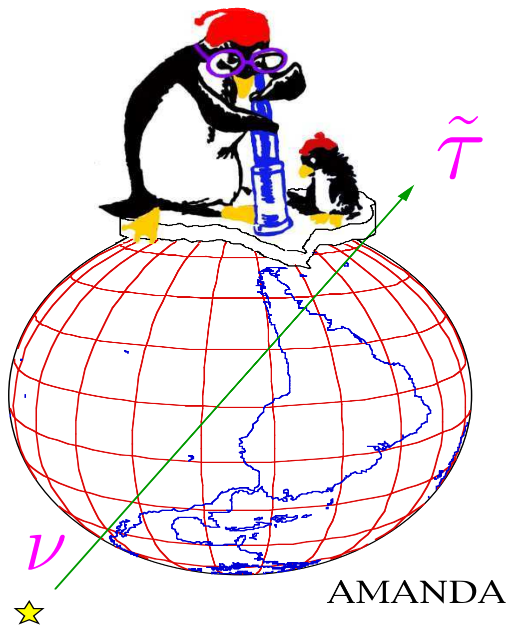
Looking for SUSY in the Ice



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Outline

- ∗ Why Supersymmetry at the weak scale ?
- ∗ Gravitino LSPs => Long Lived charged NLSPs
- ∗ Production of charged NLSPs from HE ν interactions in the Earth. HE $\gtrsim 10^5$ GeV.
- ∗ Energy Loss and Propagation of Charged NLSPs through the Earth.
- ∗ Rate of Charged NLSPs in Neutrino Telescopes.
- ∗ Signatures and Background
- ∗ Conclusions/Outlook

SUSY at the Weak Scale

* Standard Model has been a sucessful description of current experimental particle physics.
* Hierarchy problem: Weak scale is unstable under radiative corrections.
  - Field theory can't keep fundamental scalar particles as light as they should be (weak scale is set experimentally)
* SUSY solves this problem with an elegant solution: each SM fermion (boson) has a boson (fermion) SUSY partner
  - Quantum corrections are now much smaller.

$$M_{SUSY} \lesssim \vartheta(\mathrm{Tev})$$

* LHC will probe weak scale SUSY

Gravitino as LSP

- SUSY Breaking mechanism $\Rightarrow$ mass spectrum $\Rightarrow$ LSP (stable)
- LSP is determined by the scale of SUSY breaking ($\sqrt{F}$)

$$10^3 \text{ GeV} < \sqrt{F} < 10^{12} \text{ GeV}$$

- $\sqrt{F} > 10^{10}$ GeV $\Rightarrow$ LSP is neutralino
- $\sqrt{F} < 10^{10}$ GeV $\Rightarrow$ LSP is gravitino
  - graviton (spin 2)
  - gravitino (spin 3/2)
  - typically very light and gravitationally coupled

NLSP – $\tilde{\tau}_R$

- NLSP $\rightarrow$ LSP + SM
- in most of these cases: NLSP is charged slepton (typically the $\tilde{\tau}_R$ with $m = \vartheta(100 \text{ GeV})$
- NLSP decay is gravitationally suppressed: $\Gamma \propto$ (grav. coupling)^2 $\Rightarrow$ long lifetime!!

$$c\tau = \left(\frac{\sqrt{F}}{10^7 \text{ GeV}}\right)^4 \left(\frac{100 \text{ GeV}}{m_{\tilde{\tau}_R}}\right)^5 10 \text{ km} ,$$

- for $\sqrt{F} \gtrsim 10^7$ GeV and HE collisions, NLSPs travel long distances before decaying.
- Many SUSY scenarios have $\sqrt{F} \gtrsim 5 \times 10^6$

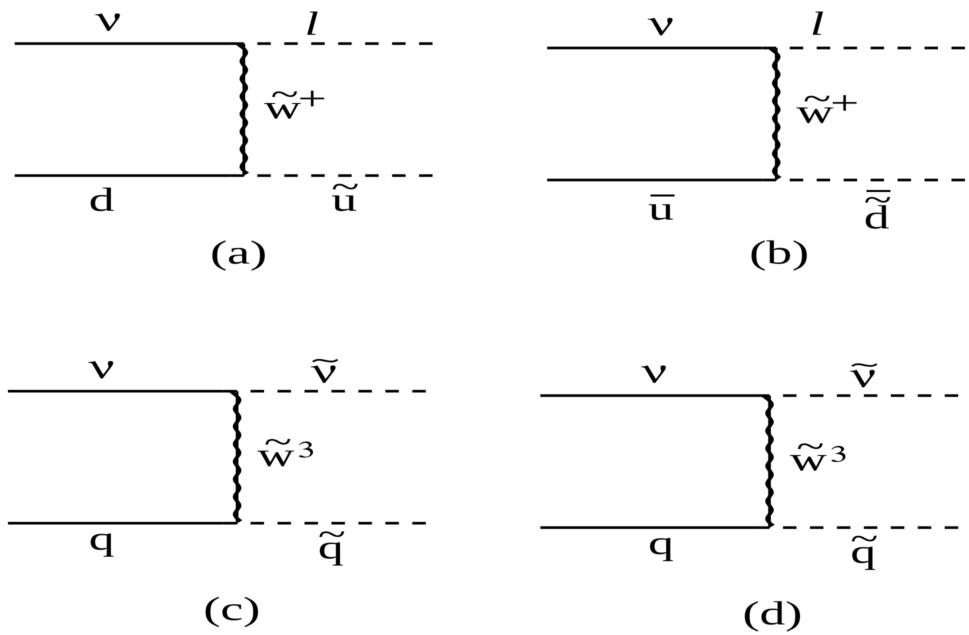
NLSP Production in the Earth

* High Energy neutrinos interacting in the Earth will produce $\tilde{\tau}_R$
* Assume the HE ν flux hitting the Earth is given by the Waxman-Bahcall limit
* $\tilde{\tau}_R$ production $\sigma << \sigma_{SM}$
* However $\tilde{\tau}_R$ range $>>$ μ range!
  - energy loss due to radiation sets in at much higher energies than for the μ
  - $\tilde{\tau}_R$ range is typically in the 100s to 1000s of km
* Large range compensates for low σ

SUSY Cross Section

* Dominant process is analogous to SM CC interactions

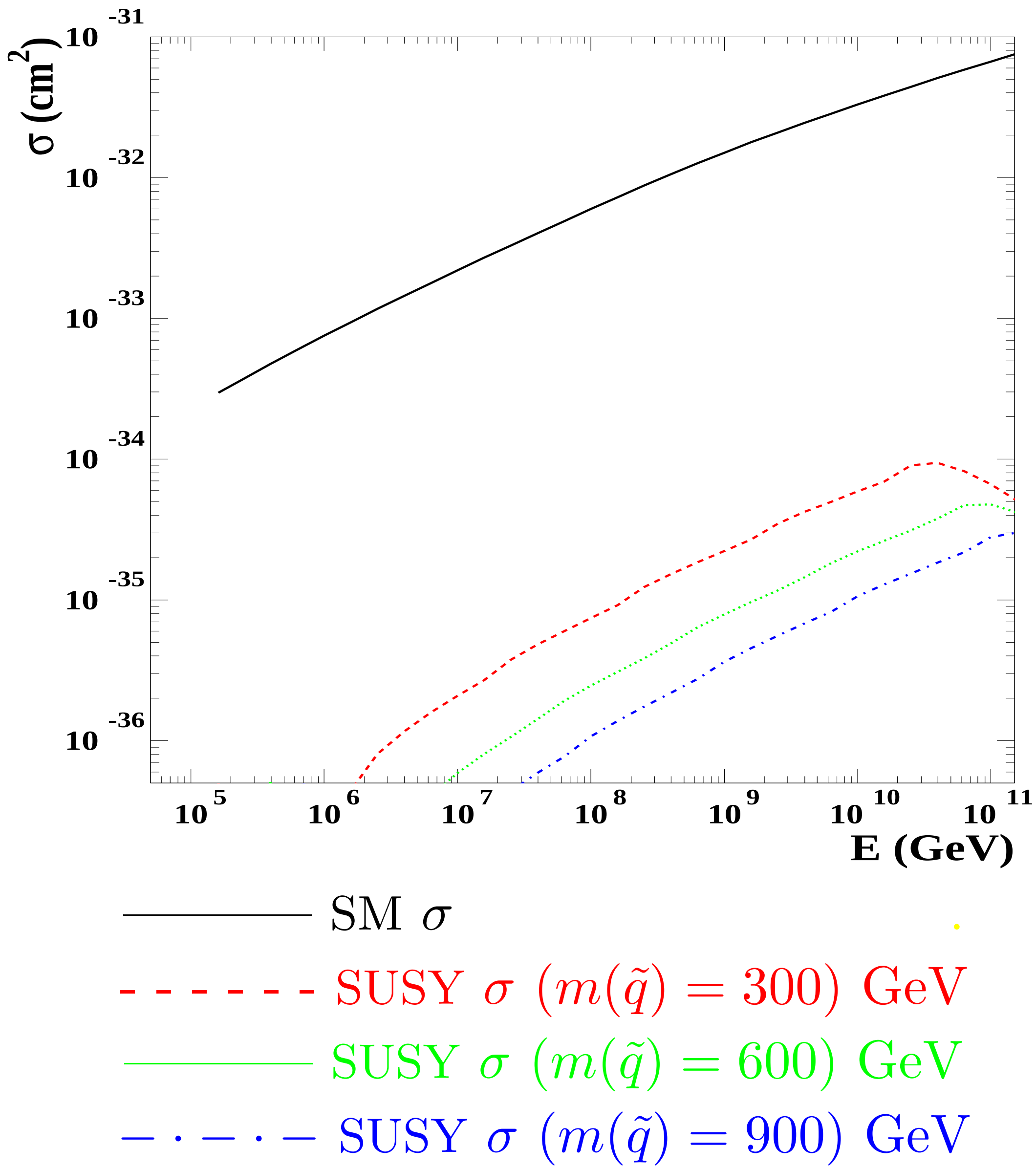
$$\nu N \rightarrow \tilde{l}_L \, \tilde{q}$$



* $\tilde{l}_L$ and $\tilde{q}$ promptly decay into X + 2 $\tilde{\tau}_R$

* Energy threshold for interaction is given by $m(\tilde{\tau}_L) + m(\tilde{q})$

* $m(\tilde{w}) = 250$ GeV; $m(\tilde{\tau}_L) = 250$ GeV; $m(\tilde{q}) = 300, 600, 900$ GeV; $m(\tilde{\tau}_R) = 150$ GeV



σ (cm^2)
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
E (GeV)
SM σ
SUSY σ $(m(\tilde{q}) = 300)$ GeV
SUSY σ $(m(\tilde{q}) = 600)$ GeV
SUSY σ $(m(\tilde{q}) = 900)$ GeV

NLSP Energy Loss

* Energy Loss:

$$-dE/dx = a(E) + b(E)\,E$$

with $a(E)$ and $b(E)$ slowly varying functions of E.

* $a(E)$: Electronic energy loss, from ionization/atomic excitation. From Bethe-Bloch eqn.

$$a(\beta\gamma) \simeq 0.08\,(17 + \ln(\beta\gamma))$$

with $\beta\gamma = p/M$. Energy and mass dependence only logarithmic.

E.g. for $M = 150$ GeV, typically $\beta\gamma \sim (10^3 - 10^6)$.

$$a \sim (2.4 - 3.6)\ \mathrm{MeV\,cm^2/gr}$$

* At higher energies radiation loss dominates $\Rightarrow b(E)$

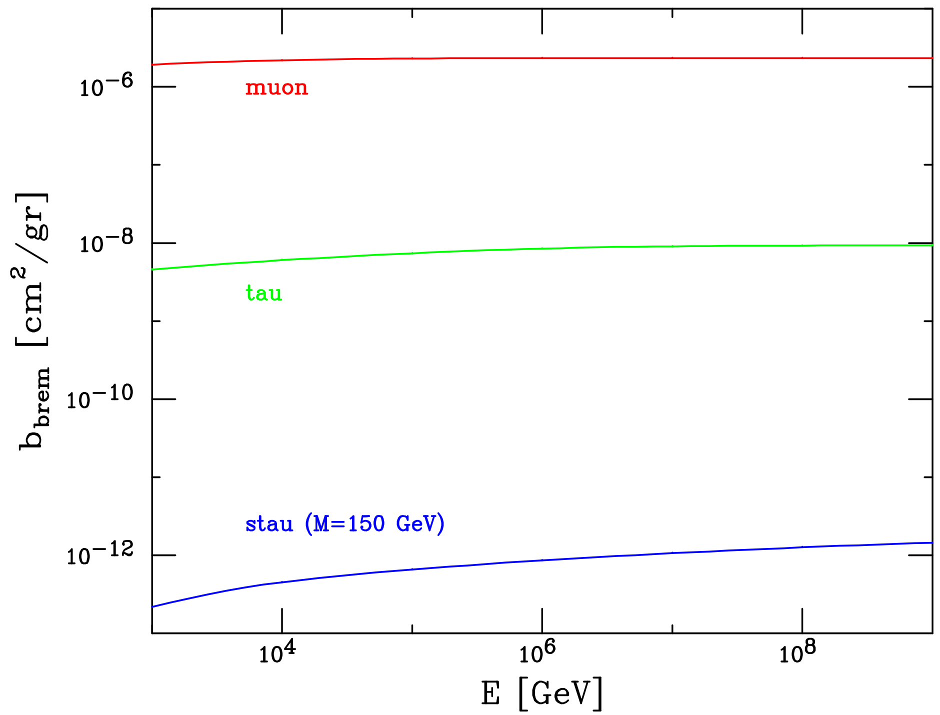
$$b = b_{\text{brem}} + b_{\text{pair}} + b_{PN}$$

* In general, average radiation loss is

$$b_i(E) = \frac{N}{A} \int_{\text{y}_{\text{min}}}^{\text{y}_{\text{max}}} dy\, y\, \frac{d\sigma_i}{dy}(E)$$

with $y = (E - E')/E$ the fractional energy loss.

∗ $b_{\rm pair}$ and $b_{\rm brem}$ are quite suppressed by the heavy NLSP mass. For instance, for Bremsstrahlung



$*$ For pair production $b_{\rm pair}$ is also suppressed

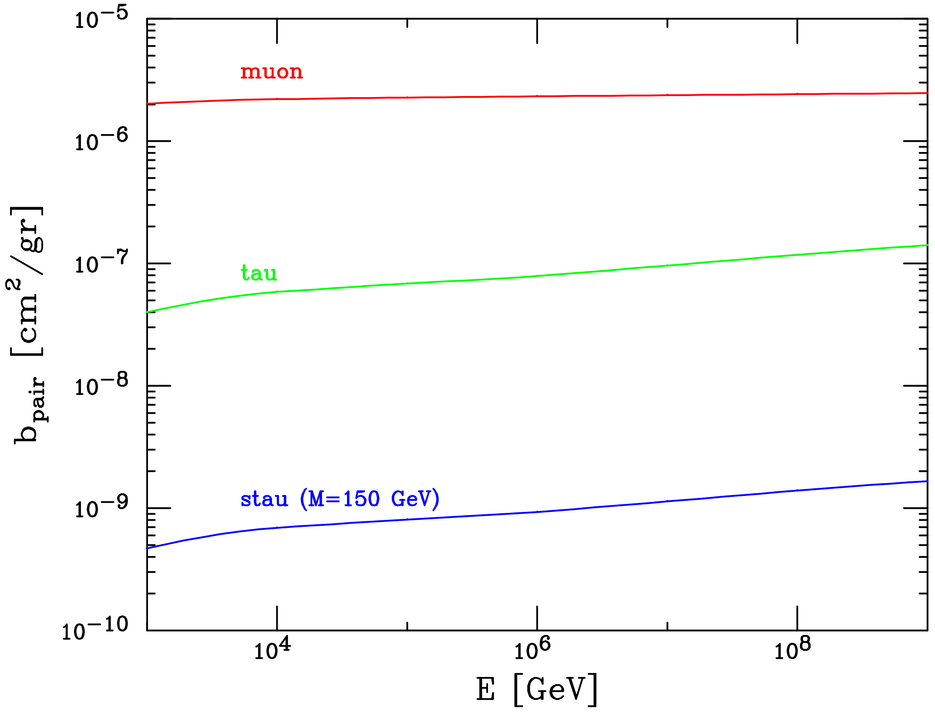
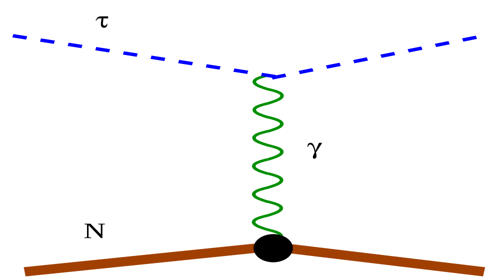


Photo-Nuclear Energy Loss

* Photo-nuclear interactions dominate tau energy loss. The will also dominate the NLSP b but is still mass suppressed.



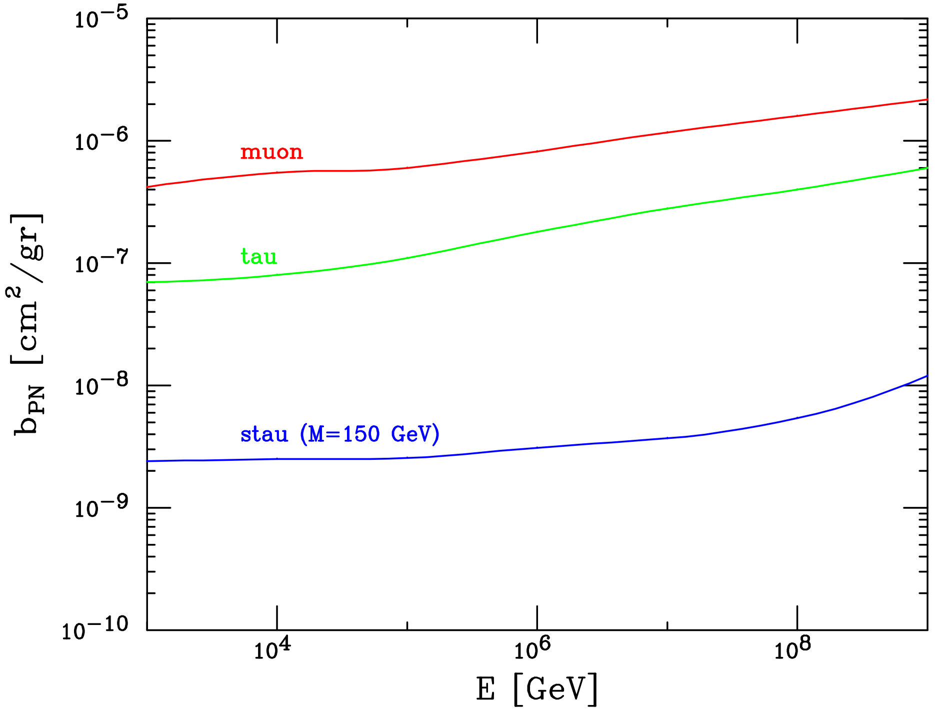
* The *minimum* Q^2 is quite large due to the heavy mass

$$b_{PN} = \frac{N}{A} \int_{\mathrm{y_{min}}}^{\mathrm{y_{max}}} dy\, y \int_{Q^2_{\mathrm{min}}}^{Q^2_{\mathrm{max}}} \frac{d^2\sigma_{\mathrm{PN}}}{dQ^2 dy}$$

with

$$Q^2_{\mathrm{min}} \simeq \frac{M^2 y^2}{1-y}$$

* The photo-nuclear cross section depends on the structure function $F_2(x, Q^2)$. Most of cross section comes from low Q^2, so a large $Q^2_{\rm min}$ suppresses the energy loss. Using the ALLM parametrization for F_2 (allowing coverage of all Q^2's), we have



* Conclusion: The NLSP energy loss is much smaller than the muon or tau energy loss. It is dominated by the photo-nuclear loss. As a result the range of the NLSP is long and in the 100s to 1000s of Km.

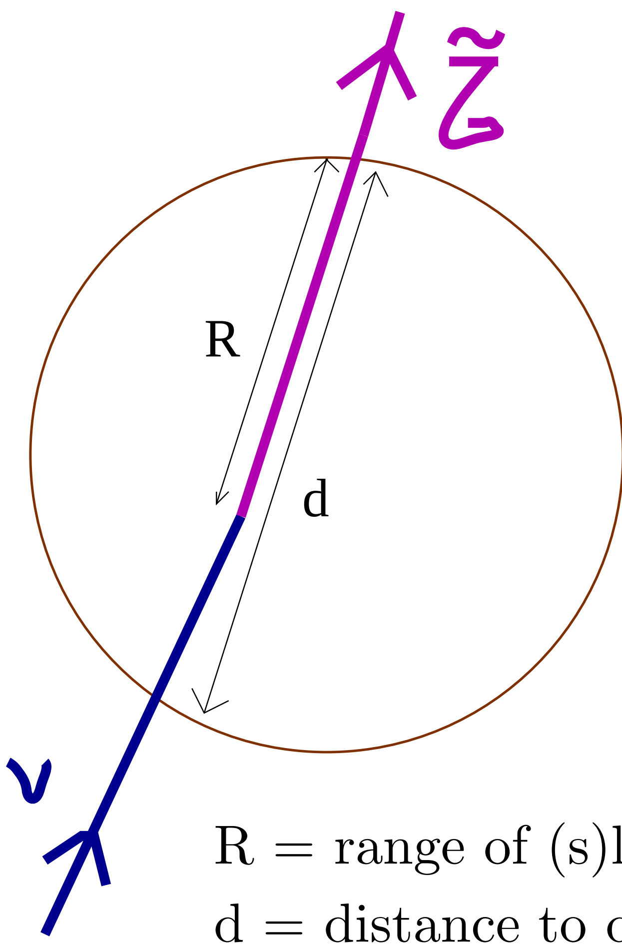
Rate of Charged NLSPs in Neutrino Telescopes

* Cosmic Neutrinos are expected due to the existence of Cosmic Rays
* neutrino flux at the Earth is taken to be as the Waxman-Bahcall limit

$$\frac{d\phi_{\nu_\mu+\overline{\nu}_\mu}}{dE} = \frac{4\times 10^{-8}}{E^2} \quad \mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$$

  - $\phi_{\nu_e} \sim \phi_{\nu_\mu} \sim \phi_{\overline{\nu}_\mu}$
  - flavor of initial neutrino does not affect result
  - mixing due to oscillation also does not affect result

NLSP Flux

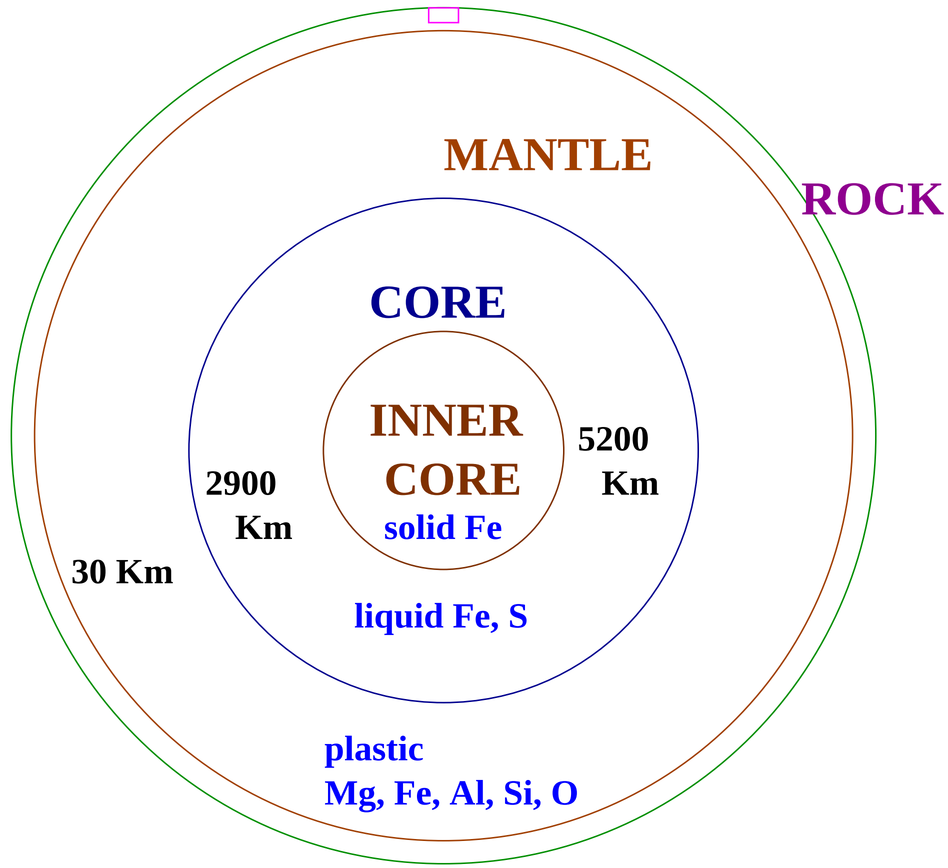


R = range of (s)lepton

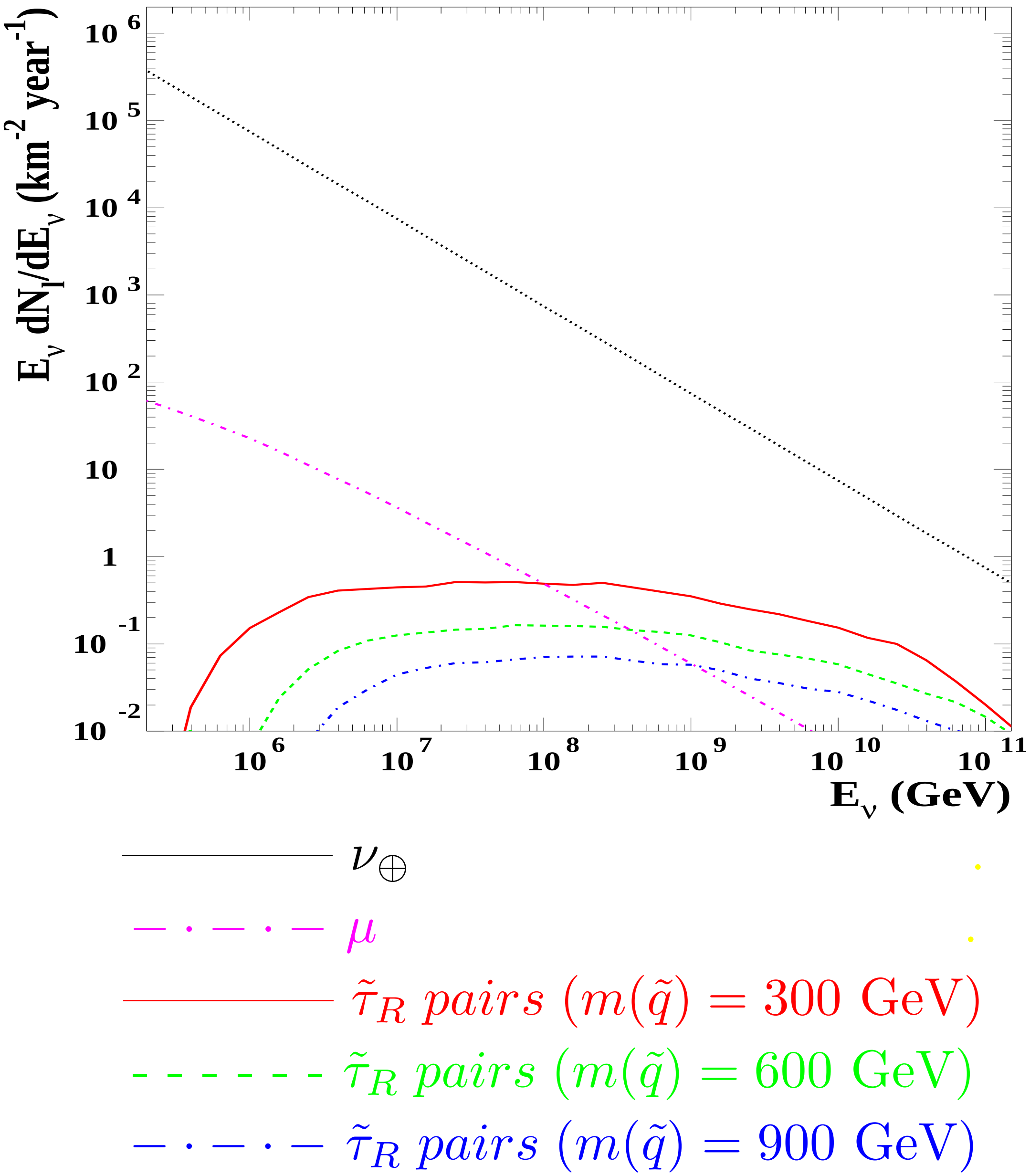
d = distance to detector

- $\phi_{l \text{ or } \tilde{l}} = \phi_{\nu\oplus} \times P_s \times P_I$
- $P_s = \exp\left(-\int n\,\sigma(E)\,dl\right)$
- $l = d - R$
- $P_I = 1 - \exp^{-\int n\,\sigma(E)\,dR}$

Model of Earth density profile



Density profile as in Gandhi, Quigg, Reno and Sarcevic - Phys. Rev. D **58** (1998)



$E_\nu\, dN_l/dE_\nu\ (km^{-2}\, year^{-1})$
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^6
10^7
10^8
10^9
10^{10}
10^{11}
E_ν (GeV)
$\nu_\oplus$
μ
$\tilde{\tau}_R\ pairs\ (m(\tilde{q}) = 300\ \mathrm{GeV})$
$\tilde{\tau}_R\ pairs\ (m(\tilde{q}) = 600\ \mathrm{GeV})$
$\tilde{\tau}_R\ pairs\ (m(\tilde{q}) = 900\ \mathrm{GeV})$

	μ	$m_{\tilde{q}} = 300$ GeV	600 GeV	900 GeV
WB	106	4	1	0.5
MPR	1085	10	3	1

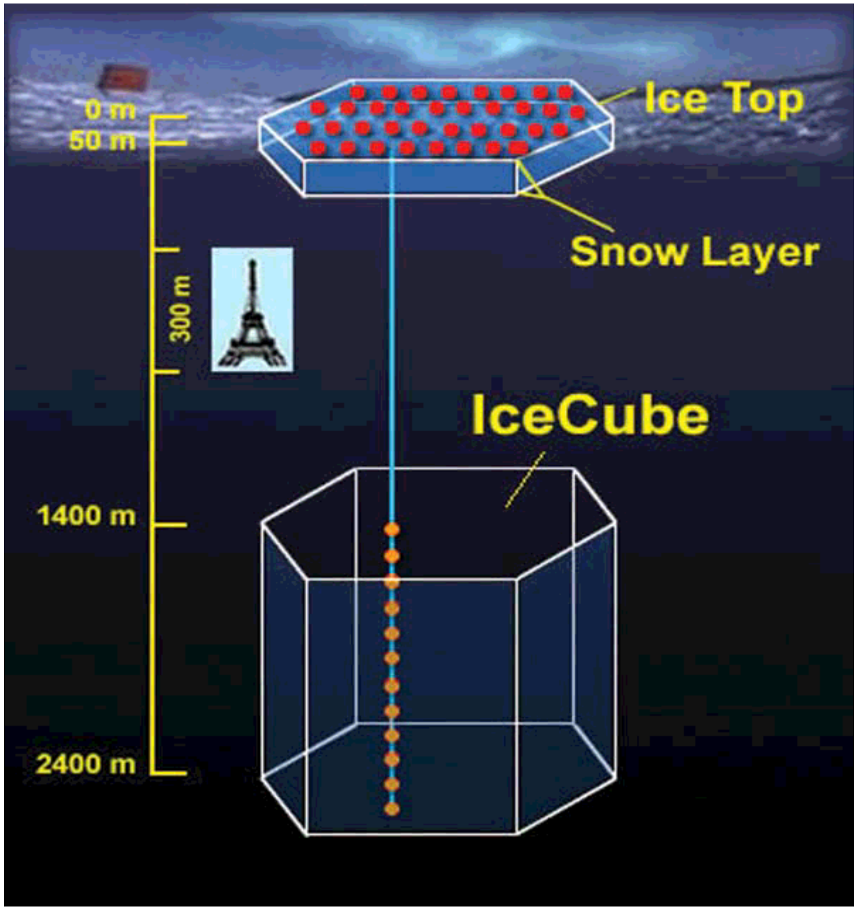
Table 1: Number of events per km^2 per year assuming the WB and MPR limits. The first column refers to upgoing muons. The last three columns correspond to upgoing NLSP pair events, for three different choices of squark masses: 300 GeV, 600 GeV and 900 GeV. The number of muon events are given for energies above threshold for production of a 250 GeV $\tilde{\ell}_L$ plus a 300 GeV squark, ie, 1.6×10^5 GeV.

	μ	$m_{\tilde{q}} = 300$ GeV	600 GeV	900 GeV
1 ring, 300 m	110	5	2	1
1 ring, 1000 m	110	6	2	1
4 rings, 300 m	131	9	3	1
4 rings, 1000 m	140	16	5	2

Table 2: Number of events for extended IceCube (Halzen and Hooper) per year assuming ν flux is given by the WB limit. The $\tilde{\ell}_L$ and squark masses and the number of muons are as in the previous Table.

Neutrino Telescopes

* measures Cherenkov light produced by a charged particle transversing either ice (AMANDA, IceCube) or ocean water (ANTARES, NESTOR)
  - Assumes particle is a muon.
  - Measures $\beta\gamma$
* current or under construction telescopes:
  - ANTARES($\sim 0,030$ km^3), AMANDA($\sim 0,016$ km^3), NESTOR($\sim 0,009$ km^3)
  - IceCube (1 km^3)



IceCube will occupy a volume of one cubic kilometer. Here we depict one of the 80 strings of opctical modules (number and size not to scale). IceTop located at the surface, comprises an array of sensors to detect air showers. It will be used to calibrate IceCube and to conduct research on high-energy cosmic rays.
Filename: schema1-300.jpg
Image by: Darwin Rianto

Original Image
Last updated April 15, 2004 by IceCube Webmaster

Signatures and Background

* NLSPs are produced in pairs, far from detector and with high energy boost

$$P \sim (10^6 - 10^8)\ \text{GeV}$$

$$\beta\gamma = \frac{P}{M} = \frac{(10^6 - 10^8)}{150} \sim 10^4 - 10^6$$

* Energy deposition will look like lower energy muon
  - A typical NLSP arriving at the detector has $E_{NLSP} = 10^6$ GeV and will look like a muon with $E_\mu \lesssim$ few TeV.

* Main signature are 2 tracks separated by ~ 100 m
  - separation (δR) is given by: $\delta R \simeq L\theta$
    * $L =$ distance to production point ($\sim 100 - 1000$ Km)
    * $\theta \simeq \frac{p^{\rm CM}_{\rm SUSY}}{p_{boost}} \simeq 10^{-3} - 10^{-4}$
  * If L is NLSP range $\Rightarrow$ in linear regime $\delta R \simeq 100m$
    when R(E) $\delta R \simeq 20 - 40m$
  * most NLSP events $\Rightarrow$ 2 parallel but well separated tracks
  * **Background:** dimuon events (coming from the production of charm and subsequent decay)

    $\Rightarrow$ These events will have smaller track separation

Conclusions and Outlook

- Neutrino telescopes are potentially sensitive to the long-lived charged NLSPs
  - These are present in a wide variety of SUSY breaking models
- Have the potential to discover the NLSP and consequently determine indirectly the dark matter particle
- Observation of the NLSP constitutes a direct probe of the scale of SUSY breaking

$$5 \times 10^6 \text{ GeV} \lesssim \sqrt{F} \lesssim 5 \times 10^8 \text{ GeV}$$

lifetime sufficiently long — Big Bang Nucleosynthesis

- Complementary search to LHC
- More detailed paper in preparation (with G.Burdman and Z. Chacko)