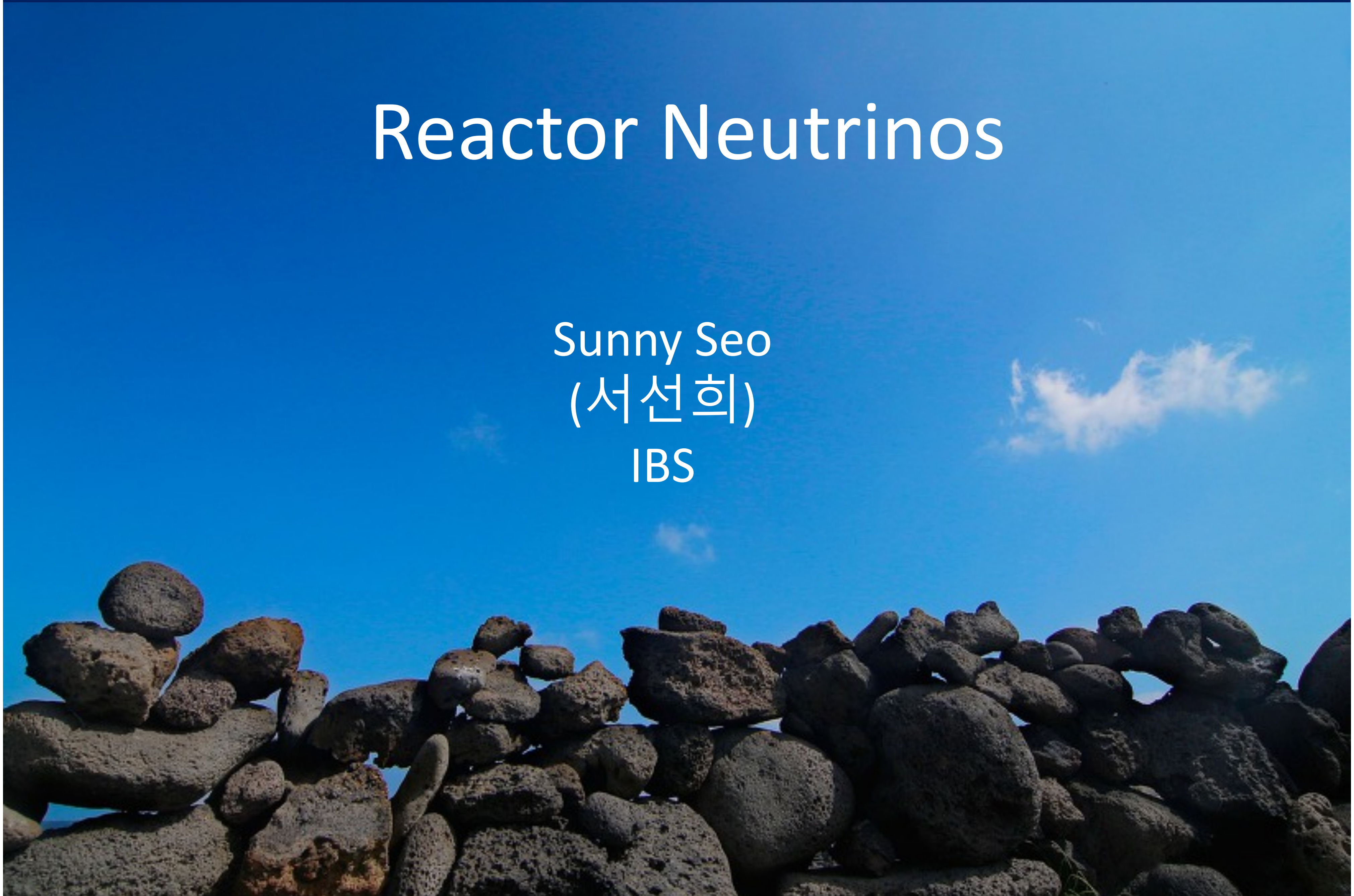
The 8th Joint workshop of FKPPL and TYL/FJPPL

Reactor Neutrinos

Sunny Seo
(서선희)
IBS



Jeju Island, May 8-10, 2019

PMNS matrix

in 1962

- Pontecorvo
- Maki
- Nakagawa
- Sakata

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

Mixing angles

$\theta_{23} = \theta_{\mu 3}$ $\theta_{13} = \theta_{e3}$ $\theta_{12} = \theta_{e2}$

$$= \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Atmos. (ν_μ, $\overline{\nu_\mu}$ deficit)
Long baseline (ν_μ deficit)

Reactor ($\overline{\nu_e}$ deficit)
Long baseline ($\nu_\mu \rightarrow \nu_e$)

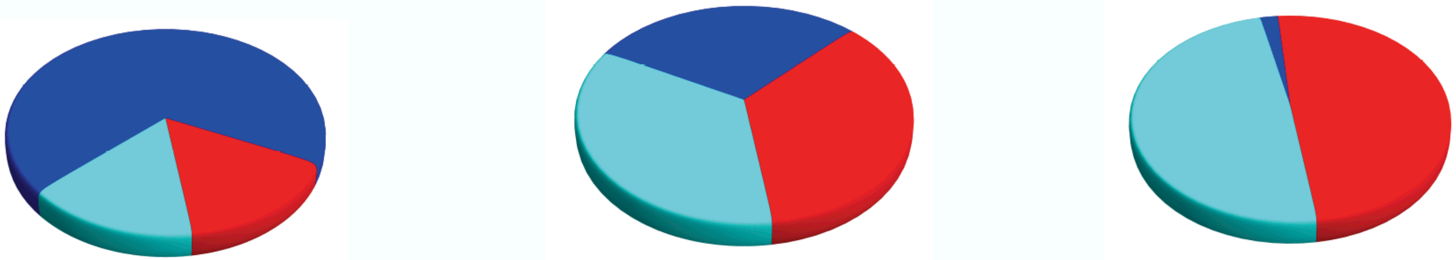
Solar (ν_e deficit)
Reactor ($\overline{\nu_e}$deficit)

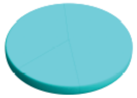
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

PMNS matrix in 1962

- Pontecorvo
- Maki
- Nakagawa
- Sakata

ν_1 most ν_e | ν_2 | ν_3 least ν_e



$\nu_e =$  $\nu_\mu =$  $\nu_\tau =$ 

Neutrino Oscillation Milestones

Neutrino has mass & oscillation

1957
B. Pontecorvo

Atmos. Neutrino Oscillation

θ_{23}

~45° (1998)
Super-K; K2K

Solar Neutrino Flavor Change

(arXiv:1609.02386)

θ_{12}

34° (2001)
SNO, Super-K;
KamLAND

2015 Nobel Prize

Reactor Neutrino Oscillation

θ_{13}

9° (2012)
Daya Bay, RENO
Double Chooz, T2K

Meaning of $\sin^2(2\theta_{13})$

➢ What is θ_{13} ?

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$|U_{e3}|^2 = \sin^2\theta_{13}$

ν_e content in ν_3

θ_{13} is the smallest neutrino mixing angle in the PMNS matrix.

➢ Physical meaning of $\sin^2(2\theta_{13})$?

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E_\nu}\right)$$

Reactor neutrino disappearance at short (1~2km) baseline

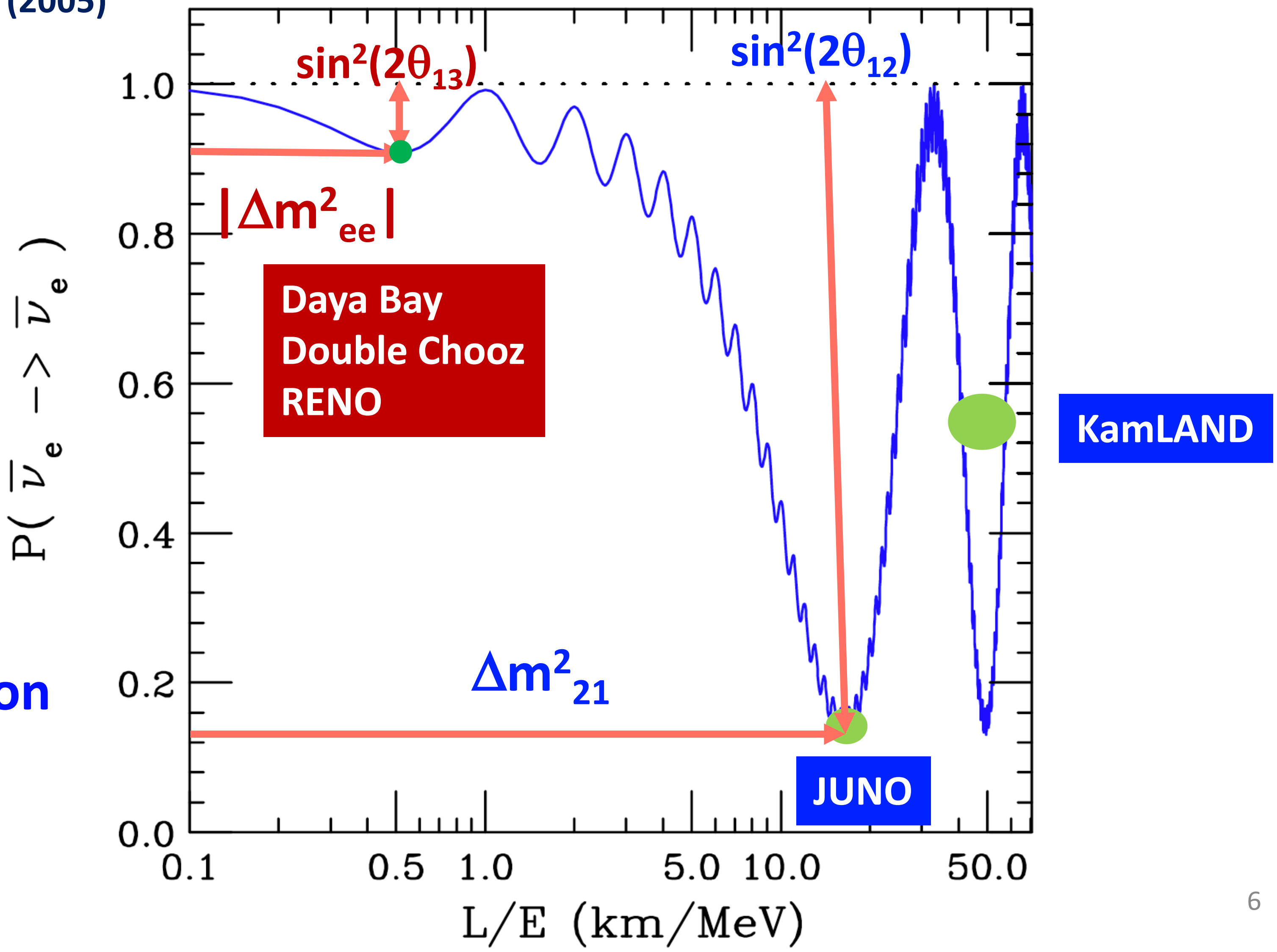
$\sin^2(2\theta_{13})$ is the oscillation amplitude of reactor neutrinos.

Short baseline O(1~2km) **Medium baseline** O(50~60km)

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

Nunokawa, Parke, Funchal
PRD 72, 013009 (2005)

$$\Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

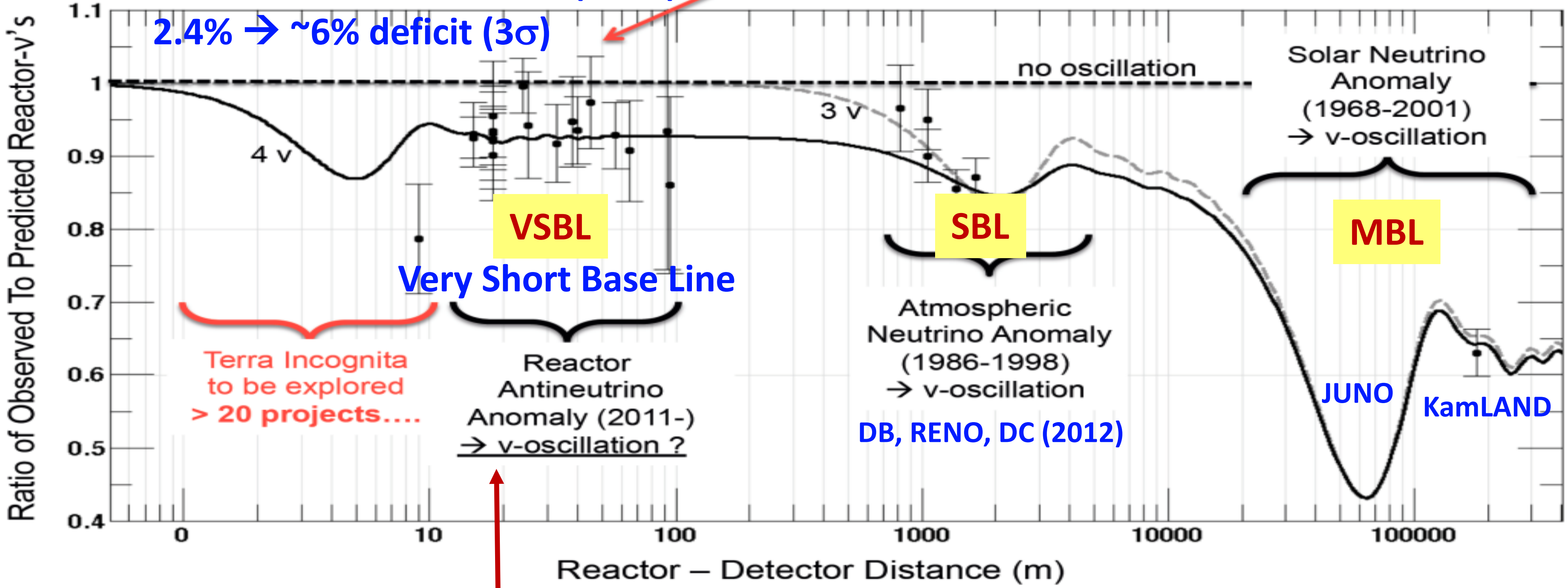


3 ν oscillation paradigm

Reactor ν "Flux" Anomaly

- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)

Mention et al. PRD83, 073006 (2011)



$$P \simeq 1 - \sin^2 2\theta_{14} \sin^2 \left[1.27 \frac{\Delta m^2_{41} L}{E_\nu} \left(\frac{\mathrm{eV}^2 \cdot \mathrm{m}}{\mathrm{MeV}} \right) \right]$$

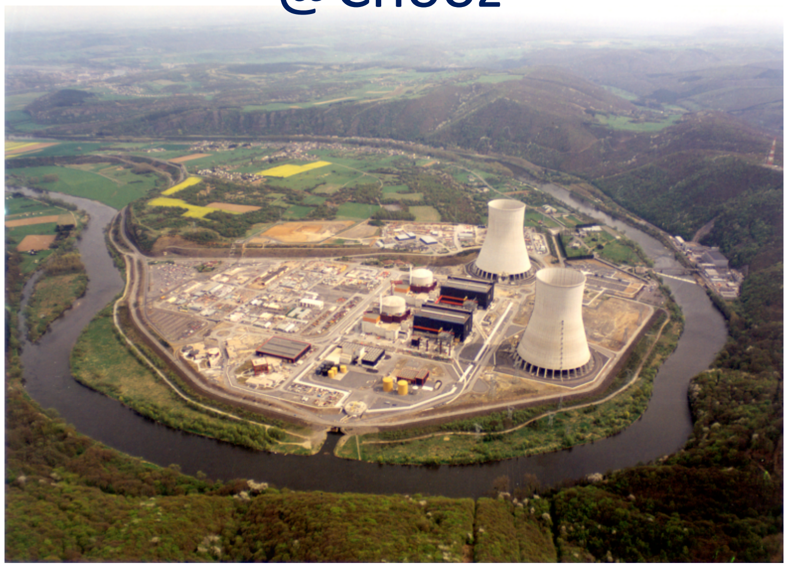
RAA = Reactor Antineutrino Anomaly

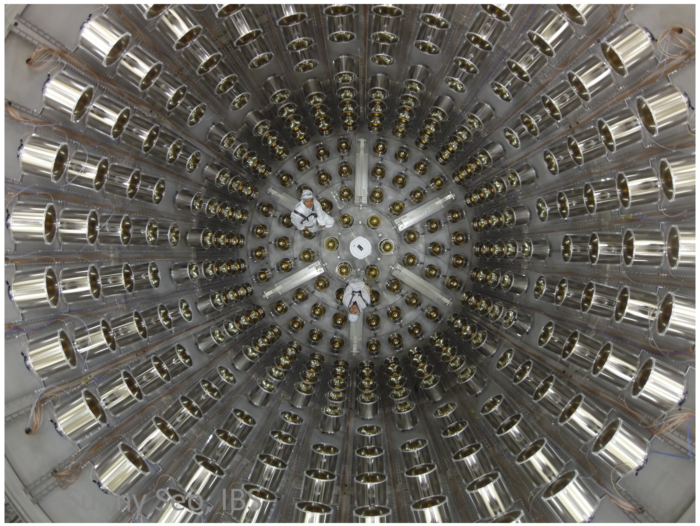
(3+1) ν RAA best fit: $\Delta m^2_{41} = 2.4\ \mathrm{eV}^2$, $\sin^2(2\theta_{14}) = 0.14$

Modern Reactor ν programs in France

(Double) Chooz

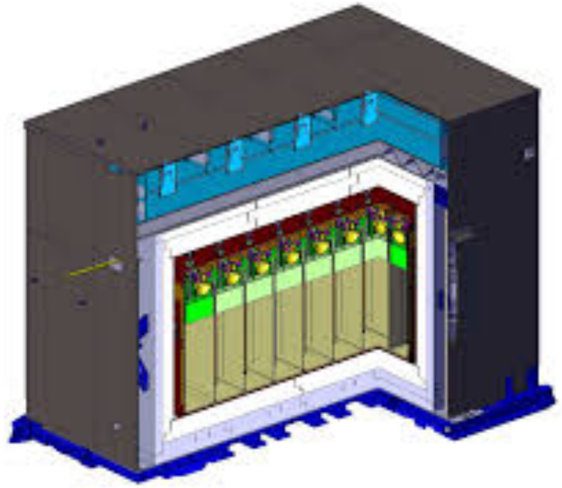
@Chooz





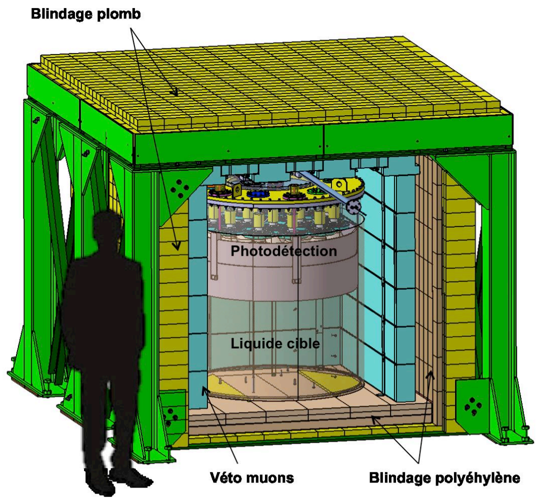
STEREO

@ILL



Nucifer (done!)

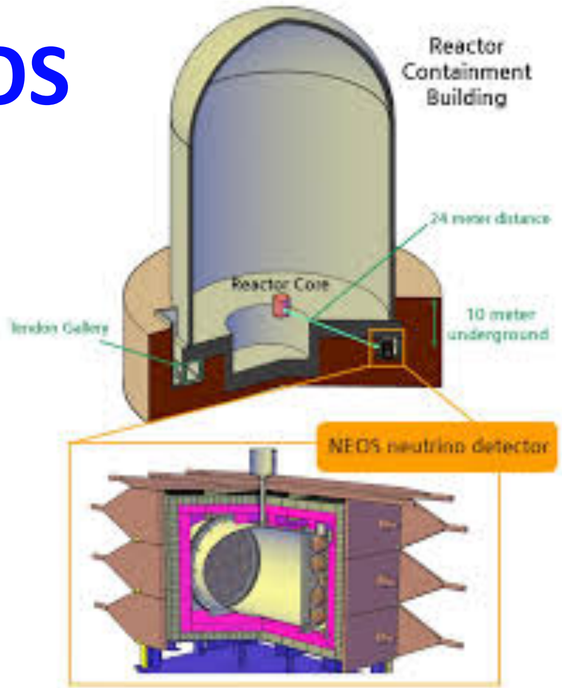
@Osiris



Reactor ν programs in Korea

RENO

NEOS

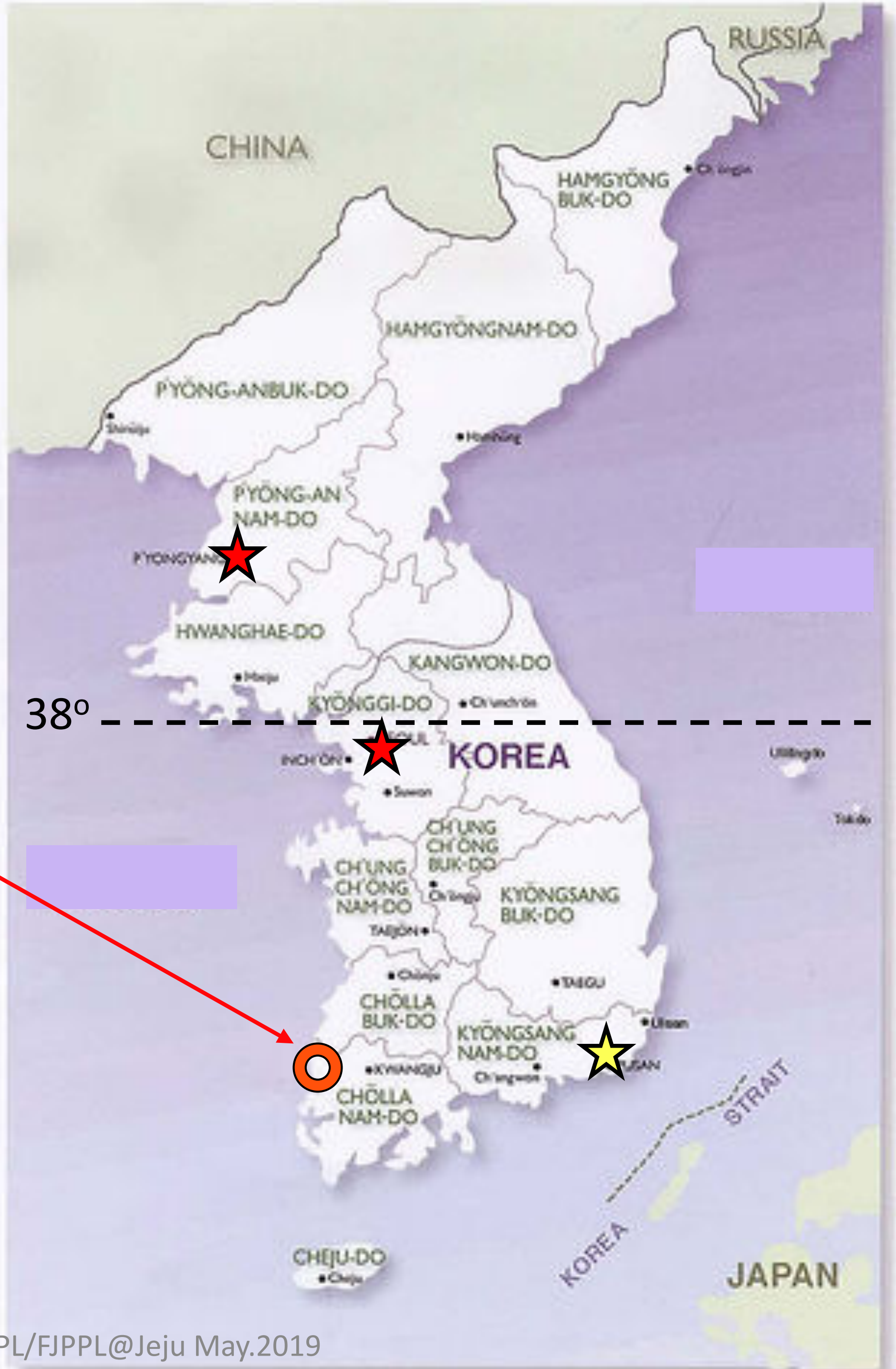


Location: YongGwang S. Korea

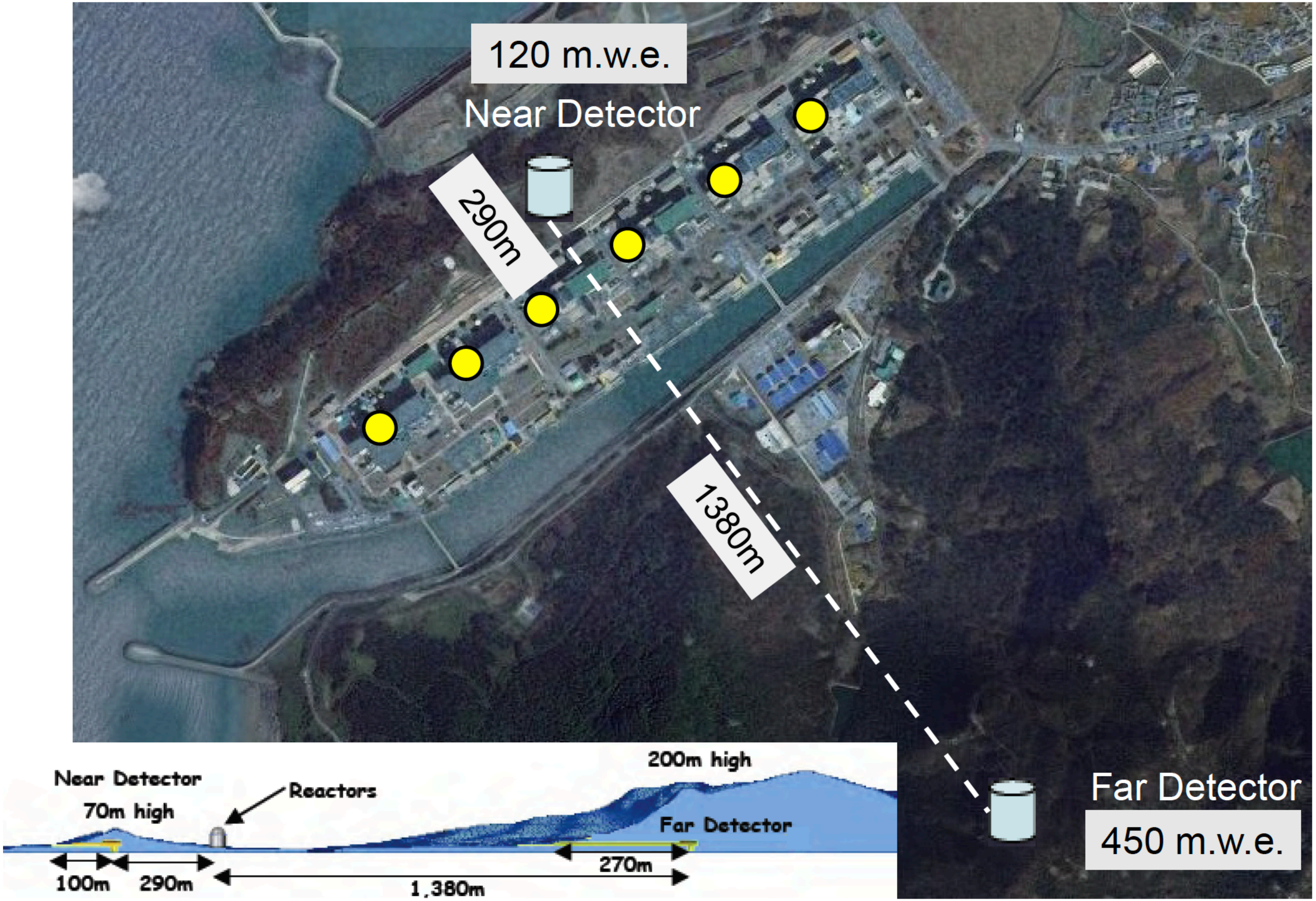
YongGwang (靈光) :

means “Glorious light”

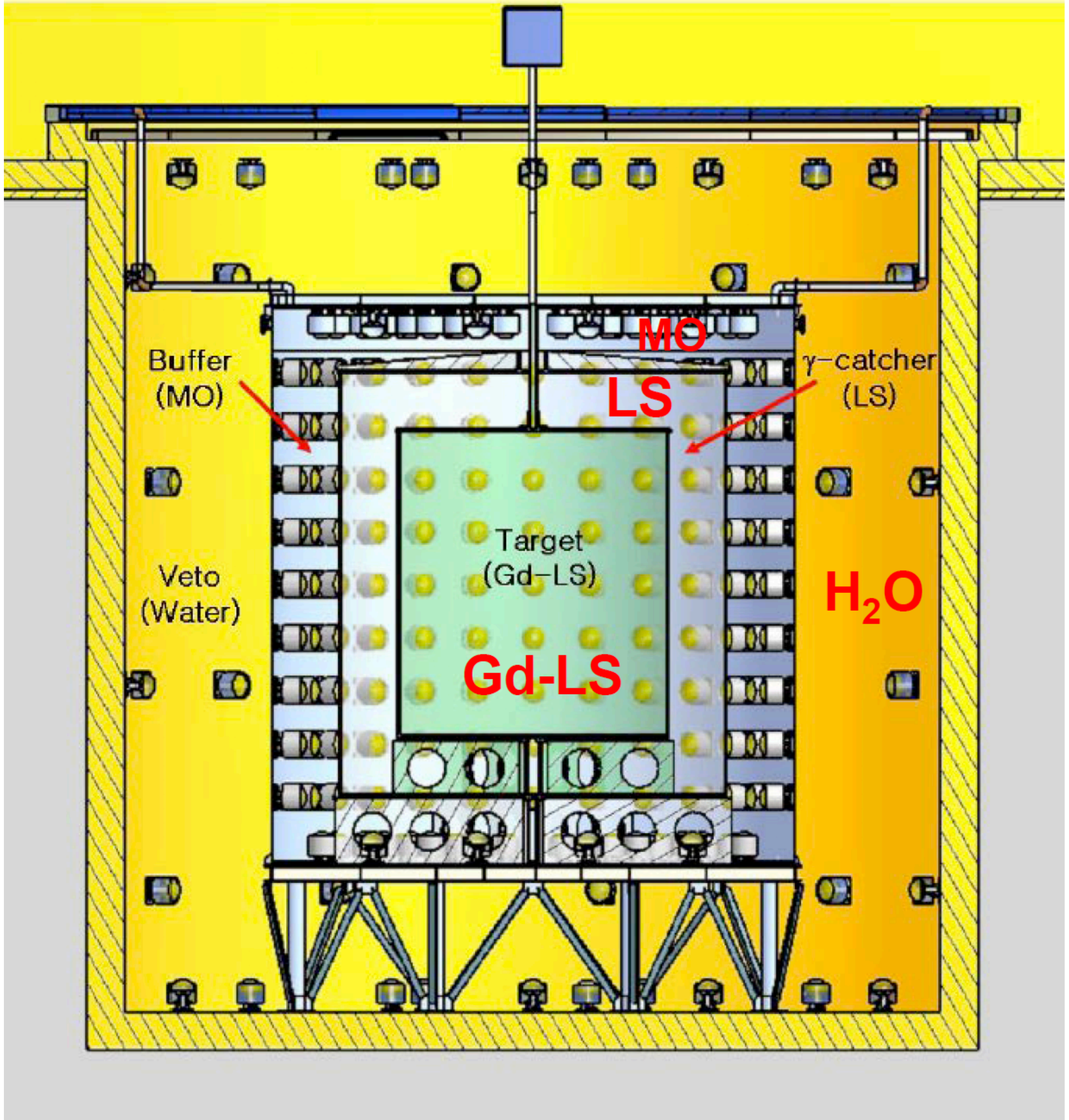
~ 4 hours driving distance from Seoul

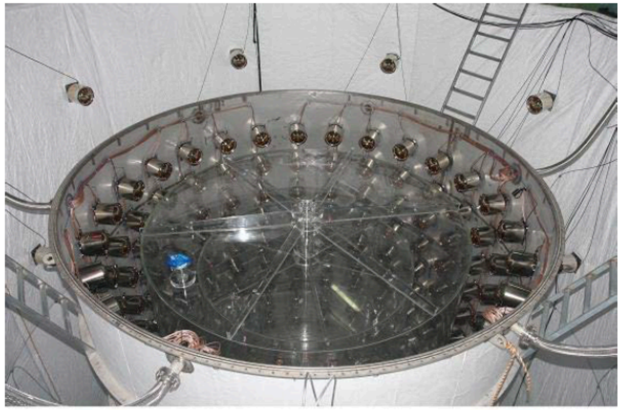


RENO Experimental Set-up



The RENO Detector





- **Target** : **16.5 ton Gd-LS**
  (R=1.4m, H=3.2m)
- **Gamma Catcher** : 30 ton **LS**
  (R=2.0m, H=4.4m)
- **Buffer** : 65 ton **mineral oil**
  (R=2.7m, H=5.8m)
- **Veto** : 350 ton **water**
  (R=4.2m, H=8.8m)

-- 354 ID 10 " PMTs

-- 67 OD 10" PMTs

New Results from RENO

- Precise measurement of $|\Delta m_{ee}^2|$ and θ_{13} using ~2200 days of data (Aug. 2011 – Feb 2018)

"Measurement of Reactor Antineutrino Oscillation Amplitude and Frequency at RENO" (*Phys. Rev. Lett. 121, 201801* (2018. 11. 15))

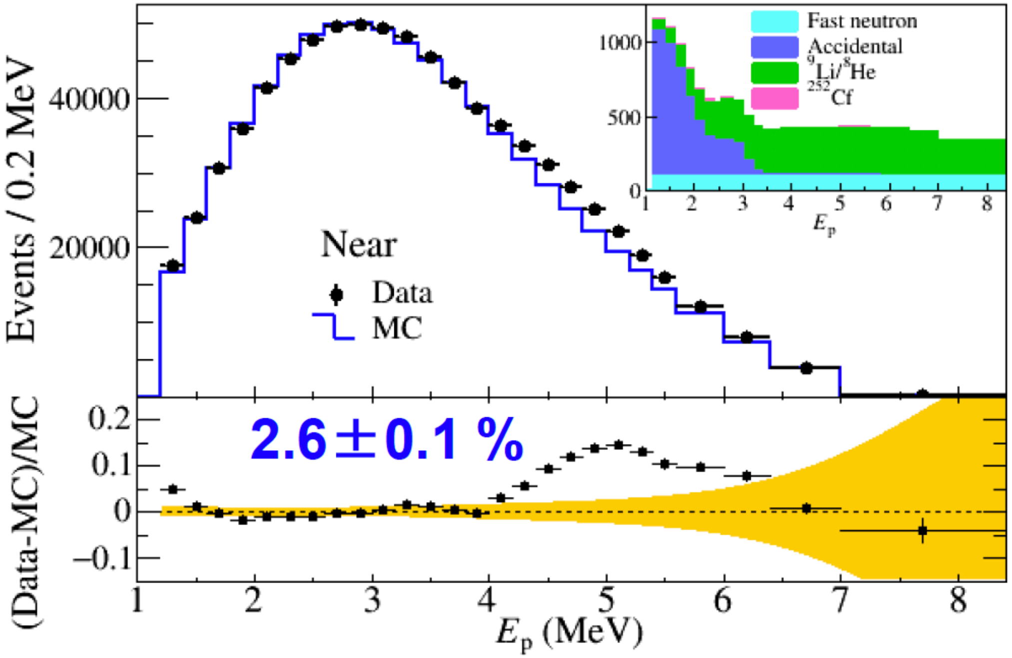
- Fuel-composition dependent reactor antineutrino yield and spectrum

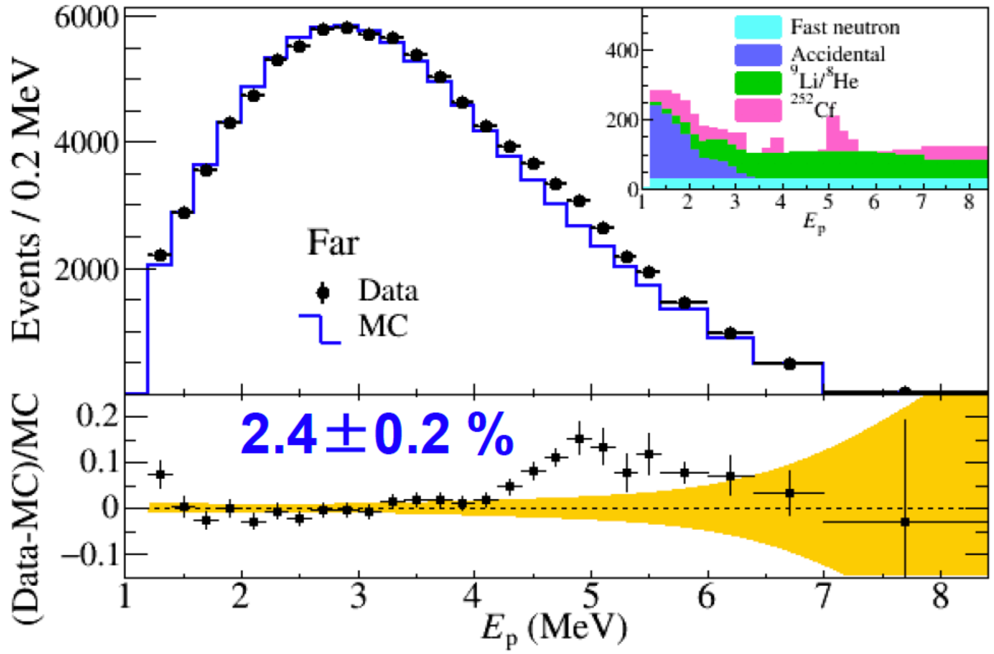
"Fuel-composition dependent reactor antineutrino yield and spectrum at RENO" (arXiv:1896.00574)

- Preliminary results on reactor antineutrino flux and spectrum

Measured Spectra of IBD Prompt Signal

Clear excess at 5 MeV



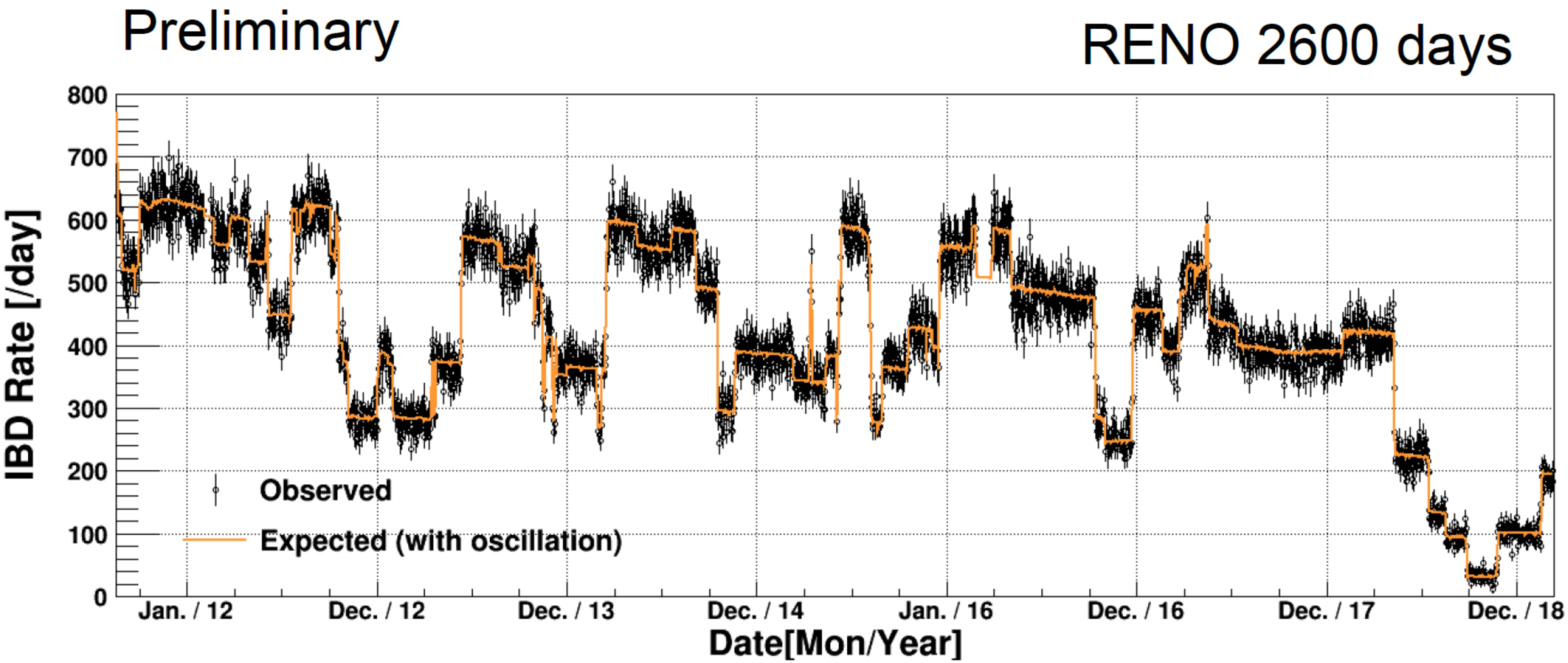


Near Live time = 1807.88 days
# of IBD candidate = 850,666
Background : 2.03±0.06%

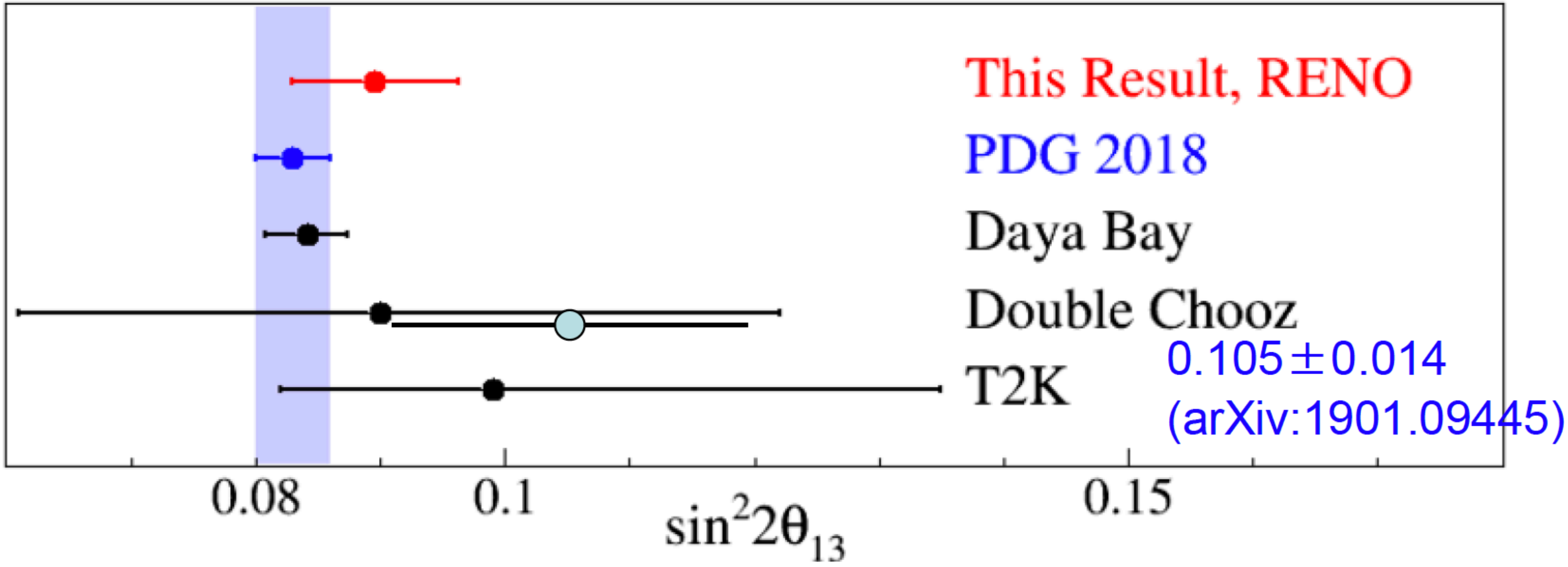
Far Live time = 2193.04 days
# of IBD candidate = 103,212
Background : 4.76±0.20%

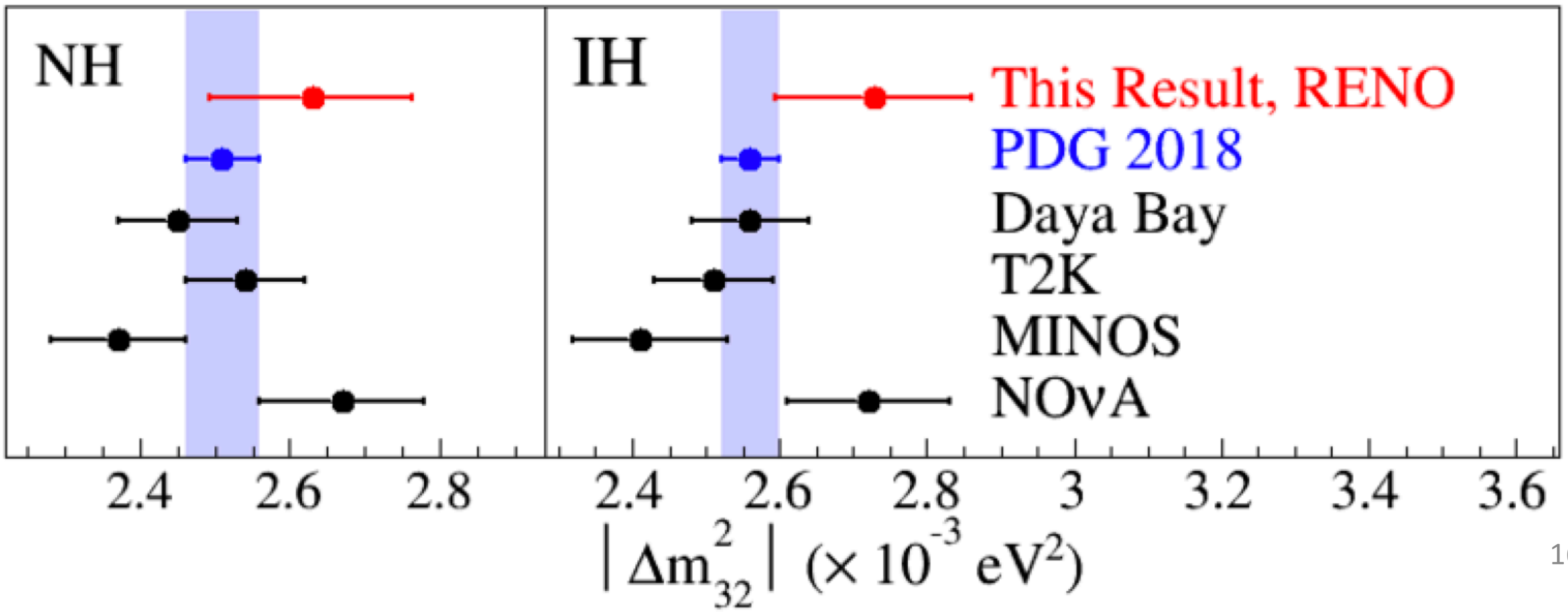
Daily Observed IBD Rate at Near Detector

4~6% accurate monitoring of daily reactor-antineutrino yield
→ Remote monitoring of reactor thermal power



Comparison of θ_{13} and $|\Delta m^2_{ee}|$ Results





Measured Reactor Antineutrino Flux

- Observed IBD yield relative to the H-M prediction using both near and far detectors (R):

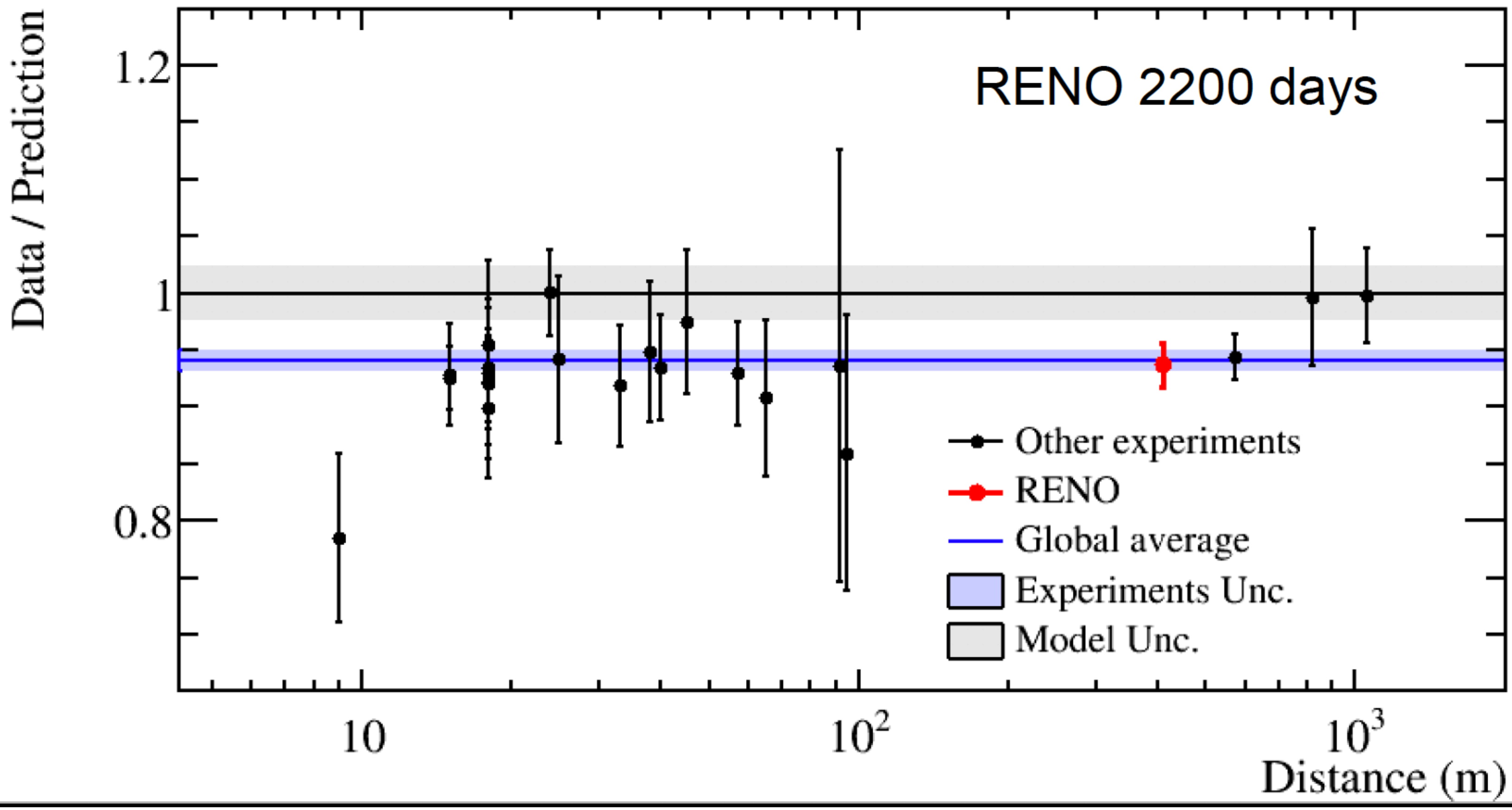
R = (93.7 ± 2.0)% of HM ← [93.7 ± 0.1(stat.) ± 2.0(syst,)]%

(98.2 ± 2.0)% of ILL+Vogel

RENO : $\overline{y}_f$ = (5.84 +- 0.13) x 10^{-43} cm^2/fission

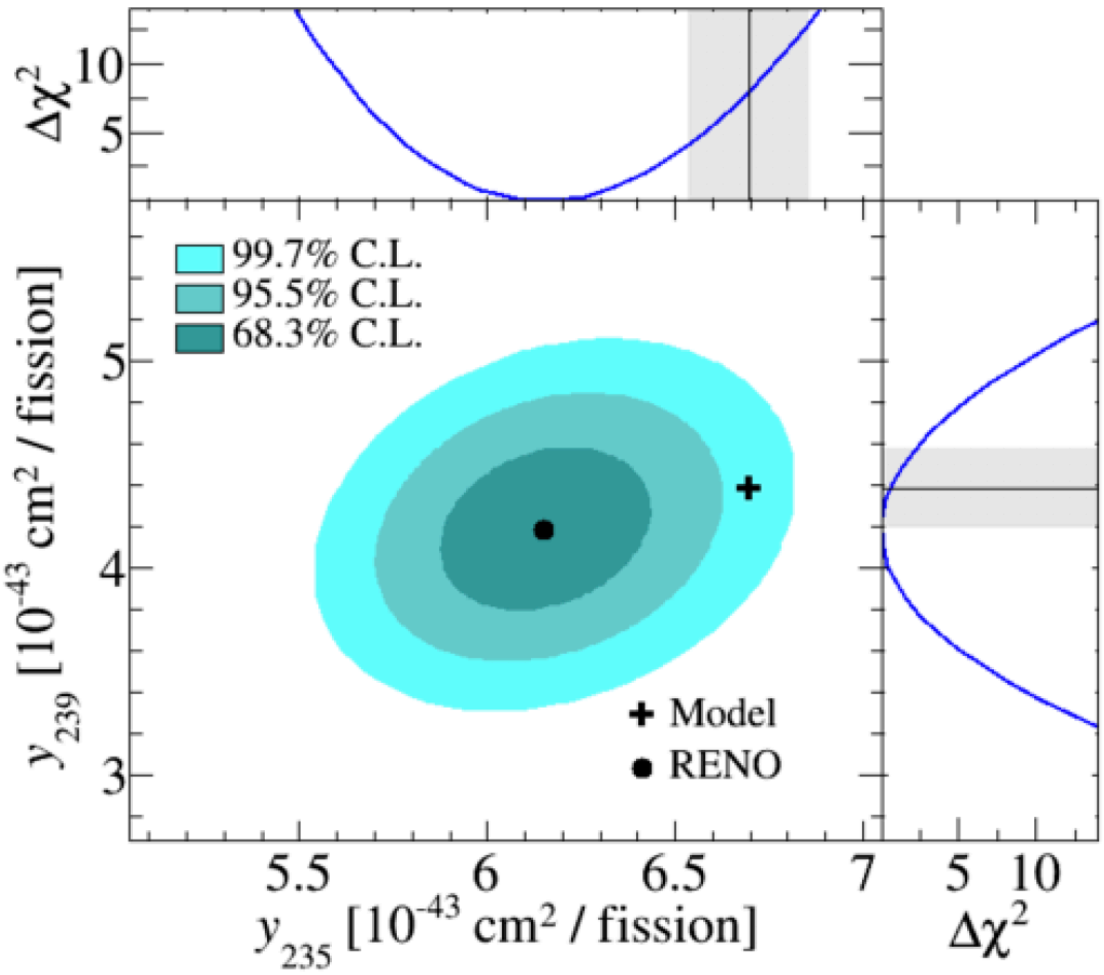
H-M model : $\overline{y}_f$ = (6.22 +- 0.15) x 10^{-43} cm^2/fission

Preliminary



Measurement of y_{235} and y_{239}

The best-fit measured yields per fission of ^{235}U and ^{239}Pu



The best-fit value of y_{235} :

2.8 σ deficit

6.15 ± 0.19/6.70 ± 0.14

The best-fit value of y_{239} :

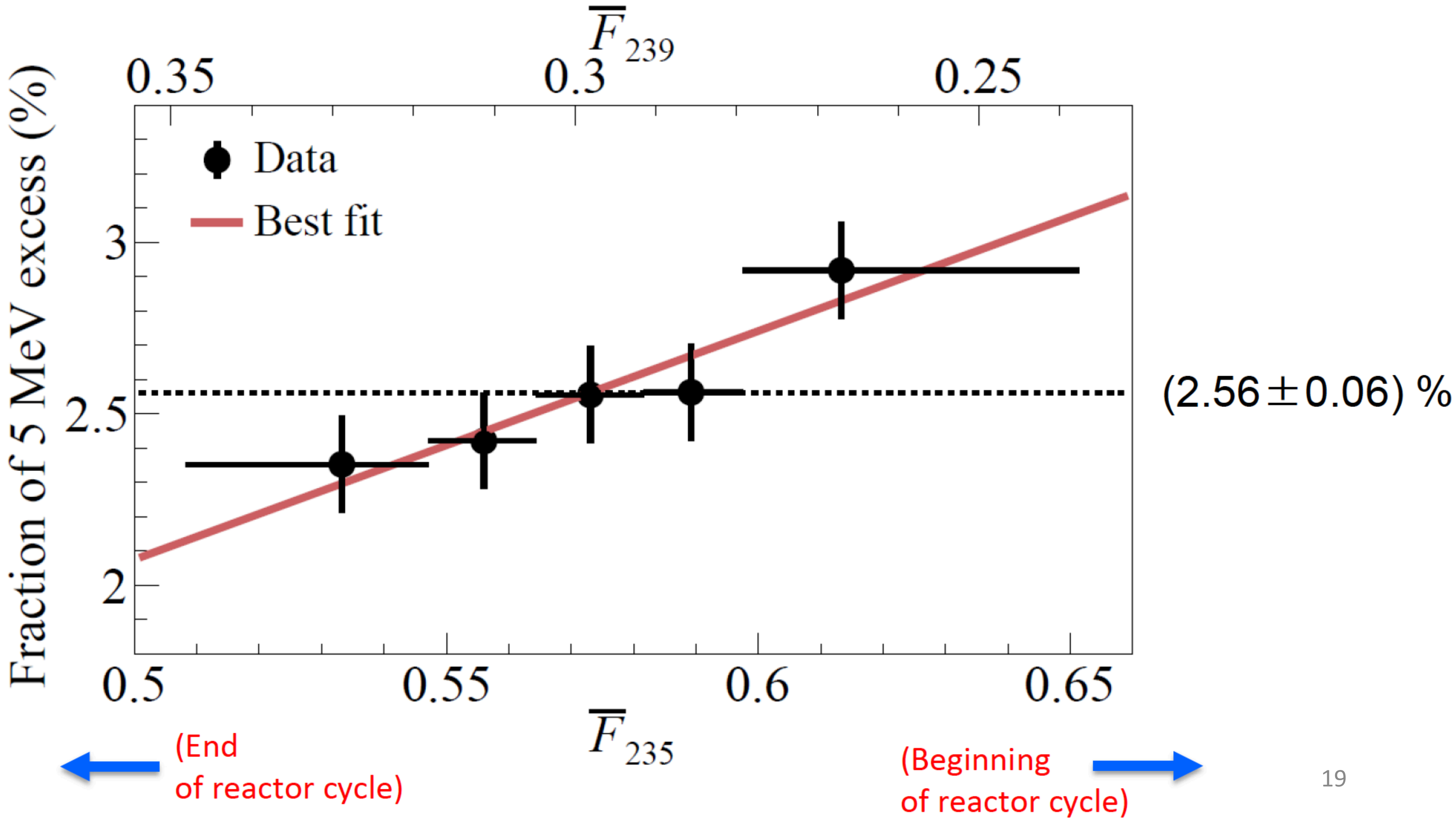
0.8 σ deficit

4.18 ± 0.26/4.38 ± 0.11

Reevaluation of the y_{235} may **mostly solve** the reactor antineutrino **anomaly.**
But ^{239}Pu is **not entirely** ruled out as a possible source of the anomaly.

Correlation of 5 MeV excess with fuel ^{235}U

2.9σ indication of 5 MeV excess coming from ^{235}U fuel isotope fission !!



Summary

- Precise measurement of reactor antineutrino flux and spectrum:
  → Confirmation of RAA with R = (93.7 ± 2.0)% of HM

- Observation of energy dependent disappearance of reactor neutrinos and improved measurement of and $|\Delta m_{ee}^2|$ and θ_{13}

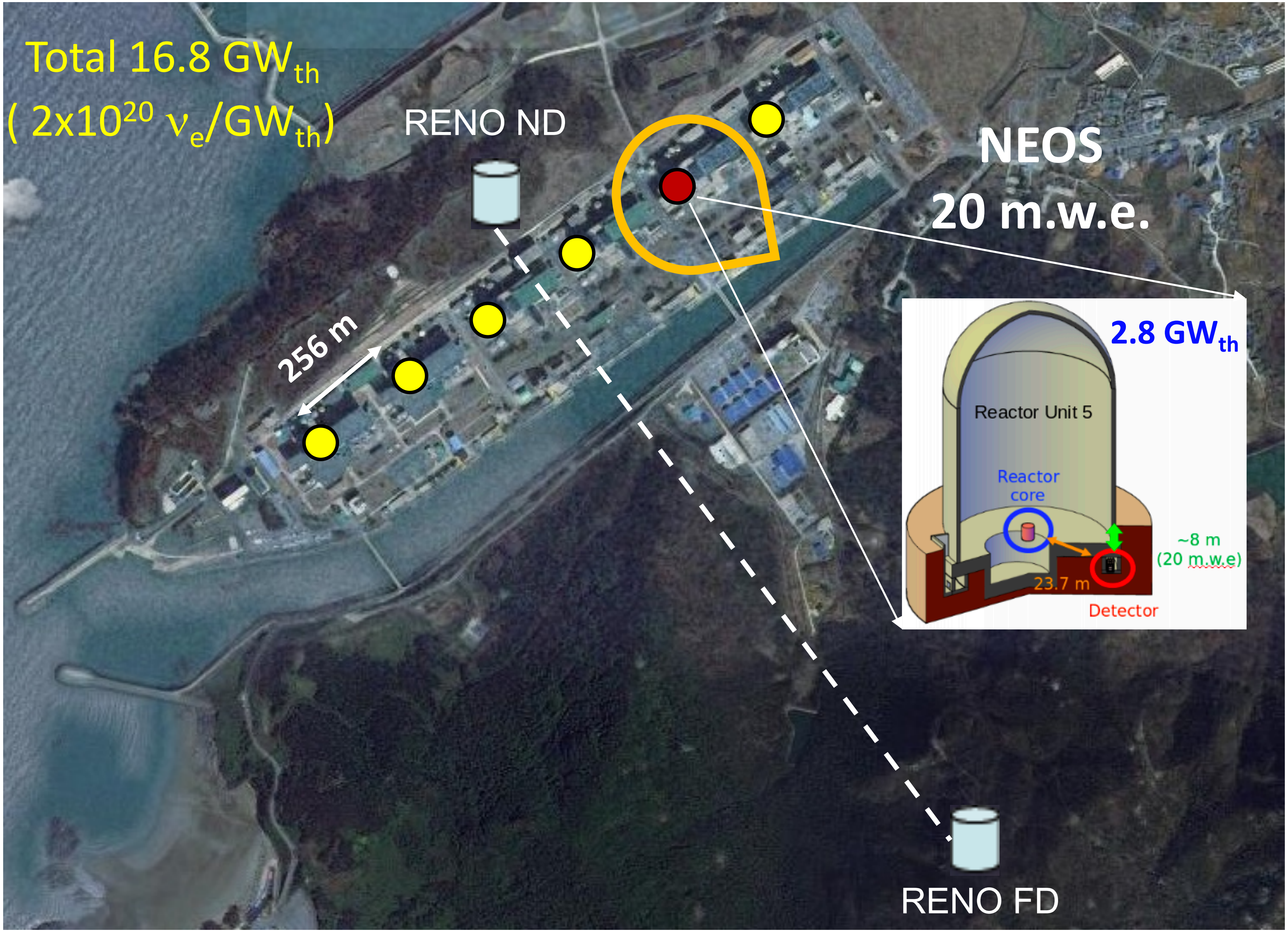
$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\text{stat}) \pm 0.0048(\text{syst})$ ±0.0068 7.6 % precision

$|\Delta m_{ee}^2| = 2.68 \pm 0.12(\text{stat}) \pm 0.07(\text{syst})\ (\times 10^{-3}\,\text{eV}^2)$ ±0.14 5.2 % precision

- Observation of fuel-composition dependent variation of IBD yield at 6.6σ CL

- First hint for 2.9σ correlation between 5 MeV excess and ^{235}U fission fraction

RENO & NEOS Site



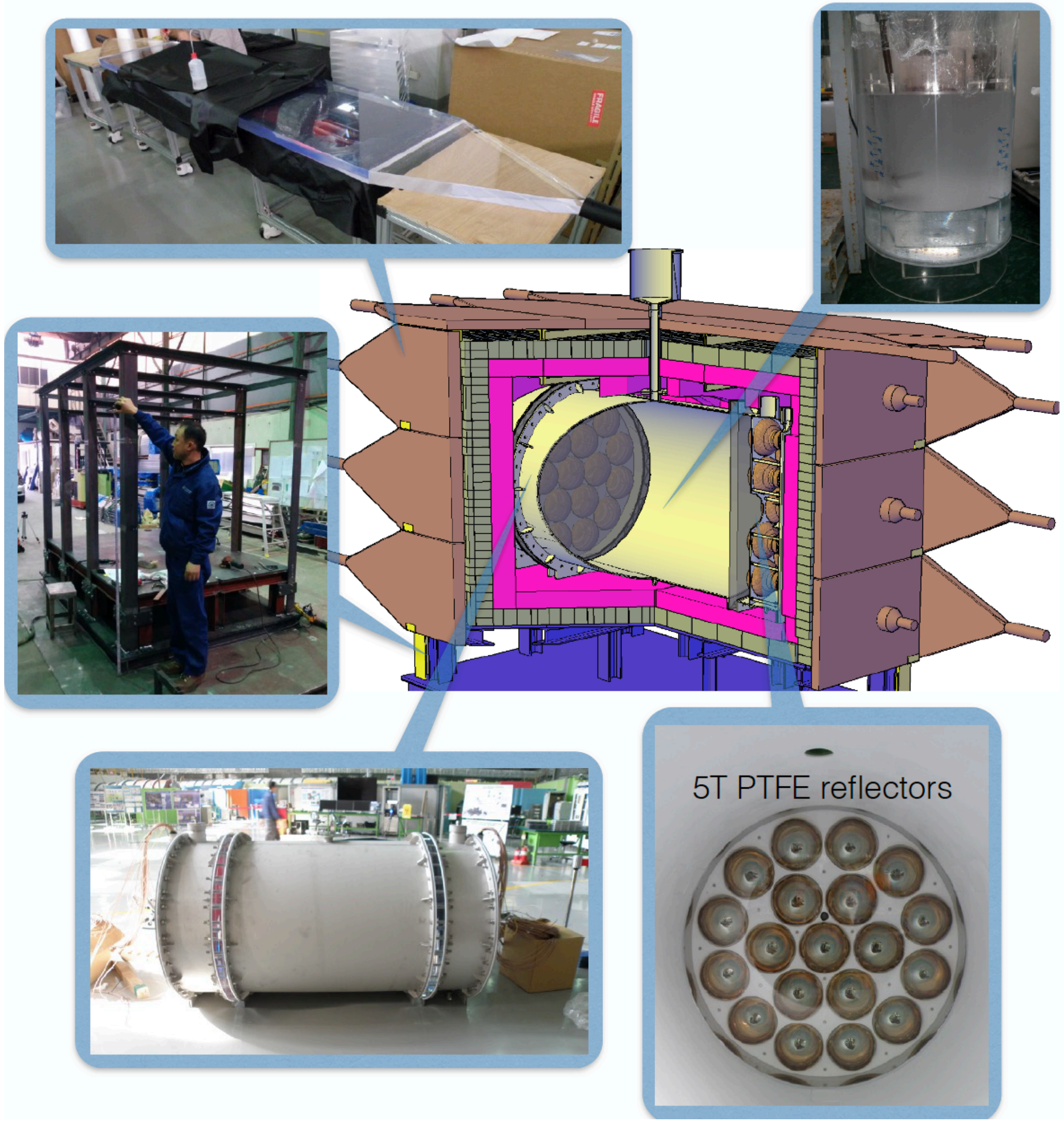
NEOS Collaboration

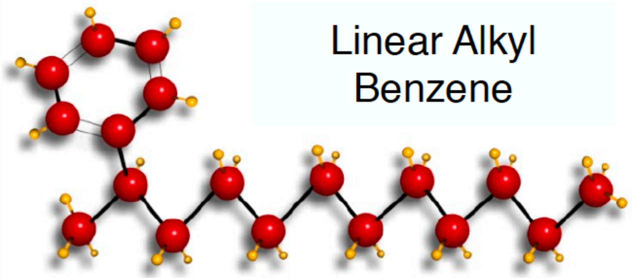
Currently, total **19** members from **7** institutions

- ❑ Chung-Ang University (CAU)
- ❑ Institute for Basic Science (IBS)
- ❑ Korea Atomic Energy Research Institute (KAERI)
- ❑ Kyungpook National University (KNU)
- ❑ Korea University (KU)
- ❑ Sejong University (SJU)
- ❑ Sungkyunkwan University (SKKU)

NEOS Detector

➢ NEOS-I and NEOS-II detectors are almost identical.





- Homogeneous LS target
  - 1008 L volume (R 51.5, L 121) cm
  - LAB+UG-F (9:1)
  - 0.5% Gd loaded for high neutron capture efficiency
  - 38 8″ PMT in mineral oil buffer

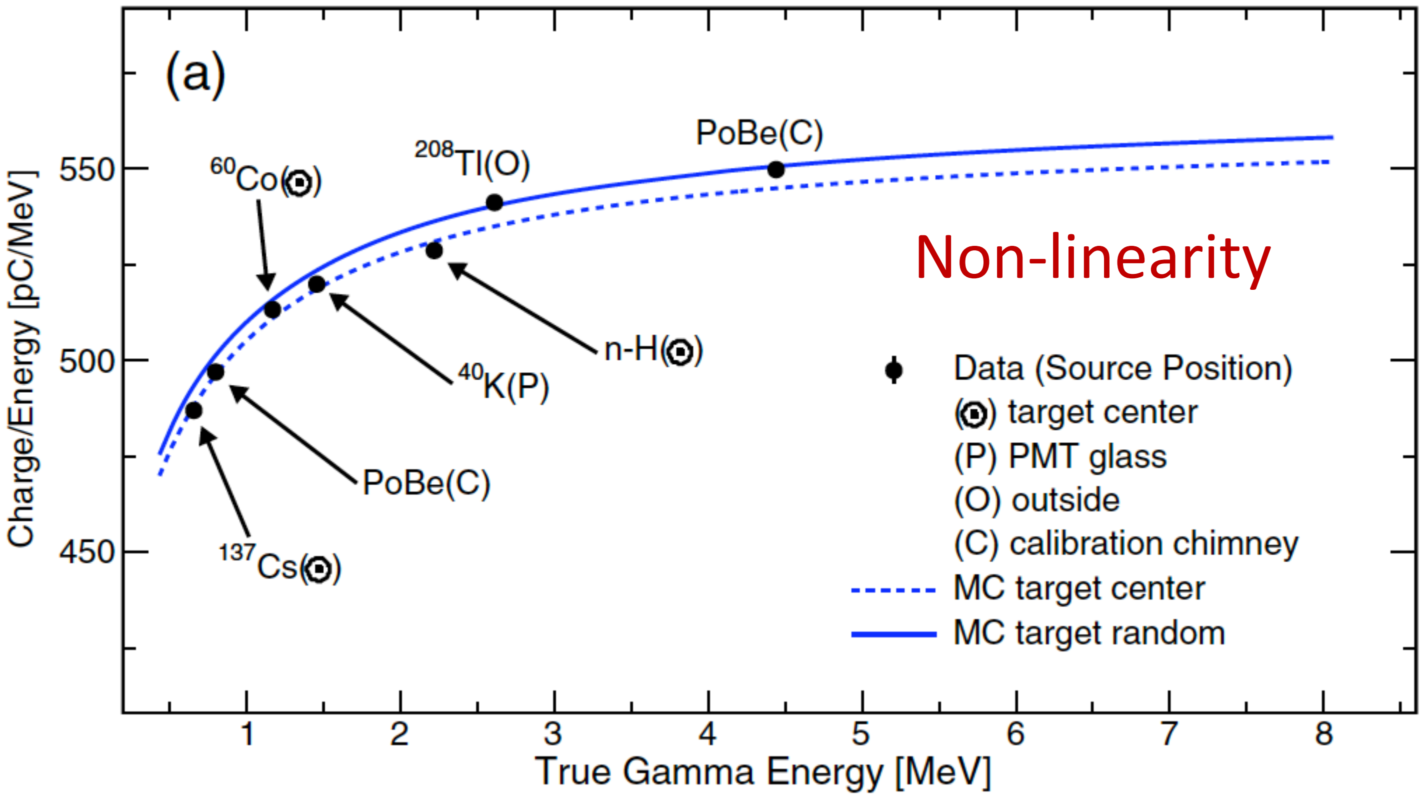
3% PPO
0.03% bis-MSB

- Shieldings
  - 10 cm B-PE (n), 10 cm Pb (γ)
  - active muon counter
- Data AcQuisition
  - 500 MS/s FADC (waveform)
  - 62.5 MS/s ADC (μ veto)
- Source calibration through chimney

Energy Conversion

NEOS-I

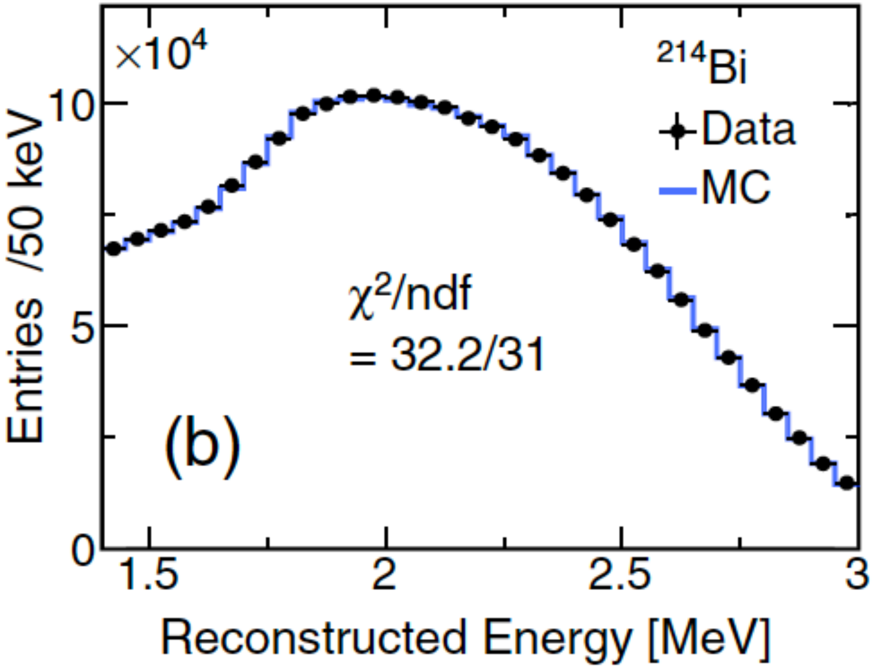
Weekly source data taking

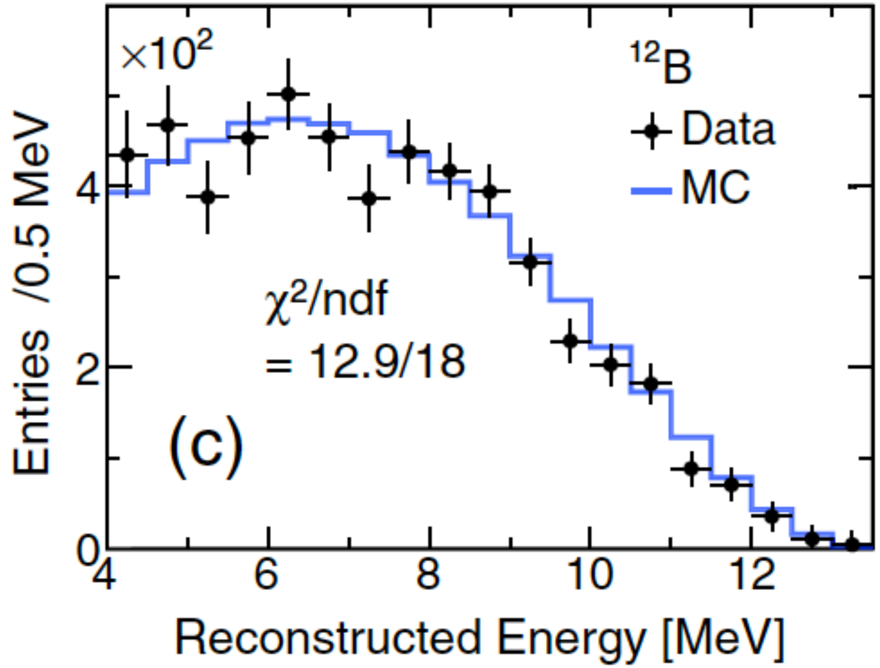


$$Q/E_\gamma = (p_0 + p_1 E_\gamma)[1 + p_2 \exp(p_3 \sqrt{E_\gamma})]$$

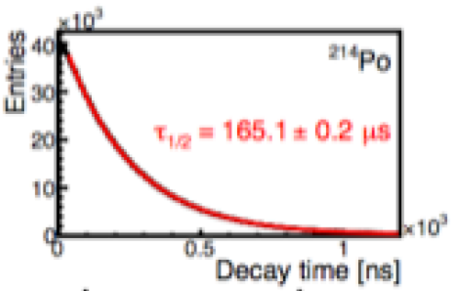
Empirical fitting function

Validation of Energy Conversion

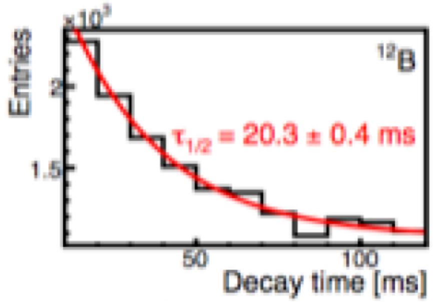




Bi214(β)-Po214(α)
time correlation



μ-12B
time correlation



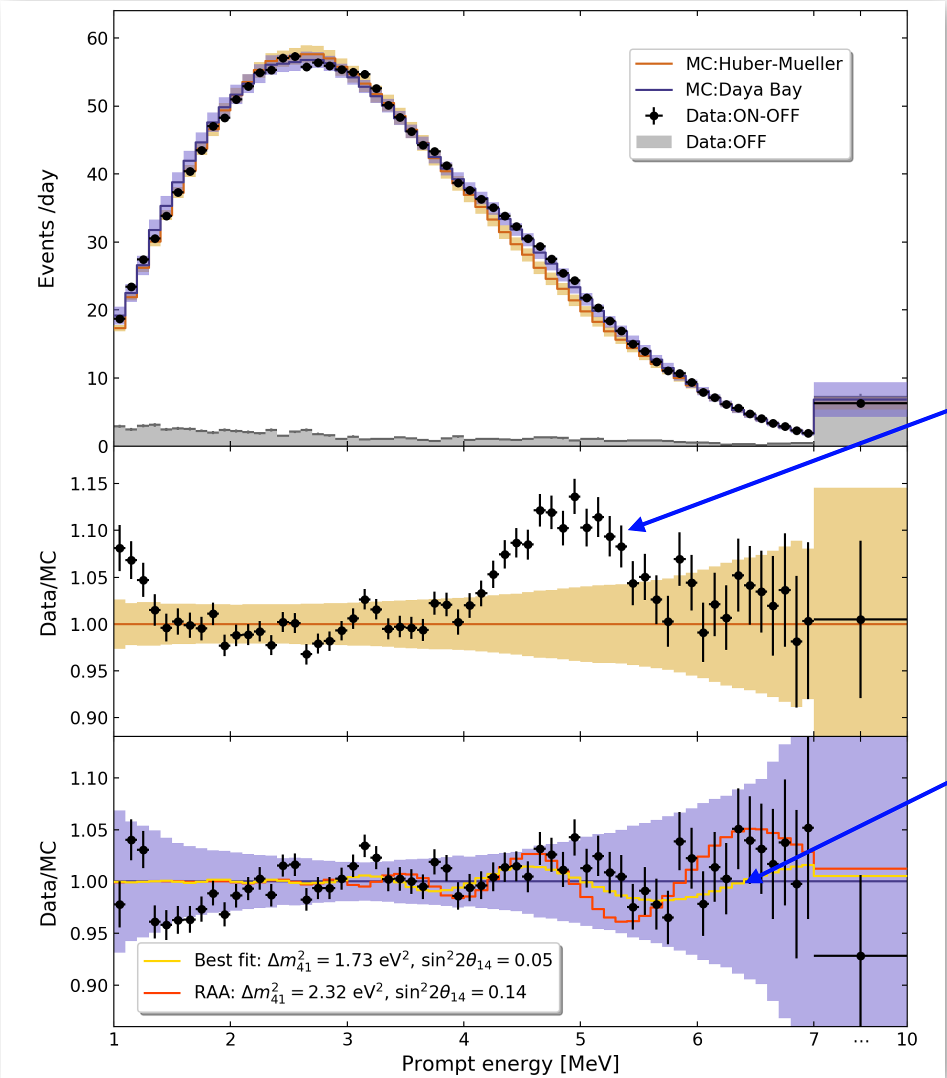
NEOS-I

Data and MC match very well in both low and high energy !

NEOS-I Results in 2017

NEOS 180 (46) days reactor-on(off)data

- 1977 (85) IBD/day during on (off) period; S/B ~ 22



PRL 118, 121802 (2017)

"5 MeV excess" observation

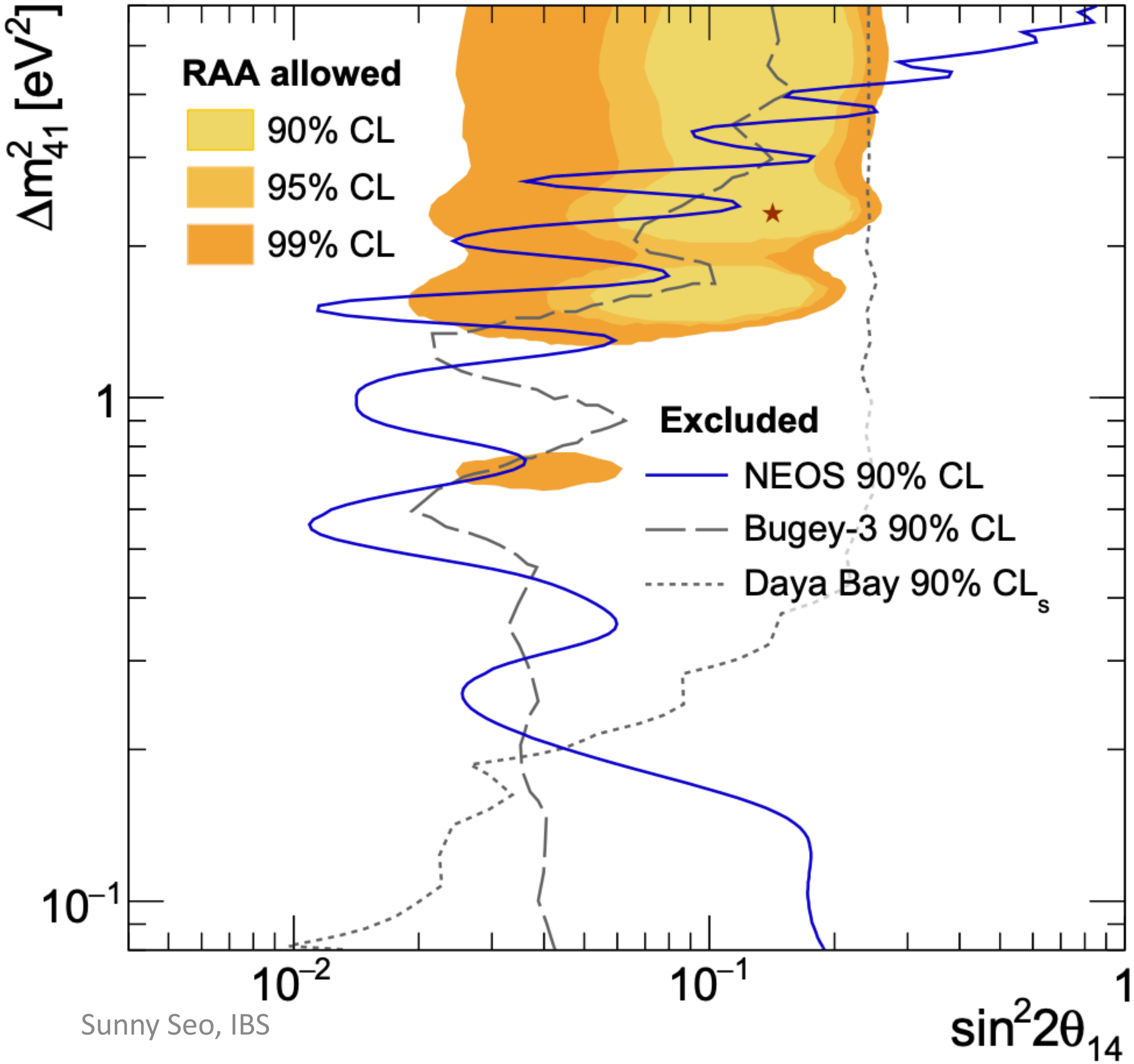
NEOS best fit values:

(1.73 eV^2, 0.05), (1.30 eV^2, 0.04)
with $\chi^2(3\nu) - \chi^2(4\nu) = 6.5$
p-value = 0.22

→ No strong evidence of active-to-sterile neutrino oscillation

NEOS-I Results in 2017

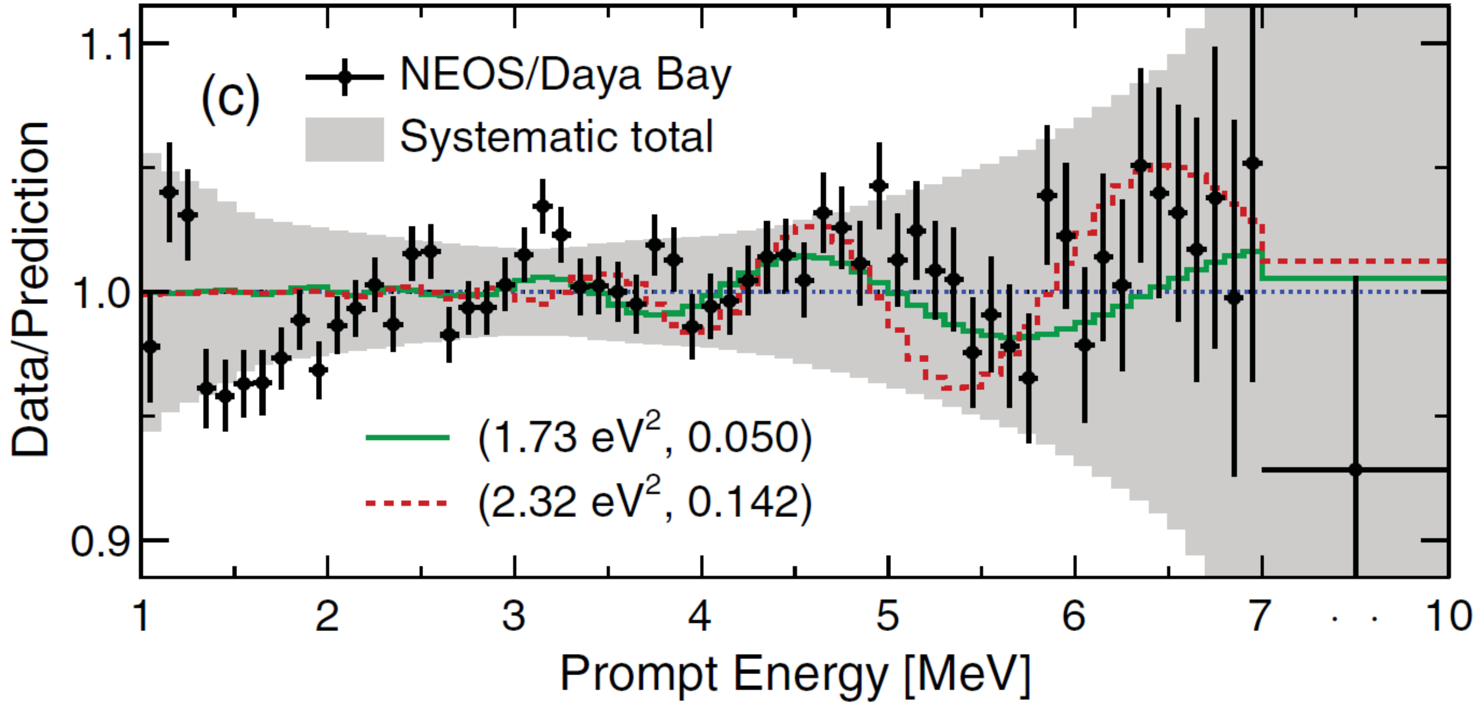
NEOS 180 (46) days reactor-on(off)data



PRL 118, 121802 (2017)

- RAA best fit is excluded at 4.3 σ.
- Limited by systematic uncertainty.

Sterile ν oscillation feature or not ???



- NEOS best fits: (1.73 eV^2, 0.05), (1.30 eV^2, 0.04) with $\chi^2(3\nu) - \chi^2(4\nu) = 6.5$, p-value = 0.22

- A. Sonzogni et al. @ AAP2018:

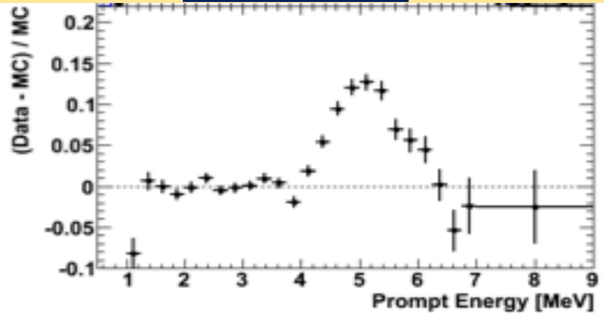
This feature is due to ^{99}Nb, ^{143}La, ^{92}Y, ^{99}Zr.

If Sonzogni et al are correct, we should observe the same feature in NEOS-II & PROSPECT data.

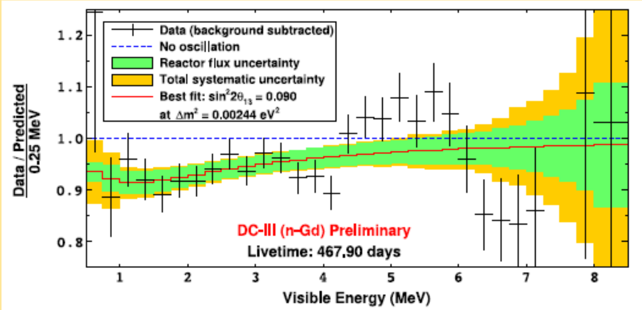
Reactor ν “Shape” Anomaly

The “5 MeV Excess” in 2014

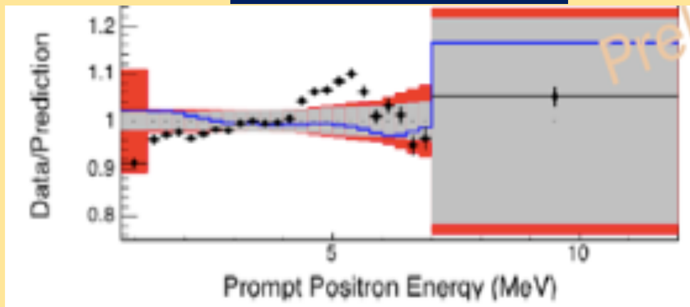
RENO



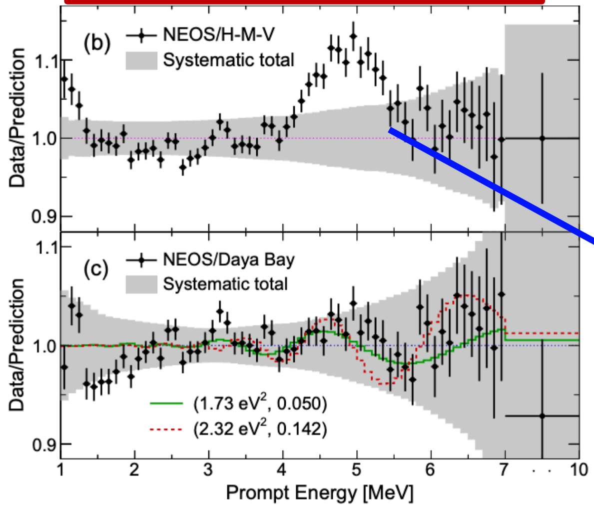
Double Chooz

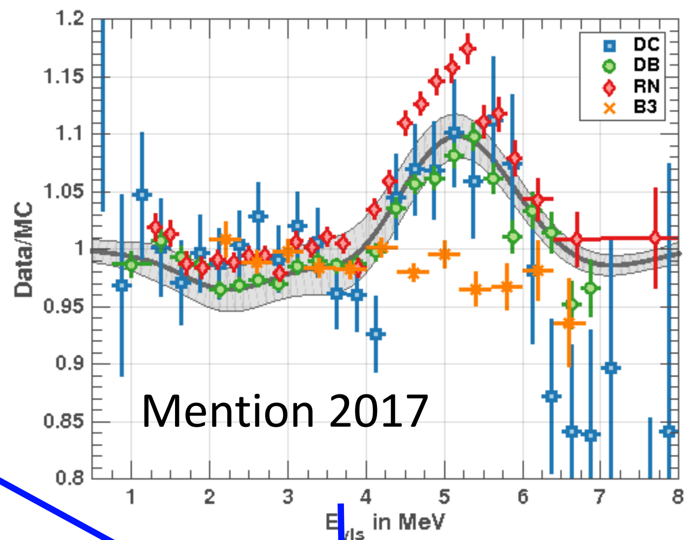


Daya Bay



NEOS in 2017





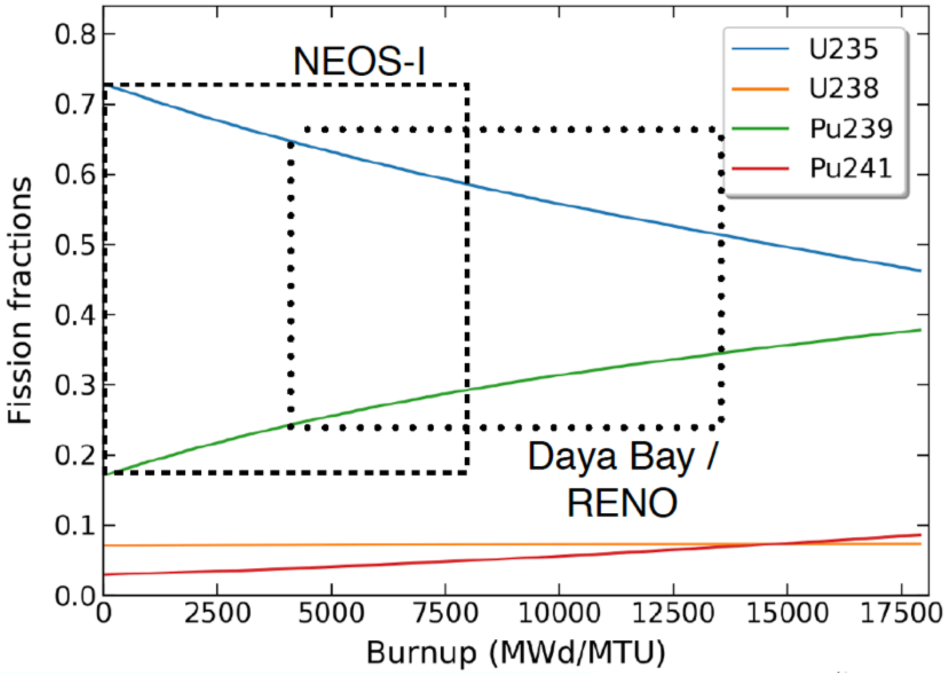
5 MeV excess compared to H&M model

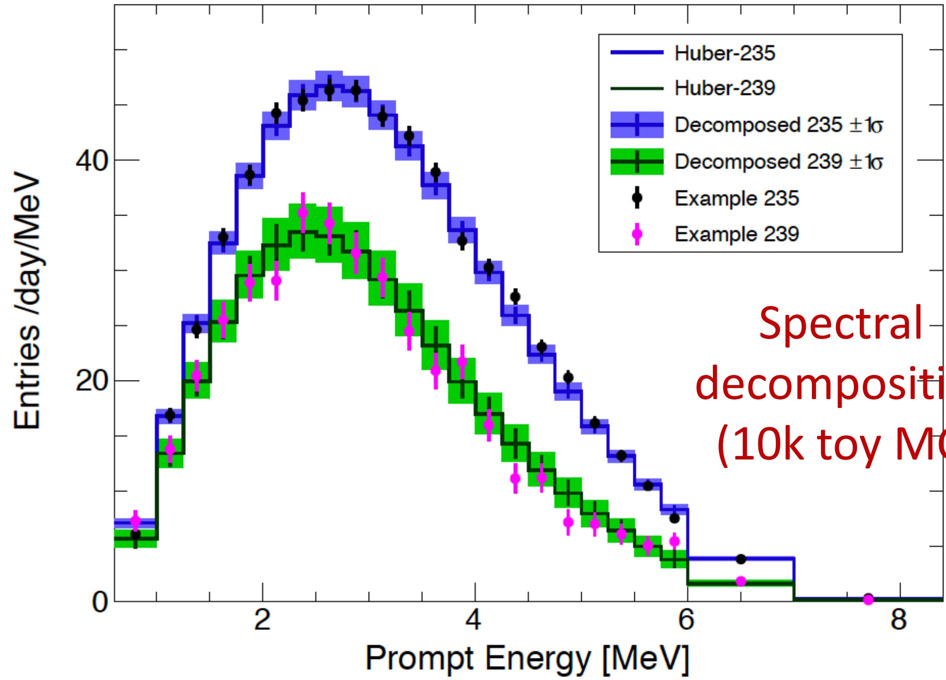
NEOS is the only VSBL (<100m) exp. which observed the 5 MeV excess.

No relation w/ sterile neutrinos

NEOS-II (Sept. 2018 --)

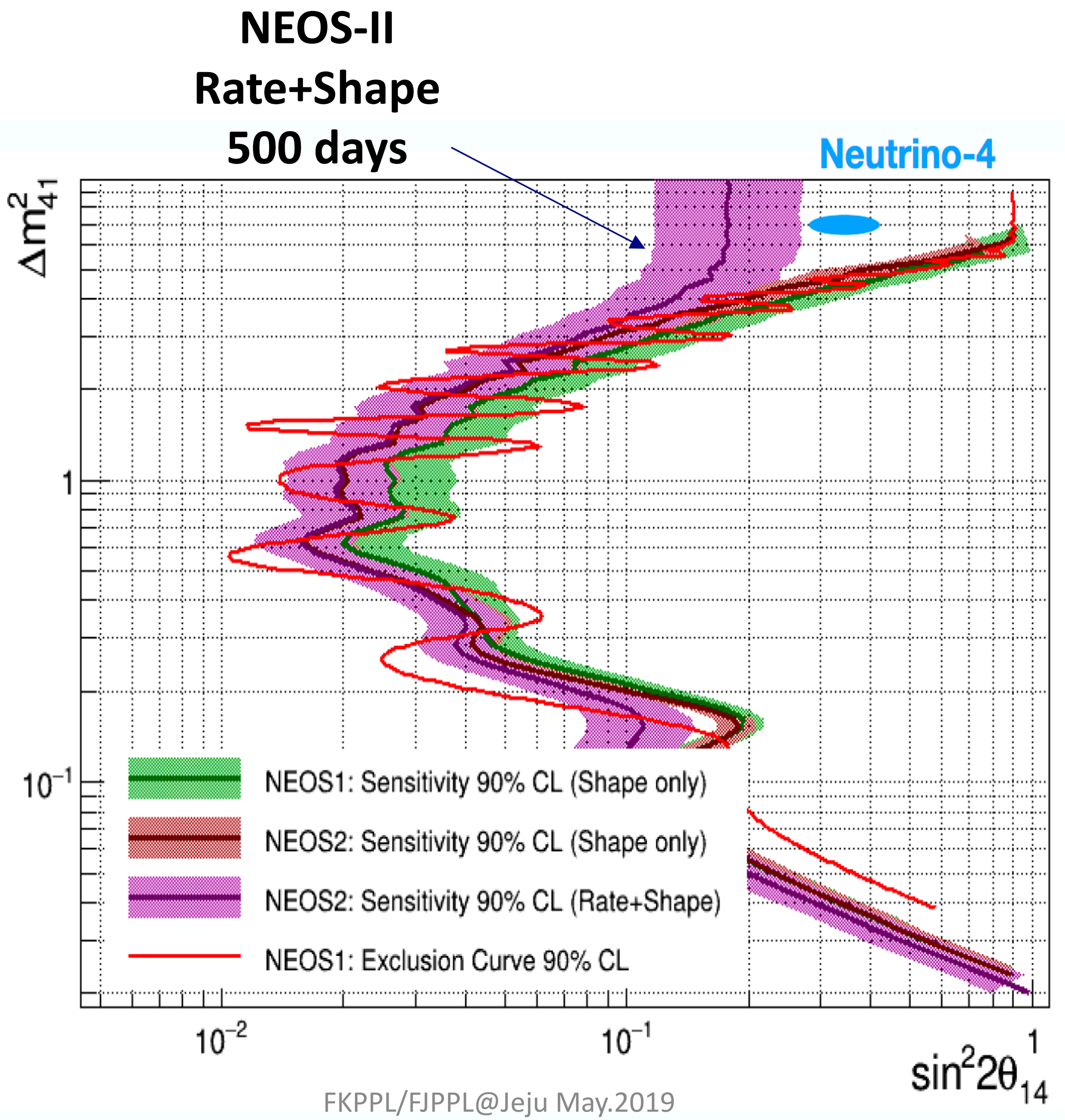
- Refurbished detector from NEOS-I.
- Plan to take ~500 days of data (full fuel cycle) + 2 OFF periods
- Time evolution of reactor ν flux/shape; spectral decomposition
- Rate+Shape analysis
- Smooth data taking is on-going.



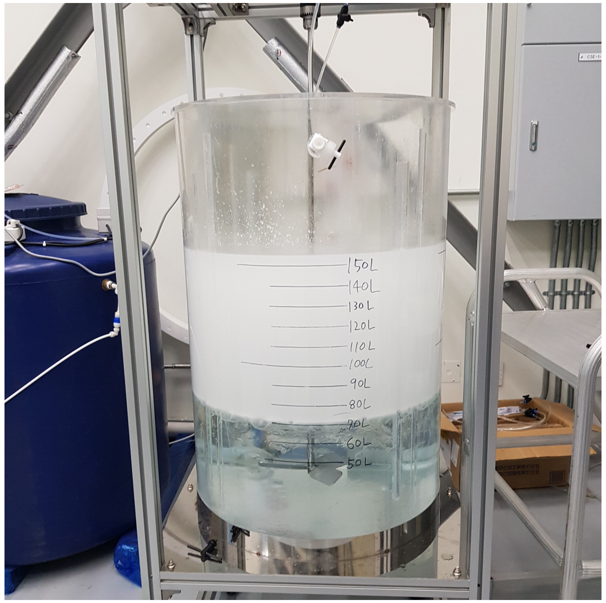


Spectral decomposition (10k toy MC)

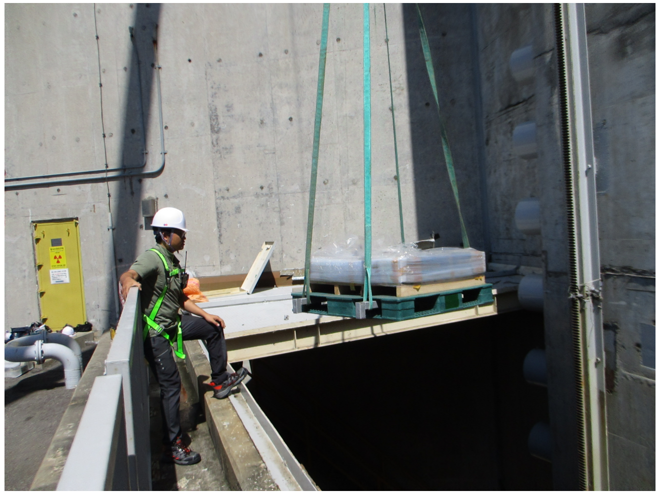
NEOS-II Sensitivity



NEOS-II Preparation (July~Sept. 2018)



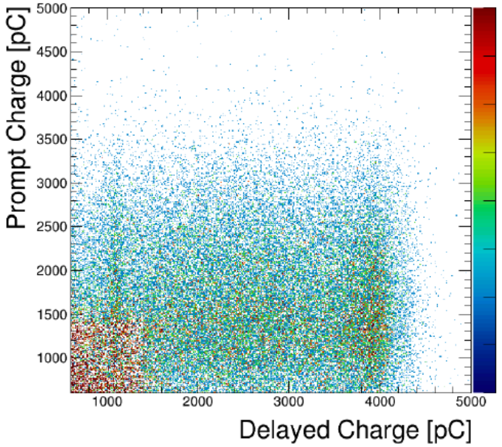
Sunny Seo, IBS

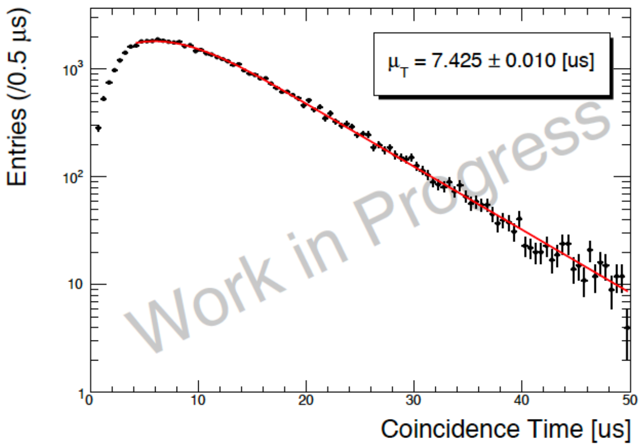


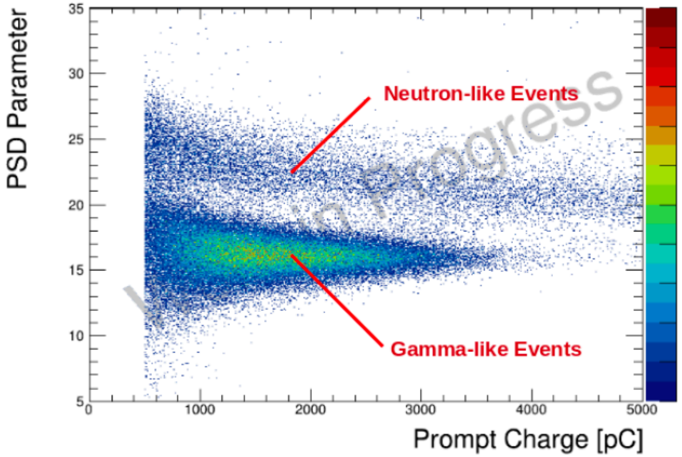

2018. Sept.

NEOS-II Initial Data

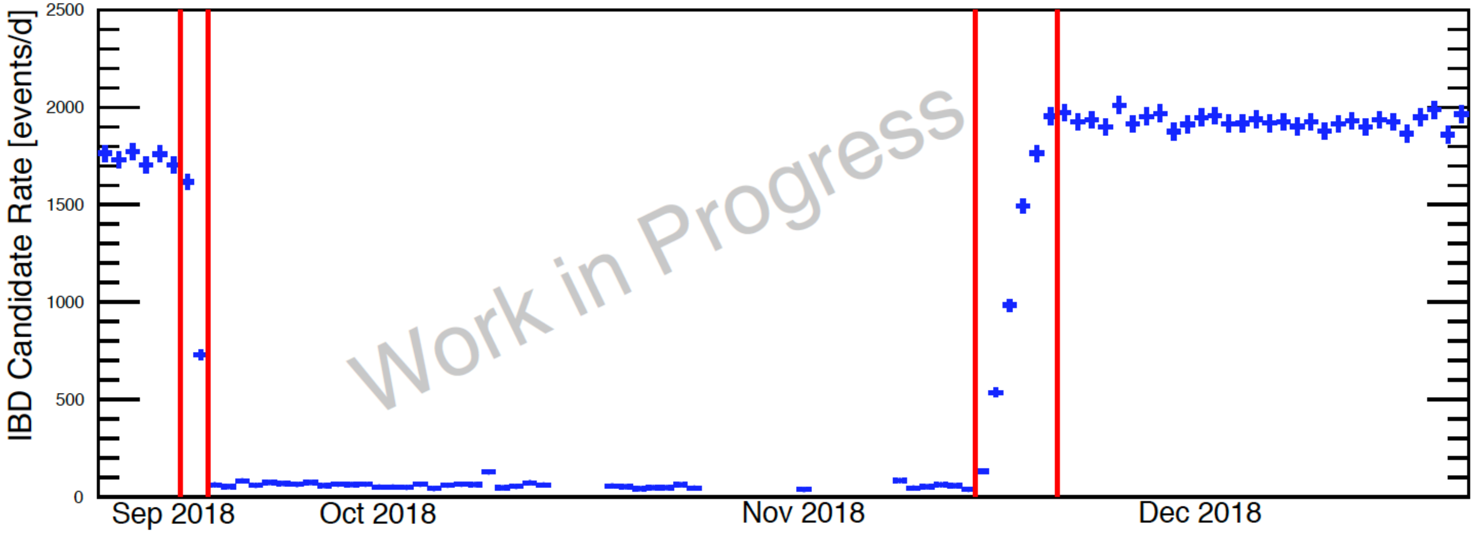
- Charge Distributions
- Coincidence Time
- Pulse Shape Discrimination





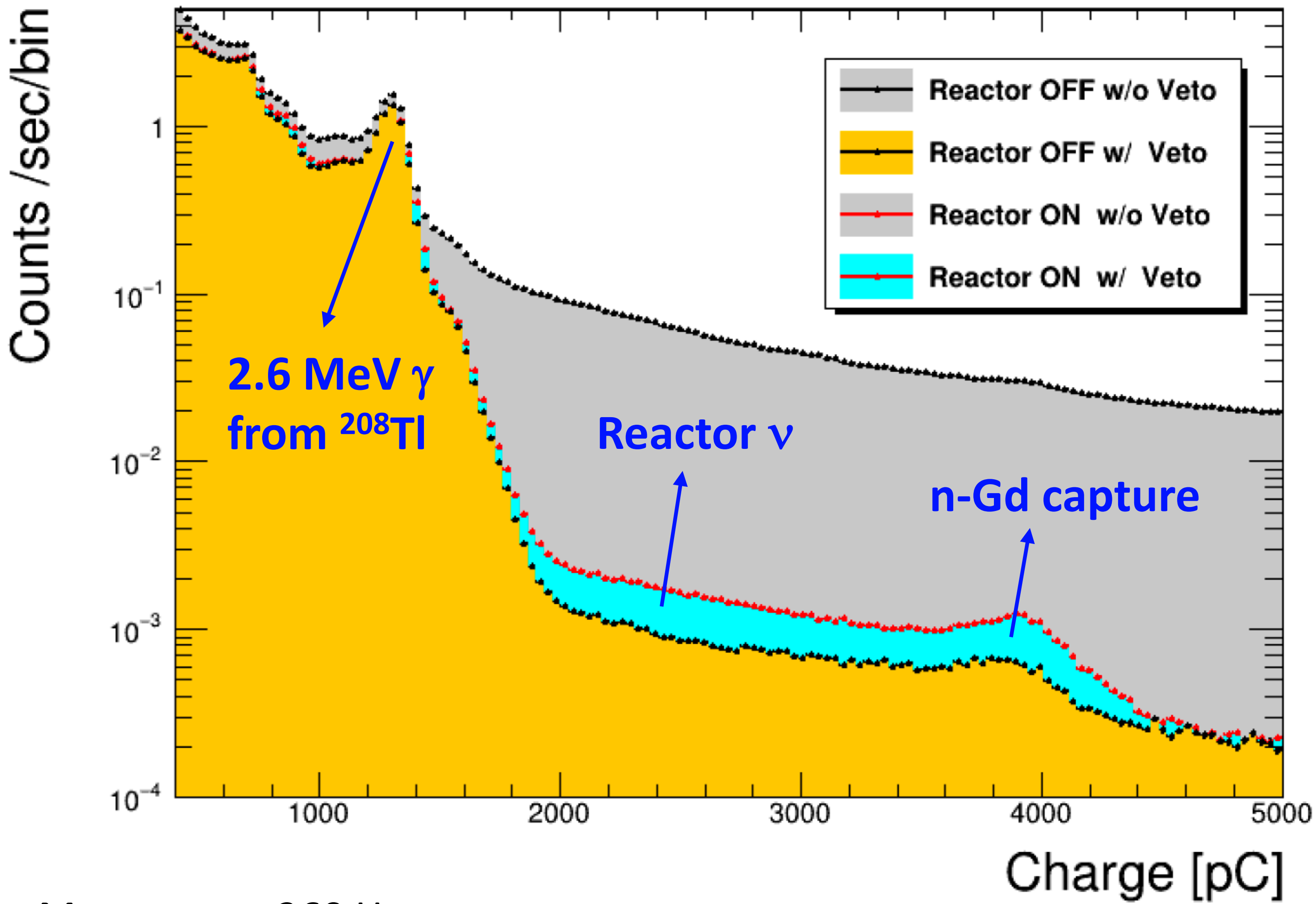


- IBD Candidate Rate (Period : Sep 2018 ~ Dec 2018)



NEOS-II Initial Data

Single Events: Charge Distribution



- Muon rate: ~260 Hz
- About 71% single events survive after muon veto cuts

NEOS Summary

❑ NEOS-I successfully measured prompt E spectrum from reactor ν using 180 (46) reactor-on (off) data.

- Reactor: Hanbit-5th (Korea) 2.8 GW_{th} LEU Reactor
- Detector: GdLS **~0.5% Gd**
- 1 m^3 (homogeneous); L = ~24 m; 20 m.w.e.; ~2000 IBDs/day
- E resolution: ~ 5%@1MeV; Good PSD → S/B ~ 22

❑ NEOS-I is the only VSBL reactor experiment which (significantly) observed the 5 MeV excess.

PRL 118, 121802 (2017)

❑ NEOS-I observed no strong evidence of sterile ν.

RAA is excluded at 4.2 σ.

❑ NEOS-II data taking goes smoothly since Sept. 2018.

Full fuel cycle; Time evolution of reactor ν flux/shape; Spectral decomposition

So far, we have worked together between Double Chooz & RENO but we could extend it to between STEREO & NEOS.

Thank you very much!