Aspen 2013

Probing Dark Matter with Neutrinos

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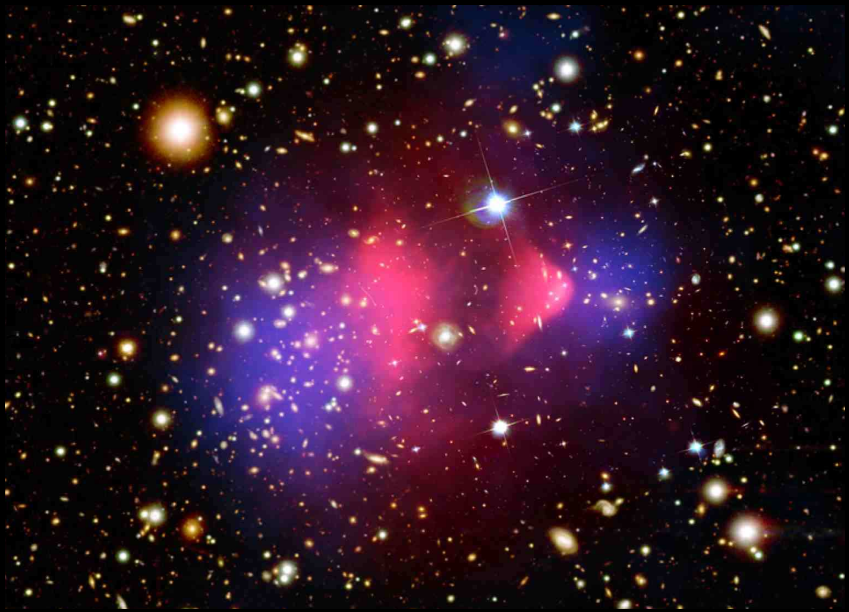
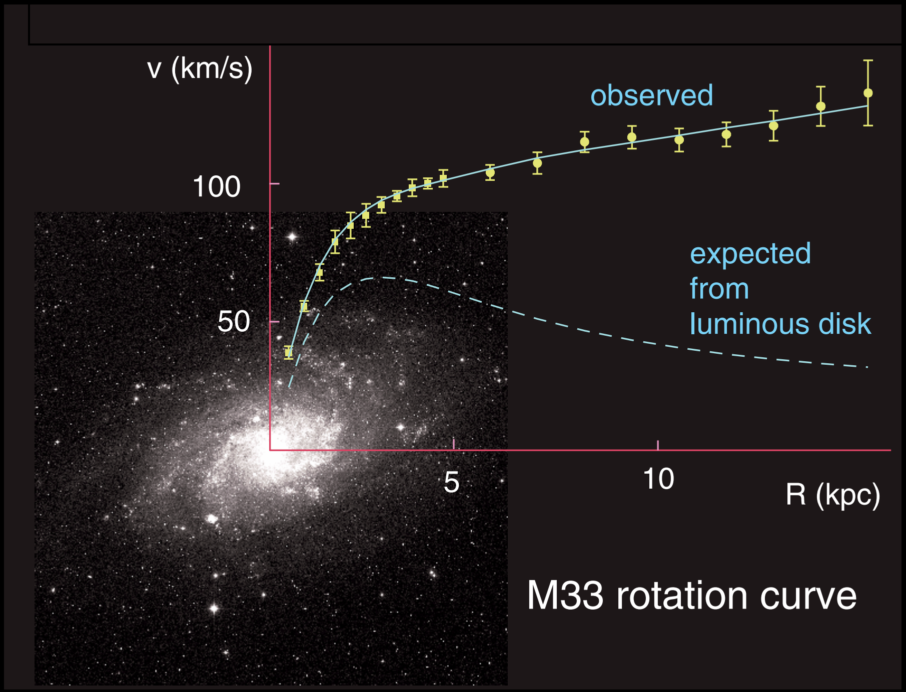


In collaboration with
Arif Erkoca, Graciela Gelmini
and Hallsie Reno

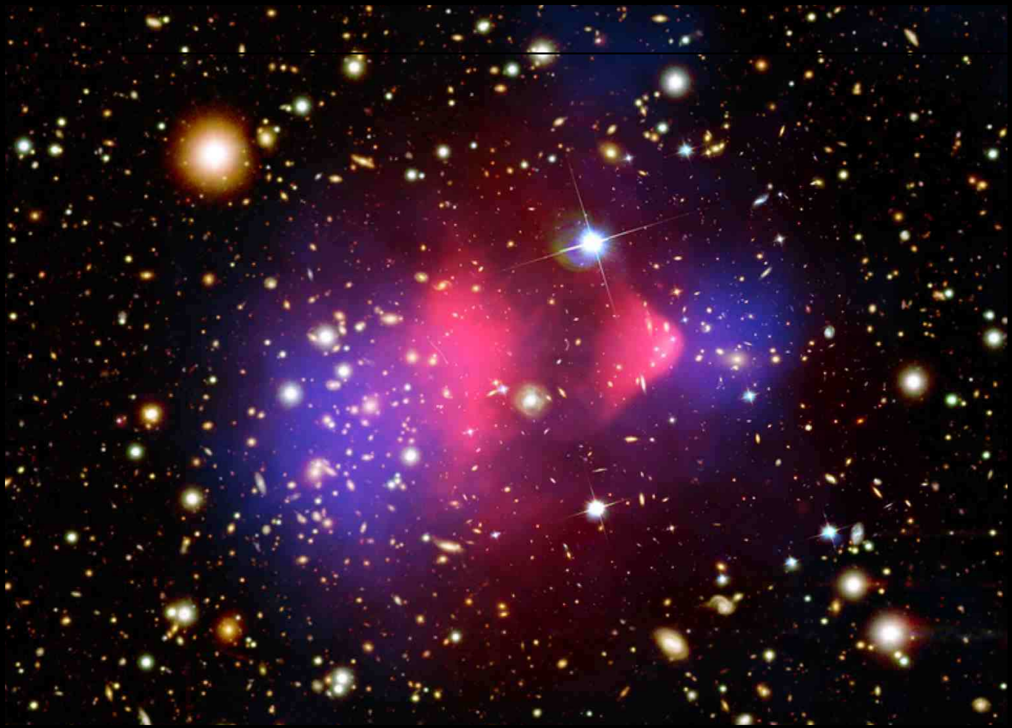
Non-baryonic Dark Matter

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

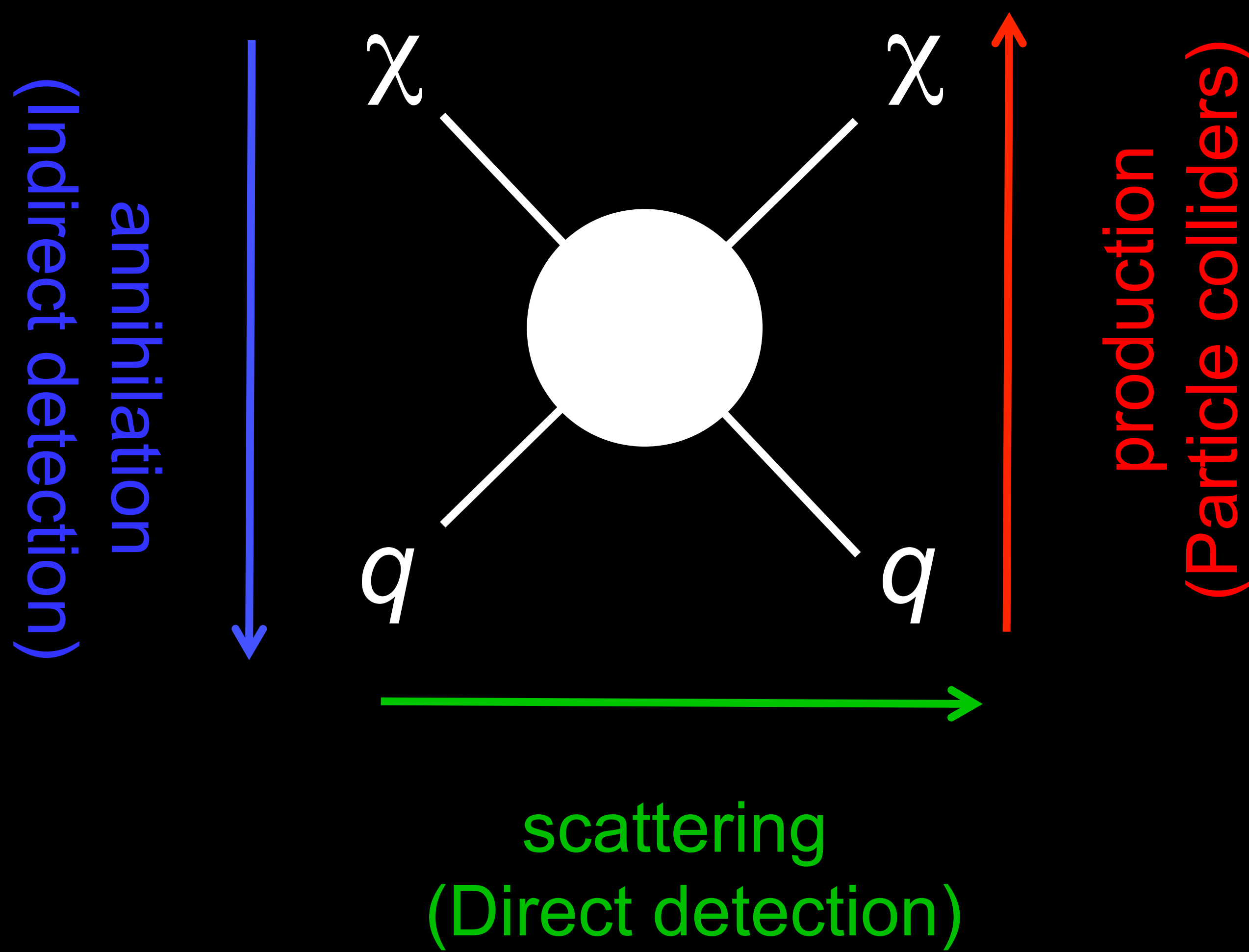
Bergstrom, Rep. Prog. Phys. 63, 793 (2000)



Bullet Cluster (IE0657-56)



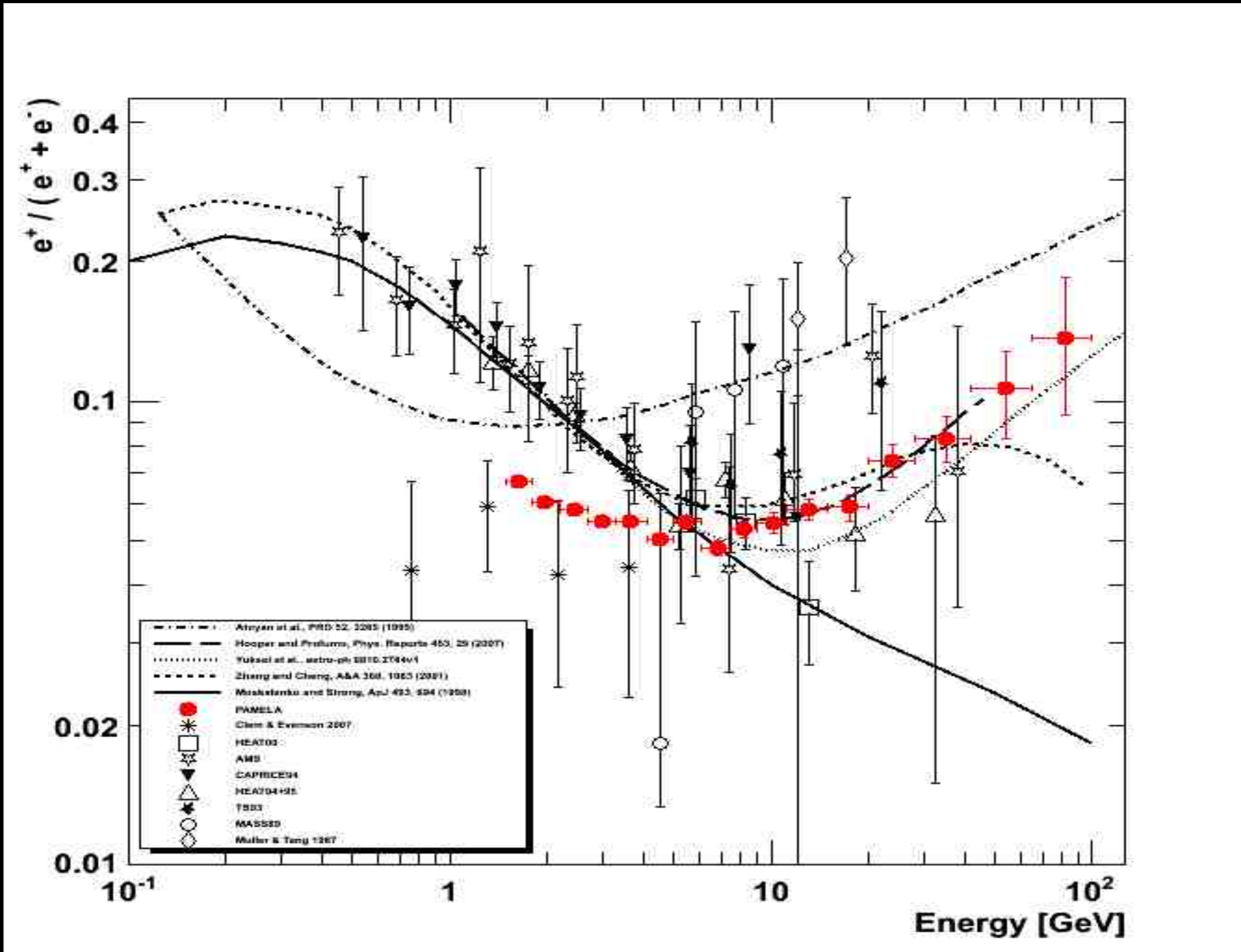
DARK MATTER DETECTION



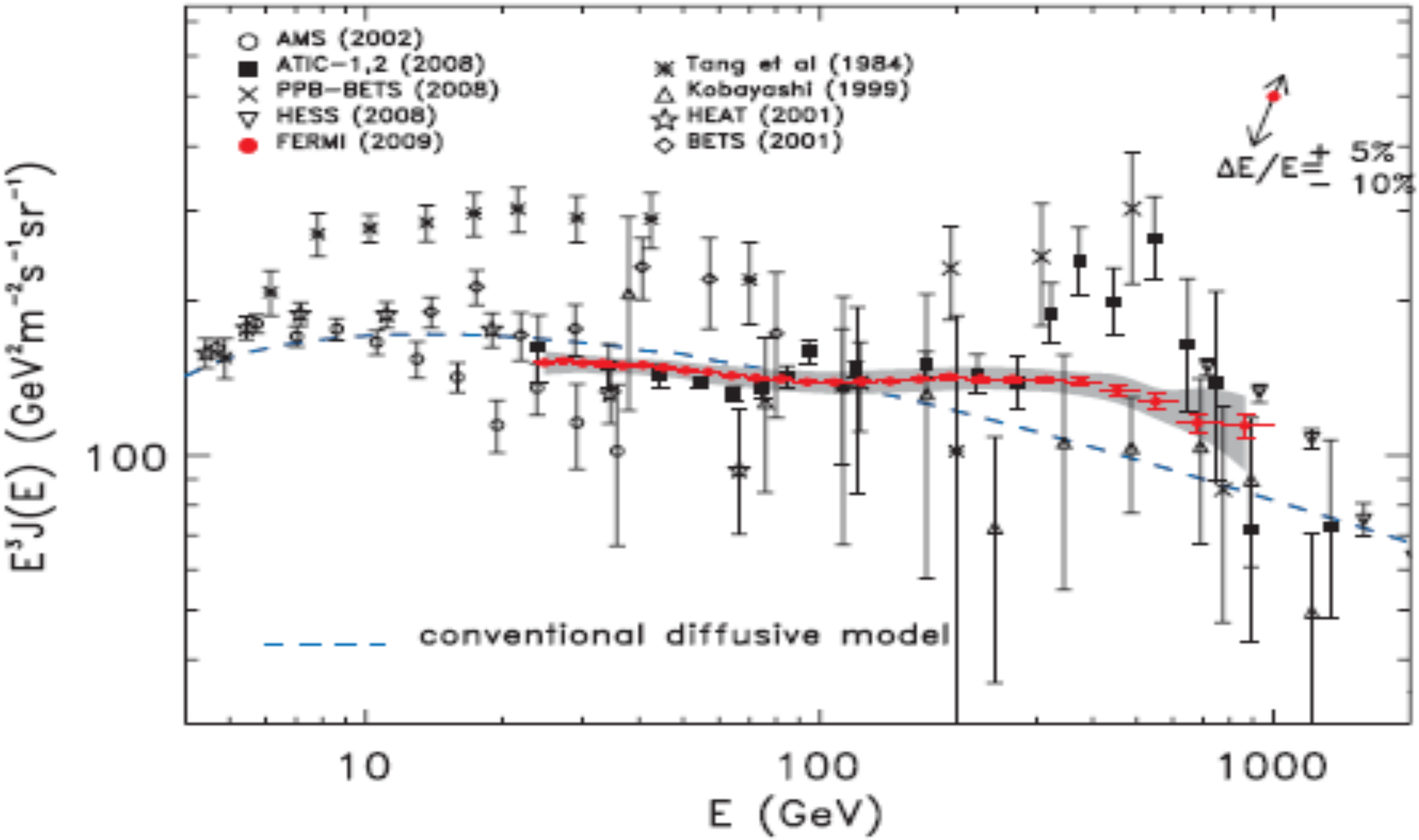
- Indirect DM searches:

  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...)

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"** :

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

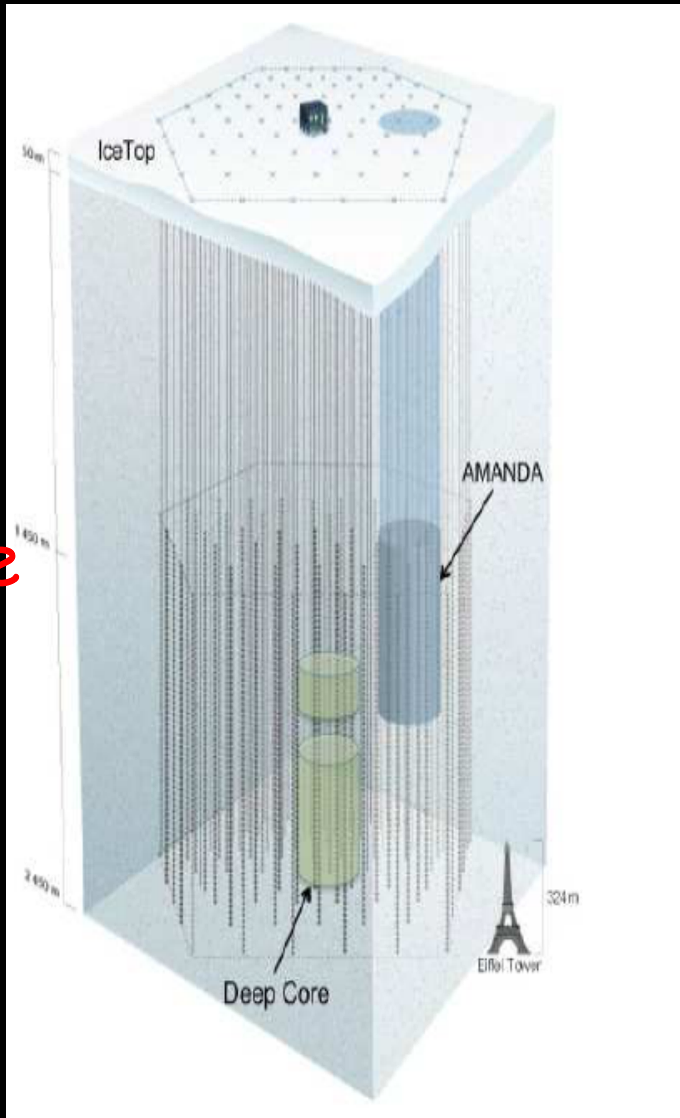
Low-velocity enhancement (particle physics)

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, produced directly or from particles that decay into neutrinos (taus, W's, b's)

Erkoca, Reno and Sarcevic, PRD 80, 043514

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

Erkoca, Gelimini, Reno and Sarcevic, PRD 81, 096007

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

Erkoca, Reno and Sarcevic, PRD 82, 113006

Neutrinos from DM annihilations in the core of the Sun

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 :

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

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

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

for the Sun

M is the mass of the Sun

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 (upward muons) or in the detector (contained muons)

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

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

Neutrinos from DM annihilations

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

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

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

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

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

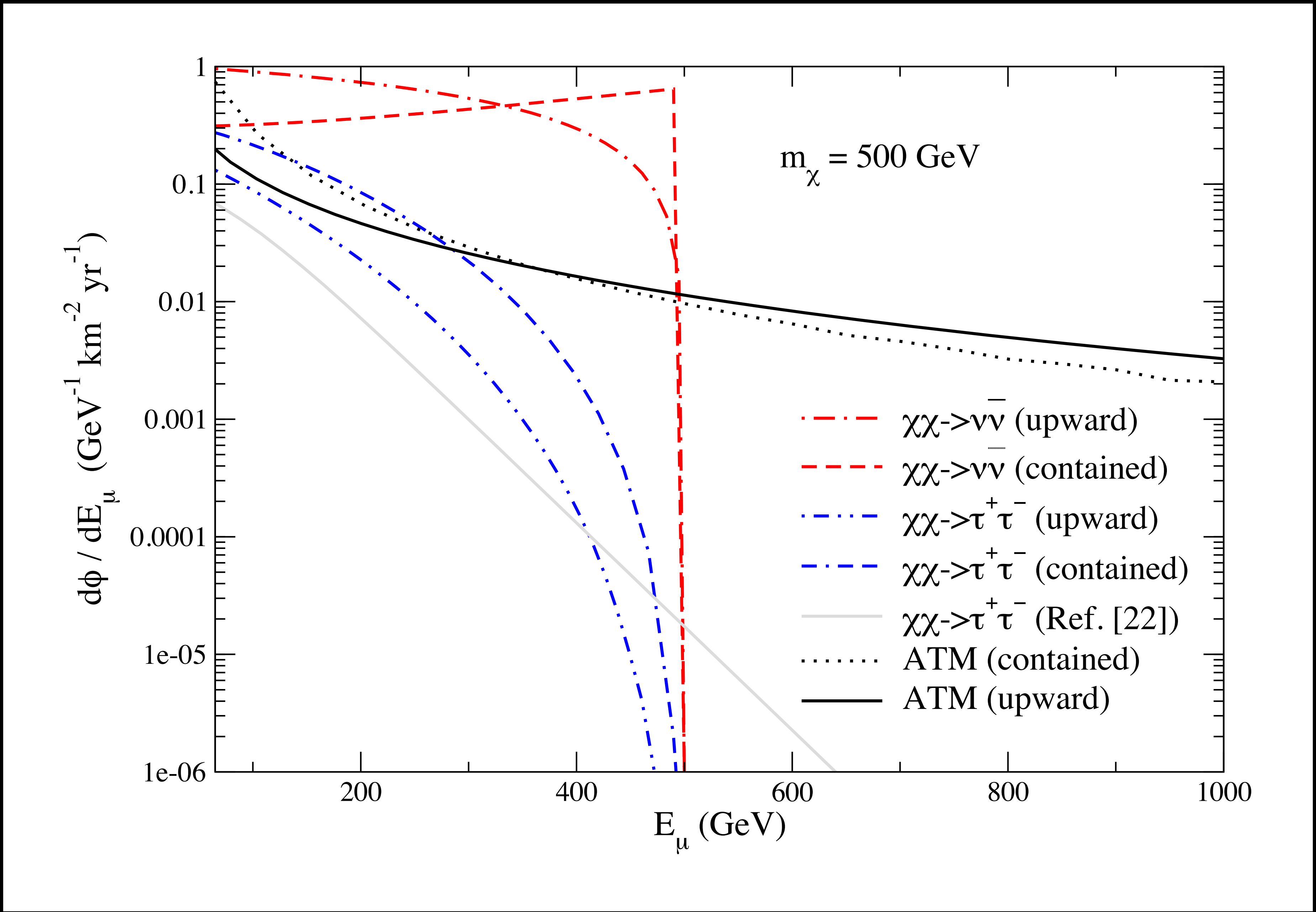
$$\rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow (cl^-\bar{\nu}_l)(l^+\nu_l)(\bar{c}l^+\nu_l)(l^-\bar{\nu}_l)$$

- Attenuation of the neutrino Flux in the Sun

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

- 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



Neutrino Flux from DM Annihilation in the Galactic Center

- 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

Erkoca, Gelmini, Reno and Sarcevic, Phys. Rev. D81, 096007

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

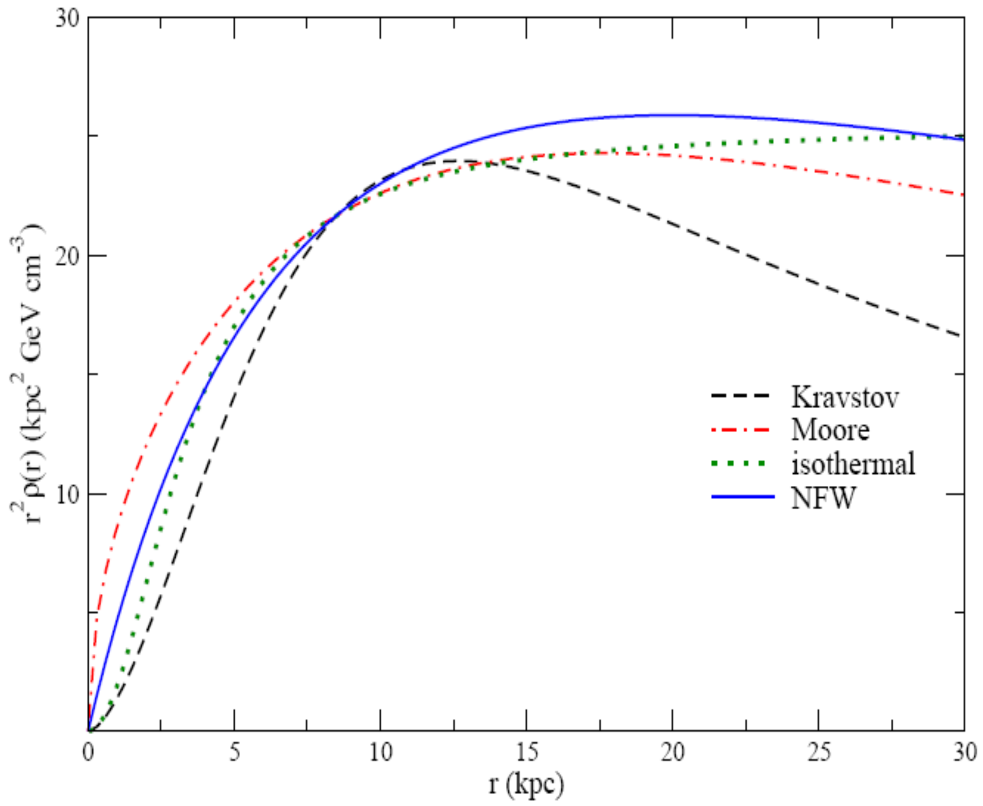
ρ_o is local dark matter density near the solar system

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

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

Dark Matter Density Profiles

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:

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

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

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

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

- 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:

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

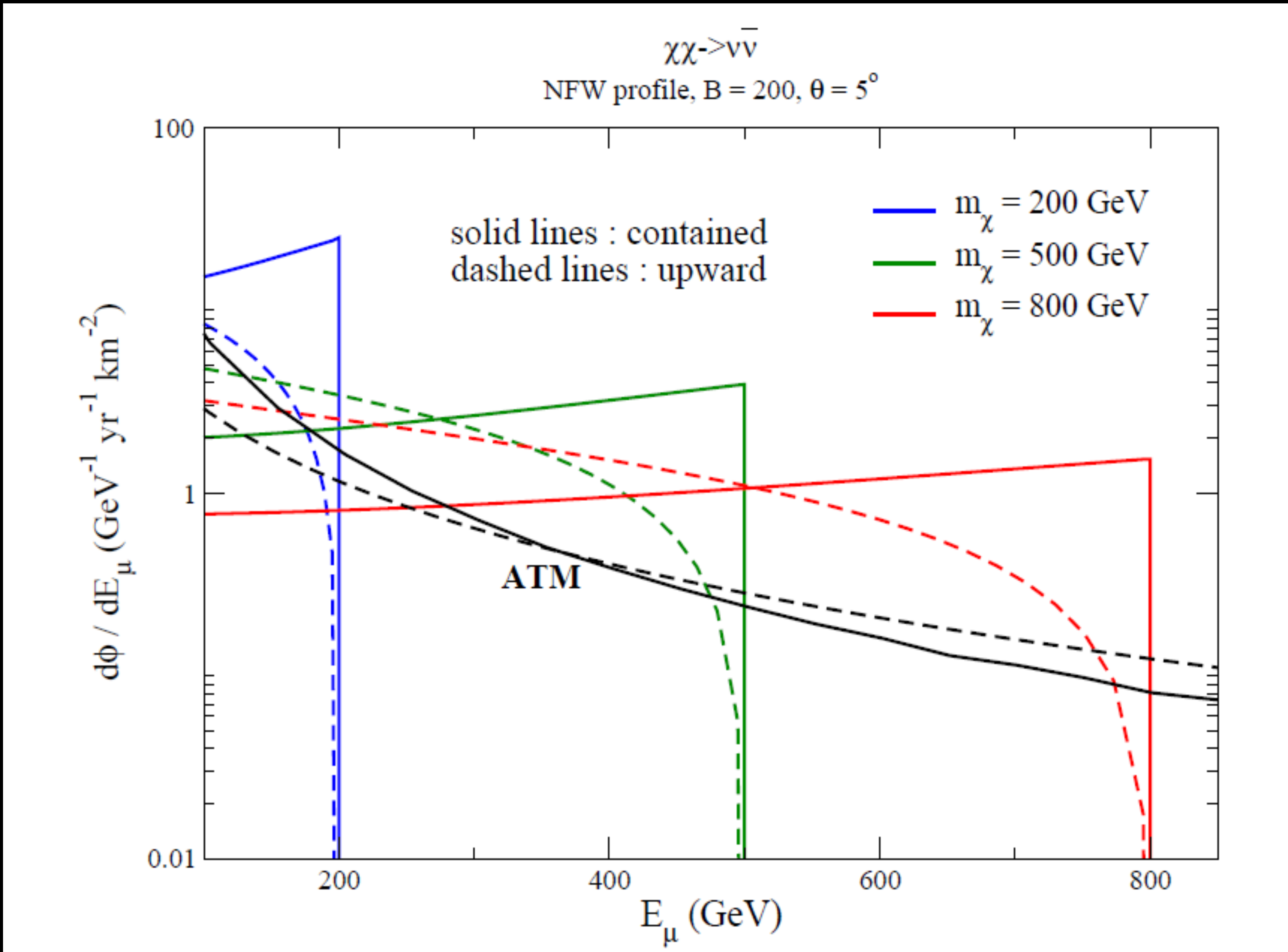
Muon range:

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

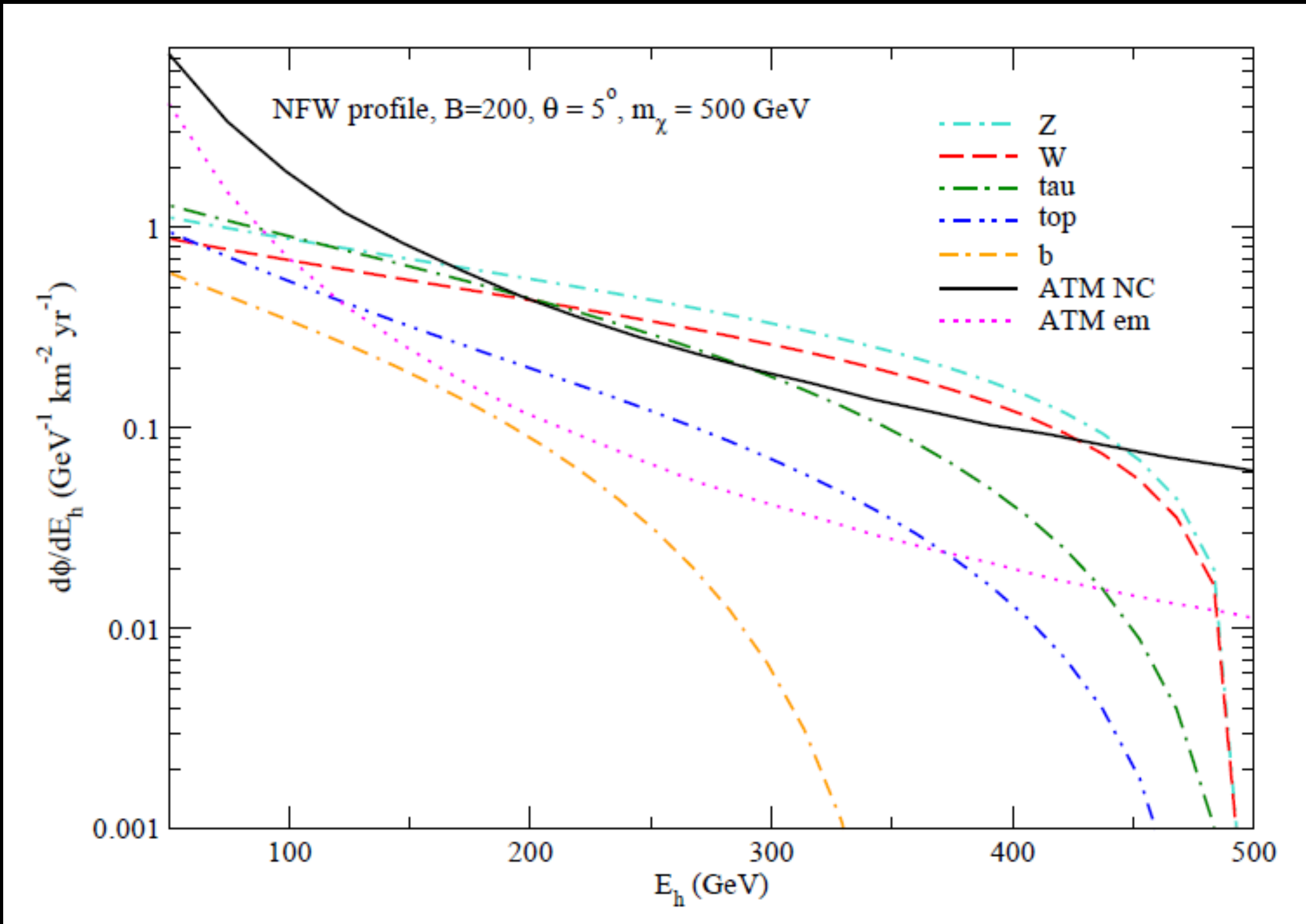
Hadronic Shower Flux

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

Muon Flux


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

Hadronic Shower Spectra without track-like events



Probing the Nature of Dark Matter with Neutrinos

Erkoca, Reno and Sarcevic, Phys. Rev. D82

- 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

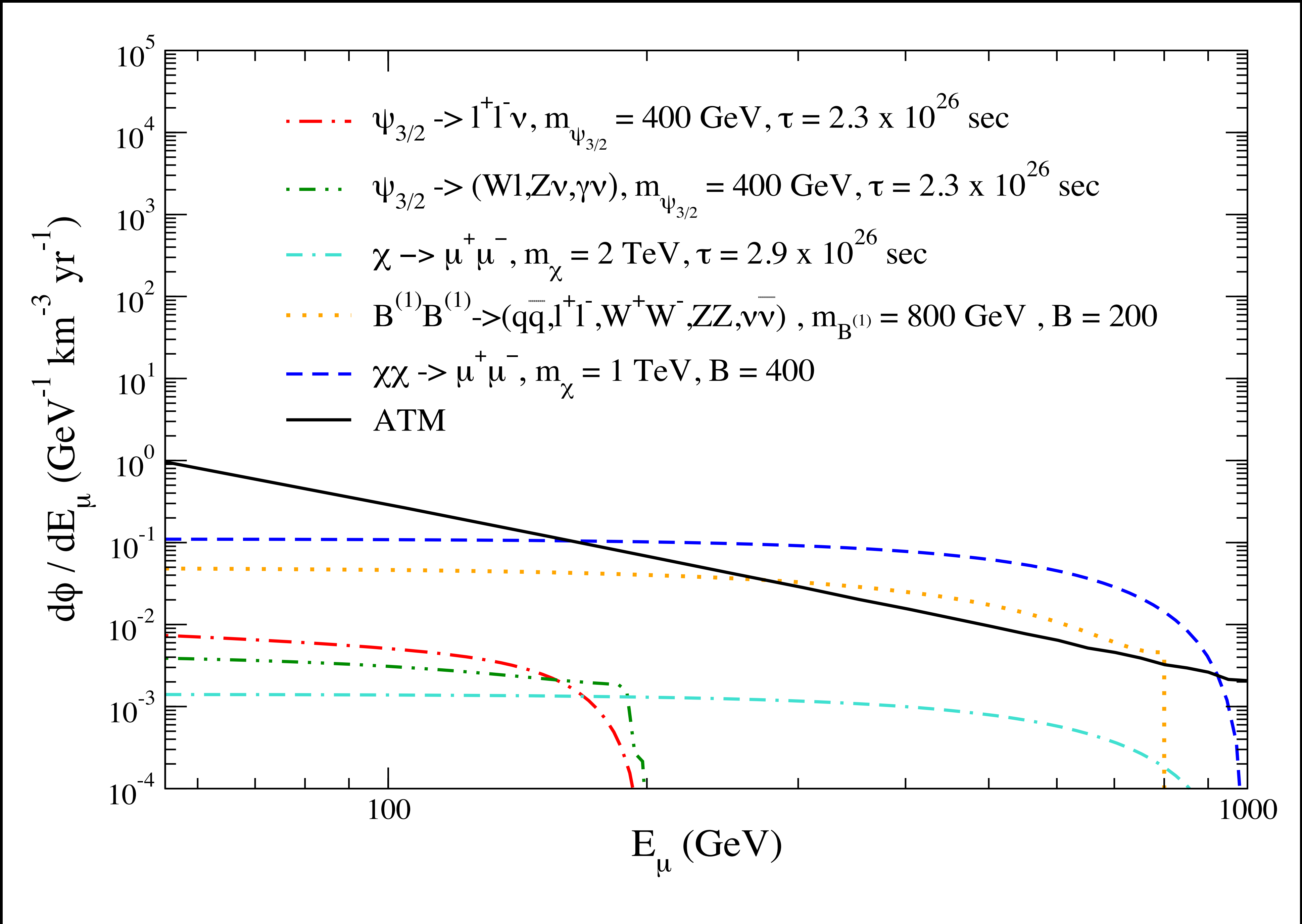
Model parameters used to explain Fermi/LAT and PAMELA

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	$B = 400$

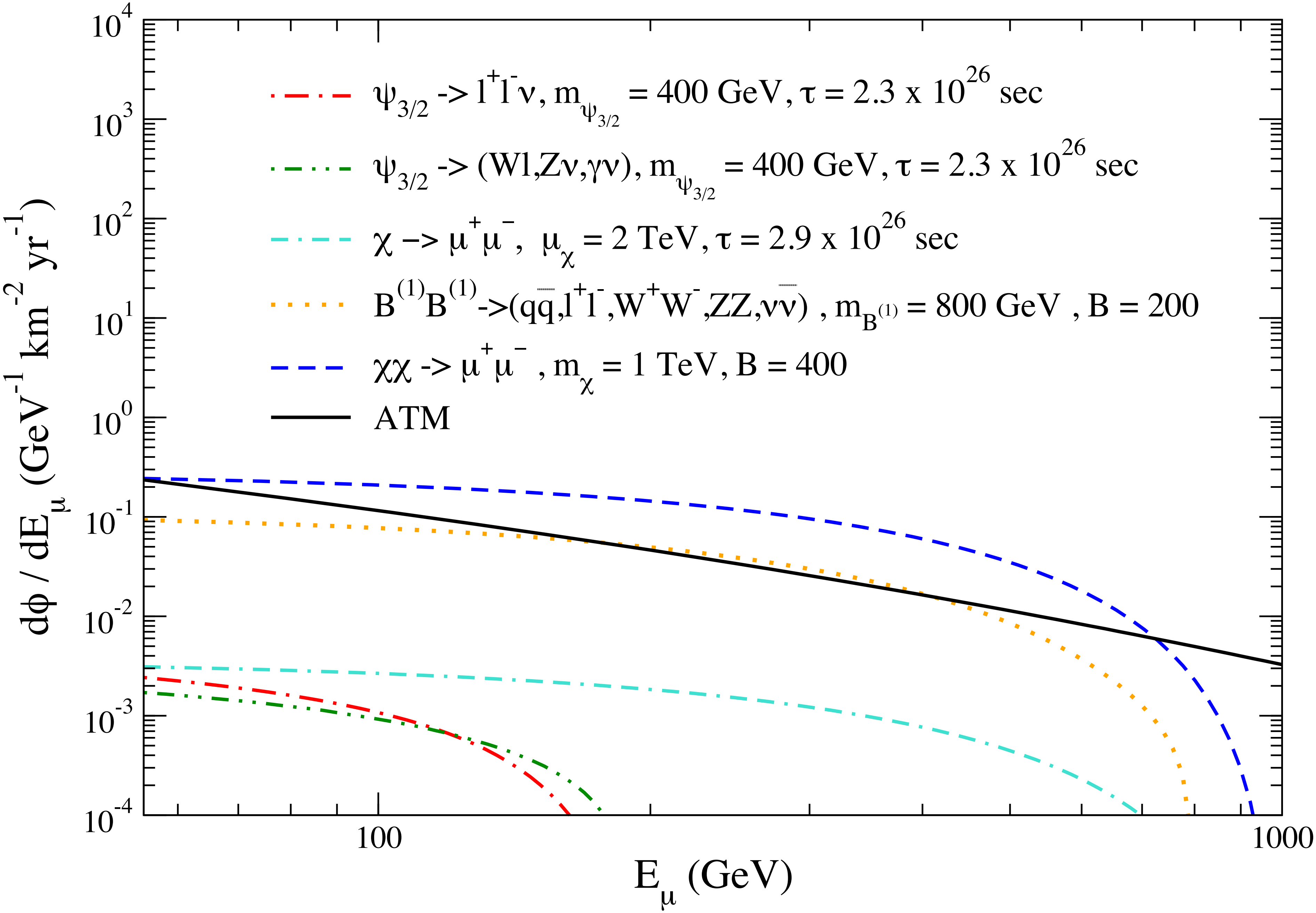
$\chi\chi \to \mu^+ \mu^-$ 1 TeV B

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

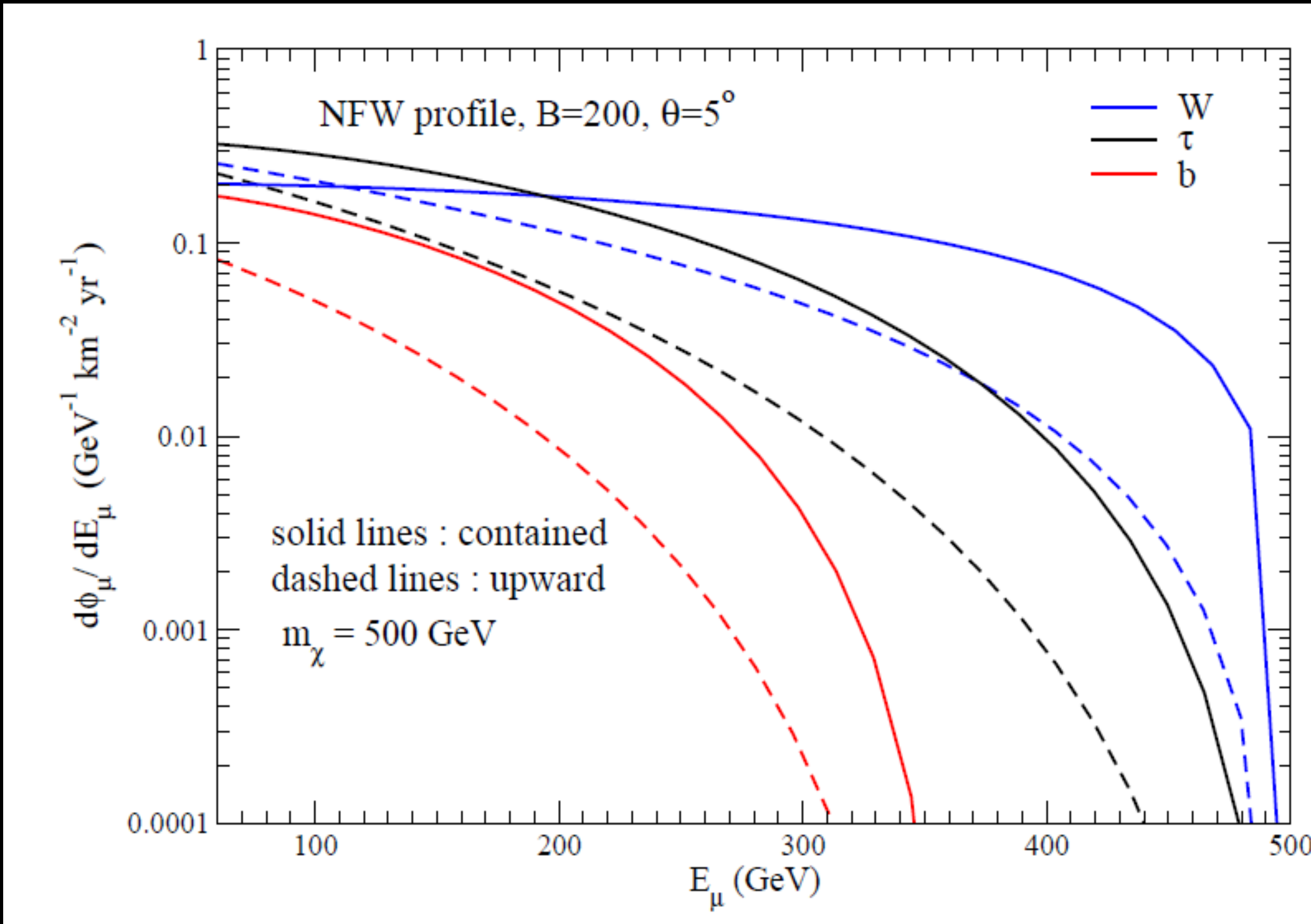
Contained Muon Flux



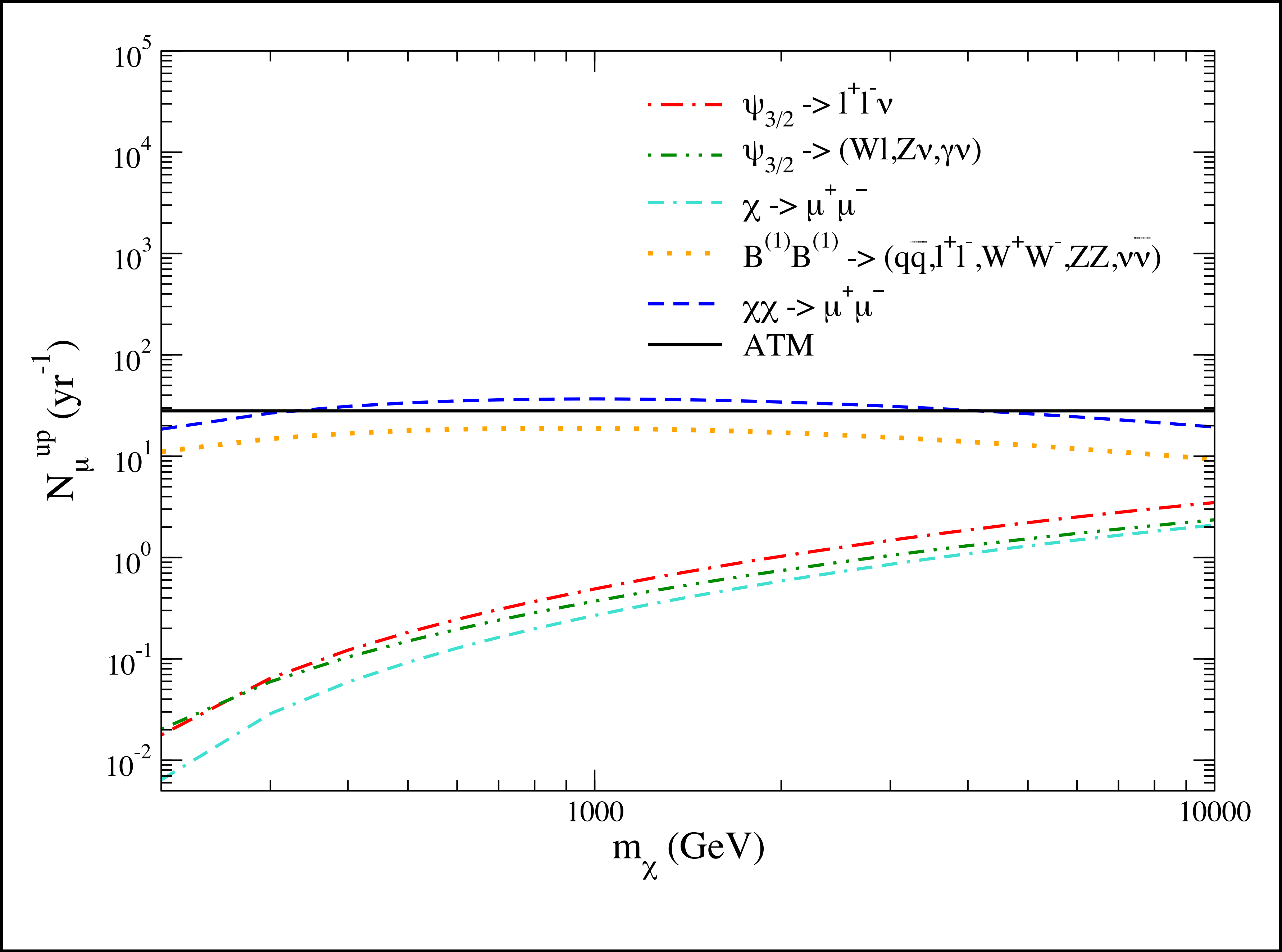
Upward Muon Flux



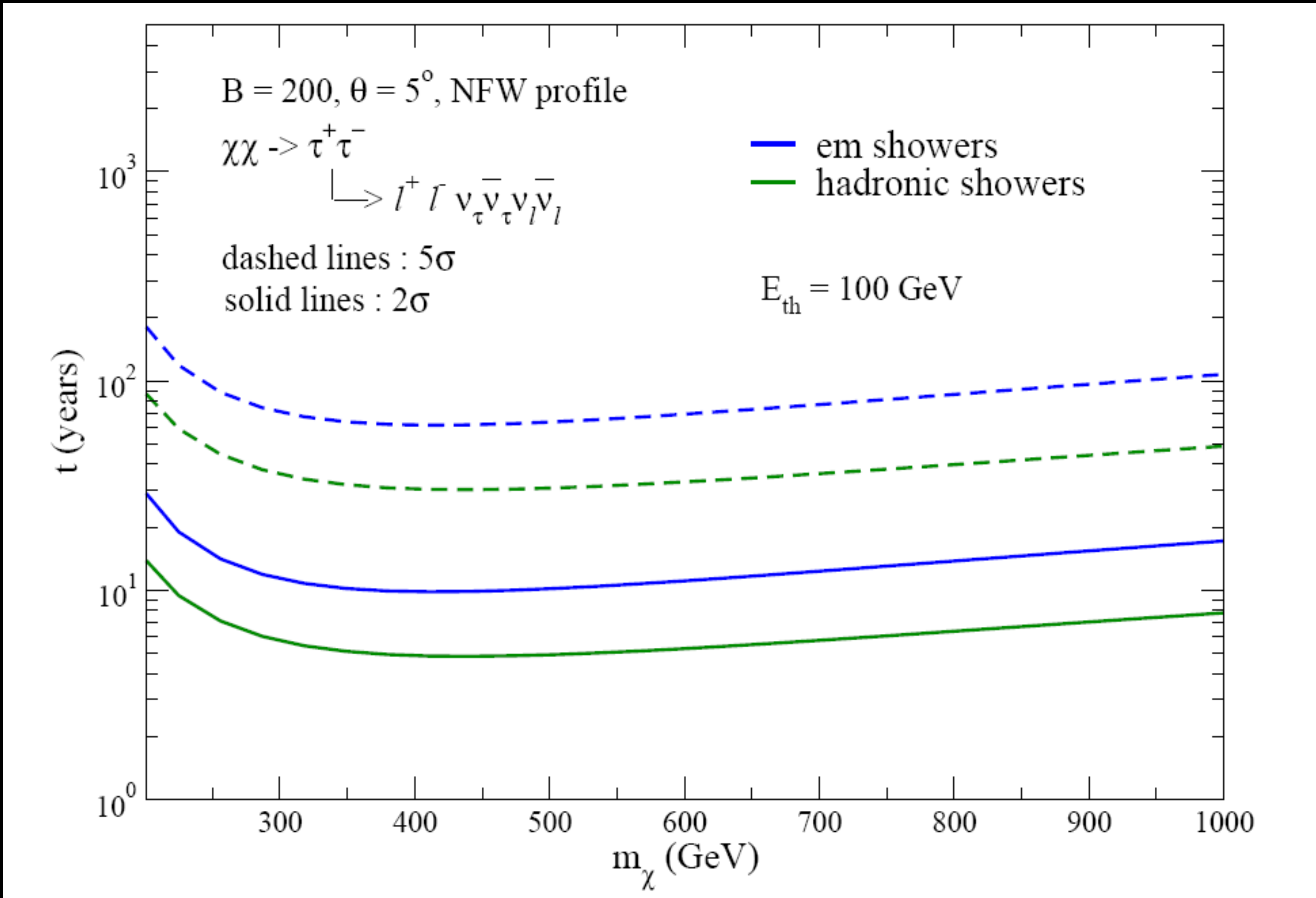
Muon Flux for Different DM Annihilation Modes



Upward Muon Rates with $E_\mu^{th} = 50\text{GeV}$



Hadronic and EM Showers



DM Detection with NeutrinoTelescopes

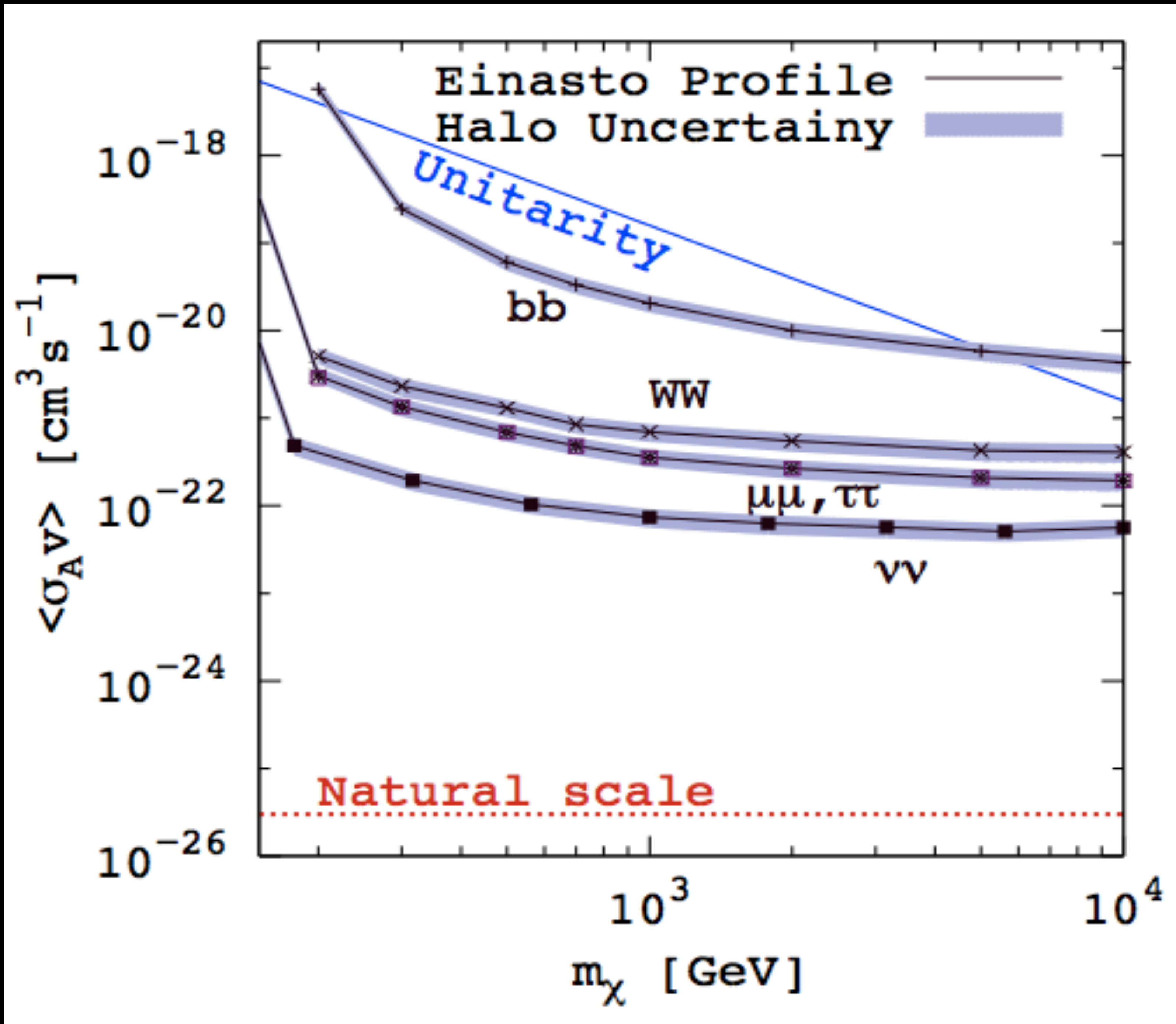
IceCUBE : 1 km^3 neutrino detector at South Pole

- 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; PRD 84 (2011))



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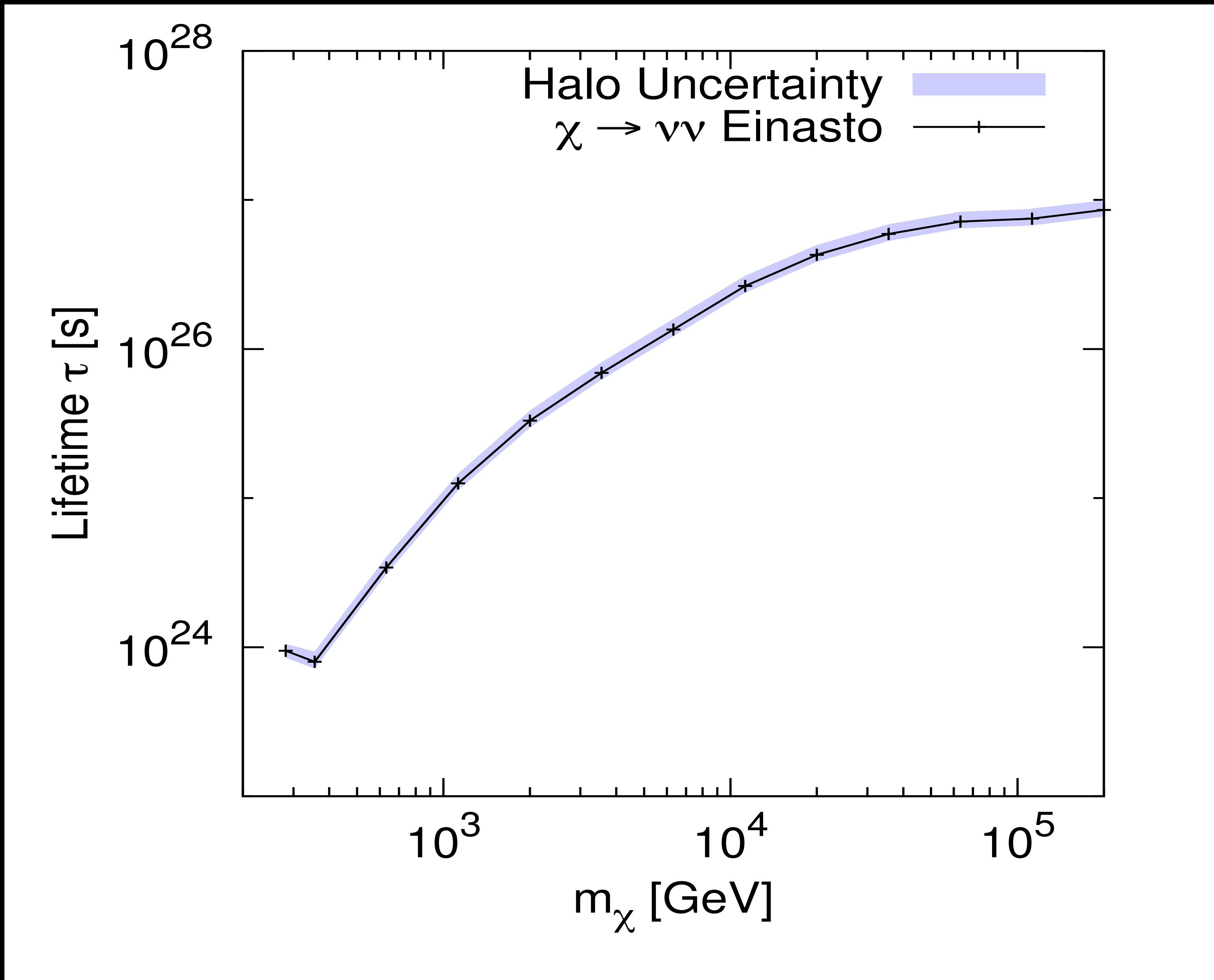

Summary

- 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