

Theoretical Elementary Particle Physics

Ina Sarcevic

(funded by DOE HEP since 1989)

Current group members:

- Anastasios Taliotis (postdoc)
- Arif Erkoca (graduate student); Galileo Circle Scholar
- Rikard Enberg (visitor) ; former postdoc, now faculty at Uppsala University, Sweden

Former Group Members

(partial list)

- Irina Mocioiu (postdoc, now faculty at Penn State)
- Jessica Uscinski (Ph.D. 2008, now faculty at American University in Washington, DC)
- Rikard Enberg (postdoc, now faculty at Uppsala University, Sweden)
- Greg Mahlon (postdoc, now faculty at Penn State)
- Jamal Jalilian-Marian (postdoc, now faculty at Baruch College, New York City)
- Peter Lipa (postdoc, now staff at University of Arizona Radiology Department)
- Kostas Orginos (postdoc, joint with Toussaint, now faculty at College of William and Mary)
- Sharada Iyer Dutta (Ph.D. 2000, research faculty at SUNY Stony Brook until 2008)
- Raj Gandhi (postdoc, now staff at HRI, India)

Current Collaborators

- Hallsie Reno (U of Iowa)
- Graciela Gelmini (UCLA)
- Chris Quigg (Fermilab)
- Gilard Perez (Weizmann, Israel)
- Haim Goldberg (Northeastern U)
- Anna Stasto (Penn State)
- Irina Mocioiu (Penn State)
- Rikard Enberg (Uppsala U)
- Richard Brower (Boston U)
- Chung-I Tan (Brown U)

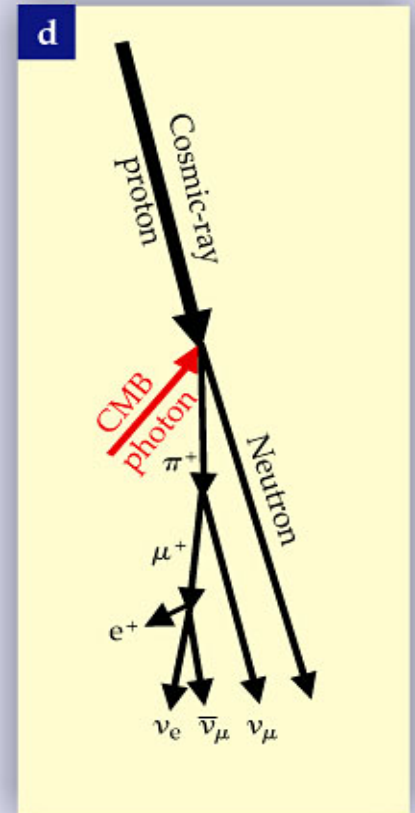
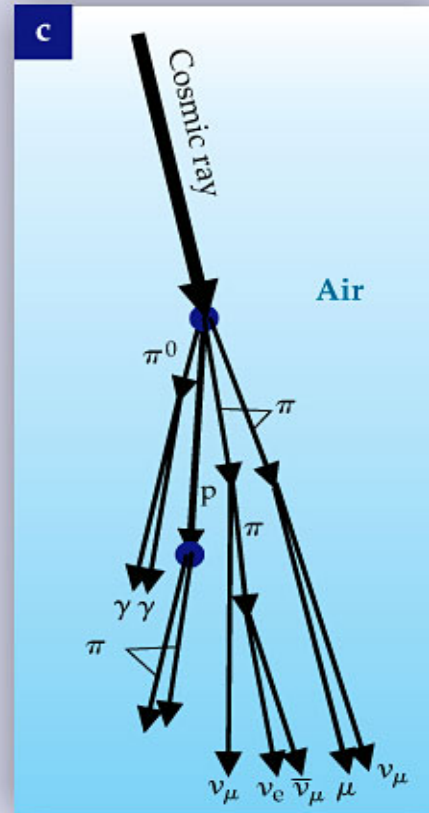
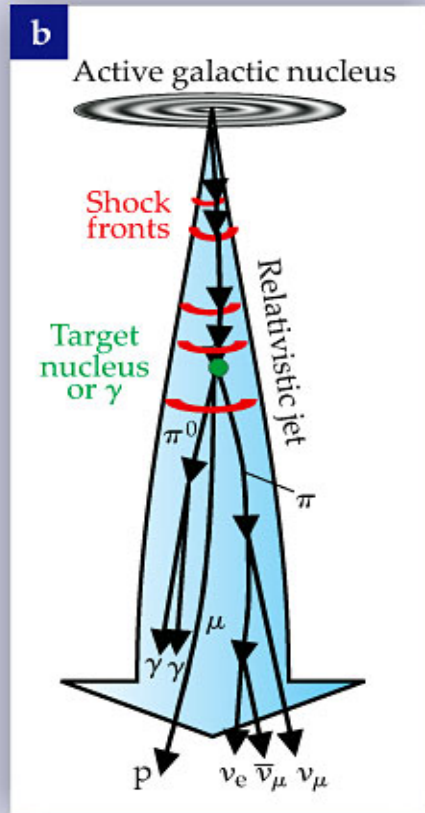
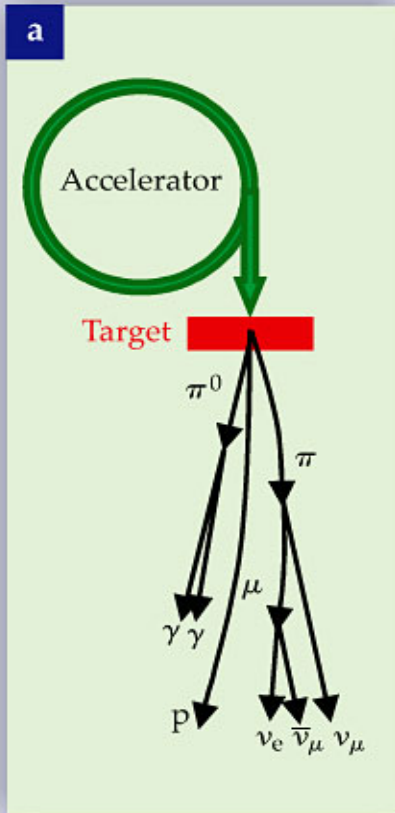
Ultrahigh Energy Neutrinos as Probes of Particle Physics

- Ultrahigh Energy Neutrino Interactions
- Probing SUSY and LED with Neutrinos
- Prompt Neutrinos from Charm
- Neutrino Signals of Dark Matter

Collider Phenomenology

- Black Hole Production at the LHC
- Heavy Quarks, Prompt Photons and Minijets
- Multiplicities, Particle Correlations at the LHC

Cosmic Accelerators



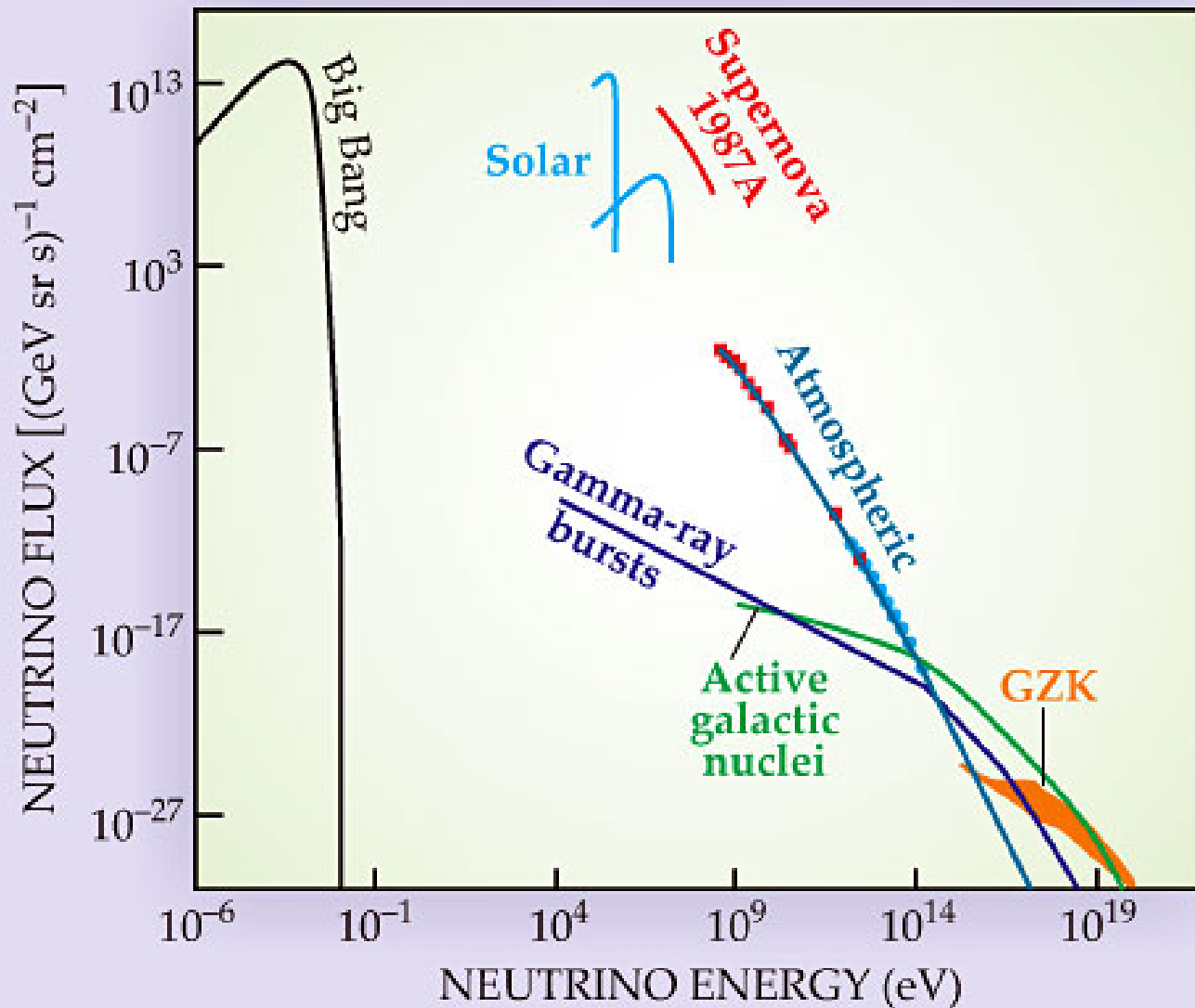
Observed High Energy Particles from the Sky

- Cosmic Rays (energy up to 10^{21} eV)
- γ - rays (energy up to 10^{13} eV)
- Atmospheric Neutrinos (energy up to 10^9 eV)

Cosmic Neutrinos

- Cosmic Neutrino Background
($T \sim 1.9\text{K}$, i.e. $E \sim 10^{-4} \text{ eV}$)
- Solar Neutrinos (MeV energies)
- SN 1987A (MeV energies)
- Atmospheric Neutrinos (GeV to TeV energies)
- Extragalactic Neutrinos (AGN, GRB, cosmogenic, etc; GeV to EeV energies)
- Neutrinos from Dark Matter Annihilation

Neutrino fluxes



Ultra-high Energy Neutrinos as Probes of Particle Physics

- Energies much higher than currently available in colliders
- UHE neutrinos could produce SUSY particles, microscopic black holes, new particles predicted in beyond the Standard Model theories
- Interactions of dark matter or dark matter decay could produce neutrinos, directly or via decay of leptons

Neutrino Detection

- Detection of neutrinos depends on their interactions, i.e. cross section
- Muon neutrinos interacting with “matter”, i.e. nucleons, producing muons
- Muons are charged, so they leave charged tracks in the neutrino detector

- The event rate for “downward” muons from neutrino interactions

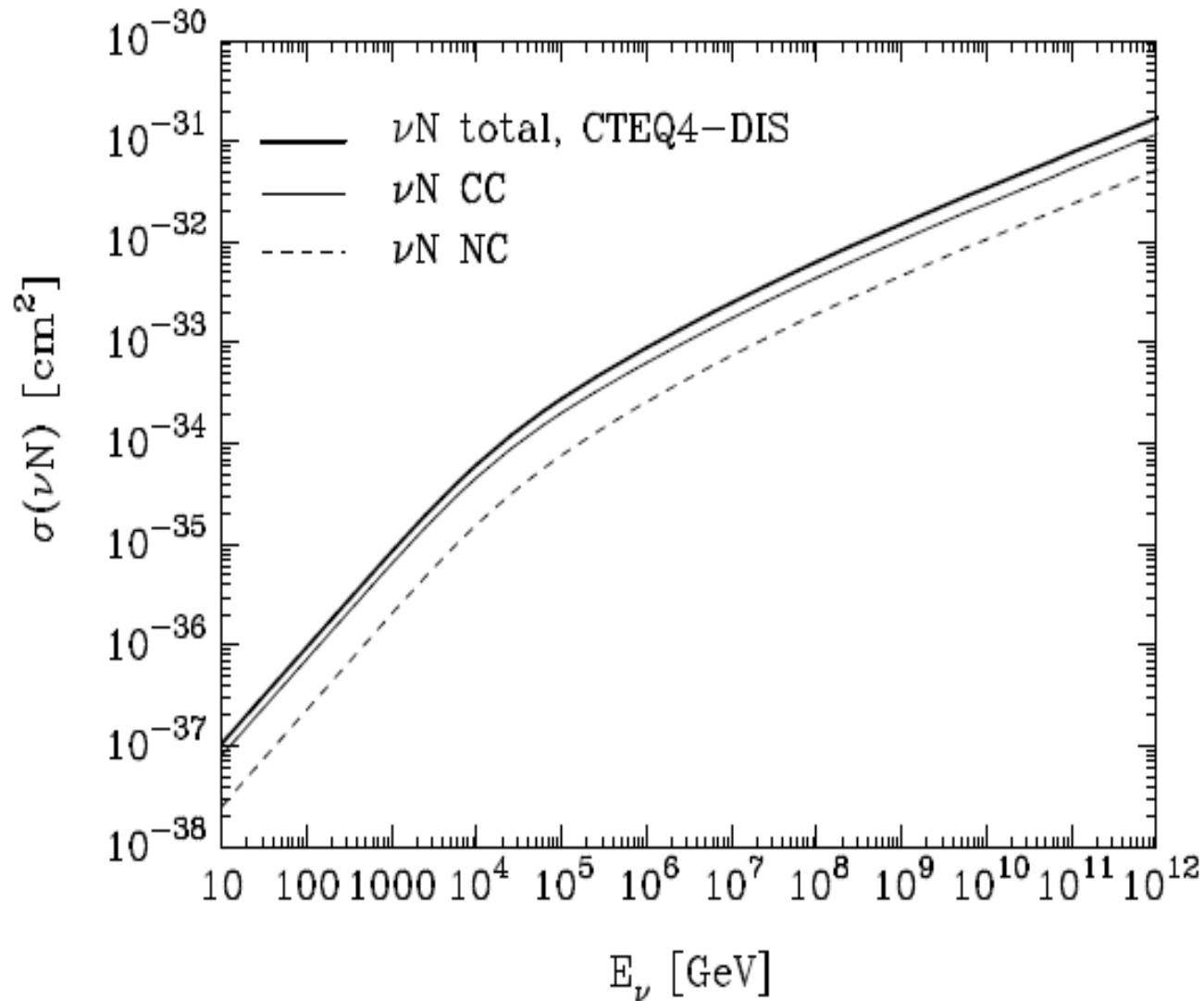
$$R = V \int dE_\nu \sigma_{cc}(E_\nu) F_\nu(E_\nu)$$

- The event rate for “upward” muons from neutrino interactions

$$R = N_A A \int dE_\nu \sigma_{cc} R_\mu S(E_\nu) F(E_\nu)$$

where $F_\nu(E_\nu)$ is neutrino flux at the source, $S(E_\nu)$ is neutrino attenuation and R_μ is muon range

Neutrino Cross Sections



Neutrino Telescopes

- AMANDA/IceCube/Hypercube
- Antares, Nestor, KM3Net
- RICE
- Anita
- Pierre Auger
- Euso, OWL

Neutrinos as Probes of Dark Matter

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

Erkoca, Reno and Sarcevic, arXiv:1009.2068, Phys. Rev. D 82 (2010).

Erkoca, Reno and Sarcevic, Phys. Rev. D80 (2009).

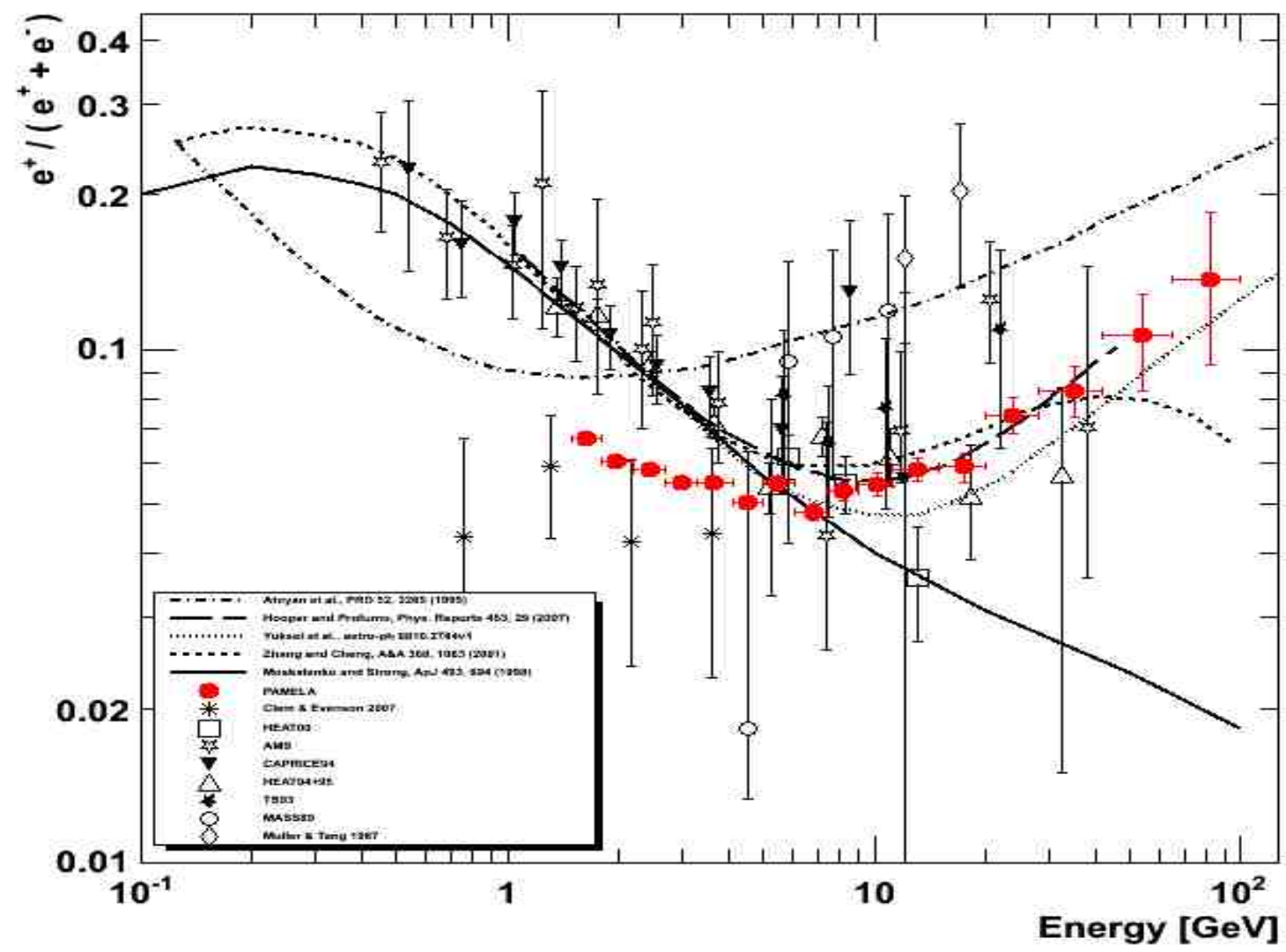
- Dark matter's presence is inferred from gravitational effects on visible matter at astronomical scales. Observations imply 23% dark matter and 4% of the total density of the Universe is baryonic matter

No viable candidate for dark matter in the Standard Model

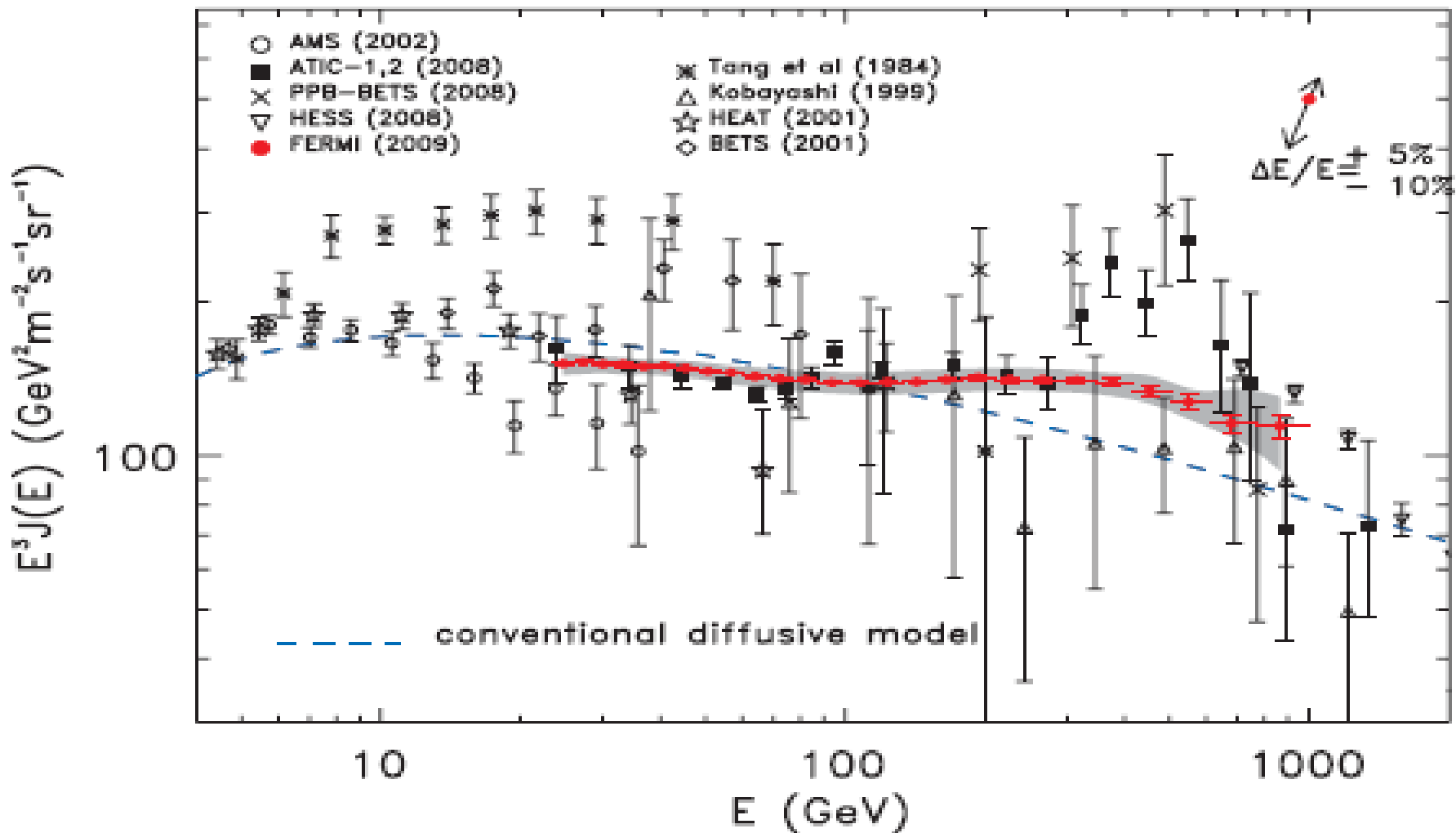
Dark Matter Searches

- Direct searches:
look for DM interactions with target nuclei (XENON, DAMA, CoGeNT)
- Indirect searches:
DM annihilation producing electrons, positrons, γ -rays (PAMELA, ATIC, FERMI/LAT, HESS ...) and neutrinos (IceCube, KM3Net...)

PAMELA Positron Fraction: Dark Matter?



FERMI Cosmic Ray Electron Spectrum



- Neutrinos from DM annihilation in the Galactic Center

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

- Probing Dark Matter models with Neutrinos from the Galactic Center

Erkoca, Reno and Sarcevic, arXiv:1009.2068, accepted for publication in Phys. Rev. D82 (2010)

- 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, etc)

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

Neutrino Flux from the Galactic Center generated by DM annihilation

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

- Neutrino induced upward and contained muon flux and cascades (showers)
- Incorporate SuperK limits
- Predictions for IceCube and Km3Net

Neutrino Flux from DM Annihilation in the Galactic Center

Neutrinos flux is given by:

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

For the case of DM annihilation:

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

while for the DM decay:

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

Define $\langle J_n \rangle_\Omega$ as:

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

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

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

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

Neutrino Flux at the Production

We have considered neutrinos produced directly or through decays of leptons, quarks and gauge bosons:

$$\chi\chi \rightarrow \nu_i \bar{\nu}_i$$

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

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

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

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

- Detection: neutrinos interacting below detector or in the detector producing muons \Rightarrow upward and contained muon flux and cascade/shower events

- Energy loss of the muons over a distance dz :

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

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

$$\frac{d\phi_{\mu}}{dE_{\mu}} = \int_{E_{\mu}}^{E_{max}} dE_{\nu} \frac{d\phi_{\nu}}{dE_{\nu}} \frac{N_A \rho}{2} \frac{d\sigma_{\nu}}{dE_{\mu}}$$

Upward muon flux is given by

$$\begin{aligned} \frac{d\phi_{\mu}}{dE_{\mu}} &= \int_0^{R_{\mu}(E_{\mu}^i, E_{\mu})} e^{\beta \rho z} dz \int_{E_{\mu}^i}^{E_{max}} dE_{\nu} \frac{d\phi_{\nu}}{dE_{\nu}} \\ &\times P_{surv}(E_{\mu}^i, E_{\mu}) \frac{N_A \rho}{2} \frac{d\sigma_{\nu}}{dE_{\mu}} \end{aligned}$$

Hadronic Shower Flux

The hadronic shower flux is given by:

$$\frac{d\phi_{\mu}}{dE_{\mu}} = \int_{E_{sh}}^{E_{max}} dE_{\nu} \frac{d\phi_{\nu}}{dE_{\nu}} \frac{N_A \rho}{2} \times$$
$$\times \frac{d\sigma_{\nu}(E_{\nu}, E_{\nu} - E_{sh})}{dE_{\mu}}$$

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 :

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

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

- $\chi\chi \rightarrow \tau^+\tau^-, \mu^+\mu^-$ channels :

$$\frac{dN_\nu}{dE_\nu} = \begin{cases} \frac{1}{E_{in}} \left(\frac{5}{3} - 3x^2 + \frac{4}{3}x^3 \right), & \mu \rightarrow \nu_\mu e \nu_e \\ \frac{0.36}{E_{in}} (1 - 3x^2 + 2x^3), & \tau \rightarrow \nu_\tau \mu \nu_\mu \end{cases}$$

where $x = \frac{E_\nu}{E_{in}} \leq 1$ and $E_{in} = m_\chi$.

Tau leptons can also decay into tau neutrinos via $\tau \rightarrow \nu_\tau M$ or $\tau \rightarrow \nu_\tau X$ where M and X are mesons and hadrons, respectively.

$$\frac{dN_\nu}{dE_\nu} = \frac{B_f}{E_{in}} \frac{1}{r_M} \quad \text{when} \quad \frac{E_\nu}{E_{in}} < r_M$$

for mesons where $r_M=0.99, 0.81, 0.52$ and $B_f=0.12, 0.26, 0.13$ for $M=\pi, \rho, a_1$ respectively, and

$$\frac{dN_\nu}{dE_\nu} = \frac{0.13}{0.3 E_{in}} \quad \text{when} \quad \frac{E_\nu}{E_{in}} < 0.3$$

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

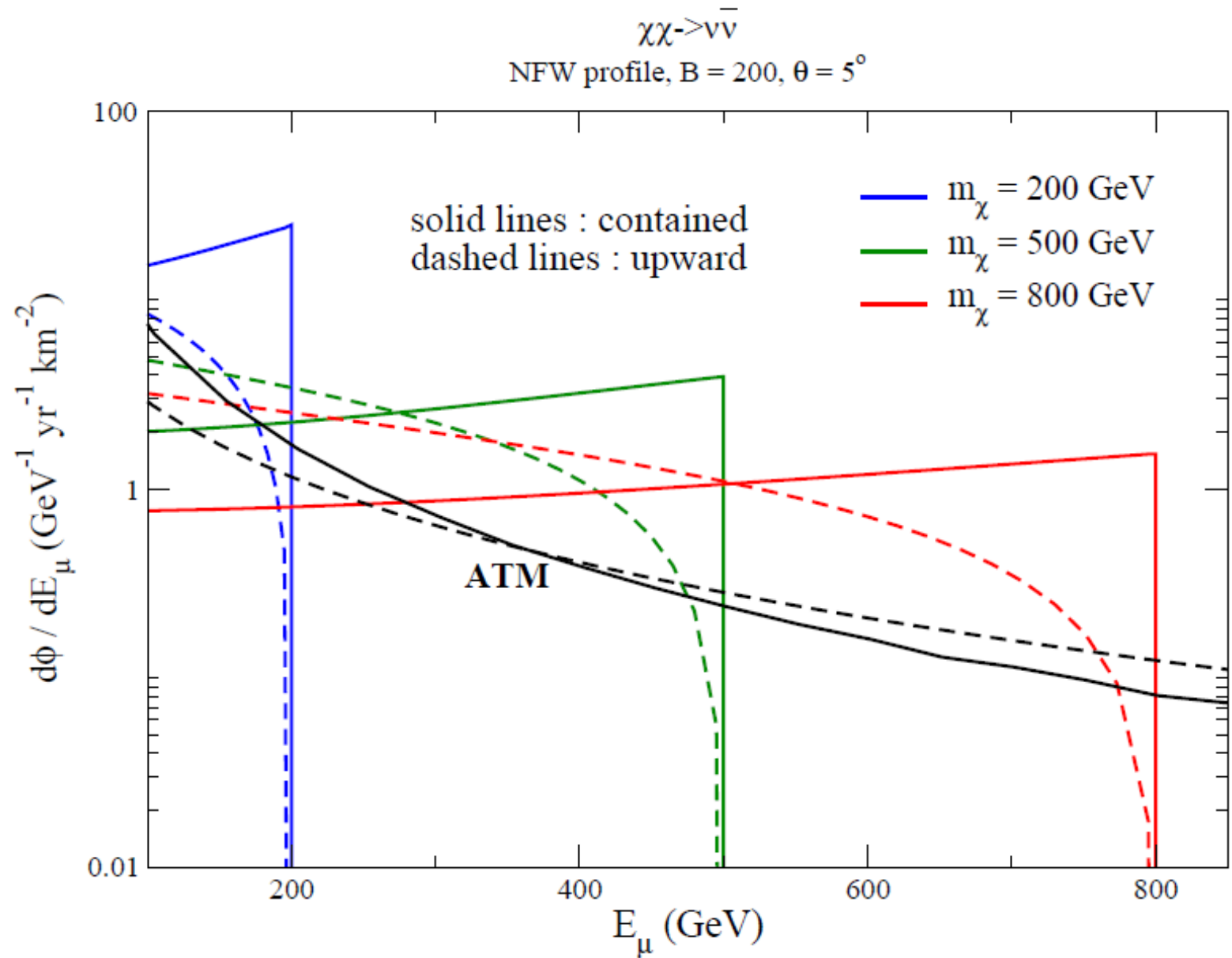
$$(n_f, B_f) = \begin{cases} (1, 0.105) & W \text{ decay,} \\ (2, 0.067) & Z \text{ decay.} \end{cases}$$

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

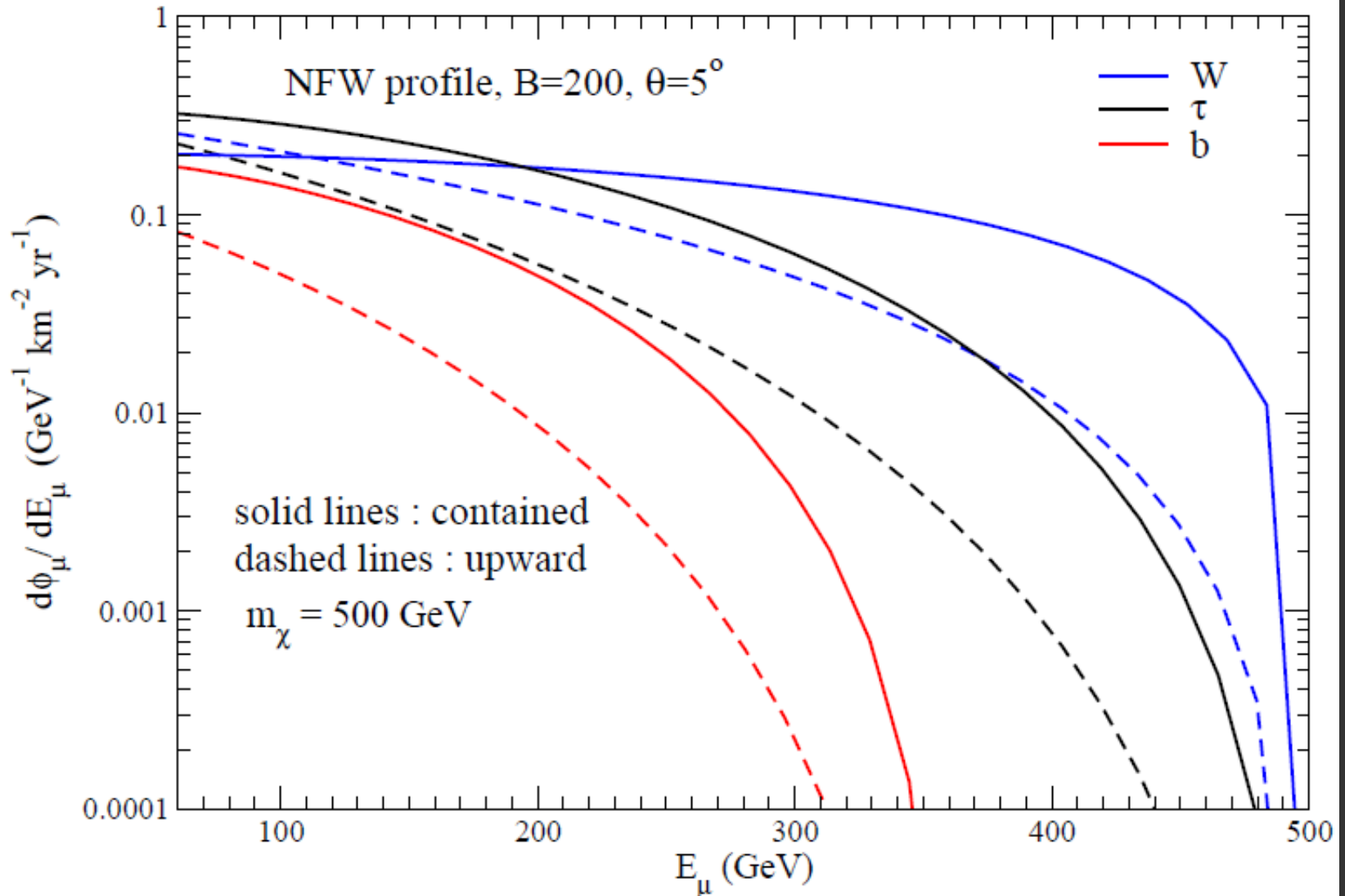
$$\left(\frac{dN_\nu}{dE_\nu}\right)_{t\bar{t}}^{\text{rest}} = \left(\frac{dN_\nu}{dE_\nu}\right)_{W+W^-} + \left(\frac{dN_\nu}{dE_\nu}\right)_{b\bar{b}}$$

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

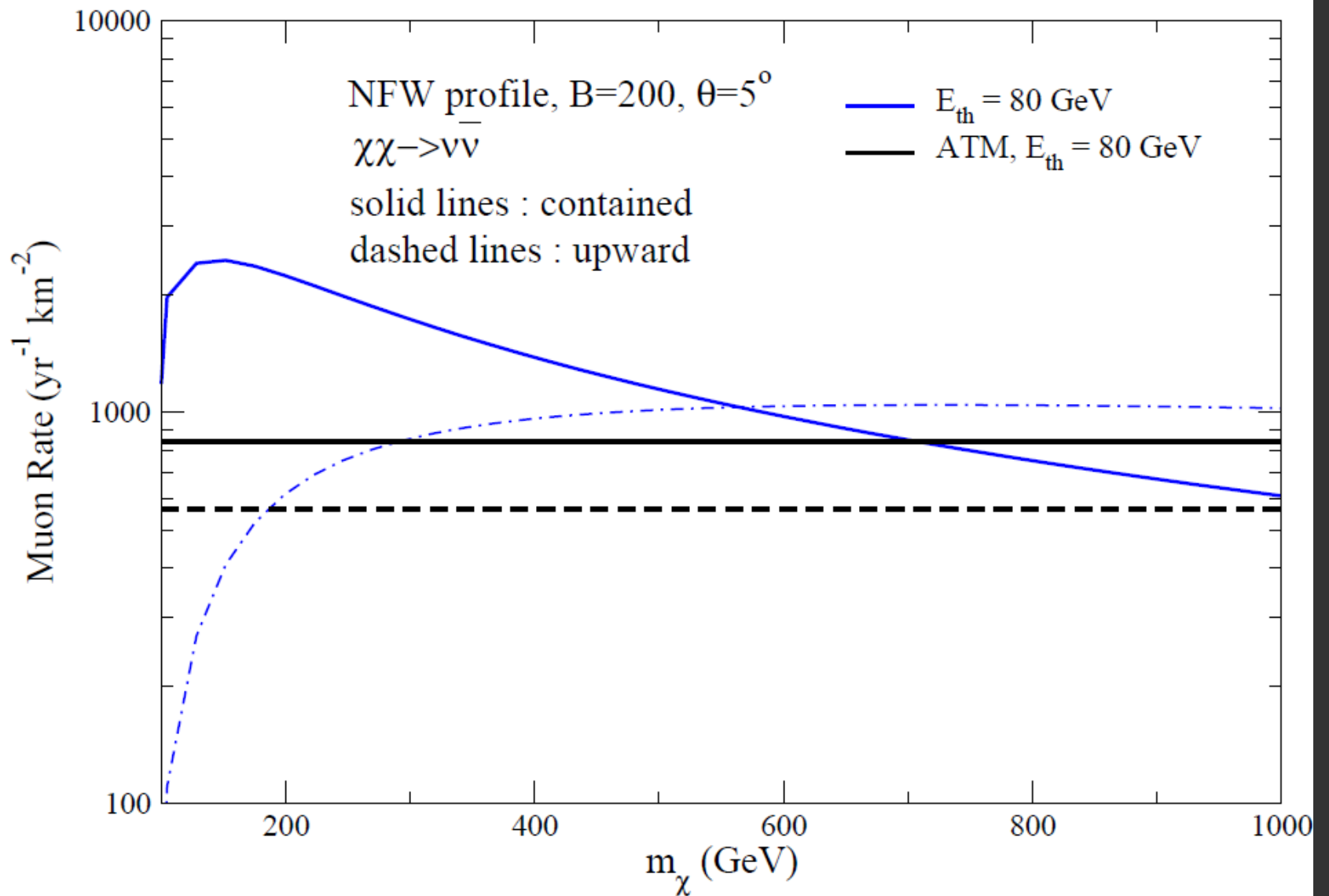
Muon Flux



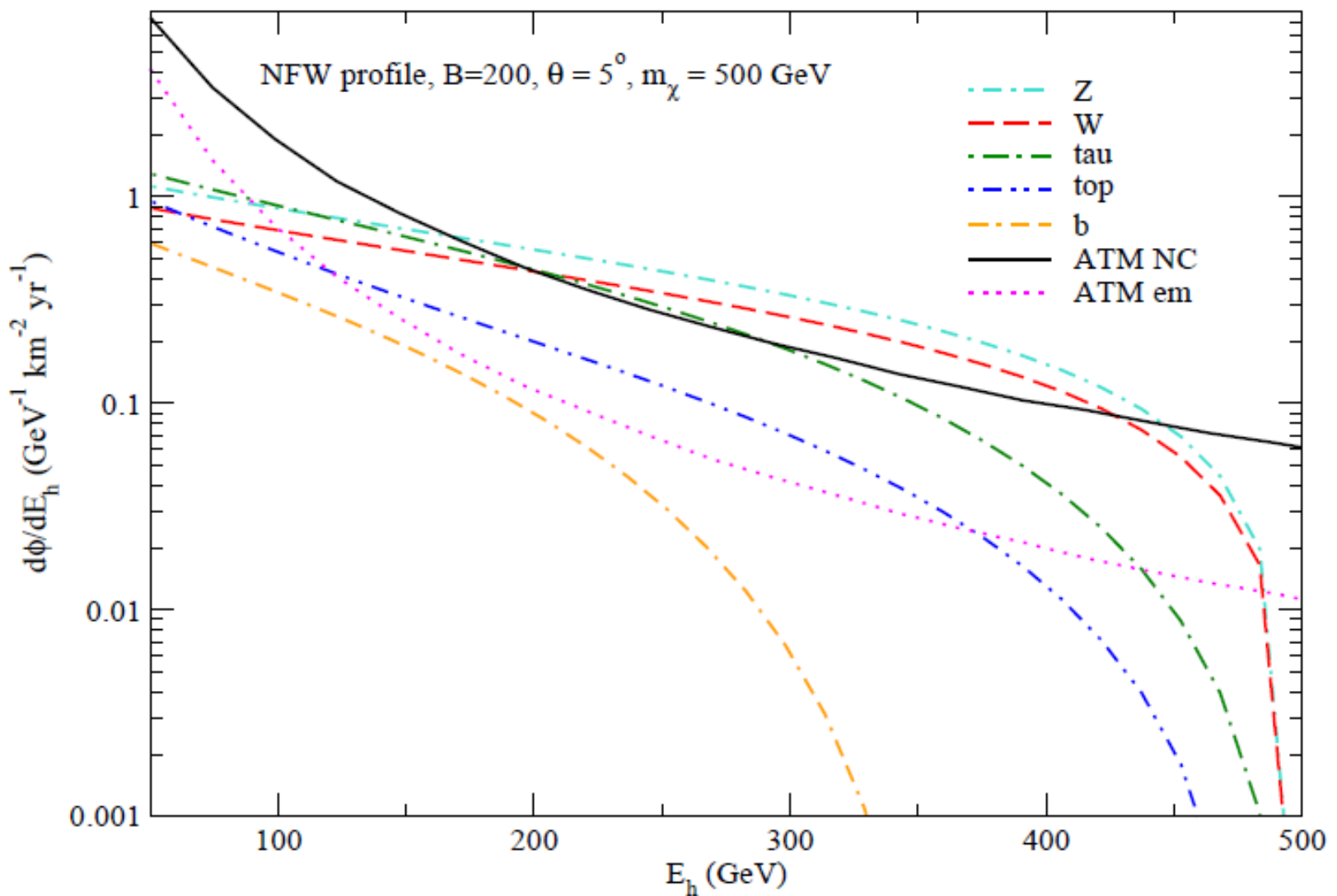
Muon Flux for Different DM Annihilation Modes



Muon Rates



Hadronic Shower Spectra without track-like events

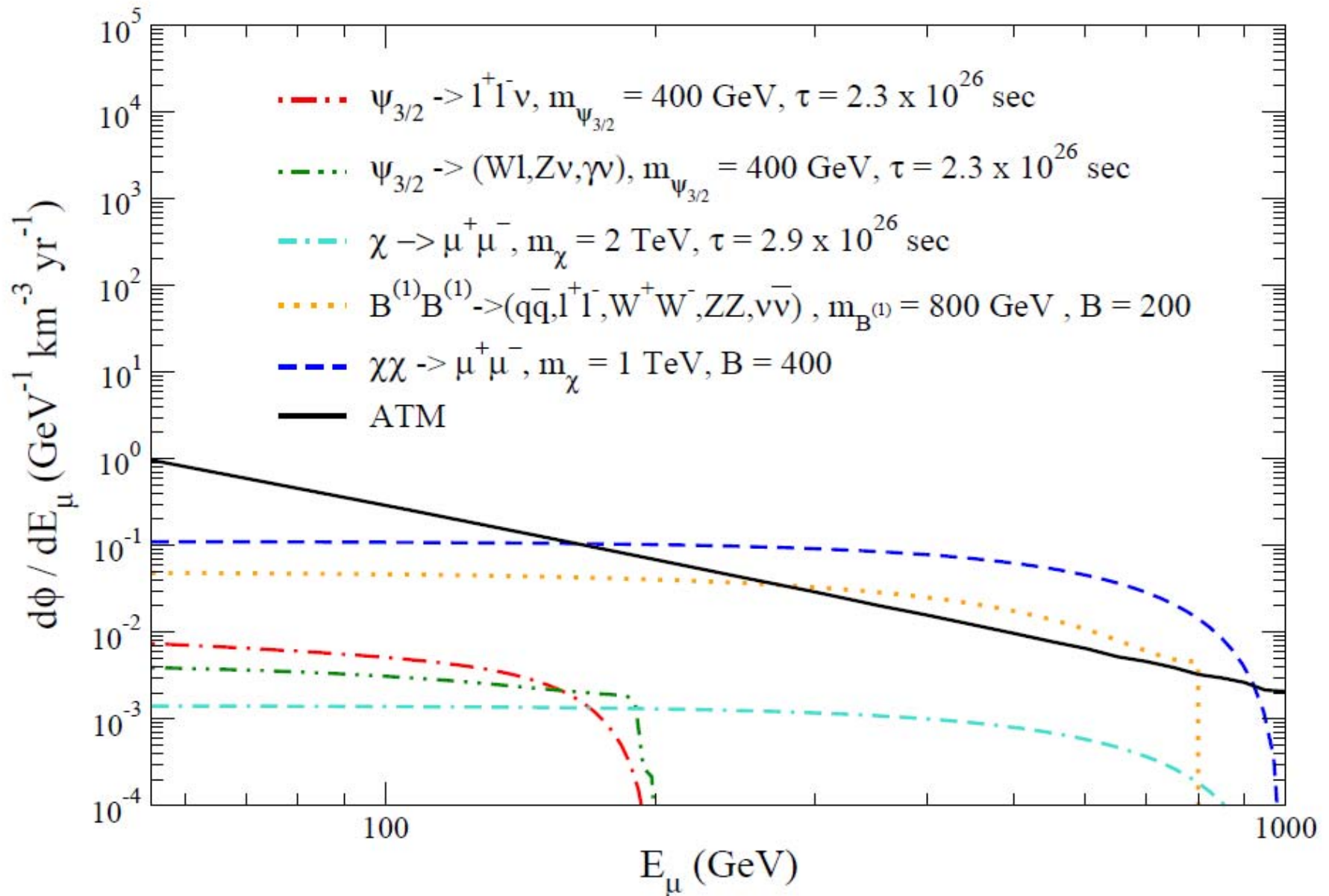


Probing the Nature of Dark Matter with Neutrinos

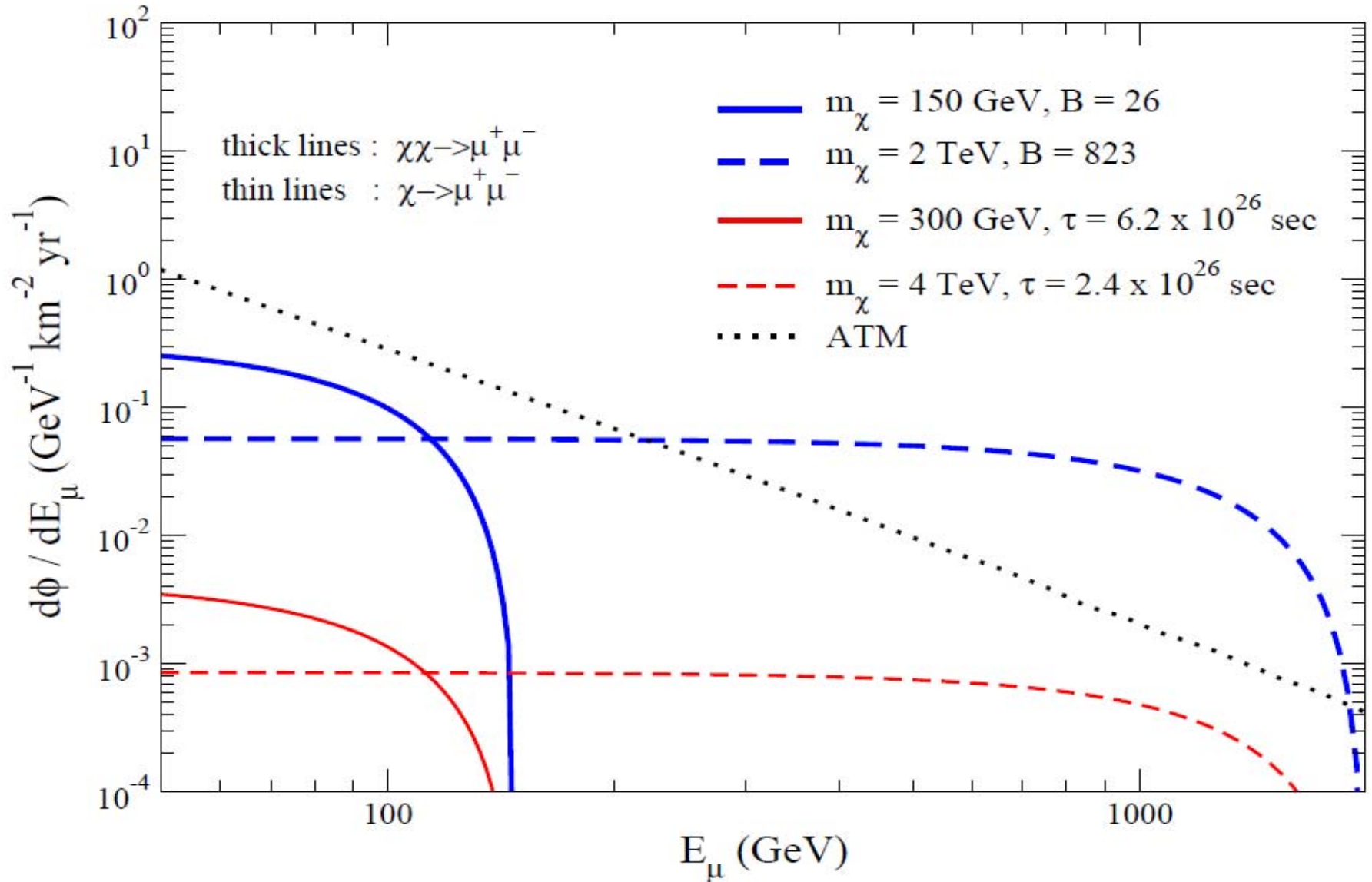
Erkoca, Reno and Sarcevic, arXiv:1009.2086,
accepted for publication in Phys. Rev. D82 (2010)

- DM candidates: gravitino, Kaluza-Klein particle, leptophilic DM particle
- 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
$\psi_{3/2} \rightarrow l^+ l^- \nu$ $B_\tau = 2.3$	$N_\mu^{ct}(50^\circ)$	4.94	11.15	13.8	15.3	16.2	18.1	19.0	19.3	19.5	19.6
	$N_\mu^{up}(50^\circ)$	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
	$\psi_{3/2} \rightarrow (Wl, Z\nu, \gamma\nu)$ $B_\tau = 2.3$	$N_\mu^{ct}(50^\circ)$	6.1	8.4	8.9	9.1	9.15	9.2	9.2	9.2	9.2
$N_\mu^{up}(50^\circ)$		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
$\chi \rightarrow \mu^+ \mu^-$ $B_\tau = 2.9$		$N_\mu^{ct}(50^\circ)$	2.13	6.45	8.43	9.5	10.2	11.5	12.2	12.4	12.5
	$N_\mu^{up}(50^\circ)$	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
	$B^{(1)} B^{(1)} \rightarrow \dots$ $B = 200$	$N_\mu^{ct}(10^\circ)$	14.2	9.8	7.2	5.6	4.6	2.4	1.25	0.84	0.63
$N_\mu^{up}(10^\circ)$		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
$\chi\chi \rightarrow \mu^+ \mu^-$ $B = 400$	$N_\mu^{ct}(10^\circ)$	40.19	29.58	22.01	17.39	14.3	7.59	3.90	2.63	1.98	1.59
	$N_\mu^{up}(10^\circ)$	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 km³ 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

- Quarter of the Universe is composed of dark matter but the microscopic identity of dark matter remains a deep mystery \Rightarrow Neutrinos can be used to detect dark matter and probe its physical origin
- Contained and upward muon flux is sensitive to the DM annihilation/decay mode and to the mass of dark matter particle

- Combined measurements of cascade events and muons from neutrino interactions when neutrinos are produced in DM annihilation in the Galactic Center with IceCube+DeepCore and KM3Net look promising
- Neutrinos can provide valuable information about properties of DM, i.e whether dark matter is a gravitino, Kaluza-Klein DM, or a particle in leptophilic models ...)

Future Plans:

- Evaluate Sommerfeld Enhancement, i.e. dark matter annihilation cross section and its effect on DM signal
- Consider the effect of energy loss of pions, kaons and charmed mesons on Waxman-Bachall neutrino bound
- Multiplicities and particle correlations at the LHC in AdS/CFT approach
- Neutrino Cross Sections at Ultrahigh Energies and small- x PDFs.

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Publications in 2009-2010

1. “High Energy Neutrinos from Charm in Astrophysical Sources”, (with R. Enberg and M. H. Reno), *Phys. Rev. D* **79**, 053006 (2009).
2. “Higgs Production and Decay from TeV Scale Black Holes at the LHC”, (with A. E. Erkoca and G. Nayak), *Phys. Rev. D* **79**, 094011 (2009).
3. “Muon Flux from Dark Matter Annihilation”, (with A. E. Erkoca and M. H. Reno), *Phys. Rev. D* **80**, 043514 (2009).
4. “Neutrino Fluxes from Astrophysical Sources, the Role of Neutrinos from Charmed Meson Production and Decay”, *Nucl. Instrum. Meth.* **A604** 88 (2009).
5. “High Energy Neutrinos from Charm in Astrophysical Sources”, in the Proceedings of the *10th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2009)*, AIP Conf. Proc. **1182** 40 (2009).
6. “Muon Flux and Showers from Dark Matter Annihilation in the Galactic Center”, (with A. E. Erkoca, G. Gelmini and M. H. Reno), *Phys. Rev. D* **81**, 096007 (2010).
7. “String-Gauge Dual Description of Deep Inelastic Scattering at Small- x ”, (with R. C. Brower, M. Djuric, and C-I Tan), arXiv:1007.2259 [hep-ph], accepted for publication in *JHEP*.
8. “Probing Dark Matter Models with Neutrinos from the Galactic Center”, (with A. E. Erkoca and M. H. Reno), arXiv:1009.2068 [hep-ph], accepted for publication in *Phys. Rev. D*.

Invited Talks in 2010

1. “Neutrinos as Signature of Dark Matter”, invited talk presented at Aspen Winter Conference on *The Revolution in Particle Physics is Here*, Aspen, Colorado, January 15-21, 2010.
2. “Dark Matter Signals with Neutrinos”, talk at American Physical Society Annual April Meeting, Washington, DC, February 13-16, 2010.
3. “Neutrinos as Signature of Dark Matter”, invited talk presented at workshop on *Dark Matter 2010*, Marina del Rey, California, February 23-27, 2010.
4. “Neutrinos as Probes of Particle Physics”, invited seminar, Department of Physics and Astronomy, UCLA, Los Angeles, California, February, 2010.
5. “Neutrinos as Signature of Dark Matter”, invited talk, *Snowbird Workshop on Particle Astrophysics, Astronomy and Cosmology (SnowPAC)*, Snowbird, Utah, March 23-30, 2010.
6. “Probing Dark Matter with Neutrinos”, invited seminar, Department of Physics and Astronomy, University of Iowa, April 15, 2010.
7. “Probing Dark Matter with Neutrinos”, invited seminar, Physics Department, University of Maryland, College Park, Maryland, May 14, 2010.
8. “Neutrinos as Signature of Dark Matter”, invited talk, Workshop on *Dark Matter: Its Origin, Nature and Prospects for Detection*, Galileo Institute for Theoretical Physics, Florence, Italy, June 2010.
9. “Small x Parton Distributions and Ultrahigh Energy Neutrino Cross Sections”, Workshop on *Small x Parton Distributions*, Kavala, Greece, June 23-27, 2010.
10. “Probing Dark Matter with Neutrinos”, invited seminar, Physics Department, Arizona State University, Phoenix, Arizona, November 10, 2010.
11. “Probing Dark Matter with Neutrinos”, invited talk to be presented at Conference on Elementary Particle Physics, Astrophysics and Cosmology (Miami 2010) , Lago Mar Resort, Ft. Lauderdale, Florida, December 14-19, 2010.
12. “Probing Dark Matter with Neutrinos”, invited talk to be presented at Aspen Winter Conference on “Indirect and Direct Detection of Dark Matter”, Aspen, Colorado, February 6-12, 2011.
13. “Probing Dark Matter with Neutrinos”, invited talk to be presented at Snowbird Workshop on Particle Astrophysics, Astronomy and Cosmology (SnowPAC 2011), Snowbird, Utah, January 30 - February 5, 2011.

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"QUARKS, NEUTRINOS, Dark Matter. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"

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: $\Gamma_A = C/2$

- ★ 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)

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 probability 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

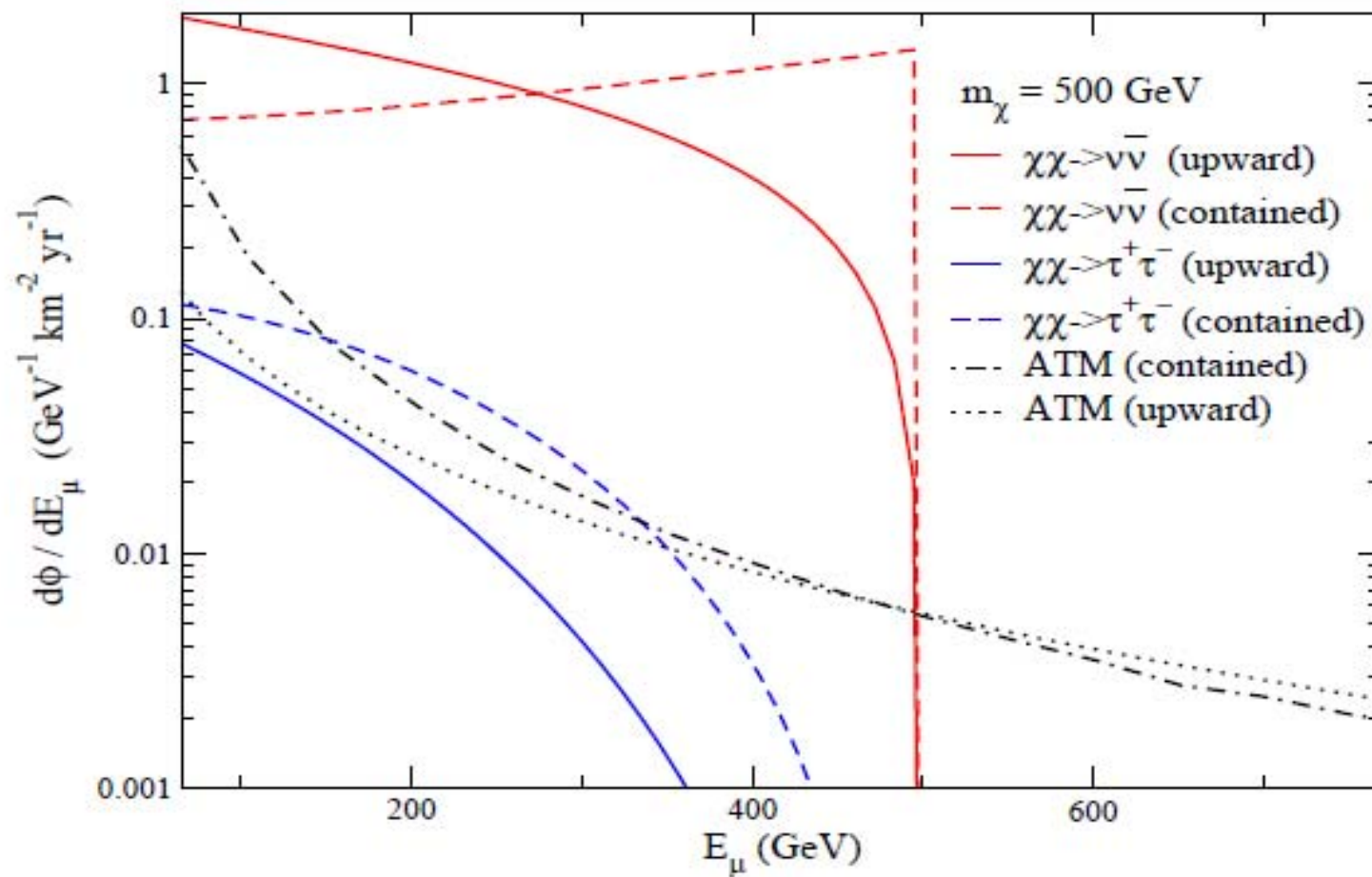
$R \simeq R_{SE} = 150$ Mkm (Sun)

- Attenuation of the neutrino Flux in the Sun

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

- 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 Earth



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

