Extreme scenarios of new physics in the UHE astrophysical neutrino flavour ratios

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in collaboration with

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Outline

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Introduction and motivation

- Neutrinos can change flavour.
- Evidence from solar, reactor and atmospheric experiments.
- Confirmed mechanism in MeV $\lesssim E \lesssim$ TeV:
  - neutrinos have different masses
  - flavour eigenstates $\neq$ mass eigenstates
- SK data: oscillation argument $\sim E^n$, with $n = -0.9 \pm 0.4$ (90% C.L.), as expected from mass-driven oscillations.
- $\therefore$ At these energies, other mechanisms are *subdominant*.
- True at higher energies?

- Focus on energy-independent contributions to the flavour oscillations.
- Corresponds to:
  - different coupling to non-zero torsion of gravitational field
  - CPT violation
- This can be probed at higher energies $\Rightarrow$ use the expected high-energy astrophysical neutrino flux.
- 3ν oscillations in the vaccum.
- We have *not* used approximations (e.g. perturbation theory).
- We have assumed fluxes at the sources to be $\phi_e^0 : \phi_\mu^0 : \phi_\tau^0 = 1 : 2 : 0$ (also, $0 : 1 : 0$ and $1 : 0 : 0$).

- Any new scalar coupling to ν's would result in contributions that go as $1/E$.
- Vector coupling introduces energy-independent contributions:

$$\mathcal{L} = \overline{\nu}^{\alpha} b_{\mu}^{\alpha\beta} \gamma^{\mu} \nu^{\beta} \ .$$

- Results in an energy-independent phase $\Delta b_{ij} \equiv b_i - b_j$, with b_i eigenvalues of the b matrix.
- Vector coupling could be induced by:
  - Different flavours have different gravitational coupling:
    - Non-symmetric connection: $\Gamma^{c}_{ab} \neq \Gamma^{c}_{ba}$
    - M. Gasperini, Phys. Rev. D **38**, 2635 (1988)
  - Violation of Lorentz invariance:
    - Standard Model Extension: $\mathcal{L}$ includes CPT-odd terms.
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Standard mass-driven oscillations

- $|\nu_\alpha\rangle = [U_m]_{\alpha i} |\nu_i^m\rangle$ $(\alpha = e, \mu, \tau; i = 1, 2, 3)$
- Evolved flavour state: $|\nu_\alpha\rangle \longrightarrow |\nu_\alpha(L)\rangle = e^{-iHL}|\nu_\alpha\rangle$
- Probability of $\nu_\alpha \to \nu_\beta$: $P_{\alpha\beta} = |\langle\nu_\beta|\nu_\alpha(L)\rangle|^2$
- Three-neutrino standard oscillation Hamiltonian:

$$H_m = U_0 M^2 U_0^\dagger = U_0 \frac{\text{diag}\left(0, \Delta m_{21}^2, \Delta m_{31}^2\right)}{2E} U_0^\dagger \; ,$$

  with $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$.
- U_0 is the PMNS matrix: $U_0 = U_{CKM}\left(\{\theta_{ij}\}, \delta_{CP}\right)$

$$U_{CKM}\left(\{\theta_{ij}\}, \delta\right) = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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Adding an energy-independent contribution

$$H_b = U_b \,\mathrm{diag}\,(0, b_{21}, b_{31})\, U_b^\dagger$$
$$U_b = \mathrm{diag}\left(1, e^{i\phi_{b2}}, e^{i\phi_{b3}}\right) U_{CKM}\left(\{\theta_{bij}\}, \delta_b\right)$$

- $|\nu_\alpha\rangle = [U_b]_{\alpha i} |\nu_i^b\rangle$
- H_b depends on eight parameters:
  - two eigenvalues: b_{21}, b_{31}
  - three mixing angles: θ_{b12}, θ_{b13}, θ_{b23}
  - three phases: δ_b, ϕ_{b2}, ϕ_{b3}

$$b_{21} \leq 1.6 \times 10^{-21}\ \text{GeV (solar, SK)}$$
$$b_{32} \leq 5.0 \times 10^{-23}\ \text{GeV (atm., K2K)}$$
$$b_{31} = b_{32} + b_{21} \leq 1.65 \times 10^{-21}\ \text{GeV}$$

J.N. Bahcall, V. Barger, D. Marfatia, Phys. Lett. B **534**, 120 (2002) [hep-ph/0201211]
M.C. Gonzalez-Garcia, M. Maltoni, Phys. Rev. D **70**, 033010 (2004) [hep-ph/0404085]
A. Dighe, S. Ray, Phys. Rev. D **78**, 0360002 (2008) [hep-ph/0802.0121]

Total Hamiltonian

$$H_f = H_m + H_b$$

- $H_m \sim 1/E \Rightarrow H_b$ contributes progressively more as E rises.
- Use expected high-energy ($E \gtrsim 1$ PeV) astrophysical ν flux.
- Let U_f be the diagonalising matrix of H_f:

$$U_f = U_f\left(\{\theta_{ij}\}, \{\theta_{bij}\}, \left\{\Delta m_{ij}^2\right\}, \{b_{ij}\}, \delta_{CP}, \delta_b, \phi_{b2}, \phi_{b3}\right) = U_{CKM}\left(\{\Theta_{ij}\}, \delta_f\right)$$

- We can find Θ_{ij} in terms of the parameters of H_m and H_b.

(i) Δm_{21}^2, Δm_{32}^2, θ_{12}, θ_{13}, θ_{23} fixed by solar, reactor, accel. and atm. exp'ts.

(ii) We have set $\delta_{CP} = \delta_b = \phi_{b2} = \phi_{b3} = 0$.

(iii) Finally, set $b_{ij} \propto \Delta m_{ij}^2/2E$ at a fixed $E^\star = 1$ PeV, i.e.

$$b_{ij} = \lambda \frac{\Delta m_{ij}^2}{2E^\star} .$$

$\Rightarrow \Theta_{ij}, \delta_f$ depend only on 4 parameters: λ, θ_{b12}, θ_{b13} and θ_{b23}.

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Flavour ratios

- Astrophysical ν's travel tens of Mpc or more: $L \gg 1$.
- *Average* flavour-transition probability:

$$\langle P_{\alpha\beta} \rangle = \sum_i \left| [U_f]_{\alpha i} \right|^2 \left| [U_f]_{\beta i} \right|^2 .$$

- Fluxes at production: $\phi_e^0 : \phi_\mu^0 : \phi_\tau^0$.
  At detection (Earth):

$$\phi_\alpha = \sum_{\beta=e,\mu,\tau} \langle P_{\beta\alpha} \rangle \phi_\beta^0 .$$

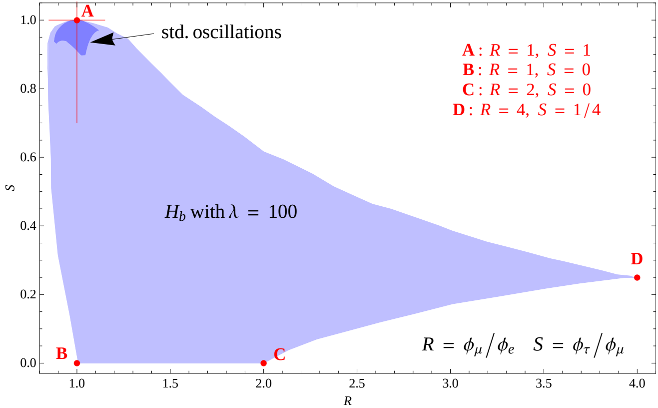
- Define the ratios:

$$R \equiv \frac{\phi_\mu}{\phi_e} \quad , \quad S \equiv \frac{\phi_\tau}{\phi_\mu} .$$

- We look for scenarios where $R, S\, (\lambda; \Theta_{ij}) \neq R, S\, (\theta_{ij})$ noticeably.

Outline

Production by pion decay: $\phi_e^0 : \phi_\mu^0 : \phi_\tau^0 = 1 : 2 : 0$

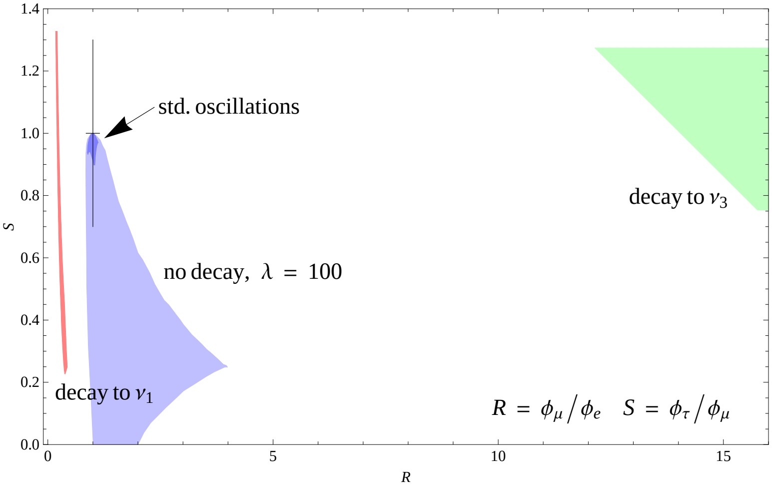


Case	$\{\Theta_{12}, \Theta_{13}, \Theta_{23}\}$	$\phi_e : \phi_\mu : \phi_\tau$	
A	$\{\theta_{12}, \theta_{13}, \theta_{23}\}$	1 : 1 : 1	Standard mixing
B	$\{\pi/4, 0, 0\}$	1 : 1 : 0	Maximal mixing $\nu_e \nu_\mu$; ν_τ's don't mix
C	$\{0, 0, 0\}$	1 : 2 : 0	No effective mixing
D	$\{\pi/2, \pi/4, 0\}$	1 : 4 : 1	Only $\nu_e \nu_\tau$ mix; $\langle P_{e\tau} \rangle = \langle P_{\tau e} \rangle = 1/2$

- Neutrino decay:

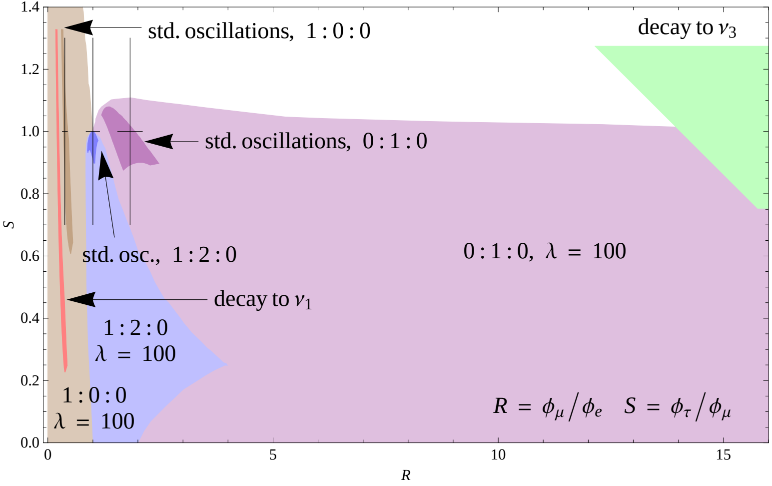
$$\nu_2, \nu_3 \rightarrow \nu_1 \text{ (normal hierarchy)} \quad , \quad \nu_1, \nu_2 \rightarrow \nu_3 \text{ (inverted hierarchy)}$$

- Assumption: decay completed when the neutrinos reach Earth.

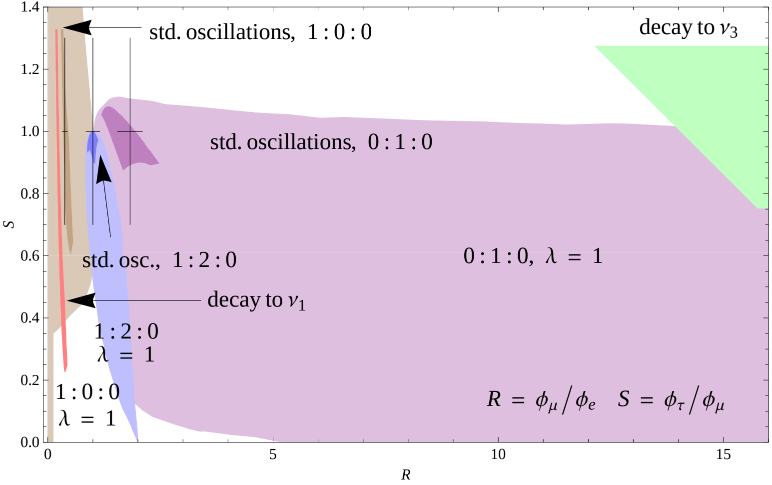


Other production mechanisms:

- Muon cooling: $\phi_e^0 : \phi_\mu^0 : \phi_\tau^0 = 0 : 1 : 0$
- β decay of neutrons: $\phi_e^0 : \phi_\mu^0 : \phi_\tau^0 = 1 : 0 : 0$



The parameter space is reduced if we set $\lambda = 1$ (i.e. $b_{ij} = \Delta m_{ij}^2 / 2E^\star$, $E^\star = 1$ PeV.)



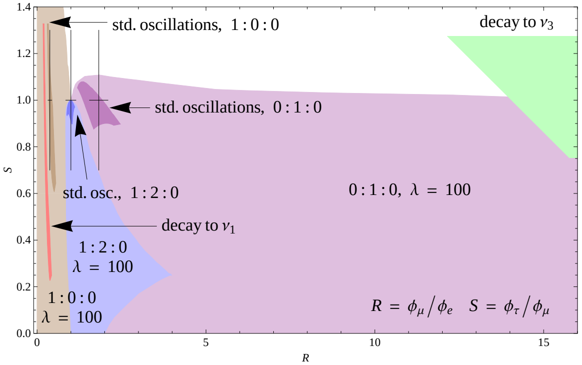
Outline

Summary

- The neutrino mixing angles might be strongly modified by an energy-indepedent contribution to the oscillation Hamiltonian.
- Large effects on the flavour ratios would be visible at higher energy $\Rightarrow$ use astrophysical ν's.
- Because $L \gg 1$, neutrino decays might show up as well.

- Assuming production by pion decay, the region of values of $R \equiv \phi_\mu/\phi_e$ and $S \equiv \phi_\tau/\phi_\mu$ accessible when H_b dominates ...
  - is much larger than the region accessible by neutrino decay; and
  - can be distinguished from it.
- In general, knowledge of both R and S is necessary to disentangle the production mechanism and any potential new physics involved (decays or H_b).
- Assuming a 15% error on R and 30% error on S, IceCube might be able to do so after $\sim$ 5 years (F. Halzen's talk tomorrow).

Backup slides



- $R, S \in$ light blue $\Rightarrow \exists H_b$ dominant, but production mechanism unknown
- $R, S \in$ light purple $\Rightarrow \exists H_b$ dominant, production ratios $0 : 1 : 0$
- $S \gtrsim 1.35 \Rightarrow \exists H_b$ dominant, production ratios $1 : 0 : 0$
- $S > 1$ or $R < 1$ or $R > 4 \Rightarrow$ production ratios not $1 : 2 : 0$
- Both decays and $0 : 1 : 0$, $1 : 0 : 0$ allow $S > 1$; R is needed to distinguish
- Decay to ν_3 and $0 : 1 : 0$, $\lambda = 100$ yield high R; S is needed to distinguish
- Decay to ν_1 indistinguishable from $1 : 0 : 0$ with $\lambda = 100$

Neutrino mixing angles - current status

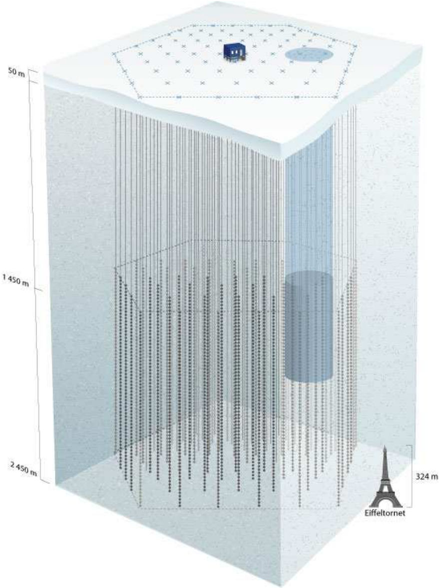
From a global analysis including solar, atmospheric, reactor (KamLAND and CHOOZ) and accelerator (K2K and MINOS) data, the current values of the standard mixing angles are (1σ):

$$\begin{aligned} \sin^2(\theta_{12}) &= 0.304^{+0.022}_{-0.016} \\ \sin^2(\theta_{23}) &= 0.5^{+0.07}_{-0.06} \\ \sin^2(\theta_{13}) &\leq 0.035 \end{aligned}$$

T.Schwetz, M.Tortola, J.Valle, New J. Phys. **10**, 113011 (2008) [hep-ph/0808.2016]

IceCube

- Under-ice Čerenkov detector optimised for TeV-PeV energies.
- Successor to AMANDA (Antarctic Muon And Neutrino Detector Array).
- Built close to the geographic South Pole.
- PMTs at depths between 1 450 and 2 450 m.
- Deployment of strings containing PMTs is half complete.
- Expected finished by 2011.



Flavour identification

- IceCube does **not** measure the flavour fluxes ϕ_α directly.
- Rather, it measures different types of events which can be used to reconstruct the ϕ_α.
- Neutral-current interactions produce hadronic showers (all flavours).
- Charged-current interactions:
  - ν_μ: muon tracks (emerging from hadronic shower)
  - ν_e: electromagnetic showers
  - ν_τ: hadronic shower (below a few PeV) or tau tracks that create second shower
- Possible to distinguish EM and hadronic showers, but very difficult.

J.Beacom *et al.* Phys. Rev. D **68**, 093005 (2003), Erratum-ibid. D **72**, 019901 (2005) [hep-ph/0307025]

Muon tracks

- Muons undergo energy loss as they propagate in the ice:

$$\frac{dE}{dX} = -\alpha - \beta E \ , \quad \begin{cases} \alpha = 2.0\text{MeV cm}^2/\text{g (loss by ionisation)} \\ \beta = 4.2 \times 10^{-6}\ \text{cm}^2/\text{g (loss through bremsstrahlung)} \end{cases}$$

- Muon range:

$$R_\mu = \frac{1}{\beta} \ln \left(\frac{\alpha + \beta E_\mu}{\alpha + \beta E_\mu^{\text{thr}}} \right)$$

$E_\mu^{\text{thr}} \sim 50 - 100$ GeV is the threshold energy that triggers the detectors.

- Probability of detecting a ν_μ traveling through the detector:

$$P_{\nu_\mu \to \mu} \simeq \rho N_A \sigma R_\mu$$

ρ: ice nucleon density
N_A: Avogadro's number
σ: CC ν-nucleon cross section

Showers

- The detector sees a 1 TeV shower as photoelectrons distributed over a $\sim$ 100 m radius sphere ($\sim$ 300 m for PeV).
- Shower sizes are smaller than muon ranges $\Rightarrow$ smaller effective volume.
- $E_{\text{sh}}^{\text{thr}} > E_{\mu}^{\text{thr}}$
- Probability of detecting a neutrino by a neutral-current shower:

$$P_{\nu\to\text{NC shower}} \simeq \rho N_A L \int_{E_{\text{sh}}^{\text{thr}}/E_\nu}^{1} \frac{d\sigma}{dy}\, dy$$

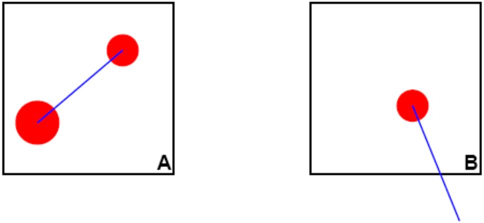
σ: NC ν-nucleon cross section
y: energy fraction transferred from the ν to the shower
L: detector length

- For ν_e, the total energy goes into the CC and NC showers, so

$$P_{\nu\to\text{shower}} \simeq \rho N_A \sigma L$$

- IceCube's energy resolution: $\sim \pm 0.1$ on $\log_{10}$ scale.
- Can reconstruct direction to $\sim 25^\circ$.

Double-bangs and lollipops



- Double bang:

$$\nu_\tau \xrightarrow{\text{CC interaction}} \text{hadronic shower} \xrightarrow{\tau\ \text{track}} \text{hadronic shower}$$

- Lollipop:

$$\tau\ \text{track} \xrightarrow{\text{CC interaction}} \text{hadronic shower}$$

Image source: IceCube Preliminary Design Document

- Tau range:

$$R_\tau\left(E_{\nu_\tau}, y\right) = \frac{(1-y)\,E_{\nu_\tau}}{m_\tau} c\tau_\tau$$

τ_τ: rest-frame lifetime

- Probability of a double bang:

$$P_{\text{db}}\left(E_{\nu_\tau}\right) \simeq \rho N_A \sigma \left[\left(L - x_{\text{min}} - R_\tau\right) e^{-x_{\text{min}}/R_\tau} + R_\tau e^{-L/R_\tau}\right]_{y=\langle y\rangle}$$

x_{min}: minimum τ range that can be resolved

- Probability of a lollipop:

$$P_{\text{lollipop}} \simeq \rho N_A \sigma \left(L - x_{\text{min}}\right) \left[e^{-x_{\text{min}}/R_\tau}\right]_{y=\langle y\rangle}$$

- We have assumed that $d\sigma/dy \simeq \sigma\delta\left(y - \langle y\rangle\right)$, with $\langle y\rangle \simeq 0.25$ at PeV scale.

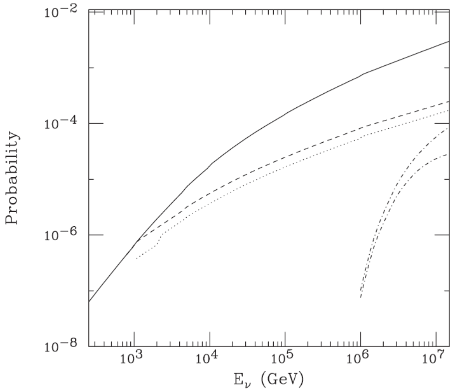


FIG. 5. Probabilities of detecting different flavors of neutrinos in IceCube versus neutrino energy, described in detail in the text. The upper solid line is the probability of a horizontal ν_μ creating a detectable muon track, and the dashed line is for downgoing ν_μ. The dotted line is the probability for ν_e to create a detectable shower (above 1 TeV), considering both charged-current and neutral-current interactions; the kink occurs when the neutral-current showers come above threshold. The dot-dashed lines are the probabilities for ν_τ to make lollipop events (upper) and double-bang events (lower).