NEON Reactor Neutrino Experiment

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CPNR workshop, October 24 – 27, 2025

NEON Experiment

NEON (Neutrino Elastic-scattering Observation with NaI)

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

Simultaneously, we use the intense photon flux from the reactor to search for dark sector particles.

~20 collaborators (IBS, SNU, UST, CAU, Jeju U. and KAERI)

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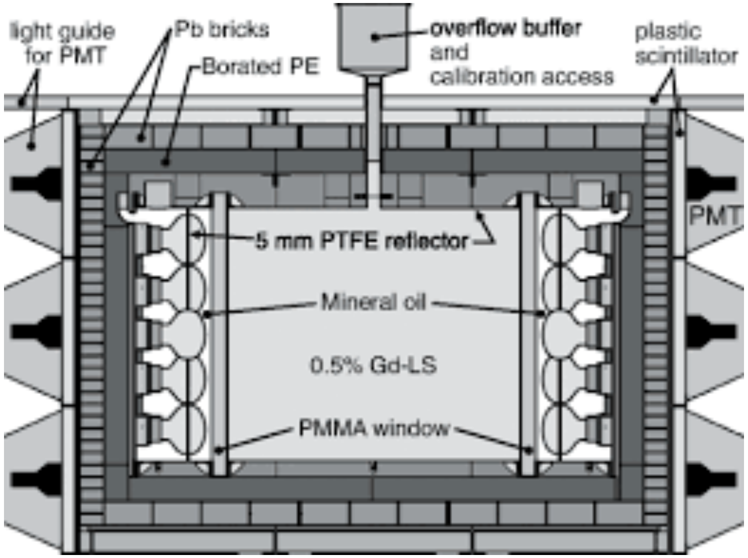
Simultaneously, we use the intense photon flux from the reactor to search for dark sector particles.

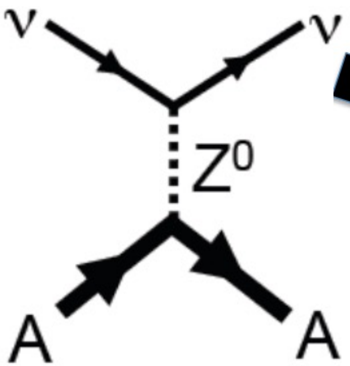
~20 collaborators with experience on NaI and/or reactor experiments

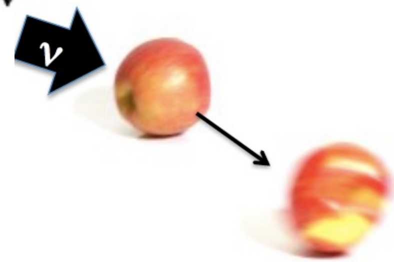
COSINE-100

NEOS

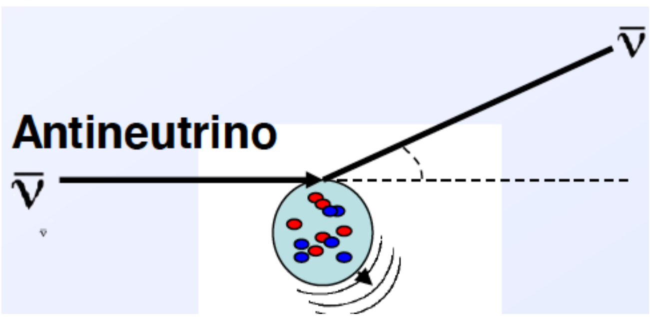


Coherent Elastic νeutrino-Nucleus Scattering (CEνNS)

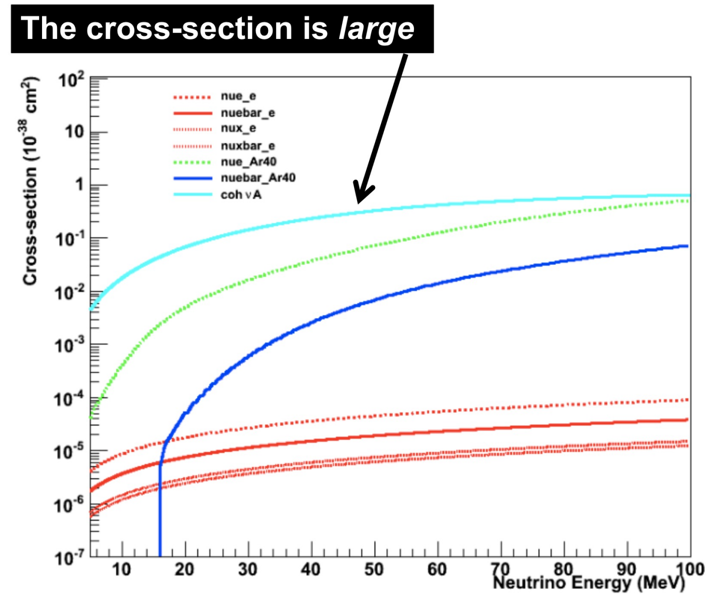


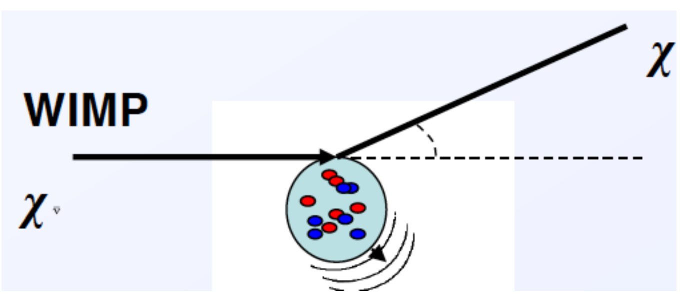


- CEνNS is a neutrino scatter off a nucleus where all target nucleons recoil in phase
- Coherence enhances the cross section depending on number of neutron



$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$





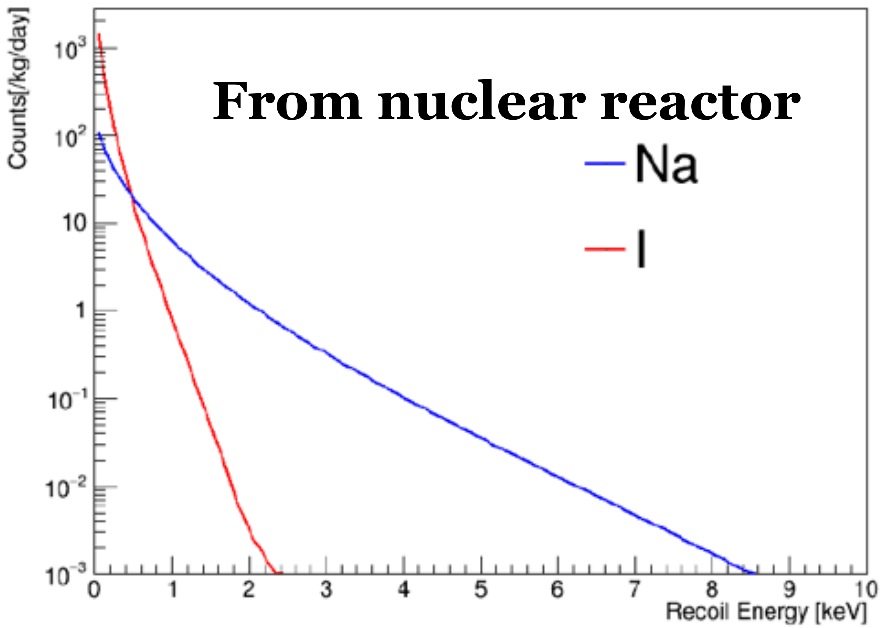
PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

Difficulty to observe CEνNS

Expected signals



Maximum recoil energy

$$E_{max} = 2E_{\nu}^{2}/M_{N}$$

Neutrino energy

Mass of target nuclei

- Need to measure ~ a few keV nuclear recoil energy
- A few 100 eV electron recoil energy
  - ~ 10% nuclear recoil quenching factor

CEνNS Observation

- First observation in 2017 by COHERENT (Spallation Neutron Source @ Oak Ridge) (~ 30 MeV neutrino)
  - ❖ CsI(Na) taget : Science 357, 1123 (2017); PRL 129, 081801 (2022) – **11.6σ**
  - ❖ Liquid Ar: PRL 126, 012002 (2021) – **3.5σ**
  - ❖ Germanium: PRL 134, 231801 (2025) – **3.9σ**

- Solar neutrino with liquid Xe (~ 7 MeV neutrino)
  - ❖ PandaX-4T : PRL 133, 191001 (2024) – **2.64σ**
  - ❖ XENONnT : PRL 133, 191002 (2024) – **2.78σ**

- Reactor neutrino with Germanium (~ 3 MeV)
  - ❖ CONUS+ : Nature 643, 1229 (2025) – **3.7σ**

Maximum recoil energy

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

Neutrino energy

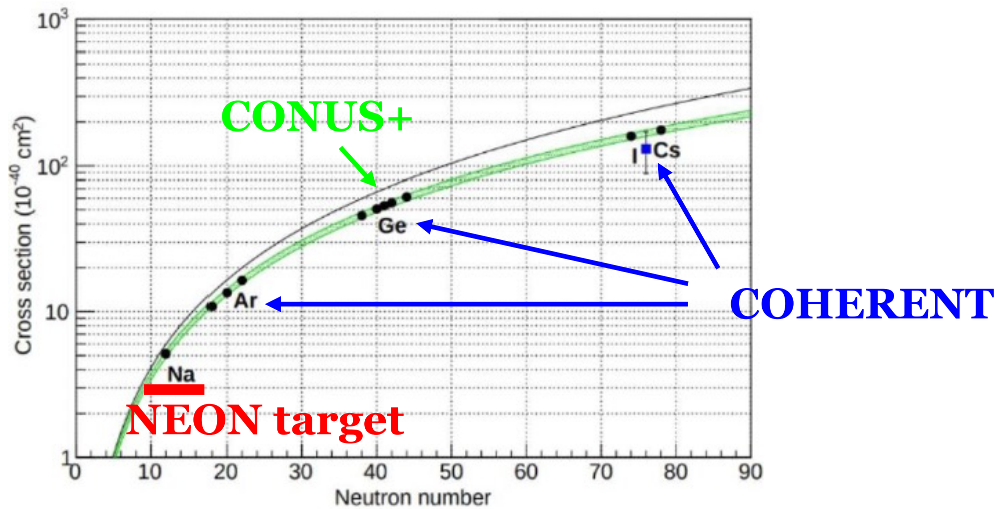
Mass of target nuclei

Why NaI(Tl) for CEνNS

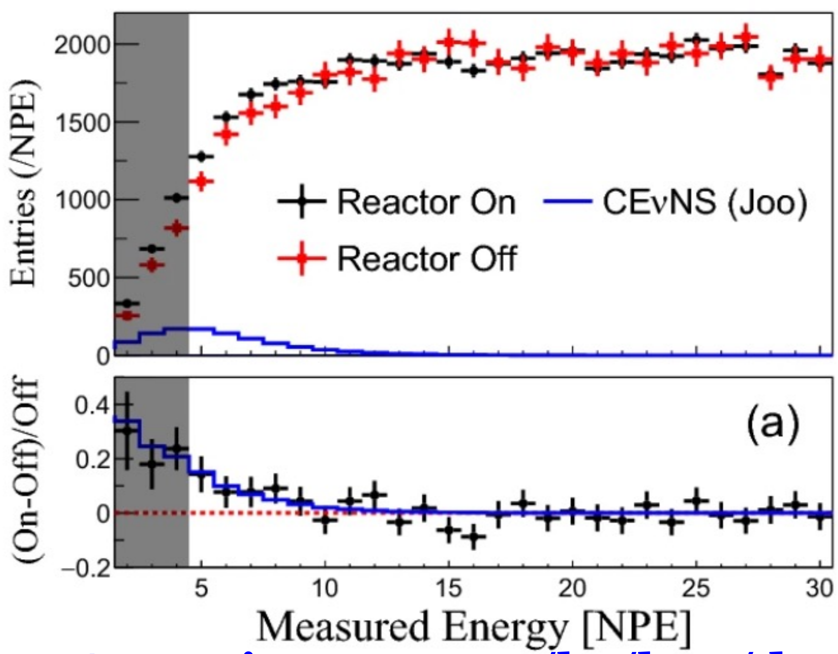
- High light yield NaI(Tl) is available (~ 23 NPE/keV$_{ee}$)
  - ❖ 5 NPE threshold in COSINE-100 is possible
    - ❑ ~ 0.2 keV$_{ee}$ threshold

NPE = Number of Photoelectrons

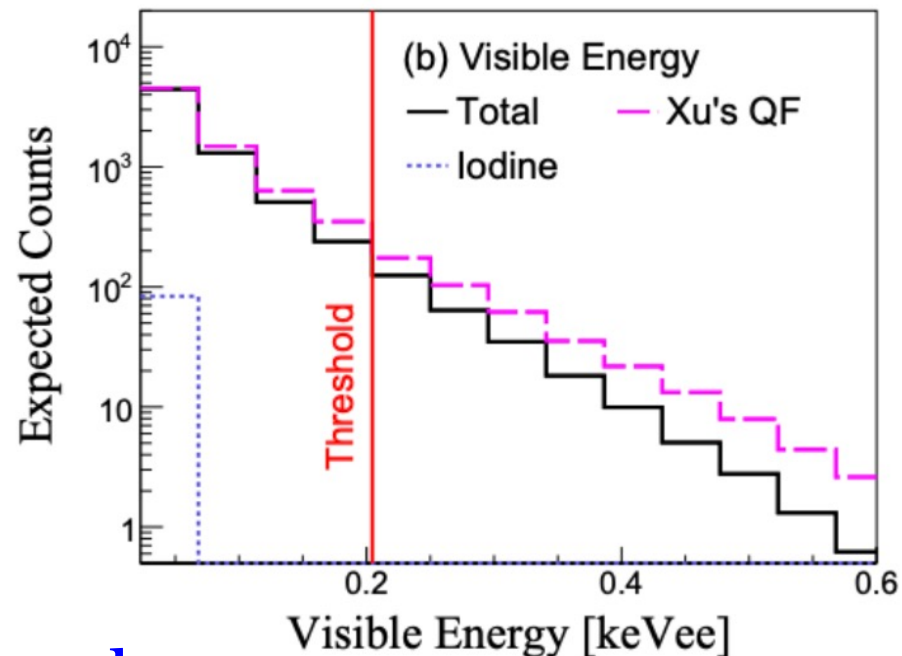
- Larger recoil energy from Na $E_{max} = 2E_\nu^2/M_N$
- N^2 dependence testable
- Lowest N element – Axial Vector Couling (BSM sensitivity)
- Easy to scale up with affordable costs for ~ 100 kg size



CEνNS analysis with NaI(Tl)



EPJC 83, 226 (2023)



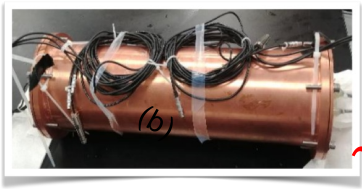
Assuming 7 counts/kg/keV/day background

- **'Reactor On - Reactor Off' remains only neutrino-induced events.**
- 1 years Reactor On & 0.2 keV threshold & 10% QF

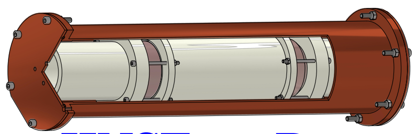
  → ~ 940 CEνNS expected (CONUS+ : 350 in 100 days)

- Can we reach to 0.2 keVee threshold with affordable background?

NEON NaI(Tl) detector



~ 24 NPE/keV



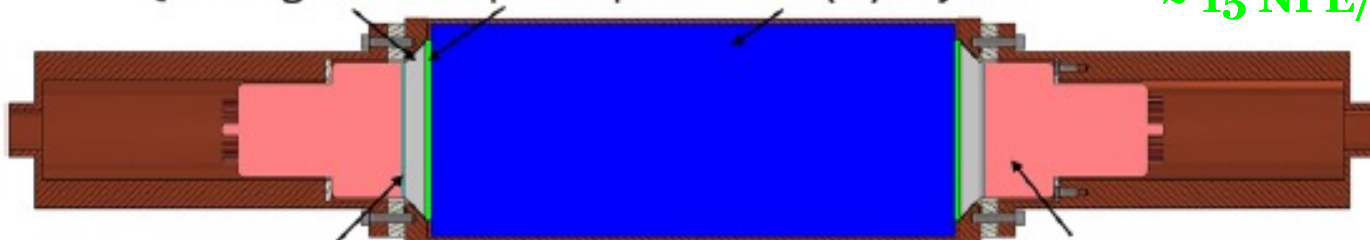
16.7 kg

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

COSINE-100

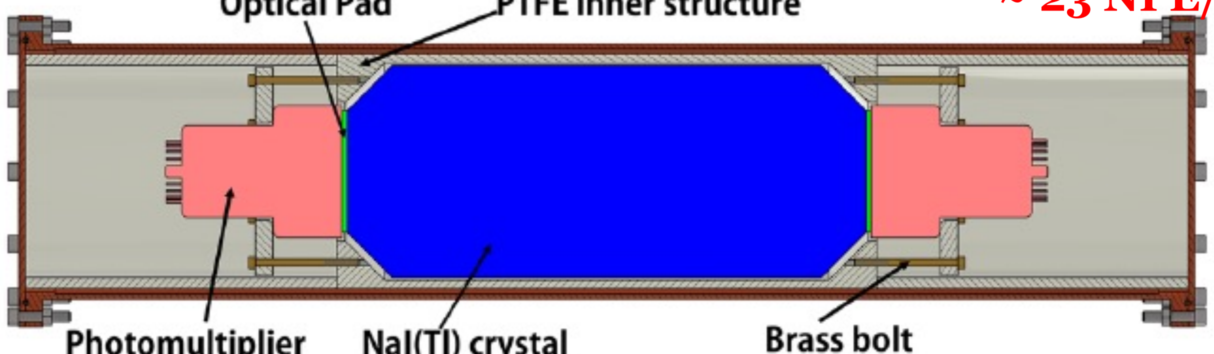
~ 15 NPE/keV



COSINE-100U

~ 23 NPE/keV

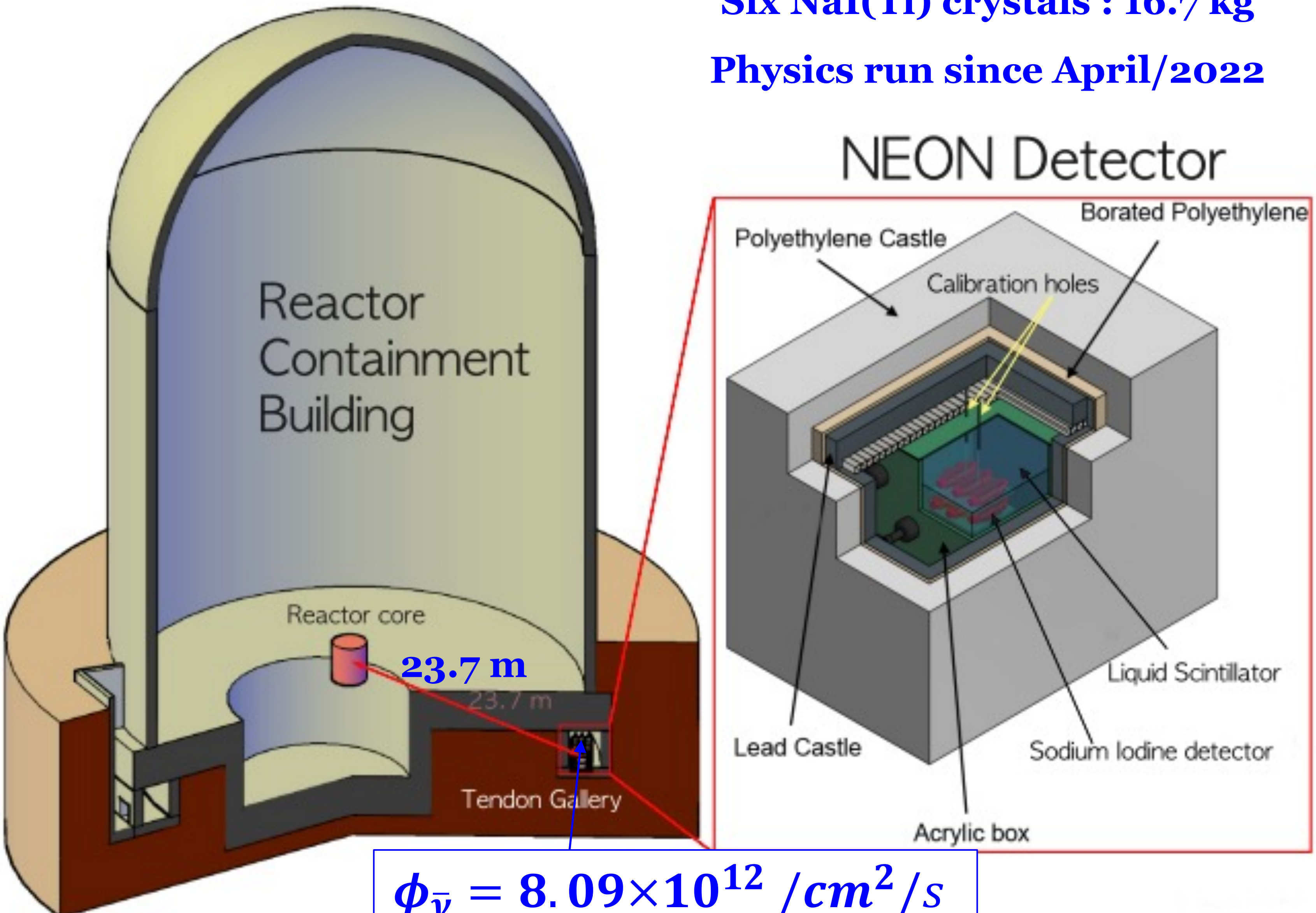
Commnun. Phys. 8, 135 (2025)



Experimental Site

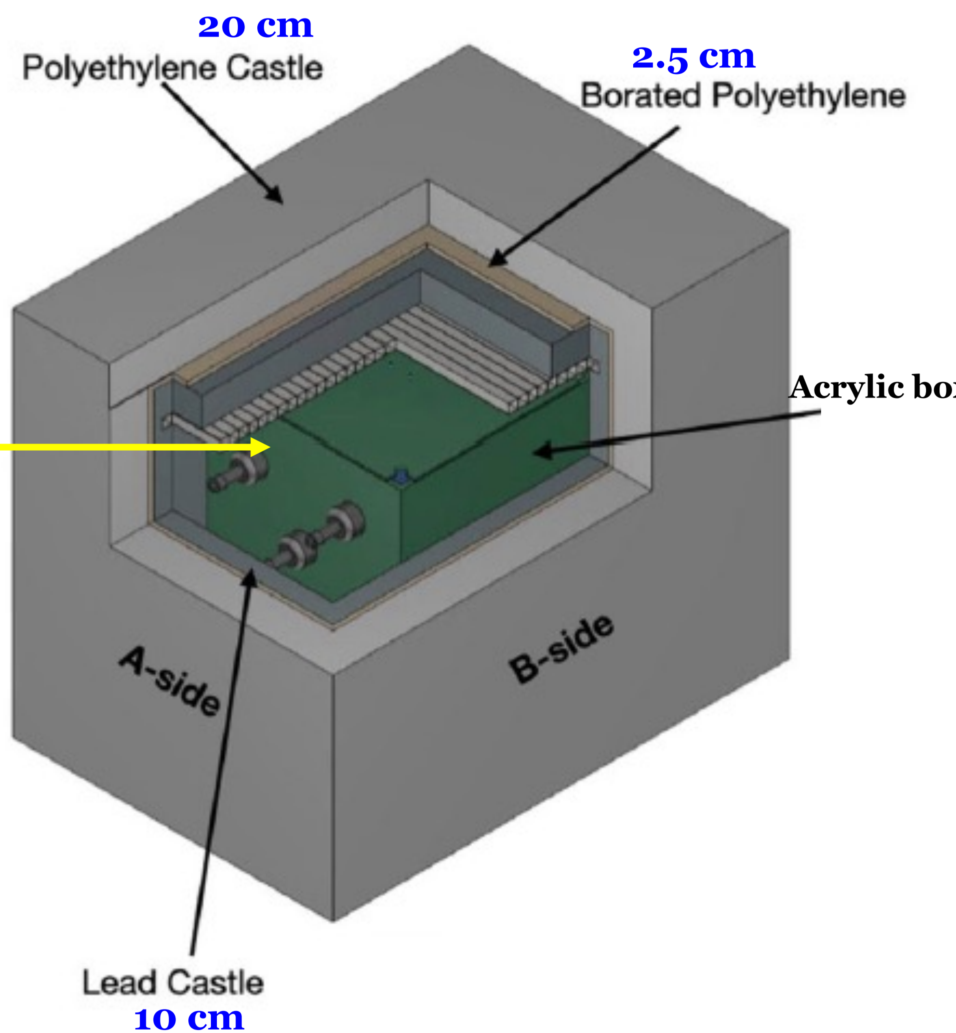
Six NaI(Tl) crystals : 16.7 kg

Physics run since April/2022



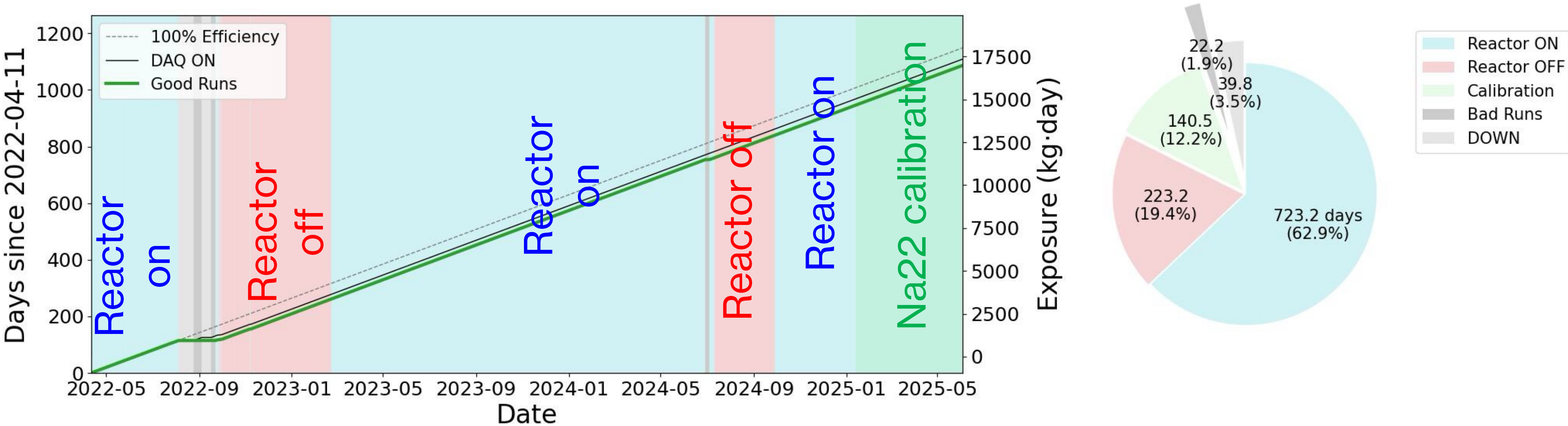
$$\phi_{\bar{\nu}} = 8.09\times10^{12}\ /cm^2/s$$

NEON detector shield



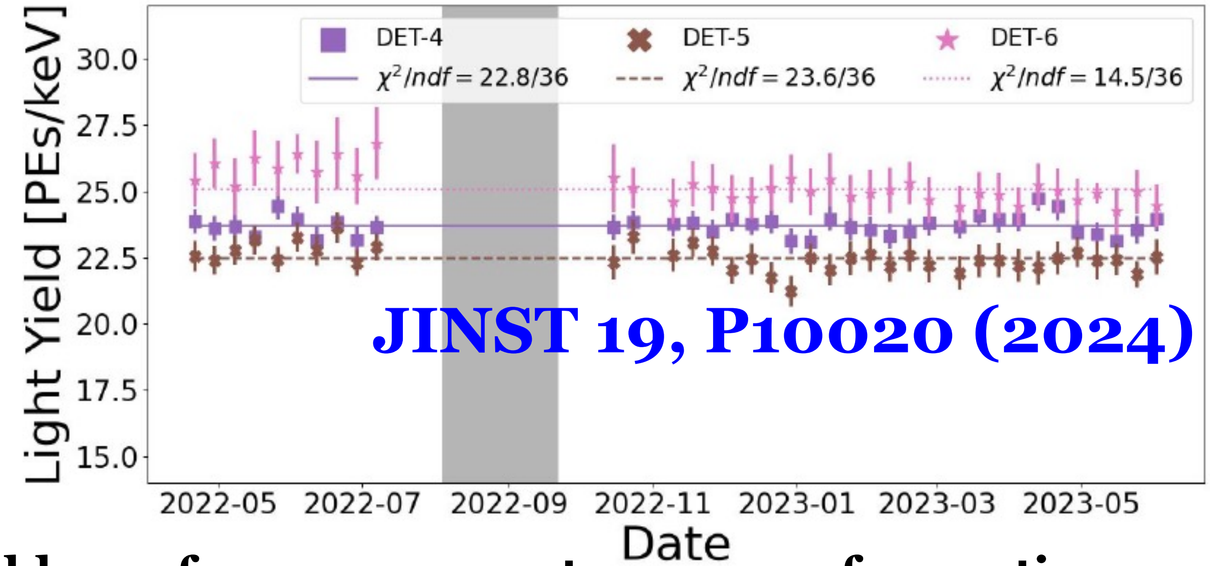
EPJC 83, 226 (2023)

Physics Operation



- Physics run started in April 2022 (> 3 years)
  - ~95% DAQ efficiency
- ~16800 kg·day exposure
- **723 days** of ON data
- **223 days** of OFF data

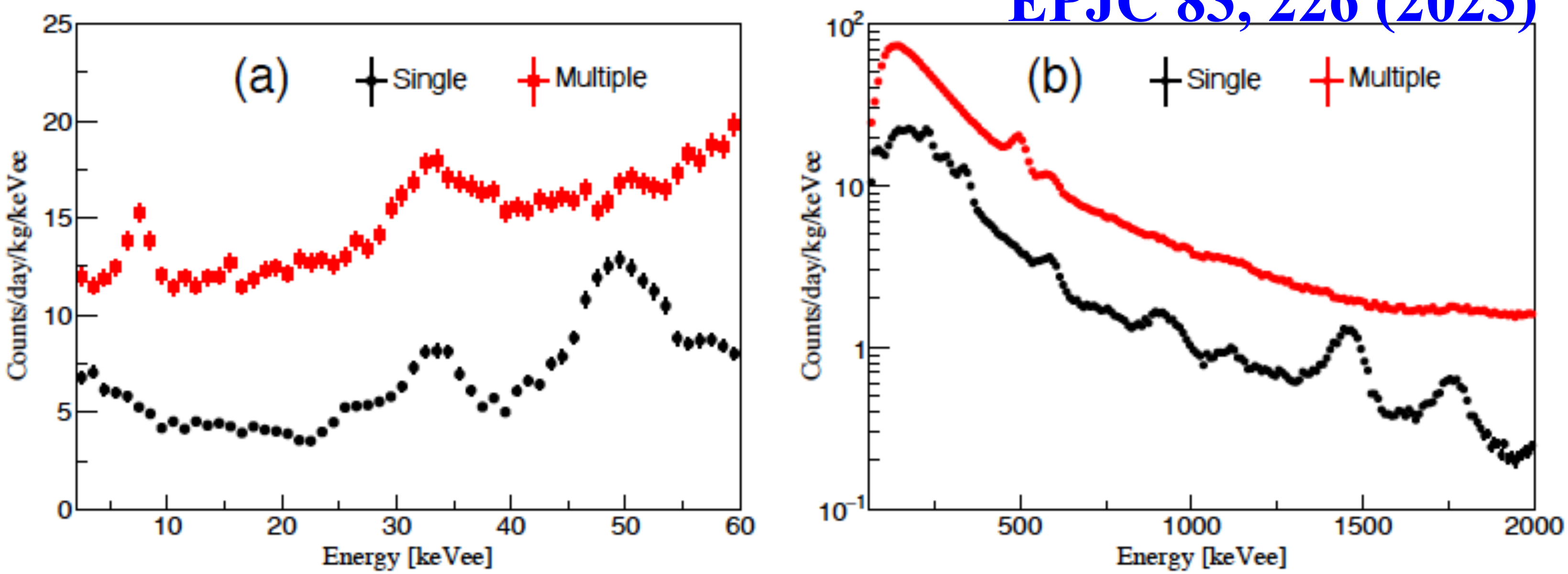
Detector performance



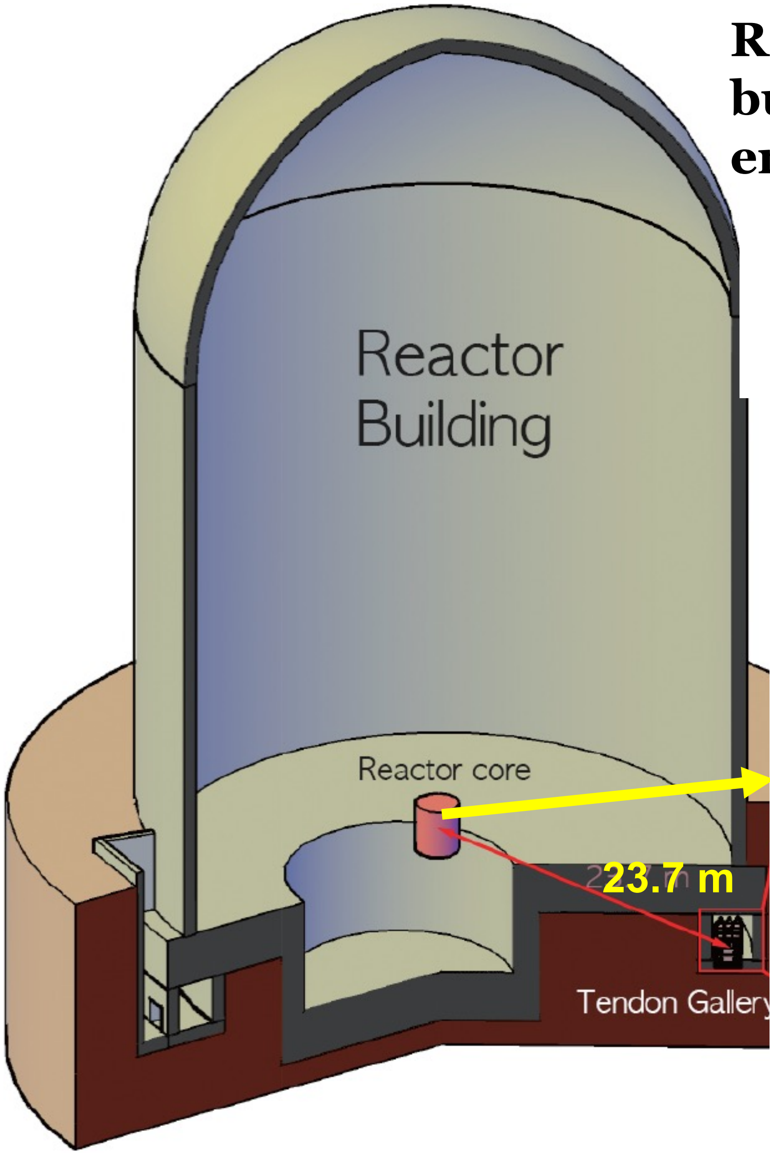
JINST 19, P10020 (2024)

Stable performance over two years of operation

EPJC 83, 226 (2023)

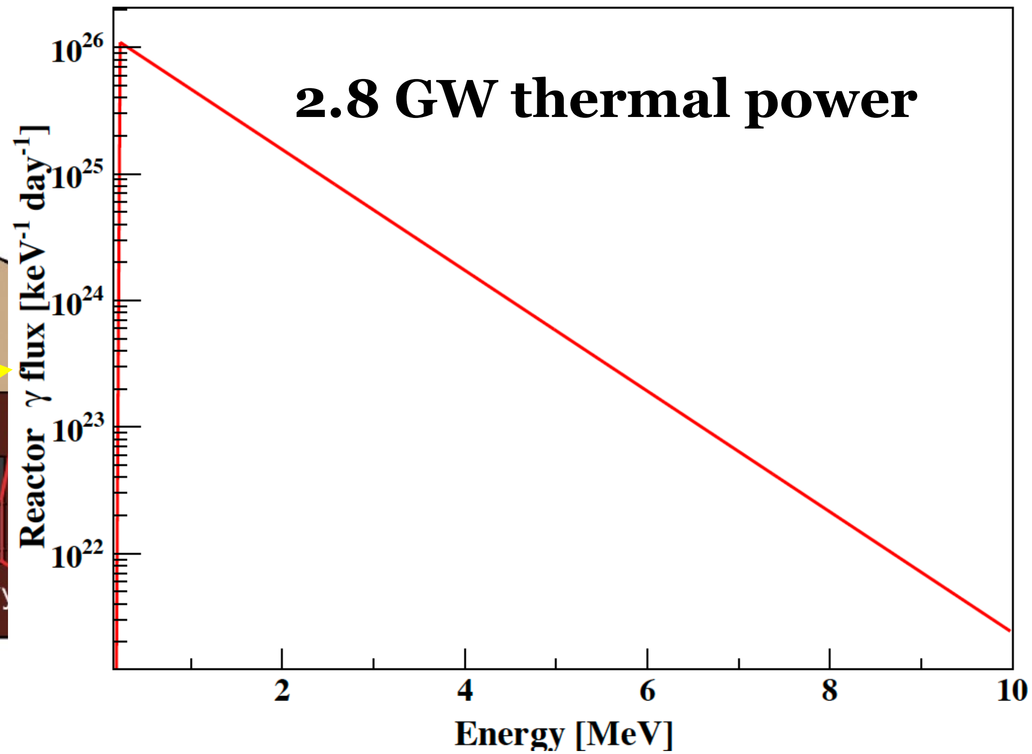


Reactor photons

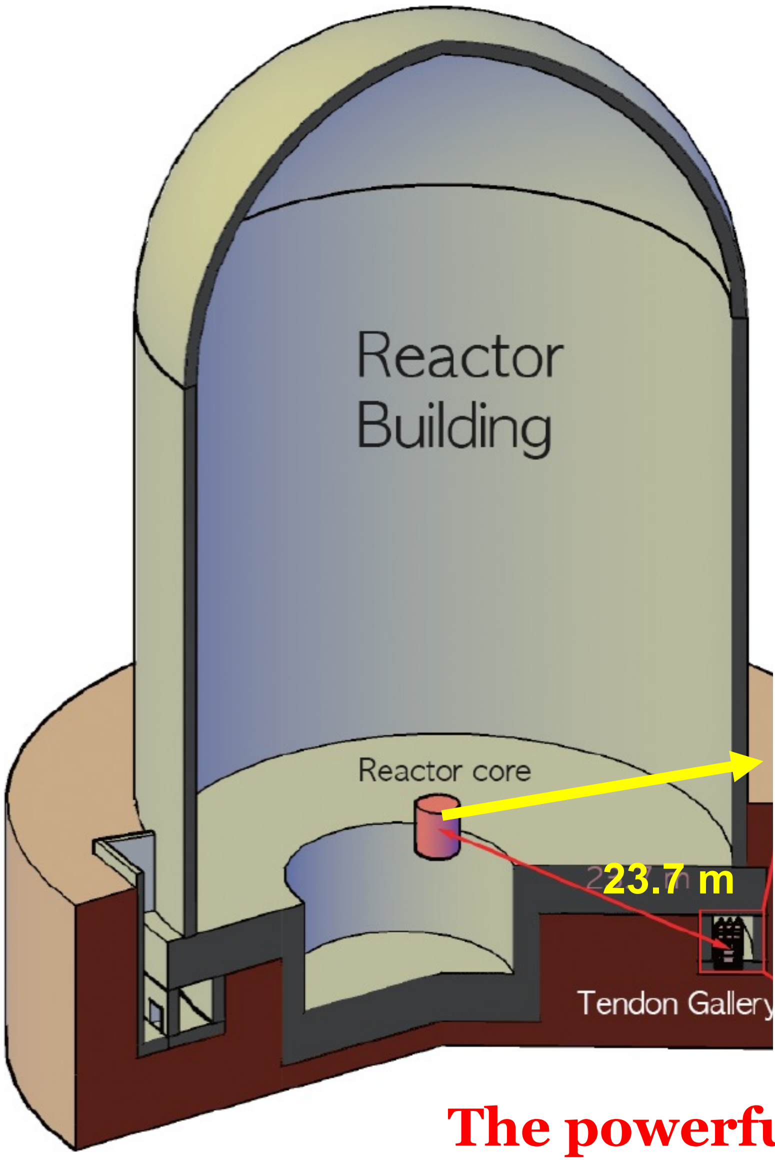


Reactor is not only an intense neutrino source but also an intense gamma source for O(MeV) energy

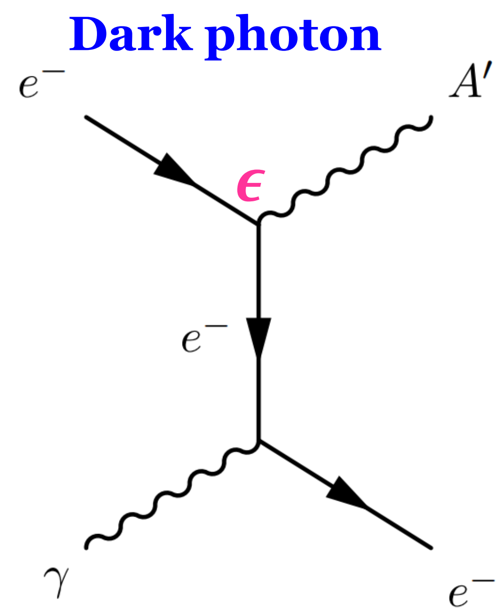
$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{5.8 \times 10^{17}}{[\mathrm{MeV}] \cdot [\mathrm{sec}]} \left(\frac{P}{[\mathrm{MW}]} \right) e^{-1.1 E_\gamma / [\mathrm{MeV}]}$$

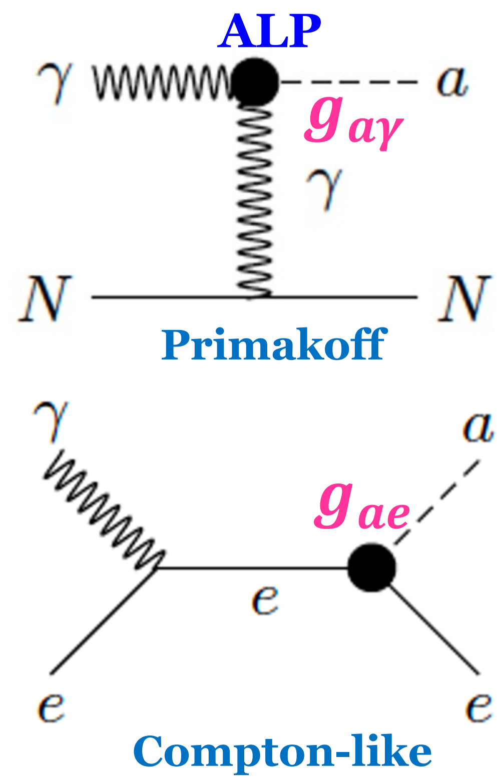


Reactor dark sector bosonic particles



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

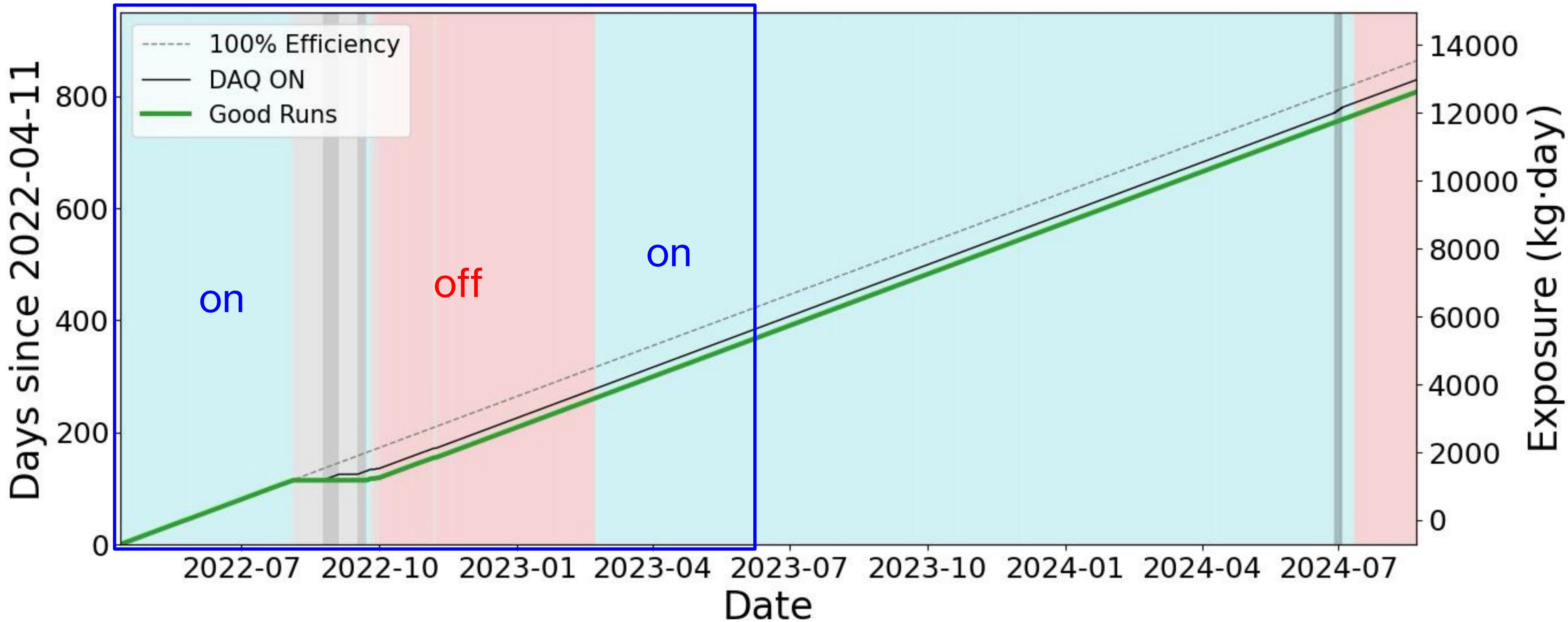




The powerful source of dark photon & ALP

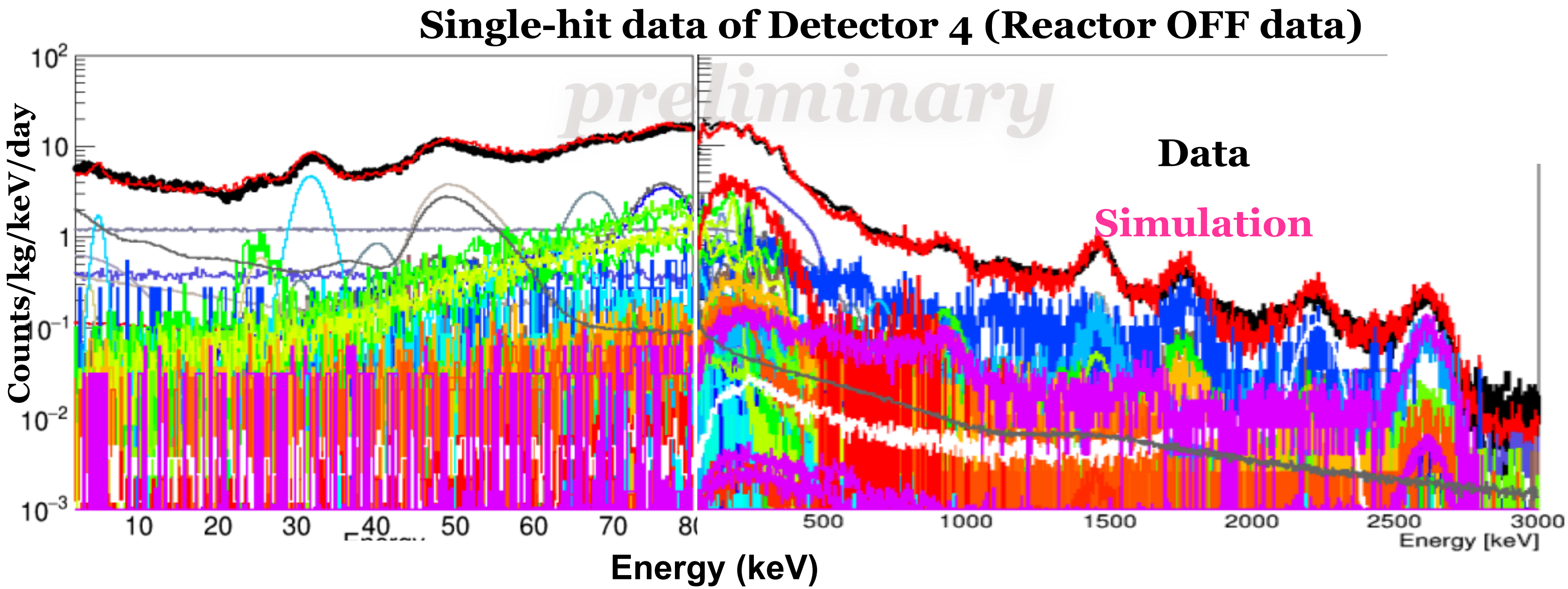
Data for dark sector searches

Initial Analysis



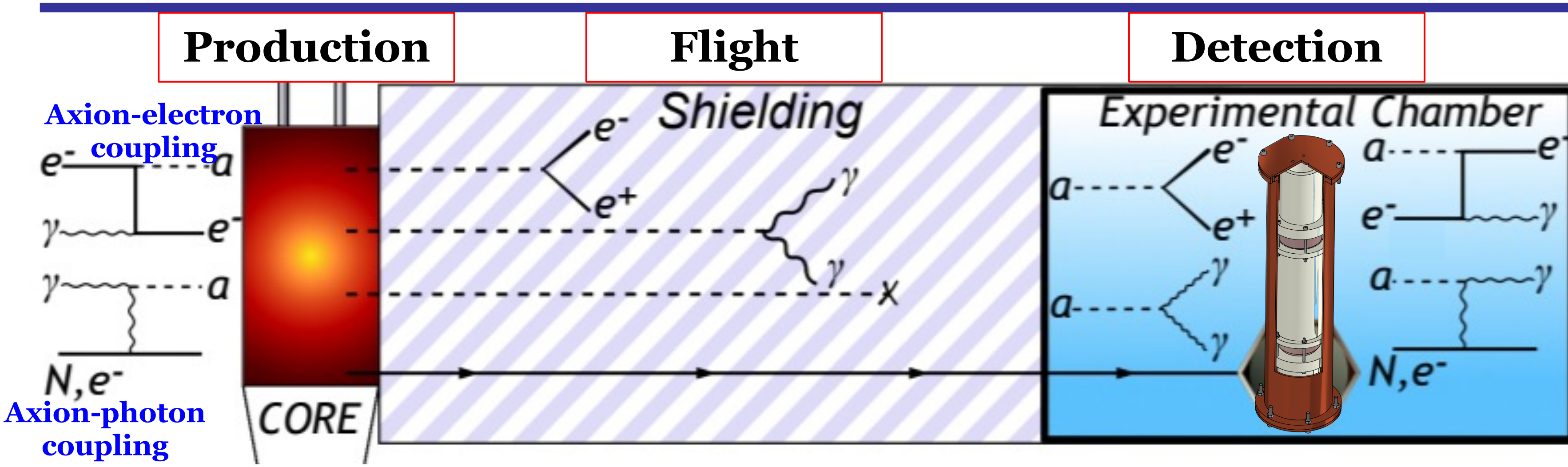
- Initial analyses used data collected during April/2022 ~ June/2023

Background understanding

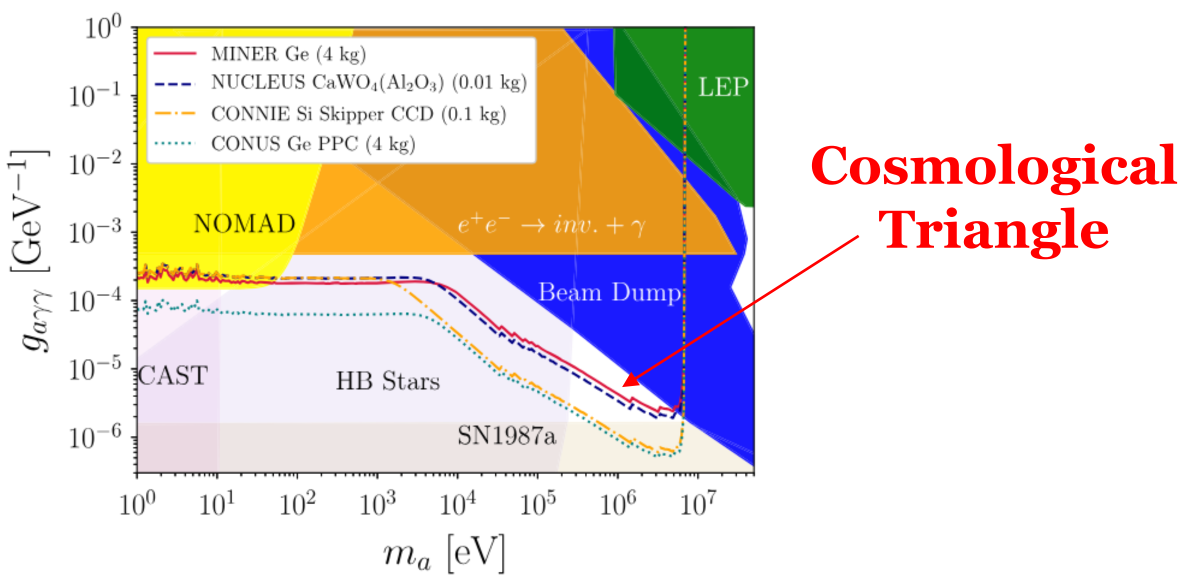


- Background understanding is based on our experience with COSINE-100 dark matter search experiment
  - EPJC 78 (2018) 490; EPJC 81 (2021) 837; EPJC 85, 32 (2025)
- 3 keV – 3 MeV are modeled

Axion-Like Particle (ALP)

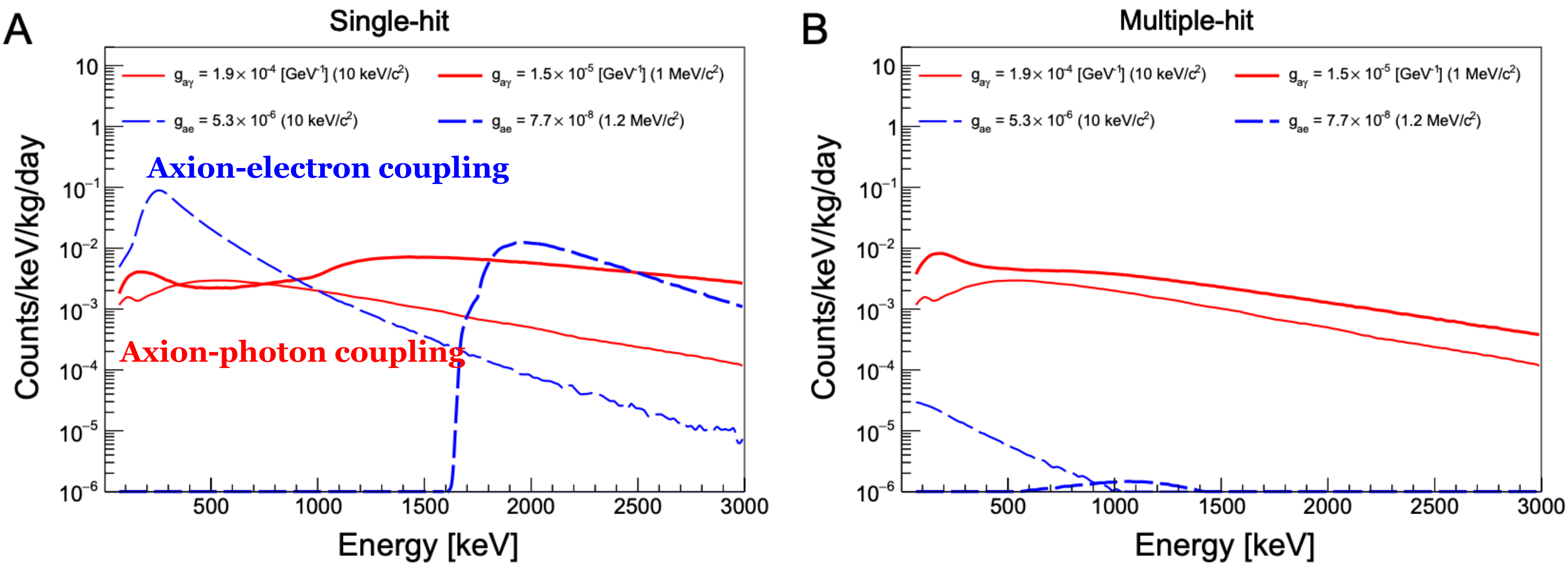


PRL 124, 211804 (2020) & JHEP 03, 294 (2021)

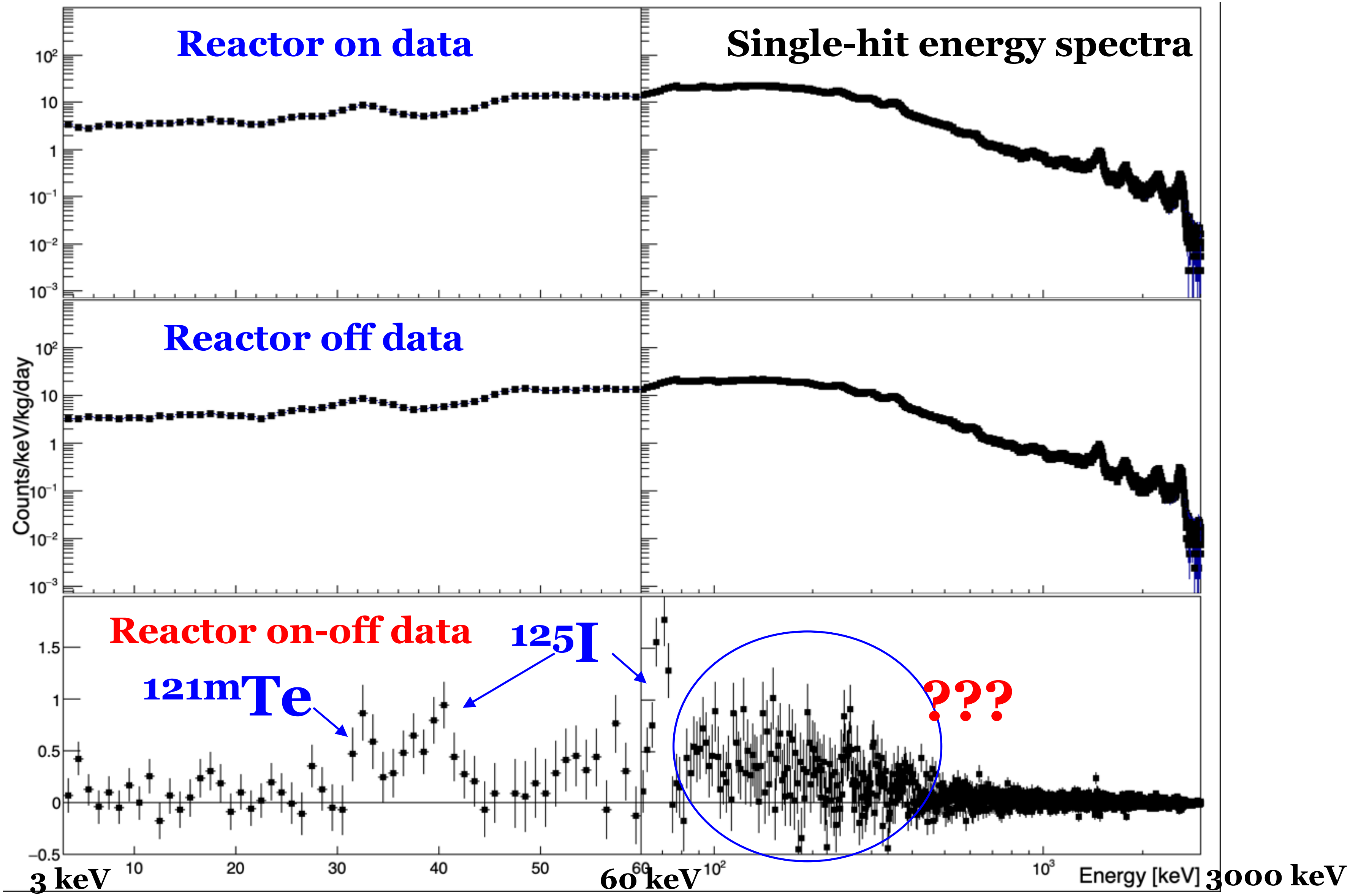


ALP signals in NEON detector

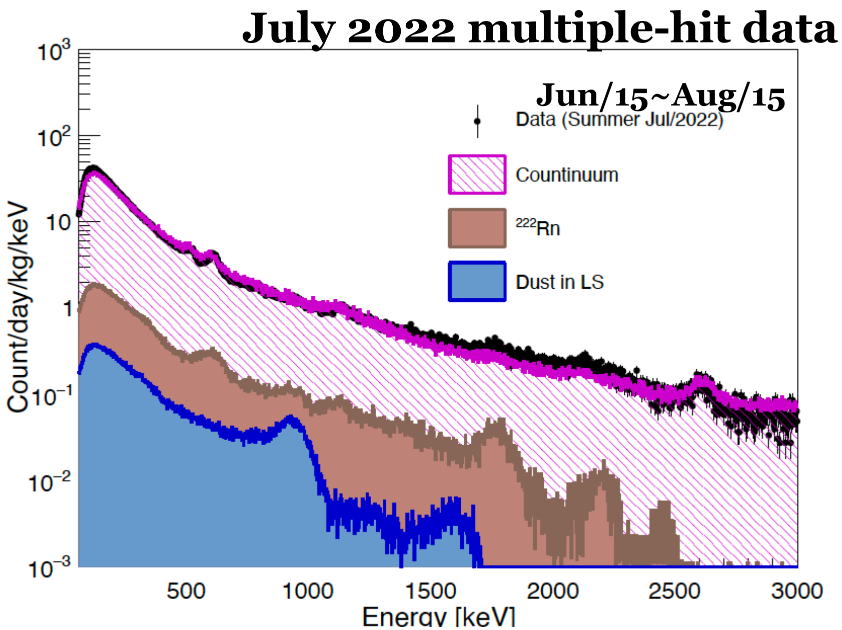
Expected ALP signals in the NEON detector

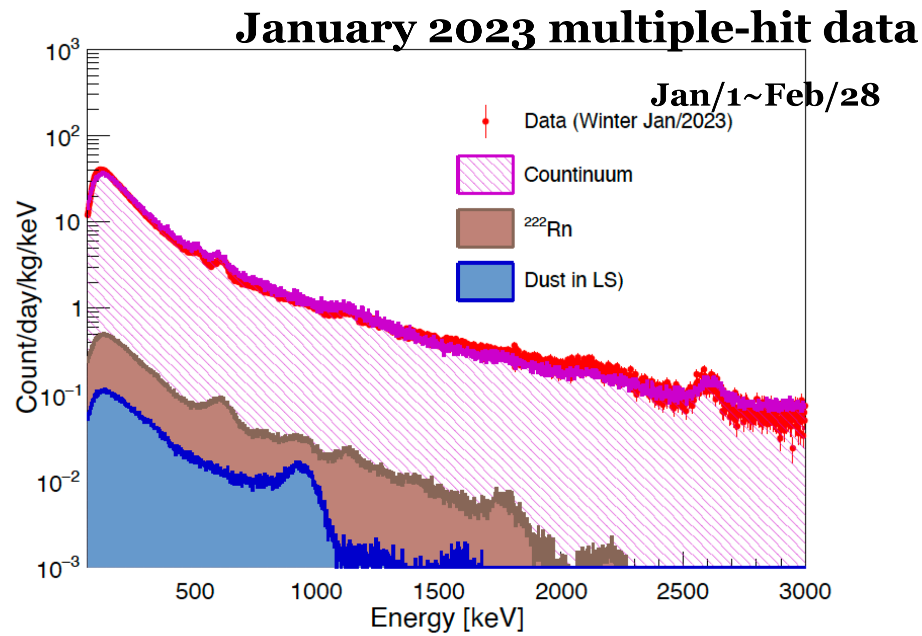


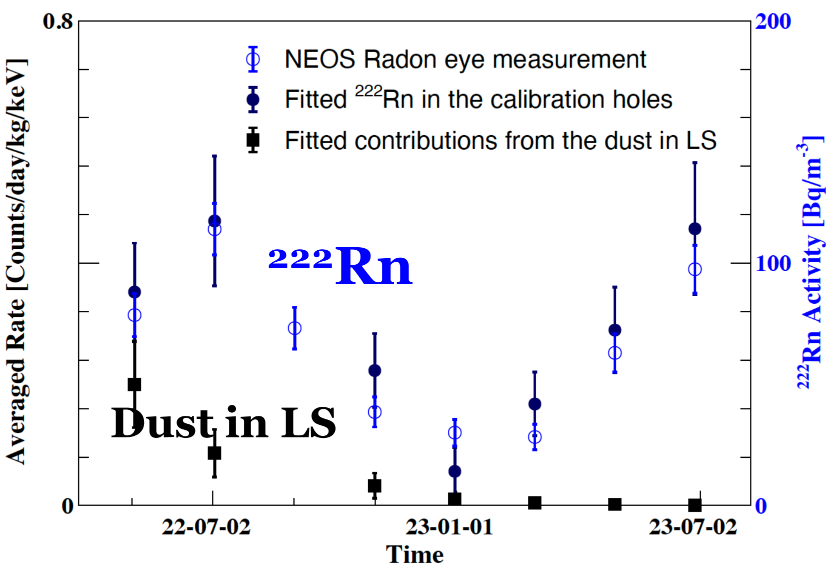
Comparison of Reactor-on and -off Data

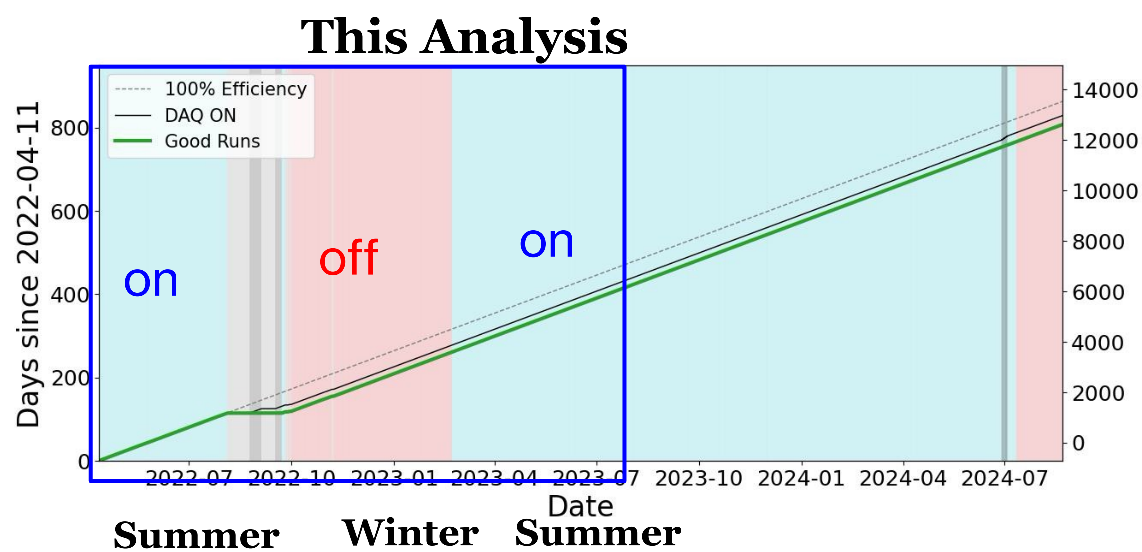


^{222}Rn contribution

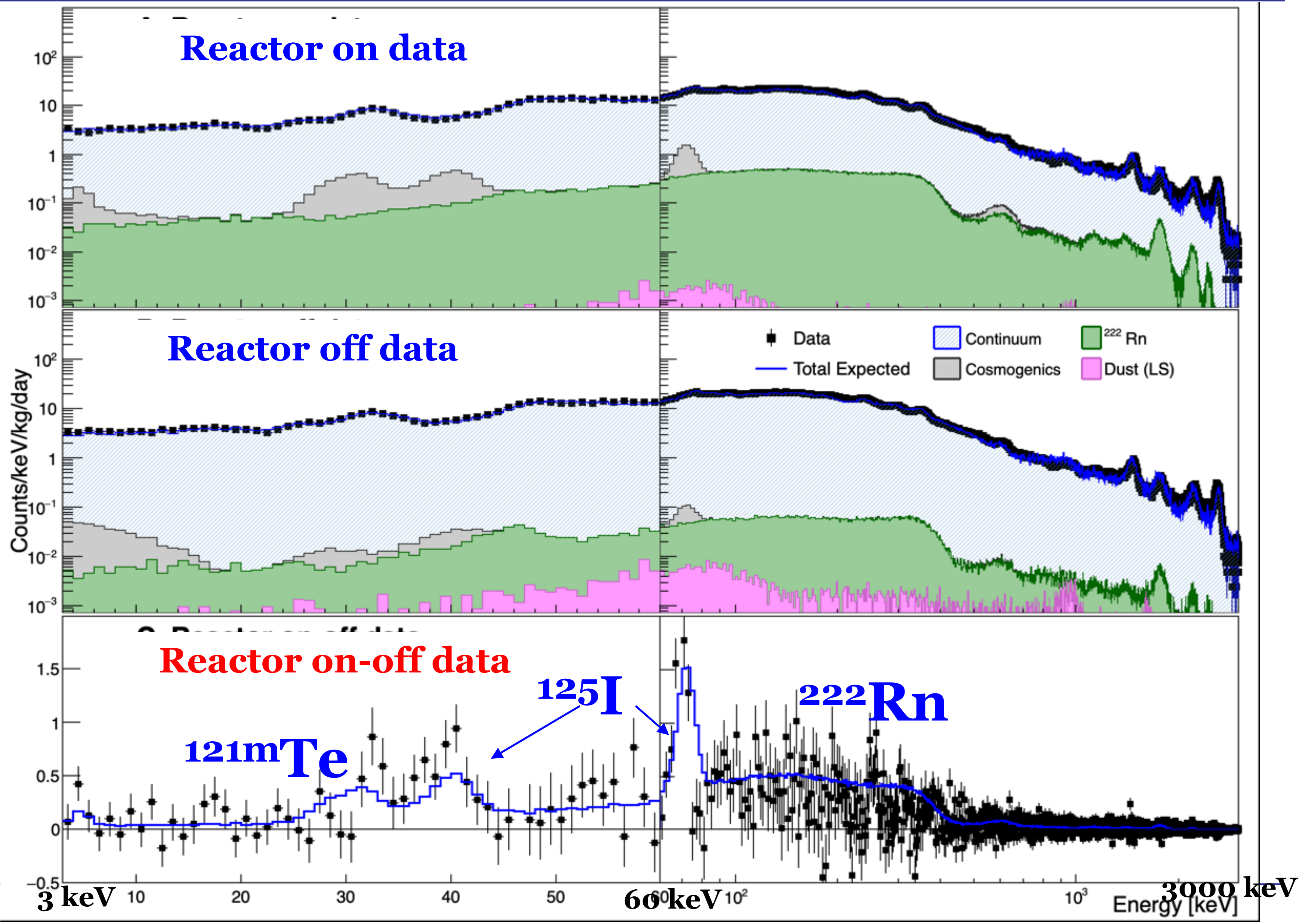




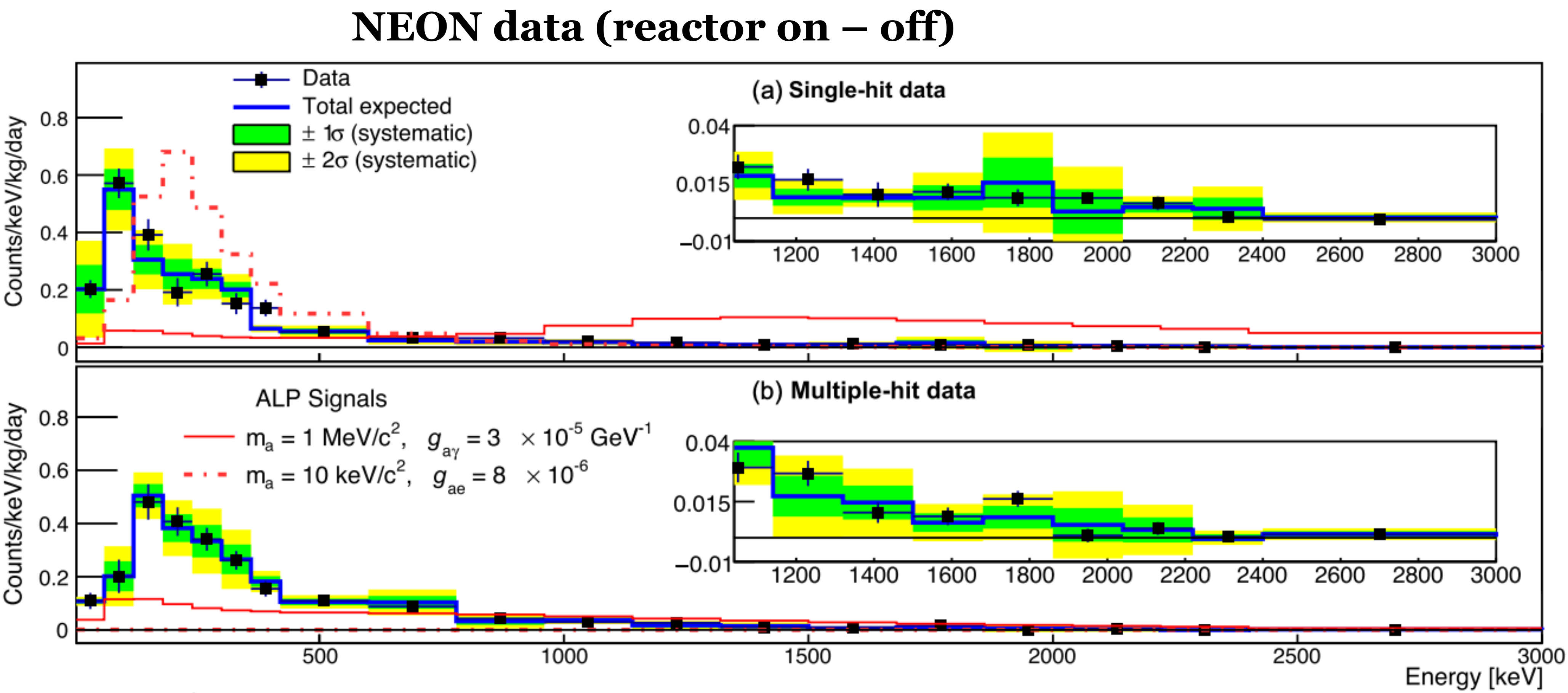




NEON On – Off data with Modeling



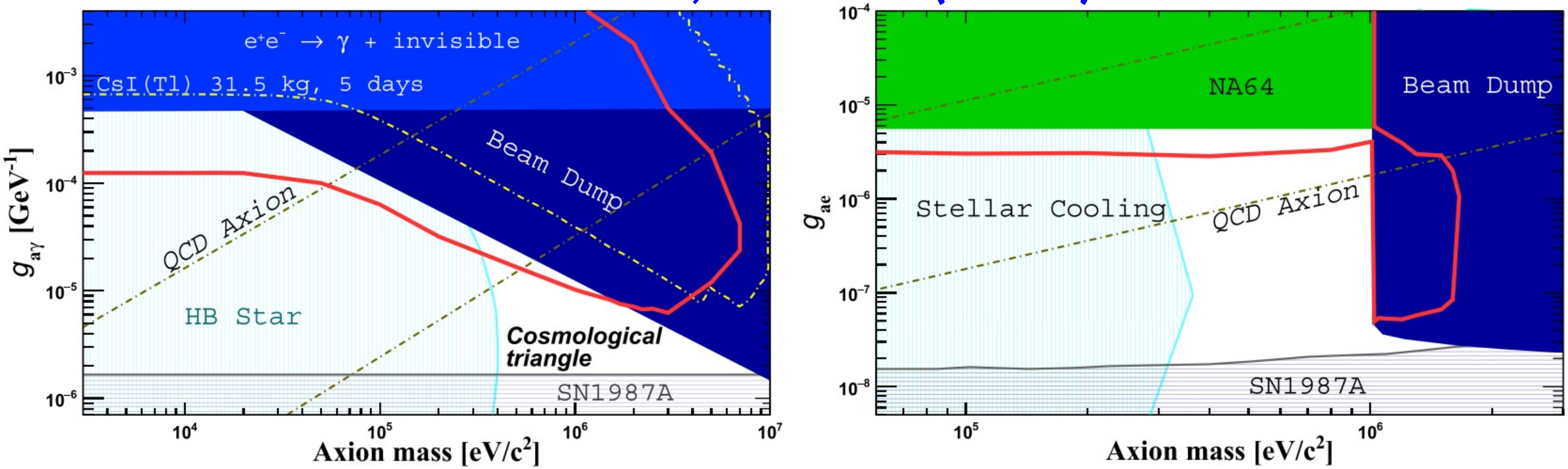
ALP search data (detector 6)



- χ^2fit to data with the expected time-dependent backgrounds and ALP signals

New Constraints on ALP Couplings from NEON

PRL 134, 201002 (2025)



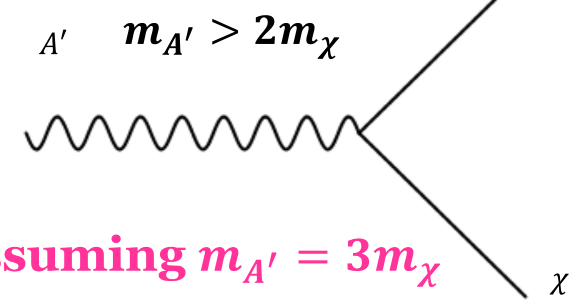
(a) Axion-photon coupling (b) Axion-electron coupling

- This work partially probes the "Cosmological Triangle" region
- **Best limits** at around **1 MeV ALP mass** on both photon and electron couplings

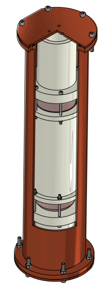
Light Dark Matter Search

- Through light dark matter (LDM) production

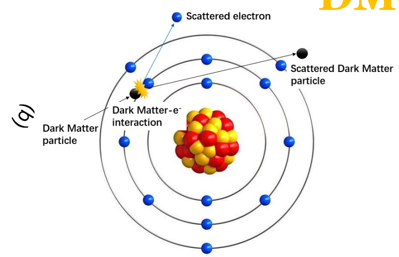
Dark photon decay @ reactor core



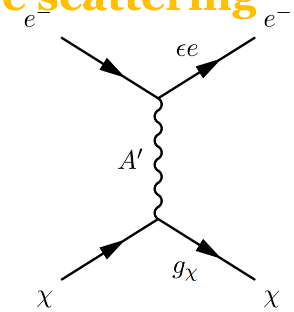
Assuming $m_{A'} = 3m_\chi$



Detector

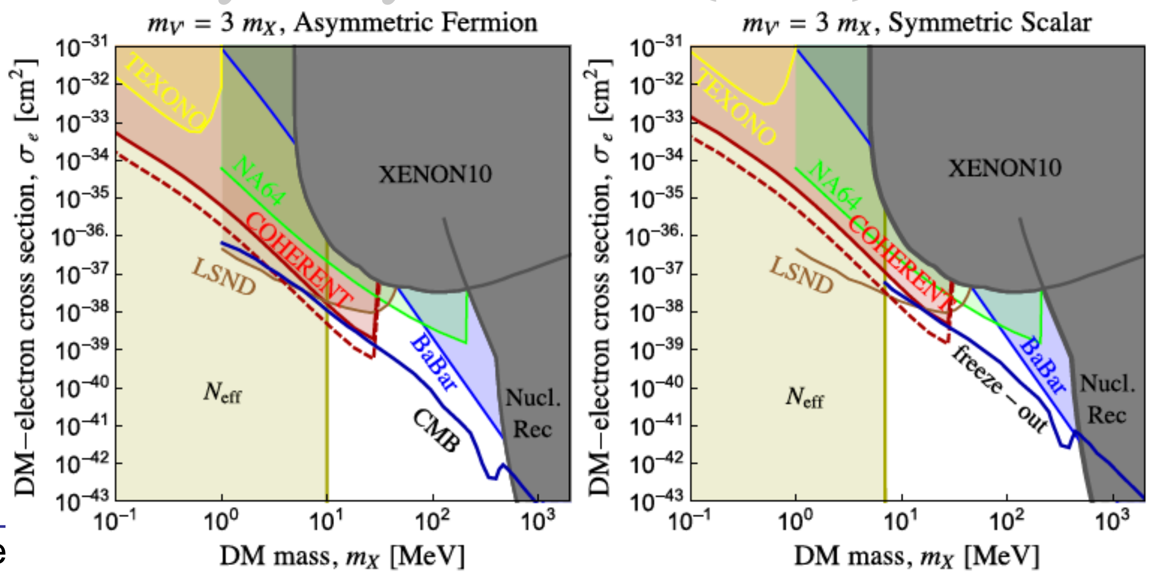


DM-e scattering



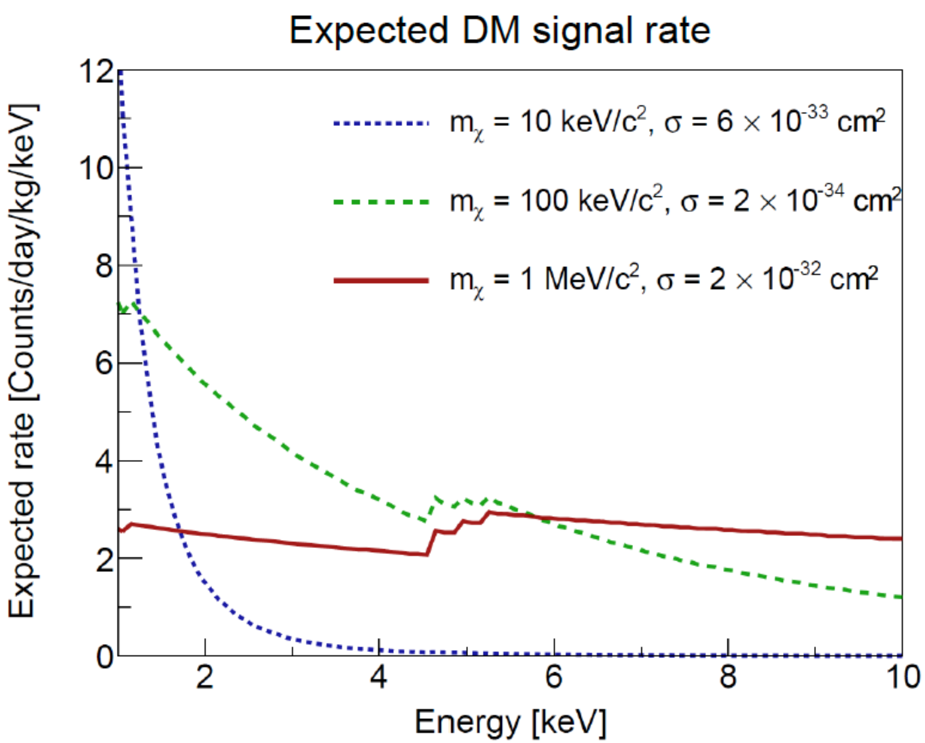
COHERENT LDM-nucleon scattering : PRL 130, 051803 (2023)

Theory study : JHEP 11 (2018) 066



Light Dark Matter Signals

- We generate the light dark matter signal in NEON detector
- We assume $m_{A'} = 3m_\chi$
- Apply atomic ionization factor PRD 108, 083030 (2023)



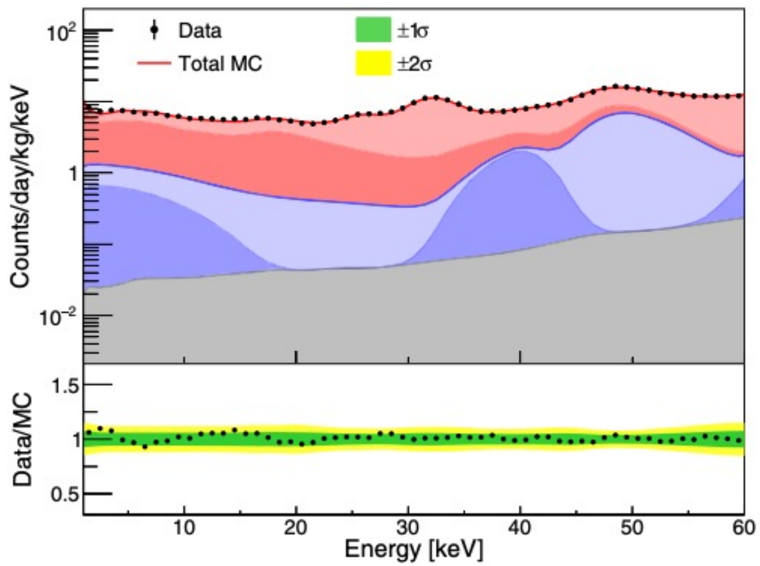
Region of Interest

1 – 10 keV

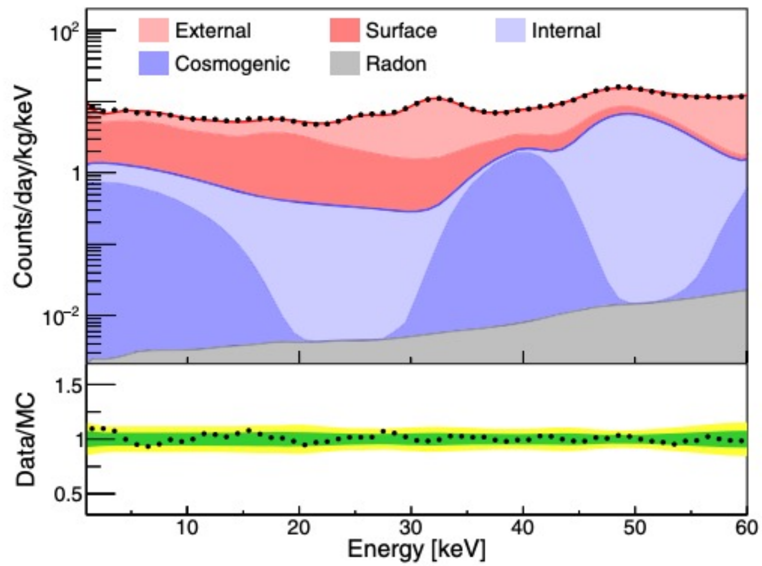
- Apply detector responses

Light Dark Matter (LDM) Search

NEON Reactor on data



NEON Reactor off data



Perform a χ^2 fit to Reactor on minus off data to extract LDM signals

Data

Background

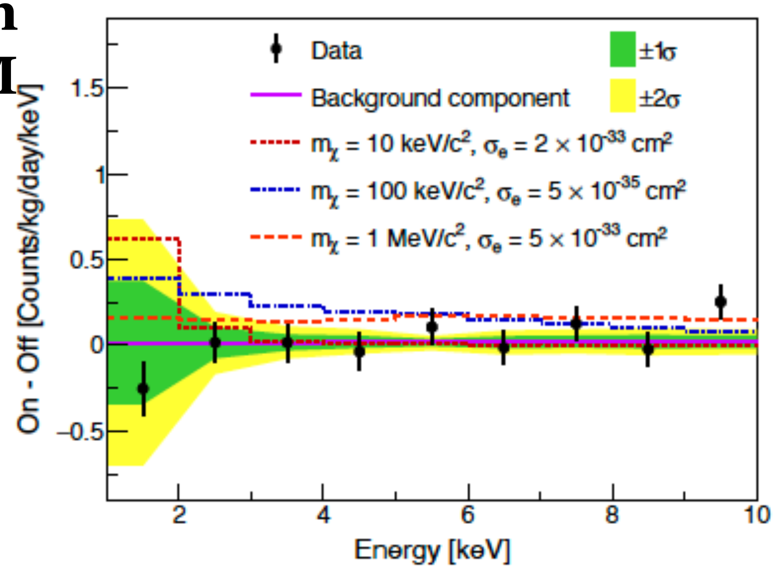
Signal

$$\chi^2 = \sum_{i,j} \frac{\left[D_{ij} - B'_{ij}(\vec{\alpha},\vec{\beta}) - r_\sigma S'_{ij}(\vec{\alpha};\sigma_0)\right]^2}{\delta D^2_{ij}} + (\text{pull})$$

Signal strength

Statistical uncertainty with error of efficiency

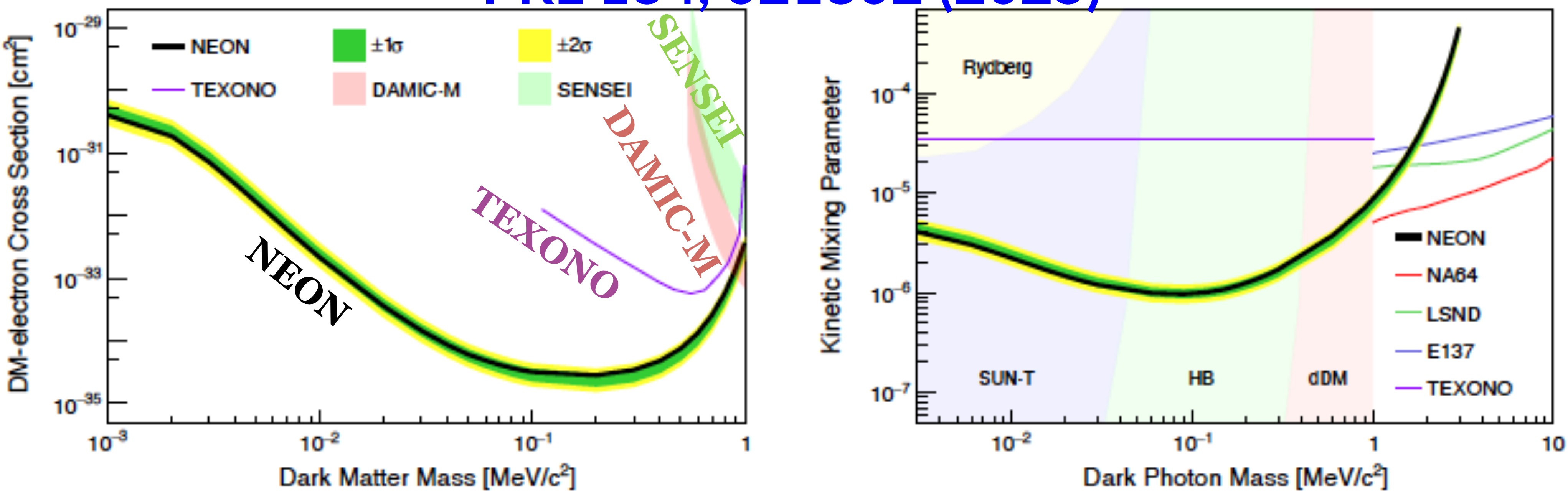
Signal region : 1-10 keV



World-Leading Limits on LDM from NEON

- No signal excess – 90% confidence level upper limit

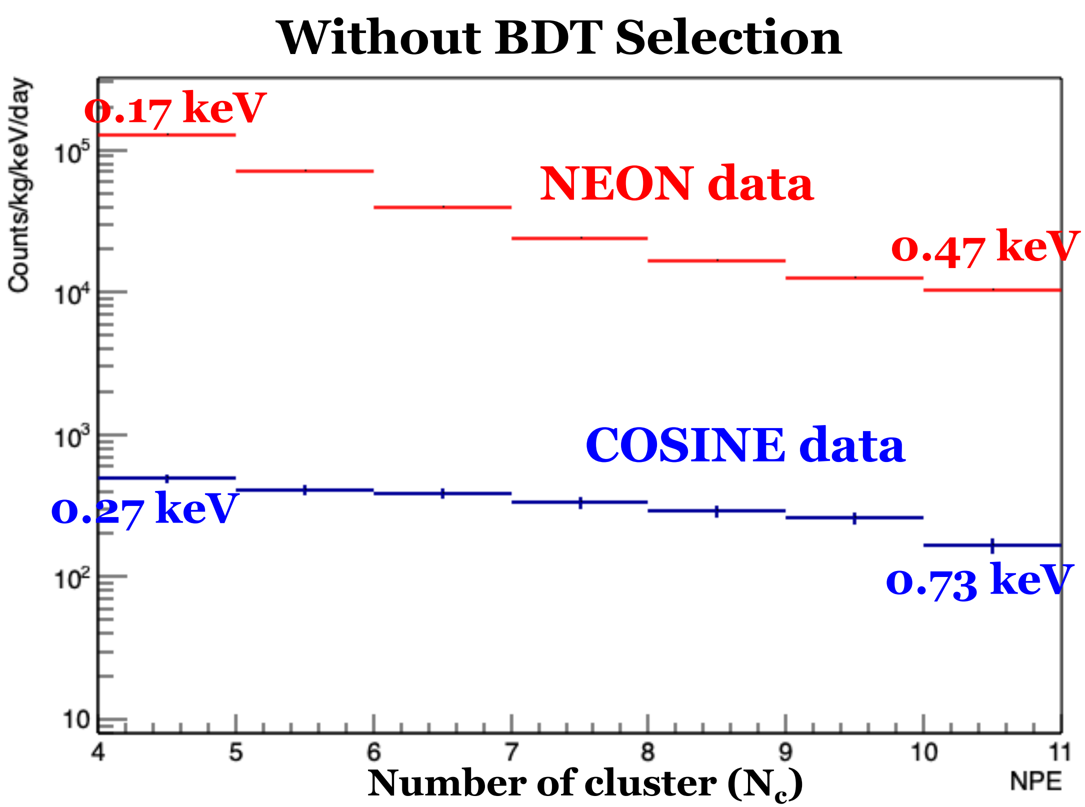
PRL 134, 021802 (2025)

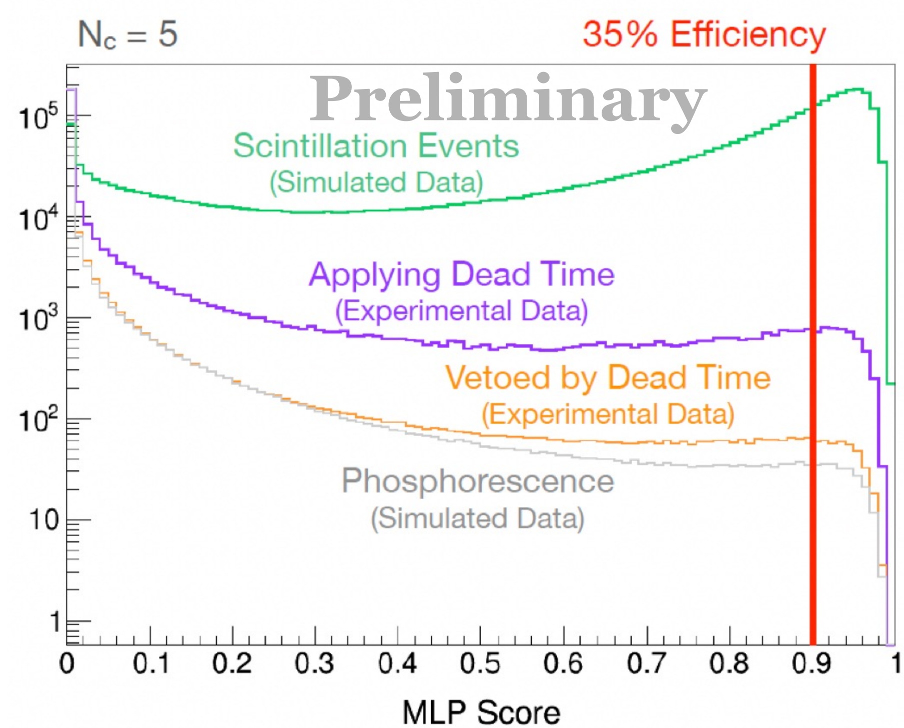


- Best Limits achieved for the Light Dark Matter Search.
- Below 1 MeV/c^2, NEON shows the best limit for DM-electron cross section and the kinetic mixing parameter for the dark photon.

CEνNS search status

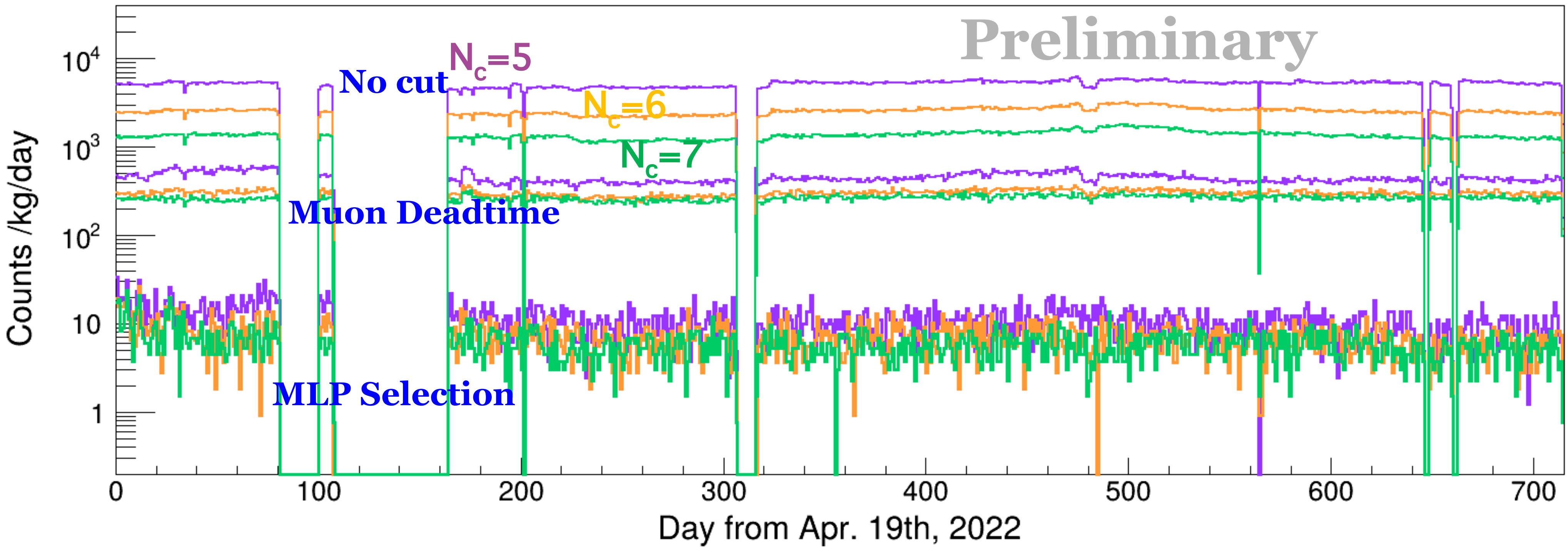
- 0.2 keV (~ 5 PE) threshold is required
- Large afterglow (phosphorus) pulses from muons
- Neural network training for the number of isolated clusters (Nc = 4, 5, 6, 7)





CEνNS search status

- **Factor ~1,000 reduction** for 5 Nc (~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

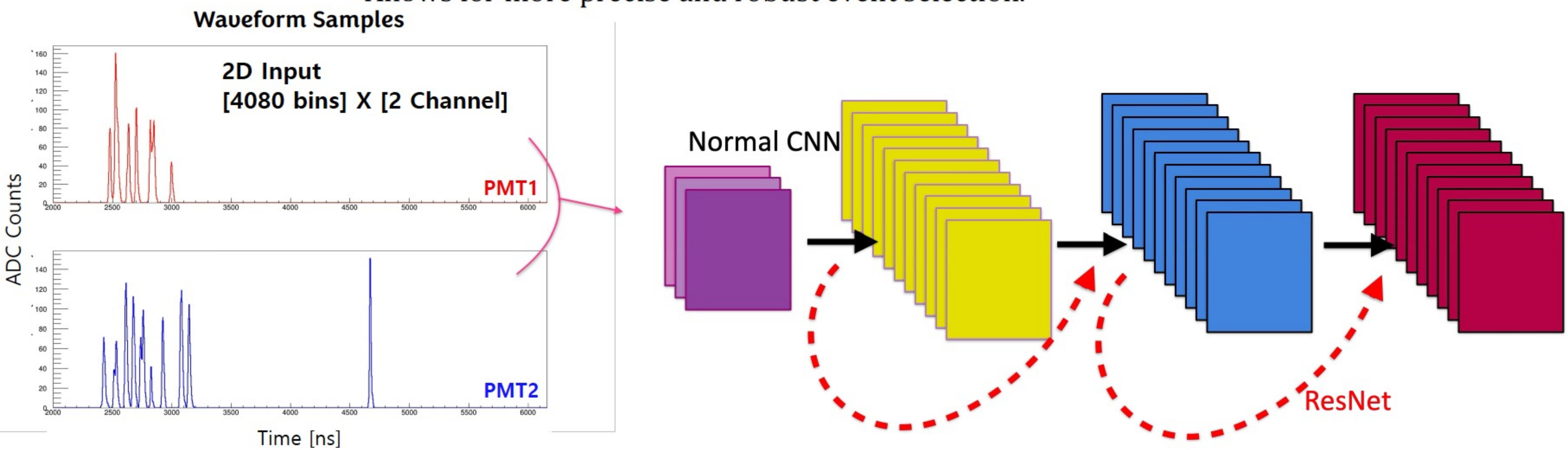
Deep learning strategy : ResNet CNN

❑ Deep learning with non-parameterized waveform shape

- Used **ResNet** model for training
- ResNet : Avoid gradient-vanishing, using 'residual connection'

  Enables deep convolutional layers of CNN training.

  - Allows for more precise and robust event selection.



Deep learning strategy : ResNet CNN

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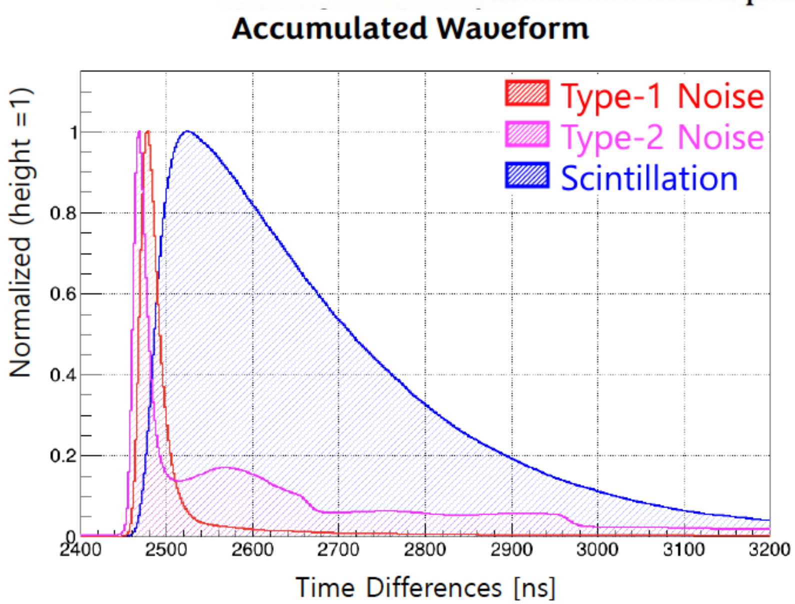
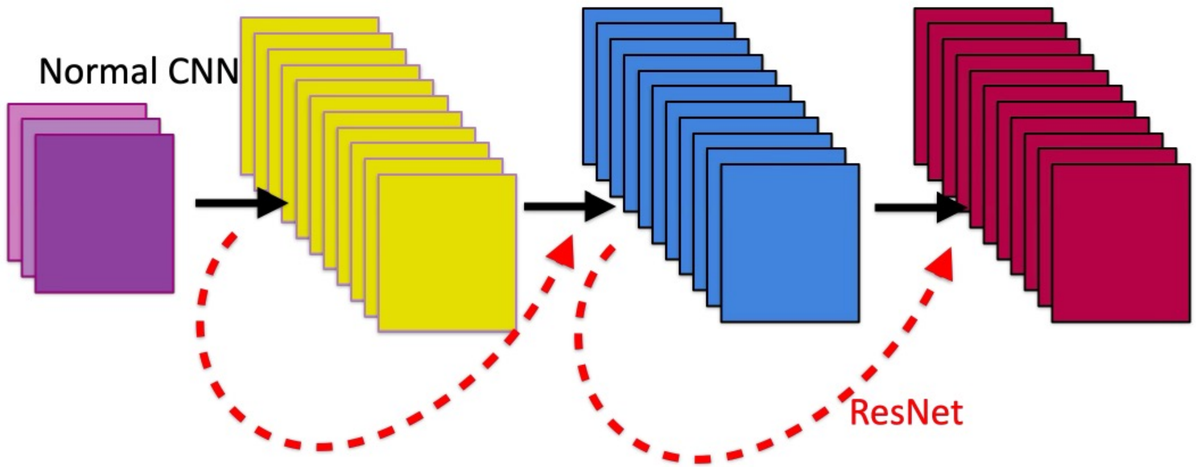
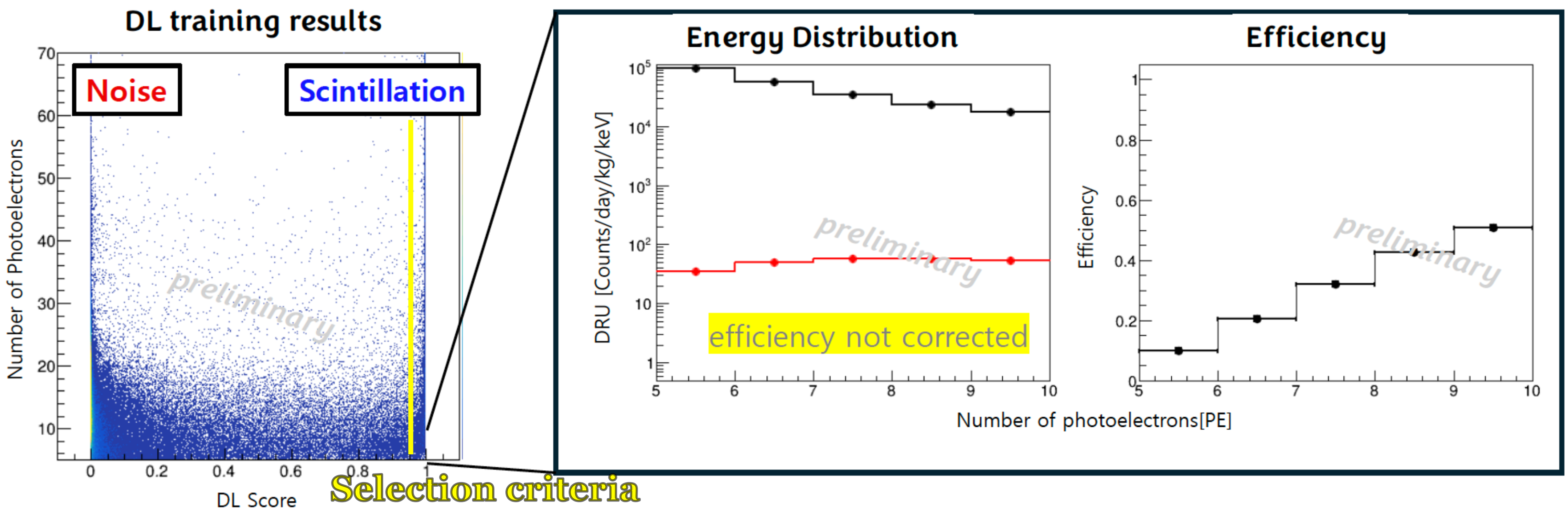




Scintillation signal samples : Waveform simulation data

Noise sample : Single-hit physics data

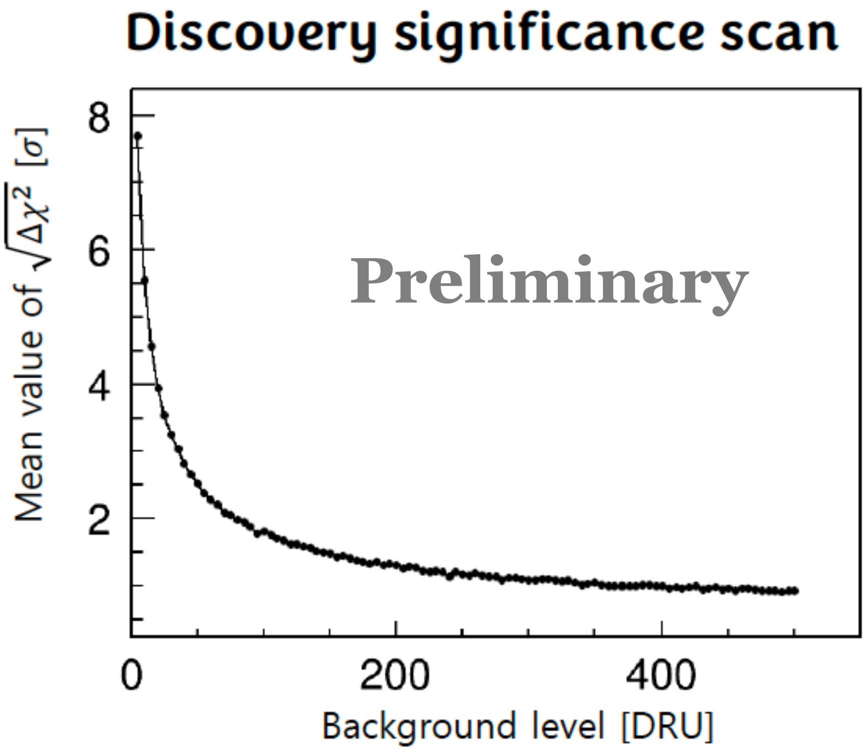
Preliminary results with deep learning



- Initial deep learning study results to reduce the background from 100,000 to 30 at 5 Nc (~photoelectrons)

Sensitivity for CEνNS

- Simulated experiments to scan discovery potential by varying the expected background level



Simple on−off analysis

No systematic uncertainty

723 days of ON data

223 days of OFF data

5σ @ ~10 dru

3σ @ ~32 dru

dru = counts/kg/keV/day

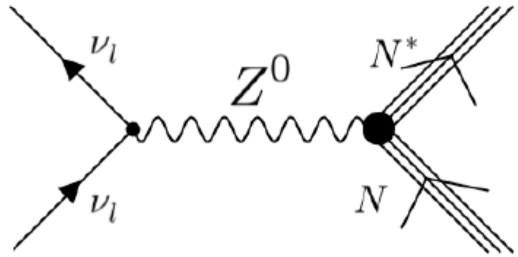
We have extensively worked for deep learning machinery development to reach the target background level

Inelastic neutrino nucleus scattering (IνNS)

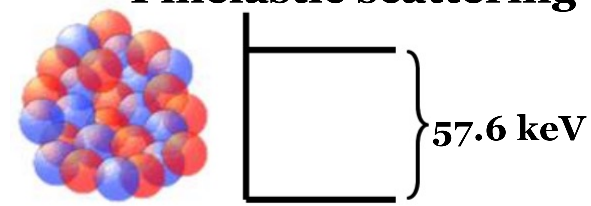
- IνNS cross section is ~ 4 order of magnitude smaller than CEνNS

arXiv:2004.04055

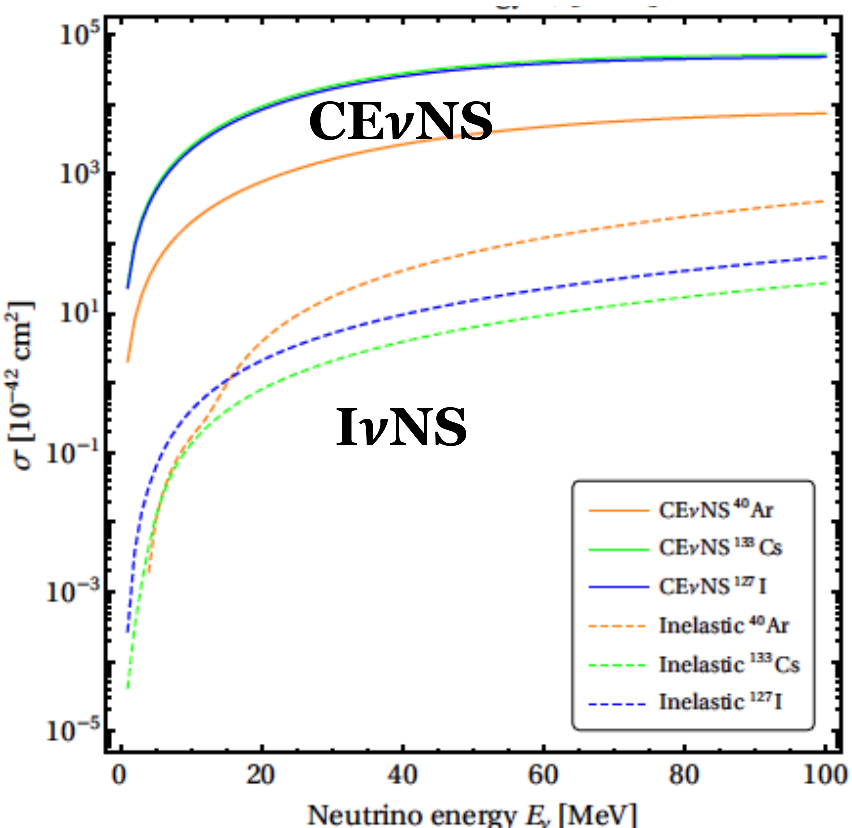
arXiv:2206.08590



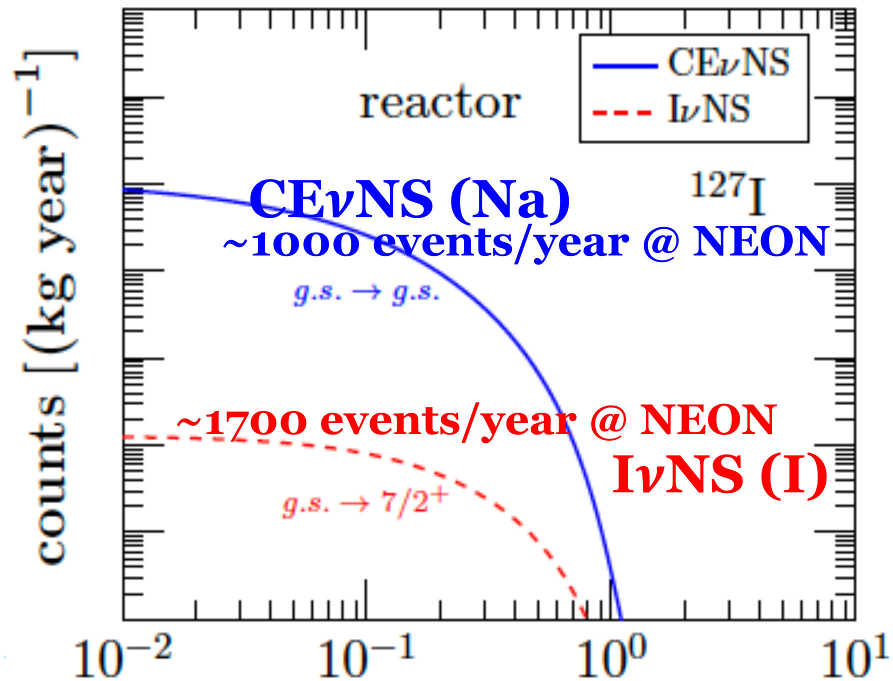
^{127}I inelastic scattering



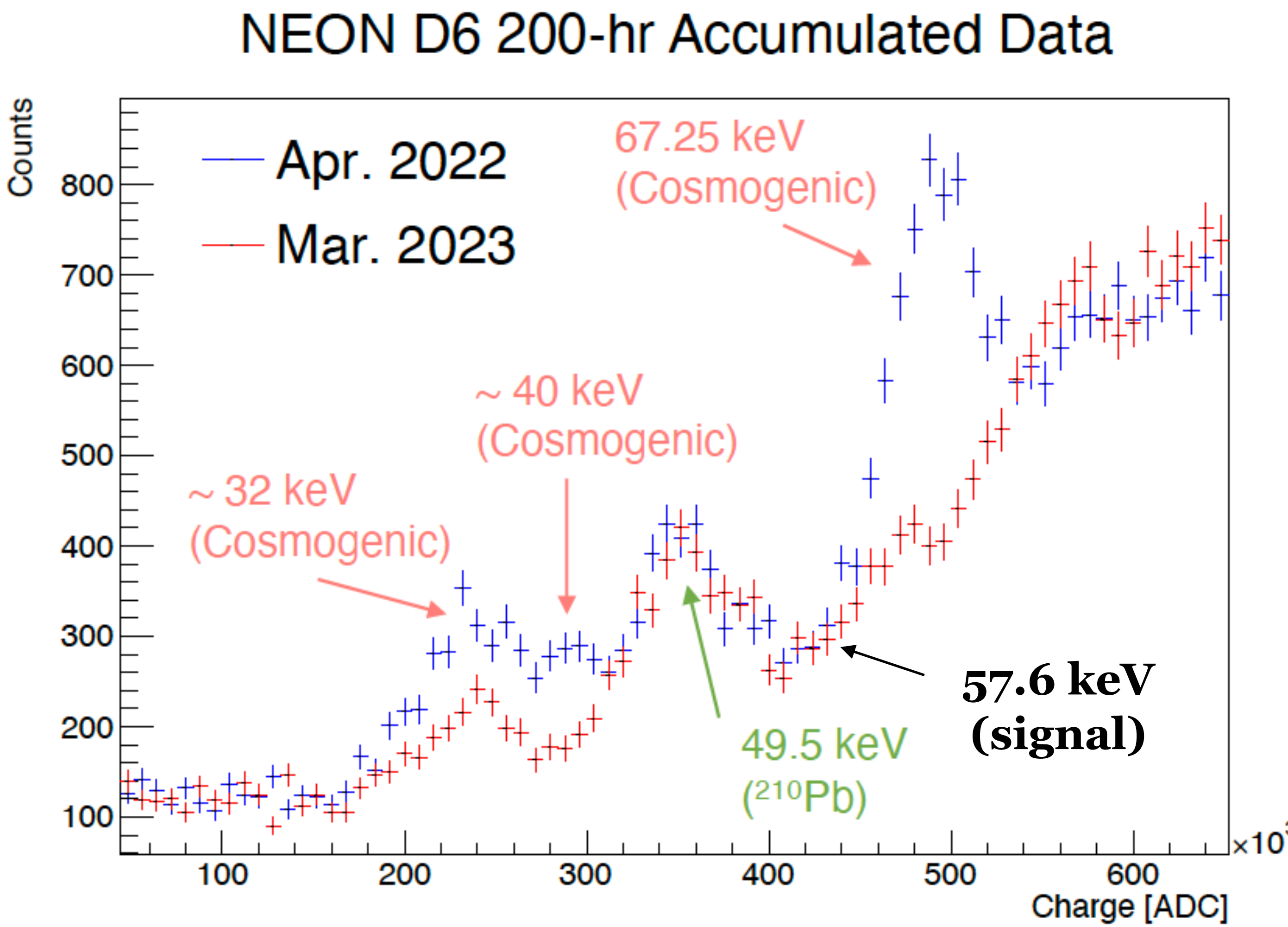
Cross section



Expected event rate (Integrated)



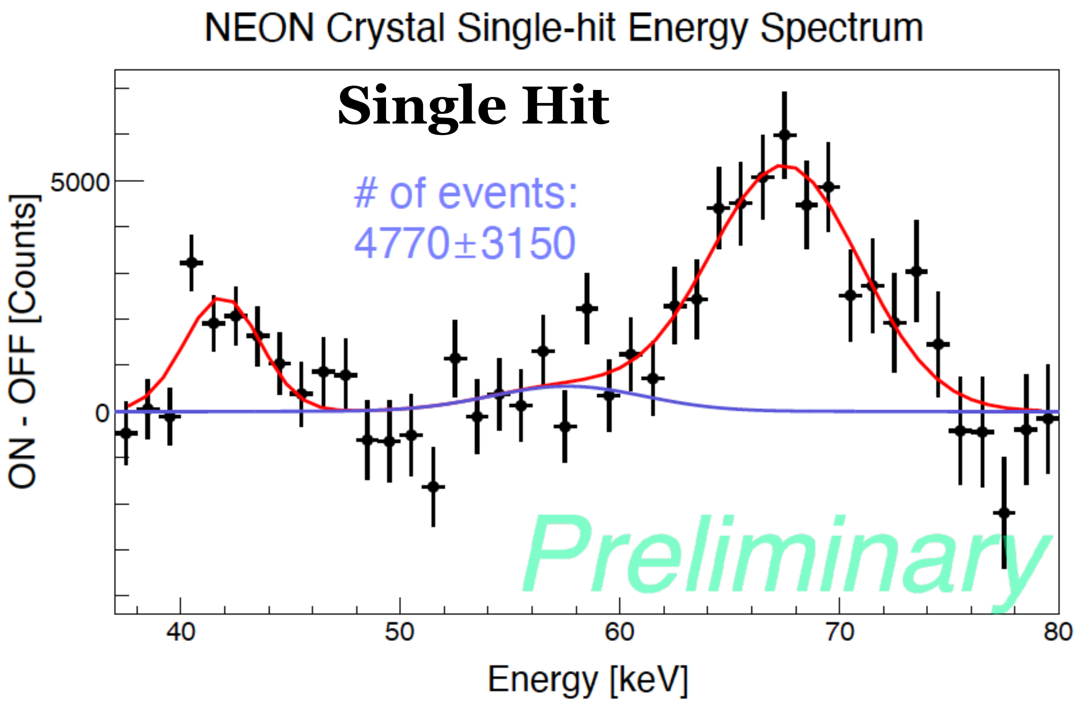
Investigation of IνNS search region

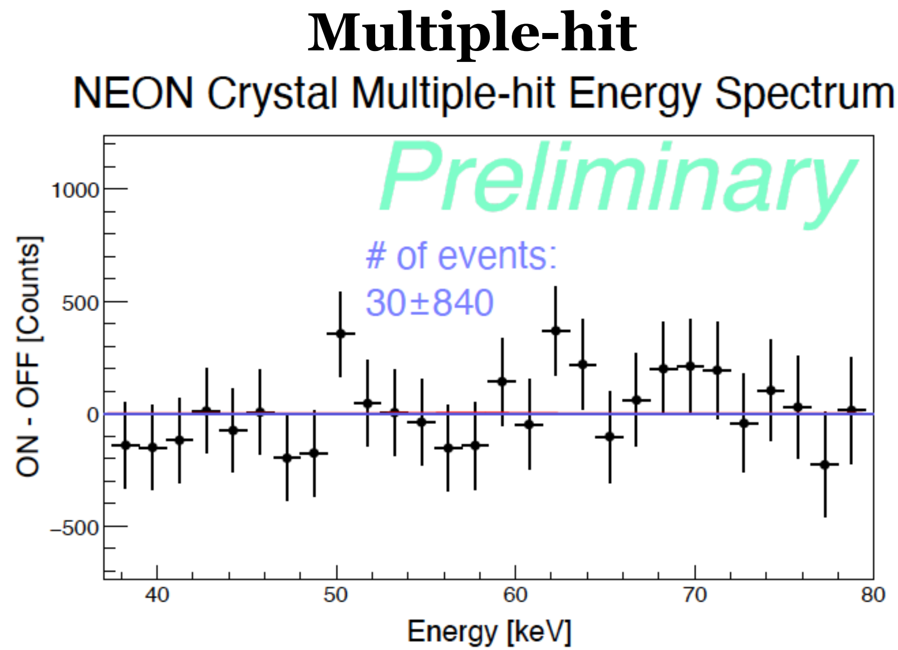


- Time-dependent background model is required

Simple on-off spectra

- ~ 3000 events are expected

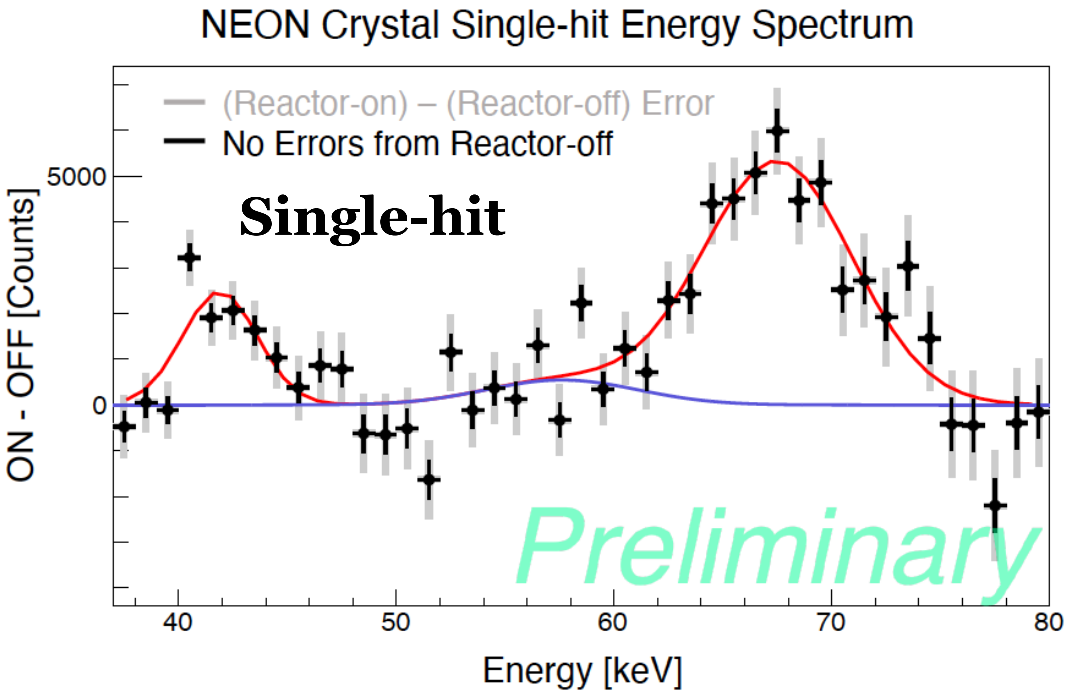


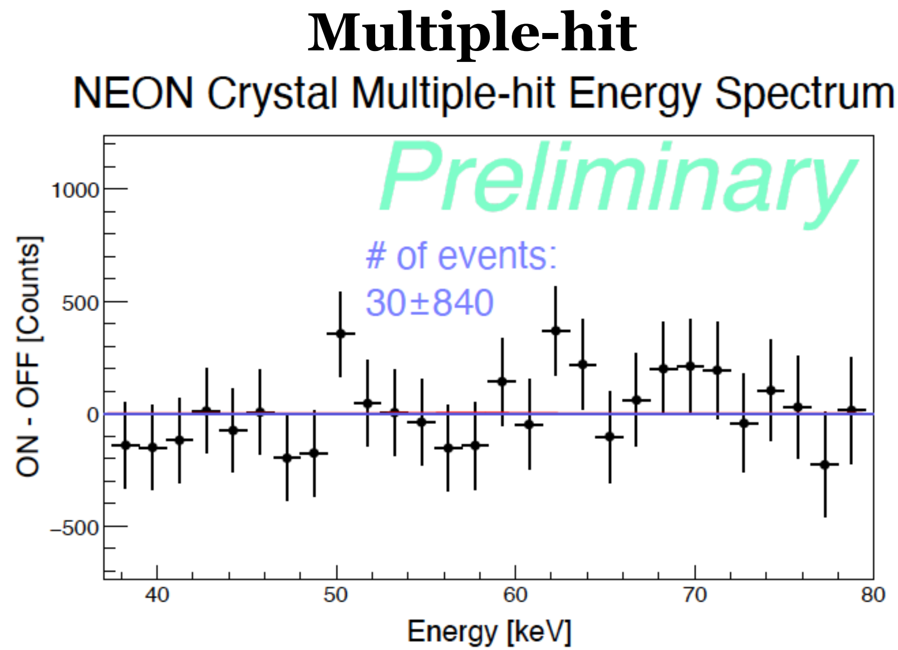


- On data model can significantly reduced the statistical uncertainty

Simple on-off spectra

- ~ 3000 events are expected



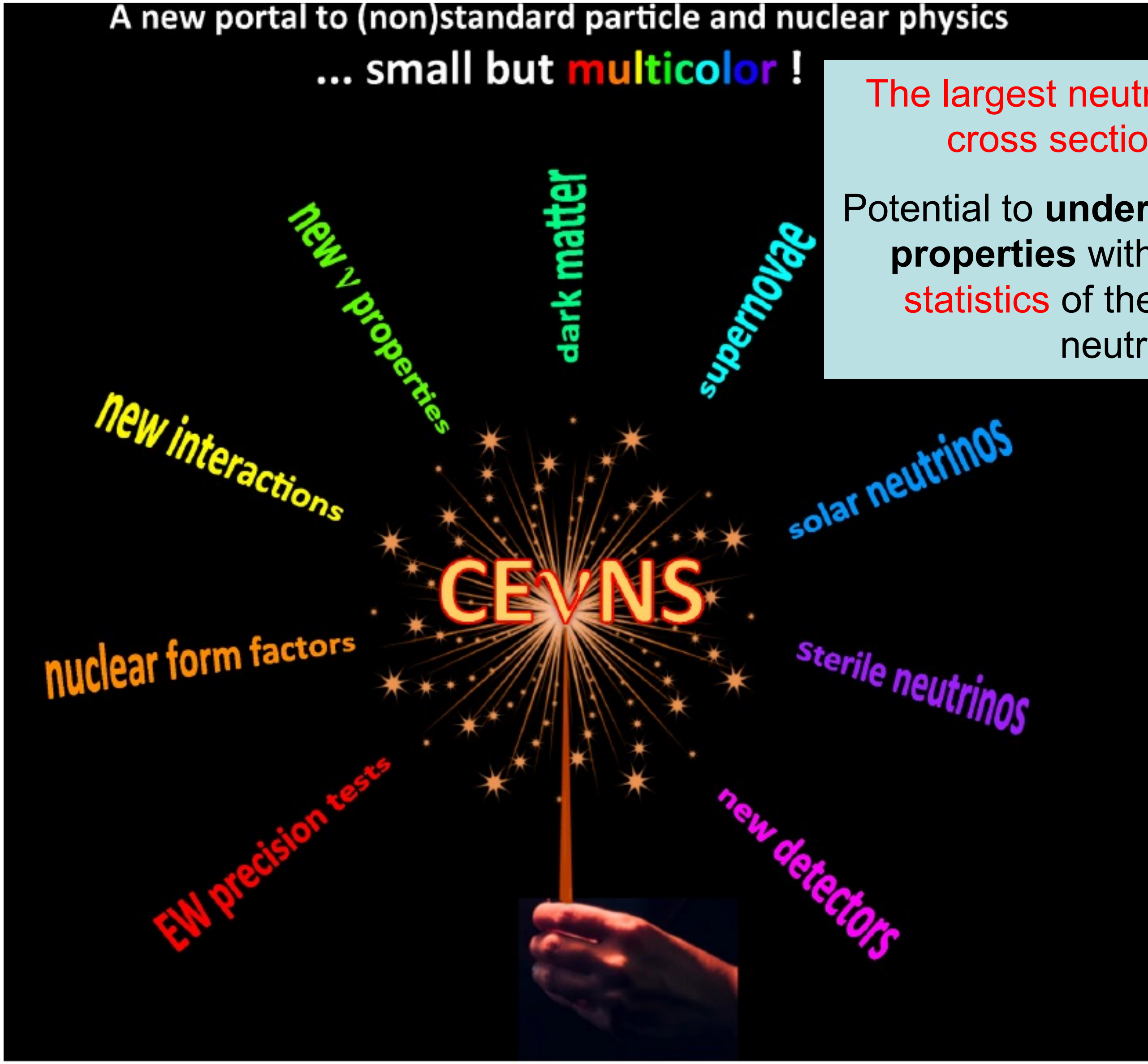


- On data model can significantly reduced the statistical uncertainty
- Background models for each two-months long data are ongoing

Summary

- NEON take ~720 days reactor on and ~ 220 days reactor off data
- NEON has searched for CEνNS and IνNS event using NaI(Tl) target
- NEON published two world leading results in dark sector particle searches
  - ❖ Demonstrating the advantages of using nuclear reactor for dark sector searches
- Detector decommissioning is planned in May 2026
  - ❖ We are looking for new experiment site

Physics potential of CEνNS



The largest neutrino interaction cross section (~x100)

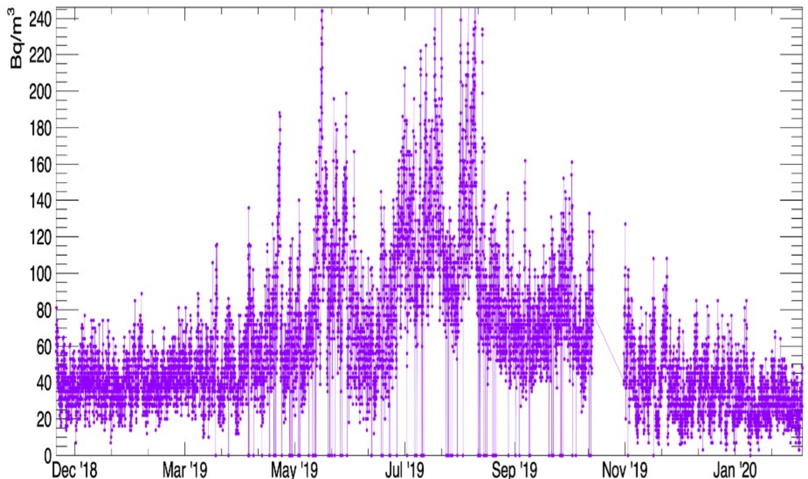
Potential to **understand neutrino properties** with much larger statistics of the low-energy neutrino

From E. Lisi

Neutrino 2018

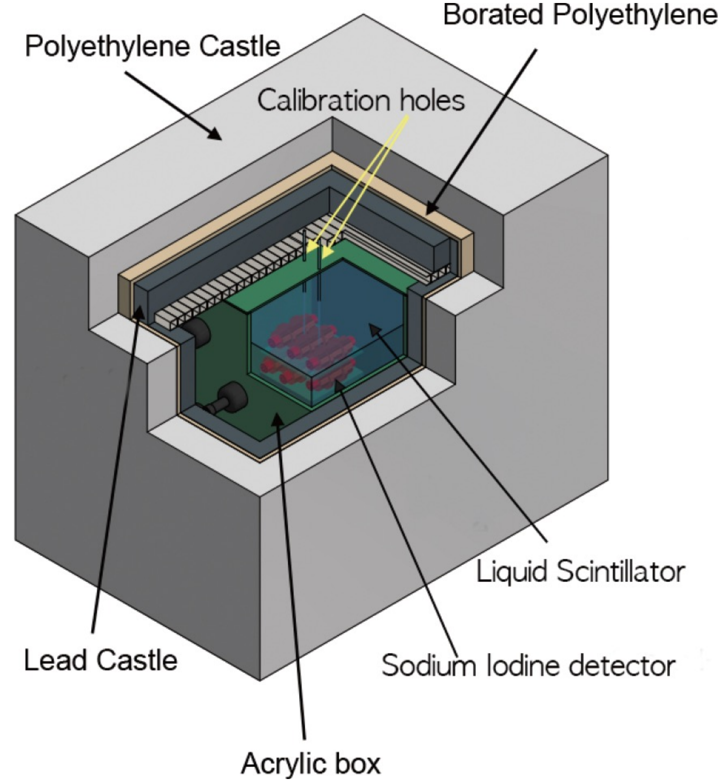
Seasonal variation of ^{222}Rn level

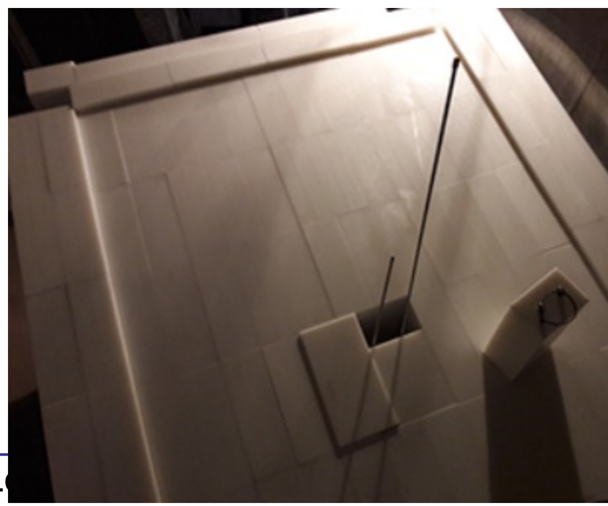
Radon eye measurement by NEOS experiment



Winter **Summer** **Winter**

Calibration holes were not closed





^{222}Rn level is higher at summer

ALP signal generation

ALP events rate at NEON detector site