



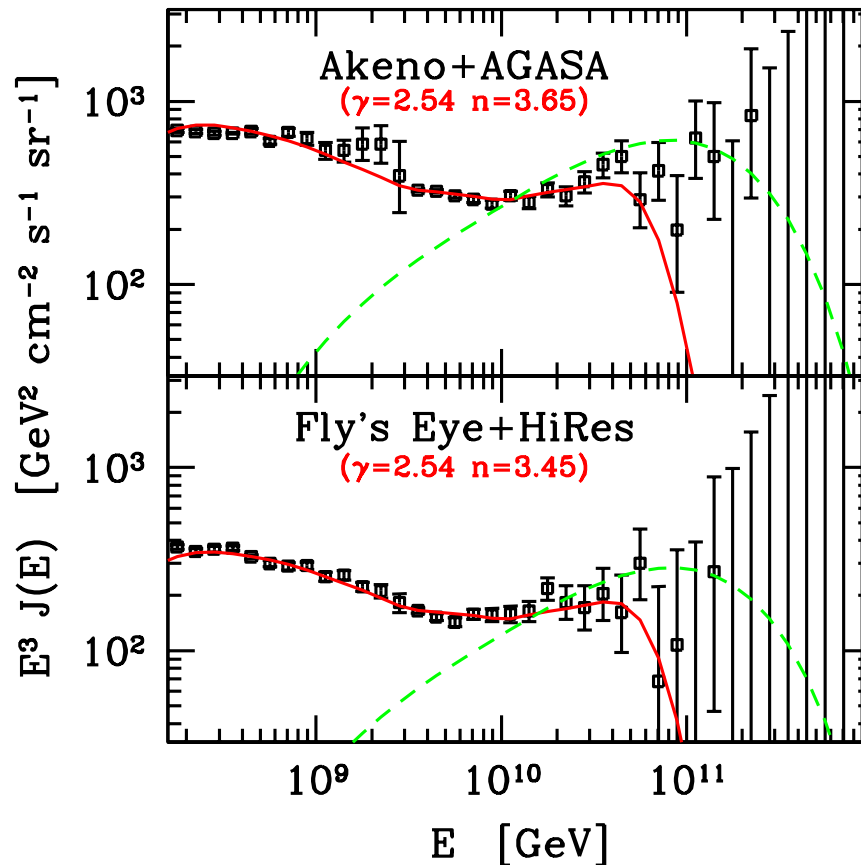
Strongly-Interacting Neutrinos as Post-GZK Events?

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Motivation



- ⑥ CR spectrum by AGASA and HiRes
- ⑥ Neutrino interactions at ultrahigh energies
- ⑥ Pierre Auger Observatory

Strongly-interacting cosmogenic neutrinos as post-GZK events at AGASA?

- ⑥ UHECR proton and cosmogenic neutrino fluxes
- ⑥ Neutrino-nucleon interactions at ultrahigh energies
- ⑥ Investigation of “strongly-interacting neutrino” scenario
- ⑥ Constraints from non-observation of neutrino-induced events
- ⑥ Prospects for Pierre Auger Observatory
- ⑥ Summary

UHECR Proton and Cosmogenic Neutrino Fluxes (I)

Assumptions:

- ⑥ Primaries all protons
- ⑥ Extra-galactic sources, isotropically distributed

Source emissivity:

$$\mathcal{L}_p(r, E_i) = \rho_0 (1 + z)^n \Theta(z - z_{\min}) \Theta(z_{\max} - z) J_p, \text{ with}$$

Injection Spectrum:

$$J_p(E_i) = J_0 E_i^{-\gamma} \Theta(E_{\max} - E_i), \text{ and}$$

$$E_{\max} = 3 \times 10^{21} \text{ eV}, z_{\min} = 0.012, z_{\max} = 2$$

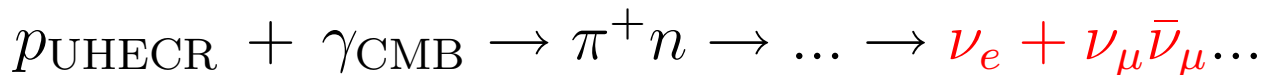
UHECR Proton and Cosmogenic Neutrino Fluxes (II): (α, n)

Propagation:

- ⑥ e^+e^- pair production
- ⑥ Photo-pion production with CMB photons
- ⑥ Energy red-shift

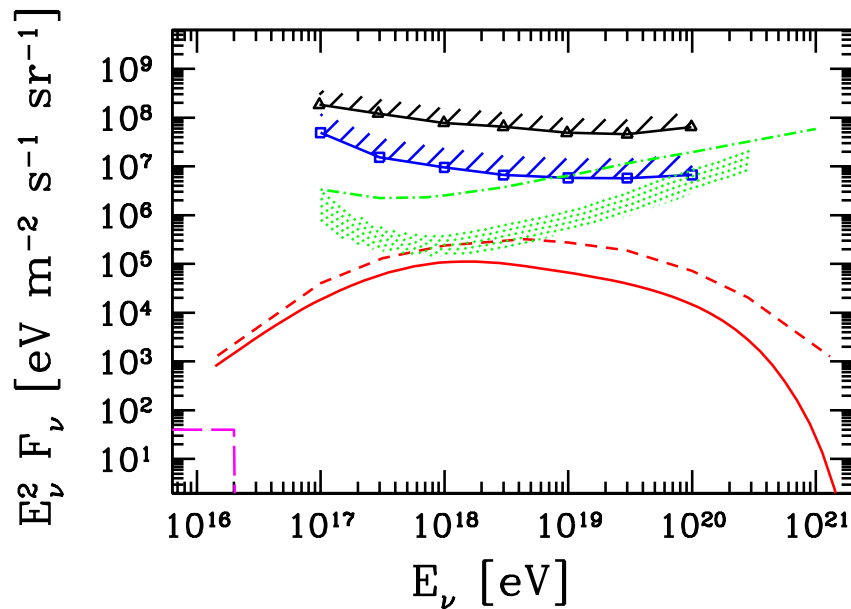
$$F_p(E) = \frac{1}{4\pi} \int dE' \int dr \left(-\frac{\partial P_{p|p}(E; E', r)}{\partial E} \right) \mathcal{L}_p(r, E')$$

“Cosmogenic” neutrinos:



$$P_{\nu|p}(E; E', r) \Rightarrow F_\nu(E)$$

Predictions of Cosmogenic Neutrino Fluxes vs. Experimental Upper Limits



- Cosmogenic ν fluxes (p)
(solid: FKRT; dashed: PJ)
- Cosmogenic neutrino flux (Fe)
- Fly's Eye + AGASA, and RICE
- Auger sensitivity (all and ν_τ)

$$N_\nu \propto t \int_{E_{th}} dE V(E) F_\nu(E) \sigma_{\nu N}(E) \cdot \text{atten.}(\sigma_{\nu N}^{inel}(E), X(\theta))$$

Spectrum Analysis (I): Neutrino Contribution to CR Spectrum

Assume

$$N_n^{\text{CR}} = \int_{E_n - \Delta E_n/2}^{E_n + \Delta E_n/2} dE \mathcal{E}(E) (F_p(E) + \mathcal{R}(\sigma_{\nu N}(E)) F_\nu(E))$$

with

$$\mathcal{R}(\sigma_{\nu N}(E)) = 1 - e^{-\frac{\sigma_{\nu N}(E) X(\theta)}{m_p}}$$

for

$0^\circ \leq \theta \leq 45^\circ$ (AGASA) and $0^\circ \leq \theta \leq 60^\circ$ (HiRes).

Also: $E_{\text{sh}} = E_\nu$

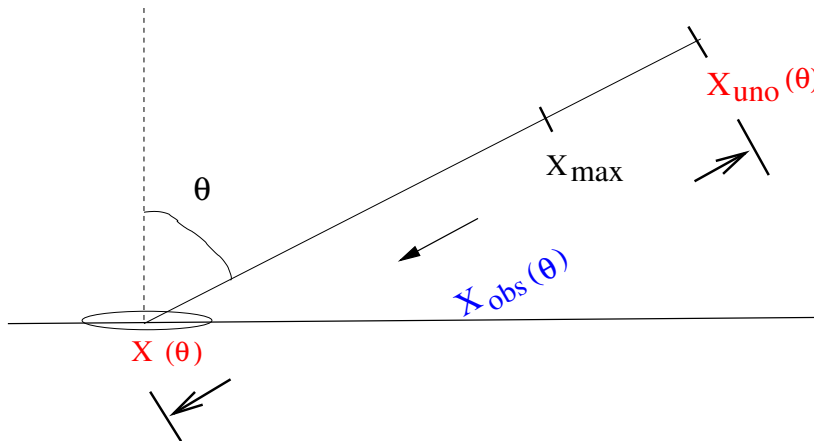
$$\Rightarrow \underbrace{(\gamma, n)}_{F(E)}, \underbrace{(a, b, \dots)}_{\sigma_{\nu N}(E)} \quad \text{Fit in } 10^{17.6} \text{ eV} \leq E \leq 10^{21} \text{ eV}$$

Spectrum Analysis (II): Constraints

(1)

Constraints: non-observation of

- quasi-horizontal ($\theta \geq 60^\circ$) air showers at AGASA
- contained events in RICE



- $N < 3.5$ (95%)

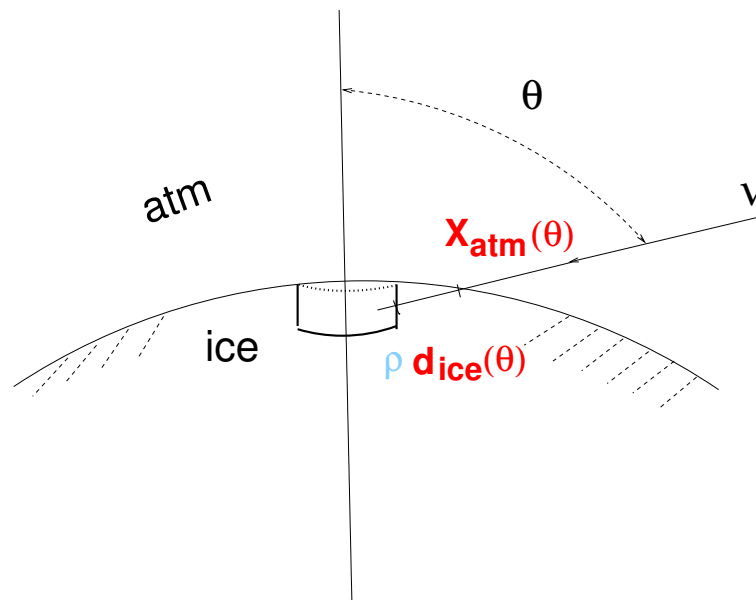
- $X_{\text{uno}}(\theta) = X(\theta) - 1300 \text{ g/cm}^2$

- $X_{\text{uno}}(\theta) \leq 1700 \text{ g/cm}^2$

Flux reduction

$$\equiv \int d \cos \theta 2\pi \cos \theta e^{-\frac{X_{\text{uno}}(\theta) \sigma_{\nu N}(E)}{m_p}} \left(1 - e^{-\frac{X_{\text{obs}}(\theta) \sigma_{\nu N}(E)}{m_p}} \right)$$

Constraints (2): from RICE



- ⑥ $N < 3.09$ (95%)
- ⑥ $0^\circ \leq \theta \leq 90^\circ$
- ⑥ $V_{\text{eff}}(E) \approx \pi r^2(E) z(E),$
 $z = 1 \text{ km}$

$$N = \frac{t \rho_{\text{ice}}}{m_p} \int dE d\Omega F(E) \sigma_{\nu N}(E) V_{\text{eff}}(E) e^{-\frac{\sigma_{\nu N}(E) x(\theta)}{m_p}}$$

Neutrino Interactions at Ultrahigh Energies

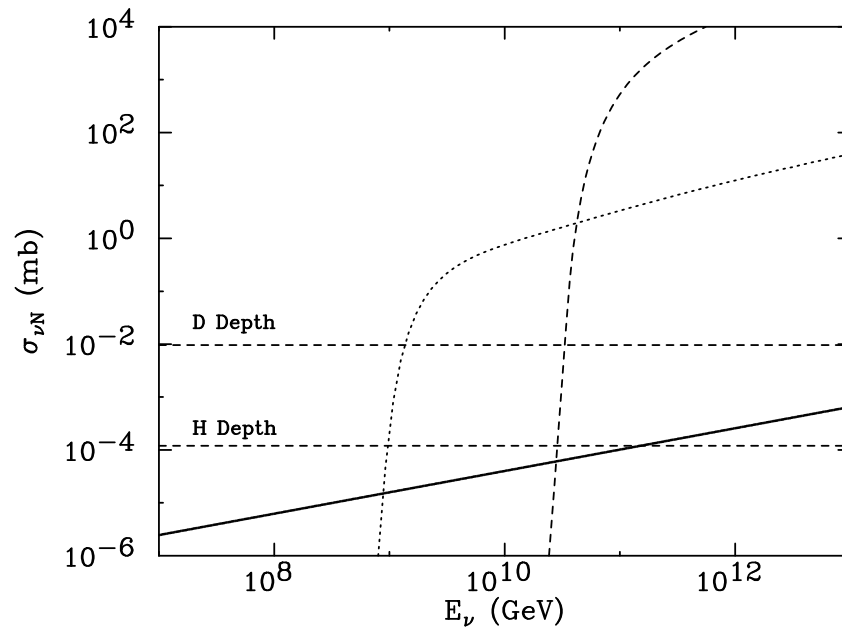
Standard Model

- ⑥ Charged-current and neutral-current interactions (parton densities extrapolated to low Bjorken x and large Q^2)
- ⑥ Electroweak instanton-induced processes*

Beyond

- ⑥ Extra dimensions: graviton KK-states
- ⑥ Production of microscopic black holes, p -branes etc.
- ⑥ Lepto-quark ...

Neutrino Interactions at Ultrahigh Energies* : EW Instanton



[Han, Hooper '04]

- Lower: [Ringwald '03]

- Higher: [Bezrukov et al. '03]

with Ringwald's pre-exponential factor from [hep-ph/0307034]

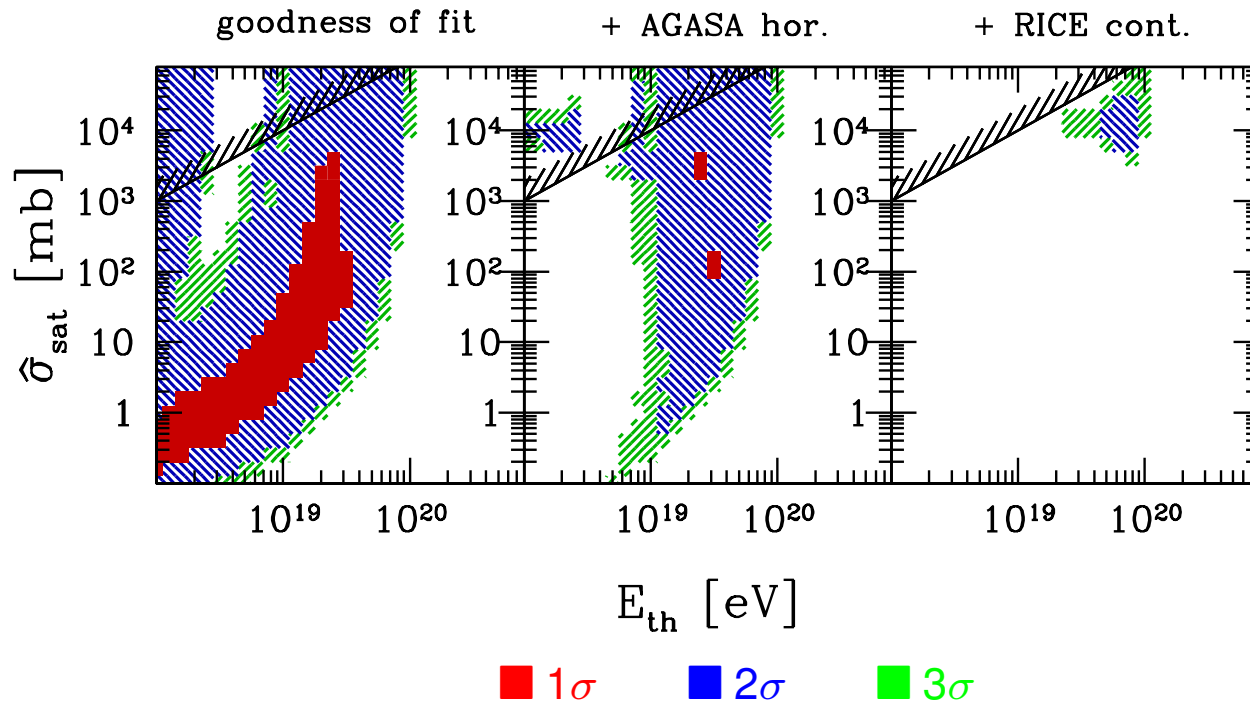
Strongly-Interacting Neutrino Scenario: Ansätze for $\sigma_{\nu N}(E)$

$$\sigma_{\nu N} = \sigma_{\text{sat}} \Theta(s - 2m_p E_{\text{th}})$$

$$\hat{\sigma}_{ij} = \hat{\sigma}_{\text{sat}} \Theta(\hat{s} - 2m_p E_{\text{th}}) \quad \Rightarrow \quad \sigma_{\nu N} = \sum_i \int dx f_i(x, \mu) \hat{\sigma}_{ij}$$

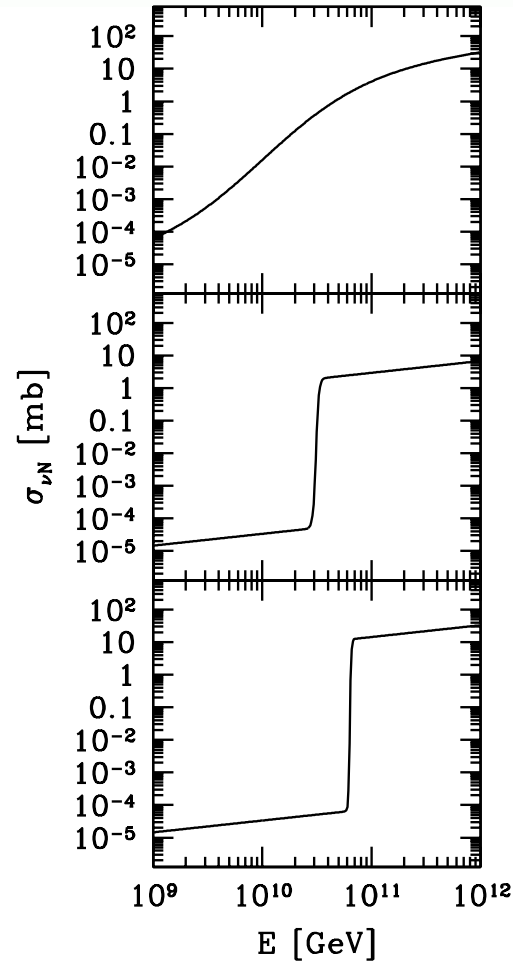
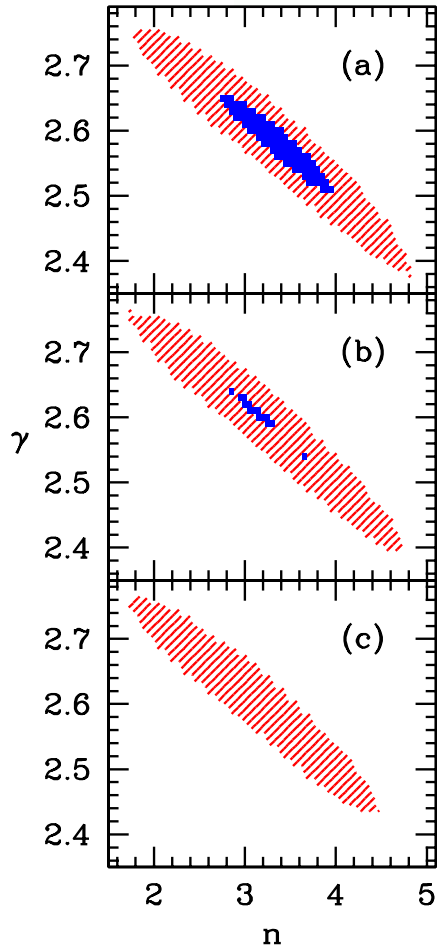
$$\log_{10} \left(\frac{\sigma_{\nu N}}{\sigma^{\text{SM}}} \right) = \frac{\alpha}{2} \left[1 + \tanh \left(\frac{\ln(E_\nu / E_{\text{th}})}{\ln(\Delta E / E_{\text{th}})} \right) \right]$$

Constraints from AGASA and RICE searches (II)



Constraints from AGASA and RICE

(III)



Prospects for Pierre Auger Observatory

- ⑥ UHECR spectrum
- ⑥ Neutrino detection:

SM neutrino event rates	FKRT flux	PJ flux
$\nu_e + \nu_\mu + \nu_\tau$	0.09	0.25
ν_τ	0.19 - 0.54	0.56 - 1.59

- ⑥ Comparison of quasi-horizontal shower rate with Earth-skimming ν_τ rate

Summary

- ⑥ Investigate scenario strongly-interacting cosmogenic neutrinos as post-GZK events
- ⑥ Flux estimation with (γ, n) , and step-function ansätze for neutrino-nucleon total inelastic cross section
- ⑥ Radio-Cherenkov neutrino detector RICE put stringent constraints
- ⑥ Pierre Auger Observatory: quasi-horizontal air showers and Earth-skimming neutrinos