Reactor Experiment for Neutrinos and Exotics

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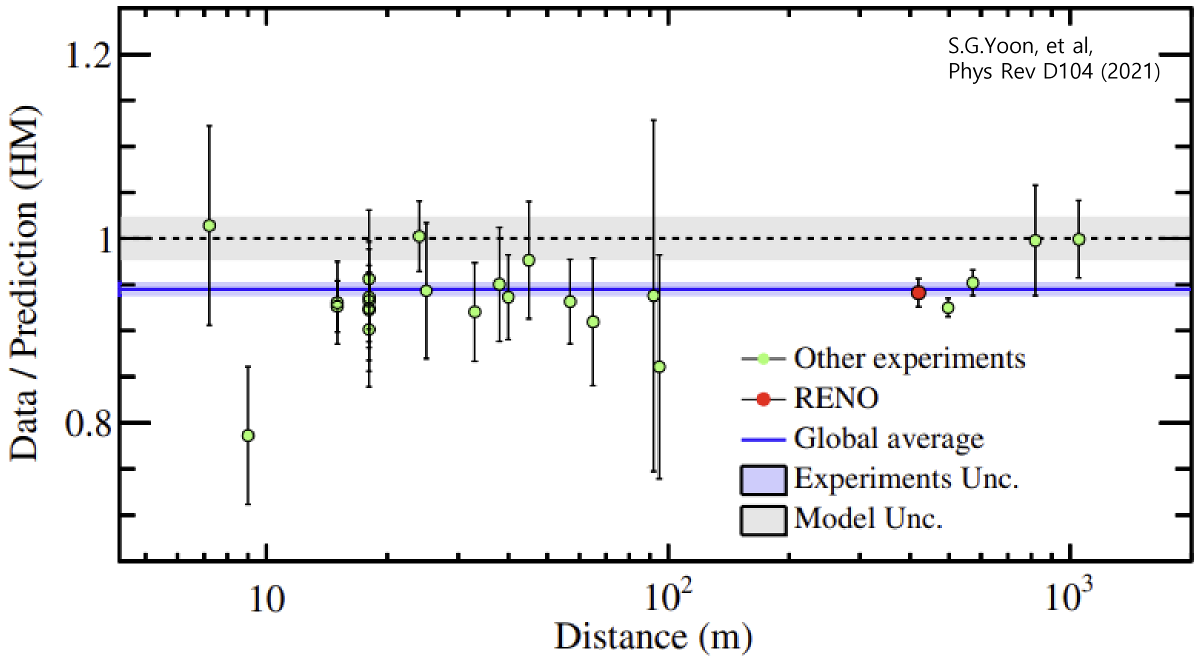
Reactor Experiment for Neutrinos and Exotics

1. INTRODUCTION

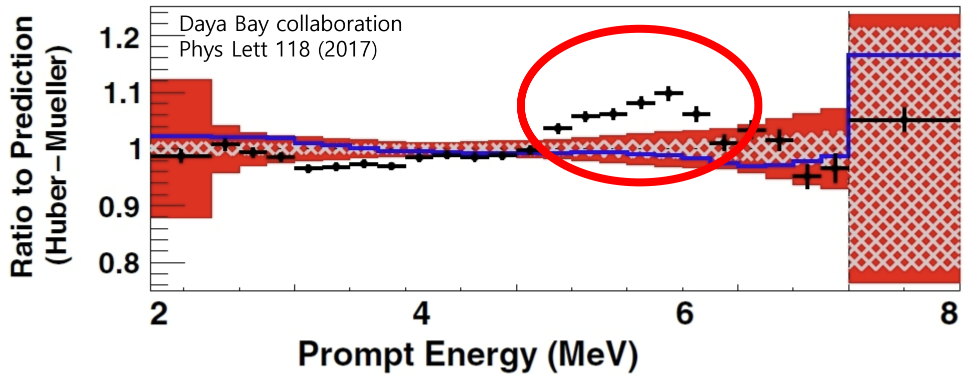
RAA: Reactor Antineutrino Anomaly

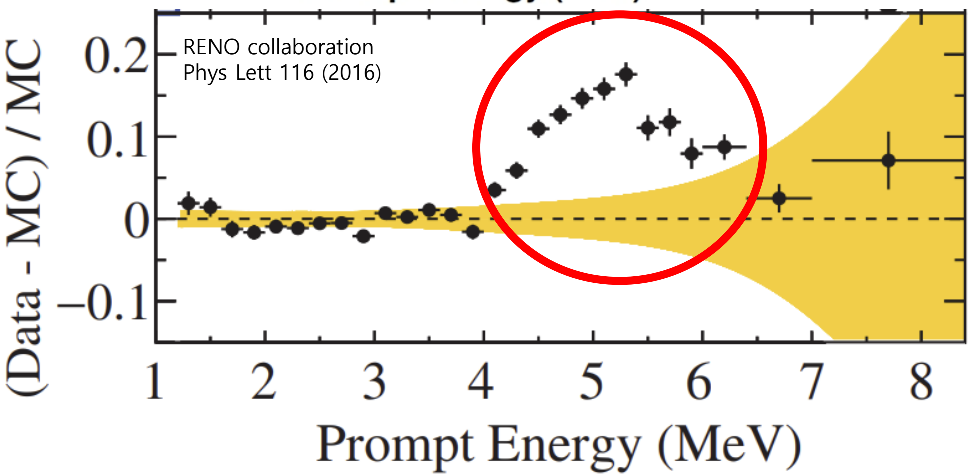
Deficit in flux about 5%



5MeV excess

An excess in the prompt spectrum



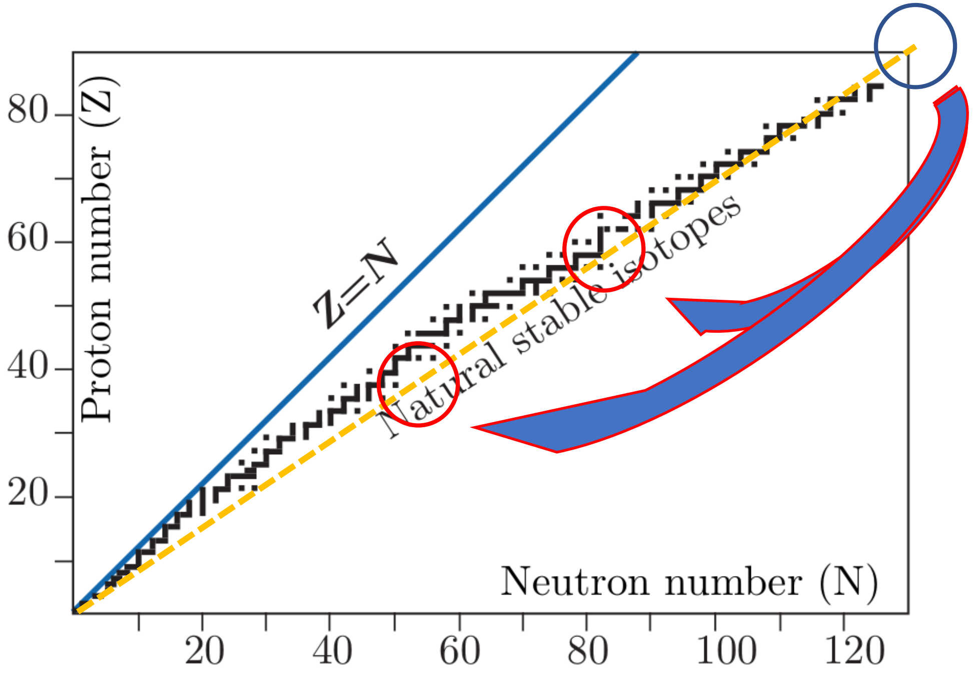


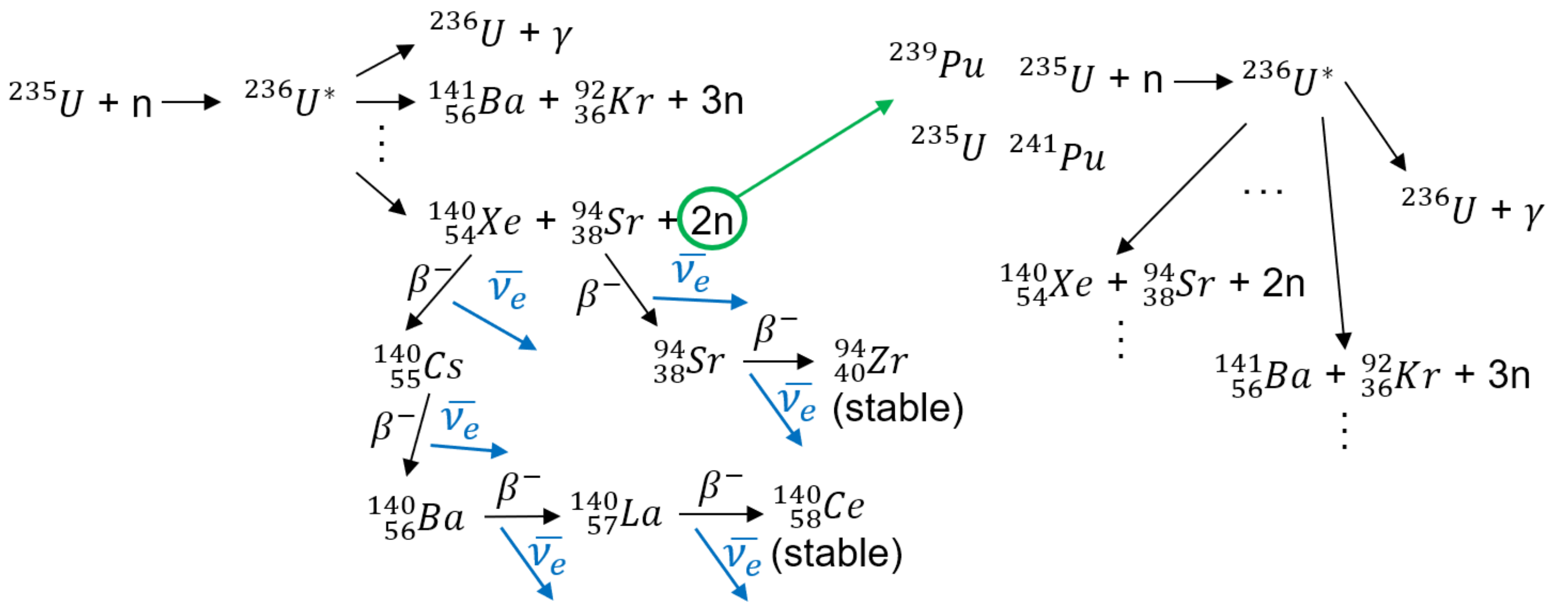
2. REACTOR NEUTRINO

Neutrinos from reactors

By nuclear fission! – Neutron absorption: $n + {}^{A-1}_{Z}X \rightarrow {}^{A}_{Z}X^{*} \rightarrow fission$

Unstable nuclei go through the beta decay to be stable. => ν





2. REACTOR NEUTRINO

Summation method model

Based on Nuclear databases
(still imperfect....)

$$S_k(E) = \sum_f A_f S_f(E)$$

$$S_f(E) = \sum_b BR_f^b S_f^b$$

e -> ν

$$S_f^b(E_\nu)$$

Sum

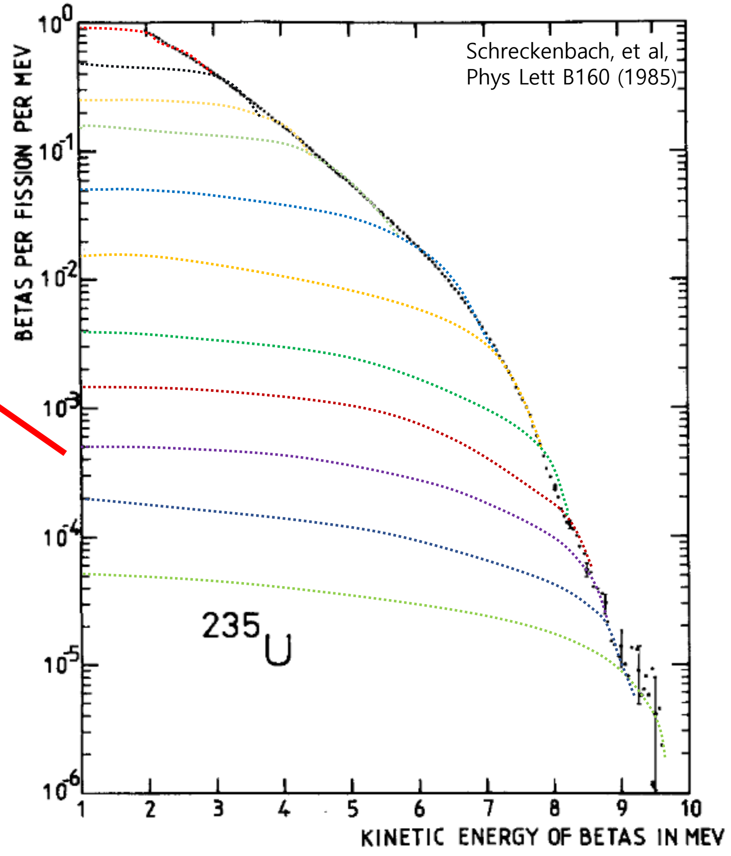
$$S_k(E_\nu)$$

Conversion method model

$$S_i^{\mathrm{vir}}(E_\nu)$$

e -> ν

Sum



2. REACTOR NEUTRINO

Summation method model

Based on Nuclear databases
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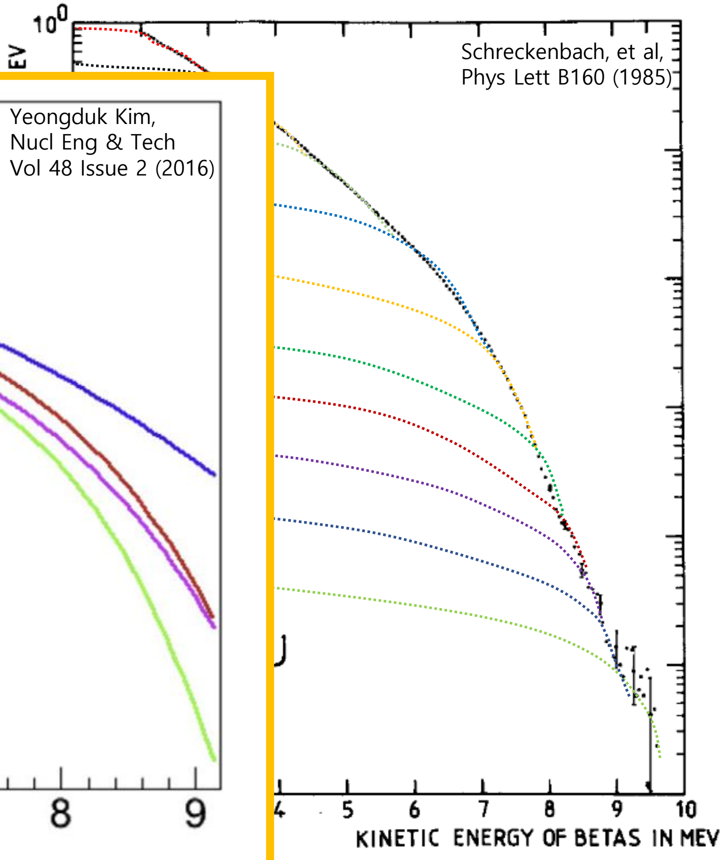
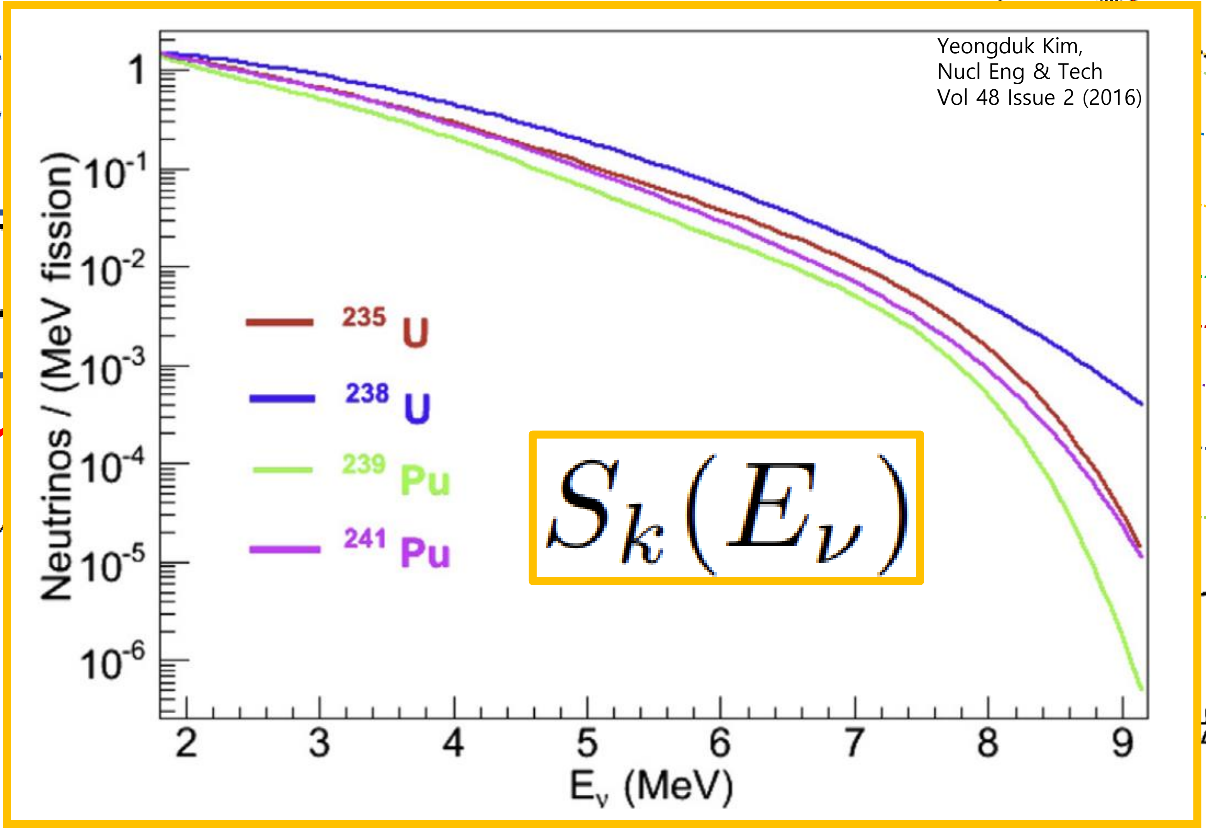
$$S_k(E) = \sum_f$$

$$S_f(E) = \sum_b$$

$$S_f^b(E_\nu$$

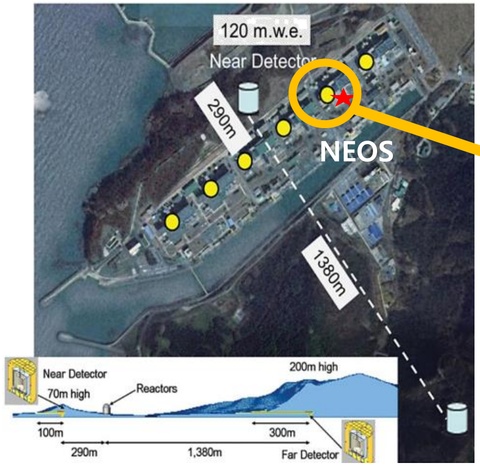
Conversion method model



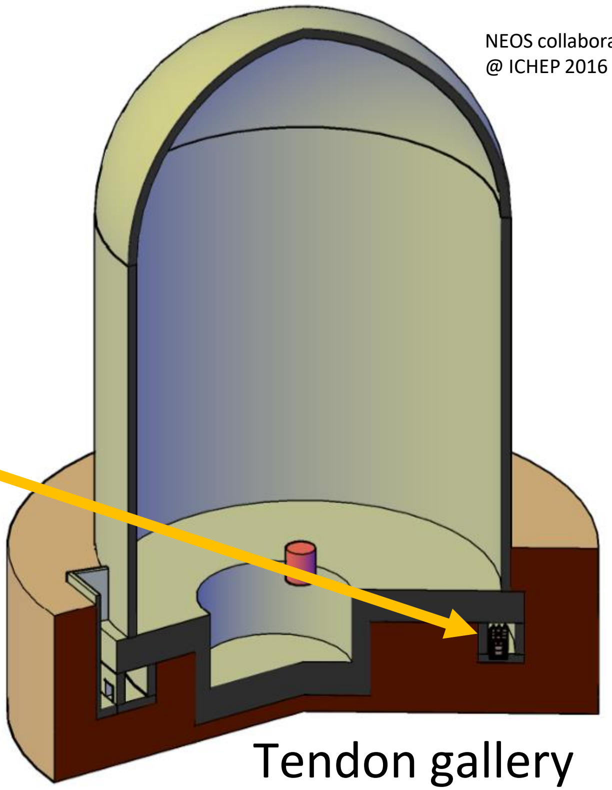


3. REACTOR NEUTRION EXPERIMENTS

RENO/NEOS



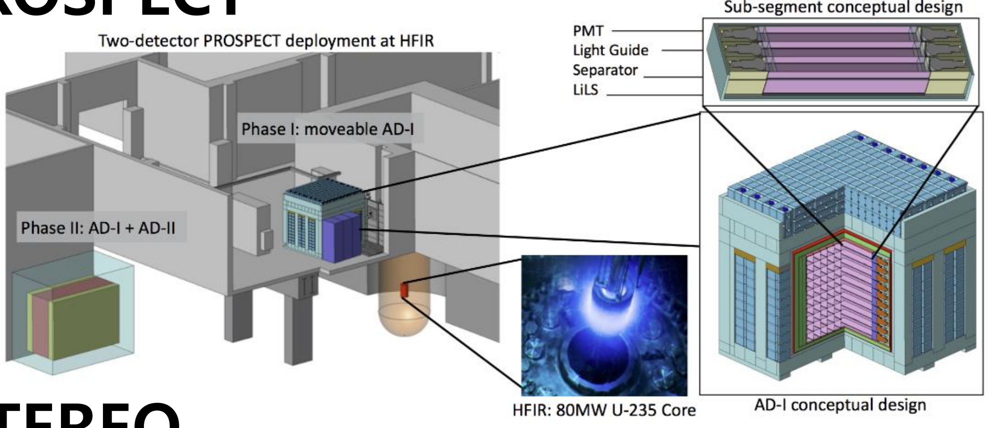
Hanbit nuclear power plant



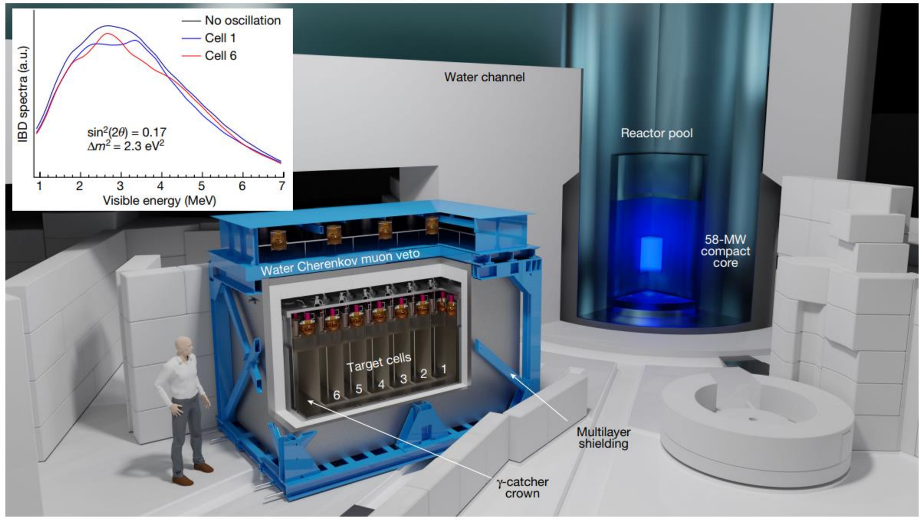
NEOS collaboration
@ ICHEP 2016

Tendon gallery

PROSPECT



STEREO

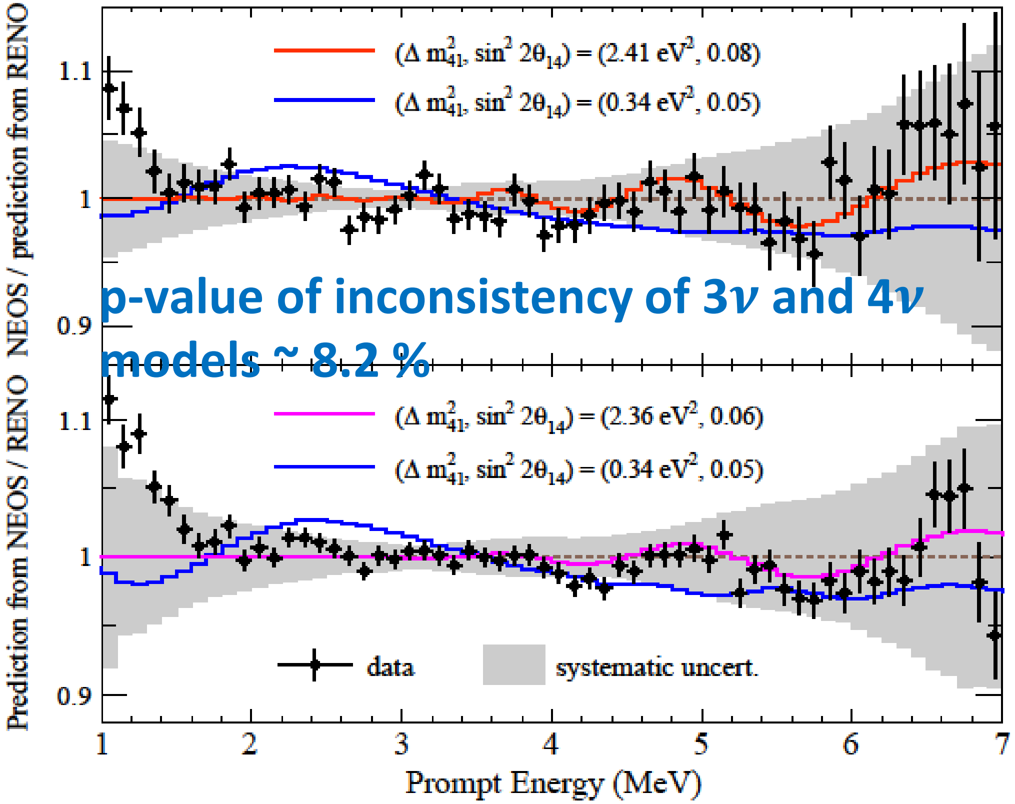


3. REACTOR NEUTRION EXPERIMENTS

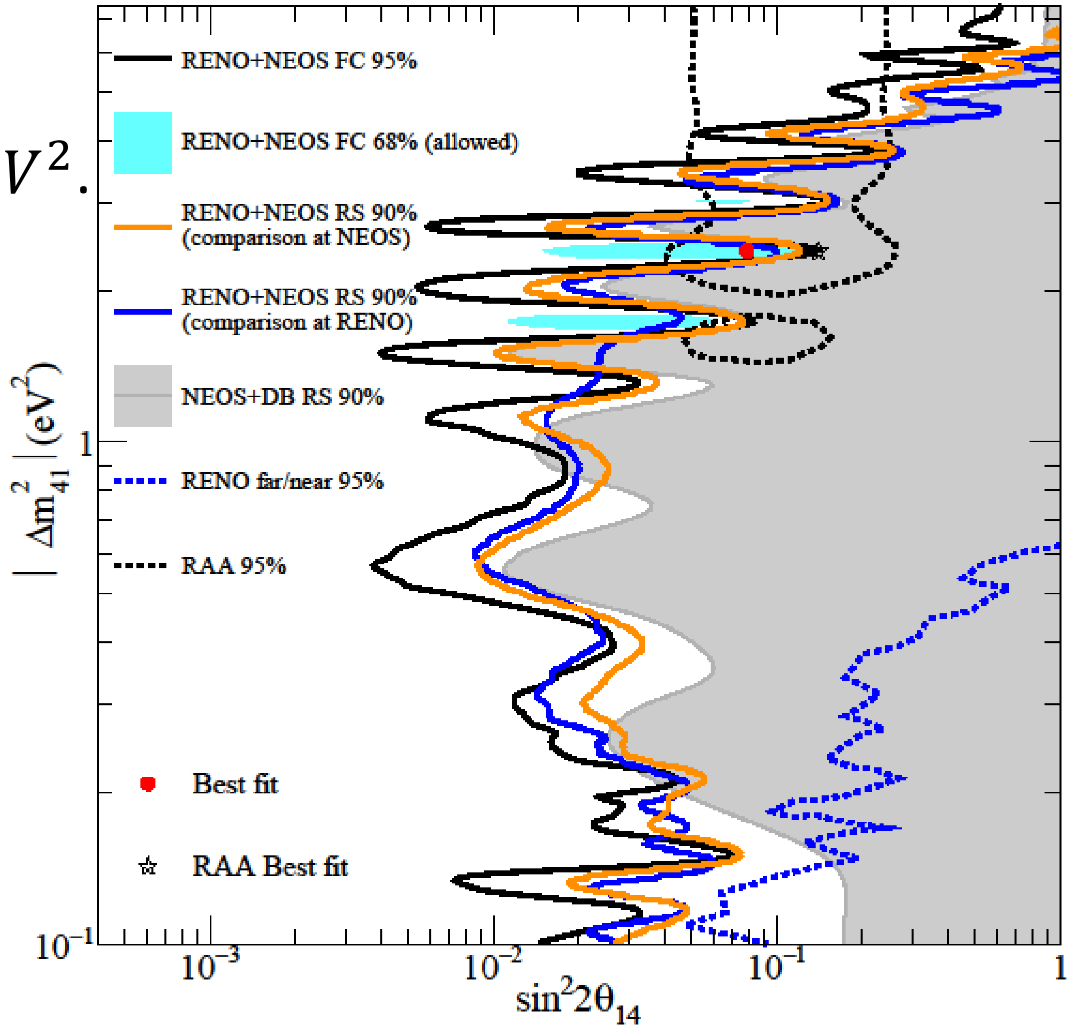
RENO/NEOS - LEU

Joint analysis result (PRD 105, 111101)

Hint for the sterile neutrino at $\Delta m_{41}^2 \sim 2\ eV^2$.



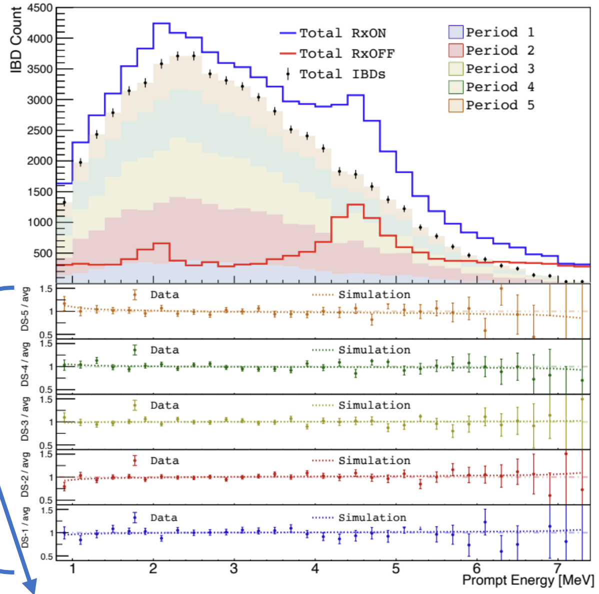
p-value of inconsistency of 3ν and 4ν models ~ 8.2 %



3. REACTOR NEUTRION EXPERIMENTS

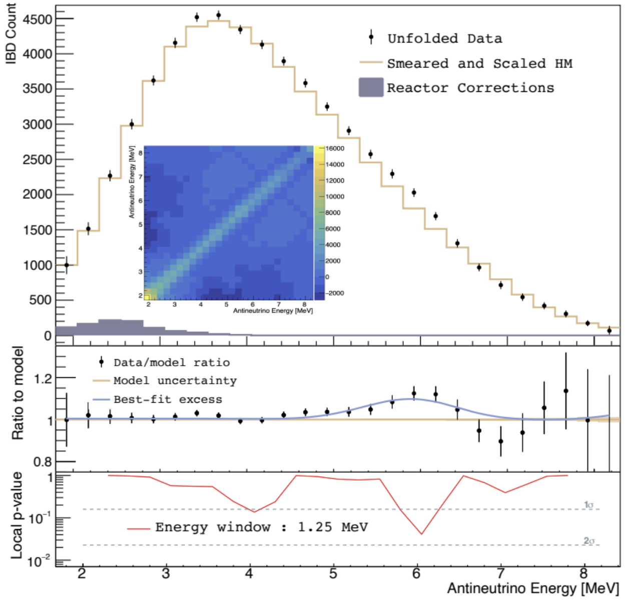
PROSPECT - HEU

Prompt spectrum

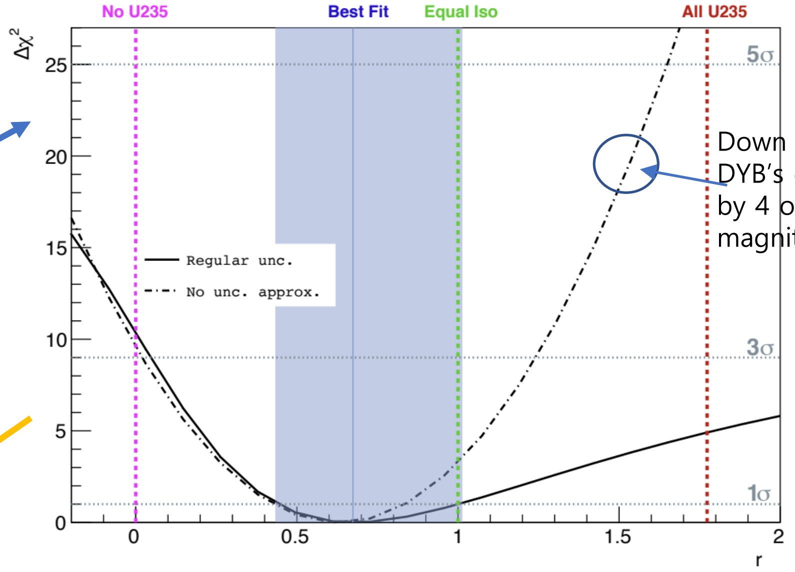


Data(1)/Data(sum)
vs MC(1)/MC(sum)

Neutrino spectrum



1. Gaussian fit to DYB 5MeV excess.
2. Using the fit function, fit PROSPECT 5MeV excess only modifying the amplitude.
3. Get the amplitude ratio “r”.



Down scaling DYB’s cov. mat. by 4 orders of magnitude.

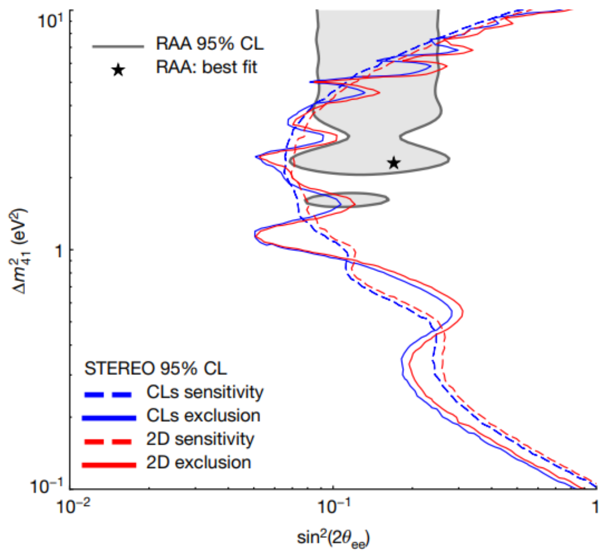
1. Reject the hypothesis that **5MeV excess doesn’t come from ^{235}U with 3.2σ**.
2. Reject the hypothesis that **5MeV excess only comes from ^{235}U with 2.2σ**.

3. REACTOR NEUTRION EXPERIMENTS

STEREO - HEU

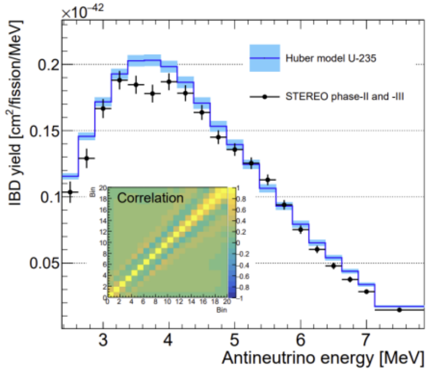
- STEREO data **reject** the "**light sterile neutrino hypothesis**".

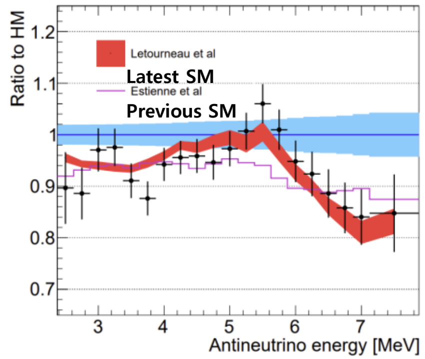
H_{41}'s p-value < 0.05 : rejected
H_{00}'s p-value = 0.52 : not rejected



- Their data suggest that **the anomalies come from biases in the nuclear experimental data** which are used for the predictions.

For **235U**, **5.5 ± 2.1 % deficit compared to the HM**.
The data **agrees with the recent SM**.





3. REACTOR NEUTRION EXPERIMENTS

Summary of the experiments

RENO/NEOS

- RENO/NEOS gives a hint for **the sterile neutrino at** $\boldsymbol{\Delta m^2_{41} \sim 2\ eV^2}$.

PROSPECT

- PROSPECT concludes that **5MeV excess doesn't come from** ^{235}U **with 3.2σ** and
- **5MeV excess only comes from** ^{235}U **with 2.2σ**.

STEREO

- STEREO data **reject** the **"light sterile neutrino hypothesis"**.
- Their data suggest that **the anomalies come from biases in the nuclear experimental data** which are used for the predictions.

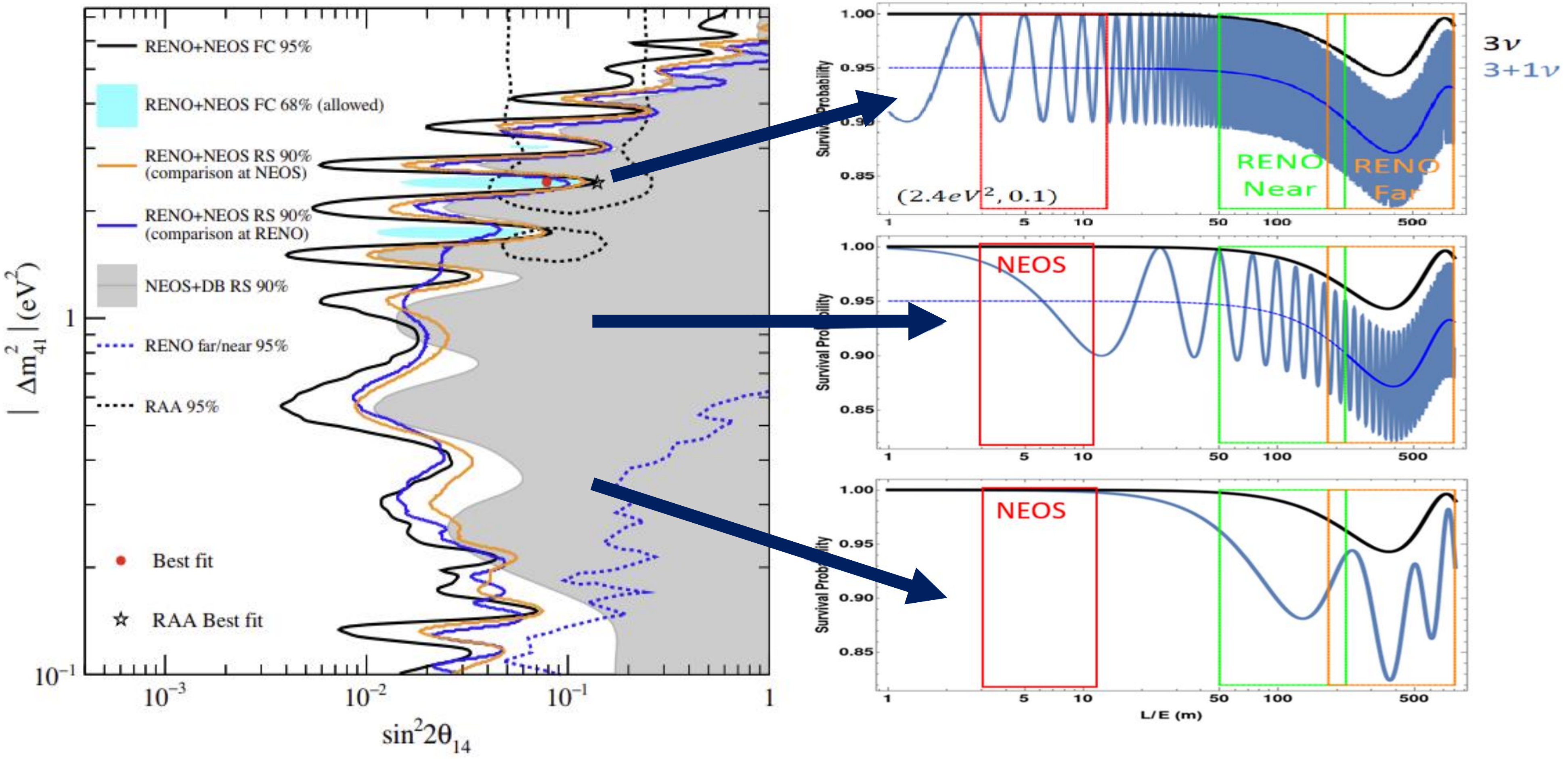
MOTIVATION

1. Search for the sterile neutrino at $\Delta m^2_{41} \sim 2\ eV^2$.
2. Precise measurement for the reactor neutrino spectrum.

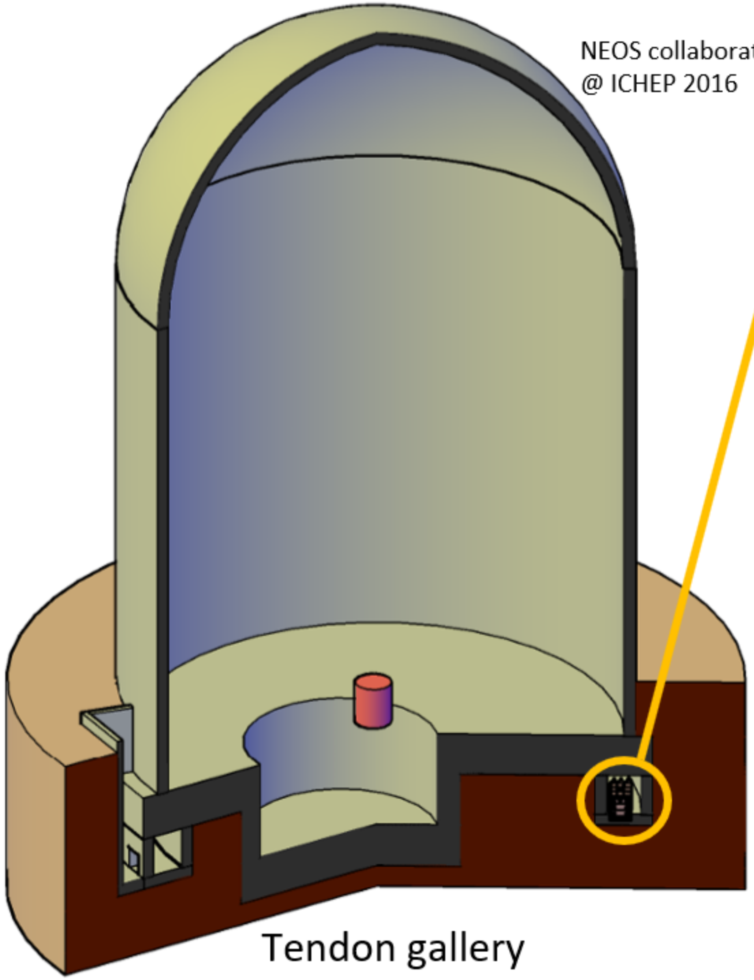
4. RENE - *Reactor Experiment for Neutrinos and Exotics*

$$P_{\overline{\nu}_e \to \overline{\nu}_e} = 1 - 4\sum_{i>j} |U_{ei}|^2 |U_{ej}|^2 \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) \quad \Delta_{ij} = 1.27\,\Delta m^2_{ij}\, L/E\ (\mathrm{eV}^2\,\mathrm{m/MeV})$$

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



4. RENE - *Reactor Experiment for Neutrinos and Exotics*



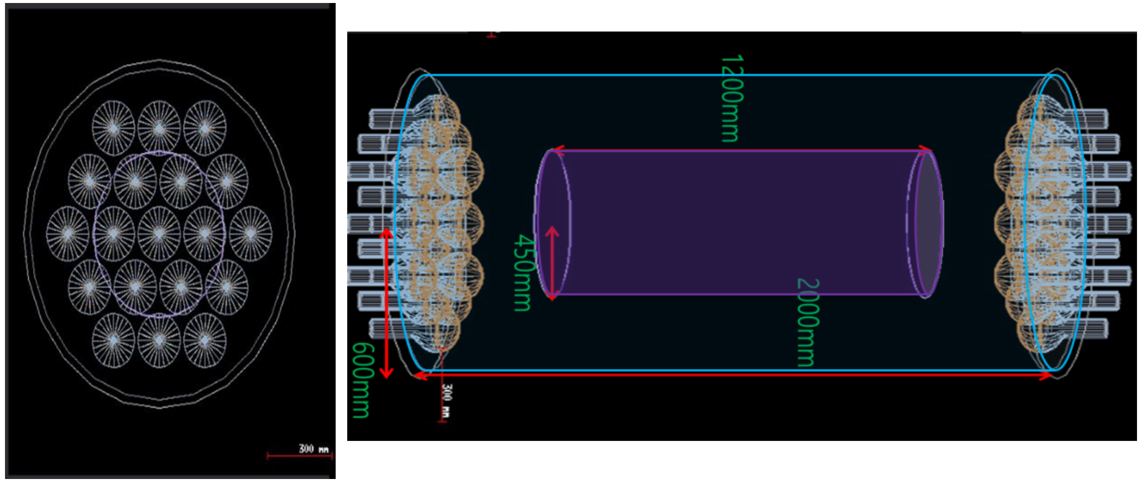
We are considering **multiple detectors**.

$$\left(\begin{array}{c}\Delta_{ij} = 1.27\,\Delta m^2_{ij}\,L/E\ (\ \mathrm{eV}^2\,\mathrm{m/MeV}\ ) \\ \pi/1.27 \sim 2.5\,\mathrm{m\ at}\ \Delta m^2 \sim 2\mathrm{eV}^2\ \mathrm{and}\ E = 4\,MeV\end{array}\right)$$

	Baseline (m)
L0	23.6
L1	22.8
L2	21.9
L3	21.7

There are **four candidate locations**, L0, L1, L2, and L3.

4. RENE - Reactor Experiment for Neutrinos and Exotics

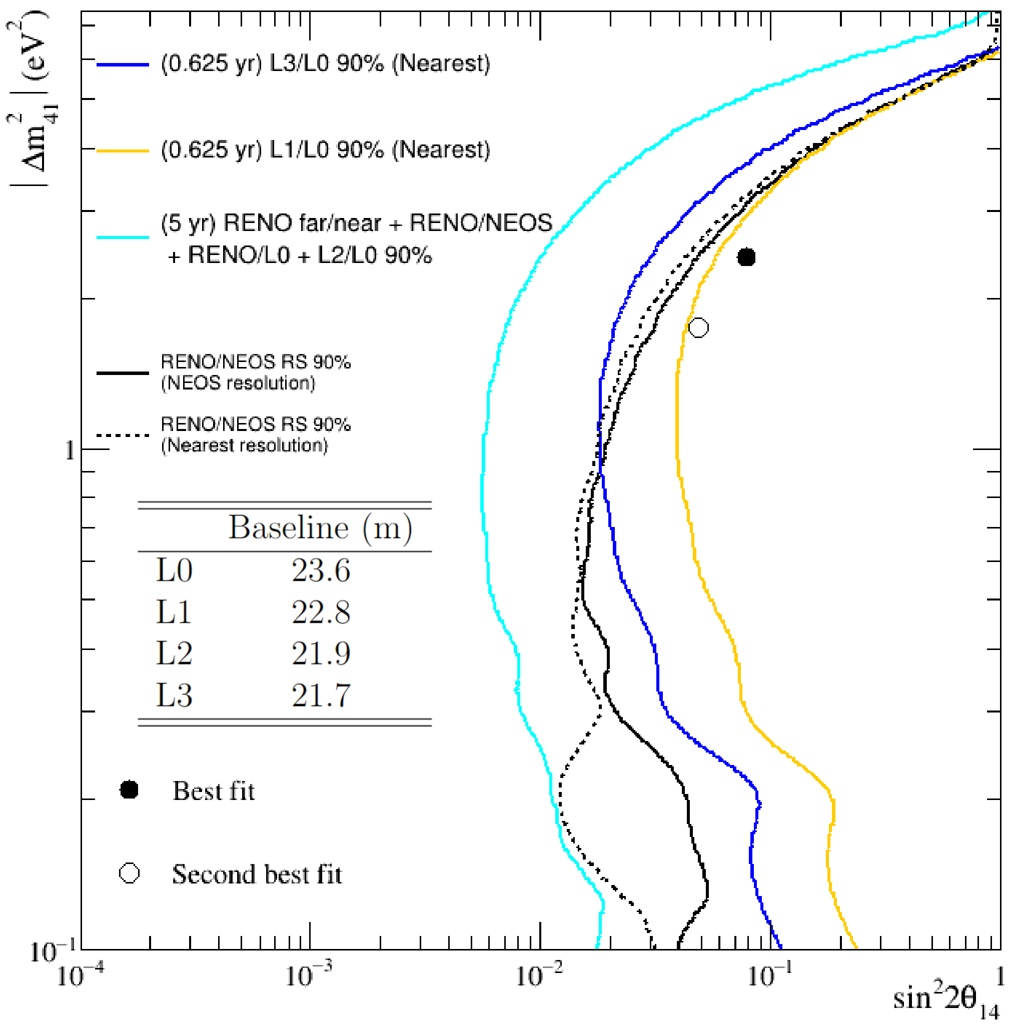


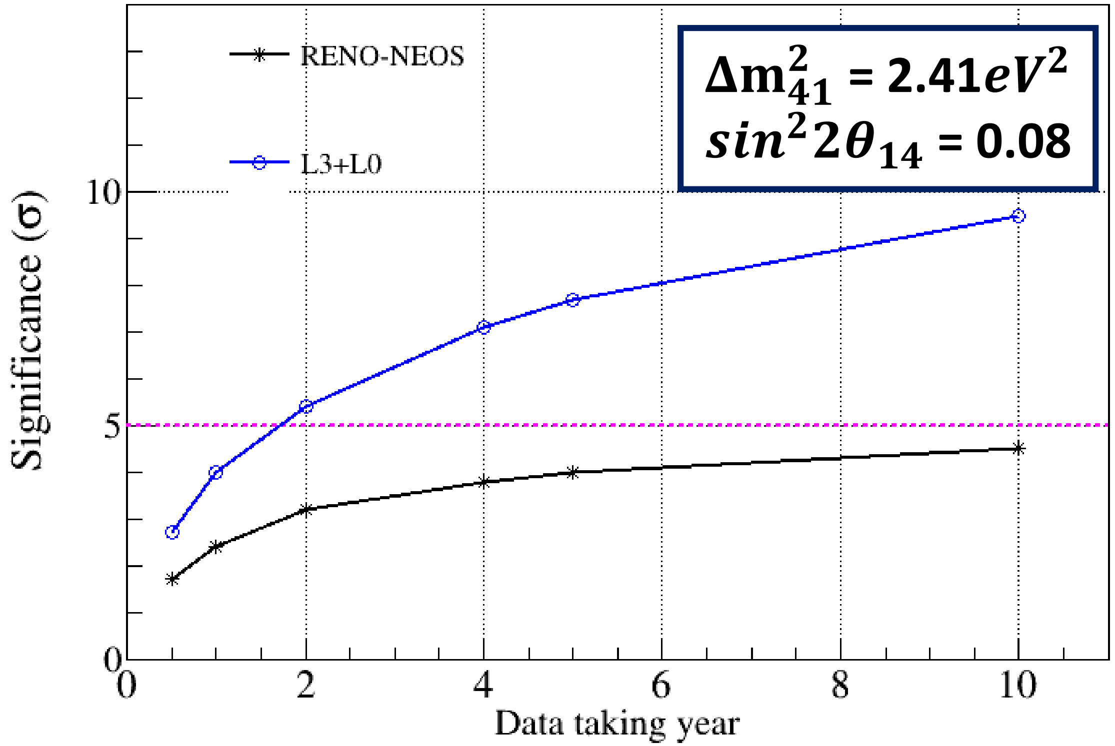
PROTOTYPE

- Total **38 8-inch pmts** on **Left & Right**
- 450 mm radius & 0.5% Gd-loaded Target
- => **763.407 L**
- 150 mm thickness Gamma catcher
- **Reflective material** on the wall of the gamma catcher

- Total **2 20-inch pmts** on **Left & Right**
- 254 mm radius & 0.5% Gd-loaded Target
- => **243.220 L**
- 150 mm thickness Gamma catcher
- **Reflective material** on the wall of the gamma catcher

4. RENE - Reactor Experiment for Neutrinos and Exotics





4. RENE - Reactor Experiment for Neutrinos and Exotics

- RENO-NEOS joint analysis shows an interesting hint **for the existence of the sterile neutrino at $\Delta m_{41}^2 \sim 2\ eV^2$.**
- To search the mass parameter region, we are considering **multiple detectors** at nearest sites in the Hanbit nuclear power plant.
- **We expect to search for the sterile neutrino at the above parameter region.**
- **After that, we have a future plan to precisely measure the neutrino spectrum at LEU and HEU reactors with the same detector.**

감사합니다.
Thank you.

BACKUP

* Backup

Fission: Break up of a nucleus

$$ {}^{A}_{Z}X \rightarrow {}^{a_1}_{z_1}M + {}^{a_2}_{z_2}N + Q_{fission} \quad \text{where } A = a_1 + a_2 \text{ and } Z = z_1 + z_2 $$

In the rest frame,

$$ m(A,Z) = Zm_p + Nm_n - B(A,Z) $$

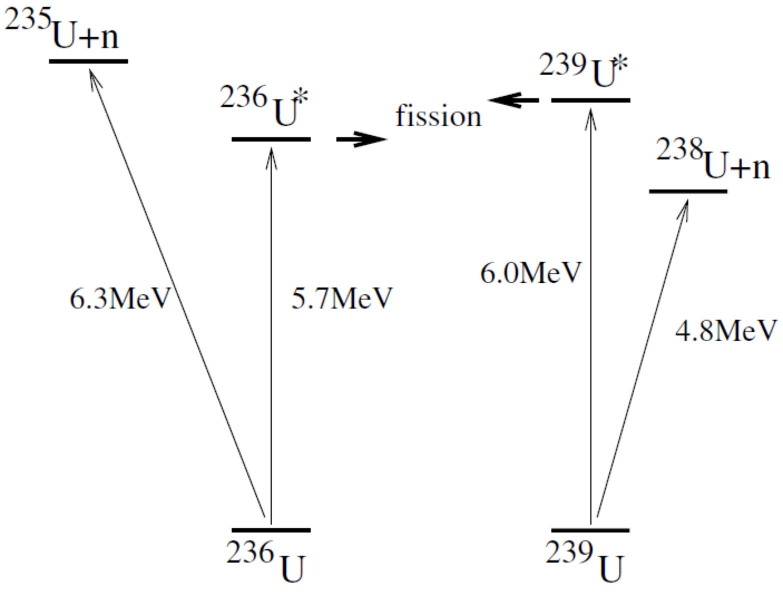
BE : The negative difference of the nuclear mass and the masses of the constituents.

$$ B(A,Z) = a_v A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - a_a \frac{(N-Z)^2}{A} + \delta(A), \qquad \delta(A) = \begin{cases} 33.6A^{-3/4} & \text{if N and Z are even} \\ -33.6A^{-3/4} & \text{if N and Z are odd} \\ 0 & \text{if A = N + Z is odd} \end{cases} $$

* Backup

- Odd N fissile material > Even N fissile material

$$n + {}^{A-1}_{Z}X \rightarrow {}^{A}_{Z}X^{*} \rightarrow fission$$



$$\begin{aligned} Q_{fis} &= m_n + T_n(A-1) \\ &\quad + Zm_z + (N-1)m_n - B(A-1,Z) \\ &\quad -[Zm_z + Nm_n - B(A,Z) + E_{ex}] \\ &= T_n(A-1) - E_{ex} \\ &\quad + B(A,Z) - B(A-1,Z), \end{aligned}$$

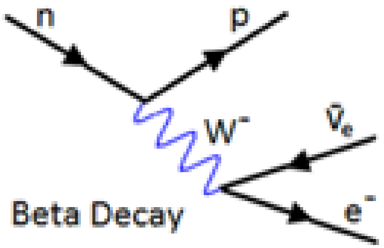
$$\begin{aligned} T_n(A-1) &= Q_{fis} + E_{ex} - S_n(A) \\ &= \Delta E(A) - S_n(A), \end{aligned}$$

$$\delta(A) = \begin{cases} 33.6A^{-3/4} & \text{if N and Z are even} \\ -33.6A^{-3/4} & \text{if N and Z are odd} \\ 0 & \text{if A = N + Z is odd} \end{cases}$$

$$\delta(A) - \delta(A-1)$$

* Backup

β decay



Start from Fermi's Golden rule

$$\lambda = \frac{2\pi}{\hbar} |V_{fi}|^2 \rho(E_f)$$

$$V_{fi} = g \int \underbrace{[\psi_f^* \, \psi_e^* \, \psi_\nu^*]}_{\text{final state}} O_x \, \psi_i \, dv$$

The allowed approximation

$$\psi_e = \frac{e^{i\,\mathbf{p}\cdot\mathbf{r}/\hbar}}{\sqrt{V}} = \frac{1 + \frac{i\,\mathbf{p}\cdot\mathbf{r}}{\hbar} + \cdots}{\sqrt{V}} \simeq \frac{1}{\sqrt{V}}$$

$$\psi_\nu = \frac{e^{i\,\mathbf{q}\cdot\mathbf{r}/\hbar}}{\sqrt{V}} = \frac{1 + \frac{i\,\mathbf{q}\cdot\mathbf{r}}{\hbar} + \cdots}{\sqrt{V}} \simeq \frac{1}{\sqrt{V}} .$$

=> **allowed transition**

If we consider higher orders of $\mathcal{O}(\mathbf{p})\&\mathcal{O}(\mathbf{q})$,

=> forbidden transition

* Backup

β decay

The partial decay rate

$$d^2n = (4\pi)^2 \frac{p^2\,dp\,q^2\,dq}{h^6} V^2$$

$$\begin{aligned} d\lambda &= \frac{2\pi}{\hbar} |V_{fi}|^2 \frac{d^2n}{dE_f} \\ &= \frac{2\pi}{\hbar} [g \int (\psi_f^* \psi_e^* \psi_\nu^*) O_x \psi_i \, dv]^2 \\ &\quad \times (4\pi)^2 \frac{p^2\,dp\,q^2\,dq}{h^6\,dE_f} V^2 \\ &= \frac{2\pi}{\hbar} g^2 [\int \psi_f^* O_x \psi_i \, dv]^2 (4\pi)^2 \frac{p^2\,dp\,q^2\,dq}{h^6\,dE_f} \\ &= \frac{2\pi}{\hbar} g^2 |M_{fi}|^2 (4\pi)^2 \frac{p^2 q^2}{h^6} \frac{dp\,dq}{dE_f}, \end{aligned}$$

$$\begin{aligned} \psi_e &= \frac{e^{i\,\mathbf{p}\cdot\mathbf{r}/\hbar}}{\sqrt{V}} = \frac{1 + \frac{i\,\mathbf{p}\cdot\mathbf{r}}{\hbar} + \cdots}{\sqrt{V}} \simeq \frac{1}{\sqrt{V}} \\ \psi_\nu &= \frac{e^{i\,\mathbf{q}\cdot\mathbf{r}/\hbar}}{\sqrt{V}} = \frac{1 + \frac{i\,\mathbf{q}\cdot\mathbf{r}}{\hbar} + \cdots}{\sqrt{V}} \simeq \frac{1}{\sqrt{V}}. \end{aligned}$$

E_f is $E_e + E_\nu = E_e + qc$

$dq/dE_f = 1/c$ at fixed E_e

* Backup

β decay

The # of e in the range p and p+dp

$$N_\beta(p)\,dp = A\,p^2\,q^2\,dp\text{, where } A = \frac{2\pi}{\hbar}\,g^2\,|M_{fi}|^2\,(4\pi)^2\,/(h^6\,c)$$

E_ν =Q−T_e the decay energy Q

$$\begin{aligned} N_\beta(p) &= \frac{A}{c}\,p^2\,(Q - T_e)^2 \\ &= \frac{A}{c}\,p^2\,(E_0 - E_e)^2 \\ &= \frac{A}{m_e^2 c^5}\,p^2\,(W_0 - W)^2, \end{aligned}$$

where W is $\frac{E_e}{m_e c^2} + 1$

$$N_\beta(W) = K\,p^2\,(W - W_0)^2\,F(Z, W)$$

The influence of the nuclear Coulomb potential

* Backup

β decay

The more correct β spectrum formula

$$N_\beta(W) = K\,p^2\,(W - W_0)^2\,F(Z, W) \times L_0(Z, W)\,C(Z, W)\,S(Z, W) \times G_\beta(Z, W)\,(1 + \delta_{WM} W),$$

The weak interaction correction for the finite size of the nucleus

The EM interaction correction for the finite size of the nucleus

The radiative correction for the virtual and real photon emissions

The weak magnetism correction

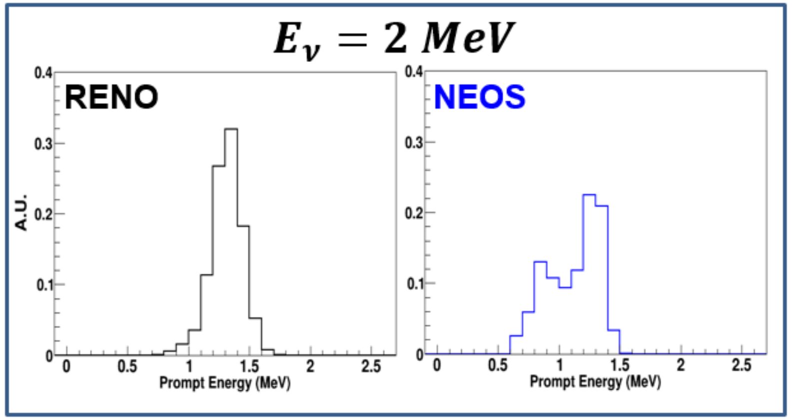
The screening effect of the nuclear charge by bound electrons

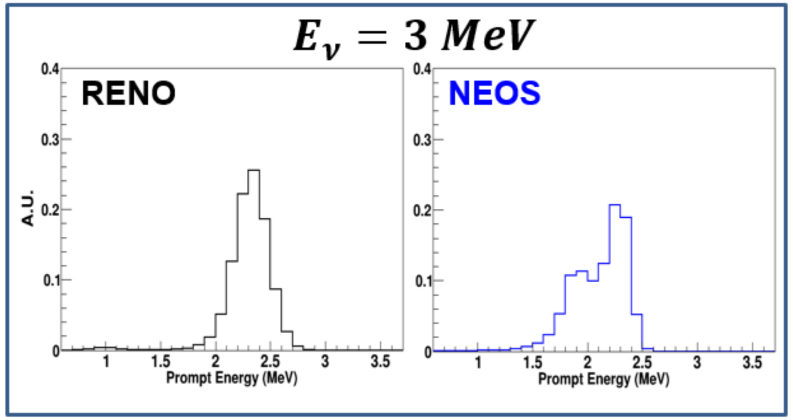
Radiative correction
It is crucial to correctly account for both the virtual and real photon contributions to ensure the proper cancellation of 3. Almost all decays relevant in our problem are of this type and the corresponding expression for Fermi decays is numerically very close. divergences.

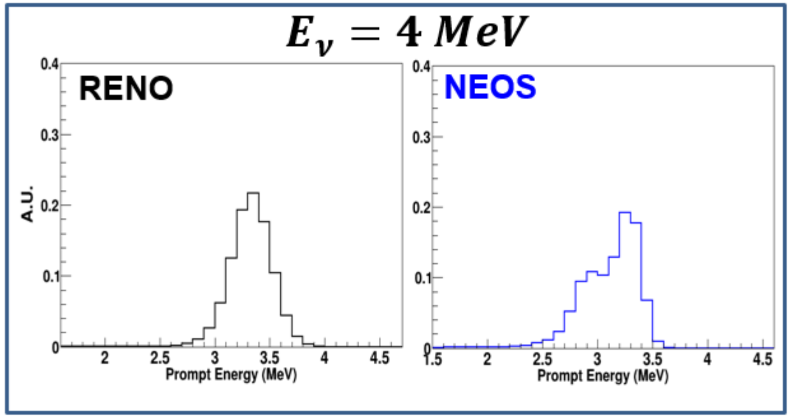
Weak magnetism
Interaction btw current and magnetic moment of nucleon

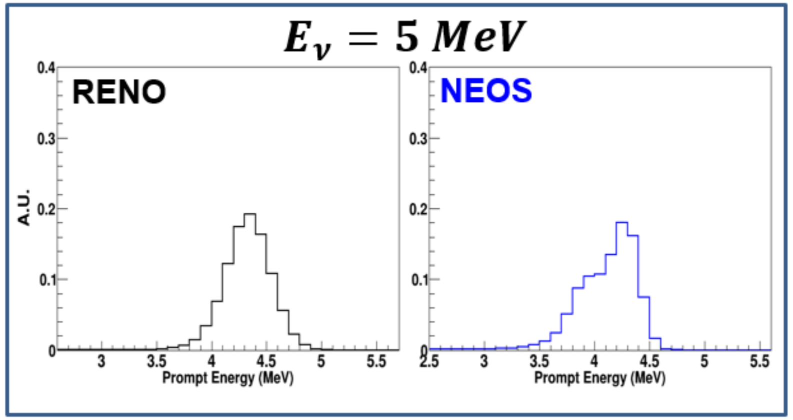
* Backup

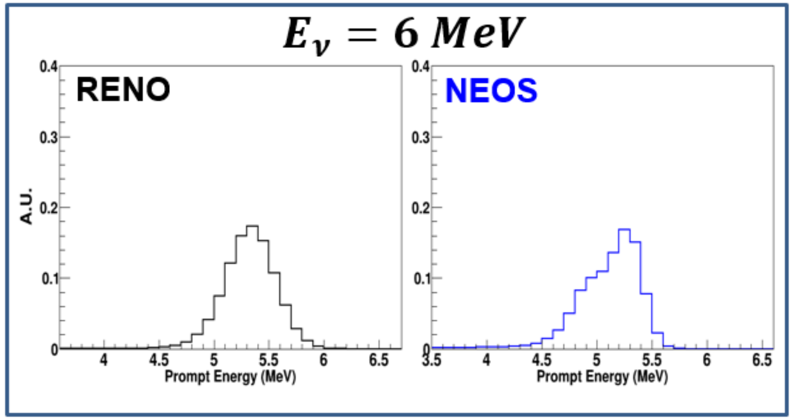
RENO & **NEOS** detector **responses** of the monochromatic neutrino energy
(PRD 104, 111301) (PRD 105, 111101)





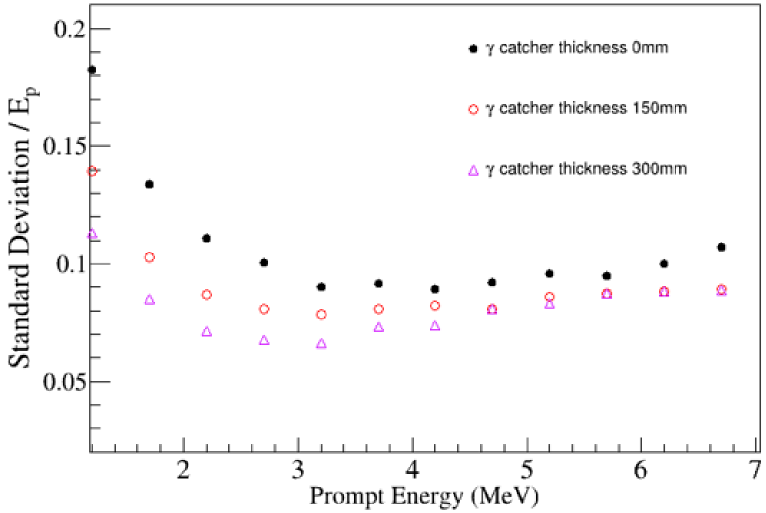




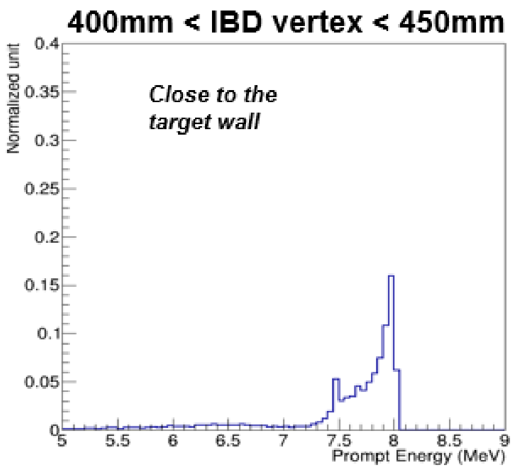


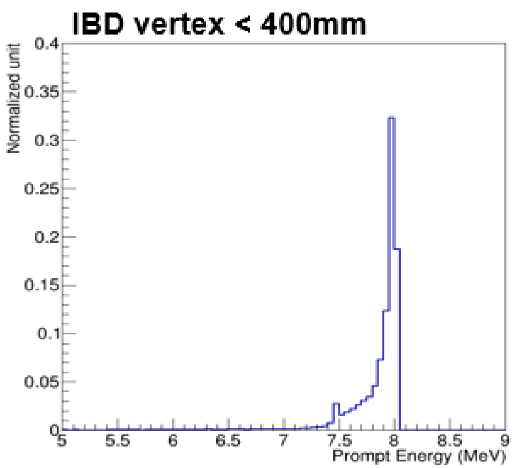
NEOS's **low energy 2nd peak** is originated by **escaping gammas from the target**.

* Backup

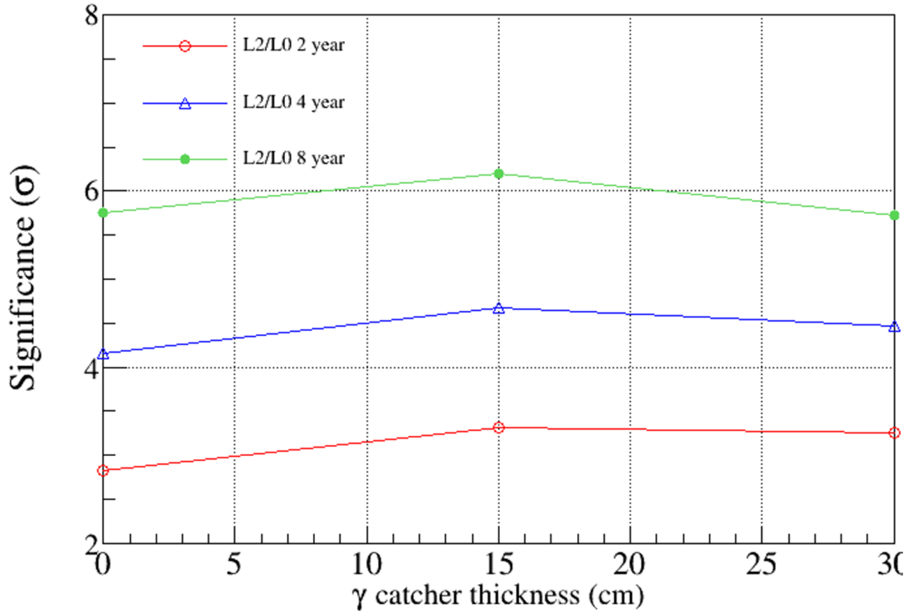


@ 7.5 MeV positron

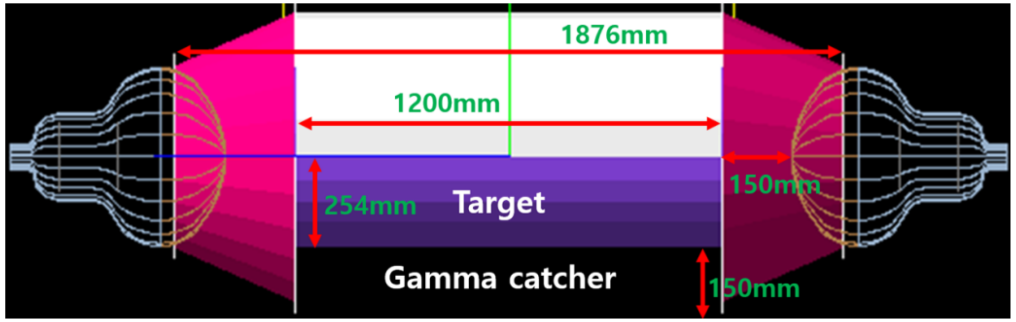


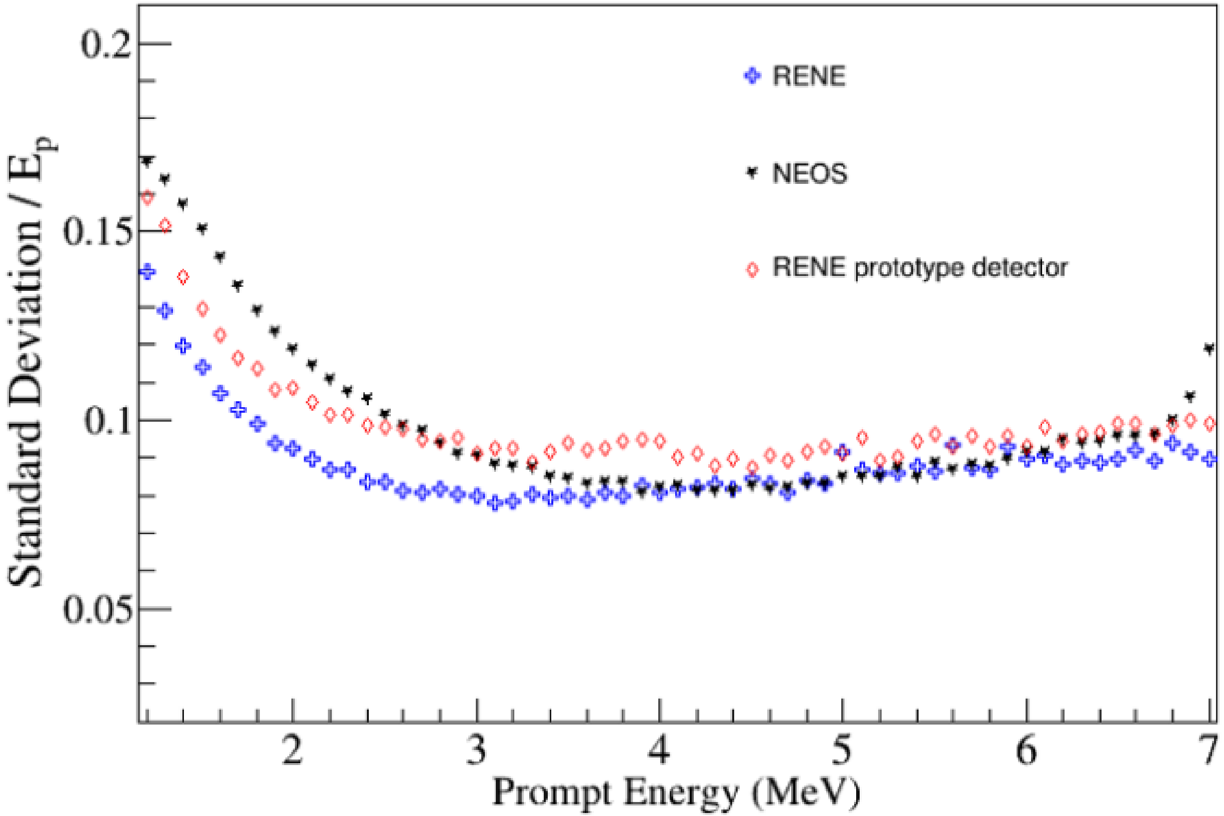


Under the size constraint and the statistics, 150mm thick gamma catcher case would be the best choice.



* *Backup*

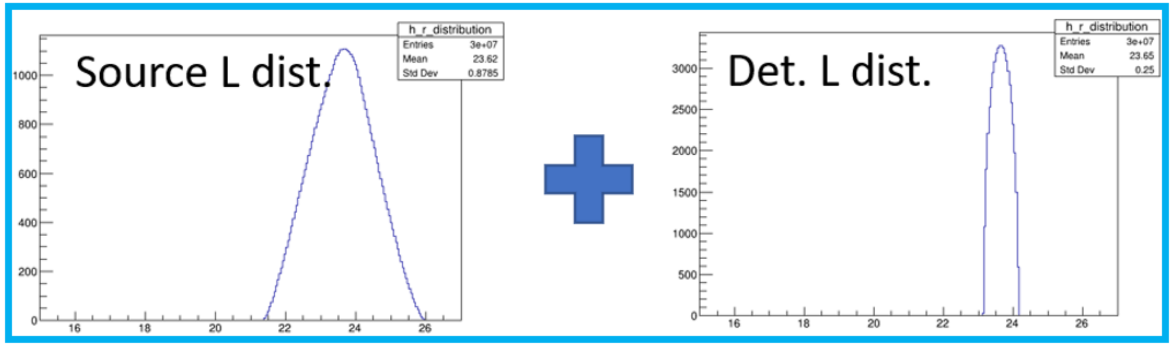




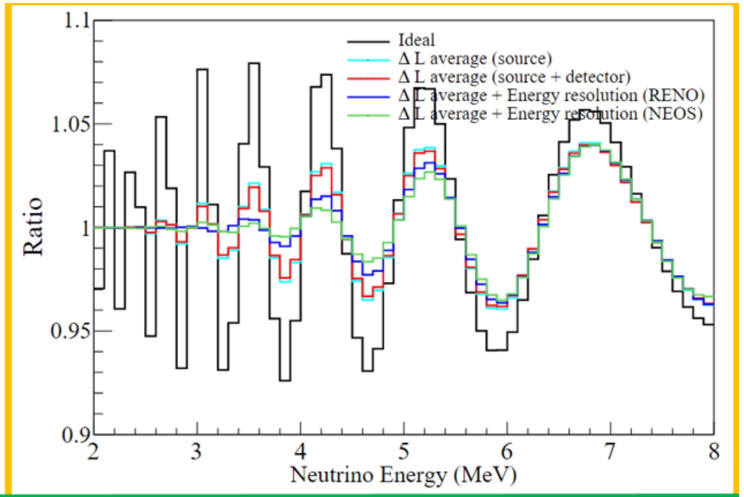
- Total **2 20-inch pmts** on **Left & Right**
- 254 mm radius & 0.5% Gd-loaded Target
- => **243.220 L**
- 150 mm thickness Gamma catcher
- **Reflective material** on the wall of the gamma catcher

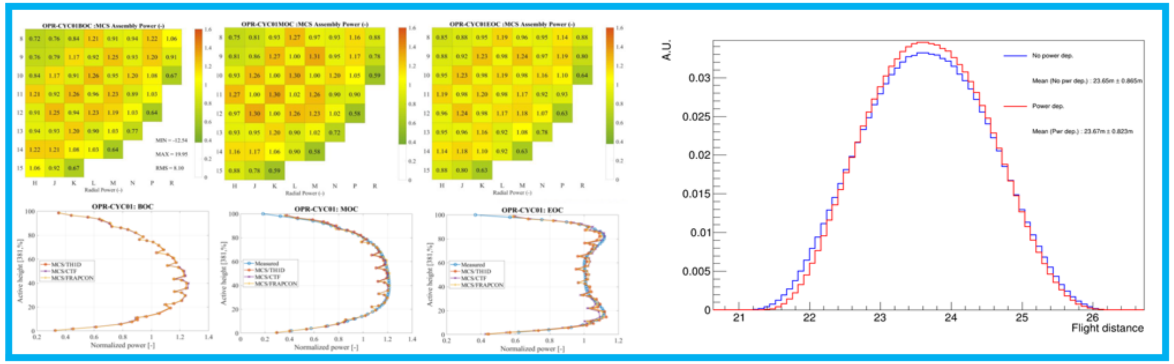
Reactor Experiment for Neutrinos and Exotics

* Backup



Reactor source core dimension effect is larger than the effect of the detector size.





The source core's power distribution doesn't affect to the prompt energy spectrum.