Probing new physics effects with astrophysical neutrinos

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Poonam Mehta[1] and Walter Winter[2]

[1]Raman Research Institute, C. V. Raman Avenue, Bangalore, India

[2]Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Germany

I. Abstract

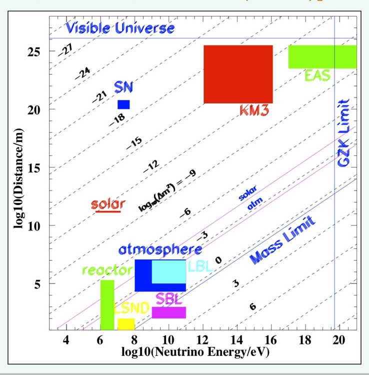
We discuss the importance of flavor ratio measurements in neutrino telescopes, such as by measuring the ratio between muon tracks to cascades, for the purpose of extracting new physics signals encountered by astrophysical neutrinos during propagation from the source to the detector.

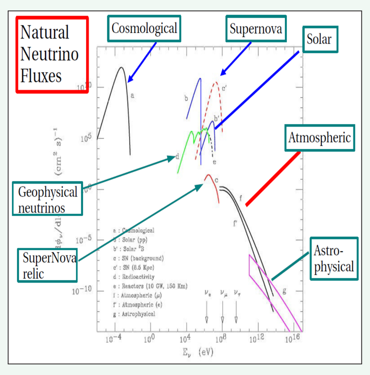
II. High energy astrophysical neutrinos

Some key features

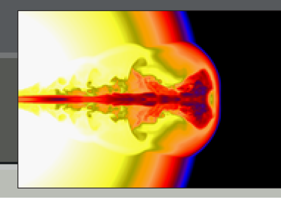
- Two extra-terrestrial sources already seen in neutrinos - Sun and SN1987A
  Low energy (MeV) neutrinos - R. Davis and M. Koshiba were awarded the Noble prize in 2002
  And, also the atmospheric neutrinos which are secondaries from cosmic rays hitting Earth's atmosphere
- HE neutrinos are neither deflected by magnetic fields nor absorbed by cosmic background radiation : unique probe sources of cosmic rays
- Oscillation studies : provide an ultimate long baseline experiment that is as large as visible Universe
- Probing new physics : extremely sensitive probes of new physics effects beyond the reach of present terrestrial experiments
- Probing UHE cross section : A 100 PeV neutrino interacting with a nucleon represents centre of mass energy around 14 TeV (LHC).
- No HE astrophysical (extra-galactic) neutrino has not been detected so far, what are the implications ?!
- The construction of the first km scale neutrino telescope "IceCube" got completed in Dec 2010.

[Credits : Beacom et al., PRL92, 011101 (2004)]





III. Flavor composition at source



Classification of sources

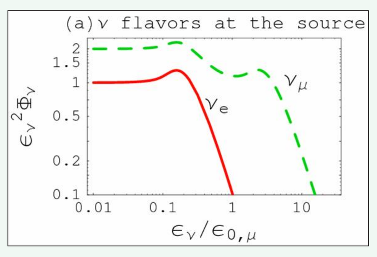
Pakvasa, MPLA23, 1313 (2008) , talk@Nusky2011 A relativistic jet [credits : Zhang and Woosley]

Source Candidates : AGN, GRB, SNR, MQ

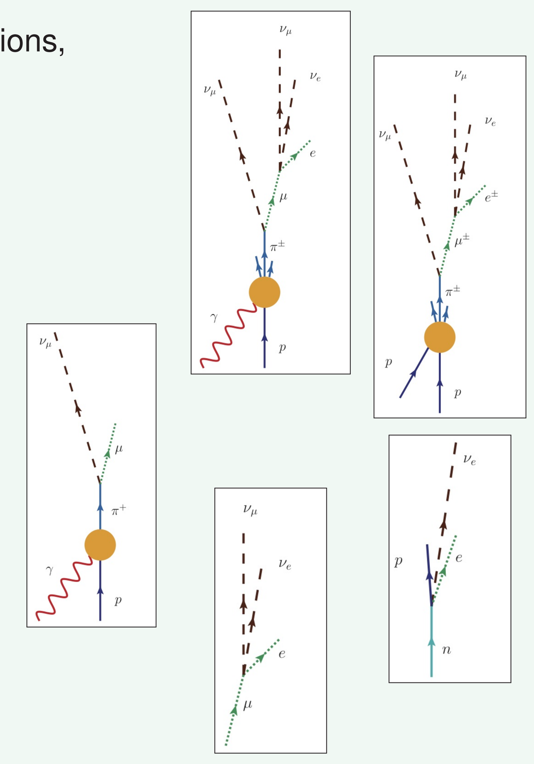
1. Conventional pion beam source :
   Cosmic rays (assumed to be p) interact with γ or p and produce charged mesons (pions, kaons) which decay to give neutrinos via the $\pi \to \mu \to e$ decay chain :
   $p\gamma : \; p + \gamma \to \pi^{\pm} + \text{all}$; $pp : \; p + p \to \pi^{\pm} + \text{all}$
2. Damped muon source : Muons lose energy prior to decay (depends on E)
3. Muon decay : Muons from damped muon source decay at lower E
4. Prompt : Decay of short-lived heavy flavors (pions interact and do not decay)
5. Neutron decay : Photodisintegration of heavy nuclei

- Source type can be characterized by $\widehat{X} = \Phi^0_e/\Phi^0_\mu$ (since Φ^0_τ is negligible)
- However same source can mimic different source types as a function of E i.e. $\widehat{X}(E)$

Kashti and Waxman, PRL95, 181101 (2005)



Source	$\widehat{X}$	$\Phi^0_e : \Phi^0_\mu : \Phi^0_\tau$
Pion beam	0.5	1:2:0
Neutron decay	>> 1	1:0:0
Muon decay/Prompt	1	1:1:0
Damped muon	0	0:1:0

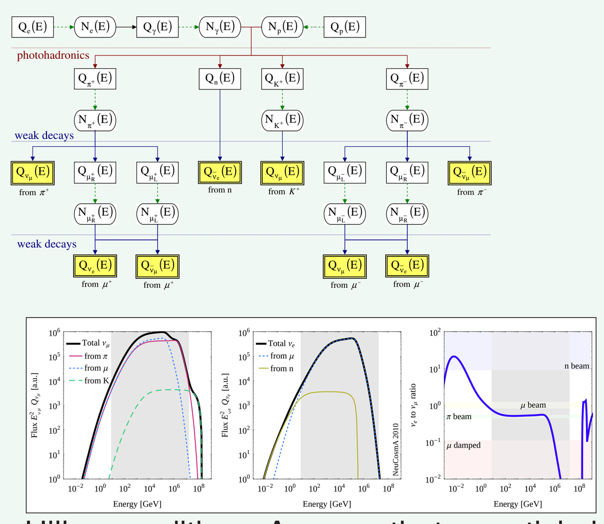


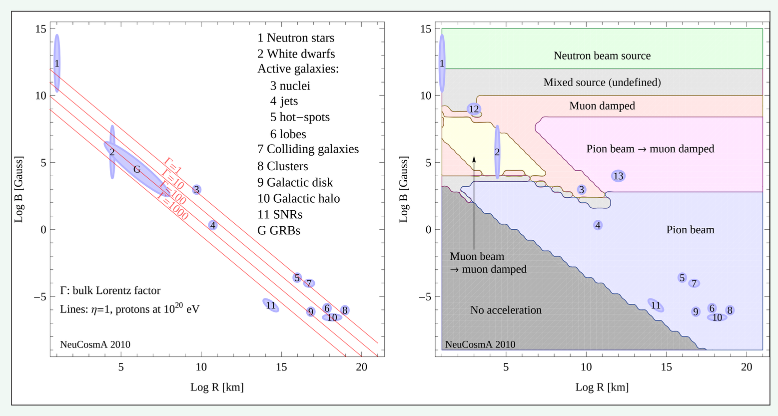
IV. Our toy model and the Hillas condition

HMWY model for photohadronic interactions

Hümmer, Maltoni, Winter and Yaguna, AP34, 205 (2010)

- A self-consistent model to compute flux at source - synchrotron radiation of co-accelerated e^- provide target photon field to p (AGN like)
- goes beyond $\Delta(1232)$ approximation, includes cooling of secondaries
- Call sources as "test points (TP)" in order to discuss energy dependent effects at source, TP13 shown
- Unconstrained neutrino production (- no bias from CR or γ ray observations) as a function of few parameters α, B, R





- Hillas condition : Assume that a particle is accelerated by electromagnetic forces within the accelerator then a geometrical constraint [Larmor radius $\leq R$] must be satisfied else it leaves the accelerator and this leads to $E \leq E_{max} = q\,B\,R$
- Hillas plot depicts the known astrophysical objects with reasonable B and R required for particle acceleration.
- Although Hillas condition strictly applied to cosmic ray accelerators, one can also use it to characterize sources with efficient HE neutrino production using the HMWY model

V. Observable quantity

Flavor flux ratio at the detector and ratio of muon tracks to cascades

- Oscillation length is much smaller than the distance to source ($L_S \simeq$Mpc) for HE neutrinos:

$$l_{osc} = \frac{\pi}{1.27} 10^{11} cm \frac{E}{[PeV]} \frac{[1\ eV^2]}{\delta m^2} \simeq 10^{-13}\ Mpc \quad << L_S$$

- In general the flavor flux at detector is given by

$$\Phi^{Det}_\beta(E) = \sum_{\alpha=e,\mu,\tau} P_{\alpha\beta}(E)\Phi^0_\alpha(E)$$

  where Φ^0_α is the flavor flux at source and $P_{\alpha\beta}$ depends upon the propagation effects discussed below.
- At IceCube, the easiest ratio to measure is that of "muon tracks to cascades" Cascade detection [IC-22, 1101.1692]

$$\widehat{R}(E) = \frac{\Phi^{Det}_\mu(E)}{\Phi^{Det}_e(E) + \Phi^{Det}_\tau(E)} = \frac{[P_{e\mu}(E)\widehat{X}(E) + P_{\mu\mu}(E)]}{[P_{ee}(E) + P_{e\tau}(E)]\widehat{X}(E) + [P_{\mu e}(E) + P_{\mu\tau}(E)]}$$

- The above expression holds even when unitarity is violated i.e. $P_{ee} + P_{e\mu} + P_{e\tau} < 1$ such as neutrino decay into invisible states.

VI. Flavor mixing during propagation from source to the detector

A. Standard oscillations

- Standard (average) oscillation probability in vacuum

$$P_{\alpha\beta} = P_{\beta\alpha} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

  which is achromatic (energy-independent) since $l_{osc} << L_S$.
- Mixing angles are close to tri-bimaximal (TBM)
  $[\theta_{13} = 0; \theta_{23} = \pi/4; \theta_{12} = \pi/6]$
- Final flavor composition for pion beam source is $1:1:1$ (irrespective of value of θ_{12})
- $\mu - \tau$ fluxes are equal irrespective of source type as long as atmospheric mixing is maximal.
- Deviation from $1:1:1$ can come from different source types, but wild deviations only due to new physics effects.
- Different sources :

Source	$\widehat{X}$	$\widehat{R}$
Pion beam	0.5	0.5
Neutron decay	>> 1	0.28
Muon decay/Prompt	1	0.44
Damped muon	0	0.64

Effects due to new (BSM) physics

B. Neutrino decay

Beacom et al., PRL90, 181303 (2003)

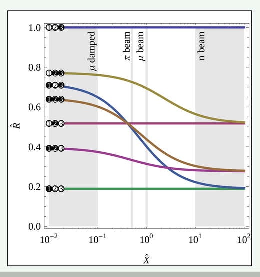
- Weak model-independent bounds do not rule out invisible neutrino decays over extragalactic distances.
- Probability gets an overall energy-dependent damping factor

$$P_{\alpha\beta} = P_{\beta\alpha} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2 D_i(E)$$

  where $D_i(E) = e^{-\hat{\alpha}_i \frac{L}{E}}$ and it characterizes complete ($D_i(E) \to 0$) and incomplete ($0 \leq D_i(E) \to 1$) decays.
- Astrophysical neutrinos probe

$$\hat{\alpha}_i^{-1} = \frac{\tau_i^0}{m_i} \leq 10^2 \frac{L}{Mpc} \frac{TeV}{E} s.eV^{-1}$$

  This is $\simeq 10^5$ larger than current limits.
- We consider $2^3 - 1 = 7$ invisible decay scenarios
- Single stable state: $\widehat{R}$ independent of $\widehat{X}$
- Pion beam : only 4 of 7 scenarios separate out
- Sources with different $\widehat{X}$ good



C. Quantum decoherence

Bennati & Floreanini, JHEP02, 032 (2000)

- Pure state to mixed state evolution

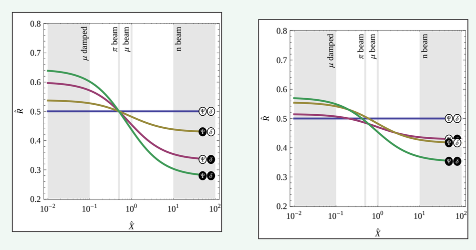
$$\dot{\rho} = -i[H, \rho] + \mathcal{D}[\rho]$$

$$P_{\alpha\beta}(t) = P_{\beta\alpha}(t) = Tr[\rho_{\nu_\alpha}(t)\rho_{\nu_\beta}(0)]$$
$$= \frac{1}{3} + \frac{1}{2}(U^2_{\alpha 1} - U^2_{\alpha 2})(U^2_{\beta 1} - U^2_{\beta 2})D_\psi + \frac{1}{6}(U^2_{\alpha 1} + U^2_{\alpha 2} - 2U^2_{\alpha 3})(U^2_{\beta 1} + U^2_{\beta 2} - 2U^2_{\beta 3})D_\delta$$

  where $D_\kappa \equiv D_\kappa(E) = e^{-2\kappa L E^n}$ with $n = -1, 0, 2$ (model-dependent).
- Astrophysical neutrinos probe (for $n = 2$ case)

$$\kappa^{-1} \leq 2 \times 10^{44} \frac{L}{Mpc} \left(\frac{E}{TeV}\right)^2 GeV$$

- For a given model (n), we have 4 sub-cases with only 2 parameters (ψ, δ) :
  1. $\psi \neq 0$ and $\delta = 0$
  2. $\delta \neq 0$ and $\psi = 0$
  3. $\psi = 0$ and $\delta = 0$
  4. $\delta \neq 0$ and $\psi \neq 0$



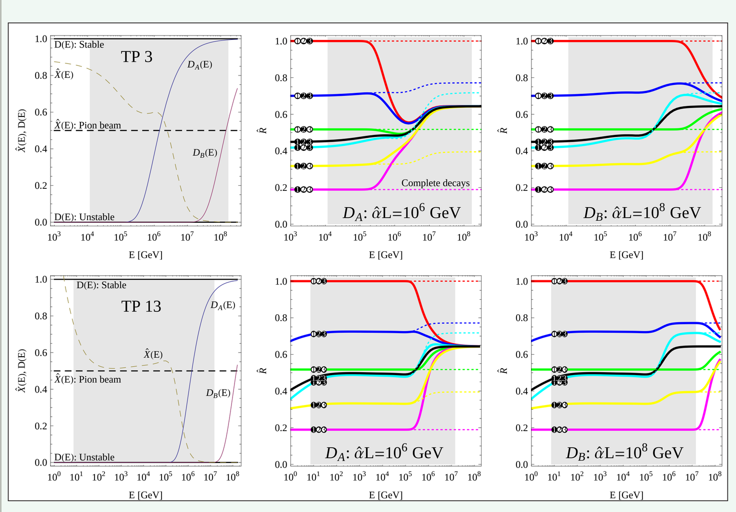
- Complete decoherence should lead to $1:1:1$ asymptotically only for case (4).
- Pion beam : TBM angles give $1:1:1$ as in standard oscillations

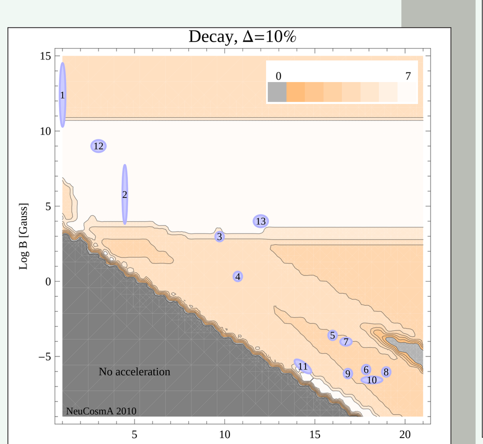
Related studies on effects of new physics in propagation [for single source type or fixed $\widehat{X}$]: Hooper et. al, PLB609, 206 (2005); PRD72, 065009 (2005); Morgan et al, AP25, 311 (2006); Bustamante et al, JHEP1004, 066 (2010) Bhattacharya et al., PLB690, 42 (2010); JCAP 1009, 009 (2010);

VII. Flavoring astrophysical neutrinos to extract new physics effects

Invisible neutrino decay

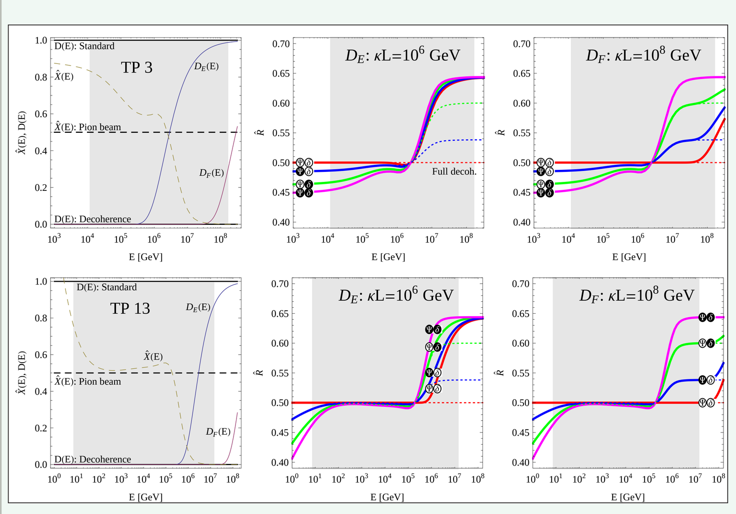
- L/E dependence, curves separate at low E
- Two test points TP3 (AGN nuclei, damped muon) and TP13 (pion beam to muon damped) shown and parameter space scan
- $D_A : \hat{\alpha}_i L = 10^6\ GeV$, $D_B : \hat{\alpha}_i L = 10^8\ GeV$
- Black disk: stable mass eigenstates; White disk: unstable mass eigenstates

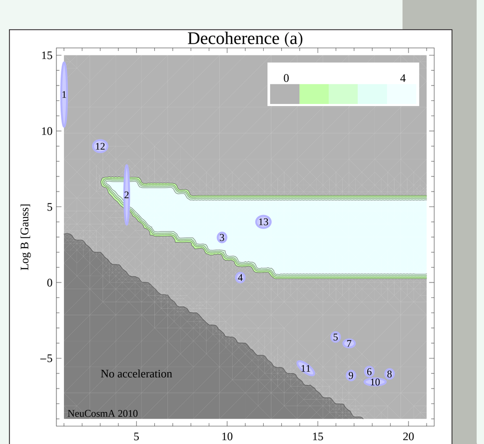




Quantum decoherence ($n = 2$)

- LE^2 dependence, curves separate at high E
- Two test points TP3 (AGN nuclei, damped muon) and TP13 (pion beam to muon damped) shown and parameter space scan
- $D_C : \kappa L = 10^{-12}\ GeV^{-2}$, $D_D : \kappa L = 10^{-16}\ GeV^{-2}$
- Black disk: $\kappa = 0$; White disk: $\kappa > 0$





Conclusions and Outlook

- We discuss the interplay of two energy dependent terms (source effects and new physics effects) in observable astrophysical flavor ratio with two examples of energy dependent new physics - neutrino decay and quantum decoherence.
- We demonstrate that flavor detection plays an extremely important role in establishing new physics effects. For instance, with muon tracks only, one cannot probe new physics scenarios.
- Effect of decay is effective at low E while quantum decoherence ($n = 2$) at high E so these operate in different E regimes.
- We perform a parameter space scan and show which parameter regions (B, R) provide best chances for new physics searches for seven decay scenarios and four quantum decoherence scenarios (for two specific values of $n = -1, 2$ for different classes of models).
  - Optimal magnetic fields : $10^3 \leq B \leq 10^6$ Gauss
  - Optimal sources : AGN cores, white dwarfs, or GRBs but not AGN jets
- The next decade will be exciting : if HE astrophysical neutrinos are seen @IceCube, with enough statistics we can see new effects or constrain them even with single source. However if no HE neutrinos are seen, it will be get even more interesting !