Undersea Korea Neutrino Observatory for CP Violation Measurement

Myeong-gi Jo

Seoul National University

2025-06-26

Contents

Baryogenesis

Big Bang

$n_B - n_{\bar{B}} = 0$

Time flows...

Current Universe

$n_B - n_{\bar{B}} > 0$

- Why does the observable universe have more matter than antimatter?

Leptonic CP Violation

- Leptonic CP violation can significantly contribute to baryogenesis.
- Measurement of leptonic δ_{CP} has been one of the most important subjects of neutrino physics.

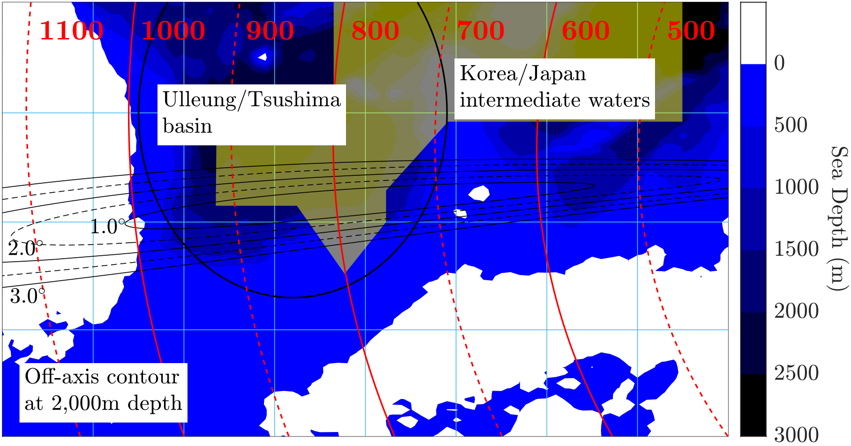
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\Delta^{\mathrm{CP}}_{\alpha\beta} \equiv \frac{1}{2}[P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)] = \sum_{j \neq k} \mathrm{Im}(U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}) \sin 2\Delta_{jk}$$

Research Background

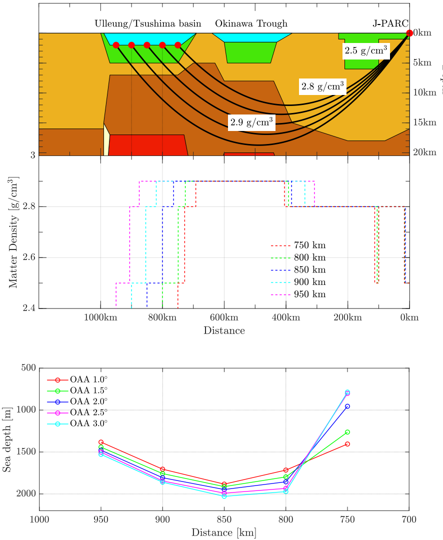
- Hyper-Kamiokande has great potential for precisely measuring the CP phase.
- It is already known that joint analysis with the Korea Neutrino Observatory detector will achieve great sensitivity.
- We introduce a novel candidate site for the Korea Neutrino Observatory detector, **Donghae**.

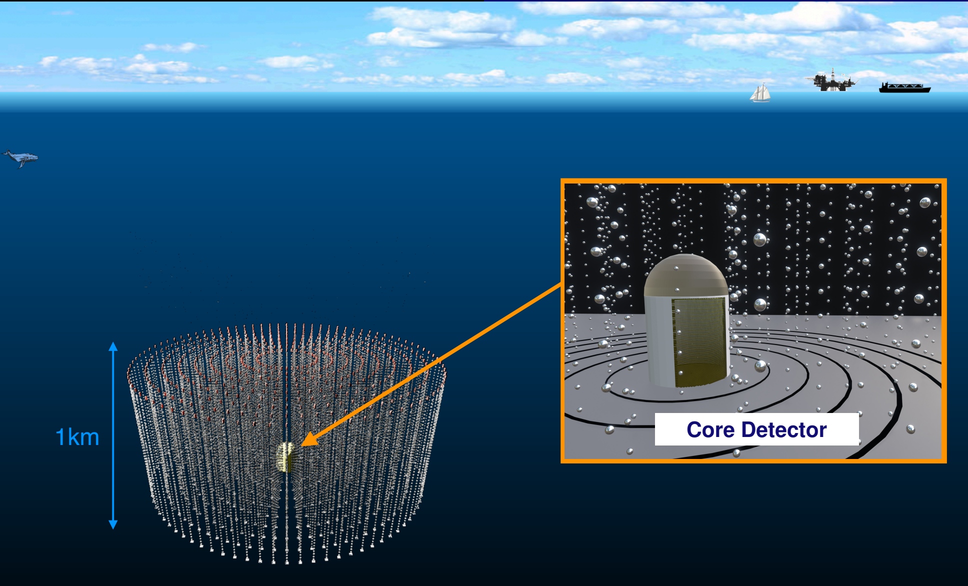
Donghae Map with OAA Contour



Geophysical Properties

- J-PARC neutrino beam covers $L = 750 - 950$ km, OAA $= 1.0° - 3.0°$.
- Average matter density $\sim$ 2.8 g/cm^3 – 2.9 g/cm^3.
- Average sea depth $\sim$ 1700 m. Deepest at $L = 850$ km.





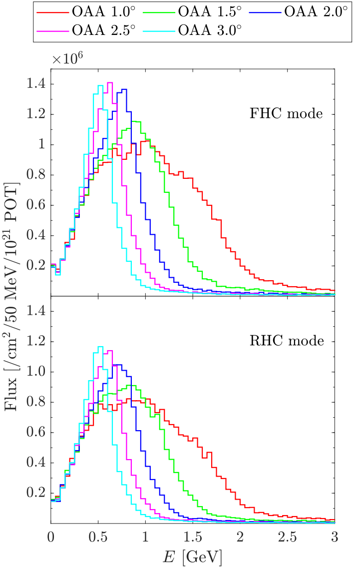
Ultimate Donghae Neutrino Telescope Complex

Detector Configuration

- A water Cherenkov detector will be installed as a core neutrino detector.
- The undersea detector does not need any excavation.
  - Time-saving
  - Free to enlarge its size as long as it endures sea pressure
- We can start from the smaller detector and extend it by installing a cylindrical module.
  - Scale-flexibility

Neutrino Flux Simulation

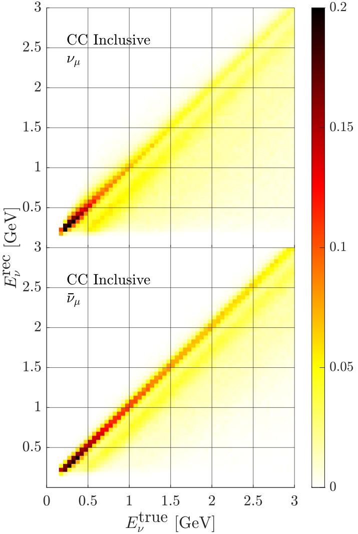
- FLUKA2024 was used for neutrino production simulation.
- Monoenergetic 30 GeV proton beam and horn current of 320 kA were used for both FHC (ν) and RHC ($\bar{\nu}$) modes.
- Plot on the right shows the flux at Hyper-K normalized with [/cm^2/50 MeV/10^{21} POT].



Neutrino-nucleus Interaction Simulation

- GENIE was used for neutrino-nucleus Interaction Simulation.
- Considered interaction types: QE, RES, MEC, and DIS.
- Plot on the right shows the response matrix for the true and reconstructed energy.

$$E_\nu^{(\mathrm{rec})}(E_l, \theta_l) = \frac{1}{2} \frac{m_l^2 + (m_n^{\mathrm{eff}})^2 - m_p^2 - 2E_l m_n^{\mathrm{eff}}}{E_l - |\vec{p}_l| \cos\theta_l - m_n^{\mathrm{eff}}}$$



Event Topologies

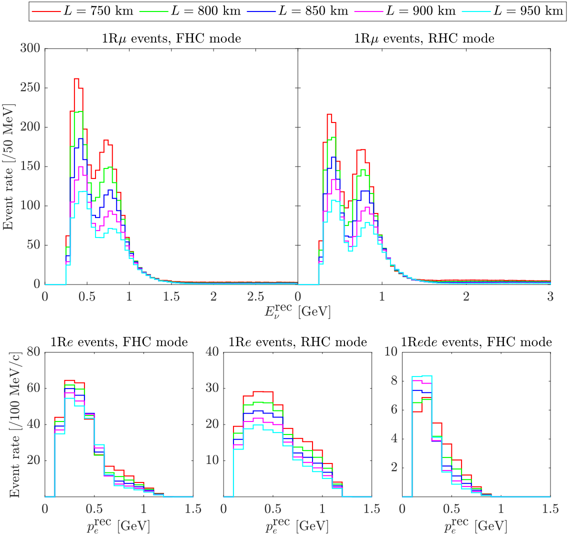
- We use five event samples.
  - 1Rμ (one μ-like ring, both horn current modes)
  - 1Re (one e-like ring, both horn current modes)
  - 1Rede (one e-like ring + decayed e-like ring, FHC mode only)
- Event selection criteria:

Criteria	1Rμ	1Re	1Rede
wall (cm)	> 50	> 80	> 50
towall (cm)	> 250	> 170	> 270
charged lepton momentum (MeV/c)	> 200	> 100	> 100
number of Michel electrons	≤ 1	0	1
$E_\nu^{(\mathrm{rec})}$ (MeV)	-	< 1250	< 1250

Event Rate at Undersea Detector

Assumptions:

- Running time: Ten years (27×10^{21} POT)
- Running partition: FHC : RHC = 1 : 3
- Detector volume: 217 kt Inner Detector



Binned Likelihood-ratio Method

- Likelihood function used for the analysis:

$$
\begin{aligned}
-2\ln\mathcal{L}_0 &= -2\ln\mathcal{L}_{\text{stat}} - 2\ln\mathcal{L}_{\text{sys}} \\
&= 2\sum_{\text{samples}}\sum_{\text{bins}}\left[N_{\text{MC}} - N_{\text{Data}} + N_{\text{Data}}\ln\frac{N_{\text{Data}}}{N_{\text{MC}}}\right] \\
&\quad + (\mathbf{f}-\mathbf{f}_0)^T V^{-1}(\mathbf{f}-\mathbf{f}_0)
\end{aligned}
$$

- Sensitivities for CP violation and mass ordering are tested.

$$
\sqrt{\Delta\chi^2} = \sqrt{\chi^2_{\text{test}} - \chi^2_{\text{best-fit}}}
$$

- Both cases of known and unknown mass orderings are considered.

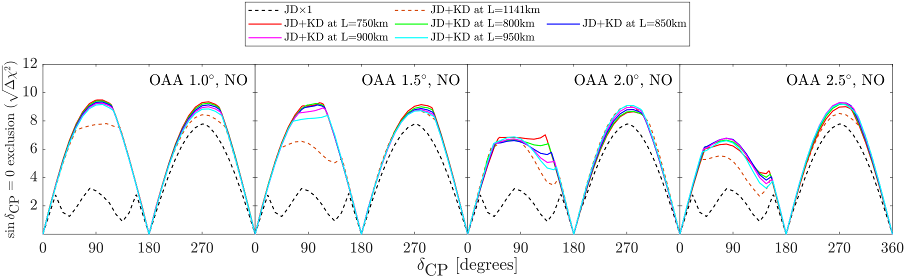
Systematic Uncertainties

- To save computation time, systematic uncertainties are quadratically summed for each event sample.

Uncertainties	1Rμ	1Re	1Rede
FHC (ν mode)	1.2%	2.1%	5.2%
RHC ($\bar{\nu}$ mode)	1.1%	2.2%	-

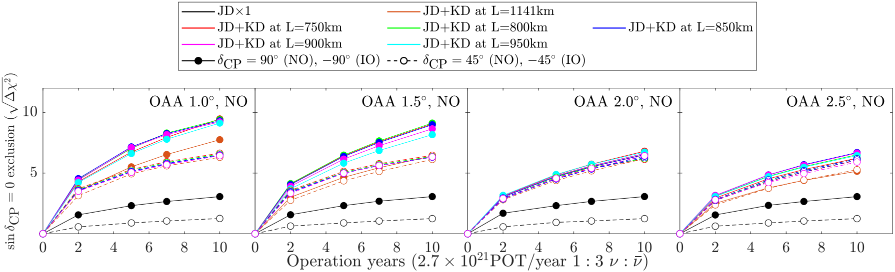
- 100% correlation is assumed between 1Rμ and 1Re samples for each horn current mode.
- Otherwise, zero correlation is assigned.

Exclusion of $\sin\delta_{CP} = 0$ (Ten Years)



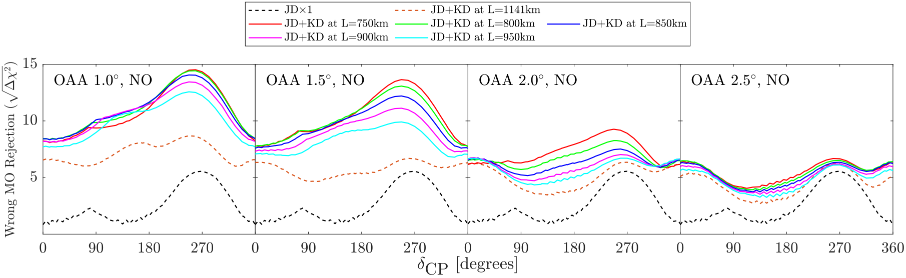
- With unknown mass ordering, the undersea detector shows higher sensitivities.
- Lower OAA has better sensitivity; the best one is OAA 1.0°, $L = 750$ km for ten years of operation.

Exclusion of $\sin\delta_{CP} = 0$ – Various Years



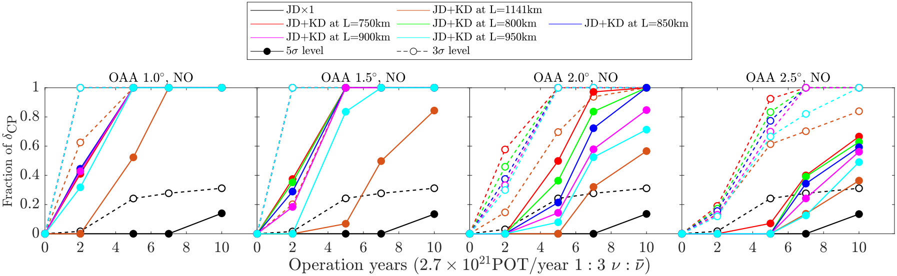
- Before ten years, the best site is $L = 800$ km (NO) or $L = 850$ km (IO) at OAA 1.0°.
- The optimal underwater detector discovers CP violation in less than 3 years.

Rejection of Wrong Ordering (Ten Years)



- The undersea detector is much stronger in mass ordering determination.
- Best sensitivity comes from OAA 1.0°, $L = 750 - 850$ km.

δ_{CP} Fraction Finding Correct Ordering



- The undersea detector at OAA 1.0° will discover the correct mass ordering for all δ_{CP} values within five years of operation.

Summary

- We propose the undersea Korean neutrino observatory detector for precise measurements of the leptonic CP phase.
- The undersea detector has advantages regarding its lower degeneracy in mass ordering and scale-flexibility.
- The undersea detector shows better sensitivity on both CP violation and mass ordering with the best candidate site of OAA $1.0°$ / $L = 750 - 850$ km.
- The undersea detector will usher in a new era of neutrino physics by the power of its flexibility and high sensitivity to mass ordering.

Thank You

Backup

Baryogenesis and CP Violation

- Consider decay processes of a very heavy particle X which violates a baryon number. Characterize final states with their baryon number B_1 and B_2 ($B_1 \neq B_2$).

$$\frac{\Gamma(X \to B_1)}{\Gamma(X \to \text{all})} := b \qquad \frac{\Gamma(X \to B_2)}{\Gamma(X \to \text{all})} := 1 - b$$

$$\frac{\Gamma(\bar{X} \to \bar{B}_1)}{\Gamma(\bar{X} \to \text{all})} := \bar{b} \qquad \frac{\Gamma(\bar{X} \to \bar{B}_2)}{\Gamma(\bar{X} \to \text{all})} := 1 - \bar{b}$$

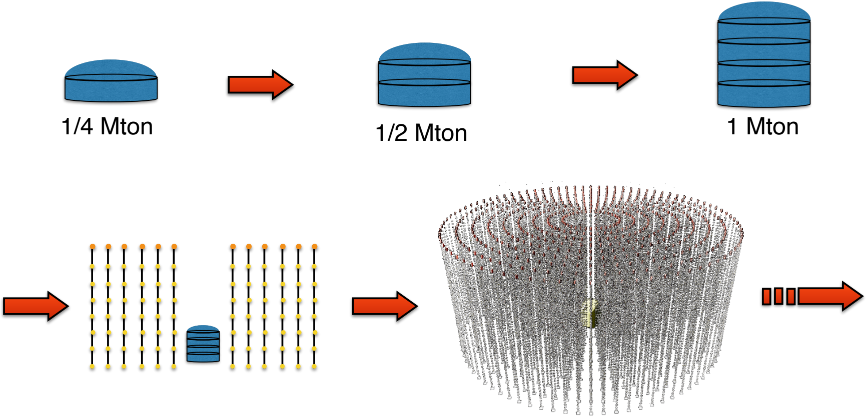
- By CPT theorem and unitarity, $\Gamma(X \to \text{all}) = \Gamma(\bar{X} \to \text{all})$, and assuming the number of X and $\bar{X}$ were equal,

$$\Delta B = (b - \bar{b})B_1 + [(1 - b) - (1 - \bar{b})]B_2 = (b - \bar{b})(B_1 - B_2) \neq 0$$

- Thus, baryogenesis requires $b \neq \bar{b}$, the CP violation.

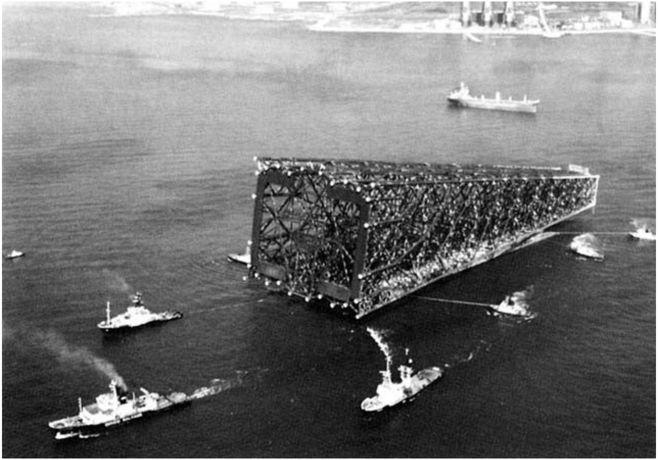
Scale-flexibility of Undersea Detector

- The detector construction can be divided into several phases depending on the physics requirement and budget.



Undersea Detector Construction

- Moving the detector structures to the Ulleung basin is absolutely possible; Hyundae did more difficult work in 1976.



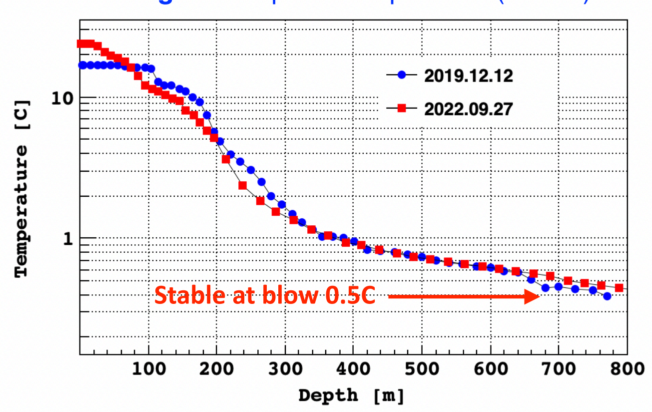
Power Station for Undersea Detector

- Generating electric power for the undersea is also possible. One possibility is Hexicon, which is a floating wind turbine that generates 40 MW of power.

Donghae Environment

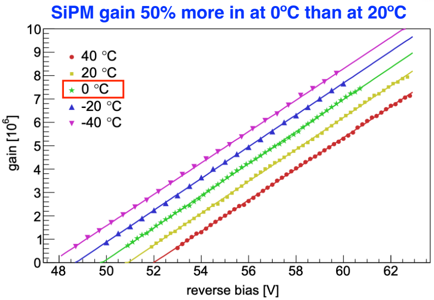
- At the candidate undersea site in Donghae, the detector will suffer pressure up to 200 atm and temperature below 0.5 °C.

Donghae deep-sea temperature (ARGO)



SiPM in Undersea Detector

- In this environment, SiPM is more favorable than PMT, as it is more resistant to pressure and performs better at low temperatures.



- We can apply the Winston cone-style waveguide to overcome the small photo-coverage of SiPM.