Beyond the Neutralino Dark Matter: Right-handed Sneutrino as a Case Study

Rouzbeh Allahverdi

University of New Mexico

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Outline:

- Introduction.
- Sneutrino dark matter.
- Sneutrino dark matter and direct detection (collider connection).
- Sneutrino dark matter and PAMELA/Fermi.
- Sneutrino dark matter and IceCube.
- Summary.

Introduction:

WIMP miracle: The relic abundance is governed by thermal freeze-out.

$$T_f \sim \frac{m_\chi}{20}$$

Correct dark matter abundance obtained for:

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

SUSY with conserved R-parity has a stable WIMP.

Experimental Searches for WIMP Dark Matter:

1) Direct detection: WIMP-nucleus scattering
(CDMS, XENON, LUX, …).

2) Indirect detection: WIMP annihilation to
Gamma rays (Fermi), Antiparticles (PAMELA),
Neutrinos (IceCube).

3) Collider signal: Missing energy (LHC, ILC).

Complementarity: different experiments probe different interactions of dark matter.

Consistency: results must agree (the same particle).

Sneutrino Dark Matter:

In MSSM dark matter is a fermion (neutralino or gravitino).

The only scalar candidate is LH sneutrino, ruled out by direct detection experiments.

RH sneutrino $\tilde{N}$ a viable candidate (N needed to explain neutrino masses and mixings with conserved R-parity).

$\tilde{N}$ a singlet under the SM gauge group, Yukawa couplings too small to yield acceptable thermal relic density.
New gauge interactions around the weak scale needed.

Non-thermal scenario discussed in:
Dutta, Leblond, Sinha, PRD80, 035014 (2009)

Simplest extension of gauge group includes a gauged $U(1)_{B-L}$ Symmetry.
(B= baryon number, L= lepton number)
Mohapatra, Marshak, PRL 44, 1316 (1980)

- Anomaly cancelation requires the existence of three fermions that are SM singlets with L=+1, i.e. RH neutrinos.
- $U(1)_{B-L}$ gauge coupling unifies with the SM gauge couplings.
- $U(1)_{B-L}$ embedded in GUTs larger than $SU(5)$.

If $U(1)_{B-L}$ is broken around TeV, we can also get:

- Thermal sneutrino dark matter.
- Radiative breaking of the symmetry.

Field content and B-L charge assignments:

	Q	L	N	H_1'	H_2' (+ SUSY Partners)
Q_{B-L}	+1/6	-1/2	-1/2	+1	-1

Also one gauge boson Z' (+ SUSY partner), $g_{B-L} \sim 0.4$.

Tevatron and LEP bound: $m_{Z'} > 1.5\ TeV$.

$$W_{B-L} = f H_2' N^c N^c + \mu' H_1' H_2'$$

The B-L spontaneously broken by the new Higgs VEVs:

$$\langle H_1' \rangle, \langle H_2' \rangle \qquad \tan\beta' \equiv \frac{\langle H_2' \rangle}{\langle H_1' \rangle}$$

There are three Higgs fields in the B-L sector:

$$\phi \qquad m_\phi^2 < m_{Z'}^2 \cos^2 2\beta'$$

$$(\tan\beta' \approx 1 \Rightarrow m_\phi << m_{Z'})$$

$$\Phi, A \qquad m_\Phi, m_A \sim m_{Z'}$$

Sneutrino $\tilde{N}$ is the LSP in parts of the parameter space.

(The other candidate is the lightest neutralino in the B-L sector.)

$$D_{B-L} \supset \frac{1}{2} g_{B-L} \left[\left(| H_1' |^2 - | H_2' |^2 \right) + \frac{1}{2} | \tilde{N} |^2 + \ldots \right]$$

$$H_1' = \frac{\langle H_1' \rangle + \cos\alpha' \Phi - \sin\alpha' \phi}{\sqrt{2}} + \frac{H_{1,I}'}{\sqrt{2}}$$

$$H_2' = \frac{\langle H_2' \rangle + \sin\alpha' \Phi + \cos\alpha' \phi}{\sqrt{2}} + \frac{H_{2,I}'}{\sqrt{2}}$$

$$V \supset -\frac{1}{2} g_{B-L} m_{Z'} [\sin(\alpha' + \beta')\phi - \cos(\alpha' + \beta')\Phi] | \tilde{N} |^2$$

$$-\frac{1}{2} g_{B-L} \cos(2\alpha')\phi^2 | \tilde{N} |^2 + \ldots$$

Annihilation channels:

$$\tilde{N}\tilde{N} \rightarrow NN$$ S-wave

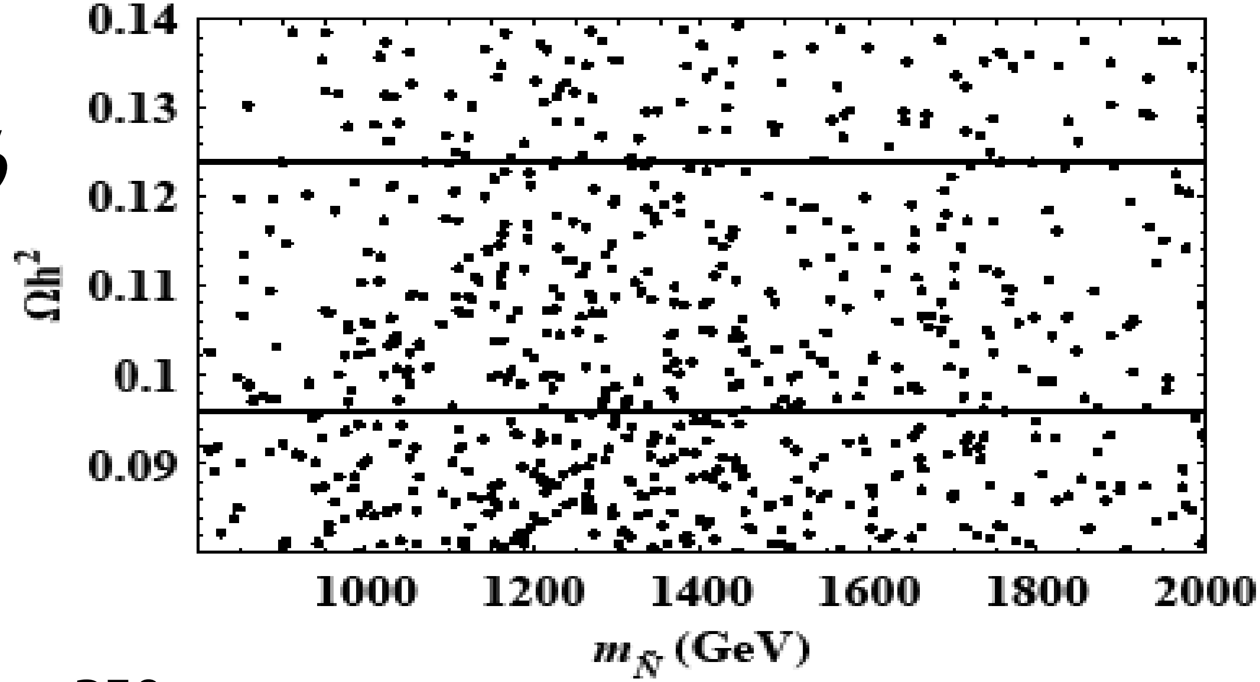
$$\tilde{N}\tilde{N}^* \rightarrow \phi\phi$$ S-wave, possible if $m_\phi < m_{\tilde{N}}$

(Annihilation to Φ, A kinematically forbidden or suppressed.)

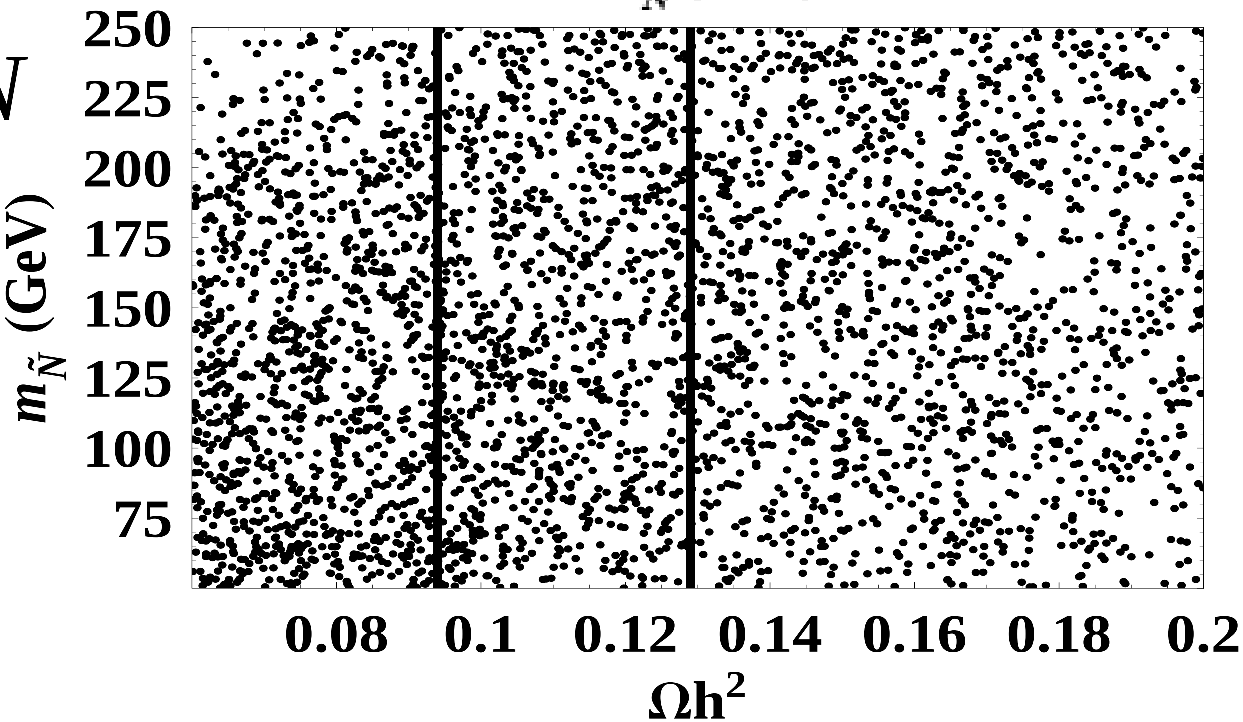
$$\tilde{N}\tilde{N}^* \rightarrow f\bar{f}$$ P-wave, negligible

Correct relic density from thermal freeze-out can be obtained.

$$\tilde{N}\tilde{N}^* \to \phi\phi$$



$$\tilde{N}\tilde{N} \to NN$$



Sneutrino Dark Matter and Direct Detection:

$\tilde{N}$ interacts with quarks via Z' exchange.

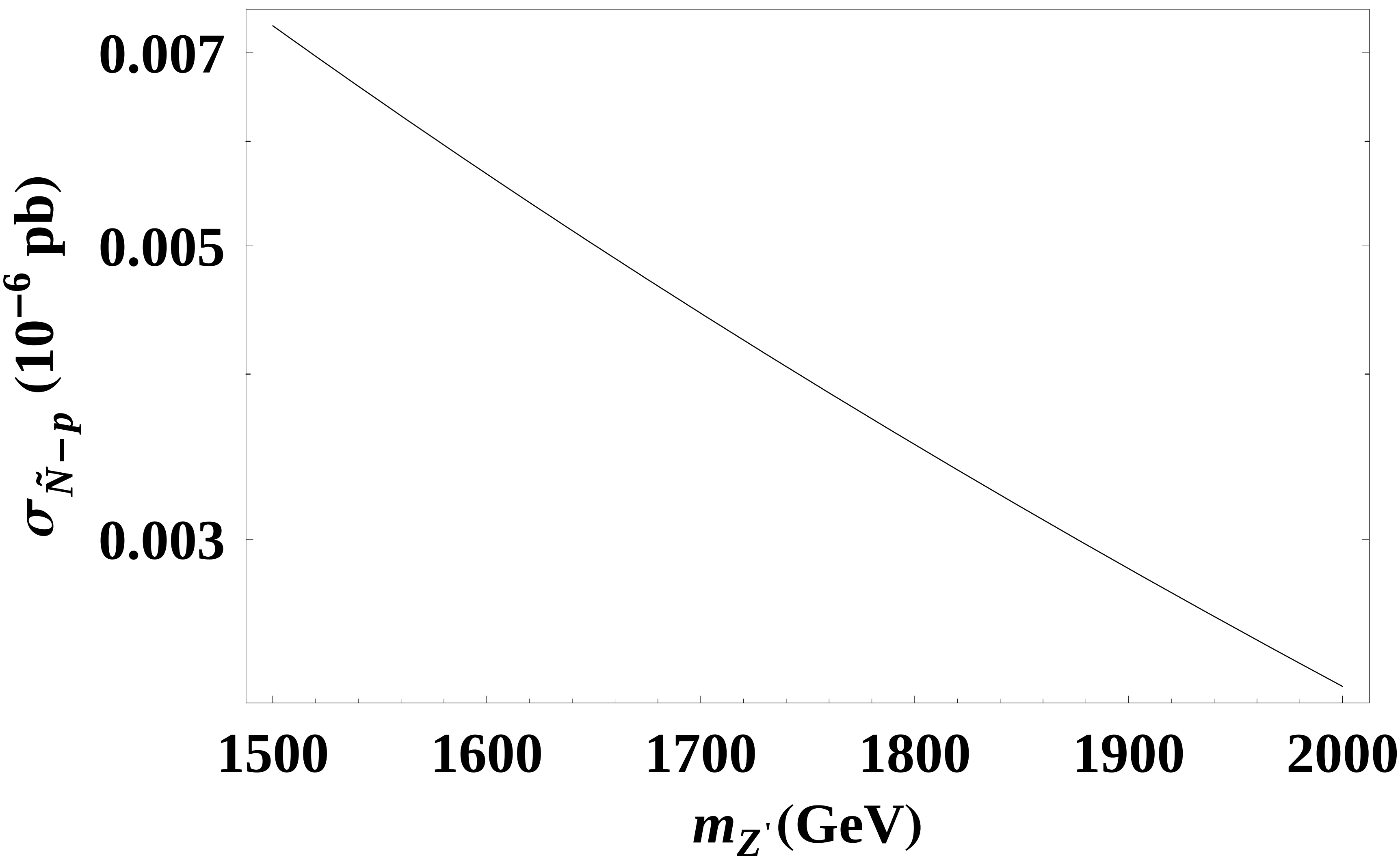
$\sigma_{\tilde{N}-proton}$ not affected by uncertainties of strange content

No spin-dependent contribution (B-L is vectorial).

LEP bound: Carena, *et al*., PRD70, 093009 (2004)

$$\frac{m_{Z'}}{g_{B-L}Q_L} > 6\,TeV$$

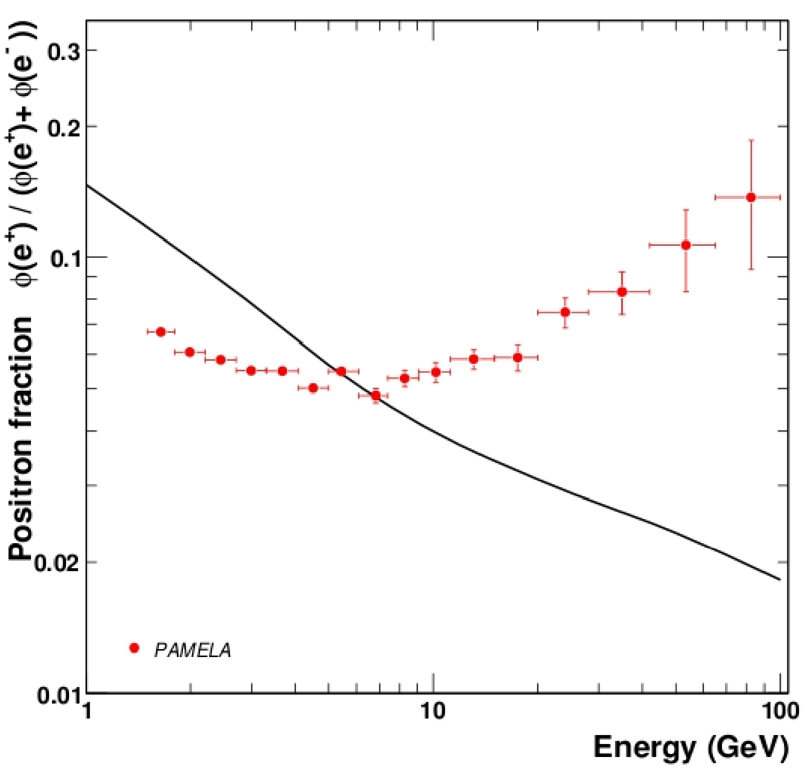
$$\Rightarrow \sigma_{\tilde{N}-proton} \propto \left(\frac{g_{B-L}Q_L}{m_{Z'}}\right)^4 \leq 8\times10^{-9}\,pb$$

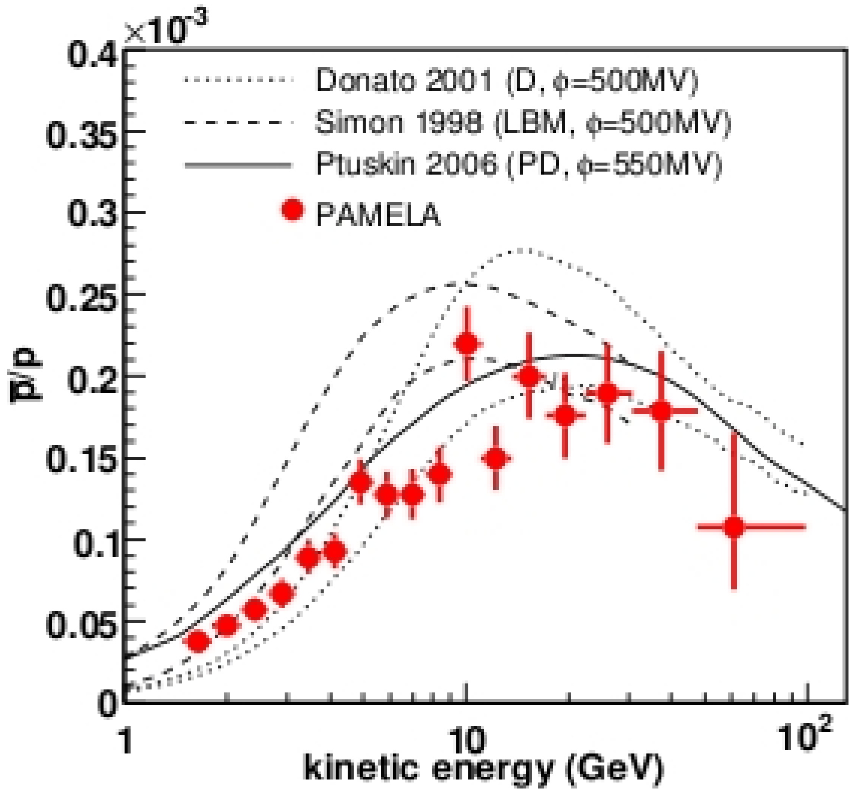


0.007
0.005
0.003
$\sigma_{\tilde{N}-p}$ (10^{-6} pb)
1500
1600
1700
1800
1900
2000
$m_{Z'}$(GeV)

Sneutrino Dark Matter and PAMELA/Fermi:

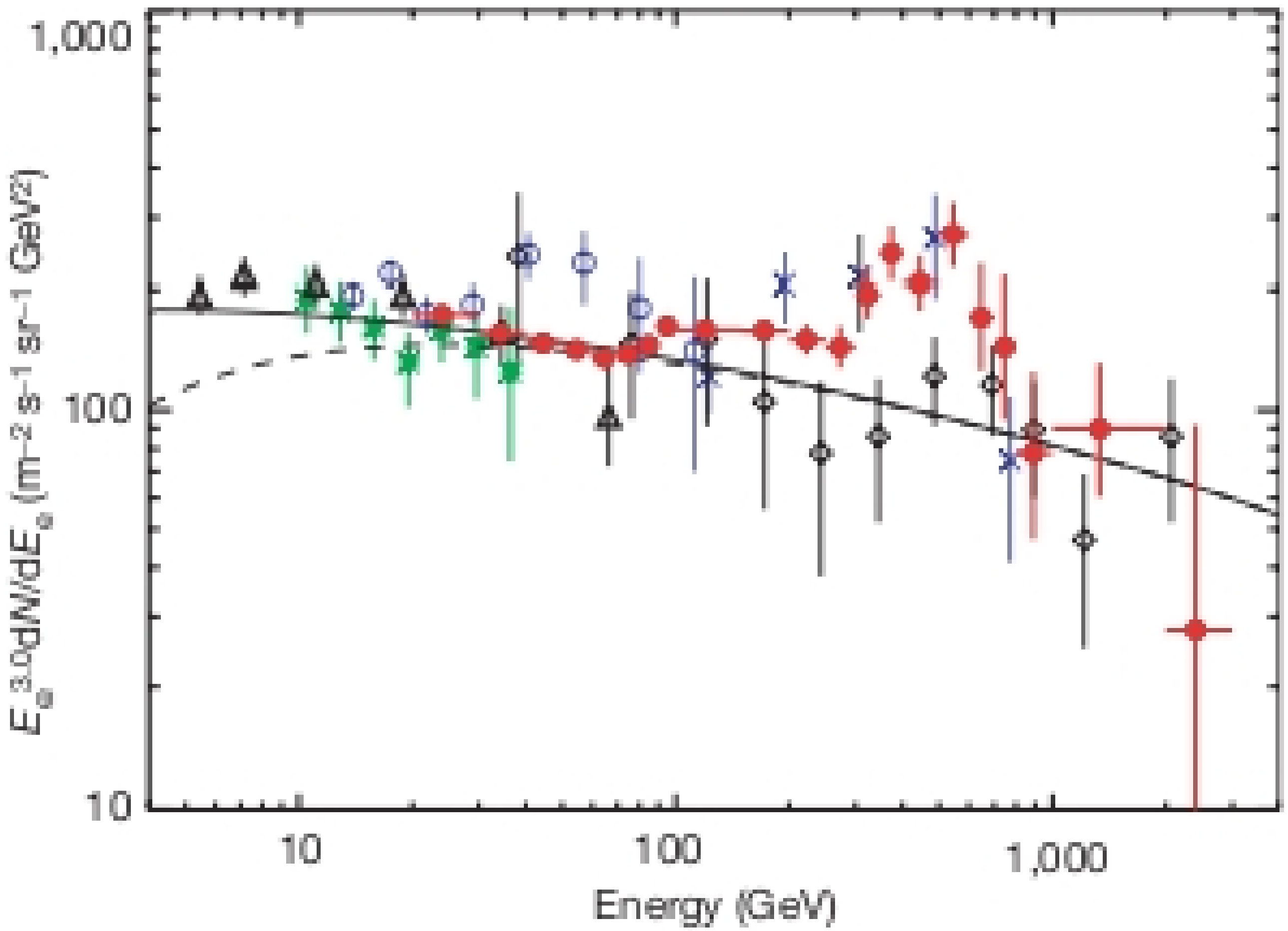
PAMELA has reported an excess of positrons up to 100 GeV, but no excess in the antiproton flux:





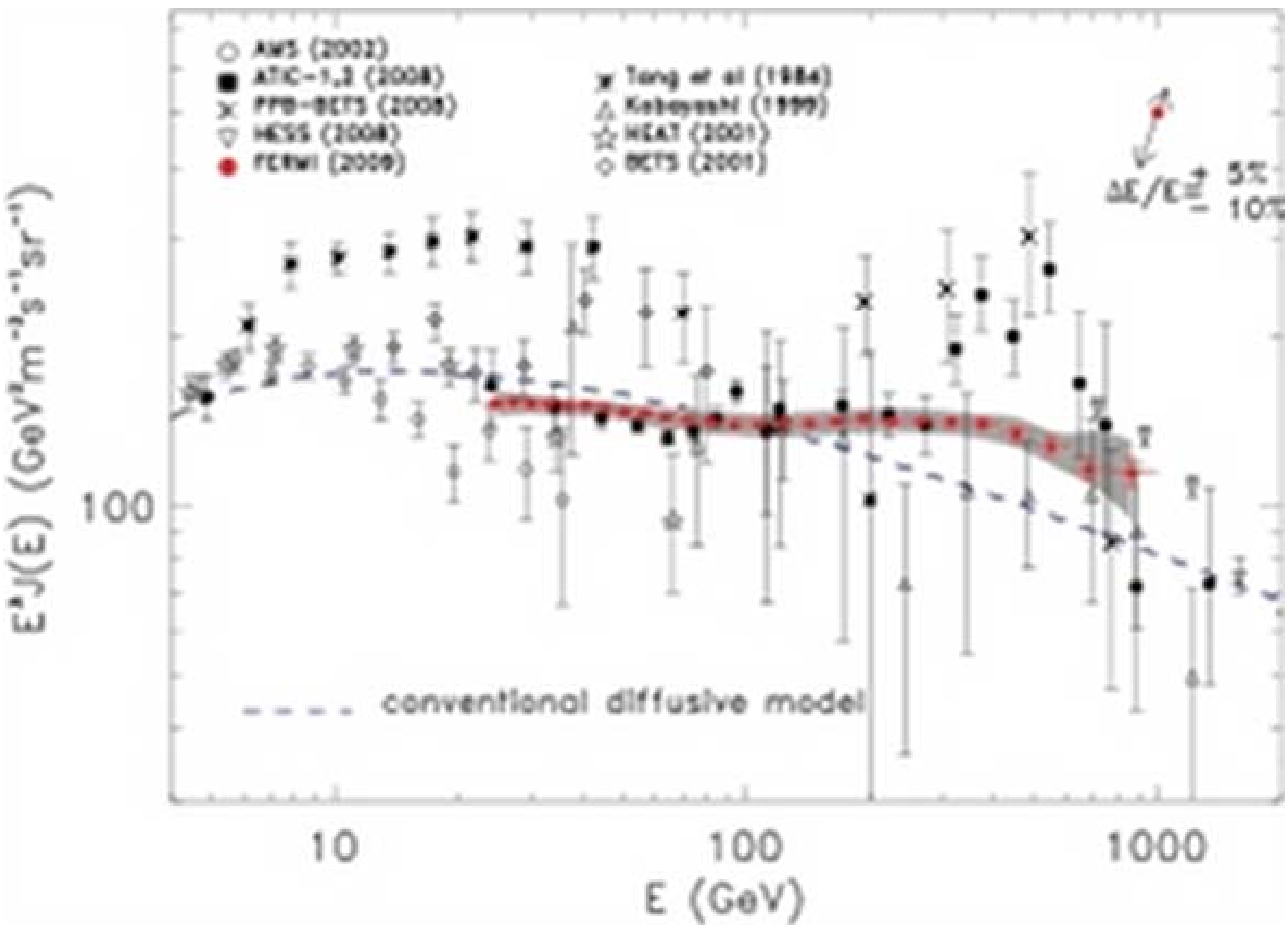
Adriani, *et. al.*, arXiv:0810.4995   Adriani, *et. al.*, arXiv:0810.4994

In addition, ATIC has reported excess in $e^{+} + e^{-}$ spectrum with a peak around 600 GeV.
Chang, *et. al.*, Nature, 456, 362 (2008)

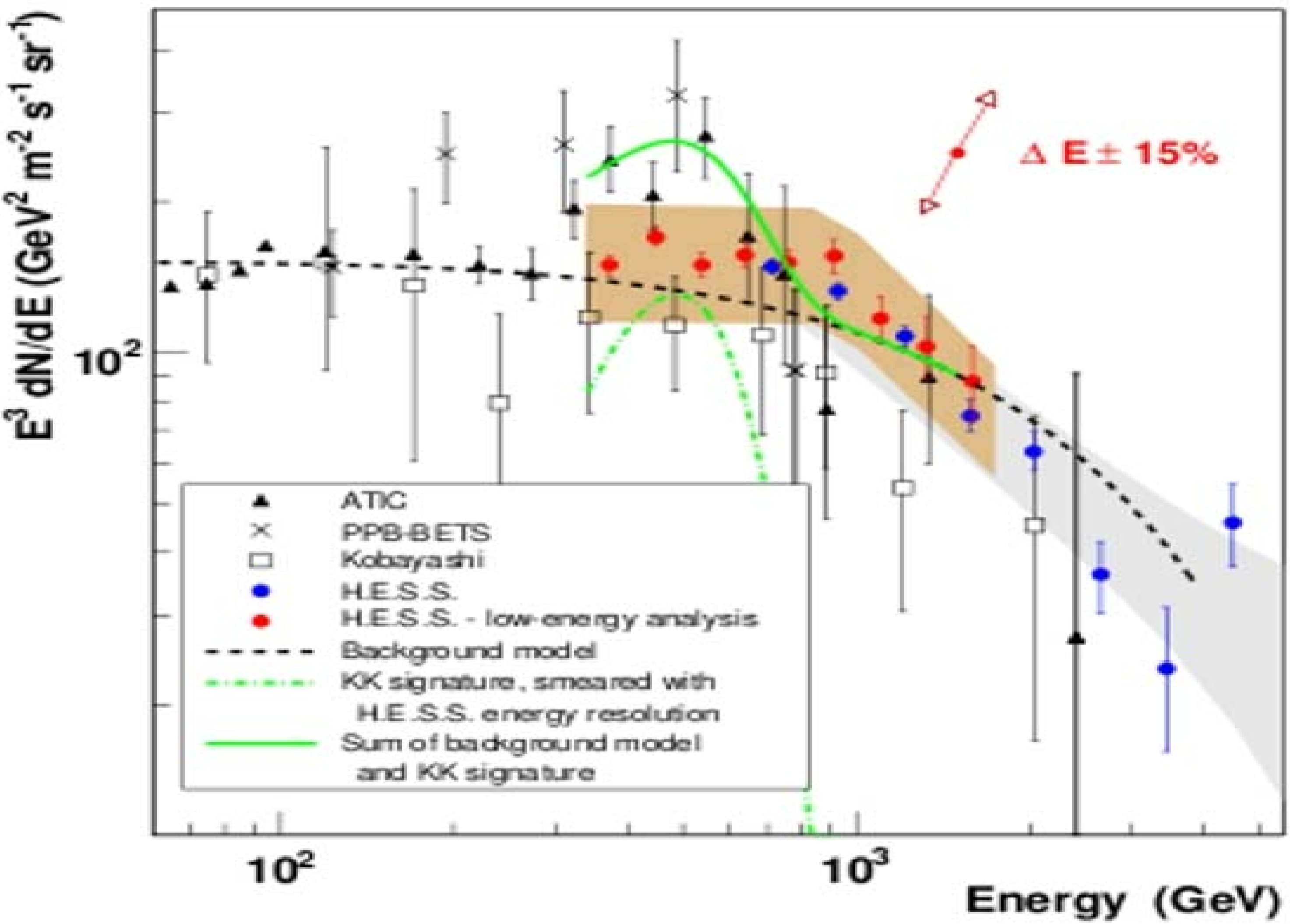


Not confirmed by the latest Fermi and H.E.S.S. results.

Fermi : Abdo, *et al.*, arXiv:0905.0025



H.E.S.S. : Aharonian, *et al*., arXiv:0905.0105



WIMPs annihilate to particle-antiparticle pairs today:

$$\Gamma_{today} = nB\langle\sigma v\rangle_f$$

B Overall factor (branching ratio, enhancement, …)

n local dark matter density (NFW or other profiles)

Model-independent analysis shows $B >> 1$ needed:

Barger, *et. al.*, arXiv:0809.0162

$B \sim O(10)$ for e^+e^- final state

$B \sim O(100)$ for W^+W^- final states

How to get a large enhancement in annihilation NOW?

Astrophysics:

Enhancing the number density, astrophysical boost factor due to local substructure in the halo.

But it is difficult to imagine a boost factor of 10^4.
May get $O(10)$ in our vicinity.

Afshordi, Mohayaee, Bertschinger, arXiv:0811.1582

Particle Physics:

Enhancing the cross section, microphysical boost factor.

We need a large cross section today as compared with the freeze-out time.

Sommerfeld Effect: Cirelli, *et. al.,* arXiv:0809.2409

Enhancement of S-wave processes in the non-relativistic limit due to attractive force from exchange of a light boson.

Requirements:

1) S-wave annihilation.

2) Light boson to generate an attractive force.

3) Leptonic final states dominant (antiproton data).

Beyond the neutralino dark matter

Arkani-Hamed, *et. al.,* arXiv:0810.0713
Pospelov, Ritz, arXiv:0810.1502
…

Sommerfeld enhancement can come from a light B-L Higgs.

R.A., Dutta, Richardson, Santoso
PRD 79, 075005 (2009) & PLB 677, 172 (2009)

Exchange of ϕ leads to an attractive force between $\tilde{N}$ quanta:

$$V(r) = -\alpha \frac{e^{-m_\phi r}}{r}$$

$$\alpha = \frac{g_{B-L} m_{Z'} \sin(\alpha' + \beta')}{4 m_{\tilde{N}}}$$

Enhancement factor saturates at $\sim \frac{m_{\tilde{N}}}{\alpha m_\phi}$.

$$\tilde{N}\tilde{N}^* \to \phi\phi$$

ϕ quanta then decay to fermion-antifermion pairs:

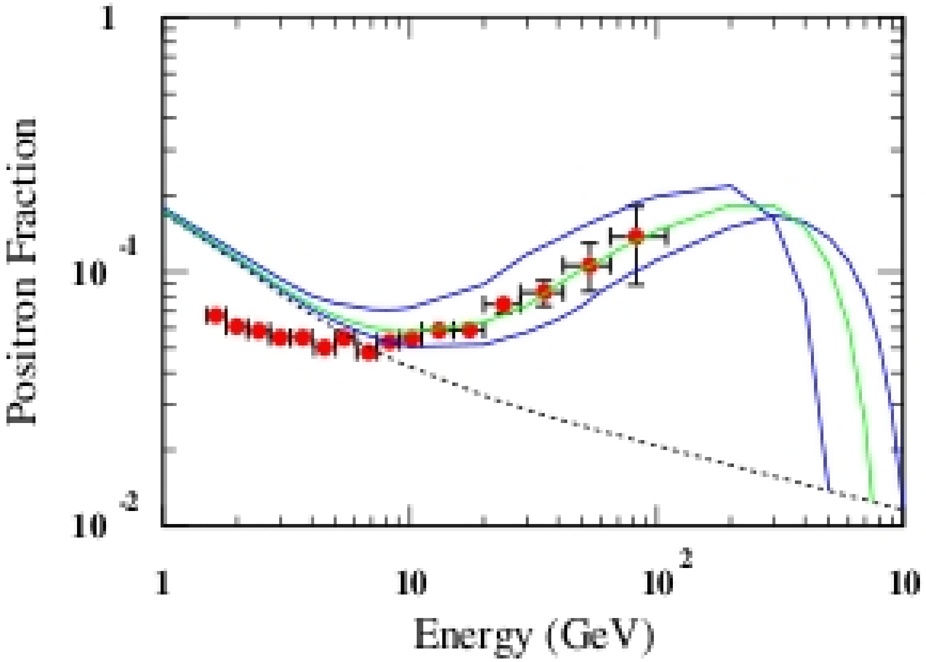
$$\Gamma_{\phi \to f\bar{f}} = \frac{C_f}{2^7 \pi^5} \frac{g_{B-L}^6 Q_f^4 Q_\phi^2 m_\phi^5 m_f^2}{m_{Z'}^6} \left(1 - \frac{4m_f^2}{m_\phi^2}\right)^{3/2}$$

Leptons favored by the virtue of B-L symmetry.

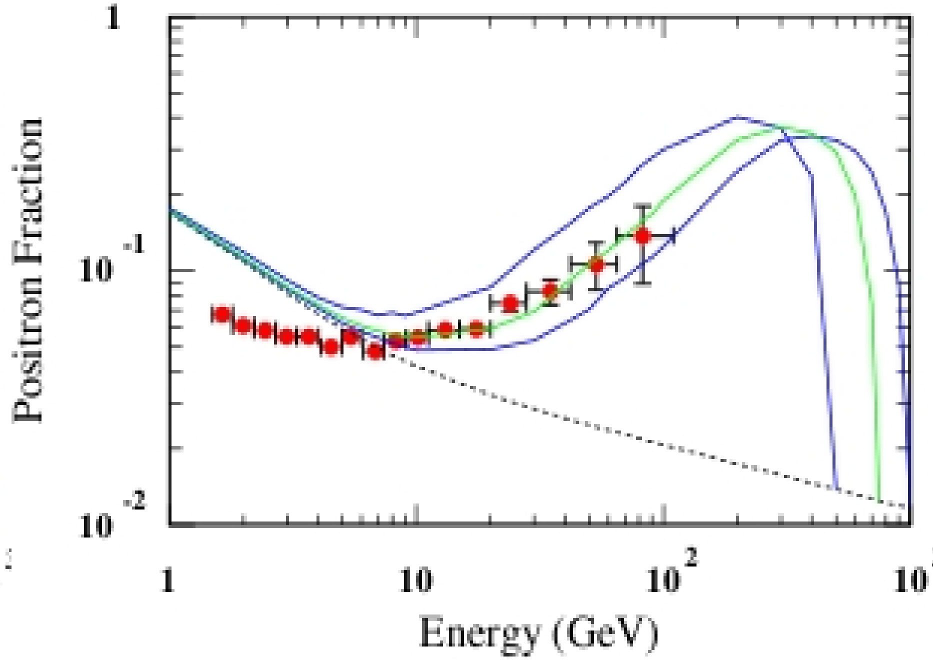
$m_\phi < 15\ GeV$ tau final states dominate

$m_\phi < 4\ GeV$ muon final states dominate

Fit to PAMELA



tau final state

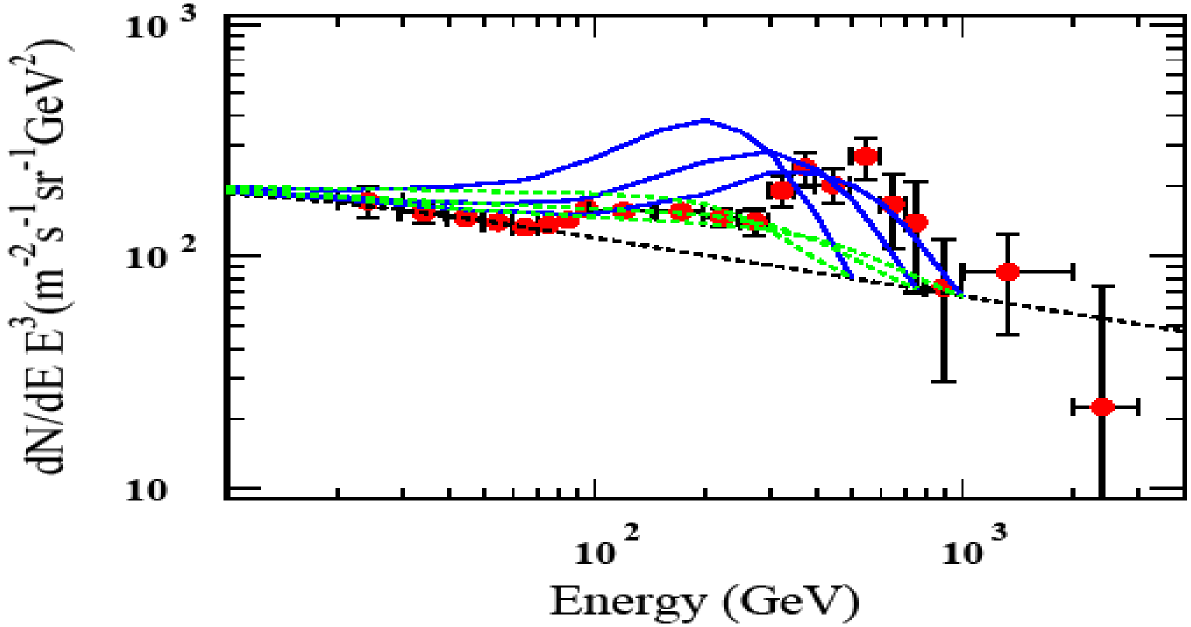


muon final state

Dark matter mass 1 TeV, 1.5 TeV, 2 TeV (bottom to top)

Enhancement factor 1000

Electron+positron spectrum



muon final state

tau final state

tau final state compatible with Fermi results

Sneutrino Dark Matter and IceCube:

Sneutrinos get captured by and pair annihilate in the Sun:

$$N(t) = \sqrt{\frac{C}{A}} \tanh \sqrt{CA}t$$

$C:$ Capture rate, depends on $\sigma_{\tilde{N}-proton}$.

$A:$ Related to σ_{ann} (at present time).

Equilibration time: $\tau_{eq} = \left(\sqrt{CA}\right)^{-1}$

$$t > \tau_{eq} \Rightarrow \Gamma_A = \frac{C}{2}$$

Equilibration inside the Sun (Erath) requires that:

$$\sigma_{ann} \geq 4\times10^{-26}(1\times10^{-18}) \ \frac{cm^3}{\sec}$$

Equilibrium is achieved in the Sun.

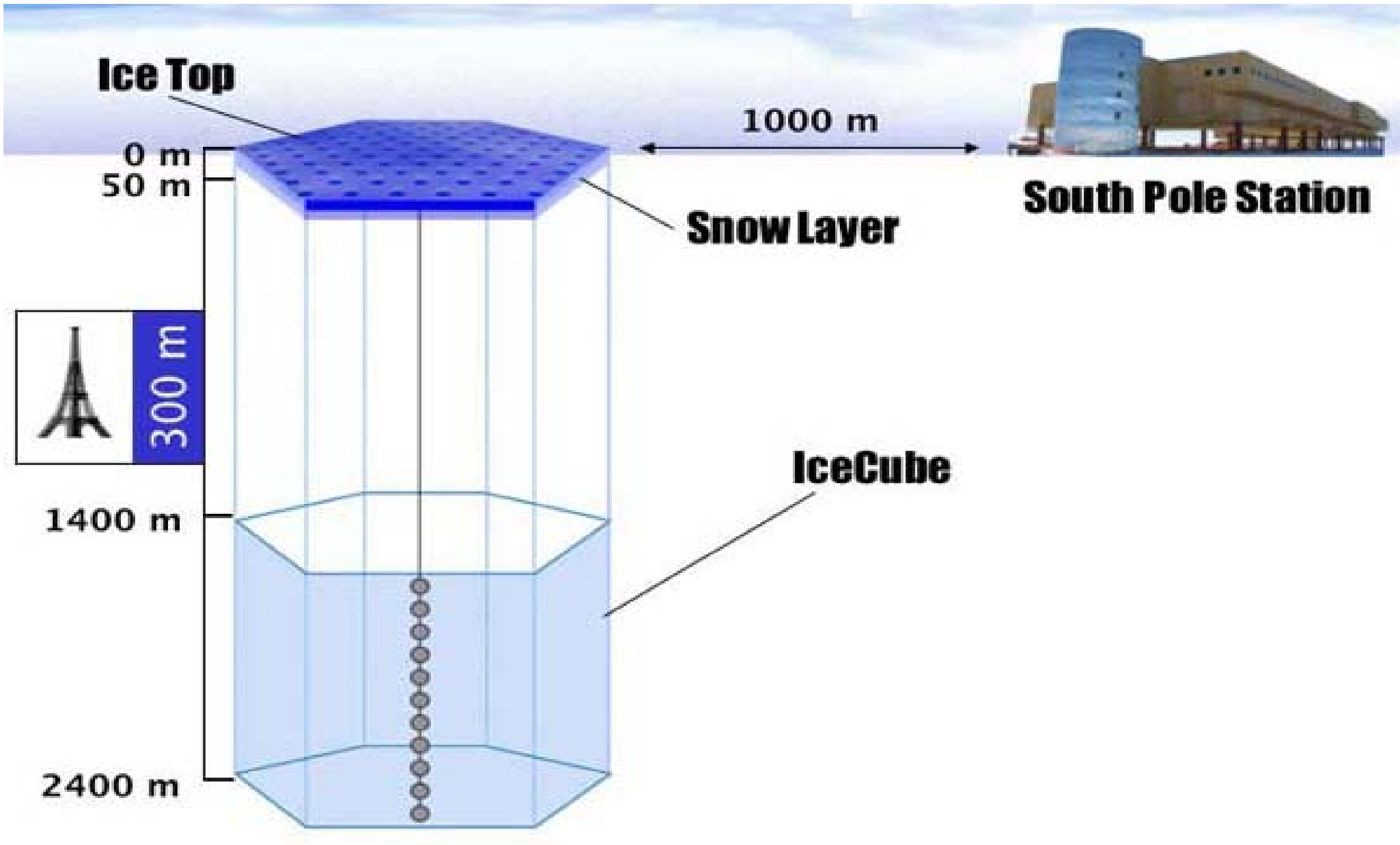
Total annihilation rate does not depend on the details of σ_{ann} (e.g., Sommerfeld enhancement).

However, the flux of neutrinos from annihilation depends on the corresponding branching ratios.

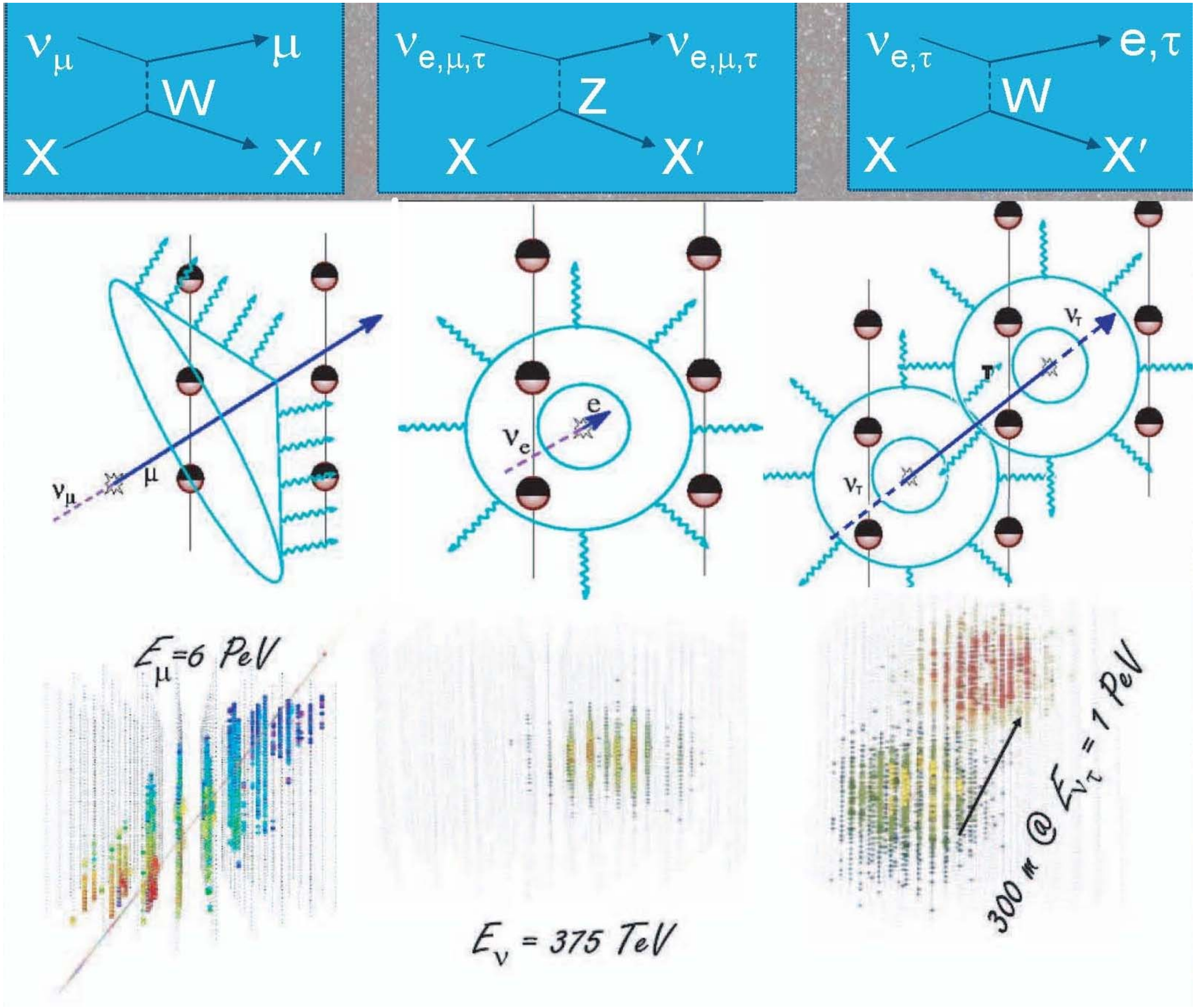
We need to understand how LH neutrinos are produced from annihilation of RH sneutrinos.

Detection of Neutrino from Dark Matter Annihilation:

IceCube is $1km^3$ neutrino detector at the south pole.



The main processes at **IceCube**:



In the energy range relevant for dark matter ~TeV, the background is from atmospheric neutrinos that is understood rather well.

IceCube looks for upward coming neutrinos to avoid the large Number of muons from cosmic rays.

ν_e, ν_τ charged currents and all neutral currents yield cascades.

Cascades are localized, detectable for much higher energies. We ignore them here.

Angle cuts to distinguish between neutrinos from Sun and Earth:

Sun: $67^\circ < \Theta < 113^\circ$ Earth: $\Theta = 180^\circ$

Neutrinos from Sneutrino annihilation:

R.A., Bornhauser, Dutta, Richardson, PRD 80, 055026 (2009)

Case 1: Heavy B-L Higgses (generic case).

$$\tilde{N}\tilde{N} \rightarrow NN$$ 100%

$$\sigma_{ann} = 3\times10^{-26}\ \frac{cm^3}{\sec}$$

$$N \rightarrow \nu h^0$$

(h^0 the lightest MSSM Higgs)

LH neutrinos produced in two-body decays.

Case 2: Light B-L Higgs ϕ.

$\tilde{N}\tilde{N}^{*} \rightarrow \phi\phi$ ~90% $\tilde{N}\tilde{N} \rightarrow NN$ ~10%

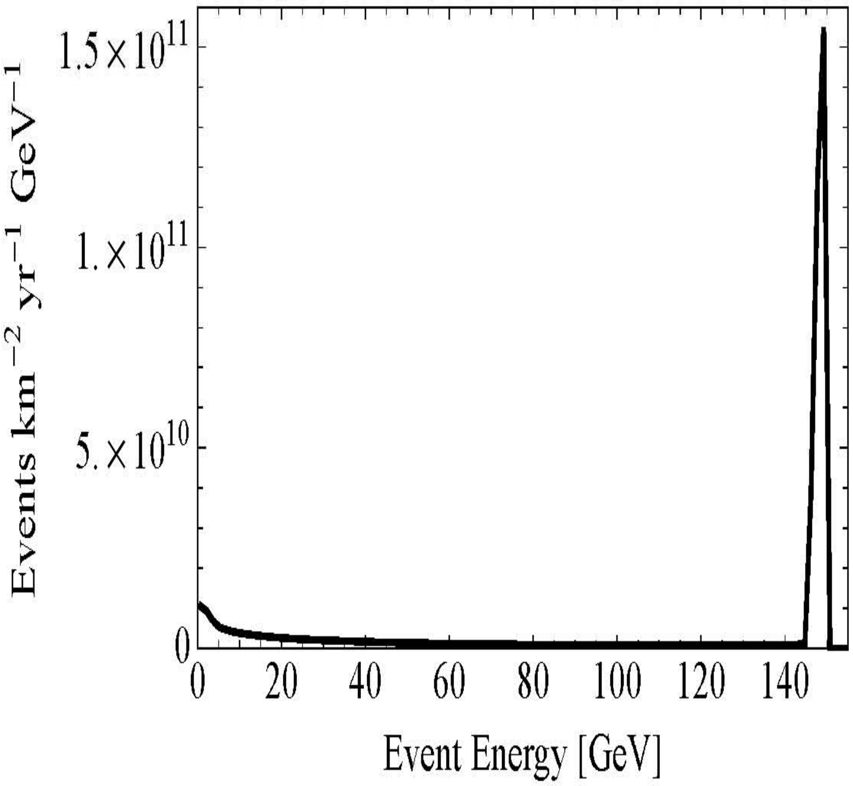
$$\sigma_{ann} = 3\times10^{-23}\ \frac{cm^3}{\sec}$$

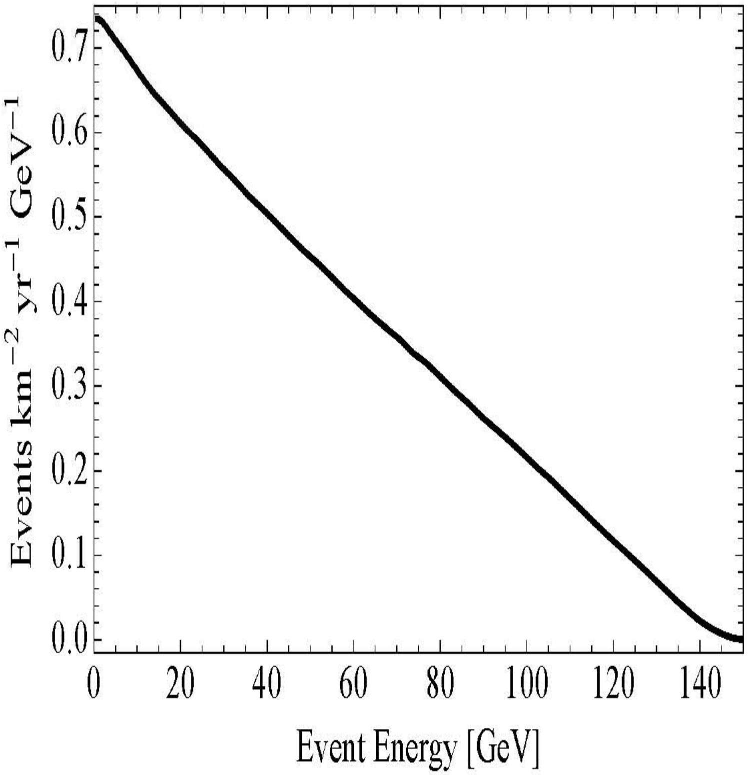
(Can explain PAMELA via Sommerfeld enhancement.)

$$\Gamma_{\phi\rightarrow f\bar{f}} \propto g_{B-L}^{6} Q_f^4 m_f^2$$

$\phi \rightarrow \tau^{+}\tau^{-}$ ~74% $\phi \rightarrow b^{+}b^{-}$ ~16%

LH neutrinos produced in three-body decays of taus.



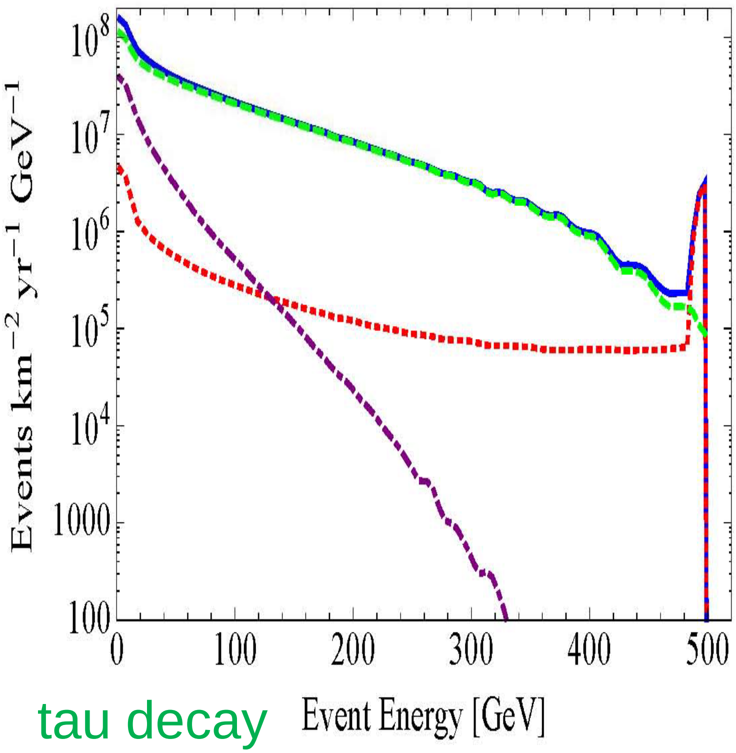


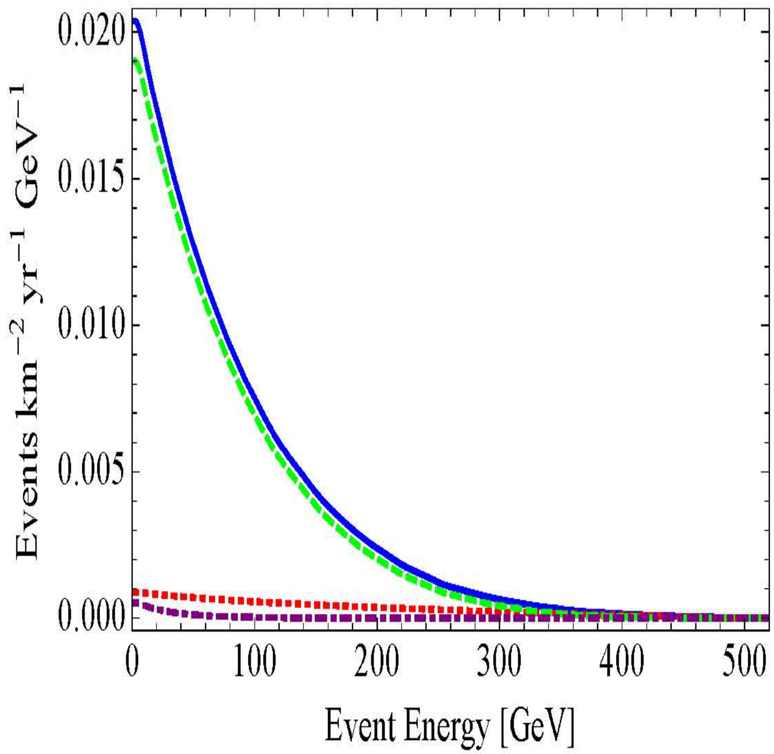
muon neutrino events

muon events

Case 1 $m_{\tilde{N}} = 300\ GeV$

(little sensitivity to the flavor composition of neutrinos produced in the Sun)





tau decay

bottom decay

N decay

muon neutrino events

muon events

Case 2 $m_{\tilde{N}} = 1\ TeV$

(essentially not sensitive to the flavor composition of neutrinos produced in the Sun)

During propagation from production point (Sun's core) to detection point (**IceCube**) neutrinos are subject to:

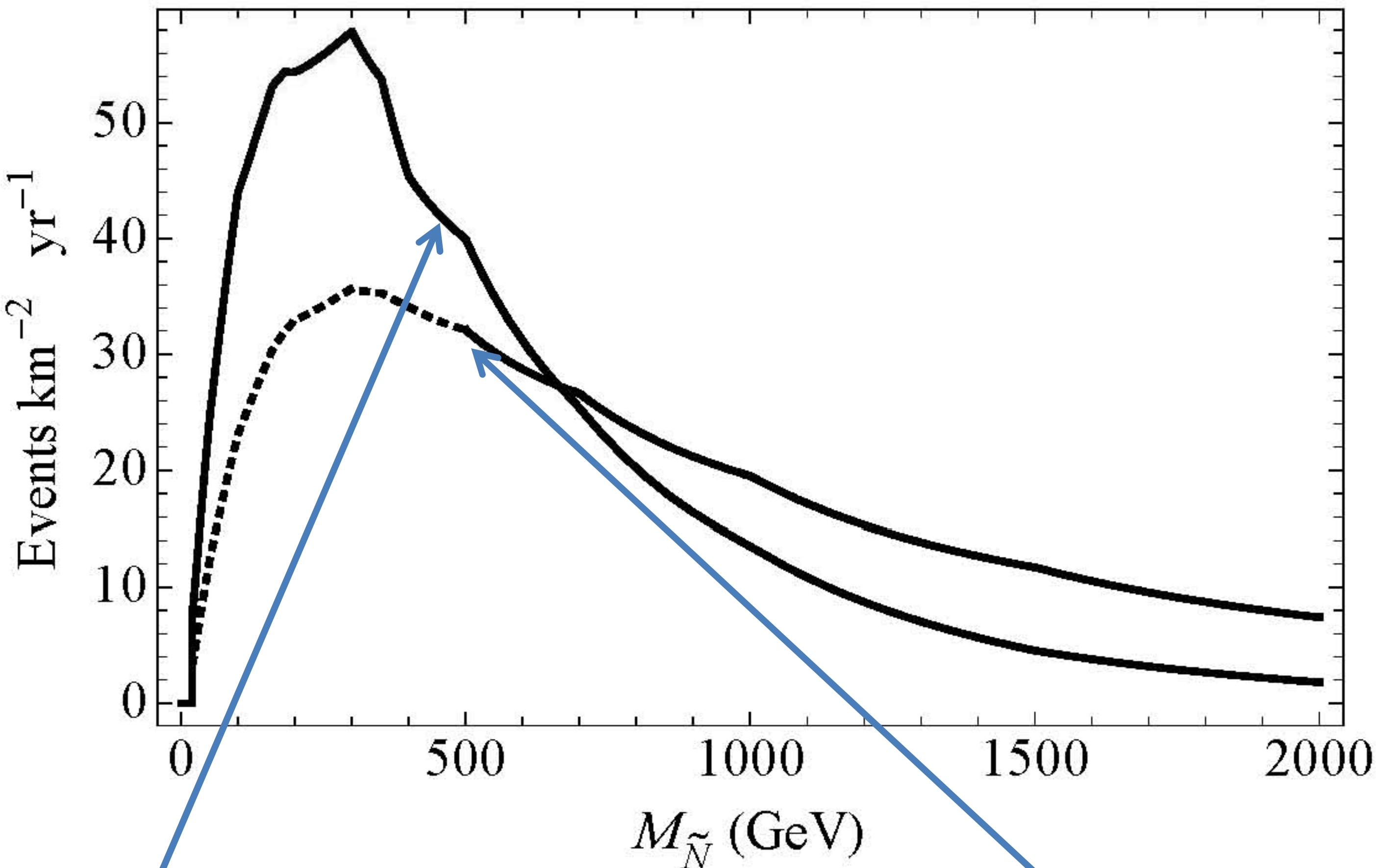
1) Energy loss and absorption inside Sun

2) Oscillations in Sun (matter effects) and from Sun to Earth

3) Interactions in the detector

1) and 3) become more important for high energy neutrinos
(cross section for neutrino interactions proportional to energy)

2) becomes less important for high energy neutrinos
(oscillation length increases)



Case 1

Case 2

Larger neutrino energies,

more muons at the detector for low masses

more scattering and absorption in the Sun for high masses

Analysis of **IceCube** snesitivity made for neutralino dark matter:
Abbasi, *et al.*, PRL 102, 201302 (2009)

Sun:

300 events for 70 GeV dark matter, 70 events for 300 GeV dark matter, remains fixed at 70 up to 4 TeV.

Sneutrino dark matter is within the reach.

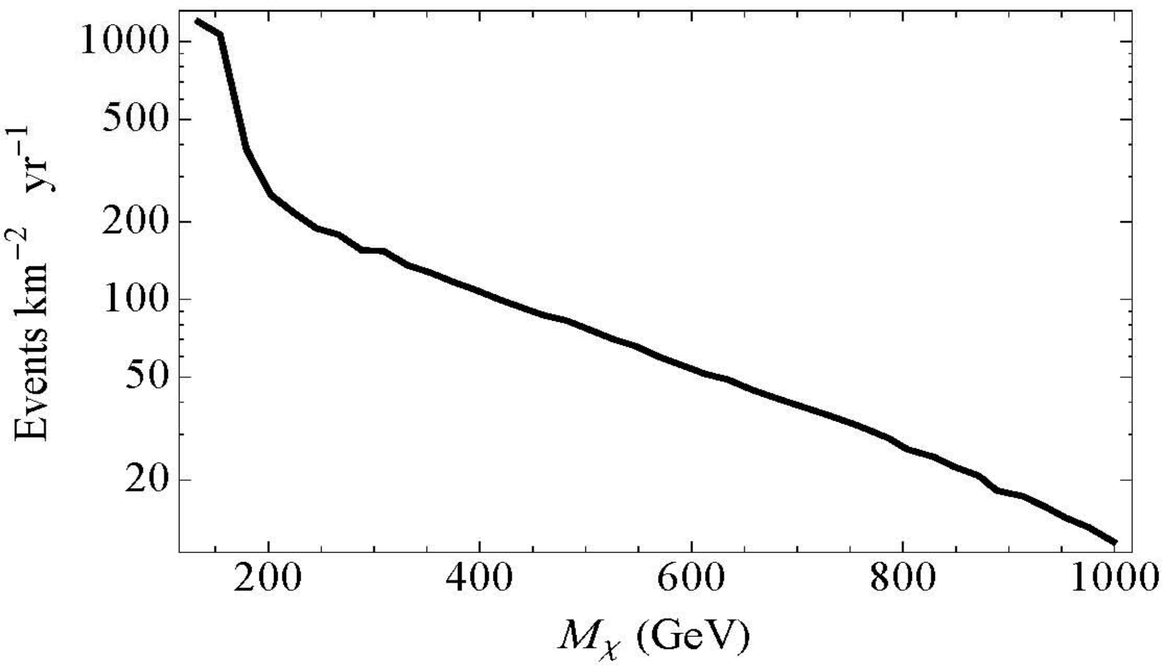
Earth:

12 events for dark matter mass between 70 GeV and 4 TeV.

Predicted rates are 6 orders of magnitude below the minimum rate.

Comparison with Neutralino Dark Matter:

In the focus point region muon event rate is high enough for detec
Large Higgsino component yields a large σ_{SD} (important in Sun)



Sneutrino dark matter yields roughly comparable rates for higher masses ($\sigma_{SD} = 0$ but leptonic final state).

Summary:

- $U(1)_{B-L}$ is a minimal and well motivated model with dark matter candidate(s) beyond the standard neutralino.

- Accommodates thermal sneutrino dark matter if B-L is broken around TeV.

- $\sigma_{SI} \leq 8\times 10^{-9} pb$ from Z' mass limits. Direct detection cross section correlated with $m_{Z'}$.

- Sneutrino annihilation has S-wave channels, produces RH neutrinos and B-L Higgses.

- Has various signatures for indirect detection.

- Can provide successful explanation of the positron excess via Sommerfeld enhancement in parts of the parameter space.

- Detectable at the IceCube. Predicted muon event rate from capture and annihilation in the Sun as large as $100\, yr^{-1} km^{-2}$.

- Roughly comparable rates with neutralino dark matter in the focus point region. Features in the spectrum, and cascades, may be used to distinguish the models.

- TeV scale $U(1)_{B-L}$ has other cosmological consequences. Can lead to inflation, unifies inflation and dark matter, generates baryon asymmetry via leptogenesis, etc.

R.A., Kusenko, Mazumdar, JCAP 0707, 018 (2007)
R.A., Dutta, Mazumdar, PRL 99, 261301 (2007)