Physics Potential of T2HKK:

Neutrino Oscillation from Tokai to Hyper-Kamiokande in Kamioka and in Korea

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based on studies done in collaboration with

N.Okamura, K.Senda, T.Kiwanami, Y.Takaesu, P.Ko, S.F.Ge

The preliminary results shown in this talk are prepared by:

Shao-Feng Ge (MPI/Heidelberg)
Naotoshi Okamura (Int.Univ. of Health & Welfare, Otawara)
Yoshitaro Takaesu (Okayama University)

Organization of the talk

- What we learned from the past **T2KK/T2KO** studies (2004-2016)
  - Merits of same **L/E** at two different L
  - 300km/0.6GeV $\sim$ 1000km/2GeV
  - High energy flux at small angle off-axis beam (**OAB**)
  - e/π^0 mis-identification at E$\gtrsim$1 GeV

- Preliminary results for **T2HKK**
  - **T2HKK** at site **H**(Mt.Bisul): L=1090km, **1.3° OAB**
  - **T2HKK** at site **C**(Mt.Bohyun): L=1040km, **2.3° OAB**
  - **T2DHK** at **Kamioka** only: L=295km, **2.5° OAB**, for comparison.

The **three neutrino model** has **9** parameters:

3 masses	$m_1,\ m_2,\ m_3$
3 angles	$\theta_{23},\ \theta_{12},\ \theta_{13}$
3 phases	$\delta_{\mathrm{MNS}},\ \phi_1,\ \phi_2$

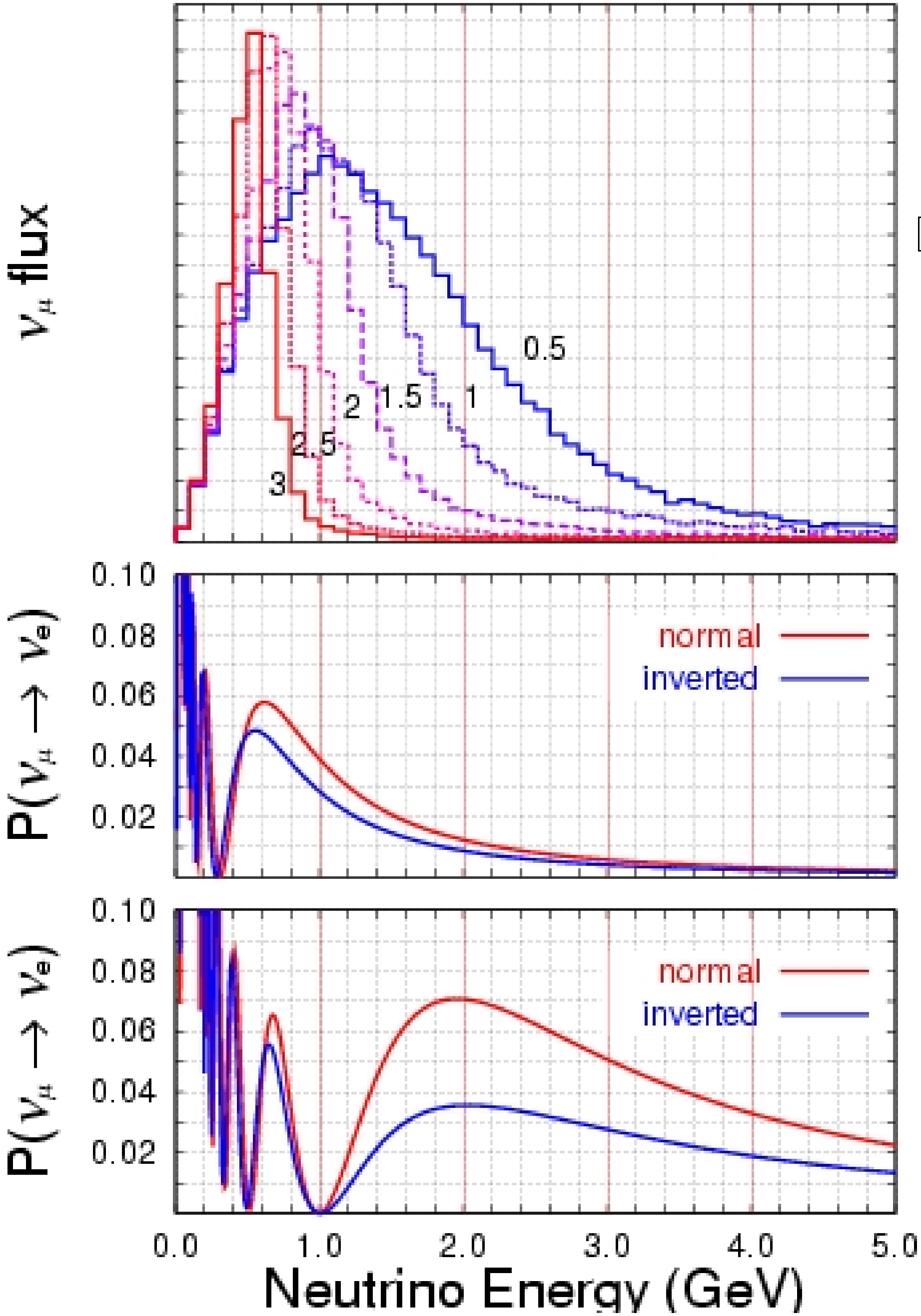
Neutrino oscillation experiments can measure **6** out of the 9 parameters:

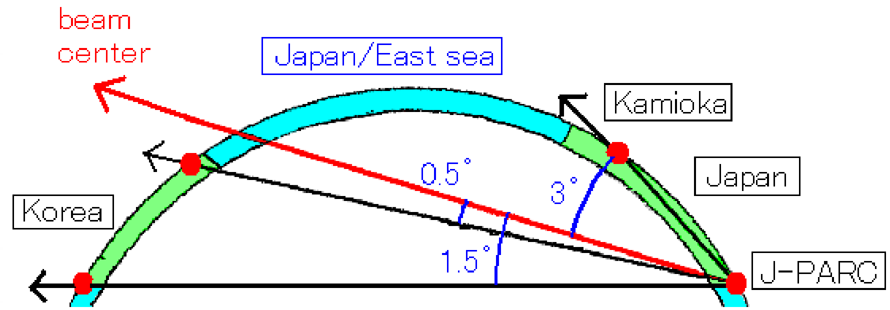
2 mass-squared differences	$m_2^2 - m_1^2,\ m_3^2 - m_1^2$
3 angles	$\theta_{23},\ \theta_{12},\ \theta_{13}$
1 phase	δ_{MNS}

Both mass-squared differences and all the 3 angles have been measured. Within the 3 neutrino standard model, the remaining tasks of future neutrino oscillation experiments are to determine:

the **mass hierarchy**	$m_3^2 - m_1^2 > 0$ or $m_3^2 - m_1^2 < 0$
the **CP phase**	δ_{MNS}
the **octant** degeneracy	$\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$

besides sharpening of the existing measurements and search for **new physics**.





← Profile of off-axis beams

← $P(\nu_\mu \to \nu_e)$ at SK

← $P(\nu_\mu \to \nu_e)$ at Korea

(L=1000km)

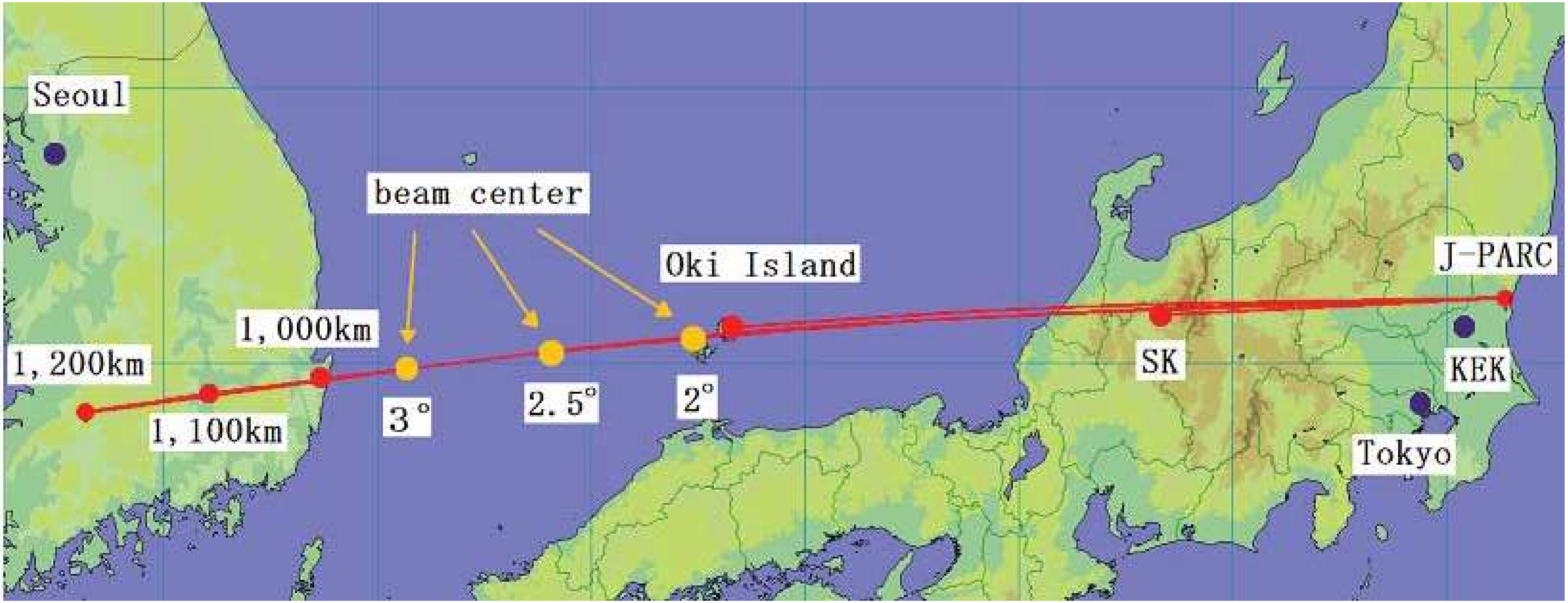


Figure 1: The surface map of the T2K, T2KO, and T2KK experiment. The yellow blobs show the center of the neutrino beam for the T2K experiment at the sea level, where the number in the white box is the off-axis angle at SK.

ν_μ Survival Probability

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{\text{atm}} \left(1 + \boxed{A^\mu}\right) \sin^2\left(\frac{\Delta_{13}}{2} + \boxed{B^\mu}\right)$$

$$A^\mu = -\frac{aL}{\Delta_{13}E} \frac{1 - 2\sin^2\theta_{\text{atm}}}{\cos^2\theta_{\text{atm}}} \sin^2\theta_{\text{rct}}$$

$$\Delta_{ij} = \frac{\delta m_{ij}^2 L}{2E}$$

$$\approx 0.018 \frac{\pi}{\Delta_{13}} \frac{L}{1000\text{km}} \left(\frac{1 - 2\sin^2\theta_{\text{atm}}}{2\cos^2\theta_{\text{atm}}}\right)\left(\frac{\sin^2 2\theta_{\text{rct}}}{0.10}\right)$$

$$B^\mu = -\frac{aL}{4E} \frac{1 - 2\sin^2\theta_{\text{atm}}}{\cos^2\theta_{\text{atm}}} \sin^2\theta_{\text{rct}}$$

$$-\frac{\Delta_{12}}{2}\left(\cos^2\theta_{\text{sun}} + \tan^2\theta_{\text{atm}} \sin^2\theta_{\text{sun}} \sin^2\theta_{\text{rct}} - \tan\theta_{\text{atm}} \sin 2\theta_{\text{sun}} \sin\theta_{\text{rct}} \cos\delta_{\text{MNS}}\right)$$

$$\approx 0.014 \frac{L}{1000\text{km}} \left(\frac{1 - 2\sin^2\theta_{\text{atm}}}{2\cos^2\theta_{\text{atm}}}\right)\left(\frac{\sin^2 2\theta_{\text{rct}}}{0.10}\right) - \left[0.037 - 0.008\left(\frac{\sin^2 2\theta_{\text{rct}}}{0.10}\right)^{1/2} \cos\delta_{\text{MNS}}\right] \frac{|\Delta_{13}|}{\pi}$$

The matter effects are expected to be small because $1-\sin^2 2\theta_{\text{atm}} < 0.1$ (90%CL) from SK, K2K, MINOS.

Oscillation Amplitude

$$P(\nu_\mu \to \nu_e) = \boxed{4\sin^2\theta_{\text{atm}}\sin^2\theta_{\text{rct}}(1+A^e)}\sin^2\left(\frac{\Delta_{13}}{2}+B^e\right)+C^e$$

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

If we know $\sin^2\theta_{\text{rct}}$ from Double CHOOZ, RENO, and Daya-Bay then the maximum of $P_{\max}(\nu_\mu \rightarrow \nu_e)$ measures $1+A^e$.

$$P_{\max}(L=1000\text{km}) > P_{\max}(L=300\text{km}) \Rightarrow \Delta_{13} > 0 \Rightarrow m_3^2 > m_1^2 \text{ (normal)}$$

$$P_{\max}(L=1000\text{km}) < P_{\max}(L=300\text{km}) \Rightarrow \Delta_{13} < 0 \Rightarrow m_3^2 < m_1^2 \text{ (inverted)}$$

Once the sign of Δ_{13} is fixed ➔ $\sin\delta_{\text{MNS}}$ can be measured.

Oscillation Phase

$$P(\nu_\mu \to \nu_e) = 4\sin^2\theta_{\rm atm}\sin^2\theta_{\rm rct}(1+A^e)\sin^2\boxed{\left(\frac{\Delta_{13}}{2}+B^e\right)}+C^e$$

$$B^e \approx -\left[0.29\frac{L}{1000\rm km}\right] + 0.15\left[\left(\frac{0.10}{\sin^2 2\theta_{\rm rct}}\right)^{1/2}\cos\delta_{\rm MNS} - 0.1\right]\frac{|\Delta_{13}|}{\pi}$$

Phase of neutrino oscillation also depend on the mass hierarchy. Around oscillation maximum ($|\Delta_{13}| \sim \pi$)

- at Kamioka ($L \sim 300\rm km$) $\cos\delta_{\rm MNS}$ term can dominate $\boxed{B^e}$
- at Korea ($L \sim 1000\rm km$) matter effect is significant

➔ $\cos\delta_{\rm MNS}$ can also be measured.

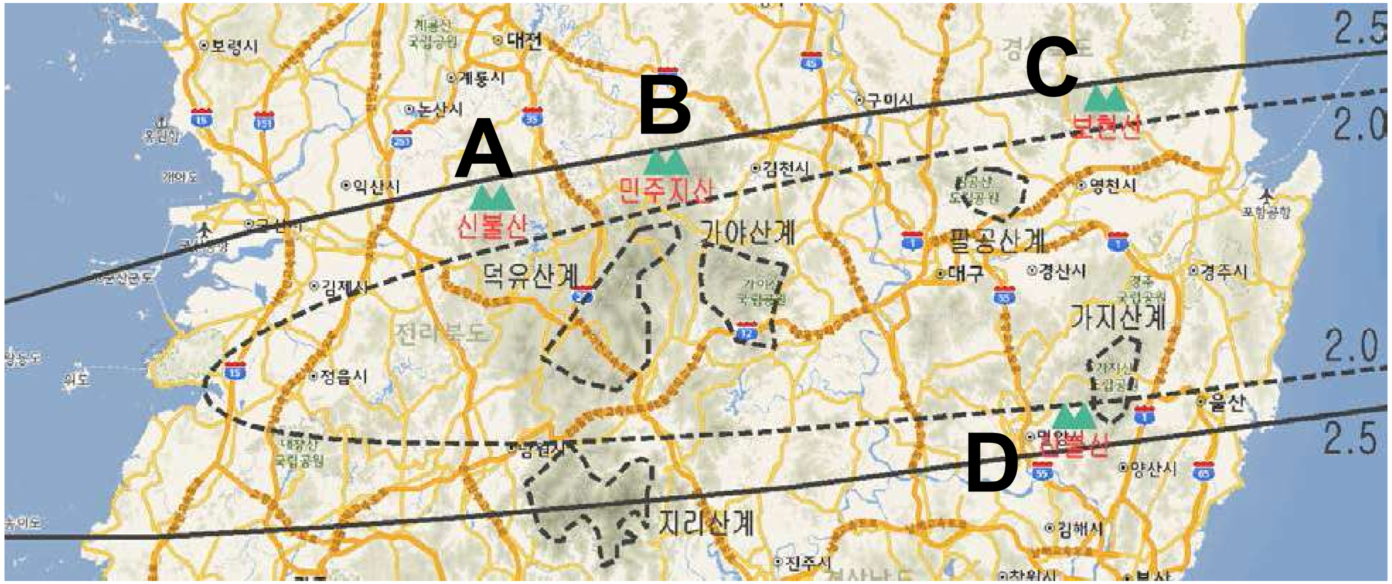
This summer, on July 16, 2016, I received an e-mail from **Soo-Bong Kim** (SNU, RENO) that he and his colleagues in Korea have been working with **Hyper-Kamiokande** team in **ICRR** (Kashiwa and Kamioka) about the possibility of realising our idea by placing

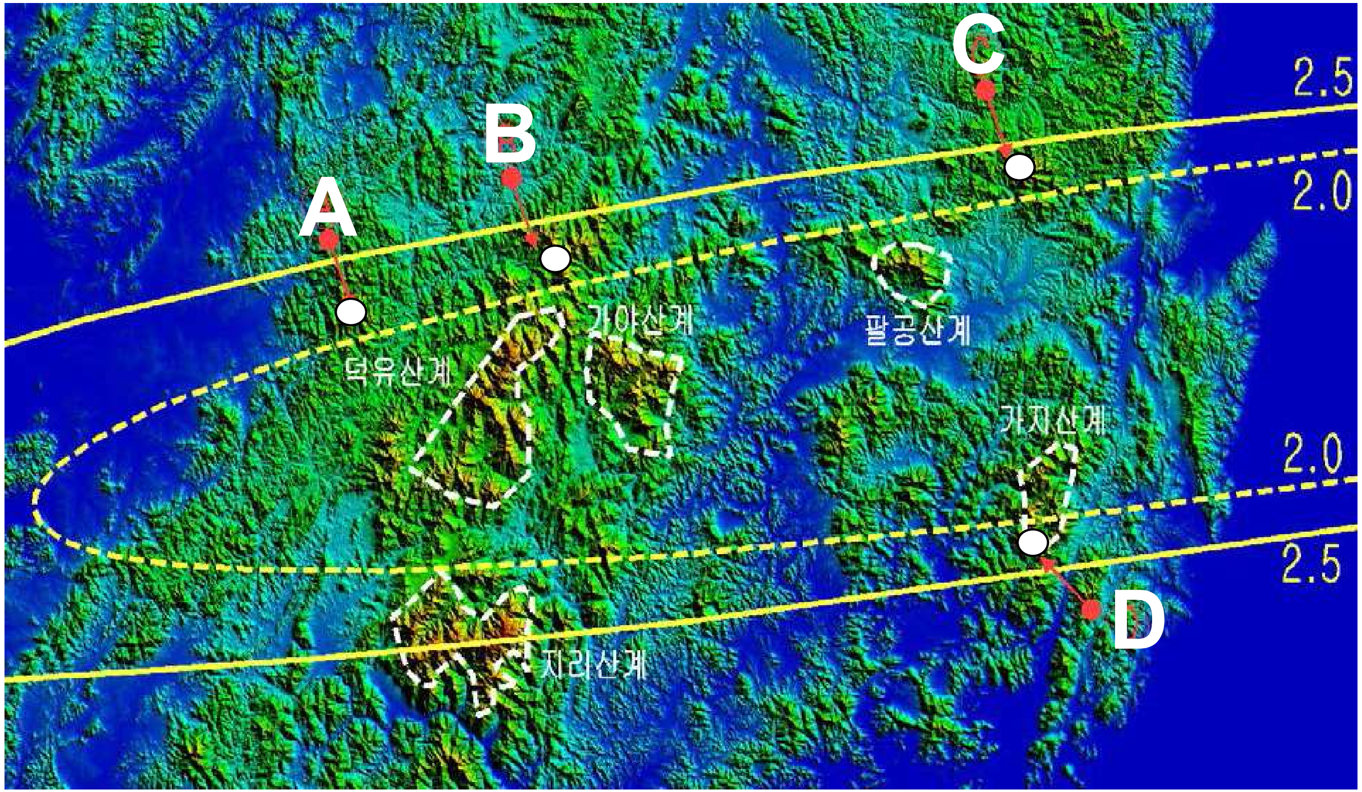
the **second Hyper-Kamiokande** (of about 1/3 the size of the original HK proposal) **in Korea**

and told me that

They have excellent candidate **sites for second HK** in Korea !

Search for candidate sites in Korea (OAB: 2.0~2.5^{0})





- **Rock condition :**

Most rocks are solid granite.
(Felsic igneous rocks: 규장질 화성암)

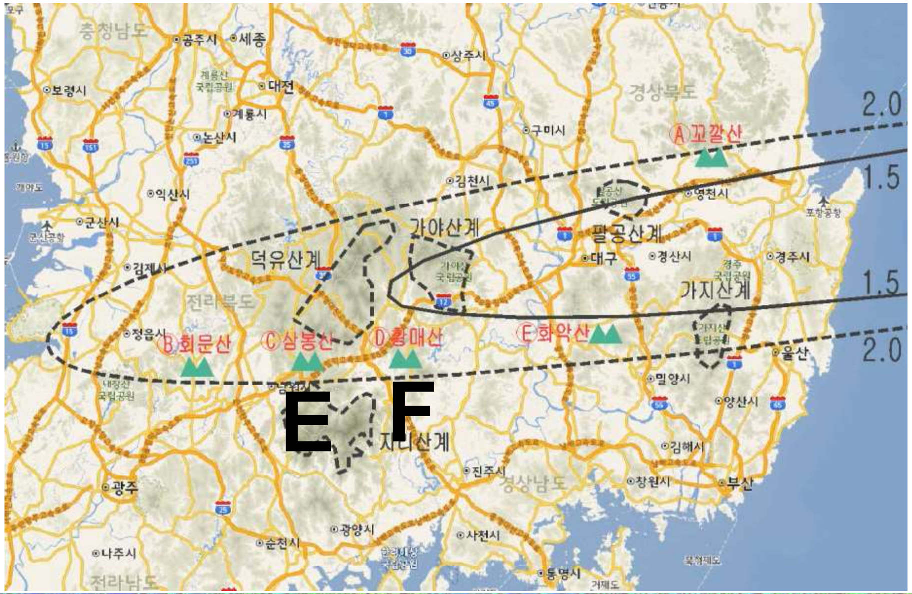
A : Mt. Unjang
(1,125 m high)
[rhyolite, granite porphyry, quartz porphyry]

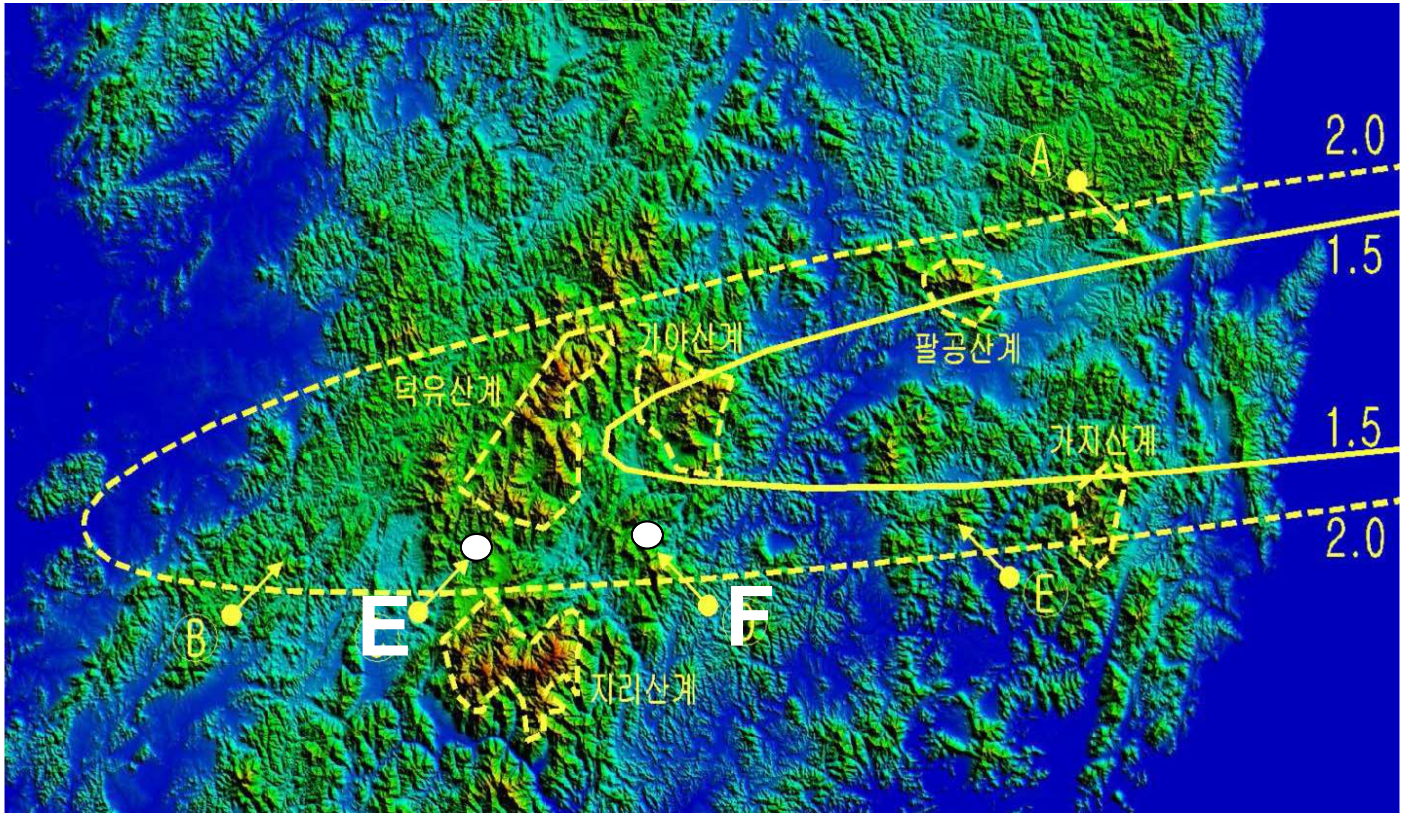
B : Mt. Minjuji
(1,242 m high)
[granite, biotite gneiss]

C : Mt. Bohyun
(1,126 m high)
[granite, volcanic rocks, volcanic breccia]

D : Mt. Shinbul
(1,159 m high)
[andesite, andesite porphyry, tuff]

Search for candidate sites in Korea (OAB: 1.5~2.0^{o})

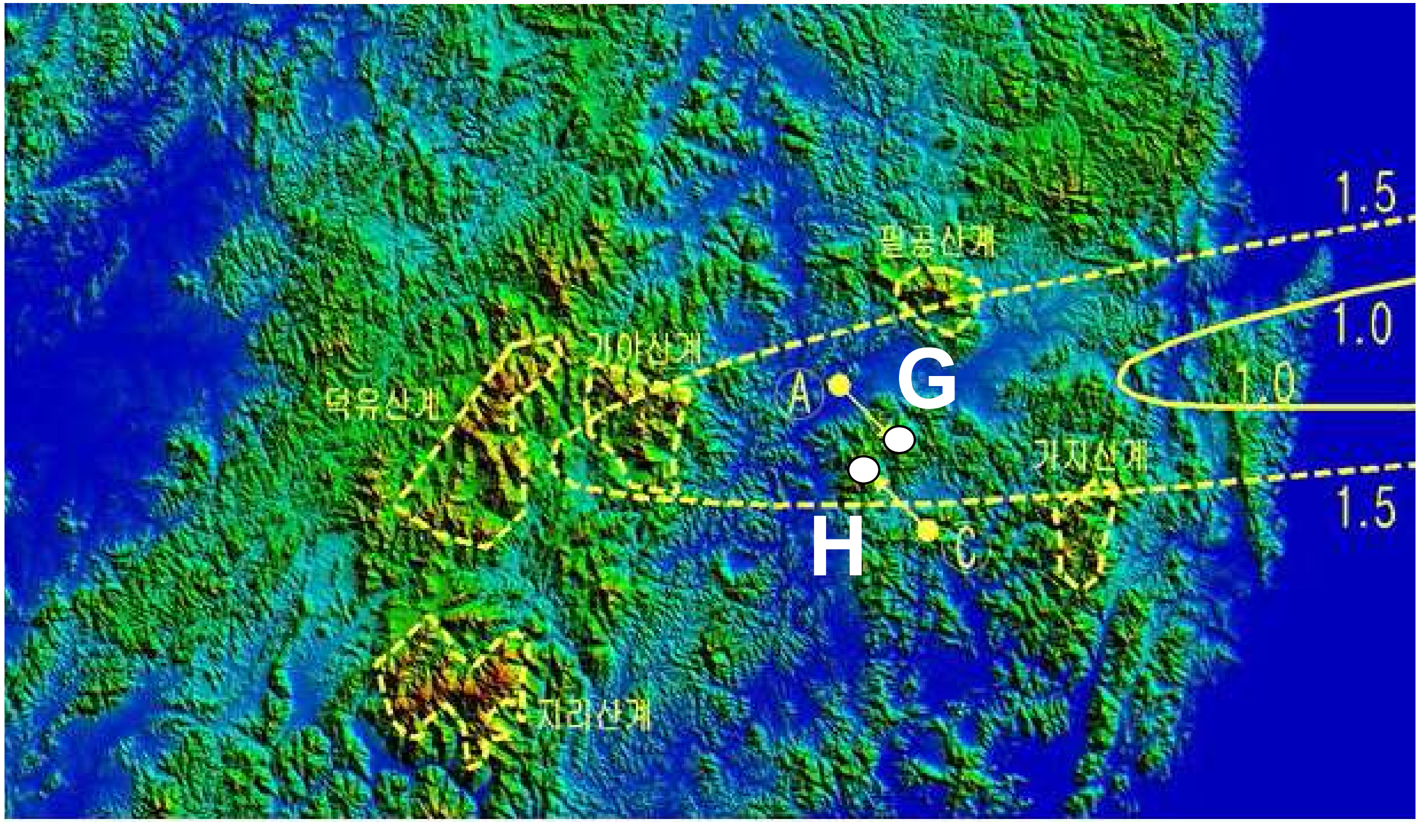




E : Mt. **Sambong**
(1,186 m high)
[porphyritic granite, biotite gneiss]

F : Mt. **Hwangmae**
(1,113 m high)
[Flake granite, porphyritic gneiss]

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



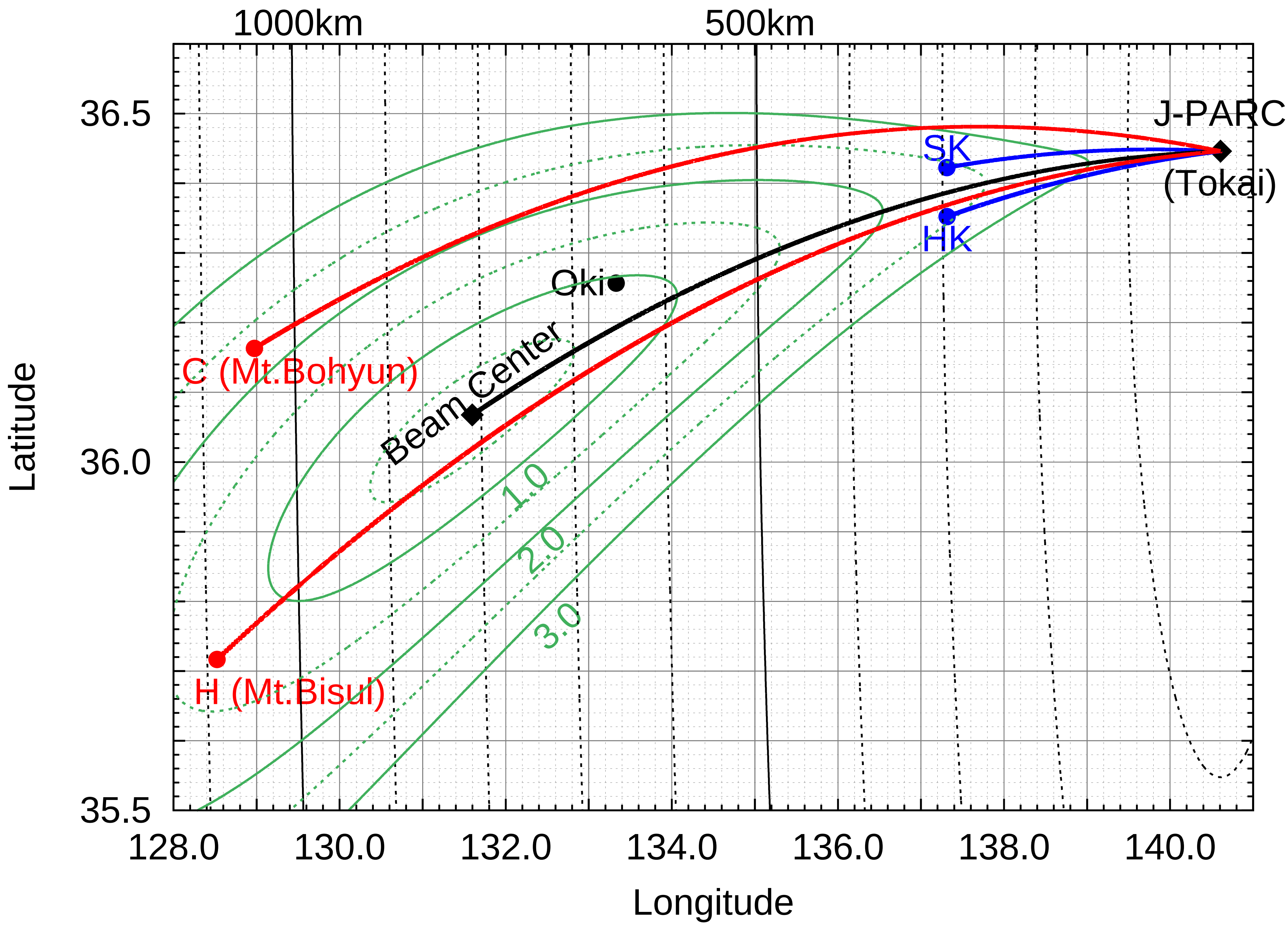
G : Mt. **Choejung**
(906 m high)
[granite porphyry, andesitic breccia]

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

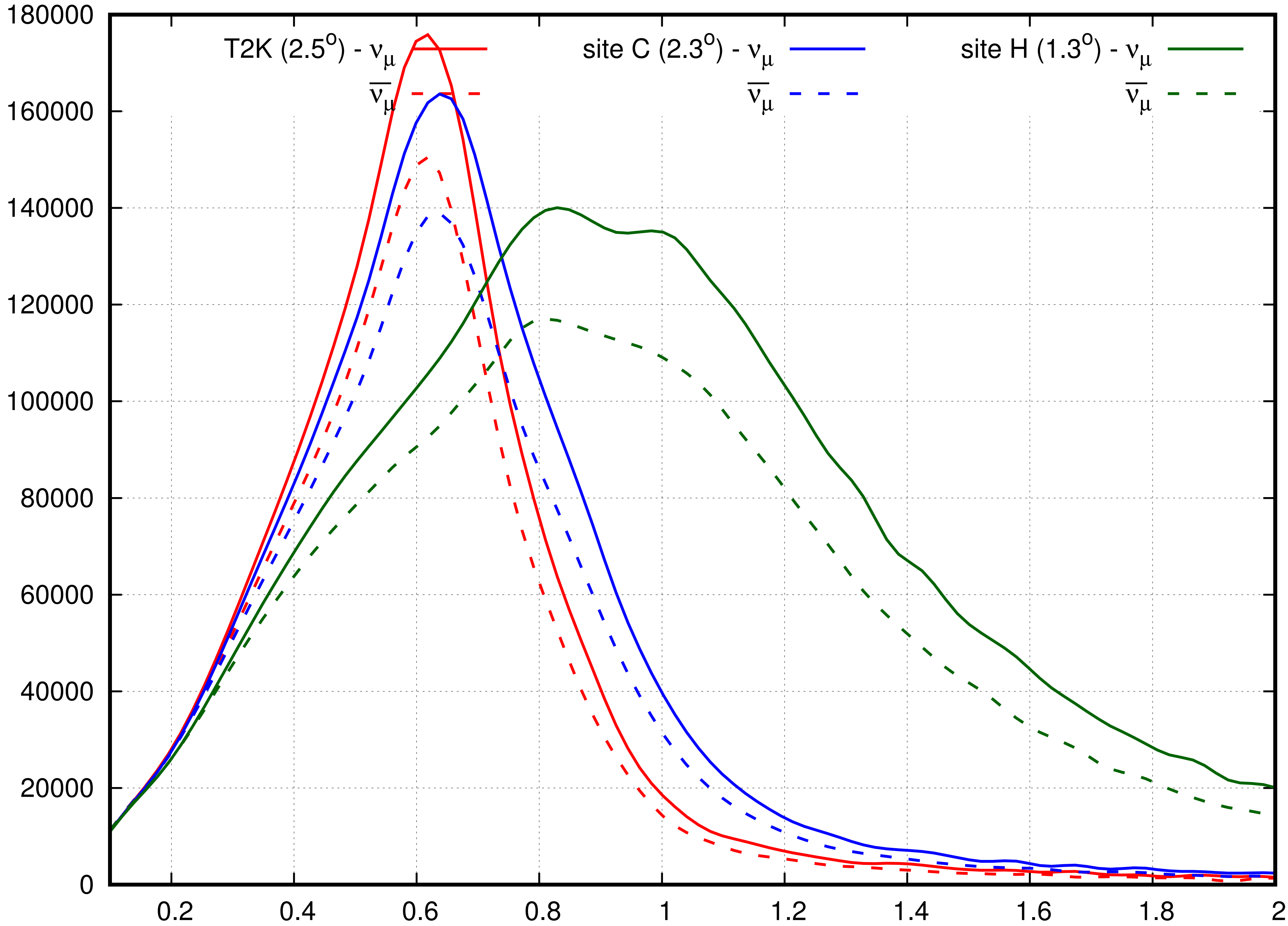
Remarks on candidate sites in Korea

- Site candidates for a 2^{nd} osc. maximum detector in Korea
  - Baselines with 1,000~1,200 km
  - 2.0~2.5^o or 1.5~2.0^o off axis beam directions
  - >1,000 m high mountains with hard granite rocks

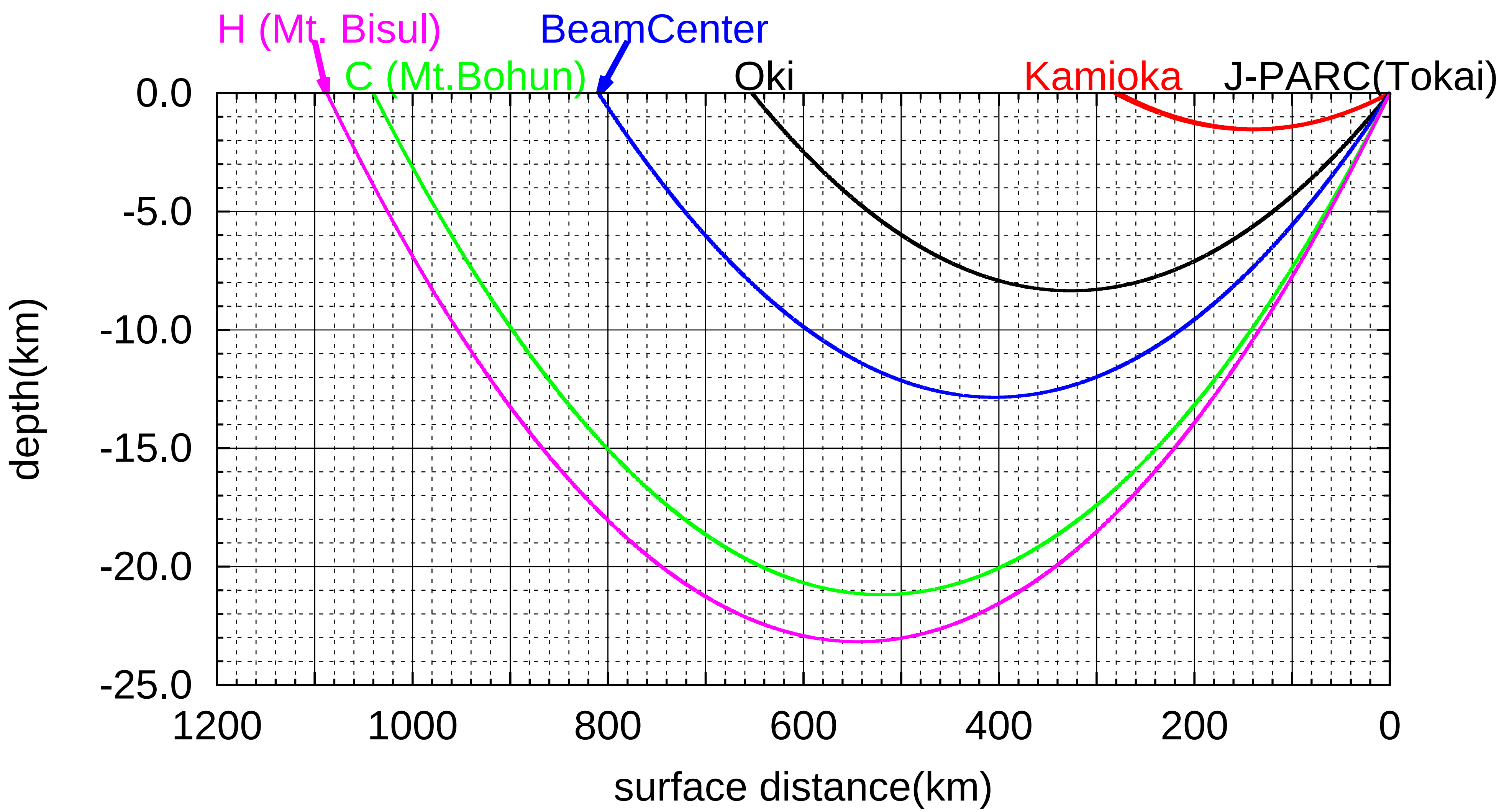
- Five candidates sites are found
  - (A) Mt. Unjang at Jinan, 1,125 m high
    ~1,190 km for baseline, ~2.2^o for OAB
  - (B) Mt. Minjuji at Youngdong, 1,242 m high
    ~1,140 km for baseline, ~2.2^o for OAB
  - (C) Mt. Bohyun at Youngcheon, 1,126 m high
    ~1,040 km for baseline, ~2.2^o for OAB
  - (E) Mt. Sambong at Namwon, 1,186 m high
    ~1,180 km for baseline, ~1.9^o for OAB
  - (F) Mt. Hwangmae at Sancheong, 1,113 m high
    ~1,140 km for baseline, ~1.8^o for OAB
  - (H) Mt. Bisul at Dalsung, 1,084 m high
    ~1,080 km for baseline, ~1.4^o for OAB



1000km
500km
J-PARC
(Tokai)
SK
HK
Oki
Beam Center
C (Mt.Bohyun)
H (Mt.Bisul)
1.0
2.0
3.0
36.5
36.0
35.5
128.0
130.0
132.0
134.0
136.0
138.0
140.0
Latitude
Longitude



T2K (2.5^{o}) - ν_μ
$\overline{\nu}_\mu$
site C (2.3^{o}) - ν_μ
$\overline{\nu}_\mu$
site H (1.3^{o}) - 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)

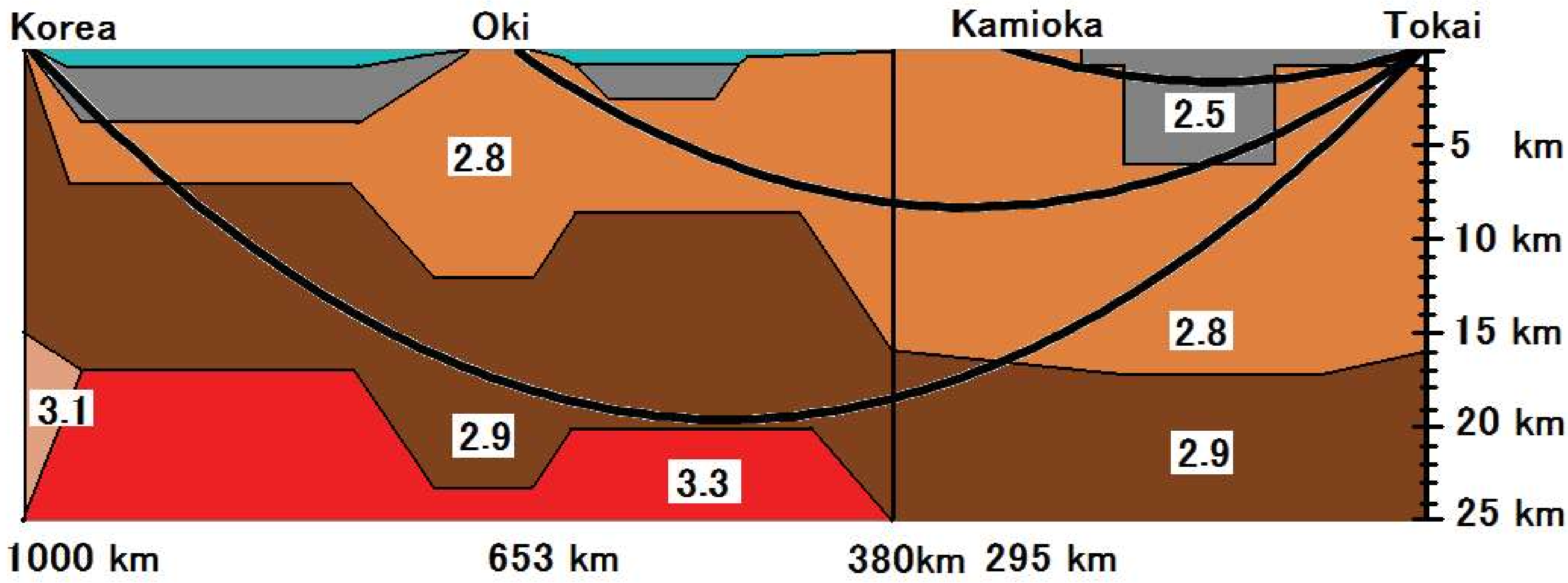
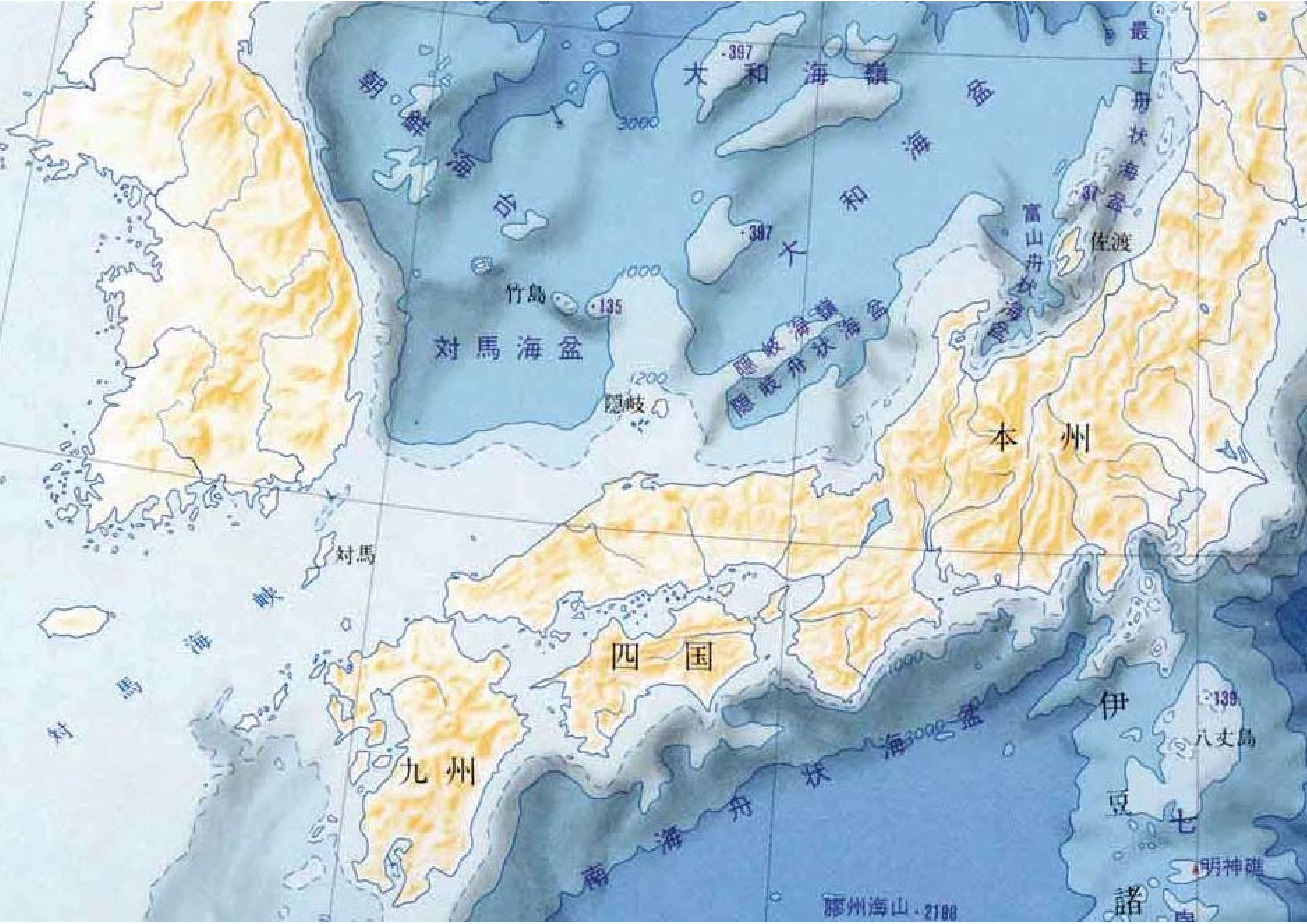
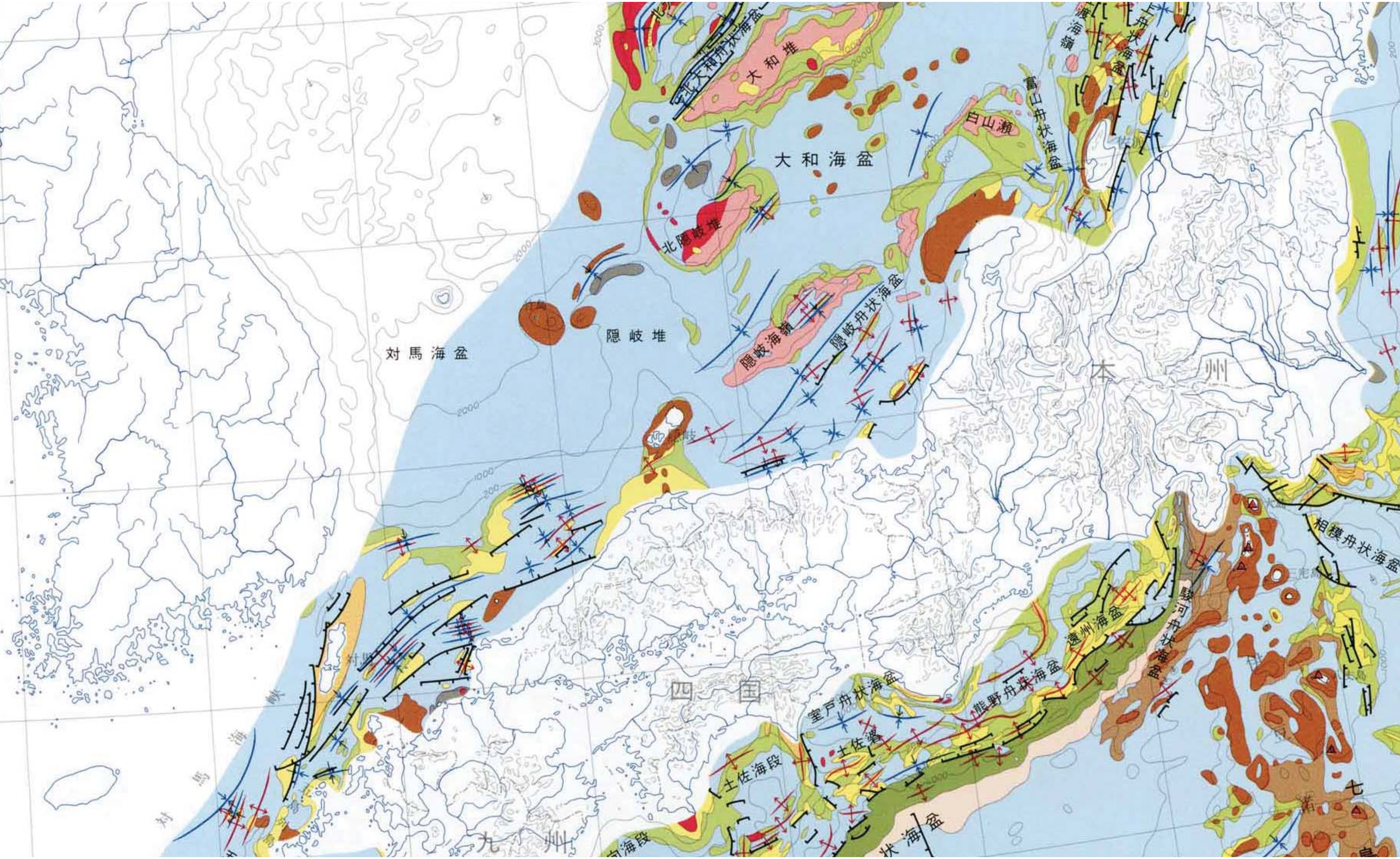
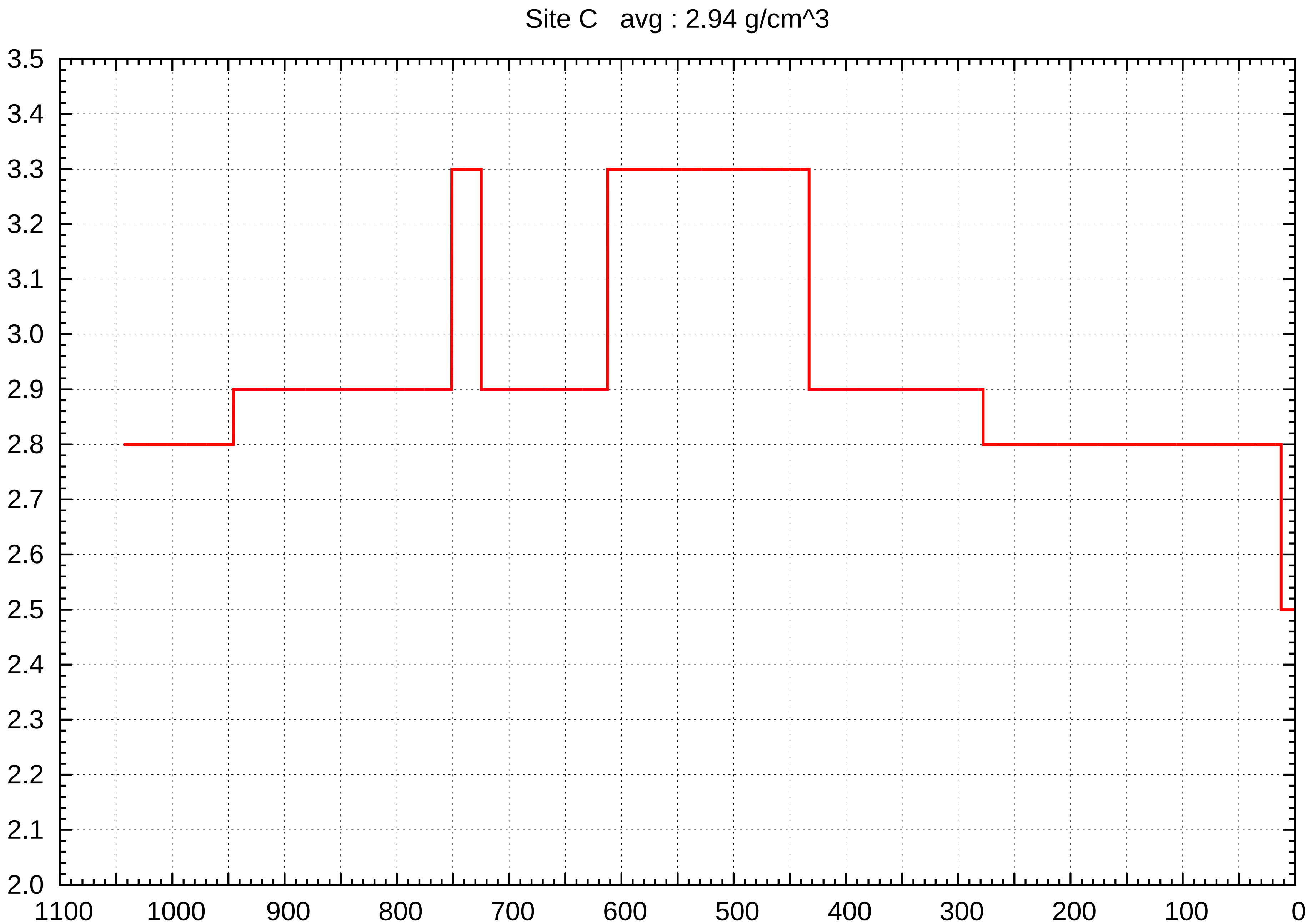


Figure 2: The cross section view of the T2K, T2KO, and T2KK experiments along the baselines, which are shown by the three curves. The horizontal scale gives the distance from J-PARC along the arc of the earth surface and the vertical scale measures the depth of the baseline below the sea level. The numbers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


大和海嶺
大和海盆
·397
·397
3000
1000
1200
最上舟状海盆
富山舟状海盆
佐渡
大和
朝鮮海台
竹島
·135
対馬海盆
隠岐海嶺
隠岐舟状海盆
隠岐
本州
対馬
対馬海峡
四国
九州
南海舟状海盆
伊豆七島
伊豆諸島
八丈島
·139
明神礁
膠州海山·2188



大和舟状海盆
大和堆
大和海盆
白山瀬
富山舟状海盆
北隠岐堆
隠岐堆
隠岐海嶺
隠岐舟状海盆
対馬海盆
本州
相模舟状海盆
駿河舟状海盆
遠州海盆
熊野舟状海盆
室戸舟状海盆
四国
土佐海段
土佐湾
九州
対馬海峡



Site C avg : 2.94 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

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

Preliminary results for T2HKK

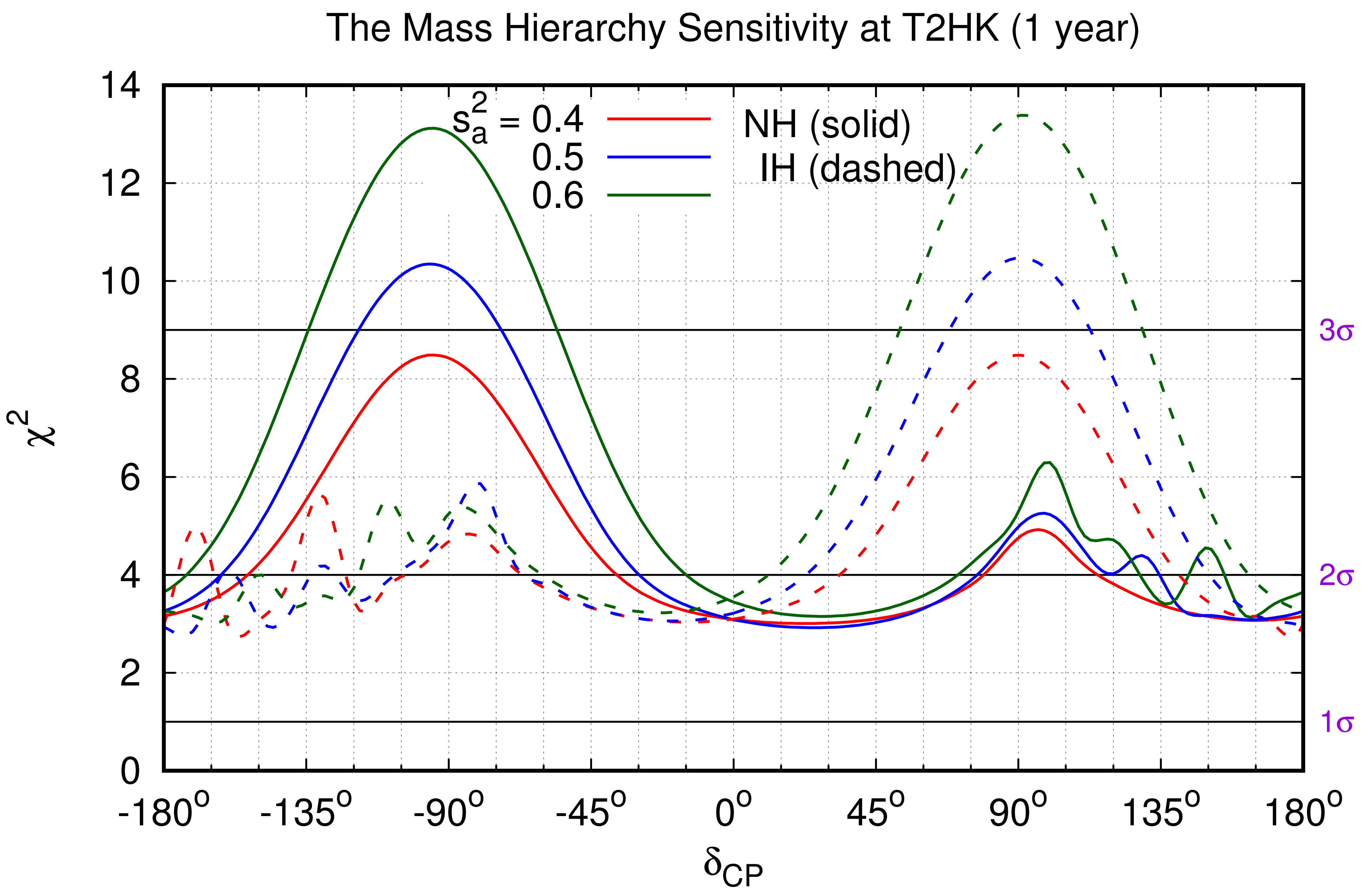
- Results obtained by **S.-F.Ge, N.Okamura, Y.Takaesu**
- Among the six candidates for the far detector sites in Korea, we examined
  - · site **H(Mt.Bisul)** (L=1090km, **1.3° OAB**)
  - · site **C(Mt.Bohyun)** (L=1040km, **2.3° OAB**)
- The three cases are compared:
  - · **T2HKK-H** (22.5+**187**)kton at Kamioka, **187**kton at site **H**
  - · **T2HKK-C** (22.5+**187**)kton at Kamioka, **187**kton at site **C**
  - · **T2DHK** (22.5+**187**+**187**)kton all at Kamioka
- The results are shown for
  - · **1 year** $(1.35\nu + 1.35\bar{\nu})\ \times 10^{21}$ POT
  - · **10 years** $(1.35\nu + 1.35\bar{\nu})\ \times 10^{22}$ POT
- Three quantities are studied:
  - · Mass Hierarchy discrimination vs $\delta_{\rm CP}$ for $\sin\theta_{23} = 0.4, 0.5, 0.6$
  - · $\delta_{\rm CP}$ determination for $\delta_{\rm CP} = 0, \pi, \pm\pi/2$ and $\sin^2\theta_{23} = 0.5$
  - · $\sin^2\theta_{23}$ determination for $\sin^2\theta_{23} = 0.4, 0.5, 0.6$ and $\delta_{\rm CP} = 0$

Physical parameters (P)	Input value ($P_{\rm input}$)	Uncertainty (δP)
$\sin^2 2\theta_{12}$	0.85	0.02 [2]
$\sin^2 2\theta_{13}$	0.085	0.005 [2]
$\sin^2 2\theta_{23}$	1.00	0.02 [2]
δm^2_{21} $[\rm eV]^2$	7.5×10^{-5}	0.2×10^{-5} [2]
$\lvert\delta m^2_{32}\rvert$ $[\rm eV]^2$	$(2.47 \times 10^{-3})^{\#1}$	0.06×10^{-3} [2]
$\delta_{\rm CP}$	0	-
$\bar{\rho}^{\rm SK}$ $[\rm g/cm^3]$	2.6	6% [1]
$\bar{\rho}^{\rm C}$ $[\rm g/cm^3]$	2.9	6% [1]
$\bar{\rho}^{\rm H}$ $[\rm g/cm^3]$	2.9	6% [1]

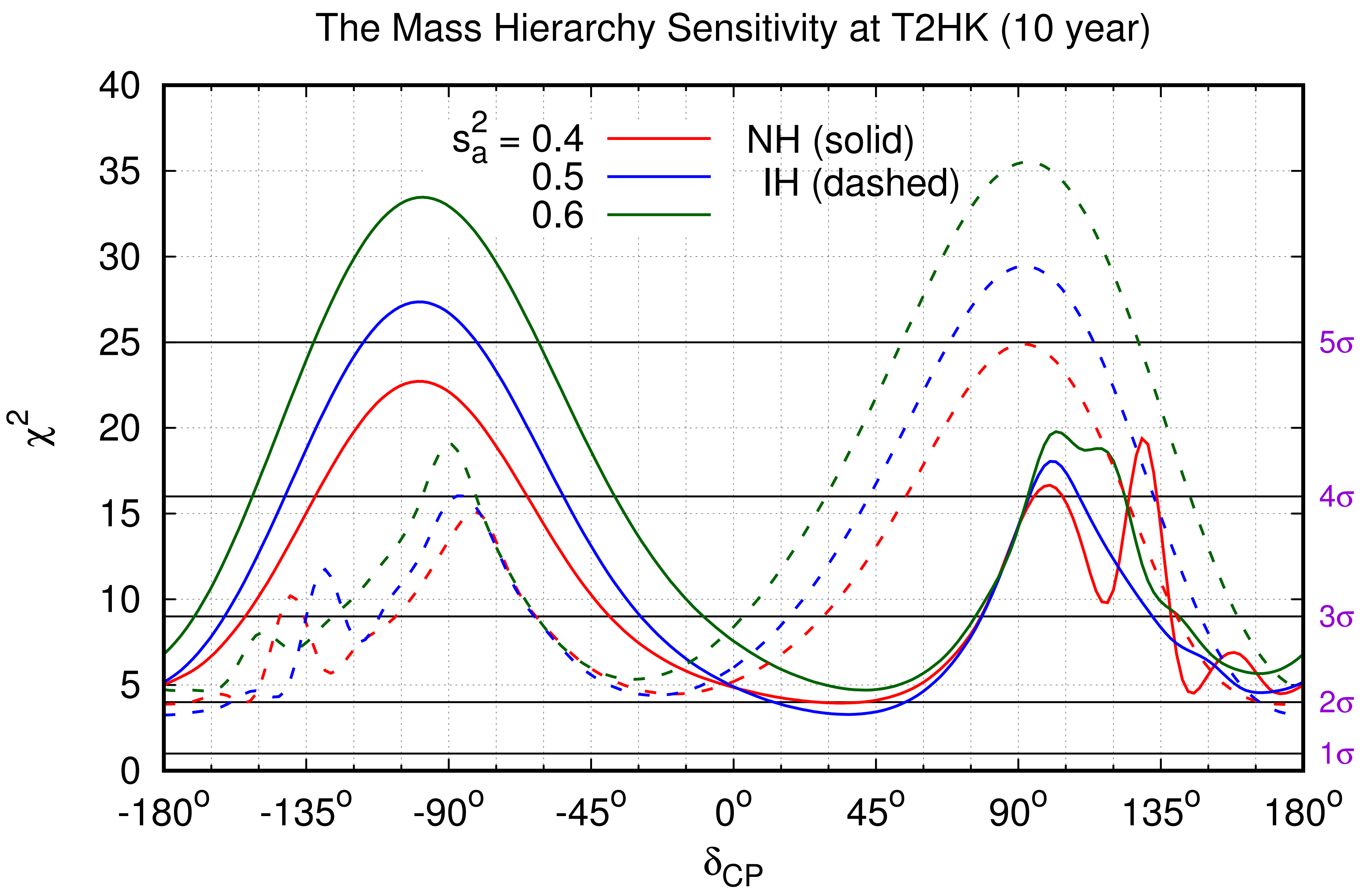
Systematic parameters (S)	Input value ($S_{\rm input}$)	Uncertainty (δS)
Fiducial volume of detectors (f_V^D)	1.00	0.03 [3]
Neutrino flux at a detector ($f_{\nu_\alpha}^D$)	1.00	0.03 [3]
CCQE cross sections ($f_{\nu_\beta}^{\rm CCQE}$)	1.00	0.03 [3]
Non-CCQE cross sections ($f_{\nu_\beta}^{\rm nonCCQE}$)	1.00	0.20 [3]
Misidentified NC π^0 events ($f_{\pi^0}^{\rm NC}$)	1.00	0.11
Misidentified NC resonant π^0 events ($f_{\pi^0}^{\rm NCRes}$)	1.00	0.13
Misidentified NC coherent π^0 events ($f_{\pi^0}^{\rm NCCoh}$)	1.00	0.15
Detection efficiency of electron Čerenkov rings (ϵ_e^D)	0.90 [3]	0.03 [4]
Detection efficiency of muon Čerenkov rings (ϵ_μ^D)	1.00	0.01 [3]
μ-to-e miss-ID probability ($P_{e/\mu}^D$)	0.01	0.01 [3]
e-to-μ miss-ID probability ($P_{\mu/e}^D$)	0.01	0.01 [3]

- Preliminary results for the **Mass Ordering** determination:
  - $\Delta\chi^2$ value of **wrong ordering assumption** is shown
  - vs $\delta_{\mathrm{CP}}^{\mathrm{true}}$ for $\sin^2\theta_{23}^{\mathrm{true}} = 0.4, 0.5, 0.6$.
  - **solid** curves when the mass oedering is **normal**,
  - **dashed** curves when it is **inverted**.

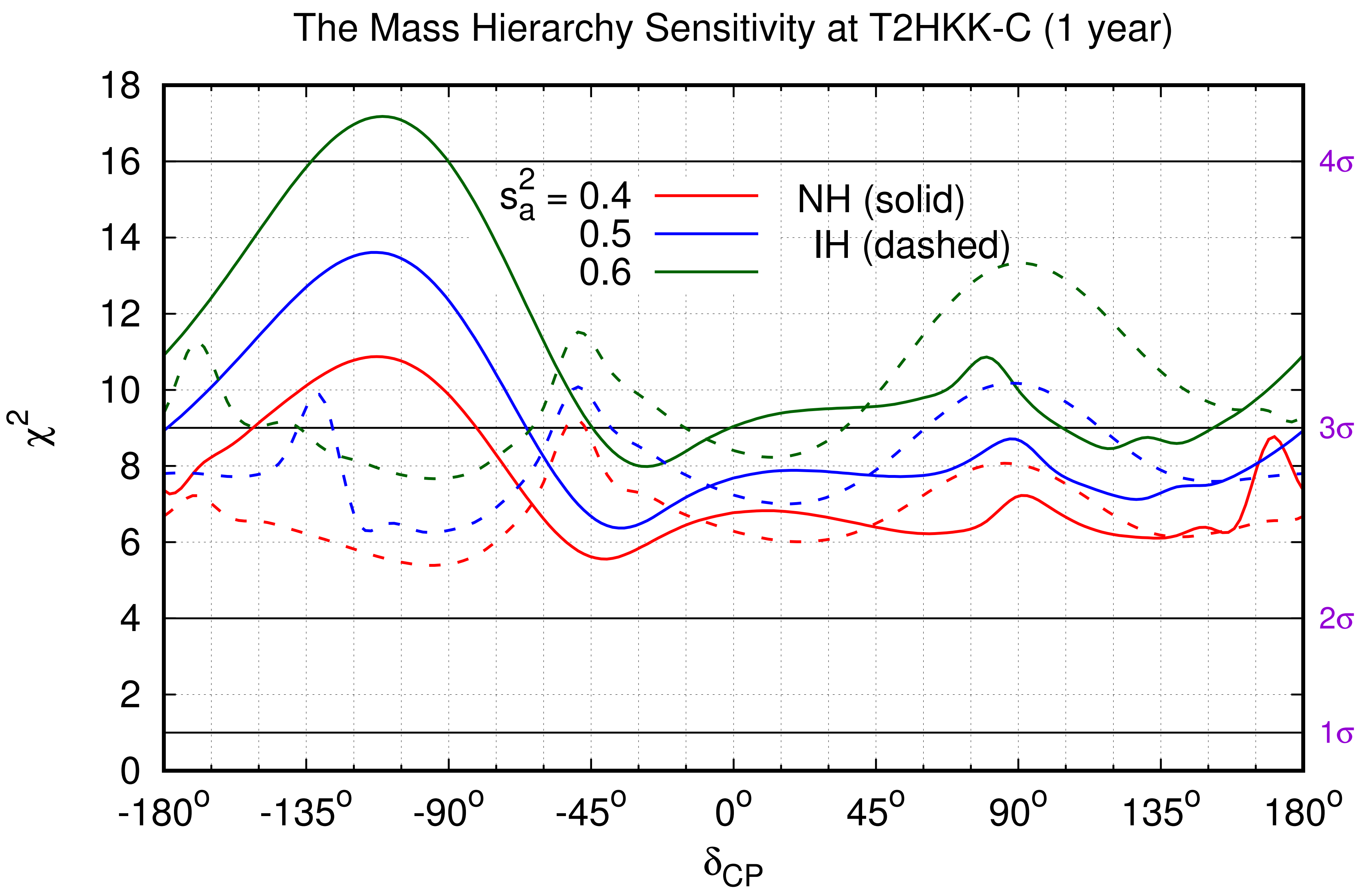
- T2DHK, T2HKK-C, T2HKK-H



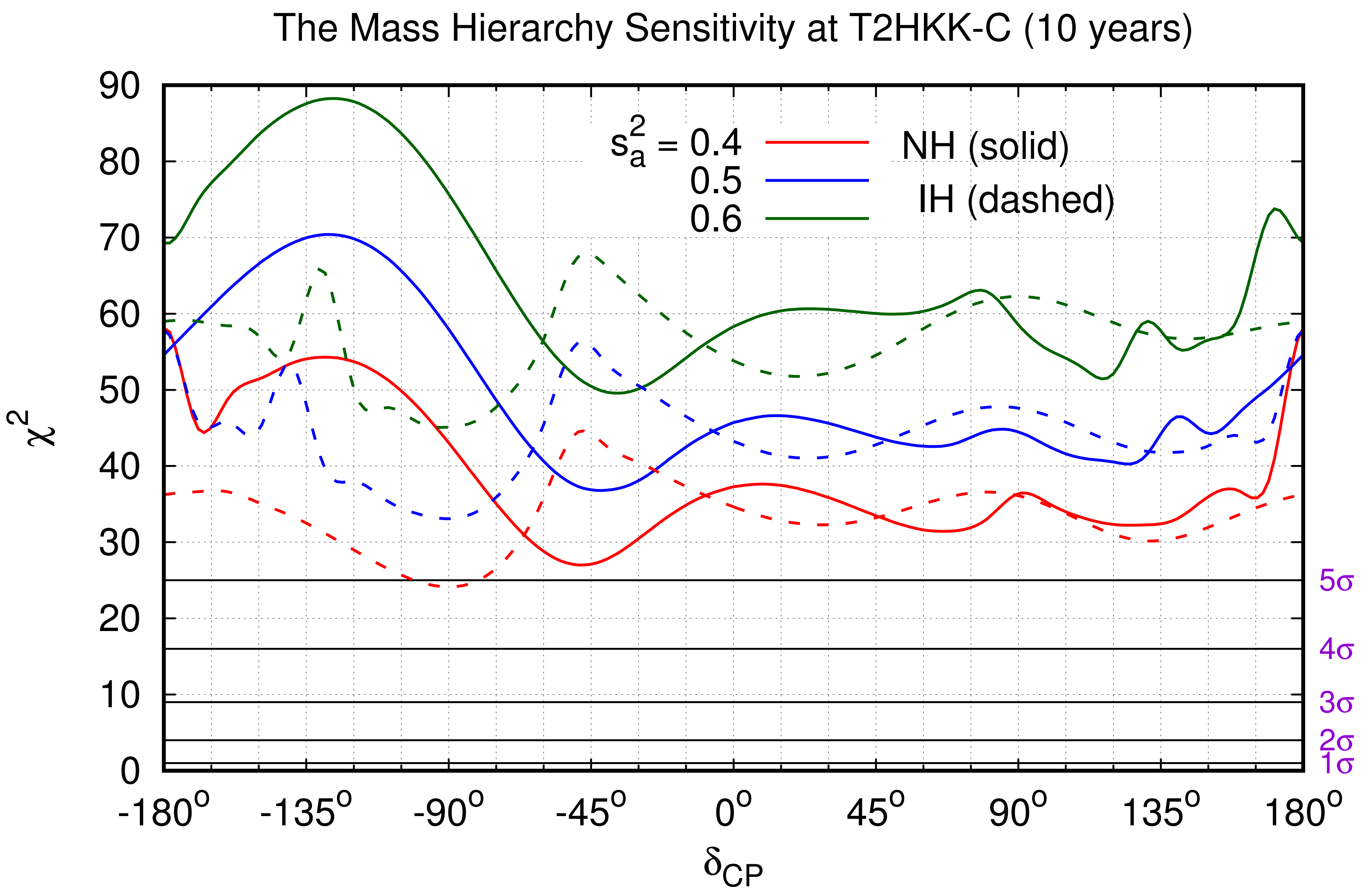
The Mass Hierarchy Sensitivity at T2HK (1 year)
s_a^2 = 0.4
0.5
0.6
NH (solid)
IH (dashed)
χ^2
δ_{CP}
0
2
4
6
8
10
12
14
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°
1σ
2σ
3σ



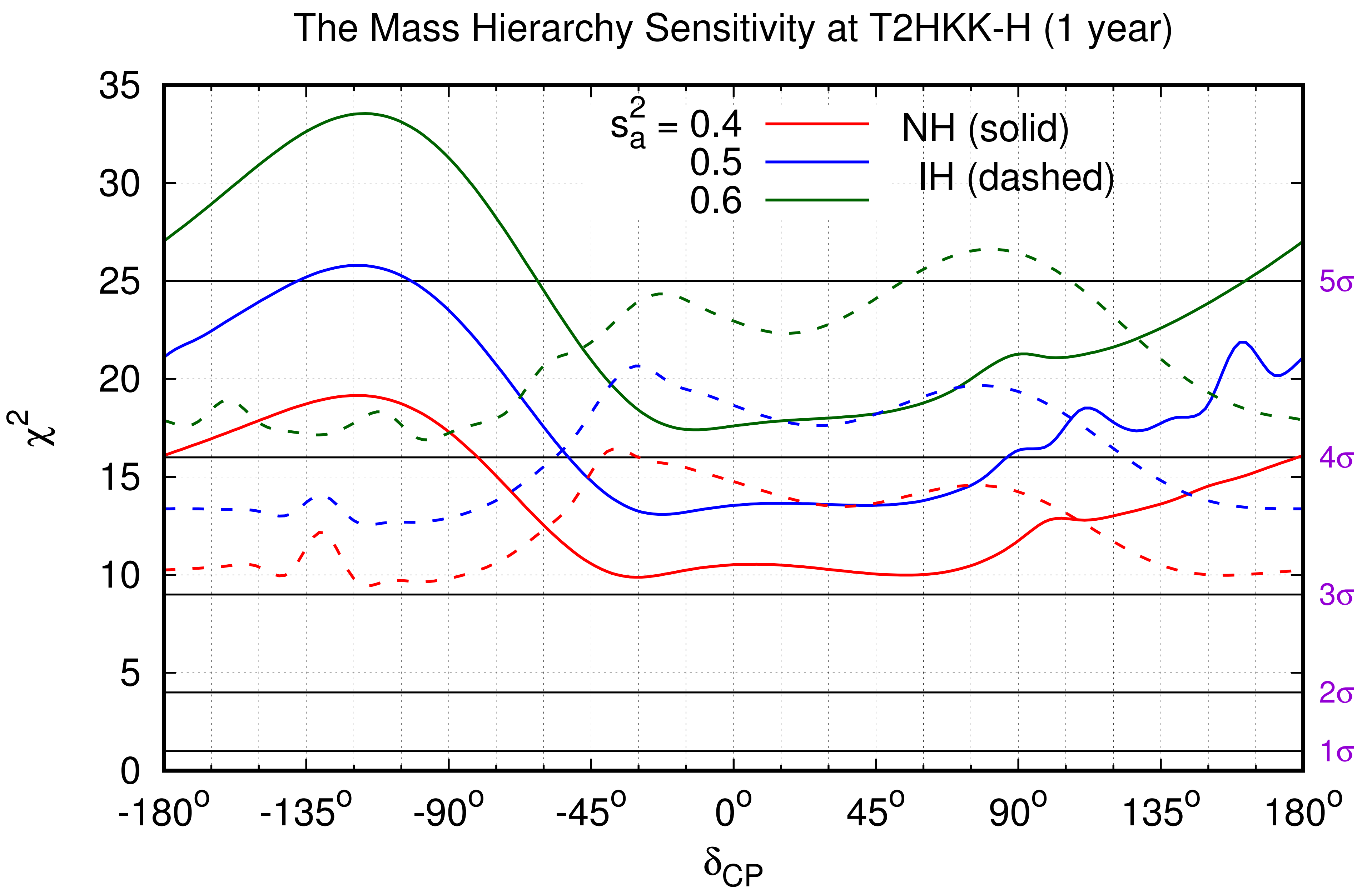
The Mass Hierarchy Sensitivity at T2HK (10 year)
s_a^2 = 0.4
0.5
0.6
NH (solid)
IH (dashed)
χ^2
δ_{CP}
0
5
10
15
20
25
30
35
40
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°
1σ
2σ
3σ
4σ
5σ



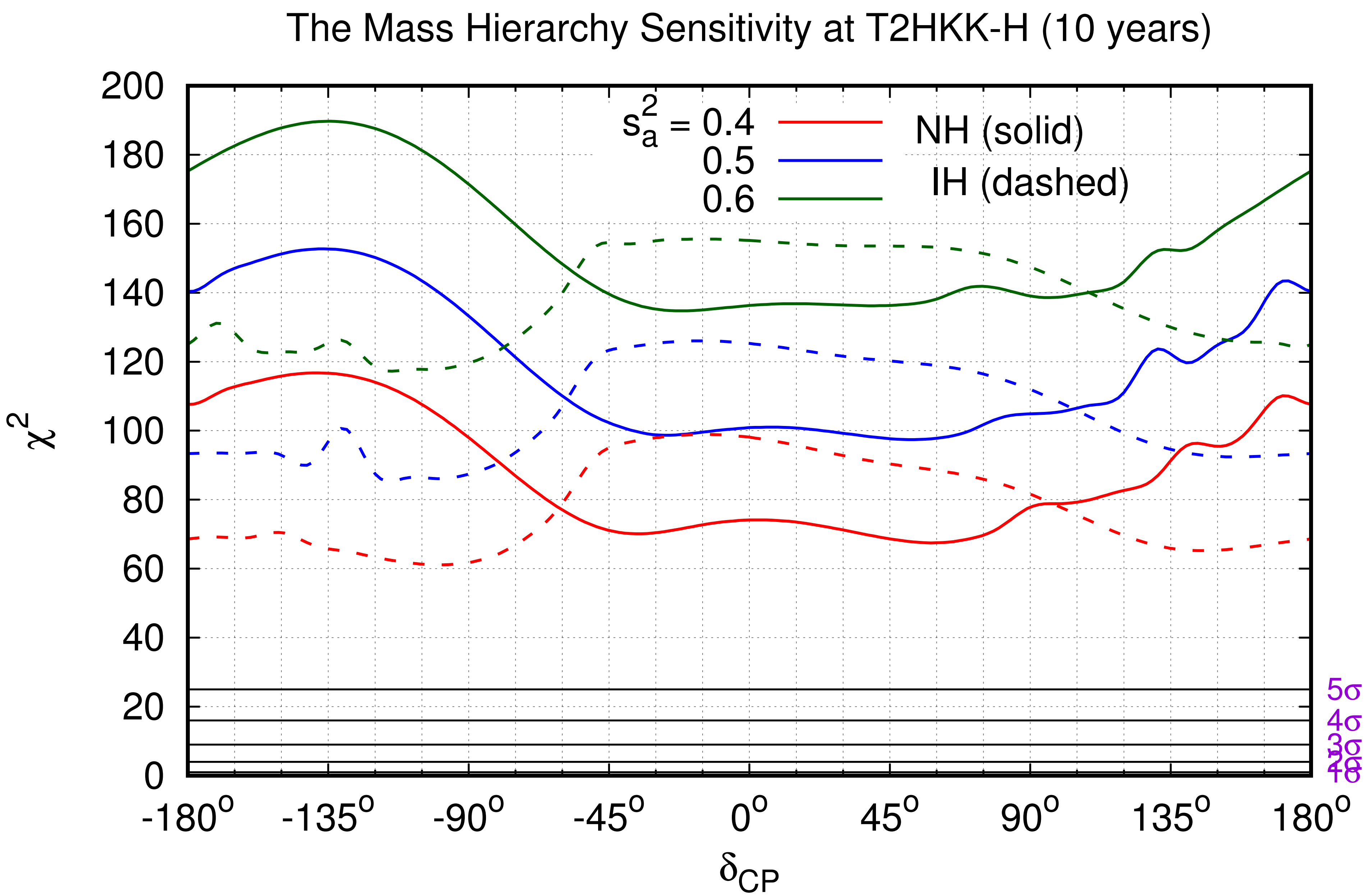
The Mass Hierarchy Sensitivity at T2HKK-C (1 year)
s_a^2 = 0.4
0.5
0.6
NH (solid)
IH (dashed)
χ^2
δ_{CP}
4σ
3σ
2σ
1σ
0
2
4
6
8
10
12
14
16
18
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°



The Mass Hierarchy Sensitivity at T2HKK-C (10 years)
s_a^2 = 0.4
0.5
0.6
NH (solid)
IH (dashed)
χ^2
90
80
70
60
50
40
30
20
10
0
5σ
4σ
3σ
2σ
1σ
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°
δ_{CP}



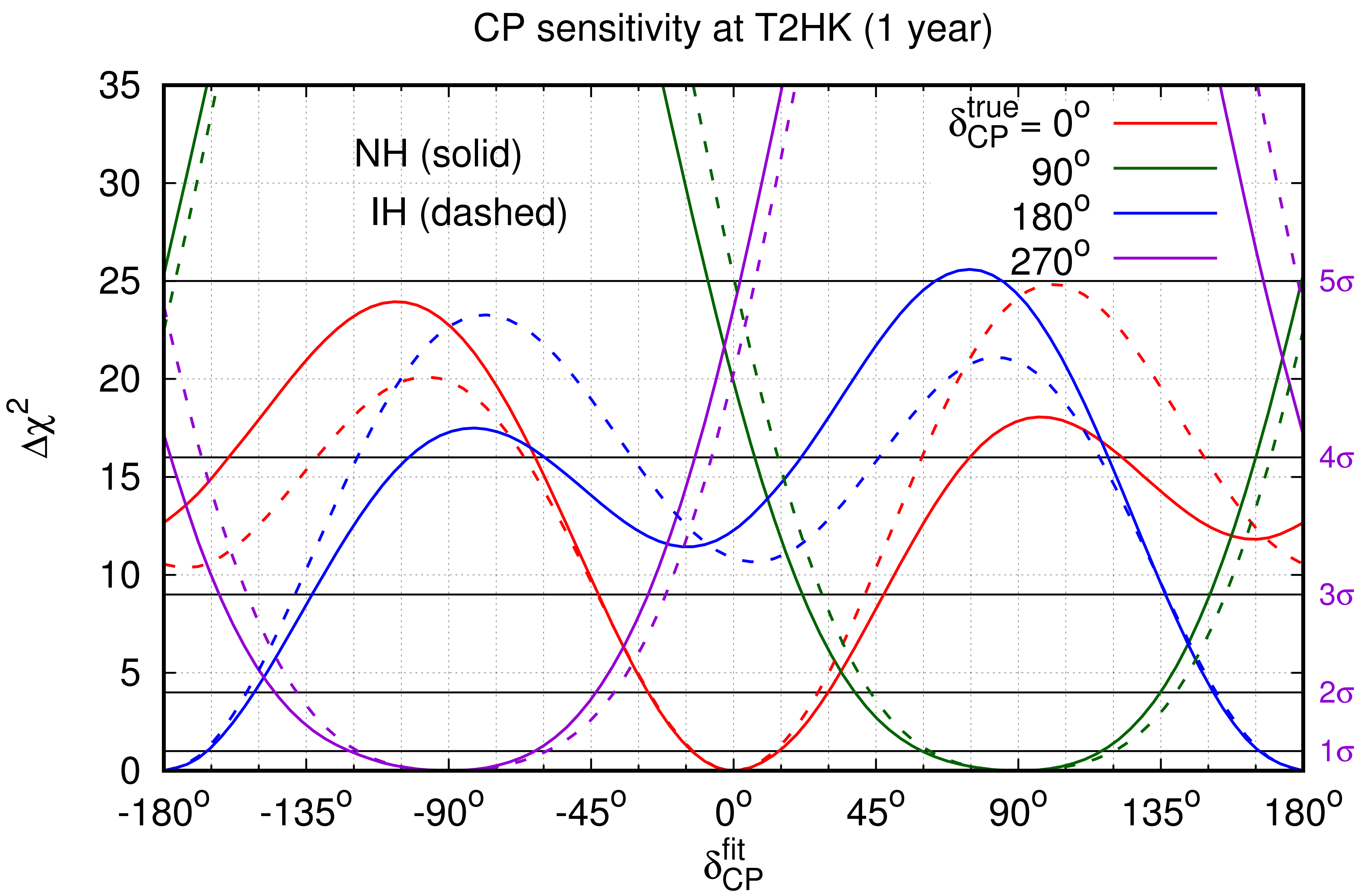
The Mass Hierarchy Sensitivity at T2HKK-H (1 year)
s_a^2 = 0.4
0.5
0.6
NH (solid)
IH (dashed)
χ^2
δ_{CP}
35
30
25
20
15
10
5
0
-180^o
-135^o
-90^o
-45^o
0^o
45^o
90^o
135^o
180^o
5σ
4σ
3σ
2σ
1σ



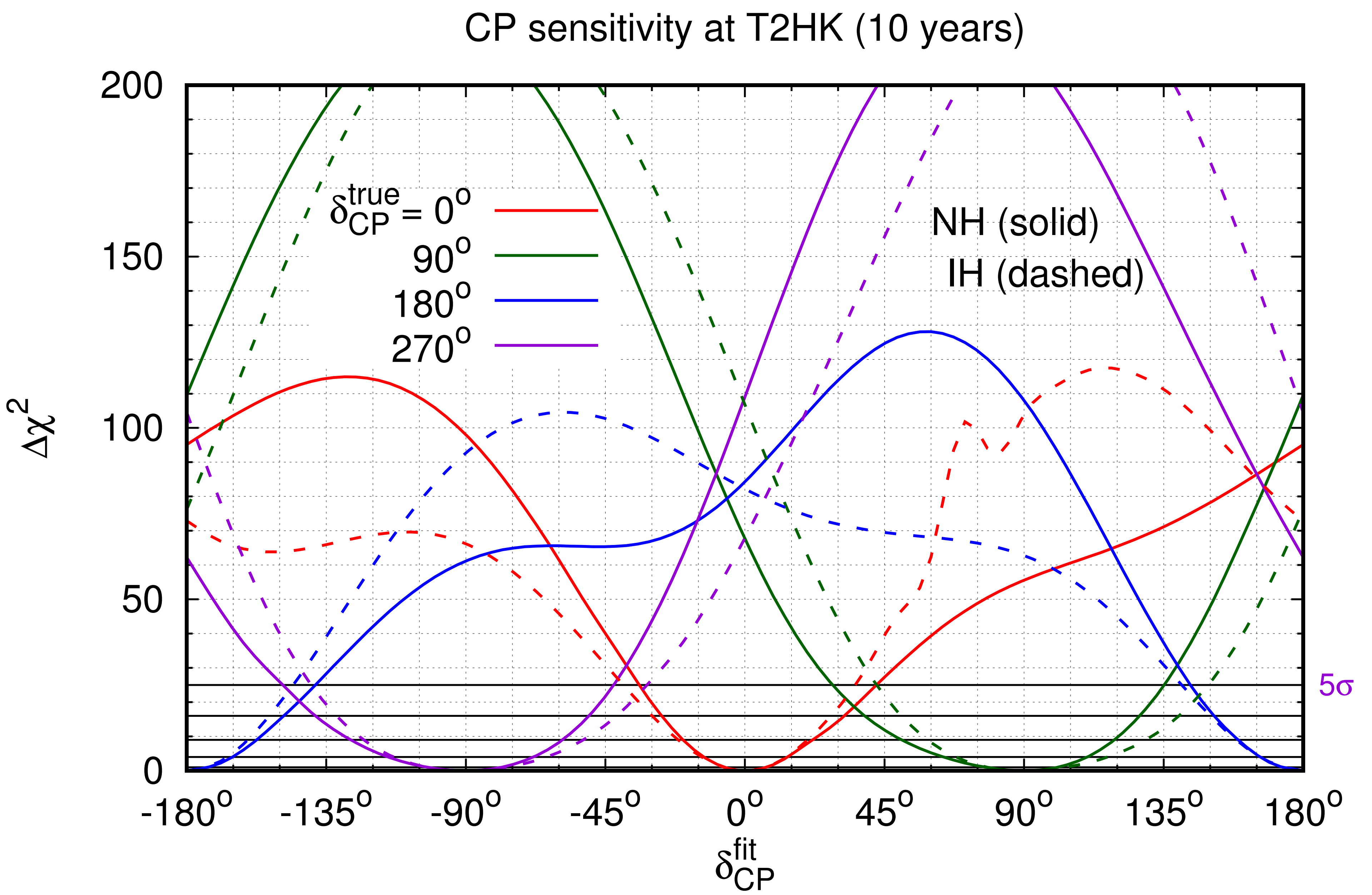
The Mass Hierarchy Sensitivity at T2HKK-H (10 years)
s_a^2 = 0.4
0.5
0.6
NH (solid)
IH (dashed)
200
180
160
140
120
100
80
60
40
20
0
χ^2
5σ
4σ
3σ
2σ
1σ
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°
δ_{CP}

- Preliminary results for the **CP phase** measruement:
  - $\Delta\chi^2$ vs $\delta_{\rm CP}$ for
  - $\delta_{\rm CP}^{\rm true} = 0, \pi, \pm\pi/2$ and $\sin^2\theta_{23}^{\rm true} = 0.5$.
  - **solid** curves when the mass oedering is **normal**,
  - **dashed** curves when it is **inverted**.

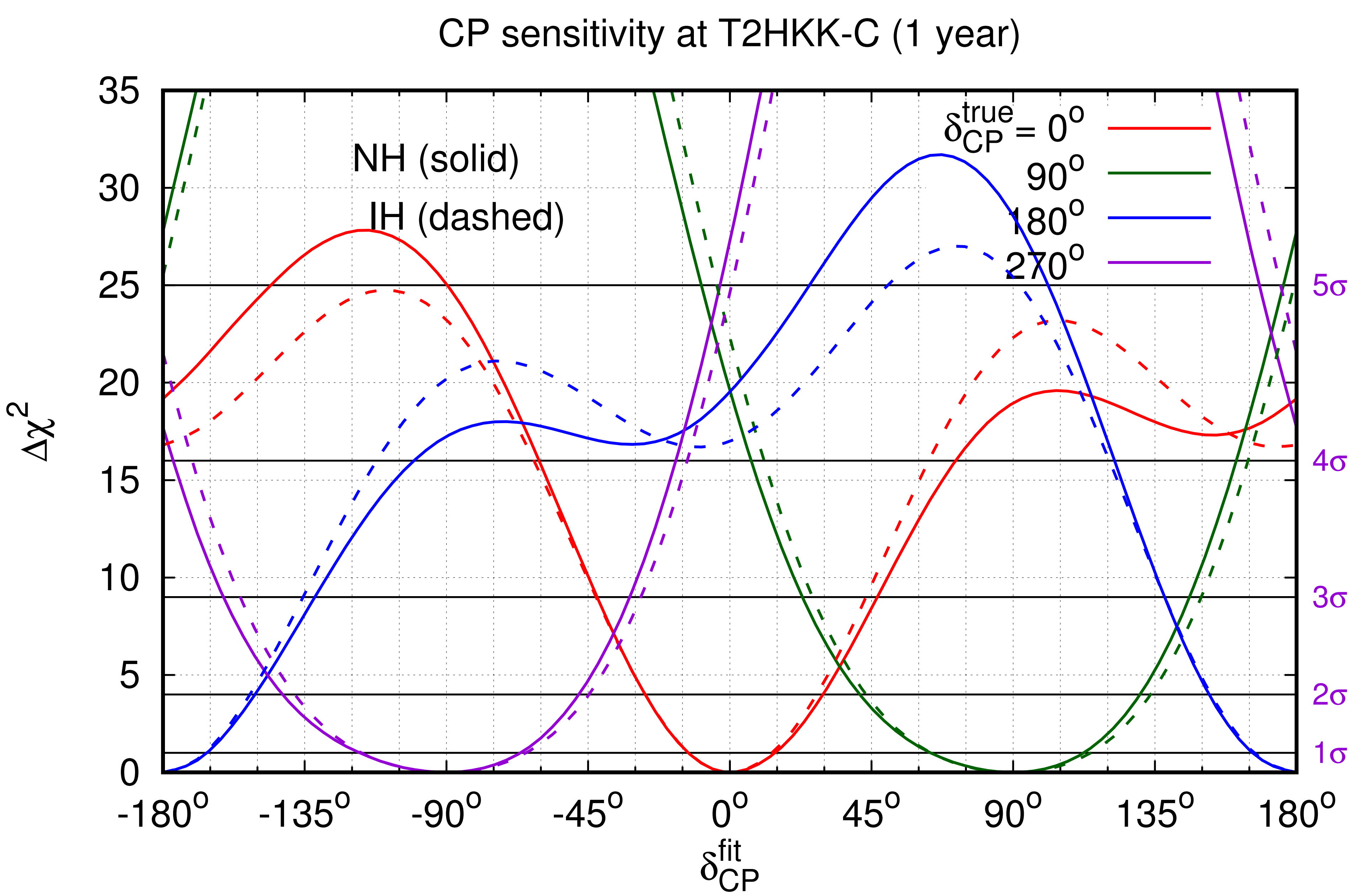
- T2DHK, T2HKK-C, T2HKK-H



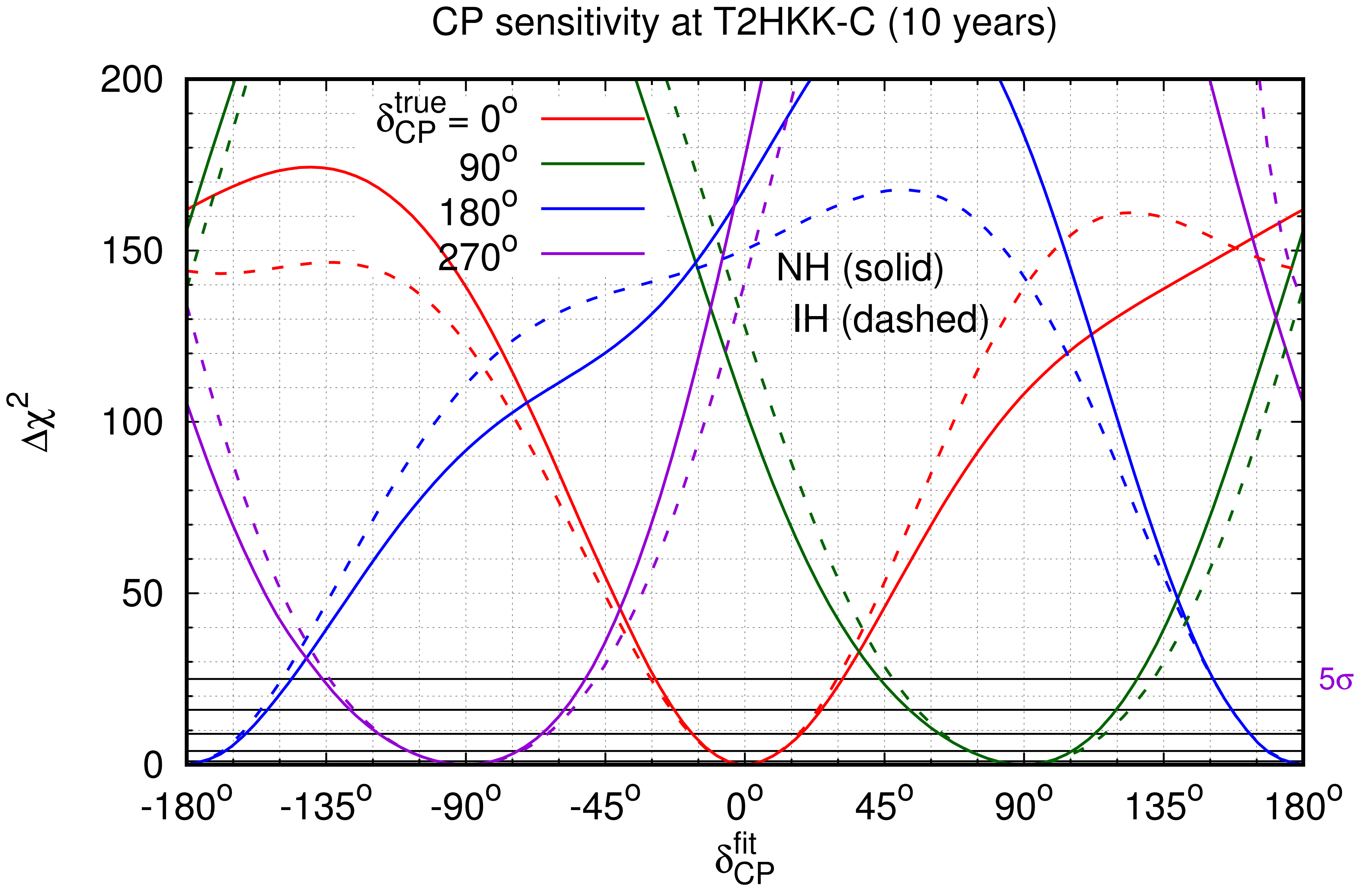
CP sensitivity at T2HK (1 year)
NH (solid)
IH (dashed)
δ_{CP}^{true} = 0°
90°
180°
270°
5σ
4σ
3σ
2σ
1σ
$\Delta\chi^2$
δ_{CP}^{fit}
35
30
25
20
15
10
5
0
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°



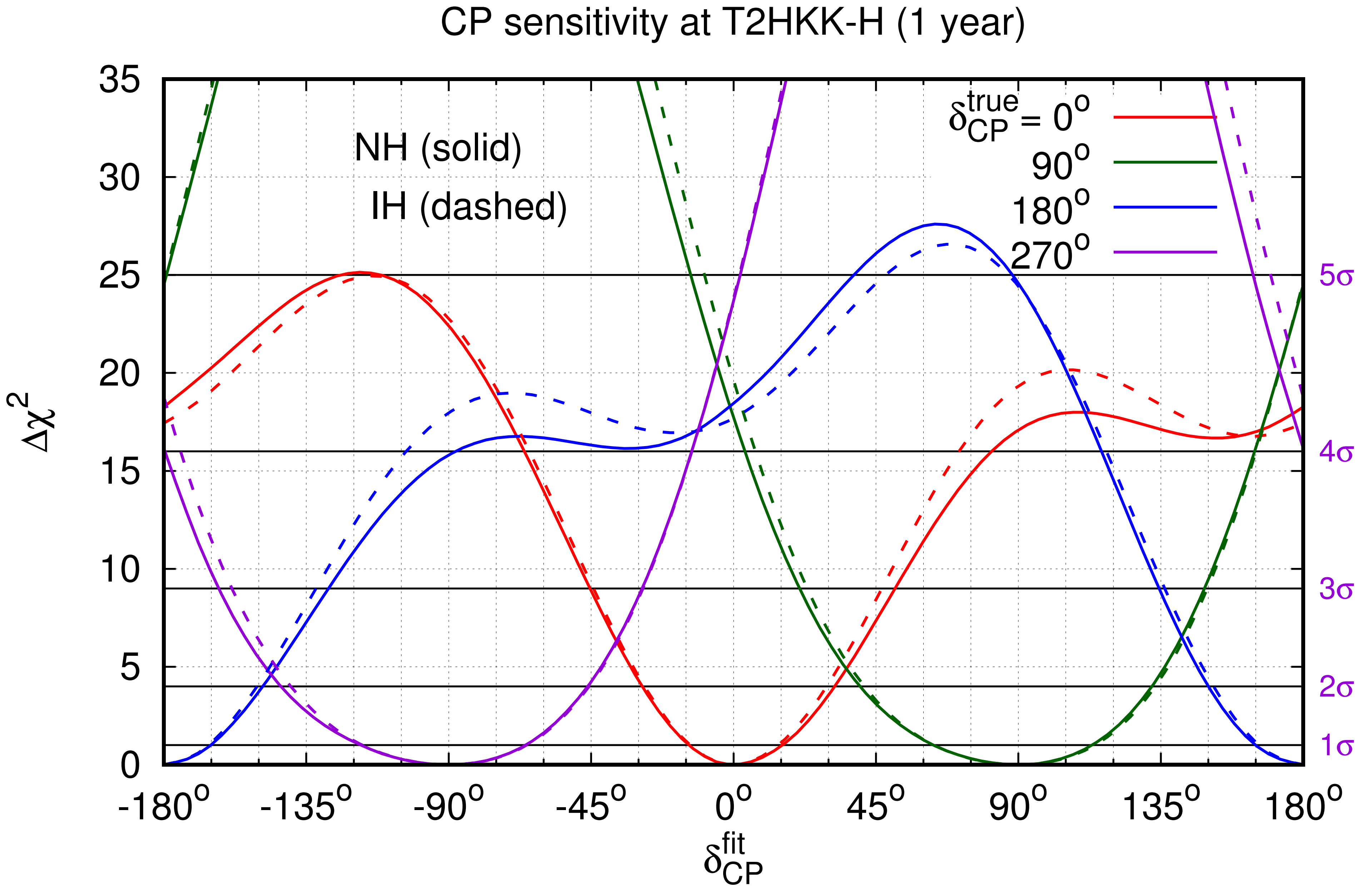
CP sensitivity at T2HK (10 years)
200
150
100
50
0
$\Delta\chi^2$
$\delta_{CP}^{true} = 0^o$
90^o
180^o
270^o
NH (solid)
IH (dashed)
5σ
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°
δ_{CP}^{fit}



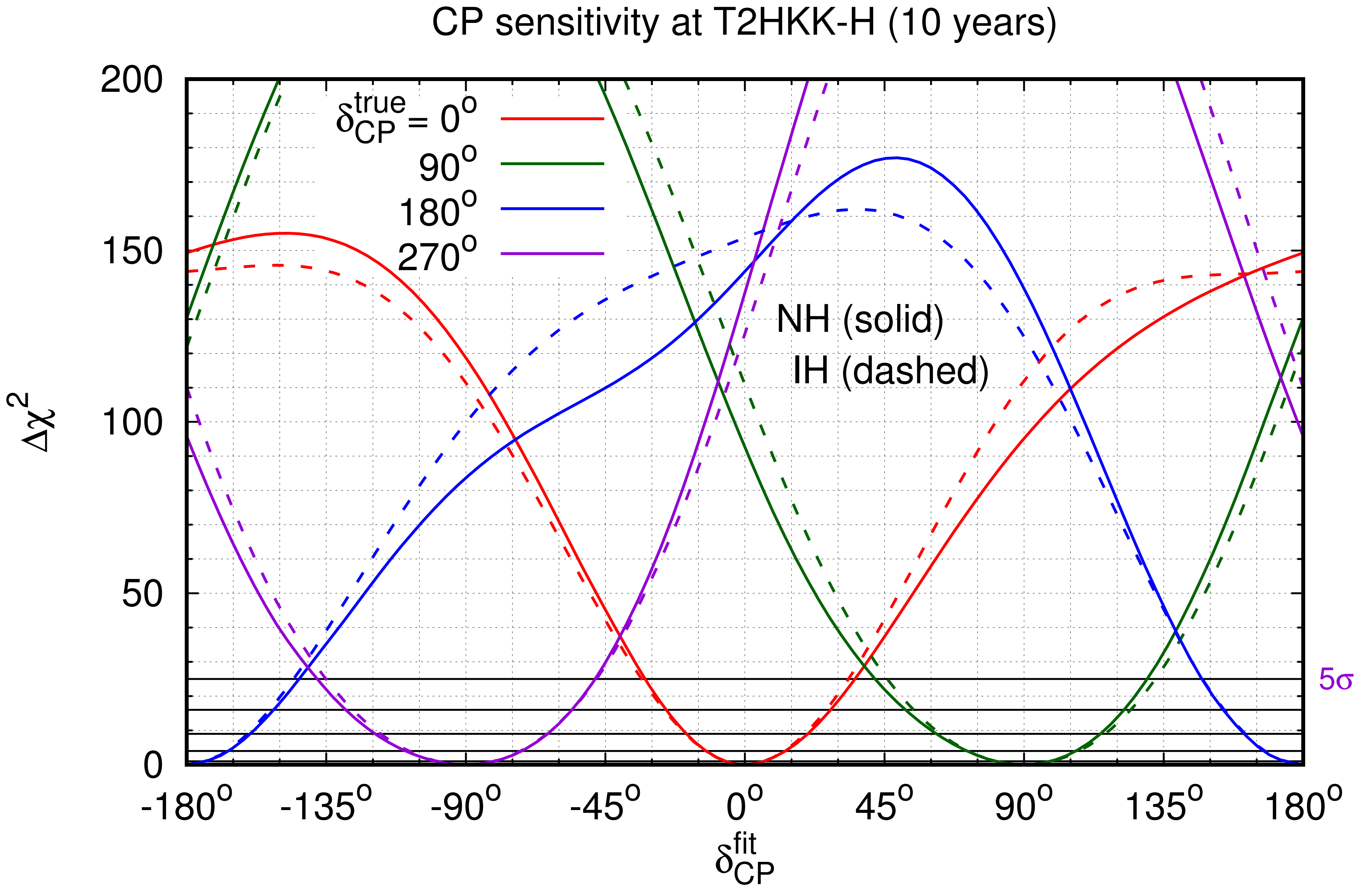
CP sensitivity at T2HKK-C (1 year)
NH (solid)
IH (dashed)
δ_CP^true = 0°
90°
180°
270°
5σ
4σ
3σ
2σ
1σ
Δχ²
δ_CP^fit
35
30
25
20
15
10
5
0
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°



CP sensitivity at T2HKK-C (10 years)
$\delta_{CP}^{true} = 0^o$
90^o
180^o
270^o
NH (solid)
IH (dashed)
5σ
$\Delta\chi^2$
200
150
100
50
0
-180^o
-135^o
-90^o
-45^o
0^o
45^o
90^o
135^o
180^o
δ_{CP}^{fit}

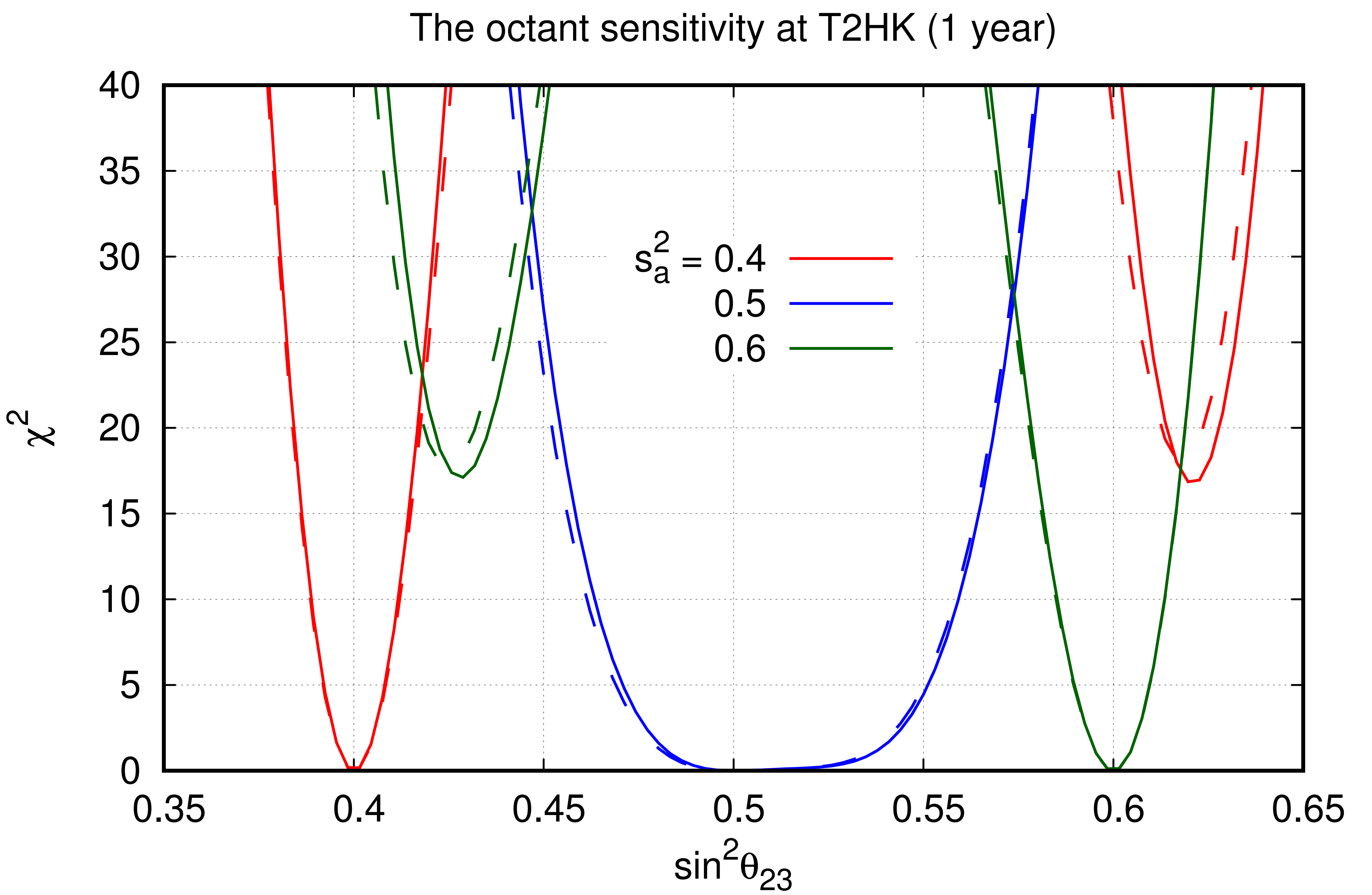


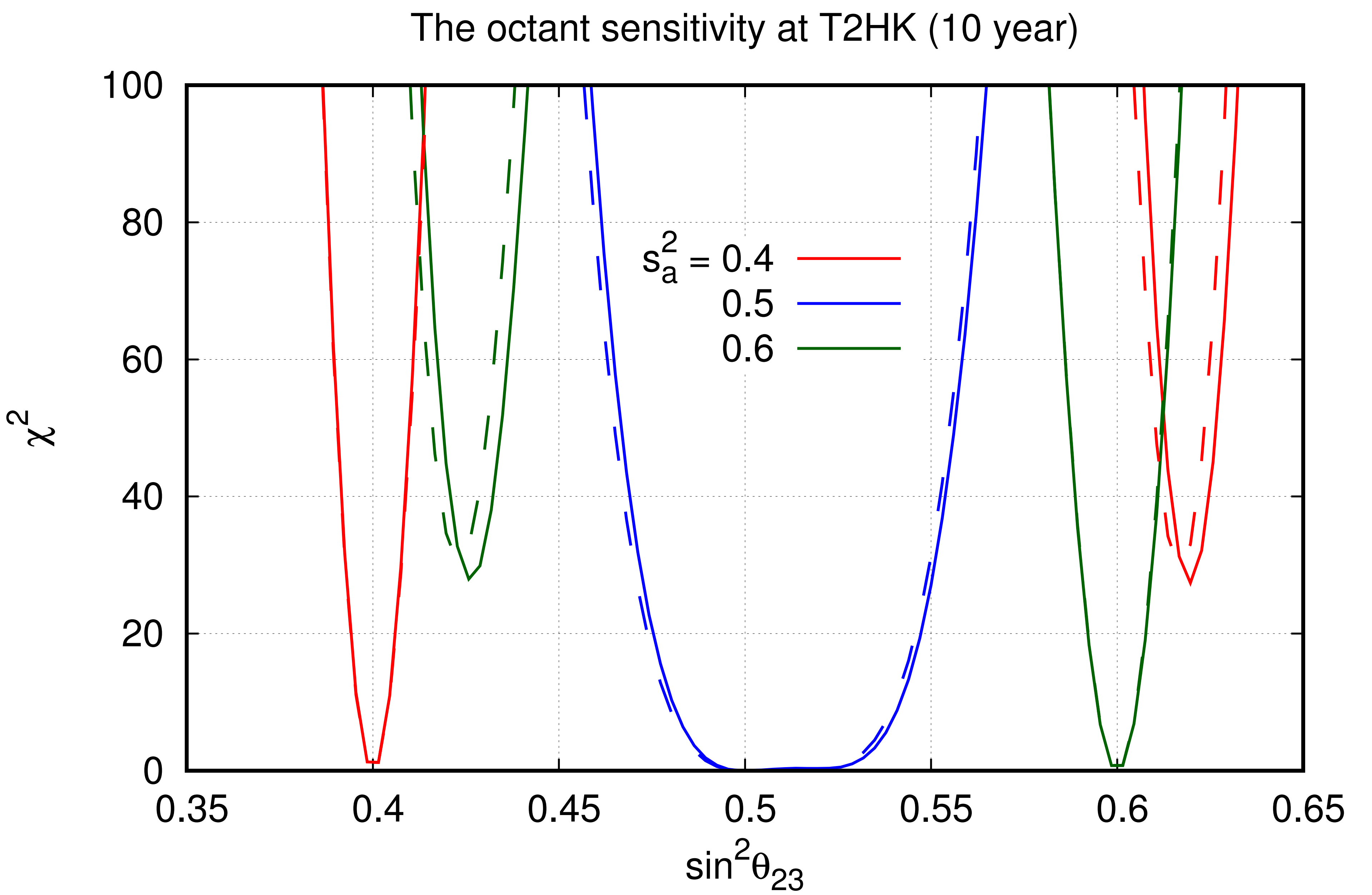
CP sensitivity at T2HKK-H (1 year)
NH (solid)
IH (dashed)
δ_CP^true = 0°
90°
180°
270°
Δχ²
δ_CP^fit
5σ
4σ
3σ
2σ
1σ
0
5
10
15
20
25
30
35
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°

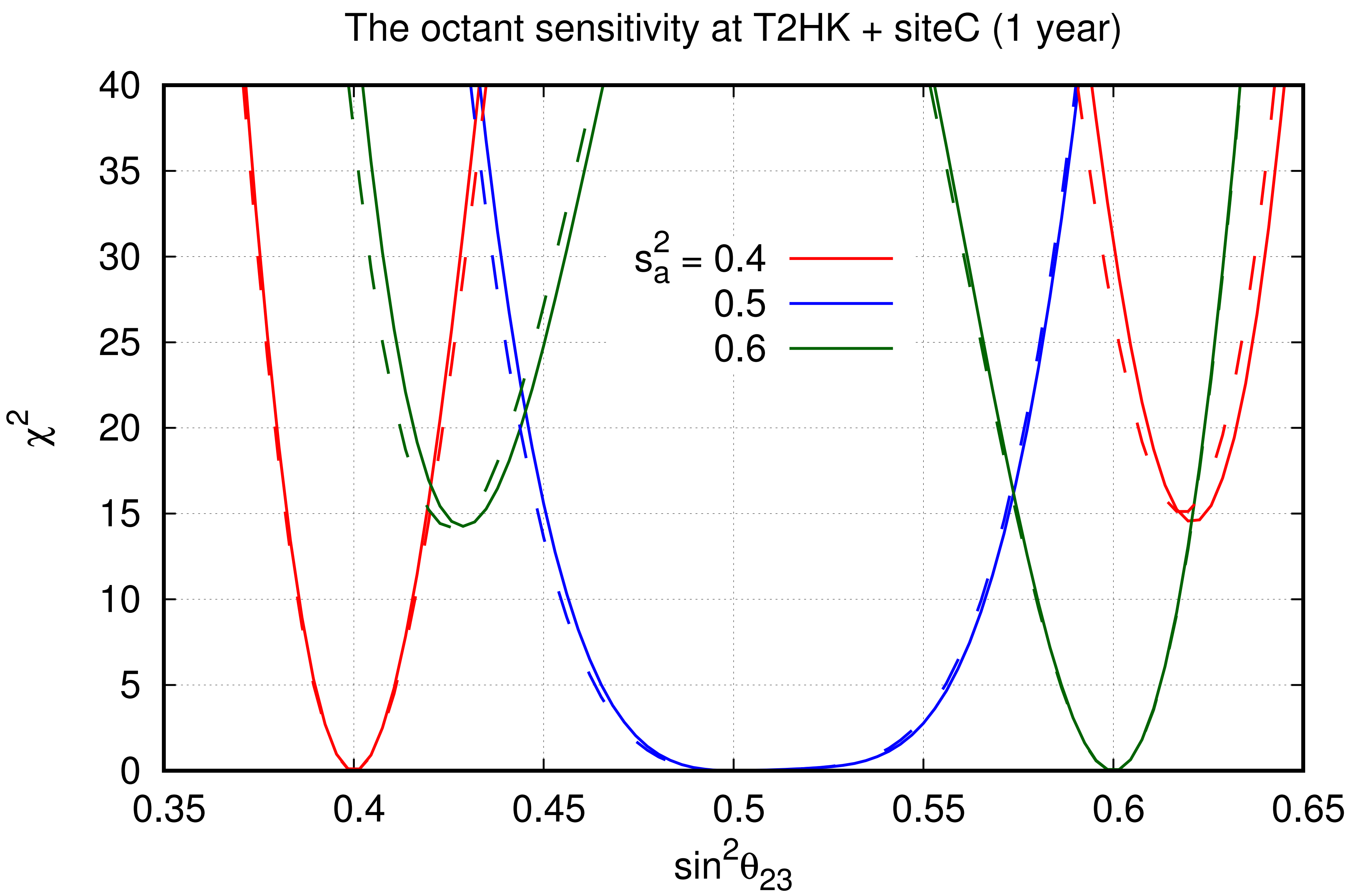

CP sensitivity at T2HKK-H (10 years)
δ_{CP}^{true} = 0°
90°
180°
270°
NH (solid)
IH (dashed)
5σ
200
150
100
50
0
$\Delta\chi^2$
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°
δ_{CP}^{fit}

- Preliminary results for the **Octant** resolution:
  - $\Delta\chi^2$ vs $\sin^2\theta_{23}$ for
  - $\sin^2\theta_{23}^{\text{true}} = 0.4, 0.5, 0.6$ and $\delta_{\text{CP}}^{\text{true}} = 0$.
  - **solid** curves when the mass oedering is **normal**,
  - **dashed** curves when it is **inverted**.

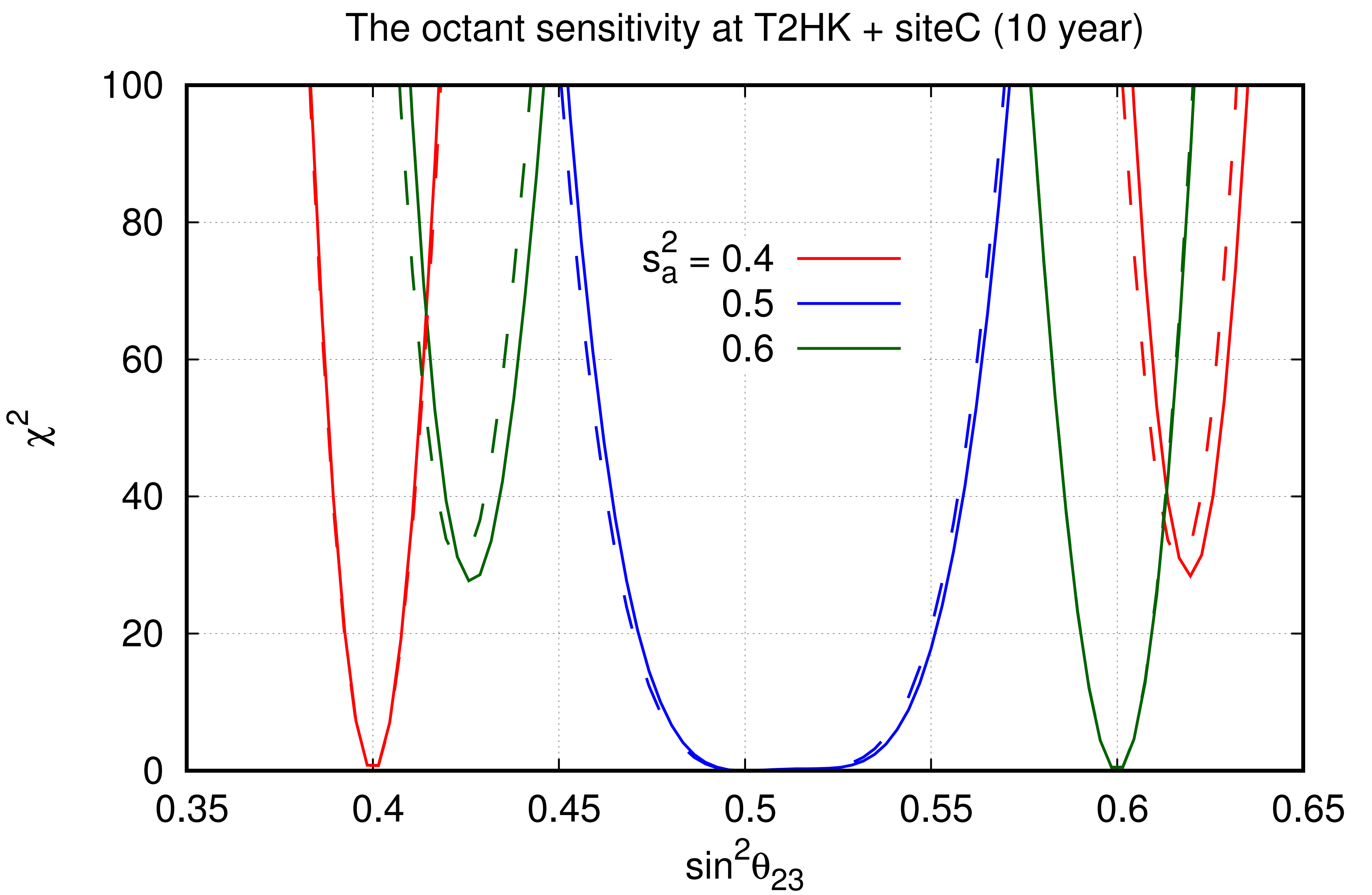
- T2DHK, T2HKK-C, T2HKK-H

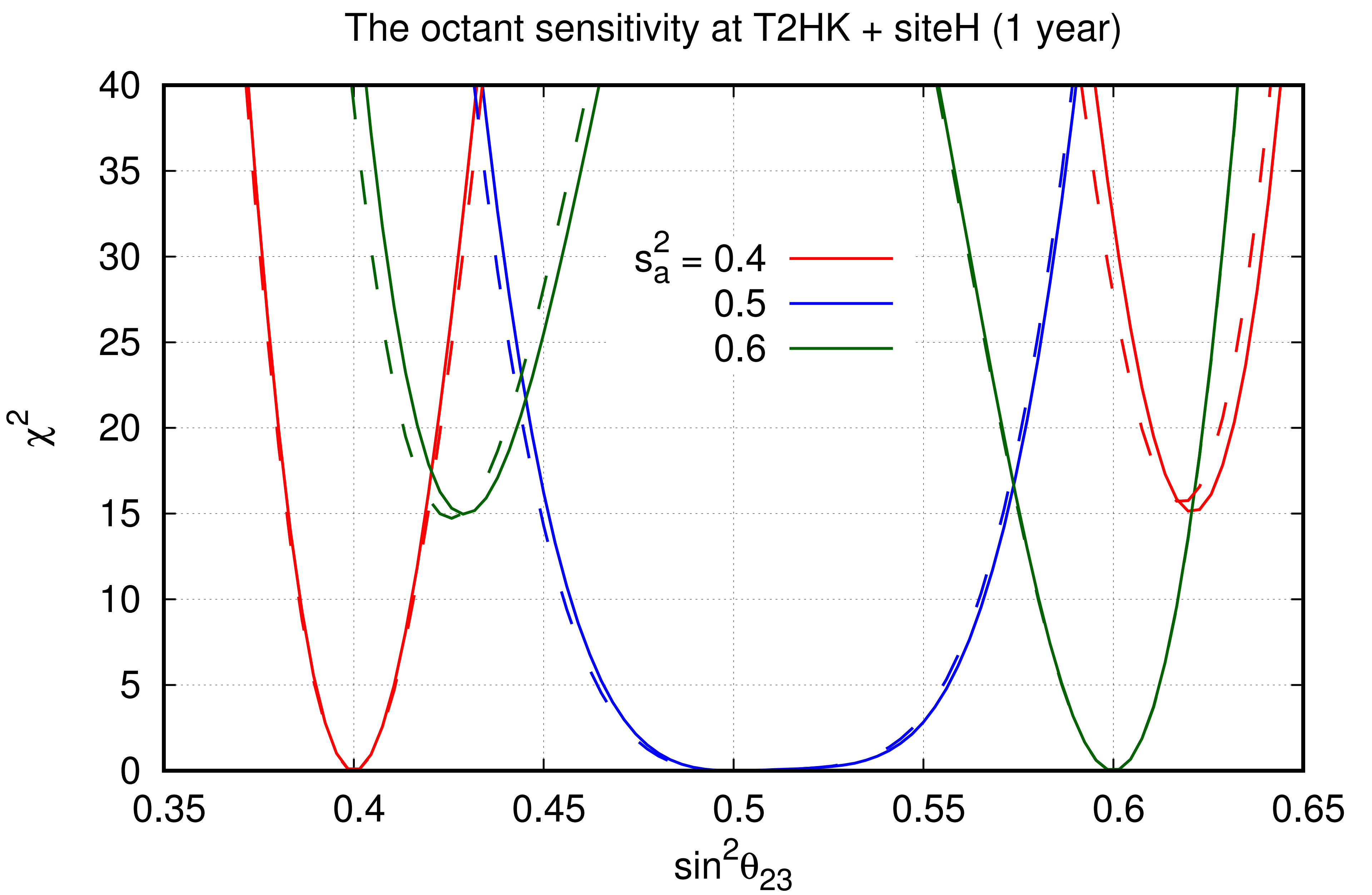

The octant sensitivity at T2HK (1 year)
χ^2
$\sin^2\theta_{23}$
s_a^2 = 0.4
0.5
0.6
0
5
10
15
20
25
30
35
40
0.35
0.4
0.45
0.5
0.55
0.6
0.65


The octant sensitivity at T2HK (10 year)
100
80
60
40
20
0
0.35
0.4
0.45
0.5
0.55
0.6
0.65
χ^2
$\sin^2\theta_{23}$
$s_a^2 = 0.4$
0.5
0.6

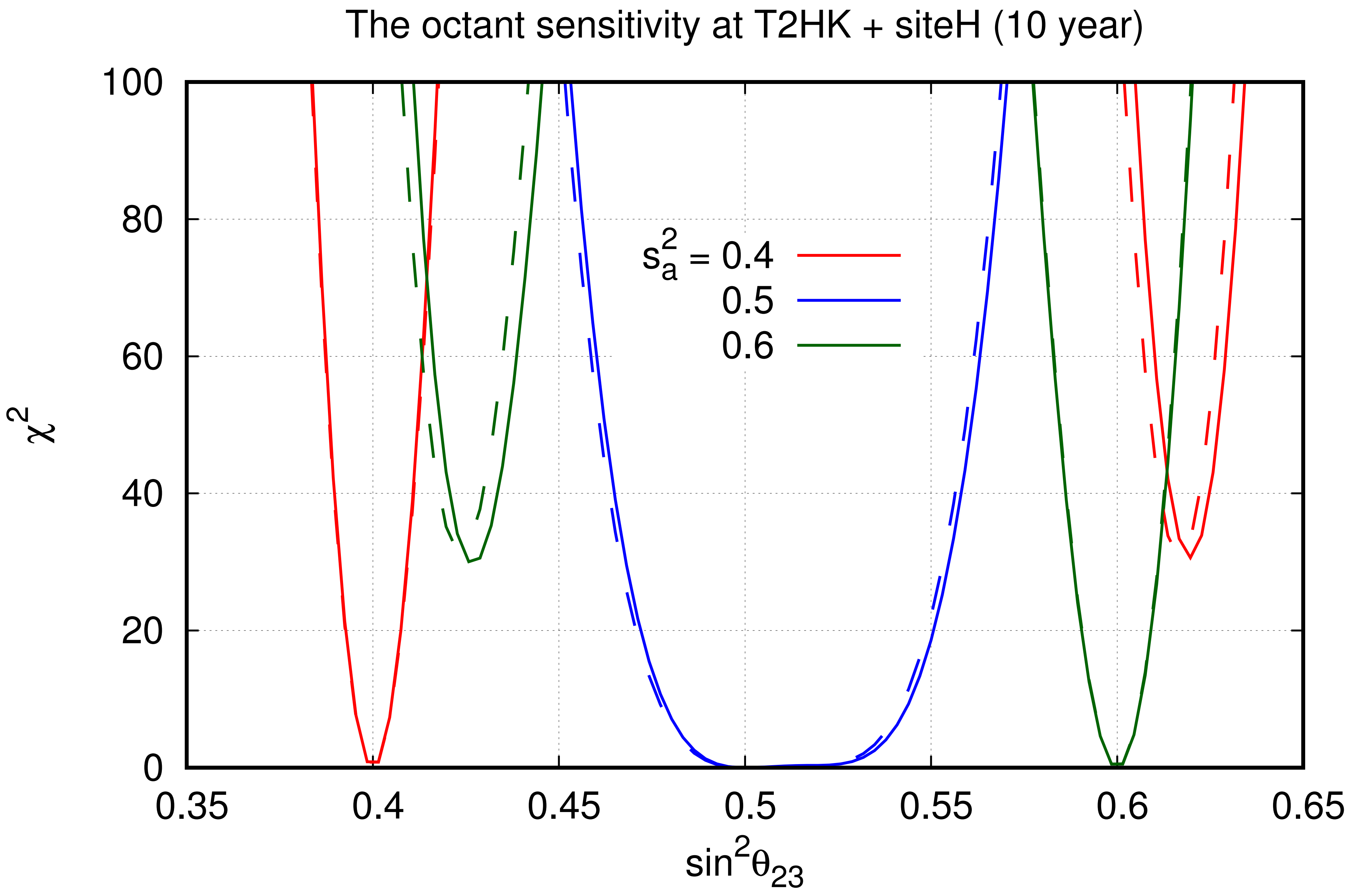


The octant sensitivity at T2HK + siteC (1 year)
s_a^2 = 0.4
0.5
0.6
χ^2
$\sin^2\theta_{23}$
0
5
10
15
20
25
30
35
40
0.35
0.4
0.45
0.5
0.55
0.6
0.65


The octant sensitivity at T2HK + siteC (10 year)
100
80
60
40
20
0
0.35
0.4
0.45
0.5
0.55
0.6
0.65
χ^2
$\sin^2\theta_{23}$
$s_a^2 = 0.4$
0.5
0.6



The octant sensitivity at T2HK + siteH (1 year)
40
35
30
25
20
15
10
5
0
0.35
0.4
0.45
0.5
0.55
0.6
0.65
χ^2
$\sin^2\theta_{23}$
s_a^2 = 0.4
0.5
0.6


The octant sensitivity at T2HK + siteH (10 year)
χ^2
$\sin^2\theta_{23}$
$s_a^2 = 0.4$
0.5
0.6
0
20
40
60
80
100
0.35
0.4
0.45
0.5
0.55
0.6
0.65

Tentative summary of our findings on T2HKK

- T2HKK with **site H(Mt.Bisul)** can resolve the **neutrino mass hierarchy** at 3-σ (8-σ) after 1 year (10 years). Site C(Mt.Bohyun) option can reach 5-σ in 10 years, but a single baseline option of T2DHK (all at Kamioka) has no sensitivity to the mass hierarchy except when $\delta \sim -90^\circ$ (normal) or when $\delta \sim 90^\circ$ (inverted).

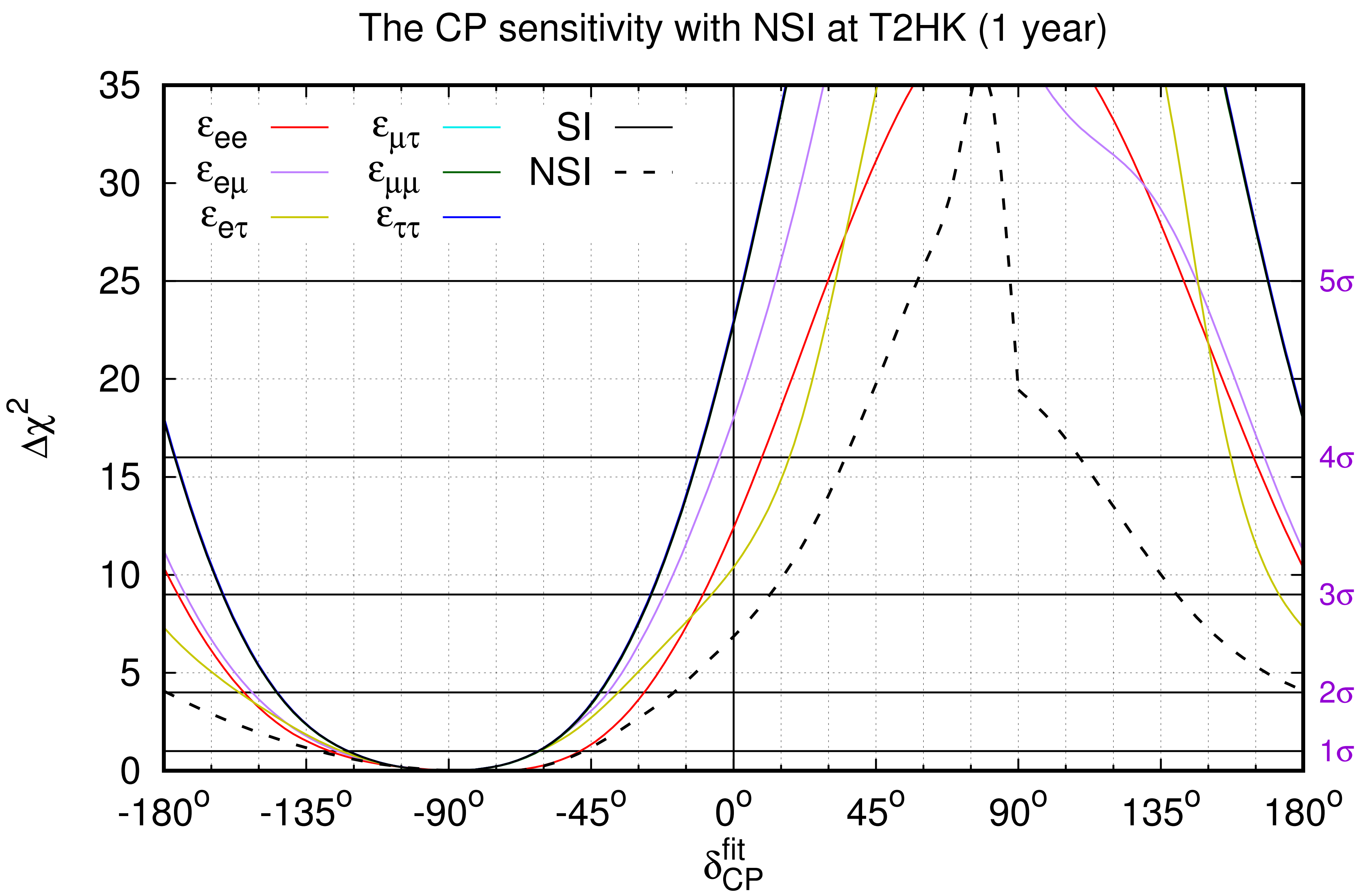
- The sensitivity to **the CP phase** δ is found to be very similar for all the three options. This is because the factor of 3 higher sensitivity to δ at the **second oscillation maximum**, observed in Korea (both site C and H), roughly compensates for a factor of 10 decrease in the flux. The δ measurement is found to be $\sim 15^\circ$ ($\sim 5^\circ$) if $\delta = 0, \pi$ while $\sim 25^\circ$ ($\sim 8^\circ$) if $\delta = \pm\pi/2$, after 1 year (10 years) for all the three cases we studied. T2HKK at site C or H has better resolution of 0-π degeneracy which is observed (at 3-σ level after 1 year) in the all-at-Kamioka option.

- The **octant resolution** capability between $\sin^2\theta_{23} = 0.4$ and 0.6 is found to be 4-σ (5-σ) after 1 year (10 years) for all three cases we studied.

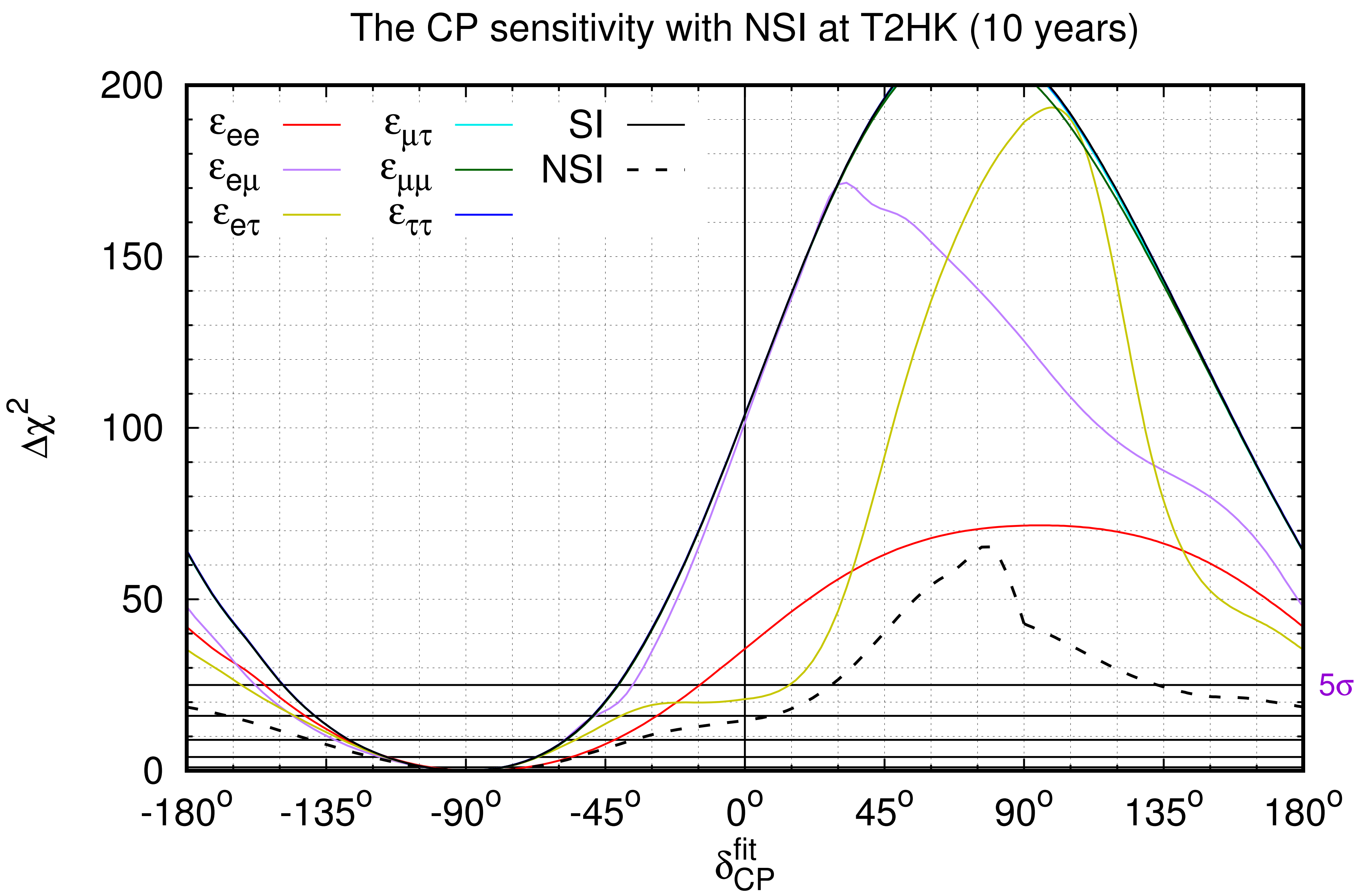
The next steps in our T2HKK studies

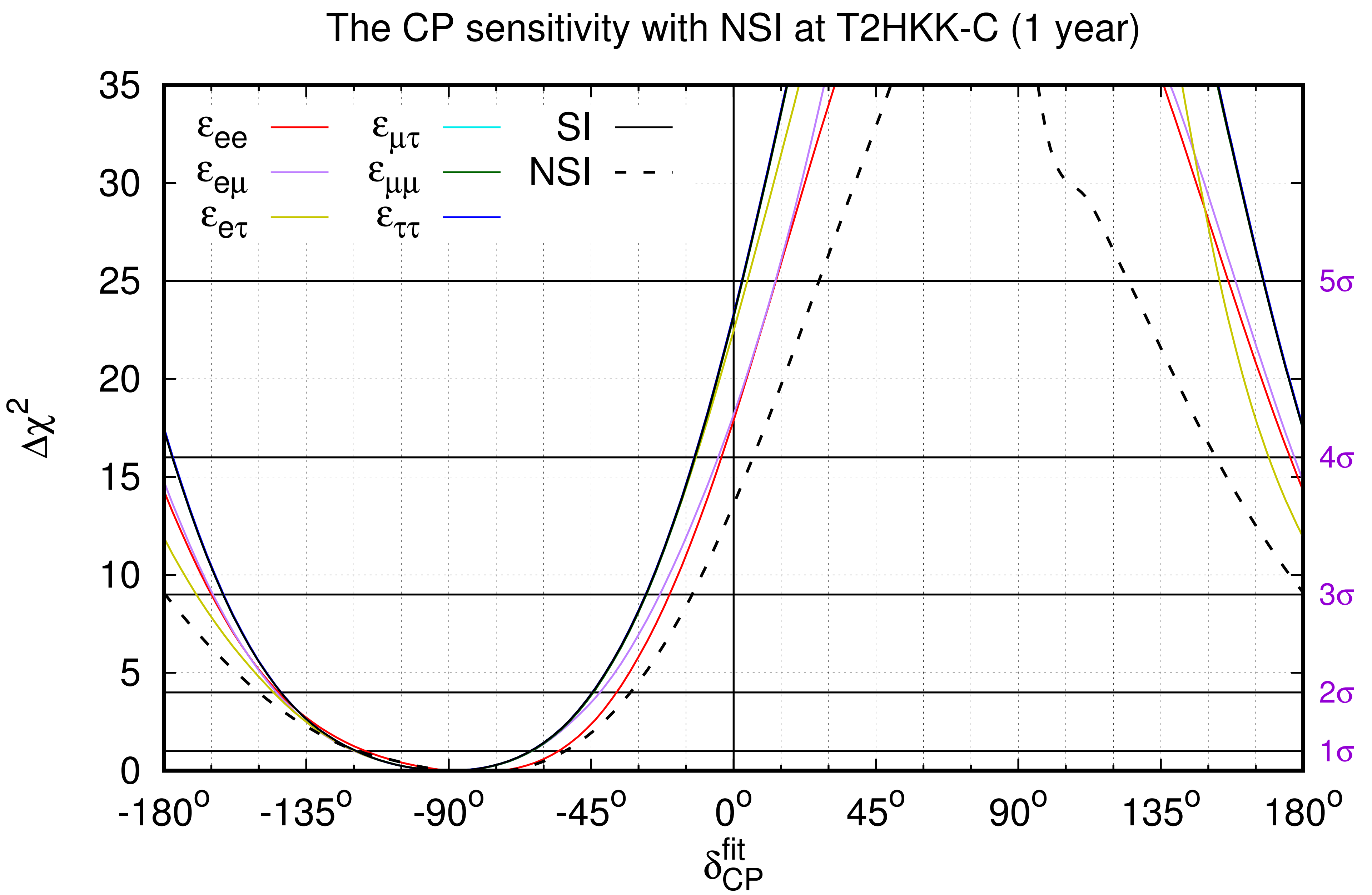
- We have not studied possible **correlations among systematic errors** at SK, HK in Kamioka and in Korea. The use of **the same beam** and **the same detector** technology should have impacts on the precision of the measurements.

- Very naively, we expect that the measurements done at two vastly difference baseline lengths (and energies for site H) should be more robust against loosening of the model assumptions, such as the existence of more than 3 neutrinos (**non-unitarity** of 3 by 3 mixing matrix) and/or **non-standard interactions** among the 3 neutrinos. Let me show very preliminary findings based on *Non-standard interactions and the CP phase measurements in neutrino oscillations at low energies* by Shao-Feng Ge and Alexei Yu. Smirnov [arXiv:1607.08513].

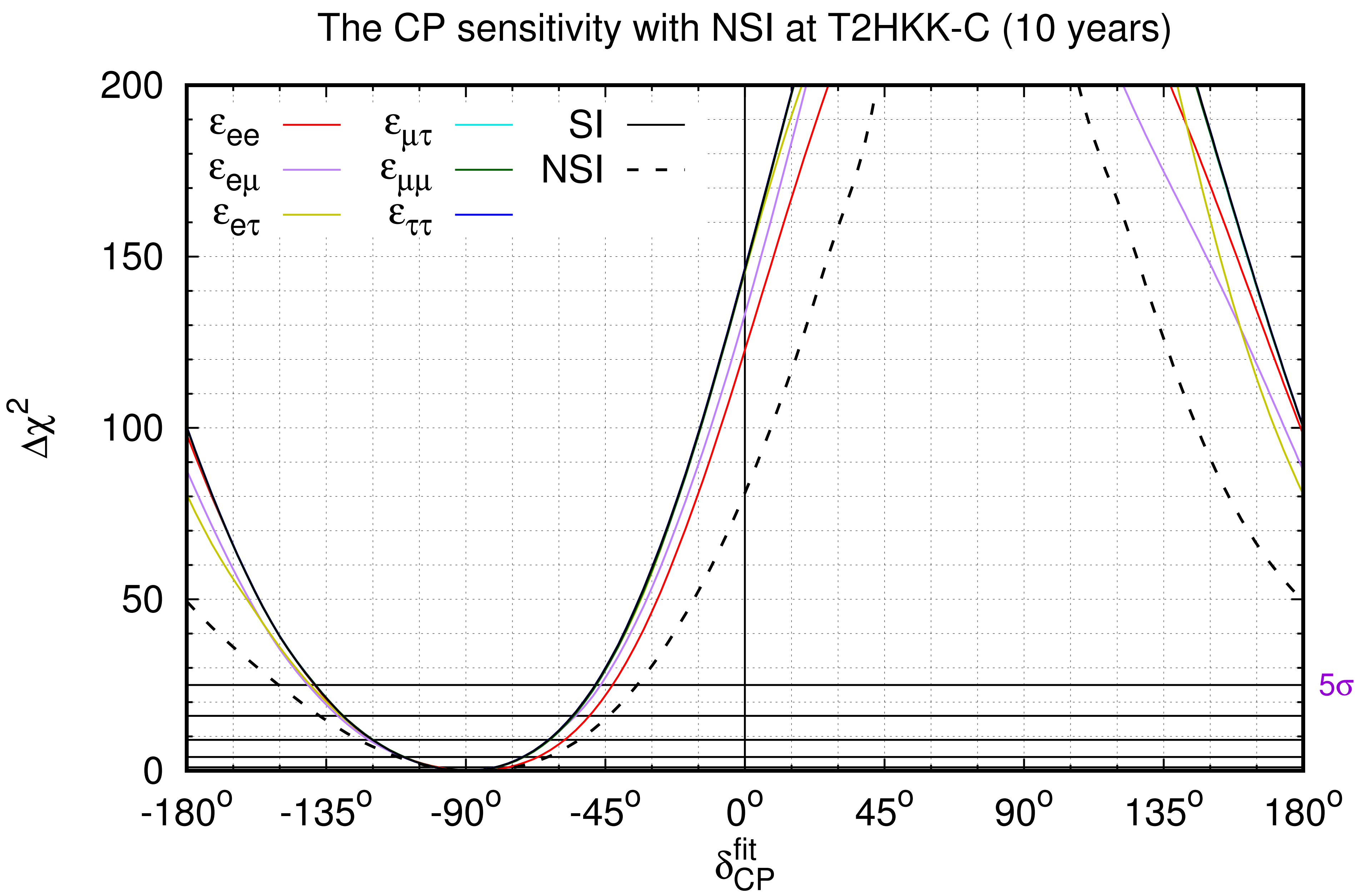


The CP sensitivity with NSI at T2HK (1 year)
ε_ee
ε_eμ
ε_eτ
ε_μτ
ε_μμ
ε_ττ
SI
NSI
35
30
25
20
15
10
5
0
Δχ²
5σ
4σ
3σ
2σ
1σ
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°
δ_CP^fit

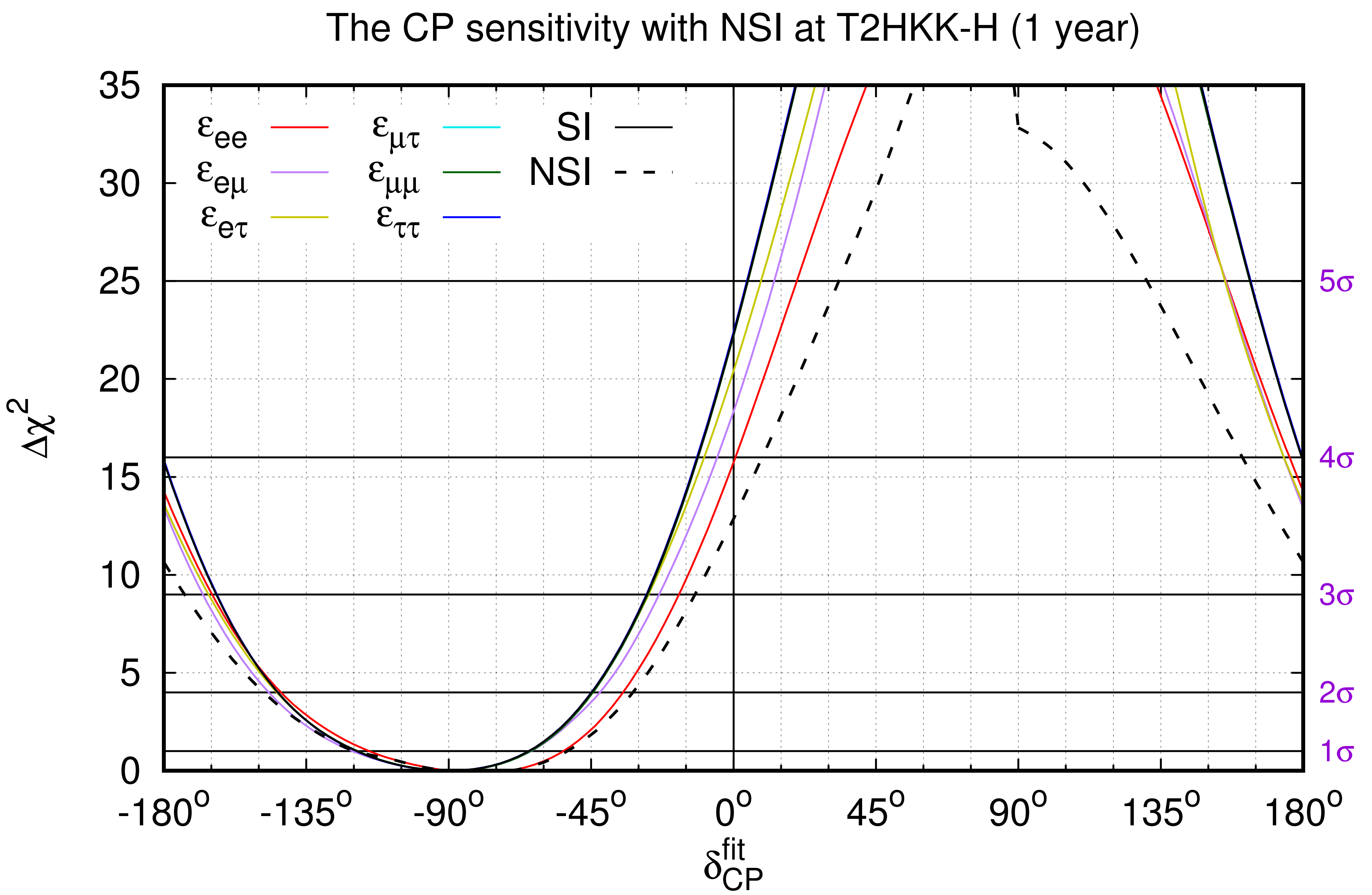

The CP sensitivity with NSI at T2HK (10 years)
ε_{ee}
$\varepsilon_{e\mu}$
$\varepsilon_{e\tau}$
$\varepsilon_{\mu\tau}$
$\varepsilon_{\mu\mu}$
$\varepsilon_{\tau\tau}$
SI
NSI
5σ
$\Delta\chi^2$
δ_{CP}^{fit}
200
150
100
50
0
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°



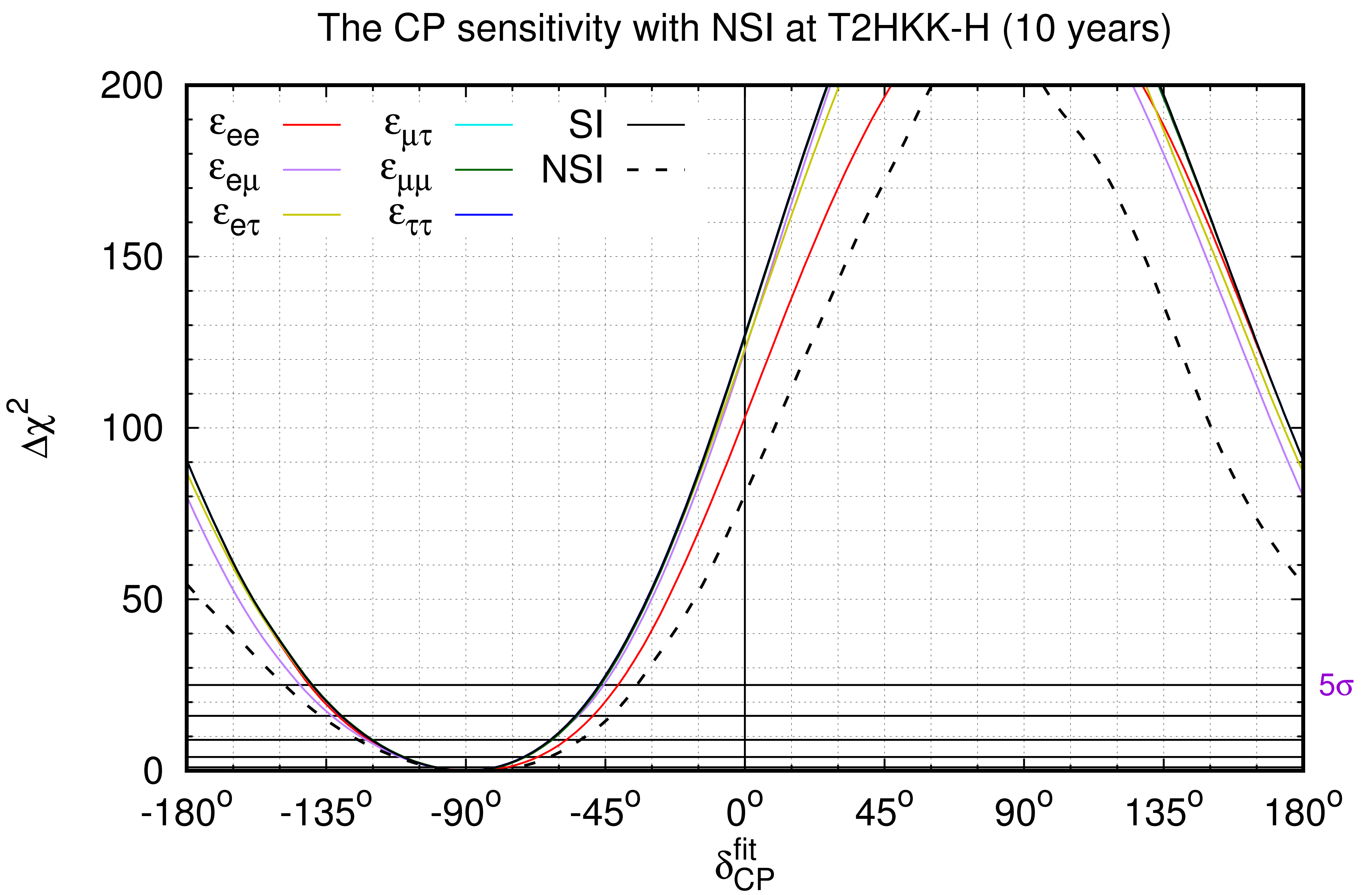
The CP sensitivity with NSI at T2HKK-C (1 year)
ε_{ee}
$\varepsilon_{e\mu}$
$\varepsilon_{e\tau}$
$\varepsilon_{\mu\tau}$
$\varepsilon_{\mu\mu}$
$\varepsilon_{\tau\tau}$
SI
NSI
$\Delta\chi^2$
δ_{CP}^{fit}
0
5
10
15
20
25
30
35
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°
1σ
2σ
3σ
4σ
5σ



The CP sensitivity with NSI at T2HKK-C (10 years)
ε_ee
ε_eμ
ε_eτ
ε_μτ
ε_μμ
ε_ττ
SI
NSI
200
150
100
50
0
Δχ²
5σ
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°
δ_CP^fit



The CP sensitivity with NSI at T2HKK-H (1 year)
εee
εeμ
εeτ
εμτ
εμμ
εττ
SI
NSI
35
30
25
20
15
10
5
0
5σ
4σ
3σ
2σ
1σ
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°
Δχ²
δCP fit



The CP sensitivity with NSI at T2HKK-H (10 years)
ε_{ee}
$\varepsilon_{e\mu}$
$\varepsilon_{e\tau}$
$\varepsilon_{\mu\tau}$
$\varepsilon_{\mu\mu}$
$\varepsilon_{\tau\tau}$
SI
NSI
$\Delta\chi^2$
200
150
100
50
0
-180^o
-135^o
-90^o
-45^o
0^o
45^o
90^o
135^o
180^o
δ_{CP}^{fit}
5σ