Comments on: Flavor Mix and Fluxes of High Energy Astrophysical Neutrinos

Sandip Pakvasa
University of Hawaii
Honolulu

Collaborators off and on in addition to John Learned:

- Tom Weiler, John Beacom, Nicole Bell, Dan Hooper, Werner Rodejohann, and more recently Anjan Joshipura and Subhendra Mohanty….

We make as many assumptions as we please:

- Assume that ν sources with energies upto and beyond PeV exist and that the ν's reach us.
- Assume that ν detectors large enuf will exist (Icecube, KM3 etc…..multi KM3)
- Assume a ν signal WILL be seen (with significant rates)
- Assume that ν flavors (e,μ,τ) CAN be distinguished

- Existence of High Energy Gammas suggests that High energy accelerators in space EXIST
- P+P and P+γ collisions produce π^0's and π^+ 's
- $\pi^0 \rightarrow \gamma$'s $\rightarrow$ observed.....(?)
- $\pi^+ \rightarrow \nu$'s.......hence high energy ν 's must exist!
- At detectable, useful fluxes?
- Maybe YES?

FLAVORS at the Source: The variety of initial flavor mixes

- Conventional: P +P → π + X, π → ν_μ + μ, μ → ν_μ + ν_e hence: $\nu_e / \nu_\mu = 1/2$
- Same for P + γ, except no anti-ν_e.
- Damped muon sources: if μ does not decay or loses energy: No ν_e's, and hence $\nu_e / \nu_\mu = 0/1$
- Pure Neutron Decay or Beta-Beam sources: n → anti-ν_e, hence $\nu_e/\nu_\mu = 1/0$
- Prompt sources, when π's absorbed and only heavy flavors contribute and $\nu_e/\nu_\mu = 1$, such a flavor mix also occurs in muon damped sources at lower energies from μ decays. (Winter et al,2010)
- In general, flavor mix will be energy dependent……

Types of sources and initial flavor mixes

Most conventional sources are expected to make neutrinos via π/K decays which leads via the decay chain π/K→μ to an approx. flavor mix:

$\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0

Sometimes μ's lose energy or do not decay, in either case the effective flavor mixed becomes:

e:μ:τ = 0:1:0

In some sources this can happen at higher energies and then the flavor mix can be energy dependent.

There are sources in which the dominant component is from neutron decays, and then resulting (beta)beam has:

e:μ:τ = 1:0:0

Recently, sources called slow-jet supernova have been

discussed, where the π's interact rather than decay, then the ν flux

is dominated by short-lived heavy flavor decays, with resulting mix (so-called prompt, due to short-lived heavy flavors):

e:μ:τ = 1:1:0

References for source types:

- **Damped muon sources: Rachen and Meszaros, PRD 58(1998), Kashti and Waxman, astro-ph/057599(2005).**
- **Beta-Beam sources: Anchordoqui et al, PLB793(2004).**
- **Prompt sources: Razzaque et al., PRD73(2006), Gandhi et al., arXiv:0905.2483.**
- **Hidden sources: Mena et al., astro-ph/061235(2006) optically thick sources.**
- **Interesting new paper: Hummer et al.:arXiv:1007.0006**

Generic accelerators on Hillas Plot

It is understood that most sources yield equal fluxes of neutrinos and anti-neutrinos with the

Neutrinos from "GZK" process: BZ neutrinos:

- Berezinsky and Zatsepin pointed out the existence/inevitability of neutrinos from :
- $P_{CR} + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$
- Flavor Mix: below 10 Pev: (n decays)pure Beta-Beam: $e:\mu:\tau = 1:0:0$
- Above 10 PeV: conventional(π decays) :$e:\mu:\tau$ =1:2:0

(due to Engel et al. PRD64,(2001))

Current Knowledge of Neutrino Mixing and Masses

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{MNSP} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\delta m_{32}{}^2 \sim 2.5\ .10^{-3}\ eV^2$, $\delta m_{21}{}^2 \sim 8\ .10^{-5}\ eV^2$

$$U_{MNSP} \sim U_{TBM} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & \varepsilon \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \end{pmatrix}$$

($\varepsilon \sim 0.15$:DB,RENO,DC(2012))

Unkown:

Mass Pattern: Normal or Inverted:

3 ________   2________

1 ________   phase δ?

2________

1________   3________

Effects of oscillations on the flavor mix are very simple:

- $\delta m^2 > 10^{-5}$ eV^2 , hence $(\delta m^2 L)/4E >> 1$ for all relevant L/E, and
- $\rightarrow \sin^2(\delta m^2 L/4E)$ averages to ½
- survival and transition probablities depend only on mixing:
- $P_{\alpha\alpha} = \sum_i |U_{\alpha i}|^4$
- $P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$

In this tri-bi-maximal approximation, the propagation

$$P = 1/18 \begin{bmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{bmatrix}$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}_{earth} = \mathbf{P} \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}_{source}$$

Flavor Mix at Earth:

Beam type	Initial	Final
Conventional (pp,pγ)	1:2:0	1:1:1
Damped Muon	0:1:0	4:7:7
Beta Beam(n decay)	1:0:0	5:2:2
Prompt	1:1:0	1.2:1:1

Damped Muon produces a pure muon decay beam at lower energies with same flavor mix as the Prompt beam!

Discriminating flavors

- The ratios used to distinguish various flavor mixes are e.g. f_e (e/(e+μ+τ) and R(μ/[e+τ])

Source type	f_e	R
Pionic	0.33	0.5
Damped-μ	0.22	0.64
Beta-beam	0.55	0.29
Prompt	0.39	0.44

- It has been shown that R and/or f_e can be determined upto 0.07 in an ice-cube type detector. Hence pionic, damped μ, and Beta-beam can be distinguished but probably not the prompt

Can small deviations from TBM be

Corrections due to ε/θ_{13} are rather small(<10%) and we will neglect them with a few exceptions…

Measuring such small deviations remains impractical for the foreseeable future

By the same token the corrections due to a small mixing with a light sterile neutrino are

In addition, sources are never "pure" meaning:

- Conventional/pp: after including μ polarization and effects due to K, D etc decays, the mix changes from1:2:0 to approx. 1:1.85:ε, (ε < 0.01)
- Damped μ sources do not have exactly 0:1:0 but probably more like δ:1:0 with δ of a few %.......and similarly for Beta-beam.
- For our present purposes, we will neglect such corrections as well.

Lipari et al(2007), Rodejohann, Weiler, SP(2008)

To summarise, small deviations in flavor content NOT easy to

But it should be possible to measure LARGE deviations from the canonical flavor mix.

For our purposes here, let us agree to

use the conventional flavor mix as canonical.

In this case the initial mix of 1:2:0 is expected to become 1:1:1; at earth.

So we look for large deviations from this.

The current bounds on non-observation of neutrinos from

- Correspond to a limit on flux of ν_μ's

to about a factor of 4(3.7) below the somewhat conservative Waxman-Bahcall bound. (the

bound is for each flavor assuming 1:1:1 mix)

So this is in addition to the factor of 2 suppression

for ν_μ inherent in the 1:1:1 mix…

Can this be due to neutrino properties or does it

have some more mundane explanation?

R. Abbasi et al. Nature, 484,351(2012)

Furthermore there has been no hints yet of a signal from

AGNS or other sources of high energy neutrinos in form of

ν_μ events………(although there are those two shower events at 1-10 PeV reported at Neutrino 2012)

The two shower events are consistent with having energies of 6.3 PeV!

An Interlude!

- Why is that interesting?
- This may be a (first) evidence of a signal from ETI
- Why would ETI send focussed beams to us?
- Don’t know and don’t care! Many possibilities……

Perhaps they have been tracking us and realise that as a TES society we are ready to receive and interpret neutrino beams!

- Beam Choice: 6.3 PeV electron anti-neutrinos! Why? The cross-section is large

due to Glashow resonant enhancement,

by(nu_e_bar+e->W)

producing an on-shell W with a resultant shower-no BG and unique energy.

Range in water at this energy about 100km,catch horizontal and downgoing events (about 1 %)

Details of the pion accelerator and artist's conception etc

And other details can be found in:

J. Learned, S. P. and A. Zee; "Galactic Neutrino Communication"; Phys. Lett. B671, 15(2009).

Large deviations:

Deviations from 1:1:1 – Particle Physics

Exotic neutrino properties

- Neutrino decay (Beacom, Bell, Hooper, Pakvasa, & Weiler)
- CPT violation (Barenboim & Quigg)
- Oscillation to steriles (Dutta, Reno and Sarcevic)
- Oscillations with tiny delta δm^2 (Crocker, Melia, & Volkas; Berezinsky et al.)
- Pseudo-Dirac mixing (Beacom, Bell, Hooper, Learned, Pakvasa, & Weiler)
- Magnetic moment transitions (Enqvist, Keränen, Maalampi)
- Mass varying neutrinos (Fardon, Nelson & Weiner; Hung & Pas)
- ...

How many ways can the flavor mix deviate from 1:1:1 ?

1. Initial flux different from canonical: e.g.

   the damped muon scenario. In this case the flavor mix will be:

   4:7:7

   similarly for the beta beam source,

   the flavor mix will be:

   5:2:2

   instead of 1:1:1

2. Neutrino Decay:

Do neutrinos decay?

Since δm's ≠ 0, and flavor is not conserved, in general ν's will decay. The only question is whether the lifetimes are short enuf to be interesting and what are the dominant decay modes.

What do we know?

- Radiative decays: $\nu_i \to \nu_j + \gamma$:

  m.e.: $\Psi_j(C + D\gamma_5)\sigma_{\mu\nu} \Psi_i F_{\mu\nu}$

SM: $1/\tau = (9/16)(\alpha/\pi)G_F^2/\{128\pi^3\}(\delta m_{ij}^2)^3/m_i |\Sigma_\alpha m^2_\alpha/m_W^2(U_{i\alpha}U_{j\alpha}^*)|^2 \rightarrow \tau_{SM} > 10^{45}$ s

(Petcov, Marciano-Sanda)(1977)

Exptl. Bounds on $\kappa = e/m_i[|C|+|D|^2]^{1/2} = \kappa_0\mu_B$

From $\nu_e + e \to e + \nu'$: $\kappa_0 < 10^{-10}$ (PDG2010), this corresponds to: $\tau > 10^{18}$ s.

Bounds for other flavors somewhat weaker but still too strong for radiative decay to be

Invisible Decays:

- $\nu_i \to \nu_j + \nu + \nu$: Exptl Bounds:

$F < \varepsilon G_F$, $\varepsilon < O(1)$, from invisible width of Z

Bilenky and Santamaria(1999):

$\tau > 10^{34}$ s

$\nu_{iL} \to \nu_{jL} + \varphi$: $g_{ij}\, \Psi_{jL}\, \gamma_\mu\, \Psi_{jL}\, d_\mu \varphi$

If isospin conserved: invisible decays of charged leptons governed by the same g_{ij}, and bounds on $\mu \to e + \varphi$, and $\tau \to \mu/e + \varphi$ yield bounds

Conclusion: Only "fast" invisible decays are Majoron type couplings

- $g\ \nu^C_{jR} \nu_{iL}\ X$:
- I(isospin) can be a mixture of 0 and 1(G-R, CMP)
- The final state ν can be mixture of flavor/ sterile states........
- Bounds on g from π & K decays
- Barger,Keung,SP(1982),Lessa,Peres(2007), $g^2 < 5.10^{-6}$
- SN energy loss bounds: Farzan(2003): $g < 5.10^{-7}$
- $g^2 < 5.10^{-6}$ corresp. to $\tau > 10^{-8}$ s/eV

Current experimental limits on τ_i:

- $\tau_1 > 10^5$ s/eV SN 1987A

  B. o. E. Careful analysis.
- $\tau_2 > 10^{-4}$ s/eV (Solar) 10^{-4}-10^{-2}s/eV Beacom-Bell(2003),KamLand(2004)

  $\tau_3 > 3.10^{-11}$s/eV (Atm) 9.10^{-11} s/eV

  Gonzalez-Garcia-Maltoni(2008)

Cosmology: WMAP→free-streaming ν's→

$\tau > 10^{10}$ s/eV at least for one ν…

Hannestad-Raffelt(2005), Bell et al.(2005)

(With L/E of TeV/Mpsc or PeV/1000Mpsc, can reach τ of 10^4 s/eV)

These bounds depend crucially on free-streaming and whether one or all neutrinos are free-streaming.

When ν_i decays, $U_{\alpha i}{}^2$ gets multiplied by the factor $\exp(-L/\gamma c\tau)$ and goes to 0 for sufficiently long L. For normal hierarchy, only ν_1 survives,

and the final flavor mix is simply (SP 1981):

$$e:\mu:\tau = |U_{e1}|^2 : |U_{\mu 1}|^2 : |U_{\tau 1}|^2$$

$$\sim 4:1:1$$

These flavor mixes are drastically different from canonical 1:1:1 and easily distinguishable.

Beacom et al(2003)

Example of large effects from a small non-zero θ_{13} and δ:

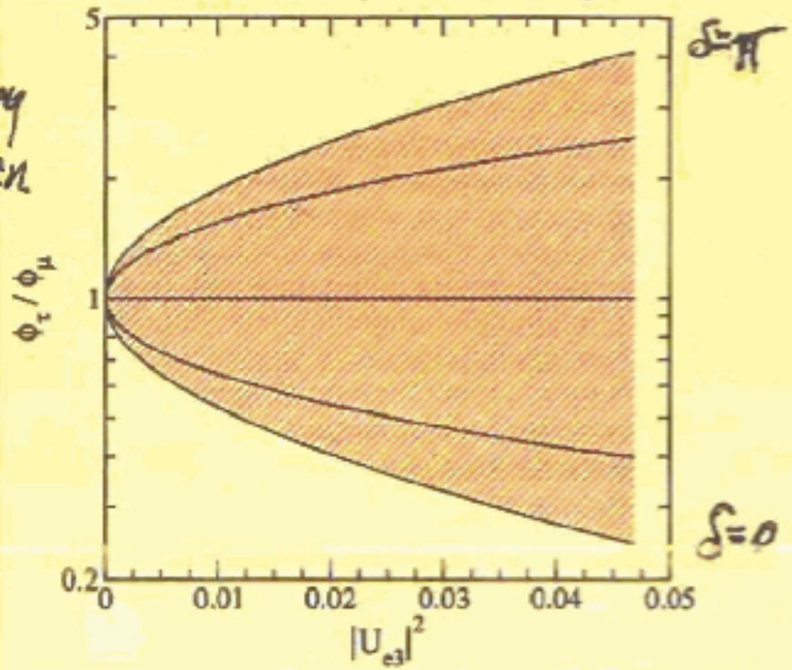
Measuring U_{e3} & δ ($\cos\delta$)

Neutrino decay, and sensitivity to θ_{13} and the CP phase δ

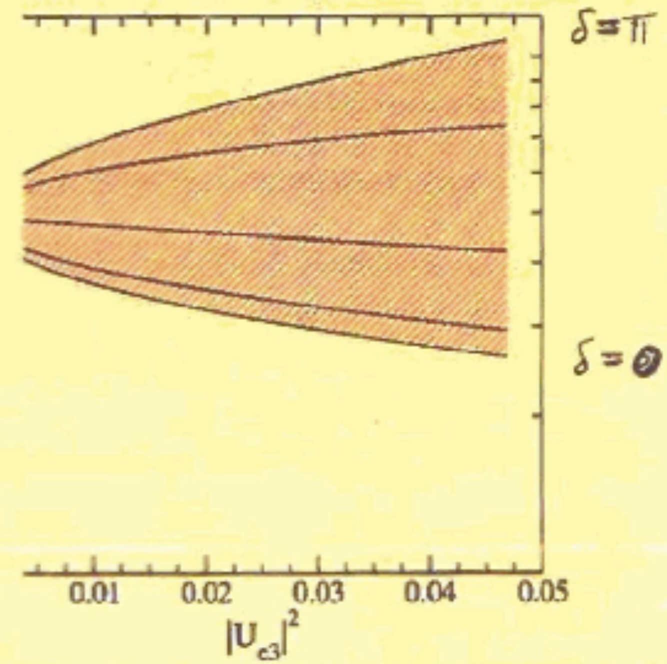
Nonzero θ_{13} breaks mu-tau symmetry

τ/μ Symmetry broken

Tau/mu components of ν_1



e/mu ratio in decay scenario



Beacom, Bell, Hooper, Pakvasa & Weiler 13

Normal Hierarchy τ/μ can be between 5 & 0.2

Caveat about inverted hierarchy and decay:

In this case things are a bit more subtle:

Since the limit on lifetime of ν_1 is 10^5 s/eV

and we are unlikely to probe beyond 10^4 s/eV (this way); ν_1's will not have had enuf time to decay and so both ν_1 and ν_3 will survive

with only ν_2 having decayed, leads

to a final flavor mix of 1:1:1…. !

Of course the net flux will have decreased by 2/3.

More complex decay scenarios in e.g.

Bhattacharya et al.arXiv:1006.3082, Meloni and Ohlsson, hep-ph/

Comments about decay scenario

- With many sources at various L and E, in principle(!) it would be possible to make a L/E plot and actually measure lifetime. E.g. one can see the e/μ ratio go from 1 to 4 for the NH case.

For relic SN signal, NH enhances the rate by about a factor of 2, whereas IH would make the signal vanish (for complete decay)! Relic SN can probe τ beyond 10^4 s/eV and so it becomes possible for ν_1 to decay as well…..

Barenboim-Quigg, Fogli et al(2004)

Effects on absolute fluxes in decay scenarios:

- In normal hierarchy, if only ν_1 survives:

  ν_μ flux goes down by a factor of 4 from the original flux at the source(a further factor of 2 from the simple oscillation).

  ν_e flux is enhanced from the original by a factor of 2.

  Early Universe neutrino count is modified to 3+4/7

This is if the decay is always into other flavor neutrinos. If the decay is into sterile neutrino…..it is a different story.

But if the decay is into a sterile neutrino then (NH)…….

ν_3 and ν_2 simply disappear and only ν_1 survives but at a smaller flux. The final fluxes are then:

ν_e : 2/3 of the original flux

ν_μ : 1/6 of the original flux

Other implications: ν-counting in early universe modified by 3 -> 4+4/7……….

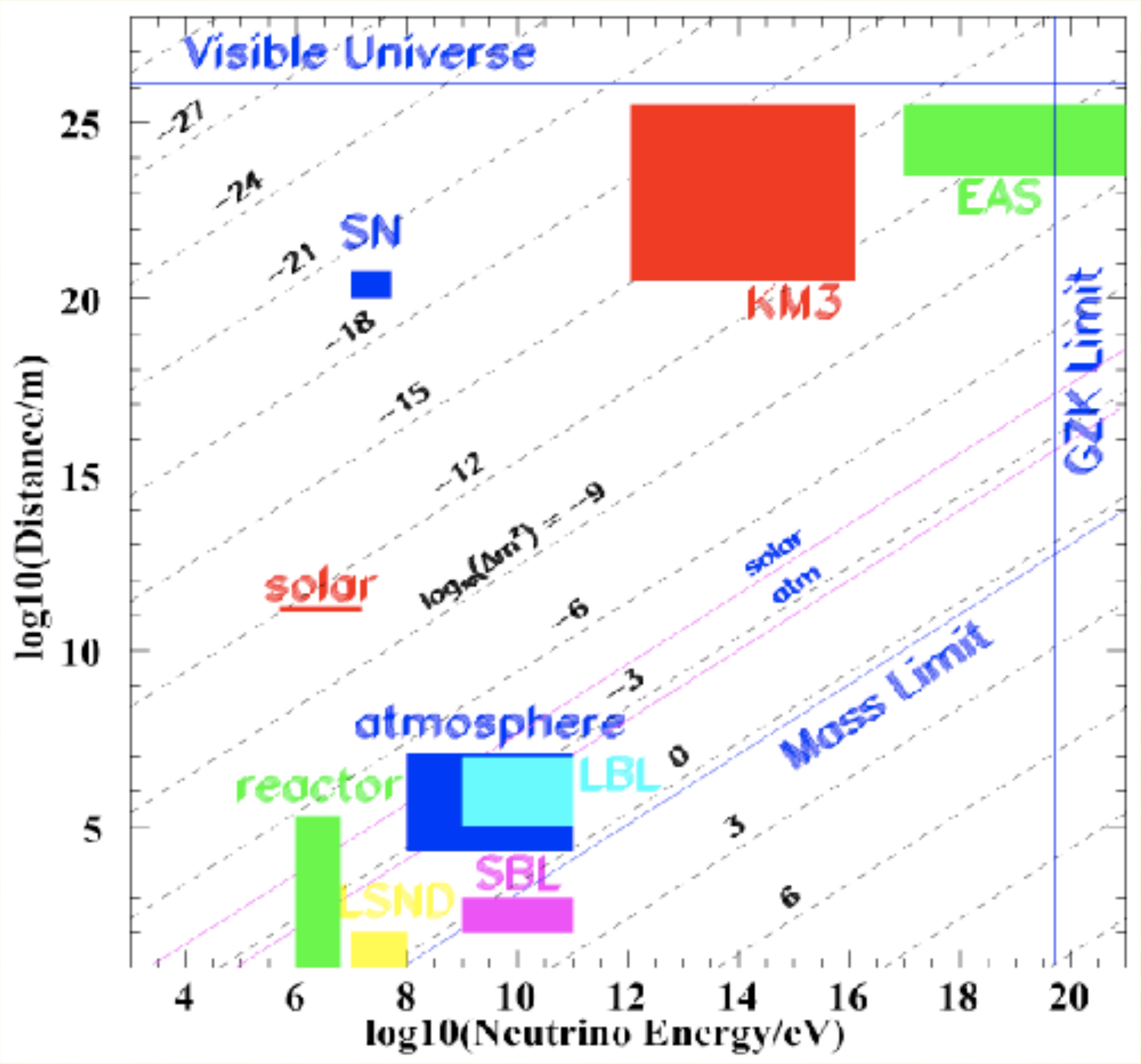
Ultimate long-baseline experiment

Astrophysical sources provide baselines almost as big as the visible universe.

This allows a sensitivity to oscillations with tiny $\delta \mathbf{m}^2$

Eg. Oscillation modes that have a sub-dominant or completely negligible effect on the solar or atmospheric neutrinos may show up here.

Crocker, Melia and Volkas (2000, 2002)
Berezinsky, Narayan and Vissani (2002)
Keranen, Maalampi, Myyrylainen and Riittinen (2003)
Beacom, Bell, Hooper, Pakvasa, Learned, and Weiler (2004)



Beacom, Bell, Hooper, Pakvasa, Learned, and Weiler (2004) PRL, 92, 011101 (2004)

4. Pseudo-Dirac Neutrinos: (Sometimes called Quasi-Dirac)

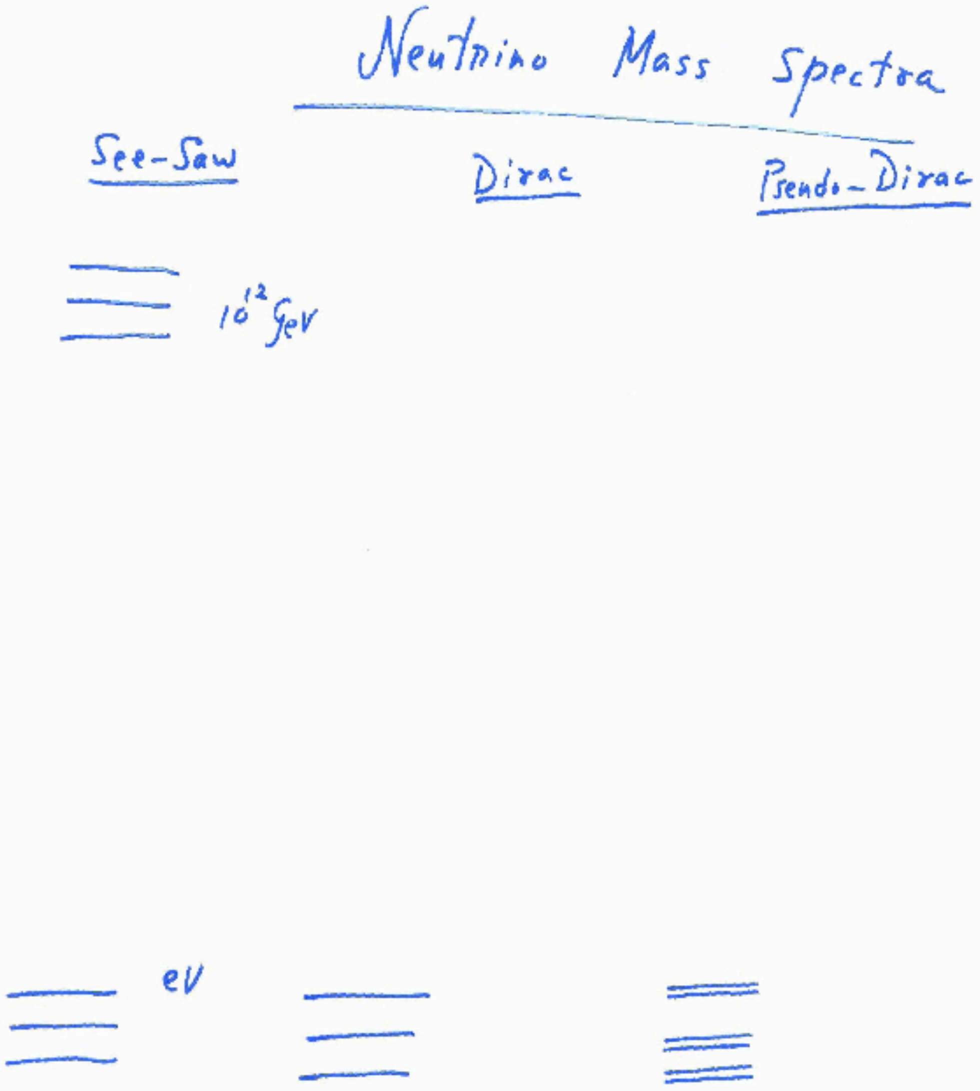
If no positive results are found in neutrino-less double-beta-decay experiments, it behooves us to consider the possibility that neutrinos are Dirac or Pseudo-Dirac

Idea of pseudo-Dirac neutrinos goes back to Wolfenstein, Petcov and Bilenky - Pontecorvo (1981-2).

Also a recent clear discussion in Kobayashi-Lim(2001).

These arise when there are sub-dominant Majorana mass terms present along with dominant Dirac mass terms.

There is a somewhat different realisation, to be discussed later…..



The three δm^2's will be different, in general.

Generic (Majorana) mass matrix: $\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$

Pseudo-Dirac limit is where: $m_{L,R} << m_D$

Two closely degenerate, maximally mixed active and sterile states

(Kobayashi, Lim)

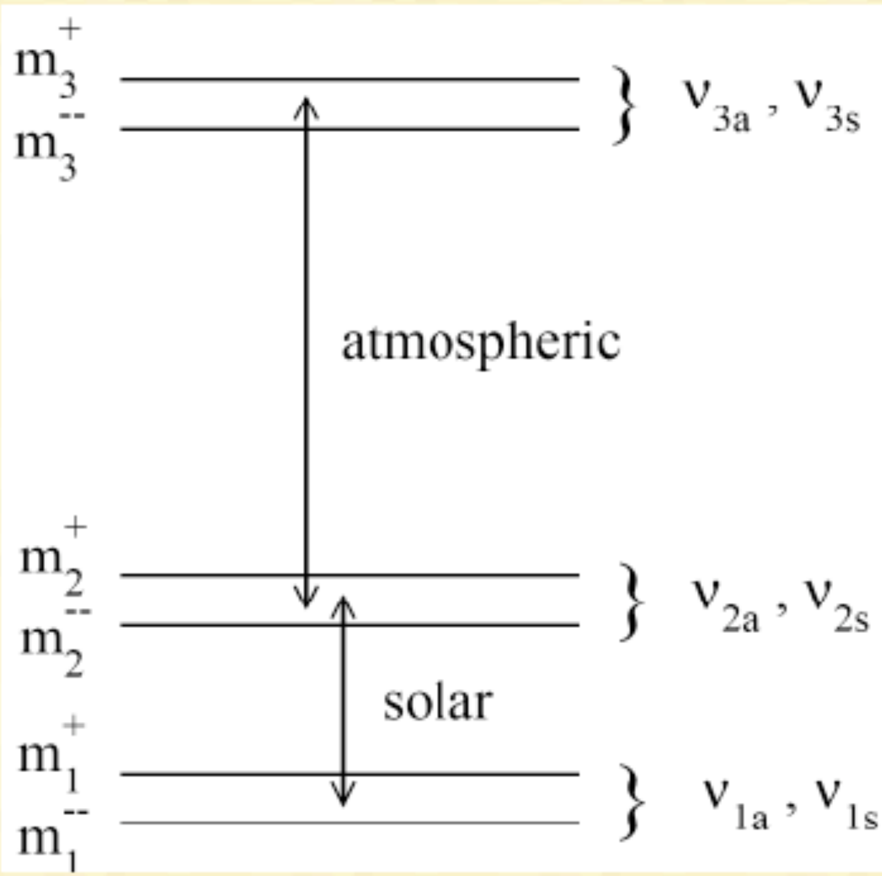
$$\nu_\alpha = \frac{1}{\sqrt{2}}\left(\nu^+ + i\nu^-\right) \qquad \nu_s = \frac{1}{\sqrt{2}}\left(\nu^+ - i\nu^-\right)$$

$m^+ \approx m^-$ $\quad$ $\delta m^2 << m^2$ $\quad$ $\theta \approx 45°$

The two closely degenerate states have opposite CP parity
– so their contributions cancel in neutrinoless double beta decay

$$\langle m \rangle_{eff}^{0\nu\beta\beta} = \sum U_{ei}^2\left(m_j^+ - m_j^-\right) \approx 0$$

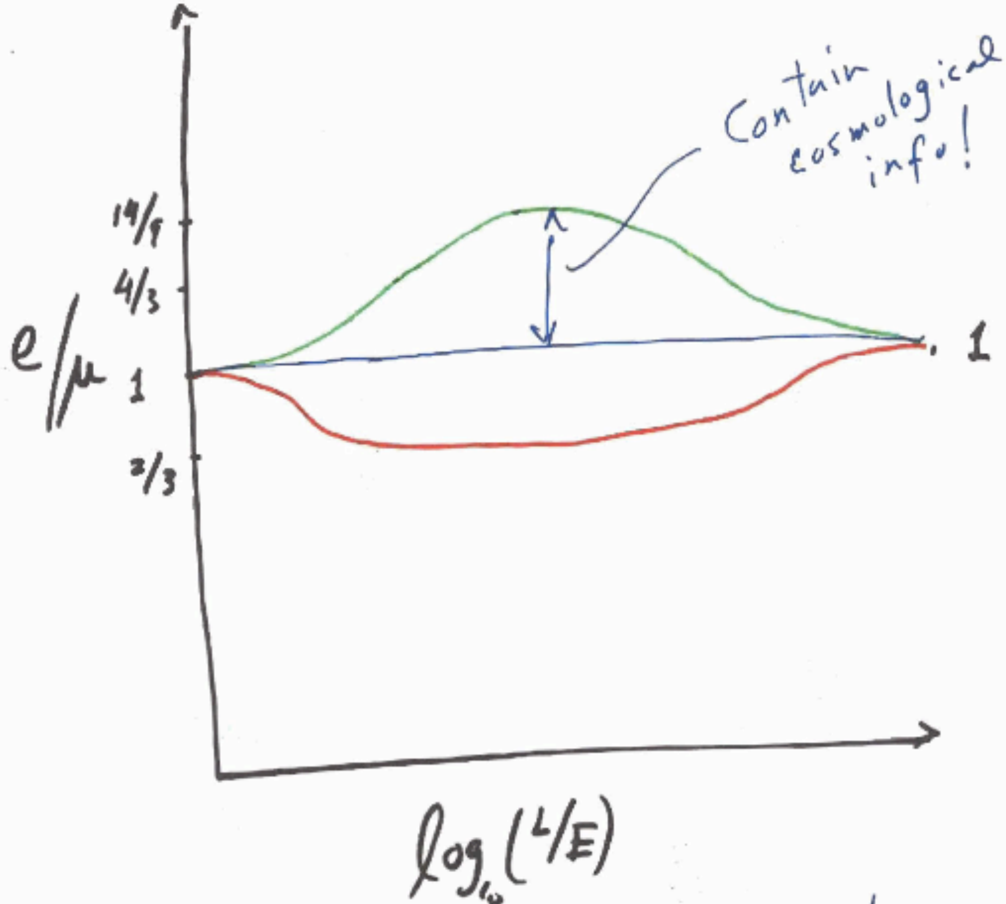
Pseudo-Dirac Neutrinos



Neutrinos appear to be Dirac, but in fact have subdominant Majorana mass terms.

→Oscillations driven by tiny mass differences.

→ Would show up in astro-nu flavor ratios.



Probing Pseudo-Dirac ν's

with $10^{-16}\,eV^2 \lesssim \delta m^2 \lesssim 10^{-12}\,eV^2$

In this case when δm^2 are as small or smaller than 10^{-12} eV^2, it is

- **The transition probability $P_{\alpha\beta}$ becomes:**

$P_{\alpha\beta} = \Sigma_j \mid U_{\alpha j} \mid^2 \mid U_{\beta j} \mid^2 (1 - \sin^2(\varphi_j))$, where

$\varphi_j = \{\delta m_j^2/4E\}f$, and f, the lookback distance is:

$f = (z/H) [1 -(3+q)/z.........]$ and z is red shift and H is Hubble parameter, q is de-acceleration etc............

And thus f contains cosmological information but measured by neutrinos. If enuf data is available, one can check whether red shift in neutrinos is identical to red shift in photons!

Implications for Neutrinoless Double Beta Decay: As mentioned before, it is unobservable!

Implications for absolute fluxes:

- When L/E becomes large enuf to separate the small δm^2s and change the flavor mix,

  the absolute flux of the flavor ν decreases by a factor of 2, and when this happens to all three, all decrease by that factor.

  So in this case the flavor fluxes decrease by another factor of 2. At very large L/E, when the fluxes have decreased by 2, the flavor mix eventually returns to the canonical 1:1:1 with half the flux gone into steriles.

Recent proposals:

- Mohapatra et al(2010): Main idea: Not all three are pseudo-Dirac, only one(or two) are pseudo-Dirac (the small mass difference generated radiatively) and the other remains Majorana

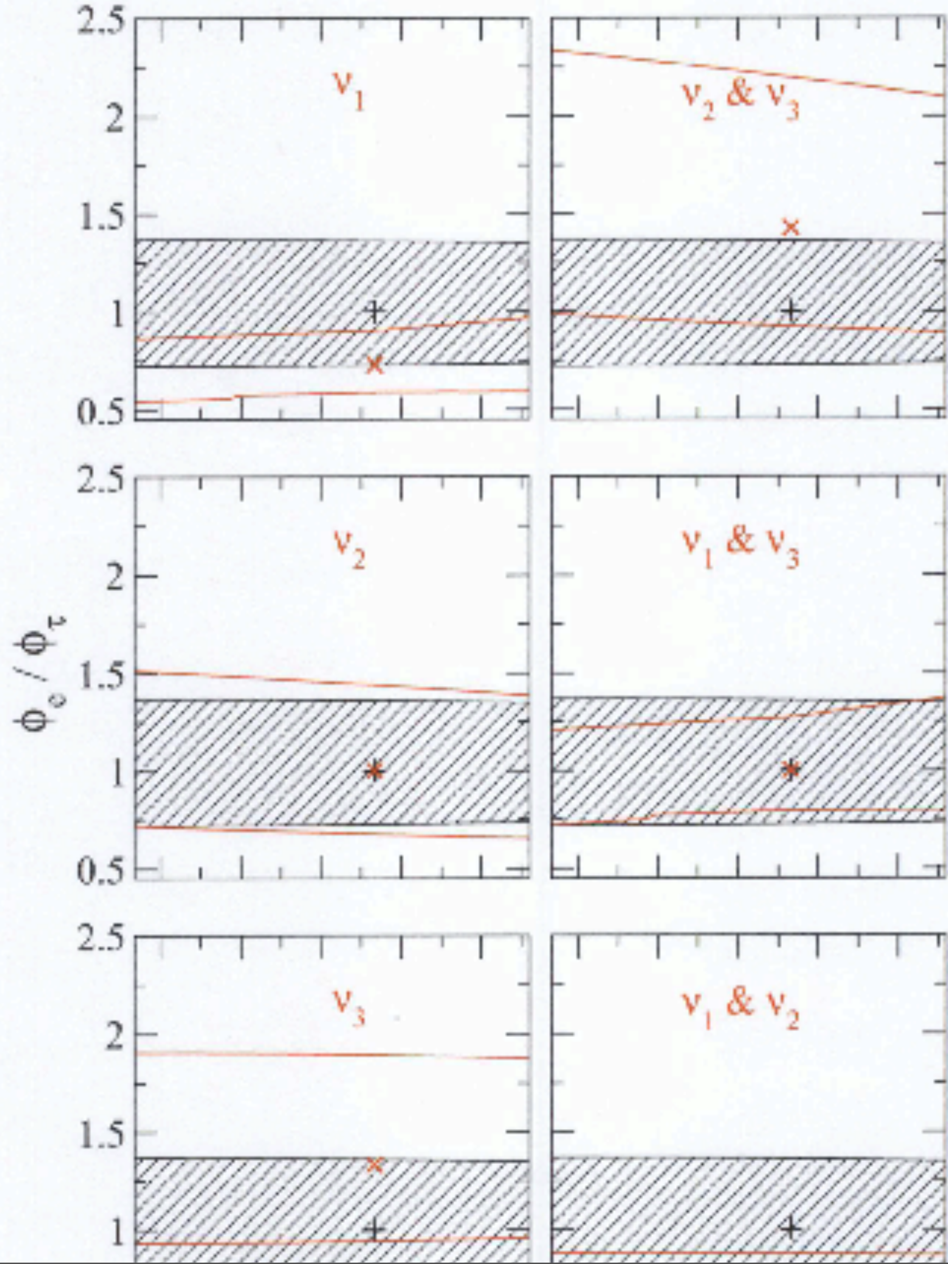
(goes under the names:Bimodal, schizophrenic)

Phenomenology essentially same as pseudo-Dirac case……for one or two flavors…..

These models were invented

for other purposes…..

Barry et al



5. A different realisation of pseudo-Dirac

- Discussed by Wolfenstein and Petcov in 1981/2
- If mass matrix for a single flavor looks like

$$\begin{matrix} a & b \\ b & -a+\delta \end{matrix}$$

When $\delta=0$ and a=b, get exact degeneracy and a Dirac state.

But when δ is not 0, the mass difference is governed by δ,

(may need fine tuning to keep mass difference small)

And the mixing angle is NOT maximal but can be arbitrary.

$\tan(2\theta) = b/a$.....Recently revived by Joshipura, Rindani and others(2000)

Why is this interesting?

For small mixing angle it may be possible to get MSW resonance effect and get a flavor convert almost completely to sterile! For example, in passage thru neutrino background .....

In this case only steriles arrive at earth! (Mohanty, Joshipura,SP)

For example: Lunardini-Smirnov(2001) showed that for large lepton asymmetries,

for δm^2 of 10^{-15} eV^2, E of a PeV, large conversion to sterile can happen..

For $E/\delta m^2 > 10^{31}$ eV^{-1}, MSW resonance can happen after production

Lunardini & Smirnov
hep-ph/009356

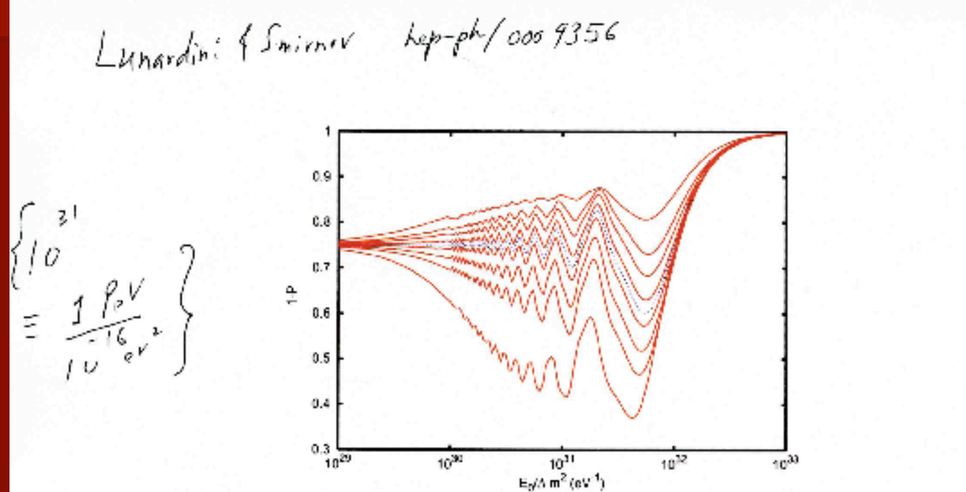


FIG. 9. The survival probability $1 - P(\nu_a - \nu_s)$ as a function of the ratio $E_0/\Delta m^2$ for various values of $F\eta$. From the upper to the lower curve: $F\eta = -20, -10, -6, -2, 0, 2, 6, 10, 20$; the dotted line represents the effect of vacuum oscillations ($F\eta = 0$). We have taken $\sin^2 2\theta = 0.5$ and production epoch $z = 3$.

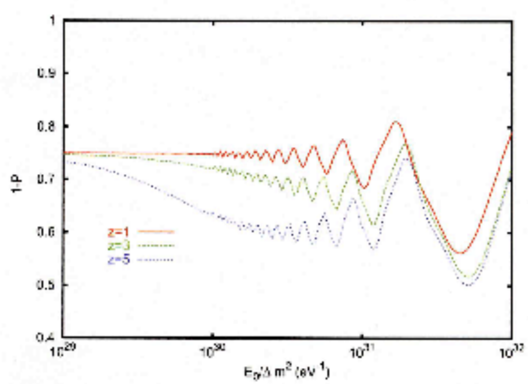


FIG. 10. The survival probability $1 - P(\nu_a - \nu_s)$ as a function of the ratio $E_0/\Delta m^2$ for various values of the production epoch z. We have taken $\sin^2 2\theta = 0.5$ and $F\eta = 6$.

Lunardini & Smirnov hep-ph/0009356

that the vacuum oscillation probability converges to $\sin^2 2\theta/2$ [7]. A substantial ($\sim 10\%$) deviation from the vacuum oscillation probability due to matter effect starts at $z \simeq 1$ for $F\eta \simeq 10$ and at $z \simeq 3$ for $F\eta \simeq 2$.

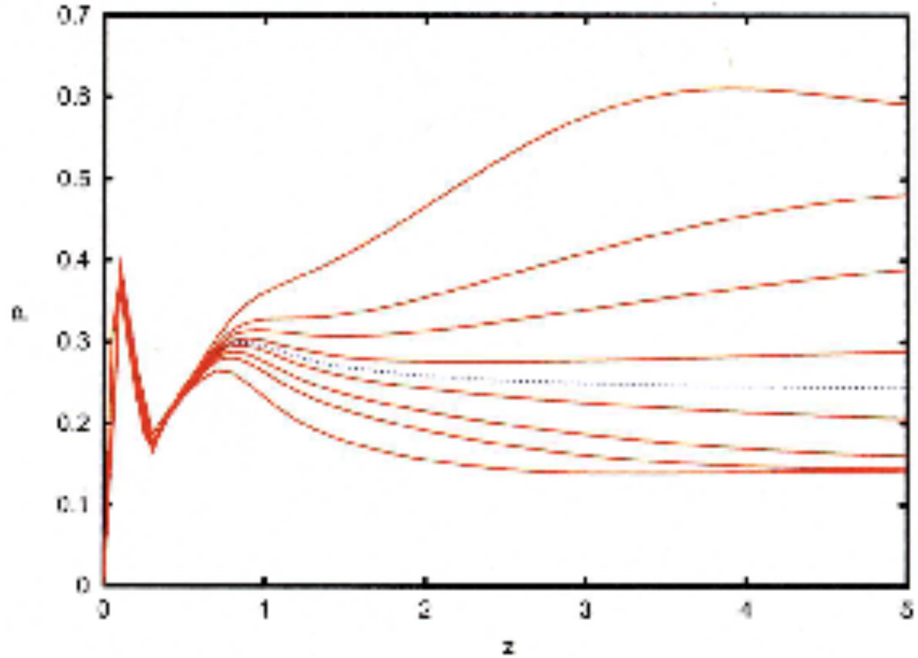


FIG. 8. The $\nu_e - \nu_s$ conversion probability P as a function of the production epoch z for various values of $F\eta$. From the upper to the lower curve: $F\eta = 20, 10, 6, 2, 0, -2, -6, -10, -20$; the dotted line represents the vacuum oscillations probability ($F\eta = 0$). We have taken $\sin^2 2\theta = 0.5$ and $E_0/\Delta m^2 = 10^{21}$ eV^{-1}.

An interesting possibility of MSW conversion of flavors into steriles in

Two recent papers have shown that high energy

ν's emitted in the annihilation of heavy dark matter wimps in the sun, may convert mostly into sterile ν's on the way out of the sun due to MSW resonance:

Arguelies and Kopp, 1202.3431, A Esmaili et al., 1202.2869

This happens at E ~ O(TeV), $\delta m^2 \sim O(eV^2)$,

small mixing and passage thru solar atmosphere.

Various possibilities for nu vs nu_bar suppression depending on the signs of δm^2's,

See the figures:

From the Esmaili et al. paper:

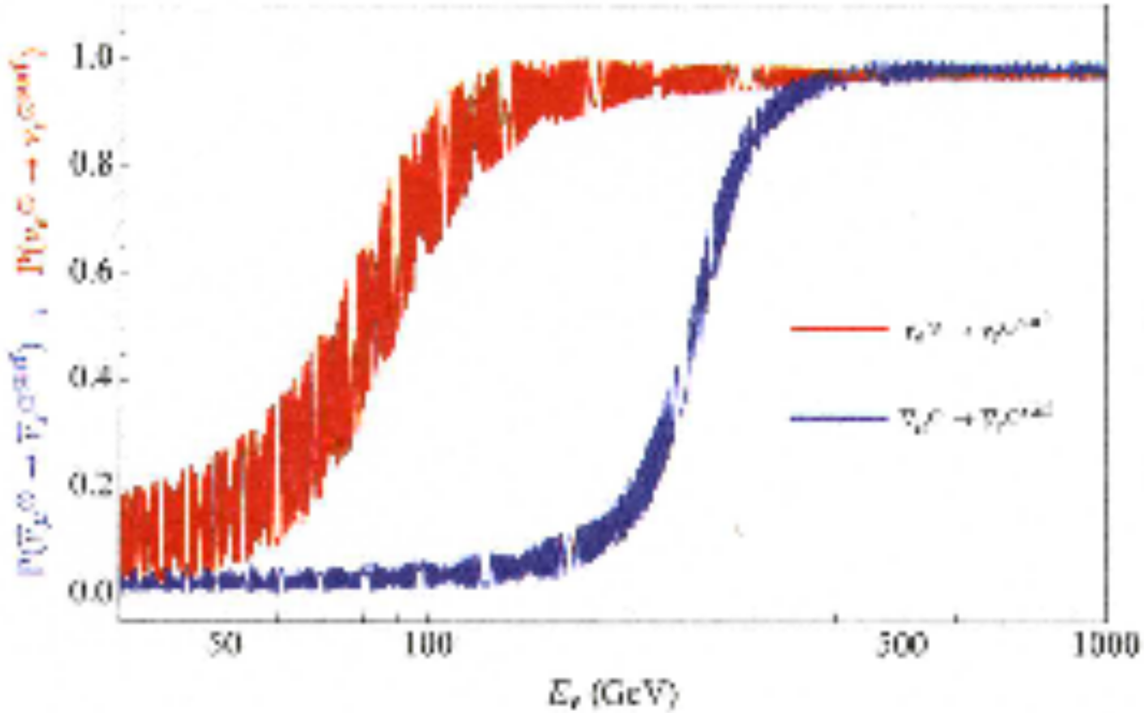


Figure 2. The probabilities $P(\nu_e^\odot \to \nu_s^{\oplus surf})$ (red curve) and $P(\bar{\nu}_\mu^\odot \to \bar{\nu}_s^{\oplus surf})$ (blue curve) with respect to the neutrino energy. In this plot we assumed ($\sin^2\theta_{14} = 0.03, \theta_{24} = 0, \theta_{34} = 0$) and ($\theta_{14} = 0, \sin^2\theta_{24} = 0.01, \theta_{34} = 0$) for $\nu_e^\odot \to \nu_s^{\oplus surf}$ and $\nu_\mu^\odot \to \nu_s^{\oplus surf}$, respectively; and for the both cases $\Delta m^2_{41} = 1\,eV^2$.

From the Kopp et al paper:

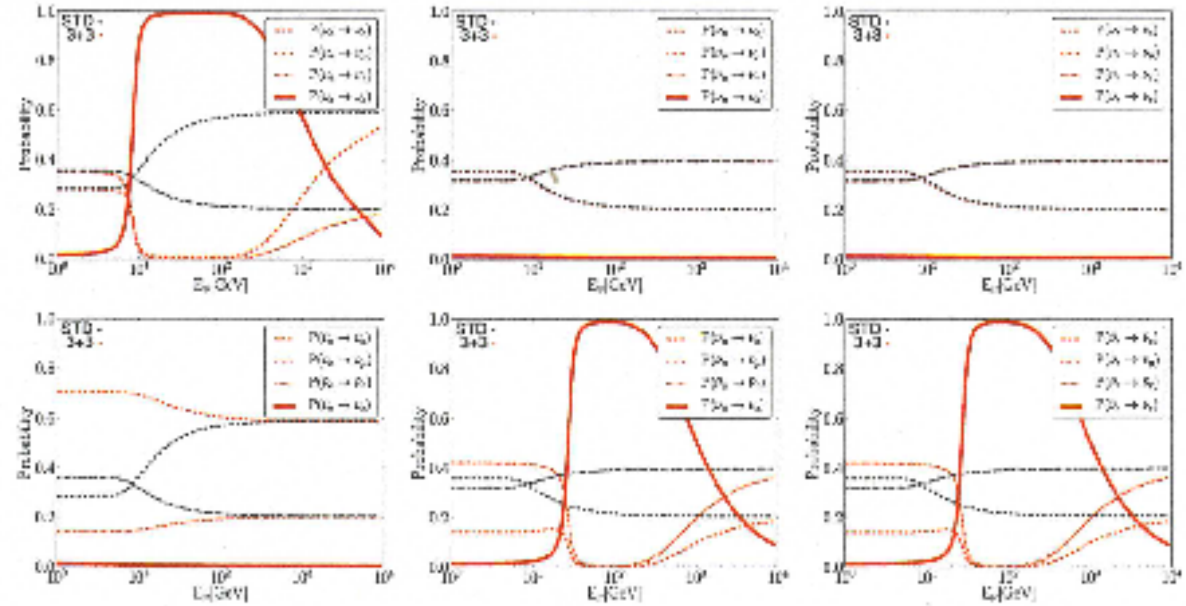
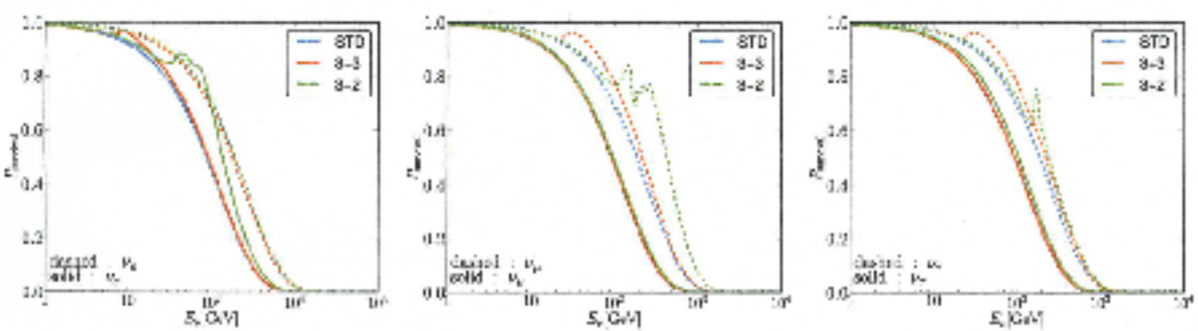


Figure 2: Flavor transition probabilities in the Sun as a function of energy for an initial ν_e (left), an initial ν_μ (center), and an initial ν_τ (right). The top plots are for neutrinos, the ones at the bottom are for anti-neutrinos. Black lines are for standard three-flavor oscillation, whereas red lines are for a "3+3" toy model with three sterile neutrinos (see text for details). Absorption and τ regeneration effects are neglected in these plots. Note that the black dotted lines ($\nu_X \to \nu_\tau$ in the SM) and the black dot dashed lines ($\nu_X \to \nu_\mu$ in the SM) lie on top of each other since ν_μ–ν_τ mixing is assumed to be maximal.



Question: Is there such an effect in GRB's or AGN's?

- Namely is it repeated for E ~ O(PeV) and and similar δm^2's and for densities in the AGN/GRB atmospheres….?

Answer: Not likely…….

6. Effects of Magnetic Fields

- In regions with large magnetic fields, neutrino magnetic transitions can modify the flavor mix.
- However, for Majorana neutrinos, the magnetic moment matrix is antisymmetric and hence, a flavor mix of 1:1:1 remains 1:1:1
- For Dirac case, possible interesting effects via RSFP (Akhmedov and Lim-Marciano) for μ_ν at the maximum allowed values of about $10^{-14}\mu_B$ and B of order of a Gauss

  In this case also, large conversion from flavor to sterile state can occur, and reduce absolute fluxes by a factor of 2 or more…..

Other possibilities

- 7. Lorentz Invariance Violation
- 8. CPT Violation
- 9. Decoherence
- 10. Mass varying Neutrinos
- 11. etc.....

Conclusions/summary

- **Neutrino Telescopes MUST measure flavors, and need to be v.v.large(Multi-KM), just OBSERVING neutrinos NOT enuf……**
- **If the flavor mix is found to be 1:1:1, it is BORING and confirms CW, even so can lead to many constraints.**
- **If it is approx ½:1:1, we have damped muon sources.**
- **If the mix is a:1:1, then a>1 may mean decays with normal hierarchy and can give info about θ_{13} and δ…..**
- **If a is <<1, then decays with inverted hierachy may be occuring..**
- **Can probe v.v. small δm^2 beyond reach of**

- ……”although tough to measure, flavor ratios are a very interesting possibility to constrain particle physics properties using astrophysical sources in parameter ranges which would otherwise NOT be accessible”

arXiv:1101.2673

As for the absolute fluxes of flavor neutrinos ....

It is possible to invent exotic scenarios in which the fluxes of ν_μ 's can be reduced quite a bit from the canonical predicted fluxes from the sources. But most of these are somewhat far-fetched and fanciful....

Fortunately, in some cases such as decays and pseudo-Dirac cases there are other implications of the proposals which render them testable in principle ....

Flux Reduction possibilities:

Neutrino Decay, esp to sterile states

Pseudo-Dirac Neutrinos

MSW with pseudo-Dirac Neutrinos travelling thru BG neutrinos+lepton asymmetry

MSW of sterile (of mass 1 eV) thru the sun at TeV extrapolated to PeV thru atm of astrophysical source?

Unknown?

Patience! Wait for more data……