Strongly-Interacting Neutrinos as Post-GZK Events?

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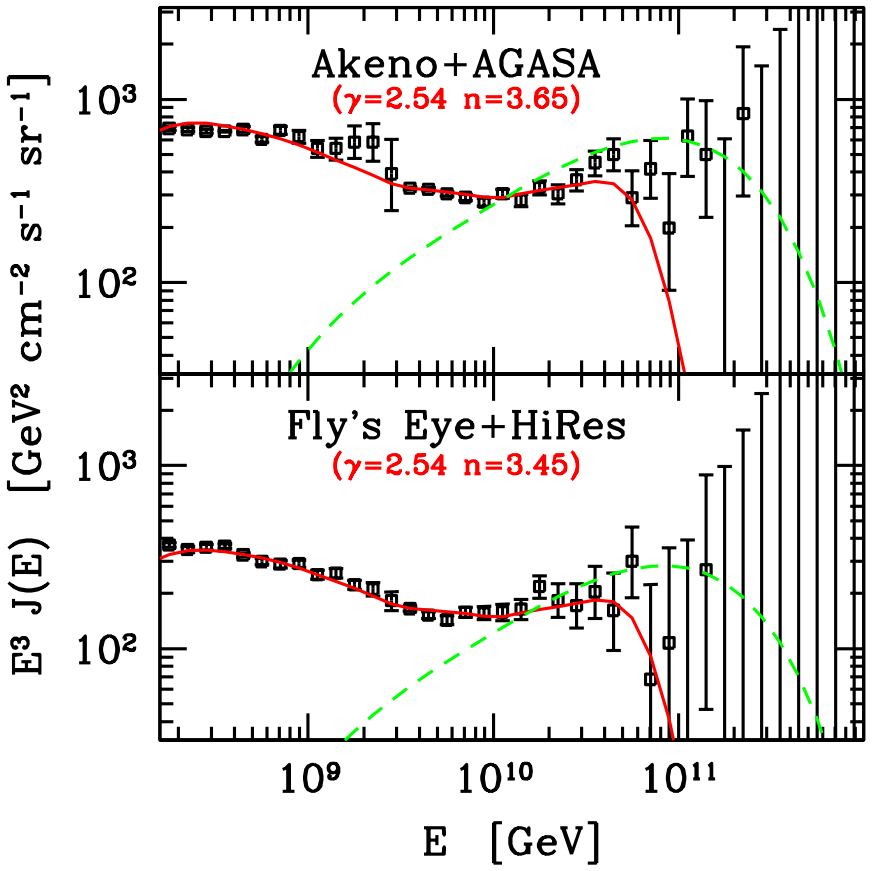
Motivation



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

Outline

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

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

UHECR Proton and Cosmogenic Neutrino Fluxes (I)

Assumptions:

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

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

Injection Spetrum:
$J_p(E_i) = J_0 \, E_i^{-\gamma} \, \Theta(E_{\rm max} - E_i)$, and

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

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

Propagation:

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

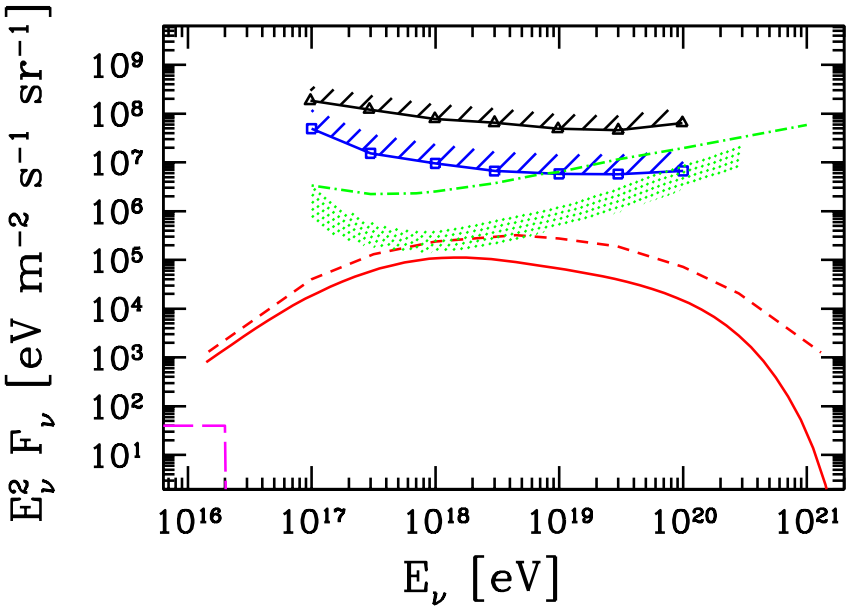
$$F_p(E) = \frac{1}{4\pi} \int dE' \int dr \left(-\frac{\partial P_{p|p}(E;E',r)}{\partial E} \right) \mathcal{L}_p(r, E')$$

"Cosmogenic" neutrinos:

$$p_{\rm UHECR} + \gamma_{\rm CMB} \rightarrow \pi^+ n \rightarrow ... \rightarrow \nu_e + \nu_\mu \bar{\nu}_\mu ...$$

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

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)

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

Spectrum Analysis (I): Neutrino Contribution to CR Spectrum

Assume

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

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: $E_{\rm sh} = E_\nu$

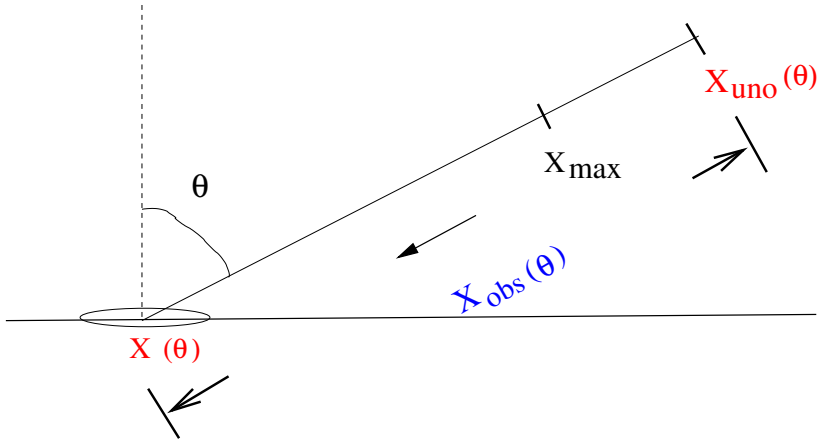
$$\Rightarrow (\underbrace{\gamma, n}_{F(E)}, \underbrace{a, b, ...}_{\sigma_{\nu N}(E)})$$

Fit in $10^{17.6}$ eV $\leq E \leq 10^{21}$ eV

Spectrum Analysis (II): Constraints (1)

Constraints: non-observation of

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

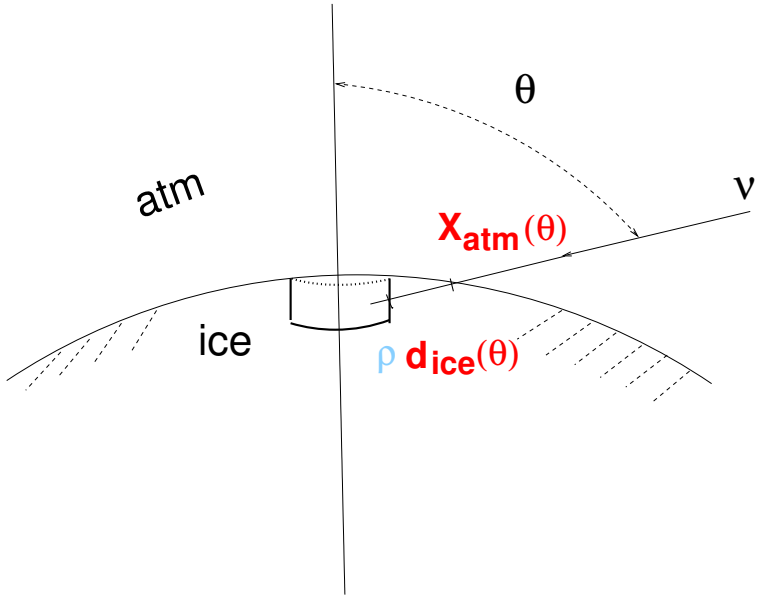


- $N < 3.5\ (95\%)$
- $X_{\rm uno}(\theta) = X(\theta) - 1300\ {\rm g/cm^2}$
- $X_{\rm uno}(\theta) \leq 1700\ {\rm g/cm^2}$

Flux reduction

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

Constraints (2): from RICE



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

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

Neutrino Interactions at Ultrahigh Energies

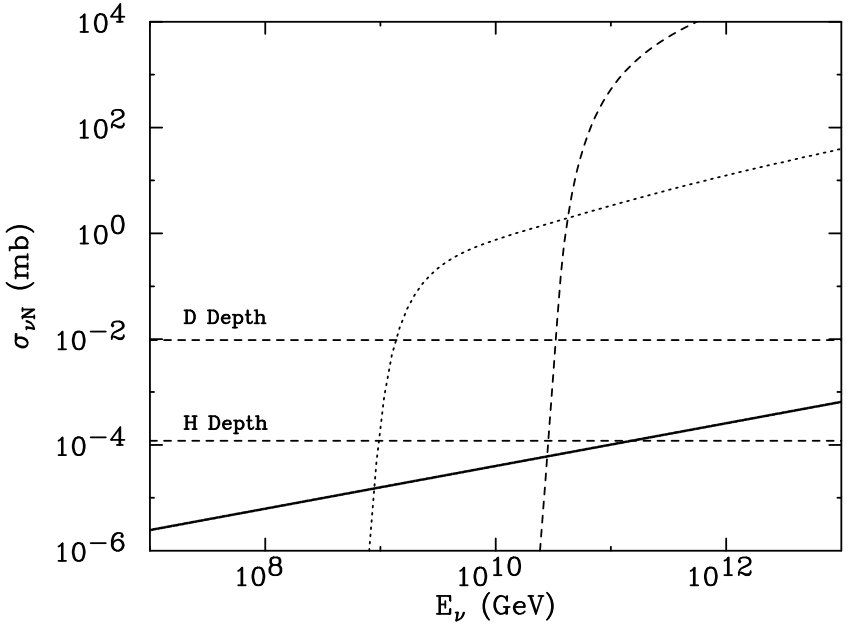
Standard Model

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

Beyond

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

Neutrino Interactions at Ultrahigh Enegies* : EW Instanton



[Han, Hooper '04]

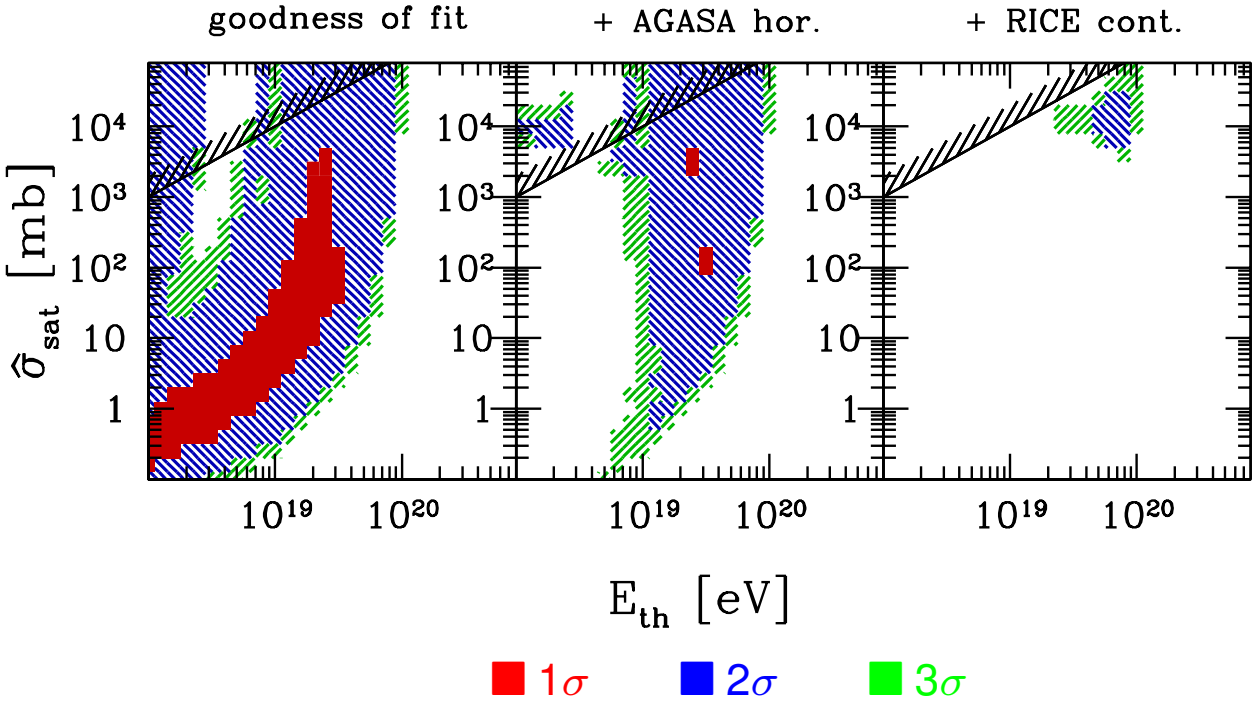
- Lower: [Ringwald '03]

- Higher: [Bezrukov et al. '03]
with Ringwald's pre-exponential factor from [hep-ph/0307034]

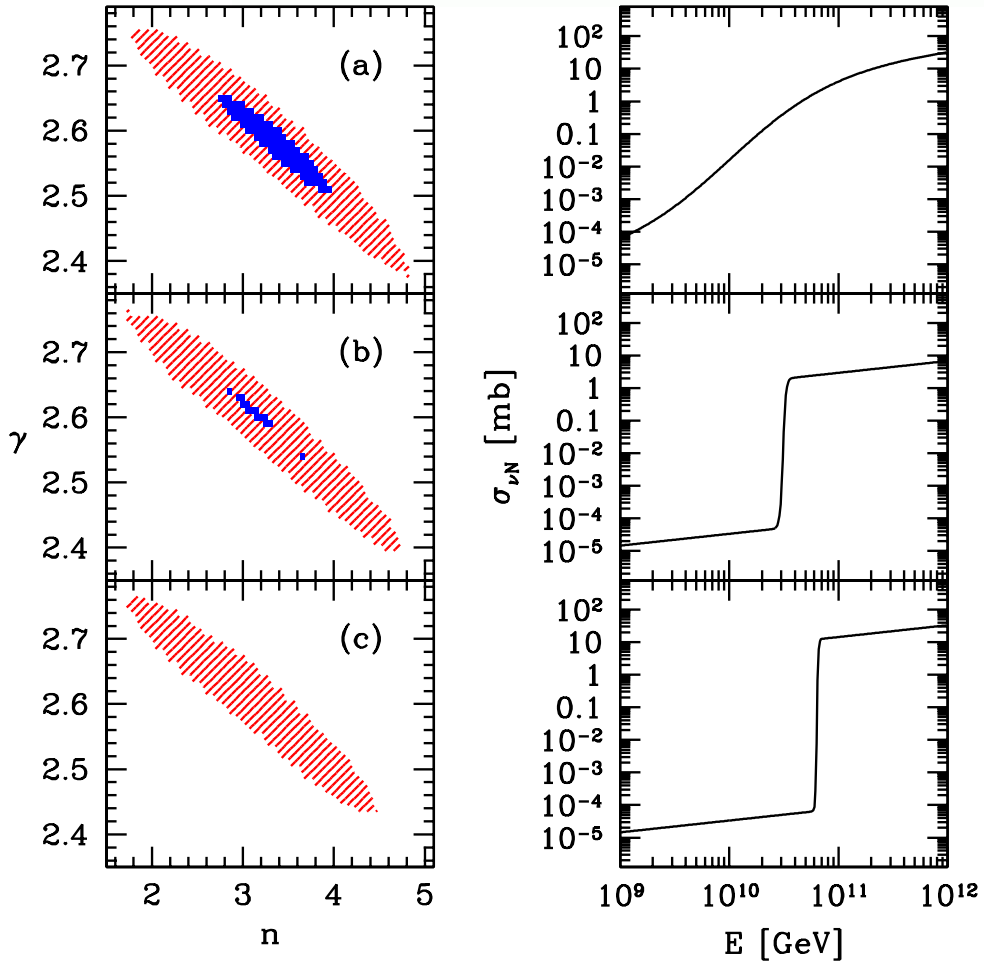
Strongly-Interacting Neutrino Scenario: Ansätze for $\sigma_{\nu N}(E)$

- $\sigma_{\nu N} = \sigma_{\rm sat}\,\Theta(s - 2m_p E_{\rm th})$
- $\hat{\sigma}_{ij} = \hat{\sigma}_{\rm sat}\Theta(\hat{s} - 2m_p E_{\rm th}) \qquad \Rightarrow \sigma_{\nu N} = \sum_i \int dx\, f_i(x,\mu)\,\hat{\sigma}_{ij}$
- $\log_{10}\left(\frac{\sigma_{\nu N}}{\sigma^{\rm SM}}\right) = \frac{\alpha}{2}\left[1 + \tanh\left(\frac{\ln(E_\nu/E_{\rm th})}{\ln(\Delta E/E_{\rm th})}\right)\right]$

Constraints from AGASA and RICE searches (II)



Constraints from AGASA and RICE (III)



Prospects for Pierre Auger Observatory

- UHECR spectrum
- 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

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

Summary

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