What can we learn from neutrinos ?

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2023.02.20

@ C.A.U. BSM Workshop

SM of particle physics before 1998 :

$$\mathcal{L}^{(0)}_{SM} = \underbrace{\mathcal{L}_{G.B.}} + \underbrace{\mathcal{L}_{\phi}\,(\text{Higgs})} + \mathcal{L}_{F} + \mathcal{L}_{Yukawa} \quad \Leftarrow \text{Why ?}$$

$SU(3)_c \times SU(2)_L \times U(1)_Y \to U(1)_{EM}$ $\Leftarrow$ $\langle\phi\rangle = \begin{pmatrix} \frac{v}{\sqrt{2}} \\ 0 \end{pmatrix}$ How ? $\quad \phi^c = -i\sigma^2\phi^*$ $\quad \langle\phi^c\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$ } Why ?

$Y = -\frac{1}{2}$ $\qquad$ SU(2) doublet 2, $Y = +\frac{1}{2}$

F :	$Q_K = \begin{pmatrix} u_{LK} \\ d_{LK} \end{pmatrix}$	u_{RK}	d_{RK}	$L_K = \begin{pmatrix} \nu_{LK} \\ l_{LK} \end{pmatrix}$	l_{RK}	(K = 1, 2, 3 generation/flavour index) Why ?
$SU(3)_c$	3	3	3	1	1	} GUT ?
$SU(2)_L$	2	1	1	2	1	
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$\leftarrow$ quantization

$$\mathcal{L}_{Yukawa} = \sum_{i,j=1}^{3} \left\{ y^u_{ij}\, Q^{\dagger}_i u_{Rj}\, \phi + y^d_{ij}\, Q^{\dagger}_i d_{Rj}\, \phi^c + y^l_{ij}\, L^{\dagger}_i l_{Rj}\, \phi^c + h.c. \right\}$$

$$\xrightarrow{\langle\phi\rangle} \sum_{i,j=1}^{3} \left\{ M^u_{ij}\, u^{\dagger}_{Li} u_{Rj} + M^d_{ij}\, d^{\dagger}_{Li} d_{Rj} + M^l_{ij}\, l^{\dagger}_{Li} l_{Rj} + h.c. \right\} \Rightarrow \text{all } \nu\text{s are massless}$$

$(\nu_e, \nu_\mu, \nu_\tau)$ in the (e, μ, τ) basis .

What we learned in 1998 ~ 2012:

1998: SK observed $\overset{(-)}{\nu}_\mu$ disappearance in Atmospheric ν's (E, L) ~ (1 GeV, 10 - 130,000 km)

1999 ~ K2K, MINOS, NOVA, T2K, --- Accelerator based LBNO experiments

Wide Band (K2K, MINOS) — NarrowBand (Off Axis) (NOVA, T2K) — (E, L) ~ (0.6 - 2 GeV, 250 - 800 km)

$\overset{(-)}{\nu}_\mu$ disappearance — $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ transitions

→ $\Delta m^2_{ATM} \sim (0.05\,eV)^2$, $\theta_{ATM} \sim 45°$ (maximum)

2001 ~ SNO — Solar $\nu_e \to \nu_\mu, \nu_\tau$ (deficit in ν_e, No deficit in N.C.)

2003 — KamLAND — Reactor $\bar{\nu}_e$ disappearance @ L ~ 200 km

(E, L) ~ (several MeV, > a few 100 km)

→ $\Delta m^2_{SOL} \sim (0.01\,eV)^2$, $\theta_{SOL} \sim 30°$

2012: DayaBay, RENO, D-Chooz observed Reactor $\bar{\nu}_e$ disappearance @ L ~ 1 km

(E, L) ~ (several MeV, ~ 1 km)

→ $\Delta m^2_{RCT} \simeq \Delta m^2_{ATM} \sim (0.05\,eV)^2$, $\theta_{RCT} \sim 12°$

⇒ All 3 mixing angles in 3×3 mixing matrix are determined.

$\Delta m^2_{SOL} = m_2^2 - m_1^2 > 0$ (matter effect in the Sun), $\Delta m^2_{ATM} = |m_3^2 - m_1^2|$ $m_3 \gtrless m_1$ (ν mass hierarchy).

What strcked us/me most by the 1998 ∼ 2012 observations ?

- ν's are massive. $\Rightarrow \mathcal{L}^{(0)}_{SM}$ should be modified. $\Rightarrow$ How ?

- ν masses are very small as compared to the other masses.

$$m_1 + m_2 + m_3 \quad \begin{matrix} > 0.06\,\mathrm{eV} \ \left(\sqrt{\Delta m^2_{ATM}} + \sqrt{\Delta m^2_{SOL}}\right) \\ \lesssim \sim 1\,\mathrm{eV} \ (\text{cosmology}) \end{matrix} \quad \ll m_e \sim 500{,}000\,\mathrm{eV}.$$

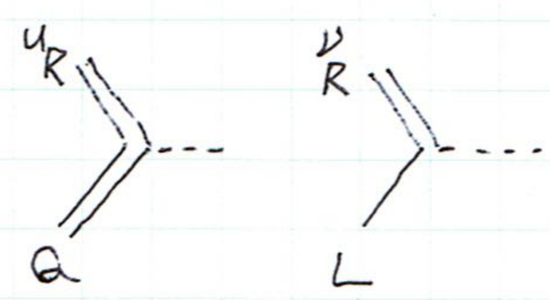
- ν mixings are very large. $\theta_{ATM} \sim 45°$, $\theta_{SOL} \sim 30°$, $\theta_{RCT} \sim 12°$ $\Leftrightarrow$ $\theta_{Cabibbo} \sim 9°$ largest in CKM.

$\Rightarrow$ Observed m_ν's are consistent with See-Saw mechanism @ GUT scale : $m_\nu \sim \dfrac{m_t^2}{M} \sim 0.03\,\mathrm{eV}$ if $M \sim 10^{15}\,\mathrm{GeV}$

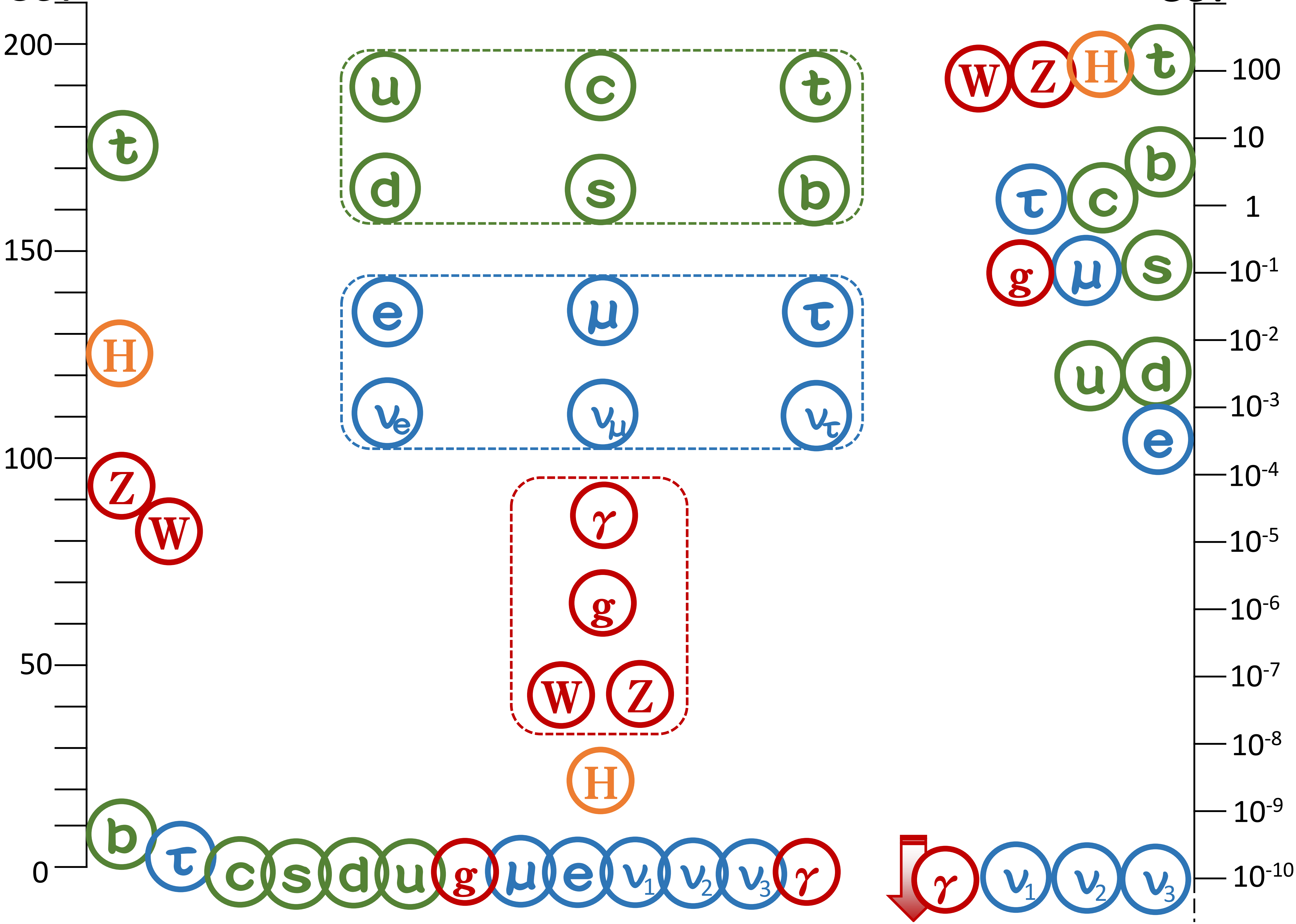
$\Rightarrow$ Large mixing for ν's may also have an origin @ GUT

- KH + N.Okamura (9811.495) In SU(5), $y^u = (y^u)^T$, $y^\ell = (y^d)^T$ $\Rightarrow$ same asymmetric y^d texture can give diagonal CKM and democratic MNS matrices.

- N.Haba (9807.552) In SU(5), $\begin{cases} \phi \in \underline{5}, \underline{5}^*, \ (d^c_R, L) \in \underline{5}^* & \Leftarrow \text{fundamental} \\ (Q, u^c_R, \ell^c_R) \in \underline{10}, \ \nu^c_R \in \underline{1} & \Leftarrow \text{composite} \end{cases}$



Elementary Particles (masses)



What are/should we study about ν's ?

- ν-mass hierarchy : $m_3^2 - m_1^2 > 0$ (normal) or < 0 (inverted)

  matter effect $\propto E_\nu$ ⇒ { two different L @ similar L/E : T2K & Korea (2004~16 slides) with N. Okamura et al
  ⇒ T2K & Dune (T2K → H)

  Atmospheric ν @ high energies : PINGU (2013 with S.F. Ge, C.R.H.)
  (precision) ⇒ SK & HK

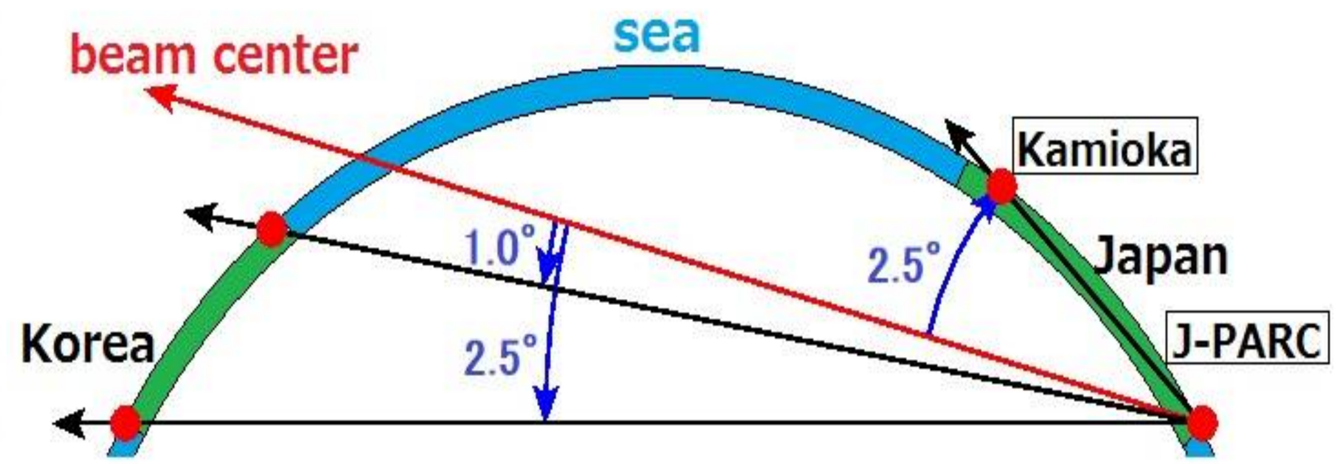
  relative phase between $(m_3^2 - m_1^2)$ & $(m_2^2 - m_1^2)$ oscillations ⇒ JUNO

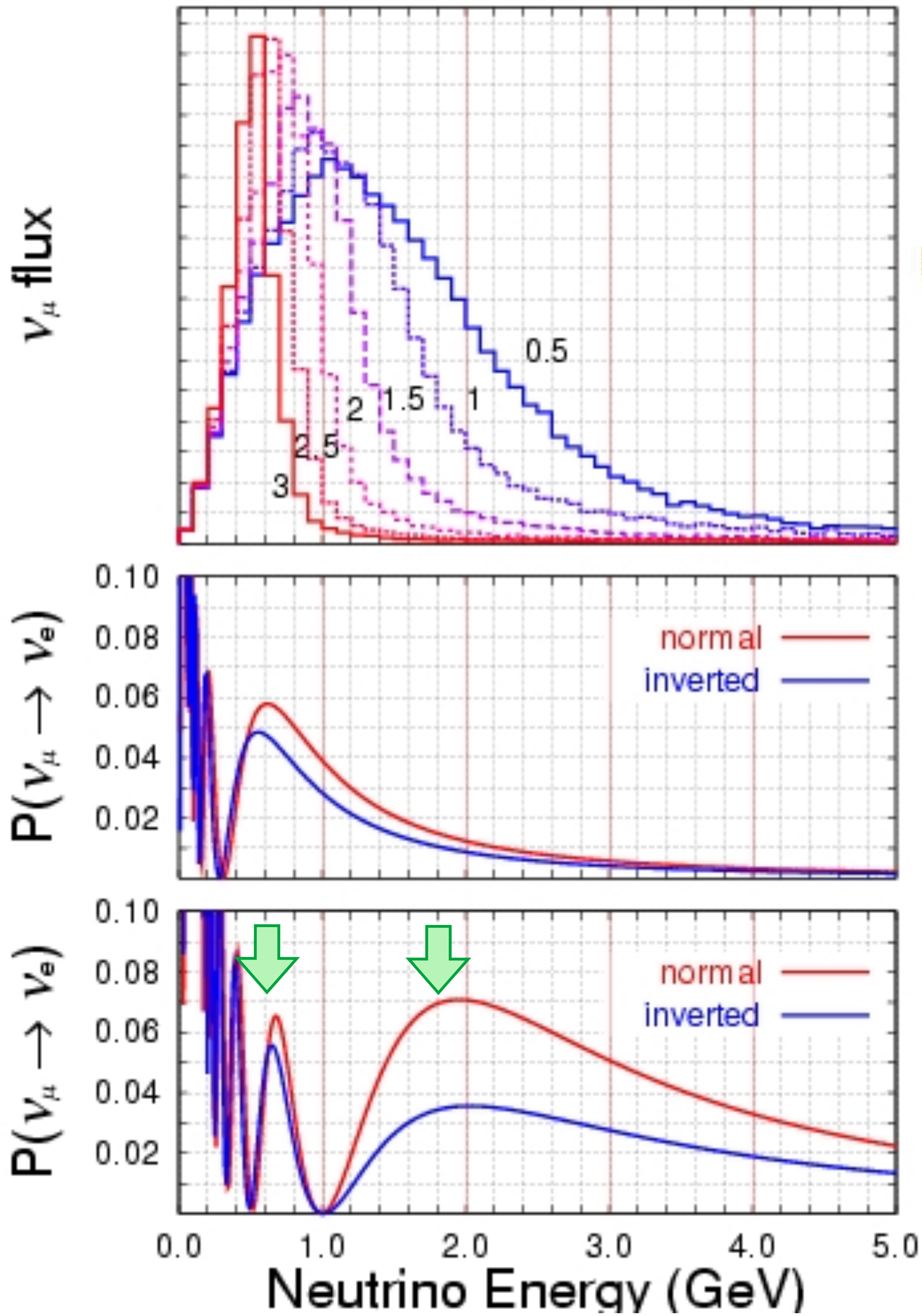
  Reactor $\bar{\nu}_e$ ($E_\nu \sim$ several MeV) @ $L \sim 60$ km

- CPV in ν-mixing matrix ⇒ Hint from T2K ($\nu_\mu \to \nu_e$ vs $\bar{\nu}_\mu \to \bar{\nu}_e$) ; resolution of mass hierarchy is necessary to determine δ.

- Dirac or Majorana mass ? ⇒ $0\nu\beta\beta$ decay expts. (LNV !)

- More ν's ? ⇒ { Sterile ν (ν_R) searches ⇒ osillations ? collider production ?
  Non-unitarity of 3×3 mixing matrix.





← Profile of off-axis beams

← $P(\nu_\mu \rightarrow \nu_e)$ at SK

← $P(\nu_\mu \rightarrow \nu_e)$ at Korea
(L=1000km)

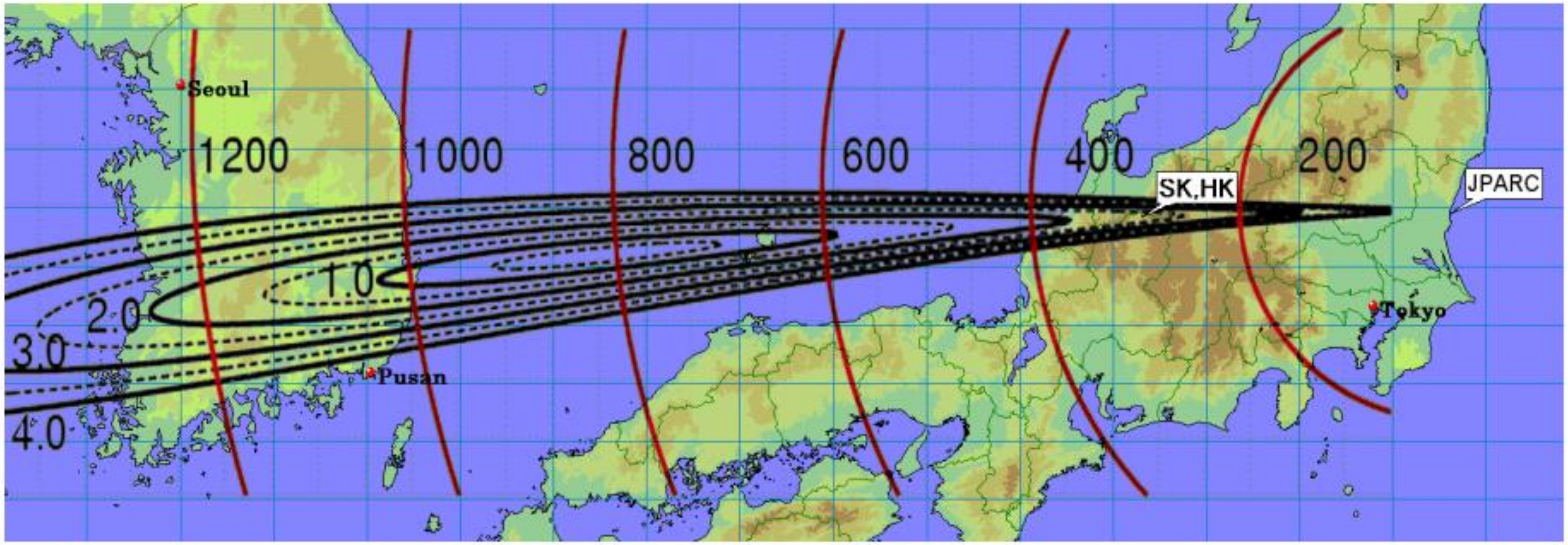


Figure 8. The fate of the OAB 2.5 degree beam from J-PARC. Surface view.

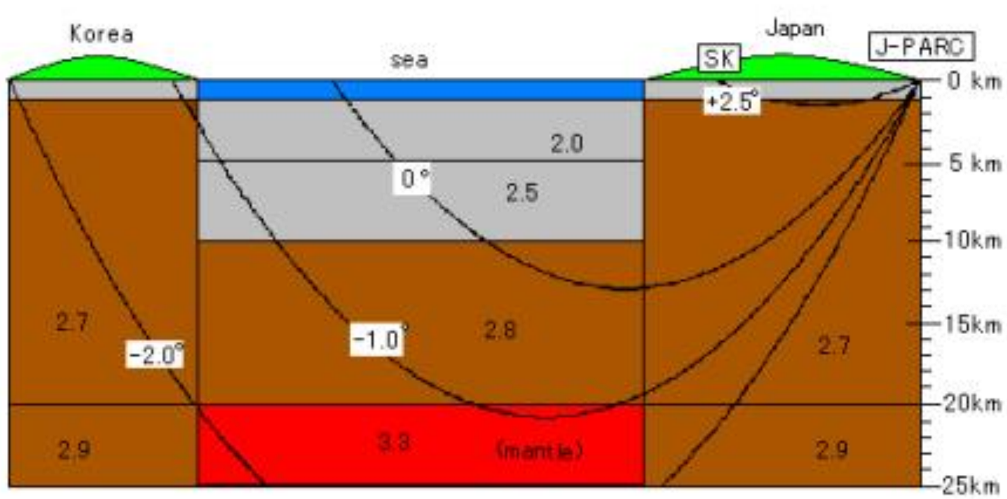
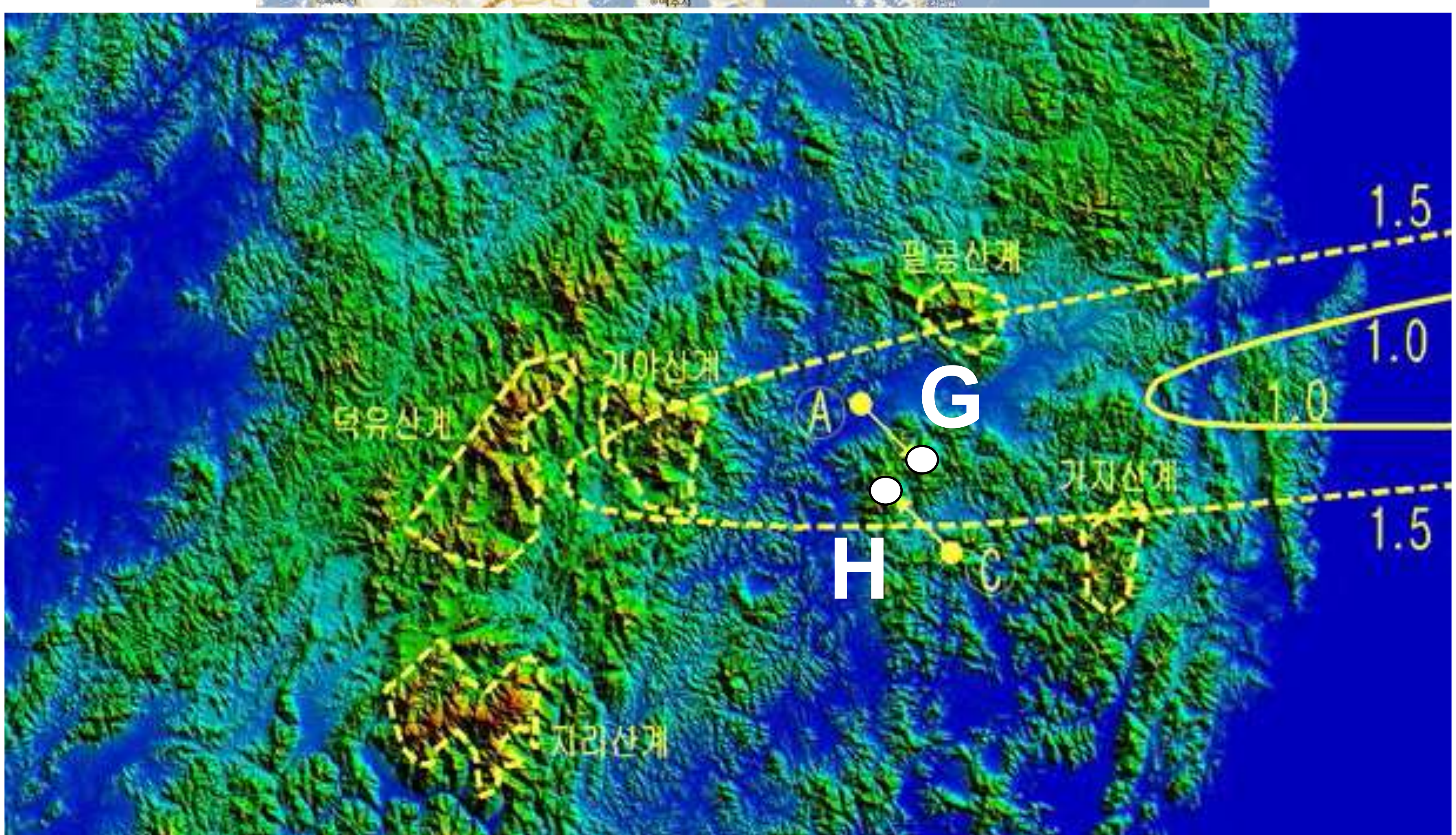


Figure 9. The fate of the OAB 2.5 degree beam from J-PARC. Vertical view.

6. High energy super beam to China

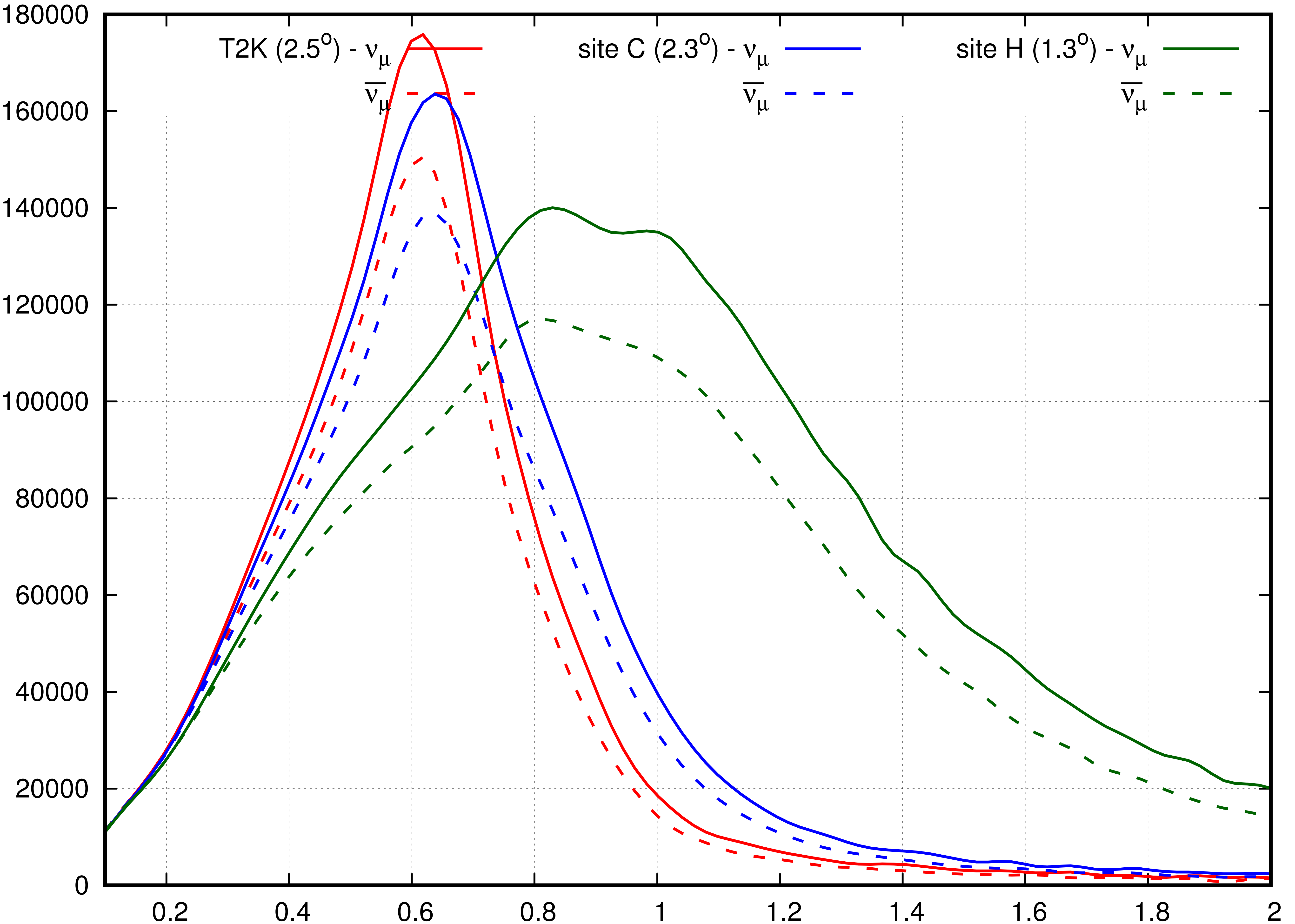
Although we do not yet know if there are strong enough interests in constructing a huge neutrino detector in Korea, strong interests have been expressed by our Chinese colleagues about the possibility of sending super neutrino beams from J-PARC at Tokai to somewhere in mainland China. A possible 100 kton level water Čerenkov detector BAND (Beijing Astrophysics and Neutrino Detector) [25] has been proposed, and if it will be placed in Beijing, the baseline length from Tokai will be about L=2,100 km. The unique capability of the BAND detector is that it is a segmented

Search for candidate sites in Korea (OAB: 1.0~1.5^{0})

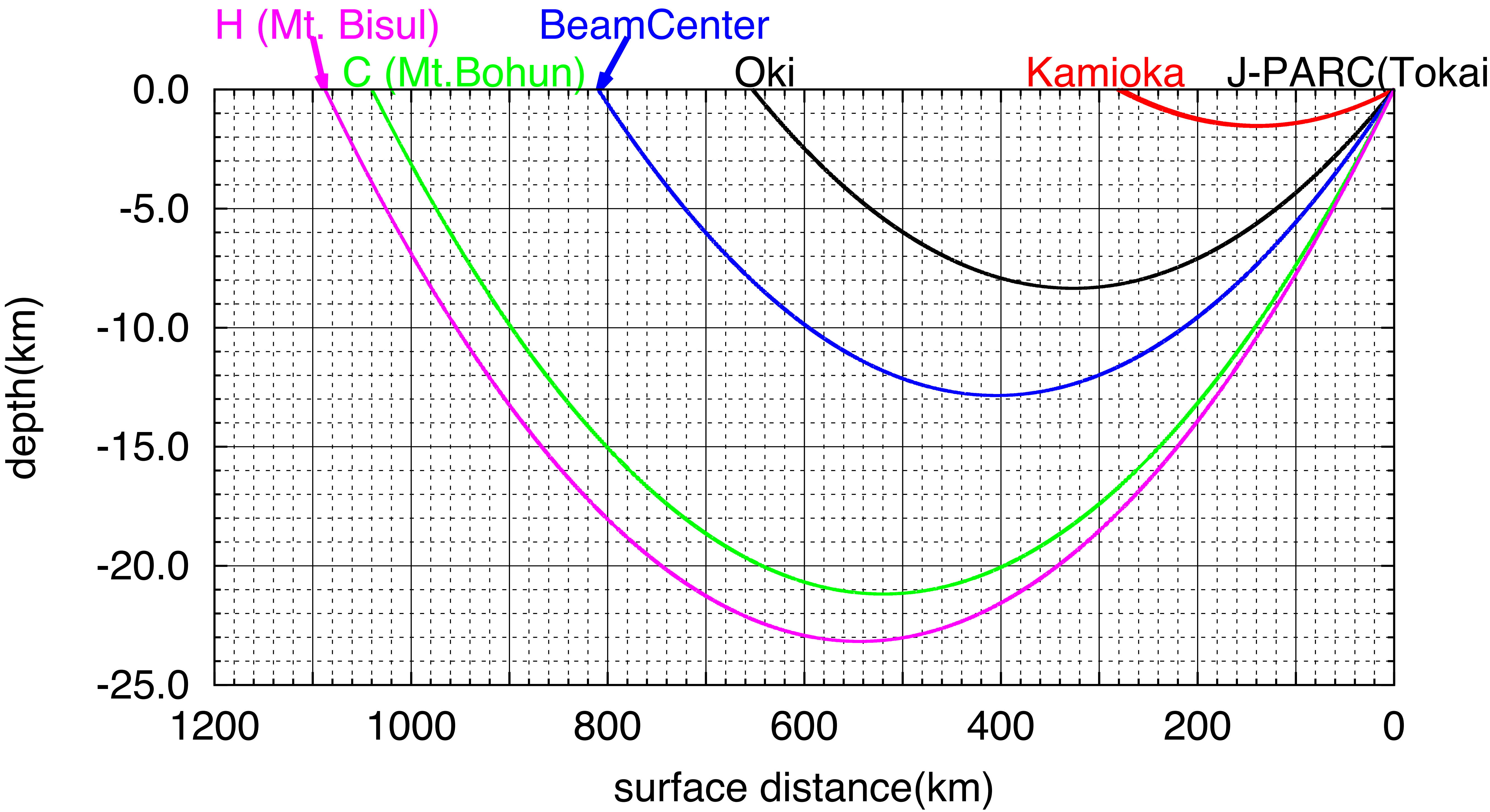


G : Mt. Choejung
(906 m high)
[granite porphyry, andesitic breccia]

H : Mt. Bisul
(1,084 m high)
[granite porphyry, andesitic breccia]



T2K (2.5°) - ν_μ
$\overline{\nu}_\mu$
site C (2.3°) - ν_μ
$\overline{\nu}_\mu$
site H (1.3°) - ν_μ
$\overline{\nu}_\mu$
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2



H (Mt. Bisul)
BeamCenter
C (Mt.Bohun)
Oki
Kamioka
J-PARC(Tokai)
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
depth(km)
1200
1000
800
600
400
200
0
surface distance(km)

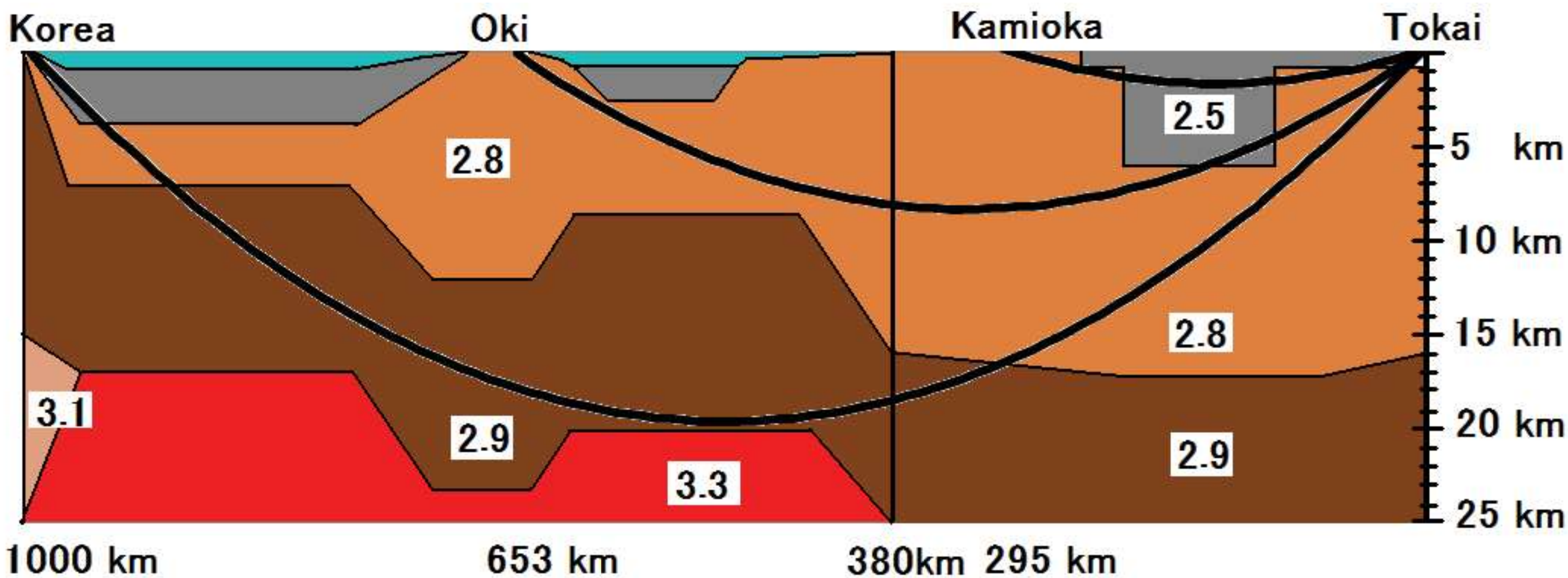
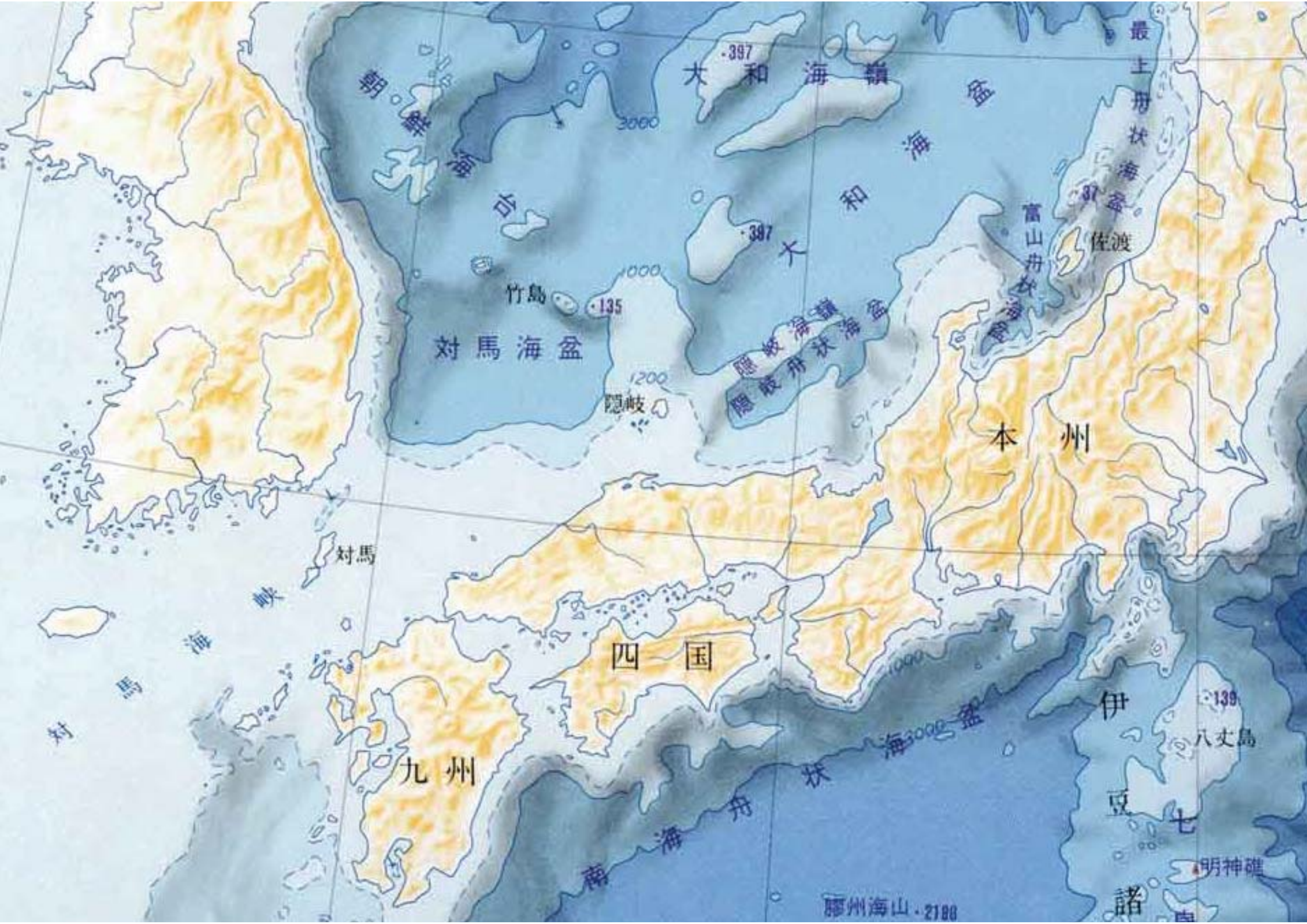
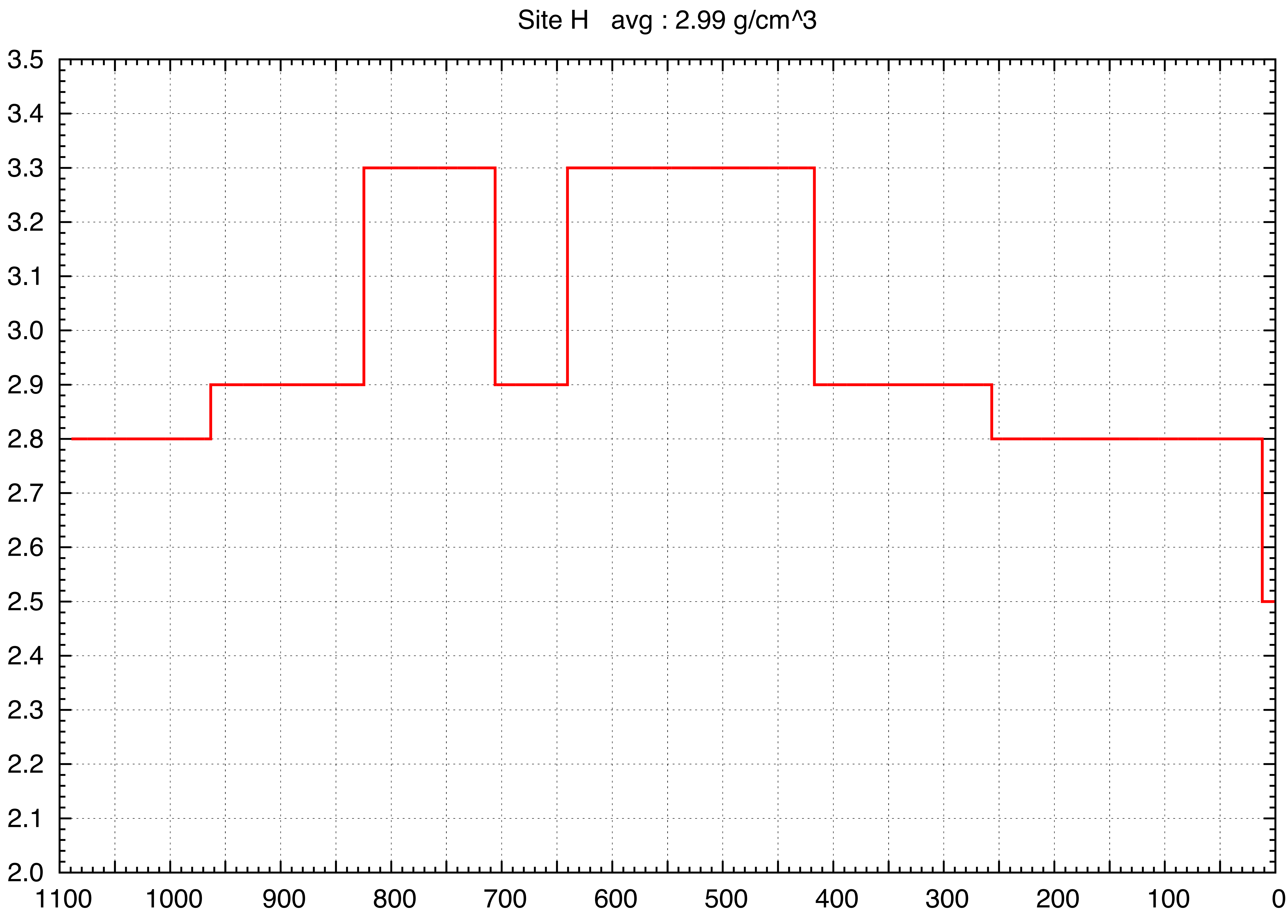
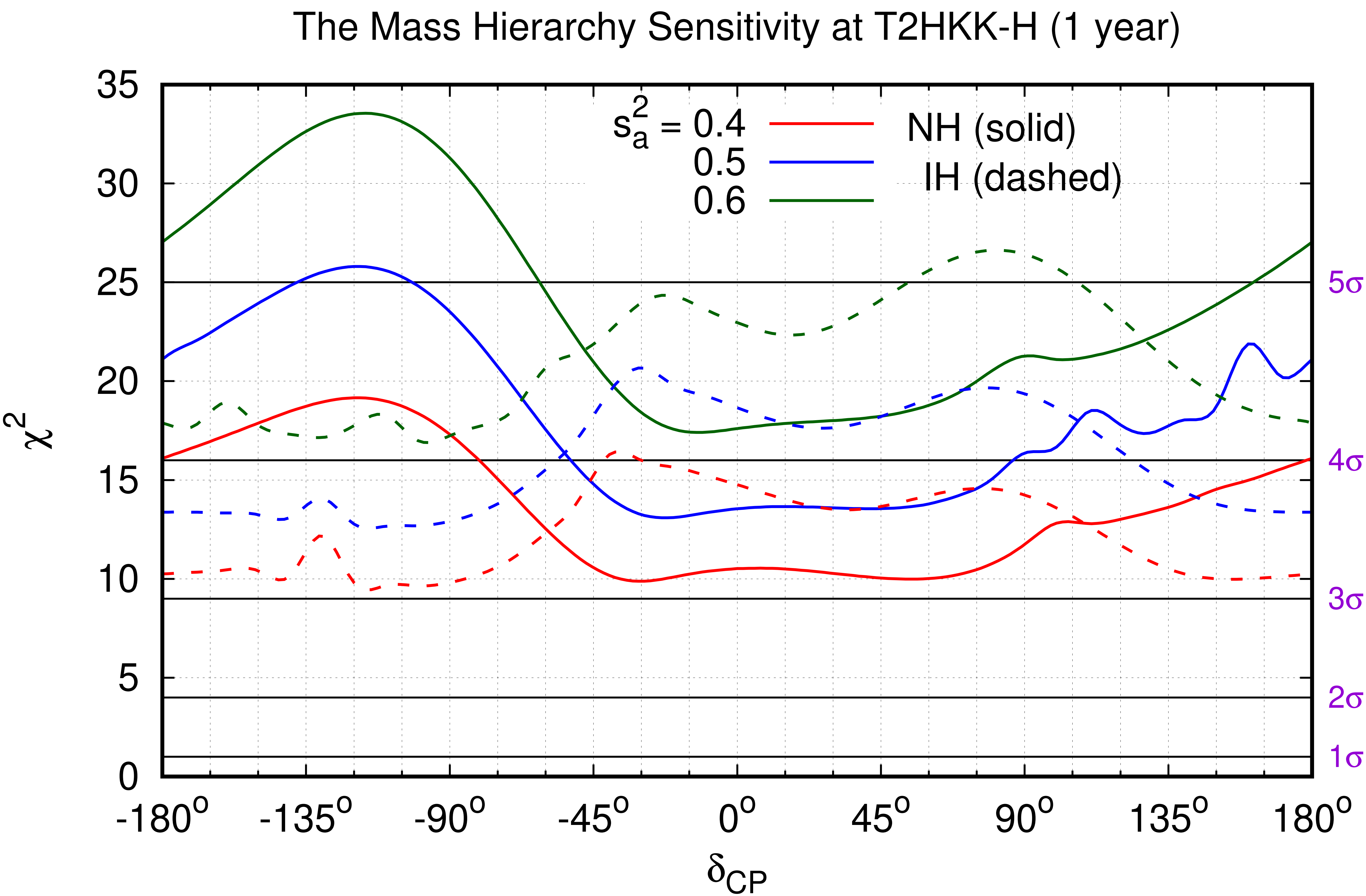


Figure 2: The cross section view of the T2K, T2KO, and T2KK experiments along the baselines, which are shown by the three curves. The horizontal scale gives the distance from J-PARC along the arc of the earth surface and the vertical scale measures the depth of the baseline below the sea level. The numbers in the white boxes are the average matter density in units of g/cm^3 [35]-[42].

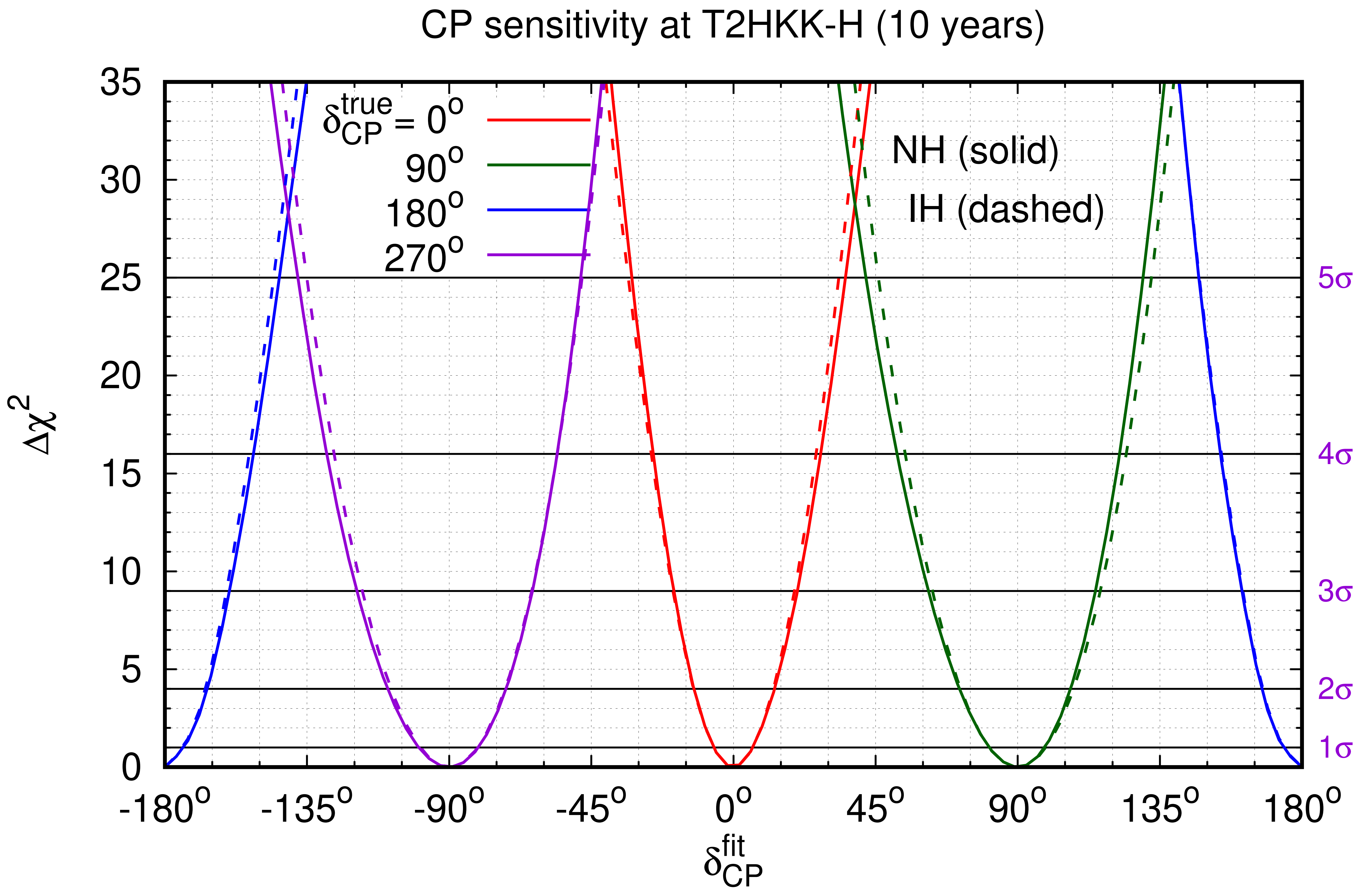


大和海嶺
397
大和海盆
朝鮮海台
最上舟状海盆
富山舟状海盆
佐渡
竹島
135
対馬海盆
隠岐海嶺
隠岐舟状海盆
隠岐
3000
1000
1200
本州
対馬
対馬海峡
四国
九州
南海舟状海盆
伊豆諸島
八丈島
139
明神礁


Site H   avg : 2.99 g/cm^3
3.5
3.4
3.3
3.2
3.1
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1100
1000
900
800
700
600
500
400
300
200
100
0



The Mass Hierarchy Sensitivity at T2HKK-H (1 year)
s_a^2 = 0.4
0.5
0.6
NH (solid)
IH (dashed)
χ^2
35
30
25
20
15
10
5
0
5σ
4σ
3σ
2σ
1σ
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°
δ_{CP}



CP sensitivity at T2HKK-H (10 years)
δ_{CP}^{true} = 0°
90°
180°
270°
NH (solid)
IH (dashed)
35
30
25
20
15
10
5
0
$\Delta\chi^2$
5σ
4σ
3σ
2σ
1σ
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°
δ_{CP}^{fit}

S.F. Ge, KH, N. Okamura, Y. Takaesu, JHEP1305:131,2013 [arXiv:1210.8141]

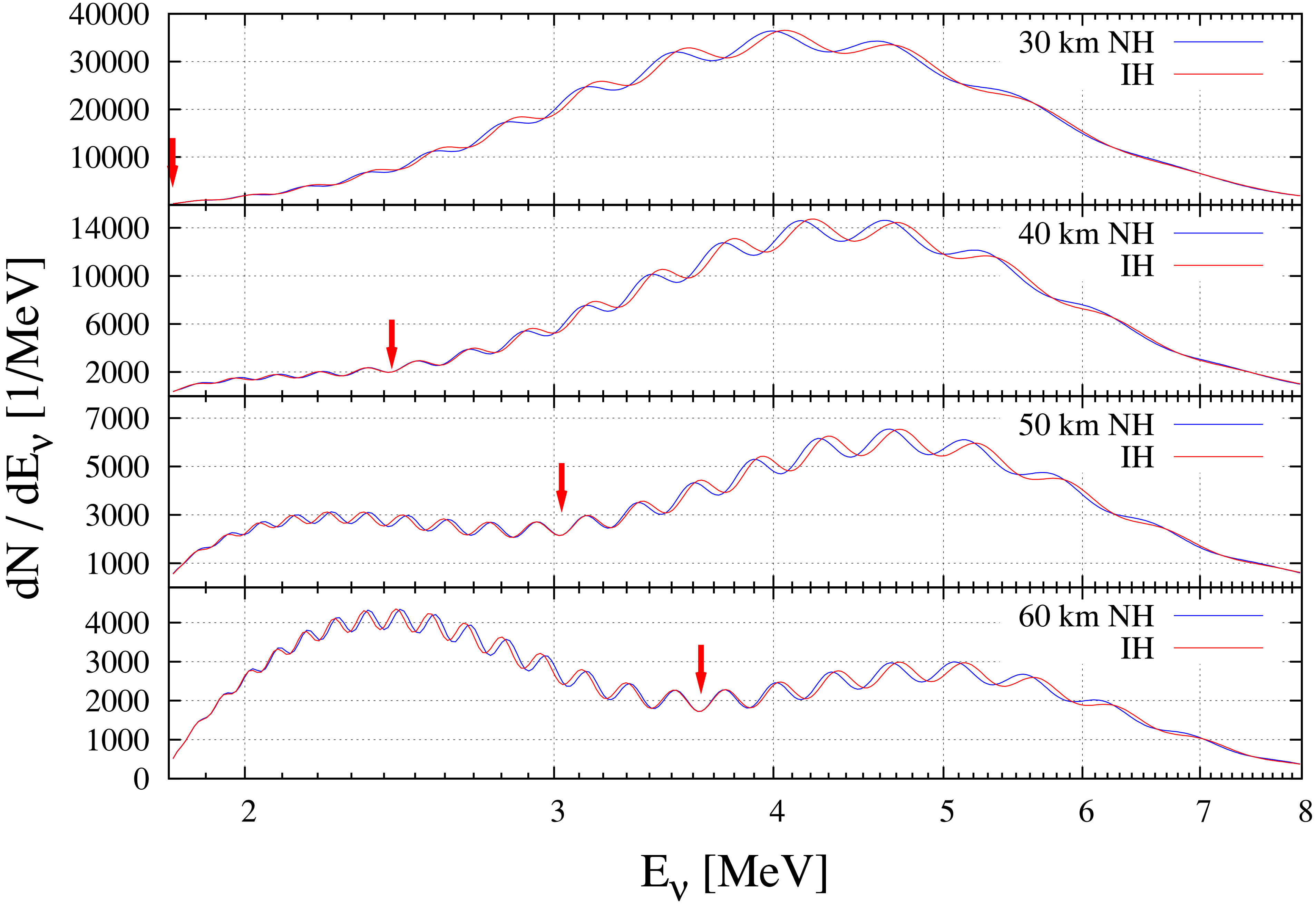
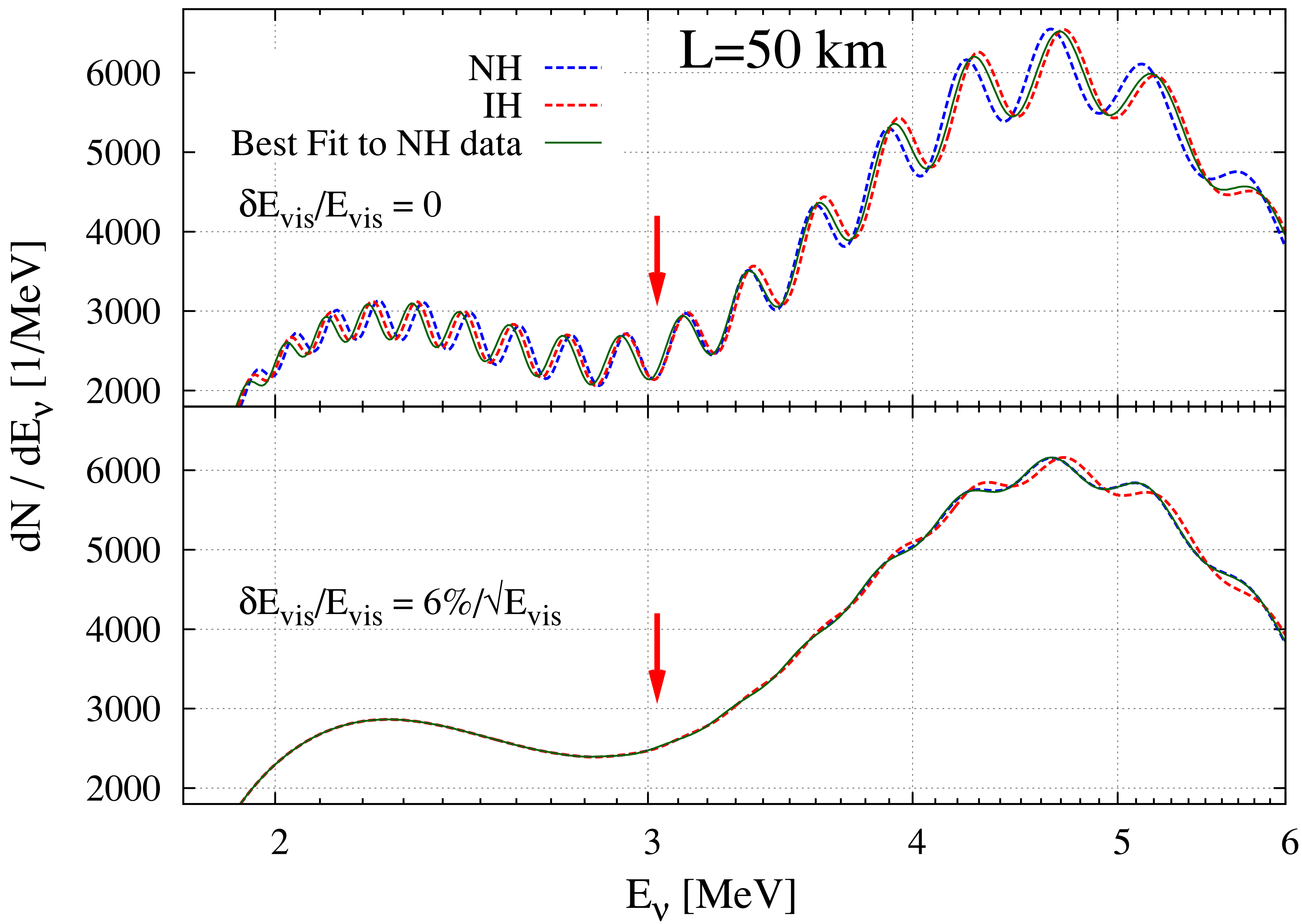


Figure 1. The energy distributions of reactor antineutrino events after $20\,\text{GW}_{\text{th}}\cdot 5\text{kt}$ (12% free-proton weight fraction)·5yrs exposure at the baseline lengths $L = 30, 40, 50$ and 60 km, in the top-down order. The blue curves are for NH, while the red ones for IH. The red arrows indicate the energies at which the difference due to mass hierarchy vanishes.

Figure 2. The energy distribution of reactor antineutrinos with baseline length $L = 50$ km and $20\,\mathrm{GW_{th}}\cdot$5kt (12% free-proton weight fraction)$\cdot$5yrs exposure. **Upper**: the case with exact E_ν measurement where the dashed blue and dashed red curves are for NH and IH, respectively. The solid curve shows the best fit of IH assumption to the NH data. The red arrow points out the energy at which the difference due to mass hierarchy vanishes. **Lower**: $6/\sqrt{E_{\rm vis}}\,\%$ energy resolution case.



How should we modify $\mathcal{L}_{SM}$ to accomodate ν masses ?

① Add ν_R's : $\Delta\mathcal{L}^{①} = \sum_{k=1}^{3} \nu_{Rk}^{\dagger} i\partial_\mu \sigma_+^\mu \nu_{Rk} + \sum_{i,j=1}^{3} \{ y_{ij}^\nu L_i^\dagger \nu_{Rj} \phi + h.c. \}$

$\Rightarrow \nu_{Rk}$'s have no gauge interactions $(1,1,0)$, $(y^\nu)_{max} \sim \frac{0.05\,eV}{v/\sqrt{2}} \sim 10^{-13} \ll y^t \sim 1,\ y^e \sim 10^{-6}$

② Add dim-5 operators : $\Delta\mathcal{L}^{②} = \sum_{i,j=1}^{3} \{ \frac{y_{ij}^\nu}{2\Lambda} (\phi^\dagger L_i)\cdot(\phi^\dagger L_j) + h.c. \}$

$\Rightarrow m_\nu \sim \frac{y^\nu v^2}{2\Lambda}$ $\Rightarrow$ tiny m_ν if $\Lambda \gg v$

$\psi_L \cdot \psi_L = (\psi_L^c)^\dagger \psi_L = (-i\sigma^2 \psi_L^*)^\dagger \psi_L = \psi_L^T (i\sigma^2) \psi_L$

$\Rightarrow$ Majorana mass : $m_\nu\, \nu_L \cdot \nu_L + h.c.$ $\Rightarrow$ LNV

③ Add ν_R's and large ν_R mass : $\Delta\mathcal{L}^{③} = \Delta\mathcal{L}^{①} + \sum_{i,j=1}^{3} \{ M_{ij}\, \nu_{Ri} \cdot \nu_{Rj} + h.c. \}$

$\Rightarrow$ reduces to $\Delta\mathcal{L}^{②}$ in the $M \gg v$ limit (See-Saw) : $m_\nu \sim \frac{D^2}{M}$ with $D \sim y^\nu v$

$\Rightarrow$ fits well to GUT : $SO(10) \longrightarrow SU(5)$ @ the scale of M (ν_R mass & Z' mass)

: 16 fermions in 1 generation $\{ \underbrace{Q,\ u_R^c,\ \ell_R^c}_{10},\ \underbrace{d_R^c,\ L}_{5^*},\ \underbrace{\nu_R^c}_{1} \} = \{ 6+3+1+3+2+1 = 16 = 2^4 \}$

SU(5)

2^4: spinor rep. of SO(10)

Lorents transformation of ψ_L & ψ_R (exercizes for theory students)

$$\psi_L \to \psi_L' = S_L(\theta_k, \eta_k)\psi_L \quad ; S_L(\theta_k,\eta_k) = \exp\left\{-i\sum_{k=1}^{3}\frac{\sigma^k}{2}(\theta_k - i\eta_k)\right\} = \exp\left\{\sum_{k=1}^{3}\frac{\sigma^k}{2}(-i\theta_k - \eta_k)\right\}$$

$$\psi_R \to \psi_R' = S_R(\theta_k, \eta_k)\psi_R \quad ; S_R(\theta_k,\eta_k) = \exp\left\{-i\sum_{k=1}^{3}\frac{\sigma^k}{2}(\theta_k - i\eta_k)\right\} = \exp\left\{\sum_{k=1}^{3}\frac{\sigma^k}{2}(-i\theta_k + \eta_k)\right\}$$

- show $S_L^\dagger(\theta_k,\eta_k)S_R(\theta_k,\eta_k) = S_R^\dagger(\theta_k,\eta_k)S_R(\theta_k,\eta_k) = 1 \Rightarrow \psi_L^\dagger\psi_R,\ \psi_R^\dagger\psi_L$ invariant

- show $\begin{cases} i\sigma^2\psi_R^* = \psi_R^c \longrightarrow \psi_R^{c\prime} = S_L(\theta_k,\eta_k)\psi_R^c & \Rightarrow (\psi_R^c)^\dagger\psi_R = \psi_R^T(-i\sigma^2)\psi_R \equiv \psi_R\cdot\psi_R \quad \text{"} \\ -i\sigma^2\psi_L^* = \psi_L^c \longrightarrow \psi_L^{c\prime} = S_R(\theta_k,\eta_k)\psi_L^c & \Rightarrow (\psi_L^c)^\dagger\psi_L = \psi_L^T(i\sigma^2)\psi_L \equiv \psi_L\cdot\psi_L \quad \text{"} \end{cases}$

- show $\begin{cases} S_L(\theta_k,\eta_k)^\dagger\sigma_-^\mu S_L(\theta_k,\eta_k) = L^\mu{}_\nu(\theta_k,\eta_k)\sigma_-^\mu & \Rightarrow \psi_L^\dagger\sigma_-^\mu\psi_L \to L^\mu{}_\nu\psi_L^\dagger\sigma_-^\mu\psi_L \\ S_R(\theta_k,\eta_k)^\dagger\sigma_+^\mu S_R(\theta_k,\eta_k) = L^\mu{}_\nu(\theta_k,\eta_k)\sigma_+^\mu & \Rightarrow \psi_R^\dagger\sigma_+^\mu\psi_R \to L^\mu{}_\nu\psi_R^\dagger\sigma_+^\mu\psi_R \end{cases}$

where $\sigma_\pm^\mu = (1, \pm\vec{\sigma})$ $\qquad L^\mu{}_\nu(\theta_k,\eta_k) = \exp\left\{-i\sum_{k=1}^{3}(J^{k\mu}{}_\nu\theta_k + K^{k\mu}{}_\nu\eta_k)\right\}$.

Cosmological connection (Baryon Asymmetry of Universe ⇒ LNV + CPV)

- Anomaly in QCD : $\Delta \mathcal{L} \sim \epsilon_{\mu\nu\rho\sigma} F^{a\mu\nu} F^{a\rho\sigma}$ ⇒ integer index (wrapping #) from surface integral
  - ⇒ different # vacuums are connected by Instantons
  - ⇒ the lowest energy vacuum becomes θ vacuum
  - ⇒ P & CP violation ⇒ P-Q symmetry ⇒ axion

- Anomaly in $SU(2)_L$: $\Delta \mathcal{L} \sim \epsilon_{\mu\nu\rho\sigma} W^{k\mu\nu} W^{k\rho\sigma}$ ⇒ # = B+L in EW theory
  - ⇒ different B+L vacuums are connected by Spharelons
  - ⇒ Sphaleron transitions are not suppressed @ $T > O(v)$.

⇒ All GUT generated BAU are washed out by Spharelon transitions if $\Delta(B-L) = \emptyset$.

⇒ If $M \nu_R \cdot \nu_R$ gives LN asymmetry, since $\Delta L = \Delta(L-B) \neq 0$ ⇒ BAU is generated @ $T < O(v$

LNV + CPV + long-living ν_R : Lepto-genesis

Can we learn about Leptogenesis from terestarial experiments ?

- Probably not if $M \gg v$ (natural scenario in $SO(10) \to SU(5)$ @ M since $m_{Z'} \sim O(M)$).

  because $\nu_{e,\mu,\tau} - \nu_R$ mixing is very small $\sim \frac{D}{M} \sim 10^{-10}$

- What if $M \lesssim O(v)$?

  ⇒ SO(10) picture should be given up because no evidence of Z'

  ⇒ Leptogenesis may be possible with degenerate ν_R's (resonance enhancements)

  ⇒ CPV and LNV and out-of-equivelium in νMSM (ν_R - oscillations)

- Since the possibility of ν_R's within our experimental reach is very interesting, I made an elementary calculation a few years ago. ⇒ no encouraging results.

  ⇒ no paper .

I studied 6x6 symmetric mass matrix of the form

$$\mathcal{L}_{mass} = \frac{1}{2}(\nu_e, \nu_\mu, \nu_\tau, \nu_{R1}^c, \nu_{R2}^c, \nu_{R3}^c) \cdot M (\nu_e, \nu_\mu, \nu_\tau, \nu_{R1}^c, \nu_{R2}^c, \nu_{R3}^c)^T + h.c.$$

with

$$M = \begin{pmatrix} 0 & 0 & 0 & d_{e1} & d_{e2} & d_{e3} \\ 0 & 0 & 0 & d_{\mu 1} & d_{\mu 2} & d_{\mu 3} \\ 0 & 0 & 0 & d_{\tau 1} & d_{\tau 2} & d_{\tau 3} \\ & & & M_1 & 0 & 0 \\ & * & & 0 & M_2 & 0 \\ & & & 0 & 0 & M_3 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{R1}^c \\ \nu_{R2}^c \\ \nu_{R3}^c \end{pmatrix}$$

and study its eigenvalues $\det(M^\dagger M - \lambda I) = (\lambda-\lambda_1)(\lambda-\lambda_2)(\lambda-\lambda_3)(\lambda-\lambda_4)(\lambda-\lambda_5)(\lambda-\lambda_6) = 0$

$\Rightarrow$ request $\lambda_1 = \lambda_2 = \lambda_3 = 0$ $\Rightarrow$

$$M_{6\times 6} = \begin{pmatrix} 0 & 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & b & 0 \\ 0 & 0 & 0 & 0 & c & 0 \\ 0 & 0 & 0 & 0 & M & 0 \\ a & b & c & M & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & M' \end{pmatrix}$$

unique solution !

$\Rightarrow$ LN conservation $(\nu_e, \nu_\mu, \nu_\tau, \nu_{R1}^c)$ have $L=1$ $\quad \nu_{R2}^c$ has $L=-1$

$M \nu_{R1}^c \cdot \nu_{R2}^c + h.c. \Rightarrow$ Dirac $N = \begin{pmatrix} \nu_{R1}^c \\ \nu_{R2} \end{pmatrix}$

$M' \nu_{R3}^c \cdot \nu_{R3}^c + h.c. \Rightarrow$ Majorana but decouples .

In this solution, a/M, b/M, c/M give mixing between ν_e-ν_R, ν_μ-ν_R, ν_τ-ν_R

⇒ can be as large as a few % which is allowed by lepton universality constraints.

I then tried to obtain observed Δm^2_{ATM}, Δm^2_{SOL} and V_{MNS} by adding tiny Majorana masses like

$$M_{6\times6} = \begin{pmatrix} 0 & 0 & 0 & 0 & a & 0 \\ 0 & 0 & 0 & 0 & b & 0 \\ 0 & 0 & 0 & 0 & c & 0 \\ 0 & 0 & 0 & \mu_{11} & M & \mu_{13} \\ a & b & c & M & \mu_{22} & \mu_{23} \\ 0 & 0 & 0 & * & * & M' \end{pmatrix}$$

μ_{11} gives $m_\nu \sim \mu_{11}$ @ tree-level (inverse See-Saw)

μ_{22} 〃 μ_{22} @ 1-loop (〃)

μ_{13}, μ_{23} 〃

But no matter how I change μ_{ij}'s, I could obtain only one massive $(\nu_e+\nu_\mu+\nu_\tau)$ combination.

This is because the $(\nu_e, \nu_\mu, \nu_\tau)$ mass matrix is dictated by on vector, (a, b, c). ⇒ rank 1 (T. Yamada)

In order to obtain two Δm^2's and realistic V_{MNS}, we should have something like

$$M_{6\times6} = \begin{pmatrix} 0 & 0 & 0 & a' & a & 0 \\ 0 & 0 & 0 & b' & b & 0 \\ 0 & 0 & 0 & c' & c & 0 \\ a' & b' & c' & \mu_{11} & M & 0 \\ a & b & c & M & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & M' \end{pmatrix}$$

explicit LNV couplings (a', b', c') of order $\sqrt{\Delta m^2}$'s

⇒ stopped (It was not very attractive to me).

⇒ may be worth studying pheno!