Search for coherent neutrino-nucleus scattering in the NEON experiment

Hyun Su Lee

Center for Underground Physics (CUP)

Institute for Basic Science (IBS)

PIC2024, October 23rd 2024

NEON Collaboration

NEON (Neutrino Elastic-scattering Observation with NaI)

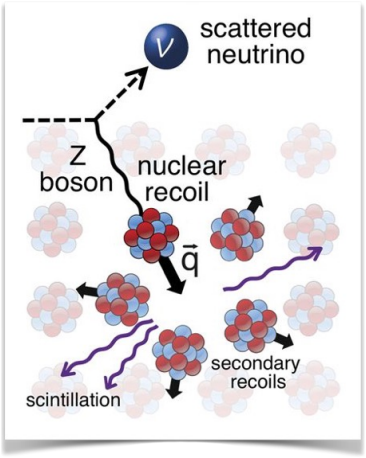
Aim to observe Coherent Elastic Neutrino Nucleus Scattering (CEνNS)
from reactor $\bar{\nu}_e$ using NaI(Tl) detector

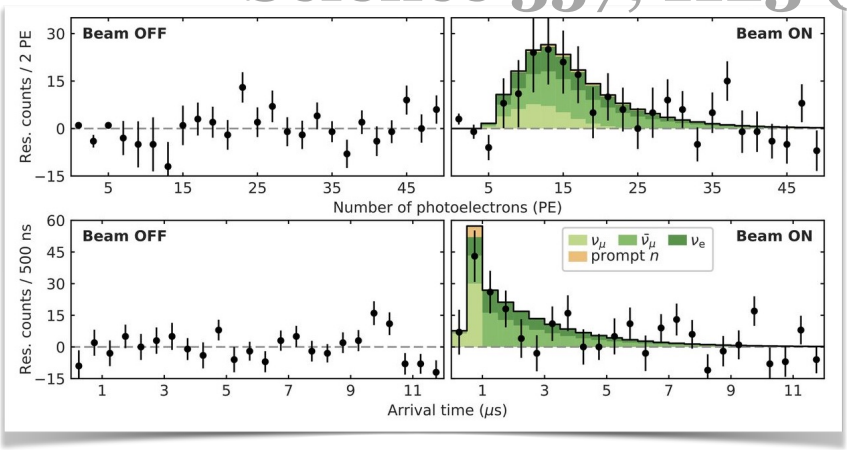
17 collaborators (active members of COSINE-100 and/or NEOS)

First observation of CEνNS (COHERENT experiment)

- The COHERENT collaboration with spallation neutron source (stopped pion source)
  - First observation with a CsI(Na)

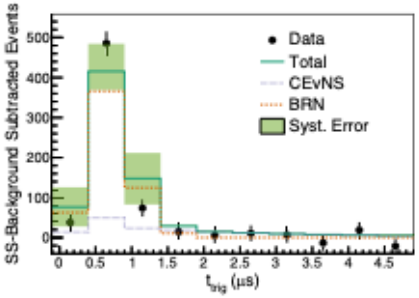
Science 357, 1123 (2017)

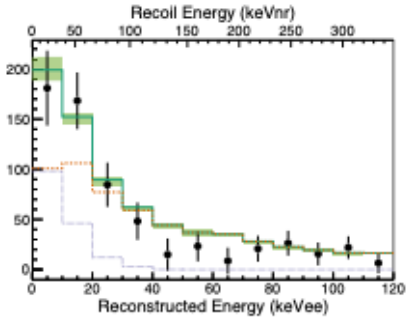


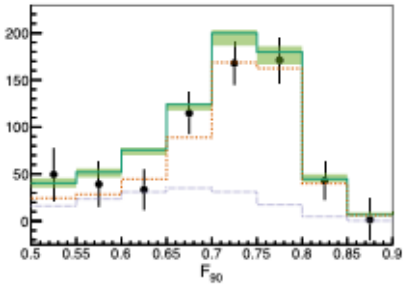


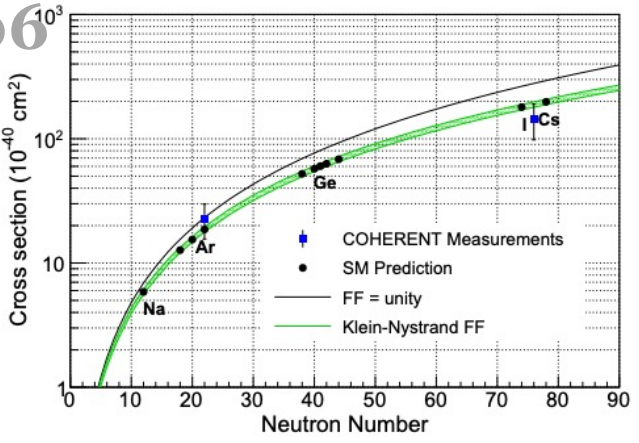
PRL 126, 012002 (2021) arXiv:2406.13806

  - Confirmation with liquid Ar & Ge



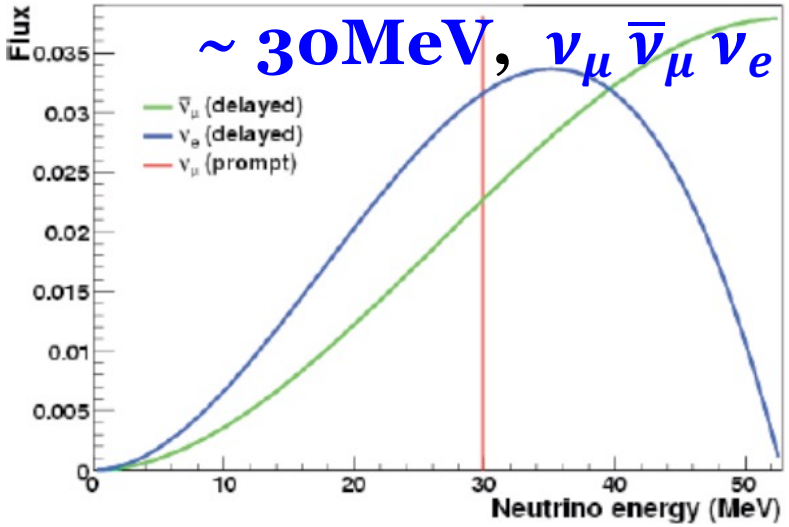






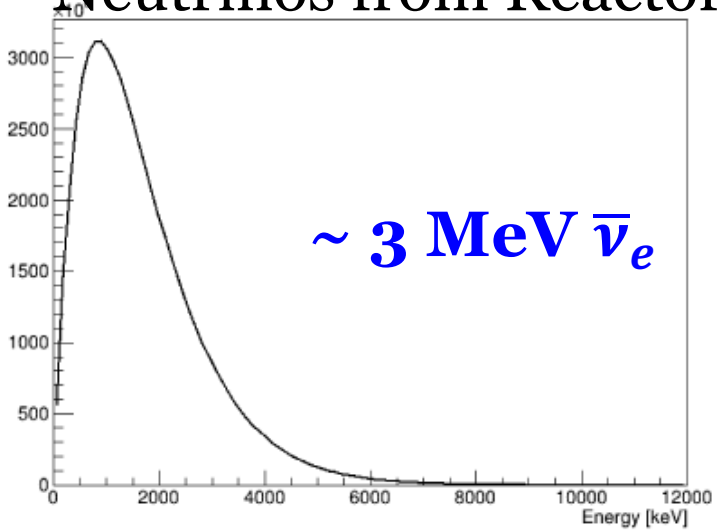
Reactor neutrinos for CEνNS

Neutrinos from SNS



Few times 10^7/s/cm² at 20 m

Neutrinos from Reactor



about 10^{13}/s/cm² at 24 m

- Much large neutrino flux
- Much lower energy deposition
- If we have a proper detector…
  - ❖ Precision measurement for neutrino properties
  - ❖ Reactor monitoring & nuclear non-proliferation
  - ❖ In principle, CEνNS can prove below IBD threshold (1.8 MeV)

Neutrino energy

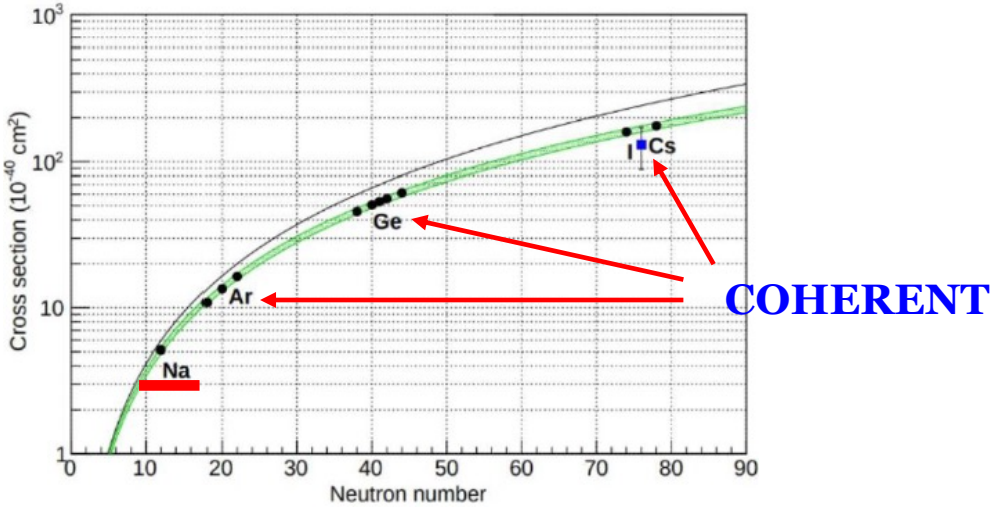
$$E_{max} = 2E_\nu^2/M_N \sim 2 \text{ keV}$$

Mass of target nucleus

NaI(Tl) for CEνNS

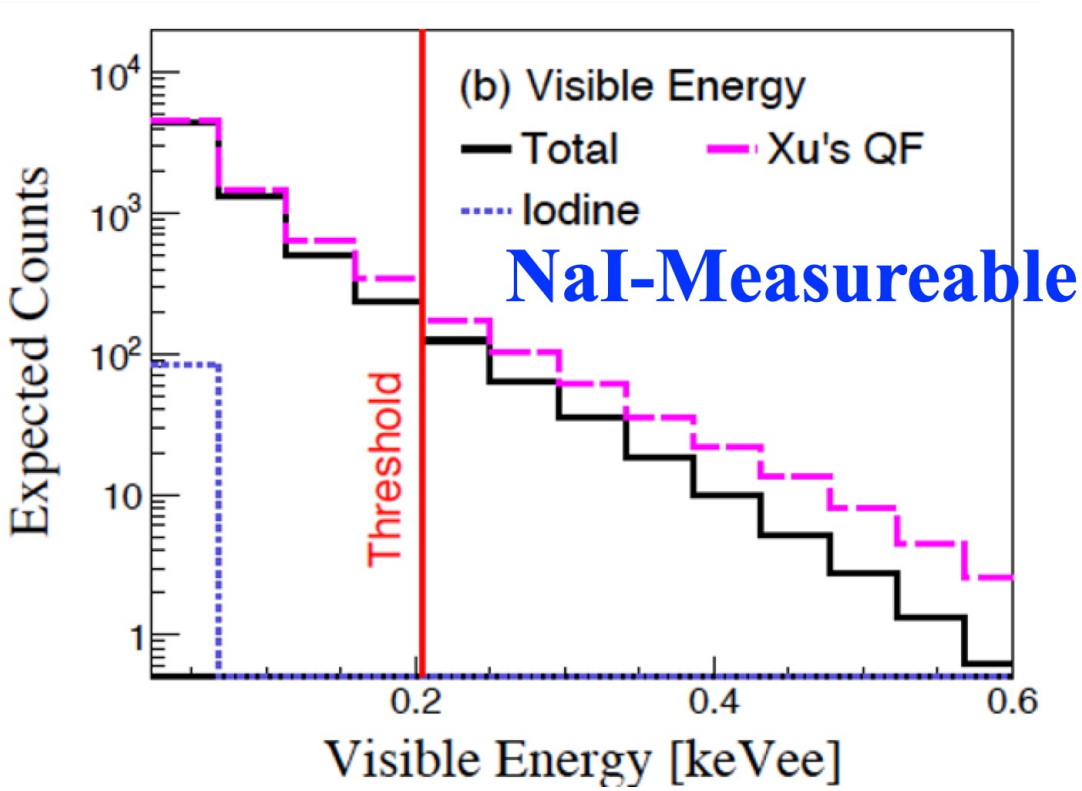
- High measured light yield (15 NPE/keV$_{ee}$ in COSINE-100)
  - ❖ Trigger threshold : 2 NPE (0.13 keV$_{ee}$) **NPE = Number of Photoelectrons**
- Larger recoil energy from Na (N^2 dependence testable)
- Easy to make large size detector O(10 kg)
- Low background detector available (3 counts/kg/day/keV=3dru)
- Easy to scale up with affordable costs O(100 kg)

COSINE-100 detector



NaI(Tl) for CEνNS

Expected Signals (13.5 kg year)



~1000 events/year with 0.2 keV threshold

>3 sigma observation!!

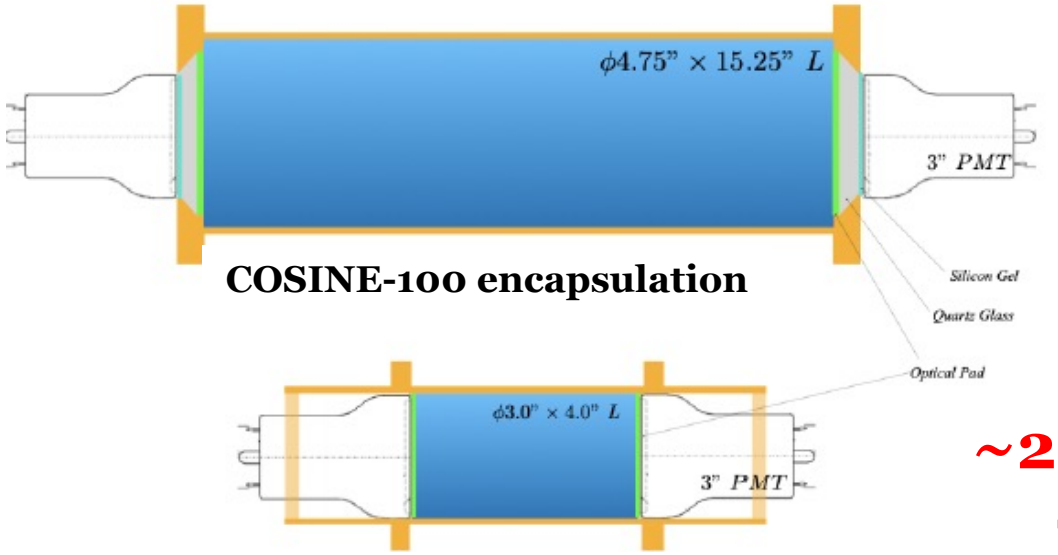
If we achieve ~ 10 counts/kg/keV/day (dru) background

EPJC 83, 226 (2023)

Can we reach to low enough energy threshold? **~0.2 keV$_{ee}$**?

High light yield NaI(Tl) detectors

NIMA 981 (2020) 164556



COSINE-100 encapsulation

NEON encapsulation

15 NPE/keV

(NPE=number of photoelectrons)

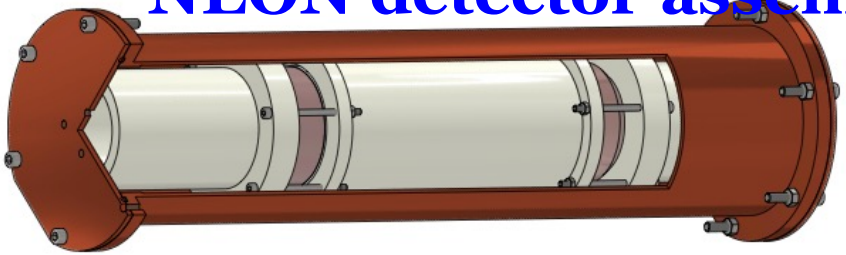
~24 NPE/keV

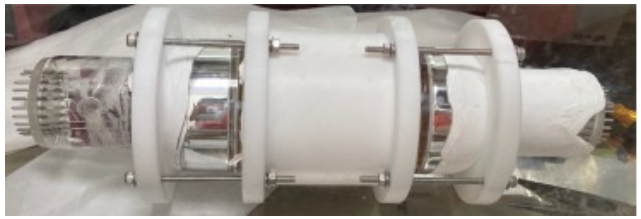
Trigger threshold ~ 0.08 keV_{ee}

- Direct attachment of NaI(Tl) to PMTs
- ~50 % increased light yield was observed
- This technique has been applied for the COSINE-100U

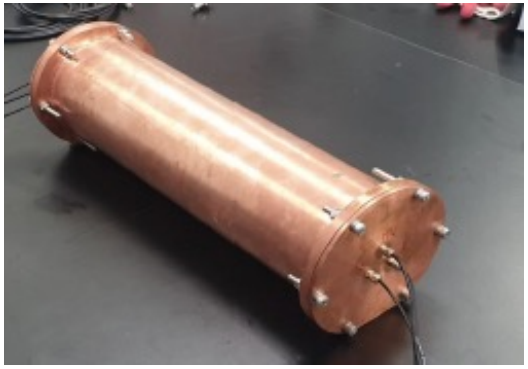
High light yield NaI(Tl) detectors

NEON detector assembly





JINST 19, P10020 (2024)



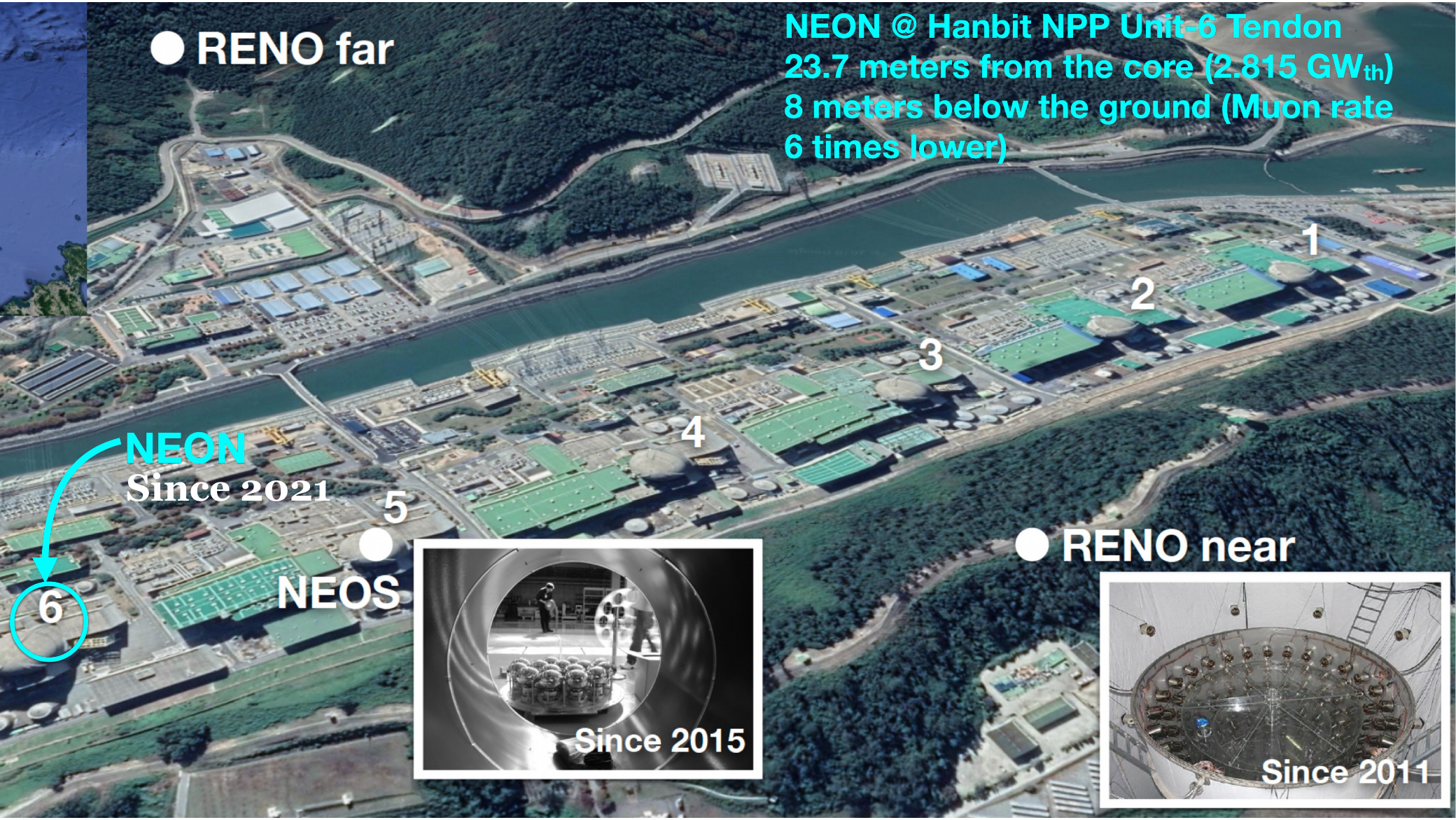
JINST 19, P10020 (2024)

Detector	Mass (kg)	size (inch, D×L)	Light yield w/o LG (PEs/keV)	Light yield w/ LG (PEs/keV)
DET-1	1.67	3 × 4	22.0±0.4	25.3±0.6
DET-2	3.34	3 × 8	25.6±1.1	27.8±1.4
DET-3	1.65	3 × 4	21.8±0.5	23.3±0.9
DET-4	3.34	3 × 8	23.7±0.4	25.4±0.7
DET-5	3.35	3 × 8	22.4±0.5	23.6±0.8
DET-6	3.35	3 × 8	25.0±0.5	27.9±0.7

Total : 16.7 kg

~24 NPE/keV

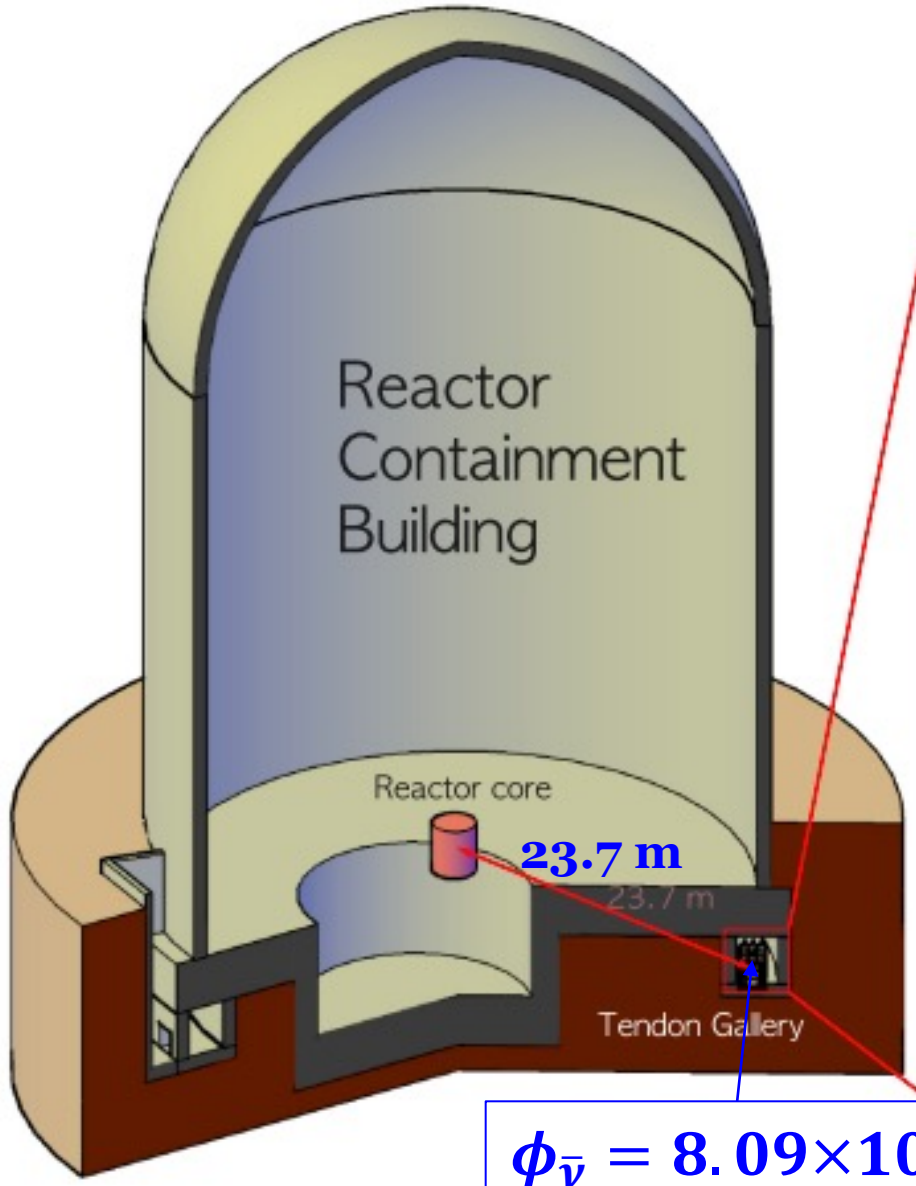
Experimental Site

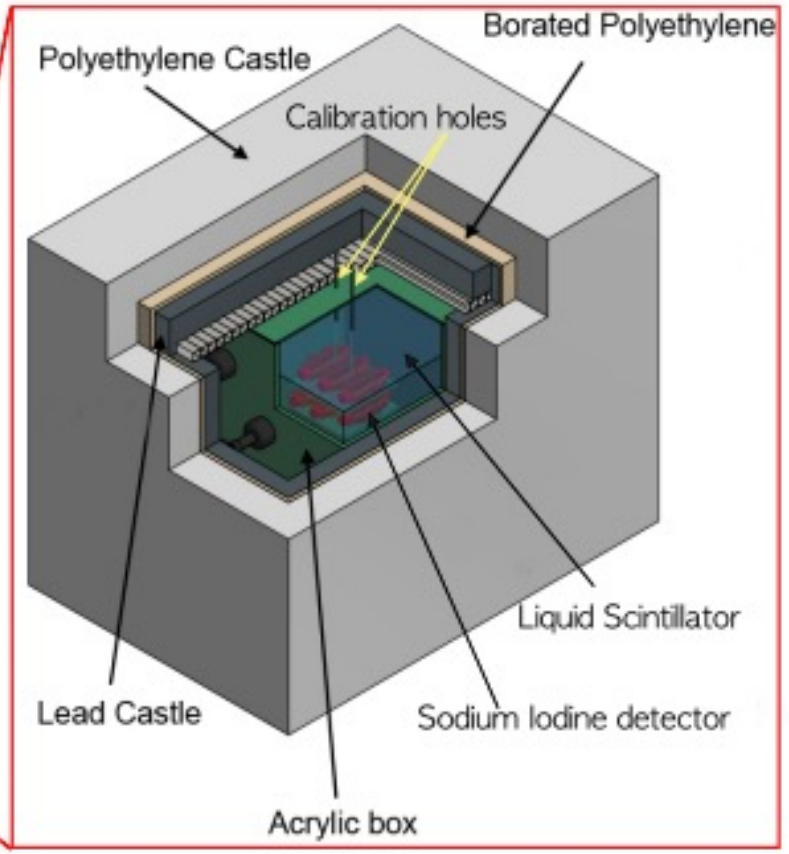


Experimental Site

Six NaI(Tl) crystals : 16.7 kg

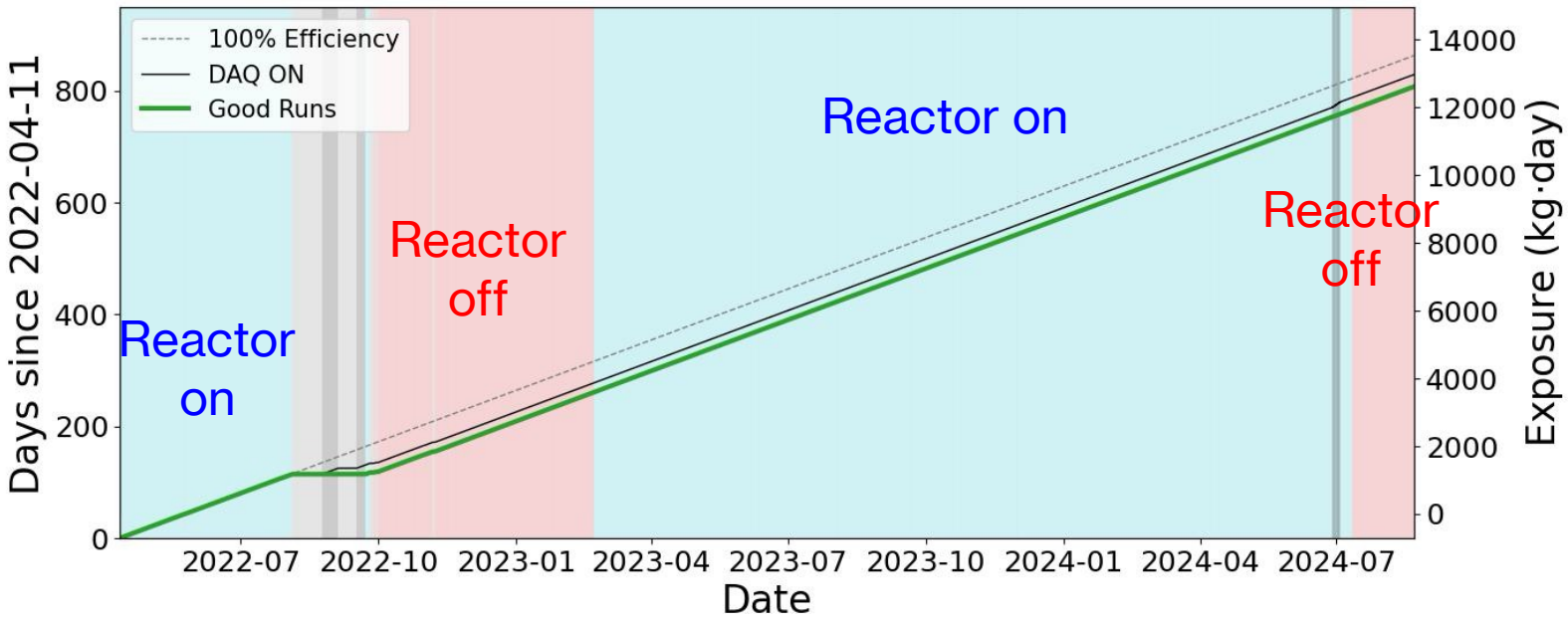
Physics run since April/2022

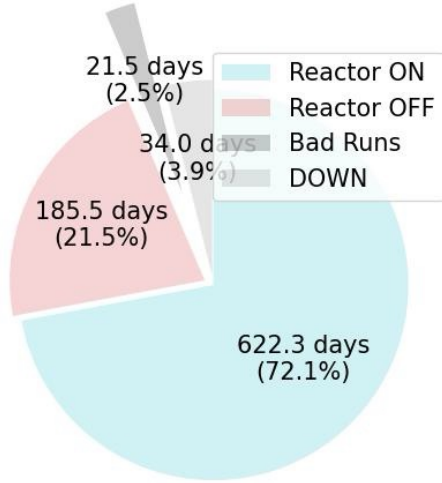




$$\phi_{\bar{\nu}} = 8.09 \times 10^{12}\ /cm^2/s$$

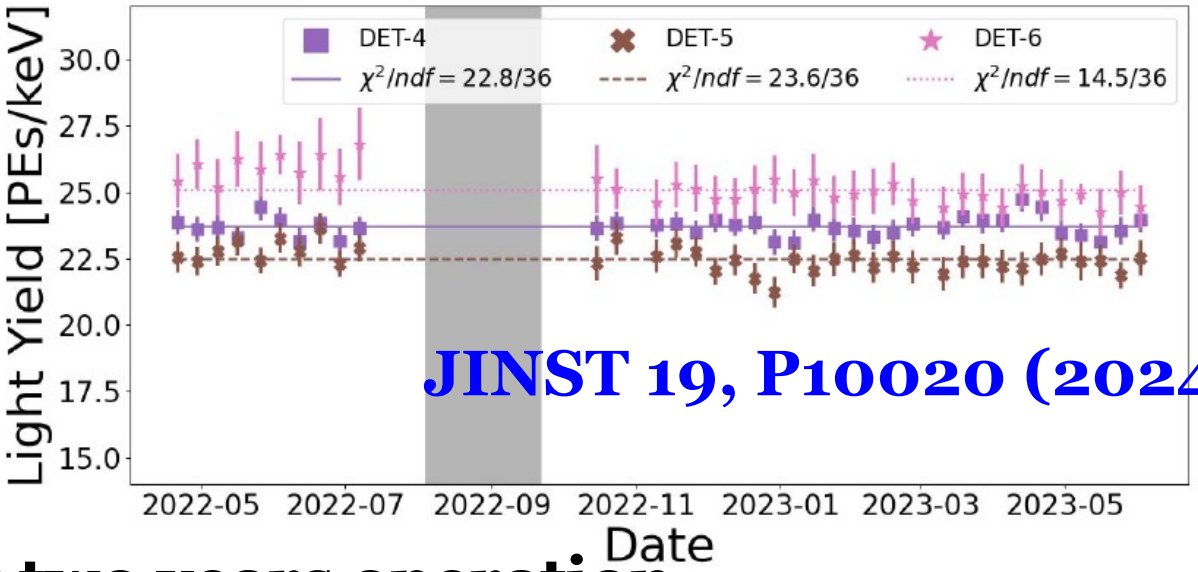
Physics Operation





- Physics run started since April 2022 (~ 2.5 years)
  - ❖ ~96% DAQ efficiency
- **623.3 days** of ON data (72%)
- **185.5 days** of OFF data (21%)
- Total 13,500 kg day exposure

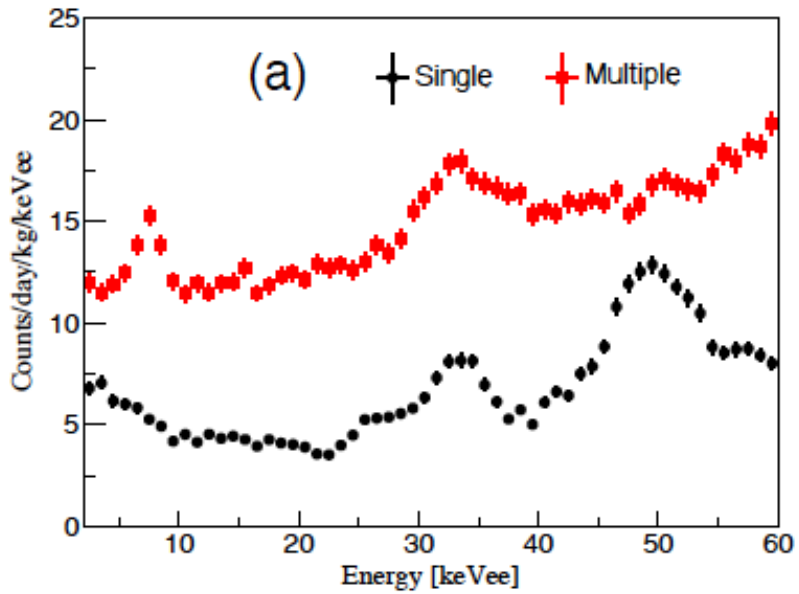
Detector performance

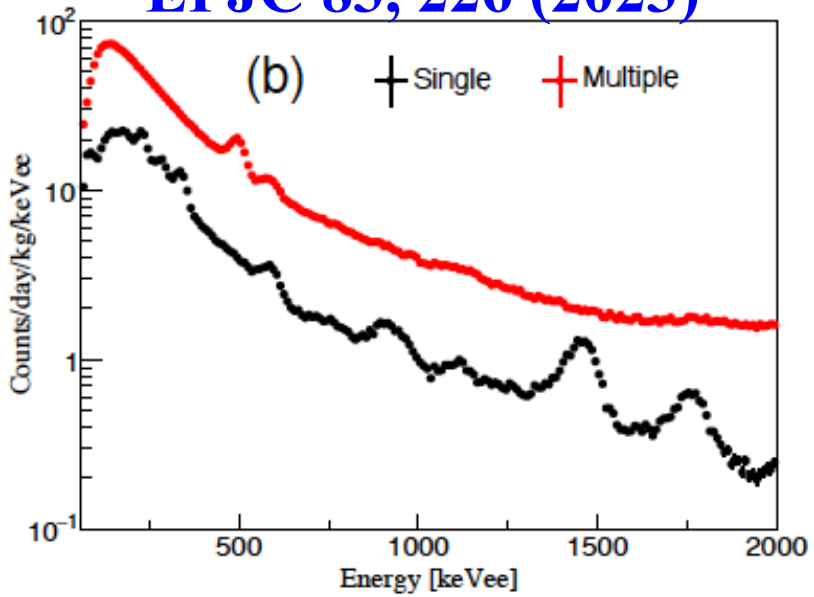


JINST 19, P10020 (2024)

Stable for two years operation

EPJC 83, 226 (2023)

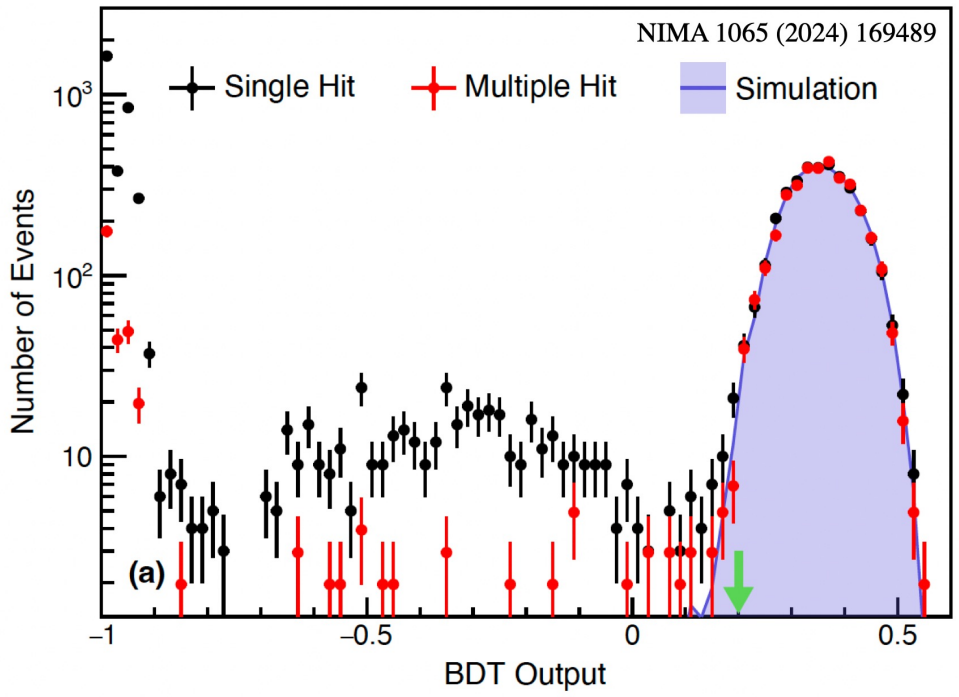


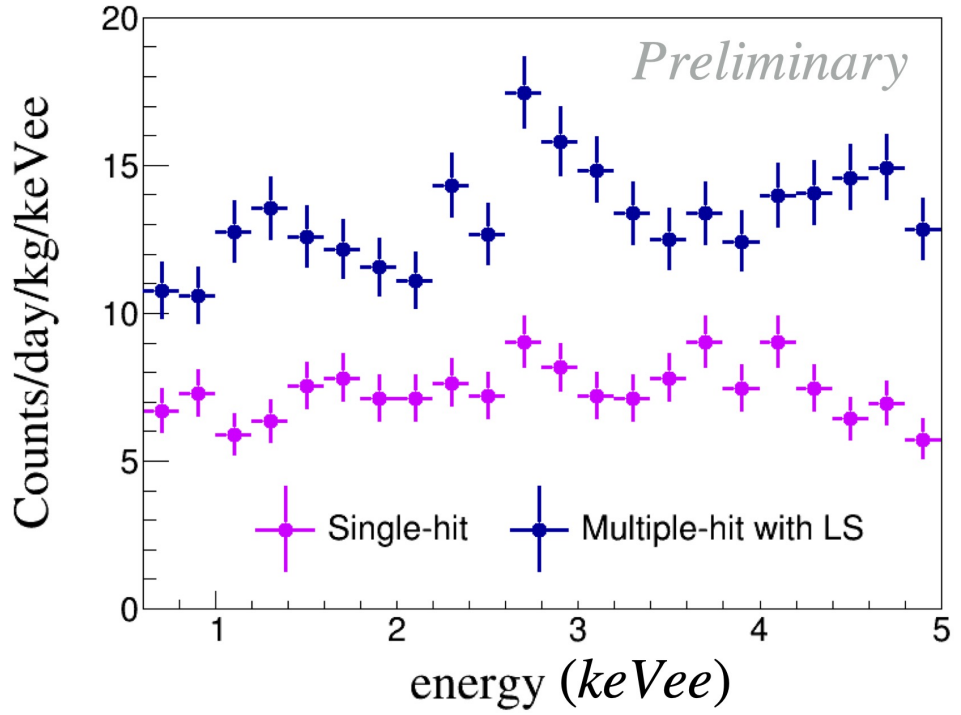


Low-energy event selection

- Develop waveform simulation package to describe low-energy scintillation events
- Multi-variable machine learning technique applied to remove PMT-induced noise events

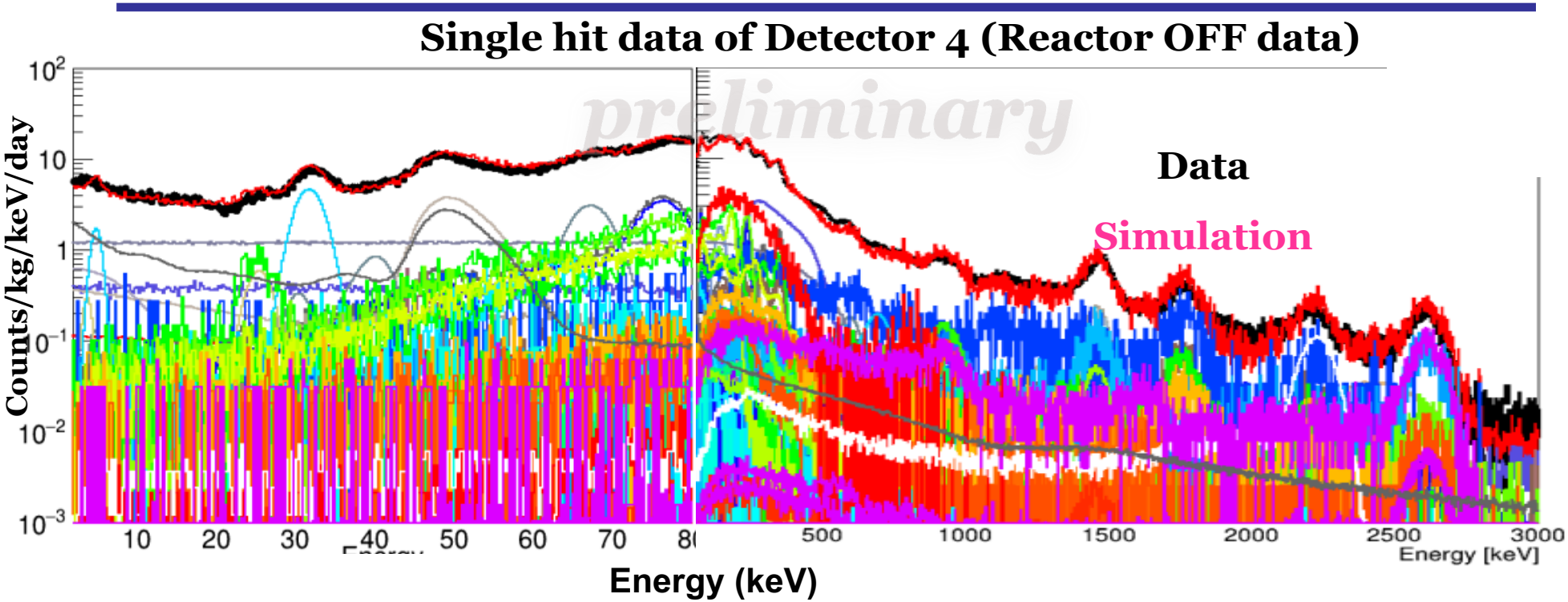
NIMA 1065 (2024) 169489





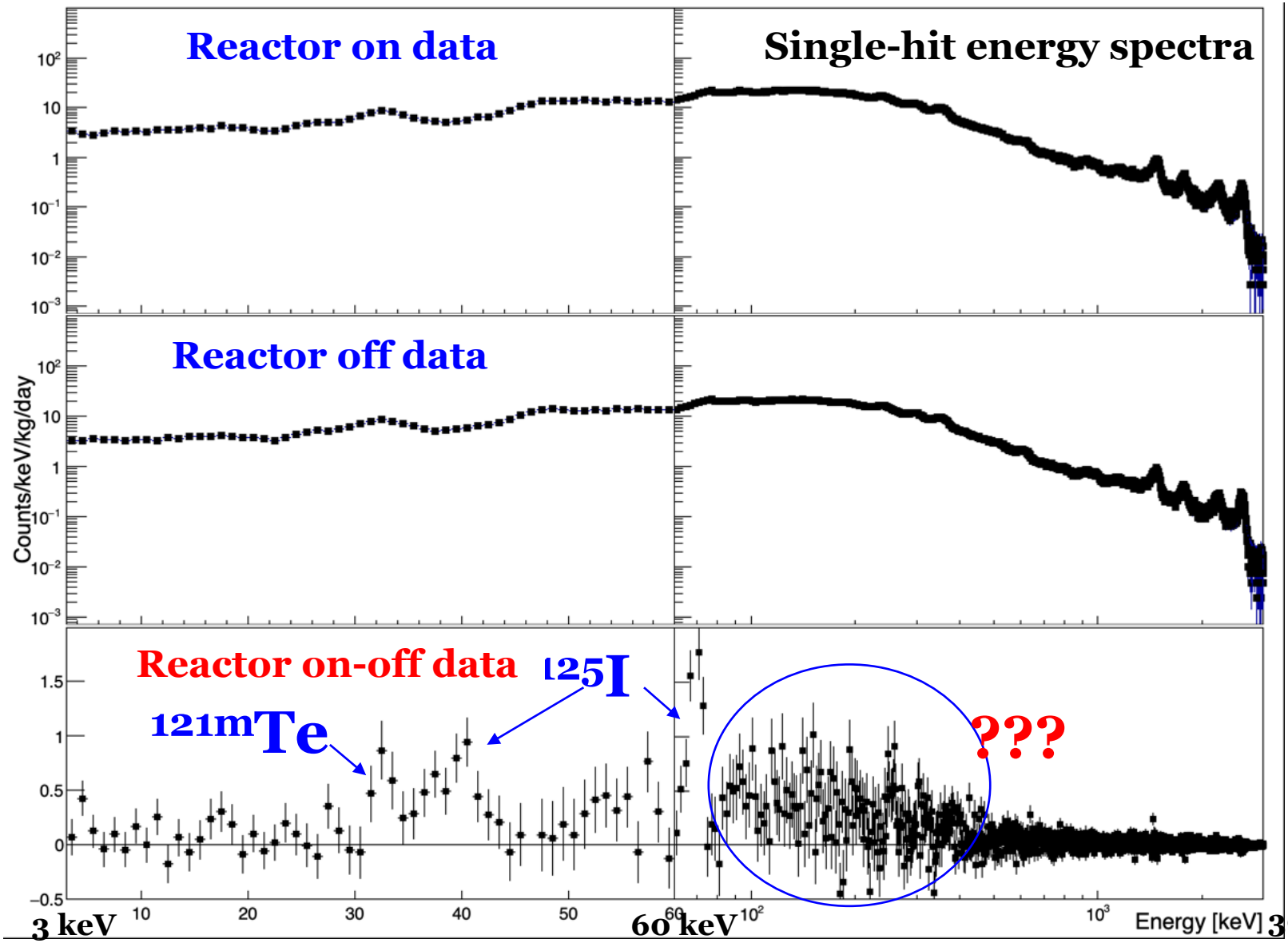
~ 7 counts/kg/keV/day @ 0.6 keV

Background understanding



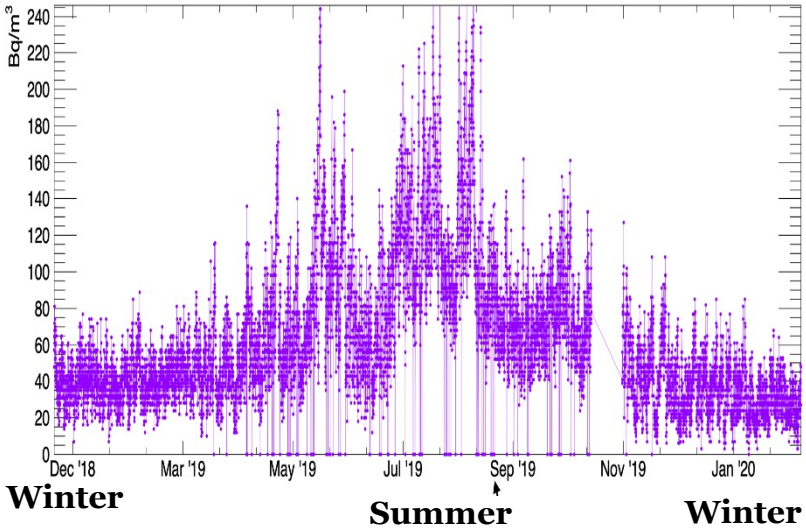
- Background understanding based on our experiences on COSINE-100 dark matter search experiment
  - ❖ EPJC 78 (2018) 490; EPJC 81 (2021) 837; arXiv:2408.09806
- 3 keV – 3 MeV are modeled

Reactor on vs off (Detector-6) for 1 year data

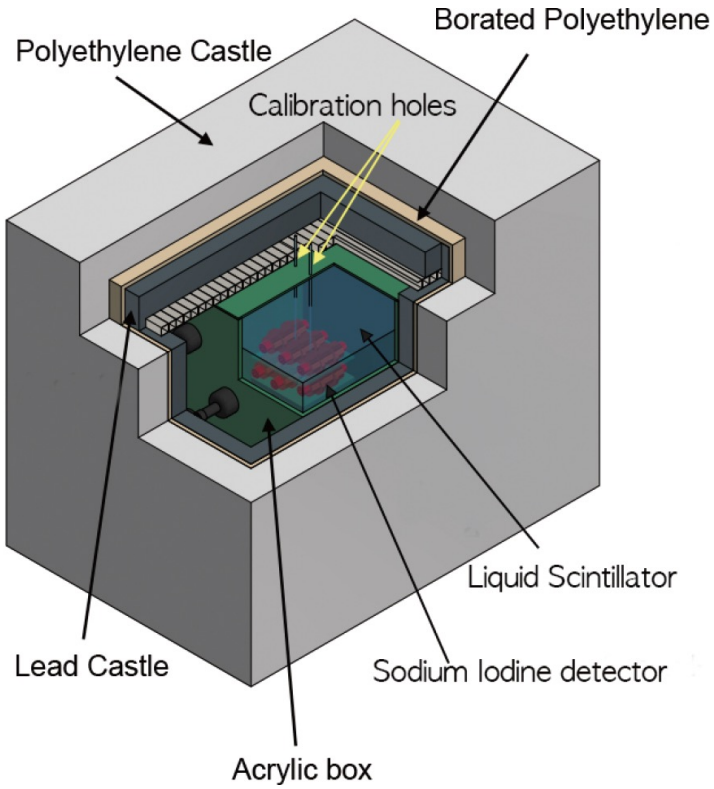


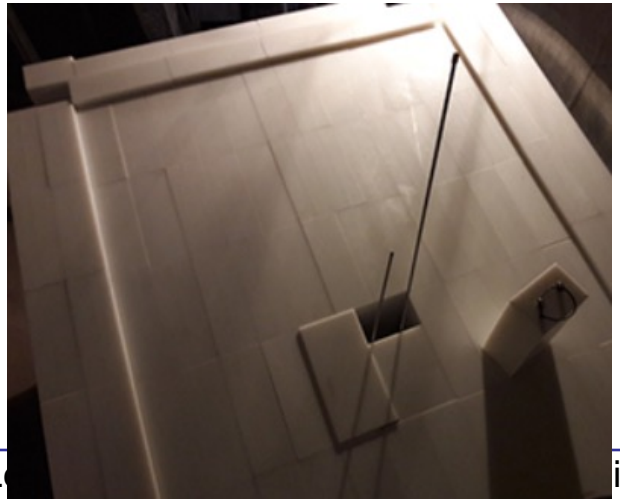
Seasonal variation of ^{222}Rn level

Radon eye measurement by NEOS experiment



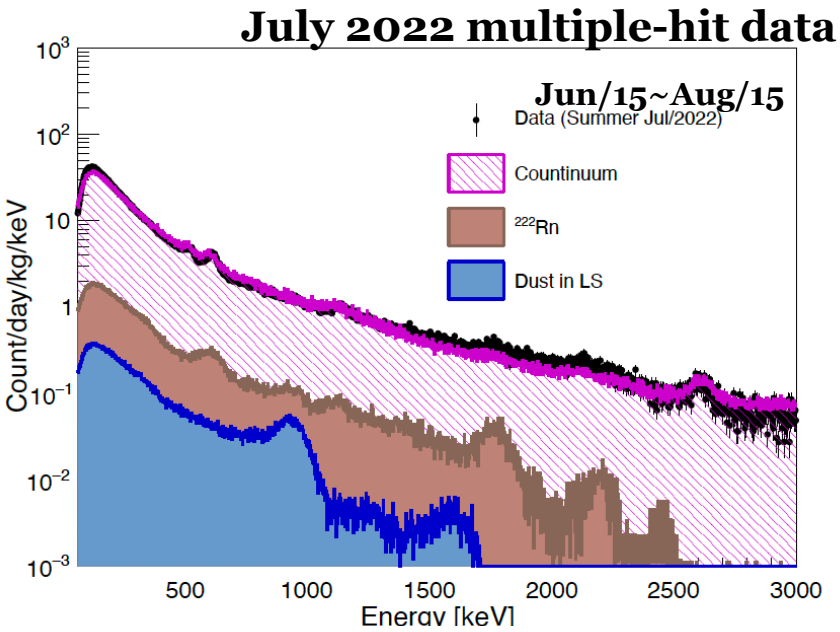
Calibration holes were opened

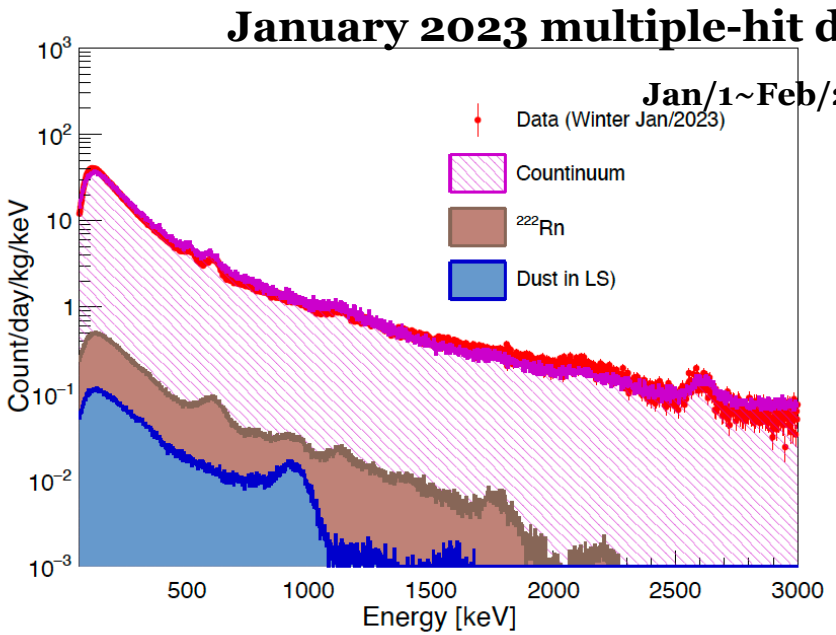


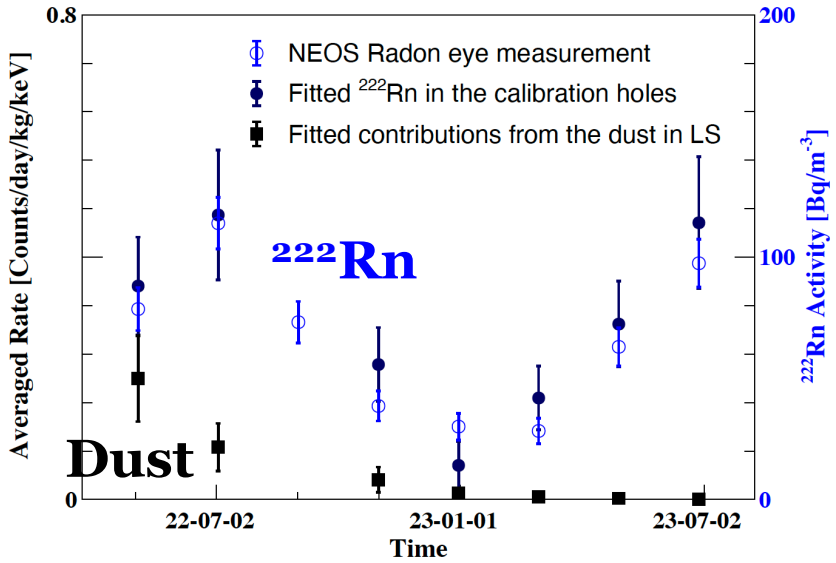


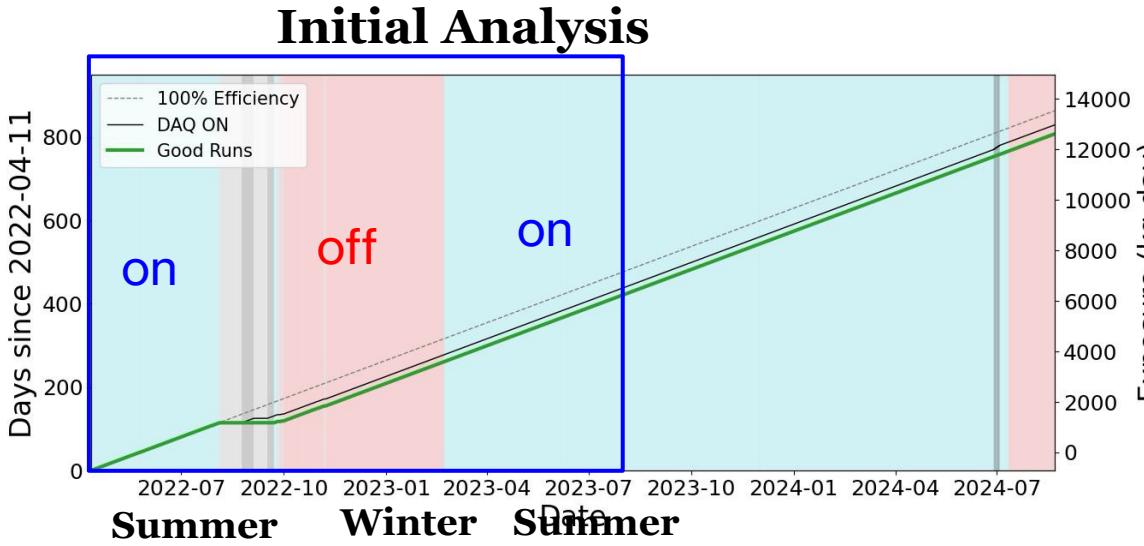
^{222}Rn level is higher at summer

^{222}Rn contribution modeling

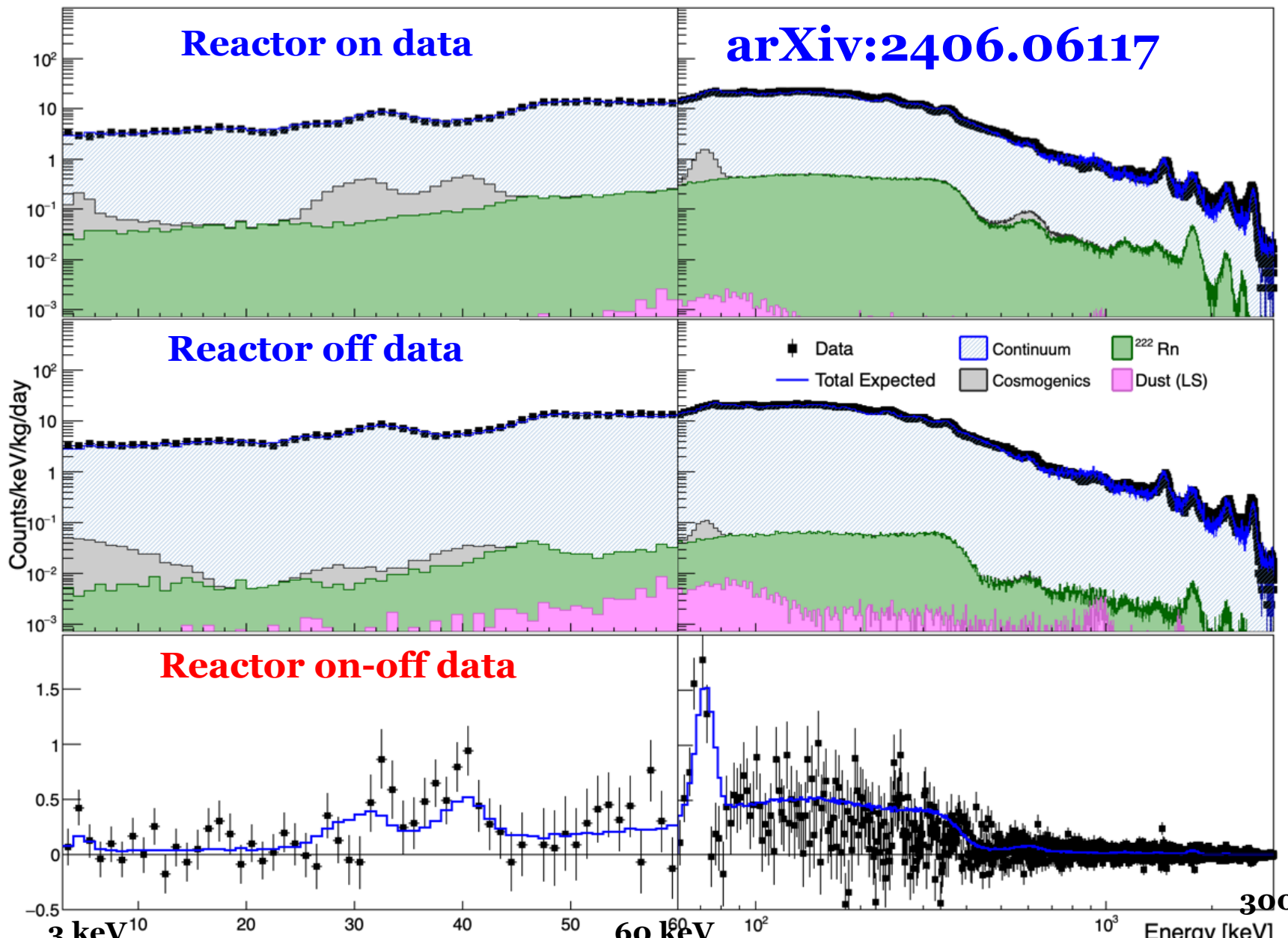






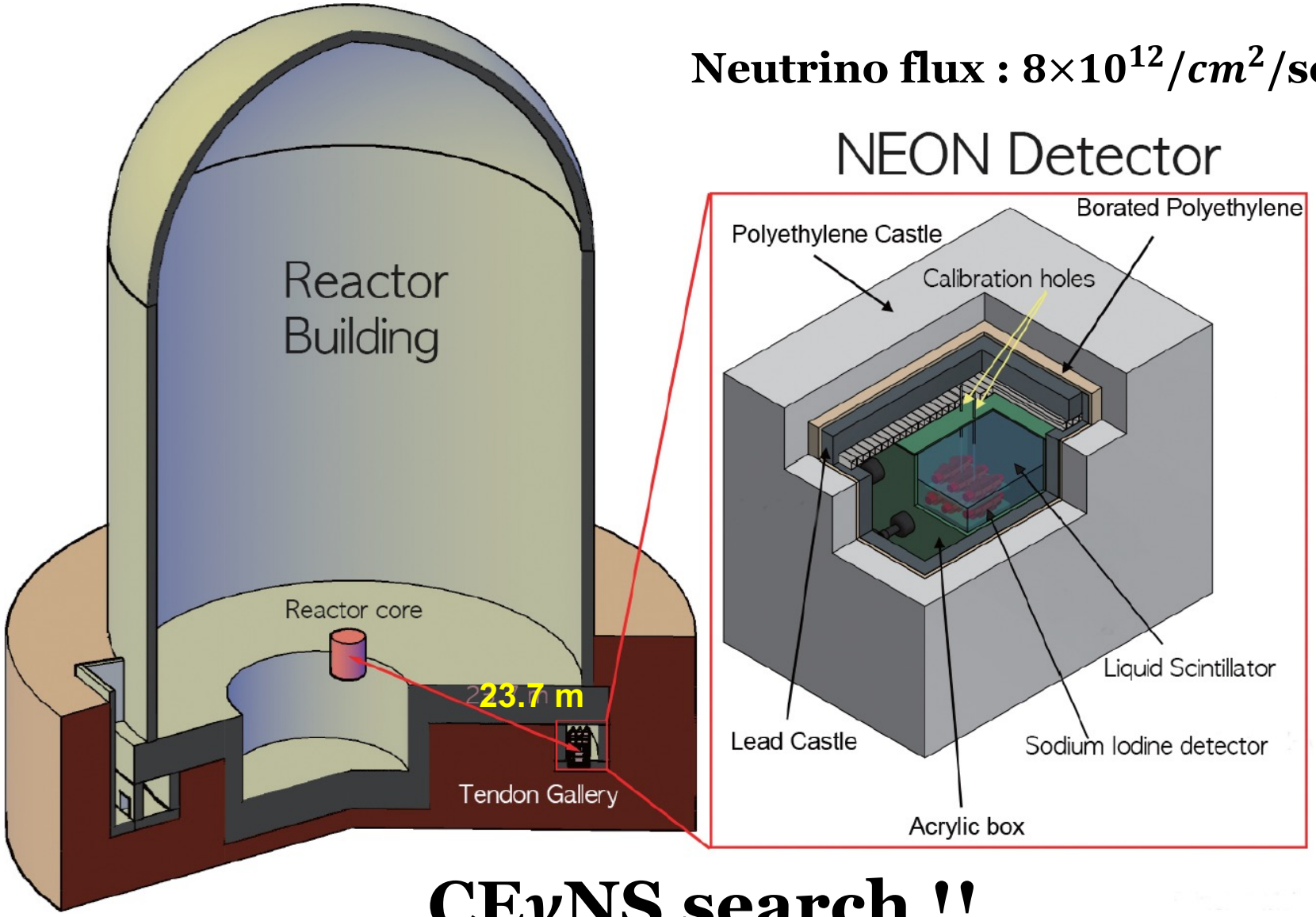


Reactor on vs off (Detector-6)



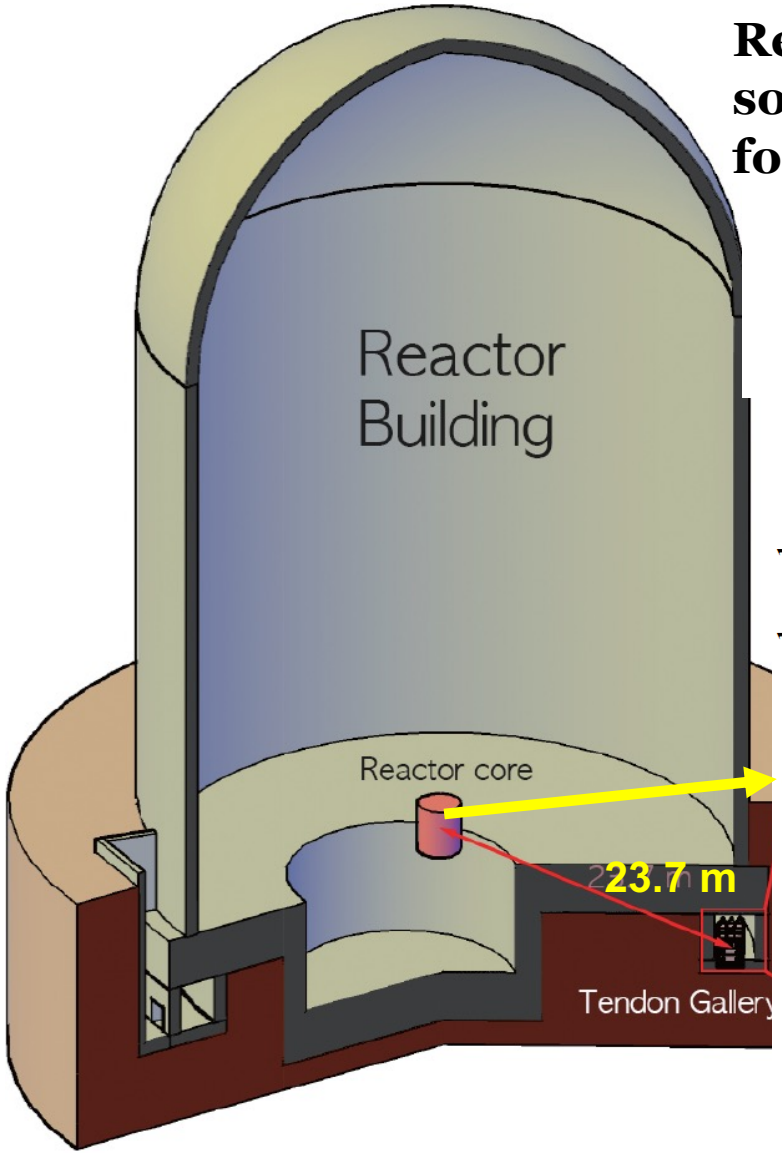
Reactor neutrinos

Neutrino flux : $8\times10^{12}/cm^2/sec$



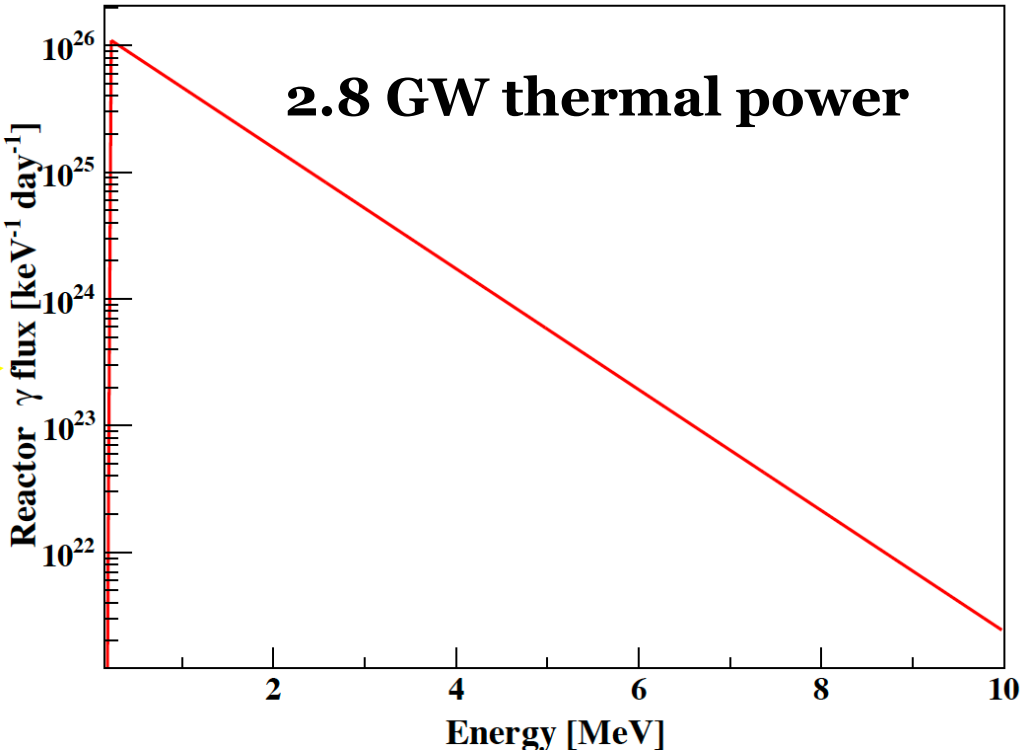
CEνNS search !!

Reactor photons

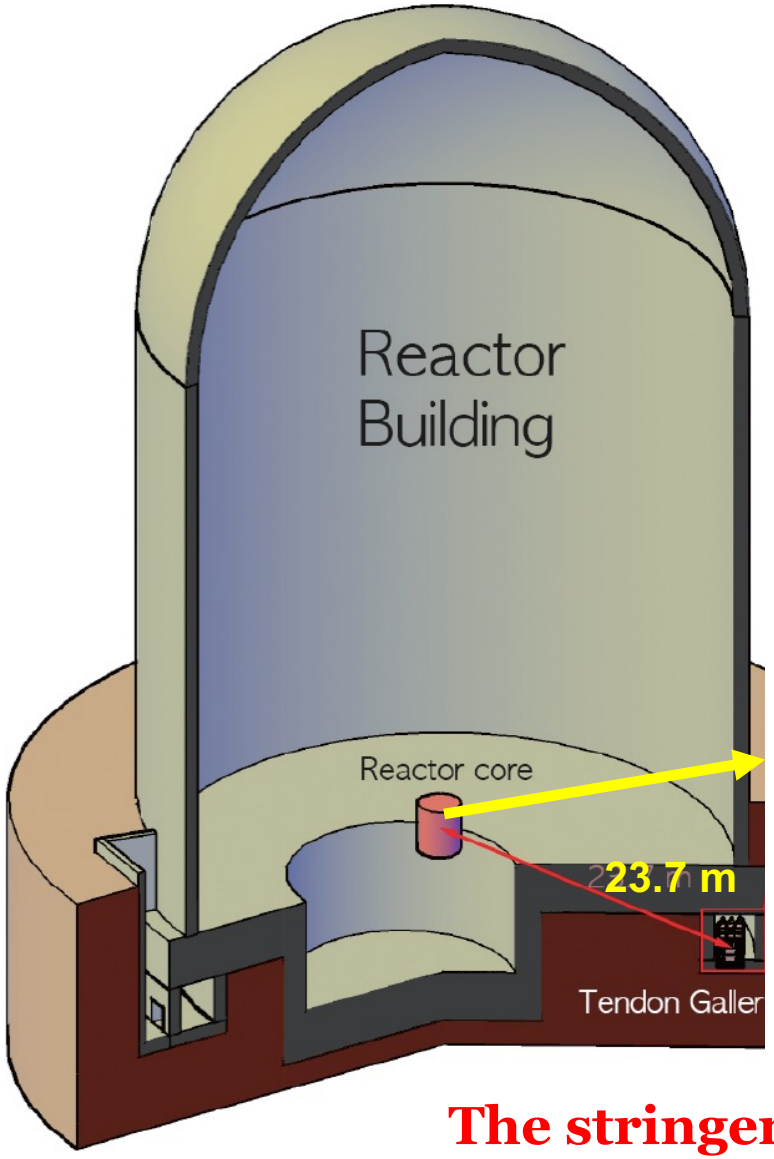


Reactor is not only the stringent neutrino source but also the stringent gamma source for O(MeV) energy

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{5.8 \times 10^{17}}{[\mathrm{MeV}] \cdot [\mathrm{sec}]} \left(\frac{P}{[\mathrm{MW}]} \right) e^{-1.1 E_\gamma / [\mathrm{MeV}]}$$

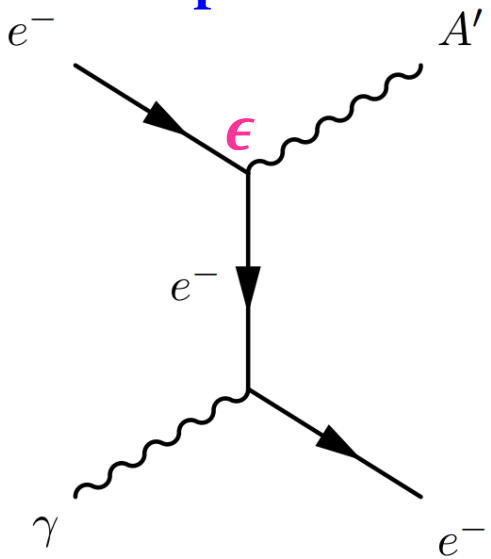


Reactor dark sector bosonic particles

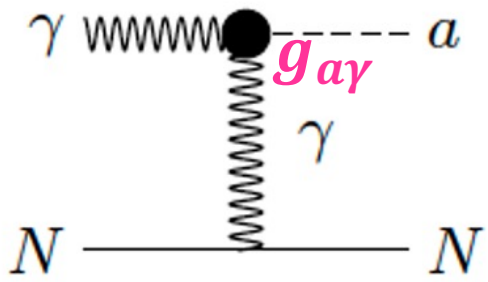


Photons can couple to dark sector bosonic particles such dark photon and axion like particle (ALP) with their mass up to O(MeV)

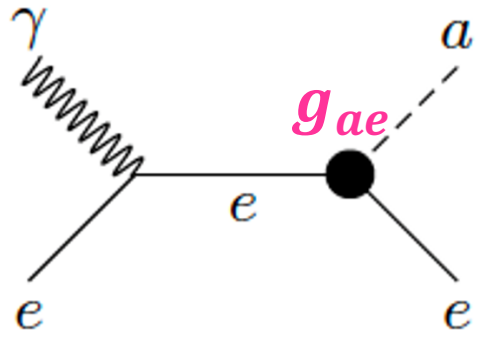
Dark photon



ALP



Primakoff



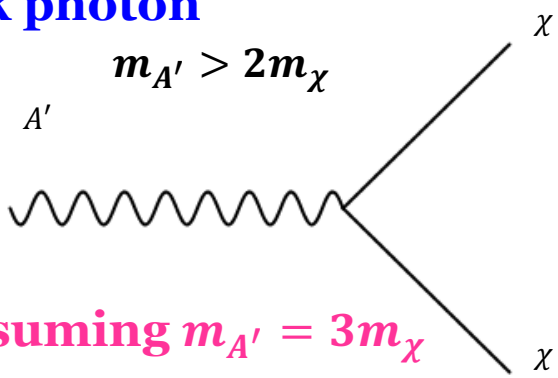
Compton-like

The stringent source of dark photon & ALP

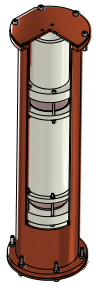
Light Dark Matter Search

- Through light dark matter (LDM) production

Dark photon

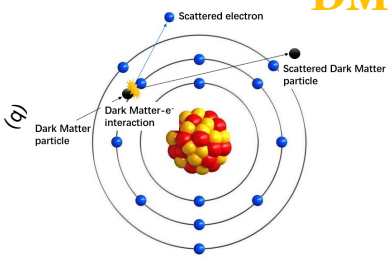


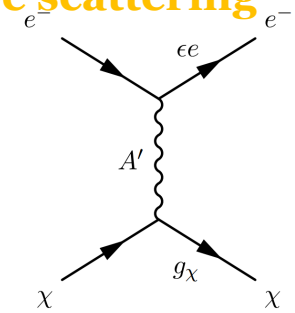
Assuming $m_{A'} = 3m_\chi$



Detector

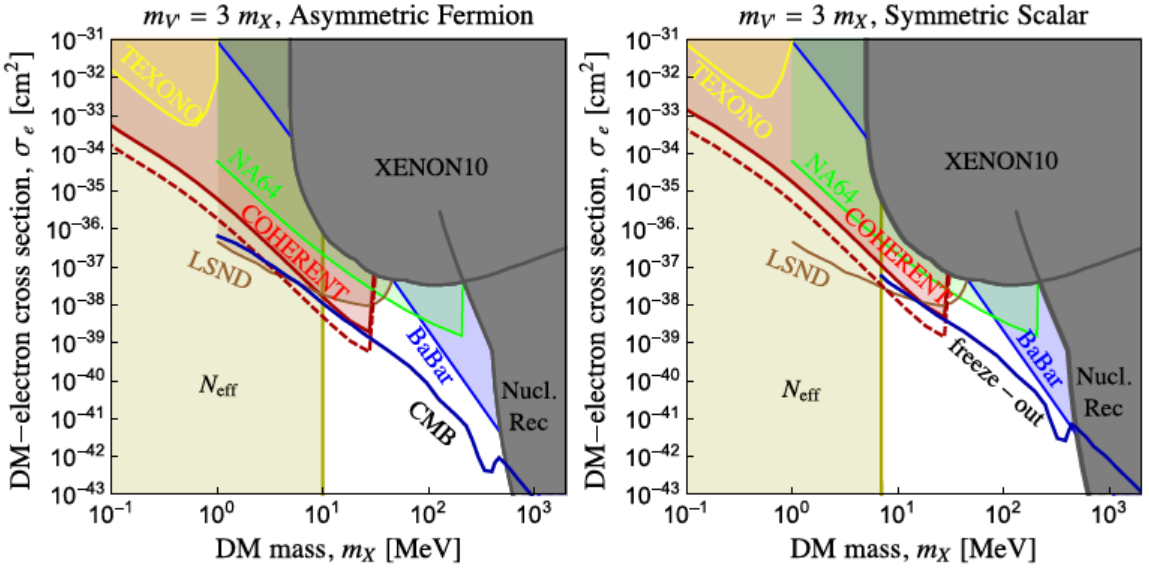
DM-e scattering



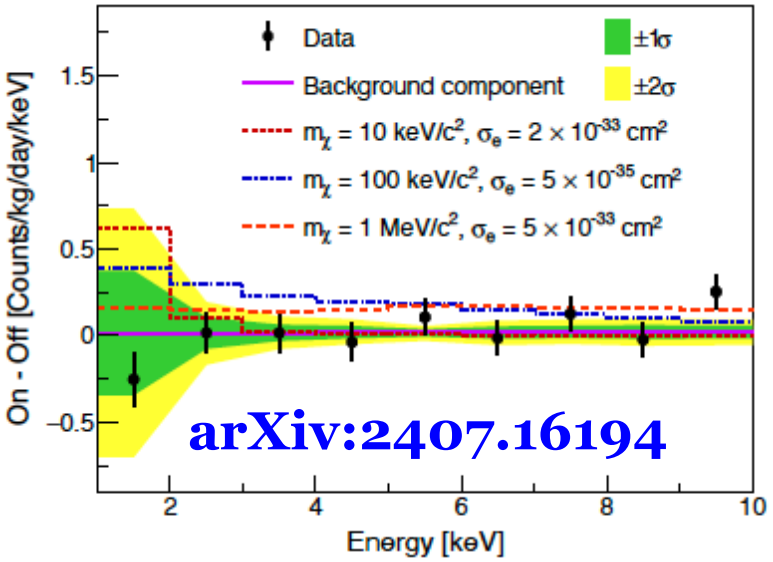


COHERENT LDM-nucleon scattering : PRL 130, 051803 (2023)

Theory study : JHEP 11 (2018) 066



Signal region : 1-10 keV

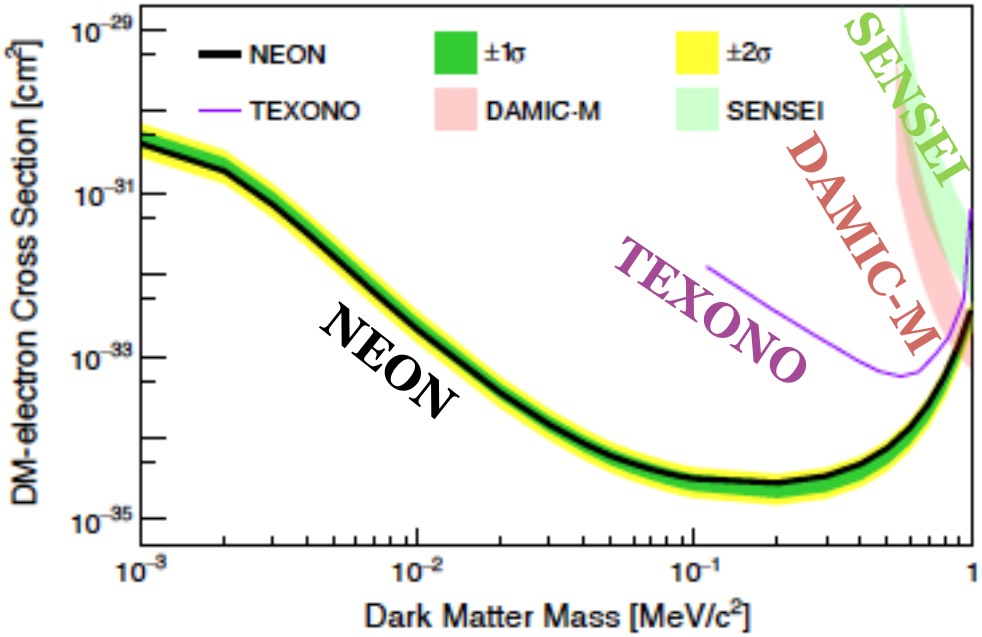


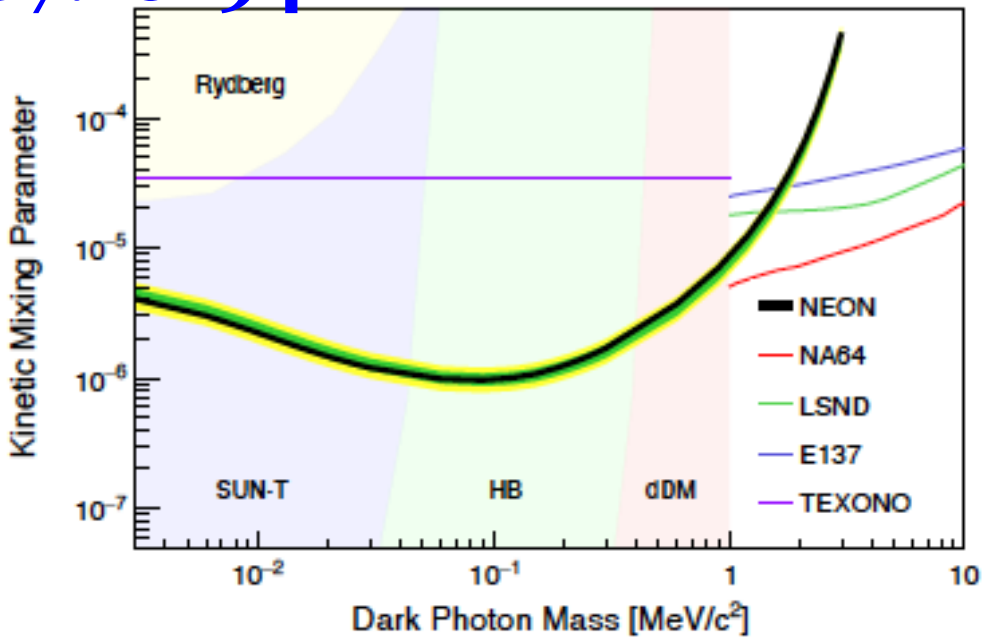
arXiv:2407.16194

Light dark matter search

- No signal excess – 90% confidence level upper limit

arXiv:2407.16194

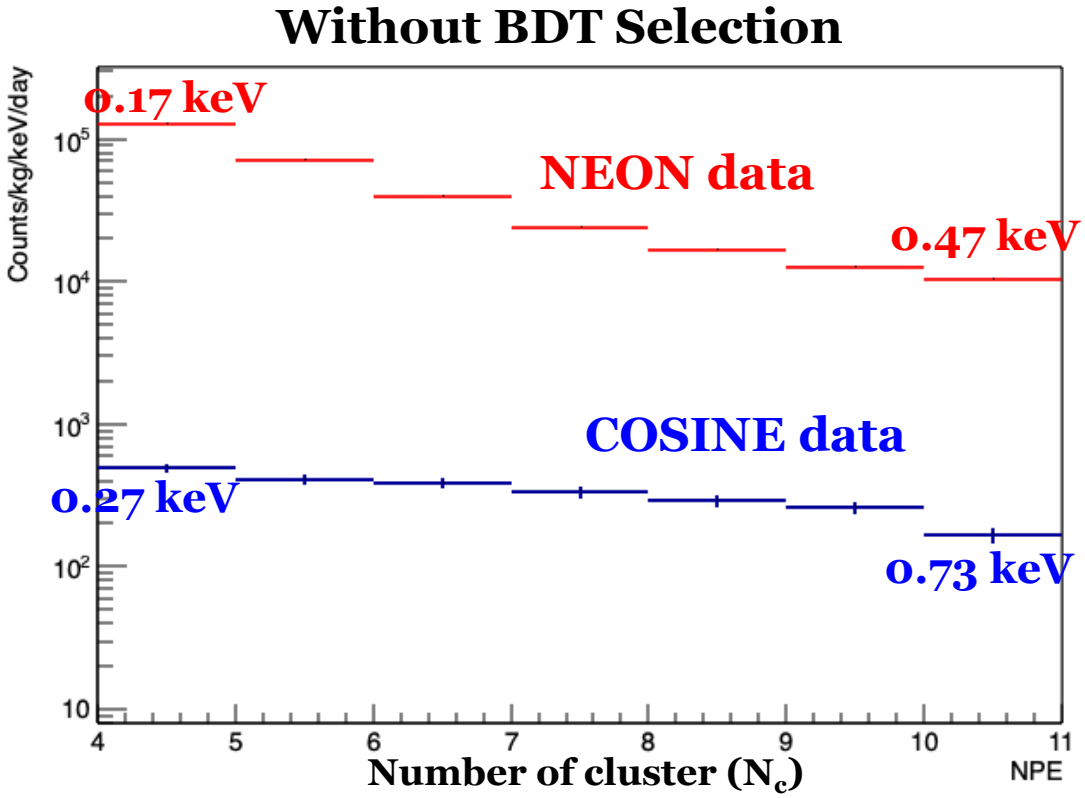


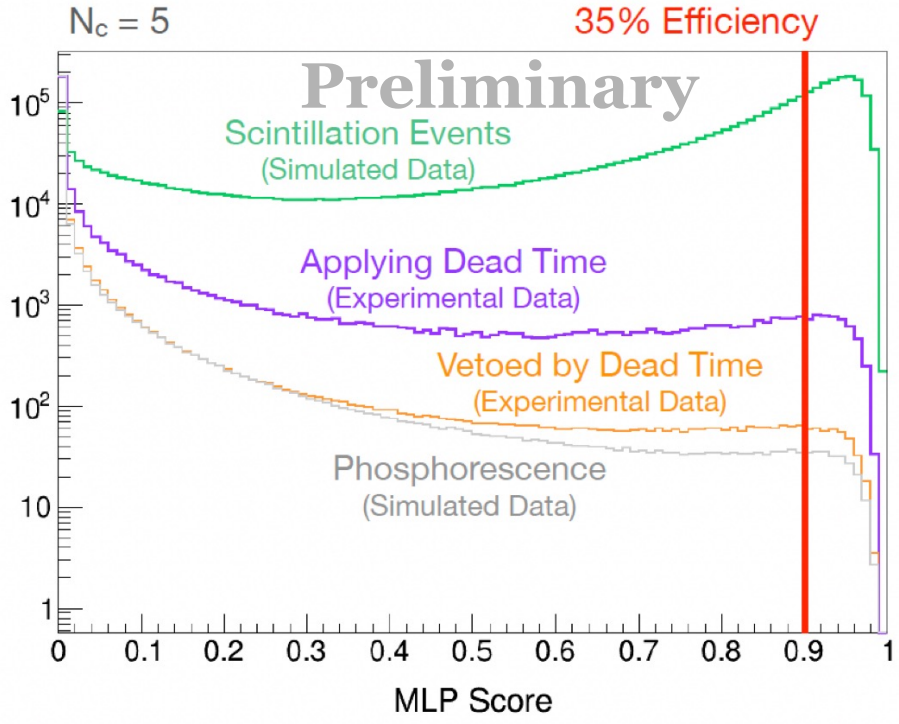


- Best Limits achieved for the Light Dark Matter Search.
- Below 1 MeV/c², NEON shows the best limit for DM-electron xsec and parameter for the Dark Photon mass.

CEνNS search status

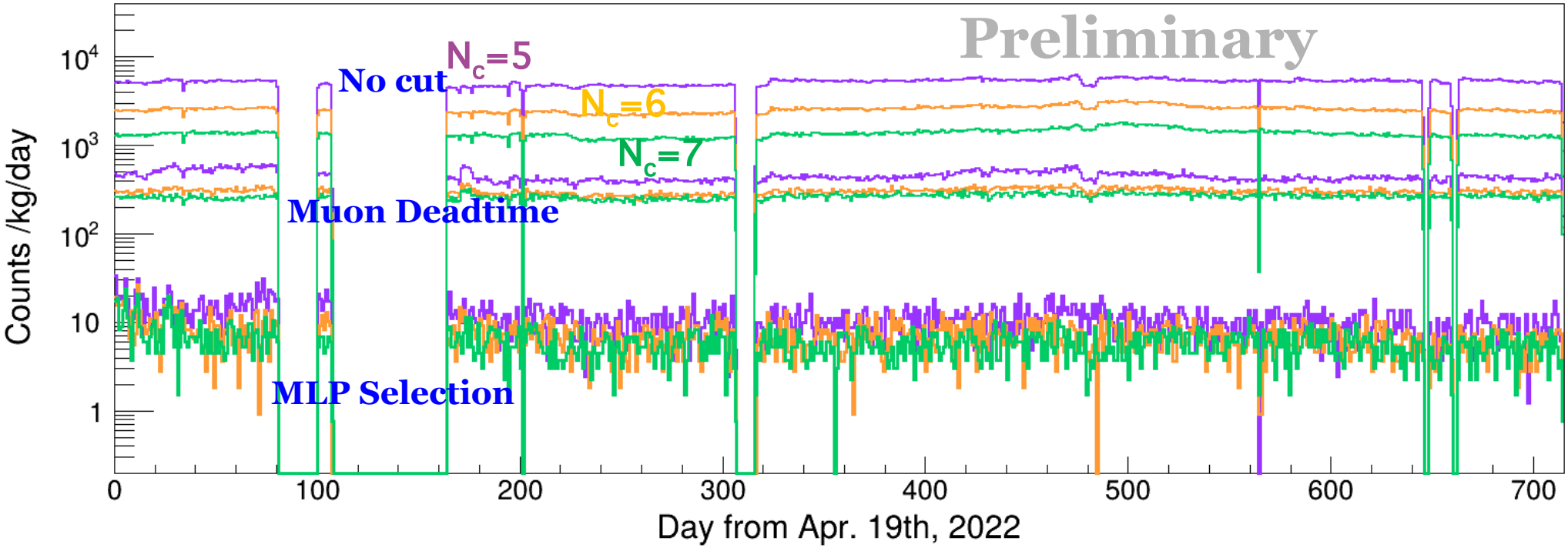
- 0.6 keV (~15 PE) threshold with Boosted Decision Tree
- 0.2 keV (~ 5 PE) threshold is required
- Large afterglow (phosphorus) pulses from muons
- Neural network training for the number of isolated clusters (Nc = 4, 5, 6, 7)





CEνNS search status

- **Factor ~1,000 reduction** for 5 N_c (~100 counts/kg/keV/day)
- We need additional factor 10 reduction of background



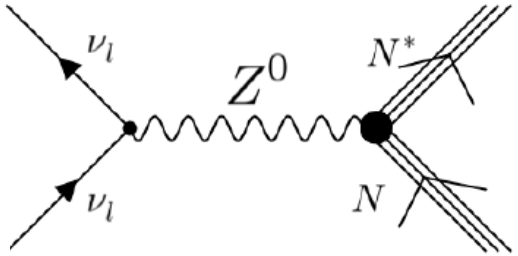
- We are employing deep machine learning
  - ❖ Directly use raw waveform for the machine learning training

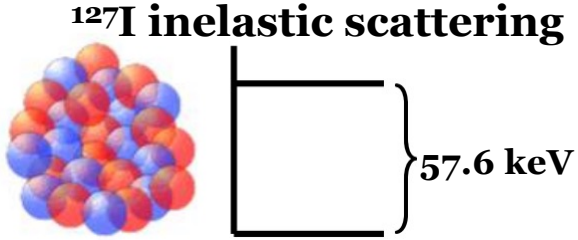
Inelastic neutrino nucleus scattering (IνNS)

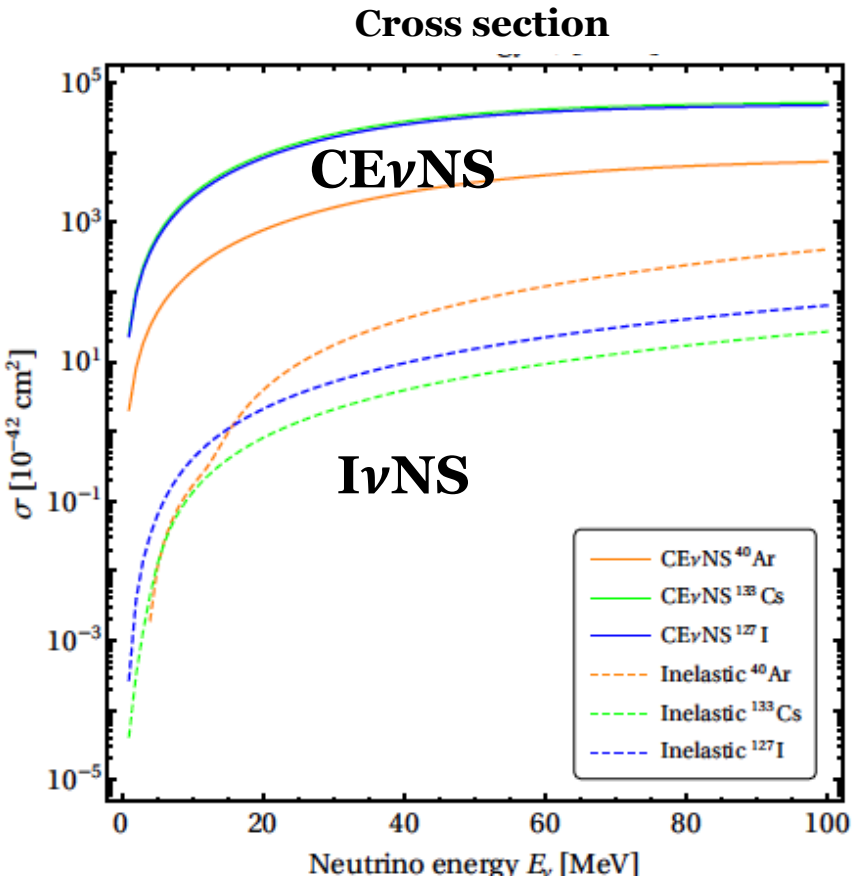
- IνNS cross section is ~ 4 order of magnitude smaller than CEνNS

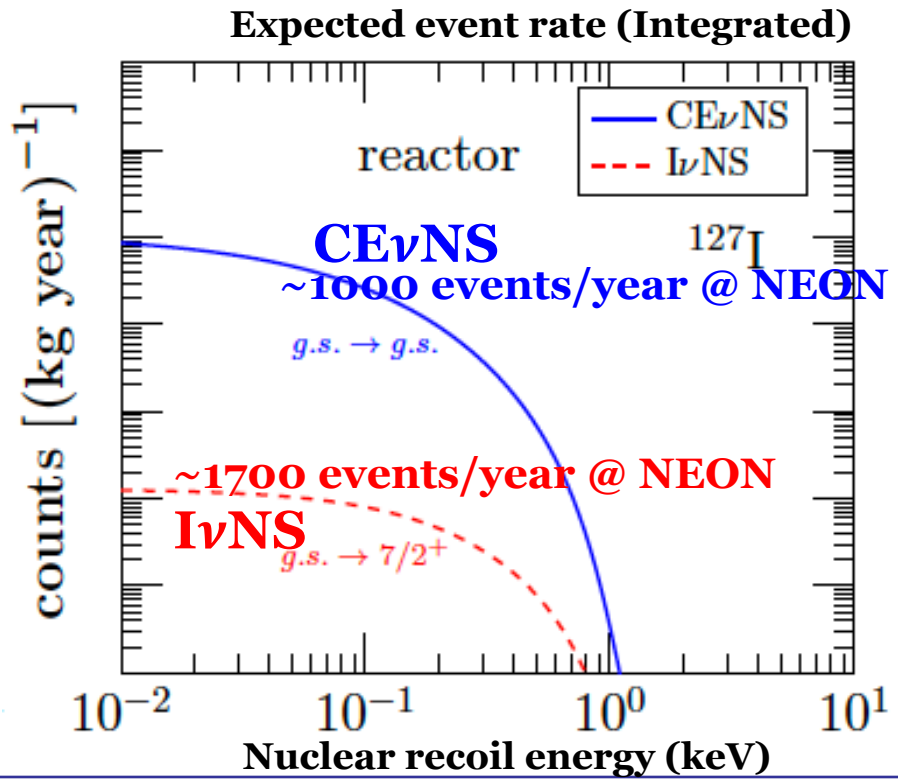
arXiv:2004.04055

arXiv:2206.08590



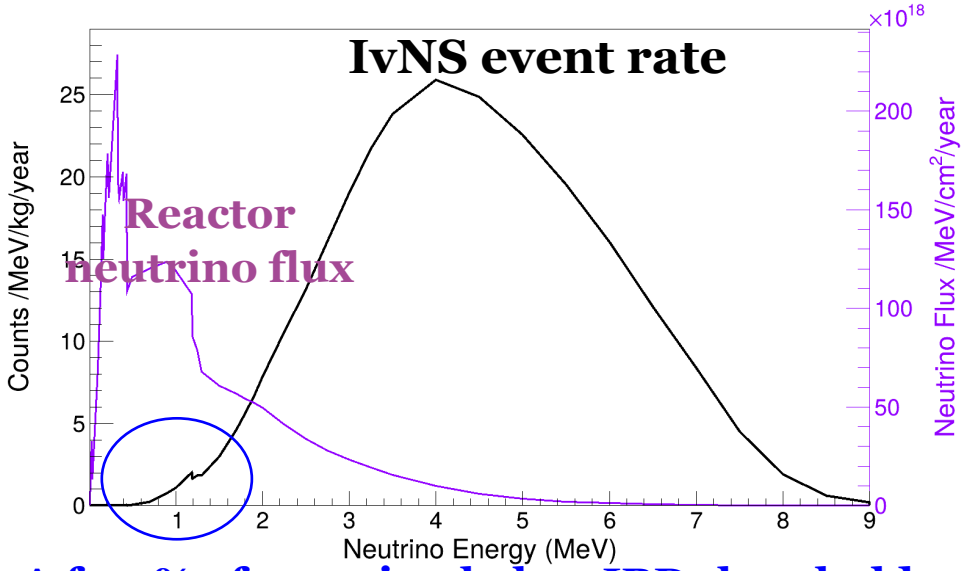






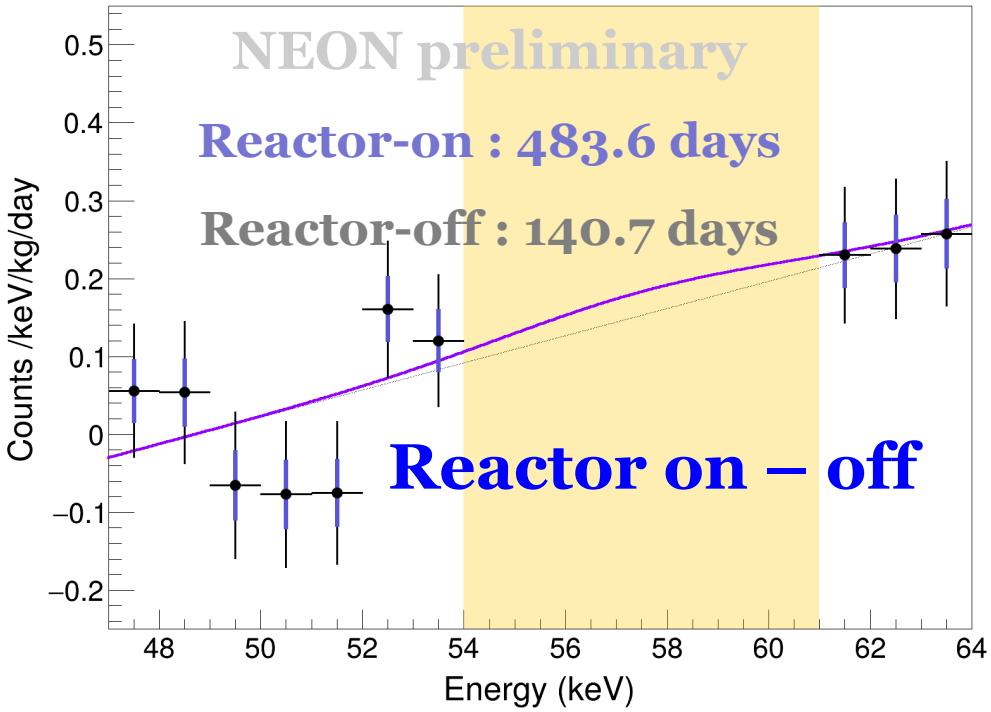
Inelastic neutrino nucleus scattering

Expected Event rate @ NEON



A few % of neutrino below IBD threshold

First look for NEON data



- Expected ~ 2–3 sigma level measurement
- Can be enhanced by precise modeling of reactor-on and off data
  - ❖ Time-binned modeling (3 months binning)

Summary

- NEON is aiming to observe CEνNS from reactor $\bar{\nu}_e$
- Stable running from April 2022 ~ present
- Good understanding of NaI(Tl) detector's backgrounds
- Light dark matter search extended low-mass dark matter parameter space as low as 1 keV with the world best limit
- Low-energy analysis for CEνNS is actively ongoing
- IνNS search is started

Stay tune!!