# Searching for Dark Sector Particles in the NEON Experiment at a Reactor Facility


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On behalf of the NEON Collaboration

15th International Workshop on the Identification of Dark Matter

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# About NEON Experiment

## COSINE-100

Dark matter direct detection experiment with NaI(Tl) crystal

## NEOS

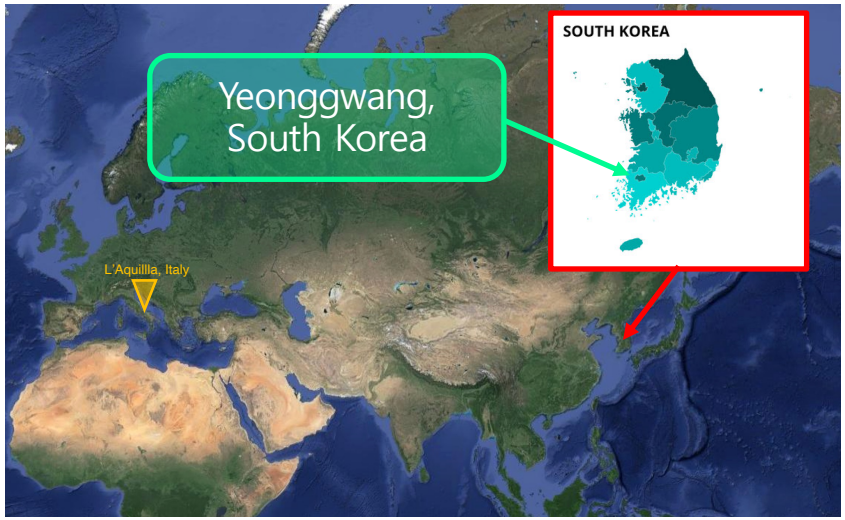
Short baseline sterile neutrino search experiment in reactor site

## NEON

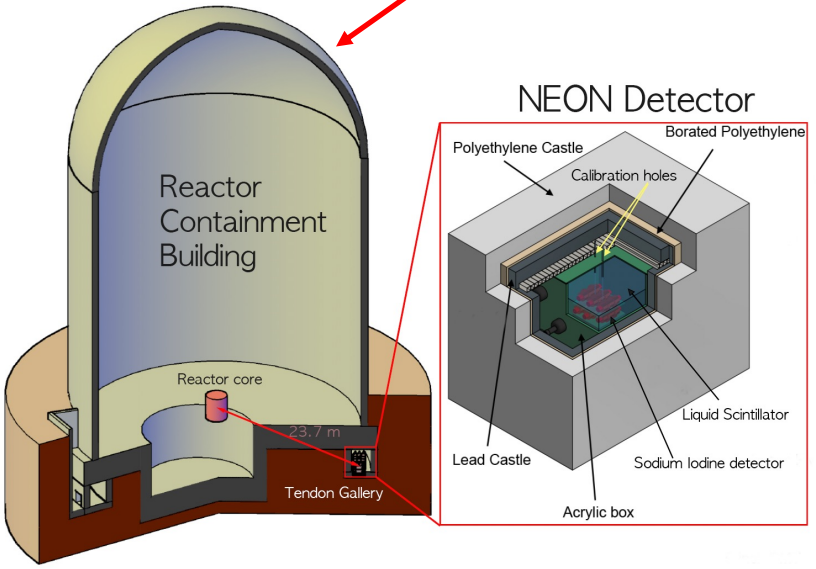
- **N**eutrino **E**lastic Scattering **O**bservation with **N**aI
- Target material: NaI(Tl)
- From the reactor
  - Coherent elastic neutrino-nucleus scattering (CE$\nu$NS)
  - Dark sector particles searches

# About NEON Experiment

## Experimental Site



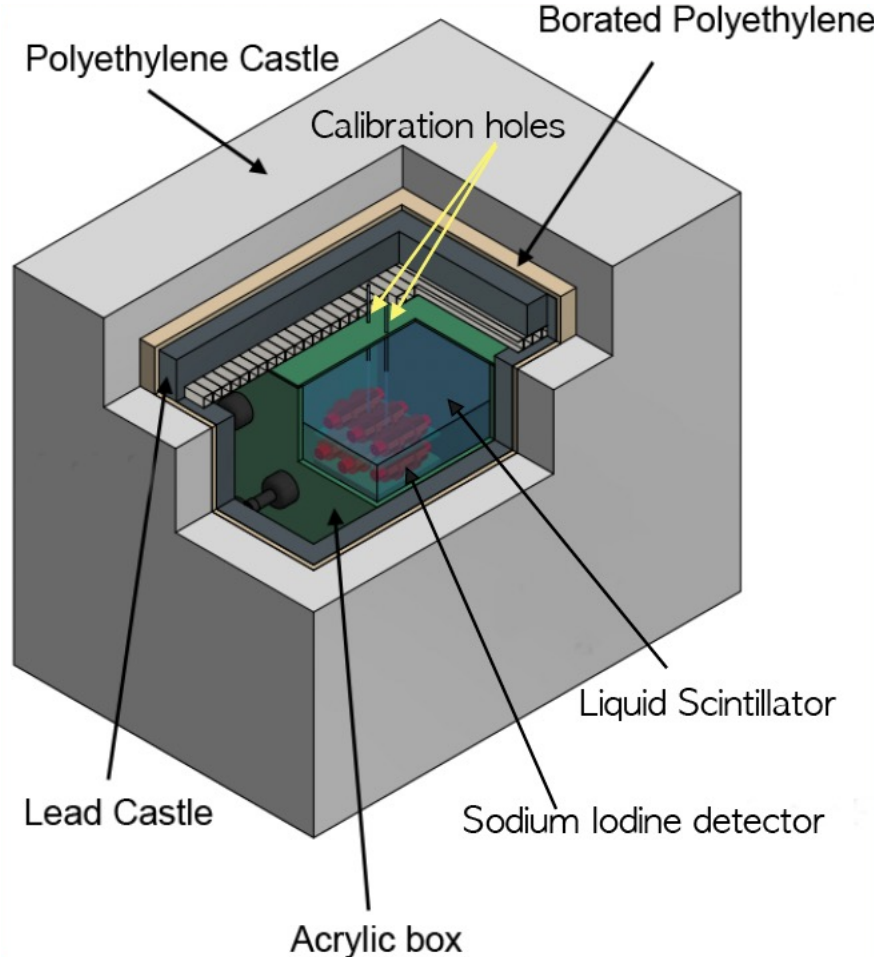





- Hanbit-6 reactor in Yeonggwang, Korea
- 2.8 GW thermal power
- Reactor core
  - Diameter: 3.1 m
  - Height: 3.8 m
  - Distance from reactor core: 23.7 m
- ~ 20 m.w.e overburden

# About NEON Experiment

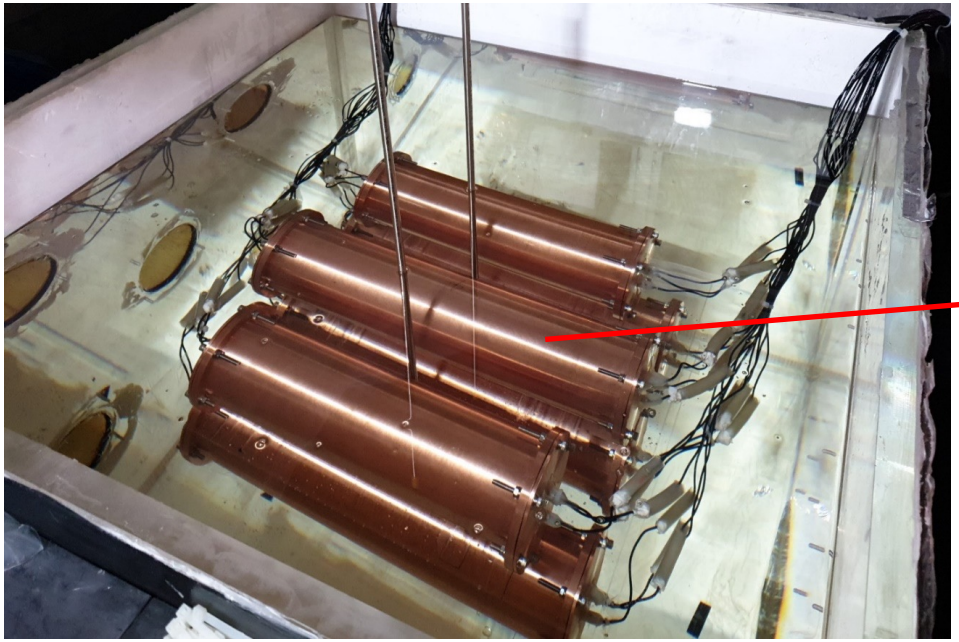
## NEON Detector Configuration

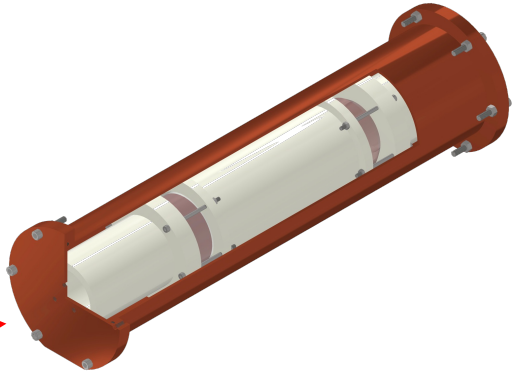



- Target: NaI(Tl) crystals
- Active veto system: ~ 800 L liquid scintillator (LAB-based LS)
- Shield design
  - 10 cm lead
  - 3 cm borated polyethylene
  - 20 cm high-density polyethylene

# About NEON Experiment

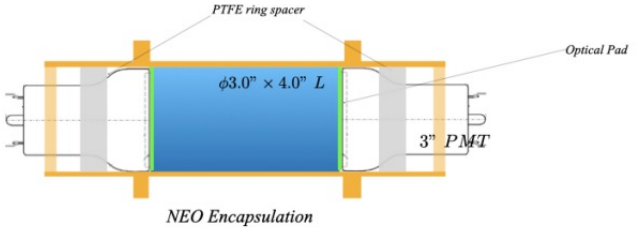
## NEON Detector Configuration





- 6 NaI(Tl) crystal detectors, 16.7 kg
- Upgraded detector encapsulation design after engineering run

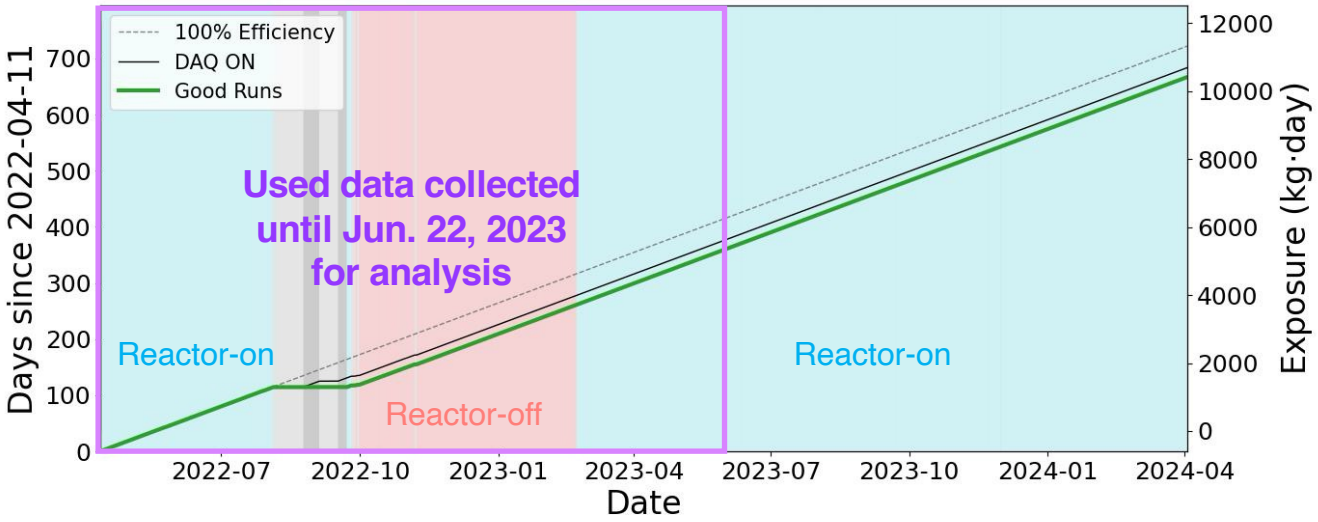
- Light yield about ~ 24 NPE/keV is stably obtained
  - High light yield compared to other NaI(Tl) experiments (COSINE-100: ~ 15 NPE/keV)

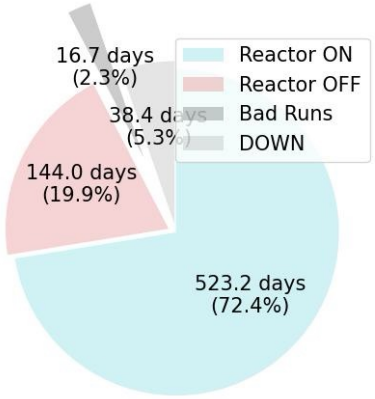



NIM-A (2020) 981:164556

# About NEON Experiment

## Operation




- Operation since Apr. 11, 2022
  - ~ 92% of DAQ efficiency
  - Largest exposure (~ 10000 kg · day) among reactor CE$\nu$NS experiments
  - Reactor-on data: ~ 523 days
  - Reactor-off data: ~ 144 days

- Data used for analysis: until Jun. 22, 2023

### CE$\nu$NS experiments

| Experiment | Detector | Mass | Threshold | Reactor/ source | Distance to source | Thermal power | Neutrino flux $\nu/cm^2/s$ | 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 $MW_{th}$ | $\sim 1*10^{12}$ | 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 $GW_{th}$ | $\sim 1*10^{13}$ | 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)

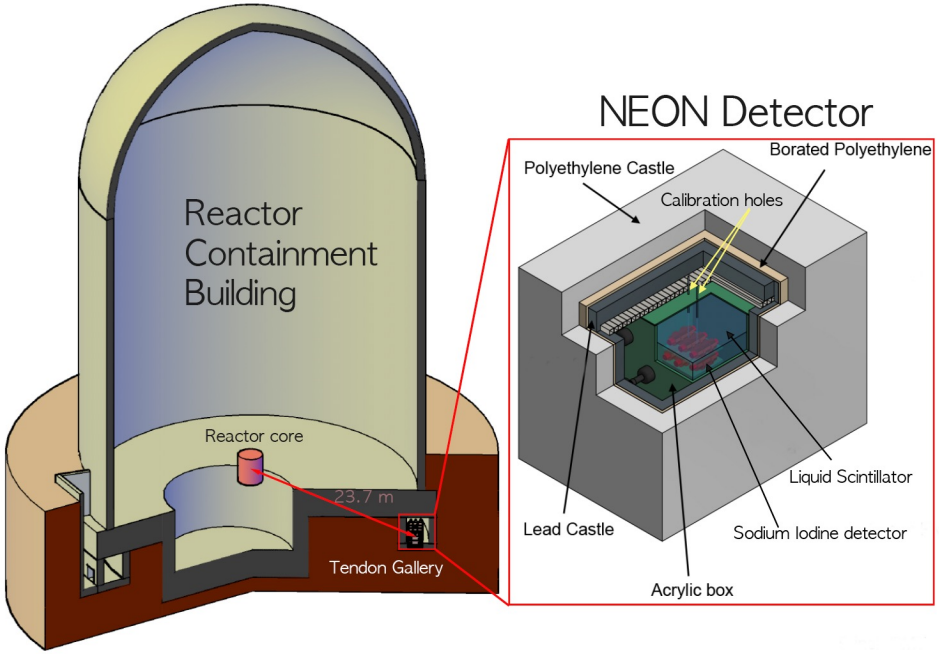
Coherent Elastic Neutrino-Nucleus Scattering 12

Aula Magna, XXXI International Conference on Neutrino Physics and Astrophysics

# Dark Sector Particles Search in NEON

- Intensive $\gamma$ source
  - $\sim 10^{26}$ /keV/day $\gamma$ flux in 2.8 $GW_{th}$ reactor core, peaking around energy 1 MeV
  - Strong $\gamma$ source compared to other experiments

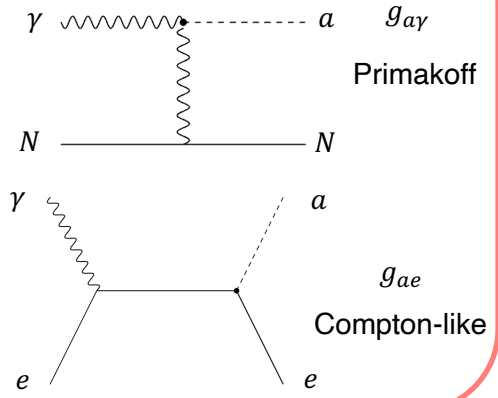
- $\gamma$ can couple to dark sector bosonic particles
  - Axion-like particles (ALPs)
  - Dark photon (DP)



# Dark Sector Particles in NEON

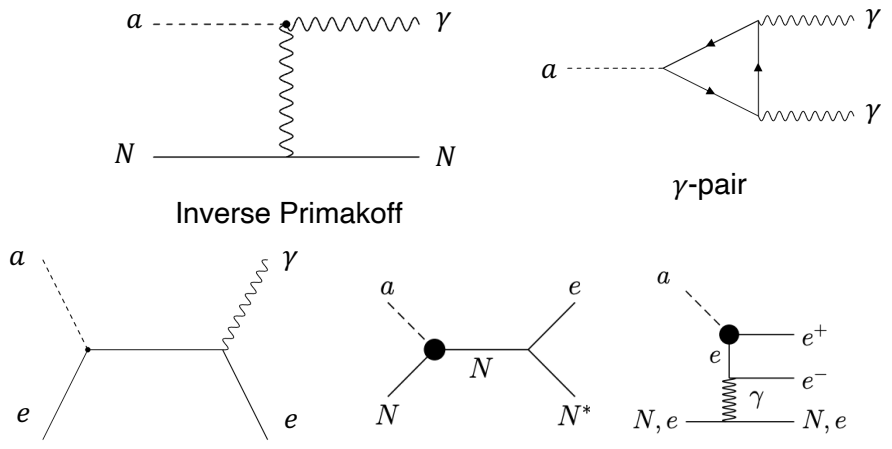
## Detection of ALP

### ALP production

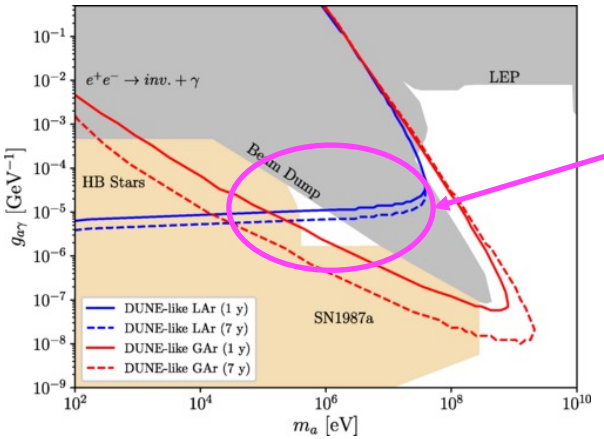



Reactor core

### ALP detection



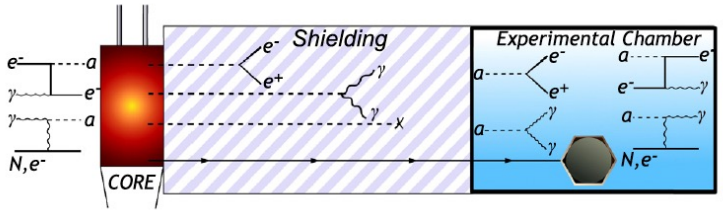

Detector




PRL (2021) 126:201801

- Focus on covering cosmological triangle

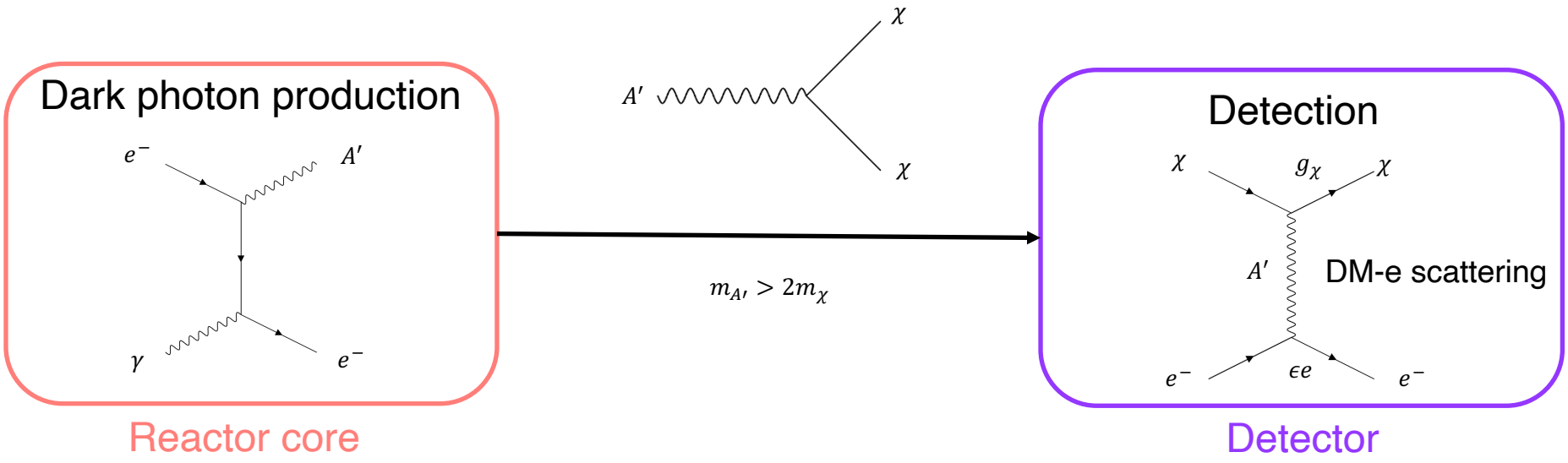
Search based on JHEP (2021) 2021, 294




PRL (2020) 124, 211804

# Dark Sector Particles in NEON

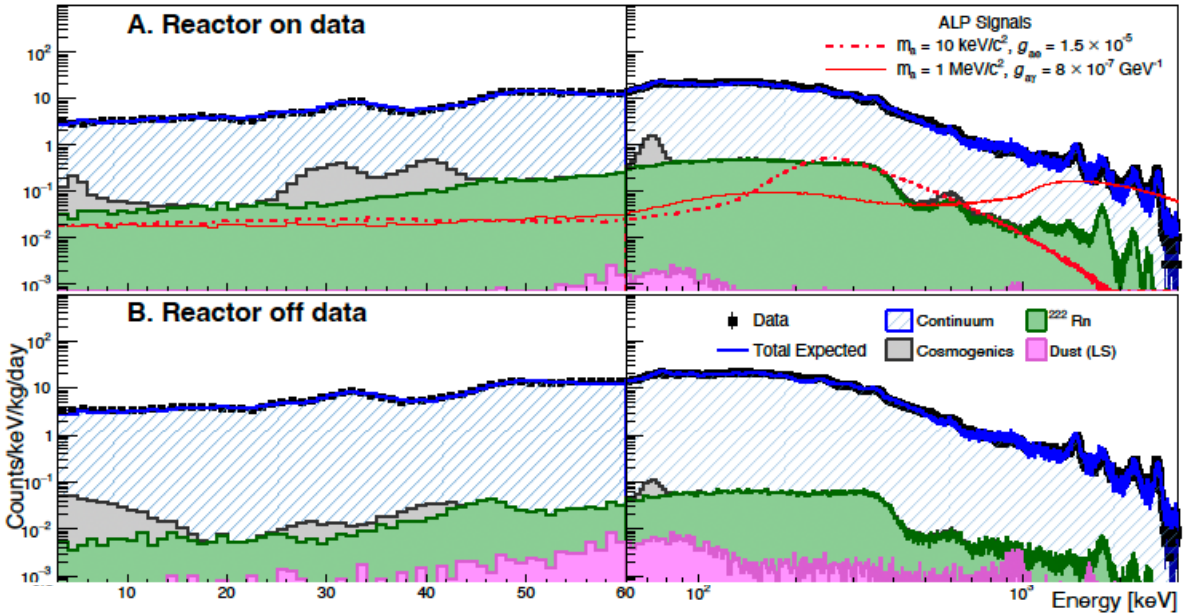
## Detection of DP




- Assumed $m_{A'} = 3m_\chi$
- Search for signal induced by dark matter (DM) scattering off electrons in the detector

# Data Analysis for NEON

## Background Modeling for ALP Search



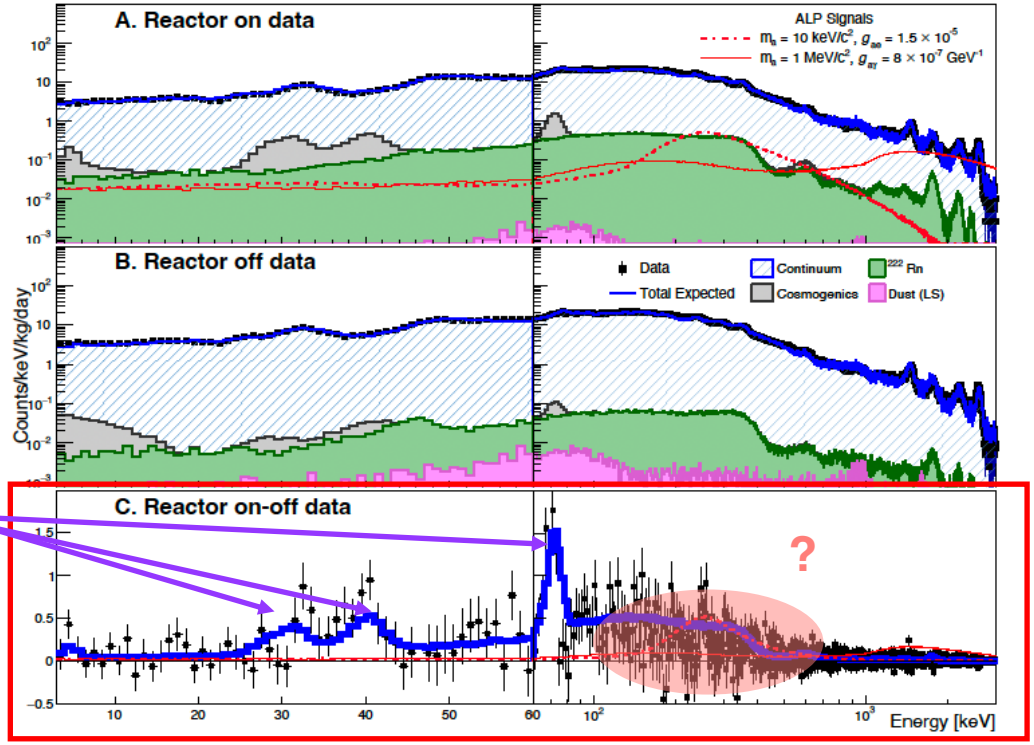

- 3 ~ 3000 keV range of background modeling to understand the detector behavior

- GEANT4 based Monte Carlo simulation was performed
  - Internal backgrounds
  - Surface contaminant
  - Cosmogenic activation
  - External backgrounds

# Data Analysis for NEON

## Background Modeling for ALP Search

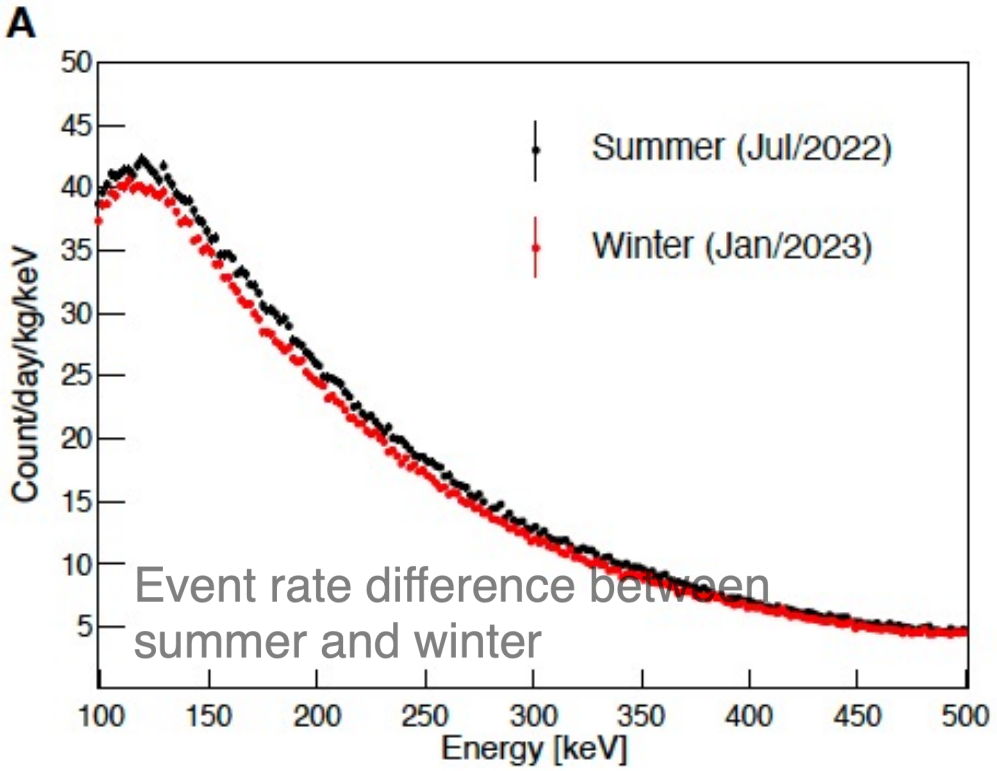
Peak from cosmogenic:
$^{121m}$Te, $^{125}$I, $^{113}$Sn, …

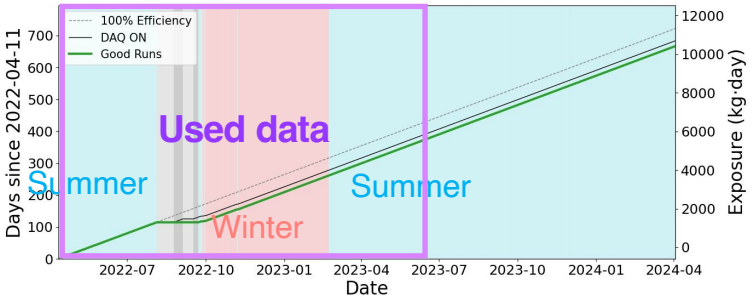


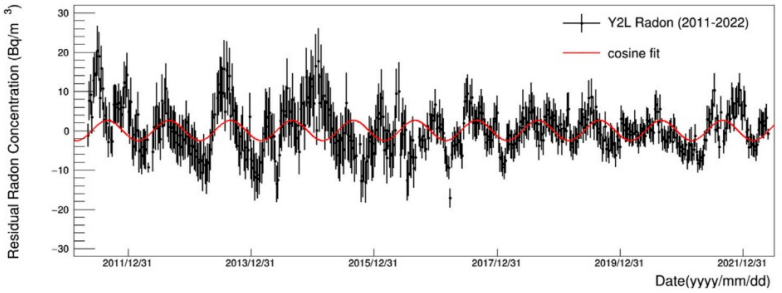

- (reactor-on) – (reactor-off) data used in analysis
- Peaks from cosmogenic activation
  + time-dependent component (?)

# Data Analysis for NEON

## Seasonal Variations in NEON Data



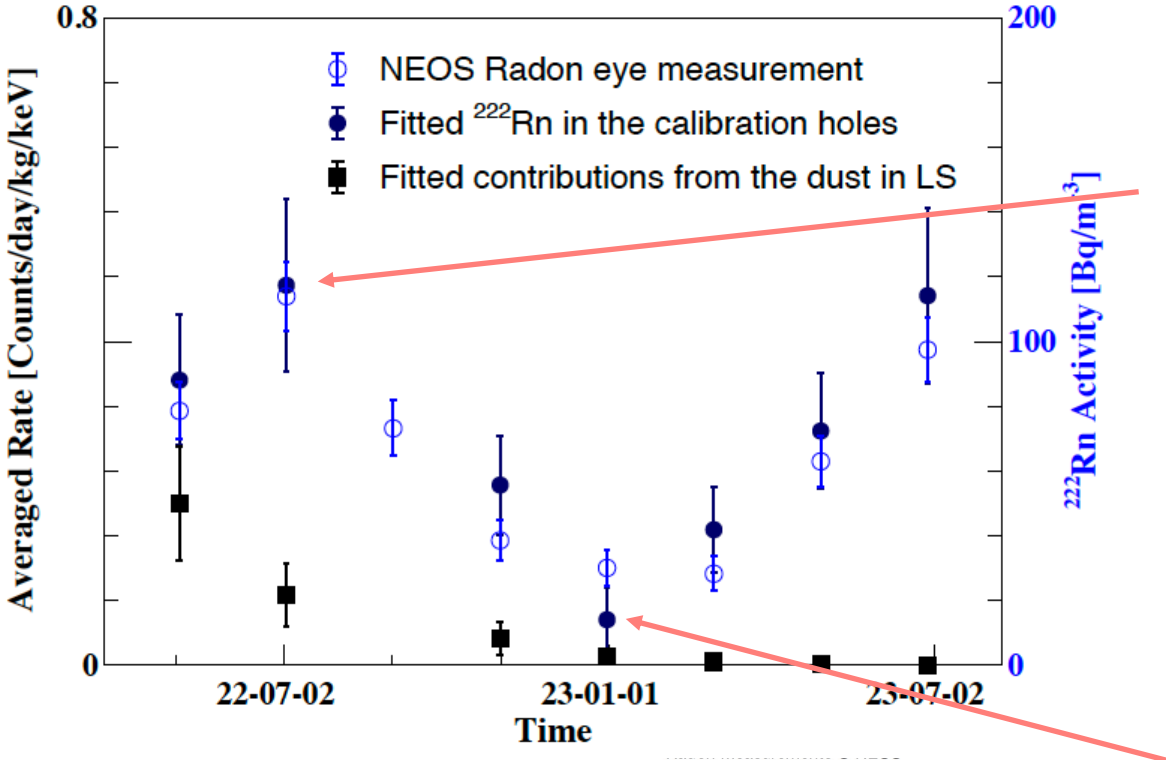



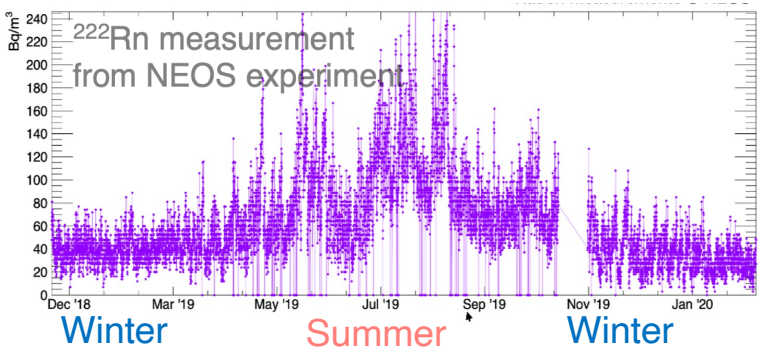

- $^{222}$Rn contamination possible through
  - Opened calibration hole
  - Dust contamination in LS

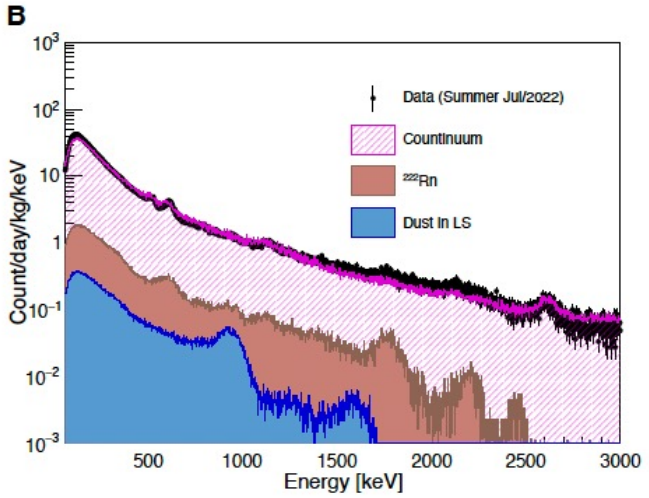
Radon concentration variations at the Yangyang underground laboratory, Front. Phys. (2022)

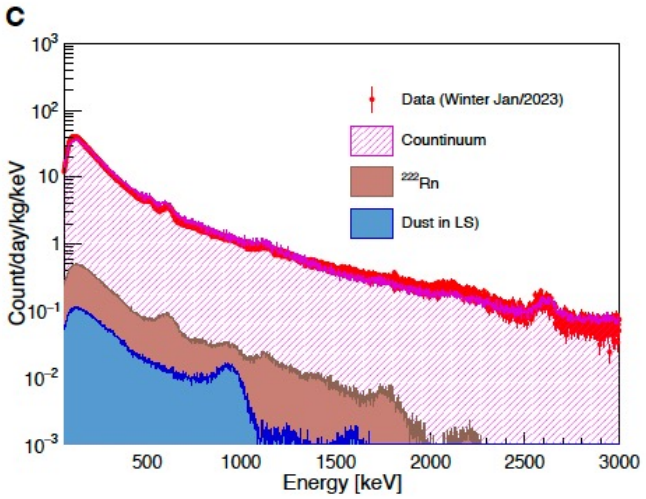
# Data Analysis for NEON

## Seasonal Variations in NEON Data



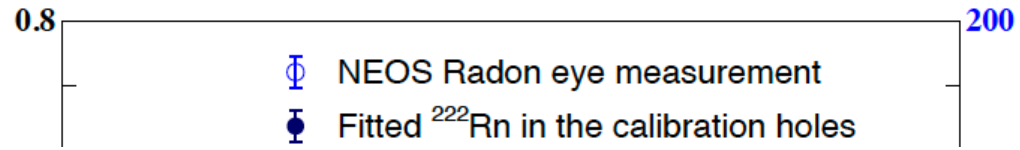




- Compared 2-month data

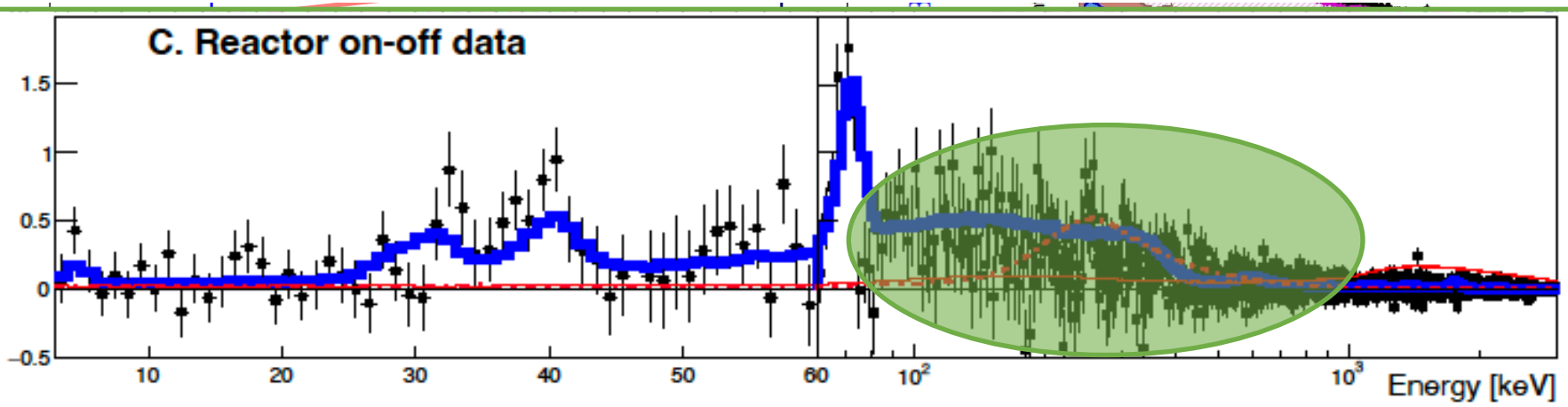
# Data Analysis for NEON

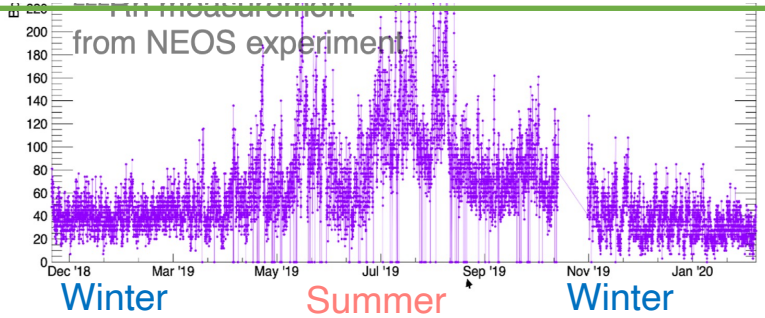
## Seasonal Variations in NEON Data

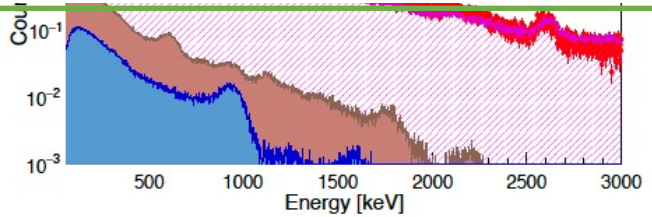




**The time-dependent component was $^{222}$Rn!**



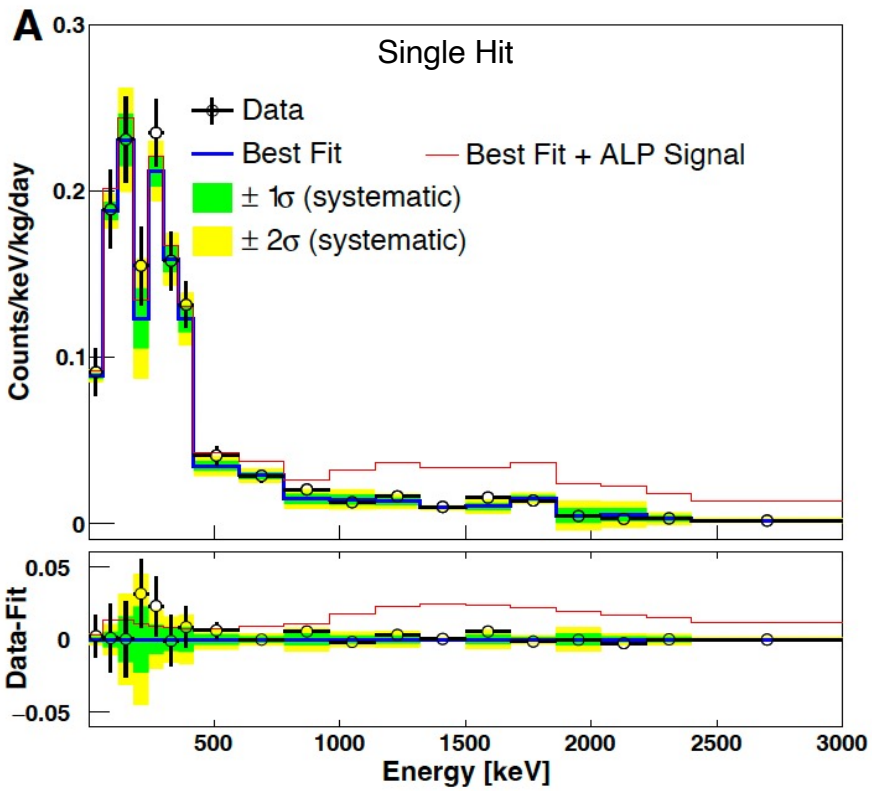



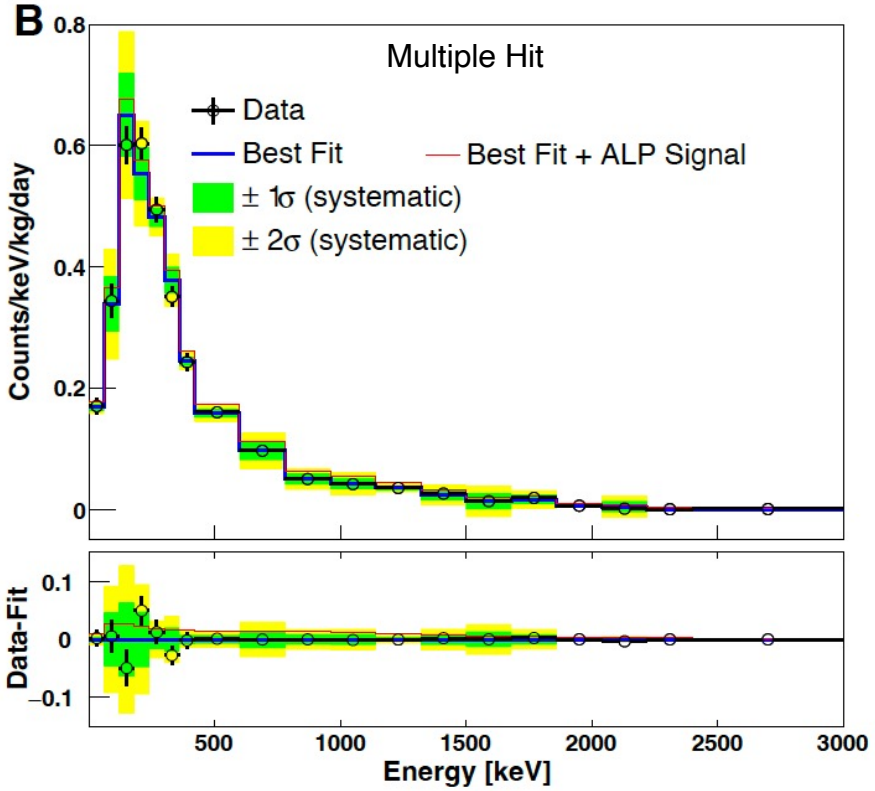

- Compared 2-month data

# ALP Search in NEON

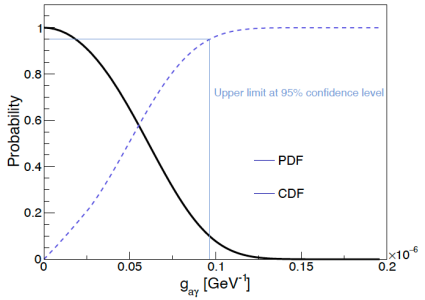
## ALP Signal Fitting

5-crystal-combined data ($m_a$ = 1 MeV/c$^2$, $g_{a\gamma}$ = 3.1 × 10$^{-7}$ GeV$^{-1}$)




- $\chi^2$ fit to (reactor-on) – (reactor-off) data with ALP signal
- No signal observed
  - 95 % C.L. upper limit ($g_{a\gamma}$ > 9.72 × 10$^{-8}$ GeV$^{-1}$ at $m_a$ = 1 MeV/c$^2$)

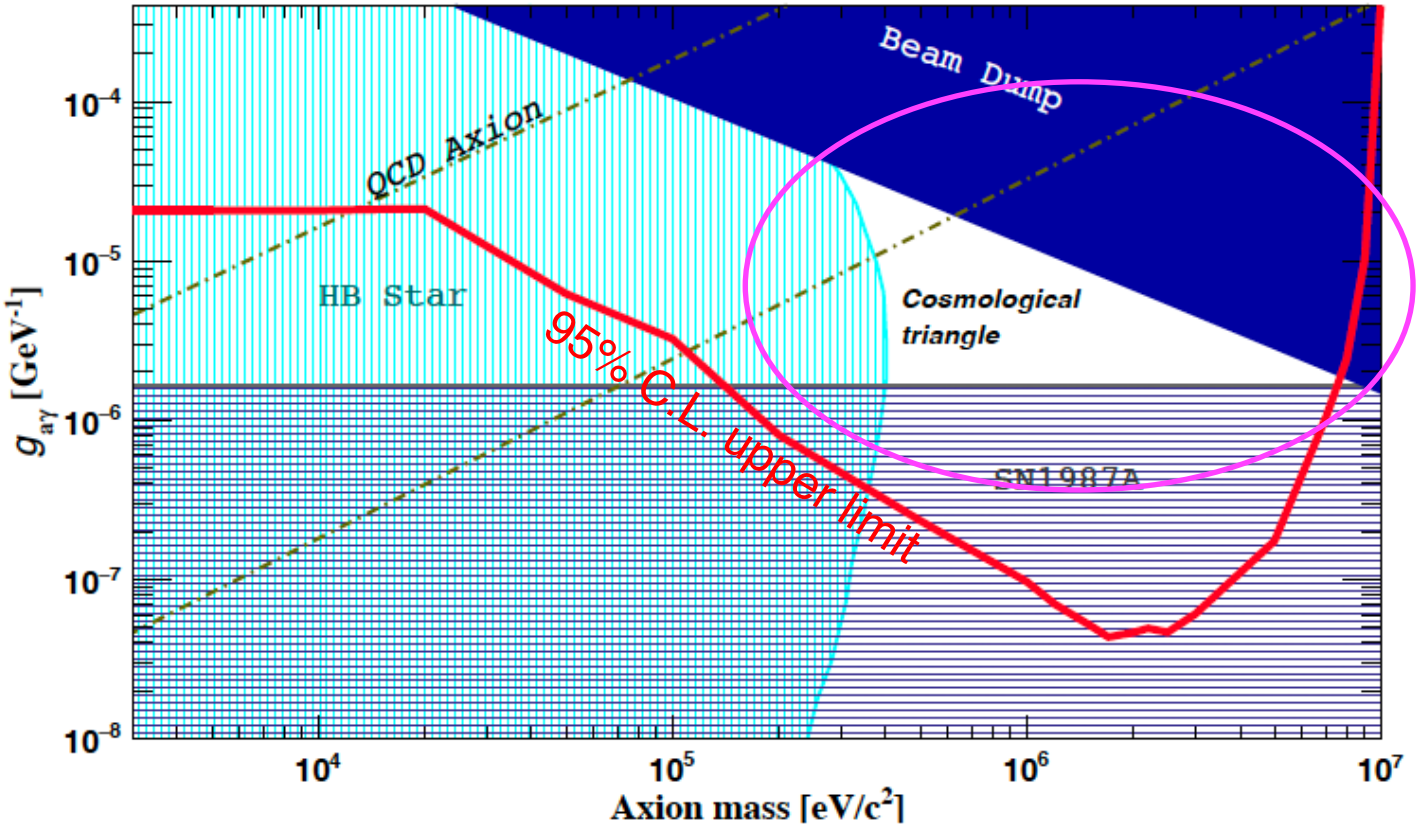


# ALP Search in NEON

## Limits for ALP Signal

Axion-photon coupling

arXiv:2406.06117

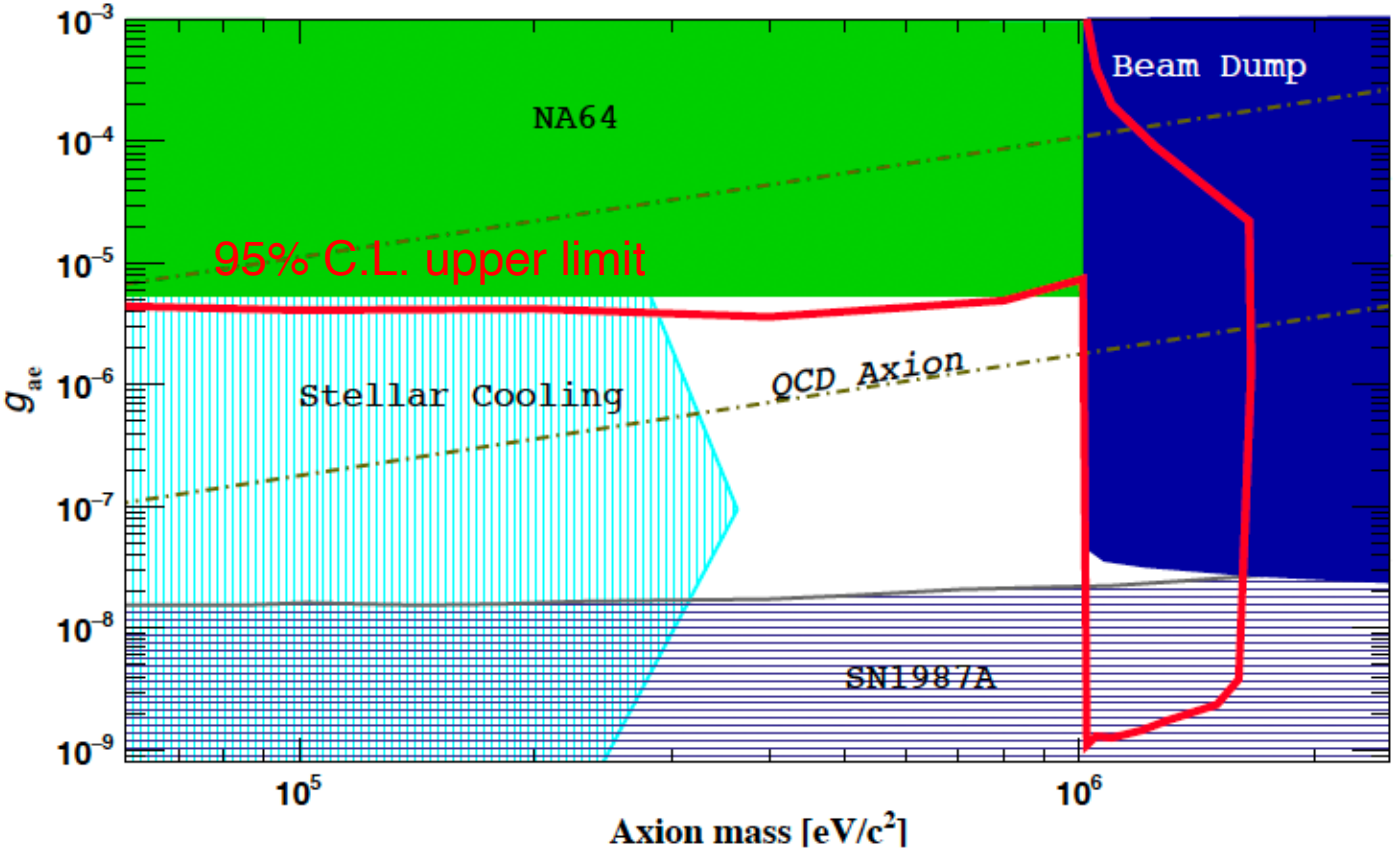



- ALP signal generated and simulated in ALP mass range 1 eV/$c^2$ ~ 10 MeV/$c^2$
- Exclusion of cosmological triangle!

# ALP Search in NEON

## Limits for ALP Signal

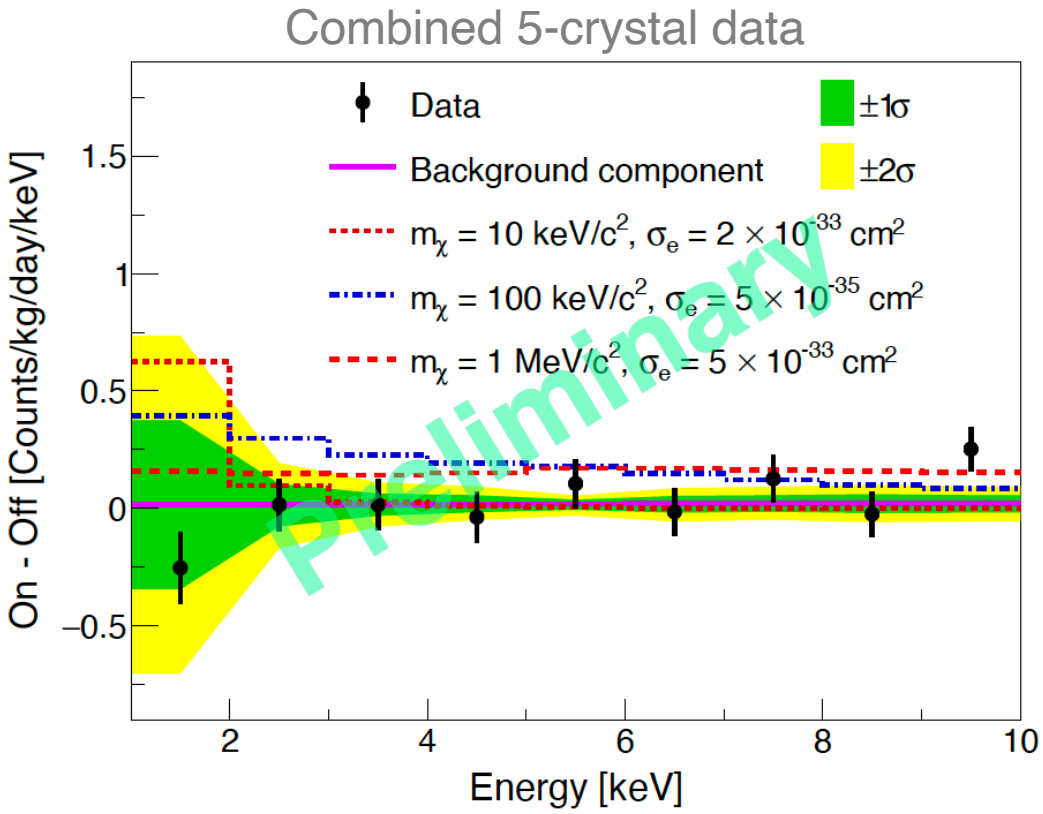
Axion-electron coupling




arXiv:2406.06117

# Dark Photon Search in NEON

## Fitting for Light Dark Matter

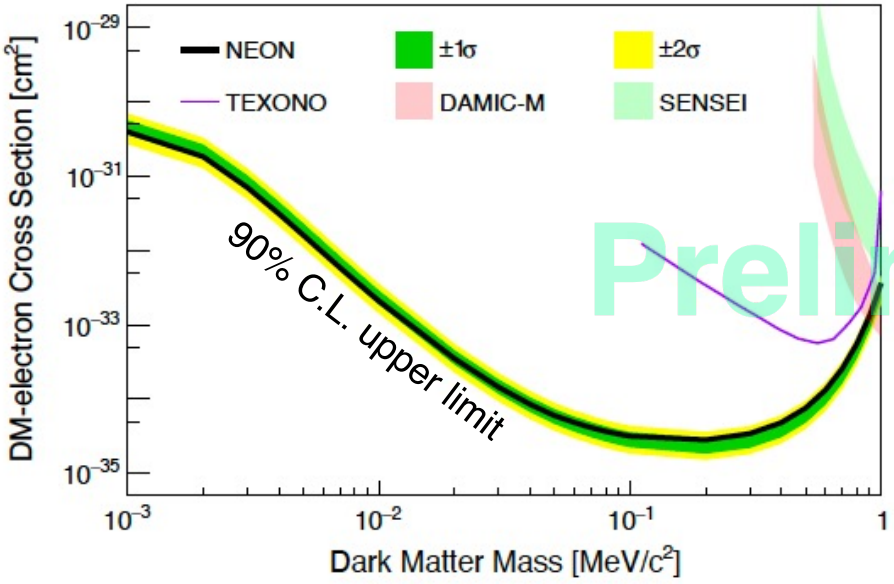


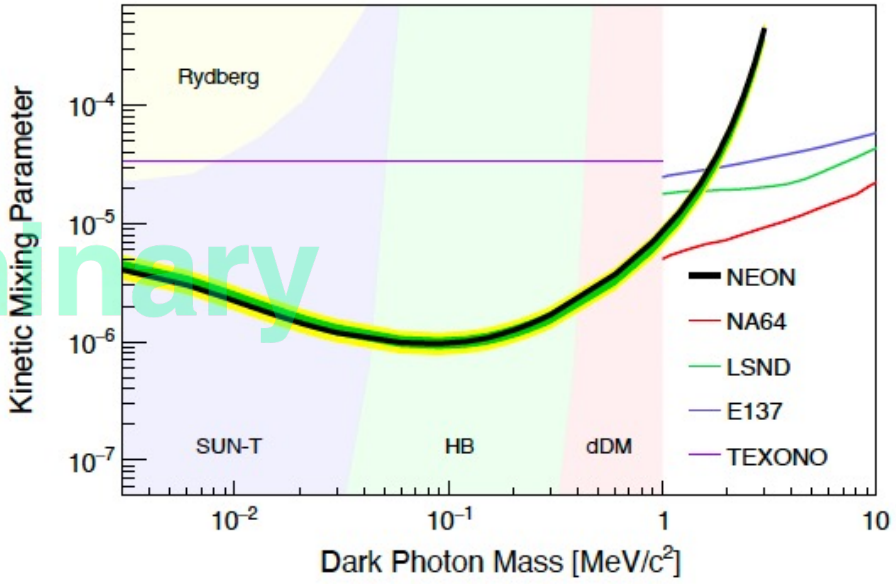

- $\chi^2$ fit to (reactor-on) – (reactor-off) data of background component
- No observation of the signal
  - 90 % C.L. upper limit: $\sigma_e = 3.17 \times 10^{-35}$ cm$^2$ at $m_\chi = 100$ keV/c$^2$

# Dark Photon Search in NEON

## Limits for Light Dark Matter

- DM signal generated in DM mass 1 keV/$c^2$ ~ 1 MeV/$c^2$
- 90% C.L. upper limit
- $m_{A'} = 3m_{\chi}$



# Summary

- NEON is stably on operation since Apr. 2022, with ~ 10000 kg • day exposure

- Good understanding of our data & background modeling

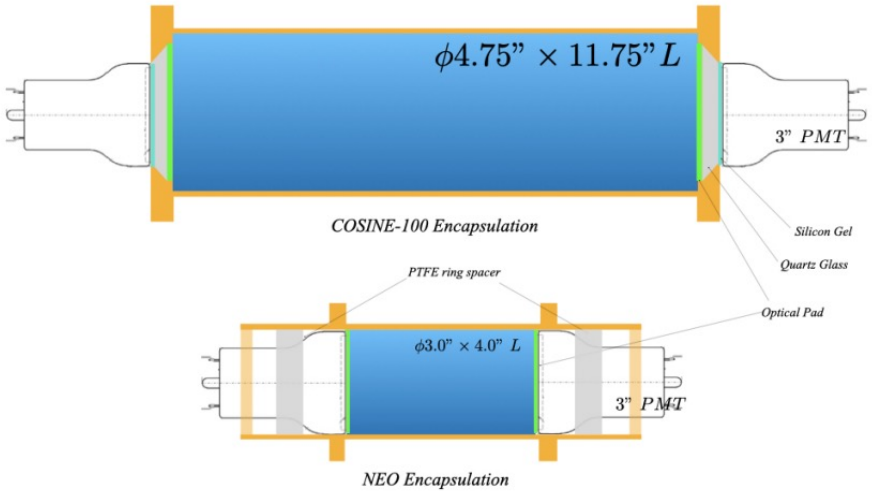
- NEON experiment search for dark sector particles
  - In ALP search, we covered the unexplored "cosmological triangle" for the first time (arXiv:2406.06117)
  - In DP search, we extend limit for low mass region (article in progress)

Thank You!

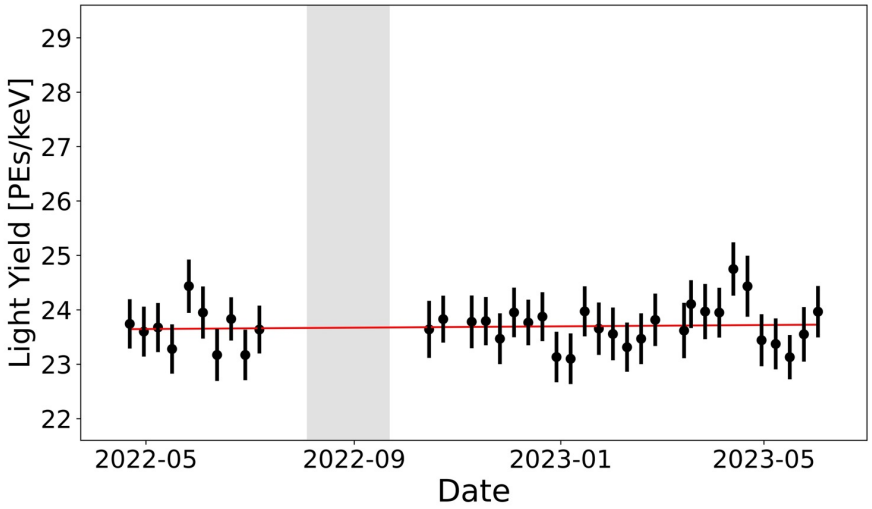
# Backup

# Crystal Encapsulation

NIM-A (2020) 981:164556




arXiv:2404.03691




- Encapsulation with quartz window between crystal and PMT
  → without quartz window

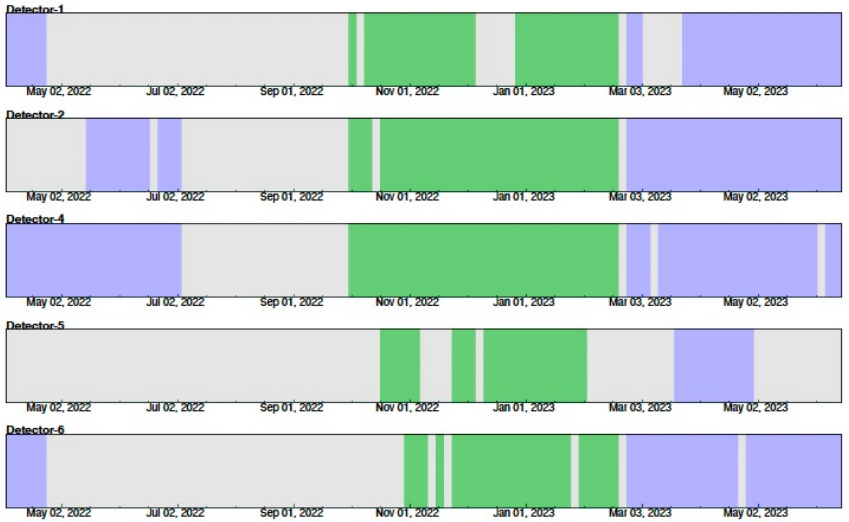
- LY ~ 24 NPE/keV

# Data Analysis for NEON

## Used Data

arXiv:2406.06117

| Detector | Mass | reactor-on data | reactor-off data |
|---|---|---|---|
| detector-1 | 1.67 kg | 165.4 kg·days | 201.2 kg·days |
| detector-2 | 3.34 kg | 413.4 kg·days | 352.3 kg·days |
| detector-3 | 1.67 kg | – | – |
| detector-4 | 3.34 kg | 527.9 kg·days | 367.6 kg·days |
| detector-5 | 3.35 kg | 160.2 kg·days | 279.8 kg·days |
| detector-6 | 3.35 kg | 329.4 kg·days | 266.0 kg·days |
| Total | 16.72 kg | 1596.3 kg·days | 1466.9 kg·days |



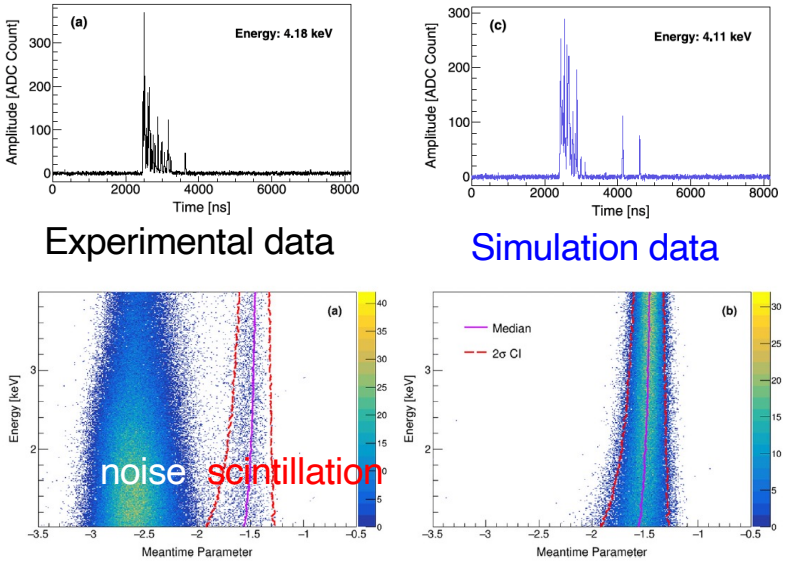

Blue: reactor-on
Green: reactor-off

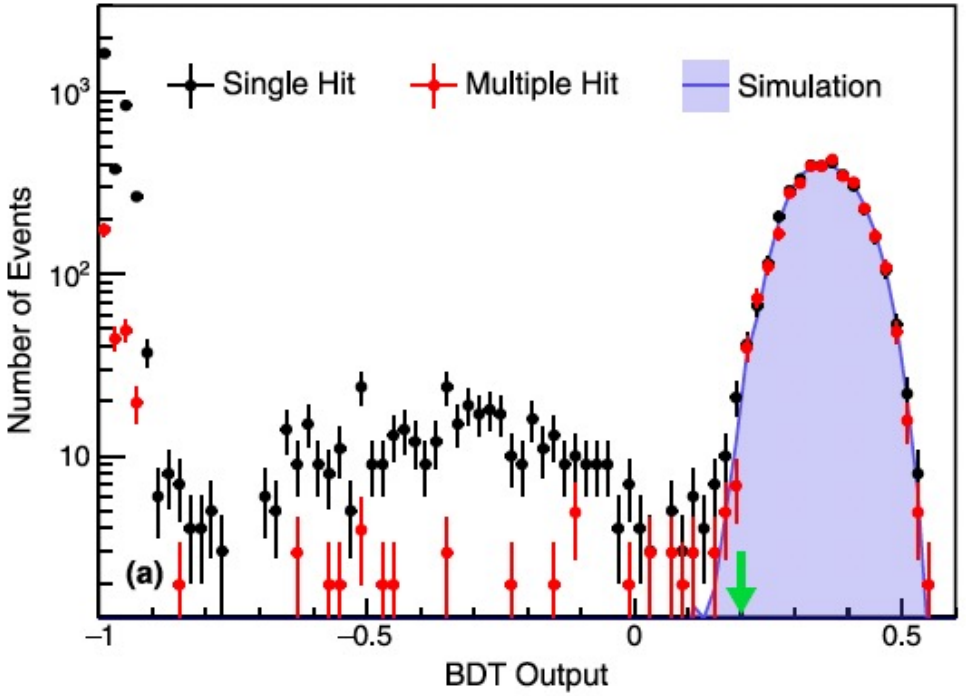
- Data used in ALP search, for each crystal
- D3 excluded because of the noise contamination

# Data Analysis for NEON

## Event Selection for Low Energy Events

NIM-A 1065 (2024) 169489



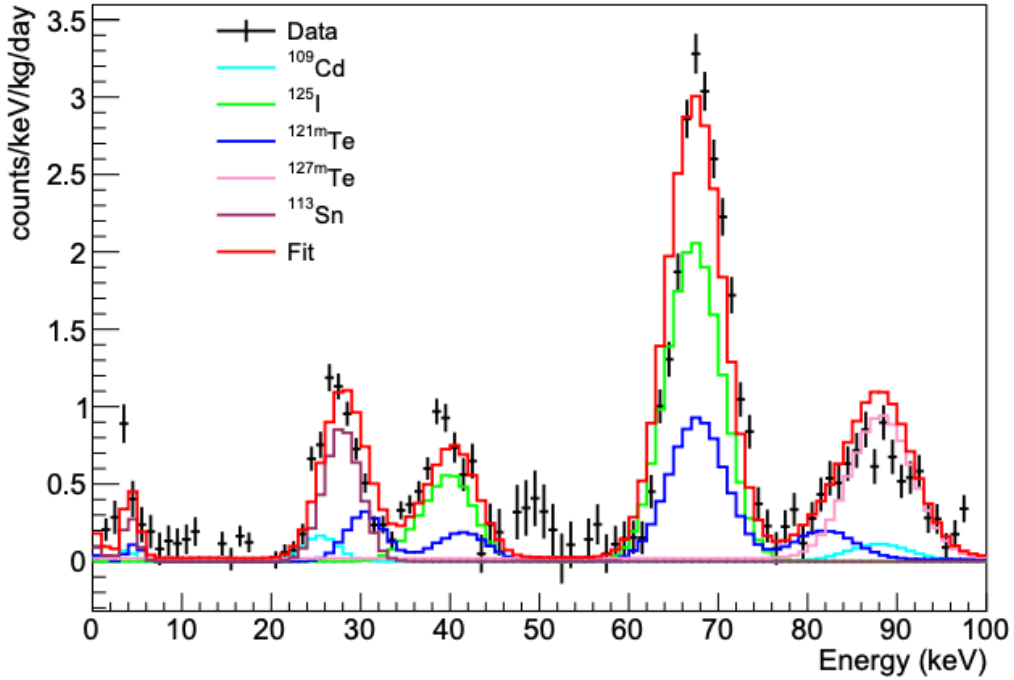

- Boosted decision tree (BDT)-based selection
- BDT training sample prepared with waveform simulation
- Noise separation down to ~ 0.6 keV

# Background Modeling for NEON

| | | | $^{40}$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

- Measured components from NEO crystals



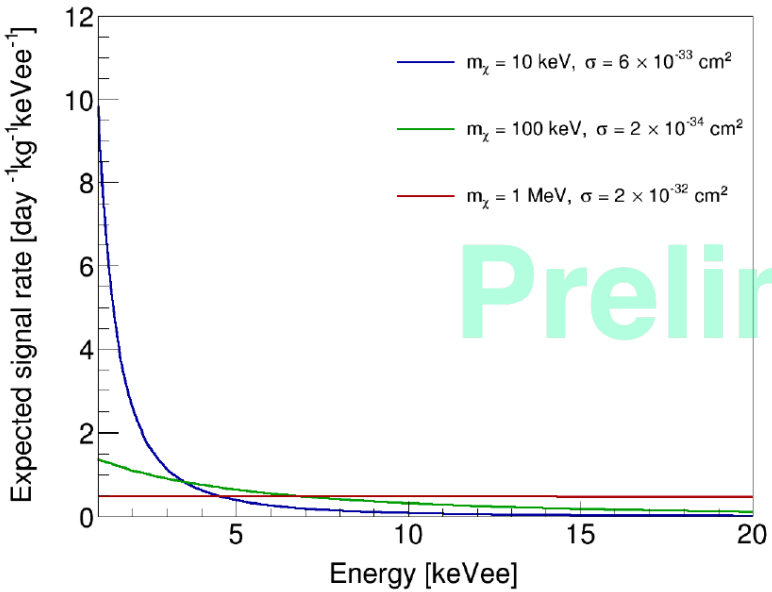

- Cosmogenic components studied on COSINE-100 experiment

Astropart. Phys. (2020) 115:102390

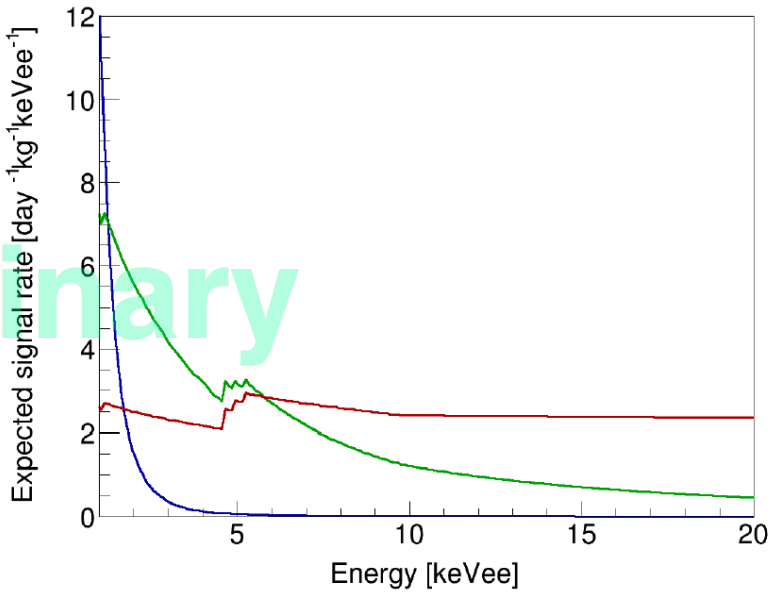
# Signal Generation for LDM

## Atomic Ionization Factor

Before applying atomic ionization factor




After applying atomic ionization factor




- To consider energy transfer of bound electron to become outgoing electron
- Ionization factor calculated in 0 ~ 10 keV (PRD (2023) 108:083030)