Ultra High Energy Neutrinos: Absorption, Thermal Effects and Signatures

Eray Sabancilar
Physics Department, Arizona State University,
Tempe AZ.

Brookhaven Forum 2013
Exploring Fundamental Interactions in the Higgs Era
BNL, Upton, NY
May 2nd, 2013.

With Cecilia Lunardini & Lili Yang @ ASU, [arxiv:1305.????].

Ultra High Energy Neutrinos

• Ultra high energy (UHE) νs with $E \gtrsim 10^{11}$ GeV provide unique opportunity to test **the fundamental interactions** at these energies.

Ultra High Energy Neutrinos

- Ultra high energy (UHE) νs with $E \gtrsim 10^{11}$ GeV provide unique opportunity to test **the fundamental interactions** at these energies.

- For such high energies, **only νs** can make it to the Earth.
  (charged leptons, nucleons and nuclei are efficiently absorbed.)

Ultra High Energy Neutrinos

- Ultra high energy (UHE) νs with $E \gtrsim 10^{11}$ GeV provide unique opportunity to test **the fundamental interactions** at these energies.

- For such high energies, **only $\boldsymbol{\nu}$s** can make it to the Earth.
 (charged leptons, nucleons and nuclei are efficiently absorbed.)

- Radio Cherenkov techniques making use of the **Askaryan effect** seem to be very successful for detecting UHEνs.

- Radio telescopes look for coherent radio burst signals from νs in matter, such as the Moon Regolith, Antarctic ice, e.g., RICE, ANITA, FORTE, NuMoon.

Ultra High Energy Neutrinos

- Ultra high energy (UHE) νs with $E \gtrsim 10^{11}$ GeV provide unique opportunity to test **the fundamental interactions** at these energies.

- For such high energies, **only νs** can make it to the Earth.
  (charged leptons, nucleons and nuclei are efficiently absorbed.)

- Radio Cherenkov techniques making use of the **Askaryan effect** seem to be very successful for detecting UHEνs.

- Radio telescopes look for coherent radio burst signals from νs in matter, such as the Moon Regolith, Antarctic ice, e.g., RICE, ANITA, FORTE, NuMoon.

- With good energy resolution, we can learn about **ν masses** and **cosmic ν background** (CνB) density.

Ultra High Energy Neutrinos

- Ultra high energy (UHE) νs with $E \gtrsim 10^{11}$ GeV provide unique opportunity to test **the fundamental interactions** at these energies.

- For such high energies, **only $\boldsymbol{\nu}$s** can make it to the Earth.
(charged leptons, nucleons and nuclei are efficiently absorbed.)

- Radio Cherenkov techniques making use of the **Askaryan effect** seem to be very successful for detecting UHEνs.

- Radio telescopes look for coherent radio burst signals from νs in matter, such as the Moon Regolith, Antarctic ice, e.g., RICE, ANITA, FORTE, NuMoon.

- With good energy resolution, we can learn about **$\boldsymbol{\nu}$ masses** and **cosmic $\boldsymbol{\nu}$ background** (CνB) density.

- There is a **caveat**: The unknown origin of UHEν fluxes.

Ultra High Energy Neutrinos

• Ultra high energy (UHE) νs with $E \gtrsim 10^{11}$ GeV provide unique opportunity to test **the fundamental interactions** at these energies.

• For such high energies, **only νs** can make it to the Earth.
(charged leptons, nucleons and nuclei are efficiently absorbed.)

• Radio Cherenkov techniques making use of the **Askaryan effect** seem to be very successful for detecting UHEνs.

• Radio telescopes look for coherent radio burst signals from νs in matter, such as the Moon Regolith, Antarctic ice, e.g., RICE, ANITA, FORTE, NuMoon.

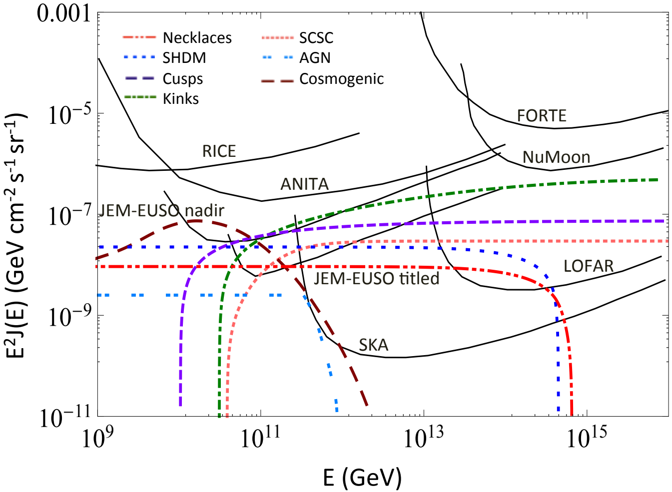
• With good energy resolution, we can learn about **ν masses** and **cosmic ν background** (CνB) density.

• There is a **caveat**: The unknown origin of UHEν fluxes.

• Thus, we should do our best to describe the "*known*" effects:

Propagation of UHEνs in the CνB.

UHE Neutrino Fluxes, Detectability Limits, Upper Bounds



Cosmic Necklaces:**Berezinsky, Martin, Vilenkin '97**; Super Heavy Dark Matter (SHDM):**Berezinsky, Kachelriess, Vilenkin '98; Kuzmin, Rubakov '98**: Cosmic String Cusps:**Berezinksy, ES, Vilenkin '11**; Cosmic String Kinks:**Lunardini, ES '12**; Superconducting Cosmic Strings:**Berezinsky, ES, Olum, Vilenkin '09**; Active Galactic Nuclei:**Kalashev, Kuzmin, Semikoz, Sigl '02**: Cosmogenic Neutrinos:**Berezinsky, Zatsepin '69; Engel, Seckel, Stanev '01**.

$\nu\nu$ Cross Section

Cross sections depend on the Mandelstam variable,

$$s = (q^\mu + p^\mu)^2 \approx 2E(1+z)\left[\sqrt{p^2(1+z)^2 + m_{\nu_j}^2} - p(1+z)\cos\theta\right], \qquad (1)$$

$$q^\mu = E(1+z)[1, \hat{\mathbf{q}}], \qquad \leftarrow \textbf{UHE}\ \boldsymbol{\nu} \qquad (2)$$

$$p^\mu = \left[\sqrt{p^2(1+z)^2 + m_{\nu_j}^2}, \mathbf{p}(1+z)\right]. \qquad \leftarrow \mathbf{C}\boldsymbol{\nu}\mathbf{B}\ \boldsymbol{\nu} \qquad (3)$$

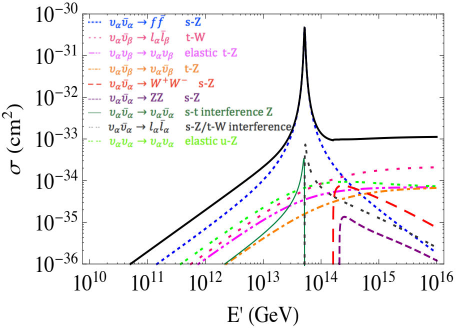


Figure : $m = 0.08$ eV, $p = 0$, no thermal effects taken into account.

Z^0-Resonance:**Weiler '82**; ν*Horizon*:**Berezinsky '92**; Propagation:**Roulet '93; Fargion et al. '99; Eberle et al. '04**; Thermal effects:**Barenboim et al. '05, D'Olivo et al. 06'**.

Cosmic Neutrino Background / Thermal Effects

$$dn_\nu(p,z) = (1+z)^3 \frac{d^3p}{(2\pi)^3} \frac{1}{e^{p/T_0}+1} \ , \tag{4}$$

$$\bar{\sigma}(E;z,m_j) = \frac{\int dn_\nu(p,z)\,\sigma(E,p;m_j,z)}{\int dn_\nu(p,z)} . \tag{5}$$

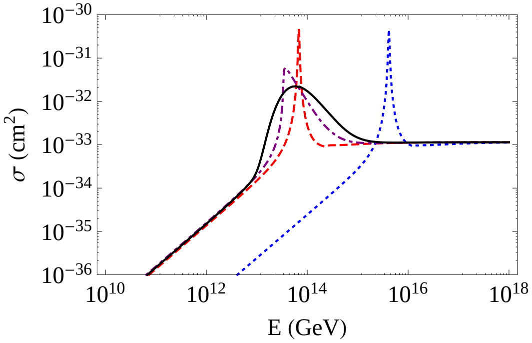


Figure : $m = 10^{-3}$eV, $z = 100$. Blue: CνB at rest, Red: $p = p_{\rm rms}$, Purple: $p = p_{\rm rms}$ averaged over angle, **Black: $\bar{\sigma} \to$ Averaged over all momenta and angle (this work).**

Flavor Averaged Transmission Probability

$$d\Gamma_\alpha(E,z) = \sum_j |U_{\alpha j}|^2 \, d\nu_j(p,z)\, \sigma(E,p;z,m_{\nu_j}), \qquad (6)$$

$$\tau_\alpha(E,z) = \int_0^z \frac{dz'}{(1+z')H(z')} \, \Gamma_\alpha(E,z') \; . \qquad (7)$$

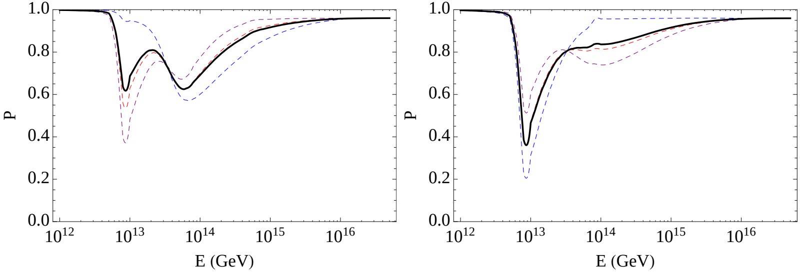


Figure : $m = 10^{-5}$ eV (ligthest), $z = 10$. Blue:P_e, Red:P_μ, Purple:P_τ, **Black:** $P \to$ **average transmission probability**.

$$P_\alpha(E,z) = e^{-\tau_\alpha(E,z)}, \qquad P(E,z) = \frac{1}{3}\sum_\alpha P_\alpha(E,z). \qquad (8)$$

UHE Neutrino Sources

The number of sources, $N_{\rm s}$, per comoving volume, per unit physical time, t:

$$\eta(z) \equiv \frac{1}{r^2}\frac{d^3 N_{\rm s}}{d\Omega dr dt}. \tag{9}$$

The spectrum of a single source

$$\phi(E,z) \equiv \frac{1}{1+z}\frac{dN_\nu}{dE}. \tag{10}$$

The diffuse observed UHE neutrino flux

$$J_\nu(E) = \frac{1}{4\pi}\int_0^\infty \frac{dz}{H(z)}\, P(E,z)\, \eta(z)\, \phi(E,z). \tag{11}$$

Observed UHE Neutrino Fluxes

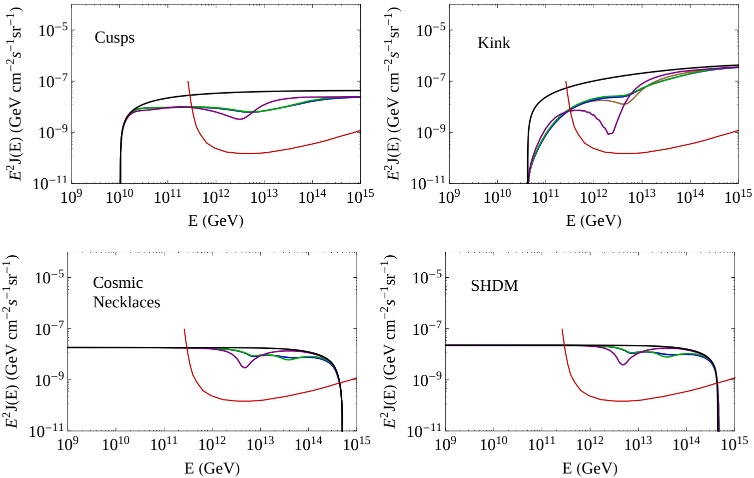


Figure : Normal hierarchy with lightest masses $m = 10^{-5}, 10^{-3}, 0.02, 0.08$ eV. Red curve represents the detectability limit of SKA.

Cosmic String Cusps:**Berezinksy, ES, Vilenkin '11**; Cosmic String Kinks:**Lunardini, ES '12**; Cosmic Necklaces:**Berezinsky, Martin, Vilenkin '97**; Super Heavy Dark Matter (SHDM):**Berezinsky, Kachelriess, Vilenkin '98; Kuzmin, Rubakov '98**.

Conclusions

• For a hierarchical neutrino mass spectrum (with at least one neutrino with mass below $\sim 10^{-2}$ eV), thermal effects are important for ultra high energy sources at $z \gtrsim 10$.

• The neutrino transmission probability shows no more than two separate suppression dips, since the two lightest mass states contribute as a single species when thermal effects are included.

• Resonant suppression effects are strong for sources that extend beyond $z \sim 10$, which can be realized for certain top down scenarios like superheavy dark matter decays, cosmic strings and cosmic necklaces.

• For these, a broad suppression valley should affect the neutrino spectrum at least in the energy interval $10^{12} - 10^{13}$ GeV.

• Observation of absorption effects would indicate:
UHEν sources beyond $z \sim 10 \rightarrow$ top-down mechanisms.
Direct evidence for the existence of CνB.
Density/distribution of CνB.

Stay tuned for UHEν broadcasts from the Moon/Antarctica.