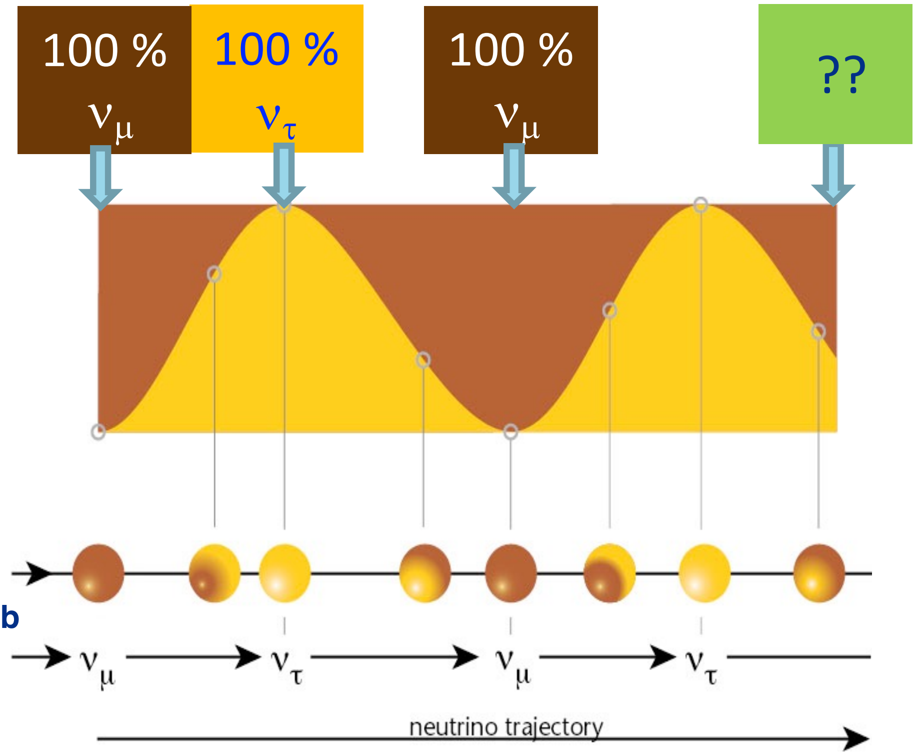
Neutrino Anomalies and NEOS-II

Sunny Seo
Wine and Cheese Seminar, FNAL
3 November 2023

Neutrino Oscillation



Fermilab

What causes ν oscillation?

(1) ν flavor eigenstate
$\neq$ ν mass eigenstate

(2) ν masses are not degenerate.

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

PMNS matrix in 1962

$$\boxed{|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle}$$

α = e, μ, τ
i = 1, 2, 3

Weak Eigen state

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \boxed{\begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

Mass Eigen state

PMNS matrix

in 1962

- **P**ontecorvo (1957)
- **M**aki
- **N**akagawa
- **S**akata

$$U = \underbrace{\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}}_{\text{Atmospheric}}\underbrace{\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}}_{\text{“CP” sector}}\underbrace{\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}}_{\text{Solar}}\underbrace{\begin{bmatrix}e^{-i\alpha_1/2} & 0 & 0\\ 0 & e^{-i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}}_{\text{Majorana}}$$

$c_{ij} \equiv \cos\theta_{ij}$

$s_{ij} \equiv \sin\theta_{ij}$

$\theta_{23} \approx 45°$

$\theta_{13} = 9°$

$\theta_{12} \approx 34°$

$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.4 \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{21} \approx 7.6 \times 10^{-5}\ \mathrm{eV}^2$

Super-K in 1998

Daya Bay, RENO in 2012

SNO in 2001

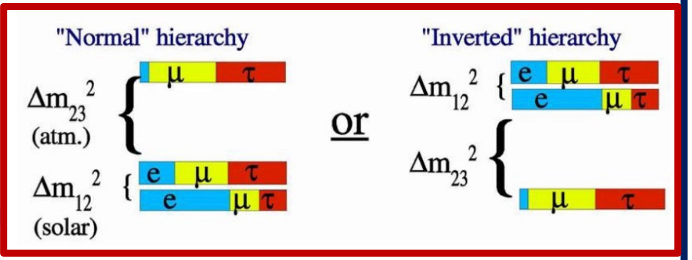
Atmos. ν osc.

Reactor ν osc.

Solar ν conversion

δ_{CP} ?

Mass Ordering (MO)



Current status of neutrino parameters: the era of very precise neutrino physics

$\sin^2\theta_{23}$ →

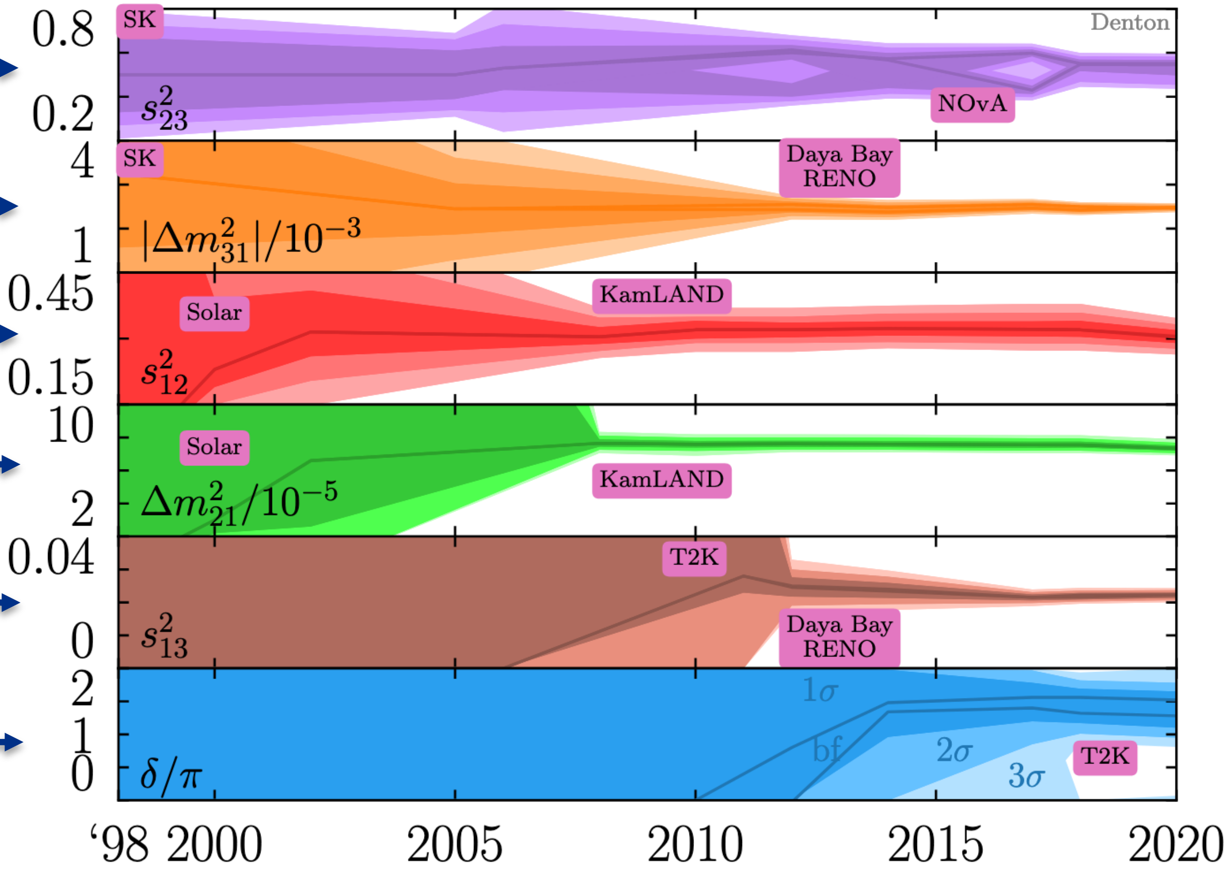
$\Delta m^2_{31}/10^{-3}$ →

$\sin^2\theta_{12}$ →

$\Delta m^2_{21}/10^{-5}$ →

$\sin^2\theta_{13}$ →

δ/π →



Neutrino 2022

See P. Denton's talk

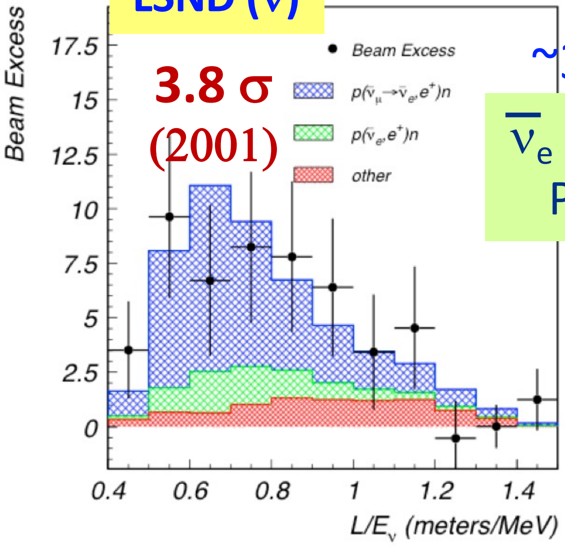
The past 20 years have seen a remarkable progress in determining neutrino properties!

Neutrinos Anomalies

LSND ($\bar{\nu}$)

3.8 σ

(2001)



~30m/30MeV

$\bar{\nu}_e$ appearance
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$

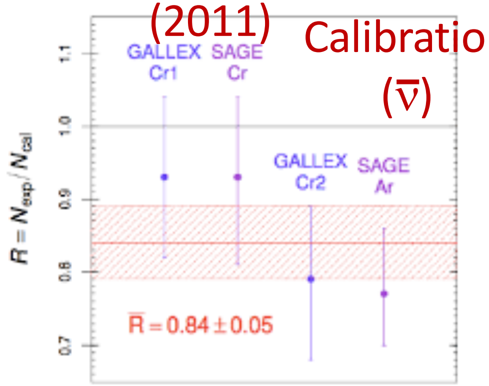
ν_e disappearance
$P(\nu_e \to \nu_e)$

GALLEX/SAGE

3σ

(2011)

Source Calibration ($\bar{\nu}$)



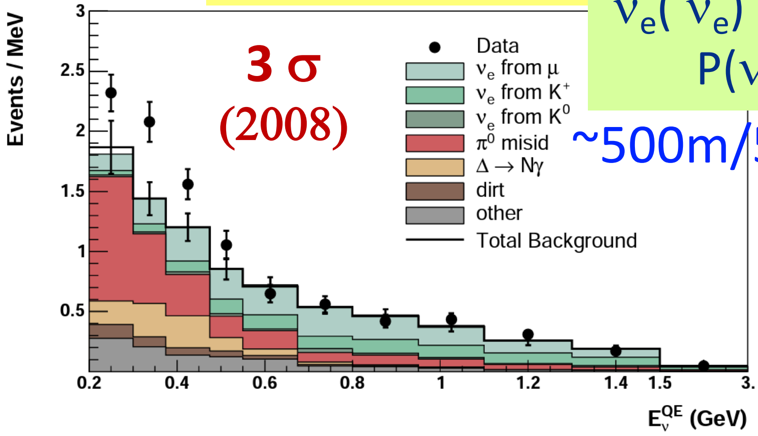
Phys. Rev. C83, 065504 (2011)

3σ~4σ anomalies

MiniBooNE ($\nu, \bar{\nu}$)

3 σ

(2008)



$\nu_e(\bar{\nu}_e)$ appearance
$P(\nu_\mu \to \nu_e)$

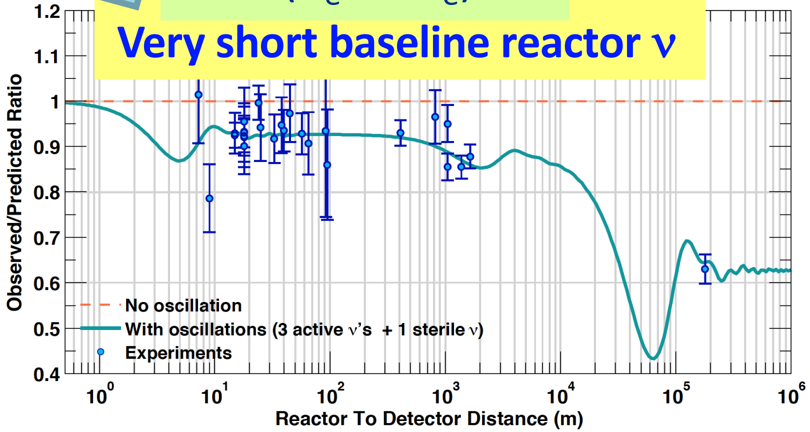
~500m/500MeV

$\bar{\nu}_e$ disappearance
$P(\bar{\nu}_e \to \bar{\nu}_e)$

3σ

(2011)

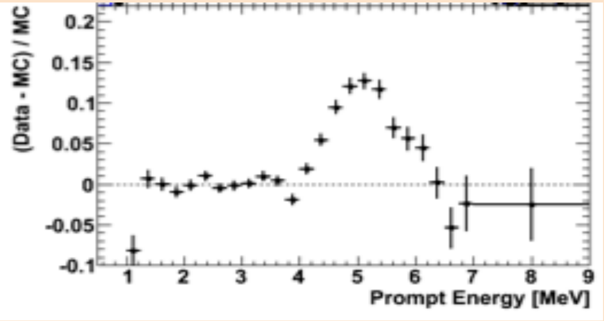
Very short baseline reactor ν



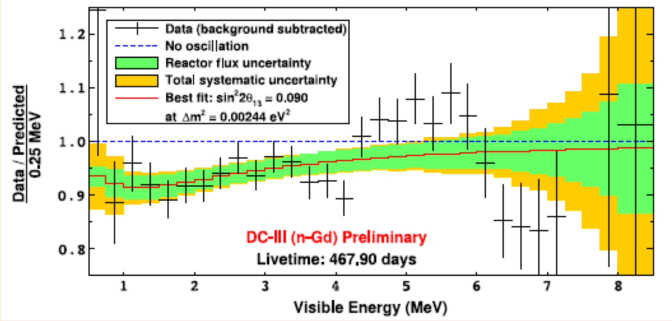
Reactor ν: 5 MeV Excess

2014

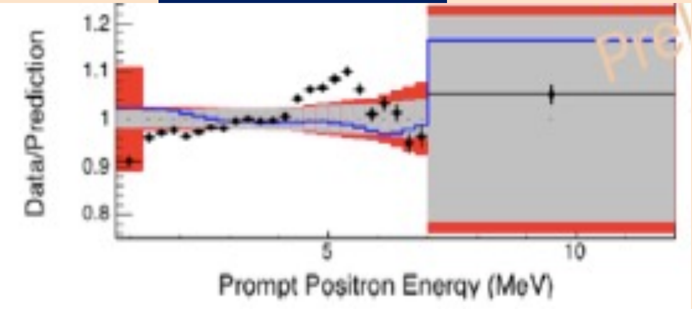
RENO



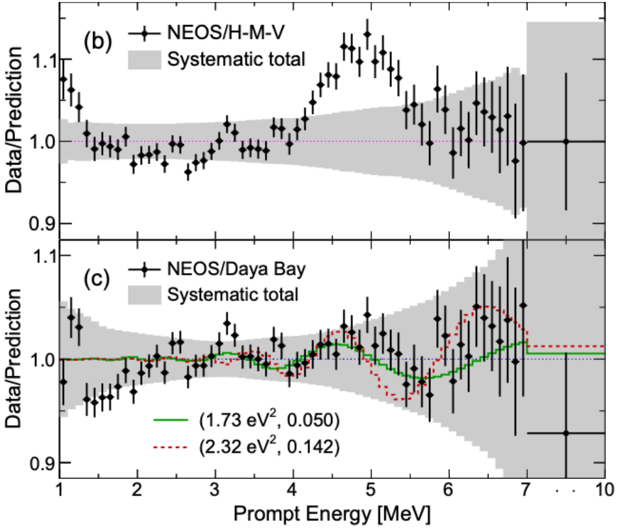
Double Chooz

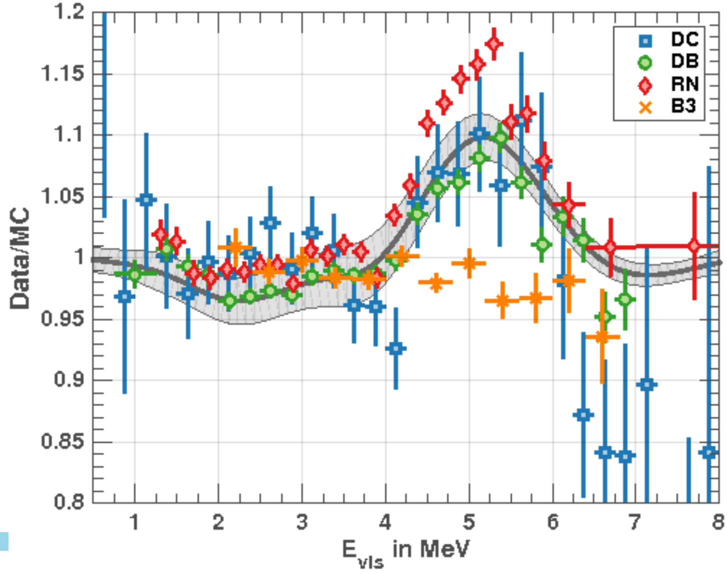


Daya Bay



NEOS in 2017





- ➢ Reactor ν model problem

Are these anomalies due to

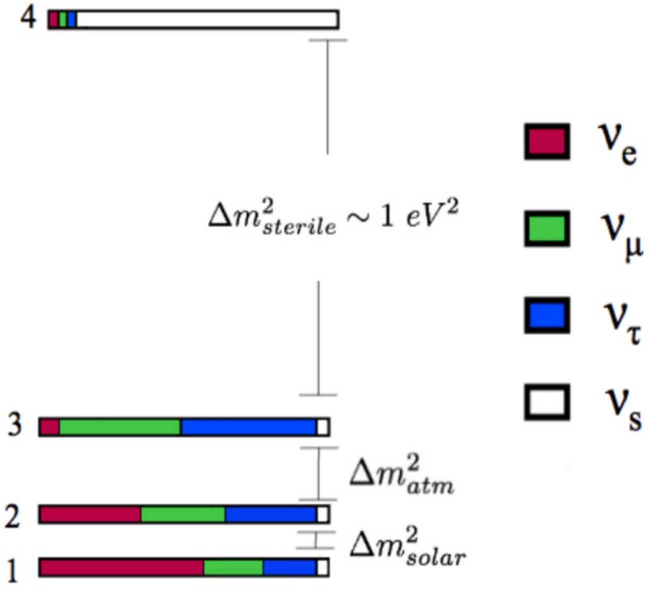
- Model problem?
- Unknown background?
- Systematic effects?
- New physics (sterile ν? etc.)

➢ We are getting to know the answers better, but not completely yet.

3+1 Neutrinos

➢ Sterile neutrinos are searched only **“via oscillation”** w/ active neutrinos.

$$\overset{\textbf{Flavor}}{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}} = \overbrace{\begin{pmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix}}^{U_{3+1}} \overset{\textbf{Mass}}{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}}$$



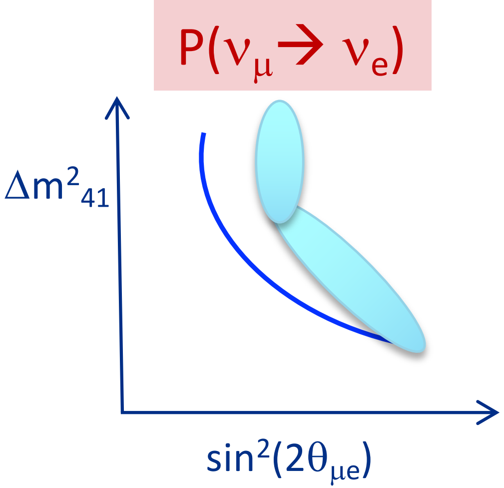
$$U_{3+1} = U(U_{PMNS},\ \underbrace{\theta_{14},\ \theta_{24},\ \theta_{34}}_{\textbf{3 mixing angles}},\ \underbrace{\delta_{14},\ \delta_{24}}_{\textbf{2 CPV phases}},\ \Delta m^2_{41})$$

Sterile ν Oscillation Probability (I)

- **Appearance channel**

$$\boxed{P(\nu_\mu \rightarrow \nu_e) \cong \sin^2(2\theta_{\mu e})\sin^2\left[\frac{1.27\Delta m^2_{41}L}{E_\nu}\left(\frac{\mathrm{eV}^2\mathrm{m}}{\mathrm{MeV}}\right)\right]}$$

$$\boxed{\sin^2(2\theta_{\mu e})} = 4|U_{e4}|^2|U_{\mu 4}|^2 = 4\sin^2\theta_{14}\sin^2\theta_{24}\cos^2\theta_{14} \cong \boxed{4\sin^2\theta_{14}\sin^2\theta_{24}}$$



→ $\theta_{\mu e}$ would be very small if θ_{14} and θ_{24} are small.

Sterile ν Oscillation Probability (II)

➢ Disappearance channels

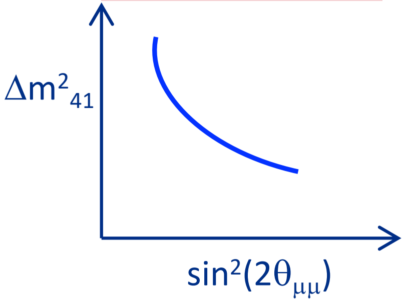
$$\boxed{P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2(2\theta_{\mu\mu})\sin^2\left[\frac{1.27\Delta m^2_{41}L}{E_\nu}\left(\frac{\mathrm{eV^2m}}{\mathrm{MeV}}\right)\right]}$$

$$\boxed{\sin^2(2\theta_{\mu\mu})} = 4|U_{\mu4}|^2(1-|U_{\mu4}|^2) \cong 4|U_{\mu4}|^2 = 4\sin^2\theta_{24}\cos^2\theta_{14} \cong \underline{4\sin^2\theta_{24}}$$

If θ_{14}, θ_{24} are small

$$\boxed{\theta_{\mu\mu} \cong \theta_{24}}$$

P($\nu_\mu \to \nu_\mu$)



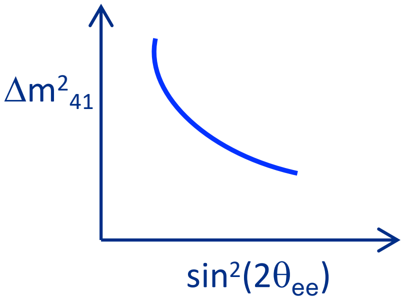
$$\boxed{P(\nu_e \to \nu_e) \cong 1 - \sin^2(2\theta_{ee})\sin^2\left[\frac{1.27\Delta m^2_{41}L}{E_\nu}\left(\frac{\mathrm{eV^2m}}{\mathrm{MeV}}\right)\right]}$$

$$\boxed{\sin^2(2\theta_{ee})} = 4|U_{e4}|^2(1-|U_{e4}|^2) \cong 4|U_{e4}|^2 = \underline{4\sin^2\theta_{14}}$$

If θ_{14} is small

$$\boxed{\theta_{ee} \cong \theta_{14}}$$

P($\nu_e \to \nu_e$)



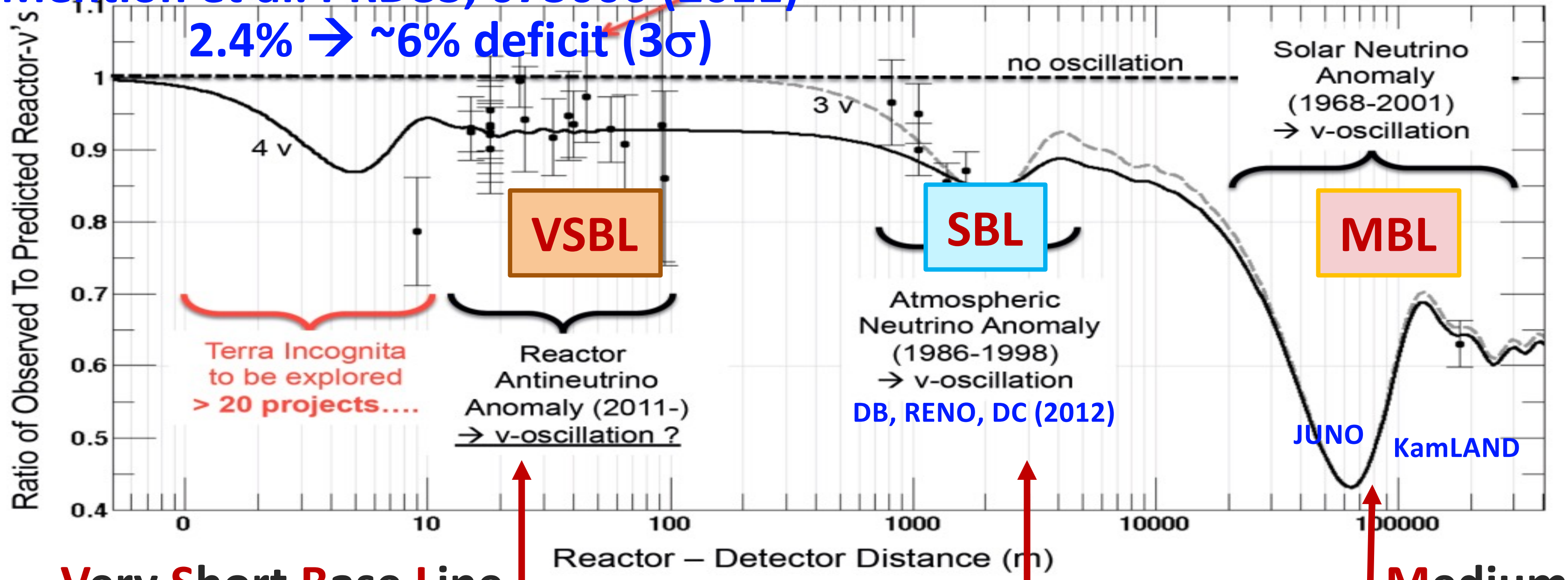
Reactor ν Flux Anomaly

- Observed/predicted averaged event ratio:

R = 0.943 +/- 0.023

Mention et al. PRD83, 073006 (2011)

2.4% → ~6% deficit (3σ)



Very Short Base Line

Short Base Line

Medium Base Line

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\Theta_{14}\sin^2\left(1.27\Delta m^2_{41}\frac{L}{E}\right) - c^4_{14}\sin^2 2\Theta_{13}\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right) - c^4_{14}c^4_{13}\sin^2 2\Theta_{12}\sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right)$$

RAA = Reactor Antineutrino Anomaly

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

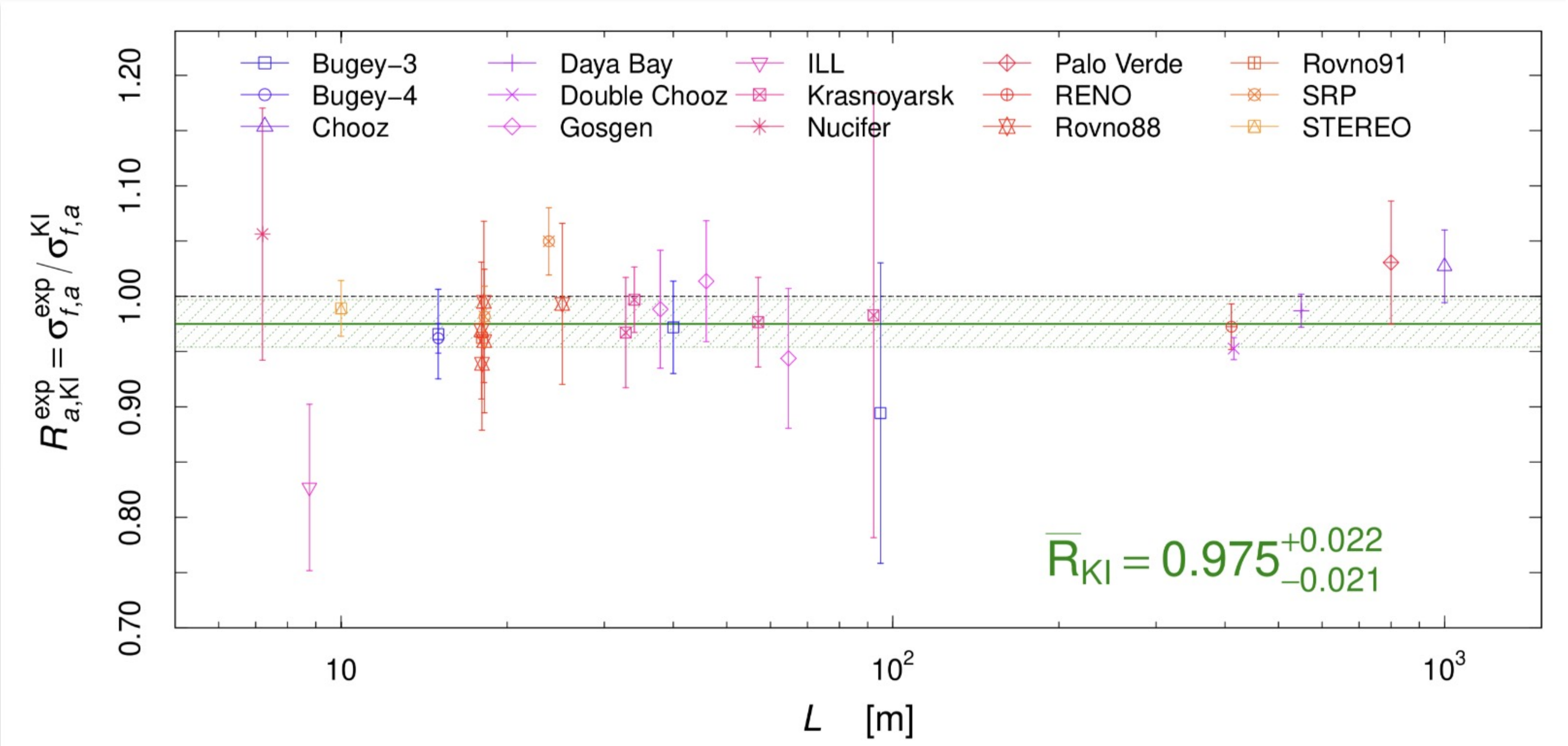
J. Kopp
@Nu2022

reactor ν

With updated input data to ~~flux calculation~~

(new β spectra from ^{235}U fission)

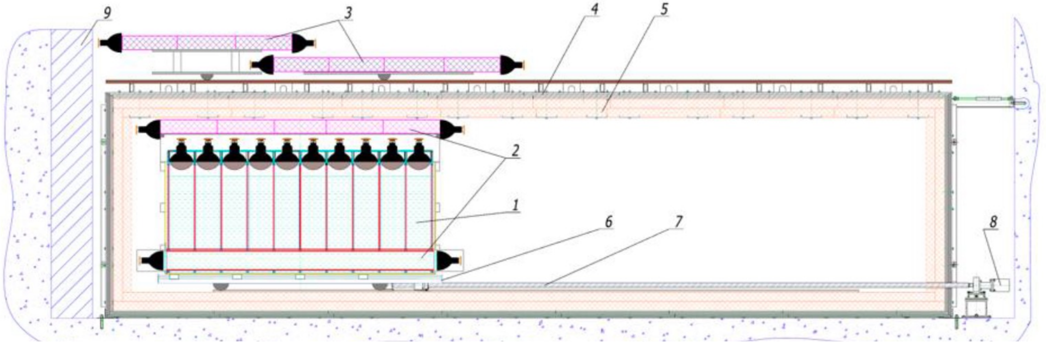
Kopeikin Skorokhvatov Titov arXiv:2103.01684
Berryman Huber arXiv:2005.01756
Giunti Li Ternes Xin arXiv:2110.06820

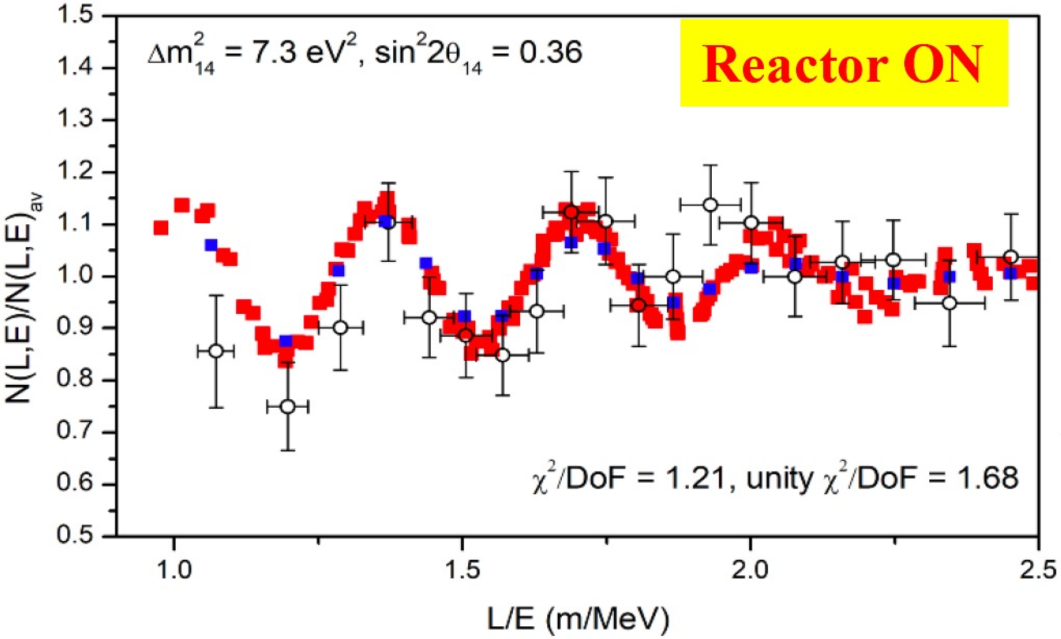


→ Reactor ν flux anomaly disappears !

Neutrino-4 (2016-2020)

- SM-3 Reactor: 100 MW_{th}
- Segmented GdLS (1.8 ton)
- Baseline: 6 -12 m





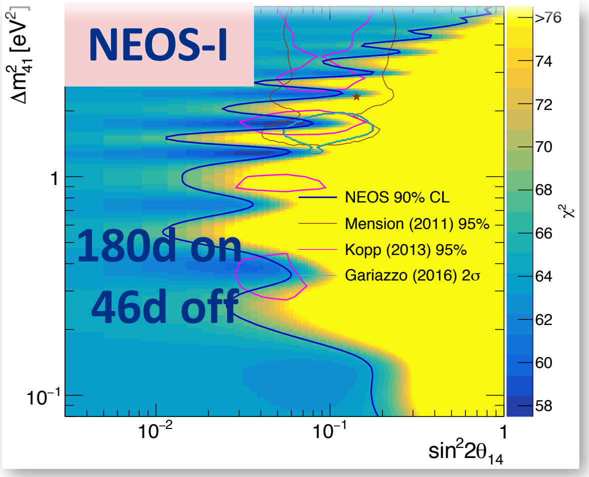
~140 K IBDs

❑ **Best fit**:

- $\Delta m_{41}^2 = 7.30 \pm 1.17\ eV^2$
- $\sin^2(2\theta_{14}) = 0.36 \pm 0.12_{stat}$ (2.9 σ)

Current VSBL Reactor (3+1) ν Limits

VSBL = Very Short Base Line

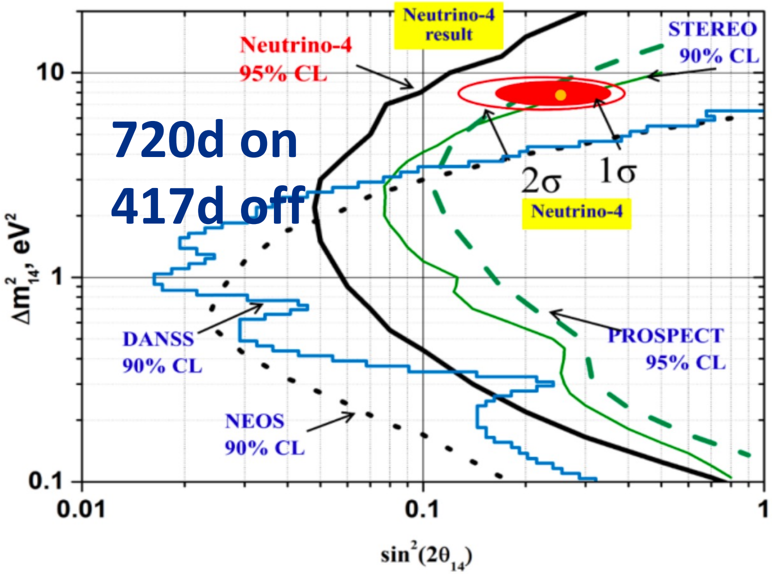


NEOS-I

180d on
46d off

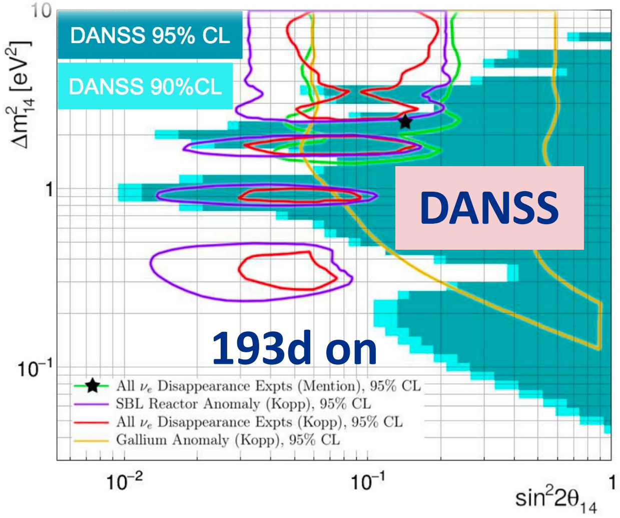
PRL 118, 042502 (2017)

Neutrino-4 2005.05301



720d on
417d off

Neutrino-4 result is partially excluded by STEREO and PROSPECT.

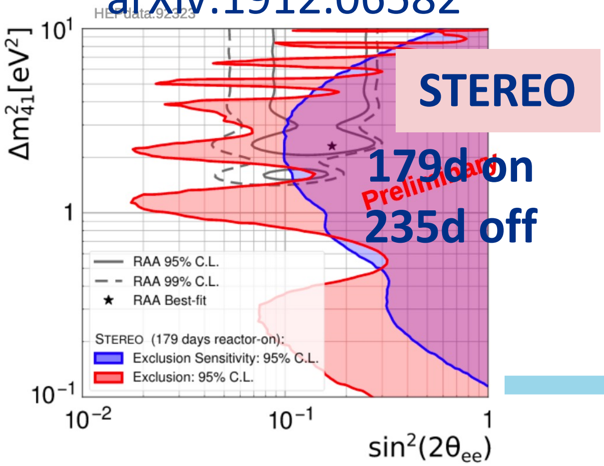


DANSS

193d on

PLB 787, (2018) 56-63

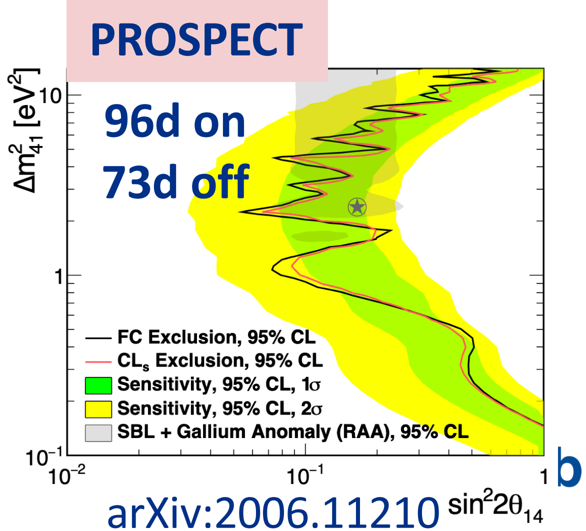
arXiv:1912.06582



STEREO

179d on
235d off

PROSPECT



96d on
73d off

arXiv:2006.11210

VSBL Near Future Plans

☐ DANSS-II

-- Data-taking until spring 2022

-- Finish upgrade of detector in 2022

E resolution goal: 13% @1MeV

☐ PROSPECT-II

-- will upgrade detector

- PMTs outside LS target
- Better isolation & control of LS
- Increase target size

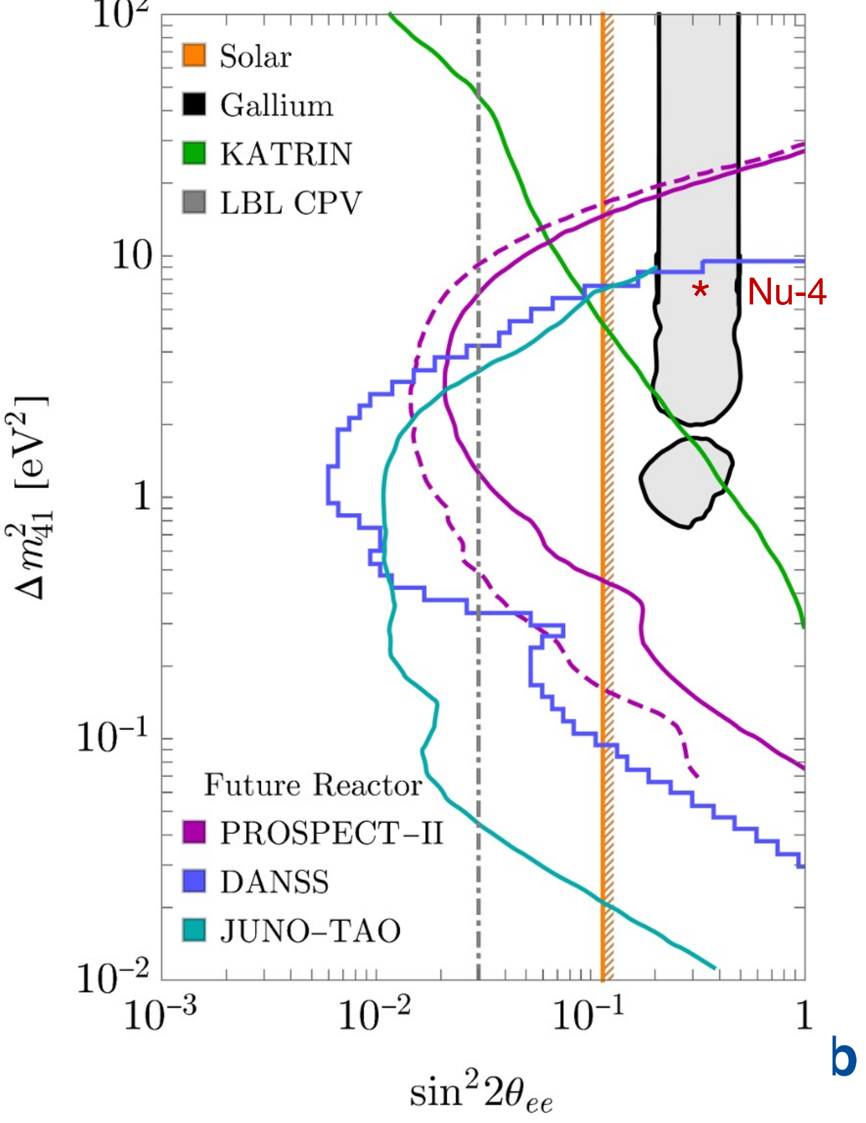
-- Data-taking: 2025 (?)

☐ Neutrino-6

-- upgrade current detector (Neutrino-4)

-- Restart of data-taking: end of 2022

2203.07213



BEST

proposal: 1006.2103, 1204.5379, ...

artificial dichromatic source:

^{51}Cr 3.4 MCi ($\Delta W/W < 0.5\%$)
4 kg

neutrino flux measurment:

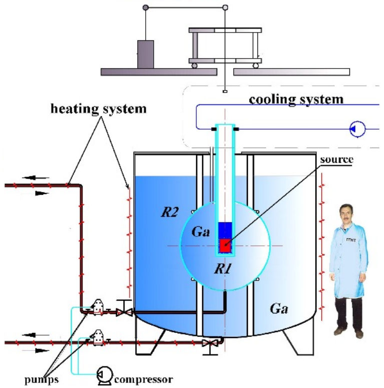
$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$

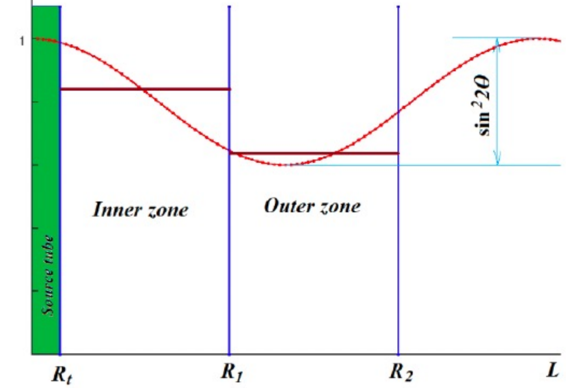
2 detector volumes: **(7.5 t, 40 t)**
for the flux cross check

geometry is chosen:
to search for $\simeq 1$ eV neutrino

data taking:
July–September 2019

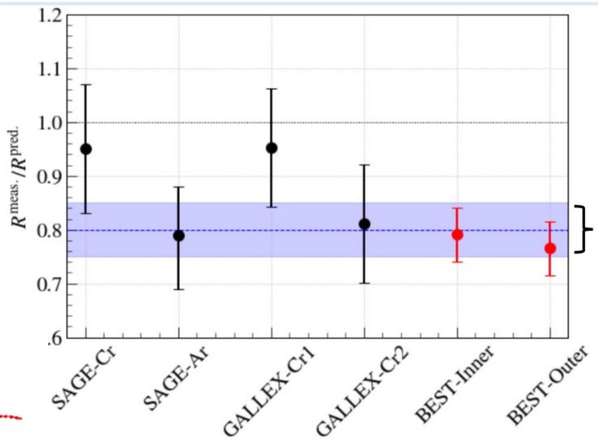
$\tau_{^{51}\mathrm{Cr}} = 27.7$d





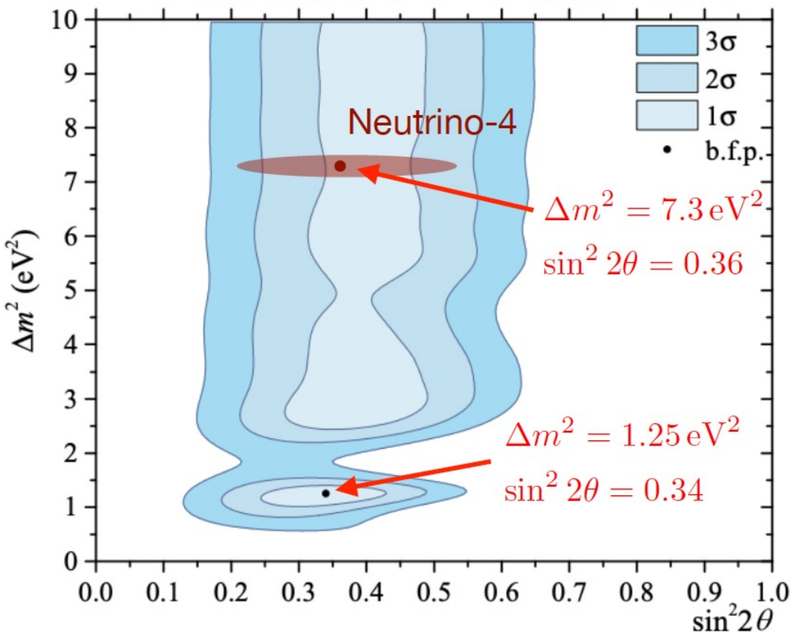
❖ Possible alternative explanations

- Cross Section
- Source Strength
- Extraction Efficiencies
- Counting Efficiencies
- Average Path Length



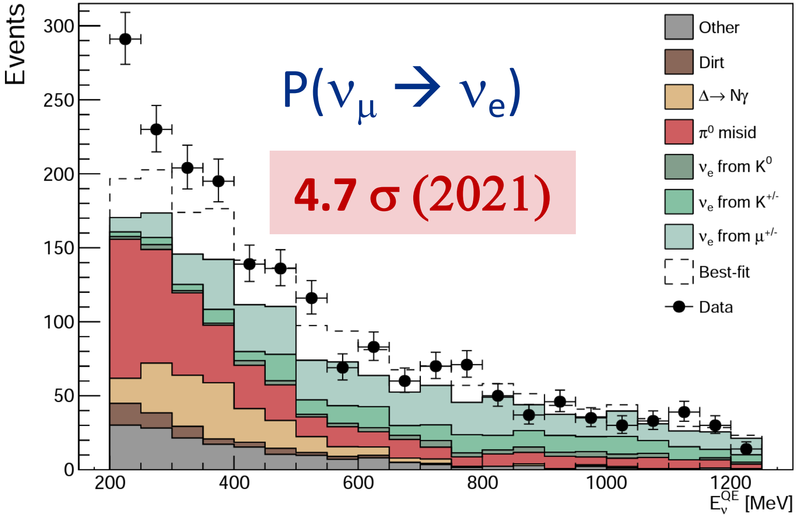
Combined result:
$R_0 = 0.80 \pm 0.05$

Combined w/ past Gallium Exps.



MiniBooNE Anomaly

ν_e : 18.75x10^{21} POT
$\overline{\nu}_e$: 11.27x10^{20} POT



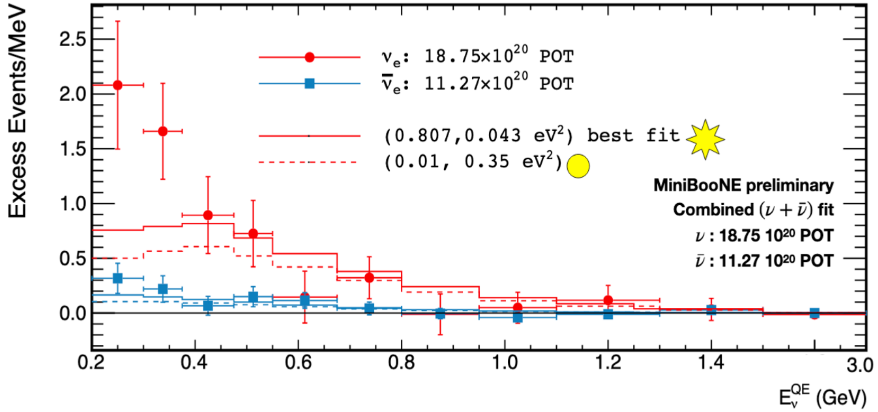
$P(\nu_\mu \rightarrow \nu_e)$

4.7 σ (2021)

- ➢ ν_e excess: 4.7 σ
638.0 ±52.1(stat.) ±122.2(sys.)

- ➢ $\overline{\nu}_e$ excess: 2.8 σ
79.3 ±20.0(stat.) ±20.5(sys.)

$\nu_e + \overline{\nu}_e$: 4.8 σ (2021)

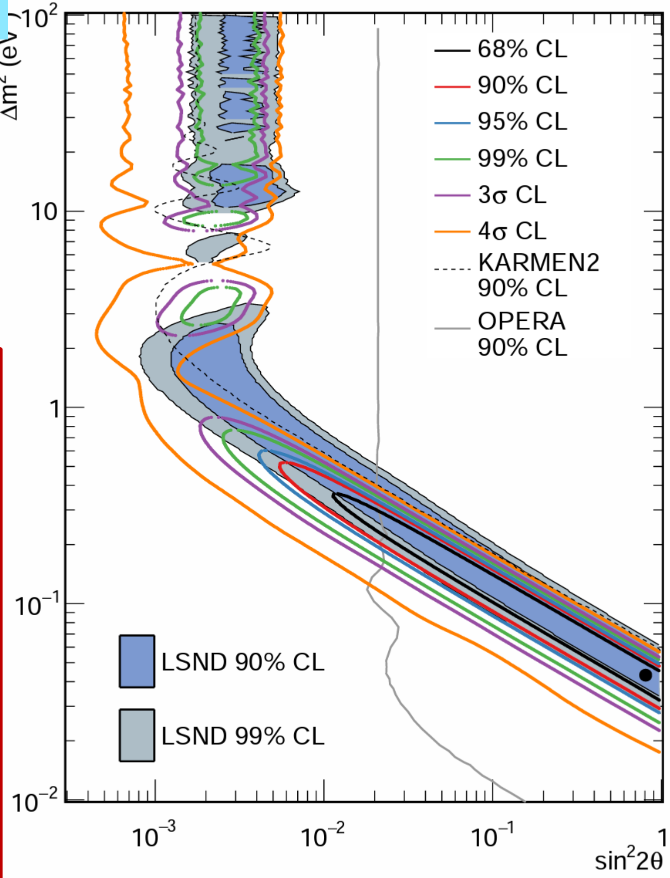


** There is an attempt to explain the LEE in ν mode due to $\overline{\nu}_e$.

2301.12573

→ $\overline{\nu}_e$ interaction/detection are poor in MicroBooNE

→ Possible source of $\overline{\nu}_e$:
 * BNB model
 * new physics



MicroBooNE

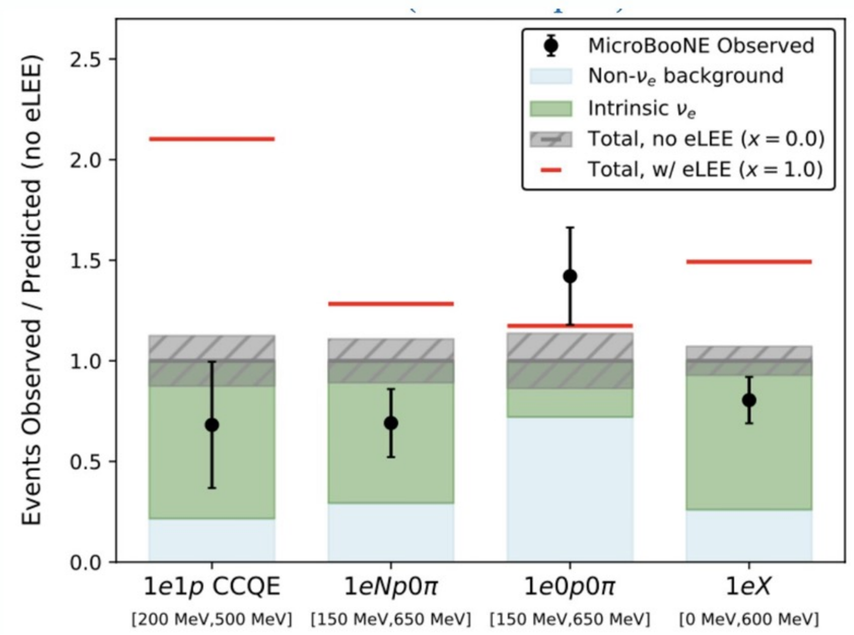
BNB: 1.56×10^{21} POT
NuMI: 2.37×10^{21} POT

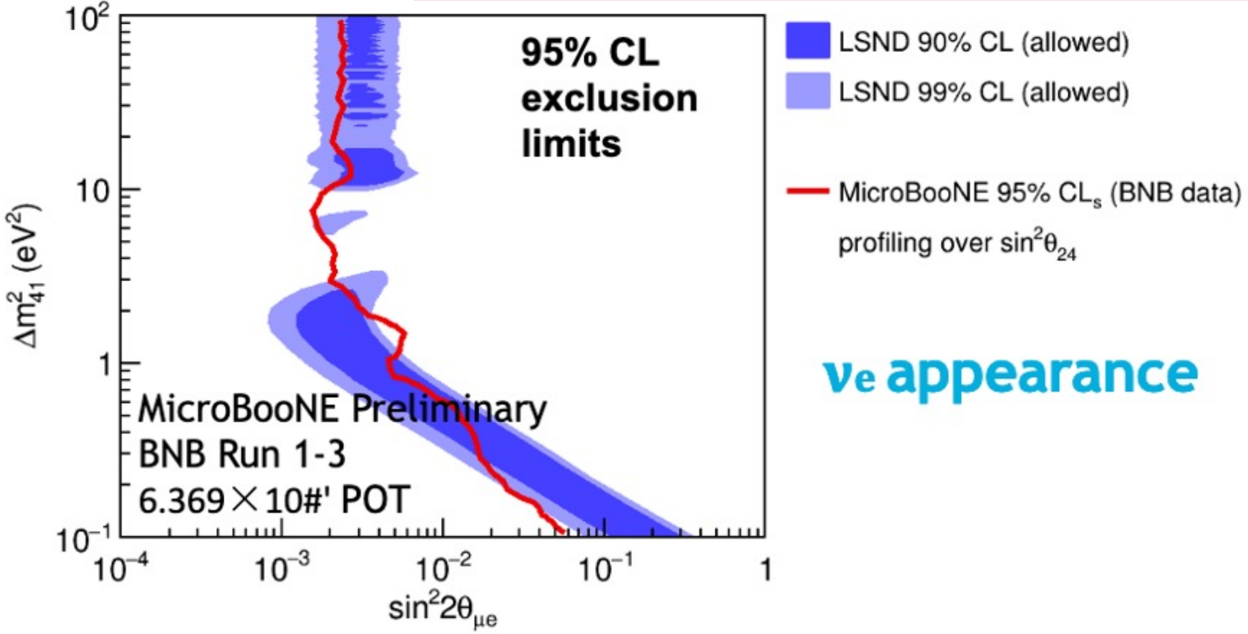
❑ **Results using ~50% data:**

* No evidence of low energy (γ, e) excess events
* (3+1)ν analysis partially excludes LSND allowed region
* Precise measurements on ν-Ar x-section
* More exciting results are expected soon.

LSND+MiniBooNE anomaly still remains

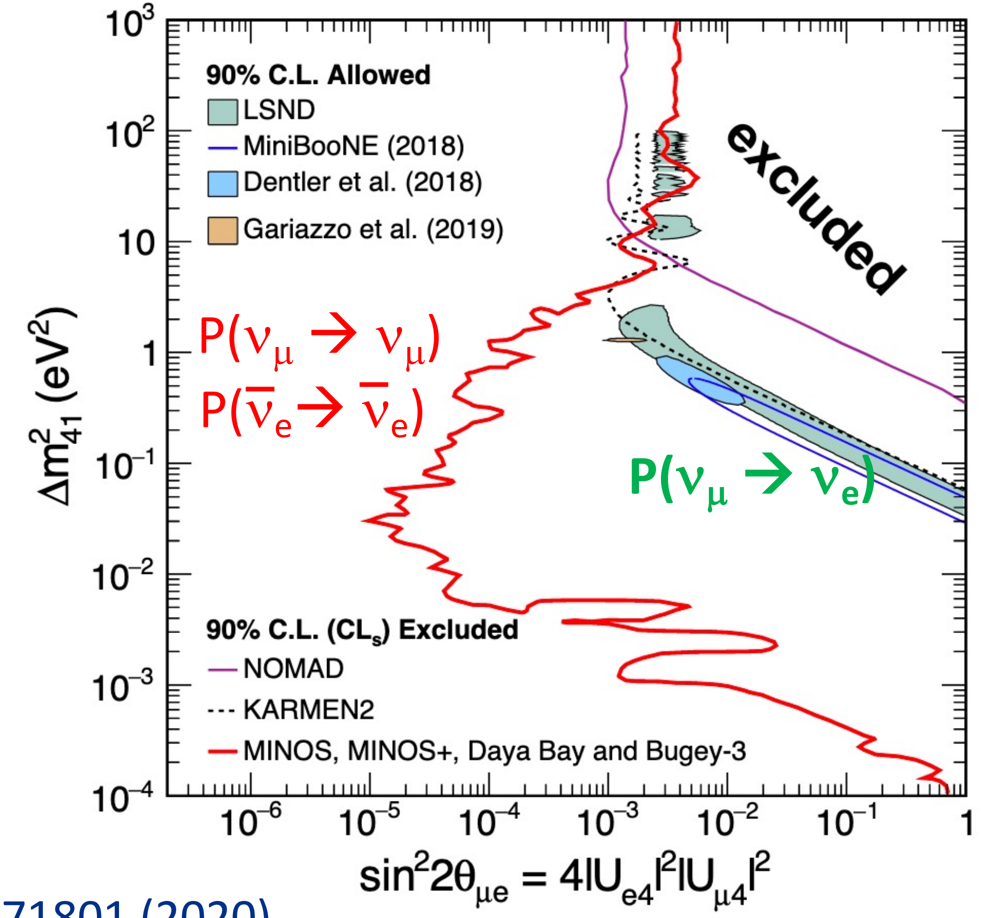
* Unknown other background?
* New physics?
* More complicated model?
    sterile ν
    + (decay, NSI, decoherence..)





νe appearance

ν_μ Disappearance vs. ν_e Appearance



PRL 125, 071801 (2020)

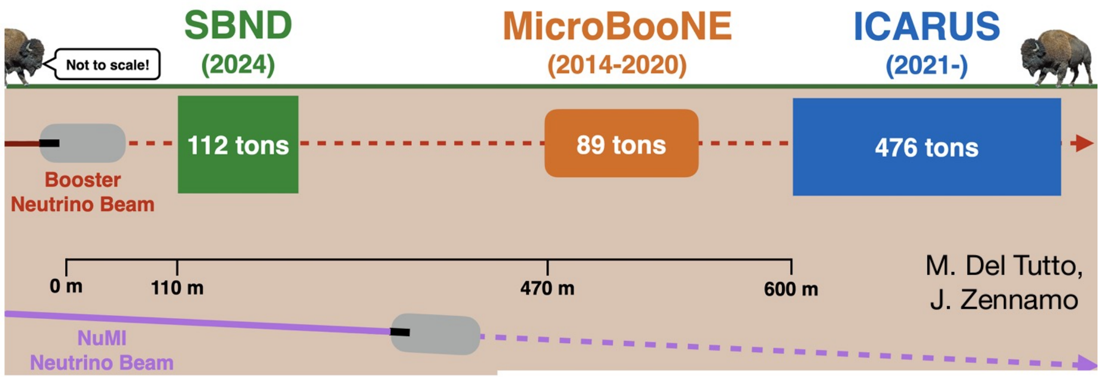
In ν_μ disappearance channel, no hint of strile ν is observed unlike ν_μ appearance channel

→ Contradiction !!

- In beam neutrinos, this contradiction should be resolved.

Short Baseline Neutrino (SBN) Status @Fermilab

NNN23



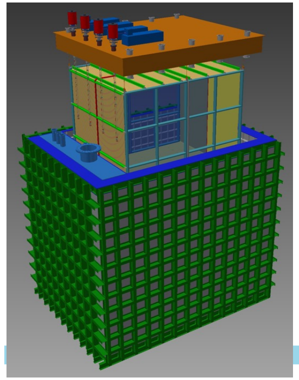
M. Del Tutto, J. Zennamo

SBND

(110 m, 112 ton)

- Detector installation: 2023
- Cryogenic commission: end of 2023
- LAr filling: early 2024

Systematic Constraint (~% level)



ICARUS

(600 m, 476 ton)

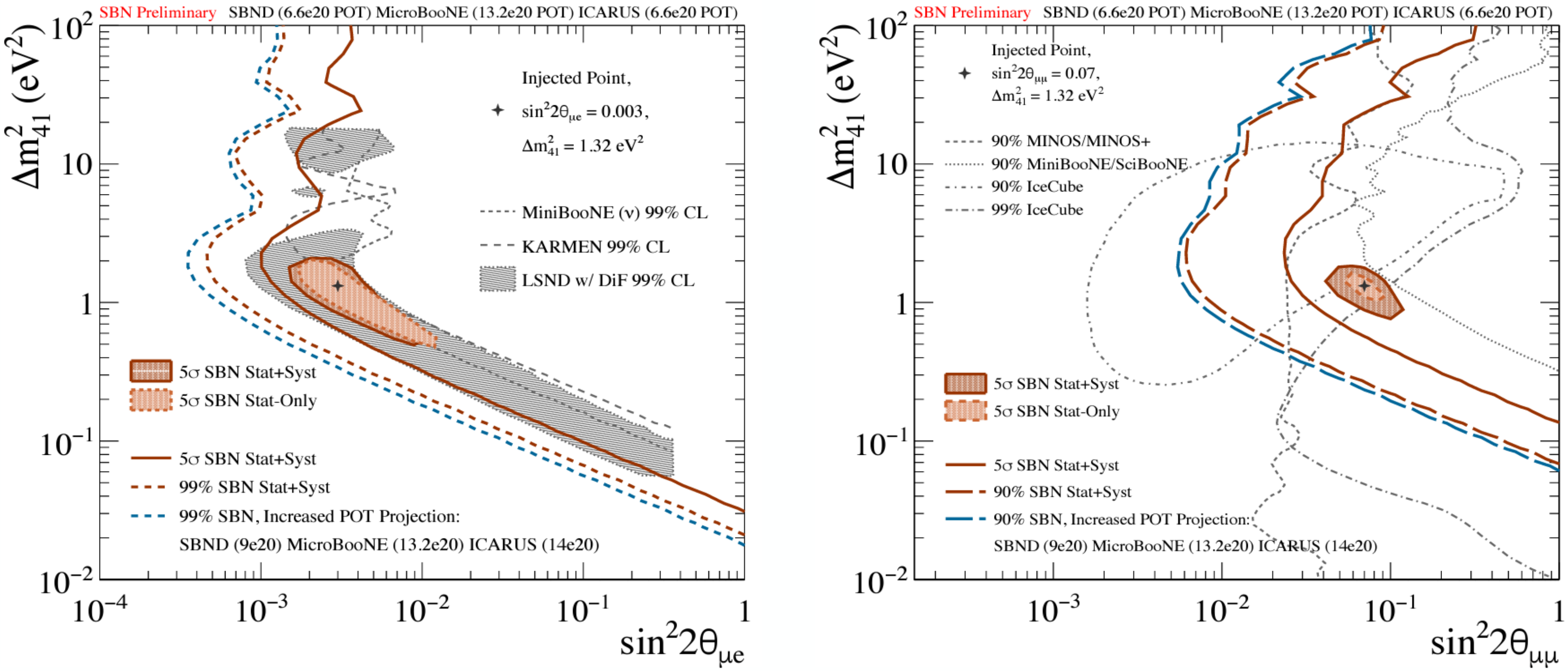
- Detector installation: July ‘18 – ’19
- Detector commissioning: 2020
- 1st Physics data: June 2022
- Has been taking data for 1 year so far

SBN@Fermilab Sensitivities

- Reach of full program
  - SBND/ICARUS (6.6e20 POT ~ 3 years)
  - MicroBooNE (13.2e20 POT ~ 6 years)

Appearance and disappearance tested in one program

SBN sensitivities for 6.6 e20 protons on the **BNB** target as per SBN proposal.



ν_e appearance

ν_μ disappearance

JSNS^2 @J-PARC

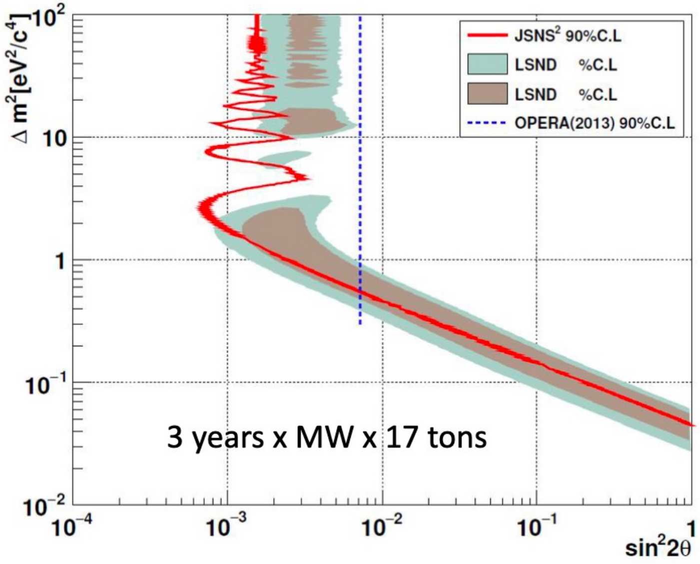
→ Direct tests for LSND

Experiment	ν-source	Energy E_ν	Distance L	Signal
LSND [1]	π DAR	40 MeV	30 m	$\bar{\nu}_\mu \to \bar{\nu}_e$
MiniBooNE [2]	π DIF	800 MeV	600 m	$\nu_\mu \to \nu_e$ / $\bar{\nu}_\mu \to \bar{\nu}_e$
FNAL SB program [7]	π DIF	800 MeV	110 m / 470 m / 600 m	$\nu_\mu \to \nu_e$ / $\bar{\nu}_\mu \to \bar{\nu}_e$
JSNS^2 [6]	π DAR	40 MeV	24 m	$\bar{\nu}_\mu \to \bar{\nu}_e$

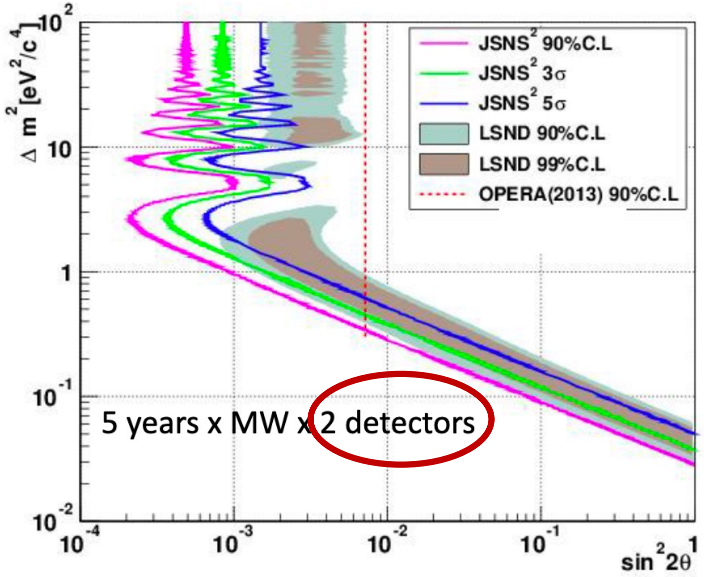
- 17 ton GdLS target (cf. LSND = 167 ton LS)
- Better E resolution than LSND (2.4 % vs 7% at 45 MeV)

JSNS^2-II

Data taking:
End of 2023



3 years x MW x 17 tons

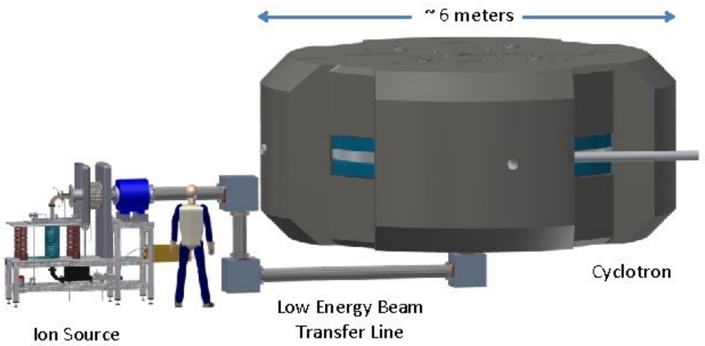


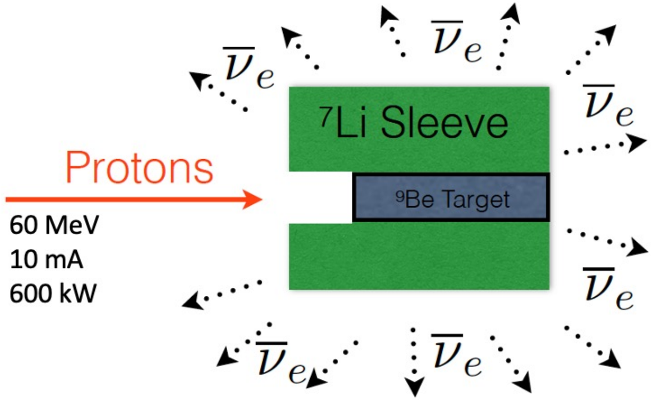
5 years x MW x 2 detectors

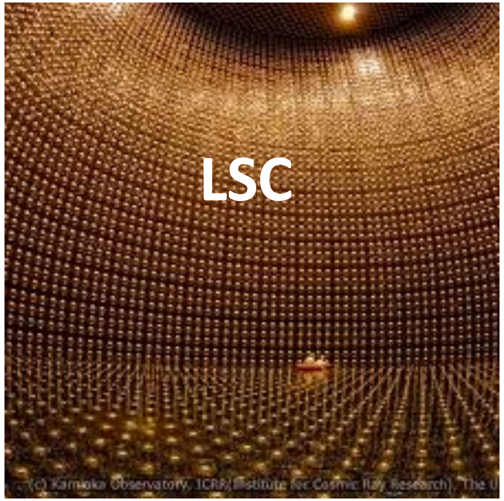
Fermilab

Sterile ν search w/ IsoDAR@Yemilab

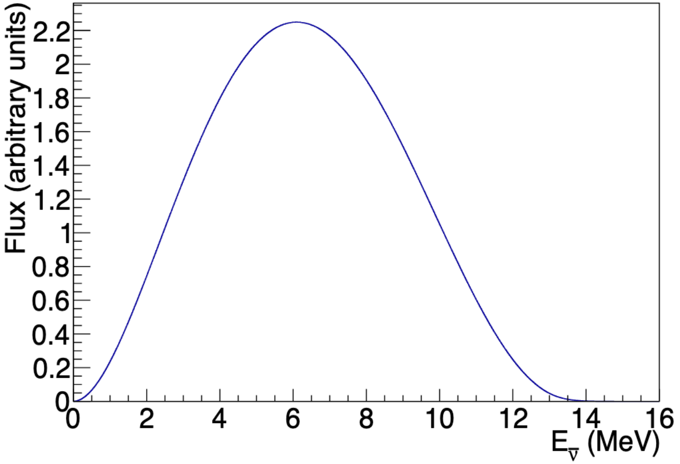
The IsoDAR Cyclotron and Ion Source







IsoDAR $\overline{\nu}$ spectrum



(1) $p + {}^9\mathrm{Be} \rightarrow {}^8\mathrm{Li} + 2p$

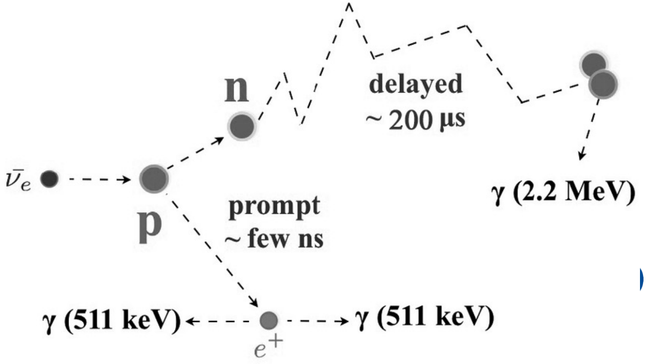
(2) $p + {}^9\mathrm{Be} \rightarrow {}^9\mathrm{B} + n$

$n + {}^7\mathrm{Li} \rightarrow {}^8\mathrm{Li} + \gamma$

$${}^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e^- + \overline{\nu}_e$$

IBD interaction

$$p^+ + \overline{\nu}_e \rightarrow e^+ + n^0$$

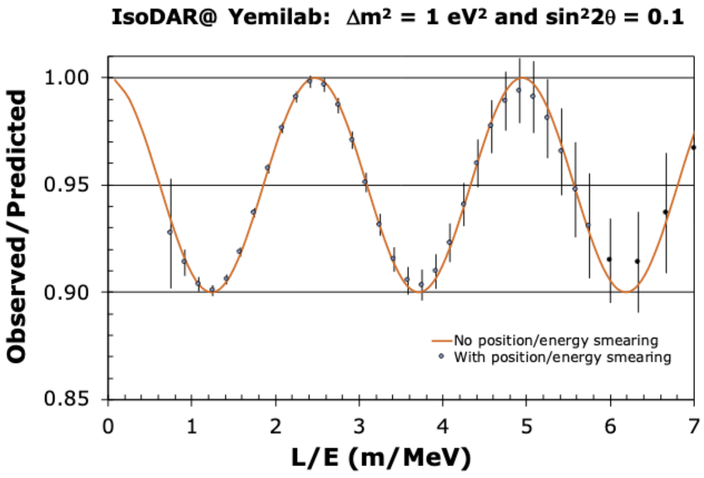


Sterile ν Search w/ IsoDAR@Yemilab

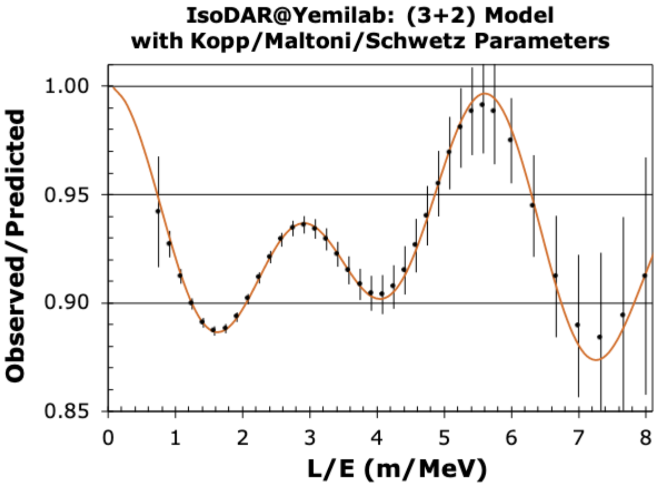
Possible Models & Signatures

arXiv:2111.09480
PRD 105 (2022) 5, 052009

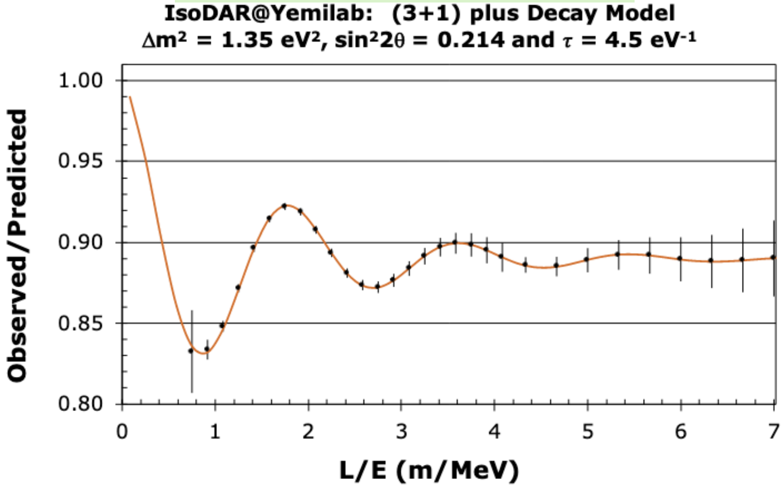
(3+1) ν


IsoDAR@ Yemilab: Δm^2 = 1 eV² and $\sin^2 2\theta$ = 0.1

(3+2) ν


IsoDAR@Yemilab: (3+2) Model
with Kopp/Maltoni/Schwetz Parameters

(3+1) ν + ν_s decay


IsoDAR@Yemilab: (3+1) plus Decay Model
Δm^2 = 1.35 eV², $\sin^2 2\theta$ = 0.214 and τ = 4.5 eV⁻¹

→ IsoDAR@Yemilab can well distinguish different new physics models.

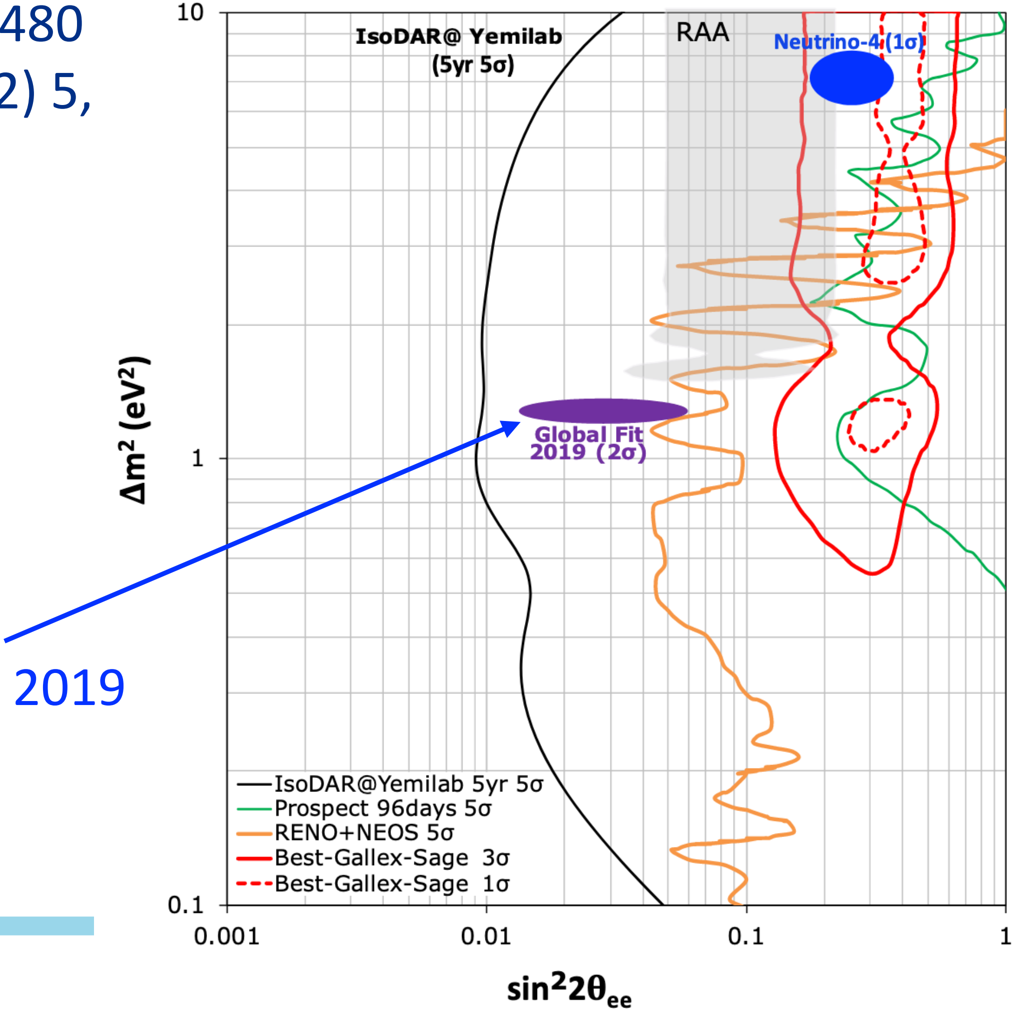
- The (3+1)+decay model significantly reduces the tension between appearance and disappearance experiments, improving the global-data goodness-of-fit.

1910.13456

Sterile neutrino search Sensitivity

IsoDAR @Yemilab $P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$

arXiv:2111.09480
PRD 105 (2022) 5, 052009



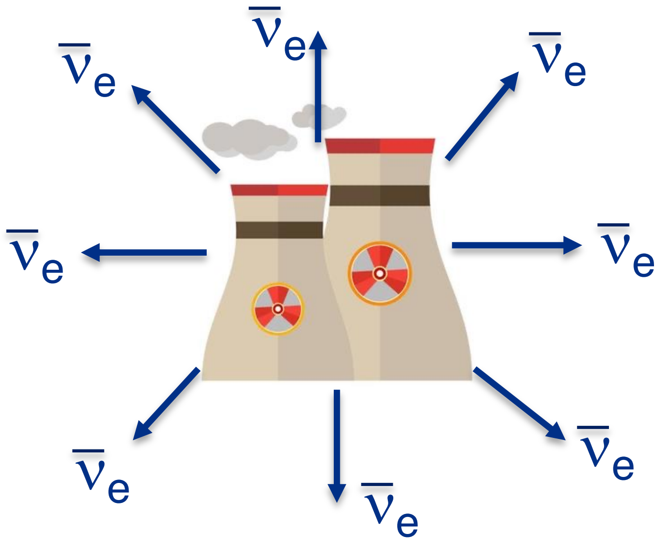
- World-leading result
- Definite conclusion on (3+1) ν or not

Advantage:
Unlike reactor/accelerator ν, IsoDAR has very well defined ν flux and shape.

NEOS-II

Neutrino **E**xperiment for **O**scillation **S**tudy

Using reactor neutrinos at very short baseline



1 $\mathrm{GW_{th}}$ reactor

→ ~$2\mathrm{x}10^{20}$ $\bar{\nu}_e$/sec

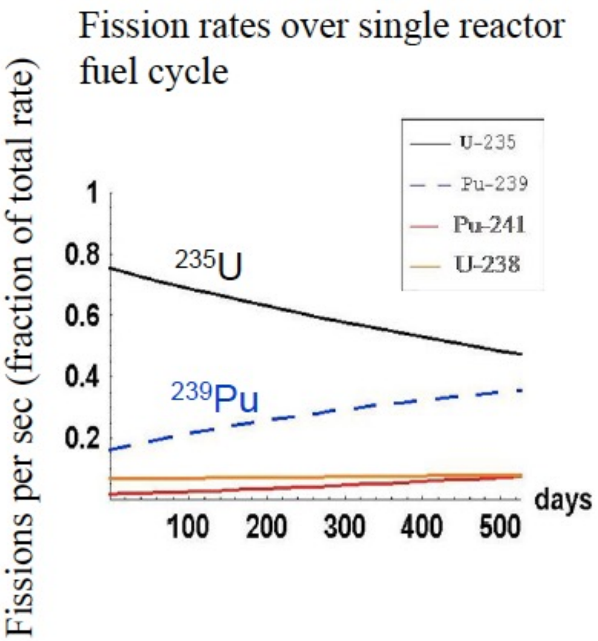
❖ Nuclear reactors are copious & isotropic sources of $\bar{\nu}_e$.

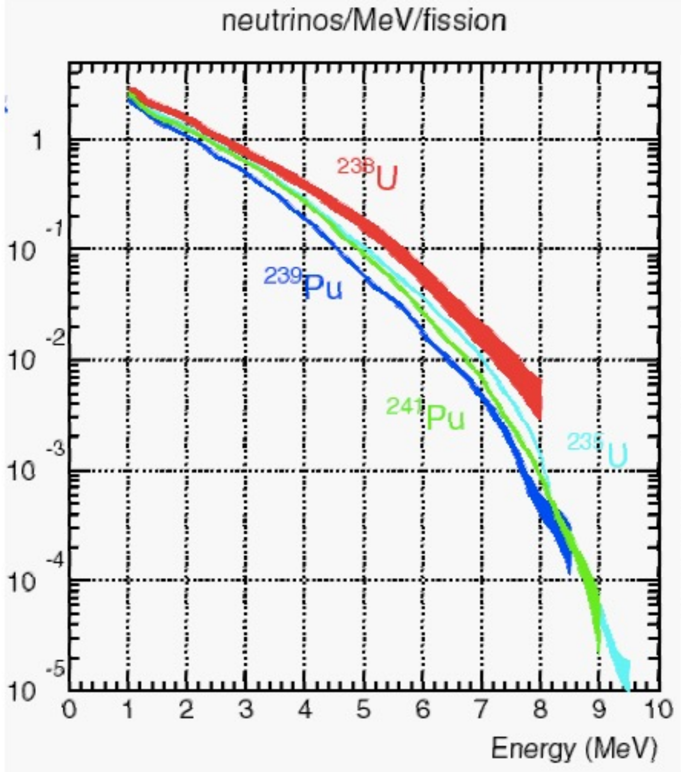
Commercial reactors

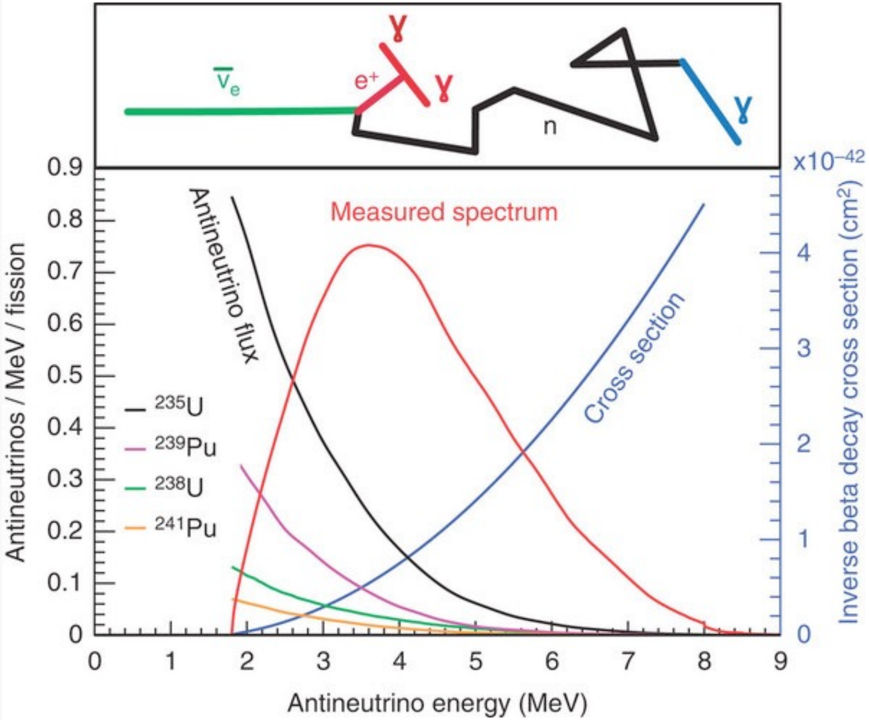
> 99.9 % $\bar{\nu}_e$ are produced by ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu

IBD interaction

$$\boxed{p^+ + \bar{\nu}_e \rightarrow e^+ + n^0}$$

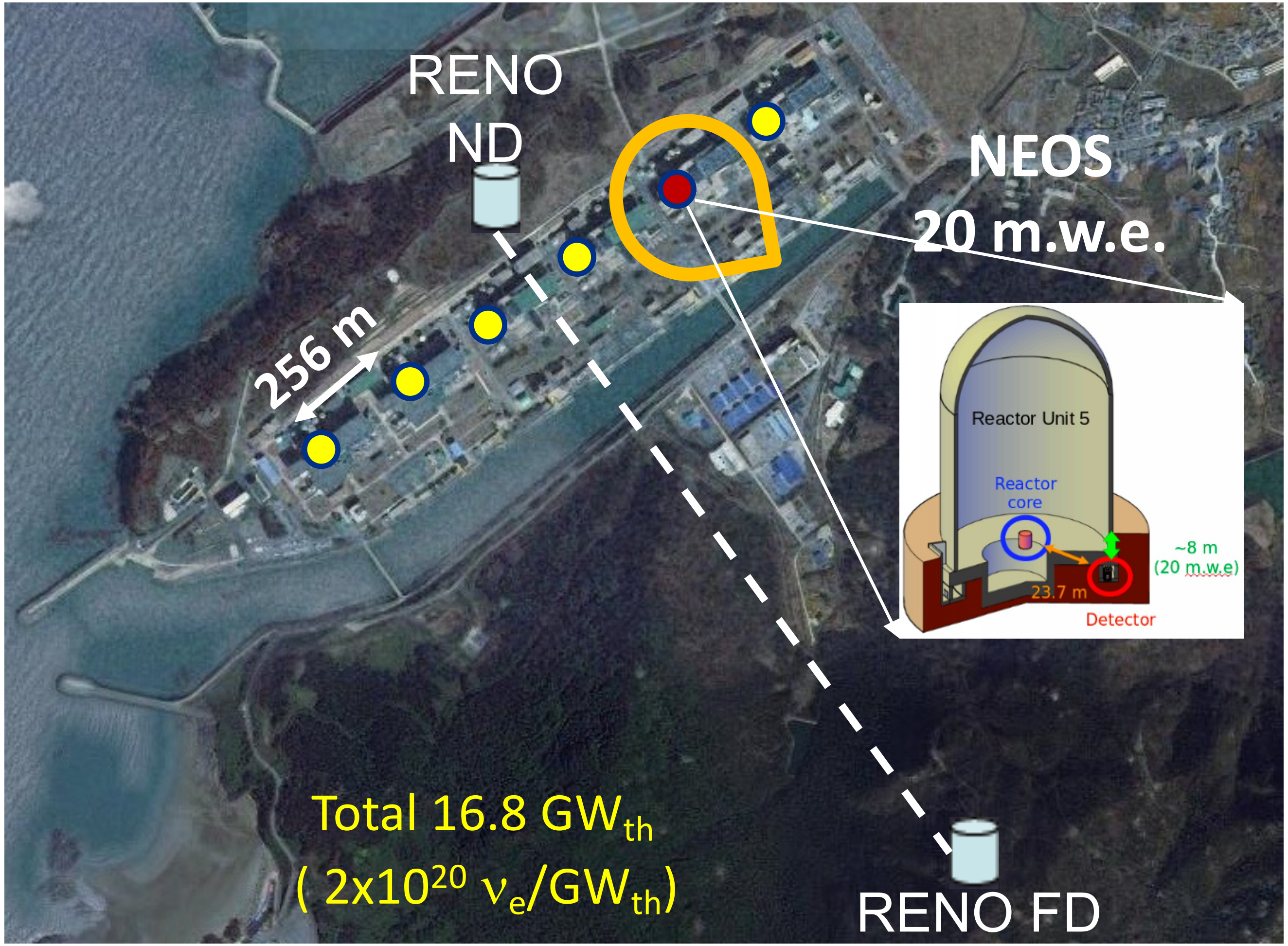






Plutonium breeding over fission cycle changes $\bar{\nu}_e$ rate by 5 ~ 10% and energy spectrum.

NEOS-I & II Site



Total 16.8 GW_{th}

($2x10^{20}$ ν_e/GW_{th})

NEOS-II Collaboration

Currently, total **20** 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-II Goals:

1. understanding of reactor neutrino **anomalies (5 MeV excess)**
2. Search for **sterile neutrinos**

❑Challenges:

1. **Decrease of light yield** during data-taking
2. **Small group** consisting of only domestic institutions & small # of students

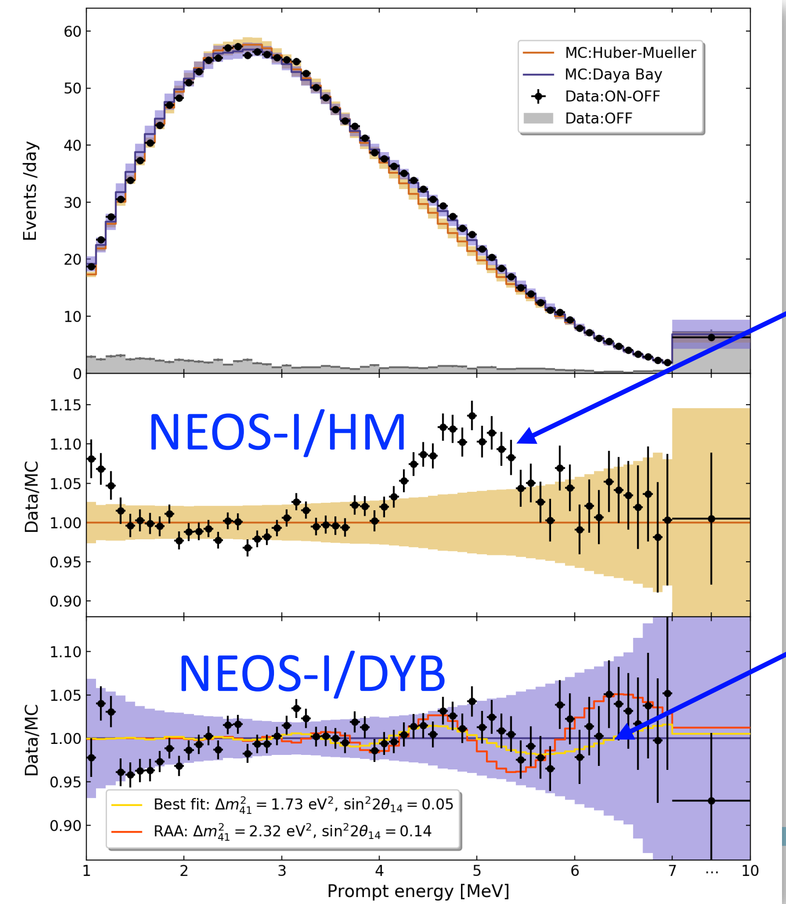
❑Opportunities:

1. NEOS-II detector has one of the **best energy resolutions** among VSBL exp.
2. High statistics (commercial reactor)
3. Low background (good overburden: ~20 m.w.e.)
4. **S/B = 29** (excellent PSD)
5. **Full Fuel cycle** data
6. Beyond NEOS-II?

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)

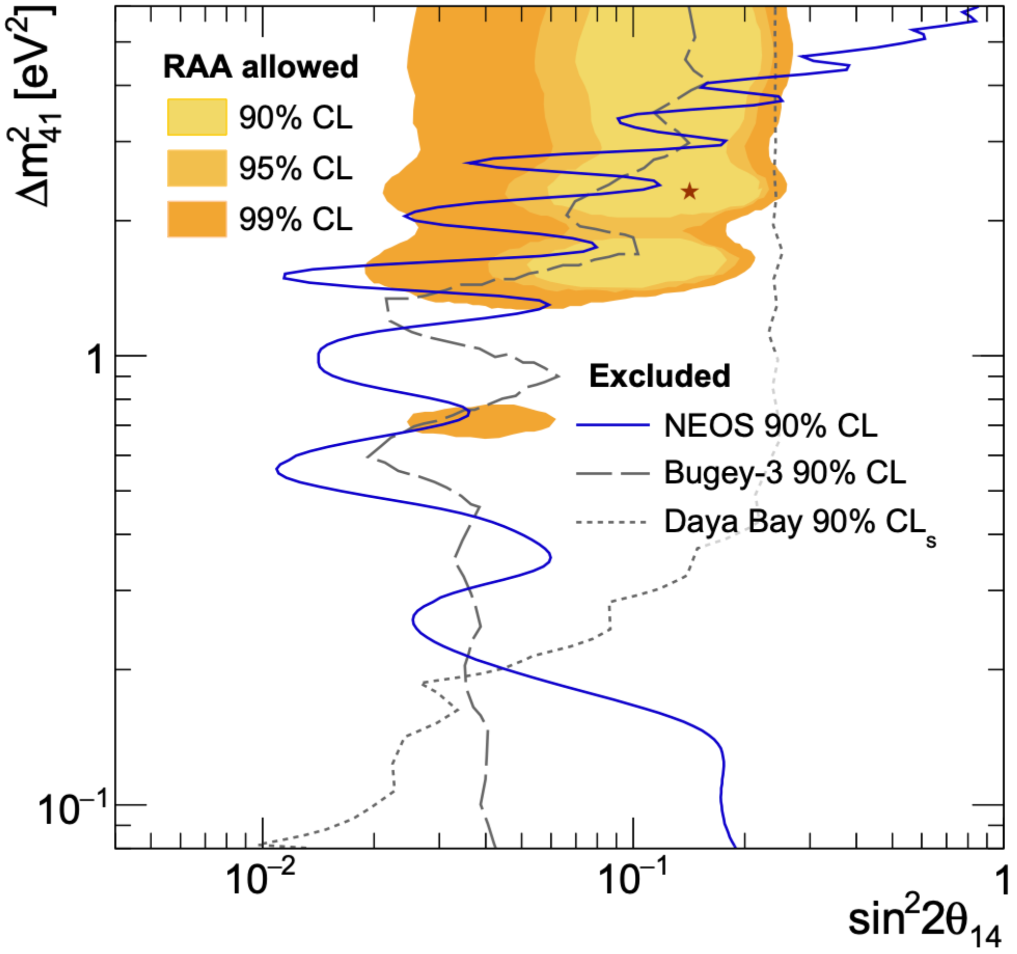
"5 MeV excess" observation

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



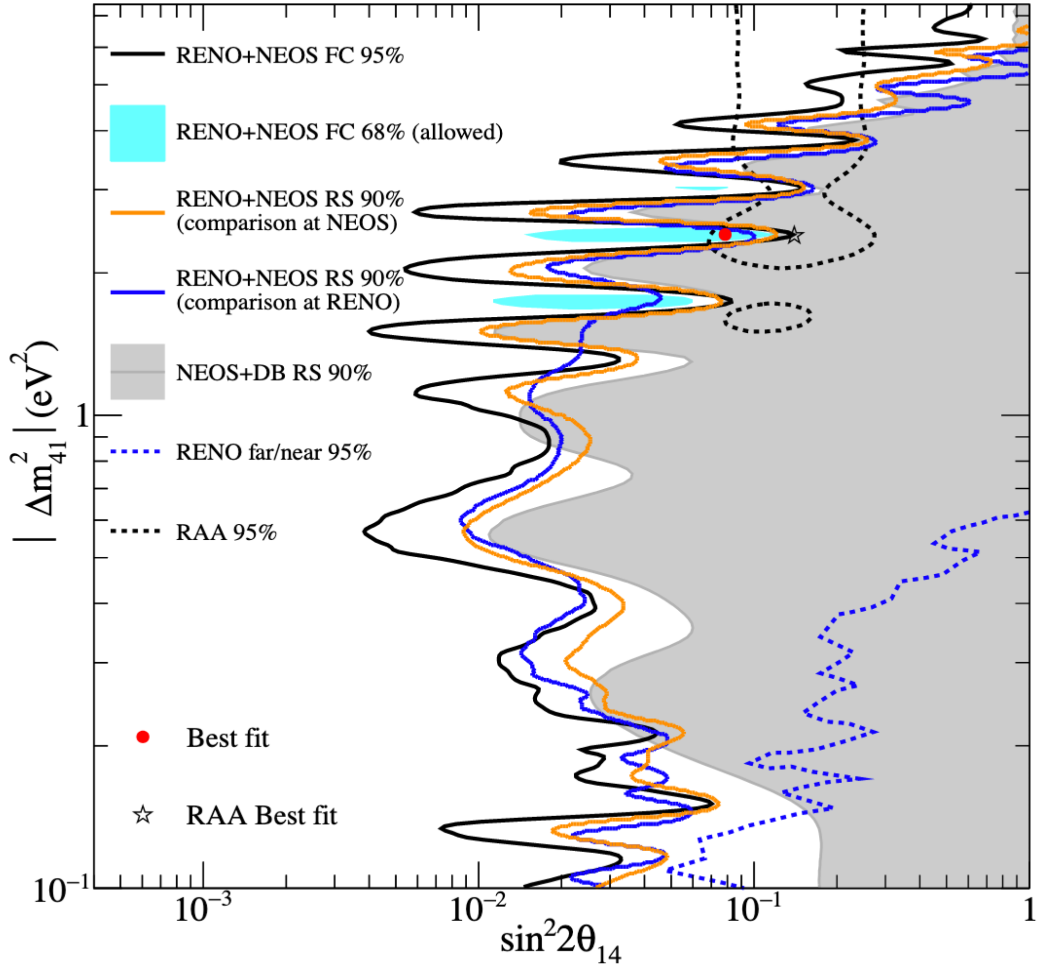
NEOS 180 (46) days reactor-on(off)data

- RAA best fit is excluded at ~4 σ.
- Limited by “**systematic**” uncertainty (model, energy scale).

** Daya Bay data was used as a reference model (3ν osc.).

PRL 118, 121802 (2017)

NEOS-I + RENO Results in 2022



** RENO data was used as a reference model (3ν osc.).

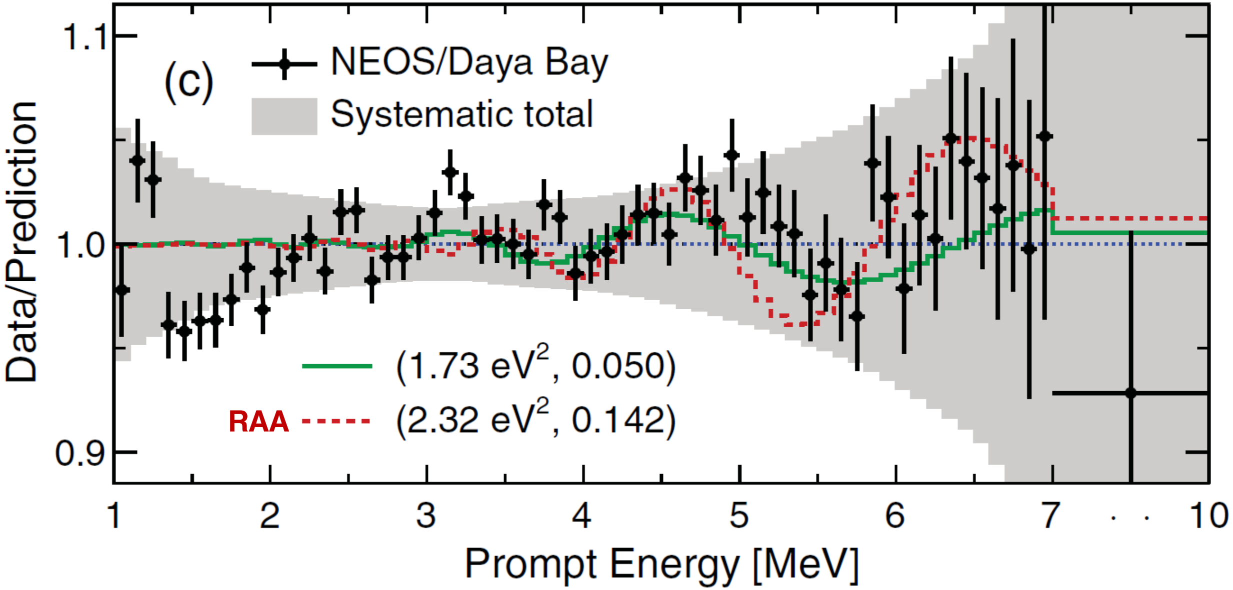
Phys. Rev. D 105, L111101 (2022)]

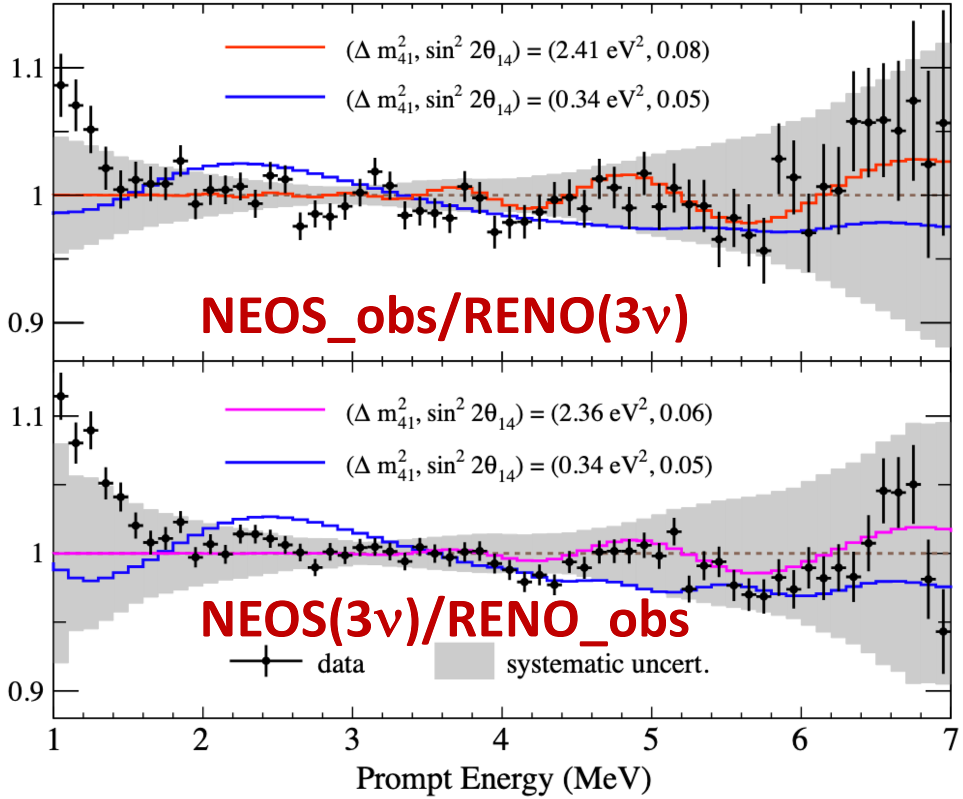
→ The NEOS-I & RENO result is improved compared to the NEOS-I & DYB result.

- The best fit falls in RAA 95% allowed region.

➢ NEOS+RENO best fit: (2.41 eV^2, 0.08) with $\chi^2(3\nu) - \chi^2(4\nu) = 8.4$, p-value = 8.2%

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 = 22%

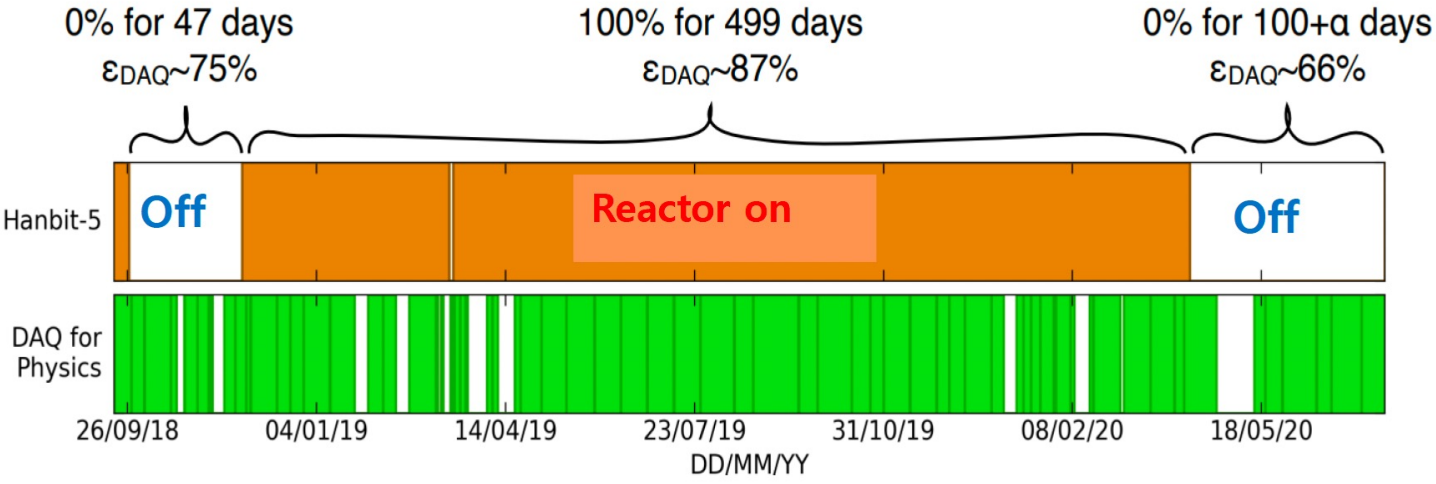
- A. Sonzogni et al. @ AAP2018:
This feature is due to ^{99}Nb, ^{143}La, ^{92}Y, ^{99}Zr.

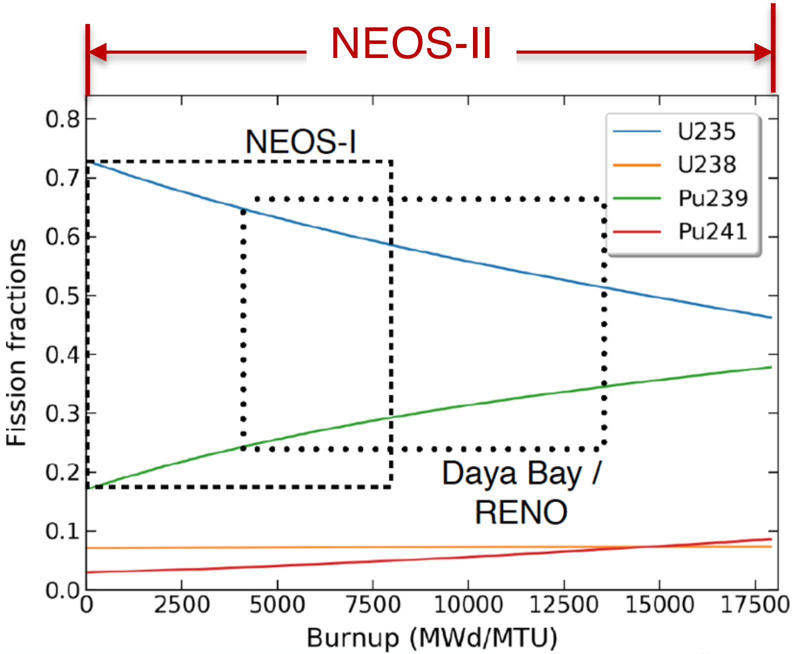
If Sonzogni et al are correct, we should observe the same feature in NEOS-II, PROSPECT, STEREO data.

- NEOS+RENO best fit: (2.41 eV^2, 0.08) with $\chi^2(3\nu) - \chi^2(4\nu) = 8.4$, p-value = 8.2%

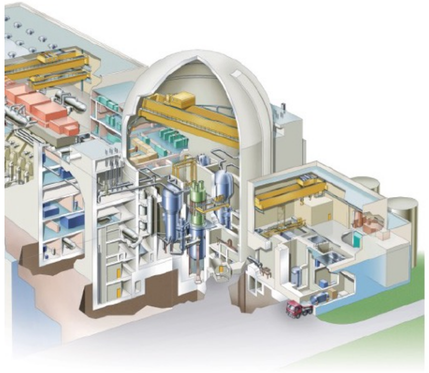
NEOS-II (Sept. 2018 – Oct. 2020)

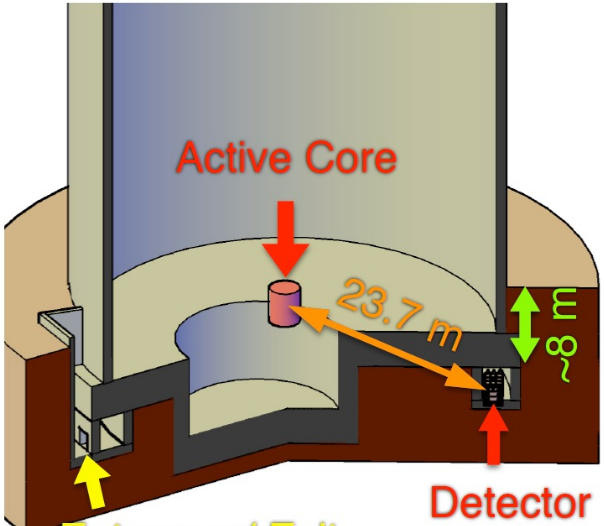
- Refurbished detector from NEOS-I.
- Took ~388 live days of data (full fuel cycle) + 2 OFF periods (45+67 days)
- Time evolution of reactor ν flux/shape; spectral decomposition (^{235}U, ^{239}Pu)
- Rate+Shape analysis on (3+1)ν oscillation

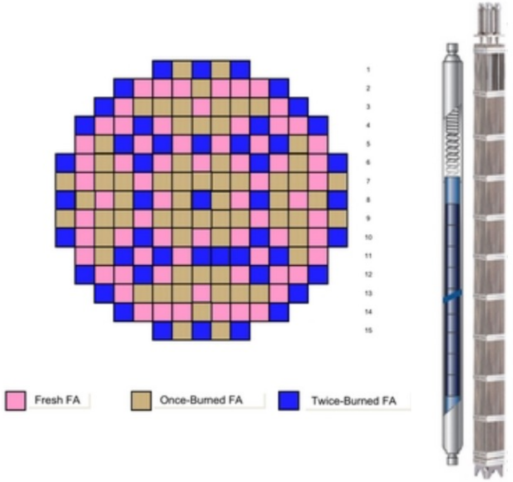




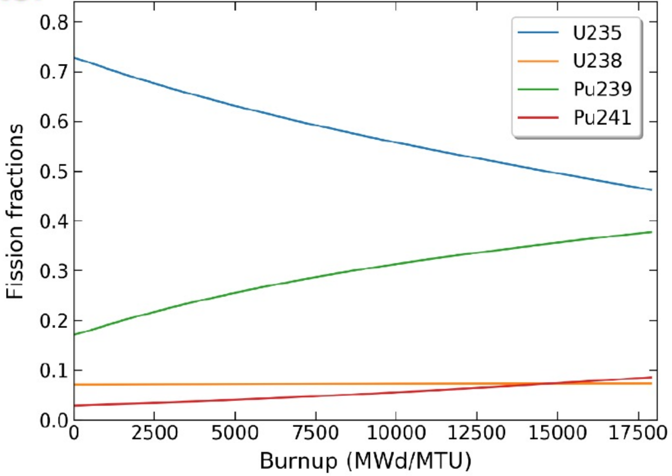
Hanbit-5 reactor and tendon gallery





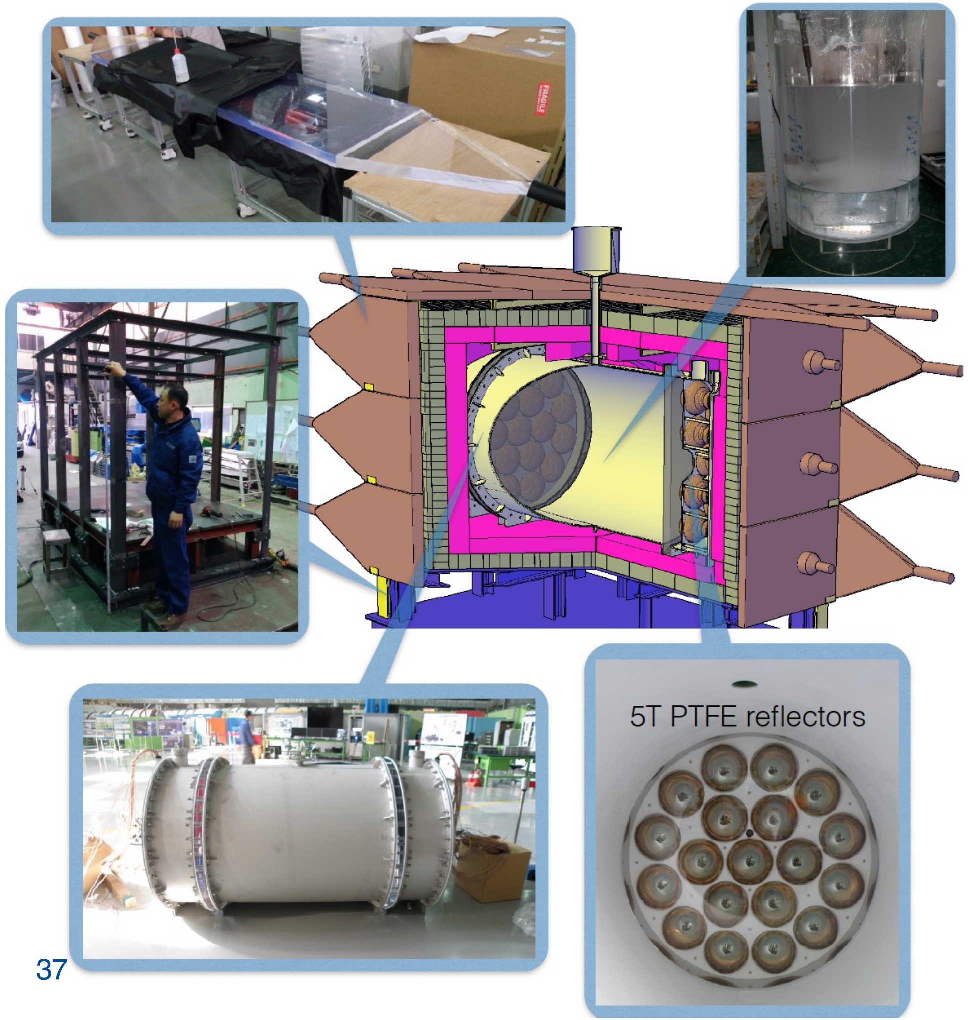


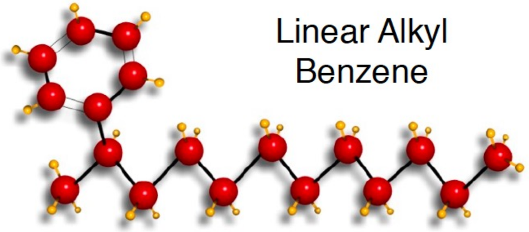
- Thermal power: 2.8 GW
- Active core size: Φ 3.1 m, H 3.8 m
- LEU fuel: ~4.x% U-235 enrichment
- Distance between neighboring cores: 256 m
- L = 23.7 m
- Overburden > 20 m.w.e.



NEOS Detector

- NEOS-II detector is refurbished from NEOS-I, almost identical.





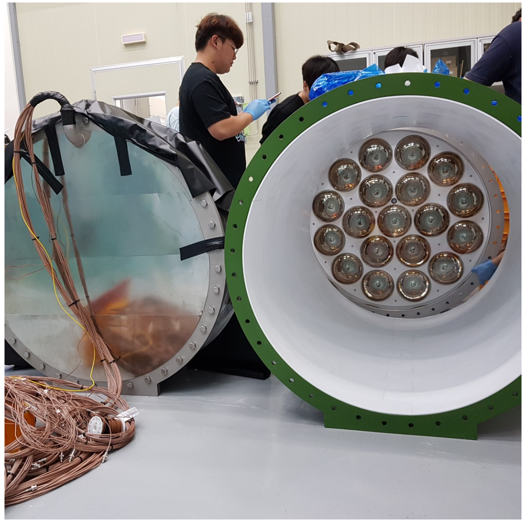
- Homogeneous LS target
  - 1008 L volume (R 51.5, L 121) cm
  - LAB+UG-F (9:1)
  - 0.5% Gd loaded for high neutron capture efficiency
  - 38 8″ PMT in mineral oil buffer
- Shieldings
  - 10 cm B-PE (n), 10 cm Pb (γ)
  - active muon counter
- Data AcQuisition
  - 500 MS/s FADC (waveform)
  - 62.5 MS/s ADC (μ veto)
- Source calibration through chimney

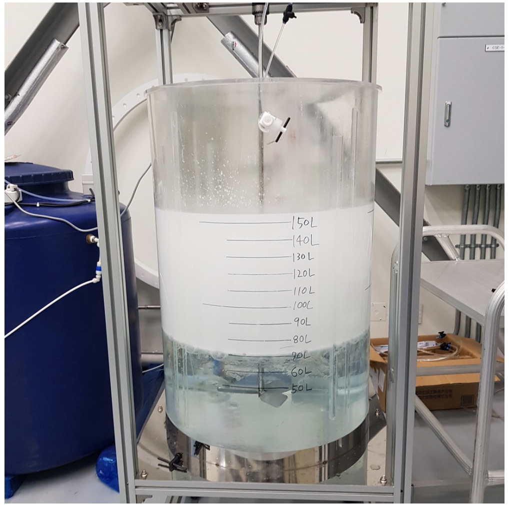
3% PPO
0.03% bis-MSB

* Newly produced Gd-LS w/ the same recipe

* 9/15 muon counters are newly prepared.

NEOS-II Preparation (July~Sept. 2018)

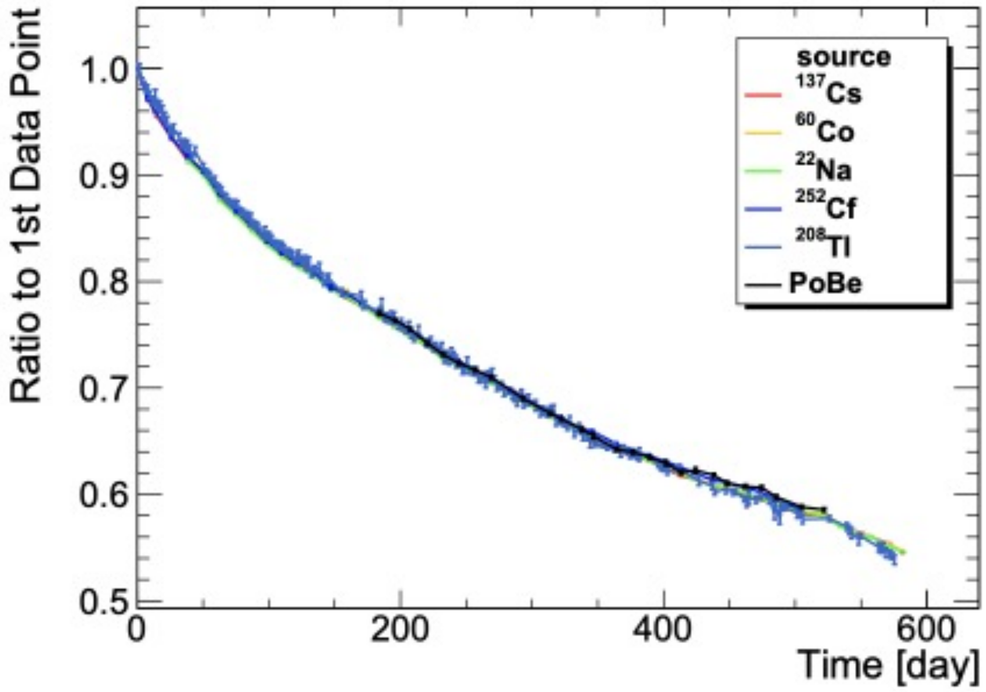


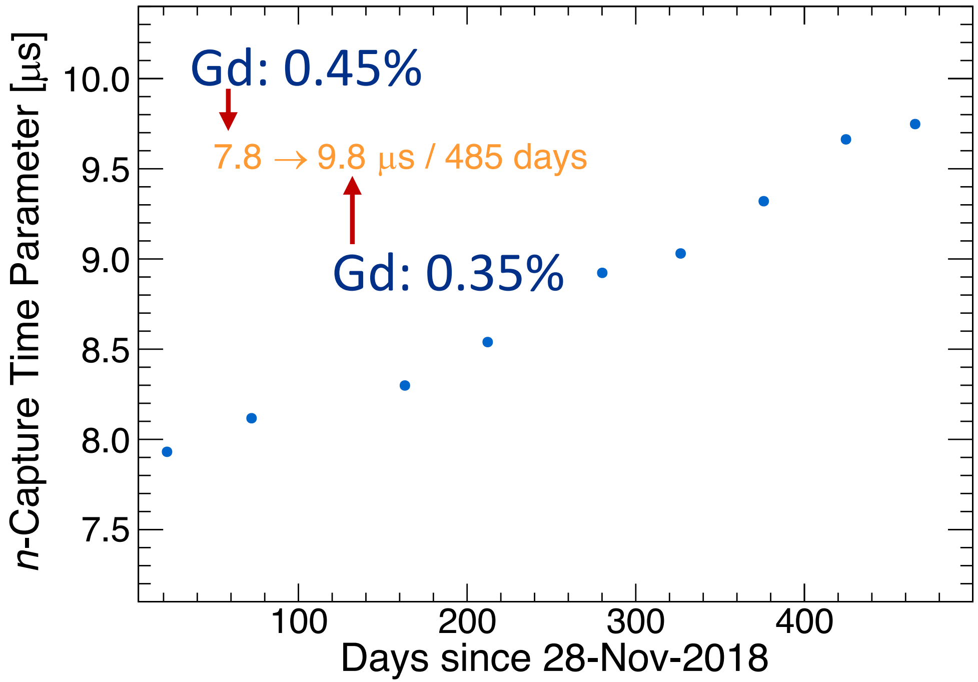


2018. Sept.

NEOS-II Challenge

- ➢ Continuous decrease of Light Yield (LY) during data-taking





Gd: 0.45%

7.8 → 9.8 μs / 485 days

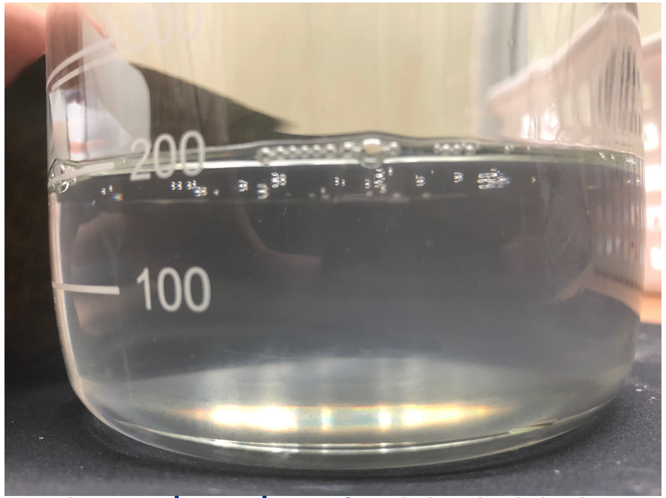
Gd: 0.35%

- ➢ ~46% decrease is observed at end of data-taking
- ➢ Light yield decrease is independent on energy.
- ➢ Delayed time increase is observed, too.

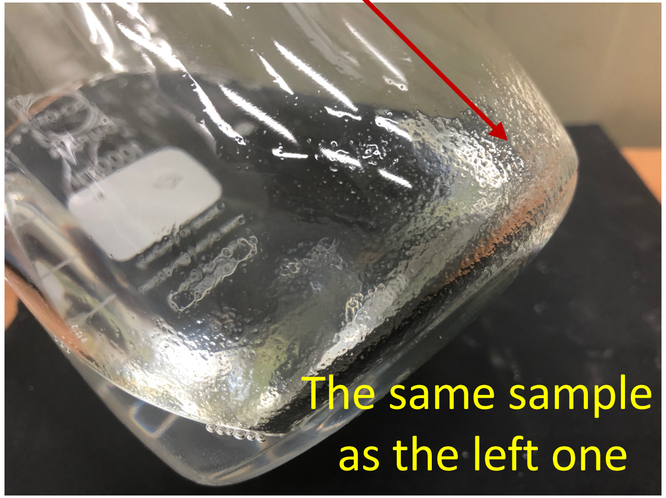
GdLS Sample from Target in 2019

* Precipitation was observed at the wall and bottom.

* Precipitation contains Gd compound.



Sample taken in 2019.03.05



The same sample as the left one

❑ Possible causes of LY decrease:

→ Inflow of humidity/oxygen to GdLS??

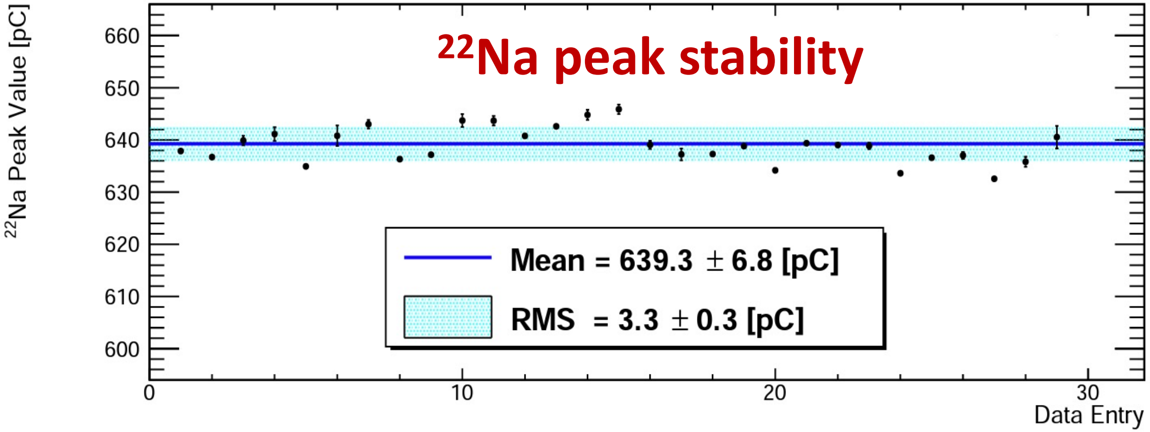
→ High concentration of Gd??

Coping w/ LY Decrease

1. Charge (pe) correction

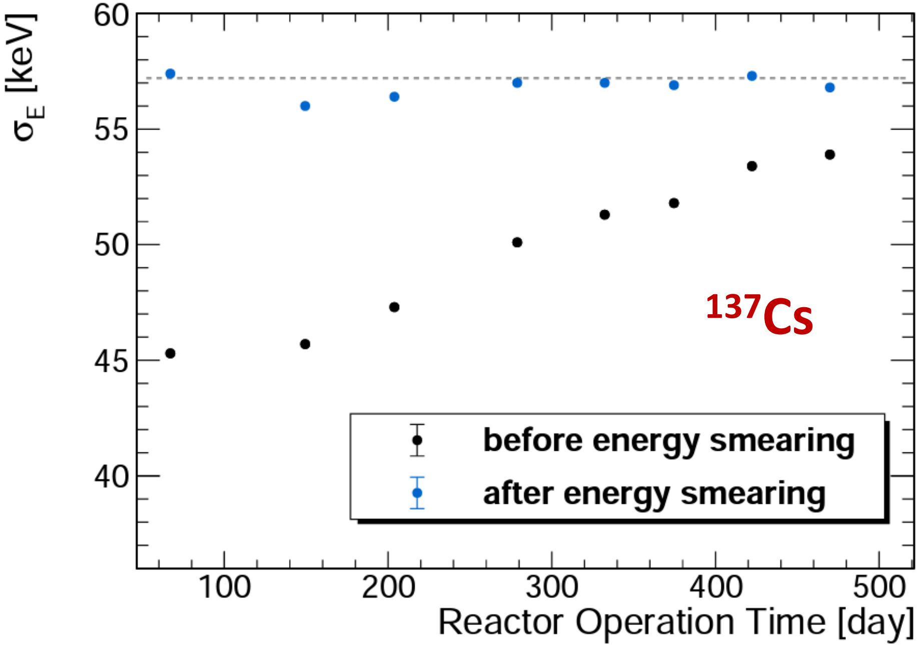
→ Reference: ^{208}Tl peak in data

→ This is always done regardless of LY decrease.



2. Energy resolution correction

→ Corrected to the worst energy resolution (7.3%)

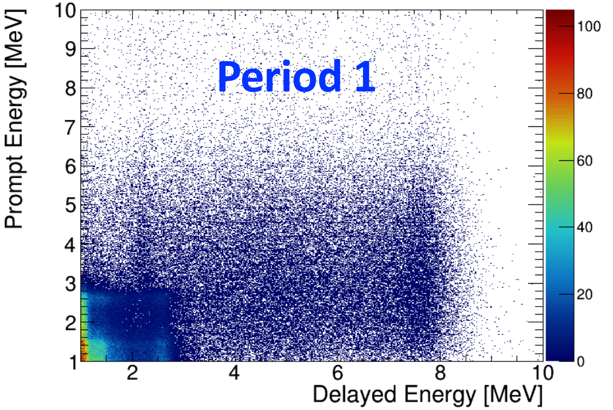


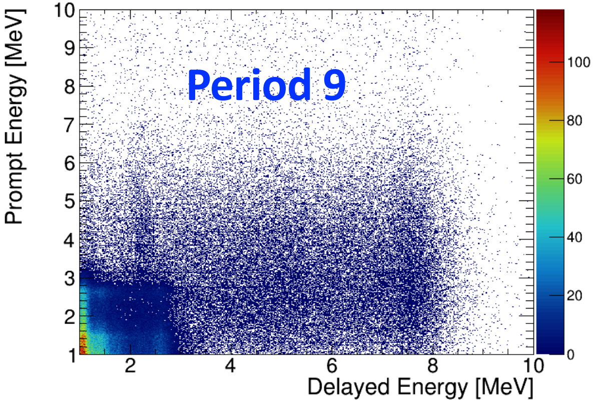
3. Change IBD selection cut values

→ To keep the same detection efficiency

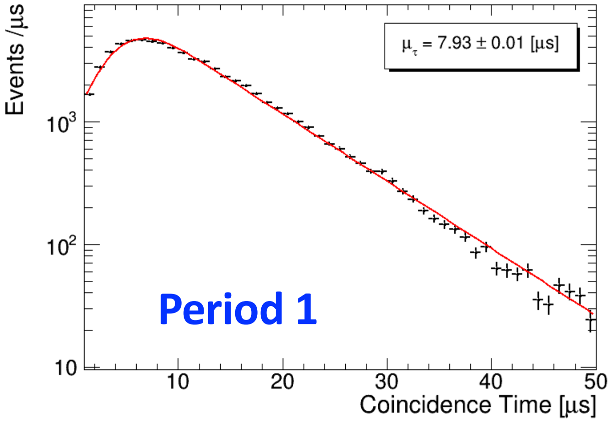
NEOS-II Initial & Last Data Sets

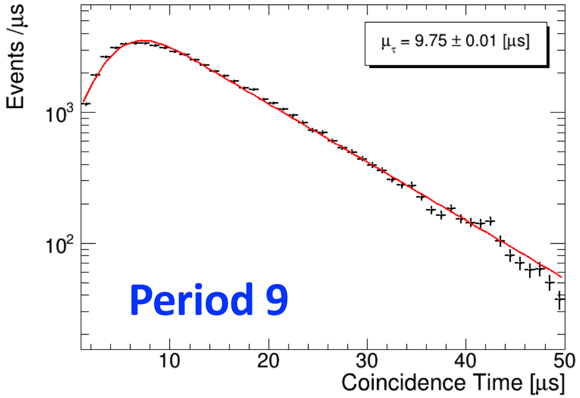
❑ Prompt Vs. Delayed Energy



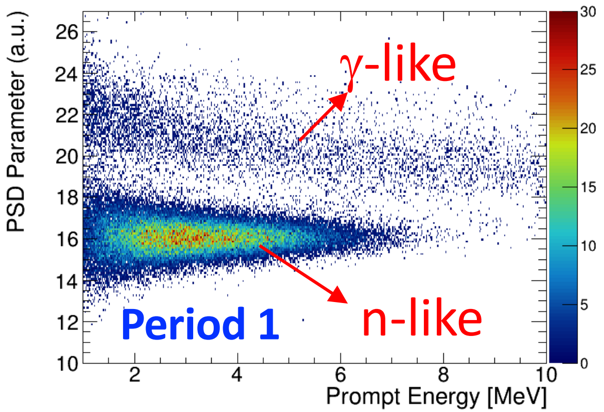


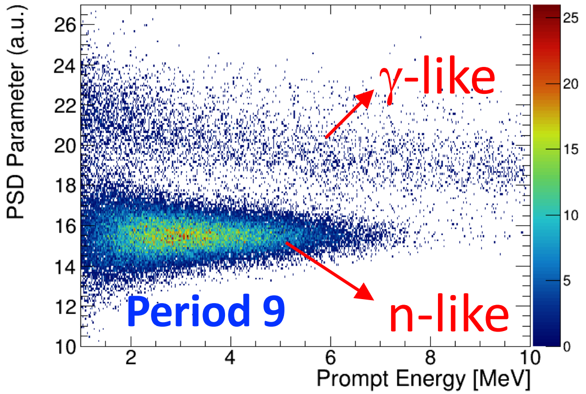
❑ Delayed Time





❑ Pulse Shape Discrimination



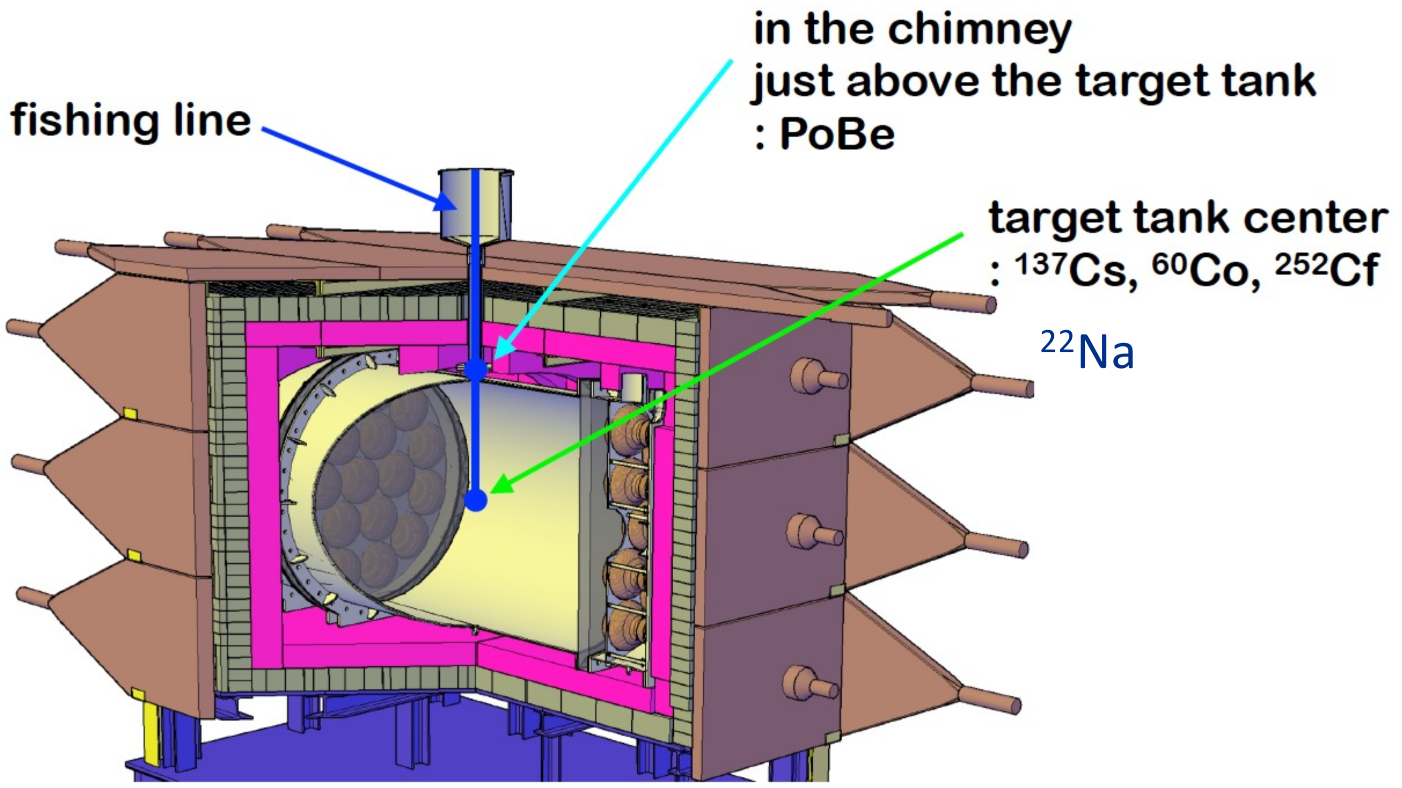


→ The latest data set (Period 9) looks fine!

Except for ΔT increase
& worse E resolution

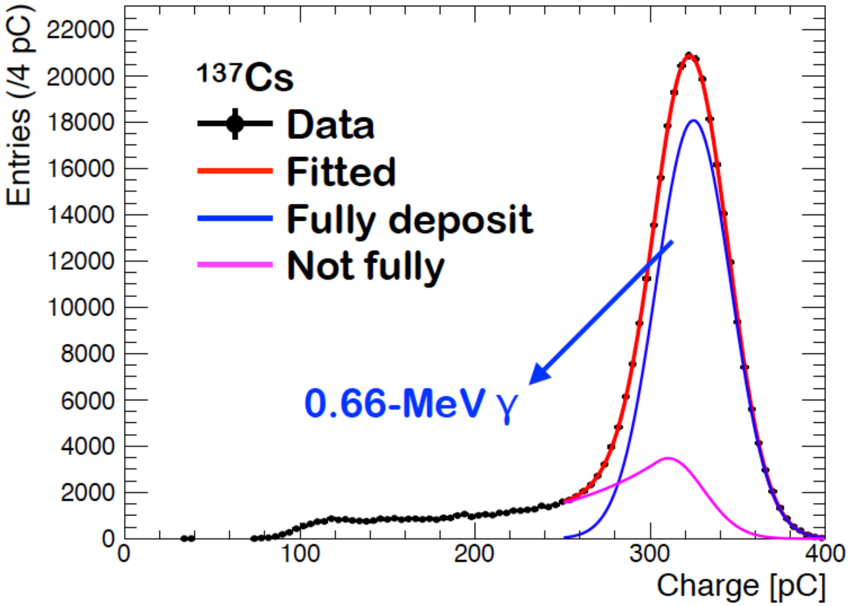
Energy Calibration (I)

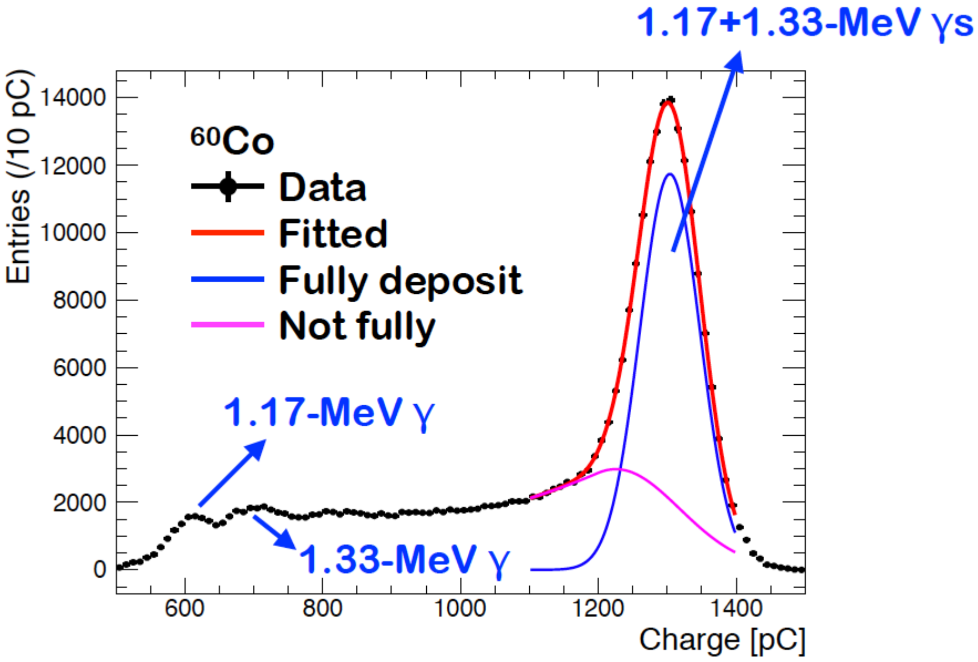
Bi-weekly, taking source data at the target center



- **^{137}Cs**: 0.66 MeV γ
- **^{22}Na**: 2.297 MeV γ
  (2x0.511+1.275) MeV
- **^{60}Co**: 2.505 MeV γ
  (1.173+1.332) MeV
- **^{252}Cf**: n-H (2.2MeV γ)
  n-Gd (~8 MeV γs)
- **PoBe**: 0.8/4.44 MeV γ + n

Energy Calibration (II)

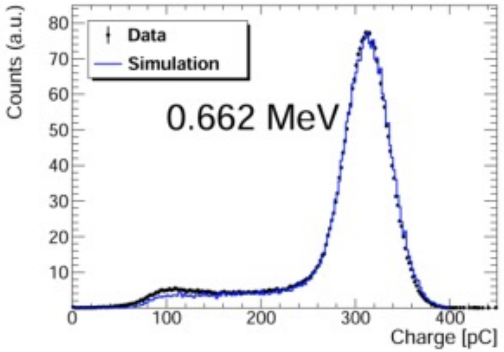




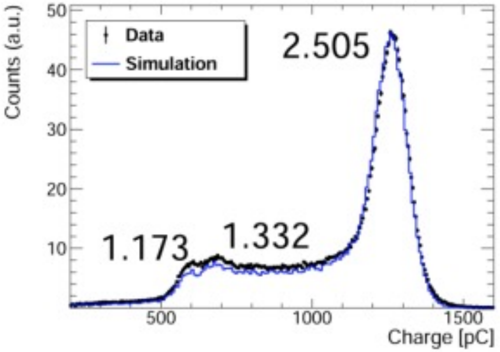
- Fully deposited γ events are modeled by a Gaussian.
- Not fully deposited γ events are fitted by a Crystal ball.

(There are many escaping γs due to the small size of the detector.)

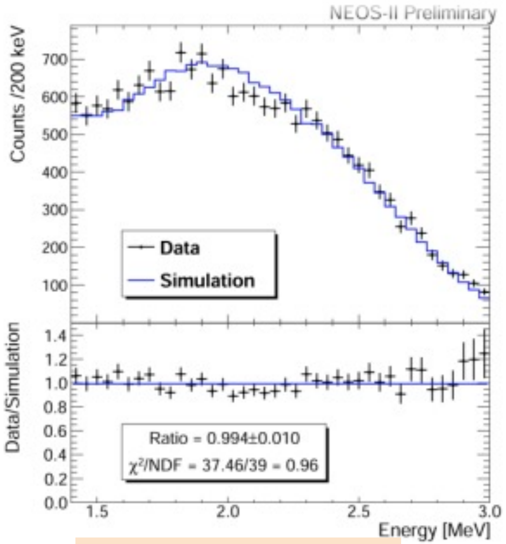
Source Data & MC



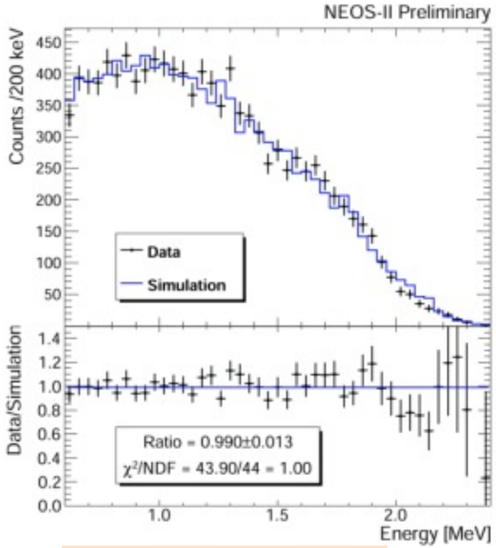
^{137}Cs



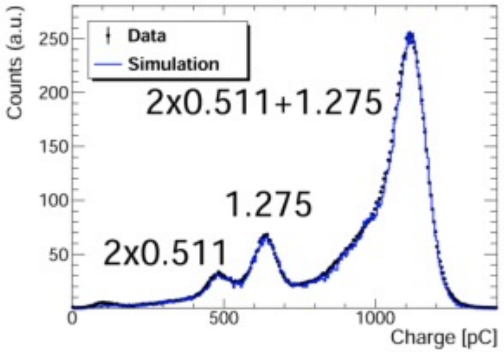
^{60}Co



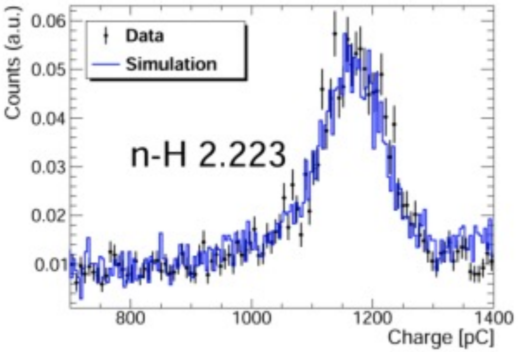
^{214}Bi → ^{214}Po



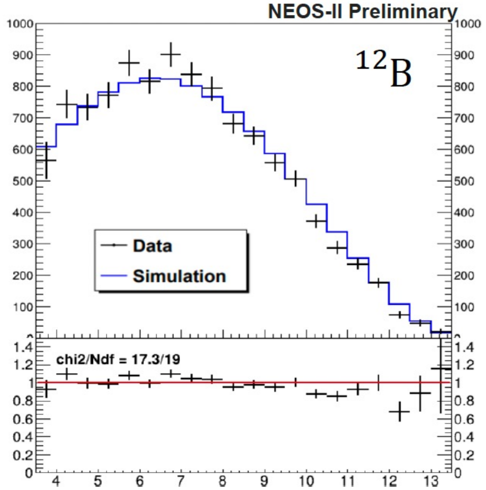
^{212}Bi → ^{212}Po



^{22}Na

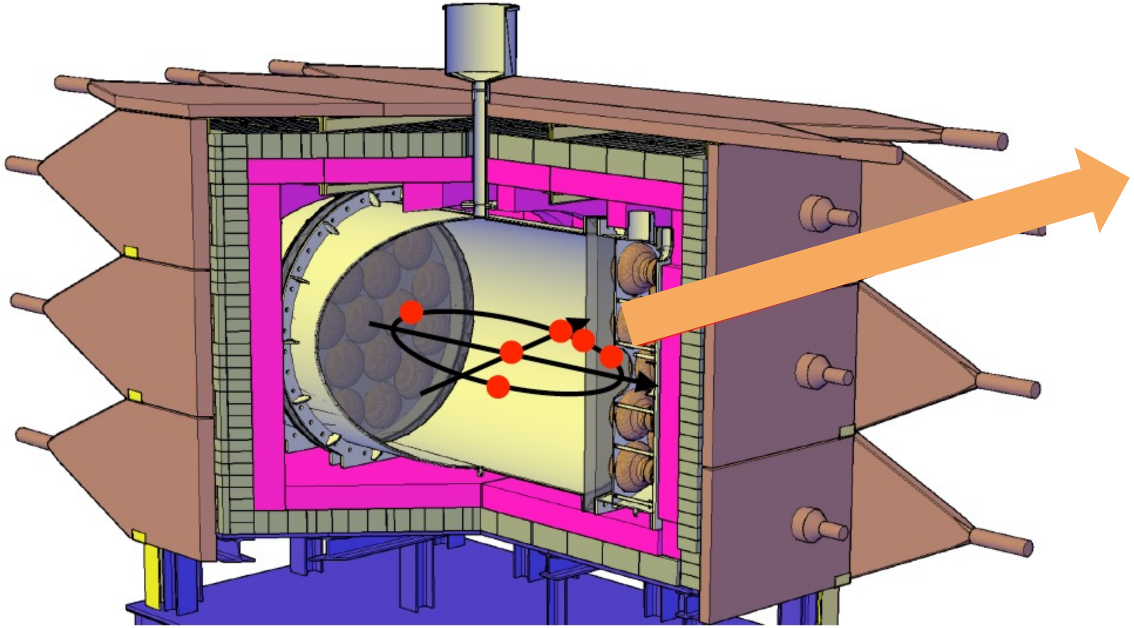


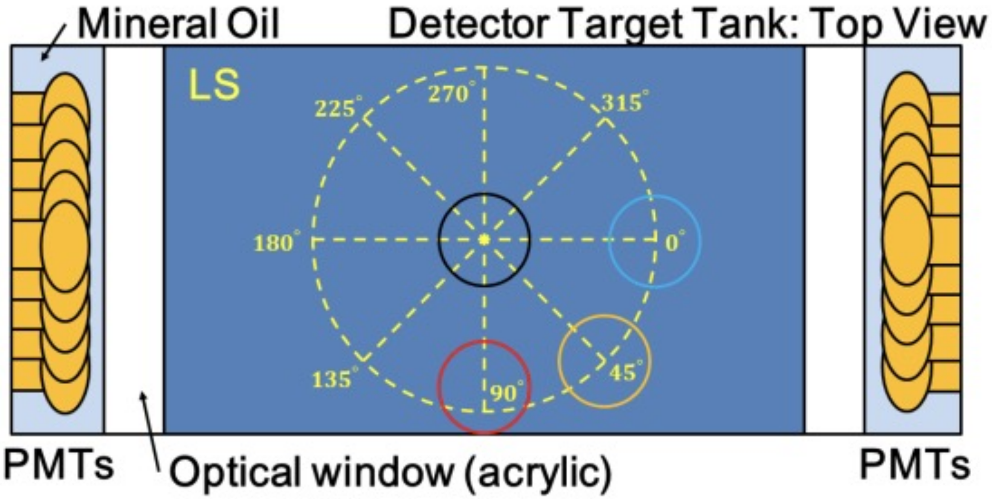
n-H

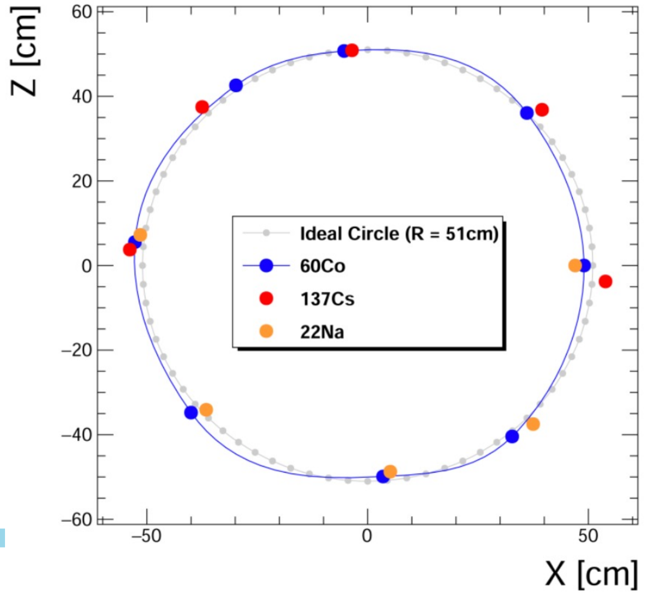


- ➢ Source Data & MC match very well!

2-D Calibration

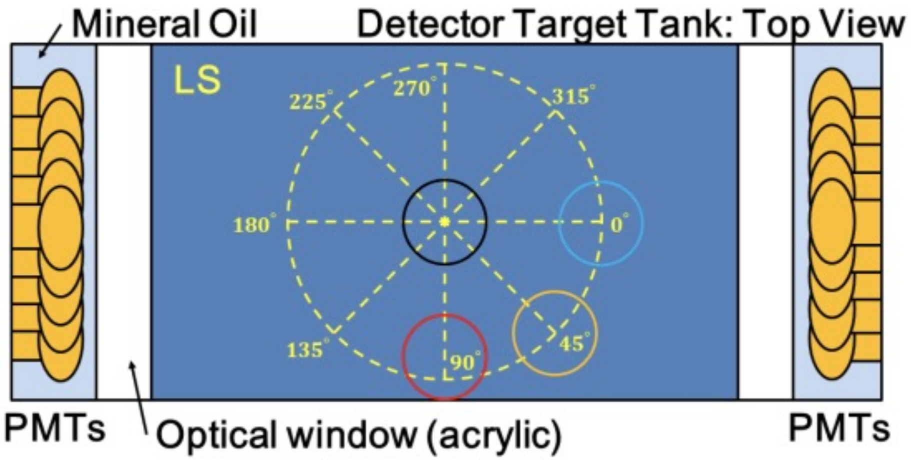




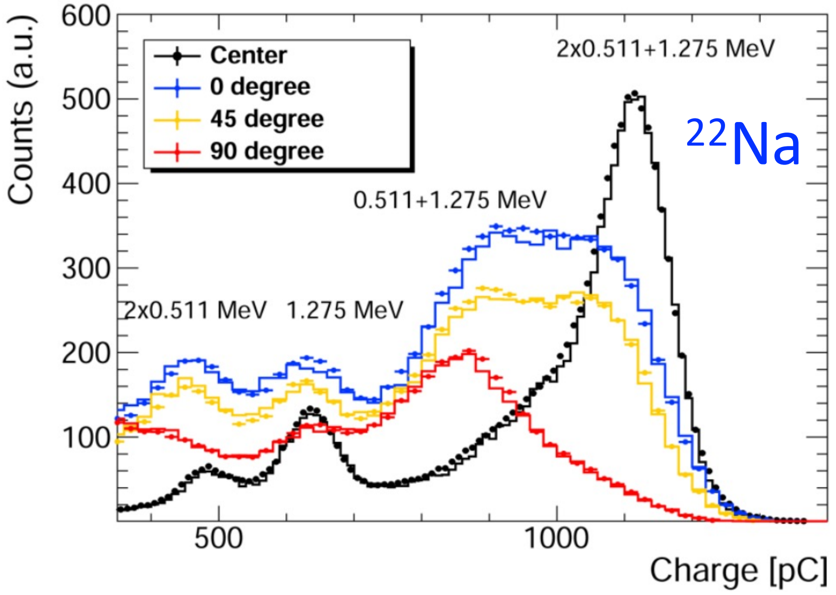


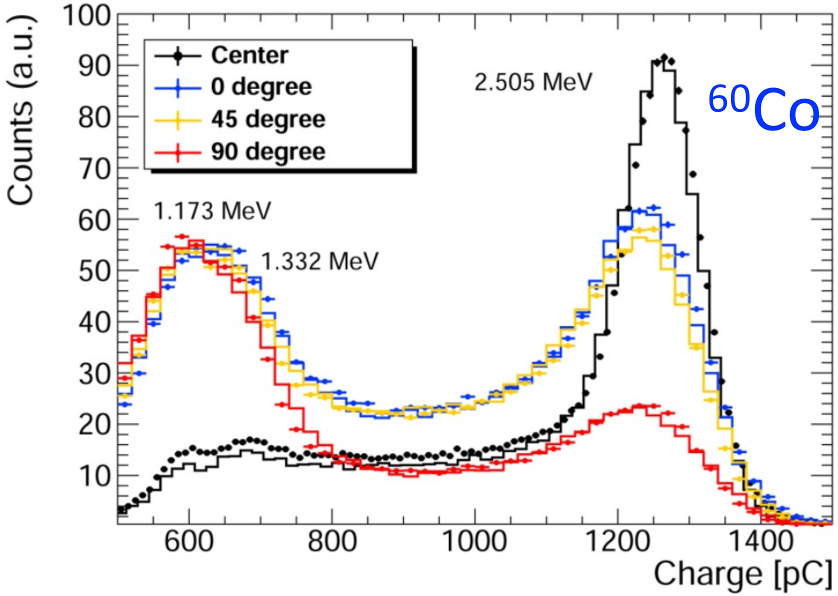
- 2-D calibration data was taken only once.

2-D Calibration

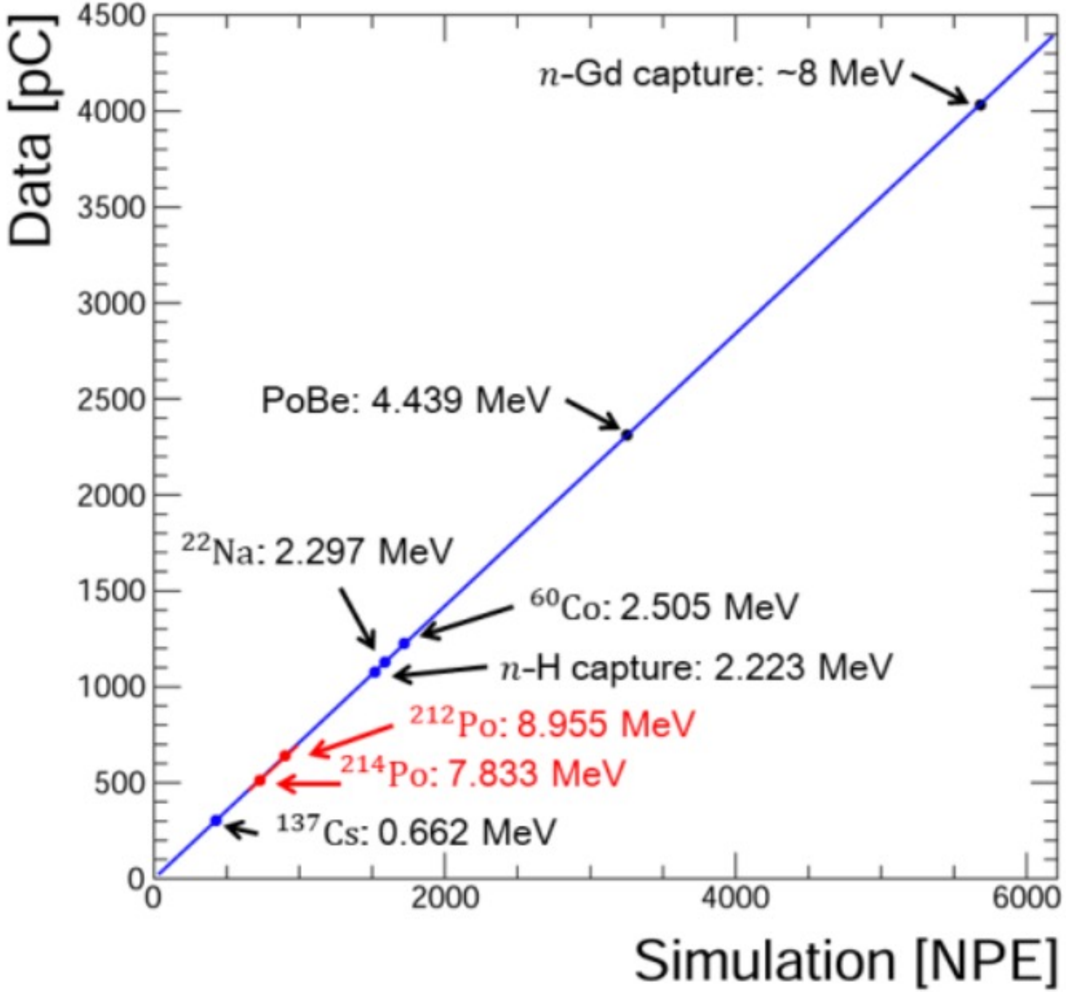


- ☐ Data and MC match well, including escaping γs.





Source Data Vs. MC



❑ Linearity between data and simulation for calibration sources

Note: all data points have participated in the fitting.

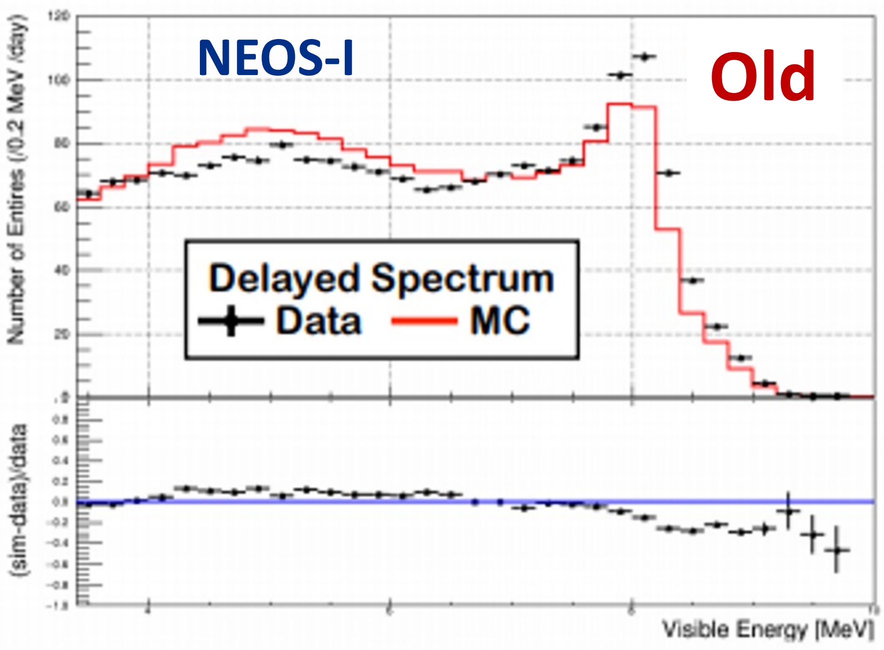
NEOS-II MC Improvement

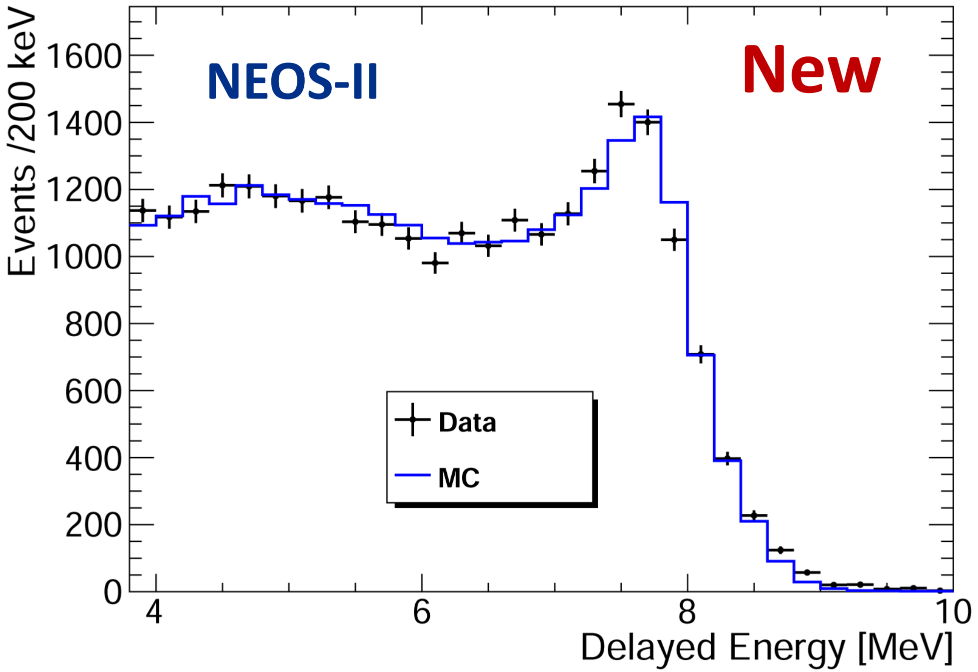
- NEOS simulation is based on Geant4.
  → full simulation including electronics simulation
- An update was made for NEOS-II.

- n-Gd MC update:
  GLG4Sim → new model (by Okayama Univ.)

ANNRI-Gd model

PTEP 2019, 023D01

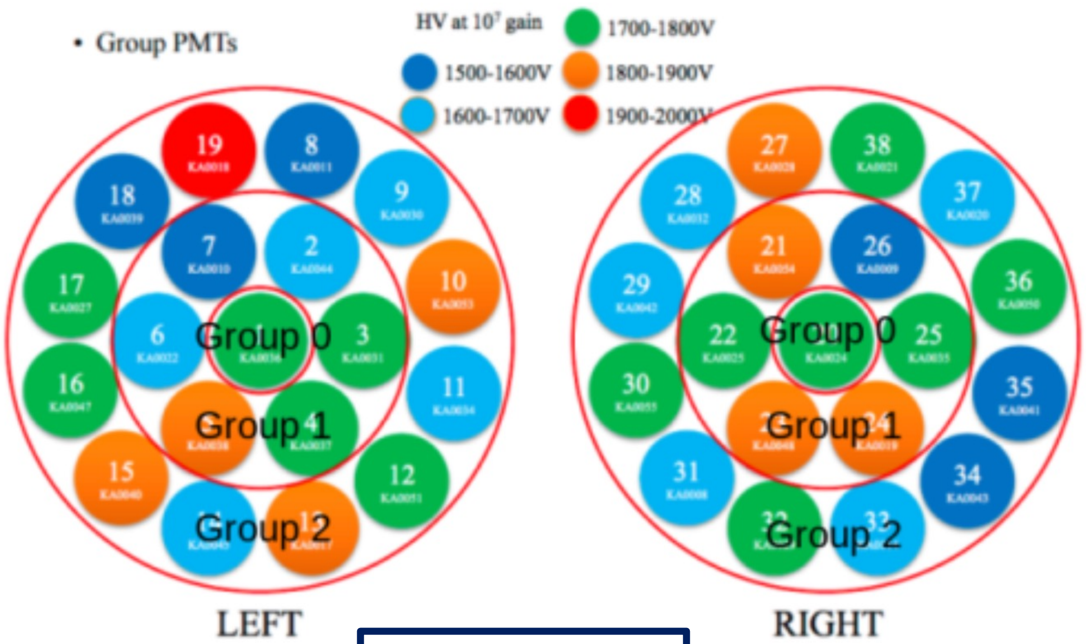


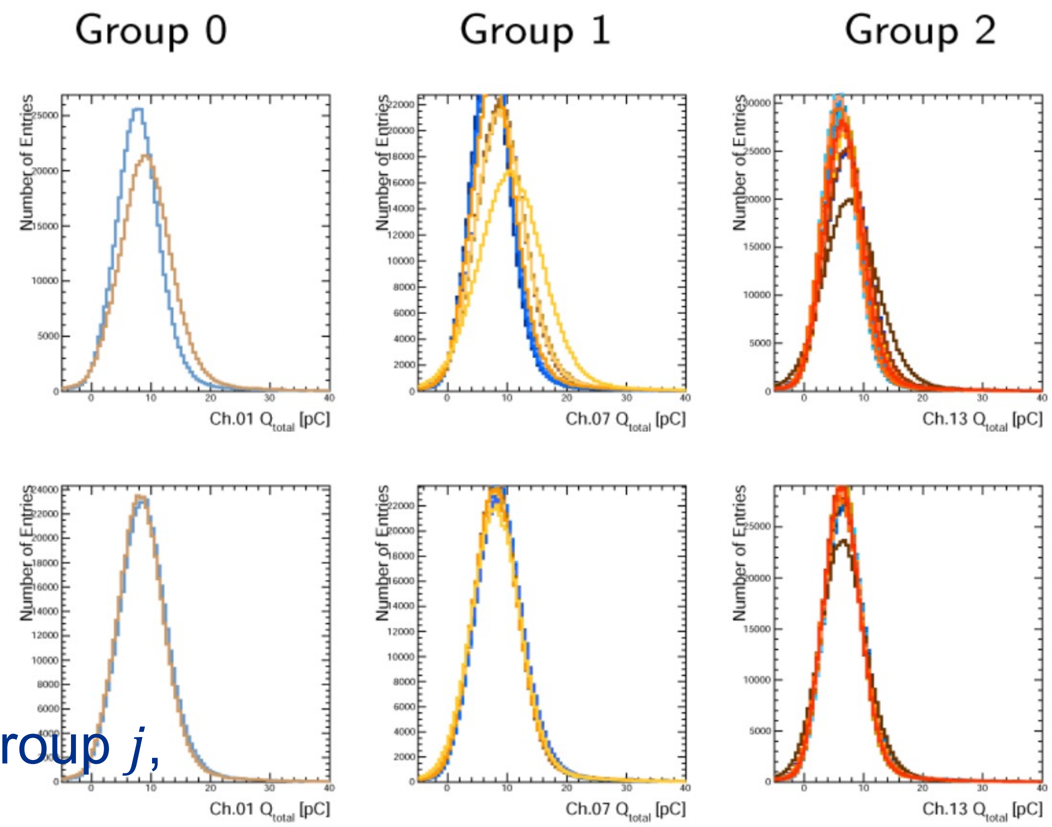


PMT Charge Correction

To correct PMT gain differences
& its drift over time

^{60}Co source data at the center position





$$C_i = \frac{< Q >_j}{\overline{Q_i}},$$

where $< Q >_j$ is the averaged charge value in group j, and Q_i is the mean charge value for i th PMT.

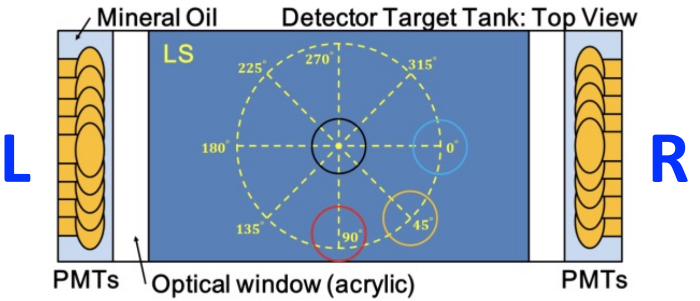
Energy Reconstruction (I)

Uniformity Correction

Stability Correction

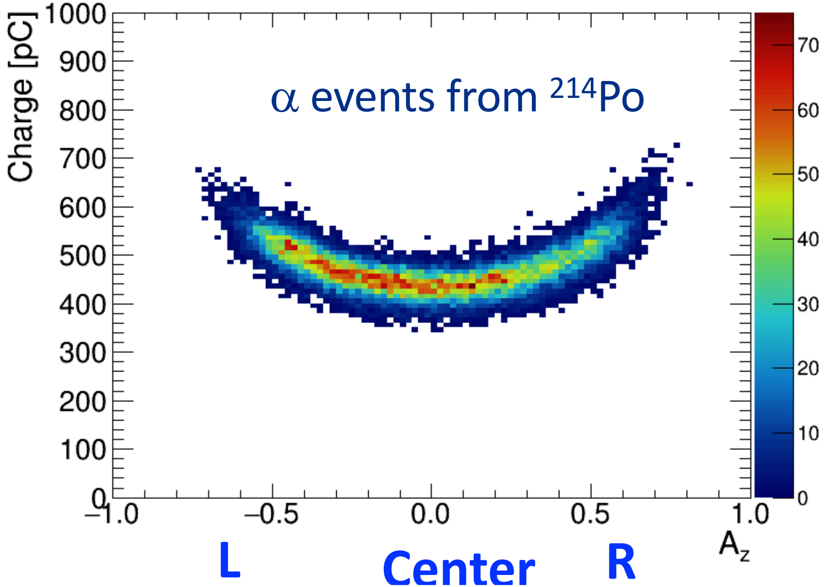
Charge to E Conversion

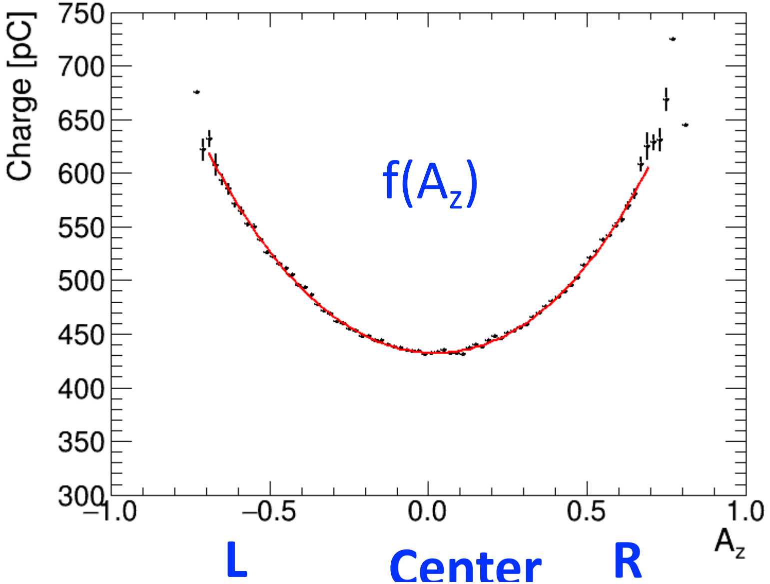
$$Q = S(t) \cdot \boxed{U(A_z)} \cdot \sum_{i}^{38} q_i$$



The charge has a position dependence along the cylindrical axis.

$$U(A_z) = \frac{f(0)}{f(A_z)}, \qquad \text{where } A_z = \frac{Q_r - Q_l}{Q_r + Q_l}$$





Energy Reconstruction (II)

Uniformity Correction

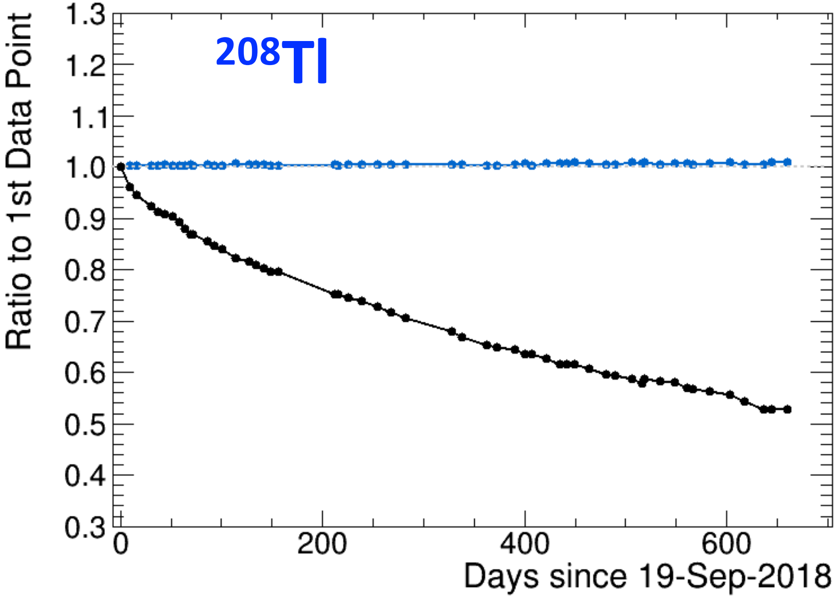
Stability Correction

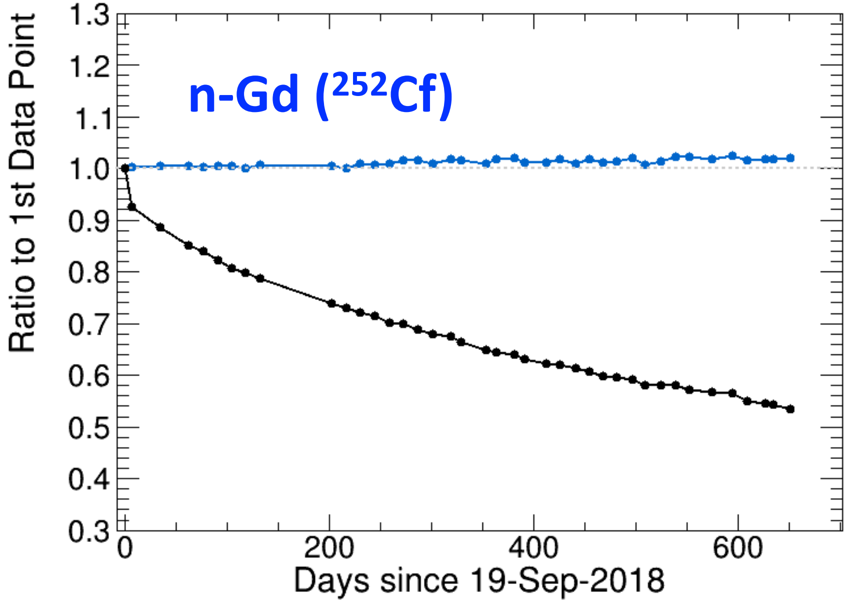
Charge to E Conversion

$$\boxed{Q = S(t) \cdot U(A_z) \cdot \sum_{i}^{38} q_i}$$

$$S(t) = \frac{Q(^{208}\mathrm{Tl}, 0)}{Q(^{208}\mathrm{Tl}, t)}$$

- ^{208}Tl is used as a reference for the stability correction.



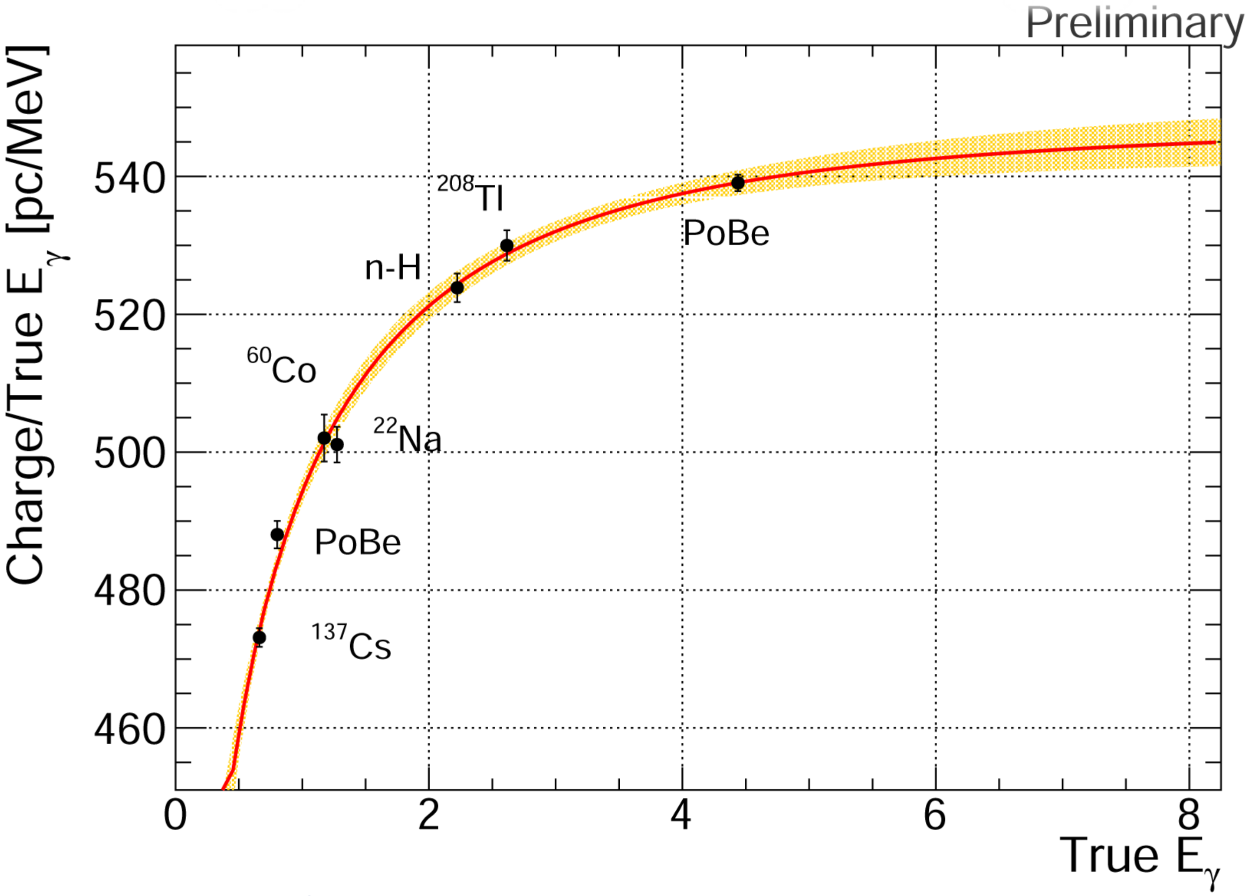


Energy Reconstruction (III)

Uniformity Correction

Stability Correction

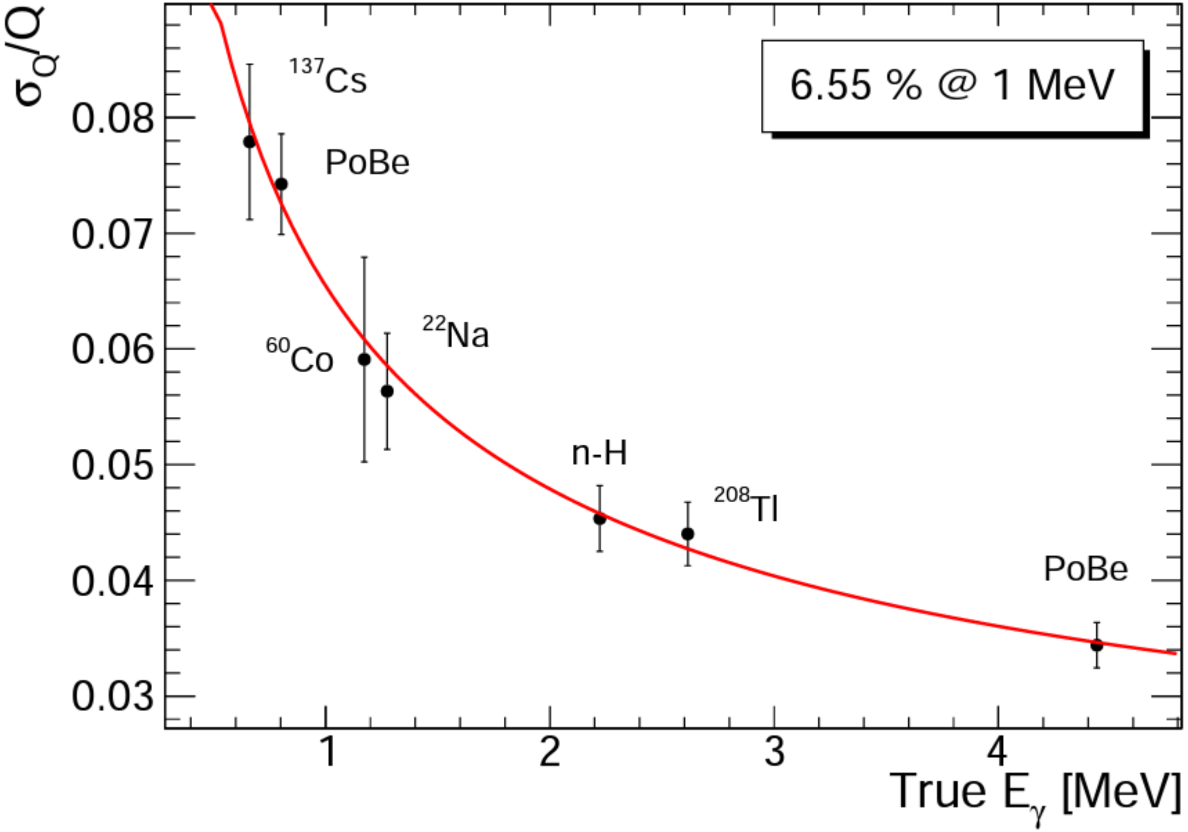
Charge to E Conversion



Fitting function:

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

Energy Resolution



All source data
are combined here.

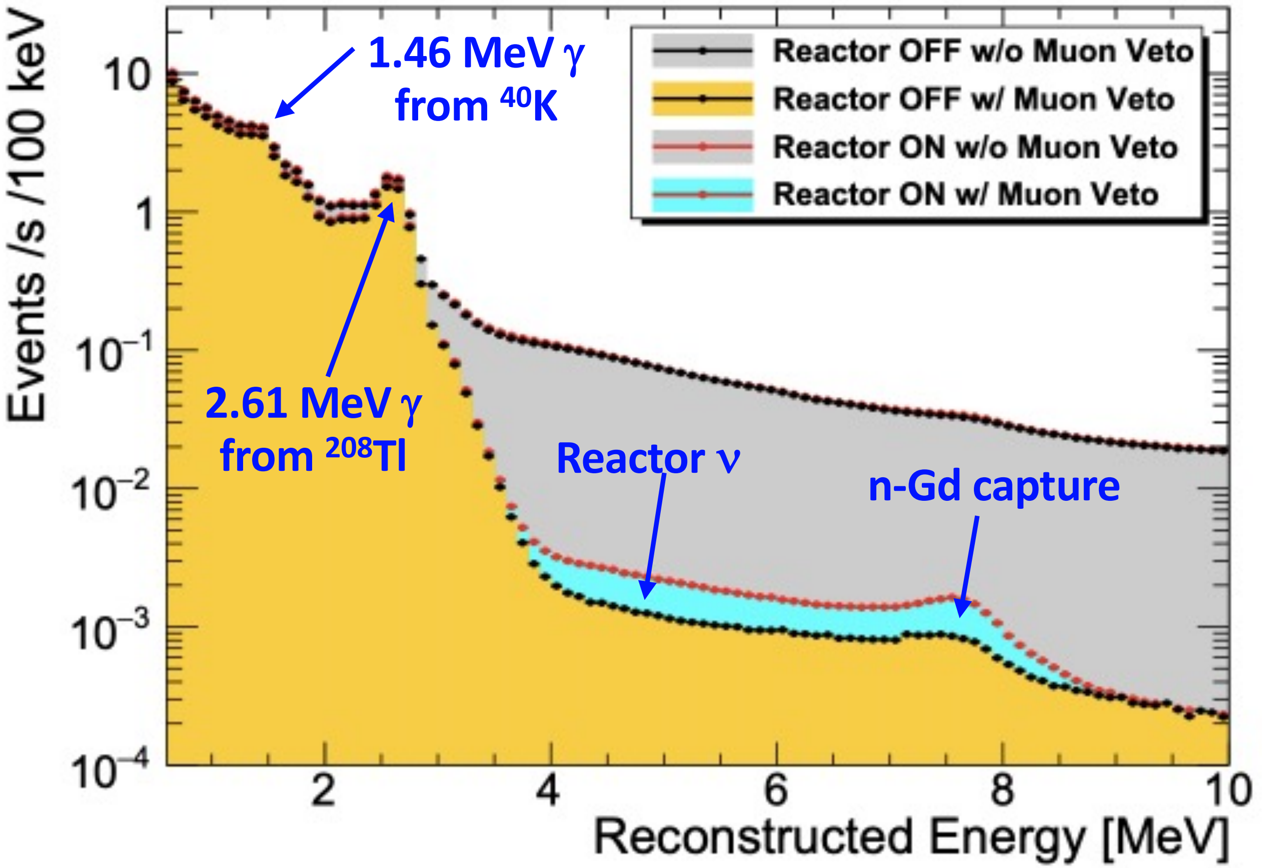
- Initial E resolution: 5.5%
- Final E resolution : 7.3%

@ 1 MeV

Fitting function

$$\frac{\sigma}{E_{\text{recon}}} = \sqrt{\frac{p_0^2}{E_{\text{recon}}} + p_1^2 + \frac{p_2^2}{E_{\text{recon}}^2}}$$

Single Event Spectrum



1.46 MeV γ from ^{40}K

2.61 MeV γ from ^{208}Tl

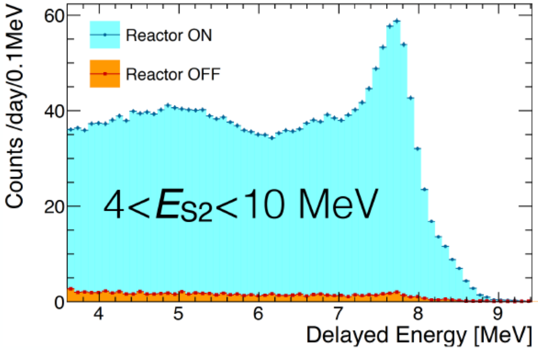
Reactor ν

n-Gd capture

- Muon rate: ~260 Hz
- About 80% single events survive after muon veto cuts

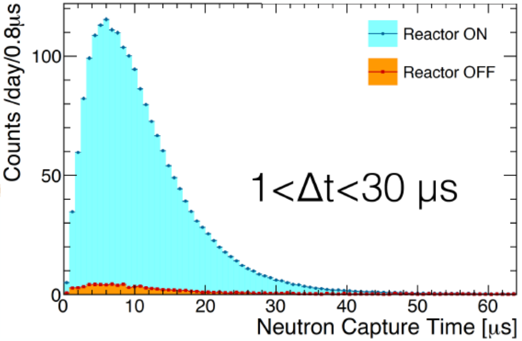
Inverse Beta Decay (IBD) Selection

$$p^{+} + \overline{\nu}_{e} \rightarrow e^{+} + n^{0}$$



Es2 cut

Δt cut



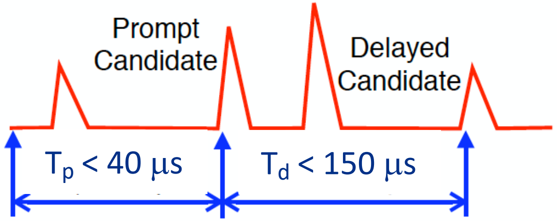
IBD Selection

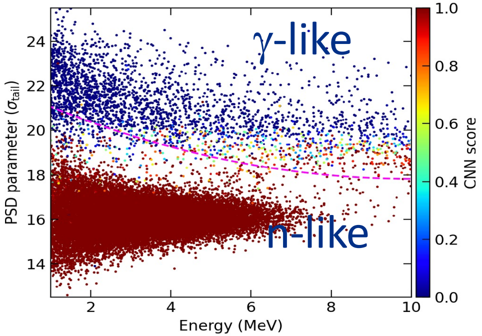
muon veto

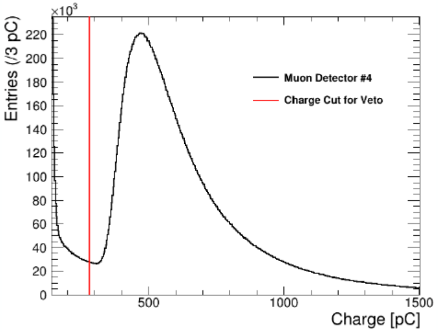
$\Delta t > 150$ μs

multiplicity cut

PSD



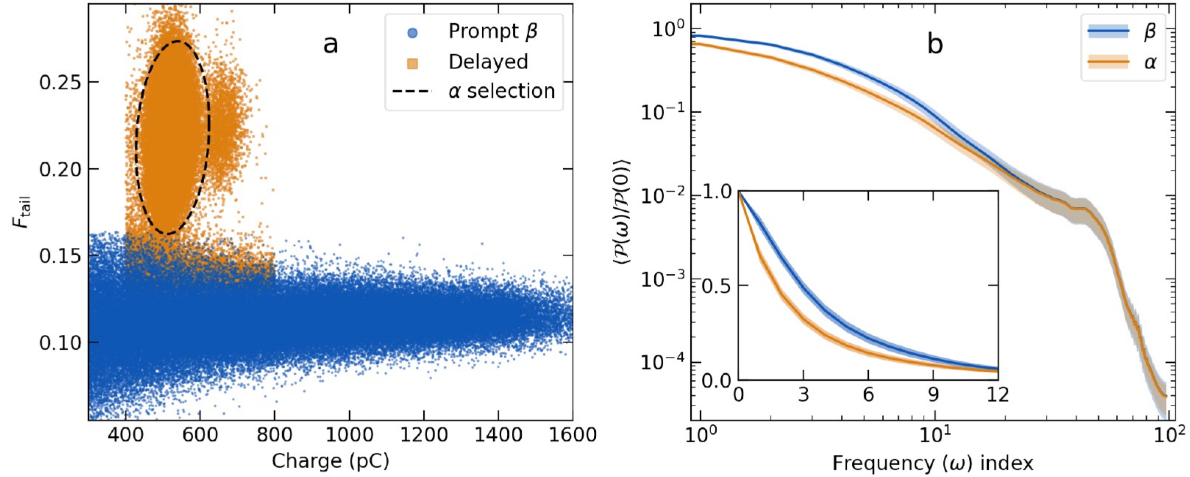


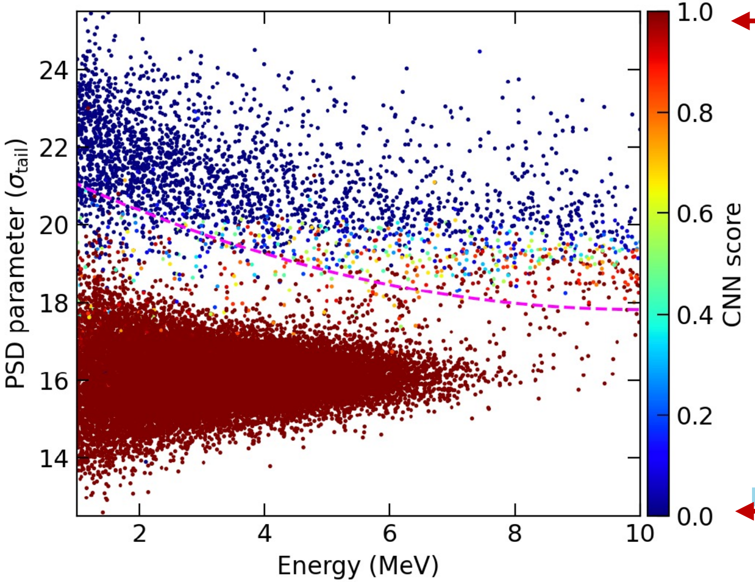


Maximum S/B

PSD Cut: CNN

- CNN + waveform (FFT)
- Low energy background reduced by up to 40% compared to Q_tail/Q_total method.

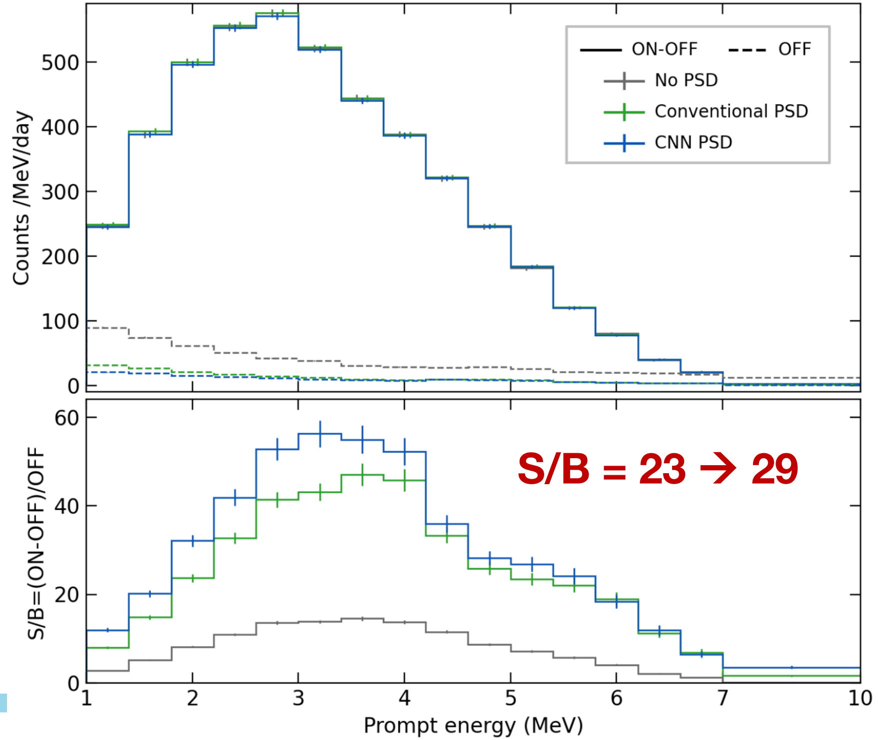




γ-like

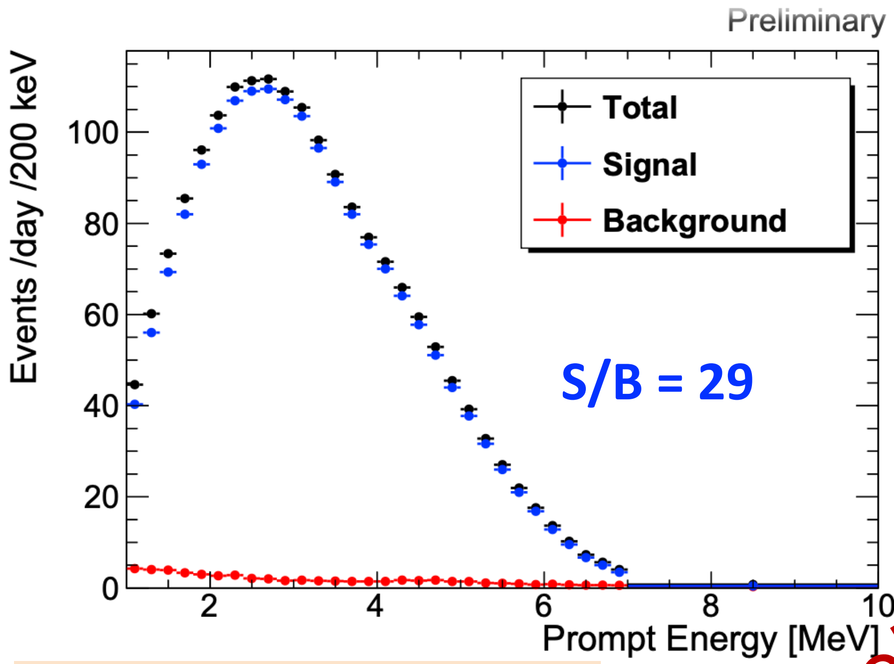
n-like

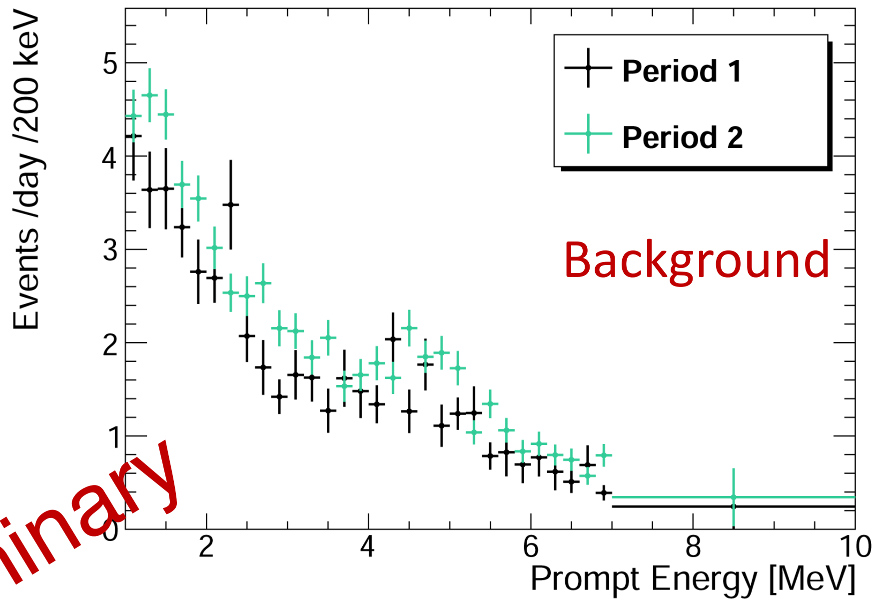
arXiv:2211.07892



S/B = 23 → 29

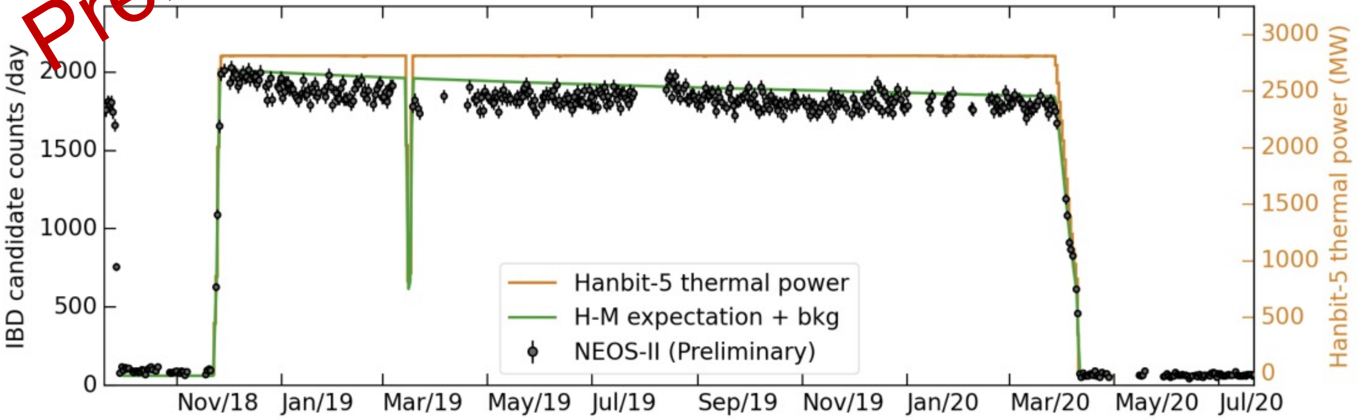
IBD Candidates & Background





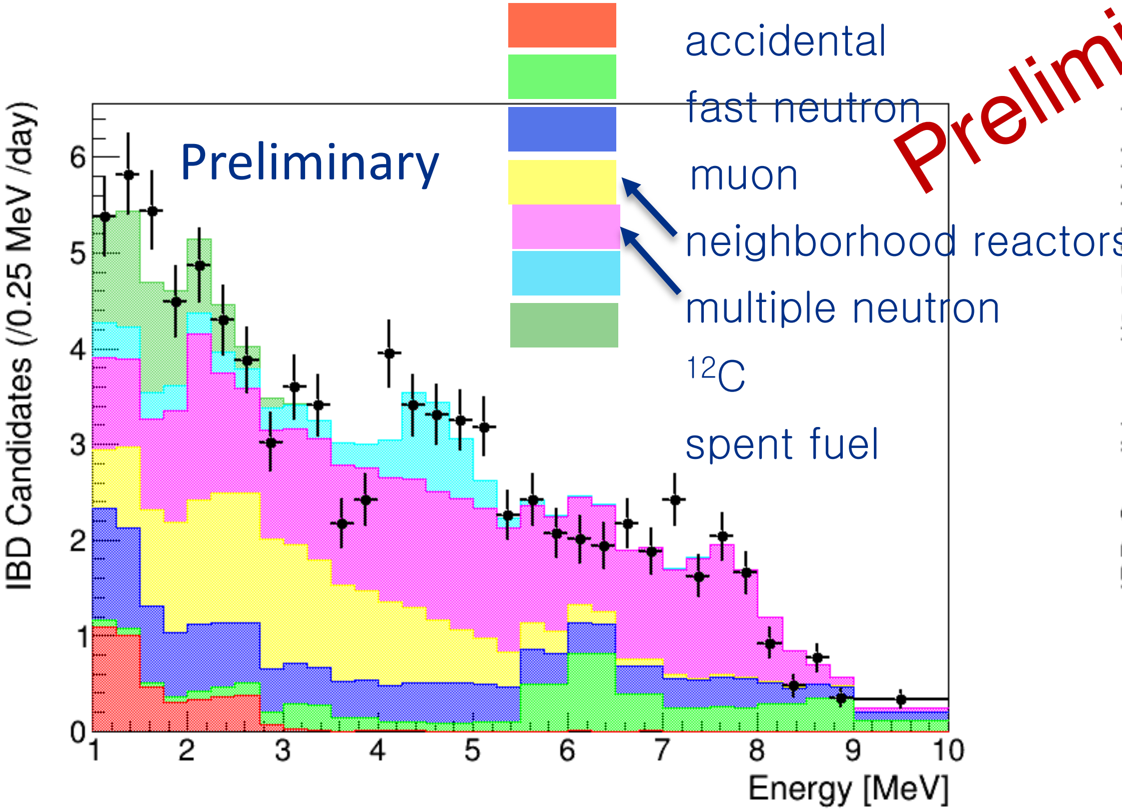
Preliminary

- ☐ **IBD Candidates:**
  (1846.1 +/-2.2)/day
- ☐ **Background:**
  (61.3 +/- 0.4)/day
- ☐ IBD Signal:
  (1784.8 +/-2.1)/day

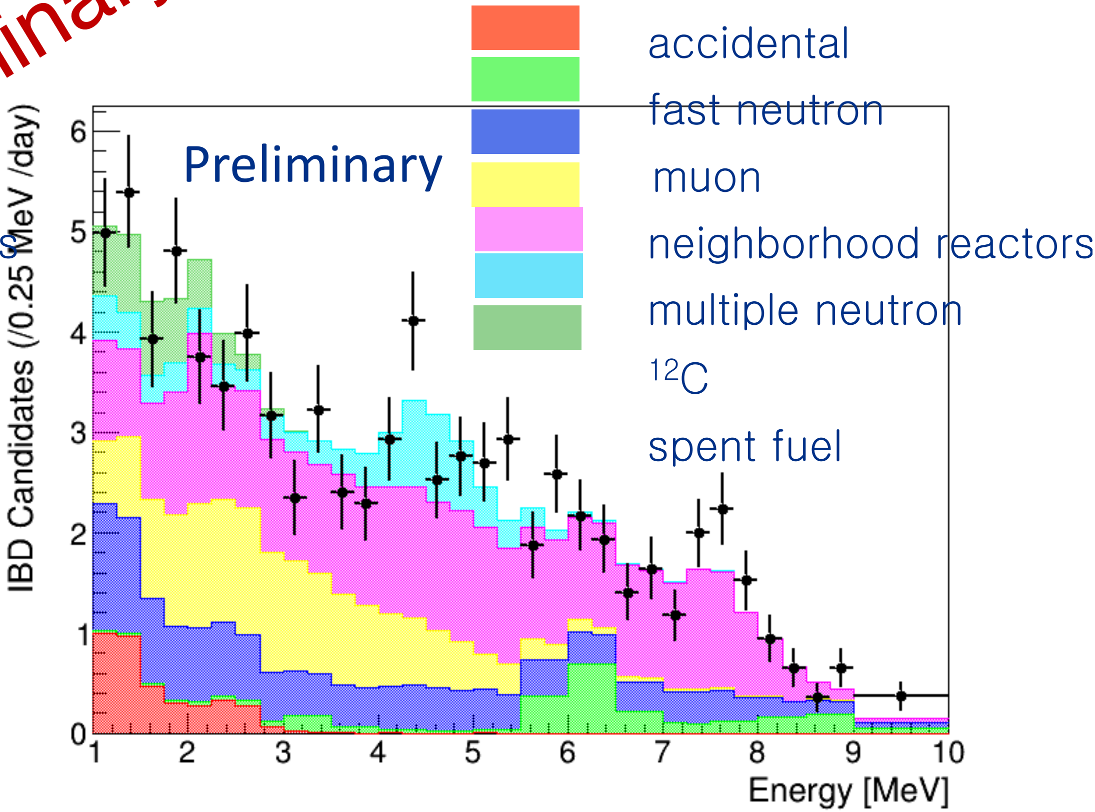


NEOS-II Background Compositions

Preliminary

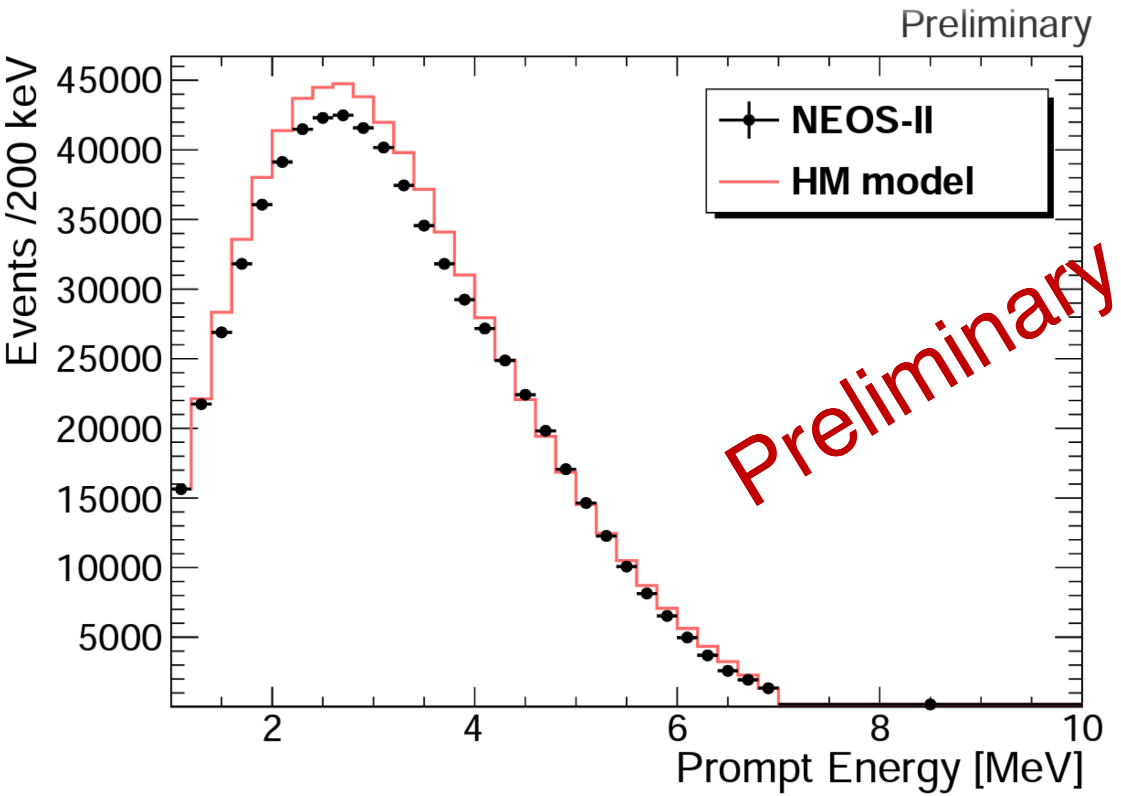


Reactor-OFF 1 (45 live days)

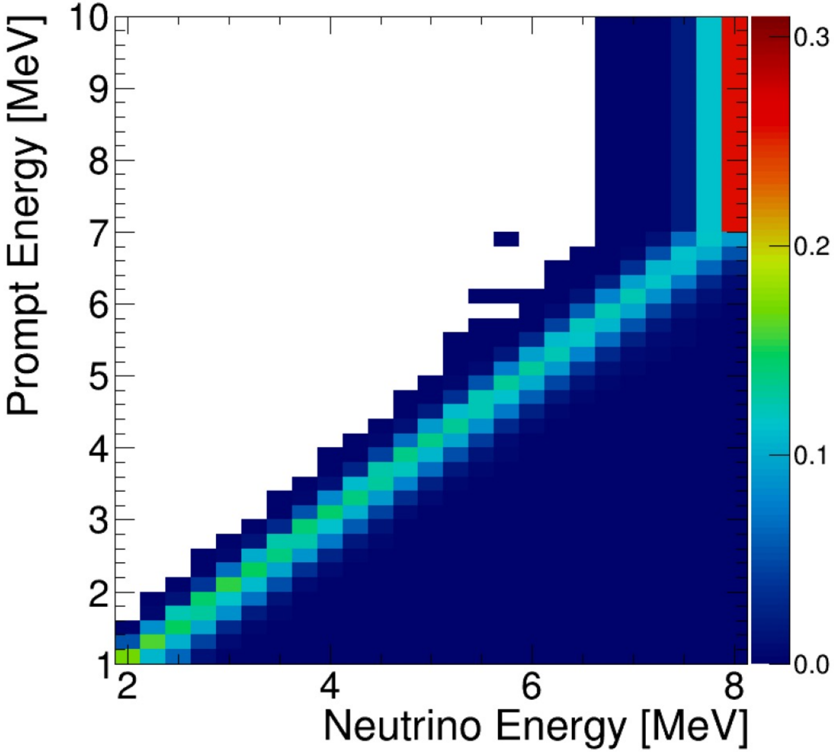


Reactor-OFF 2 (67 live days)

IBD Prompt Spectrum



- Detector response matrix

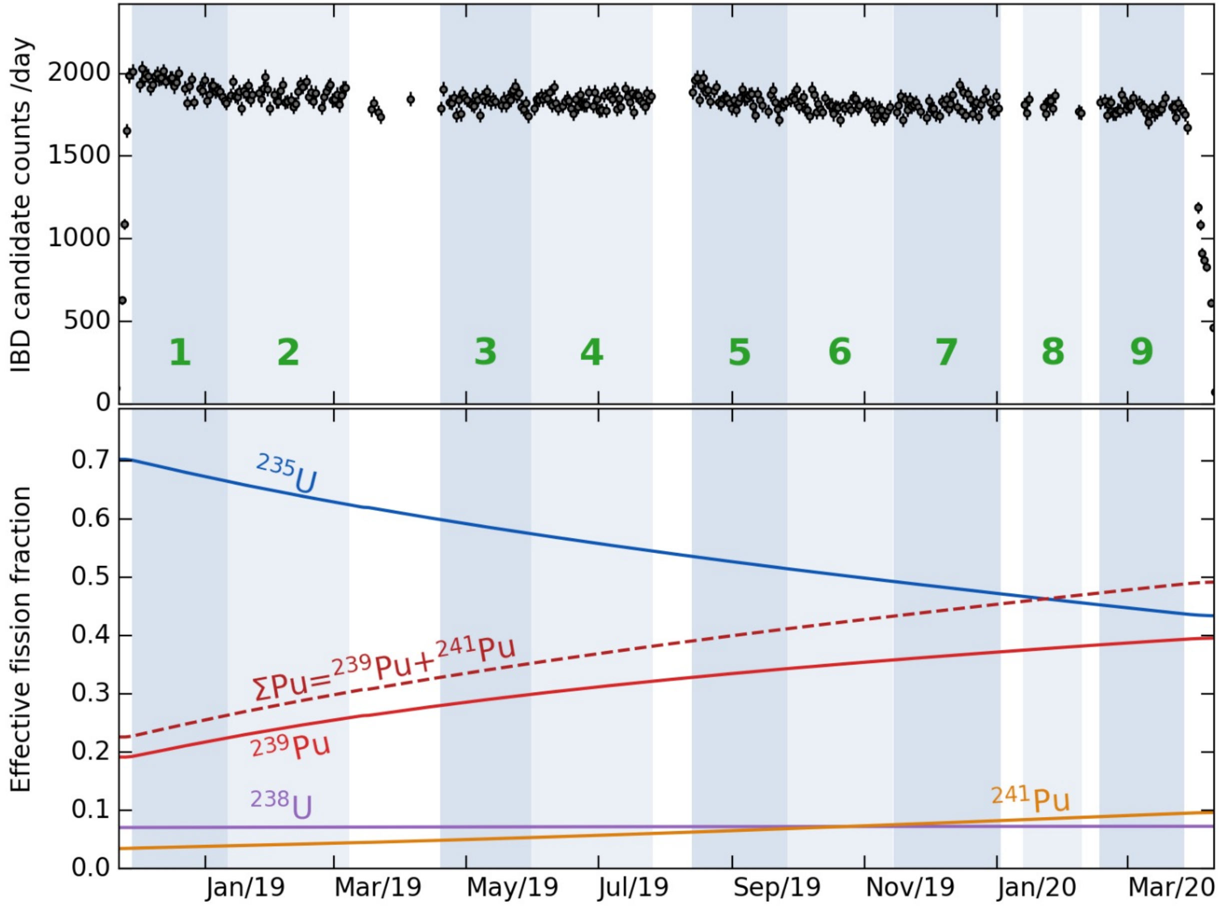


- The Averaged Fission Fractions

Fission Isotope	^{235}U	^{239}Pu	^{238}U	^{241}Pu
NEOS-II	0.57	0.30	0.07	0.06

Huber-Mueller (HM) model

9 Groups of Data

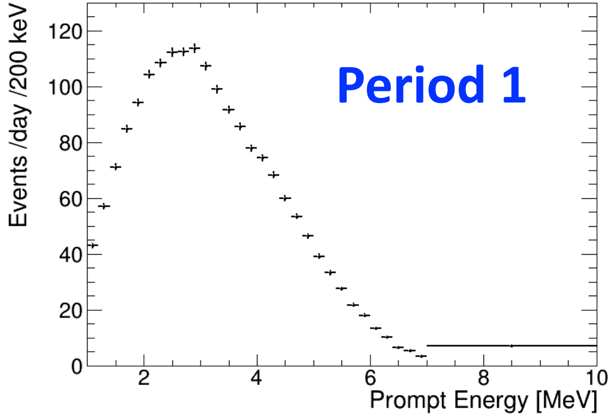


time

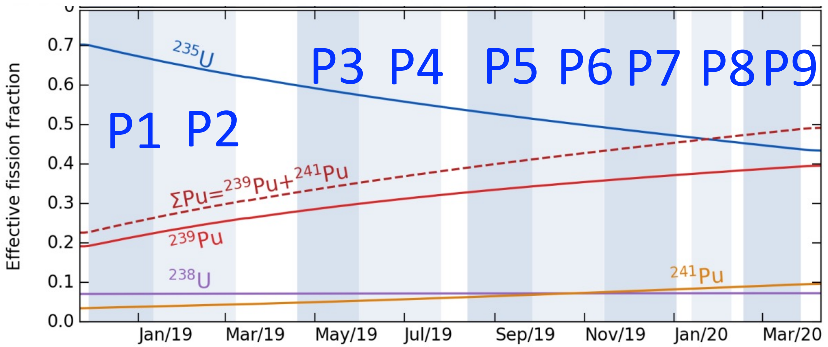
- Data is grouped into 9 to observe the evolution of reactor ν flux/shape.

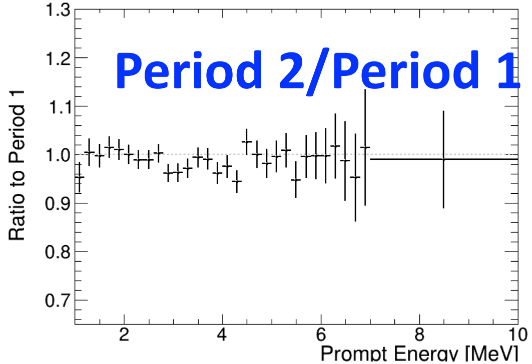
- IBD selection cuts are applied to each group of data to keep the same detection efficiency.

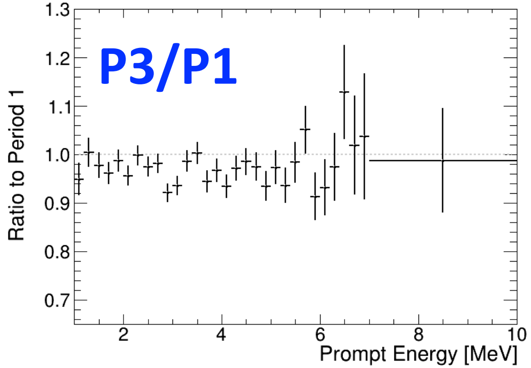
Evolution of Reactor ν spectra

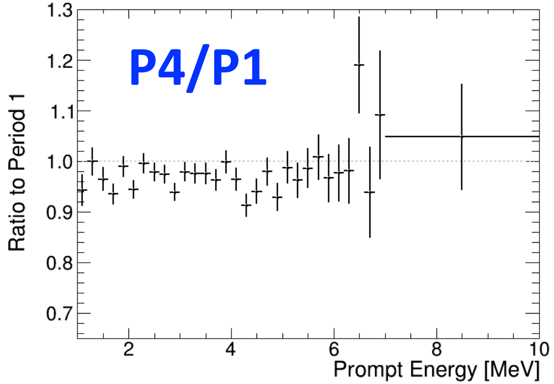


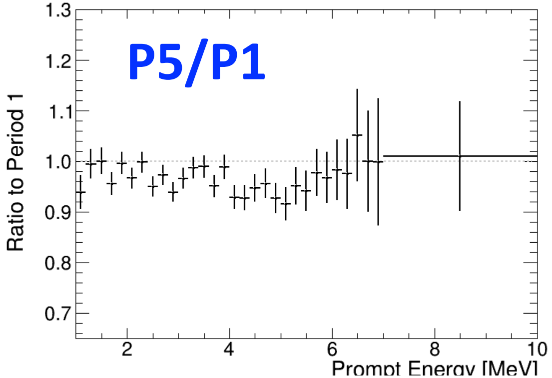
Preliminary

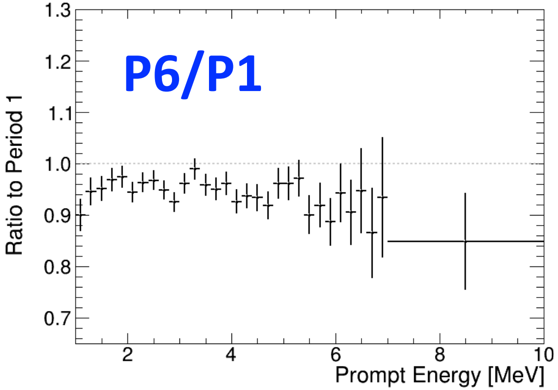


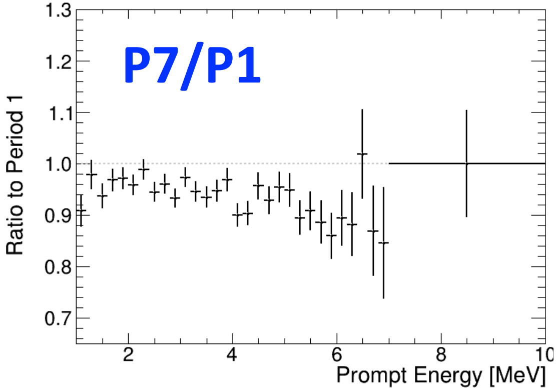


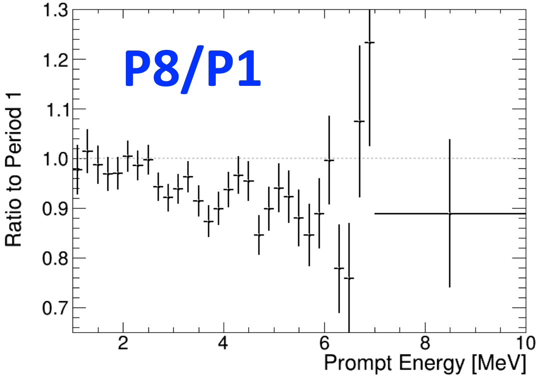


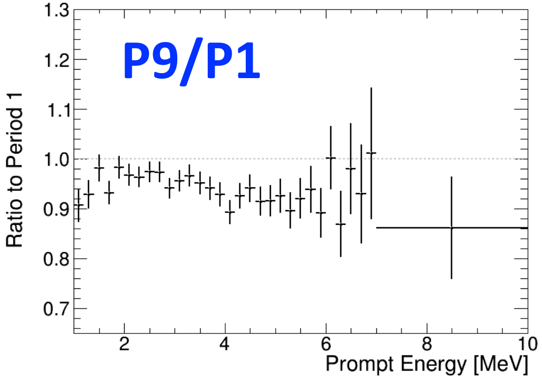












NEOS-II Systematic Uncertainties

preliminary

Parameter	Value / efficiency	Uncertainty
Number of target proton	6.20×10^{28}	1%
Distance	23.7 m	2%
Delayed energy, n-capture time	49%	0.5%
Muon veto, multiplicity	95.7%	< 0.1%
PSD	99.5%	< 0.5%
Prompt energy	97.5%	< 1%
Energy scale	-	0.5%
U-238, Pu-241 flux	Huber-Mueller	10%

Preliminary

χ^2 Formula for ^{235}U & ^{239}Pu Spectrum Separation

$$\chi^2 = \sum_{i}^{N_\mathrm{E}} \sum_{j}^{N_\mathrm{t}} \frac{\left(M_{ij}^{\mathrm{on}} - (1+\beta)\frac{T^{\mathrm{on}}}{T^{\mathrm{off}}} M_{ij}^{\mathrm{off}} - S_{ij}\right)^2}{U_{ij}} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2 + \eta^2 + \sum_{m}^{N_{EC}} \xi_m^2 + \left(\frac{\lambda}{\sigma_\lambda}\right)^2 + \left(\frac{\zeta}{\sigma_\zeta}\right)^2$$

N_E = 31 (# of E bins, i)
N_t = 9 (# of data sets, j)
N_{EC} = 3 (# of E corr bkg, m)

Normalization
(2.2%)

Background
(0.06%)

E scale
(0.5%)

E correlated
(PSD, E_d, ΔT: < 1%)

^{238}U IBD yield
(10%)

^{241}Pu IBD yield
(10%)

$$S_{ij} = (1+\alpha)\left(1+\eta\sigma_{ij}^{\eta}\right)\prod_{m}^{3}\left(1+\xi_m\sigma_{im}^{\xi}\right) \times \frac{N_p}{4\pi L^2}\,\epsilon_{ij}^{d}\,T_j^{\mathrm{on}}\sum_{k}^{N_{iso}} F_{jk} X_k^{eq}\, y_{ik}$$

$$F_{jk} = f_{jk}\frac{P_{th}}{\sum_l f_l E_l}$$

→ Total fission rate for k isotope in j period

X_k^{eq}: off-equilibrium correction

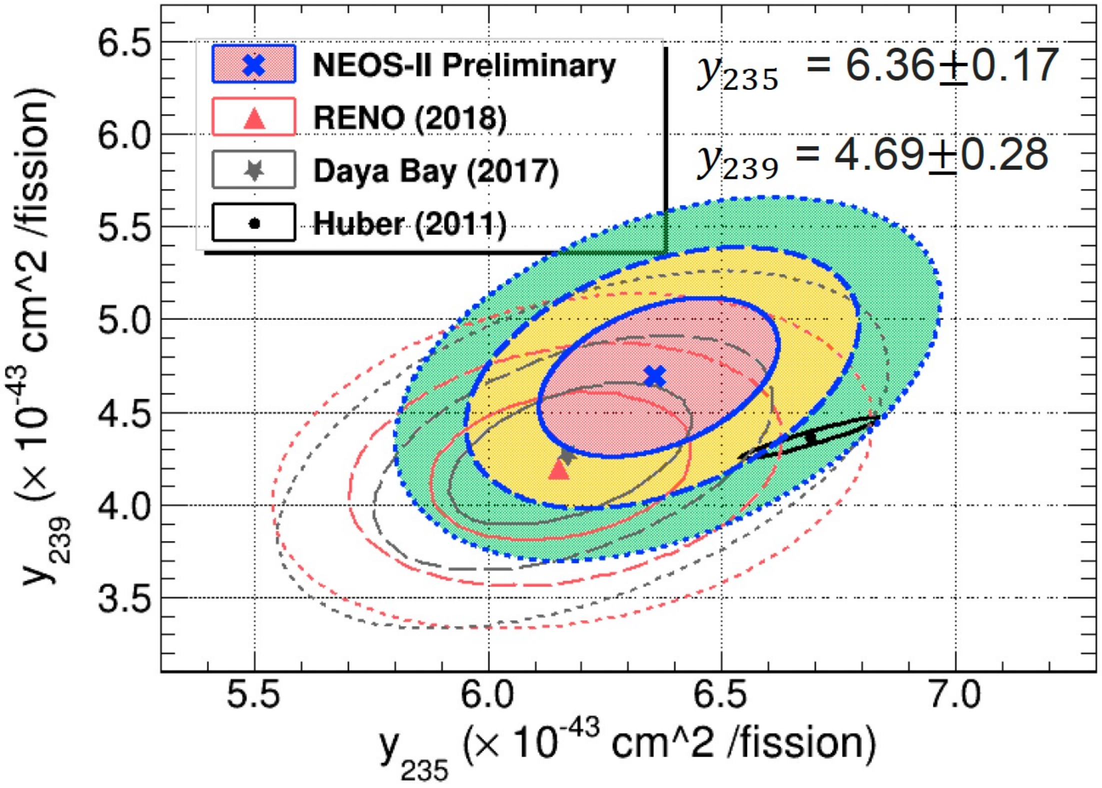
$$\boxed{y_{ik} = \sigma_i(E_\nu)\phi_{ik}(E_\nu)}$$

→ Integration over energy bins gives IBD yield for k isotope.

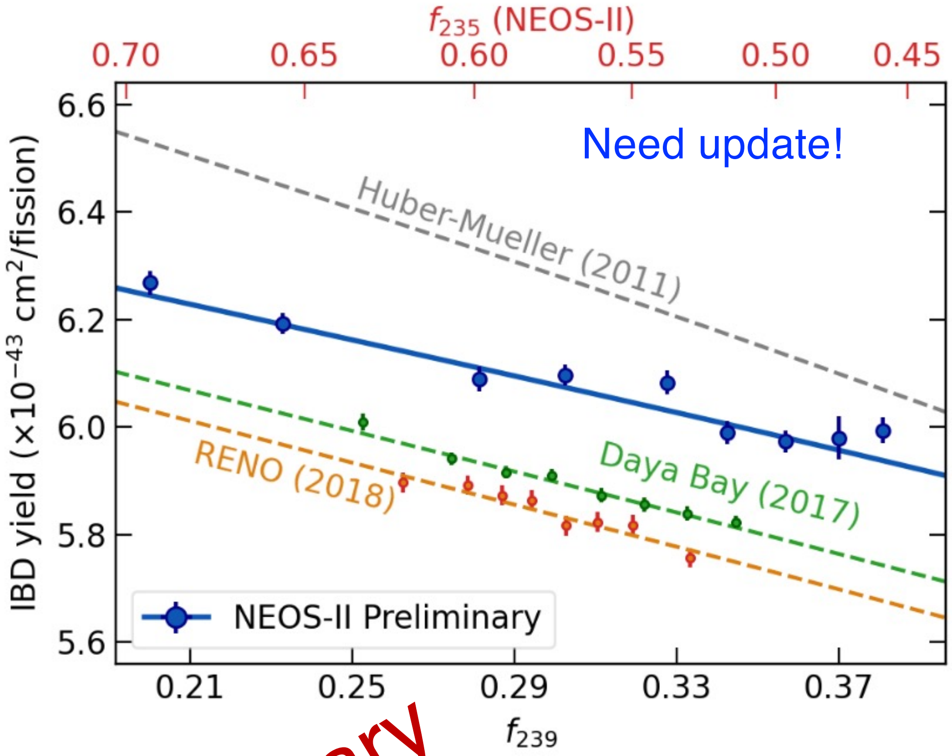
IBD x-section

Neutrino spectrum per fission

IBD Yields



Fresh fuel → Burnt fuel

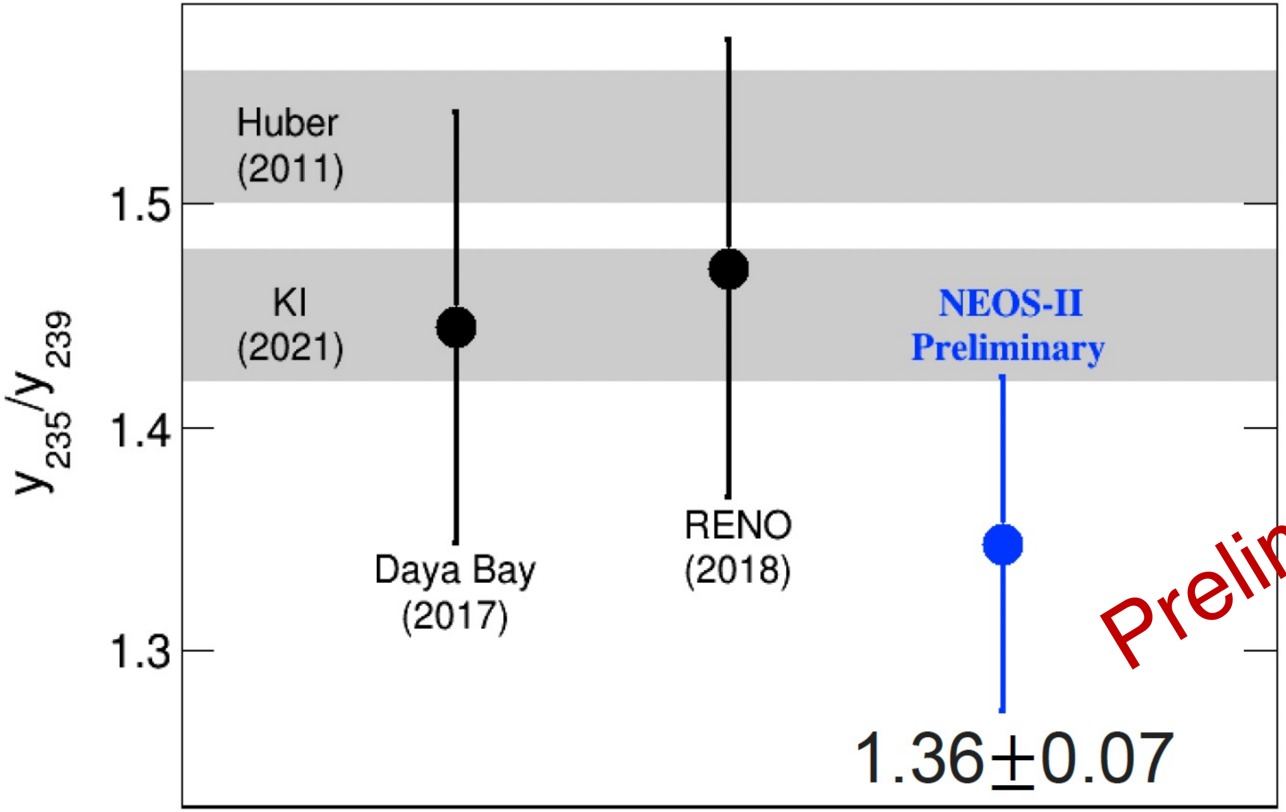


Detection Efficiency: 46 ± 1.3%

$$y_{235} = 6.36 \pm 0.17\ [10^{-43}\text{cm}^2/\text{fission}]$$
$$y_{239} = 4.69 \pm 0.28\ [10^{-43}\text{cm}^2/\text{fission}]$$

Preliminary

IBD Yield Ratio



Preliminary

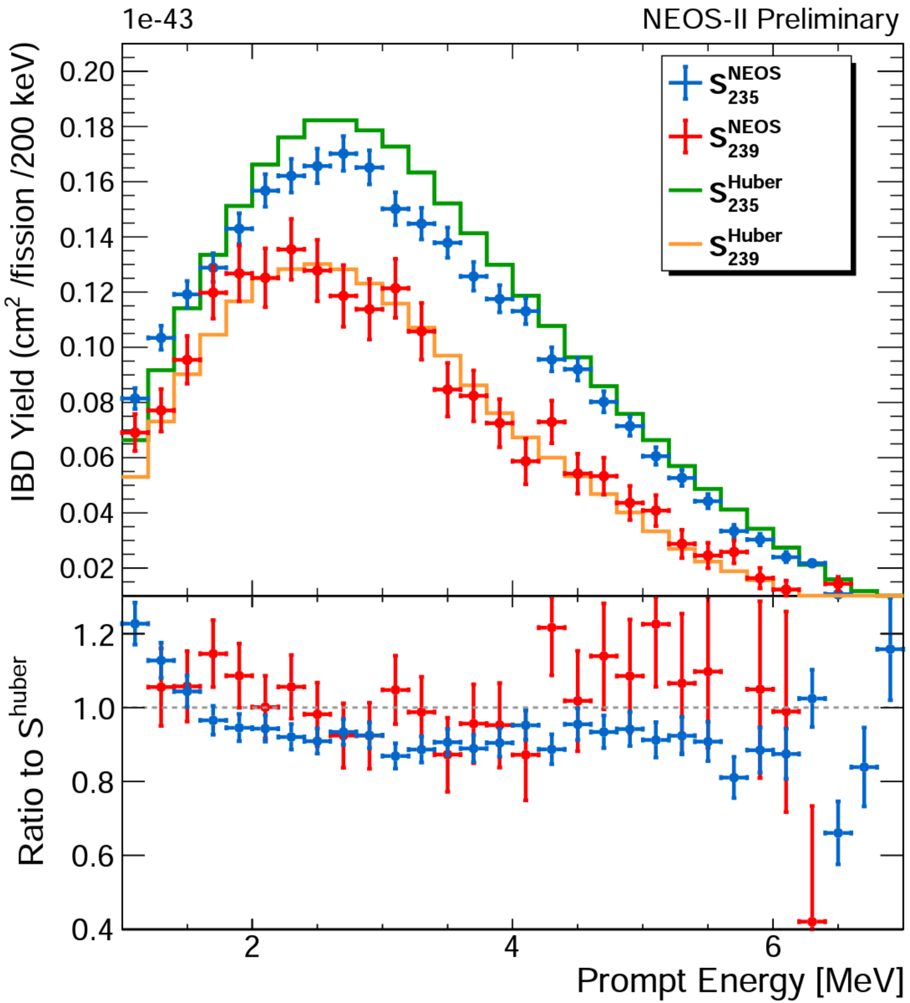
KI (2021) model:

V. Kopeikin et al.
"Reevaluating reactor antineutrino spectra with new measurements of the ratio between ^{235}U and ^{239}Pu β spectra" PRD 104, L071301 (2021)

NEOS-II:
y_{235}/y_{239} = 1.36 +/- 0.07

→ NEOS-II result has a tension with the Huber model.

Spectral Decomposition



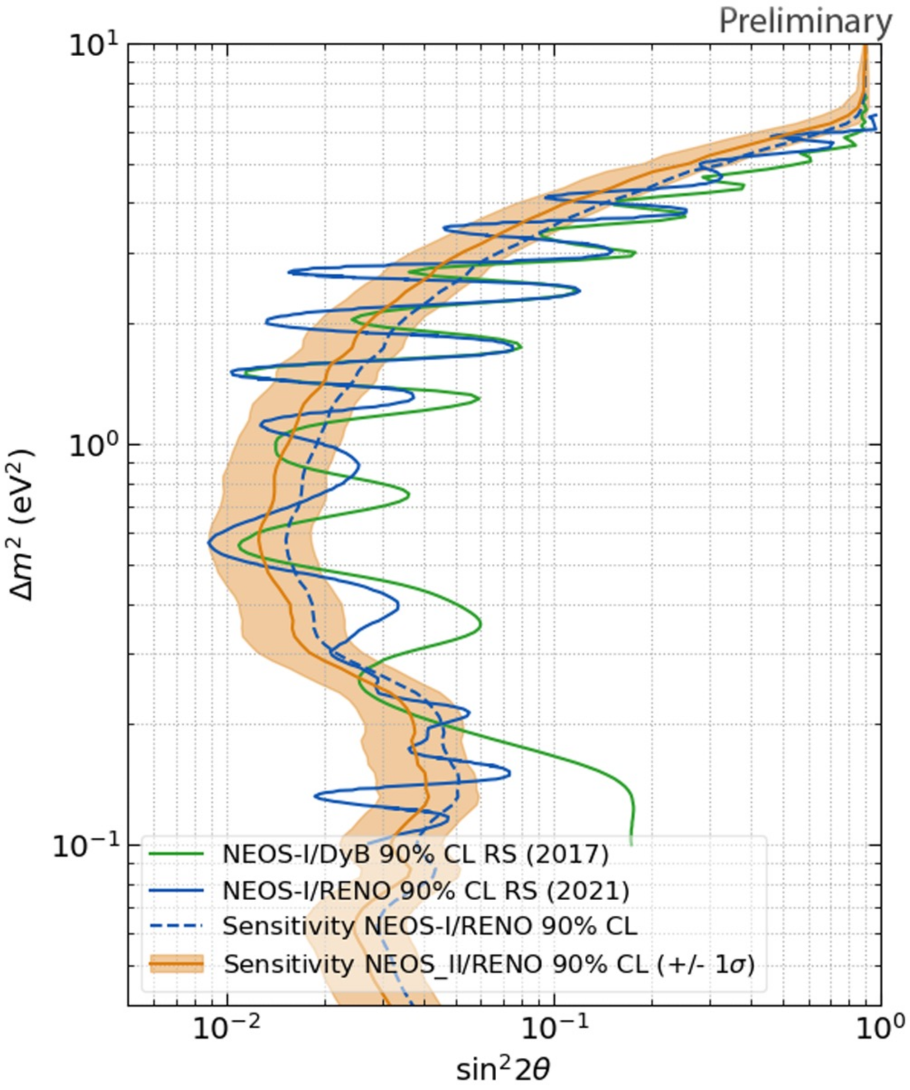
→ The "5 MeV bump" is seen in ^{235}U

→ but inconclusive for ^{239}Pu.

(stat. error is big)

Preliminary

NEOS-II: Sterile ν Search Sensitivity



- Rate+Shape analysis is on-going.
- Slightly better sensitivity due to statistical improvement. (x 2)
- A preliminary result is expected soon.

Preliminary

Summary

- ☐ Neutrino oscillation physics has been very successful, but the neutrino anomalies (4~5 σ) still need to be resolved.

- ☐ Some on-going & future ν experiments could shed light on the ν anomalies.

SBN JSNS^2-II, IsoDAR, PROSPECT-II, DANSS-II, Neutrino-6 , BEST-II etc.

- ☐ NEOS-II is to separate ^{235}U and ^{239}Pu reactor ν spectra, and to search for a sterile neutrino. Data-taking is finished.

- ☐ Light Yield decrease was well handled. Its effect is marginal.

- ☐ IBD Yields & ^{235}U and ^{239}Pu separation analysis are being finalized.
  - Preliminary result on sterile neutrino search is expected soon.