3+2 Sterile Neutrinos in IceCube and Astrophysical Flavor Ratios

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Anomalies: A case for sterile neutrinos

- A handful of anomalous results, which cannot be fully described by SM neutrinos, may indicate that there is new physics
  - LSND, MiniBooNE, reactor experiments (CHOOZ, Bugey, Grenoble, ROVNO, Krasnoyarsk, Goesgen, Savannah River), Gallium, solar neutrino spectrum
- Not indisputable
- Variety of anomalies, not clearly consistent with one another
- LSND anomaly suggests new mass scale $\Delta m^2 \sim 1\ \mathrm{eV}^2$

3 + 2 Minimal Extension

- A sterile neutrino with $m \sim 1\ \mathrm{eV}$ might be compatible with anomalous data
- 3 + 2 minimal model: minimal extension of SM
- 4 mixing angles + 3 phases
- Few parameters than phenomenological model (9 angles + 5 phases), highly predictive
  - One new angle and mass scale drive both low and high energy phenomena
- Fits all current experiment data as well as anomalous data

3 + 2 minimal model

- New complex angle $z_{45} = \theta_{45} + i\gamma_{45}$ mixes the 4th and 5th new mass eigenstates
- New mixing matrix $R = \begin{pmatrix} \cos(\theta_{45} + i\gamma_{45}) & \sin(\theta_{45} + i\gamma_{45}) \\ -\sin(\theta_{45} + i\gamma_{45}) & \cos(\theta_{45} + i\gamma_{45}) \end{pmatrix}$
  - Non-trivial mixing with the PMNS matrix
  - Details in arXiv: 1205.5230

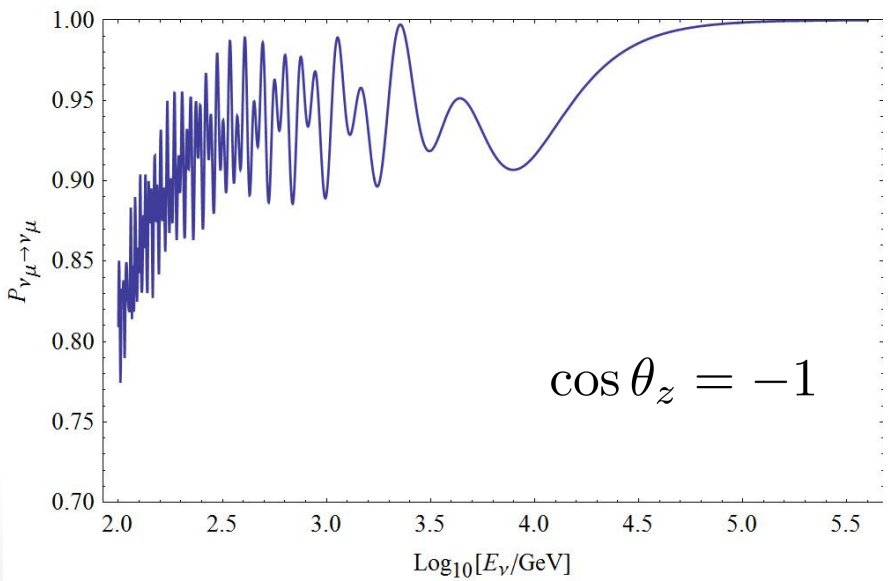
- Results of constraints to experiment

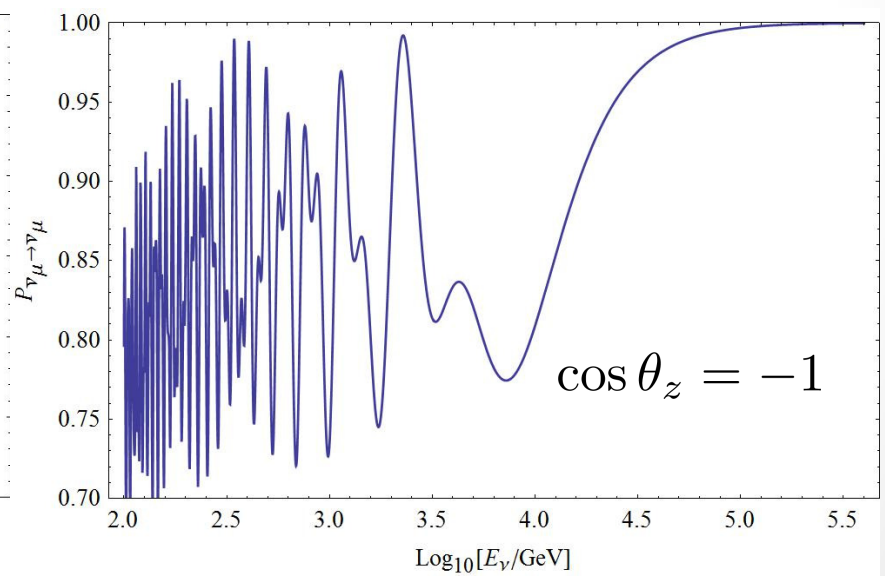
$$|U_{e4}| = 0.149,\ |U_{e5}| = 0.127,\ |U_{\mu 4}| = 0.112,\ |U_{\mu 5}| = 0.127$$

$$\phi_{45} = \mathrm{Arg}(U_{e4}^* U_{e5} U_{\mu 4} U_{\mu 5}^*) = 1.8\pi$$

IceCube Oscillations

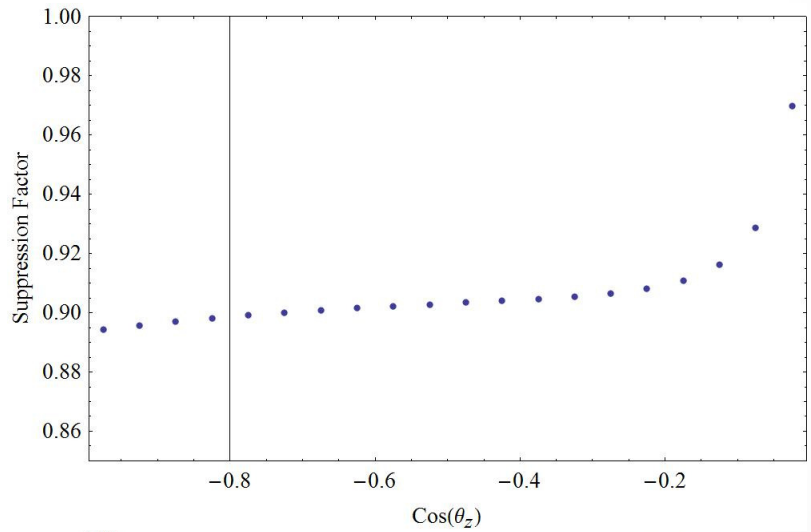
- Include charged current and neutral current matter interactions
- Consider propagation through the Earth (PREM model)

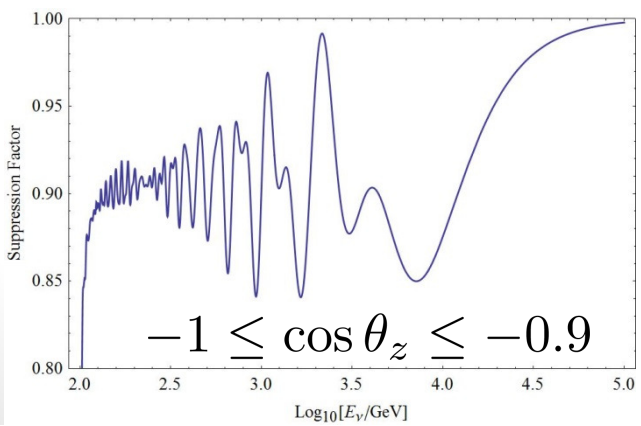


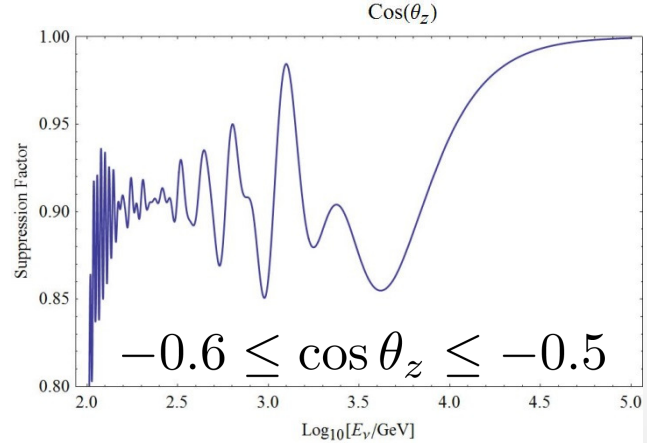


Results

- Compare the number of events predicted by oscillations with steriles to the numbers from 3 flavor oscillations
- Largest contribution in near vertical bins
- Lose information when we integrate over all energies
- Get ~15% suppression in certain energy bins







Astrophysical Neutrinos
(arXiv:1301.5313)

- Examine energy dependent flavor ratios from astrophysical sources (GRB, AGN)
- Flavor ratios depend on the cooling mechanism at the source
  - Can we learn about the source properties by measuring flavor ratios?
- Measuring the flavor ratios can also potentially tell us whether we have sterile neutrino oscillations
- Neutrinos from

$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \to e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_{\mu}(\bar{\nu}_{\mu})$$

produced by γp or $p - \mathrm{nucleon}$ interactions

$$\Phi^{d}_{\nu_{\alpha}}(E_{\nu}) = \sum P_{\alpha\beta}\Phi^{s}_{\nu_{\beta}}(E_{\nu})$$

Probabilities and Source Fluxes

- Astrophysical sources, very long propagation length
- Probabilities take on average value due to rapid oscillations

$$L/E \gg 1$$

$$P_{\alpha\beta} = \langle P_{\alpha\beta}(L/E) \rangle = \delta_{\alpha\beta} - 2\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U^*_{\beta j} U_{\alpha j}) = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

- Charged leptons and pions at the source are subject to cooling effects before they decay
  - Cooling mechanisms: synchrotron radiation, adiabatic expansions of the charged plasma

- Suppose energy dependences on pion spectrum and losses

$$\Phi_\pi \propto E^{-2} \qquad \frac{dE_x}{dt} \propto E_x^n$$

- n = 1 (adiabatic), n = 2 (synchrotron)

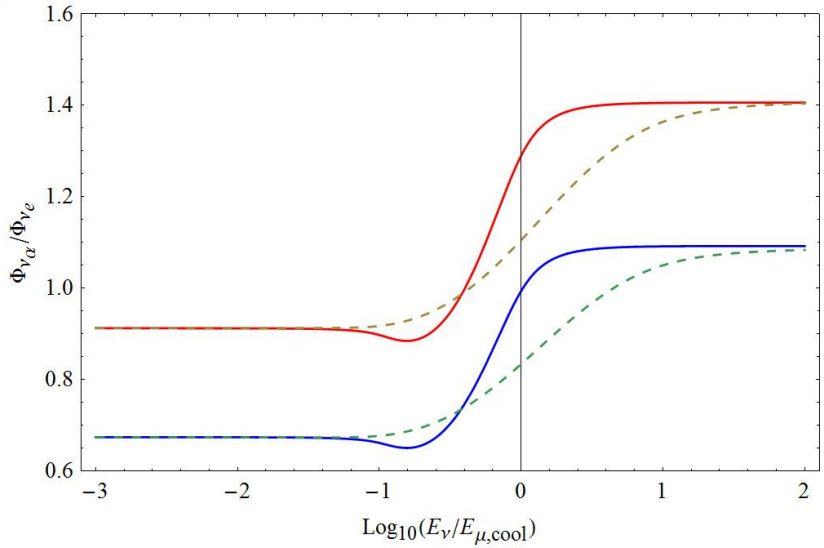
$$\Phi^s_{\nu_\mu}(E_\nu) = -\partial_{E_\nu} \int_{4E_\nu}^{\infty} dE_i \Phi_\pi(E_i) P(E_i, 4E_\nu)$$

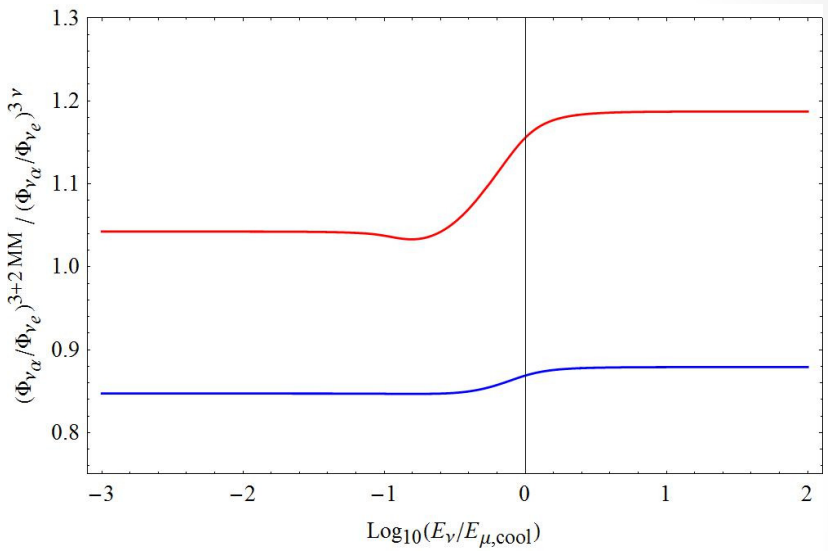
$$\Phi^s_{\nu_\mu}(E_\nu) = \partial_{E_\nu} \int_{3E_\nu}^{\infty} dE_\mu \int_{\frac{4}{3}E_\mu}^{\infty} dE_i \Phi_\pi(E_i) P(E_\mu, 3E_\nu) \partial_{E_\mu} P(E_i, \frac{4}{3}E_\mu)$$

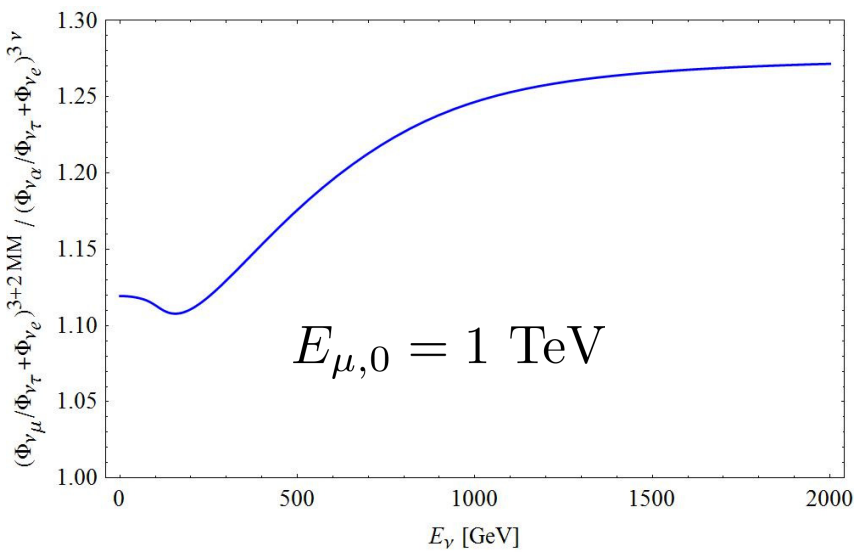
$$P(E_i, E_f) = 1 - Exp[-E_0^n(E_f^{-n} - E_i^{-n})/n]$$

- The cooling energy contains information about the source, such as magnetic field strength
  - Can be extracted from measurements of flavor ratios

Results


$\Phi_{\nu_\alpha}/\Phi_{\nu_e}$
$\mathrm{Log}_{10}(E_\nu/E_{\mu,\mathrm{cool}})$


$(\Phi_{\nu_\alpha}/\Phi_{\nu_e})^{3+2\,\mathrm{MM}}\,/\,(\Phi_{\nu_\alpha}/\Phi_{\nu_e})^{3\,\nu}$
$\mathrm{Log}_{10}(E_\nu/E_{\mu,\mathrm{cool}})$


$(\Phi_{\nu_\mu}/\Phi_{\nu_\tau}+\Phi_{\nu_e})^{3+2\,\mathrm{MM}}\,/\,(\Phi_{\nu_\alpha}/\Phi_{\nu_\tau}+\Phi_{\nu_e})^{3\,\nu}$
$E_{\mu,0} = 1$ TeV
E_ν [GeV]

Conclusions

- ~15% maximal suppression from 3 flavor predictions in IceCube
  - Possibility for sterile effects to be seen with careful energy and zenith angle selection
- Measurements of tracks - cascades ratio can help to determine the astrophysical source
  - Muon cooling energy depends on the source properties (ie. Magnetic field strength)
  - Can deduce the cooling energy from the ratio spectrum
- Determine whether there are sterile neutrinos from flavor ratios