중성미자 하이라이트

양병수 (전남대)

2025.11.22

전남대학교

한국물리학회 핵,입자,천체물리학 분과 합동 워크샵 및
한국고에너지물리학회 2025 가을학술대회

소개하는 실험들

도움주신 분들: 김시연, 서지웅, 안무현, 유인태, 유종희, 이강영, 주경광, 정다은, 하창현

- RENO
- RENE
- IceCube
- Super-Kamiokande
- Hyper-Kamiokande
- KNO
- Donghae

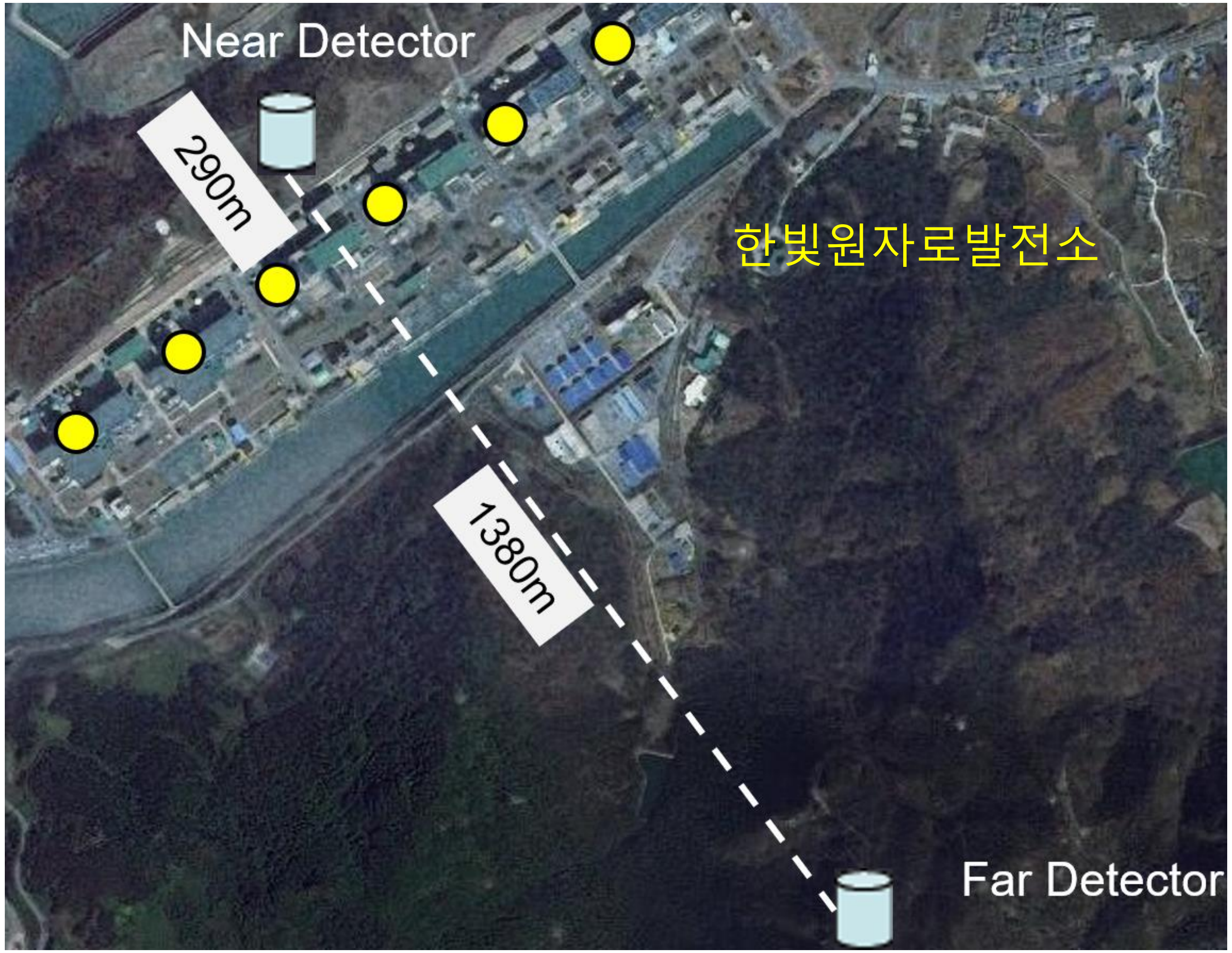
- DUNE
- JSNS^2
- COHERENT: CENNS-1ton
- SND@LHC

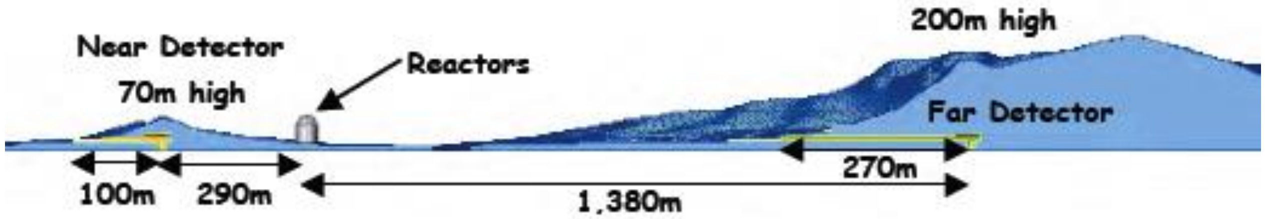
IBS 중성미자 실험 발표
- Highlight from IBS-Center for Underground Physics (김영덕 (IBS))
- 예미랩 중성미자 검출기 (원은일 (고려대학교))

RENO

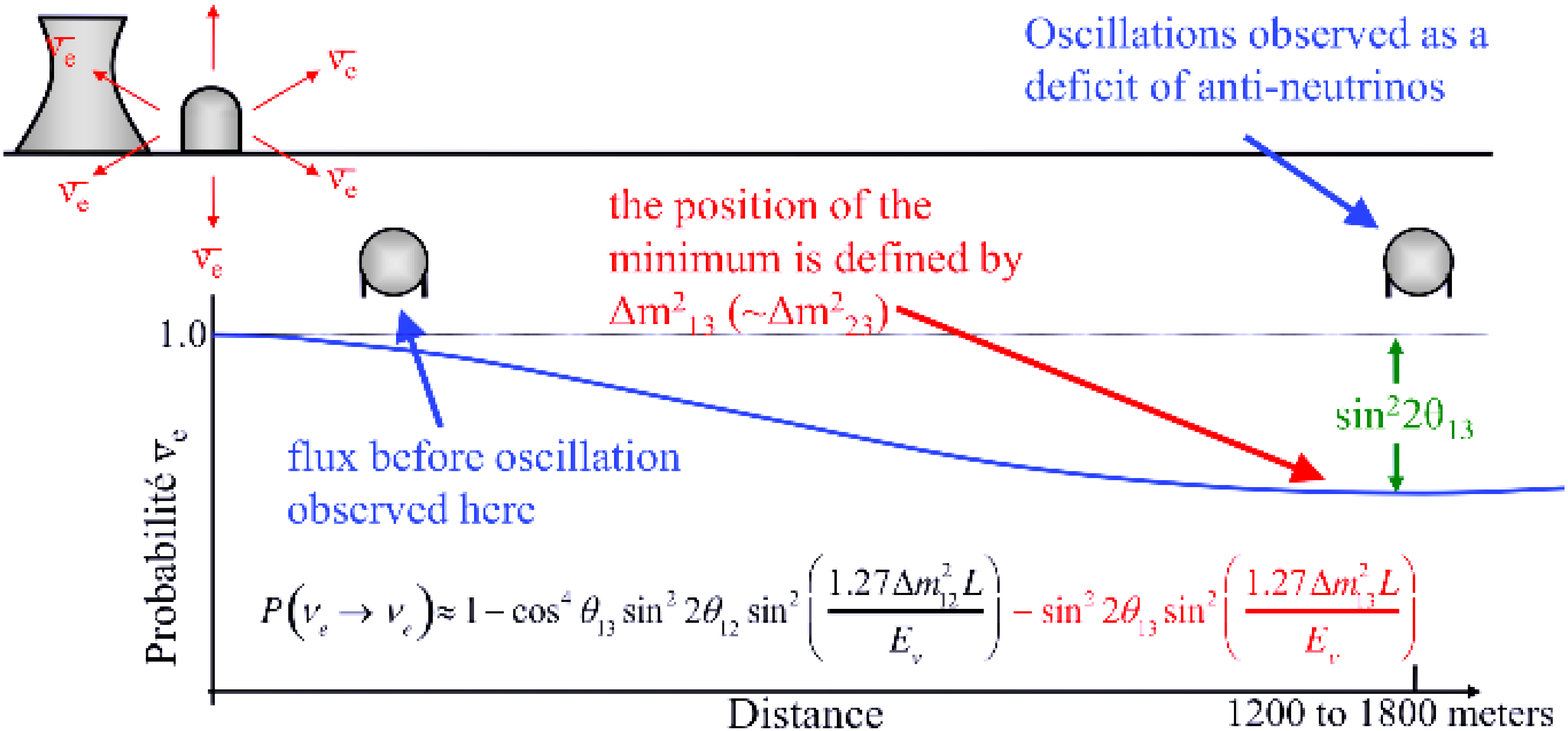
(Reactor Experiment for Neutrino Oscillation)

- 중성미자 진동 파라메터인 θ_{13} 측정 목표.
- 현재 7개 기관에서 약 30명 참여.
- 2011.08 – 2023.03 데이터 수집.





RENO 실험의 방법


Oscillations observed as a deficit of anti-neutrinos
the position of the minimum is defined by Δm^2_{13} ($\sim\Delta m^2_{23}$)
flux before oscillation observed here
1.0
$\sin^2 2\theta_{13}$
Probabilité ν_e
Distance
1200 to 1800 meters
$P(\nu_e \to \nu_e) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{1.27\Delta m^2_{12}L}{E_\nu}\right) - \sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{13}L}{E_\nu}\right)$

RENO 연구단의 현황

- RENO 근거리 근시일 내 재가동 예정. RENE와 함께 데이터 수집 예정.
- RENO 3800일 데이터를 사용한 최종 결과 출판 혹은 준비 중.
  - 2025년 6월: nGd 채널을 사용한 중성미자 진동 파라메터 측정 결과 출판
  - 그 외 다른 연구도 근시일 내 투고 예정

PHYSICAL REVIEW D **111,** 112006 (2025)

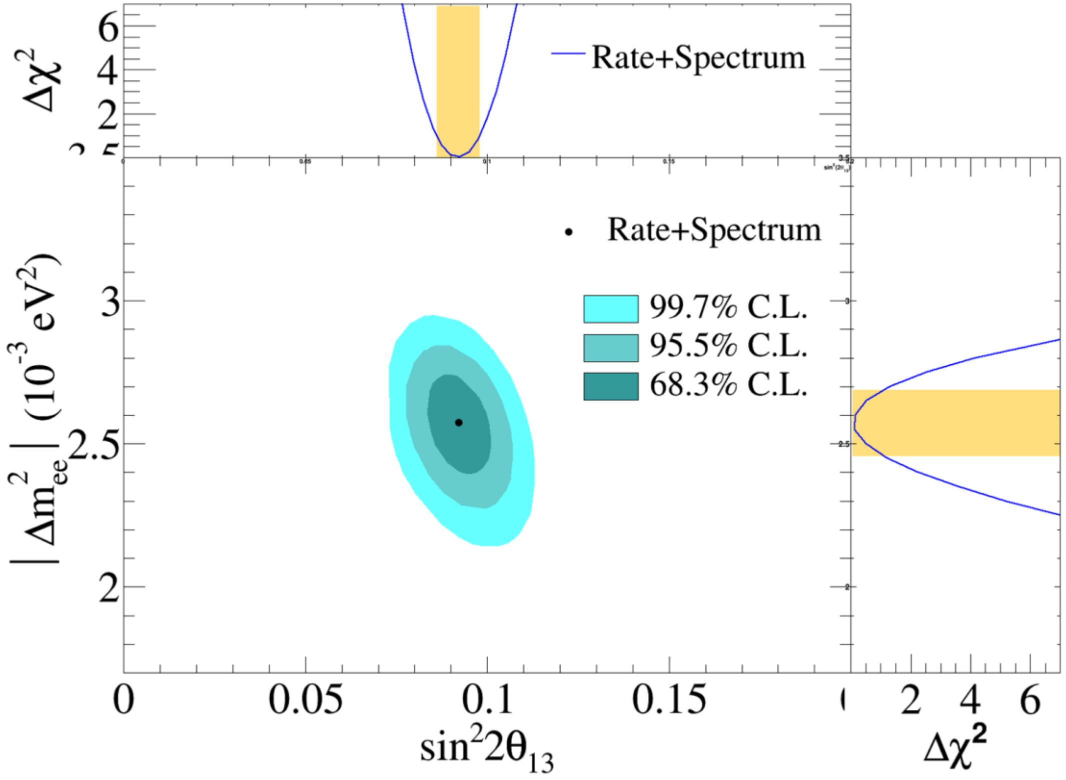
Measurement of reactor antineutrino oscillation parameters using the full 3800-day dataset of the RENO experiment

S. Jeon,[1,2,3] H. I. Kim,[2] J. H. Choi,[1] H. I. Jang,[4] J. S. Jang,[5] K. K. Joo,[6] D. E. Jung,[6] J. G. Kim,[7] J. H. Kim,[7] J. Y. Kim,[6] S. B. Kim,[2] S. Y. Kim,[6] W. Kim,[8] E. Kwon,[7] D. H. Lee,[9] H. G. Lee,[6] W. J. Lee,[2] I. T. Lim,[6] D. H. Moon,[6] M. Y. Pac,[1] J. S. Park,[8] R. G. Park,[6] H. Seo,[2] J. W. Seo,[7] C. D. Shin,[9] B. S. Yang,[6] J. Yoo,[2] S. G. Yoon,[2] I. S. Yeo,[1] and I. Yu[7]

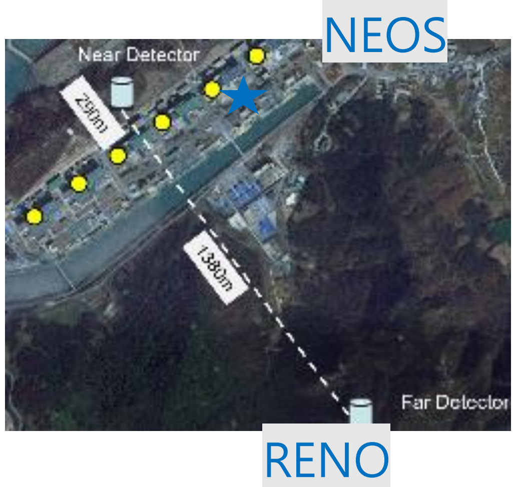
(RENO Collaboration)

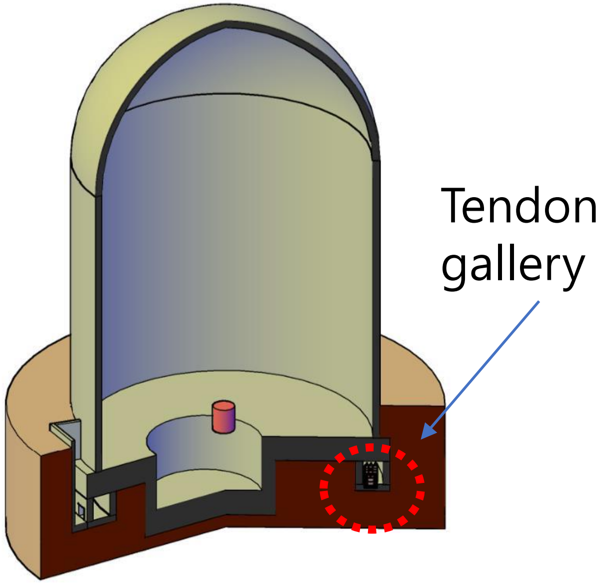
[1]*Institute for High Energy Physics, Dongshin University, Naju 58245, Korea*
[2]*Department of Physics and Astronomy, Seoul National University, Seoul 08826, Korea*
[3]*Global—Learning and Academic research institution for Master's PhD students, and Postdocs, Kyungpook National University, Daegu 41566, Korea*
[4]*Department of Fire Safety, Seoyeong University, Gwangju 61268, Korea*
[5]*Gwangju Institute of Science and Technology, Gwangju 61005, Korea*
[6]*Department of Physics, Chonnam National University, Gwangju 61186, Korea*
[7]*Department of Physics, Sungkyunkwan University, Suwon 16419, Korea*
[8]*Department of Physics, Kyungpook National University, Daegu 41566, Korea*
[9]*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan*

(Received 1 January 2025; accepted 22 April 2025; published 17 June 2025)



RENE
(Reactor Experiment for Neutrino and Exotics)





- RENO-NEOS 공동연구의 결과에서 얻어진 불활성중성미자 진동의 흔적을 검증. (PRD 105 (2022) 111101)
- 한빛 원자력 발전소 단지 내 원자로 텐던 갤러리에 위치할 예정.
- 원자로와 거리 약 ~23m.

RENE 연구단

7th RENE collaboration meeting (2025.08.25)

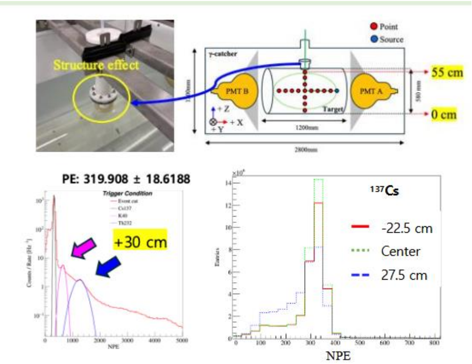
CPNR
주축

- 2022년 가을 발족.
- 11개 연구소, 약 30여명

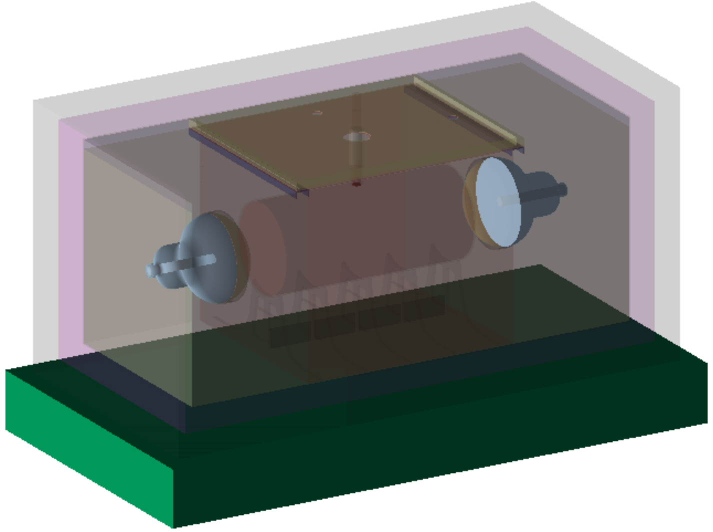
RENE Detector Construction @CNU

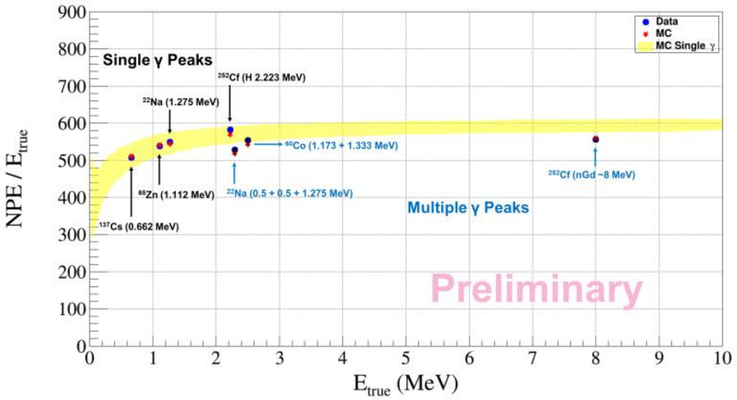
RENE Detector Commissioning @CNU

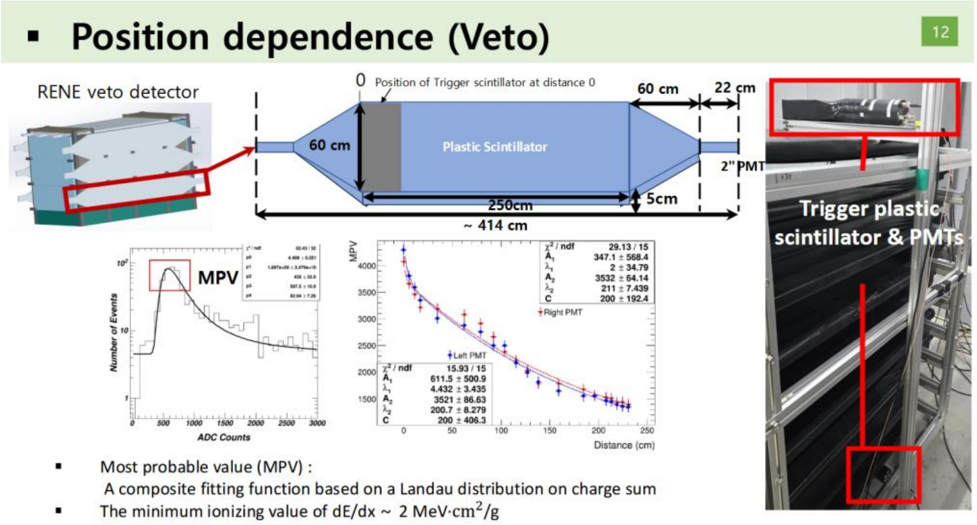
Calibration rod



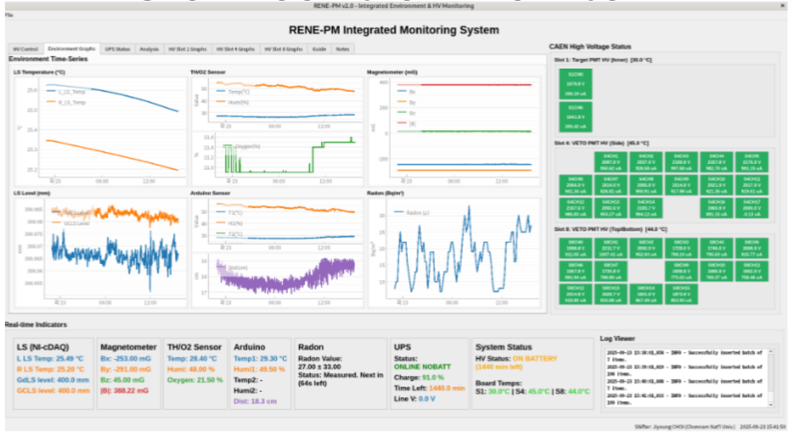
MC simulation







Slow control monitor



RENE 연구단의 현황

- 전남대에서 검출기 시운전 및 성능 검증.
- 가까운 시일 내 영광 이동 예정

- 검출기 관련 논문 출판 완료 혹은 예정.
  - 2025년 9월: Technical design report 출판
  - PMT 캘리브레이션 논문 심사 중
  - SCM 근 시일 내 투고 예정.

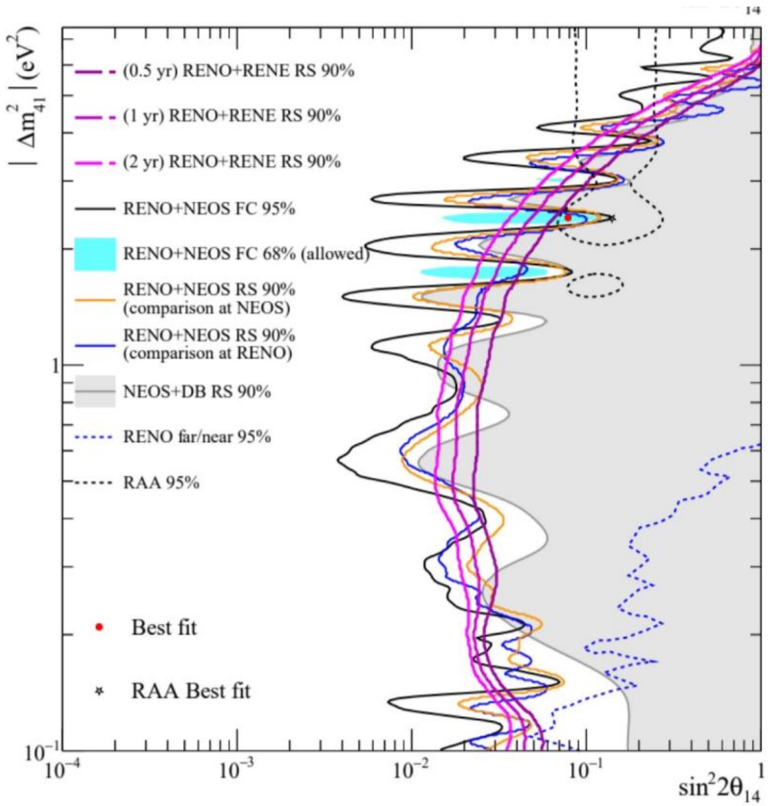

PTEP

Prog. Theor. Exp. Phys. 2025 093C03 (42 pages)
DOI: 10.1093/ptep/ptaf101

Reactor Experiment for Neutrinos and Exotics (RENE) for the Sterile Neutrino Search Using Reactor Neutrinos

Byeongsu Yang[1], Da Eun Jung[1], Dong Ho Moon[1,*], Eungyu Yun[1], HyeonWoo Park[1], Jae Sik Lee[1], Jisu Park[1], Ji Young Choi[1], Junkyo Oh[1], Kyung Kwang Joo[1], Ryeong Gyoon Park[1], Sang Yong Kim[1], Sunkyu Lee[1], Insung Yeo[2], Myoung Youl Pac[2], Jee-Seung Jang[3], Eun-Joo Kim[4], Hyunho Hwang[5], Junghwan Goh[5,†], Wonsang Hwang[5], Jiwon Ryu[6], Jungsic Park[6,‡], Kyu Jung Bae[6,§], Mingi Choe[6], SeoBeom Hong[6], Jubin Park[7], Myung-Ki Cheoun[7], Hyunsoo Kim[8], Han Il Jang[9], Dojin Kim[10], Jonghee Yoo[10], Seok-Gyeong Yoon[10], Wonjun Lee[10], and Intae Yu[11]

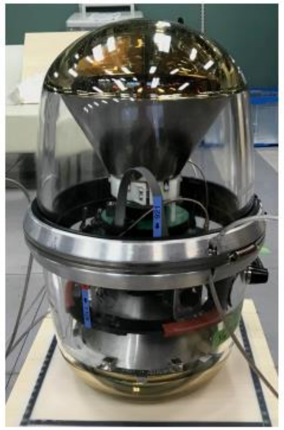
[1]*Center for Precision Neutrino Research (CPNR), Department of Physics, Chonnam National*

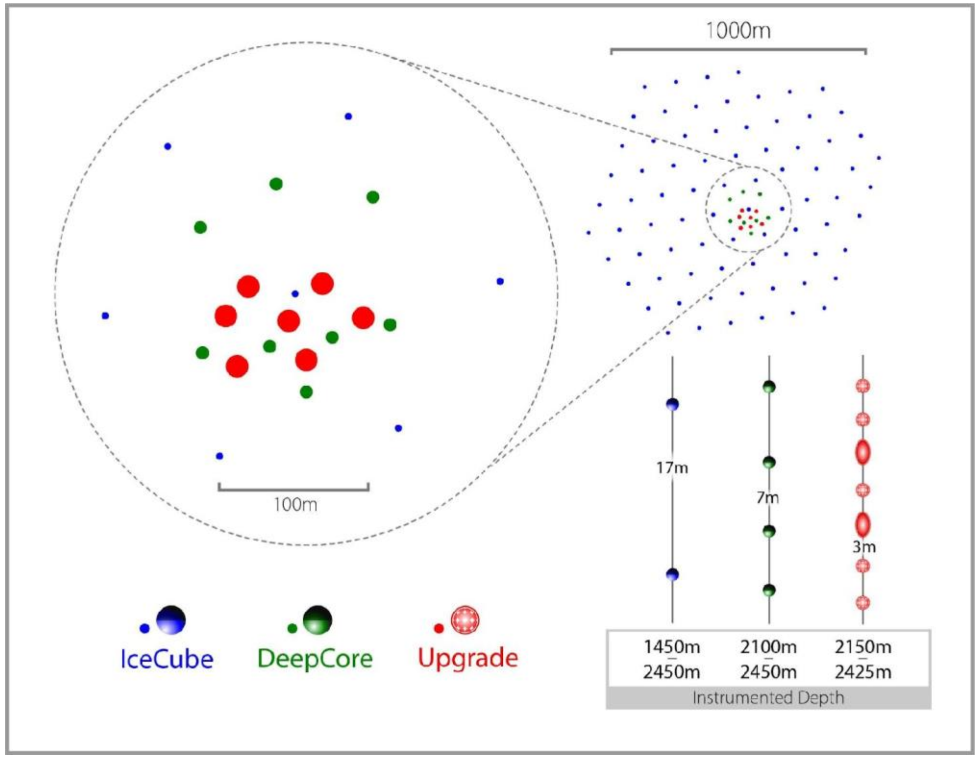


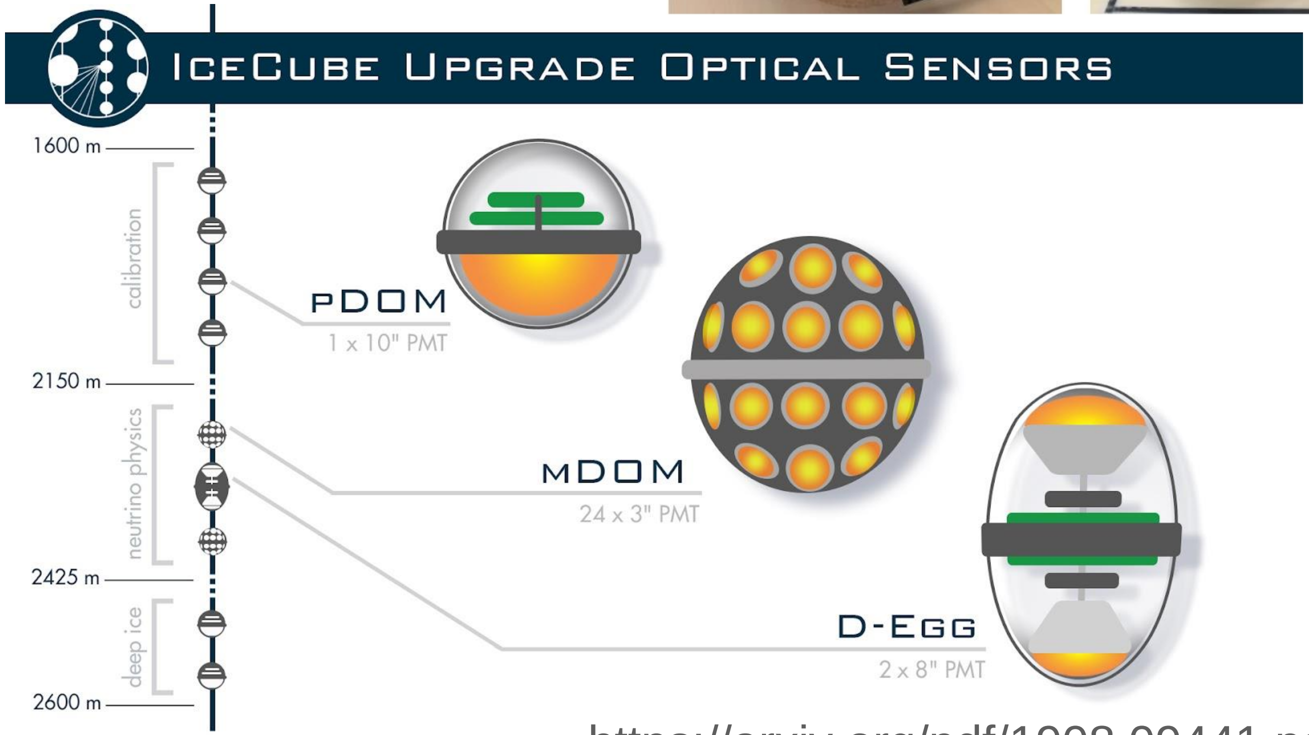
The IceCube Upgrade is starting Nov. 2025 (now)

- Instrument additional 7 strings
  - 60-100 DOMs in each string
- Detect neutrinos below 10 GeV
- Construction began and full deployment in 2025/2026
- Testbed for IceCube-Gen2

- Neutrino Oscillations study,
- Neutrino Mass Hierarchy measurement with the Upgrade.
- Neutrinos with Earth matter and density effect in varying baseline
  - Understanding the systematics is the key to the measurement
  - Additional calibration devices is going to be added







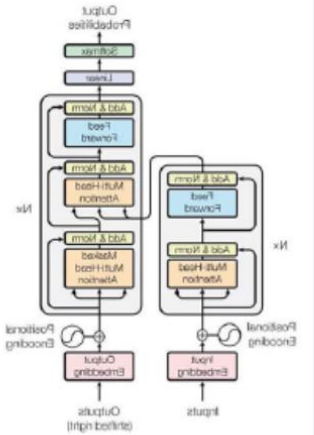
https://arxiv.org/pdf/1908.09441.pdf

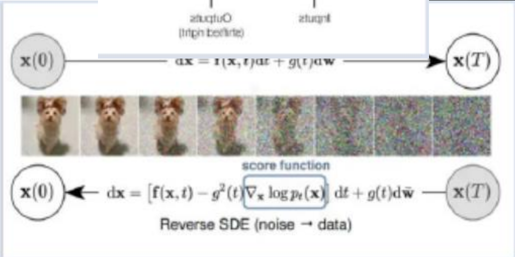
Korea IceCube Activities

IceCube @ Chung-Ang University

- Study atmospheric neutrinos. Especially electron neutrinos
- Participation in the IceCube-Upgrade simulations. i.e. Photon Propagation & mDOM response.
- Develop a low-energy reconstruction tools using Transformer-based neural network

Chang Hyon Ha Hani Kimku Sooa Kim Minsu Kwak



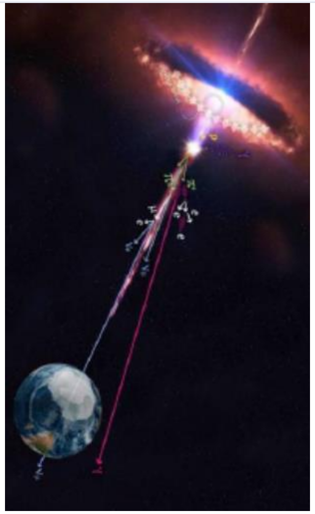


The 4th K-IceCube Workshop 2025/06/25

IceCube @ Sungkyunkwan University

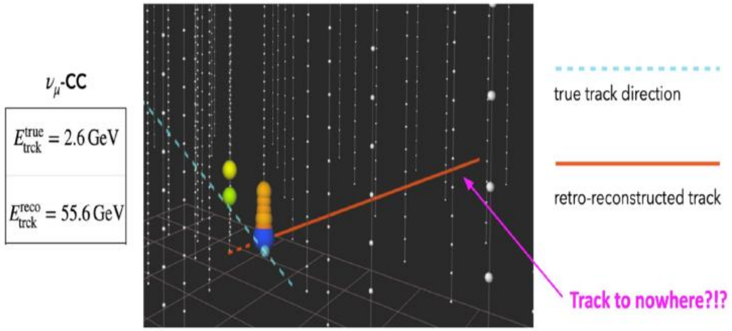
- Muon-track reconstruction using a neural network that fits Gupta–Kundu–based arrival-time PDFs
- Generative model for IceCube neutrino event simulation and end-to-end reconstruction using flow and diffusion model
- Optimize pulse cleaning and upgrade PMT noise model based on its timing and charge characteristics

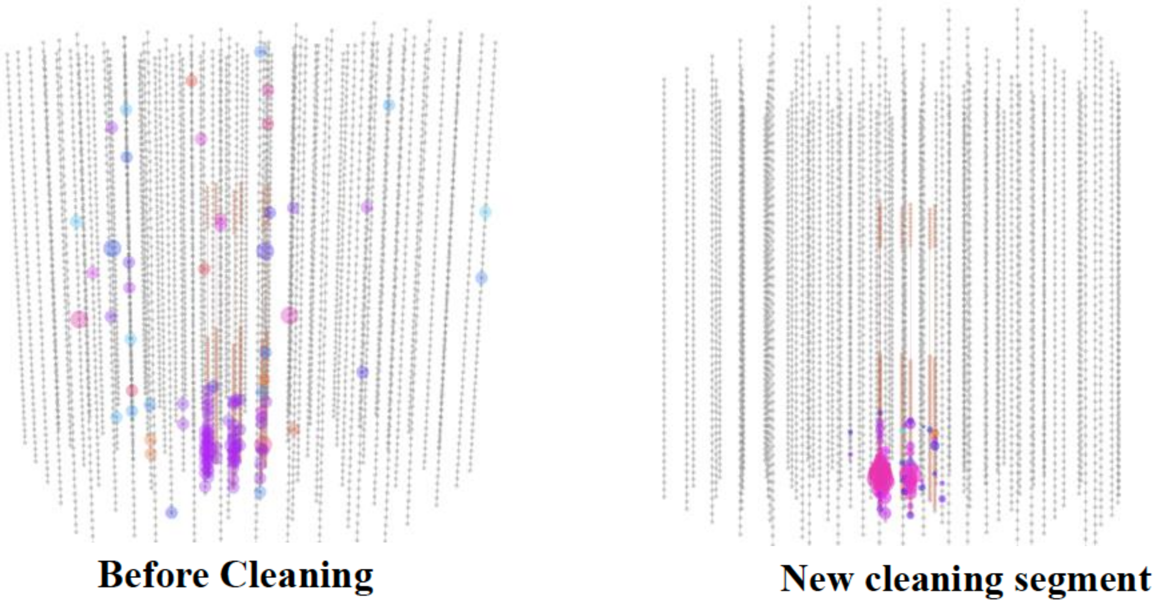
Chang Dong Rho Taeyun Kim Minje Park Jiyeong Son

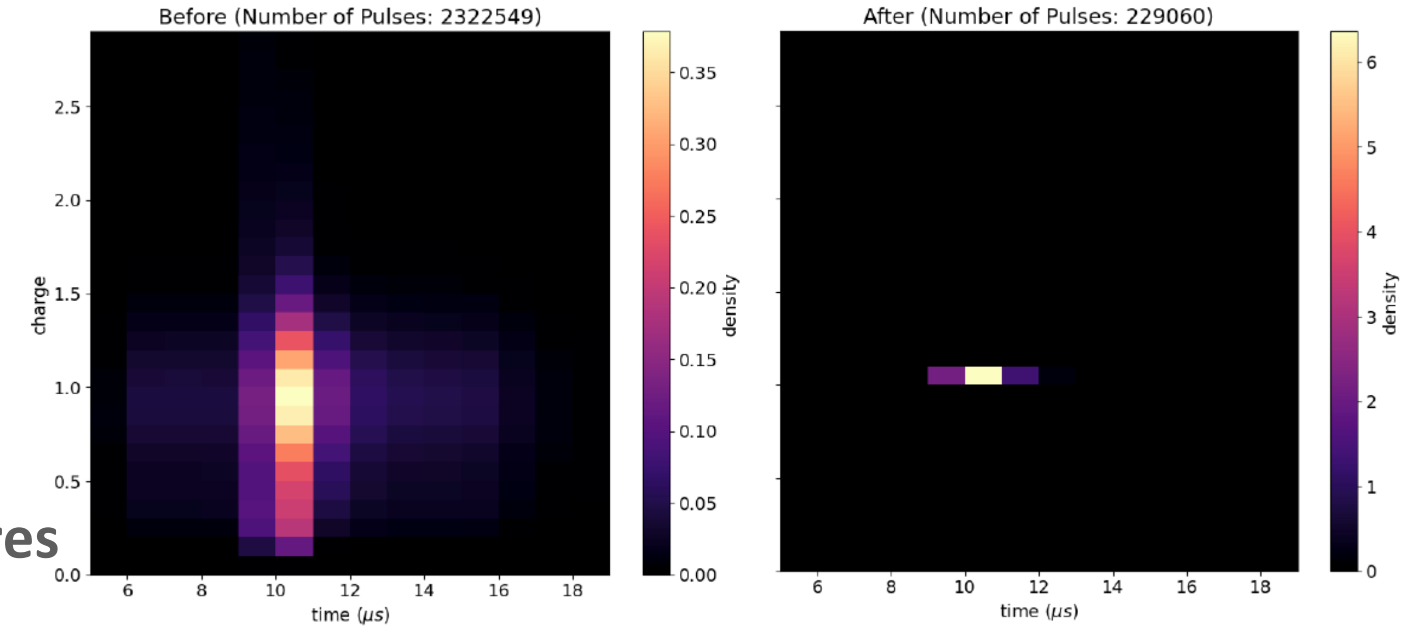


The 3rd K-IceCube Workshop 2025/02/26

IceCube Upgrade Pulse Cleaning : Modularization and Optimization (SKKU)



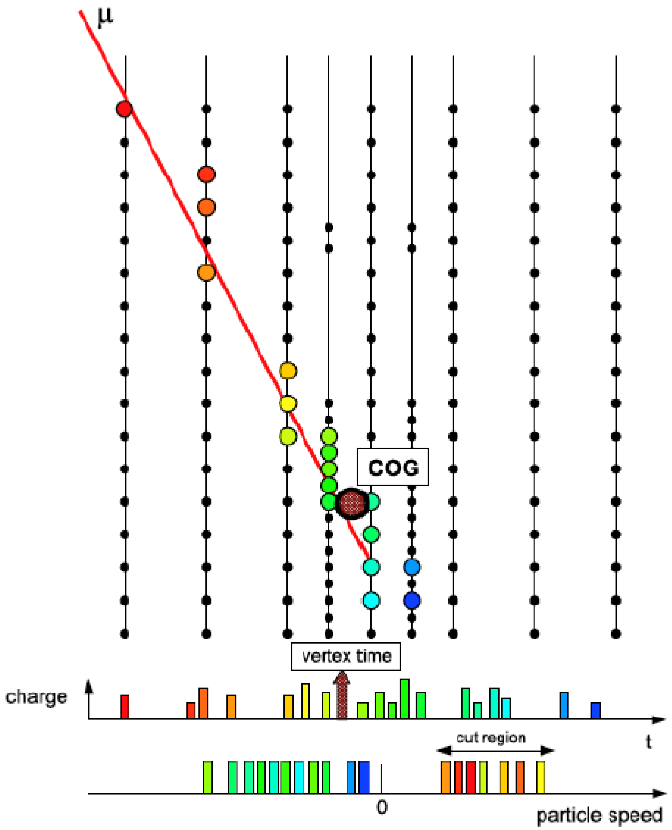


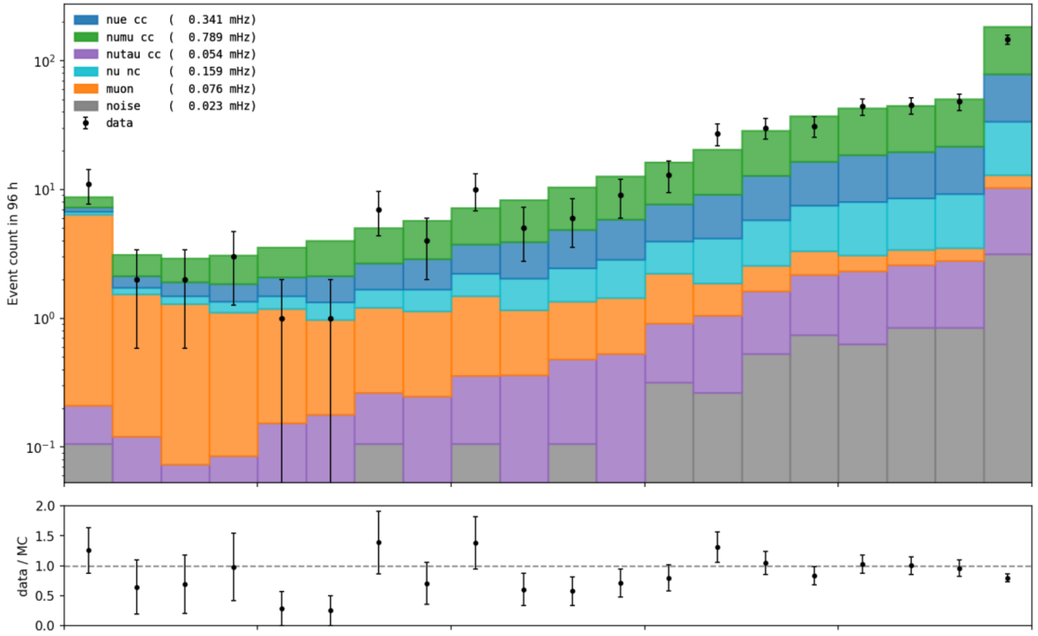


We will have ~700 PMTs in Ice which requires a superior noise cleaning.

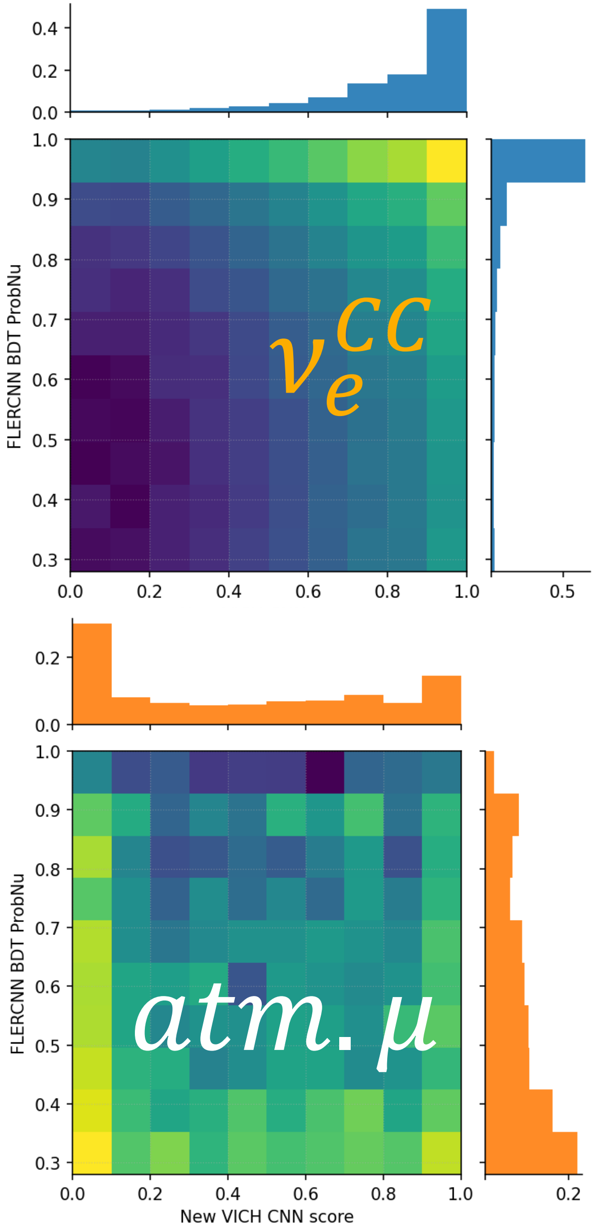
Atmospheric Neutrino Oscillation Physics at CAU

New Veto Algorithms (VICH) by CAU
Towards the Upgrade ν_e appearance analysis





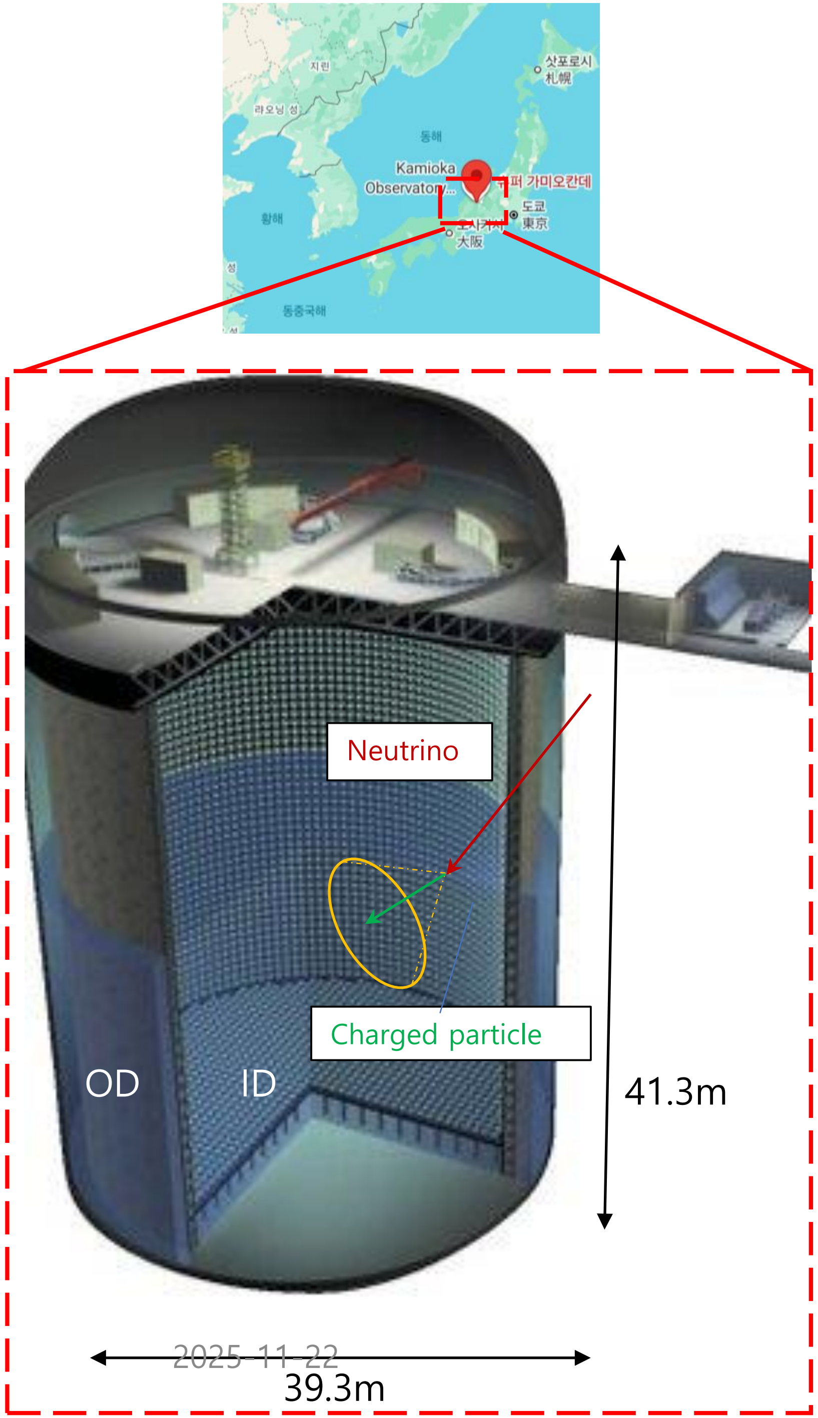
$VICHCNNScores$

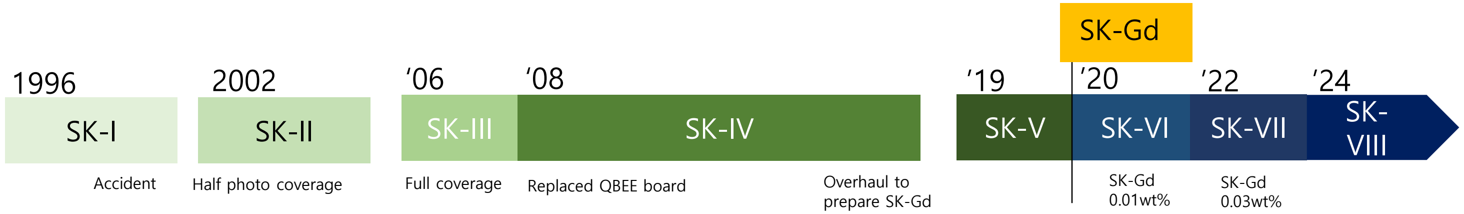


It is clear that reconstruction and PID will be two challenges in the Upgrade.

CAU will work on those in $\nu_\mu \to \nu_e$ analysis

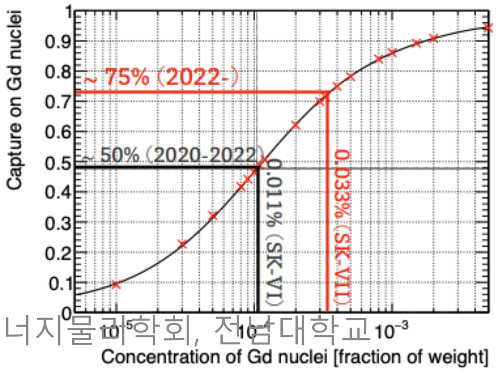
Super-Kamiokande





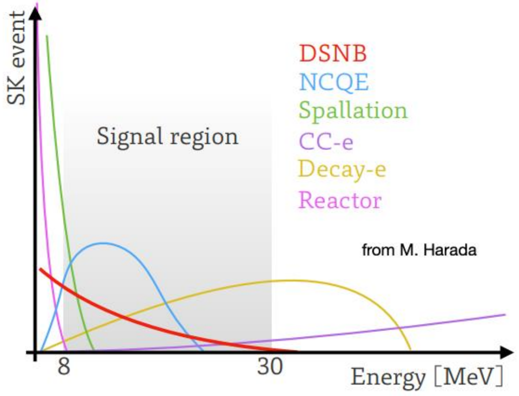
- Water Cherenkov detector
- Situated 1,000 meters underground beneath Mt. Ikenoyama
- **50kton water**
  - 1996~2020 : pure water
  - 2020~ : Gadolinium loaded water

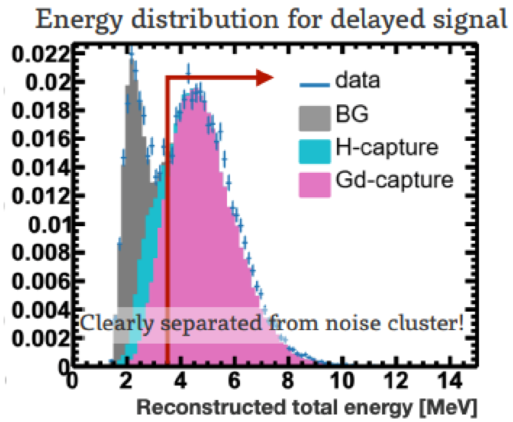
- Inner detector : 11,129 20-inch PMTs
  → Physics events of interest
- Outer detector : 1,885 8-inch PMTs
  → Background veto
- Sensitive energy : O(1)MeV~ TeV



Effect from Gd-loaded water

Study in diffuse supernova υ

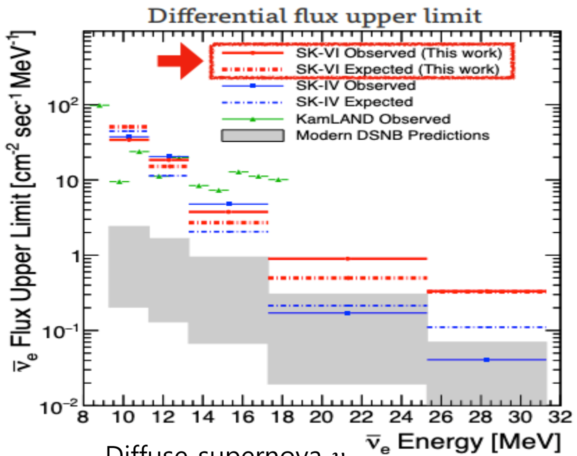




- 552.2 days with 0.01% Gd concentration (SK-VI)
- Cut based simple neutron reduction thanks to Gd

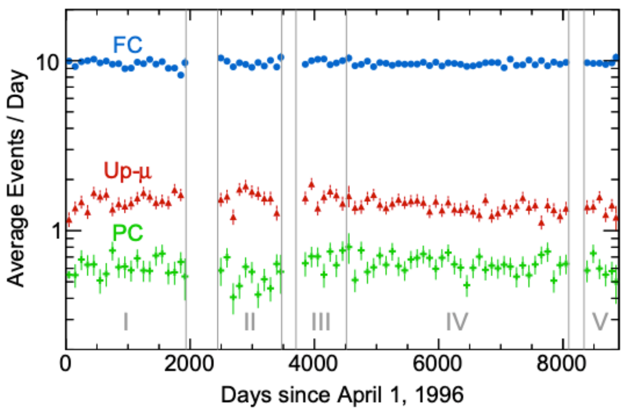
→ **36%** of n-tag. Efficiency

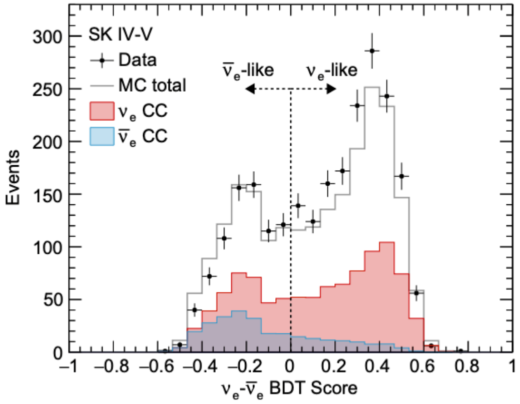
- Nn=1 event are selected as IBD candidate
- Close to 2970 days of pure-water SK (SK-IV) limit



Diffuse supernova υ

Study on Oscillation of atmospheric υ

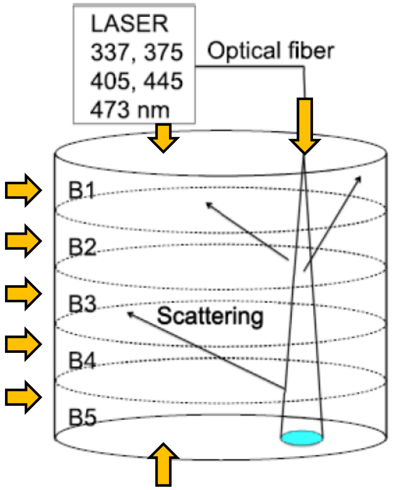


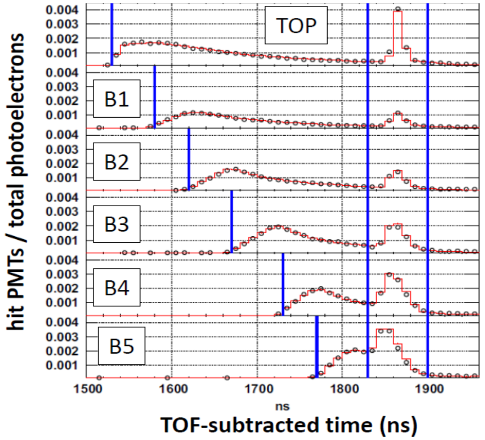


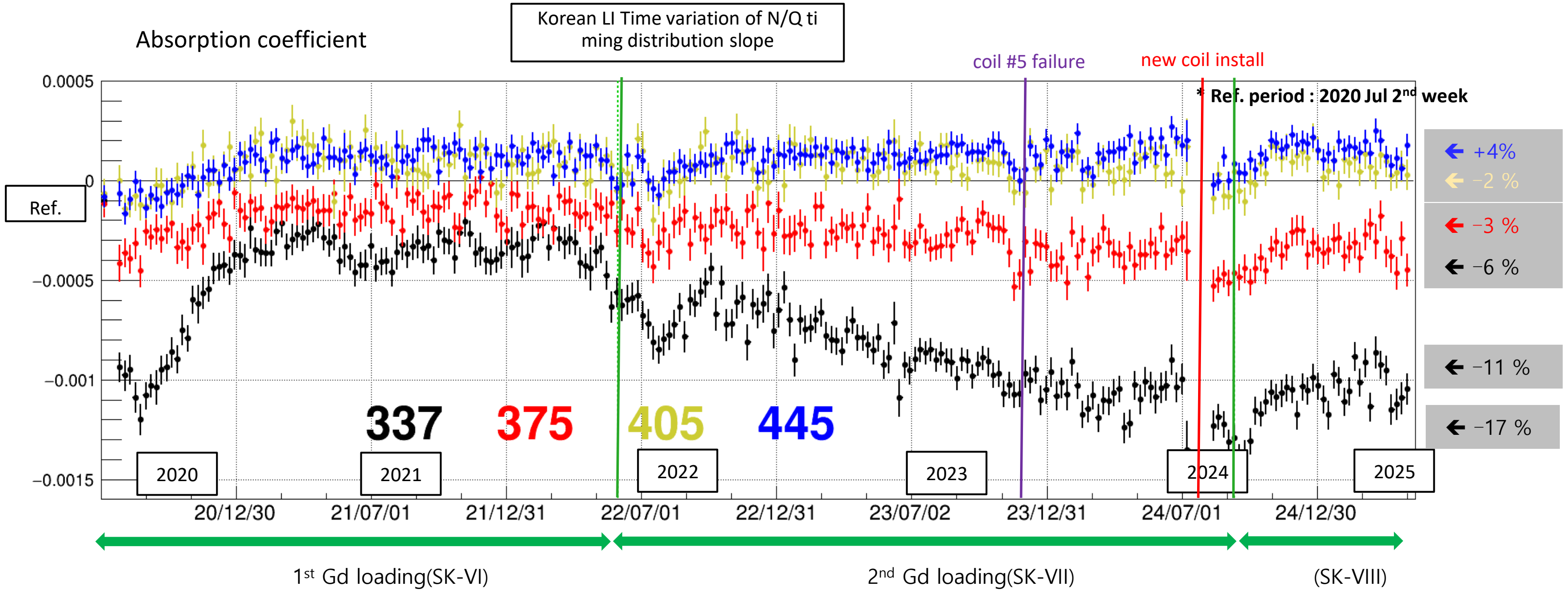
- Neutron tagging efficiency for **hydrogen** ~26 % (SK-IV, SK-V)
- Boosted decision tree (BDT) is used to classify multi ring events as νe-like, ¯νe-like. μ-like or else
- Can be compared with the result of SK-Gd phase
- Myung-gi Jo (SNU) takes a important role for this work.

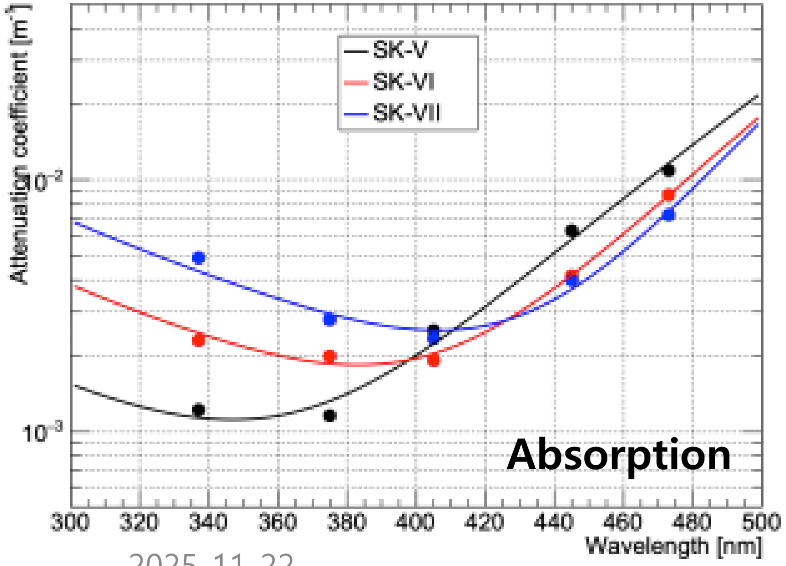
M.Harada (Neutrino2024)
M. Harada et al. (Super-Kamiokande Collaboration) AstroPhys. J. L 951 L27 (2023)

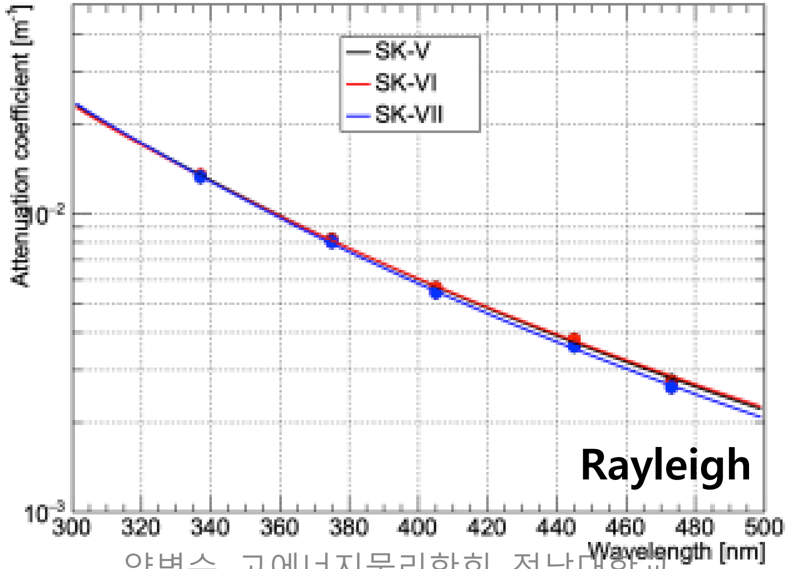
Measurement of water transparency& absorption

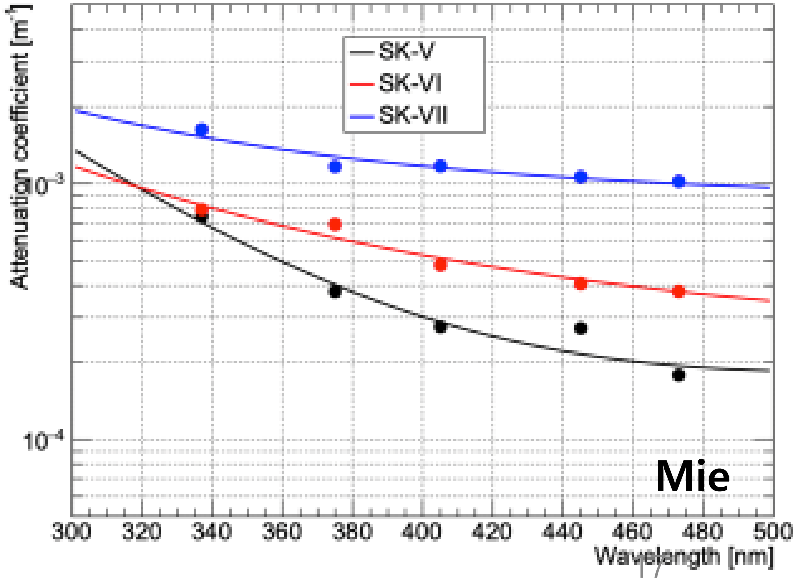






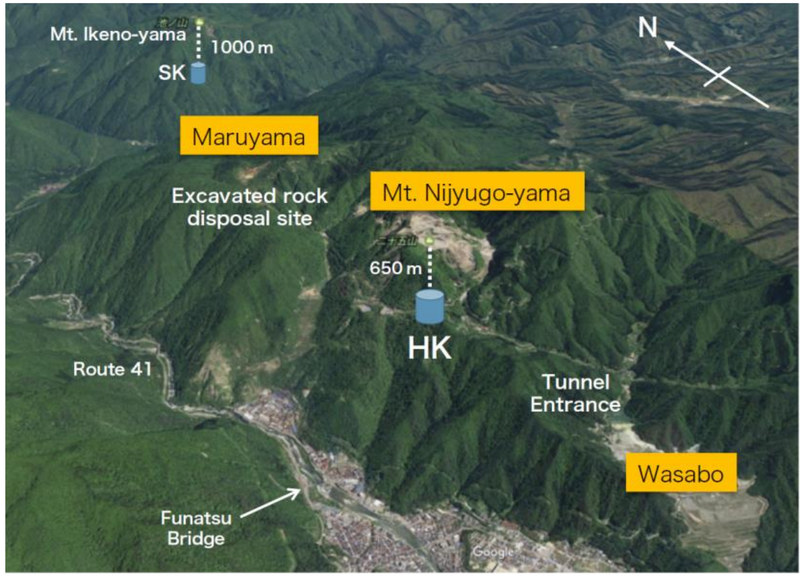




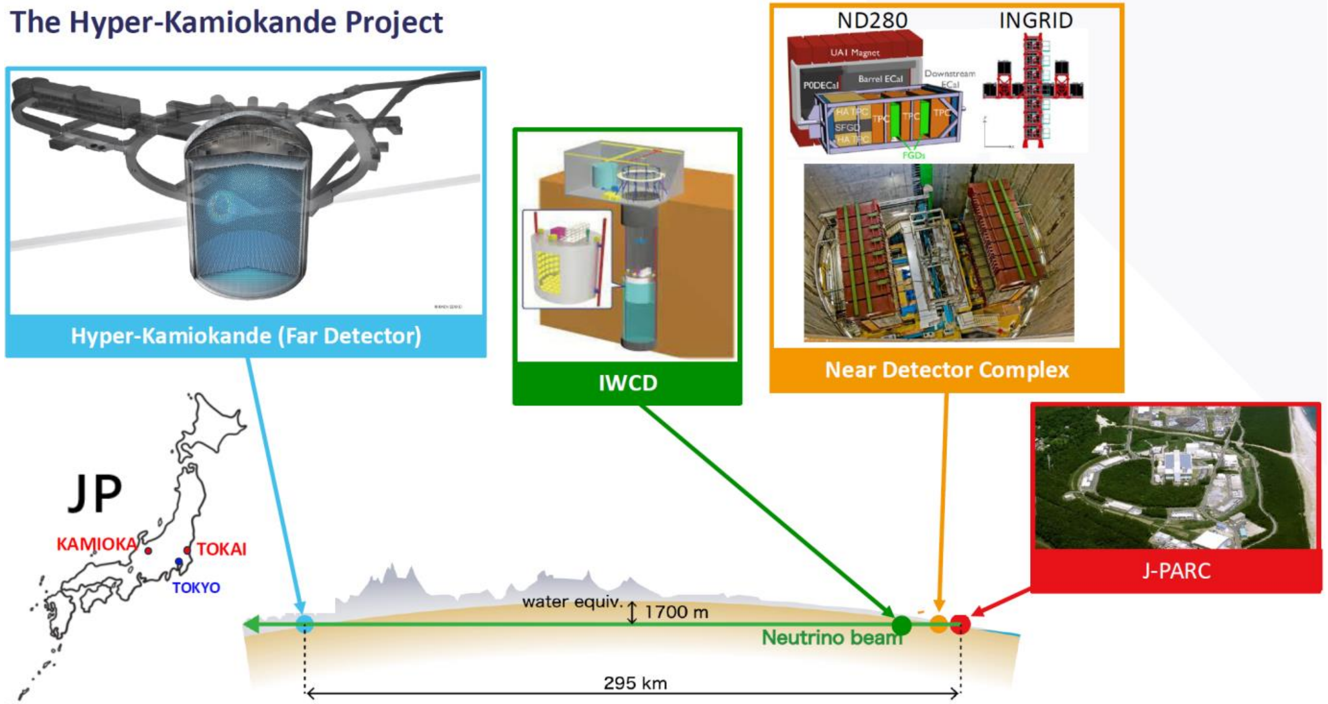


Hyper-Kamiokande

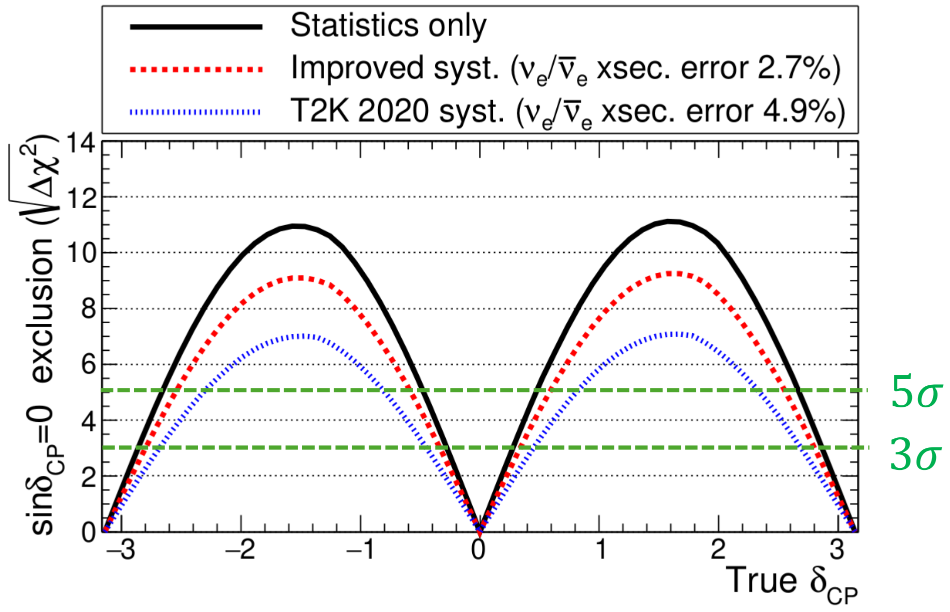
- 3rd generation large water Cherenkov detector in Kamioka
  - Diameter ~70m, height ~70m
  - with ~260 kt ultra pure water
  - providing ~190 kt fiducial volume (~8.4 Super-K)



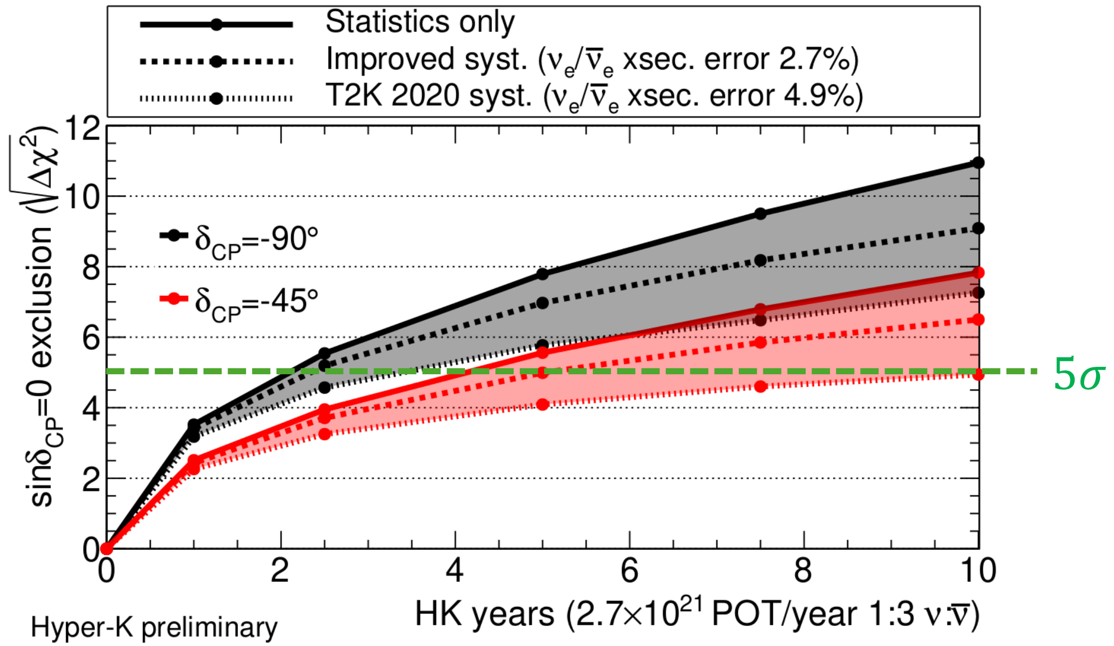
- Upright cylindrical shape
  - Diameter ~70 m
  - Height ~70 m
  - ~20k 50cm PMTs will be installed at inner detector
    - Photo coverage (20%)
    - x2 higher photo sensitivity than Super-K PMT
  - ~4k 8cm PMTs mounted at WLS plate will be installed at outer detector



CP violation



Hyper-K preliminary
True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$



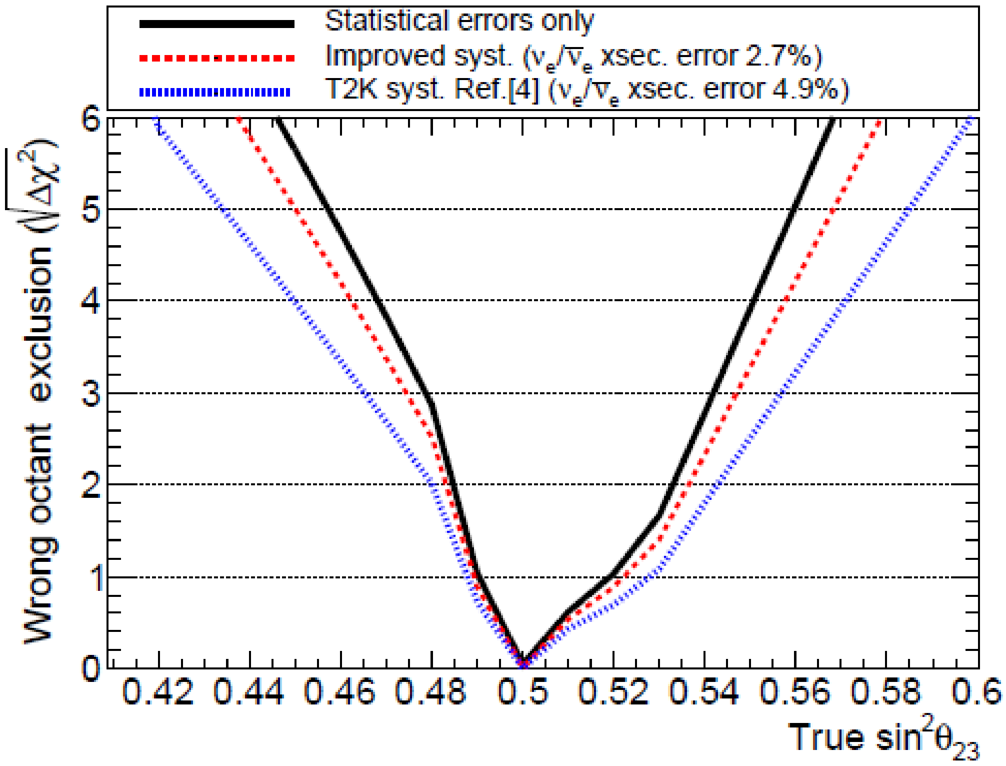
Hyper-K preliminary
True normal ordering (known)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$

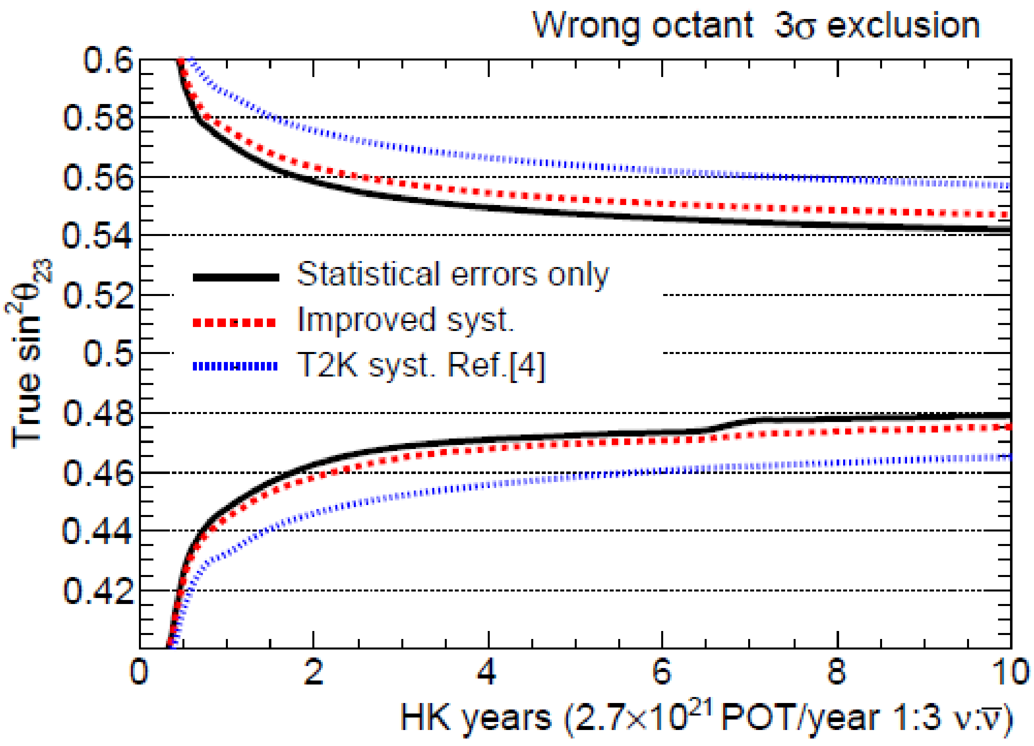
- Hyper-K uses the J-PARC neutrino beam to precisely measure CP violation in the lepton sector
  - The paper titled *"Sensitivity of the Hyper-Kamiokande experiment to neutrino oscillation parameters using acceleration neutrinos"* has been accepted for publication in EPJC

- After 10 years of operation, ~60% of δ_{CP} values to be excluded at > 5σ
- For maximal CP violation and improved systematics, 5σ discovery in < 3 years
- The plots assume MO is known

More details in **arXiv:2505.15019**

$\sin^2\theta_{23}$ octant





- Above 3σ wrong $\sin^2\theta_{23}$ octant exclusion for $\sin^2\theta_{23} < 0.47$ and $\sin^2\theta_{23} > 0.55$
- Wrong $\sin^2\theta_{23}$ octant can be excluded at $\sim 3\sigma$ significance after about 6 years of Hyper-K data taking

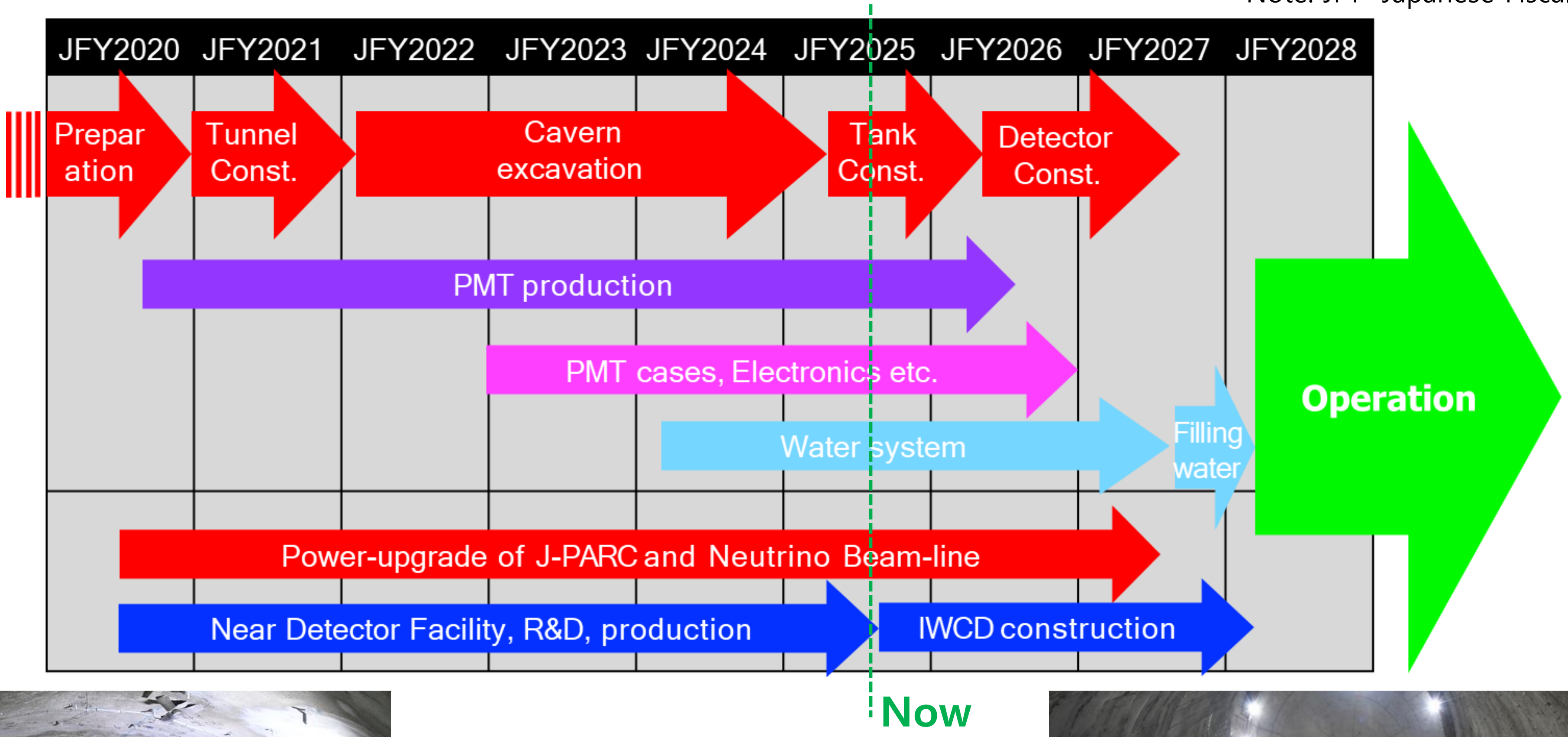
More details in **arXiv:2505.15019**

Timeline of Hyper-Kamiokande

Note: JFY=Japanese Fiscal Year starts on April 1st

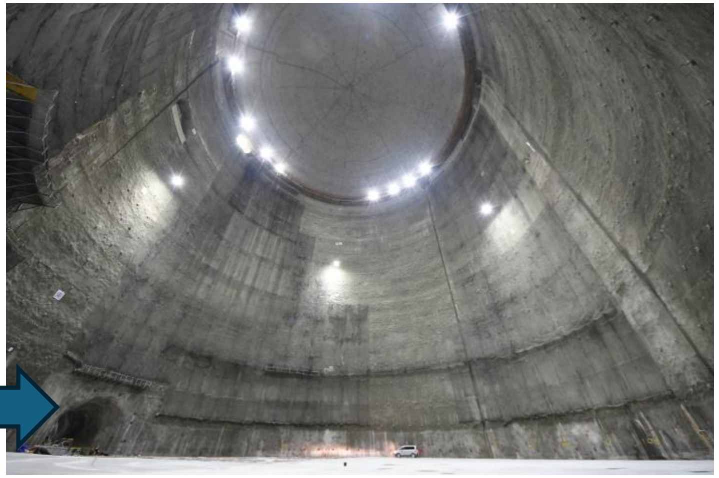
Far detector

Accelerator
Near detector

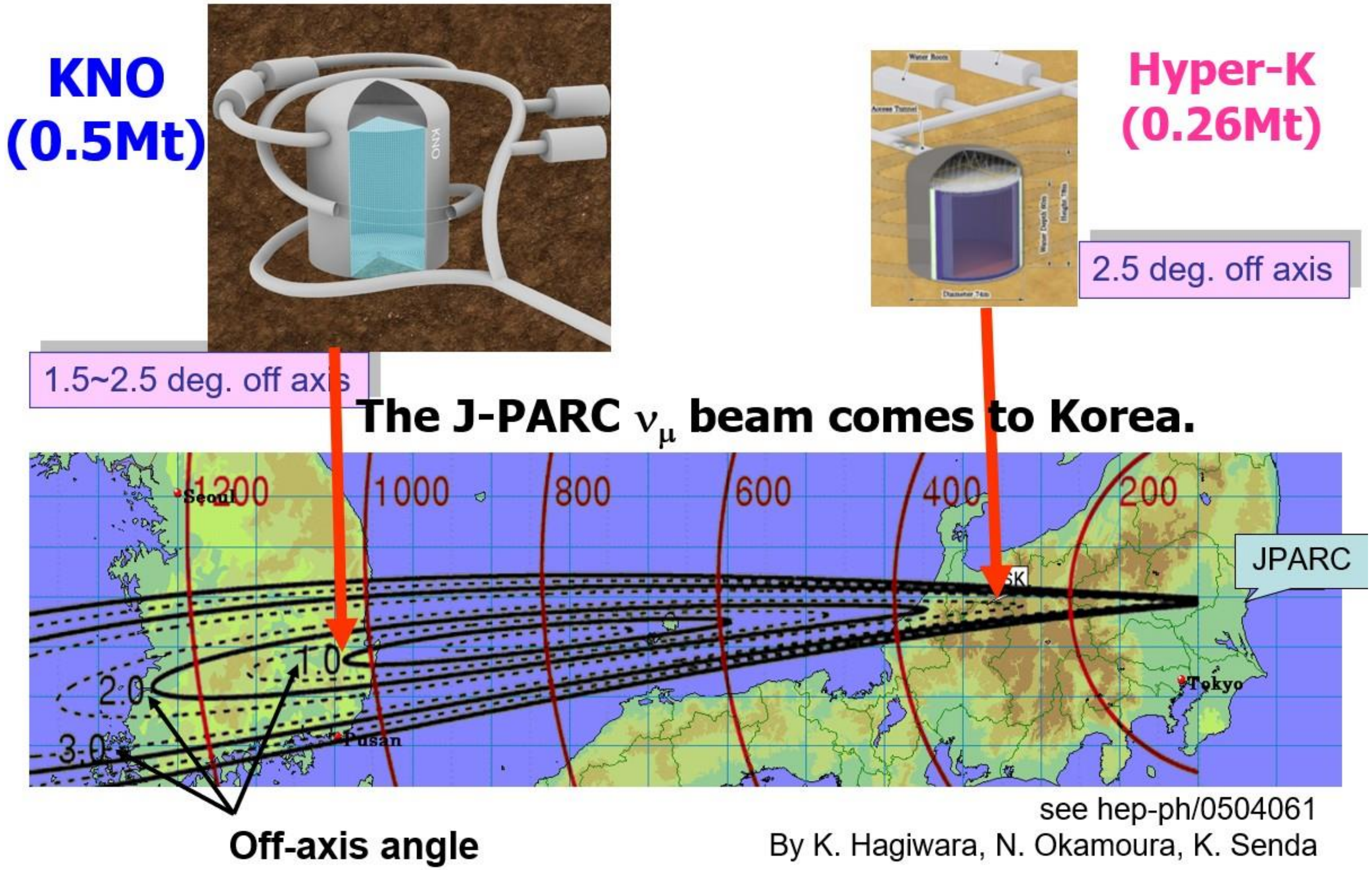


Completion of the main cavern dome October 3, 2023

The main cavern excavation completed July 31, 2025



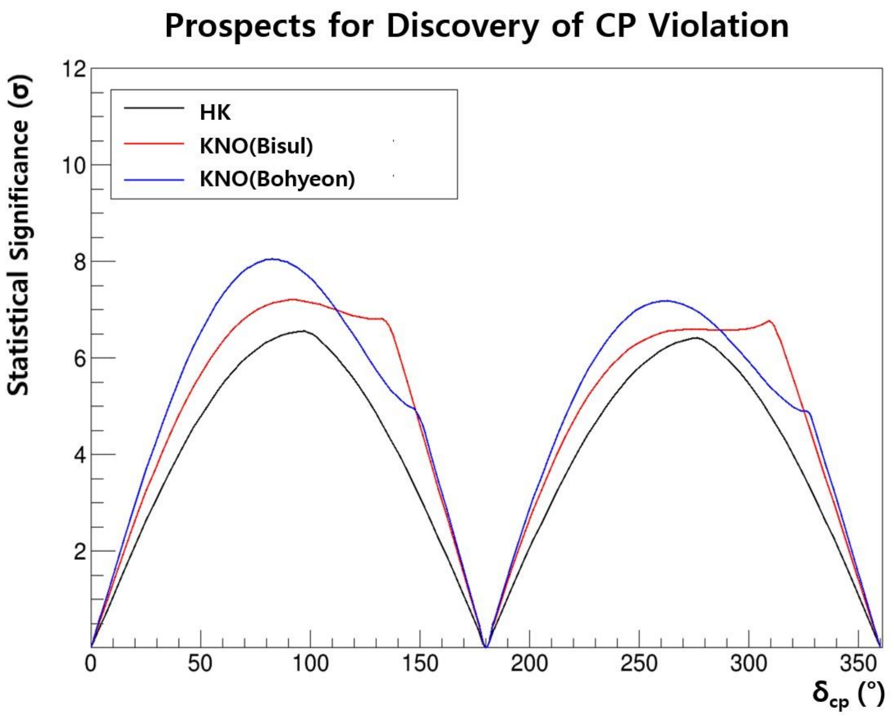
KNO and HK

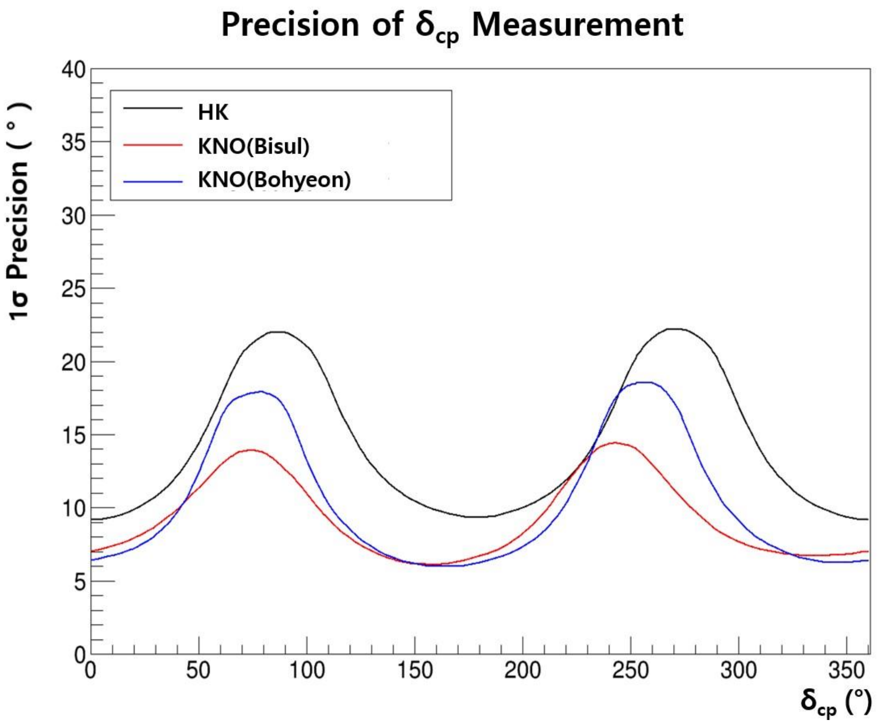


- 두무산 (합천), 비슬산 (달성), 보현산(영천) 등이 KNO의 유력한 후보지

CP Violation at KNO: δ_{cp}

- Prospects of discovery of CP violation in the neutrino sector

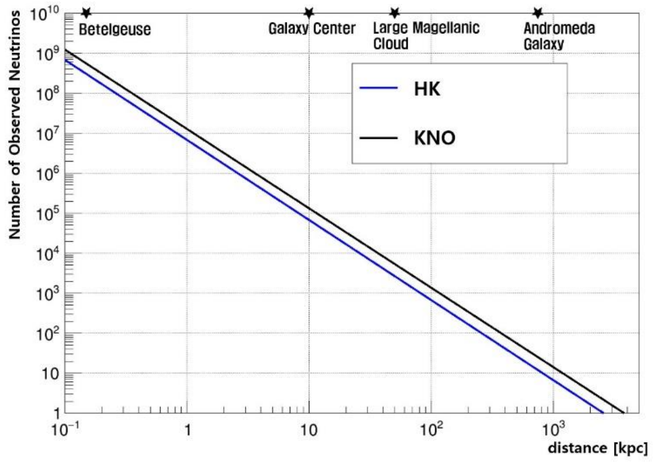




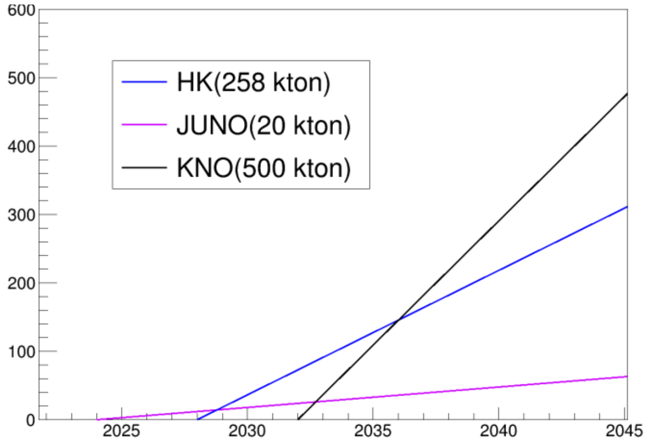
- 10 years of Operation with 1.3MW of J-PARC Beam
- KNO (0.5Mt) and HK (0.26Mt)
- Sensitivity at Mt. Dumu is similar to that of Mt. Bisul

Supernova Neutrinos & Proton Decay at KNO

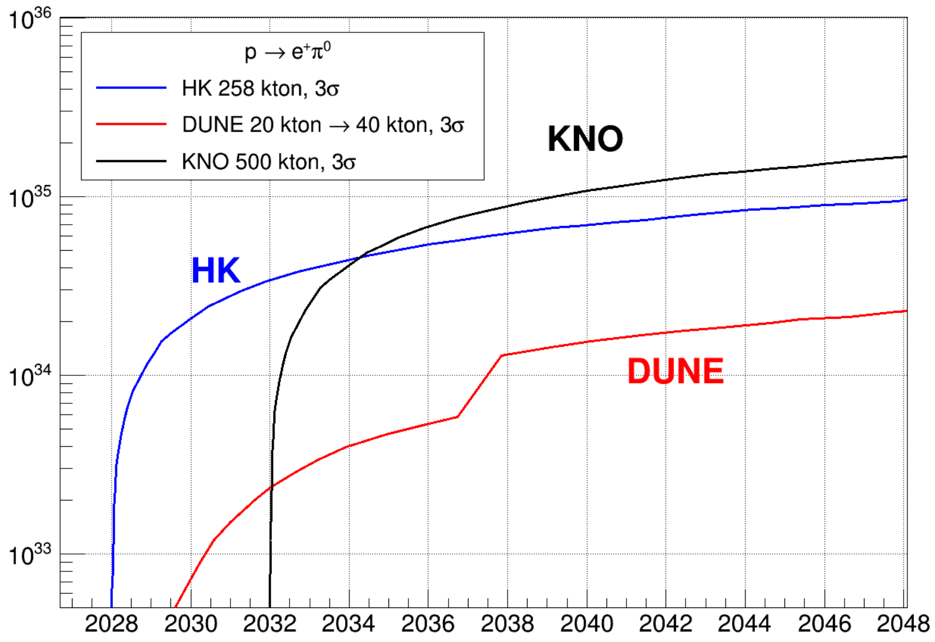
Supernova Neutrino



Diffused Supernova Neutrino Background



Proton Decay

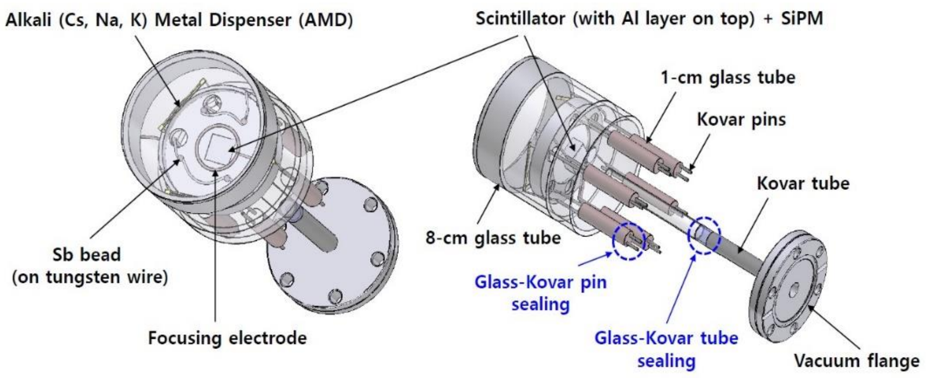


- Assume that KNO starts at 2032

Status of KNO

- R&Ds on PMT, water purification system, radon system are in progress

PMT prototype

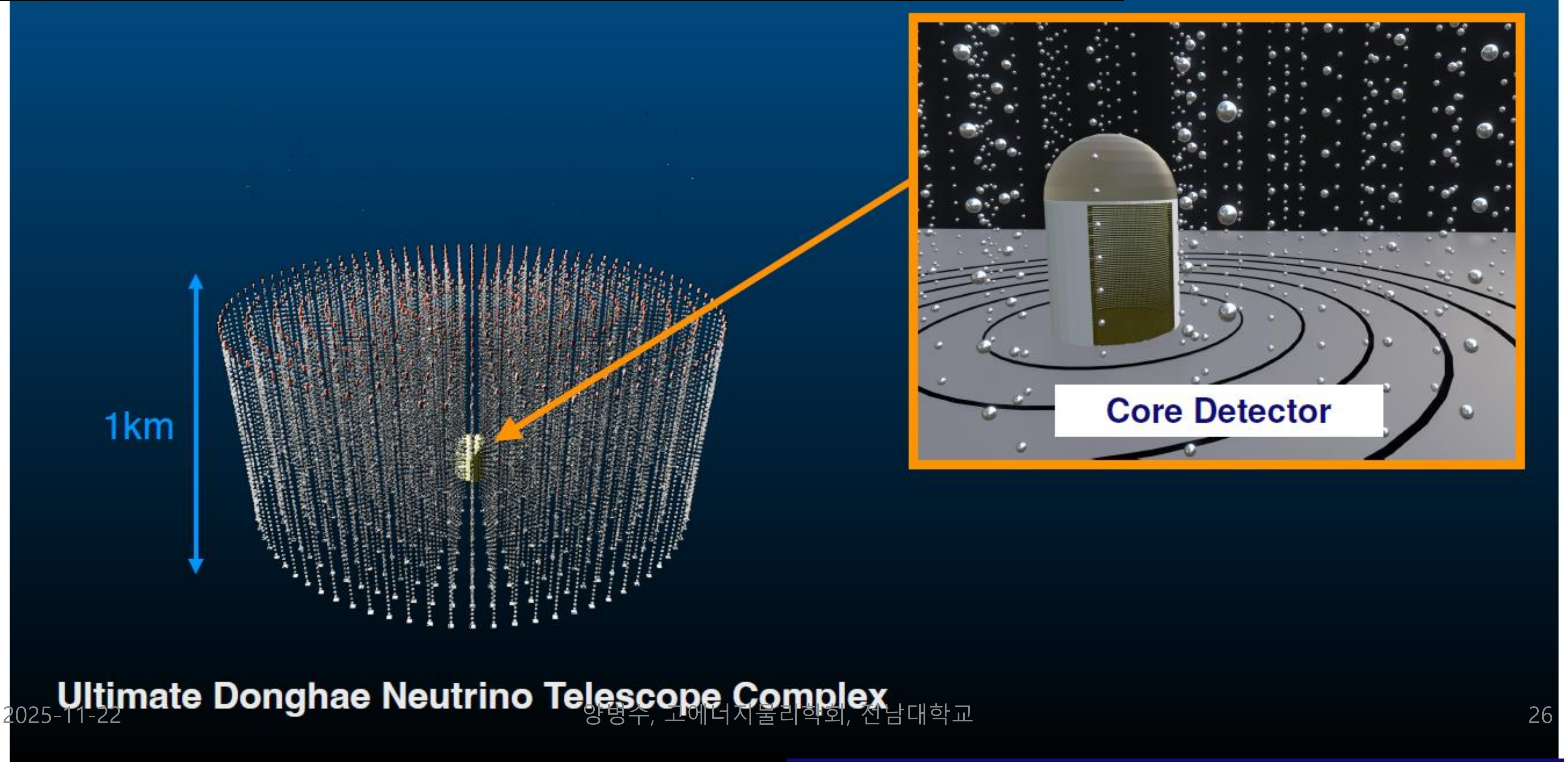


Radon system

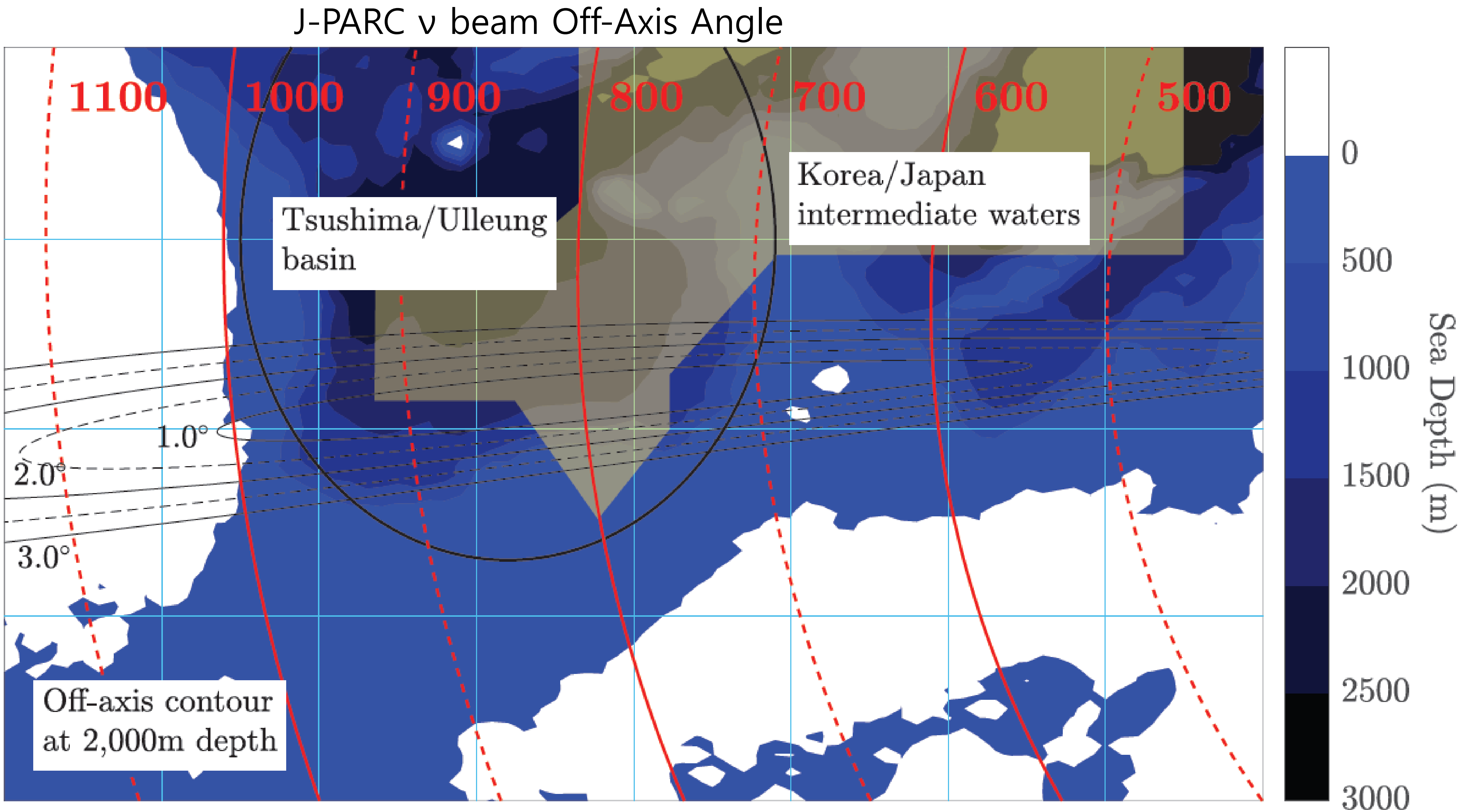
- Software packages for KNO reconstruction has been developed to study physics sensitivities of KNO

- 기획과제 “한국 중성미자 관측소 예비타당성 조사를 위한 사전기획연구 " 보고서 과기부 제출 (2024)
  - R&D 사업 예비타당성 조사 폐지에 따르는 후속 사전점검 체계에 대한 준비
  - 중성미자 분야 뿐만 아니라 전체 고에너지물리분야 (입자, 핵, 천체)의 적극적 지지와 참여가 KNO사업에 핵심적인 역할

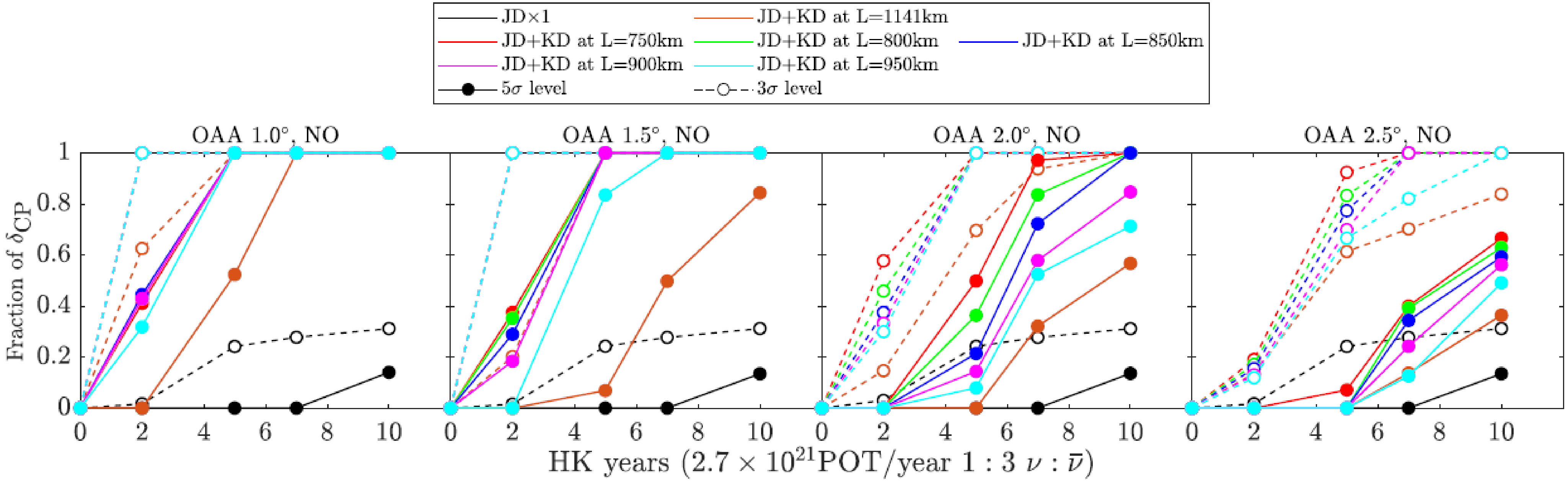
Ultimate Donghae Neutrino Telescope Complex



Donghae Map with OAA Contour

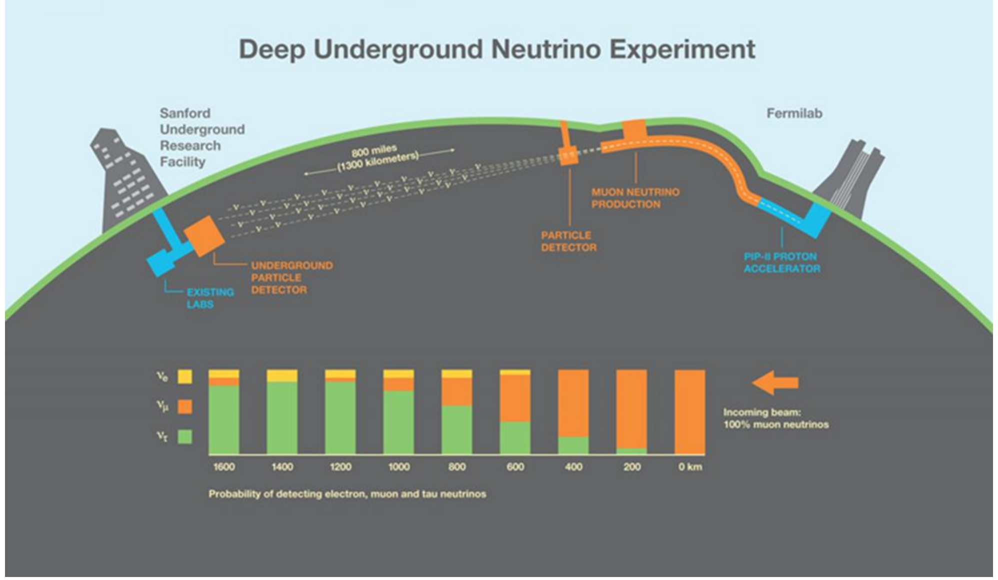


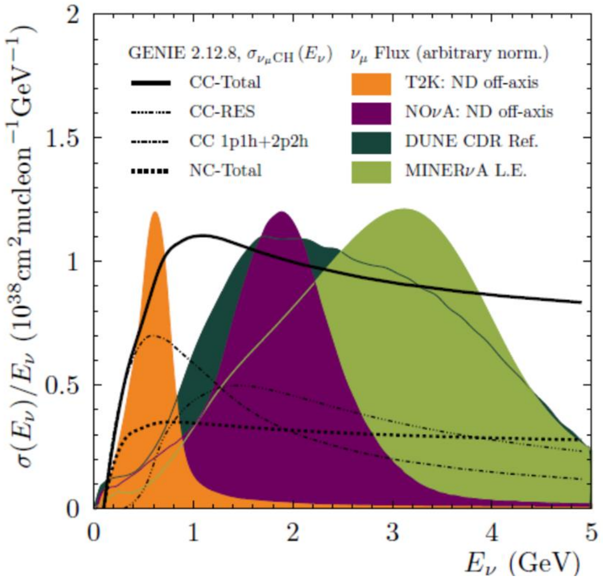
δ_{CP} Fraction Finding Correct Ordering



- The undersea detector at OAA 1.0° will discover the correct mass ordering for all δ_{CP} values within five HK years.
- ...while the land detector can discover it with only 52% of δ_{CP} values with the same operation time.

• Long-baseline oscillation DUNE





Experiment	Beam Source	Detector (threshold)	Interaction	Flavors	Physics	Status
DUNE	PIP-II NuMI (0.5~10 GeV)	L-Ar Time Projection Chamber, (a few MeV)	NC, CC, ES	all	Oscillation Interaction	Construction

Korean members of DUNE Collaboration
(2025년 10월 현재)

Chung-Ang University
: Kim, Siyeon (Professor, IR)

: Gwon, Sunwoo (Research Fellow)
: Masud, Mehedi (Research Fellow)

: Park, Juseong (Grad Student)
: Kim, Sunhong (Grad Student)
: Nam, Hokyeong (Grad Student)
: Park, Yujin (Undergraduate)

Jeon-Buk National University
: Shin, Seodong (Professor, IR)

Jeju National University
: Ko, Young Ju (Professor, IR)

Seoul national Univ. of Science & Technology
: Park, Myeonghun (Professor, IR)

LArTPC technology provides exquisite re solution

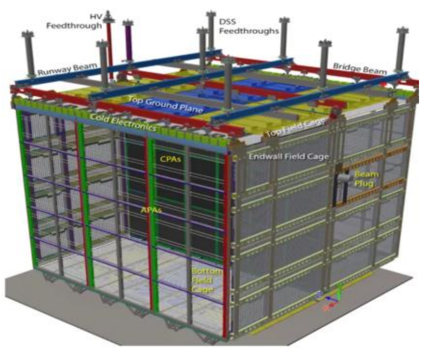
- Clean separation of ν_μ and ν_e charged currents
- Precise energy reconstruction over broad E_ν range
- High Resolution & Low thresholds:
  - sensitivity to few-MeV neutrinos, hadrons
  - excellent for LE neutrino and BSM Search

FD 두가지 타입
- Horizontal Drift (HD)
- Vertical Drift (VD)

2025 ProtoDUNE Run-II (2단계)
HD, VD 모두 실제 검출된 데이터
(Cosmic & Beam) 분석 실행

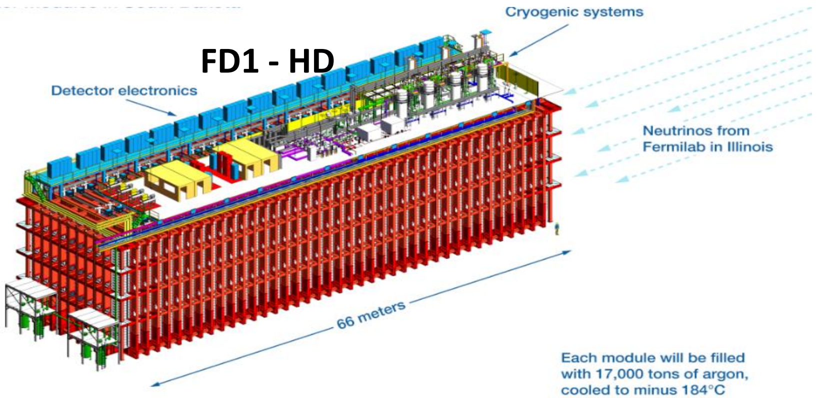
2026-2027 DUNE FD VD 설치
2027-2028 DUNE FD HD 설치

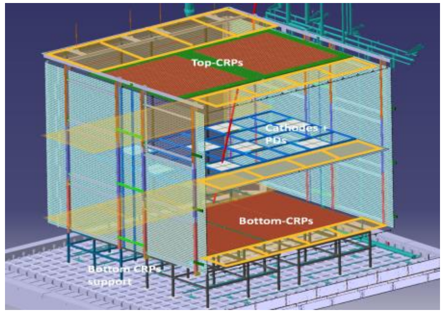
2029 DUNE FD Physics Starts



ProtoDUNE - HD

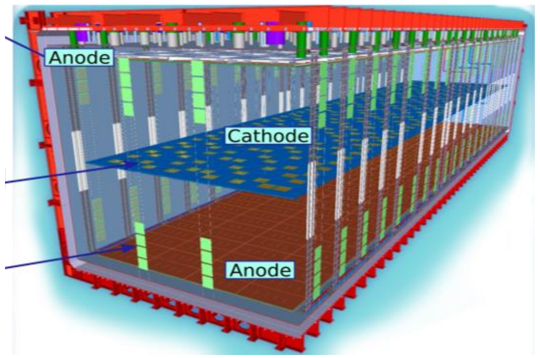
FD1 - HD





ProtoDUNE - VD

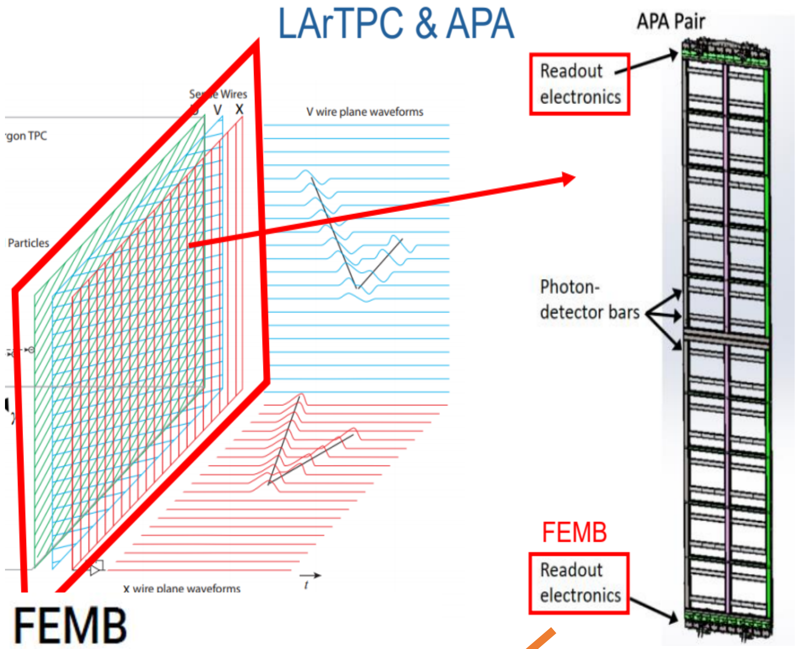
FD2 - VD 14m x 14m x 60m

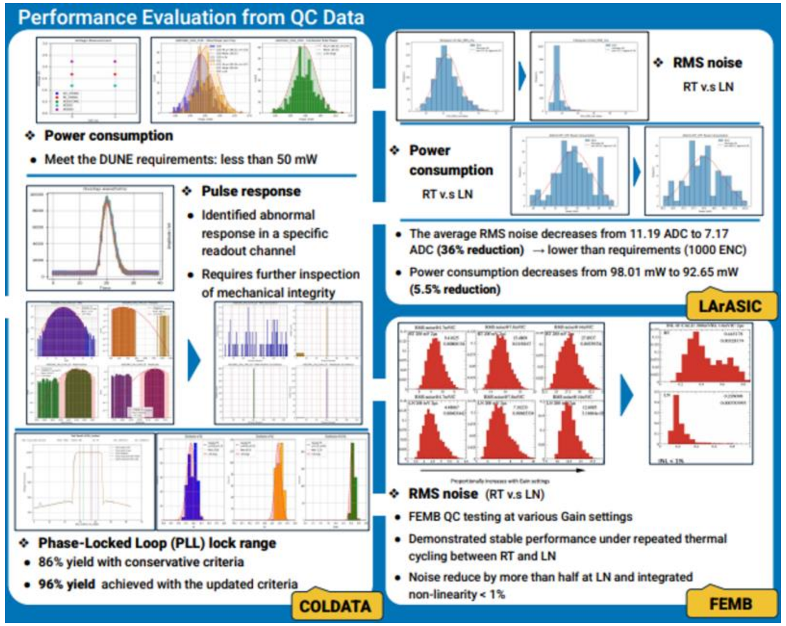


Cryogenic Readout Electronics

K-DUNE Activities

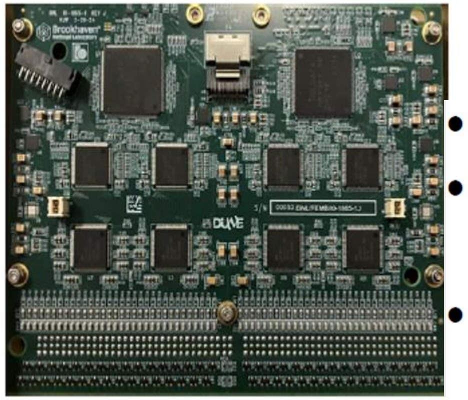
LArTPC U, V, X wires → Cold Electronics → Warm Electronics → DAQ → Data Processing → Event Selection → Reconstruction → Physics Analysis





2025-11-18, 중앙대 남호경, Masud 외
Internal Report DUNE-doc-35313.

❖ FEMB



- COLDATA configures and controls 4 COLDADCs and 4 LArASICs
- LArASIC provides front-end amplification
  - Four adjustable gain levels: 4.7, 7.8, 14, 25 mV/fC
- Front-End Motherboard (FEMB) integrates **All ASICs** :
  - 8 x LArASIC, 8 x ColdADC, 2 x COLDATA

DUNE Software Development

K-DUNE Activities

Event Generation > Simulation

Data Processing > Event Selection > Reconstruction > Physics Analysis

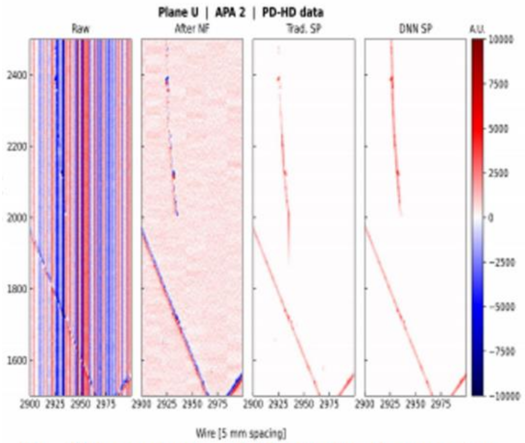
Wire-Cell Toolkit

Part 1:	Part 2:	Part 3:
Simulation	3D imaging	3D vertexing
Noise Filtering	Clustering	Particle Identification
Signal Processing	Charge-Light Matching	3D Pattern Recognition
	Neutrino Event Selection	

MicroBooNE → SBND, ProtoDUNE-HD, ProtoDUNE-VD, DUNE FD

Liquid Argon Software: Simulation and reconstruction packages for LArTPC detectors

- **Event generation:** Genie, CORSIKA, CRY, SingleGen module
- **Simulation:** GEANT4, FLUKA
- **Reconstruction:** **Wire-Cell**, Pandora



❑ 2D waveform evolution in signal processing

Raw data > noise filtering > traditional signal processing > DNN signal processing

Wire Cell (Leader Xin Qian at BNL)
- Fully validated with MicroBooNE

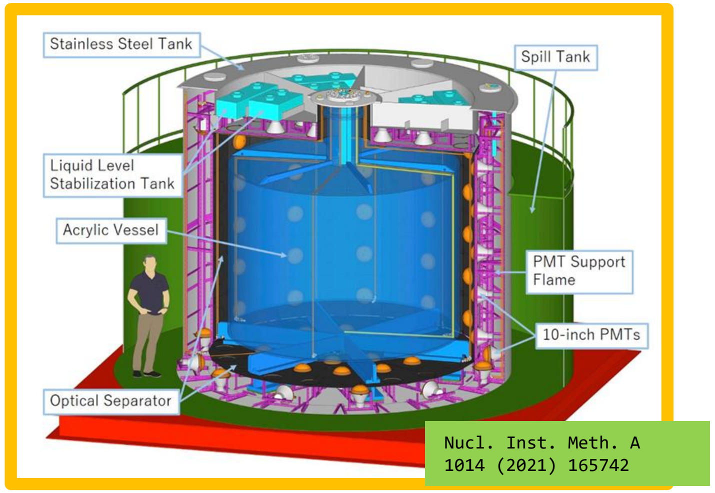
K-DUNE Activities

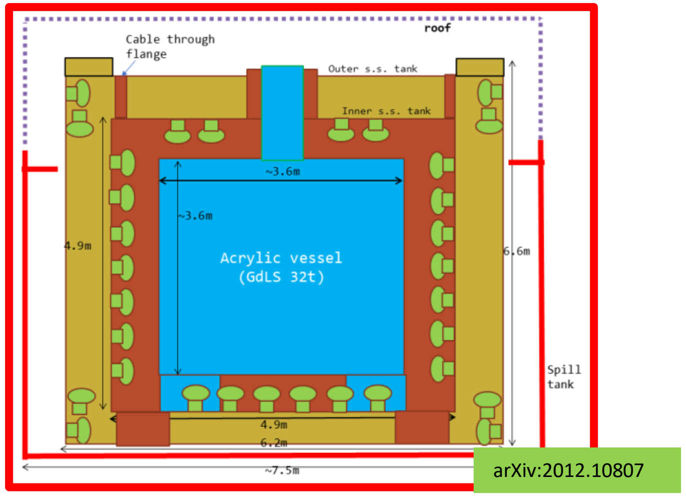
- Extension to ProtoDUNE
- Extension to DUNE FD
- Upgrade to DNN Wire Cell
- Test of Quantum ML

- Currently working on ProtoDUNE
- Stronger team with more CAU, Seoul Tech, and Jeju University.

JSNS^2 & JSNS^2-II

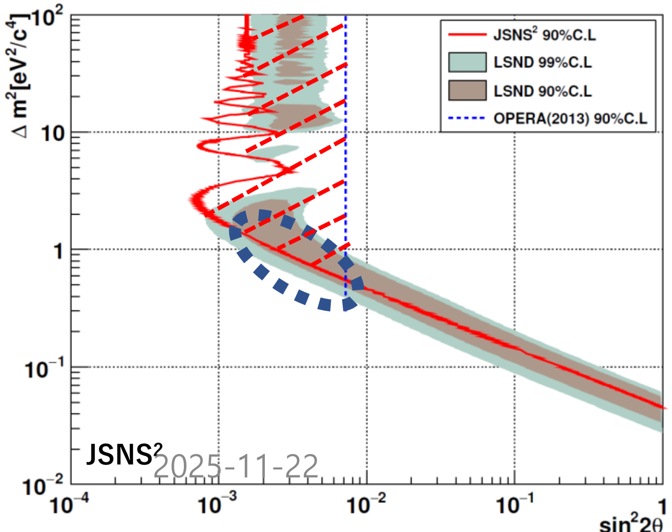
J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source

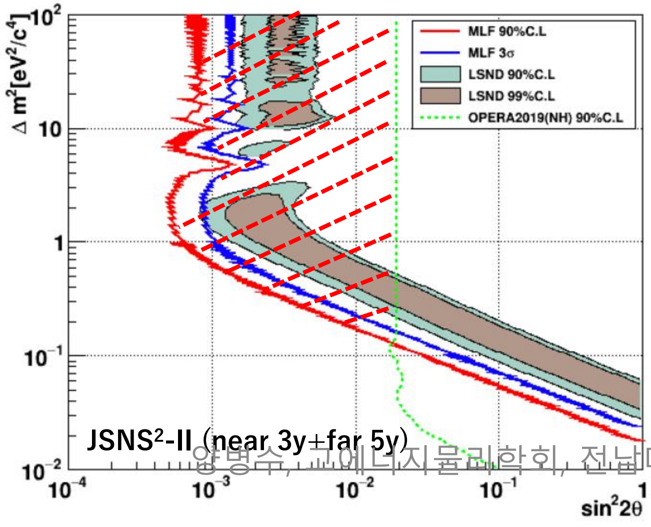




(JSNS2-I, JSNS^2-II near detector
17 t GdLS fiducial
(4.6 m diameter x 4.0 m height, 120 10" PMTs)

(JSNS^2-II: Far detector)
32 t GdLS
(6.2 m dia x 6.2 m (h) 228 10" PMTs)





LSND anomaly in same method

- neutron source(μ decay at rest)
- target(H)
- the detection principle (IBD)

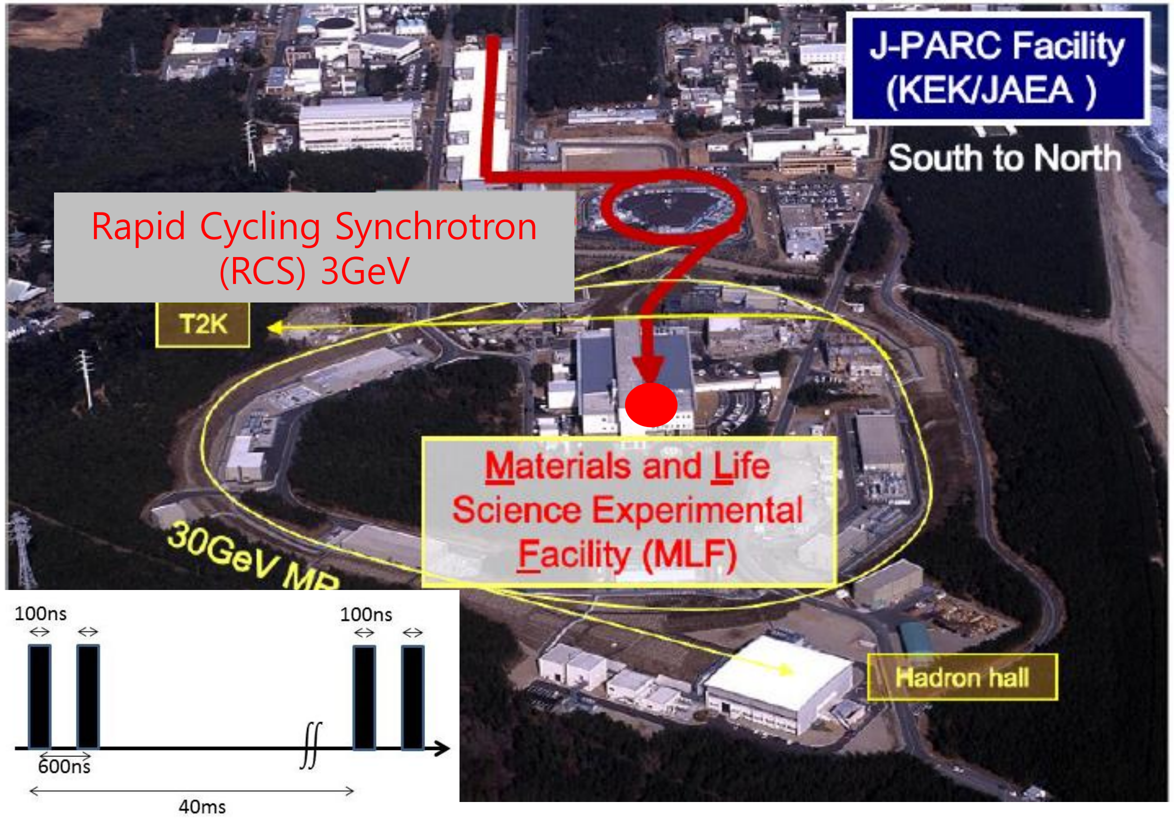
JSNS^2 : 1MW x 3 years (near only)

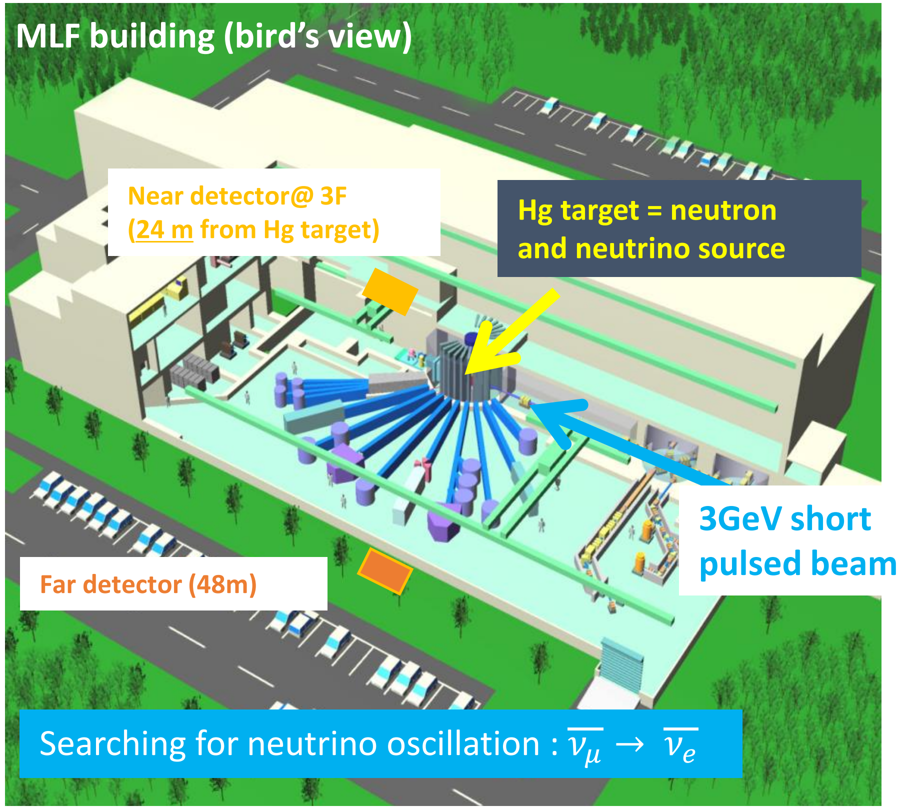
- Near detector : fiducial 17 tons and 24m location
- GdLS+DIN(10%) for target, pure LS for gamma-catcher and veto
- Physics run starts from 2021

JSNS^2 –II : 1MW x 5 years

- Proposed in 2020 (arXiv:2012.10807)
- Far detector: fiducial 32 tons and 48 m location
- Two detectors with two different baselines
  → a solid conclusion on LSND anomaly
- Construction is done. **On commissioning**

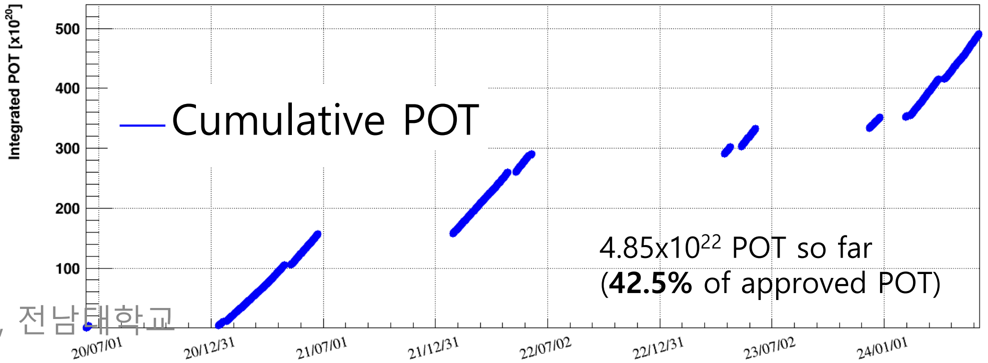
J-PARC facility & Accelerator





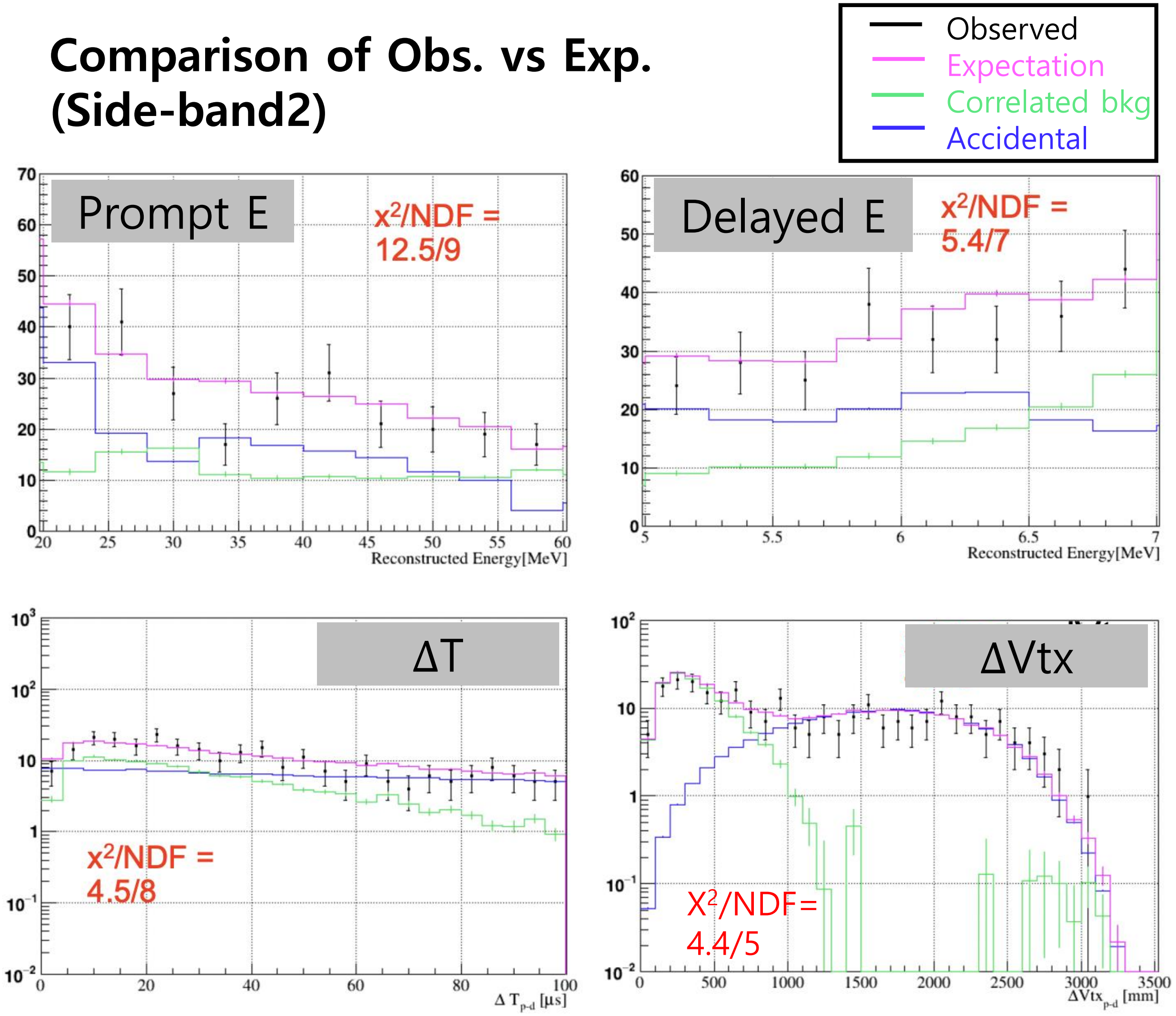
- 25Hz, 1 MW (design)
- Two-bunch structure
- short pulsed beam (100ns)

Beam power
2021 : 0.6-0.7MW
2022 : 0.7-0.8MW
2023 : 0.84MW
2024 : 0.73-**0.95MW**

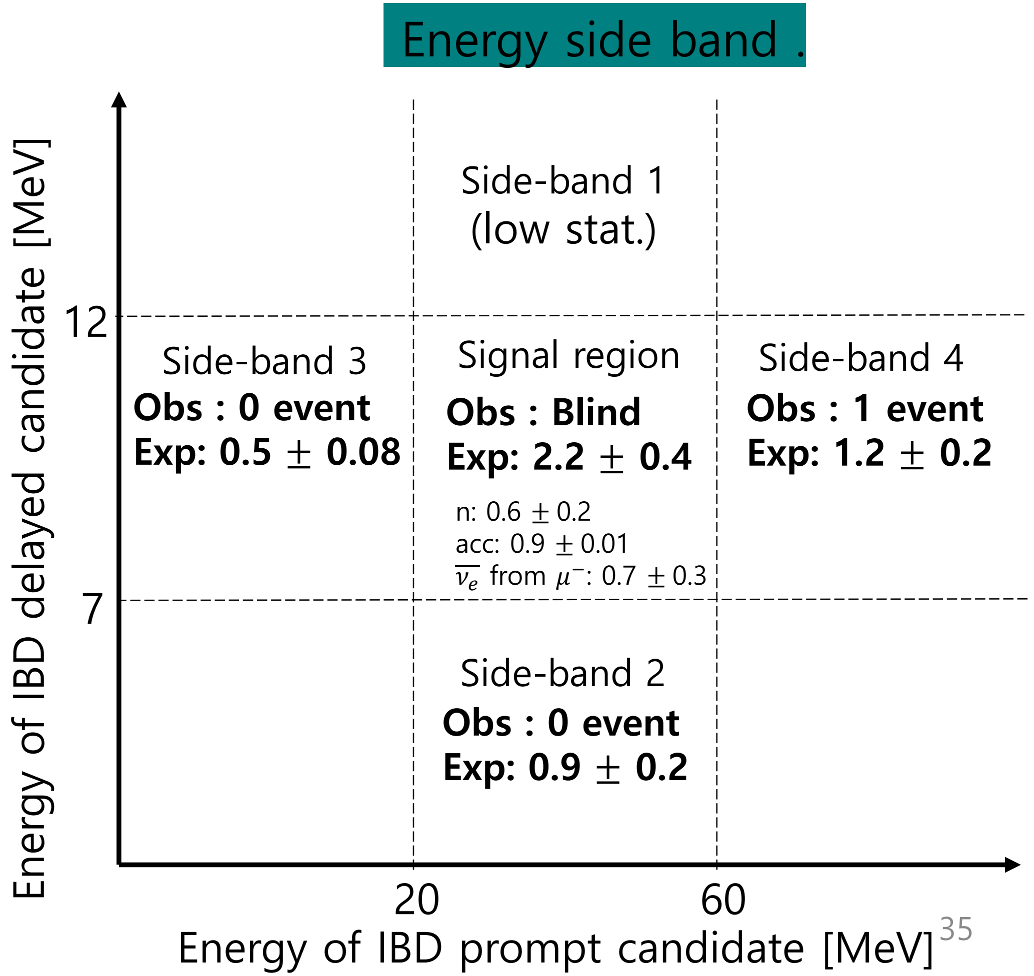


Sterile Blind analysis
Observation & Expectation in signal region & side-bands

Comparison of Obs. vs Exp. (Side-band2)



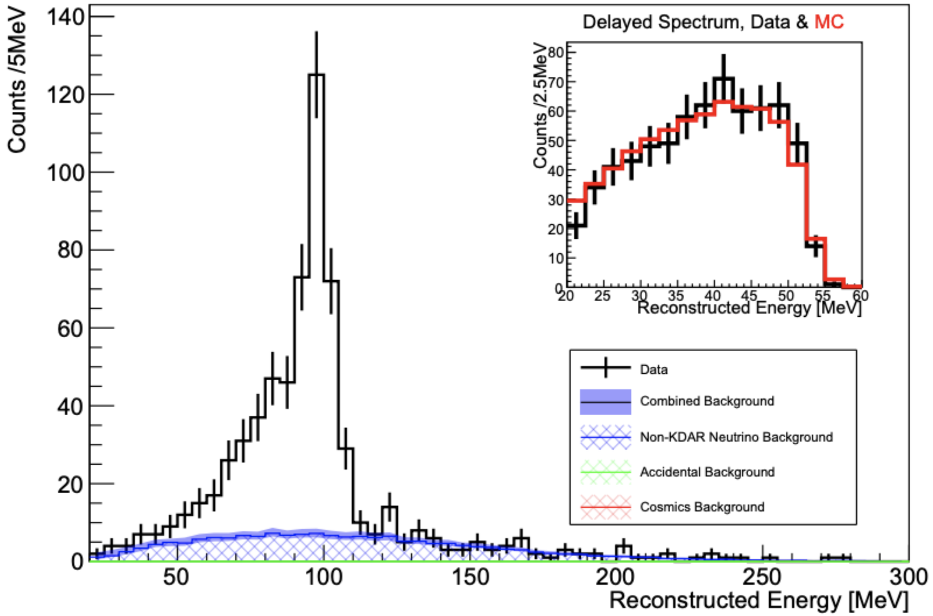
<u>**Good consistency**</u> with applying PSD & likelihood
(Using ~7% of JSNS^2 approved POT)



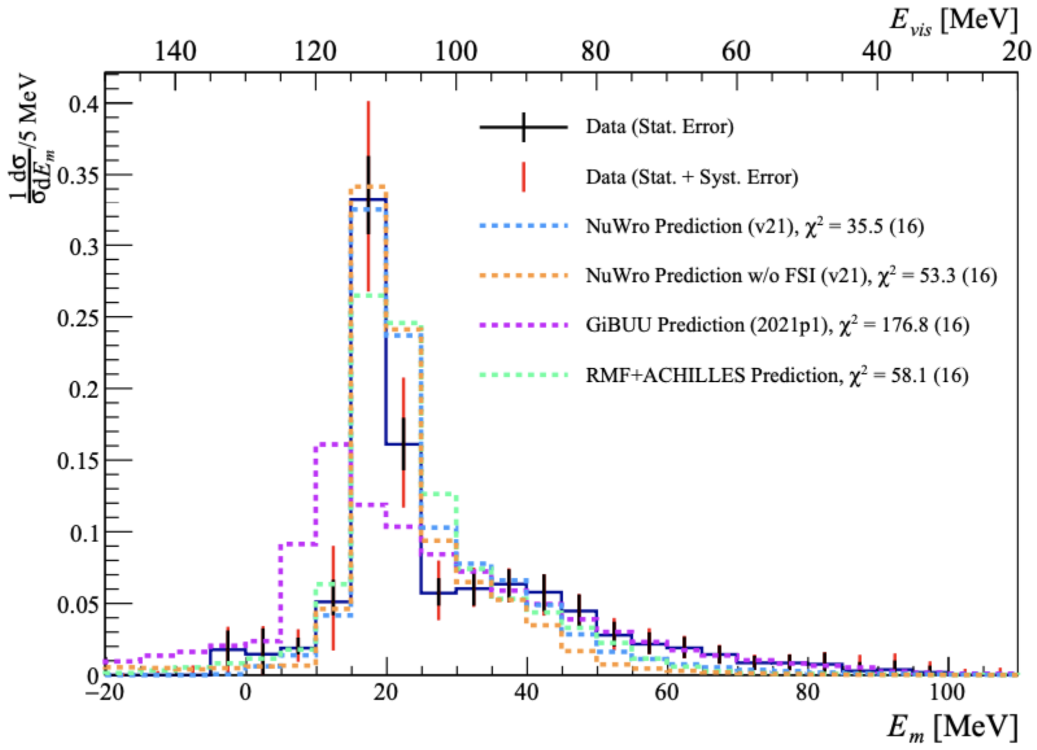
KDAR Results

- 2021 physics data is used. (1.4×10^{22} POT)
- KDAR candidates : 621 events
- Best Fit Bkg : $144.4^{+21.3}_{-21.1}$ events
  (πDIF ν dominant)

	Prompt	Delayed
Energy	20~150MeV	20~60MeV
Timing	2 x 150ns (Beam centered windows)	ΔT < 10μs
Positio n	R < 140cm -100cm < z < 50cm	ΔVTX < 30cm

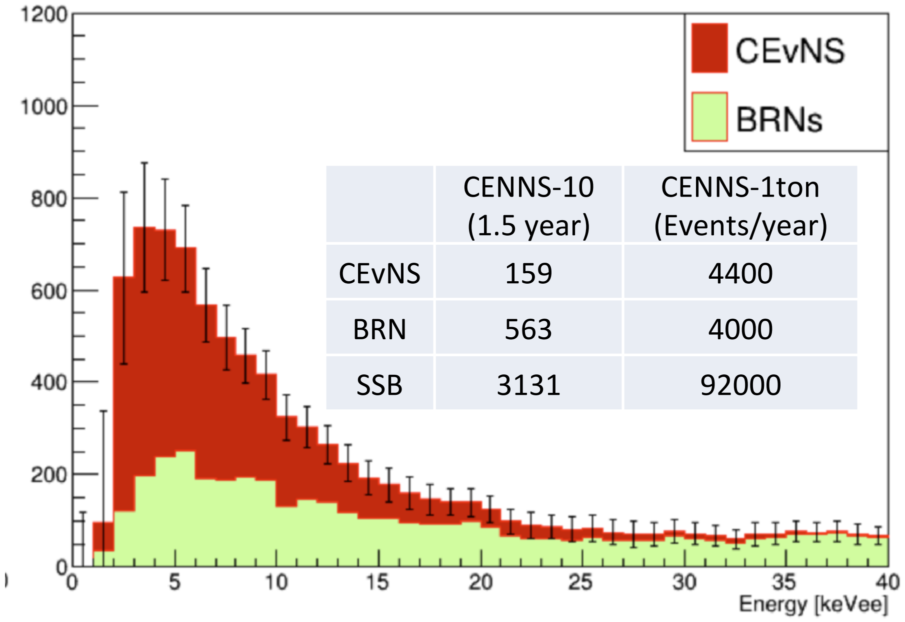


- **mono-energy (235.5MeV) of KDAR neutrino**
- **The first measurement of Missing Energy** due to nuclear effects (shape-only analysis)
  => By using the KNOWN neutrino energy.
  $E_m (missing\ energy) = E_\nu - m_\mu - E_{vis}$
  <=Unfolded E_{vis} is used.
- Standard candle for improving the understanding of the low energy neutrino-nucleus interaction.

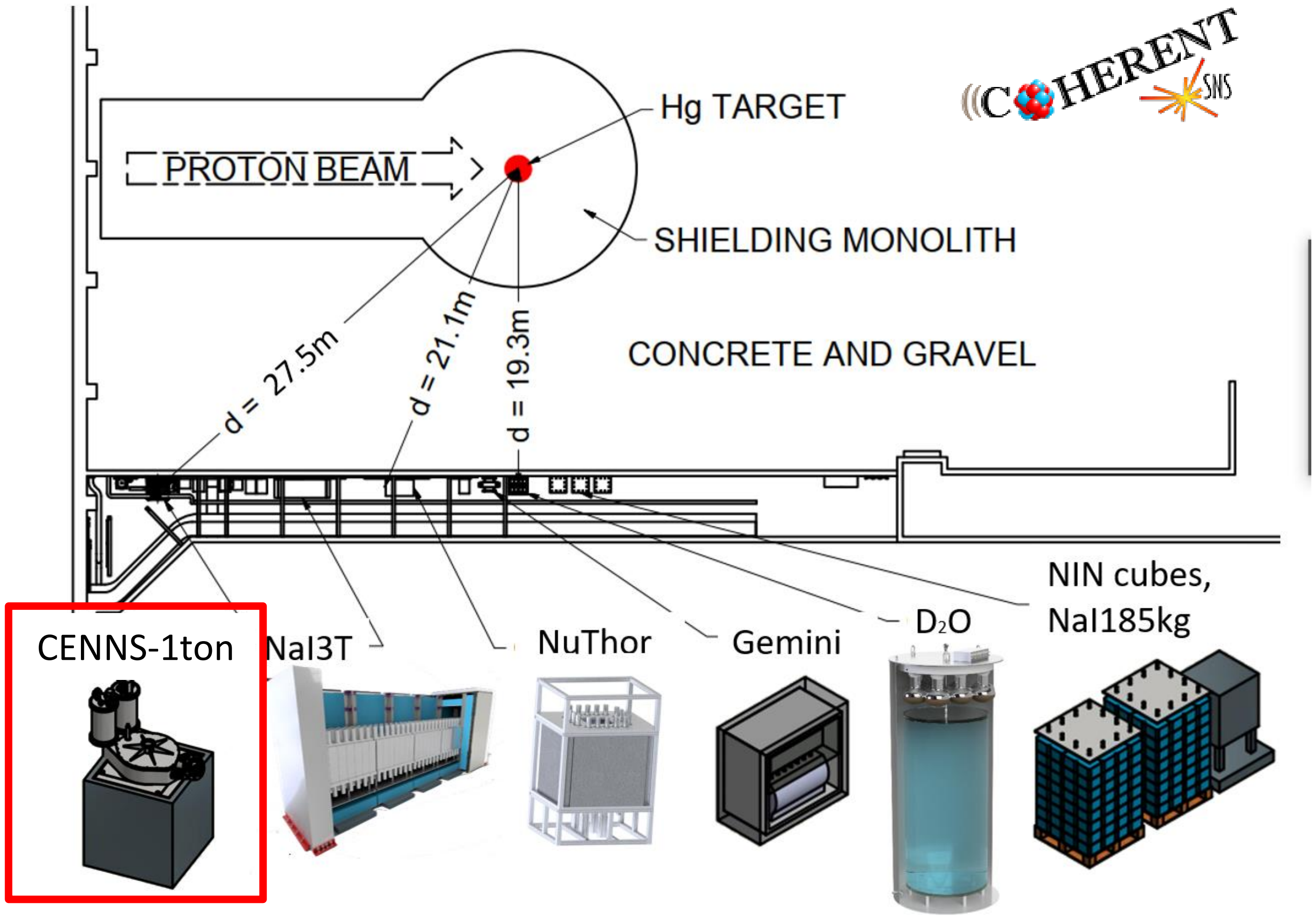


CENNS-1ton

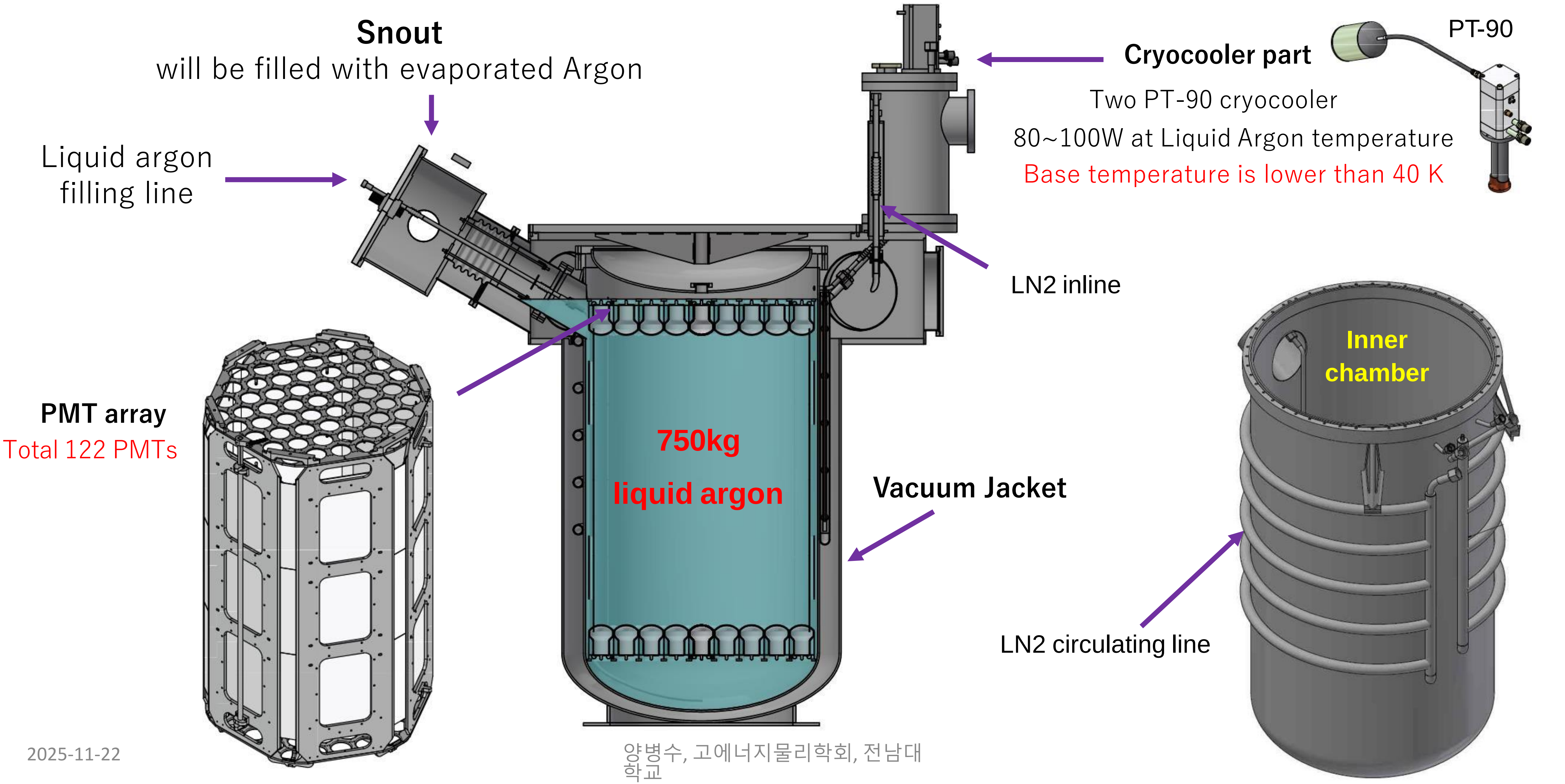
- 750kg Liquid Argon detector with 122 PMTs
- Replacing CENNS-10 at the same location (Neutrino Alley at ORNL)
- Expect ~4400 CEvNS event/year.
- Measure CEvNS with 5% precision in 3 years.
- Precision physics study.



	CENNS-10 (1.5 year)	CENNS-1ton (Events/year)
CEvNS	159	4400
BRN	563	4000
SSB	3131	92000



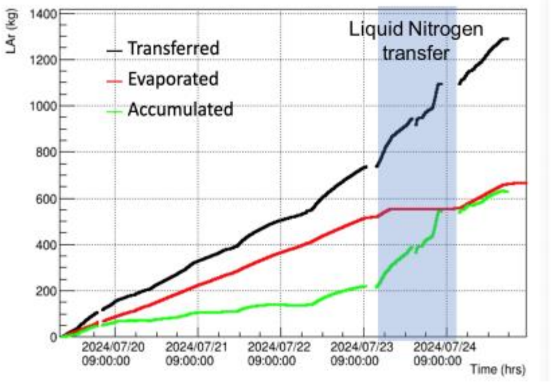
CENNS-1ton detector overview



CENNS-1ton progress

CENNS-1ton chamber test at SNU

- 1 ton chamber fabricated by Korean company
- Delivered and Assembled at SNU
- Vacuum test done
- Ar condensing and LAr transfer tested
- LN2 precooling worked well



Liquid Argon Transfer test.

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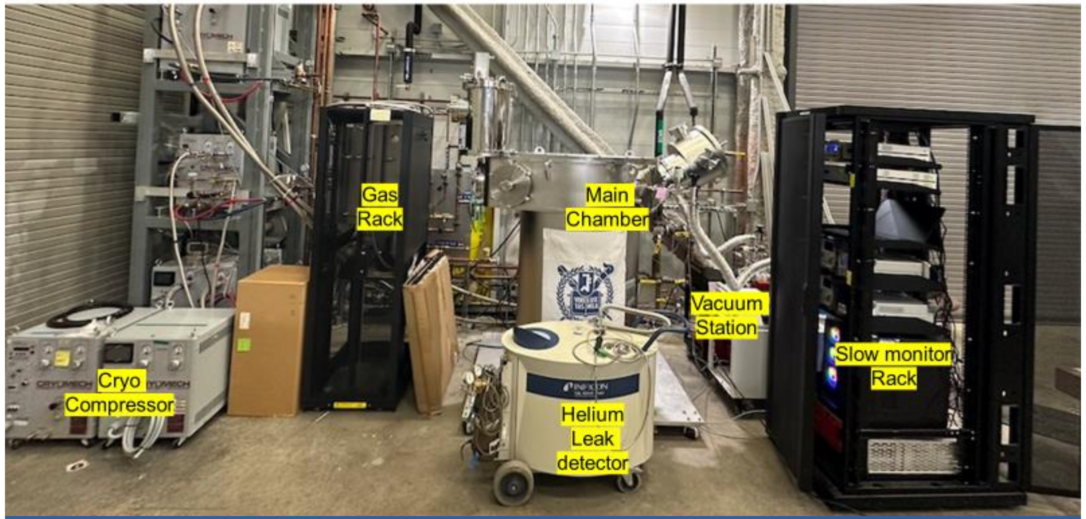
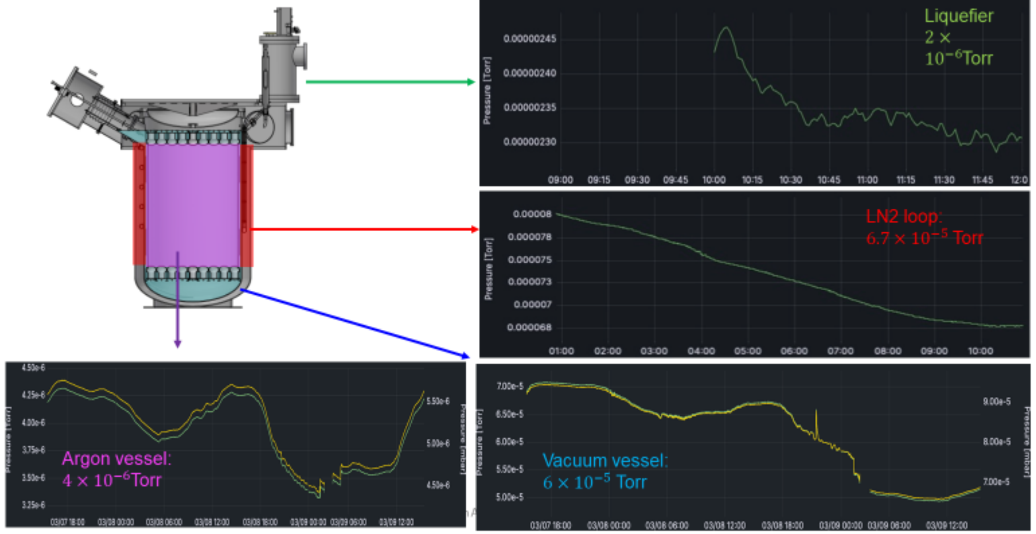
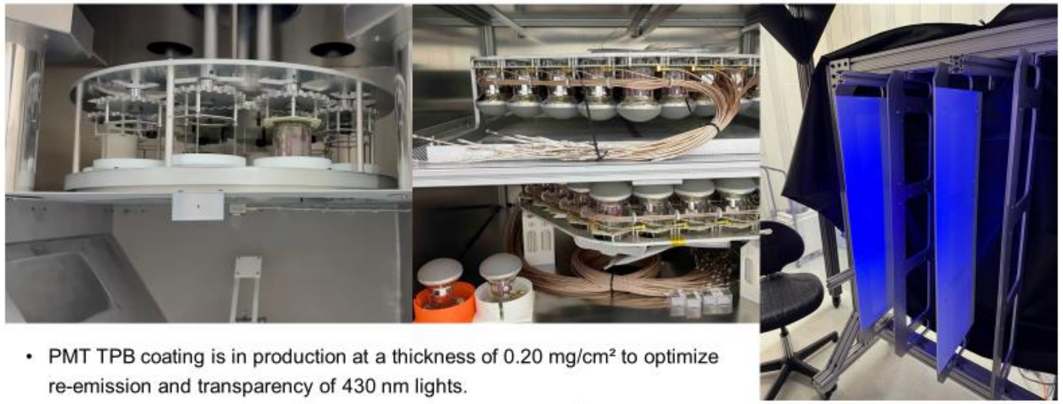
Test Setup at ORNL



CENNS-1ton detector Vacuum Test at ORNL



TPB coating and PMT assembly



- PMT TPB coating is in production at a thickness of 0.20 mg/cm² to optimize re-emission and transparency of 430 nm lights.
- The coating thickness is verified by measuring the weight of a witness plate.
- TPB coating on PMT and PTFE plates are completed.
- PMTs are installed on the end plates and completed the signal line works.

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CENNS-1ton Future plan

2026-02 2026-03 2026-04

Operational test → Nu Alley Install → Safety Review Commissioning → Experiment

- CENNS-10 (24kg) observed CEvNS in 2020, with 30% uncertainty
- CENNS-1ton (610kg) will reduce uncertainty 5% in 3 years
- 1ton detector is fabricated, assembled, and tested ay SNU
- 1ton detector has been delivered to ORNL after performance test.
- Assembly has been completed at ORNL and Vacuum test was done.
- RTD install and TPB coating were completed.]
- We will take data next year.

LHC

Scattering and Neutrino Detector at the LHC

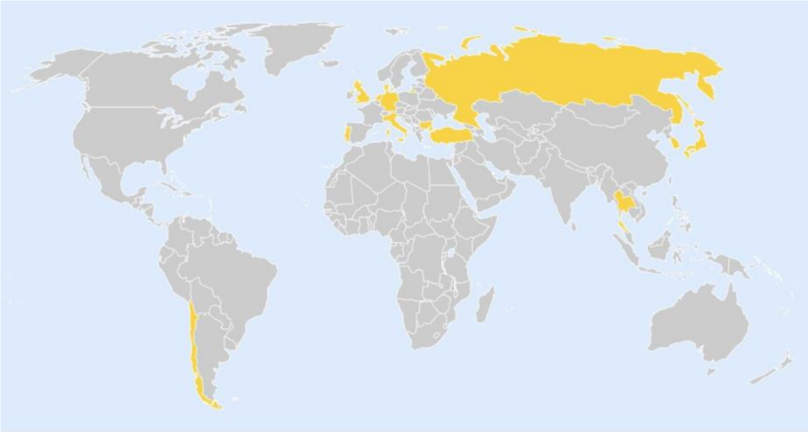
Status of SND@LHC

S.H. Kim, K.Y. Lee, B.D. Park, J.Y. Sohn, C.S. Yoon
(Gyeongsang National University)

K-Y. Choi, S.M. Yoo
(Sungkyunkwan University)

Y.G. Kim
(Gwangju National University of Education)

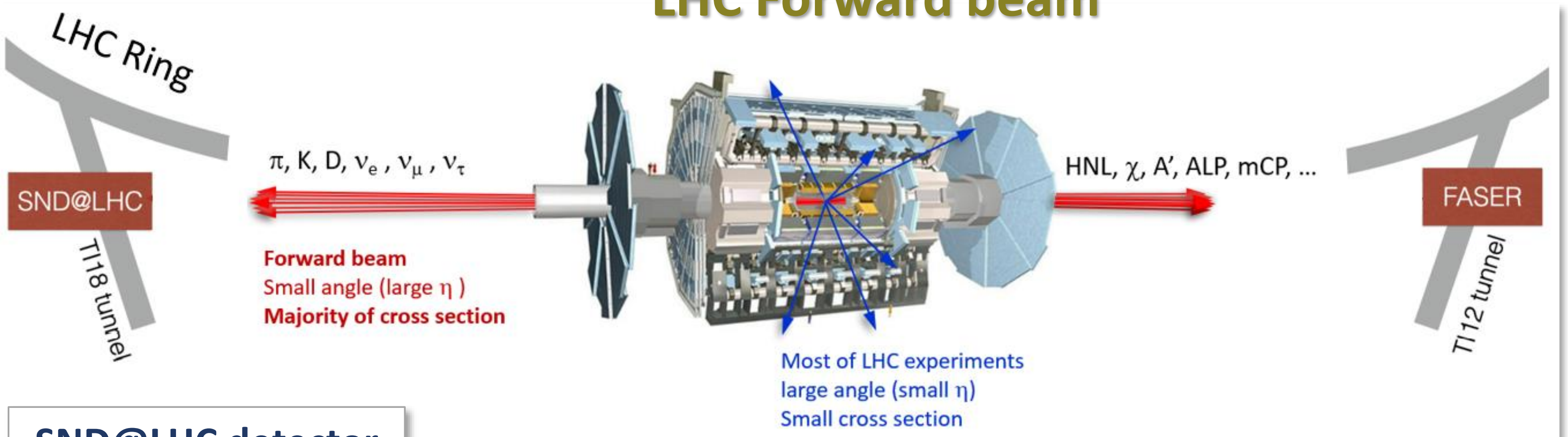
K.S. Lee
(Korea University)

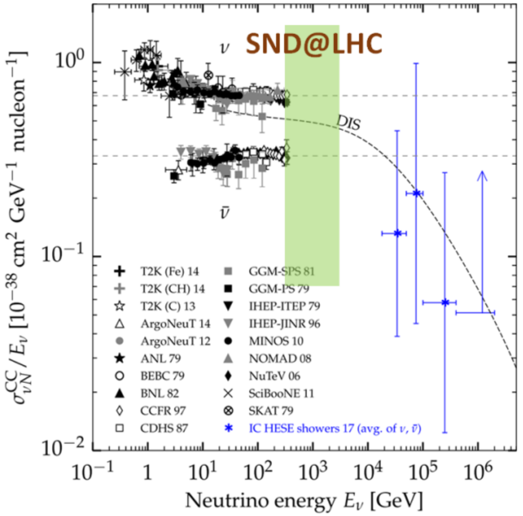


~150 members
24 Institutes in 14 Countries and CERN

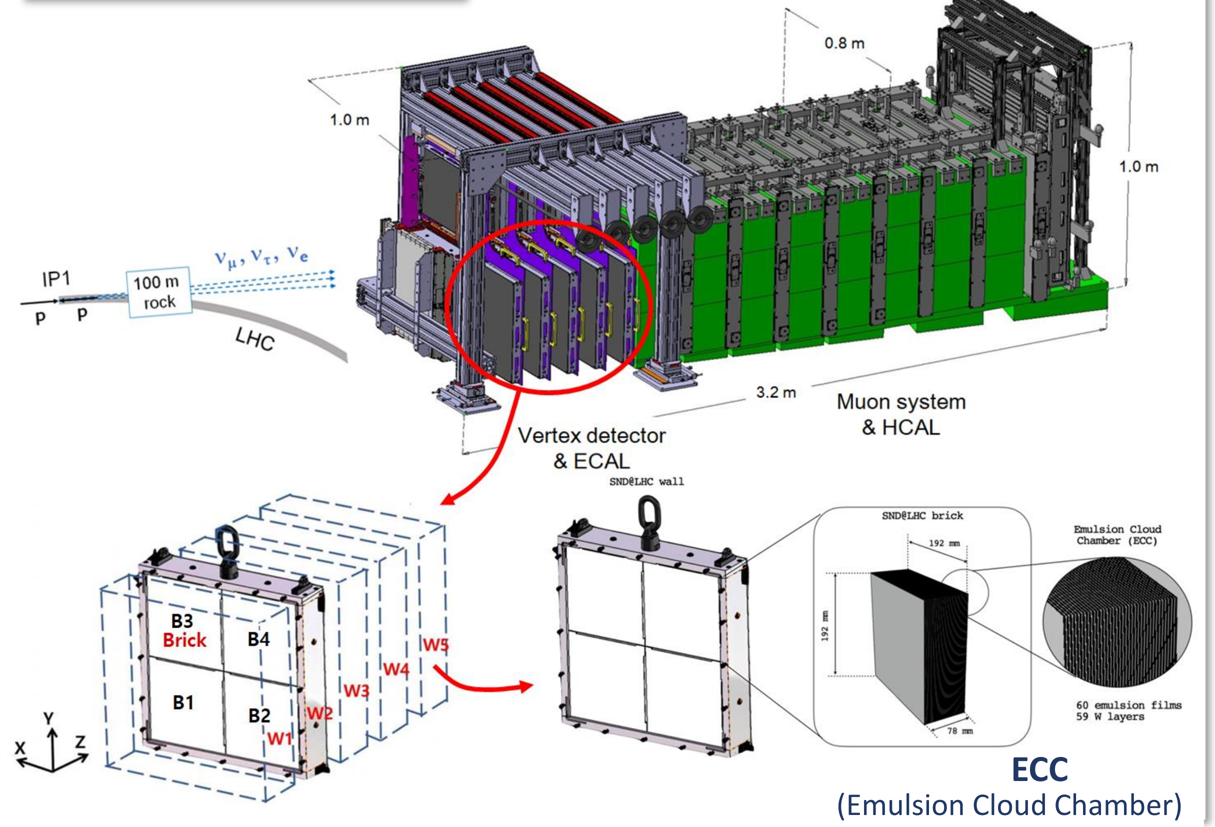
KSHEP & KPS DPF Workshop
2025. 11. 19 - 22 at JNU

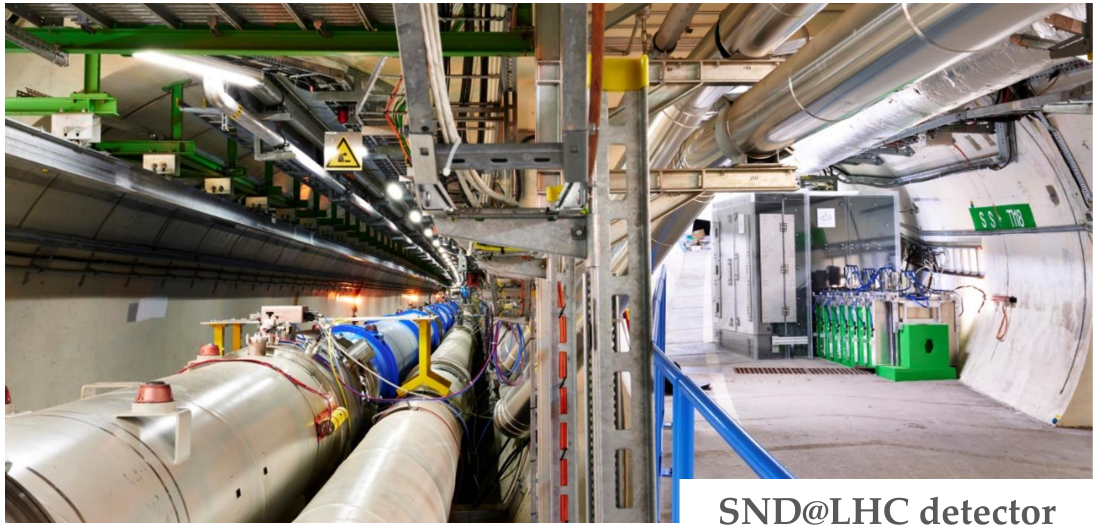
LHC Forward beam





SND@LHC detector





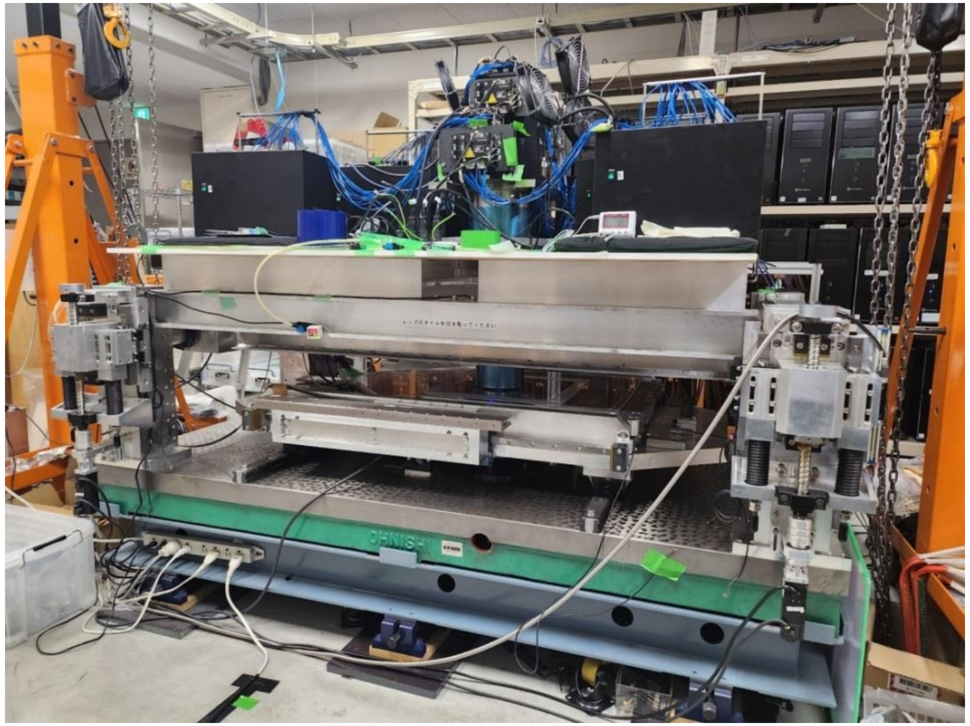
LHC Ring

SND@LHC detector

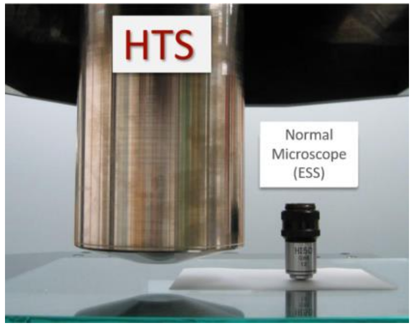
The SND@LHC is a new experiment to study the forward produced Neutrinos and Feebly interacting particles in the unexplored regions of energy (350 GeV – 10 TeV) and pseudo-rapidity (7.2 < η < 8.4).

HTS2 (Hyper Track Selector)

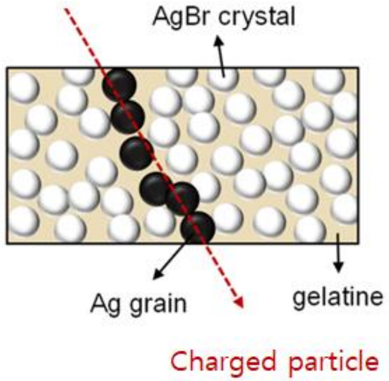
- **Scanning** → Automatic formation of Micro-tracks
- **Off-line analysis** → Reconstruction of Base-tracks, Volume-tracks & Vertices

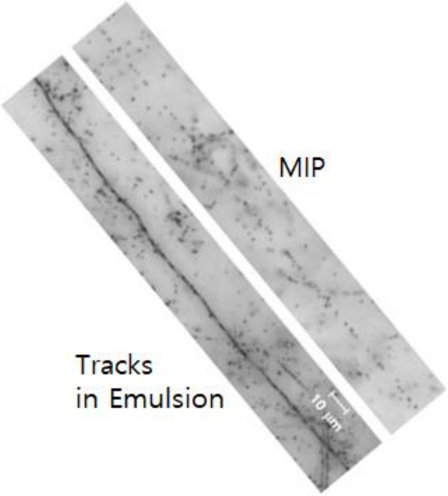


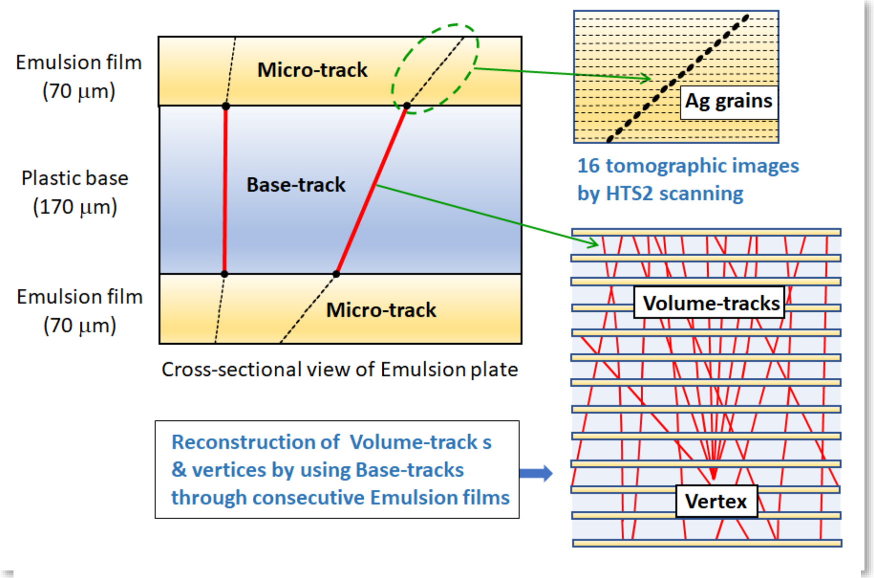
Fastest Emulsion automatic-scanning system developed by Nagoya group



9.5 x 5.3 mm^2 0.2 x 0.2 mm^2
Field of View



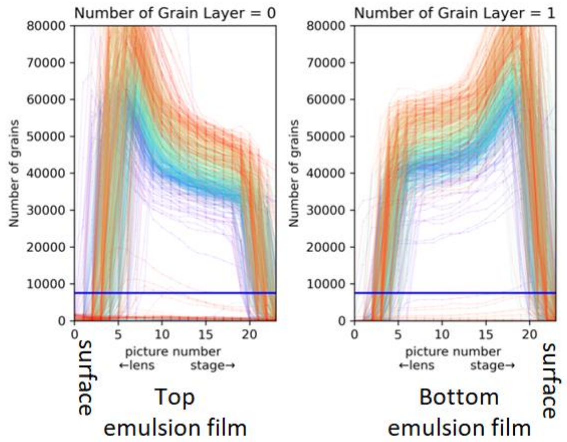




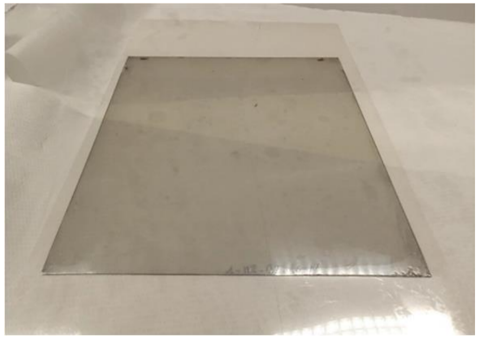
Cross-sectional view of Emulsion plate

Reconstruction of Volume-track s & vertices by using Base-tracks through consecutive Emulsion films

Number of grains obtained by HTS2

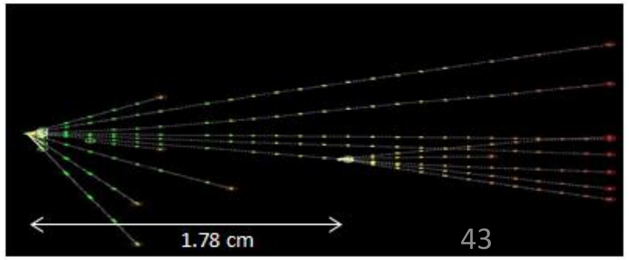


Scanning speed
~ 10 min/film



Emulsion film
19.2 x 19.2 cm^2
310 μm thick

HTS2 Scanning → Micro-tracks → Base-tracks → Volume-tracks → Vertex reconstruction



Reconstructed event with 2 vertices

Observed Collider neutrinos in SND@LHC

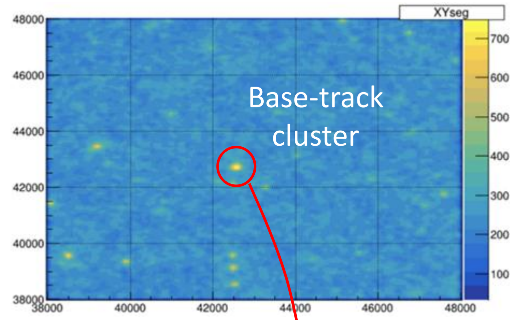
ν_μ candidates (1μ): **32 events** PRL 131, 031802 (2023)
ν_e or NC candidates (0μ): **9 events**

1μ paper

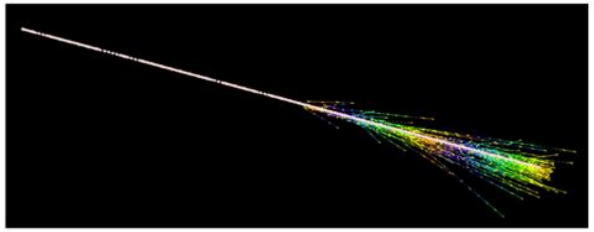
PHYSICAL REVIEW LETTERS **134**, 231802 (2025)

Observation of Collider Neutrinos without Final State Muons with the SND@LHC Experiment

0μ paper

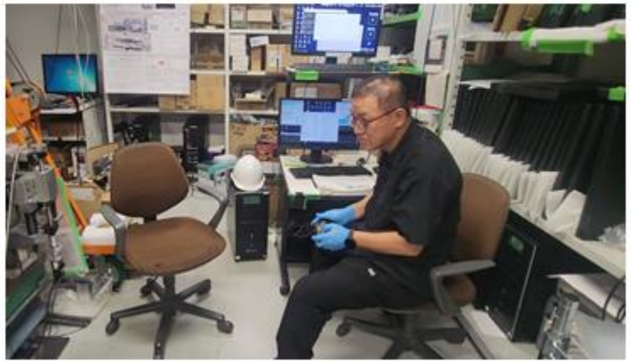


All segments (Base-tracks) along beam-direction



Candidate of ν_e CC event using the Base-track cluster



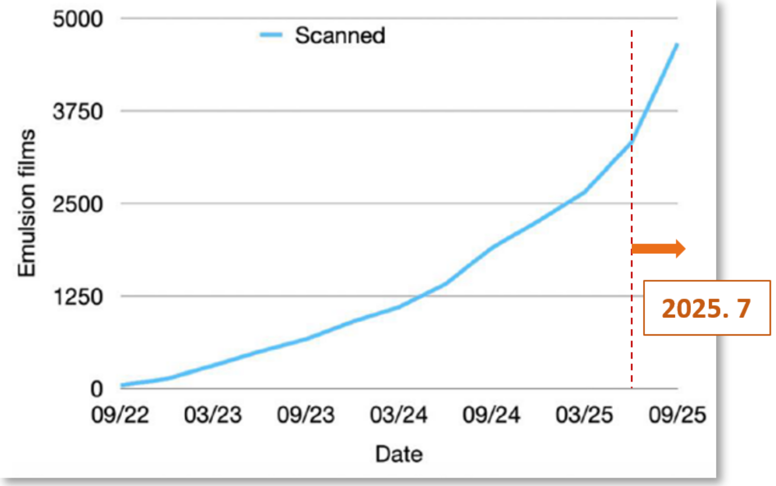



Emulsion scanning using HTS2 at Nagoya

(July - Aug 2025)

Total scanned films: 702

- 21 ECC targets have been replaced from 2022 to Oct 2025.
- About 7,000 films were exposed and developed (~ 258 m²).



- Our group just started Emulsion scanning using HTS2 for SND@LHC
  - about 700 films in 2 months.
- To the next step, we will proceed off-line analysis in order to reconstruct the Volume-tracks and Neutrino vertices.
- In parallel, we will continue Emulsion scanning to get the Micro-tracks.

요약

- 국내외 주요 중성미자 실험 참여
  - RENO, RENE, 등 국내 기반 실험
  - IceCube, Super-K/Hyper-K, DUNE, JSNS2, COHERENT, SND@LHC 등 국제 협력 실험
  - KNO, Donghae준비 단계
- 한국 연구진의 기여
  - 장기간 데이터 분석과 새로운 채널 활용 성과
  - 국제 대형 실험에서 핵심 역할 수행
  - 차세대 관측소(KNO)로 연구 허브 도약 준비

IBS 중성미자 실험 발표
- Highlight from IBS-Center for Underground Physics (김영덕 (IBS))
- 예미랩 중성미자 검출기 (원은일 (고려대학교))

backup

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

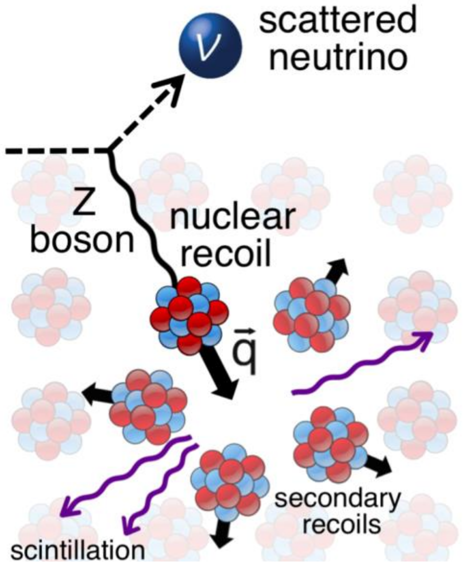
- CEvNS theorized in 1974
- First observed CEvNS using CsI[Na] in 2017 [Akimov et al., Science 357, 1123–1126 (2017)]
- Neutrino interacts with a whole nucleus when QR < 1
- Precise cross section for spoin-0 nuclei within the Standard Model

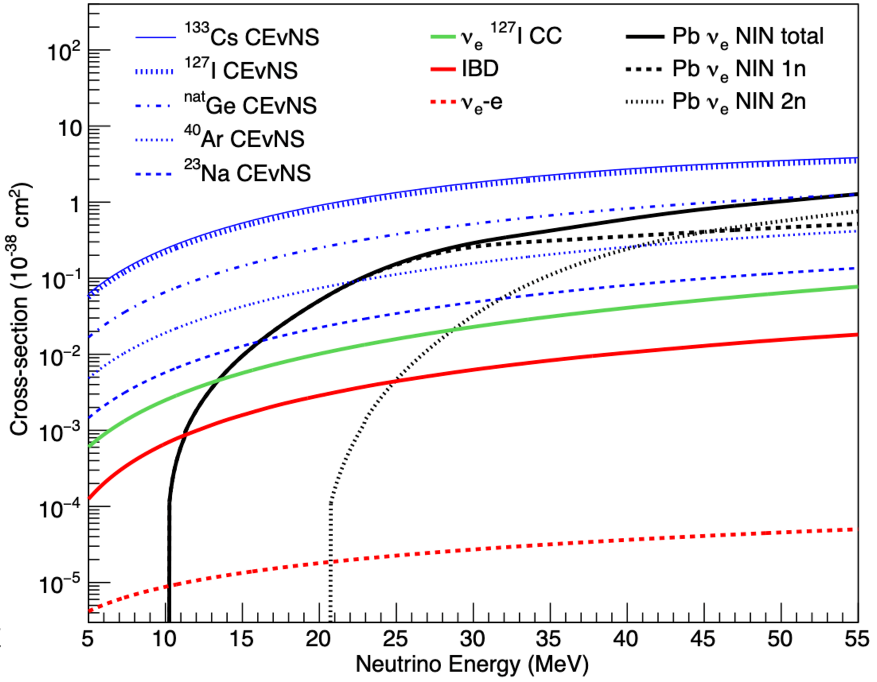
$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\left(2 - \frac{2T}{E_\nu} + \frac{T^2}{E_\nu^2} - \frac{MT}{E_\nu^2}\right)\frac{Q_W^2}{4}F^2(Q^2)$$

M: Nucleus mass, T: recoil energy

F: Nuclear form factor Q: momentum transfer

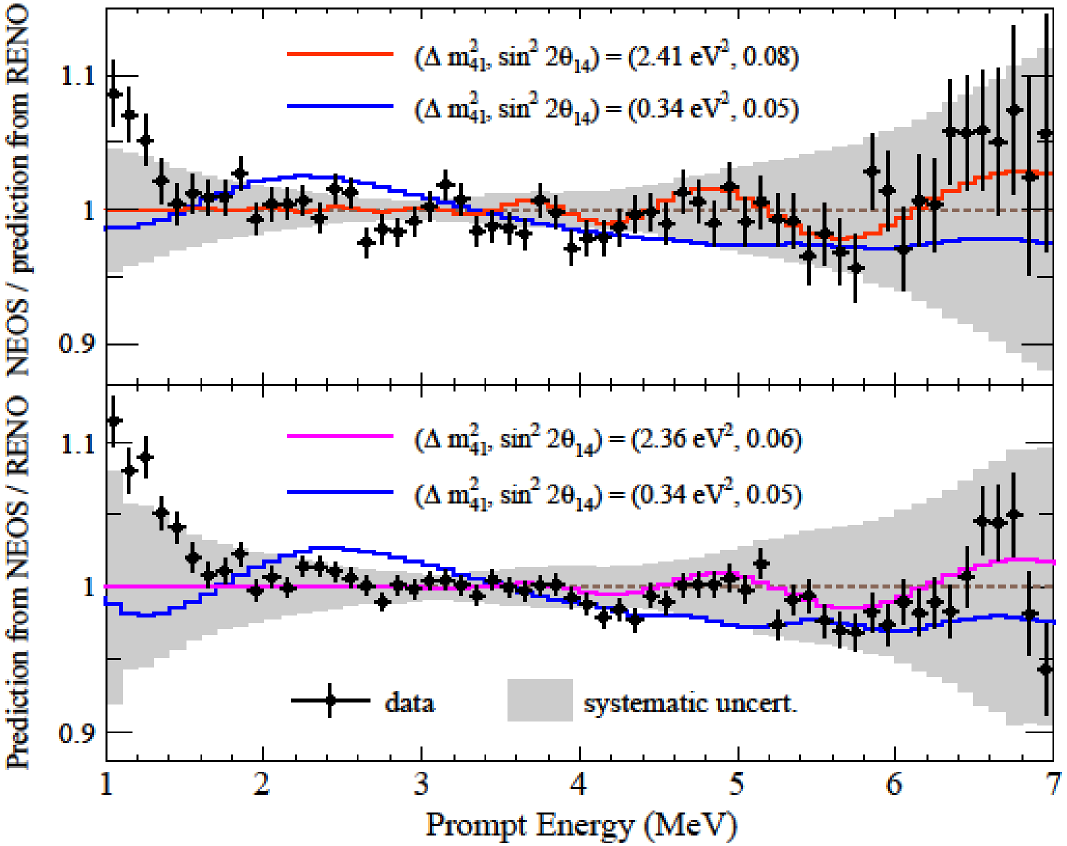
- N^2 dependent cross section
  $(Q_W^2 = (N - (1 - 4sin\theta_W^2)Z)^2 \cong N^2)$
- Dominant process in low energy (< 100 MeV)
- Max recoil energy $\cong 2E^2/M < 100$ keV



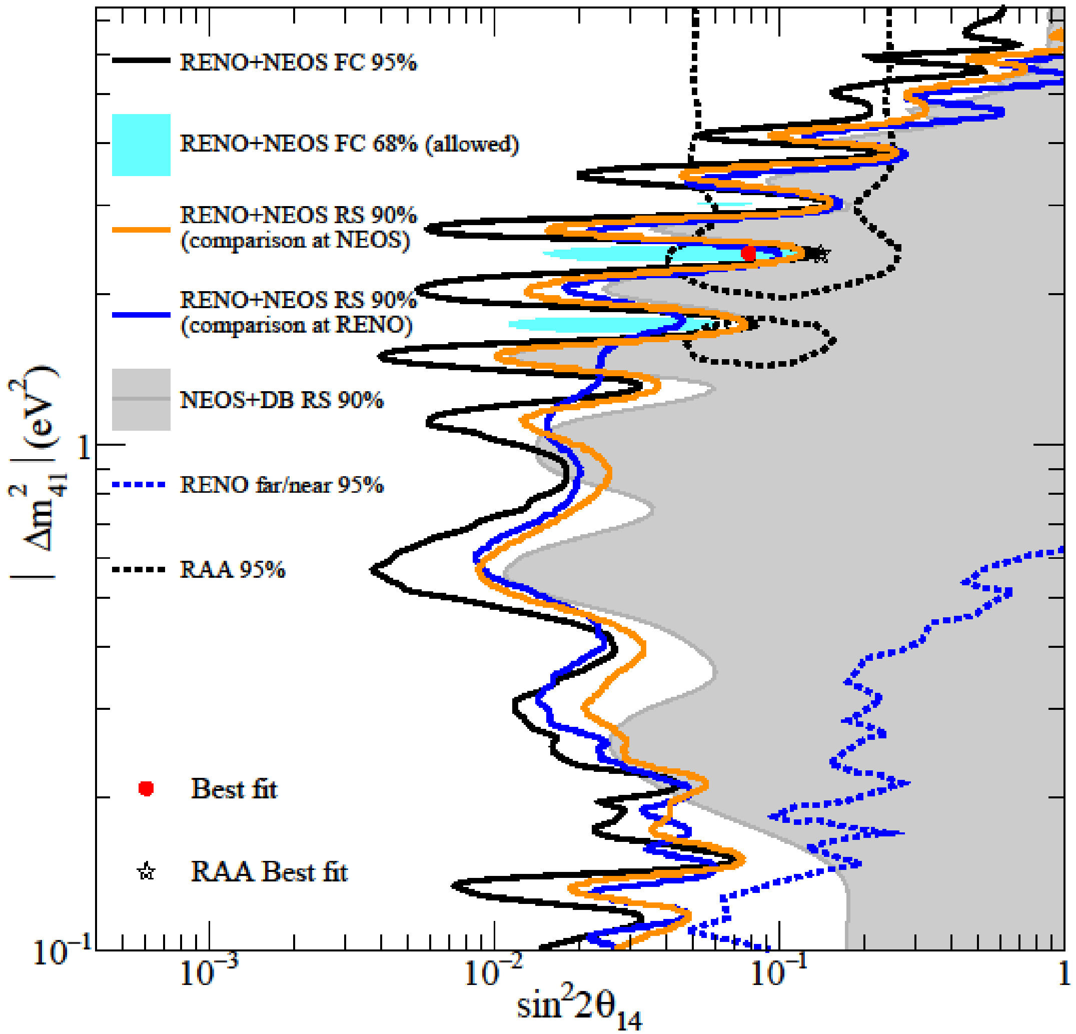


RENE 실험의 동기

RENO-NEOS 공동연구에서 4번째 중성미자의 가능성을 발견

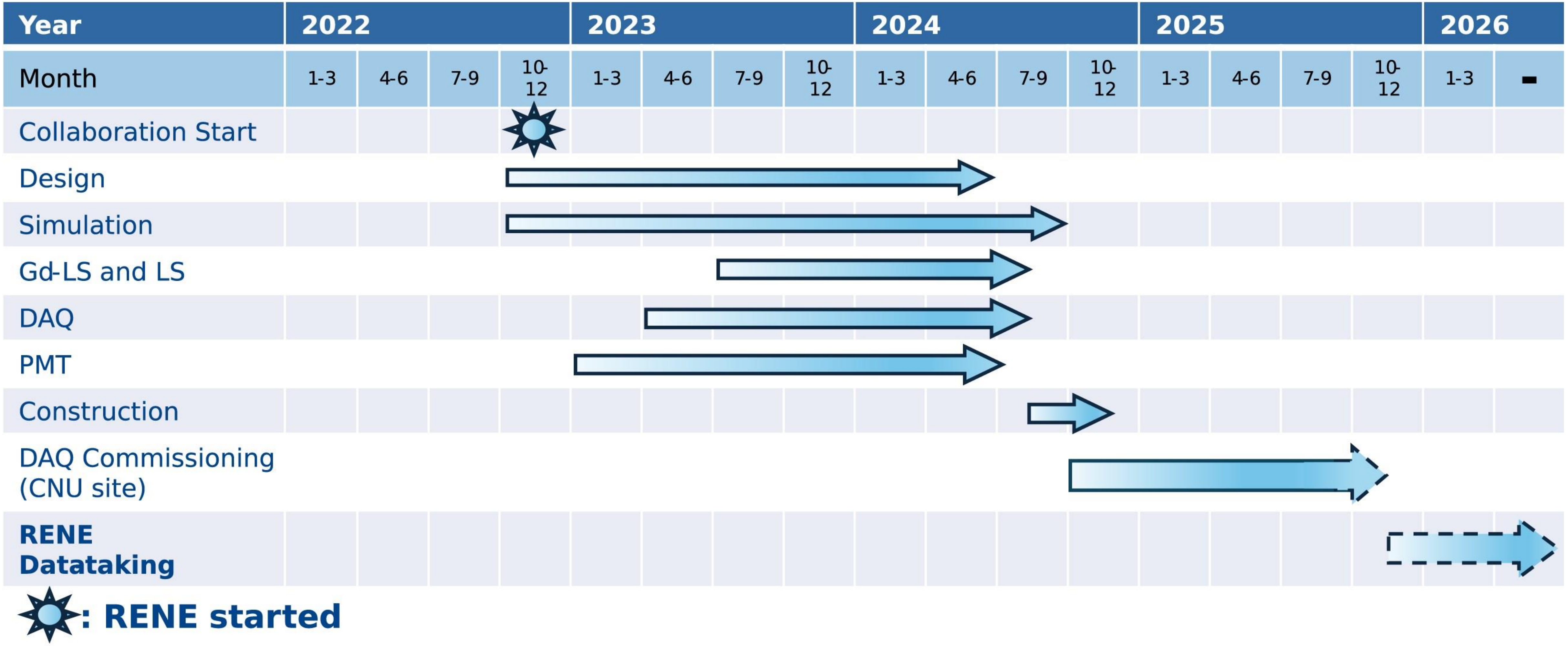


PRD 105 (2022), L111101



- 증명 위해 실험의 계통 오차 줄여야 함.

RENE 일정



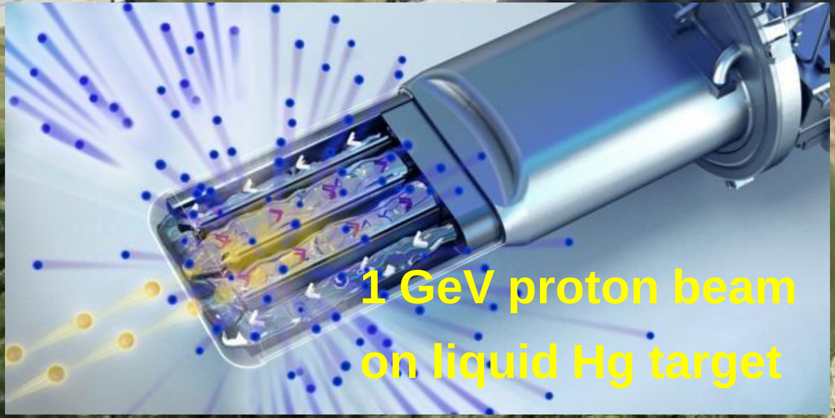
Year
2022
2023
2024
2025
2026
Month
1-3
4-6
7-9
10-12
1-3
4-6
7-9
10-12
1-3
4-6
7-9
10-12
1-3
4-6
7-9
10-12
1-3
-
Collaboration Start
Design
Simulation
Gd-LS and LS
DAQ
PMT
Construction
DAQ Commissioning (CNU site)
RENE Datataking
: RENE started

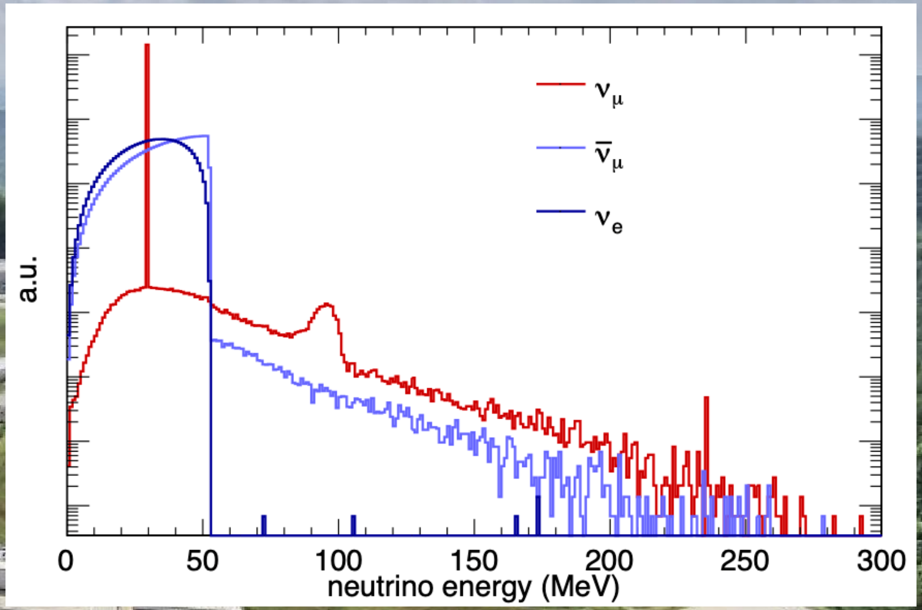
Spallation Neutron Source (SNS) at ORNL

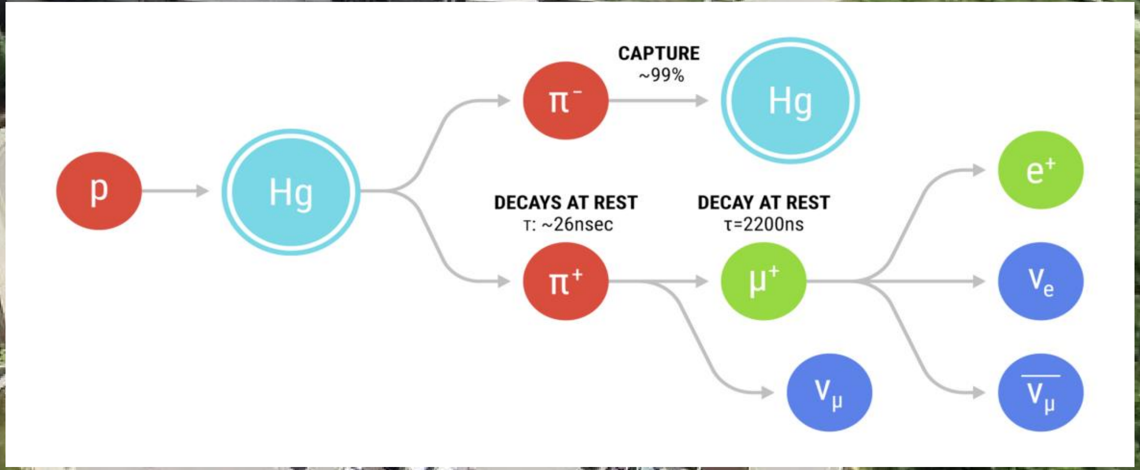
Proton LINAC

Proton beam energy: 0.9-1.3 GeV

Total power: ~1.4 MW







CENNS-1ton: Related physics