An Analysis of Cosmic Neutrinos
Flavor Composition at Source and Neutrino Mixing Parameters

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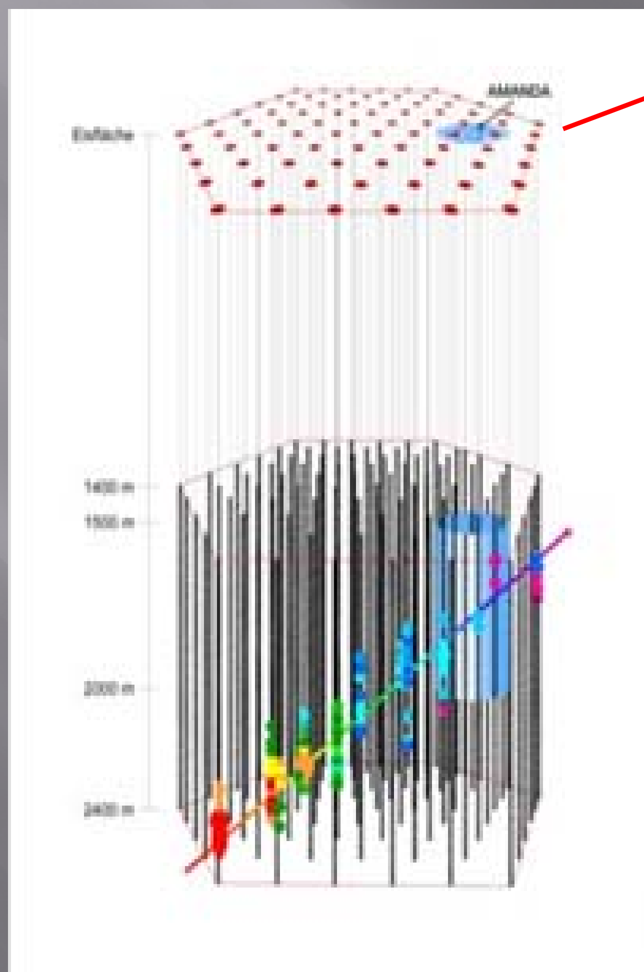
A. E. and Yasaman Farzan; Nucl.Phys.B 821:197-214,2009; [arXiv:0905.0259]
A. E., [arXiv:0909.5410]

Current upper limit on the diffuse flux of neutrinos from AMANDA experiment

A. Gross, [astro-ph/0505278]

$$E_\nu^2 \frac{dF_\nu}{dE_\nu} \le 8.2 \quad \mathrm{GeV\ cm^{-2}\ sr^{-1}\ yr^{-1}}$$

Depth of the ice at the IceCube site ~ 2850 m



Ice top

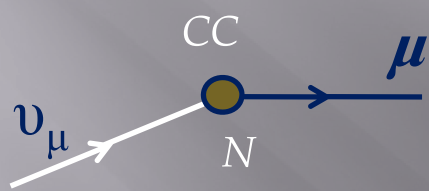
PMTs loaded from 1450 m to 2450 m

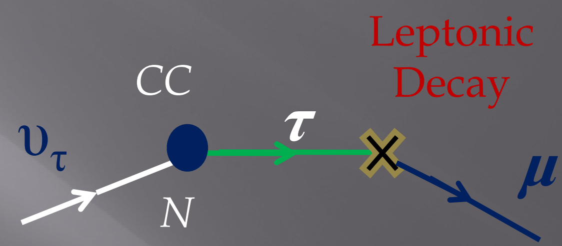
Flavor Identification

IceCube can distinguish two types of events

Muon-track events

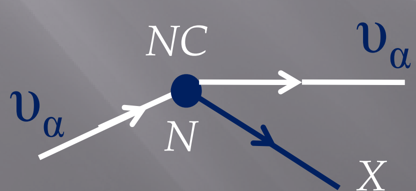
- CC interaction of ν_μ
- CC interaction of ν_τ

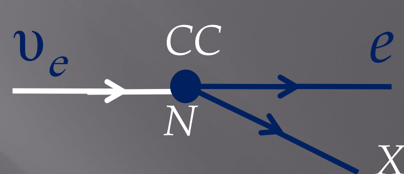


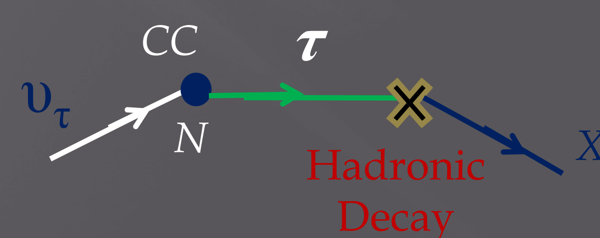


Shower-like events

- NC interaction of ν_α
- CC interaction of ν_e
- CC interaction of ν_τ







The quantity that can be measured in IceCube

$$R = \frac{\text{Number of Muon-track events}}{\text{Number of Shower-like events}}.$$

~ one order of magnitude lower than the present upper bound

With a neutrino flux

$$E_\nu^2 dF_\nu/dE_\nu = 0.25 \text{ GeV cm}^{-2} \text{ sr}^{-1} \text{ yr}^{-1}$$

According to J. F. Beacom *et al.*, Phys. Rev. D 68 (2003)

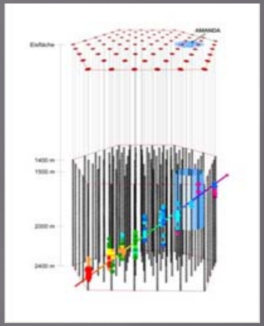
A few hundreds of events in a couple of years

R can be measured by ***7%*** precision

Set-up :

Traveling distance

L ~ 100 Mpc



P. Serpico, M. Kachelriess, Phys.Rev.Lett.94,2005

J.F.Beacom, *et. al.*, Phys.Rev.D69,2004;

S. Pakvasa, *et. al.*, JHEP 0802,2008

D. Meloni, T. Ohlsson, Phys.Rev.D75,2007

W. Winter, Phys.Rev.D74,2006

Y. Farzan, A. Yu. Smirnov, Phys.Rev.D65,2002

Production of neutrinos at the source with flavor ratio

$$w_e^0 : w_\mu^0 : w_\tau^0$$

1 : 2 : 0

At the Earth the flavor ratio will be

$$\sum_\alpha w_\alpha^0 P_{\alpha e} : \sum_\alpha w_\alpha^0 P_{\alpha\mu} : \sum_\alpha w_\alpha^0 P_{\alpha\tau}$$

$$P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Inputs and Uncertainties

Spectrum of the incoming flux of neutrinos :

$$\frac{dF_\nu}{dE_\nu} = N_\nu E_\nu^{-\alpha}$$

Models of neutrino production (Fermi acceleration) predict $\alpha = 2$

But, considering non-linear effects

$1 < \alpha < 3$

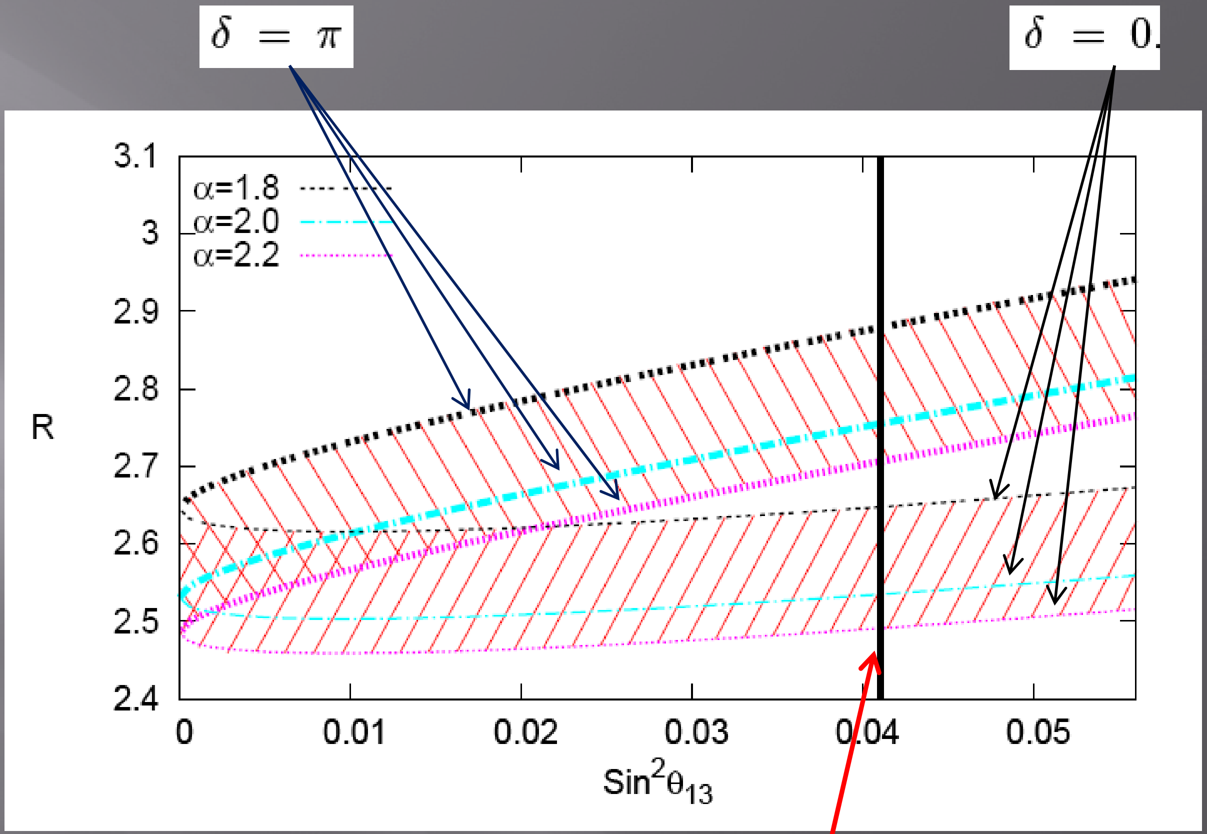
$$\mathcal{N}_{\nu_\mu} = \mathcal{N}_{\bar{\nu}_\mu}$$

$$0 < \mathcal{N}_{\bar{\nu}_e}/\mathcal{N}_{\nu_e} < 1.$$

Can be measured by 10% precision in IceCube

J. F. Beacom *et. al.*, Phys. Rev D68 (2003)

Sensitivity to s_{13}^2



$$(\mathcal{N}_{\bar{\nu}_\mu} + \mathcal{N}_{\nu_\mu})/(\mathcal{N}_{\bar{\nu}_e} + \mathcal{N}_{\nu_e}) = 2$$

$$\mathcal{N}_{\bar{\nu}_e}/\mathcal{N}_{\nu_e} = 0.5$$

θ_{12} and θ_{23} → Best fit values

The present bound on s_{13}^2 at 3σ

- R is more sensitive to s_{13}^2 in the case δ = π (~ 10 %)
- Even for δ = π , the sensitivity of R is obscured by the 10 % uncertainty in α
- For $s_{13}^2 > 0.02$, it is possible to distinguish δ = 0 from δ = π
- The effect of the uncertainty in α decreases by increasing the value of α

Sensitivity to s_{13}^2

$\lambda \equiv \mathcal{N}_{\bar{\nu}_e} / \mathcal{N}_{\nu_e}$

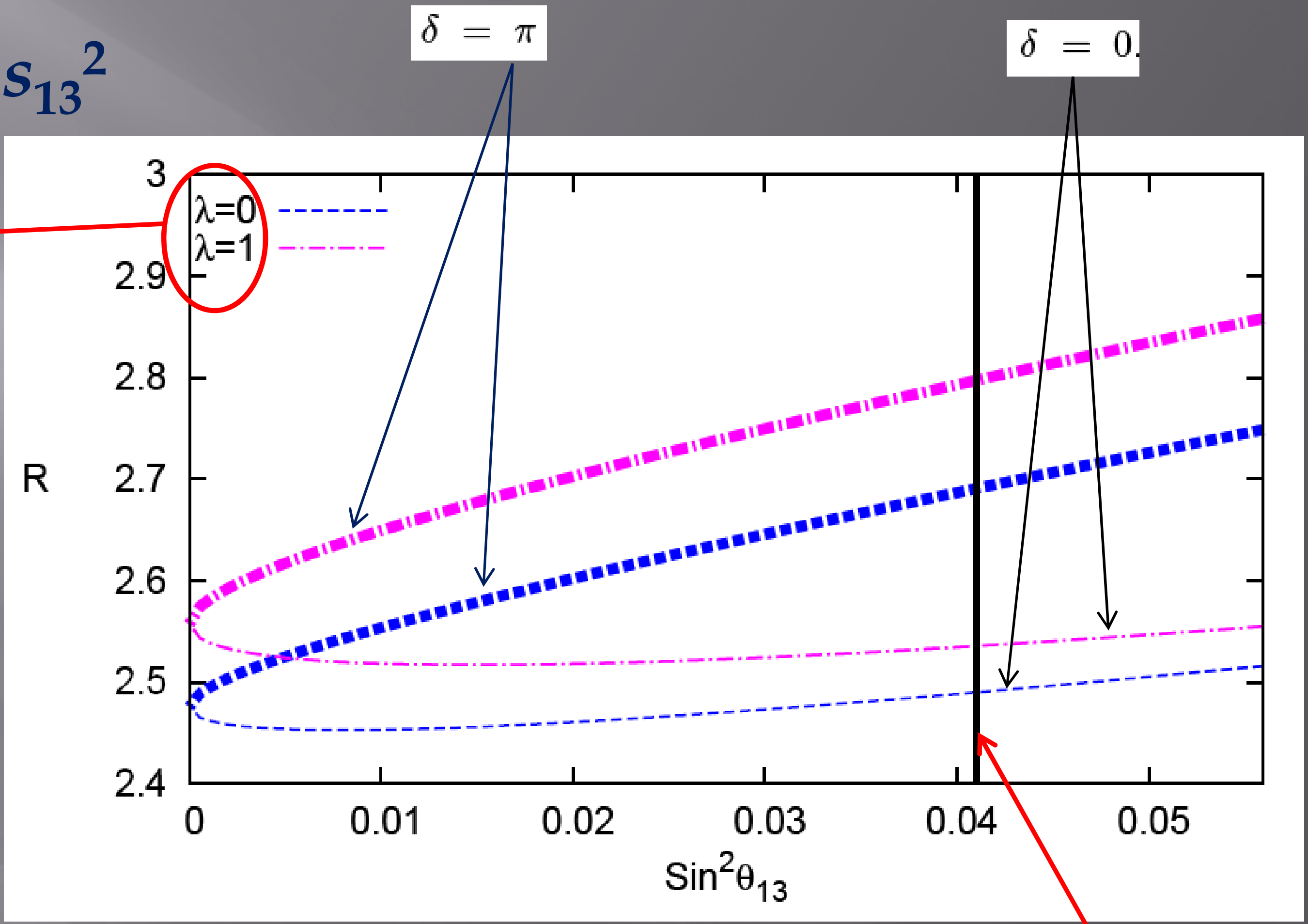
$w_e^0 : w_\mu^0 : w_\tau^0 = 1 : 2 : 0$

$\boxed{\alpha = 2}$

θ_{12} and θ_{23}

↓

Best fit values



The present bound on s_{13}^2 at 3σ

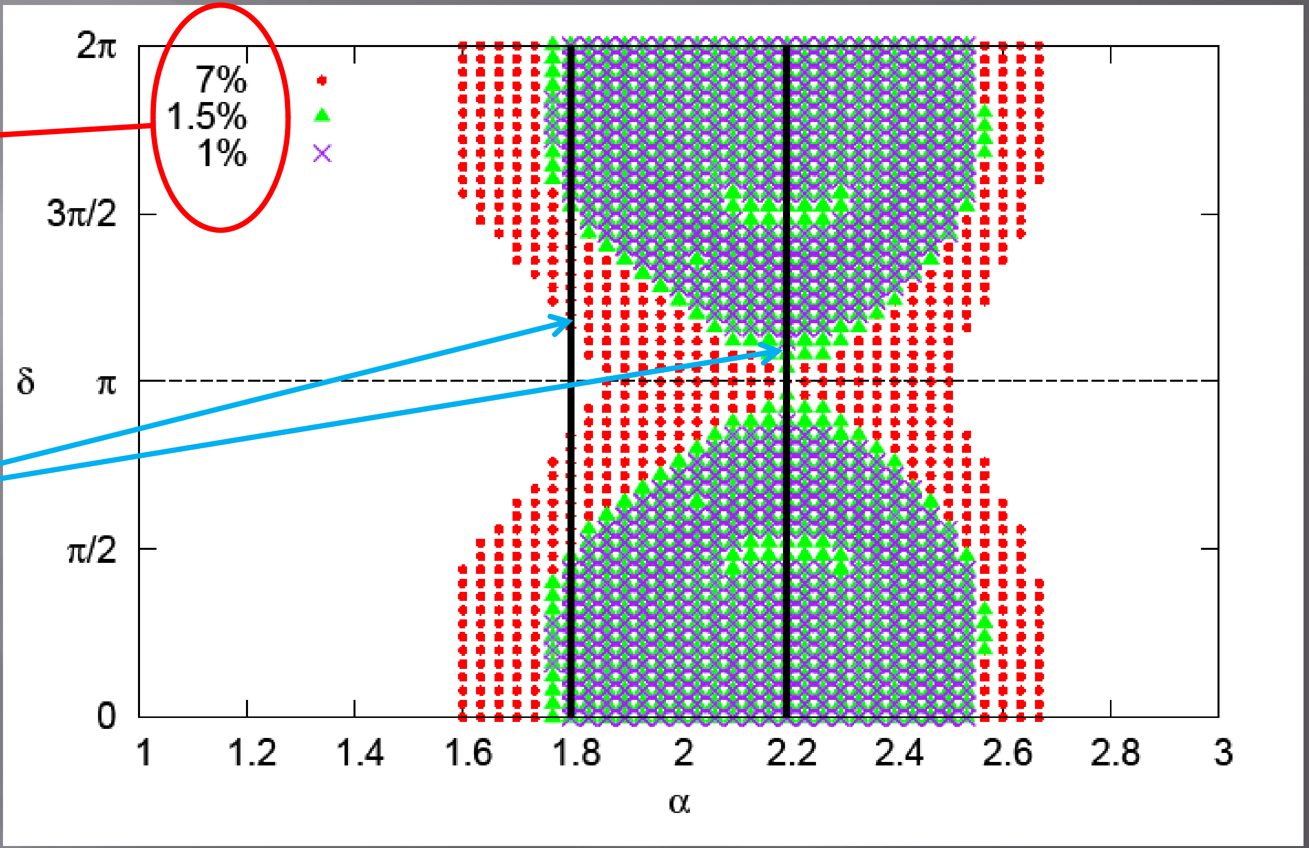
- ♠ Variation of λ in the interval [0,1] causes a 5 % change in ***R***
- ♠ For $s_{13}^2 > 0.005$, lack of knowledge about the content of the incoming beam will not cause a problem to distinguish $\delta = 0$ from $\delta = \pi$

Determination of δ

$\delta = \pi/2$ & $w_e^0 : w_\mu^0 : w_\tau^0 = 1 : 2 : 0$

Uncertainty in the measurement of *R*

10 % precision in the measurement of α with central value α = 2



$\sin^2\theta_{13} = 0.03^{+0.002}_{-0.002}$

$\sin^2\theta_{23} = 0.5^{+0.03}_{-0.03}$

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

$N_{\bar{\nu}_e}/N_{\nu_e} \in (0,1)$

- ♠ ***R*** depends on δ through cos δ , symmetry under δ → 2π − δ
- ♠ By measuring ***R*** with 7 % precision, δ cannot be constrained
- ♠ By measuring ***R*** with 1 % precision, regions around δ = π can be excluded

Flavor Composition at the Source

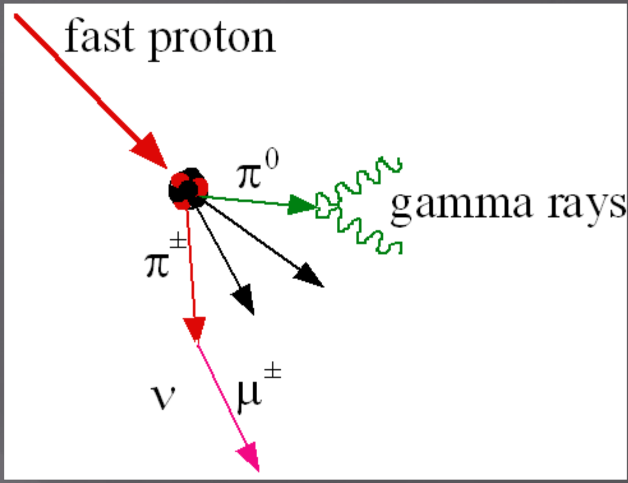
$$\begin{aligned} \pi^- &\rightarrow \mu^- \bar{\nu}_\mu \\ \mu^- &\rightarrow e^- \nu_\mu \bar{\nu}_e \end{aligned}$$

Main mechanism of neutrino production

(Pion sources)

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ \nu_\mu \\ \mu^+ &\rightarrow e^+ \bar{\nu}_\mu \nu_e \end{aligned}$$

$$w_e^0 : w_\mu^0 : w_\tau^0 = 0.5 : 1 : 0$$



$$w_e^0 : w_\mu^0 : w_\tau^0 = 0 : 1 : 0$$

Stopped-muon source

$$w_e^0 : w_\mu^0 : w_\tau^0 = 1 : 0 : 0$$

Neutron source

Flavor Composition at the Source

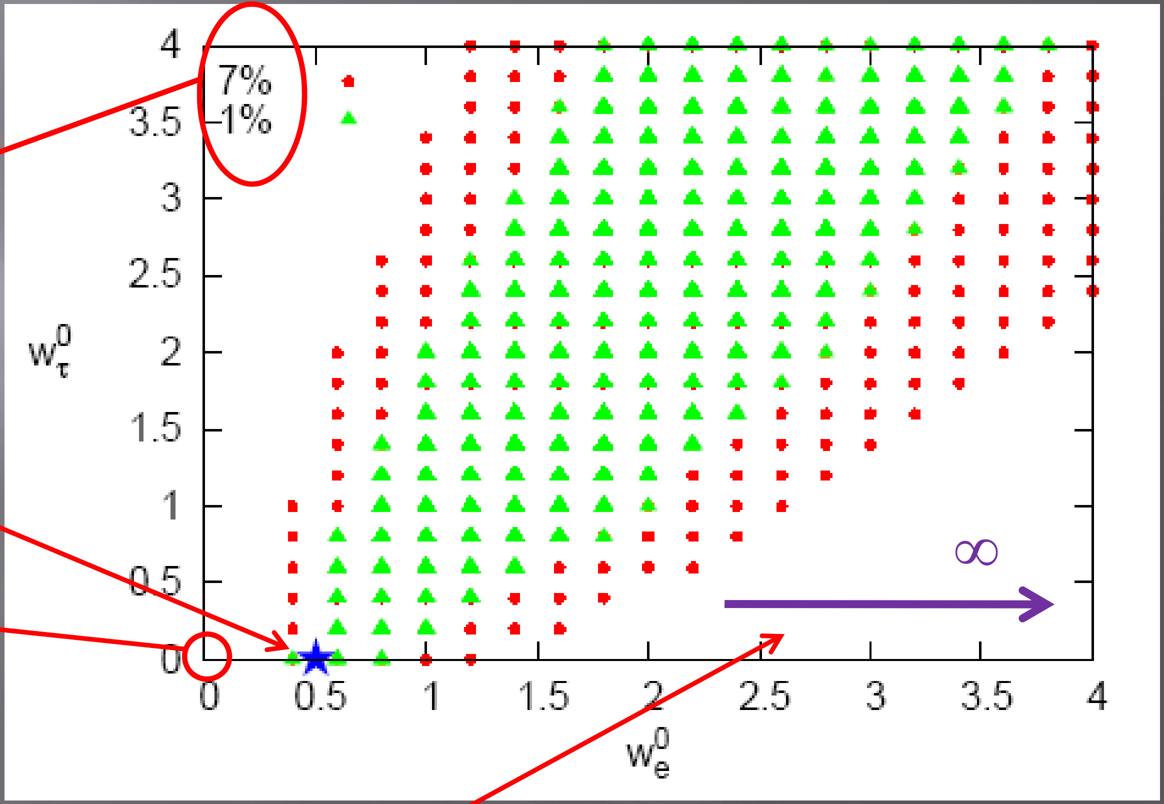
Pion Source

$$w_e^0 : w_\mu^0 : w_\tau^0 = w_e^0 : 1 : w_\tau^0$$

Uncertainty in the measurement of ***R***

Pion Source

Stopped-Muon Source



Neutron Source

- By 7 % precision in the measurement of ***R*** , Pion source can be completely distinguished from the Stopped-muon and Neutron sources

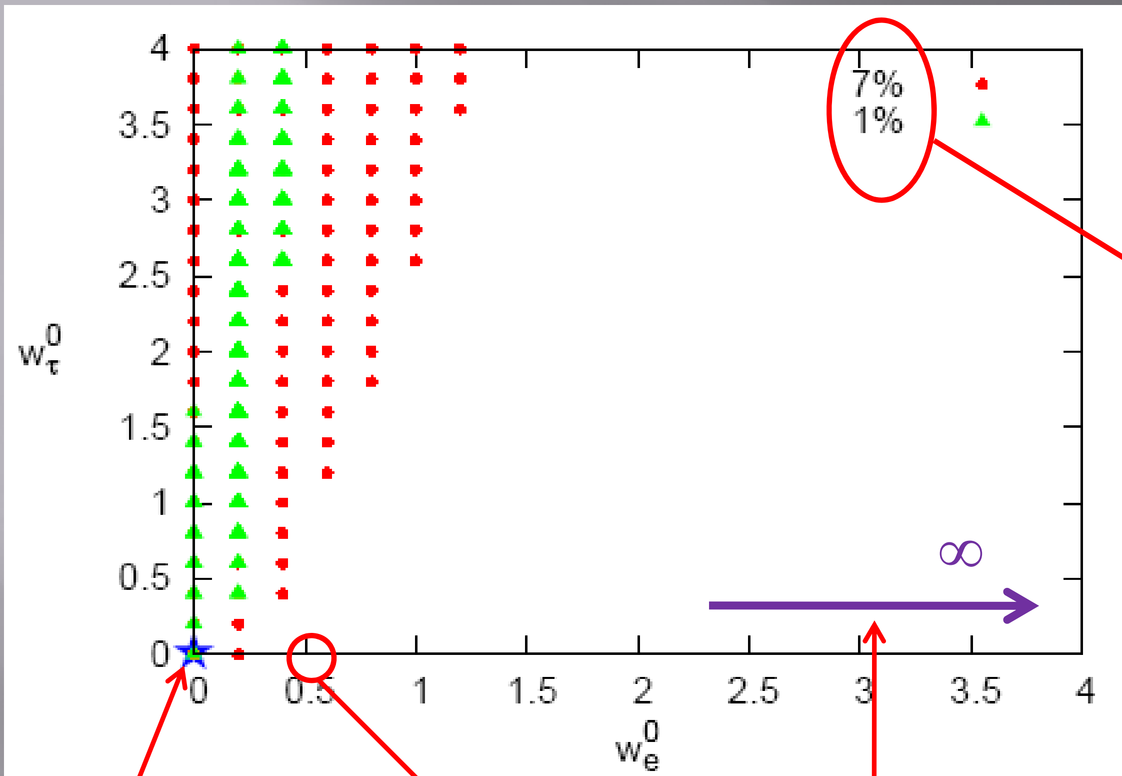
$$\sin^2\theta_{13} \in (0, 0.003)$$

$$\delta \in (0, 2\pi)$$

$$\alpha \in (1.8, 2.2)$$

$$N_{\bar{\nu}_e}/N_{\nu_e} \in (0, 1)$$

Flavor Composition at the Source: Stopped-Muon source



Stopped-Muon Source

Pion Source

Neutron Source

$$w_e^0 : w_\mu^0 : w_\tau^0 = w_e^0 : 1 : w_\tau^0$$

Uncertainty in the measurement of ***R***

$$\sin^2\theta_{13} \in (0, 0.003)$$

$$\delta \in (0, 2\pi)$$

$$\alpha \in (1.8, 2.2)$$

$$\mathcal{N}_{\bar{\nu}_e}/\mathcal{N}_{\nu_e} \in (0, 1)$$

♠ By 7 % precision in the measurement of ***R*** , Stopped-Muon source can be completely distinguished from the Pion and Neutron sources

Probing Pseudo-Dirac Scenario of Neutrinos using Cosmic Neutrinos

Described in the poster!!

Conclusion

- For $\delta = 0$, dependence of ***R*** on $\sin^2\theta_{13}$ is very mild (~ 2 %), but for $\delta = \pi$, ***R*** changes by about 10 % by varying $\sin^2\theta_{13}$ from zero to the present upper bound
- 10 % uncertainty in the spectral index α is the main source of error in the extraction of $\sin^2\theta_{13}$ from the measurement of ***R***. By reducing this uncertainty to 5 % , it is possible to derive $\sin^2\theta_{13}$ from the measurement of ***R***
- By varying $\lambda \equiv \mathcal{N}_{\bar{\nu}_e}/\mathcal{N}_{\nu_e}$ between 0 and 1, ***R*** changes by ~ 5 %, which is comparable to the effect of $\sin^2\theta_{13}$. No way to measure this ratio; we should rely on models to predict the value of this ratio.
- Even with 1 % precision in the measurement of ***R*** , CP-violation cannot be established (*i. e.*; even for maximal CP violation $\delta = \pi/2$, $\delta = 0$ cannot be ruled out)
- The initial flavor ratio of neutrinos can be determined by the measurement of ***R*** . By 7 % precision, the pion (1:2:0), stopped-muon (0:1:0) and neutron (1:0:0) can be completely distinguished.

Back up

Probability density of the emission of muon

At the rest frame of tau lepton

$$f(E_\tau, E_\mu) \equiv \frac{1}{\Gamma}\frac{d\Gamma(\tau(E_\tau) \to \mu(E_\mu)\bar{\nu}_\mu\nu_\tau)}{dE_\mu}$$

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{dE_\mu d\Omega}dE_\mu d\Omega = \frac{1}{\Gamma'}\frac{d^2\Gamma'}{dE'_\mu d\Omega'}dE'_\mu d\Omega'$$

&

$$\frac{1}{\Gamma'}\frac{d^2\Gamma'}{dE'_\mu d\Omega'} = \frac{12}{\pi m_\tau^3}\left(1 - \frac{4E'_\mu}{3m_\tau}\right)E'^2_\mu$$

$$\gamma = E_\tau / m_\tau$$

$$\beta = \sqrt{1 - 1/\gamma^2}$$

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{dE_\mu d\Omega}dE_\mu d\Omega = \frac{12}{\pi m_\tau^3}\left[1 - \frac{4}{3m_\tau}\gamma(1-\beta\cos\theta)E_\mu\right]\gamma(1-\beta\cos\theta)E_\mu^2 dE_\mu \sin\theta d\theta d\phi$$

$$0 \le \phi < 2\pi, \qquad 0 < E_\mu < \frac{E_\tau}{2}(1+\beta), \qquad 0 \le \theta \le \theta_{max}$$

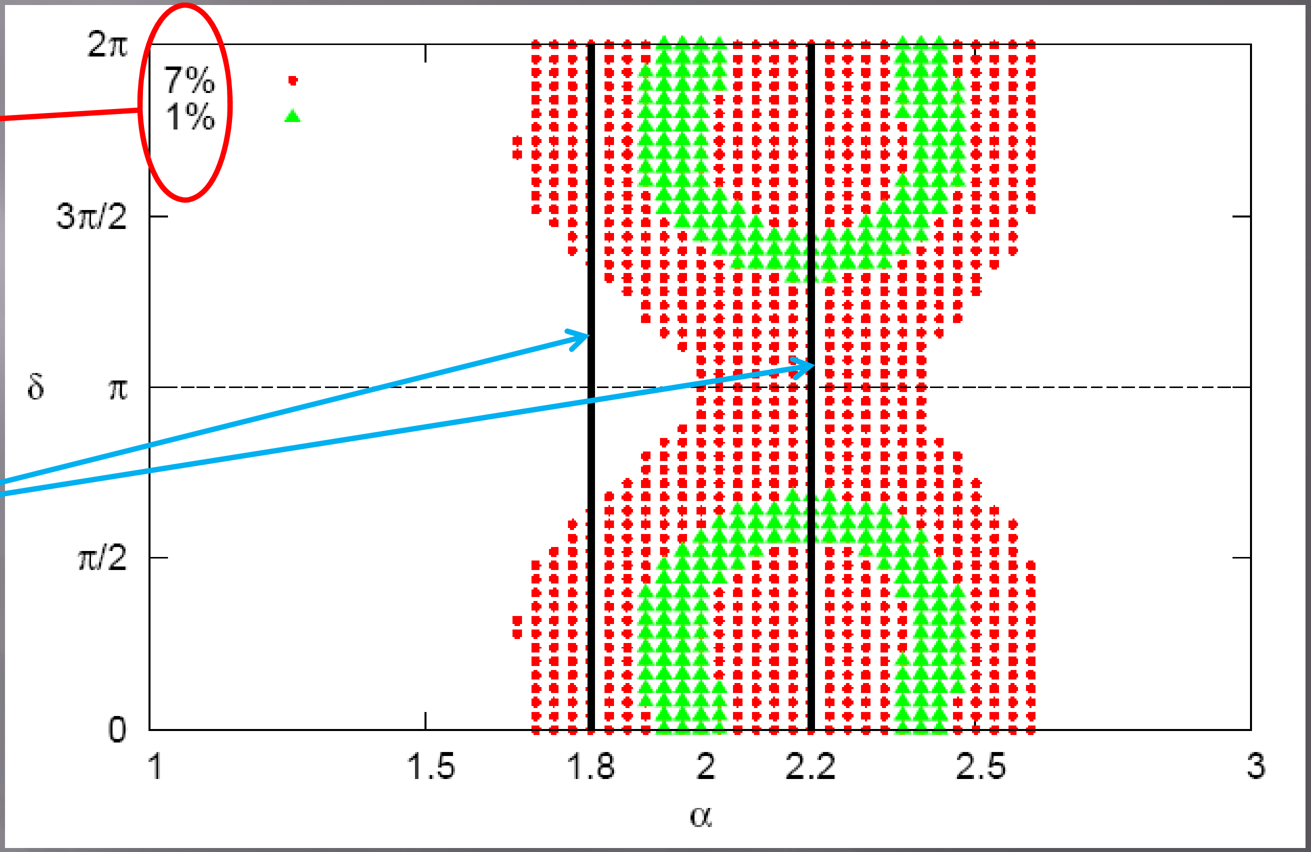
$$\theta_{max} = \arccos\left[\max\left\{\frac{1}{\beta}\left(1 - \frac{m_\tau}{2\gamma E_\mu}\right), -1\right\}\right].$$

Determination of δ

$\delta = \pi/2$ & $w_e^0 : w_\mu^0 : w_\tau^0 = 1 : 2 : 0$

Uncertainty in the measurement of *R*

10 % precision in the measurement of α with central value α = 2



$\sin^2\theta_{23} = 0.5^{+0.005}_{-0.005}$

$\sin^2\theta_{13} = 0.03$

$\sin^2\theta_{12} = 0.32$

$N_{\bar{\nu}_e}/N_{\nu_e} = 0.5$

Fixed to their central values

Varied in the 1 % precision interval

- ♠ ***R*** is significantly sensitive to the uncertainty in θ_{23}
- ♠ Reducing the uncertainty in $\sin^2\theta_{23}$ from 6 % to 1 % removes a substantial part of spurious solutions

Determination of δ

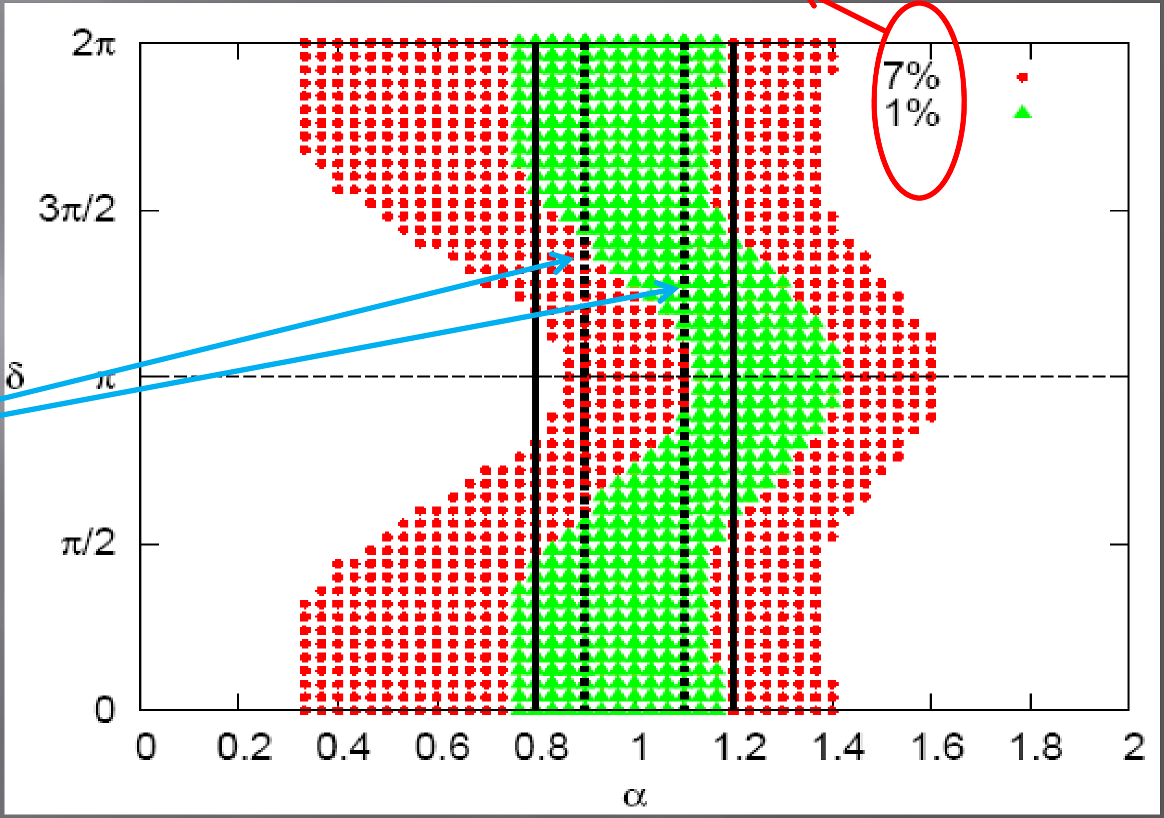
$$w_e^0 : w_\mu^0 : w_\tau^0 = 1 : 2 : 0$$

&

$$\delta = \pi/2$$

Uncertainty in the measurement of R

10 % precision in the measurement of α with central value α = 1



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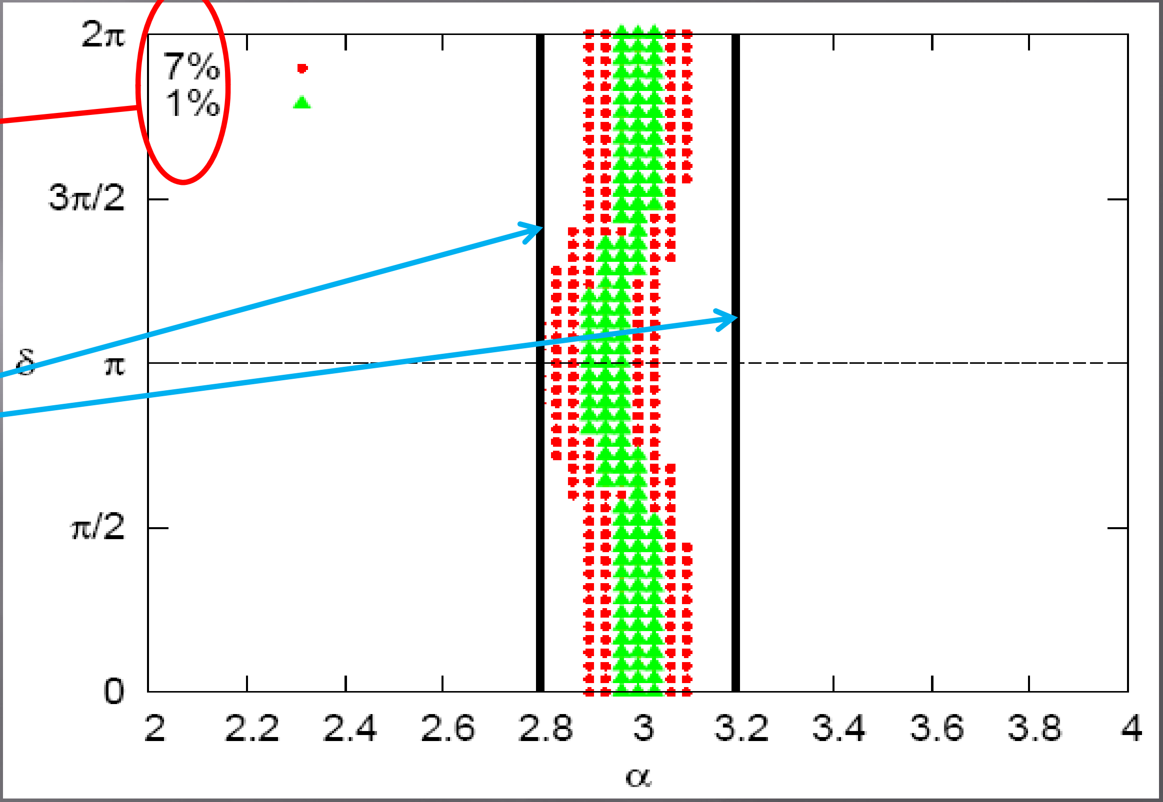
$$\mathcal{N}_{\bar{\nu}_e}/\mathcal{N}_{\nu_e} \in (0,1)$$

- By measuring ***R*** with 1 % precision, regions around δ = π can be excluded

Determination of δ

$\delta = \pi/2$ & $w_e^0 : w_\mu^0 : w_\tau^0 = 1 : 2 : 0$

Uncertainty in the measurement of *R*



10 % precision in the measurement of α with central value α = 3

$\sin^2\theta_{13} = 0.03^{+0.002}_{-0.002}$

$\sin^2\theta_{23} = 0.5^{+0.03}_{-0.03}$

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

$\mathcal{N}_{\bar{\nu}_e}/\mathcal{N}_{\nu_e} \in (0,1)$

Flavor Composition at the Source

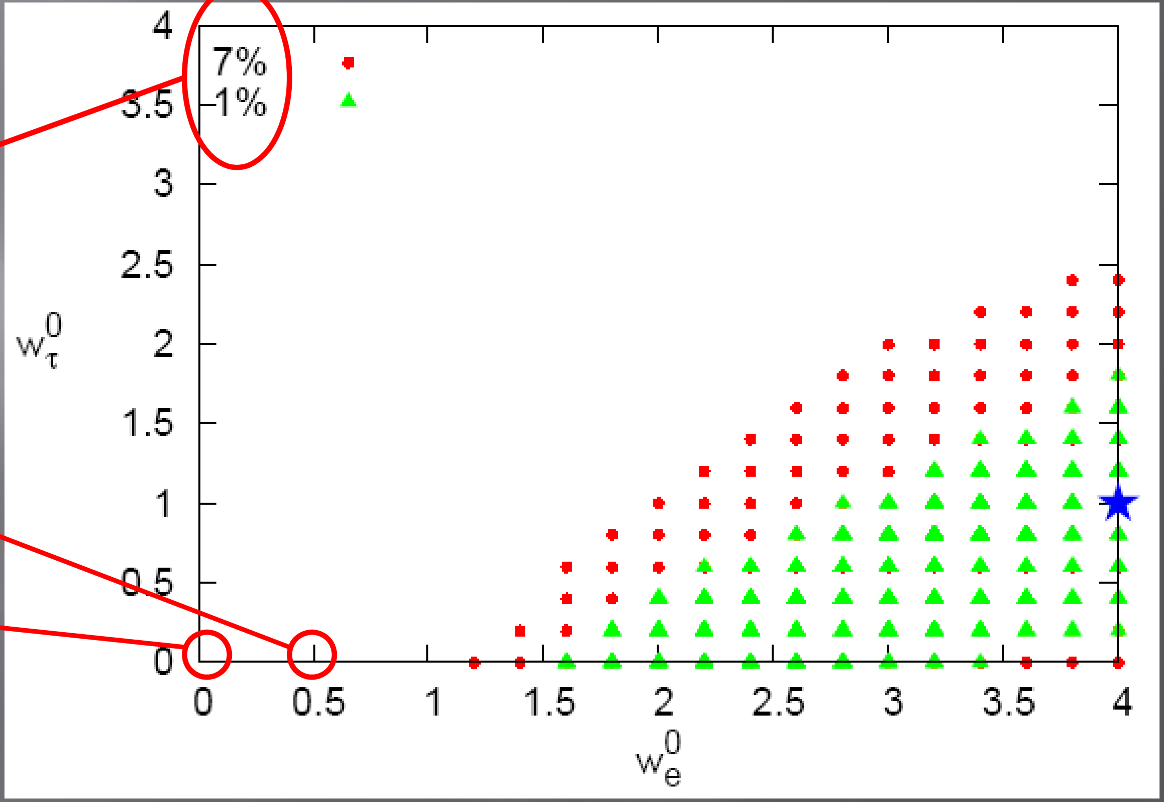
Exotic Source 4 : 1 : 1

$$w_e^0 : w_\mu^0 : w_\tau^0 = w_e^0 : 1 : w_\tau^0$$

Uncertainty in the measurement of ***R***

Pion Source

Stopped-Muon Source



$\sin^2\theta_{13} \in (0, 0.003)$

$\delta \in (0, 2\pi)$

$\alpha \in (1.8, 2.2)$

$N_{\bar{\nu}_e}/N_{\nu_e} \in (0, 1)$

♠ By 7 % precision in the measurement of ***R*** , the 4:1:1 source can be completely distinguished from the Pion and Stopped-muon sources