EPS 2011, Grenoble France

Probing Flavor Transition Mechanisms of Astrophysical Neutrinos

By G.-L Lin

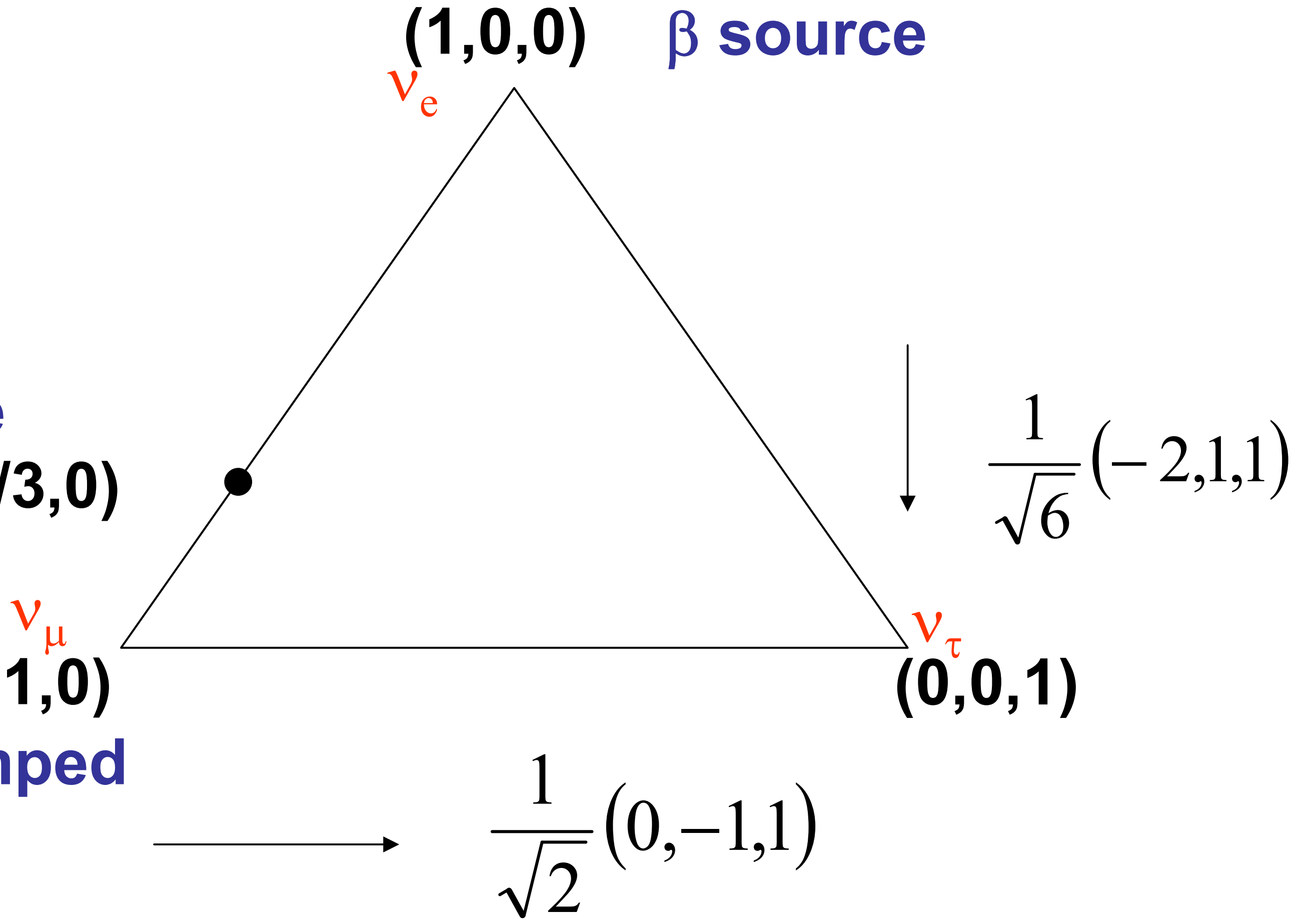
National Chiao-Tung U. Taiwan

K.-C. Lai, G.-L. Lin and T. C. Liu,
Phys. Rev. D 82, 103003 (2010)
T. C. Liu, M. A. Huang and G.-L. Lin, arXiv:1005.5154
F.-S. Lee, G.-L. Lin, T. C. Liu and Y. Yang, in progress

Outline

- Review on possible types of astrophysical neutrino sources
- Model-independent parameterization of neutrino flavor transition mechanisms
- Probing flavor transition mechanisms by neutrino telescopes
- Conclusion

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)

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

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

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

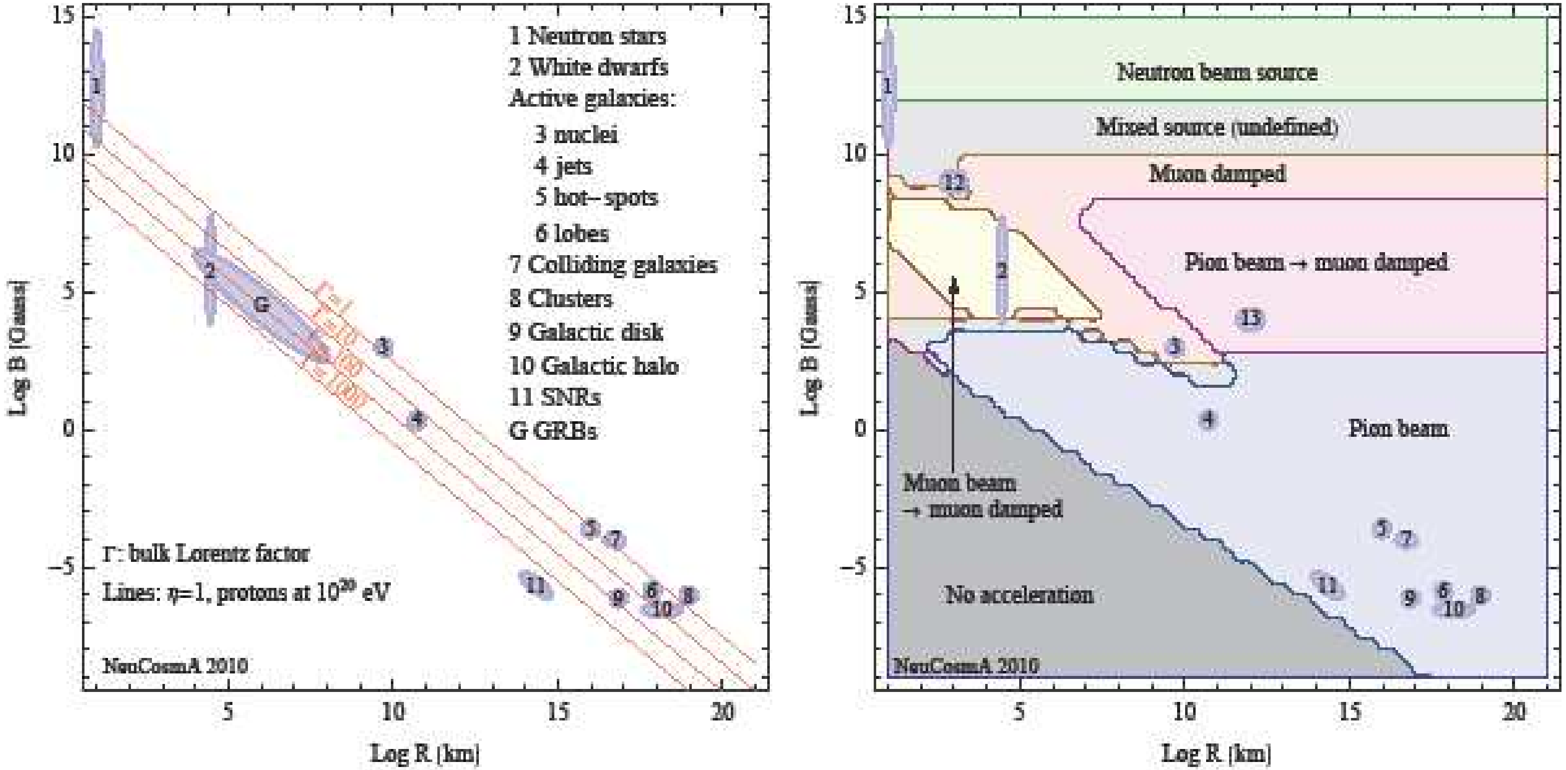
In general, flavor ratio depends on neutrino energy

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

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

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).

Model-independent parameterization of neutrino flavor transition mechanisms

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)

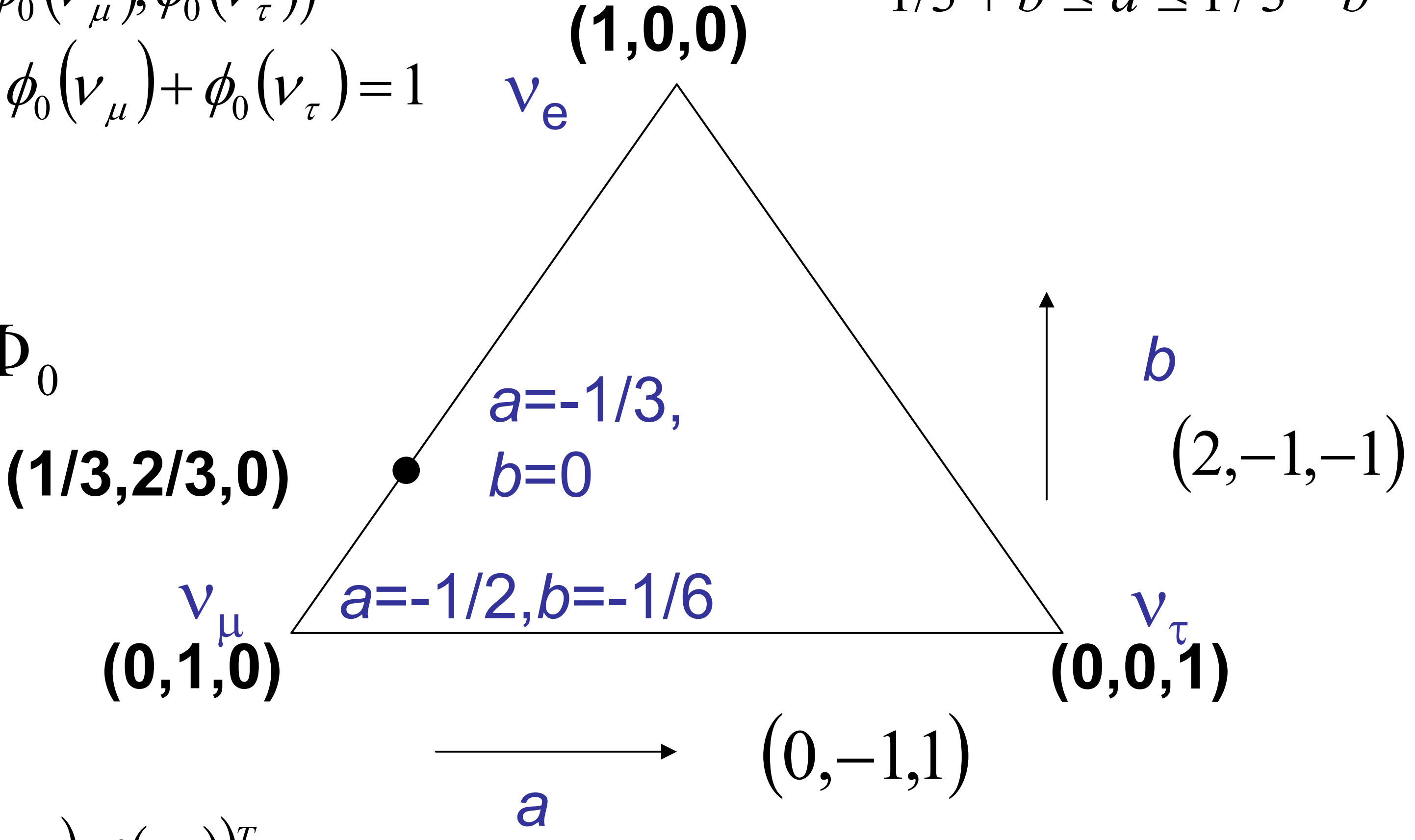
$$\Phi_0 = \frac{1}{3}(1,1,1)^T + a(0,-1,1)^T + b(2,-1,-1)^T, -1/6 \le b \le 1/3$$

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

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

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

$$\Phi = P\Phi_0$$



(1,0,0)

ν_e

a=-1/3,

b=0

(1/3,2/3,0)

ν_μ

a=-1/2,*b*=-1/6

(0,1,0)

ν_τ

(0,0,1)

b

$(2,-1,-1)$

a

$(0,-1,1)$

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

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

κ =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 $Q_{\rm ij}$ 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

Q matrix for standard oscillation

$$Q = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1/3 \end{pmatrix}$$

i.e., Q_{31}=0, Q_{33}=1/3

Evaluated in tribimaximal limit:

$$\sin^2\theta_{23} = 1/2,$$

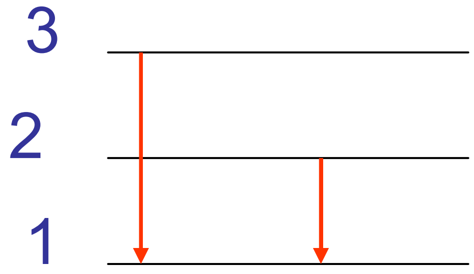
$$\sin^2\theta_{12} = 1/3,$$

$$\sin^2\theta_{13} = 0$$

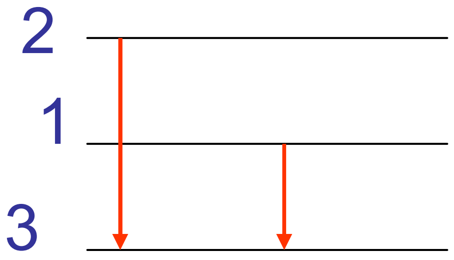
May need to be corrected in view of recent T2K and MINOS results

Q matrix for neutrino decays

Normal hierarchy



Inverted hierarchy



$$Q = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 1/2 & 0 & 0 \end{pmatrix}$$

$$Q = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ -1/2 & 0 & 0 \end{pmatrix}$$

i.e., Q_{31}=0.5, Q_{33}=0

i.e., Q_{31}=-0.5, Q_{33}=0

Accuracy for flavor ratio determination: E_ν <10^{16} eV

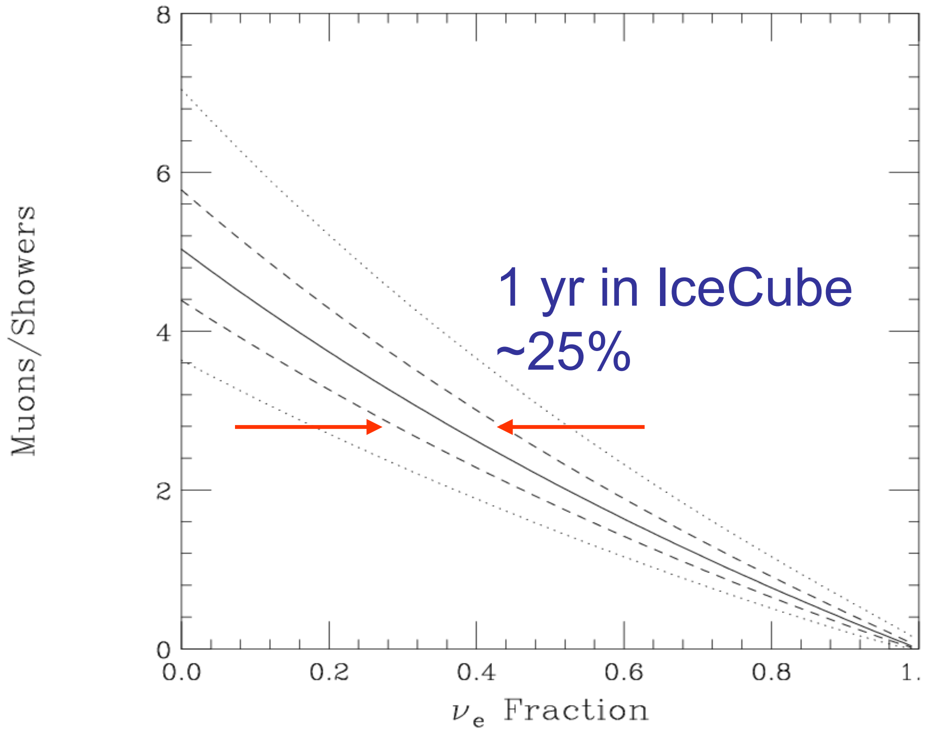
J. F. Beacom *et al.*
Phys. Rev. D 2003, arXiv: hep-ph/0307027v3

- 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. Expect similar accuracy in KM3NeT.

ARA Collaboration
P. Allison et al.
arXiv: 1105.2854

$E_{\nu} > 10^{16}$ eV

ν_e may be separated from other flavors by LPM effect

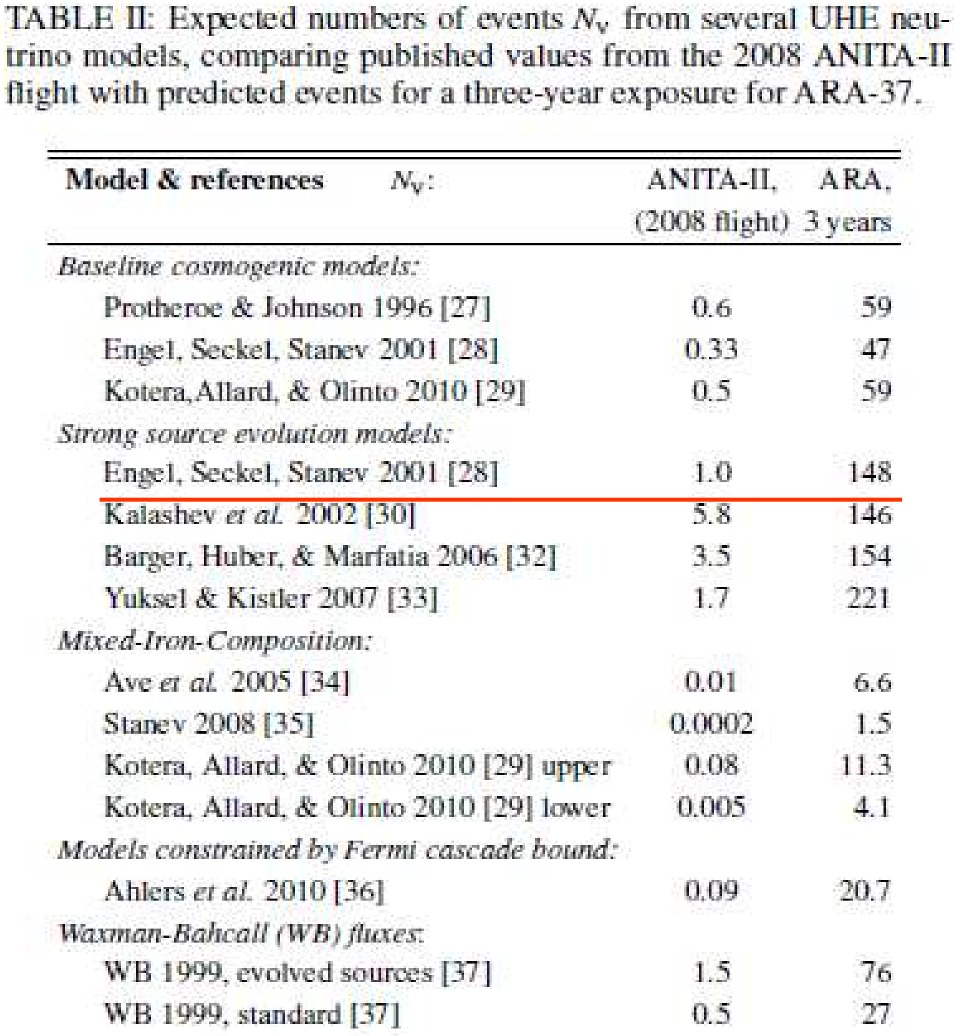
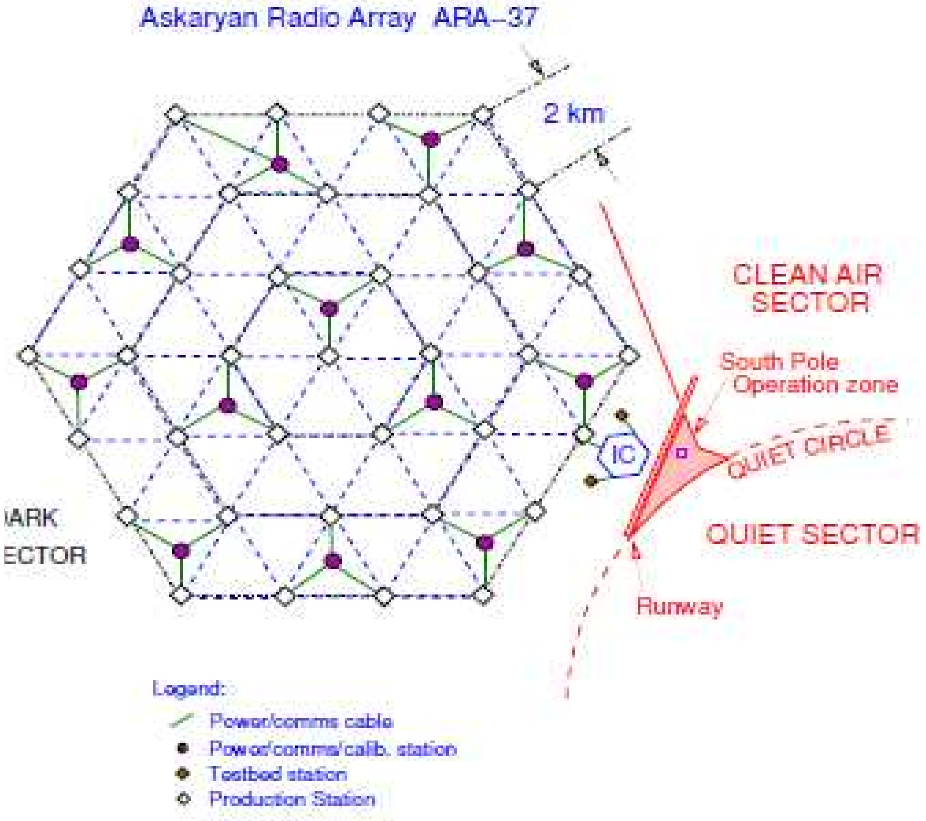


TABLE II: Expected numbers of events N_ν from several UHE neutrino models, comparing published values from the 2008 ANITA-II flight with predicted events for a three-year exposure for ARA-37.

Model & references N_ν:	ANITA-II, (2008 flight)	ARA, 3 years
Baseline cosmogenic models:		
Protheroe & Johnson 1996 [27]	0.6	59
Engel, Seckel, Stanev 2001 [28]	0.33	47
Kotera, Allard, & Olinto 2010 [29]	0.5	59
Strong source evolution models:		
Engel, Seckel, Stanev 2001 [28]	1.0	148
Kalashev *et al.* 2002 [30]	5.8	146
Barger, Huber, & Marfatia 2006 [32]	3.5	154
Yuksel & Kistler 2007 [33]	1.7	221
Mixed-Iron-Composition:		
Ave *et al.* 2005 [34]	0.01	6.6
Stanev 2008 [35]	0.0002	1.5
Kotera, Allard, & Olinto 2010 [29] upper	0.08	11.3
Kotera, Allard, & Olinto 2010 [29] lower	0.005	4.1
Models constrained by Fermi cascade bound:		
Ahlers *et al.* 2010 [36]	0.09	20.7
Waxman-Bahcall (WB) fluxes:		
WB 1999, evolved sources [37]	1.5	76
WB 1999, standard [37]	0.5	27



15%~20% accurate FD possible

Fitting results-pion source+muon damped source $E_\nu < 10^{16}$ eV

Pion source

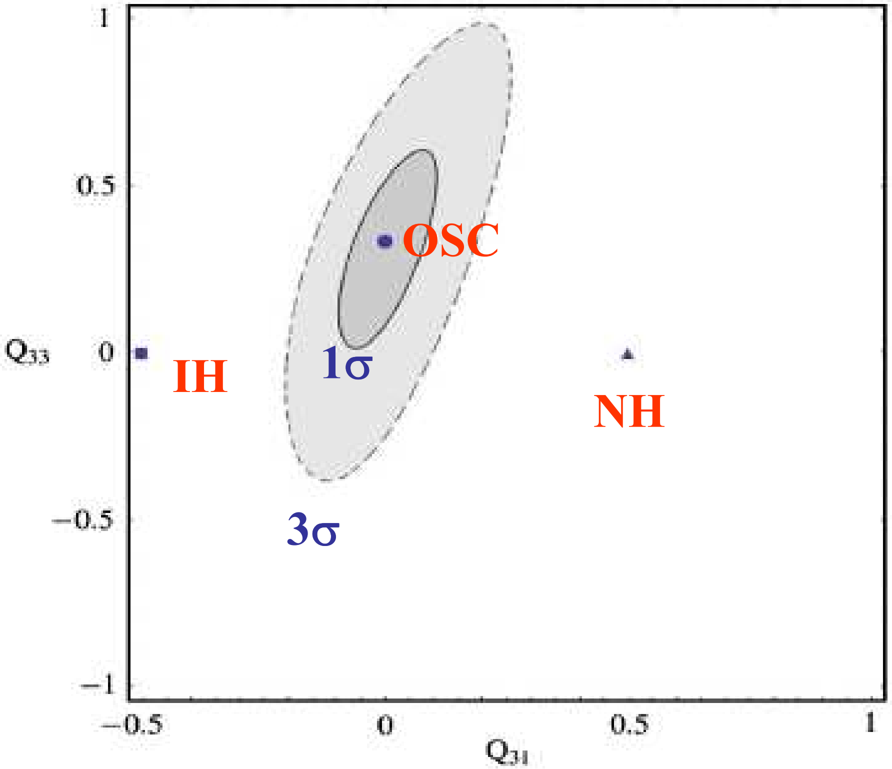
$$\begin{pmatrix} 1/3 \\ \rho \\ \lambda \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ Q_{31} & 0 & Q_{33} \end{pmatrix} \begin{pmatrix} 1/3 \\ -1/3 \\ 0 \end{pmatrix} \Rightarrow \lambda = Q_{31}/3$$

Muon-damped source

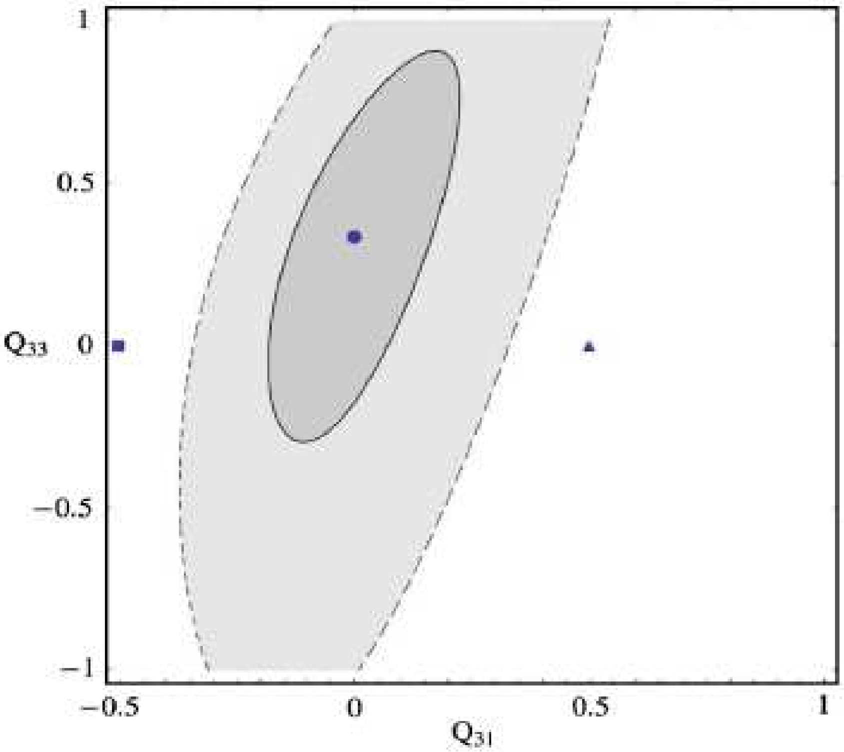
$$\lambda \equiv \frac{1}{3}\left(\phi(\nu_e) - \frac{\phi(\nu_\mu) + \phi(\nu_\tau)}{2} \right)$$

$$\begin{pmatrix} 1/3 \\ \rho \\ \lambda \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ Q_{31} & 0 & Q_{33} \end{pmatrix} \begin{pmatrix} 1/3 \\ -1/2 \\ -1/6 \end{pmatrix} \Rightarrow \lambda = Q_{31}/3 - Q_{33}/6$$

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



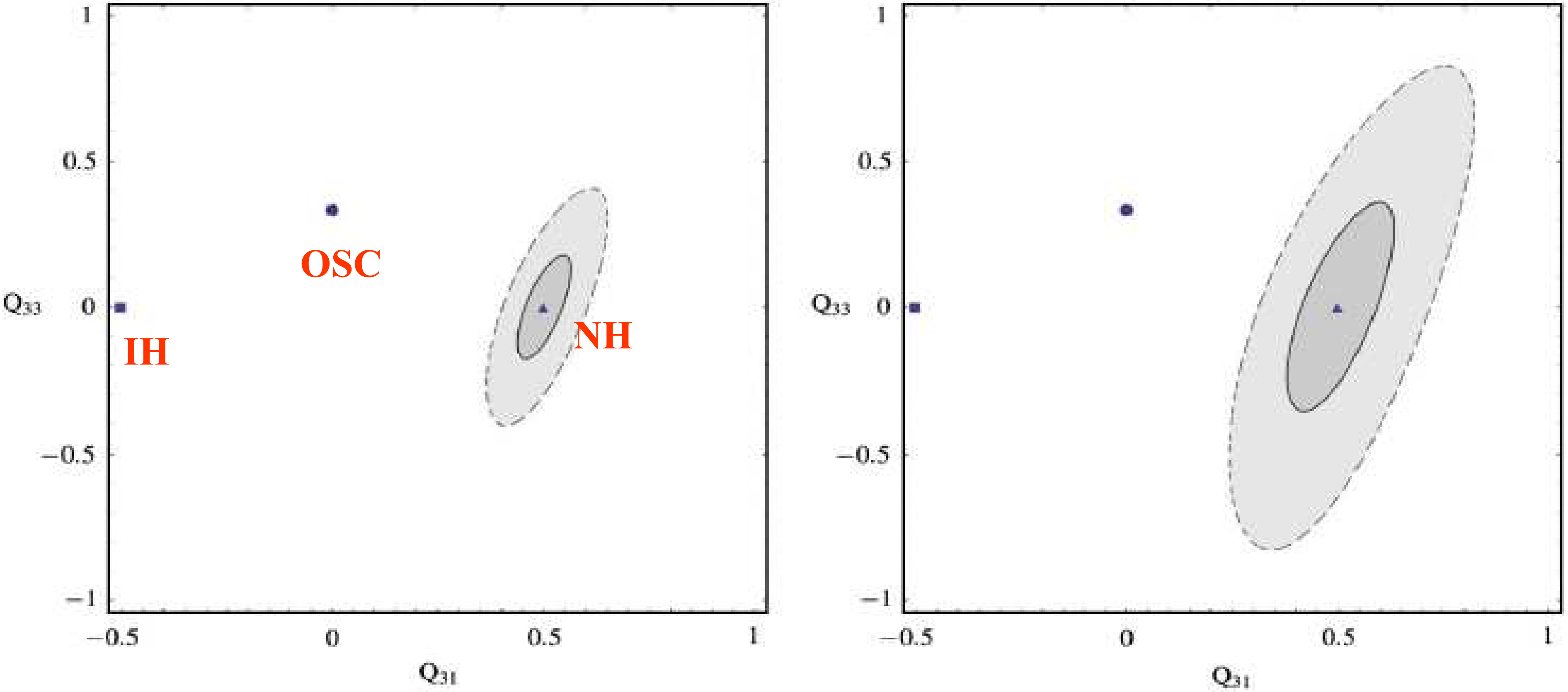
$\Delta R_\pi / R_\pi = \Delta R_\mu / R_\mu = 10\%$



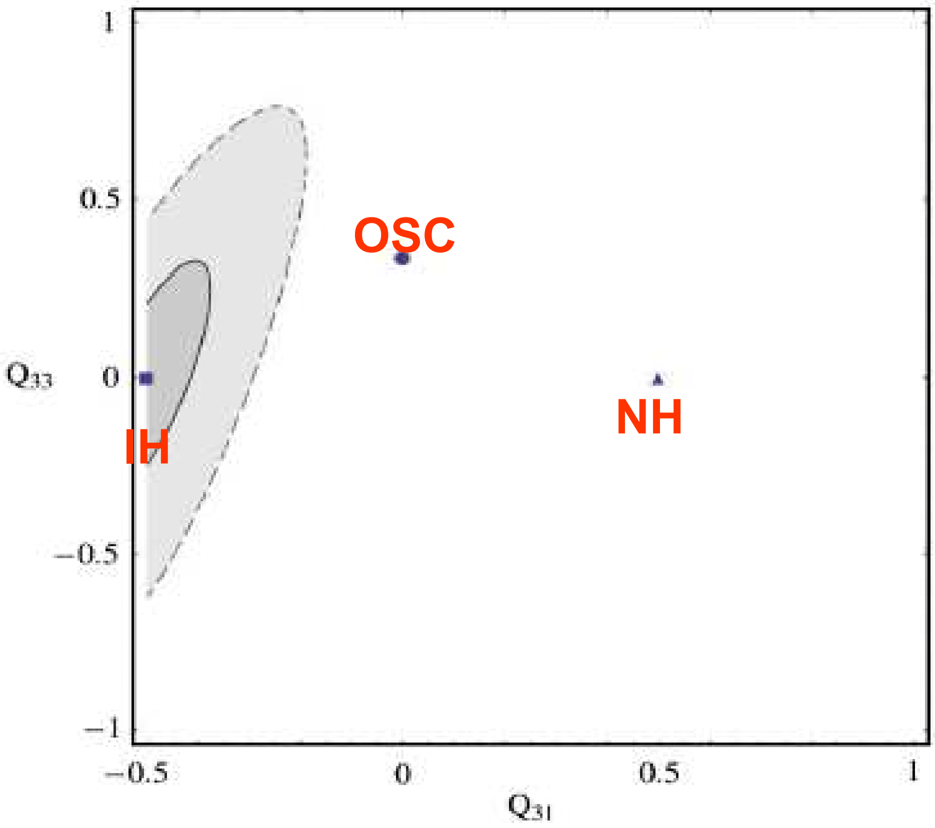
$\Delta R_\pi / R_\pi = \Delta R_\mu / R_\mu = 20\%$

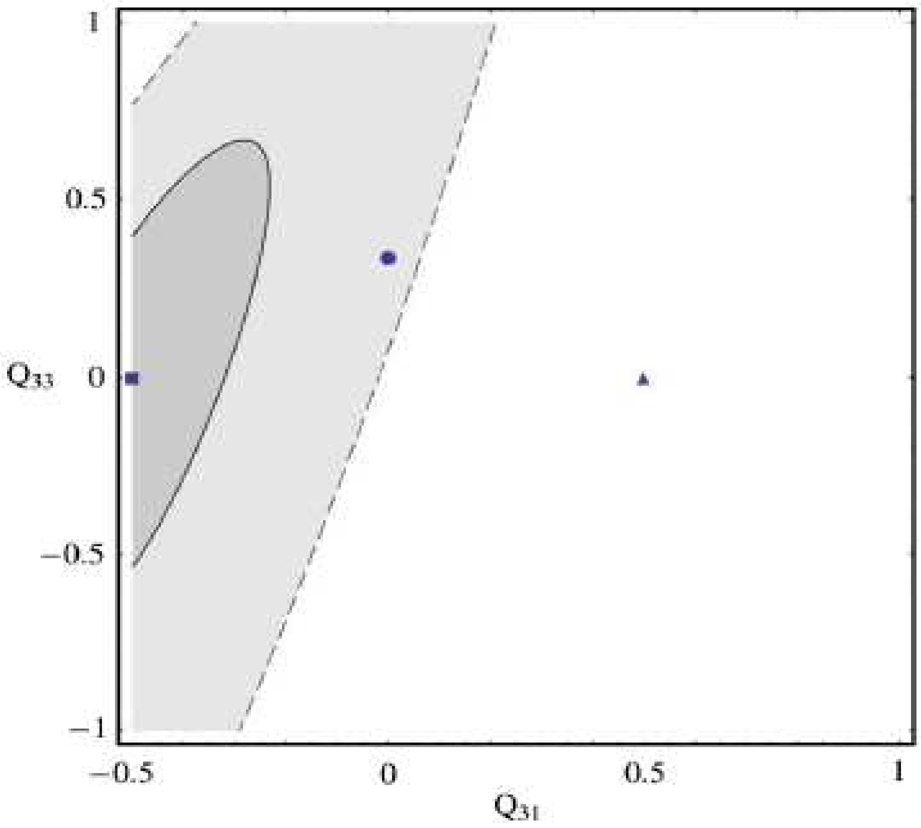
$$R = \frac{\phi(\nu_\mu)}{\phi(\nu_e) + \phi(\nu_\tau)}$$

Change the input model



Change the input model--continued





GZK neutrino dominates at $E_\nu > 10^{17}$ eV

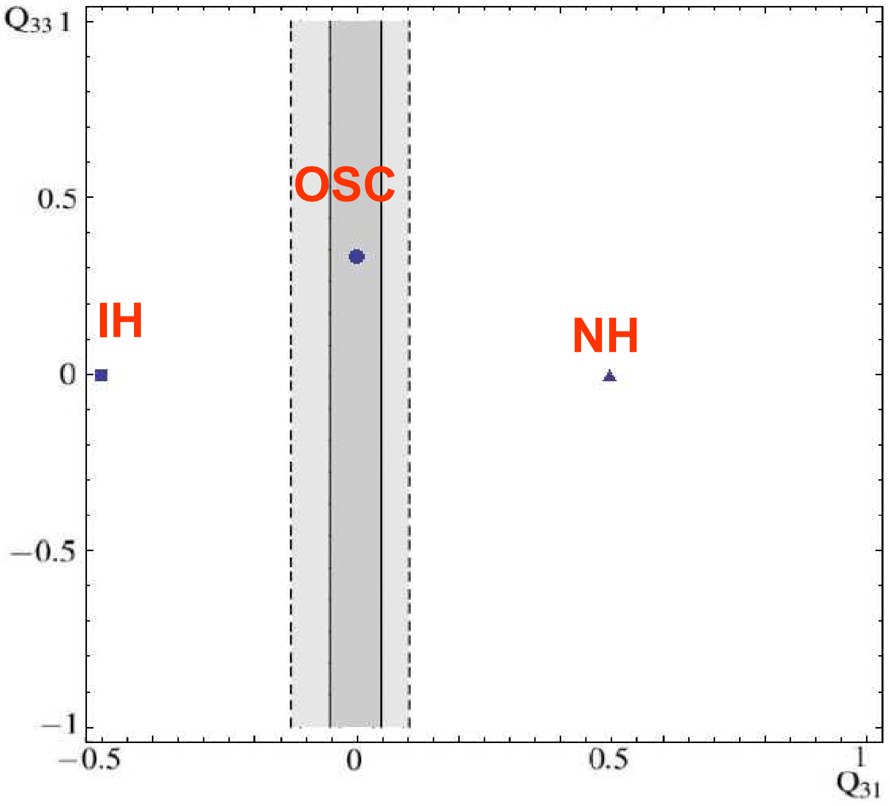
We have a pure pion source

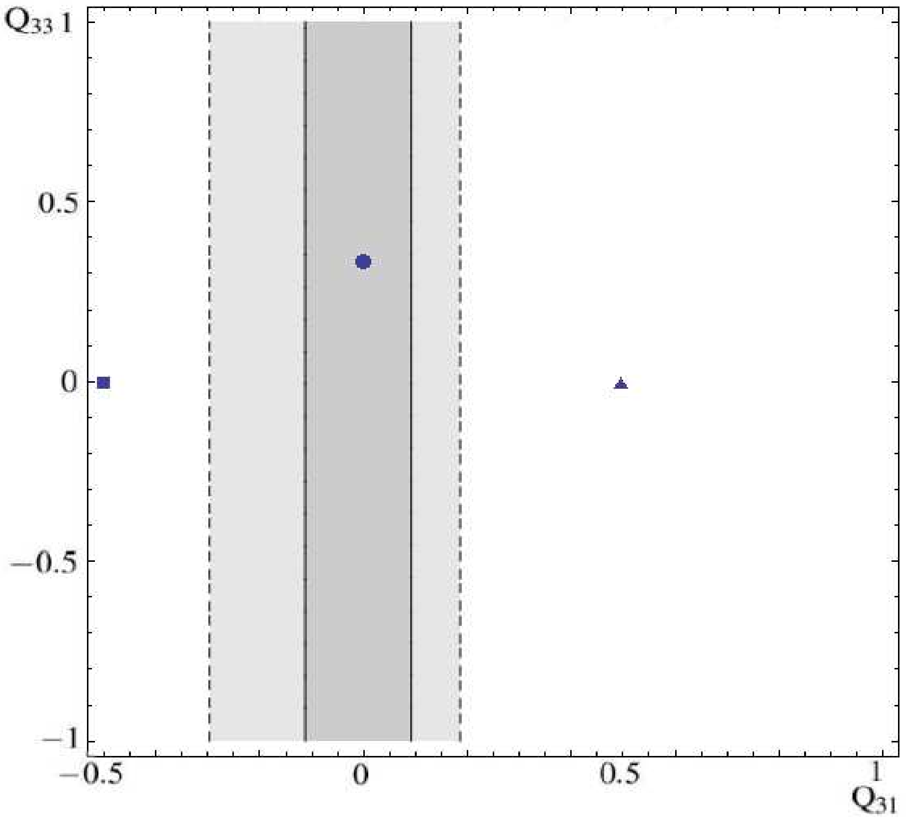
$$\begin{pmatrix} 1/3 \\ \rho \\ \lambda \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ Q_{31} & 0 & Q_{33} \end{pmatrix} \begin{pmatrix} 1/3 \\ -1/3 \\ 0 \end{pmatrix}, \text{so}$$

$$\lambda \equiv \frac{1}{3}\left(\phi(\nu_e) - \frac{\phi(\nu_\mu) + \phi(\nu_\tau)}{2} \right) = Q_{31}/3$$

Pion source can only probe Q_{31}

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





$\Delta R / R = 10\%$

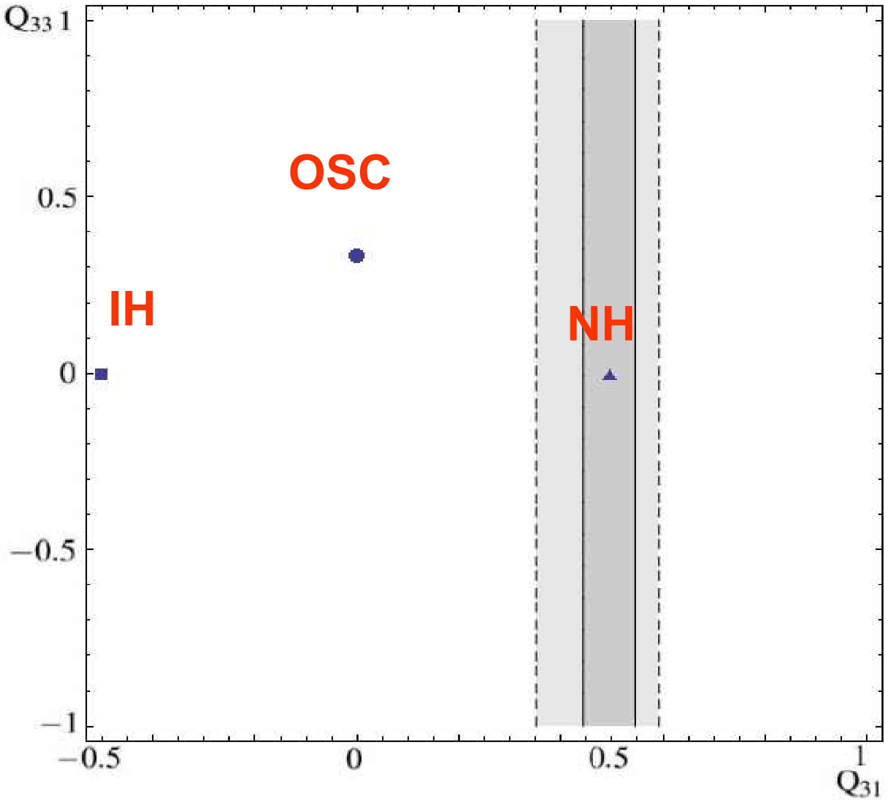
$\Delta R / R = 20\%$

$$R = \frac{\phi(\nu_e)}{\phi(\nu_\mu) + \phi(\nu_\tau)}$$

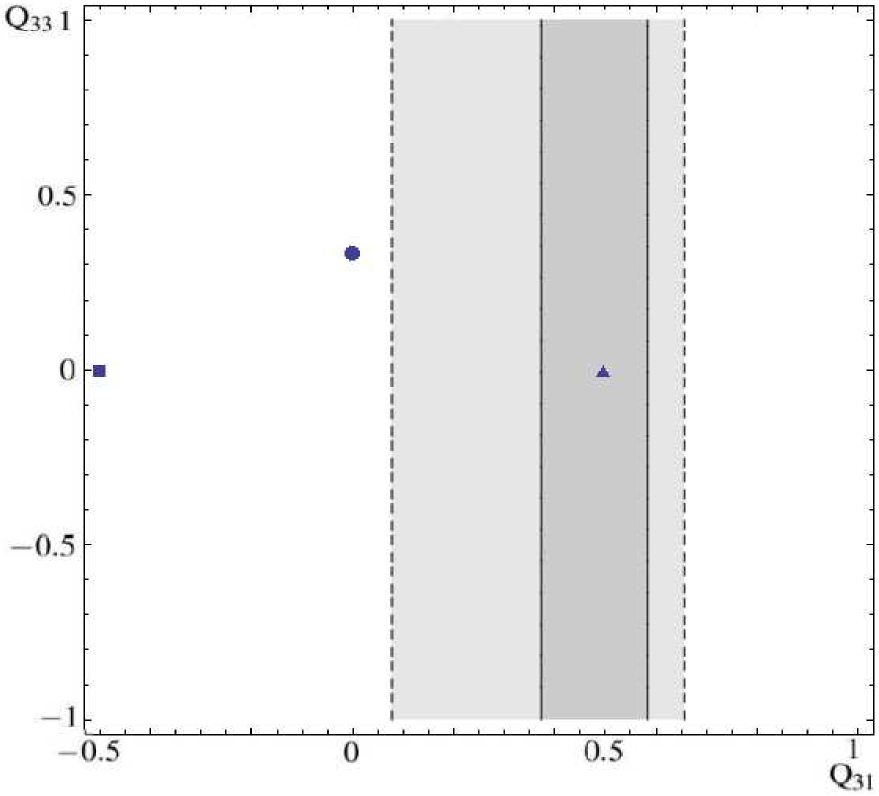
$$R_{\text{osc}} = 0.5$$

Change the input model

$$R_{\mathrm{NH}} = 2$$



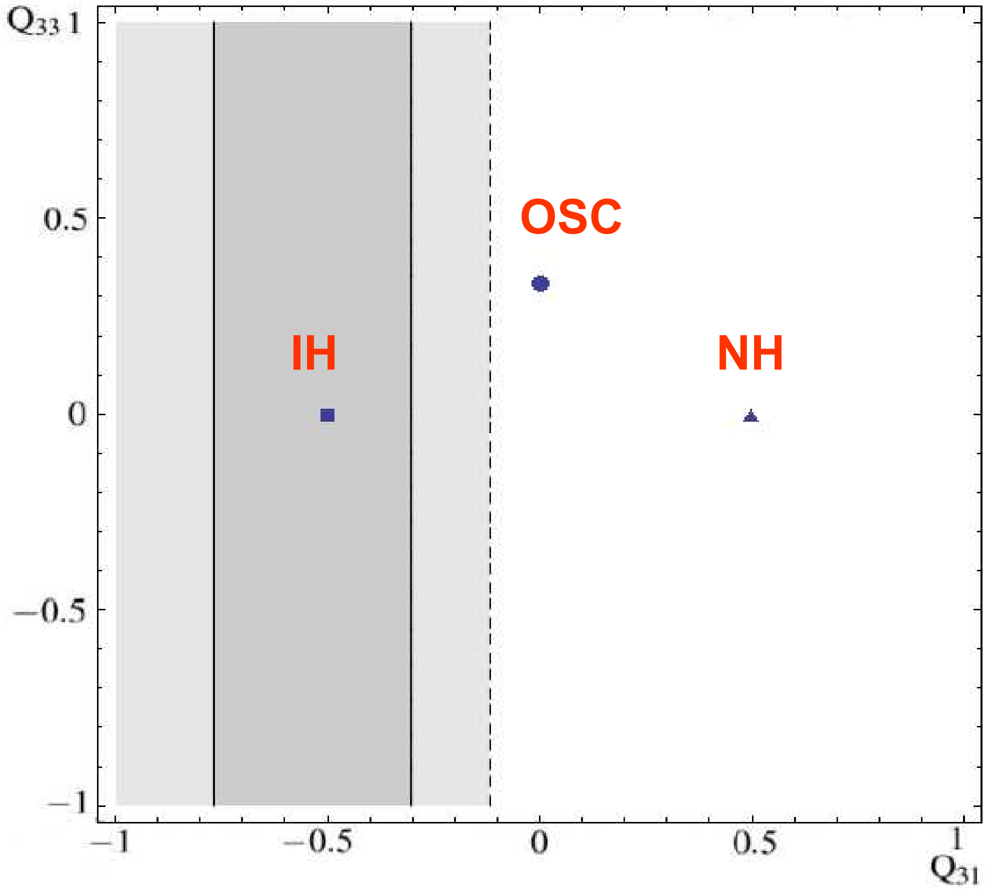
$$\Delta R / R = 10\%$$



$$\Delta R / R = 20\%$$

Change the input model

$$R_{\mathrm{IH}} = 0$$



Assume ΔR_{IH}=0.1

Summary (I)

- We have proposed a model-independent parameterization, the *Q* matrix, for flavor transition mechanisms (standard oscillations and beyond) of astrophysical neutrinos.
- Each row of matrix *Q* carries a definite physical meaning. Q_{1i} for normalization, Q_{2i} for μ-τ symmetry breaking and Q_{3i} governing the flux difference

$$\phi(\nu_e)-\frac{\phi(\nu_\mu)+\phi(\nu_\tau)}{2}$$

- In the μ-τ symmetry limit with flux conservation, only Q_{31} and Q_{33} are non-vanishing. They are useful for classifying neutrino flavor transition models.

Summary (II)

- Kilometer size neutrino telescopes such as IceCube and KM3NeT are suitable for detecting neutrinos with energies up to few tens of PeV. They are capable of distinguishing track and shower signals. The parameters Q_{31} and Q_{33} can both be probed by simultaneously observing pion source and muon-damped source. However, an astrophysical neutrino source is generally a mixture of the two, and the degree of the mixture depends on the neutrino energy.

Summary (III)

- For $E_\nu > 10^{17}$ eV, one expects the dominance of GZK neutrino flux which is a pion source.
- The Askaryan Radio Array (ARA) experiment is optimized for observing GZK neutrino flux. The discrimination of ν_e from ν_μ and ν_τ can help to probe the parameter Q_{31}.
- A 20% accurate measurement on flavor ratio is generally sufficient to distinguish neutrino decay models (H,M→L) from standard neutrino oscillations at the 3σ level.