Liquid Scintillator Detectors in Korea: Past, Present, and Future

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Particle Detector Workshop 2026

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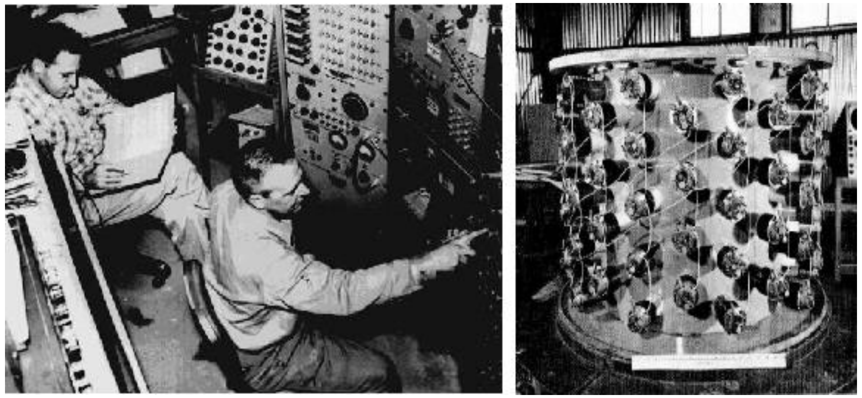
Contents

- Review of Completed Projects
  - Technical milestones achieved through **RENO**, **NEOS**, and **JSNS²**.
- Ongoing Project: **RENE**
  - Currently in upgrading for the next-generation reactor neutrino experiment.
- Experience in Active Shielding
  - Development and operation of LS-based Active Shields and Muon Veto systems for underground experiments.
- Future Program: **νEYE**
  - Proposal for a multi-purpose neutrino observatory targeting solar neutrinos, sterile neutrinos, and rare decays.

Overview of Liquid Scintillator Detectors

- Detection Principle
  - Scintillation: Ionizing energy → Excitation → Scintillation photons.
  - Signal: Fast light pulses captured by photosensors.
- Key Features
  - High light yield: ~10,000 ph/MeV and Excellent linearity
  - Fast Time: ~ a few ns of decay time
  - Low radioactivity: ~ 10^{-13} g/g (^{238}U, ^{232}Th)
  - Metal loaded LS: Gd, B, In, Te, Sn, …
- Basic Structure
  - Scalable LS Target: Homogeneous or Segmented
  - Photosensors: High-sensitivity sensors (PMTs or SiPMs)
  - Various Shielding: Passive buffers and active vetoes for background suppression.



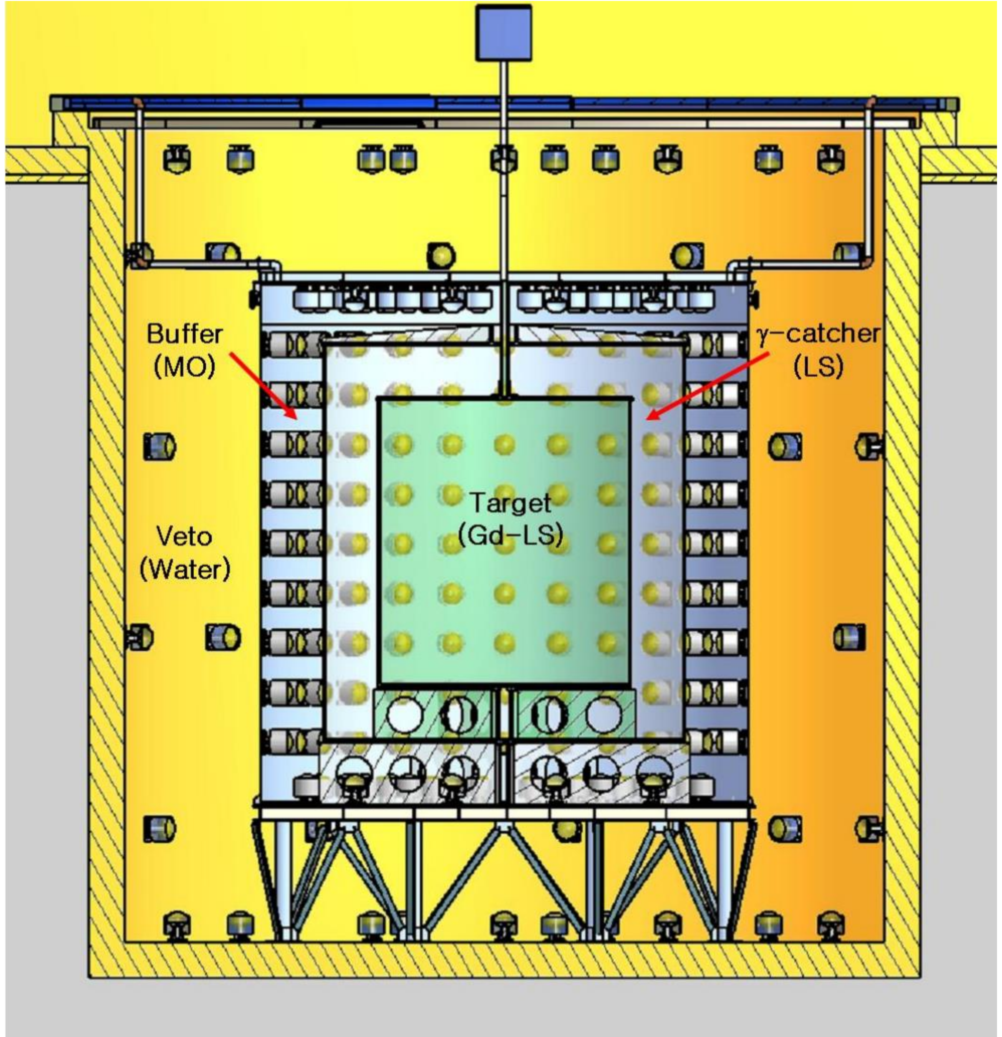
Cowan and Reines experiment

RENO: Reactor Experiment for Neutrino Oscillation

- Overview
  - Neutrino detection: $\bar{\nu}_e + p \longrightarrow e^+ + n$ (inverse beta decay)
  - One of world's first measurements of the smallest mixing, θ_{13}.
  - Long-term Operation: Successful data taking for over a decade (2011–2021).
- Key Physics Achievements
  - Precise Oscillation Parameters: High-precision measurement of $\sin^2\theta_{13}$ and $|\Delta m^2_{ee}|$
  - Spectral Shape Abnormality: Discovery and precise measurement of the "5 MeV excess" in the prompt energy spectrum of reactor neutrino.
  - Sterile Neutrino Search: Broad-range search for light sterile neutrino oscillations addressing the Reactor Antineutrino Anomaly.

RENO: Detector Design & Technology

- Detector Configuration
  - Identical two Detectors: Near (294 m) and Far (1383 m) to cancel rector neutrino flux uncertainties.
  - Multi-layer Structure: Target(GdLS) → Gamma-catcher(LS) → Buffer(MO) → Veto(water)
  - Photosensors: 354 low-background 10-inch PMTs per detector.
- LS Technology
  - 0.1% Gd-loaded LS: developed in Korea and 10+ years of stability.
- Background Suppression
  - Passive Buffer: 60 tons of Mineral Oil to shield radioactivity from PMTs and rocks.
  - Active Veto: Water Cherenkov detector to identify muon and reject muon induced neutron background.

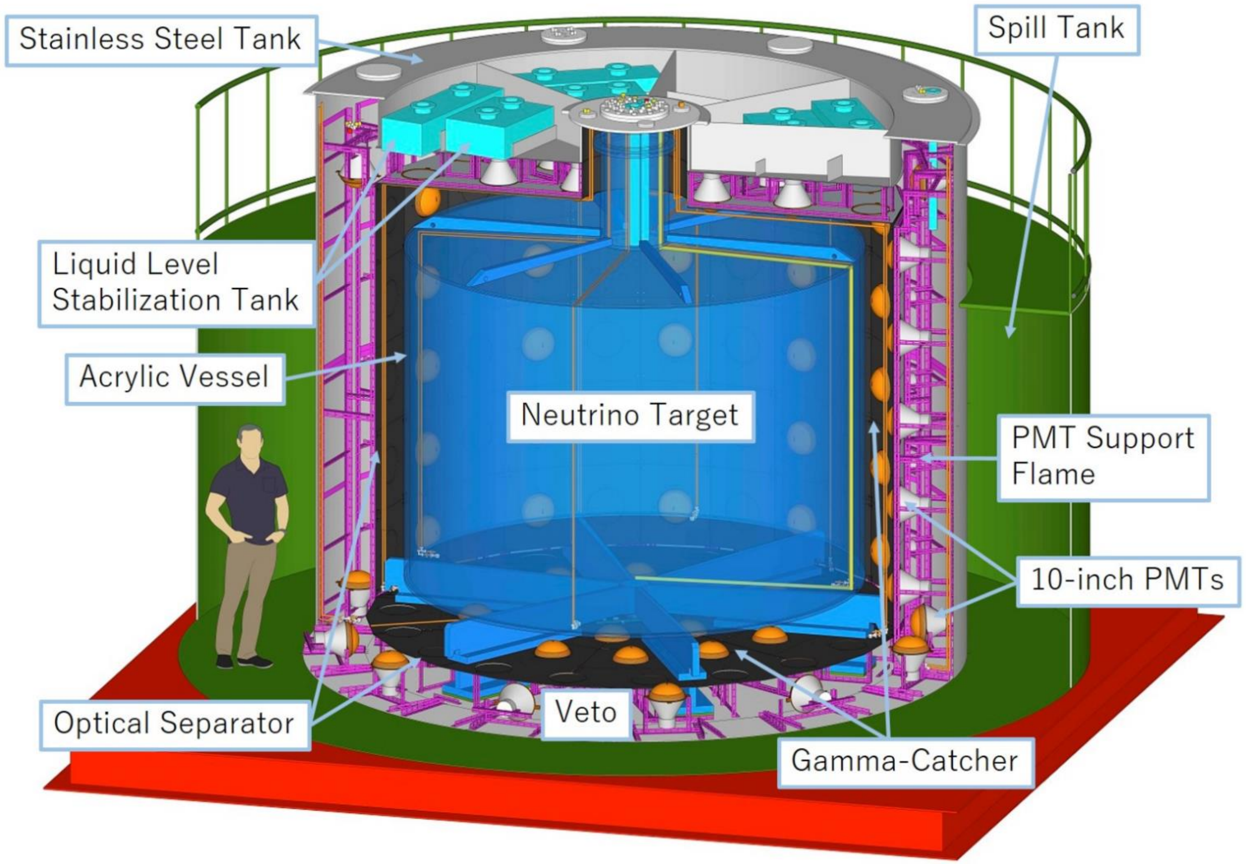


RENO: Lessons Learned & Technical Legacy

- Liquid Scintillator Expertise
  - Metal-loading Technology: Proven 10-year stability (chemical & optical) of Gd-LS.
  - Purification & Handling: Established steps for mass production and purification.
- Detector Design & Operation
  - Designing and constructing Large-scale LS Detector
  - DAQ & Monitoring: Robust, high-duty-cycle operation with real-time monitoring.
  - Long-term Reliability: Over a decade of stable hardware and detector response.
- Foundation for Future Projects
  - Practical utilization of RENO's infrastructure, equipment, and validated techs for follow-up experiments.
  - Growth of a research community specialized in LS-based neutrino physics in Korea.

JSNS²: J-PARC Sterile Neutrino Search

- Direct test of the LSND anomaly through $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ oscillation.
- Located at the J-PARC MLF, 24m from the neutrino source.
- Detector Configuration:
  - Fiducial Volume: 17 tons of Gd-LS stored in a cylindrical acrylic vessel.
  - Multi-layer Design: Target (Gd-LS) → Gamma-catcher (LS) → Veto (LS).
  - Photosensor: 120 10-inch PMTs installed in a stainless steel tank.
- Operational Environment: Designed to handle high-intensity, pulsed neutrino beams from a spallation neutron source.

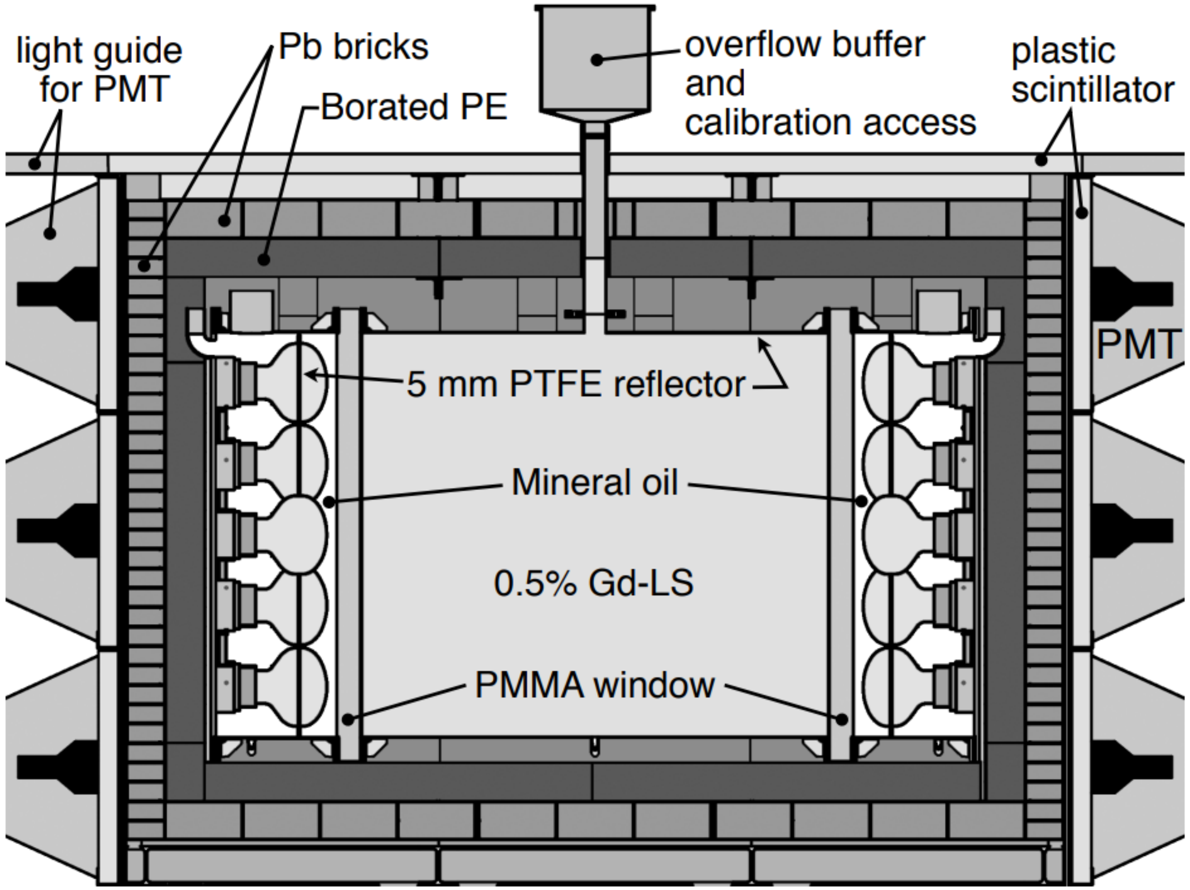


JSNS^2: Korean Contributions

- LS Production & Logistics
  - Produced 31 tons of high-purity LS at the refurbished RENO facility in Korea.
  - Managed international sea transport and quality stability using ISO tanks.
- Lead Detector Construction
  - Directed the overall technical integration and successfully completed detector construction.
- Performance Optimization (PSD)
  - Developed an LS cocktail (DIN mixture) with enhanced Pulse Shape Discrimination (PSD) for effective background rejection.
- Systems & DAQ Infrastructure
  - Developed the Slow Monitoring and HV control system.
  - DAQ and monitoring/display software.

NEOS: Neutrino Experiment for Oscillation at Short-baseline

- Direct test of the Reactor Antineutrino Anomaly (RAA) and search for sterile neutrinos.
  - Tendon gallery of Hanbit Nuclear Power Plant Unit 5 (Shallow depth ~20 m.w.e.).
  - Extremely short baseline of 23.7 meters from the reactor core.
- Detector Configuration:
  - Target: 1-ton (1,000 L) of 0.5% Gd-loaded LS viewed by 38 8-inch PMTs.
  - Passive Shielding: Multi-layer structure consisting of Borated Polyethylene and Lead.
  - Muon veto detector made of plastic scintillator panels.
- Project Phases:
  - Phase-I (2015): Search for sterile neutrino.
  - Phase-II (2018–2020): Precise measurement of the reactor antineutrino spectrum.

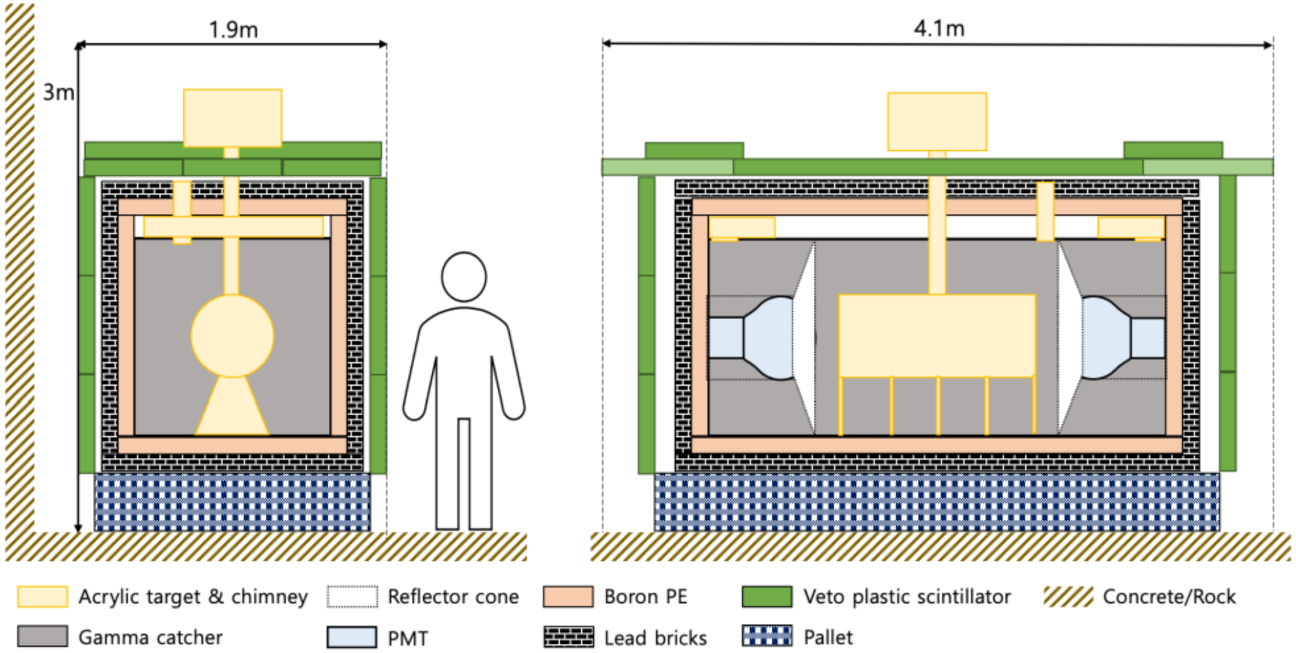


NEOS: Short-baseline neutrino detection

- High-Concentration Gd-LS for Compact Target
  - Extreme spatial constraints limited the target volume to 1 ton.
  - Developed 0.5% Gd-loaded LS to maximize neutron capture probability within the compact target.
  - Increased the detection efficiency to compensate for the small target size.
- Background Suppression at Shallow Depth
  - High cosmic-ray flux near the surface leads to significant muon-induced neutron backgrounds.
  - Optimized PSD capability to effectively distinguish IBD signals from fast neutrons. (10% DIN mixing)
- Performance & Operational Stability
  - Achieved an exceptional Signal-to-Background (S/B) ratio of 20:1 at a shallow-depth site.
  - Energy Resolution: Reached ~5% at 1 MeV, enabling the precise identification of the "5 MeV bump."

RENE: Reactor Experiment for Neutrinos and Exotics

- Scientific Goal: Directly exploring the allowed region predicted by the combined RENO and NEOS joint analysis, $|\Delta m^2_{41}| \sim 2\ eV^2$.
- Detector Configuration: multi-layer design
  - Target: 270 L of 0.5% Gd-loaded LS.
  - γ-catcher: 15-cm thick unloaded LS layer for missing energy recovery.
  - Shielding & Veto: Multi-layer passive shielding (Borated PE, lead) and plastic scintillator muon veto detectors.



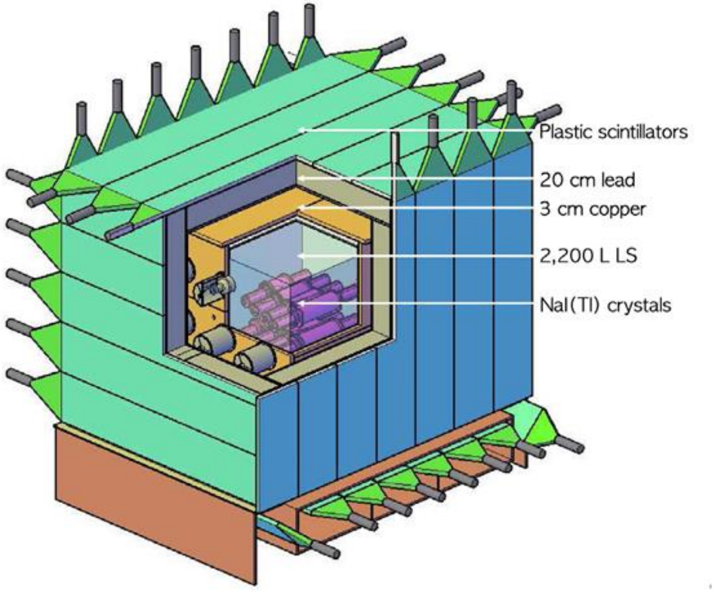
- Status: Construction completed in 2024; After commissioning, the detector is currently being updated.

RENE: Key Technologies & Performance

- Enhanced Energy Resolution via Gamma-Catcher
  - Captures escaping photons from the target, resolving the energy leakage issue of target-only designs.
  - Improved energy resolution, enhancing sensitivity to neutrino oscillation patterns.
- Optimized Scintillator & Background Rejection
  - 0.5% Gd-loading for high neutron capture efficiency in a compact volume.
  - Optimization of **PSD** through **10% DIN mixing** to effectively reject fast neutron backgrounds.
- Advanced Photosensor System
  - Utilization of two high-quantum-efficiency **20-inch PMTs (Hamamatsu R12860)**.
  - Implementation of **reflector cones** to maximize light yield and energy resolution.
  - Double-layer Permalloy magnetic shielding to ensure stable PMT operation.

LS Detector as Active Shielding in Dark Matter Searches

- KIMS: Muon veto detector
  - 7,800 L of LS (95% Mineral Oil + 5% PC/PPO/POPOP) surrounding the main CsI(Tl) crystal detectors
  - Vetoes cosmic muons to suppress muon-induced neutrons
  - Measured a muon flux of 2.7x10^{-7} /cm^2/s with ~98% detection efficiency.



- COSINE-100: LS Veto System
  - 2,200 L LAB-based LS monitored by 18 5-inch PMTs surrounding NaI(Tl) crystals.
  - Active coincidence tagging of ^{40}K backgrounds (1.46 MeV gamma-ray) with ~80% efficiency.

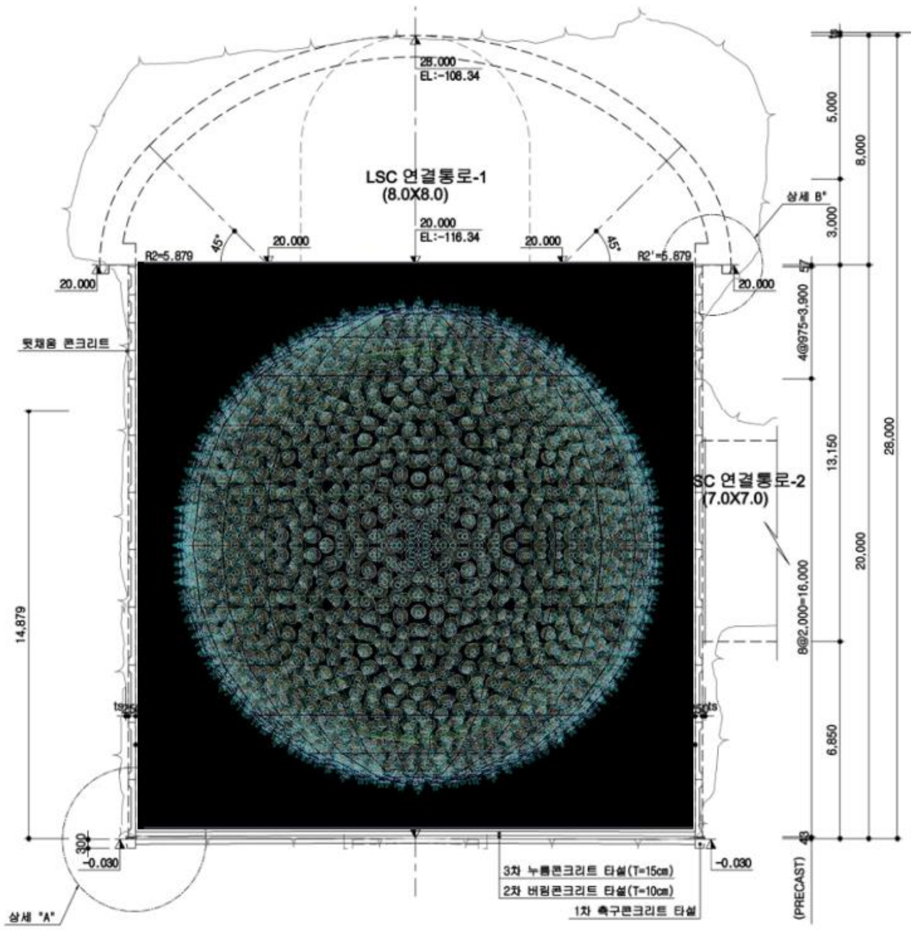
νEYE: Neutrino Experiment at YEmilab (Proposal)

- Concept & Infrastructure
  - Next-generation large-scale neutrino telescope at Yemilab (1,000m depth, 2,500 m.w.e.).
  - Utilizing the LSC Pit: A cylindrical space (~20 m diameter, ~20 m height) with a volume of approximately 6,300 m^3.

- Primary Scientific Programs
  - Sterile Neutrino Search: IsoDAR (Cyclotron) and radioactive sources (^{51}Cr, ^{144}Ce).
  - Solar Neutrinos: Precise measurement of pp, ^{7}Be, and CNO neutrinos.
  - Astrophysical & Geo-neutrinos: supernova neutrino bursts and geo-neutrinos.
  - Exploring Beyond the Standard Model (BSM) physics through rare decay searches and dark matter detection.

νEYE: Detector Concept

- Target: 14.5 m diameter Acrylic Sphere containing Liquid Scintillator (Volume ~1,600 m^3, mass ~1.4 kTon).
- Buffer: 17 m diameter shielding layer (Water or Mineral Oil) to suppress radioactivity from PMTs.
- Veto: 19.5 m (D) x 20 m (H) cylindrical water tank for 4π active muon rejection.
- Photosensor: about 4,000 20-inch PMTs mounted on a spherical stainless steel support frame or tank.
- Optical Coverage: Optimized PMT density and light concentrator to achieve high light collection efficiency and energy resolution.



νEYE: R&D for Next-Generation Technologies

- Ultra-low Background Purification
  - Establish an advanced purification system (distillation, water extraction, and gas stripping) to reach radio-purity levels of 10^{-17} g/g (U/Th).
  - Essential for the precise measurement of solar neutrinos (pp, CNO) by minimizing internal backgrounds.
- Slow Liquid Scintillator (Slow LS)
  - Separation of Cherenkov and Scintillation signals by utilizing slow-timing fluorophores.
  - Provides directionality for incoming neutrinos, a crucial tool for background rejection and signal identification in solar neutrino physics.
- Metal-loaded LS for 0νββ Search
  - Exploring stable loading of isotopes such as ^{124}Sn (Tin) or ^{130}Te (Tellurium).
  - To probe the Majorana nature of neutrinos and determine the effective neutrino mass through neutrinoless double beta decay searches.

Summary

- Established Technical Heritage
  - Successful discovery of θ_{13} and over a decade of stable operation with RENO.
  - Technical milestones in high-concentration Gd-LS and PSD optimization through NEOS and JSNS2.
- Present Milestone: RENE
  - Currently exploring the sterile neutrino with enhanced energy resolution via the Gamma-Catcher.
- Proven capability in active shielding for dark matter searches (KIMS & COSINE-100).
- The Future: νEYE at Yemilab
  - Transitioning to a large-scale multi-purpose observatory at 1,000m underground.
  - Targeting solar neutrinos, sterile neutrinos, and astrophysical neutrino bursts.
- Korea holds a leading position in LS-based neutrino physics, bridging past successes to a large-scale multi-purpose detector.