Decay of High Energy Astrophysical Neutrinos

(Some more Uses of Neutrino Telescopes – 2001)

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· Do neutrinos decay?

· Since $m_i \neq 0$ & flavor mixing occurs, surely heavier ν decays to lighter ones.

· The only questions are:
  · what are the decay modes?
  · how long are the lifetimes?
  · short enuf to be interesting?

· What can we say at the moment about these?

· We will assume all ν-masses in eV range or less.

- $m_{\nu_i} \neq 0$
- $\theta_{ij} \neq 0$
- Expect heavier ν to decay in general.
- Real Question:
  - Decay Modes?
  - lifetimes?
  - too long or interesting?

- Expectations in SM $(+\, m_{\nu_i} \neq 0,\ U_{\nu_{ij}} \neq 0)$

- $\nu_i \to \nu_j + \gamma$

$$\frac{1}{\tau} = \Gamma = \frac{9}{16}\frac{\alpha}{\pi}\frac{G_F^2}{128\pi^3}\frac{(\delta m_{ij}^2)^3}{m_i}\left|\sum_\alpha \frac{m_\alpha^2}{m_W^2} U_{i\alpha}^* U_{\alpha j}\right|^2$$

(Petcov 1977)

- for $m_i \gg m_j$
- $m_i \sim O(eV)$
- $(4 U_{i\tau} U_{\tau j})^2 \sim O(1)$
- $m_\alpha \sim m_\tau$.

$$\Gamma_{SM} \sim 10^{-45}\ sec^{-1} \to \underline{\tau \sim 10^{45}\ sec}.$$

$$(\tau_{Hubble} \sim 10^{18}\ sec).$$

- In matter Γ_{SM} enhanced by (Nieves, Pal 1981)

$$10^{24}\left(\rho_e / 10^{24}/cc\right)^2 \left(\frac{1eV}{m_i}\right)^4 F \sim 10^{16} \quad \left\{F \to \frac{4 m_{\nu_i}}{E_i}\right\}$$

$E_i \sim 100\ MeV$

$$(\Gamma_{SM})_{matter} \sim 10^{-29}\ sec^{-1}.$$

Caveat: Only Γ_{SM} enhanced (Γ_{SM}^{e}) not any old Γ!!

(Not any old $\Gamma_{non\text{-}SM}$!)

Transition Moments & Radiative Decay Beyond SM.

$$m \sim \frac{e}{m_i + m_j} \bar{\psi}_j \sigma_{\mu\nu} (c + D\gamma_5) \psi_i F_{\mu\nu}$$

$$k_{ij} = \sqrt{|c|^2 + |D|^2} \left(\frac{e}{m_i + m_j}\right) \equiv k_0 \mu_{Bohr}$$

$\left(\mu_{Bohr} = \frac{e}{2m_e}\right)$

expt'l. Bounds:

	SM
$K_0^e < 10^{-10}$	$< 2 \cdot 10^{-18}$
$K_0^\mu < 10^{-9}$	$< 5 \cdot 10^{-14}$
$K_0^\tau < 5 \cdot 10^{-7}$	$< 10^{-11}$

using exptl. Bounds on m_{ν_i}

. $m_i >> m_j$

$$\Gamma = \frac{\alpha}{2m_e^2} m_i^3 k_0^2$$

$\rightarrow$ for $m_i \sim O(eV)$:

$\tau_{\nu_e} > 5 \cdot 10^{18}$ sec

$\tau_{\nu_\mu} > 5 \cdot 10^{16}$ sec.

$\tau_{\nu_\tau} > 2 \cdot 10^{11}$ sec.

Caveat: In decays $\mu_0^{ij}(q^2)$ eval. at $q^2 \approx 0$

Exptl. Bounds for $\mu_0(q^2)$ at $q^2 \sim$ few MeV

{Frere et al. 1998} Except for truly bizarre behavior should be OK.

Exptl. & Obs. Bounds on $\nu \rightarrow \nu' + \gamma$

From SN1987A & Non-obs. of γ's.

$\tau > 6 \cdot 10^{15}$ sec. $(m_i \sim O(eV))$

(applies to all ν's if SN conventional definitely to ν_e's).

$\tau > 7 \cdot 10^{9}$ s (x & γ-ray fluxes)

$\tau > 300$s (Reactor $\bar{\nu}_e$'s)

$\tau > 15.4$ s (ν_μ).

Caveats: { Bounds depend on $m_{\nu_i} >> m_{\nu_j}$; Not valid if $\delta m_{ij}^2 << m_i^2$ }

Invisible Decays

- $\nu_i \to \nu_j \nu \bar{\nu}$
  - Absent in SM.
  - If FCNC @ level of εG_F
  - $(m_i >> m_j)$.

$$\Gamma = \frac{\varepsilon^2 G_F^2 m_i^5}{192\pi^3} \Rightarrow \tau_\nu \sim 2 \cdot 10^{34} s \begin{cases} \varepsilon \sim O(1) \\ m_i \sim O(1) \end{cases}$$

Current Bound on ε: $\varepsilon < 100$ from Z (Smirnov et al.) $\to \tau \sim 2 \cdot 10^{38} s$

Old Bound: $\varepsilon < 10^5$ Bardin, Bilenky, Pontecorvo

- $\nu_{\alpha_L} \longrightarrow \nu_{\beta_L} + \chi$

$\chi \sim m \sim 0,\ J \sim 0,\ I_w = 0,\ L = 0$

$g_p \bar{\Psi}_{\beta L} \gamma_\mu \Psi_{\alpha L} \partial_\mu \chi \Rightarrow$ also $\ell_\alpha \to \ell_\beta + \chi$.

hence strongly constrained.

$$\Gamma_{\nu_\alpha} = \frac{g_p^2 m_\alpha^3}{16\pi}.$$

Also possible $g_v \bar{\Psi}_{\beta_L} \gamma_\mu \Psi_{\alpha_L} V_\mu$

(7)

$SU(2)_L \Rightarrow$

$$\tau_{\nu_\alpha} = \frac{\tau_{\ell\alpha} \left(m_{\nu_\alpha} / m_{\ell\alpha} \right)^{-3}}{B.R.(\ell_\alpha \to \ell_\beta + \chi)}$$

Current Bounds:

$\mu \to e \chi < 2 \cdot 10^{-6}$ Jodidio et al. 1986

$\tau \to \binom{\mu}{e} \chi < 7 \cdot 10^{-6}$ PDG

For $m_{\nu_\alpha} \sim O(eV), >> m_{\nu_\beta}$:

$\tau_{\nu_\mu} > 10^{24}\ s$

$\tau_{\nu_e} > 10^{20}\ s.$

(8

The only possibility for fast, invisible ν decays:

Majoron Couplings:

- $g\, \overline{\nu^c_{\beta R}}\, \nu_{\alpha L}\, J$ (Gelmini - Roncadelli 1981)
  - $\Delta L = 2$, $J \Rightarrow I_W = 1$
  - $\nu_\alpha \longrightarrow \bar{\nu}_\beta + J$. ($\nu_\mu \to \bar{\nu}_e + J$ etc.)
- $f\, \overline{\nu^c_{\beta R}}\, \nu_{\alpha R}\, J$ (Chicasige - Mohapatra - Peccei 1981)
  - $\Delta L = 2$, $J \Rightarrow I_W = 0$
  - $\nu_\alpha \longrightarrow \bar{\nu}_\beta + J$
- or J = a mixture of these two

and/or ν_α, ν_β mixtures of flavor + sterile

Valle, Gelmini, Joshipura etc.

(

Such Models

- unconstrained by μ, τ decays.
- $I_W = 1$ coupling constrained by $Z \to$ invisible width
- g_μ & g_e constrained by $\pi \to \mu/e$ & $K \to \mu/e$ Decays & Universality

Barger Keung SP 1982: $\left\{ \begin{array}{l} g_\mu^2 < 2.4 \cdot 10^{-4} \\ g_e^2 < 10^{-5} - 10^{-6} \end{array} \right\}$

For short lifetimes:

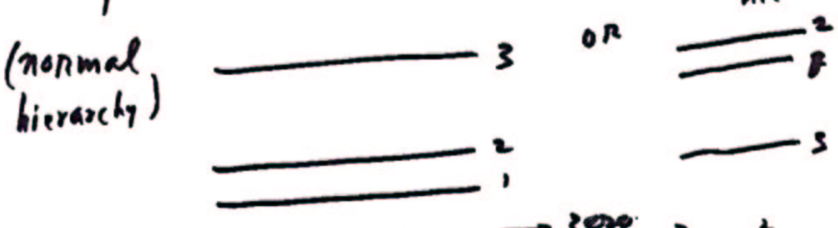
- Potential problems with BBN. N_ν^{eff} increases to 4 - 4.5
- SN Dynamics may change.

- Cosmic ν fluxes: Only the final daughter ν's will arrive at earth.

- Note: Decaying states are mass e-states, not flavor.
- mixings are large:

$$U \sim \begin{pmatrix} c & -s & \varepsilon \\ s/\sqrt{2} & c/\sqrt{2} & -1/\sqrt{2} \\ s/\sqrt{2} & c/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

- $\varepsilon < 0.2$
- $\theta \sim 30^\circ$ (Solar LMA + KAMLAND)
- possible mass pattern:



$$\delta m^2_{32} \sim \Delta_A \sim (3-6)\,10^{-3}\,eV^2$$

$$\delta m^2_{21} \sim \delta_S \sim (6-10)\,10^{-5}\,eV^2$$

What are the current bounds (or potential best bounds) on lifetimes of ν_i?

Source	flavor	which mass e-state	L/E	τ (m/eV)
Lab	ν_μ, ν_e	ν_1, ν_2	30m/10MeV	10^{-14} s
ATM.	ν_μ ν_e	ν_3 ν_2	10^4 km/GeV	10^{-10} s
Sun	ν_e	ν_2	500s/MeV	10^{-4} s
SN (Galax)	$\bar{\nu}_e$	$\bar{\nu}_2$	10kpc/10MeV	10^5 s
AGN	ν_μ	ν_3	100Mpc/TeV	10^4 s.

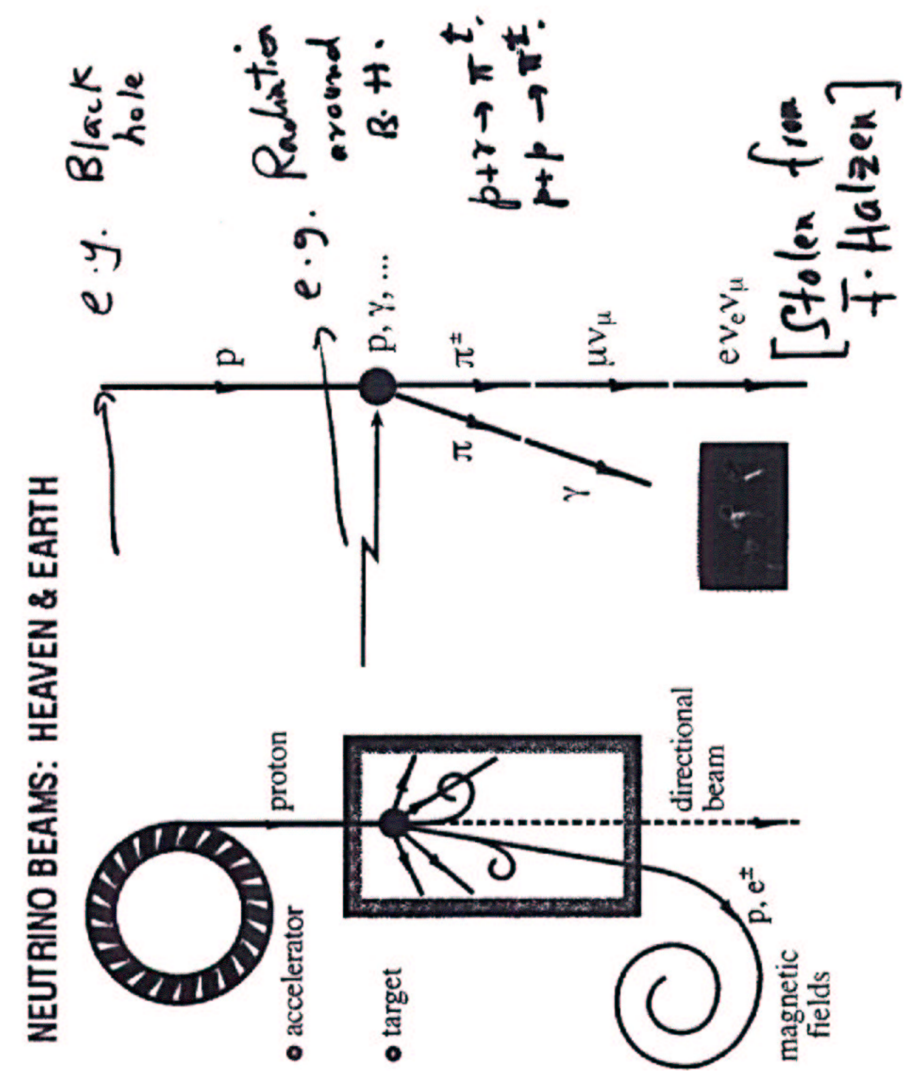
(current: Lab, ATM., Sun; potential: SN, AGN)

$\rightarrow$ ν's may be unstable

Astrophysical ν's may place better bounds on or reveal positive evidence for decay.

To proceed further, make two working assumptions:

- Sources emitting v.H.E. ν's ($\gtrsim$ PEV) with significant fluxes to be detectable at earth at distances $\sim 10^3$ MPC
  Best Candidates: AGN's. GRB's at lower energies
- Existence of large ν Detectors:
  ICECUBE @ South Pole
  KM3: One in Medit [from ANTARES, NESTOR ...] [Water-ice $\hat{c}$]
  Other technologies, larger: AUGER, EUSO-OWL, ANITA, - - - -
  Good instrumentation, E resolution, angular resolution, low E threshold — - -



Sources & ν-flavors at Source

- Most AGN neutrino emission models favour beam dumps (little absorption).
- Dominant processes:

$$\gamma p \to \Delta, \pi N \longrightarrow \pi \to \mu \nu_\mu$$
$$\mu \to e \bar{\nu}_\mu \nu_e$$

$$pp \to \pi X \longrightarrow \pi \to \mu \nu_\mu \hookrightarrow e \nu_e \nu_\mu$$

leads to $\nu_e / \nu_\mu / \nu_\tau = 1/2/0$

Caveat: If some absorption and/or (B) fav large scale magnetic fields, μ may lose energy before decay, and

$$\boxed{\nu_e / \nu_\mu / \nu_\tau \longrightarrow 0/1/0.}$$

(as in atmosphere at high E). [Also $\tau \to \ldots$ 1/1/1]

- Sub-dominant processes:
pp or $\gamma p \to D, D_s, B, B_s \ldots + X$ which Decays give "prompt" ν's have $\nu_e/\nu_\mu/\nu_\tau = 1/1/\varepsilon$ [redacted]

- $\Delta E_\nu \sim 1\text{-}10$ PeV $\sim 2:1:0$ ...
- Assuming $\nu_\mu : \nu_e : \nu_\tau$ (SM)
- $\nu_\mu - \nu_\tau$

- Det ~1KM3
- Det. Eff. ~100%

expect
~1000 ν_τ DB
~1000 $\nu_\mu \to \mu$
~1800 showers
in 1 yr.

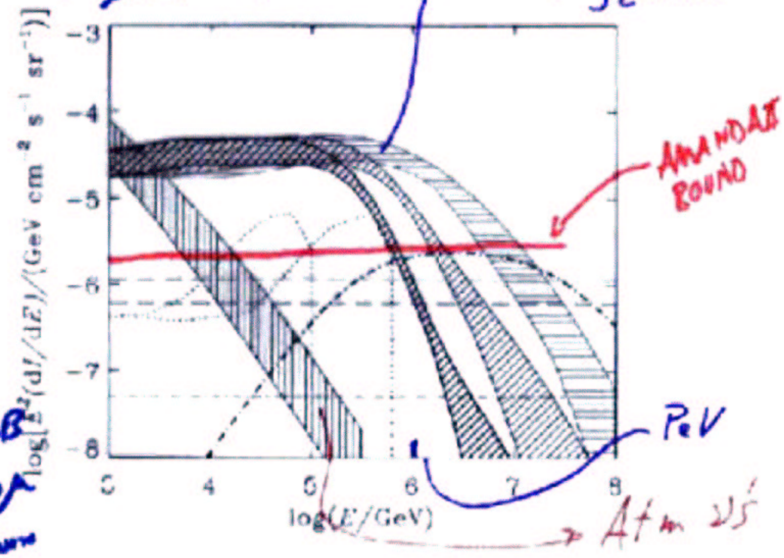


Figure 12: The expected diffuse $\nu_\mu + \bar{\nu}_\mu$ intensity at Earth. The hatched bands show the spread in results obtained using both spectrum (a) and spectrum (b), and models (a) to (e) of Morisawa et al. [56] and the model of Maccacaro et al. [57] for the luminosity function. Results are shown for b=1 (horizontal hatching), b=10 (thin oblique hatching) and b=100 (thick oblique hatching). An integration over a flat distribution in $\log x_1$ has been made for $10 < x_1 < 100$. Also shown: Stecker et al. [25,26] (chain curve), Sikora and Begelman [37] (dotted curves) for [illegible] 3, Biermann [63] (lower dashed line), and blazar contributions calculated by Stecker [28] (chain line), and Nellen et al. [61] (upper dashed line). The atmospheric neutrino intensity [58] is shown by the vertical hatched band: the upper curve corresponds to zenith angle $\theta = 90°$ and the lower curve corresponds to $\theta = 0°$.

ν_μ flux & spectrum from all AGN's.

Estimate of ε

ν_τ can come from

$D_s \to \tau \nu_\tau$ (B.R. ~ 3-4 %), $b \to \tau \nu_\tau X \ldots$

↳ largest.

· $\sigma(pp \to D_s) / \underbrace{\sigma(pp \to D)}_{\text{most of "prompt"}} \sim 15\%$

So $\varepsilon \sim \dfrac{B.R.(D_s \to \nu_\tau)}{B.R.(D \to \nu_\mu)} \dfrac{\sigma(pp \to D_s)}{\sigma(pp \to Dx)}$

$\varepsilon \lesssim 5 \cdot 10^{-2}$. ([redacted])

"Prompt" rate / Total rate

$\sim \sigma(pp \to D) / \sigma(pp \to \pi)$

$\lesssim 10\% \sim 0.1$

Hence the $\nu_e / \nu_\mu / \nu_\tau \approx 1/2/0$ modified v. little (by $10^{-3} - 10^{-4}$).

Effect of Oscillations on flavor mix

· all $\delta m^2 > 10^{-5}\ eV^2$

· osc. argument $\dfrac{\delta m^2 L}{E} >> 1$.

(for $L > \text{Mpc}$, $E \sim \text{PeV}$)

$\Rightarrow \quad \sin^2\left(\dfrac{\delta m^2 L}{4E}\right) \approx 1/2$.

osc. average out.

Hence survival & conversion probabilities are:

$$P_{\alpha\alpha} = \sum_i |U_{\alpha i}|^4$$

$$P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

· There are no significant matter effects en-route.

If densities were high enough for that, ν's would be absorbed anyway!

From current knowledge of U

Construct propagation matrix P.

$$P = \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{\mu e} & P_{\mu\mu} & P_{\mu\tau} \\ P_{\tau e} & P_{\tau\mu} & P_{\tau\tau} \end{pmatrix}$$

Find: $(\theta_s \approx 30^\circ)$

$$P = \frac{1}{32}\begin{pmatrix} 20 & 6 & 6 \\ 6 & 13 & 13 \\ 6 & 13 & 13 \end{pmatrix}$$

Final flavor mix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = P \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_{initial}$$

J. Learned & S.P. (1995)

$$\longrightarrow = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \text{ if } \begin{pmatrix} \; \end{pmatrix}_{ini} = \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix}$$

Note: General result for many U's for (1,2,0)

$$= \begin{pmatrix} 1 \\ 2 \\ 2 \end{pmatrix} \text{ if } \begin{pmatrix} \; \end{pmatrix}_{ini} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

· $U_{e3} \simeq 0$ & $\nu_\mu - \nu_\tau$ mixing max.

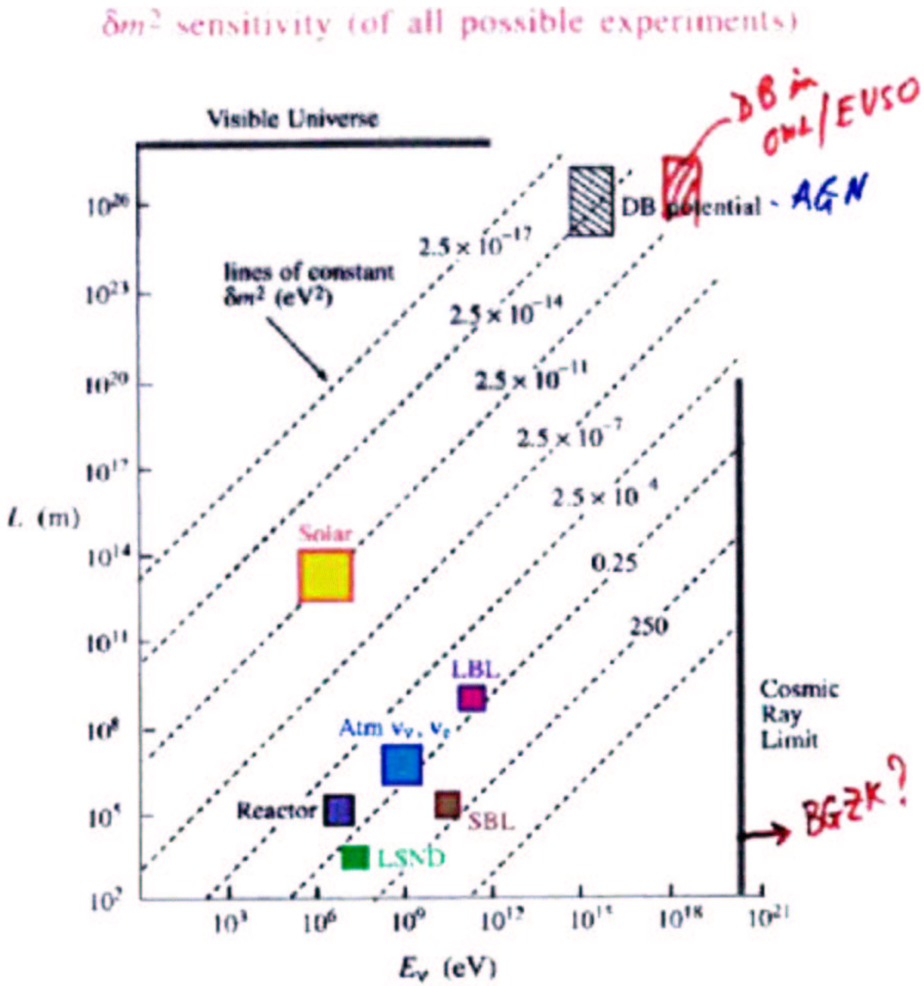
$\Rightarrow$ $e/\mu/\tau = 1/1/1$ if start w. 1/2/0.

$$U = \begin{pmatrix} c & s & 0 \\ -s/\sqrt{2} & c/\sqrt{2} & 1/\sqrt{2} \\ s/\sqrt{2} & c/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

$$\Rightarrow \quad P = \begin{pmatrix} 1-\frac{1}{2}A & \frac{1}{4}A & \frac{1}{4}A \\ \frac{1}{4}A & \frac{1}{2}(1-\frac{1}{4}A) & \frac{1}{2}(1-\frac{1}{4}A) \\ \frac{1}{4}A & \frac{1}{2}(1-\frac{1}{4}A) & \frac{1}{2}(1-\frac{1}{4}A) \end{pmatrix}$$

$$\Rightarrow \quad P\begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}.$$

Deviations from 1/1/1 go as $U_{e3}^2 \lesssim$ 3-4 %



The "Learned" Plot

When is final flavor mix NOT

$\nu_e/\nu_\mu/\nu_\tau = 1/1/1$?

1. When initial flux is NOT 1/2/0. (environment at production)

2. ν Decay:

If ν_i is unstable, then in propagation matrix $|U_{\alpha i}|^2$ is now

$$|U_{\alpha i}|^2 \exp\left(-\frac{L}{E}\frac{m_i}{\tau_0^i}\right)$$

rest frame lifetime

If τ_0^i short enuf, this term goes to zero.

If only the lightest survives, then either ν_1 (normal hierarchy) or ν_3 (inverted ") arrives at earth.

If ν_1 survives:

Flavor mix on arrival:

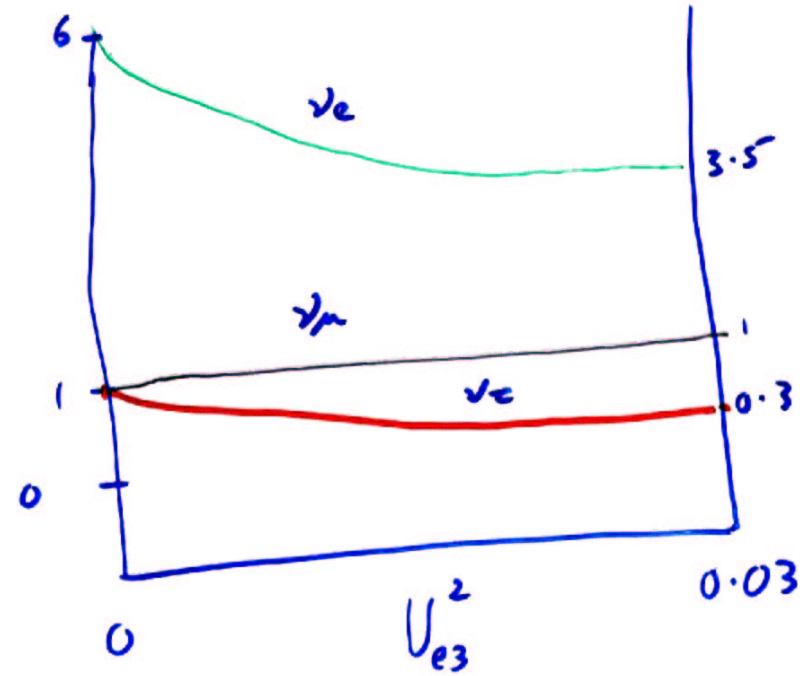
$$\nu_e/\nu_\mu/\nu_\tau = |U_{e1}|^2/|U_{\mu 1}|^2/|U_{\tau 1}|^2$$
$$= c^2/\tfrac{1}{2}s^2/\tfrac{1}{2}s^2$$
$$= 6/1/1 \quad (\text{for } \theta \sim 30^\circ)$$

If ν_3 survives:

$$\nu_e/\nu_\mu/\nu_\tau = \varepsilon^2/1/1 \sim \underline{0/1/1}$$
$$\varepsilon^2 < 0.04$$

These flavor mixes are very different from the 1/1/1 and from each other & distinguishable. Signatures for Decays.

Effect of $U_{e3} \neq 0$ on Decay Signature.



$\longrightarrow$ $e/\mu/\tau = 3.5/1/0.3$

Still far from 1/1/1

Daughters

In decay models:

$$\left.\begin{aligned}\nu_i &\to \nu_{jL} + \chi \\ &\to \bar{\nu}_{jR} + \chi\end{aligned}\right\}\ \text{Both take place}$$

Majorana : Both active

Dirac : One active.

Include daughters (with degraded energies). [Depends on δm^2_{ij}]. [& or not]

· full energy: $\phi_\alpha(E)$

$$\longrightarrow \sum_{i,\beta} \phi^\circ_\beta(E)\, U^2_{\beta i}\, U^2_{\alpha i} + \sum_{ij\beta} \phi^\circ_\beta(E)\, |U_{\beta j}|^2 |U_{\alpha i}|^2 B_{i\to}$$

(This when i & j nearly degenerate)

· When $m_i \gg m_j$, energy is degraded.

$$\phi_\alpha(E) = \sum_{i,\beta} \phi^\circ_\beta(E)\, |U_{\beta i}|^2 |U_{\alpha i}|^2$$

$$+ \int_E^\infty dE' \sum_{ij\beta} \phi^\circ_\beta(E')\, |U_{\beta j}|^2 |U_{\alpha i}|^2 B_{j\to i} \times \frac{1}{\Gamma(E')} \frac{d\Gamma(E', E)}{dE}$$

$$\frac{1}{\Gamma}\frac{d\Gamma(E', E)}{dE} = \frac{E}{E'^2} \quad (\text{non-flip})\ \nu \to \nu$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{dE} = \frac{E' - E}{E'^2} \quad (\text{flip})\ \nu \to \bar{\nu}$$

(only Majorana)

To proceed further, assume ϕ° (source spectrum) is power law:

$$\phi^\circ(E) \sim E^{-\alpha}. \Rightarrow$$

$$\phi_\alpha(E) = \sum_{i\beta} \phi^\circ_\beta(E)\, |U_{\alpha i}|^2 |U_{\beta i}|^2 + \frac{1}{\alpha} \sum_{ij\beta} \phi^\circ_\beta(E)\, |U_{\beta j}|^2 |U_{\alpha i}|^2 B_{j\to i}$$

· Normal Hierarchy

Unstable States	B.R.	Daughters	$\nu_e / \nu_\mu / \nu_\tau$
3,2	–	–	6/1/1
3	–	sterile	2/1/1
3	$B_{32} = 1$	full E	1.4/1/1
		degr. ($\alpha=2$)	1.6/1/1
3	$B_{31} = 1$	full E	2.8/1/1
		degr ($\alpha=2$)	2.4/1/1
3	$B_{31} = 1/2$, $B_{32} = 1/2$	deg.	2/1/1

These signatures quite unique.
No other physics seems to duplicate them. (e.g. magn. moments)

Hence:

if $\nu_e/\nu_\mu/\nu_\tau = 1/1/1$

→ oscillations (conventional)

if $\nu_e/\nu_\mu > 1$ (significantly)

⇒ · Decay & normal hierarchy.

$\nu_e/\nu_\mu << 1$

· Decay w. inverted hierarchy

(or initial flux not normal)

Detection of flavors

ν_μ's : μ Tracks thru the Detector with long range.

ν_e's : E.M. Showers [competetion with hadronic showers from N.C. showers events from all flavors. ν_e, ν_μ, ν_τ]

ν_τ's: "Double Bang" events. Learned & S.P. (1995)

At $E_\nu \sim$ PeV, $L_{abs} \sim D_\oplus$, so only downgoing events.

Idea of Double Bang

for $E > 10$ PeV, $L > 1$ km

Need other techniques. Air Showers

Decay Length of τ

$L \sim \gamma c \tau_0$

~ 100 m @ $E_\tau \sim 1$ PeV.

CC interaction $\nu_\tau \to \tau + x.$ (E_1)

x: hadron shower

$\to$ # photons in $\hat{c}$ $\sim 10^{11}$

$\tau \to$ 100m Track minimum ionizing # phot $\sim 10^6$

τ decay (E_2) $\tau \to h\nu$, $\to e\nu$ } 80 % B.R.

$\to$ second shower # $\gamma \sim 2 \cdot 10^{11}$.

· The Distance Bet. showers = c × Time Delay.

- Other signatures:

$$E_2 \sim 2E_1$$

(Because $E_1 \sim \langle y \rangle E_\nu \sim 1/4\, E_\nu$

$E_2 \sim (1-\langle y \rangle) \times \frac{2}{3} \times E_\nu \sim 1/2\, E_\nu$)

- $L \lesssim 10$m.
- Other BG's small.

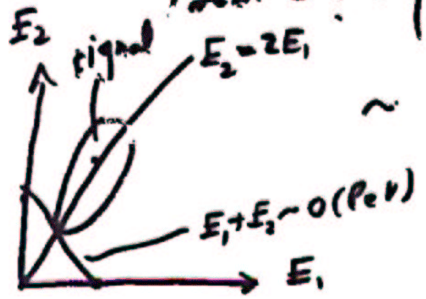
e.g. $\nu_e + N \to D_s \to \tau$ $\sim 10^{-3}$

most serious: $\nu_\mu \to \mu \to$ travels 1km without rad.

& has "catastrophic" Brem. fakes Double Bang

$$\text{Prob.} = ? \sim \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{10\,\text{cm}}{R_\mu}\right)\left(\frac{\Delta E}{E}\right)$$

$\sim 0.3\ \%$ (of ν_μ cc)



Event Classification

- Double Bang / single bang (Lollipop) $\longrightarrow$ $\nu_\tau + \bar{\nu}_\tau$
- μ Tracks $\longrightarrow$ $\nu_\mu + \bar{\nu}_\mu$
- cascades $\longrightarrow$ $\nu_e + \bar{\nu}_e$ (CC+NC)
  $\left.\begin{array}{l}\nu_\mu + \bar{\nu}_\mu \\ \nu_\tau + \bar{\nu}_\tau\end{array}\right\}$ {NC}

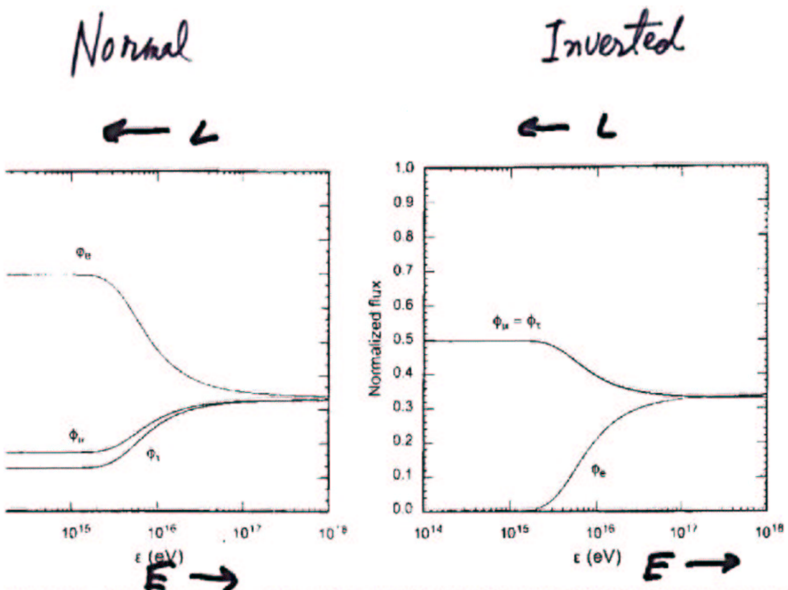
- Glashow Resonance events $\bar{\nu}_e$

$\bar{\nu}_e + e^- \to W^- \to X$
(on shell)

$E_{\bar{\nu}_e} \sim 6.4$ PeV

From these determine relative fluxes of

ν_e, ν_μ, ν_τ.



...ependence of normalized ν_e, ν_μ and ν_τ fluxes for the two-body decay of the two upper mass eigenstates ... source at $L = 100$ Mpc from Earth and $\tau/m = 1$ s/eV. The left pane shows the result for a normal mass ... ht pane shows the result for an inverted mass hierarchy. With suitable rescaling of the neutrino energy (cf ... plots apply for any combination of path length and reduced lifetime.

Barenboim & Quigg

In principle, with enuf events at different energies (or distances) τ can be measured with changes in flavor mixes.

Similar to L/E plot for oscillations (Super-K)

If flavor mix identified for a few (~ few dozen?) events in KM3, Then, find

$$e/\mu/\tau = \alpha/1/1$$

$\alpha = 1 \Rightarrow$ { Confirm SM · Initial 1/2/0 · Osc. OR Source → 1/1/1 !! e.g. Z decays!

$\alpha \simeq 1/2 \Rightarrow$ { Source emits 0/1/0 & Osc.

$\alpha > 1$ Decay w. Normal Hierarchy

$\alpha \ll 1$ [$\tau < 10$ s/eV] Decay w. Inverted Hierarchy.