Hunting for Ultra High Energy Neutrinos

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Los Alamos National Laboratory,
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Cecilia Lunardini, ES, Lili Yang, JCAP 1308, 014 (2013).
Cecilia Lunardini, ES, PRD 86, 085008 (2012).
Veniamin Berezinsky, ES, Alexander Vilenkin, PRD 84, 085006 (2011).
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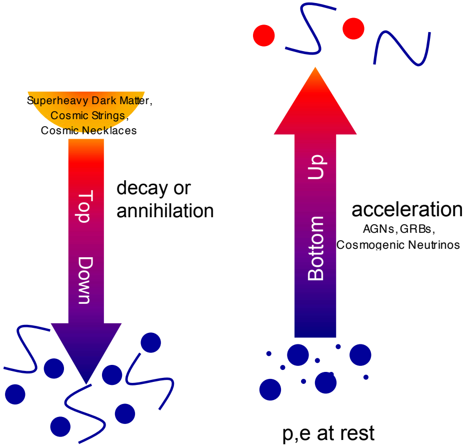
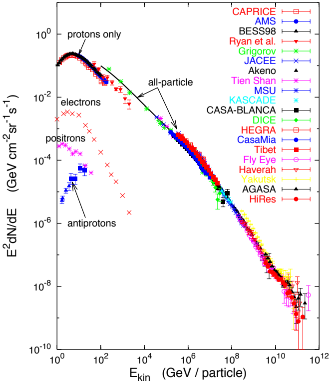
INTRODUCTION

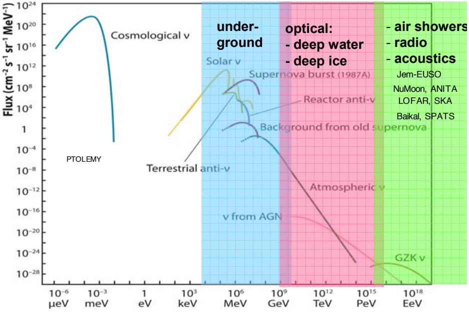
Neutrino Sources: Top-Down or Bottom Up?



Courtesy of Berg&Scholten '09.

Cosmic Ray/Neutrino Flux





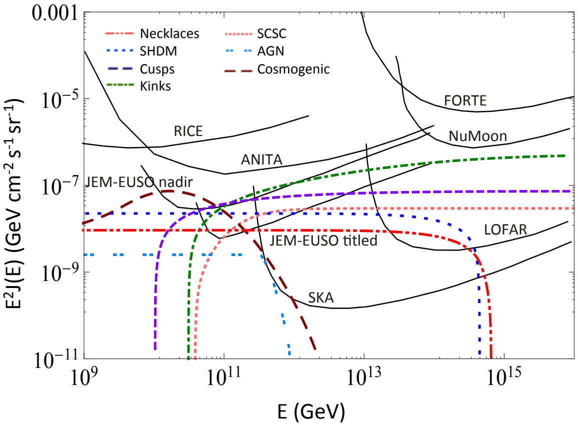
Figures from: Hillas '06 and Spiering '12.

Status of (Ultra) High Energy Neutrino Detectors

Experiment	Location	Technique	Status
DUMAND	Hawaii	Water Cherenkov	turned down 1996
NT200+	Lake Baikal	Water Cherenkov	operating
GVD	Lake Baikal	Water Cherenkov	design phase
AMANDA	South Pole	Water Cherenkov	terminated 2009
IceCube	South Pole	Water Cherenkov	operating
ANTARES	Mediterranean	Water Cherenkov	operating
NESTOR	Mediterranean	Water Cherenkov	R&D for KM3NeT
NEMO	Mediterranean	Water Cherenkov	R&D for KM3NeT
KM3NeT	Mediterranean	Water Cherenkov	design phase
HIRES	USA	Air shower	terminated 2009
Auger	Argentina	Air shower	operating
TA	USA	Air shower	operating
JEM-EUSO	Satellite	Air shower	construction
ASHRA	Hawaii	air shower	partial operation
CRTNT	China	air shower	planned
ANITA	Antarctica (balloon)	Radio (ice)	flights continuing
RICE	South Pole	Radio (ice)	terminated
ARA	South Pole	Radio (ice)	construction stage 1
ARIANNA	Antarctic shelf	Radio (ice)	construction stage 1
SALSA	open	Radio (salt mine)	conceptual phase
SAUND	Caribbean Sea	Acoustic	terminated
SPATS	South Pole	Acoustic	test array operating
AMADEUS	Mediterranean Sea	Acoustic	test array operating
ONνDE	Mediterranean Sea	Acoustic	test array finished
Baikal	Lake Baikal	Acoustic	R&D
GLUE	USA	Radio (moon)	terminated
NUMOON	Netherlands	Radio (moon)	operating
Kalyzhin	Russia	Radio (moon)	operating
LORD	Satellite	Radio (moon)	planned
FORTE	Satellite	Radio (Earth)	terminated

Spiering '12.

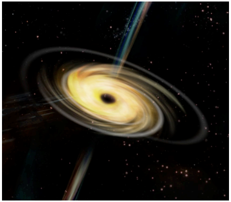
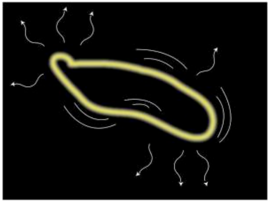
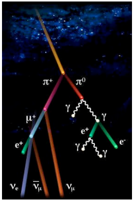
UHE Neutrino Fluxes, Detectability Limits/Upper Bounds Fig from Lunardini, ES, Yang '13



Cosmic Necklaces:**Berezinsky, Martin, Vilenkin '97**; Super Heavy Dark Matter (SHDM):**Berezinsky, Kachelriess, Vilenkin '98; Kuzmin, Rubakov '98; Esmaili, Ibarra, Peres '12**: 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**.

Cosmic Messengers: Ultra High Energy Neutrinos

- Neutrinos only interact weakly with the cosmic neutrino background (CνB).
- Neutrinos can propagate to us from very high redshifts, $z_\nu \sim 220 E_{11}^{-2/5}$. Berezinsky '92
- Astrophysical mechanisms may produce UHE neutrinos with $E \lesssim 10^{11}$ GeV.
- Neutrinos with $E > 10^{11}$ GeV could be a signature of top-down mechanisms.

- Ultra high energy (UHE) νs provide a unique opportunity to test **the fundamental interactions** at these energies.
- For such high energies, **only νs** can make it to the Earth.
- The flux of neutrinos produced by decays of pions and kaons is constrained from above by the observed diffuse gamma ray background. **Berezinsky, Smirnov '75.**

PROPAGATION OF UHE NEUTRINOS

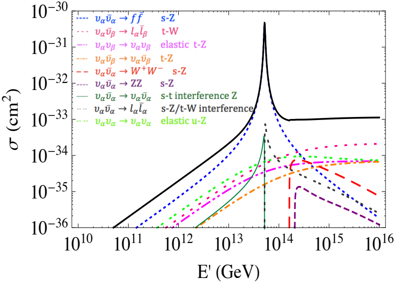
$\nu\nu$ Cross Section

Cross sections depend on the Mandelstam variable s:

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

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

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



$m = 0.08$ 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

- The Hubble expansion rate:

$$H(z) = \frac{\dot{a}}{a} = H_0 \sqrt{\Omega_{\mathrm{r}}(1+z)^4 + \Omega_{\mathrm{m}}(1+z)^3 + \Omega_\Lambda}. \tag{4}$$

- Neutrinos decouple from the primordial plasma when $\Gamma_{\mathrm{scat}} \sim H$ ($T_{\mathrm{dec}} \sim 1\mathrm{MeV}$):

$$dn_\nu(p,z) = (1+z)^3 \frac{d^3p}{(2\pi)^3} \frac{1}{e^{p/T_0}+1} \ . \tag{5}$$

- The average momentum of a background neutrino is $p \approx 3.6\,T_0 \approx 6.1 \times 10^{-4}\ \mathrm{eV}$.

- Thermal effects become important when $\bar{p}\ (1+z_{\mathrm{th}}) \sim m_j$:

$$1 + z_{\mathrm{th}} \sim 16 \frac{m_j}{10^{-2}\ \mathrm{eV}}. \tag{6}$$

Cosmic Neutrino Background / Thermal Effects

$$\bar{\sigma}(E; z, m_j) = \frac{\int dn_\nu(p,z)\, \sigma(E, p; m_j, z)}{\int dn_\nu(p,z)}. \tag{7}$$

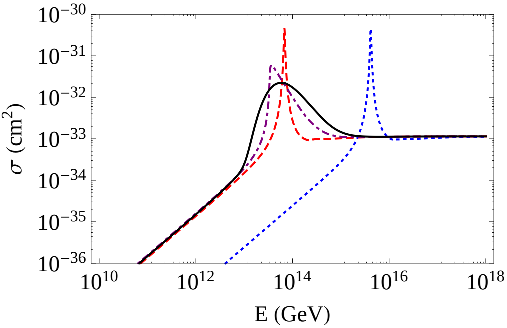


Figure : $m = 10^{-3}$eV, $z = 100$. Blue: CνB at rest, Red: $p = p_{\rm rms}$, Purple: $p = p_{\rm rms}$ averaged over angle, **Black: $\bar{\sigma} \rightarrow$ Averaged over all momenta and angle (this work).**

Neutrino Absorption

- An UHE neutrino is absorbed when $\tau_\alpha = \int dt \sigma_\nu n_\nu \gtrsim 1$.
- The total non-resonant cross section at $s \gtrsim m_W^2$: $\sigma_{\rm nr} \approx 7.8\ G_F^2\ m_W^2/\pi$:

$$\tau_{\rm nr} \approx 1.0 \left(\frac{1+z}{140}\right)^{3/2}. \tag{8}$$

- The maximum value of the resonant cross section, $\sigma_{\rm r} \sim 5 \times 10^{-32}\ {\rm cm}^2$:

$$\tau_{\rm r} \approx 1.0 \left(\frac{1+z}{10}\right)^{3/2}. \tag{9}$$

- Resonant absorption occurs at

$$E'_{\rm res} \sim m_Z^2/\sqrt{\bar{p}_0^2(1+z)^2 + m_j^2}, \qquad z \gtrsim z_{\rm dip} \approx 10. \tag{10}$$

Flavor Averaged Transmission Probability

$$d\Gamma_\alpha(E,z) = \sum_j |U_{\alpha j}|^2 \, dn_{\nu_j}(p,z)\, \sigma(E,p;z,m_{\nu_j}), \tag{11}$$

$$\tau_\alpha(E,z) = \int_0^z \frac{dz'}{(1+z')H(z')}\, \Gamma_\alpha(E,z')\ . \tag{12}$$

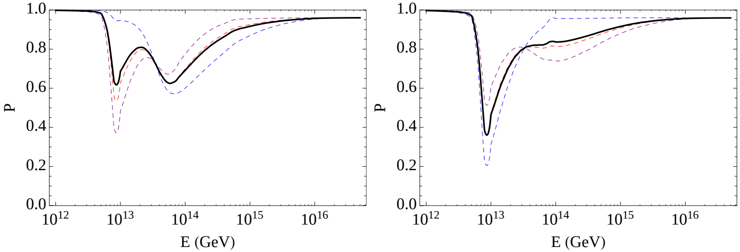


Figure : $m = 10^{-5}$ eV (ligthest) Blue:P_e, Red:P_μ, Purple:P_τ, **Black:** $P \rightarrow$ **average survival probability**.

$$P_\alpha(E,z) = e^{-\tau_\alpha(E,z)}, \qquad P(E,z) = \frac{1}{3}\sum_\alpha P_\alpha(E,z). \tag{13}$$

UHE NEUTRINO SOURCES

UHE Neutrino Flux

The number of sources, N_s, per comoving volume, per unit physical time, t:

$$\eta(z) \equiv \frac{1}{r^2} \frac{d^3 N_\mathrm{s}}{d\Omega dr dt} \ , \tag{14}$$

The spectrum of a single source

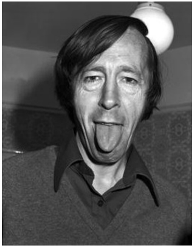
$$\phi(E') \equiv \frac{dN_\nu}{dE'} \tag{15}$$

The diffuse observed UHE neutrino flux

$$J_\nu(E) = \frac{1}{4\pi} \int_0^\infty \frac{dz}{H(z)} \ P(E,z) \ \mathcal{L}_\nu(E',z). \tag{16}$$

Cosmic Strings

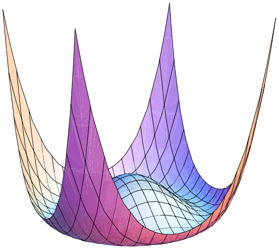
• In '76, Tom Kibble classified the theories with spontaneous symmetry breaking according to the topology of their vacuum configurations.
• Non-trivial topology leads to topological defects: domain walls, cosmic strings, monopoles.

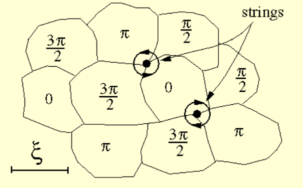


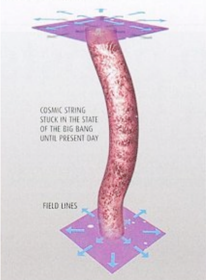

• Monopoles and domain wall are problematic, but cosmic strings are compatible with the standard cosmology.
• In '85, Ed Witten showed for a U(1)×U(1) that strings can be superconducting.

Gauge Strings

$$\mathcal{L} = D_\mu^* \phi^* D^\mu \phi - \frac{1}{4}\lambda(\phi^*\phi - \eta^2)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad \phi_0 \sim \eta e^{i\theta} \tag{17}$$







- The fundamental homotopy group of the vacuum manifold is non-trivial: $\pi_1(U(1)) = \mathbb{Z}$.
- The model admits vortex solution.
- Cosmic strings can form via Kibble mechanism.

Cosmic String Network

- A network of cosmic string forms after the symmetry breaking with correlation length $\xi \sim t$.

Courtesy of Martins and Shellard [1]

- The density of long strings can be estimated as $\rho \sim \frac{\mu}{t^2}$.

[1] http://www.damtp.cam.ac.uk/research/gr/public/movies/small-erc.mpg

Scalar Particle Radiation from Loops

- The effective action:

$$S = -\int d^4x \left[\frac{1}{2}(\nabla\phi)^2 + \frac{1}{2}m^2\phi^2 + \frac{\sqrt{4\pi}\alpha}{m_p}\phi T^\nu_\nu \right] - \mu \int d^2\sigma \sqrt{-\gamma}. \tag{18}$$

- The power spectrum:

$$\frac{dP_n}{d\Omega} = \frac{G\alpha^2}{2\pi}\omega_n k |T(\mathbf{k}, \omega_n)|^2. \tag{19}$$

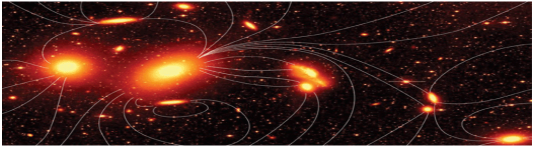
- The particle radiation rate from cusps and kinks **Berezinsky, ES, Vilenkin '11; Lunardini, ES '12**

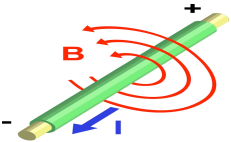
$$\frac{d^2N_c}{dkdt} \sim \alpha^2 G\mu^2 L^{-1/3} k^{-7/3} \qquad \text{(cusp)}, \tag{20}$$

$$\frac{d^2N_k}{dkdt} \sim \alpha^2 G\mu^2 k^{-2} \qquad \text{(kink)}. \tag{21}$$

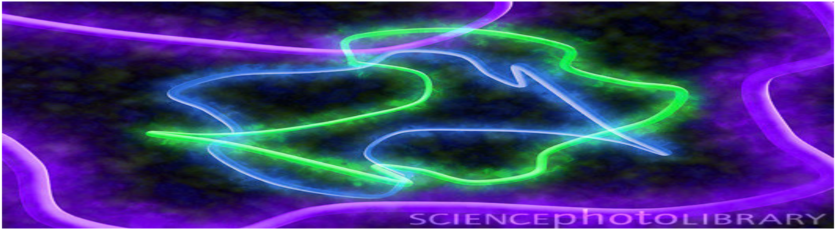
Superconducting Cosmic Strings

- In many field theory models, cosmic strings respond to external magnetic fields, develop currents and act as superconductors [Witten '85].





- Superconducting strings can emit electromagnetic radiation and charge carriers.

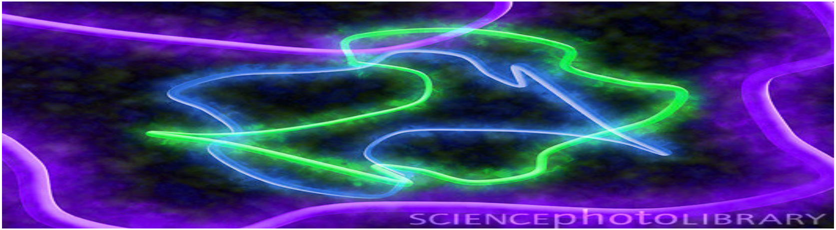


Radiation from Superconducting Loops

• Superheavy charge carriers are ejected from parts of strings, where the current is saturated Berezinsky, Olum, ES, Vilenkin '09.

$$\frac{dN_X}{dt} \sim 2I^2/e\, I_{max}, \tag{22}$$

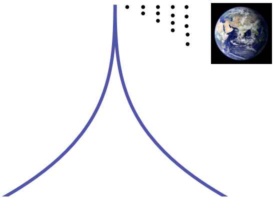
$$I \lesssim I_{max} \sim i_c e\eta, \quad i_c \lesssim 1. \tag{23}$$



• String tension: $G\mu \sim \eta^2/m_p^2$.
• Mass of the charge carrier: $m_X \sim i_c\eta$.

Particle Radiation from Cusps and Kinks

- Particles can be emitted both from cusps and kinks on cosmic string loops.
- These particles are emitted with Lorentz factors of $\gamma_c \sim \sqrt{mL} >> 1$ into a narrow opening angle $\theta_c \sim 1/\gamma_c$.



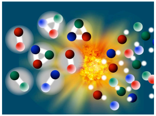
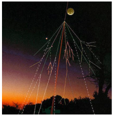
- The decays of these particles into gluons will create a hadronic cascade, hence numerous UHE neutrinos are produced.

Fragmentation Function

- The fragmentation function for the hadronic cascade: $dN/dE \propto E^{-2}$

Berezinsky, Kachelriess '01.

- The minimum neutrino energy: $E_{min} \sim (1\,\mathrm{GeV})\gamma/(1+z)$.

Luminosity of Neutrinos from Cosmic Strings

Scalar particle radiation model: **Berezinsky, ES, Vilenkin '11; Lunardini, ES '12**

$$\mathcal{L}_\nu^{\rm cusp} = 9.5 \times 10^{23} \frac{\alpha^2 (G\mu)^{1/2} \ln[(G\mu)^{1/2} m_p/m]}{p(1+z)^5} \frac{m_p}{E^2 t_p^{1/2} t(z)^{7/2}}, \quad (24)$$

$$\mathcal{L}_\nu^{\rm kink} = 1 \times 10^{23} \frac{\alpha^2 (m_p/m)^{1/2}}{p(1+z)^5} \frac{m_p}{E^2 t(z)^4}. \quad (25)$$

Superconducting string model: **Berezinsky, Olum, ES, Vilenkin '09**

$$\mathcal{L}_\nu^{\rm sup} = 1.4 \times 10^{22} \frac{i_c f_B}{(1+z)^{5/2}} \frac{B m_p t_p^{1/2}}{E^2 t(z)^{5/2}}. \quad (26)$$

Cosmic Necklaces

• Cosmic necklaces are topological defects made up of strings and monopoles, and are predicted in models with symmetry breaking sequence $G \to H \times U(1) \to H \times Z_2$.

Berezinsky, Martin Vilenkin '97, Berezinsky, Vilenkin '97

• As the monopoles and antimonopoles on loops of necklaces meet, they annihilate into heavy X-bosons $\to$ UHE neutrinos via hadronic cascade.

$$\mathcal{L}_{\nu}^{\rm neck} = \frac{\Theta[m_X - E(1+z)]e^{-E(1+z)/m_X}}{2\ln[m_X/(1\mathrm{GeV})](1+\mathrm{z})^6}\frac{r}{E^2 m_p t_p t(z)^3}. \quad (27)$$

Superheavy Dark Matter

- The dark matter sector may consist of multiple particle species.

- There could exist a long lived superheavy dark component (X) with small abundance, $\Omega_{\rm SHDM} \equiv \xi_X \Omega_{\rm CDM}$ with $\xi_X \ll 1$. **Berezinsky '92; Berezinsky, Kachelriess, Vilenkin '97; Kuzmin, Rubakov '97; Chung, Kolb, Riotto '98; Esmaili, Ibarra, Peres '12**

$$\mathcal{L}_\nu^{\rm SHDM} = \frac{3 r_x \Omega_{\rm CDM}}{16\pi} \frac{\Theta[m_X - E(1+z)] e^{-E(1+z)/m_X}}{\ln[m_X/(1{\rm GeV})](1+{\rm z})^2} \frac{m_p H_0^2}{E^2 t_0 t_p}. \tag{28}$$

Cosmogenic Neutrinos

• The cosmic ray protons propagating in the background photons (mostly CMB) are efficiently absorbed above the GZK cutoff energy $E_p \gtrsim 5 \times 10^{10}$ GeV (for CMB background). **Greisen '66; Zatsepin, Kuzmin '66**

$$p\,\gamma \to \Delta^+ \to p\,\pi^0, \tag{29}$$

$$p\,\gamma \to \Delta^+ \to n\,\pi^+. \tag{30}$$

• UHE neutrinos produced as a by-product as π^+ and n decays are called cosmogenic neutrinos. **Berezinsky, Zatsepin '69**

• The luminosity: **Engel, Seckel, Stanev '01; Kalashev, Kuzmin, Semikoz, Sigl '02**

$$\mathcal{L}_\nu^{\rm cosm} = \mathcal{N}_0 (1+z)^{n-1} \phi(E'). \tag{31}$$

Astrophysical Sources

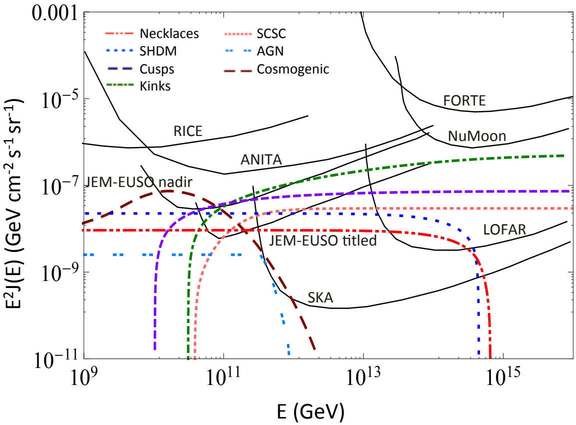
• Gamma ray bursts and active galactic nuclei can also produce UHE neutrinos as the accelerated protons from these sources interact with the ambient photons in those sources. **Waxman, Bachall '97; Stecker, Done, Salamon, Sommers '91**

• The redshift evolution of these sources is stronger than the star formation rate history ($\beta_{\rm grb} \approx 1.5$, $\beta_{\rm agn} \approx 2$). **Robertson, Ellis '12; Hasinger, Miyaji, Schmit '05**

$$\frac{dN}{dz} = A\, \eta_{SFR}(z)(1+z)^{\beta}\, \frac{dV_c}{dz}\frac{1}{1+z}, \tag{32}$$

$$\mathcal{L}_{\nu}^{\rm GRB} = j_0 \frac{dN}{dz}\left[\frac{E(1+z)}{E_{\rm max}}\right]^{-2} \Theta[E(1+z) - E_{\rm min}]\, \Theta[E_{\rm max} - E(1+z)]\ . \tag{33}$$

UHE Neutrino Fluxes, Detectability Limits/Upper Bounds Fig from Lunardini, ES, Yang '13



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Observed UHE Neutrino Fluxes

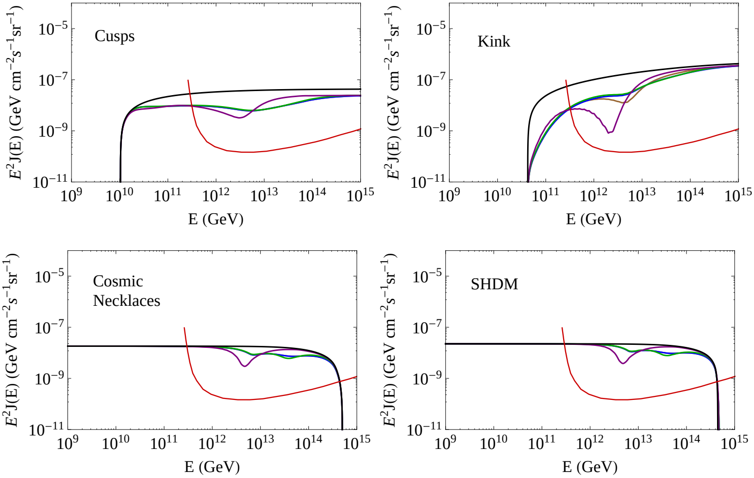

Figure : Normal hierarchy with lightest masses $m = 10^{-5}, 10^{-3}, 0.02, 0.08$ eV. Red curve represents the detectability limit of SKA.

Conclusions

• For a hierarchical neutrino mass spectrum (with at least one neutrino with mass below $\sim 10^{-2}$ eV), thermal effects are important for UHE neutrino 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**.
Existence of CνB.
Density/distribution of CνB.

Stay tuned for the UHEν broadcasts @ Moon/Antarctica.