NEON

(Neutrino Elastic-scattering Observation in NaI)

Chang Hyon Ha on behalf of NEON

Korea-ν Symposium 2024, Gwangju

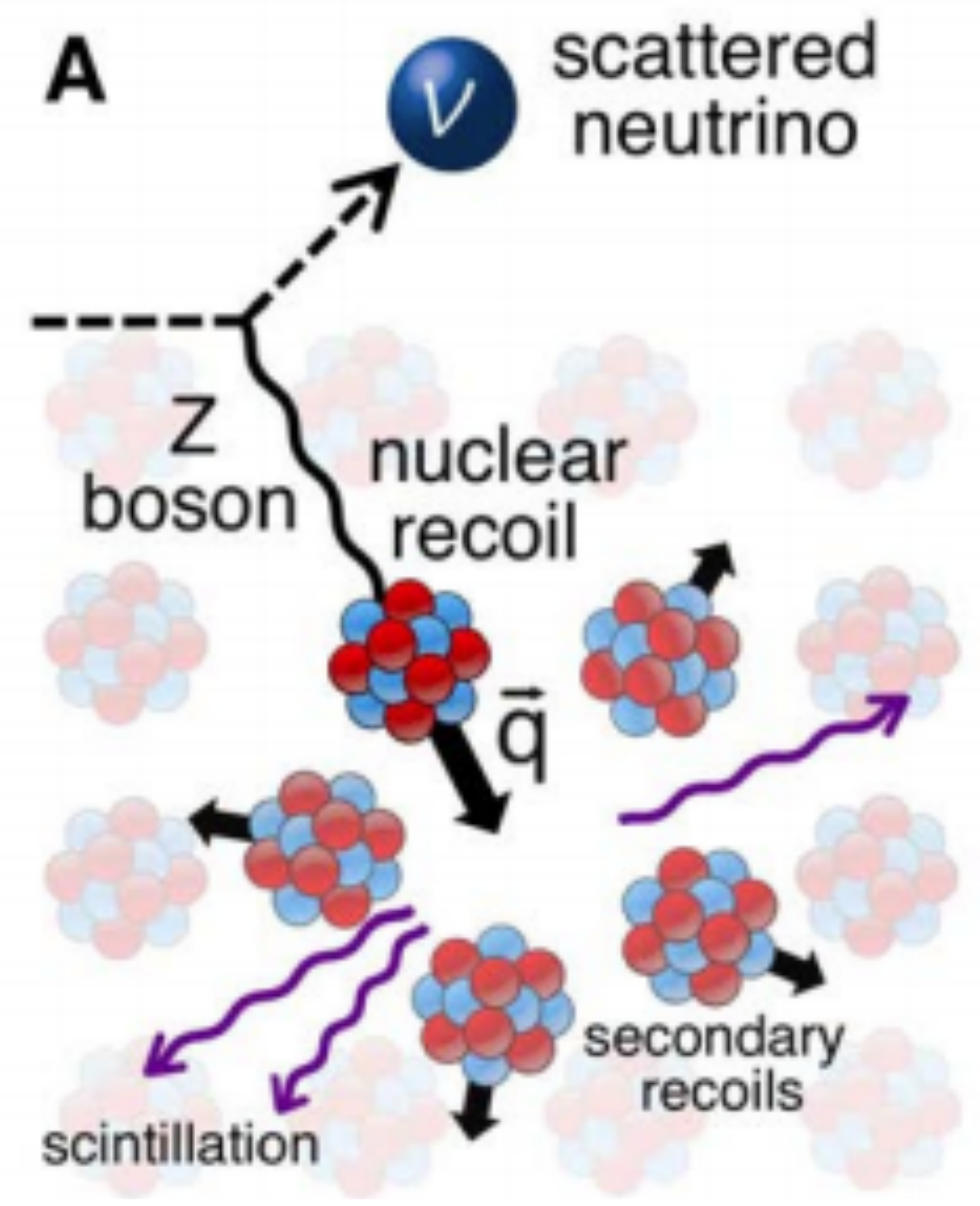
CAU 중앙대학교 CHUNG-ANG UNIVERSITY

$\bar{\nu}_e$ ON

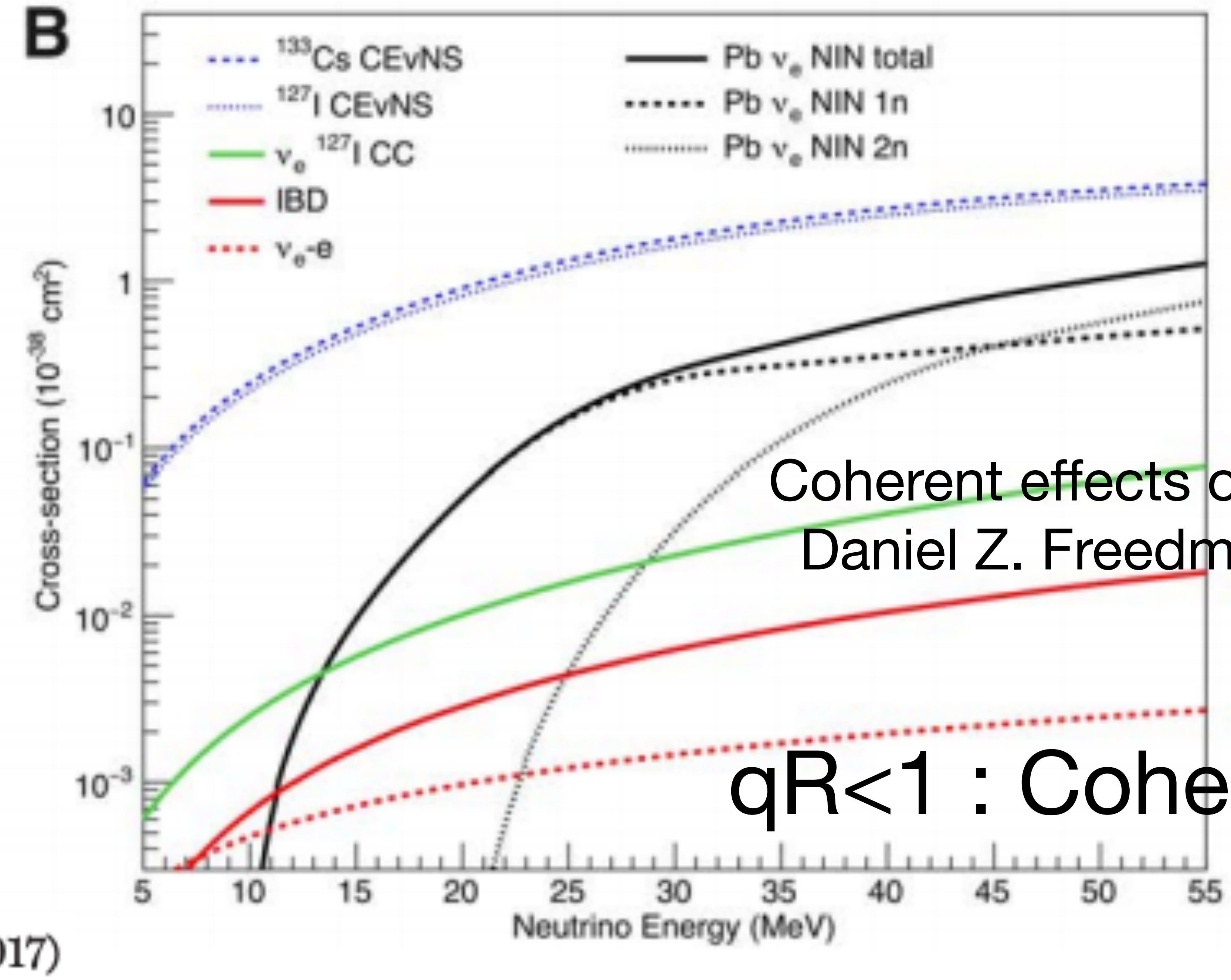
Motivation for the NEON experiment

- The process predicted 50 years ago and the first measurement came seven years ago (stopped pion) by the COHERENT collaboration.
- Aim at detection of Coherent scattering in reactors.
  - Single flavor (electron anti-neutrino) & N^2 dependence
- Tests for BSM physics parameters (Light DM, Axion, Dark Photon, …)
  - Reactors produce a large amount of the photon flux.

- Neutrino Magnetic Moment
- Neutrino Non-Standard Interactions
- Neutrino-electron scattering.
- Sterile neutrinos (reactor anomaly)

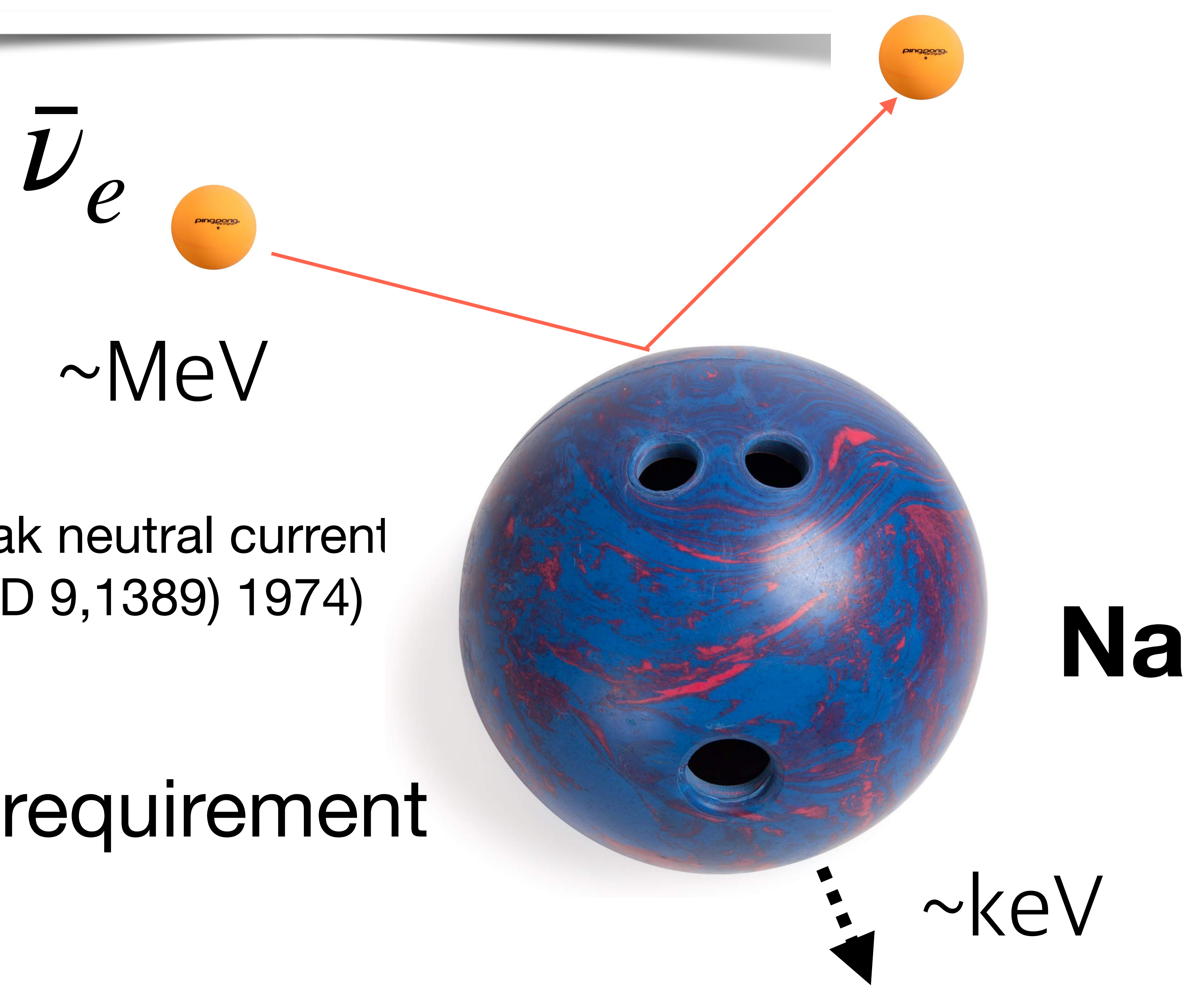


Akimov *et al.*, *Science* **357**, 1123–1126 (2017)



Coherent effects of a weak neutral current
Daniel Z. Freedman (PRD 9,1389) 1974)

qR<1 : Coherent requirement



Coherent Scattering Experiment Review

Many jump into bandwagon but still challenging in reactor.

Status and prospects on CEνNS
by Irina Nasteva (Neutrino 2024)

Optimistic overview for coherent scattering!

Experiment	Detector	Mass	Threshold	Reactor/ source	Distance to source	Thermal power	Neutrino flux ν/cm^2/s	Location
COHERENT	CsI, Ar, Ge, NaI	15-185 kg	6.5-20 keVnr	πDAR	19-28 m		4.3*10^7	USA
nuESS*	CsI, Ge, Xe, Ar			πDAR				Sweden
CICENNS*	CsI(Na)	300 kg	2 keVnr	πDAR	10.5 m		2*10^7	China
Atucha-II	Si CCDs	2.5 g	40 eVee	Atucha-II	12 m	2 GW_{th}	2*10^{13}	Argentina
BULLKID*	Si/Ge cryogenic	20 g	160 eV					Italy
CONNIE	Si CCDs	0.5 g	15 eVee	Angra-II	30 m	3.9 GW_{th}	7.8*10^{12}	Brazil
CONUS	HPGe	3.74 kg	210 eVee	Brokdorf	17 m	3.9 GW_{th}	2*10^{13}	Germany
CONUS+	HPGe	3.74 kg	150 eVee	Leibstadt	20.7 m	3.6 GW_{th}	1.45*10^{13}	Switzerland
MINER*	Ge, Si, Al_2O_3 cryogenic	1 kg	100 eVnr	TRIGA / HFIR*	2-10 m	1 MW_{th}	~1*10^{12}	USA
NCC-1701	HPGe	3 kg	200 eVee	Dresden-II	8 m	2.96 GW_{th}	8.1*10^{13}	USA
NEON	NaI(Tl)	16.7 kg	200 eVee	Hanbit	23.7 m	2.815 GW_{th}	~1*10^{13}	Korea
NEWS-G3*	Ar+2%CH4			tbc				Canada
NUCLEUS*	$CaWO_4$, Al_2O_3 cryogenic	10 g	20 eVnr	Chooz	77 m, 102 m	2x2.45 GW_{th}	1.7*10^{12}	France
NUXE*	LXe	10 kg		tbc				
nuGEN	HPGe	1.4 kg	200 eVee	Kalinin	11-12 m	3.1 GW_{th}	5.4*10^{13}	Russia
RED-100	LXe, Lar*	200 kg		Kalinin	19 m	3.1 GW_{th}	1.35*10^{13}	Russia
RECODE*	HPGe	1-2,10 kg	160 eVee	Sanmen	11, 22 m	3.4 GW_{th}	Up to 5.6*10^{13}	China
RELICS*	LXe	50 kg	1 keVnr	Sanmen	22 m	3.4 GW_{th}	1.4*10^{13}	China
Ricochet*	Ge, Zn, Al, Sn cryogenic	680 g	160 eVee, 300 eVnr	ILL-H7	8.8 m	58 MW_{th}	1.6*10^{12}	France
SBC*	Ar	10 kg	100 eVee	tbc				USA
TEXONO	HPGe	1.43 kg	200 eVee	Kuo-Sheng	28 m	2.9 GW_{th}	6.4*10^{12}	Taiwan

* in preparation

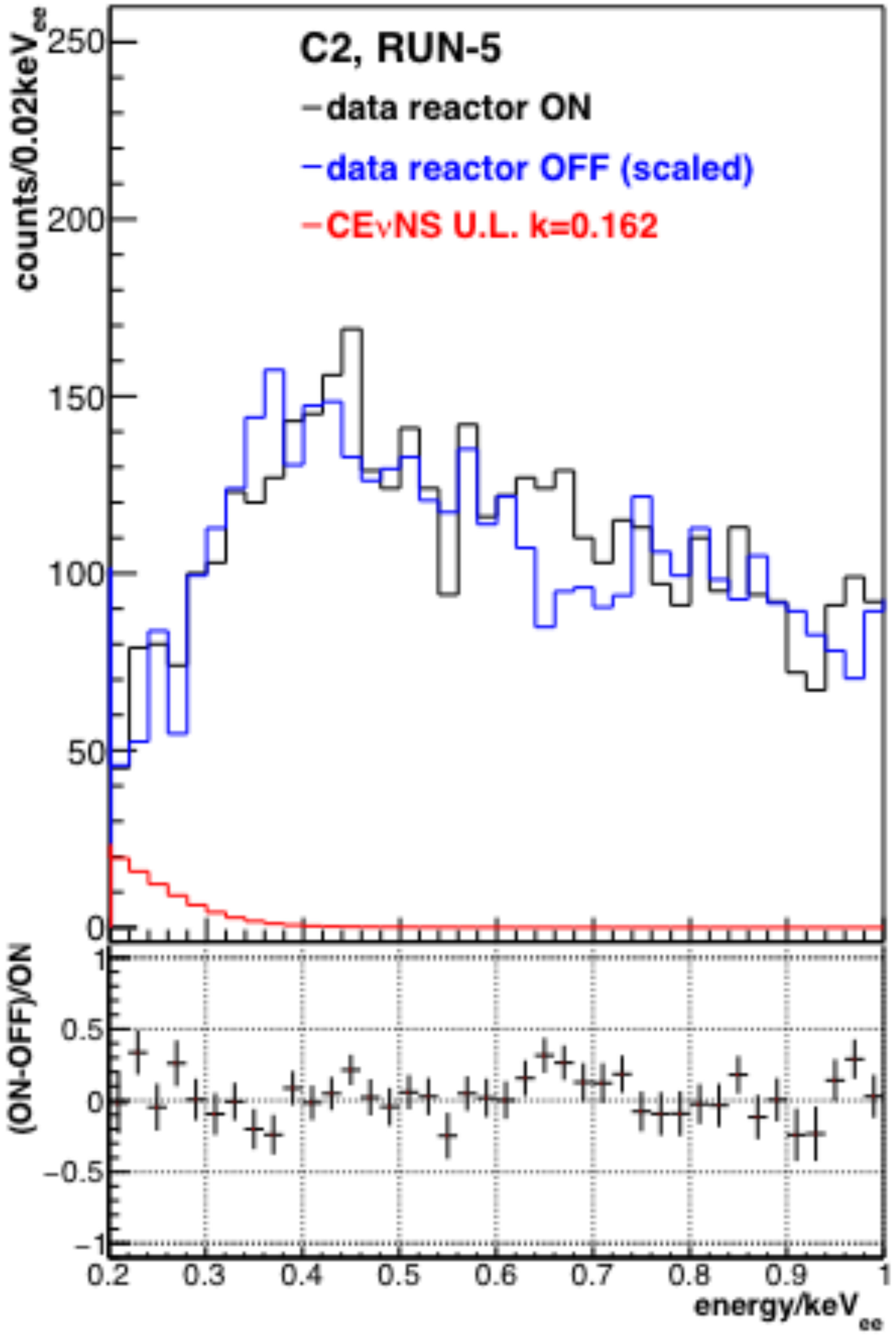
Germanium Silicon Noble gases Cryogenic Scintillator

(the list may be incomplete)

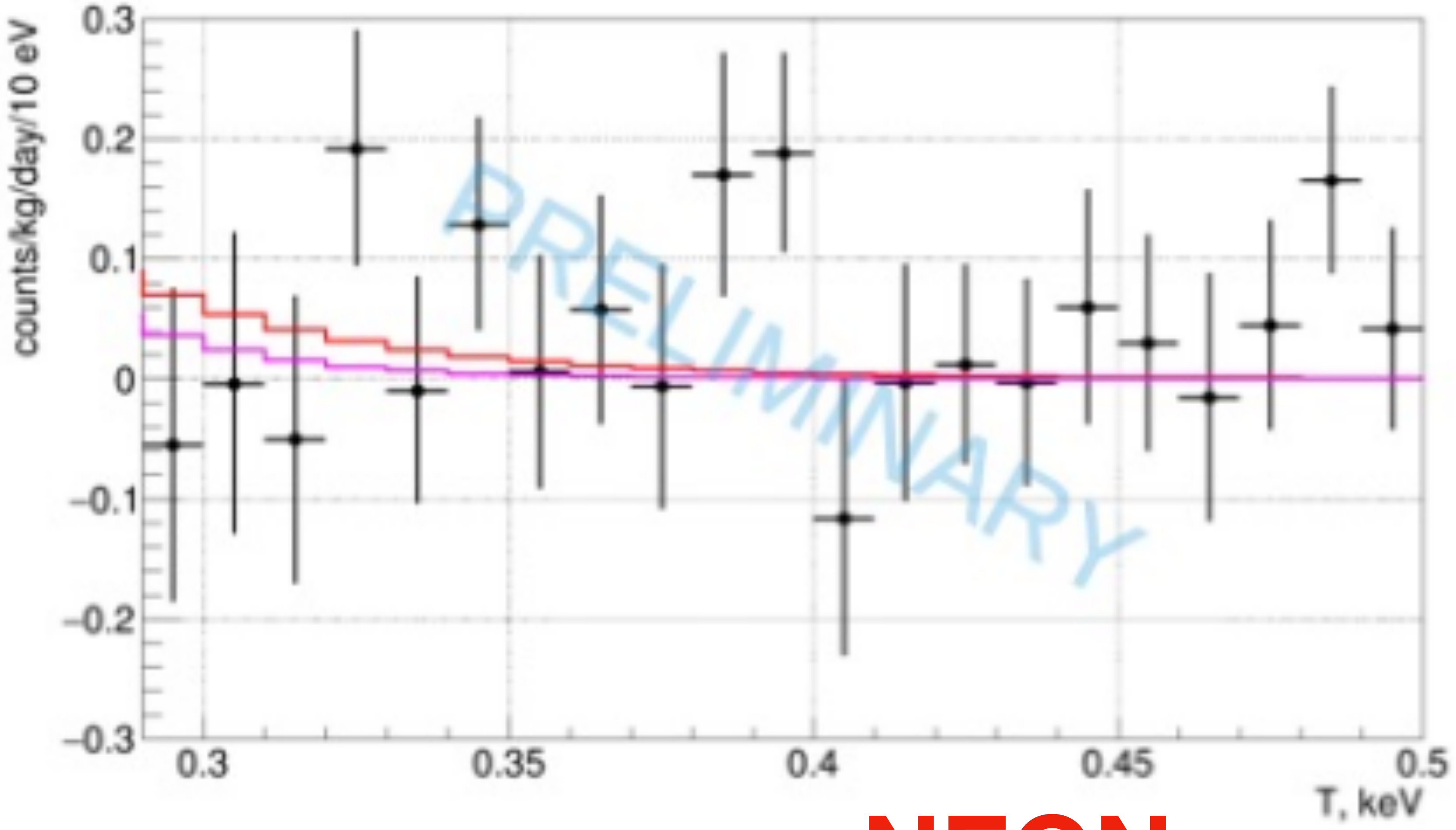
Status and prospects on CEνNS by Irina Nasteva (Neutrino 2024)

Long way to go : Challenging Field (Neutrino 2024)

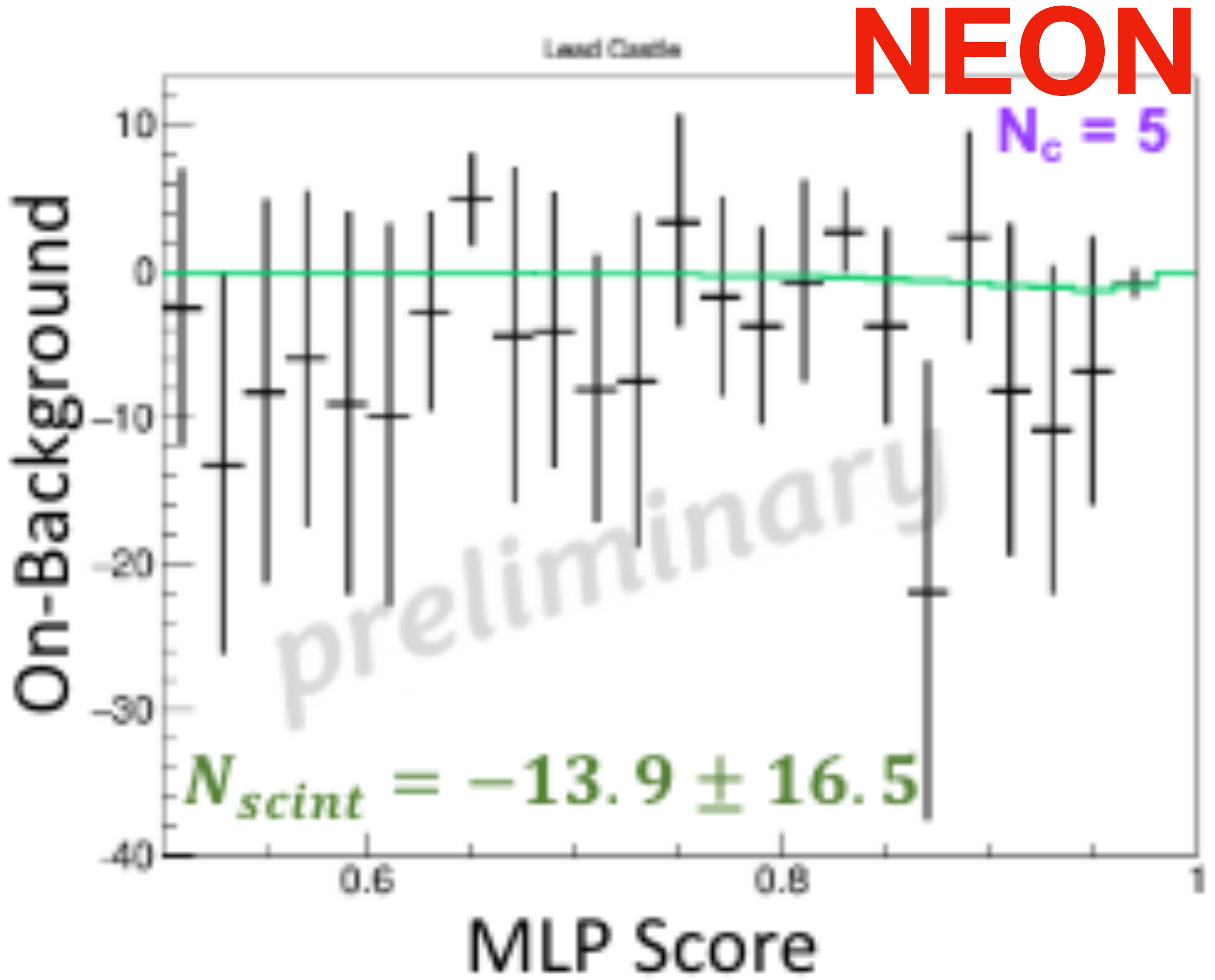
CONUS



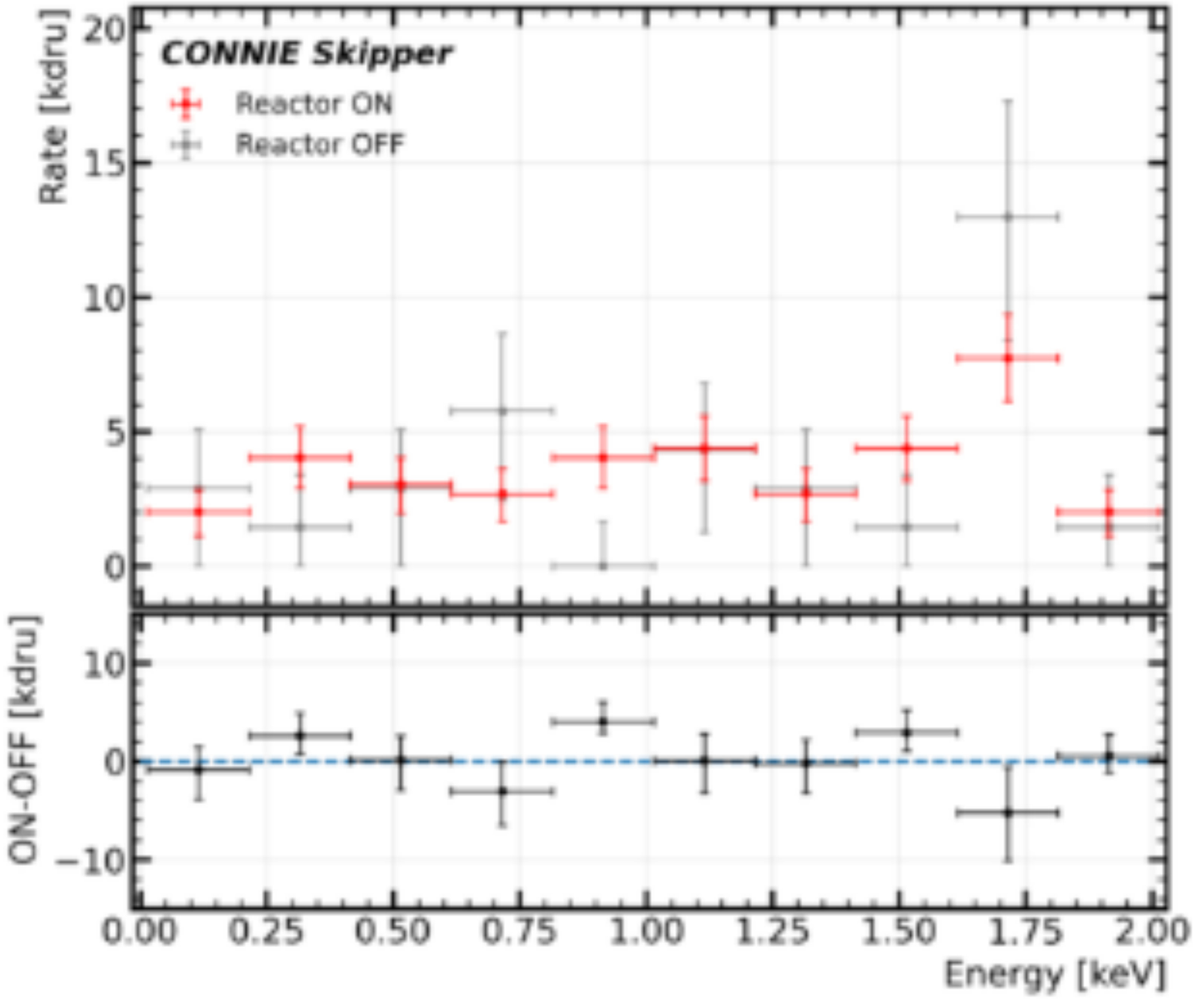
nuGeN



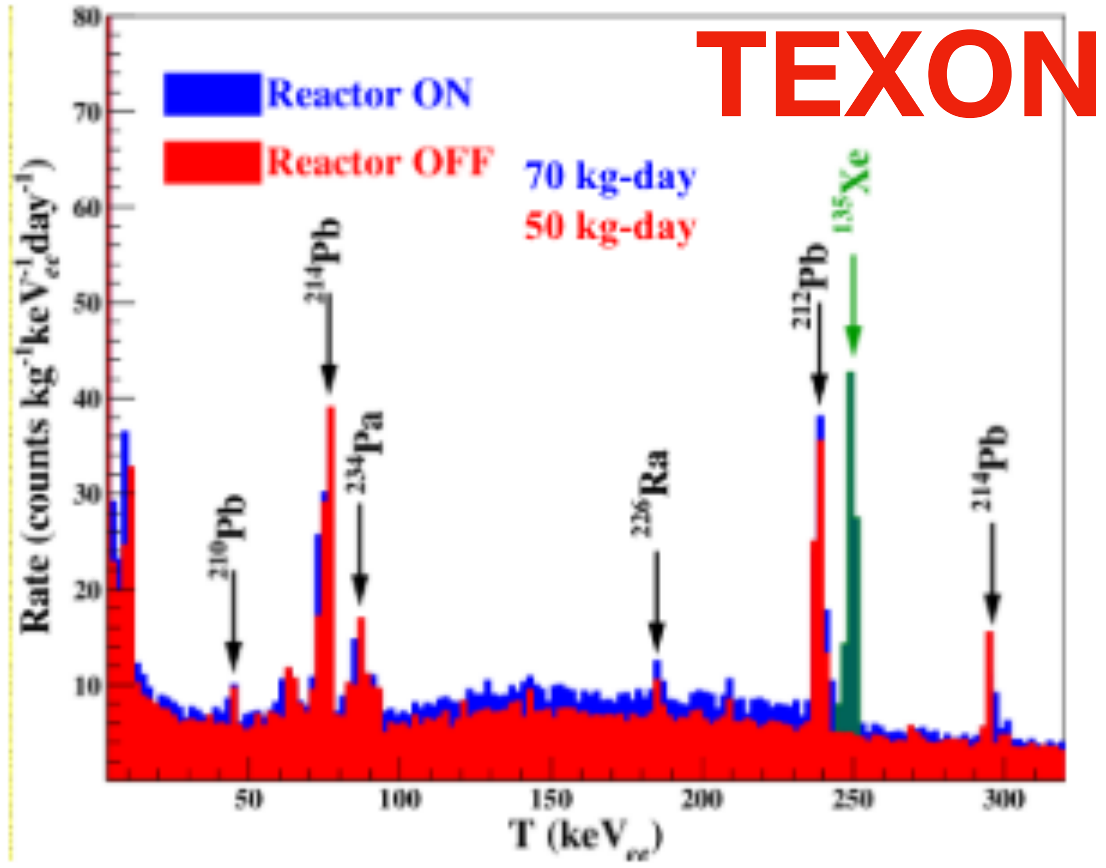
NEON



CONNIE

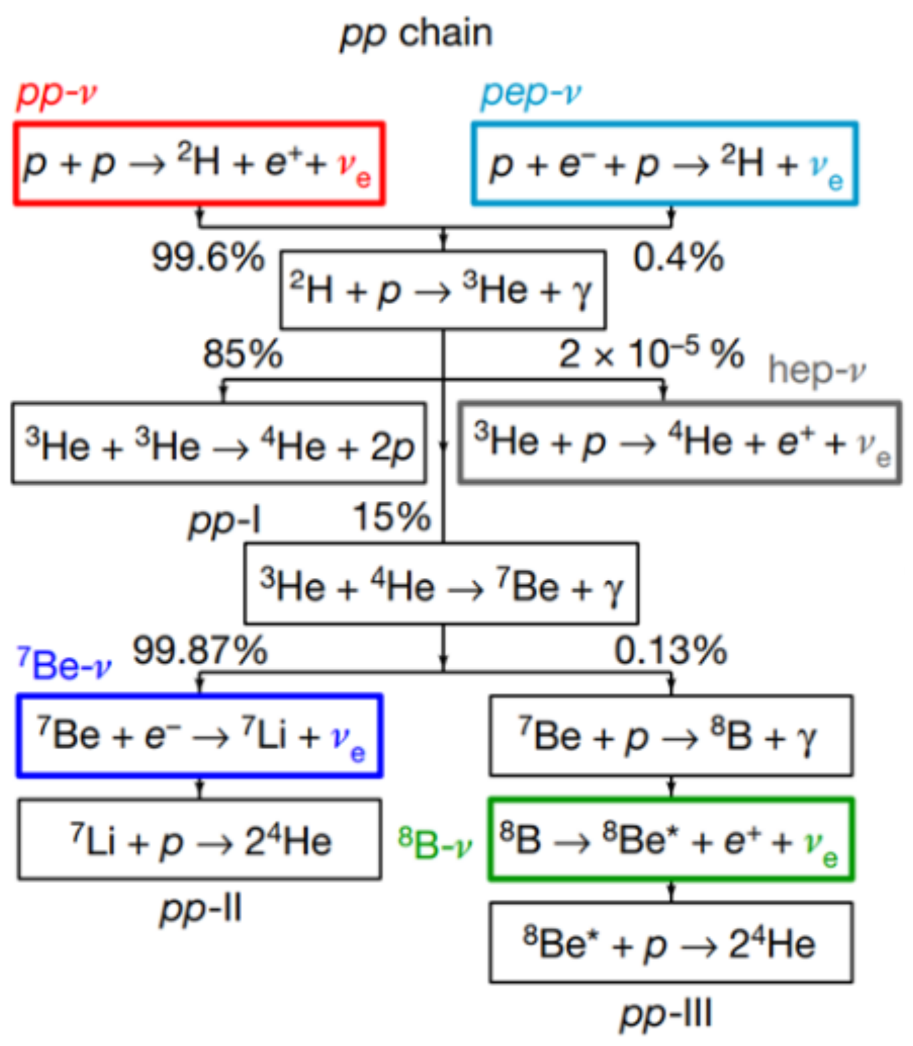


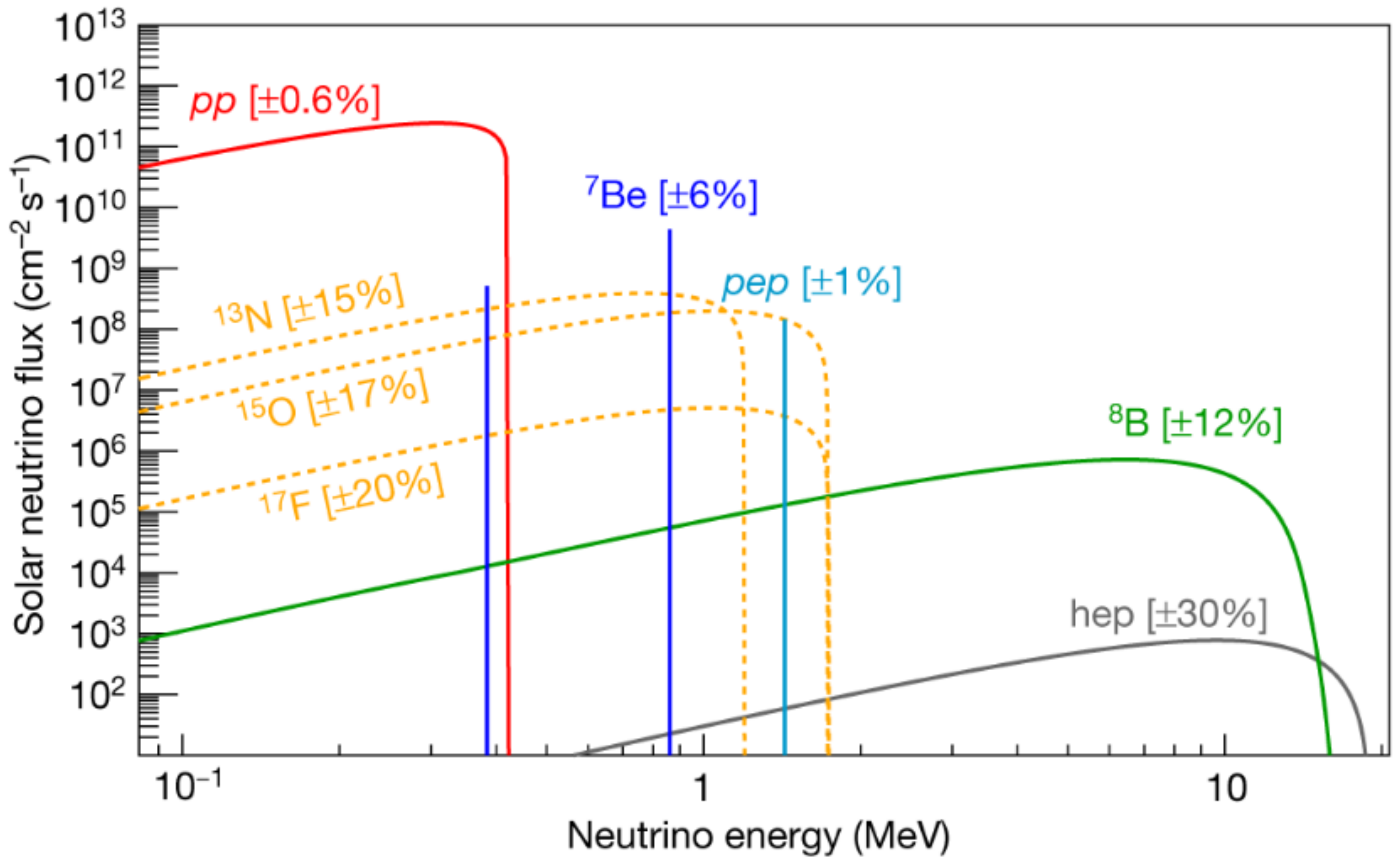
TEXONO

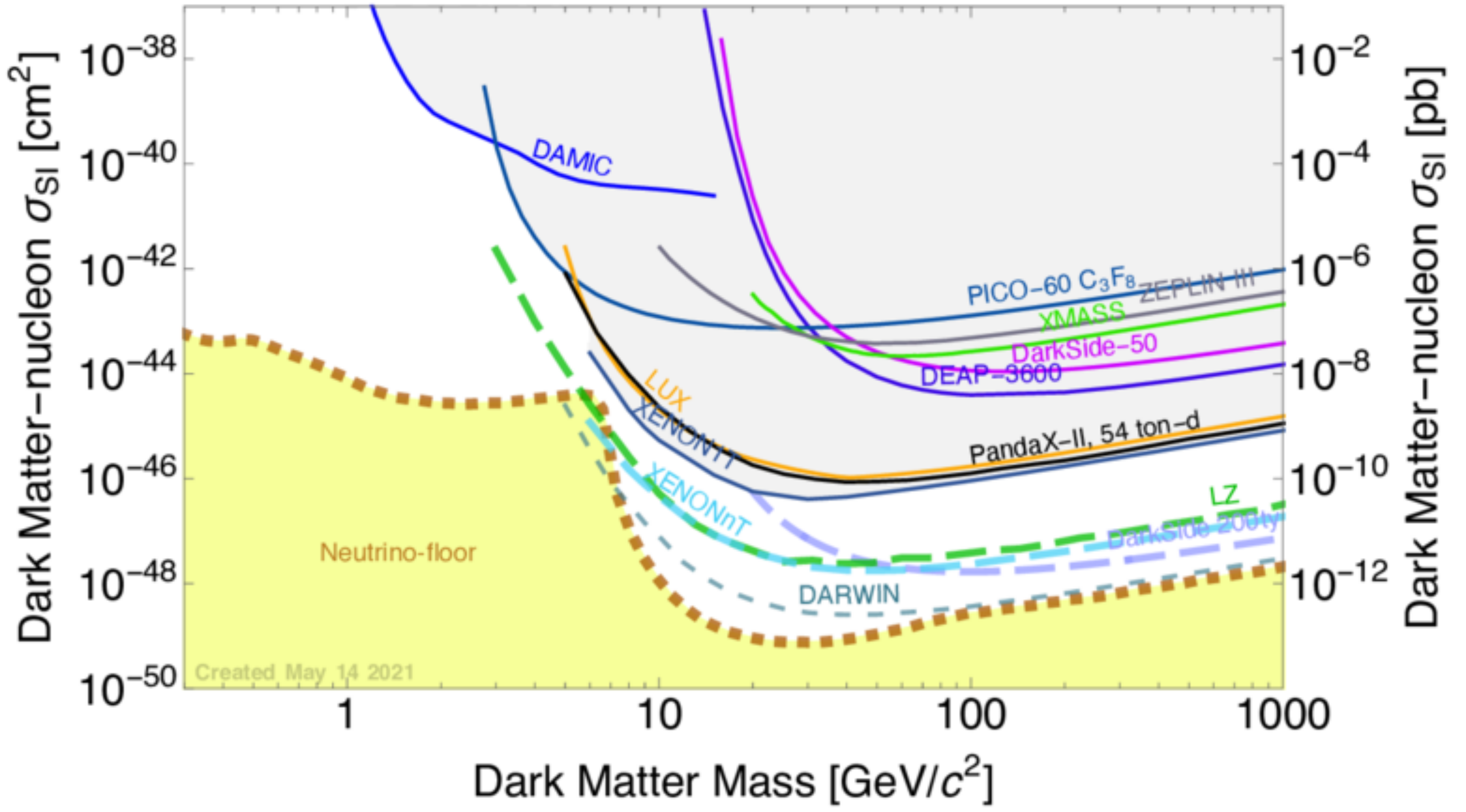


IDM-2024 (Coherent Scattering with Solar ν)

^{8}B **neutrinos from Sun scatter off of Xenon Nuclei (XENONnT Dark Matter Direction detection)**







Mass difference between ^{8}B **and** ^{8}Be **is large (**$Q \sim 17\ MeV$**).**

$E_{rec}^{max} \sim 4\ keV$ **on** ^{132}Xe **detectable in Dark Matter detectors.**

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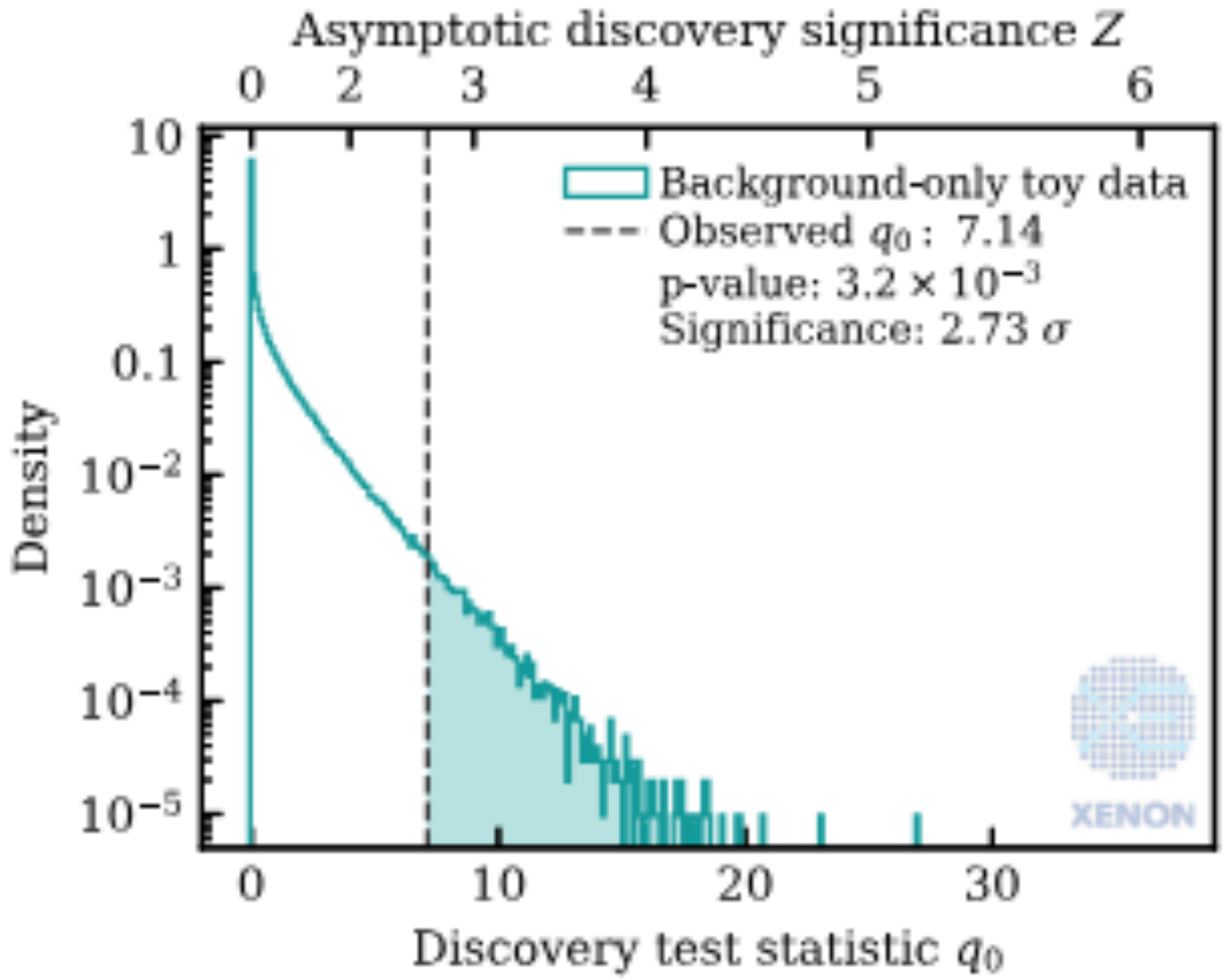
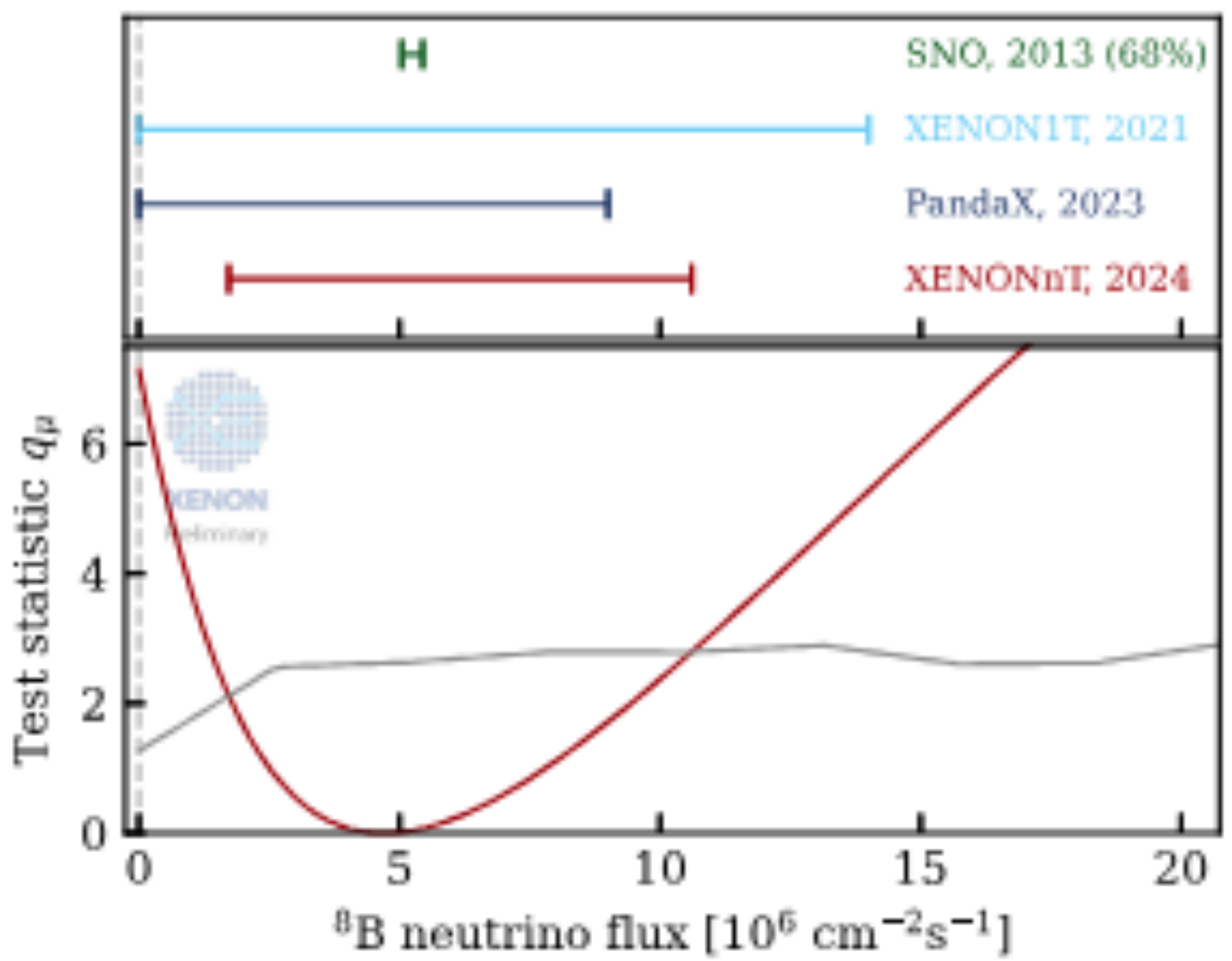
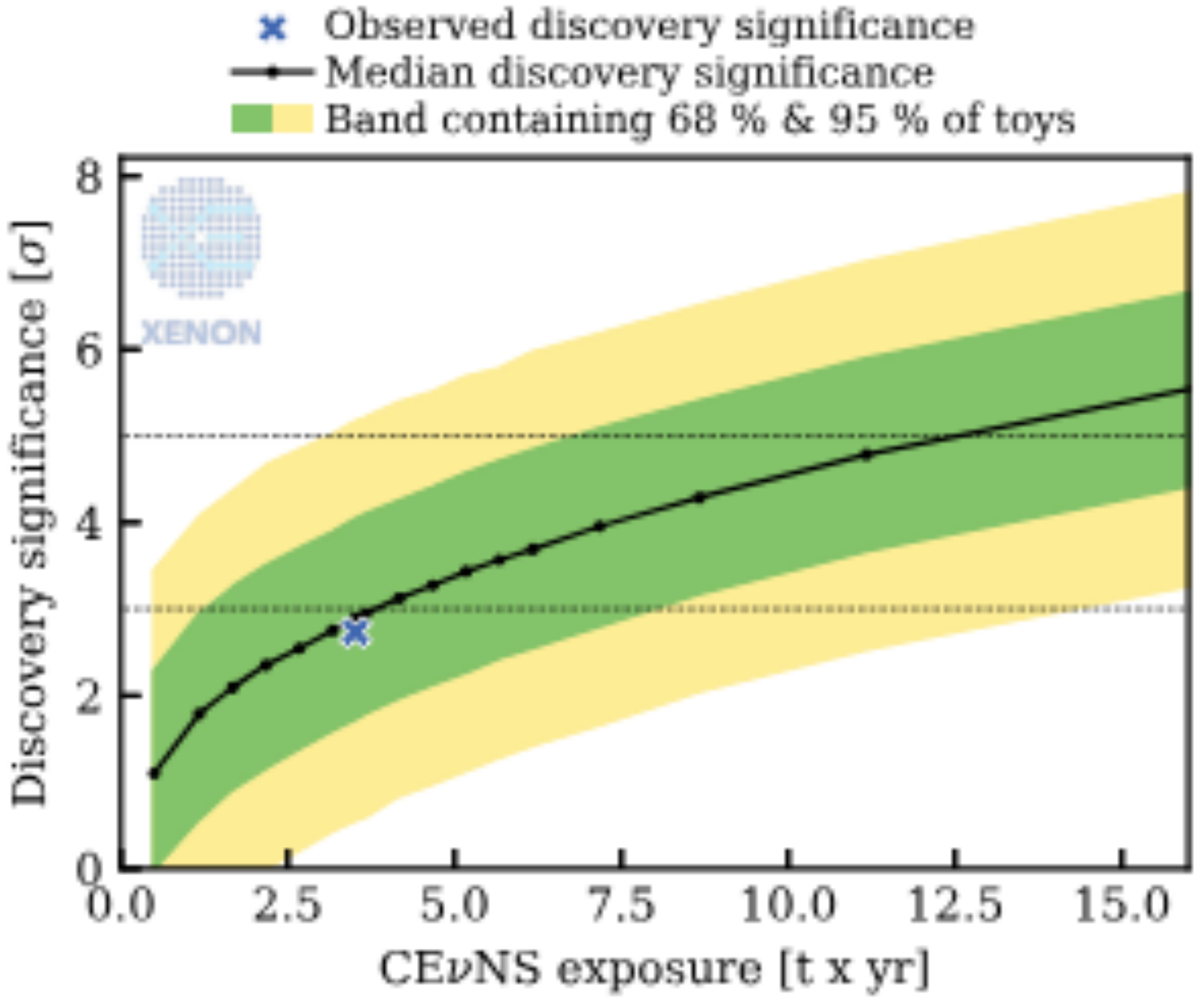


Publication in preparation



XENONnT measures the CEvNS signal in Xe from solar ^{8}B neutrinos for the first time!



With more exposure, we expect to measure the solar ^{8}B neutrino signal at higher significance and to better constrain the ^{8}B neutrino flux

The background-only hypothesis is disfavored at 2.73 σ

The NEON Collaboration

Active Members of COSINE and NEOS

IBS Center for Underground Physics (CUP) IBS School, University of Science and Technology (UST)	박병주, 전은주, 김경원, 김성현, 김영덕, 고영주, 이서현, 이인수,이현석, 이현수, 이재승, 오유민
Seoul National University	최재진, 김선기
Korea Atomic Energy Research Institute	김진유
Chung-Ang University	고병철, 하창현

Past one year activity of NEON

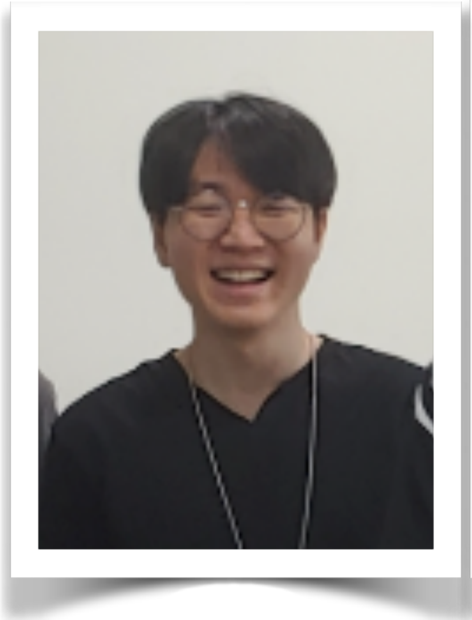
Publications

- First Direct Search for Light Dark Matter Using the NEON Experiment at a Nuclear Reactor, e-Print: 2407.16194
- Exclusion of the Cosmological Triangle in Reactor-Based Search for Axion-Like Particles, e-Print:2406.06117
- Upgrade of NaI(Tl) crystal encapsulation for the NEON experiment, e-Print: 2404.03691
- Waveform Simulation for Scintillation Characteristics of NaI(Tl) Crystal, *Nucl.Instrum.Meth.A 1065 (2024) 169489*
- Exploring coherent elastic neutrino-nucleus scattering using reactor electron antineutrinos in the NEON experiment, Eur.Phys.J.C 83 (2023) 3, 226

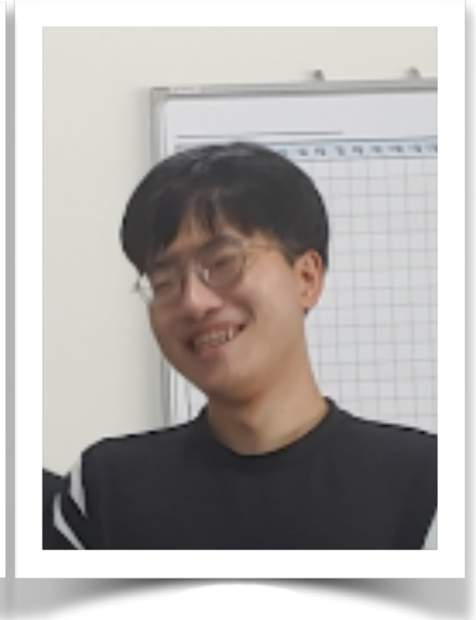
Milestones

- **Stable Operations (exposure~11,000 kg · day)**
- **Finished Two Analyses (Two Ph.D.)**
- **Identification of External Background components (Radon-related)**

Doctor! Doctor!



박병주



최재진

NaI(Tl) crystal scintillators for *CEνNS*

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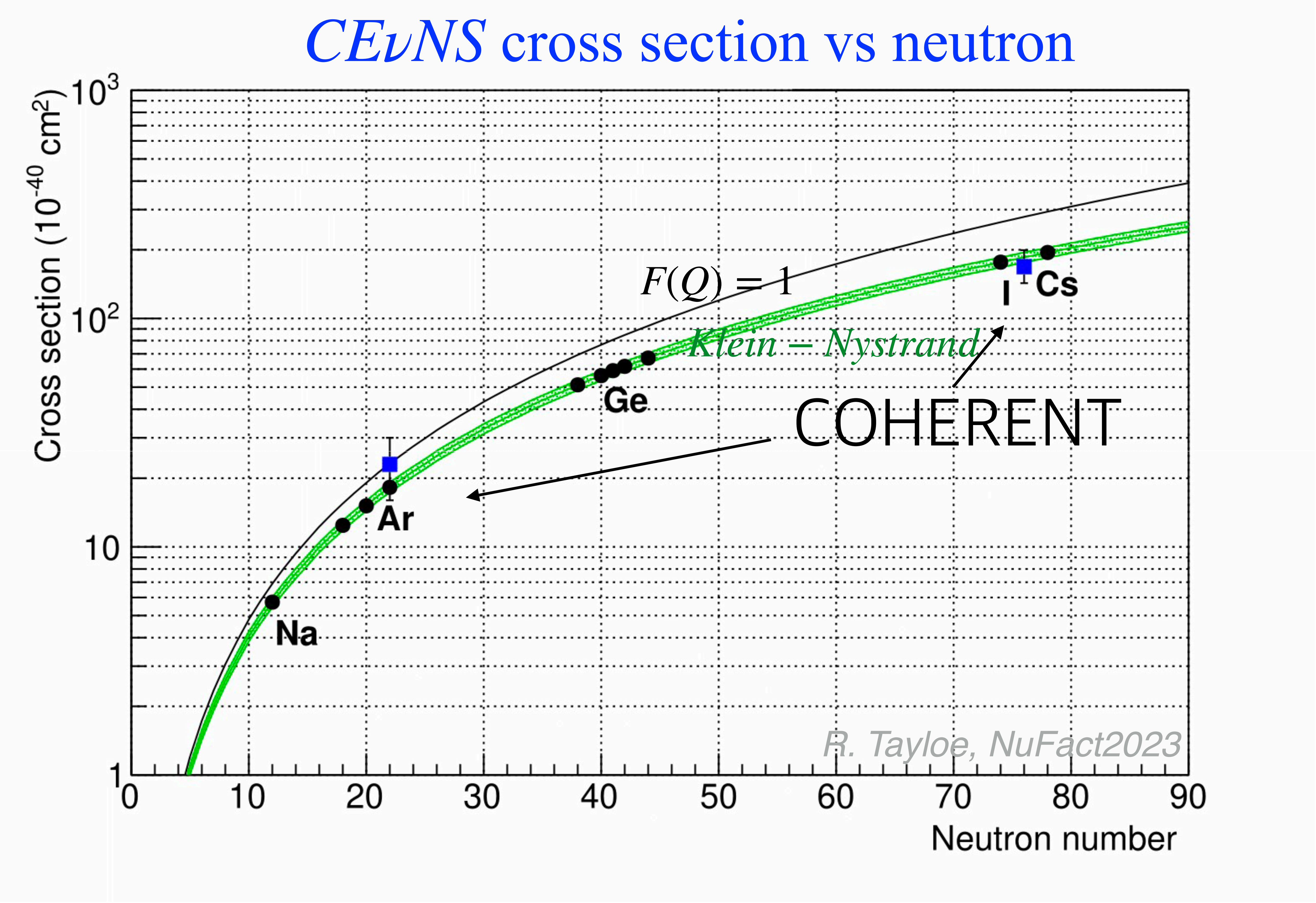

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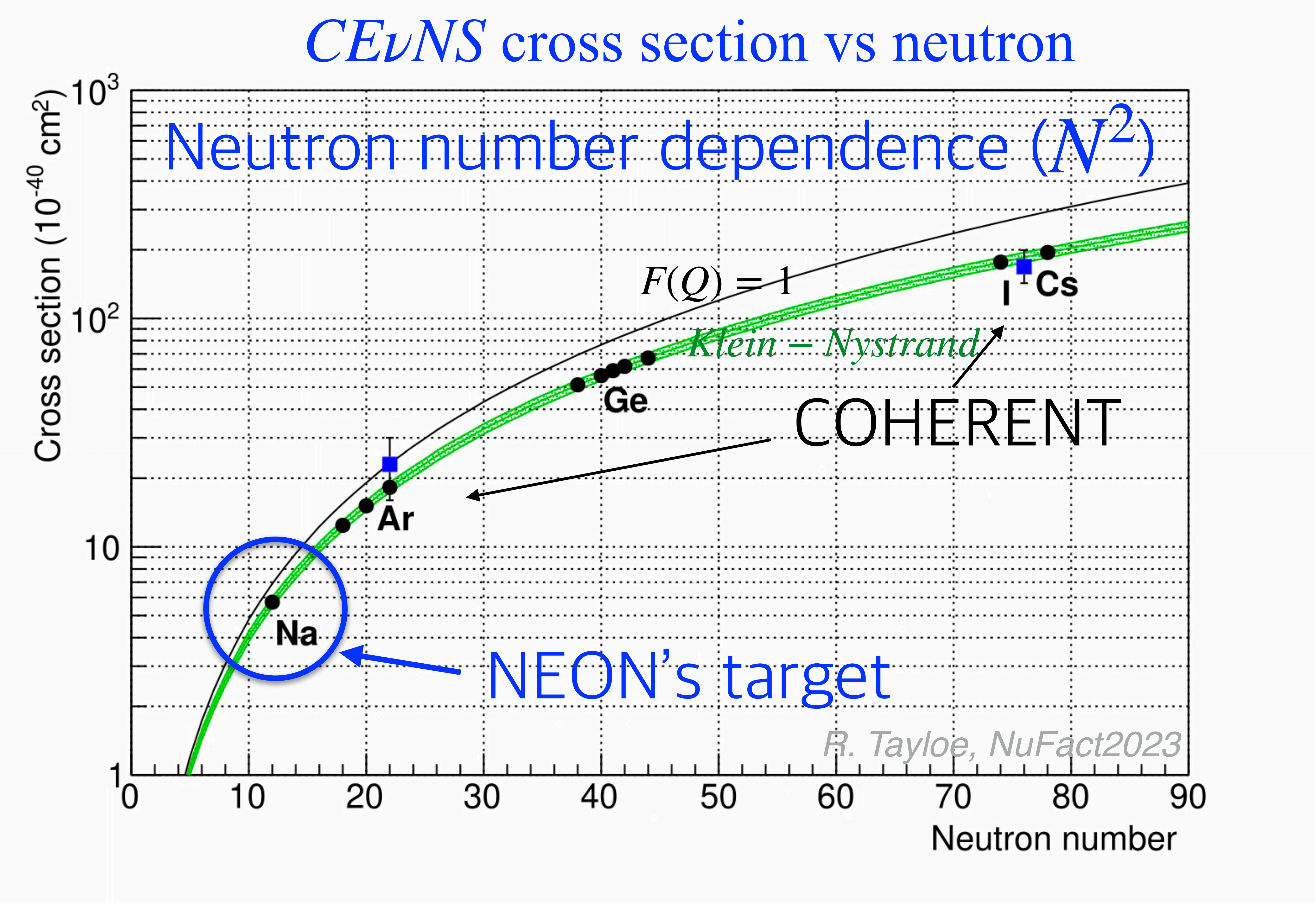
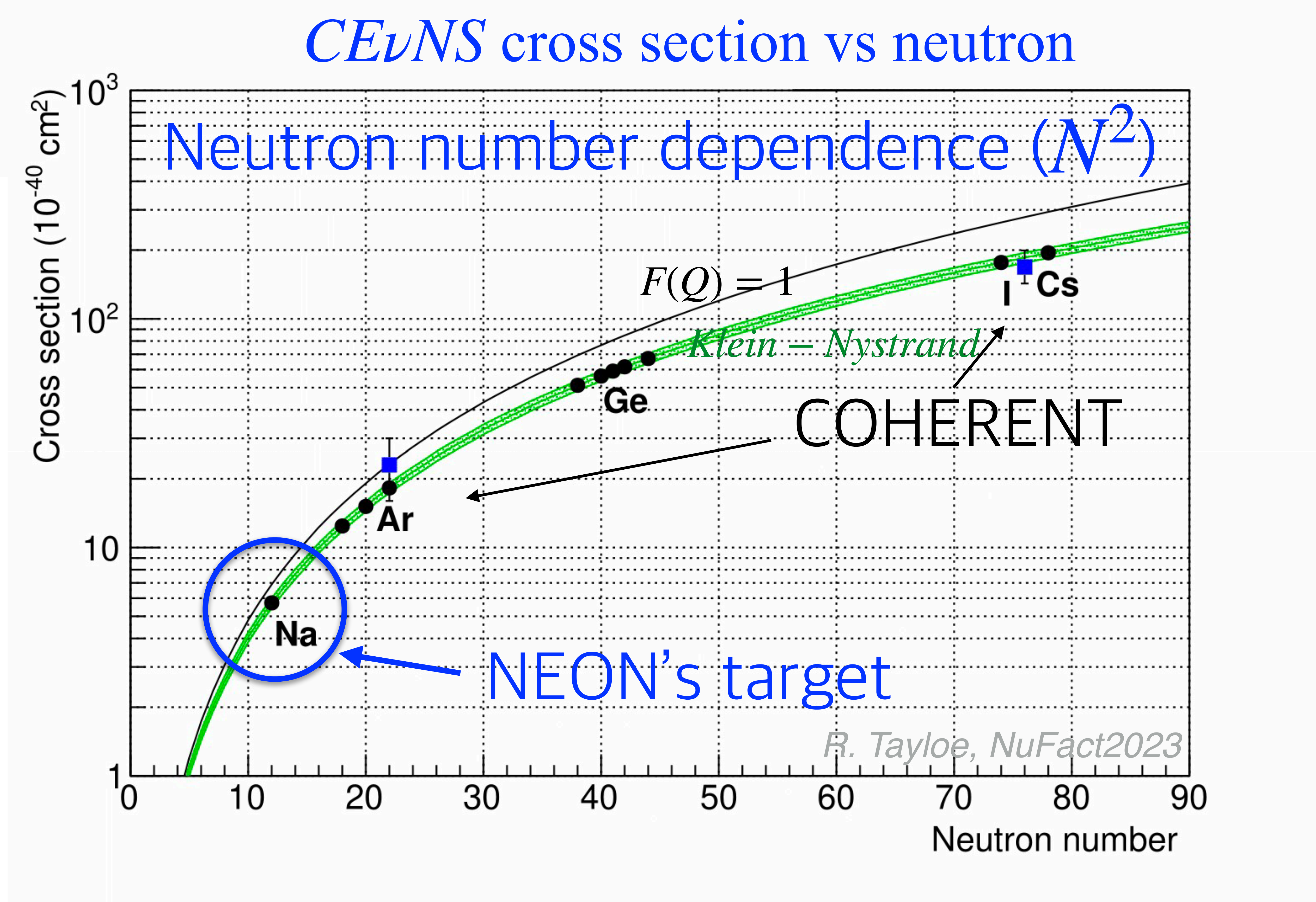


NaI(Tl) crystal scintillators for *CEνNS*

- Very high light output crystal
  - COSINE-100 measures 15 P.E. / keVee



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- Relatively large nuclear recoil of Na
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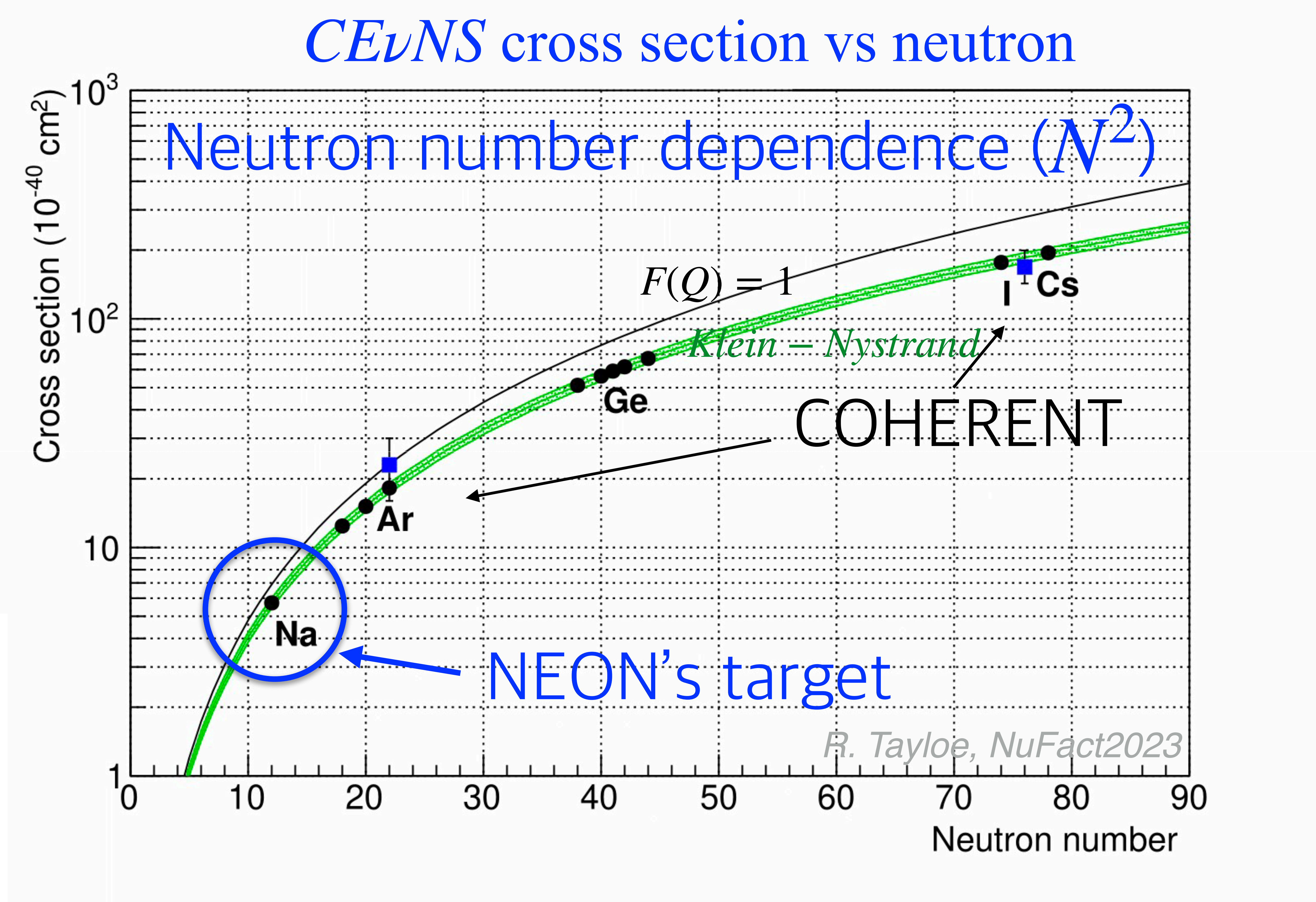
  - E.g. for 10 MeV ν, the max nuclear recoil energy is 8.7 keV on Sodium and 1.6 keV on Iodine



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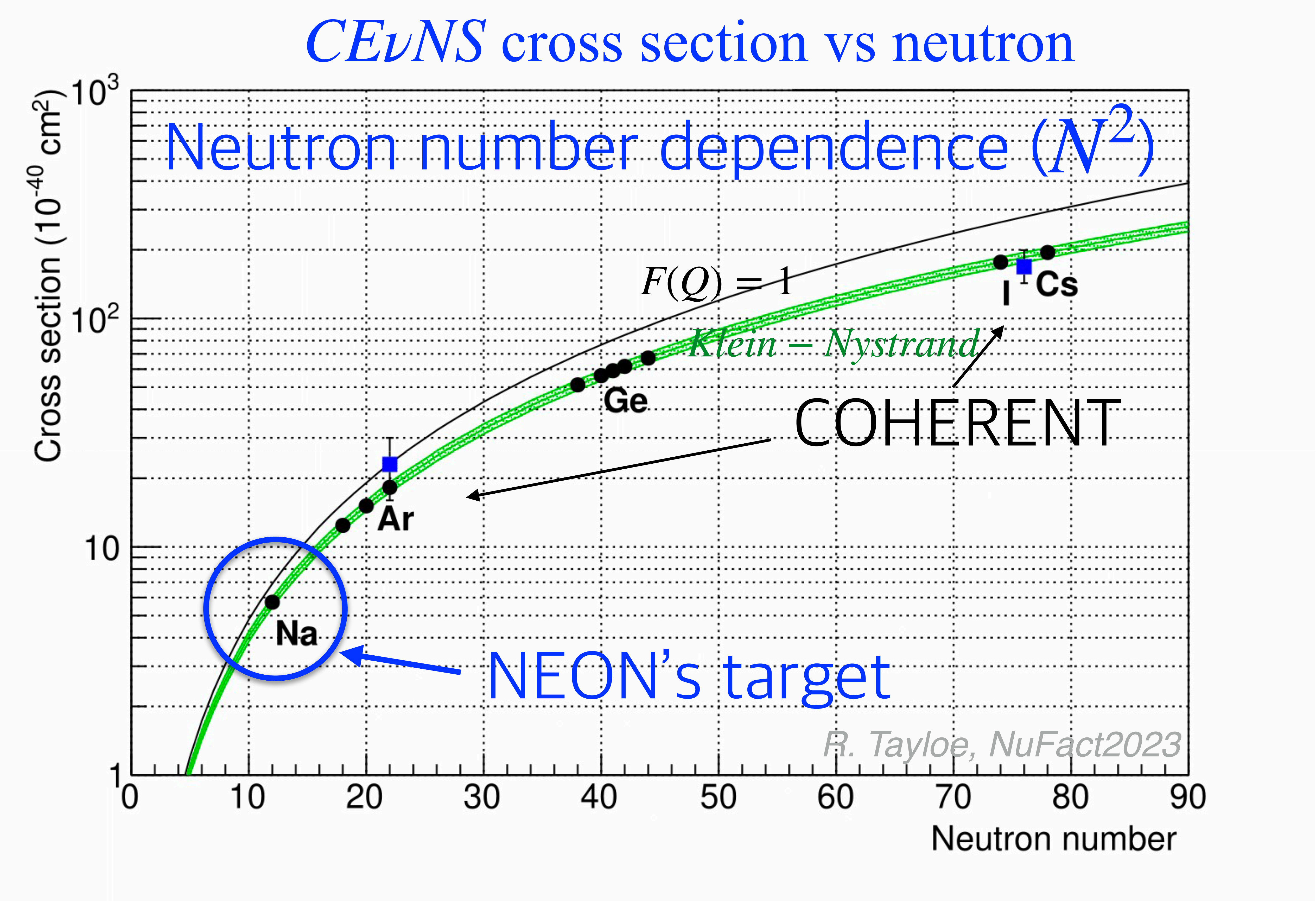
- Background under control and easily scalable
  - COSINE-100 shows 2.5 counts/day/kg/keV (internal origin) at 1 keV threshold.



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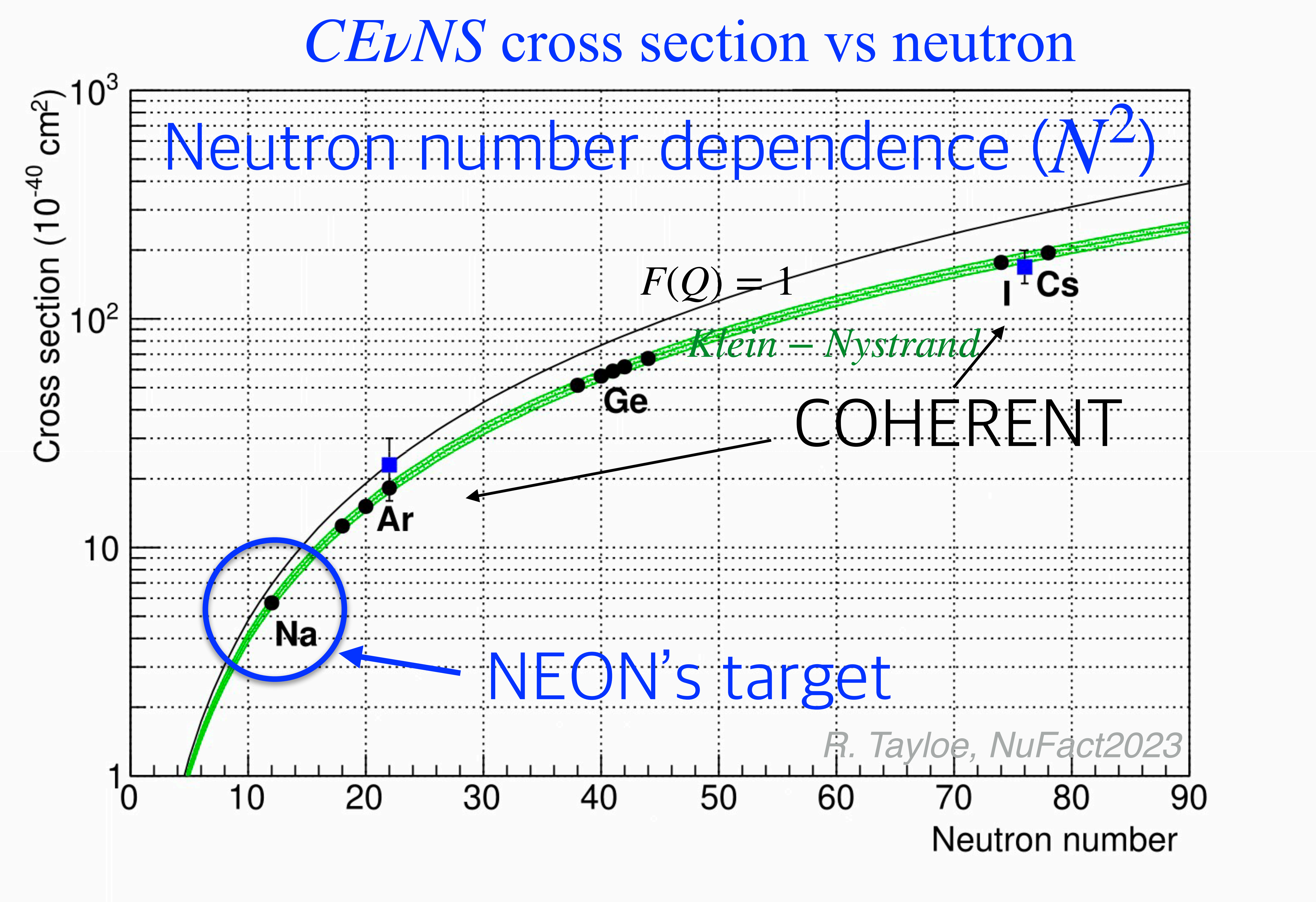

Natural Opportunities for *CEνNS*, Synergy with dark matter detection, and Possible new physics : However, 0.2 keVee threshold is required.

CEνNS Event Rate & Requirement on NaI(Tl)

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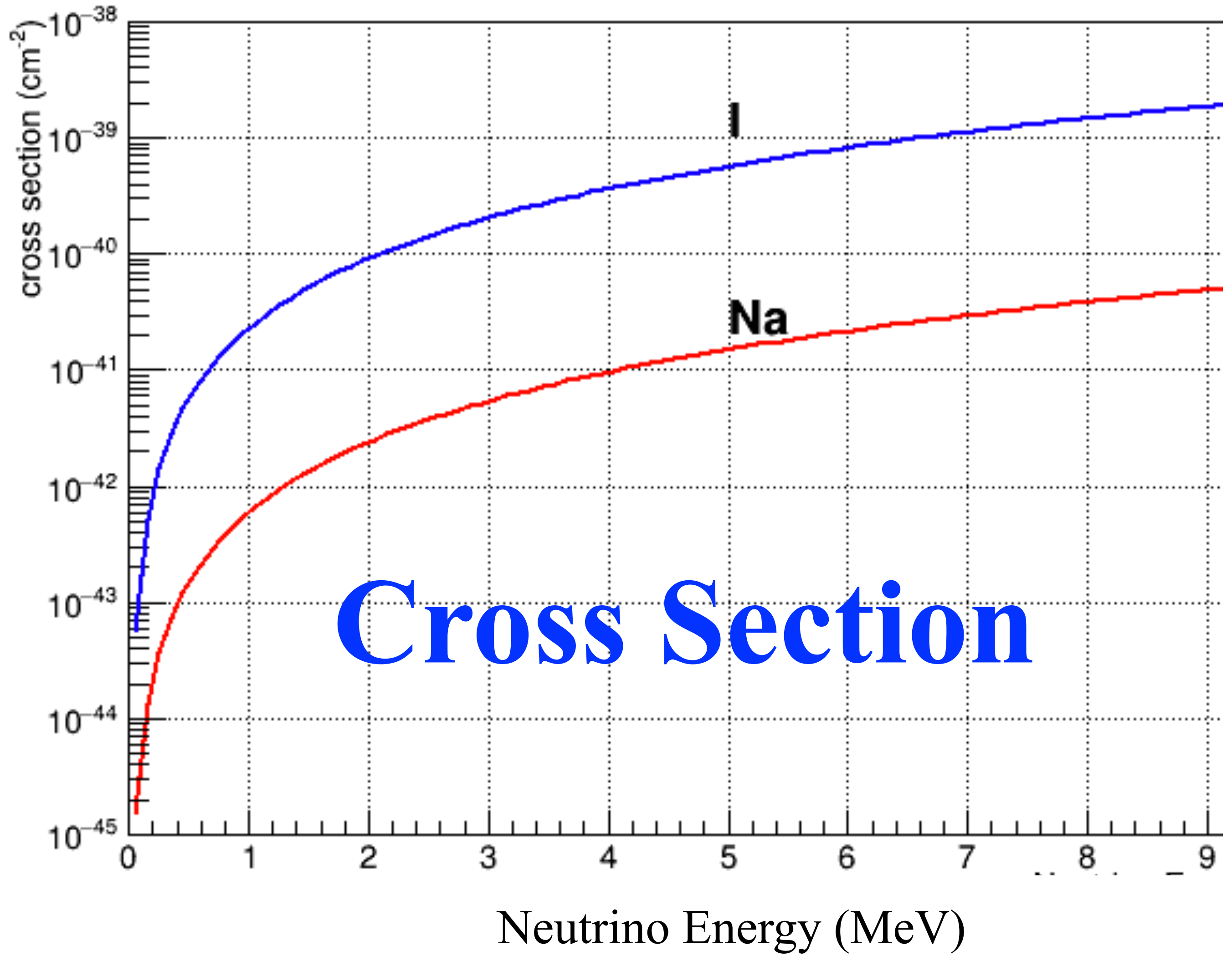

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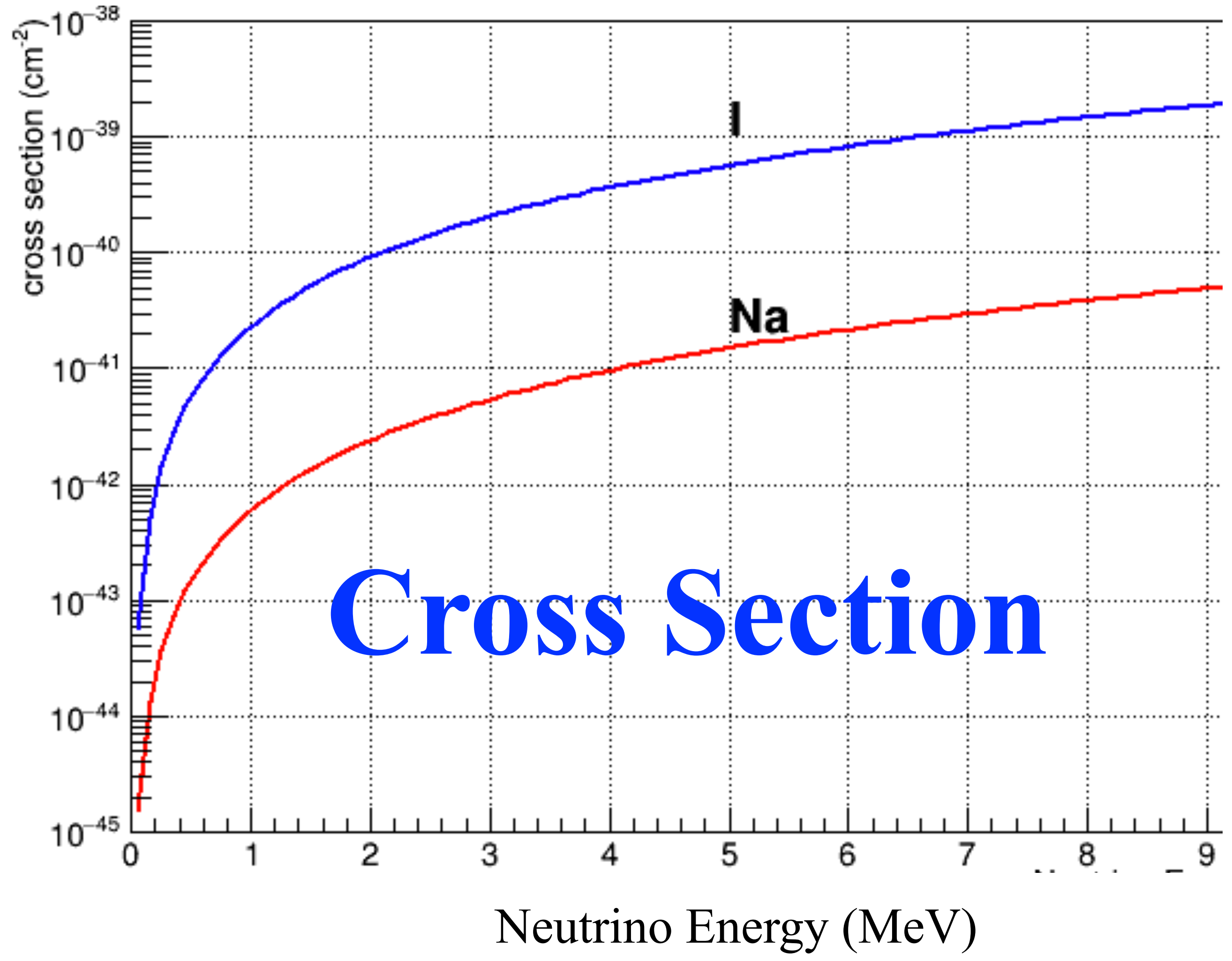

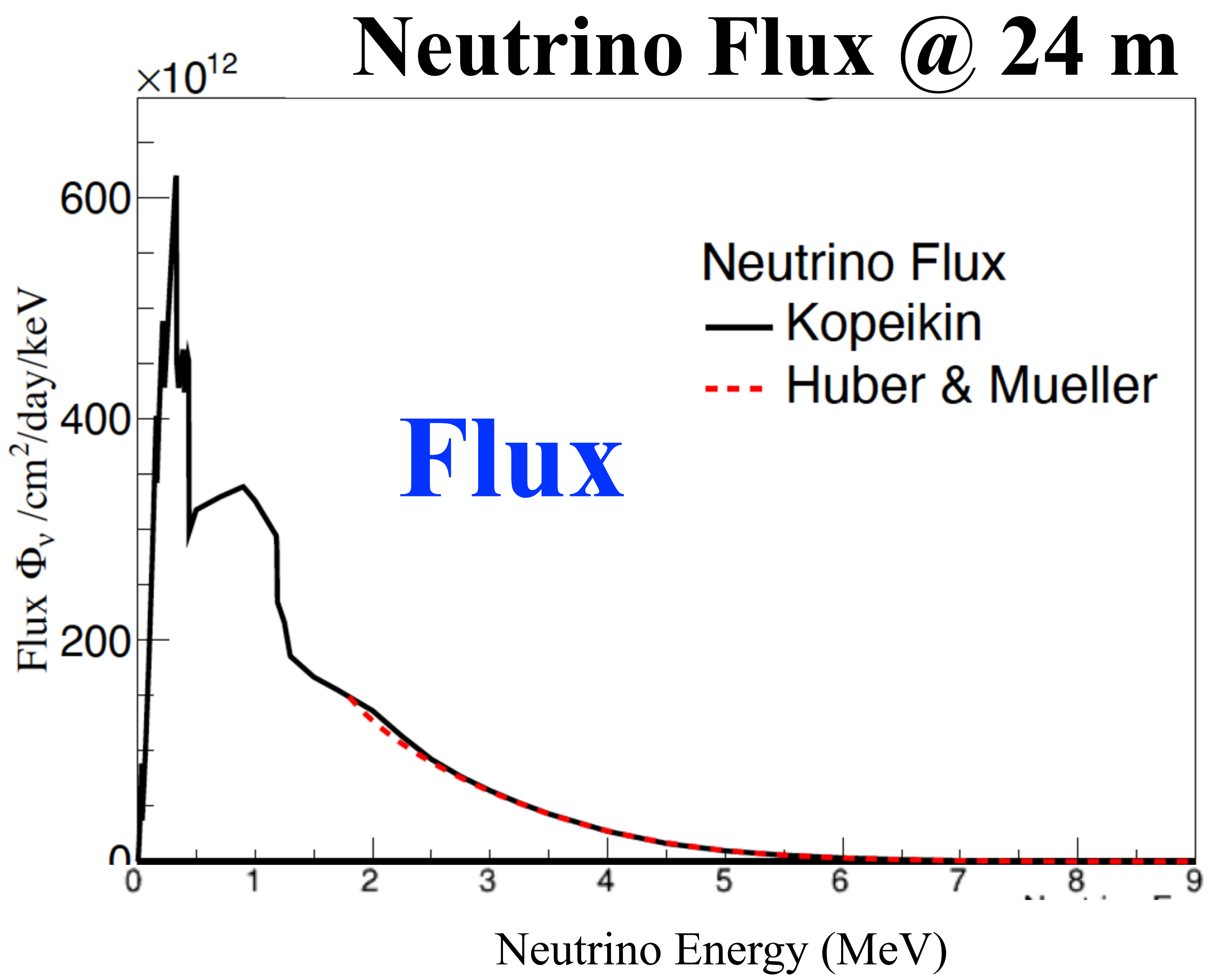

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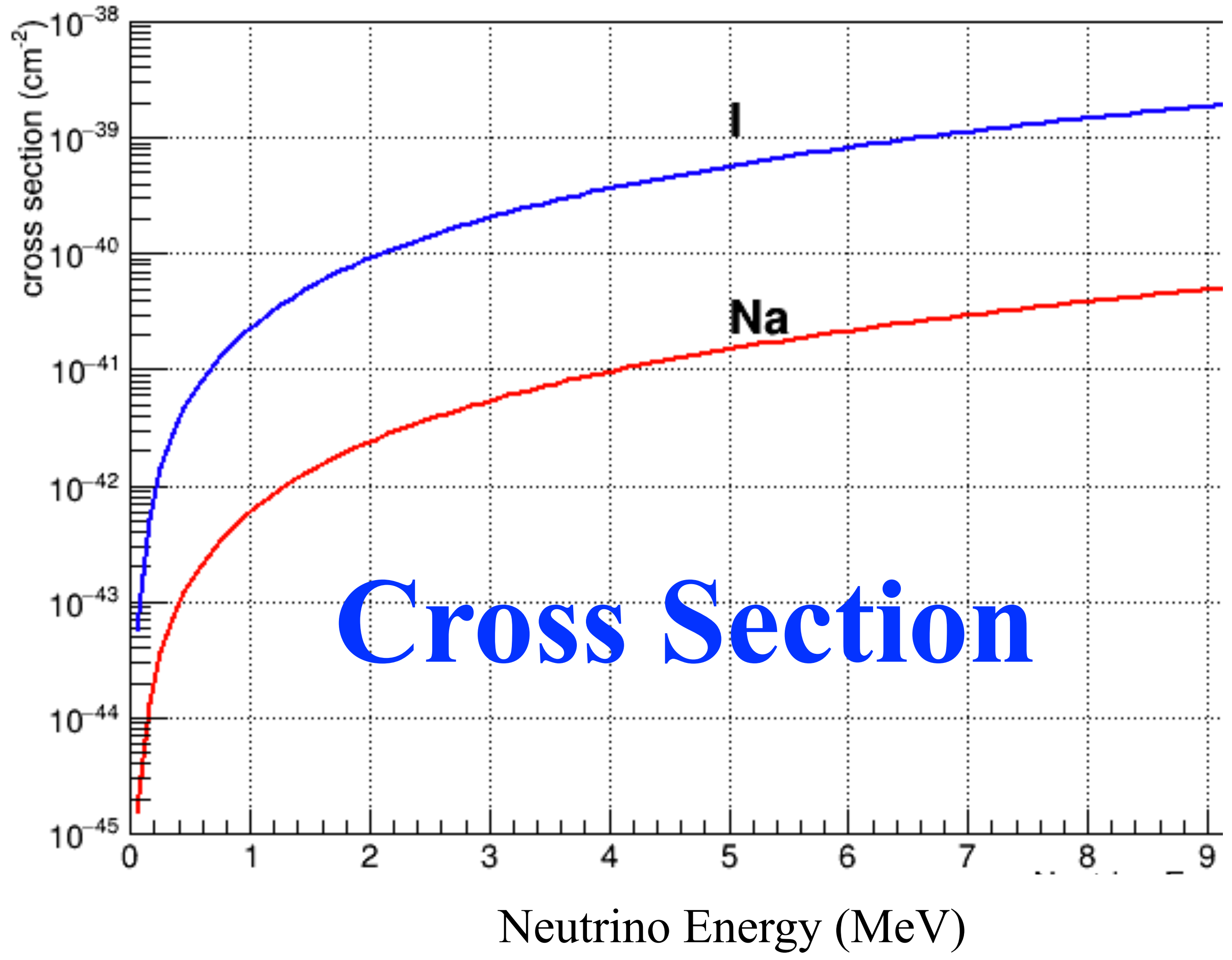
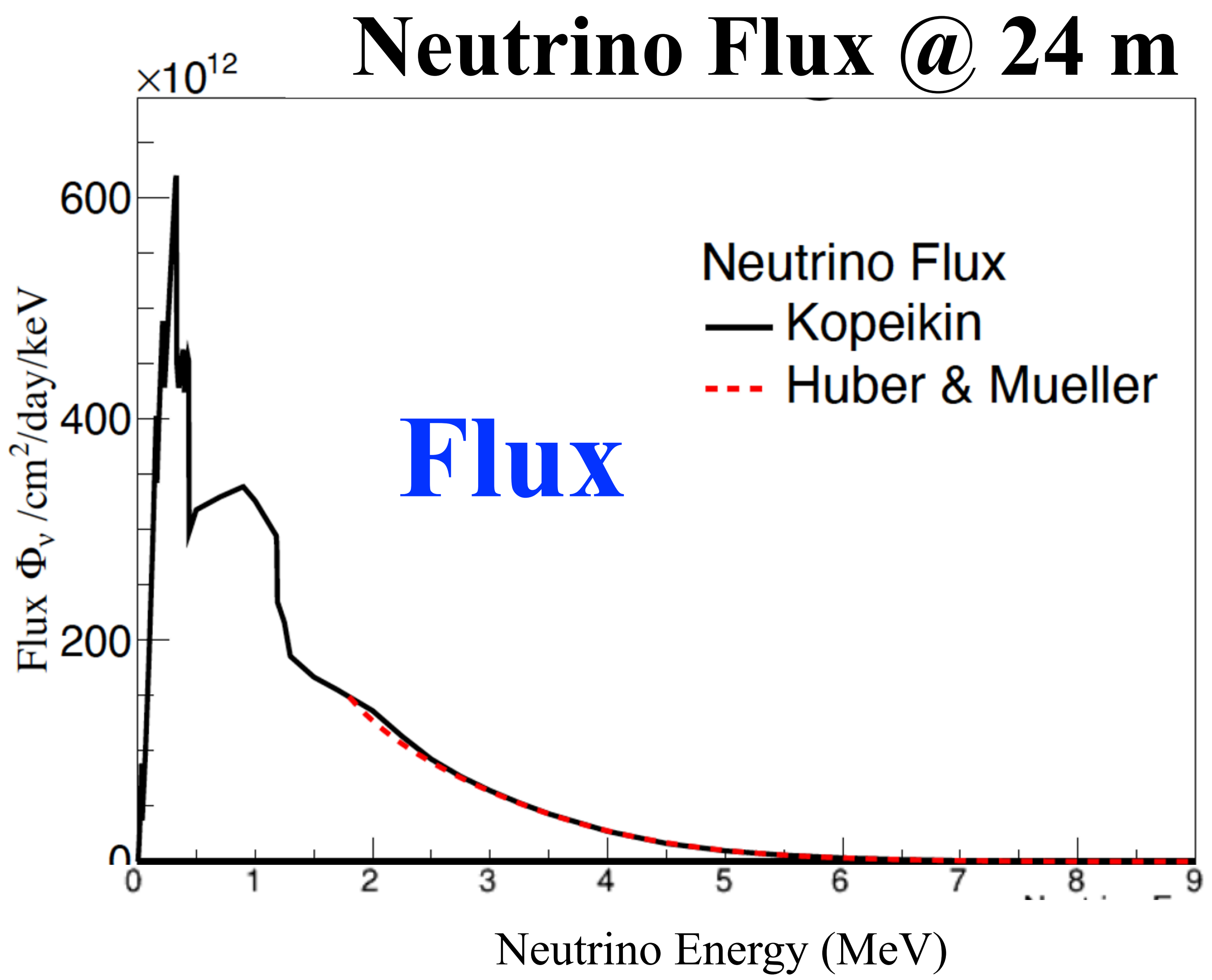
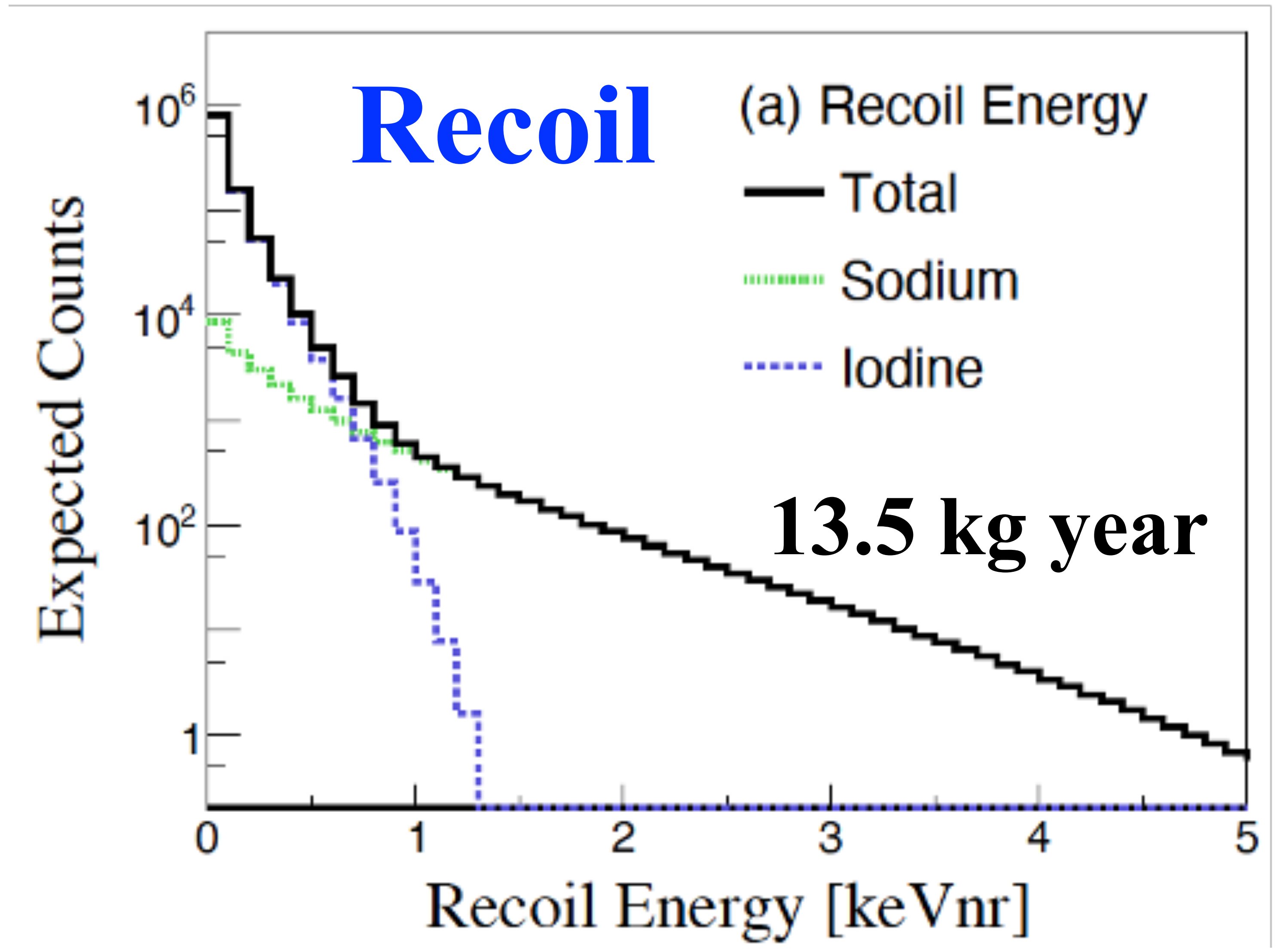
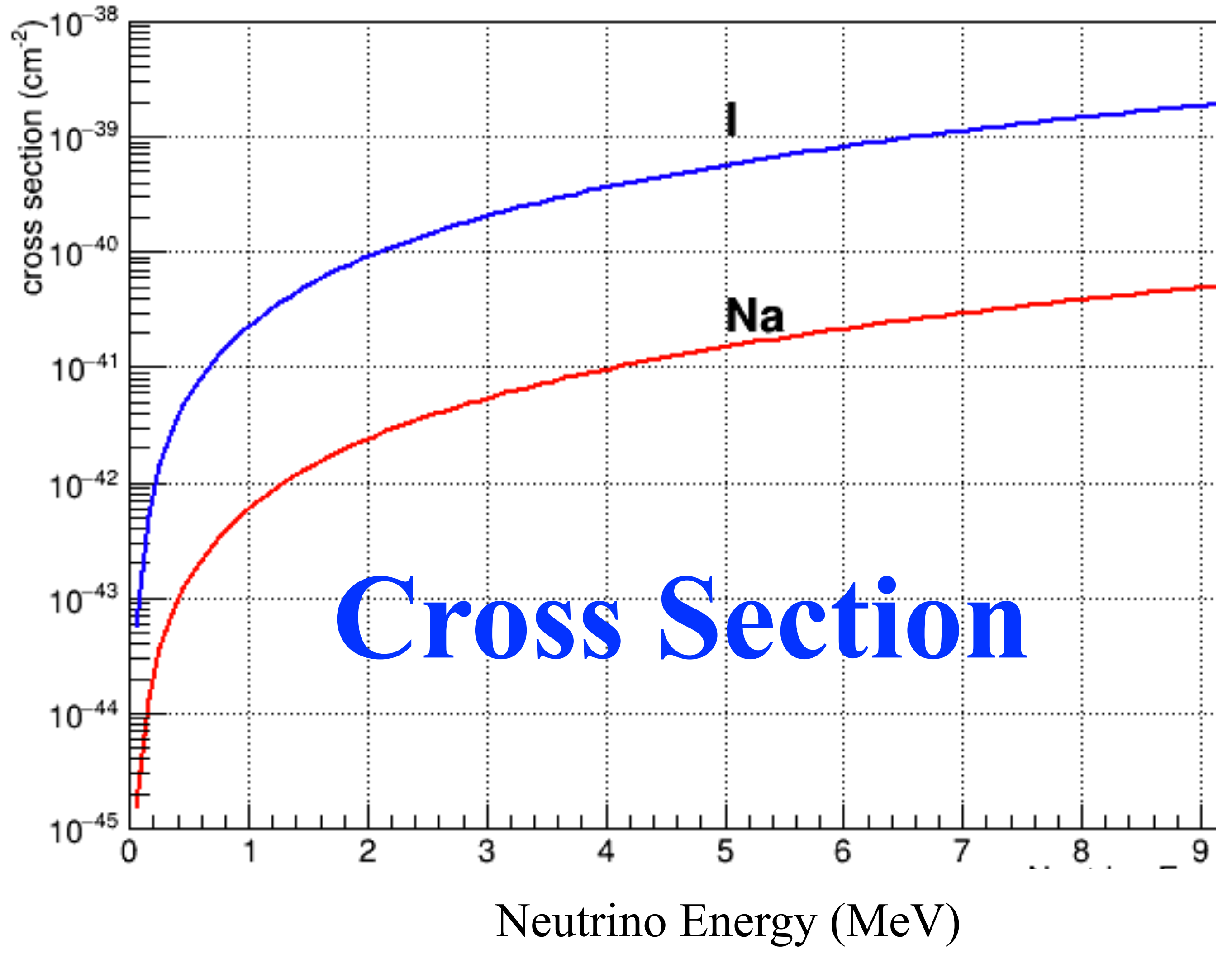




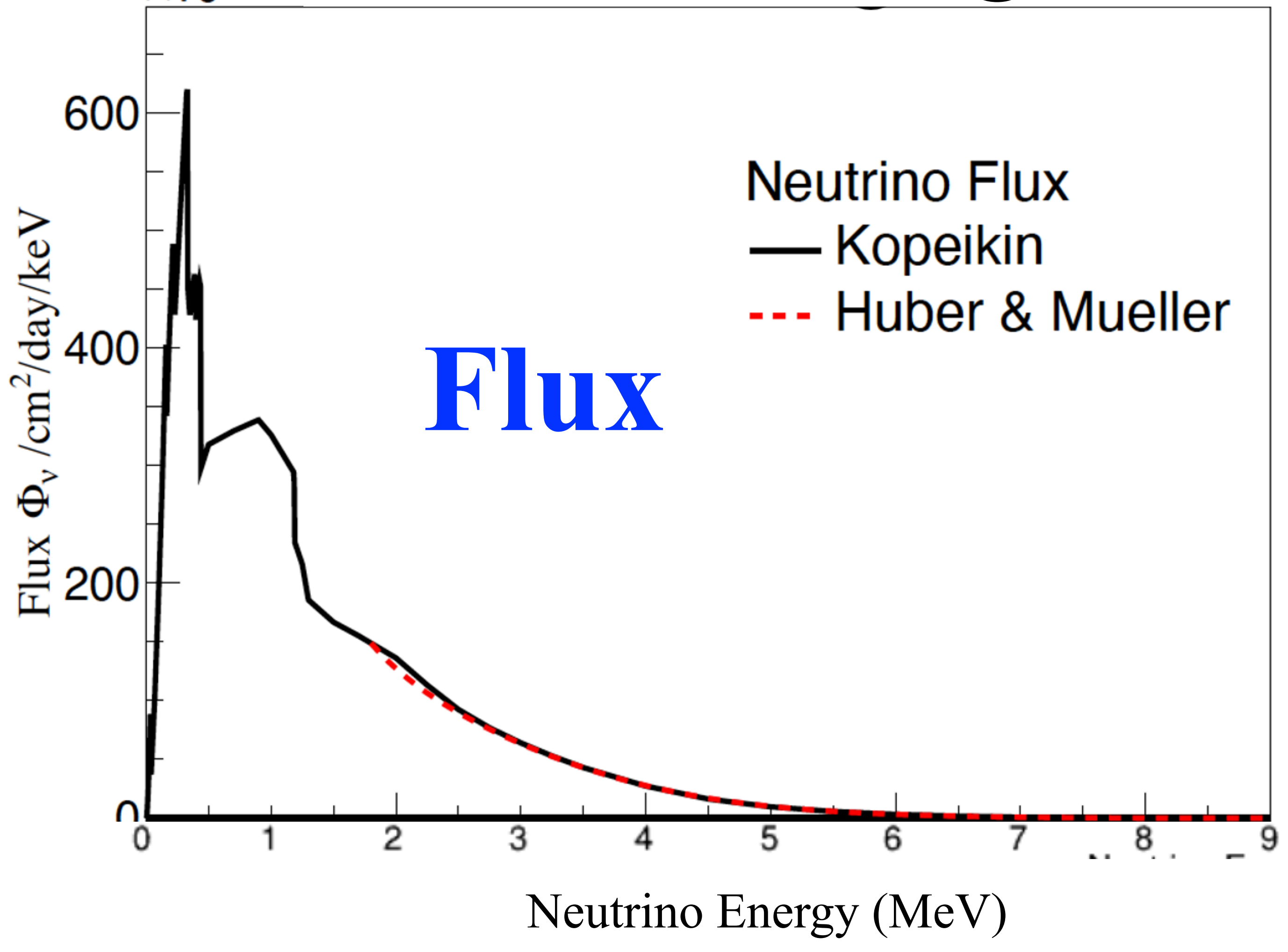


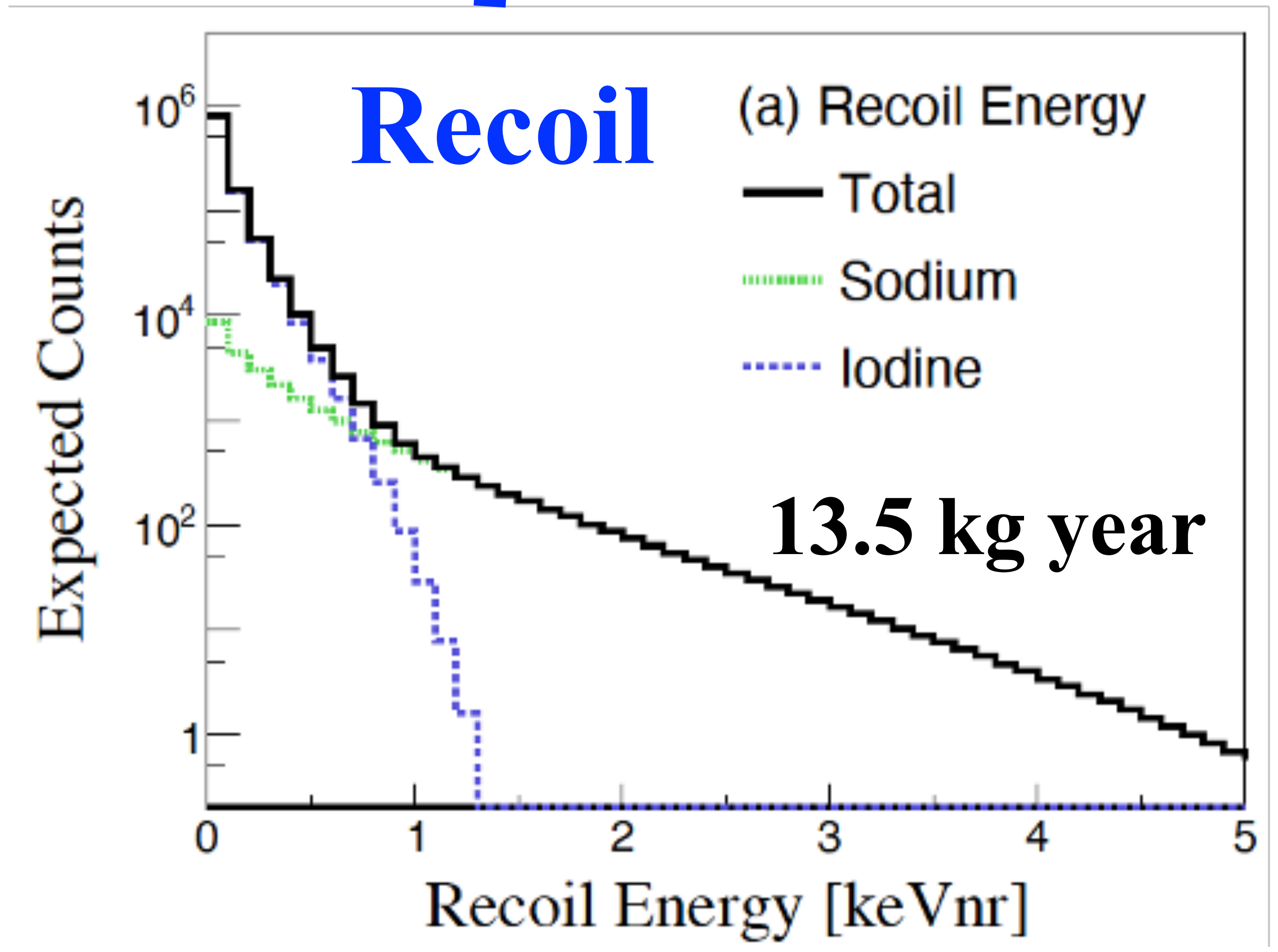
CEνNS Event Rate & Requirement on NaI(Tl)

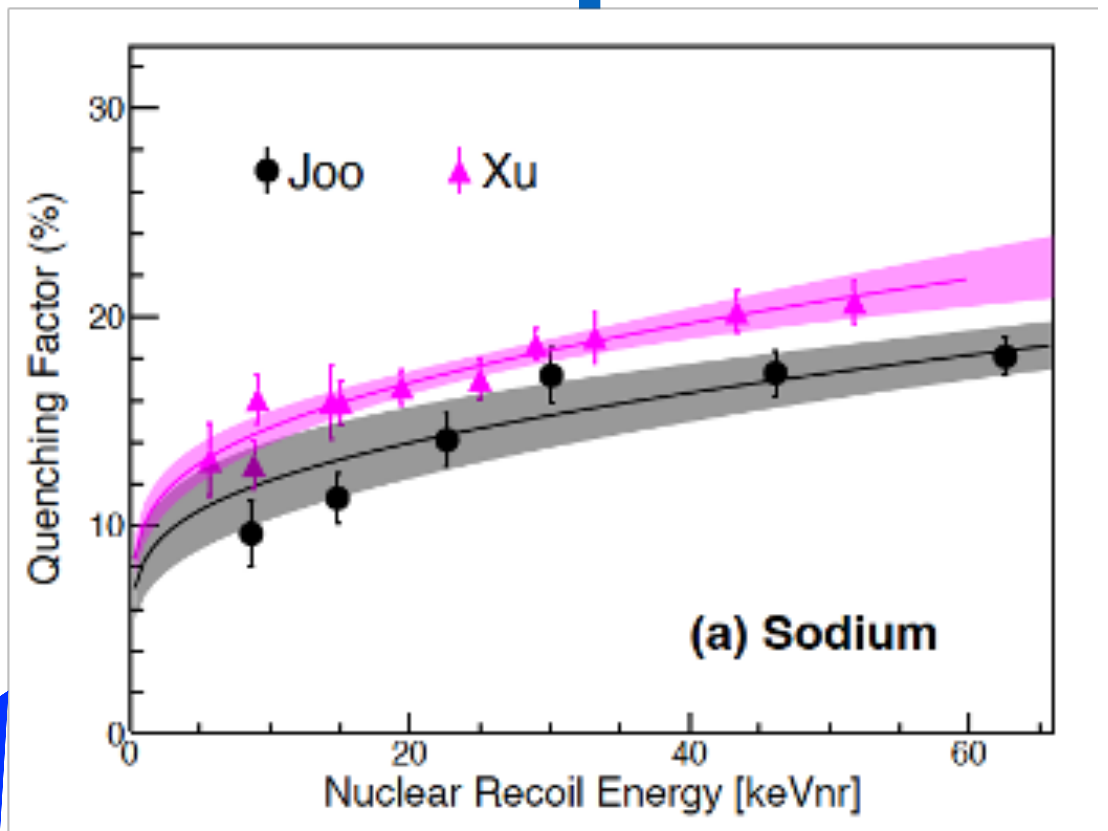
$$QF(E_{dep}) = \frac{E_{ee}}{E_{nr}} = \frac{E_{vis.}}{E_{dep.}}$$



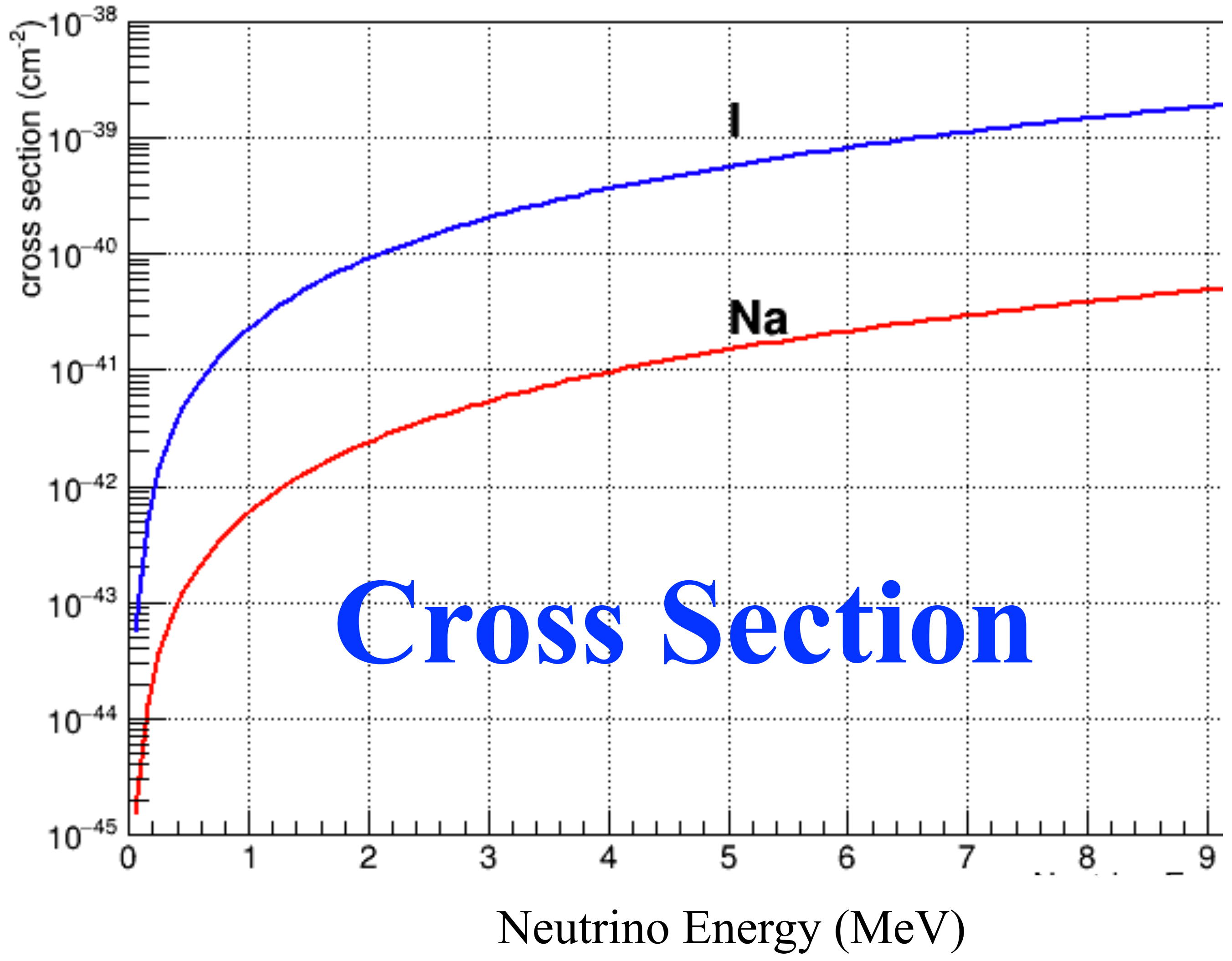
Neutrino Flux @ 24 m

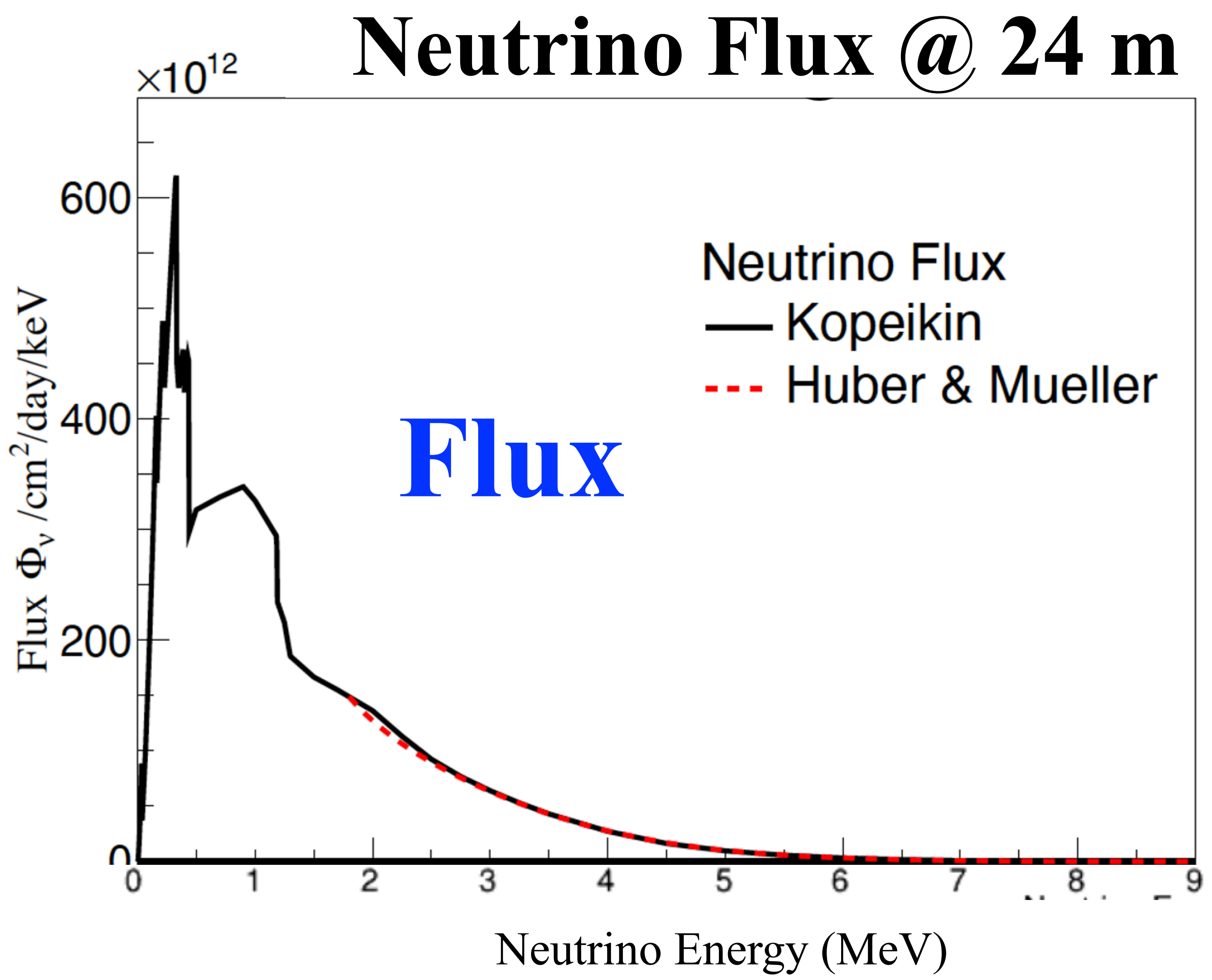


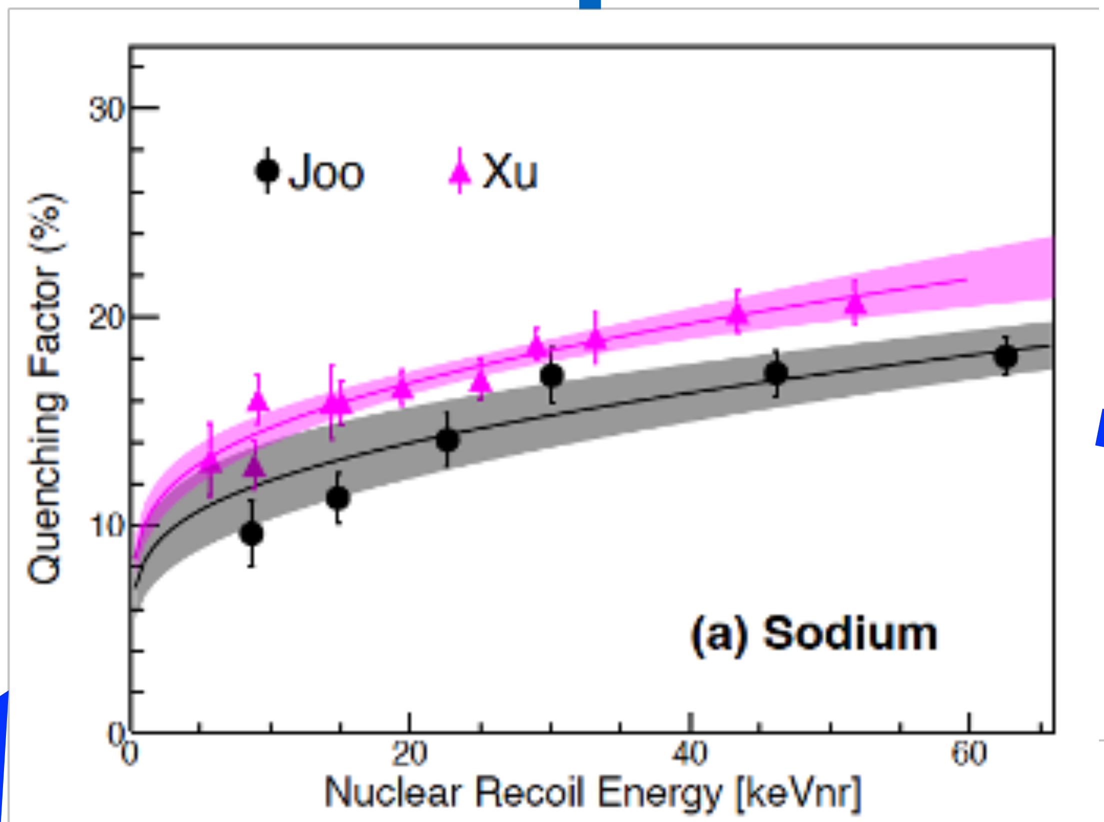




CEνNS Event Rate & Requirement on NaI(Tl)

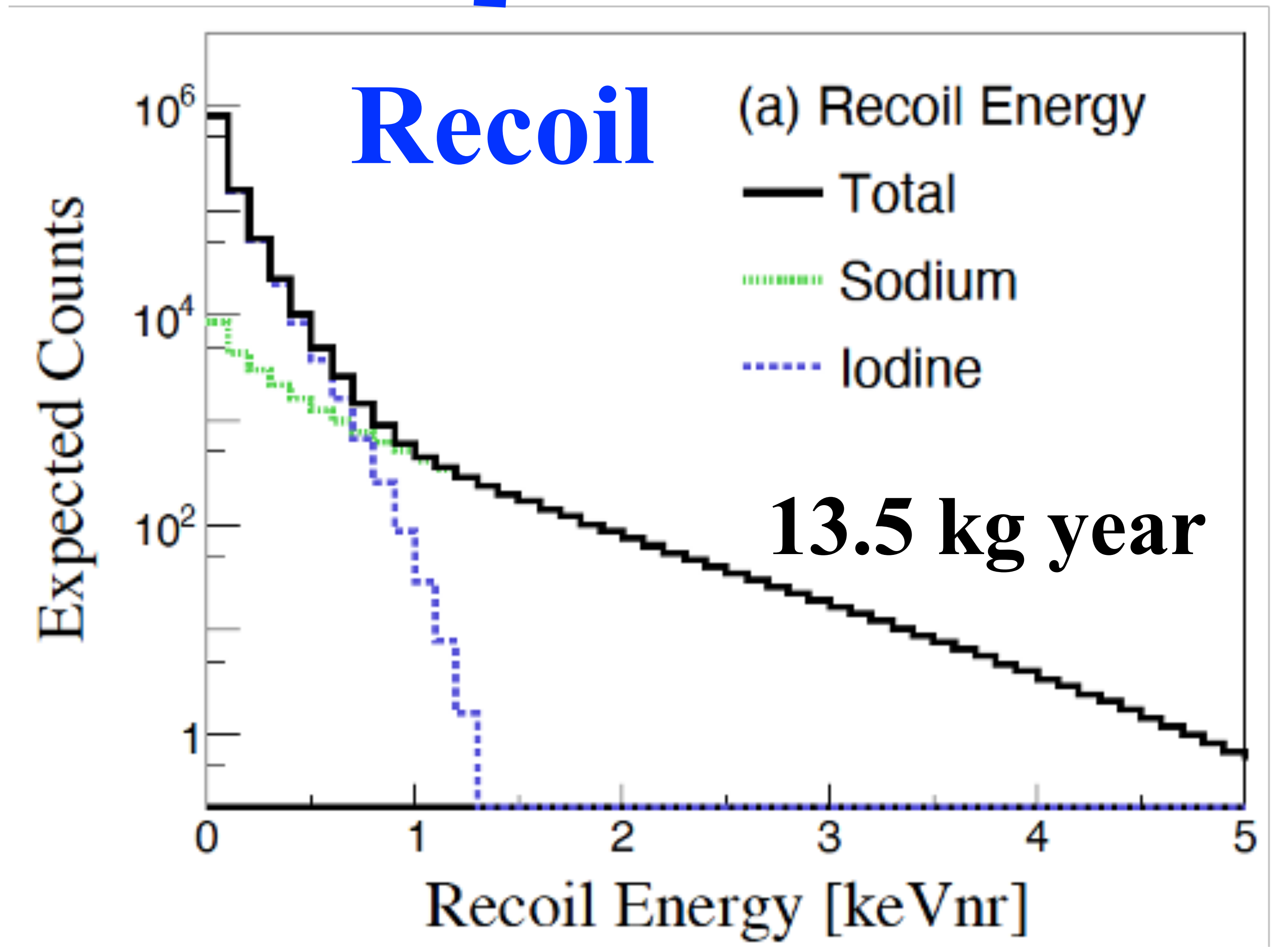


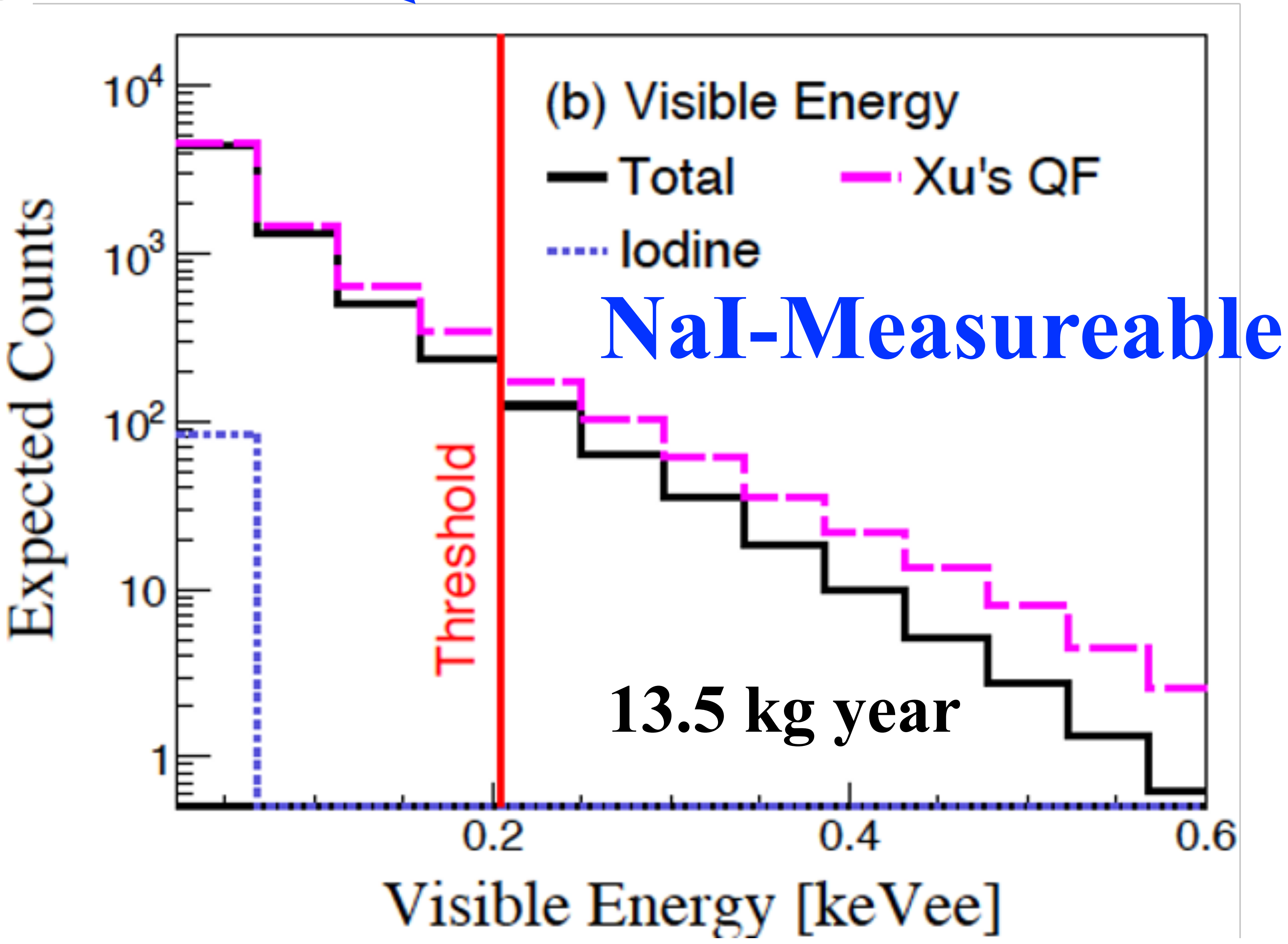




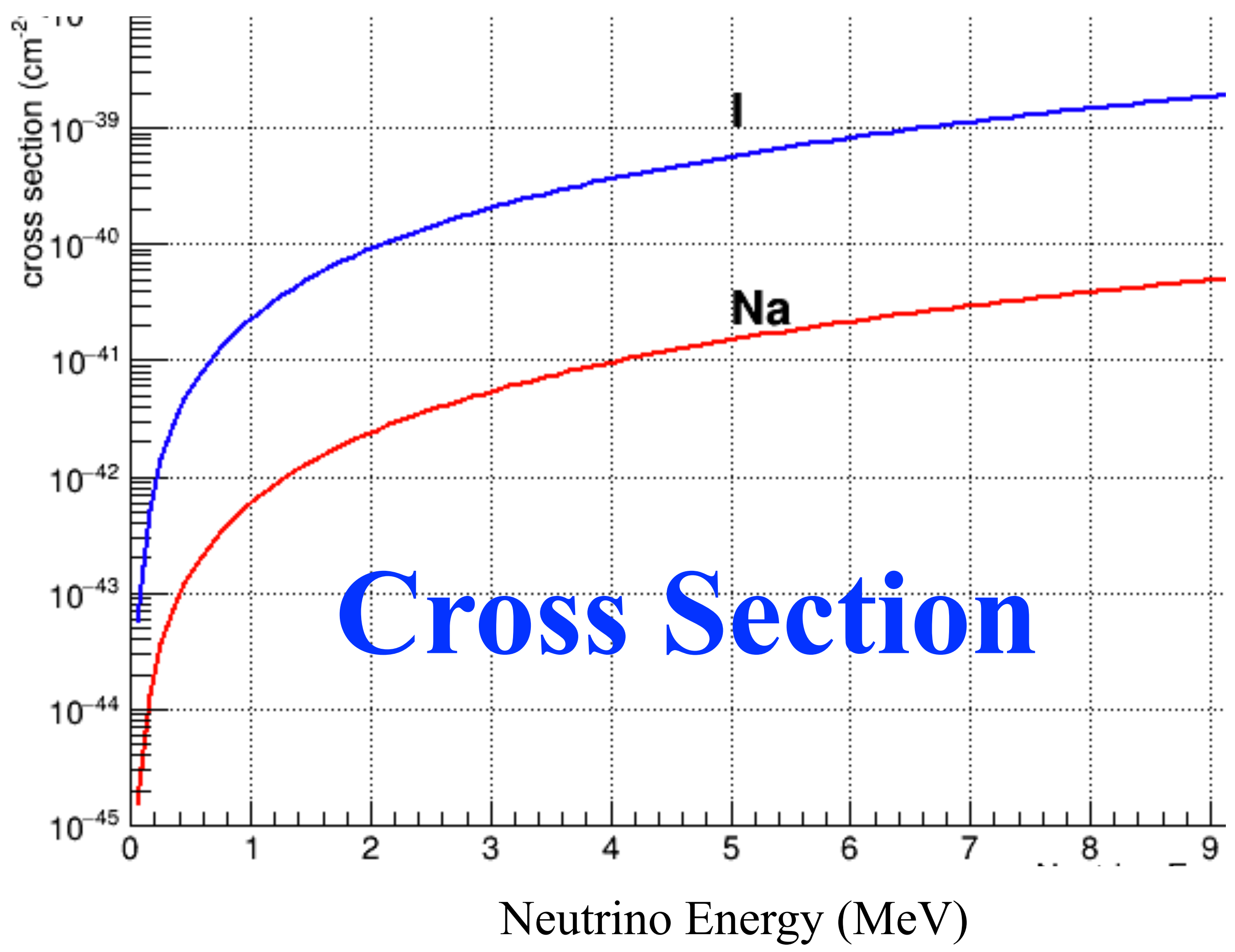
$$QF(E_{dep}) = \frac{E_{ee}}{E_{nr}} = \frac{E_{vis.}}{E_{dep.}}$$

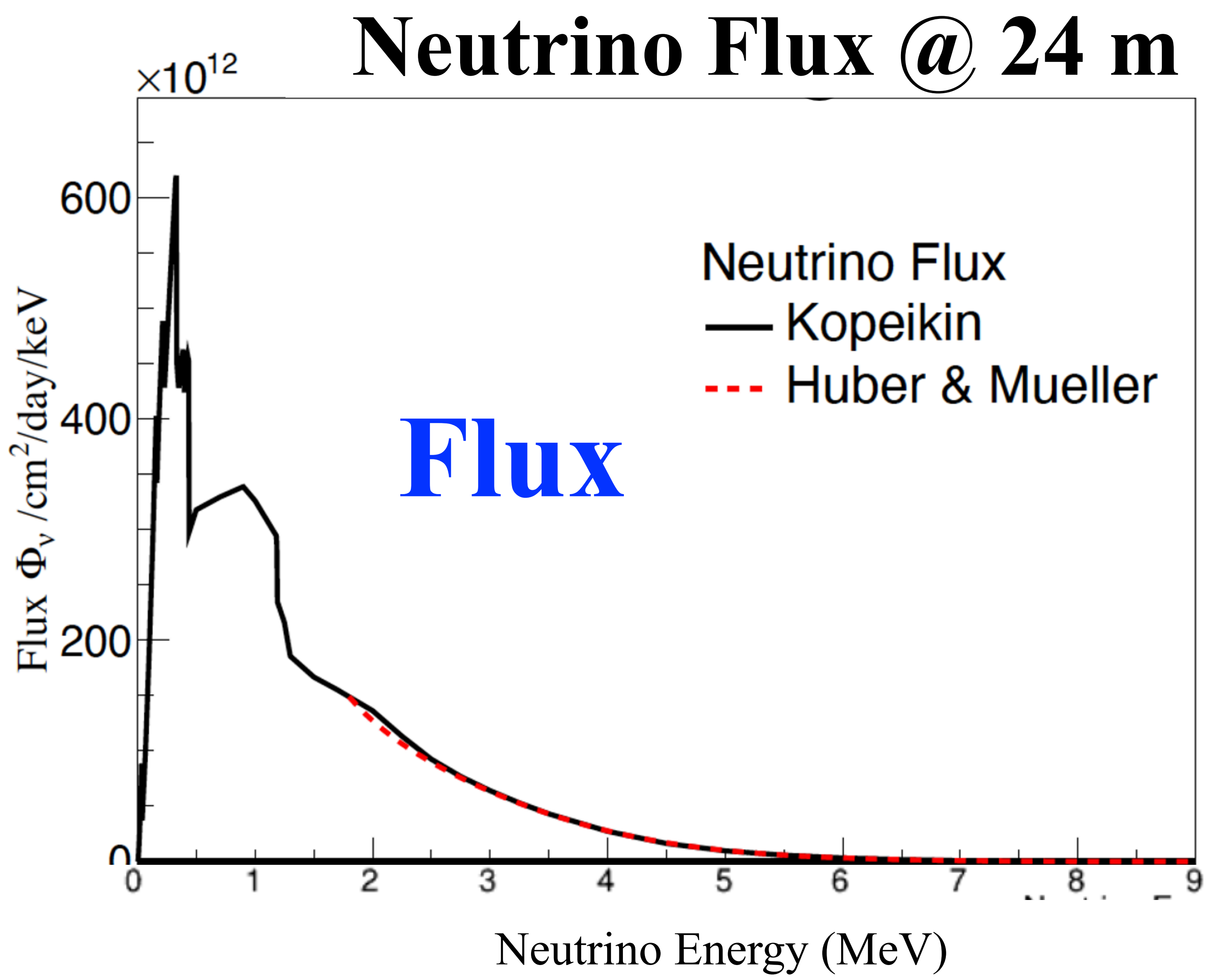
Iodine recoil
scintillation negligible

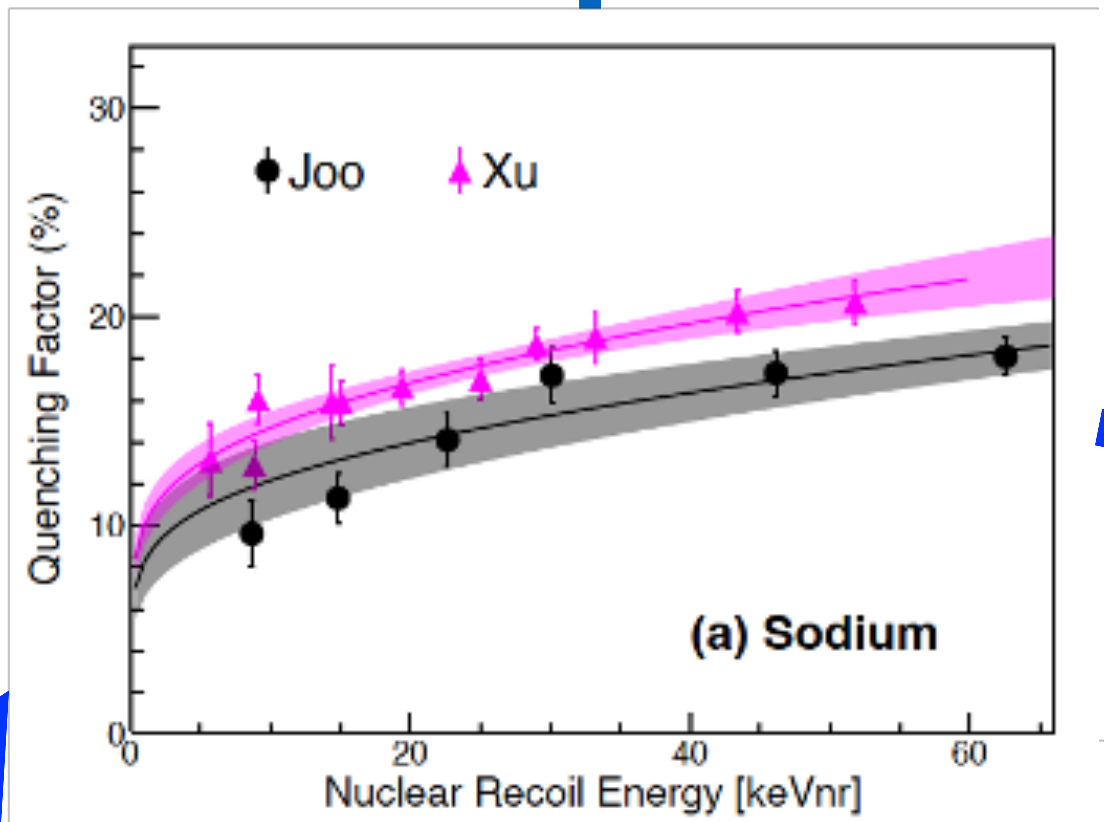




CEνNS Event Rate & Requirement on NaI(Tl)

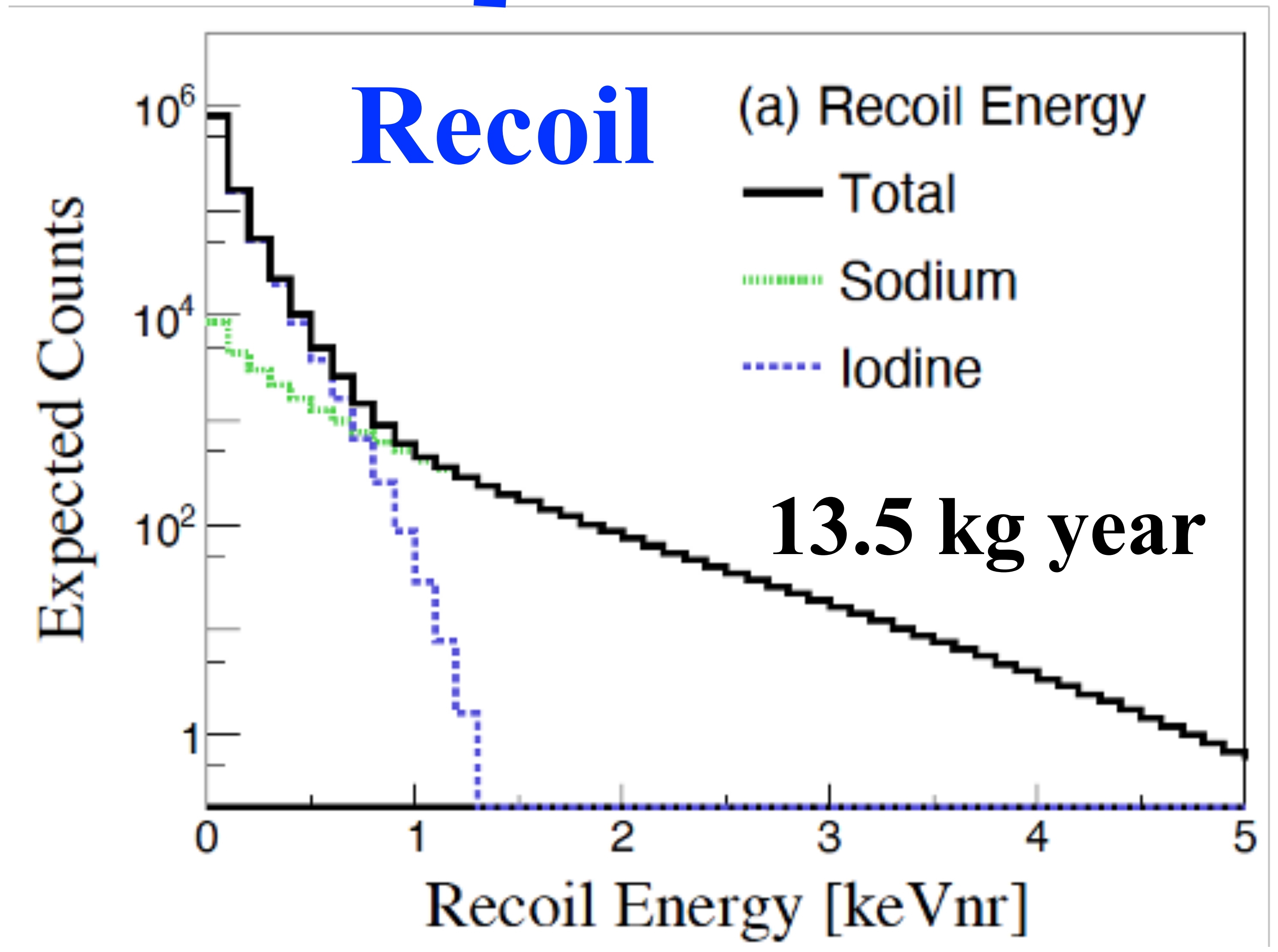


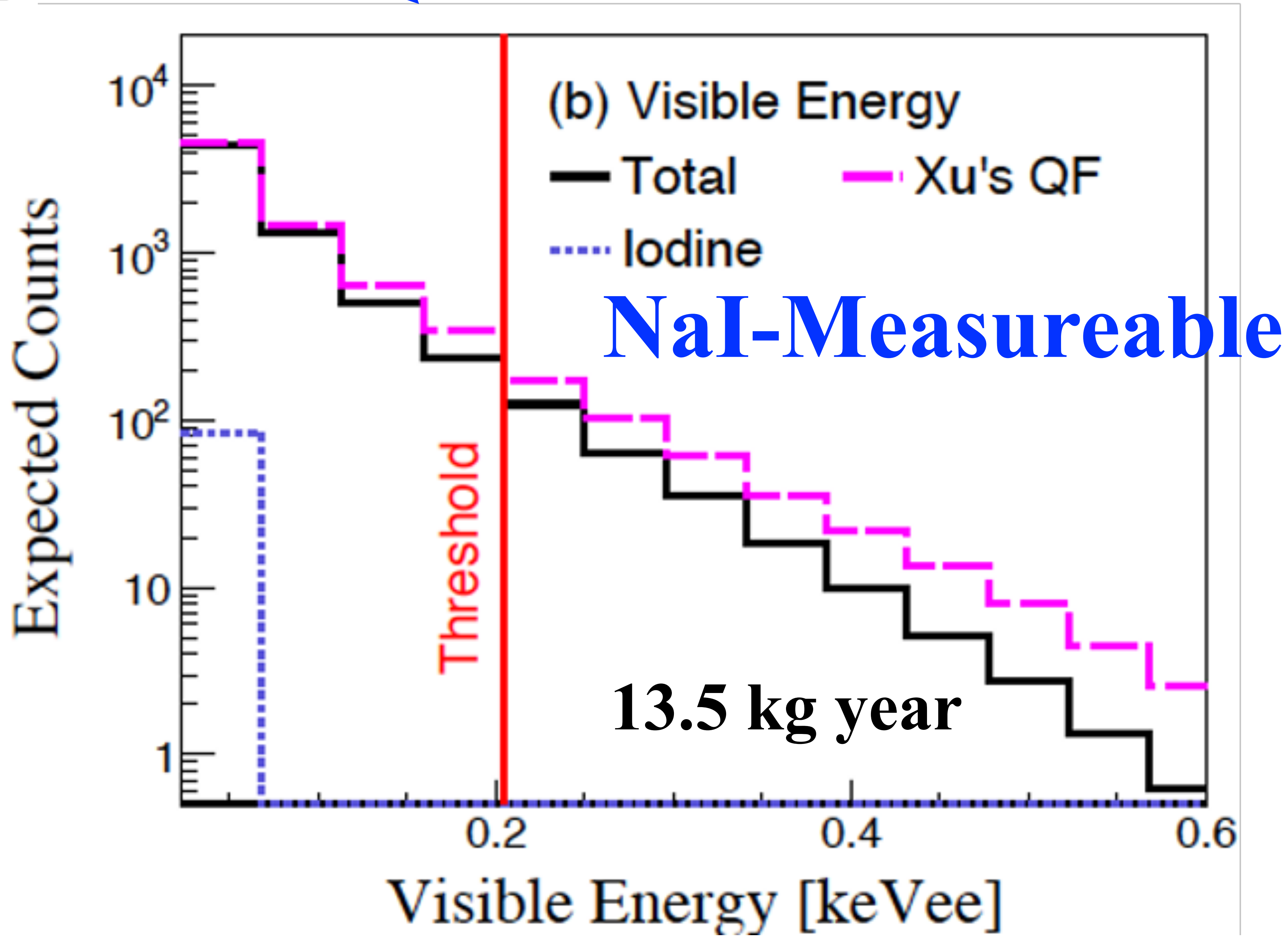




$$QF(E_{dep}) = \frac{E_{ee}}{E_{nr}} = \frac{E_{vis.}}{E_{dep.}}$$

Iodine recoil scintillation negligible



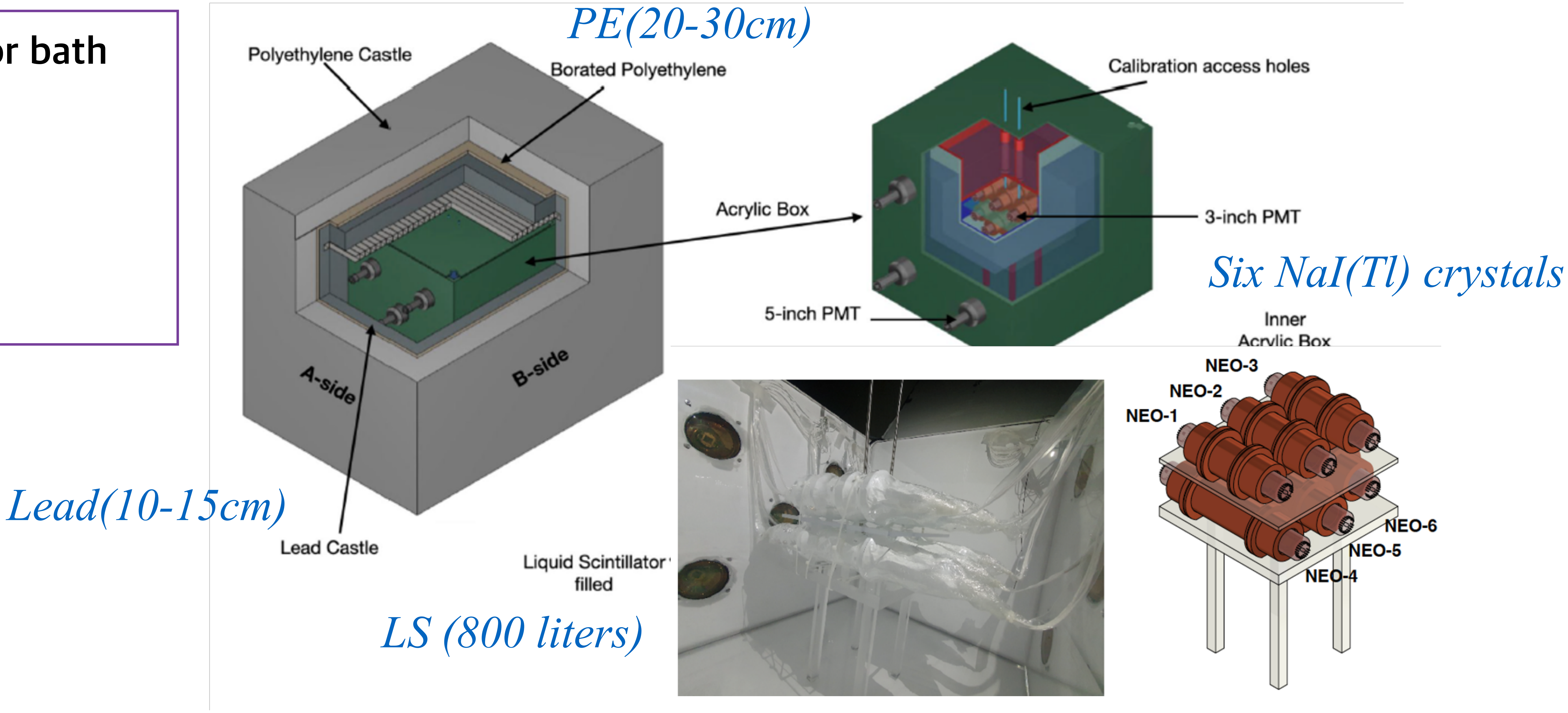


Energy Threshold & **Quenching** are two key factors

Experimental Setup and Conditions

Experimental Setup and Conditions

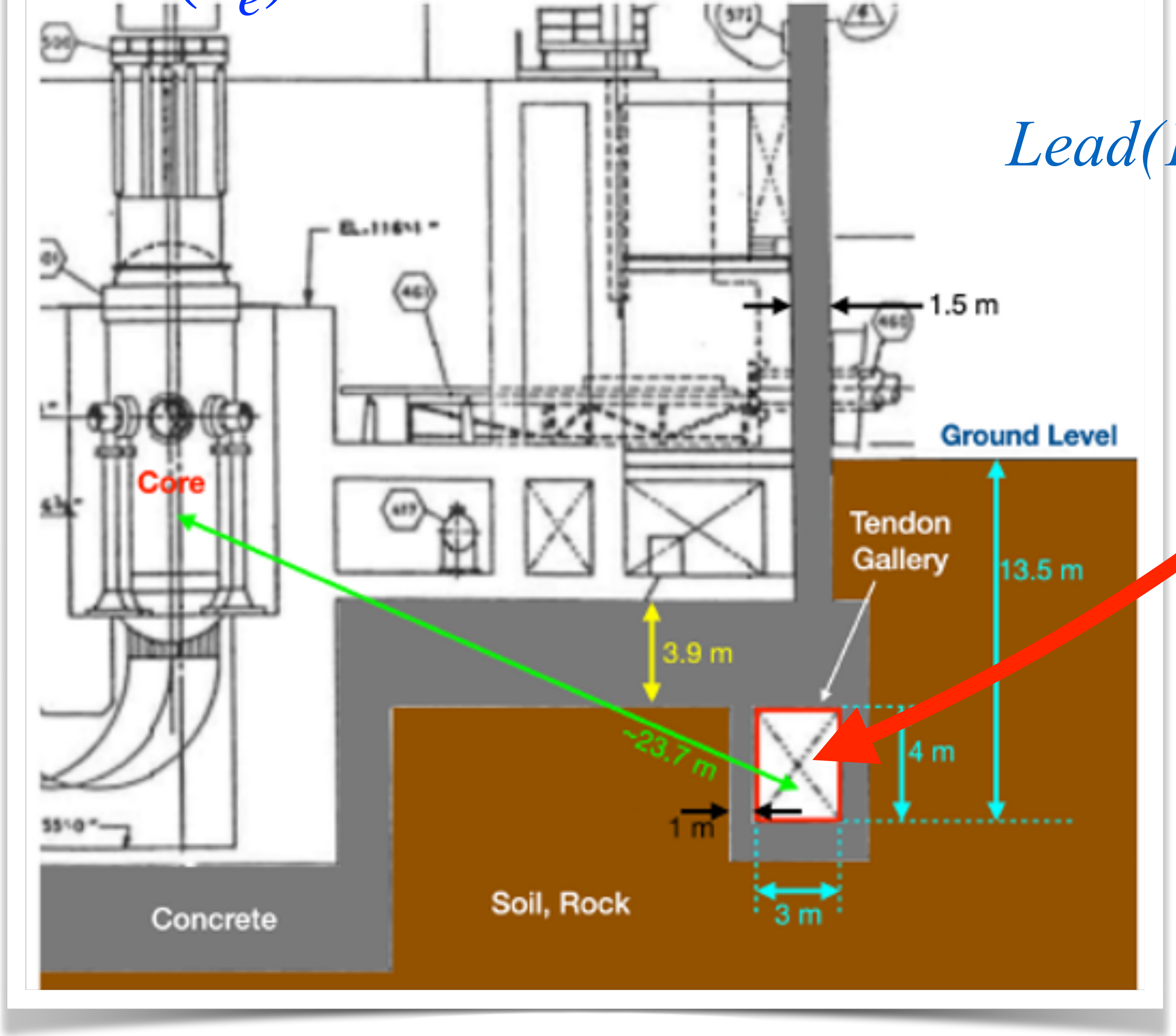
- NaI(Tl) crystals in a Liquid Scintillator bath



Experimental Setup and Conditions

- NaI(Tl) crystals in a Liquid Scintillator bath
- Located at ~24 m from reactor core (Tendon)
- 10 m concrete overburden (x6 less muon flux)

$$F(\bar{\nu}_e) = 8.09 \times 10^{12}\ cm^{-2}\ sec^{-1}$$

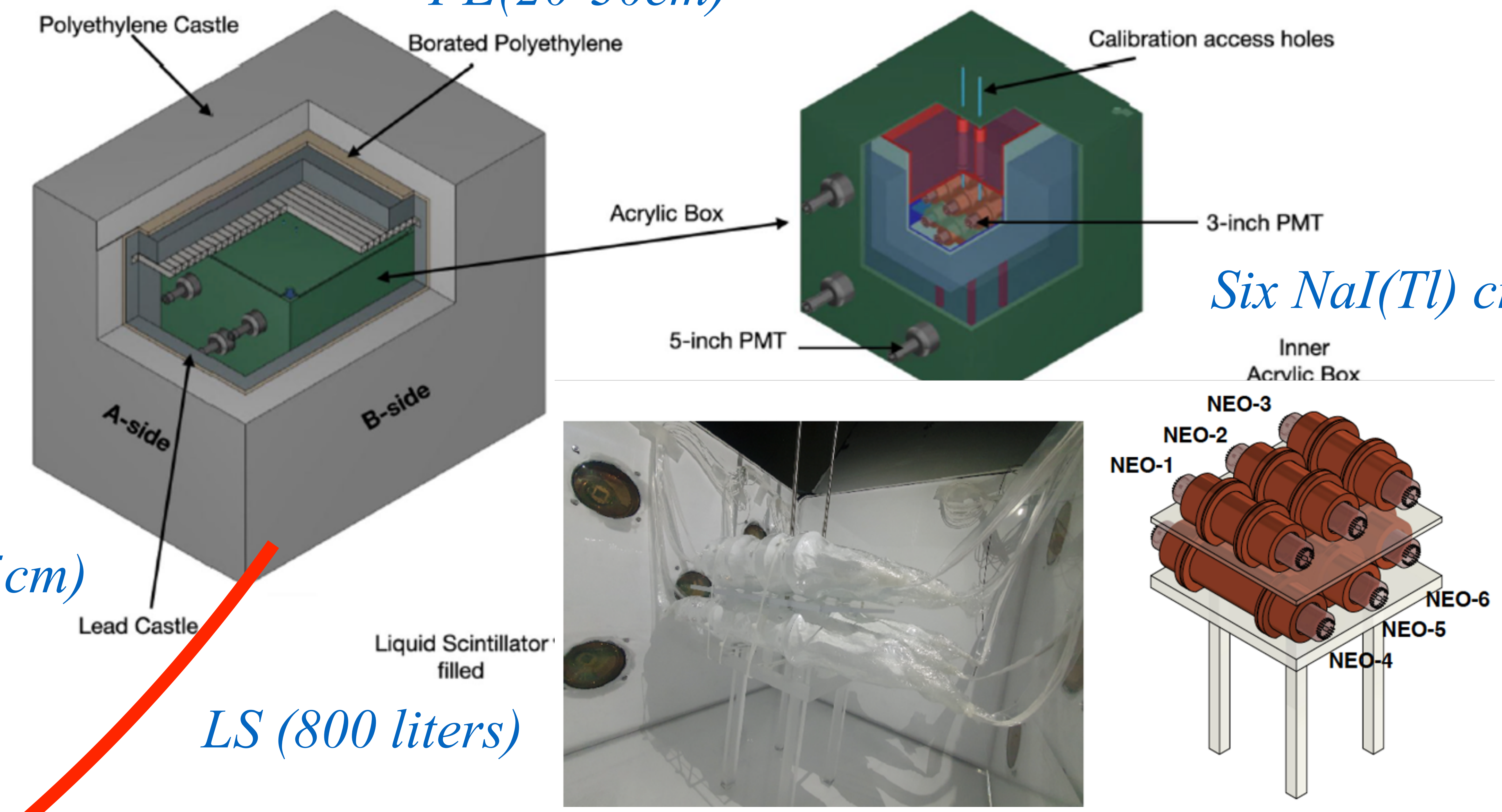


PE(20-30cm)

Lead(10-15cm)

LS (800 liters)

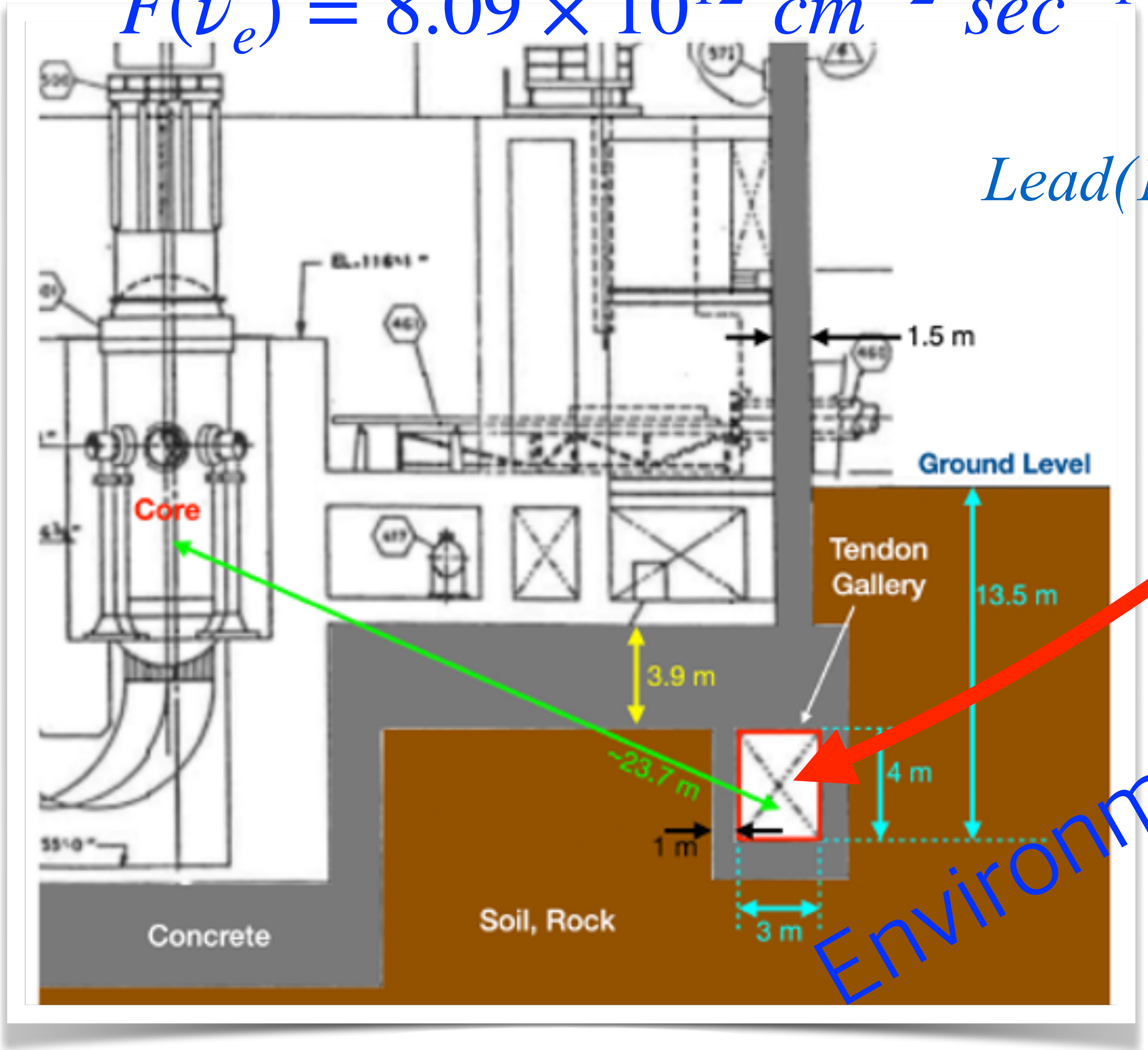
Six NaI(Tl) crystals

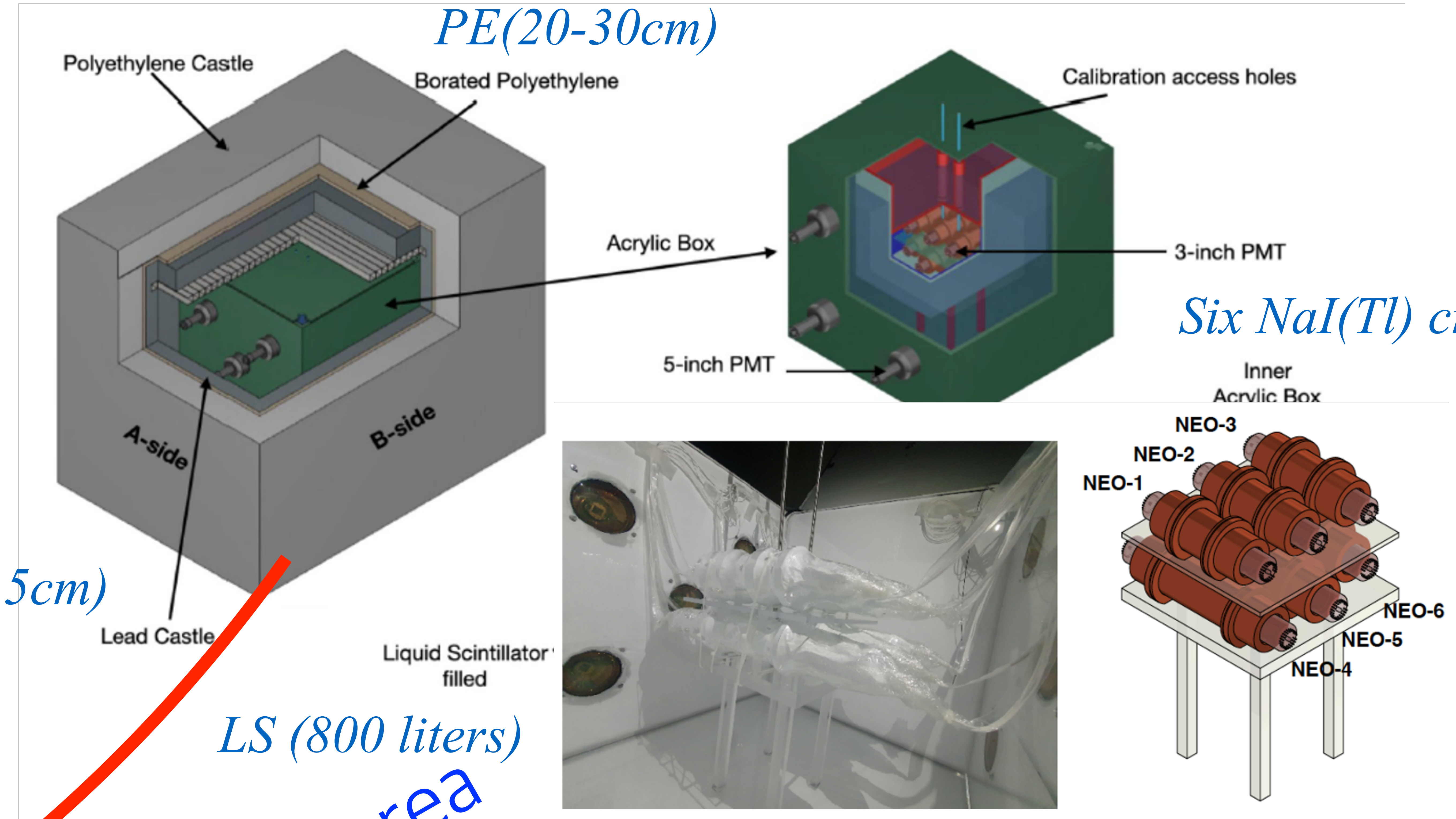


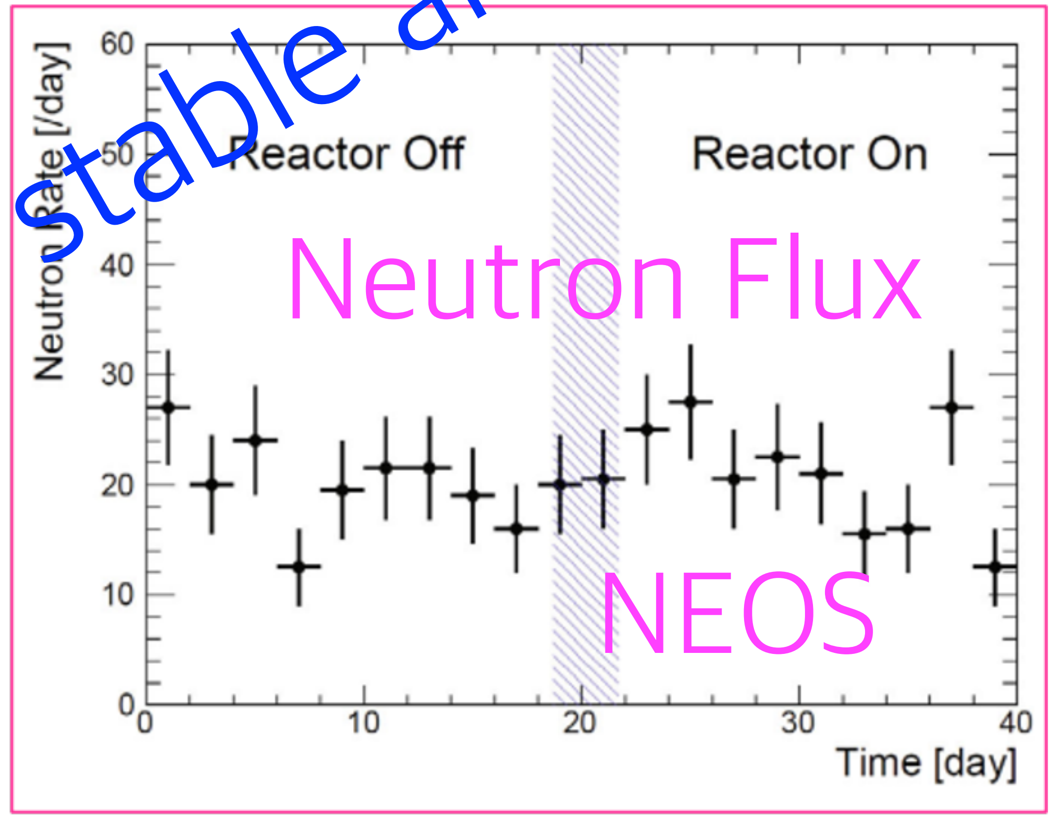
Experimental Setup and Conditions

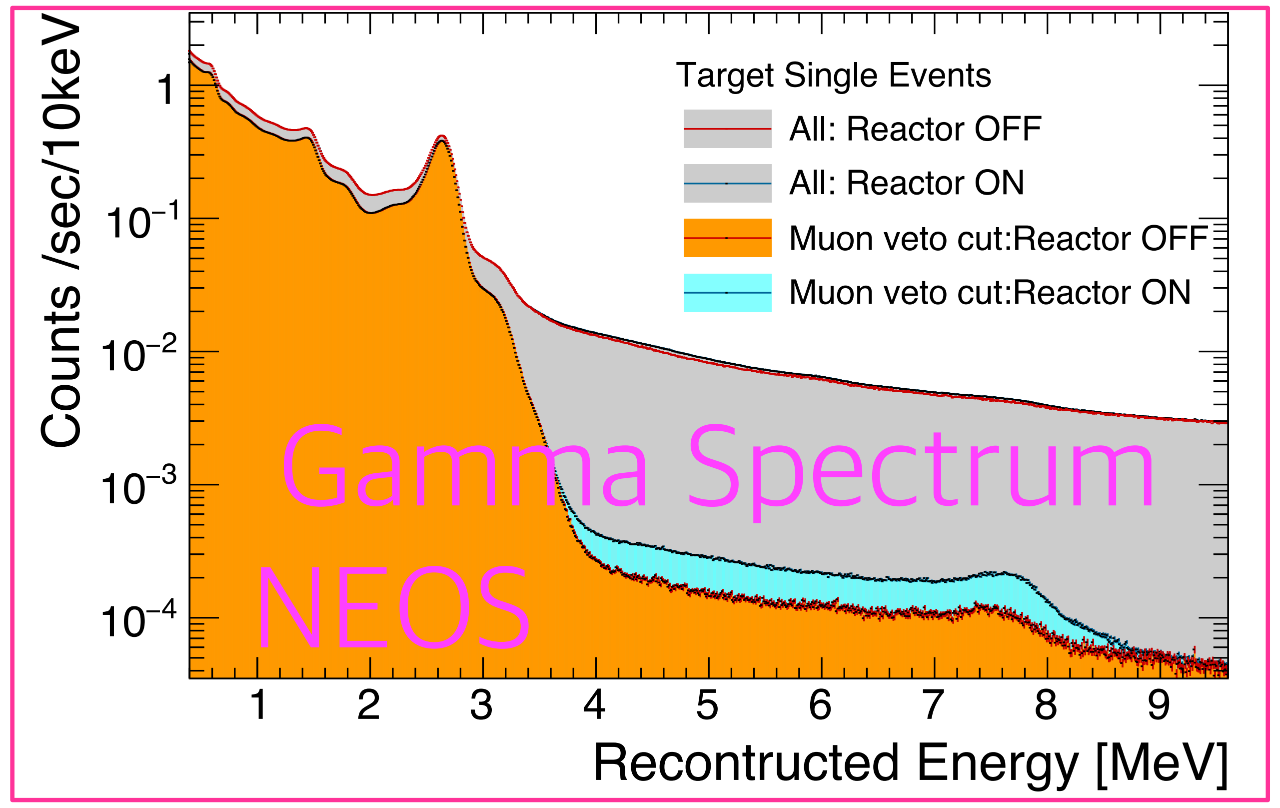
- NaI(Tl) crystals in a Liquid Scintillator bath
- Located at ~24 m from reactor core (Tendon)
- 10 m concrete overburden (x6 less muon flux)
- No change in Neutron/Gamma flux at Tendon

$$F(\bar{\nu}_e) = 8.09 \times 10^{12}\ cm^{-2}\ sec^{-1}$$

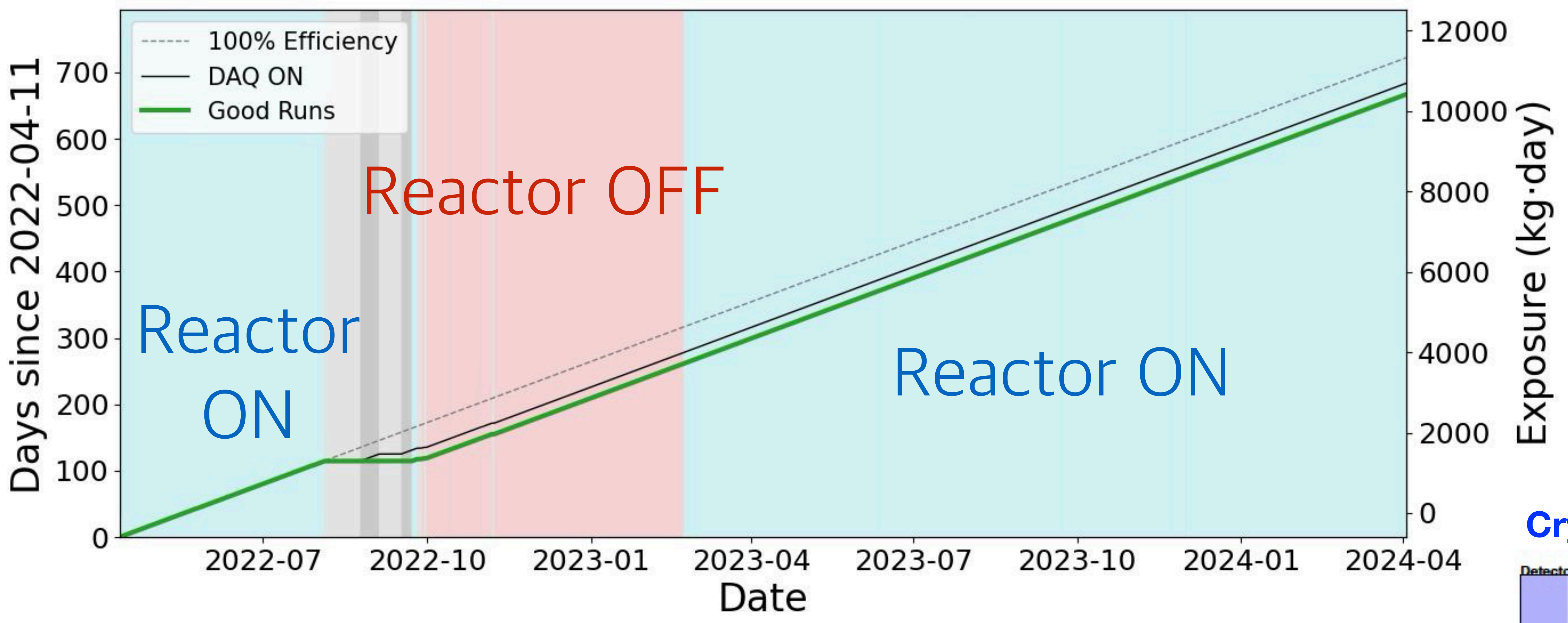


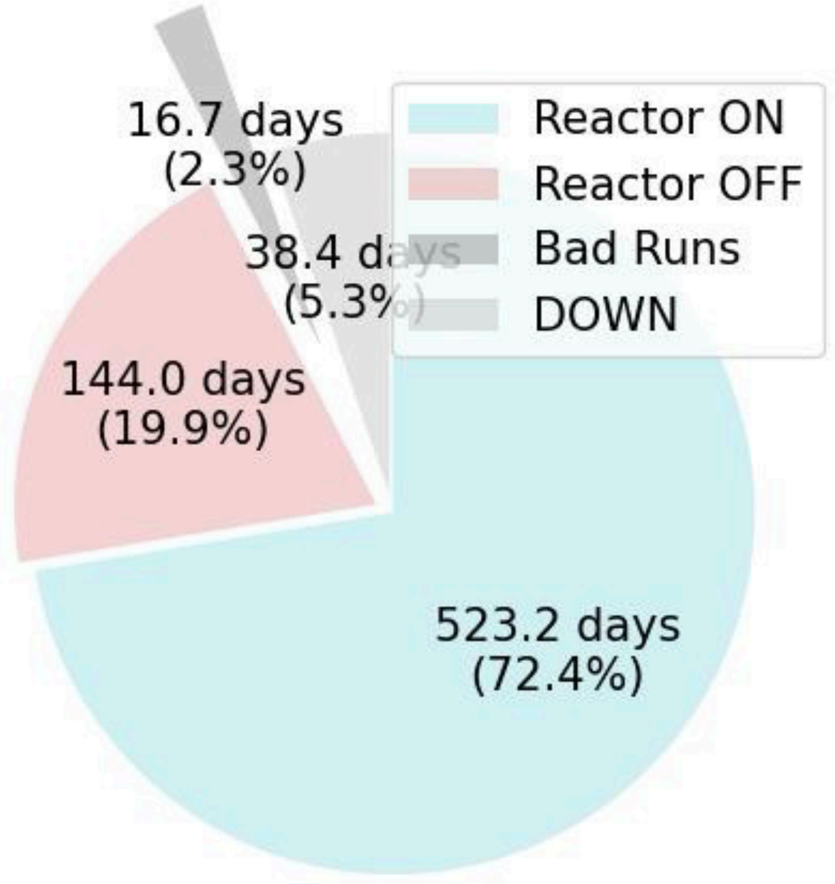






NEON Data Collection and Operations

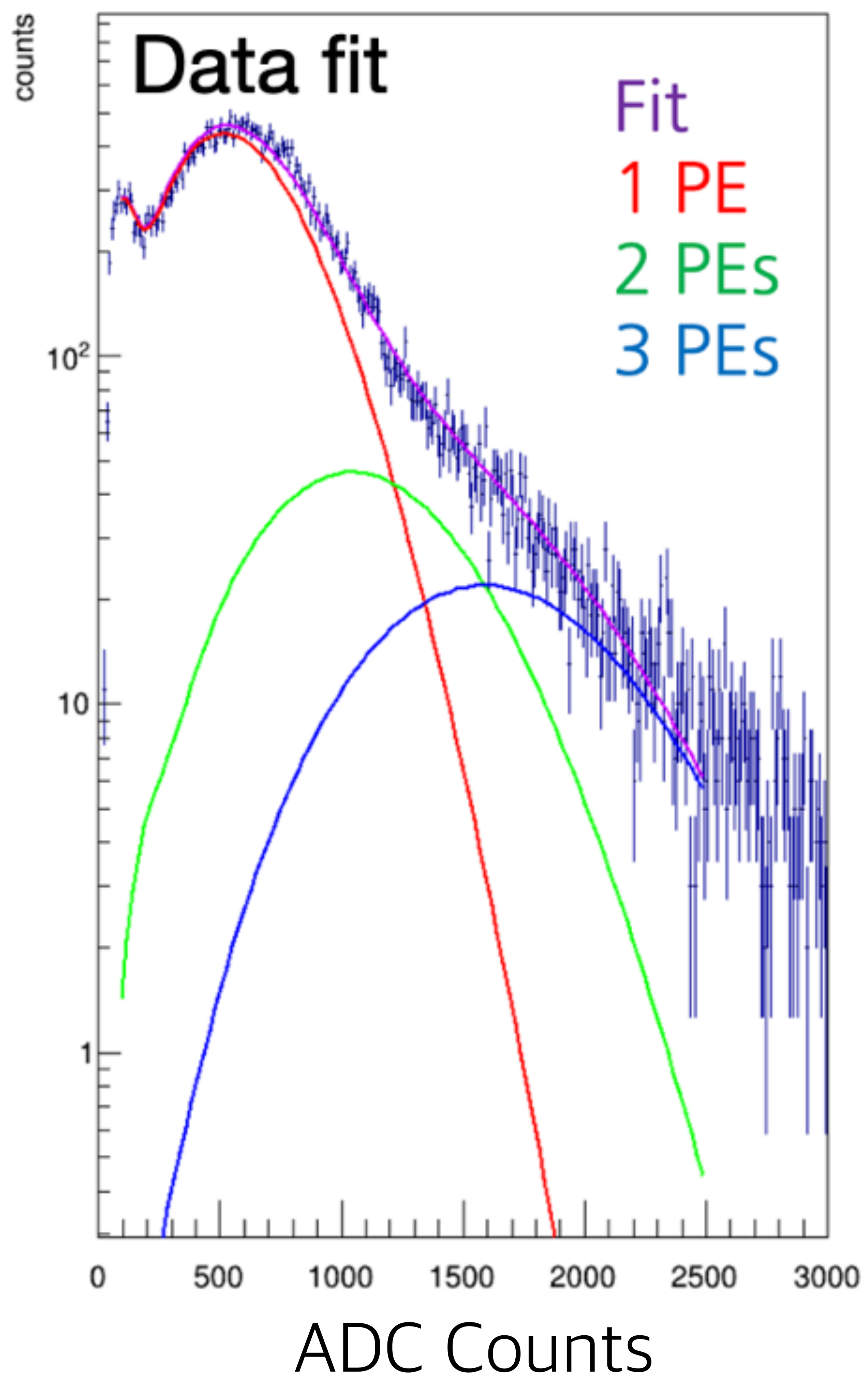


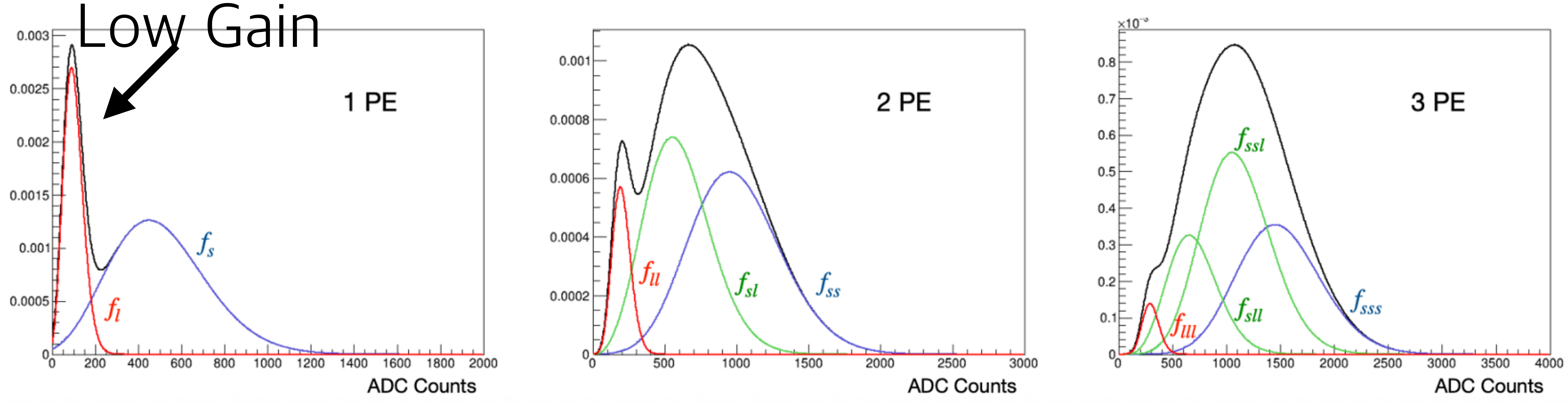


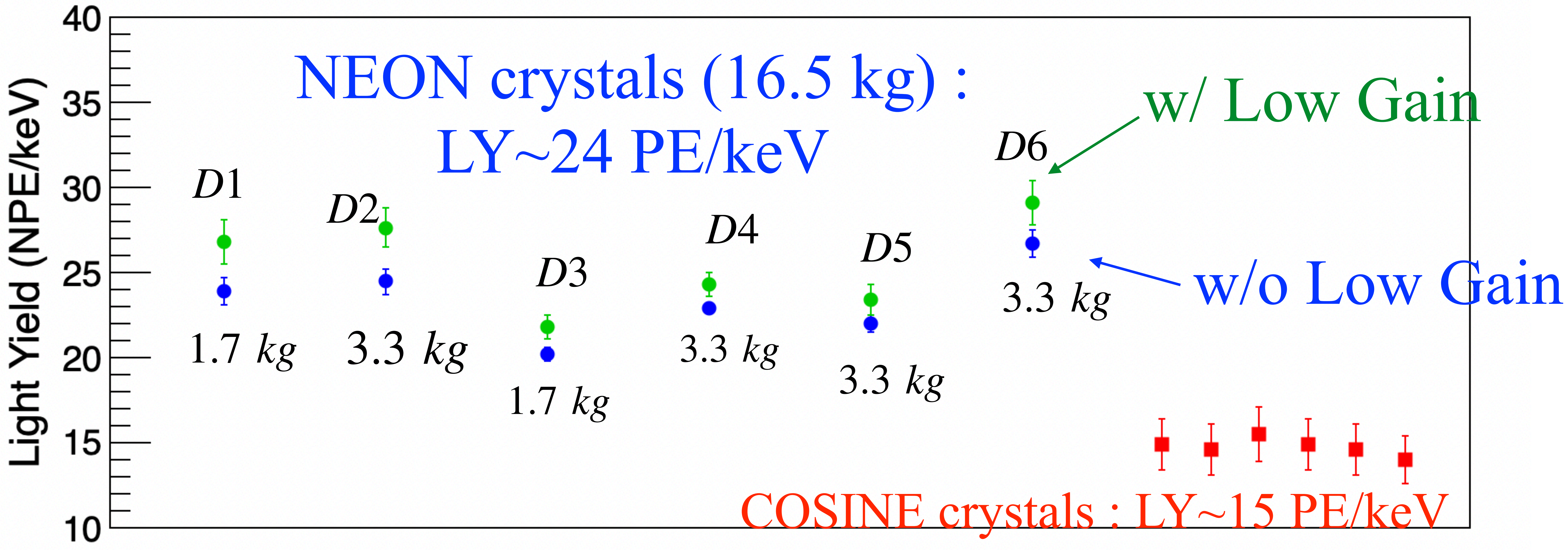
Crystal-wise Data Collection (April, 2022—April, 2023)

- Physics run started since April 2022 (~2.0 years) with 92% DAQ efficiency.
- 523 days of ON data (72%) & 144 days of OFF data (20%) : 11,000 kg day exposure

NEON crystal light yields

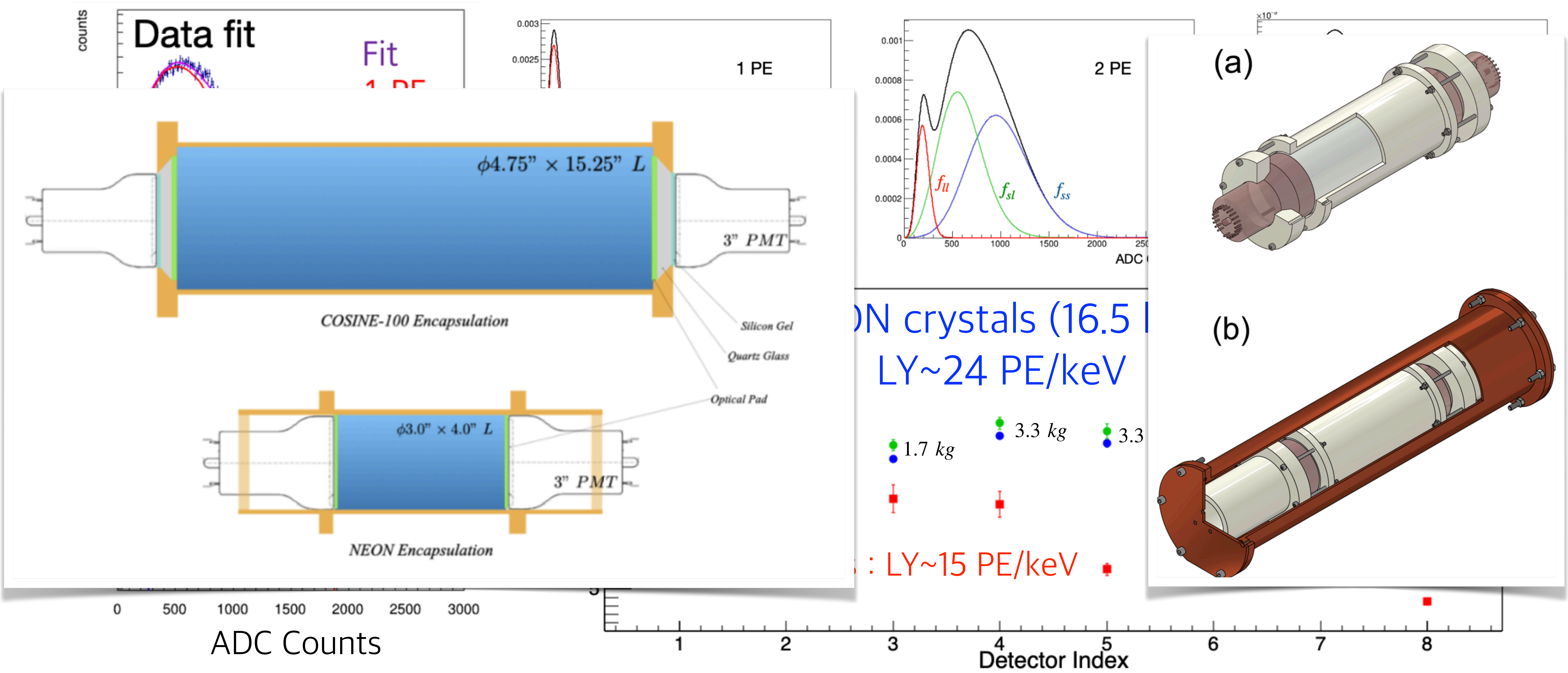






NEON crystals show high light yields (size matching & simpler coupling)

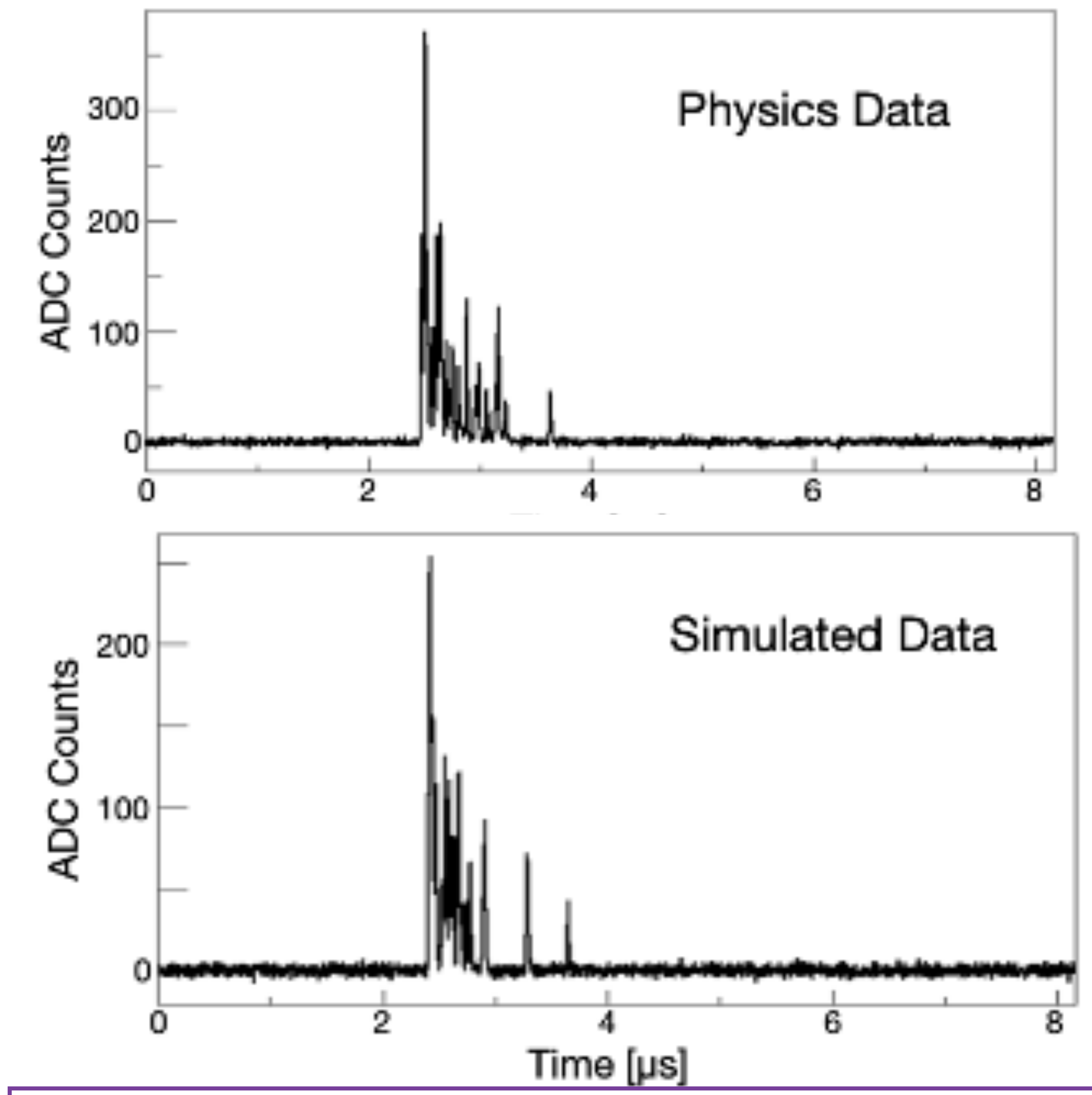
NEON crystal light yields



NEON crystals show high light yields (size matching & simpler coupling)

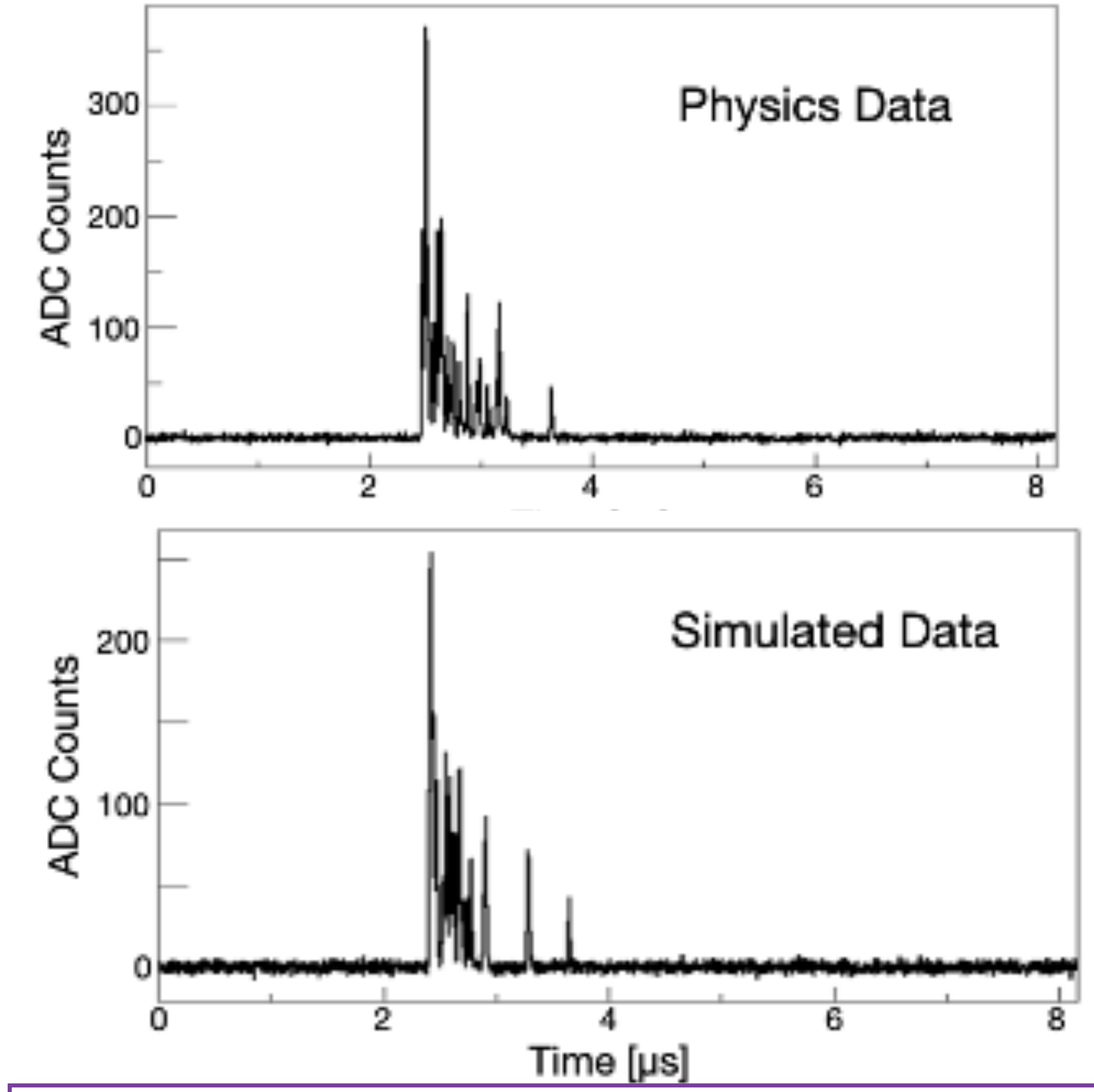
Waveform Simulation and Validations

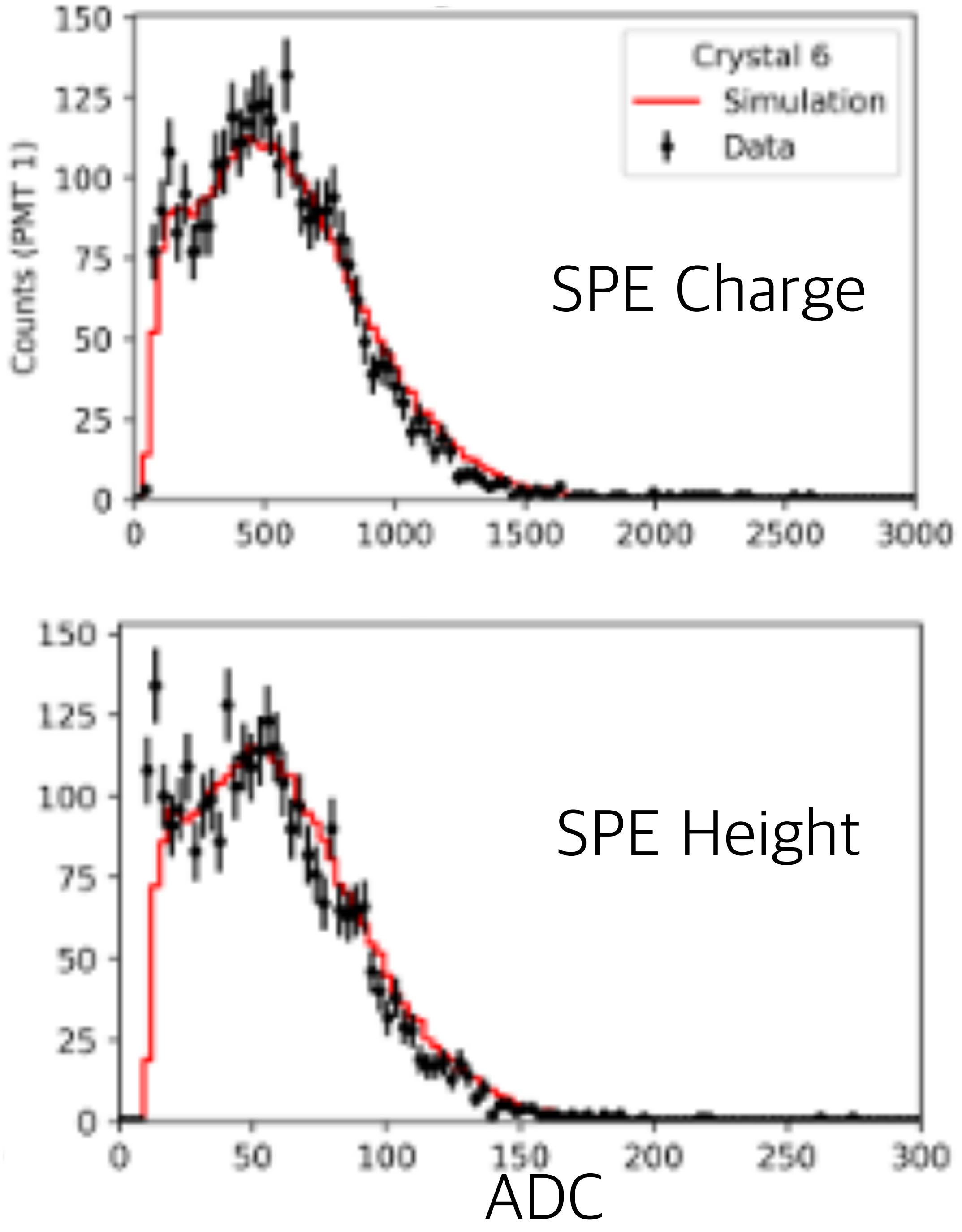
Waveform Simulation and Validations



- Waveform simulation is developed to characterize the keV~sub keV scintillation signals.
- Simulation generates raw waveforms as same as the real data

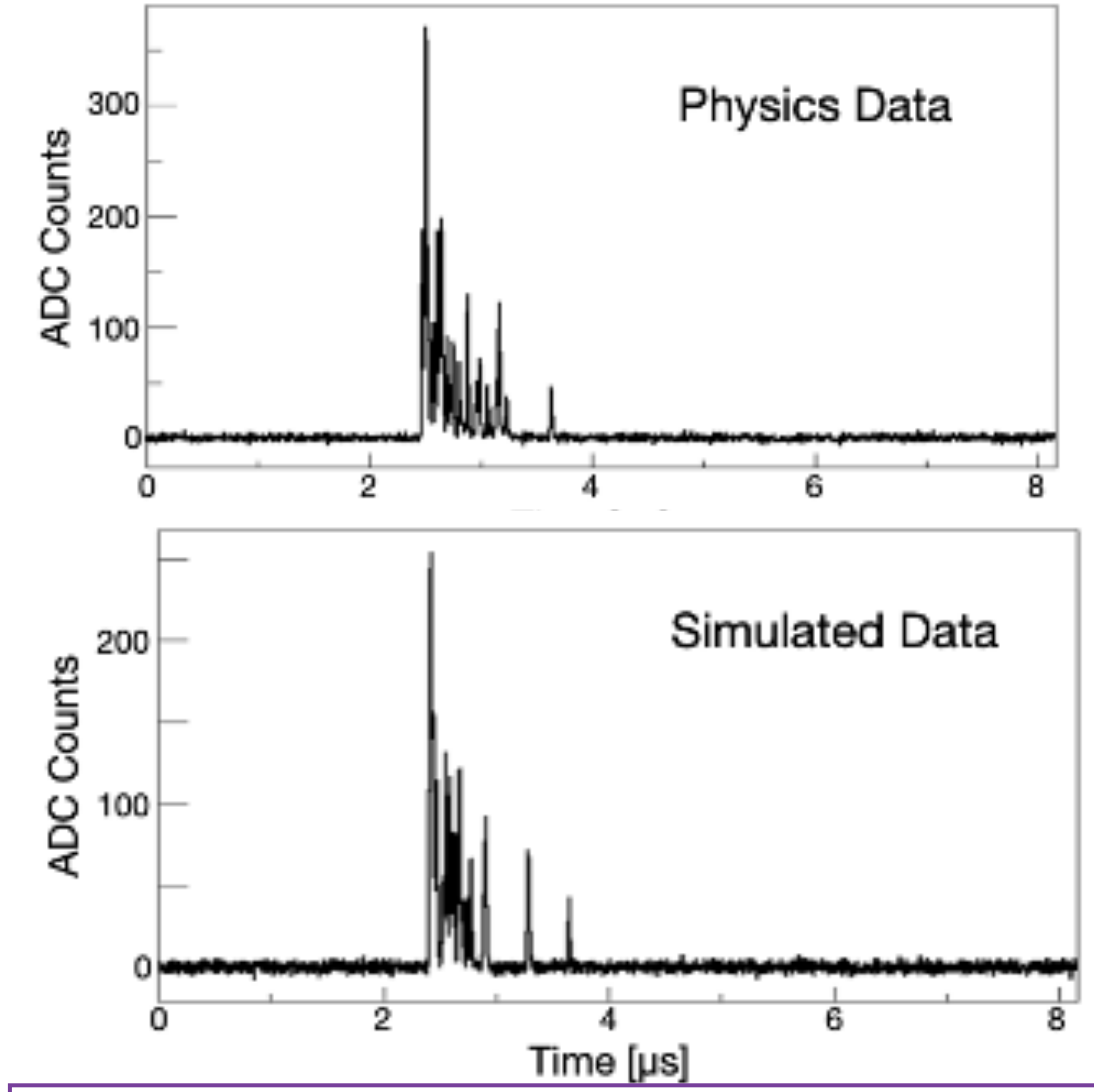
Waveform Simulation and Validations

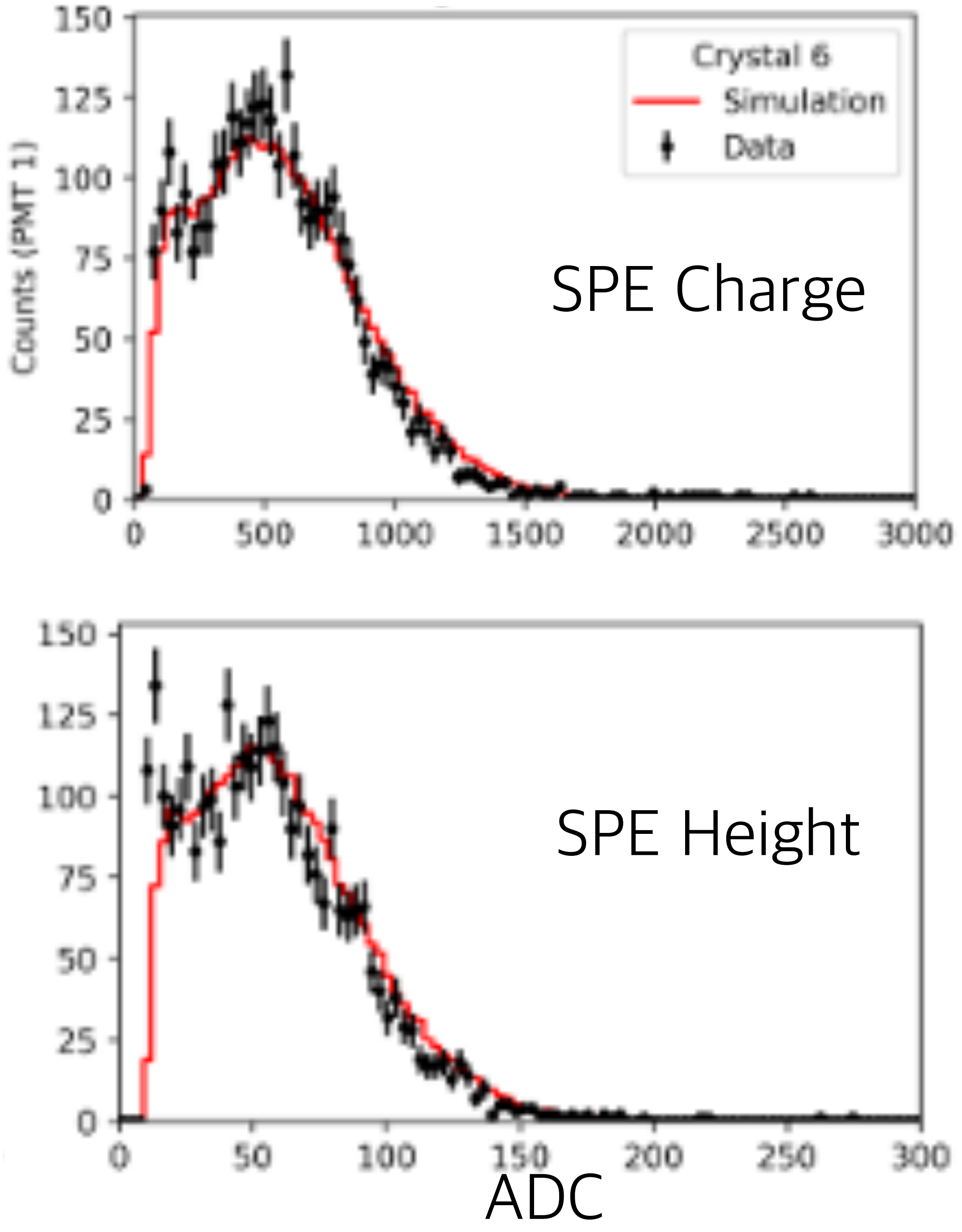




- Waveform simulation is developed to characterize the keV~sub keV scintillation signals.
- Simulation generates raw waveforms as same as the real data
- SPE parameters are tuned to match the real data

Waveform Simulation and Validations





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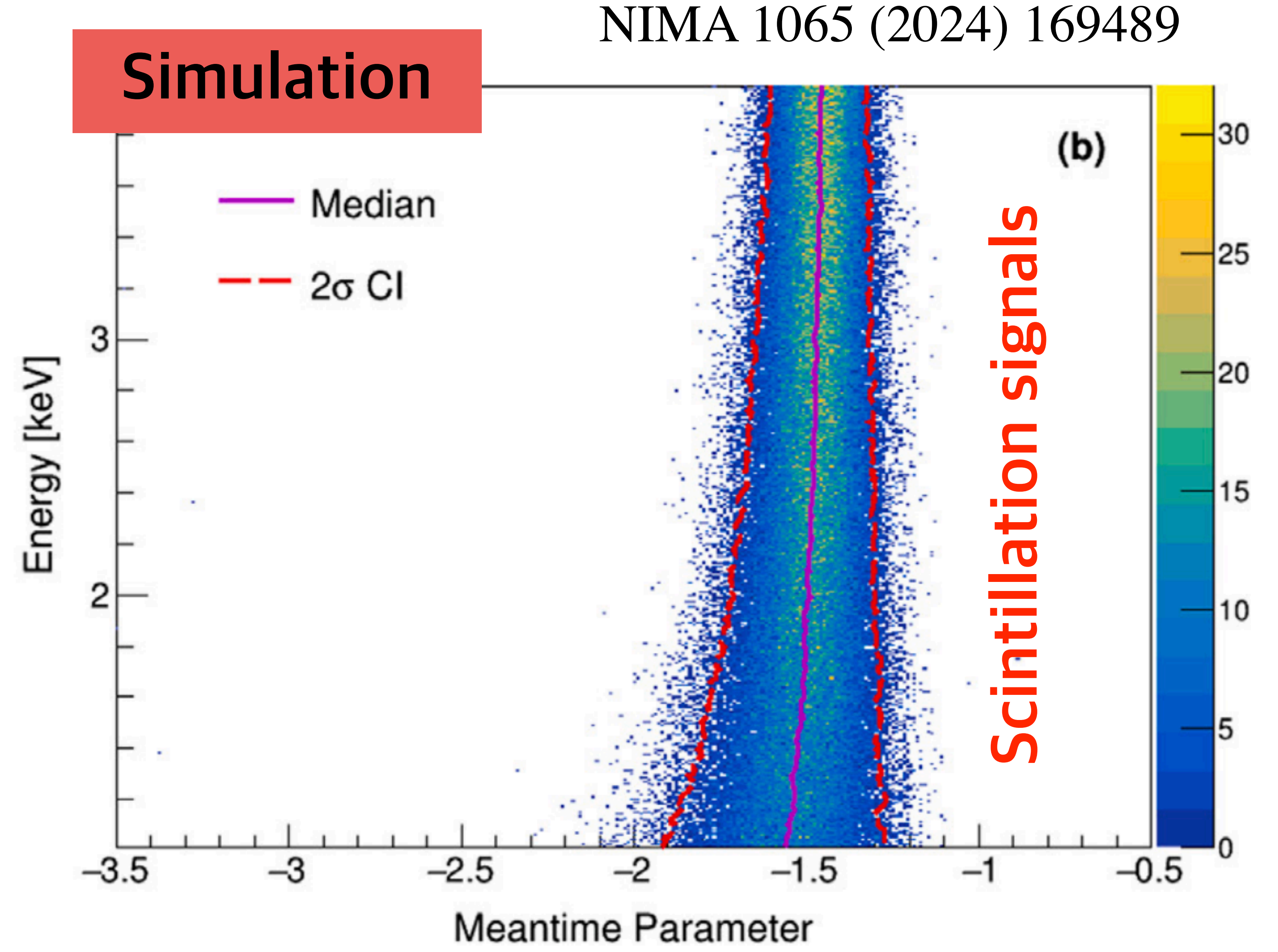
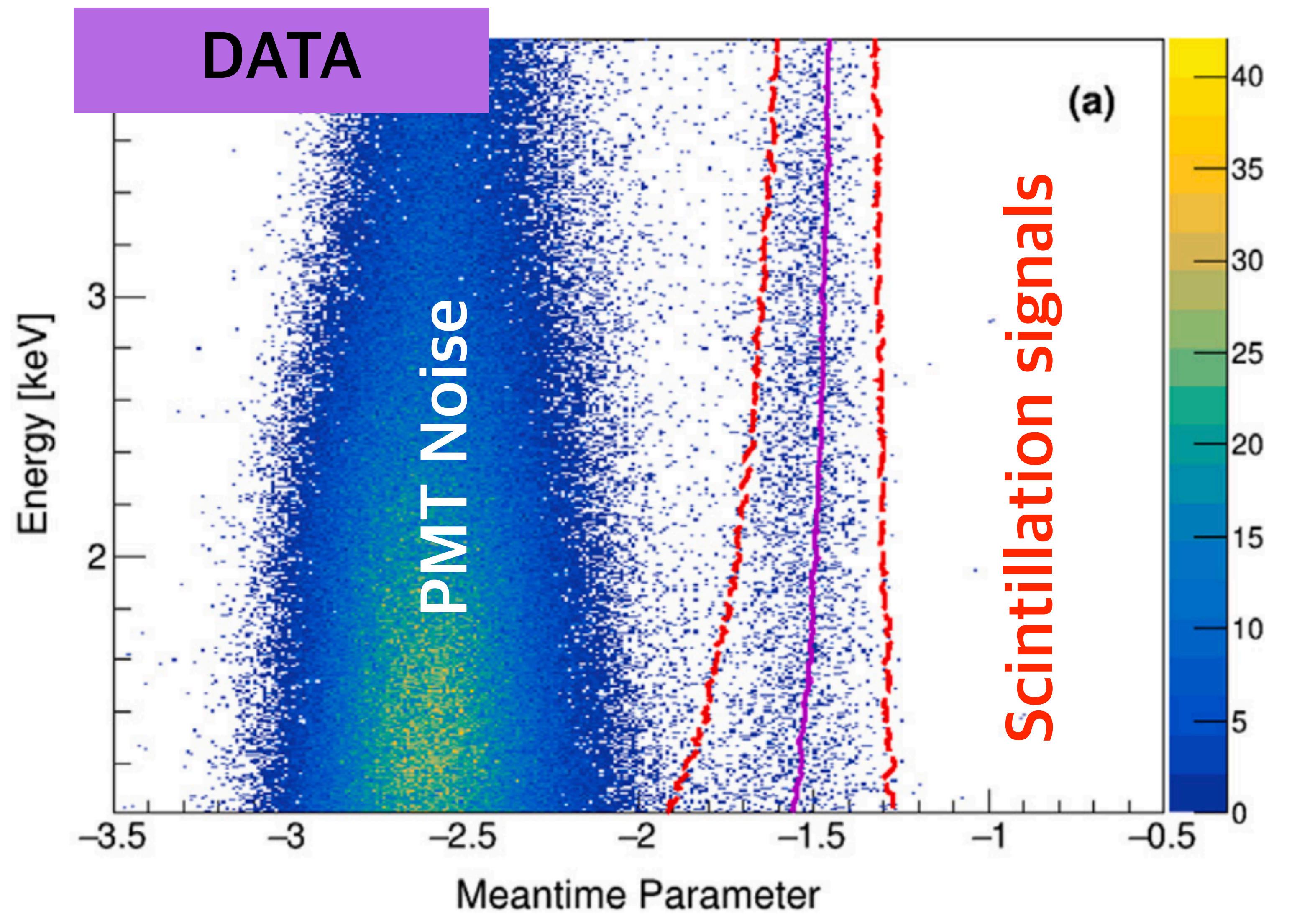
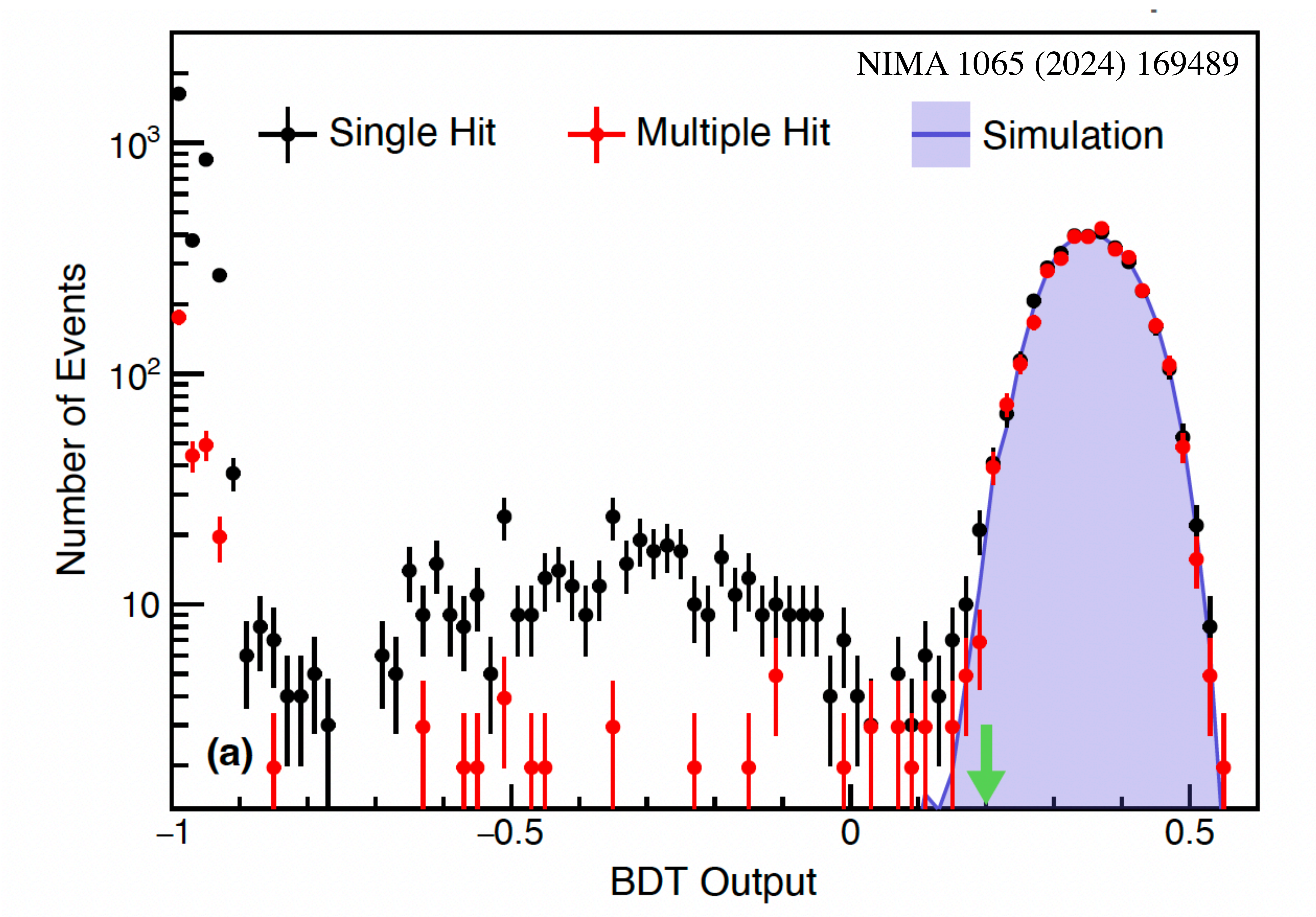


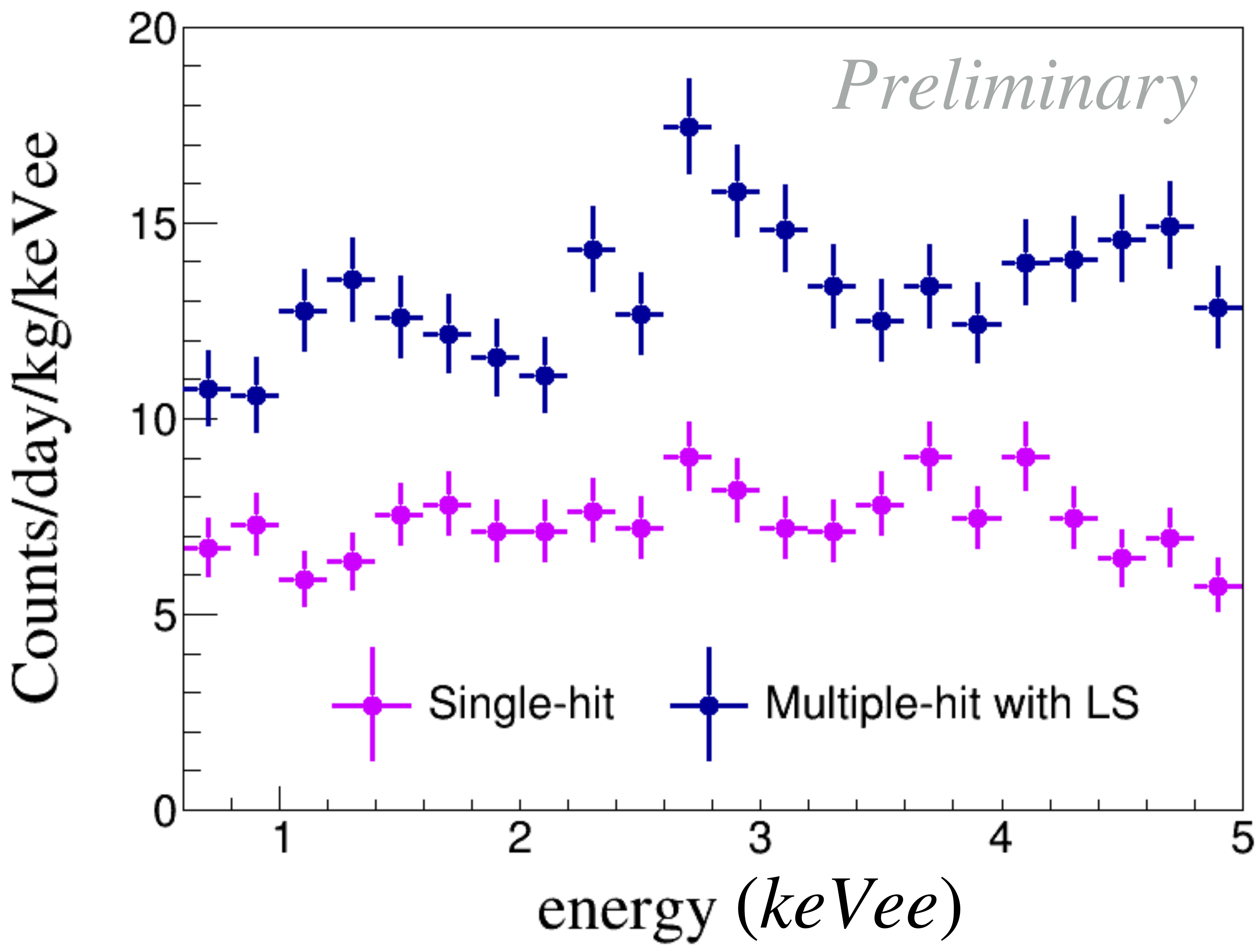


- Waveform simulation is developed to characterize the keV~sub keV scintillation signals.
- Simulation generates raw waveforms as same as the real data
- SPE parameters are tuned to match the real data
- Simulation and real data for the physics variables agree very well (within a few percent level).
- Low energy simulation signals are used for high level variables e.g. Boosted Decision Tree (BDT) score calculation.

Low Energy Spectrum

Event selection is done with a series of BDT output variables characterizing different types of PMT noises

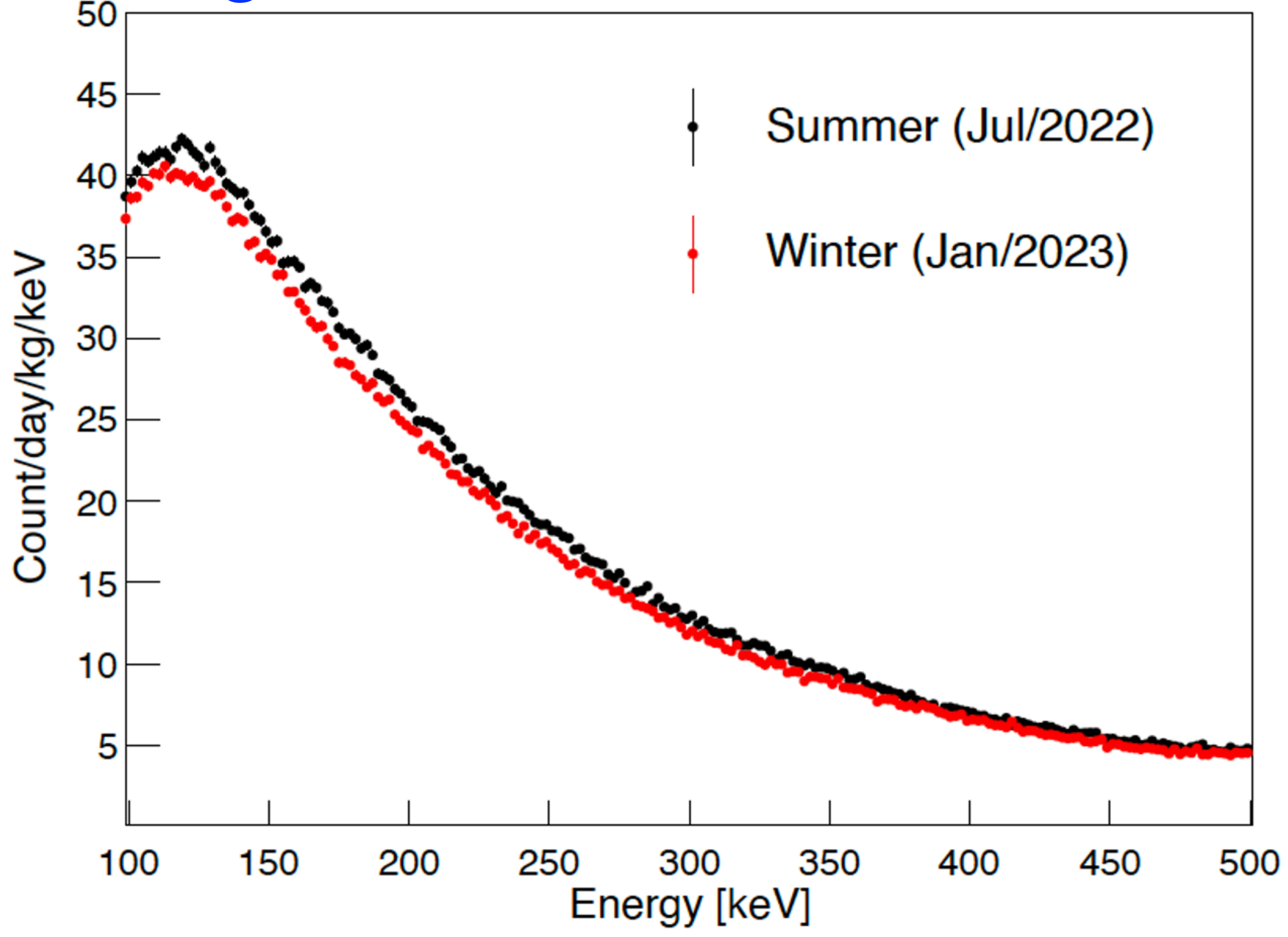




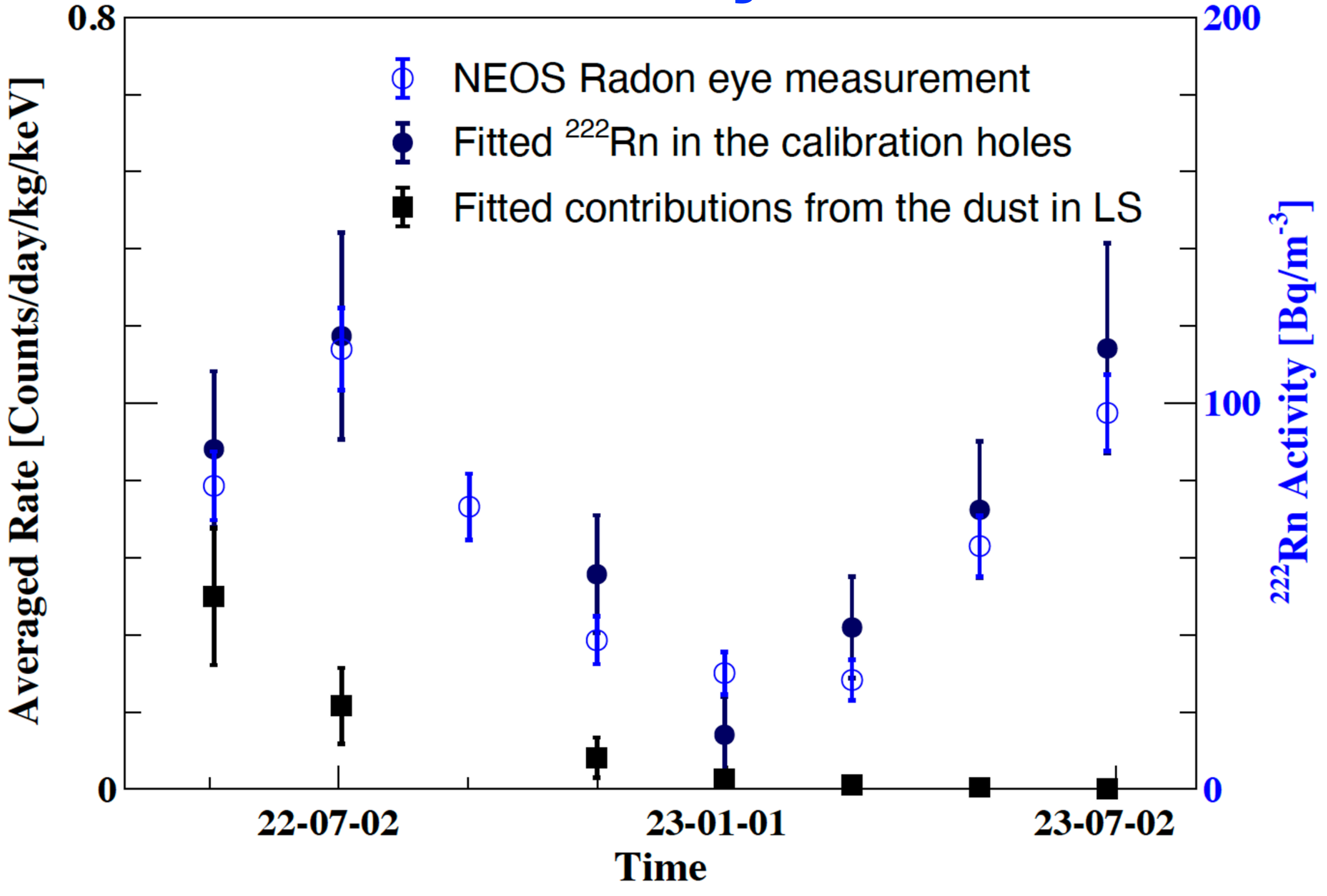
With the current algorithms, a threshold of 0.6 keVee with 7 counts/day/kg/keVee is achieved after BDT event selections

Radon concentration variation by season

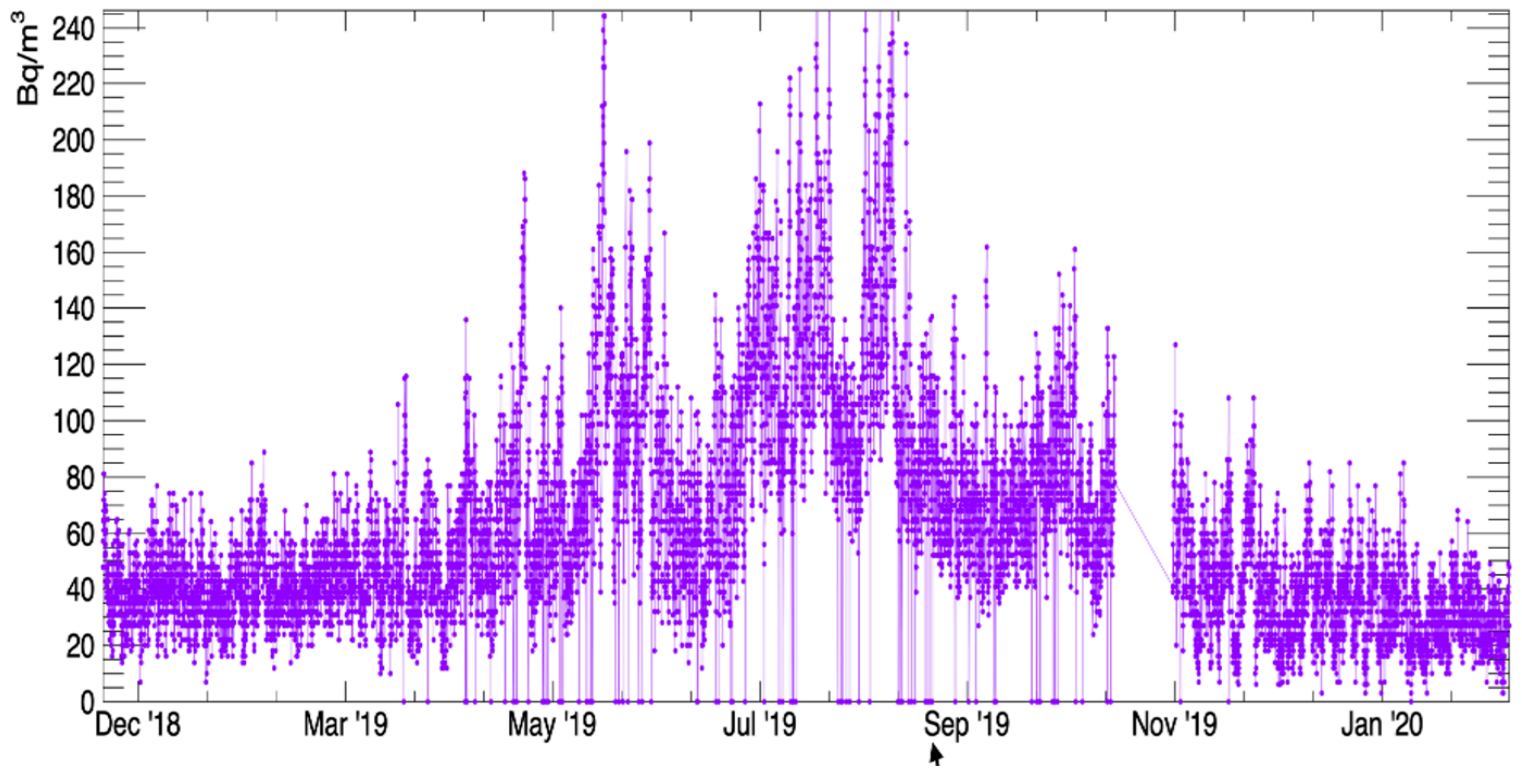
Higher Radon in Summer



Similar seasonal effect measured by NEOS



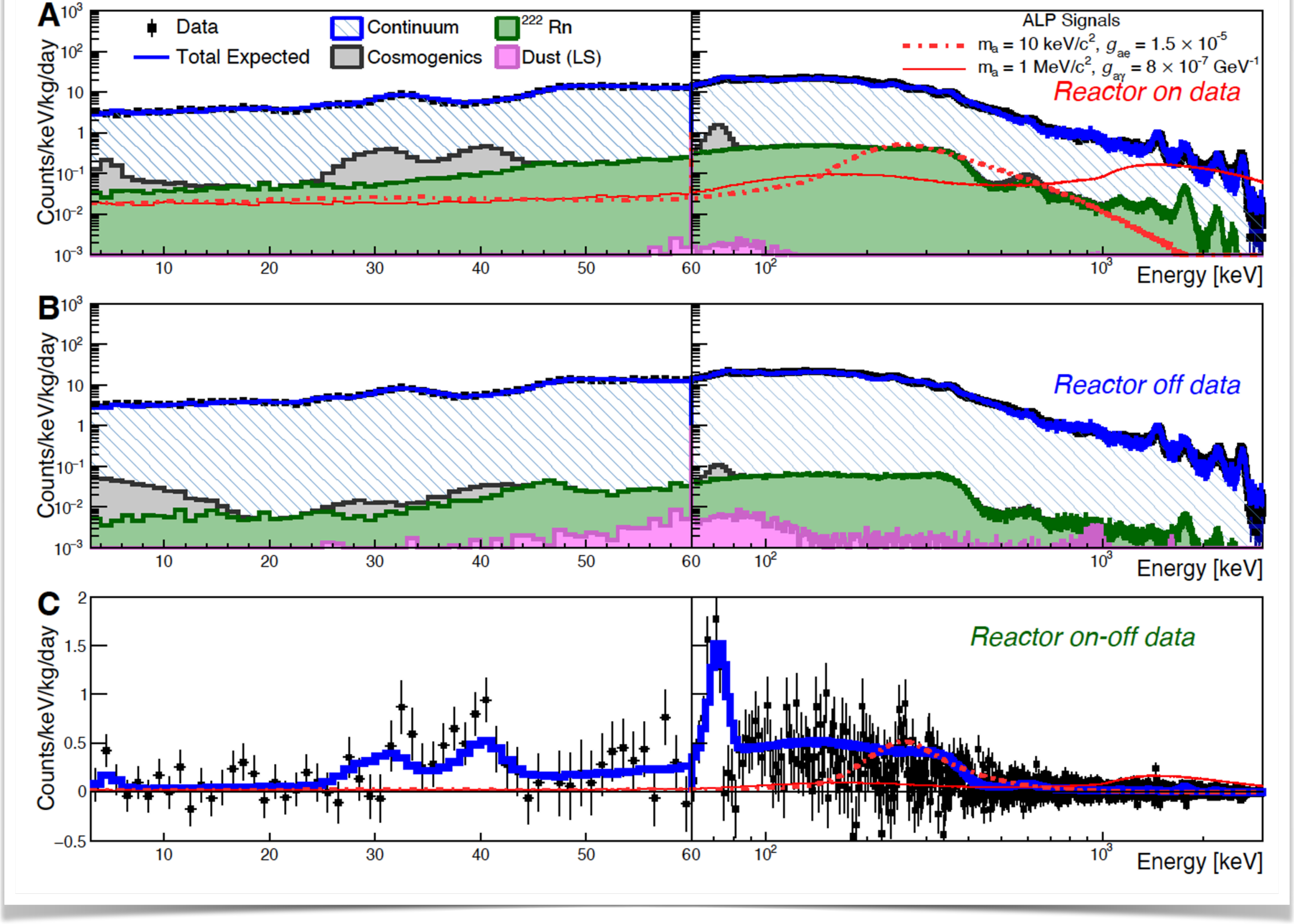
NEOS Radon Measurement



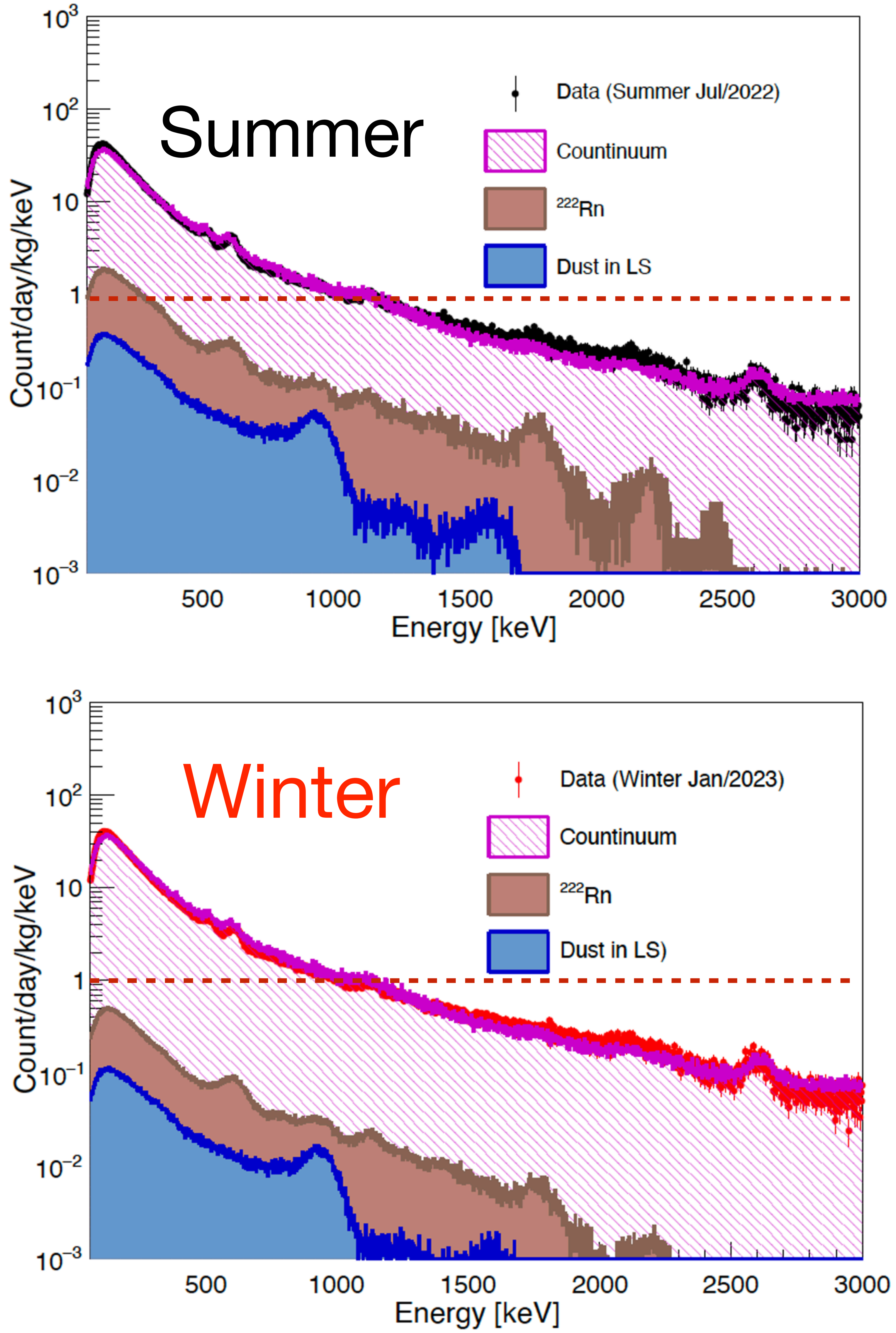
- Radon rate higher in summer due to air circulation and emanation effect.
- Reactor OFF period occurred in WINTER. (Lower radon rate)

Background Understanding of Data

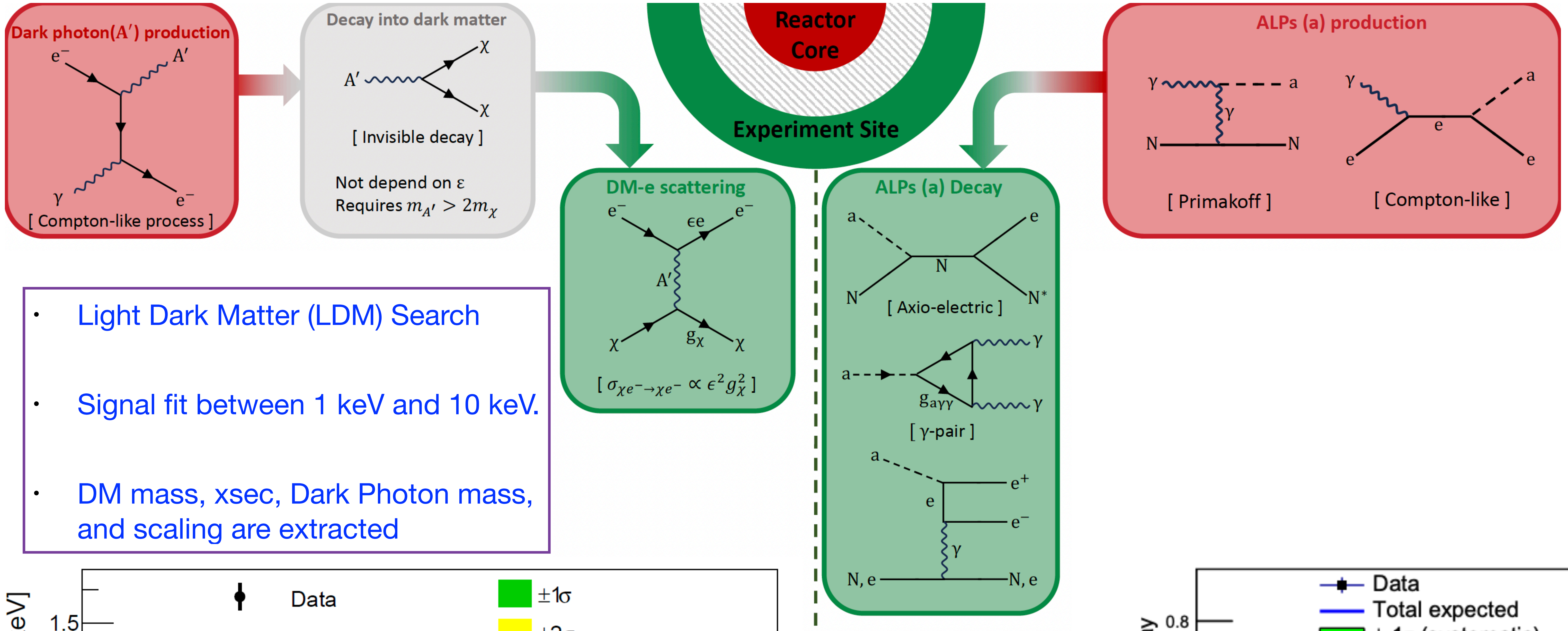
ON versus OFF



Summer vs Winter

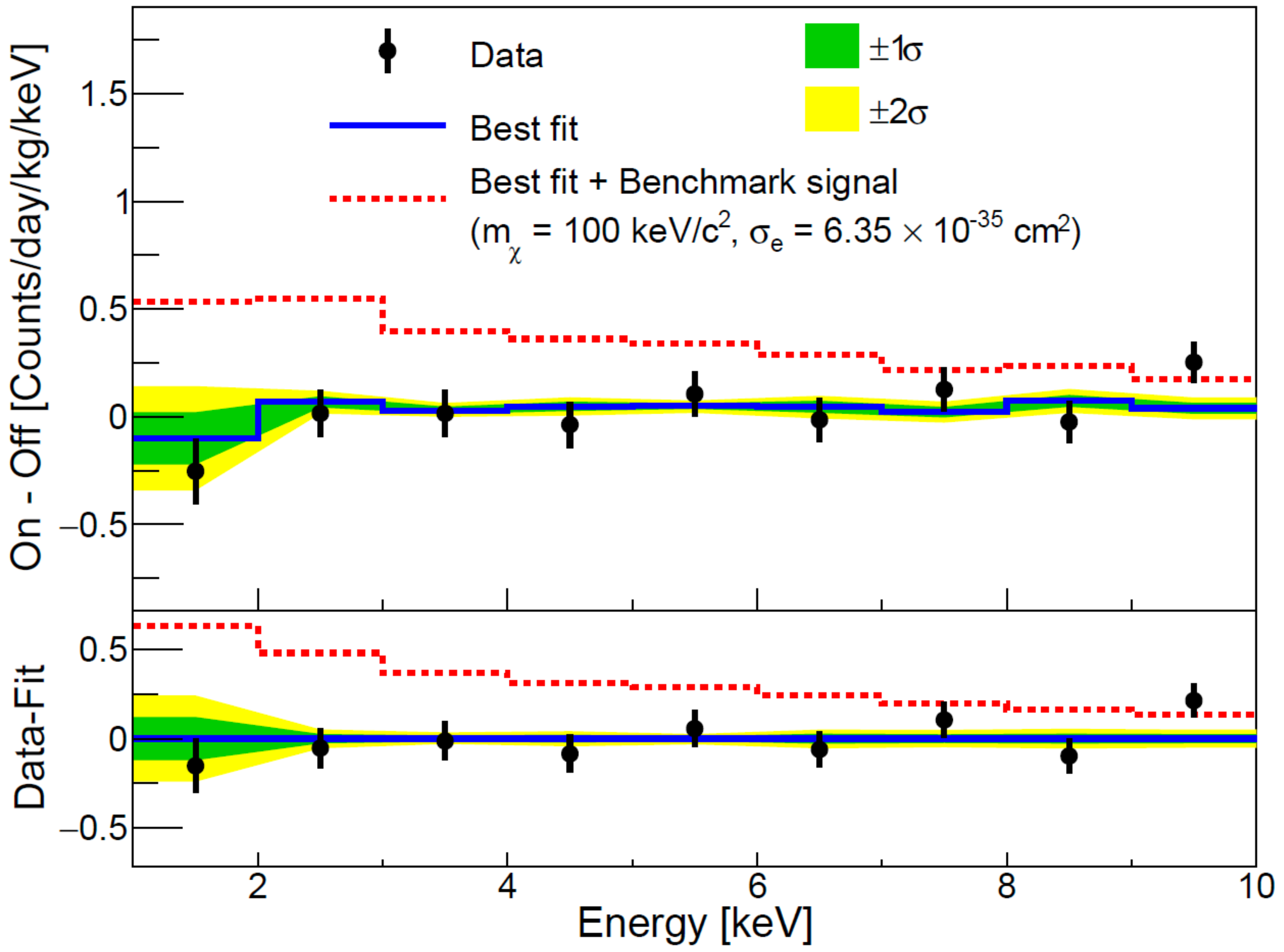


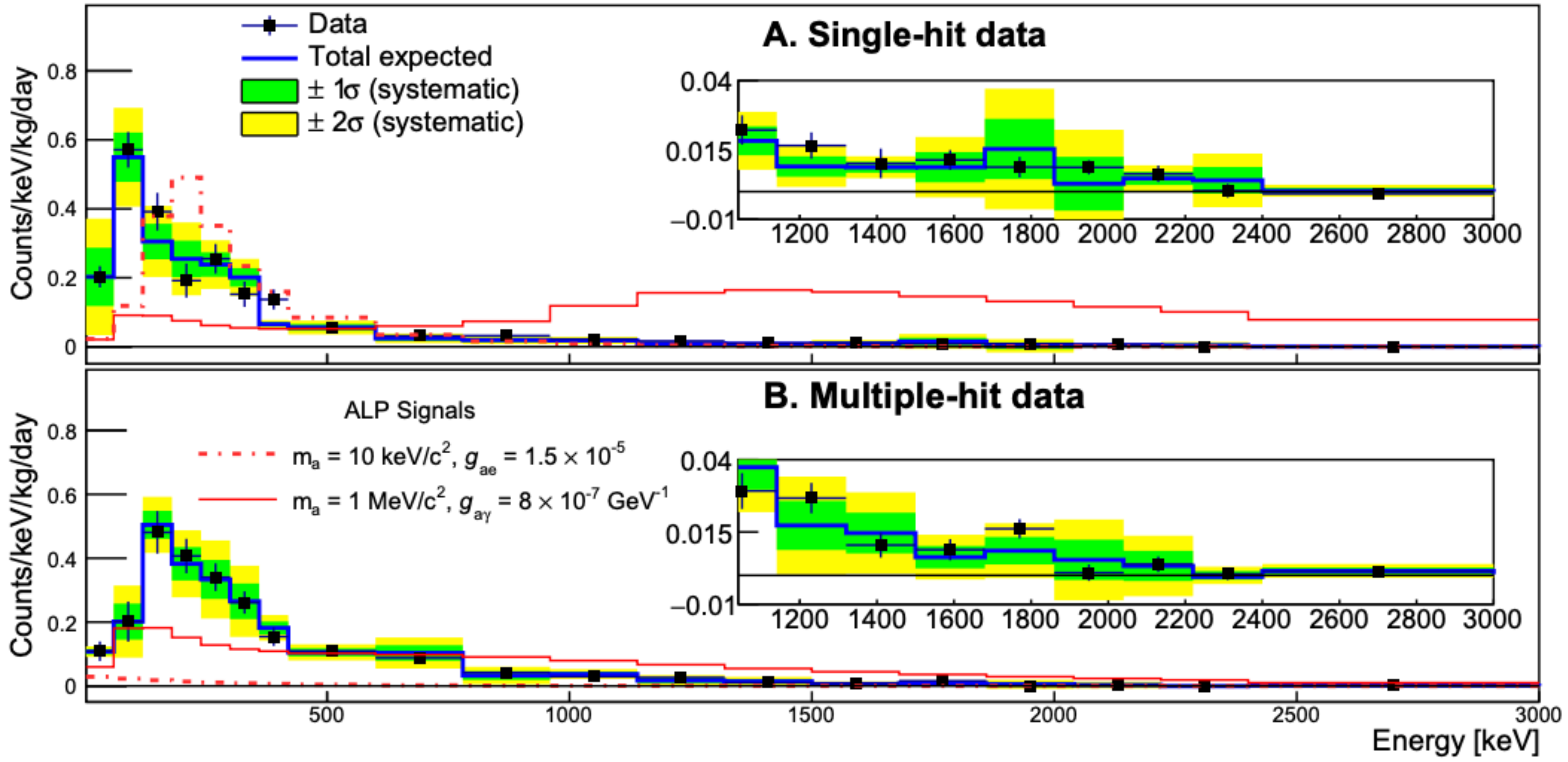
BSM Physics Analyses



- Light Dark Matter (LDM) Search
- Signal fit between 1 keV and 10 keV.
- DM mass, xsec, Dark Photon mass, and scaling are extracted

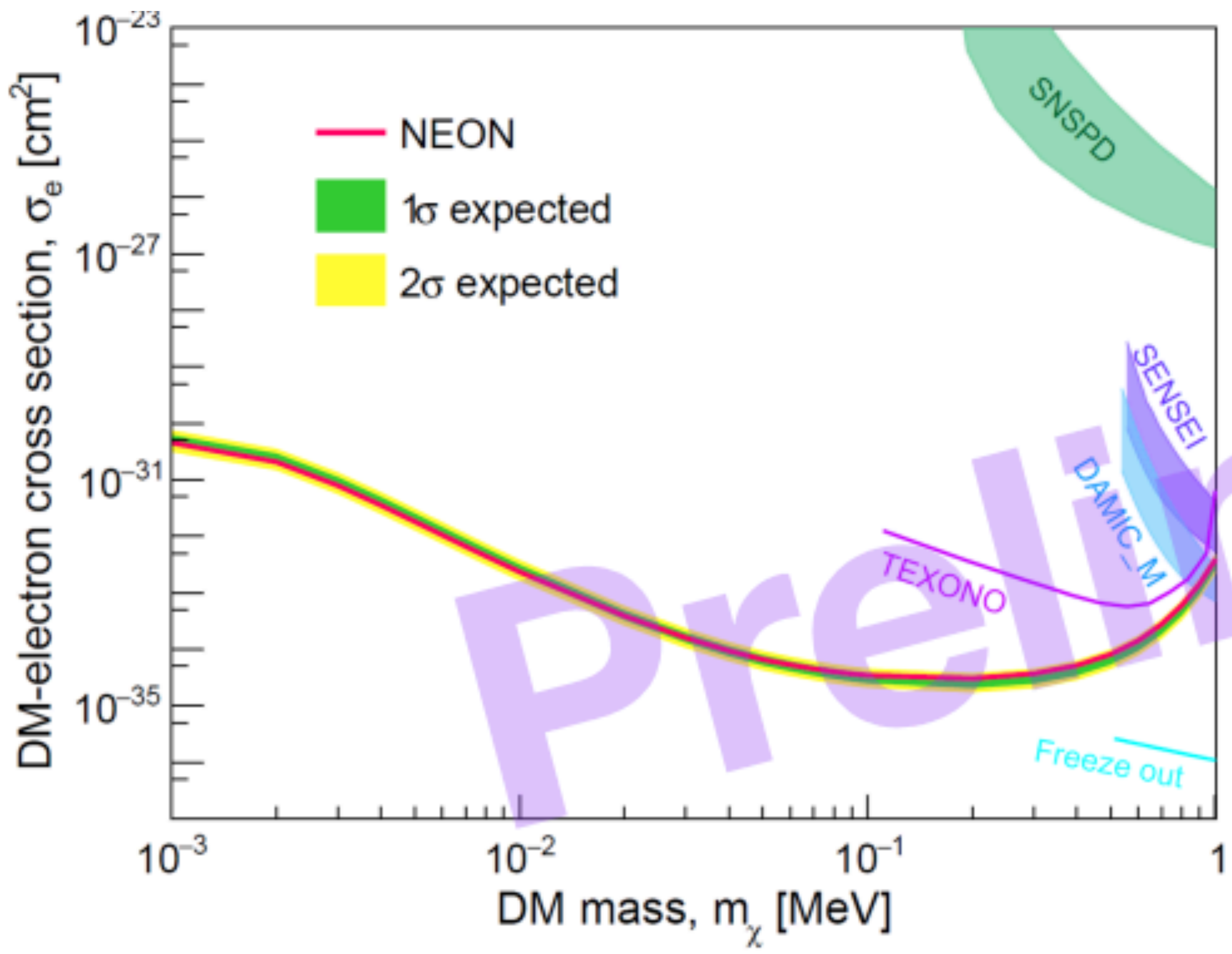
- Axion-Like Particle (ALP) Search
- Signal fit between 3 keV and 3000 keV depending on Axion mass and couplings

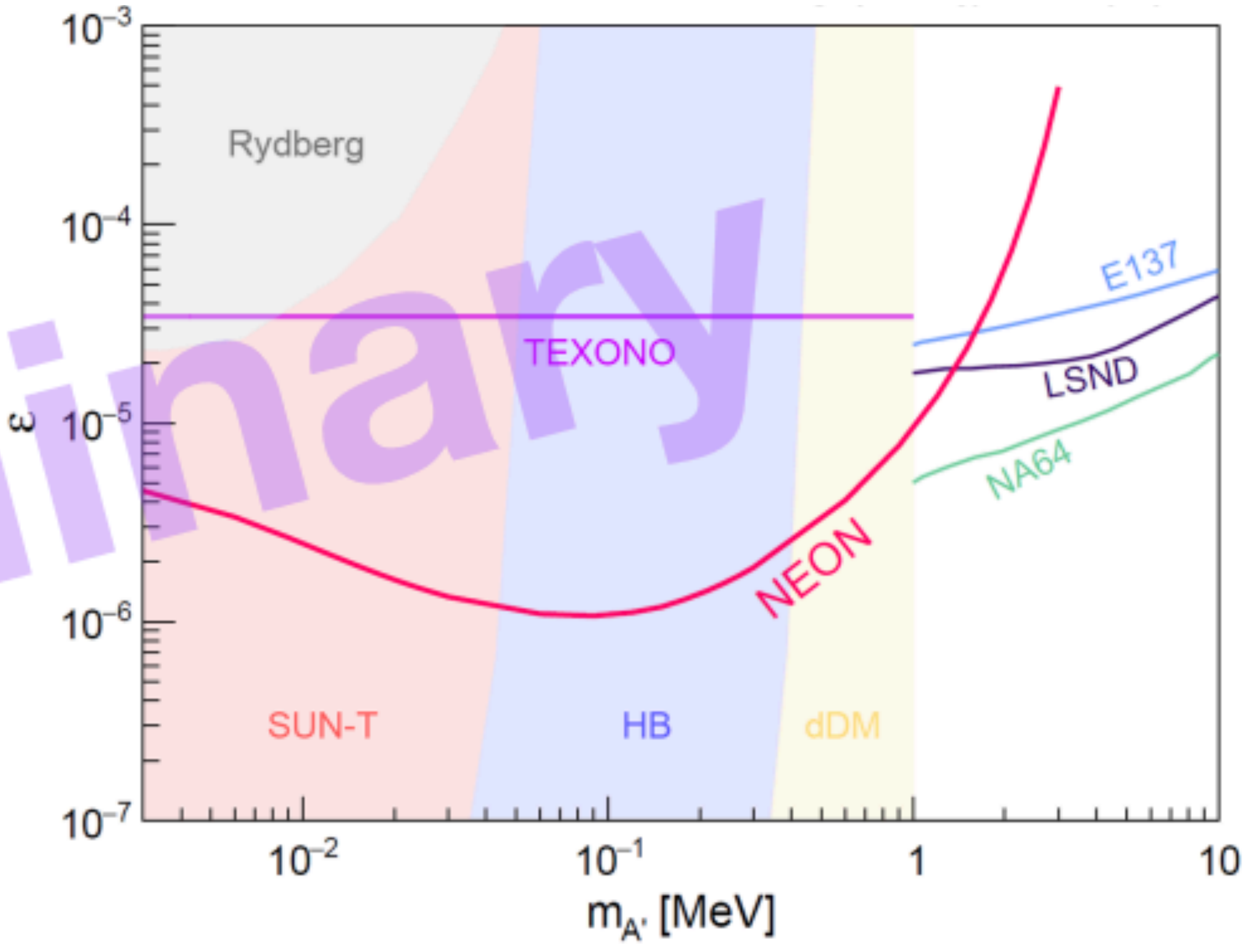


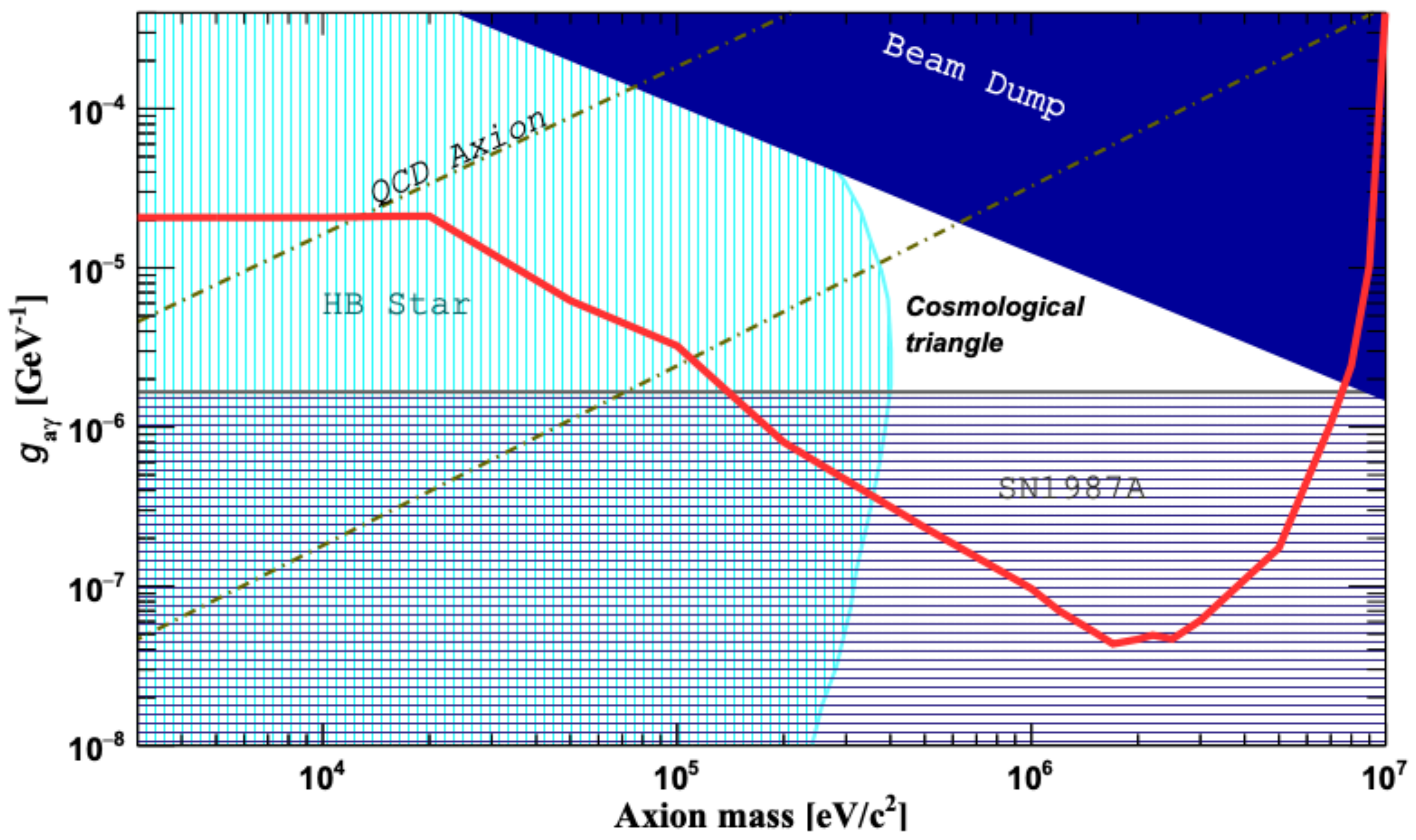


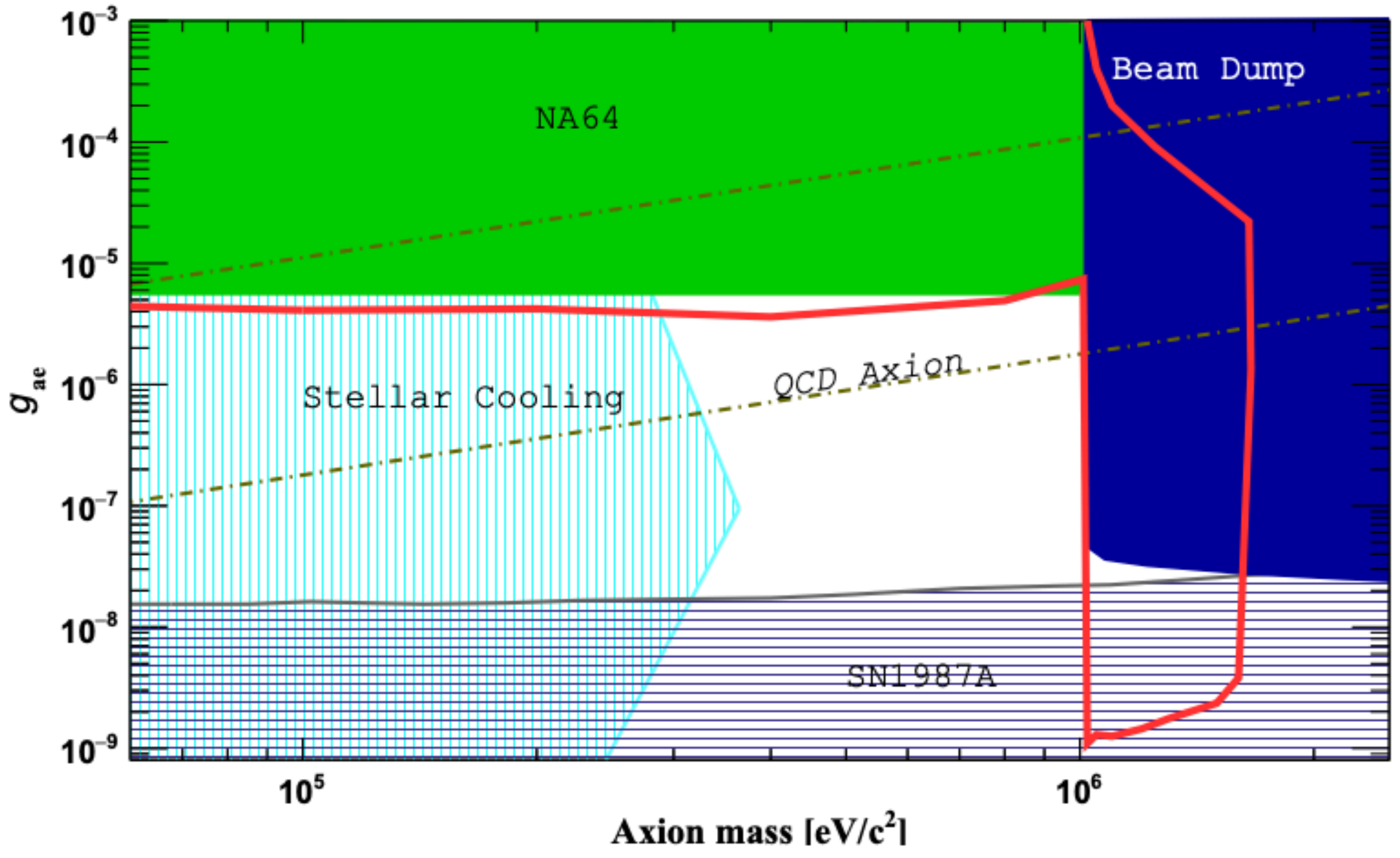
BSM Physics Analyses

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





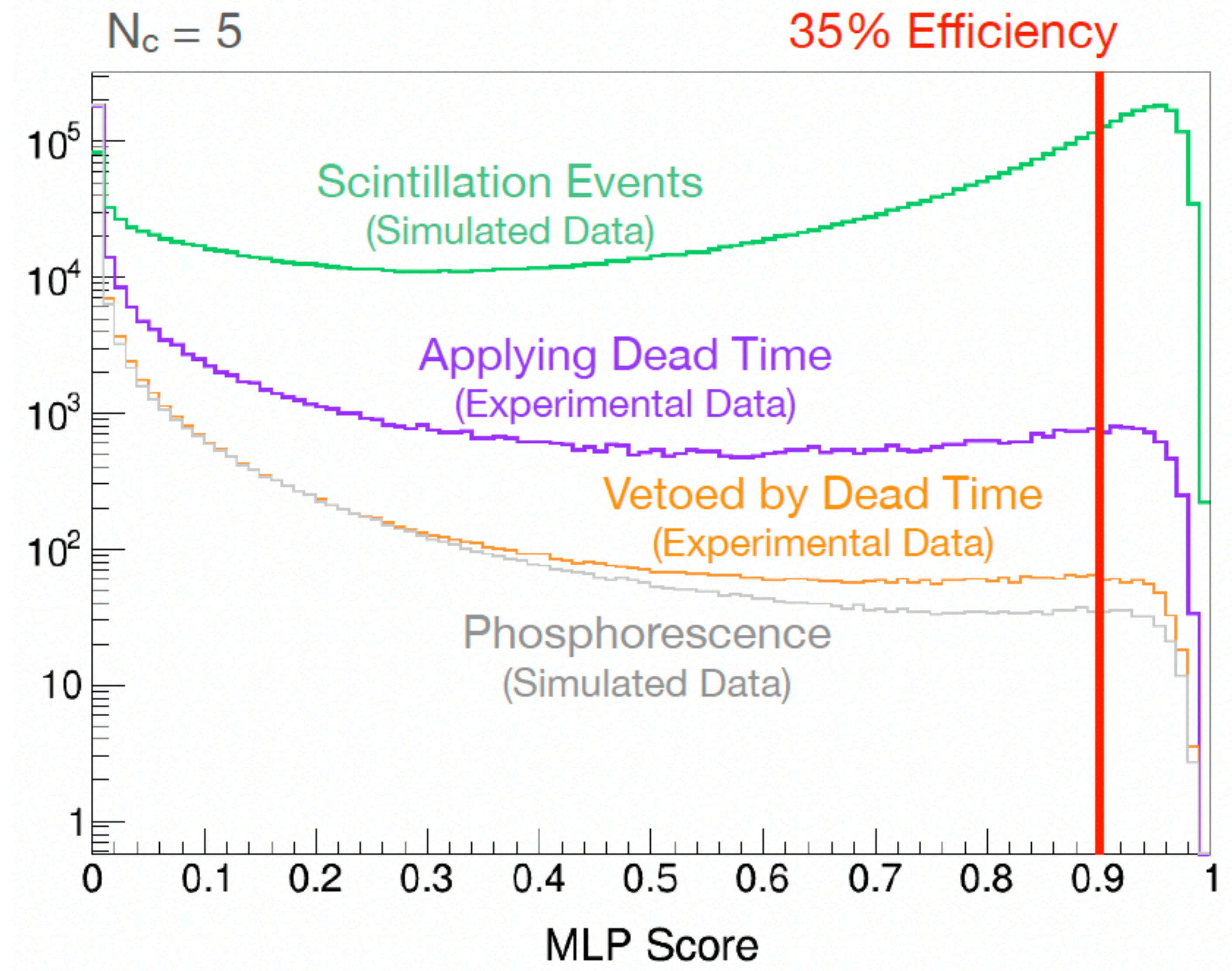


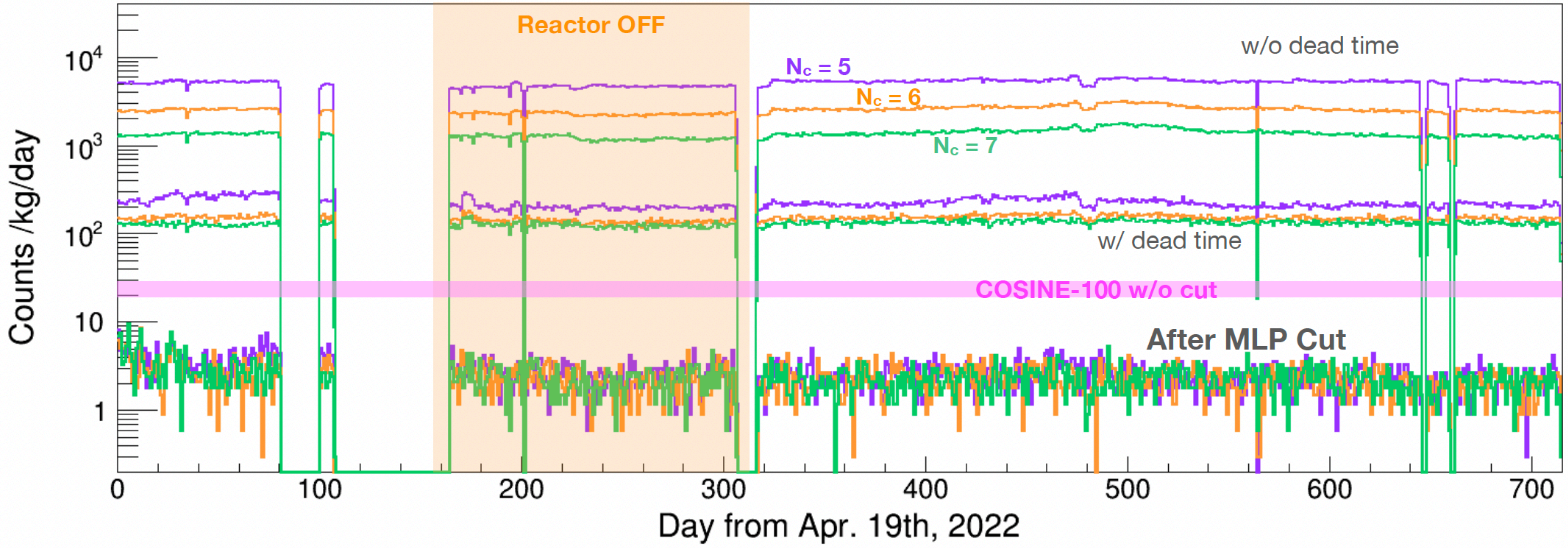


- Best ALP limits by NEON.
- Complete coverage for the Cosmological triangle
- Better limits for the Beam Dump experiments.

CEνNS Analysis

- We successfully lowered energy threshold down to 0.6 keV (~14 PE)
- *CEνNS* analysis uses Photoelectron(PE)-based approach.
    - Separate Selections for the Number of PEs (N_c)
    - Develop SPE-level discrimination parameters.
    - Then, run MLP Neural Network Algorithms for $N_c = 5,6,7$
- Dead Time is required to suppress cosmic-ray muon induced phosphors against scintillations (50% efficient & >90% rejections).



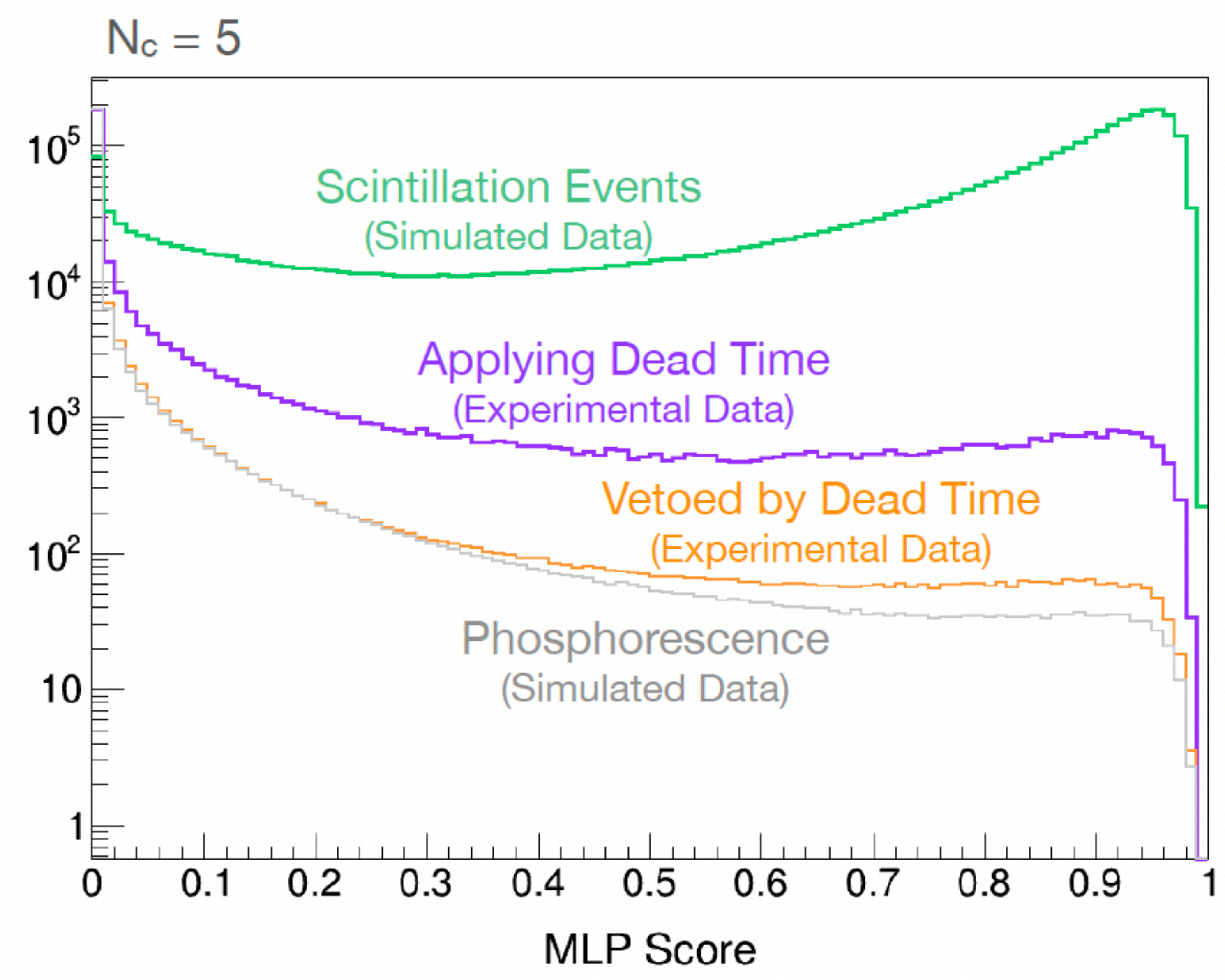


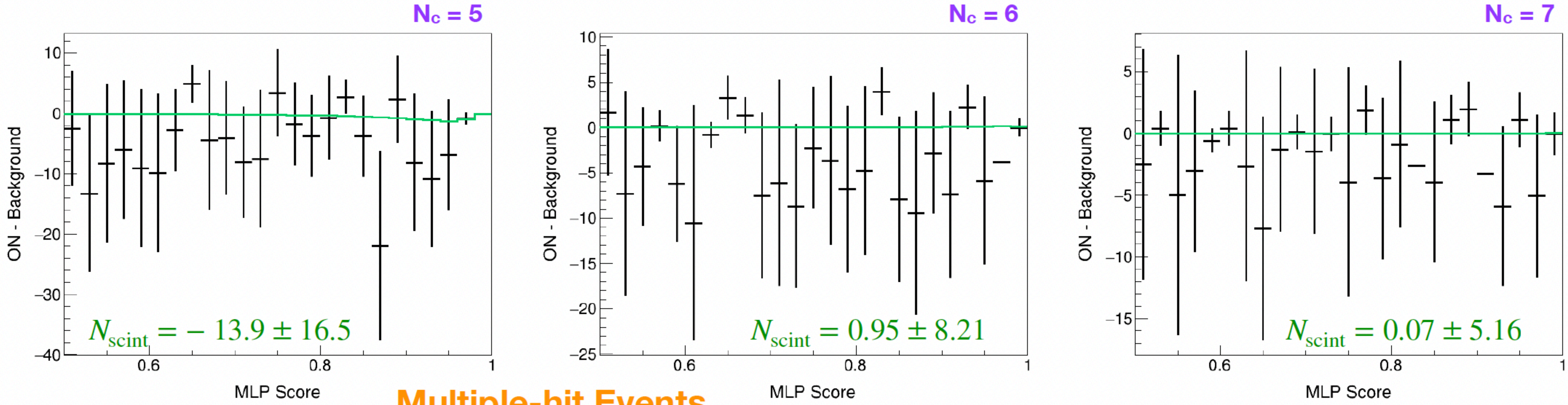
- At the Low PE level, MLP cut reduces data to several counts/kg/day rate.
- Rejected Events for Exp. and Phosphor Sim. data agree to each other.
- Therefore, those samples are used for training of background.

CEνNS Analysis

- Analysis Developed for each N_c using χ^2 method.
- Developing the framework for the fitting algorithm using Multiple-hit data.
- Unblinding the Single-hit data for the final best fit.

$$\chi^2 = \sum_i \frac{\left(M_i^{ON} - \tau M_i^{OFF} - \sum_j \beta_j B_i^j - \sigma S_i\right)^2}{M_i^{ON} + \tau^2 M_i^{OFF}} + \left(\frac{\tau - t^{ON}/t^{OFF}}{\sigma_t}\right)^2$$





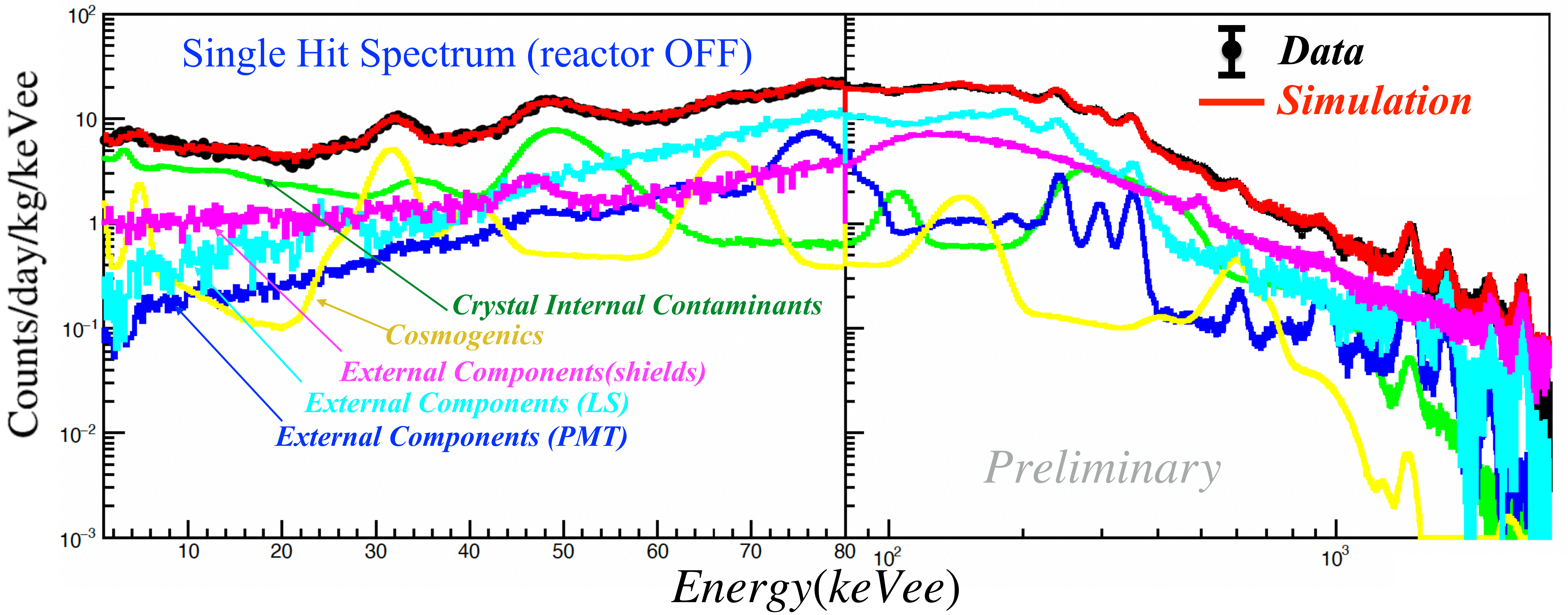
Multiple-hit Events

Summary and Outlook

- $CE\nu NS$ for reactor $\bar{\nu}_e$ opens up several physics opportunities.
- NEON is poised to measure the $CE\nu NS$ process in an array of NaI(Tl) crystals with high light yields of 24 PEs/keVee.
- The experiment is running stably since April 11, 2022, accumulating 523 (144) ON(OFF)-day data.
- Background modeling (~7 counts/day/kg/keV below 5 keV).
- In the meantime, we performed searches for Light Dark Matter and Axion-Like Particle and obtained the world best limits.
- For $CE\nu NS$ analysis, MLP method is used to select low-NPE scintillation signal more efficiently.
- The χ^2 fit method with the low-NPE sample has been on-going and unblinding is expected.

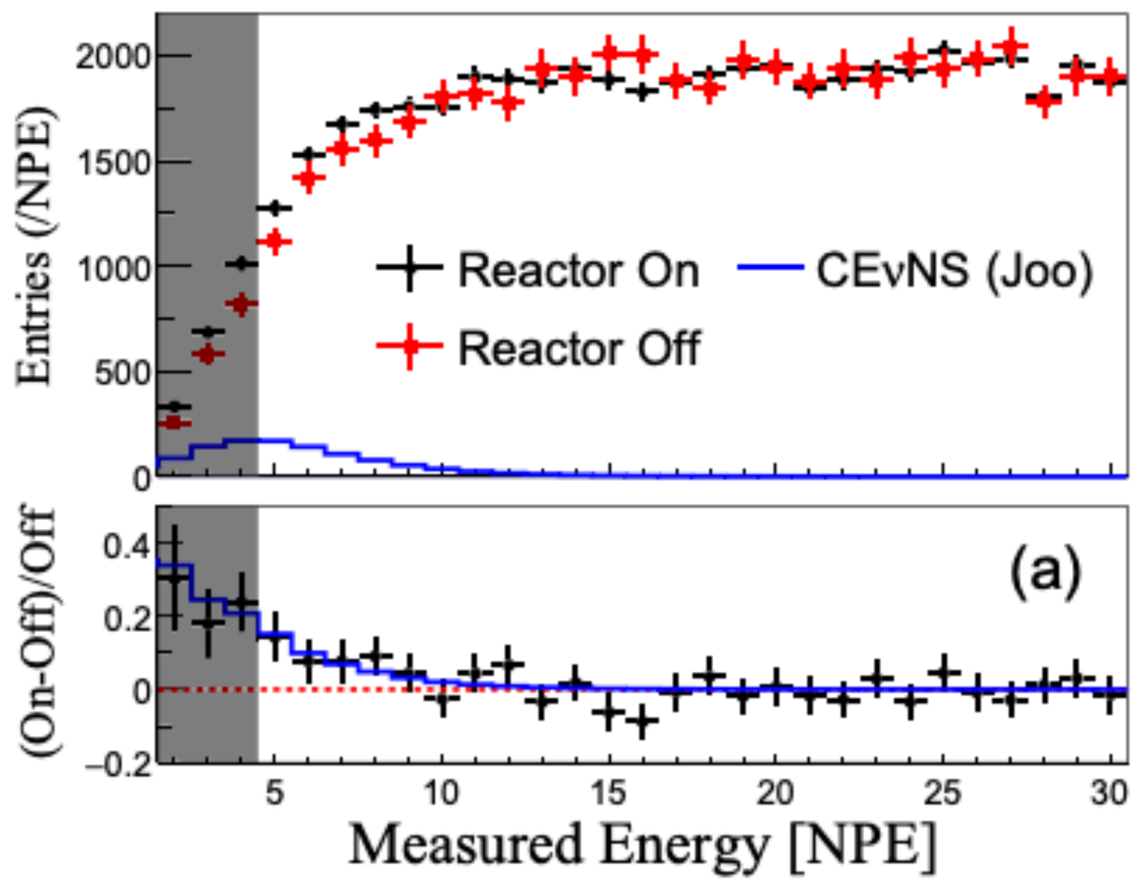
BACK

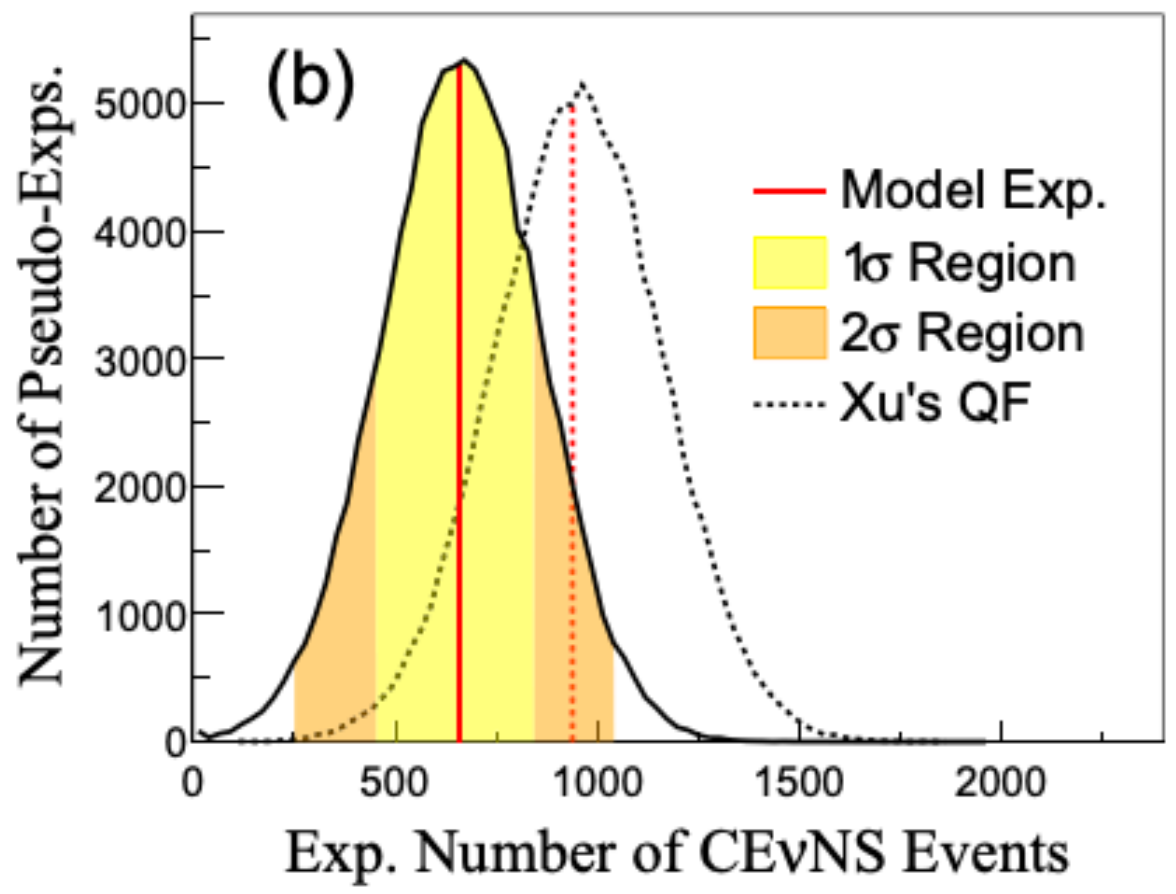
Background Understanding

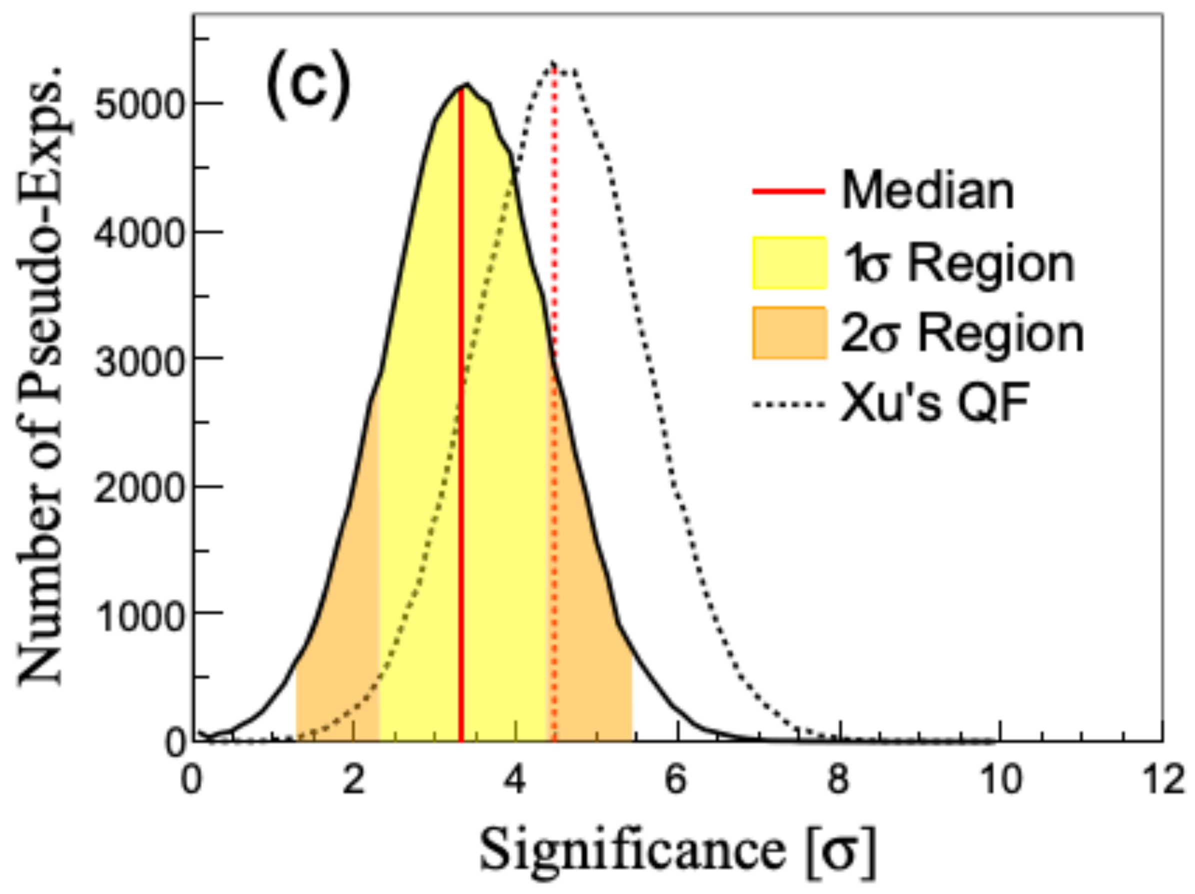


- Background Modeling is actively on-going up to 3 MeV.
- Single hit low energy at 1~10 keV region : ~ 7 counts/day/kg/keV
- Composition : internal ~60%, cosmogenic~20%, external~20%, muon phosphor~1%

Expected Rate and Sensitivity for NEON







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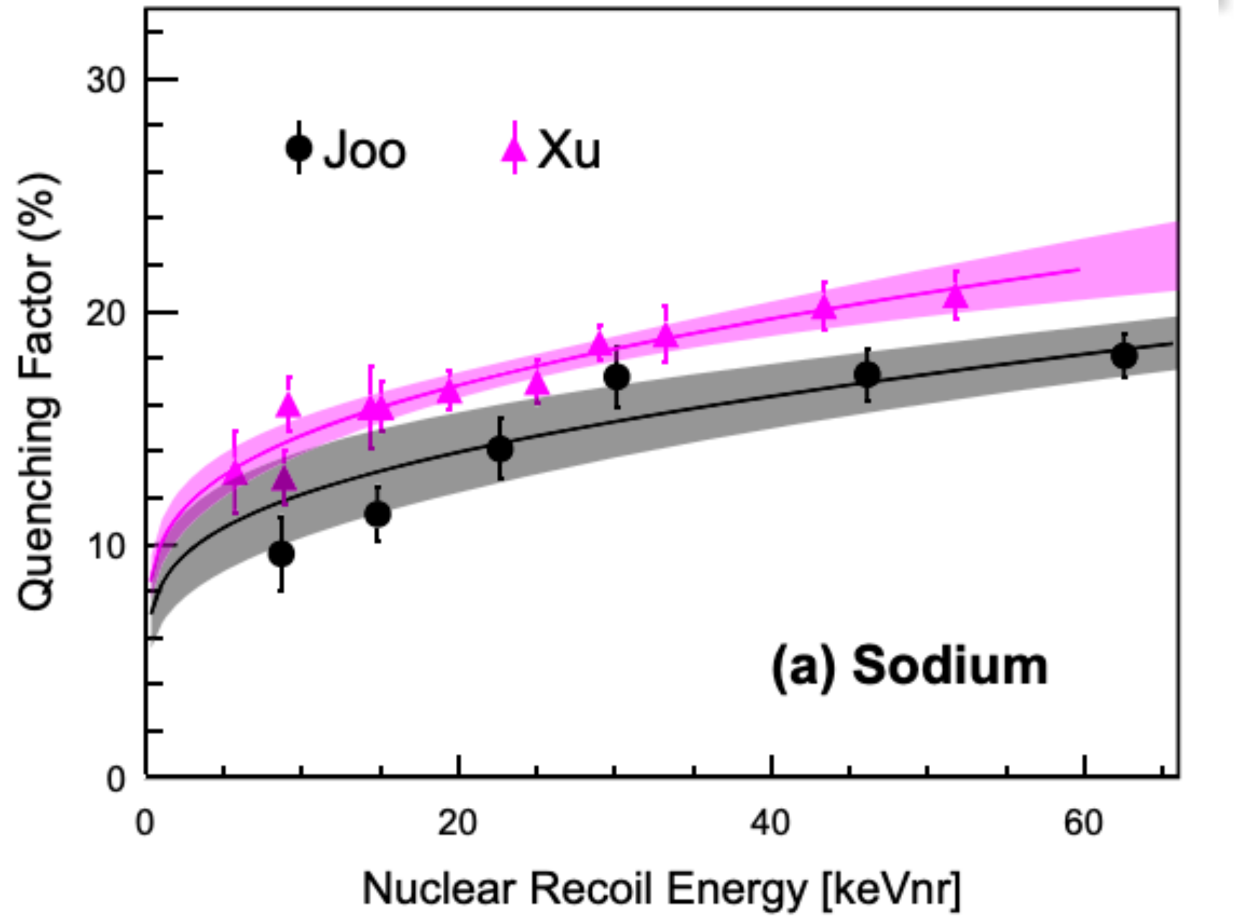
$$\chi^2 = \sum_i \frac{(N_{\mathrm{on},i} - \alpha_t N_{\mathrm{off},i} - \psi E_i)^2}{N_{\mathrm{on},i} + \alpha_t^2 N_{\mathrm{off},i}}$$

- 10^5 Pseudo-experiments



•Assumption for sensitivity study

✓ 22-photoelectrons/keV(PEs/keV) light yield

✓ 13.5-kg mass of detector

✓ 7-counts/kg/day/keV flat background

✓ 5-PEs threshold (Currently 14 PEs threshold)

✓ 365/100-days reactor-on/-off data

650 ± 197 *(Joo QF)*

941 ± 209 *(Xu QF)*

Sensitivity estimation shows that more than 3σ detection is possible assuming the 5-PE threshold is reached.