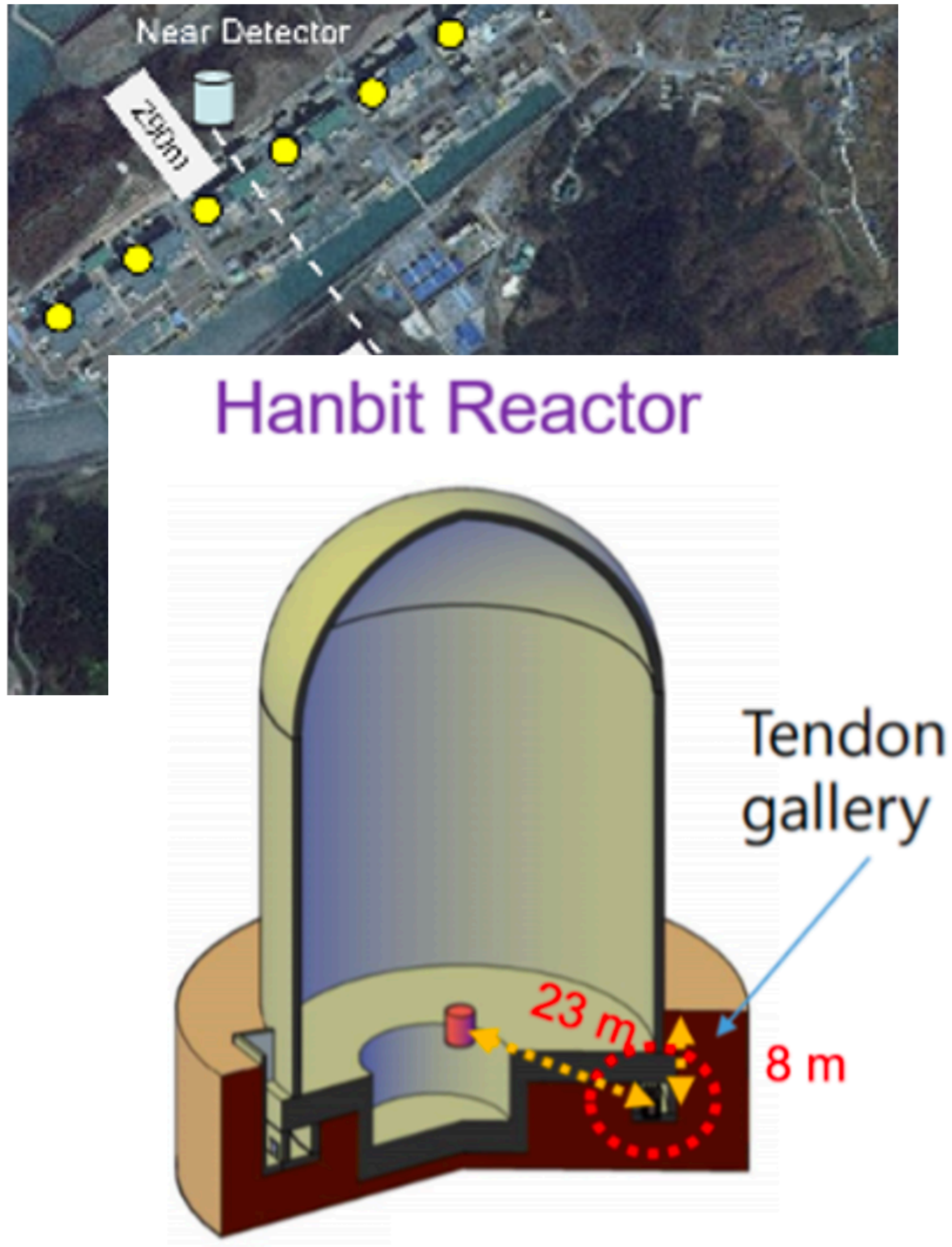
Status of the RENE Experiment

Jungsic Park (Kyungpook National University)
On behalf of the RENE collaboration

3^{rd} IAEA TM, April 7 - 11, 2025

RENE
(Reactor Experiment for Neutrinos and Exotics)



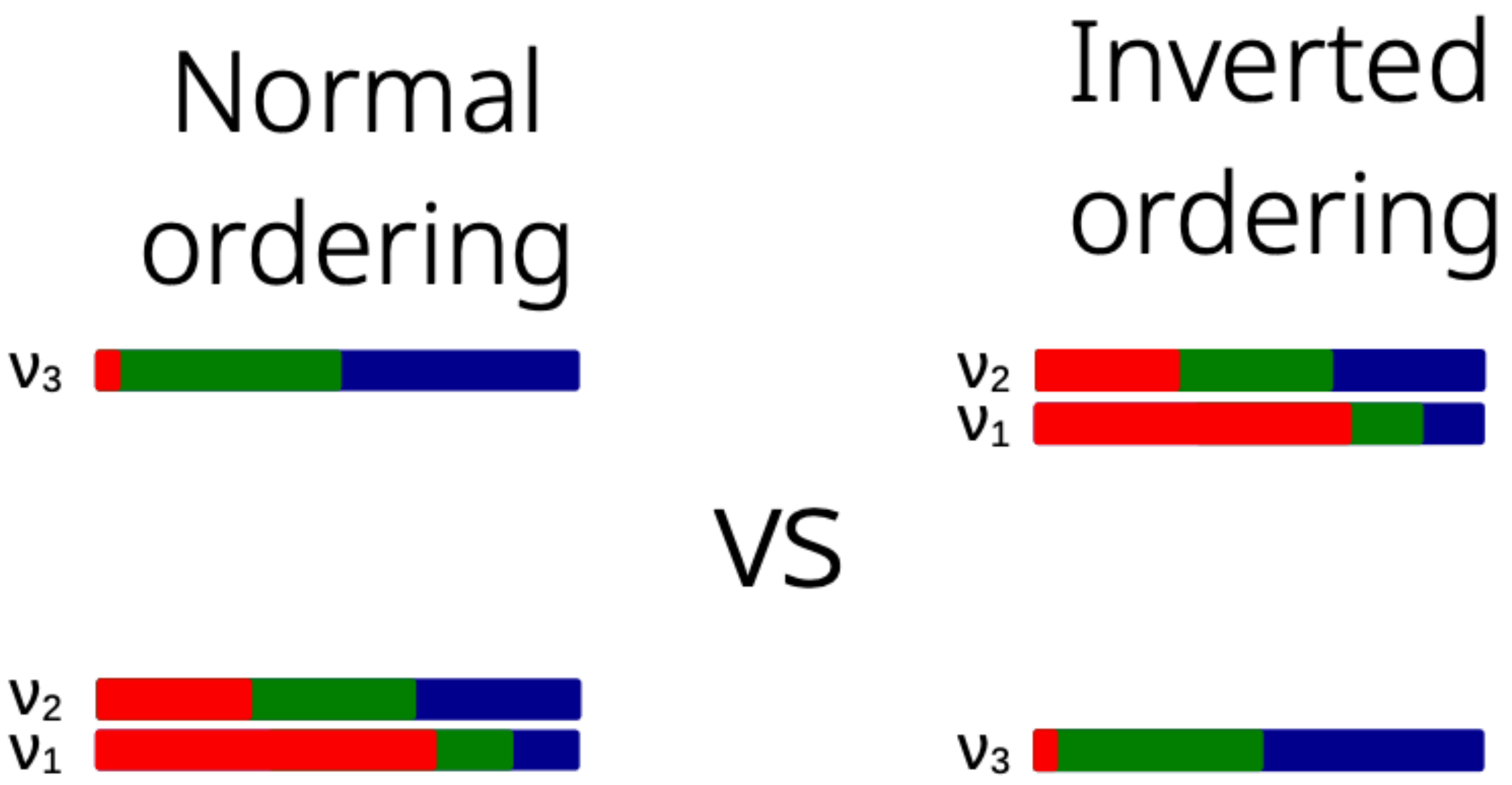
- RENE aims to investigate the"**sterile neutrino**" oscillation at $|\Delta m^2_{41}| \sim 2\mathrm{eV}^2$
- Can provide precise measurements of the flux and energy spectrum of the reactor electron antineutrino ($\bar{\nu}_e$) separately from ^{235}U and ^{239}Pu
- Will be installed in the Tendon gallery of a reactor in the Hanbit Nuclear Power Plant Complex

RENE collaboration

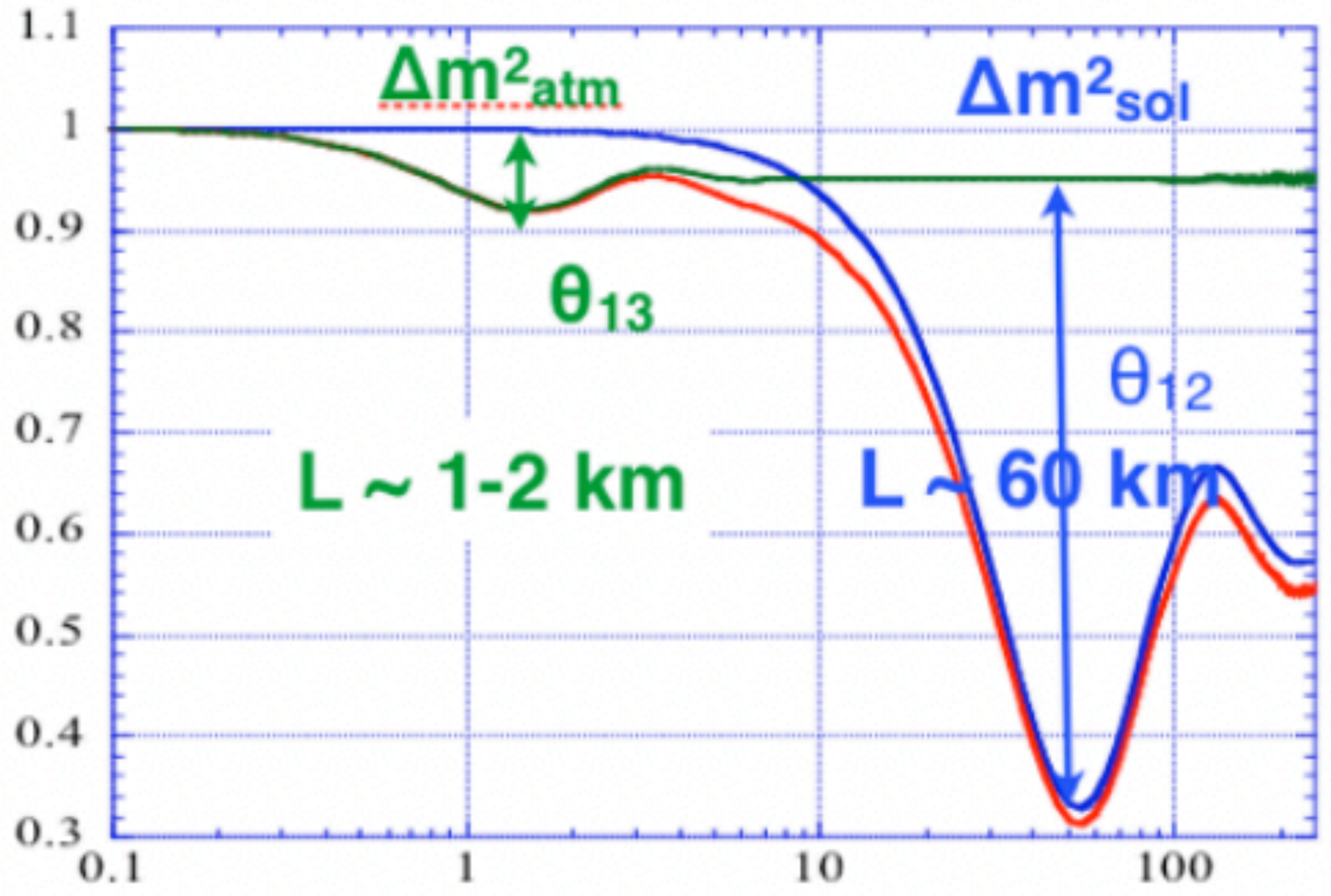
Collaboration meeting in 2023

12 institutions & about 30 members

3-Neutrino Mixing from Reactors



$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$



- Δm_{ij}^2 : mass splitting
- L : distance from a reactor core
- E_ν : electron antineutrino energy (spectrum)

From 2023 PDG

- $\Delta m_{21}^2 \sim 7.5 \times 10^{-5} eV^2$
- $\Delta m_{32}^2 \sim 2.5 \times 10^{-3} eV^2$

LSND overview

(Nucl. Instrum. Meth. A 388 (1997) 149-172 and arXiv:1204.5379)

- 800 MeV proton beam hits the target and produces pions and muons
- Muon antineutrinos are produced from muon decay-at-rest
- Search electron antineutrino appearance signals by oscillation at 30 m baseline
- Sensitive to measure $\Delta m^2 \sim 1\ eV^2$

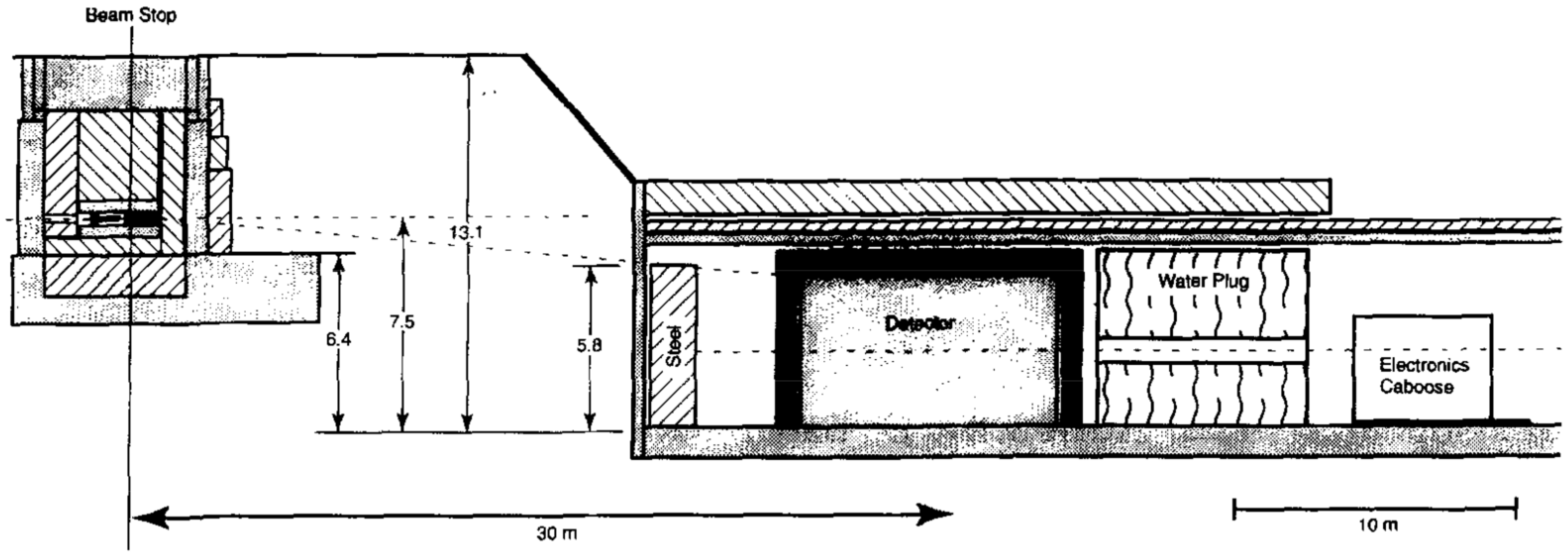
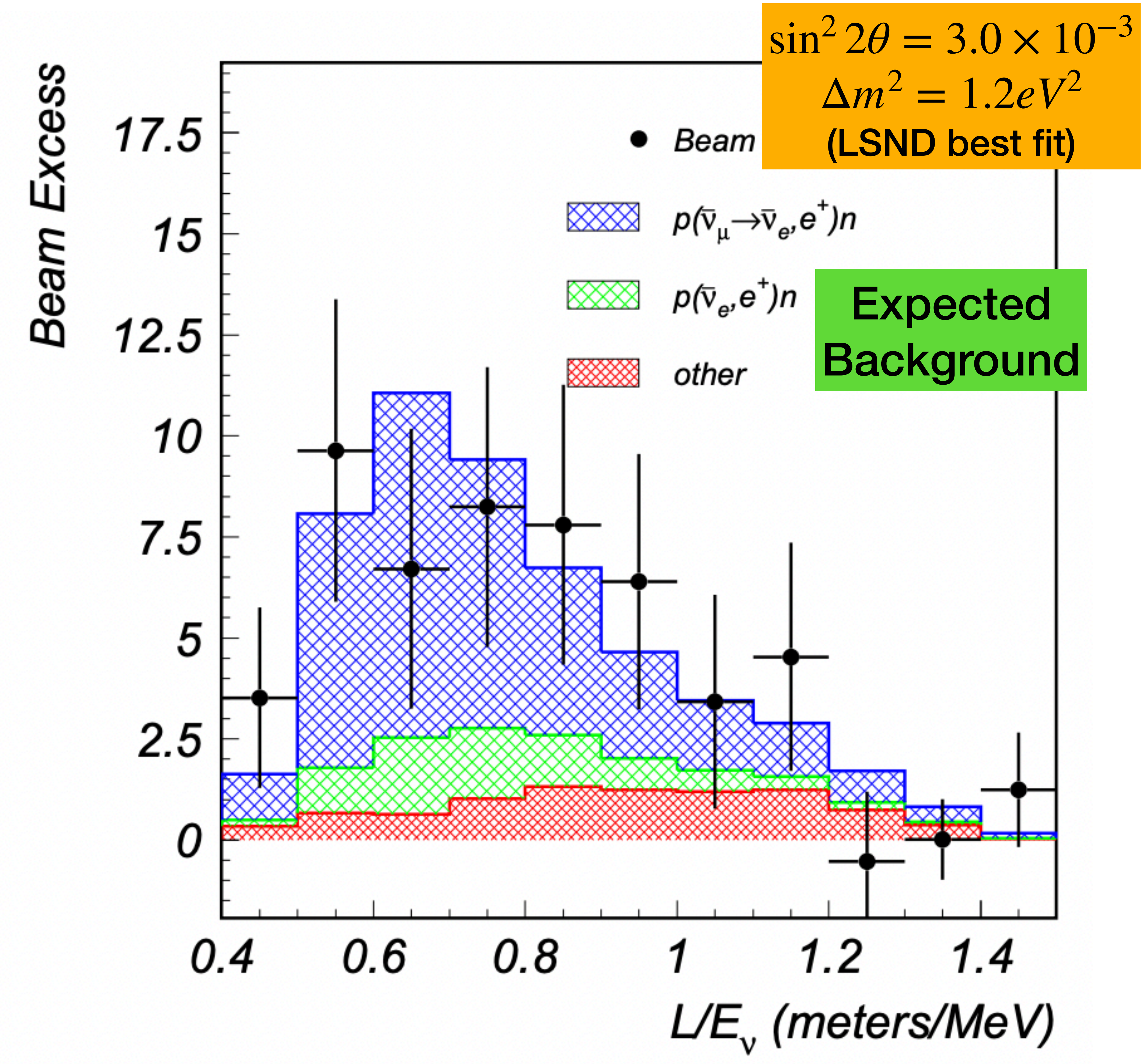


Fig. 1. Detector enclosure and target area configuration, elevation view.

Indication of a sterile neutrino ($\Delta m^2 \sim 1$ eV^2)

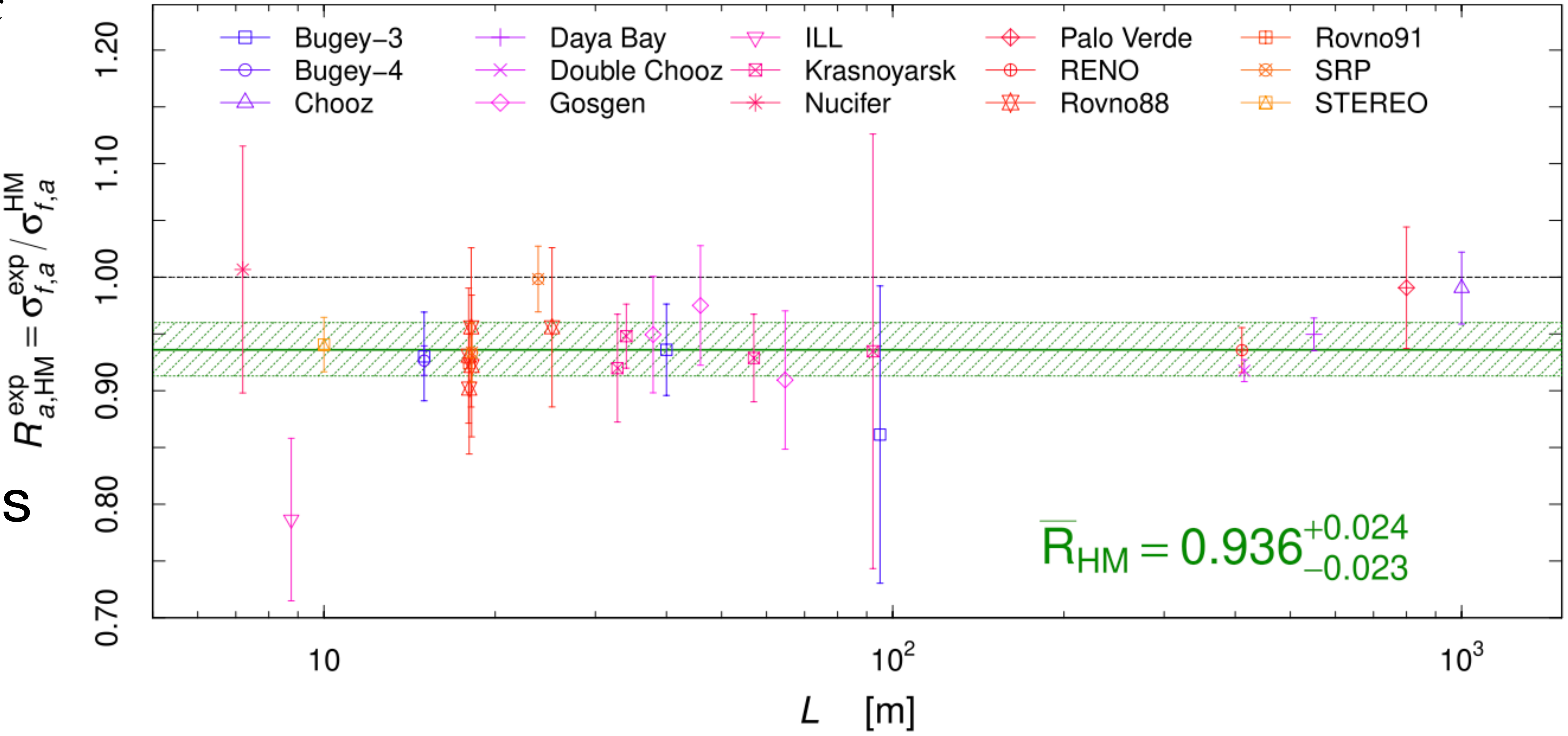


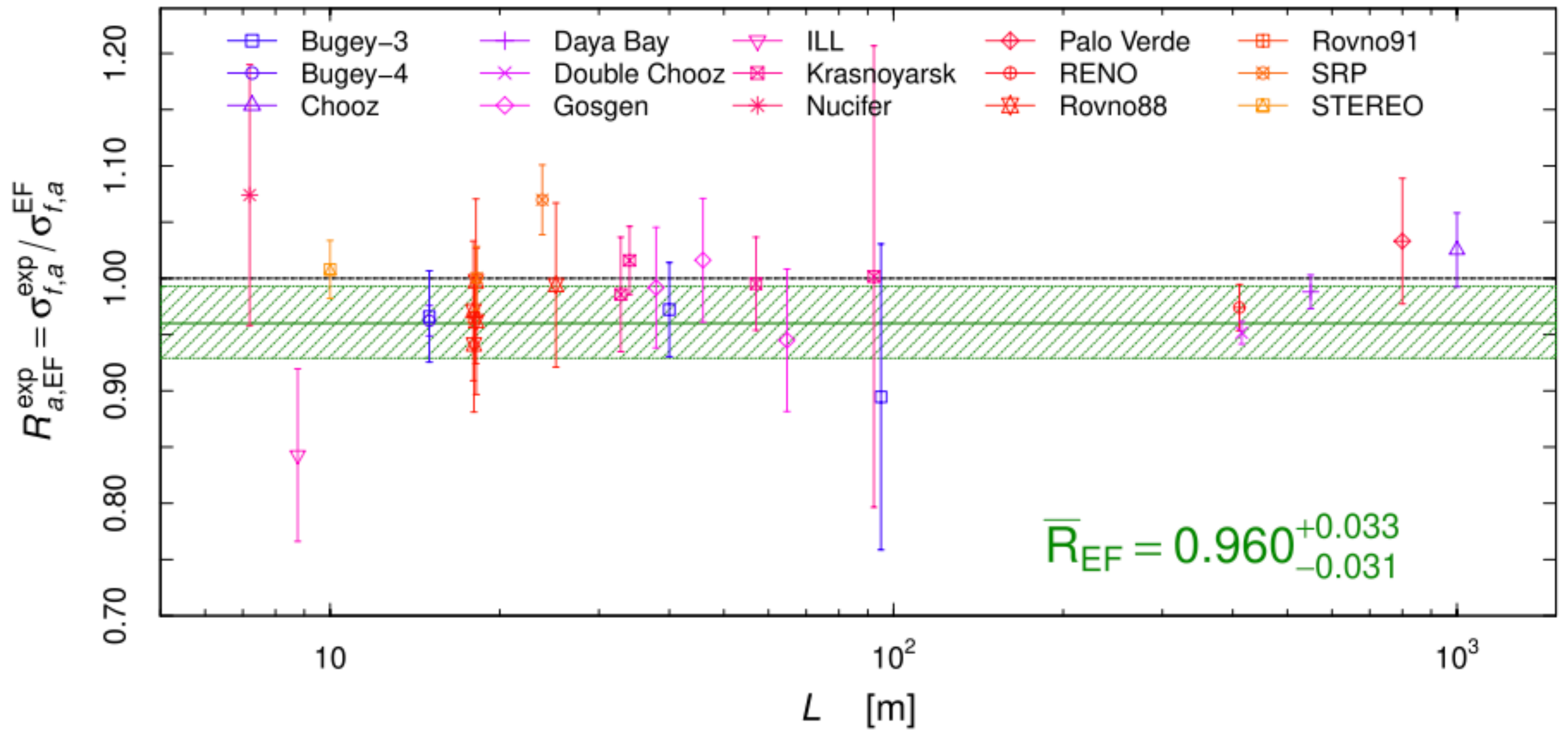
- Mysterious excess in LSND data (1998)
- Introduce an additional type of neutrino, known as the **sterile neutrino**, which does not participate in weak interactions but can oscillate with other neutrinos type
- LSND result could be explained by the existence of a sterile neutrino ($\bar{\nu}_\mu \rightarrow \nu_s \rightarrow \bar{\nu}_e$)

Recent flux model refinements

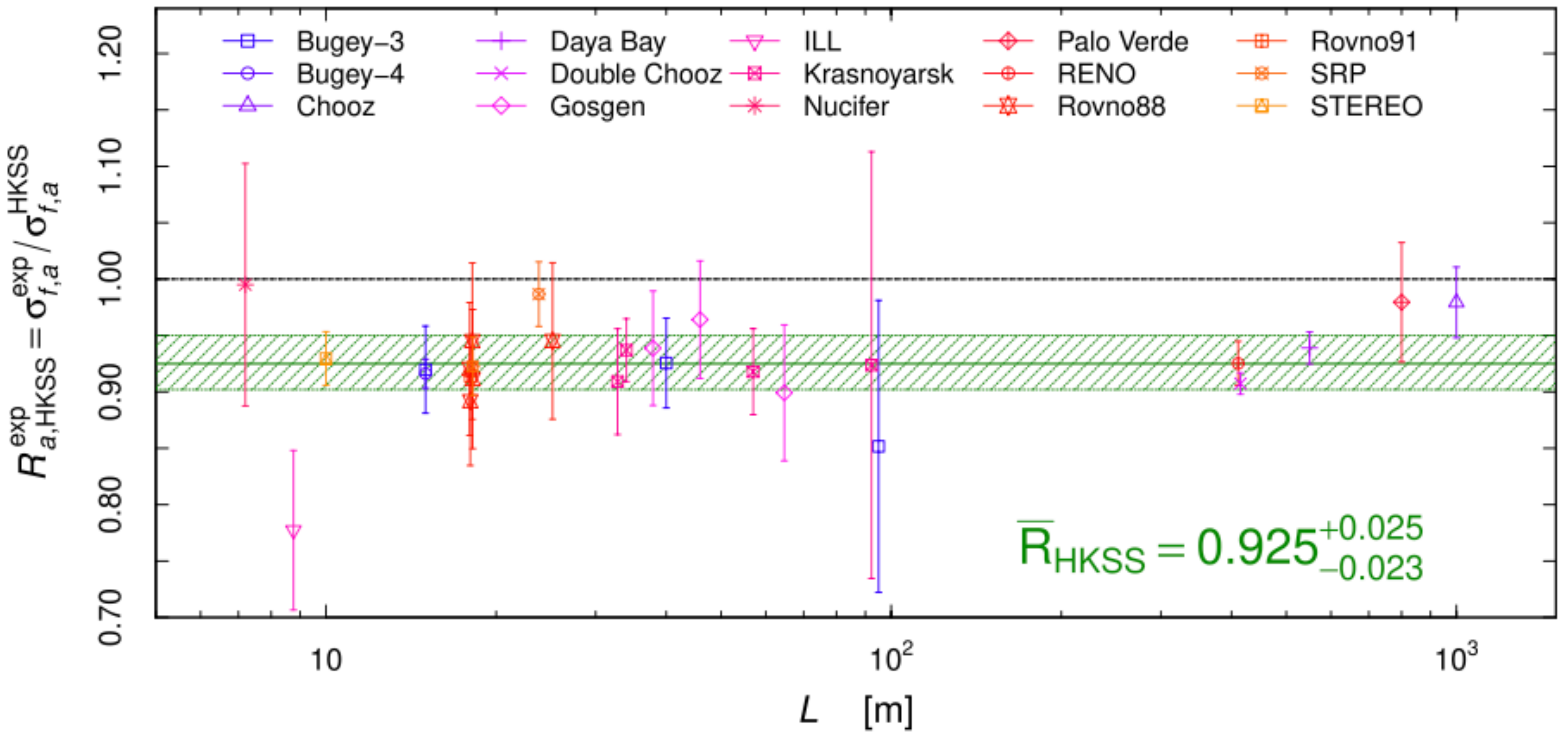
(Physics Letters B 829 (2022) 137054)

- Reactor Antineutrino Anomaly (RAA, mainly seen by HM model) also could be explained by $\bar{\nu}_e \rightarrow \bar{\nu}_x$
- The paper discussed
  - HM,
  - EF, HKSS,
  - KI, HKSS-KI models

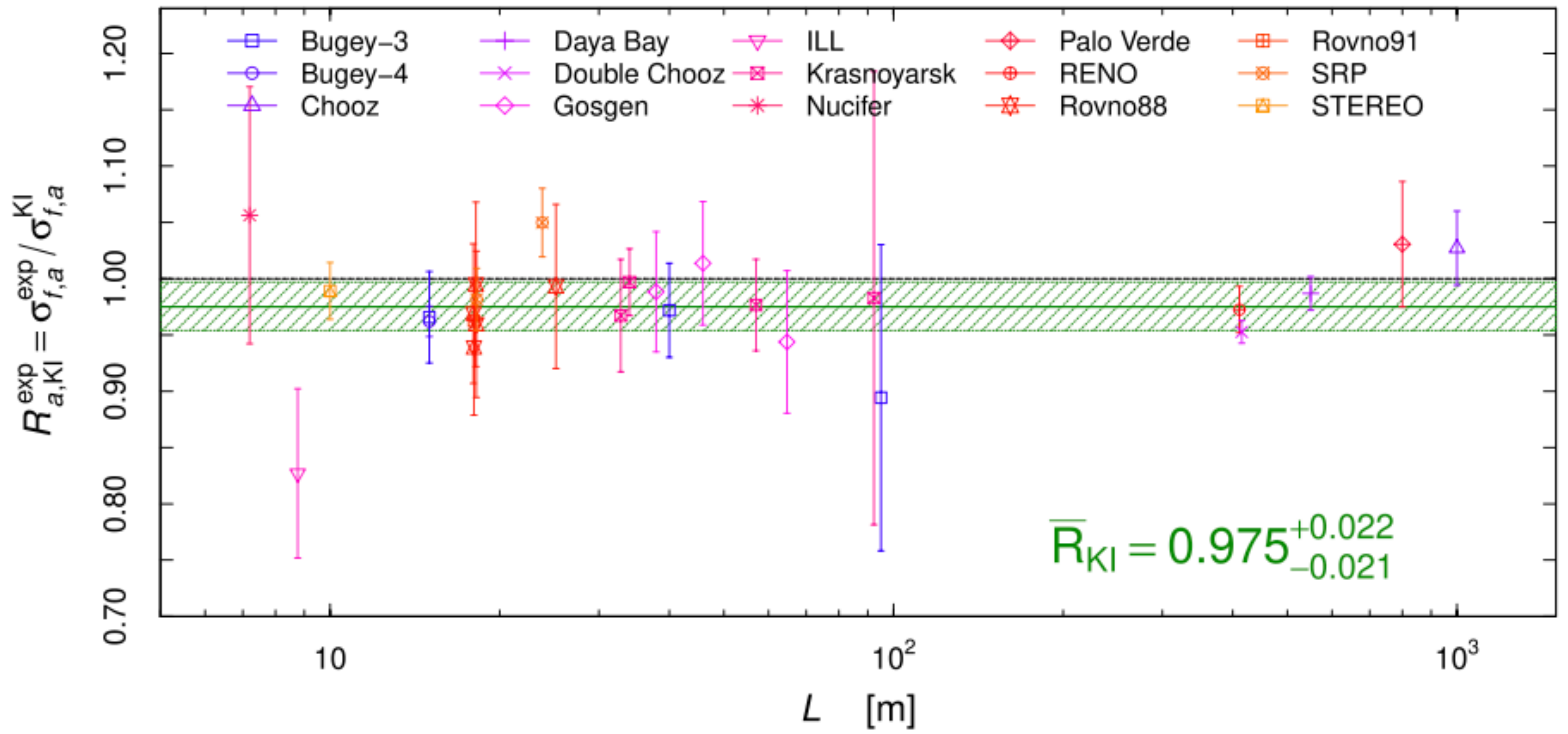




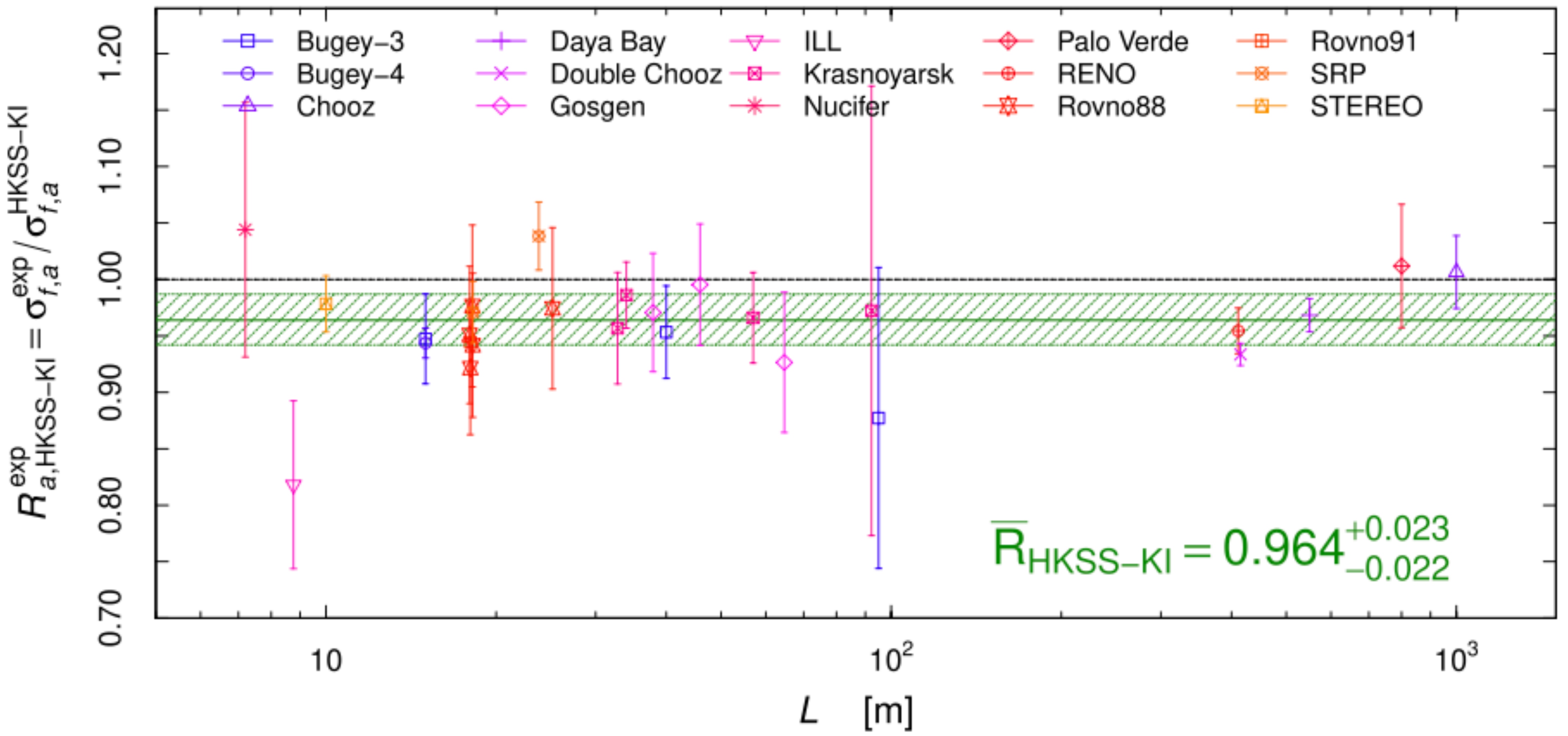
(a) EF model [18]: no RAA (1.2 σ).



(b) HKSS model [22]: RAA (2.9 σ).



(c) KI model [24]: no RAA (1.1 σ).



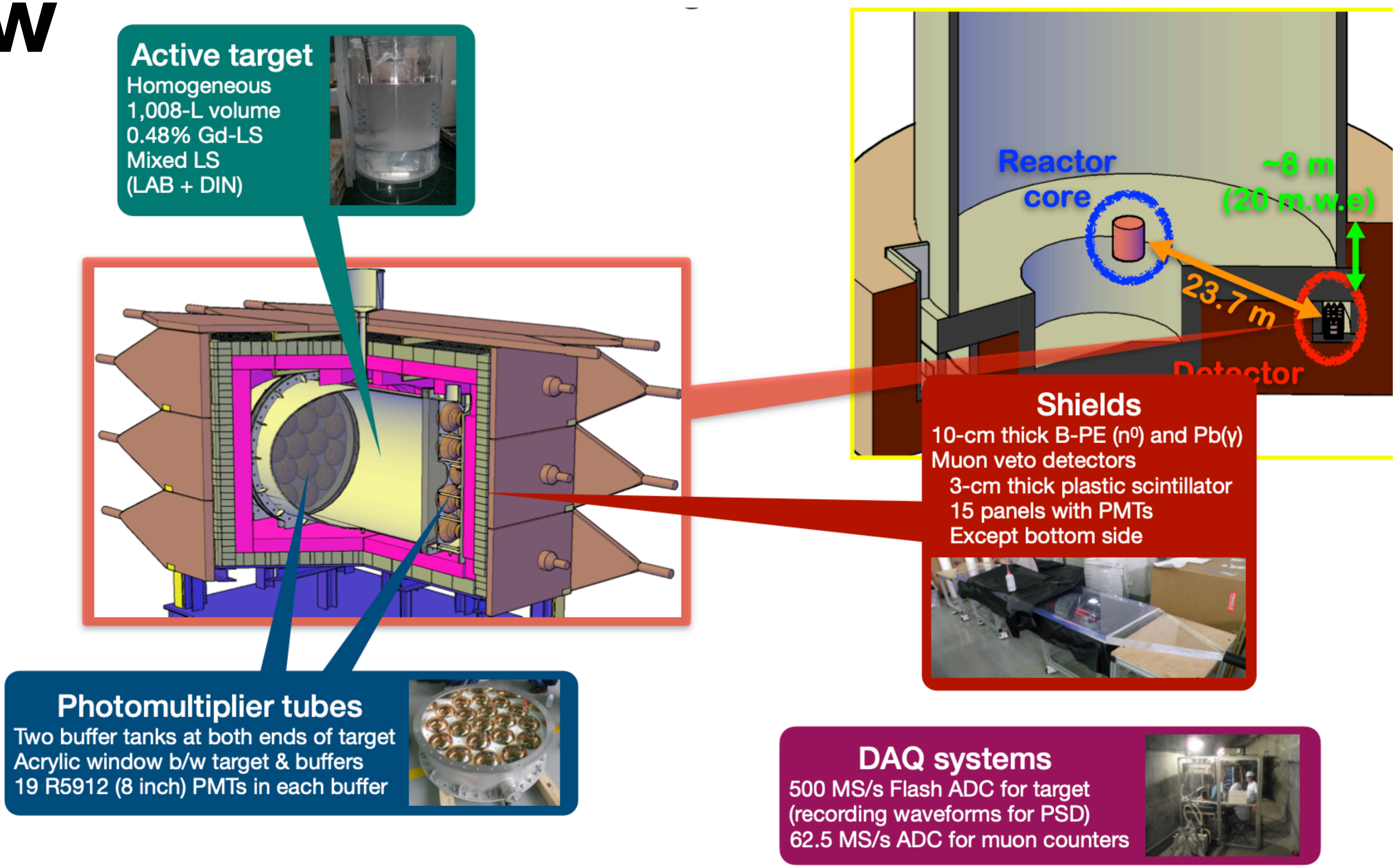
(d) HKSS-KI model: no RAA (1.5 σ).

NEOS overview
(From NPN 2024)

- Testing the (3+1)ν framework
- Hanbit-5 reactor
- 23.7 m baseline
- No strong evidence

  of light sterile neutrino

  PRL 118, 121802 (2017)



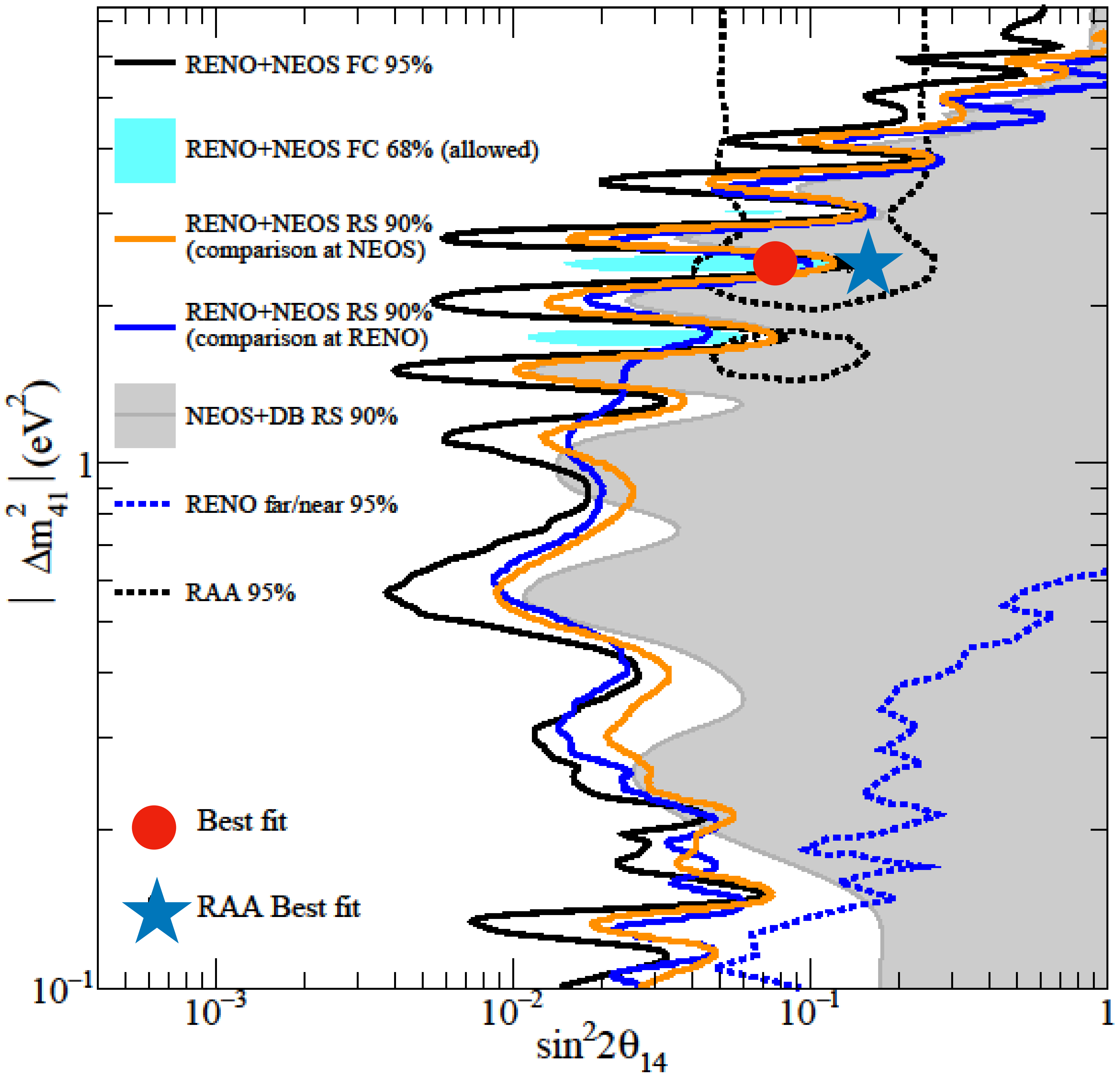
RENO and NEOS joint analysis

- The neutrino survival probability in a short baseline

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - 4 \sum_{i>j} |U_{ei}|^2 |U_{ej}|^2 \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

$$\simeq 1 - \sin^2 2\theta_{14} \sin^2 \Delta_{41} - \sin^2 2\theta_{13} \sin^2 \Delta_{31}$$

- $|U_{ei}|, |U_{ej}|$: elements of the neutrino mixing matrix
- L: baseline distance between the reactor and detector
- E and Δm_{ij}^2 : $\bar{\nu}_e$ energy and mass splitting
- Δ_{ij} : shorthand notation of $\Delta m_{ij}^2/4E$
- Δm_{41}^2, θ_{14} : between electron neutrino and the sterile neutrino



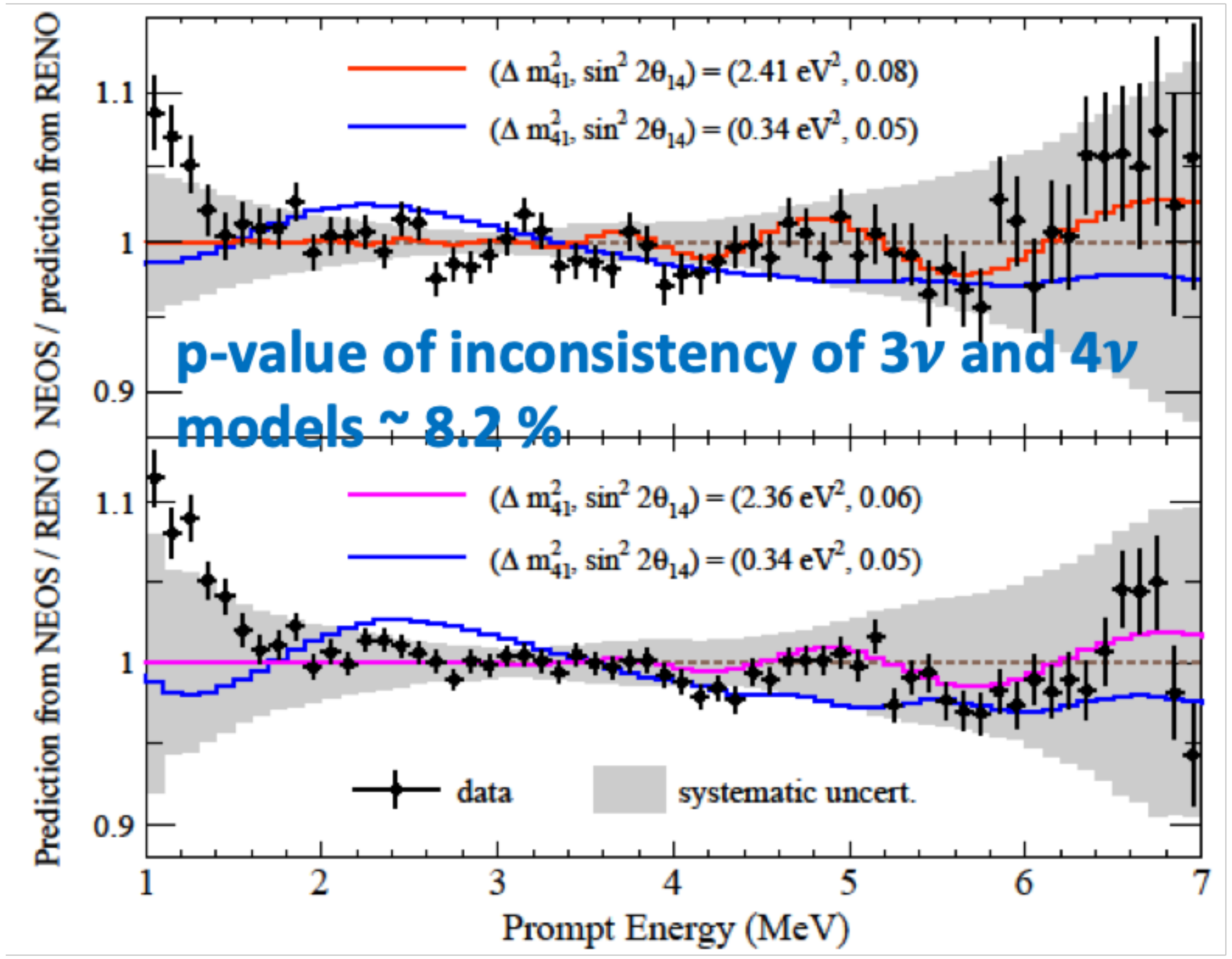
RENO and NEOS joint analysis

- Best-fit point:
  $|\Delta m^2_{41}| = 2.41\ eV^2,\ \sin^2 2\theta_{14} = 0.08$

- Nonzero Δm^2_{41} suggests the possible existence of the sterile neutrino

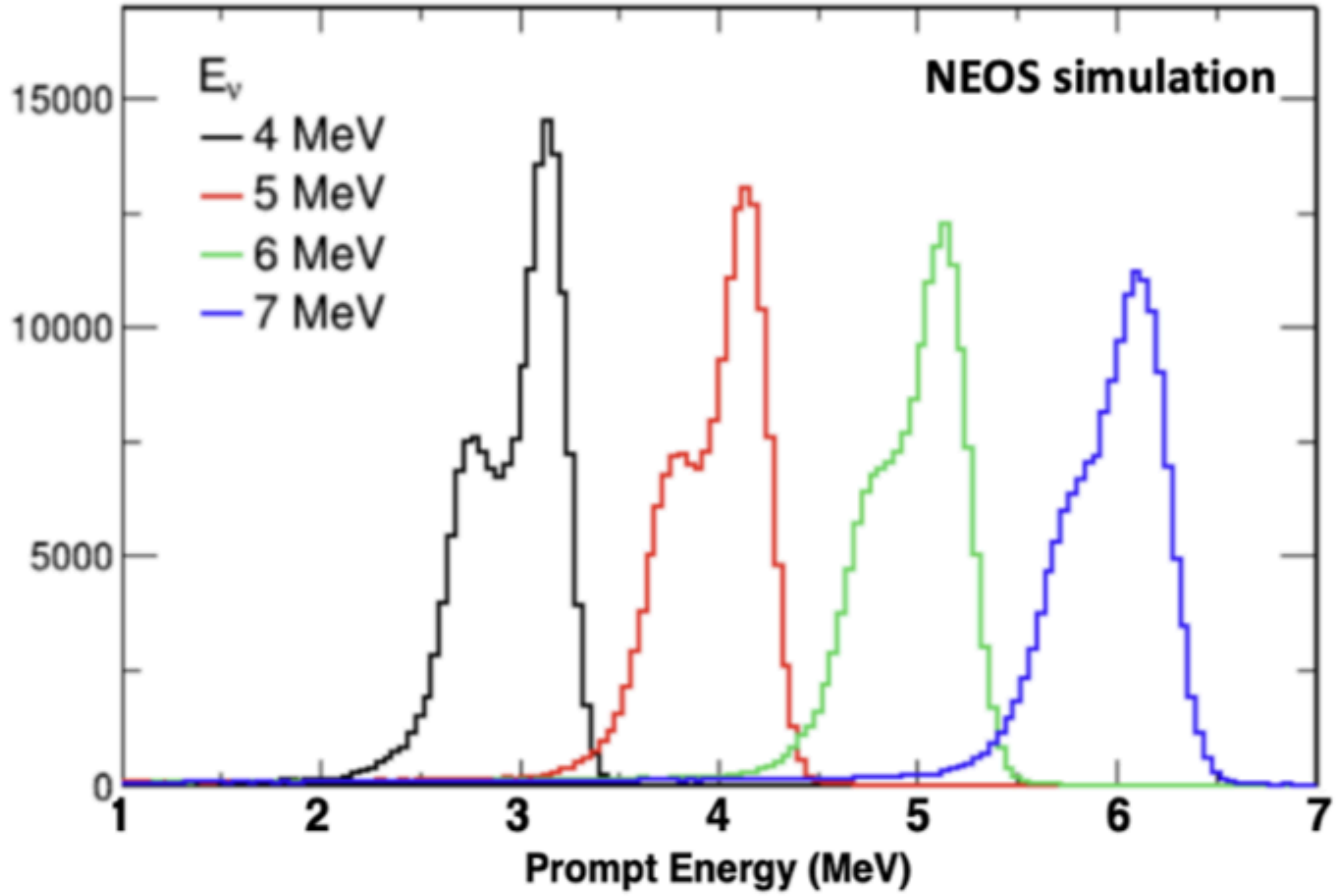
- RENE aims to confirm the allowed region for the sterile neutrino search

- Reduction of systematic uncertainties is needed to narrow down the remaining parameter space

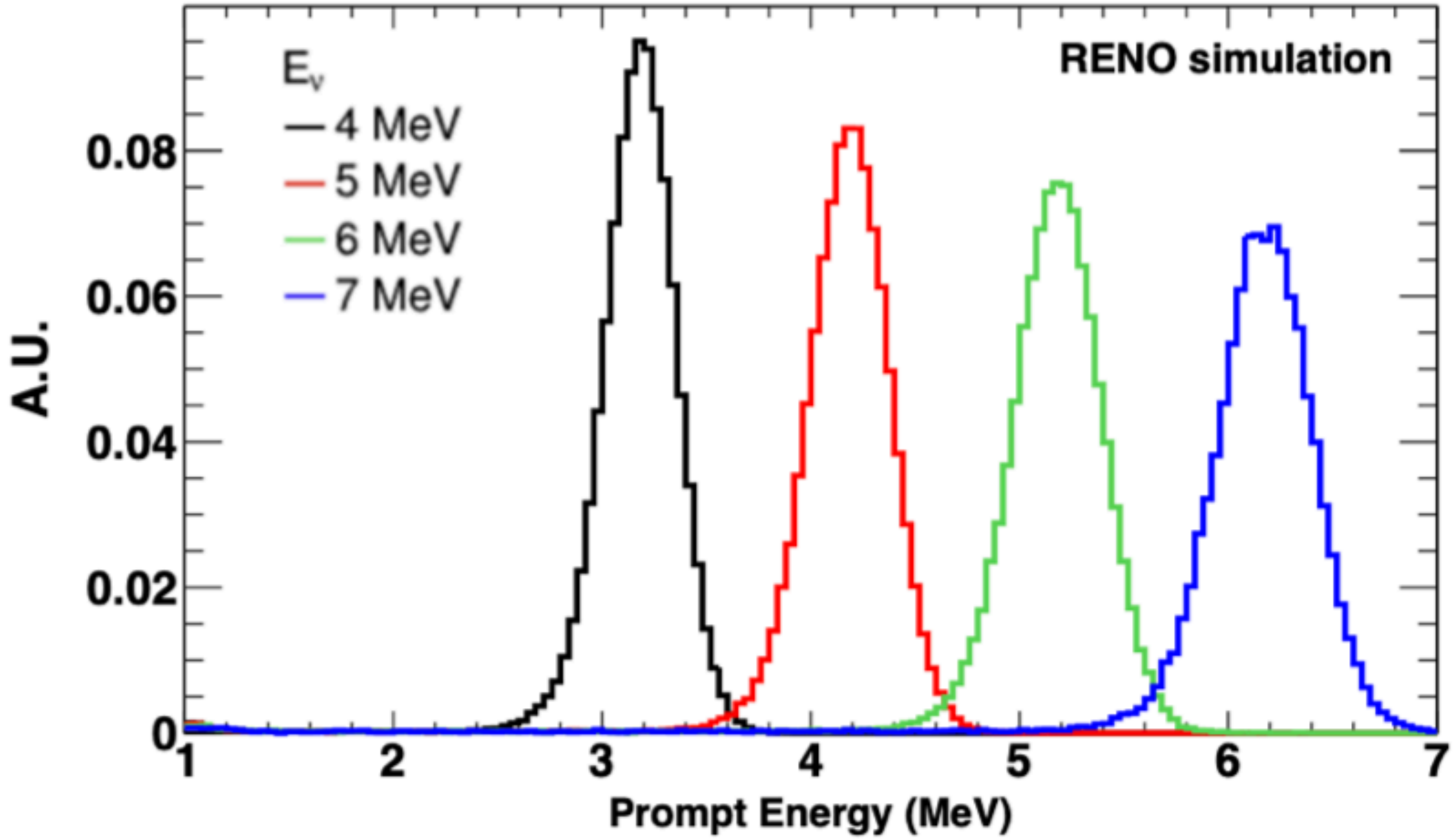


Detector response (simulation)

Neutrino-target-only design



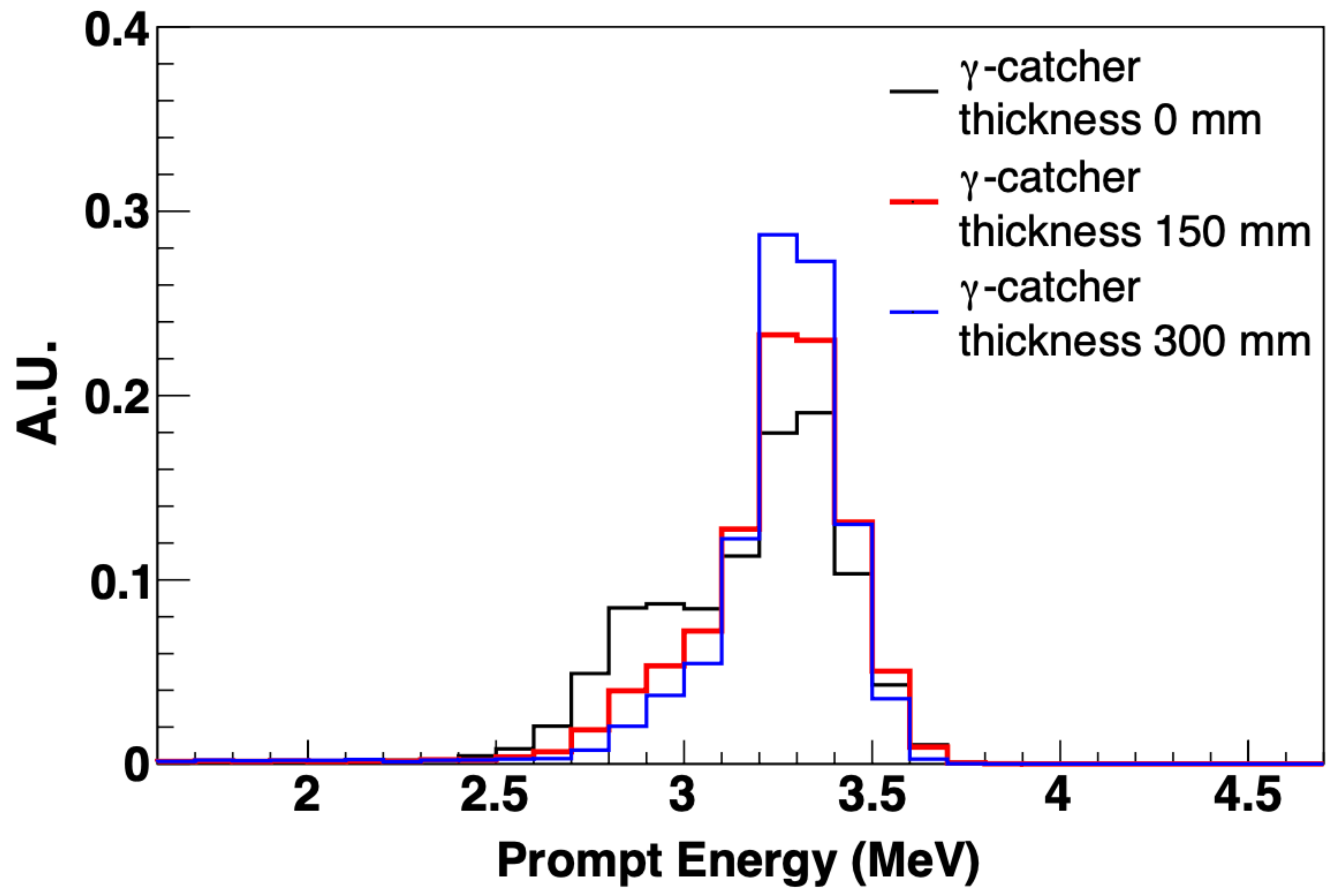
target plus γ-catcher design



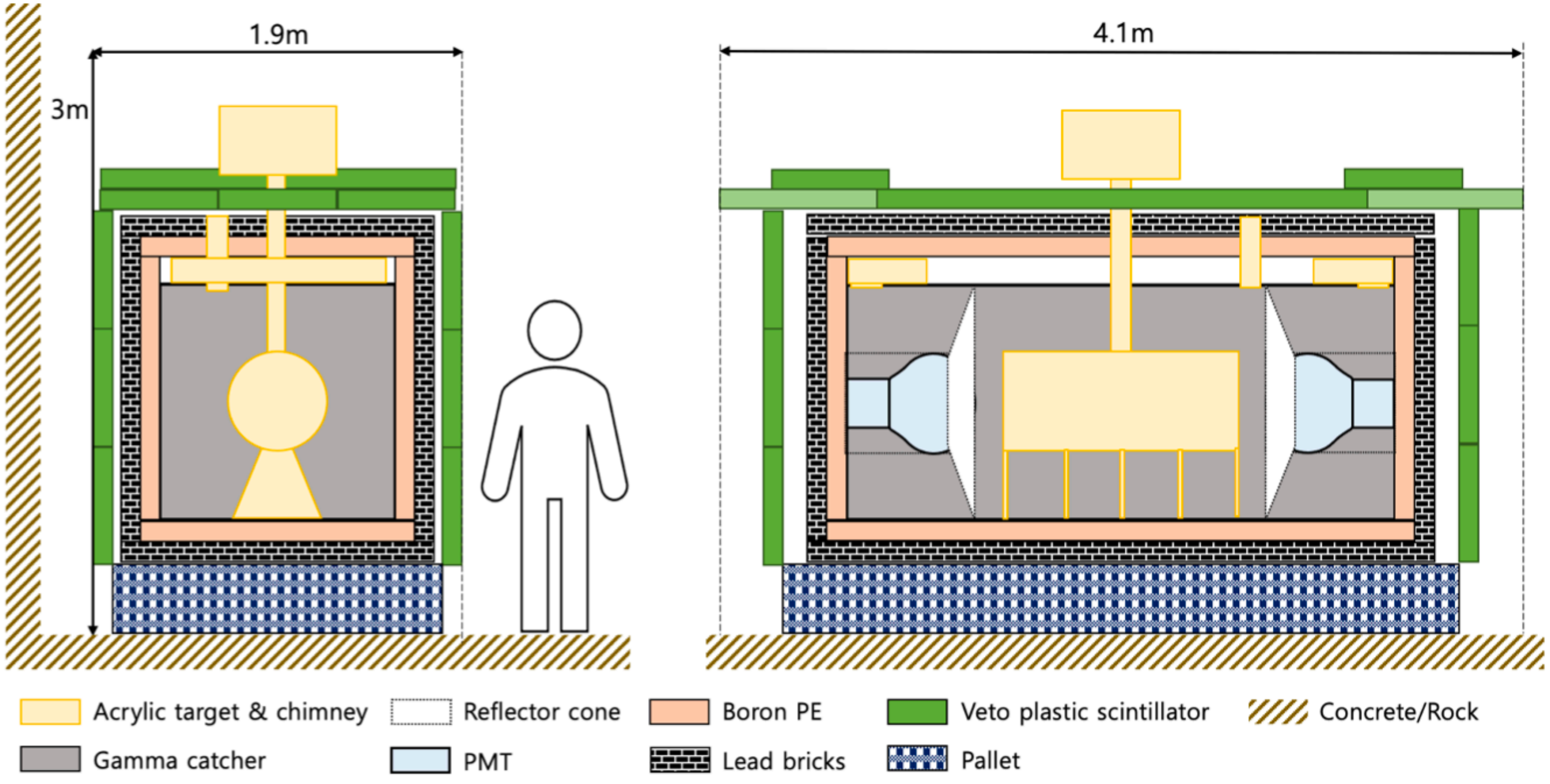
- Geant4-based Monte-Carlo simulations of positrons corresponding to neutrino energies from 4 to 7 MeV
- The low-energy secondary peaks and tails can be observed due to escaping gammas.
- We propose a new reactor neutrino experiment named RENE.

Optimization of γ-catcher thickness (simulation)

- The key design feature of the RENE detector is improving energy resolution by
  - Increasing the thickness of the γ-catcher
  - While maintaining an acceptable reduction in the target volume
- MC simulation presents the prompt energy distributions of 4 MeV positrons for NEOS-sized generic detectors varying γ-catcher volumes
- 150 mm thickness is deemed optimal

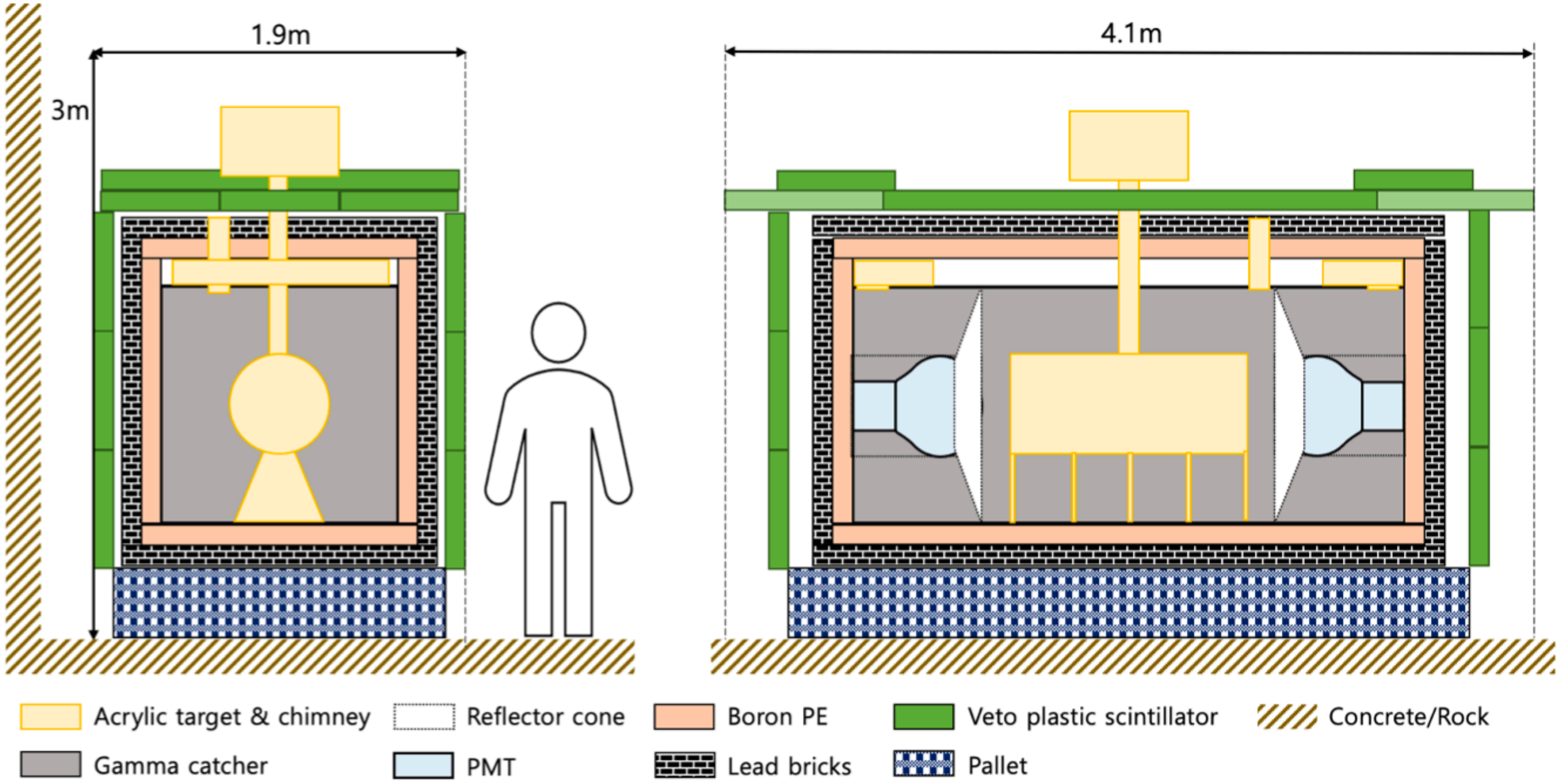


Detector (Overall Design) - Inner



- Cylindrical-shaped acrylic target vessel, filled with 0.5 % Gd-LS + 10 % DIPN (total 270 L)
- Box-shaped stainless steel gamma catcher chamber, filled with unloaded LS
- Two 20-inch PMTs on both sides
- Reflector cones are attached to each PMT to enhance overall detection efficiency

Detector (Overall Design) - Outer

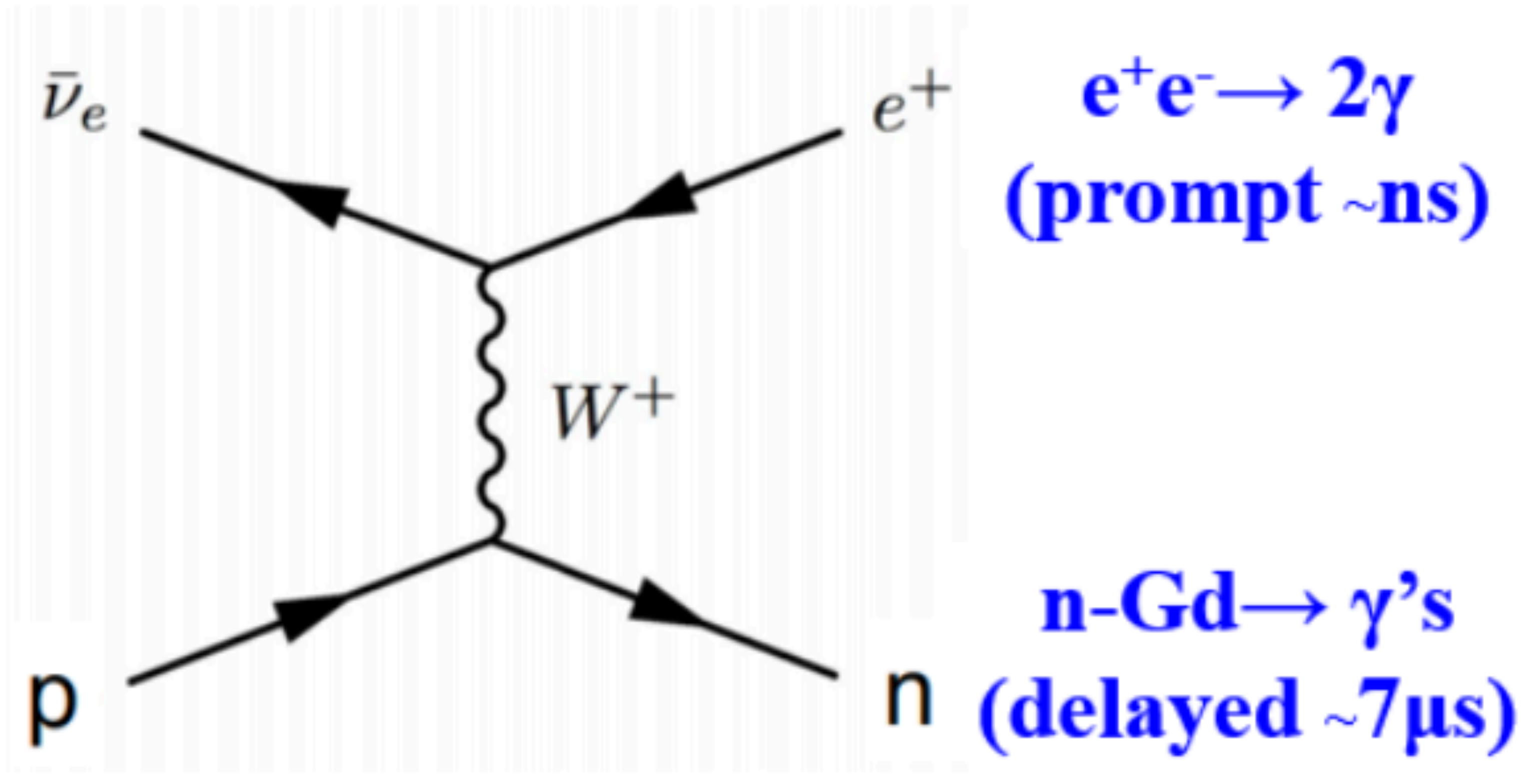


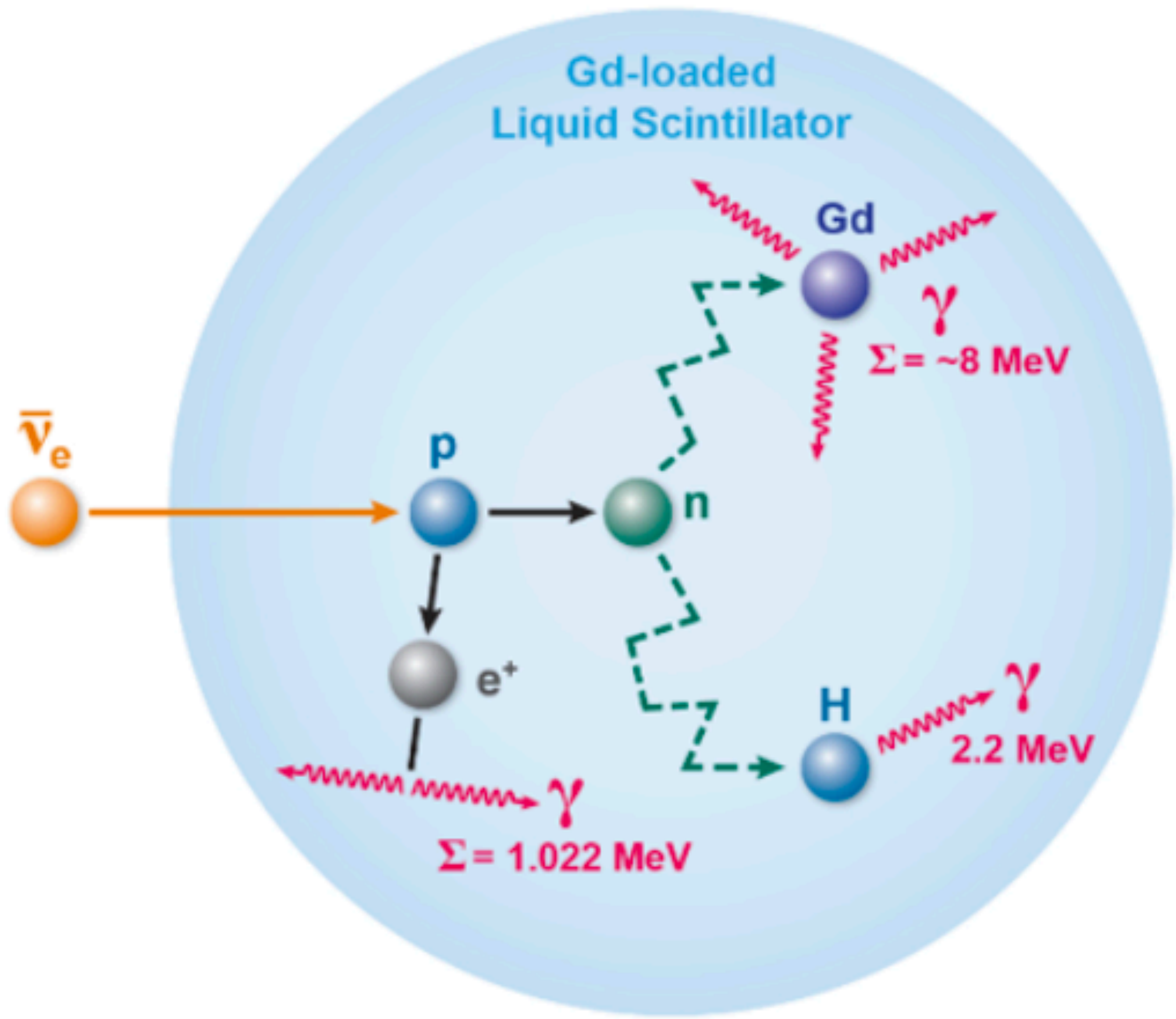
- The VETO system forms the outermost part of the detector to reject cosmic muon-induced events
- Surrounding the γ-catcher chamber with the plastic scintillators.
- Borated polyethylene and lead bricks between the γ-catcher chamber and the VETO system as passive shielding

Electron antineutrino detection

	Timing	Energy
prompt	Immeately	$1 \leq E \leq 8$ MeV
delayed	$\Delta T_{p\text{-}d}$<30 μs	$6 \leq E \leq 10$ MeV

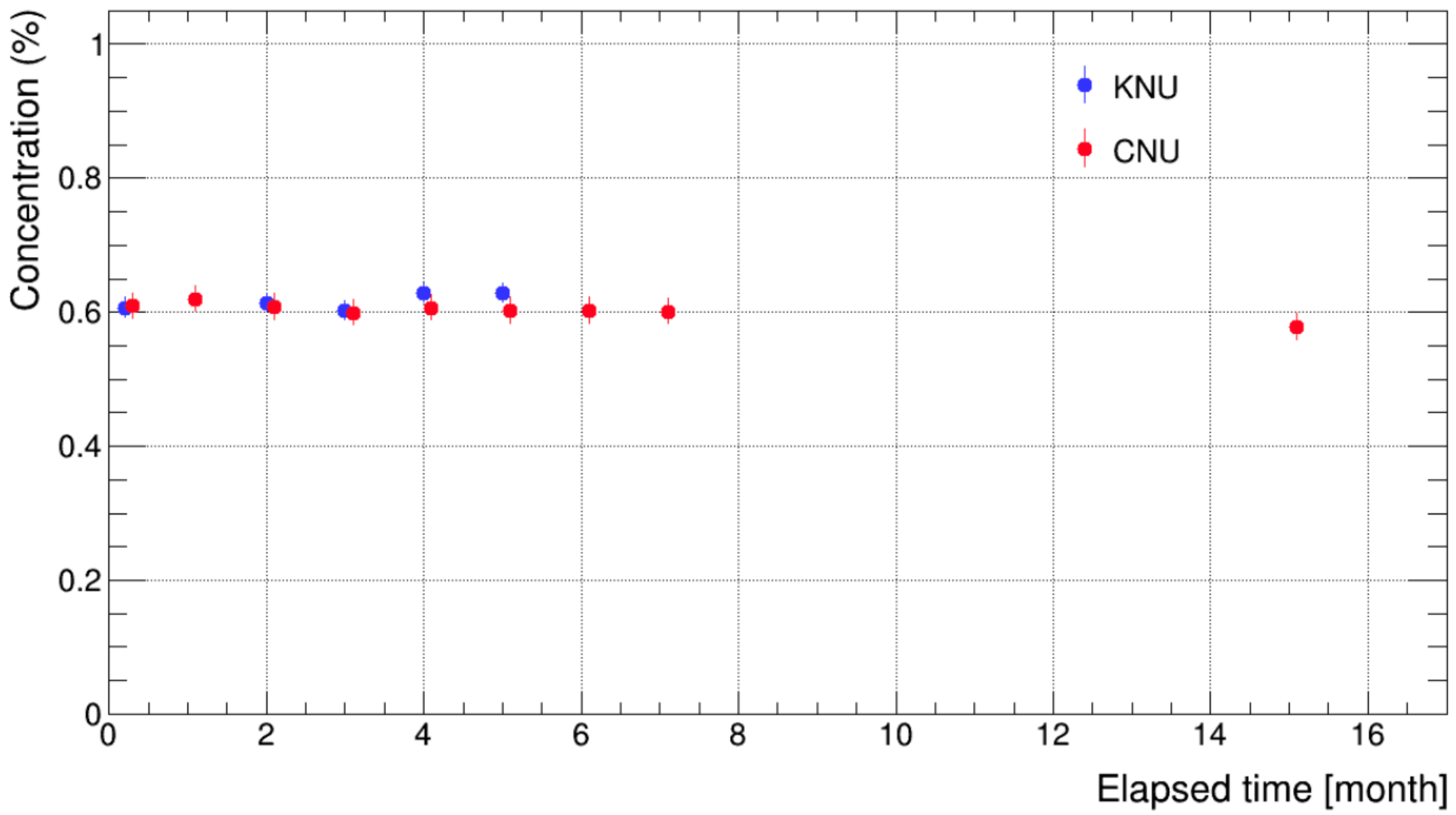
$$\mathrm{IBD:}\ \ \bar{\nu}_e + p \rightarrow n + e^+$$

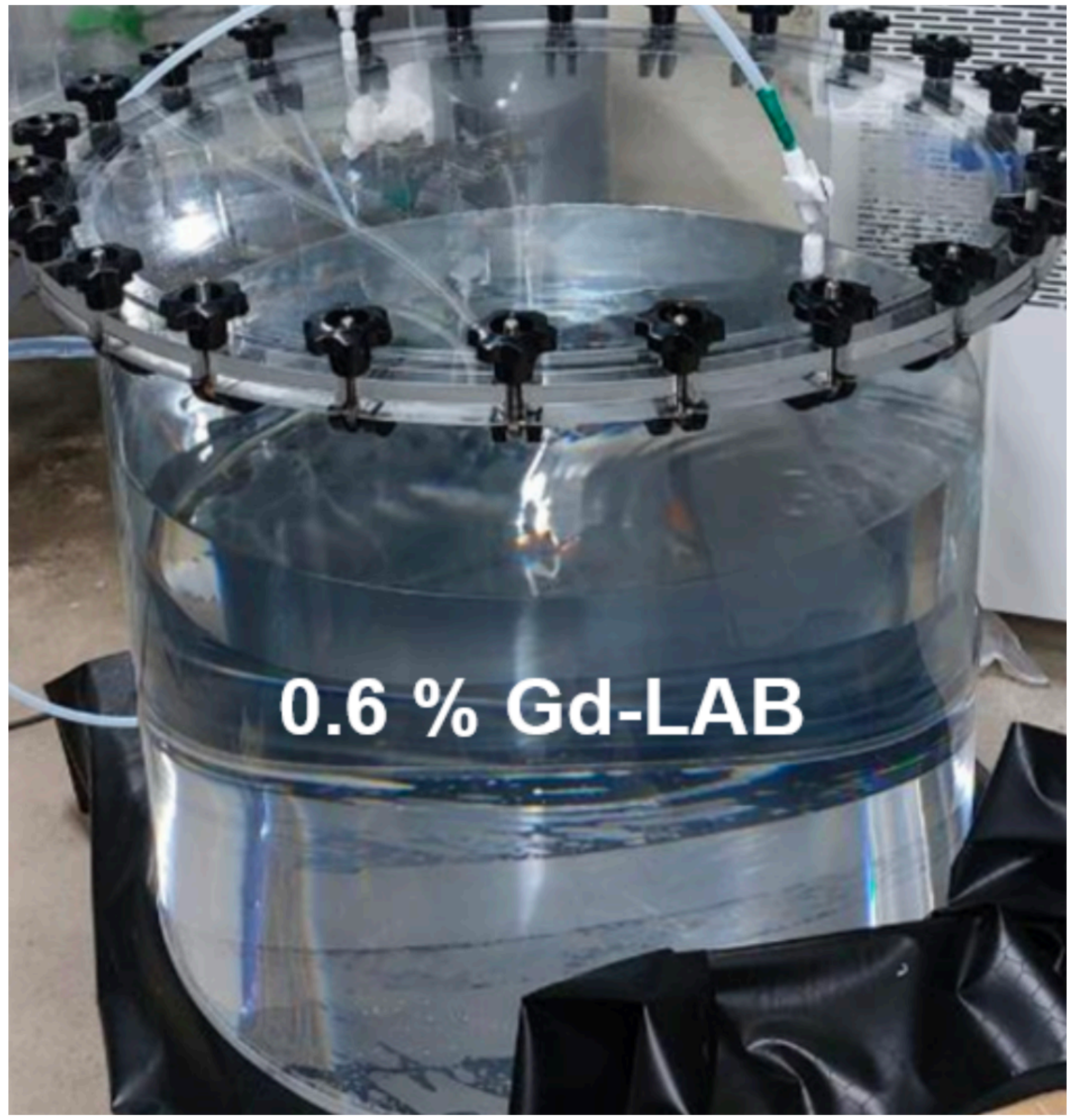




- The thermal neutron capture cross-section of Gd isotopes is significantly higher than that of free protons.
- Higher energy output provides a clearer signal.

Gd-loaded Liquid Scintillator





- A total of 240 L of 0.6% Gd-LAB solution was produced at the refurbished RENO LS facility in 2023. Later, the LS master solution will be added to produce the G.d-LS.
- The Gd-LAB has been stable for over one year.
- To enhance pulse shape discrimination performance (PSD), 10% by weight of EJ-309 is incorporated into the Gd-LS

Assemble of the Veto Detector

1. Polishing

2. Shielding tyvek

3. Shielding aluminum foil

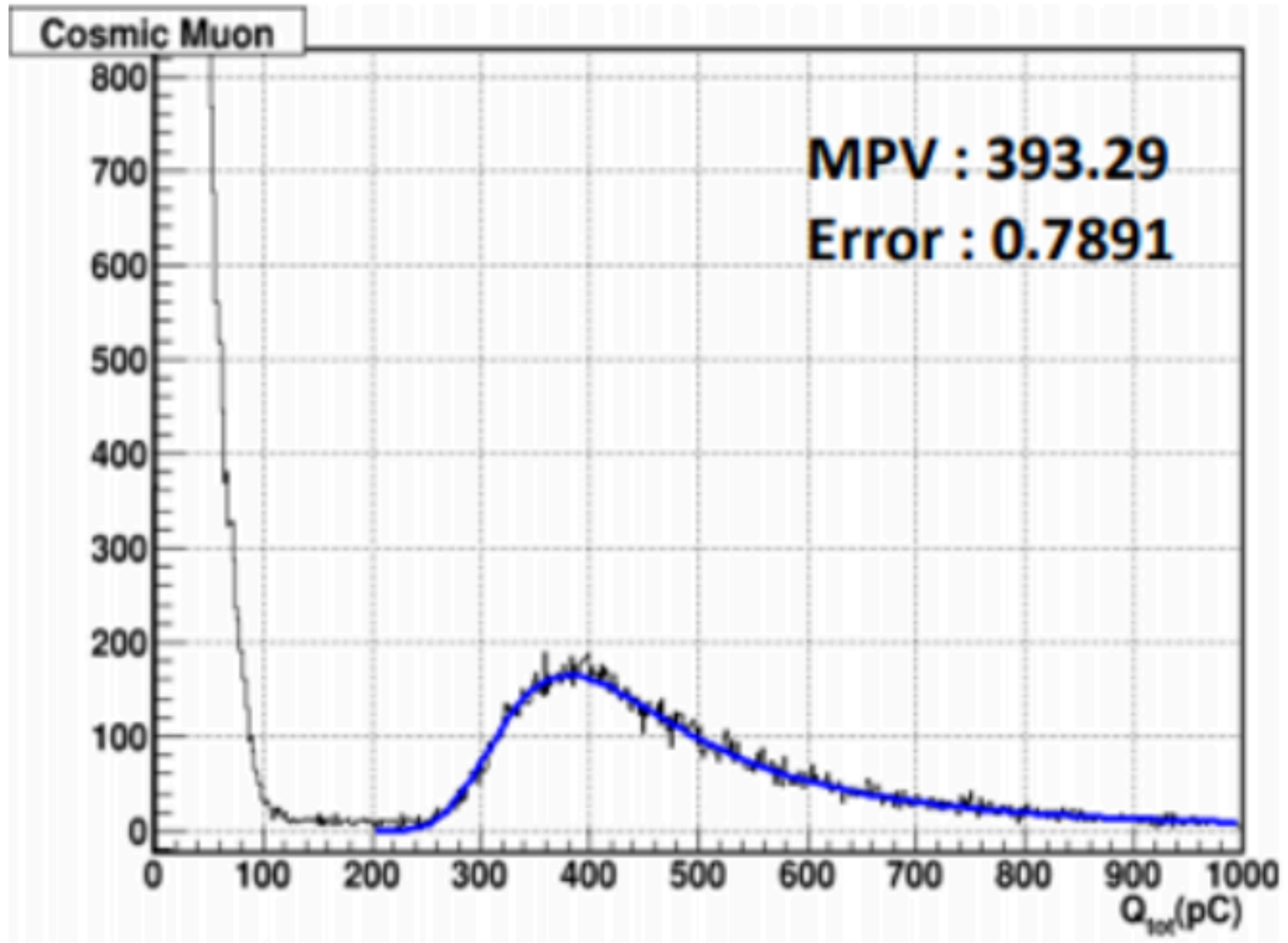
4. Shielding blacksheet

5. Mount PMT

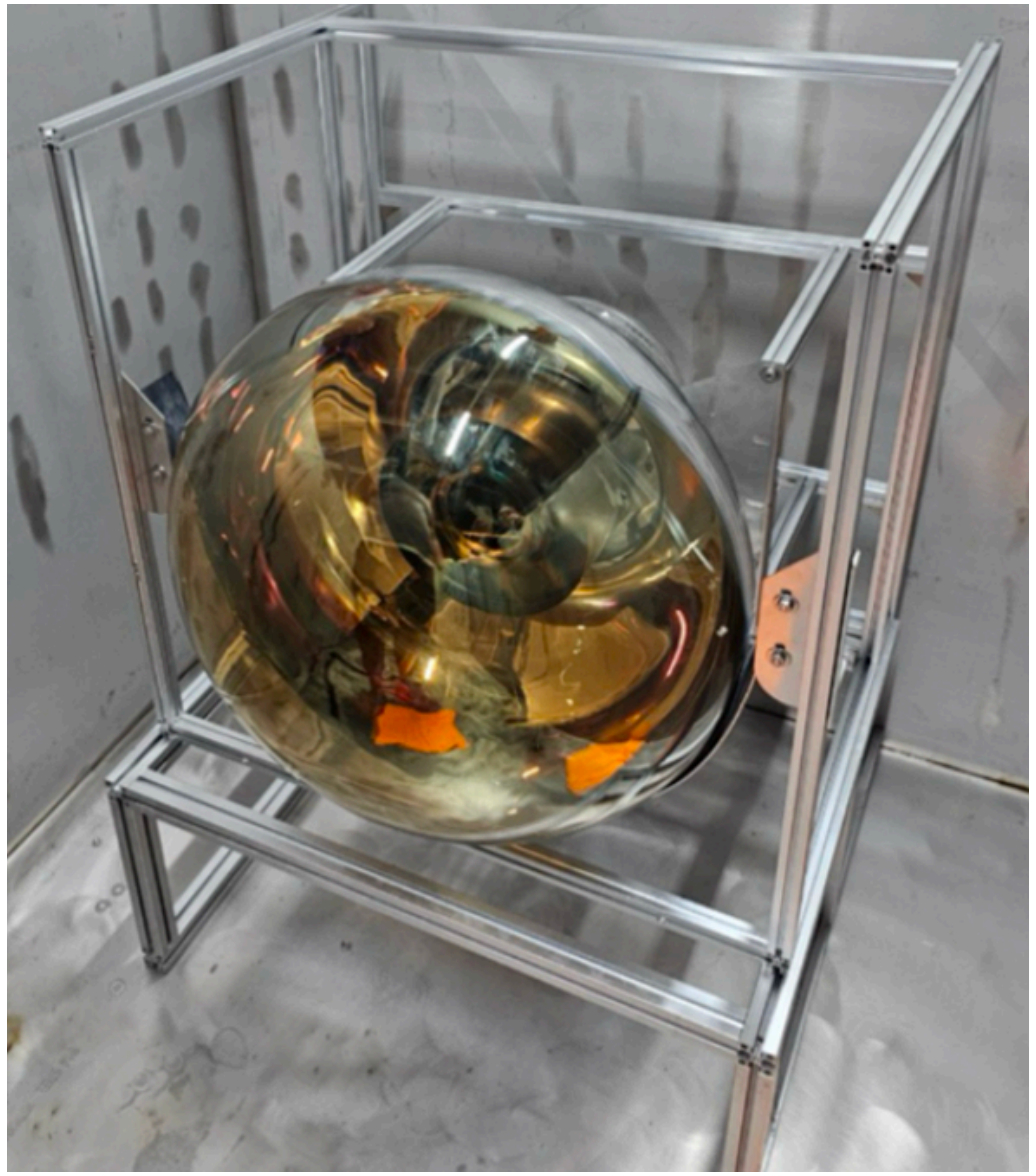
6. Mount PMT support

7. Completion

- 7 sequential steps.
- Charge distributions of cosmic muons confirms the performance



20-inch PMTs
(Hamamatsu R12660)



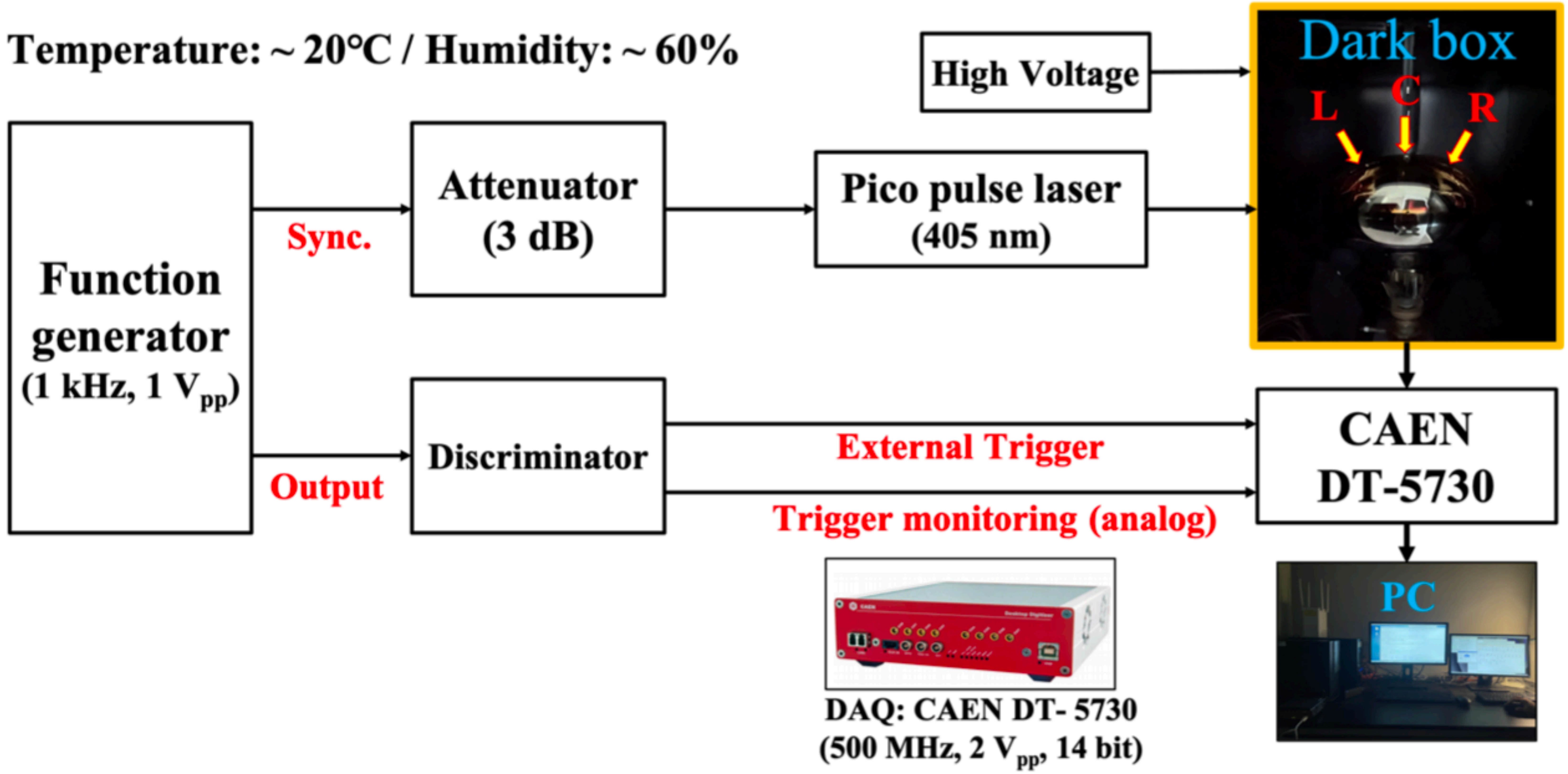
Ref. Hamamatsu Handbook

- Box (Efficient collection) and Line (Uniform drift path) type dynode structure
- Fast time response and High stability (TTS ~ 2ns)
- 30% Quantum efficiency

To evaluate the performance of the PMTs, dark condition and pico-pulse laser tests were conducted

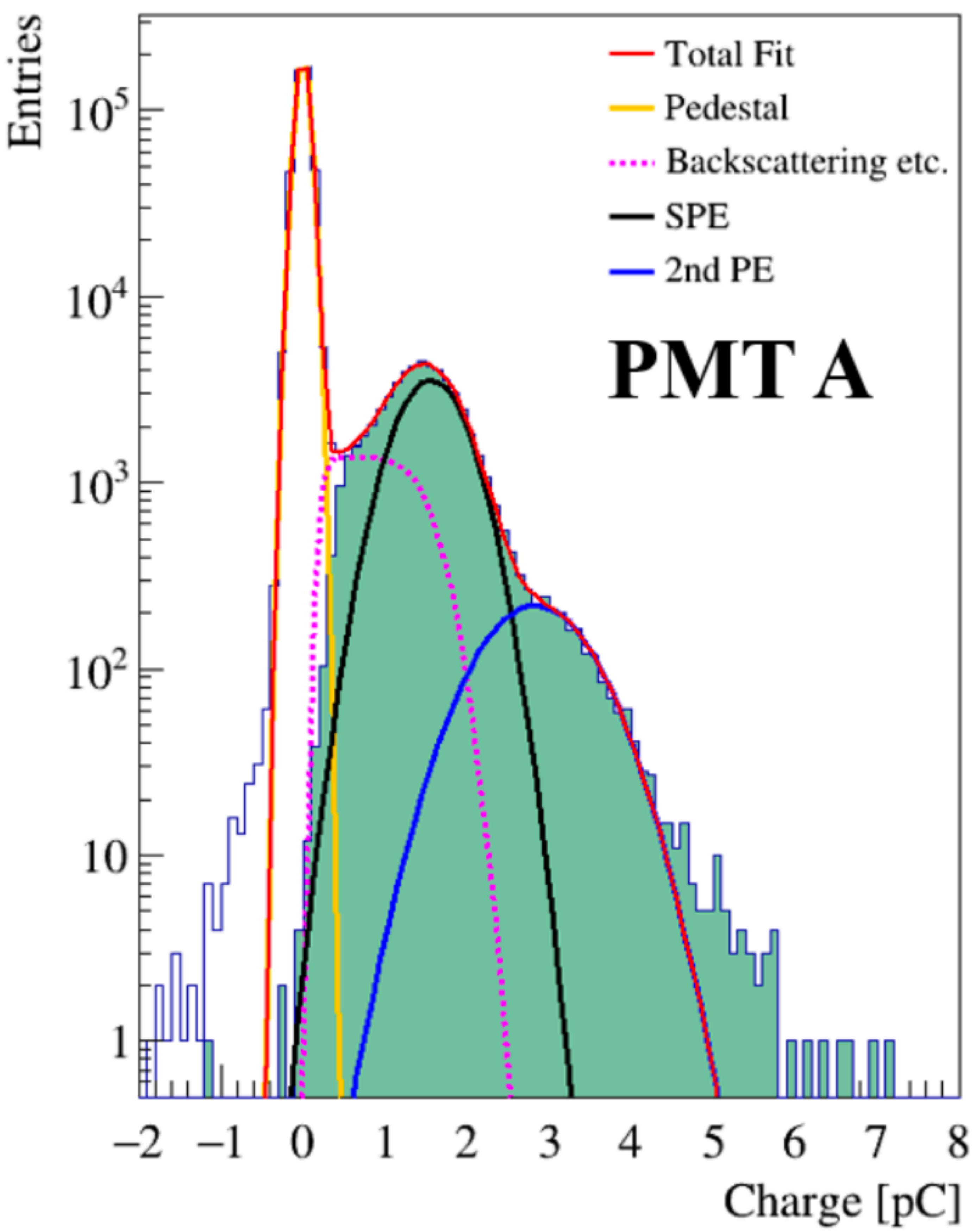
Assessing PMT characteristics

Measurement setup

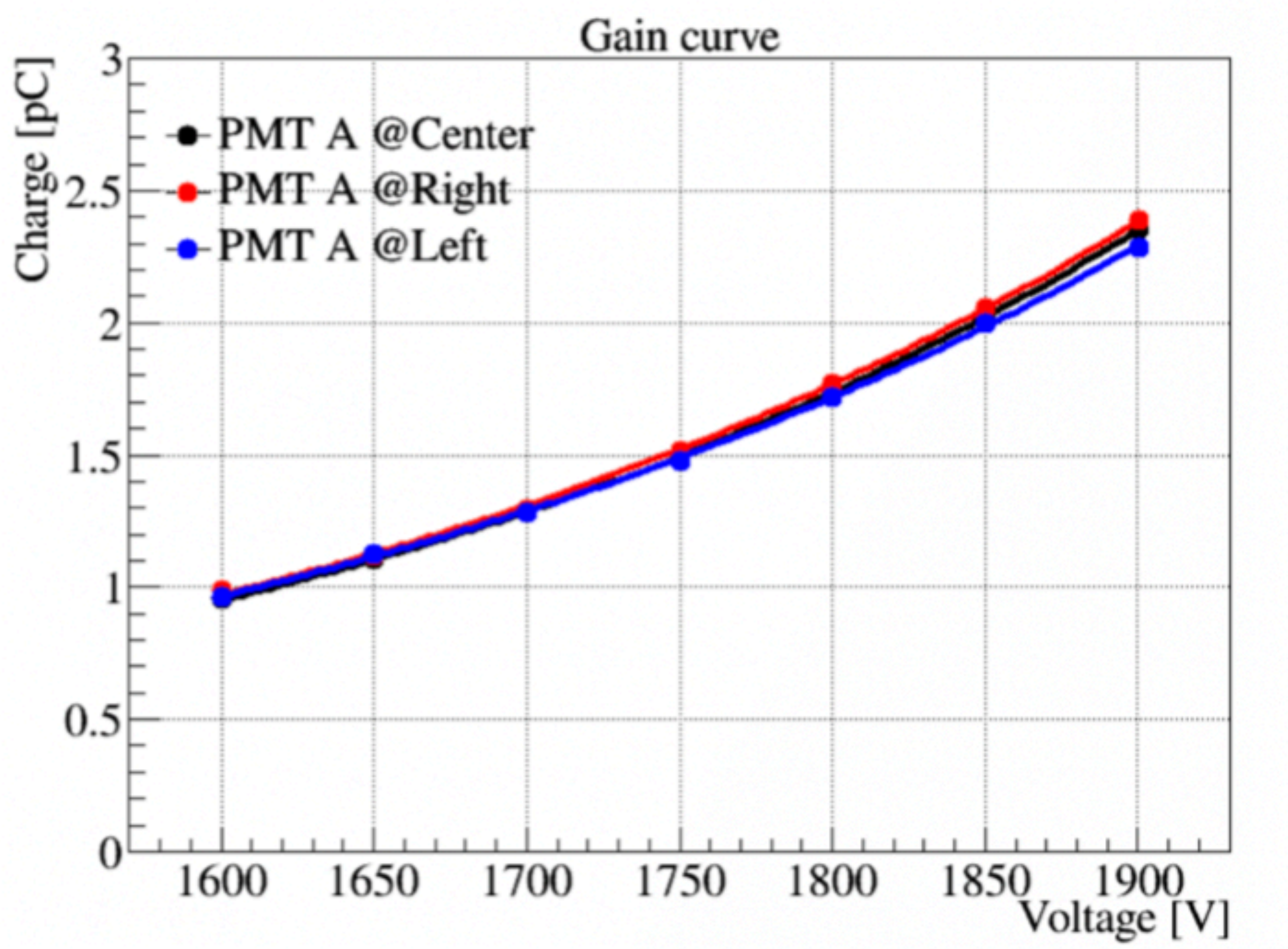


- Dark rate : ~ 3 kHz
- Single photoelectron
- Gain curve
- Position dependence
- Transit time spread
- Afterpulse

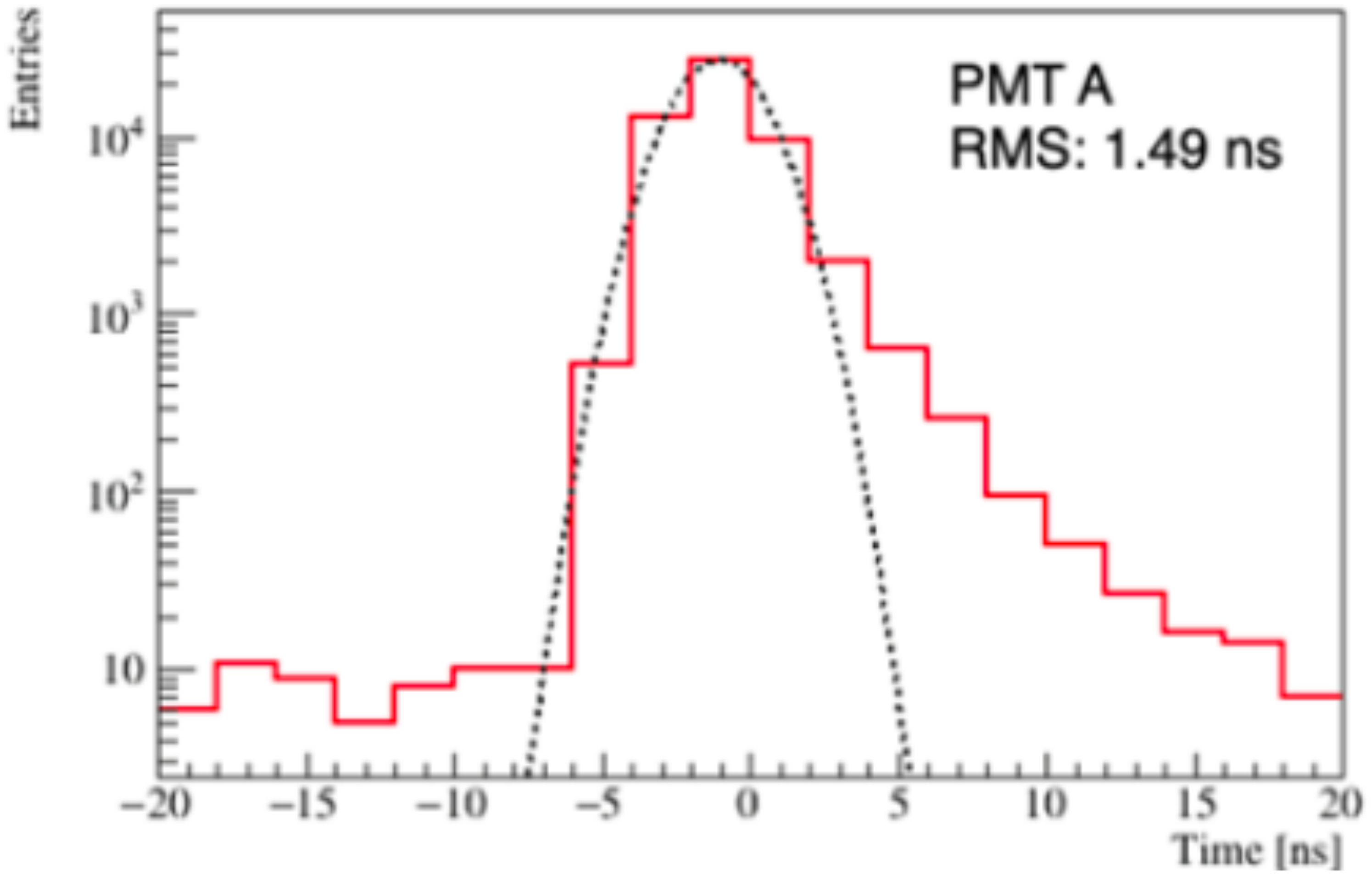
Single photoelectron



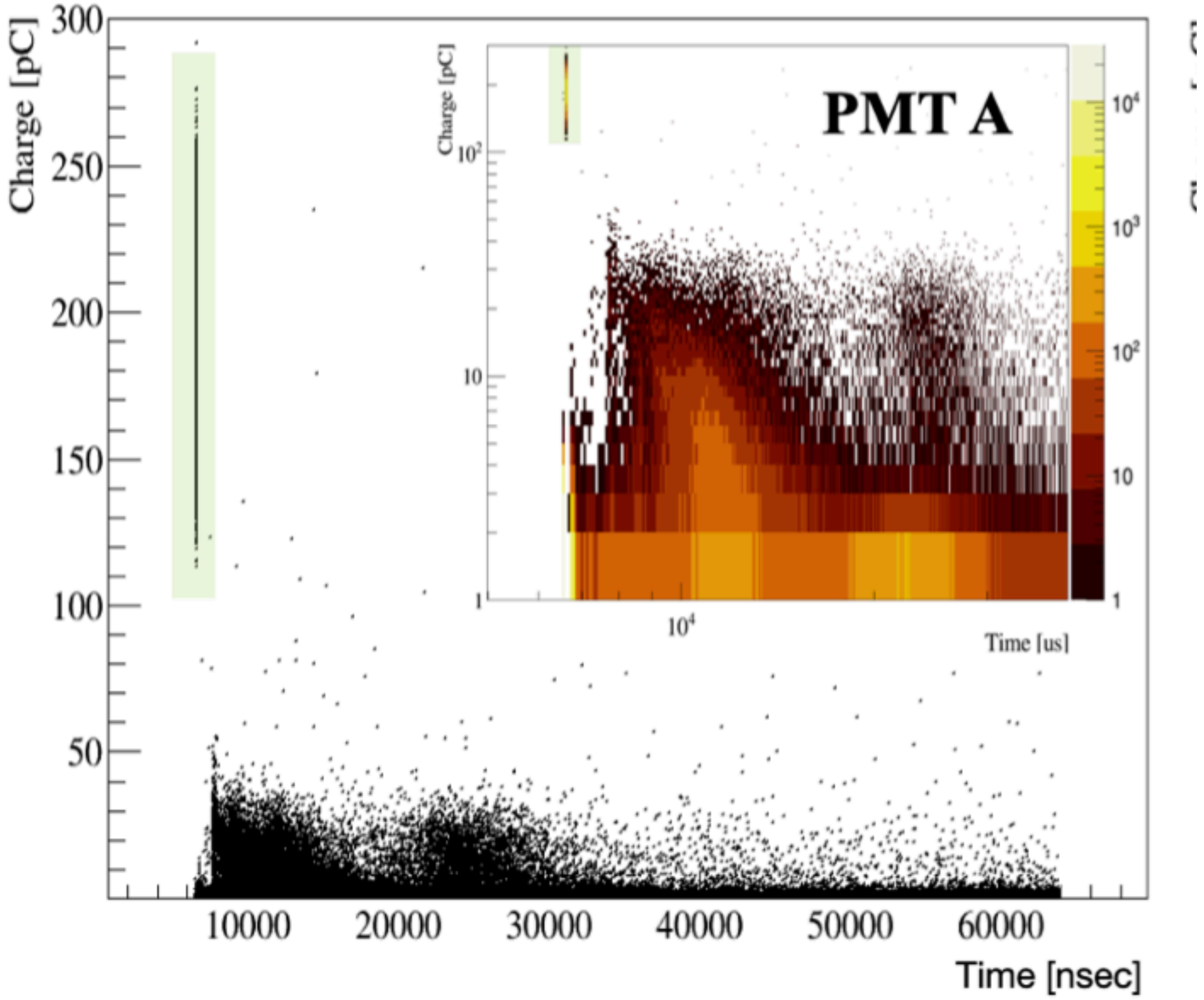
Gain curve



Transit time spread

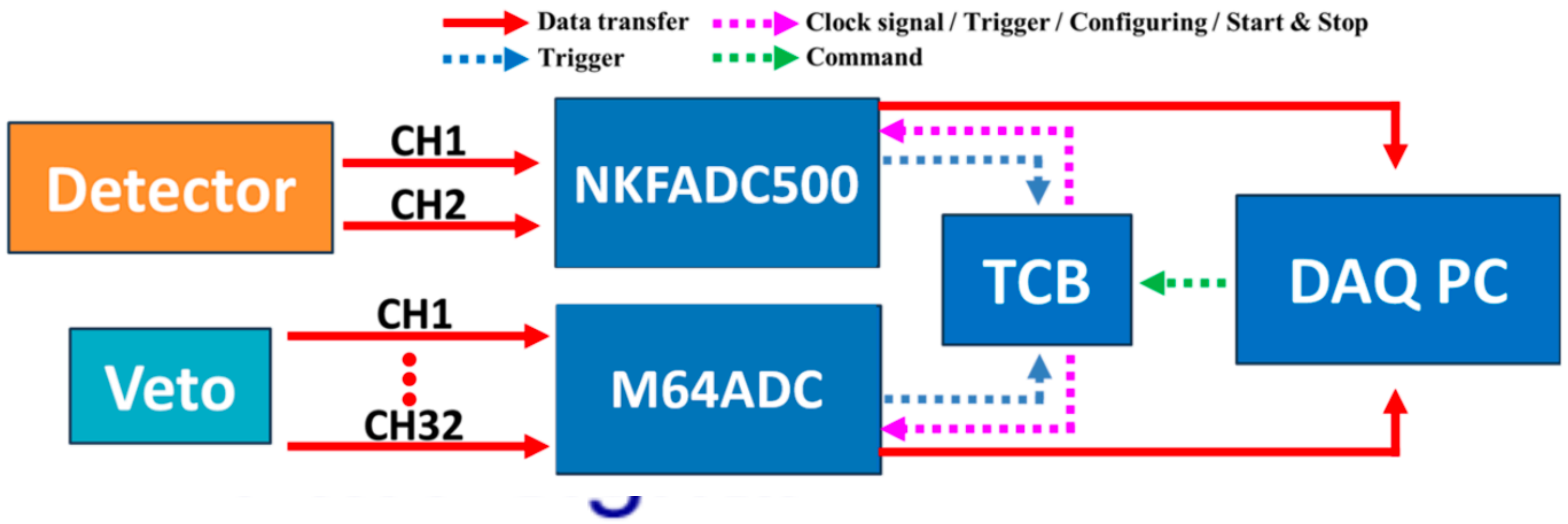


Afterpulse



- It matches the reference and published paper well.

Data Acquisition System
(Developed by a domestic company)



NKFADC500

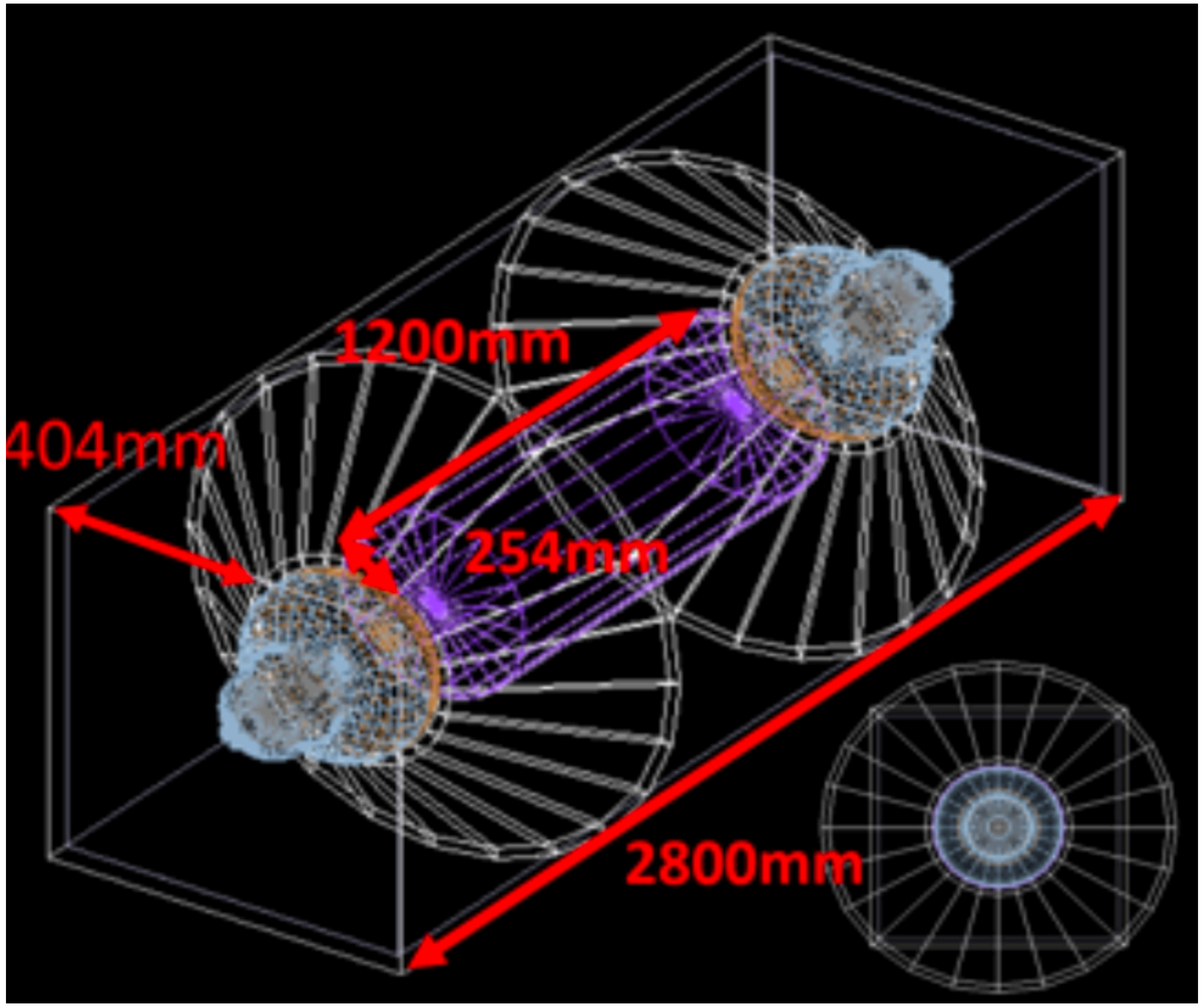
M64ADC

TCB

- NKFADC500 for two 20-inch PMTs
  - 12 bit resolution, 2.5 Vpp dynamic range, 500 MS/s, 4+4 channels
- M64ADC for the veto detectors
  - 12 bit resolution, 2 Vpp dynamic range, 62.5 MS/s, 32 channels
- Trigger Control Board (TCB) for synchronization of trigger and clock
  - Up to 40 modules, RJ-45 port

Detector Performance (Based on GLG4SIM)

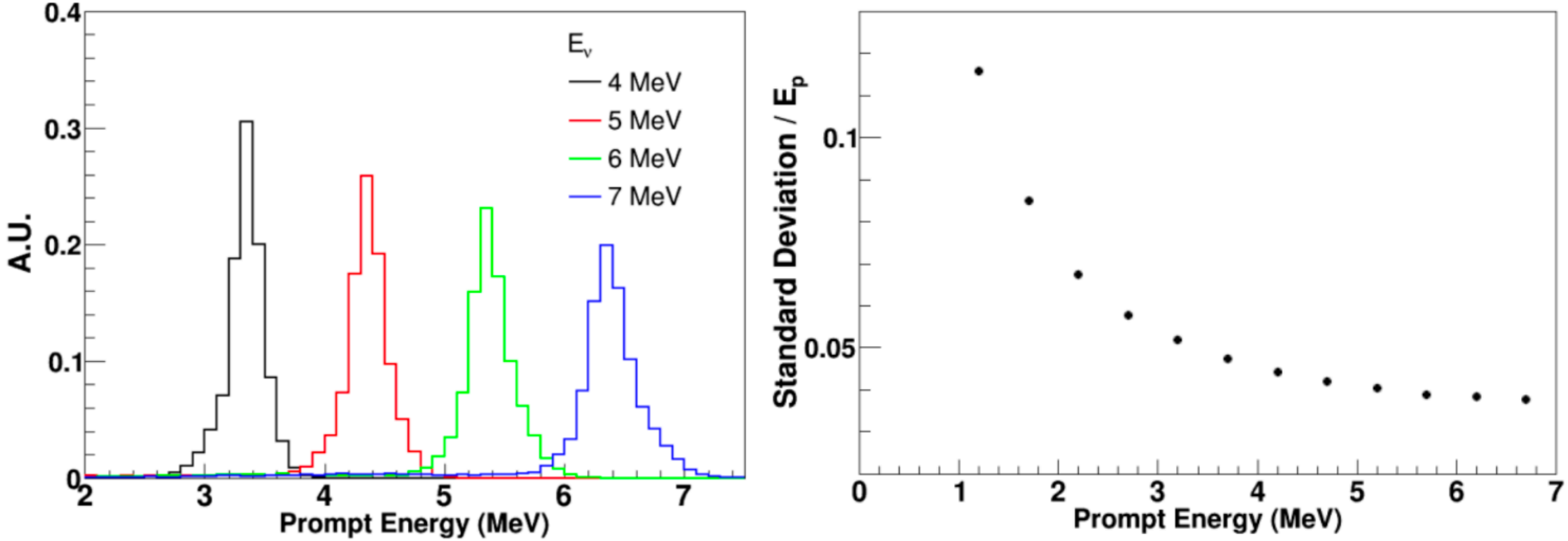
Schematic view of the RENE detector in MC



- Designed to analyze the detector's response to IBD events
- The simulation includes the target vessel, γ-catcher, reflector cones, and 20-inch PMTs (actual detector design)
- Simulation framework (GLG4SIM) was selected to its remarkable capabilities in modeling LS detectors.

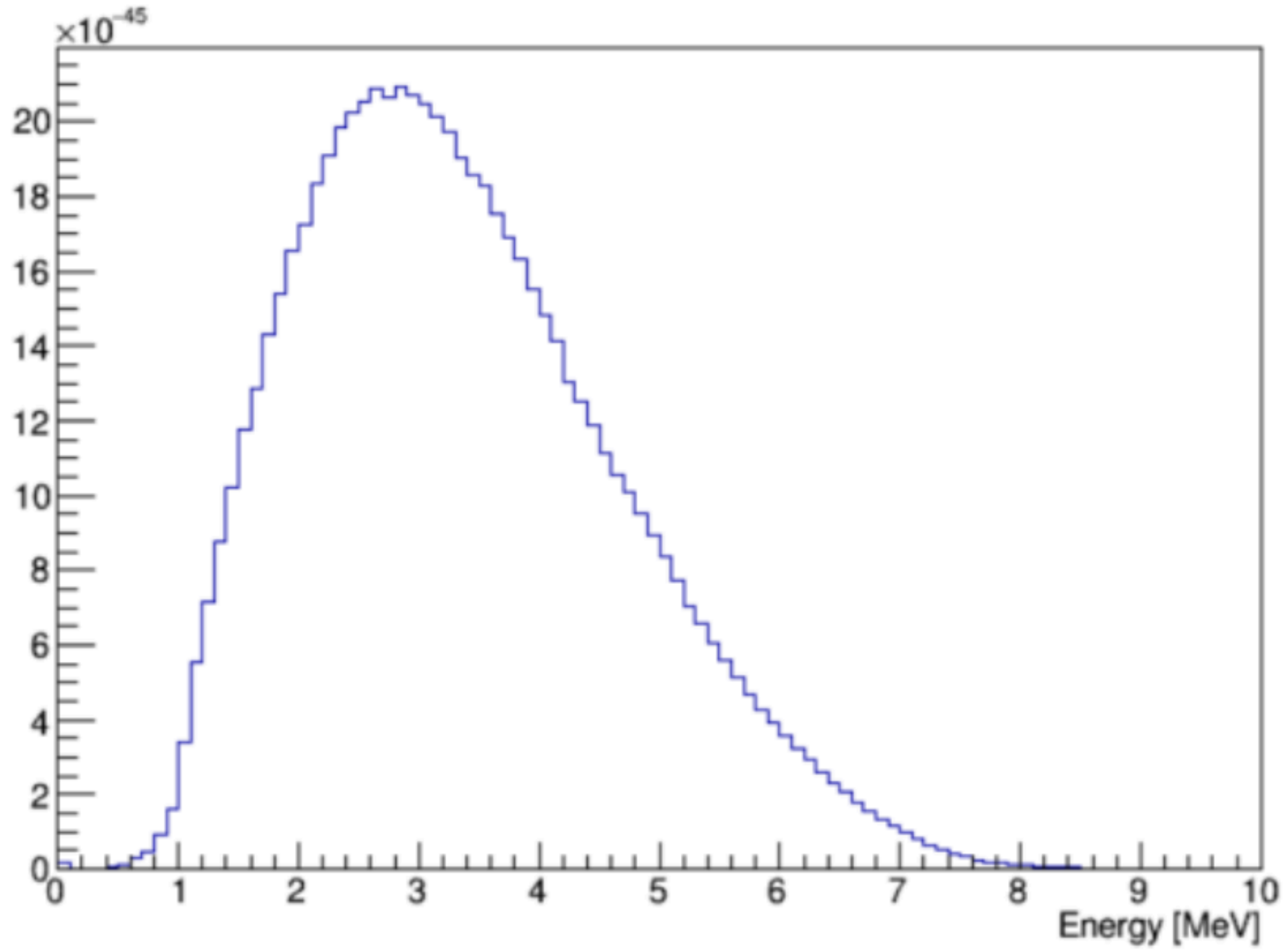
Energy resolution

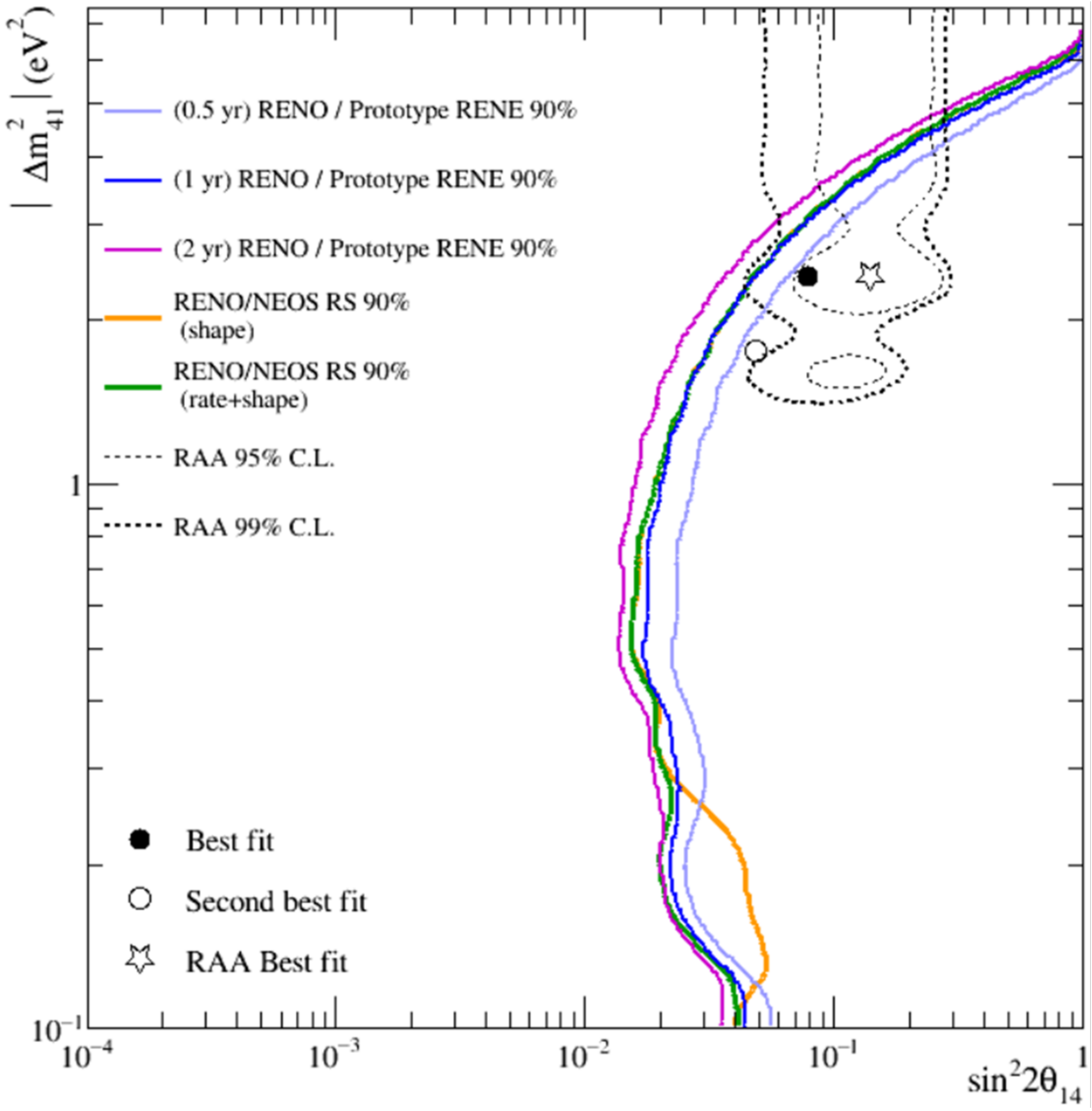
- The energy resolution was evaluated using positrons from IBD events
- It was determined as the standard deviation divided by the corresponding energy



Expected energy spectrum and sensitivity

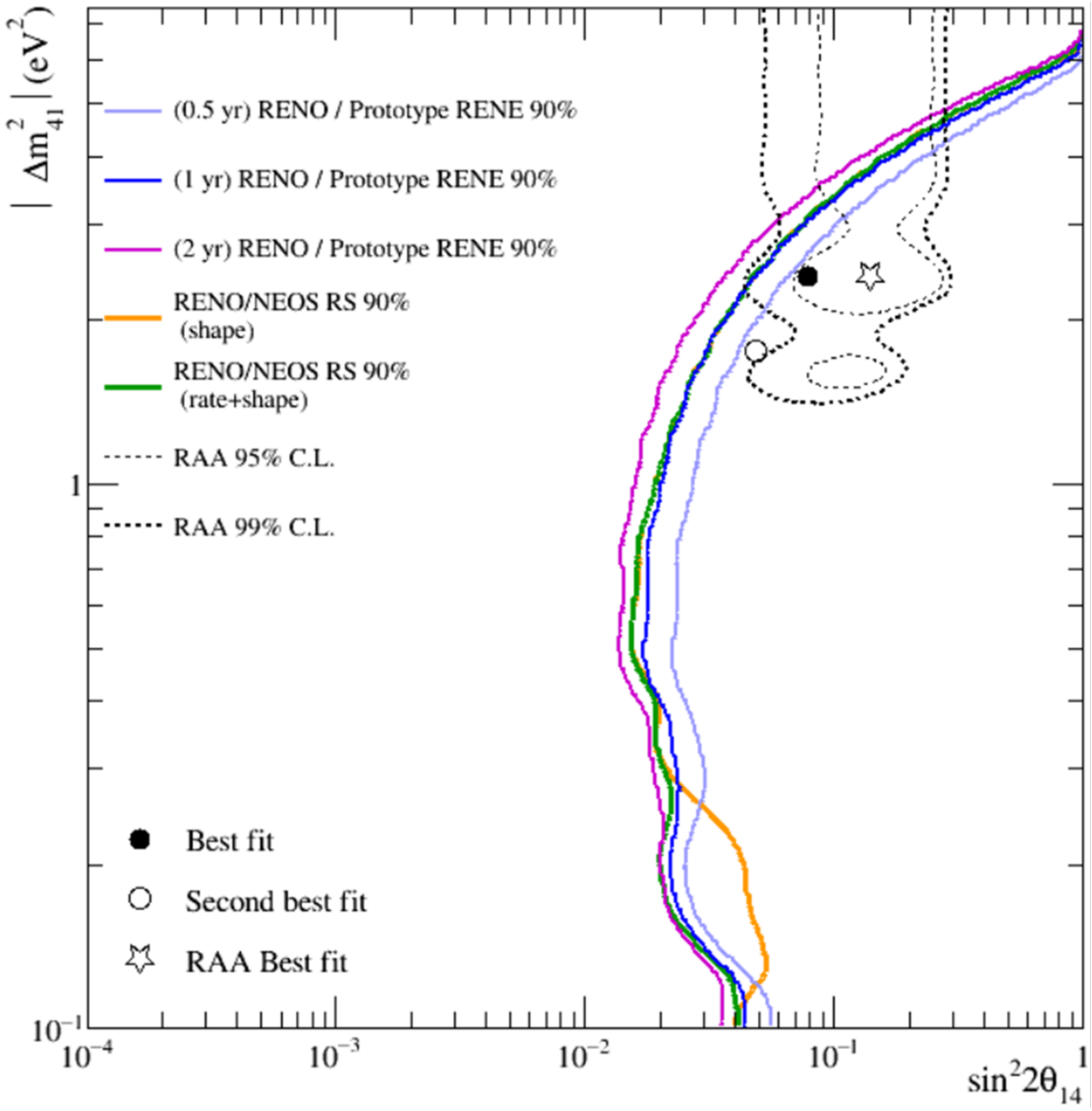
- 300 IBD events per day combined with energy resolution
- The sensitivity was calculated using the χ^2 method



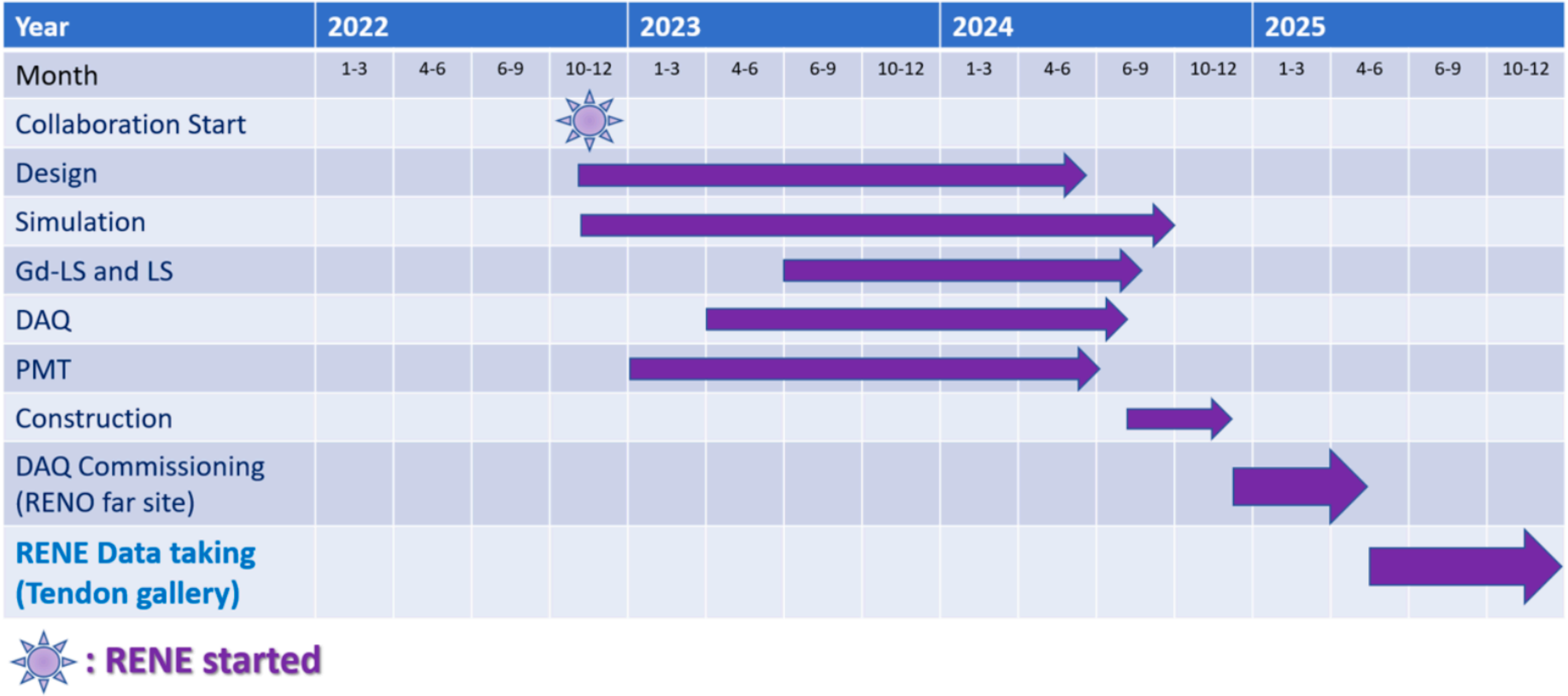


Expected energy spectrum and sensitivity

- 300 IBD events per day combined with energy resolution
- The sensitivity was calculated using the χ^2 method
- The displayed sensitivity assumes a data-taking period ranging from 0.5 to 2 years
- Combines with the “RENO near detector data”



Project Schedule



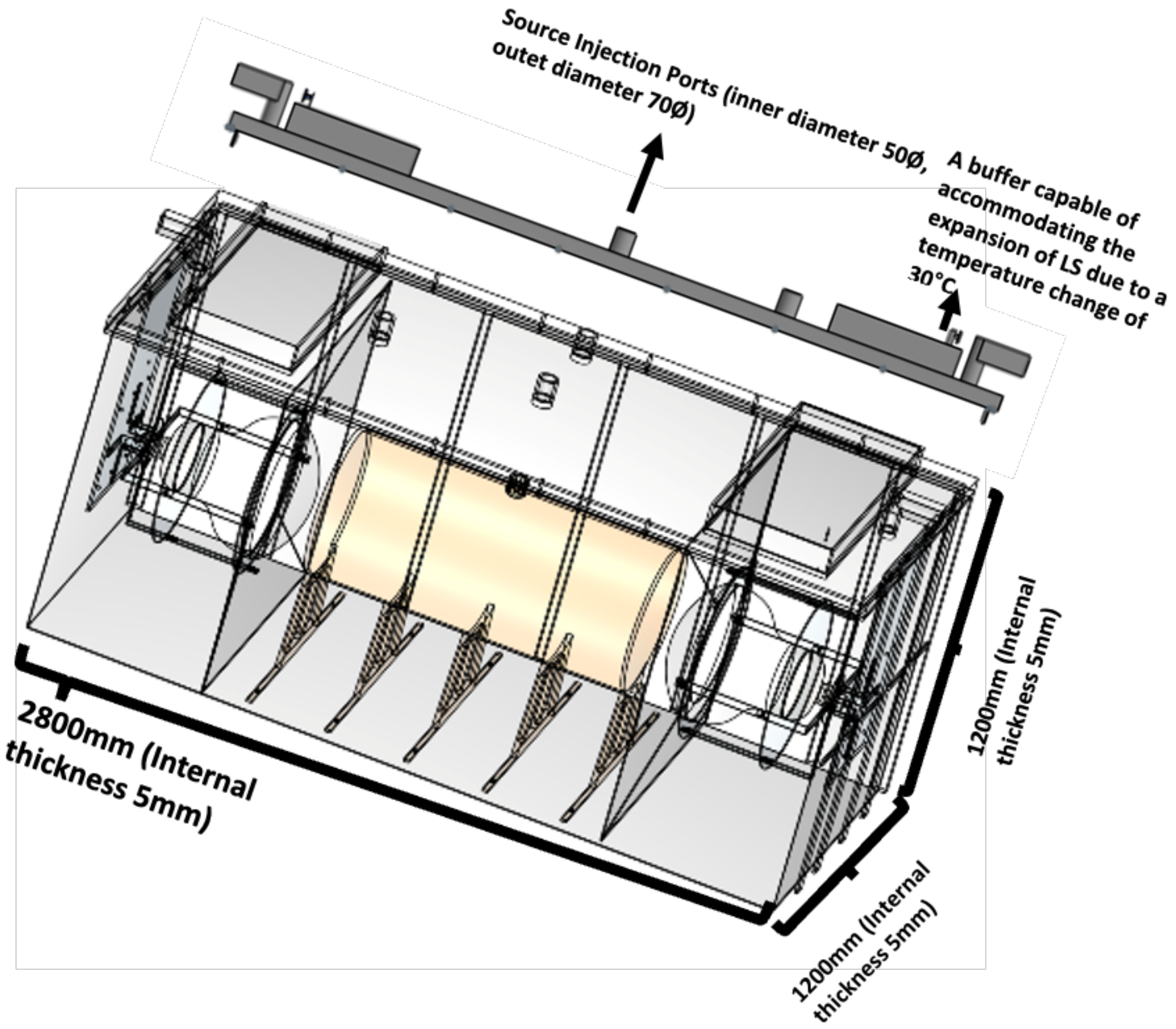
Detector commissioning is on-going @ CNU !!

Summary

- RENE (Reactor Experiment for Neutrino and Exotics) aims to search for the sterile neutrino oscillation around $\Delta m_{41}^2 \sim 2eV^2$, hinted by RENO-NEOS joint analysis
- The detector construction is done, and test data taking is ongoing at CNU
- The RENE detector will be installed in the Tendon gallery and is expected to start physics data taking within this year

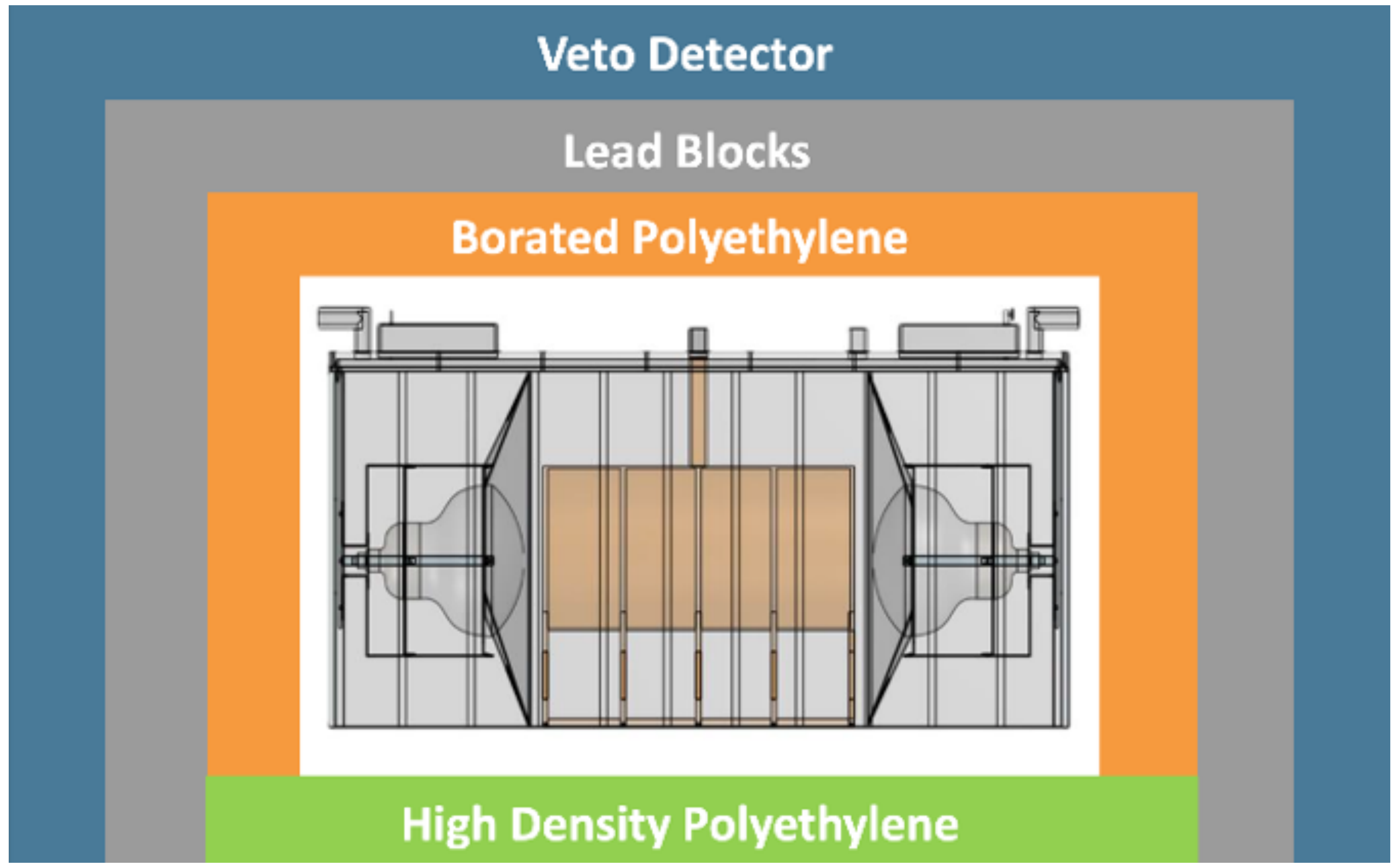
Backup

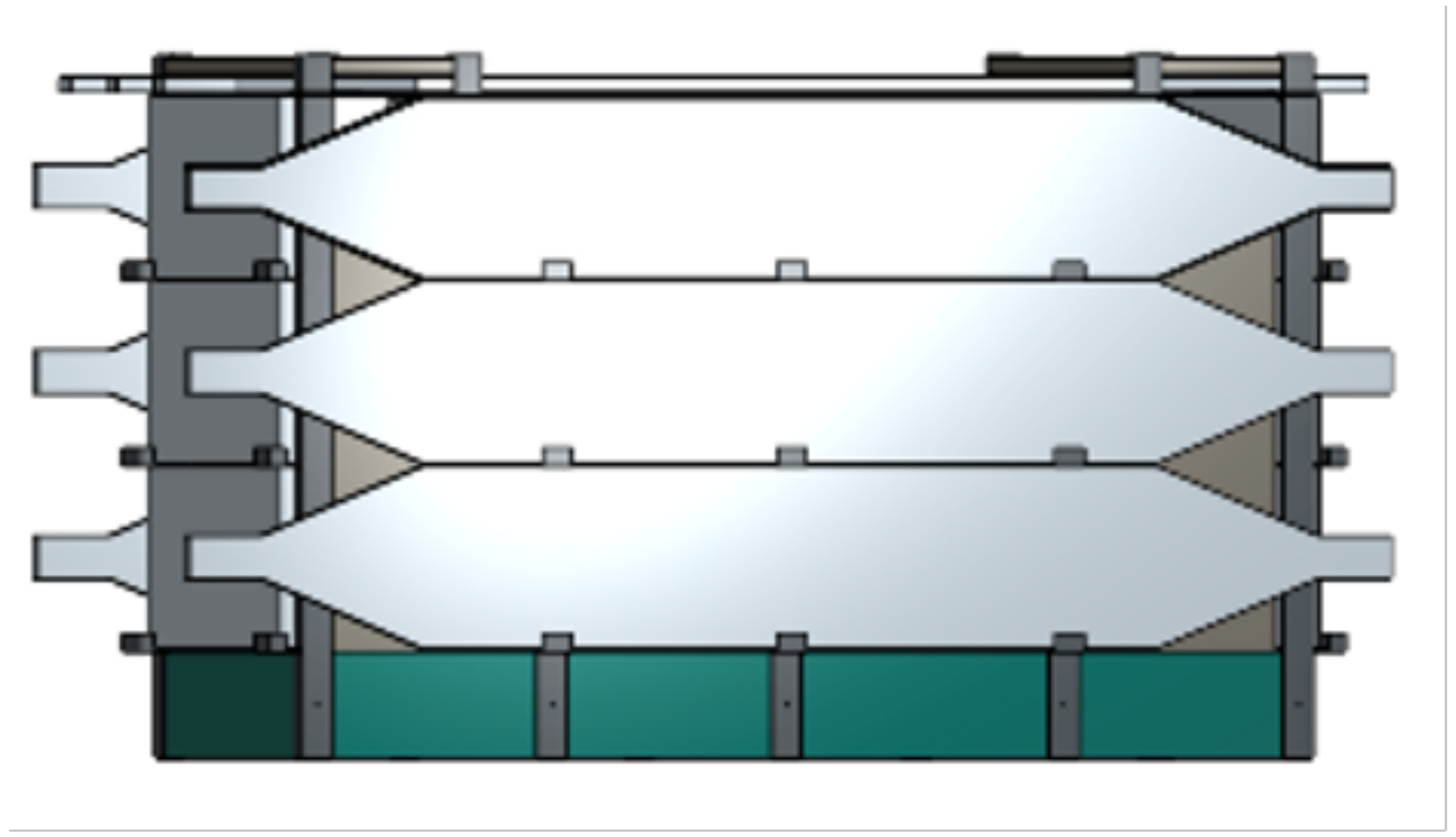
RENE Detector (Inner)



- Cylinder shape acrylic target filled with 0.5 % Gd-LS + 10 % DIPN
- Box shape stainless steel gamma catcher filled with unloaded LS
- Reflection plates for effective optical photon collection
- Two 20-inch PMTs on both sides

RENE Detector (shielding + outer)





Passive Shielding

- Borated and high-density PE plates with 100 mm thickness
- ~ 3300 lead bricks with 100 mm thickness
- Mainly to reduce neutron and external gamma-ray

Veto Detectors

- 15 plates of plastic scintillators from the NEOS collaboration
- Thirty-two 2-inch PMTs for cosmic ray tagging