APS-DPF 2006

Ultrahigh Energy Cosmic Neutrinos and the Physics Beyond the Standard Model

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Ultrahigh Energy Neutrinos

- **Neutrinos are highly stable, neutral particles ⇒ Thus cosmic neutrinos point back to astrophysical point sources and bring information from processes otherwise obscured by a few hundred gm of a material.**
- **Interaction length of a neutrino is**

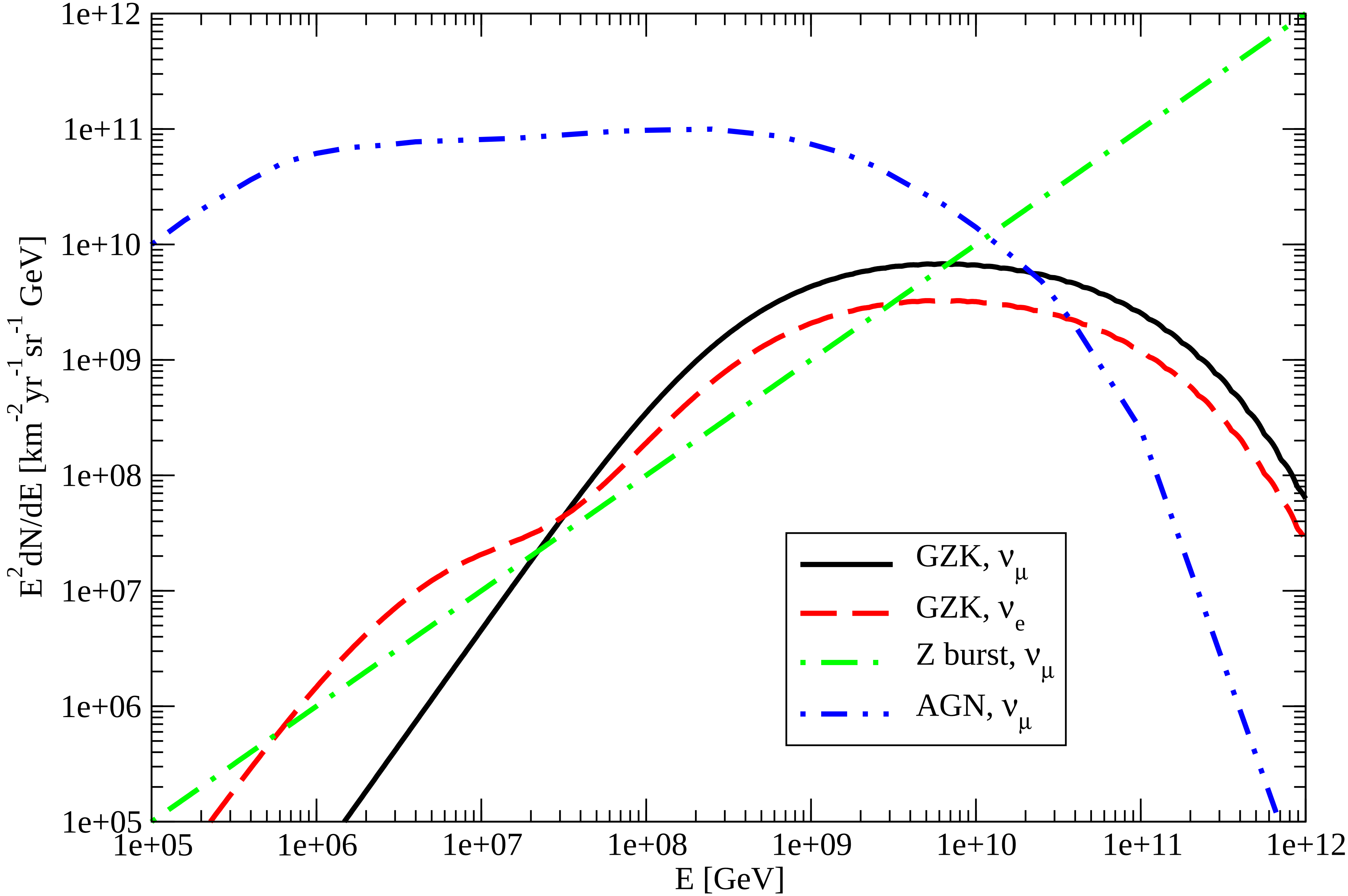
$$\mathcal{L}_{\text{int}} \equiv \frac{1}{\sigma_{\nu N}(E_\nu)\cdot N_A}$$

Interaction length of 1TeV neutrino is 250 kt/cm^2 or column of water of 2.5 million km deep.

- **Neutrino astronomy ⇒ a unique window into the deepest interiors of stars and galaxies**
  (HE photons get absorbed by a few hundred gm of a material).

Sources of very high energy neutrinos

- **Cosmogenic (“GZK”) neutrinos (interactions of cosmic rays with microvawe background radiation)**
- **Active Galactic Nuclei (AGN)**
- **Gamma Ray Bursts (GRB’s)**
- **Z burst**
- **Topological Defects**
- **...**



1e+12
1e+11
1e+10
1e+09
1e+08
1e+07
1e+06
1e+05
E^2 dN/dE [km^-2 yr^-1 sr^-1 GeV]
1e+05
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12
E [GeV]
GZK, ν_μ
GZK, ν_e
Z burst, ν_μ
AGN, ν_μ

- **Basic processes of neutrino production in extragalactic sources:**

$$p + \gamma \to n + \pi^+$$

$$\hookrightarrow n + \gamma \to p + \pi^-$$

$$\hookrightarrow \pi^\pm \to \mu^\pm + \nu_\mu$$

$$\hookrightarrow \mu^\pm \to e^\pm + \nu_\mu + \nu_e$$

$$p + \gamma \to p + \pi^o$$

$$\hookrightarrow \pi^o \to \gamma\gamma$$

- **The probability for $\nu_\mu \to \nu_\tau$ oscillations is given by**

$$P(\nu_\mu \to \nu_\tau; L) = \sin^2 2\theta \ \sin^2(\frac{1.27\Delta \mathrm{m}^2 \mathrm{L(Km)}}{\mathrm{E(GeV)}})$$

- **For astronomical distances ($L \sim 1000 Mpc$) and for large mixing angles, $P(\nu_\mu \to \nu_\tau; L) = 1/2$. This implies $F_{\nu_\mu} = F_{\nu_\tau}$**

Probing Neutrino Flavor Mixing

- **source:** π **decays** $\Rightarrow \nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

- **propagation towards Earth: neutrino oscillations**
  - $\star$ ν_μ **and** ν_τ **maximally mixed** $\Rightarrow \nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

- **If** $F^0_{\nu_e} : F^0_{\nu_\mu} : F^0_{\nu_\tau} \neq 1 : 2 : 0$ **then three flavor mixing is relevant**

$$F_{\nu_e} = F^0_{\nu_e} - \frac{1}{4}\sin^2 2\theta_{12}(2F^0_{\nu_e} - F^0_{\nu_\mu} - F^0_{\nu_\tau})$$

$$F_{\nu_\mu} = F_{\nu_\tau} = \frac{1}{2}(F^0_{\nu_\mu} + F^0_{\nu_\tau}) + \frac{1}{8}\sin^2 2\theta_{12}(2F^0_{\nu_e} - F^0_{\nu_\mu} - F^0_{\nu_\tau})$$

Jones, Mocioiu, Reno and Sarcevic, PRD 69 (2004)

- **Detection of HE neutrinos with neutrino telescopes depends strongly on neutrino interactions and their cross section:**

- **Event rates for *downward* muons (leptons/sleptons or hadrons) from neutrino interactions:**

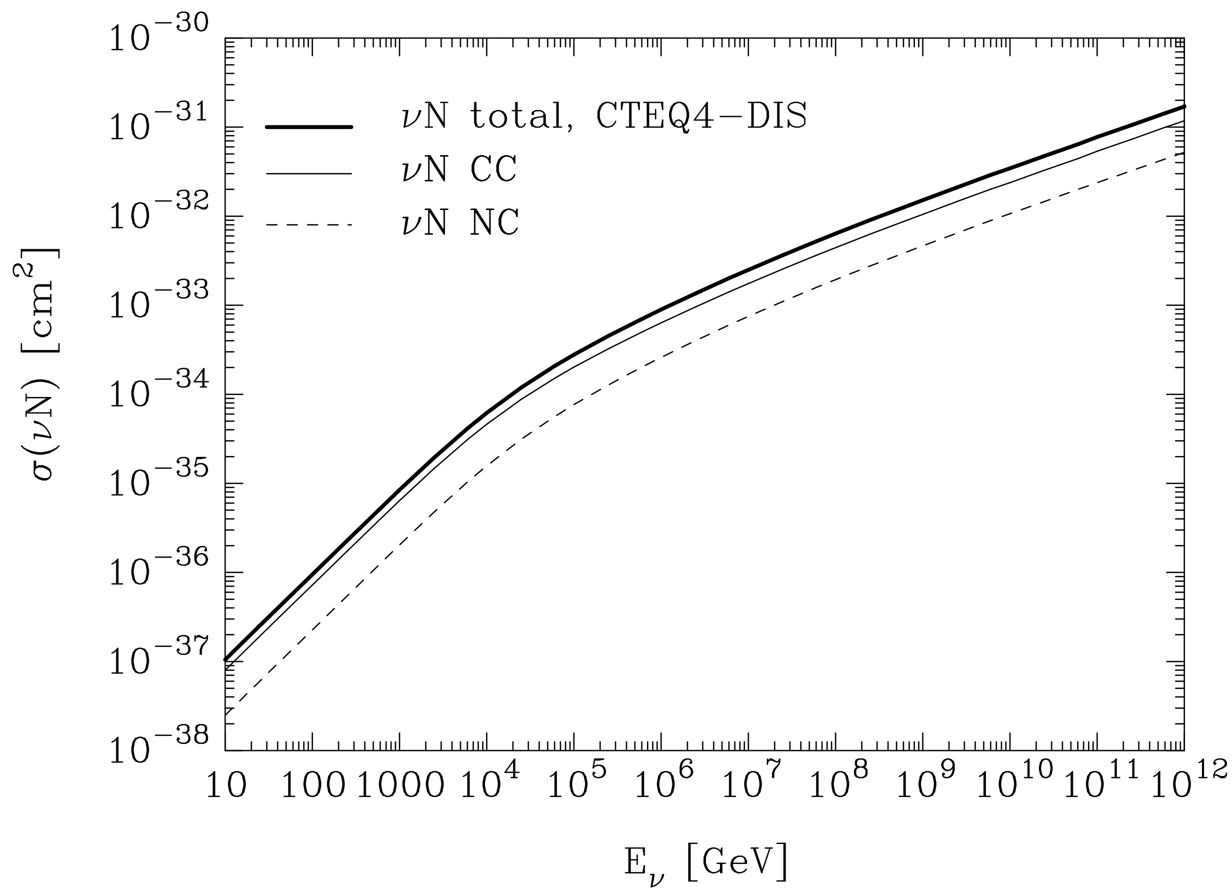
$$R_\nu = V \int dE_\nu \ \sigma_{cc}(E_\nu) \ F_\nu(E_\nu)$$

- **Event rates for *upward* muons (leptons/sleptons) from neutrino interactions:**

$$R_\nu = AN_A \int dE_\nu R(E_\nu, E_\mu) \sigma_{cc}(E_\nu) S(E_\nu) F_\nu(E_\nu, X)$$

where $R(E_\nu, E_\mu)$ is the muon range and $S(E_\nu)$ is the neutrino attenuation factor.

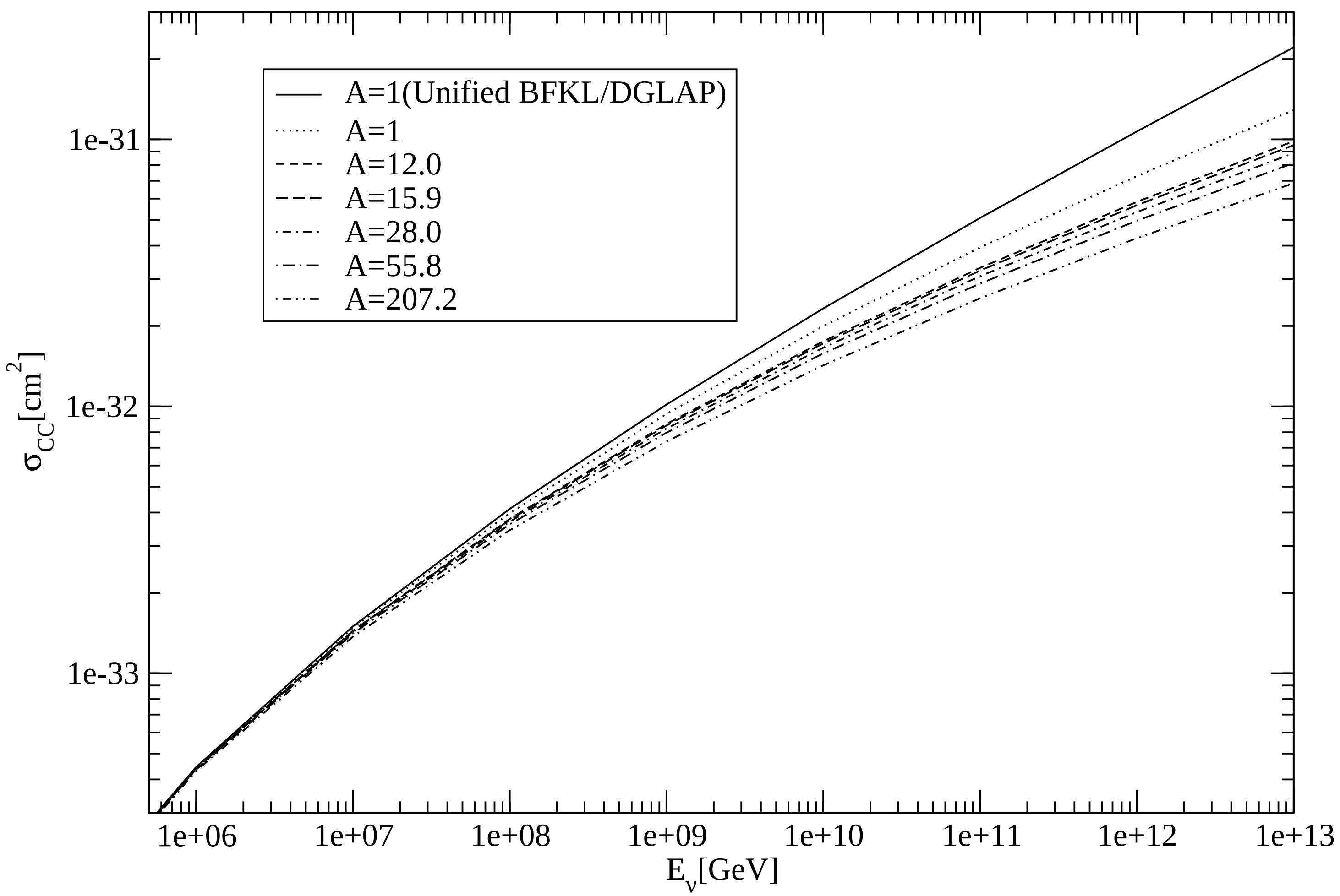
- At low energies SM neutrino cross section is under control thanks to HERA measurements of the structure functions. At higher energies, we require knowledge of small x parton distributions ⇒ DGLAP/BFKL approach including non-linear effects.



R. Gandhi, C. Quigg, M.H. Reno and I.S., PRD58, 093009 (1998)

- **New physics can also alter neutrino interactions**

- **Theoretical uncertainty due to small x extrapolation:**



- **Non-linear corrections large at high energies, above $\sim 10^9$ GeV**

Detection of Cosmic Neutrinos

- **Muon tracks (ICECUBE, RICE)**
- **Electromagnetic and Hadronic Showers (ICECUBE, RICE, ANITA, Auger, OWL, EUSO)**
- **To determine the energy flux (muons or showers) that reaches the detector we need to consider propagation of neutrinos and leptons through the Earth and ice**
- ν_τ **give different contribution from** ν_μ **due to the very short** τ **lifetime, i.e. the regeneration effect.**
- **New physics manifested via production of new particles in neutrino interactions, such as supersymmetric charged sleptons, staus, which after interactions with matter produce charge tracks similar to muons, or hardonic showers.**

Propagation through the Earth/ice

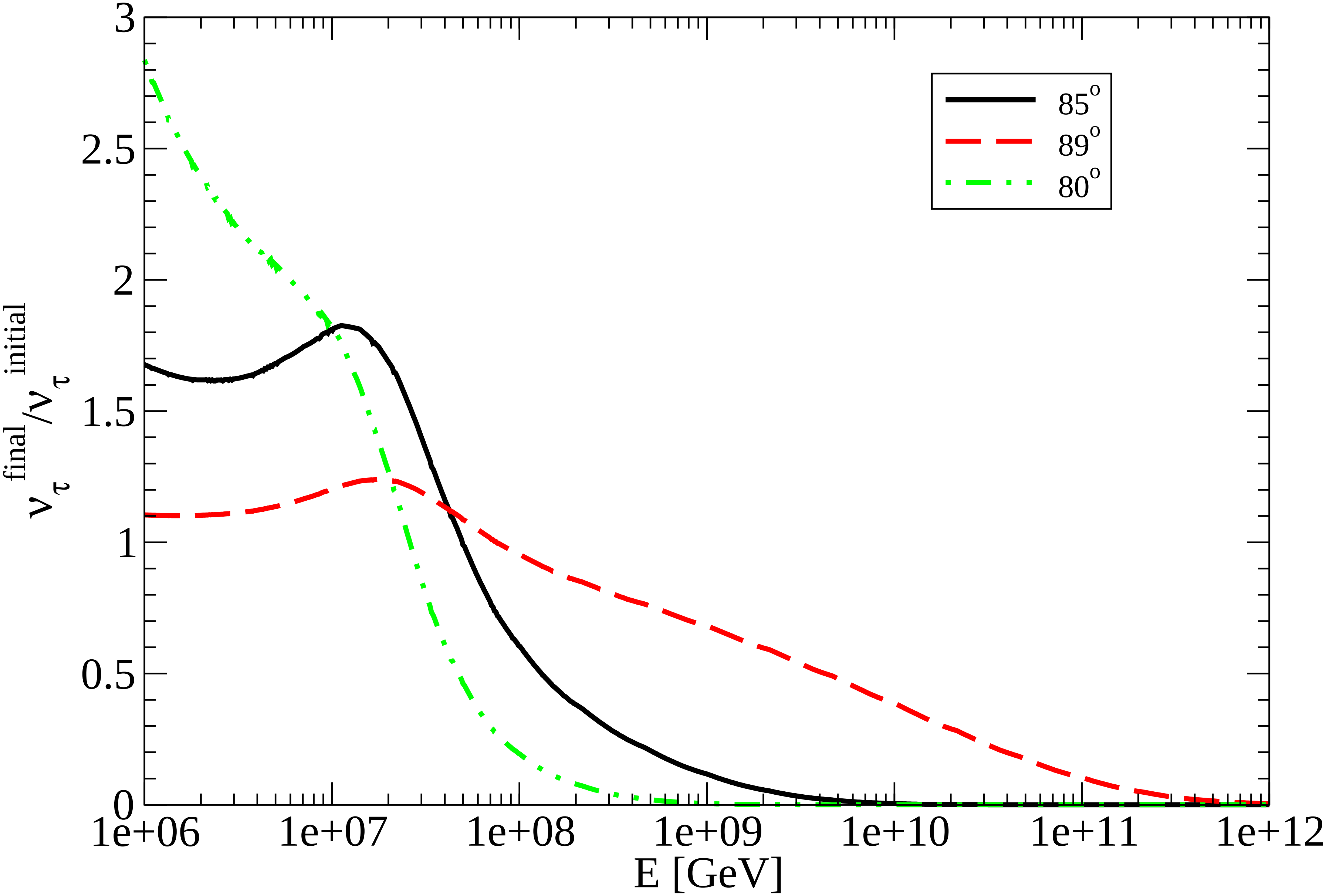
- ν **attenuation due to charged (CC) and neutral current (NC) interactions**
- **NC gives** ν **with lower energy**
- **regeneration of** ν **from** τ **decay**

$$
\begin{aligned}
\frac{\partial F_{\nu_\tau}(E,X)}{\partial X} &= -N_A \sigma^t(E) F_{\nu_\tau}(E,X) + N_A \int_E^\infty dE_y F_{\nu_\tau}(E_y,X) \frac{d\sigma^{NC}}{dE}(E_y,E) \\
&+ \int_E^\infty dE_y \frac{F_\tau(E,X)}{\lambda_\tau^{dec}} \frac{dn}{dE}(E_y,E)
\end{aligned}
$$

- τ **decay**
- **CC production of** τ

$$
\frac{\partial F_\tau(E,X)}{\partial X} = N_A \int_E^\infty dE_y F_{\nu_\tau}(E_y,X) \frac{d\sigma^{CC}}{dE}(E_y,E) - -\frac{F_\tau(E,X)}{\lambda_\tau^{dec}(E,X,\theta)}
$$

- τ **energy loss:** $dE_\tau/dX = \alpha_\tau + \beta_\tau E_\tau$



3
2.5
2
1.5
1
0.5
0
$\nu_\tau^{final}/\nu_\tau^{initial}$
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12
E [GeV]
85°
89°
80°

Observables: showers in ice

- **Electromagnetic showers:**

  Tau decay: $\tau \rightarrow e + \bar{\nu}_e + \nu_\tau$

  ν_e **CC interactions:** $\nu_e + N \rightarrow e + X$

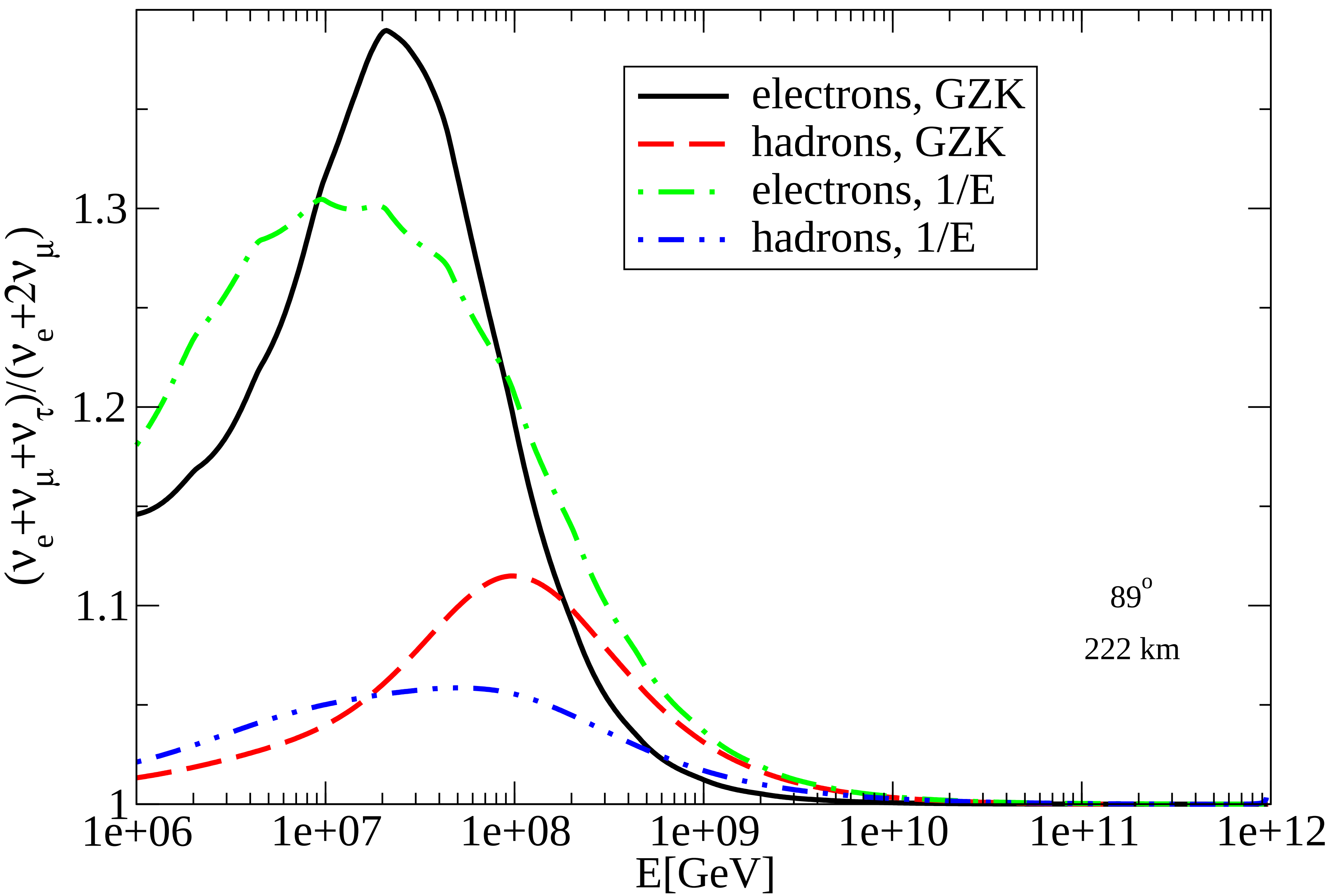
- **Hadronic showers**

  Tau decay: $\tau \rightarrow \nu_\tau + X$

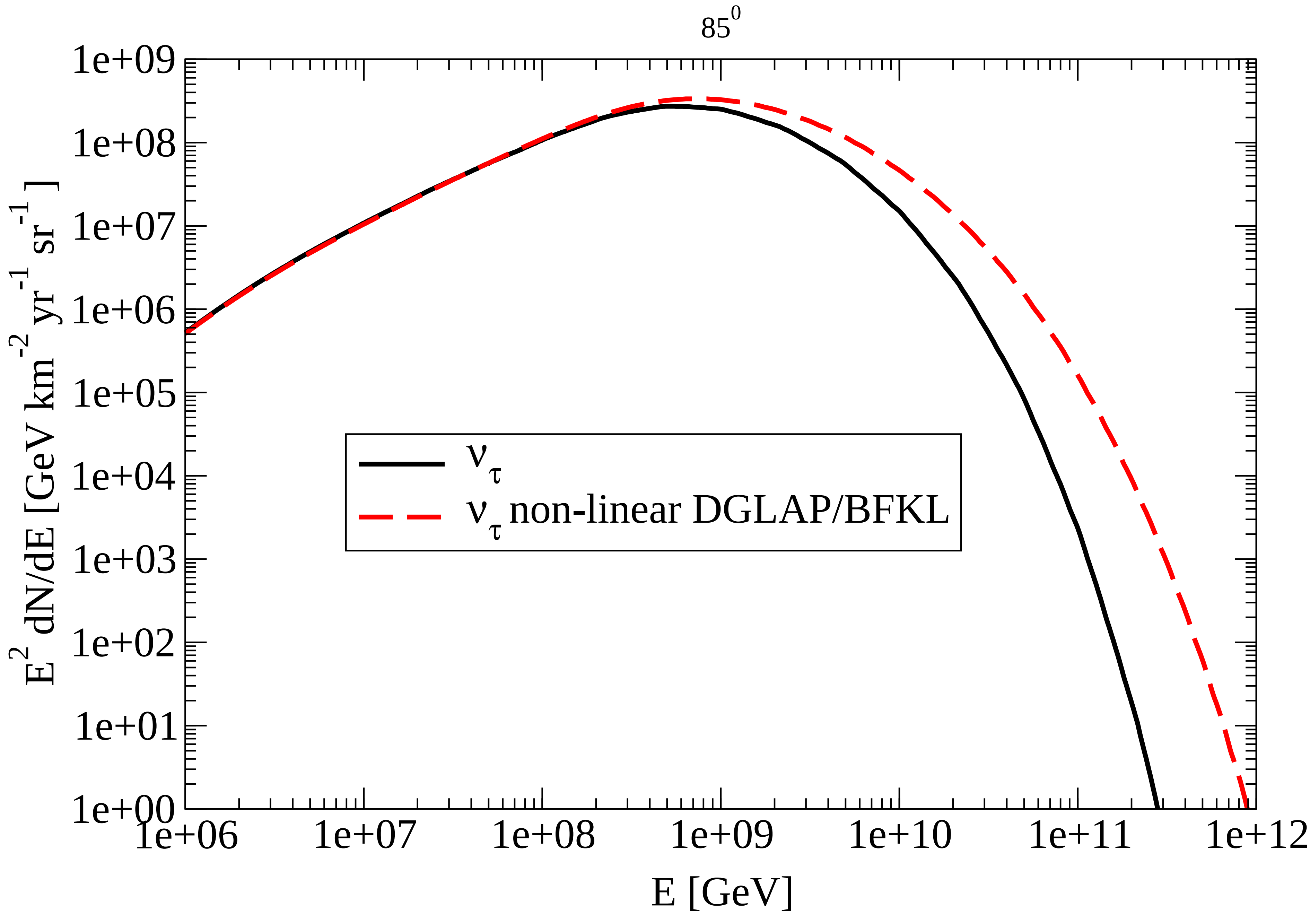
  ν_τ **NC interactions:** $\nu_\tau + N \rightarrow \nu_\tau + X$

  ν_τ **CC interactions:** $\nu_\tau + N \rightarrow \tau + X$

  $\nu_{e,\mu}$ **NC and CC interactions**



electrons, GZK
hadrons, GZK
electrons, 1/E
hadrons, 1/E
89°
222 km
1.3
1.2
1.1
1
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12
E[GeV]
(ν_e+ν_μ+ν_τ)/(ν_e+2ν_μ)



85^0
1e+09
1e+08
1e+07
1e+06
1e+05
1e+04
1e+03
1e+02
1e+01
1e+00
1e+06
1e+07
1e+08
1e+09
1e+10
1e+11
1e+12
E^2 dN/dE [GeV km^{-2} yr^{-1} sr^{-1}]
E [GeV]
ν_τ
ν_τ non-linear DGLAP/BFKL

- **Above 10^8 GeV, tau energy loss is important.**

- **For $E_\nu > 10^8$ GeV, ν_τ flux resembles ν_μ flux, due to the tau energy loss.**

- **Bellow 10^8 GeV, regeneration of ν_τ becomes important while ν_μ are strongly attenuated.**

- **The regeneration effect depends strongly on the shape of the initial flux and it is larger for flatter fluxes.**

- **The enhancement due to regeneration also depends on the amount of material traversed by neutrinos and leptons, i.e. on nadir angle.**

- **The non-linear effects in small-x evolution of the parton distribution become important for energies above 10^8 GeV**

- **Very high energy cosmic neutrinos also present unique opportunity to study the interactions of elementary particles at energies beyond those obtainable in current or planned colliders.**

- **Cosmic neutrinos with energies E_ν above 10^{17} eV probe neutrino-nucleon scattering at center-of-mass (c.m.) energies above**

$$\sqrt{s_{\nu N}} \equiv \sqrt{2 m_N E_\nu} \simeq 14 \left(\frac{E_\nu}{10^{17}\ \mathrm{eV}} \right)^{1/2} \ \mathrm{TeV}$$

- **These energies are beyond the proton-proton c.m. energy $\sqrt{s_{pp}} = 14$ TeV of the LHC, and Bjorken-x values below**

$$x \simeq 2 \times 10^{-4} \left(\frac{Q^2}{m_W^2} \right) \left(\frac{0.2}{y} \right) \left(\frac{10^{17}\ \mathrm{eV}}{E_\nu} \right)$$

Neutrinos as Probes of Physics Beyond the Standard Model

- **Microscopic black holes as predicted in TeV scale gravity models**
- **Exchange of Kaluza-Klein gravitons**
- **Production of charged sleptons in HE neutrino interactions (probing SUSY)**
- **...**

Measurements of neutrino interactions at extremely high energies can provide powerful tests of fundamental physics at and beyond a scale of 1-10TeV.

Probing Extra Dimensions with Neutrinos

- **Possibility that we live in $4 + n$ spacetime dimensions has profound implications. If gravity propages in these extra dimensions, the fundamental Planck scale, M_D, at which gravity becomes comparible in strength to other forces, may be in TeV range, leading to a host of potential signatures for high energy physics $\Rightarrow$ one of the most striking consequences of low-scale gravity is the possibility of black hole creation in high-energy particle collisions.**

- **Gravitation processes involving graviton emission and exchange, analyses rely on a perturbative description that breaks down for energies of M_D and above.**

- **In contrast, black hole properties are best understood for energies above M_D, where semiclassical and thermodynamic descriptions become increasingly valid.**

Black Hole Production and Decay

- **In a high energy parton-parton collision, when the impact parameter is smaller than the Schwarzschild radius in d dimensions, a d-dimensional black hole is formed with the geometrical cross-section,**

$$\hat{\sigma}_{BH} = \pi r_S^2 (M_{BH} = \sqrt{\hat{s}}) \theta(\sqrt{\hat{s}} - M_{BH}^{min})$$

where r_S is Schwarzschild radius in d dimensions given by

$$r_S = \frac{1}{\sqrt{\pi}} \frac{1}{M_P} \left[\frac{M_{BH}}{M_P} \left(\frac{8\Gamma(\frac{n+3}{2})}{n+2} \right) \right]^{\frac{1}{n+1}}$$

and $\sqrt{\hat{s}}$ is the center of mass energy of parton-parton collision.

- **To avoid stringy effects and be able to use semi-classical approach we consider $M_{BH} >> M_D$**

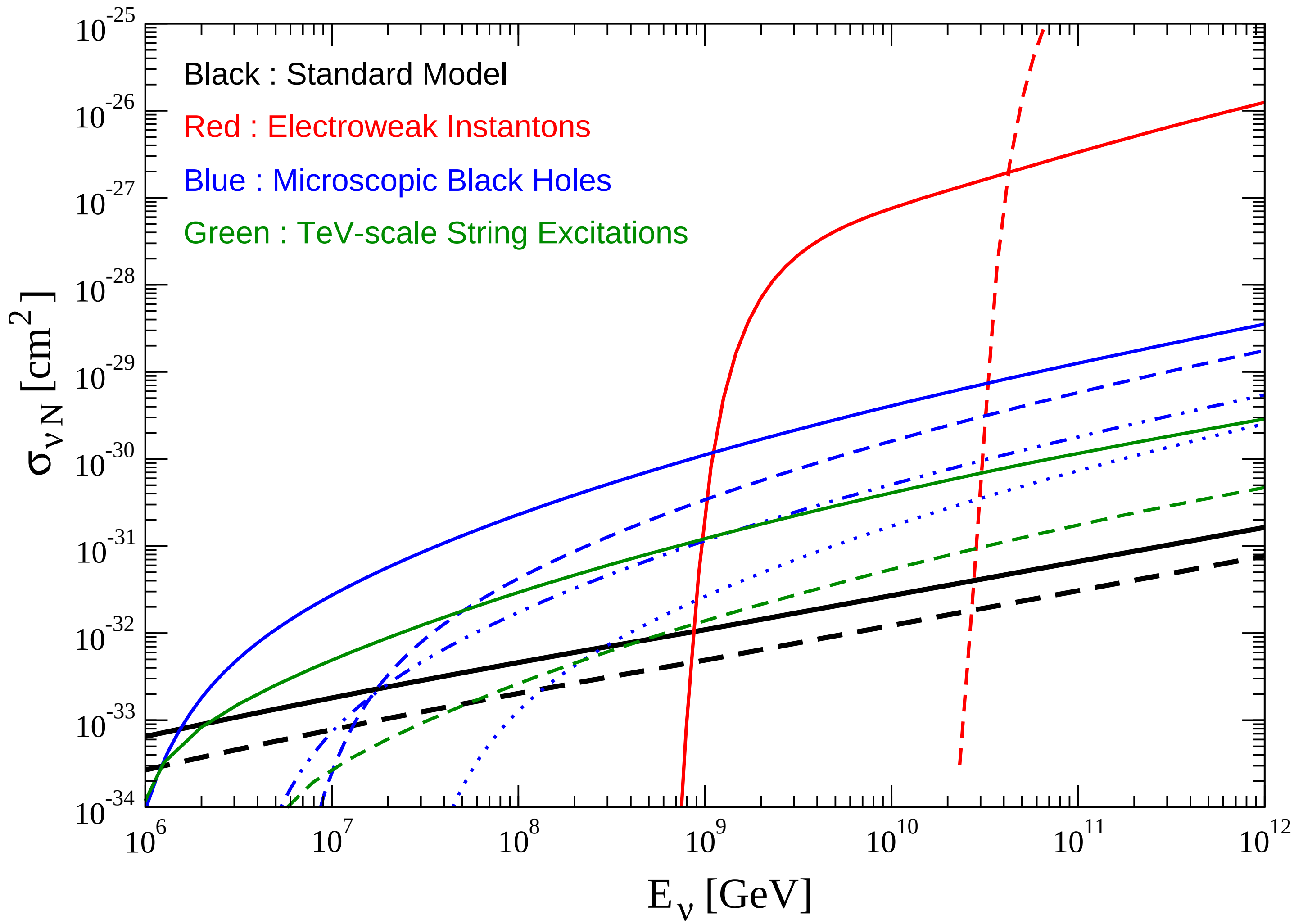
- **Decay: BH evaporation at the original temperature**

- **BH radiates mainly on the brane**

- **Most of the decay is hadronic**

- **Typical lifetime 10^{-27} s.**

- **Lack of knowledge of quantum gravity effect close to the Planck scale – theoretical input needed**



Black : Standard Model
Red : Electroweak Instantons
Blue : Microscopic Black Holes
Green : TeV-scale String Excitations
$\sigma_{\nu N}$ [cm^2]
E_ν [GeV]
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}

Black Holes in Neutrino Telescopes

- **The contained event rate for black hole production is**

$$Rate = \int dE_\nu N_A V_{eff}\, \sigma_{BH}(E_\nu) \frac{dN_\nu}{dE_\nu}$$

N_A **is Avogadro's number**

$\frac{dN_{\nu_\mu}}{dE_{\nu_\mu}}$ **is the neutrino flux that reaches the detector**

V_{eff} **is the effective volume of the detector.**

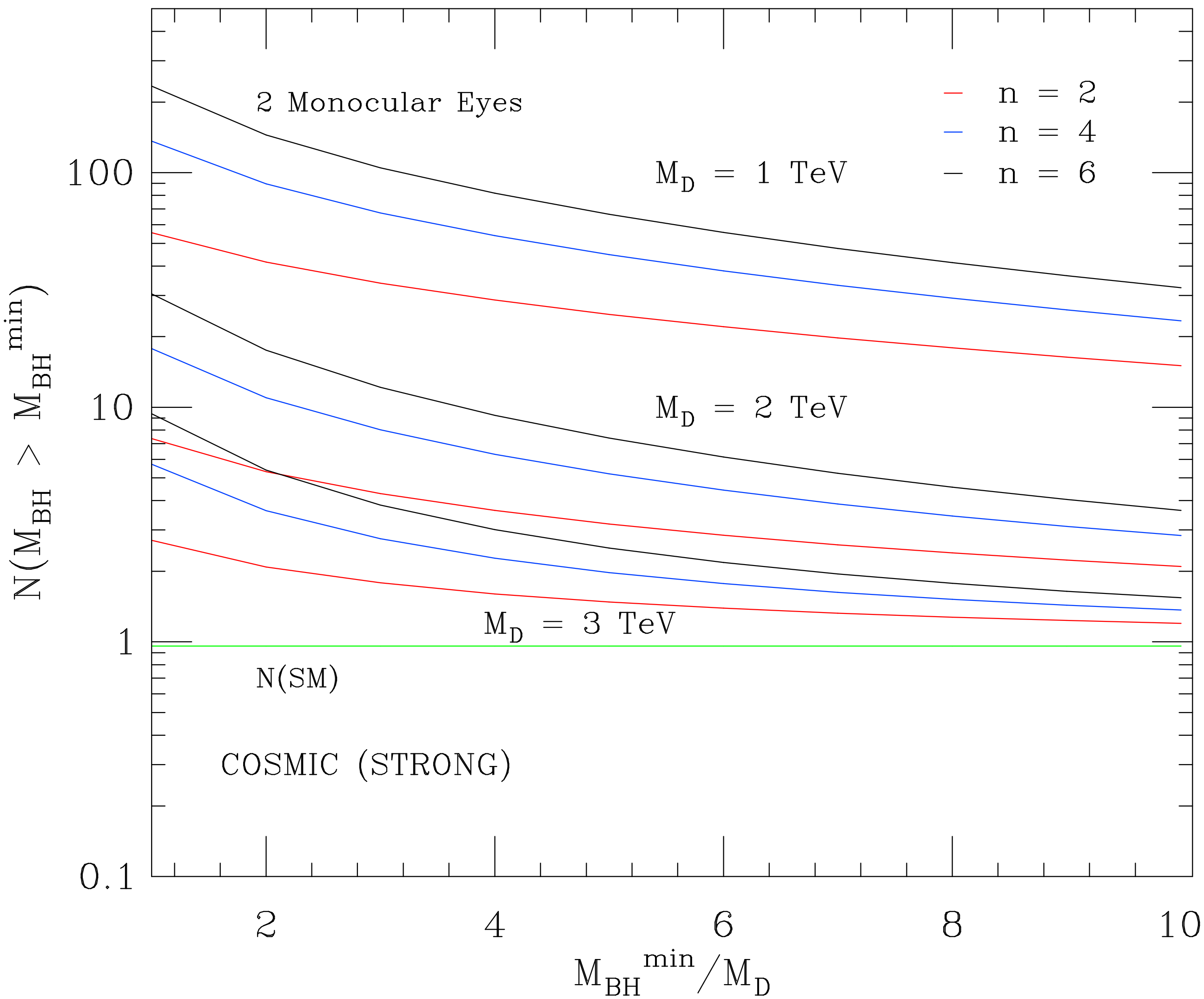
- **The event rate for black hole production with OWL is given by**

$$N = T \int \epsilon A(E_\nu) \frac{dN}{dE_\nu} \sigma_{BH}(E_\nu) dE_\nu$$

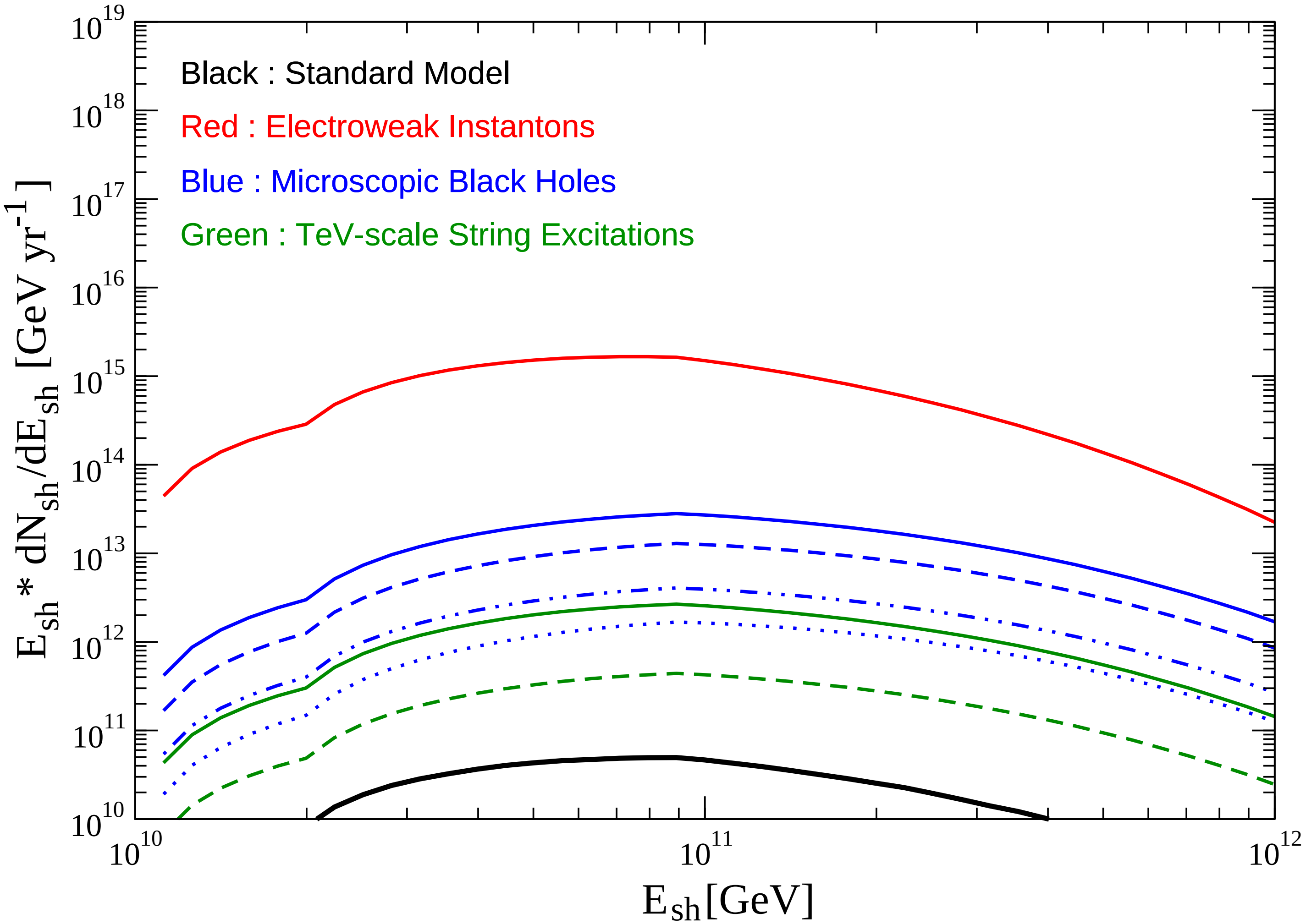
where $A(E_\nu)$ **is the OWL effective aperture,** ϵ **is a duty cycle and** T **is the duration of data taking.**

Black Holes with OWL

Dutta, Reno and Sarcevic, PRD 66 (2002)



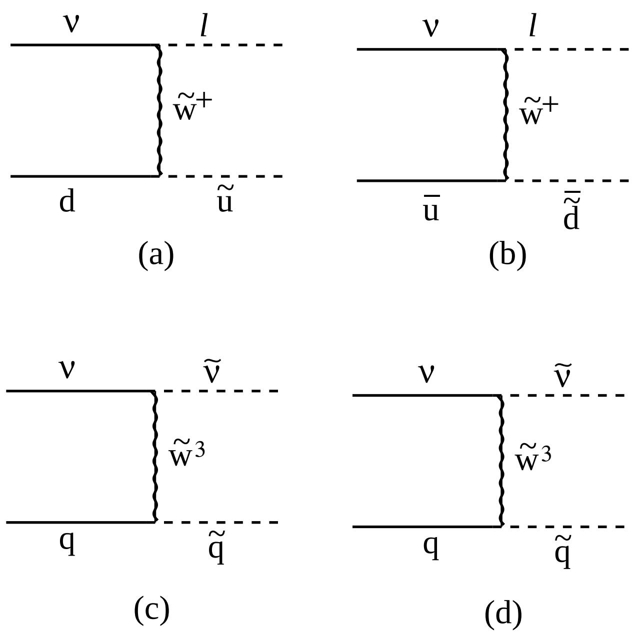
Probing the Physics Beyond the Standard Model with EUSO

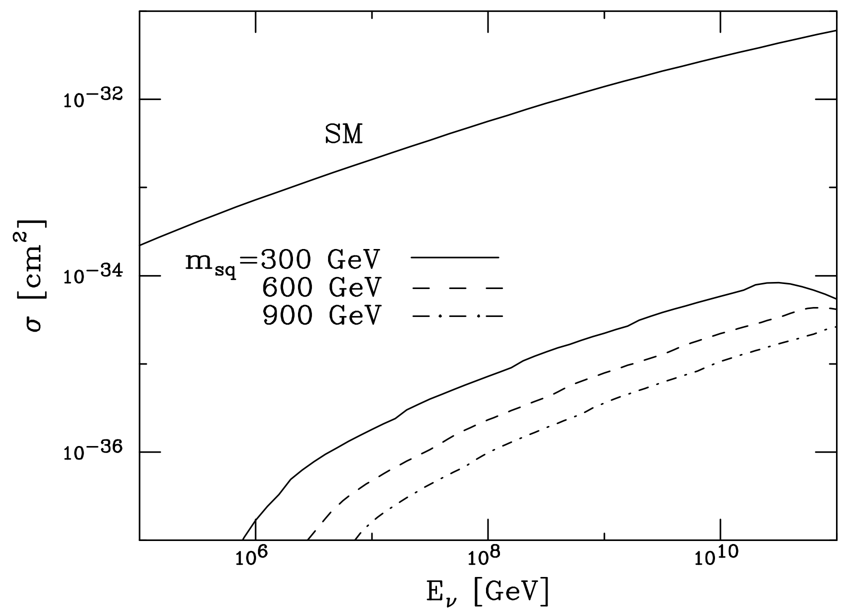


Probing SUSY with Neutrinos

Albuquerque et al., PRL 92 (2004); hep-ph/0605120
Ahlers, Kersten and Ringwald, hep-ph/0604188
Reno, Sarcevic and Su, Astropart. Phys. **24** (2005)
Huang, Reno, Sarcevic and Uscinski, hep-ph/0607216

- **In low scale supersymmetric models, lightest supersymmetric particle (LSP) is the gravitino. NSLP is typically a long lived charged slepton.**
- **Collisions of high energy neutrinos with nucleons in the earth can result in the production of sleptons. Their very high boost means they travel very long distances before decaying.**
- **Sleptons traverse the earth losing their energy via bremsstrahlung, pair production, photonuclear interactions and weak interactions. Energy dependence of the energy loss translates into energy spectrum of the staus that reach the detector.**





Lifetime of the stau: $c\tau = \left(\frac{\sqrt{F}}{10^7 GeV}\right)^4 \left(\frac{100 GeV}{m_{\tilde{\tau}}}\right)^5 10\text{km}$

I. Albuquerque et al., PRL 92 (2004)

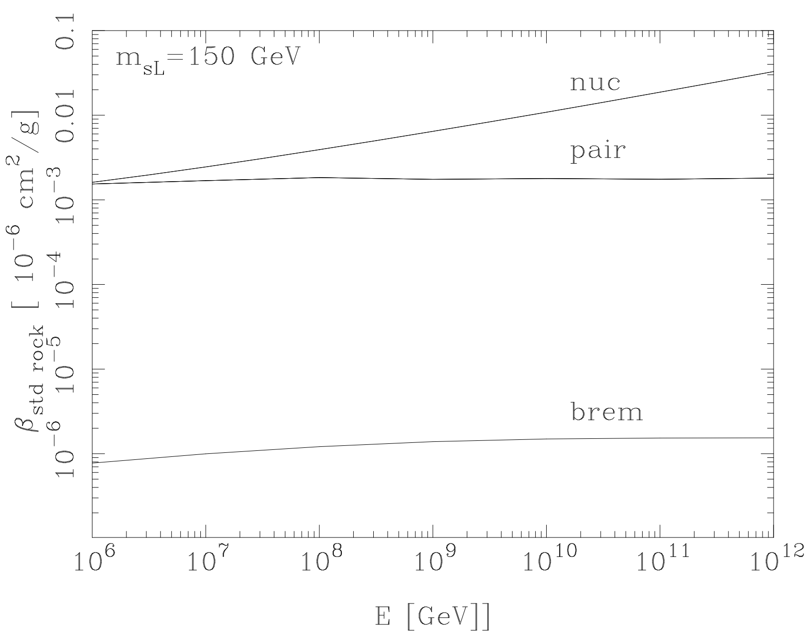
Energy Loss of Stau

M.H. Reno, I.S. and S. Su, Astropart. Phys. **24** (2005)

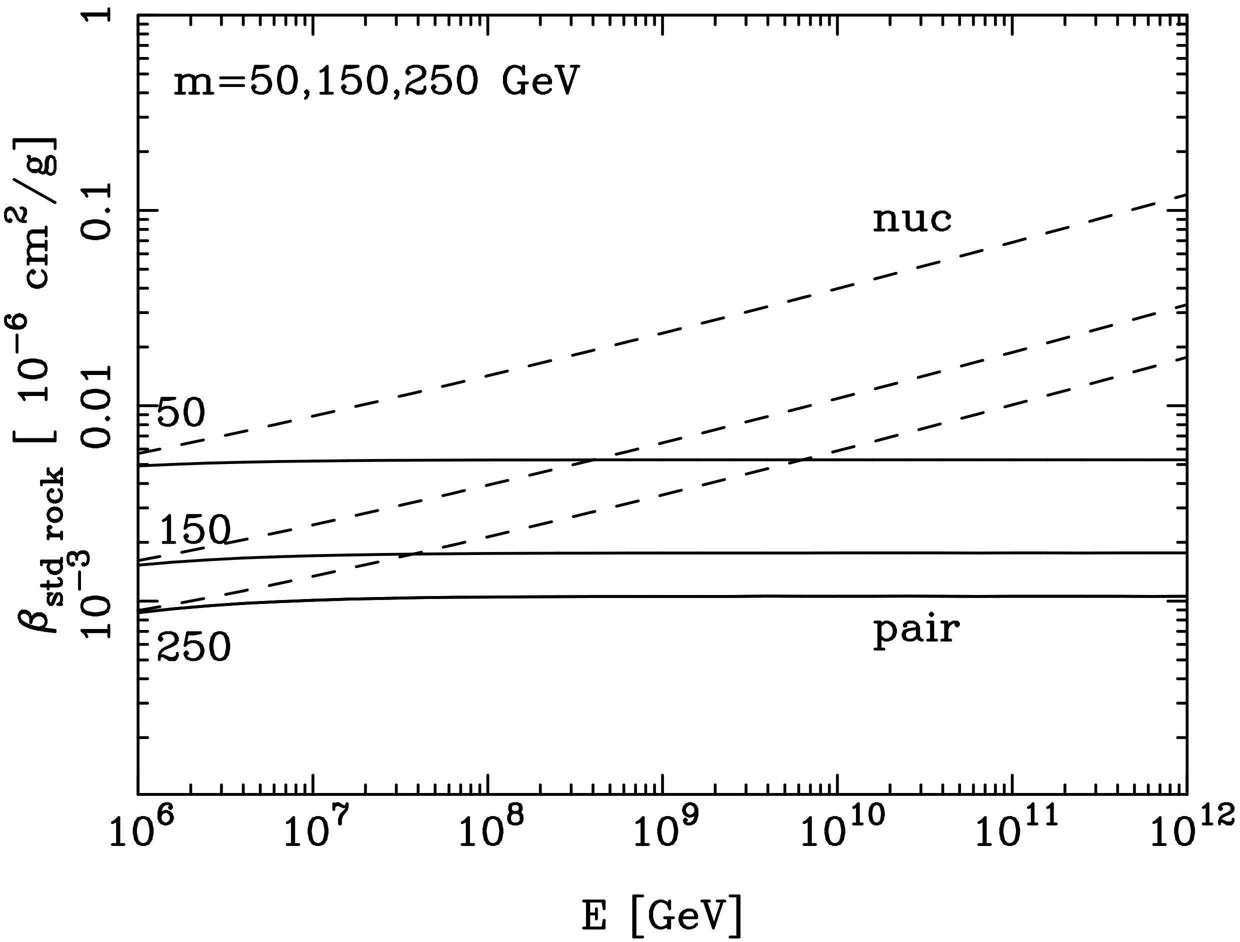
The average energy loss of a stau traversing a distance X

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

α is the ionization energy loss, and β is the radiative energy loss (bremsstrahlung, pair production, photonuclear).

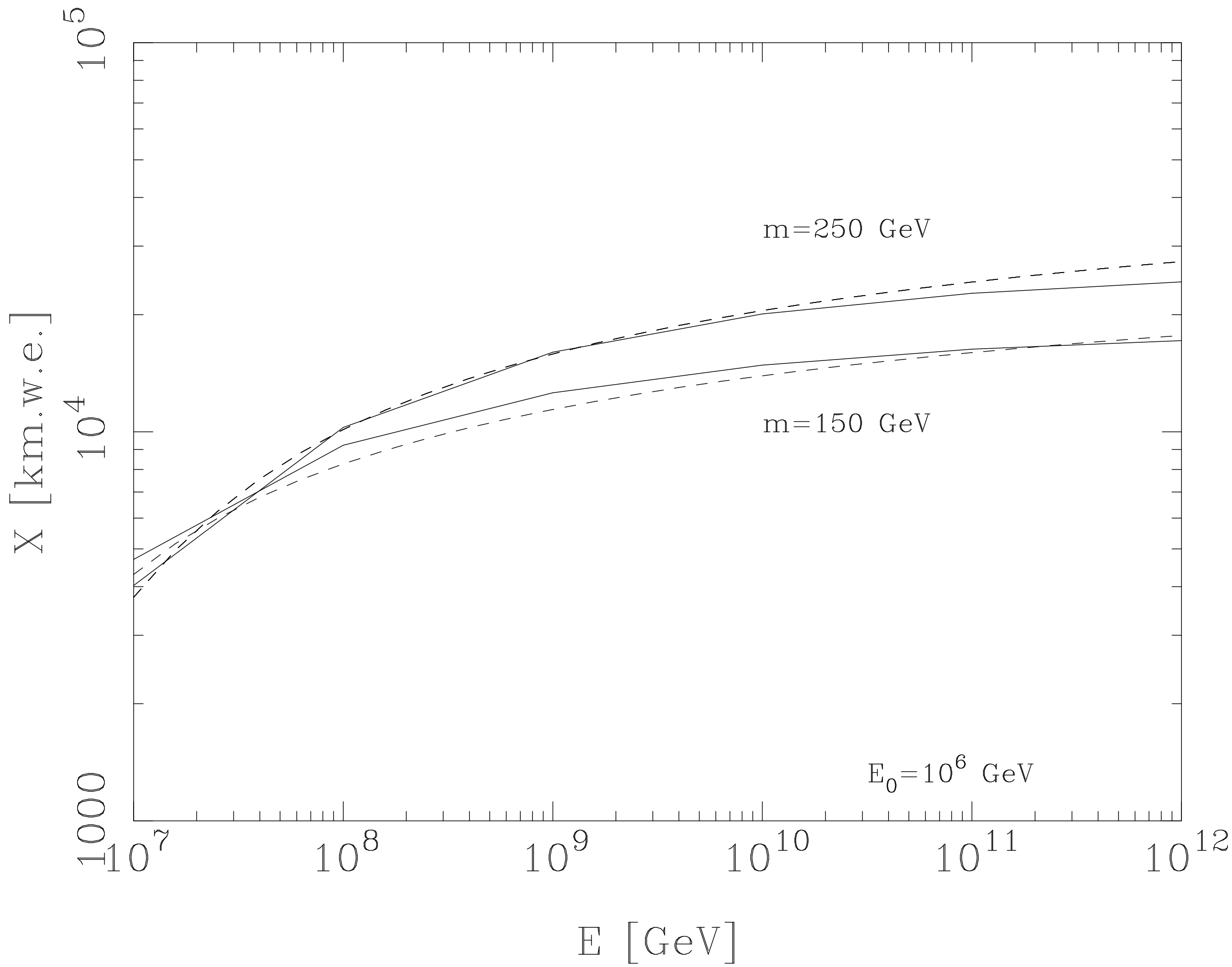


Mass Dependence of the Stau Photonuclear Energy Loss



M.H. Reno, I.S. and S. Su, Astropart. Phys. **24** (2005)

Stau Range



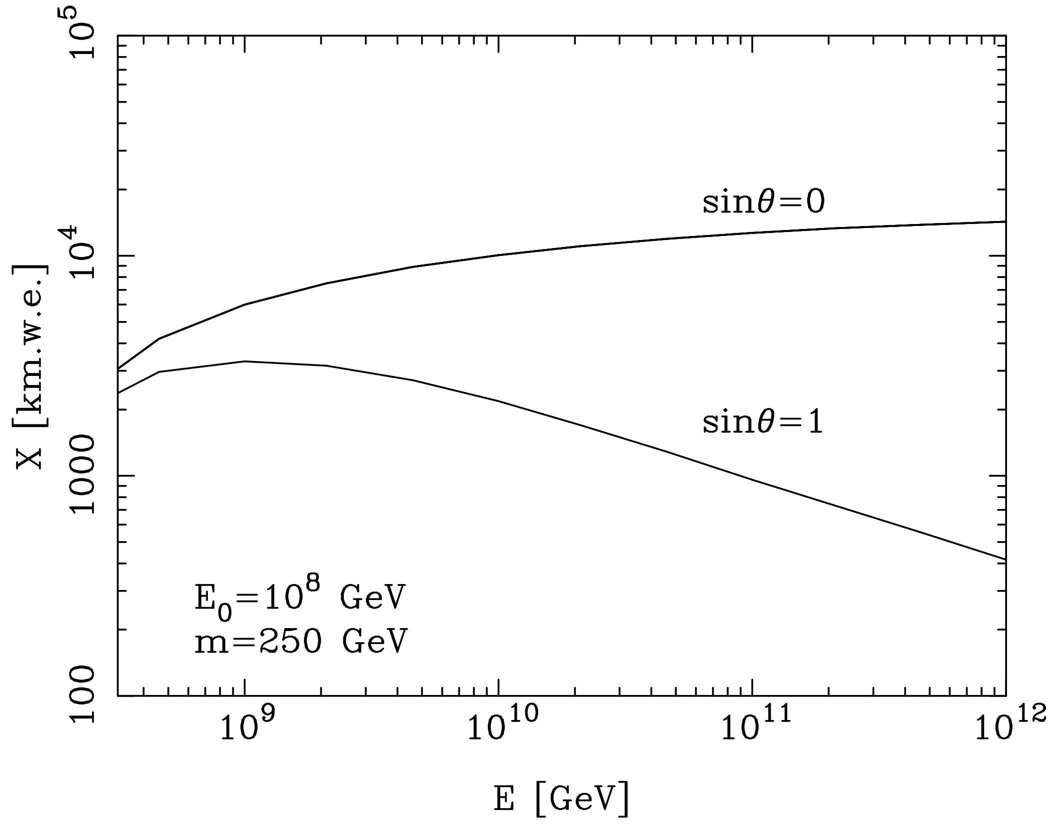
M.H. Reno, I.S. and S. Su, Astropart. Phys. **24** (2005)

What is the effect of Weak Interactions?

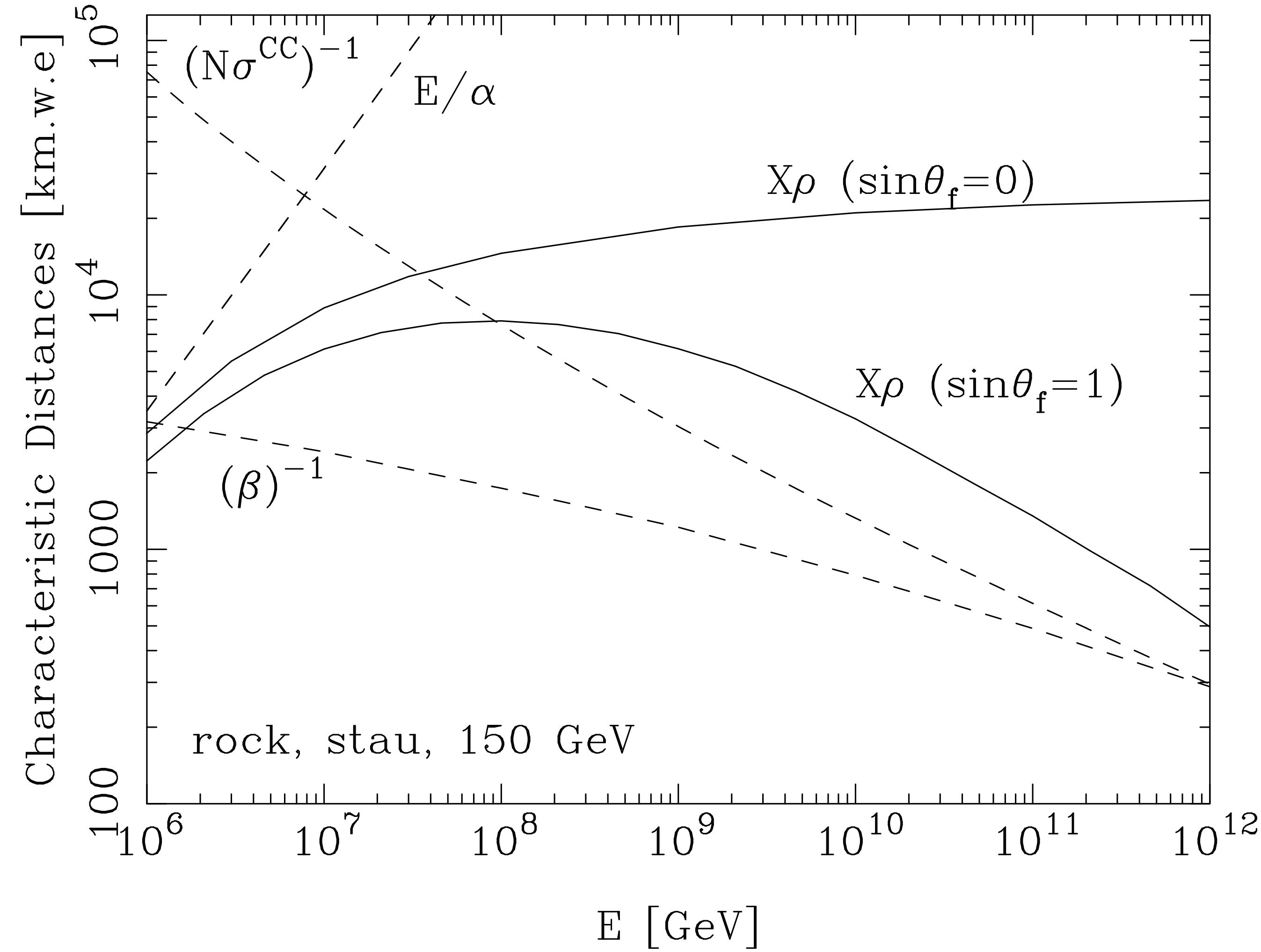
- **Weak interations:**

Neutral Current ($\tilde{\tau} N \to \tilde{\tau} X$) contributes to β_{NC}

Charged Current ($\tilde{\tau} N \to \nu X$) removes staus



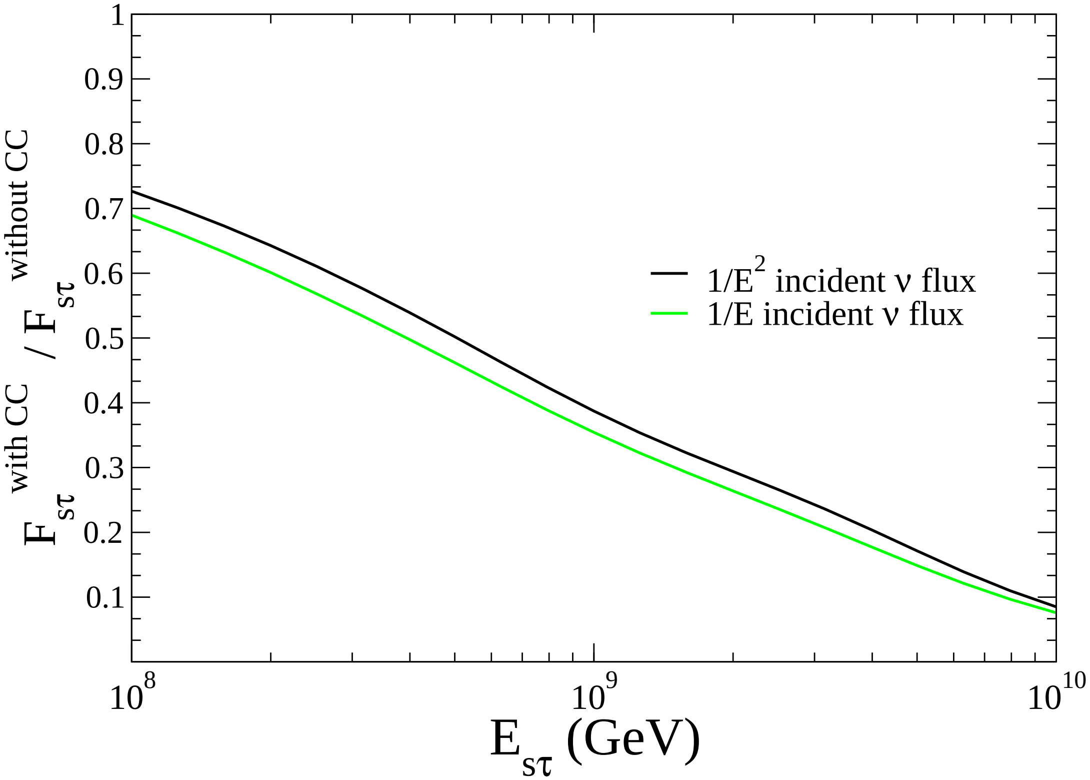
Y. Huang, M.H. Reno, I.S. and J. Uscinski, hep-ph/0607216



Y. Huang, M.H. Reno, I.S. and J. Uscinski, hep-ph/0607216

Stau Flux at the Detector

- **Astrophysical sources of neutrinos**
- **Neutrino interactions in Earth (attenuation)**
- **Stau production in $\nu + N$ interactions; small cross section**
- **Stau propagation and energy loss; large stau range**



- **The energy spectrum of staus at the detector depends on intial neutrino flux, neutrino-nucleon interactions and on slepton energy loss.**

- **Weak interactions of staus are important for energies above 10^8 GeV. For large mixing angle, stau range is significantly reduced at ultrahigh energies**

- **Interactions of staus in ice, to produce showers, is predominantly via weak interactions – of relevance to Anita.**

- **Neutrino telescopes (ICECUBE, ANITA) have unique ability to provide the first evidence for supersymmetry at weak scale.**

SUMMARY

- **Neutrinos provide a new window to the Universe**
- **High energy neutrinos are unique probes of particle physics, astrophysics and cosmology**
- **High energy neutrinos probe new energy and density regimes**
- **High energy neutrino telescopes may reveal existence of physics beyond the standard model (low scale supersymmetry, TeV scale gravity, extra dimensions...)**
- **IceCube, Rice, ANITA, OWL, Euso, Auger, SALSA, LOFAR ...**