Ultrahigh Energy Neutrinos

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Ultrahigh Energy Neutrinos?

- UHECR: if they contain nucleons and come from extragalactic sources, then there will be cosmogenic neutrinos from $p\gamma \to \pi^+ n$
- at lower energies, if photons come from $\pi^0 \to \gamma\gamma$, then neutrinos come from $\pi^\pm \to \mu\nu_\mu$, $\mu \to \nu_\mu e \nu_e$ $\Rightarrow$ $2 N_e = N_\mu$
- given bi-maximal mixing of $\nu_\mu \leftrightarrow \nu_\tau$, $N_{\nu_e} = N_{\nu_\mu} = N_{\nu_\tau}$

E_ν determines the detection method:

$\hookrightarrow$ $E_\nu \lesssim 10^6$ GeV: detection of upward muons and showers. Attenuation of the flux in the Earth is important.

$\hookrightarrow$ $E_\nu \gtrsim 10^8 - 10^9$ GeV: horizontal air showers, radio detection

$\hookrightarrow$ intermediate energy – double bang: produce tau and look for decay [Learned & Pakvasa]; tau-watch: use the Earth as a neutrino converter [Fargion; Hou & Huang; Feng et al.]

$\sigma(\nu N)$ is reasonably well known:

- HERA gives ep CC cross section at $E = 50$ TeV
- Measurements ($p_q = xP_N$):

$$x \sim 10^{-6} \quad Q^2 \sim 0.1 \text{ GeV}^2 \quad \text{[HERA]}$$
$$x \sim 10^{-3} \quad Q^2 \sim M_W^2 \quad \text{[D0]}$$

Note, $xy = Q^2/2ME_\nu$, $y = (E_\nu - E_\ell)/E_\nu$. For UHE ν:

$$x \sim \frac{M_W^2}{2ME_\nu} \text{ for } UHE\ \nu$$

$$E_\nu = 10^6 \text{ GeV} \Rightarrow x \sim 10^{-2}$$
$$E_\nu = 10^{12} \text{ GeV} \Rightarrow x \sim 10^{-8}$$

- theoretical justification of $xq(x, Q = M_W) \sim x^{-\lambda},\ \lambda \simeq 0.3$ for $x \ll 1$ [Ellis, Kunszt & Levin]

see Gandhi et al. (1998) for discussion

Modern $xg(x,Q) \sim x^{-\lambda}$, $\lambda \sim 0.3 - 0.4$ and extrapolations by power law agree well with DGLAP solutions

- Glück, Kretzer and Reya [1999] using Glück, Reya and Vogt pdf [1998]
- Kwiecinski, Martin and Stasto use BFKL-type evolution at small-x yielding substantial agreement [1999]

$g \to q\bar{q}$ responsible for sea quark distributions

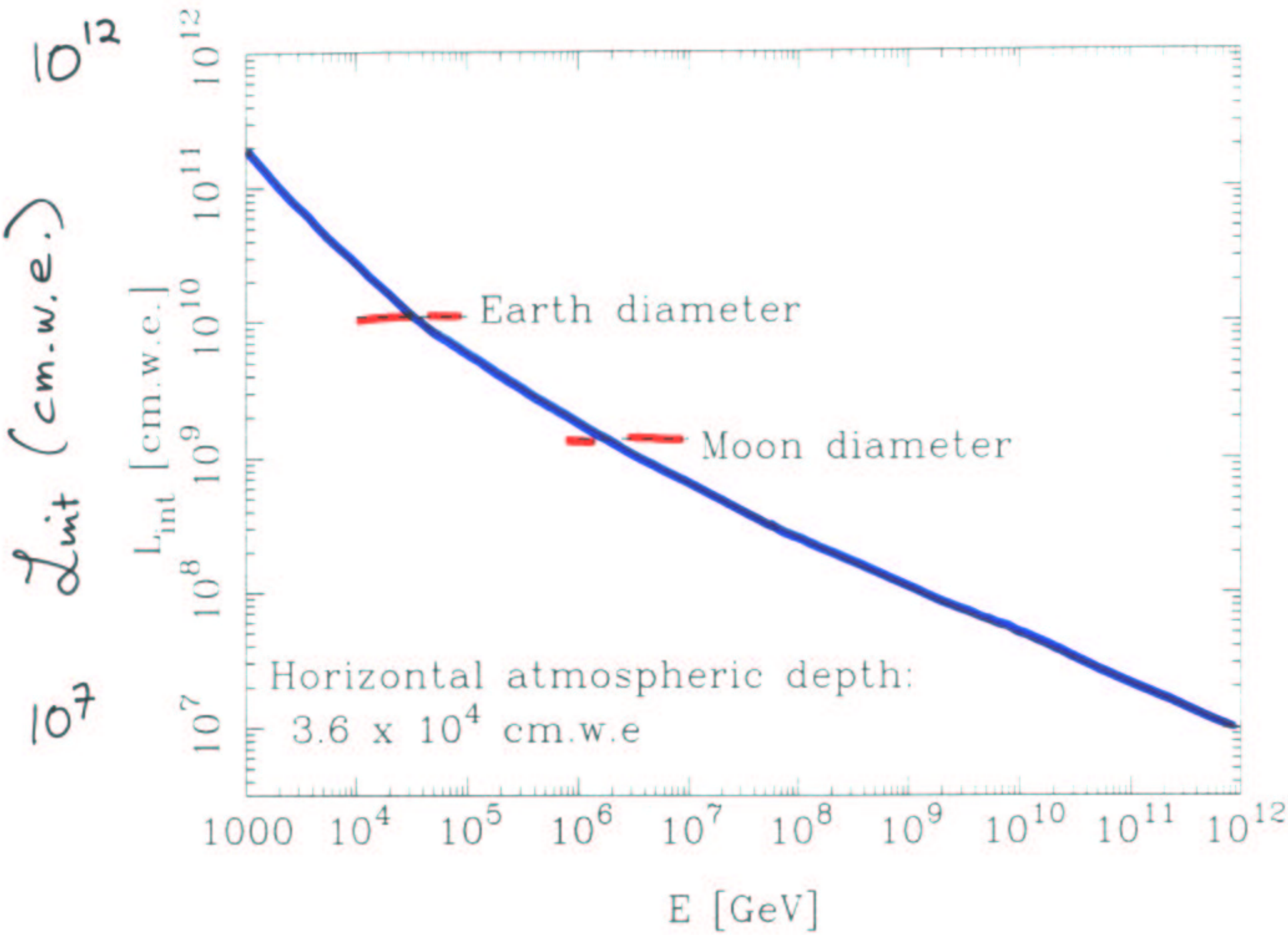
Unitarity constraints are not violated by UHE νN cross section. See Reno, Sarcevic, Sterman, Stratmann & Vogelsang [hep-ph/0110235] response to Dicus, Kretzer, Repko & Schmidt [2001].

Gluon recombination $gg \to g$ negligible. Saturation scale [Golec-Biernat & Wüsthoff, 1999; Levin 2001]

$$Q_s^2 = 1\ \mathrm{GeV}^2 \cdot \left[\frac{3 \times 10^{-4}}{x}\right]^\lambda$$

For UHE $\sigma(\nu N)$, very little contribution from saturation region.

Interaction Length

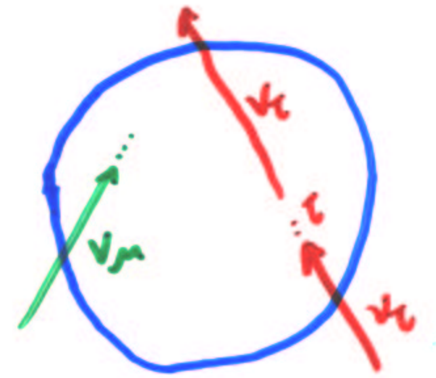


$$\mathcal{L}_{int} = \frac{1}{N_A \sigma_{\nu N}}$$

$\underline{E_\nu \lesssim 10^6 \text{ GeV}}$

- upward flux $\rightarrow$ attenuation in the Earth is important.
- new physics: $\nu_\mu \leftrightarrow \nu_\tau$,
  - attenuation for ν_μ different than for ν_τ since $\nu_\tau \rightarrow \tau \rightarrow \nu_\tau$ [Halzen & Saltzberg]
  - search for $\nu_\tau \rightarrow \tau$ via ν_τ pileup
    $\hookrightarrow$ $\nu_\tau \rightarrow \tau \rightarrow$EM/hadronic showers, $\nu_i \rightarrow \nu_i$ NC events compared with $\nu_\mu \rightarrow \mu$ and $\nu_\tau \rightarrow \tau \rightarrow \mu$[DRS]
    $\hookrightarrow$ enhancement of secondary ν_μ from $\nu_\tau \rightarrow \tau \rightarrow \nu_\mu$ [Beacom Crotty Kolb, DRS]
- some possibility of new physics, e.g. black holes in models with large extra dimensions [Alvarez-Muñiz et al.].

Transport Equations



$$\frac{\partial F_{\nu_\tau}(E,X)}{\partial X} = -\frac{F_{\nu_\tau}(E,X)}{\mathcal{L}_\nu^{int}(E)}$$

$$+ \int_E^\infty dE_y \, [G^{\nu_\tau \to \nu_\tau}(E, E_y, X) + G^{\tau \to \nu_\tau}(E, E_y, X)$$

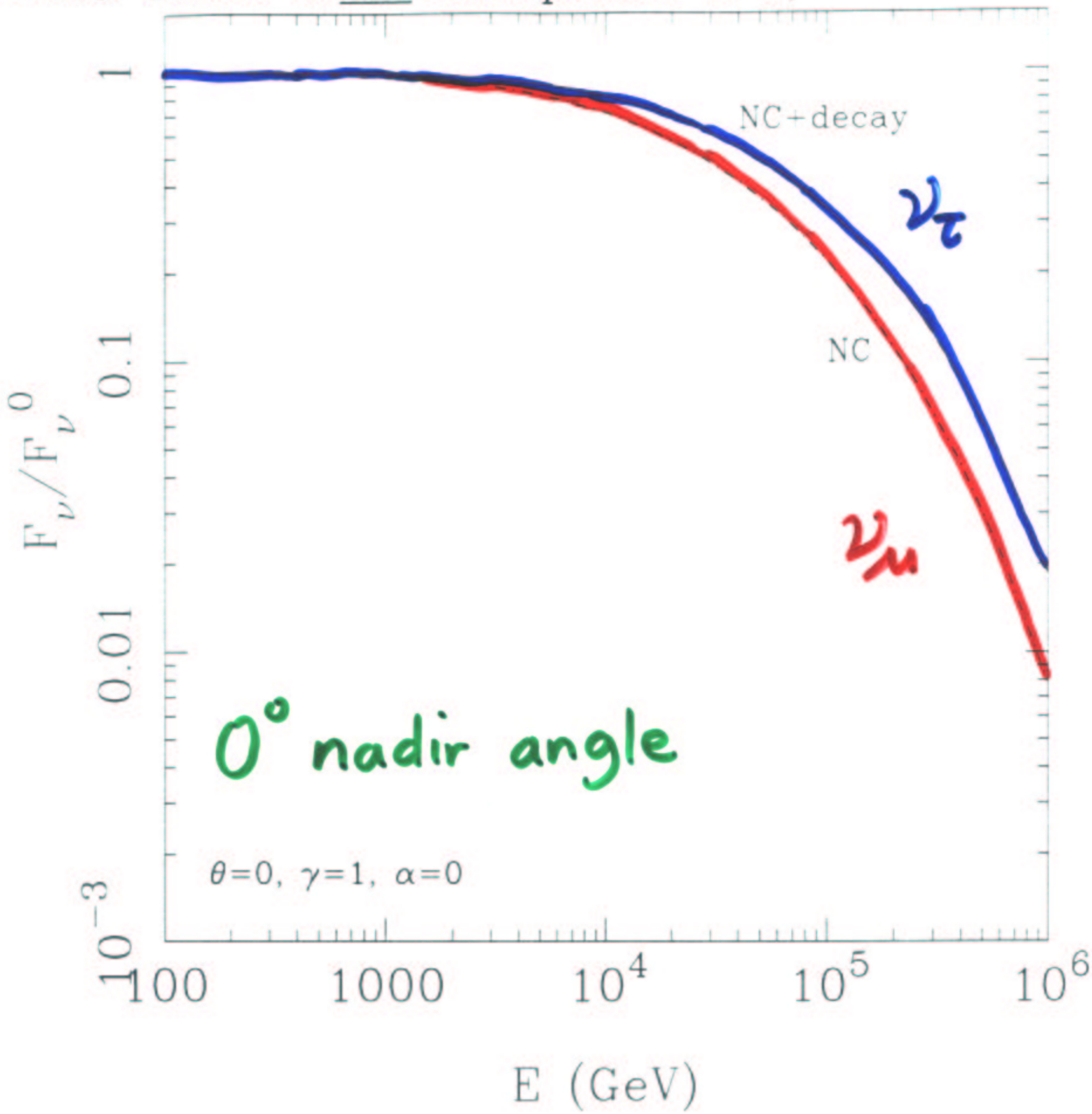
$$\frac{\partial F_\tau(E,X)}{\partial X} \simeq -\frac{F_\tau(E,X)}{\mathcal{L}_\tau^{dec}}$$

$$+ \int_E^\infty dE_y \, G^{\nu_\tau \to \tau}(E, E_y, X)$$

$$G^{\nu_\tau \to \nu_\tau}(E, E_y, X) = \left[\frac{F_\nu(E_y, X)}{\mathcal{L}_\nu^{int}}\right] \frac{dn^{NC}}{dE}(E_y, E) \; .$$

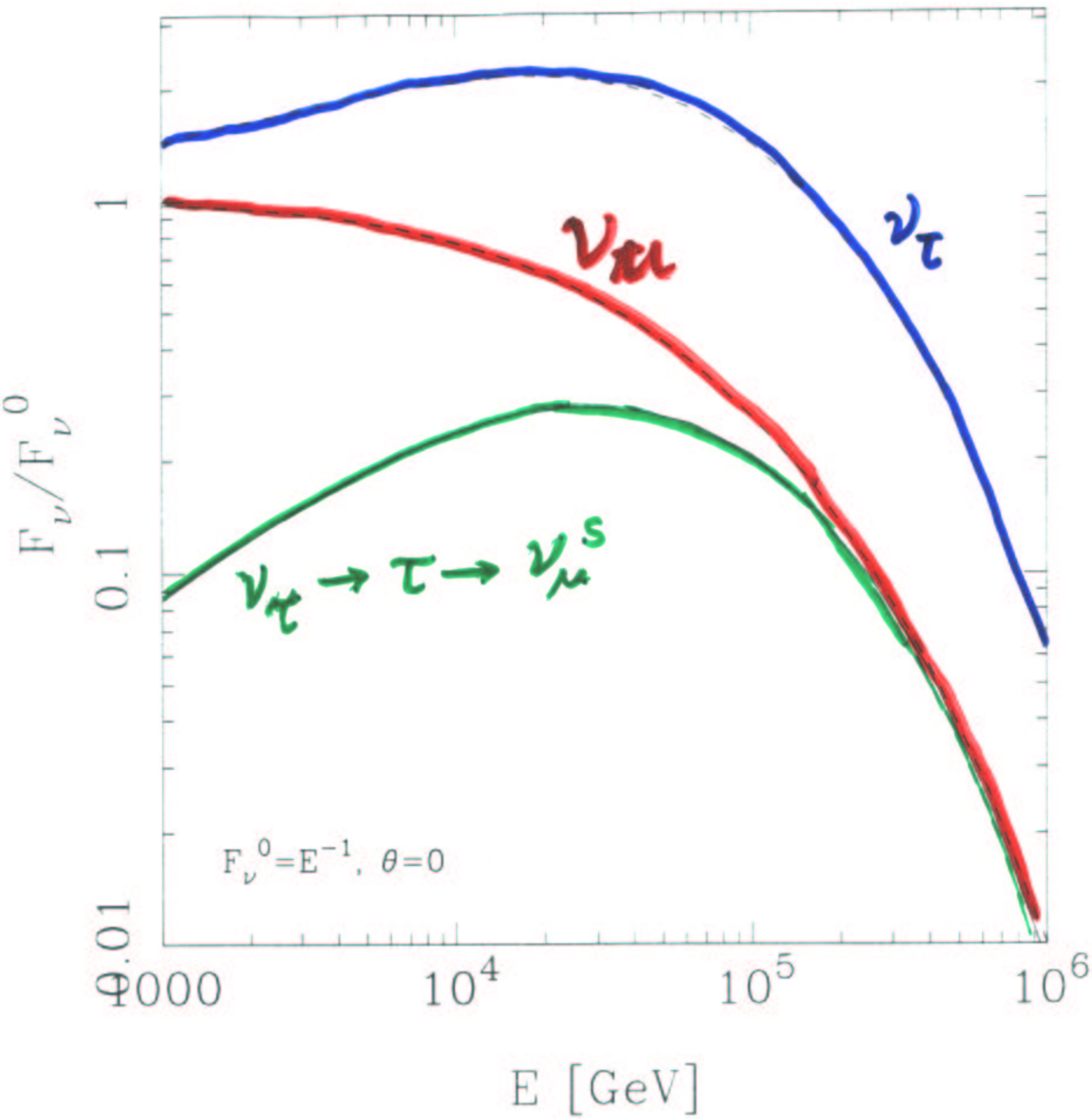
—— only these terms for ν_μ

Note: Earth is <u>not</u> transparent to ν_τ



$F_\nu^0 = E_\nu^{-2}$

[DRS, Becattini & Bottai]



$F_\nu^0 = E_\nu^{-1}$, nadir angle 0, most enhancement of the secondary flux of ν_μ (solid line)

Conclusions

- detection of $\nu_\tau \to \tau$ may enhance signals of neutrinos, diagnostics include shower to muon ratios.
- at highest energies, assuming cosmogenic flux, can test and limit nonstandard contributions to the cross section, e.g., black hole production and decay.
- broader range of tests of nonstandard model physics (supersymmetry, heavy X decay, etc.) which contribute to the neutrino flux.

$$R = \frac{N(\nu N \to \text{EM shr/ hadrons})}{N(\nu N \to \mu X)}$$

→ NC
$\nu_e N \to e X$
$\nu_\tau N \to \tau X$
↳ had.

→ $\nu_\mu N \to \mu X$
$\nu_\tau N \to \tau X$
↳ $\mu \nu_\mu \nu_\tau$

Integrated over angle

E^{-2} $R(E_{shr,\mu} > 10\ \text{TeV}) \simeq$
- 1.1 $\nu_\mu \leftrightarrow \nu_\tau$
- 0.4 SM

E^{-1} $R(E_{shr,\mu} > 10\ \text{TeV}) \simeq$
- 0.7 $\nu_\mu \leftrightarrow \nu_\tau$
- 0.25 SM

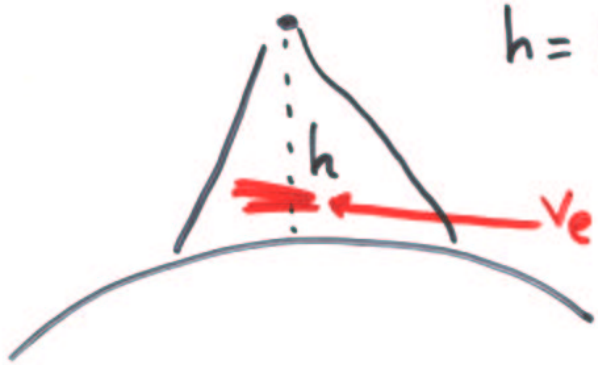
[DRS]

Horizontal Air Showers

- $L_{int} \gg$column depth of atmosphere so neutrinos can penetrate deep into the atmosphere
- The AGASA, Fly's Eye lack of observed enhancement of horizontal air shower events limits a combination of $\sigma(\nu N)$ and the neutrino flux.
- Using cosmogenic neutrino flux – from the scattering of protons off of the 3K microwave background, producing pions which decay to $\mu + \nu_\mu$, it is possible to set limits on non-standard contributions to the cross section.
- Popular extension of the standard model: black hole production in models with large extra dimensions.
- OWL has the possibility of detecting cosmogenic flux with black hole production.

Orbiting Wide-Angle Light-Collectors (OWL)

Extreme Universe Space Observatory (EUSO)



h = 640 km OWL

(380 km EUSO)

M_D is Planck mass

M_{BH} is black hole mass

4+n dimensions

r_S is a Schwarzschild radius

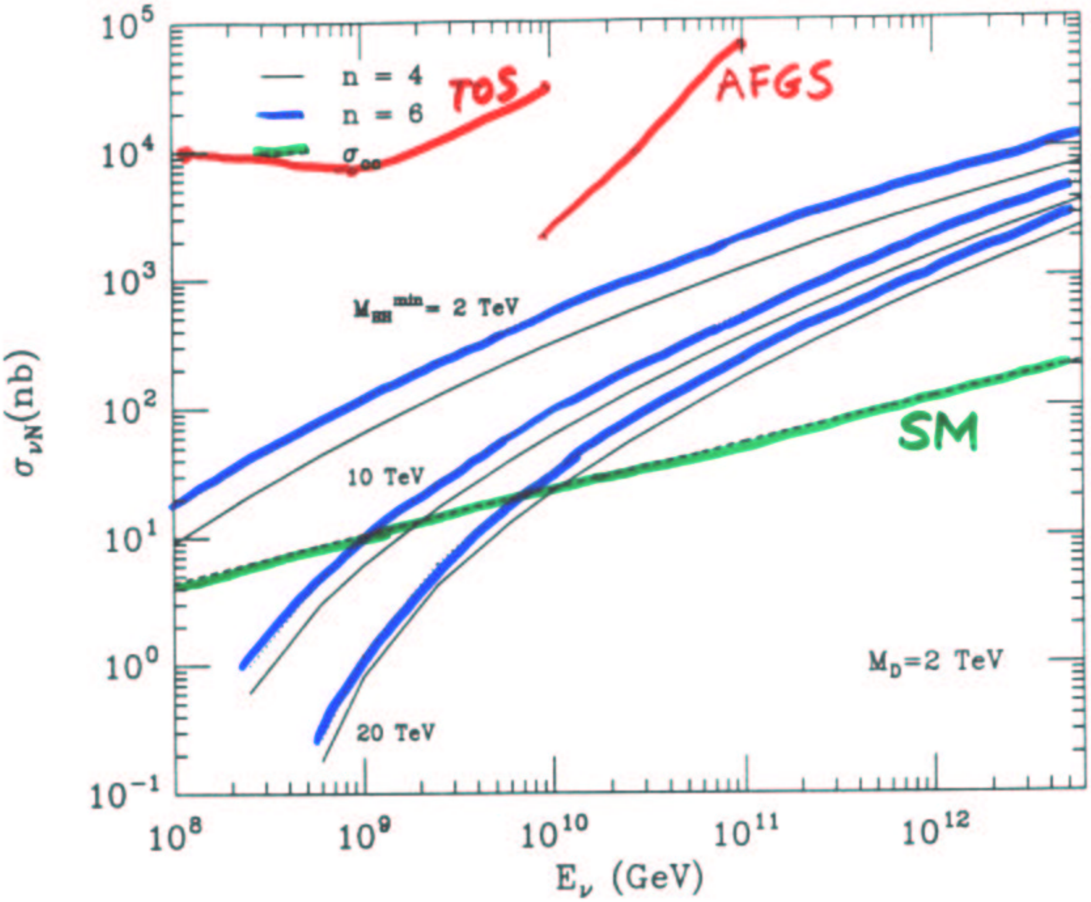
$$r_S = \frac{1}{M_D}\left[\frac{M_{\rm BH}}{M_D}\left(\frac{2^n \pi^{\frac{n-3}{2}}\,\Gamma\left(\frac{3+n}{2}\right)}{2+n}\right)\right]^{\frac{1}{1+n}}$$

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

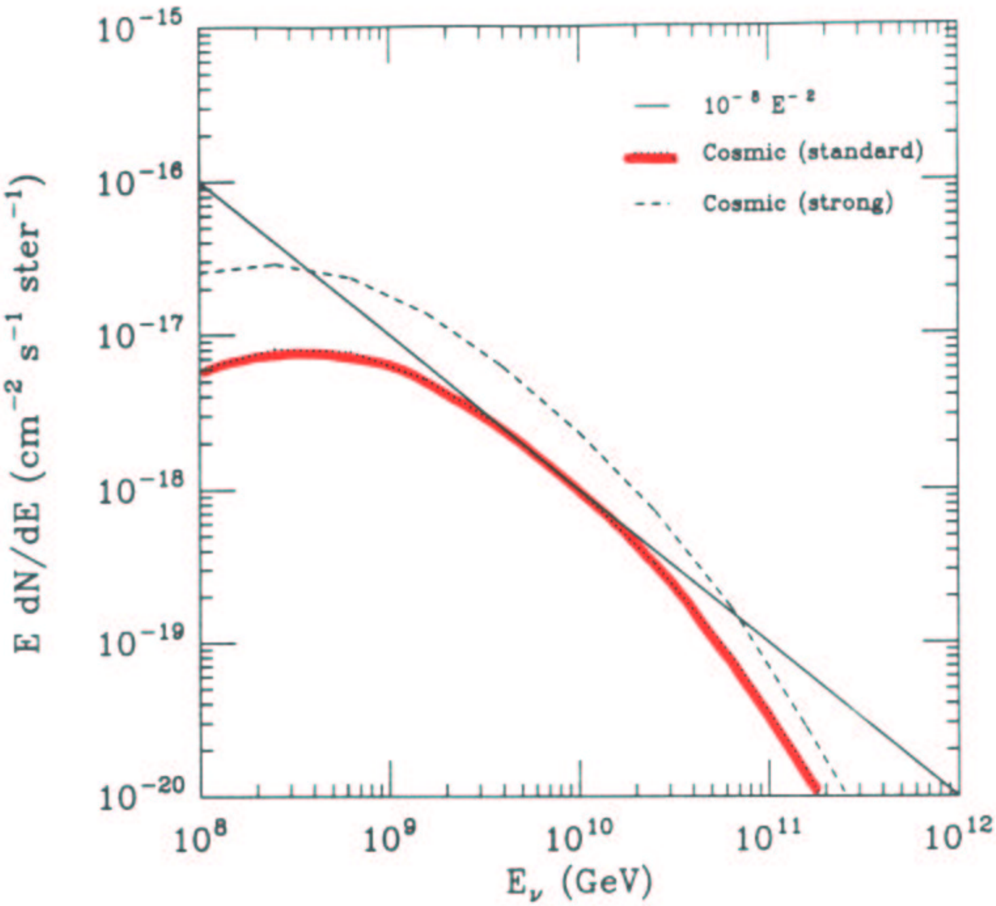
$$\sigma(\nu N \to {\rm BH}) = \sum_i \int_{\frac{(M_{BH}^{\rm min})^2}{s}}^{1} dx\; \hat{\sigma}_i^{BH}(xs)\; f_i(x, Q^2)$$

Assume that all of the energy of the black hole goes into the shower it produces.

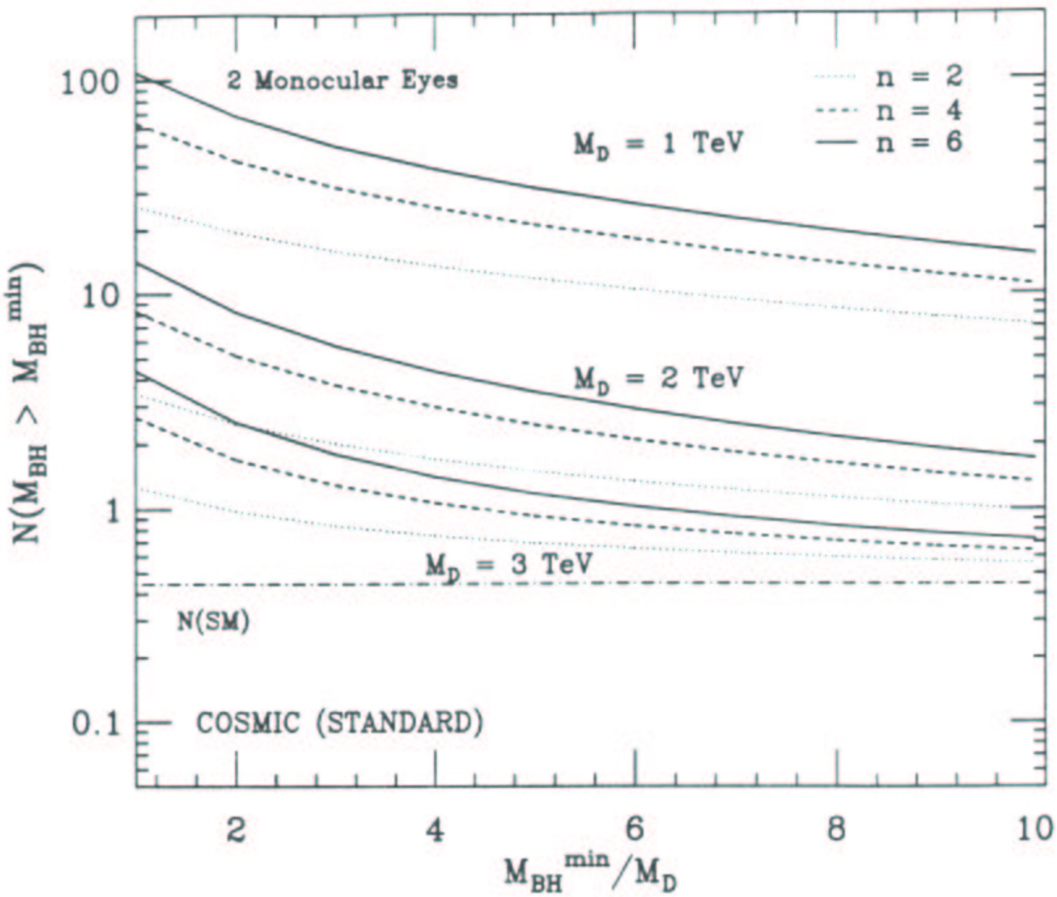
e.g., Feng & Shapere



$M_D = 2$ TeV. Also curves of Tyler, Olinto and Sigl [TOS] and Anchordoqui, Feng, Goldberg and Shapere [AFGS] (all energy into shower)



Cosmogenic electron $\nu + \bar{\nu}$ flux of Engel, Seckel and Stanev.



OWL event rates (2 monocular eyes), $E_\nu > 10^{10}$ GeV, for ESS cosmogenic flux (per year)

multiply by 3 for ν_e, ν_μ, ν_τ

EUSO: multiply by 1/5

[DRS]