1/8/04, Ashra meeting

Earth Skimming VHE Neutrinos

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Outline

- **Neutrino oscillations and Astrophysical Tau Neutrino Fluxes**
- **The Rationale for Detecting Earth-Skimming or Mountain-Penetrating Neutrinos**
- **The Rough Estimate of Tau Lepton Fluxes**
- **Tau Lepton Fluxes from Mountain-Penetrating AGN, GRB, and GZK Tau Neutrinos**
- **Tau-Lepton Energy Fluctuations and Advantages for Detecting Mountain-Penetrating Neutrinos**
- **Conclusions**

Neutrino oscillations and astrophysical ν_τ fluxes

- Although ν_τ flux from the source is suppressed compared to that of ν_μ and ν_e, the oscillation effects make the flux of each flavor comparable at the earth.

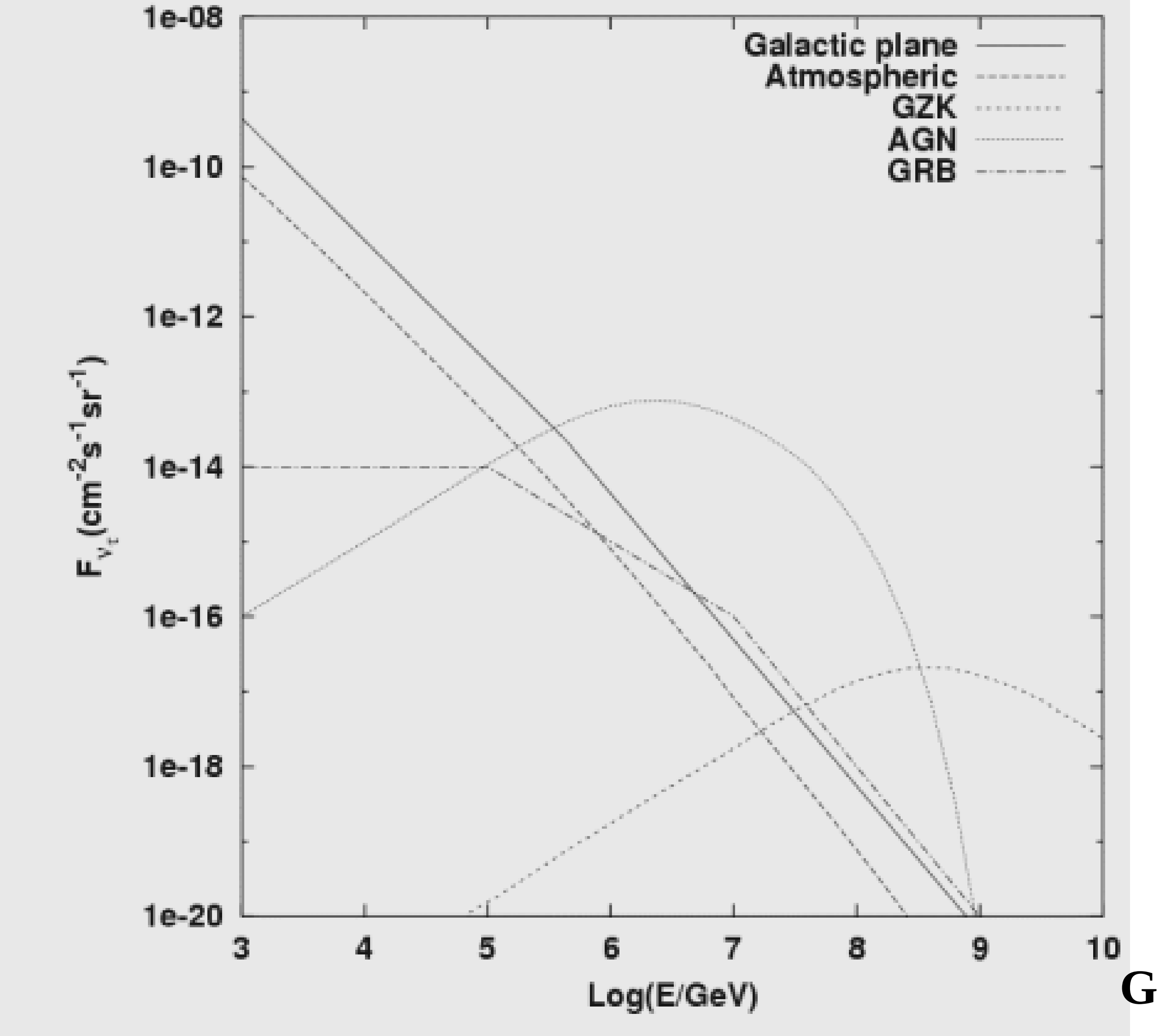
The idea of observing ν_τ in view of neutrino oscillations, was suggested sometime ago.

Learned and Pakvasa 1995

For a source in a cosmological distance, with $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$, the oscillation effects taking place as the neutrinos reach the terrestrial detector make $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$.

Athar, Jezabek, Yasuda 2000

Tau neutrino fluxes



GZK 10^9 GeV

Athar, Tseng and Lin, ICRC 2003

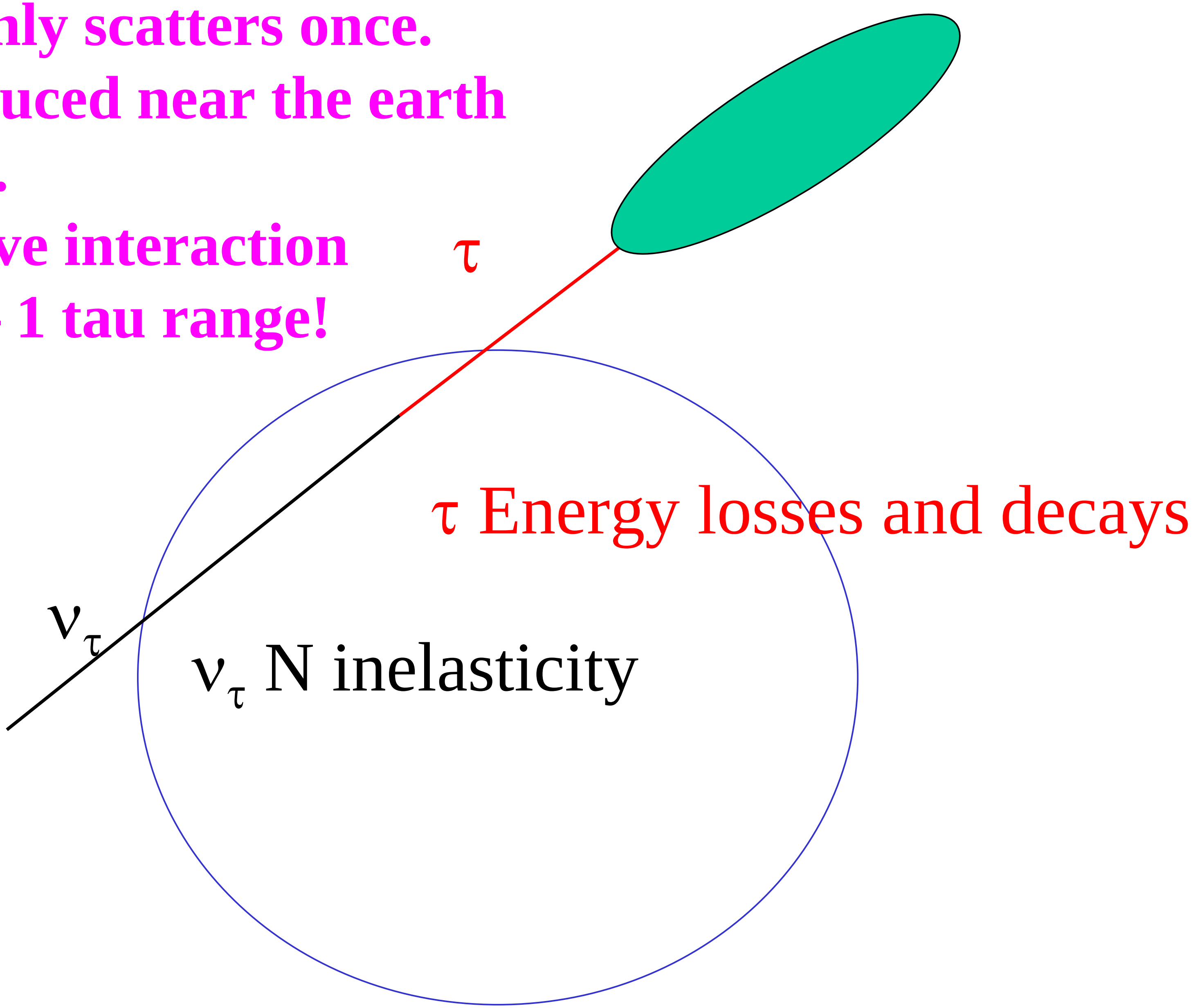
Detecting Earth-Skimming ν_τ

The Rationale

The idea of detecting earth-skimming neutrinos….

Domokos and Kovesi-Domokos, 1998
Fargion, 1997, 2002
Bertou et al., 2001
Feng et al., 2001
Bottai and Giurgola, 2002
Tseng et al., 2003

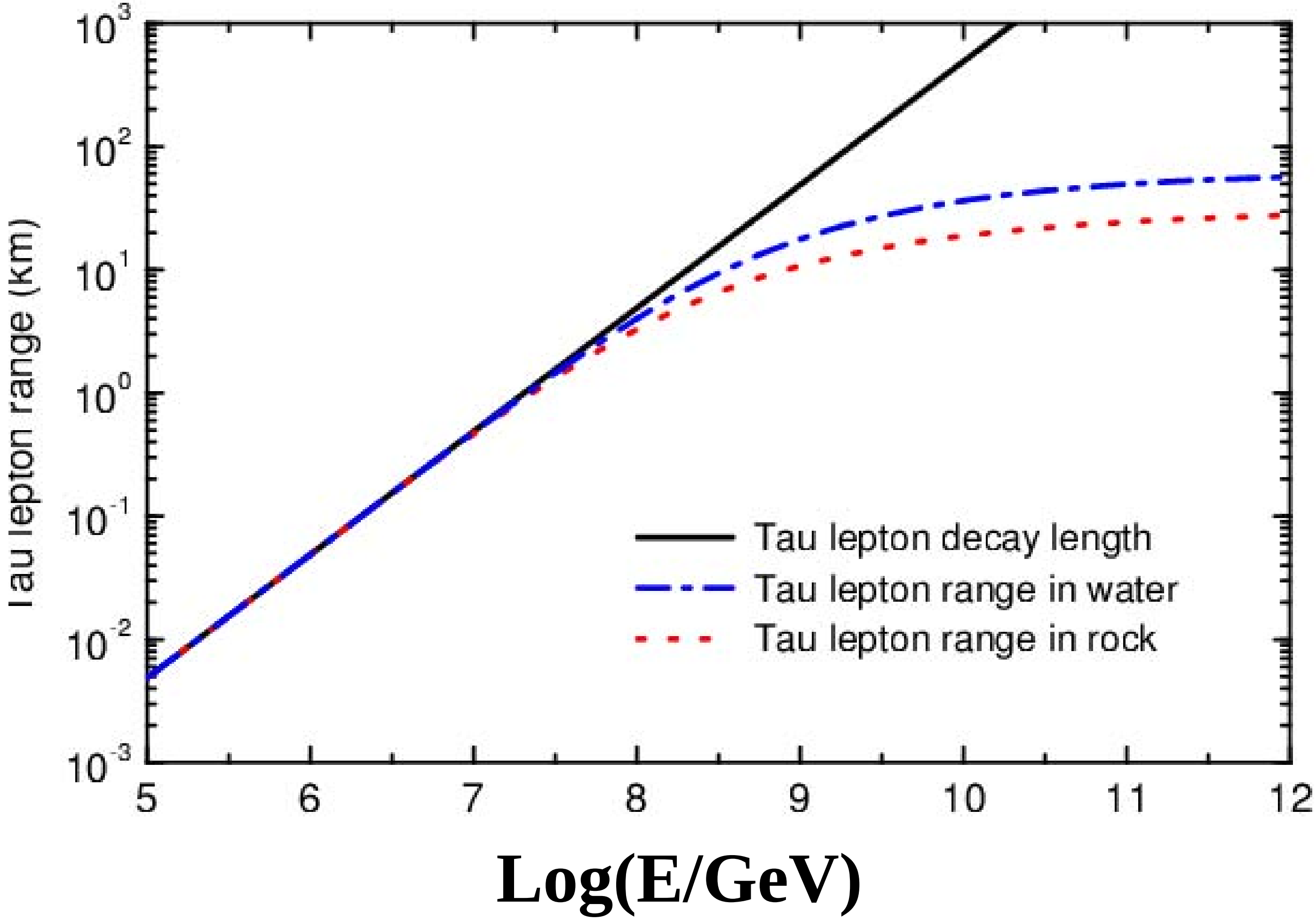
- **ν_τ N only scatters once.**
- **τ produced near the earth surface.**
- **effective interaction region– 1 tau range!**



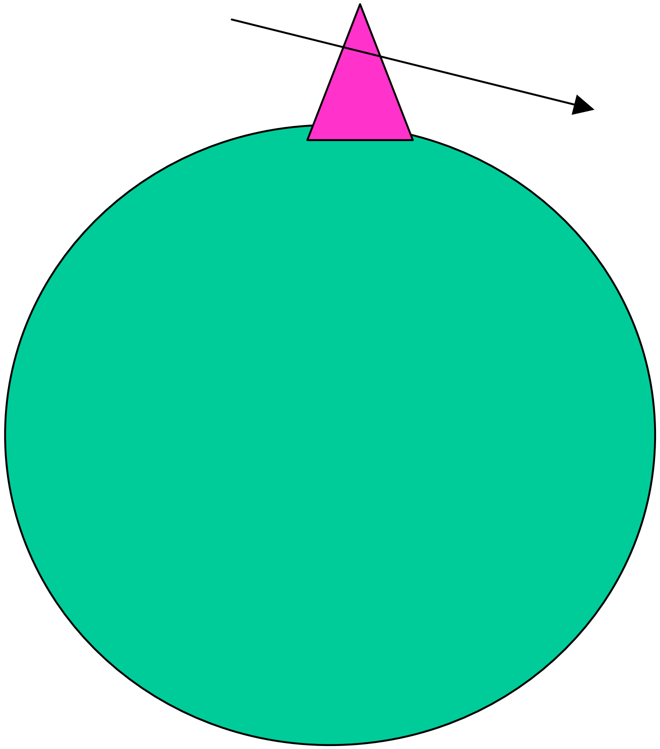
The “effective” tau lepton production probability =Tau Range(R_τ) /ν_τ N interaction length(λ_τ)

- R_τ increases with energy, while λ_τ decreases with energy. Hence it is favorable to detect neutrinos of higher energies!

Iyer Dutta, Reno, Sarcevic, & Seckel, 01
Tseng, Yeh, Athar, Huang, Lee, & Lin, 03



Tau lepton range approaches to 20 km in rock.
Mountain-penetrating is sufficient!

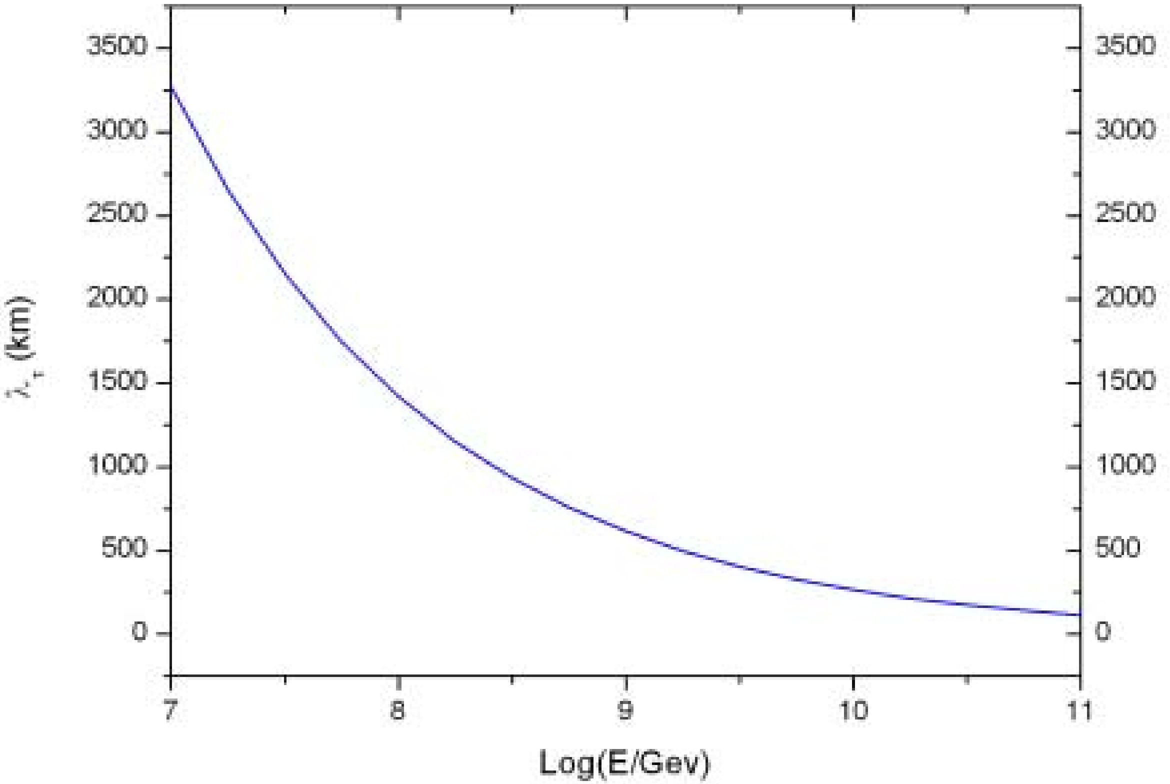


Mountain-penetrating tau neutrinos/tau leptons

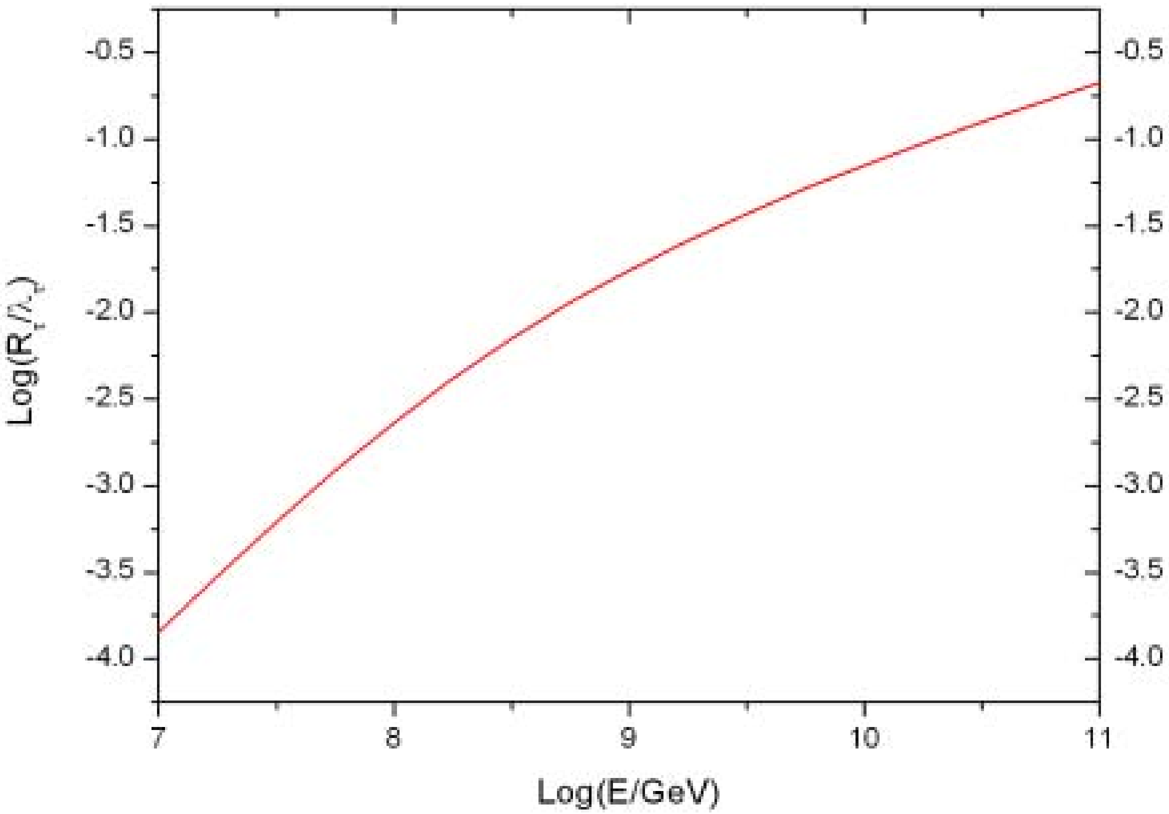
Gandhi, Quigg, Reno, Sarcevic, 1998

The ν_τN interaction length:

$$2\times10^4\,\mathrm{km}\left(\frac{1g/\mathrm{cm}^3}{\rho}\right)\left(\frac{E_\nu}{10^{15}\ \mathrm{eV}}\right)^{-0.363},\ \rho = 2.65\,\mathrm{g/cm}^3 \text{ in rock}$$



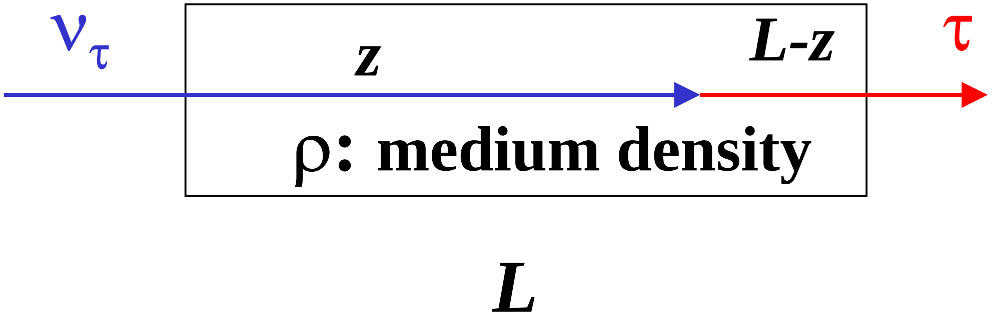
The “effective” tau lepton production probability



The Rough Estimate of Tau Lepton Fluxes

A qualitative picture:

$$-\frac{dE_\tau}{dX} = \alpha + \boxed{\beta E_\tau}$$



ν_τ

z

L-z

τ

ρ: **medium density**

L

$$P_T = \int_0^z dz P_s\left(E_\nu, z\right) p_{cc}\left(E_\nu\right) P_\tau\left(E_\tau, L - z\right)$$

$$P_s = \exp\left(-\frac{z}{\lambda_\nu^{cc}\left(E_\nu\right)}\right),\ p_{cc} = \frac{1}{\lambda_\nu^{cc}\left(E_\nu\right)},$$

$$P_\tau\left(E_\tau, x\right) = \exp\left[-\frac{1}{\beta\rho d_\tau\left(E_\tau\right)}\left(\exp\left[\beta\rho x\right] - 1\right)\right].$$

Let us take $E_\tau^i = E_\nu \equiv E$ and define $r = \log_{10}\left(\dfrac{E}{E'}\right)$, where

E' is the exiting tau lepton energy.

$$\frac{dP_T}{dr} = \exp\left(-\frac{1}{\lambda_\nu^{cc}(E)}\left(L - \frac{r\ln(10)}{\beta\rho}\right)\right) \times \frac{\ln(10)}{\beta\rho\lambda_\nu^{cc}(E)}$$

$$\times \exp\left[-\frac{1}{\beta\rho d_\tau(E)}\left(10^r - 1\right)\right]$$

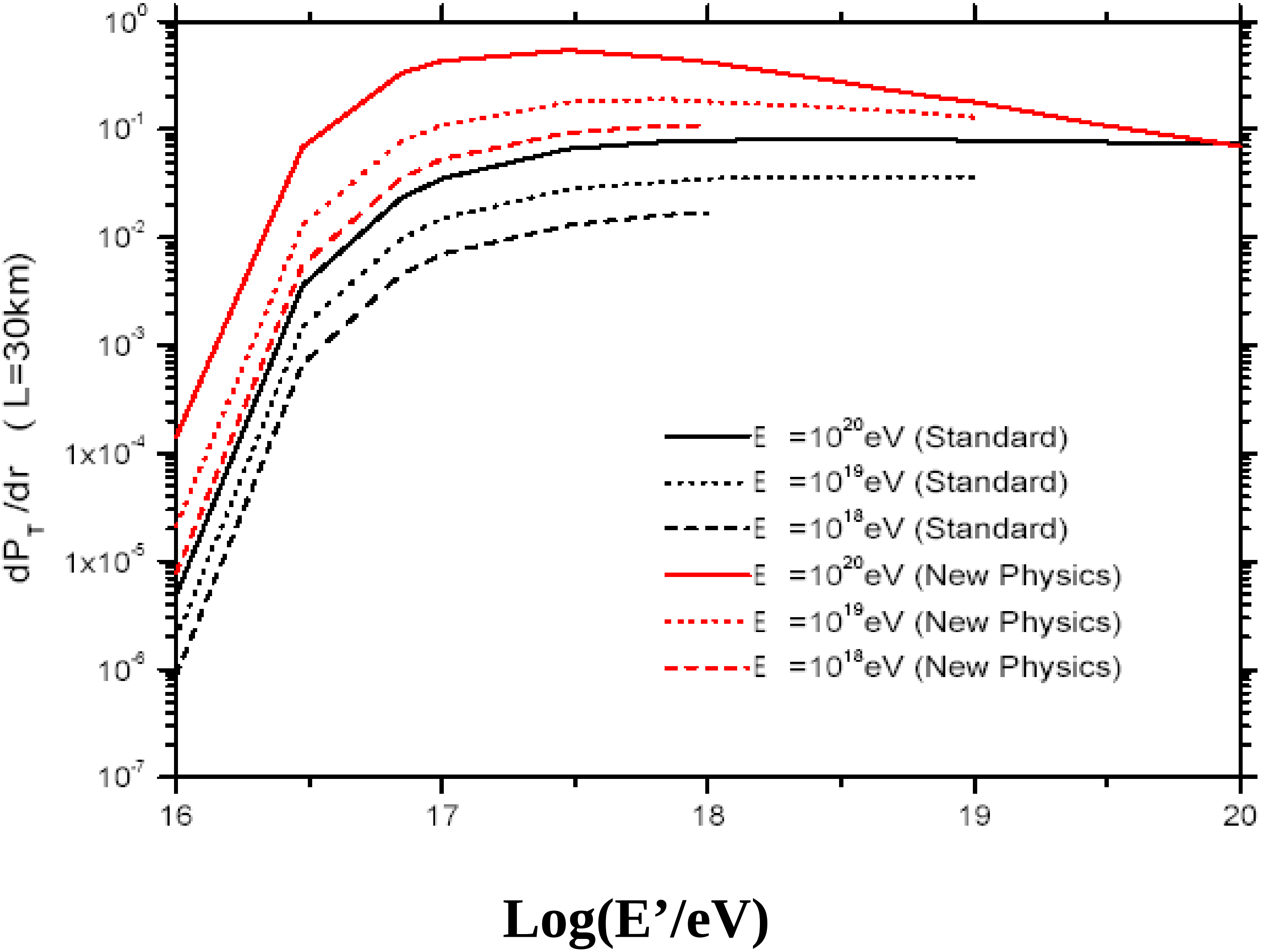
For E around 10^{18} eV, $\beta \approx 8\times10^{-7}\ \mathrm{g}^{-1}\ \mathrm{cm}^2$

$$0 \le r \le \frac{\beta\rho L}{\ln(10)} \approx (L/10\ \mathrm{km})$$

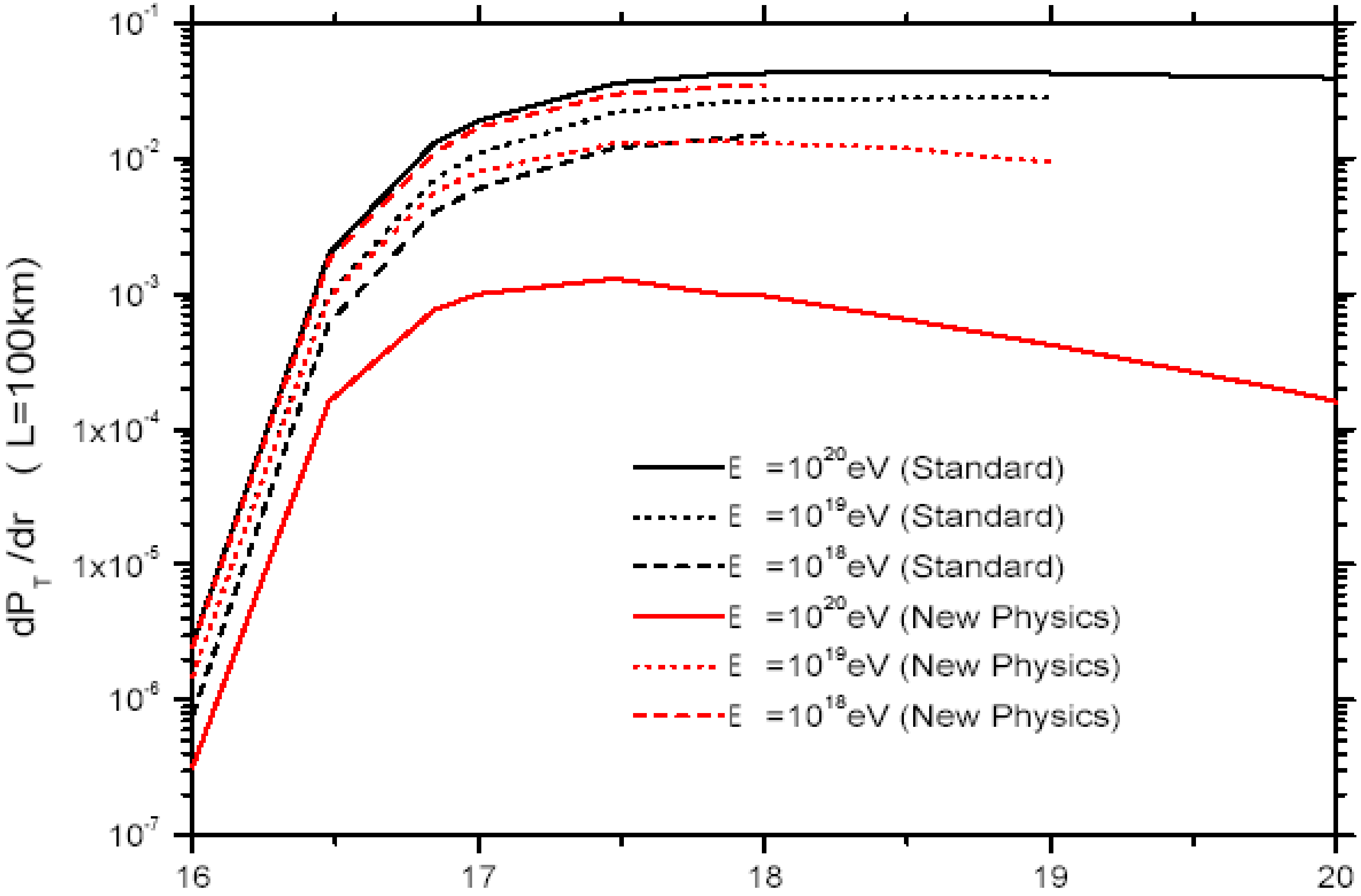
$$\beta\rho d_\tau(E) = 10\times\left(\frac{E}{10^{18}\ \mathrm{eV}}\right)$$

E: initial ν_τ energy, E': final τ energy, r=Log(E/E')

New physics means a factor of 10 enhancement on $\sigma_{\nu N}$



E: initial ν_τ energy, E': final τ energy, r=Log(E/E')



Log(E'/eV)

- **The differential spectrum dP_T/dr remains rather flat for $E' \geq 10^{17}$ eV. This causes a pile up of tau leptons at $E' \approx 10^{17}$ eV.**

- **The energy reconstruction for the initial neutrino energy becomes a challenge beyond 10^{17} eV!**

- **The enhancement on $\sigma_{\nu N}$ generally brings enhancement on dP_T/dr for L=30 km. It is not the case for L=100 km due to the medium absorption.**

Tau Lepton Fluxes

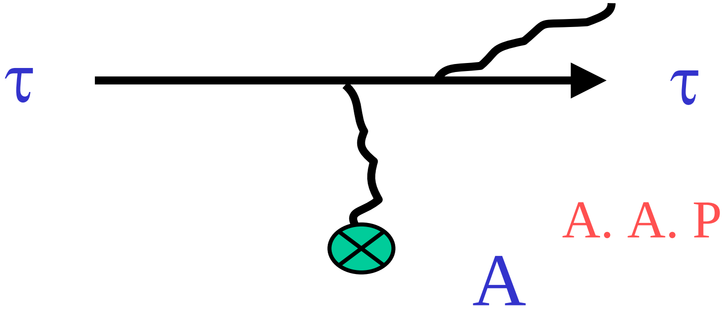
The detailed calculations

(A). The Tau Lepton Range

The tau lepton loses its energy in the rock through 4 kinds of interactions:

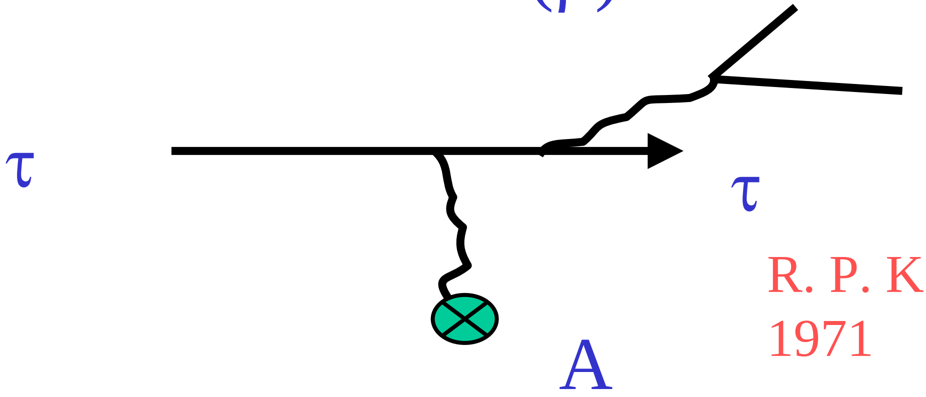
(1). Ionization (α): the tau lepton excites the atomic electrons. H. A. Bethe 1934

(2). Bremsstrahlung (β):



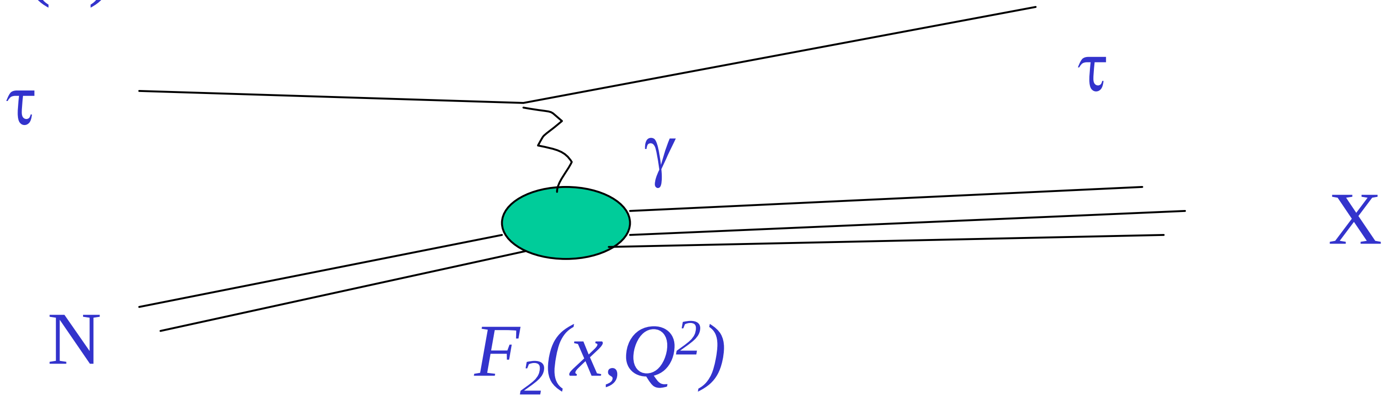
A. A. Petrukhin &V.V. Shestakov, 1968

(3). Pair Production (β):



R. P. Kokoulin & A. A. Petrukhin, 1971

(4). Photo-nuclear interaction:



Basic component

The nucleus shadowing effect is considered:

$$a(A,x,Q^2) = \frac{F_2^A(x,Q^2)}{AF_2^N(x,Q^2)}$$

Brodsky & Lu, 1990; Mueller & Qiu 1986;
E665 Collab. Adams *et al.*, 1992

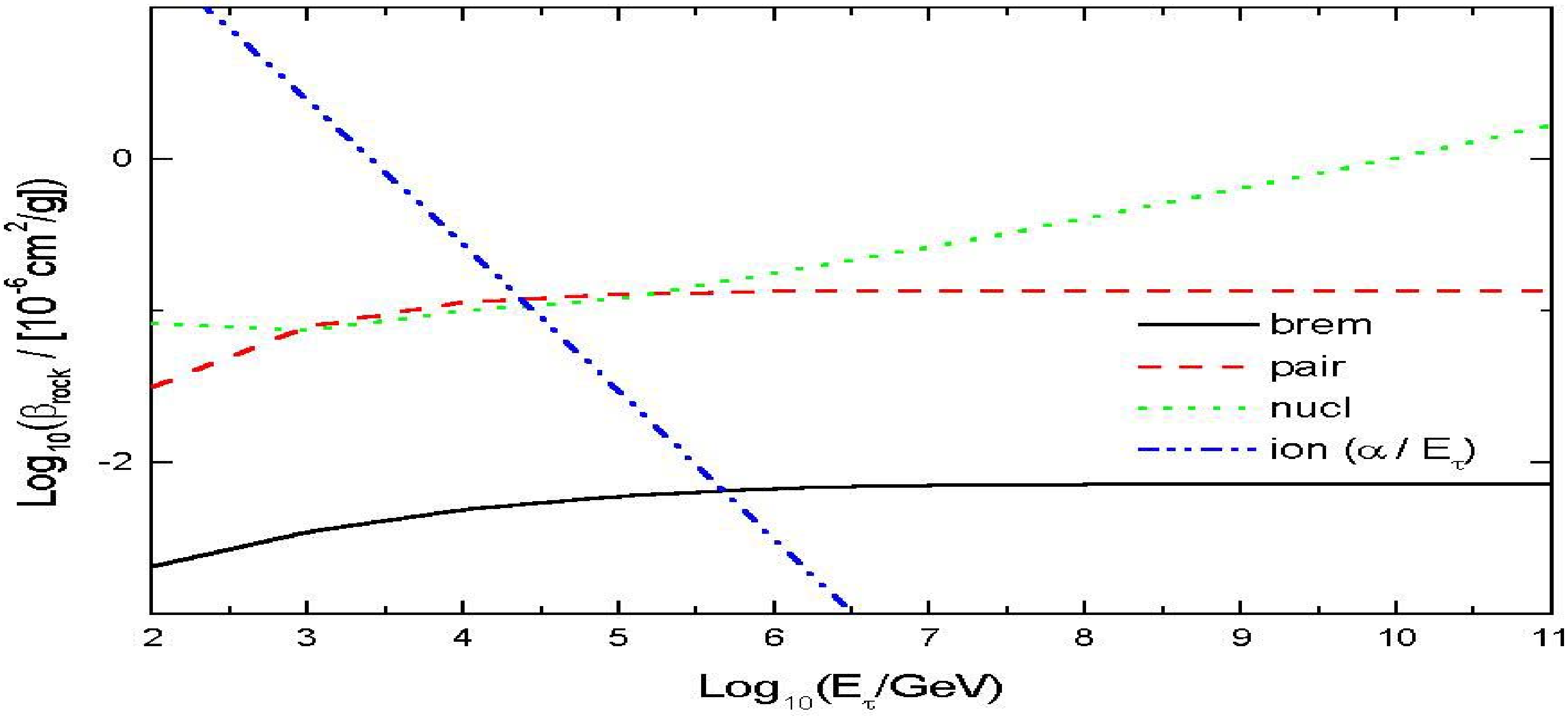
Summarizing all these:

The τ energy loss:

Iyer Dutta, Reno, Sarcevic, & Seckel, 01

$$-\frac{dE_\tau}{dX} = \alpha + \left(\sum_i \beta_i\right) E_\tau, \; X \text{ in units of g/cm}^2,$$

α and β_i's are plotted below.



The Tau Lepton Range:

$$\frac{dP(E,X)}{dX} = -\frac{P(E,X)}{d_\tau(E)\rho(X)}, -\frac{dE}{dX} = \alpha + \beta(E)E.$$

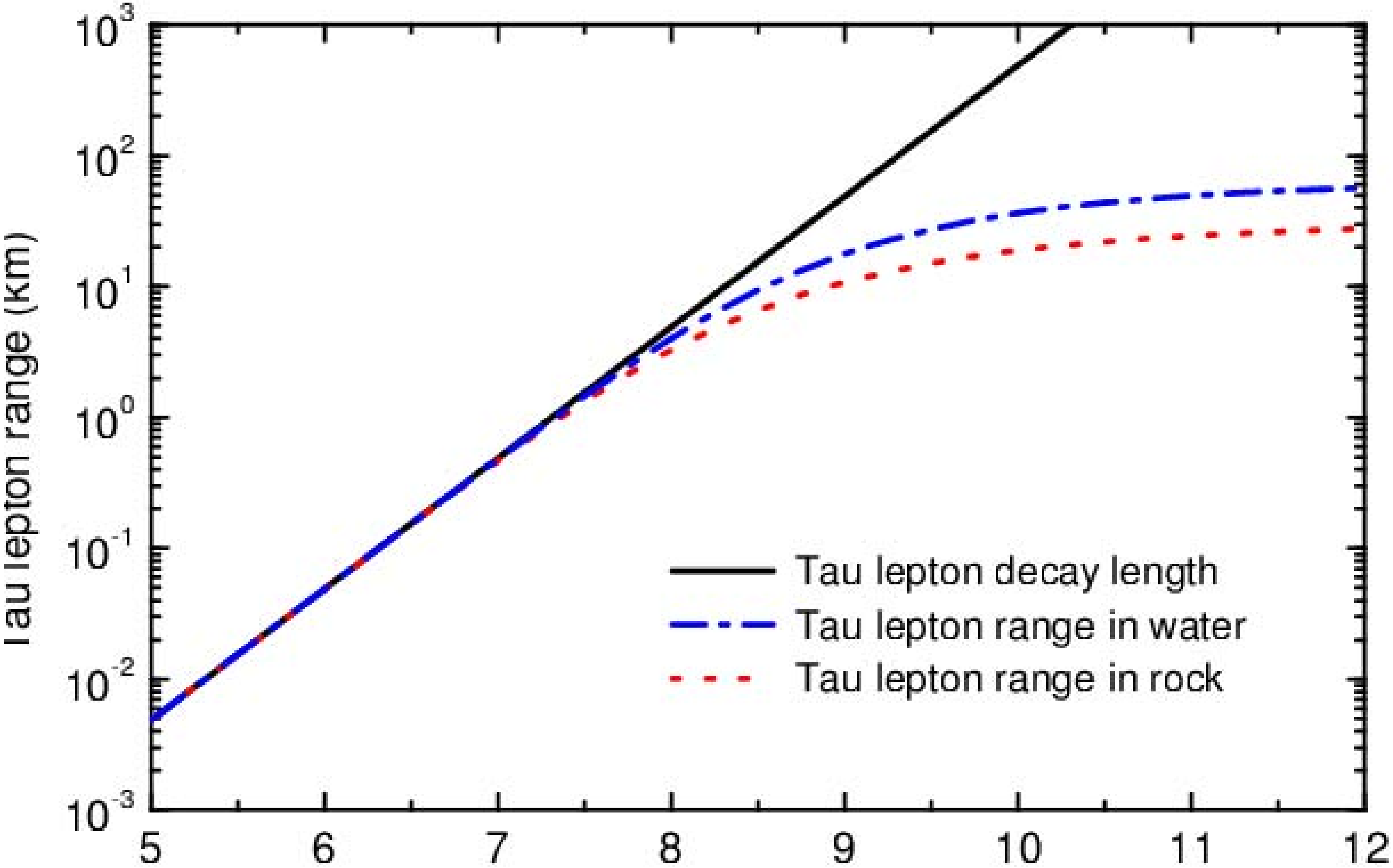
Then $R_\tau(E_0) = \int_0^\infty dX \;\, P(E_0, X).$

Note that we can parameterize

$$\beta(E) = \left[1.6 + 6\left(E/10^{18}\ \mathrm{eV}\right)^{0.2}\right] \times 10^{-7}\ \mathrm{g}^{-1}\ \mathrm{cm}^{2}$$

Iyer Dutta, Reno, Sarcevic, & Seckel, 01

Tseng, Yeh, Athar, Huang, Lee, & Lin, 03



Log(E/GeV)

cc important for
E > 10^9 GeV

(B). The Tau Lepton Fluxes

The transport equations:

For the τ lepton :

$$\frac{\partial F_\tau(E,X)}{\partial X} = -\frac{F_\tau(E,X)}{\rho d_\tau} + \frac{\partial}{\partial E}\left[\gamma(E) F_\tau(E,X)\right] + G_\nu(E,X),$$

with $G_\nu(E,X) = N_A \int_{y_{\min}}^{y_{\max}} \frac{dy}{1-y} F_\nu(E_y, X) \frac{d\sigma_{\nu N \to \tau Y}}{dy}(y, E_y),$

and $\gamma(E) \equiv \alpha + \beta(E)E = -\frac{dE}{dX}.$

One can solve for $F_\tau(E,X)$ to obtain

$$F_\tau(E,X) = \int_0^T dT\, G_\nu\left(\overline{E}(X-T;E), T\right) \times$$

$$\exp\left[\int_T^X dT' \left(-\frac{m_\tau c}{\tau_0 \overline{E}(X-T';E)\rho} + \gamma'\left(\overline{E}(X-T';E)\right)\right)\right]$$

For the resonant scattering at the W boson peak,

we set $G_\nu(E,X) = N_A \int_{y_{\min}}^{y_{\max}} \frac{dy}{1-y} F_{\bar{\nu}_e}(E_y, X) \frac{d\sigma_{\bar{\nu}_e e^- \to \bar{\nu}_\tau \tau^-}}{dy}(y, E_y).$

For neutrinos,

$$\frac{\partial F_{\nu_\tau}(E,X)}{\partial X} = -\frac{F_{\nu_\tau}(E,X)}{\lambda_{\nu_\tau}} + N_A \sum_{i=1}^{3} \int_{y^i_{\mathrm{min}}}^{y^i_{\mathrm{max}}} \frac{dy}{1-y} F_i\left(E_y, X\right) \frac{d\sigma^i_{\nu_\tau}}{dy}\left(y, E_y\right),$$

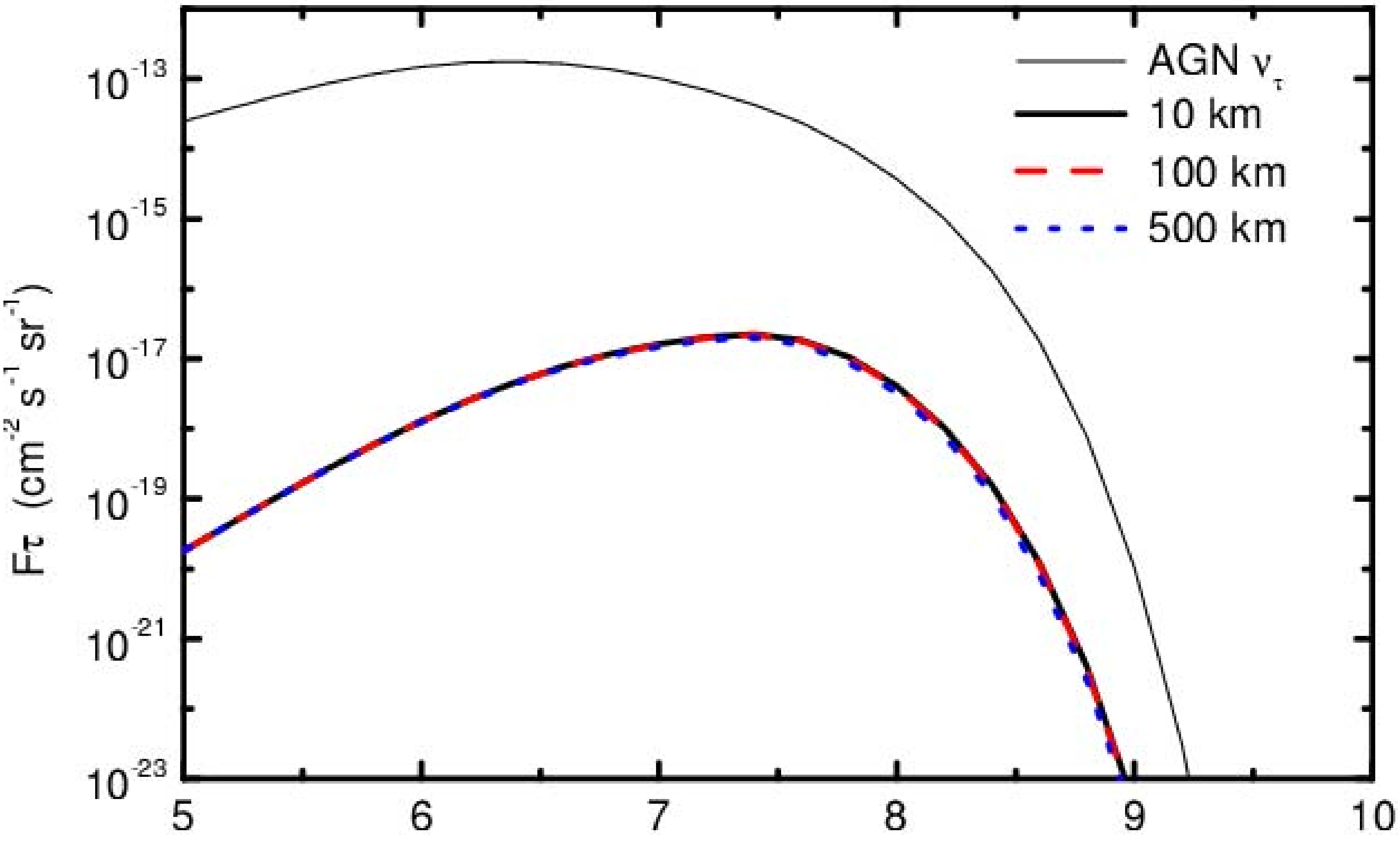
where $\sigma_\nu^{1,2,3}$ are $\sigma\left(\nu_\tau N \to \nu_\tau Y\right)$, $\Gamma\left(\tau \to \nu_\tau Y\right)/c$, and $\sigma\left(\tau N \to \nu_\tau Y\right)$.

For $\overline{\nu}_{\mathrm{e}}$, we have

$$\frac{\partial F_{\overline{\nu}_e}(E,X)}{\partial X} = -\frac{F_{\overline{\nu}_e}(E,X)}{\lambda_{\overline{\nu}_e}} + N_A \int_{y_{\mathrm{min}}}^{y_{\mathrm{max}}} \frac{dy}{1-y} F_{\overline{\nu}_e}\left(E_y, X\right) \frac{d\sigma_{\overline{\nu}_e e^- \to \overline{\nu}_\tau \tau^-}}{dy}\left(y, E_y\right).$$

Note $F_i(E,X) \equiv \dfrac{dN_i}{d\left(\log_{10} E\right)}$ is in units of $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$.

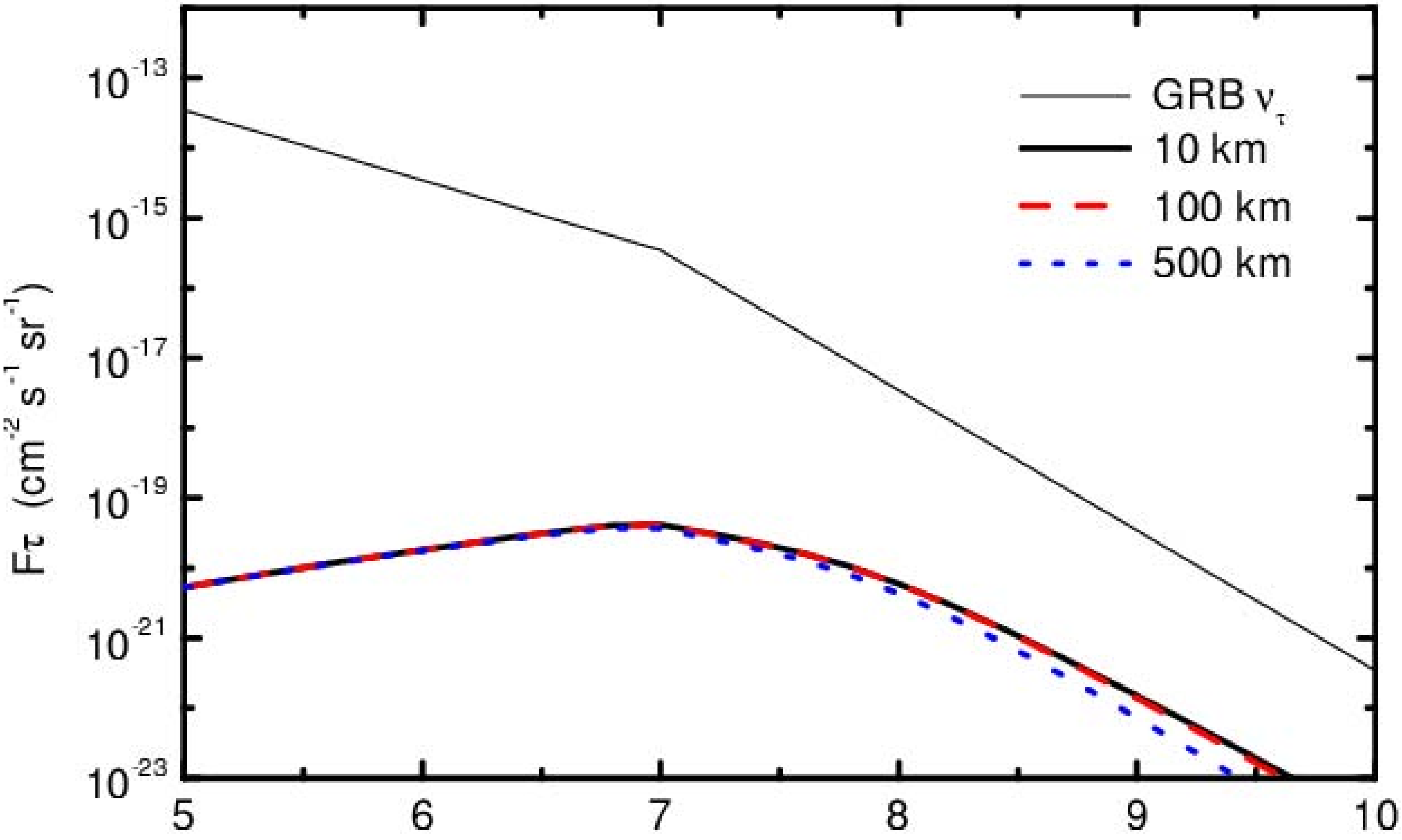
AGN ν_τ flux inferred from Kalashev, Kuzmin, Semikoz, and Sigl, 03



Log(E/GeV)

Tseng et al., 03

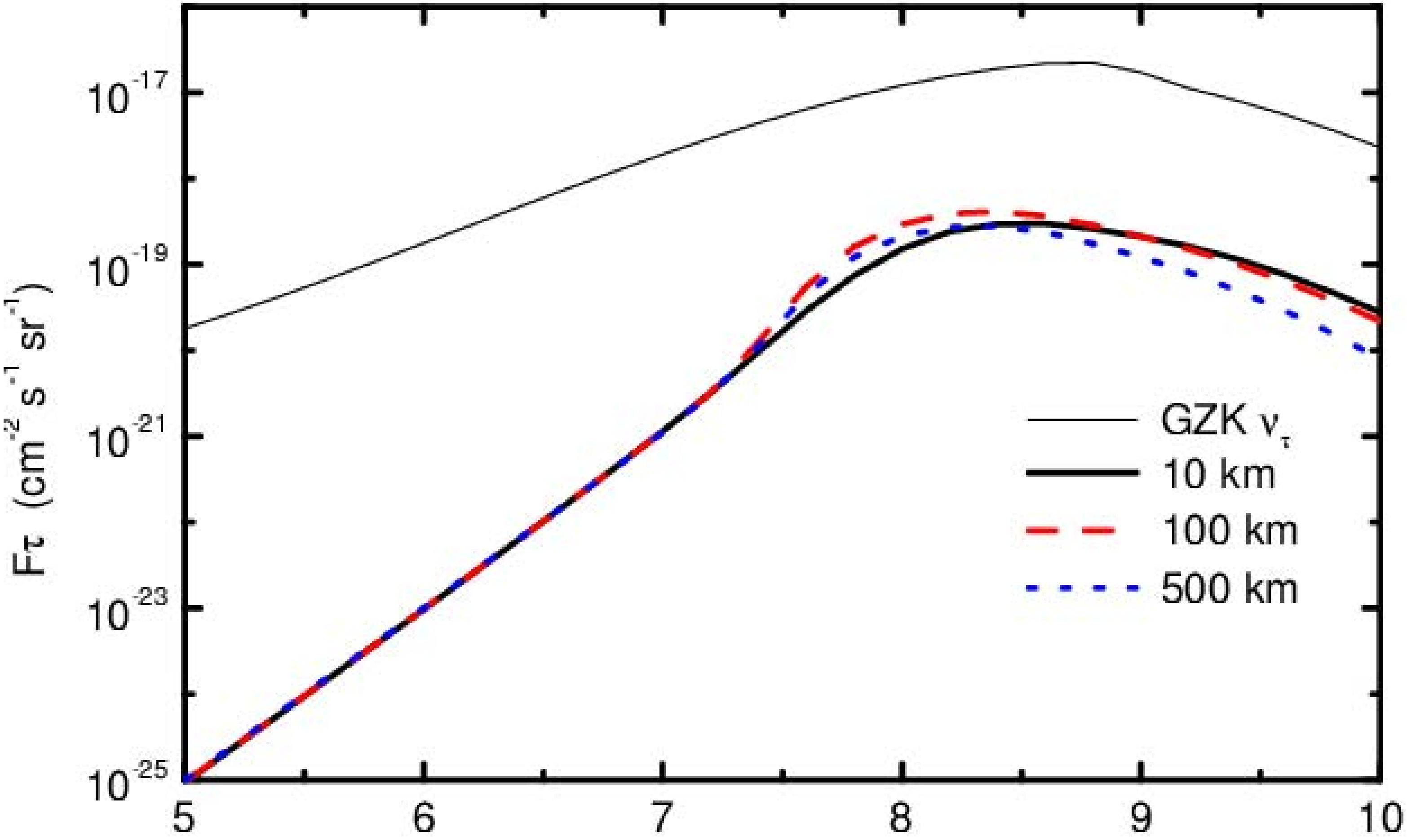
GRB ν_τ flux inferred from Waxman and Bahcall 1997



Log(E/GeV)

Tseng et al., 03

GZK ν_τ flux inferred from Engel, Seckel, and Stanev, 01



Log(E/GeV)

Tseng et al., 03

W boson contribution

Glashow resonance 1960

$$\bar{\nu}_e e^- \to W^- \to \bar{\nu}_\tau \tau^-$$

$$F_\tau(E,x) = F_{\bar{\nu}_e}(E_R,0) \times 3.3 \cdot 10^{-4} \times \left(\frac{E}{E_R}\right) \times \left(1 - \frac{E}{E_R}\right)^2 \cdot \exp\left(-\frac{X}{L_R}\right),$$

where $E_R \equiv \dfrac{m_W^2}{2m_e} = 6.3 \times 10^6$ GeV is the resonant energy;

$L_R = 60$ kmwe is the resonant scattering length

Integrated tau lepton flux in units of $km^{-2}yr^{-1}sr^{-1}$

Energy & flux	AGN	GRB	GZK
10^{15}-10^{16} eV	2.2	9.6×10^{-3}	7.4×10^{-5}
10^{16}-10^{17} eV	4.9	7.1×10^{-3}	1.1×10^{-2}
10^{17}-10^{18} eV	0.2	5.4×10^{-4}	8.2×10^{-2}
10^{18}-10^{19} eV		1.1×10^{-5}	3.3×10^{-2}

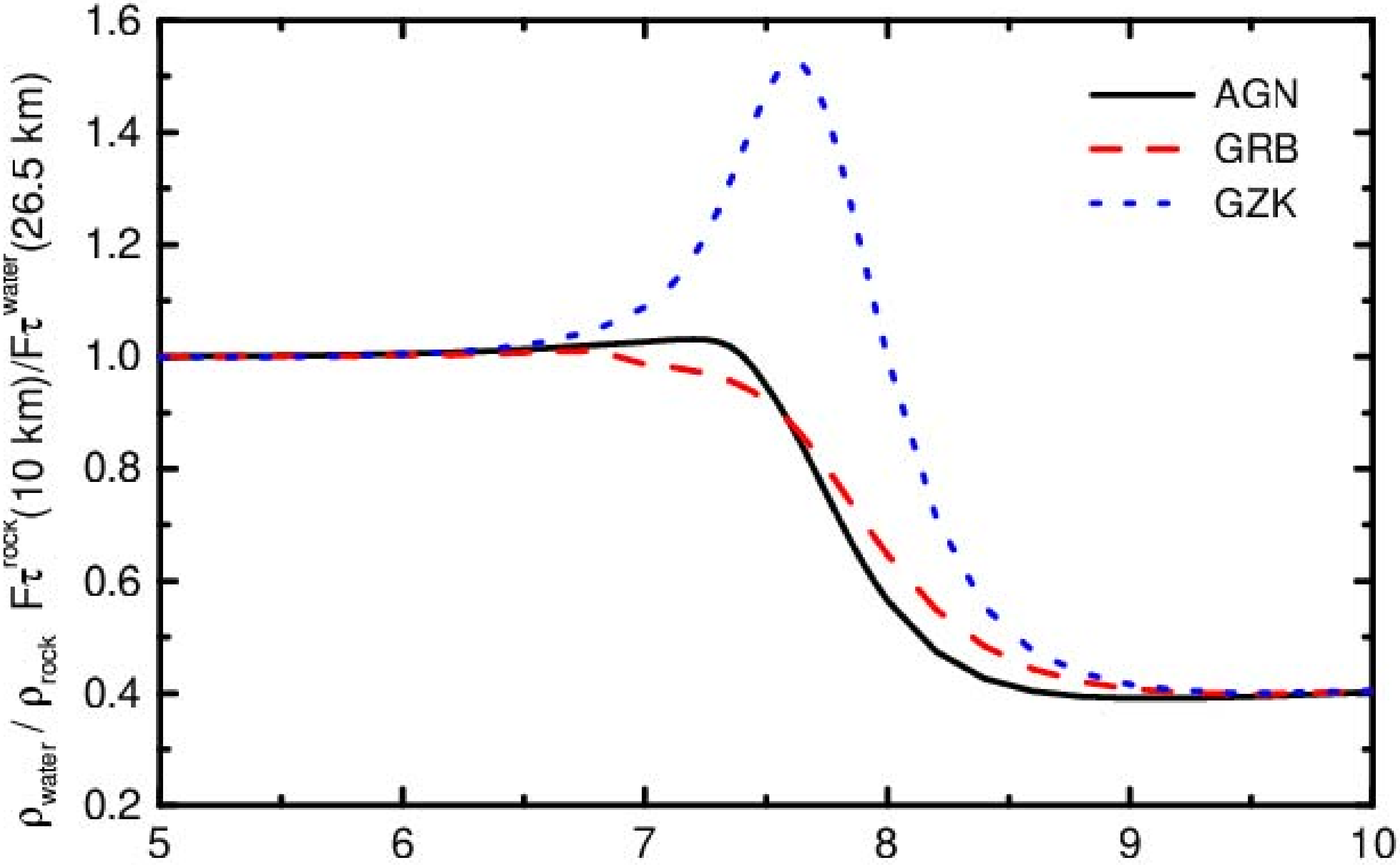
W resonance (AGN) 0.08

Effective aperture $(A\Omega)_{\mathrm{eff}}$ required for 1 event/yr, assuming a 10% duty cycle.

Energy & Aperture (km^2 sr)	AGN	GRB	GZK
10^{15}-10^{16} eV	4.5	1000	
10^{16}-10^{17} eV	2.0	1400	910
10^{17}-10^{18} eV	50	19000	120
10^{18}-10^{19} eV			290

Can we identify the source of neutrinos?

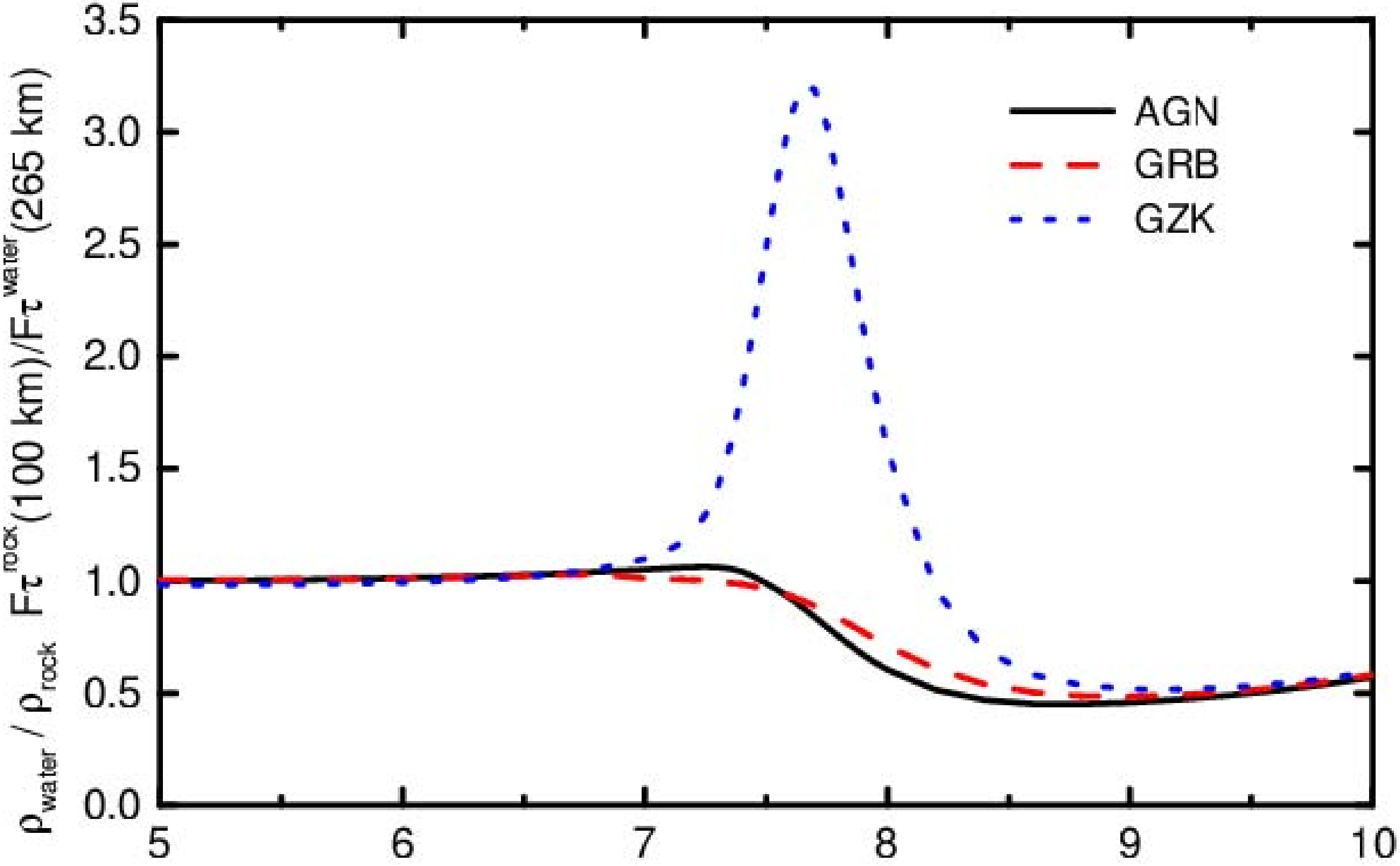
Sensitive to spectral indices



Log(E/GeV)

Tseng et al., 03

Sensitive to spectral indices

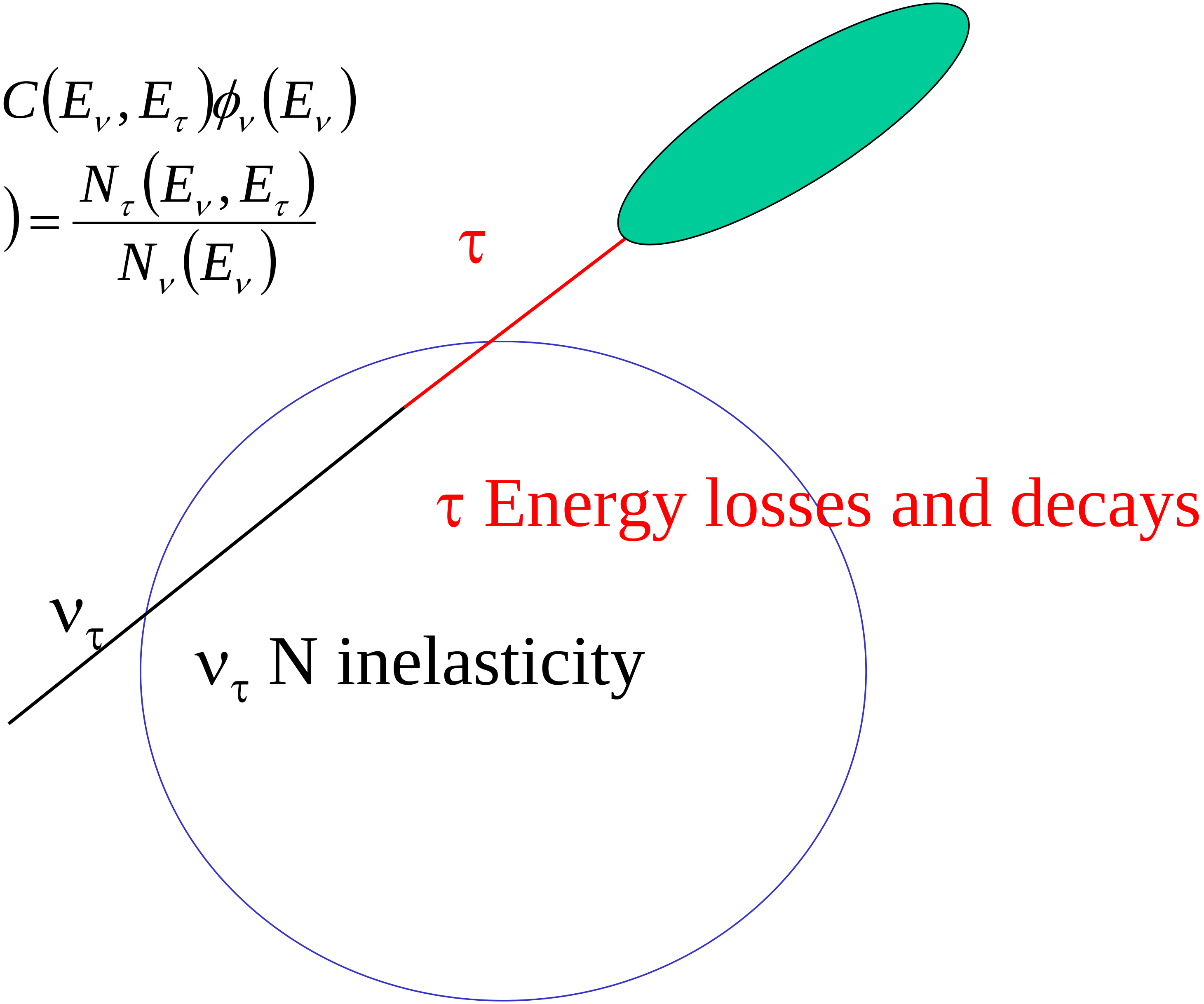


Tseng et al., 03

Tau lepton energy fluctuations

$$\phi_\tau(E_\tau) = C(E_\nu, E_\tau)\phi_\nu(E_\nu)$$

$$C(E_\nu, E_\tau) = \frac{N_\tau(E_\nu, E_\tau)}{N_\nu(E_\nu)}$$



τ

τ Energy losses and decays

ν_τ

ν_τ N inelasticity

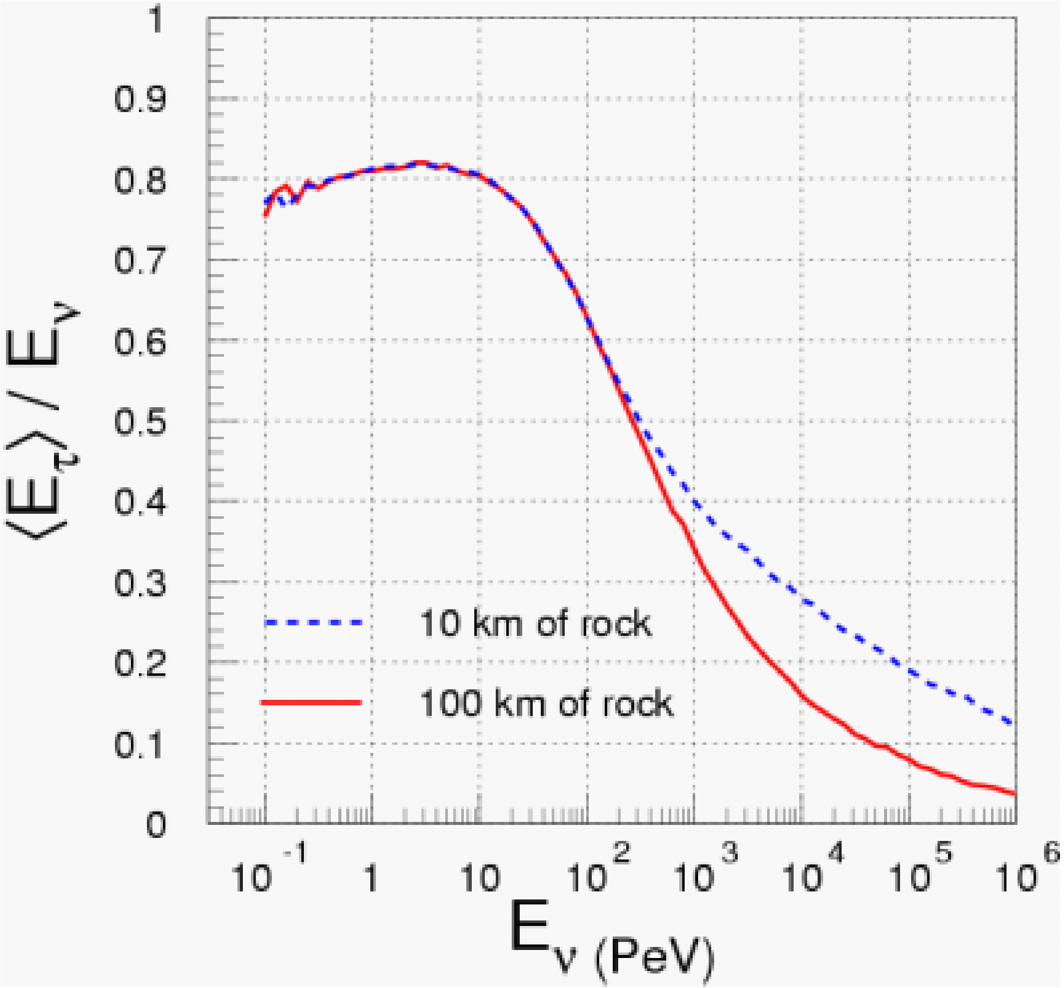
Assume averaged energy loss for each step.

Huang, Tseng and Lin, ICRC 2003

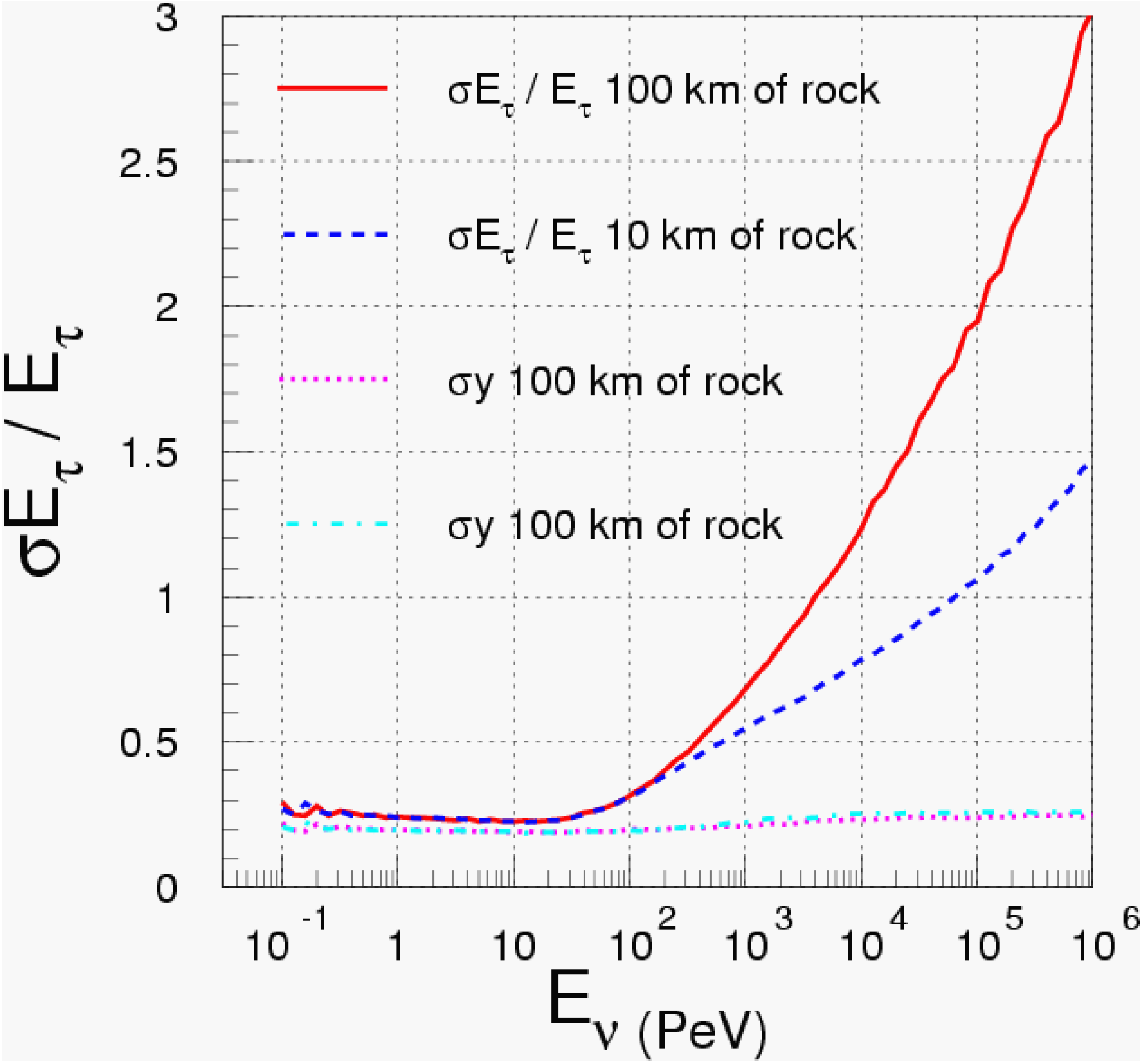
Full simulation (take into account stochastic nature of tau-lepton energy loss) is in progress…

Huang, Iong, Lin and Tseng

Huang, Tseng and Lin, ICRC 2003



Huang, Tseng and Lin ICRC 2003

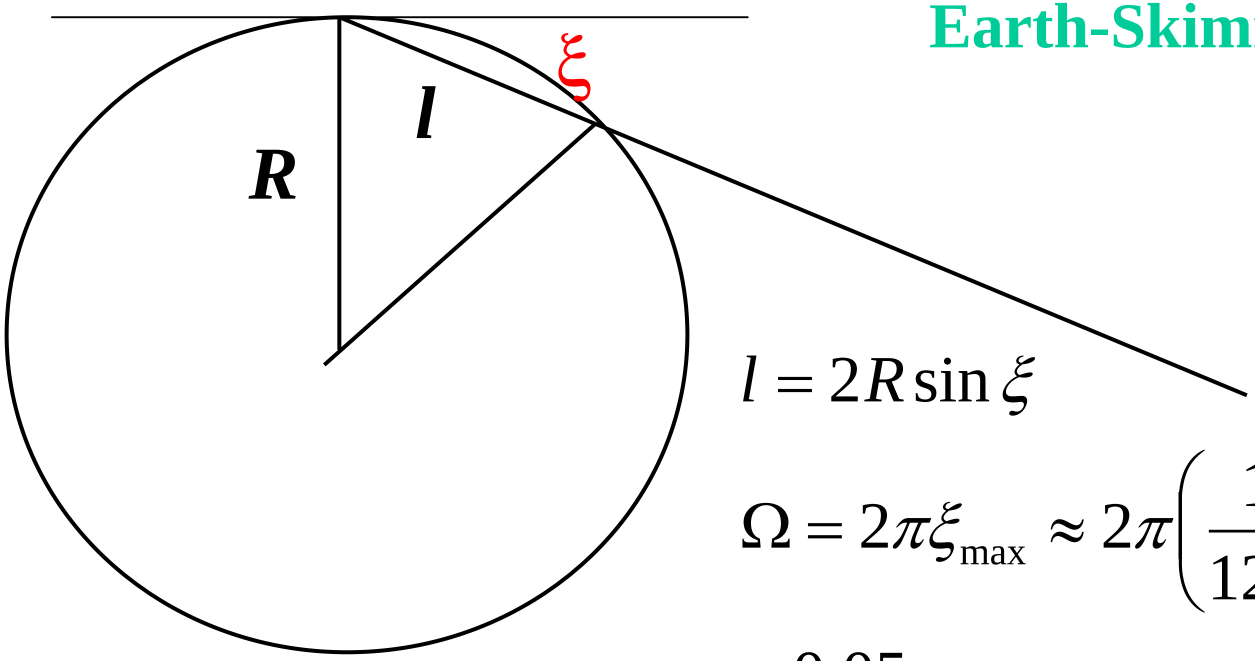


Conservative estimate !

This is essentially the pileup of tau lepton events at 10^{17} eV as seen before! In other words, the tau lepton energy resolution gets worse for $E_\tau > 10^{17}$ eV!

Advantages for Detecting Mountain-Penetrating Neutrinos over the Earth-Skimming Ones

Comparison of solid-angle coverage of earth-skimming and mountain-penetrating tau-neutrino experiment:



Earth-Skimming

$$l = 2R\sin\xi$$

$$\Omega = 2\pi\xi_{\max} \approx 2\pi\left(\frac{100\text{ km}}{12800\text{ km}}\right)$$

$$= 0.05$$

For the mountain-penetrating case:

$$w = 20\ \text{km}$$

$$l\ (\text{distance from mountain to detector})$$

$$= 20\ \text{km}$$

$$h\ (\text{height of the mountain}) = 2\ \text{km}$$

The solid angle is

$$\frac{\left(20 \times 2\ \text{km}^2\right)}{\left(20^2\ \text{km}^2\right)} = 0.1$$

Both cases are comparable if 100 km is acceptable for energy resolution. But the latter is preferred if better energy resolution is required!

For a smaller medium depth, say *L* about few tens of kilometer, the enhancement on $\sigma_{\nu N}$ also brings an enhancement on the tau lepton flux.

p. 16, 17

Conclusions

- We have presented the essential features of detecting Earth-skimming or mountain-penetrating ν_τ .
- The tau lepton flux resulting from mountain-penetrating ν_τ is calculated. ***The flux shows rather weak dependence on the traveling distance of ν_τ/τ inside the mountain. It is controlled by the tau lepton range inside the earth.***

The tau lepton flux already reaches its maximum for 20 km of medium depth. Larger medium depth results in poorer energy resolutions. ***This justifies the observations of mountain-penetrating neutrinos.***

We give effective aperture required for detecting 1 event/yr assuming a 10% duty cycle.

The tau lepton flux resulting from mountain-penetrating neutrinos could be enhanced by anomalously large neutrino-nucleon scattering cross section at high energies.