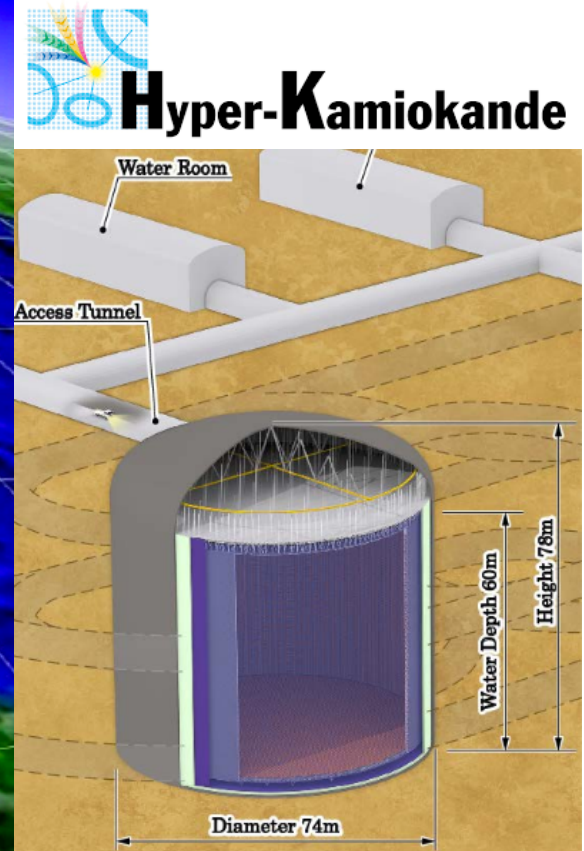


The 2nd Hyper-K detector in Korea: T2HKK



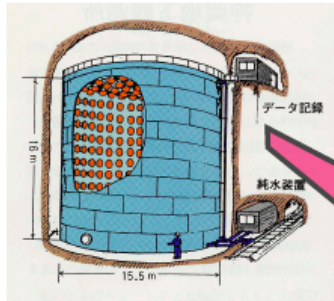
HEP Workshop
Jan. 13th 2017,
IAS, HKUST

Overview

- Introduction & Motivation
- What is T2HKK ?
- T2HKK sensitivity: CP phase, ν Mass Ordering
- HKK as a Neutrino Telescope
- Candidate Sites in Korea
- Summary

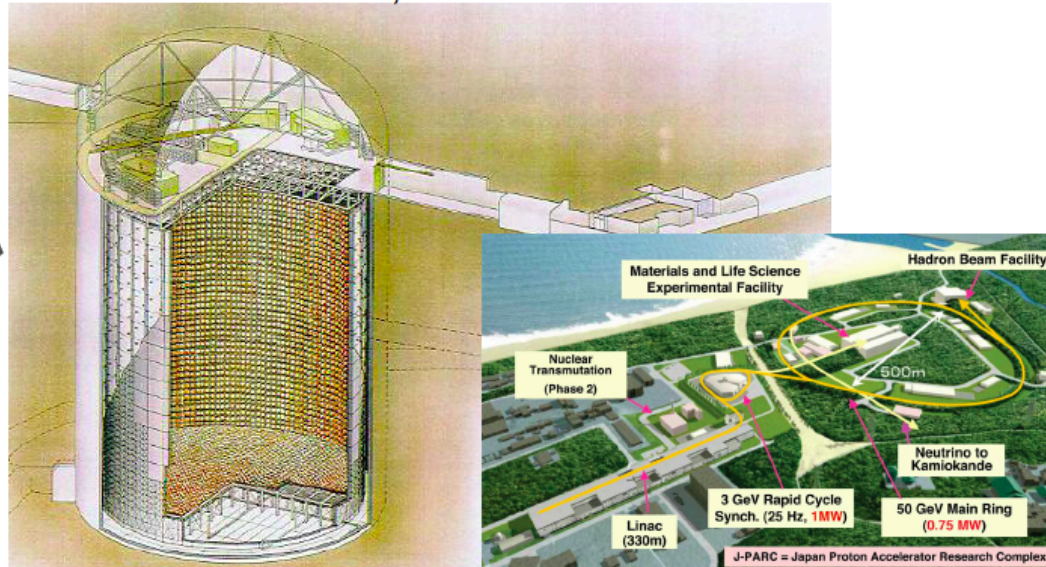
2 Generations of Kamiokande

Kamiokande
1983-1996
3,000ton



Super-Kamiokande
1996-
50,000ton

+KEK-PS (K2K)
+J-PARC (T2K)



Scientific Achievements

- **1987**: Supernova 1987a
- **1998**: Discovery of neutrino oscillation using atmospheric ν
- 2001: Establishment of solar ν oscillations together with SNO
- 2011: Discovery of electron neutrino appearance by T2K,
World best limit on proton lifetime $> 10^{34}$ years



Remaining Problems

- **Full picture of neutrino oscillations**

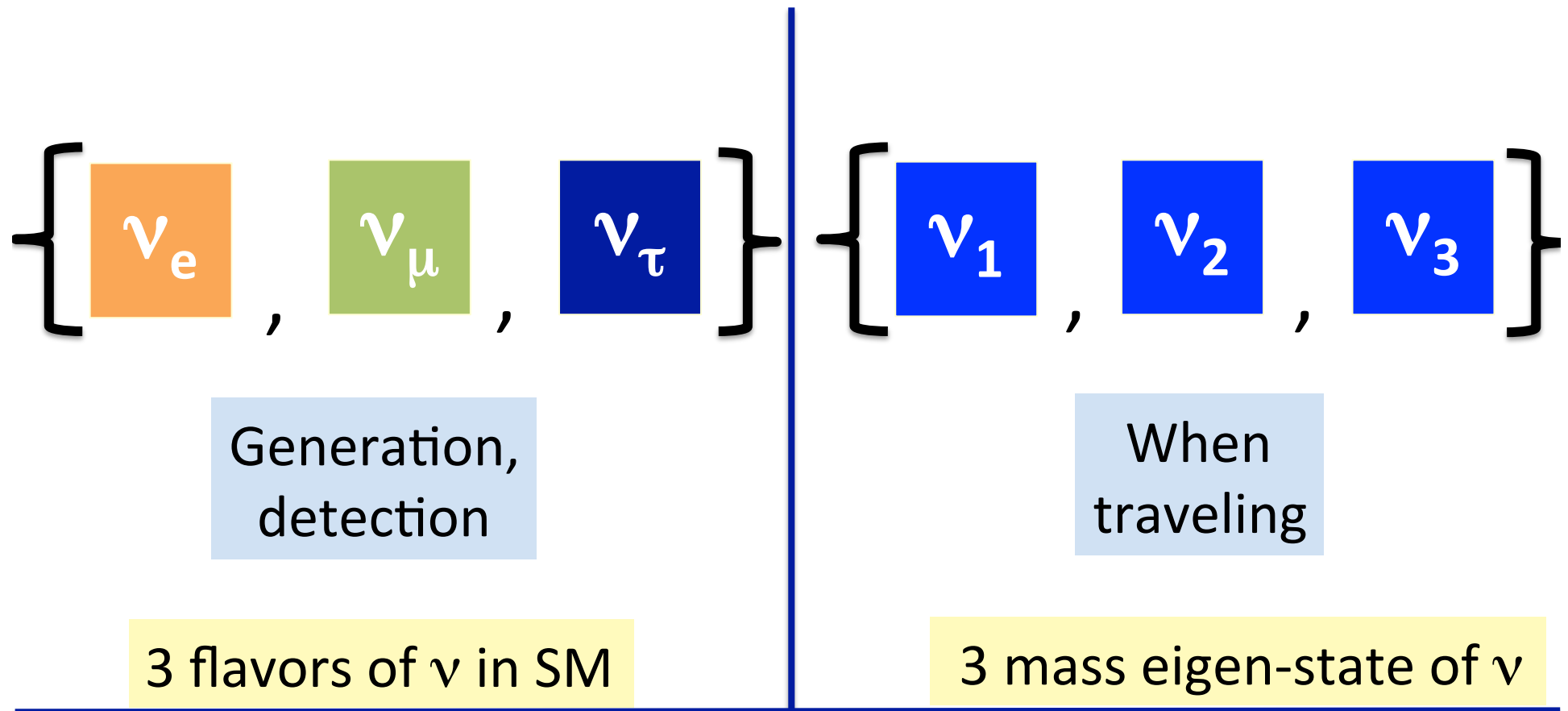
- δ_{CP} , Mass Hierarchy, θ_{23} octant are still to be experimentally determined
- Origin of CP asymmetry, PMNS or beyond?

- **Extension of neutrino astrophysics**

- Precision meas. of solar ν_e (not reactor $\bar{\nu}_e$), Supernova burst and relic, Indirect WIMP searches

- **Proton decay discovery to reveal Grand Unification**

- Unification scale, local gauge symmetry...



$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- Pontecorvo
- Maki
- Makagawa
- Sakaga

PMNS matrix in 1962

PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

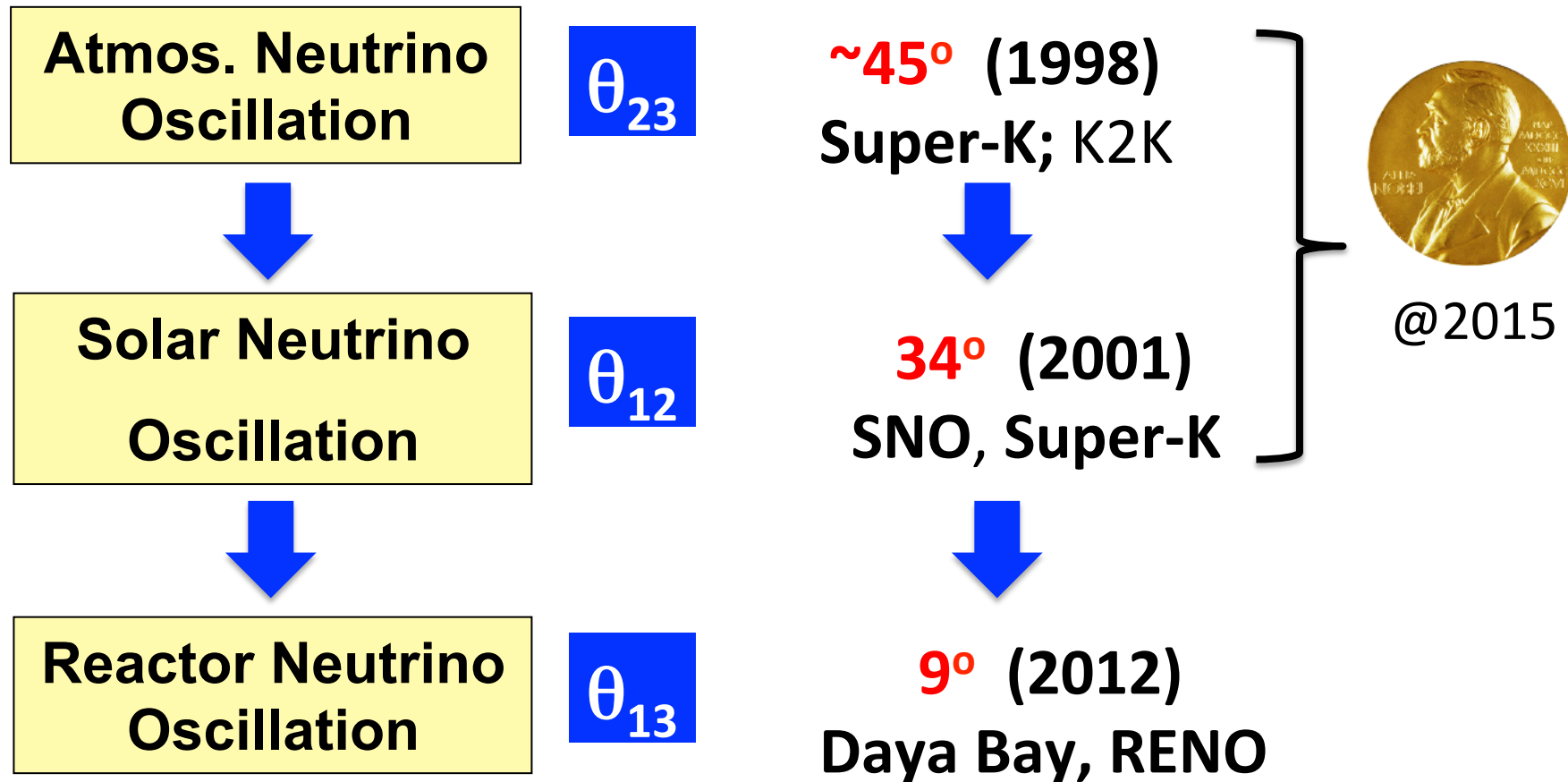
$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmos. ($\nu_\mu, \bar{\nu}_\mu$ deficit)
Long baseline (ν_μ deficit)

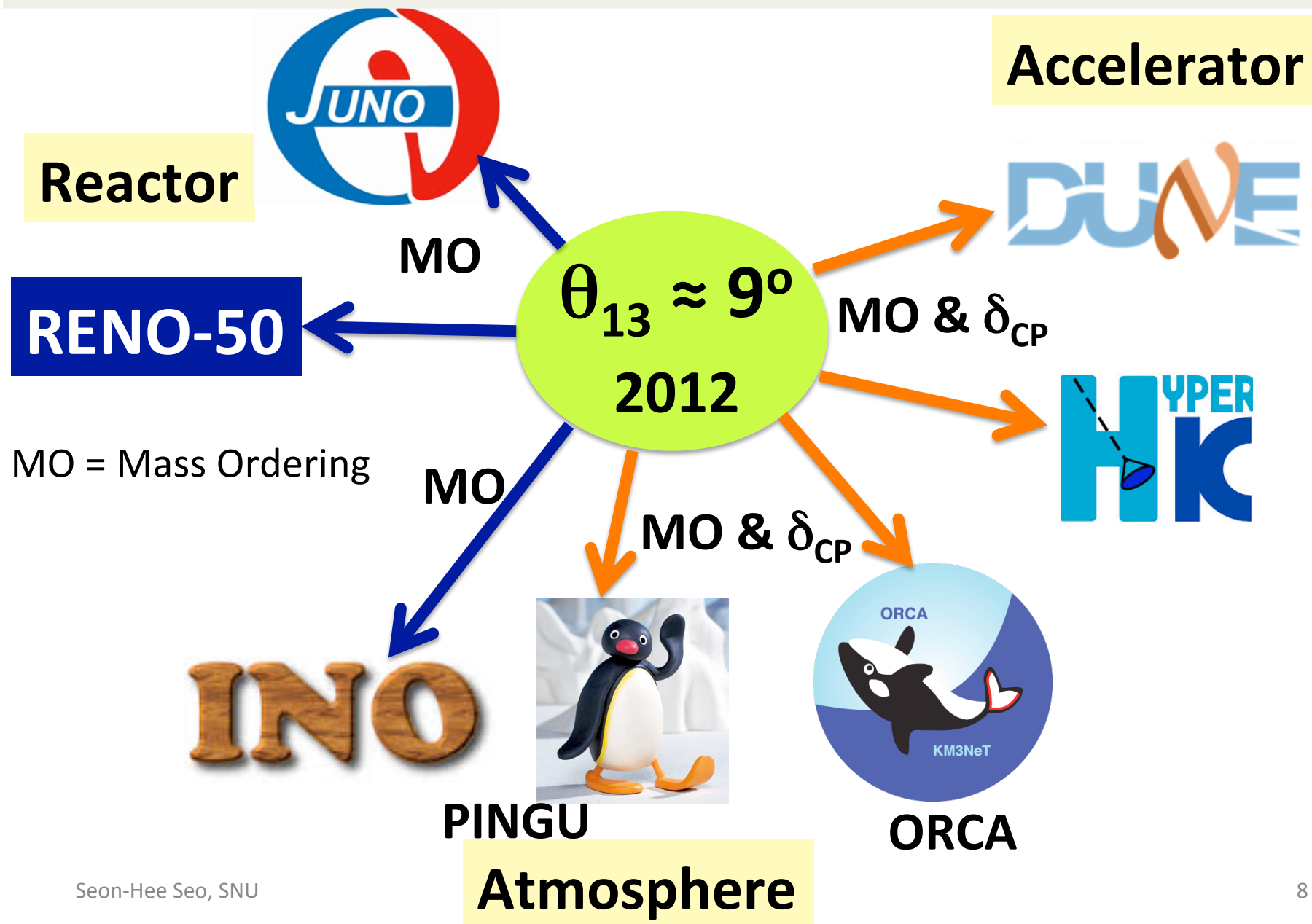
Reactor ($\bar{\nu}_e$ deficit)
Long baseline ($\nu_\mu \rightarrow \nu_e$)

Solar (ν_e deficit)
Reactor ($\bar{\nu}_e$ deficit)

Neutrino Oscillation

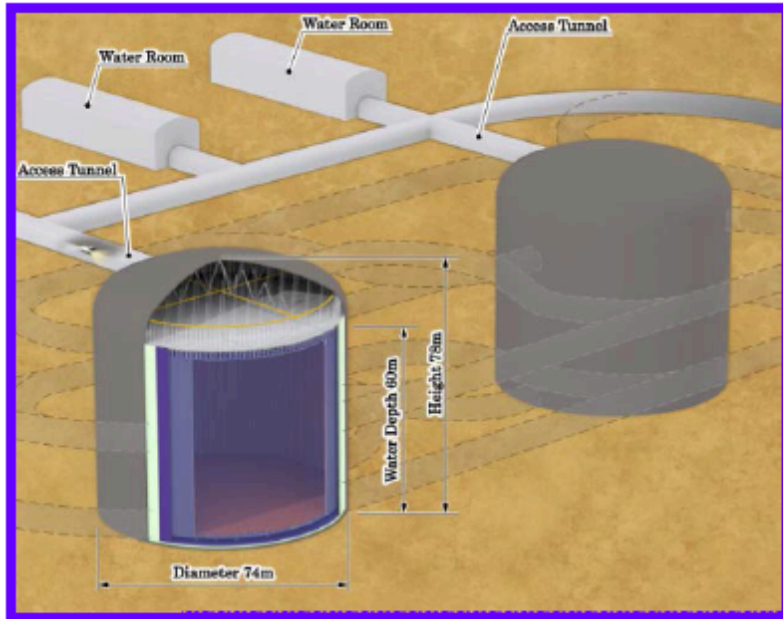


θ_{13} and Future Experiments

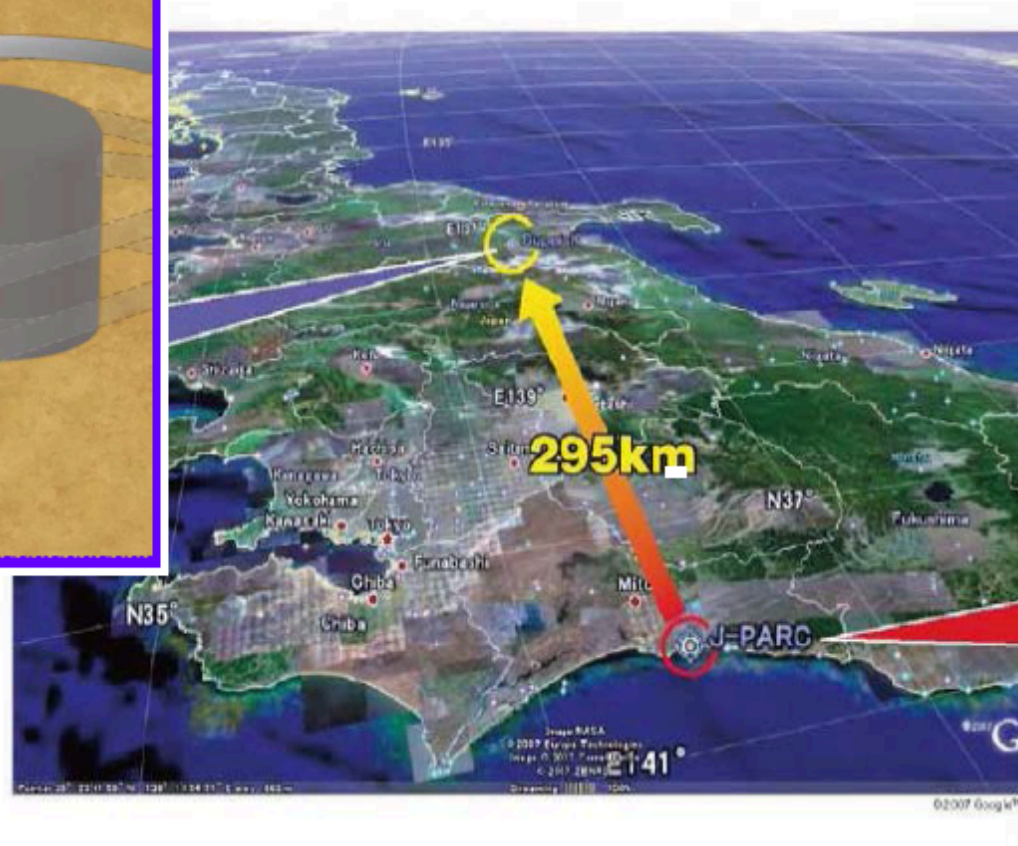


Hyper-Kamiokande

Inauguration: Jan. 2015



Hyper-K

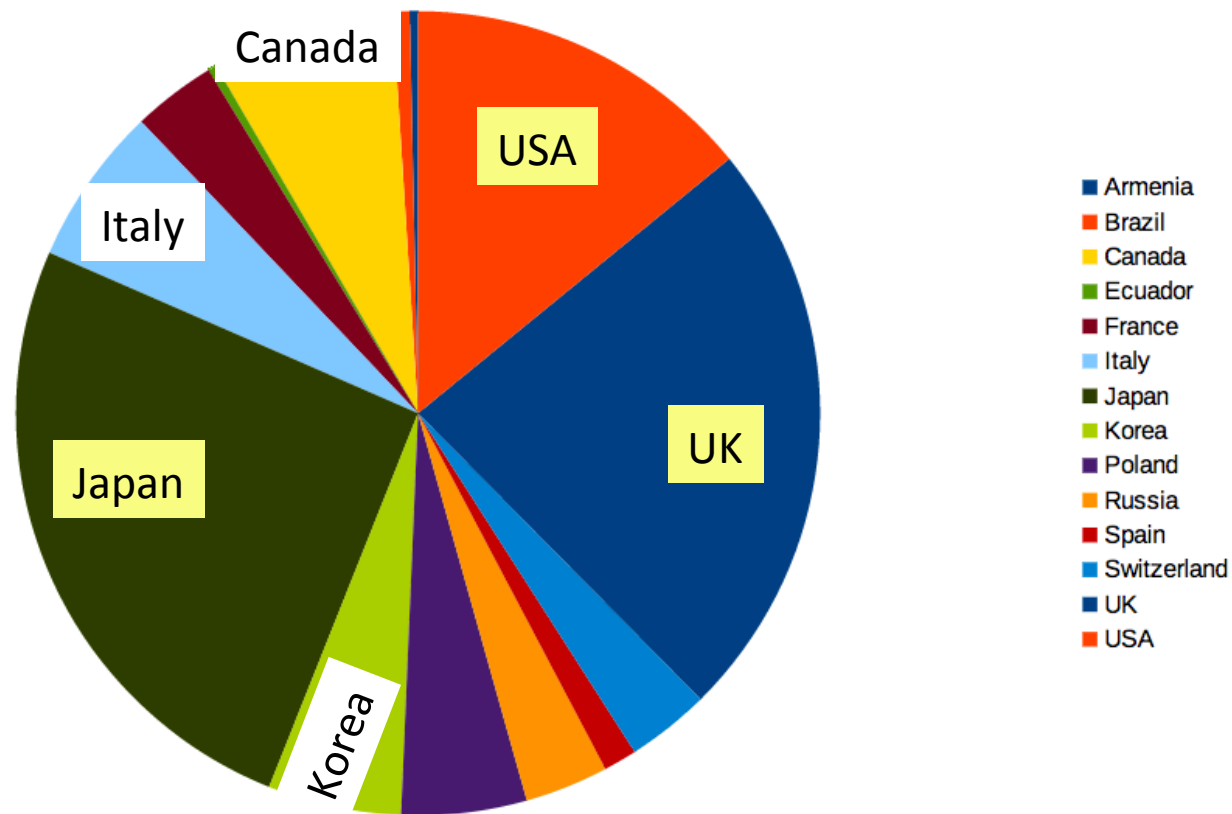


J-PARC

Hyper-K proto-collaboration: 12 countries, ~250 members and growing



Hyper-K Proto-Collaboration



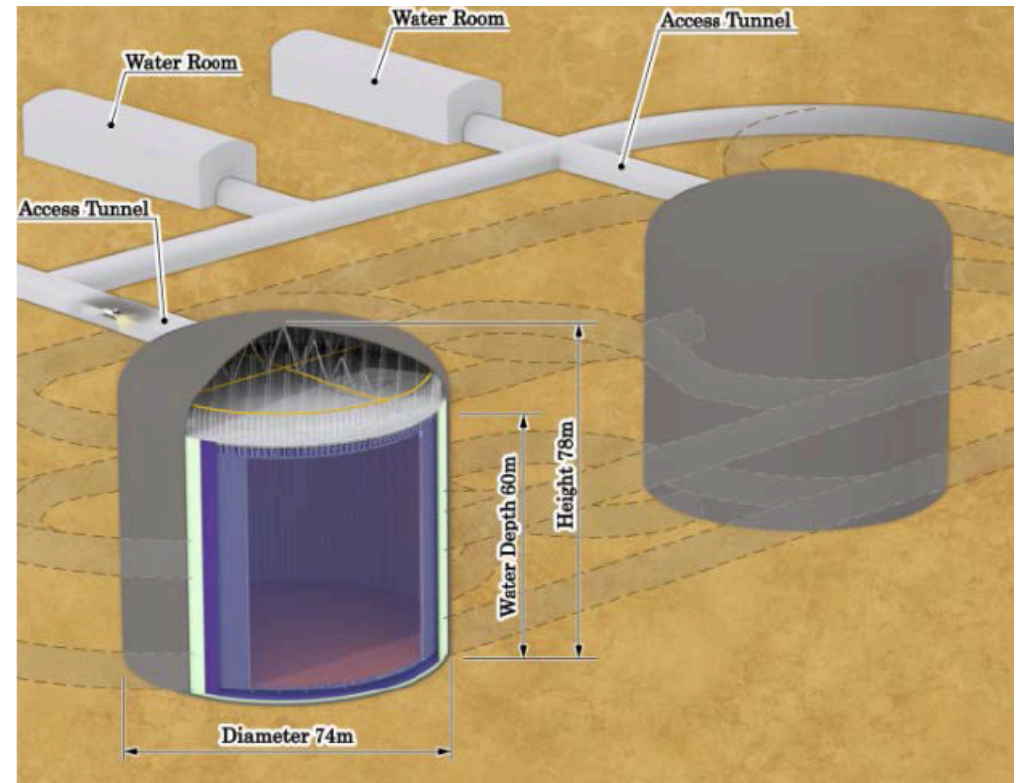
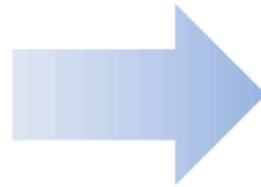
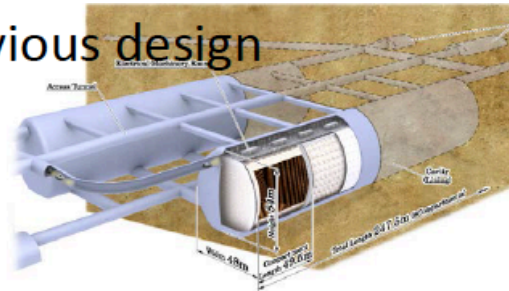
14 Countries, 72 institutes, ~300 members and growing.
75% international collaborators

Hyper-K Design



Hyper-Kamiokande

Previous design



- ✓ Super-K-like structure
- ✓ 2 tanks with staging
(2nd tank assumed to be ready 6 years later)
- ✓ 1 tank will be;
 - 60m(H)×74m(D)
 - Total volume: 260 kton
 - Fiducial volume(FV): 190 kton
~10 x Super-K FV
 - PMT coverage 40%, 40,000 ID-PMT, 6,700 OD-PMT
- ✓ The candidate site is ~8km south of SK (2.5 degree off axis beam, L=295km)

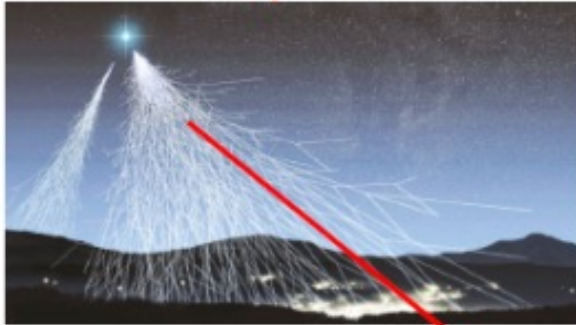
Well proven, scalable technique



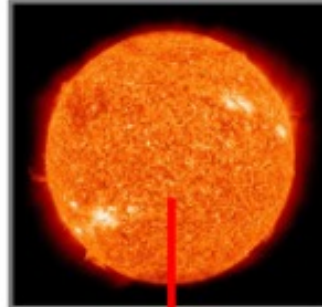
- Feasibility of ~Mton size detector confirmed with various studies over past decade
 - 20 years experience with Super-Kamiokande
- “Ready-for-construction” design developed

Hyper-K Physics: Overview

Atmospheric ν



Solar ν



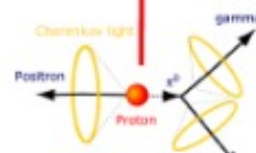
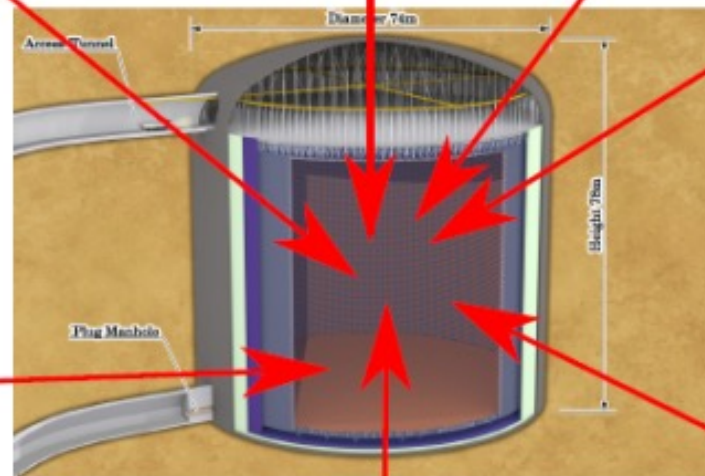
Supernova ν



WIMP $\chi\chi \rightarrow \nu\nu$

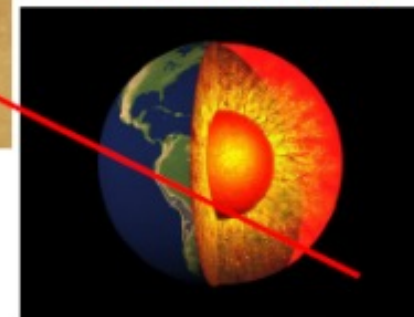


Beam ν



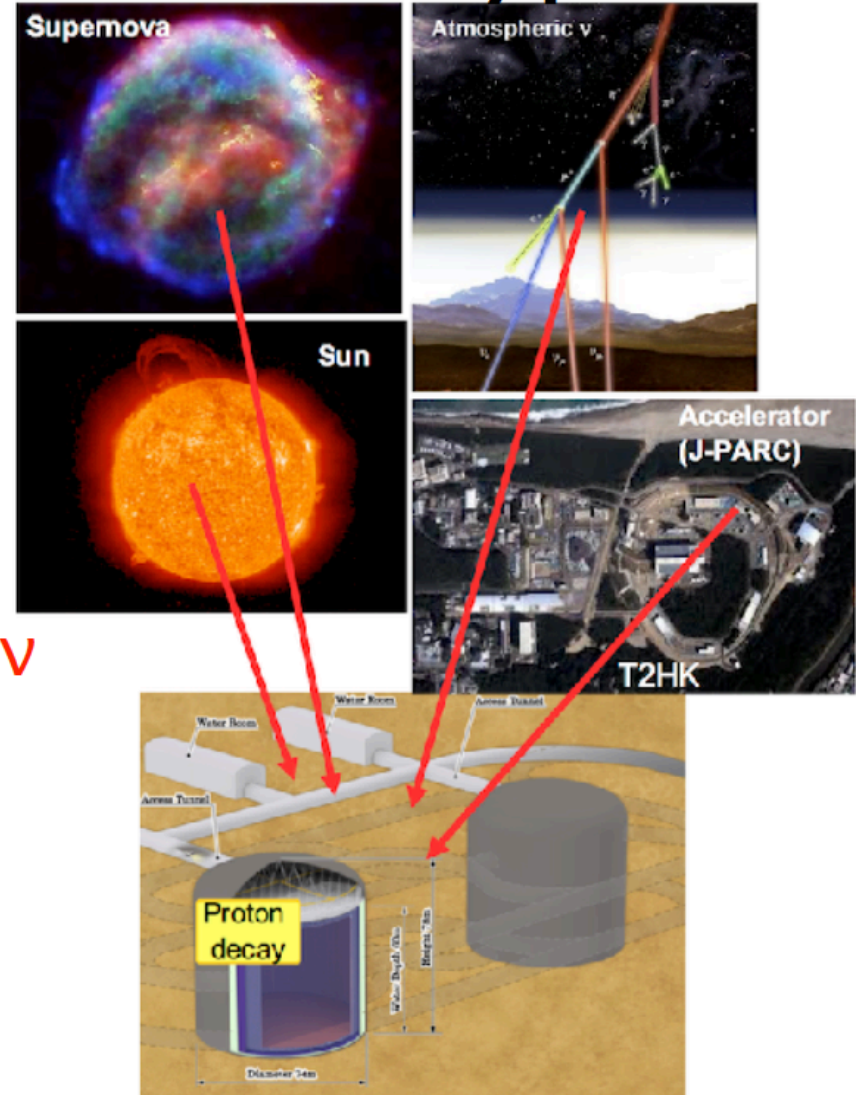
Nucleon Decay

ν Tomography



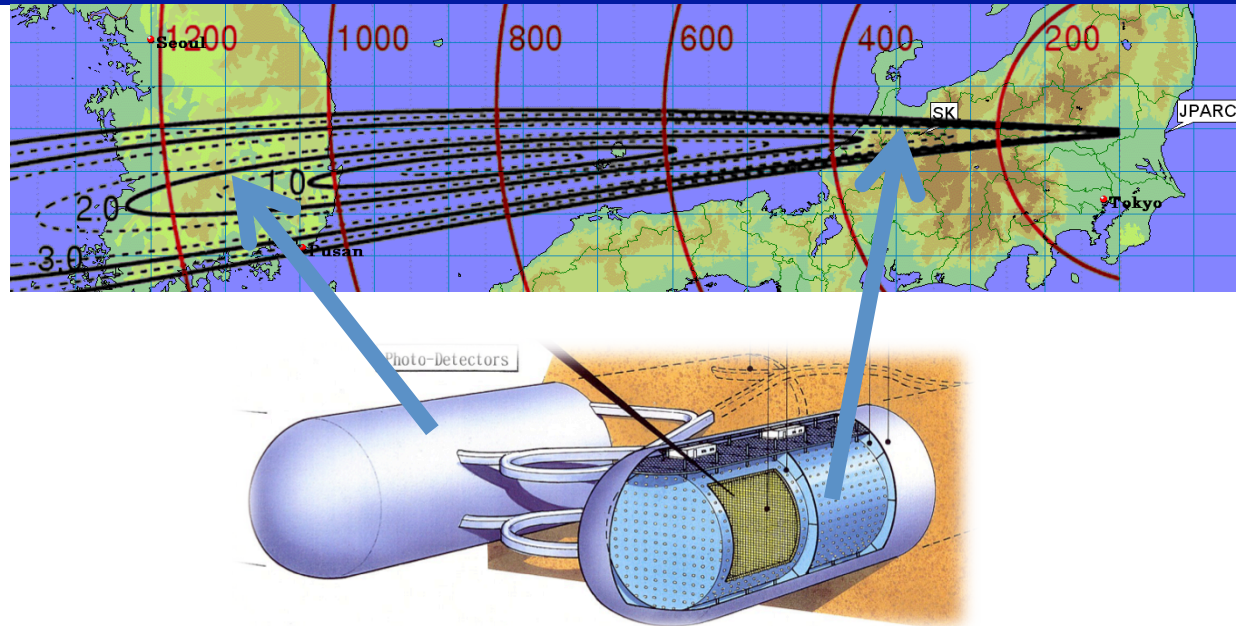
Broad science program with Hyper-K

- Neutrino oscillation physics
 - Comprehensive study with beam and atmospheric neutrinos
- Search for nucleon decay
 - Possible discovery with $\sim \times 10$ better sensitivity than Super-K
- Neutrino astrophysics
 - Precision measurements of solar ν
 - High statistics measurements of SN burst ν
 - Detection and study of relic SN neutrinos
- Geophysics (neutrinoigraphy of interior of the Earth)
- Maybe more (unexpected)



Extend highly successful
program of Super-K

Motivation of the 2nd Detector in Korea



Instead of Hyper-K (0.25 + 0.25 Mt) alone w/ 2.5° OAB,
HK(0.25 Mt) w/ 2.5° + Korean Detector (0.25 Mt) w/ $1\sim 3^\circ$ OAB
will improve δ_{CP} and mass ordering measurements.

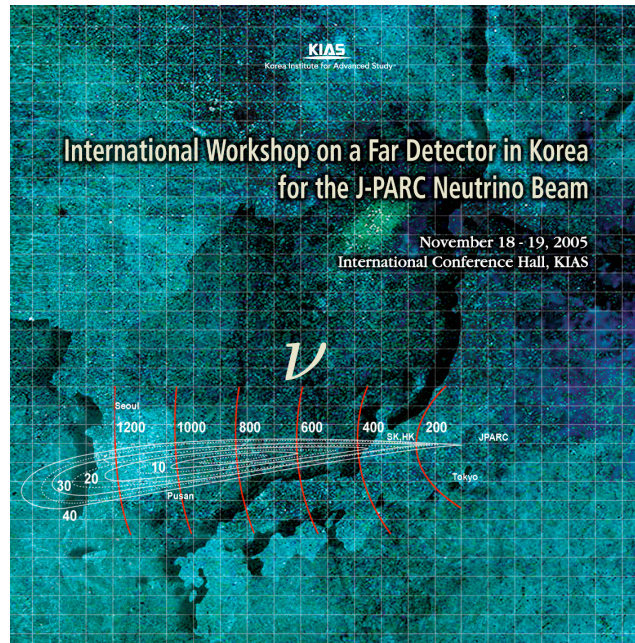
Because oscillation parameter degeneracy is resolved.

Past Three T2KK Workshops

2005
KIAS

2006
SNU

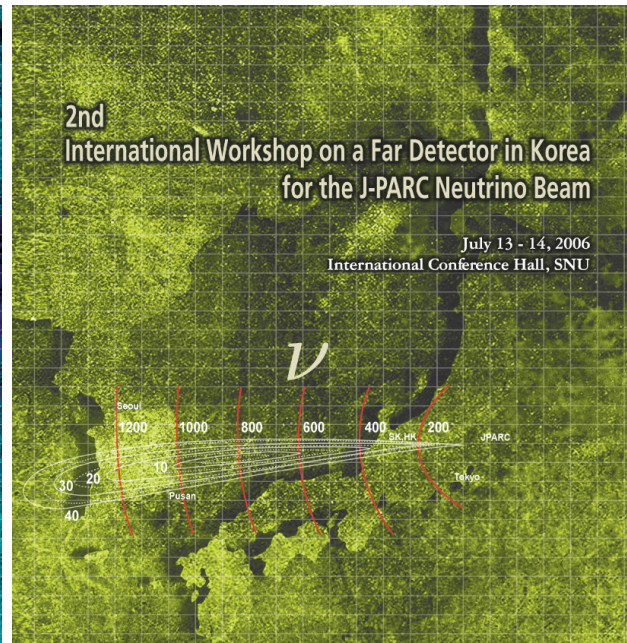
2007
U. Tokyo



Organizing committee

E.J. Chun
T. Kajita
S.B. Kim
P. Ko
K. Nakamura
K. Nishikawa

For general information, please visit <http://conf.kias.re.kr>
or contact psec@kias.re.kr



Program Committee

E. J. Chun (KIAS)
T. Kajita (ICRR)
S. B. Kim (SNU)
P. Ko (KIAS)
K. Nakamura (KEK)
K. Nishikawa (KEK)
H. Sobel (UCI)

Local Organizing Committee

E. J. Jeon (SNU)
K. K. Joo (SNU)
K. Kaneyuki (ICRR)
K. Okumura (ICRR)



For general information, please visit <http://T2KK.snu.ac.kr>
or contact kwonjin@phys.snu.ac.kr



Program Committee

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S. B. Kim (SNU)
P. Ko (KIAS)
K. Nakamura (KEK)
A. Rubbia (ETHZ)
H. Sobel (UCI)

Local Organizing Committee

K. K. Joo (CNU)
K. Kaneyuki (ICRR)
K. Okumura (ICRR)

For general information, please visit <http://www.rcn.icrr.u-tokyo.ac.jp/workshop/T2KK07/>

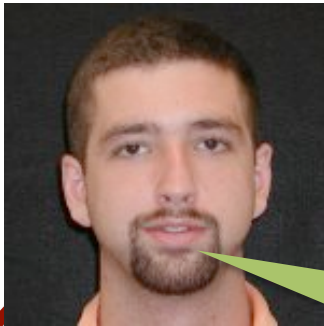


E. Witten

“Why don’t you bring one of the 2 tanks to Korea ?”
@EPP2010

The first 3 minutes of T2HKK

March 20th 2016, Fermilab



Michael Wilking

Korea is a good candidate site for a future neutrino physics using ν beam from J-PARC.

Yes !



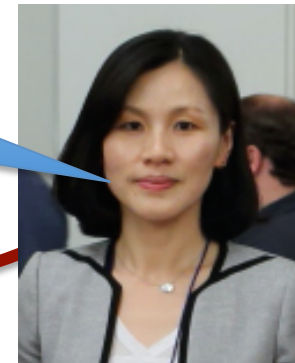
Akira Konaka

Yes !



Mark Hartz

Are you guys really interested in doing this (= T2HKK) ?



Sunny Seo

T2HKK Inauguration

July 10th 2016, London

Meeting after the first T2HKK proposal talk in QMUL



T2HKK White Paper

November 21st 2016



~ 4 months later
from the inauguration

[arXiv:1611.06118](https://arxiv.org/abs/1611.06118)

(60 pages)



Physics Potentials with the Second Hyper-Kamiokande Detector in Korea

(Hyper-Kamiokande Proto-Collaboration)

K. Abe,^{57,59} Ke. Abe,²⁴ H. Aihara,^{59,60} A. Aimi,¹⁸ R. Akutsu,⁵⁸ C. Andreopoulos,^{28,43}
I. Anghel,²¹ L.H.V. Anthony,²⁸ M. Antonova,²⁰ Y. Ashida,²⁵ M. Barbi,⁴⁴ G.J. Barker,⁶⁶
G. Barr,⁴⁰ P. Beltrame,¹¹ V. Berardi,¹⁶ M. Bergevin,³ S. Berkman,² T. Berry,⁴⁵
S. Bhadra,⁷³ F.d.M. Blaszczyk,¹ A. Blondel,¹² S. Bolognesi,⁶ S.B. Boyd,⁶⁶ A. Bravar,¹²

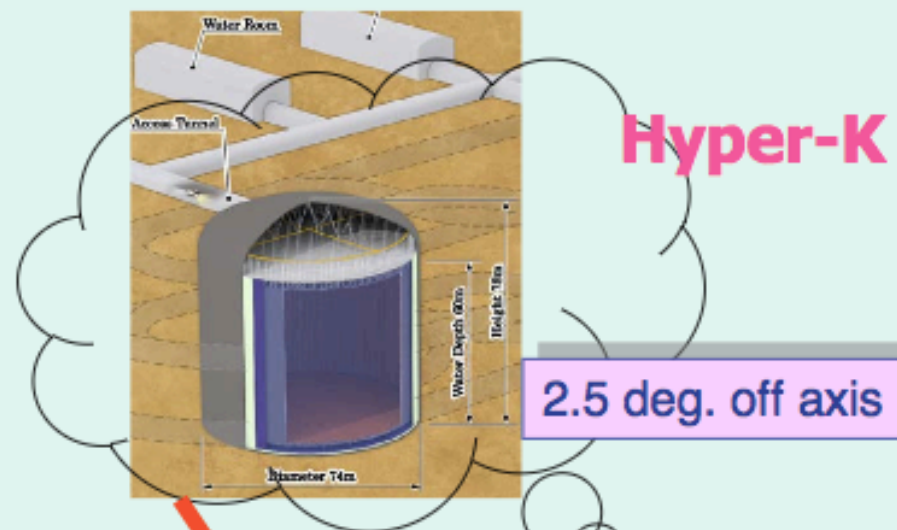
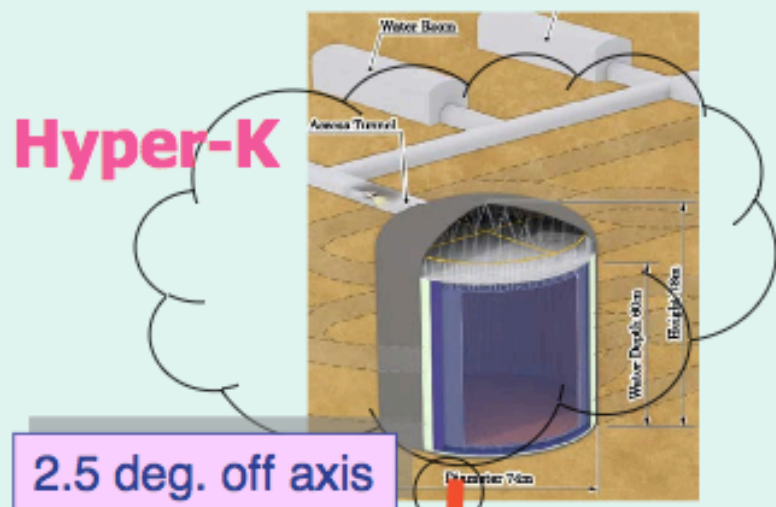
Brief History of T2HKK (I)

- ❑ 2005/2006/2007: a large Cherenkov detector in Korea using J-PARC neutrino beam (T2KK) by T. Kajita.
→ 3 joint workshops supported by KOSEF and JSPS.
- ❑ 2015: staged construction of two HK detectors at Kamioka
2 X 260 kton
- ❑ March 20, 2016: re-birth of T2KK → T2HKK
- ❑ May 31, 2016: offline meeting to begin discussions
(Canada/Japan/Korea/USA)
- ❑ June 2016: a working group effort for sensitivity study

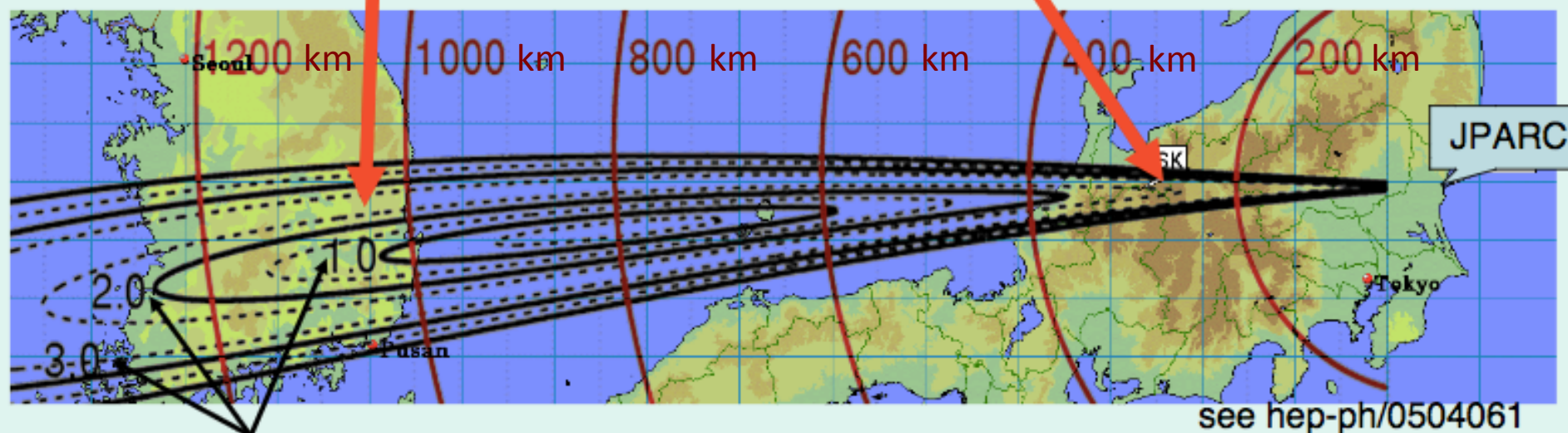
Brief History of T2HKK (II)

- ❑ July 10, 2016: official kick-off meeting in London
→ T2HKK proposal accepted in Hyper-K (Seon-Hee Seo)
- ❑ T2HKK working group in Hyper-K (convener: Seon-Hee Seo)
Regular working group meeting for sensitivity studies
and construction plan including white paper
- ❑ Sept. 2, 2016: 1st Korean T2HKK workshop at SNU
- ❑ Oct. 20, 2016: KPS pioneer symposium on T2HKK
- ❑ Nov.19, 2016: T2HKK white paper release to arXiv
- ❑ Nov. 21-22 2016: 1st International T2HKK workshop at SNU

T2HKK

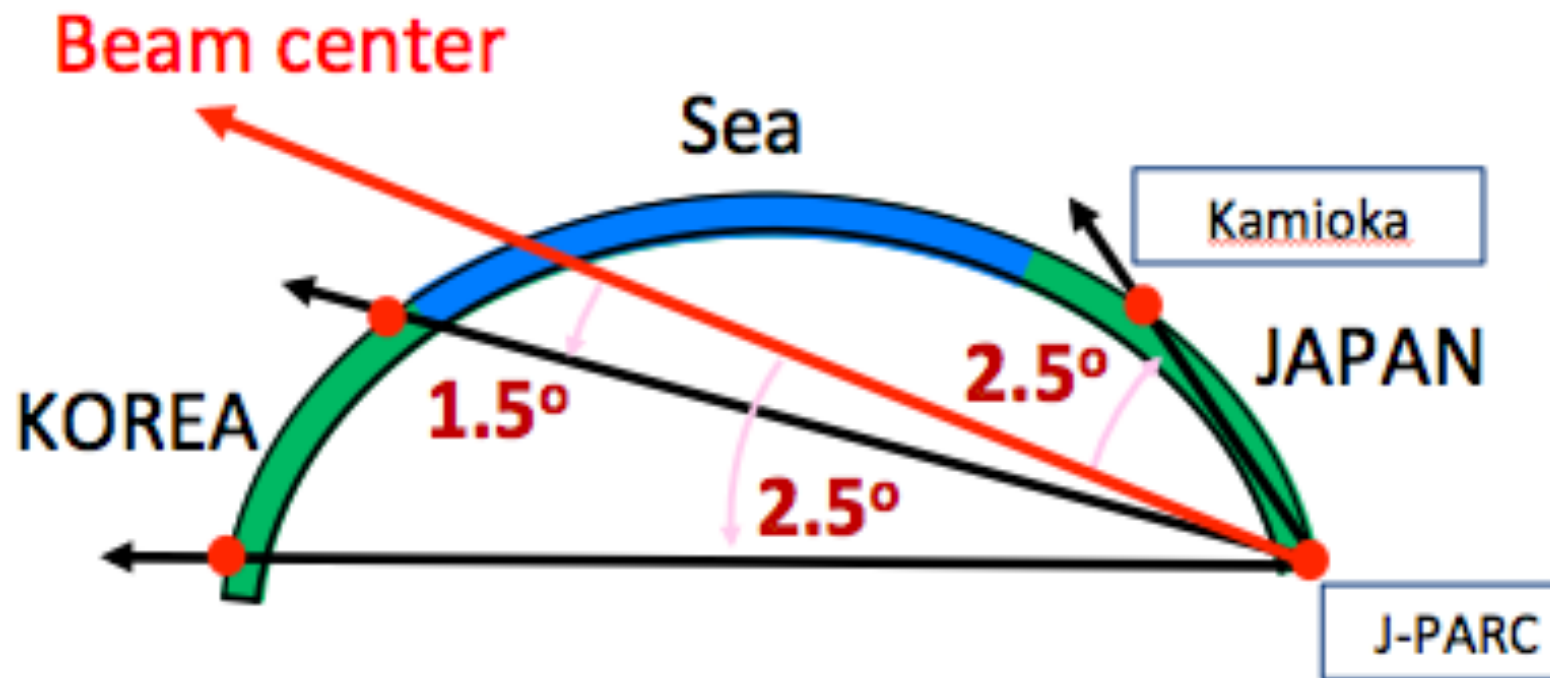


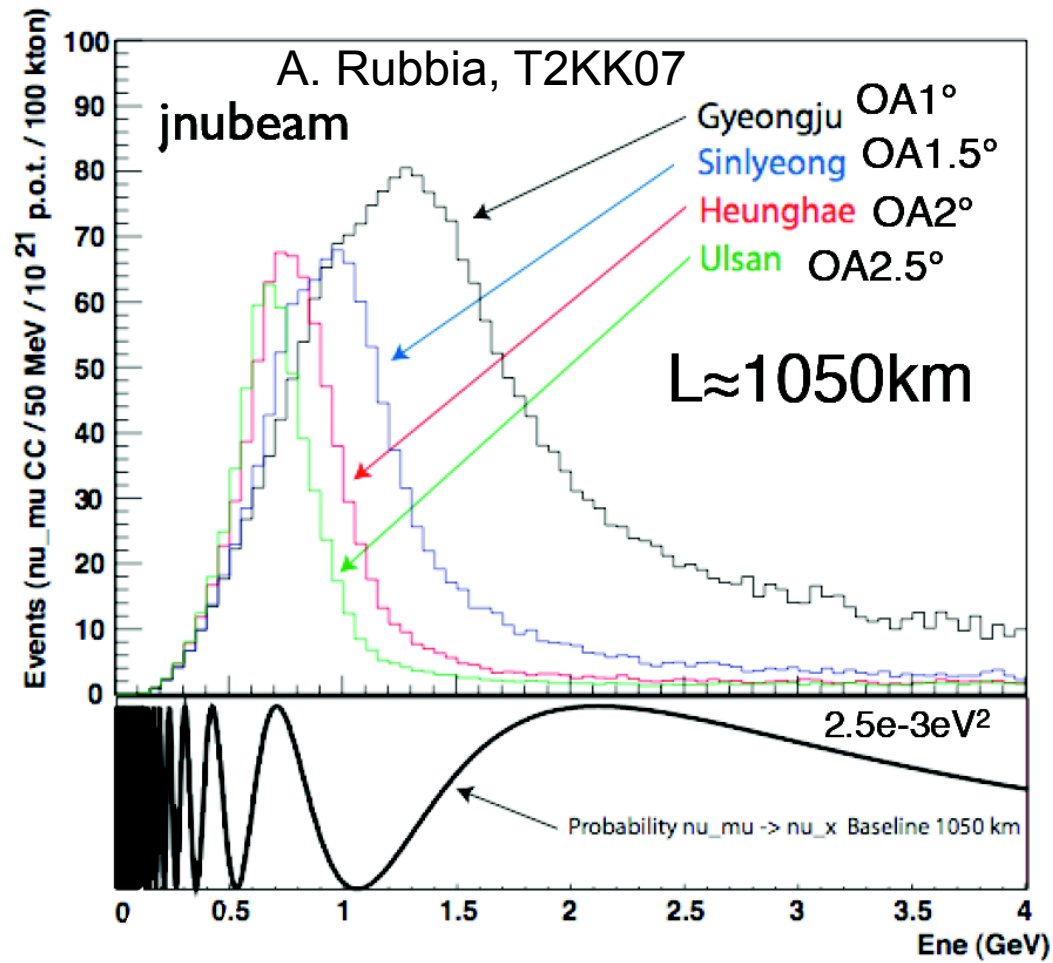
The J-PARC ν beam comes to Korea.



By K. Hagiwara, N. Okamura, K. Senda

Off-axis Beam



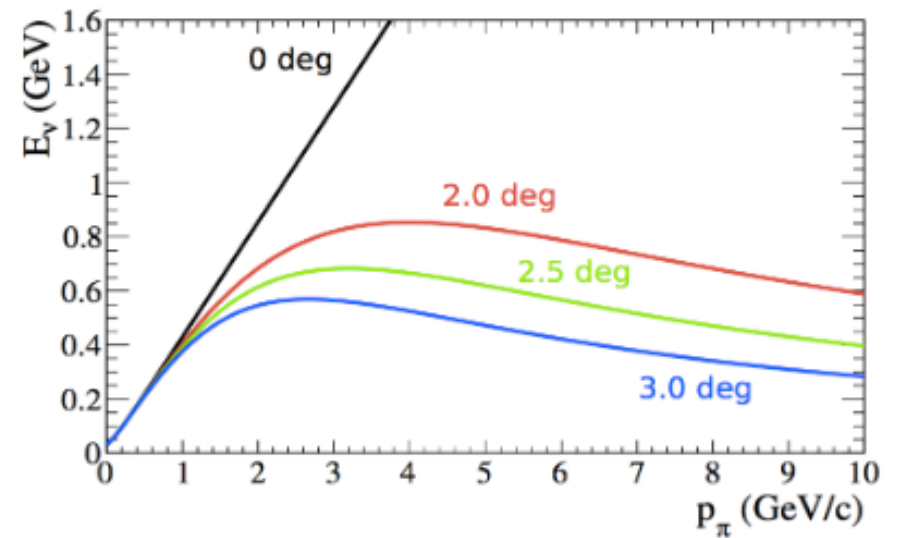


Pion mass

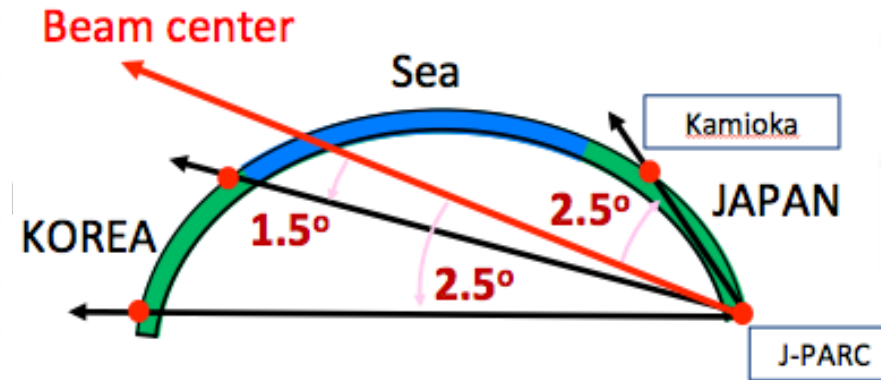
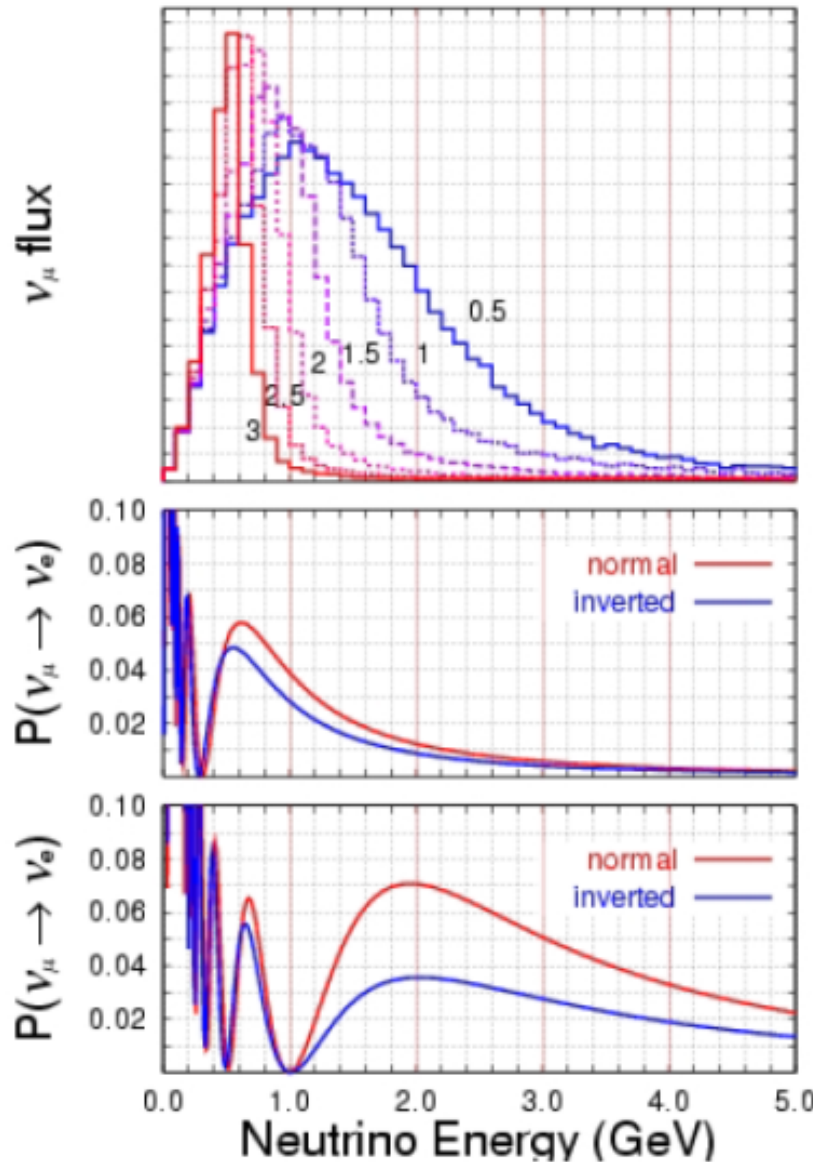
$$E_\nu = \frac{M^2 - m_\mu^2}{2(E - p \cos \theta)}$$

Pion energy

Pion momentum



Neutrino Oscillations in Kamioka & Korea



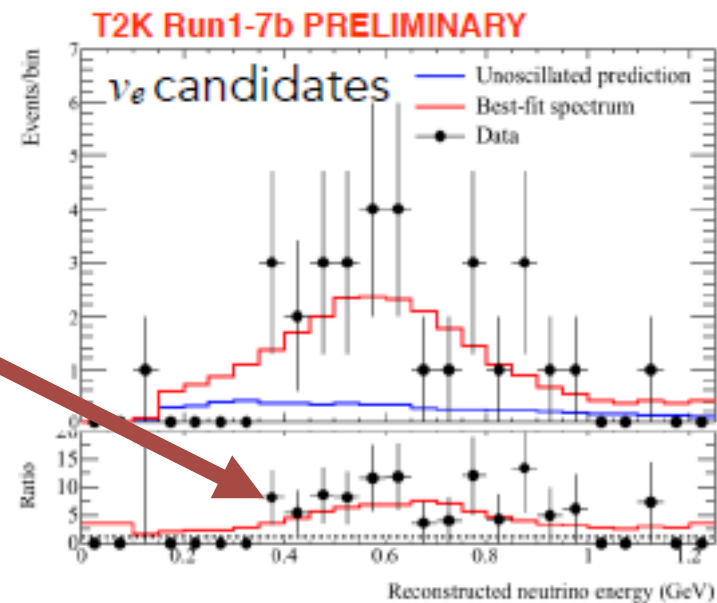
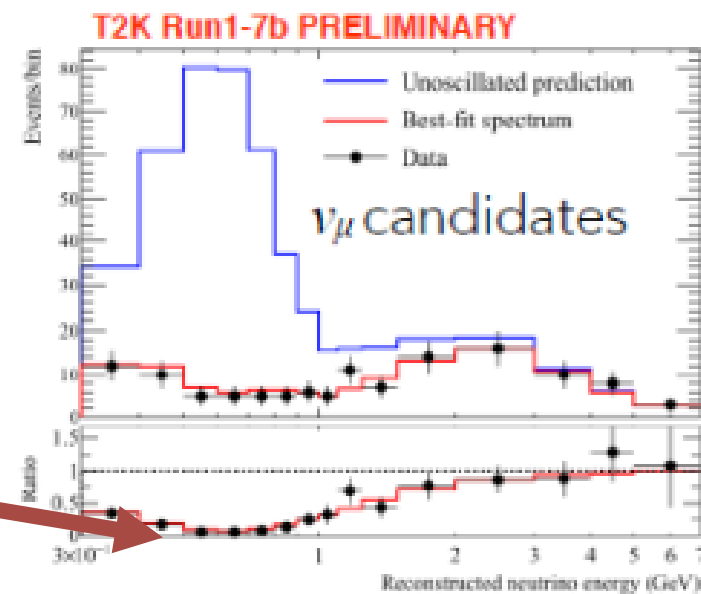
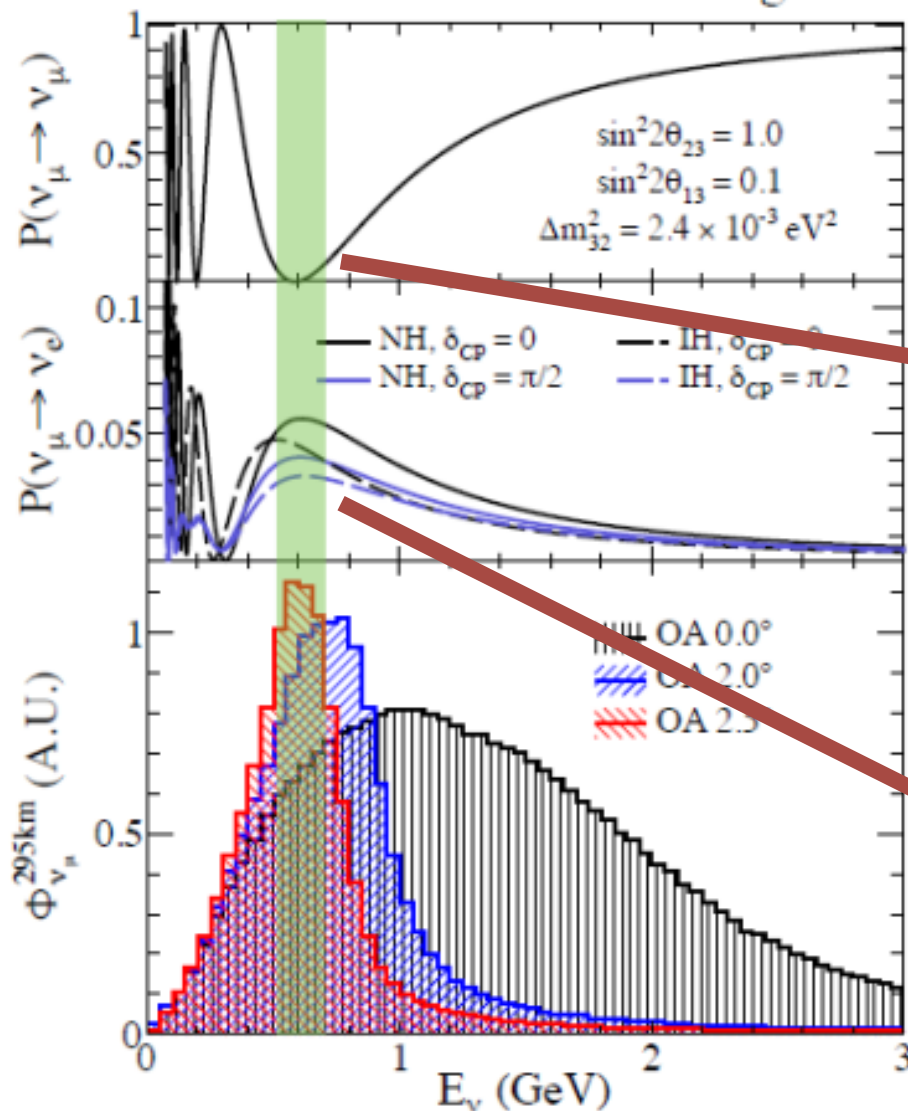
← Profile of off-axis beams

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

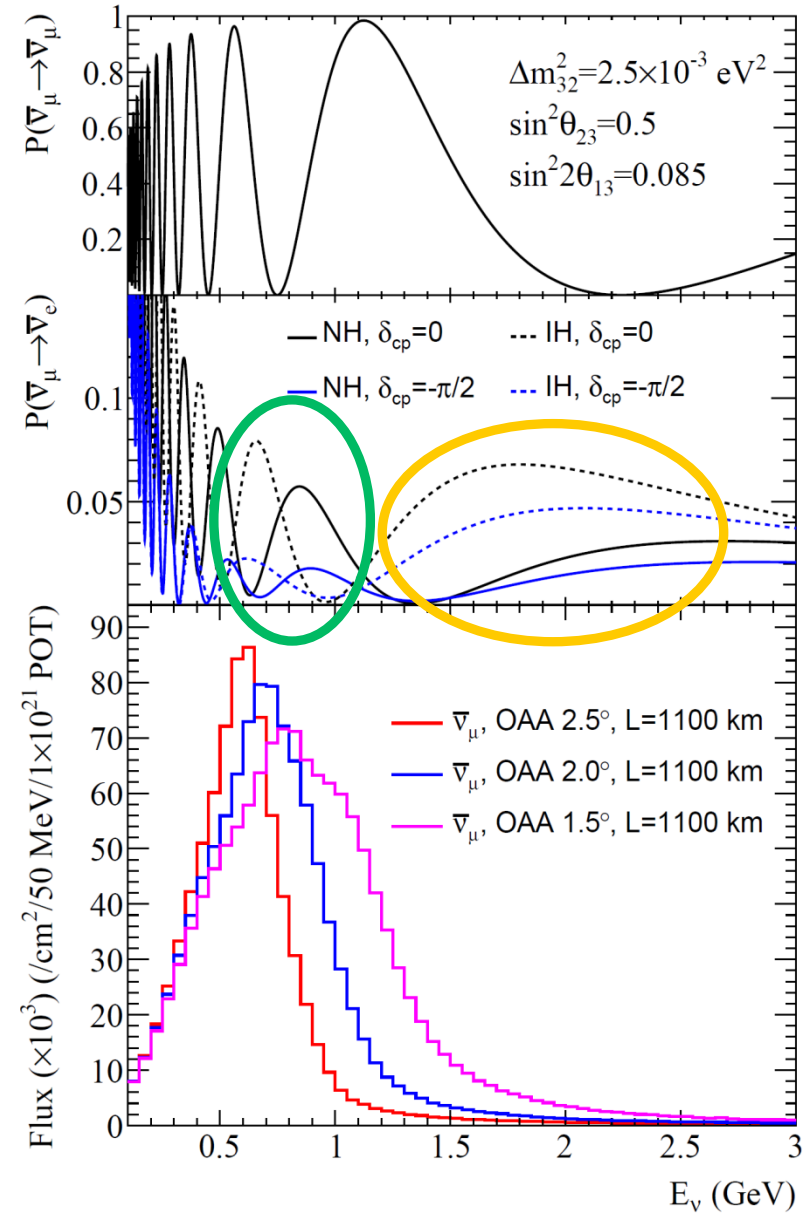
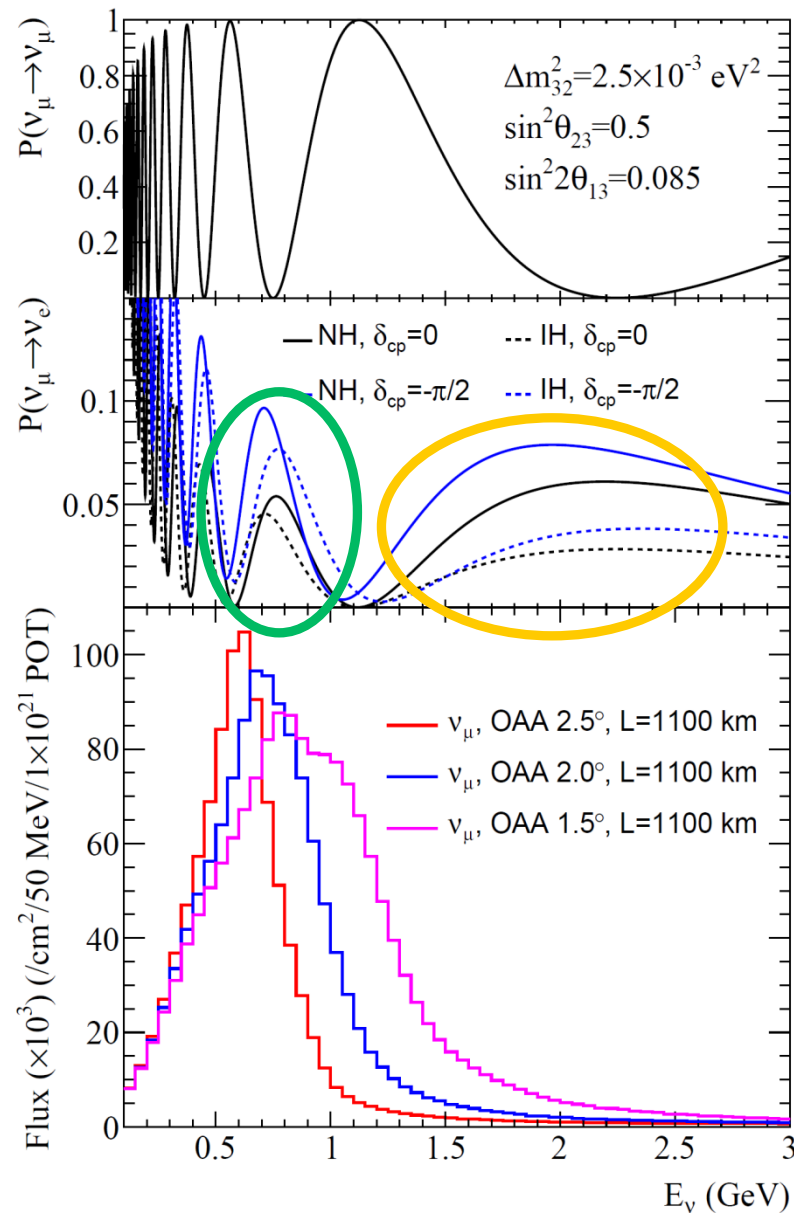
← $P(\nu_\mu \rightarrow \nu_e)$ at Korea
($L=1000\text{km}$)

1st Oscillation Maximum in Kamioka

T2K far detector flux prediction
at different off-axis angle



1st and 2nd Oscillation Maxima in Korea



T2HKK Physics Reach

- ☐ Physics programs: the same as the Hyper-K
- ☐ **Physics sensitivities: better** in the following topics

- **CP violation phase measurement**
- **Neutrino mass ordering determination**
- Non-standard neutrino interaction

Beam
Neutrinos
(T2HKK)

- Solar neutrinos physics
- Supernova burst/relic neutrinos
- Neutrino geophysics
- Low energy dark matter search
- etc...

neutrinos
from nature
(HKK)



HKK can serve as a neutrino telescope for ~30 years.

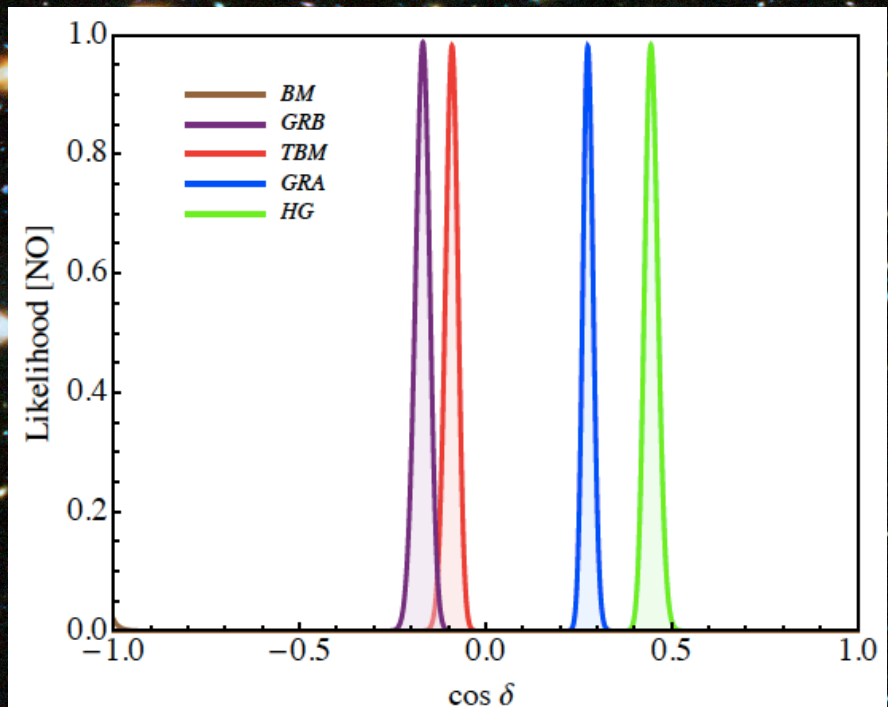
CP violation in leptonic sector

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \quad ?$$

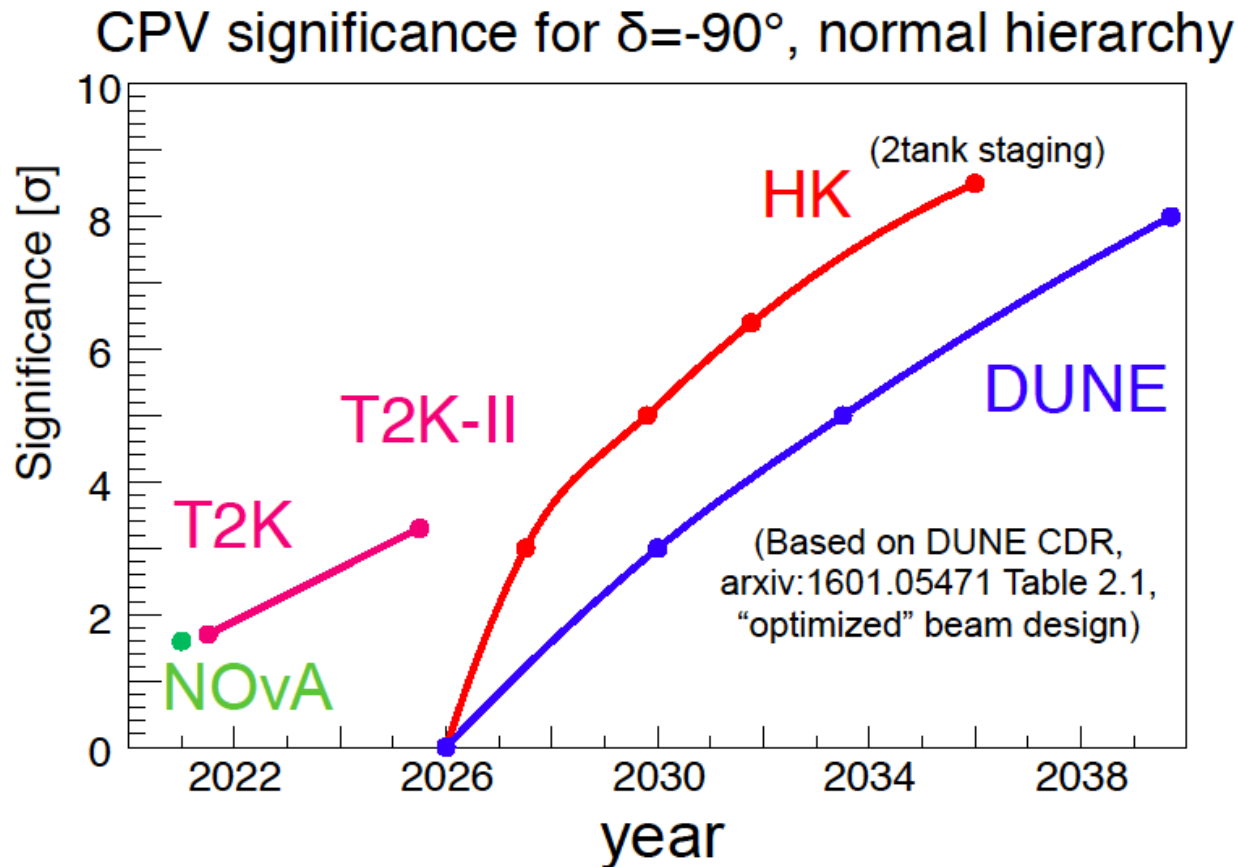
- Matter anti-matter asymmetry



- flavor symmetry models of neutrino mixing



CPV Sensitivities

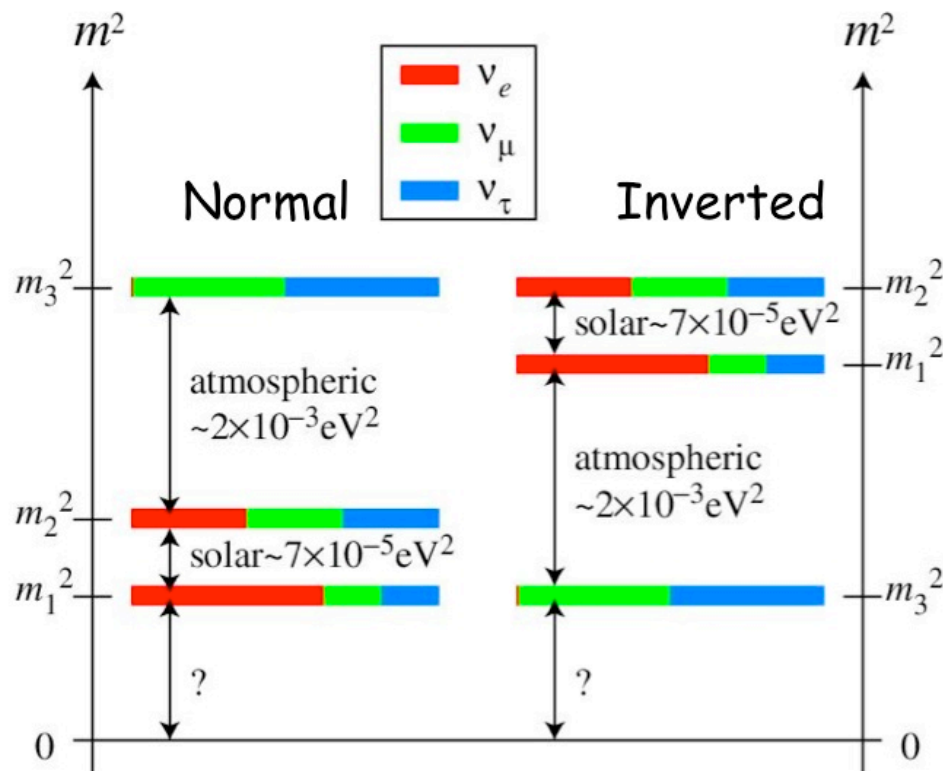


❖ DUNE is the future flagship neutrino experiment in USA.

❖ T2HKK sensitivity is better than HK sensitivity in this plot.

Neutrino mass ordering

NO: Normal Ordering
IO: Inverted Ordering



- GUT $\rightarrow$ NO
- Origin of the universe $\rightarrow$ IO
- Connection to Dirac or Majorana nature of ν

ν_e appearance probability: address 3 key parameters

If Normal/Inverted Ordering,
 (-/+) sign is for ν
 (+/-) sign is for $\bar{\nu}$

$$\begin{aligned}
 P(\overset{(\quad)}{\nu}_\mu \rightarrow \overset{(\quad)}{\nu}_e) \approx & 4s_{23}^2 s_{13}^2 \frac{1}{(1 \mp r_A)^2} \sin^2 \frac{(1 \mp r_A) \Delta_{31} L}{4E} \\
 & + \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \left(\frac{\Delta_{21} L}{2E} \right) \sin \frac{(1 \mp r_A) \Delta_{31} L}{4E} \cos(\pm \delta - \frac{\Delta_{31} L}{4E}) \\
 & + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21} L}{4E} \right)^2 - 4s_{23}^2 s_{13}^4 \frac{1}{(1 \mp r_A)^2} \sin^2 \frac{(1 \mp r_A) \Delta_{31} L}{4E}
 \end{aligned}$$

solar term: suppressed by Δ_{21}^2

$O(10^{-3})$ @ 1st osc. Max
 $O(10^{-2})$ @ 2nd osc. Max

suppressed by $\sin^4 \theta_{13}$

2% correction to the 1st term

ν_e appearance probability (mass ordering)

If Normal/Inverted Ordering,
 (-/+) sign is for ν
 (+/-) sign is for $\bar{\nu}$

Mass ordering

$$r_A = 2\sqrt{2}G_F N_e E_\nu / \Delta m_{31}^2$$

$$r_A = 6\% \text{ @ } 0.6 \text{ GeV}$$

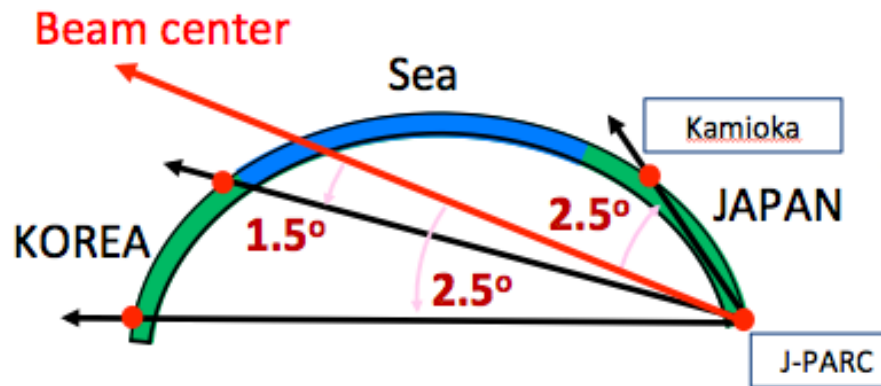
$$9\% \text{ @ } 0.9 \text{ GeV}$$

$$12\% \text{ @ } 1.2 \text{ GeV}$$

$$\begin{aligned}
 P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx & 4s_{23}^2 s_{13}^2 \frac{1}{(1 \mp r_A)^2} \sin^2 \frac{(1 \mp r_A) \Delta_{31} L}{4E} \\
 & + \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \left(\frac{\Delta_{21} L}{2E} \right) \sin \frac{(1 \mp r_A) \Delta_{31} L}{4E} \cos(\pm \delta - \frac{\Delta_{31} L}{4E}) \\
 & + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21} L}{4E} \right)^2 - 4s_{23}^2 s_{13}^4 \frac{1}{(1 \mp r_A)^2} \sin^2 \frac{(1 \mp r_A) \Delta_{31} L}{4E}
 \end{aligned}$$

- 1) The amplitude of the oscillation is enhanced or suppressed via the $(1 \mp r_A)^2$ in the denominator, which is $\pm 24\%$ effect at 1.2 GeV.
- 2) the energy position of the oscillation extremum, this especially apparent in the 1st oscillation minimum, i.e. $L/E \approx 4\pi / (\Delta_{31} * (1 \mp r_A))$, matter term changes the energy position of the first oscillation minimum by $\pm 10\%$.

Off-axis Beam and Matter Density



Matter term:

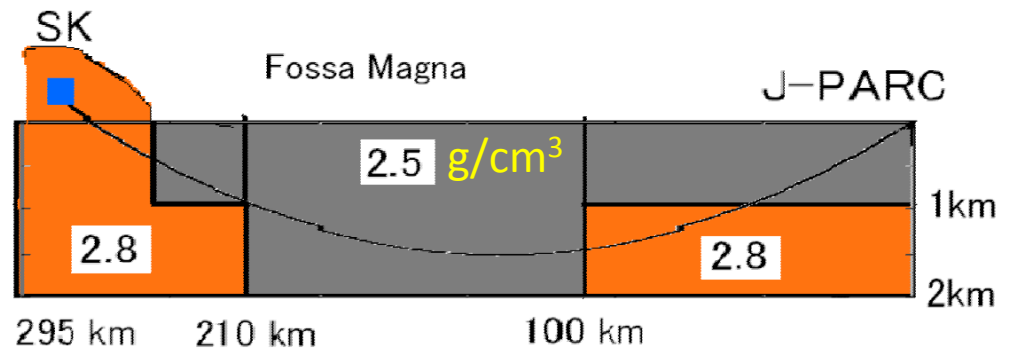
$$r_A = 2\sqrt{2}G_F N_e E_\nu / \Delta m_{31}^2$$

More matter effects

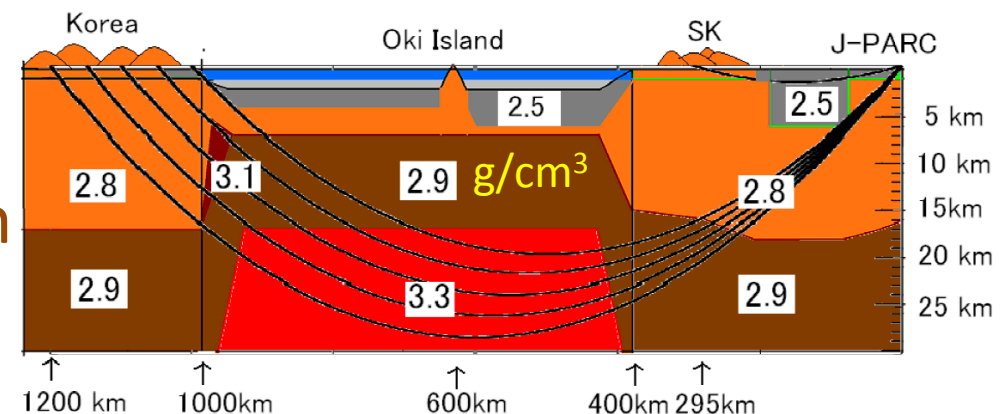
→ better MO determination

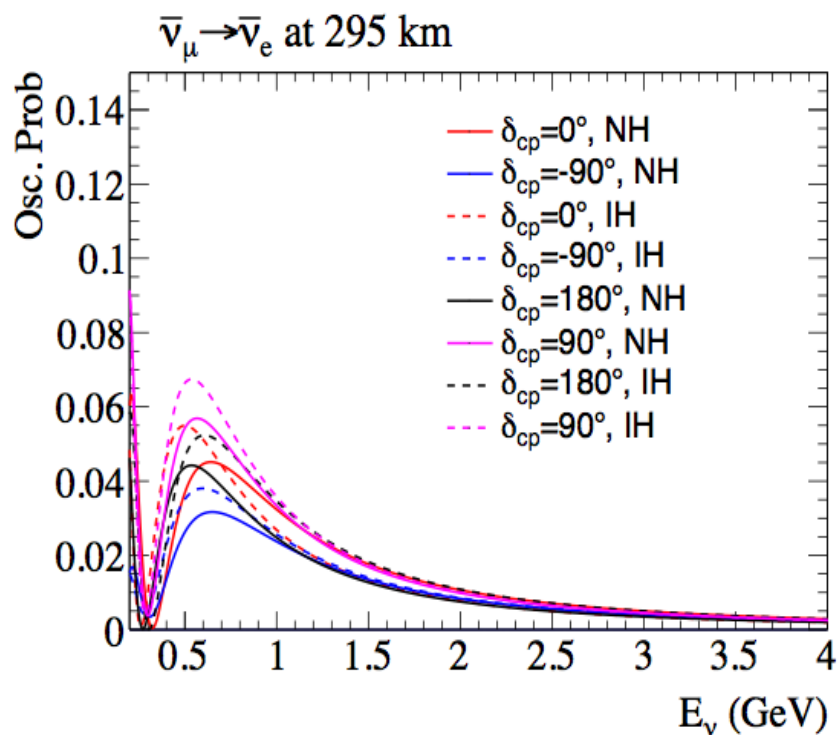
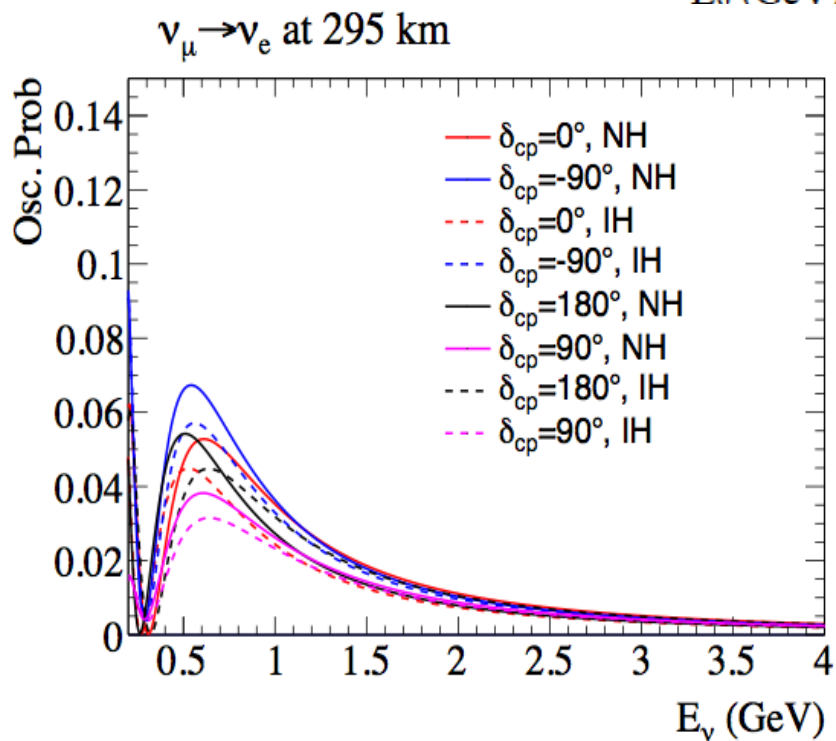
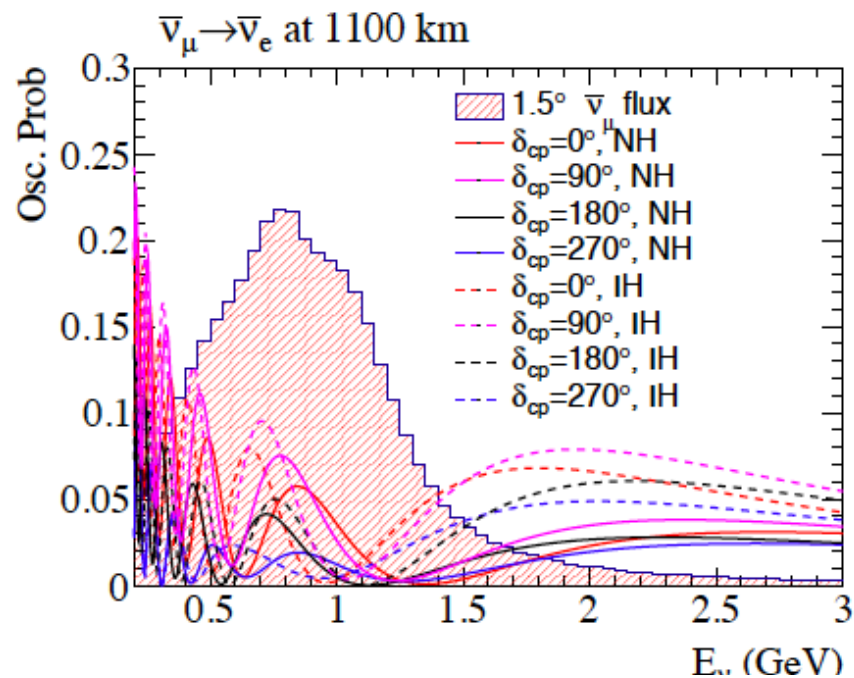
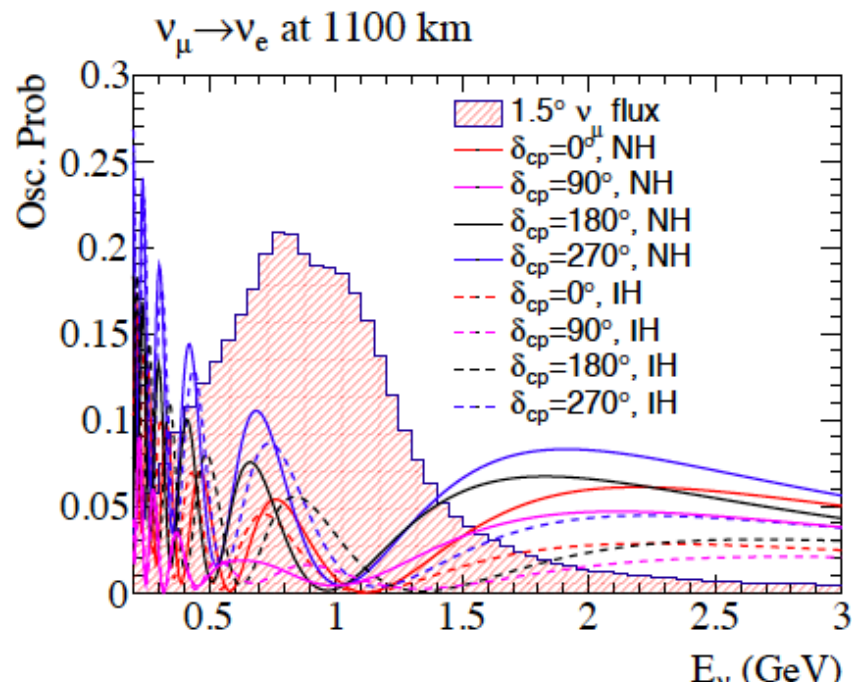
- Longer baseline
- Higher matter density
- Higher neutrino energy

Matter profile along the T2K baseline



Matter profile along the Tokai-to-Korea baseline





δ_{CP} & MO Sensitivity Studies

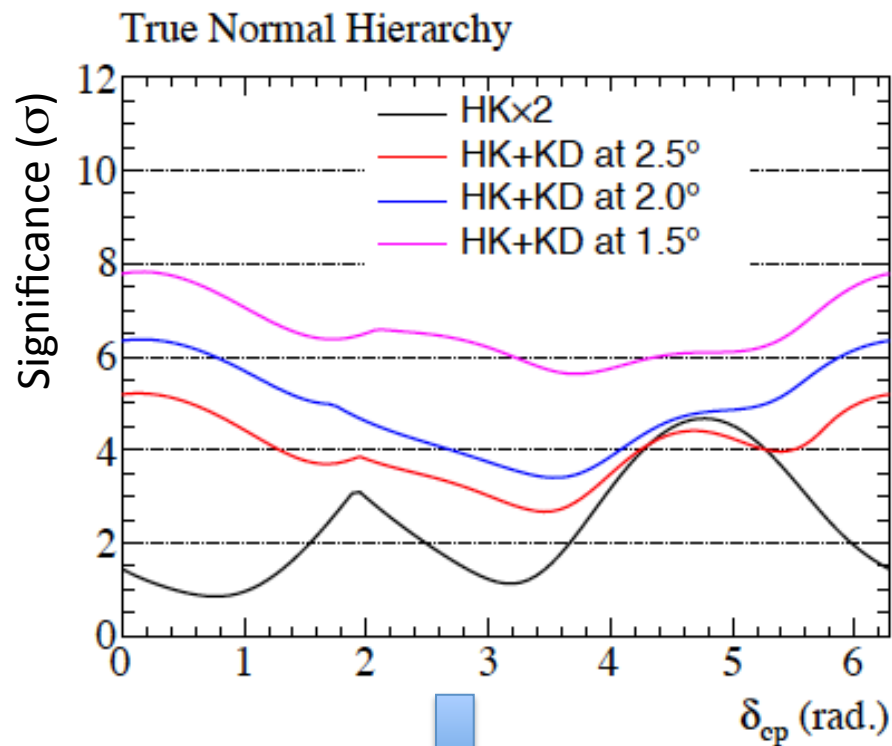
Simulation parameters

- 2.7×10^{22} POT with $\nu : \bar{\nu} = 1 : 3$ operation ratio
→ 10 years of operation with 1.3 MW beam
- 187 kton fiducial volume (compared to 22.5 kton for SK)
- Baseline to Korea is 1100 km
- Off-axis beam: $1.5^\circ, 2.0^\circ, 2.5^\circ$
- Oscillation parameters: 

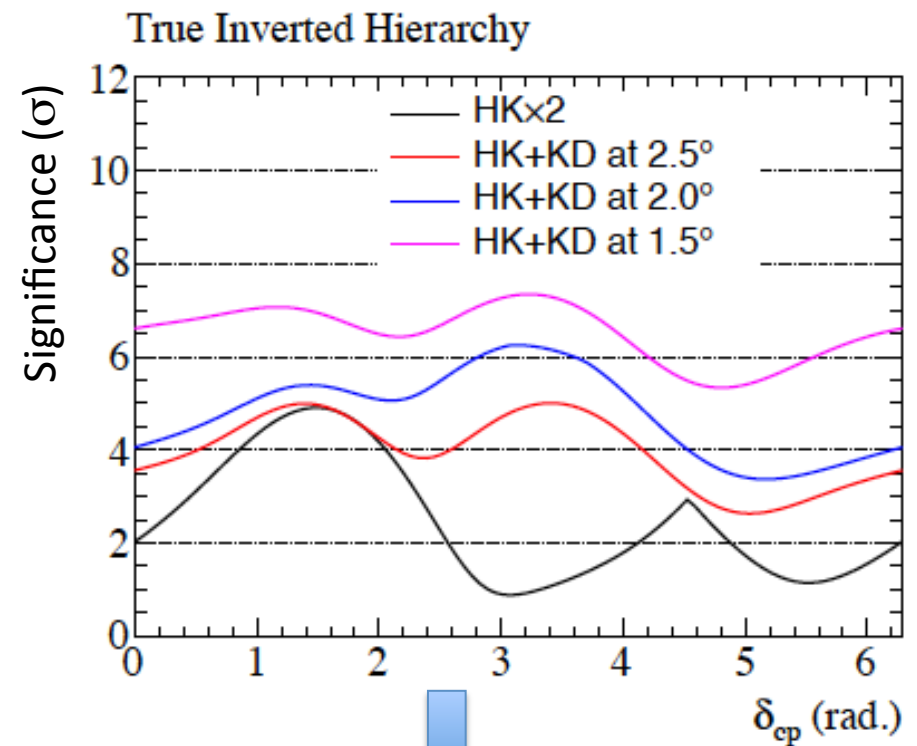
$$\begin{aligned} |\Delta m_{32}^2| &= 2.5 \times 10^{-3} \text{ eV} \\ \sin^2 \theta_{23} &= 0.5 \\ \sin^2 2\theta_{13} &= 0.085 \\ \Delta m_{21}^2 &= 7.53 \times 10^{-5} \text{ eV} \\ \sin^2 \theta_{12} &= 0.304 \\ \delta_{cp} &= 0, \pi/2, \pi, 3\pi/2 \end{aligned}$$

◆ Note: Relatively simple systematic uncertainty model is used.
More realistic systematic uncertainty implementation is needed.

Mass Ordering Sensitivities



HK+KD 1.5° : $6 \sim 8 \sigma$ for all δ_{CP}
 HK x2 : $1 \sim 4.5 \sigma$ for all δ_{CP}
 ($< 3 \sigma$ for most cases)



HK+KD 1.5° : $5.5 \sim 7 \sigma$ for all δ_{CP}
 HK x2 : $1 \sim 5 \sigma$ for all δ_{CP}
 ($< 3 \sigma$ for most cases)

ν_e appearance probability: CP violation

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \approx & 4s_{23}^2 s_{13}^2 \frac{1}{(1 \mp r_A)^2} \sin^2 \frac{(1 \mp r_A) \Delta_{31} L}{4E} \\
 & + \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \left(\frac{\Delta_{21} L}{2E} \right) \sin \frac{(1 \mp r_A) \Delta_{31} L}{4E} \cos(\pm \delta - \frac{\Delta_{31} L}{4E}) \\
 & + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21} L}{4E} \right)^2 - 4s_{23}^2 s_{13}^4 \frac{1}{(1 \mp r_A)^2} \sin^2 \frac{(1 \mp r_A) \Delta_{31} L}{4E}
 \end{aligned}$$

CP
↓

$L/E = (\pi/2)\chi(4/\Delta_{31})$ for 1st max. and $(3\pi/2)\chi(4/\Delta_{31})$ for 2nd max.:

$L/E \rightarrow$ x3 more CP effect @ 2nd max

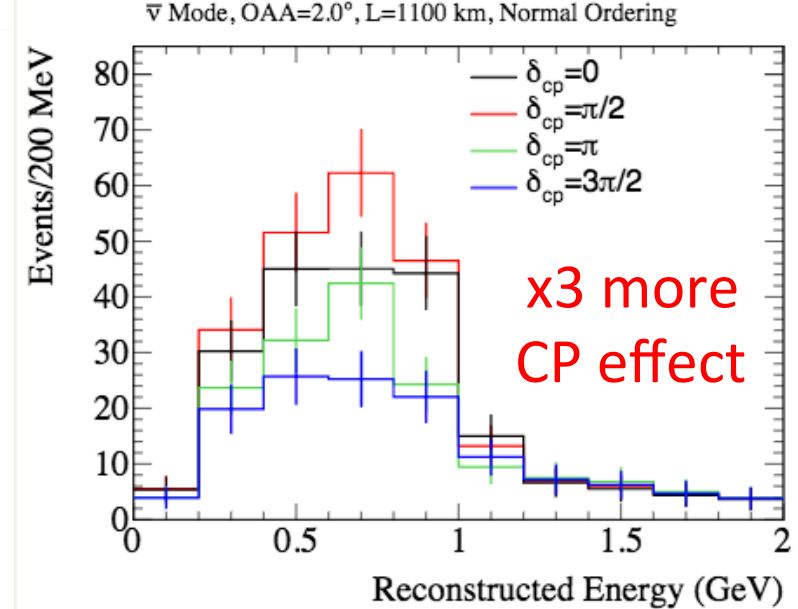
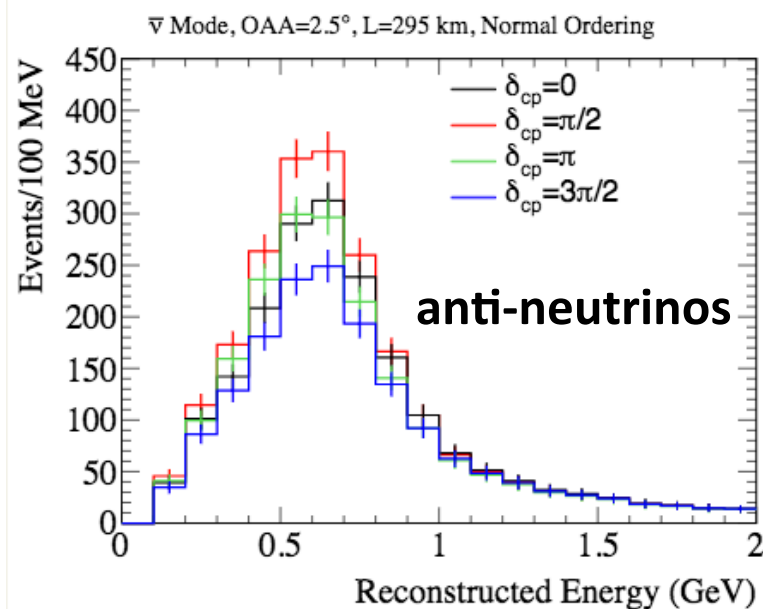
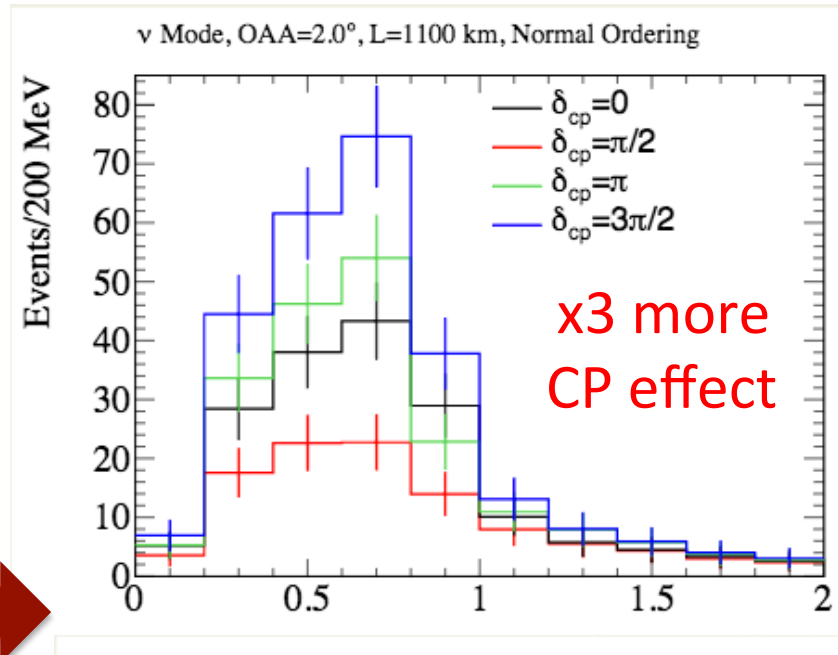
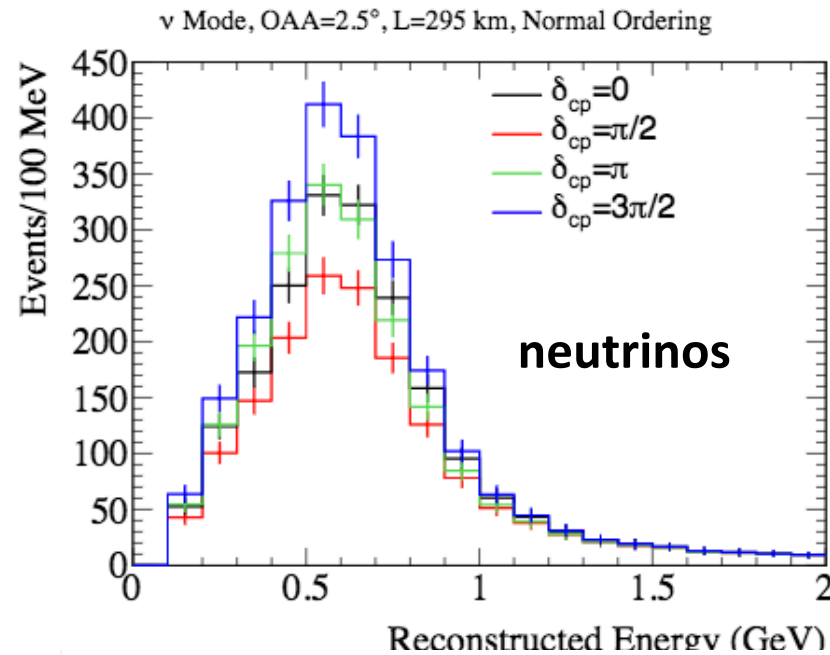
Degeneracies

- $\sin 2\theta_{23} \rightarrow$ More precise study to be done by T2K/HK
- matter term, $(1 \mp r_A)$, causes “discrete” degeneracy with CP when MO is unknown
- degeneracy in phase with Δ_{31} limits CP phase resolution: 2nd max. @T2HKK needed

HK x 1 (295 km)

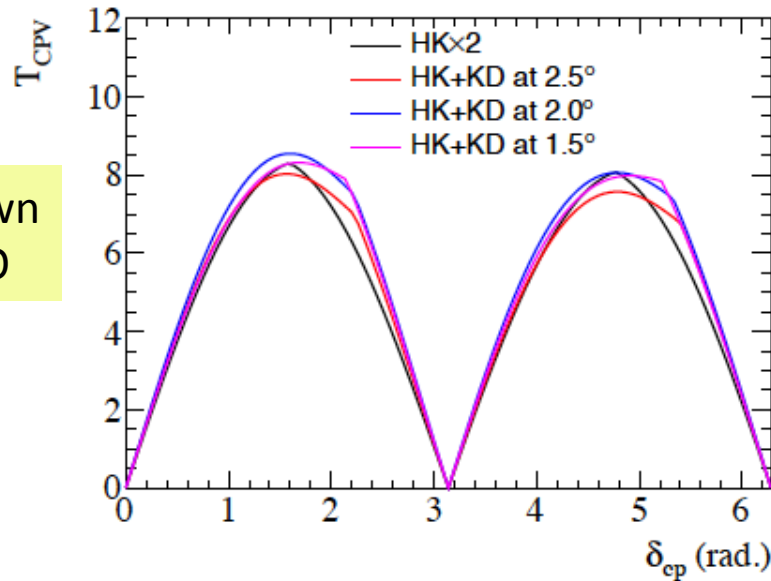
ν_e candidates

KD (1100 km)



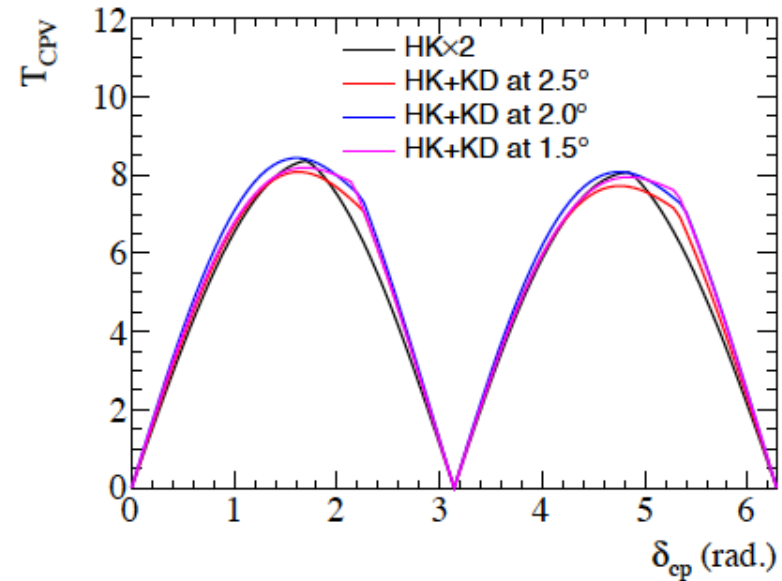
δ_{CP} Sensitivities

True Normal Hierarchy, Hierarchy Known

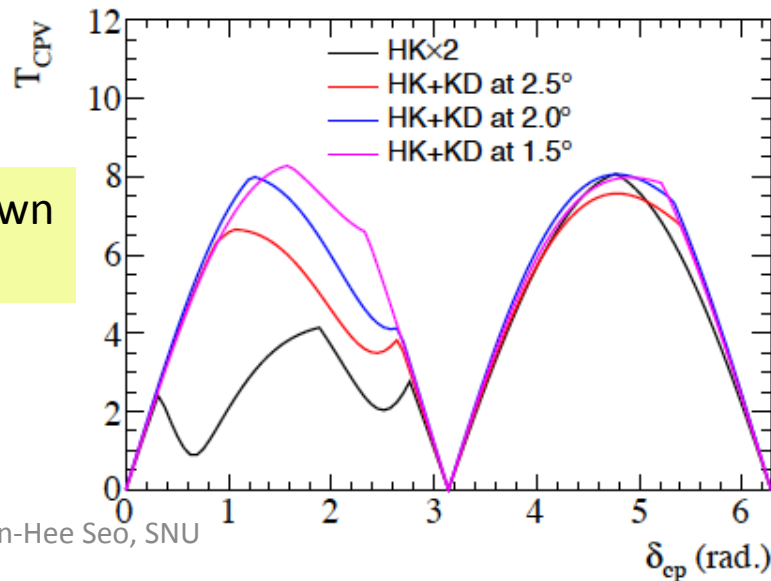


Known
MO

True Inverted Hierarchy, Hierarchy Known

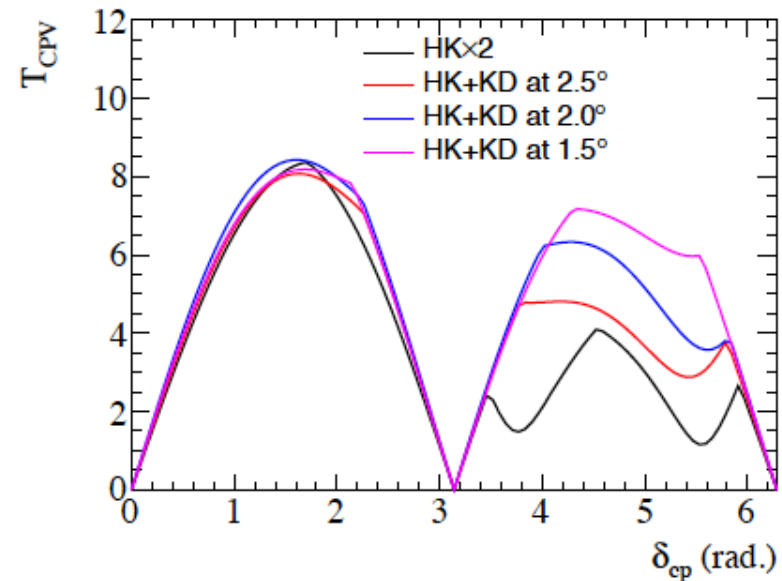


True Normal Hierarchy, Hierarchy Unknown



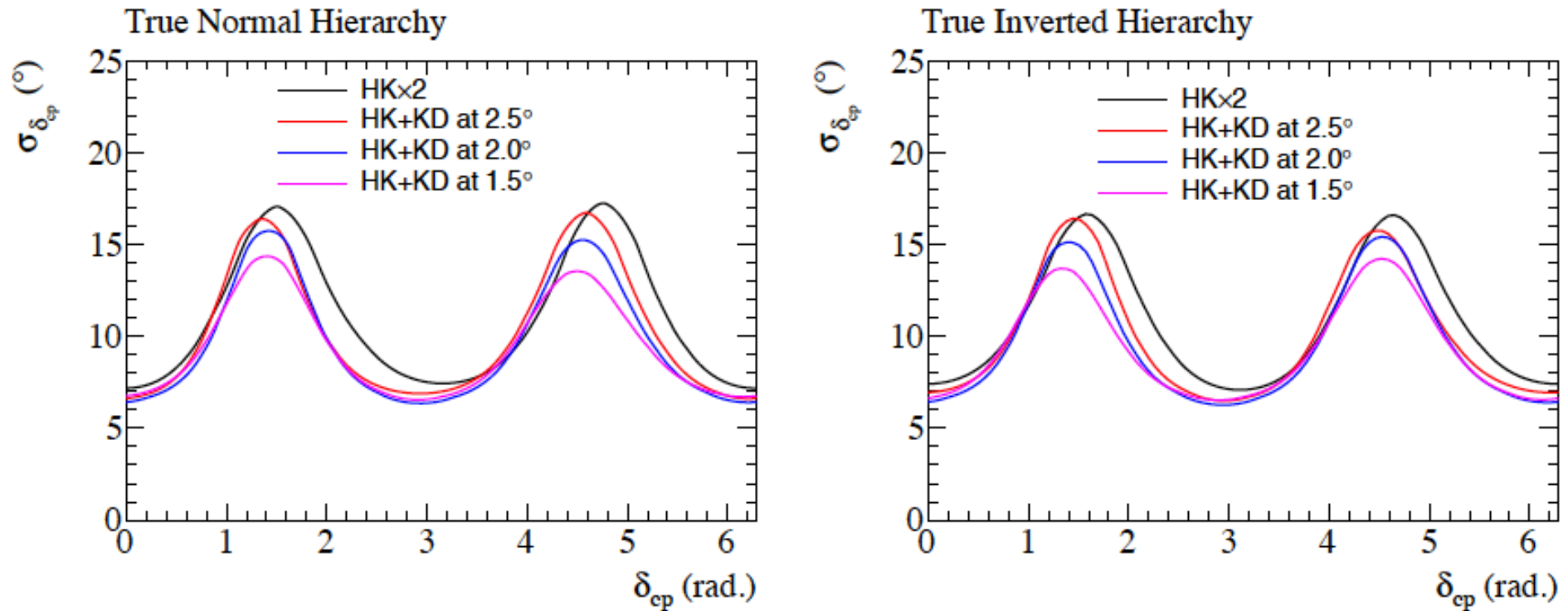
Unknown
MO

True Inverted Hierarchy, Hierarchy Unknown



δ_{CP} Precision Sensitivities

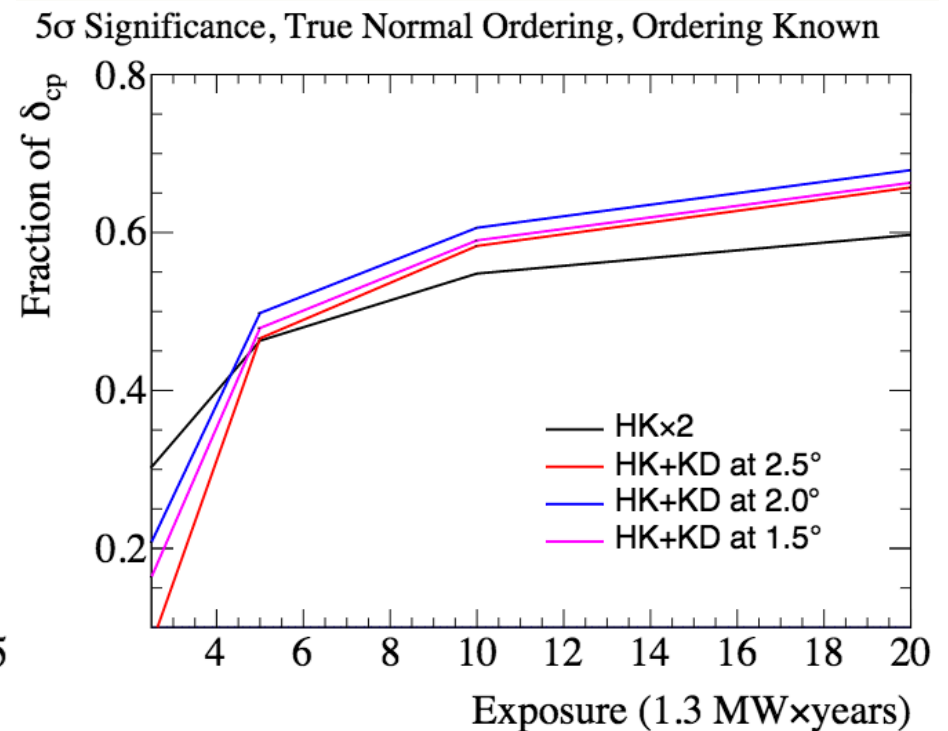
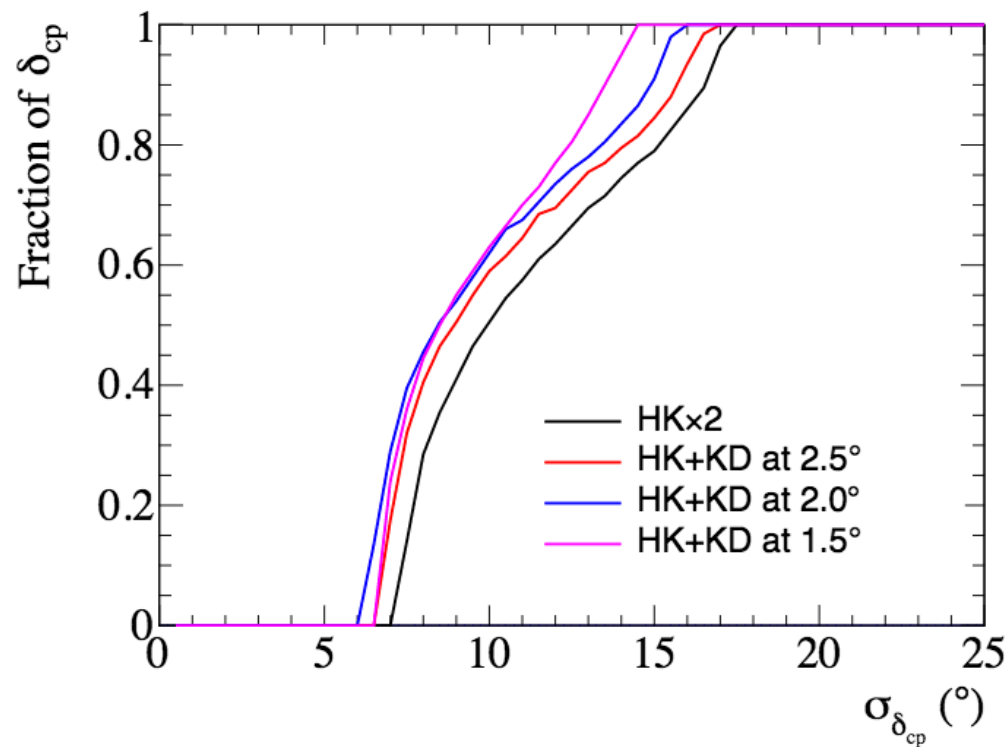
→ Important for flavor symmetry model of neutrino mixing



At maximum CP violation: HK+KD 1.5°: $\sigma(\delta_{CP}) = 13 \sim 14$ degree
HK x2 : $\sigma(\delta_{CP}) \sim 17$ degree

Fraction of δ_{CP}

How much fraction of δ_{CP} can we cover ?



Additional benefits

sources

2. Deeper site:

lower muon flux,
lower spallation BKG

3. Geographical separation:

signal coincidence,
degeneracy break-up

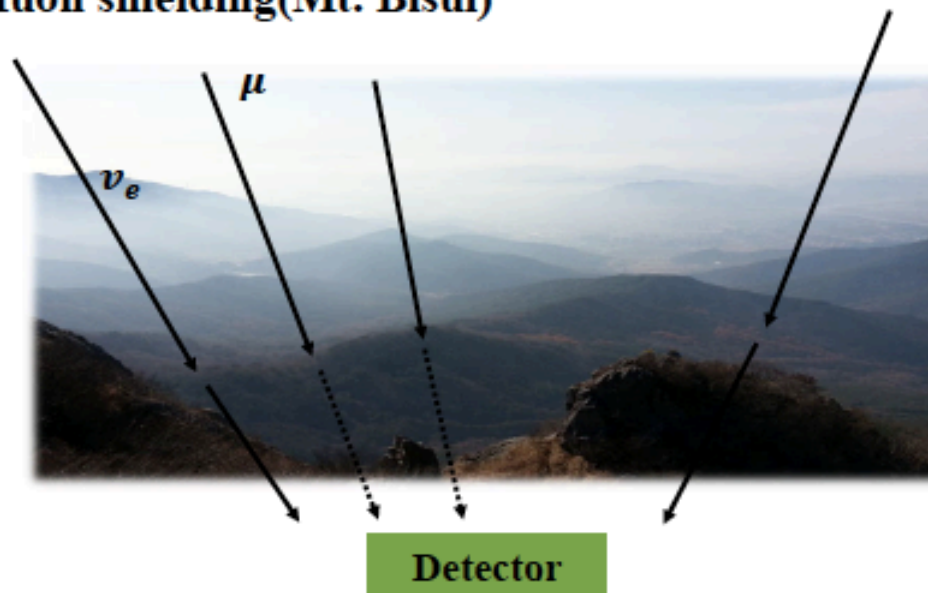
1. Longer baseline:

2nd osc. max,
matter effect

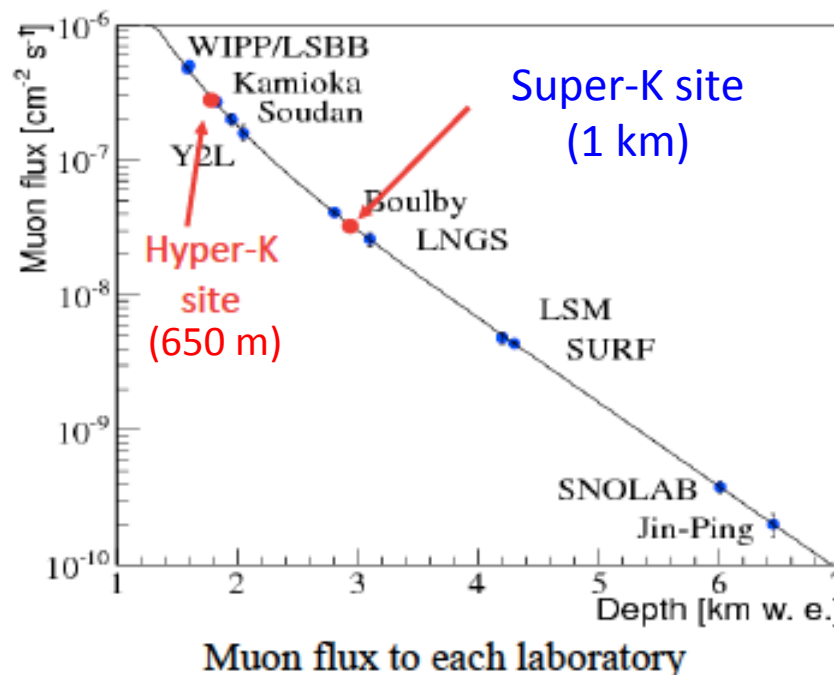
→ δ_{CP} , mass ordering

Seon-Hee Seo, SNU

Muon shielding(Mt. Bisul)



Due to the detector being located deep underground,
The background level is decreased



Additional benefits

☐ Solar neutrino physics

- (1) Day/night asymmetry due to MSW matter effect in Earth
- (2) HEP solar neutrinos
- (3) energy spectrum upturn

} **Sensitivity improves**

☐ Super-Nova Relic neutrino detection

- (1) SRN detection capability below 20 MeV improves
- (2) Detection efficiency is more than twice in [16, 18] MeV than HK site.

☐ Neutrino geophysics; Low energy DM

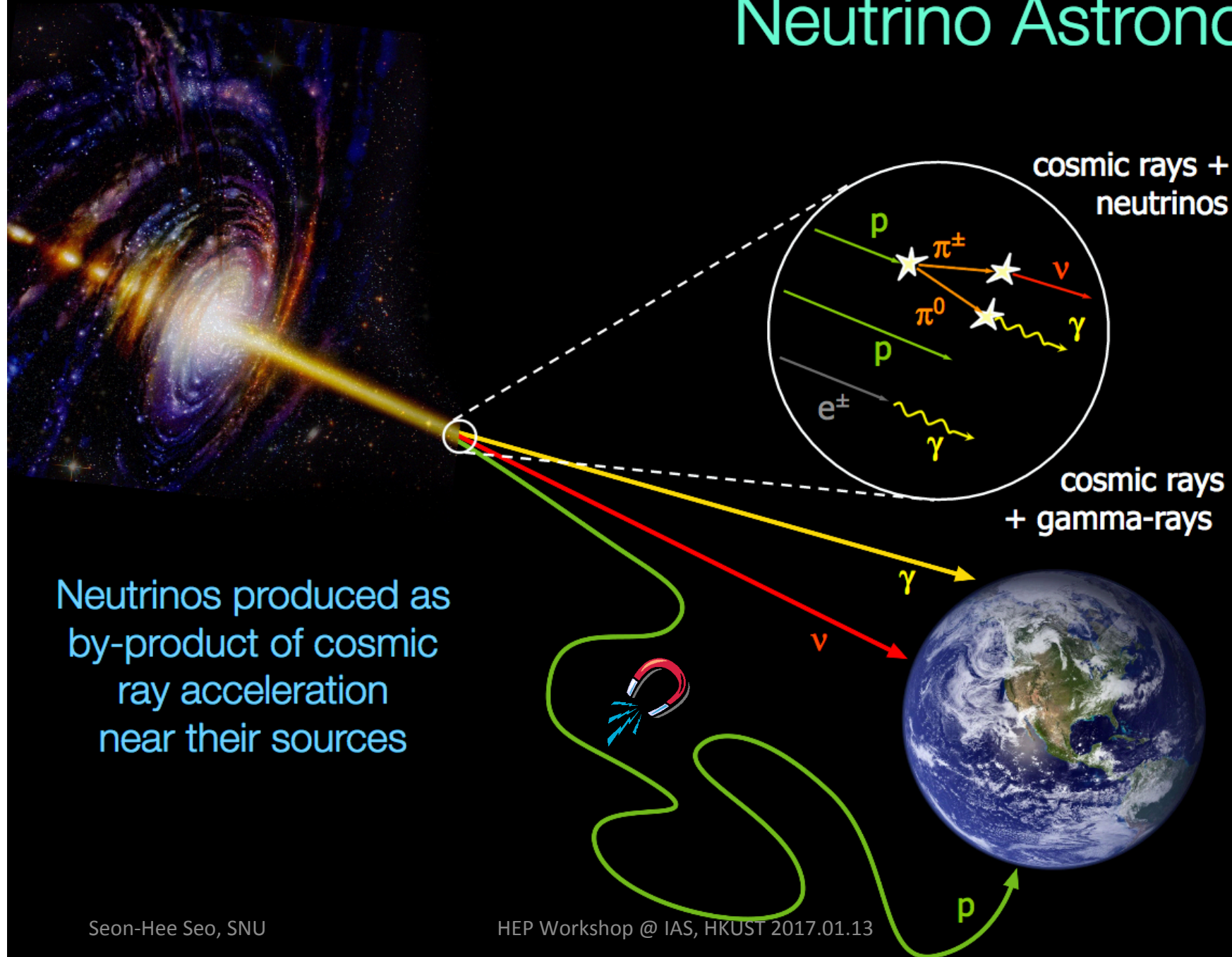
☐ Non-standard new physics

- { (1) Quantum decoherence,
- (2) tiny violation of Lorentz symmetry without/with CPT invariance,
- (3) nonstandard neutrino interactions with matter

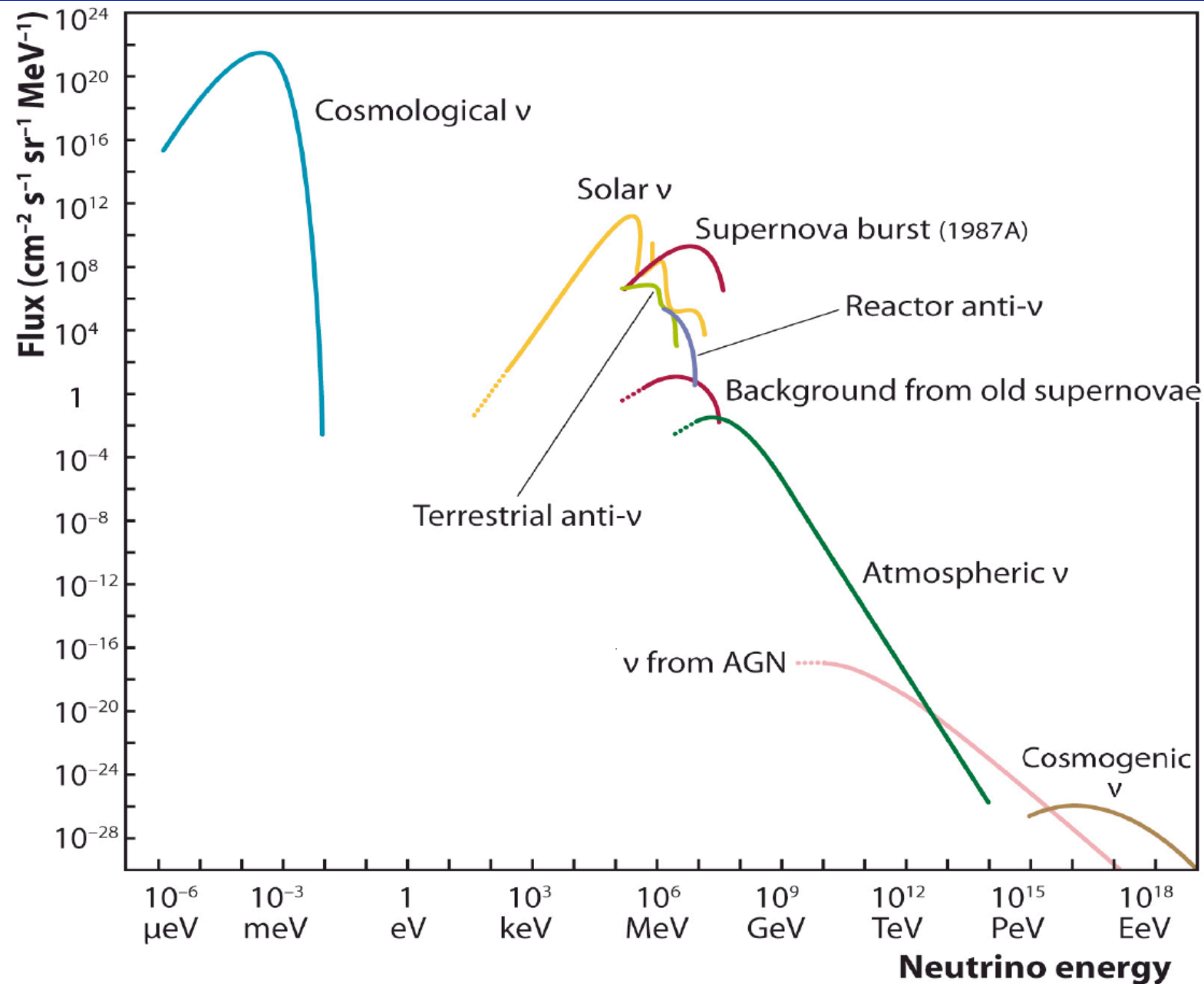
Phys. Rev. D 77, 073007 (2008)

→ In most cases, these are improved with T2HKK configuration

Neutrino Astronomy



Neutrino Sources & Fluxes



Even bananas...



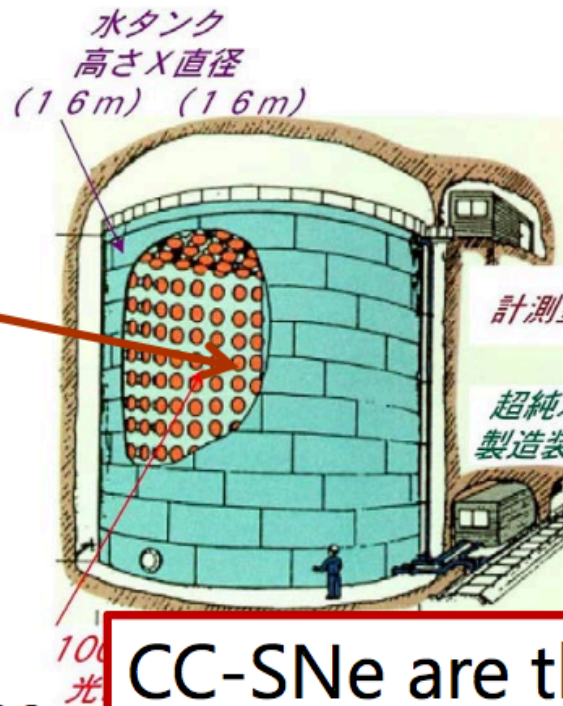
1 million neutrinos/day per banana

from the decay of naturally occurring radioactive potassium atoms they have.

→ 0.1 microsievert (μSv)

Cf) chest X-ray : 0.1 mSv
Chernobyl exposure: 350 mSv

SN 1987A



Nobel prize in 2002 is awarded to Prof. Koshiba and Kamiokande



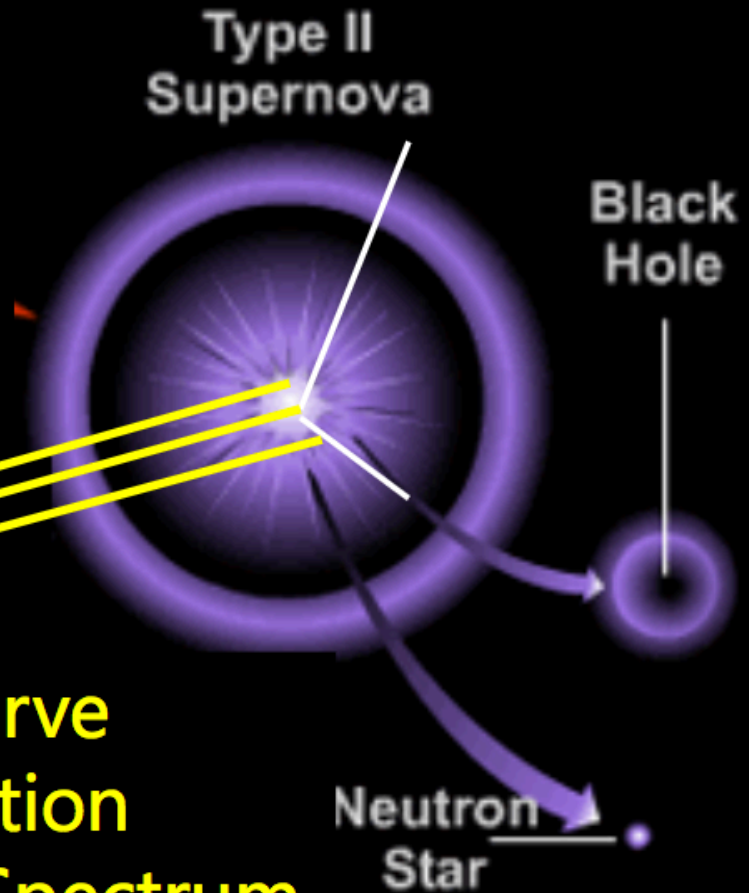
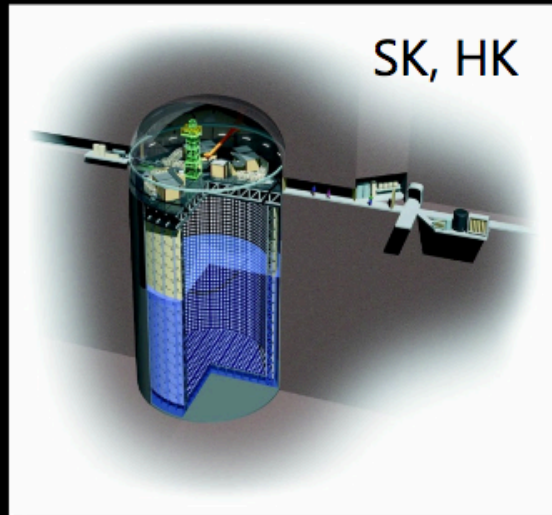
SN explosion happened in the next galaxy. Luminosity of SN was comparable to that of the galaxy.

CC-SNe are the death of massive stars, that emits huge neutrinos whose energy corresponds the gravitational energy release at the birth of neutron star.

Rough sketch has been made.

Qualitative => Quantitative. HK is necessary.

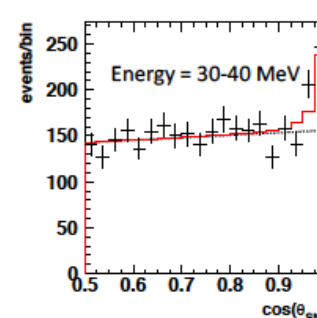
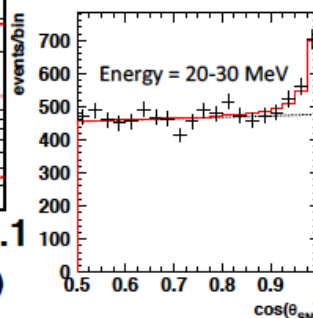
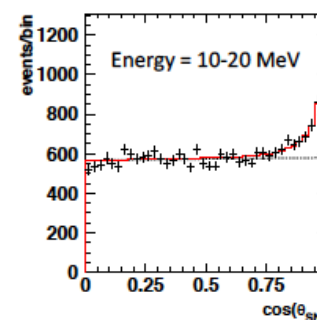
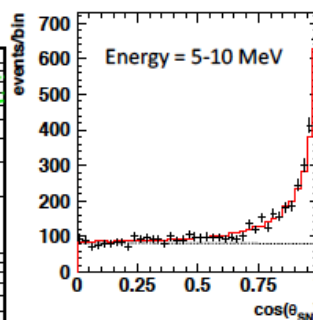
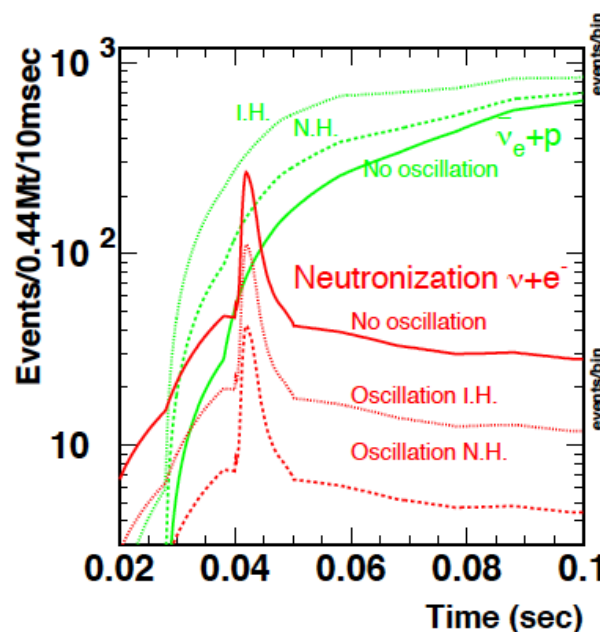
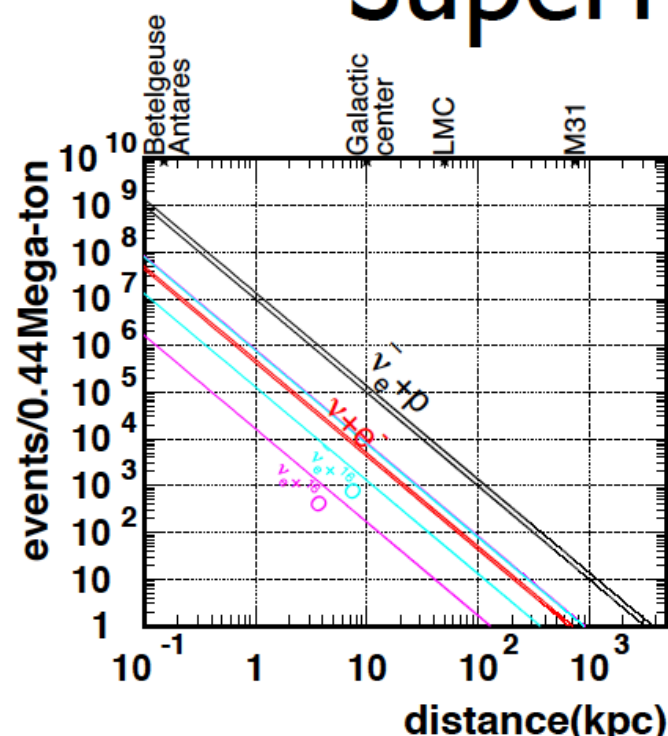
Available information of Neutrino Signal



1. Light Curve
2. Sky Position
3. Energy Spectrum

→ Supernova explosion mechanism could be revealed.

Supernova burst neutrino



SN explosion mechanism

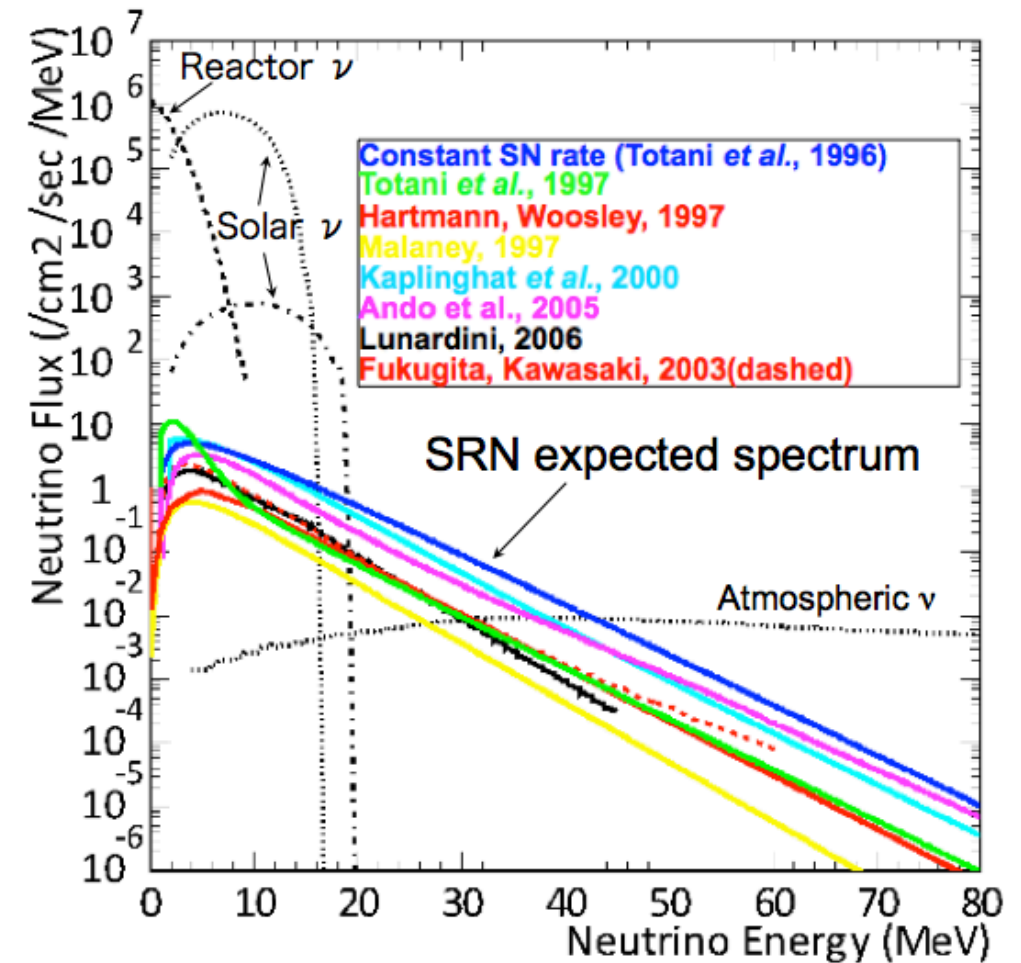
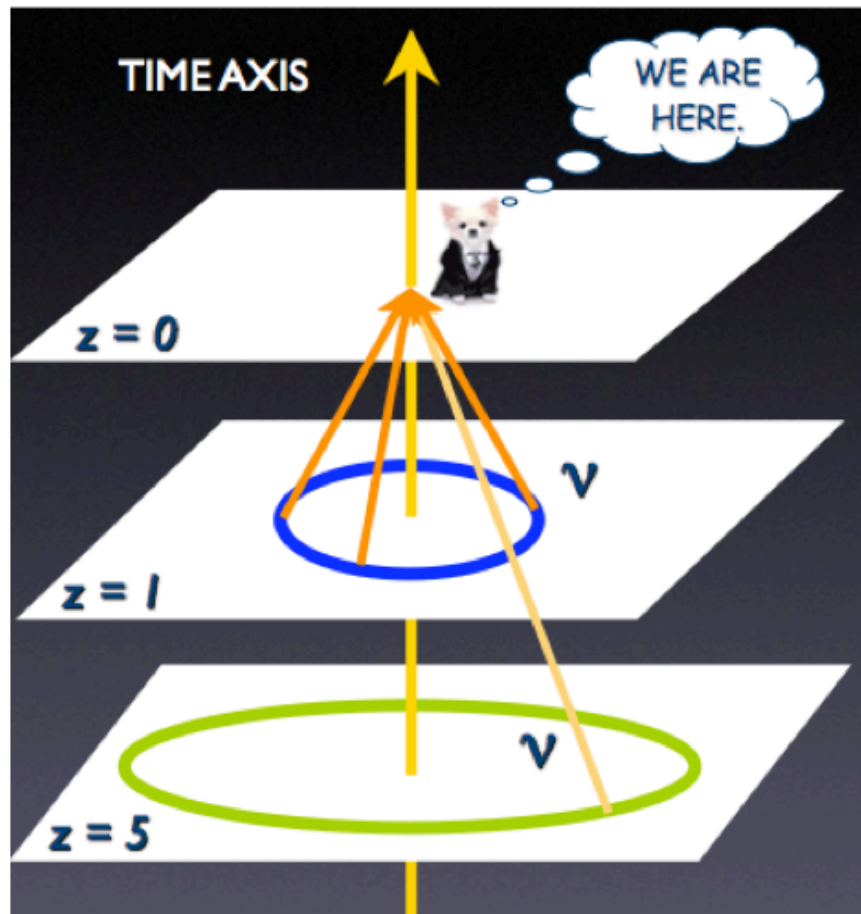
SN directional info.
by $\nu + e$ scattering

- Large statistics for galactic SN
 - Precise timing and energy information to probe SN mechanism
 - Pointing (2deg@10kpc) and timing for multi-messenger astronomy
- Nearby (>1Mpc) SN
 - Check of dim SN, coincidence with GW telescope, ...

Supernova Relic Neutrinos (SRN)

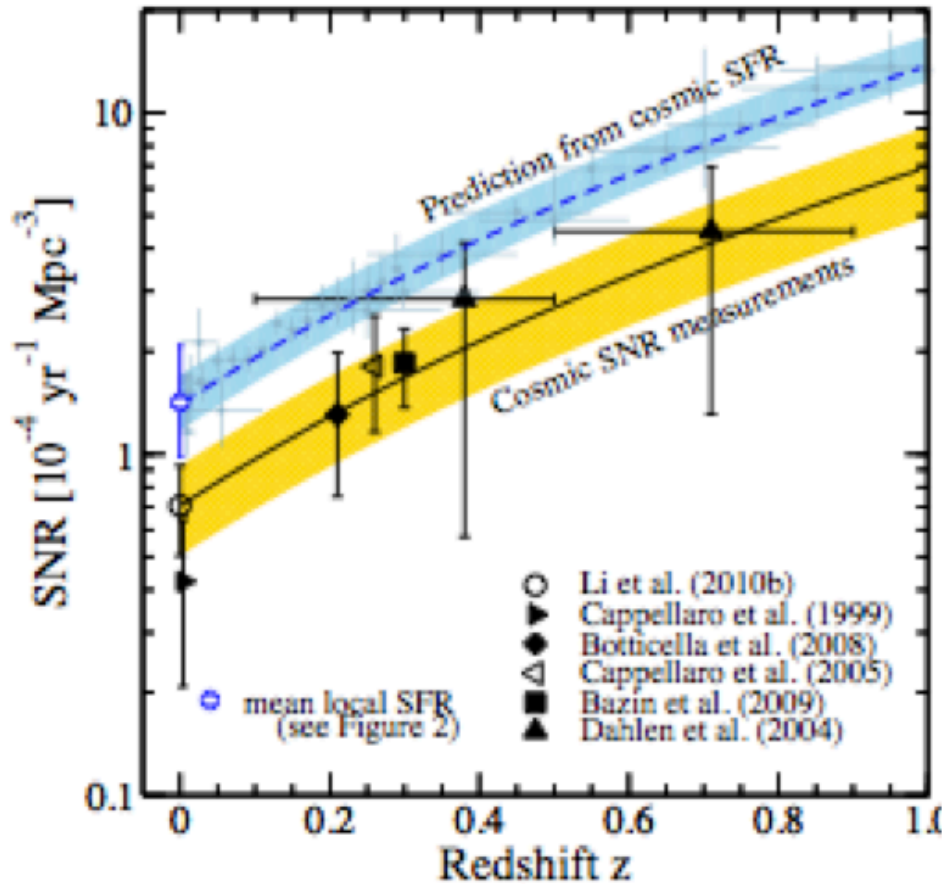
Neutrinos emitted from past supernovae

S.Ando



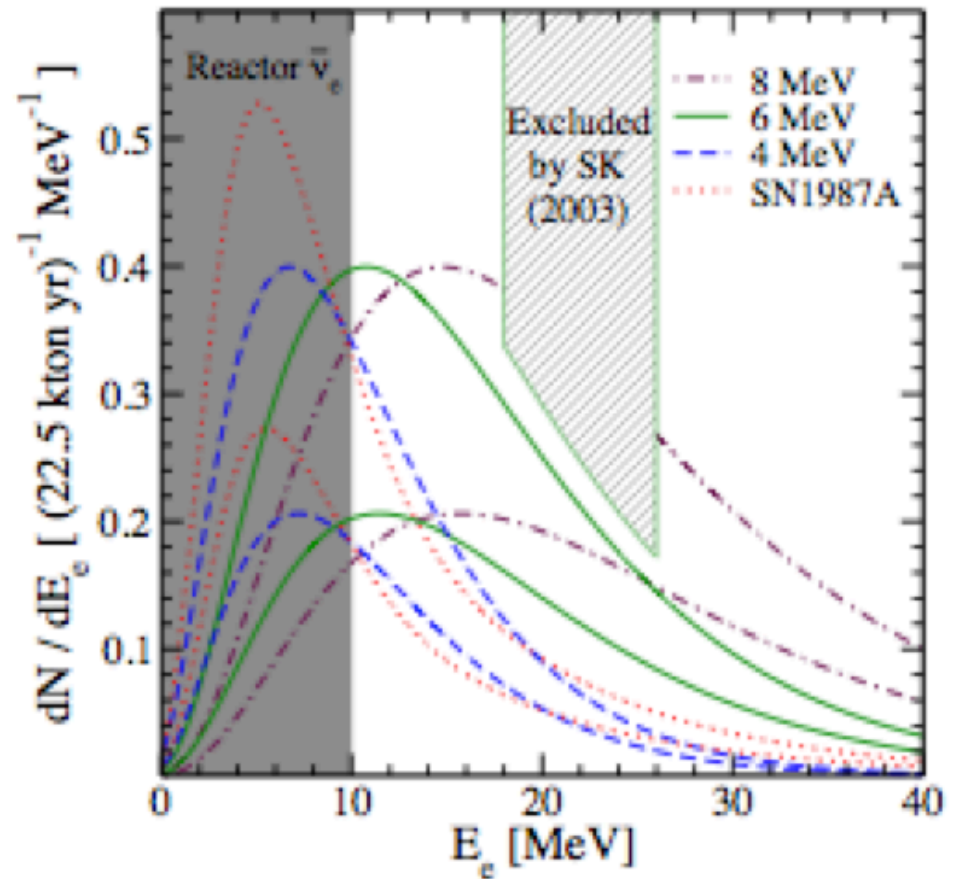
SRN: Physics Motivation

S.Horiuchi et.al. (2010)



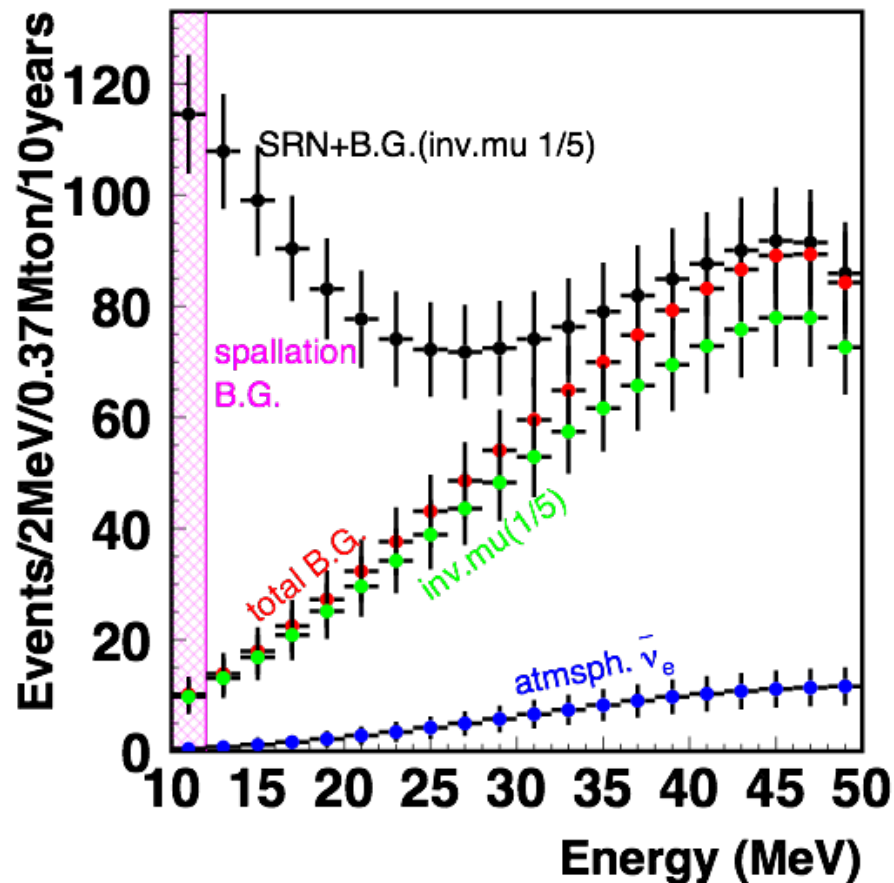
Supernova rate problem: $\sim 1.8^{+1.6}_{-0.6}$

S.Horiuchi et.al. (2008)

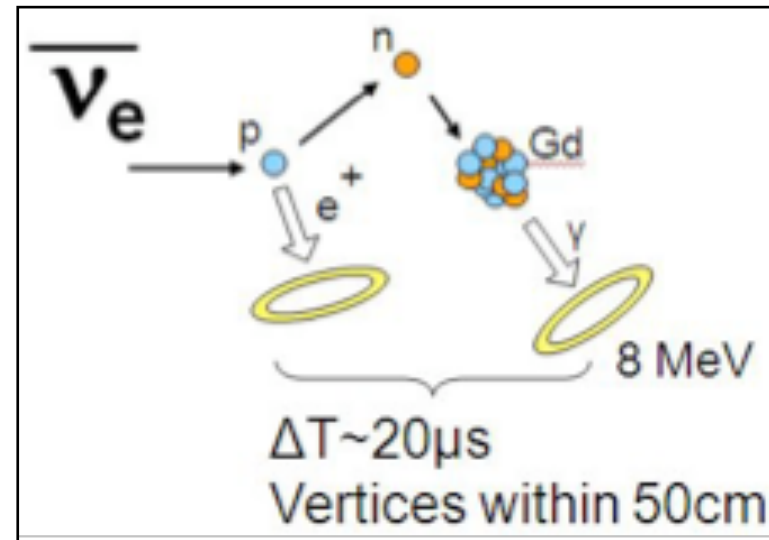


SRN spectrum may solve the supernova rate problem.

Supernova Relic Neutrinos in HK



With Gadolinium loading option



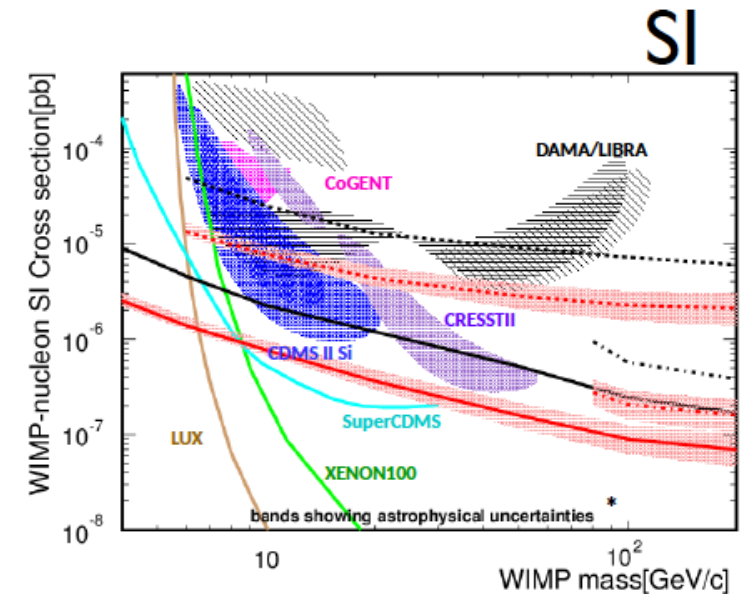
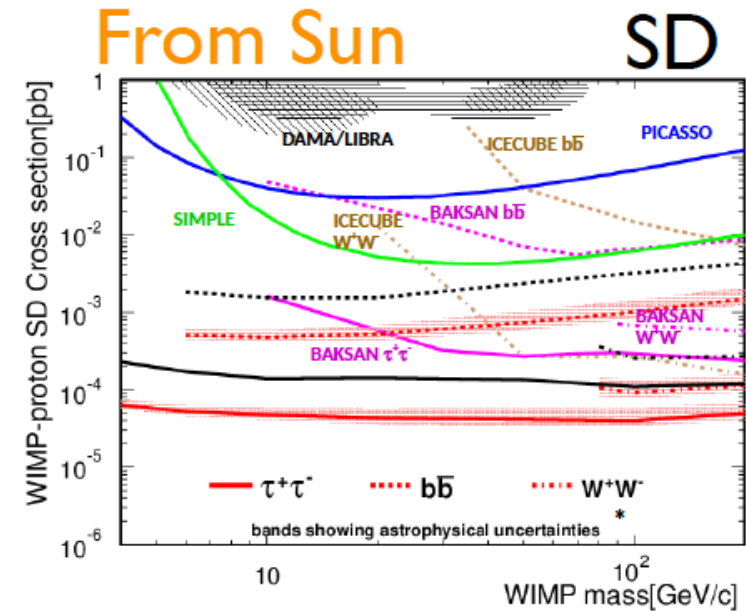
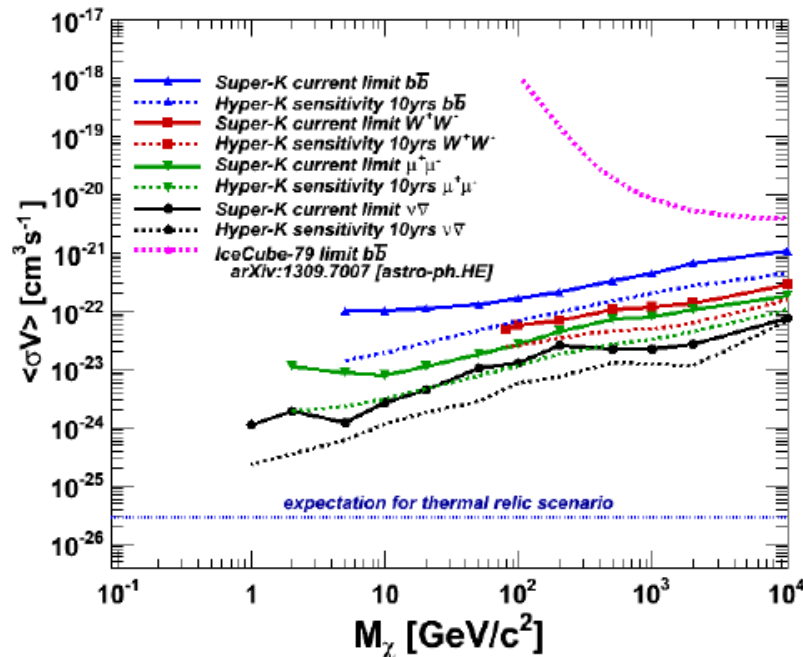
- Neutron tagging capability reduces background drastically.

- To detect diffuse neutrinos from SN
- 98 +/- 20 events (4.8 σ) are expected in 10 years.

Indirect Dark Matter Search

- Unique sensitivities, especially for low mass region
- Improve $\times 3$ -10 over SK limit

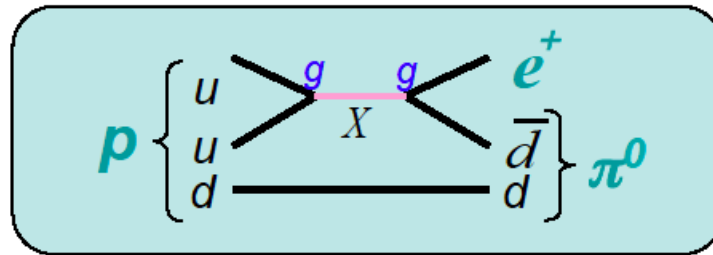
From Galactic center



Proton Decay Search

- Only way to directly probe Grand Unified Theory
- Two major modes predicted by many models

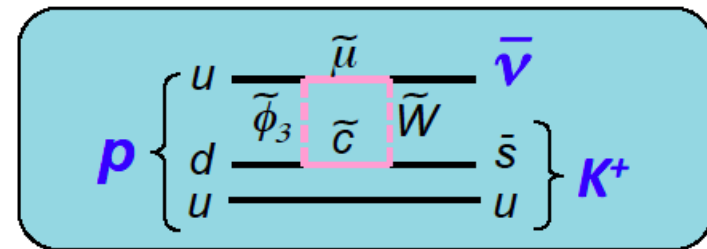
Mediated by gauge bosons



$p \rightarrow e^+ \pi^0$

$$\Gamma(p \rightarrow e^+ \pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

SUSY mediated

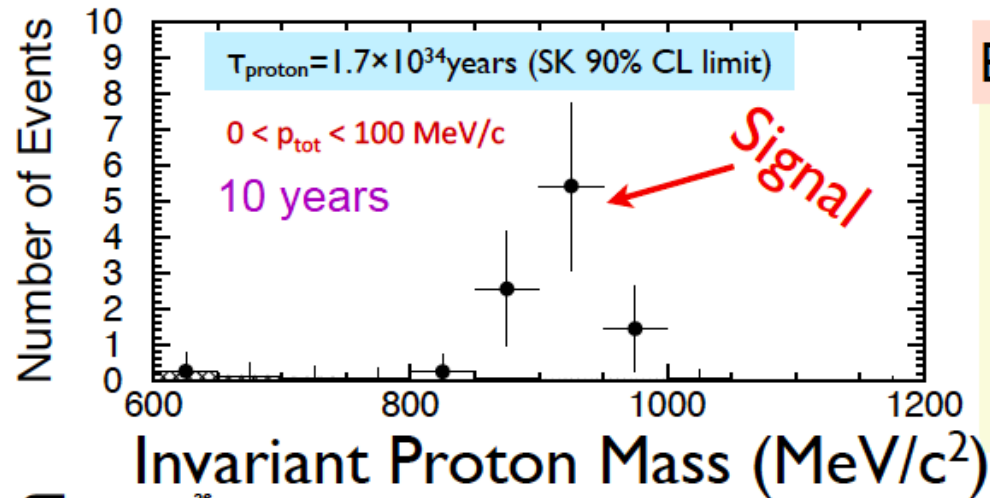
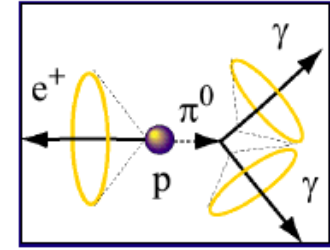


$p \rightarrow \bar{\nu} K^+$

$$\Gamma(p \rightarrow \bar{\nu} K^+) \sim \frac{\tan^2 \beta \times m_p^5}{M_{\tilde{q}}^2 \times M_3^2}$$

- Need broad searches including other possible modes

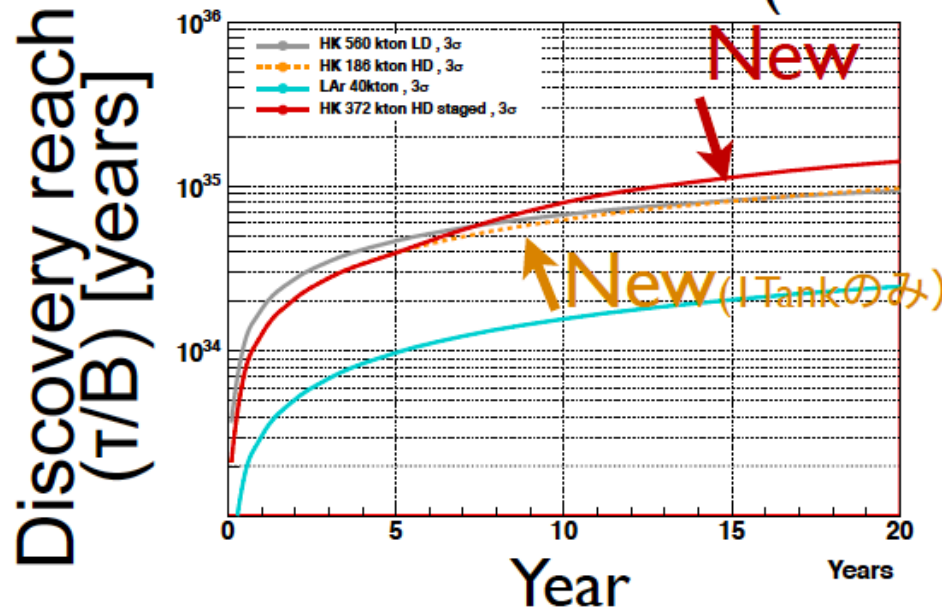
$p \rightarrow e^+ \pi^0$ search in Hyper-K



BG free by high-sensitive PMTs

For the case of
 $T_{\text{proton}} = 1.4 \times 10^{34} \text{ years}$
 (Super-K limit)

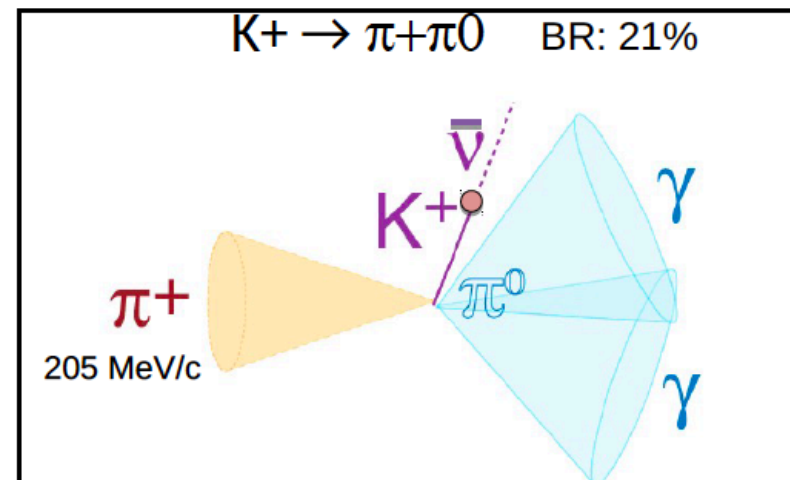
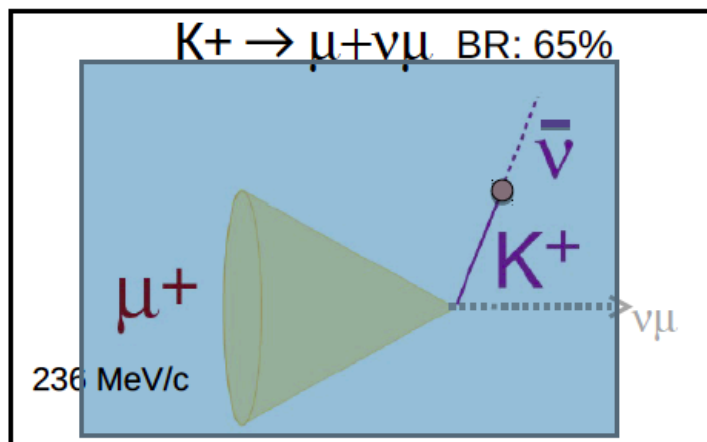
$\sim 9\sigma$ discovery@HK



- Only realistic proposal to reach to 10^{35} years@ 3σ

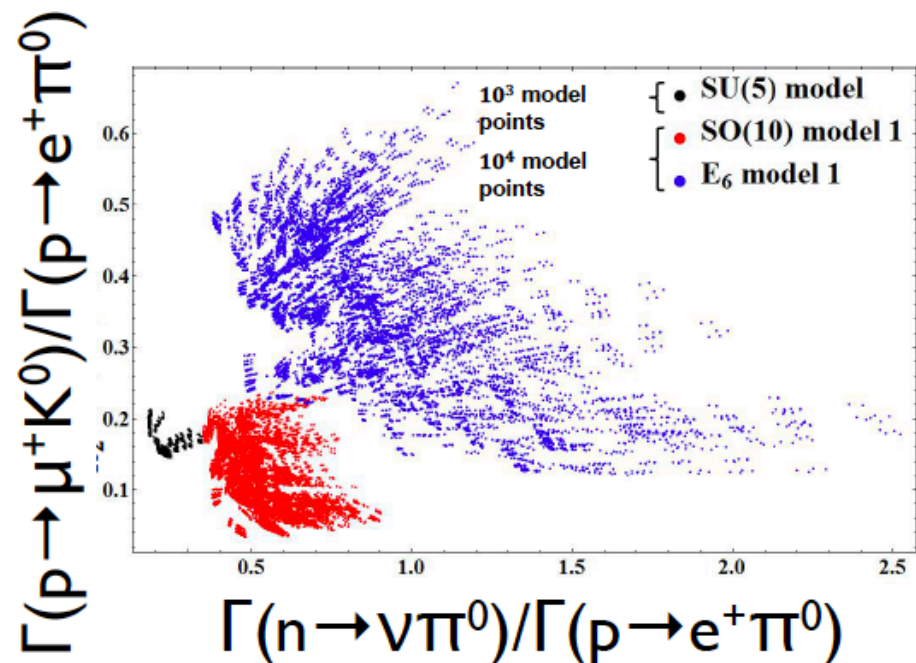
$$p \rightarrow \bar{\nu} K^+$$

- K^+ invisible (below Cherenkov threshold)
- $K^+ \rightarrow \mu \nu$ (Br: 63.5%)
 - Method 1: Tag with nuclear de-excitation γ
 - Method 2: Search excess in P_μ distribution
- $K^+ \rightarrow \pi^+ \pi^0$ (Br: 20.7%)
 - 205 MeV/c π^0 + activity in opposite direction (π^+ just above threshold)
- Better timing and efficiency of photosensor enhances reach



Other modes are also important

- First discovery might happen in exotic decay modes.
 - Many models predicts branching ratio of $p \rightarrow e^+ \eta$, $e^+ \rho$, $e^+ \omega$ are 10~20%
 - Flipped SU(5) (Ellis) predicts $\text{Br}(p \rightarrow e^+ \pi^0) \sim \text{Br}(p \rightarrow \mu^+ \pi^0)$
- We expect to identify details of unification picture, e.g. gauge group and other symmetries
 - $\Gamma(n \rightarrow \nu \pi^0) / \Gamma(p \rightarrow e^+ \pi^0)$ depends on SU(5), SO(10), E₆ (Y. Muramatsu)



Hyper-K's sensitivities

Improvements in many modes by a factor ~ 10

Open for many decay modes including $p \rightarrow e^+ \pi^0$, $p \rightarrow \nu K^+$

Good chance for discovery!

	3σ discovery potential (10yrs)	Current limit (90%CL)
$p \rightarrow e^+ \pi^0$	8.0×10^{34}	1.4×10^{34}
$p \rightarrow \nu K^+$	2.5×10^{34}	0.7×10^{34}
$p \rightarrow \mu^+ \pi^0$	8.7×10^{34}	1.1×10^{34}
$p \rightarrow e^+ \eta^0$	4.0×10^{34}	0.4×10^{34}
$p \rightarrow \mu^+ \eta^0$	8.3×10^{34}	0.1×10^{34}
$n \rightarrow e^+ \pi^-$	1.7×10^{34}	0.2×10^{34}
$p \rightarrow \mu^+ \pi^-$	1.1×10^{34}	0.1×10^{34}

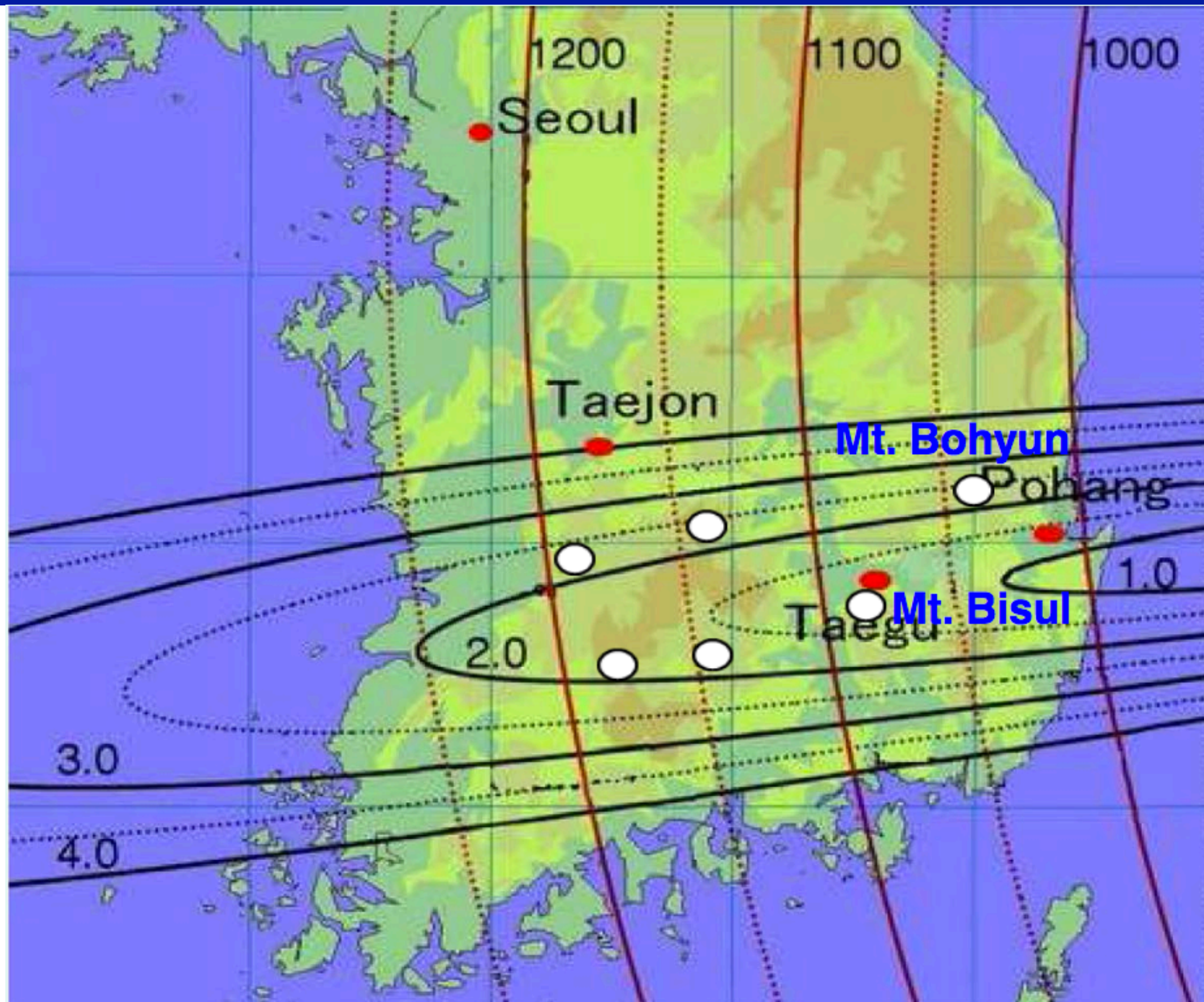
Some candidate sites in Korea

Site candidates for a 2nd osc. maximum detector in Korea

- Baselines with 1,000~1,200 km
- 2.0~2.5° or 1.5~2.0° off axis beam directions
- >1,000 m high mountains with hard granite rocks

Site	OAB	Baseline [km]	Height [m]
Mt. Bisul	~1.3°	1088 km	1084 m
Mt. Hwangmae	~1.8°	1140 km	1113 m
Mt. Sambong	~1.9°	1180 km	1186 m
Mt. Bohyun	~2.2°	1040 km	1126 m
Mt. Minjuui	~2.2°	1140 km	1242 m
Mt. Unjang	~2.2°	1190 km	1125 m

Some Candidate Sites



Mt. Bisul at Dalsung (1,084m high)



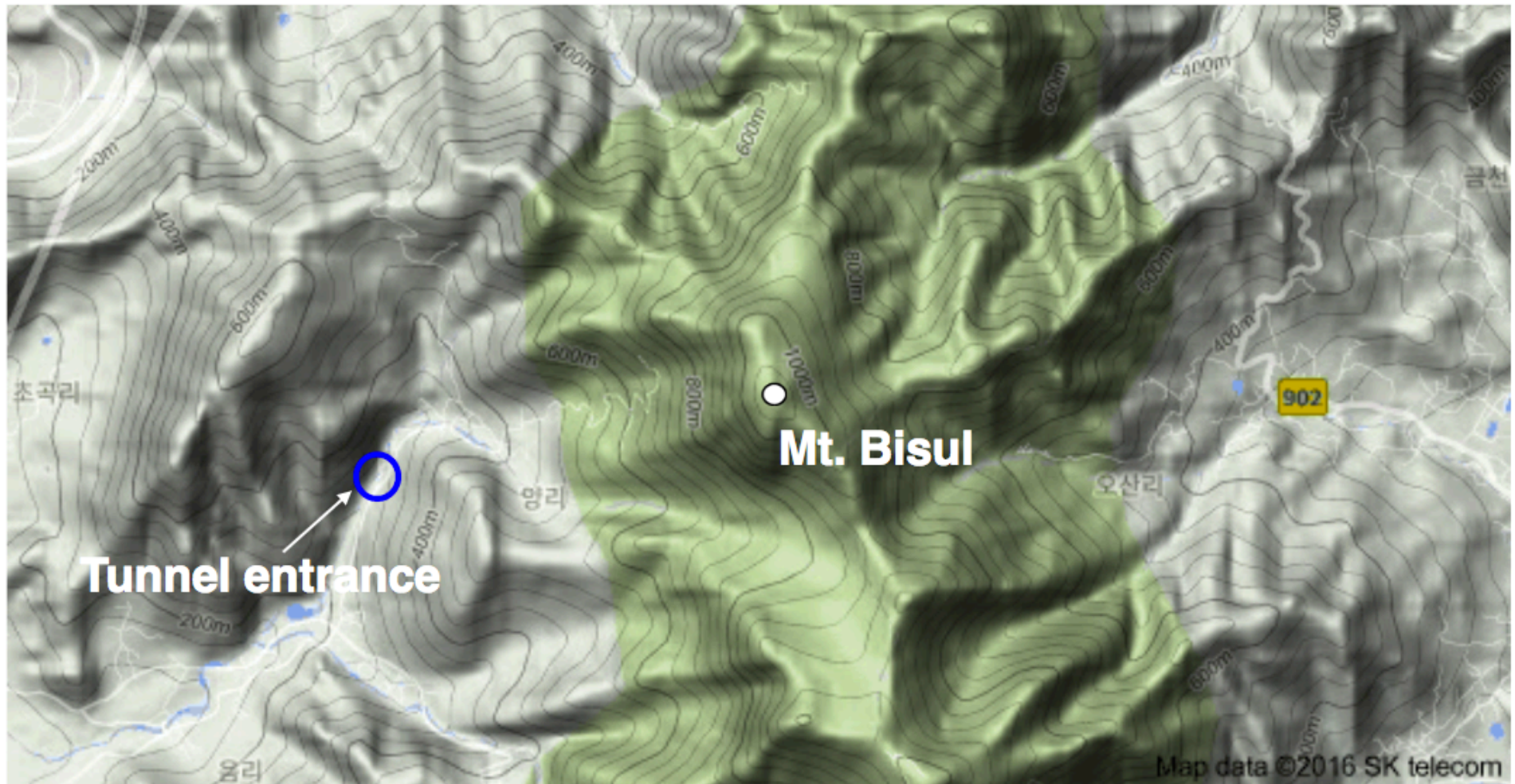
- Excellent accessibility: Dalsung district in the city of Daegu
← near Technopolis area, KTX from Seoul, access road, electricity, water

Mt. Bisul (II)



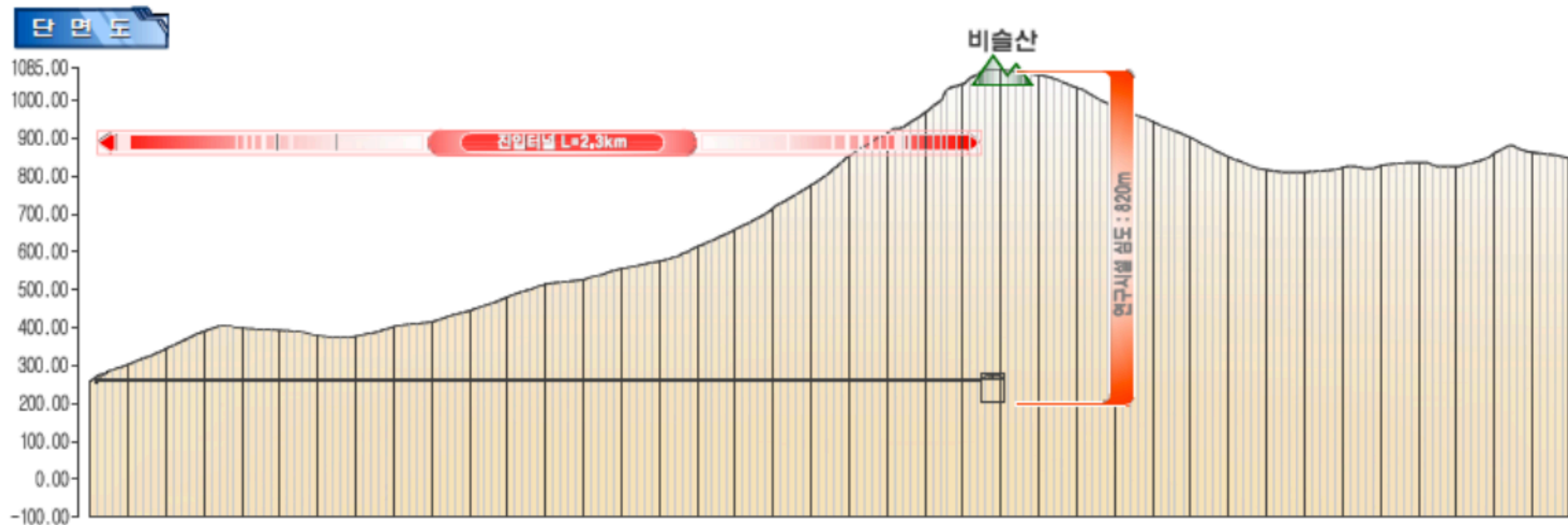
Mt. Bisul (III)

~1,088 km baseline, ~ 1.3° OAB, 1,084 m height



Latitude: N 35° 43' 00" longitude: E 128° 31' 28"

Mt. Bisul (IV)



- Overburden: ~820 m (horizontal tunnel)
~1000 m (inclined tunnel)
- Access tunnel: ~2.3 km long
- Cost estimate including geological survey will be done

Mt. Bohyun at Pohang (1,1126 m high)

~1,040 km baseline, ~ 2.2° OAB, 1,126 m height



latitude N 36° 09' 47"
longitude E 128° 58' 26"

1st T2HKK Workshop @SNU

□ 1st T2HKK workshop (Nov. 21-22) at SNU was successfully finished.



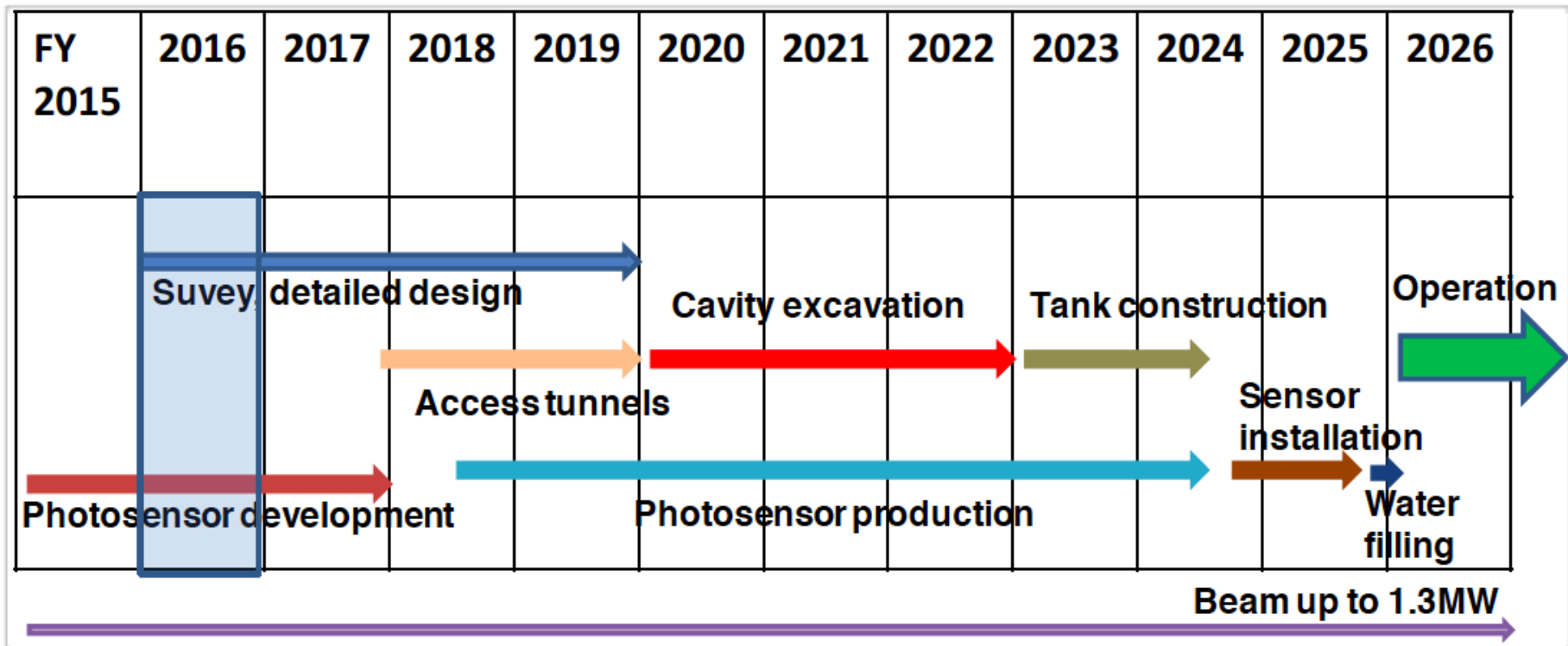
1st T2HKK Workshop @SNU



1st T2HKK Workshop Drinks

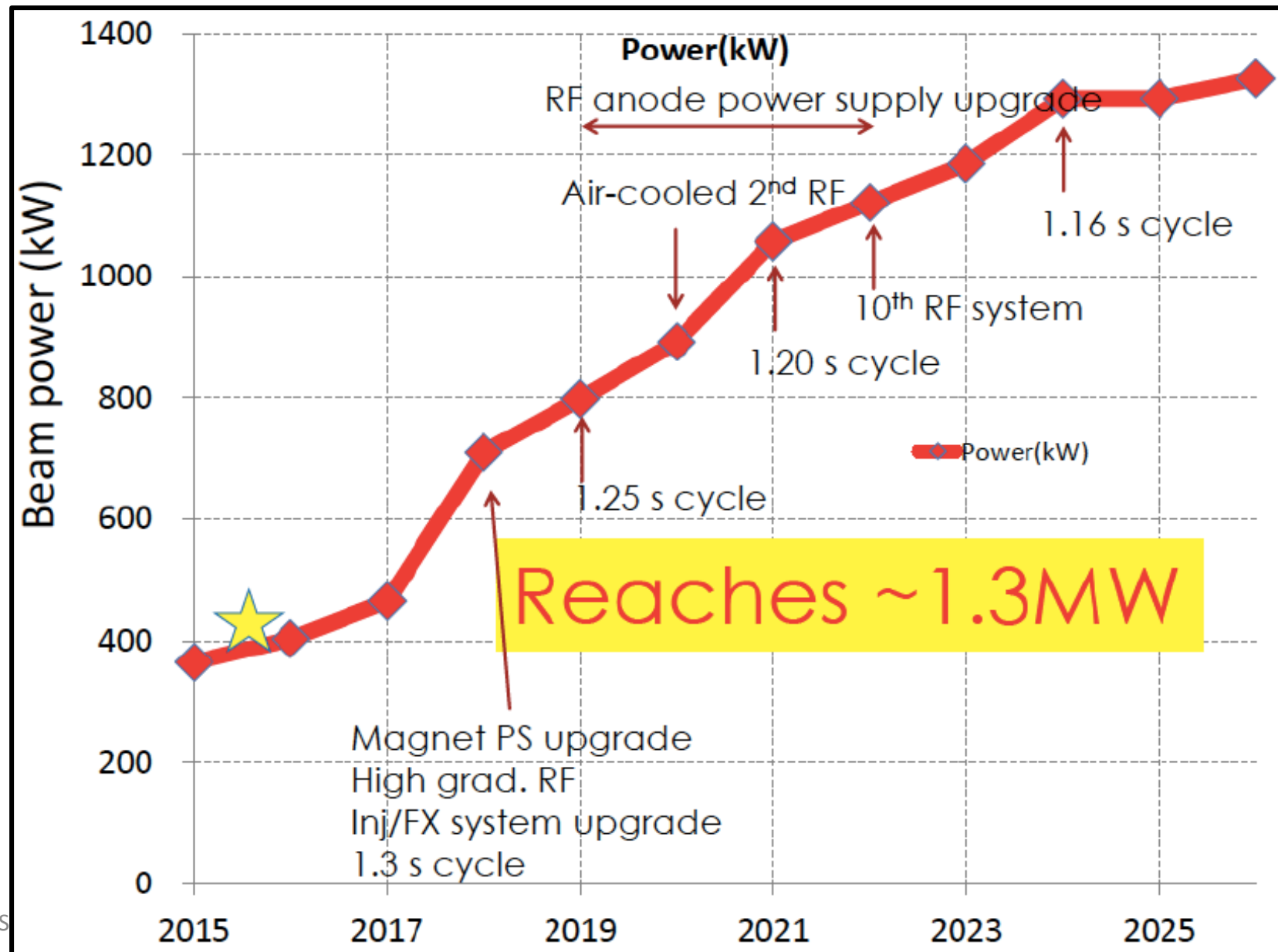


Hyper-K Construction Timeline



- Assuming funding from 2018
- The 1st detector construction in 2018~2025
 - Cavern excavation: ~5 years
 - Tank (liner, photosensors) construction: ~3 years
 - Water filling: 0.5 years

J-PARC Beam Power



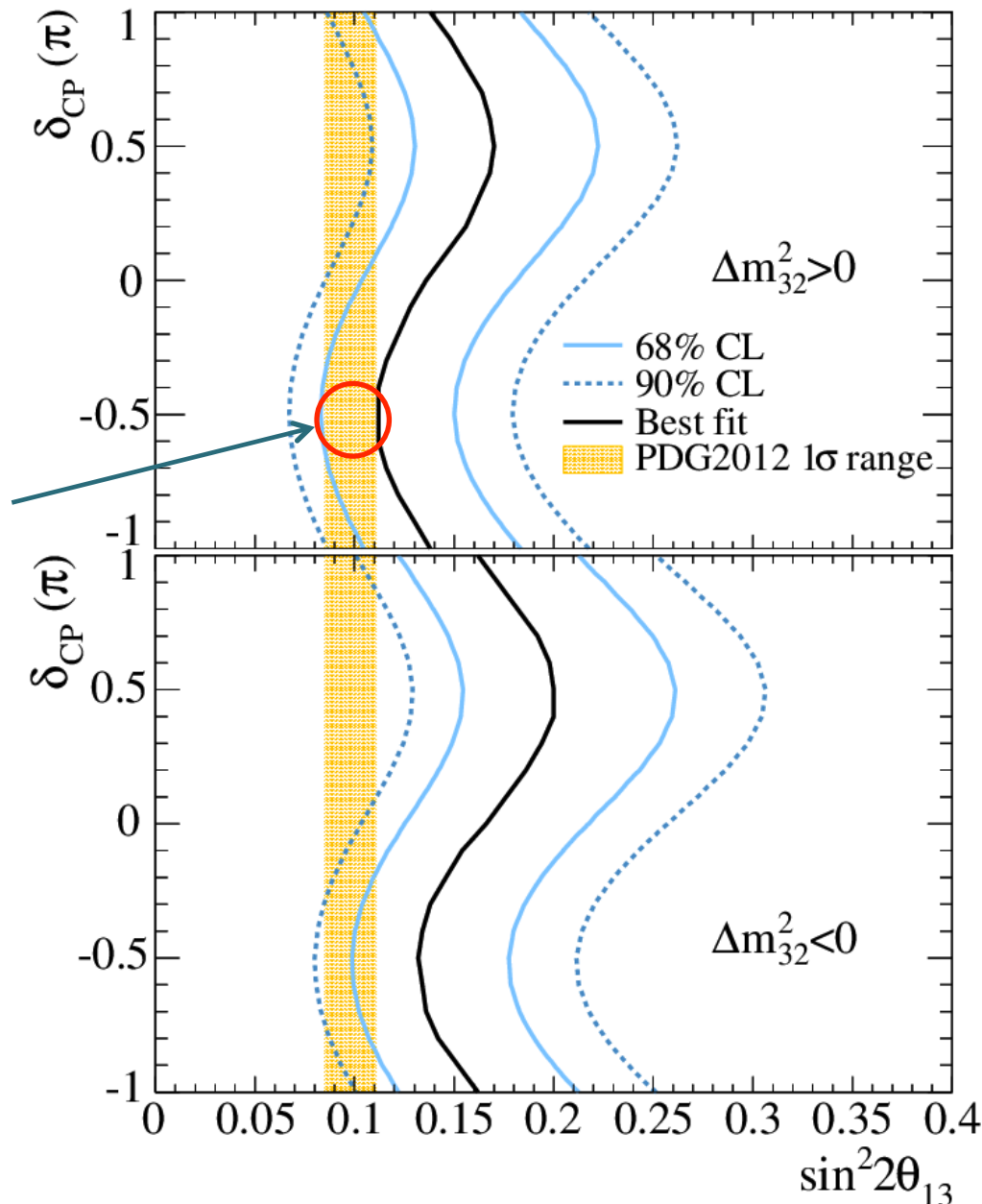
Summary

- ✓ The last and smallest neutrino mixing angle, θ_{13} , is discovered by Daya Bay and RENO in 2012.
→ open up window for CP phase & ν mass ordering exp.
- ✓ Hyper-K is a **multi-purpose** detector from particle physics to neutrino astronomy. It can take data for ~ 30 years.
- ✓ T2HKK is a better configuration than 2 detectors in Japan.
- ✓ Neutrino beams from Japan is coming to Korea at this moment. → It's better to build it in Korea ASAP.
- ✓ **World class discoveries are expected.**
- ✓ **We need you to work on T2HKK !!**

Thank you very much for your attention !



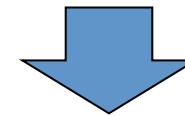
θ_{13} from Reactor and Accelerator Experiments



First hint of δ_{CP} combining
Reactor and Accelerator data

Best overlap is for
Normal hierarchy & $\delta_{CP} = -\pi/2$

Is Nature very kind to us?
Are we very lucky?
Is CP violated maximally?



Strong motivation for
anti-neutrino run and precise
measurement of θ_{13}

T2HK (Japan) Physics Potentials

		HK (2TankHD w/ staging)
LBL (13.5MWyr)	δ precision	7° - 21°
	CPV coverage ($3/5\sigma$)	78%/62%
	$\sin^2\theta_{23}$ error (for 0.5)	± 0.017
ATM+LBL (10 years)	MH determination	$>5.3\sigma$
	Octant ($\sin^2\theta_{23}=0.45$)	5.8σ
Proton Decay (10 years)	$e^+\pi^0$ 90%CL	1.2×10^{35}
	νK 90%CL	2.8×10^{34}
Solar (10 years)	Day/Night (from 0/from KL)	$6\sigma/12\sigma$
	Upturn	4.9σ
Supernova	Burst (10kpc)	104k-158k
	Nearby	2-20 events
	Relic (10 yrs)	98evt/ 4.8σ

CP Violation

- Why our universe consists of almost matter ?
 - Where is anti-matter ?
 - Why not matter & anti-matter annihilated completely ?

A possible explanation:

- At big bang, there were large amount of matter & anti-matter
 - most of them annihilated
 - but tiny excess of matter due to small asymmetry
 - Andrej Sacharow in 1967 listed conditions for such asymmetry and CP violation is one of them.

$$P(\nu_{\mu} \rightarrow \nu_e) \neq P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e) \text{ ?}$$