T2KKの物理的可能性

an extension of the T2K neutrino oscillation experiment with a far detector in Korea

岡村直利（京大・基研）

関西セミナーハウス（2007/03/17）

based on

hep-ph/0504061 [Phys.Lett.B637,266 (2006)]

hep-ph/0607255

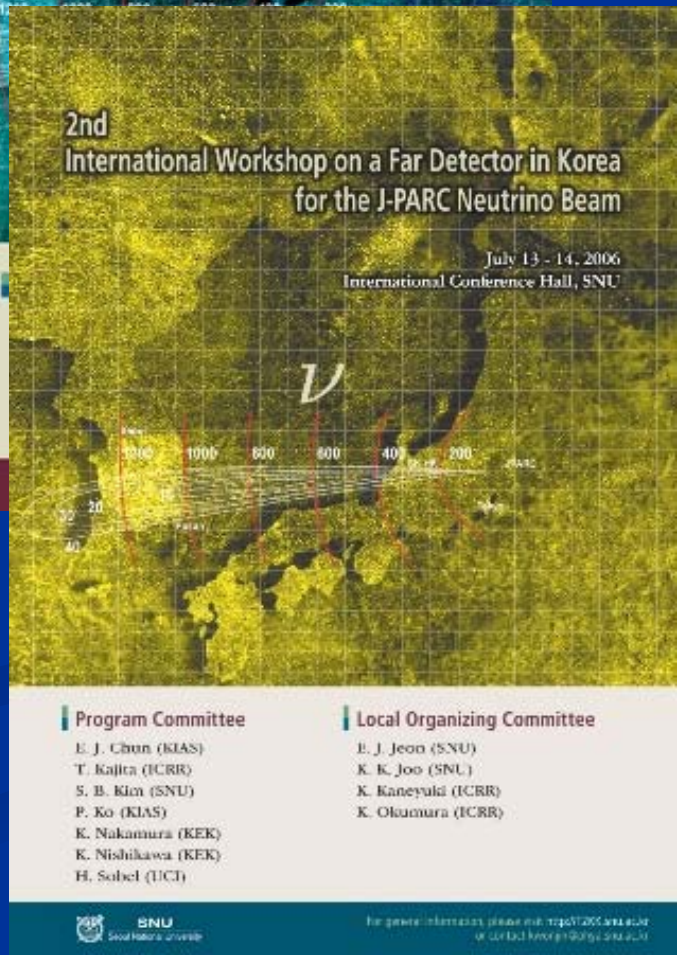
hep-ph/0611058

with 萩原薫，泉田賢一（KEK,総研大）

T2KKの注目度

- 2005年11月18日、19日
  - KIAS（韓国）
  - http://newton.kias.re.kr/~hepph/J2K
- 2006年07月13日、14日
  - SNU（韓国）
  - http://t2kk.snu.ac.kr/
- 2007年　夏
  - 日本（？）

- 実施されるかは不定
- 多くの人が興味を持っている。



目次

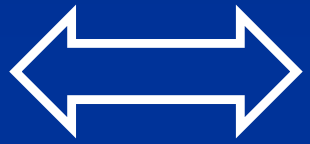
- Short Review
  - 今日まで、そして、残された課題
- T2KK
  - J-PARC, SK, and Korea
- 最適地
  - 質量階層性,　CP phase,　octant,
- まとめ

Short Review

Parameters (3gene.)

Neutrino Physics 7/9 parameters

- neutrino masses
  - m_1 m_2 m_3
- flavor mixing angles
  - θ_{12} θ_{23} θ_{13}
- CP phase
  - δ
- Majorana phases
  - ϕ_1 ϕ_2



Neutrino Oscillation 6 parameters

- squared-differences
  - δm^2_{12} δm^2_{13} $(\equiv m^2_3 - m^2_1)$
- flavor mixing angles
  - θ_{12} θ_{23} θ_{13}
- CP phase
  - δ
- Majorana phases
  - nothing

現状

$\sin^2 2\theta_{12} = 0.84 \pm 0.07$ $\left(\theta_{12} < 45^\circ\right)$

$\delta m^2_{12} = \left(8.3 \pm 0.6\right) \times 10^{-5}\,\mathrm{eV}^2$ $\left(\delta m^2_{12} > 0\right)$

full 100%

solar neutrino (SK,SNO), reactor (KamLAND)
物質効果の有効利用

$\sin^2 2\theta_{23} = 0.96 - 1.00$ $\left(\theta_{23} = 45^\circ \pm 5^\circ\right)$

$\left|\delta m^2_{13}\right| = \left(2.5 \pm 0.5\right) \times 10^{-3}\,\mathrm{eV}^2$ (絶対値だけ)

half 50%

atmospheric neutrino (SK), long-baseline (K2K)
振動確率が偶関数

$\sin^2 2\theta_{13} < 0.16$ (上限値だけ)

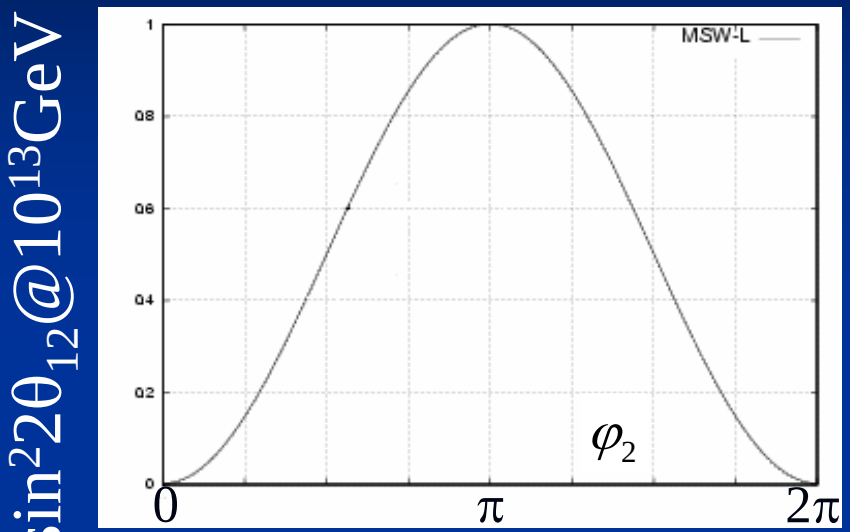
δ_{MNS} (未知量)

non 0%

reactor neutrino exp.(CHOOZ)
将来的に測定されるだろう。

もしも“inverted”なら

- 量子補正が無視できない



m_3 = 0.0, $\sin^2 2\theta_{12}$=1.0 @ M_Z [GeV]
inverted hierarchy and large tanβ

$\varphi_2=\pi$: large mixing angle は量子補正で変化しない。

$\varphi_2=0$: large mixing angle は量子補正で変化する。

[hep-ph/0005075]

- Effective mass of $0\nu 2\beta$ decay

$$\langle m_{ee} \rangle = \left| m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{-i\varphi_2} + m_3 U_{e3}^2 e^{-i\varphi_3} \right|$$

inverted hierarchy + large tanβ + φ_2~0.0
⇔ θ_{12}:large mixing angle は量子補正由来

T2KK

T2K実験

+

large detector in 韓国

基本戦略（定性的）

$$P(\nu_\mu \to \nu_e) = 2(1+q)\sin^2\theta_{\rm rct}\left(1+A^e\right)\sin^2\left(\frac{\Delta_{13}}{2}+B^e\right)$$

hierarchy

$$q \equiv 2\sin^2\theta_{\rm atm} - 1, \qquad \Delta_{ij} \equiv \left(\delta m^2_{ij}/2E\right)L$$

$$A^e = \frac{aL}{\Delta_{13}E}\cos^2 2\theta_{\rm rct} - \frac{\Delta_{12}}{2}\frac{\sin 2\theta_{\rm sun}}{\sin\theta_{\rm rct}}\sqrt{\frac{1-q}{1+q}}\sin\delta_{\rm MNS} \qquad a = 2\sqrt{2}G_F E n_e$$

$$\approx 0.37\frac{\pi}{\Delta_{13}}\frac{L}{1000\text{km}} - \left[0.29\sqrt{\frac{1-q}{1+q}}\left(\frac{0.10}{\sin^2 2\theta_{\rm rct}}\right)^{1/2}\sin\delta_{\rm MNS}\right]\frac{|\Delta_{13}|}{\pi}$$

$$B^e = -\frac{aL}{4E}\cos 2\theta_{\rm rct} + \frac{\Delta_{12}}{2}\left(\frac{\sin 2\theta_{\rm sun}}{2\sin\theta_{\rm rct}}\sqrt{\frac{1-q}{1+q}}\cos\delta_{\rm MNS} - \sin^2\theta_{\rm sun}\right)$$

~1st maximum

$$\approx -0.29\frac{L}{1000\text{km}} + \left[0.15\sqrt{\frac{1-q}{1+q}}\left(\frac{0.10}{\sin^2 2\theta_{\rm rct}}\right)^{1/2}\cos\delta_{\rm MNS} - 0.015\right]\frac{|\Delta_{13}|}{\pi}$$

“matter effect” ⇔“base-line length”

hep-ph/0602115

T2Kのビームは韓国へ

Off-Axis-Beam (OAB) : 円錐状に広がる

Super-K

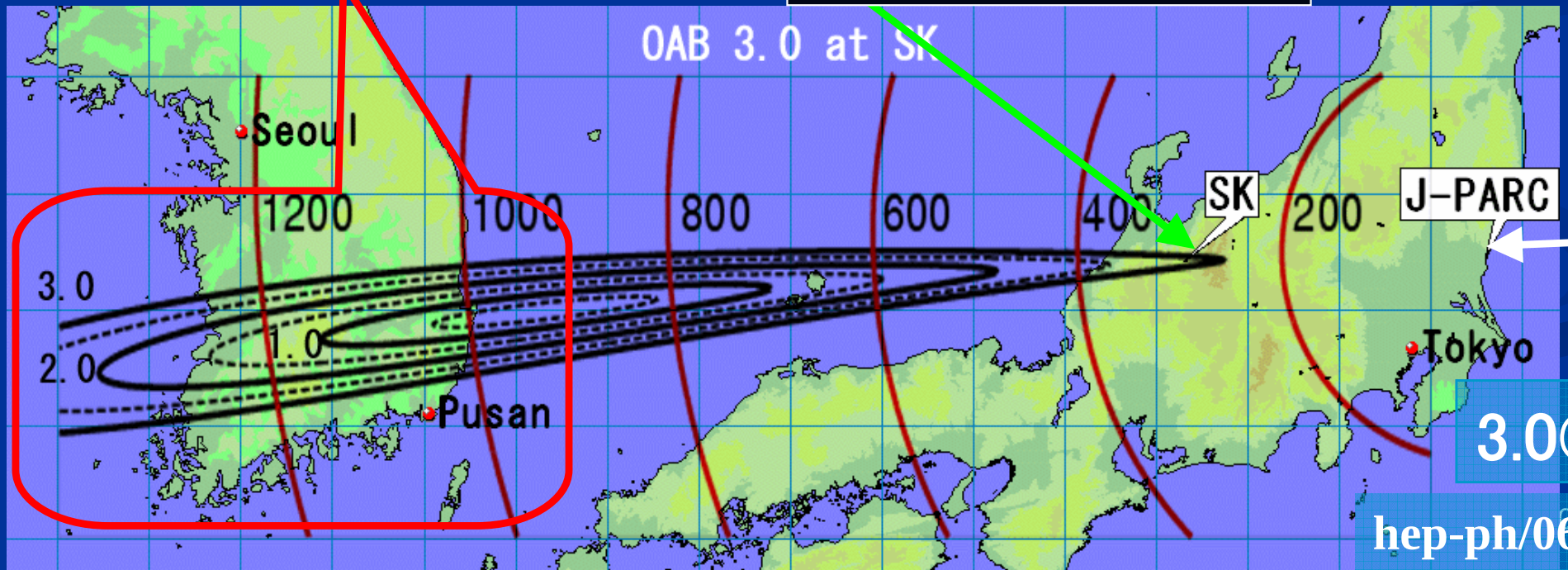
on-axis

L=295km,
θ=2.0°-3.0°

J-PARC

L=1000-1200km,
θ=1.0°-4.0°

S-Korea



hep-ph/0607255

条件

- **fiducial volume (100% efficiency)**
  - SK : 22.5 kton　　Korea : 100 kton

- **露出時間**
  - ５年（10^{21} POT/year ,0.8MW）, T2K-I running time
  - anti-neutrino は<u>使わない</u>

- **基線長と角度**
  - SK: L=295km　　with　θ=2.5^{o} or 3.0^{o}
  - KR: L=1000-1200 km　with　θ=(0.5^{o} ~ 3.0^{o}) / 0.5^{o} step

韓国での角度は距離とSKでの角度に依存する

Event Number

- **CCQE event**
  - easy reconstruct the neutrino energy
  - easy distinguish, *e*-like, μ-like
- **ビン切り**
  - ビン幅: 200MeV (Fermi motion 80MeV)
  - 領域 (#event > 10)
    - 0.4 - 5.0 GeV for μ-like (SK/Korea)
    - 0.4 - 1.2 GeV for *e*-like (SK)
    - 0.4 - 2.8 GeV for *e*-like (Korea)
- **バックグラウンド**
  - beam contaminationsは含む (another flavor in beam)
  - NC backgroundは含まない ($\pi^0 ! \gamma\gamma \Leftrightarrow$ *e*-shower)

入力値

- 太陽
  - $\sin^2 2\theta = 0.83 \pm 0.07$, $\delta m^2 = (8.2 \pm 0.6) \times 10^{-5}$ eV^2
- 大気
  - $\sin^2 2\theta = 1.00 \Leftrightarrow 0.96$, $\delta m^2 = 2.5 \times 10^{-3}$ eV^2
- 物質密度（不定性: ±3%）
  - $\rho = 2.8 / 3.0$ (g/cm^3) (SK/Korea)
- その他（systematic）（不定性: ±3%）
  - flux normalization (each species)
  - CCQE cross section (ν / anti-ν)
  - fiducial volume (SK / Korea)

#total parameters:16

χ^2 -rule of the game-

$$\chi^2 = \sum_{\substack{i:\text{bin} \\ \alpha:e,\mu}} \left(\frac{\left(N_\alpha^i\right)^{\text{fit}} - \left(N_\alpha^i\right)^{\text{input}}}{\sqrt{\left(N_\alpha^i\right)^{\text{input}}}} \right)^2$$

event number

sys. error

$$+ \sum_{\text{all flavor}} \left(\frac{f_{\nu_\beta}^{flux} - 1.0}{0.03} \right)^2 + \sum_{\nu,\bar{\nu}} \left(\frac{f_{\nu_\alpha}^{QE} - 1.0}{0.03} \right)^2 + \sum_{\text{SK,Kr}} \left\{ \left(\frac{f_\rho - 1.0}{0.03} \right)^2 + \left(\frac{f_V^{\text{SK/Kr}} - 1.0}{0.03} \right)^2 \right\}$$

$$+ \left(\frac{\left(m_2^2 - m_1^2\right)^{\text{fit}} - 8.2\times10^{-5}\left(\text{eV}^2\right)}{0.6\times10^{-5}\left(\text{eV}^2\right)} \right)^2 + \left(\frac{\left(\sin^2 2\theta_{\text{sun}}\right)^{\text{fit}} - 0.83}{0.07} \right)^2$$

$$+ \left(\frac{\left(\sin^2 2\theta_{\text{rct}}\right)^{\text{fit}} - \left(\sin^2 2\theta_{\text{rct}}\right)^{\text{input}}}{0.01} \right)^2$$

原子炉実験
Double CHOOZ

parameter error

問題を解くのに重要
T2KKは原子炉実験に比べて不利

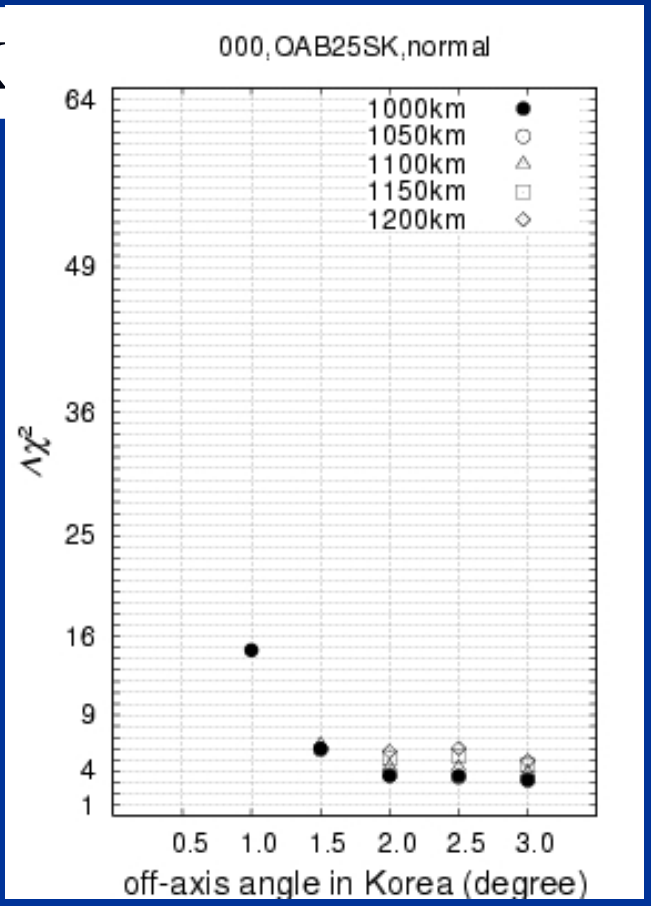
最適地

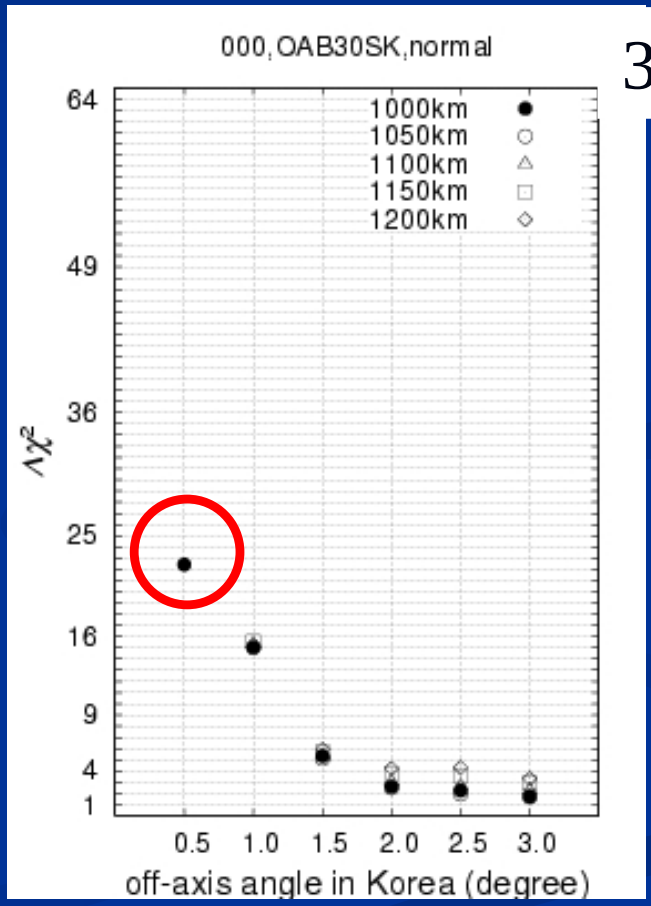
質量階層性

true : "normal"
fit : "inverted"

true : $\sin^2 2\theta_{13} = 0.1$ ⇔ free : *fit*
$\delta = 0.0$ ⇔ free

2.5@SK



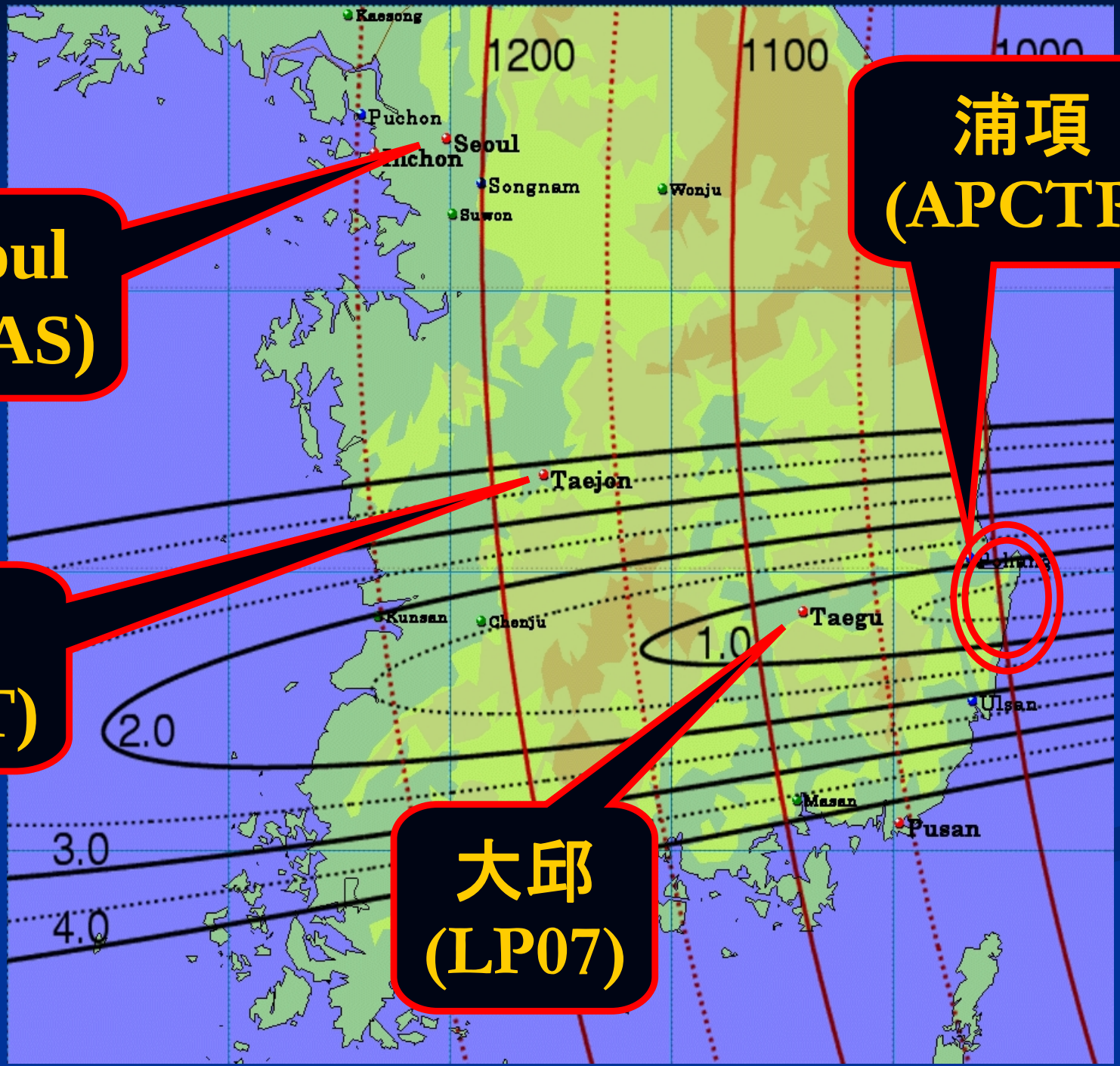


3.0@SK

最適地: L=1000km with 0.5º and 3.0º@SK

$L = 1000$ km and $\theta = 0.5^o$

$SK : \theta = 3.0^o$



Seoul (KIAS)

浦項 (APCTP)

大田 (KAIST)

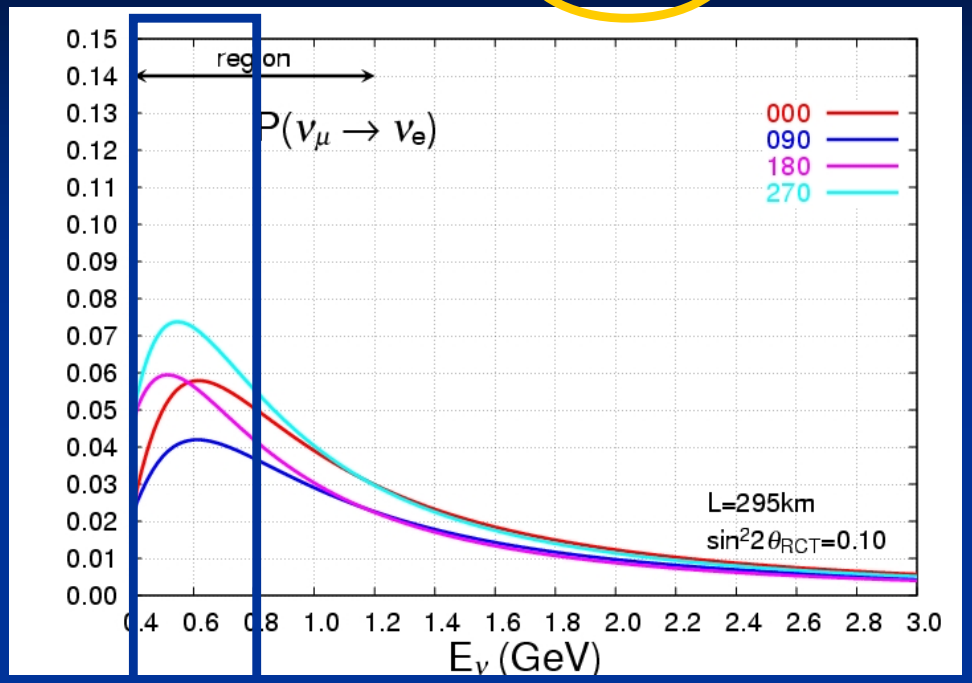
大邱 (LP07)

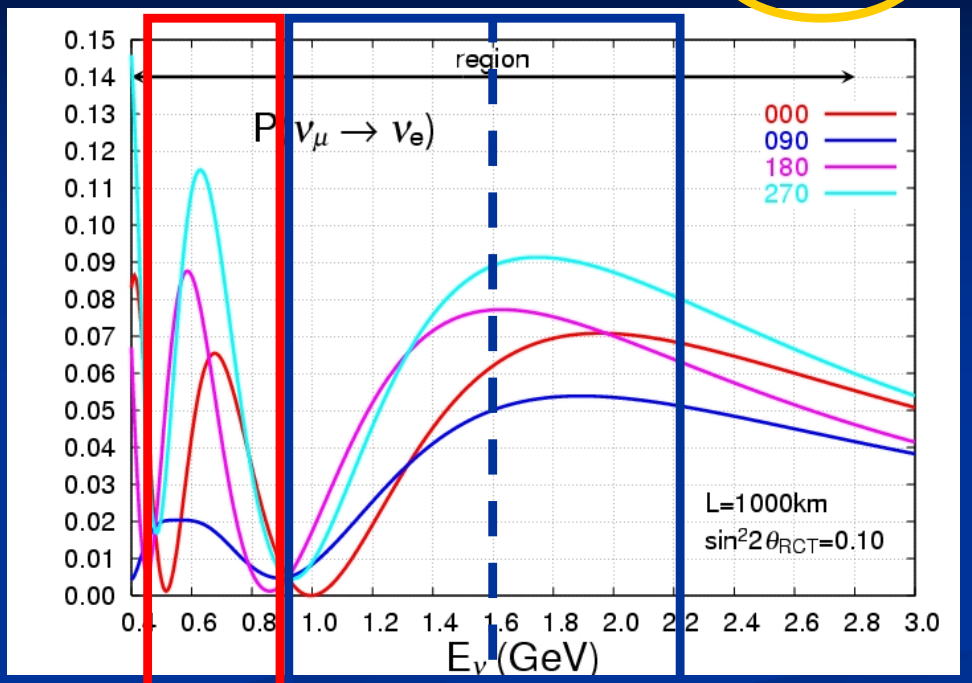
hep-ph/0504061

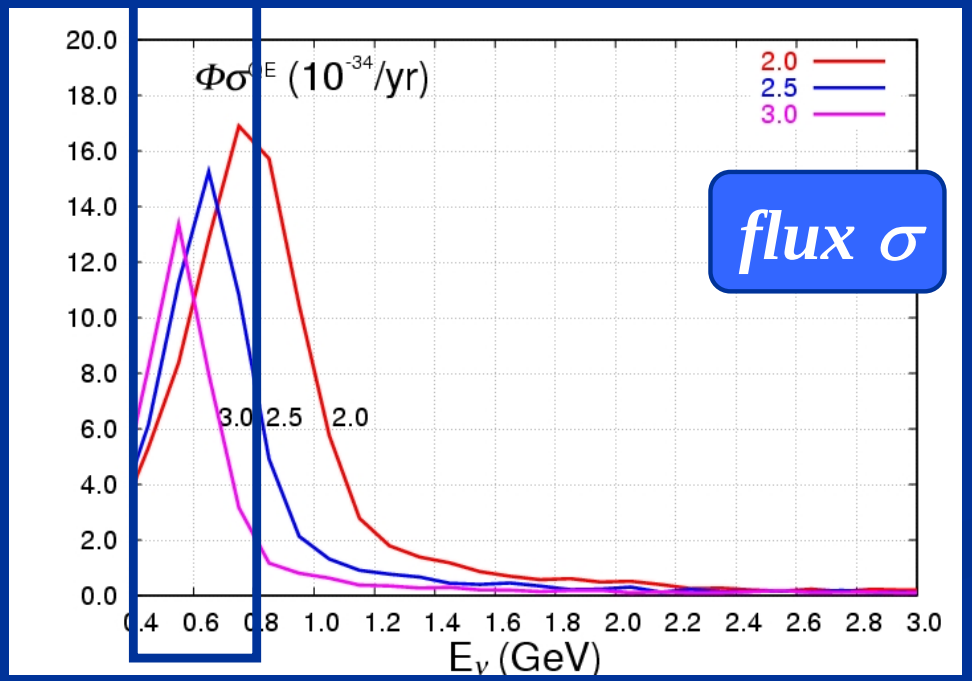
理由

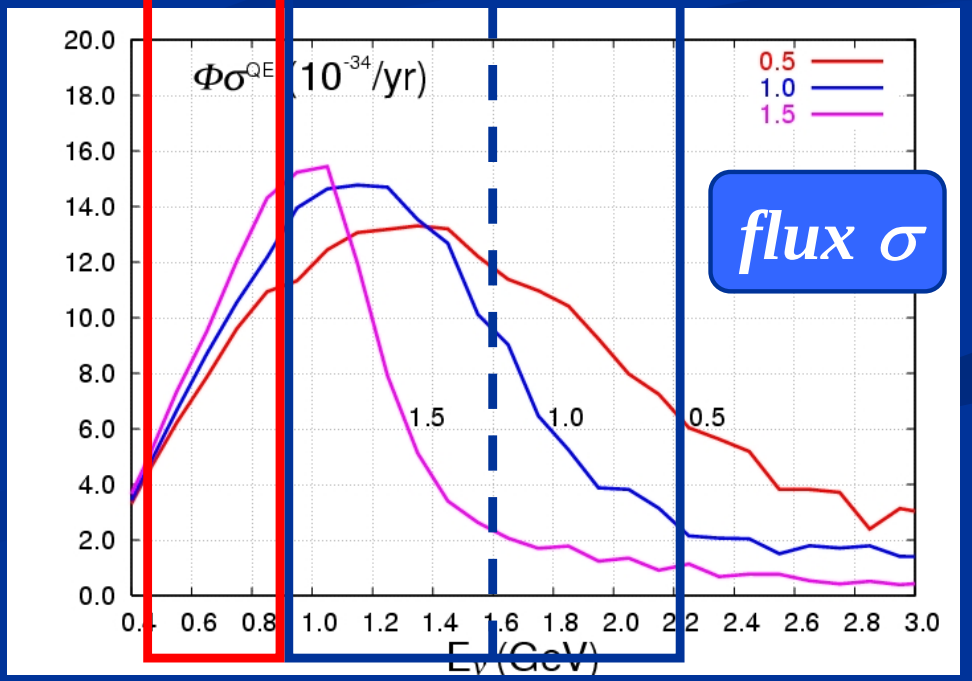
SK

Kr

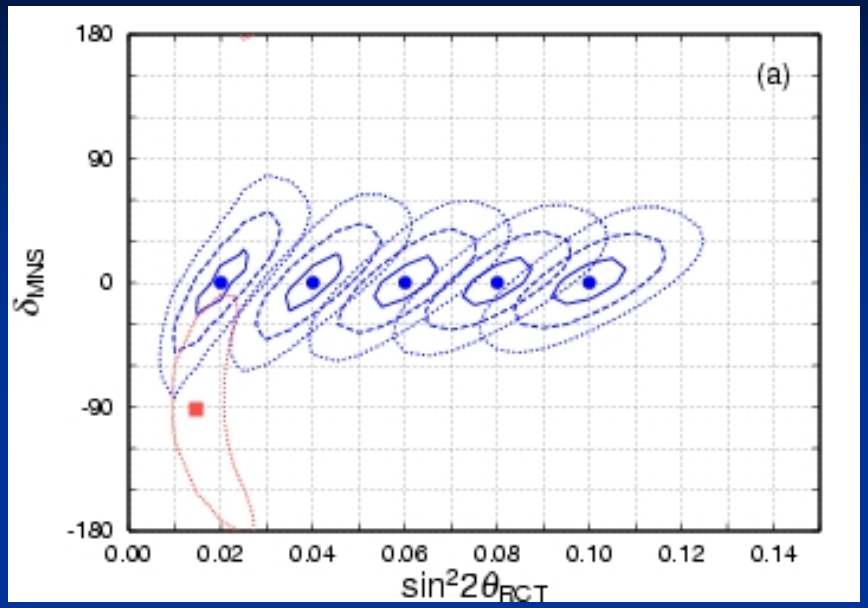

region
$P(\nu_\mu \to \nu_e)$
000
090
180
270
L=295km
$\sin^2 2\theta_{RCT}$=0.10
E_ν (GeV)

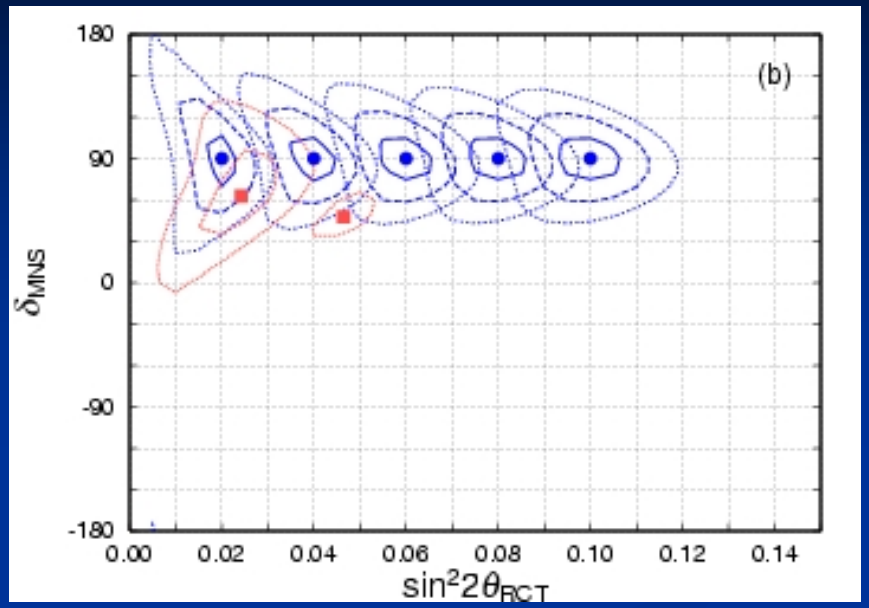

region
$P(\nu_\mu \to \nu_e)$
000
090
180
270
L=1000km
$\sin^2 2\theta_{RCT}$=0.10
E_ν (GeV)

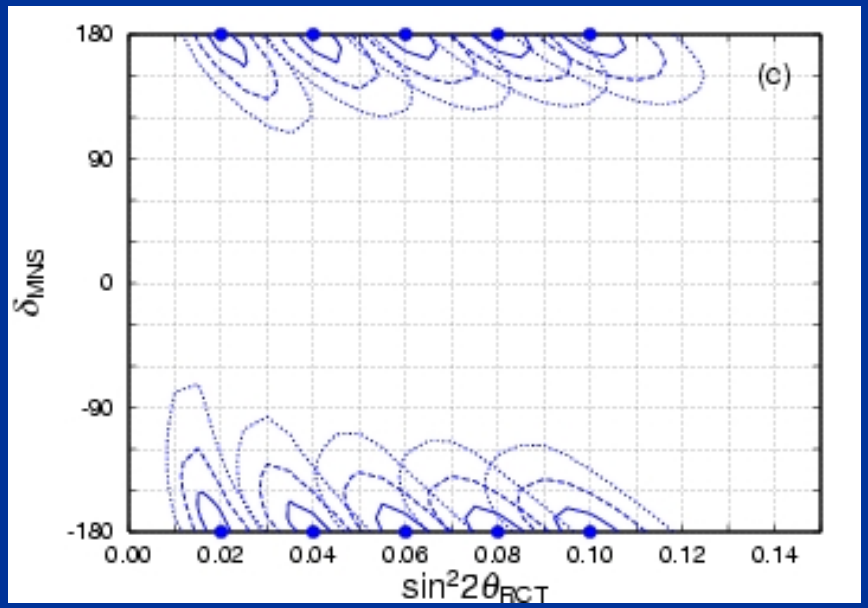

$\Phi\sigma^{QE}$ (10^{-34}/yr)
2.0
2.5
3.0
3.0
2.5
2.0
flux σ
E_ν (GeV)

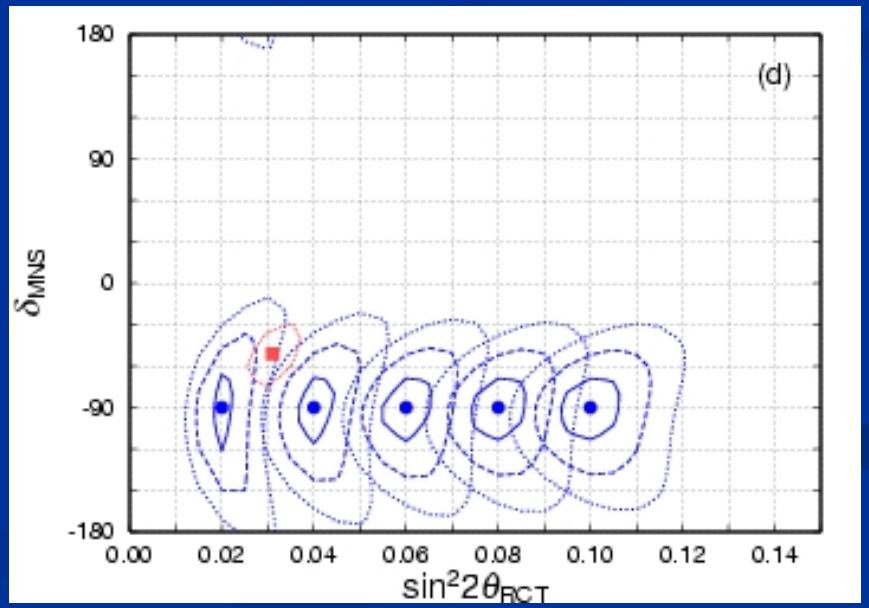

$\Phi\sigma^{QE}$ (10^{-34}/yr)
0.5
1.0
1.5
1.5
1.0
0.5
flux σ
E_ν (GeV)

CP位相（normal hierarchy）



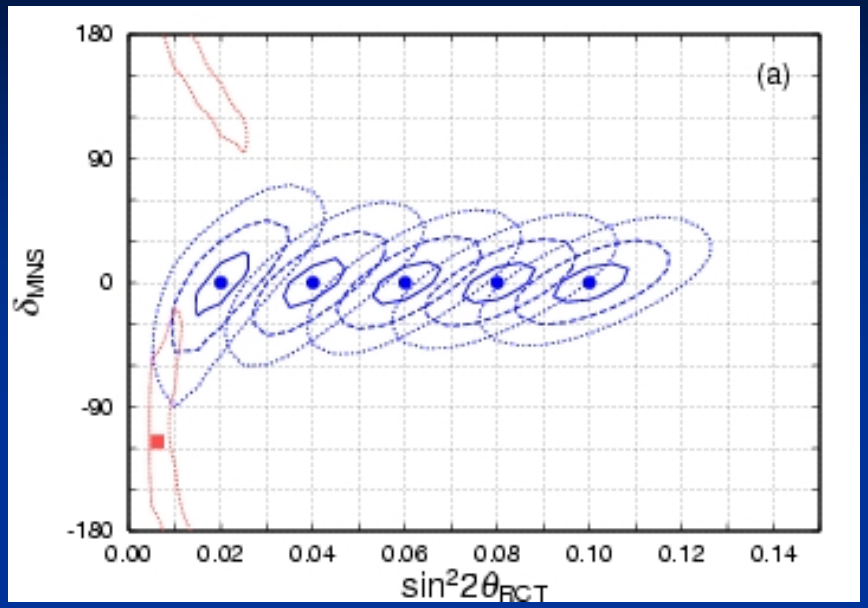


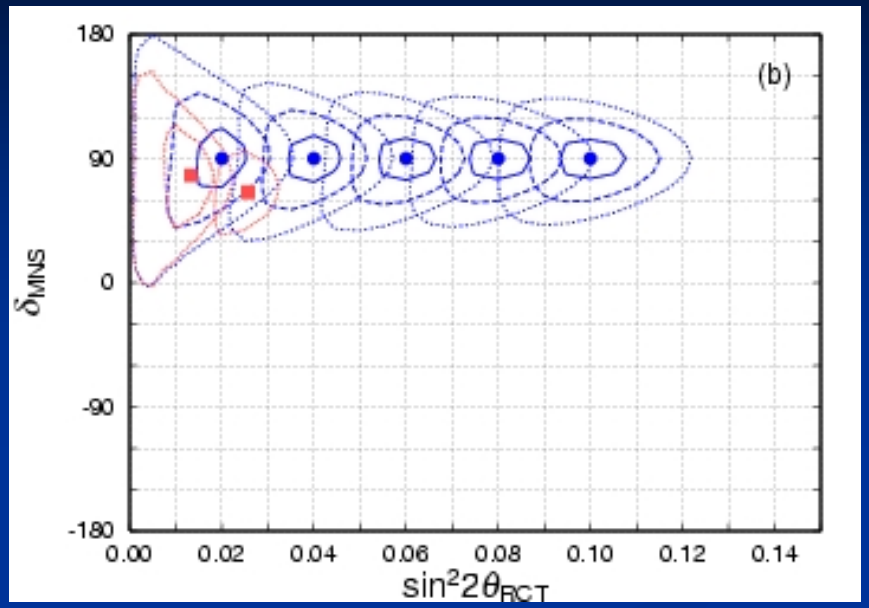


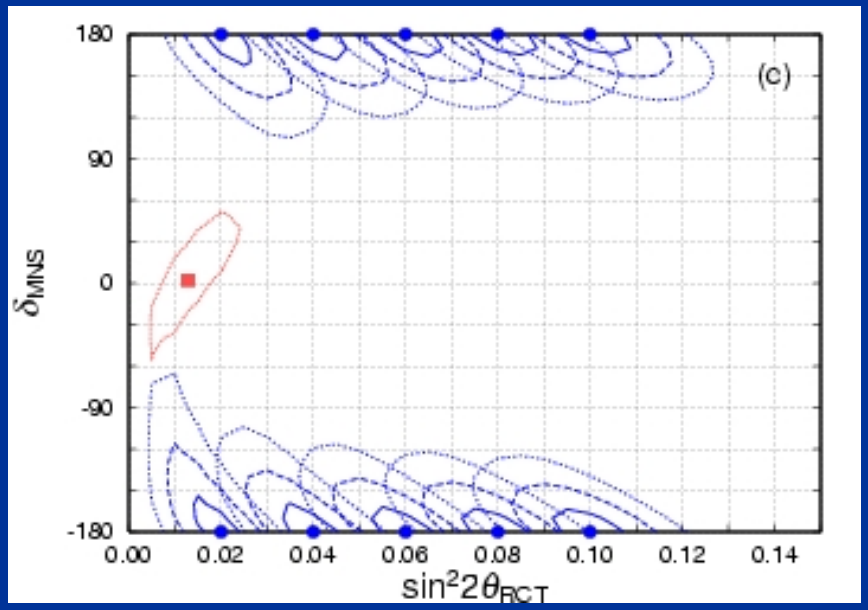


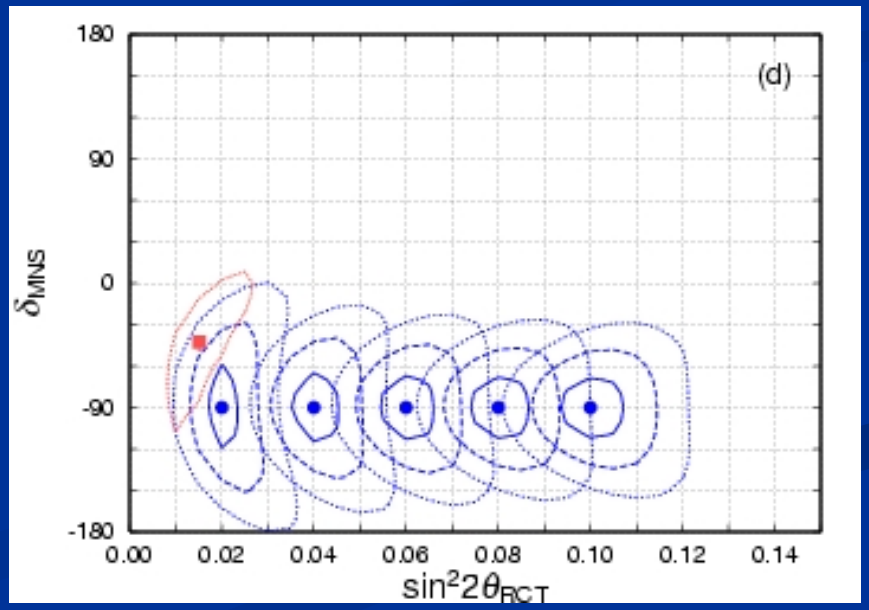
without anti-neutrino

CP位相（inverted hierarchy）



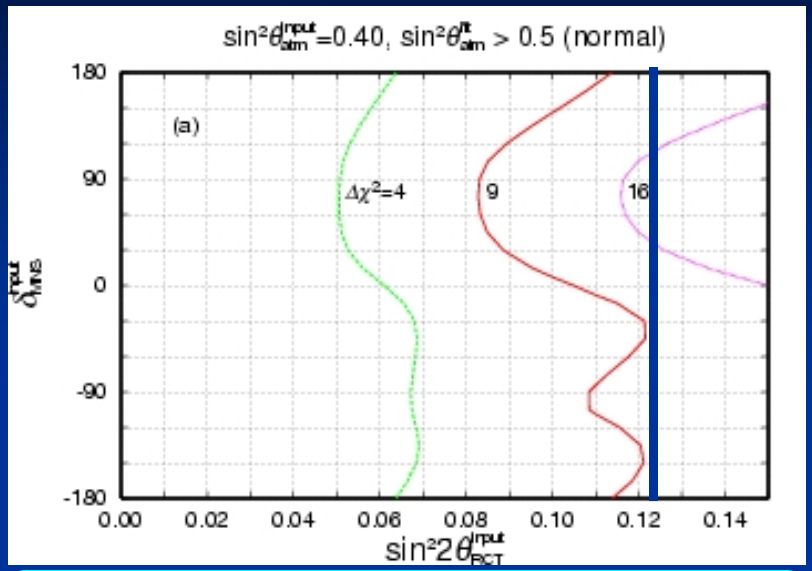




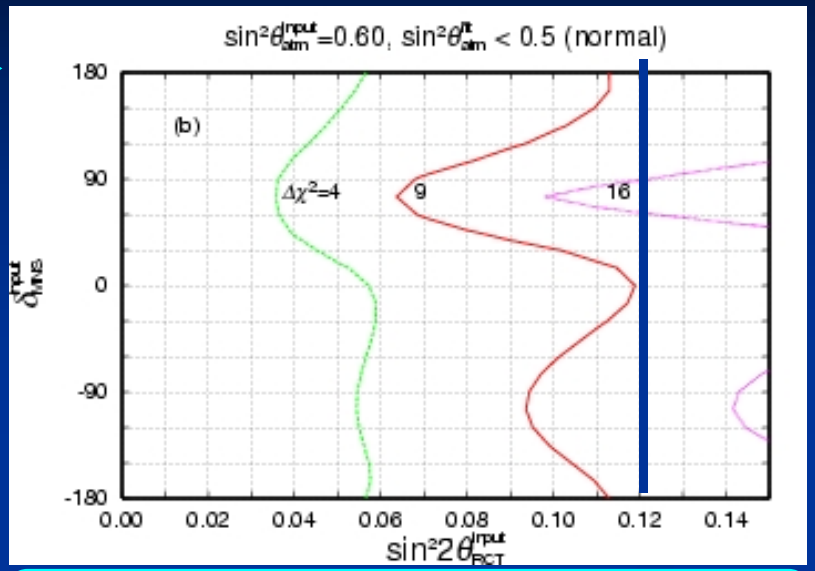


without anti-neutrino

octant



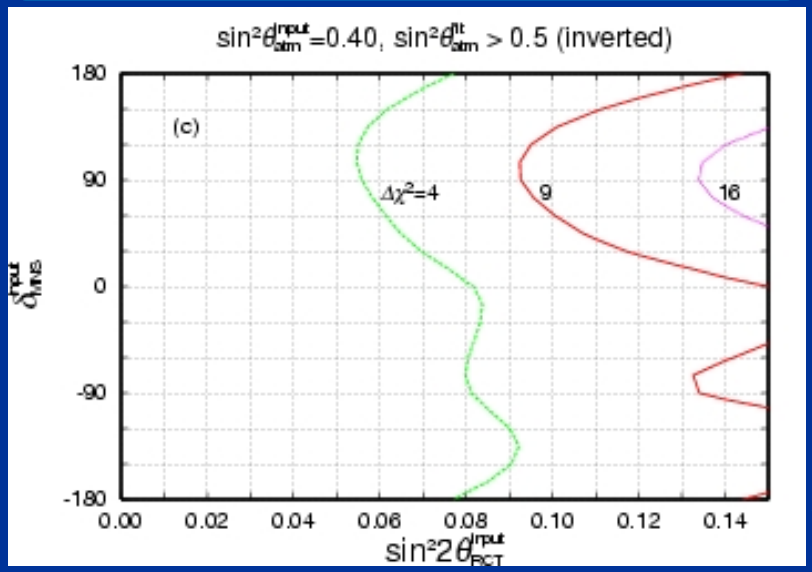
nor



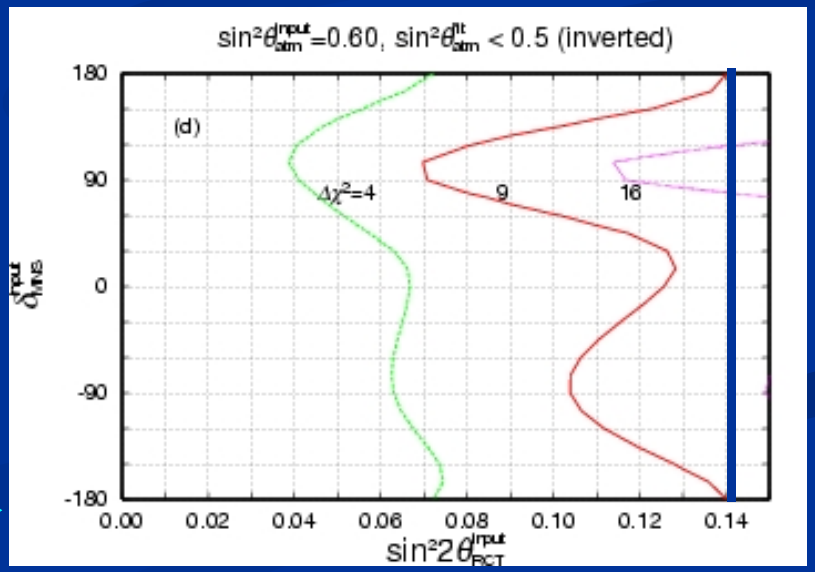
input : θ<45º fit : θ>45º

0.96

input : θ>45º fit : θ<45º



inv

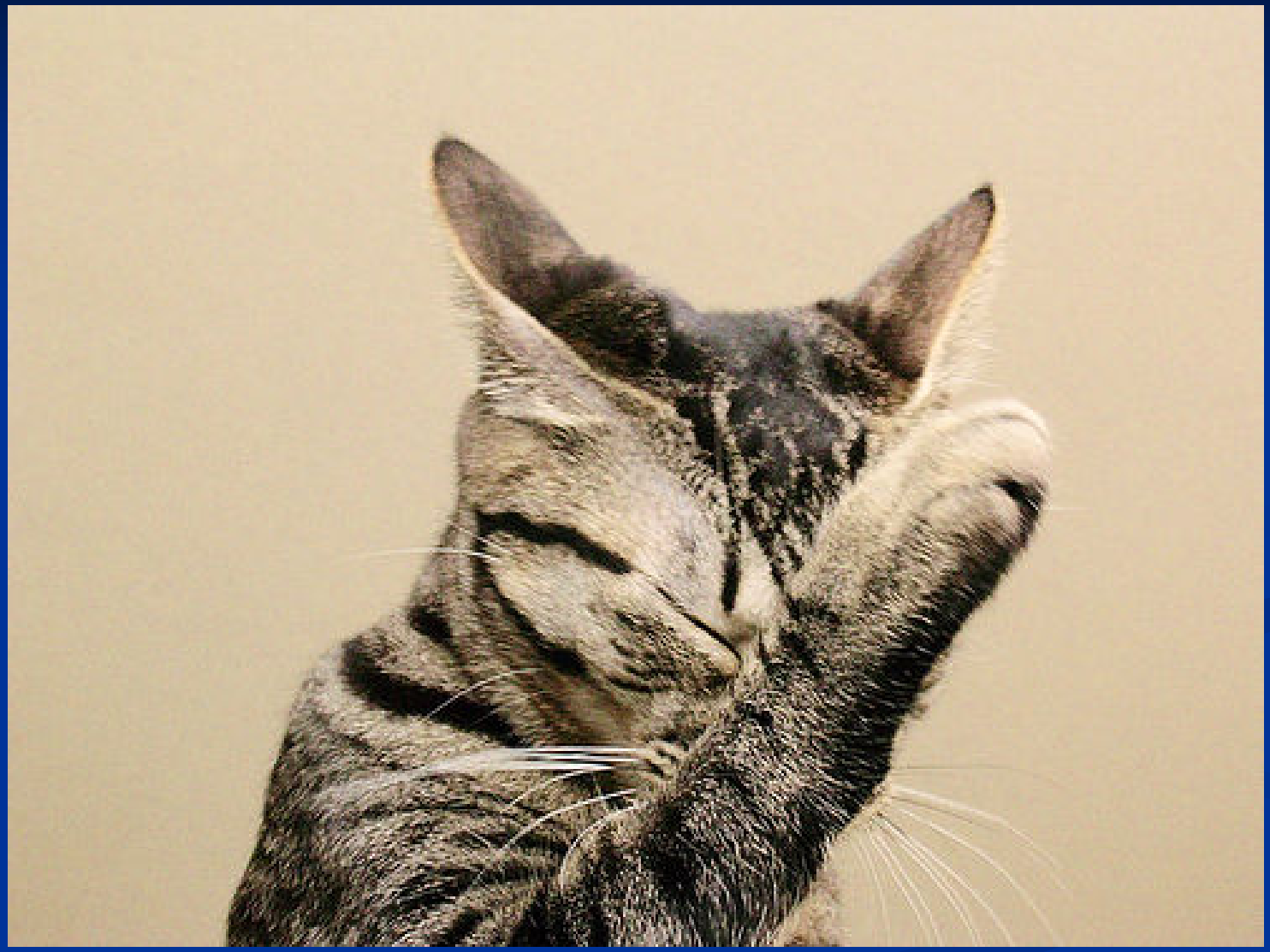


まとめ

- T2KK
  - T2K+ Large Detector (100kton) in Korea
  - 物質効果の大きさ（距離に比例）の違いが決め手
    質量階層性、CP位相、octant

- T2KK + 原子炉実験（Double CHOOZ）
  - 質量階層性　　(3σ: $\sin^2 2\theta_{13} \sim 0.05$)
  - CP位相　　($\pm 30^o$ ： without anti-neutrino)
  - Octant(0.40⇔0.60)　(3σ: $\sin^2 2\theta_{13} \sim 0.12$)

thank you for your attention



N.Okamura, okamura@yukawa.kyoto-u.ac.jp