Determining the Neutrino Flavor Ratio at the Astrophysical Source

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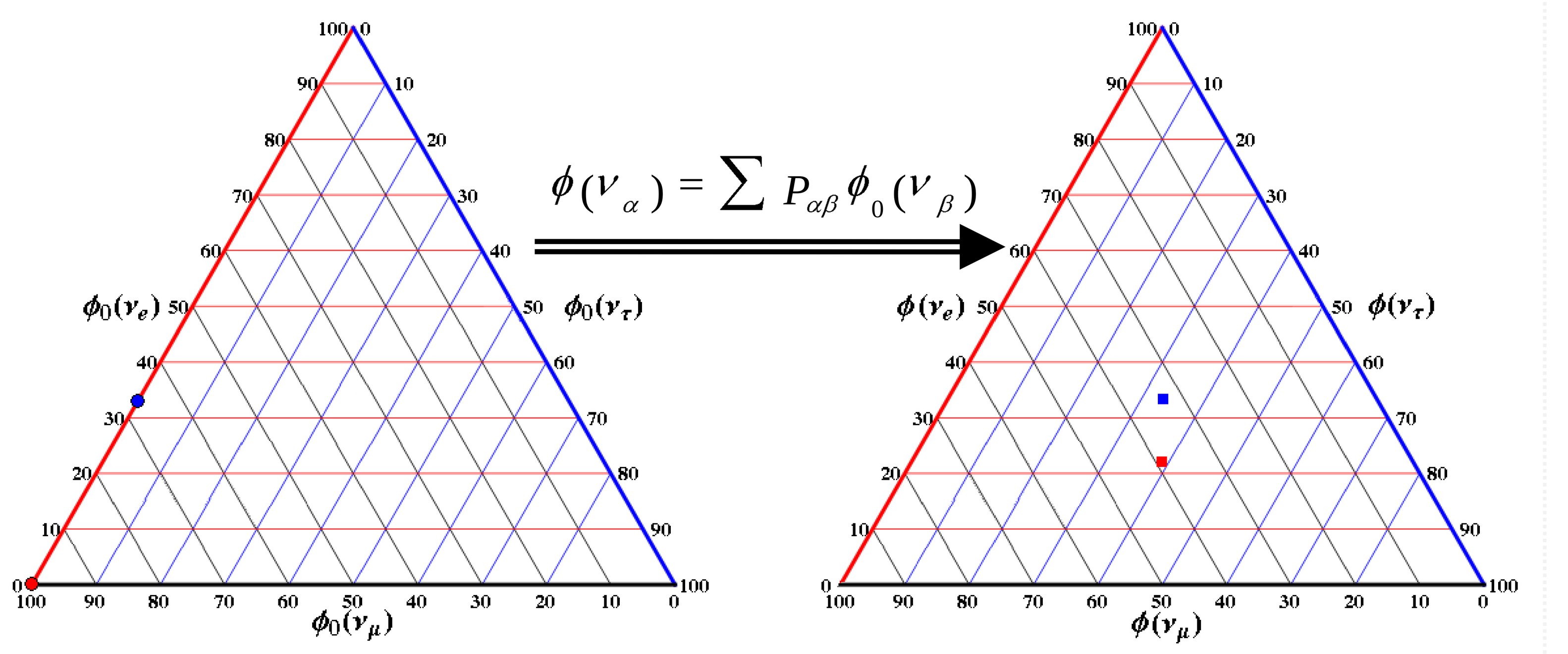
We discuss the reconstruction of neutrino flavor ratios at astrophysical sources through the future neutrino telescope measurements.[1] Taking the ranges of neutrino mixing parameters θ_{ij} as those given by the current global fit, we demonstrate by a statistical method that the accuracies in the measurements of neutrino flux ratios between different flavors should both be better than 10% in order to distinguish between the pion source and the muon-damped source at the 3 σ level.

Flavor Ratios at Source and Earth

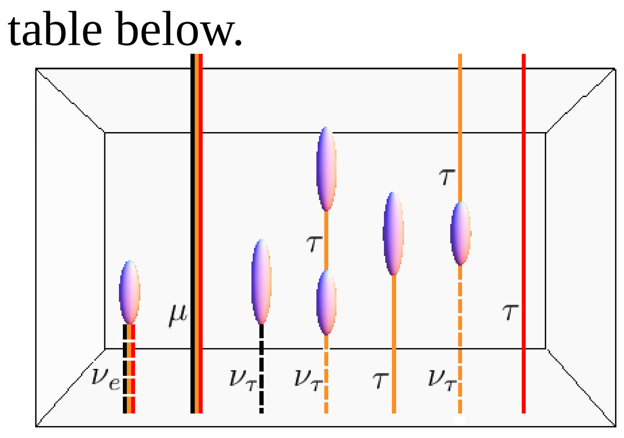
The evolution of neutrino flavor ratio from the source to the Earth is given by the probability matrix $P_{\alpha\beta}$. The figure below shows the evolution of neutrino flavor ratio for pion source (blue circle) and muon-damped source (red circle).



Parameter Definitions

Tau neutrino signal changes with the energy. We define E_l and E_h as the transition energy for tau neutrino signal. For instance, E_l and E_h correspond to 3.3 and 33.3 PeV respectively in km^3 size detector.[2] The figure in this panel shows different types of neutrino-induced events. Dashed lines and solid lines correspond to paths of neutrinos and leptons respectively. Black and red colors denote energy levels less than E_l and larger than E_h respectively. Orange color indicates an energy level in between E_l to E_h. The ellipsoids are showers. We define measurable ratio parameters as listed in the table below.

Condition I ($E_\nu < E_h$)	Condition II ($E_\nu > E_h$)
$R^I = \phi(\nu_\mu) / (\phi(\nu_e) + \phi(\nu_\tau))$ [3]	$R^{II} = \phi(\nu_e) / (\phi(\nu_\mu) + \phi(\nu_\tau))$
$S^I = \phi(\nu_e) / \phi(\nu_\tau)$[4]	$S^{II} = \phi(\nu_\mu) / \phi(\nu_\tau)$



Statistical Analysis

The relations between the measurement errors $\Delta R^a/R^a$ and $\Delta S^a/S^a$ with $a = I$ and II respectively are assumed to be dominated by statistical errors, which imply[5]

$$\frac{\Delta S^a}{S^a} = \frac{1+S^a}{\sqrt{S^a}}\sqrt{\frac{R^a}{1+R^a}}\frac{\Delta R^a}{R^a}$$

The statistical analysis is performed according to the following formula

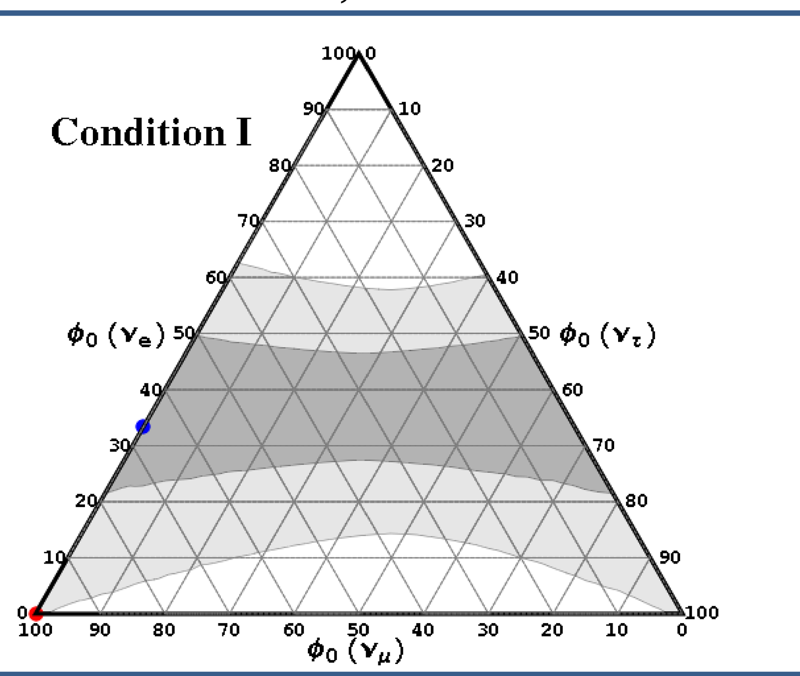
$$\chi^2 = \left(\frac{R^a_{th} - R^a_{exp}}{\sigma R^a_{exp}}\right)^2 + \left(\frac{S^a_{th} - S^a_{exp}}{\sigma S^a_{exp}}\right)^2 + \sum_{ij=12,13,23} \chi^2_{\theta_{ij}},$$

$$\sigma R^a_{ex} = (\Delta R^a / R^a) R^a_{exp}, \sigma S^a_{ex} = (\Delta S^a / S^a) S^a_{exp}.$$

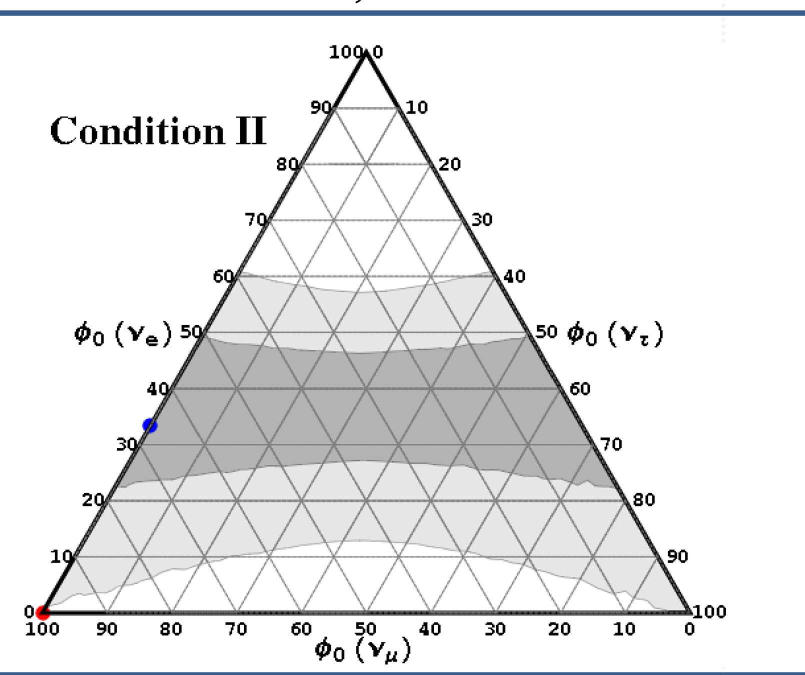
The best-fit values of mixing angles and allowed 1σ and 3σ ranges are $\sin^2\theta_{12} = 0.29^{+0.028,0.09}_{-0.024,0.06}$, $\sin^2\theta_{23} = 0.5^{+0.072,0.18}_{-0.069,0.16}$, $\sin^2\theta_{13} < 0.012\ (0.047)$ [6]

Pion Source, $\{\phi(\nu_e) : \phi(\nu_\mu) : \phi(\nu_\tau)\} = \{0.33 : 0.66 : 0\}$[7]

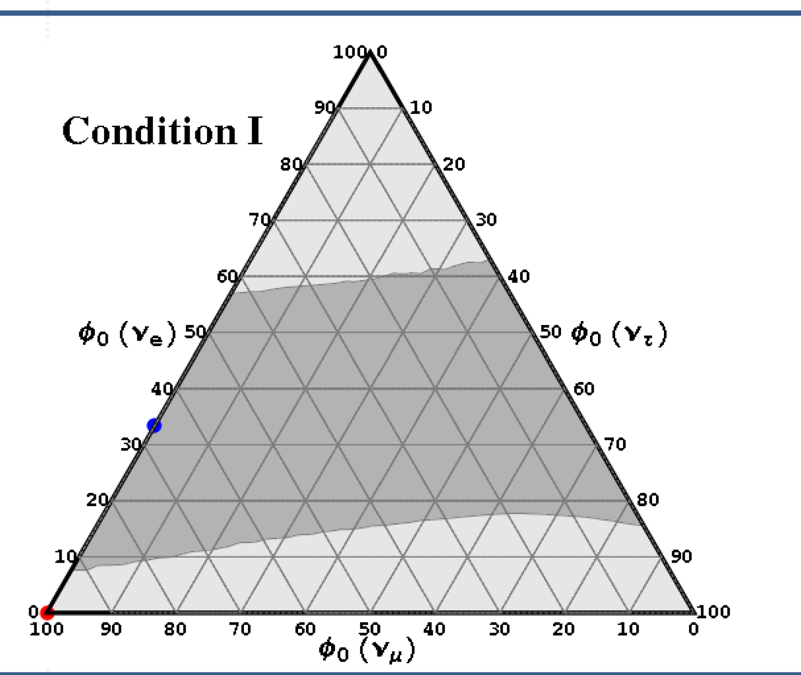
$\Delta R^I / R^I = 10\%$, $\Delta S^I / S^I = 11.4\%$



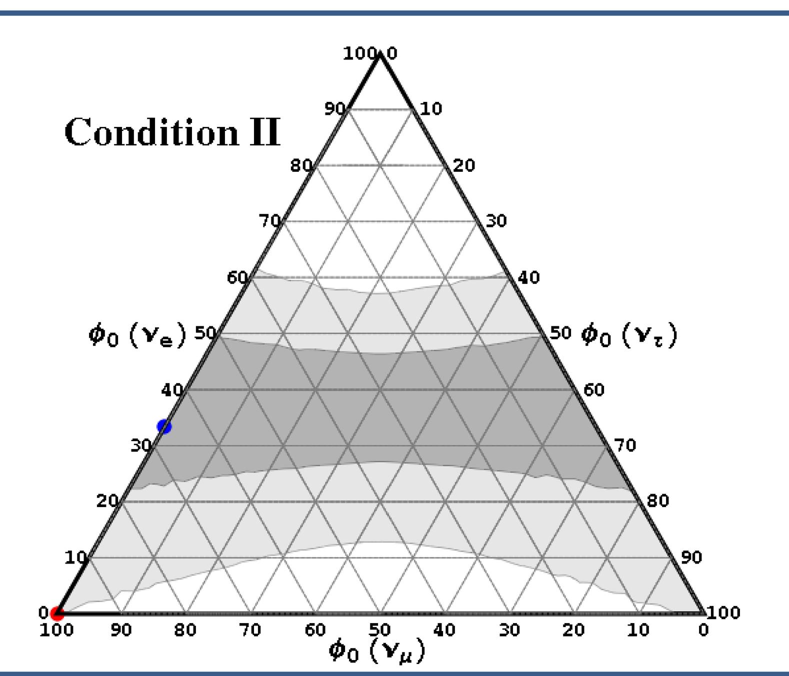
$\Delta R^{II} / R^{II} = 10\%$, $\Delta S^{II} / S^{II} = 11.7\%$



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

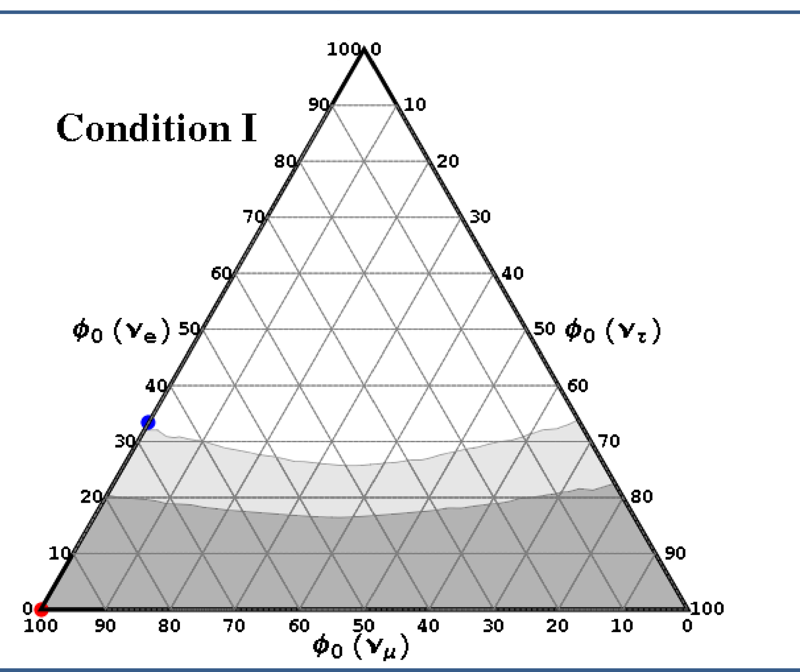


$\Delta R^{II} / R^{II} = 10\%$

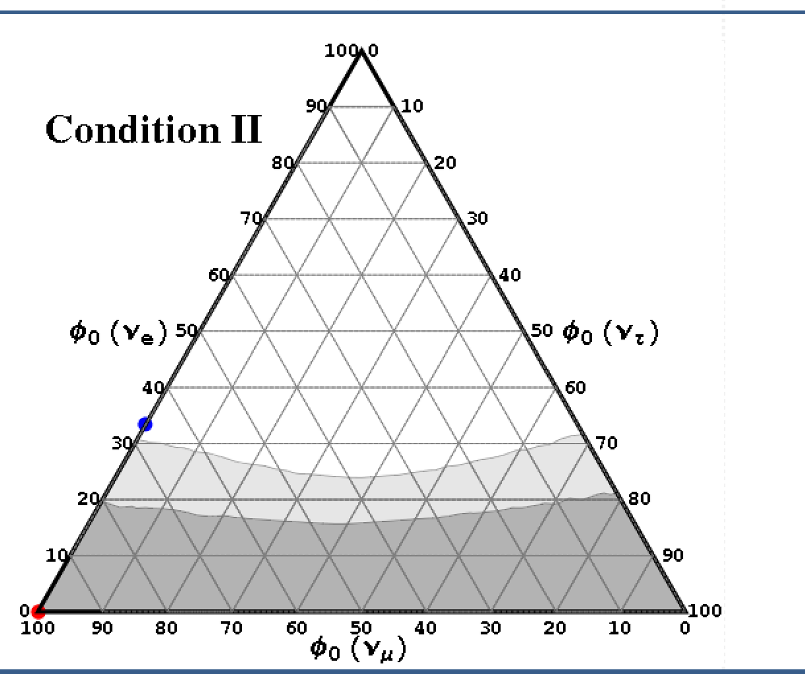


Muon-damped Source, $\{\phi(\nu_e) : \phi(\nu_\mu) : \phi(\nu_\tau)\} = \{0 : 1 : 0\}$[8]

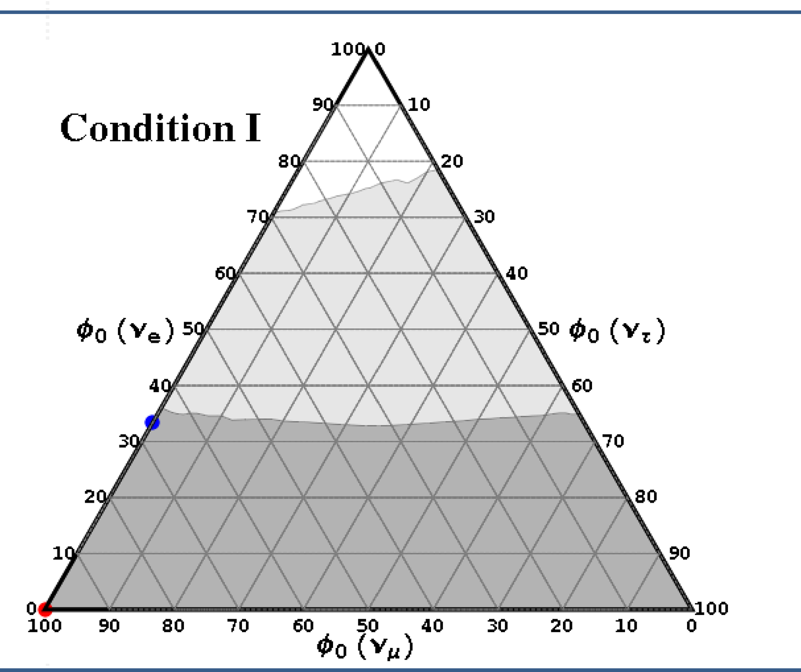
$\Delta R^I / R^I = 10\%$, $\Delta S^I / S^I = 12.57\%$



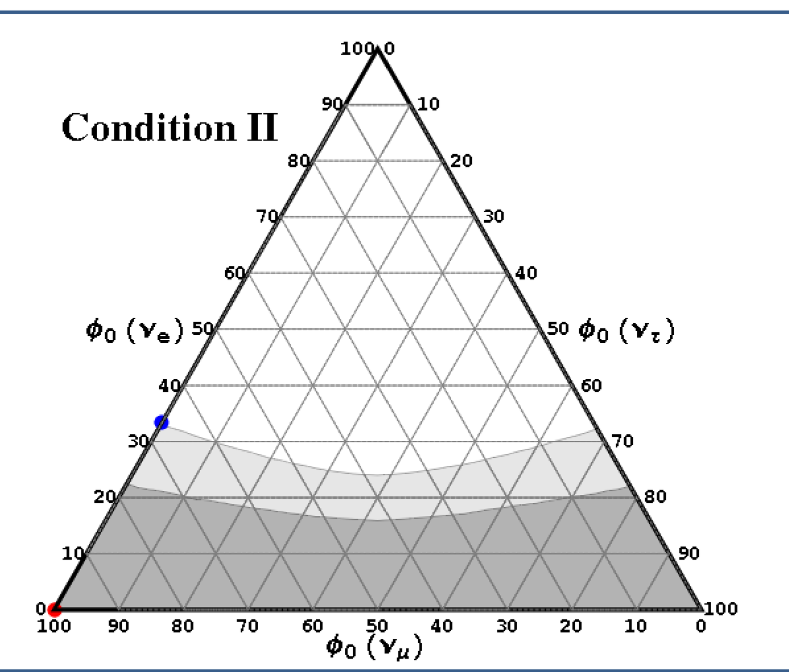
$\Delta R^{II} / R^{II} = 10\%$, $\Delta S^{II} / S^{II} = 9.7\%$



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



$\Delta R^{II} / R^{II} = 10\%$



Conclusion:

Reconstructing the neutrino flavor ratio at the astrophysical source requires a huge statistics for distinguishing between the pion source and the muon-damped source. In the low energy case, both R and S should be measured for effectively distinguishing different sources. In the high energy case, it is sufficient to just measure R. However, the neutrino flux in this case is expected to be suppressed.

References:

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