

Flavoring Astrophysical Neutrinos: Flavor Ratios Depend on Energy

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High Energy Astrophysical Neutrinos

Motivation:

- ▶ Ice Cube, Antares, NESTOR, NEMO:
measure $\epsilon > 1$ TeV neutrinos and their flavor.
- ▶ Come from high energy cosmic rays.
- ▶ Identify the sources of cosmic rays
and study their physics.
- ▶ Flavor ratios can test neutrino properties:
 ν decay, new physics.
- ▶ Show: Flavor ratios depend on energy and prob the source.

Astro Neutrino Production

- ▶ Pion production by cosmic rays

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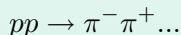
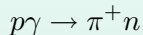
- ▶ The pion decay chain:

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

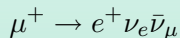
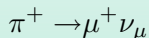
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

Astro Neutrino Production

- ▶ Pion production by cosmic rays



- ▶ The pion decay chain:



- ▶ $\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau} = 1 : 2 : 0 \xrightarrow{\text{oscillations}} 1 : 1 : 1$
 \Rightarrow Deviation from 1 : 1 : 1 probe new physics.

Decay vs. Cooling

- ▶ Electromagnetic losses of π^\pm and μ^\pm : $\dot{\epsilon} \propto -m^x \epsilon^n$
e.g. synchrotron cooling: $\dot{\epsilon} = -Cm^4 \epsilon^2 U_B$.

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- ▶ $\tau_{0,\pi} < \tau_{0,\mu} \Rightarrow \epsilon_{0,\mu} < \epsilon_{0,\pi}$

$$\frac{\epsilon_{0,\mu}}{\epsilon_{0,\pi}} \sim \left(\frac{\tau_{0,\mu}}{\tau_{0,\pi}} \right)^{-1/n} \sim 10^{2/n}$$

Decay vs. Cooling: Flux

- At $\tau_{cool} < \tau_{decay}$

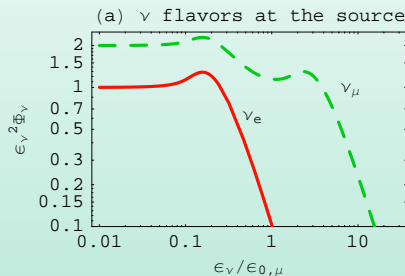
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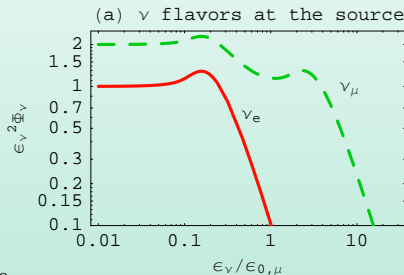


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- For $\epsilon \gg \epsilon_{\mu,0}$

$$\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau} = 0 : 1 : 0 \xrightarrow{\text{oscillations}} 1 : 1.8 : 1.8$$

Prediction for a Transition

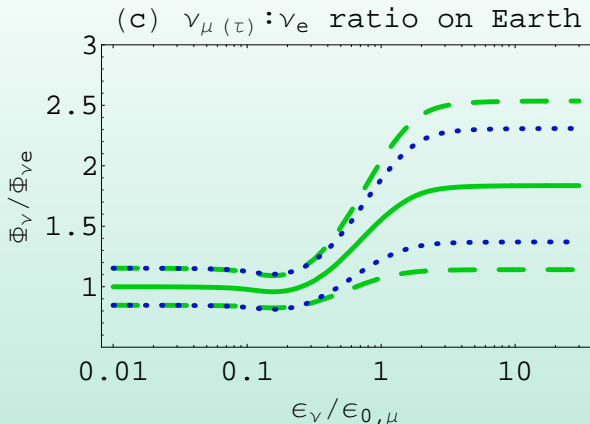


Figure: $\Phi_\pi \propto 1/\epsilon_\pi^2$ and $\dot{\epsilon}_x \propto \epsilon_x^2$, 90%CL: ν_μ (green), ν_τ (blue).

The $\Phi_{\bar{\nu}_e} : \Phi_{\nu}^{\text{total}}$ Transition

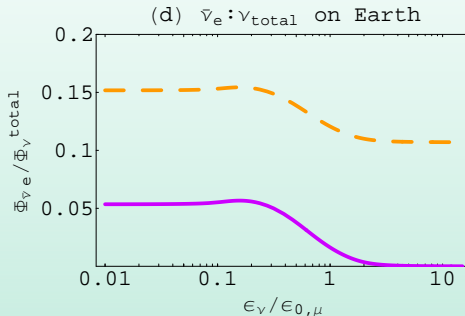


Figure: $p\gamma$ (solid) and pp (dashed).

Neutrinos from Specific Sources

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$$\epsilon_{0,\mu} \approx 1000 \text{ TeV}$$

- ▶ Possible detection.
- ▶ Probe energy density at the source.
- ▶ $\epsilon_0 < 6$ PeV - W resonance ⇒ effect $\bar{\nu}_e : \nu_{tot}$.

Conclusions

1. Energy losses \Rightarrow

$$\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau} \quad 1 : 1 : 1 \xrightarrow{\epsilon \gg \epsilon_0} 1 : 1.8 : 1.8$$

$$\Phi_{\bar{\nu}_e} : \Phi_{\nu}^{\text{total}} \quad pp \quad 1 : 6 \xrightarrow{\epsilon \gg \epsilon_0} 1 : 9$$

$$p\gamma \quad 1 : 15 \xrightarrow{\epsilon \gg \epsilon_0} 0$$

2. Deviation from 1 : 1 : 1 does NOT necessarily imply new physics.
3. Handle on source properties (energy density, cooling process).

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Neutrinos from Specific Sources

1. Active galactic nuclei: $\epsilon_{0,\mu} \approx 4 \times 10^6$ TeV
 \Rightarrow too small number of neutrinos to see a transition.
2. Gamma-ray bursts:

$$\epsilon_{0,\mu} \approx 1000 \text{ TeV} \frac{\Gamma_{2.5}^4 \Delta t_{-3}}{L_{53}^{1/2}}$$

- ▶ $\Gamma = 10^{2.5} \Gamma_{2.5}$ is the wind Lorentz factor,
- ▶ $L = 10^{53} \text{ erg/s} L_{53}$ is the kinetic energy luminosity of the wind,
- ▶ $\Delta t = 10^{-3} \text{ s} \Delta t_{-3}$ is the observed variability time scale of the γ -ray signal.

\Rightarrow Measuring the transition gives a handle on source properties!

Analytic expression for flux ratio

- ▶ The differential number flux of ν_μ 's from π^+ decay is

$$\Phi_{\nu_\mu}^0(\epsilon_\nu) = -\partial_{\epsilon_\nu} \int_{4\epsilon_\nu}^{\infty} d\epsilon_i \Phi_\pi(\epsilon_i) P_\pi(\epsilon_i, 4\epsilon_\nu).$$

ϵ_i - pion energy at production,

$P_\pi(\epsilon_i, 4\epsilon_\nu)$ - the probability for decay before $\epsilon_\pi < 4\epsilon_\nu$,

$\Phi_\pi(\epsilon_i) \propto \epsilon_\pi^{-k}$ production rate of π .

- ▶ Get analytic solution:

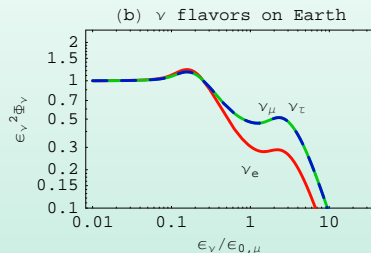
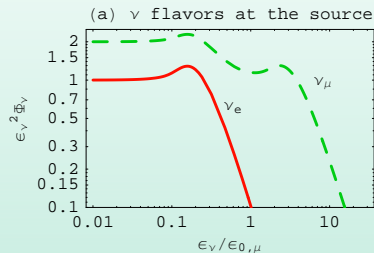
$$\frac{\Phi_{\nu_\mu}^0(\epsilon_\nu)}{\Phi_0^{(\text{no loss})}} = s(-s)^{\frac{1-k}{n}} e^{-s} \gamma\left(\frac{k-1}{n}, -s\right).$$

Here $s \equiv (\epsilon_{0,\pi}/4\epsilon_\nu)^n/n$,

$\gamma(a, z)$ is the lower incomplete gamma function,

$\Phi_0^{(\text{no loss})}$ is the flux without energy losses.

The Flavor Ratios as a Function of Energy



The energy fluxes of astrophysical neutrinos
for $\Phi_\pi \propto 1/\epsilon_\pi^2$ and $\dot{\epsilon}_x \propto \epsilon_x^2$.

The $\Phi_{\bar{\nu}_e} : \Phi_{\nu}^{\text{total}}$ transition

At 6.3×10^3 TeV we can measure $\bar{\nu}_e$.

Common wisdom: $\bar{\nu}_e$ flux differ between $p\gamma$ and pp .

$$p\gamma \rightarrow \pi^+ n, \quad \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$

$$pp \rightarrow \pi^- \pi^+ \dots$$

	$\epsilon \ll \epsilon_0$	$\epsilon \gg \epsilon_0$
$\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau}$	1 : 1 : 1	1 : 1.8 : 1.8
$\Phi_{\bar{\nu}_e} / \Phi_{\nu}^{\text{total}}$ pp	1 : 6	1 : 9
$p\gamma$	1 : 15	0