Neutrino Oscillation Parameters & Korean Efforts

*International workshop on **new physics** at the **low energy scales***
NEPLES-2019, KIAS, Sep. 23-27, 2019

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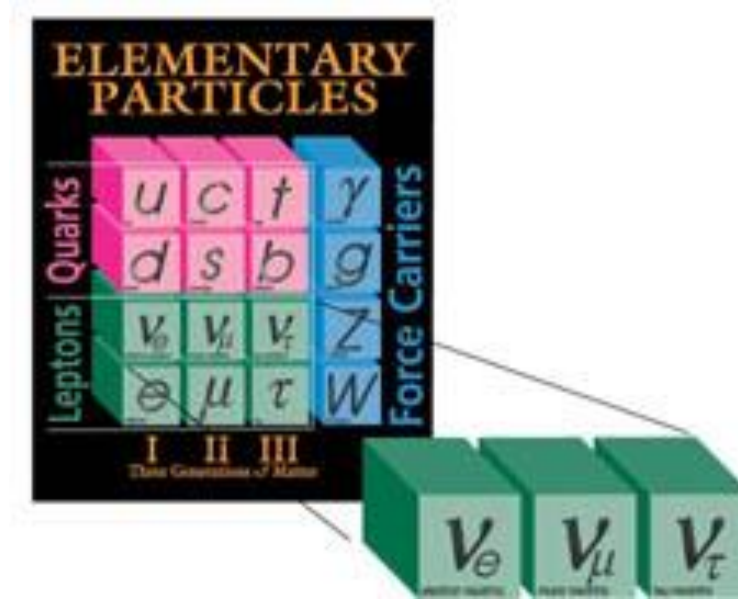
Neutrino Oscillation

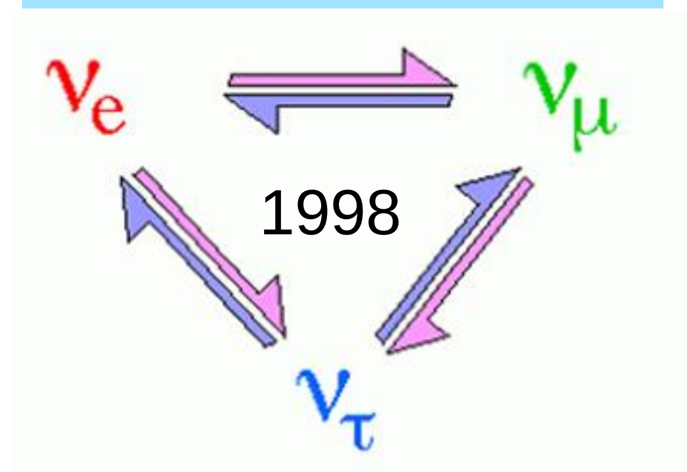
Wolfgang Pauli
(1900 - 1958)
Invention of neutrino

Frederick Reines
(1918 - 1998)
Detection of neutrino

Bruno Pontecorvo
(1913 - 1993)
Invention of neutrino oscillation



Neutrino oscillation



Neutrino Mixing Angles

Atmospheric Neutrino Oscillation — θ_{23}

~45° (1998)
Super-K; K2K

↓

Solar Neutrino Oscillation — θ_{12}

34° (2001)
SNO, Super-K;
KamLAND

2015 Nobel Prize

↓

Reactor Neutrino Oscillation — θ_{13}

9° (2012)
Daya Bay, RENO
Double Chooz

"Neutrino has mass"
"Established three-flavor mixing framework"

Neutrino Oscillation Parameters

In vacuum, $\nu_\alpha \rightarrow \nu_\beta$ transition probability :

$$P\left(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta\right) = \delta_{\alpha\beta} - 4\sum_{i<j} \mathrm{Re}(U_{\beta i}U^*_{\beta j}U_{\alpha i}U^*_{\alpha j}) \sin^2\left(\Delta m^2_{ji}\frac{L}{4E_\nu}\right)$$

$$\overset{(-)}{+} 2\sum_{i<j} \mathrm{Im}(U_{\beta i}U^*_{\beta j}U_{\alpha i}U^*_{\alpha j}) \sin\left(\Delta m^2_{ji}\frac{L}{2E_\nu}\right)$$

=0 if δ =0 in U, $\alpha = \beta$

- Neutrino oscillation experiments can determine
  - θ_{12} , θ_{23} , θ_{13} , Δm^2_{21} , Δm^2_{31} , δ

In matter:

mass ordering
CP violation
matter

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) &= 4c^2_{13}s^2_{13}s^2_{23}\sin^2\Delta_{31} \\ &+ 8c^2_{13}s_{13}s_{23}c_{23}s_{12}c_{12}\sin\Delta_{31}\left[\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta\right]\sin\Delta_{21} \\ &- 8c^2_{13}s^2_{13}s^2_{23}s^2_{12}\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\ &+ 4c^2_{13}s^2_{12}\left[c^2_{12}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\right]\sin^2\Delta_{21} \\ &- 8c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})\frac{aL}{4E_\nu}\sin\Delta_{31}\left[\cos\Delta_{32} - \frac{\sin\Delta_{31}}{\Delta_{31}}\right]. \end{aligned}$$

Measured Oscillation Parameters

(1) Well determined parameters (PDG 2019):

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$ [4.2%]

$\sin^2(\theta_{13}) = (2.18 \pm 0.07)\mathrm{x}10^{-2}$ [3.2%]

$\Delta m_{21}{}^2 = (7.53 \pm 0.18)\mathrm{x}10^{-5}\ \mathrm{eV}^2$ [2.4%]

$\Delta m_{32}{}^2 = (2.444 \pm 0.034)\mathrm{x}10^{-3}\ \mathrm{eV}^2$ [1.4%] (normal)

$= (-2.55 \pm 0.04)\mathrm{x}10^{-3}\ \mathrm{eV}^2$ [1.6%] (inverted)

(2) Not-so-well determined parameters (PDG 2019):

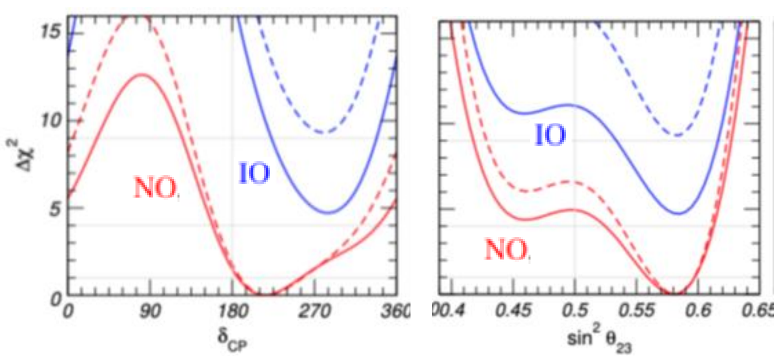
δ/π, CP violating phase = $1.37^{+0.18}_{-0.16}$ [13.1%]

$\sin^2(\theta_{23}) = 0.512^{+0.019}_{-0.022}$ [3.9%] (normal, octant I)

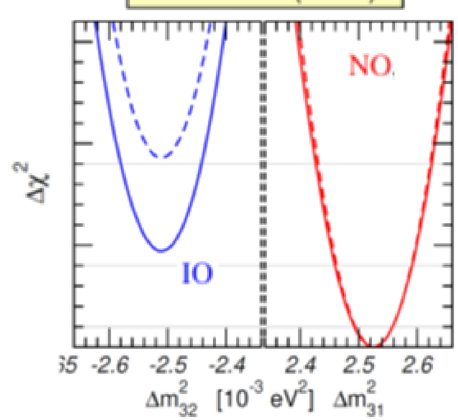
$= 0.542^{+0.019}_{-0.022}$ [3.9%] (normal, octant II) preferred

$= 0.536^{+0.023}_{-0.028}$ [4.7%] (inverted)

mass ordering: NO is preferred over IO.



NuFIT 4.0 (2018)



Future Precision

Expected precision of neutrino oscillation parameters:

$\sin^2(\theta_{12})$ 4.2% → 0.54% (JUNO)
$\sin^2(\theta_{13})$ 4.2% → ?? (RENO-II, ….)
Δm_{21}^2 2.4% → 0.24% (JUNO)
Δm_{32}^2 1.5% → 0.27% (JUNO), 0.5% (HK/KNO, DUNE)

$\sin^2(\theta_{23})$ ~4% → 1.8% (HK/KNO), 1% (DUNE)
θ_{23} octant determination (3σ) ?? → 2.3° (HK/KNO), 3° (DUNE)
δ/π, CP phase 13% or 32.4° → 9.3% or 23° (HK),
5.3% or 13° (HK/KNO)
4.1% or 10° (DUNE)
MO determination <~3σ → ~3σ (JUNO), 3.8σ (HK),
6~7σ (HK/KNO), ~7σ (DUNE)

Reactor Neutrino Oscillation

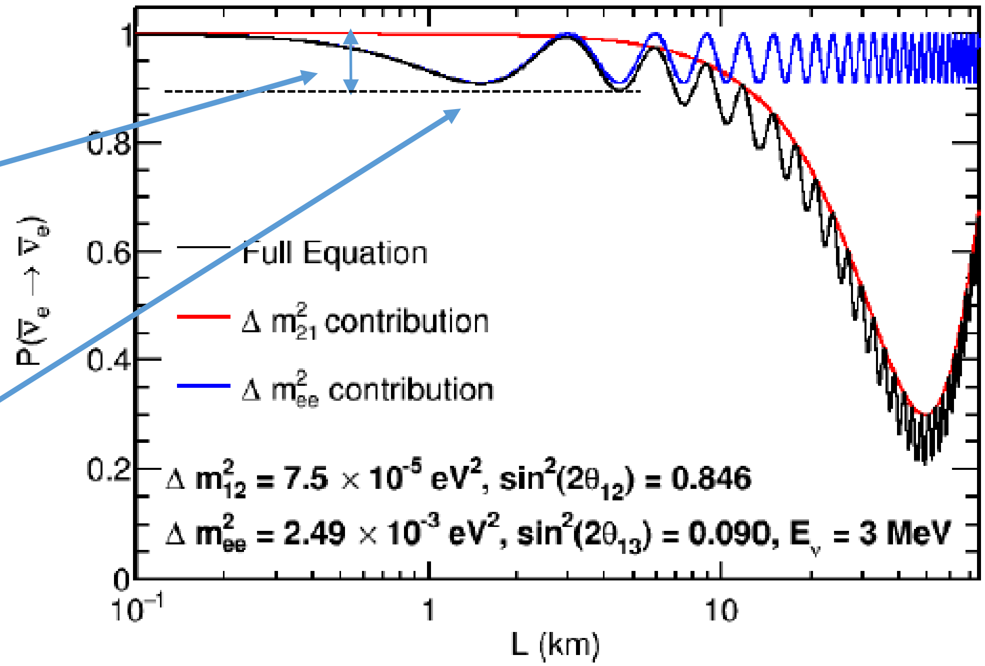
$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E}\right)$$

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

$\Delta m_{21}{}^2$ term is negligible compared to $\Delta m_{ee}{}^2$ term for ~1km baseline.
($\Delta m_{21}{}^2 \sim 7.5 \times 10^{-5} eV^2, \quad \Delta m_{ee}{}^2 \sim 2.5 \times 10^{-3} eV^2$)

$\sin^2(2\theta_{13})$ is determined by **oscillation amplitude.**

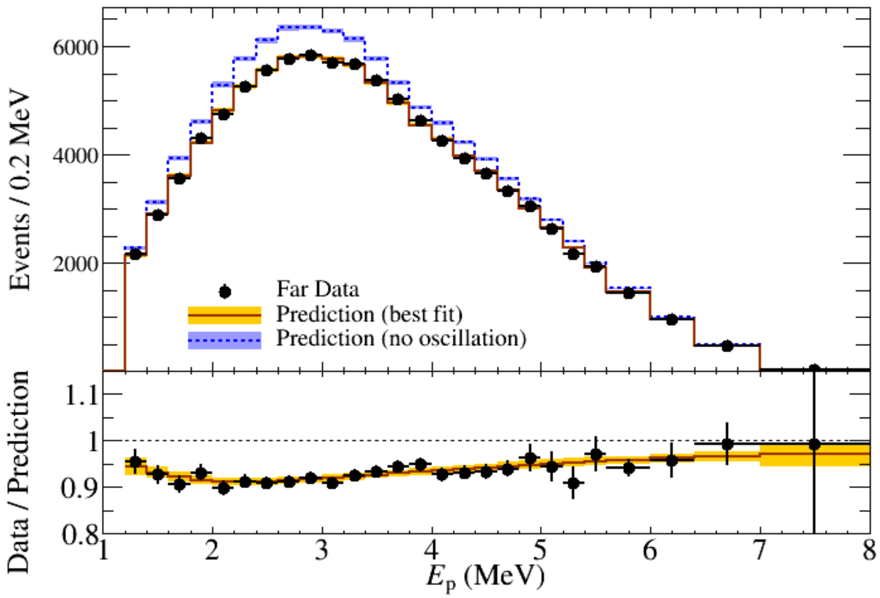
$\Delta m_{ee}{}^2$ is determined by **maximum oscillation energy (frequency).**

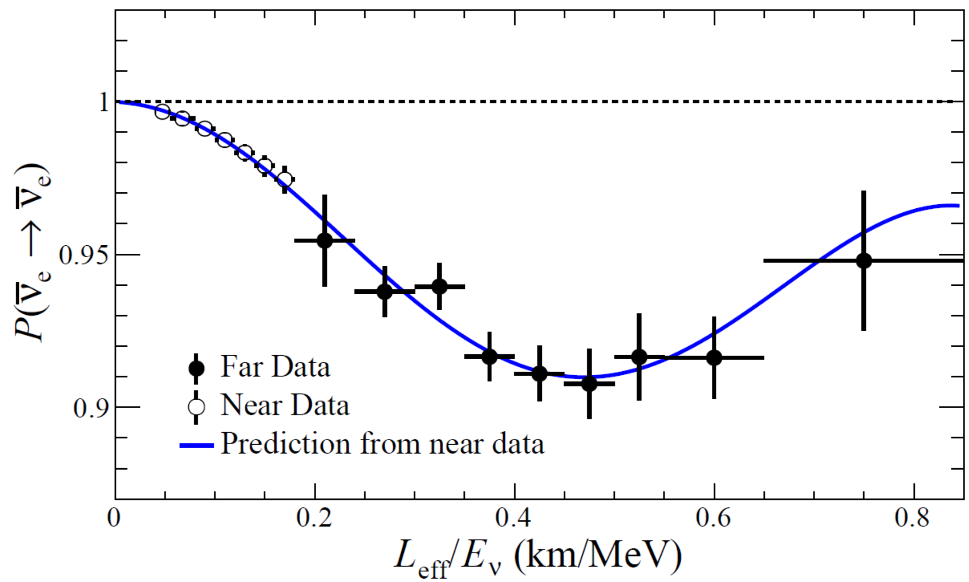


Measurement of θ_{13} and $|\Delta m_{ee}^2|$

Energy and baseline dependent disappearance of reactor antineutrinos

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m_{ee}^2 \frac{L}{4E_\nu}\right)$$



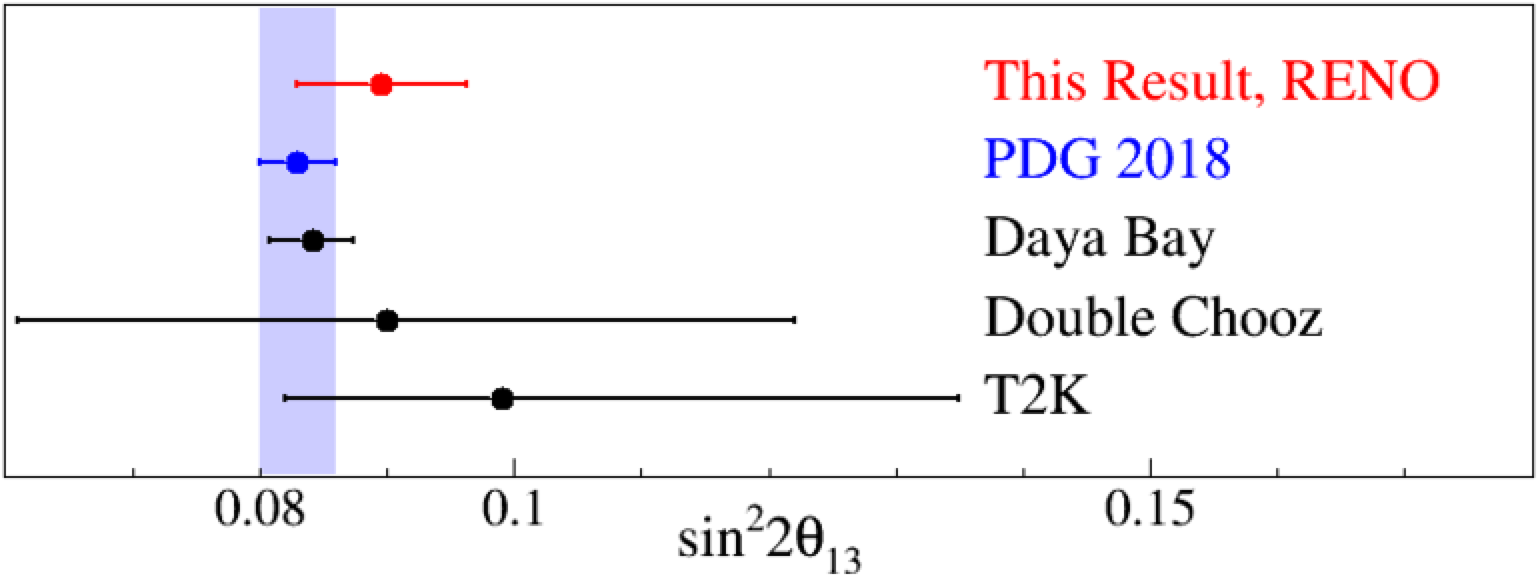


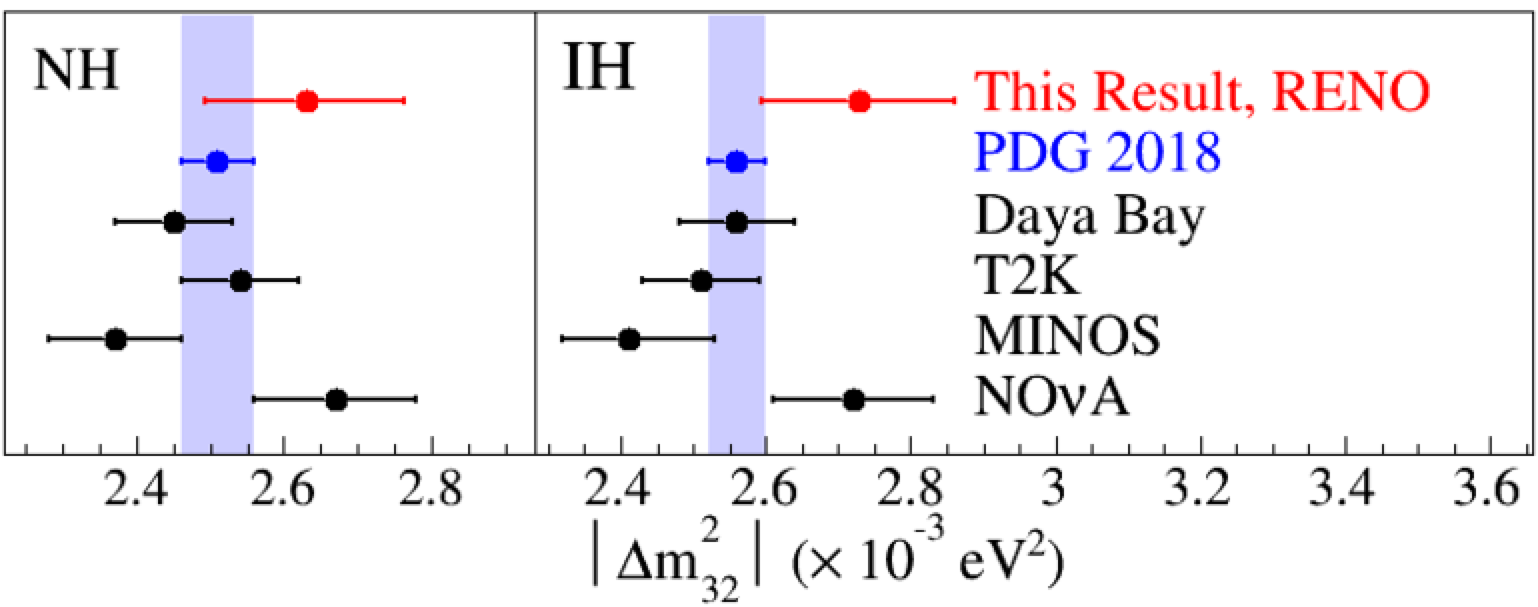
<2200 days>

$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\text{stat.}) \pm 0.0048(\text{syst.})$ (± 7.6 %)

$|\Delta m_{ee}^2| = 2.68 \pm 0.12(\text{stat.}) \pm 0.07(\text{syst.})(\times 10^{-3}\text{eV}^2)$ (± 5.2 %)

Comparison of θ_{13} and $|\Delta m_{ee}^2|$ Results





Impact and Significance of θ_{13} Measurement

- The measured non-zero value of θ_{13} rejects the Tri-bimaximal mixing hypothesis (Harrison, Perkins and Scott, 2002).

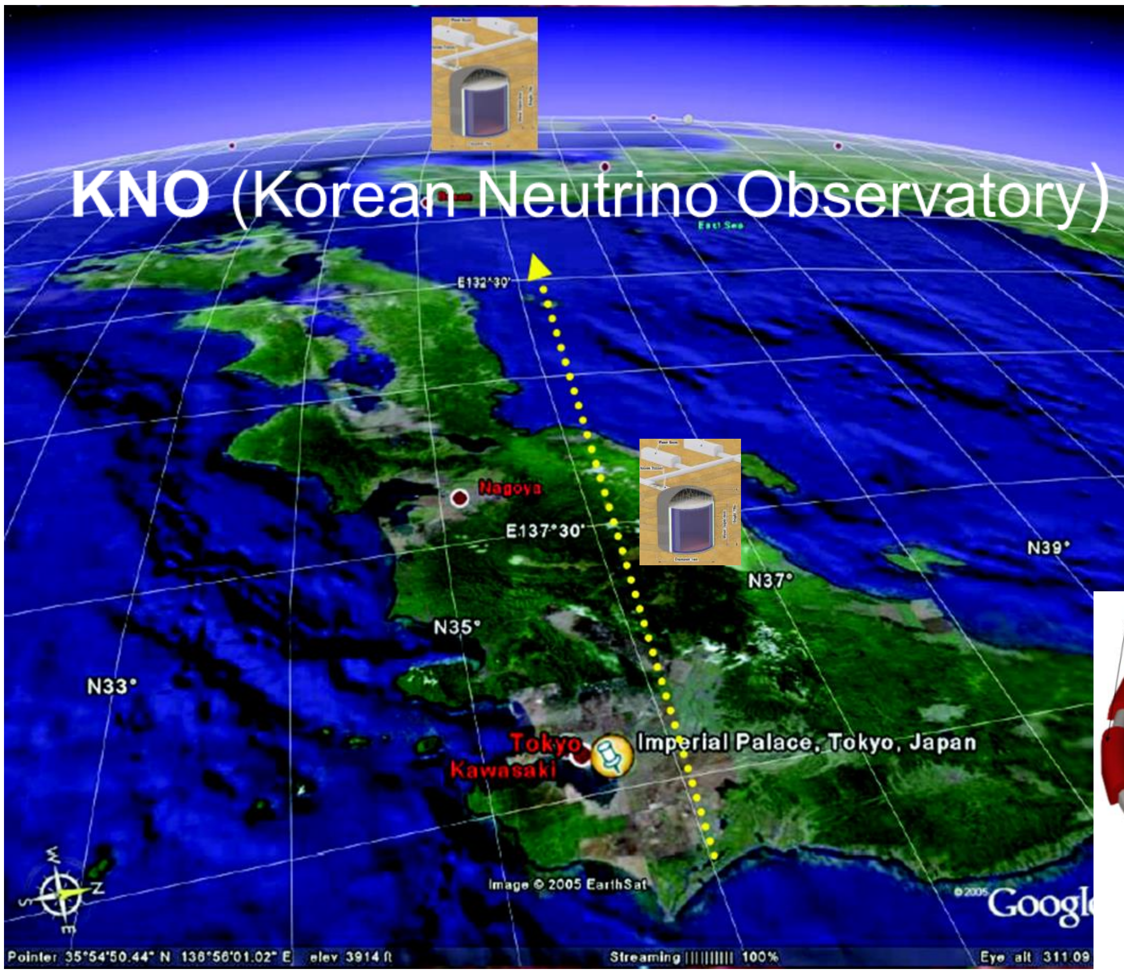
$$\theta_{13} \approx 0; \quad \theta_{23} \approx 45^0; \quad \theta_{12} = \sin^{-1}\left(\frac{1}{\sqrt{3}}\right) \approx 35.3^0$$

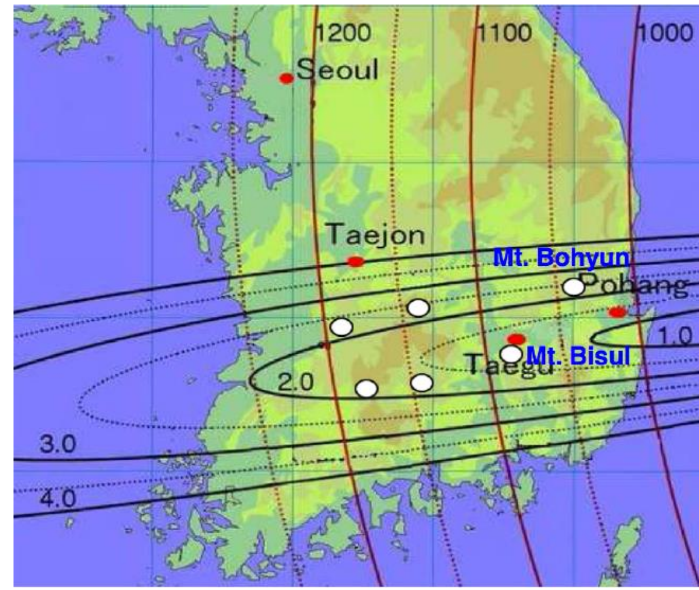
- Definitive measurement of the *smallest neutrino mixing angle* θ_{13}, *rather larger than thought*, based on the disappearance of reactor electron antineutrinos

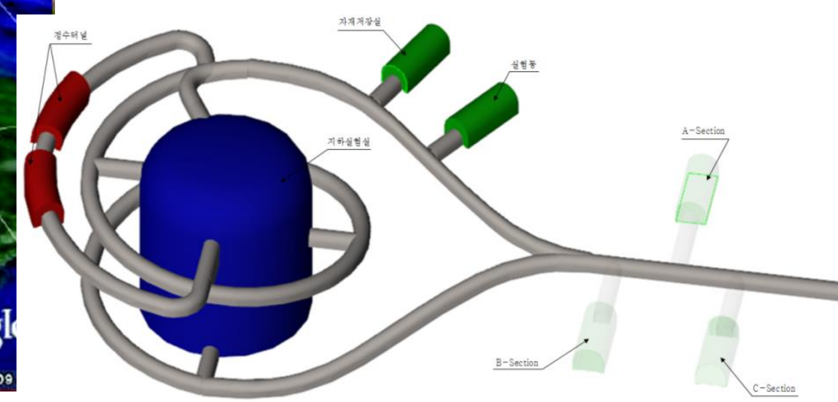
→ Open a new window for determining
(1) CP violating phase, and
(2) neutrino mass ordering without a neutrino factory

For example, Hyper-Kamiokande(+ KNO), DUNE, JUNO, PINGU, INO, …..

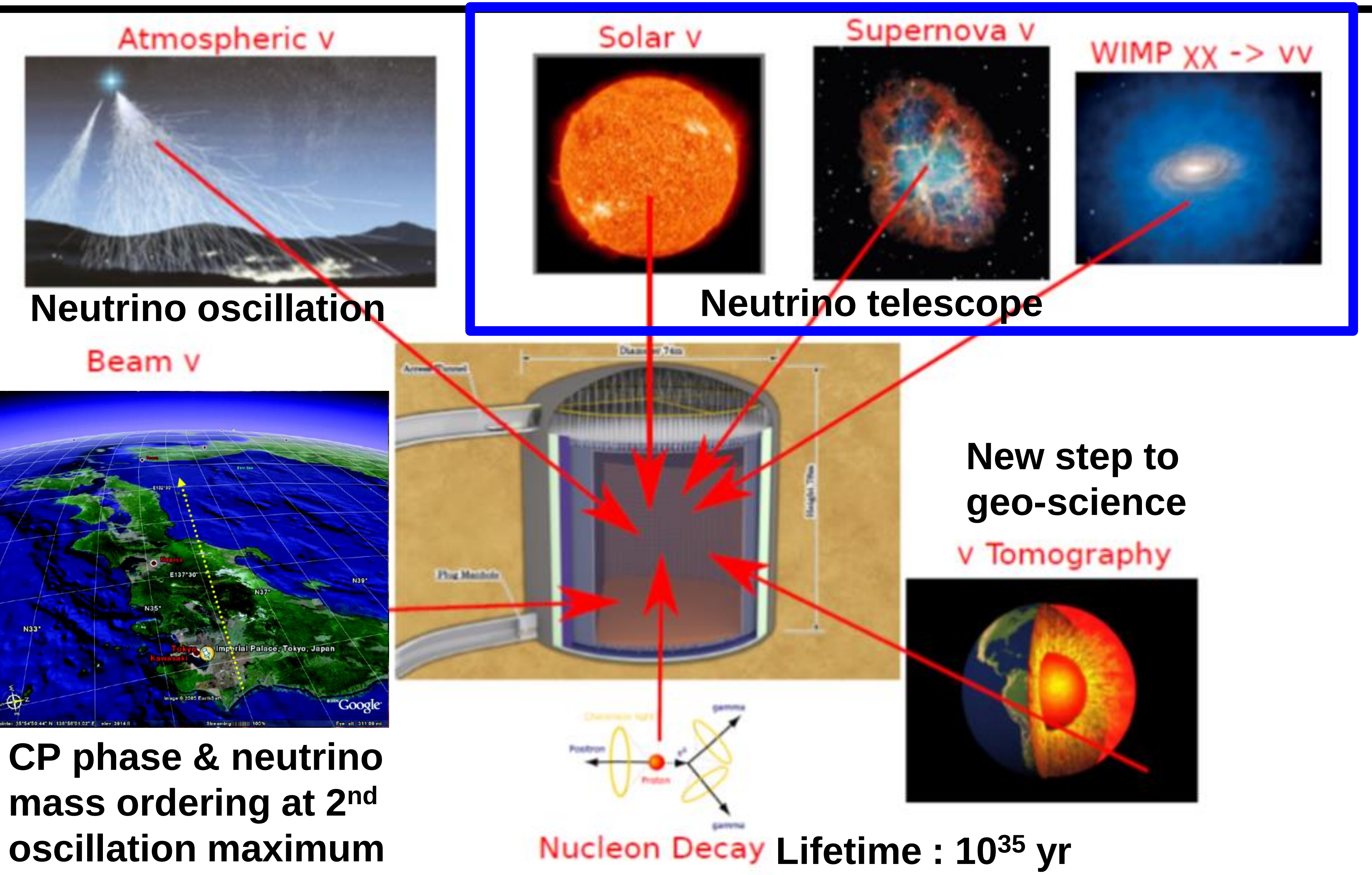
KNO (Korean Neutirno Observatory)



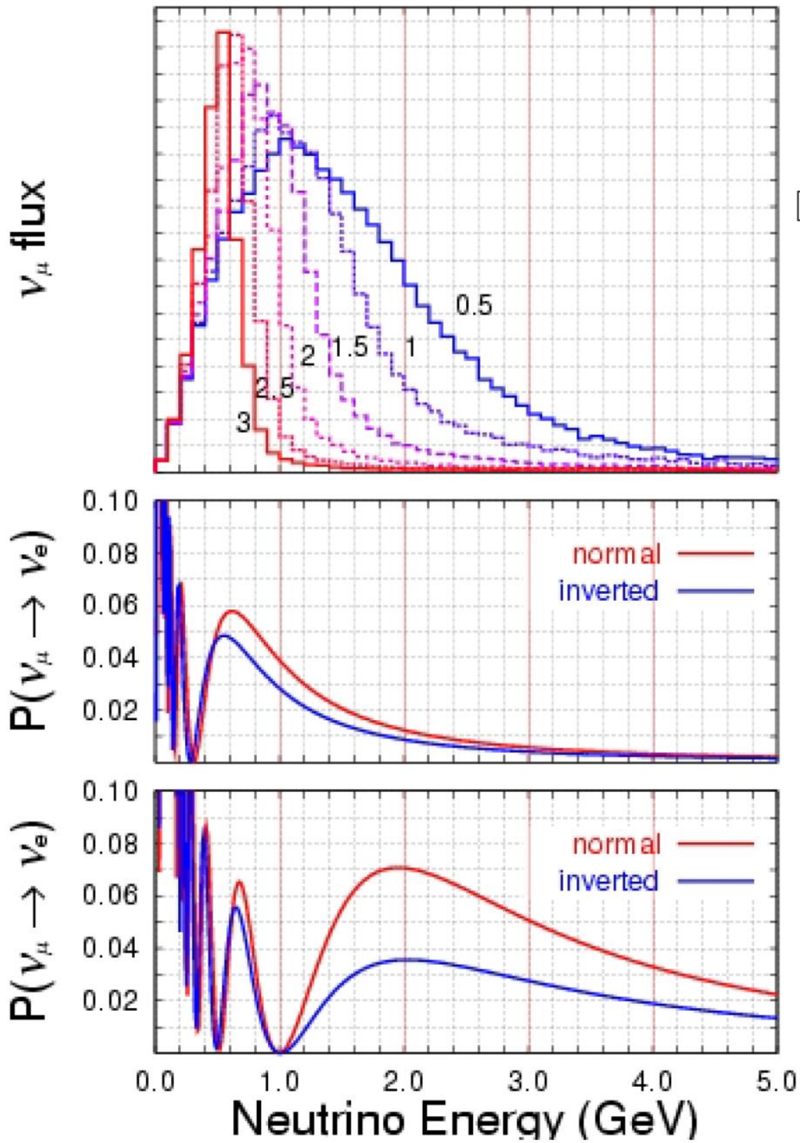


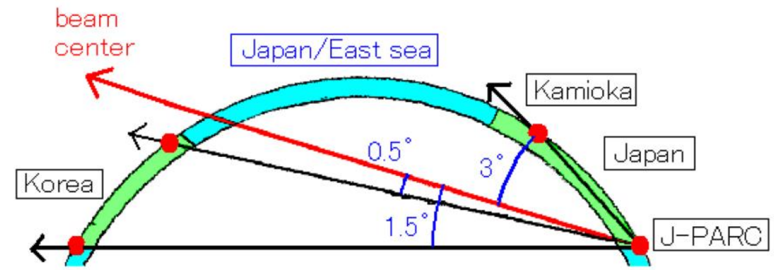


KNO Scientific Goals



Neutrino Oscillations in Kamioka & Korea



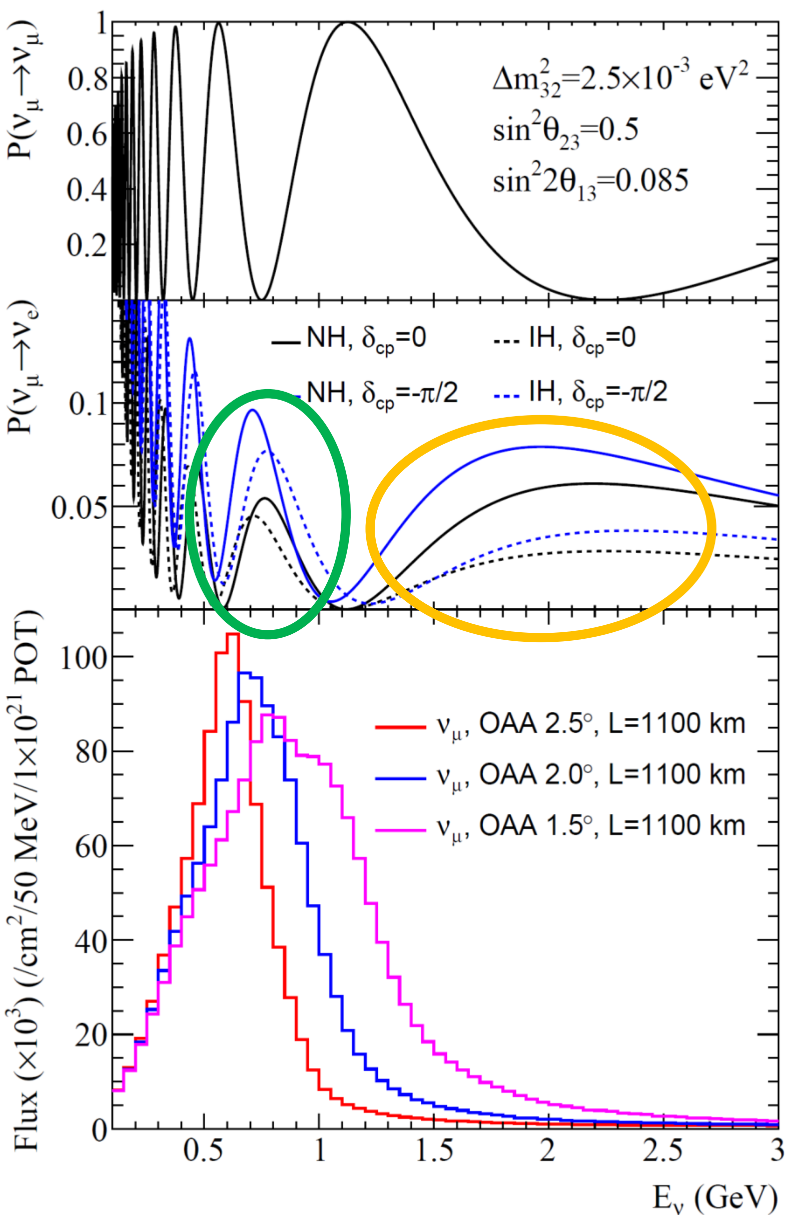


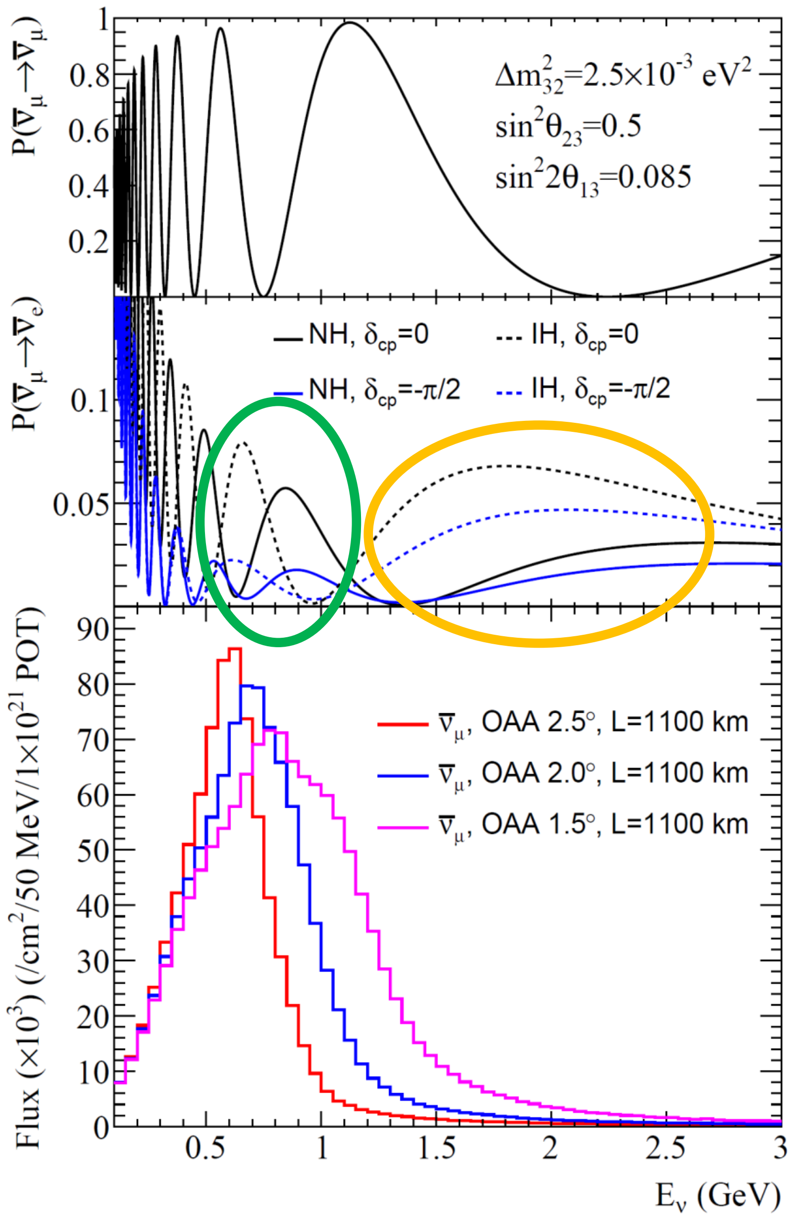
← Profile of off-axis beams

← $P(\nu_\mu \to \nu_e)$ at SK

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

1st and 2nd Oscillation Maxima in Korea





Why 2nd Detector in Korea?

▪ The same physics programs as the Hyper-Kamiokande with better sensitivities

(1) Longer baseline (~1100 km) neutrino beam for *T2HKK*
→ 2nd oscillation maxiumum

- Measurement of leptonic CP violating phase
- Determination of neutrino mass ordering
- Probe of non-standard neutrino interaction

(2) Larger overburden (~1000 m) for a *neutrino telescope*
→ smaller cosmogenic background

- Proton decay search
- Detection of supernova neutrinos
- Solar neutrino physics
- Earth tomography with atmospheric neutrinos
- Dark matter search

Brief History of KNO (a.k.a. T2HKK)

▪ Oct. 17, 2000: Another far detector using a JHF neutrino beam by S.B. Kim (KOSEF-JSPS Joint Seminar at KIAS)

▪ 2005/2006/2007: A large Cherenkov detector in Korea using a J-PARC neutrino beam (T2KK) by T. Kajita.
→ 3 joint workshops supported by KOSEF and JSPS

▪ 2011: Proposal of 0.5 Mton water Cherenkov Hyper-Kamiokande detector at Kamioka

▪ 2015: Staged construction of two HK detectors of each 0.25 Mton at Kamioka

▪ July 10, 2016: The first kick-off meeting in London
→ present a proposal to the HK collaboration
→ HK working group of T2HKK (convener: Seon-Hee)

Efforts on KNO

- Sep. 2, 2016: Workshop on KNO in Korea (SNU)

- Oct. 20, 2016: Pioneering Symposium at KPS (Gwangju)

- Nov. 2016: A white report on KNO is released and published in Prog. Theor. Exp. Phys. (2018)

- 2011: Proposal of 0.5 Mton water Cherenkov Hyper-Kamiokande detector at Kamioka

- Nov. 21-22, 2016: International workshop on KNO

- Nov. 2017/Nov. 2018: 1st and 2nd KNO workshops

- Aug. 25, 2019: KNO meeting at NuFact 2019

Status of KNO Realization

- Oct. 20, 2018: Kick-off meeting for KNO organization including particle physicists and astronomers

- Five working groups formed to have regular meetings.

- Detector R&D work in progress

- Funding discussion has begun with the Korean government.

- Several options for KNO detector under consideration

KNO Working Groups

- Funding Working Group
- Detector R&D Working Group
- Science Working Group (particle physics and astrophysics)
- Proposal Preparation Working Group
- International Relation Working Group

- Current participation: ~40 particle physicists and
  ~15 astronomers
- Expect expansion of the Korean participation

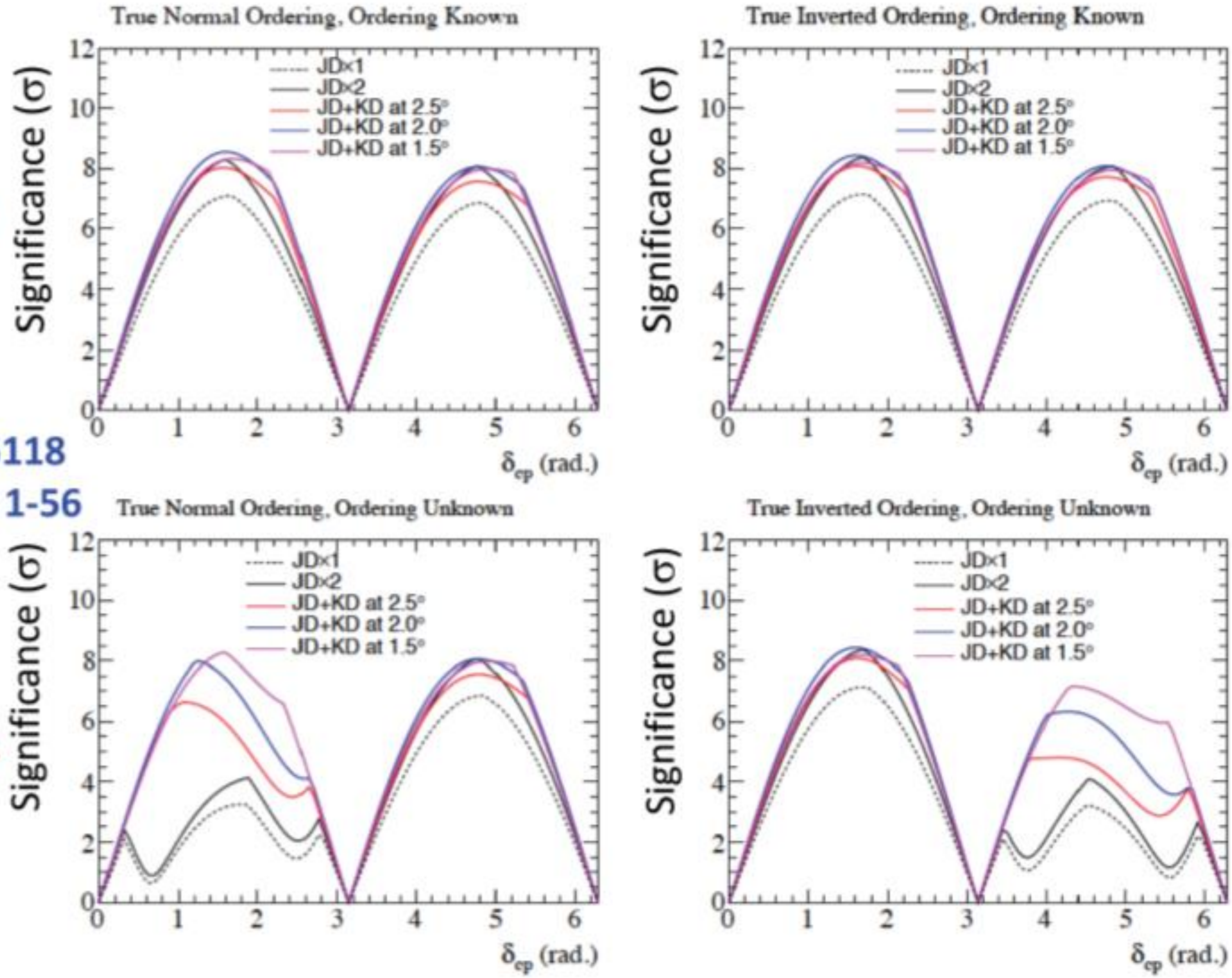
Physics Potential at KNO: δ_{CP}

Known MO

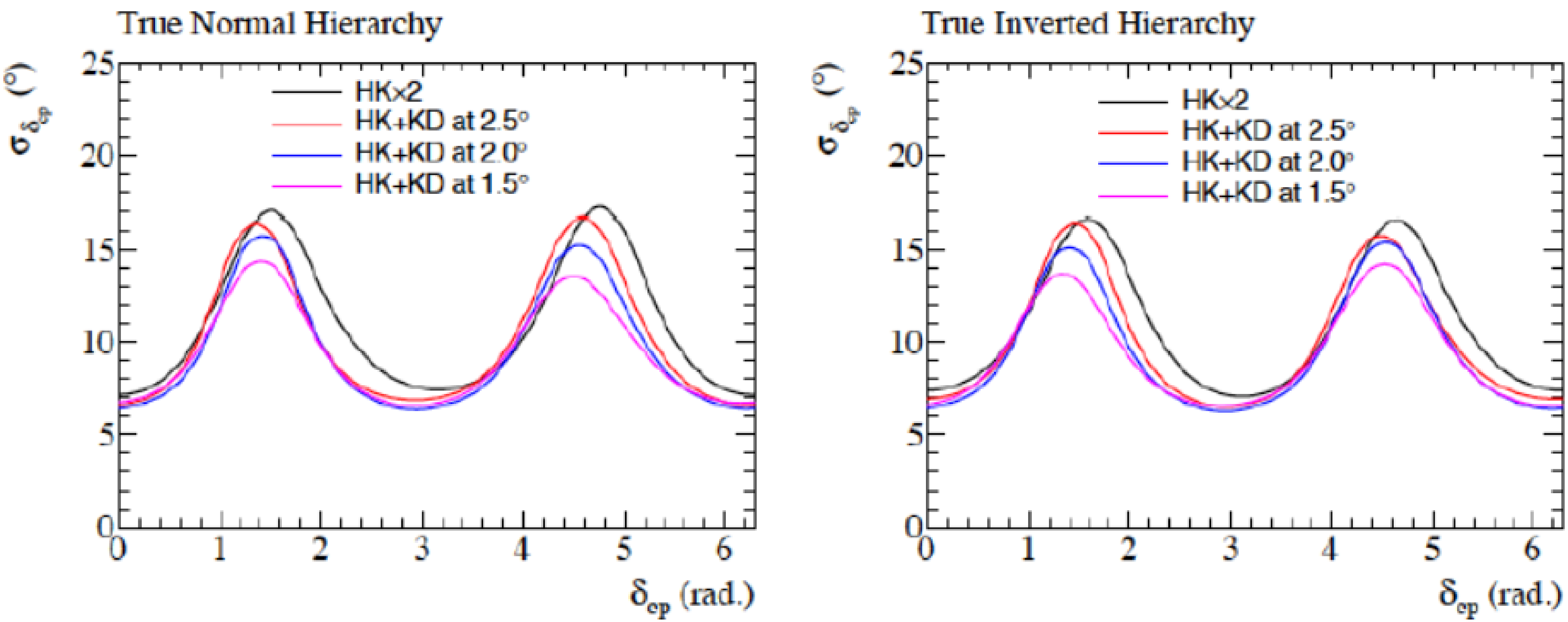
Unknown MO

arXiv:1611.06118

PTEP 2018, 6, 1-56



δ_{CP} Precision at KNO



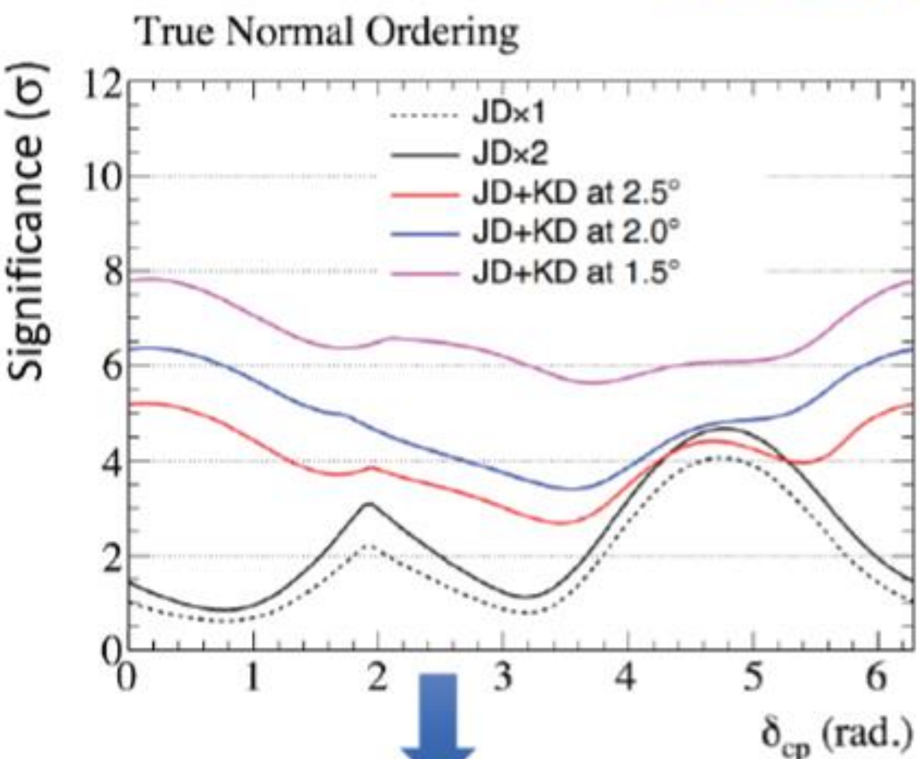
At maximum CP violation: HK+KD 1.5°: $\sigma(\delta_{CP})$ = 13~14 degree
HK x2 : $\sigma(\delta_{CP})$ ~ 17 degree

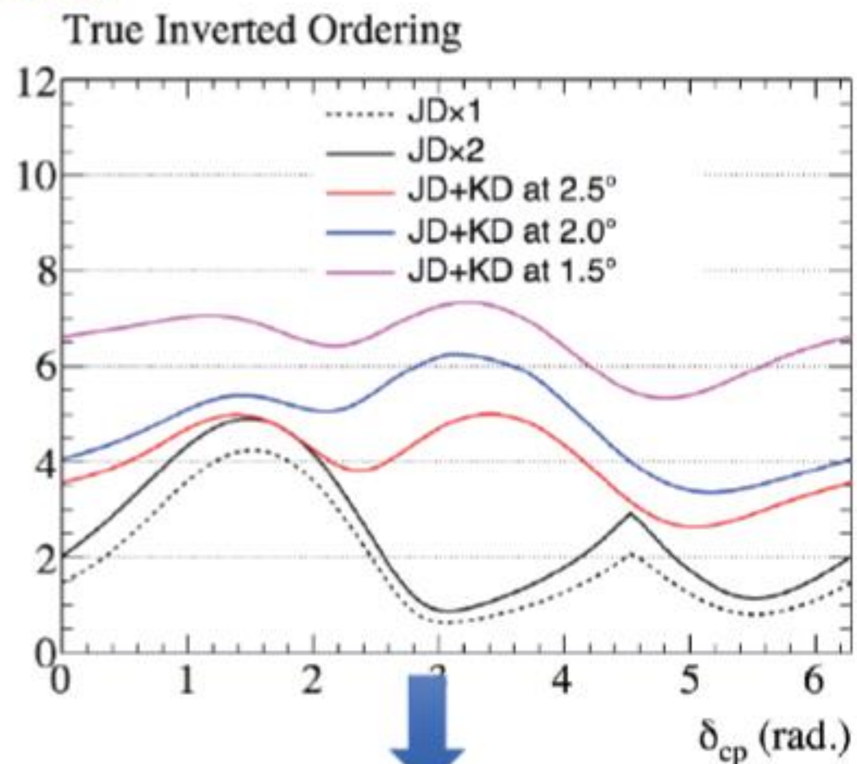
Physics Potential at KNO: Mass Ordering

Normal

arXiv:1611.06118
PTEP 2018, 6, 1-56

Inverted



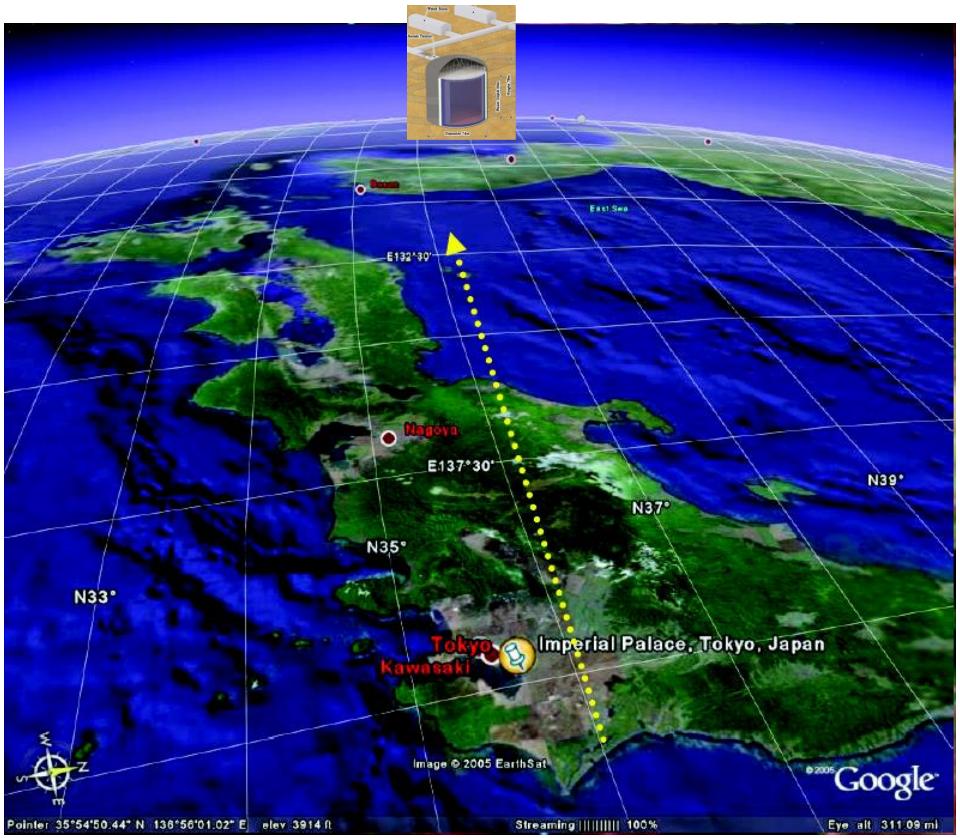


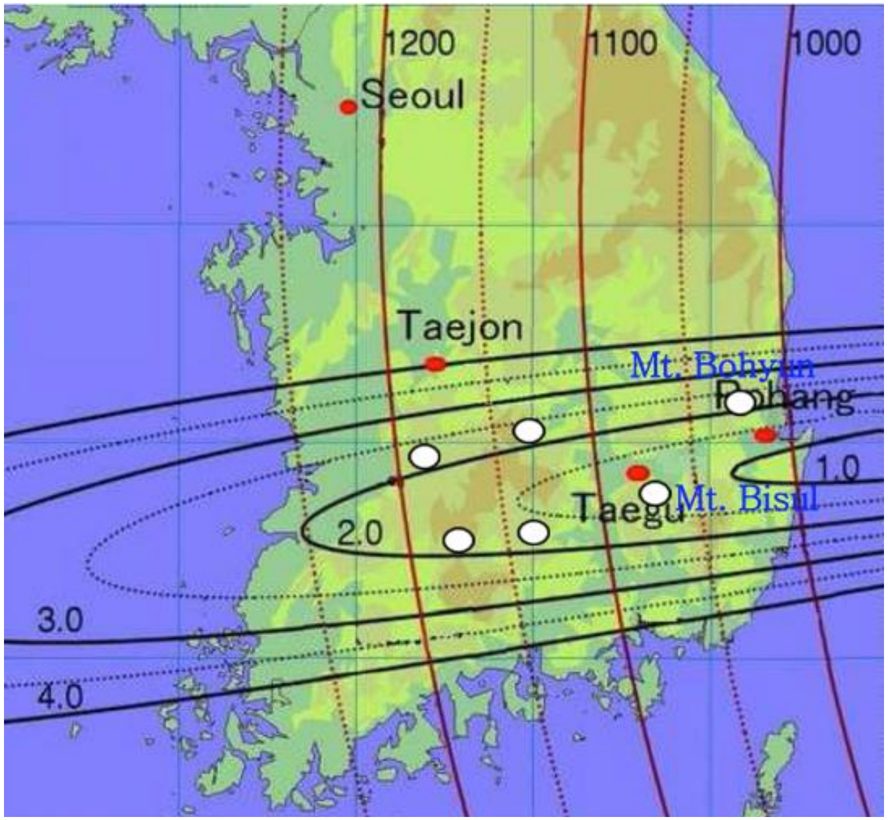
JD+KD 1.5°: 6 ~ 8 σ for all δ_{CP}
JD x2 : 1 ~ 4.5 σ for all δ_{CP}
(< 3 σ for most cases)

JD+KD 1.5°: 5.5 ~ 7 σ for all δ_{CP}
JD x2 : 1 ~ 5 σ for all δ_{CP}
(< 3 σ for most cases)

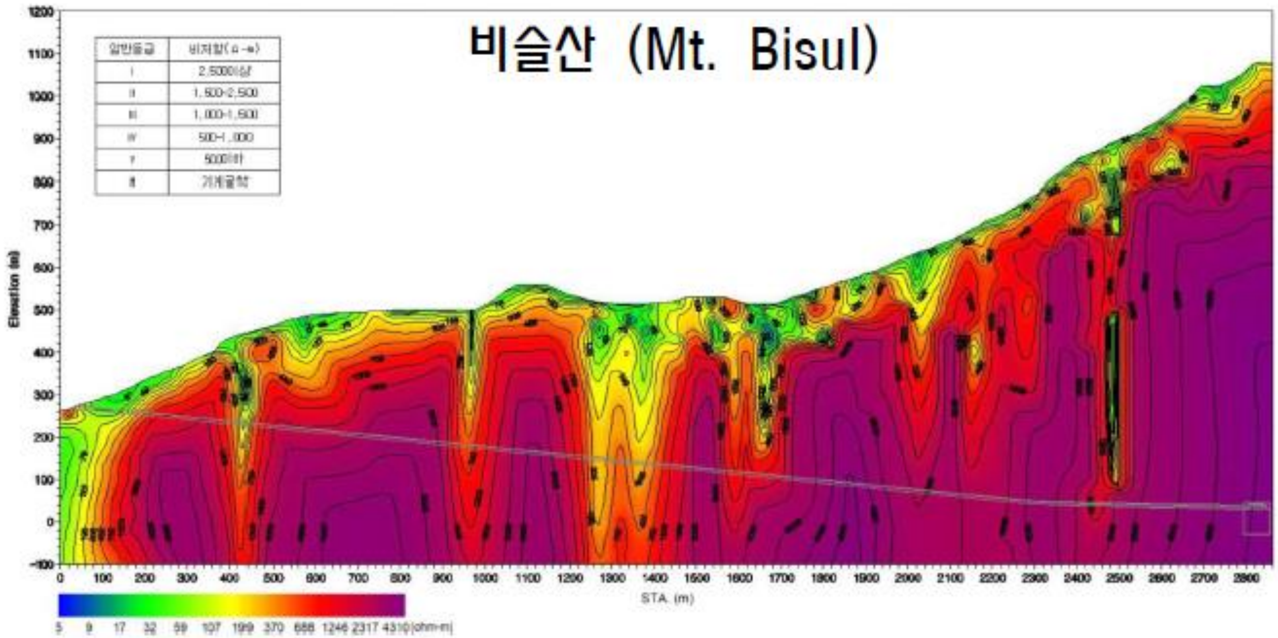
KNO Candidate Sites

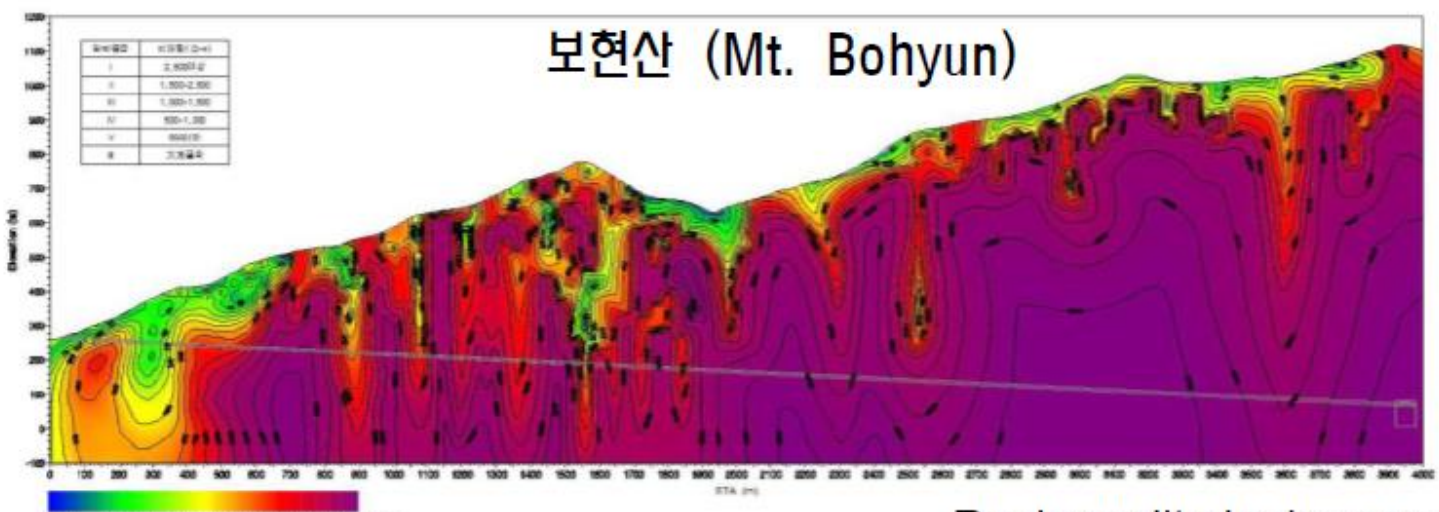
• Mt. Bisul at Daegu: 1,084 m high, L=1,088 km, 1.3° for OAB
Mt. Bohyun at Youngcheon: 1,126 m high, L=1,040 km, 2.2° for OAB





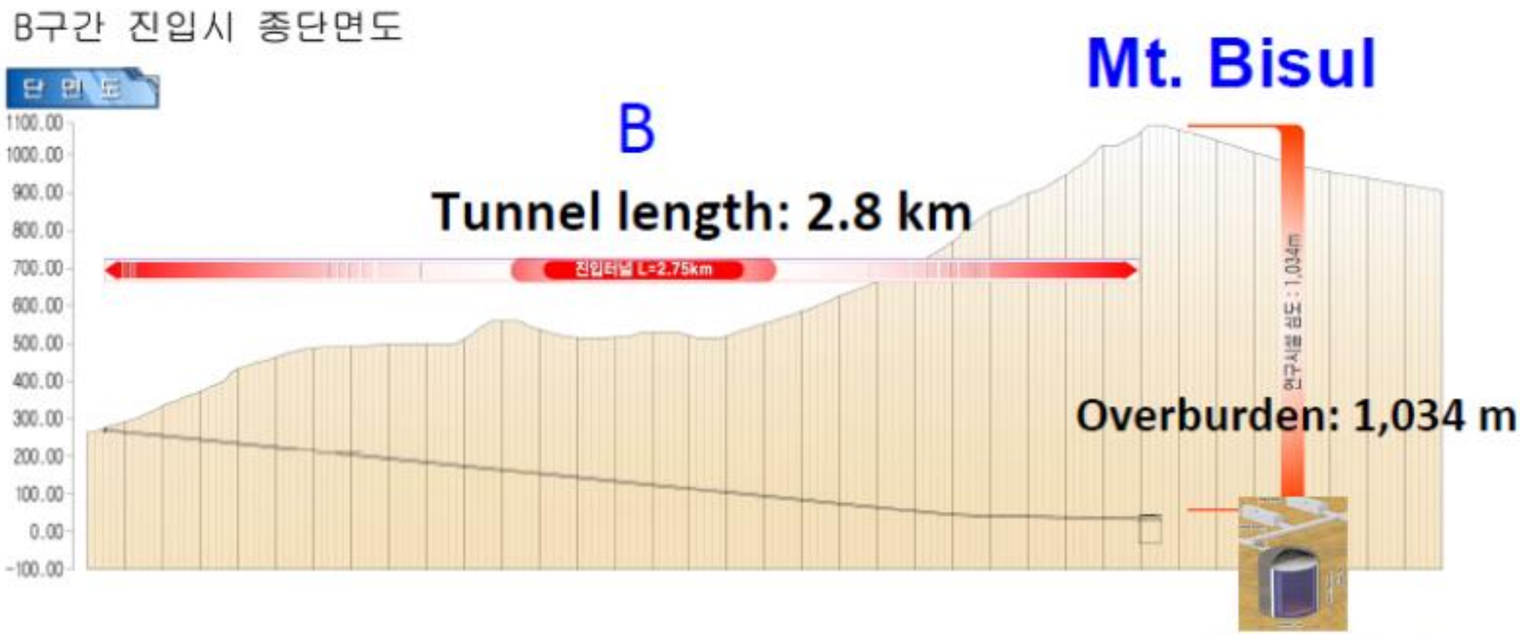
KNO Underground Rock Strength

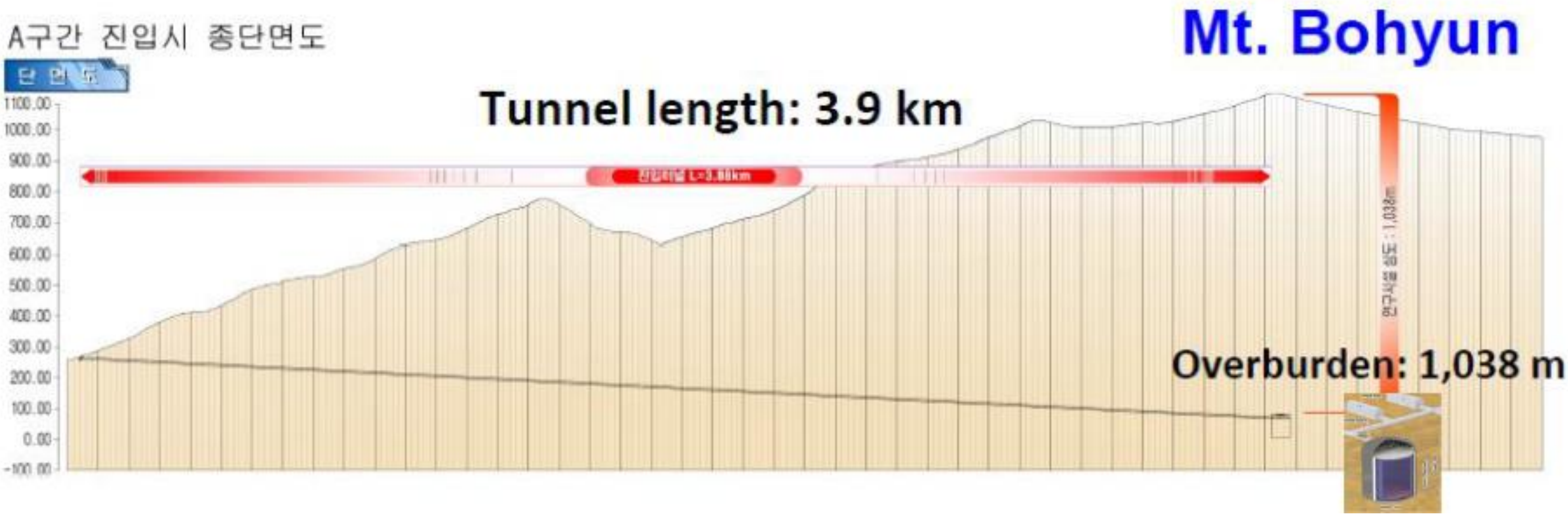




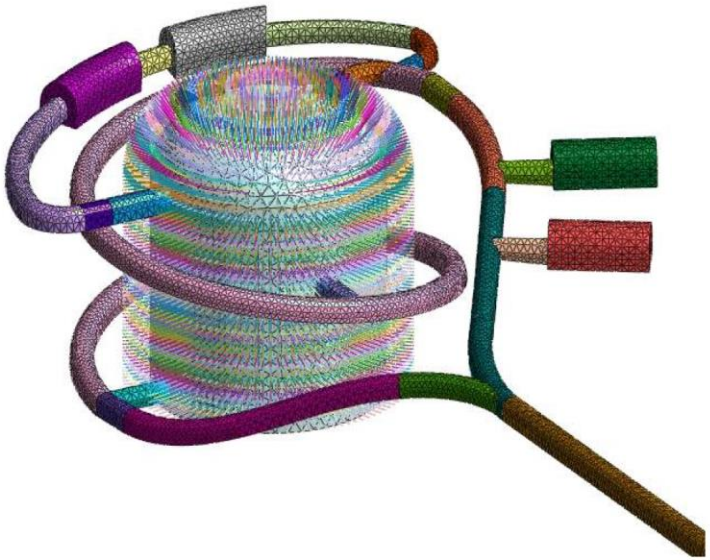
Rock quality looks good

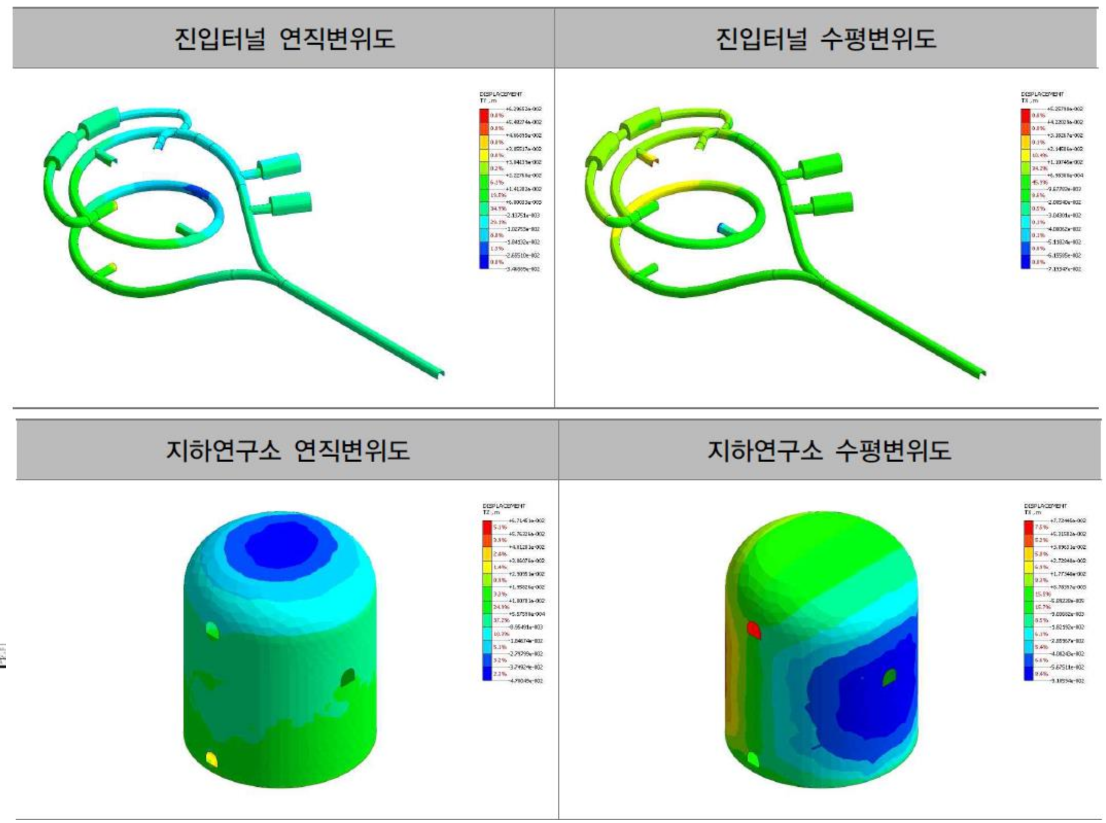
KNO Underground Access Tunnels

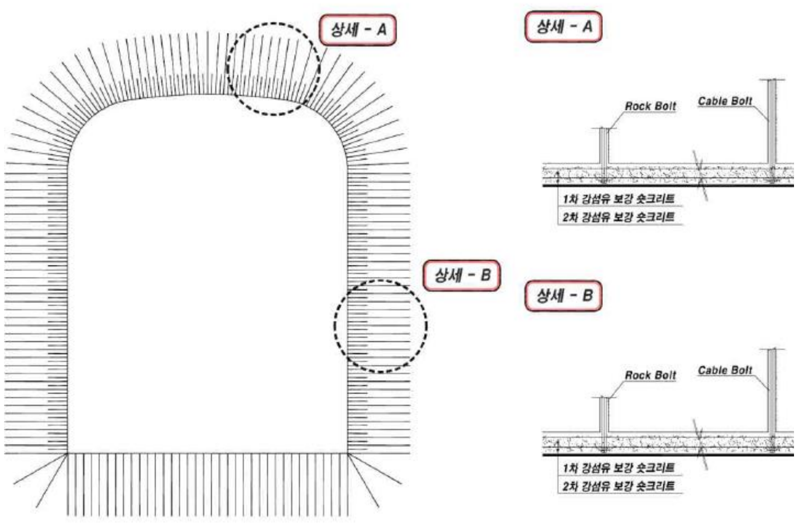




Stress Analysis and Reinforcement







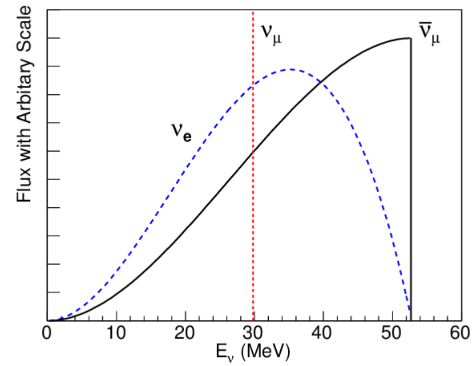
JSNS^2 Experiment

(*J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source*)


JSNS^2 Collaboration
JAEA
KEK
Kitasato
Kyoto
Osaka
Tohoku
Soongsil
Dongshin
GIST
Seoyeong
Chonnam
Seoul
Chonbuk
Kyungpook
Sungkyunkwan
Seoul Sci Tech
Alabama
BNL
Florida
Michigan
Sussex

LSND $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Signal

1998 at LANL ($\overline{\nu}_e$ appearance)



$$\pi^+(\text{stop}) \rightarrow \mu^+ + \nu_\mu$$ DAR

$$\hookrightarrow \mu^+(\text{stop}) \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

800MeV p

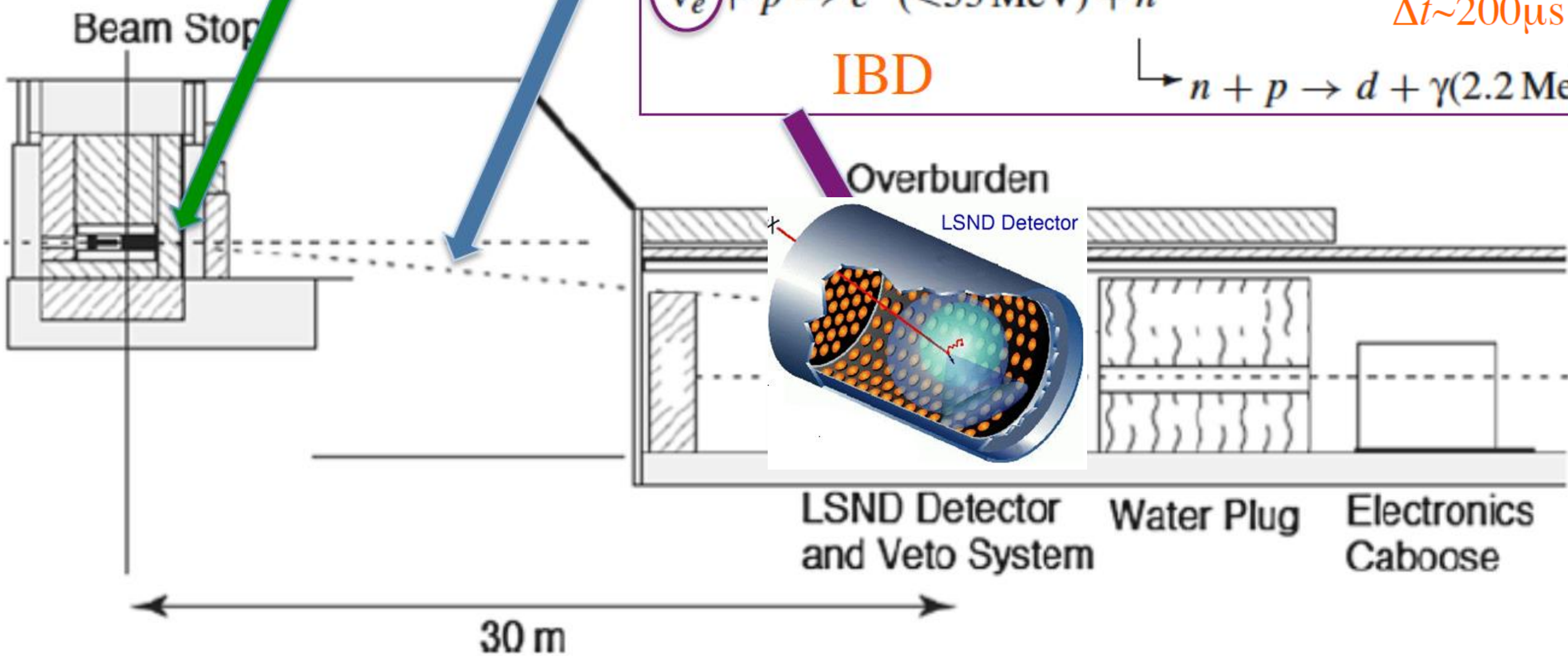
Liquid Scintillator

$$\overline{\nu}_e + p \rightarrow e^+(<53\,\text{MeV}) + n$$

IBD

$$\hookrightarrow n + p \rightarrow d + \gamma(2.2\,\text{MeV}).$$

Delayed Coincidence Δt~200μs

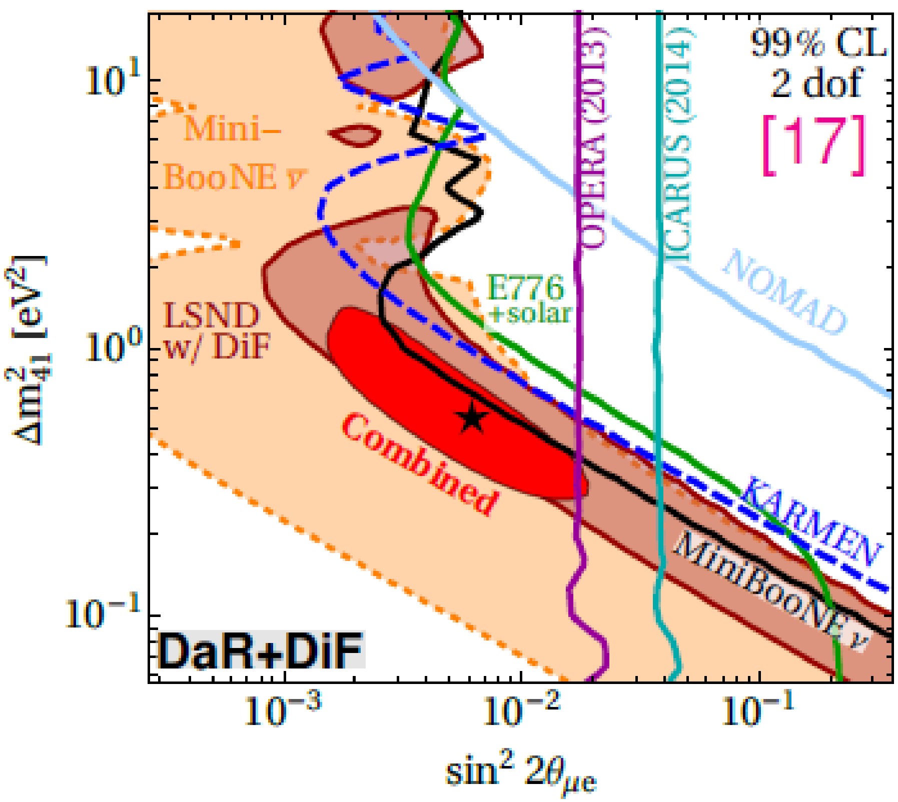


Sterile Neutrino Oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

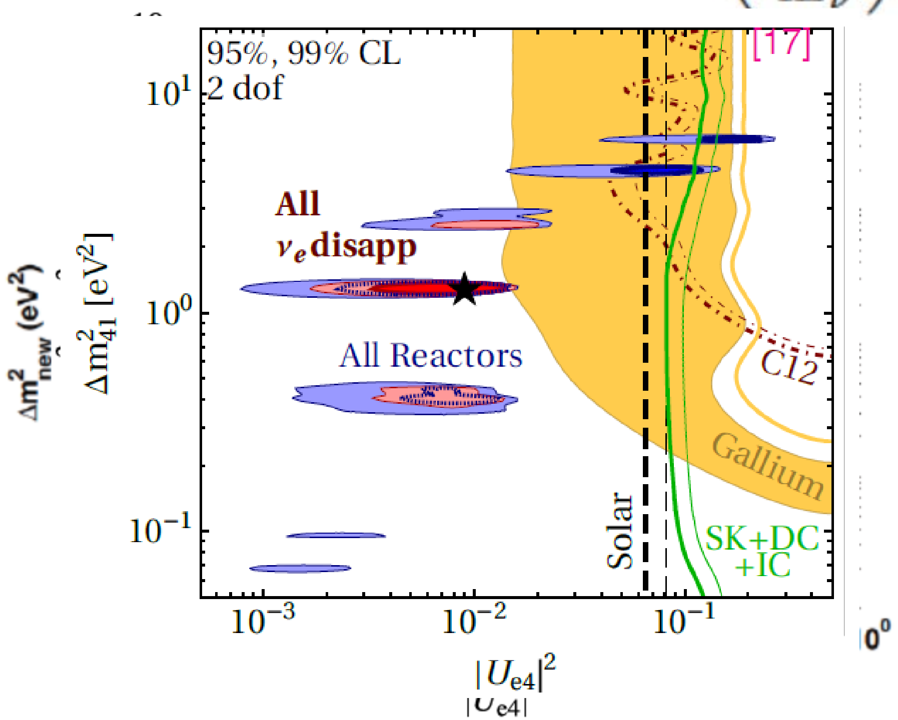
$$|U_{s4}|^2 \sim 0.9, \quad |U_{e4}|^2 \sim 0.1, \quad |U_{\mu 4}|^2 \sim 0.01$$
$$m_4 > 1eV$$

ν_e Appearance

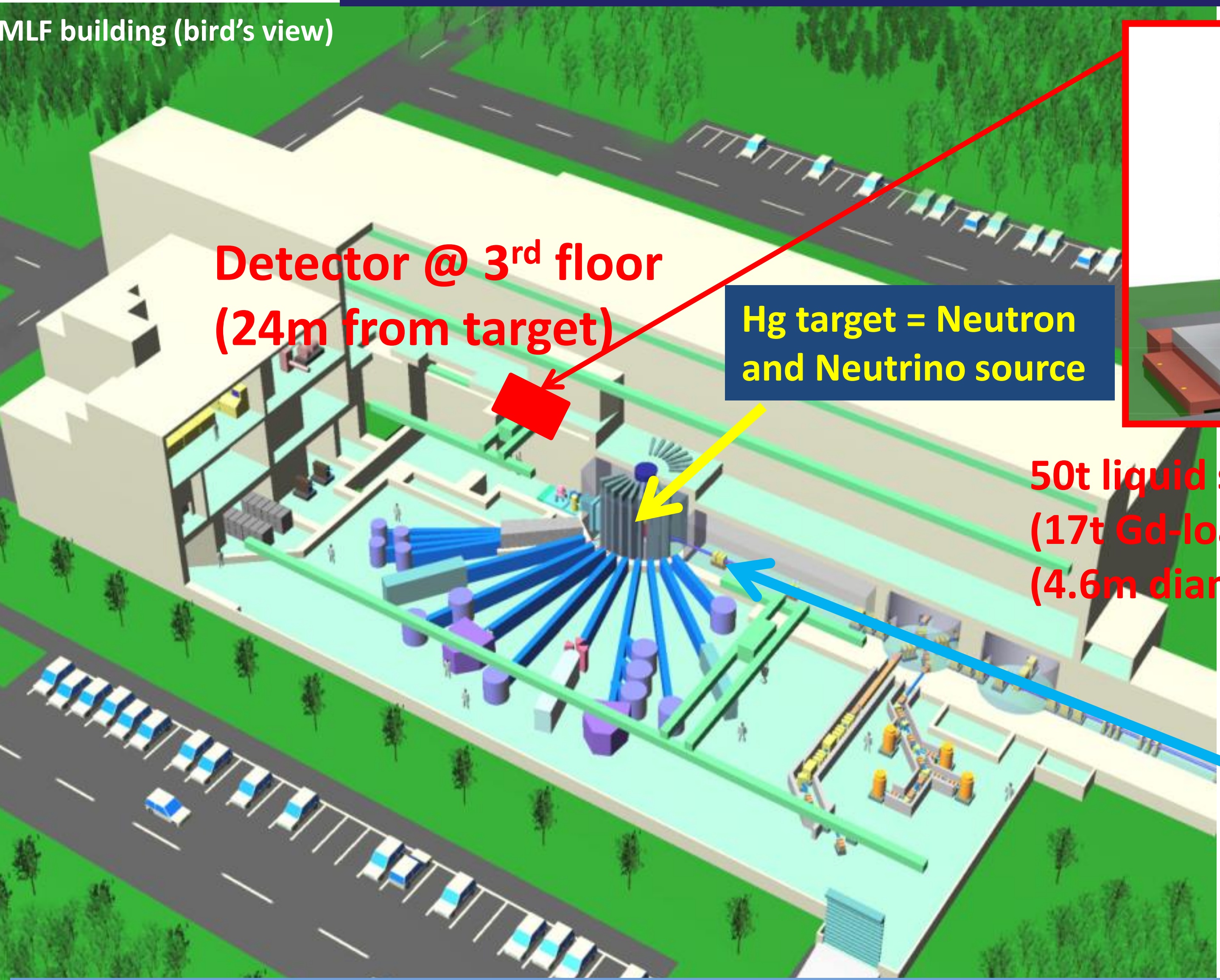


ν_e Disappearance

$$P_{\nu_e \to \nu_e} \sim 1 - 4|U_{s4}|^2|U_{e4}|^2 \sin^2\left(\frac{m_4^2 L}{4E_\nu}\right)$$



JSNS^2 at J-PARC MLF



Searching for neutrino oscillation : $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ with baseline of 24m.
no new beamline, no new buildings are needed → quick start-up

Improved Search at JSNS^2

- **Direct test of the LSND with better sensitivity**
  - Muon antineutrino beam from muon Decay At Rest (DAR)

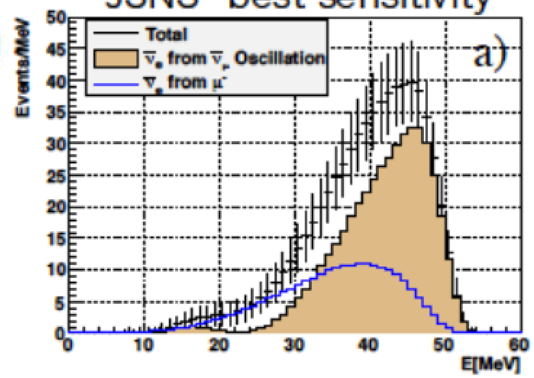
- ***Narrow (~9 μs) pulsed (every 40 ms) neutrino beam*** **at J-PARC MLF : (vs. continuous beam used by LSND)**
  - Pure muon decay at rest
  - Narrow timing window for cosmic ray rejection
  - No decay-in-flight source
  - No beam induced fast neutrons
  - The neutrino energy spectrum is perfectly known
  - The neutrino beam already available

- **Improved detector :**
  - *Gd doped LS*
  → significant reduction of backgrounds by a tighter (~1/6) time coincidence and a higher (2.2 → 8 MeV) delayed energy + well-known cross section of IBD

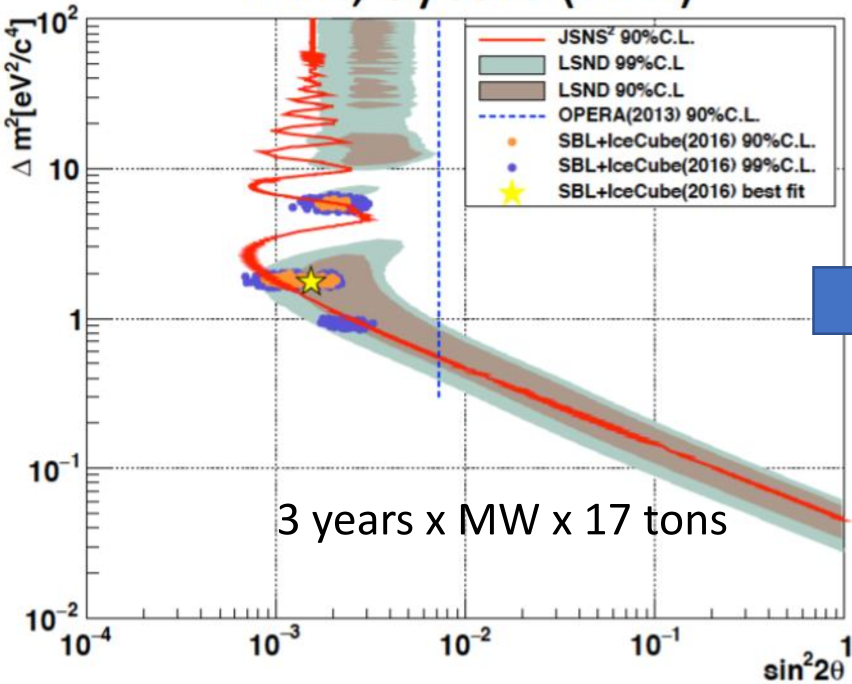
Signal Extraction & Sensitivity

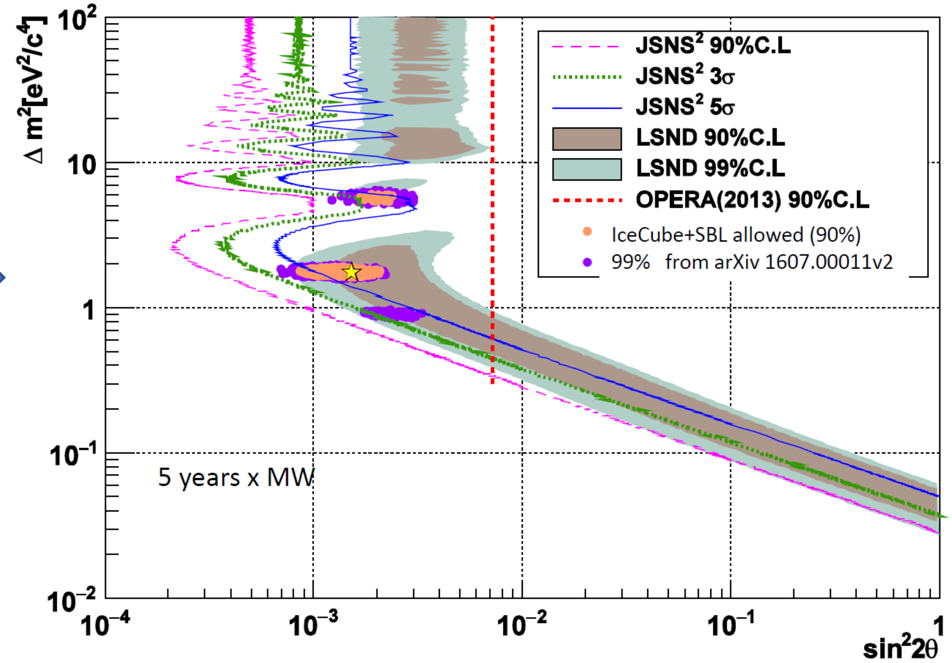
- Signal events can be distinguished from the dominant background (from another neutrino process) by using the difference of energy distributions
- Most of the parameter region indicated by LSND exp. can be explored with more than 5σ significance in 5 years with 1MW beam power

JSNS^2 best sensitivity



24m, 3years (TDR)





SUS Tank and Acrylic Vessel at J-PARC

- The stainless steel tank and the acrylic vessel are ready to perform the experiment.
- On 2019-Feb, we already had rehearsal of the installation of the acrylic vessel. → succeeded.
- They are waiting for completion of PMT installation.

PMT Installation

PMT support structure

Reflection sheet

PMT installation

PMT

- **105 PMTs from RENO, Korea**
  23 PMTs from DC, Japan
- **33 PMTs installed and ~40 will be installed till Oct. 2019.**
- **50 more PMTs will arrive before Dec. 2019.**

Current status

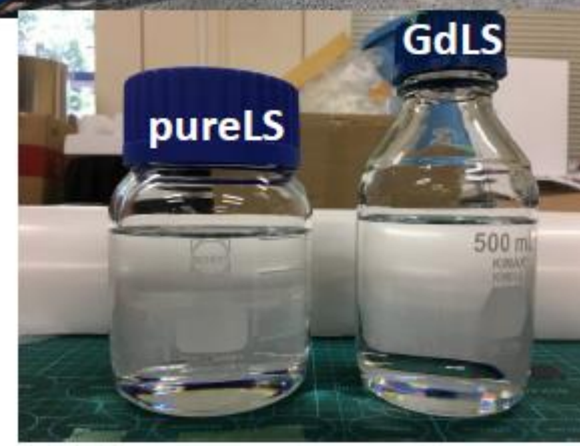
Liquid Scintillator by Ko

35 tons of LS was produced at RENO site and delivered t

Date (2018)	J
Sep. 12 - 18	R
Sep. 28	IS
Oct. 1 - 22	L

21 batches in t
- 4 peoples pe
- 2 of ISO tank

LS and GdLS storage in Japan



-- **Daya-Bay experiment kindly donated 20 tons of GdLS.**
-- arrived at Japan on 2019-Aug-1.
-- Now both GdLS and LS are stored at Kawasaki in Japan.
-- quality is OK.

Summary

- Confirming or refuting existence of “sterile neutrino oscillation” results has been one of the hottest topics in the neutrino physics in the last two decades.

- The JSNS^2 experiment will begin data taking in early 2020 and provide an ultimate test of the LSND anomaly without any ambiguity.

- If sterile neutrino oscillation is indeed found, it will be a big discovery of a dark matter candidate.

- The Korean group has been actively participating in the detector construction including delivering 36 tons of liquid scintillator and ~100 10-inch PMTs. We expect to play an important role in obtaining results.

Thank you for your attention!

Implications of Current Oscillation Parameters

borrowed from SK Kang

- ✓ $\theta_{12} + \theta_C = \pi/4$ satisfied within 2 σ.

  → quark−lepton complementarity (Raidal, Smirnov, Minakata, SK, Kim,....'04)

- ✓ Non-maximal θ_{23} is favored at 2 (1.5) σ level for NO (IO)

  → could be related to $\sqrt{m_2/m_3}$ similar to Gatto-Sartoti-Tonin

- ✓ Zero θ_{13} is excluded at 10 σ. → test for flavor models

- ✓ Two large angles → hint for discrete flavor symmetry?

- ✓ $\delta \simeq 3\pi/2$ is favored by LBL exps.

  → could be related with mixing angles, flavor symmetries etc. ?