Diffuse Ultrahigh Energy Neutrino Fluxes and Physics beyond the Standard Model

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work done with Atri Bhattacharya, Sandhya Choubey and Atsushi Watanabe
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Although the neutrino is the most abundant particle in the universe after the photon, the only extra-terrestrial neutrinos observed are those from the sun and the few events from SN1987A.
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ANTARES, NEMO Cerenkov detectors in the Mediterranean, eventually to be part of KM3NET. AMADEUS, an acoustic detector taking data since Dec 07, is also part of ANTARES setup.
**Current and Future Detectors**

- **AUGER** in Argentina, for UHE CR showers and GZK neutrino detection, with charged particle detection (water tanks) and Flourecence (telescope array) detection capabilities. Bound set on $\nu_\tau$ flux.
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**ANITA**, a balloon payload experiment over the Antarctic, monitoring an effective volume of $10^6 \text{ Km}^3$ (!) of Ice for Radio emission by EM showers created by neutrino events with energies in excess of $10^9 \text{ GeV}$ (Askaryan effect). Bound on total $\nu$ flux at these energies set.
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Flavour identification of muons possible via the long charged track and (hadronic) shower characteristic of $\nu_\mu$ CC interactions.

Counting of the combined total of $\nu_e$ CC and NC interactions of all flavours via identification of electromagnetic and hadronic showers unaccompanied by long charged lepton track.
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The 3 categories of detected events are thus:

- Long muon tracks, counting $\nu_\mu$ CC events
- Showers, counting $\nu_e$ CC + NC, $\nu_\tau$ (CC at lower E) + NC and $\nu_\mu$ NC.
- Double bang and lollipops, counting $\nu_\tau$ above a few PeV.
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The number of shower events in the energy bin then becomes a measure of the distortion from the spectral shape set by the muon events.
The Generic UHE Accelerator . . .

(Fig from Halzen 07.)
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interactions. Pions decay to \(\mu\) and \(\nu\), protons tend to stay confined, neutrons and neutrinos leave the accelerator, with the former later decaying to give protons.
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The branching ratios, all of \(\sim O(1)\) are known from particle physics, giving comparable and co-related fluxes for CR, \(\gamma\) rays and \(\nu\). Observations of TeV \(\gamma\) rays and CR thus can put bounds on the UHE \(\nu\) fluxes

(Waxman and Bahcall; Mannheim, Protheroe and Rachen)
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Once the source flux of neutrons (protons), photons and neutrinos is known, two important steps are necessary to arrive at a prediction for the diffuse neutrino flux at Earth.
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The flux is integrated over the source distribution and normalized using the observations of the Extra Galactic Gamma Ray background and the measured flux of UHE Cosmic Rays. (Mannheim, Protheroe and Stanev, Protheroe and Johnson, Waxman and Bahcall; Mannheim, Protheroe and Rachen)
This normalization leads to upper bounds on the UHE neutrino fluxes. (Waxman and Bahcall; Mannheim, Protheroe and Rachen)
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Since the bounds are obtained using maximal values of the flux possible at a given energy, flux distortions (enhancements, suppressions) are reflected by them. We use them as a means of studying the effects of physics beyond the SM.
**Diffuse Fluxes . . . **

All reference plots

- **Bounds on Diffuse optically thin (neutron transparent) source fluxes** (Waxman and Bahcall, Mannheim, Protheroe and Rachen)

- **Maximal Diffuse flux from Optically thick (neutron opaque) sources** (Mannheim, Protheroe and Rachen)

- **Note that all bounds are flavour-independant, since oscillations democratize flavours in a standard source**
Diffuse Fluxes . . .

Diffuse muon neutrino flux

\[ \Phi E^{-2} \left[ \text{GeV sr}^{-1} \text{s}^{-1} \text{cm}^{-2} \right] \]

- Atmospheric
  - AMANDA-II (1yr) [\(1\)]
  - AMANDA (4yr) [\(2\)]
- MPR
  - MPR bound [\(3\)]
- Gravitational waves (GRB) [\(4\)]

WB

100 - 500 events per km\(^2\) year

Full IceCube, 1 year

HBL blazars

\[ \log(E_\nu / \text{GeV}) \]

High Energy Neutrinos . . .

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R. Gandhi  -- p. 16
Neutrinos from pion decay have the flavour content

\[ \nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0. \]

With \( L_{osc} = \frac{4\pi E_\nu}{\Delta m^2} \sim 2.5 \times 10^{-24} \frac{E}{1\text{eV}} \text{Mpc} \), oscillations over cosmological length scales average out and give a flavour content at Earth \( \nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1 \).

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We note that oscillations make the flavour spectra identical in shape due to averaging. Muon events provide the most reliable mode of measuring this common spectral shape, expected to follow an \( E^{-2} \) behaviour.
Knowing that shower events comprise $\nu_e$ CC and all NC events, one can infer, given the spectral shape from muon events and the $1:1:1$ ratio induced by oscillations (for the standard source ratio $1:2:0$) the expected number of shower events in an appropriate energy bin.
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Distortions in the expected spectrum of shower versus muon events would be indicative of non-standard physics, some possibilities of which we examine here.
Two body neutrino decay
\[ \nu_i \rightarrow \nu_j + X, \nu_i \rightarrow \bar{\nu}_j + X \]
where \( X \) is a light or massless are only weakly constrained, with the limit being \( \tau/m \geq 10^{-4} \text{ sec/eV} \).

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Depending on the hierarchy, for decays which are complete, ratios will change from \( \nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1 \) to \( 6 : 1 : 1 \) (NH) or \( 0 : 1 : 1 \) (IH)

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Ratios will exhibit energy dependance if decays are incomplete

(Barenboim and Quigg)
Decay in the Normal hierarchy leads to large number of shower events, comparable (but less) muon flux.

Decay in the Inverted hierarchy case leads to highly suppressed shower fluxes.
The flux at Earth for a given flavour $\alpha$ is

$$\phi_{\nu_\alpha}(E) = \sum_{i\beta} \phi_{\nu_\beta}^{\text{source}}(E) |U_{\beta i}|^2 |U_{\alpha i}|^2 e^{-L/\tau_i(E)}$$  \hspace{1cm} (1)$$

$$L \gg \tau_i \rightarrow \sum_{i(\text{stable}),\beta} \phi_{\nu_\beta}^{\text{source}}(E) |U_{\beta i}|^2 |U_{\alpha i}|^2 ,$$  \hspace{1cm} (2)$$

Besides partial decay, other new physics, in combination or by itself, like CP violation, Lorentz Violation and the presence of Pseudo-Dirac neutrino states would affect the final magnitude and spectral shape of the flux of flavour $\nu_\alpha$. 
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Diffuse Fluxes ... Decay...

Decay effects: \( t_2/m = 0.1, t_3/m = 0.1 [\text{ev/s}] \), Normal hierarchy.

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\tau/m = 0.1 \text{sec/eV}, \text{ Normal Hierarchy, Optically Thin Sources}
\]

Shower Events significantly rise above Muon events below \( 10^7 \) GeV and become equal thereafter.
Decay effects: $t_2/m = 0.1$, $t_3/m = 0.1$ [ev/s]. Inverted hierarchy.

- $\tau/m = 0.1\text{sec/eV}$, Inverted Hierarchy, Optically Thin Sources
- Shower Events significantly below Muon events for energy $< 10^7$ GeV and become equal thereafter.
- Decay offers high level of sensitivity to the hierarchy, and the possibility of ball-park estimations of lifetimes.
Diffuse Fluxes... Decay...

Decay effects: $t_2/m = 0.1$, $t_3/m = 0.1$ [ev/s], Normal hierarchy.

- $\tau/m = 0.1$ sec/eV, Normal Hierarchy, Optically Thick Sources
- Shower Events above Muon events for $10^8$ GeV and become equal thereafter. Spectral shapes similar.
- Sensitivity in the range $10^3 \geq \tau/m \geq 10^{-3}$ sec/eV
**Diffuse Fluxes**

Decay effects: $t_2/m = 0.1$, $t_3/m = 0.1$ [eV/s], Inverted hierarchy.

- $\tau/m = 0.1$ sec/eV, Inverted Hierarchy, Optically Thick Sources
- Shower Events undetectably below Muon events for energy $< 10^7$ GeV and rising between $10^7 - 10^8$ GeV, become equal thereafter. Spectral shapes distinguishably altered
- Sensitivity in the range $10^3 \geq \tau/m \geq 10^{-3}$ sec/eV
Decay . . . Sensitivity to $\theta_{13}$ . . .

Effect of $\theta_{13}$ variation on Decay: $t_2/m = 0.1$, $t_3/m = 0.1$ [ev/s]. Inverted hierarchy.

\[ \tau/m = 0.1 \text{sec}/\text{eV}, \text{ Inverted Hierarchy, Optically Thin Sources} \]

- Shower Events significantly below Muon events for energy $< 10^7$ GeV and become equal thereafter.
- Shower events above Icecube threshold for non-zero $\theta_{13}$ and undetectably low as it approaches zero.
A non-zero CP phase $\delta$ for decaying neutrinos imposes a $\cos \delta$ dependance on the fluxes. (Beacom, Bell, Hooper, Pakvasa, Weiler)
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Large correlated variations in the $\nu_\tau$ and $\nu_\mu$ fluxes for normal hierarchy, reflected in the relative number of long track muon events versus showers.
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Large correlated variations in the $\nu_\tau$ and $\nu_\mu$ fluxes for normal hierarchy, reflected in the relative number of long track muon events versus showers.

Heightened sensitivity to variations in $\theta_{13}$. Detection of $\tau$ events assumes importance here. (Beacom, Bell, Hooper, Pakvasa, Weiler)
Sensitivity to the CP Phase \ldots Decay.. 

Effect of CP violation on Decay, $\tau/m = 0.1$ [sec/eV], Normal hierarchy.

\[ E^2(E) \text{ [GeV cm}^{-2} \text{s}^{-1} \text{ sr}^{-1}] \]

\[ F \text{ [sec/cm}^2 \text{s}^{-1} \text{ sr}^{-1}] \]

- $v_\mu$ flux without Decay
- $v_\mu$ flux, CP phase from 0 to $\pi$, $\theta_{13} = \text{max}$
- $v_e$ flux, CP phase from 0 to $\pi$, $\theta_{13} = \text{max}$

\begin{itemize}
  \item \( \tau/m = 0.1 \text{ sec/eV, Normal Hierarchy, Optically Thick Sources} \)
  \item Shower Events versus long track events very sensitive to this variation which causes a large change in number of muon events
\end{itemize}
Sensitivity to the CP Phase

\[ \theta_{13} \text{ variation effect on CP violation, } t/m = 0.1 \text{ [ev/s], Normal hierarchy.} \]

\[ \tau/m = 0.1 \text{ sec/eV, Normal Hierarchy, Optically Thick Sources CP phase effect enhanced if variation over range of } \theta_{13} \]
The presence of very small Majorana mass terms (compared to the Dirac mass scale) leads to almost degenerate Majorana states, each of mass $m_D$. 
Sensitivity to Pseudo-Dirac Neutrino States

The presence of very small Majorana mass terms (compared to the Dirac mass scale) leads to almost degenerate Majorana states, each of mass $m_D$.

UHE neutrinos provide perhaps the only possibility of probing mass differences much smaller than solar and atmospheric $\Delta m^2$.

(Keranen, Maalampi and Myyrylainen; Beacom, Bell, Hooper, Pakvasa, Weiler)
Sensitivity to Pseudo-Dirac neutrino States

Pseudo-Dirac effects, $\delta m^2 = 1 \times 10^{-18} \text{[eV$^2$]}$.

\[ \Delta m^2 = 10^{-14} \text{eV}^2, \text{Optically Thick Sources} \]

Flux distortions small, with factor of 2 fall where oscillations present.

Sensitivity in the range $\Delta m^2 = 10^{-12} - 10^{-17} \text{eV}^2$
Small mass particles travelling large distances provide an opportunity to detect tiny violations of Lorentz invariance and CPT via oscillations. This would be reflected in UHE fluxes and event rates.
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As a simple example, we consider Lorentz violations arising from differences in propagation for different flavours, parametrised by an off diagonal parameter in a 2 flavour effective Hamiltonian. (Kostelecky and Mewes; Hooper, Morgan and Winstanley)
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As a simple example, we consider Lorentz violations arising from differences in propagation for different flavours, parametrised by an off diagonal parameter in a 2 flavour effective Hamiltonian. (Kostelecky and Mewes; Hooper, Morgan and Winstanley)

Fluxes and bounds strongly sensitive to LV.
Lorentz Violation induced Flux changes . . .

Effect of Lorentz violation, $\alpha_1 = 1 \times 10^{-26}$ GeV$^{-1}$.

- $\tau$ events completely suppressed, Optically Thick Sources
- AUGER, ICECUBE would record deficit of double-bang, lolipop and earth-skimming events
Lorentz Violation induced Flux changes . . . .

Effect of Lorentz violation, $a_1 = 1 \times 10^{-30}$ GeV$^{-1}$.

Sensitivity range covers 4-5 orders of magnitude

In general, muon events enhanced, whereas shower and tau events supressed.
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Diffuse fluxes of all flavours are massaged into a common spectral shape by oscillations, and MPR and WB bounds tell us their max values using EGRB and CR data.
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BSM physics changes this picture, e.g. if neutrinos decay with lifetimes in the range $\tau/m = 10^{-3} - 10^3$ sec/eV, with/without a non-zero CP phase, or pseudo Dirac neutrinos with very small mass differences are present, or we have Lorentz violation or some combination of these effects.
Conclusions . . .

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Future detectors using different techniques may play an important role towards distinguishing between various scenarios.