Pacific 2011, Moorea

Probing Flavor Ratios and Flavor Transitions Mechanisms of Astrophysical Neutrinos by Neutrino Telescopes

By G.-L Lin

National Chiao-Tung U. Taiwan

K.-C. Lai, G.-L. Lin and T. C. Liu,
Phys. Rev. D 80, 103005 (2009); 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

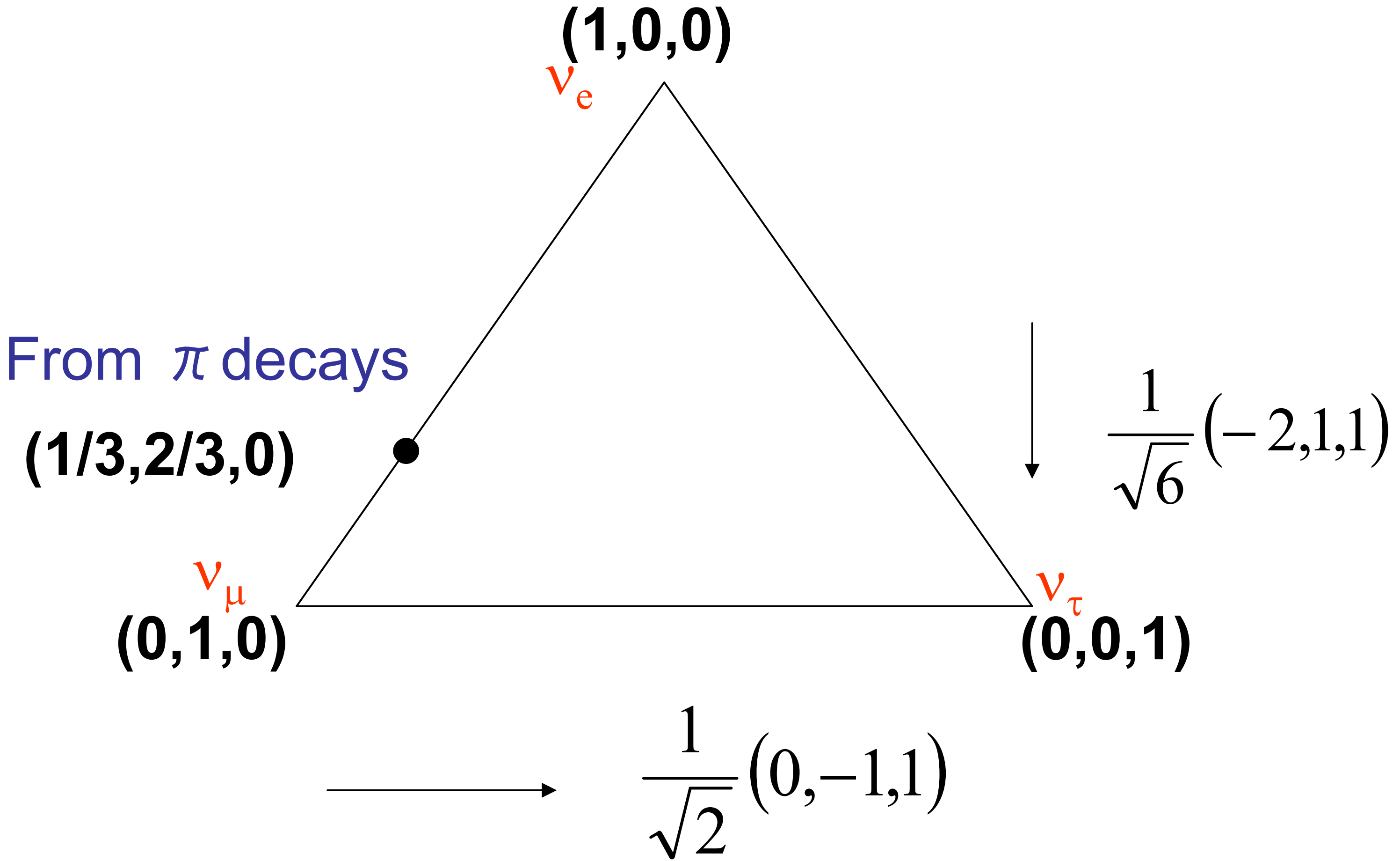
Outline

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

  (1) the original neutrino flavor ratio at astrophysical source-assuming three flavor oscillations

  (2) the neutrino flavor transition mechanism during its propagation from source to Earth—with a clear knowledge on the source flavor ratio
- Answering the above questions by flavor discriminations in neutrino telescopes

Common astrophysical neutrino sources



(1,0,0) ν_e

From π decays

(1/3,2/3,0)

ν_μ **(0,1,0)**

ν_τ **(0,0,1)**

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

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

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

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

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

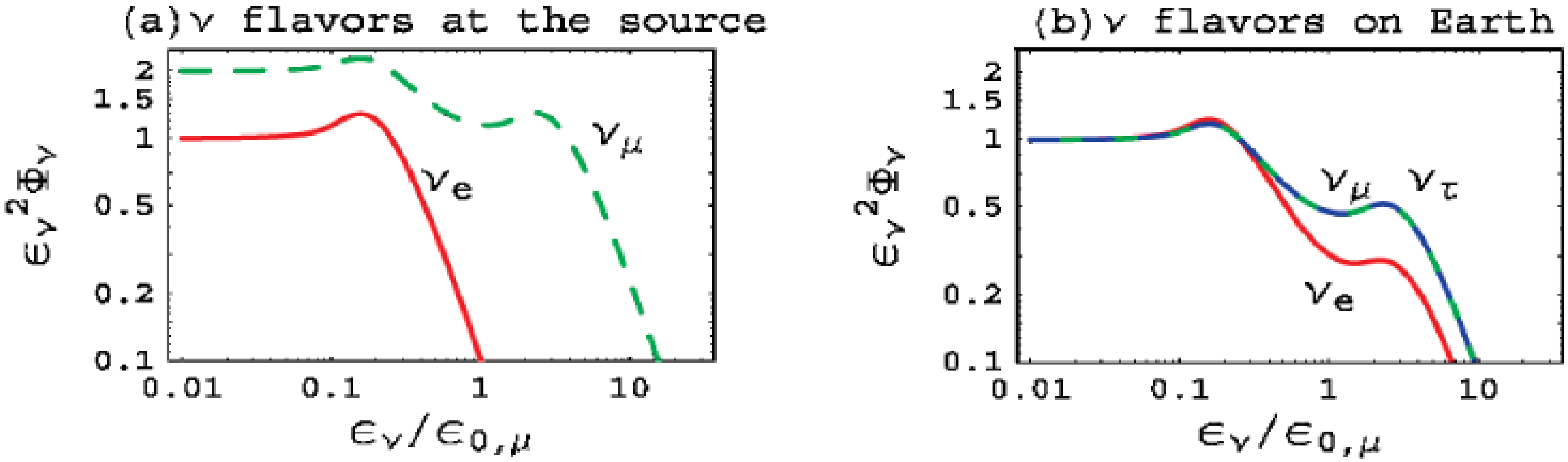
M. Kacherliess, O. Ostapchenko and R. Tomas, arXiv: 0708.3007

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

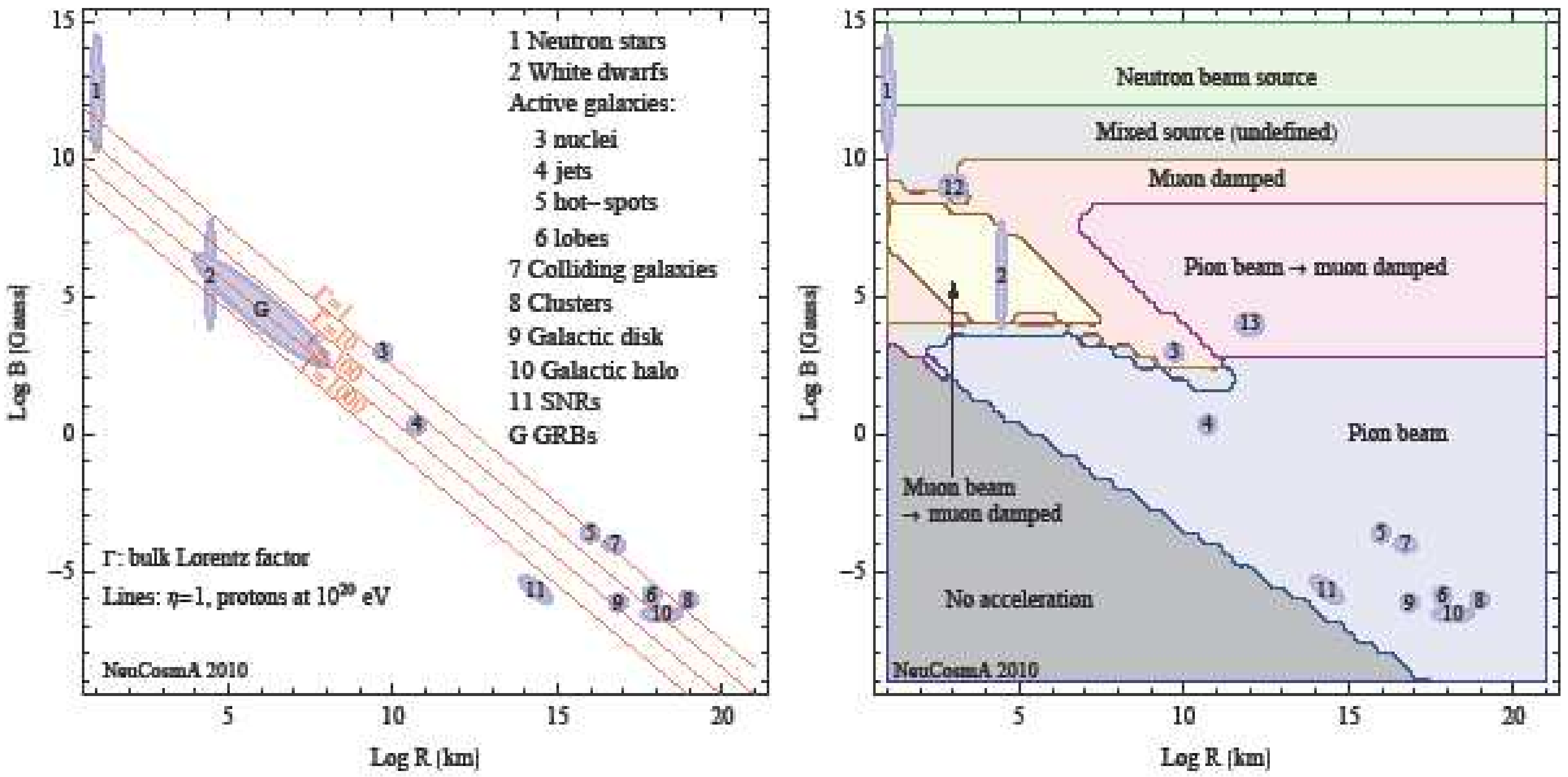


T. Kashti and E. Waxman Phy. Rev. Lett. 2005

Transition from pion source to muon-damped source
⇒due to particle density and background field
strength at the source

Systematically studying sources on Hillas plot

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



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

Sources with significant ν_τ fractions

Neutrinos from WIMP annihilations

$$\chi\chi \to \tau^+\tau^-, b\bar{b}$$

Tau lepton and b can decay into ν_τ

Reconstructing the neutrino flavor ratio at the source

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

Standard neutrino oscillations

Measured flux Φ

Source flux Φ_0

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

Flavor Eigenstate

Mass Eigenstate

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

Reconstructing the neutrino flavor ratio at the source--continued

- How well can we distinguish astrophysical sources with different neutrino flavor ratio, assuming three flavor neutrino oscillations?
- This depends on our understanding of neutrino mixing parameters and flavor discrimination capabilities in neutrino telescopes.

1 σ

$$\sin^2\theta_{12} = 0.304^{+0.022,0.066}_{-0.016,0.054}, \quad \sin^2\theta_{23} = 0.5^{+0.07,0.17}_{-0.06,0.14}, \quad \sin^2\theta_{13} = 0.01^{+0.009}_{-0.006},$$

$\sin^2\theta_{13} \le 0.35$ **3 σ** **Normal hierarchy**

T. Schwetz, M. Tortola and J. W. F. Valle, New J. Phys. **13**, 063004 (2011).

Flavor discrimination capability

At water Cherenkov detectors such as ANTARES, IceCube and KM3NeT, track to shower event ratio can be used to extract the flux ratio

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

In appropriate energy window, one can further identify tau shower so that one can measure

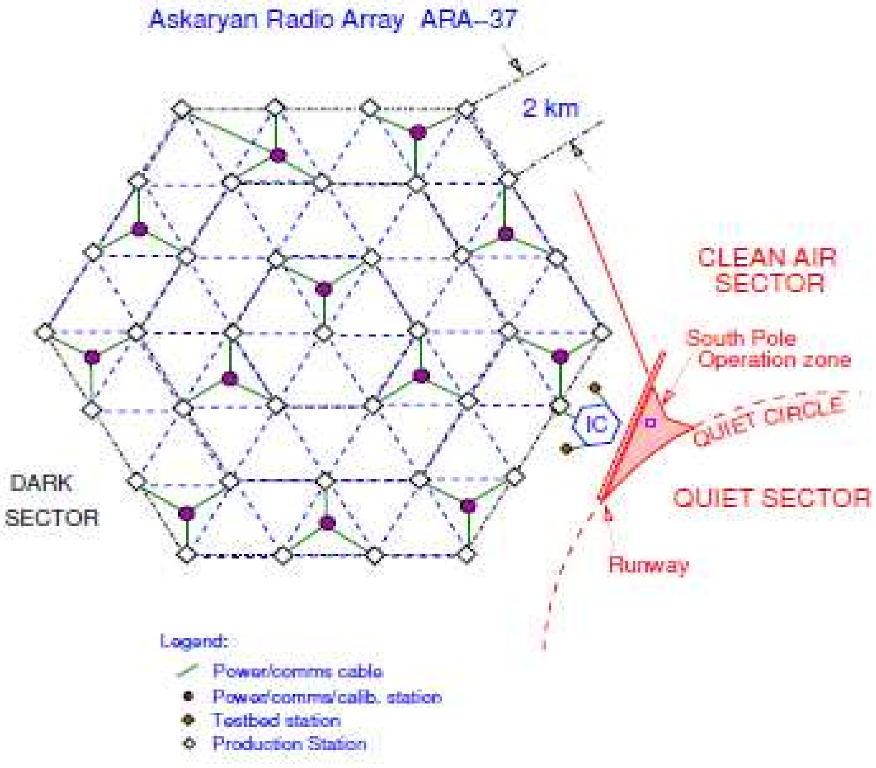
$$S = \frac{\phi(\nu_e)}{\phi(\nu_\tau)}$$

J. F. Beacom *et al.* Phys. Rev. D 2003, arXiv: hep-ph/0307027v3
W. Winter, Phys. Rev. D 74, 033015 (2006).

Flavor discrimination--continued

In newly proposed Askaryan Radio Array (ARA)
with $E\nu > 10^{17}$ eV, ν_e may be separated from other flavors
By LPM effect. One can determine

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



ARA Collaboration: P. Allison et al.
arXiv: 1105.2854

At this energy, it is difficult
to measure

$$S' = \frac{\phi(\nu_\mu)}{\phi(\nu_\tau)}$$

E. Bugaev *et al.*, Astropart. Phys. 21, 491 (2004).

ARA sensitivity on GZK neutrinos

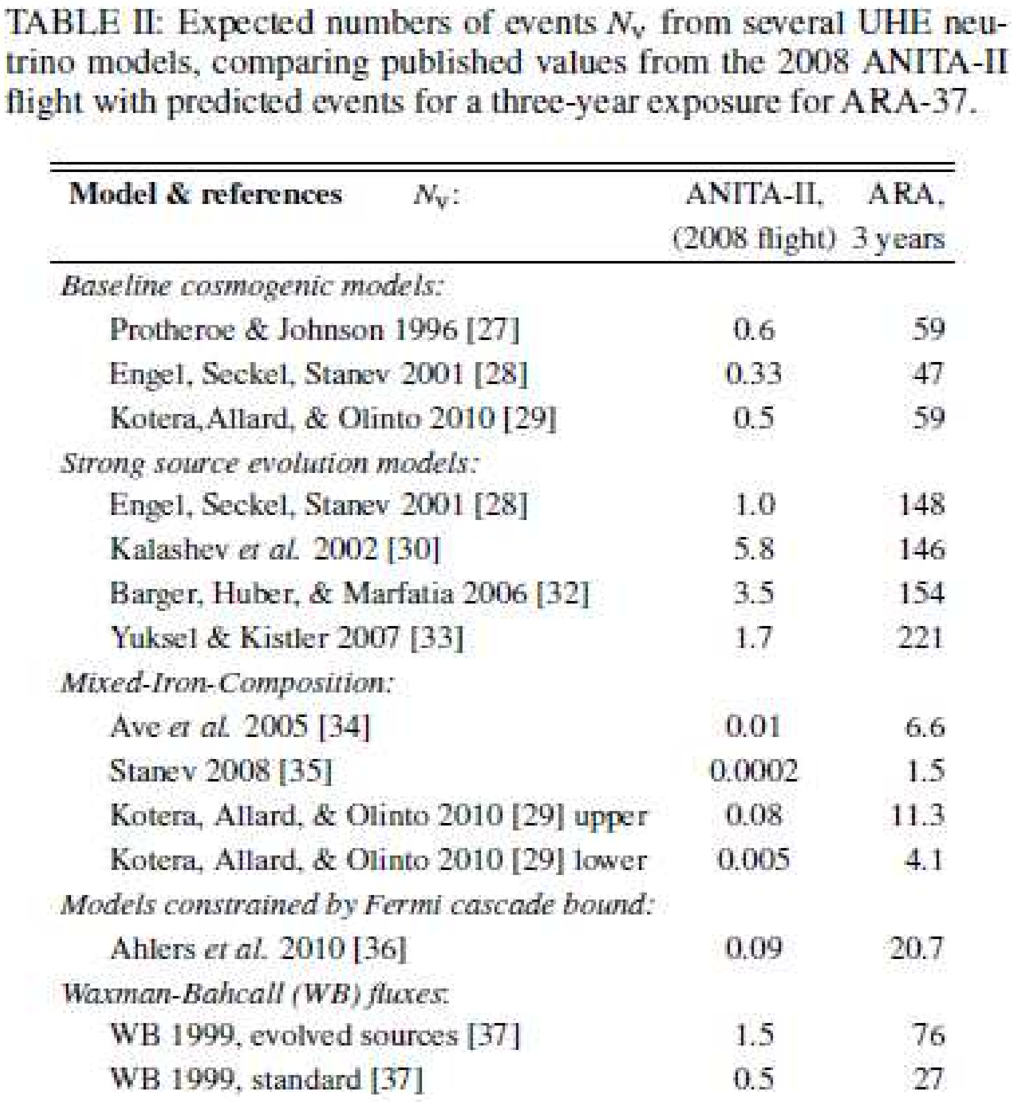
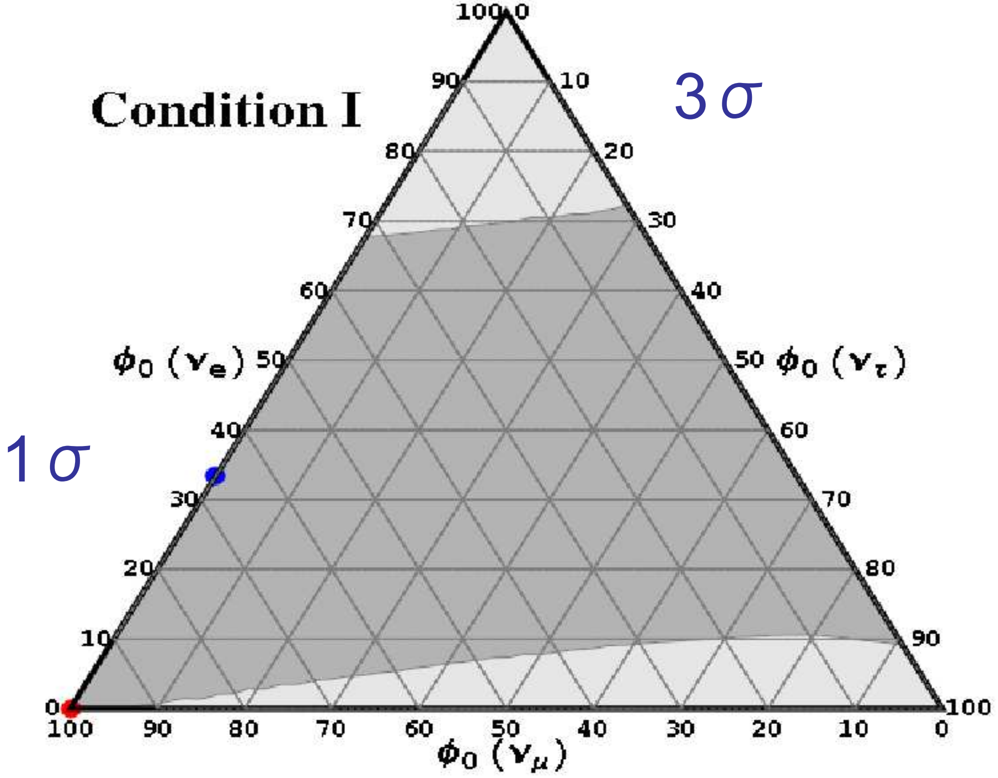


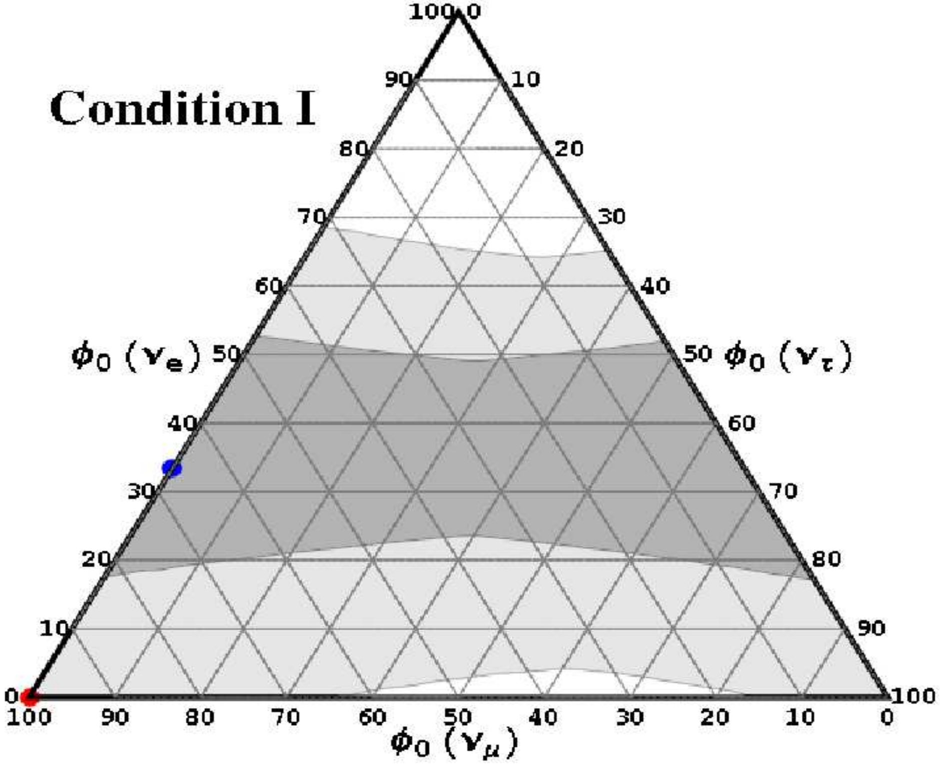
TABLE II: Expected numbers of events N_ν from several UHE neutrino models, comparing published values from the 2008 ANITA-II flight with predicted events for a three-year exposure for ARA-37.

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

Water Cherenkov detectors (astrophysical sources)



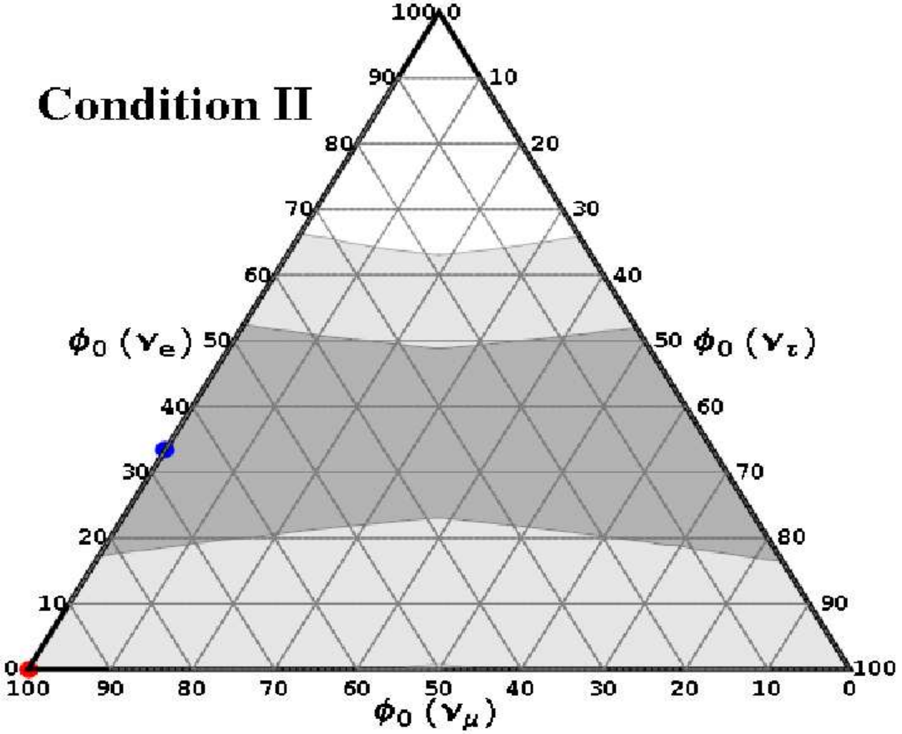
Only *R* is measured



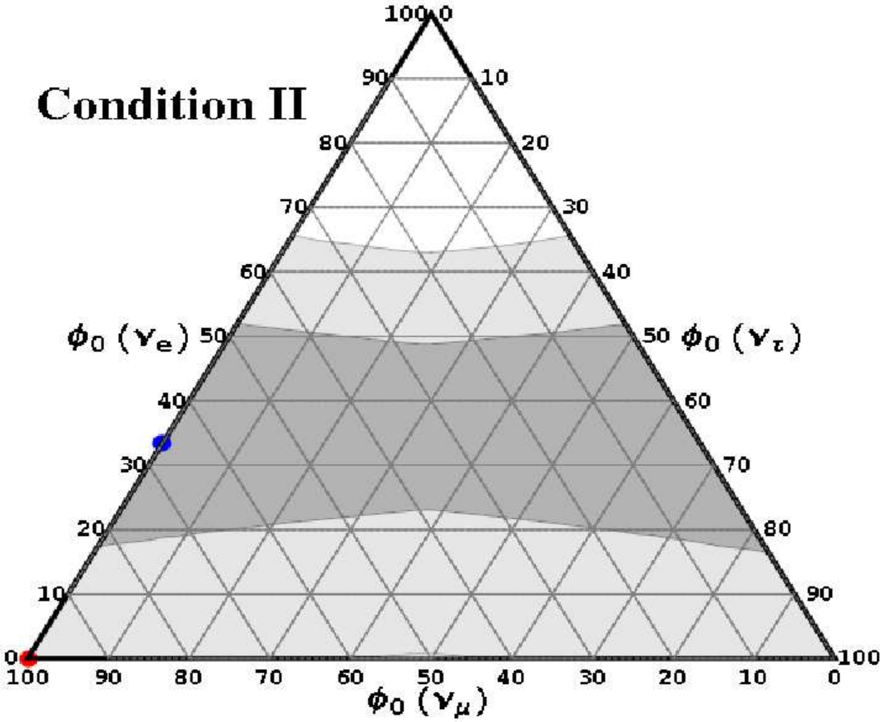
Both *R* and *S* are measured

15% accuracy
(~100 events)

Radio wave detectors (GZK neutrinos)



Only *R'* is measured



Both *R'* and *S'* are measured

15% accuracy
(~100 events)

Summary for part I

- We have reviewed various sources of astrophysical neutrinos with different neutrino flavor ratios.
- The possibility of reconstructing the above flavor ratios through flavor discrimination in neutrino telescopes is discussed.

Probing neutrino flavor transition mechanisms—model independent parameterization

The flavor transition mechanisms of astrophysical neutrinos might be probed.

terrestrially measured flux $\Phi = \boxed{P}\Phi_0$ 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)

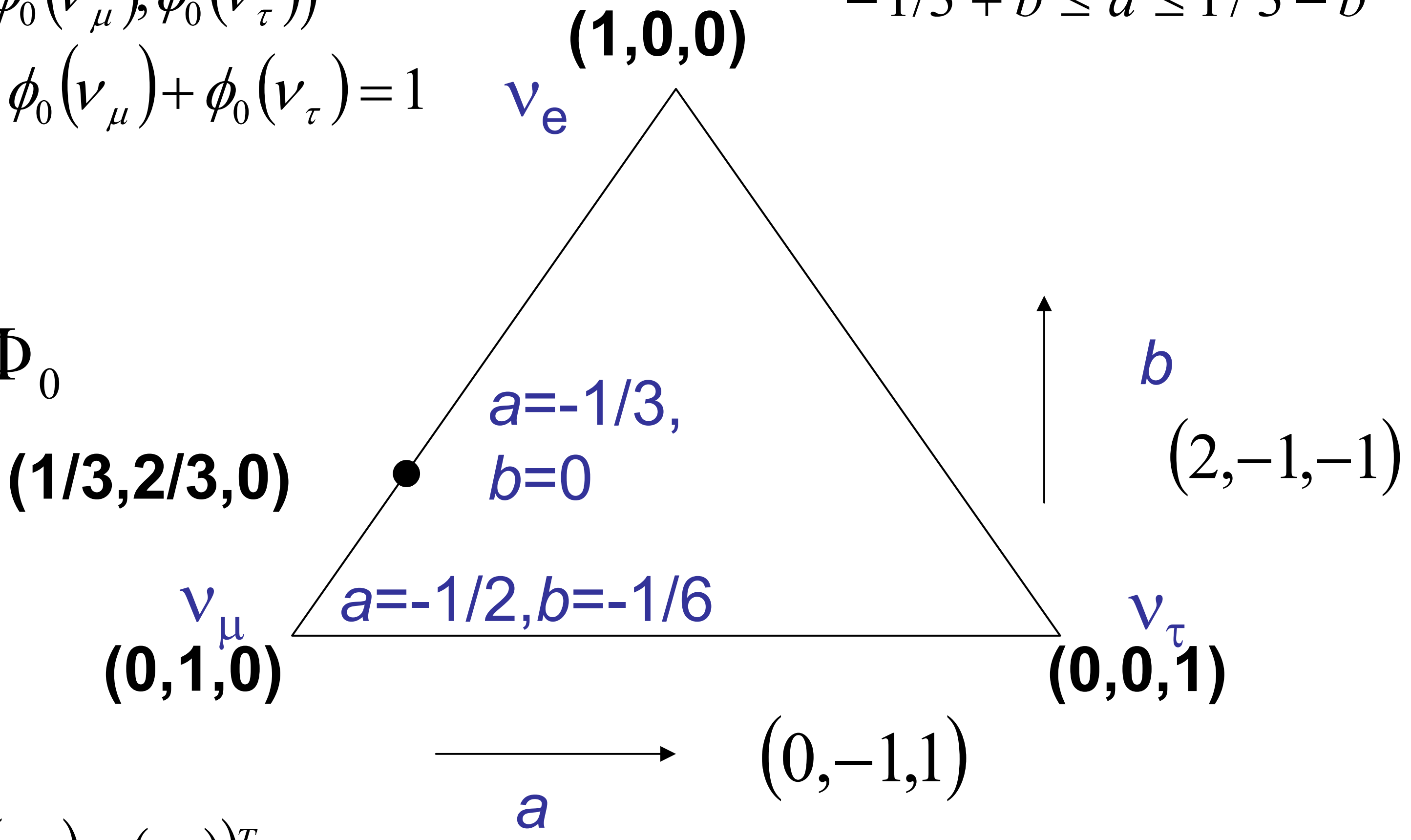
$$\Phi_0 = \frac{1}{3}(1,1,1)^T + a(0,-1,1)^T + b(2,-1,-1)^T, -1/6 \le b \le 1/3$$

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

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

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

$$\Phi = P\Phi_0$$



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

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

κ =1/3 corresponds to conservation of neutrino flux

A simple transformation

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

$$P_{\alpha\beta} \equiv P(\nu_\beta \rightarrow \nu_\alpha)$$

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

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

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

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

$$\sum_\alpha P_{\alpha\beta}=1 \Rightarrow Q_{11}=1, Q_{12}=Q_{13}=0$$

This then implies $\kappa = 1/3$

Gives the meaning of Q matrix

Classify flavor transition models

Flux conservation

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

$\theta_{23} = 45^\circ, \theta_{12} = 0^\circ$ limit

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

Recent T2K result makes it more complicated.

Q matrix for standard oscillation

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

Evaluated in tribimaximal limit:

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

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

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

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

To the first order in $\varepsilon \equiv 2\cos 2\theta_{23}/9 + \sqrt{2}\sin\theta_{13}\cos\delta/9$

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

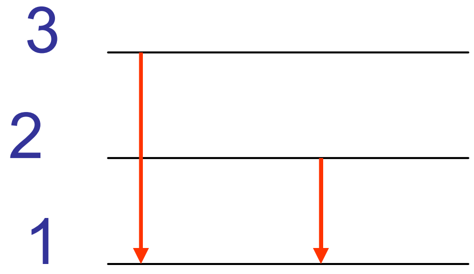
$-3\varepsilon = -0.24/3$ Normal hierarchy

$= -0.27/3$ Inverted hierarchy

Take T2K best fit: $\sin^2 2\theta_{13}$=0.11 (N), 0.14 (I) at δ=0
Also assume $\theta_{23} = \pi/4$

Q matrix for neutrino decays—just for illustration

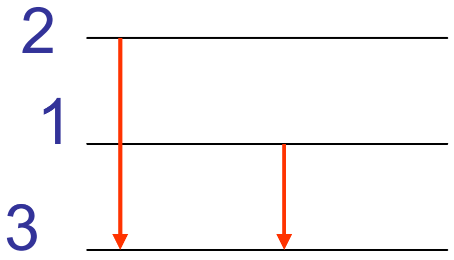
Normal hierarchy



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

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

Inverted hierarchy



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

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

Observing pion source and muon damped source to determine Q_{31} and Q_{33}

Pion source

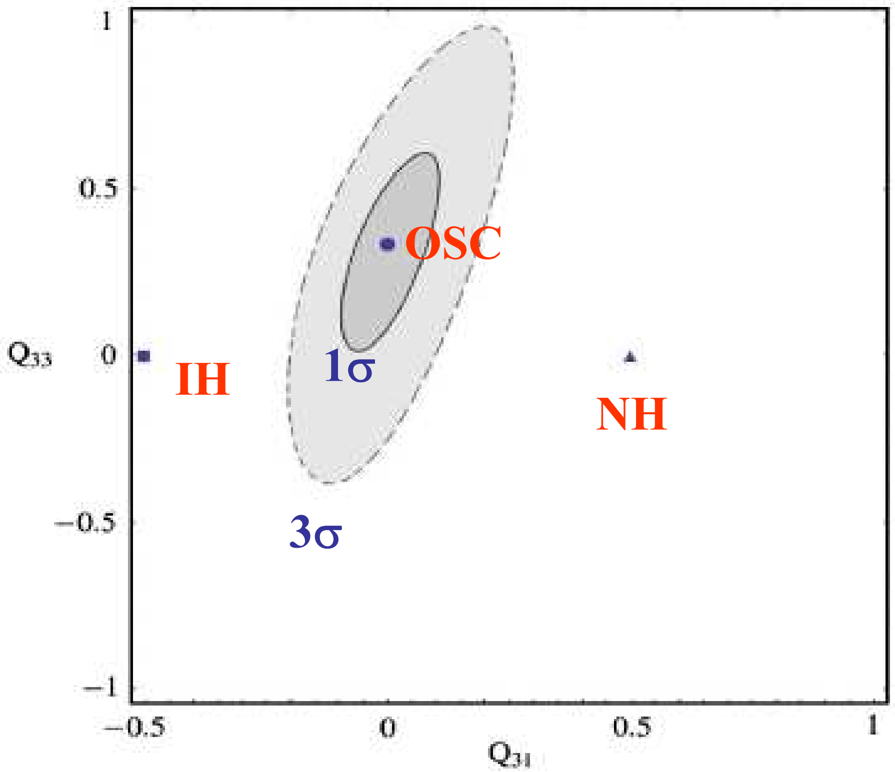
$$\begin{pmatrix} 1/3 \\ \rho \\ \lambda \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ Q_{31} & 0 & Q_{33} \end{pmatrix} \begin{pmatrix} 1/3 \\ -1/3 \\ 0 \end{pmatrix} \Rightarrow \lambda = Q_{31}/3$$

Muon-damped source

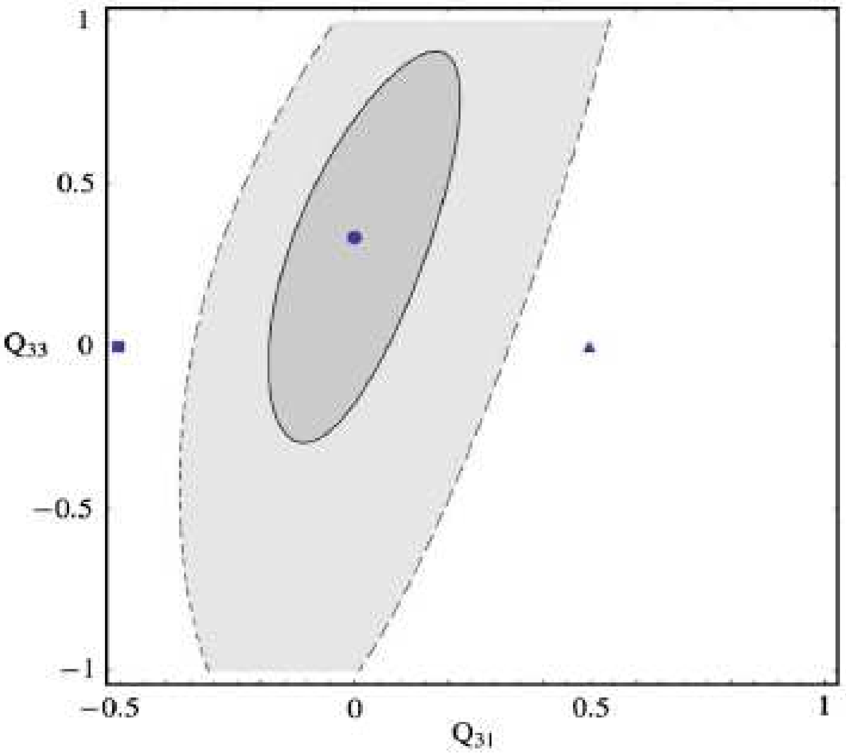
$$\lambda \equiv \frac{1}{3}\left(\phi(\nu_e) - \frac{\phi(\nu_\mu) + \phi(\nu_\tau)}{2} \right)$$

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

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



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



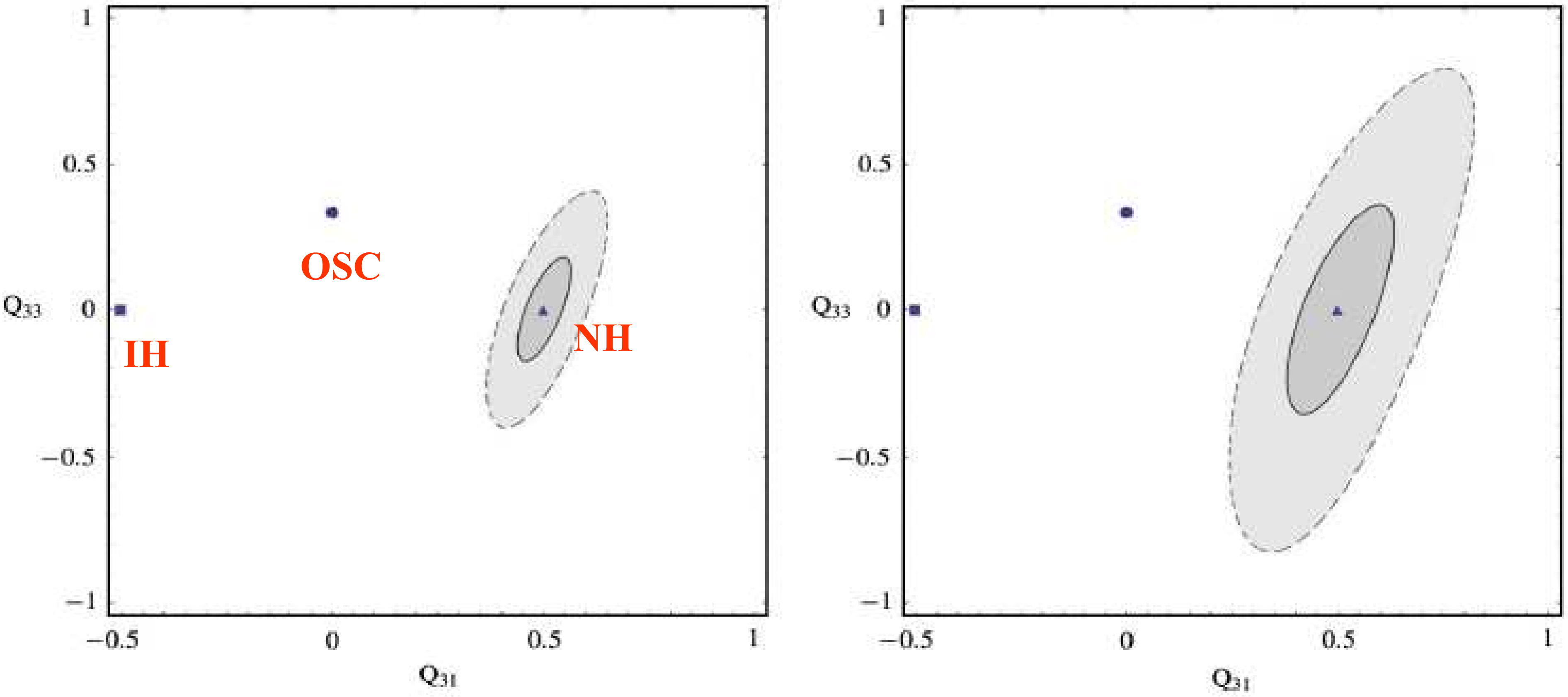
$\Delta R_\pi / R_\pi = \Delta R_\mu / R_\mu = 20\%$

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

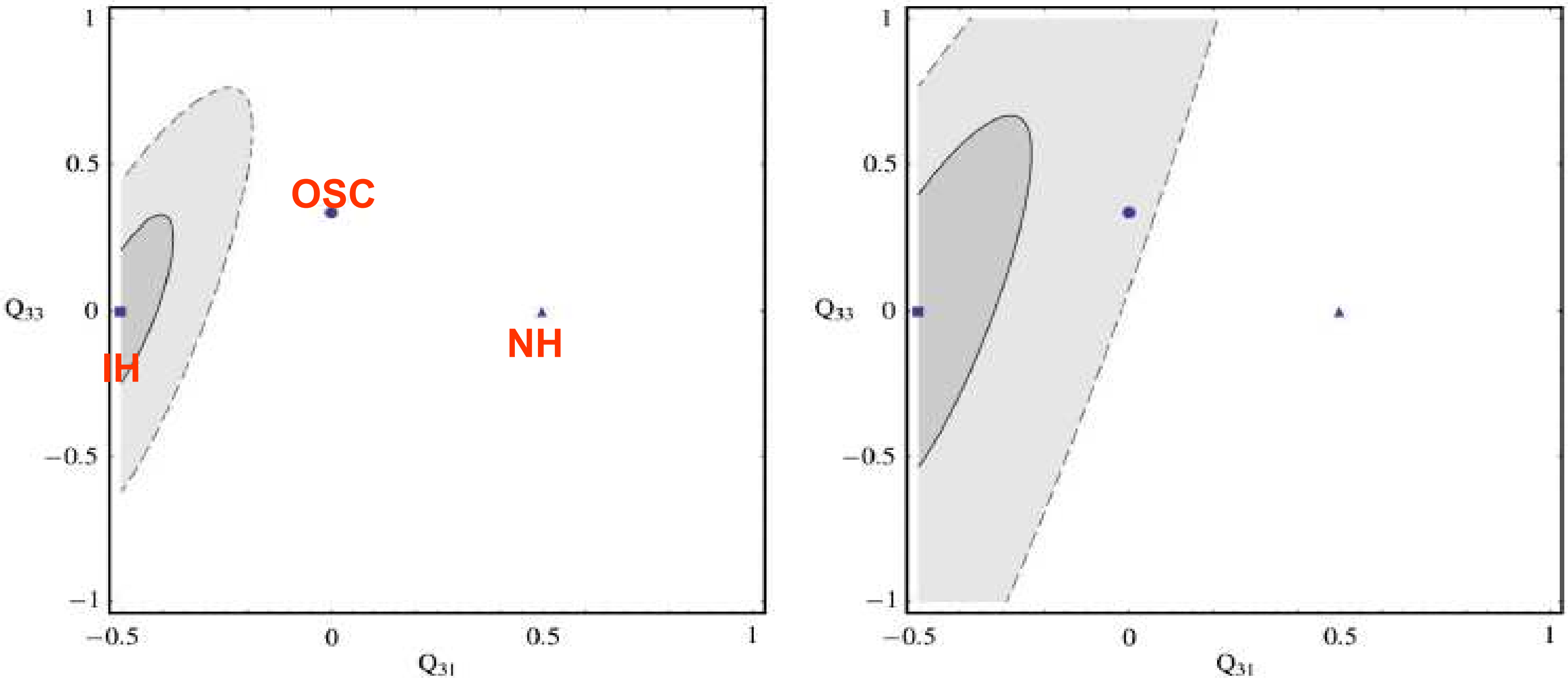
Water Cherenkov detector

~50 events

Change the input model



Change the input model--continued



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

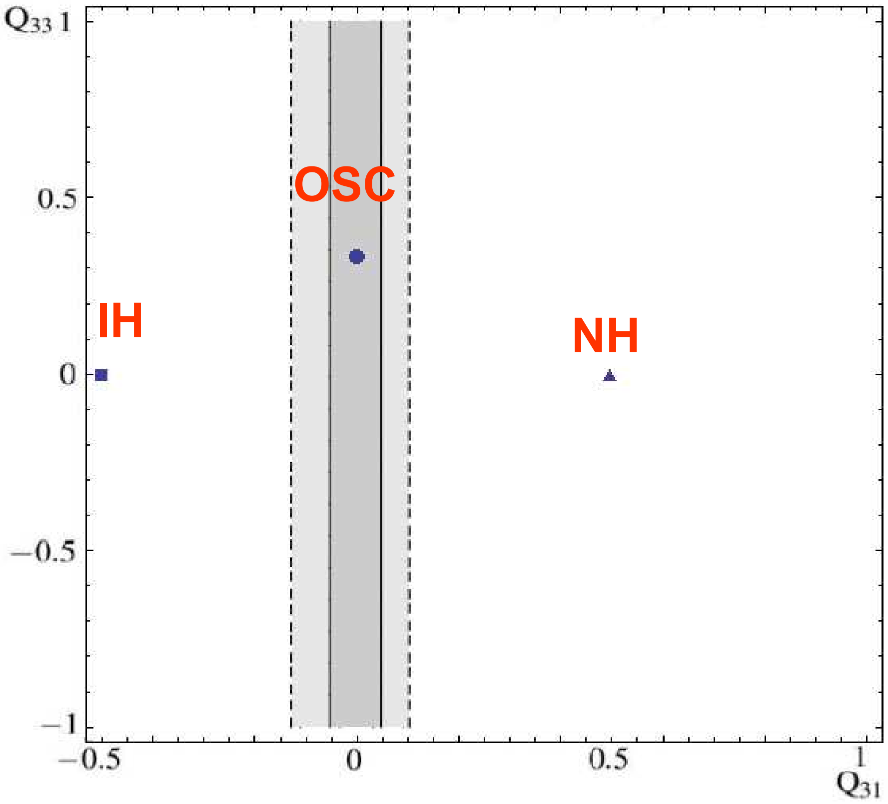
We have a pure pion source

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

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

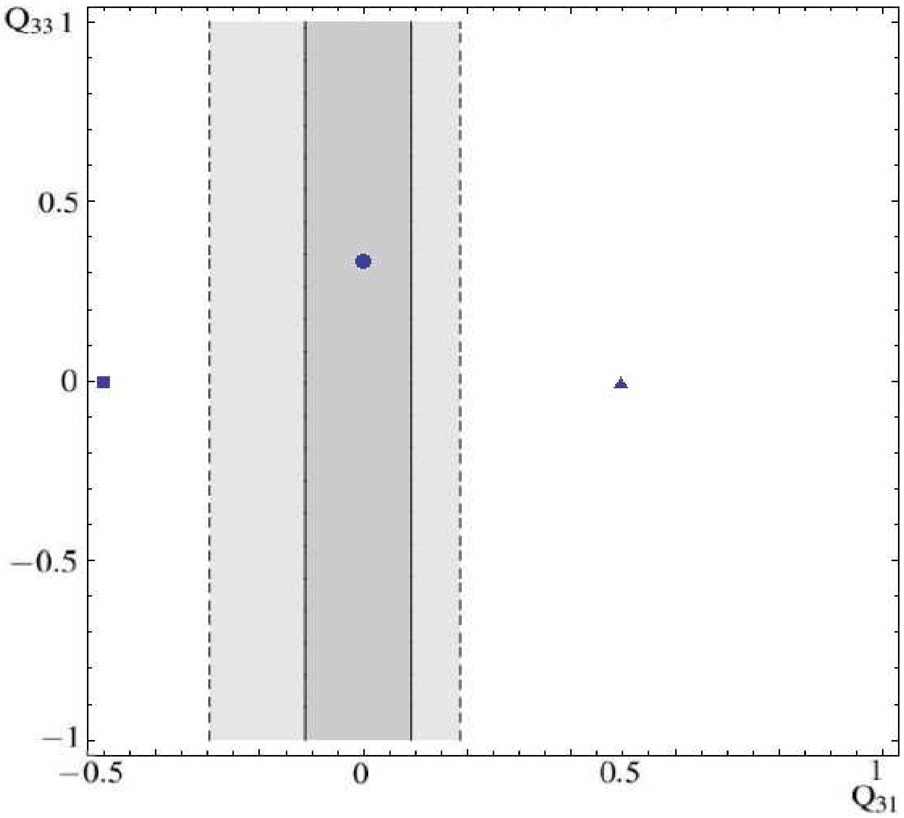
Pion source can only probe Q_{31}

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



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

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



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

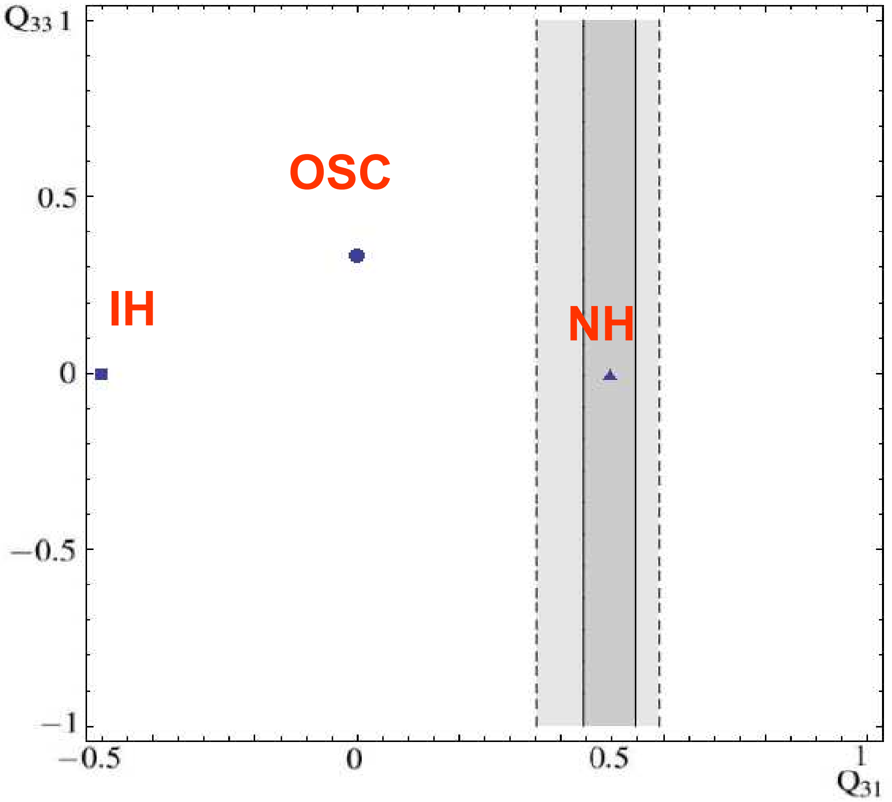
$$R'_{\mathrm{osc}} = 0.5$$

~50 events

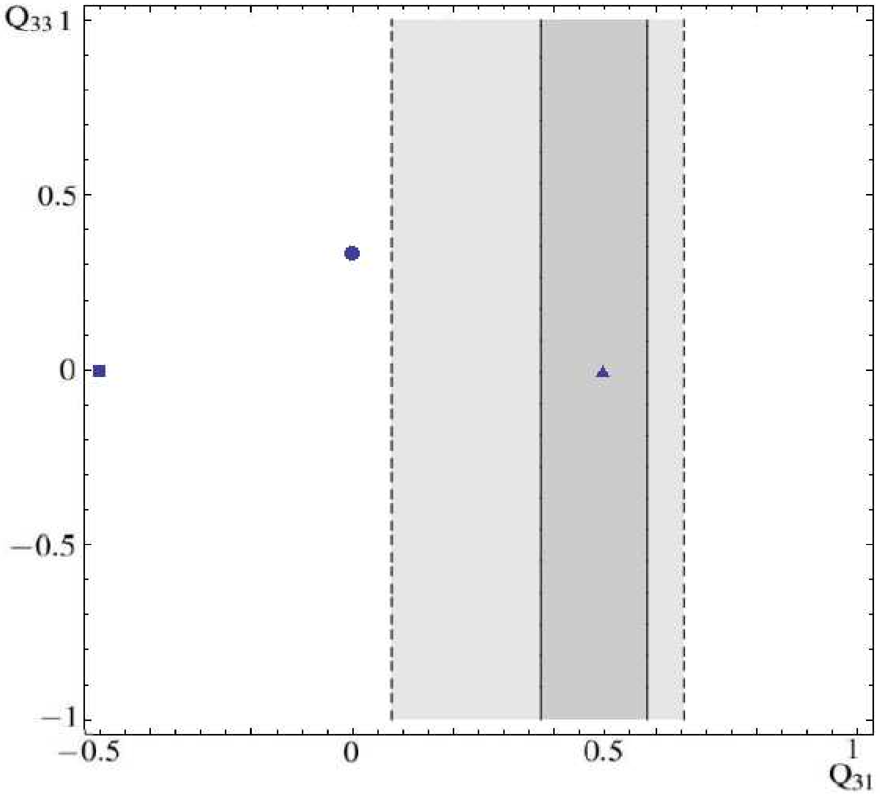
Radio wave detection

Change the input model

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



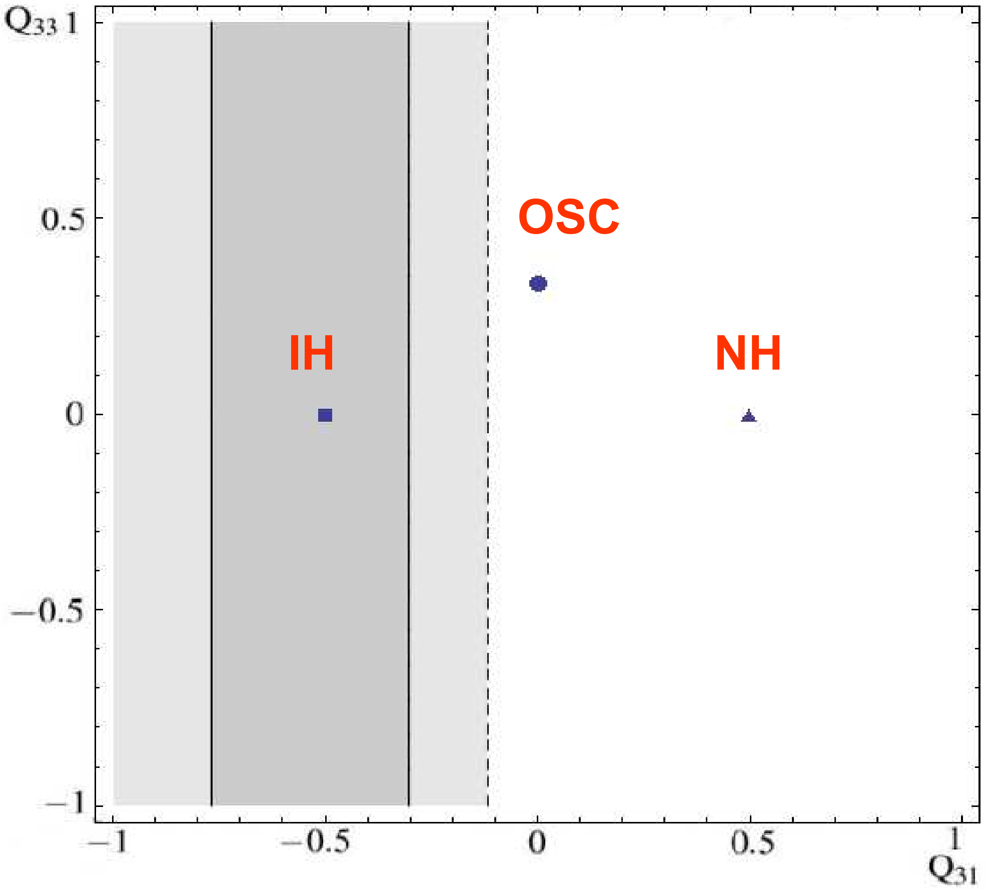
$$\Delta R' / R' = 10\%$$



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

Change the input model

$$R'_{\mathrm{IH}} = 0$$



Assume $\Delta R'_{\mathrm{IH}}$=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.