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

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- 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?
- We know now that the answer is yes….

Possible neutrino sources: (i) GRB’s as suggested by Waxman and Bahcall (ii) AGN’s

Recent revival of 1991 model for AGN neutrinos, F. Stecker(2013)

Neutrino flux has a broad peak at about 1 PeV.Basic process:

P+gamma -> delata+ -> n +pi_0

FLAVORS at the Source: The variety of initial flavor mixes

- Conventional: P +P → π + X, $\pi \rightarrow \nu_{\mu} + \mu$, $\mu \rightarrow \nu_{\mu} + \nu_{e}$ 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……
- See for example papers by Walter Winter et al……

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:μ : τ = 1:0:0
- Above 10 PeV: conventional(π decays) :e:μ : τ =1:2:0

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

also Stanev(2009))

This is for Primaries being Primarily protons!

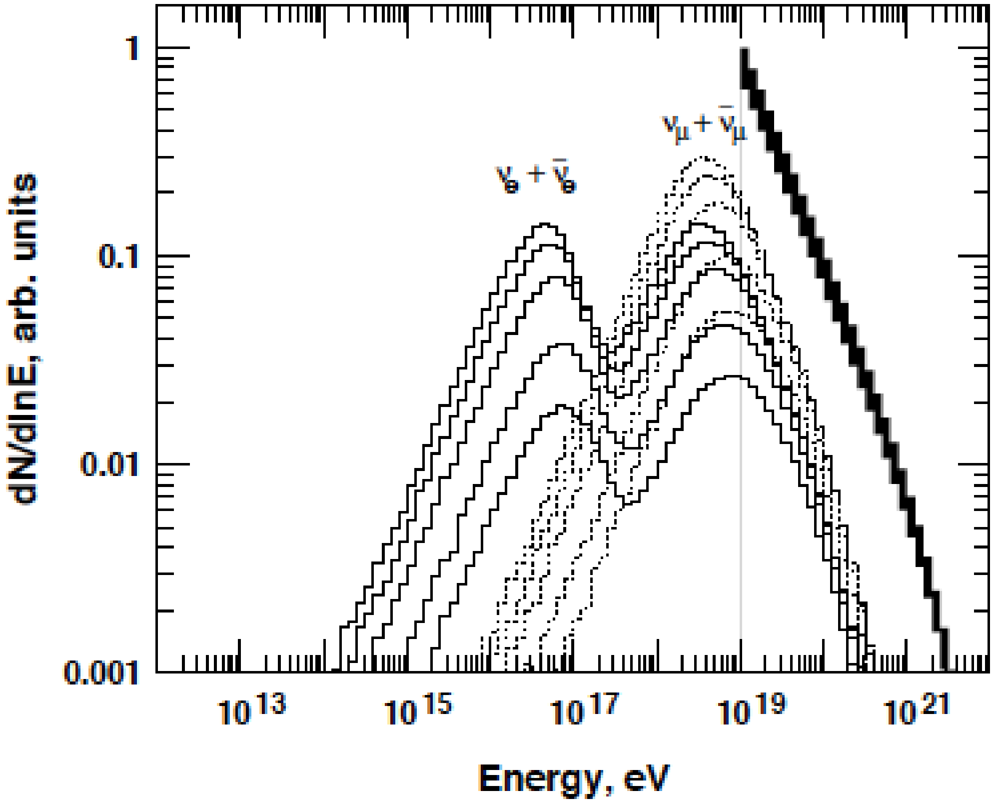


FIG. 2. Neutrino fluxes produced during the propagation of protons over 10, 20, 50, 100, and 200 Mpc (from bottom up) in a 1 nG random magnetic field. The heavy histogram shows the proton injection spectrum defined in Eq. (1).

Current Knowledge of Neutrino Mixing and Masses

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

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

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

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

Unkown:

Mass Pattern: Normal or Inverted:, phase δ

3 ________ 2________
1 ________

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, e.g. in one light day,

already this osc argument even for E~(PeV) is >>1 and

- $\rightarrow \sin^2(\delta m^2 L/4E)$ averages to ½
- survival and transition probablities depend only on mixing angles:
- $P_{\alpha\alpha} = \sum_i |U_{\alpha i}|^4$
- $P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$

In this tri-bi-maximal approximation, the propagation matrix P is:

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

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

Using the most recent best fit from e.g. Schwetz et al, the propagation matrix P becomes

0.5543	0.28/0.186	0.164/0.22
0.28/0.186	0.346/0.41	0.378/0.371
0.164/0.219	0.3775/0.3713	0.47/0.4325

(the two values correspond to $\delta = 0$ or π)

Flavor Mix at Earth (using Tri-Bi-Max mixing):

Beam type	Initial	Final
Conventional (pp,p γ)	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!

Using the mixing from most recent best fits(e.g. Schwetz et al):

- 1:1:1 can become

  1:0.86:0.86 to 1.0:1.05:1.01

These numbers include the “known” corrections to the standard 1:2:0 due to muon polarization effects, K’s etc.

Discriminating flavors

- The ratios used to distinguish various flavor mixes are e.g. f_e $(e/(e+\mu+\tau)$ and $R(\mu/[e+\tau])$

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
- (Beacom et al. PRD69(2003).{Esmaili(2009).Choubey(2009).}

Can small deviations from TBM be measured in the flavor mixes?

- Corrections due to $\varepsilon / \theta_{13}$ 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
- also rather small and we will neglect those as well again with some exceptions!

Some examples of exceptions:

1. Pseudo-Dirac Neutrinos, where the Mixing angle is maximal, but δm^2 Is very small: $< 10^{-12}$ eV^2

2. Mixing angle with sterile ν enhanced over some range of E and L due to a MSW-like resonant effect (e.g. Sterile ν taking short-cut in bulk a la the model of Paes et al).

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 measure in near future.

- 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.

Current Icecube bounds on GRB ν's 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)

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

Also there has been no hints yet of a signal from

AGNS or other sources of high energy neutrinos in form of ν_μ events.........

Caveat: Recent modified versions of WB can accommodate lower fluxes.....

e.g. P. Hummer et al., Z. Li(2012).

If we take the two PeV shower events at face value(and one shower event at 2 PeV) assuming they are CC ν_e events

then ν_e's are NOT depleted.....but ν_μ's maybe?

BTW decay length for a 2 PeV τ is 100m....

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 significantly 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 (But this is unlikely at ALL energies.)

   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 δ m's $\neq$ 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: $\nu_i \rightarrow \nu_j + \gamma$:

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

Bounds for other flavors somewhat weaker

but still too strong for radiative decay to be

Of practical interest. {Caveat: the two processes are at very different momentum transfers}

Invisible Decays:

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

F < ε G_F, ε < O(1), from invisible width of Z

Bilenky and Santamaria(1999):

$\tau > 10^{34}$ s

$\nu_{iL} \rightarrow \nu_{jL} + \phi$: $g_{ij} \Psi_{jL} \gamma_\mu \Psi_{jL} d_\mu \phi$

If isospin conserved: invisible decays of charged leptons governed by the same g_{ij}, and bounds on $\mu \rightarrow e + \phi$, and $\tau \rightarrow \mu/e + \phi$ yield bounds such as: $\tau > 10^{24}$ s.

{Jodidio et al. (1986), PDG(1996)}

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

- g $\nu^{C}_{jR} \nu_{iL} \chi$:
- 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
- $g < 5.\ 10^{-7}$ corresp. to $\tau > 0.1$ s/ev

Current experimental limits on τ_i:

- $\tau_1/m_1 > 10^5$ s/eV SN 1987A
  B. o. E. Careful analysis.
- $\tau_2/m_2 > 10^{-4}$ s/eV (Solar) 10^{-4}-10^{-2} s/eV
  Beacom-Bell(2003),KamLand(2004)

$\tau_3/m_3 > 3.10^{-11}$ s/eV (Atm) 9.10^{-11} s/eV

Gonzalez-Garcia-Maltoni(2008)

Cosmology: WMAP/PLANCK → 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, $U_{\alpha i}$ gets multiplied by the factor exp(-L/ γ c τ) and goes to 0 for sufficiently long L.

For normal hierarchy, only ν_1 survives, and the final flavor mix is simply (SP 1981):

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

$$\sim 4:1:1$$

or even 10:1:1 with the new best fits...

These flavor mixes are drastically different from canonical 1:1:1 and easily distinguishable. Some sensitivity to cos(δ)...

{Inverted hierarchy leads to strong depletion of electorn neutrino flux}

Beacom et al(2003)

Effects on absolute fluxes in decay scenarios:

- In normal hierarchy, if only ν_1 survives:

  ν_μ flux can go down by as much as a factor of 0.1 from the original flux at the source. .

  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 allowed by PLANCK and BBN).

  (As pointed out by Weinberg(2013), a Goldstone boson also would give the same factor of 4/7 modified by the factor depending on the time of decoupling)

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, this is in some conflict with PLANCK + BBN.

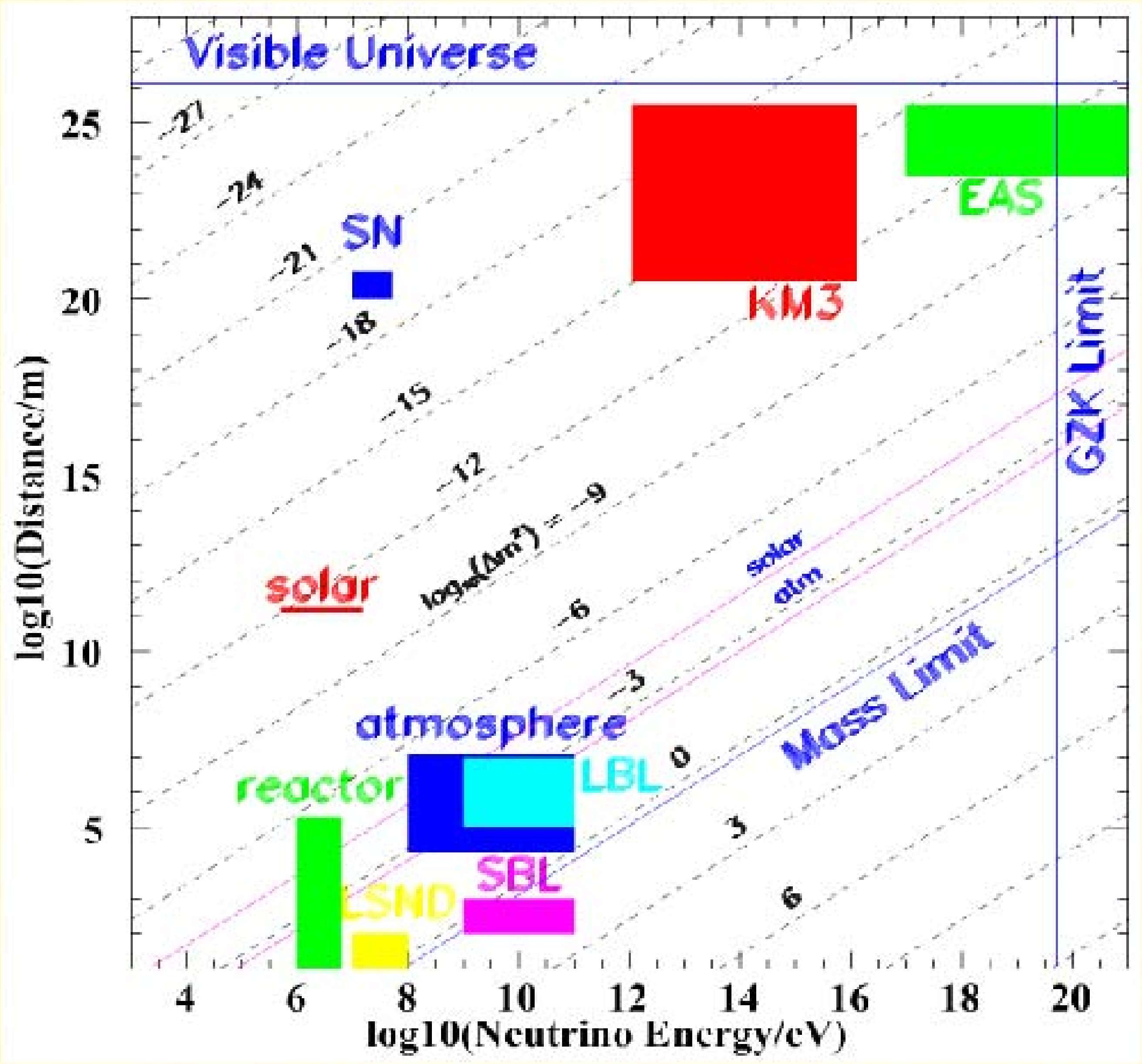
Ultimate long-baseline experiment

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)

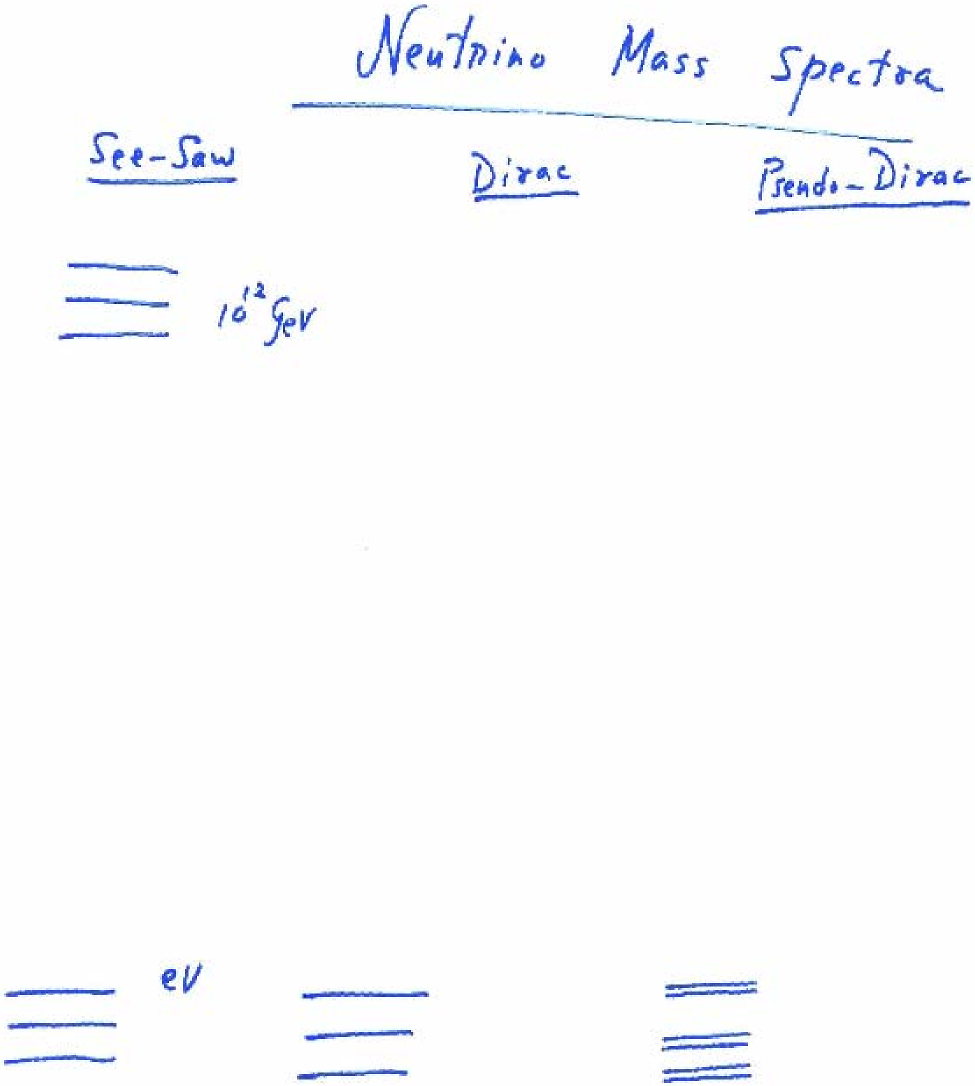
4. Pseudo-Dirac Neutrinos: (Sometimes called Quasi-Dirac)

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.



The three δm^2's will be different, in general. Deltam^2 has to be smaller than 10^-12 eV^2 so as not to disturb solar nu fits.

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)

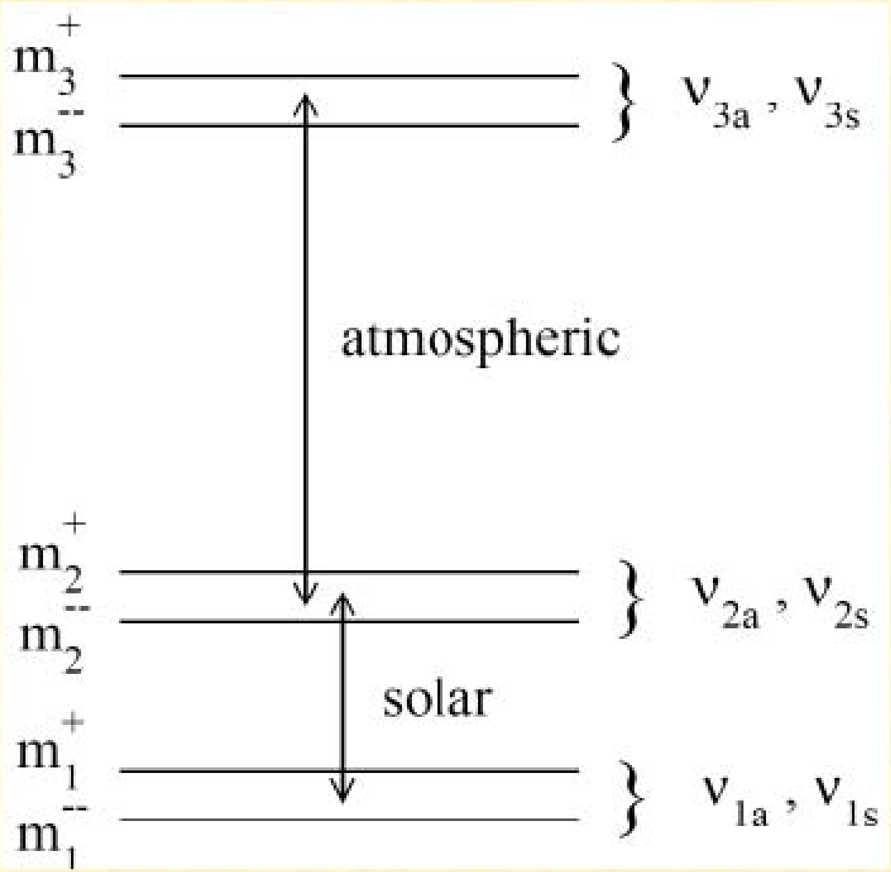
$$\nu_a = \frac{1}{\sqrt{2}}\left(\nu^+ + i\nu^-\right) \qquad \nu_s = \frac{1}{\sqrt{2}}\left(\nu^+ - i\nu^-\right)$$

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

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

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

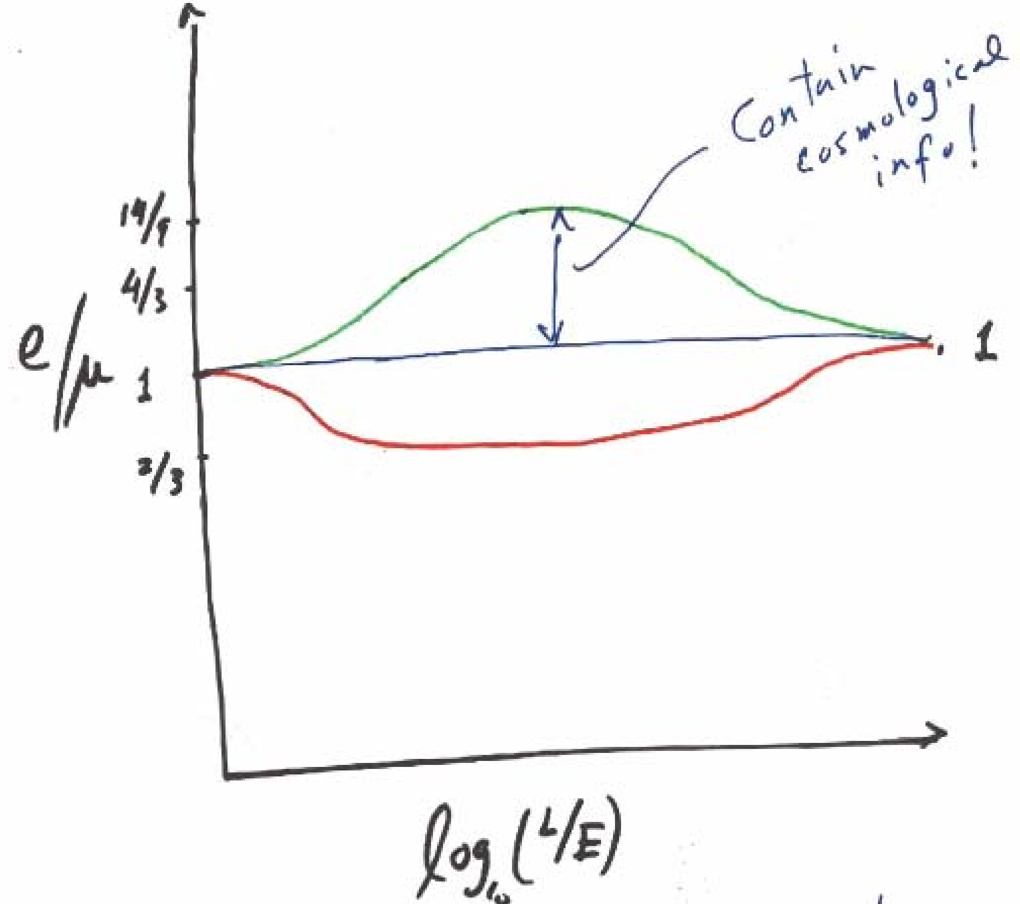
Pseudo-Dirac Neutrinos



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 principle, there is some sensitivity to cosmolgical parameters:

The oscillation phase at great distances depends on the redshift z, the Hubble constant H etc.. and may not average out …

And if there are enuf data points, one can measure the redshift in neutrinos, rather than photons!

Implications for absolute fluxes:

- In particular, if the separation for the δm^2_1 is much smaller than for the other two, ν_μ's get depleted almost by a factor of 2. And in a model with mirror matter one can get a further factor of 2, yielding a net suppression of factor 4.
- Eventually, when L/E gets large enuf all flavors get suppressed by the factor of 1/2 and the flavor mix returns to the canonical 1:1:1

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

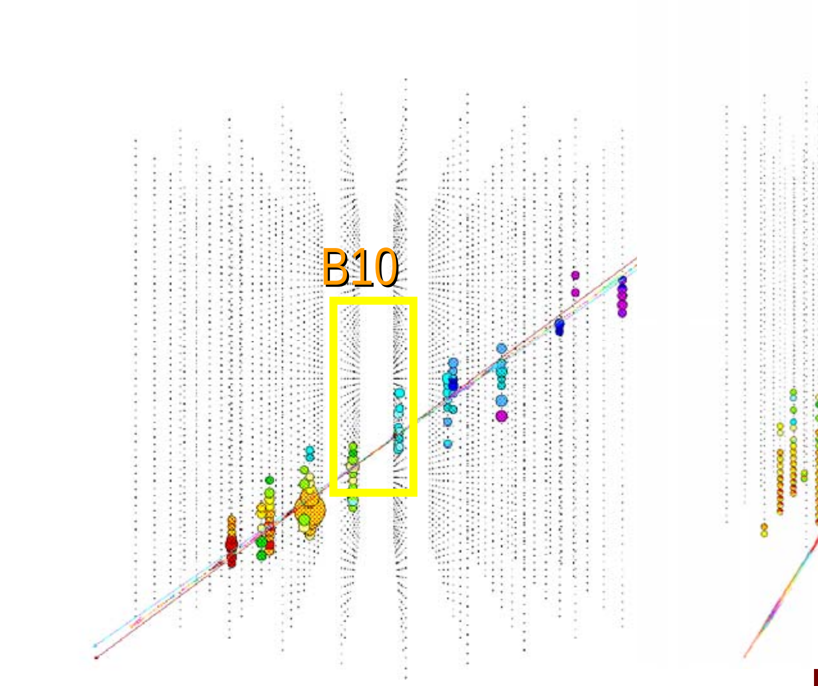
In this case, large conversion from flavor to sterile state can occur, and reduce absolute fluxes by a factor of 2 or more.….

Other possibilities

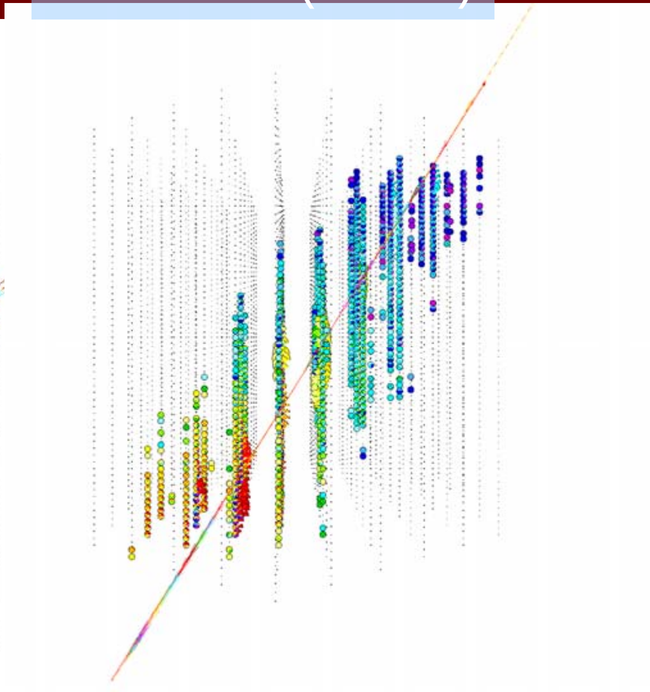
- 7. Lorentz Invariance Violation
- 8. CPT Violation
- 9. Decoherence
- 10. Mass varying Neutrinos
- 11. etc.....

Flavor Signatures in IceCube ...

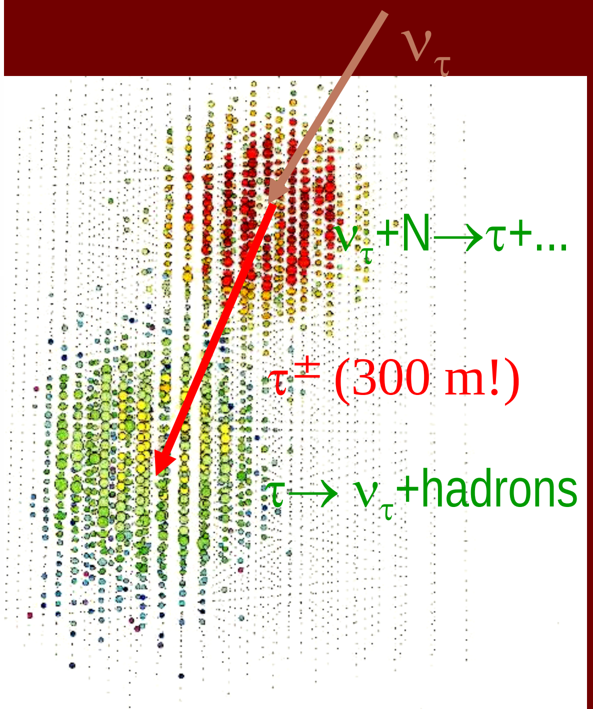
10^{13} eV (10 TeV)



$6x10^{15}$ eV (6 PeV)



Multi-PeV



signature of ν_μ

signature of

ν_τTηε □Tηε Δουβλε

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 hiera r chy may be occuring..**
- **Can probe v.v. small δm^2 beyond reach of neutrinoless double beta decay….**
- **Anisotropy can be due to flavor violating gravity?**

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

There are two new physics scenarios can account for the suppression of fluxes of ν_{μ} 's without affecting ν_{e} very much:

(i) Neutrino Decay and (ii) pseudo-Dirac neutrinos

In both cases there are other implications of the proposals which render them testable in principle ....e.g. the neutrino counting in early universe being 3+4/7 for decay and lack of observable neutrinoless double beta decay for pseudo-Dirac case.(Joshipura,Mohanty and SP PRL,110,171802(2013).

Same thing can be done for suppression of electron neutrinos...