Search for the ν-Nucleus Scatterings in the NEON Experiment

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On behalf of the NEON Collaboration

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Topics in Astroparticle and Underground Physics

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Introduction

The NEON Collaboration

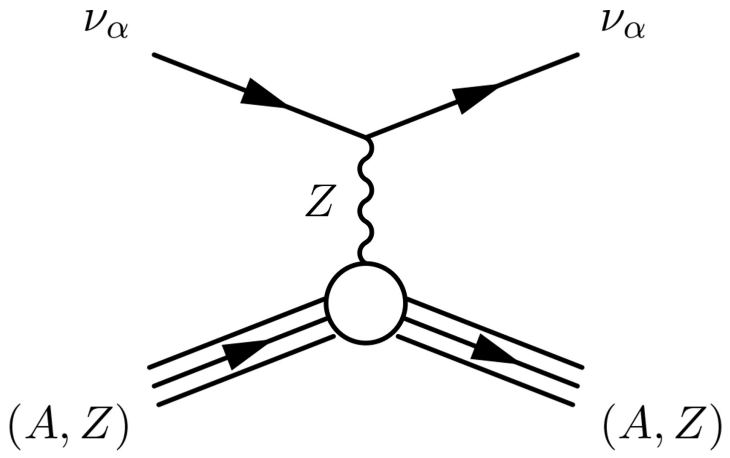
- NEON: Neutrino Elastic Scattering Observation with NaI
  - Detection of ν interactions with reactor ν, using NaI(Tl) crystal
- ~ 20 collaborators
  - Experts from the COSINE-100 experiment and the NEOS experiment

CENTER FOR UNDERGROUND PHYSICS

Introduction

ν-Nucleus Scattering

Papoulias *et al.*, *Front. Phys.* 7:109 (2019)



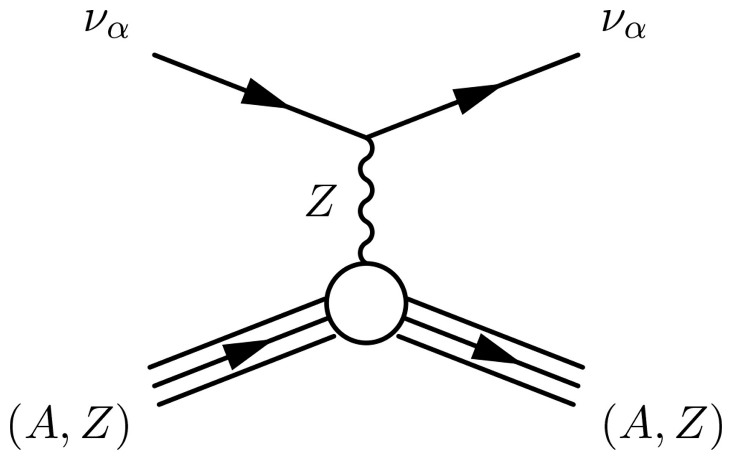
CEνNS

- Coherent elastic ν-nucleus scattering (CEνNS)
  - Predicted in 1974, first measurement of CEνNS by COHERENT collaboration, 2017 (Akimov *et al.*, *Science* 357, 1123–1126 (2017))
    - Stopped pion source, CsI(Na) target
  - Observed by the CONUS+ collaboration, 2025, (Ackermann *et al.*, *Nature* 643, 1229–1233 (2025))
    - Reactor ν, Ge target
- Reactor ν for CEνNS search with NaI
  - Comparatively large neutrino flux in controlled environment
  - Low ν energy for low recoil energy measurement
  - Understanding of nuclear structure
    - Test for N^2 dependence
    - Weinberg angle
  - Reactor monitoring

Introduction

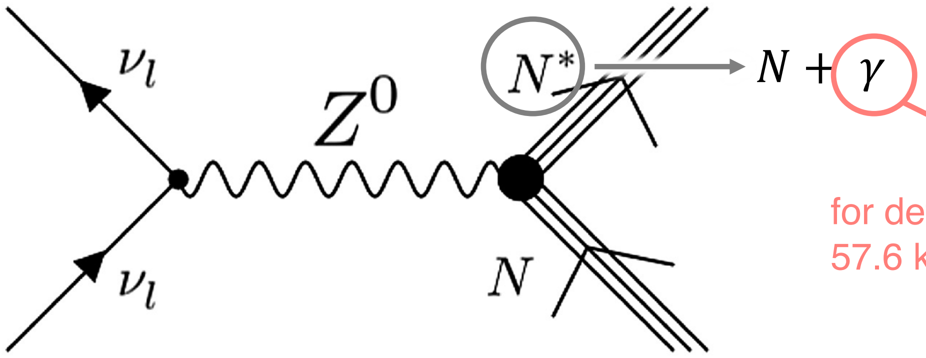
ν-Nucleus Scattering

Papoulias *et al.*, *Front. Phys.* 7:109 (2019)



CEνNS

Dutta *et al.*, *Phys. Rev. D* 106, 113006 (2022)



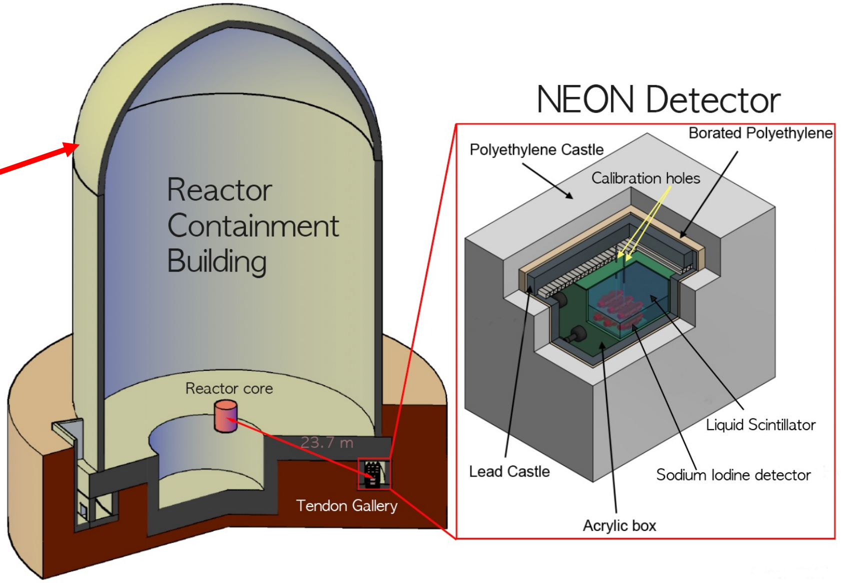
IνNS

for detection,
57.6 keV

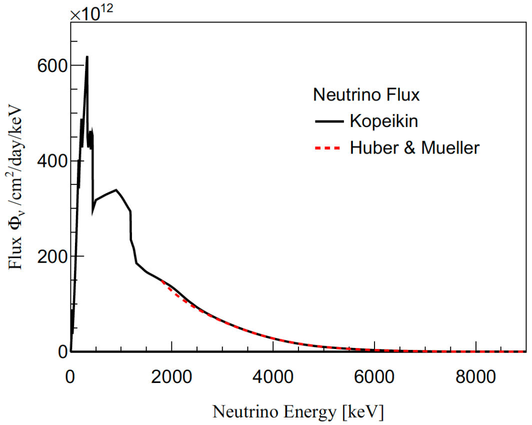
- Coherent elastic ν-nucleus scattering (CEνNS)
  - Reactor ν for CEνNS search with NaI
    - Comparatively large neutrino flux in controlled environment
    - Low ν energy for low recoil energy measurement
    - Understanding of nuclear structure
      - Test for N^2 dependence
      - Weinberg angle
    - Reactor monitoring
- Incoherent ν-nucleus scattering (IνNS)
  - **Possible detection of γ from excited state of the nucleus**
    - ^{23}Na
      - nuclear transition: g.s. $\rightarrow J = 5/2^+$
      - level energy 440 keV
    - **^{127}I**
      - nuclear transition: g.s. $\rightarrow J = 7/2^+$
      - level energy **57.6 keV**

The NEON Experiment

Experimental Site



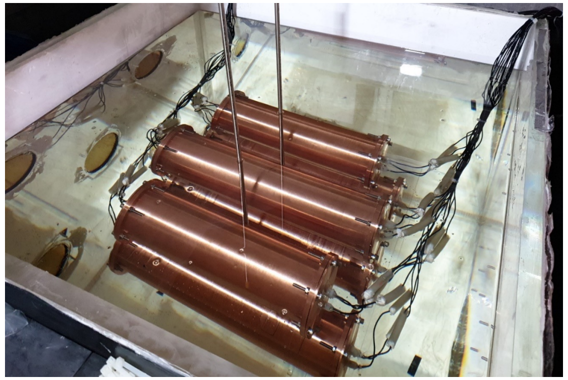
- Experimental site: Hanbit-6 reactor (Yeonggwang, South Korea)
  - 2.8 GW thermal power
  - Neutrino flux at the tendon gallery $\sim 8.09\times 10^{12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Distance from the reactor core: 23.7 m
  - ~ 10 m concrete & rock overburden

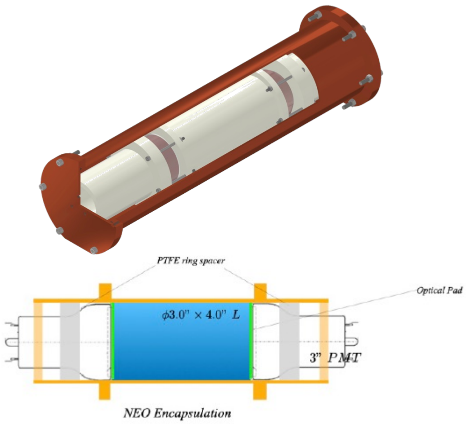


The NEON Experiment

Detector of the NEON Experiment

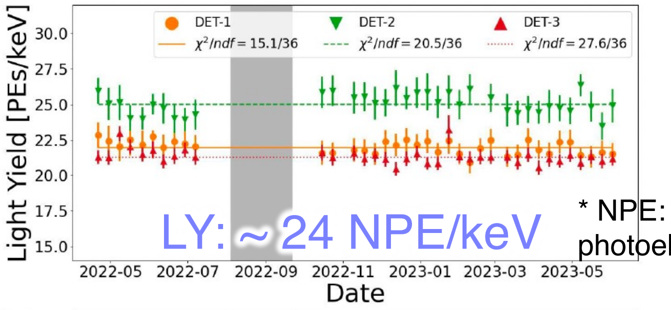
Choi *et al.*, *Eur. Phys. J. C* (2023) 83:226



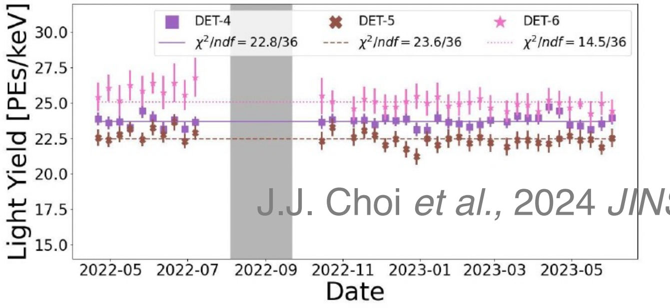


- 6 NaI(Tl) crystal detectors, 16.7 kg
  - Relatively large recoil energy for Na
  - Available in large volumes
  - High light yield, controlled background

- Light yield about 24 NPE/keV is stably obtained
  - High light yield compared to other NaI(Tl) experiments
  - Upgraded detector encapsulation design after engineering run, optical coupling PMT and crystal **without quartz window**



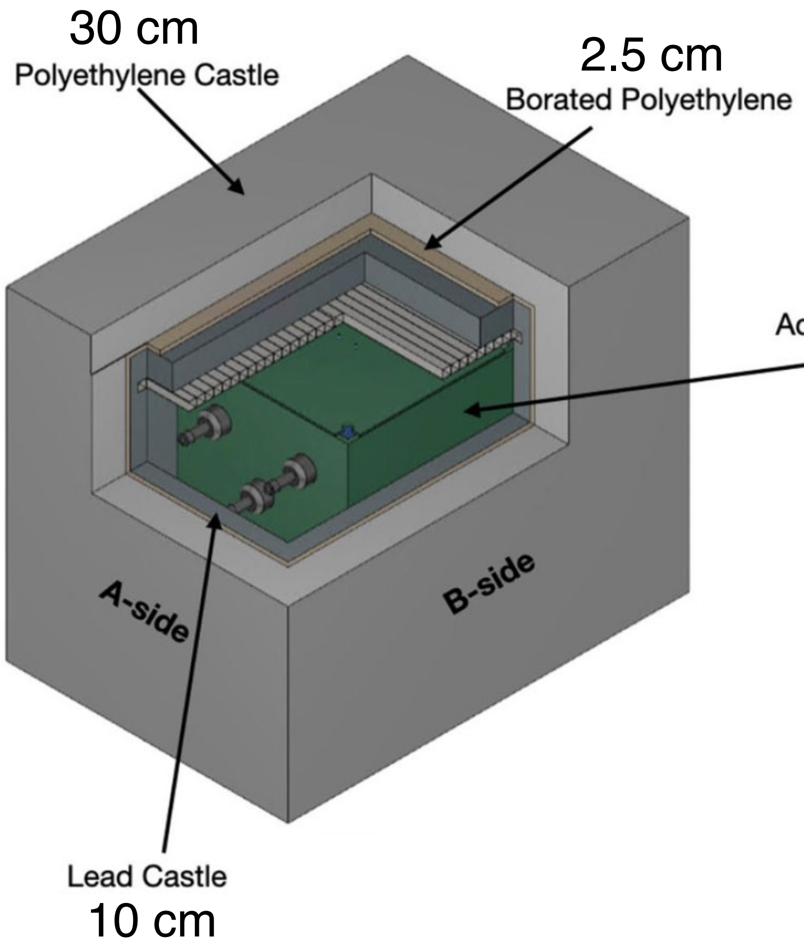
* NPE: number of photoelectrons

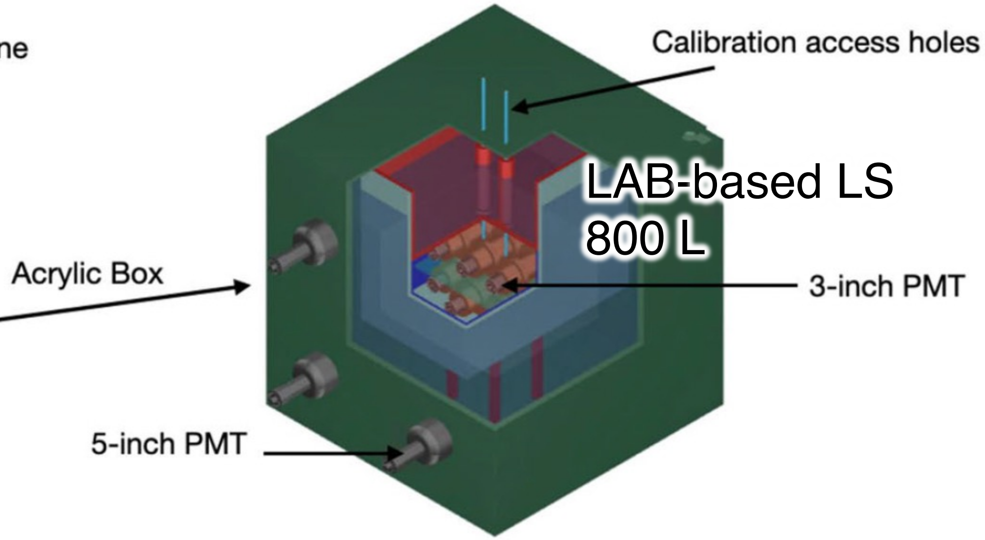


J.J. Choi *et al.*, 2024 *JINST* 19 P10020

The NEON Experiment

Shielding Design

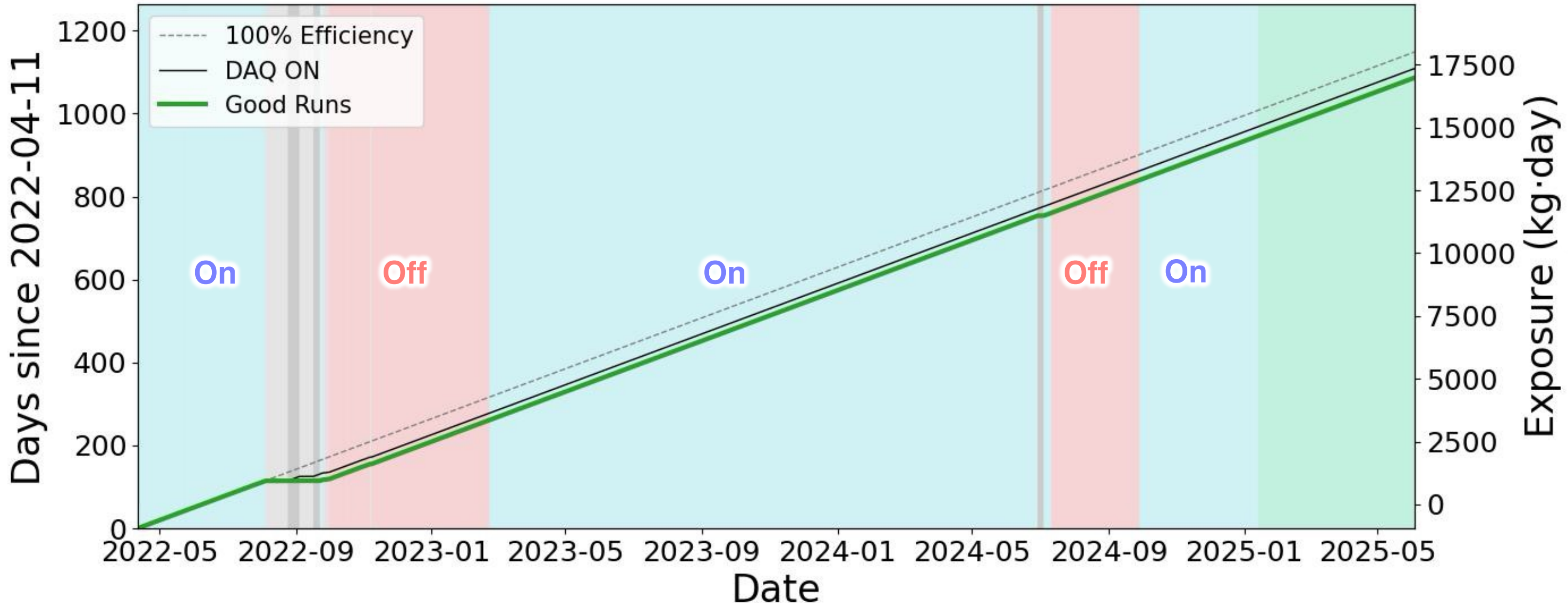


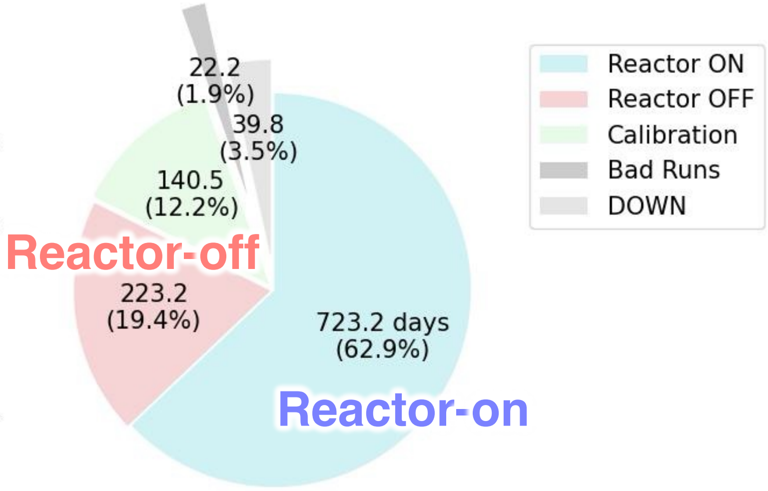


- Shielding materials
  - 30 cm high-density polyethylene
  - 2.5 cm borated polyethylene
  - 10 cm lead
- 800 L of liquid scintillator (LS) as an active veto
  - LAB based LS

The NEON Experiment

Operational Status of the NEON Experiment



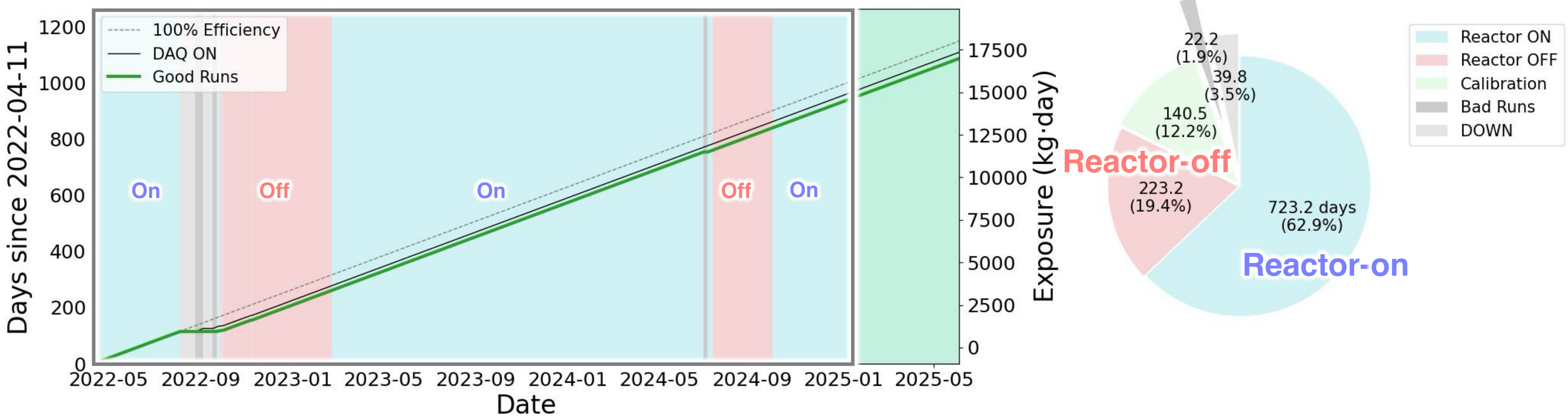


- Operation since Apr. 11, 2022 ~ ongoing

The NEON Experiment

Operational Status of the NEON Experiment

Analysis Dataset

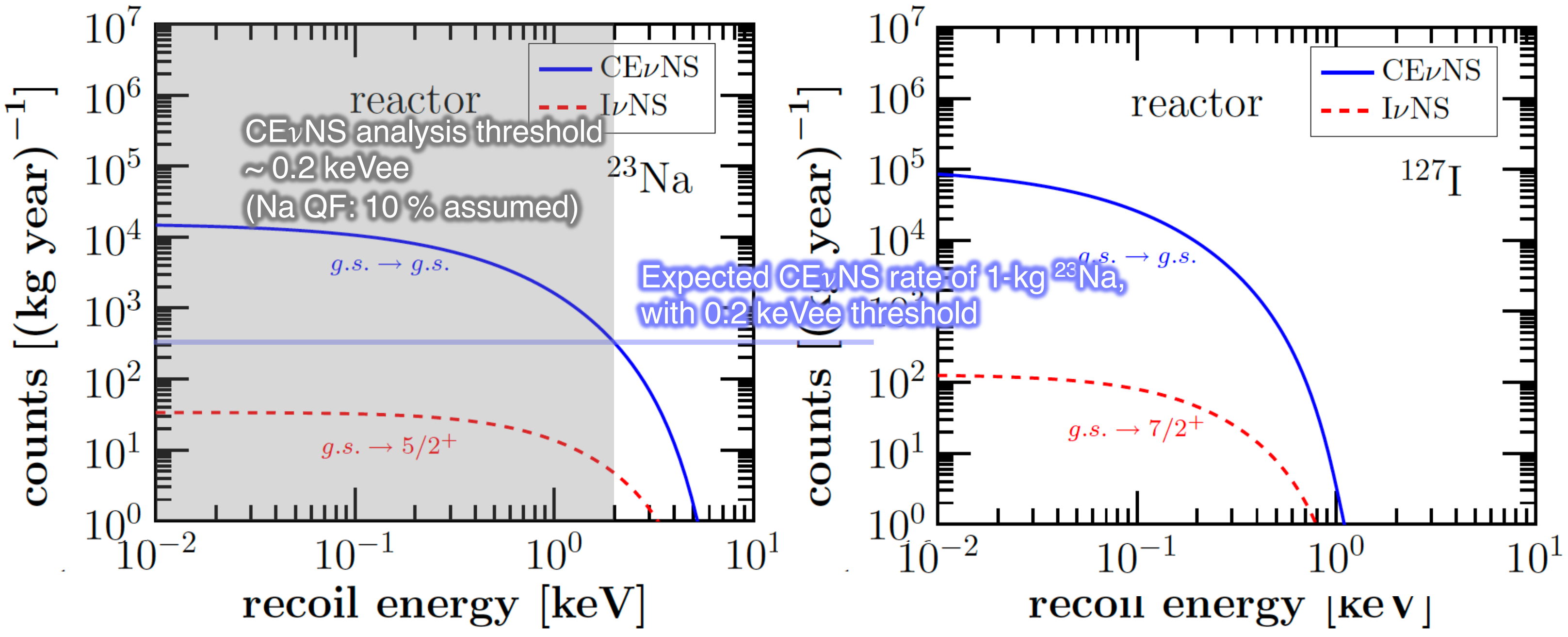


- Operation since Apr. 11, 2022 ~ ongoing
- Dataset for analysis (946 days)
  - **Reactor-on periods: 723 days**
  - **Reactor-off periods: 223 days**

Physics Prospects in the NEON Experiment

Potential for ν-Nucleus Scattering Search

Integrated event rates as a function of the nuclear recoil energy



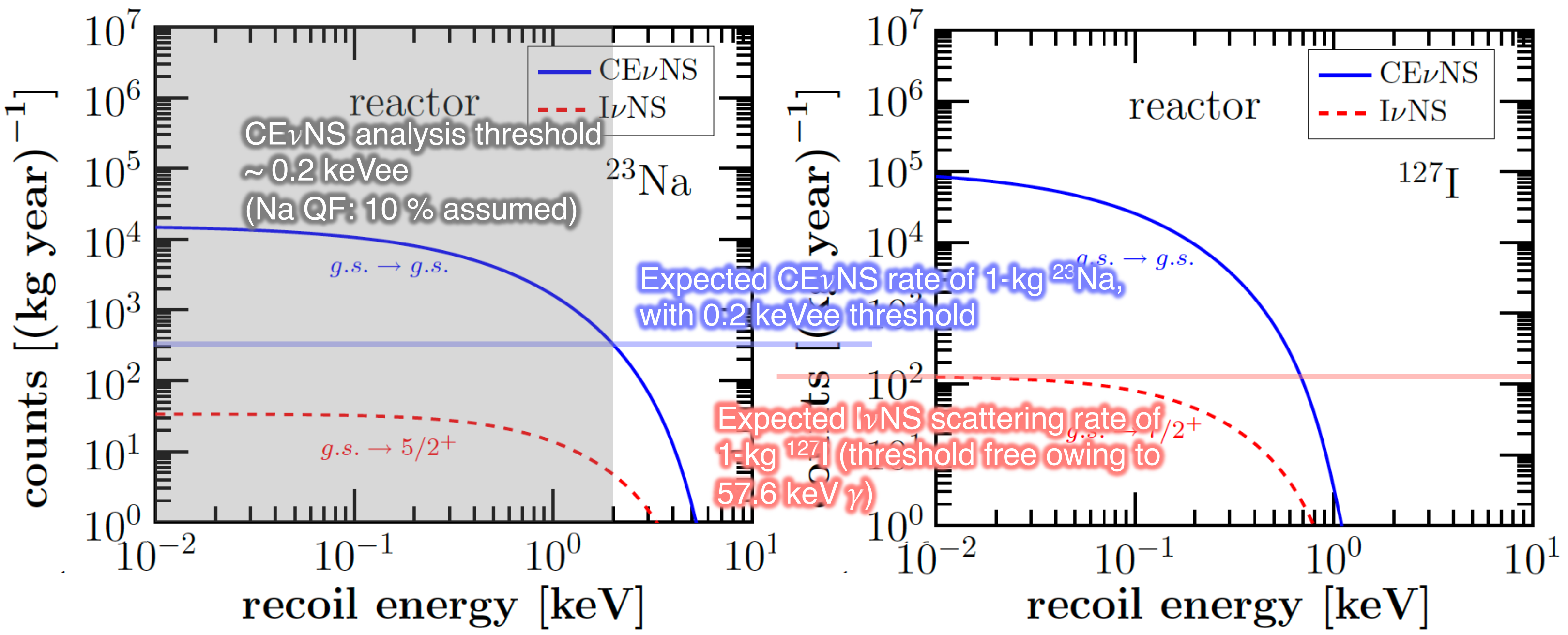
R. Sahu *et al.*, *Phys. Rev. C* 102, 035501 (2020)

- 700 days exposure at reactor-on status assumed
- Neutrino flux: $8.09\times10^{12}\text{cm}^{-2}\text{s}^{-1}$
- **~ 1290 CEνNS event** assumed
  - 2.59 kg Na in the NEON detector
  - ~ 320 counts/kg/year integrated event rate for Sodium from ref.
  - 0.2 keVee threshold, 10% quenching factor

Physics Prospects in the NEON Experiment

Potential for ν-Nucleus Scattering Search

Integrated event rates as a function of the nuclear recoil energy

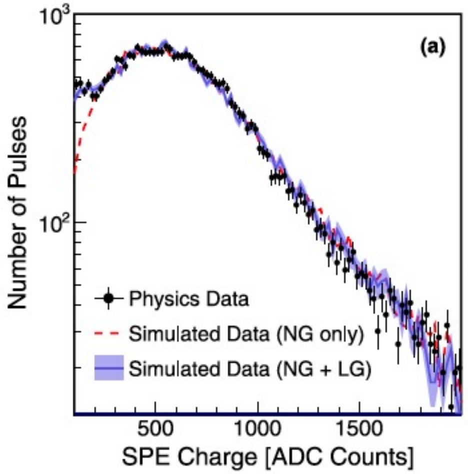


R. Sahu *et al.*, *Phys. Rev. C* 102, 035501 (2020)

- 690 days exposure at reactor-on status assumed
- Neutrino flux: $8.09\times10^{12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- **~ 1290 CEνNS event** assumed
- **~ 2690 events of IνNS** assumed
  - 14.11 kg I in the NEON detector
  - ~ 123 counts/kg/year integrated event rate for Iodine from ref.
  - Observation of 57.6 keV γ from Iodine

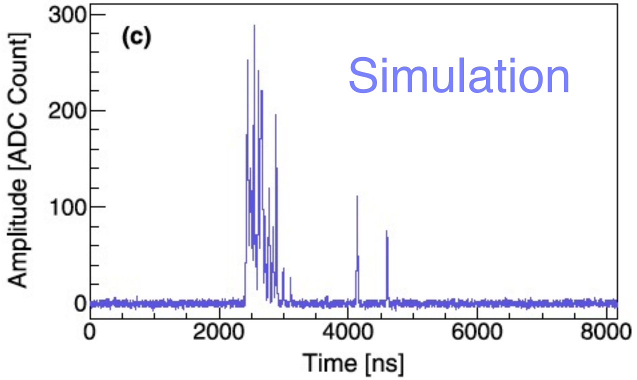
Event Selection for CEνNS Search

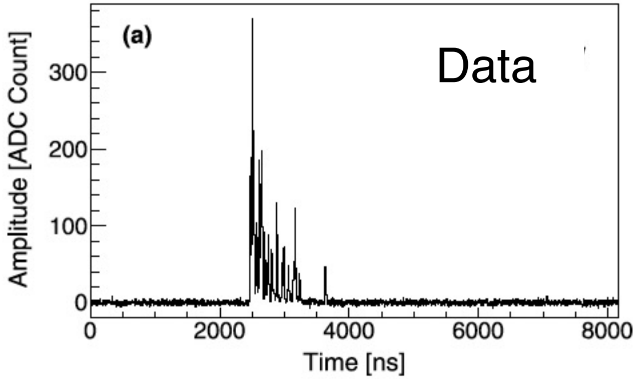
Waveform Simulation



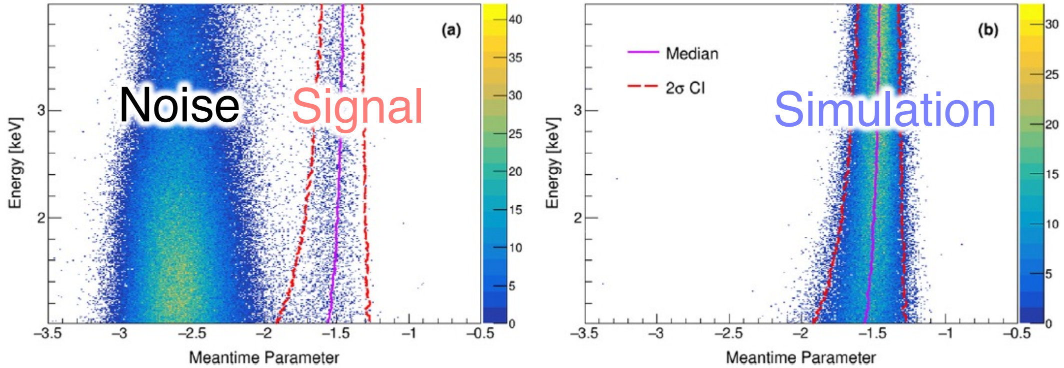
- Waveform simulation
  - Reproduce scintillation signals in the keV to sub-keV energy range
  - Use for pulse-shape discrimination parameter(PSD) development
  - Use for signal training sample for machine learning / deep learning

Choi *et al.*, *NIMA* 065 (2024) 169489



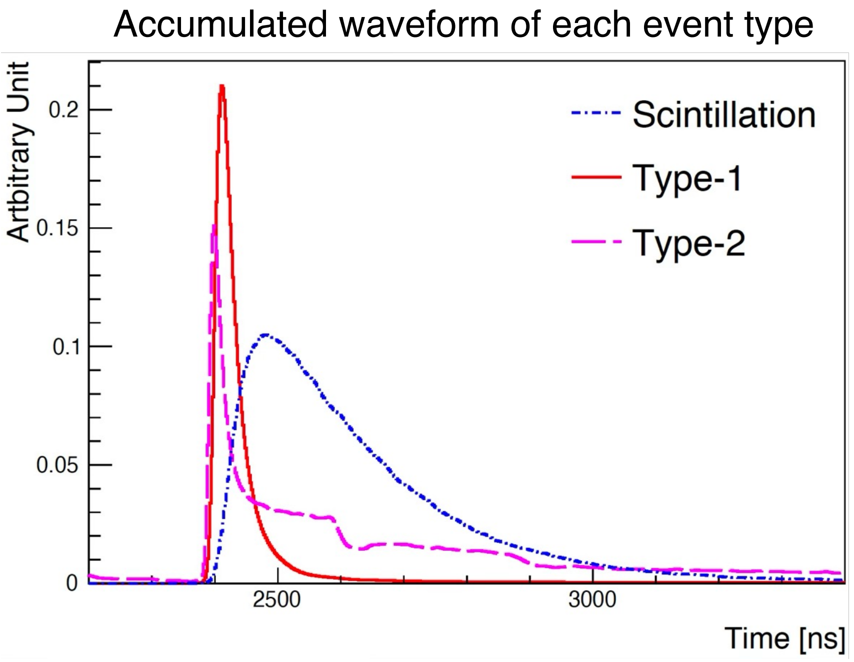


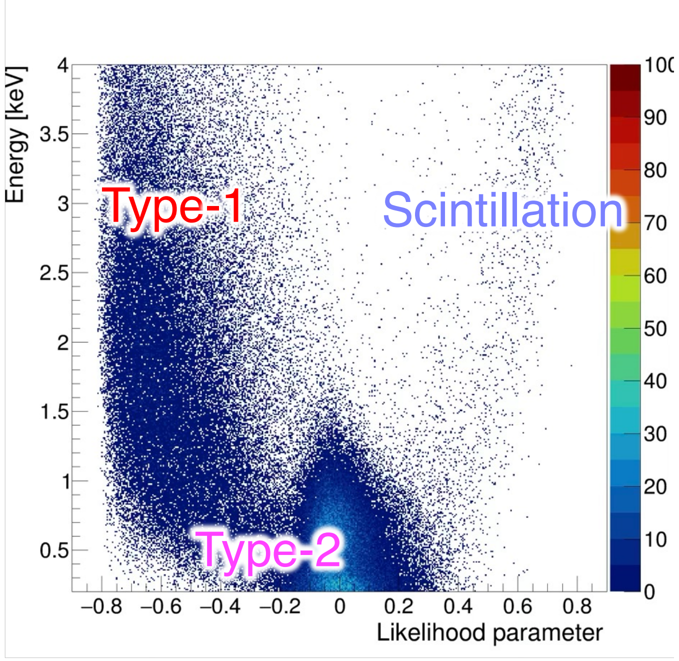
Validation of simulated waveform w/ PSD parameter



Event Selection for CEνNS Search

Noise Types in the NEON Data

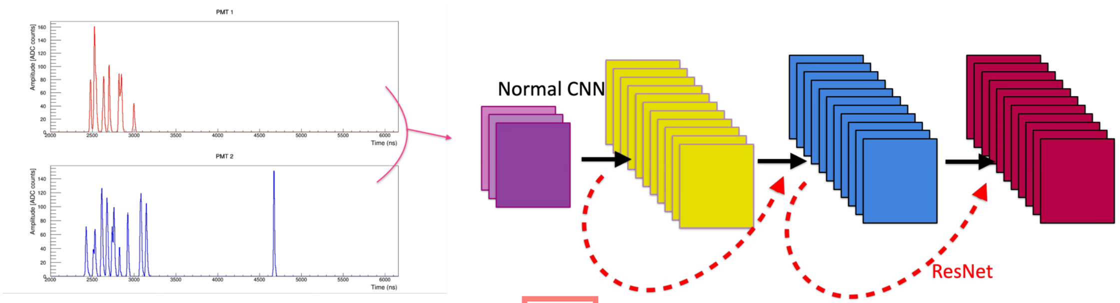




- Type 1 (PMT-induced noise)
  - Short pulses (< 50 ns), fast decaying distribution → easy to be separated
- Type 2 (High energy late-pulse)
  - Dominated in 2 keV. Slowly decaying distribution → hard to be separated from scintillation

Event Selection for CEνNS Search

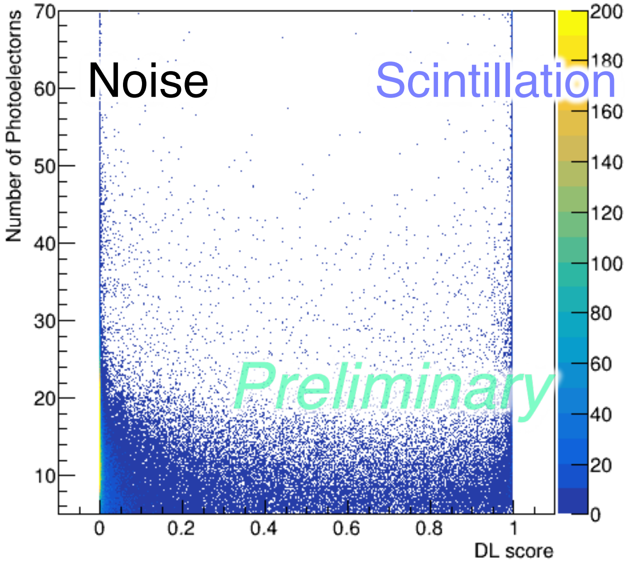
Deep Learning with ResNet

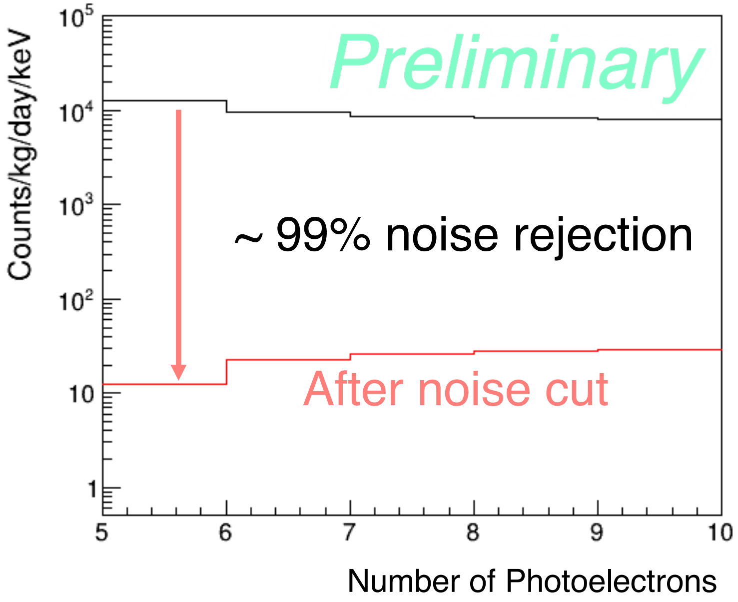


- Deep learning with non-parameterized waveform shape
  - Used **ResNet** model for training
- Conducted training focusing 2 noise types
- Noise rejection to ~ 10 counts/kg/days/keV

  (Efficiency 6 NPE (~ 0.3 keV): about 25 %)

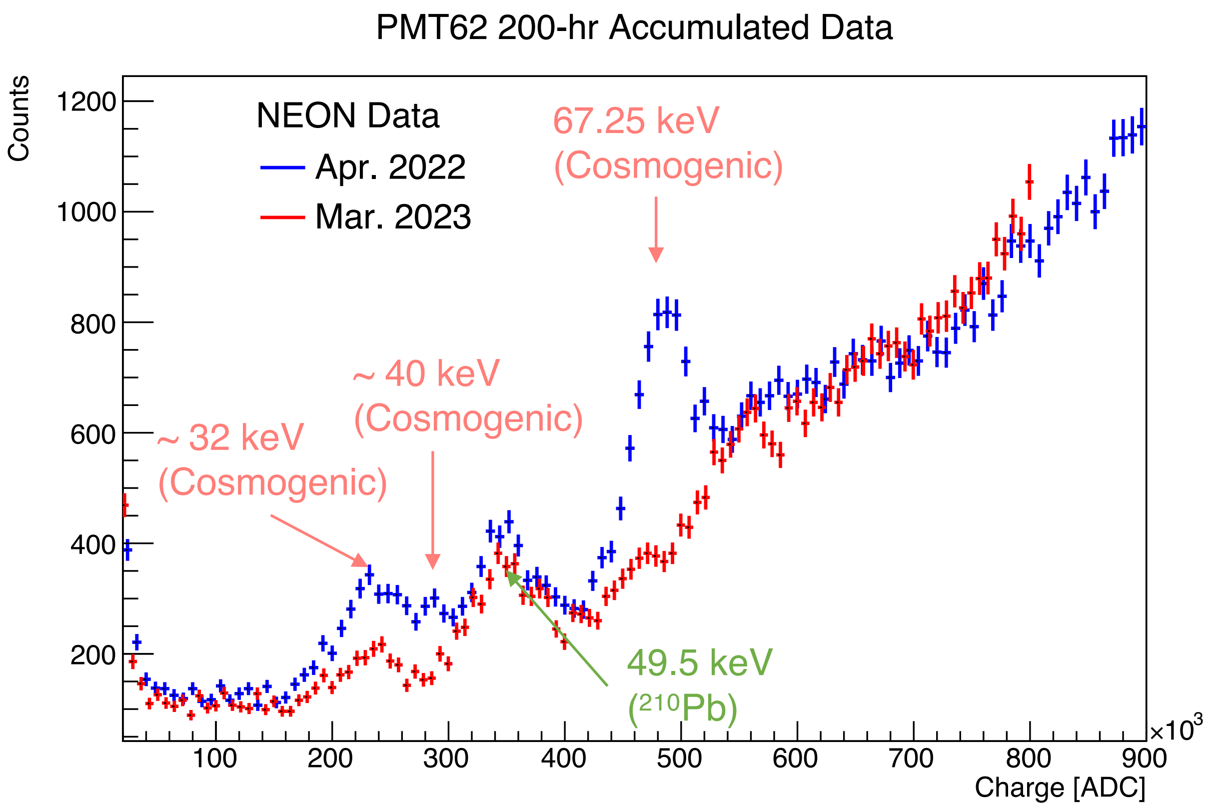
Training result





IνNS Search in the NEON Experiment

Investigation Around 57.6 keV ROI in the NEON Data

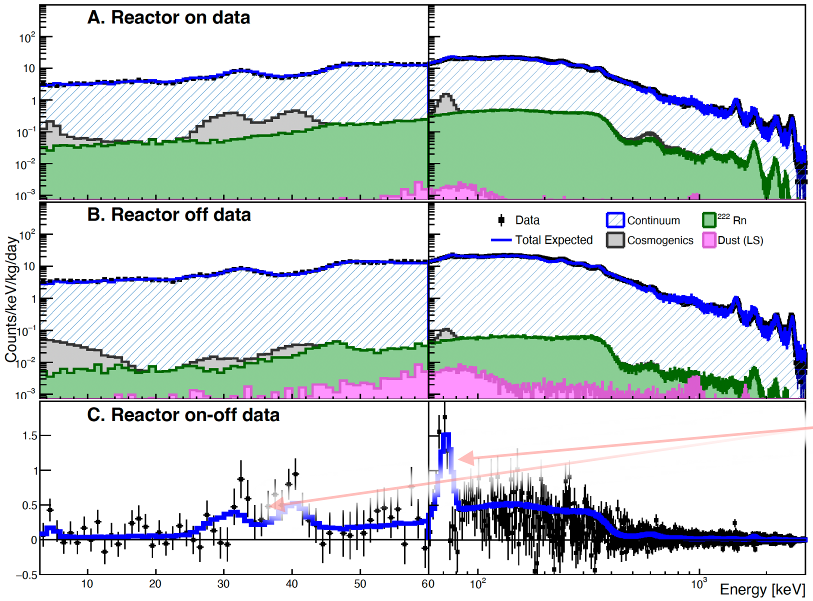


- ^{210}Pb 49.5 keV peak right next to 57.6 keV, for calibration
- Components with temporal behaviour
  - Cosmogenic components
    - ^{125}I ~ 40 keV, 67.25 keV
    - ^{121m}Te ~ 30 keV, ~ 40 keV
    - ^{126}I, ~ 30keV

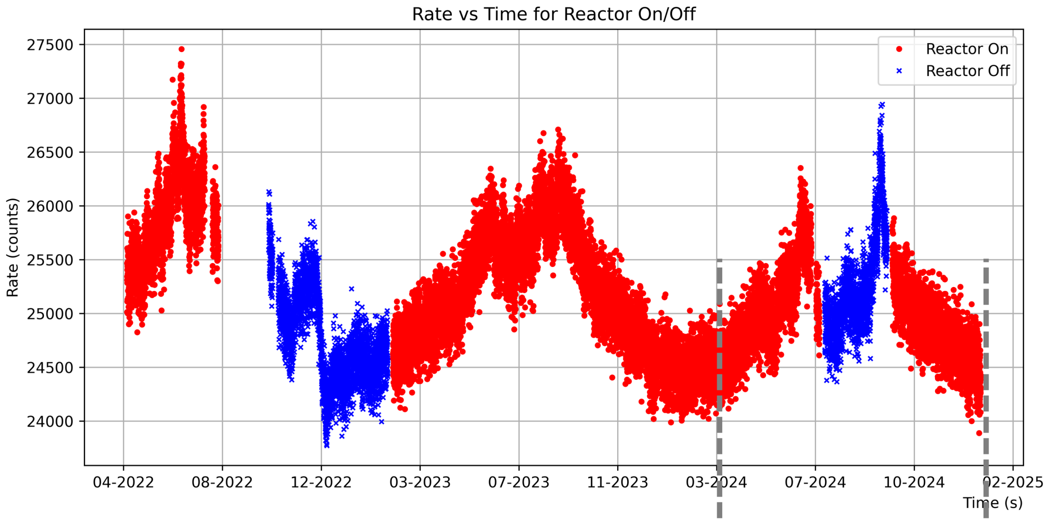
IνNS Search in the NEON Experiment

Time Binned Analysis for the Time-dependent Components

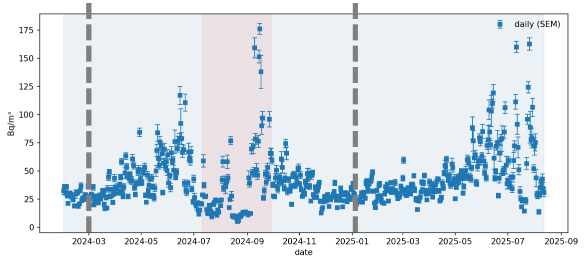
- Background modeling of analysis dataset time binned ~ 2 months
  - To consider reactor-on/-off period
  - To consider time-dependent components in the NEON data
    - Cosmogenic components
    - Seasonal variation of ^{222}Rn through opened calibration hole



Peaks from cosmogenic components in (on – off) data



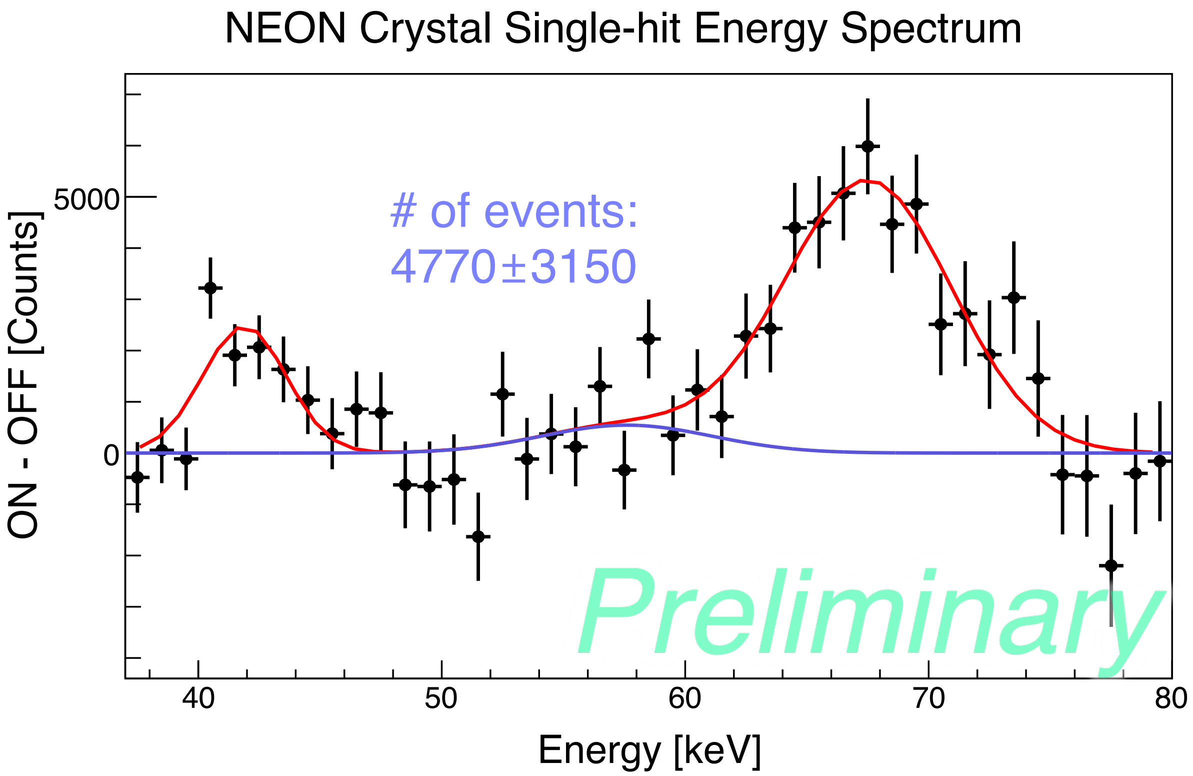
Event rate fluctuation matches with ^{222}Rn measurement



RadonEye measurement at NEON experimental site

IνNS Search in the NEON Experiment

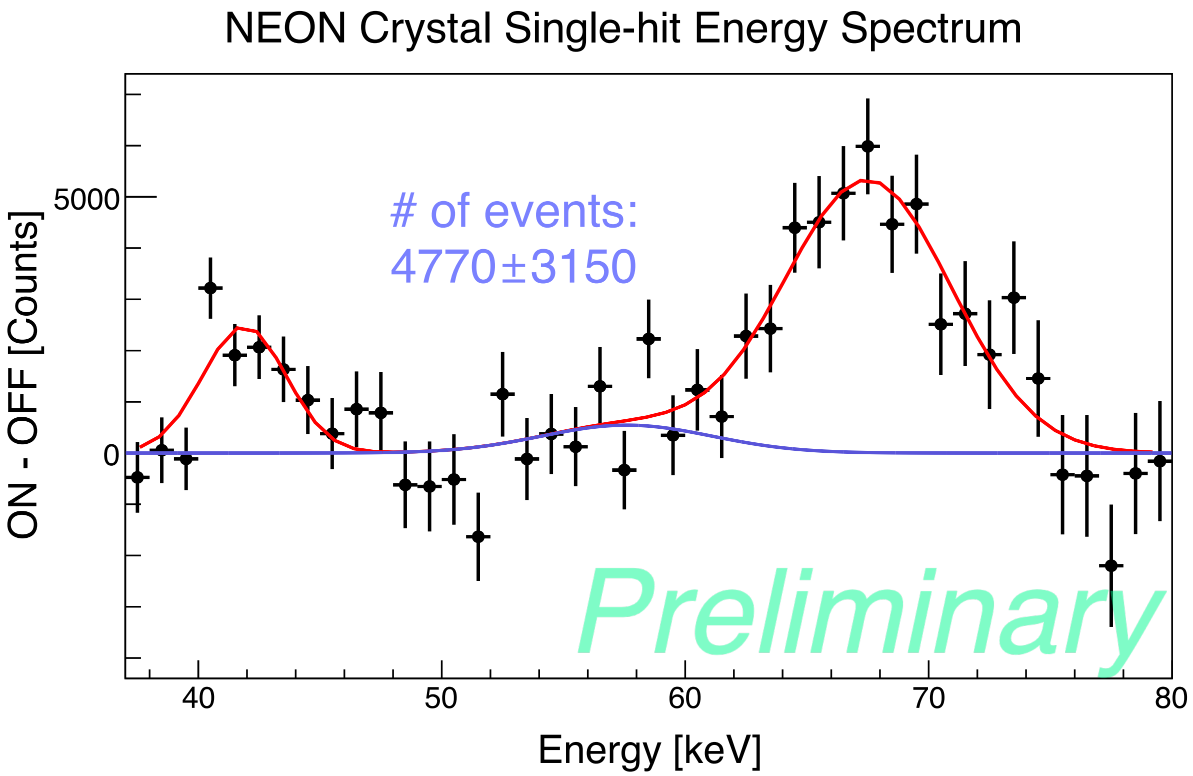
Expected Signal of IνNS in the NEON Data

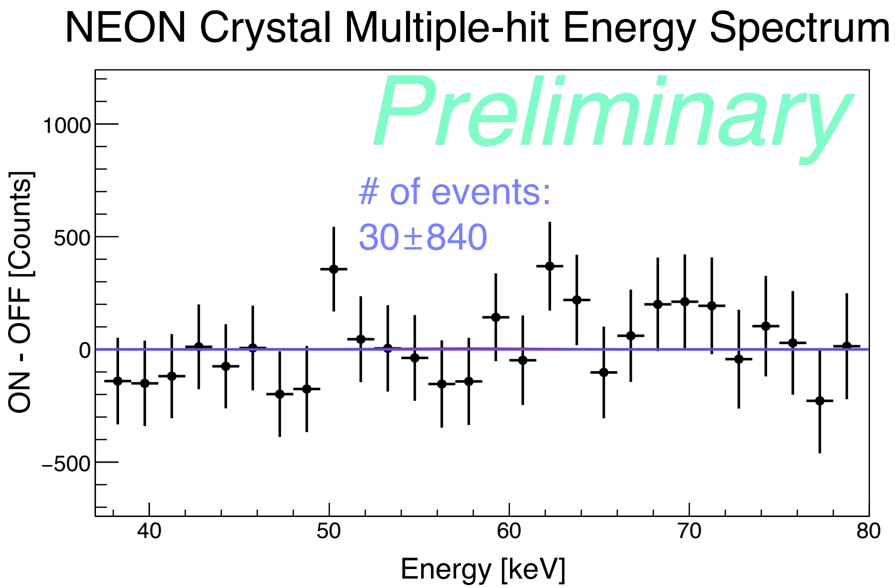


- (Reactor-on) – (Reactor-off) data analysis at 40 ~ 80 keV energy region for 57.6 keV signal search
  - Assumption
    - Signal mean at 57.6 keV
    - Cosmogenic peak ~ 67 keV and ~ 40 keV

IνNS Search in the NEON Experiment

Expected Signal of IνNS in the NEON Data





- (Reactor-on) – (Reactor-off) data analysis at 40 ~ 80 keV energy region for 57.6 keV signal search
  - Assumption
    - Signal mean at 57.6 keV
    - Cosmogenic peak ~ 67 keV and ~ 40 keV
- No signal on crystal multiple-hit energy spectrum
- Improvements through detailed modeling of the on and off data

Summary

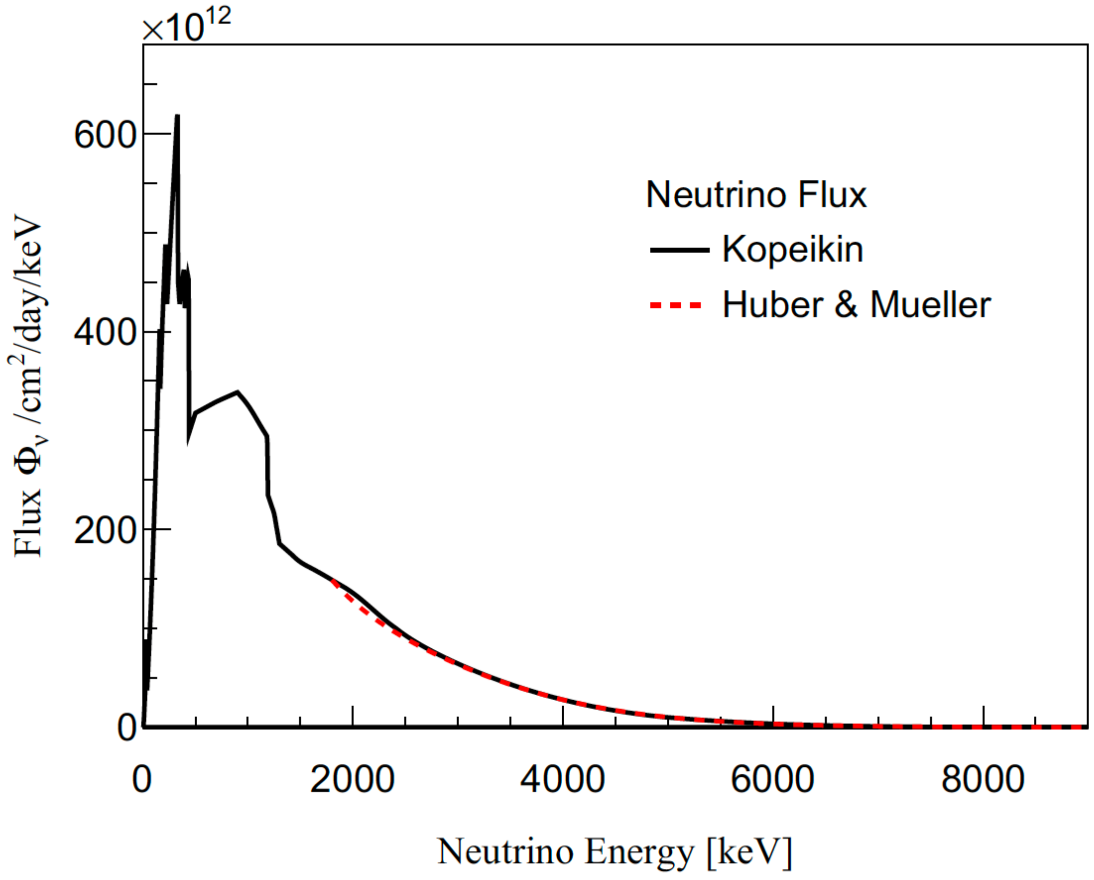
- The NEON experiment aims to detect CEνNS with reactor ν
  - Event selection for CEνNS improvement via deep learning

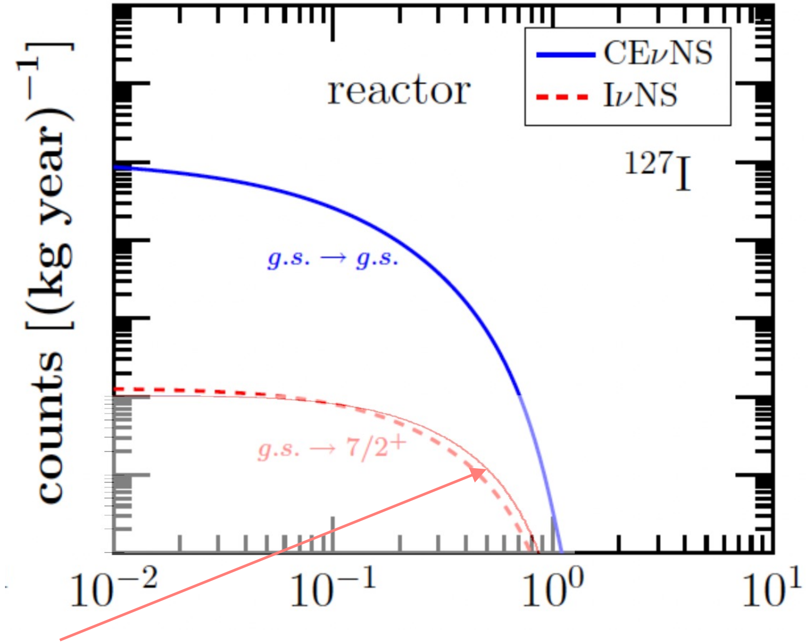
- Also expanded its search to include IνNS recently
  - Improvement through detailed background modeling
    - Time-binned analysis for time-dependent components in our data

Thank You

Reactor ν Flux at the NEON Experiment

- Neutrino flux at the tendon gallery $\sim 8.09 \times 10^{12} \mathrm{cm}^{-2} \mathrm{s}^{-1}$





Red solid:
IνNS rate calculated with ν flux at the NEON experimental site

ν-Nucleus Scattering Event Rates in NaI

- Differential rates

$$\frac{dR_x}{dT_A} = \mathcal{K} \int_{E_\nu^{\min}}^{E_\nu^{\max}} \frac{d\sigma_x}{dT_A}(E_\nu, T_A)\lambda_\nu(E_\nu)\, dE_\nu, \quad x = \text{coh, inc},$$

$$\mathcal{K} = t_{\text{run}}\Phi_\nu N_{\text{targ}}$$

$\lambda_\nu(E_\nu)$: relevant neutrino energy distribution function characterizing the neutrino source

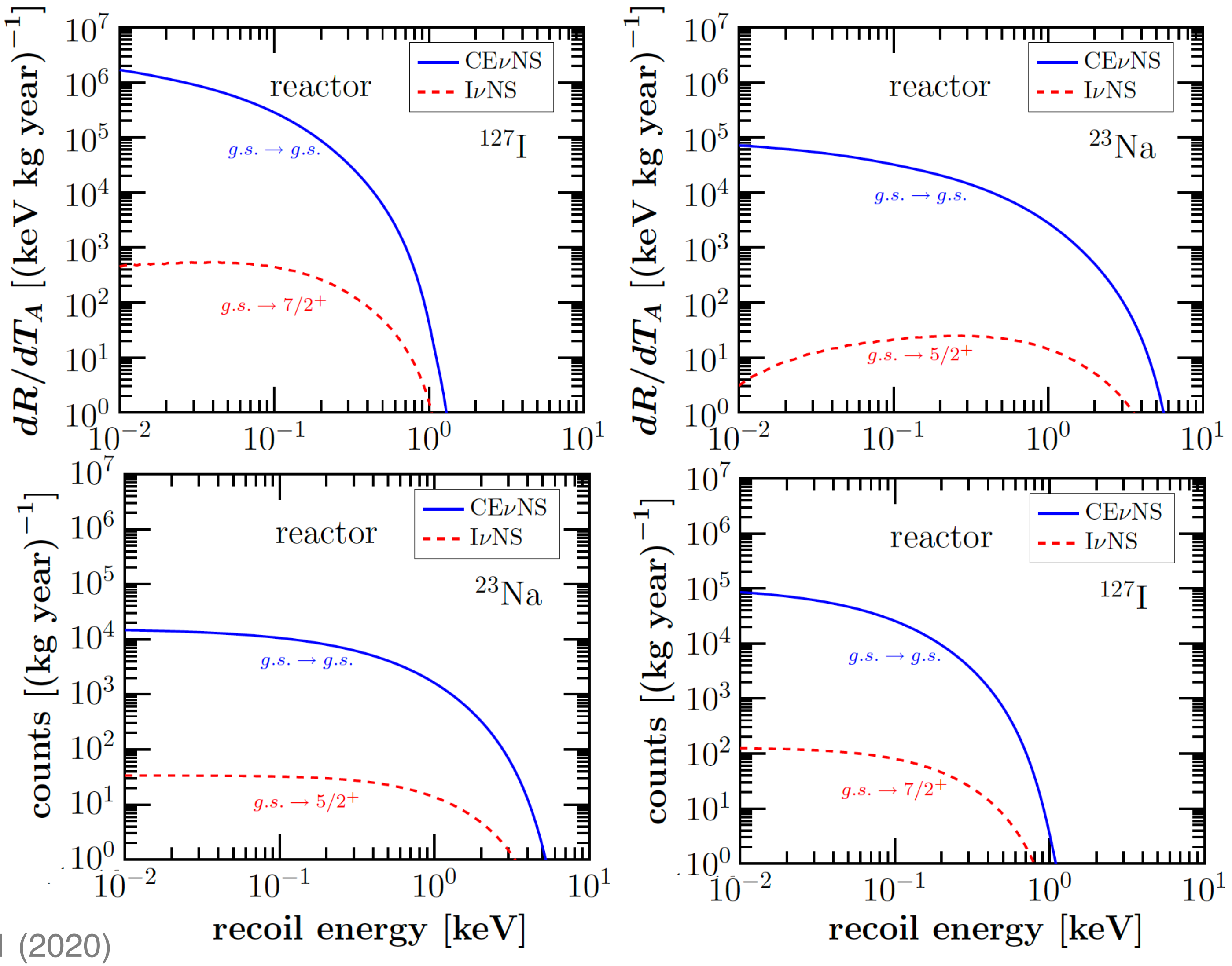
- Cross sections

$$\frac{d\sigma_{\text{coh}}}{dT_A} = \frac{4G_F^2 m_A}{\pi}(1-a)\left|\sum_{f=n,p}\sqrt{g_{\text{coh}}^f}F_f\left(A_+^f[g_L^f - g_R^f ab(1-b)] + A_-^f g_R^f[1-ab(1-b)]\right)\right|^2$$

$$\frac{d\sigma_{\text{inc}}}{dT_A} = \frac{4G_F^2 m_A}{\pi}\sum_{f=n,p} g_{\text{inc}}^f(1-|F_f|^2)\left[A_+^f\left((g_{L,f} - g_{R,f}ab^2)^2 + g_{R,f}^2 ab^2(1-a)\right) + A_-^f g_{R,f}^2(1-a)(1-a+ab^2)\right]$$

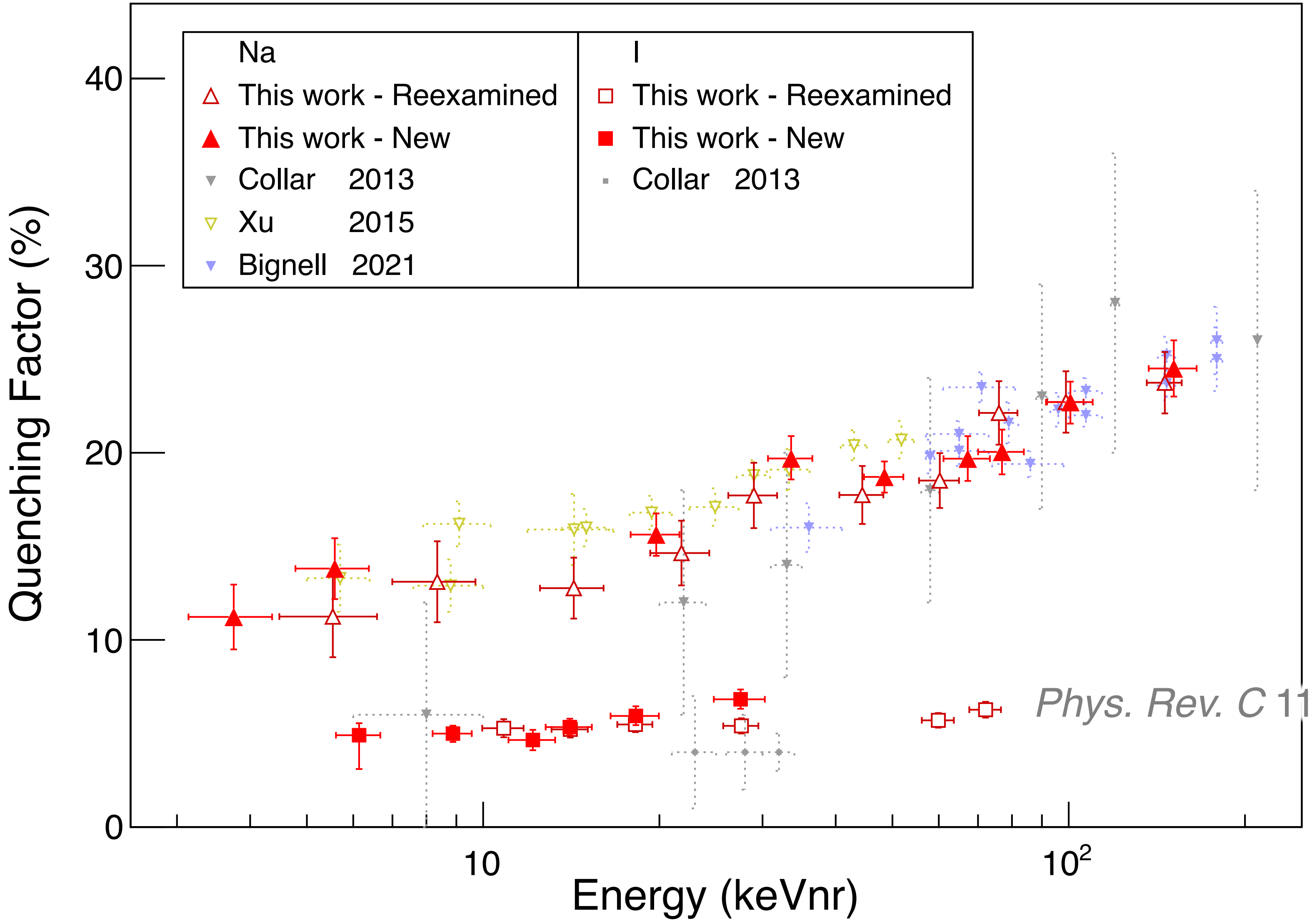
$$a = \frac{q^2}{q_{\min}^2} \simeq \frac{T_A}{T_A^{\max}}, \quad b^2 = \frac{m_f^2}{s}.$$

Nuclear structure calculation based on the deformed shell model (DSM)



R. Sahu *et al.*, *Phys. Rev. C* 102, 035501 (2020)

Measured Quenching Factor of NaI(Tl)



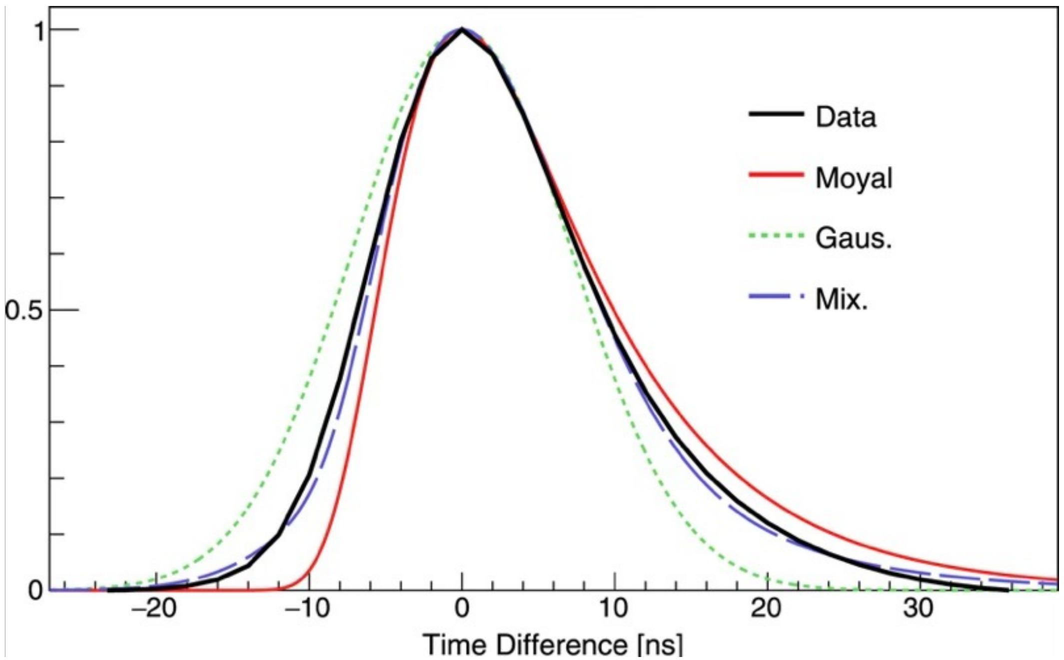
Phys. Rev. C 110, 014614 (2024)

Waveform Simulation for the NEON Data

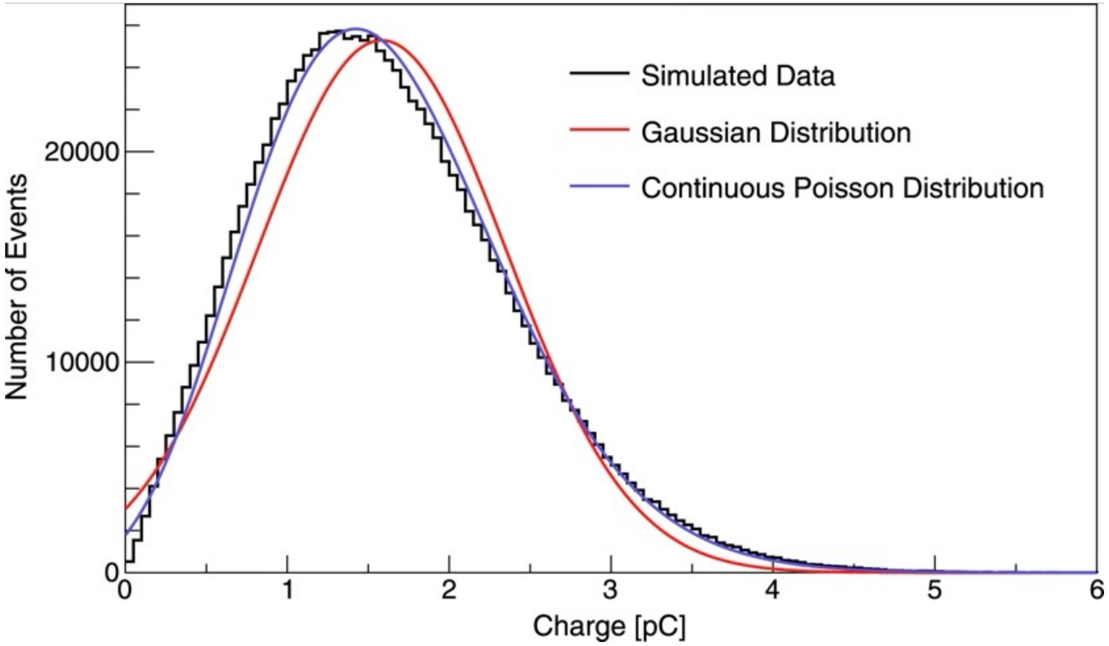
Modeled SPE

- Waveform simulation with precisely modeled single photon pulse / charge / time distribution

Single photon pulse function



Single photon charge function

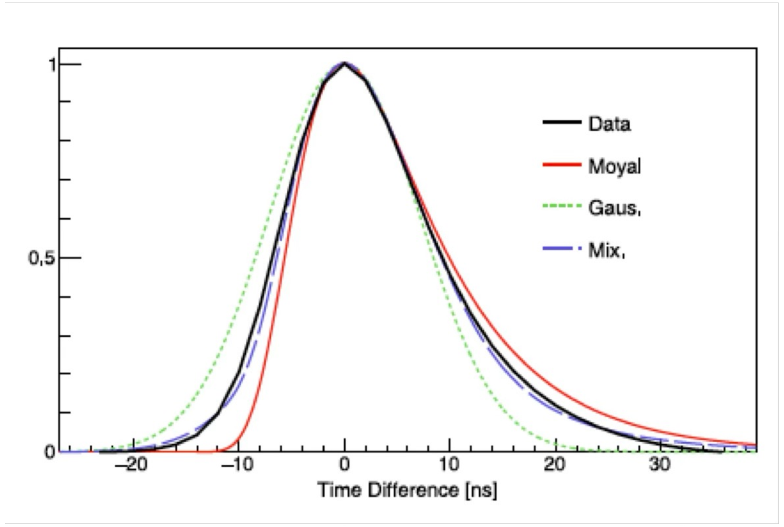


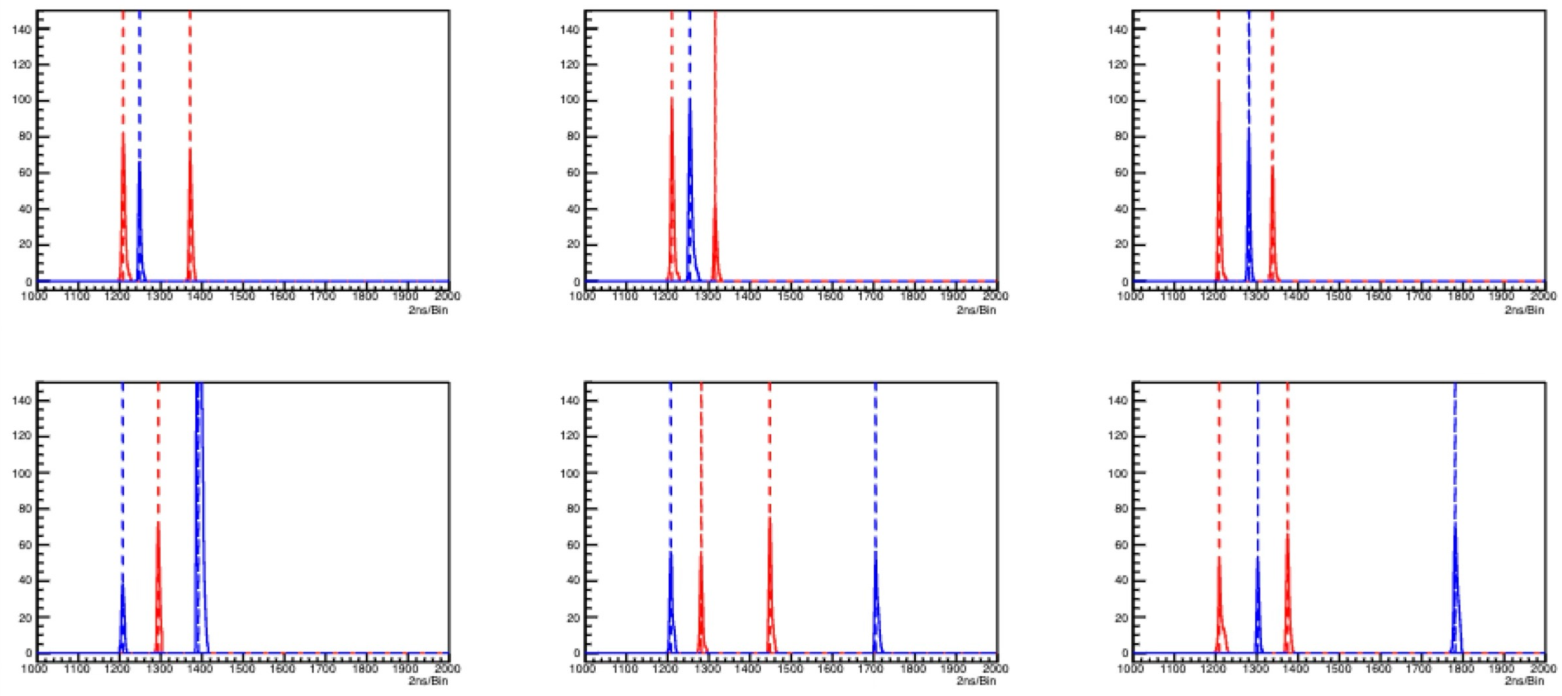
Choi *et al.*, *NIMA* 065 (2024) 169489

Waveform Simulation for the NEON Data

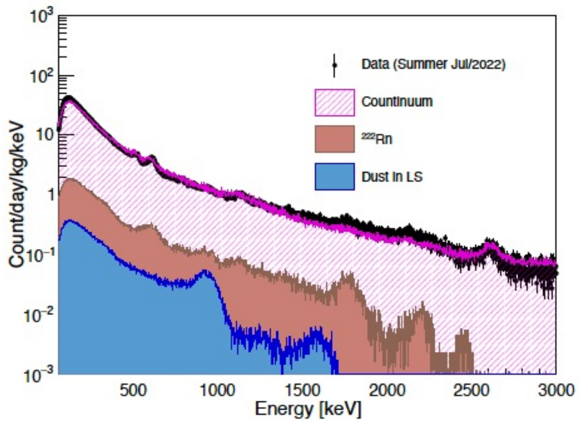
Degenerating waveform

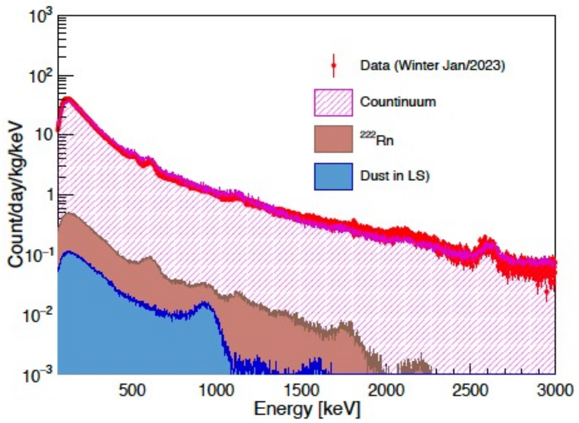
- To remove SPE shape problem, stronger degeneration criteria applied
- Waveform total charge only saved in cluster-peak position

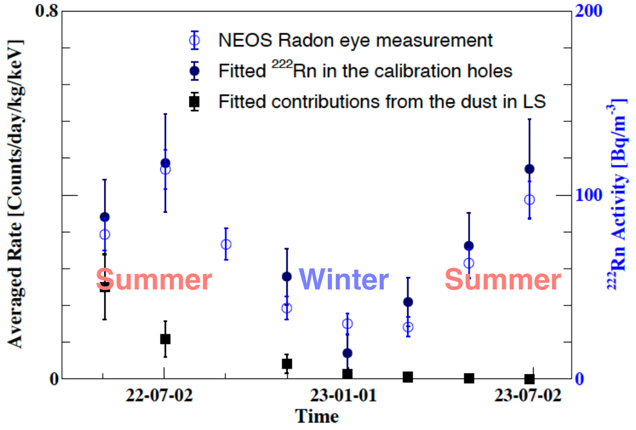




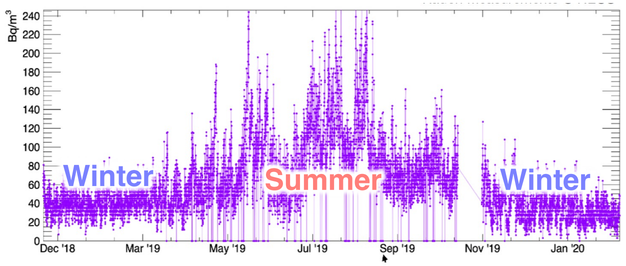
Seasonal Variation of ^{222}Rn







^{222}Rn at tendon gallery measured by NEOS experiment



arXiv:2406.06117

- Time-dependent components in the NEON data
  - Seasonal variation of ^{222}Rn through opened calibration hole
    - Exposed to the same level of ^{222}Rn as the experimental tunnel
  - Dust inside the LS

- Modeling with time-binned dataset, 2 months

Background Components in the NEON Experiment

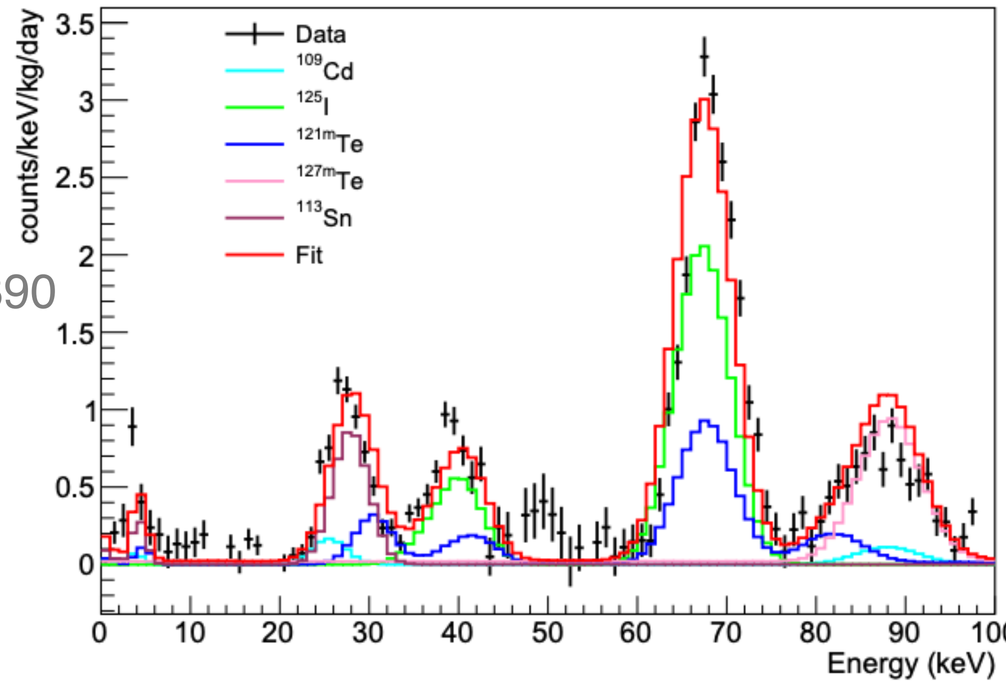
- Internal components measured for the NEO crystals

			^{40}K		^{210}Pb	^{232}Th	^{238}U	
Crystal	Mass (kg)	Size (inch, D × L)	^{nat}K (ppb)	α Rate (mBq/kg)	^{210}Pb (mBq/kg)	^{216}Po (μBq/kg)	^{218}Po (μBq/kg)	Light yield (NPE/keV)
NEO-1	1.62	3 × 4	50 ± 20	2.16 ± 0.02	1.89 ± 0.26	1.6 ± 0.7	10.6 ± 4.2	20.5 ± 0.9
NEO-2	1.67	3 × 4	137 ± 28	7.78 ± 0.03	7.46 ± 0.73	< 59.8	< 57.2	19.3 ± 0.9
NEO-3	1.67	3 × 4	46 ± 20	0.56 ± 0.01	0.53 ± 0.13	< 3.6	< 11.2	21.8 ± 0.9
NEO-4	3.35	3 × 8	22 ± 11	0.76 ± 0.01	0.69 ± 0.18	1.6 ± 0.8	< 3.3	22.4 ± 1.0
NEO-5	3.35	3 × 8	< 29	0.76 ± 0.01	0.68 ± 0.17	1.6 ± 0.5	2.9 ± 1.6	21.8 ± 0.9
NEO-6	1.65	3 × 4	< 38	0.94 ± 0.01	0.88 ± 0.21	5.8 ± 1.3	11.0 ± 3.3	21.7 ± 1.0
COSINE-100(C6)	12.5	4.8 × 11.8	17 ± 3	1.52 ± 0.04	1.46 ± 0.07	2.5 ± 0.8	< 0.25	14.6 ± 1.5

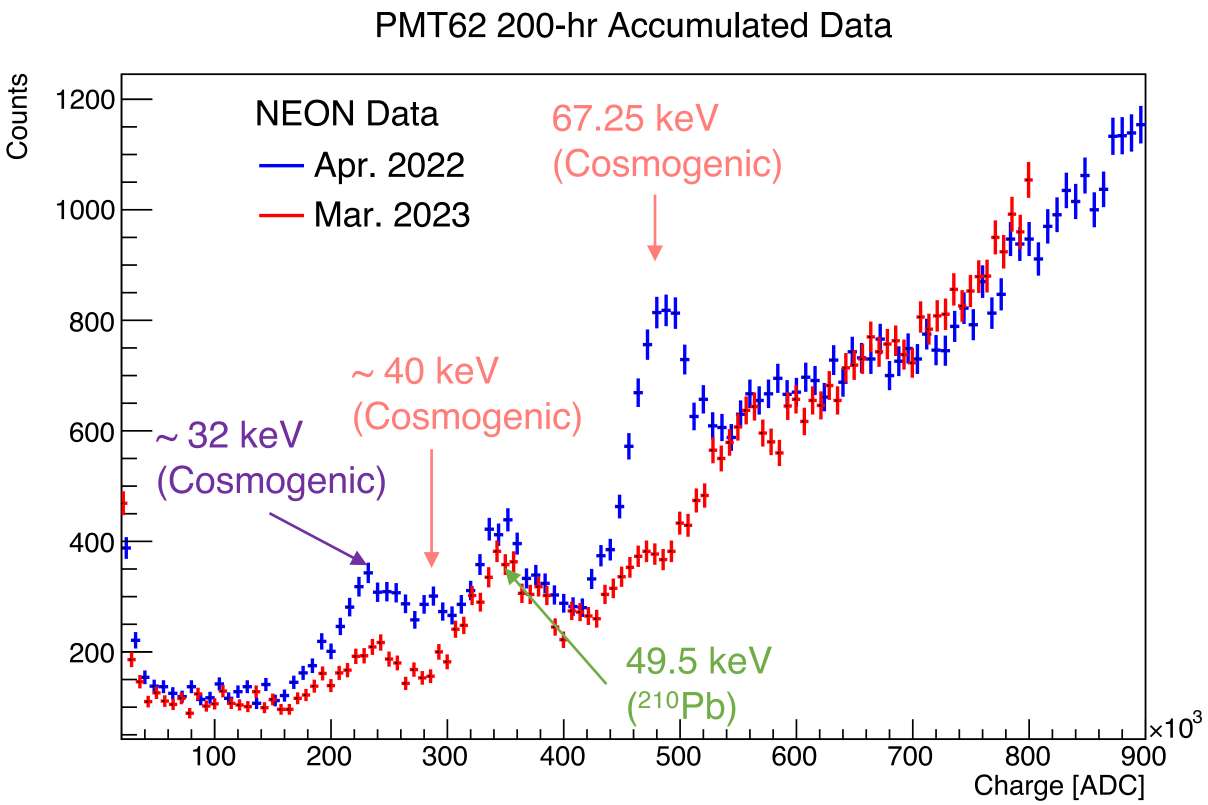
EPJC (203) 83:226

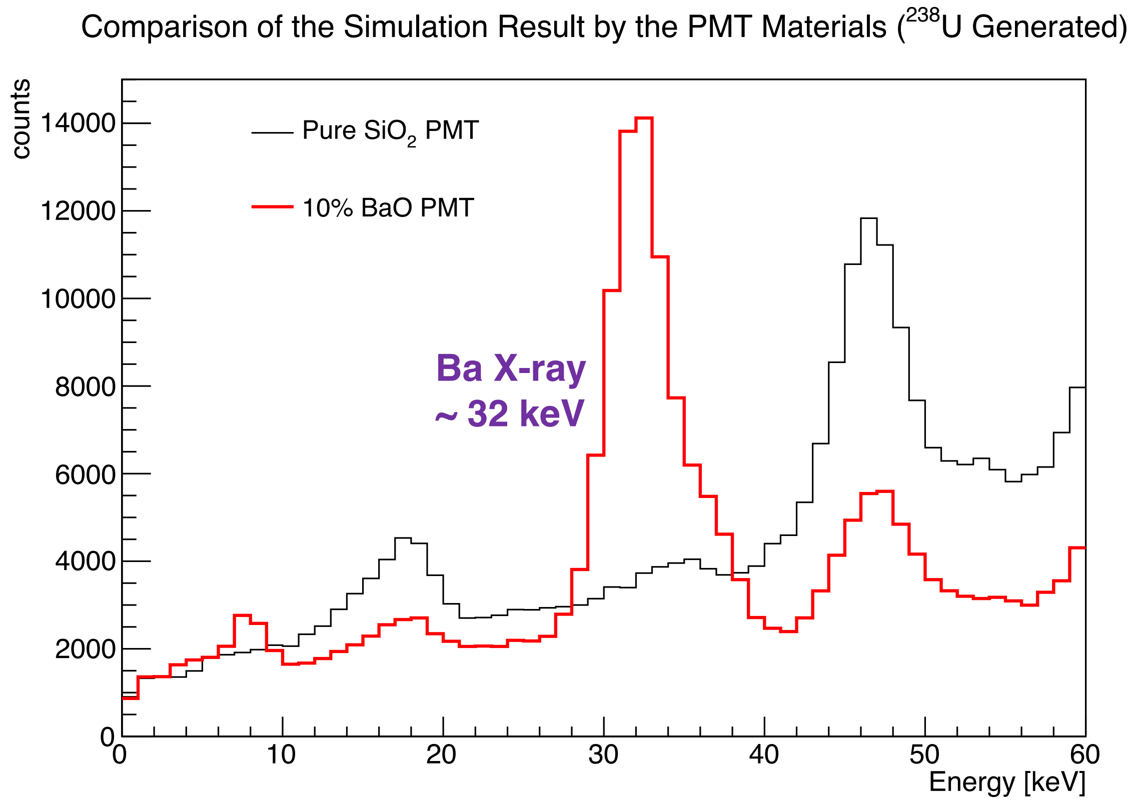
- Cosmogenic components studied on the COSINE-100 experiment

Astropart. Phys. (2020) 115:102390



Simulations for the Background Modeling





- Updates on the detector simulation for unexplained components
  - Explanation around non-temporal 32 keV peak component
    - Ba X-ray ~ 32 keV, from PMT glass
    - Optimization of simulation on material composition is required