“Search for sterile neutrino mixing using three years of IceCube DeepCore data”

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arXiv:1702.05160 [hep-ex], 16 February 2017

For Journal Club 13, April 21, 2017

What is Sterile neutrino ?

It is beyond my capacity to clearly answer it, I pick up here the sentences from a reference

"Sterile Neutrinos: An Introduction to Experiments"
J. M. Conrad and M. H. Shaevitz, arXiv:1609.07803 [hep-ex]

" Right-handed neutrinos would be weak isospin singlets with no weak interactions except through mixing with the left-handed neutrinos. For this reason, the right-handed neutrinos are referred to as sterile neutrinos "

" the sterile neutrino is more broadly defined as a neutral lepton with no ordinary weak interactions except those induced by mixing. "

A two neutrino oscillation model

-- simple model to explain the oscillation --

・The flavor eigenstates (α, β = e, μ, τ) can be written as a function of the mass eigenstate

$$|\nu_\alpha> = \sum_j U_{\alpha j} |\nu_j>$$

or concretely

$$\begin{aligned} |\nu_e> &= \cos\theta |\nu_1> + \sin\theta |\nu_2> \\ |\nu_\mu> &= -\sin\theta |\nu_1> + \cos\theta |\nu_2> \end{aligned}$$

・Since each mass eigenstates propagate with different frequency as bellow :

$$|\nu_\alpha(t)> = \sum_j U_{\alpha j} |\nu_j> e^{-iE_j t}, \quad E_j = \sqrt{p^2 + m_j^2} \simeq p + \frac{m_j^2}{2E}$$

This is different in each

As a result, the probability to change the flavor can be calculated as :

$$\begin{cases} P(\nu_e \to \nu_\mu; t) = |<\nu_\mu|\nu_e(t)>|^2 = |\sin\theta\cos\theta(1 - e^{-i(E_1-E_2)t})|^2 \\ \qquad = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} L \quad = \sin^2 2\theta \sin^2 1.27 \frac{\Delta m^2 (eV)^2}{E(GeV)} L(km) \\ \Delta m^2 = |m_1^2 - m_2^2|, \quad L = ct \end{cases}$$

The oscillation wavelength

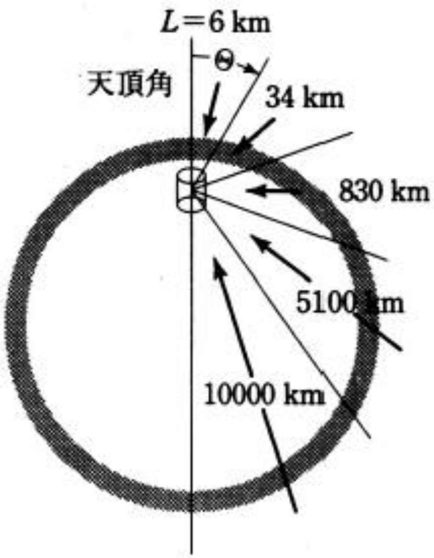
This mixing angle term decides the oscillation amplitude

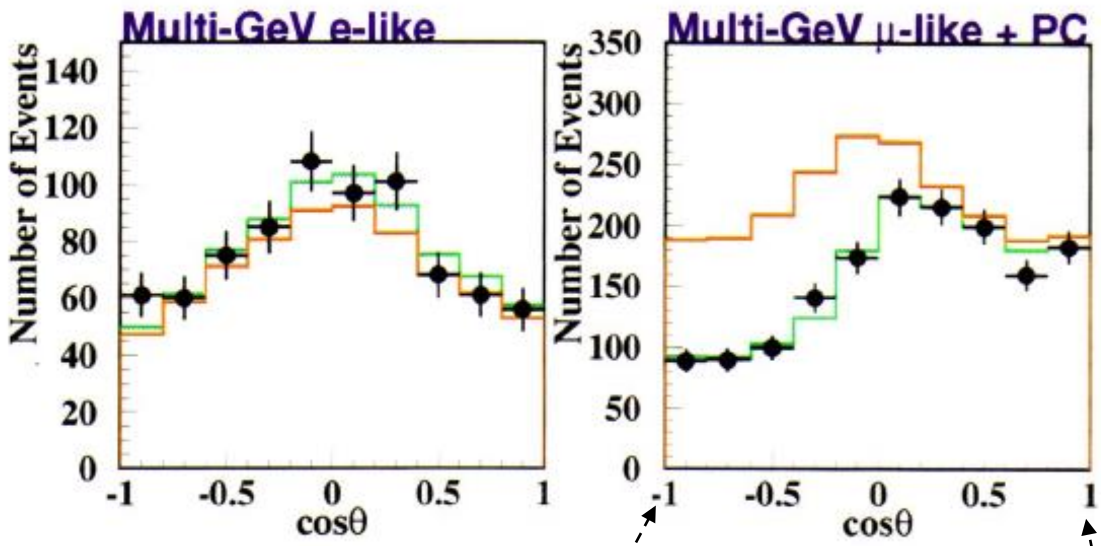
$$\Delta m^2 L/E \sim 1$$

can maximize the oscillation

(Example)   result from SK (Super-Kamiokande experiment)

In 1998





L ~ 12000km

L ~ 15km

Orange line : wo oscillation

Green line : w oscillation

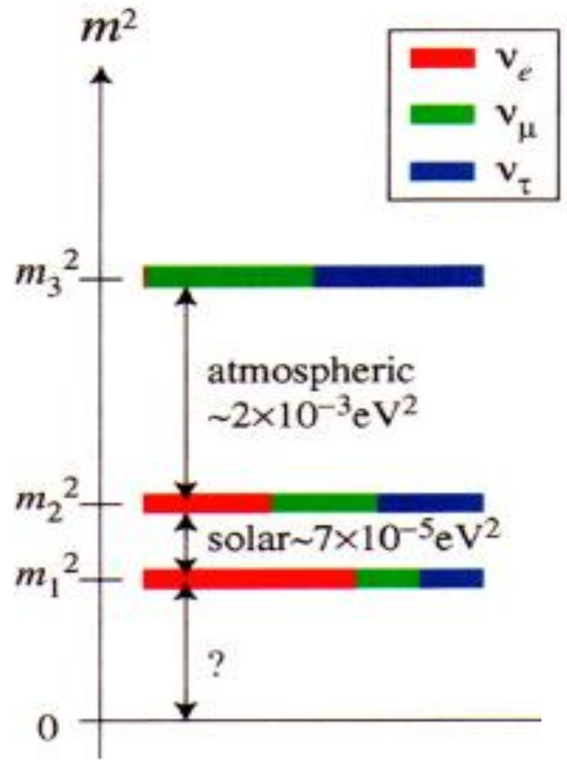
$$\sin^2 2\theta_{atm} \simeq 1, \quad \Delta m^2_{atm} \simeq 2 \times 10^{-3} eV^2$$

A three neutrino oscillation case , , ,

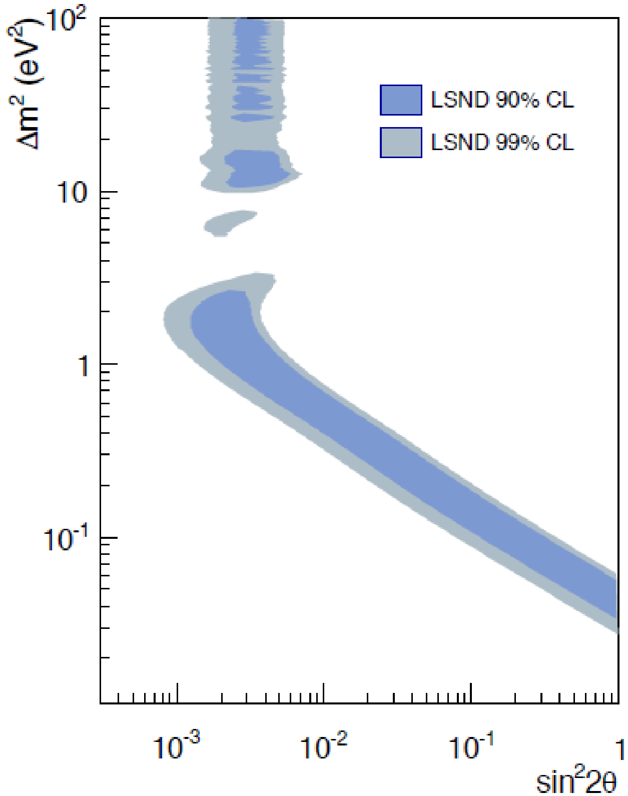
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = V_{PMNS} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

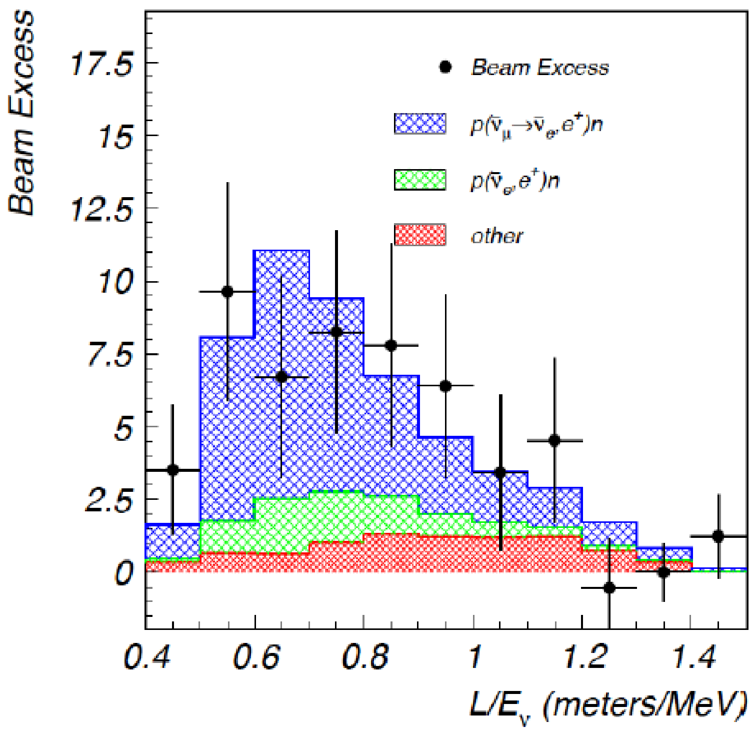
$$V_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\begin{cases} \theta_{atm} & = \theta_{23} \simeq \frac{\pi}{4} \\ \Delta m^2_{atm} & = |\Delta m^2_{23}| \simeq |\Delta m^2_{13}| \simeq \underline{2 \times 10^{-3} eV^2} \\ \theta_\odot & = \theta_{12} = 32.5^{\circ}{}^{+2.4}_{-2.3} \\ \Delta m^2_\odot & = |\Delta m^2_{12}| = \underline{7.1^{+1.2}_{-0.6} \times 10^{-5} eV^2} \\ |s_{13}| & < 0.18 \end{cases}$$



LSND (the Liquid Scintillator Neutrino Detector) excess indicating possible $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance

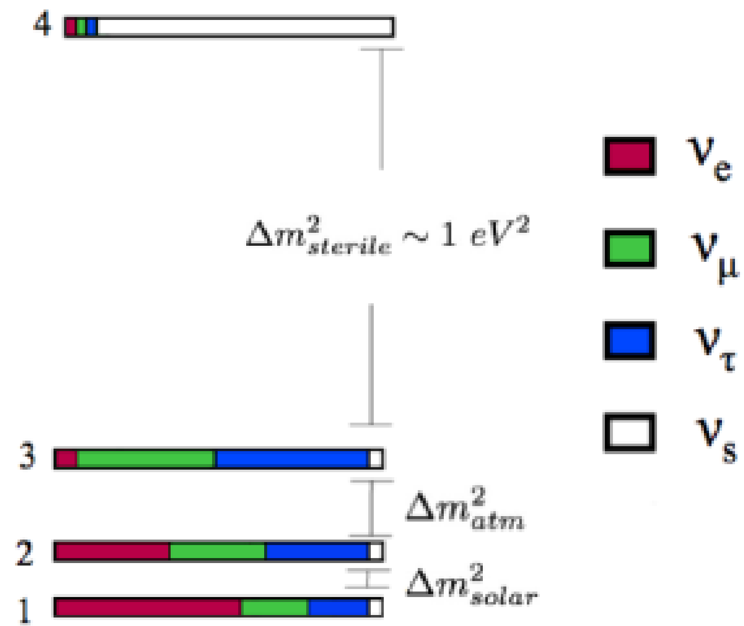




A. Aguilar-Arevalo *et al.* [LSND Collaboration], "Evidence for neutrino oscillations from the observation of anti-neutrino(electron) appearance in a anti-neutrino(muon) beam," Phys. Rev. D **64**, 112007 (2001) [hep-ex/0104049].

Beyond a three neutrino model ?

$$U_{3+1} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ \vdots & & \vdots & U_{\mu 4} \\ \vdots & & \vdots & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$



But , we know the precise measurements of the Z^0 width at LEP, which determined that there are only three generations of light-mass weakly-interacting neutrinos.

Motivation of the 4th but not weakly-interacting neutrino = sterile

Reference : Allowed regions for 3+1 scheme

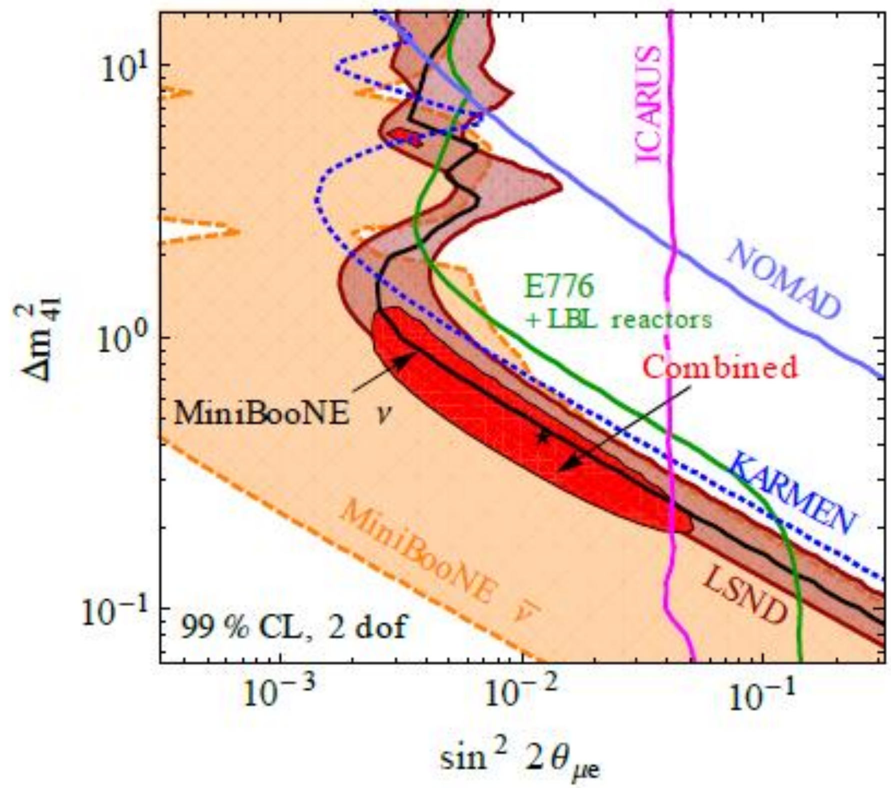
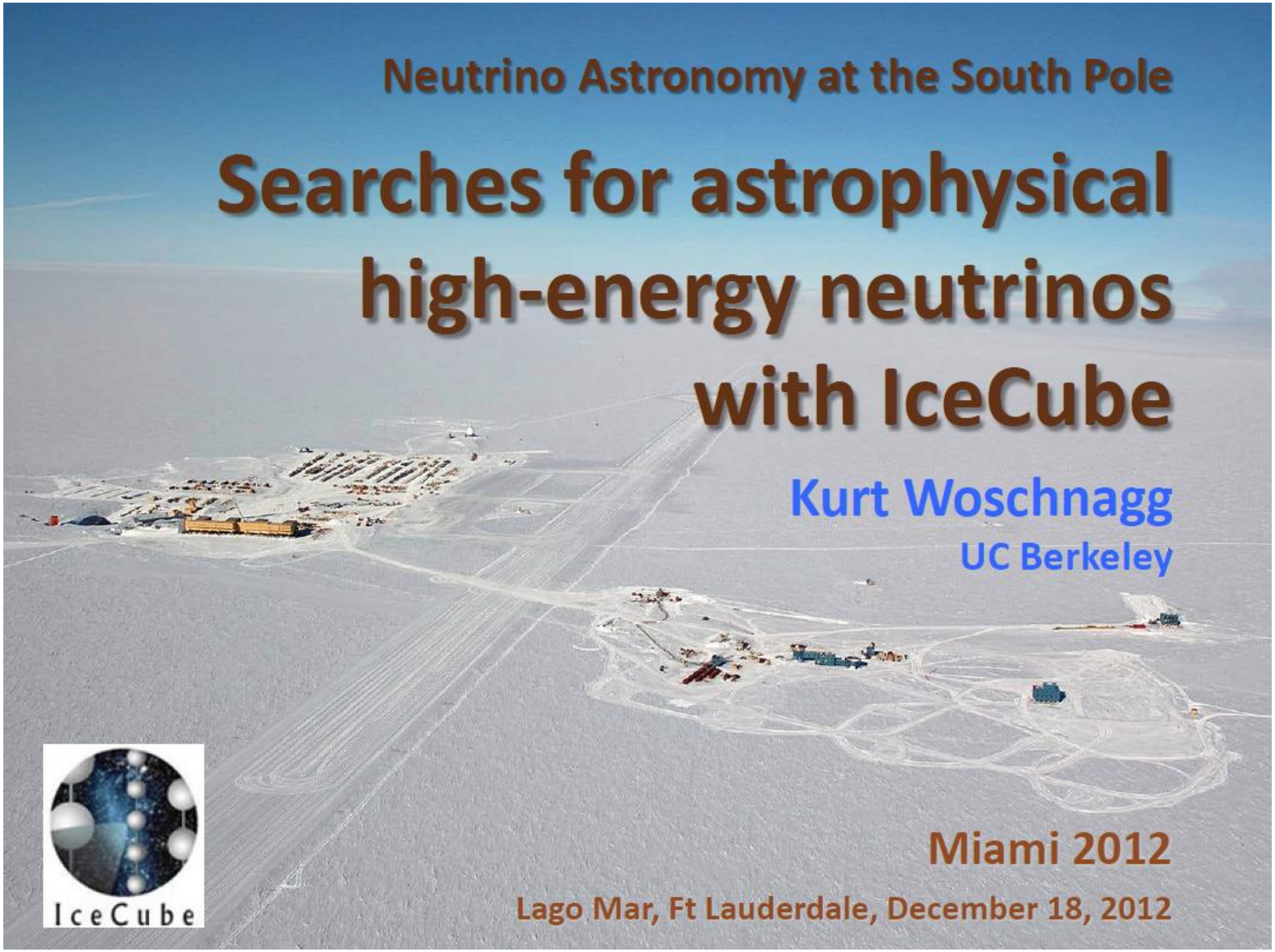
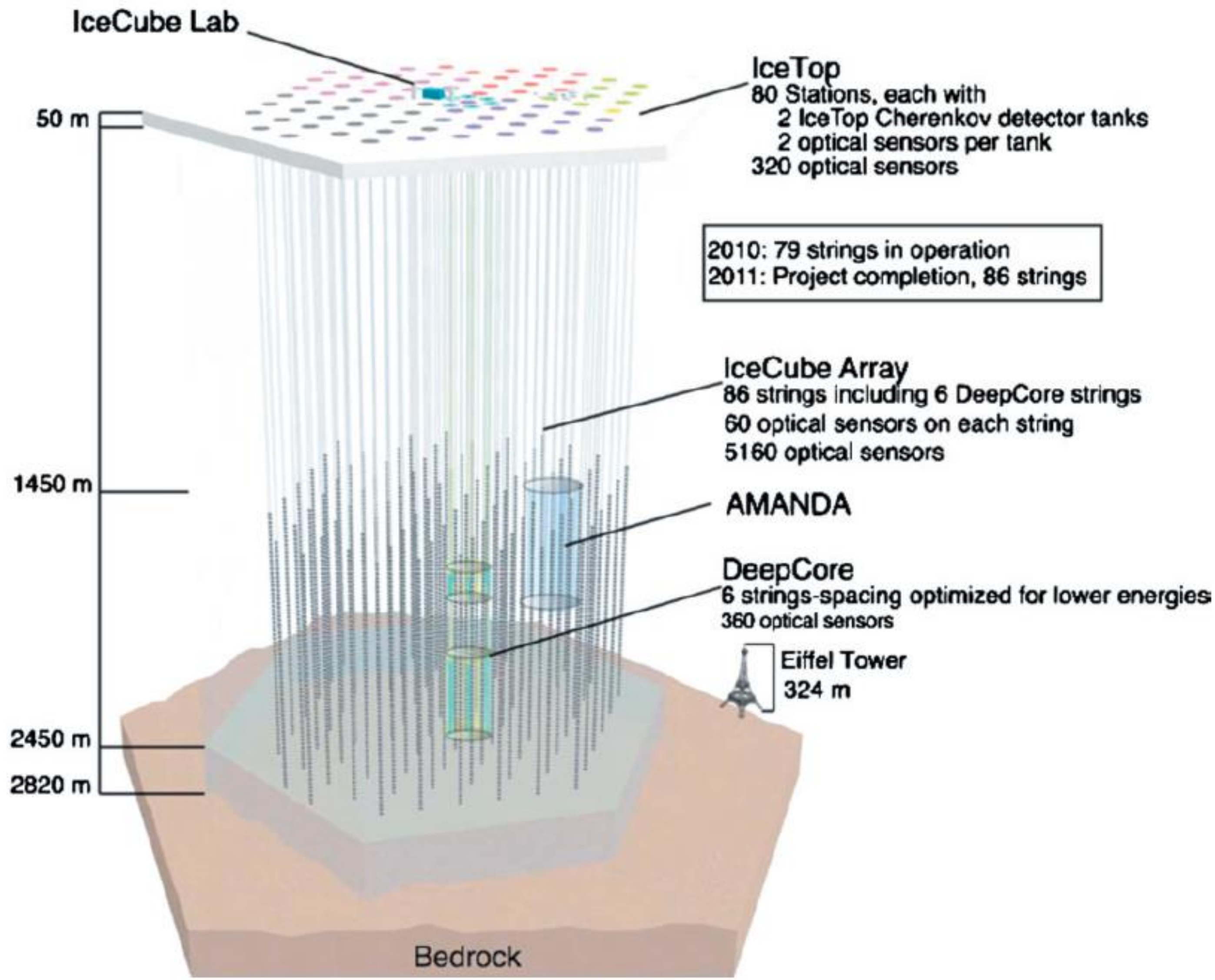


Figure 9: Allowed regions and upper bounds at 99% CL (2 dof) for muon to electron flavor appearance experiments in the 3+1 scheme. The red region corresponds to a combined fit of all $\nu_\mu \to \nu_e$ appearance data sets, with the star indicating the best fit point. (From Ref. [39])

[39] J. Kopp, P. A. N. Machado, M. Maltoni and T. Schwetz, JHEP **1305**, 050 (2013) [arXiv:1303.3011 [hep-ph]].

IceCube

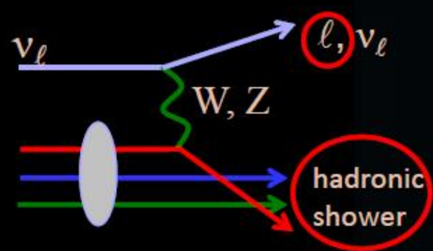

Neutrino Astronomy at the South Pole
Searches for astrophysical high-energy neutrinos with IceCube
Kurt Woschnagg
UC Berkeley
Miami 2012
Lago Mar, Ft Lauderdale, December 18, 2012
IceCube



Conceptual design of a large neutrino detector

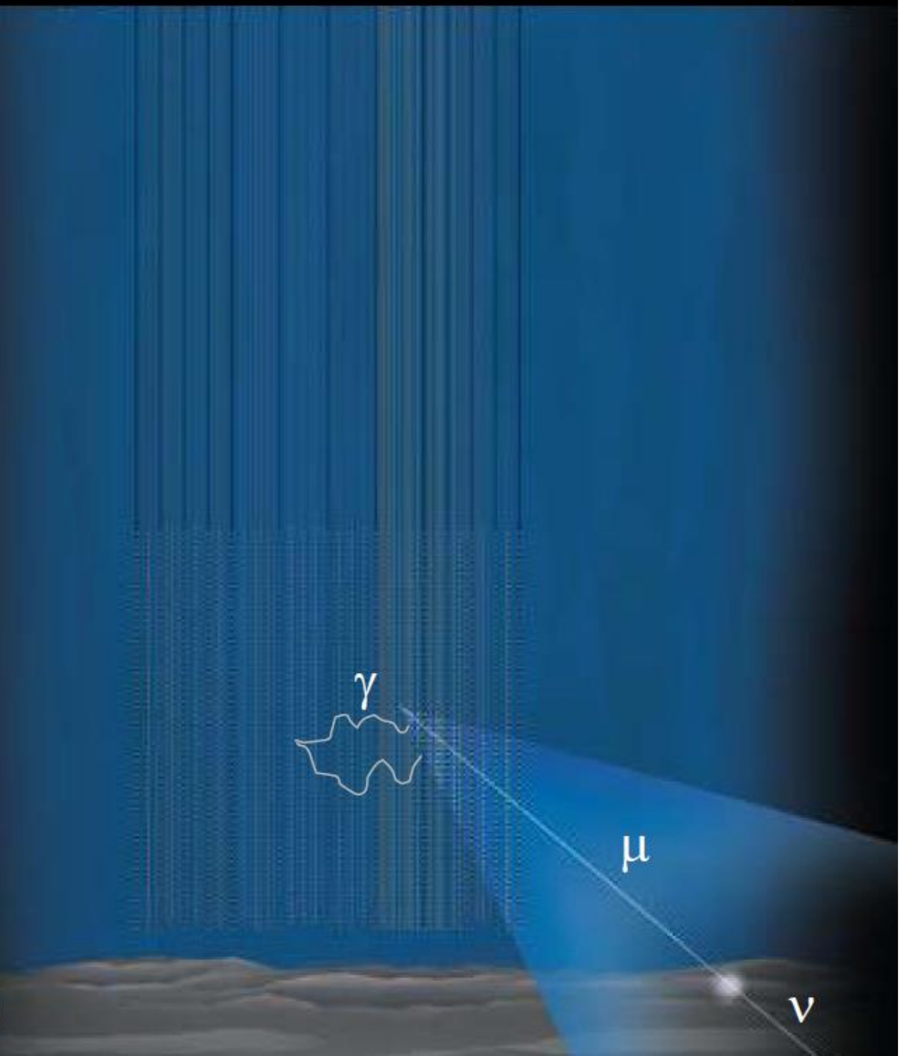
Neutrino Detection Principle

Observe the charged *secondaries* via Cherenkov radiation detected by a 3D array of optical sensors



Need a huge volume (km^3) of an optically transparent detector material

Antarctic ice is the most optically transparent natural solid known (absorption lengths up to 200+ m)



DeepCore

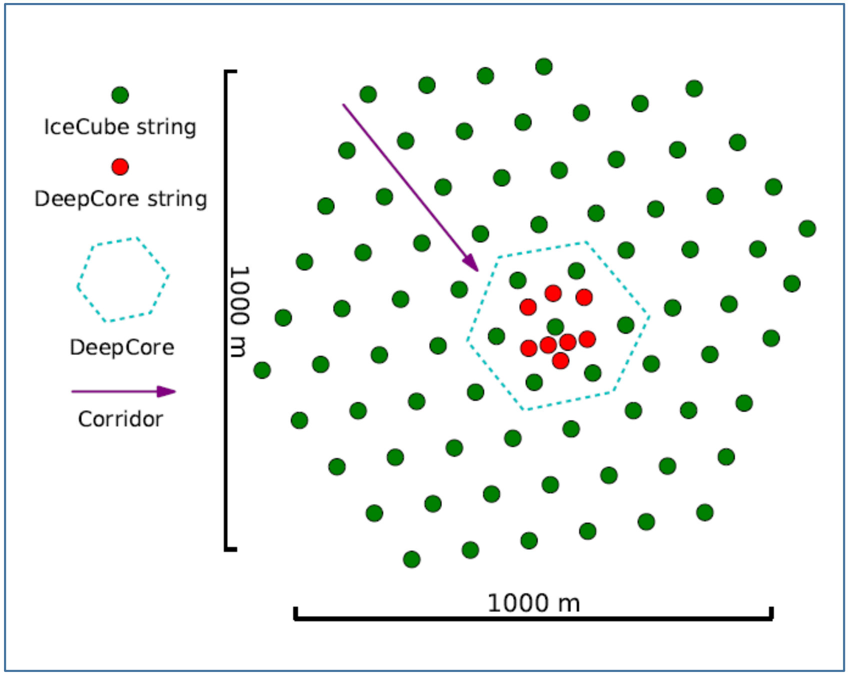


Fig 2. Top view of IceCube

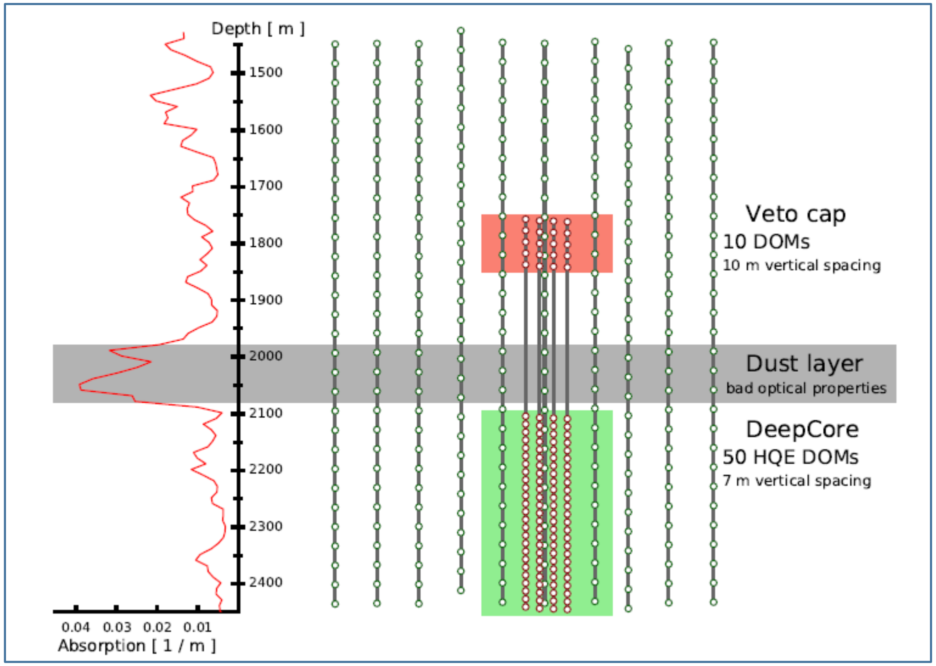


Fig 3. Side view of IceCube

Sterile neutrino hypothesis and observation

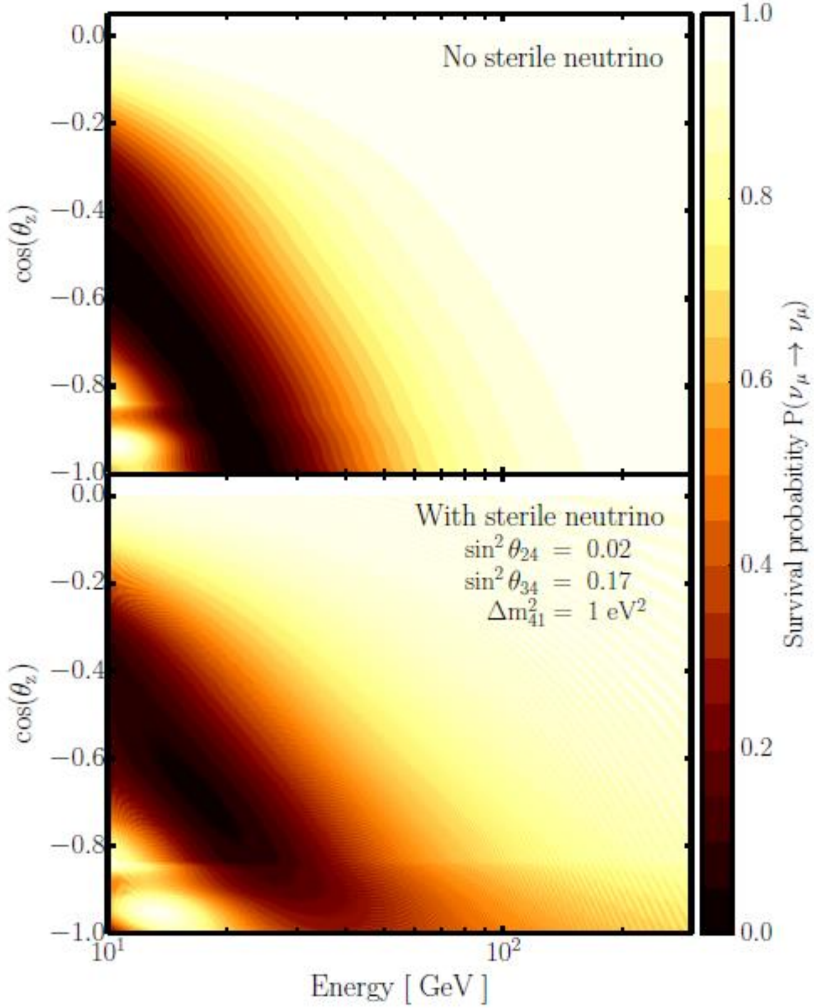


FIG. 1. The muon neutrino survival probability for (top) the standard three neutrino oscillations and (bottom) "3+1" sterile neutrino model as function of true muon neutrino energy and the cosine of the true neutrino zenith angle θ_z. Values $\Delta m^2_{32} = 2.51 \cdot 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.51$ are assumed for the standard atmospheric mixing parameters.

Fig 1. muon neutrino survival probability

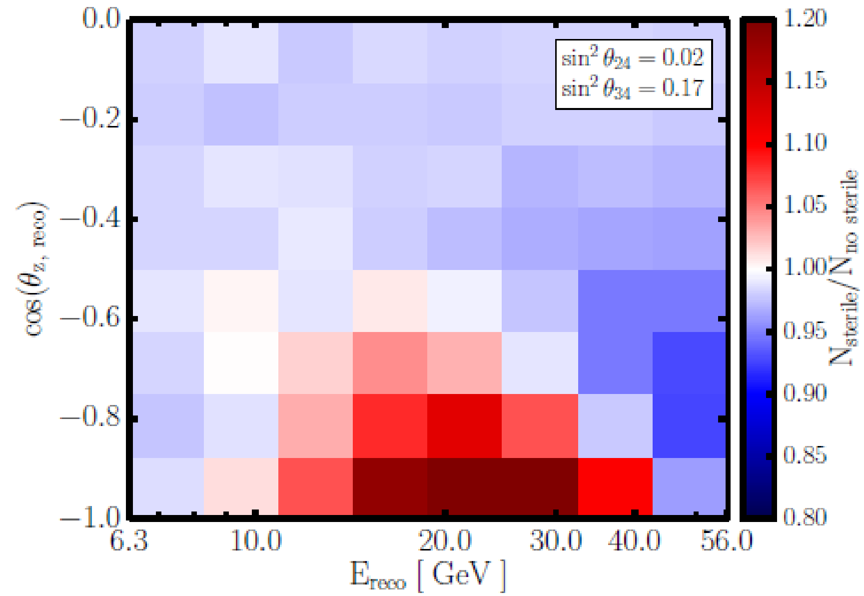


FIG. 5. The ratio of the expected event counts for a sterile neutrino hypothesis and the case of no sterile neutrino. Sterile neutrino mixing parameters $\sin^2\theta_{24} = 0.02$ and $\sin^2\theta_{34} = 0.17$ are assumed. The values $\Delta m^2_{32} = 2.52 \cdot 10^{-3}$ eV^2 and $\sin^2\theta_{23} = 0.51$ are assumed for the standard atmospheric mixing parameters. Both expectations are normalized to the same total number of events.

Fig 5. ratio of the expected event counts for sterile neutrino hypothesis

Comparison the data with expectation

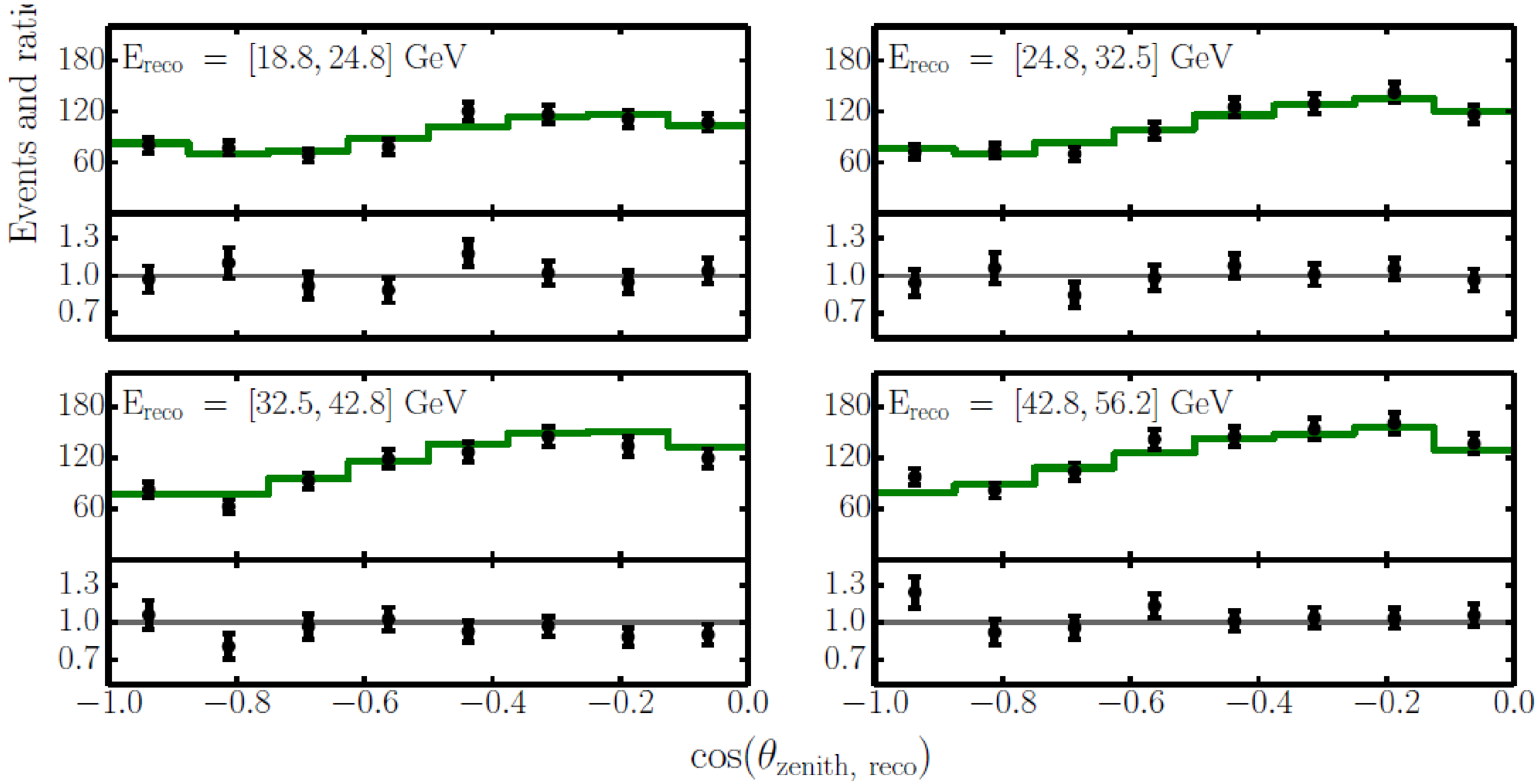


FIG. 6. The comparison of the data (black dots) and the expectation at the best fit point for the bins used in the analysis. The expectation at the best fit includes a full calculation of the oscillation probabilities for the "3+1" model, impact of systematic uncertainties and background.

(I think) the "3+1" model is expected here, therefore, the shape of the green line is also constrained during the fitting.

2D significance map

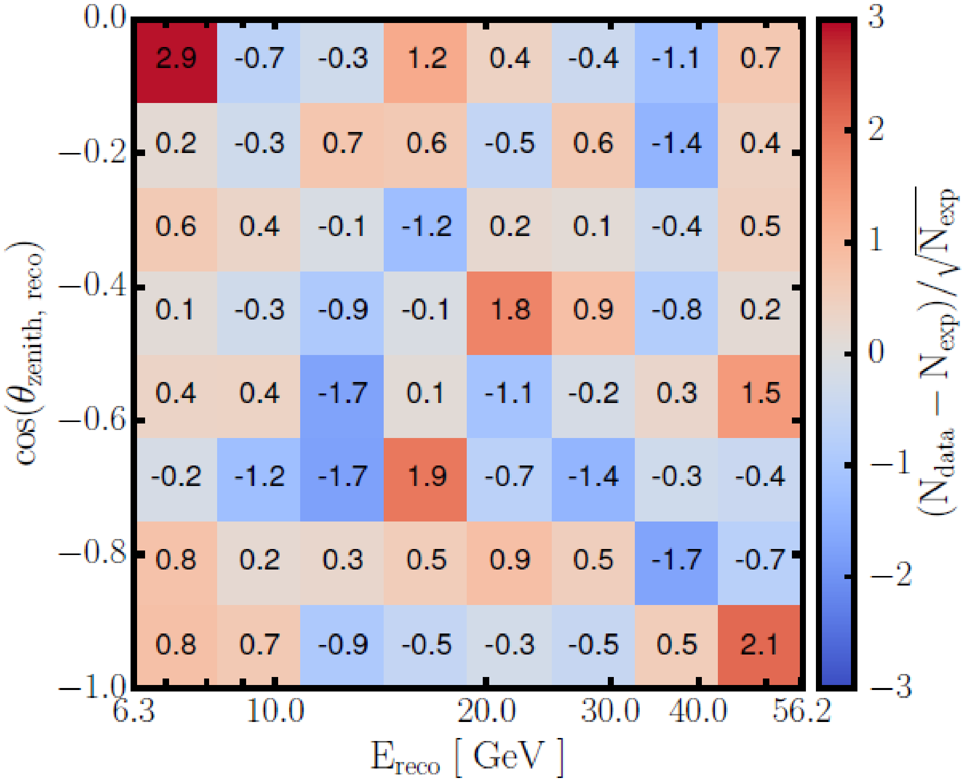
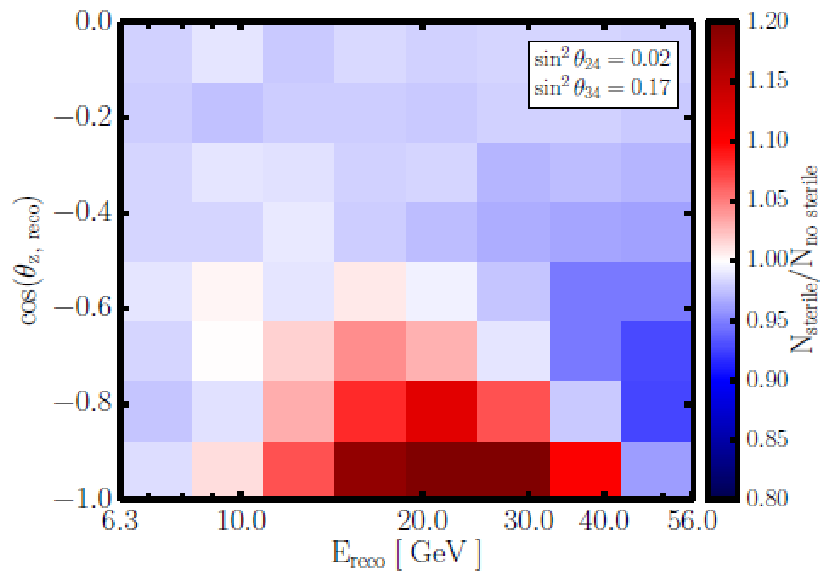


FIG. 7. Statistical pulls between data and expectation for the best fit point.



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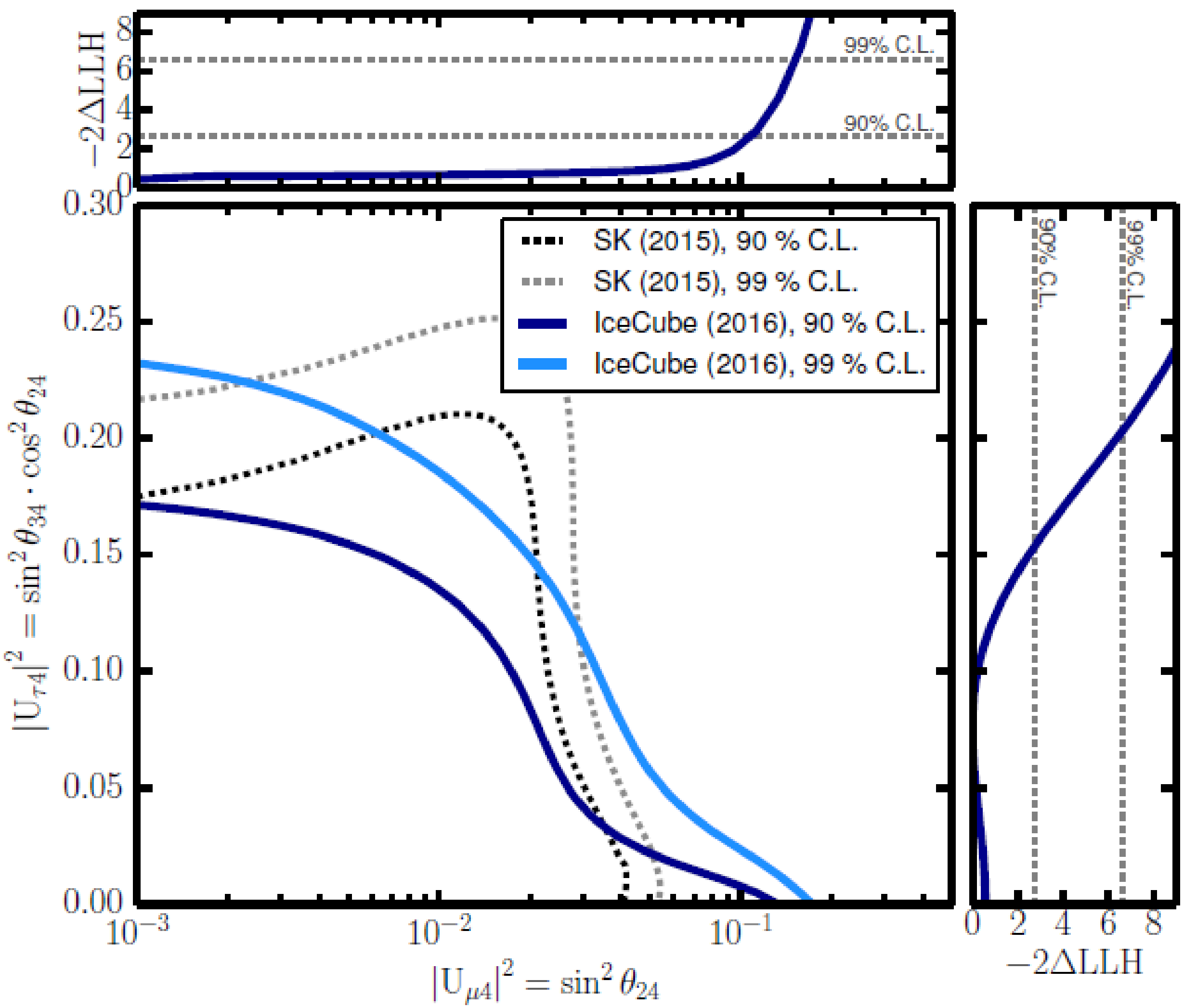
Exclusion Limit



Summary

-- The search of sterile neutrino (3+1) model with DeepCore detector at IceCube presented a exclusion limits on mixiing angle space.

-- The value of Δm_{41} is fixed at 1.0 eV during the study, and it is almost no impact on the exclusion limit.

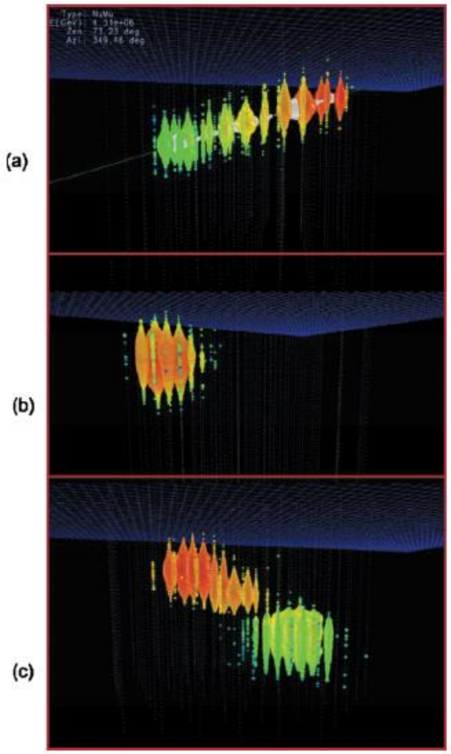
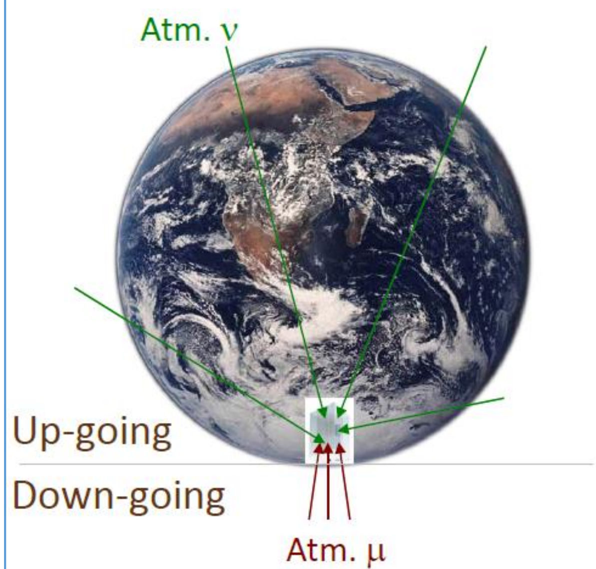


FIG. 22. (Color) Simulated events of the three types of neutrino interactions in IceCube: (a) $\nu_\mu N \rightarrow \mu X$ (top), (b) $\nu_e N \rightarrow$ cascade (middle), and (c) a double bang, from $\nu_\tau N \rightarrow \tau$ cascade$_1 \rightarrow$ cascade$_1$cascade$_2$ (bottom). Each circle represents one active optical module; the size of the circles shows the number of detected photons, while the color represents the time, from red (earliest) to blue (latest). In the top panel, the white shows the stochastic muon energy deposition along its track (Ref. 14).

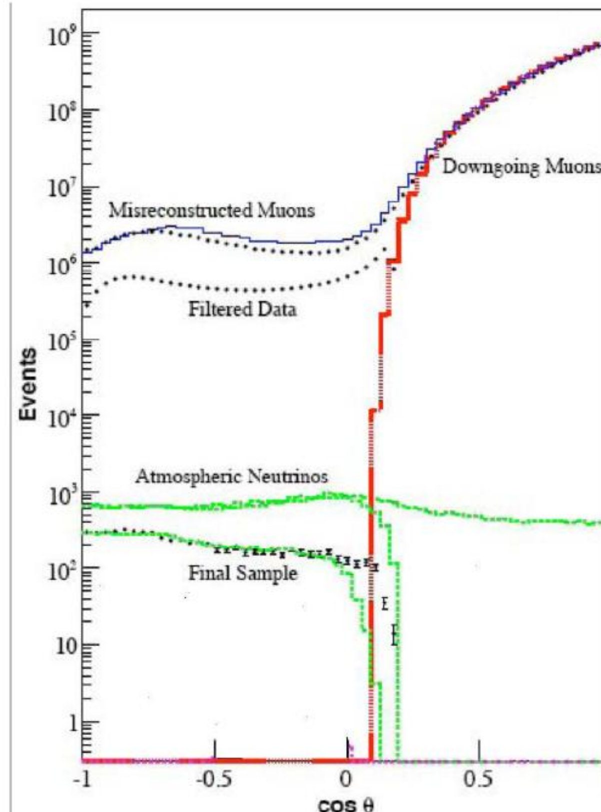
Background Rejection



Muons: 2800 Hz

Neutrinos: 1 per 10 min

Need 10^6 background rejection



IceCube Construction