Search for sterile neutrinos by IceCube shower events

Yabin Wang & Osamu Yasuda

Tokyo Metropolitan University

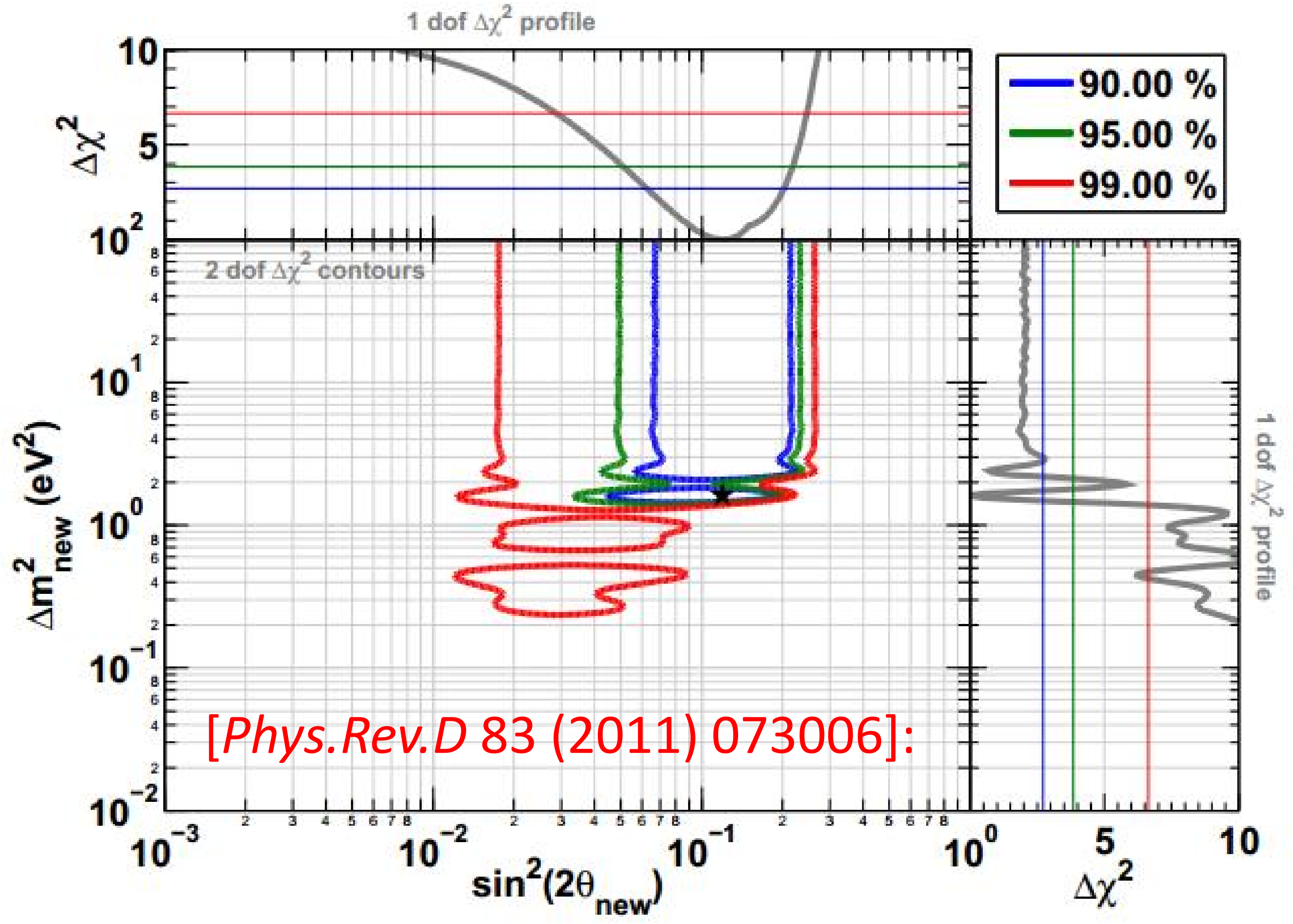
2022/03/08

Part 1. Research Background

- 1.1 Motivation: Reactor neutrino anomaly & gallium neutrino anomaly

Sterile neutrino with

$\Delta m^2 = O(1)\ eV^2$?



[*Phys.Rev.D* 83 (2011) 073006]:

Part 1. Research Background

- 1.2 Advantage of searching for sterile neutrinos at IceCube

Condition of maximal oscillation: $\frac{\pi}{2} = 1.27 \frac{(\Delta m^2/eV^2)\cdot(L/m)}{(E/MeV)}$ for e.g., $\Delta m^2 = 10\ eV^2$:

Reactor neutrino : $E = 4\ MeV$

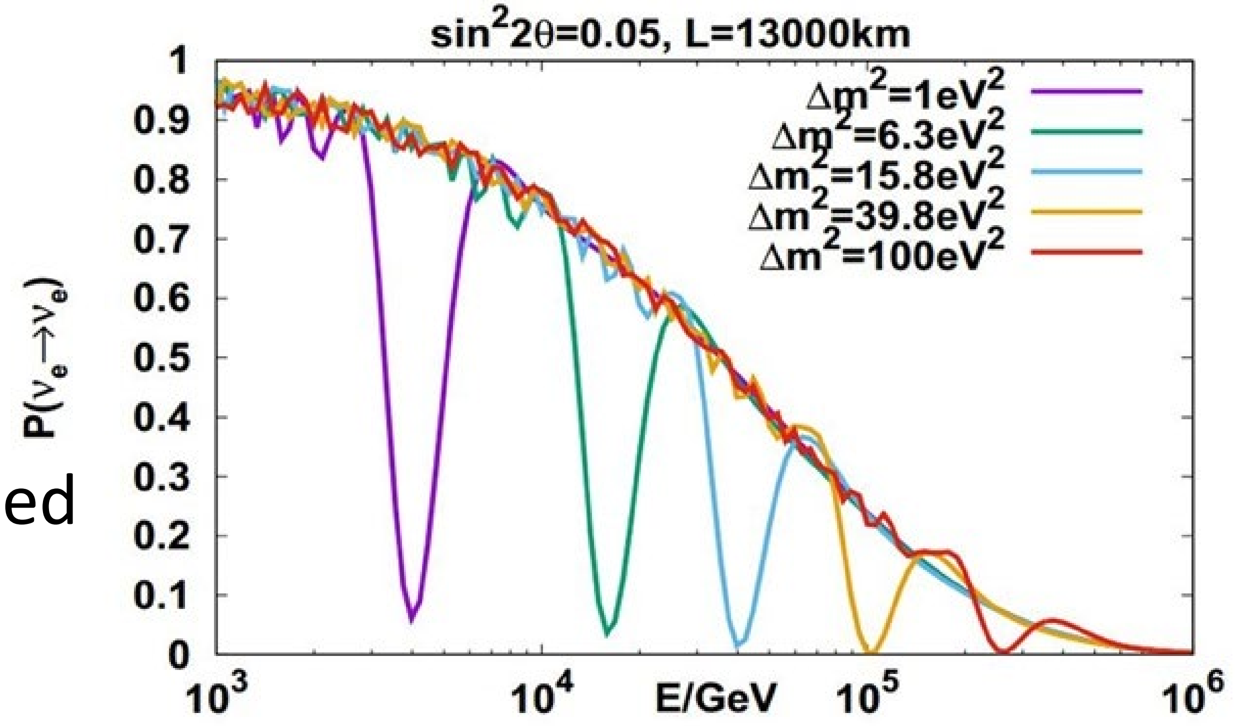
- $L \simeq 0.5\ m$ → L is too short to see the oscillation pattern
- Mixing angle θ_{14} in vacuum is probably too small to see

IceCube : $E = 10\ TeV$

Mixing angle θ_{14} in matter:

$$\tan 2\tilde{\theta}_{14} = \frac{\Delta m^2 \cdot \sin 2\theta_{14}}{\Delta m^2 \cdot \cos 2\theta_{14} - 2AE}$$

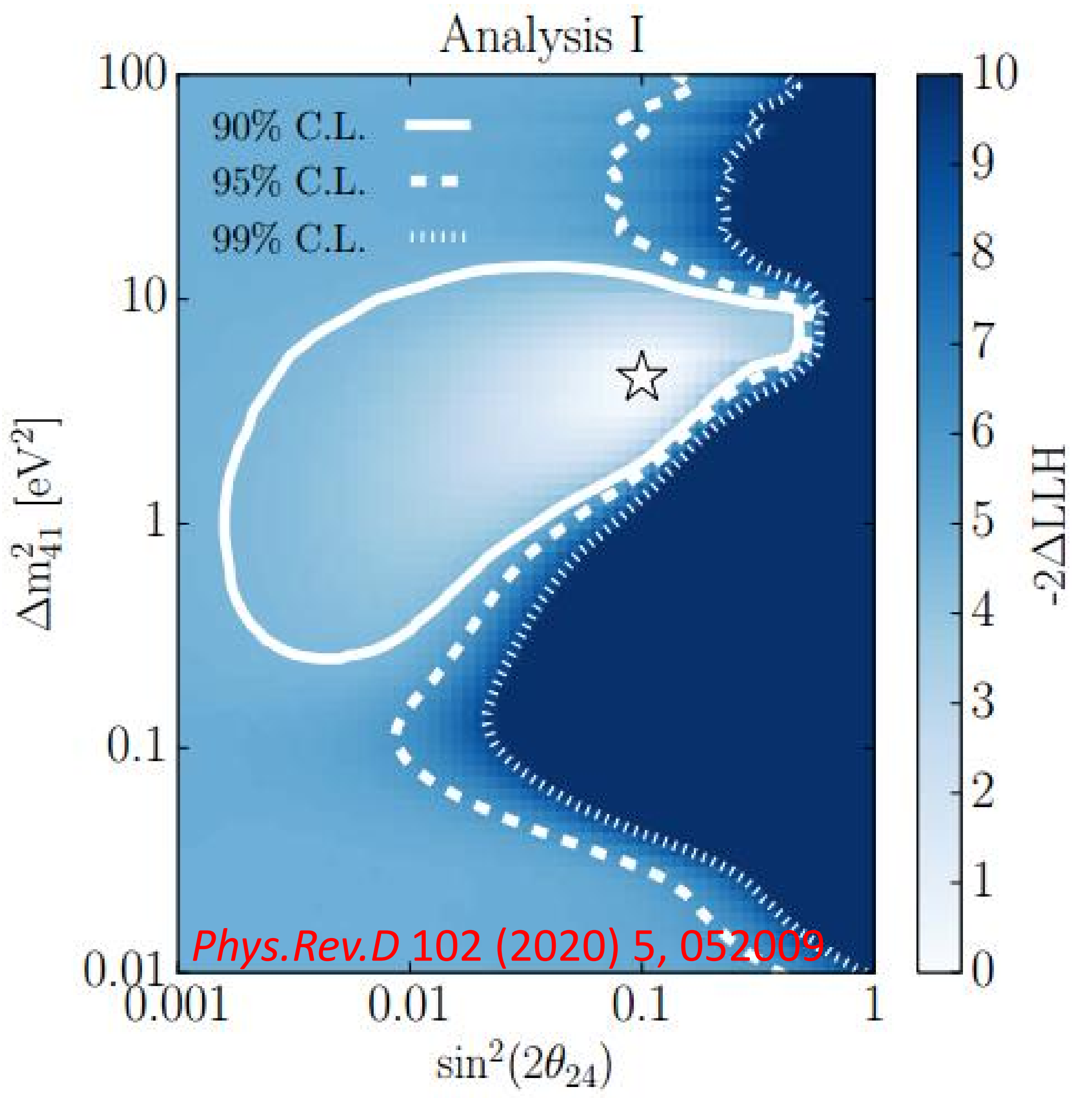
Because of matter effect, even though θ_{14} in vacuum is small, $\tilde{\theta}_{14}$ can be enhanced
→ Maybe possible to see the dip
in disappearance channel $\nu_e \rightarrow \nu_e$.



Part 1. Research Background

- 1.2 Advantage of searching for sterile neutrinos at IceCube

In the case of $\nu_\mu \rightarrow \nu_\mu$, this was done using track events by IceCube Collaboration (Phys. Rev. D 102 (2020) 052009).



Part 1. Research Background

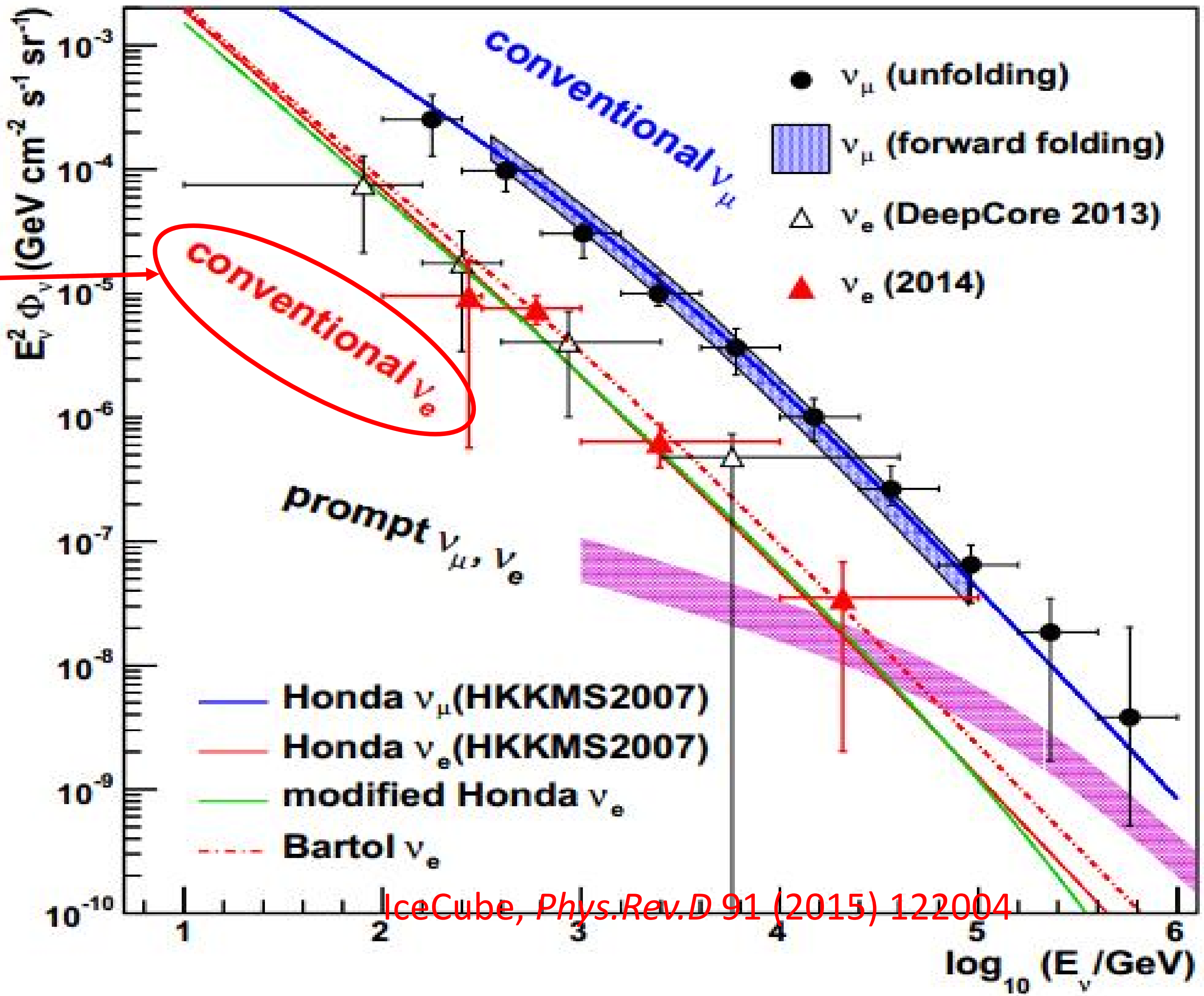
- 1.3 Challenge of sterile neutrino search with shower events at IceCube

This work: instead of **track** events, we use atmospheric ν_e (**shower** events) to study the oscillation $\nu_e \rightarrow \nu_e$.

Problem with atmospheric ν_e : (conventional) atmospheric neutrino flux of $\nu_e + \overline{\nu}_e$ is much smaller than that of $\nu_\mu + \overline{\nu}_\mu$:

$$(\nu_\mu + \overline{\nu}_\mu):(\nu_e + \overline{\nu}_e) \cong 30 : 1$$

→ We have to assume a possible future extension of IceCube with larger volume to gain statistics.



IceCube, *Phys.Rev.D* 91 (2015) 122004

Part 1. Research Background

- 1.4 (3+1) scheme

We adopt (3+1) scheme: $$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \left[U\begin{pmatrix}0 & 0 & 0 & 0\\ 0 & \Delta E_{21} & 0 & 0\\ 0 & 0 & \Delta E_{31} & 0\\ 0 & 0 & 0 & \Delta E_{41}\end{pmatrix}U^{-1} + \begin{pmatrix}A_e & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & -A_n\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}$$

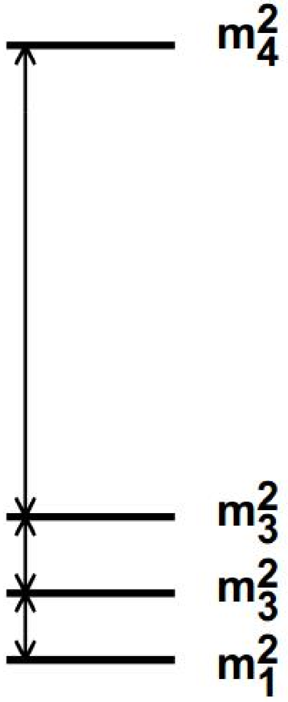
$U = R(\theta_{34}, \delta_{34}) \cdot R(\theta_{24}, \delta_{24}) \cdot R(\theta_{14}, 0) \cdot R(\theta_{23}, 0) \cdot R(\theta_{13}, \delta_{13}) \cdot R(\theta_{12}, 0)$,

$\Delta E_{jk} = \Delta m_{jk}{}^2/(2E)$, $A_e = \sqrt{2}G_F N_e$, and $A_n = -G_F N_n/\sqrt{2}$. We assume $N_e = N_n$.

For simplicity, here we consider the case where $\theta_{24} = \theta_{34} = 0$ and the only nonzero sterile mixing angle is θ_{14} .

For ν_{atm} with $E \gtrsim 1\ \text{TeV}$, we can approximately assume $\Delta E_{21} = \Delta E_{31} = 0$ because $|\Delta m_{21}^2/2E| \ll 1$, $|\Delta m_{31}^2/2E| \ll 1$.

For ν_{ast} with astronomical baseline length, all ΔE_{jk} contribute to the oscillation probability.



Part 2. The method of analysis

- 2.1 Setup

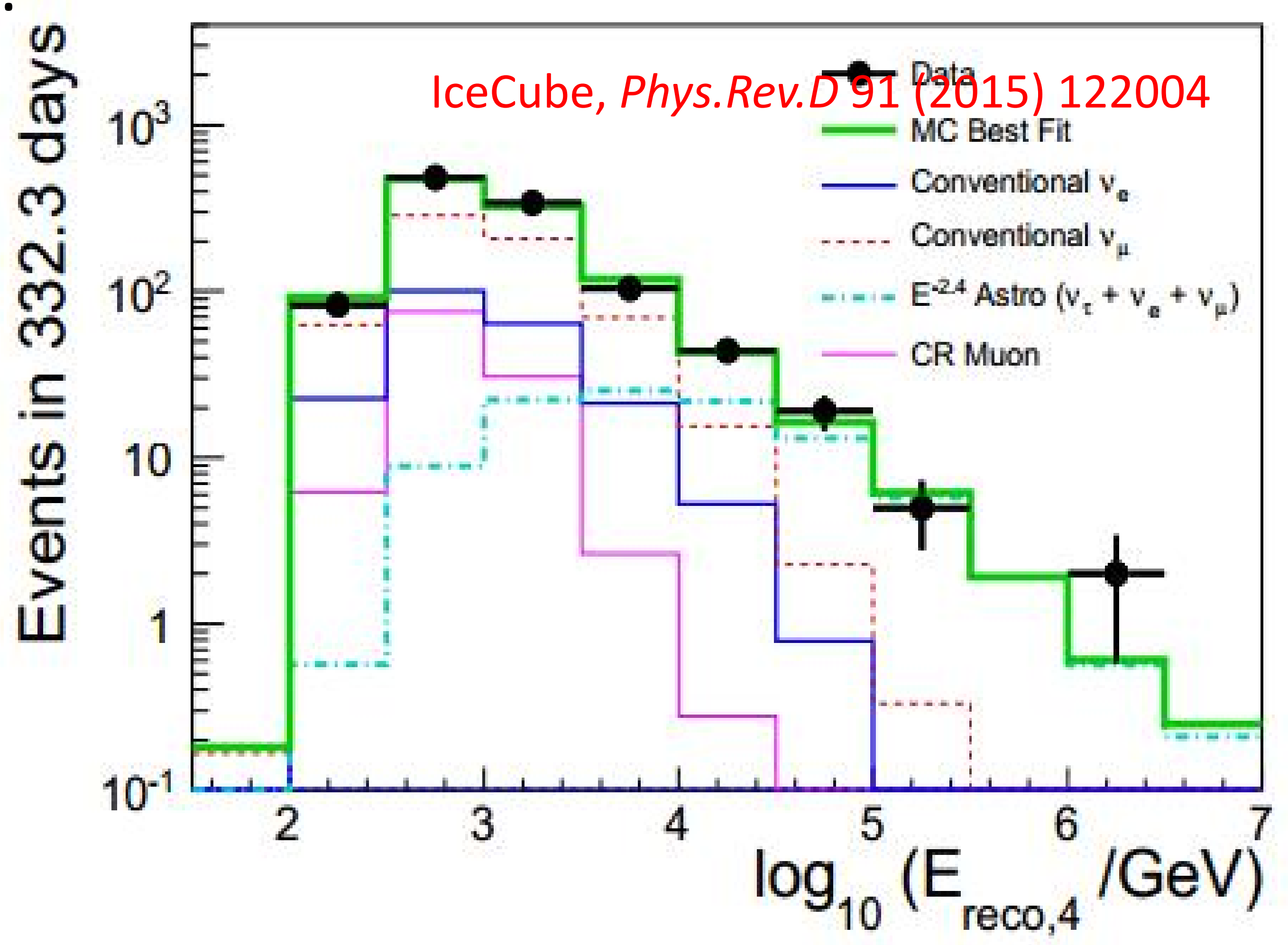
We assume the result of ν_e observation by IceCube [*Phys.Rev.D* 91 (2015) 122004].

Shower events: conventional atmospheric neutrinos ($\nu_{\rm atm}$; $\nu_e + \bar{\nu}_e$ and some fraction of $\nu_\mu + \bar{\nu}_\mu$)

astrophysical neutrinos ($\nu_{\rm ast}$) and

CR-μ BG.

We assume no prompt neutrinos for simplicity.



Part 2. The method of analysis

- 2.2 Definition of χ^2

$$\chi_0^2 \equiv 2\sum_{jk}\left[Y_{jk} - N_{jk} - N_{jk}\log\left(\frac{Y_{jk}}{N_{jk}}\right)\right],$$

$$Y_{jk} \equiv (1+\alpha)N_{jk}^{atm}(osc) + (1+\beta)N_{jk}^{cosmic-ray\,\mu}$$

$$+(1+\gamma)N_{jk}^{ast}(osc),$$

$$N_{jk} \equiv N_{jk}^{atm}(no-osc) + N_{jk}^{cosmic-ray\,\mu} + N_{jk}^{ast}(no-osc).$$

$$\chi_1^2(\alpha,\beta,\gamma) = \chi_0^2 + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2 + \left(\frac{\gamma}{\sigma_\gamma}\right)^2,$$

$$\chi^2 = min_{(\alpha,\beta,\gamma)}\chi_1^2(\alpha,\beta,\gamma).$$

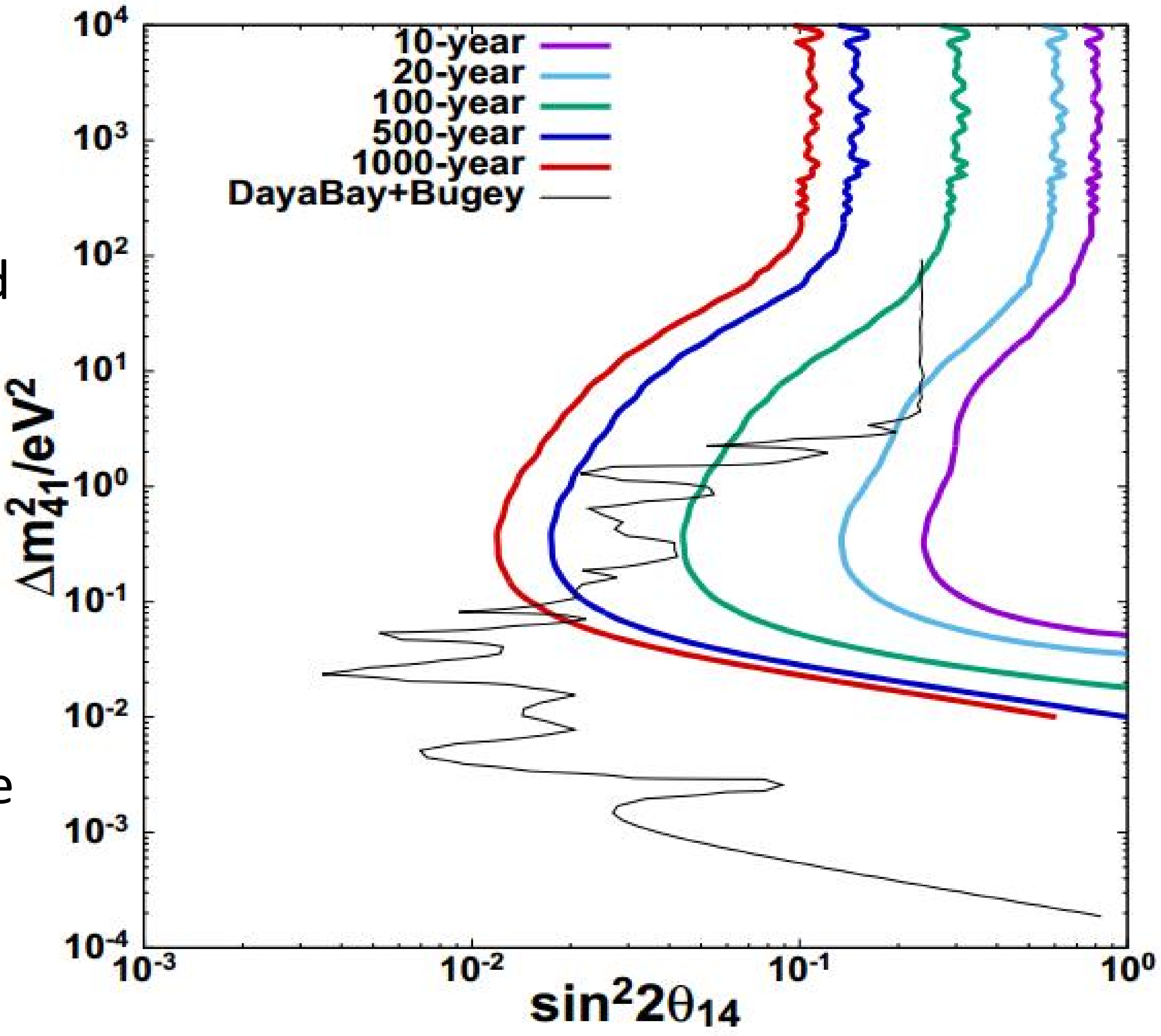
σ_α , σ_β, σ_γ : systematic errors ($\sigma_\alpha = \sigma_\beta = \sigma_\gamma = 0.4$)

Part 3. Results and Discussion

- 3.1 Sensitivity

Compared to Daya Bay+Bugey, sensitivity to θ_{14} can be improved for $1\ eV^2 < \Delta m^2 < 100\ eV^2$, if we have 100 years of number of events.

→ Volume of IceCube should be extended at least 10 times as large as that of the present one assuming the measurement for 10 years.



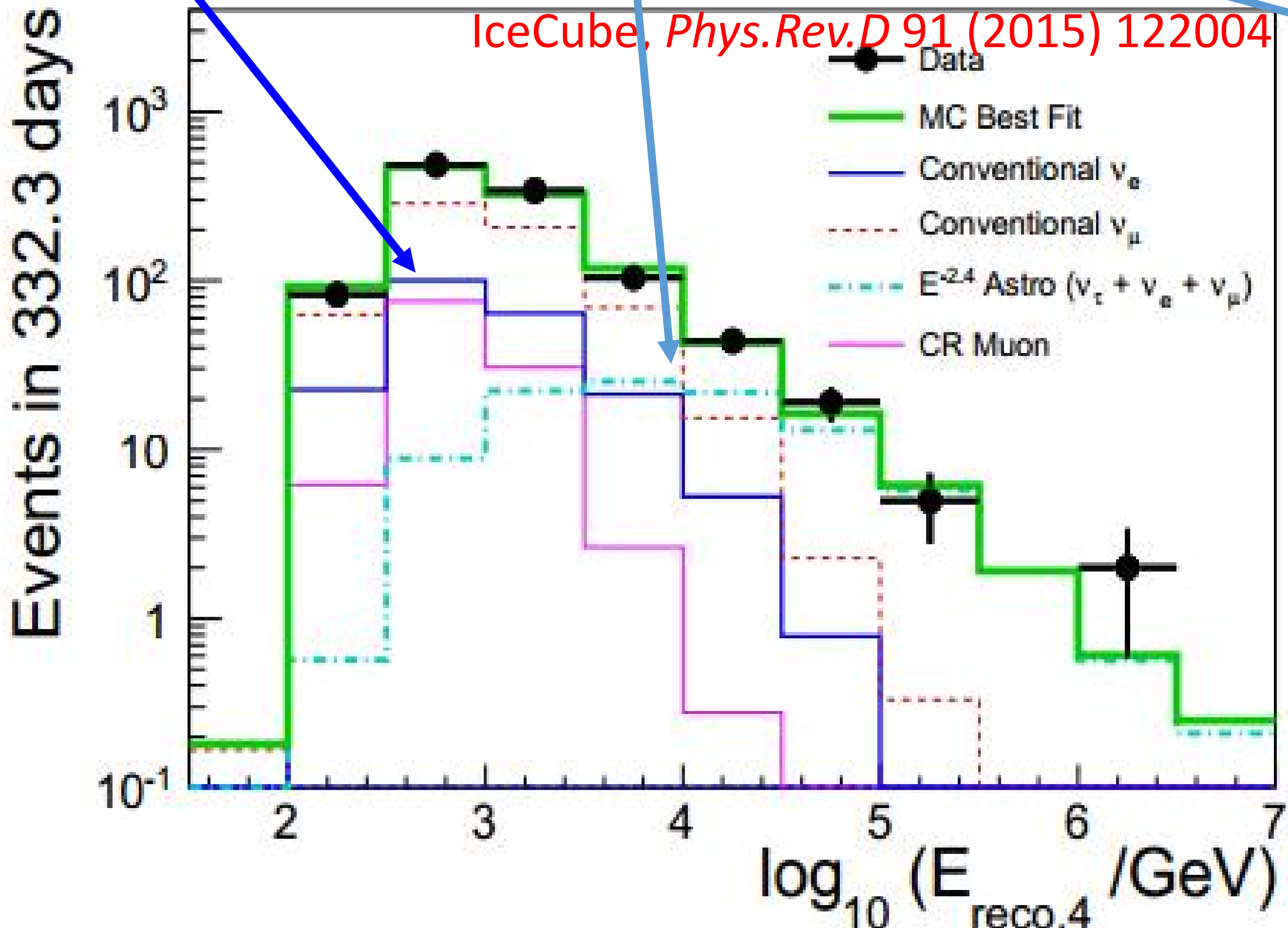
Part 3. Results and Discussion

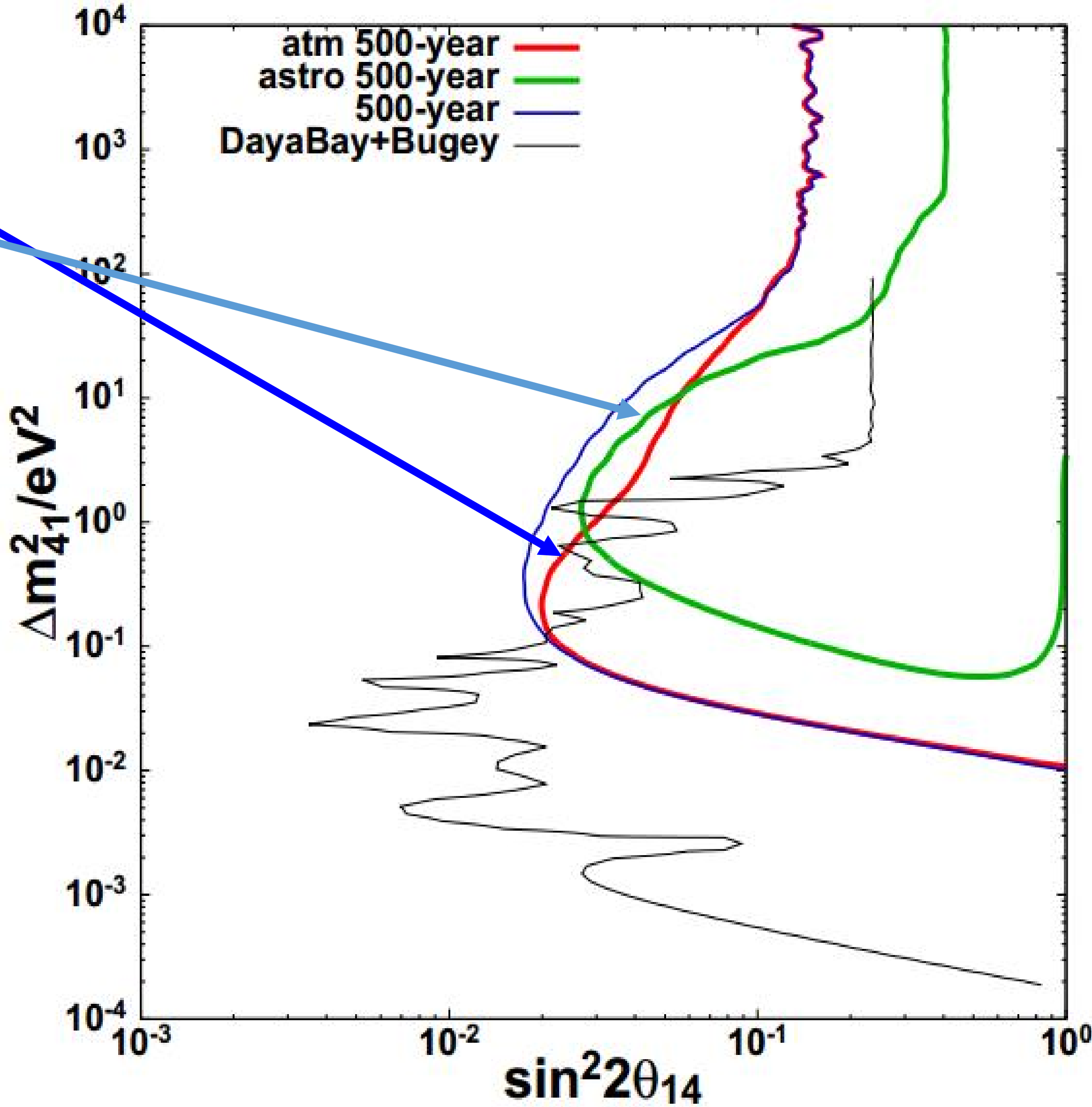
- 3.2 Atmospheric neutrinos Vs Astrophysical neutrinos

ν_{atm}: E_ν~1TeV → $\Delta m^2 \sim 0.1\ eV^2$

ν_{ast}: E_ν~10TeV→ $\Delta m^2 \sim 1\ eV^2$

IceCube, *Phys.Rev.D* 91 (2015) 122004





Part 3. Results and Discussion

#(ν_{atm}) > #(ν_{ast}) → ν_{atm} contributes more to the sensitivity.

Resonance condition: $\tan 2\tilde{\theta}_{14} = \frac{\Delta m^2 \cdot \sin 2\theta_{14}}{\Delta m^2 \cdot \cos 2\theta_{14} - 2AE} \to +\infty$.

The best sensitivity is obtained from the peak of each energy spectrum:

$E \sim 1\ TeV$ for ν_{atm} → $\Delta m^2 \sim 0.1\ eV^2$

$E \sim 10\ TeV$ for ν_{ast} → $\Delta m^2 \sim 1\ eV^2$

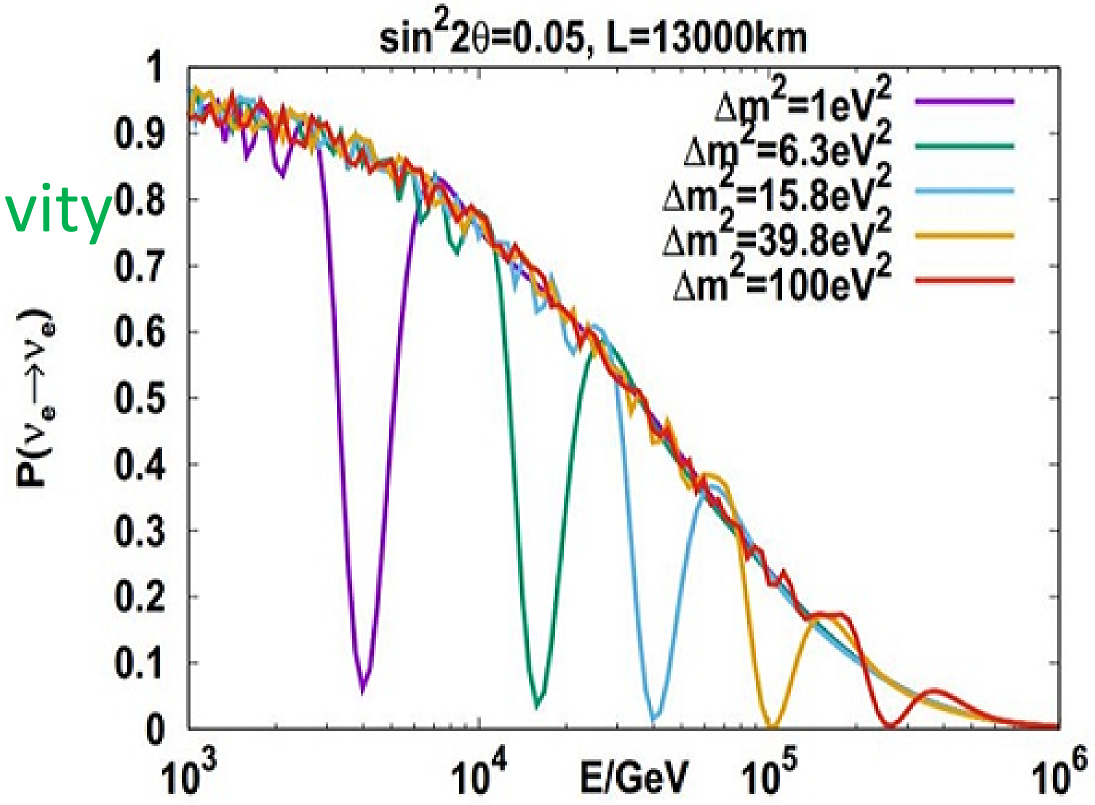
- 3.3 Upper bound of Δm^2 for improving sensitivity

For $\Delta m^2 > 100\ eV^2$, resonance condition

requires $E_\nu > 500\ TeV$

→ little number of events for this energy

because of absorption.



Part 4. Summary

For investigating reactor ν anomaly & gallium ν anomaly, observation of high energy ν_e is more promising than low energy & short baseline experiments.

We studied shower events of a possible future IceCube-type facility.

Sensitivity to θ_{14} (mixing angle of reactor ν anomaly) can be improved for $1\ eV^2 < \Delta m^2 < 100\ eV^2$ if we can build a detector whose volume is at least 10 times as large as the present IceCube.

Backup

Part 5: Analytical treatment

- 5.1 The case of $\theta_{14} \neq 0, \theta_{24} = \theta_{34} = 0$

Sterile mixing angle in matter

$$\tan 2\tilde{\theta}_{14} = \frac{\Delta E \cdot \sin 2\theta_{14}}{\Delta E \cdot \cos 2\theta_{14} - \frac{1}{2} A_e}$$

When $\Delta E \cdot \cos 2\theta_{14} = \frac{1}{2} A_e$, $\tan 2\tilde{\theta}_{14} \to +\infty$.

We know there can be resonance in the neutrino mode ($\Delta E, A_e > 0$).

Inclusion of small $\theta_{24} \neq 0, \theta_{34} \neq 0$ is expected to be small perturbation.

$\rightarrow$ Small $\theta_{24} \neq 0, \theta_{34} \neq 0$ is not expected to affect the resonance in the neutrino mode and therefore the sensitivity to θ_{14} very much.

Part 5: Analytical treatment

- 5.2 The case of $\theta_{14} = 0, \theta_{24} \neq 0, \theta_{34} \neq 0$

  Mixing angle in matter

$$\tan 2\tilde{\varphi}_{13} = \frac{\Delta E \cdot \sin 2\varphi_{13}}{\Delta E \cdot \cos 2\varphi_{13} - \frac{1}{2} A_e}$$

$$\sin \varphi_{13} \equiv \cos \theta_{24} \cdot \cos \theta_{34}$$

When $\Delta E \cdot \cos 2\varphi_{13} = -\frac{1}{2} A_e$, $\tan 2\tilde{\varphi}_{13} \to +\infty$.

We know there can be resonance in the anti-neutrino mode (ΔE>0, $A_e < 0$).

Inclusion of small $\theta_{14} \neq 0$ is expected to be small perturbation.

→ Small $\theta_{14} \neq 0$ is not expected to affect the resonance in the anti-neutrino mode very much.