RICAP07

Ultrahigh Energy Neutrinos as Probes of Physics

Ina Sarcevic
University of Arizona

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High Energy Cosmic 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

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

  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).

- **UHE Cosmic Neutrinos: Probes of Particle Physics and Astrophysics**
  - ⋆ **Energy Much Higher than Available in Colliders**
  - ⋆ **Escape from Extreme Environments**
  - ⋆ **Point Back to Sources**
  - ⋆ **A New Window to the Universe**

Cosmic Neutrinos

- ⋆ **Cosmic Neutrino Background ($T \sim 1.9K$, i.e. $E_\nu \sim 10^{-4} eV$)**
- ⋆ **Solar Neutrinos (MeV energies)**
- ⋆ **SN 1987A (MeV energies)**
- ⋆ **Atmospheric Neutrinos (GeV to TeV energies)**
- ⋆ **Extragalactic Neutrinos (AGN, GRB, cosmogenic, etc; GeV to EeV energiesi)**

Neutrino Flavors

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

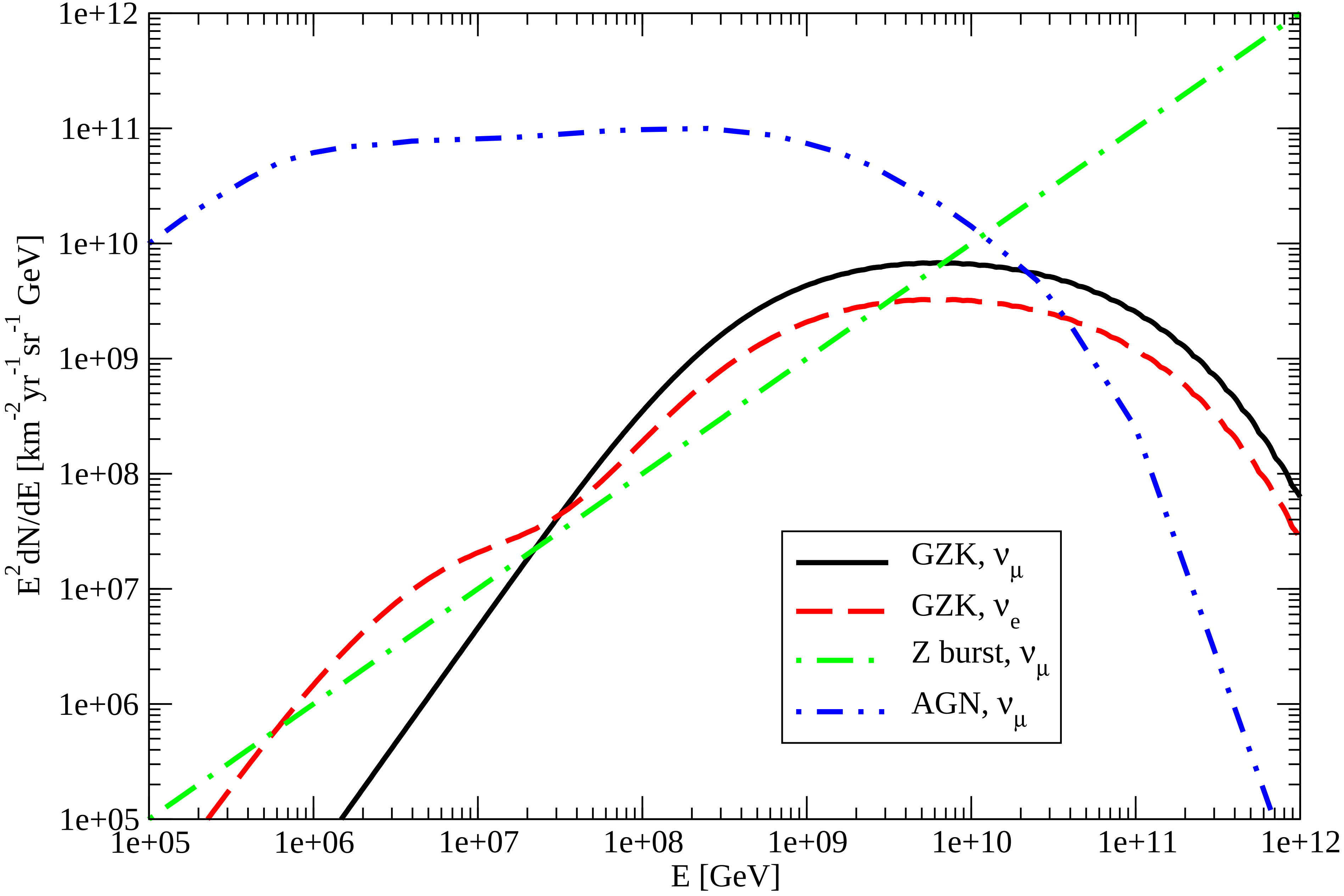
- **propagation towards Earth: neutrino oscillations**
  - ⋆ ν_μ **and** ν_τ **maximally mixed** $\Rightarrow \nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

- **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)


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

- 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:

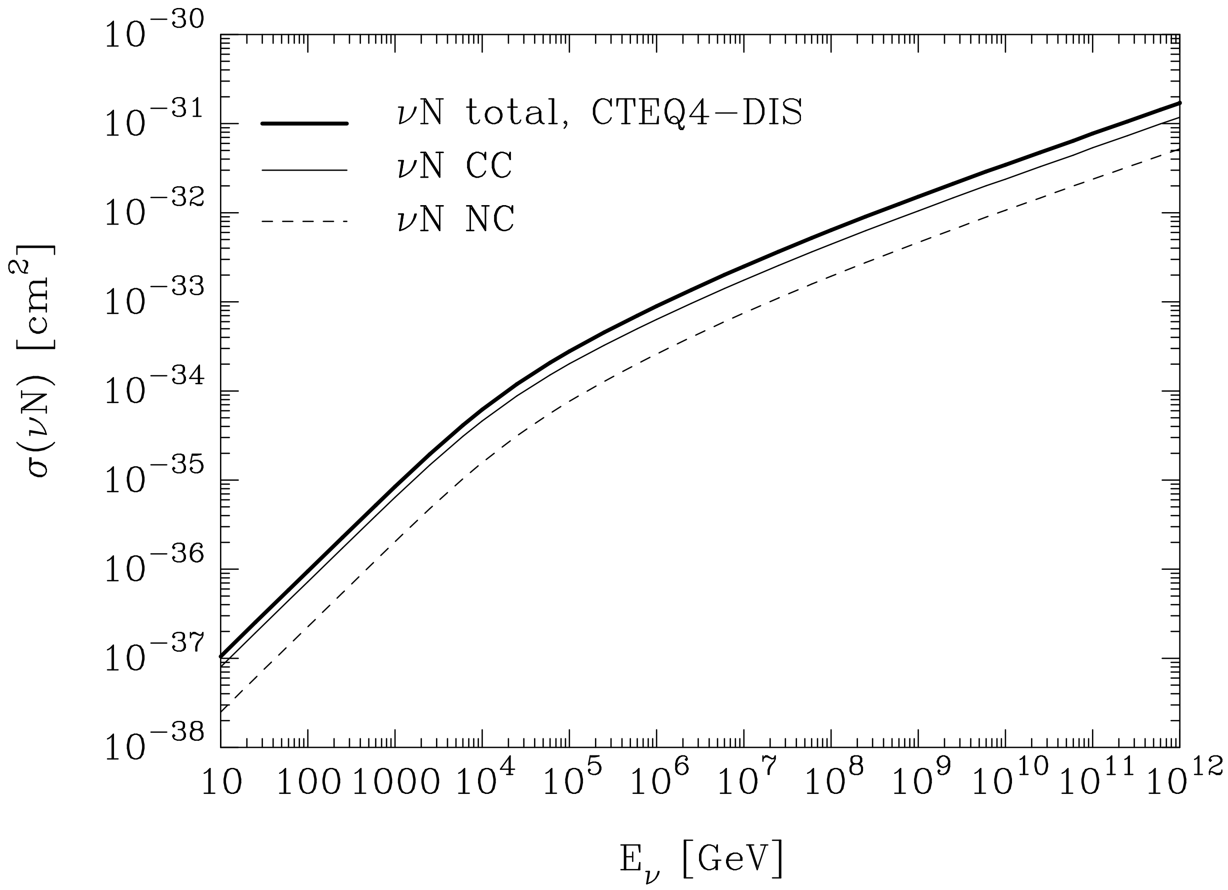
$$R_\nu = V \int dE_\nu \;\; \sigma_{cc}(E_\nu) \;\; F_\nu(E_\nu)$$

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

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

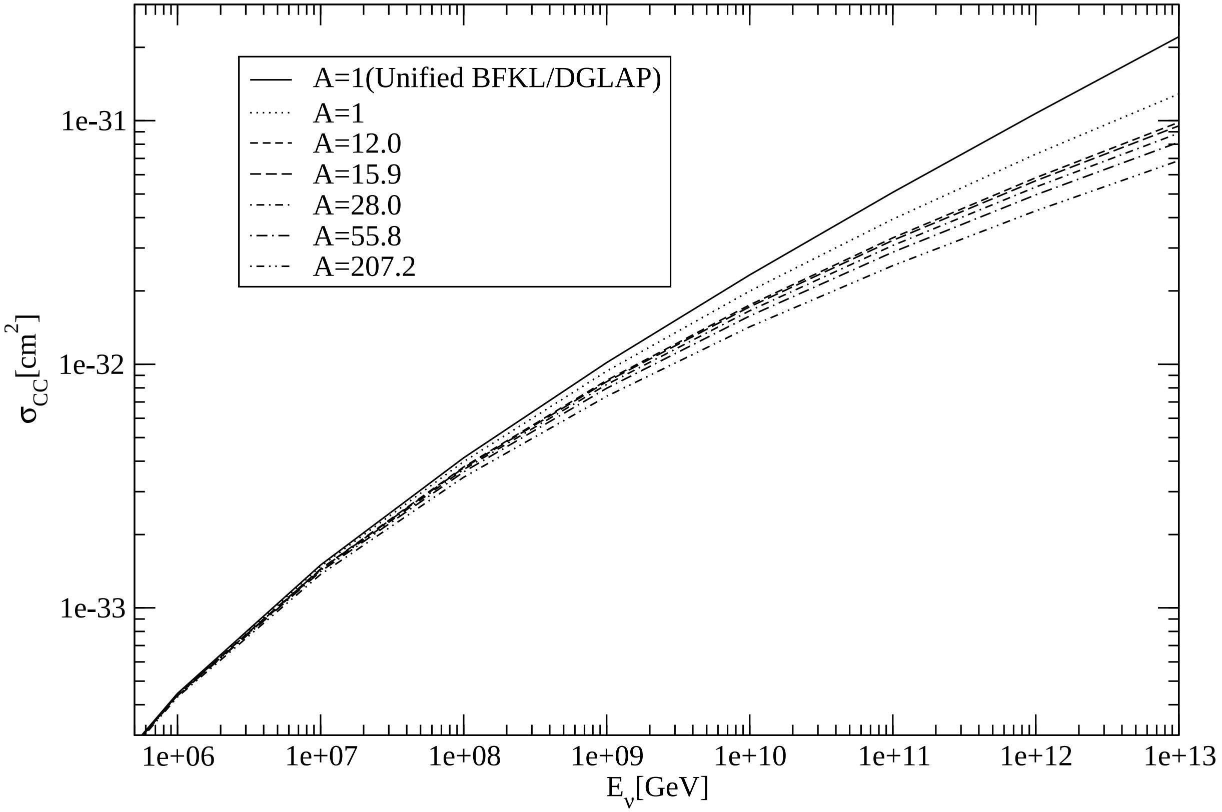
  where $R(E_\nu, E_\mu)$ is the muon range and $S(E_\nu)$ is the neutrino attenuation factor.

- 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 (1998)

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



- **Non-linear corrections large at high energies, above $\sim 10^9$ GeV**
- **New physics can also alter neutrino interactions at ultrahigh energies**

Experiments

- **AMANDA/ICECUBE/ICECUBE-PLUS/HYPERCUBE**
- **ANTARES, NESTOR**
- **RICE**
- **ANITA**
- **PIERRE AUGER**
- **EUSO, OWL**
- **SalSA, LOFAR ...**

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 may be 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

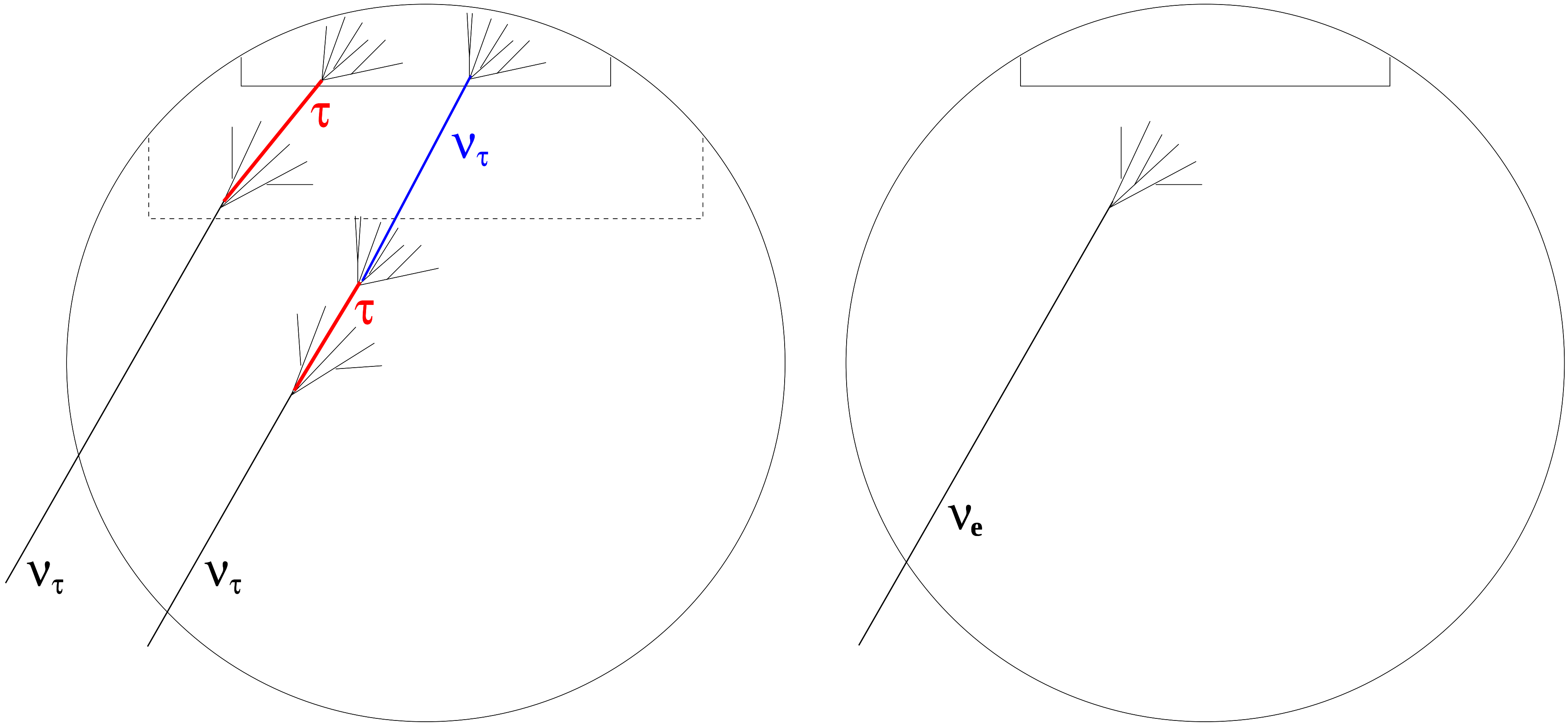
- ν **attenuation due to charged (CC) and neutral current (NC) interactions**
- **NC gives** ν **with lower energy**
- **regeneration of** ν **from** τ **decay**

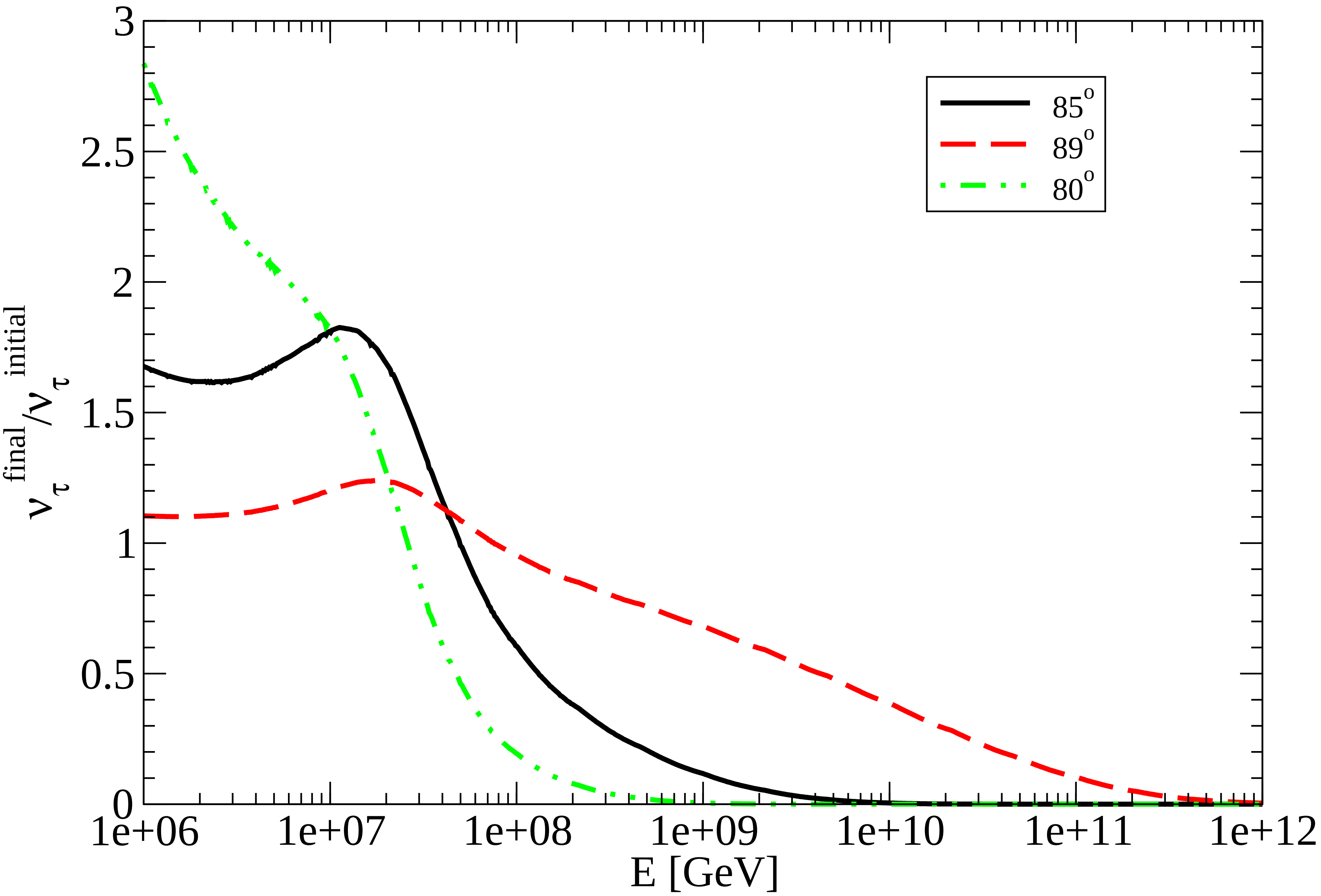
$$\begin{aligned}\frac{\partial F_{\nu_\tau}(E,X)}{\partial X} &= -N_A\sigma^t(E)F_{\nu_\tau}(E,X)+N_A\int_E^\infty dE_y F_{\nu_\tau}(E_y,X)\frac{d\sigma^{NC}}{dE}(E_y,E)\\ &+ \int_E^\infty dE_y \frac{F_\tau(E,X)}{\lambda_\tau^{dec}}\frac{dn}{dE}(E_y,E)\end{aligned}$$

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


τ
ν$_\tau$
τ
ν$_\tau$
ν$_\tau$
ν$_e$



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

Probing Particle Physics with UHE Neutrinos

- **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**

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

Probing Extra Dimensions

- **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 comparable in strength to other forces, may be in TeV range, leading to a host of potential signatures for high energy physics ⇒ one of the most striking consequences of low-scale gravity is the possibility of black hole creation in high-energy particle collisions.**

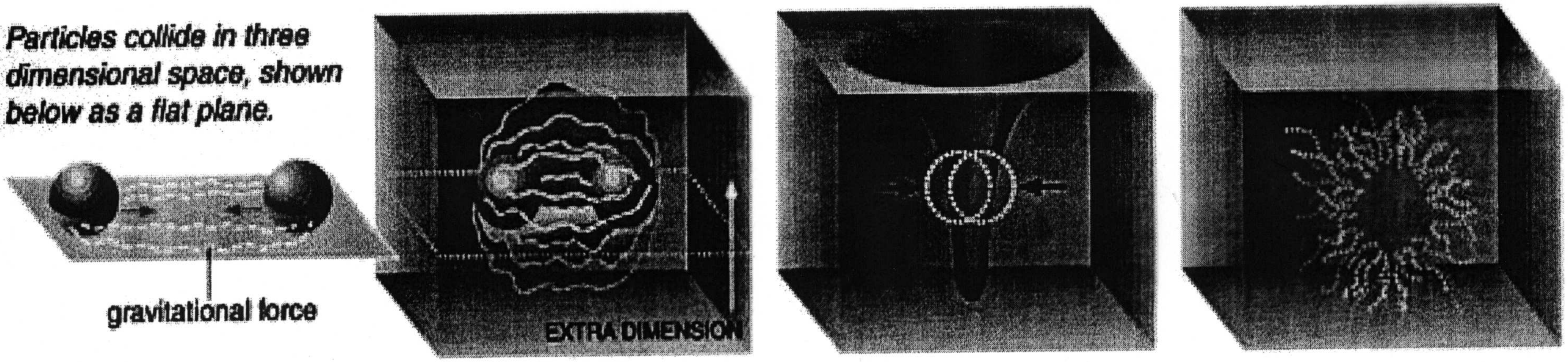
- **Gravitation processes involving graviton emission and exchange, analyses rely on a perturbative description that breaks down for energies of M_D and above.**

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

The New York Times ON THE WEB

Black Holes on Demand

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:



Particles collide in three dimensional space, shown below as a flat plane.

As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

Black Hole Production by UHE Neutrinos

- **Black hole can be produced in scattering of UHE neutrinos on nucleons in the atmosphere or in the Earth. The neutrino-nucleon cross section for black hole production is given by**

$$\sigma(\nu N \to \mathrm{BH}) = \sum_i \int_{M_{BH}^{\min}}^{1} dx\ \hat{\sigma}_i(xs)\ f_i(x, Q^2),$$

where

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

$\hat{s} = xs$, s **is the center of mass energy,** $s = 2m_N E_\nu$

$f_i(x, Q^2)$**'s are parton distribution functions**

$M_{BH}^{\min}$ **is the minimum black hole mass for which**

semiclassical approximation above is valid $(M_{BH}^{\min} >> M_D)$

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

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

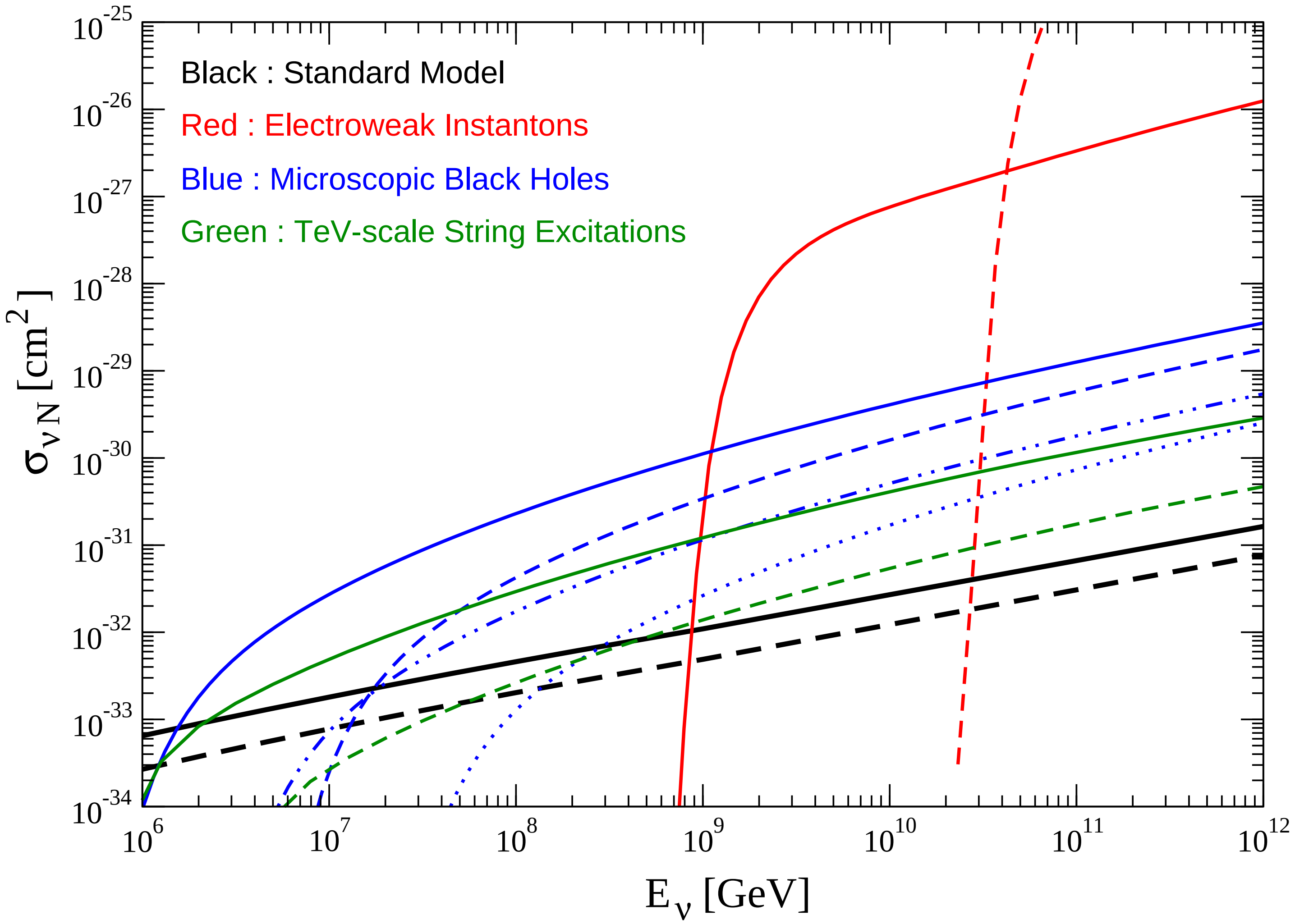
- **BH radiates mainly on the brane**

- **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**

Neutrino Cross Sections



Black Holes in Neutrino Telescopes

Alvarez-Muniz, et al. PRD 65, 124015 (2002)

Kowalski, Ringwald and Tu, PL B529, 1 (2002)

Dutta, Reno and Sarcevic, PR D66, 033002 (2002)

- **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.**

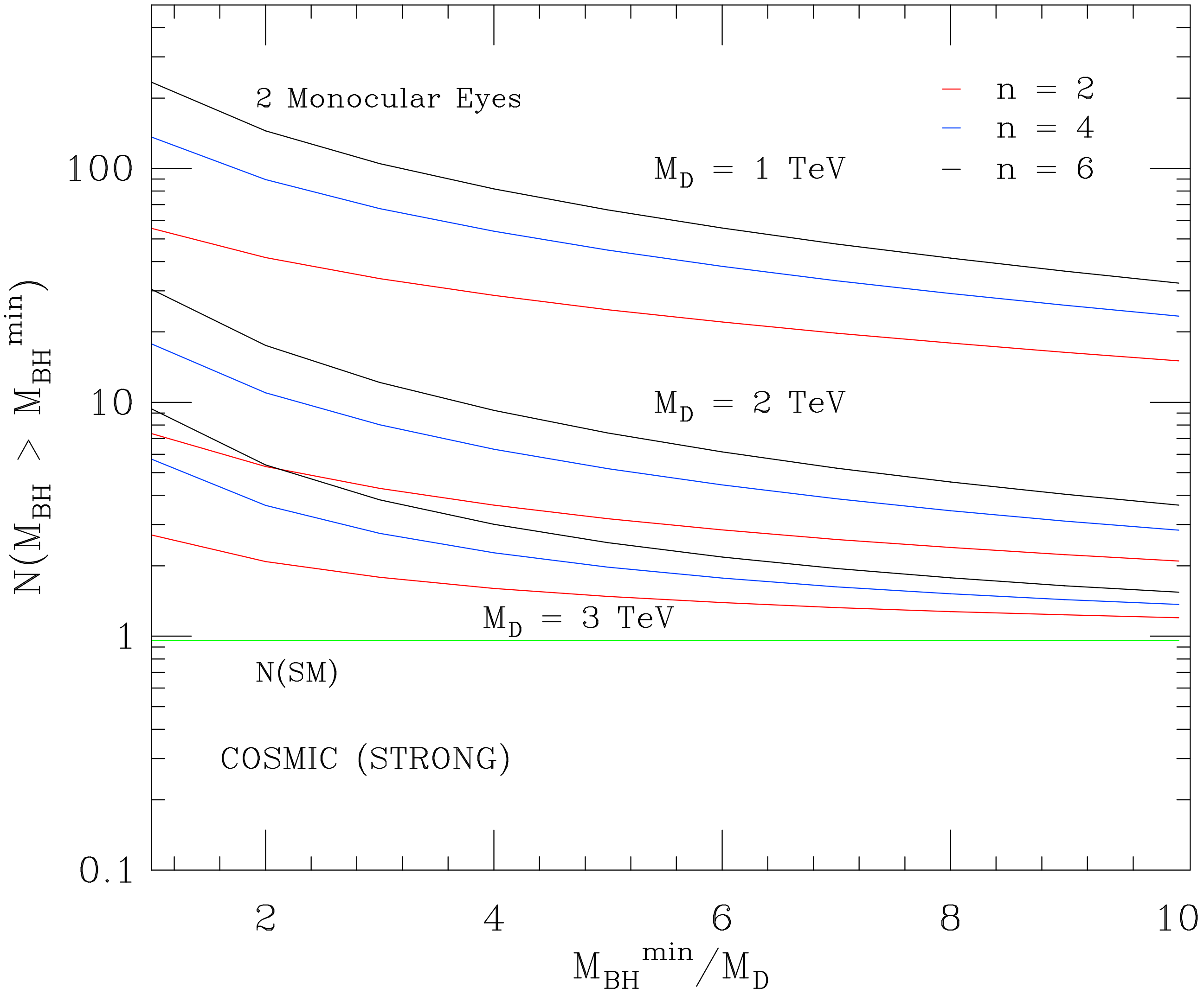
- **The event rate for black hole production with OWL is given by**

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

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, PR D66, 033002 (2002)

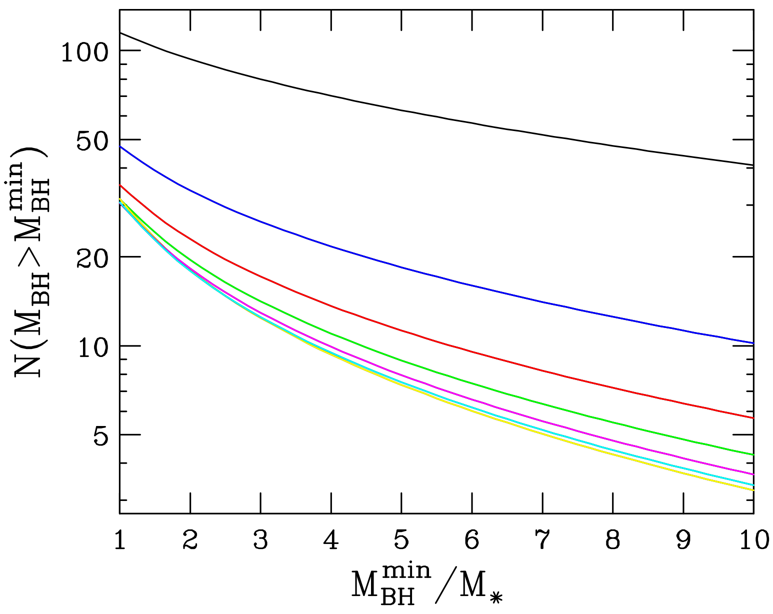


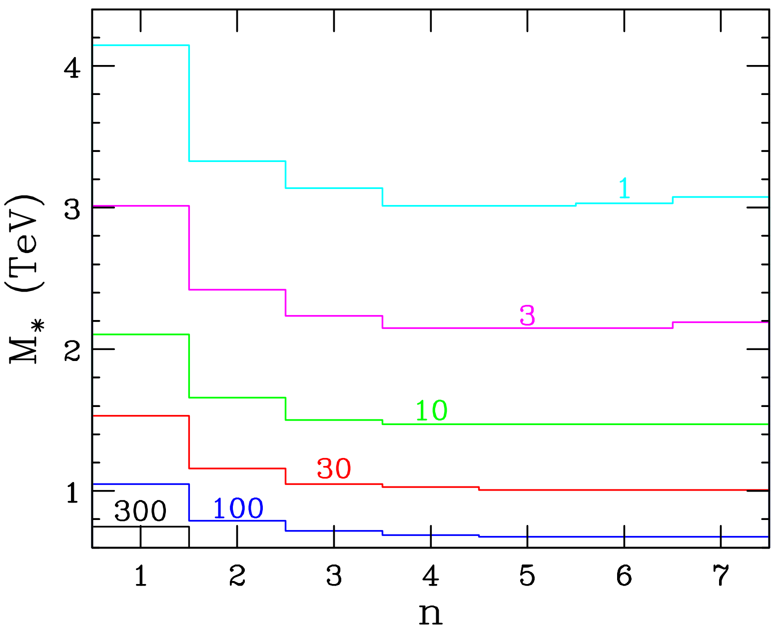
Black Holes in Cosmic Rays

Feng and Shapere, PRL 88 (2002) 021303.

Anchordoqui, Feng, Goldberg and Shapere, PRD65 (2002).

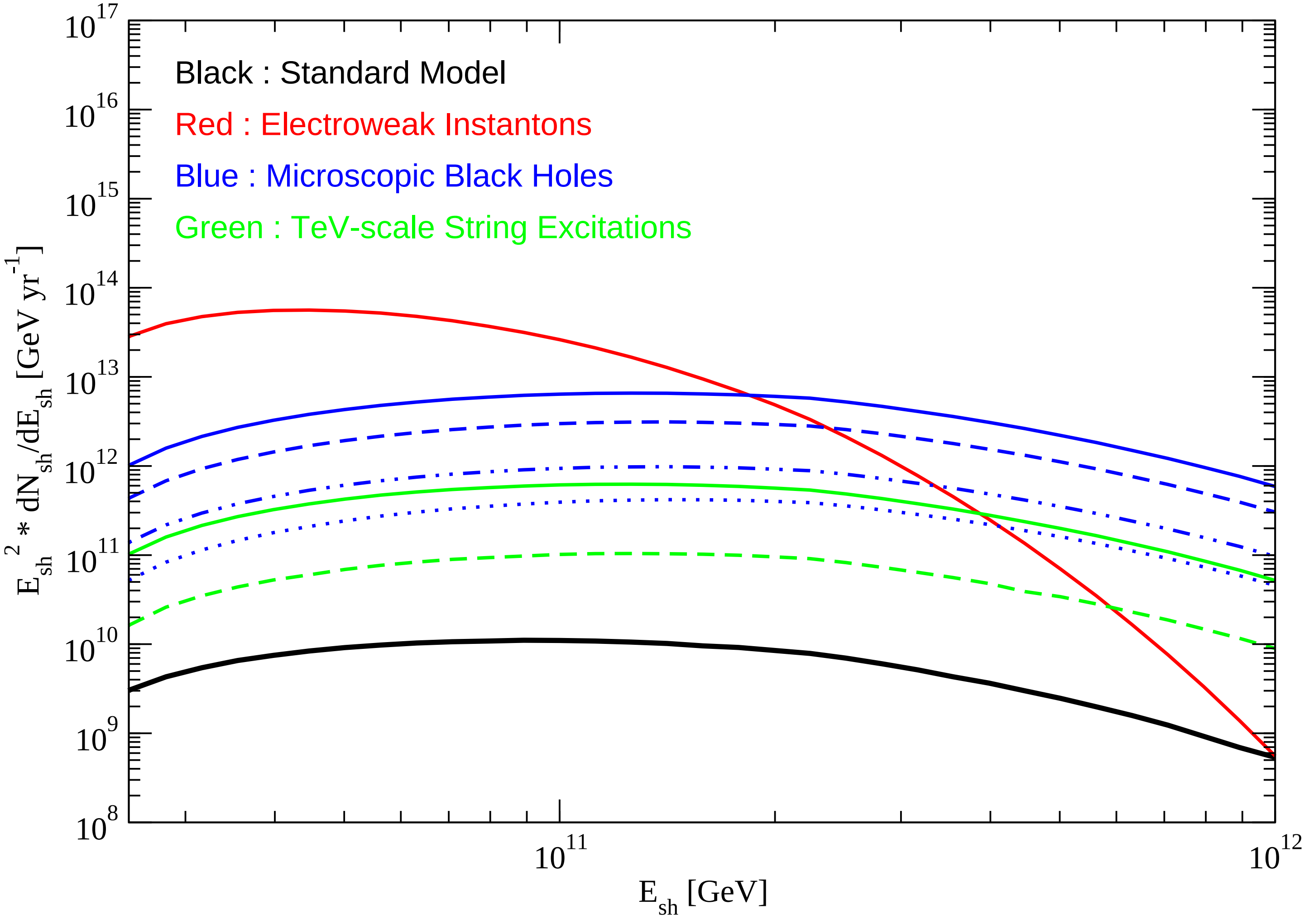
- **Limits from non-observation of horizontal showers by the Fly's Eye Collaboration and Akeno Giant Air Shower Array (AGASSA): $M_D \approx 1$TeV -1.4 TeV excluded for $n \geq 4$.**
- **Detect BH in the Pierre Auger fluorescence experiment or AGASSA $\Rightarrow$ few to a hundred BHs can be detected before the LHC turns on. If no black holes are found then $M_D = 2$ TeV is excluded for any n.**





Probing the Physics Beyond the Standard Model with EUSO

Shower Fluxes for GZK ν Flux



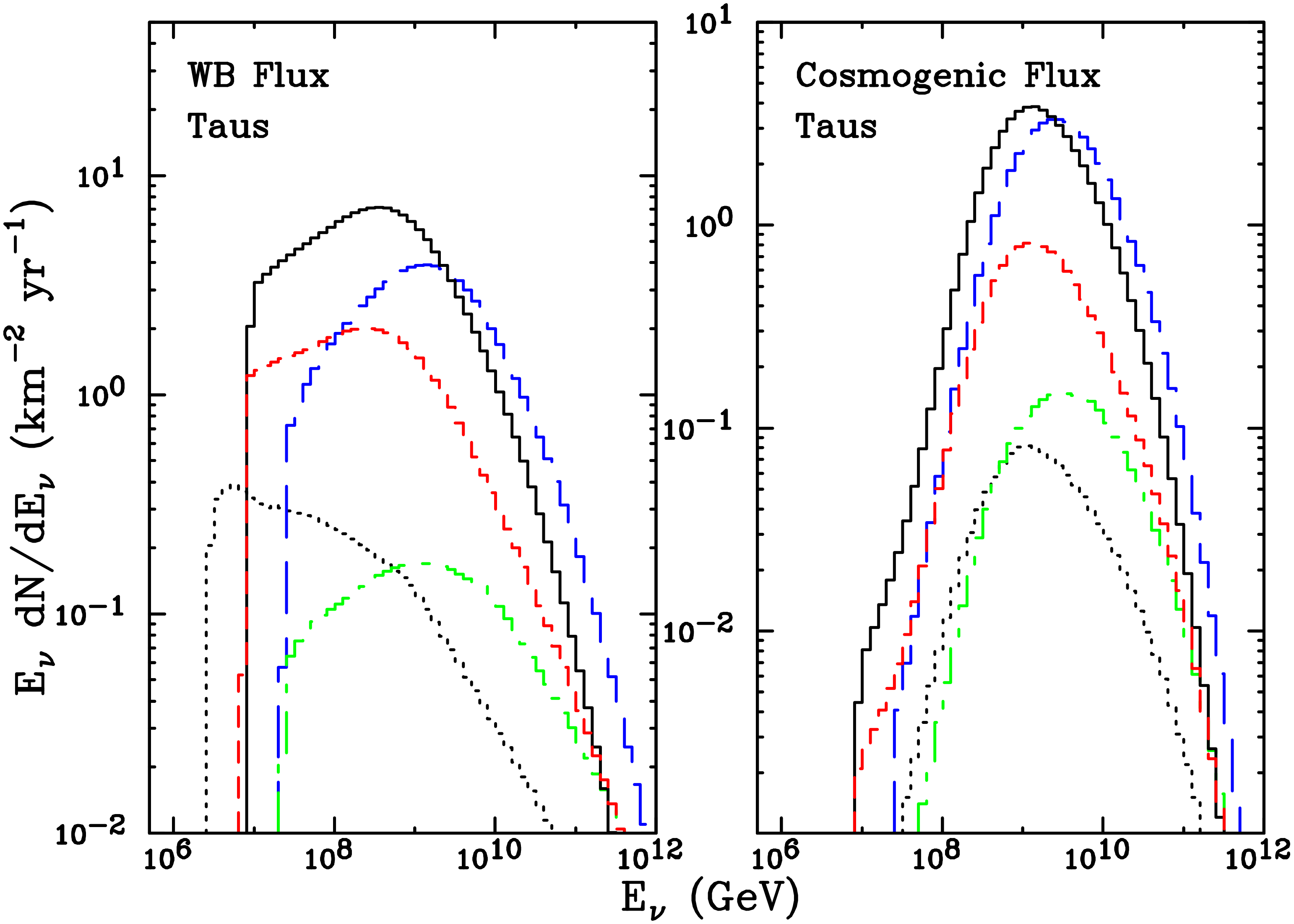
ν **Event Rates : EUSO**

$\sigma_{\nu N}^{(\mathrm{NP})}$	GZK	WB
SM	0.36	4.8
BH (1)	156	1269
BH (2)	71	604
BH (3)	23	193
BH (4)	9.2	84
SR (1)	15	123
SR (2)	2.5	23

EUSO Collaboration : protons : $N_{\mathrm{p}}^{(\mathrm{GZK})} \gtrsim 1200\ \mathrm{yr}^{-1}$ for $E_{\mathrm{p}} > 10^{10}$ GeV

Tau Events in km^3 Detector from BH Production

Alvarez-Muniz *et al.*, PR D65 (2002) 124015.



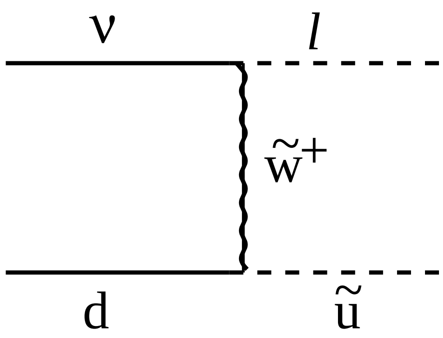
Energy distribution of down-going taus with with $E_\tau^{thr} = 2.5 \times 10^6$GeV

Probing Supersymmetry with Neutrinos

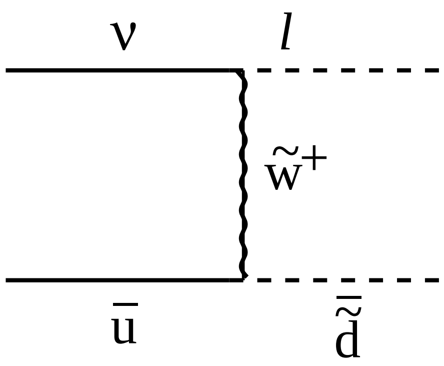
I. Albuquerque, G. Burdman, Z. Chacko, PRL 92 (2004)
M.H. Reno, I.S. and S. Su, Astropart. Phys. 24 (2005)
M.H. Reno, I.S. and J. Uscinski, Phys. Rev. D74 (2006)
I. Albuquerque, G. Burdman, Z. Chacko, PRL 92 (2006)
M. Ahlers, J. Kersten and A. Ringwald, hep-ph/0604188

- **Ultrahigh energy neutrinos interact with nucleons in Earth producing supersymmetric charged sleptons**
- **In SUSY models with low scale supersymmetry breaking scale, LSP is gravitino and NLSP is charged slepton (stau)**
- **Stau has long lifetime, can travel large distances through Earth and be detected in neutrino telescopes**
  - ⋆ **Interactions of stau, i.e. propagation and energy loss are important for detection**

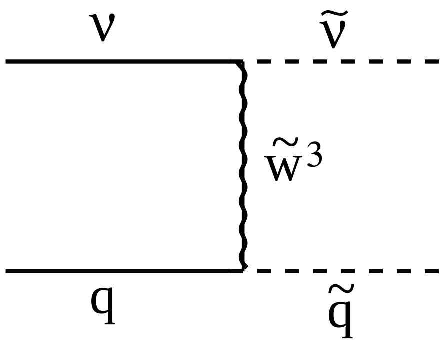
Stau Production in Neutrino Interactions



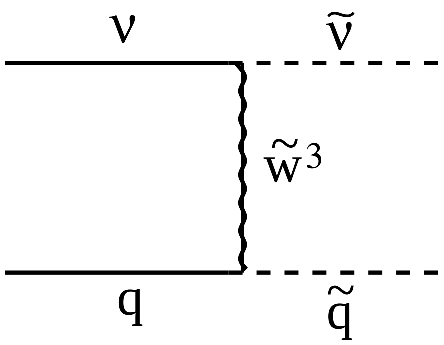
(a)



(b)



(c)



(d)

Charged Particle Energy Loss

Energy loss is given by

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

- **E - particle energy**
- **X - range of particle**
- α **- ionization energy loss** $\sim 2 \cdot 10^{-3}$ **GeV cm^2/g, dominant at low energies**
- β **- radiative energy loss, dominant at high energies**

Iyer Dutta, Reno, Sarcevic and Seckel, Phys. Rev. D63 (2001)

Energy loss parameter β is given by

$$\beta^i(E) = \frac{N_A}{A} \int dy \; y \frac{d\sigma^i(y,E)}{dy}$$

y is fraction of lepton (slepton) energy loss

$$y = \frac{E - E'}{E}$$

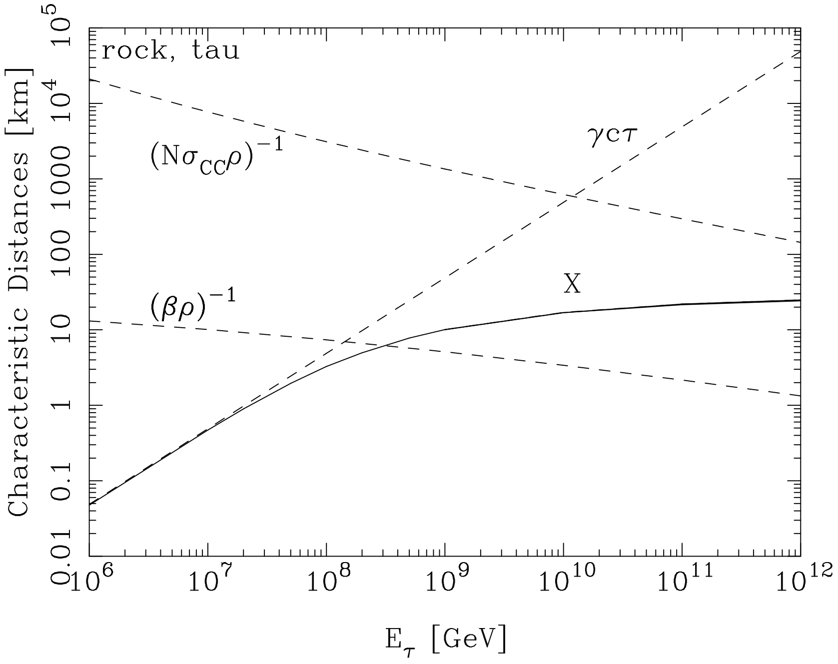
Stau Energy Loss Processes

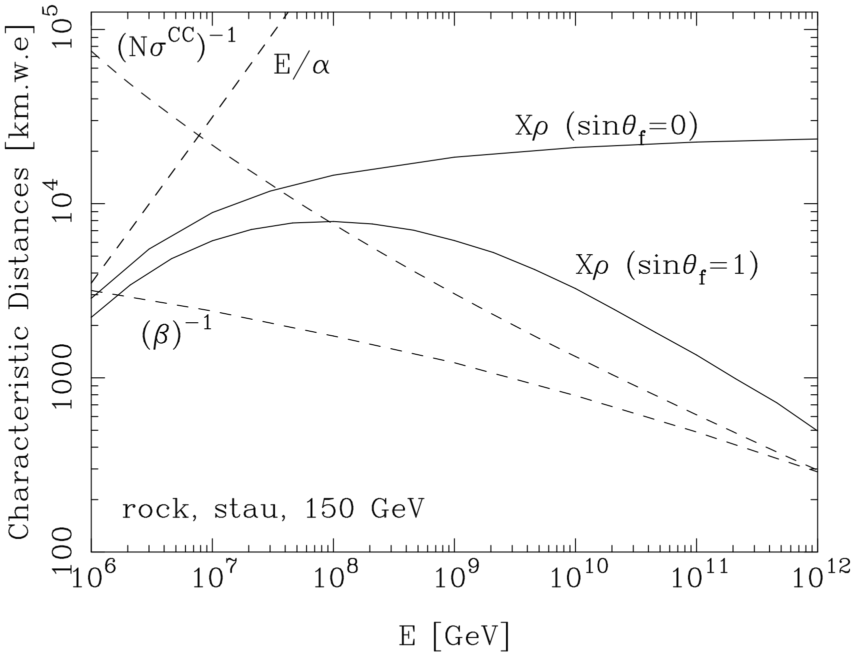
- **Bremsstrahlung:** $\tilde{\tau} Z \to \gamma \tilde{\tau} Z$
- **Pair production:** $\tilde{\tau} Z \to \tilde{\tau} Z e^+ e^-$
- **Photonuclear:** $\tilde{\tau} N \to \tilde{\tau} X$ $\to$ **dominant for E** $> 10^6$ **GeV, scales as** $\frac{1}{m}$
- **Neutral current:** $\tilde{\tau} N \to \tilde{\tau} X$
- **Charged current:** $\tilde{\tau} N \to \tilde{\nu} X$ $\to$ **removes particle**

M. H. Reno, I. Sarcevic and S. Su, Astropart. Phys. 24, 107 (2005)

M. H. Reno, I. Sarcevic and J. Uscinski, PRD 74 (2006)

Tau and Stau Range





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

Lifetime and Range

Competing processes, decay and energy loss:

$$c\tau = \left(\frac{\sqrt{F}}{10^7 GeV}\right)^4 \left(\frac{100GeV}{m}\right)^5 10km$$

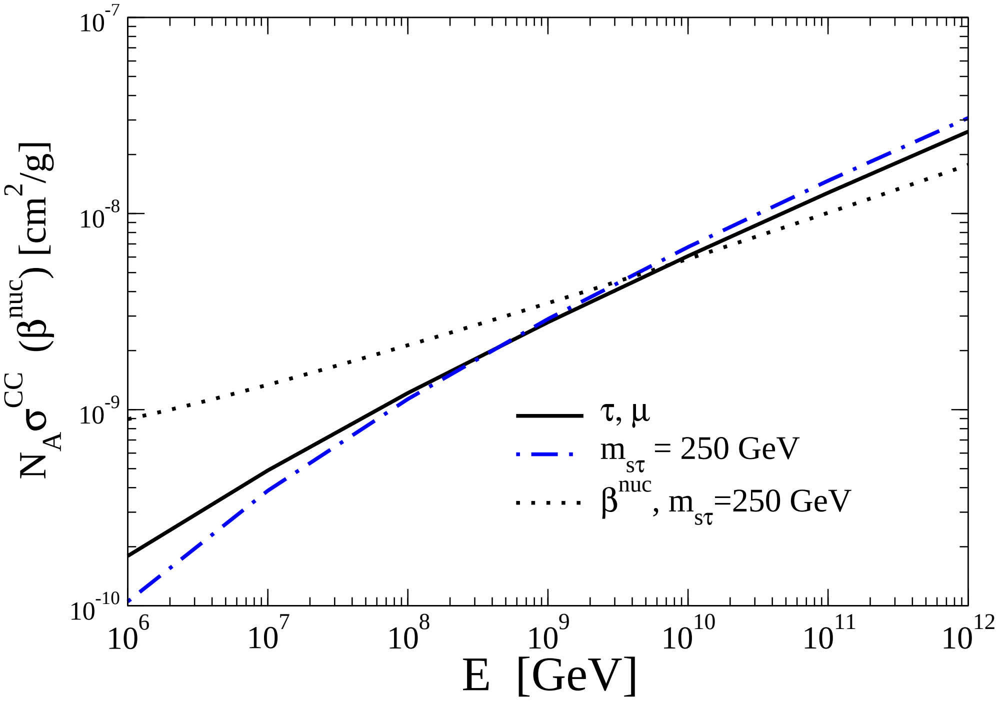
$$X(E, E_0) = \int dX' P(E, E_0, X')$$

Without including weak interactions:

- **Characteristic range for staus is 10^4 km**
- **Characteristic range for taus is 10 km (for comparison)**

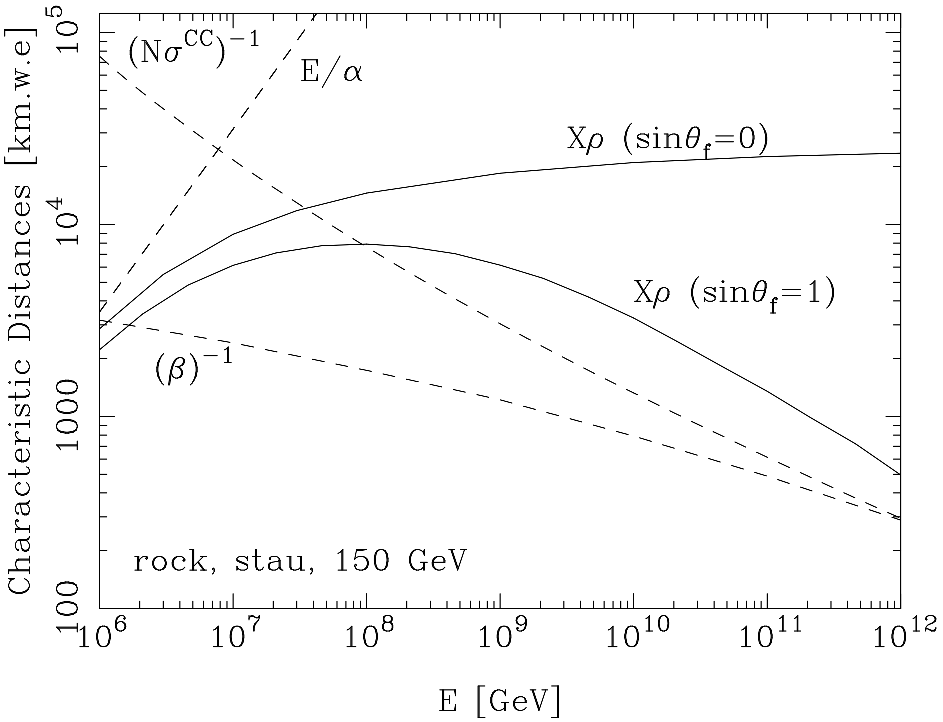
Does weak interaction contribution to the energy loss have an effect on the range?

CC Interactions



- **Stau cross section is roughly equal to lepton case $\cdot$ $\sin^2\theta_f$ - indicates mixing of LH and RH staus.**
- **CC interactions become significant at higher energies**
- β^{NC} **is small when compared to** $\beta^{nuc} \sim 10^{-8}$ **cm^2/g**

Characteristic Distances: Stau



- **At low energies, ionization energy loss dominates**
- **For energies $\sim 10^8$ GeV, CC interaction dominates for $\sin\theta_f = 1$**

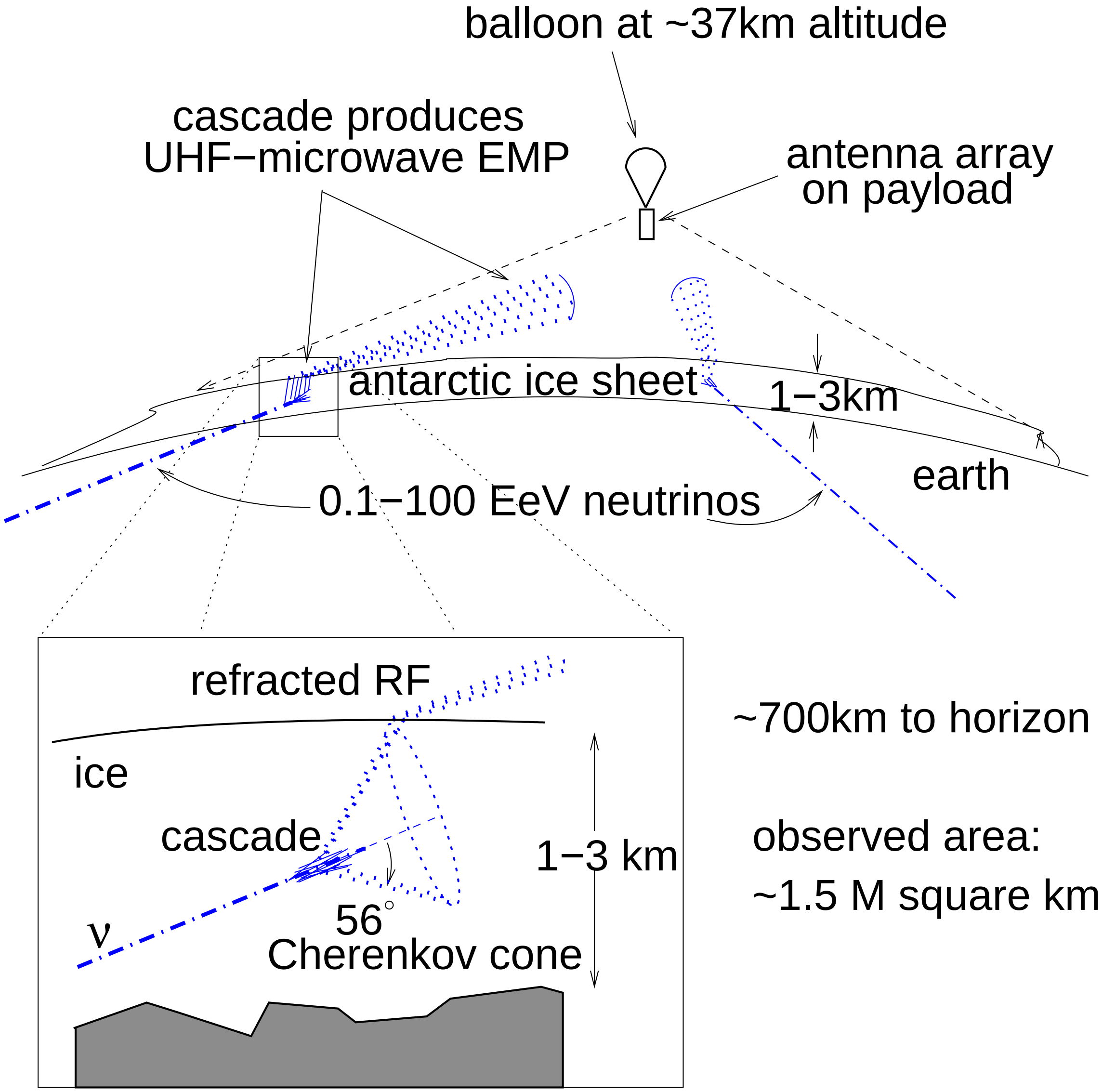
M.H. Reno, I.S. and J. Uscinski, PRD74 (2006)

- **The energy spectrum of stau at the detector depends on initial neutrino flux, neutrino-nucleon interactions and on slepton energy loss.**
- **Neutrino telescopes (ICECUBE, ANITA) have unique ability to provide the first evidence for supersymmetry at weak scale.**

What is the stau flux at the detector?

- **Astrophysical sources of neutrinos**
- **Neutrino interactions in Earth (attenuation)**
- **Stau production** $(\nu + N \to ...\tilde{\tau} + \tilde{\tau})$**: small cross section**
- **Stau propagation and energy loss**

ANITA: Antarctic Impulsive Transient Antenna

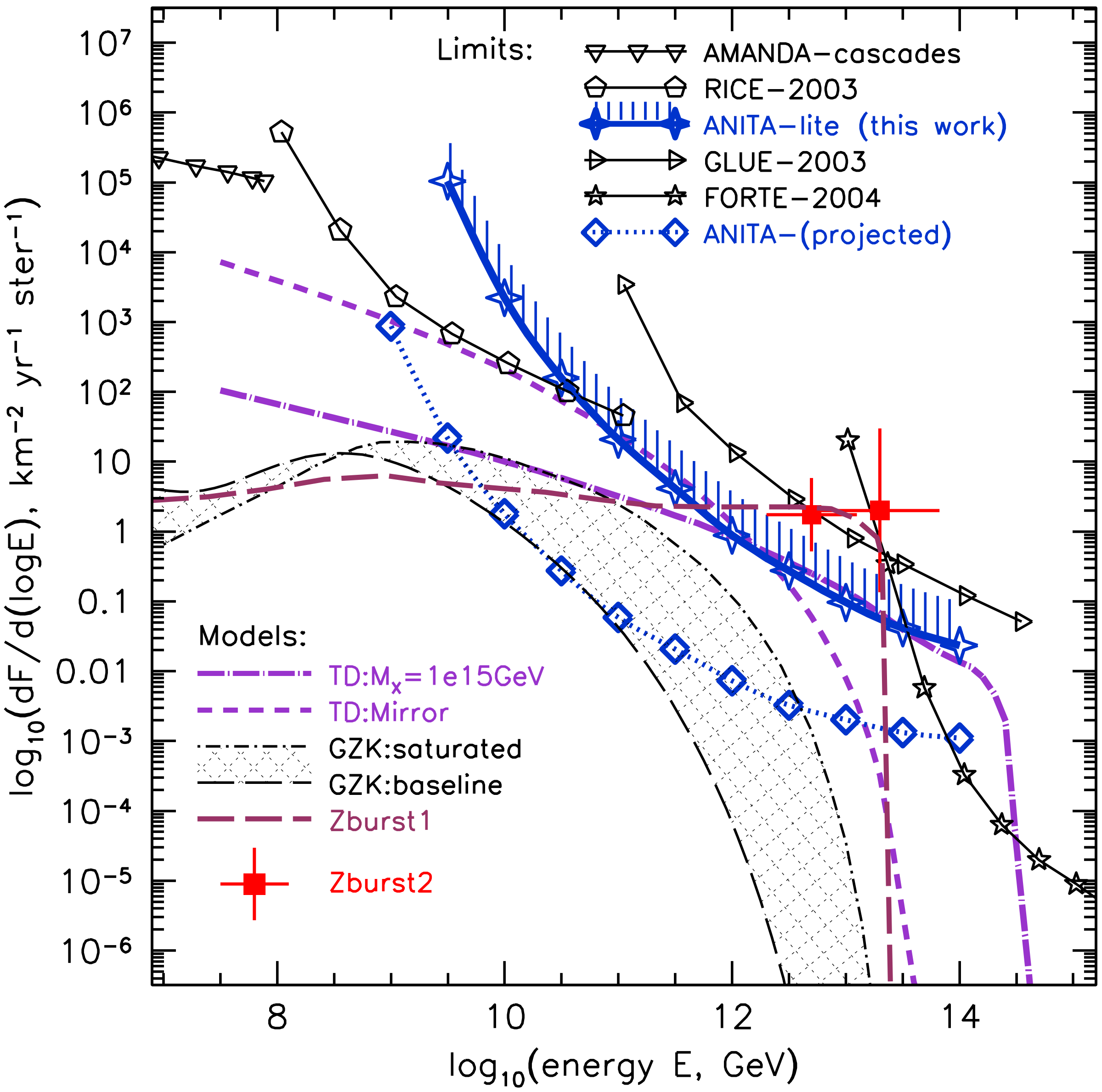


~700km to horizon

observed area:

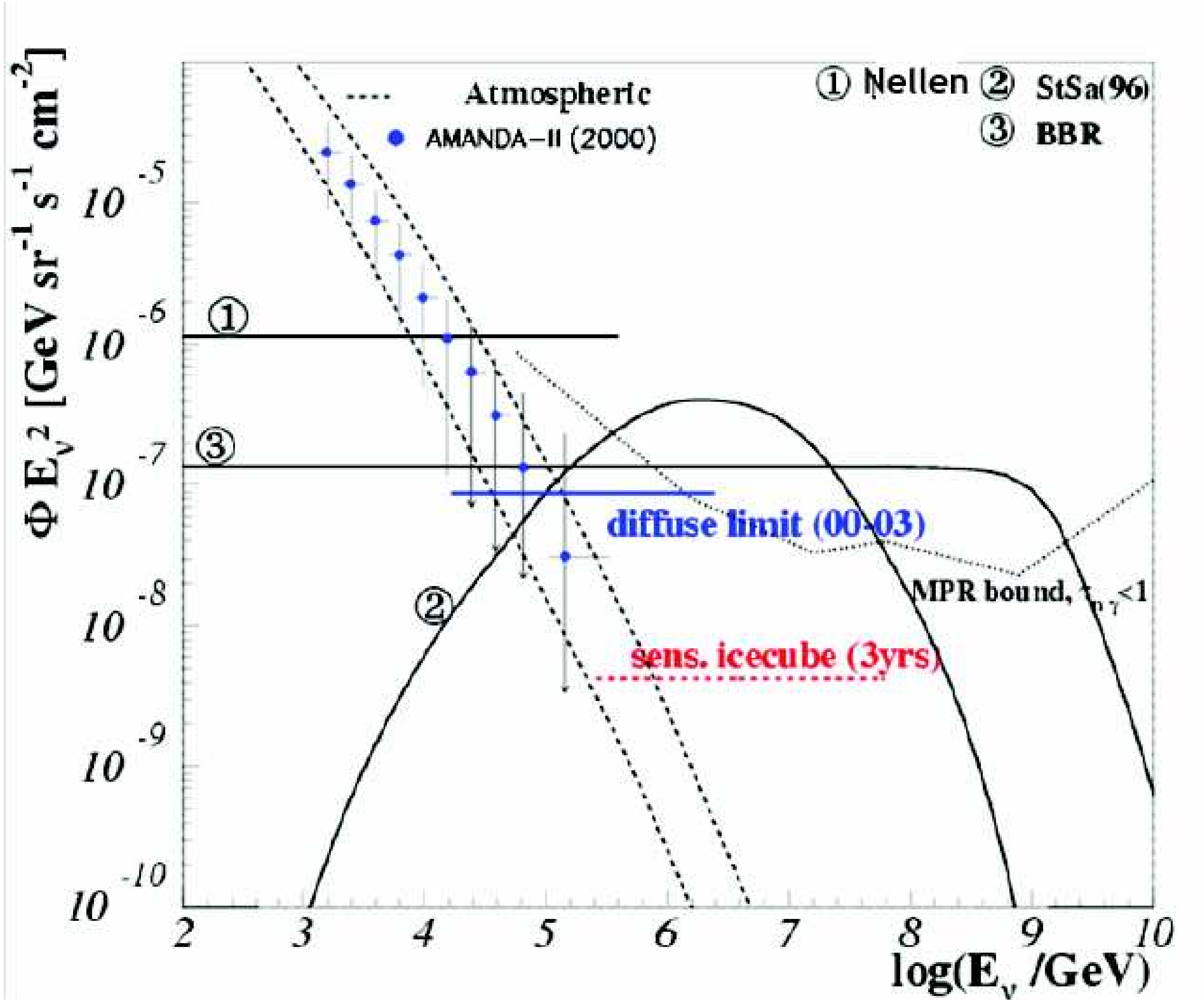
~1.5 M square km

Neutrino Flux limits (ANITA and ANITA-lite)



Anita Collaboration, PRL 96 (2006)

Amanda neutrino flux limit and IceCube sensitivuty



IceCube Collaboration, presented at TeV Particle Astrophysics Workshop, Madison, August 2006

Stau Flux at the Detector

Flux of charged staus reaching the detector is given by

$$\frac{dN_{\tilde{\tau}}(E_{\tilde{\tau}}, \cos\theta, \phi)}{dE_{\tilde{\tau}}\, d\cos\theta\, d\phi} = \frac{1}{2\pi}\int dE_\nu \frac{dN_\nu(E_\nu)}{dE_\nu} K(E_\nu, \theta; E_{\tilde{\tau}})$$

- $\frac{dN}{dE_\nu}$ - initial neutrino flux
- $K(E_\nu, \theta; E_{\tilde{\tau}})$ - probability that neutrino entering Earth with energy E_ν and nadir angle θ will produce stau that reaches detector with energy $E_{\tilde{\tau}}$
  - ⋆ the probability of neutrino surviving a distance z in the Earth
  - ⋆ probability that neutrino converts to a stau
  - ⋆ probability that the created stau reaches the detector
  - ⋆ the stau's energy and position when produced are such that it reaches the detector with energy $E_{\tilde{\tau}}$.

Probability for a neutrino with energy E_ν and nadir angle θ to survive for a distance z is

$$P_a = \exp\left[-\int_0^z \frac{dz'}{L^{\nu}_{CC}(E_\nu, \theta, z')}\right] ,$$

The probability for neutrino conversion to a charged stau in the interval $[z, z + dz]$ is $dz/L^{\nu}_{CC}(E_\nu, \theta, z)$ is given by

$$P_b = \frac{dz}{L^{\nu}_{CC\,s}(E_\nu)} ,$$

where $L^{\nu}_{CC\,s}(E_\nu) = [\sigma^{\nu}_{CC}(E_\nu)\rho_s N_A]^{-1}$.

The survival probability P_c for a charged stau losing energy as it moves through the Earth is described by the coupled differential equations

$$\begin{aligned} dE_{\tilde{\tau}}/dz &= -\left(\alpha_{\tilde{\tau}} + \beta_{\tilde{\tau}} E_{\tilde{\tau}}\right) \rho(r(\theta, z)) \\ dP_c/dz &= -P_c/(c\tau_{\tilde{\tau}} E_{\tilde{\tau}}/m_{\tilde{\tau}}) , \end{aligned}$$

The stau's energy and location when produced must be consistent with an exit energy $E_{\tilde{\tau}}$. For constant density ρ_s and negligible $\alpha_{\tilde{\tau}}$, this condition is given by

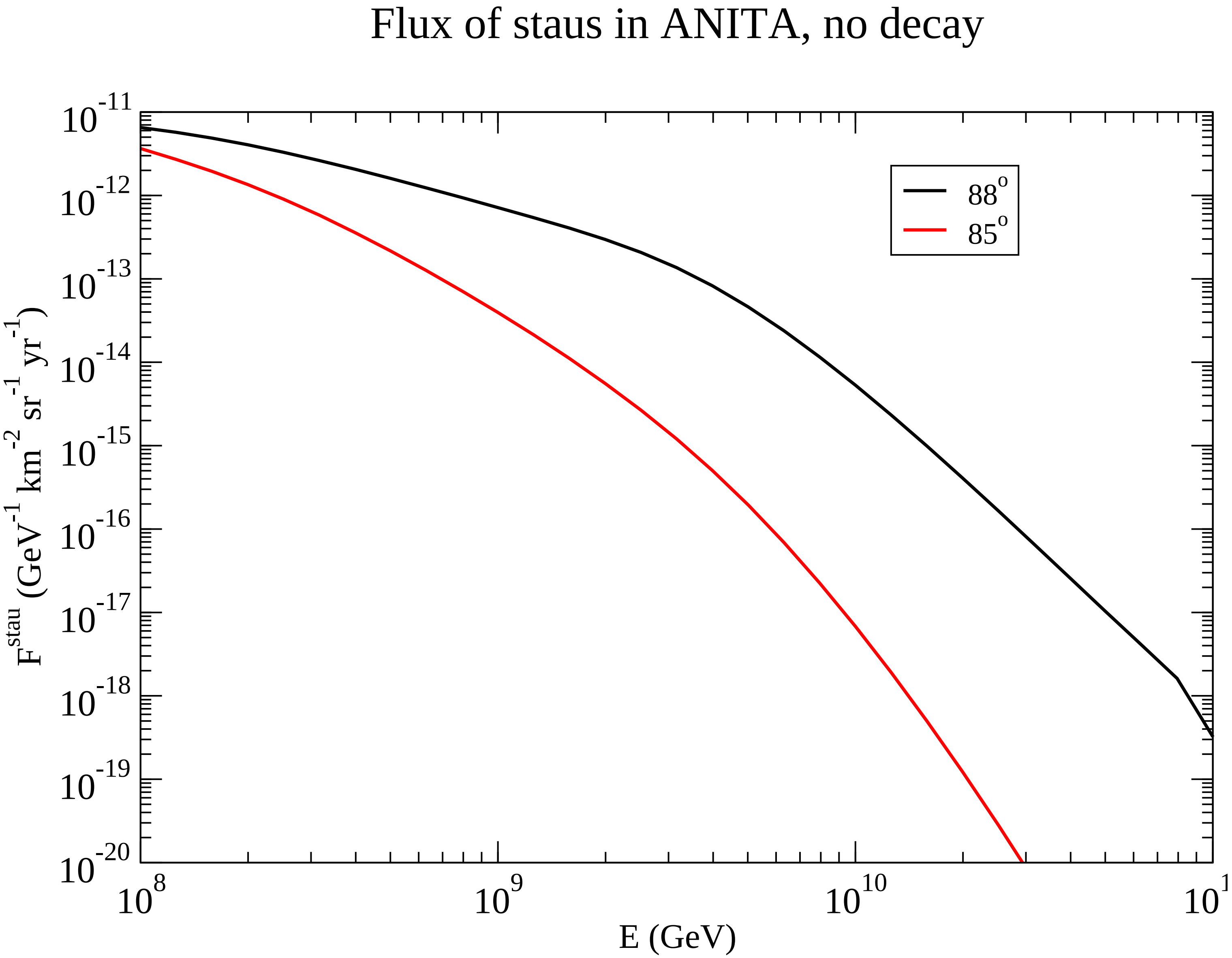
$$P_d = \delta\left(E_{\tilde{\tau}} - E_\nu e^{-\beta_{\tilde{\tau}}\rho_s(2R_E\cos\theta - z)}\right) \ .$$

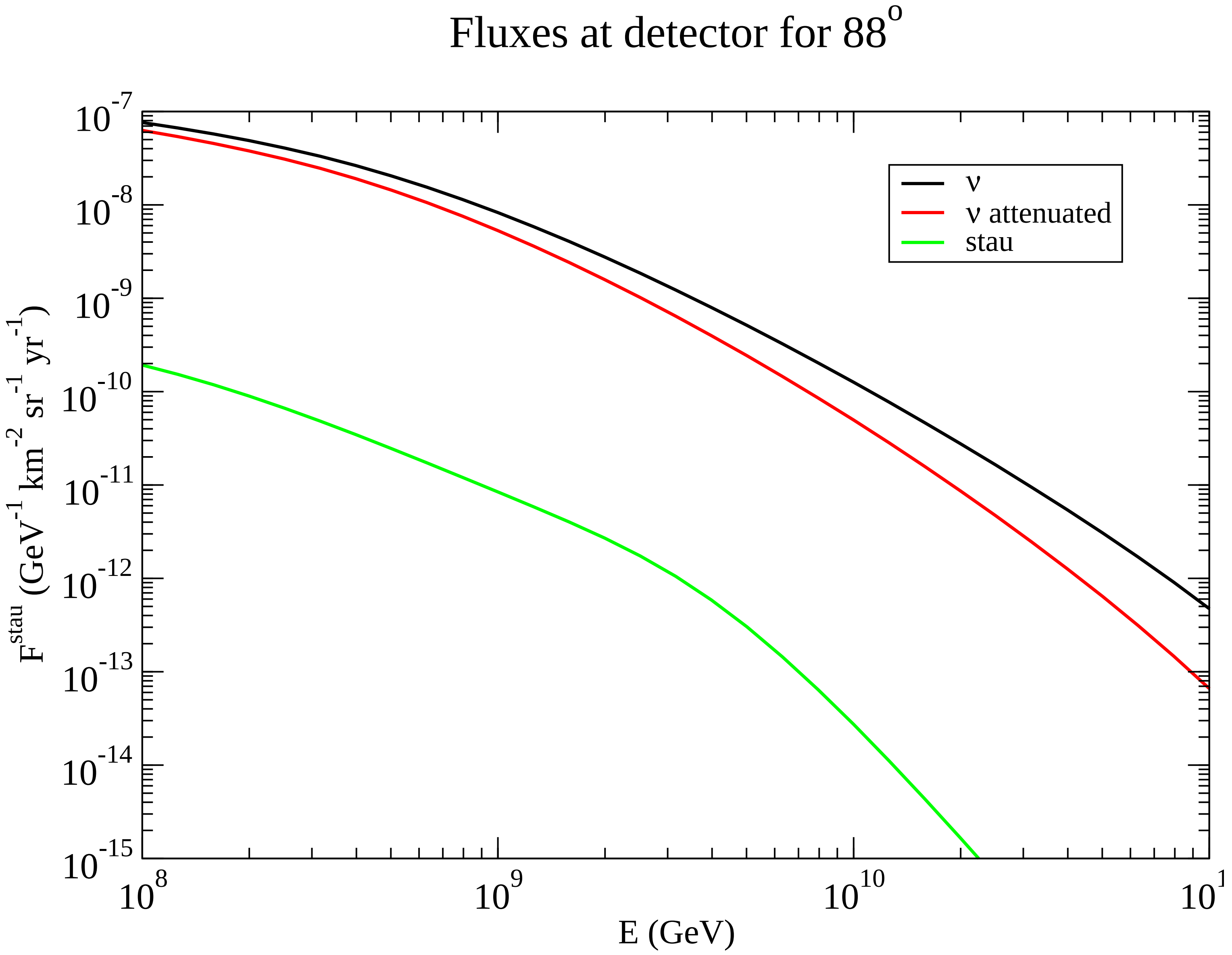
Combining probabilities, the kernel is then

$$K(E_\nu,\theta;E_{\tilde{\tau}}) = \int_0^{2R_E\cos\theta} P_a P_b P_c P_d \ .$$

The kernel is dominated by the contribution from $z \approx 2R_E\cos\theta$, and we may replace z with $2R_E\cos\theta$ in P_a. The only remaining z-dependence is in P_d. Using $\int dz\,\delta(h(z)) = |dh/dz|^{-1}_{h=0}$, the z integration yields

$$\begin{aligned} K(E_\nu,\theta;E_{\tilde{\tau}}) \quad &\approx \quad \frac{1}{L^\nu_{CC\,s}(E_\nu)} e^{-\int_0^{2R_E\cos\theta}\frac{dz'}{L^\nu_{CC}(E_\nu,\theta,z')}} \\ &\times \quad \exp\left[\frac{m_{\tilde{\tau}}}{c\tau_{\tilde{\tau}}\beta_{\tilde{\tau}}\rho_s}\left(\frac{1}{E_\nu} - \frac{1}{E_{\tilde{\tau}}}\right)\right]\frac{1}{E_{\tilde{\tau}}\beta_{\tilde{\tau}}\rho_s} \ . \end{aligned}$$


Flux of staus in ANITA, no decay



Fluxes at detector for 88^{o}
F^{stau} (GeV^{-1} km^{-2} sr^{-1} yr^{-1})
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{8}
10^{9}
10^{10}
10^{1}
E (GeV)
ν
ν attenuated
stau

- **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...)
- Cosmic neutrinos detection in the future: IceCube, ANITA, Auger, OWL, Euso, SALSA, LOFAR ...