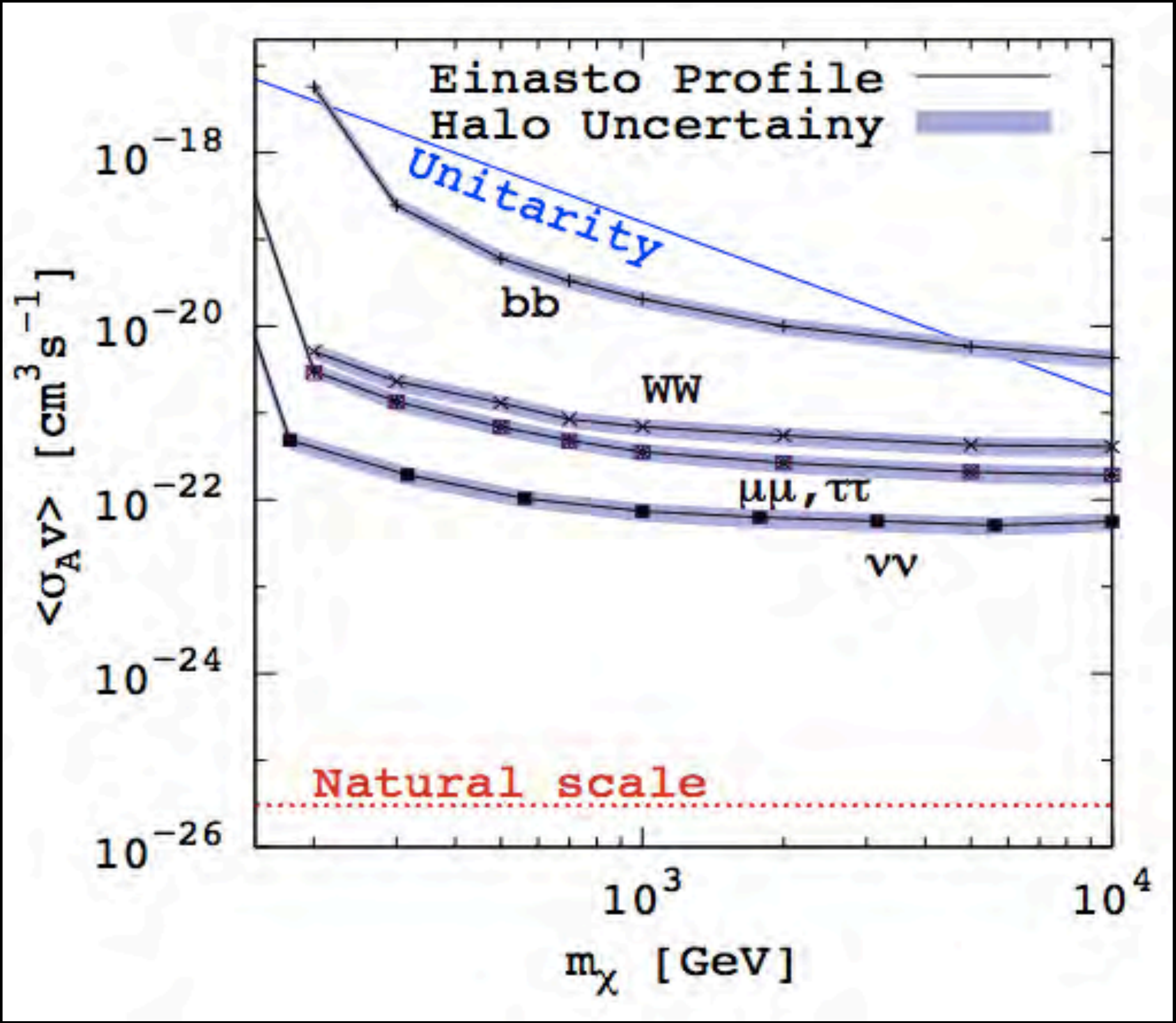
IceCUBE : 1 km^3 neutrino detector at South Pole

- 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

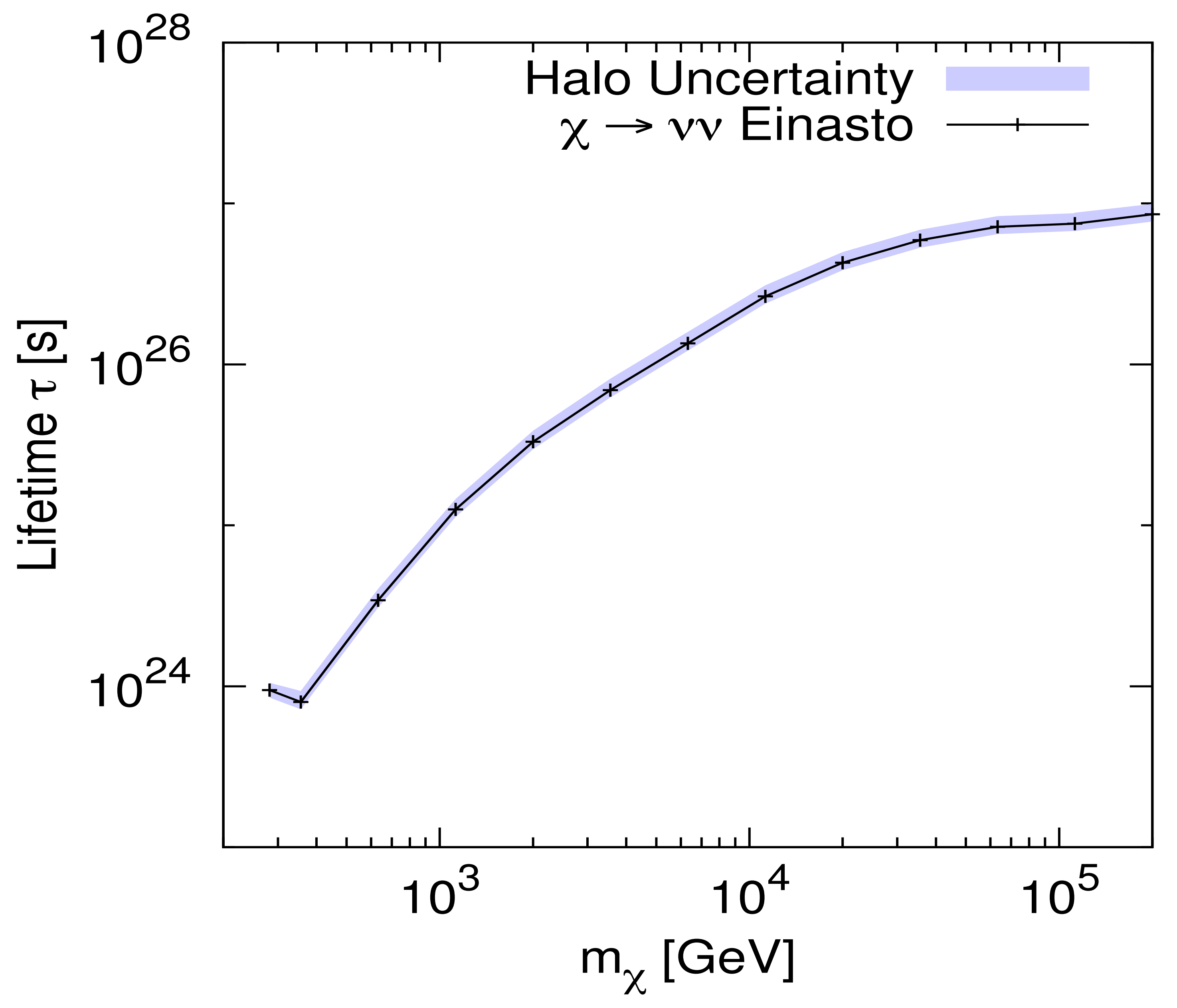
KM3Net : a future deep-sea neutrino telescope

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

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



IceCube DM search from the Galactic Hallo
(arXiv:1101.3349; PRD 84 (2011))



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