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.

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

Decay vs. Cooling

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

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

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

Decay vs. Cooling: Flux

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$$P_{decay} \cong 1 - e^{-\tau_{\rm cool}/\tau_{\rm decay}} \cong \frac{\tau_{\rm cool}}{\tau_{\rm decay}} \propto \epsilon^{-n}$$

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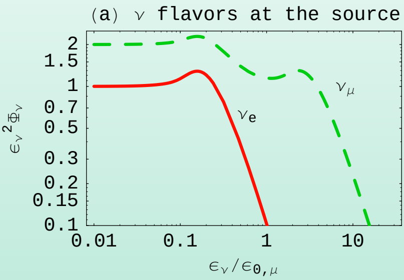

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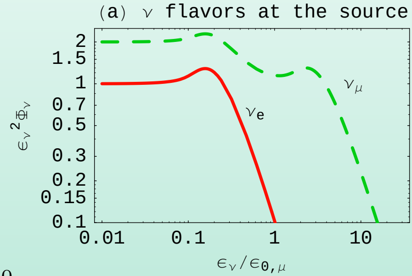

- For $\epsilon \gg \epsilon_{\mu,0}$

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

Prediction for a Transition

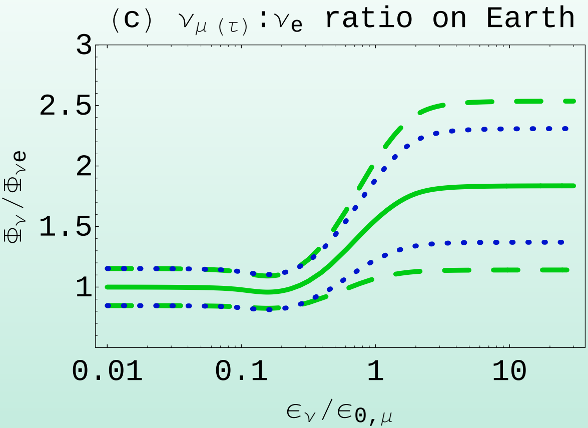

Figure: $\Phi_\pi \propto 1/\epsilon_\pi^2$ and $\dot{\epsilon}_x \propto \epsilon_x^2$, 90%CL: ν_μ (green), ν_τ (blue).

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

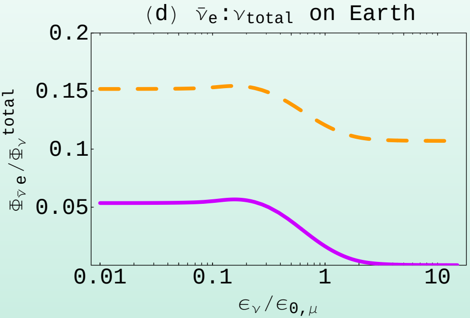

Figure: $p\gamma$ (solid) and pp (dashed).

Neutrinos from Specific Sources

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

Conclusions

1. Energy losses ⇒

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

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

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

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,
- $L = 10^{53}$ erg/sL_{53} is the kinetic energy luminosity of the wind,
- $\Delta t = 10^{-3}$ sΔt_{-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

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

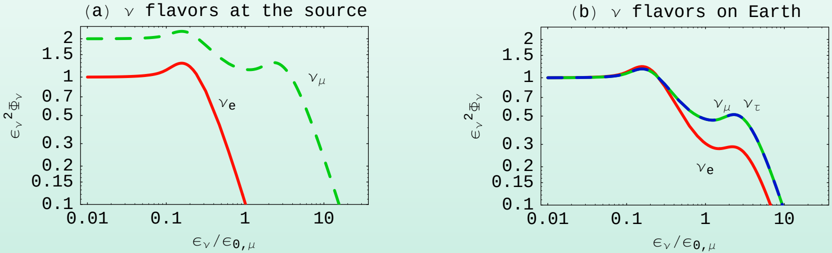
  ϵ_i - pion energy at production,
  $P_\pi(\epsilon_i, 4\epsilon_\nu)$ - the probability for decay before $\epsilon_\pi < 4\epsilon_\nu$,
  $\Phi_\pi(\epsilon_i) \propto \epsilon_\pi^{-k}$ production rate of π.

- Get analytic solution:

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

  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.

$$p\gamma \to \pi^+ n, \qquad \pi^+ \to \mu^+ \nu_\mu \to e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$
$$pp \to \pi^- \pi^+ ...$$

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