Atmospheric Sterile Neutrinos

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Reference: arXiv:1202.0725

§1

Introduction

Neutrino oscillations

- Flavor oscillations of three massive neutrinos

Global 3ν oscillation analysis

$\Delta m^2_{\rm atm}$	$(2.06-2.67)\cdot 10^{-3}\ {\rm eV}^2$
$\Delta m^2_{\rm sol}$	$(6.99-8.18)\cdot 10^{-5}\ {\rm eV}^2$
$\sin^2\theta_{23}$	$0.34-0.64$
$\sin^2\theta_{12}$	$0.265-0.364$
$\sin^2\theta_{13}$	$0.005-0.050$

Fogli, Lisi, Marrone, Plazzo, Rotunno ('11)
[3σ range with new reactor fluxes]

Non-zero θ_{13}

T2K ('11)
$\sin^2 2\theta_{13} = 0.03(0.04) - 0.28(0.34)$ for NH(IH)

Double Chooz ('11)
$\sin^2 2\theta_{13} = 0.086 \pm 0.041 \pm 0.030$

Daya Bay ('12)
$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$

- Need for physics beyond the SM !
  - *"What is the origin of neutrino masses?"*
  - *"How do we test it experimentally?"*

Extension by RH neutrinos

- Introduce three RH neutrinos $\nu_{R1}, \nu_{R2}, \nu_{R3}$

$$\delta L = i\overline{\nu_{RI}}\partial_\mu \gamma^\mu \nu_{RI} - F_{\alpha I}\overline{L_\alpha}\nu_{RI}\Phi - \frac{M_I}{2}\overline{\nu_{RI}}\nu_{RI}^c + \text{h.c.}$$

- Seesaw mechanism $(M_D \ll M_M)$

$$-L = \frac{1}{2}(\overline{\nu_L}, \overline{\nu_R^c})\begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c = \frac{1}{2}(\overline{\nu}, \overline{N^c})\begin{pmatrix} M_\nu & 0 \\ 0 & M_M \end{pmatrix}\begin{pmatrix} \nu^c \\ N \end{pmatrix} + h.c.$$

  - Active neutrinos
    ν_1, ν_2, ν_3

$$\begin{cases} M_D = F\langle\Phi\rangle & M_M = diag(M_1, M_2, M_3) \\ M_\nu = -M_D^T \dfrac{1}{M_M} M_D & U^T M_\nu U = diag(m_1, m_2, m_3) \end{cases}$$

  - Sterile neutrinos
    N_1, N_2, N_3

$$\begin{cases} N_I \simeq \nu_{RI} \\ M_M = diag(M_1, M_2, M_3) \end{cases}$$

- Flavor mixing in CC current

$$\nu_{L\alpha} = U_{\alpha i}\,\nu_i + \Theta_{\alpha I}\,N_I$$

active-sterile mixing

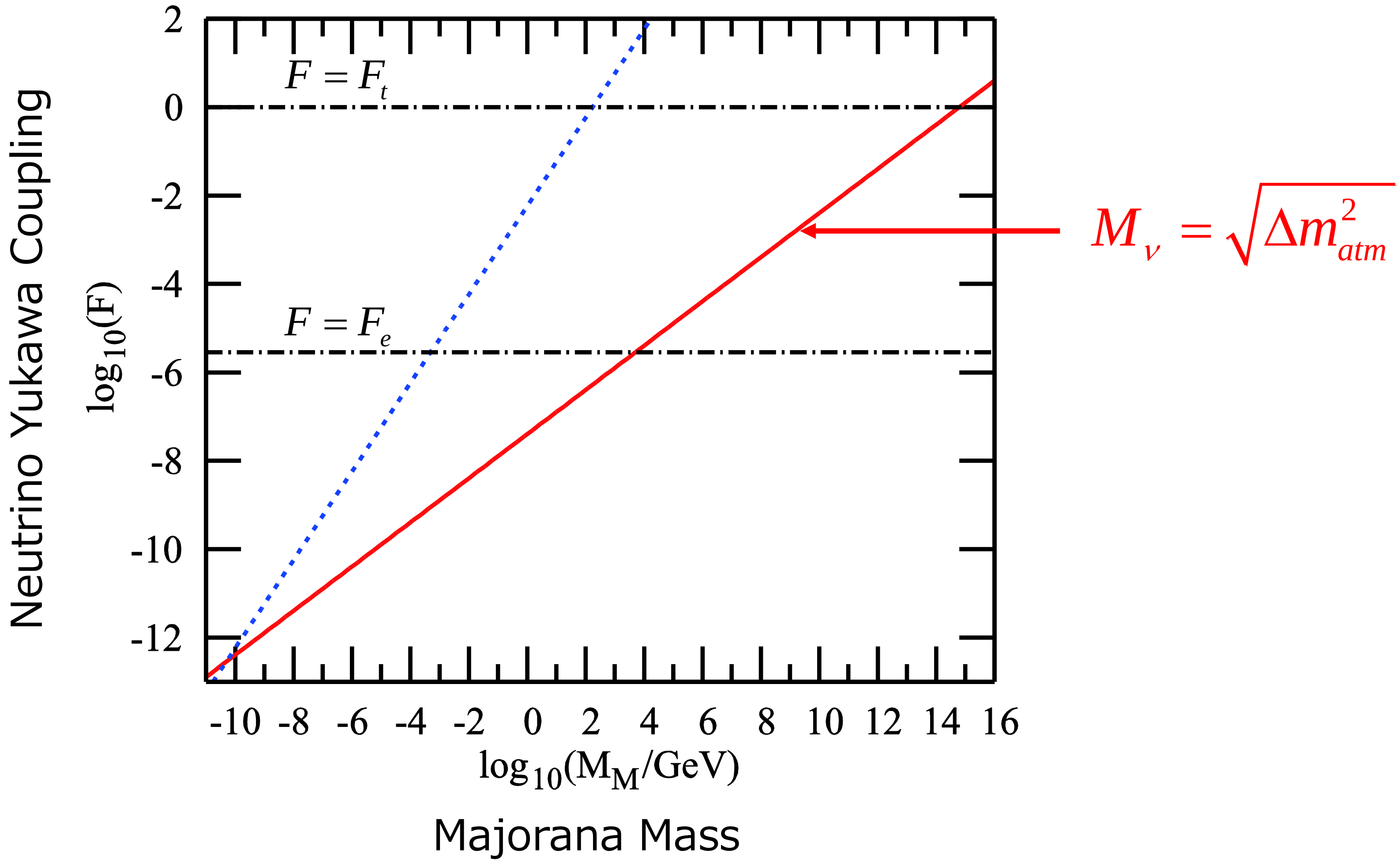
$$\Theta_{\alpha I} = [M_D]_{\alpha I}/M_I \ll 1$$

Scale of Majorana mass

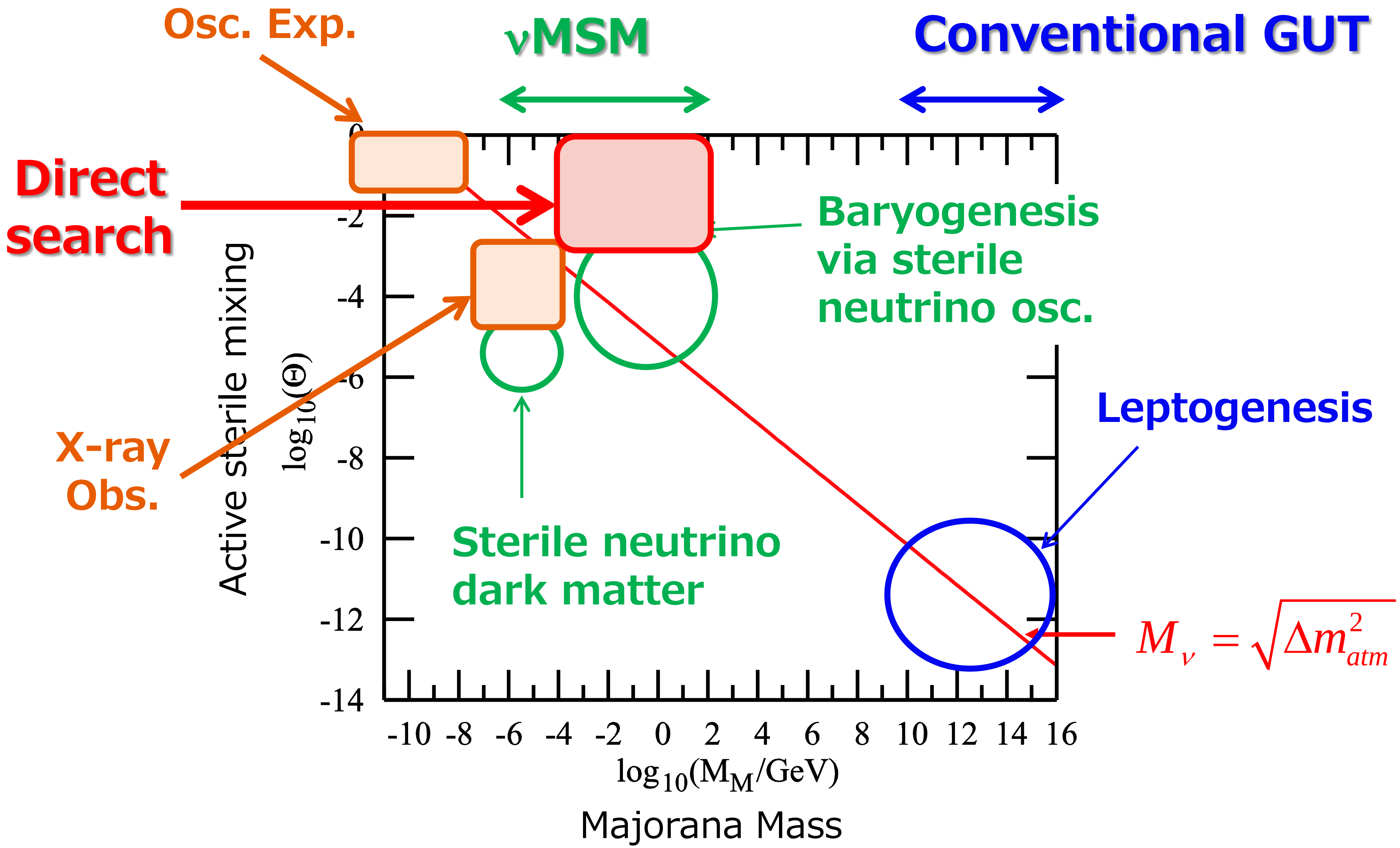
- The simplest case: one pair of ν_L and ν_R

$$M_\nu = -M_D^T \frac{1}{M_M} M_D \quad \Rightarrow F^2 = M_M M_\nu / \langle \Phi \rangle^2$$

$$\Theta = \frac{M_D}{M_M} = \frac{F \langle \Phi \rangle}{M_M}$$



Scale of Majorana mass



In this talk

- We consider one Majorana sterile neutrino N with
  - M_M~1-100MeV
  - Mix only with ν_μ

$$\nu_\mu = U_{\mu i}\,\nu_i + \Theta_\mu N$$

Can we observe such sterile neutrinos produced in atmosphere at Super-Kamiokande (SK)?

- Kusenko, Pascoli, Semikoz (JHEP11, '05, 028)
- TA, Watanabe (arXiv:1202.0725)

- Contents

  § Production in atmosphere

  § Detection at SK

  § Summary

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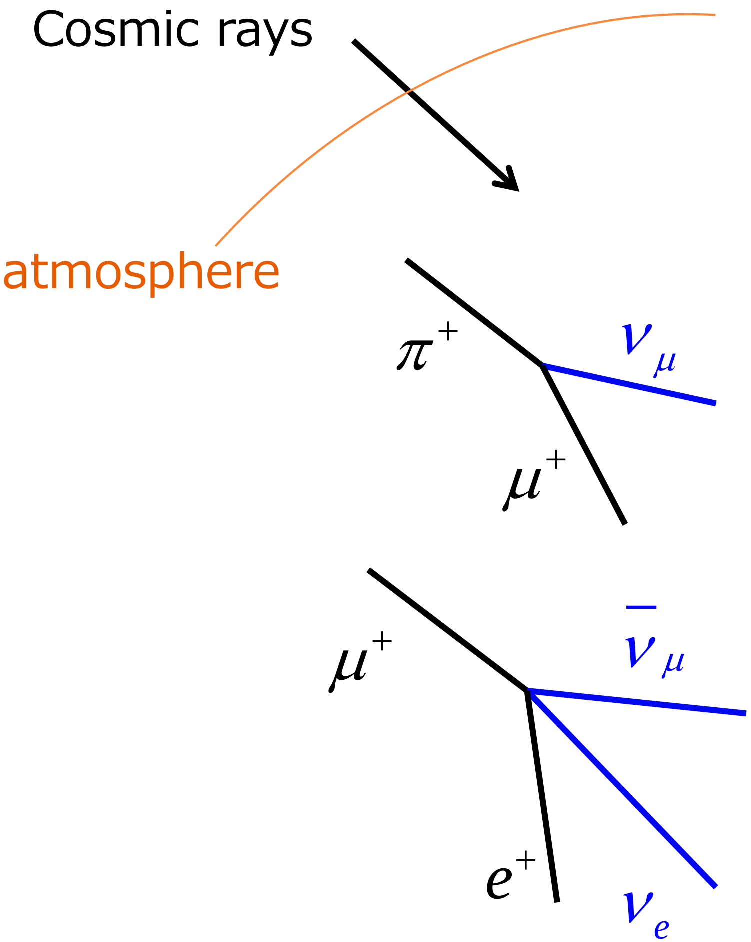
Production of sterile neutrinos in atmosphere

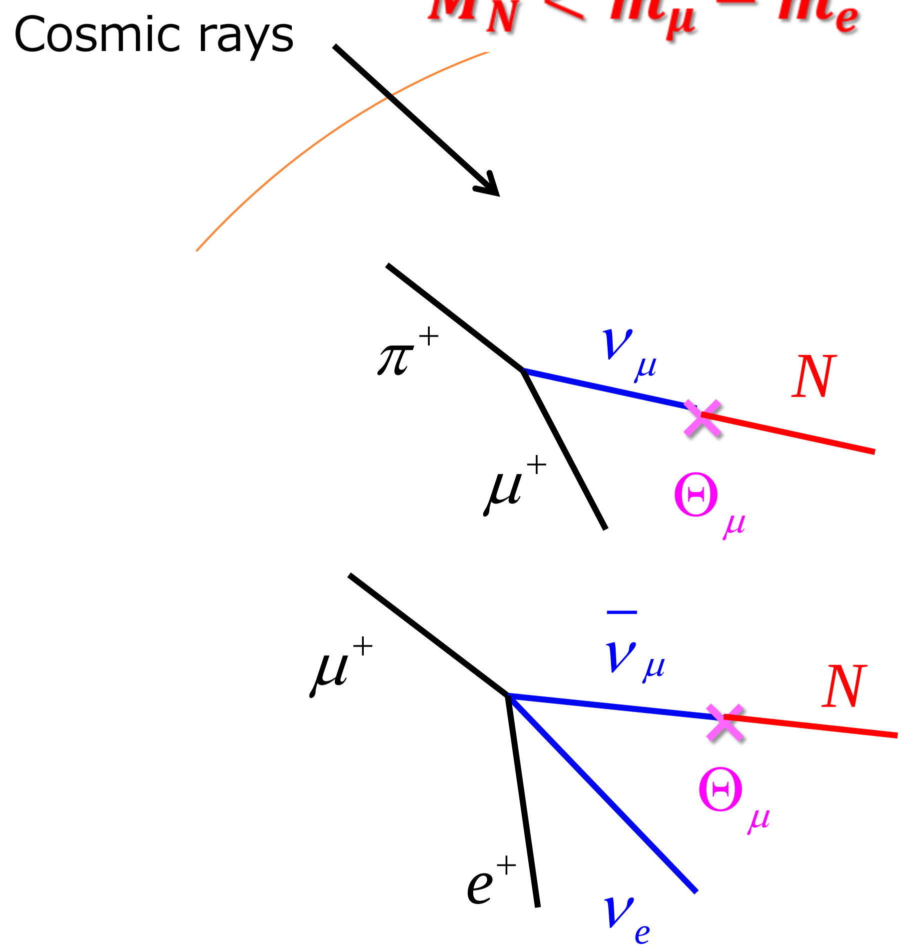
Production of ATM neutrinos

Active neutrinos



Sterile neutrinos

$M_N < m_\mu - m_e$



Fluxes of ATM neutrinos

- Active neutrinos (E<GeV)
  - Estimation is very complicated
    - Effects of solar activity, geomagnetic fields, ⋯
  - Now, 3D Monte Carlo calculations have been done

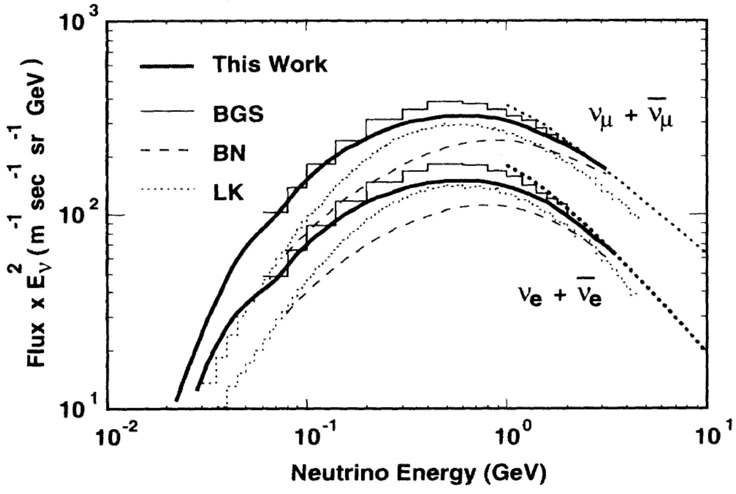
Volkova ('80); Mitsui, Midorikawa, Komori ('86); Butkevich, Dedenko, Zhelsnykh ('89); Gaisser, Stanev, Barr ('88); Lipari ('93); Honda, Kajita, Kasahara, Midorikawa ('95); ⋯ Battistoni, Ferrari, Montaruli, Sata ('02); ⋯; Honda, Kajita, Kasahara, Midorikawa ('11);⋯

- Sterile neutrinos (E<GeV)
  - Naively, $\phi_N = |\Theta_\mu|^2 \phi_{\nu_\mu + \bar{\nu}_\mu}$

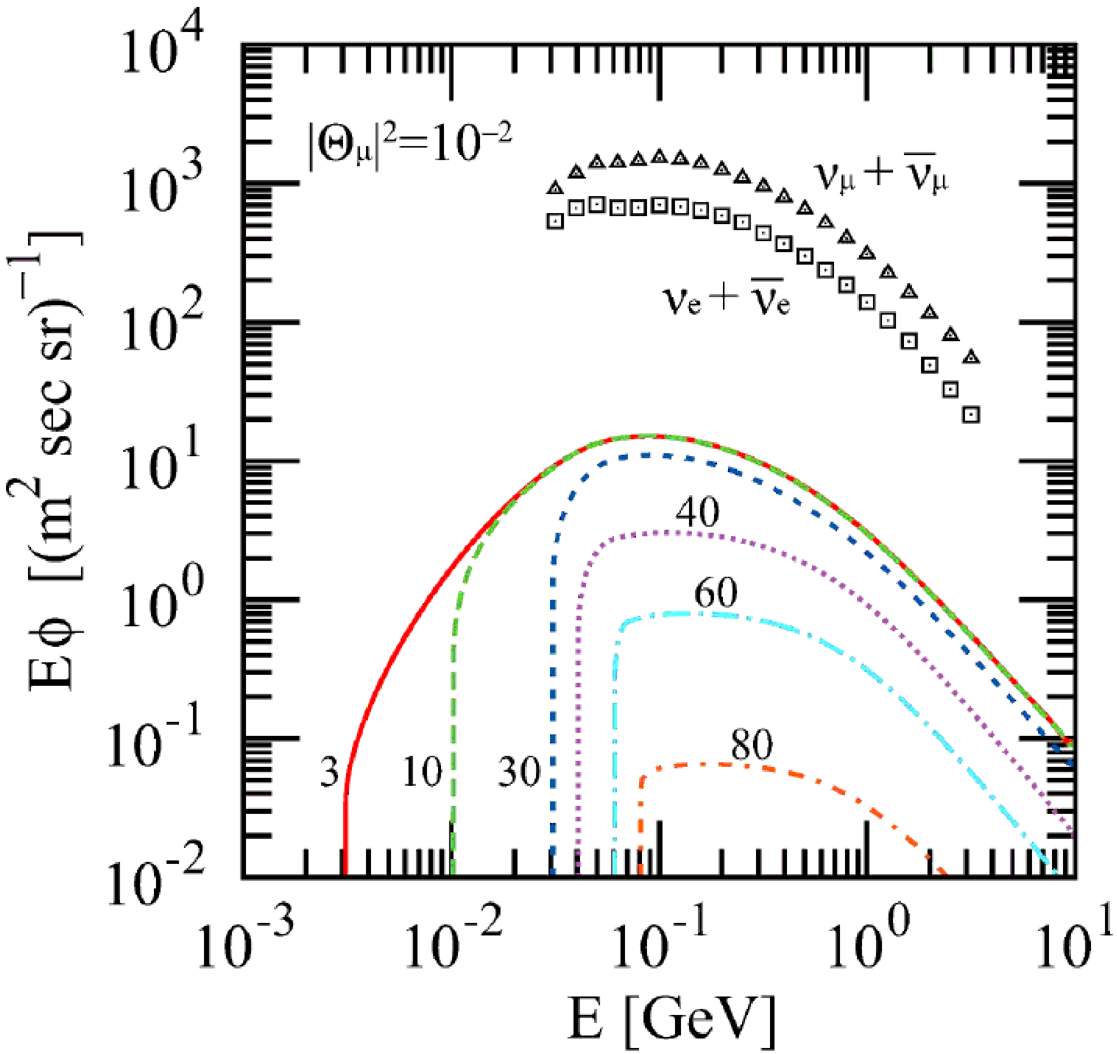
Kusenko, Pascoli, Semikoz ('05)

  - We estimate ϕ_N
    - Reconstruct fluxes of $\pi^\pm$ and $\mu^\pm$
    - Take into account the correct kinematics (non-zero M_N) of $\pi^+ \to \mu^+ N$ and $\mu^+ \to e^+ \nu_e N$

Honda, Kajita, Kasahara, Midorikawa ('95)



Flux of ATM sterile neutrino



- When $M_N > m_{\pi^\pm} - m_\mu$, $\pi^+ \to \mu^+ N$ is forbidden
- When $M_N \sim m_\mu - m_e$, $\mu^+ \to e^+ \nu_e N$ is suppressed due to small phase space

Flux of N is much smaller than the previous estimate

$$\phi_N = |\Theta_\mu|^2 \phi_{\nu_\mu + \bar{\nu}_\mu}$$

for $M_N \gg 30$ MeV

§3

Detection of sterile neutrinos at SK

How to detect N at SK?

Find two e–like ring events from N decays inside SK detector !!

- Decay mode / BR

Decay mode	BR
$N \to \nu\bar{\nu}\nu$	88 %
$N \to e^- e^+ \nu$	12 %
$N \to \gamma\nu$	$O(\alpha_{em}^2)$

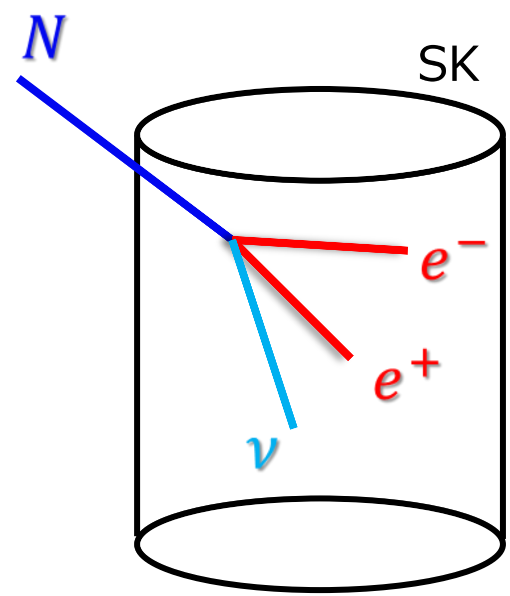
$M_N > 2m_e$

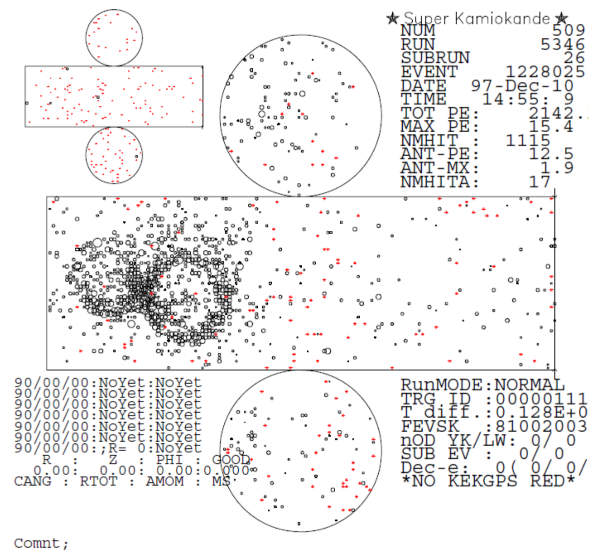
$$\tau_N = 1.3\times10^{-2}\,\mathrm{sec}\,\frac{10^{-4}}{|\Theta_\mu|^2}\left(\frac{100\mathrm{MeV}}{M_N}\right)^5$$

- Decay length $(@E = 2M_N)$

$$\lambda_{\rm dec} = 6600\mathrm{km}\,\frac{10^{-4}}{|\Theta_\mu|^2}\left(\frac{100\mathrm{MeV}}{M_N}\right)^5$$

⇨ comparable to earth's radius ≈ 6400km



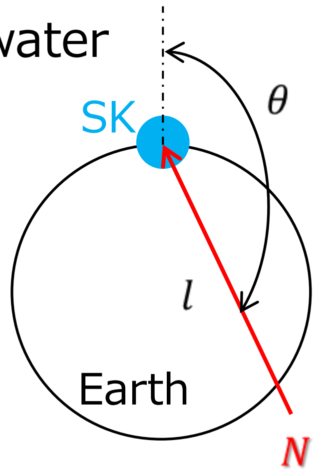


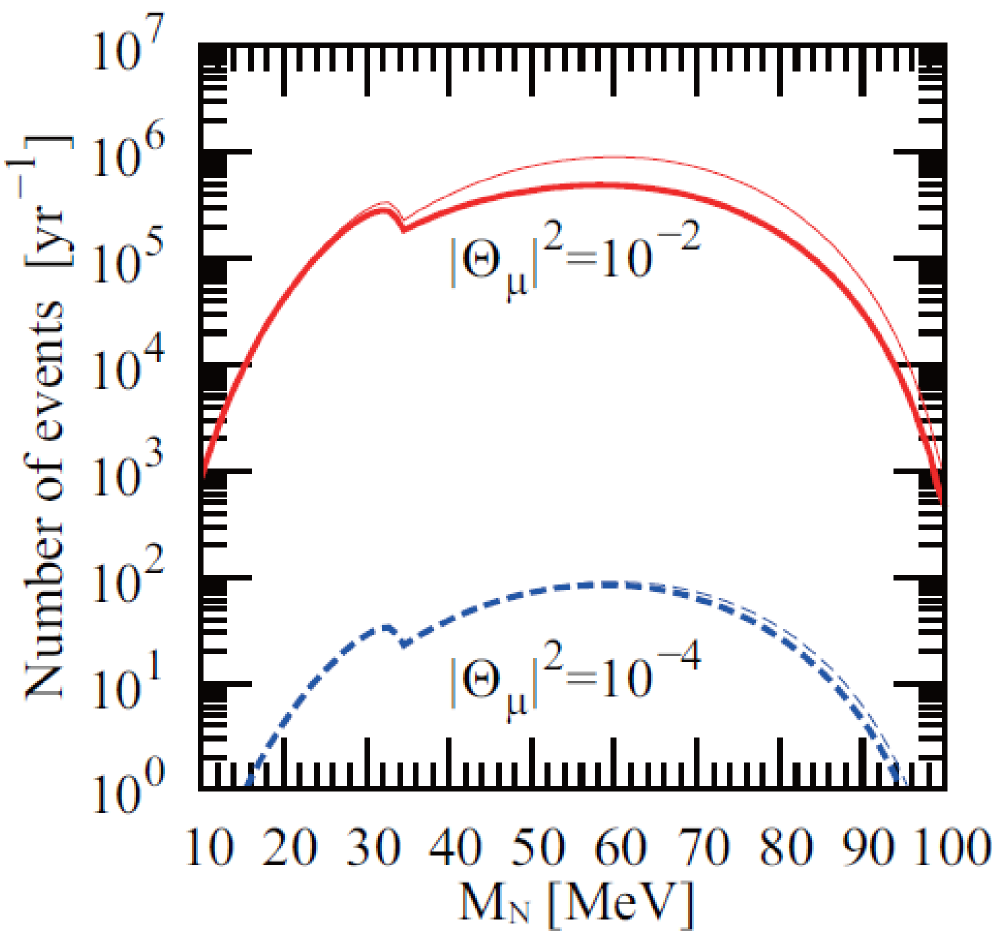
PhD Thesis by S. Nakayama '03

Event rate

- Number of event decays inside fiducial volume with 22.5kt water

$$\text{Rate} = \int_{M_N}^{\infty} dE_N \phi_N r_{SK}^2 \int dcos\theta d\phi \int_{l}^{l+2r_{SK}} dr\, \Gamma_{eev}\, e^{-\Gamma_N r} \int dX \frac{1}{\Gamma_{eev}} \frac{d\Gamma_{eev}}{dX}$$





X: observables of interest

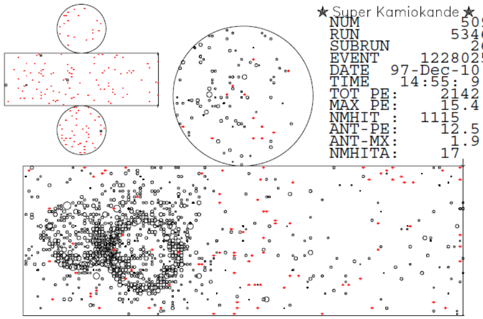
- **Event rate $\propto |\theta_\mu|^4$**, since
  production rate $\propto |\Theta_\mu|^2$
  decay rate $\propto |\Theta_\mu|^2$
- When $|\Theta_\mu|^2 > 10^{-4}$, decays from ATM to SK become significant.
  ⇨ **up/down asymmetry!**

Two e–like ring events

- π^0 decay: $\pi^0 \rightarrow \gamma\,\gamma$
  - Emitted γ's produce showering two e–like ring events !

How we distinguish between π^0 and N decays ?

A typical event in the π^0 sample

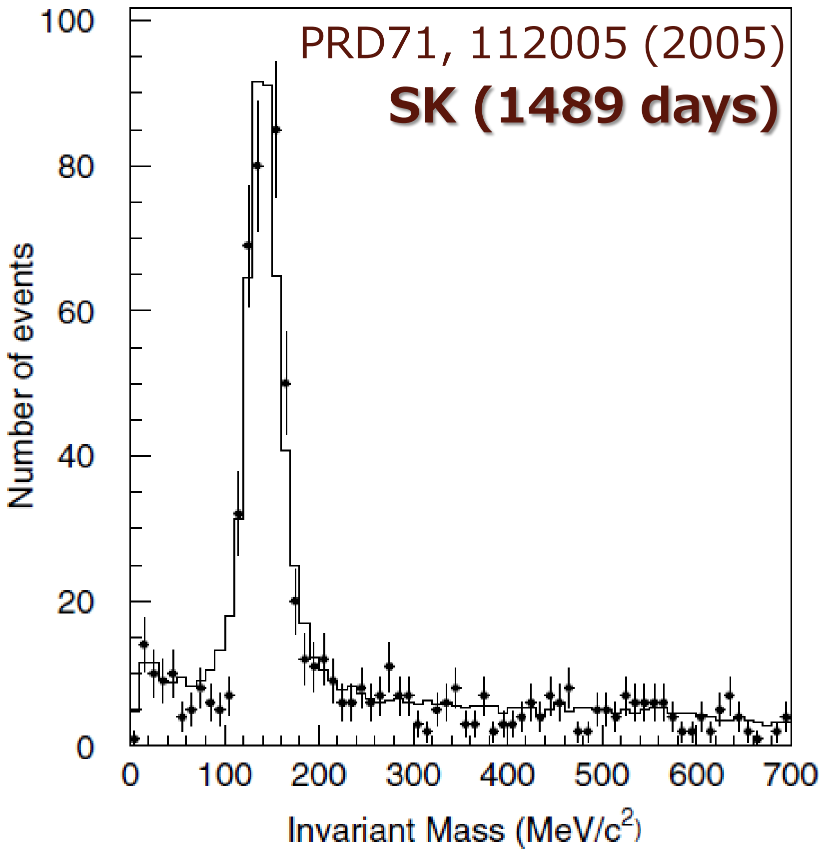


Invariant mass of two rings

- $\pi^0 \rightarrow \gamma\,\gamma$ ⇨ 2-body decay

$$M_{\gamma\gamma}^2 = (p_{\gamma 1} + p_{\gamma 2})^2 = m_{\pi^0}^2$$

- Invariant mass distribution of events has **a sharp peak at $M_{\gamma\gamma} = m_{\pi^0}$!**



Invariant mass distribution

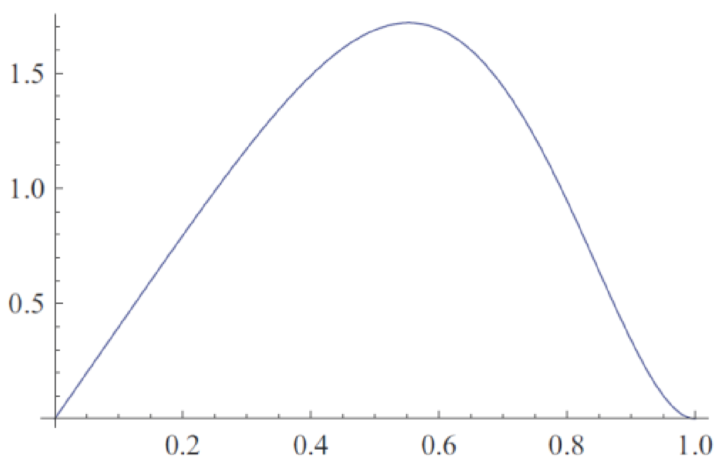
- $N \to e^- e^+ \nu$ ⇨ 3-body decay $\quad M_{ee}^2 = (p_{e^-} + p_{e^+})^2 = M_N^2 - 2M_N E_\nu^{\text{rest}}$

$$\langle E_\nu^{\text{rest}} \rangle \simeq \frac{M_N}{3} \quad \Rightarrow \quad \langle M_{ee}^2 \rangle \simeq \frac{M_N^2}{3} < M_{\gamma\gamma}^2 = m_{\pi^0}^2$$

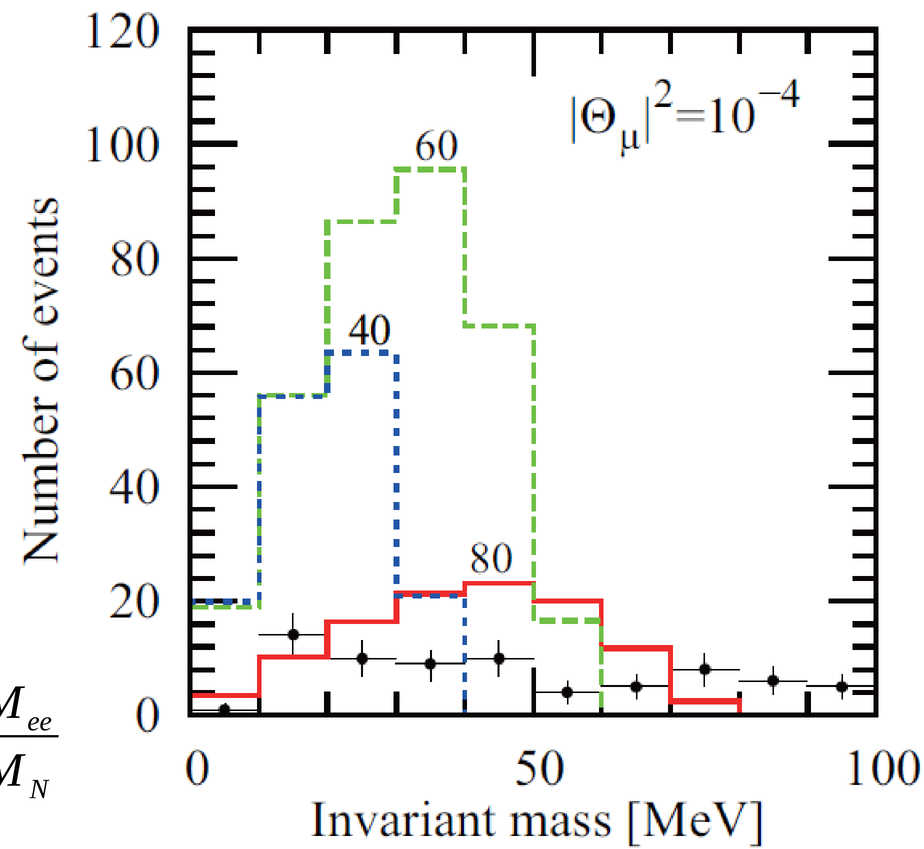
- **M_{ee} distribution of $N \to e^- e^+$**

$$\frac{1}{\Gamma_N}\frac{d\Gamma_N}{dM_{ee}} = \frac{4}{M_N} y_{ee}(1-y_{ee}^2)^2(1+2y_{ee}^2)$$

Max. at $M_{ee} = 0.55 M_N$

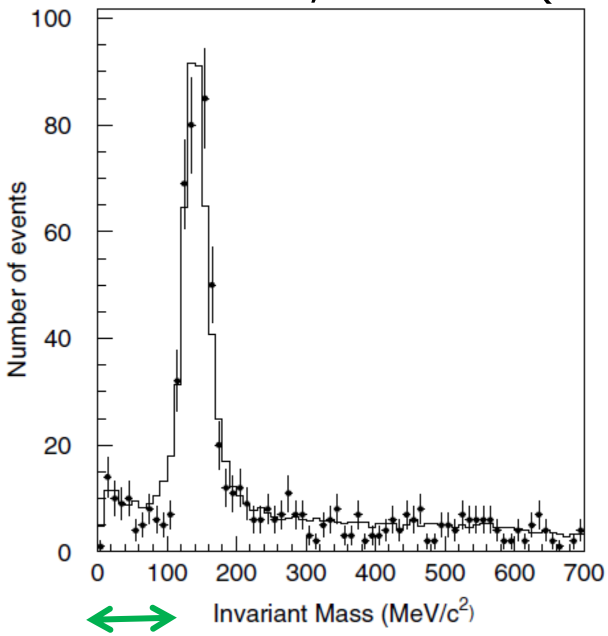


$$y_{ee} = \frac{M_{ee}}{M_N}$$

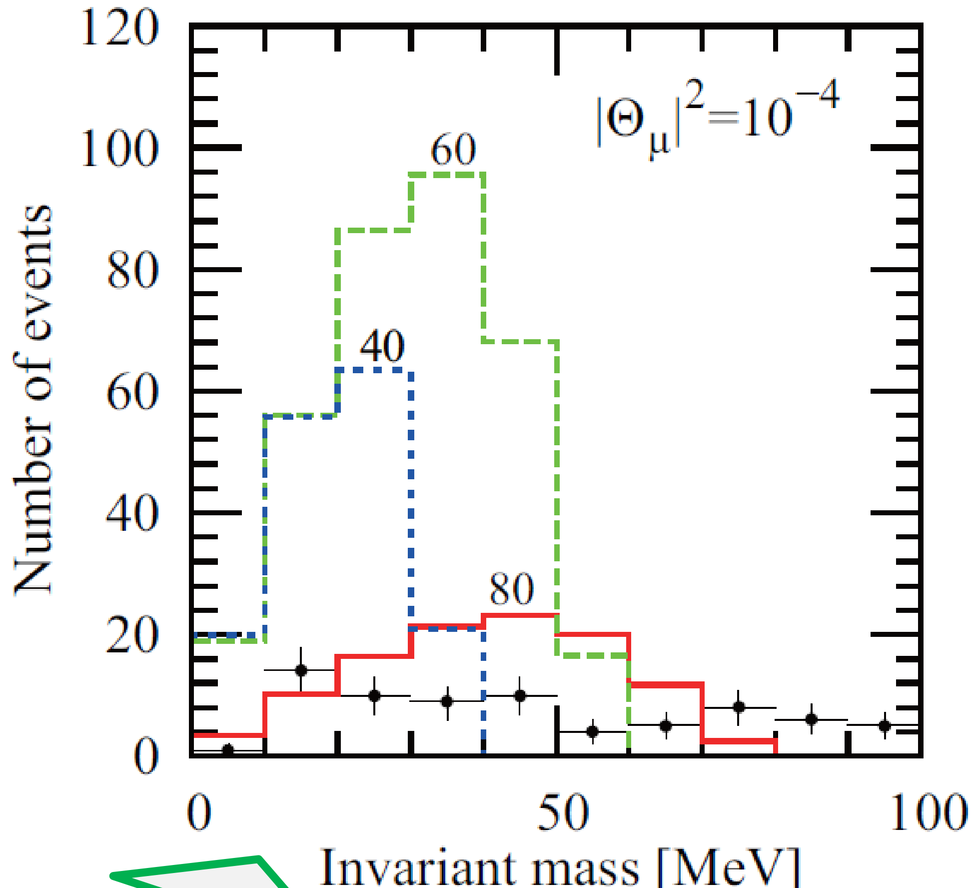


How to detect *N* at SK?

SK data (1489 days)
PRD71, 112005 (2005)



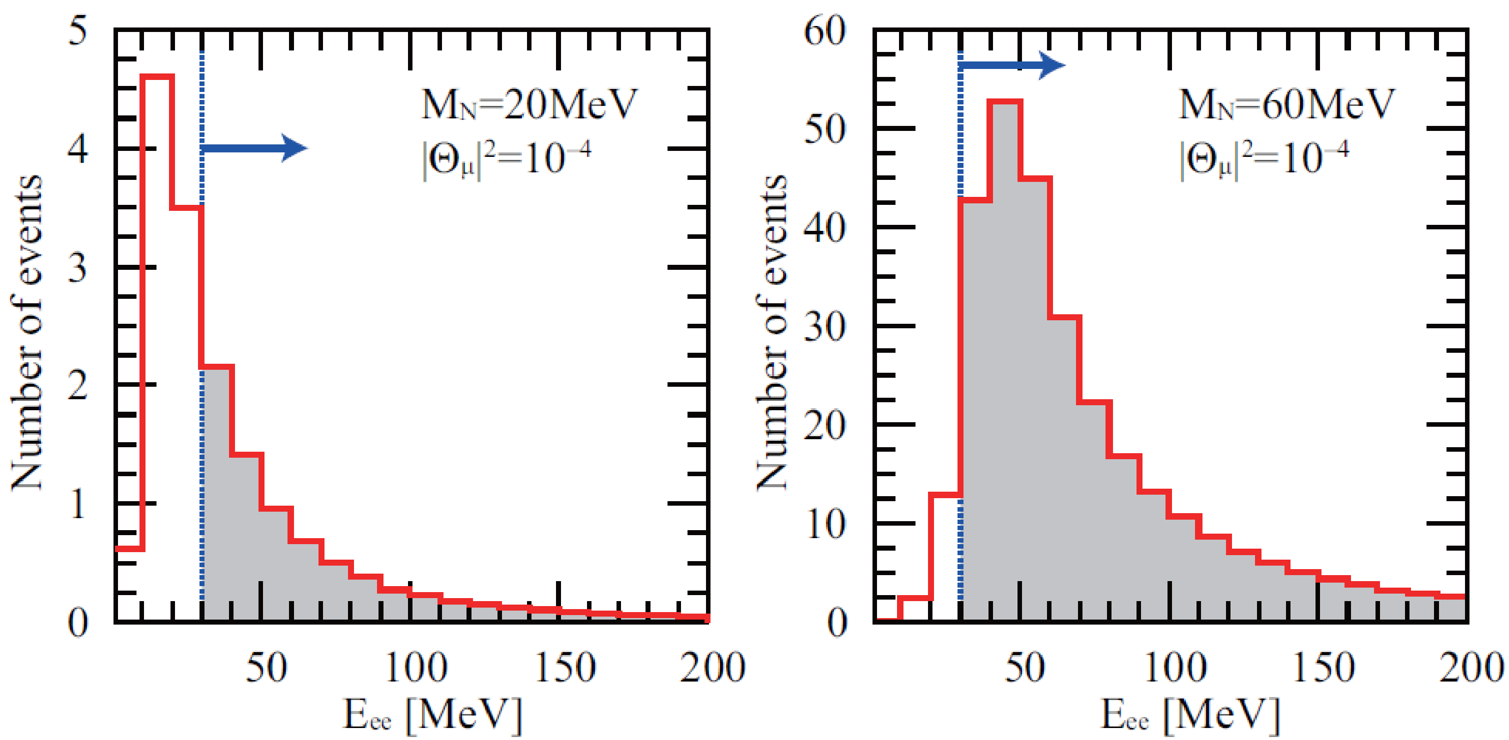
Find additional broad peak at tail of π^0-like events !



Visible energy

- SK analysis imposes the visible energy $E_{\text{vis}} > 30\text{MeV}$ for Fully-Contained events

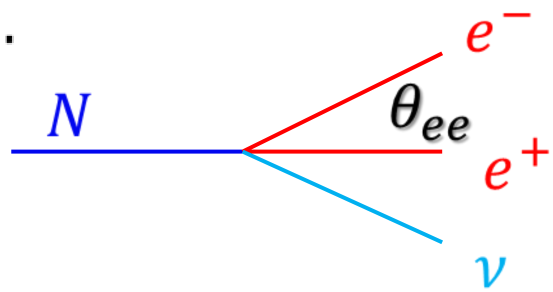
$$N \to e^- e^+ \nu \qquad E_{\text{vis}} = E_{ee} = E_{e^-} + E_{e^+}$$

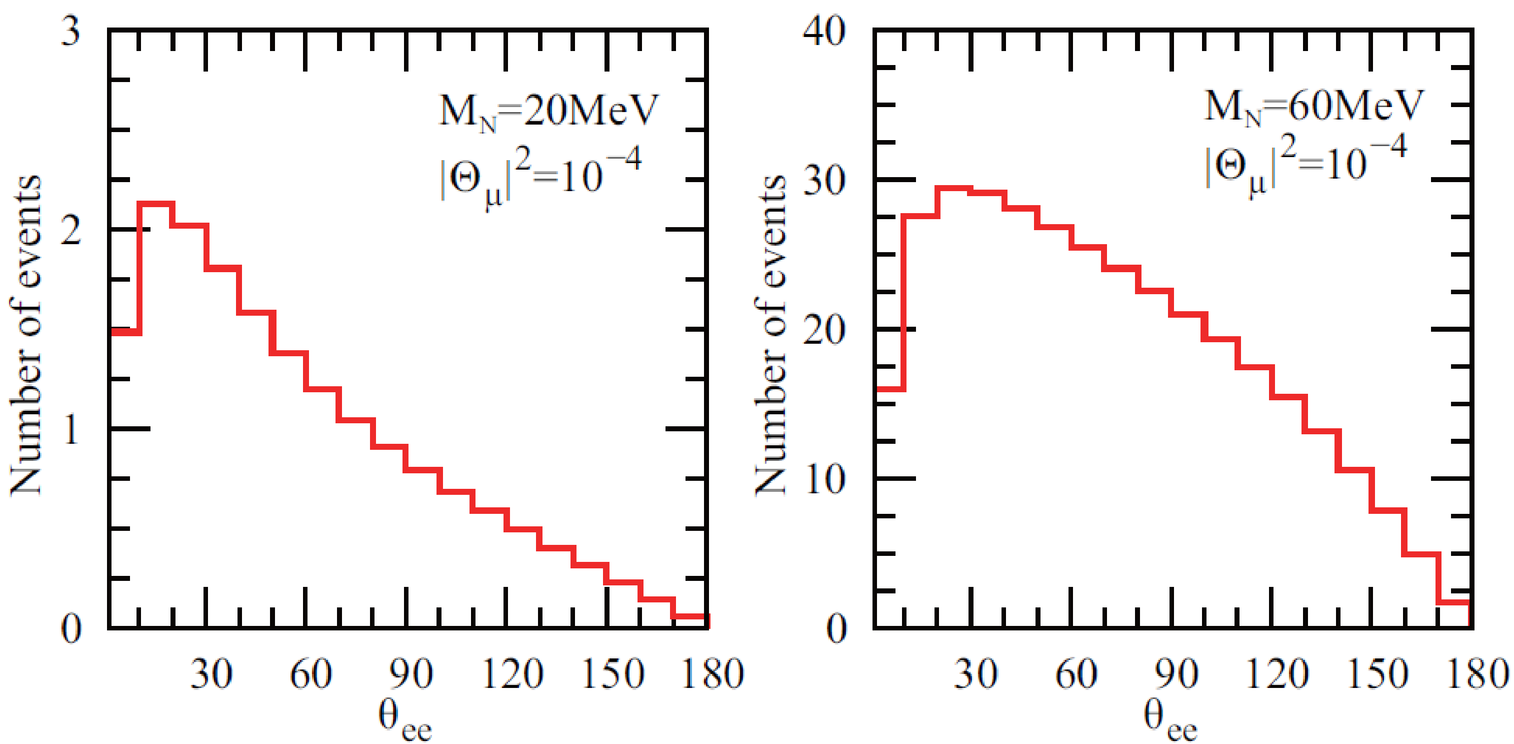


Opening angle

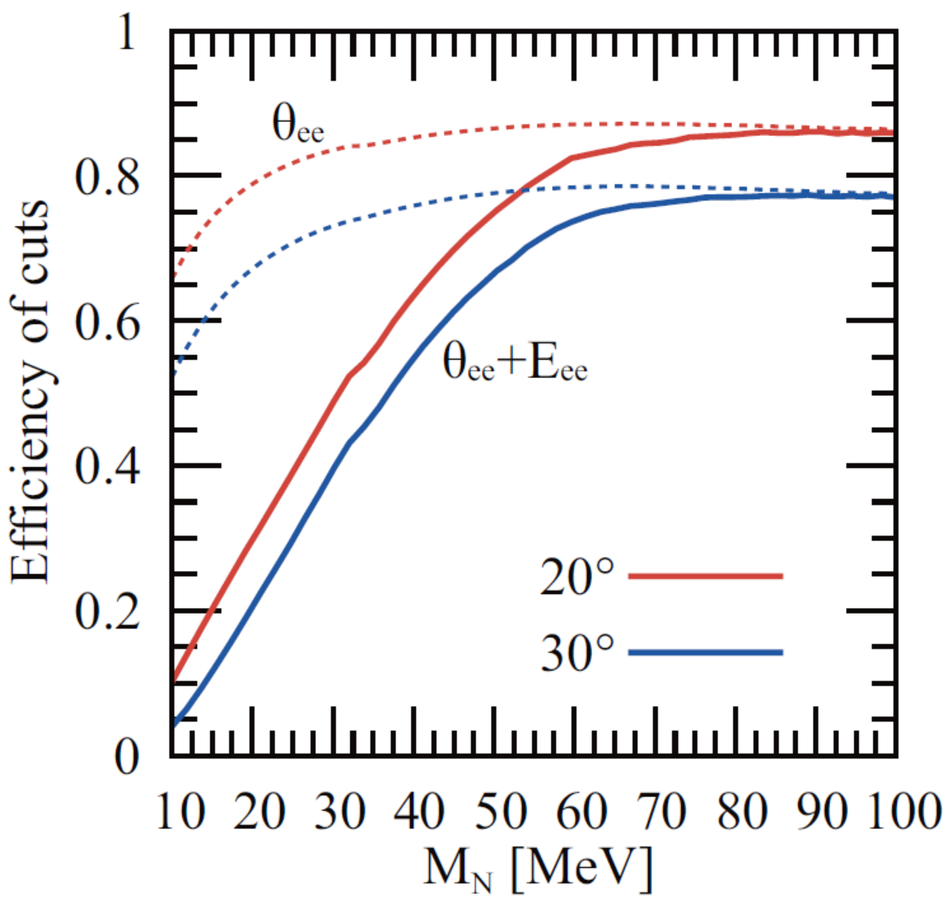
- When θ_{ee} becomes small, two-ring event may be misidentified with single-ring event.

$N \rightarrow e^- e^+ \nu$





Impacts of Evis and θee cuts



Cut on θ_{ee}

- We do not know how to apply it. *(Please tell us!!)*
- We take here $\theta_{ee} > 20^0$

Events is reduced by 15% for $M_N > 30$ MeV.

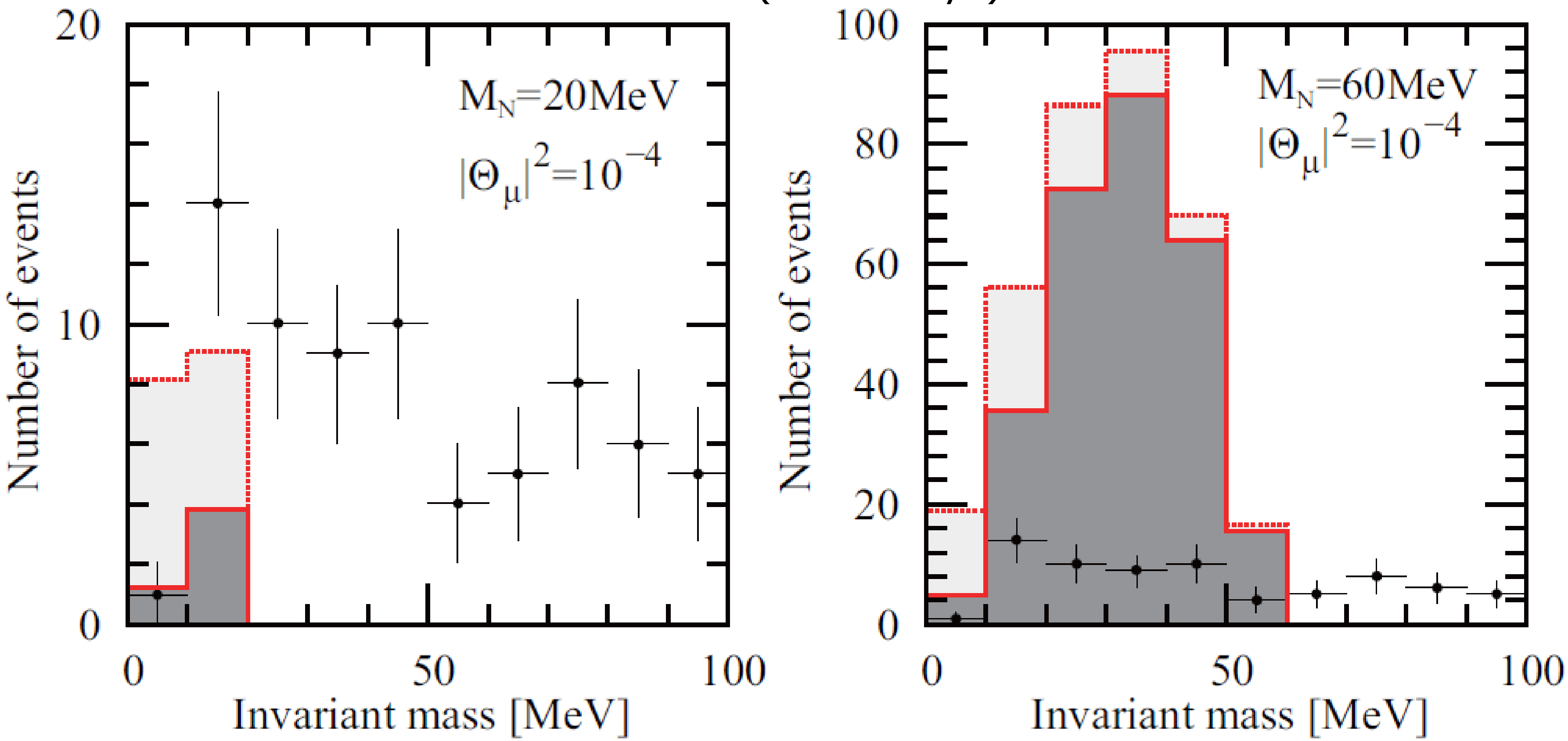
Cut on Evis

- **$E_{vis} > 30$MeV**

Events are significantly reduced for $M_N \lesssim 50$MeV

Invariant mass distribution with cuts

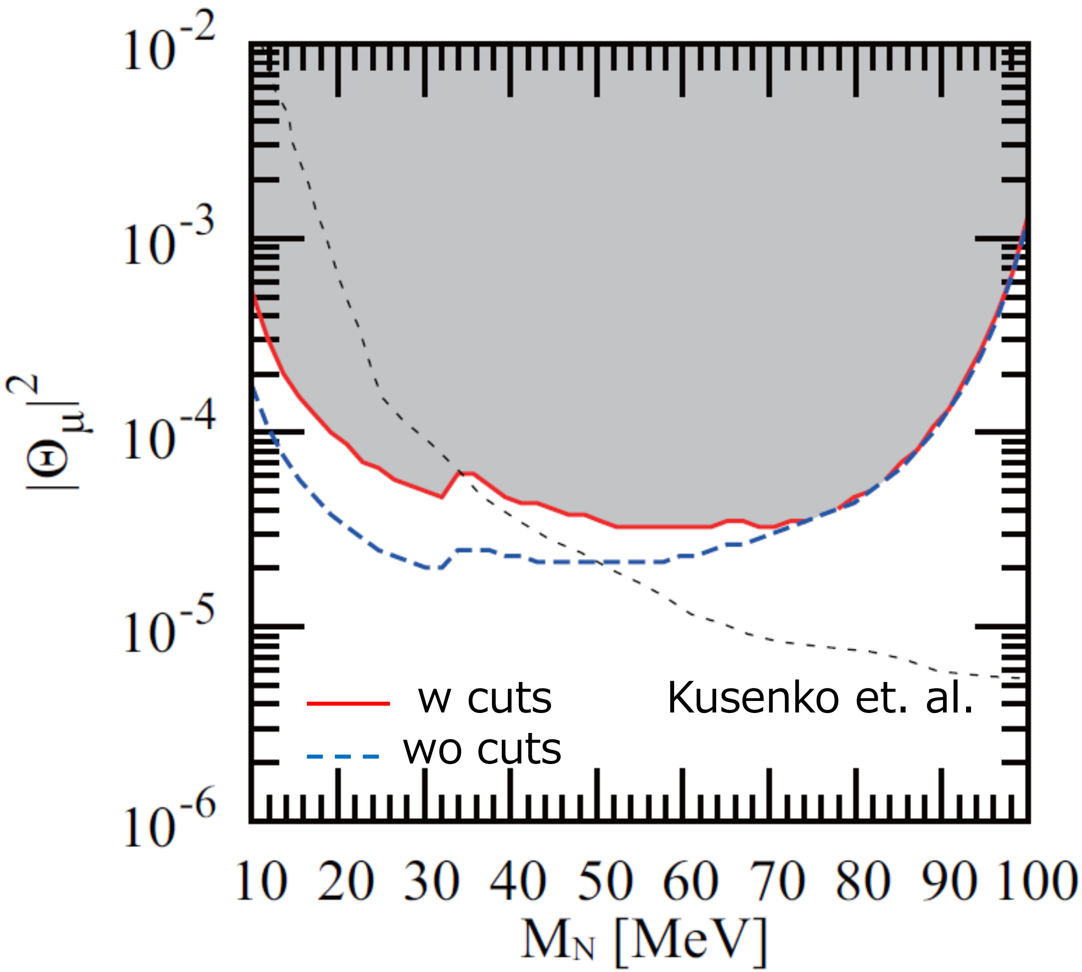
SK data (1489 days)



Upper bound on $|\Theta_\mu|^2$ is obtained by requiring that the signal events of all bins are smaller than the OBS data.

Upper bound on mixing -1-

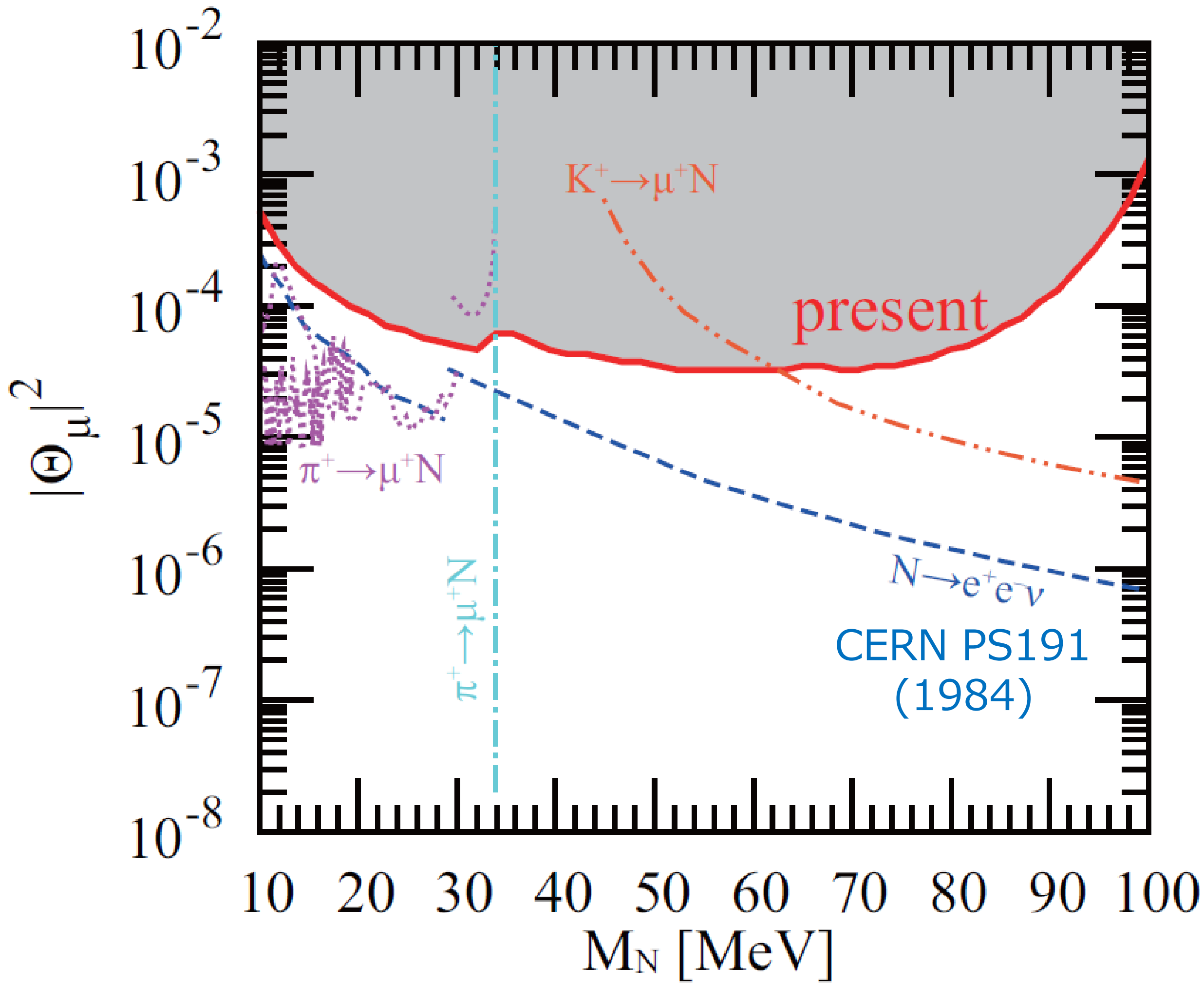
- Comparison with previous analysis



- **Bound is relaxed significantly for large M_N region,** since production by $\mu^+ \to e^+ \nu_e N$ is suppressed due to small PS and $\phi_N \ll |\Theta_\mu|^2 \phi_{\nu_\mu + \bar{\nu}_\mu}$.
- **There is a dip at $M_N \simeq 35$ MeV,** since production by $\pi^+ \to \mu^+ N$ is forbidden for $M_N \gtrsim 35$MeV

Upper bound on mixing -2-

- Comparison with other search experiments



§5

Summary

Summary

- **Atmospheric Sterile Neutrinos at SK**
  - **Test for ATM sterile neutrinos with M_N~1-100 MeV**
    - Production by decays of $\pi^\pm$ and $\mu^\pm$ in atmosphere
    - Detection by two e-like ring events from $N \to e^- e^+ \nu$
  - **Improvements of the estimations**
    - Flux of N with correct kinematics of $\pi^\pm$ and $\mu^\pm$ decays
    - Effects of visible energy E_{ee} and opening angle θ_{ee} cuts
  - **Competitive and complementary test**
    to peak search/beam dump accelerator experiments with artificial neutrinos

Summary -2-

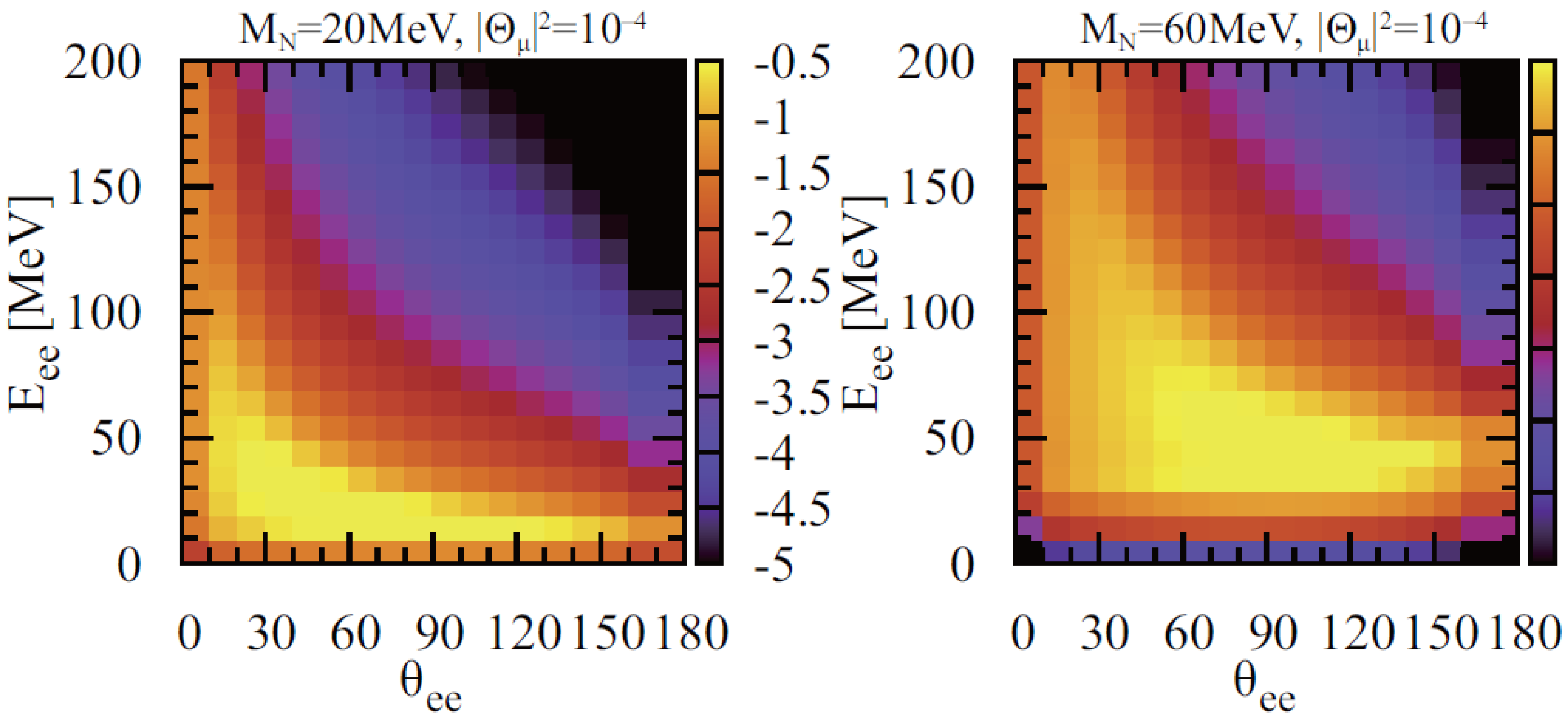
- **For better sensitivity**
  - **More advanced analysis**
    - Prediction vs Observational data
    - Understanding of BG properties, ···
  - **More statistics with larger detection volume**

We would like to ask you (experimentalists) for any suggestions and comments on (1) θ_{ee} cut, (2) BG for two e-like ring events, ···

There will be a good chance to discover atmospheric sterile neutrino with the refinements of analysis and the upgrade of facility (e.g. HK) !!!

Backup

Event distribution



Up-down asymmetry in events

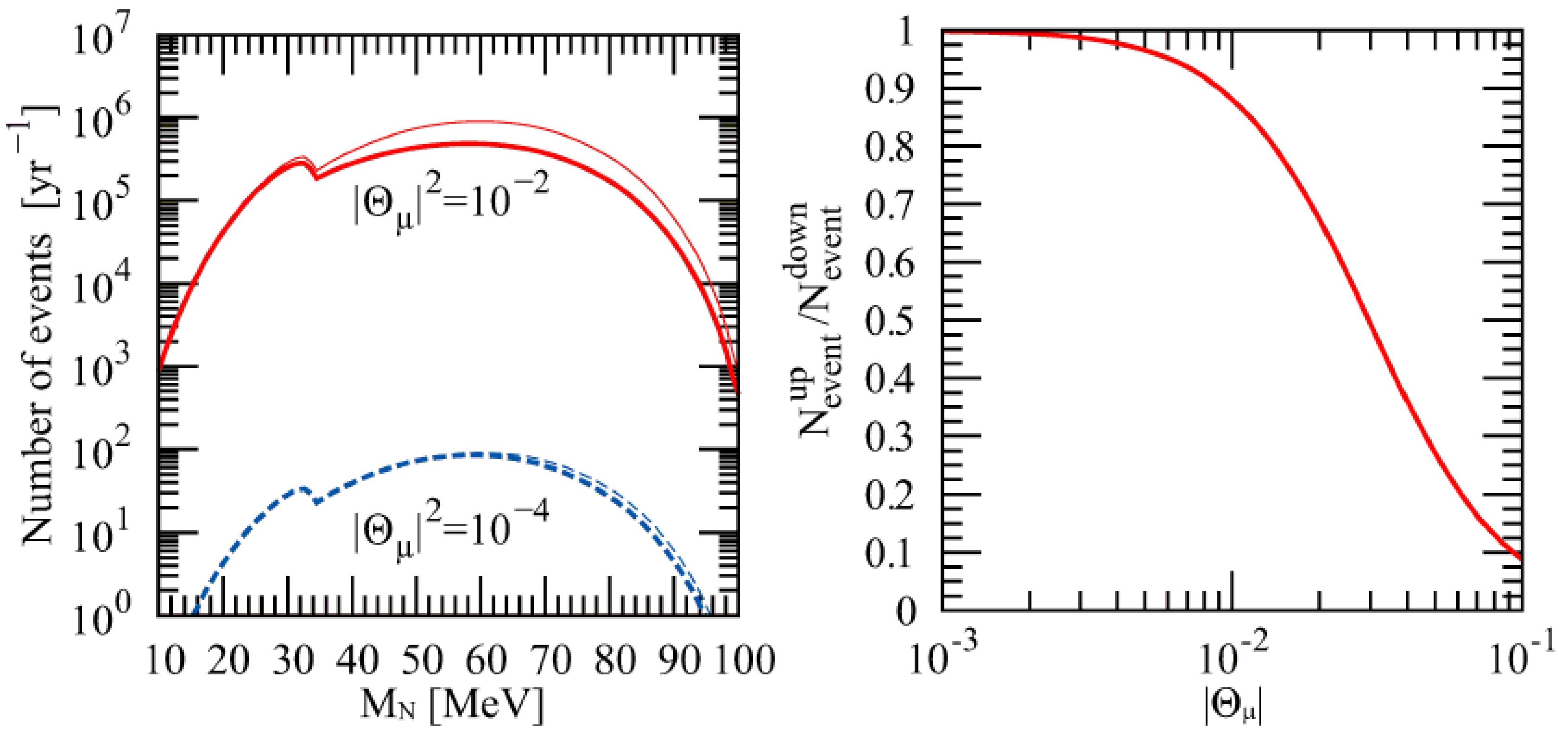


Figure 2: Left panel: Number of events ($N \to e^- e^+ \nu$) at SK per year. The red solid (blue dotted) lines shows the case when $|\Theta_\mu|^2 = 10^{-2}(10^{-4})$. The thick and thin lines are with and without the effect of N decay from atmosphere to detector. Right panel: Up-down asymmetry in number of events. Here we take $M_N = 60$ MeV.