WIND
Water In Neutrino Detectors

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for

The 4th K-Neutrino Symposium

June 25 ~ 27, 2025

Based on discussions with

- BNL: Minfang Yeh, Guang Yang, Milind Diwan
- CAU: Mehedi Masud, 권순우, 박주성
- CNU: 양병수
- JNU: 고영주
- KNU: 박정식
- SNU: 유종희

Water In Neutrino Detectors

- Water-based Liquid Scintillator into RENO Detectors

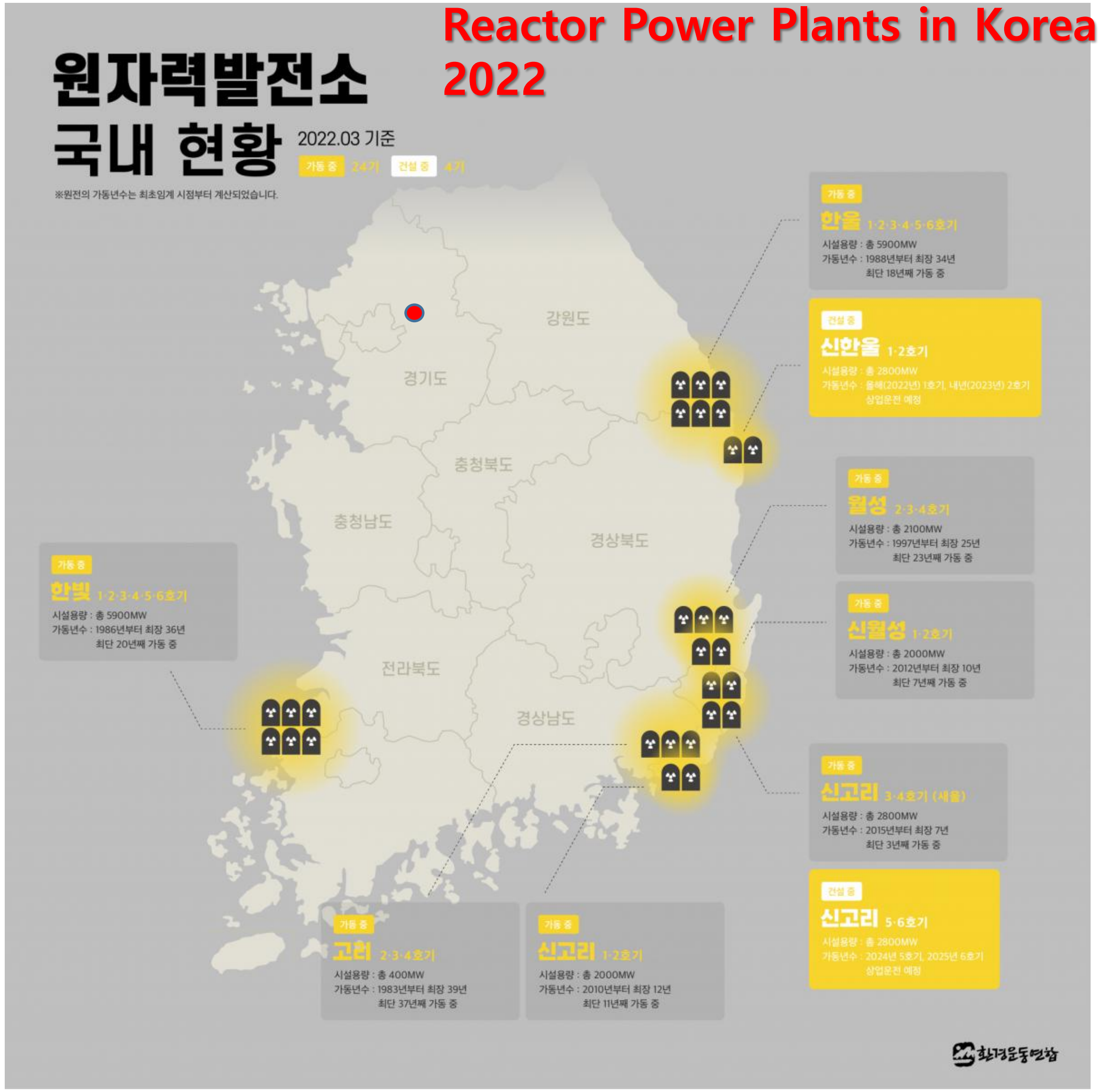
  - Kilo-ton Scale Detector R&D
  - GeV-scale neutrino detection
  - MeV-scale neutrino detection

  - BNL WbLS R&D with 1-ton and 30-ton prototype
  - Renovate and reuse the RENO facilities
  - Plan to monitor all reactors in Korea

RENO

Reactor No.	Near Detector (m)	Far Detector (m)
1	667.9	1556.5
2	451.8	1456.2
3	304.8	1395.9
4	336.1	1381.3
5	513.9	1413.8
6	739.1	1490.1

Table 1.2: Distances of the reactor cores from the near and far detectors.

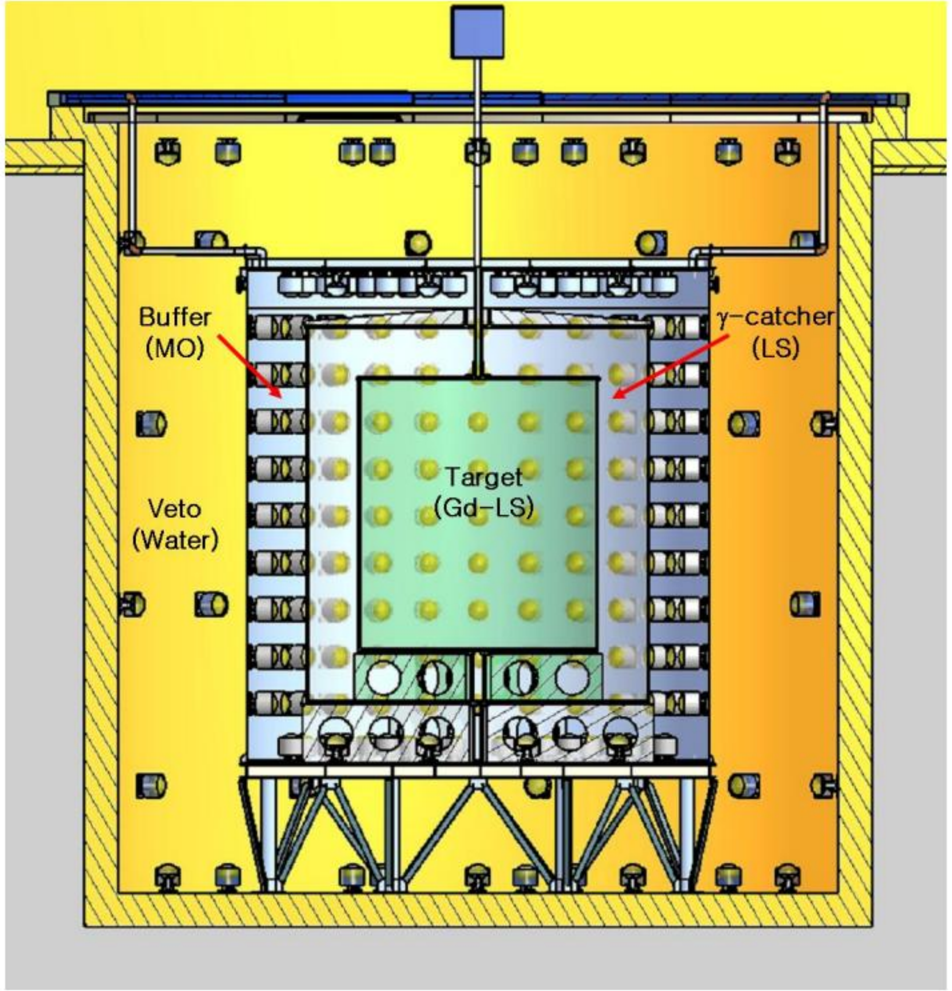


RENO

- Overburden: ND 120 m.w.e.
  FD 450 m.w.e.
- Target: 16-ton Liquid Scintillator with 0.1% Gd
- PMT: 354 10-inch Hamamatsu (R7081)
- 14% photo-sensitive surface area coverage
- IBD rate per day without background :
  FD 46.8 / ND 464 for 1.2 MeV<E_p<8 MeV

Detector Component	Outer Diameter(mm)	Outer Height(mm)	Thickness (mm)	Material	Volume (m^3)	Mass (tons)
Target	2750	3150	–	Gd-loaded LS	18.70	16.08
Target Vessel	2800	3200	25	Acrylic	0.99	1.18
γ-catcher	3940	4340	570	LS	33.19	28.55
γ-catcher Vessel	4000	4400	30	Acrylic	2.38	2.83
Buffer	5388	5788	694	Oil	76.46	64.22
Buffer Vessel	5400	5800	6/12*	SUS	1.05	8.39
Veto	8400	8890	1500	Water	354.84	354.84

Table 3.1: Dimensions of the mechanical structure of the detector. (*)The buffer vessel thickness is 6 mm for the top and barrel sections and 12 mm for the bottom section.

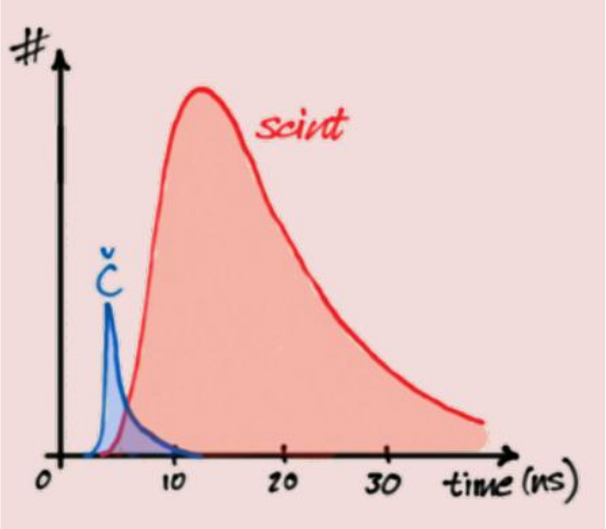


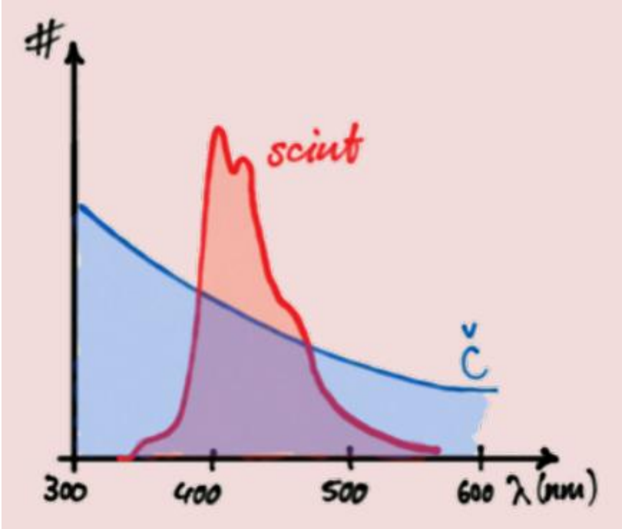
WbLS basic performance

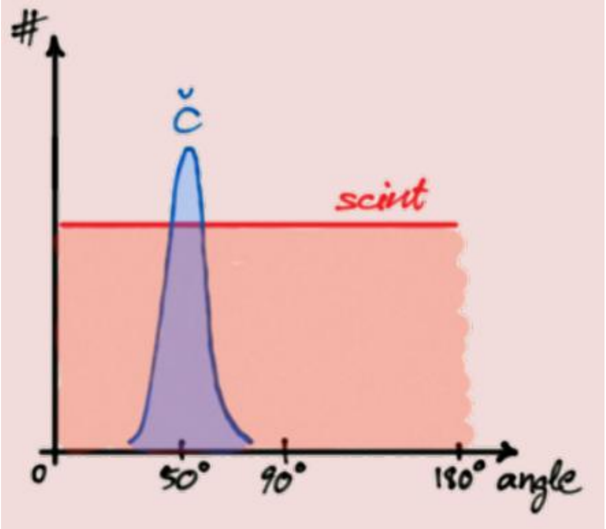
- Developed and characterized a variety of WbLS formulas for multiple frontiers.
- In the context of neutrino physics, Cherenkov and Scintillation light separation is a key feature.

In general:

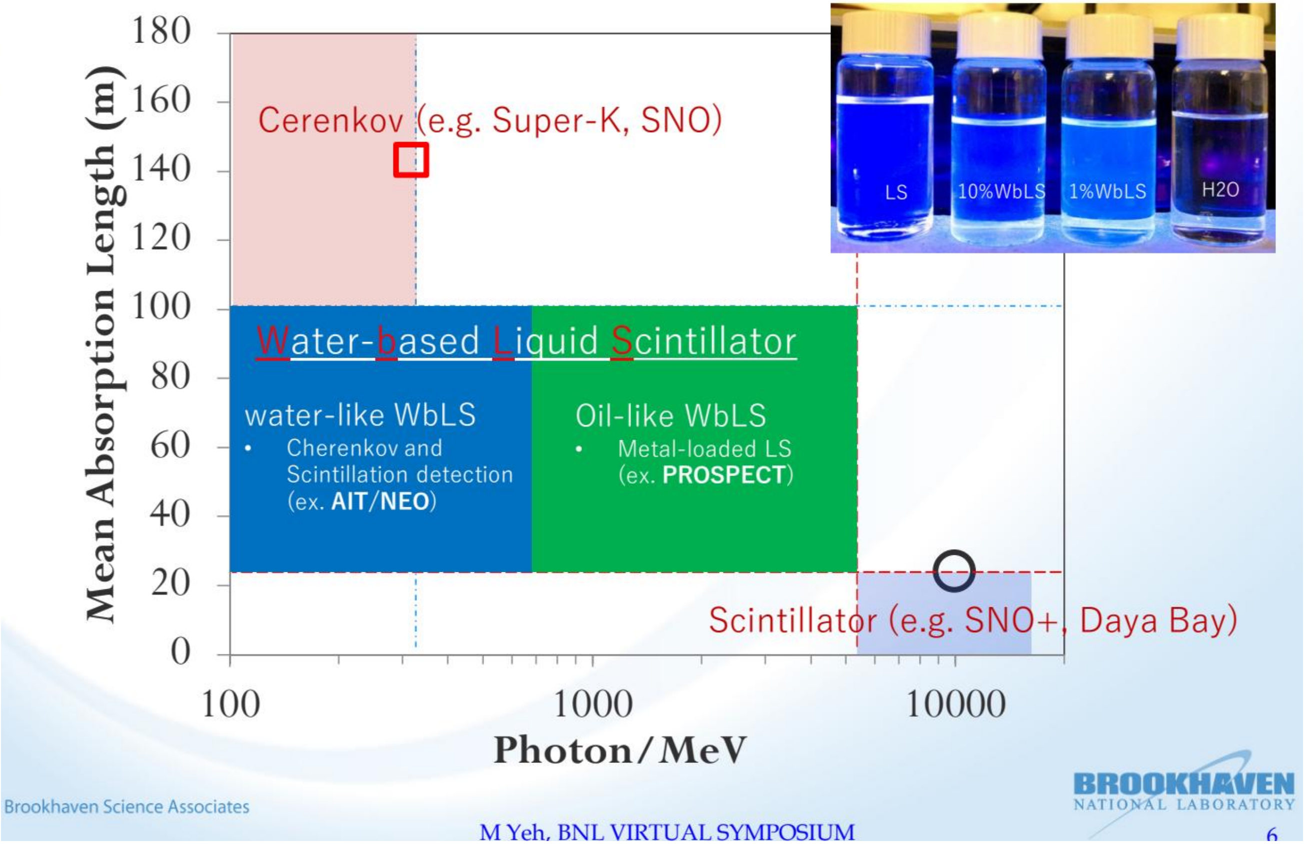
- Scintillation light yield proportional to WbLS concentration
- Scintillation light later than Cherenkov light
- Scintillation light with a narrower wavelength distribution than Cherenkov light
- Scintillation light generated isotropically



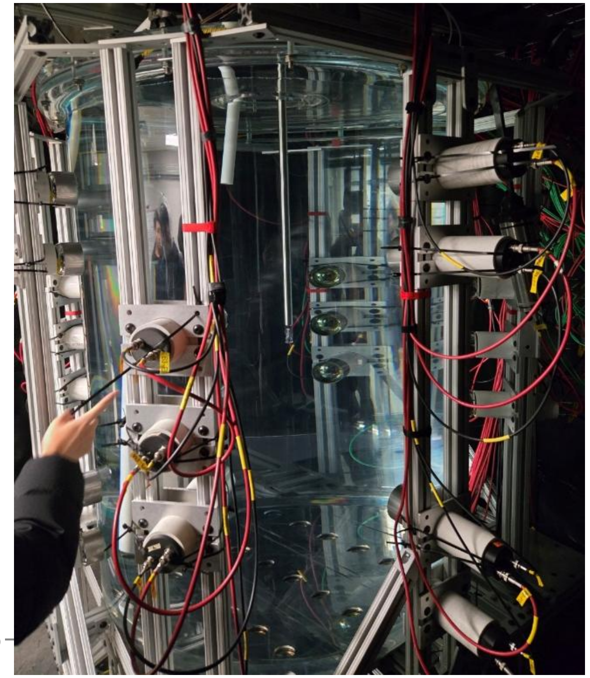


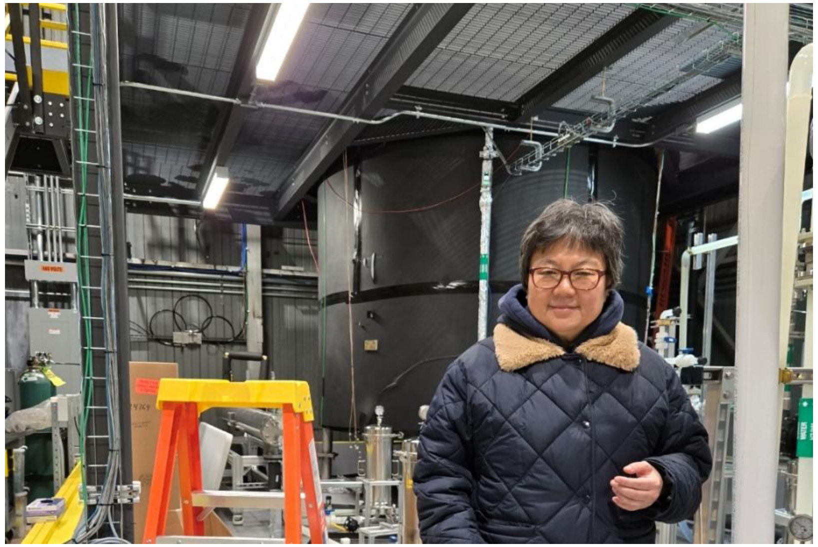


1ton under UV

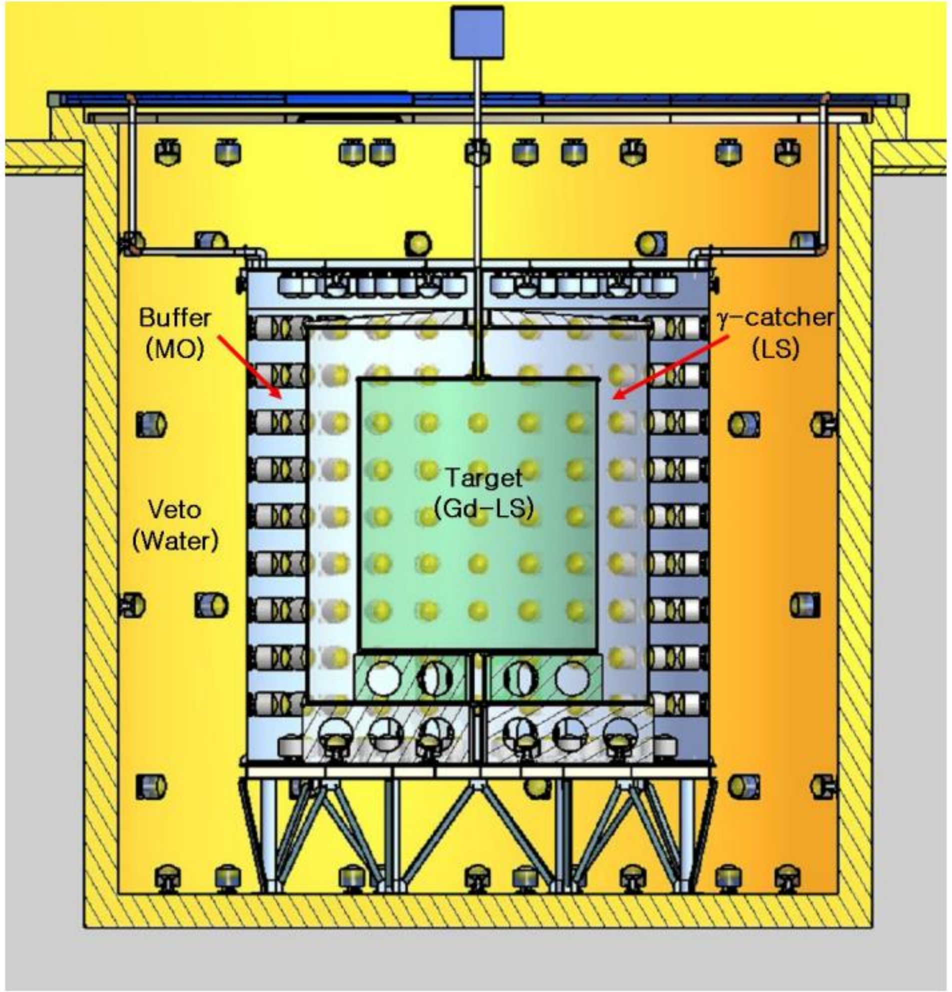


Cooperation of CAU Nula and BNL WbLS Group





RENO Detector



	U-235	U-238	Pu-239	Pu-241
Fission Fraction	57.4%	7.3%	29.8%	5.5%
Released Energy [MeV]	202.36	205.99	211.12	214.26

Phys. Rev. D **104**, L111301

Phys. Rev. C **88**, 014605

$$\langle Y_{IBD} \rangle = 5.891 \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$

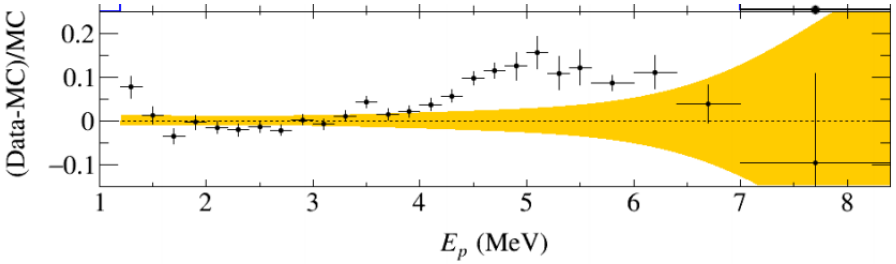
RENO's average IBD yield

Phys. Rev. D **104**, L111301

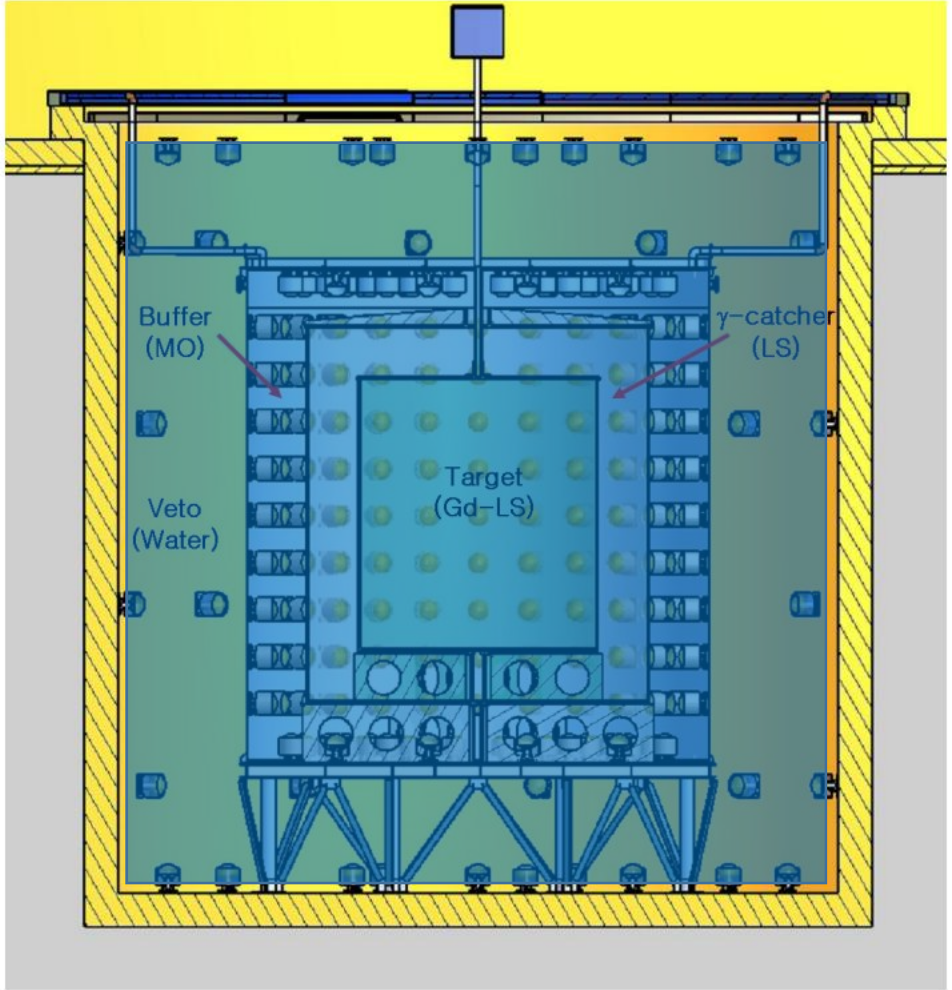
From Yang's Slide "RENO"

- 1,211,995(144,667) $\bar{\nu}_e$ candidate events observed for near(far).

Detector	Near	Far
IBD rate	366.47 ± 0.33	38.70 ± 0.10
after background subtraction	357.39 ± 0.38	36.64 ± 0.16
total background rate	9.08 ± 0.18	2.06 ± 0.13
live time [days]	3307.25	3737.85



Water In the Neutrino Detector



- Water 450 m^3
- Inner surface 270 m^2
- 350 PMT -> photo-cathode coverage 6.5%
  1500 (2000) PMTs -> 27.8% (37.0%)
- Number of protons N_p = 3.02 x 10^{31}
- Efficiency ε= 70%
  - Cf: RENO 76.5%, Daya Bay 78.8%
- Number of neutrino events

$$N_\nu = \sum_i^6 \frac{N_p \epsilon}{4\pi L_i^2} \langle Y_{IBD} \rangle \frac{P_{th,i}}{\langle E_{rel} \rangle}$$

- 2,090 per day >>> 763,000 per year
  - Cf: RENO 144,667 / 3800 days
- Sufficient statistics for 5-MeV excess using the target H_2O.

Thanks to
고영주

Monitoring system for Korean reactors

Thermal Capacity (MWth)	
Hanbit	L (meters)
2787	1556
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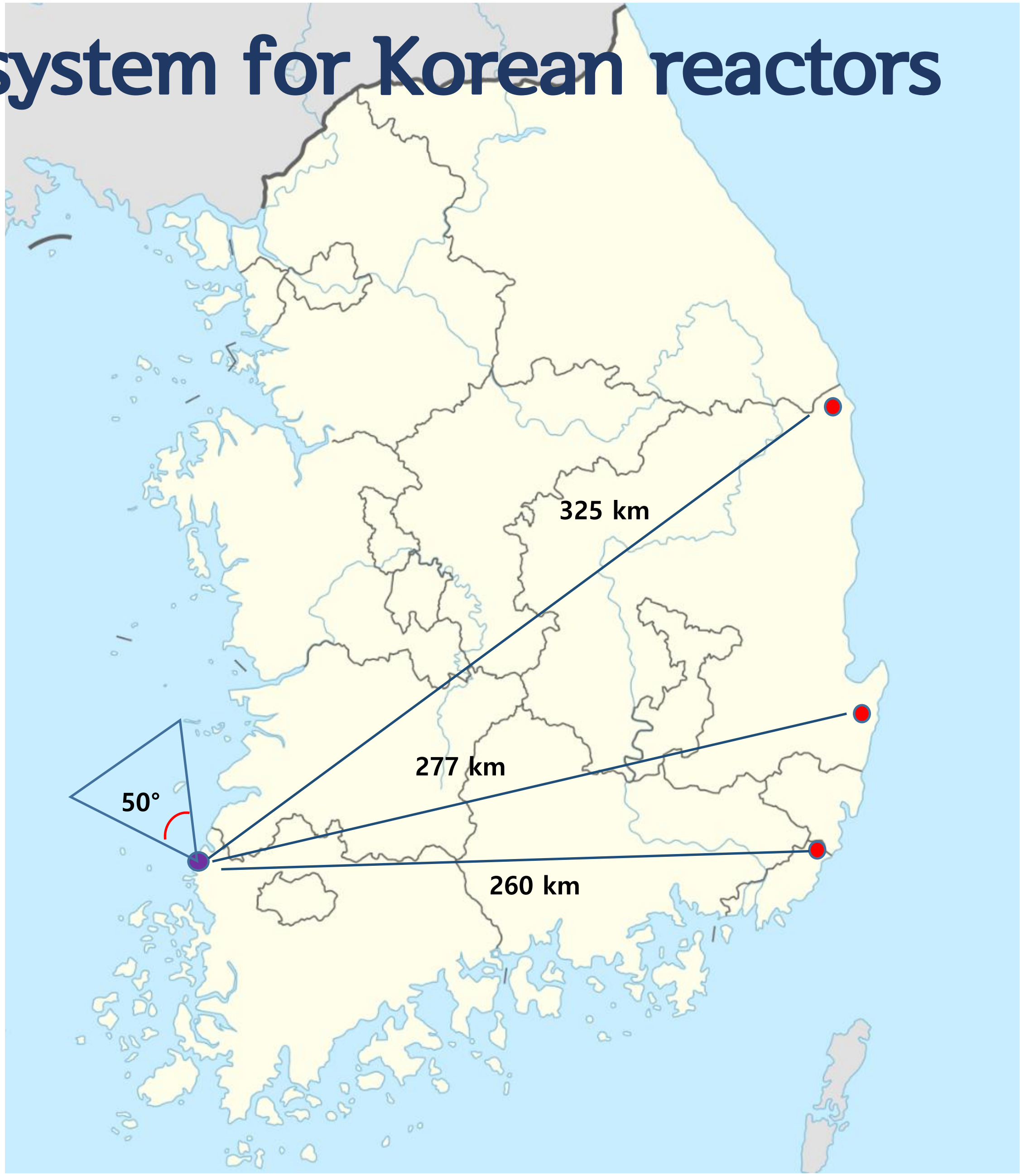
2825	1396
2825	1381
2825	1413
2825	1490
total	16.9 GWth



Thermal Capacity (MWth)	
Hanul	Shin-Hanul
2775	3983
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2825	
2825	
2825	
2825	
total	24.8 GWth
Wolsong	Shin-Wolsong
~~2061~~	2825
2061	2825
2061	
2061	
total	16.0 GWth
Kori	Shin-Kori
~~1723~~	2825
1882	2825
2912	
2912	
total	13.4 GWth

From PRIS at IAEA.org

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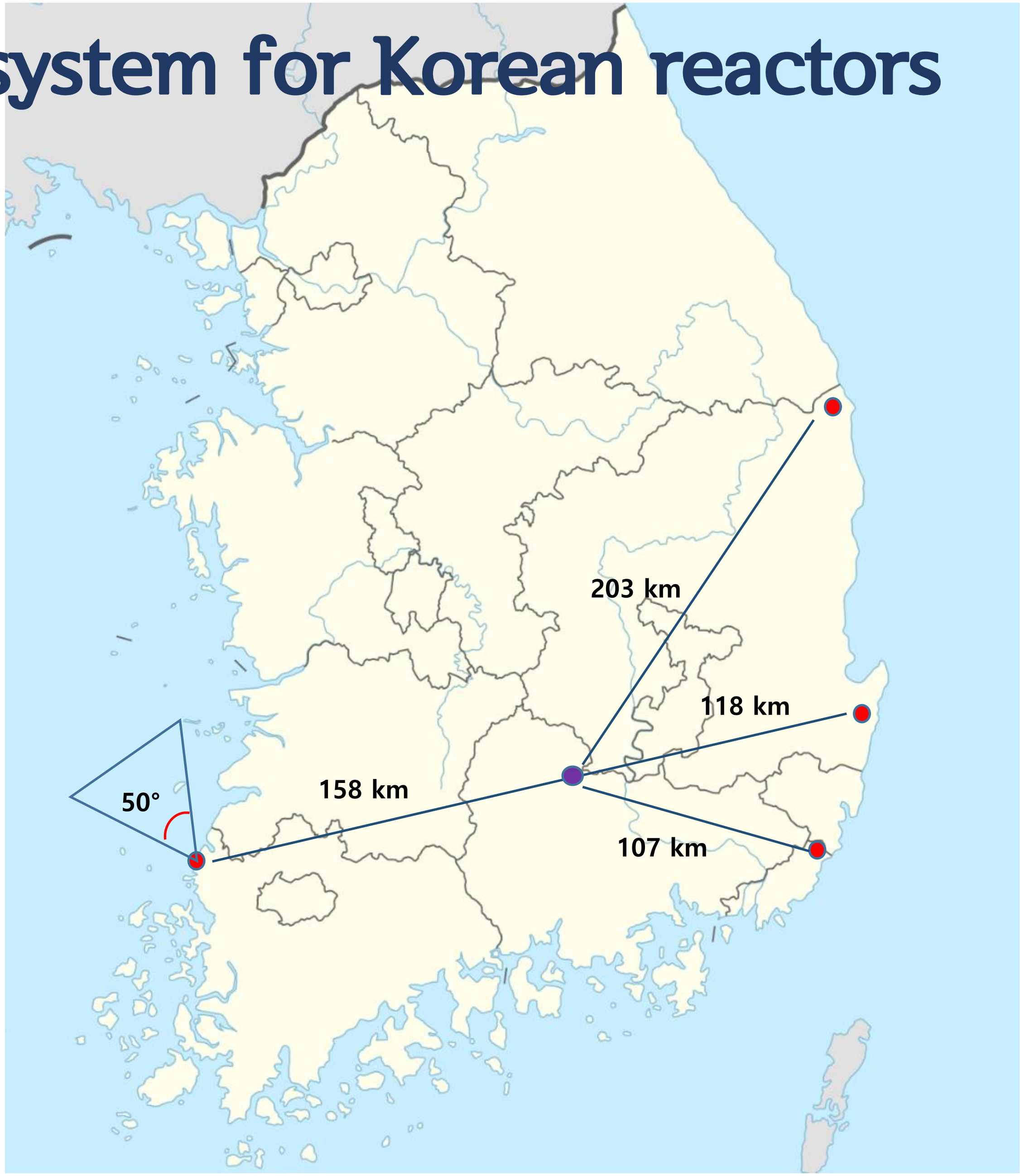

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From PRIS at IAEA.org

Eos
Neutrino Detection
Technology Demonstrator
Logan Lebanowski

Novel directional β source

Directionality clear.
Reconstruction performs well.

Goals: Direction

Source(s): $^{90}Sr \rightarrow {}^{90}Y$, endpoint 2.3 MeV
$^{106}Ru \rightarrow {}^{106}Rh$, endpoint 3.5 MeV

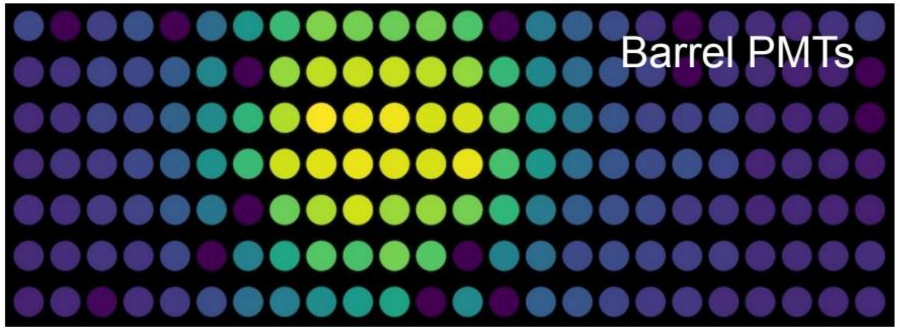
Design:

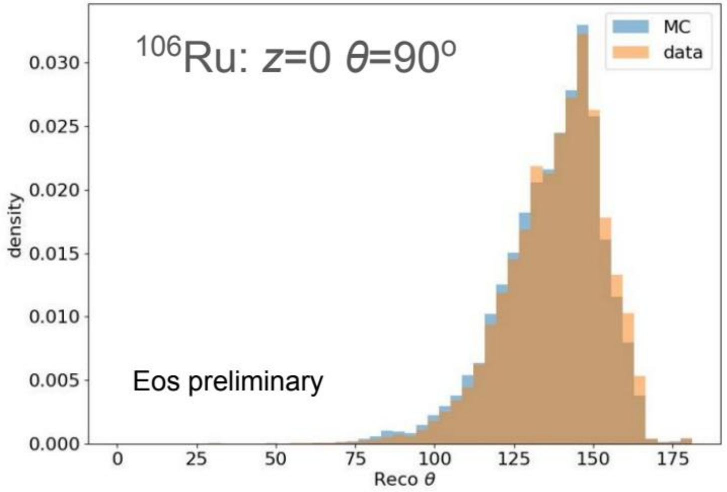
- Modestly narrow beam of collimated electrons.
- Triggering on scintillating fibers (0.2 mm ⇐⇒ 33%) viewed by two Silicon PhotoMultipliers (SiPMs).
- ~Hz of tagged events (coinc. with detect.).
- Deployed at various polar & azimuthal orientations.

Status:

- Very good performance.
- More smaller sources under construction.

θ=90°





Boston University

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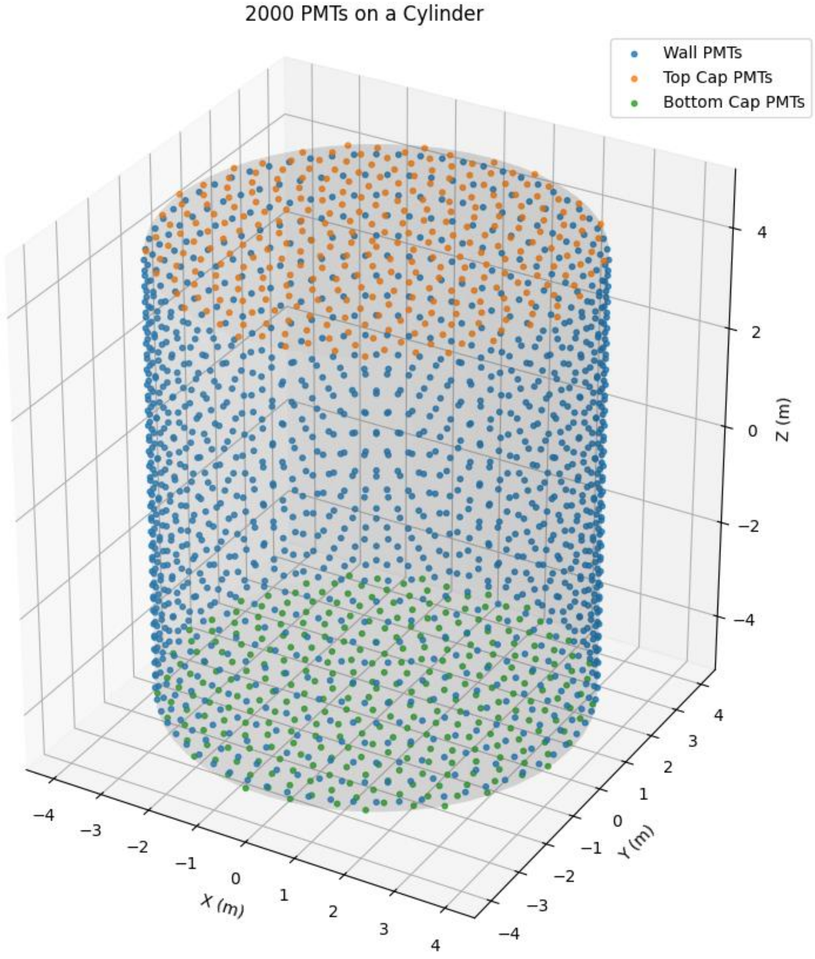
Directional Resolution of Cherenkov Light

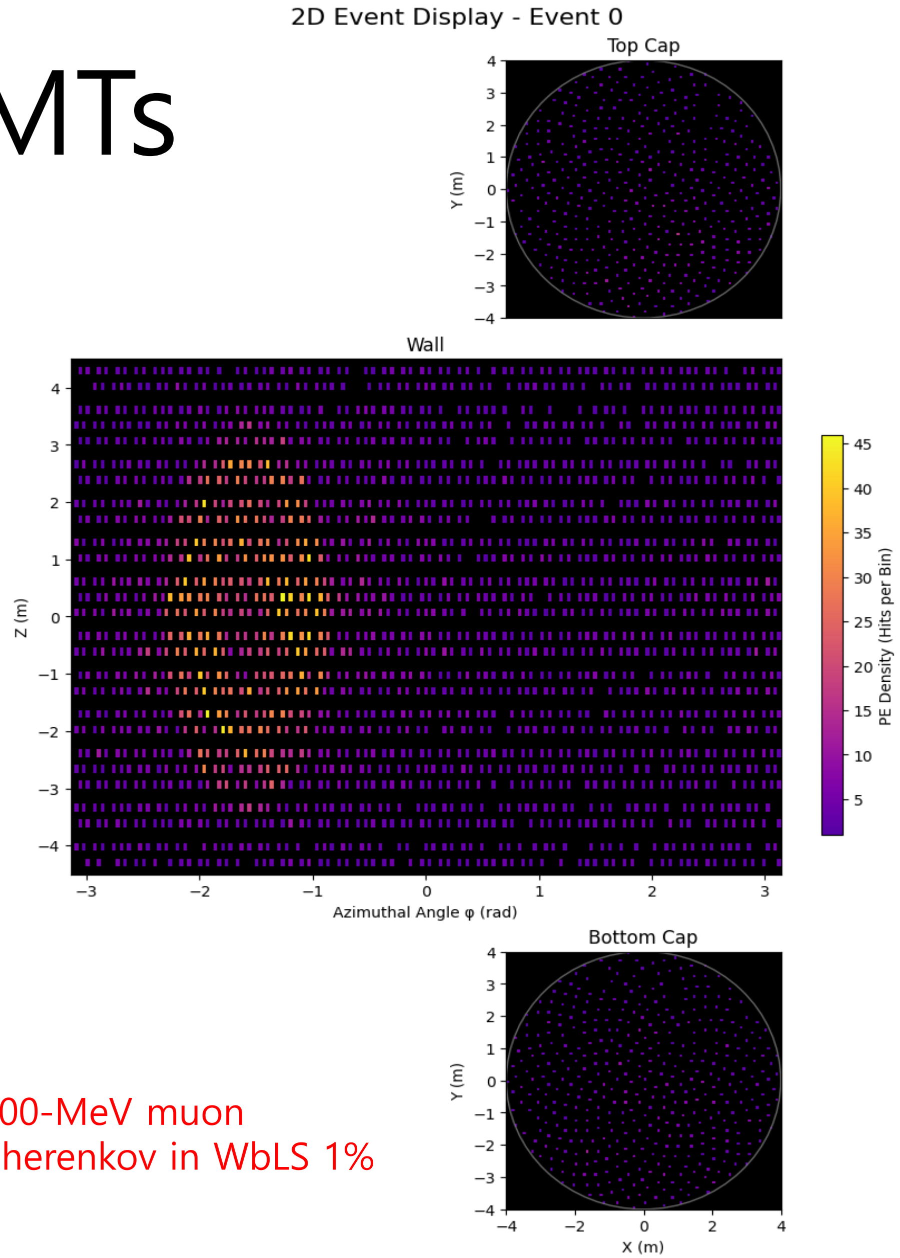
- Low-energy electrons(positrons) travel only centimeters in water.
  Length of the cone = track length
  The light from a few centimeter–cone can be detected by kton detector?

- Scattering angles are big for IBD events.
  How big?
  80~90 degree or isotropic?

RENO Well with 2000 PMTs

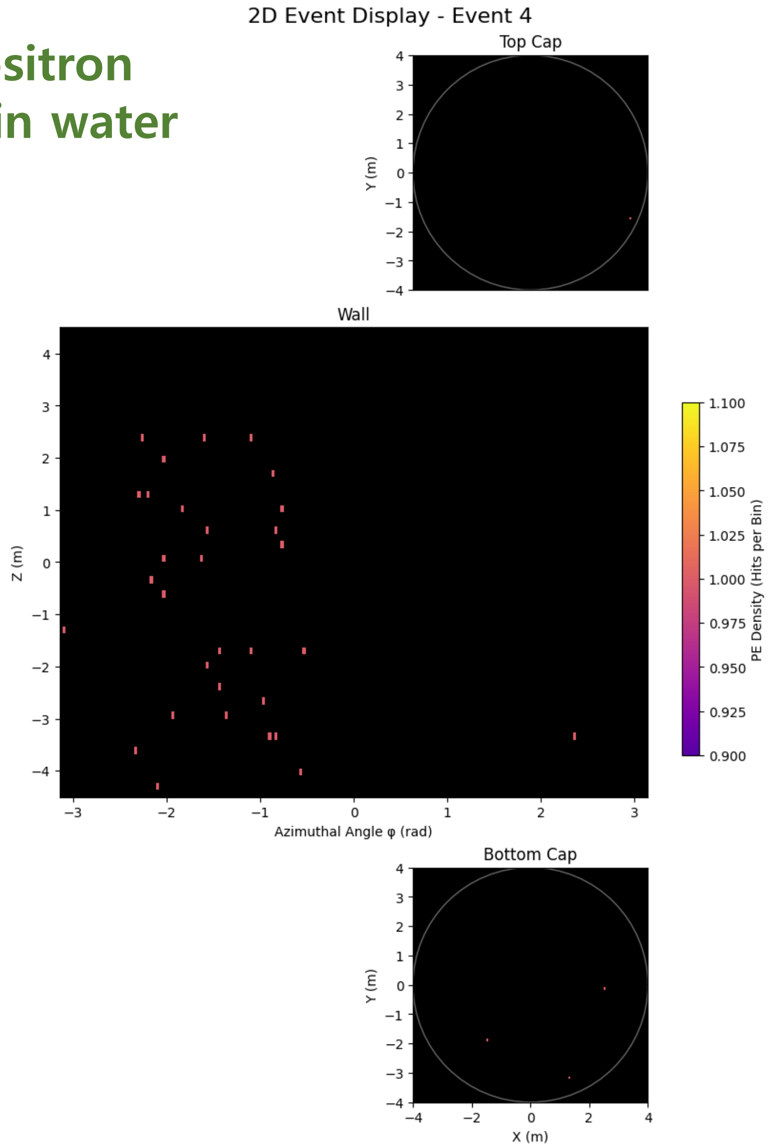
Thanks to
권순우
(RatPAC)



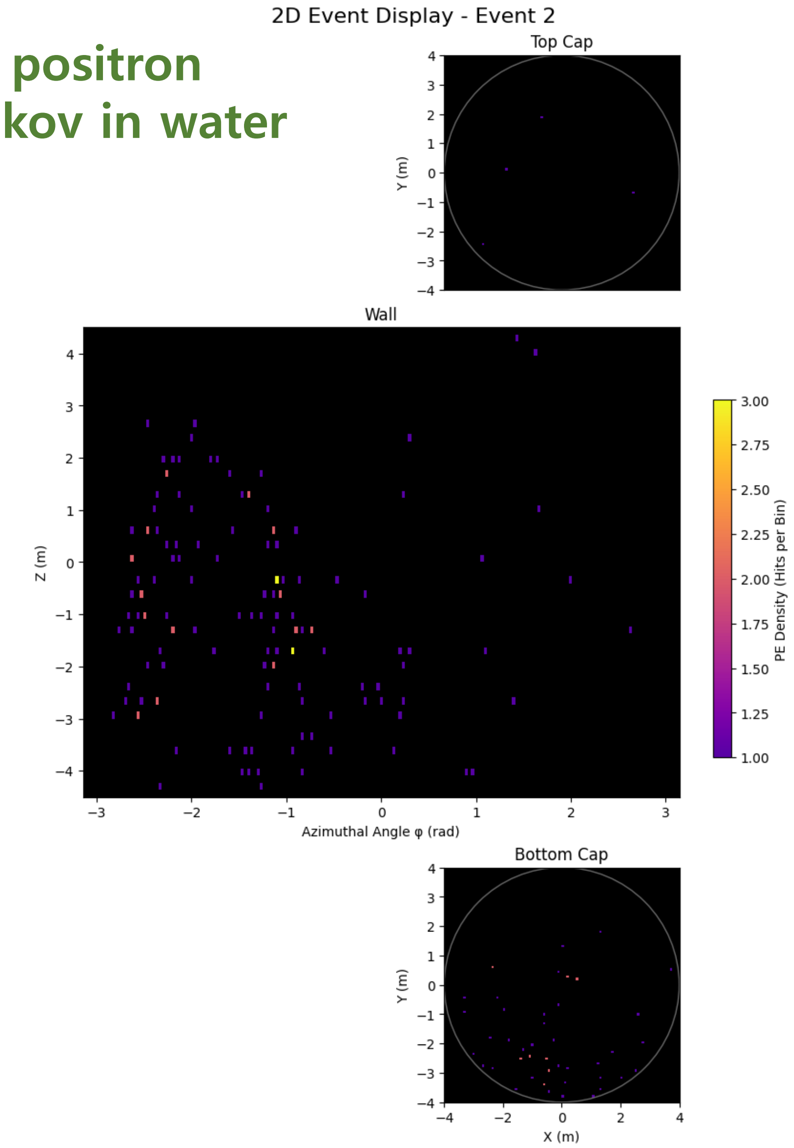


500-MeV muon
Cherenkov in WbLS 1%

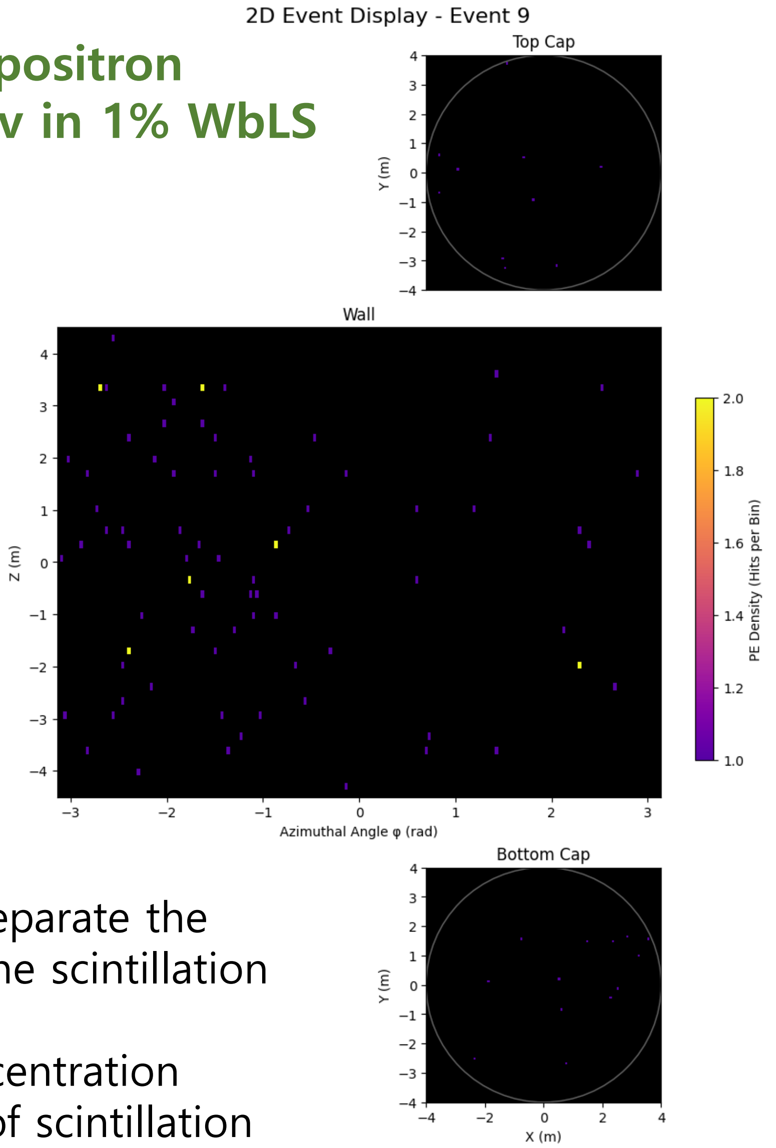
2.7-MeV positron Cherenkov in water



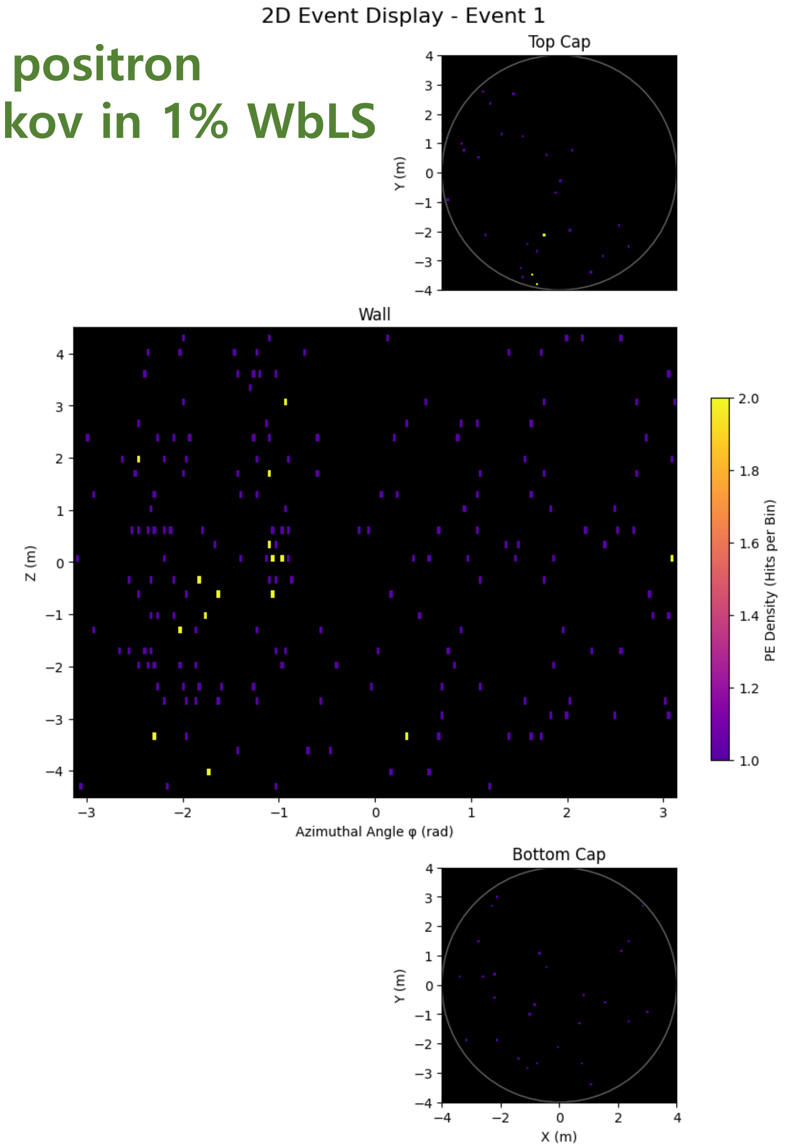
8-MeV positron Cherenkov in water



2.7-MeV positron Cherenkov in 1% WbLS



8-MeV positron Cherenkov in 1% WbLS



Find the way to separate the Cherenkov from the scintillation
- # of PMT's
- Reduce the concentration
- Delay the time of scintillation

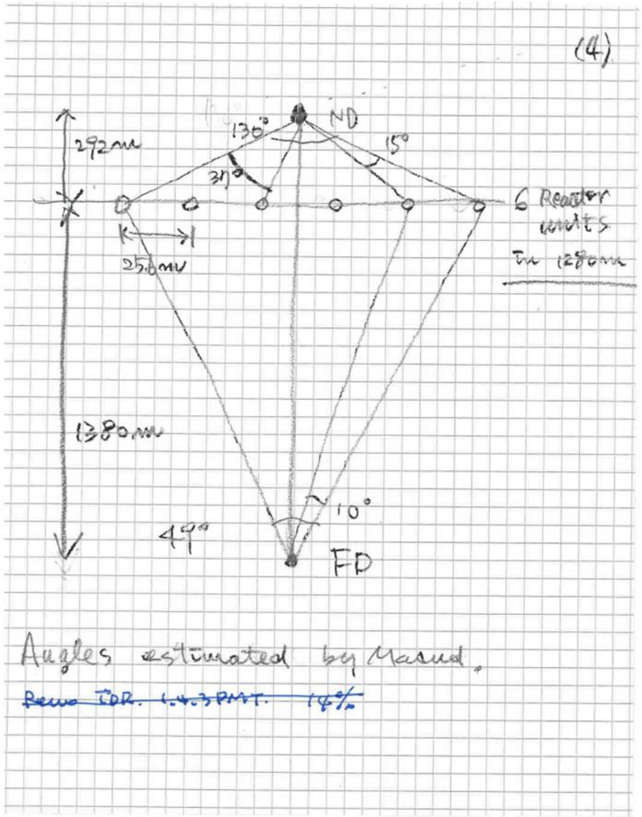
Angular distribution of neutron inverse beta decay, anti-neutrino(e) + p ---> e+ + n

P. Vogel (Caltech), John F. Beacom (Caltech)

Mar, 1999

10 pages
Published in: *Phys.Rev.D* 60 (1999) 053003

- Scattering by 91~93 degree -> Slightly backward!



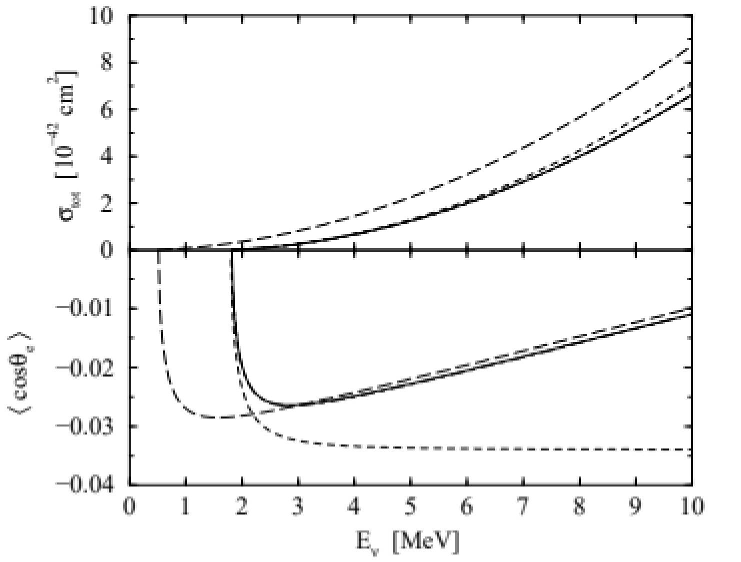


FIG. 1. Upper panel: total cross section for $\bar{\nu}_e + p \rightarrow e^+ + n$; bottom panel: $\langle \cos\theta \rangle$ for the same reaction; both as a function of the antineutrino energy. The solid line is our $\mathcal{O}(1/M)$ result and the short-dashed line is the $\mathcal{O}(1)$ result. The

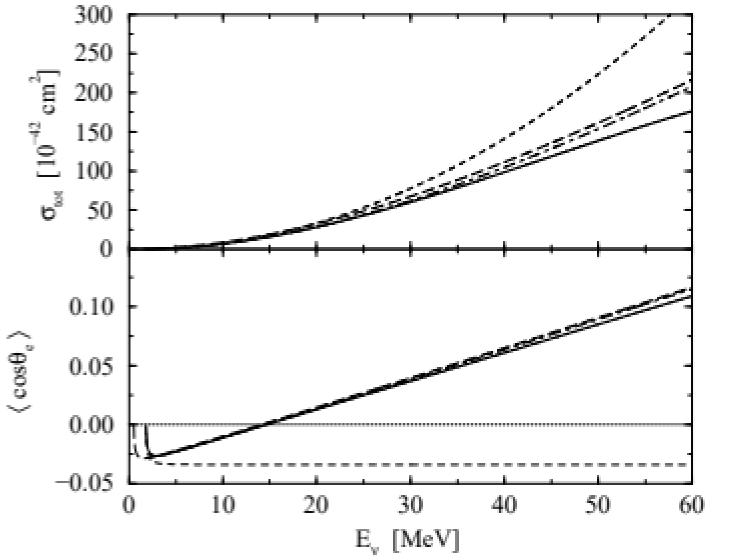


FIG. 2. The same as Fig. 1, but over a larger range of antineutrino energy. The long-dashed and dot-dashed lines are nearly indistinguishable in the lower panel.

Concluding Remarks

WIND (WbLS in RENO FD)

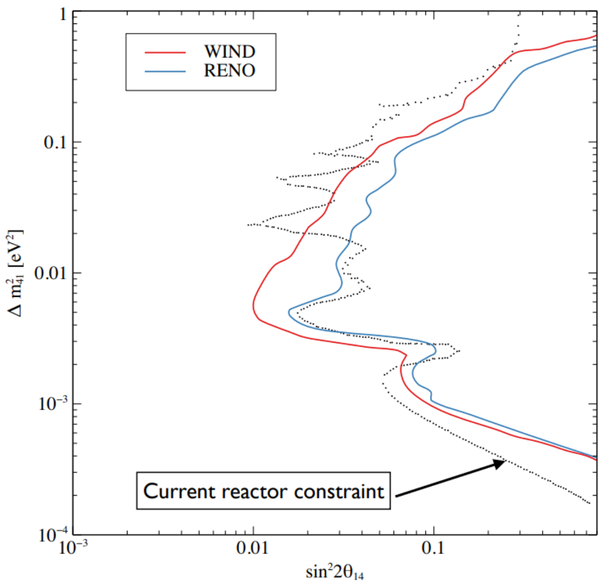
WbLS is a novel type of particle detector to take advantage of both Cherenkov and scintillation light detection.

- Cherencov >> Directional info and fast timing
- Scintillation >> High LY and good energy resolution

RENO Site
- Renovate and reuse the neutrino detector hall and the well.
- Good size and distances from reactor plants in South Korea.
- Chance to validate the 5-MeV excess issue with water target.

Mehedi Masud for KPS 2025

WIND : sterile neutrino



$$P_{ee} \simeq 1 - \sin^2\theta_{ee}\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

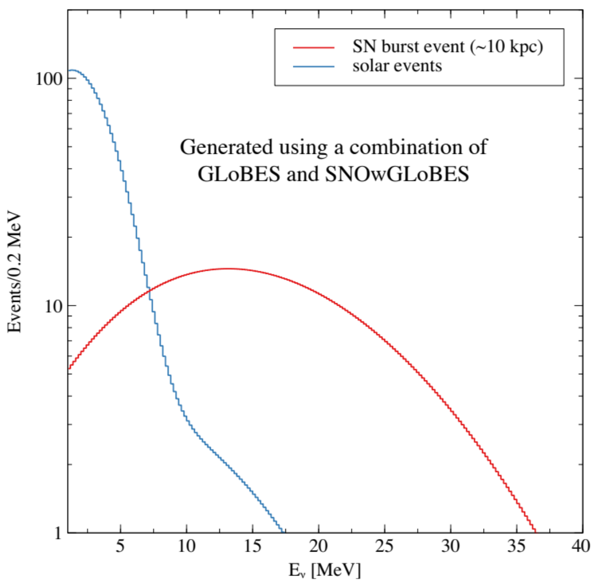
where

$$\sin^2\theta_{ee} = \sin^2\theta_{ee}(\theta_{14}, \theta_{12}, \theta_{13})$$

$$\chi^2 = \sum_{i=1}^{N_E} \frac{\left(O_i^{F/N} - T_i^{F/N}\right)^2}{U_i^{F/N}} + \sum_{d=N,F}\left(\frac{b^d}{\sigma^d_{\rm bkg}}\right)^2 + \sum_{r=1}^{6}\left(\frac{f_r}{\sigma^r_{\rm flux}}\right)^2 + \left(\frac{\epsilon}{\sigma_{\rm eff}}\right)^2 + \left(\frac{\eta}{\sigma_{\rm scale}}\right)^2,$$

GLoBES can be used for implementing sterile neutrinos and various systematic uncertainties for χ^2 calculation

WIND : looking into the sky



Substantial events from Sun and a future galactic Supernova burst

Directionality can be leveraged to identify events

Possibility of:

- Precision study for $\Delta m^2_{21}, \theta_{12}$
- Day-night asymmetry, matter effects, NSI
- Supernova constraints (e.g., using light bosons)
- ……

Projects of Water-Based Liquid Scintillator

Project	Size	Purpose	Status
BNL 1-ton WbLS	1 ton	- Study light yield, timing, and scaling potential	Operation
BNL 30-ton WbLS	30 ton	- To characterize the properties of WBLS as prototype for large-scale neutrino experiments - Aiming to evaluate the scalability and stability - Testbed for refining WbLS formulations, purification techniques, and deployment methods.	Operation Mixing LS
EOS (UC Berkeley)	4 ton	- 240 PMT - The separation of Cherenkov and scintillation at a multi-ton scale. - Directional Resolution with beta sources. - Advanced photodetector technologies, e.g., fast-timing PMTs and Dichroic filters for spectral photon sorting. - Expecting insights for the design of larger-scale detectors	Commissioning
Theia-25 Theia-100	25 kton 100 kton	DUNE FD4 Neutrinoless Double Beta Decays	Conceptual Design

Projects of Water-Based Liquid Scintillator

Project	Size	Purpose	Status
ANNIE (Accelerator Neutrino Neutron Interaction Experiment)	366 liters	- Neutron yields from nu-nucleus interaction - Fermilab - Neutron tagging in a beam environment	Operation
CHESS (Cherenkov and Scintillation Separation)	~liters	- Tabletop scale - To study the separation of Cherenkov and scintillation light in WbLS operation	R&D
WATCHMAN (WATer Cherenkov Monitor for Anti-Neutrinos)	1 kton	- Under consideration for AIT-NEO (Advanced Instrumentation Testbed-Neutrino Expt. One) - The feasibility of remote monitoring of nuclear reactors via antineutrino detection. - To utilize WbLS to improve sensitivity to antineutrino signals - USA and UK	Under Development

WATCHMAN for Non-Proliferation

- 1100-m Boulby Underground Laboratory
- 1-kton WATCHMAN
- 30-ton BUTTON (Boulby Underground Technology Testbed for Observing Neutrinos)
  >> Button1000
- Hartlepool Reactor
  - 26 km from Boulby
  - 2 cores of 1.5 GW$_{th}$
- Heysham Reactor
  - 148 km from Boulby
  - 4 cores of 1.5 GW$_{th}$