Search for Dark Sector Particles at a Nuclear Reactor from the NEON Experiment

Hyun Su Lee

Center for Underground Physics (CUP)

Institute for Basic Science (IBS)

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CENTER FOR UNDERGROUND PHYSICS ibs

$\bar{\nu}_e$ ON

NEON Experiment

NEON (Neutrino Elastic-scattering Observation with NaI)

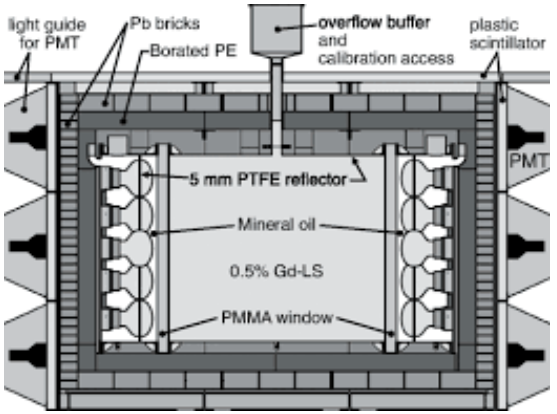
Aims to observe Coherent Elastic Neutrino Nucleus Scattering (CEνNS) from reactor $\bar{\nu}_e$ using NaI(Tl) detector

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

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

COSINE-100

NEOS



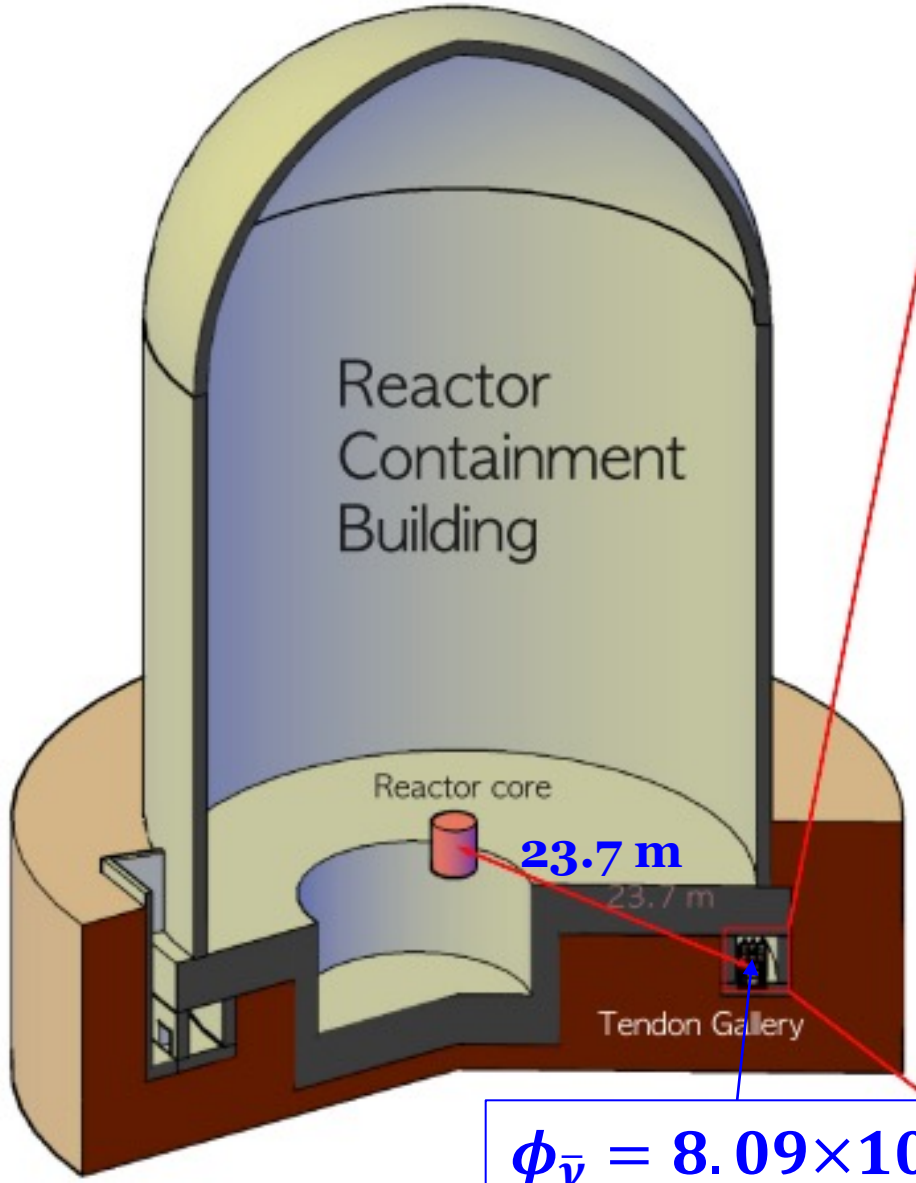
See Seohyun's talk for CEνNS measurement

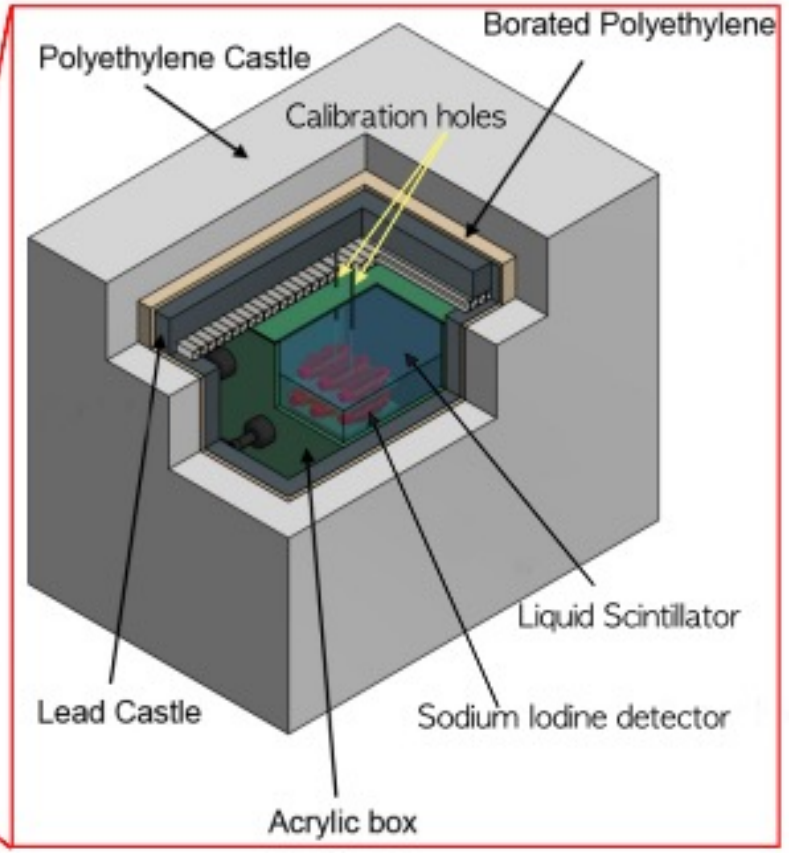
Neutrino session, Today 6:00 PM

Experimental Site

Six NaI(Tl) crystals : 16.7 kg

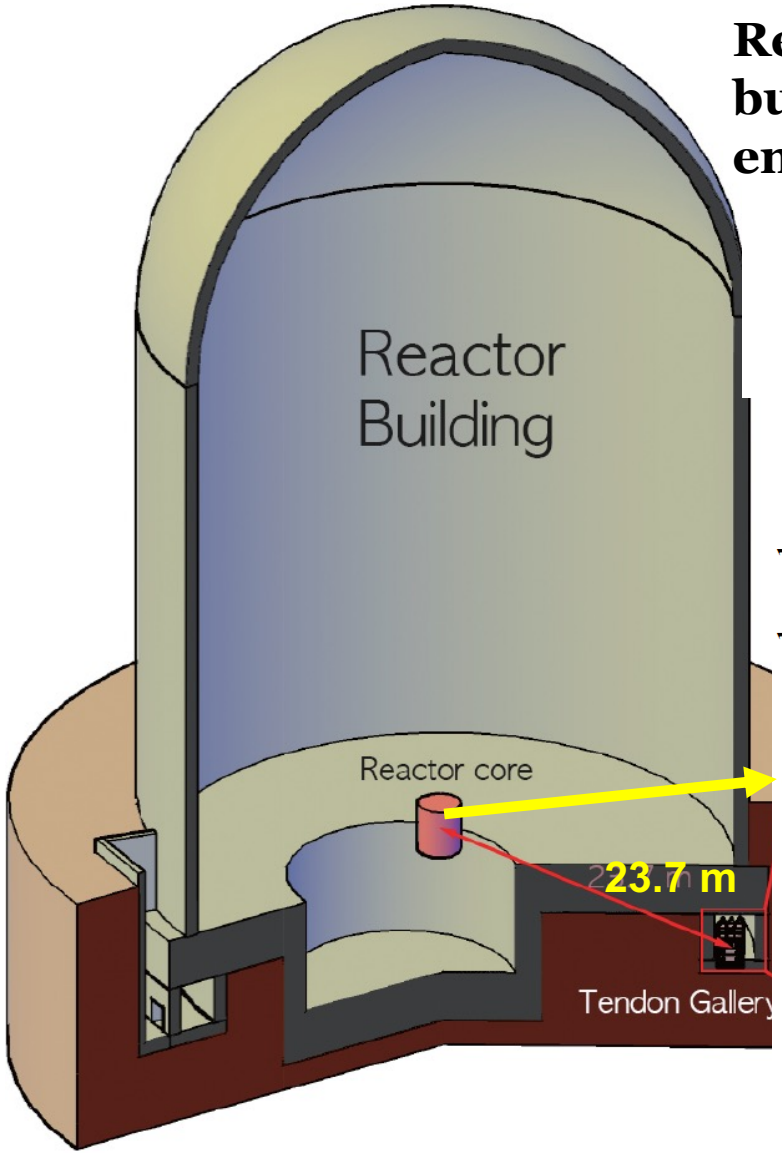
Physics run since April/2022





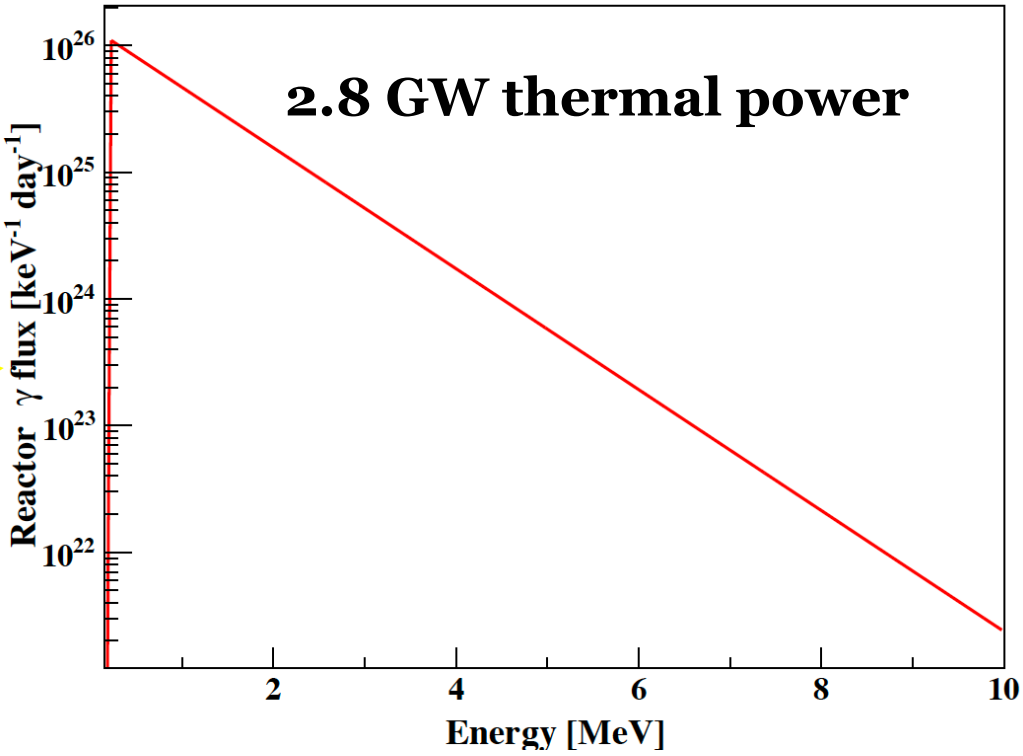
$$\phi_{\bar{\nu}} = 8.09 \times 10^{12}\ /cm^2/s$$

Reactor photons

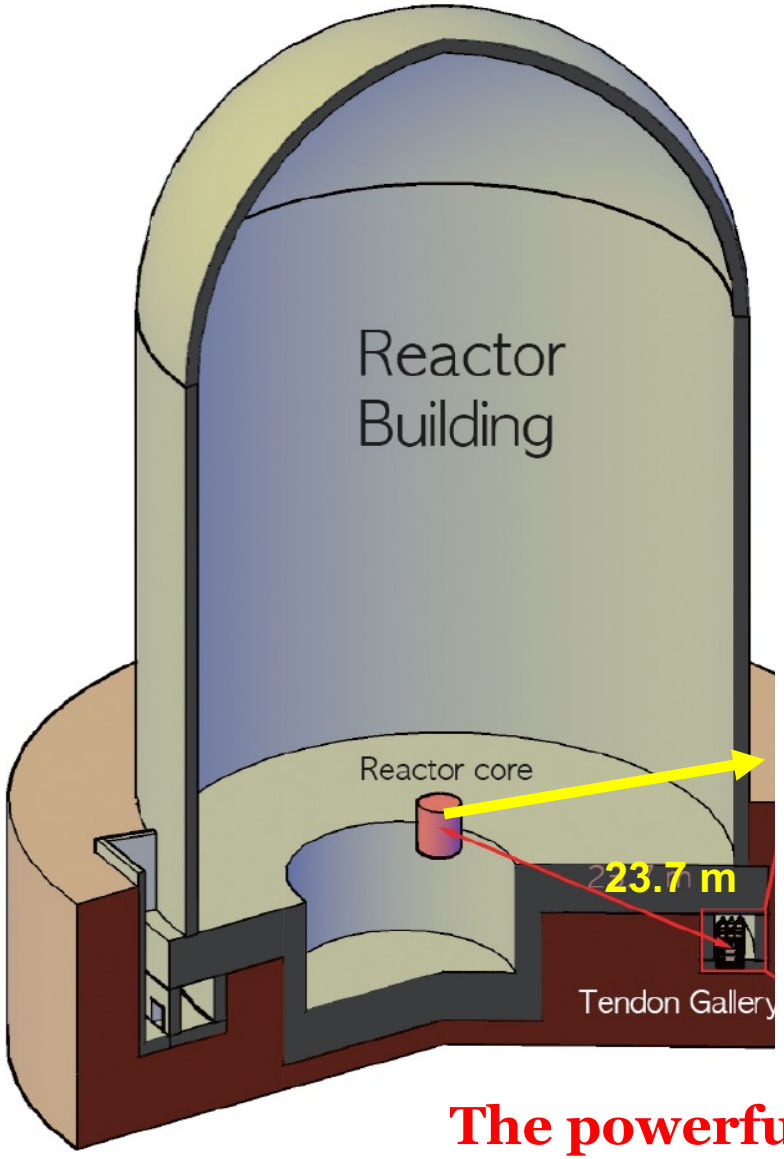


Reactor is not only an intense neutrino source but also an intense gamma source for O(MeV) energy

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

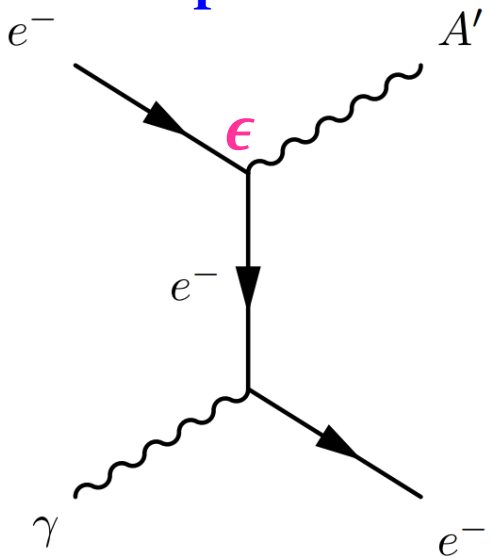


Reactor dark sector bosonic particles

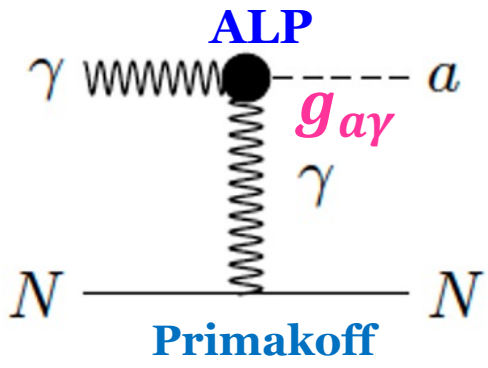


Photons can couple to dark sector bosonic particles such the dark photon and the axion like particle (ALP) with their mass up to O(MeV)

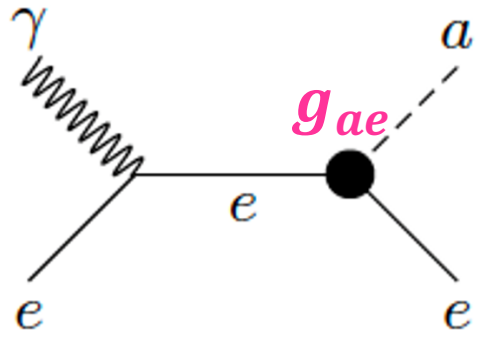
Dark photon



ALP



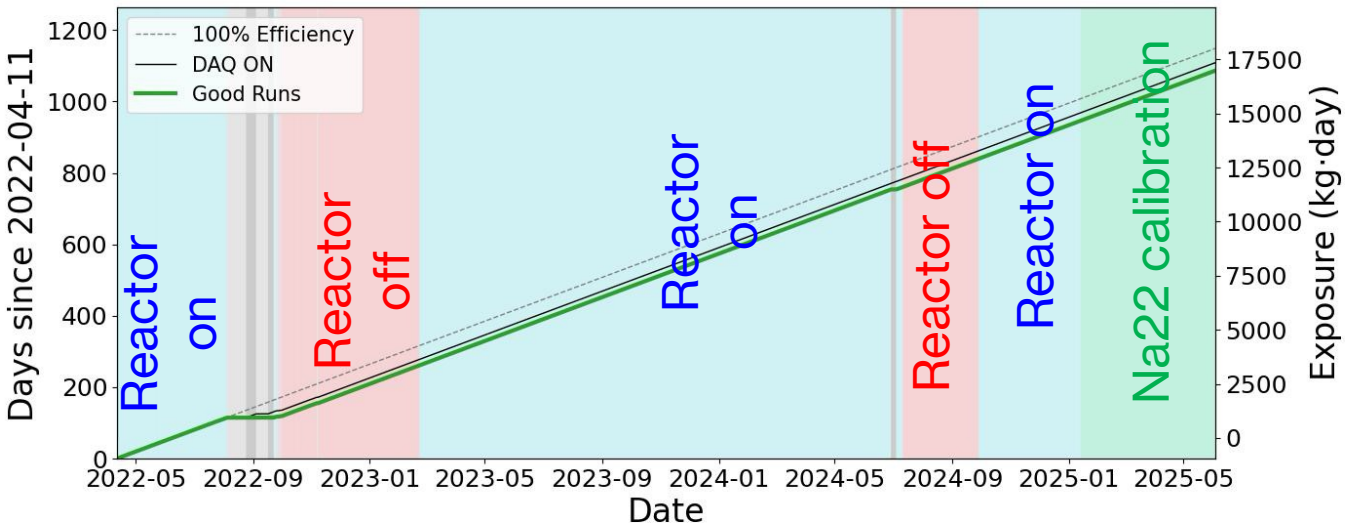
Primakoff

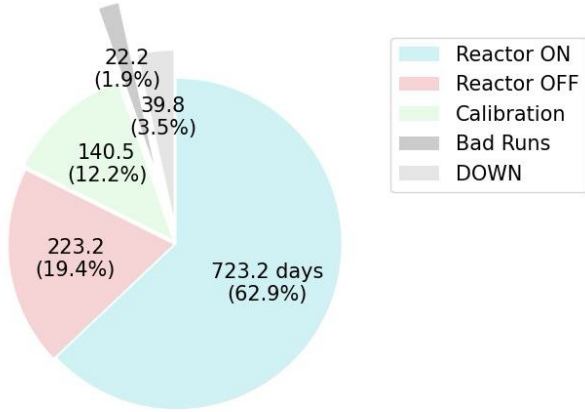


Compton-like

The powerful source of dark photon & ALP

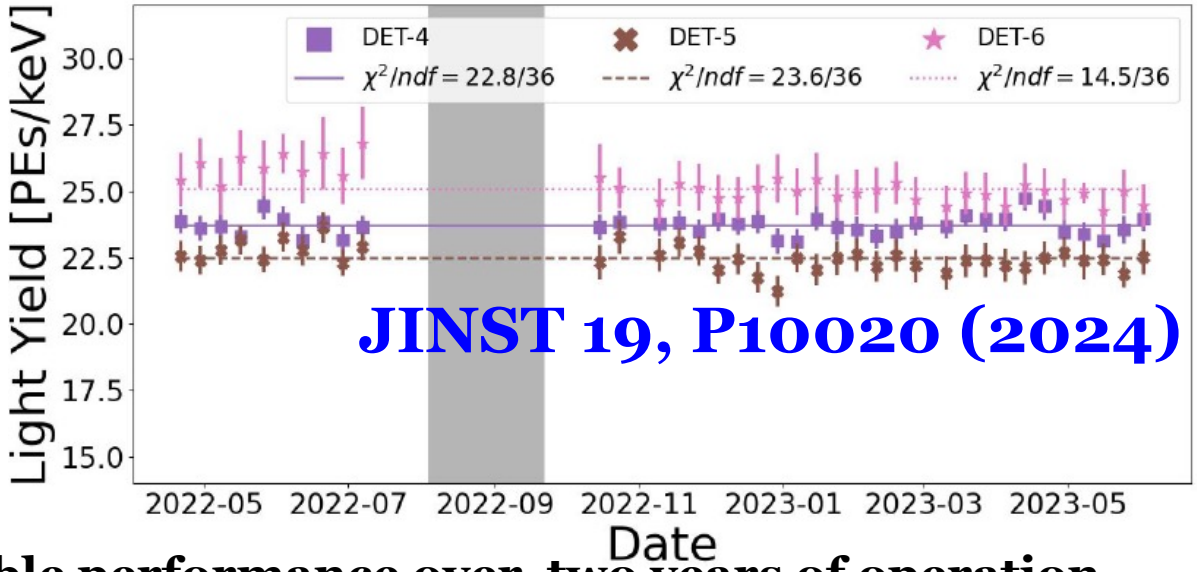
Physics Operation





- Physics run started in April 2022 (> 3 years)
  - ❖ ~95% DAQ efficiency
- **723 days** of ON data
- **223 days** of OFF data
- 140 days of Na22 calibration

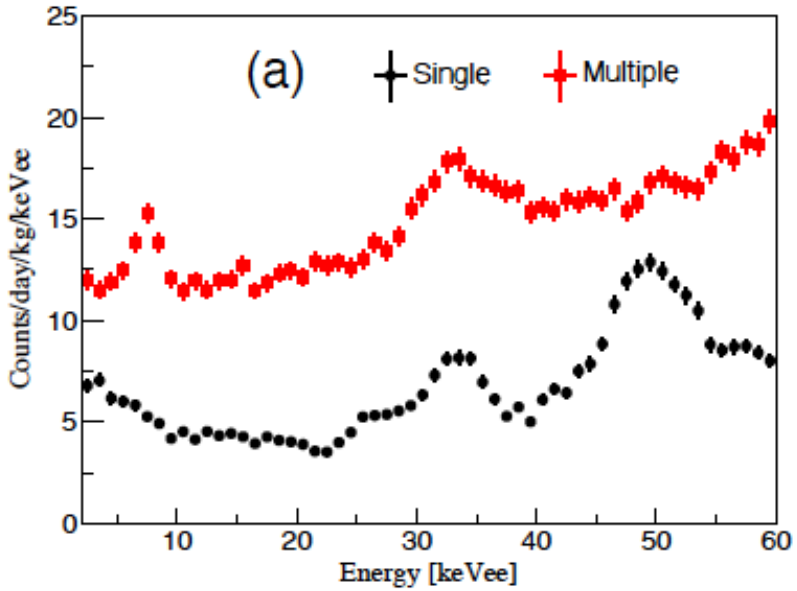
Detector performance

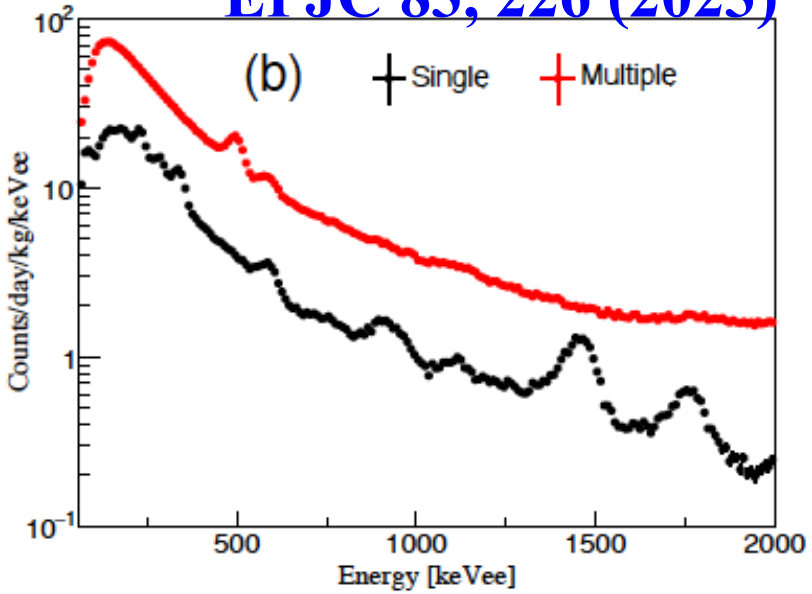


JINST 19, P10020 (2024)

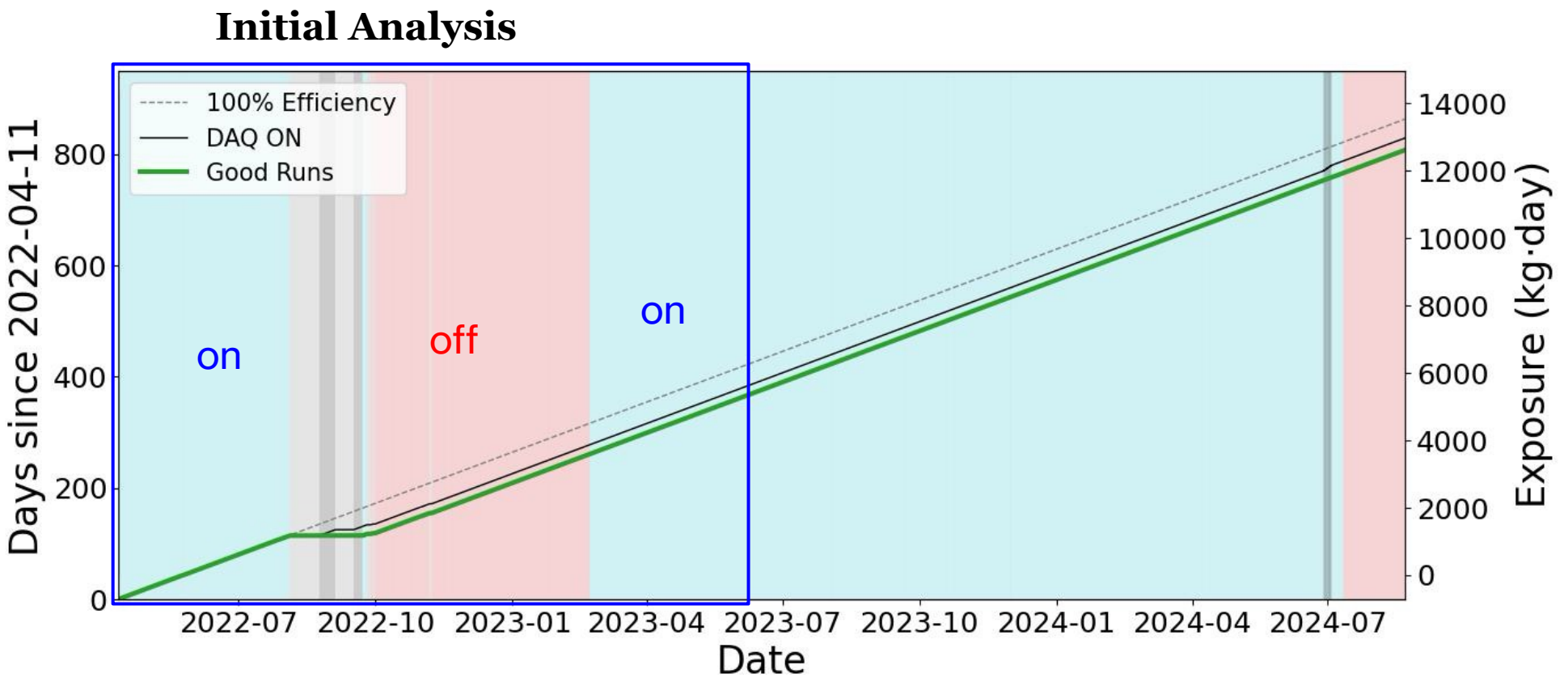
Stable performance over two years of operation

EPJC 83, 226 (2023)



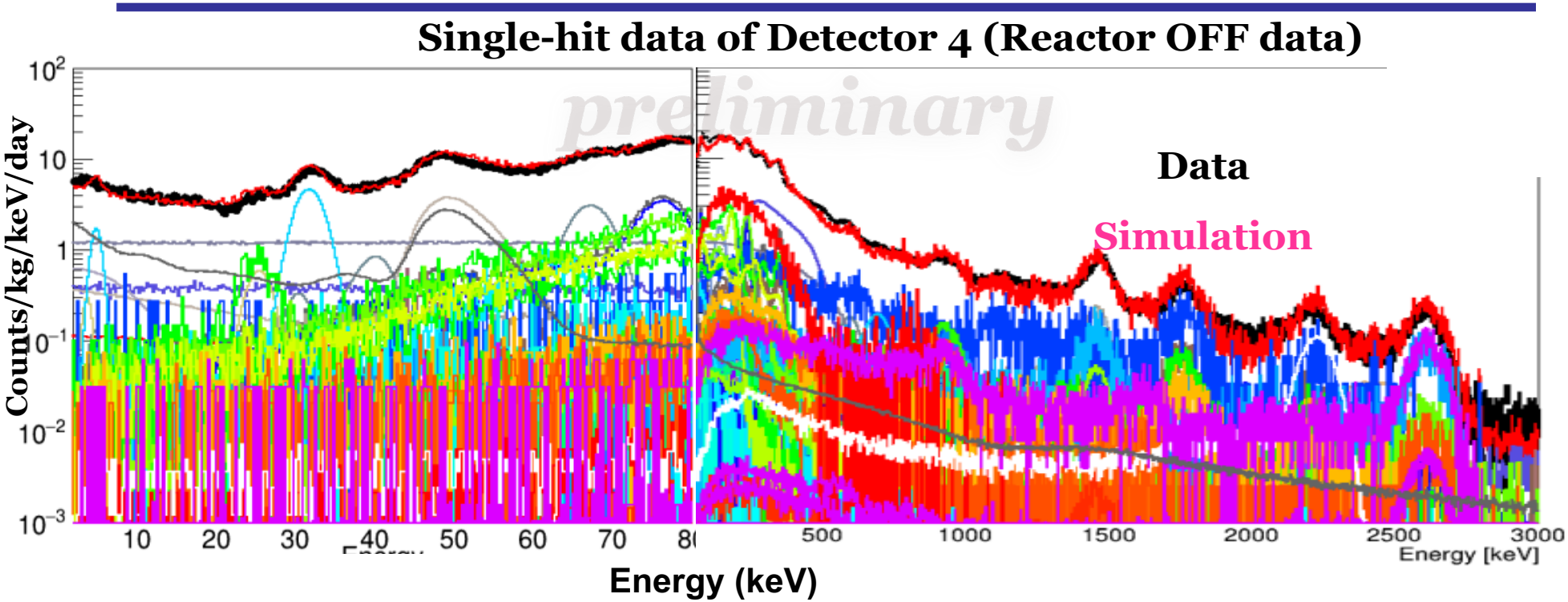


Analyzed data



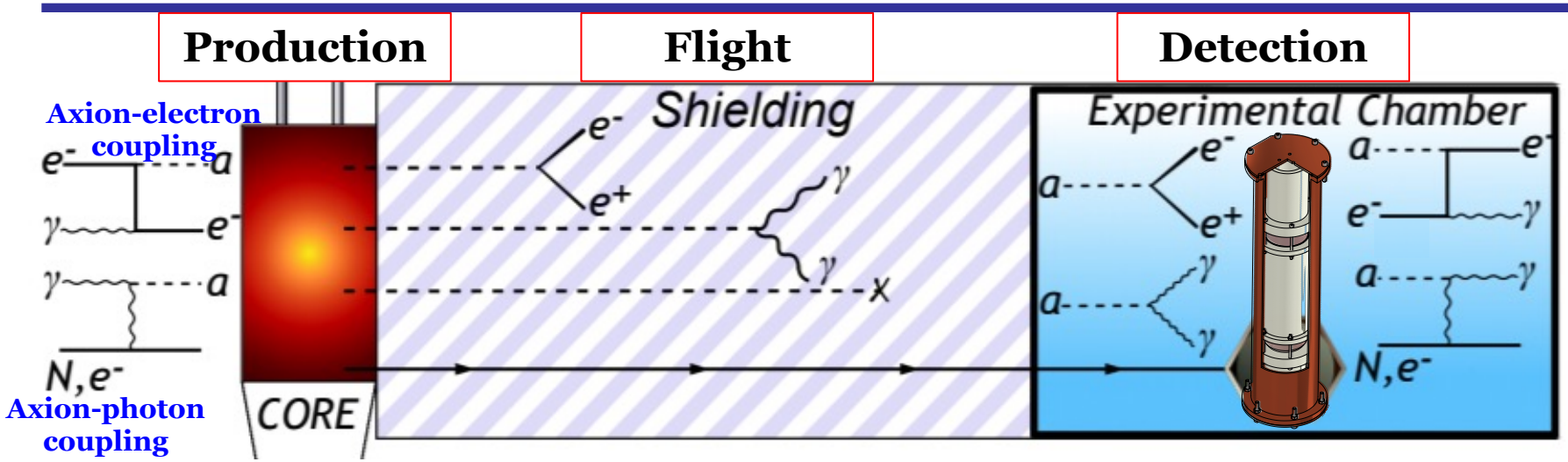
- Initial analyses used data collected during April/2022 ~ June/2023

Background understanding

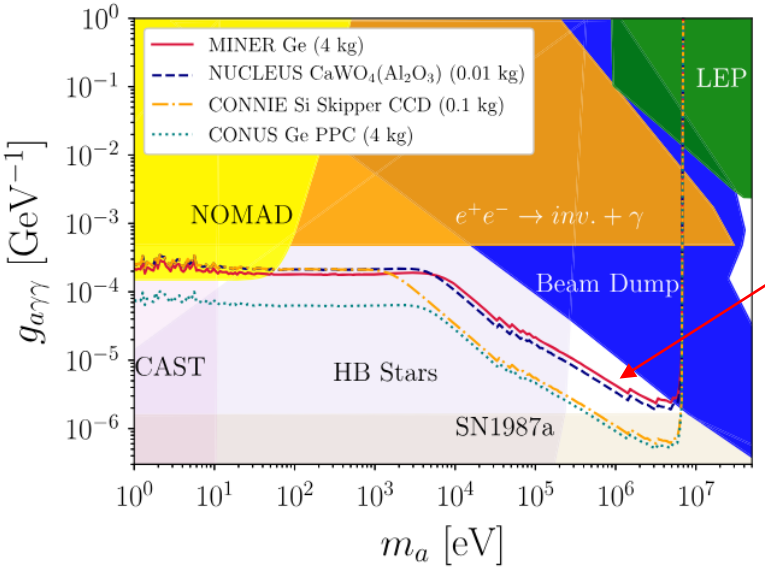


- Background understanding is based on our experience with COSINE-100 dark matter search experiment
  - ❖ EPJC 78 (2018) 490; EPJC 81 (2021) 837; EPJC 85, 32 (2025)
- 3 keV – 3 MeV are modeled

Axion-Like Particle (ALP)



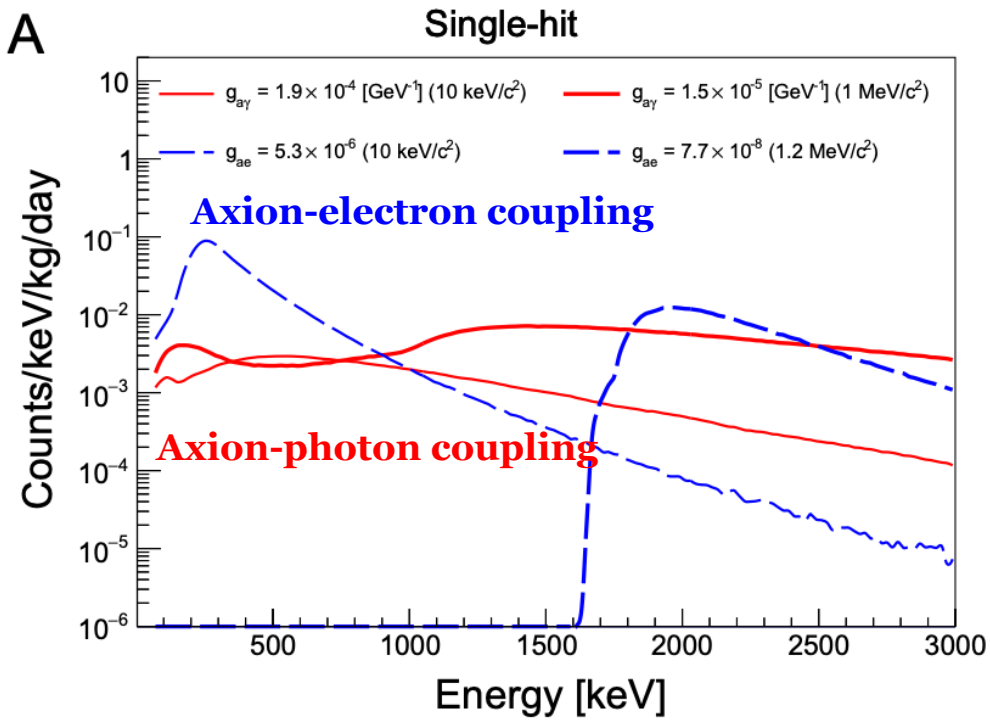
PRL 124, 211804 (2020) & JHEP 03, 294 (2021)

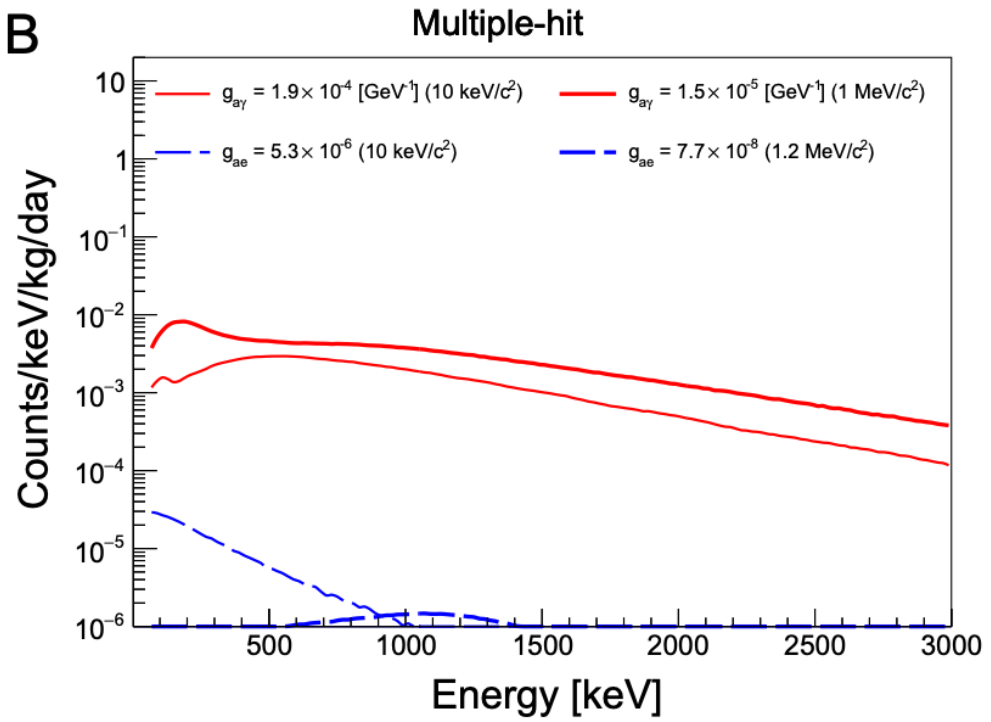


Cosmological Triangle

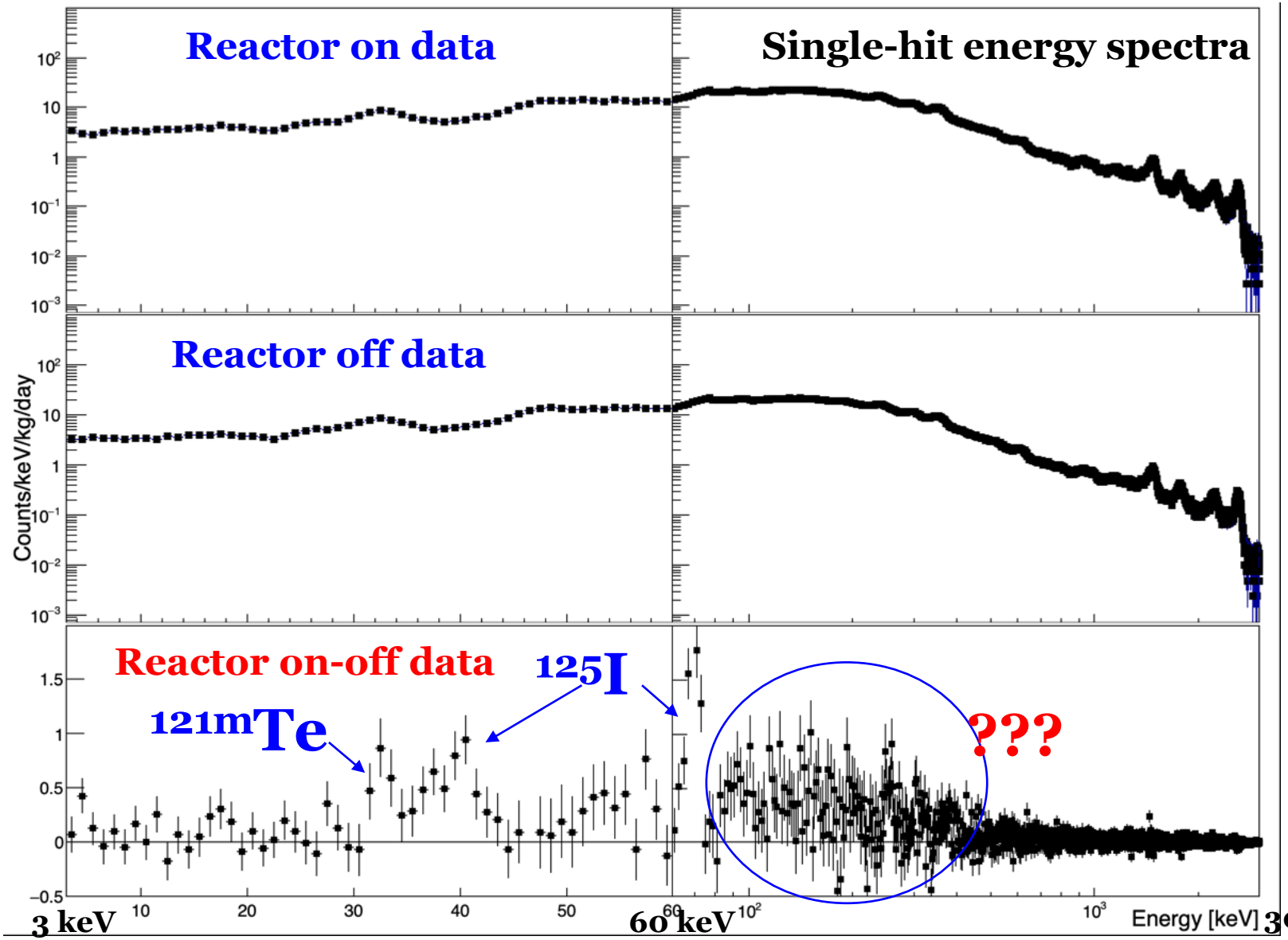
ALP signals in NEON detector

Expected ALP signals in the NEON detector

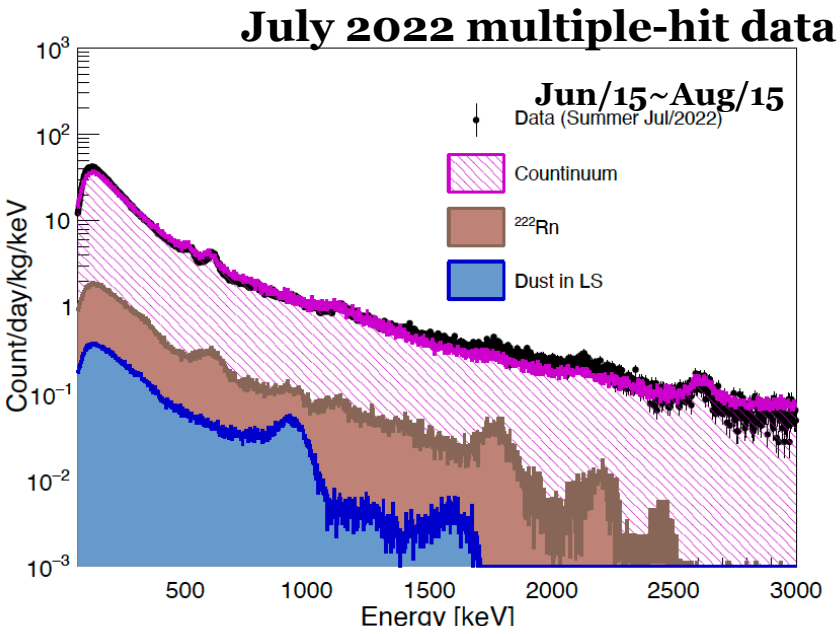


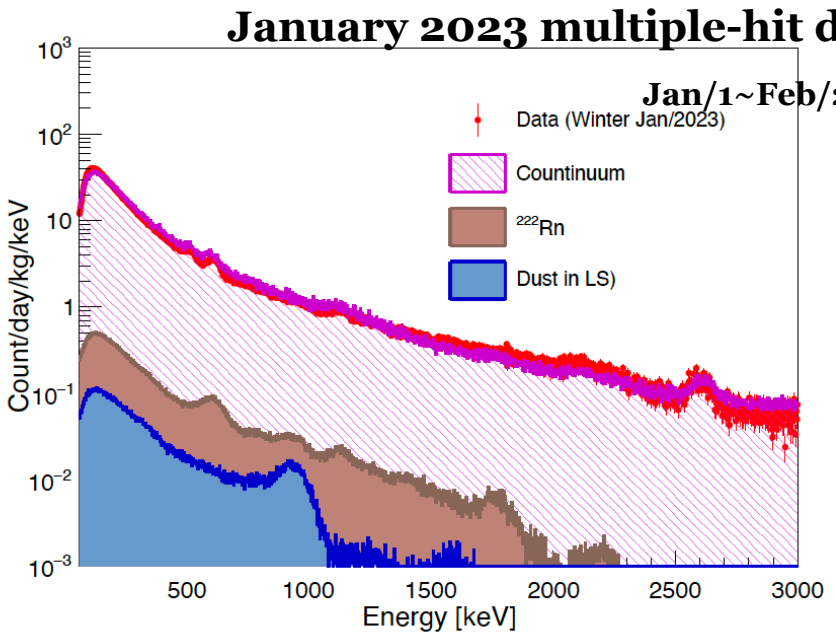


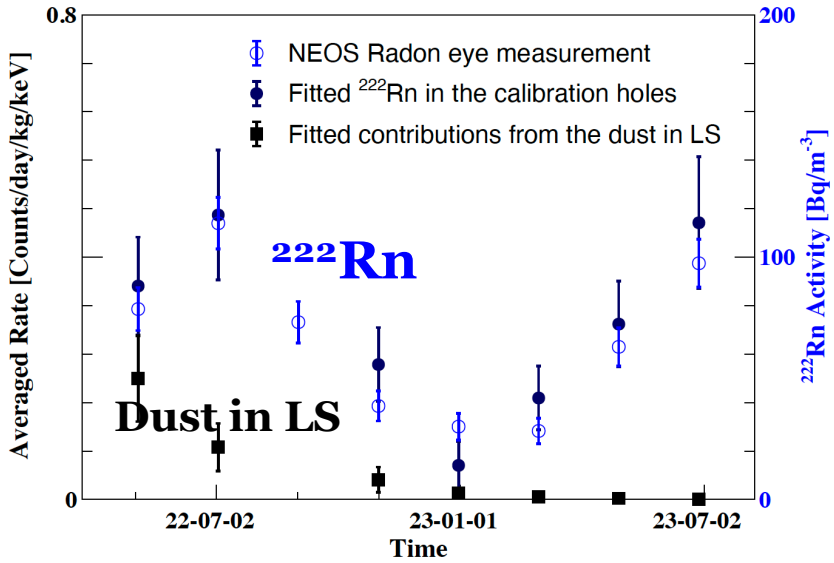
Comparison of Reactor-on and -off Data

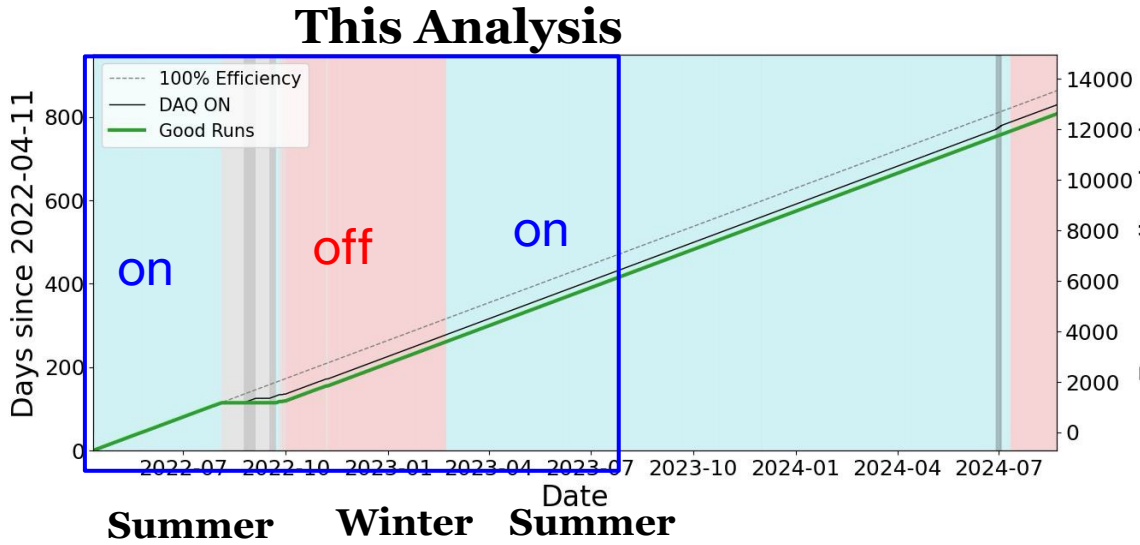


^{222}Rn contribution

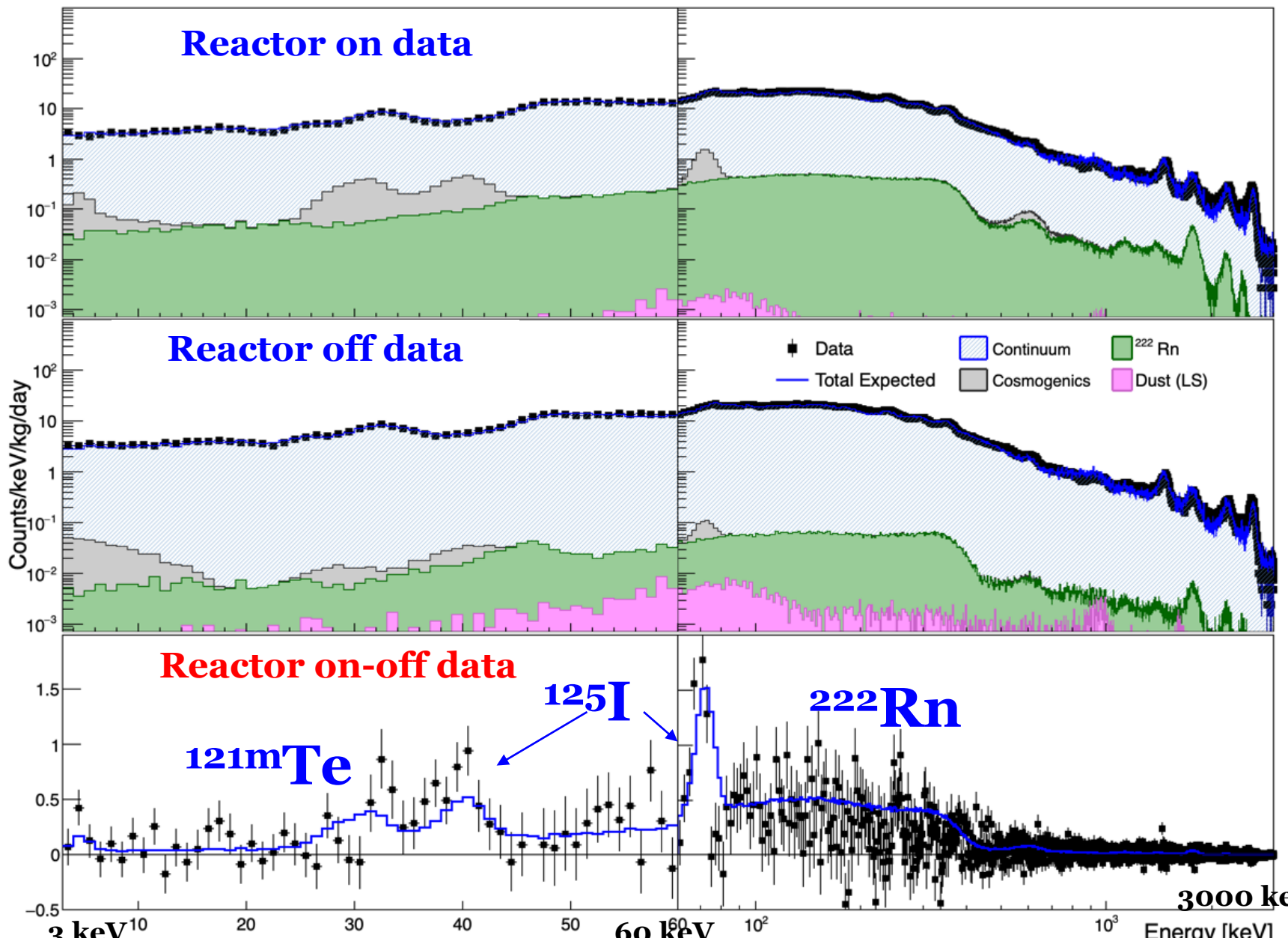




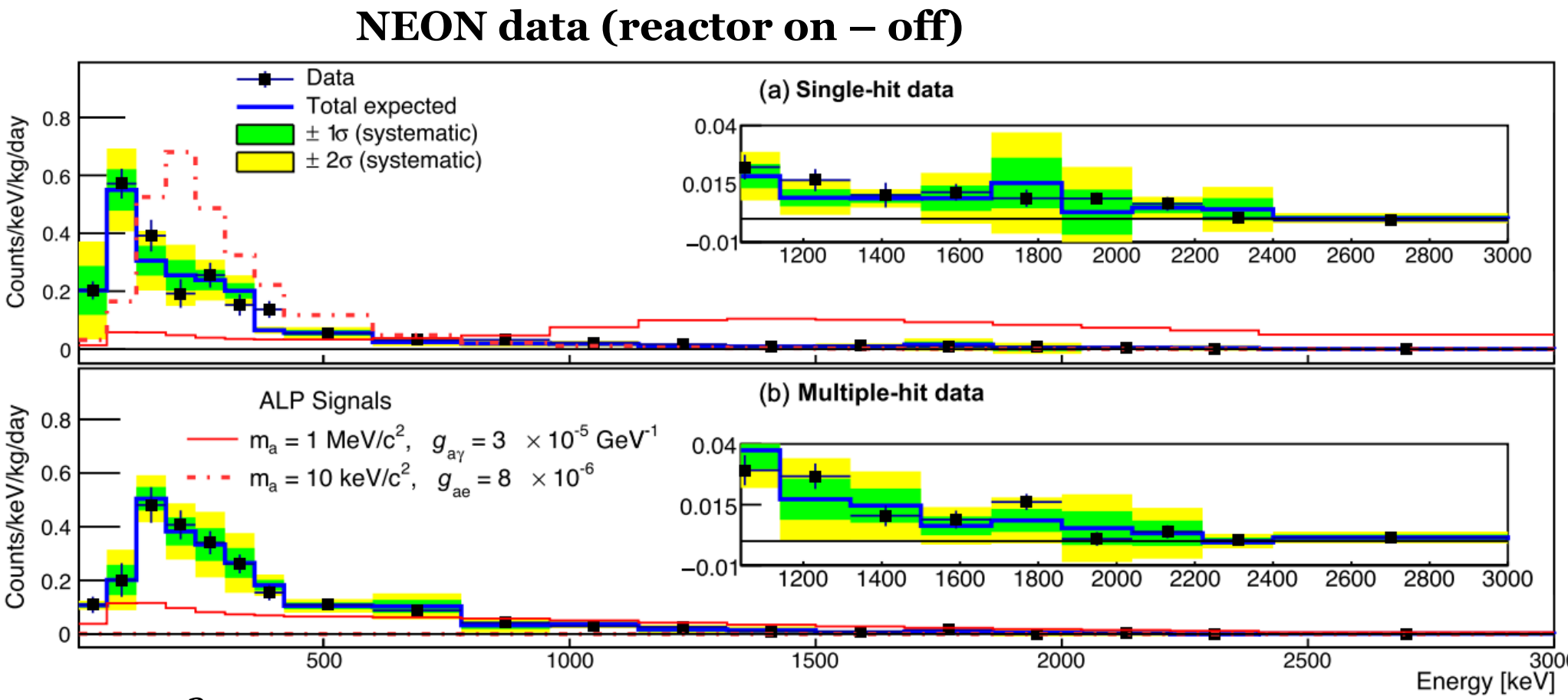




NEON On – Off data with Modeling



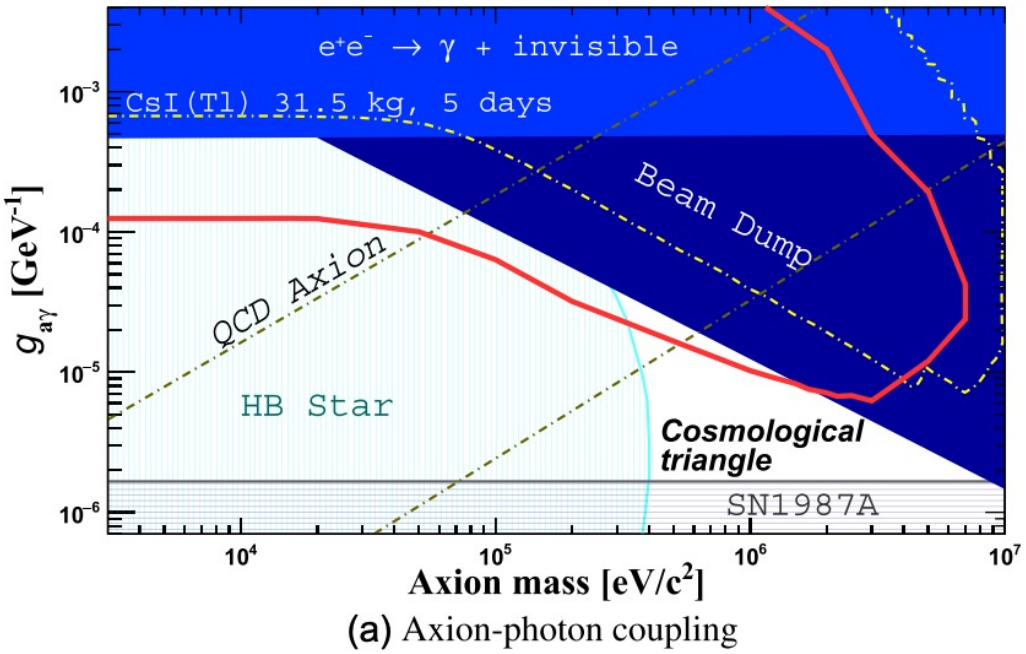
ALP search data (detector 6)



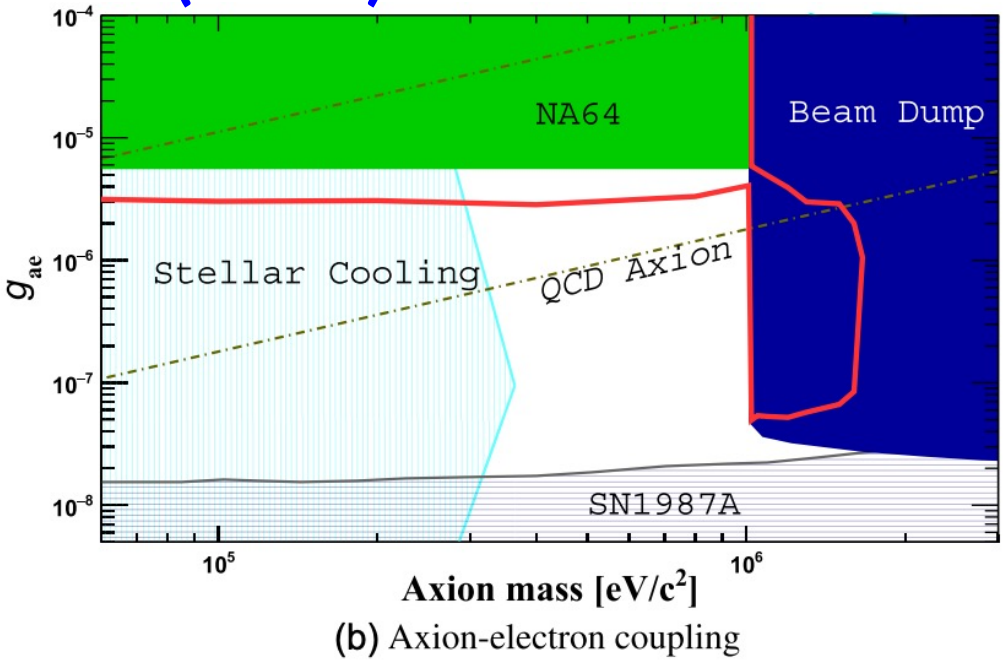
- χ^2 fit to data with the expected time-dependent backgrounds and ALP signals

New Constraints on ALP Couplings from NEON

PRL 134, 201002 (2025)



(a) Axion-photon coupling



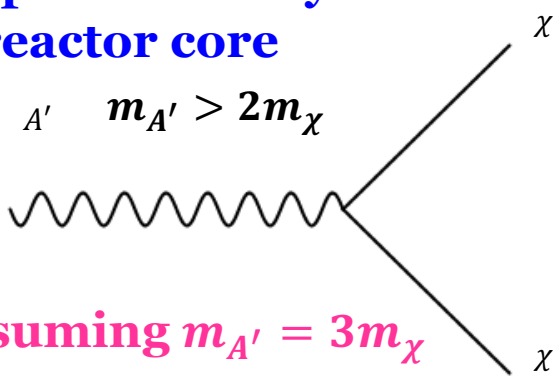
(b) Axion-electron coupling

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

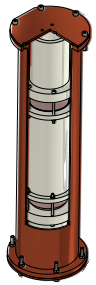
Light Dark Matter Search

- Through light dark matter (LDM) production

Dark photon decay @ reactor core

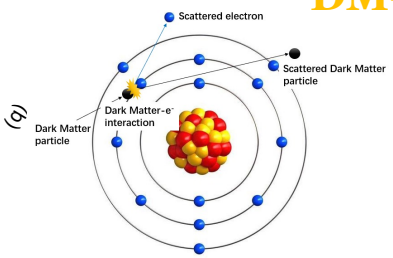


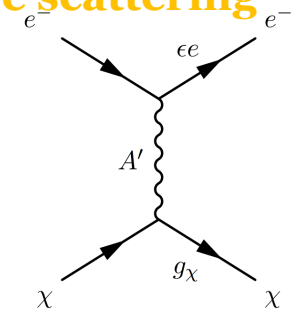
Assuming $m_{A'} = 3m_\chi$



Detector

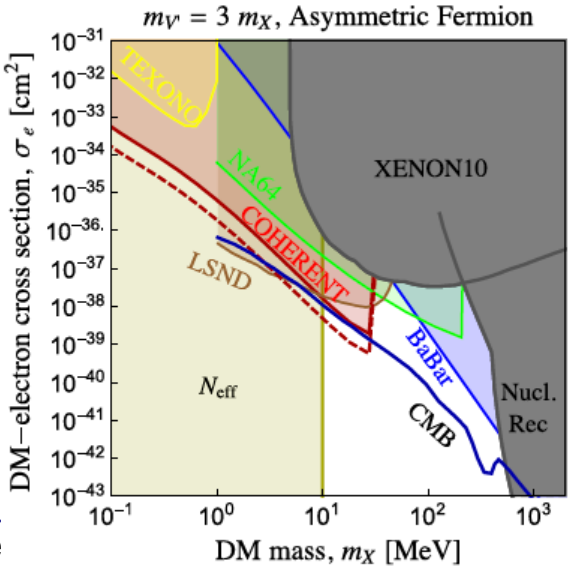
DM-e scattering

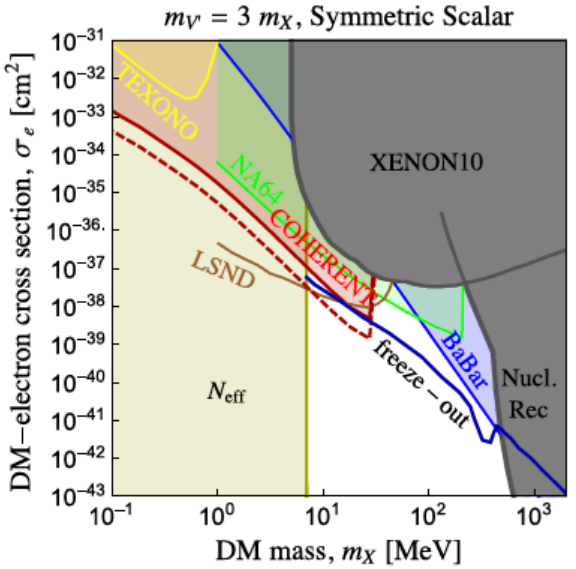




COHERENT LDM-nucleon scattering : PRL 130, 051803 (2023)

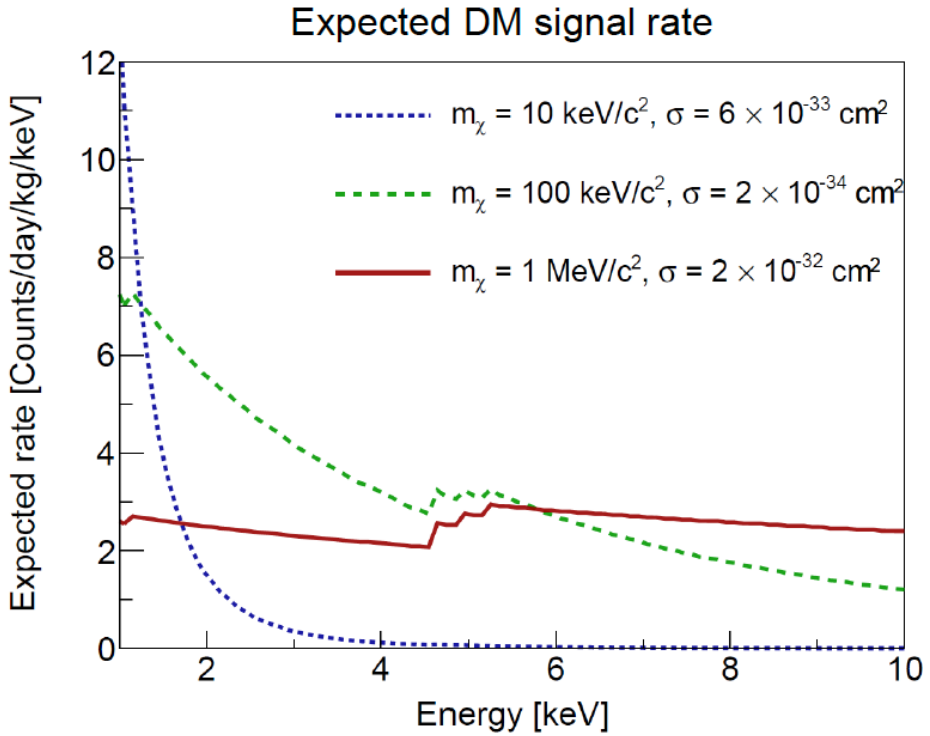
Theory study : JHEP 11 (2018) 066





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)



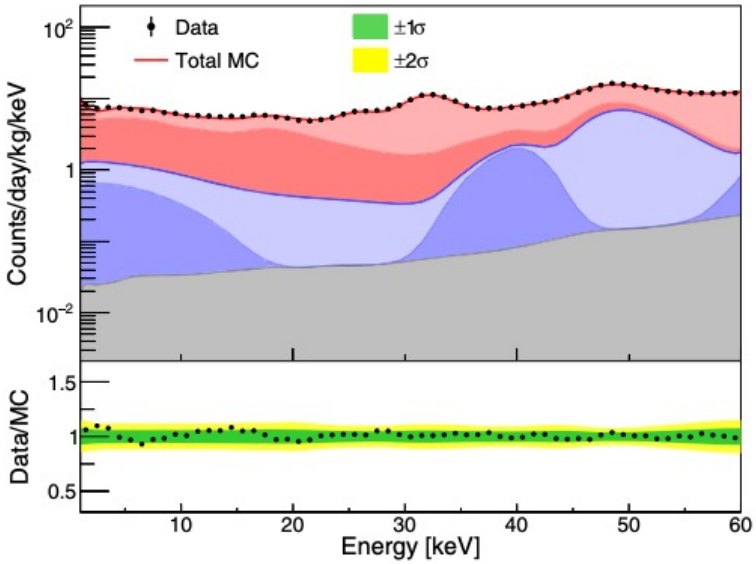
Region of Interest

1 – 10 keV

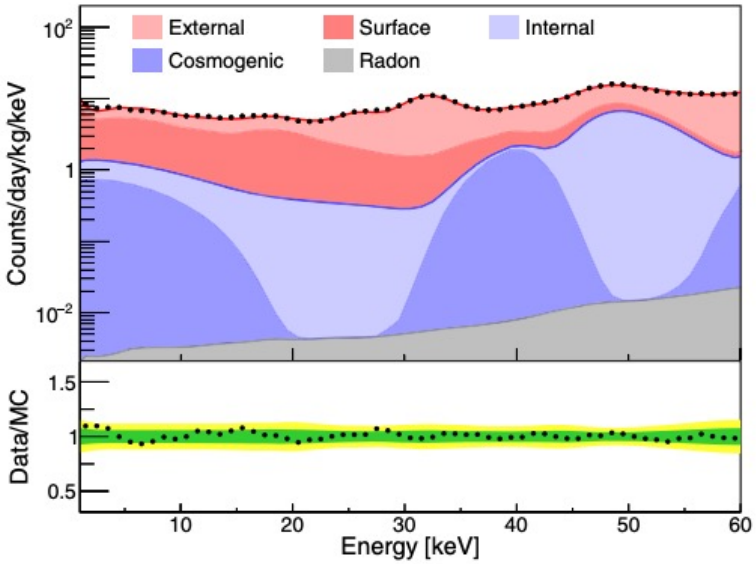
- Apply detector responses

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

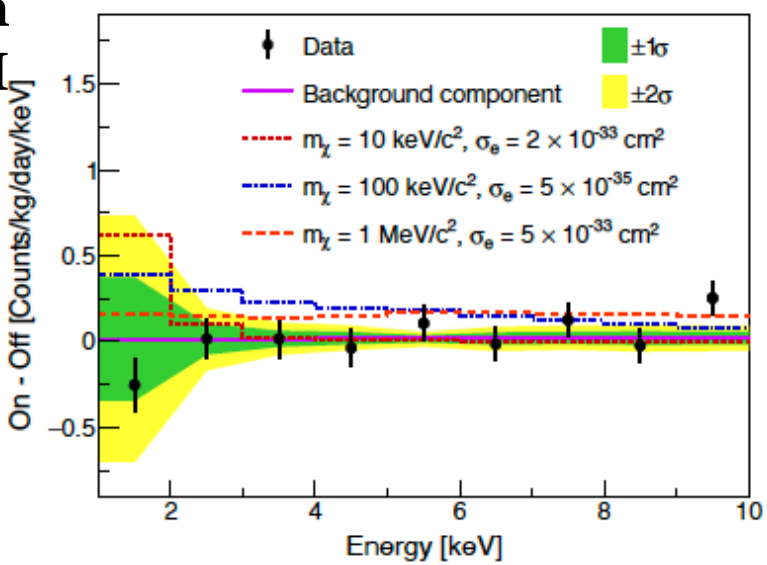
Data Background Signal

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

Signal strength

Statistical uncertainty with error of efficiency

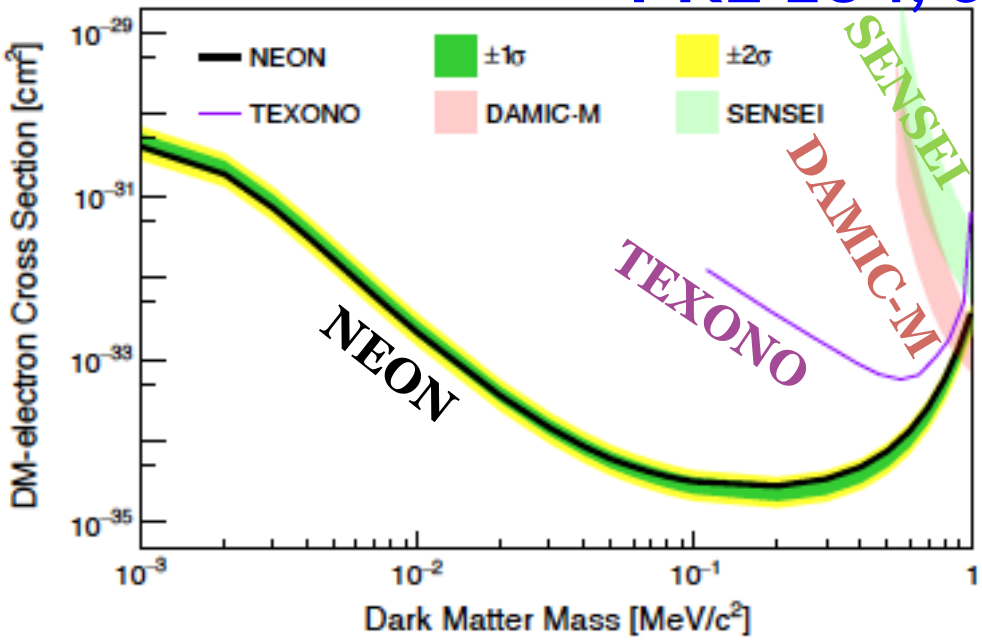
Signal region : 1-10 keV

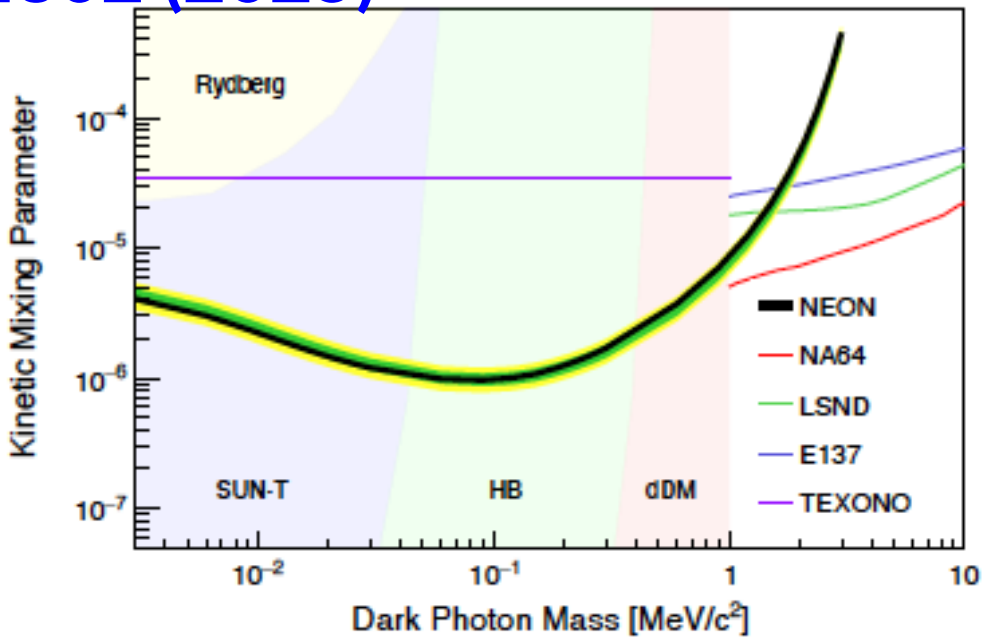


World-Leading Limits on LDM from NEON

- No signal excess – 90% confidence level upper limit

PRL 134, 021802 (2025)



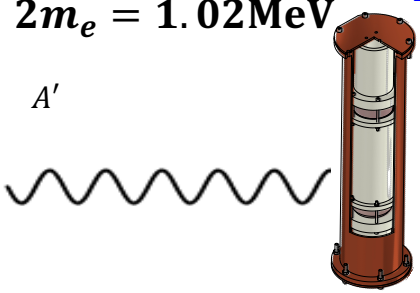


- Best Limits achieved for the Light Dark Matter Search.
- Below 1 MeV/c^2, NEON shows the best limit for DM-electron cross section and the kinetic mixing parameter for the dark photon.

Dark photon search (another channel)

$m_{A'} < 2m_{\chi}$

$m_{A'} < 2m_e = 1.02\text{MeV}$

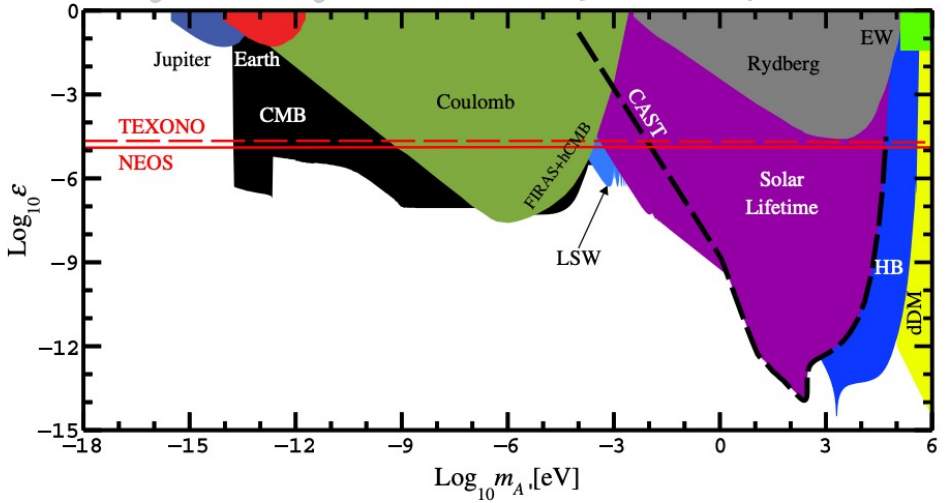


Detector

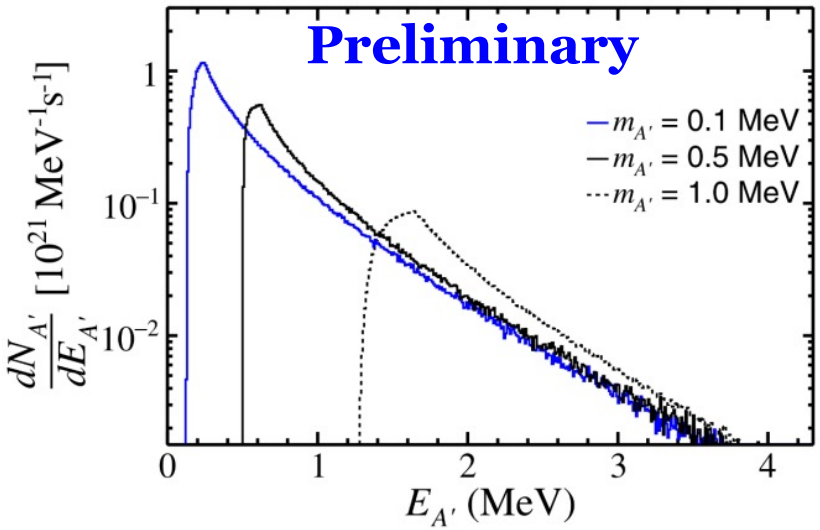
Detection : Dark Photon Absorption
(Inverse Compton-like process)

$$A'e^- \rightarrow \gamma e^-$$

Theory study : PRL 119 (2017) 081801



Ongoing analysis



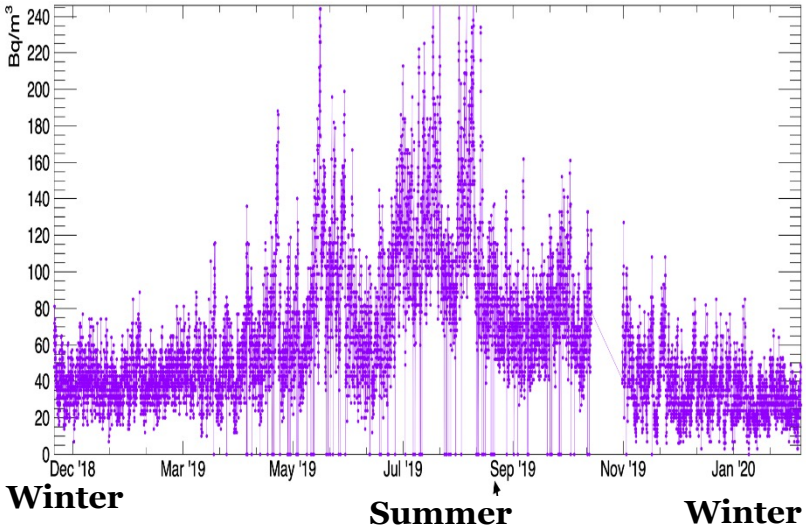
A generator for dark photon interaction in the NEON detector has been developed. It will be incorporated into the detector simulation to extract the dark photon signal.

Summary

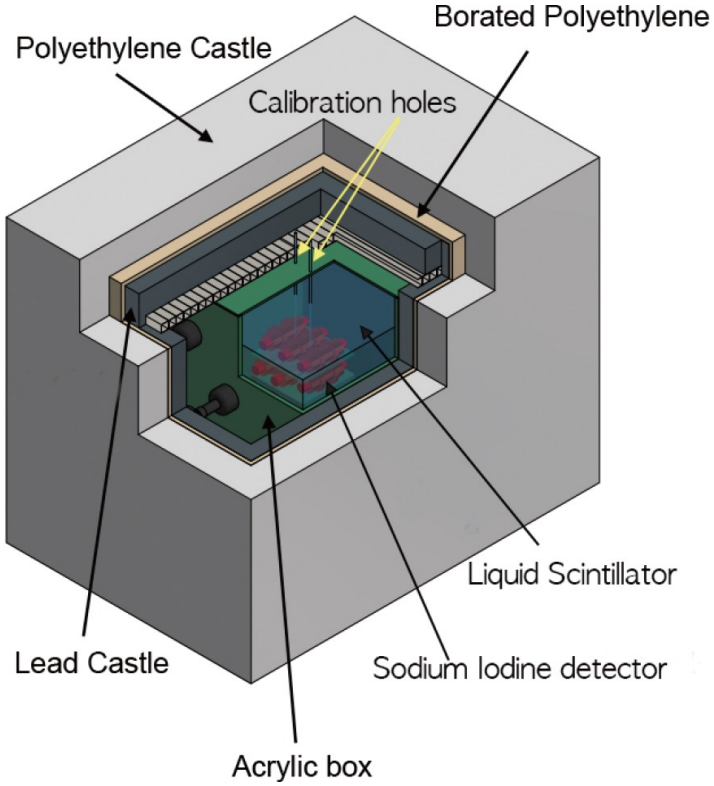
- The ALP search explore “cosmological triangle” for the first time
- Light dark matter search extended low-mass dark matter parameter space as low as 1 keV with the world best limit
- This work demonstrates the advantages of using nuclear reactors for dark sector searches and provides results that are supplementary to other experiments.

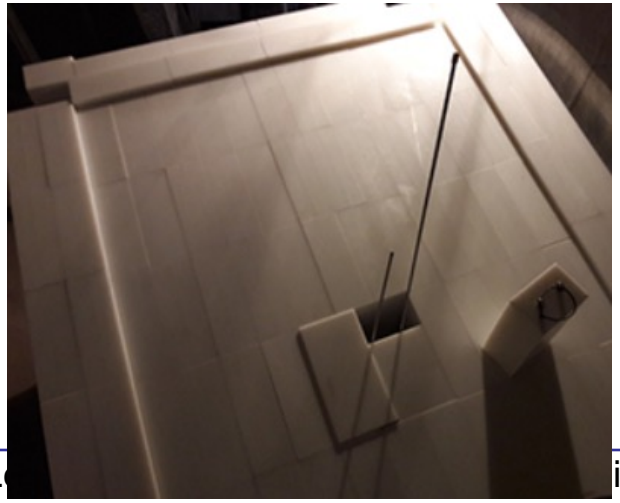
Seasonal variation of ^{222}Rn level

Radon eye measurement by NEOS experiment



Calibration holes were not closed



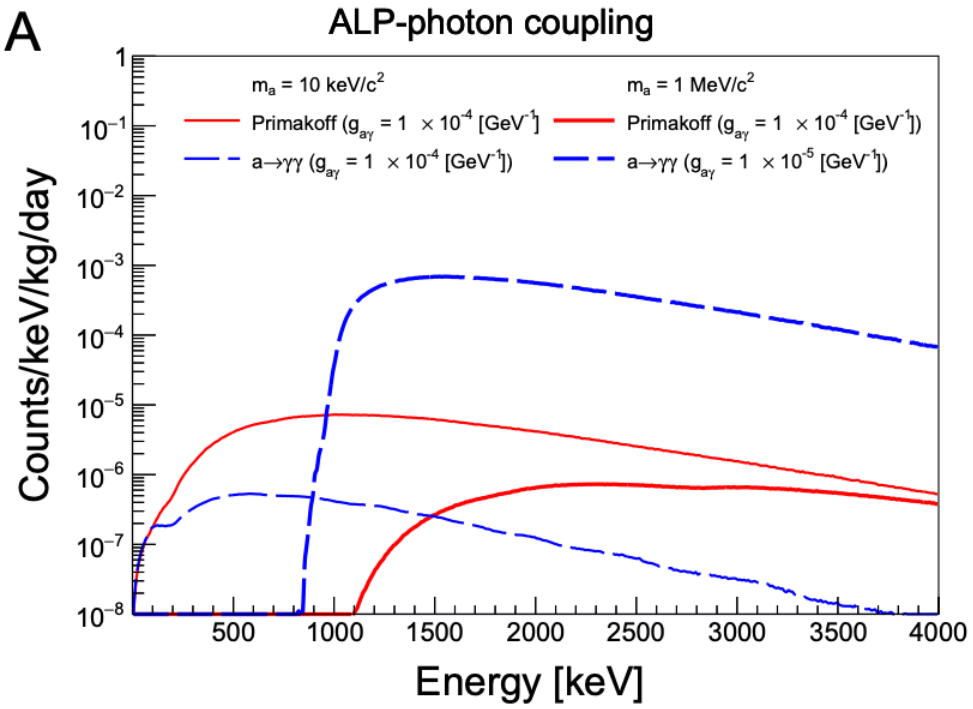


^{222}Rn level is higher at summer

ALP signal generation

ALP events rate at NEON detector site

A



B