Neutrino Flavor Physics and Astronomy

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K.-C. Lai, G.-L. Lin and T. C. Liu,
Phys. Rev. D 82, 103003 (2010)
Prog.Part. Nucl. Phys. 64, 420 (2010)
Phys. Rev. D 80, 103005 (2009)
T. C. Liu, M. A. Huang and G.-L. Lin, arXiv:1005.5154

Outline

- Review on possible types of astrophysical neutrino sources
- What can we learn by detecting these neutrinos?

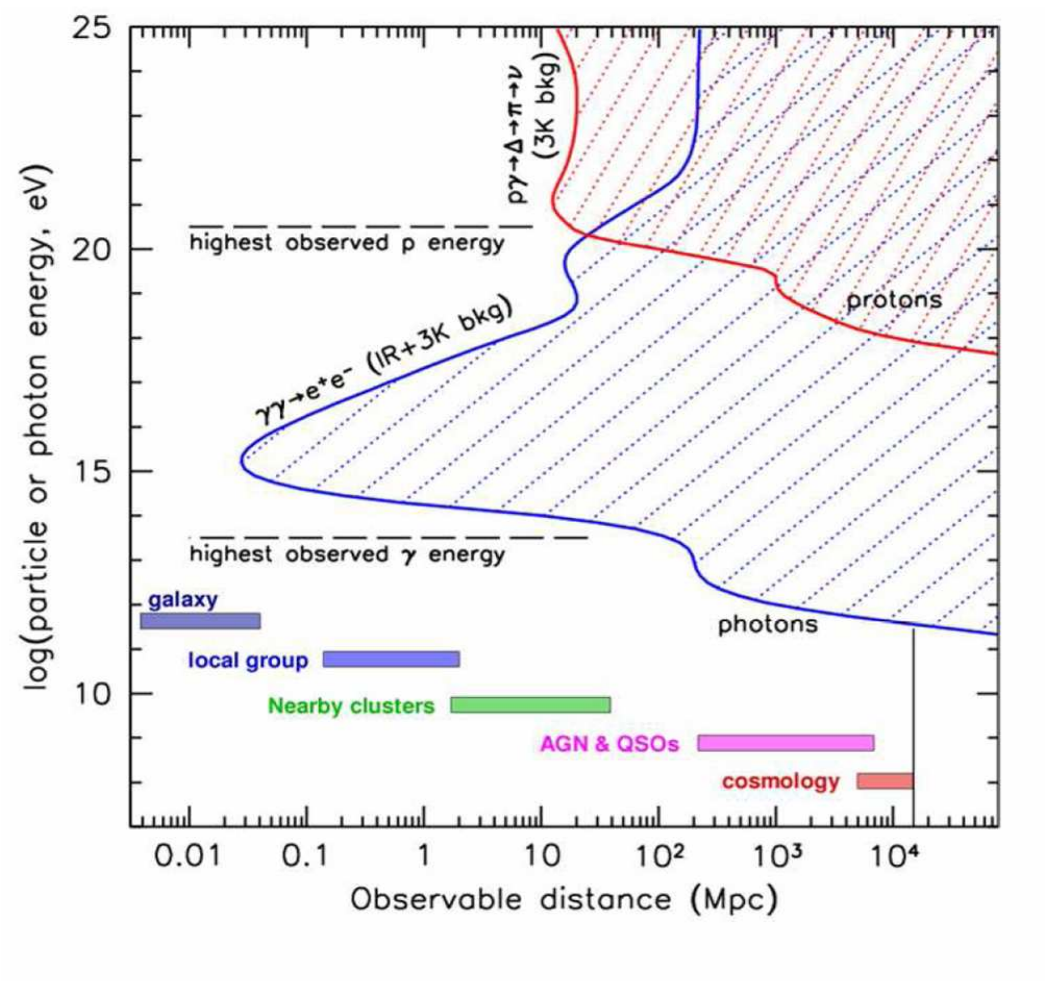
  (1) the astrophysical source

  (2) the neutrino flavor transitions
- The requirements on neutrino telescopes

The motivation for detecting astrophysical neutrinos

- Both neutrinos and photons are produced by high energy hadronic collisions—likely to in AGN, GRB,…
- The universe becomes opaque for any photon with an energy $>10^{14}$ eV
- On the other hand, a neutrino propagates freely due to its weak-interacting nature—a complementary astrophysical probe

P. Allison et al., arXiv:0904.1309.



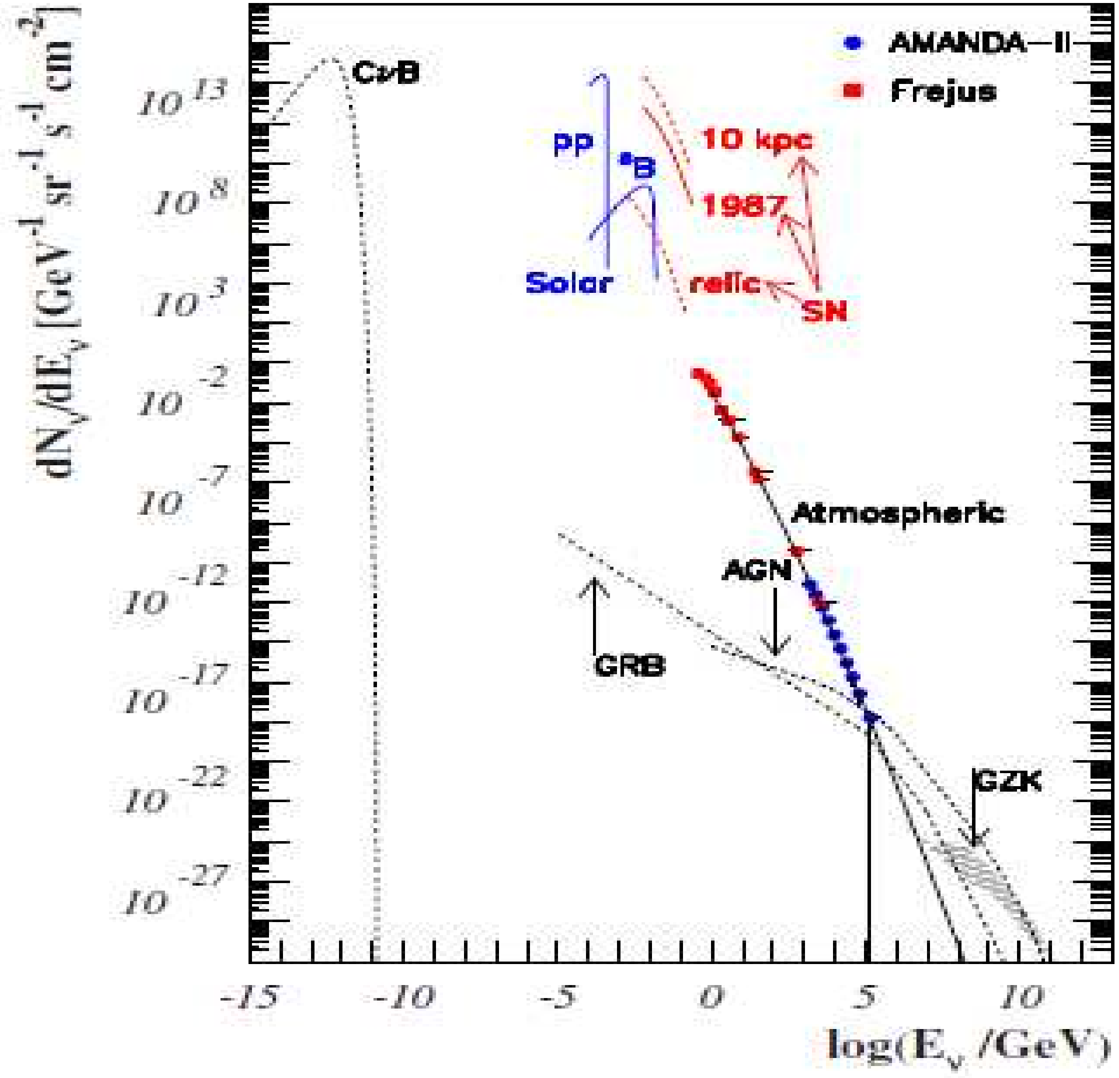
Fluxes of astrophysical neutrinos

Atm:
$PA \rightarrow \pi, K$

GRB, AGN
$P\gamma \rightarrow \Delta \rightarrow n\pi$

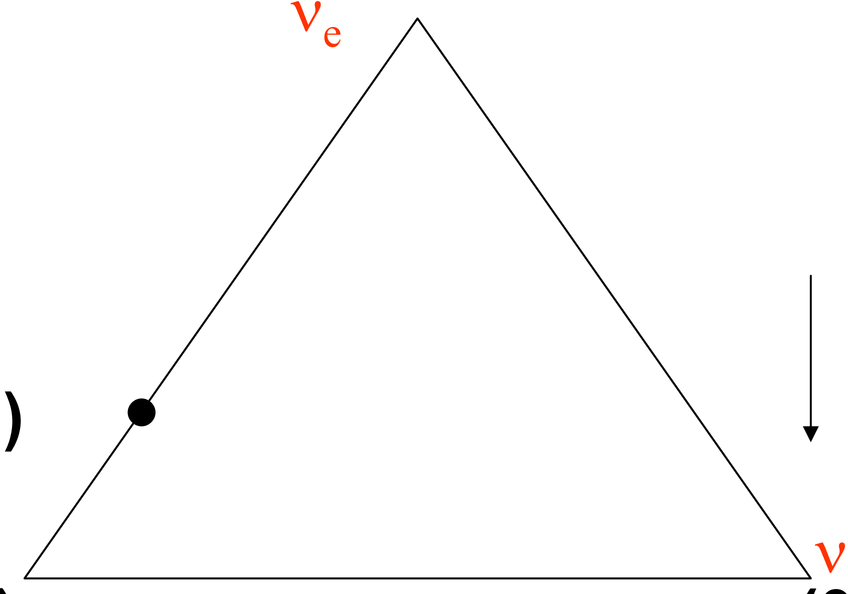
GZK
$P\gamma_{CMB} \rightarrow \Delta \rightarrow n\pi$

Neutrino arises from
π, K decays



F. Halzen and S. R. Klein, 2010

Common astrophysical neutrino sources



(1,0,0) **β source**

ν_e

Pion source

(1/3,2/3,0)

ν_μ

(0,1,0)

ν_τ

(0,0,1)

$$\frac{1}{\sqrt{6}}(-2,1,1)$$

Muon damped source

$$\frac{1}{\sqrt{2}}(0,-1,1)$$

$$\Phi_0 = \left(\phi_0(\nu_e), \phi_0(\nu_\mu), \phi_0(\nu_\tau)\right)$$

$$\phi_0(\nu_e) + \phi_0(\nu_\mu) + \phi_0(\nu_\tau) = 1$$

Pion source (1/3,2/3,0)

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to \overline{\nu}_\mu + e^+ + \nu_e$$

Energies of various neutrinos are comparable, i.e., muon decays before losing its energy by interactions.

Cosmogenic (GZK) neutrinos produced by $p + \gamma_{CMB} \to \Delta^+ \to n + \pi^+$ **and the subsequent pion decay fit into this category.**

Muon damped source (0,1,0)

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow \overline{\nu}_\mu + e^+ + \nu_e$$

Muon loses significant amount of energy before it decays:

(1) muon interacts with matter

J. P. Rachen and P. Meszaros, 1998

(2) Muon interacts with background photon field

M. Kacherliess, O. Ostapchenko and R. Tomas,
arXiv: 0708.3007

Neutrino flux from muon decays is negligible

See more detailed studies in

T. Kashti and E. Waxman Phy. Rev. Lett. 2005

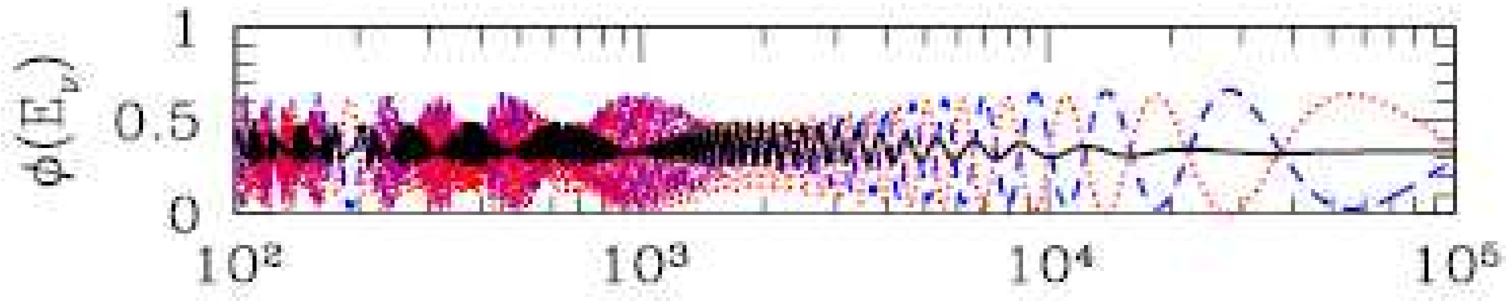
P. Lipari, M. Lusignoli and D. Meloni, Phys. ReV. D 2007

Source with a significant tau neutrino flux

Optically thick sources: highly relativistic GRB jets

Neutrinos already oscillate inside the object.

O. Mena, I. Mocioiu and S. Razzaque, 2006



—— ν_e

- - - ν_μ

⋯⋯ ν_τ

$$\phi_0(\nu_e):\phi_0(\nu_\mu):\phi_0(\nu_\tau)=\frac{1}{3}:a:\left(\frac{2}{3}-a\right)$$

for $E_\nu > 10^4$ GeV

The β source (1,0,0)

Motivated by the correlation of the arrival direction of the cosmic rays to the Galactic Plane (GP) near EeV (10^{18} eV) energies

AGASA 1998; Fly's Eye 1998

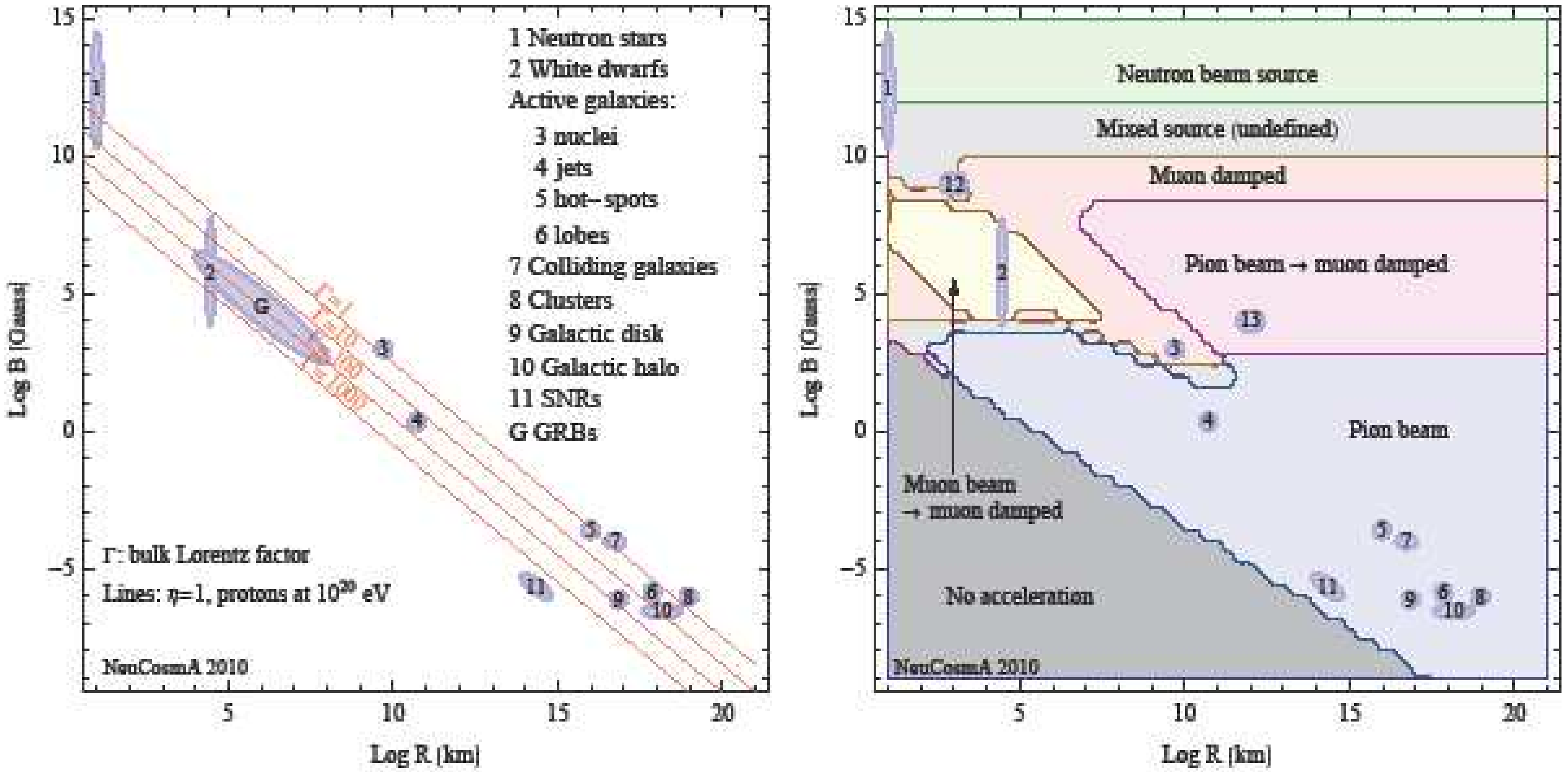
Directional signal requires relatively-stable neutral primaries.

Neutron decay length is about 10 kpc for E_n=1 EeV.
Smaller energy neutrons can decay $n \rightarrow p + e^{-} + \overline{\nu}_e$

L. A. Anchordoqui, H. Goldberg, F. Halzen
and T. J. Weiler, 2004

Scanning sources on Hillas plot

$$\phi(E_p) \propto E_p^{-2}$$



S. Hummer, M. Maltoni, W. Winter,and C. Yaguna, Astropart. Phys. 34, 205 (2010).

Detectors of High Energy Astrophysical Neutrinos

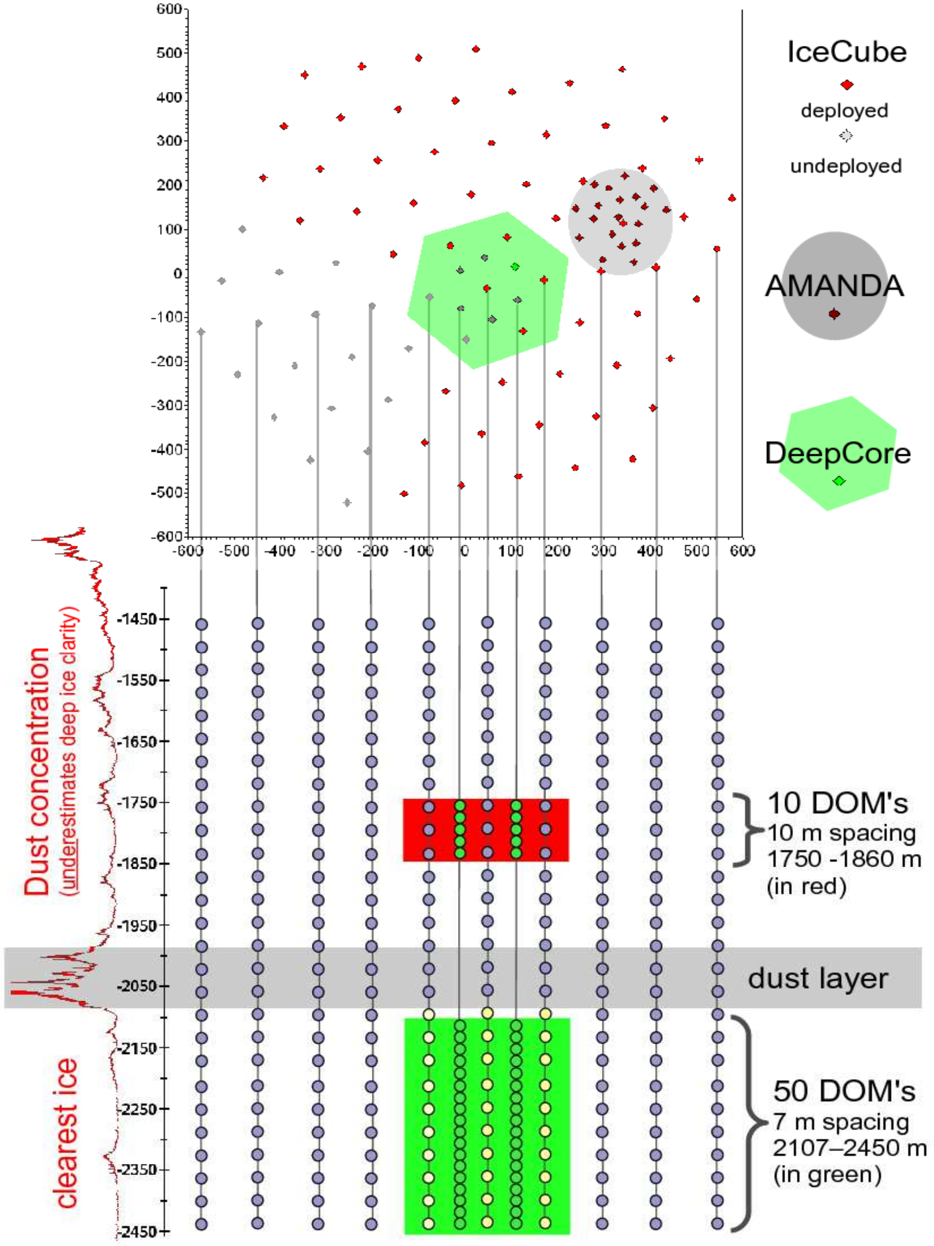
- IceCube—PMT array in South Pole ice
- ANTARES→KM3Net—PMT array in the Mediterranean
- ANITA—radio wave detector above South Pole
- Pierre Auger—earth skimming tau neutrinos
- ARA—radio extension of IceCube

IceCube layout

Top view

Side view

C. Wiebusch, ICRC 2009



The track signature

$$CC\ \nu_{\mu} + N \rightarrow \mu^{-} + X$$

Muon deposits energies as it passes through the detector volume.

The shower signature

- $$CC\,\nu_e + N \rightarrow e^- + X\ \text{EM} + \text{Hadronic}$$
  $$\text{NC}\,\nu_e + N \rightarrow \nu_e + X\ \text{Hadronic}$$

- $$NC\,\nu_\mu + N \rightarrow \nu_\mu + X,\ \text{suppressed by}\ \langle \text{y} \rangle^{(\gamma\text{-}1)} \times \sigma_{\text{NC}}/\sigma_{\text{CC}}$$

$$2 \times 10^6\ \text{GeV} < E_\tau < 2 \times 10^7\ \text{GeV}$$

◆ $$CC\ \ \nu_\tau + N \rightarrow \tau^- + X,\ \tau^- \rightarrow \text{hadrons (double bang)}$$
$$NC\,\nu_\tau + N \rightarrow \nu_\tau + X$$

ν_μ fraction can be extracted. Rather difficult to identify ν_τ due to the detector size (IceCube for example).

Accuracy for flavor ratio determination

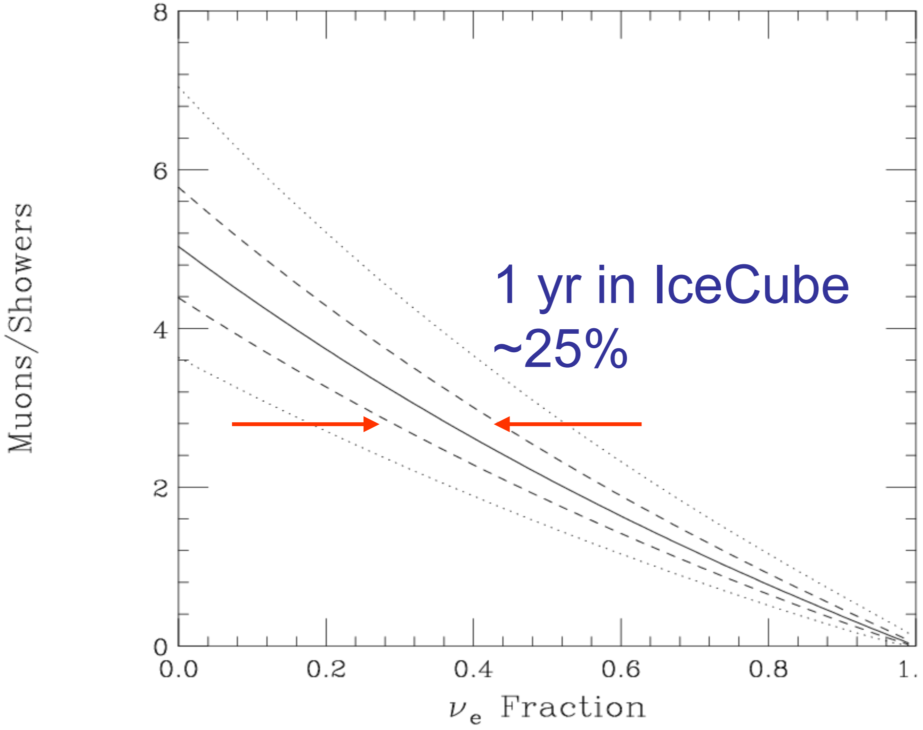
J. F. Beacom *et al.*
Phys. Rev. D 2003, arXiv: hep-ph/0307027v3

- Assume ν_μ--ν_τ symmetry
- Muon energy threshold at 100 GeV, shower energy threshold energy at 1 TeV.
- Flux analyzed:

$$E_{\nu_e}^2 \frac{dN_{\nu_e}}{dE_{\nu_e}} = 0.5 E_{\nu_\mu}^2 \frac{dN_{\nu_\mu}}{dE_{\nu_\mu}} = 10^{-7}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$$

$\sim$Waxman-Bahcall bound

Waxman and Bahcall 1998



1 yr in IceCube
~25%

Can be translated to ~10% accuracy in separating ν_μ from ν_e and ν_τ in a decade of data taking in IceCube

What can we learn by detecting astrophysical neutrinos?

(I). The neutrino flavor ratio at the source might be probed.

Earlier discussions on this issue:

G. Barenboim and C. Quigg, Phys. Rev. D 2003;
Z. Z. Xing and S. Zhou, Phys. Rev. D 2006

Our analysis takes into account errors in neutrino telescope measurements--

K. C. Lai, GLL, T.C. Liu, Phys. Rev. D, 2009.

See also

A. Esmaili and Y. Farzan, Nucl. Phys. B, 2009.

Flavor transitions for a large neutrino propagation distance

$$\begin{pmatrix}\phi(\nu_e)\\ \phi(\nu_\mu)\\ \phi(\nu_\tau)\end{pmatrix} = \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau}\\ P_{\mu e} & P_{\mu\mu} & P_{\mu\tau}\\ P_{\tau e} & P_{\tau\mu} & P_{\tau\tau}\end{pmatrix}\begin{pmatrix}\phi_0(\nu_e)\\ \phi_0(\nu_\mu)\\ \phi_0(\nu_\tau)\end{pmatrix}$$

Standard neutrino oscillations

Measured flux Φ

Source flux Φ_0

$$P_{\alpha\beta} \equiv P(\nu_\beta \to \nu_\alpha) = \sum_{i=1}^{3} \left|U_{\beta i}\right|^2 \left|U_{\alpha i}\right|^2, \text{ where } \nu_\alpha = U^*_{\alpha i}\nu_i$$

Flavor Eigenstate

Mass Eigenstate

$\boldsymbol{U_{\alpha i}}$ contains 3 mixing angles--θ_{12}, θ_{23}, and θ_{13}
one CP phase δ

The exact form of oscillation probability matrix

$$
\begin{aligned}
P_{ee} &= \left(1-\frac{1}{2}\omega\right)(1-D^2)^2+D^4, \\
P_{e\mu} &= \frac{1}{4}(1-D^2)\left[\omega(1+\Delta)+(4-\omega)(1-\Delta)D^2+2\sqrt{\omega(1-\omega)(1-\Delta^2)}D\cos\delta\right], \\
P_{e\tau} &= \frac{1}{4}(1-D^2)\left[\omega(1-\Delta)+(4-\omega)(1+\Delta)D^2-2\sqrt{\omega(1-\omega)(1-\Delta^2)}D\cos\delta\right], \\
P_{\mu\mu} &= \frac{1}{2}\left[(1+\Delta^2)-(1-\Delta)^2D^2(1-D^2)\right] \\
&- \frac{1}{8}\omega\left[(1+\Delta)^2+(1-\Delta)^2D^4-(1-\Delta^2)D^2(2+4\cos^2\delta)\right] \\
&- \frac{1}{2}\sqrt{\omega(1-\omega)(1-\Delta^2)}\left[(1+\Delta)-(1-\Delta)D^2\right]D\cos\delta, \\
P_{\mu\tau} &= \frac{1}{2}(1-\Delta^2)(1-D^2+D^4) \\
&- \frac{1}{8}\omega\left[(1-\Delta^2)(1+4D^2\cos^2\delta+D^4)-2(1+\Delta^2)D^2\right] \\
&+ \frac{1}{2}\sqrt{\omega(1-\omega)(1-\Delta^2)}\Delta(1+D^2)D\cos\delta, \\
P_{\tau\tau} &= \frac{1}{2}\left[(1+\Delta^2)-(1+\Delta)^2D^2(1-D^2)\right] \\
&- \frac{1}{8}\omega\left[(1-\Delta)^2+(1+\Delta)^2D^4-(1-\Delta^2)D^2(2+4\cos^2\delta)\right] \\
&+ \frac{1}{2}\sqrt{\omega(1-\omega)(1-\Delta^2)}\left[(1-\Delta)-(1+\Delta)D^2\right]D\cos\delta, \qquad \text{(A1)}
\end{aligned}
$$

$\omega \equiv \sin^2 2\theta_{12}, \Delta \equiv \cos 2\theta_{23}, D \equiv \sin\theta_{13}$

δ CP phase

Our understandings of neutrino mixing parameters

$$\sin^2\theta_{12} = 0.32^{+0.02}_{-0.02},$$

$$\sin^2\theta_{23} = 0.45^{+0.09}_{-0.06},$$

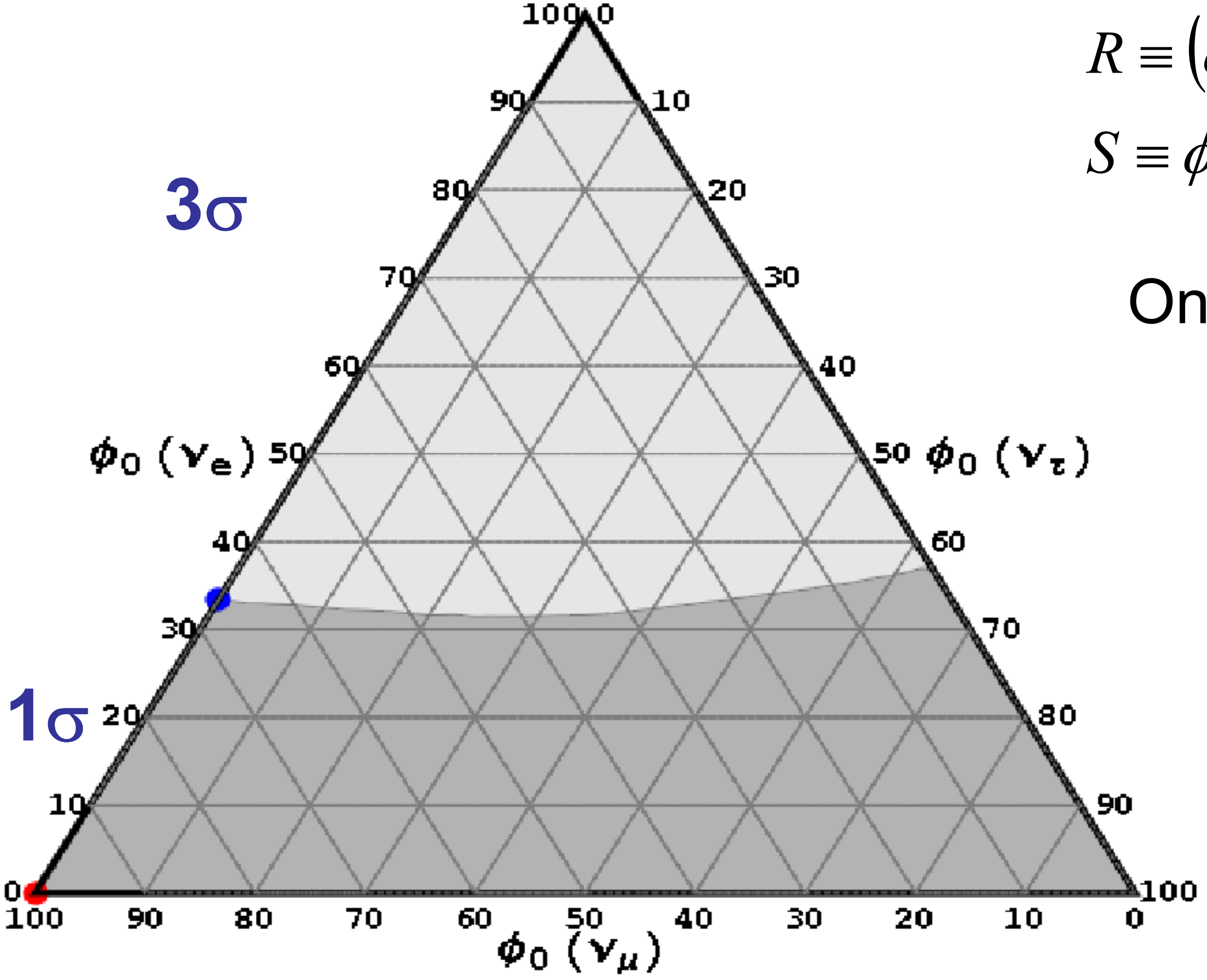
$$\sin^2\theta_{13} < 0.019\ (90\%\ \mathrm{C.L.})$$

M.C. Gonzalez-Garcia and
M. Maltoni, Phys. Rept. 2008

Δm^2 not required in this analysis

Results for the Reconstruction of Source Flavor Ratio

Muon-damped source as the input



$$R \equiv (\phi(\nu_\mu))/(\phi(\nu_e)+\phi(\nu_\tau))$$

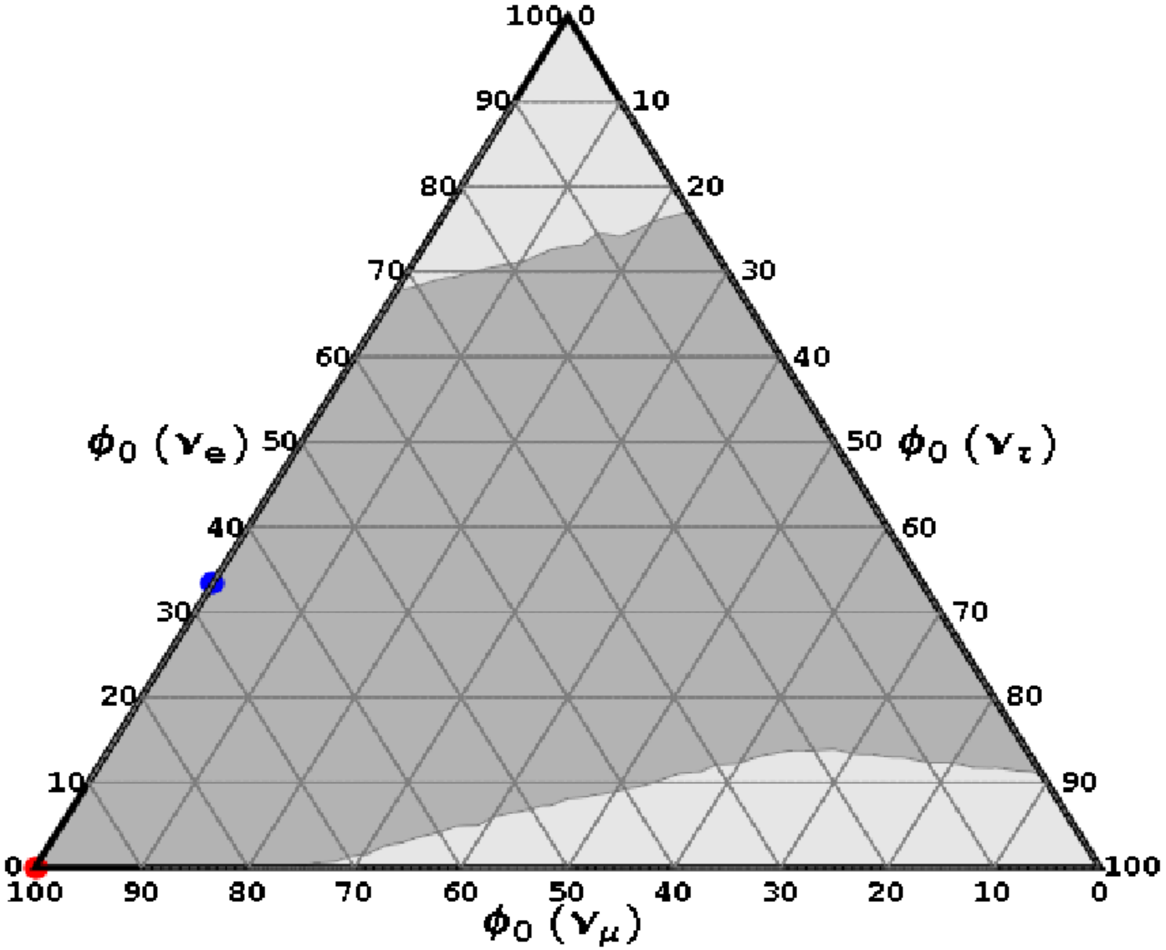
$$S \equiv \phi(\nu_e)/\phi(\nu_\tau)$$

Only *R* is measured

$$\Delta R / R = 10\%$$

Degeneracy

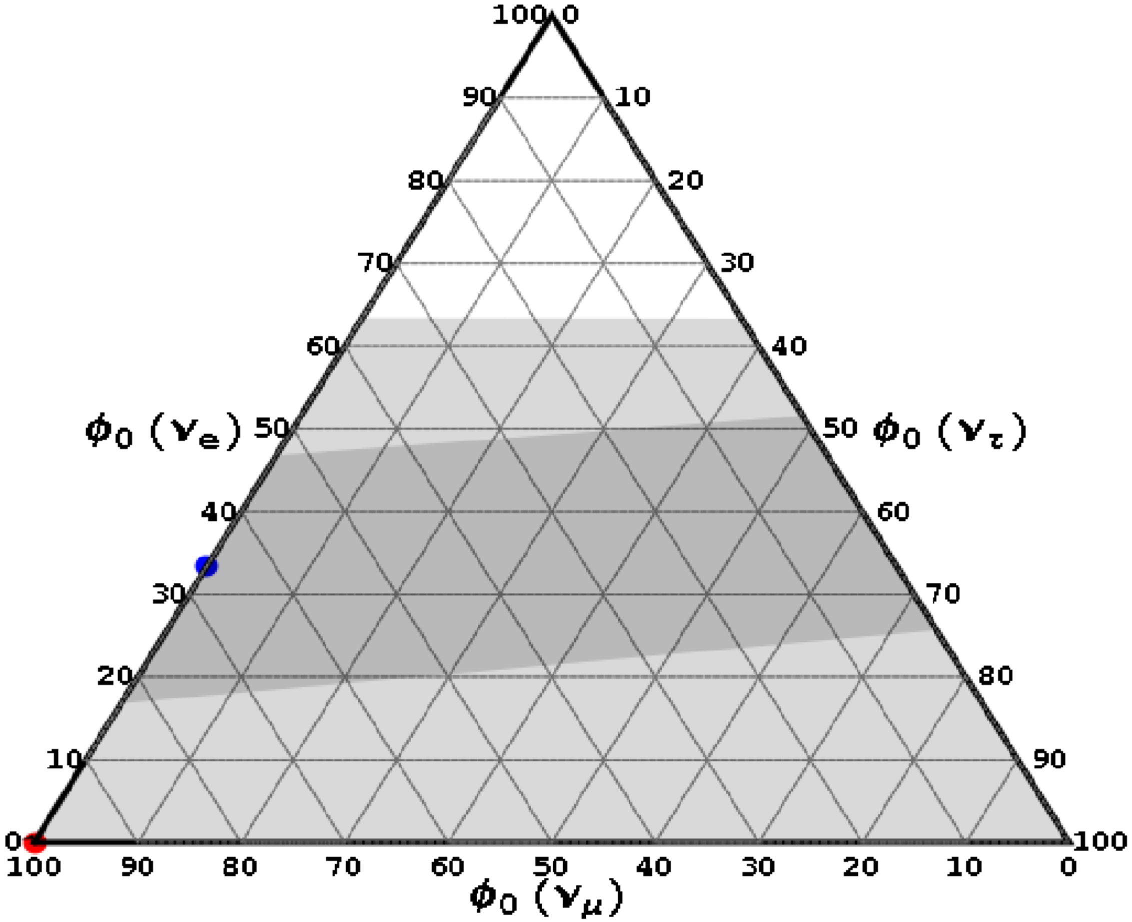
Pion source as the input



Only *R* is measured

$$\Delta R / R = 10\%$$

Pion source as the input



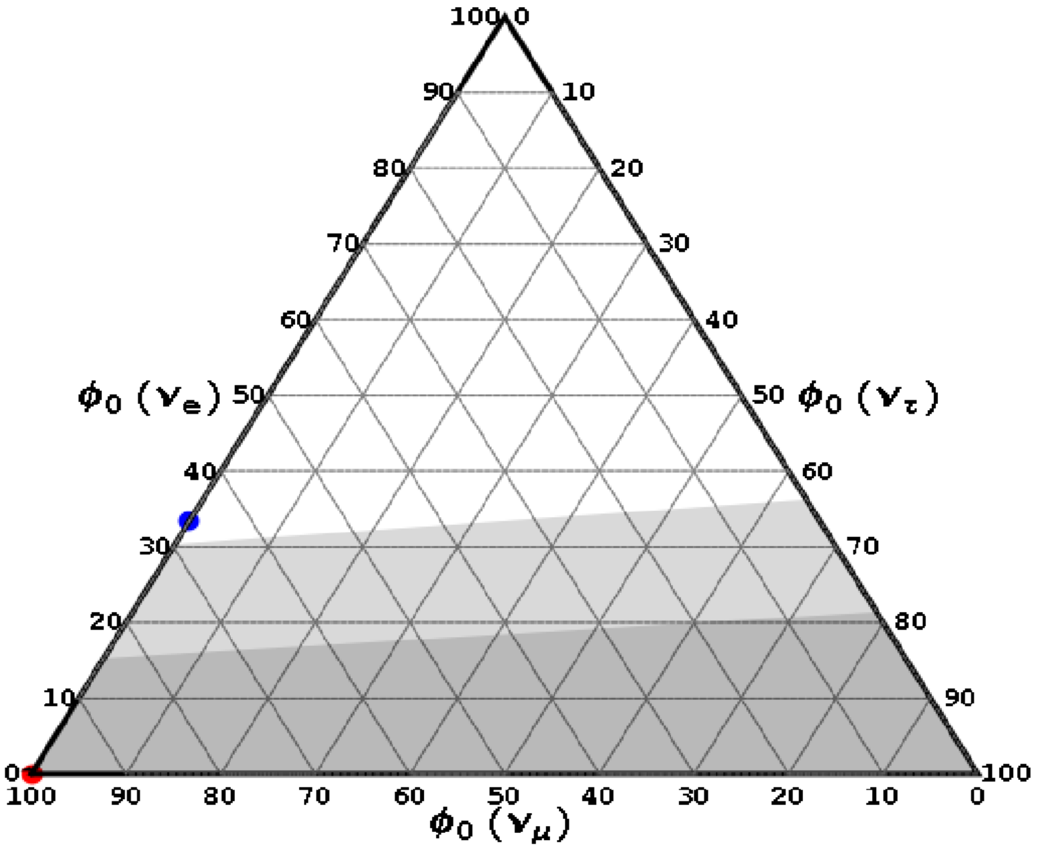
Both *R* and *S* are measured

$$\Delta R / R = 10\%$$

$$\Delta S / S = 1.2 \Delta R / R$$

Assuming ΔR and ΔS are dominated by statistical errors

Muon-damped source as the input



Both *R* and *S* are measured

$$\Delta R / R = 10\%$$

$$\Delta S / S = 1.3 \Delta R / R$$

Assuming ΔR and ΔS are dominated by statistical errors

Tau neutrino identification is very important!

Summary and remarks for part (I)

- We have presented the attempt to reconstruct flavor ratios of astrophysical neutrinos at the source, using IceCube as an example.
- Using Waxman-Bachall bound as a reference point, it has been shown previously that ν_μ fraction can be measured to 10% accuracy for a decade of data taking in IceCube. However, the ν_τ fraction is not easy to extract.
- With only ν_μ fraction measured, it is challenging to discriminate astrophysical neutrino sources with different flavor ratios. ***Effective tau neutrino identification is needed.*** Larger detector or larger density of detector modules?

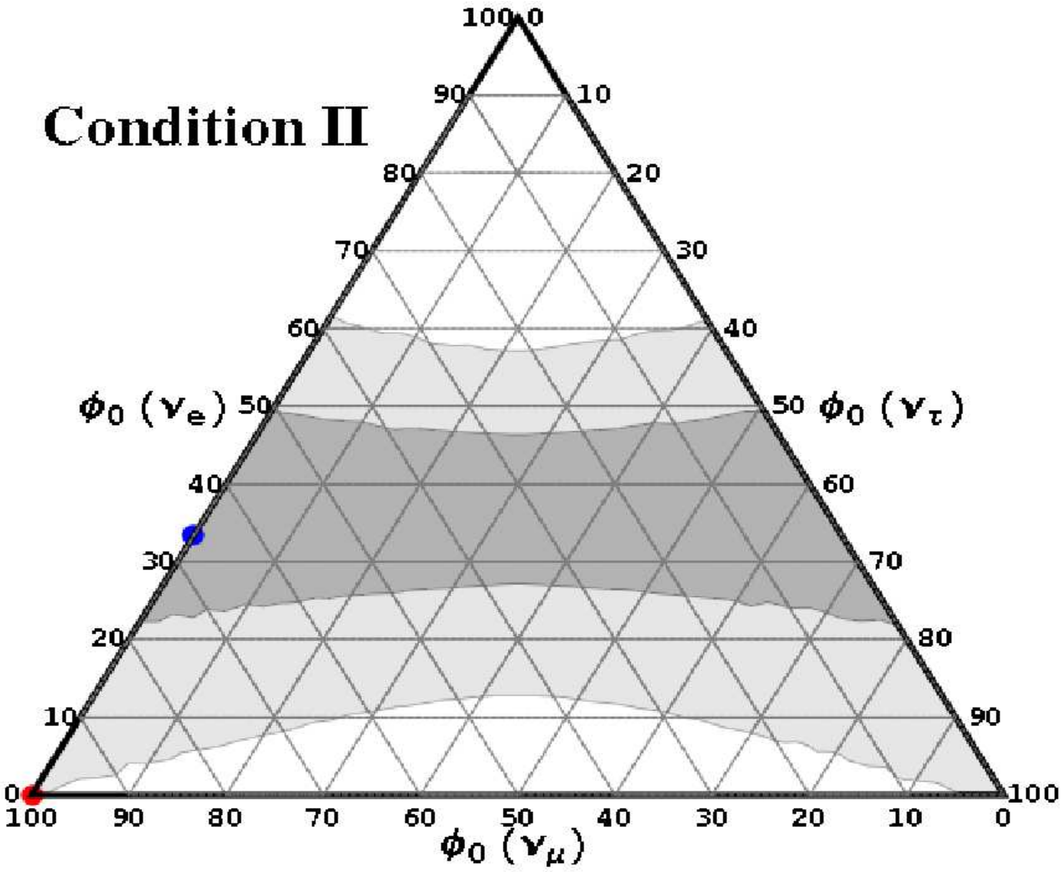
- For neutrino energies higher than 3×10^7 GeV, tau neutrino also has a track-like signature similar to muon neutrino, while electron neutrino still has a shower signature.
- The ratio variable one can extract from the neutrino telescope measurement becomes

$$R' = \phi(\nu_e)/(\phi(\nu_\mu)+\phi(\nu_\tau)).$$

- The variable $S' = \phi(\nu_\mu)/\phi(\nu_\tau)$ is more difficult to determine. Nevertheless it is not important due to ν_μ--ν_τ symmetry.

T. C. Liu, M. A. Huang and GLL, arXiv:1005.5154

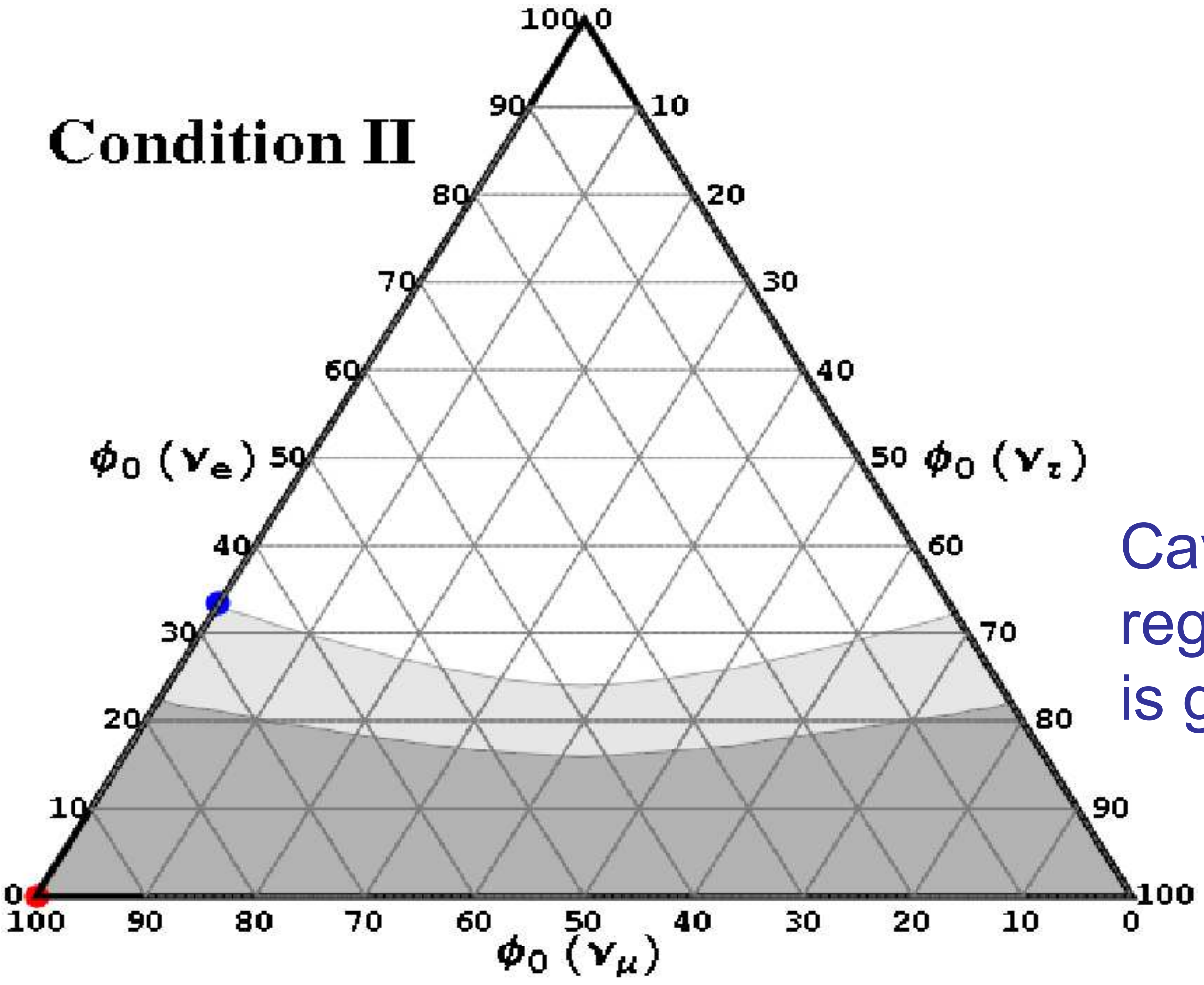
♦Pion source (such as GZK ν) as the input



Only *R'* is measured

$$\Delta R' / R' = 10\%$$

♦Muon-damped source as the input



Only *R*' is measured

$$\Delta R' / R' = 10\%$$

Caveat: In high energy regime, neutrino flux is generally suppressed!

What can we learn by detecting astrophysical neutrinos?

(II).The flavor transition mechanisms of astrophysical neutrinos might be probed.

terrestrially measured flux $\Phi = P\Phi_0$ source flux

Earlier discussions on this issue:

G. Barenboim and C. Quigg, Phys. Rev. D 2003,
J. Beacom *et al.* Phys. Rev. Lett. 2003 …

Work out *P* model by model and calculate the resultant Φ which is to be tested by neutrino telescope.

However, we perform a transformation $Q = A^{-1}PA.$
Classification of flavor transition models can be done easily on *Q*. Fit *Q* to the measurement.

K.-C. Lai, G.-L. Lin and T. C. Liu,
Phys. Rev. D 82, 103003 (2010)

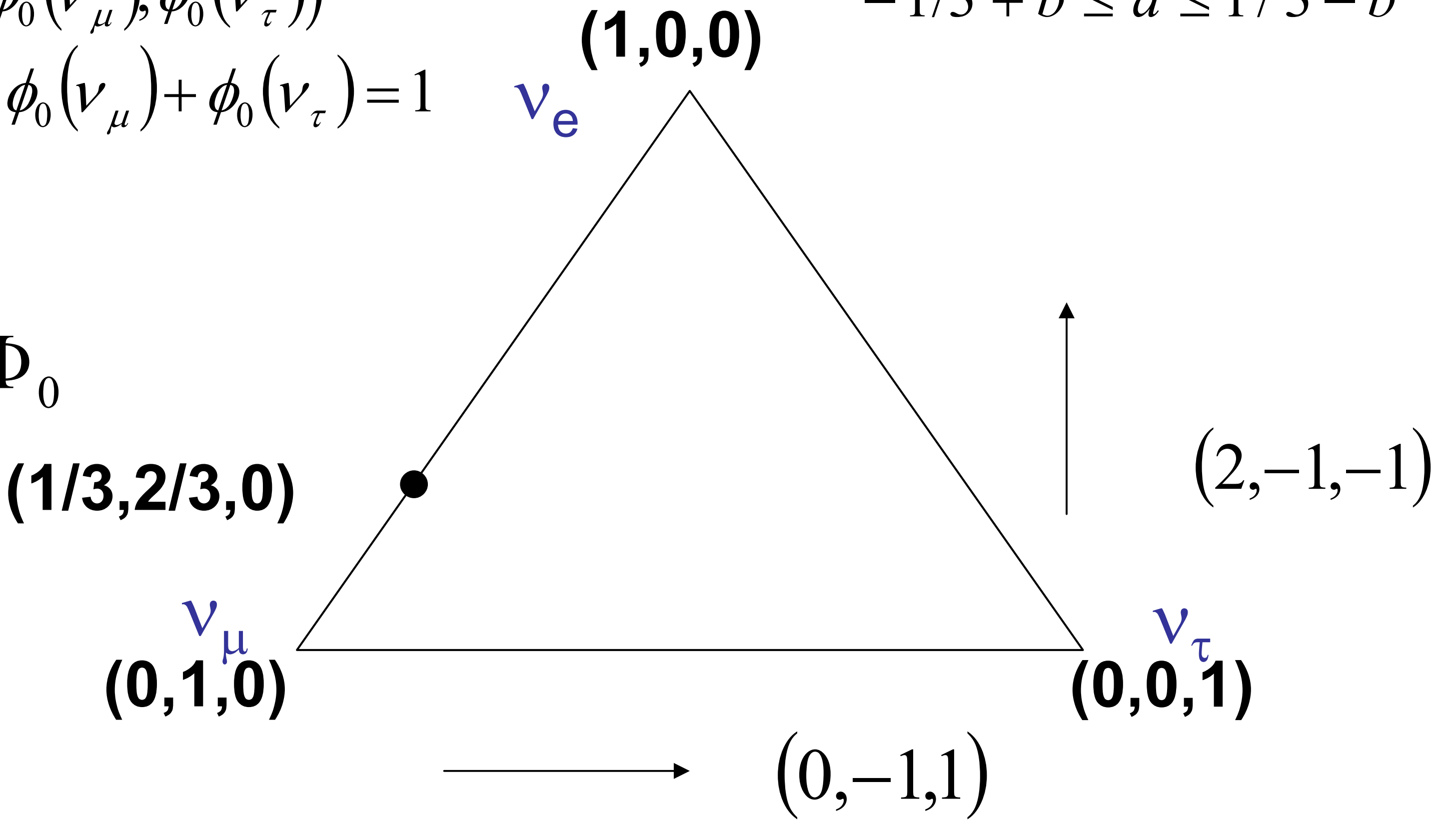
$$\Phi_0 = \frac{1}{3}(1,1,1)^T + a(0,-1,1)^T + b(2,-1,-1)^T, -1/6 \le b \le 1/3$$

$$\left(\phi_0(\nu_e), \phi_0(\nu_\mu), \phi_0(\nu_\tau)\right)^T$$

$$-1/3 + b \le a \le 1/3 - b$$

$$\phi_0(\nu_e) + \phi_0(\nu_\mu) + \phi_0(\nu_\tau) = 1$$

$$\Phi = P\Phi_0$$



$$\left(\phi(\nu_e), \phi(\nu_\mu), \phi(\nu_\tau)\right)^T$$

$$\Phi = \kappa(1,1,1)^T + \rho(0,-1,1)^T + \lambda(2,-1,-1)^T$$

$\kappa = 1/3$ corresponds to conservation of neutrino flux

A simple transformation

$$\begin{pmatrix} \kappa \\ \rho \\ \lambda \end{pmatrix} = \begin{pmatrix} Q_{11} & Q_{12} & Q_{13} \\ Q_{21} & Q_{22} & Q_{23} \\ Q_{31} & Q_{32} & Q_{33} \end{pmatrix} \begin{pmatrix} 1/3 \\ a \\ b \end{pmatrix}, \text{ where}$$

$$\begin{pmatrix} Q_{11} & Q_{12} & Q_{13} \\ Q_{21} & Q_{22} & Q_{23} \\ Q_{31} & Q_{32} & Q_{33} \end{pmatrix} = A^{-1} \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{\mu e} & P_{\mu\mu} & P_{\mu\tau} \\ P_{\tau e} & P_{\tau\mu} & P_{\tau\tau} \end{pmatrix} A \text{ with}$$

$$A = \begin{pmatrix} 1 & 0 & 2 \\ 1 & -1 & -1 \\ 1 & 1 & -1 \end{pmatrix}.$$

$$\rho = \frac{1}{2}\left(\phi(\nu_\tau) - \phi(\nu_\mu)\right), \lambda = \frac{1}{3}\left(\phi(\nu_e) - \frac{\phi(\nu_\mu) + \phi(\nu_\tau)}{2}\right)$$

$$\phi(\nu_e) + \phi(\nu_\mu) + \phi(\nu_\tau) = 3\kappa$$

κ =1/3 is ensured by Q_{11}=1, Q_{12}=Q_{13}=0

The meanings of Q_{ij} are clear!

Classify flavor transition models

Flux conservation

$$Q = \begin{pmatrix} 1 & 0 & 0 \\ Q_{21} & Q_{22} & Q_{23} \\ Q_{31} & Q_{32} & Q_{33} \end{pmatrix}$$

Flux conservation+ν_μ--ν_τ symmetry

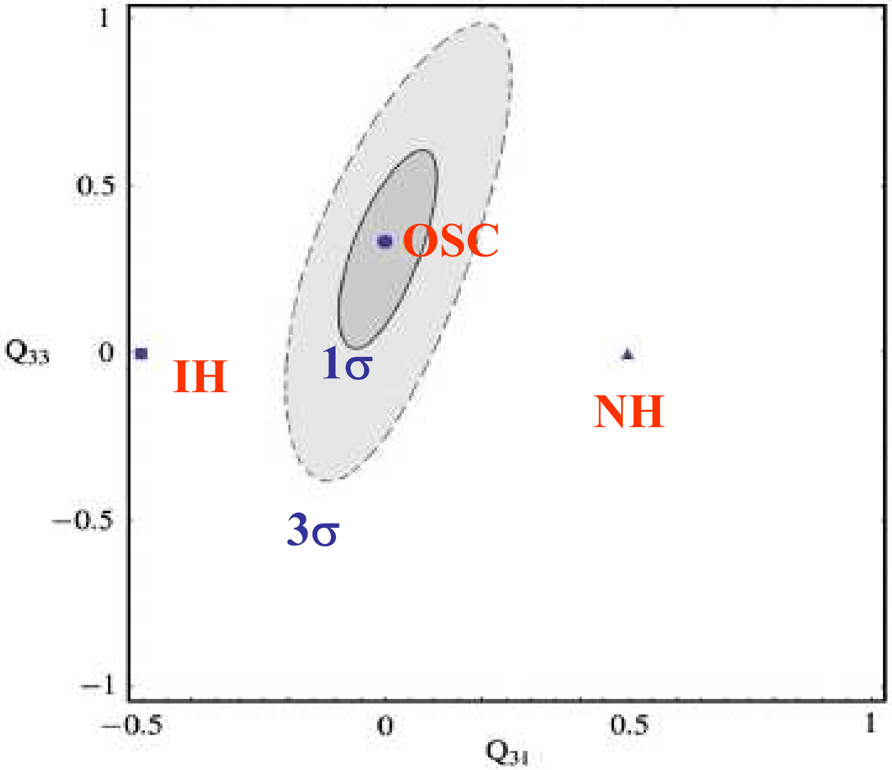
$$Q = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ Q_{31} & 0 & Q_{33} \end{pmatrix}$$

Values for Q_{31} and Q_{33} determine the model

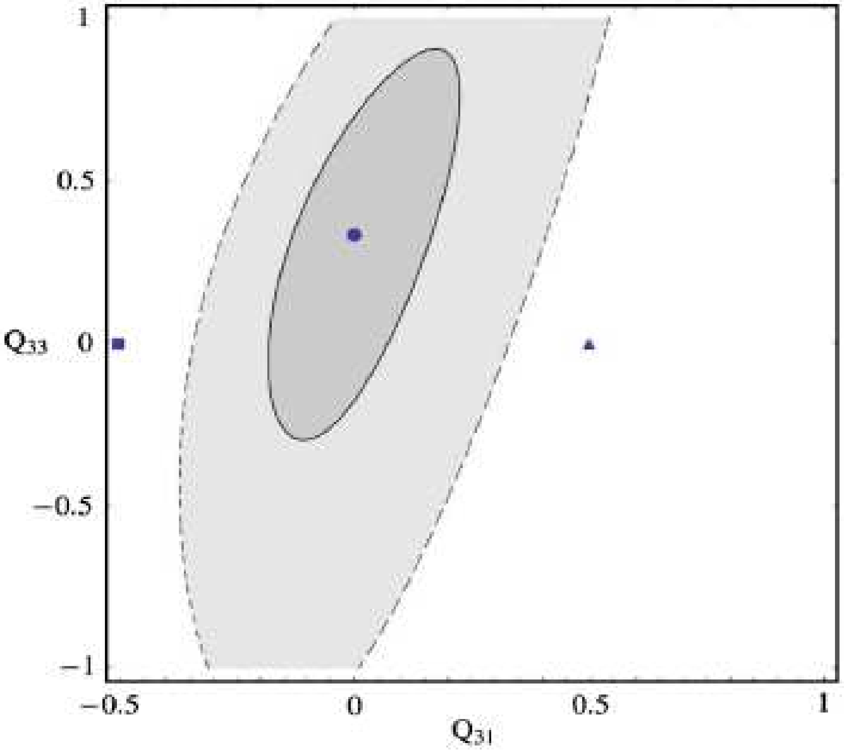
Fit Q_{31} and Q_{33} to the data

Fitting results—pion source+muon damped source

Compare oscillation with neutrino decays (H, M→L)

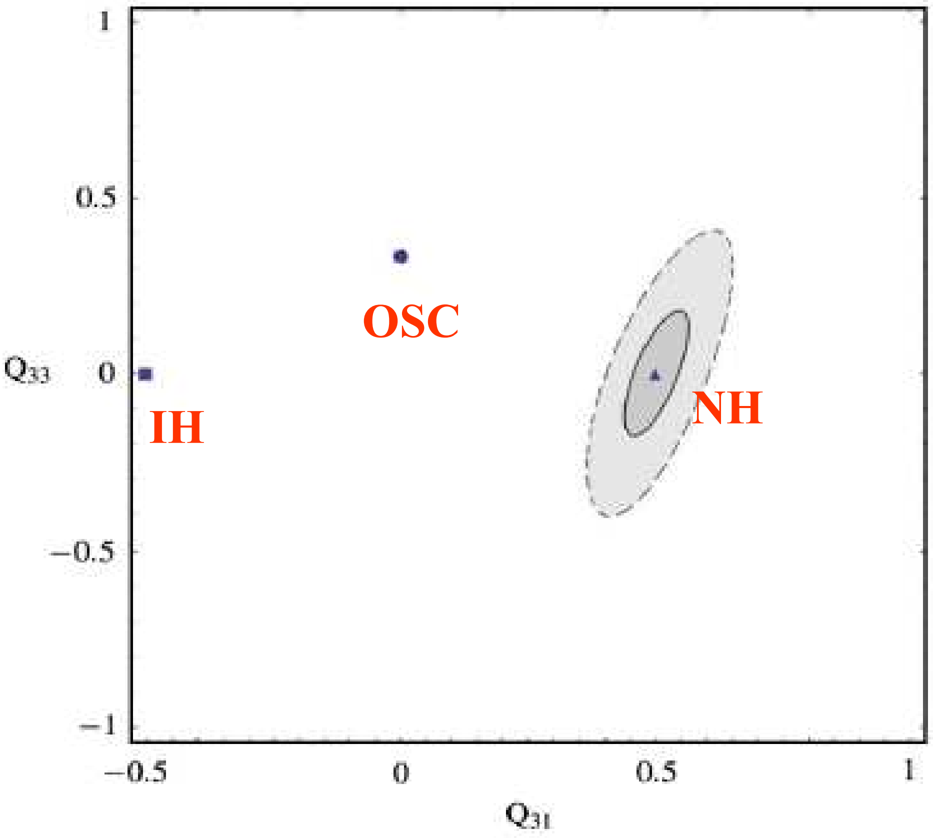


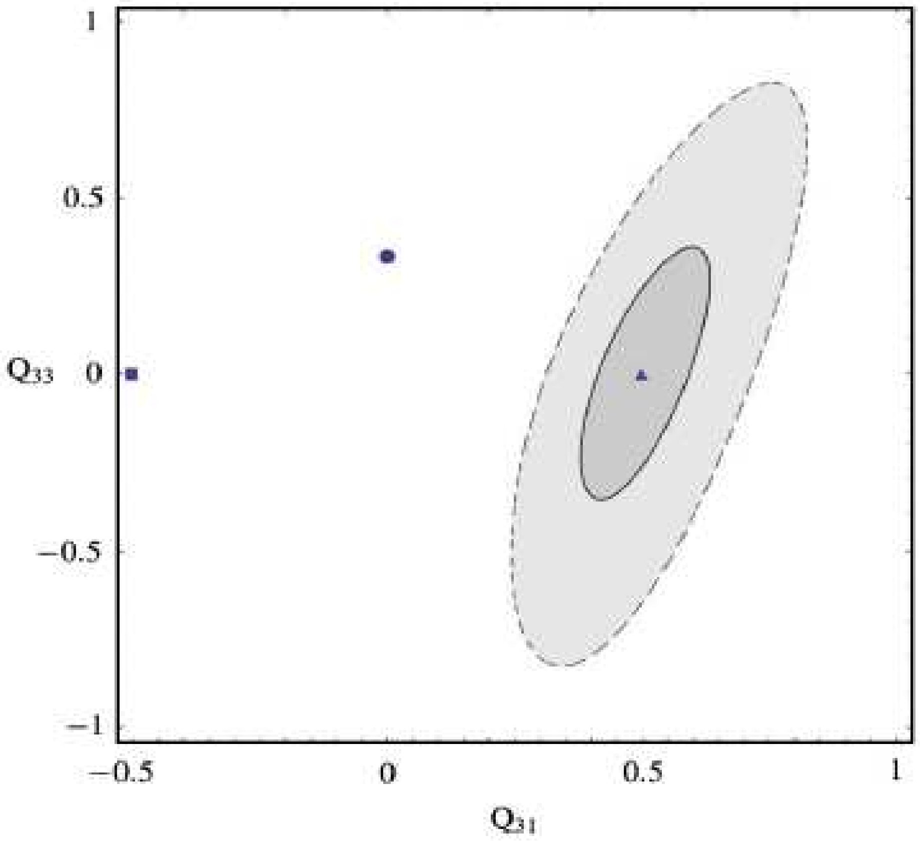
$\Delta R_\pi / R_\pi = \Delta R_\mu / R_\mu = 10\%$



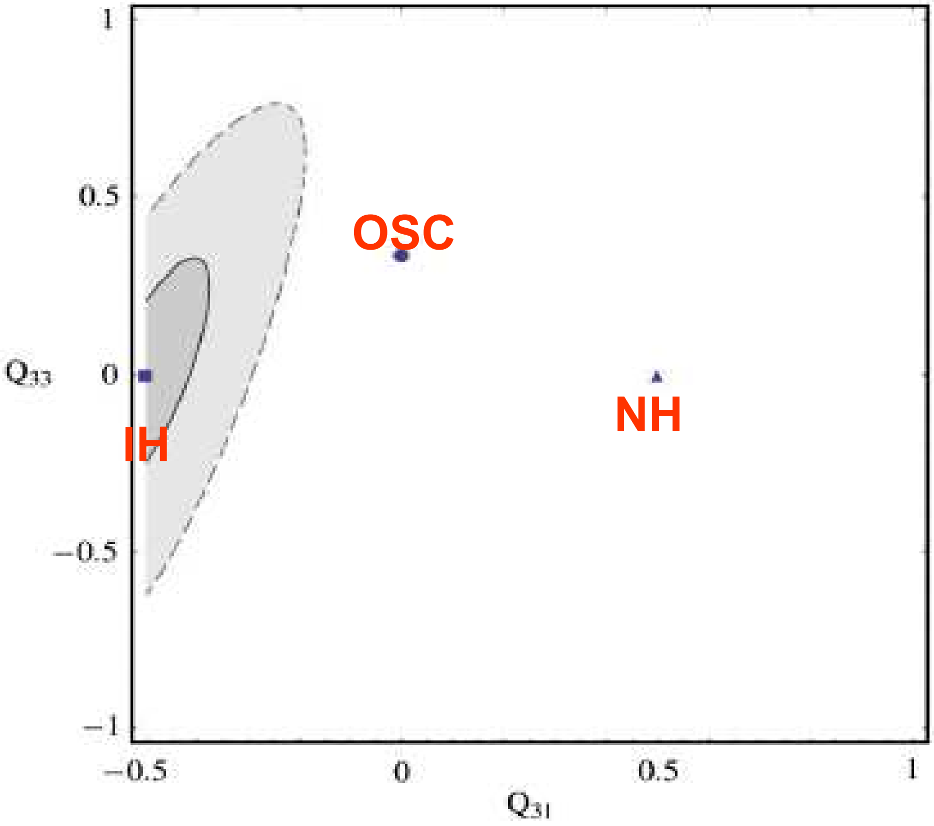
$\Delta R_\pi / R_\pi = \Delta R_\mu / R_\mu = 20\%$

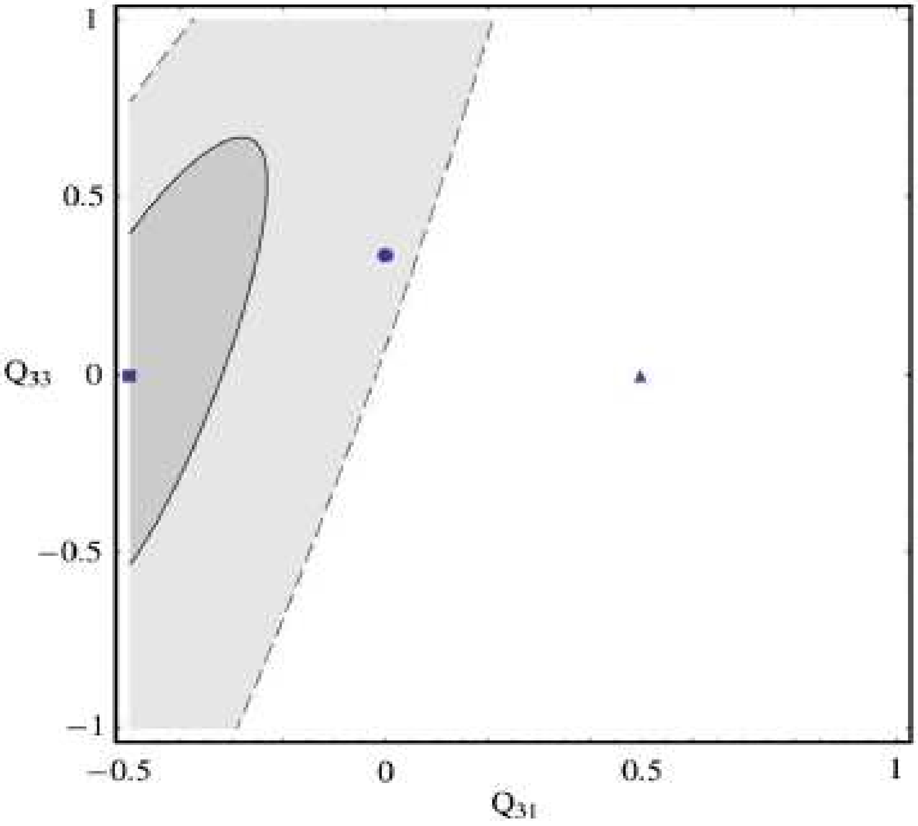
Change the input model





Change the input model--continued





Summary for part (II)

- We have proposed to parameterize the flavor transitions of propagating astrophysical neutrinos by the matrix *Q.*
- Each row of matrix *Q* carries a definite physical meaning.
- The matrix element of *Q* can be probed by measuring the flavor ratios of astrophysical neutrinos arriving on the earth.