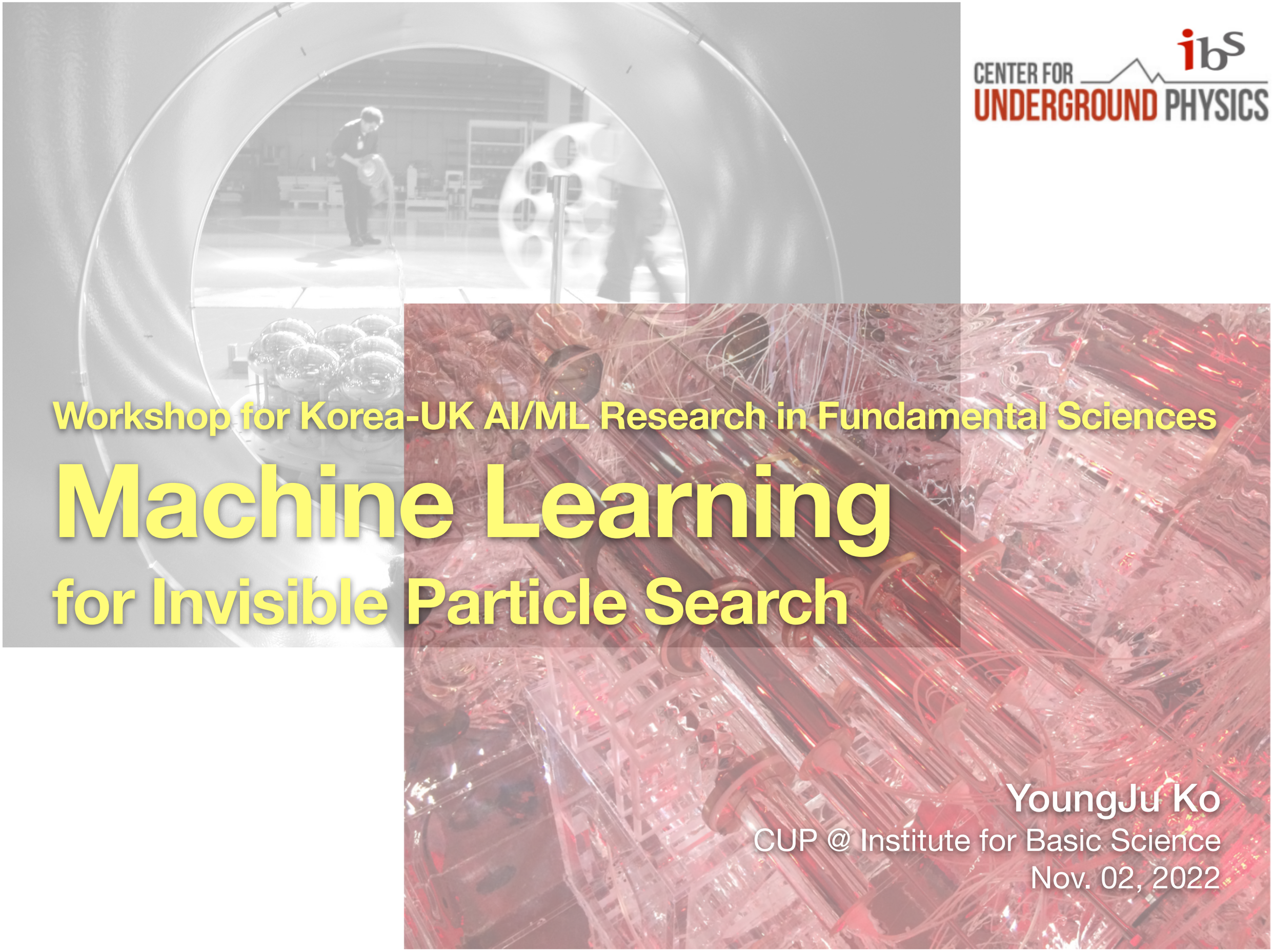


CENTER FOR UNDERGROUND PHYSICS

Workshop for Korea-UK AI/ML Research in Fundamental Sciences

Machine Learning for Invisible Particle Search

YoungJu Ko
CUP @ Institute for Basic Science
Nov. 02, 2022

Contents

- Introduction to NEOS
  - RAA & Sterile Neutrino
  - Results from NEOS-I
  - Introduction to phase-II
- Deep Learning in NEOS
  - Conventional PSD
  - Background Reduction via CNN

- Introduction to COSINE-100
  - DAMA/LIBRA Experiment
  - Experimental Site & Detector Configuration
  - Results from COSINE-100
- Machine Learning in COSINE-100
  - Parameter development
  - Event Selection via Boosted Decision Tree
  - Current Status

NEOS Experiment
for Sterile Neutrino Search

NEOS

RAA

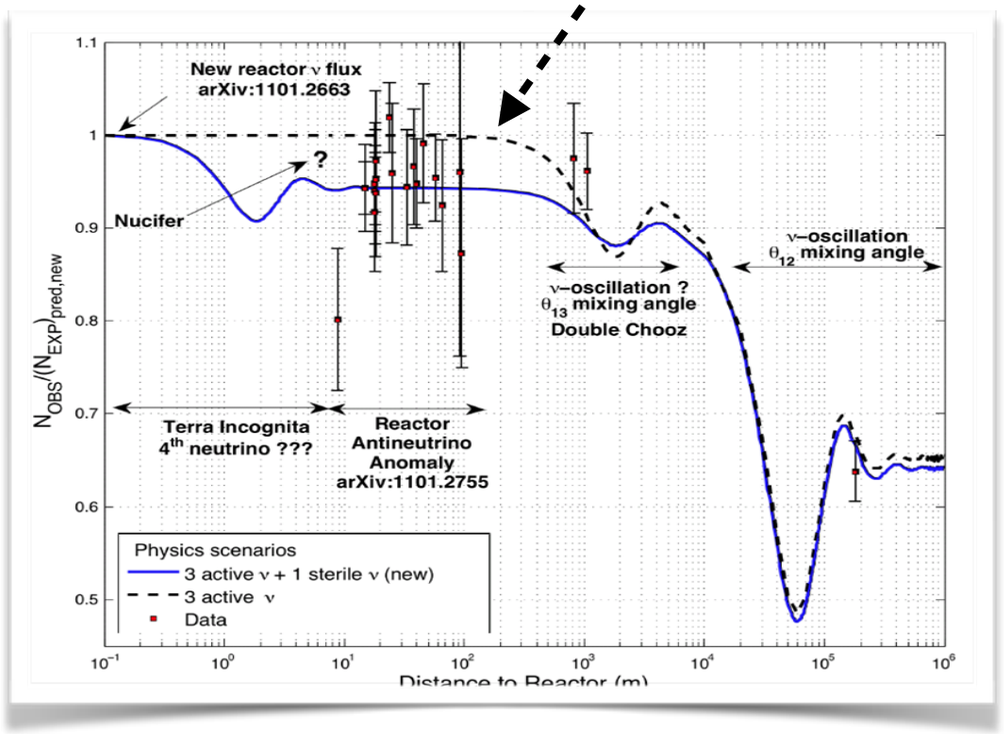
- Reactor neutrino oscillation

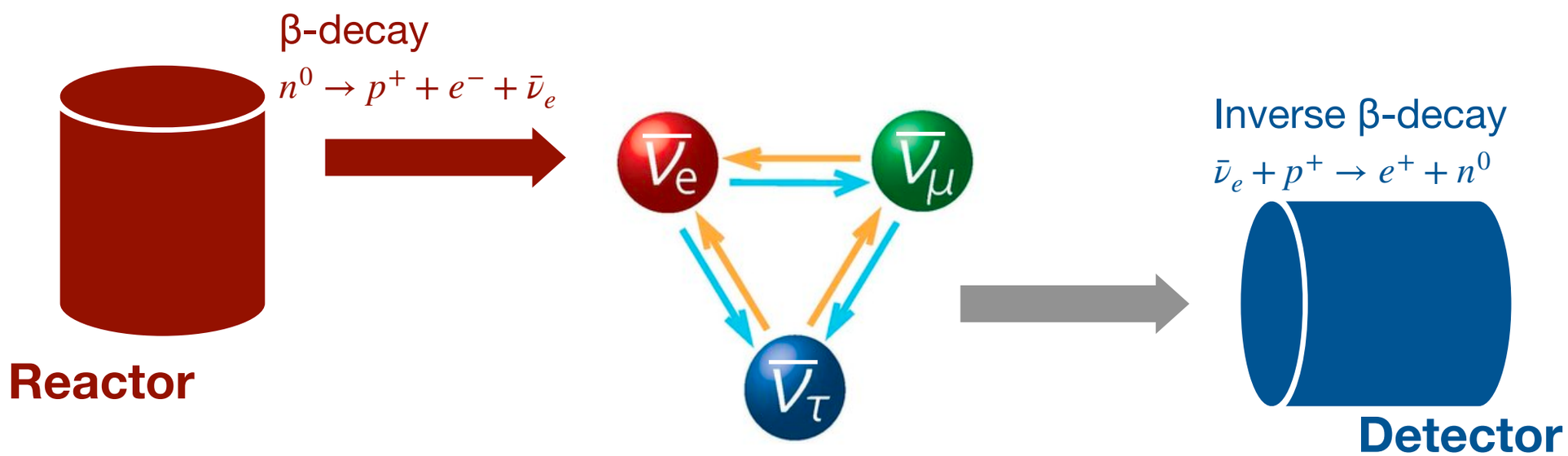
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(E_\nu, L;\, \theta_{1j}, \Delta m^2_{j1}) = 1 - \sin^2 2\theta_{1j} \sin^2\left(1.27 \frac{\Delta m^2_{j1} L}{E_\nu}\right)$$

  - No oscillation < 100 m ($\Delta m^2_{31} \sim 2.3 \times 10^{-5}\,\mathrm{eV}^2$)

Phys. Rev. D ***83***, *073006 (2011)*

Survival probability





NEOS

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Phys. Rev. D ***83****, 073006 (2011)*

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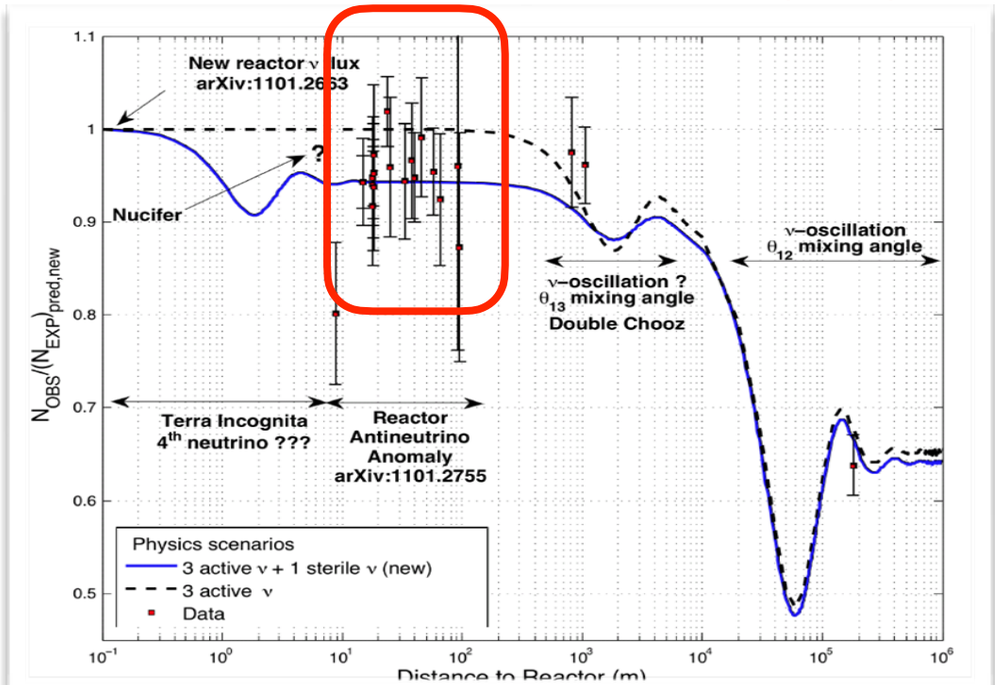
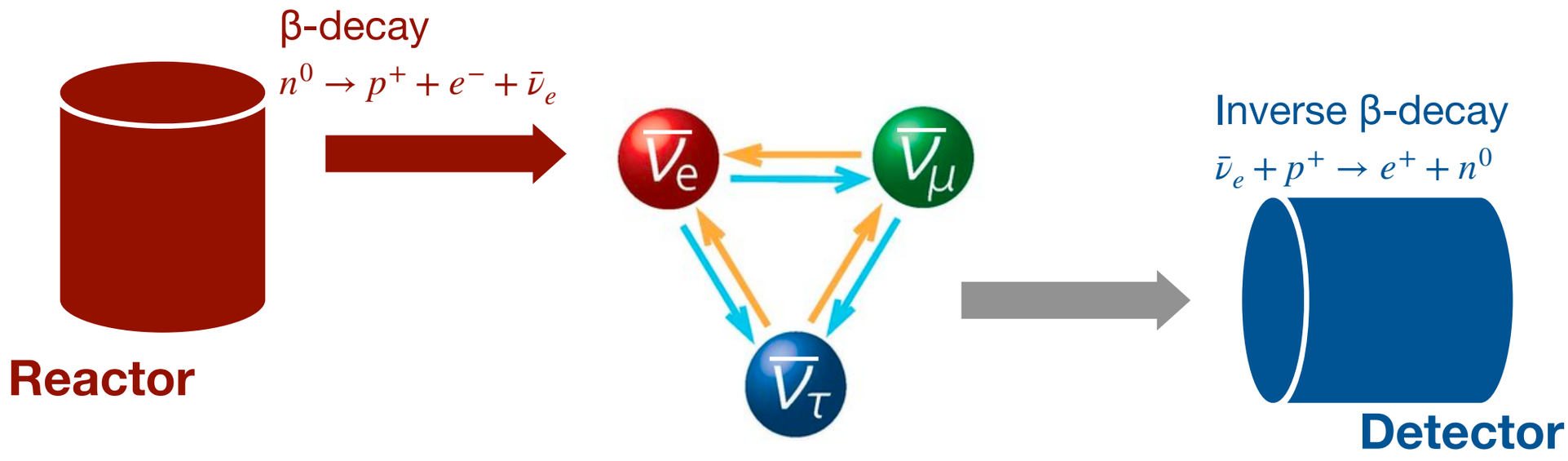
  - Deficit in measurements

    (Short baseline reactor experiments; < 100 m)
  - Measured to predicted ratio = 0.94 ± 0.02

Deficit in measurements (RAA)





NEOS

RAA & Sterile Neutrino

Phys. Rev. D ***83****, 073006 (2011)*

Survival probability
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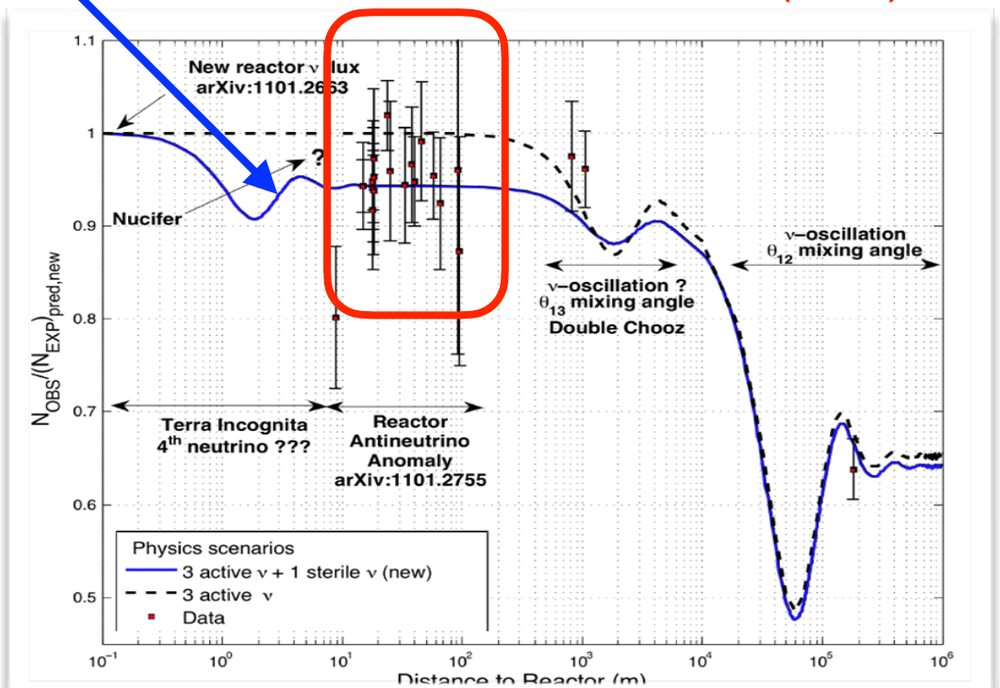

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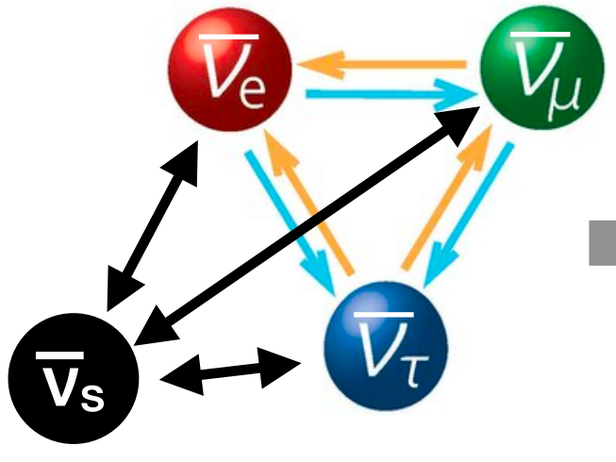
  - Adding a eV-scale sterile neutrino
  - $\bar{\nu}_e$ oscillating to $\bar{\nu}_s$



Inverse β-decay

$\bar{\nu}_e + p^+ \to e^+ + n^0$

Detector

NEOS

RAA & Sterile Neutrino

*Phys. Rev. D **83**, 073006 (2011)*

- Reactor neutrino

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(E_\nu, L;\ \theta_{1j}, \Delta n$$

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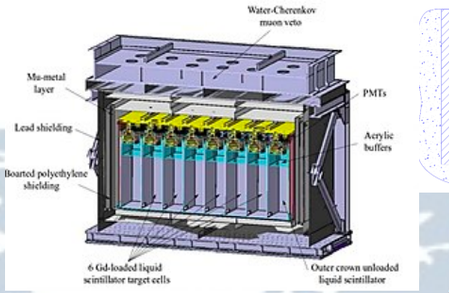
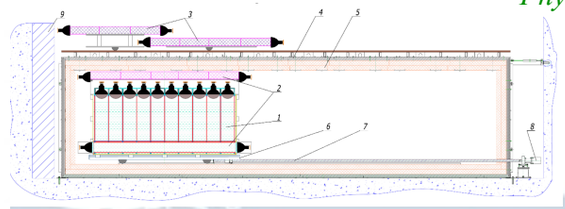
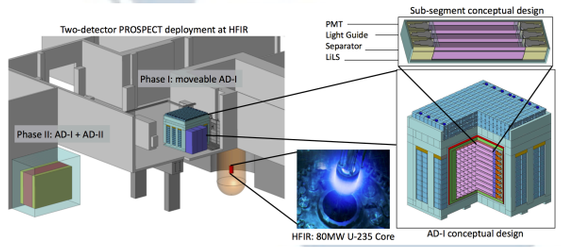




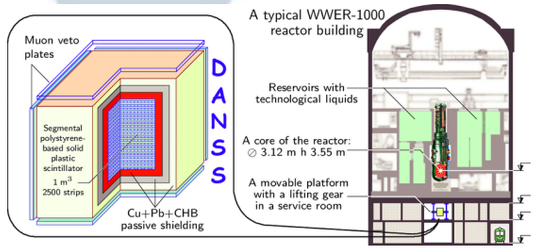
Neutrino-4

STEREO ★

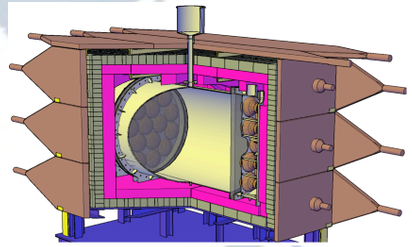
★ PROSPECT

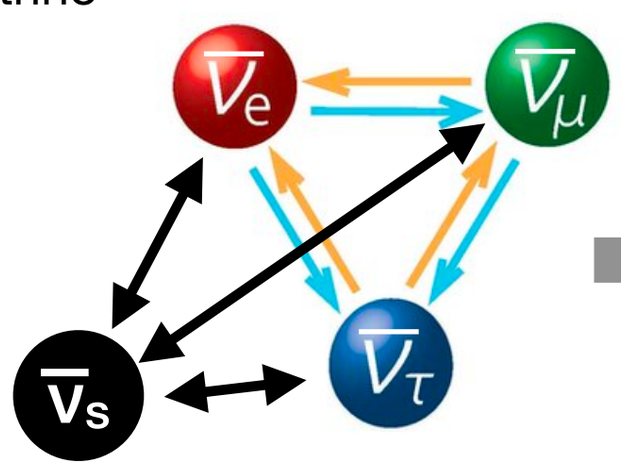


DANSS



★ NEOS





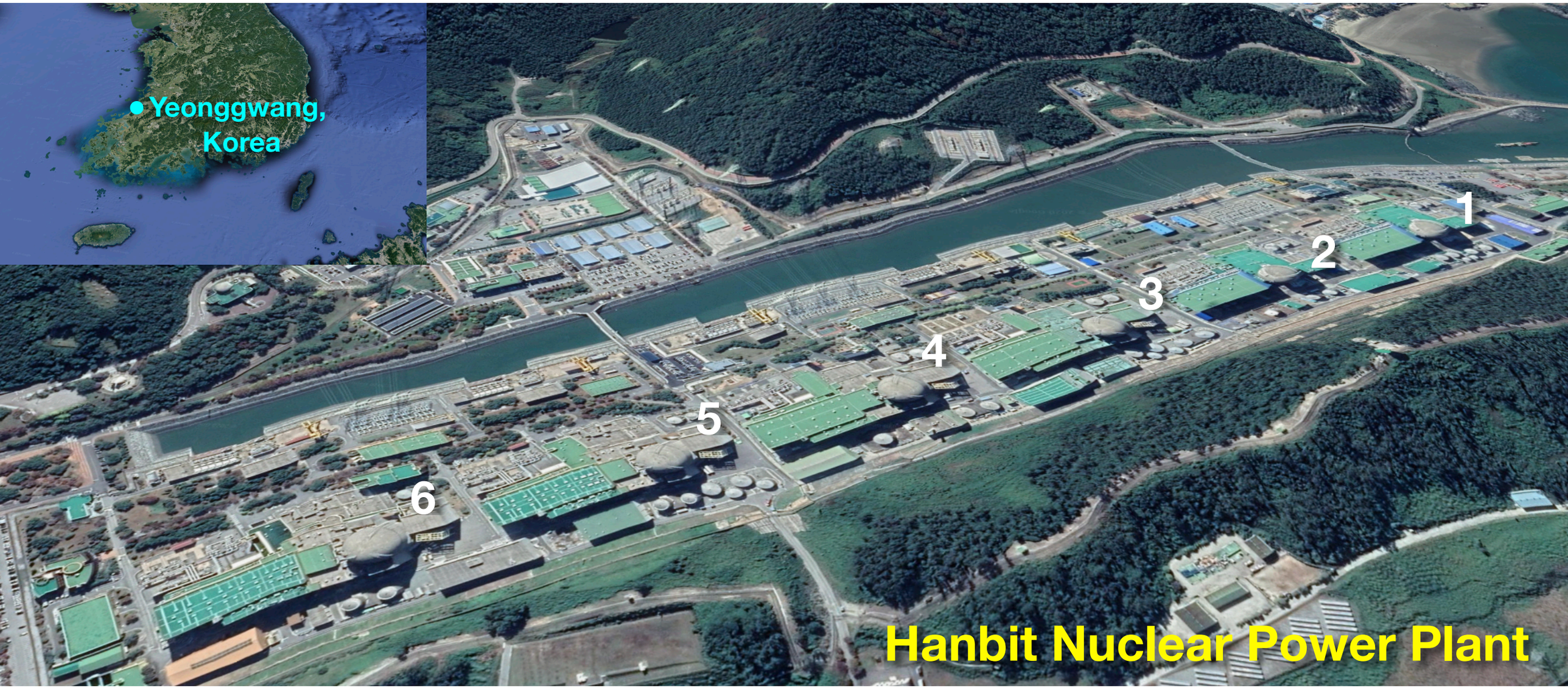
Inverse β-decay

$\bar{\nu}_e + p^+ \to e^+ + n^0$

NEOS

NEOS-I Experiment

- Mecca for Korea Neutrino Experiment



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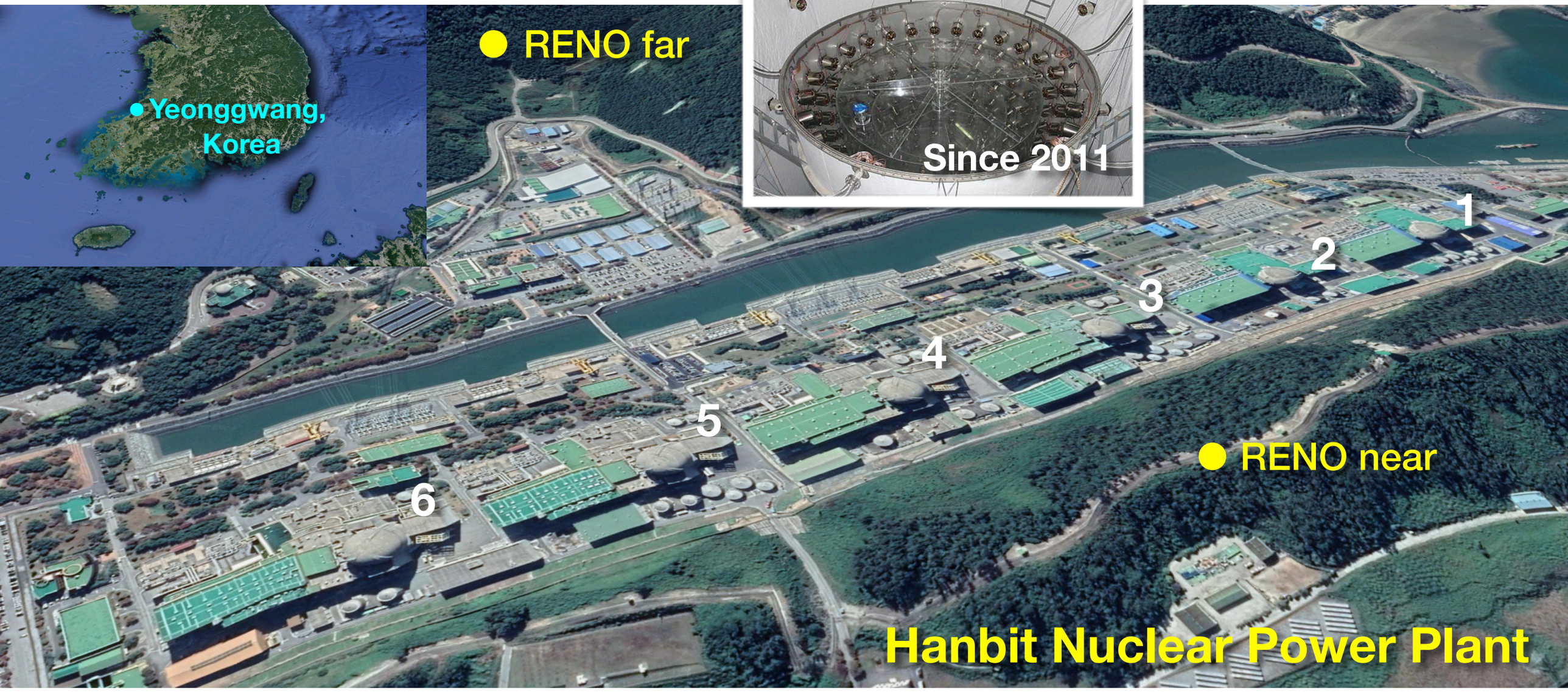

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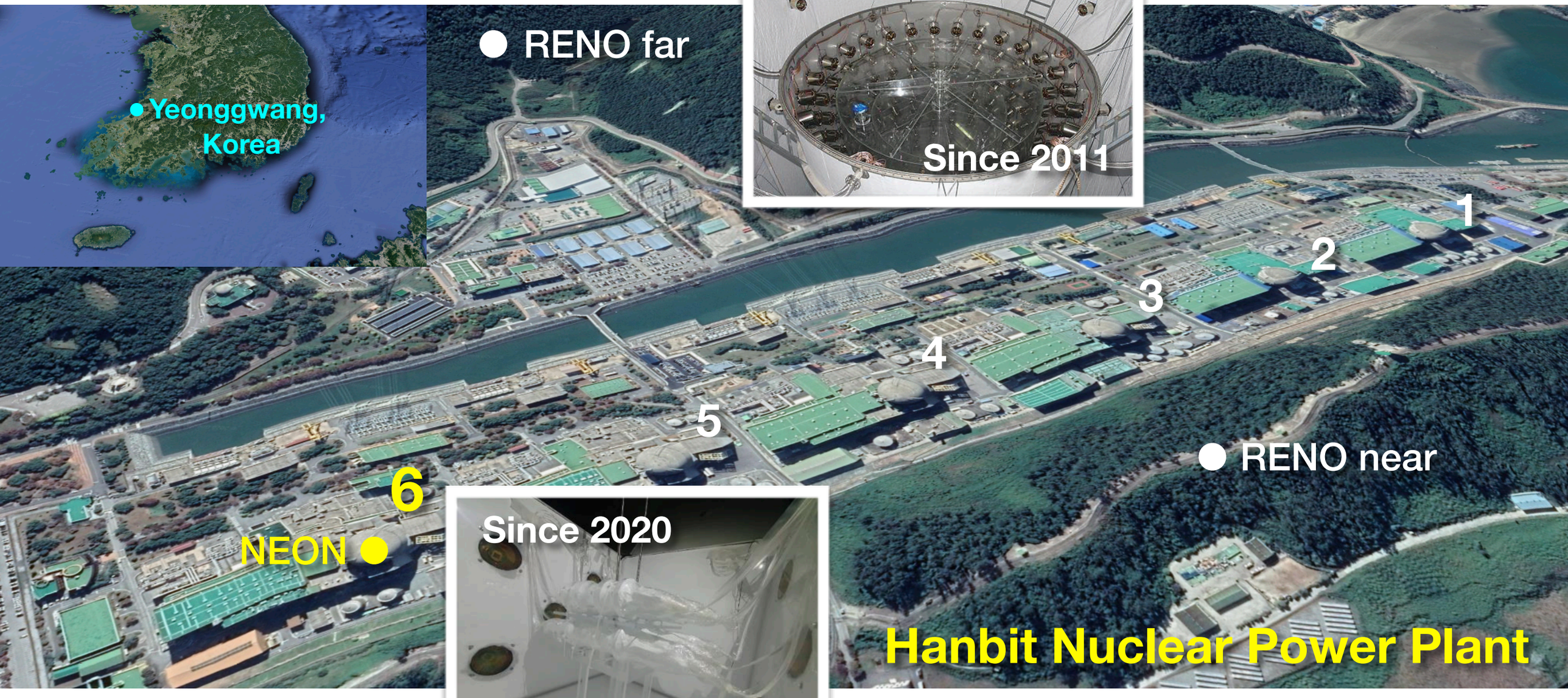

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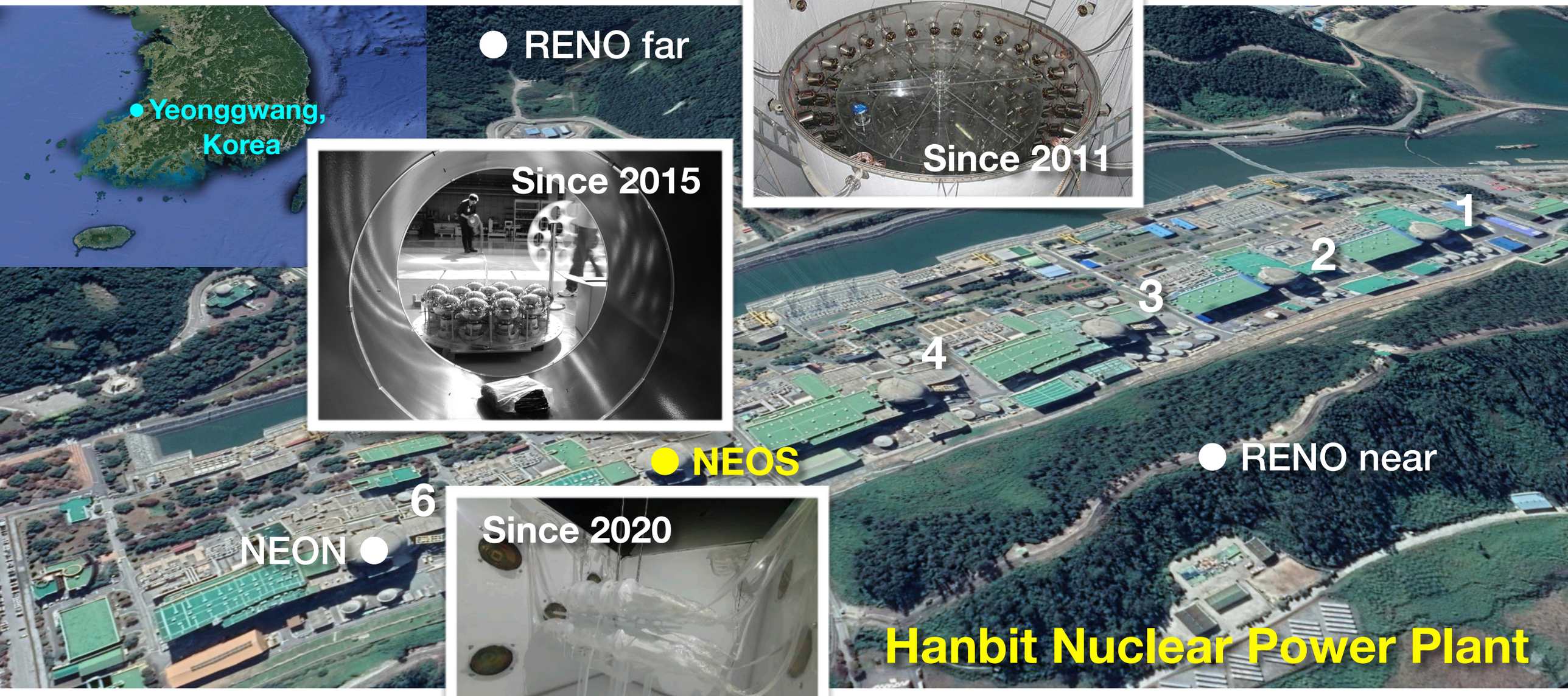

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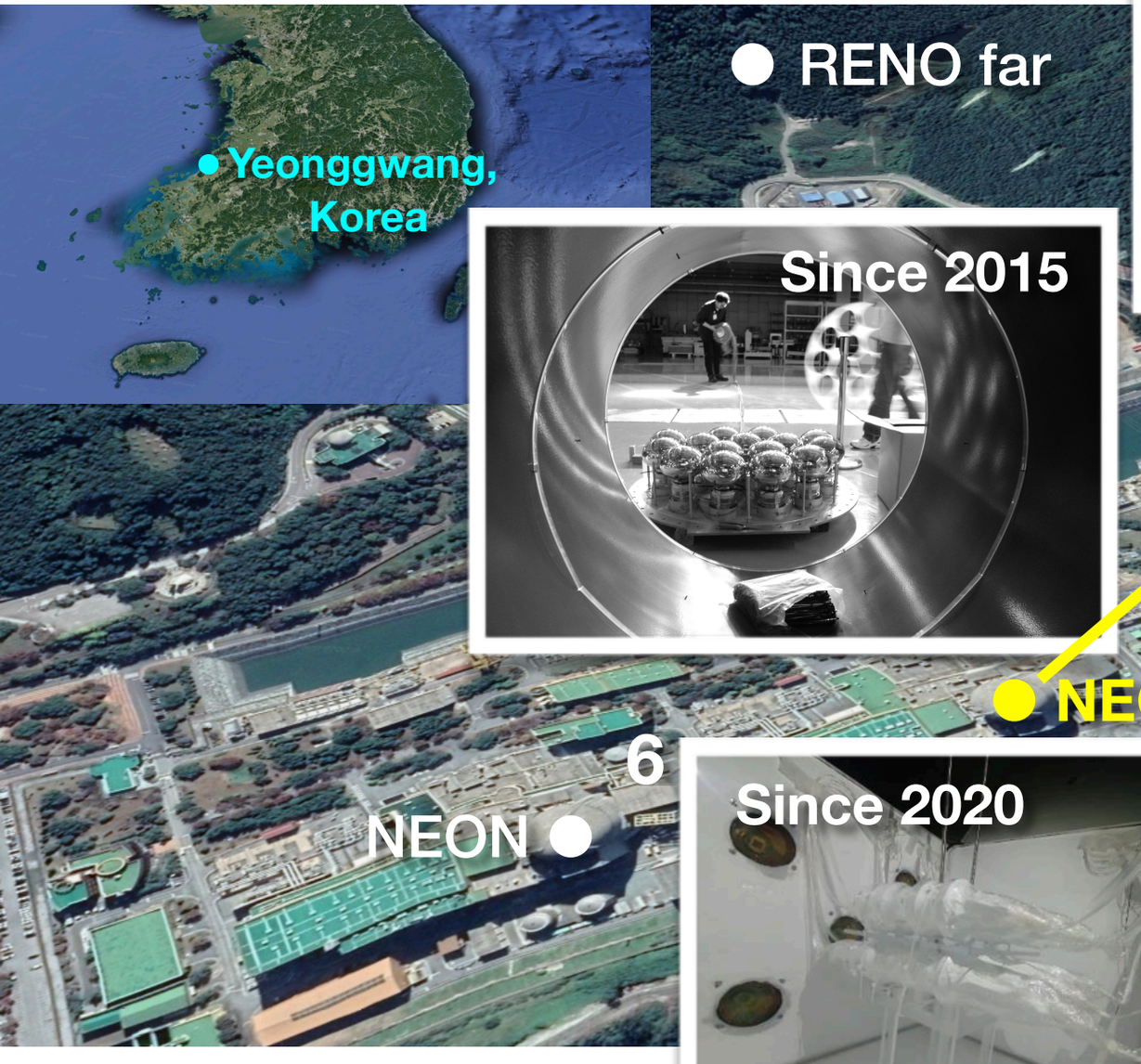
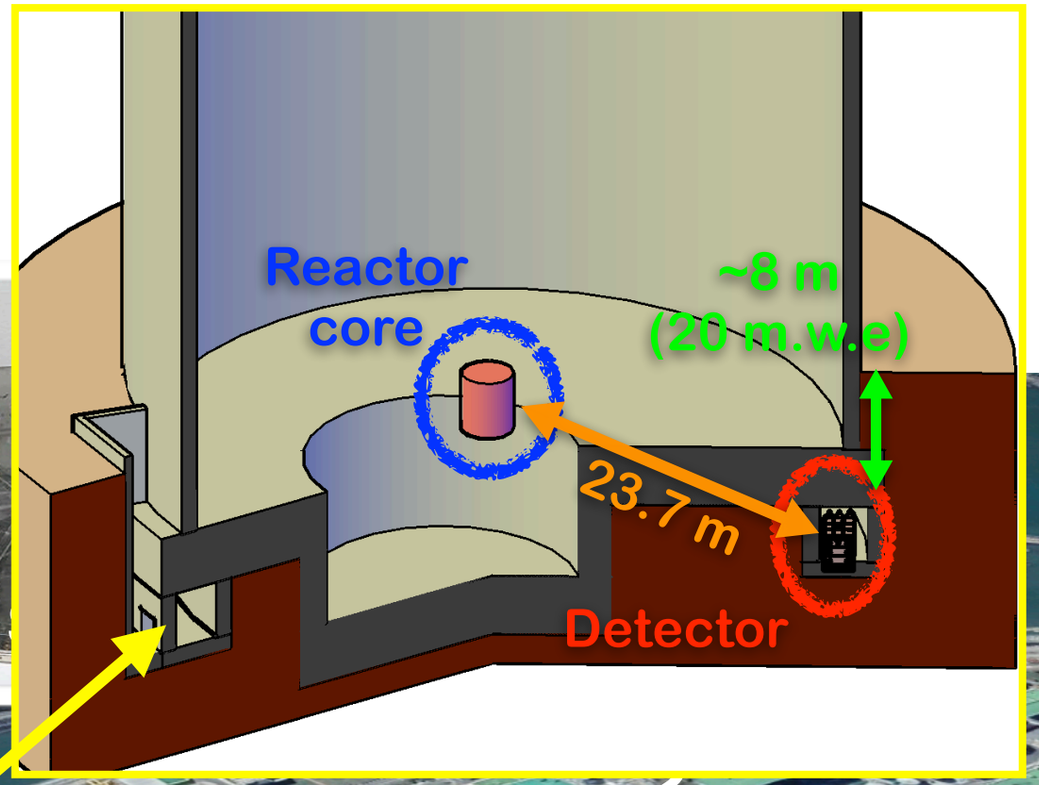


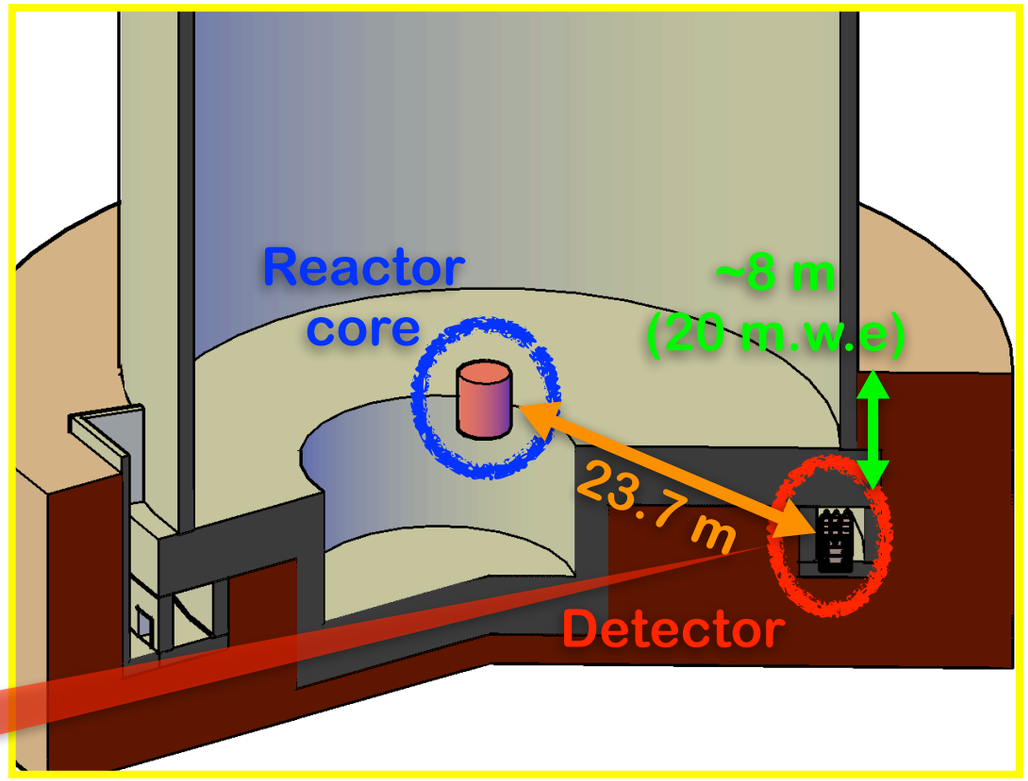


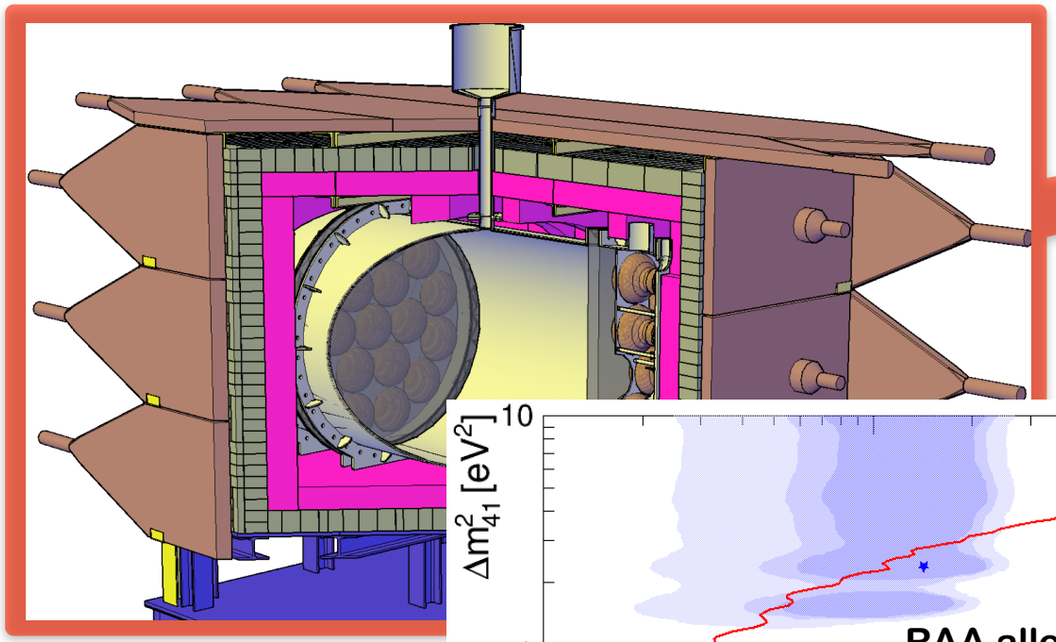
- Tendon gallery at reactor unit 5
  - 2.8-GW_{th} commercial reactor
  - Low enriched uranium fuel (4.6% ^{235}U)
  - 23.7-m baseline & 20-mwe overburden

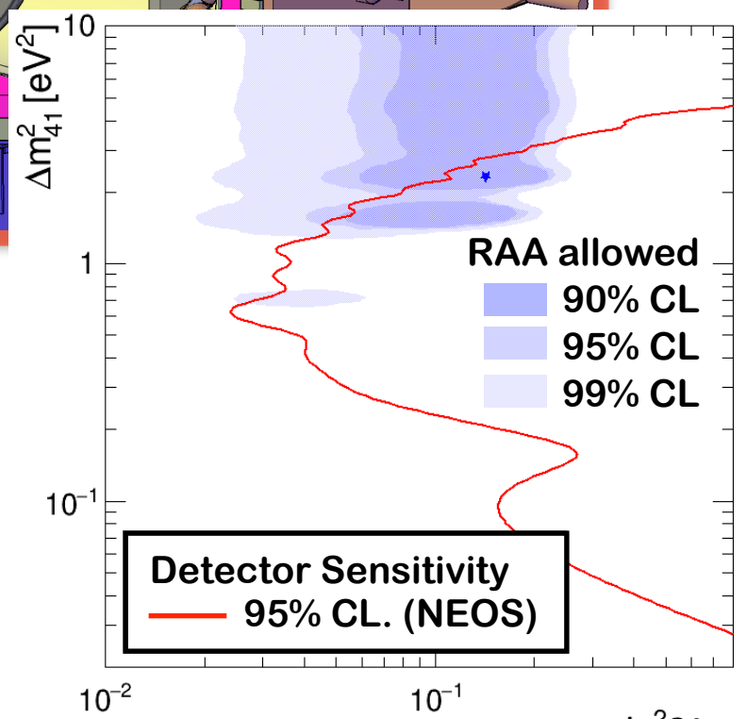
Hanbit Nuclear Power Plant

NEOS

NEOS-I Experiment







- Tendon gallery at reactor unit 5
  - 2.8-GW_{th} Commercial reactor
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  - 23.7-m baseline & 20-mwe overburden
  - Most sensitive range for ~eV sterile neutrino

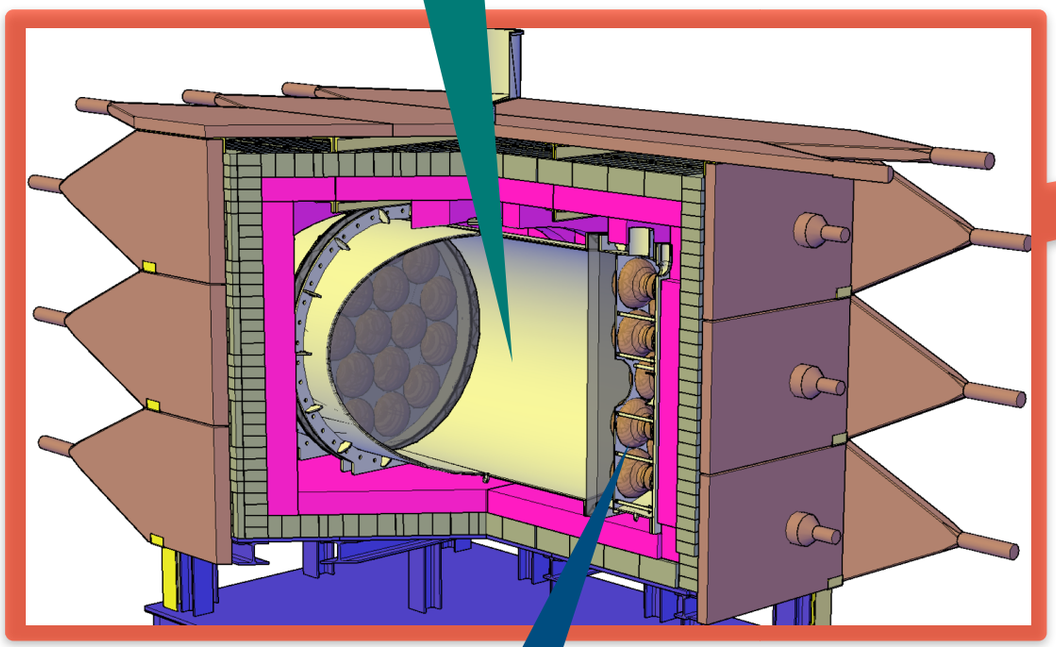
NEOS

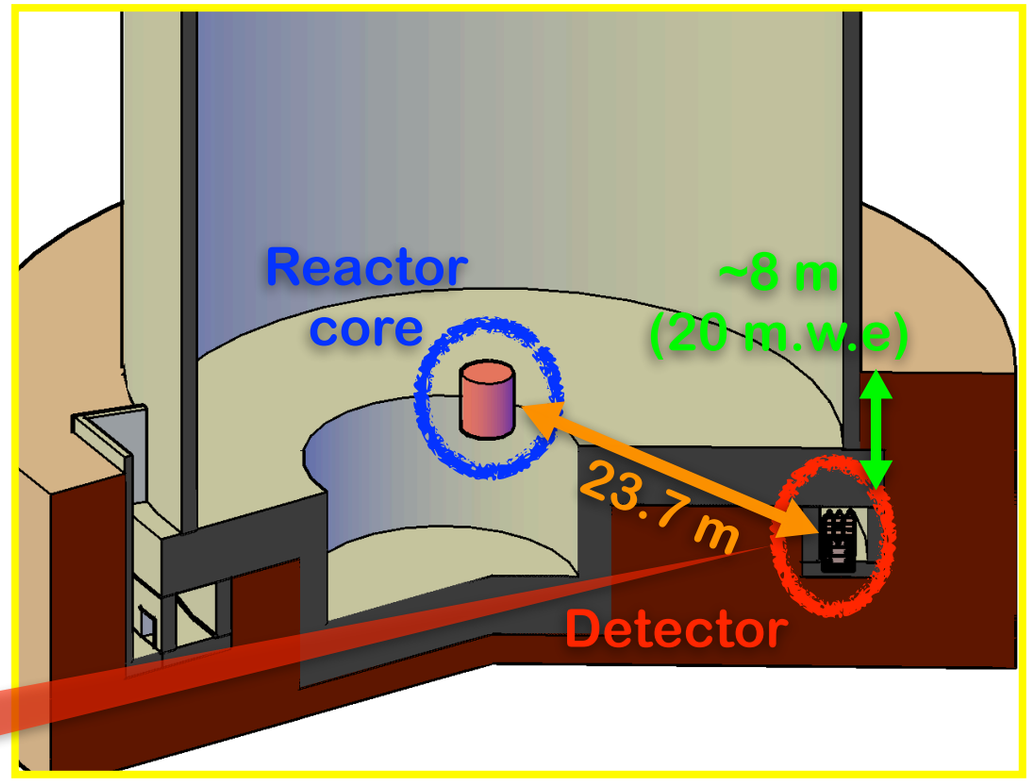
NEOS-I Experiment

Active target

Homogeneous
1,008-L volume
0.48% Gd-LS
Mixed LS
(LAB + DIN)

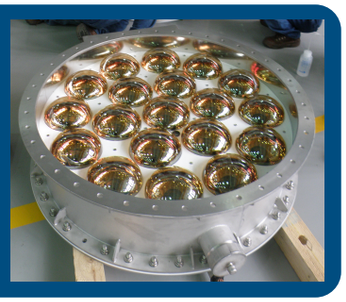
LAB: linear alkylbenzene
DIN: di-isopropylnaphthalene





Photomultiplier tubes

Two buffer tanks at both side of target
Acrylic window b/w target & buffers
19 R5912 (8 inch) PMTs in each buffer



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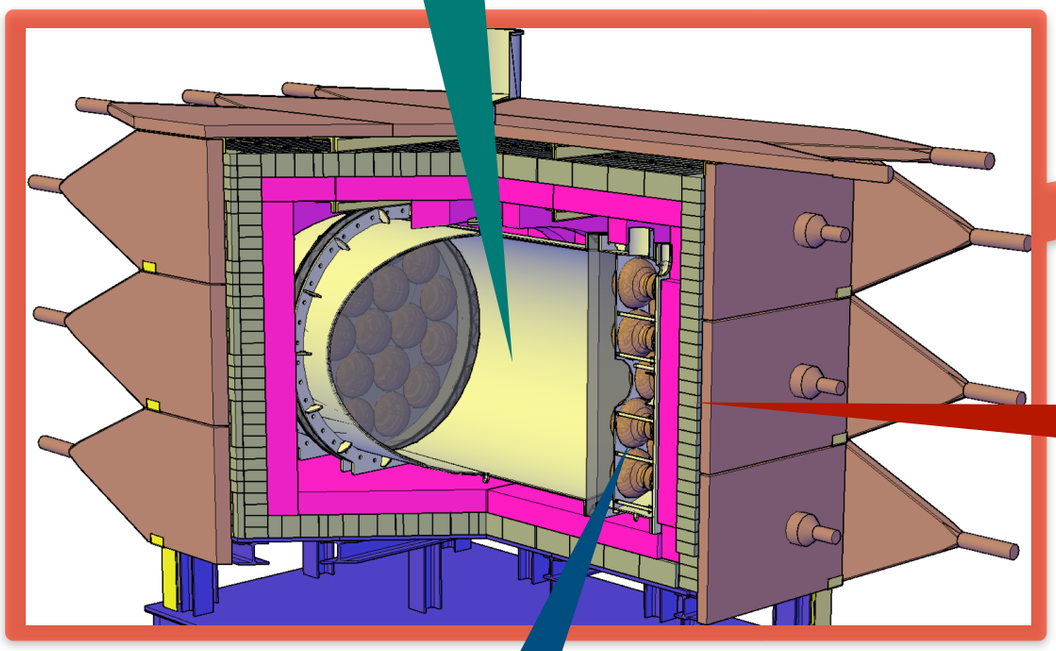

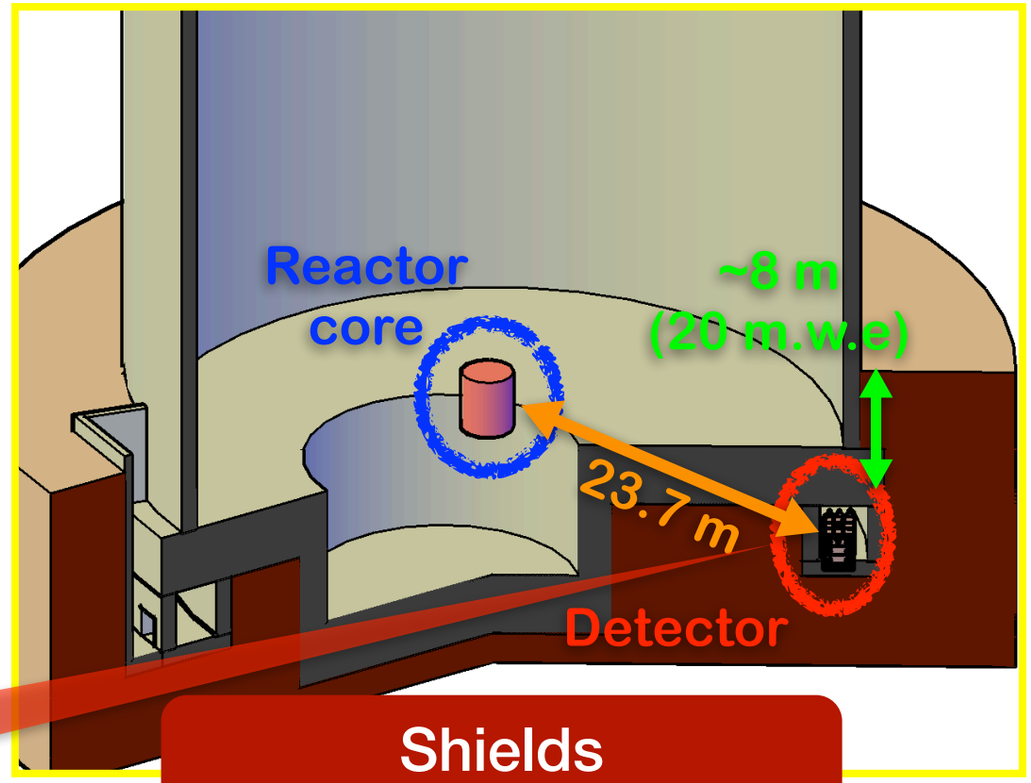

Shields

10-cm thick B-PE (n^0) and Pb(γ)
Muon veto detectors
3-cm thick plastic scintillator
15 panels with PMTs
Except bottom side

Photomultiplier tubes

Two buffer tanks at both side of target
Acrylic window b/w target & buffers
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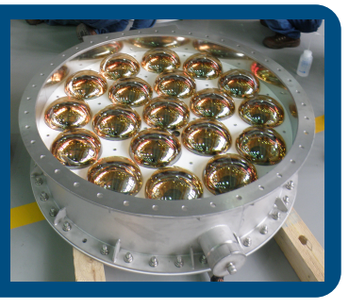


DAQ systems

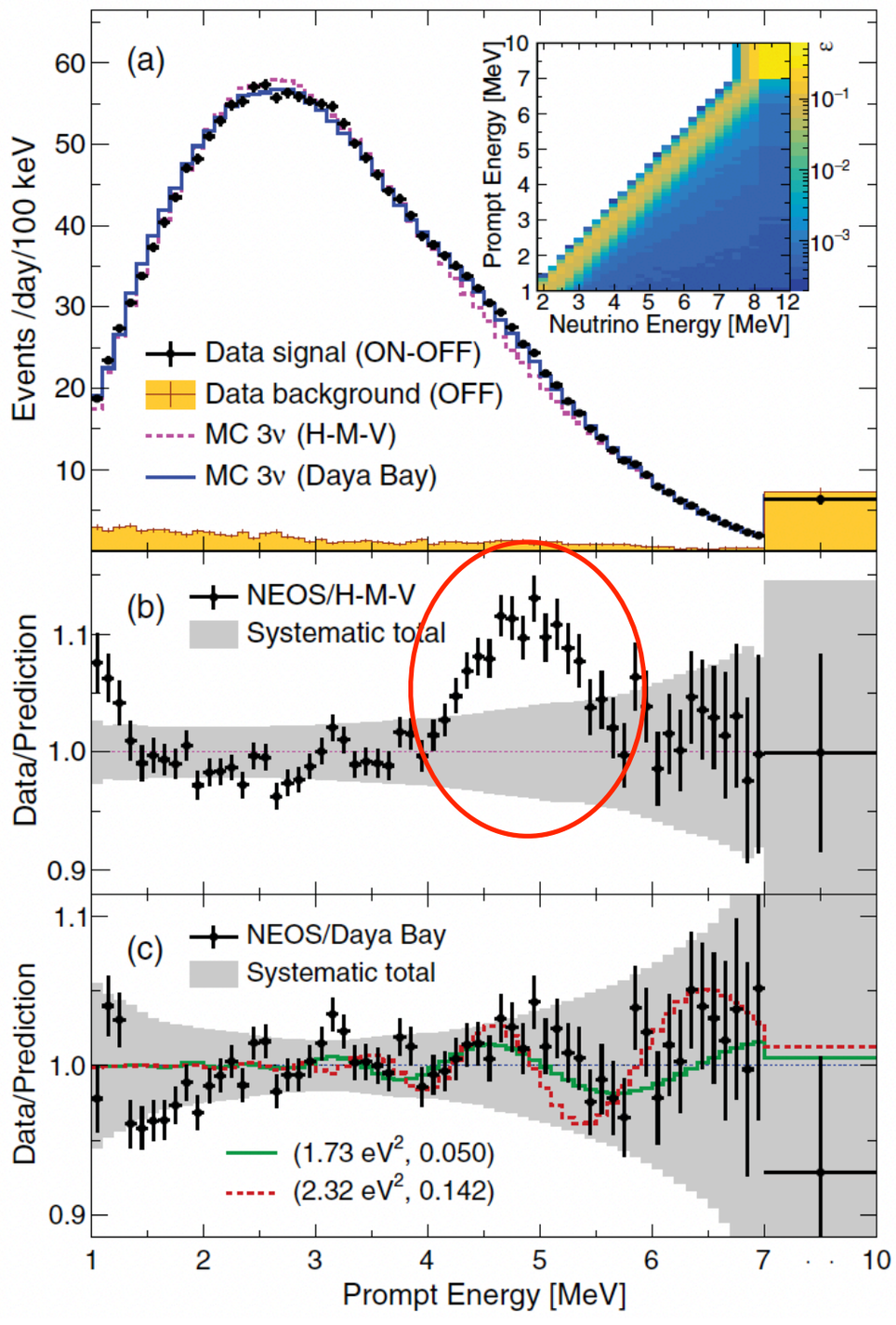
500 MS/s Flash ADC for target
(recording waveforms for PSD)
62.5 MS/s ADC for muon counters

NEOS

NEOS-I Results

- ~22 S/B ratio
  - IBD candidates: ~2000/day (on) & ~85 /day (off)
- Comparison w/ models
  - HM model: spectral anomaly, 5-MeV excess
  - Daya Bay
    - Generally in an agreement
    - Spectral shape analysis

Phys. Rev. Lett. ***118***, *121801 (2017)*



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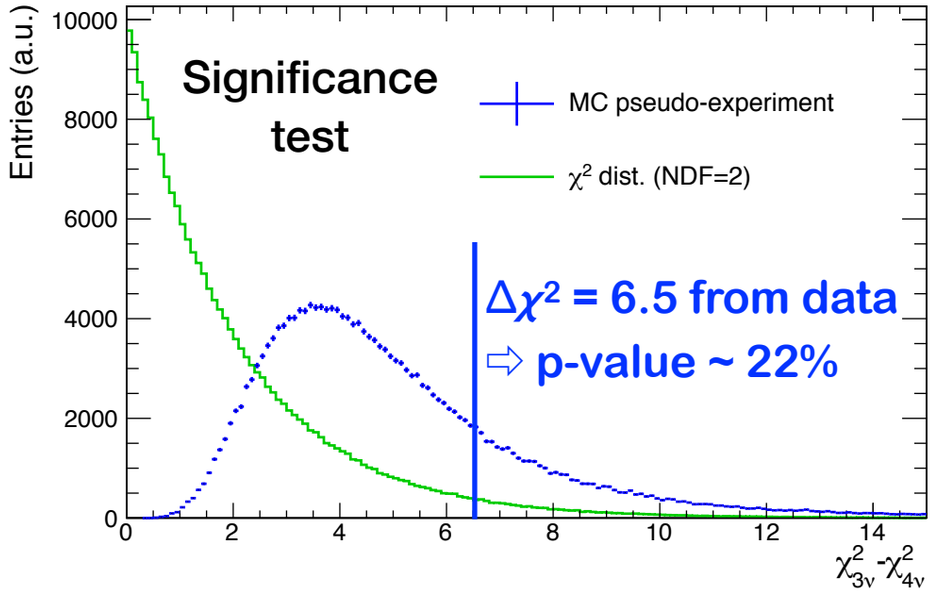

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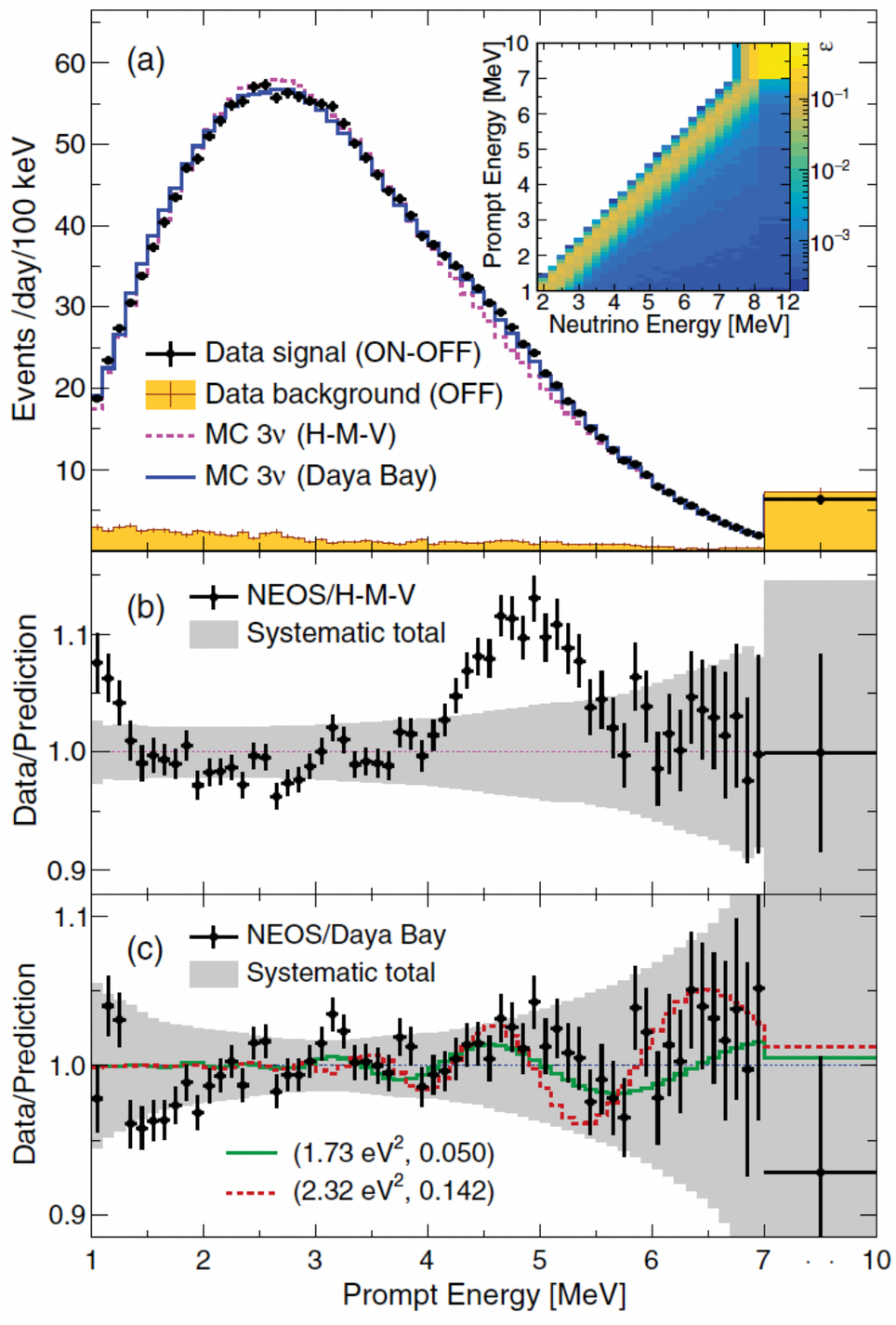

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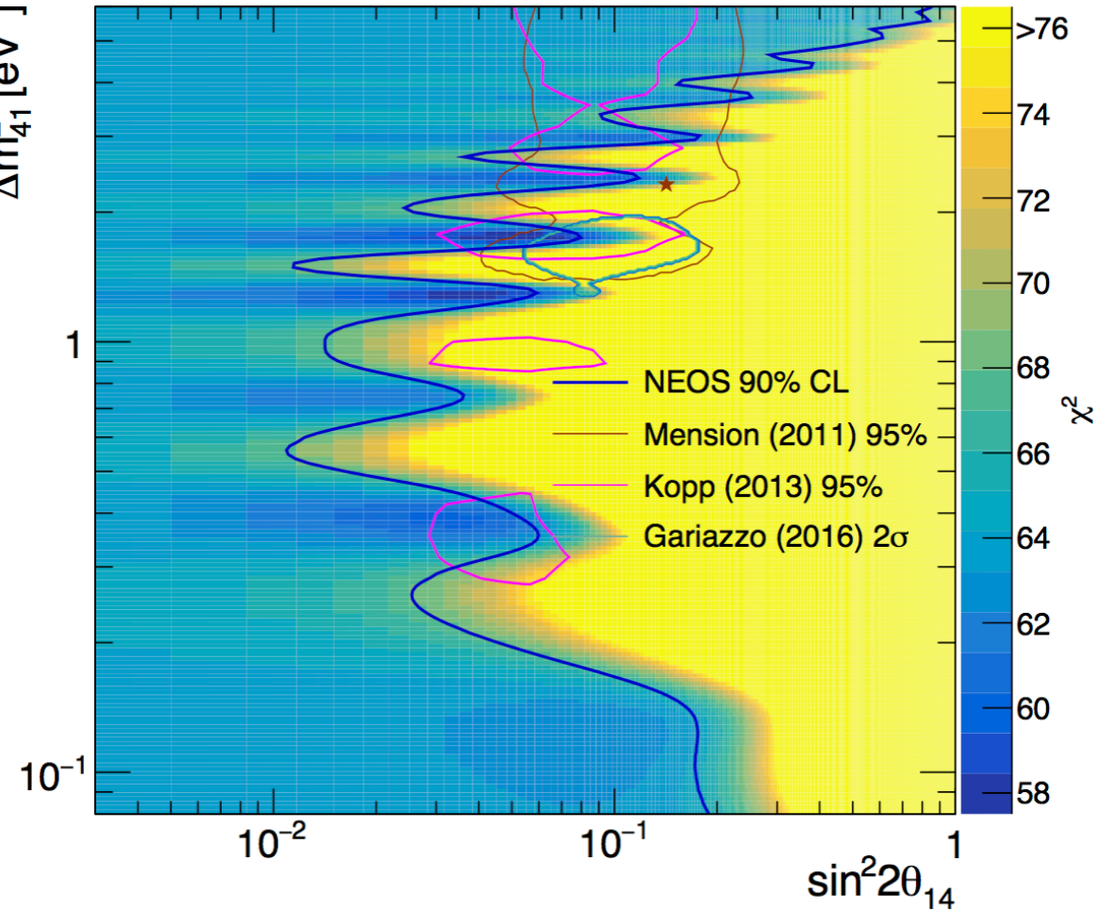
- Exclusion limits
  - Raster scan w/ χ^2 distribution
  - First results since the RAA was raised



NEOS

NEOS-II Experiment

- 5-MeV excess
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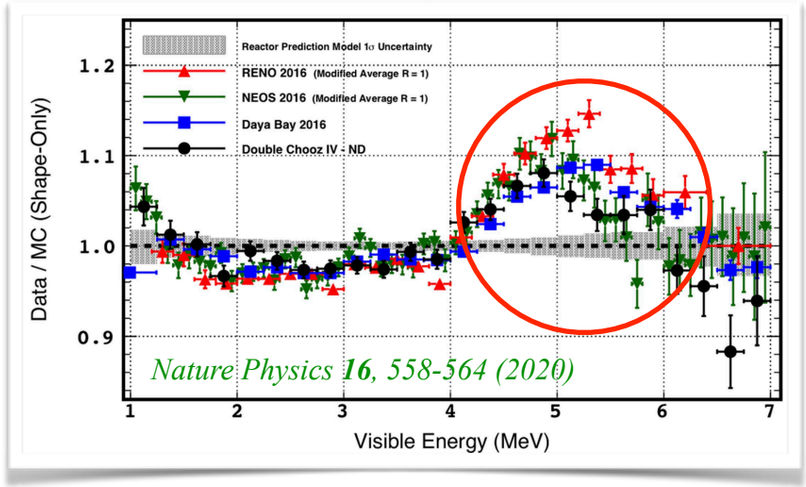
  - Is ^{235}U the source of the excess?



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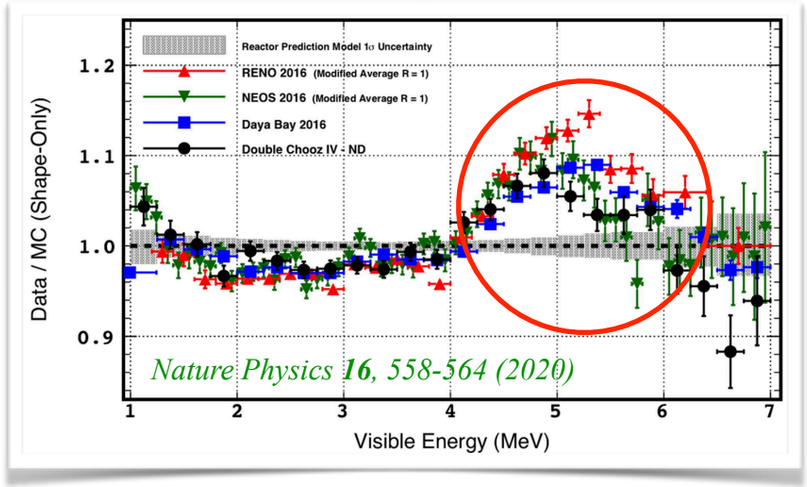

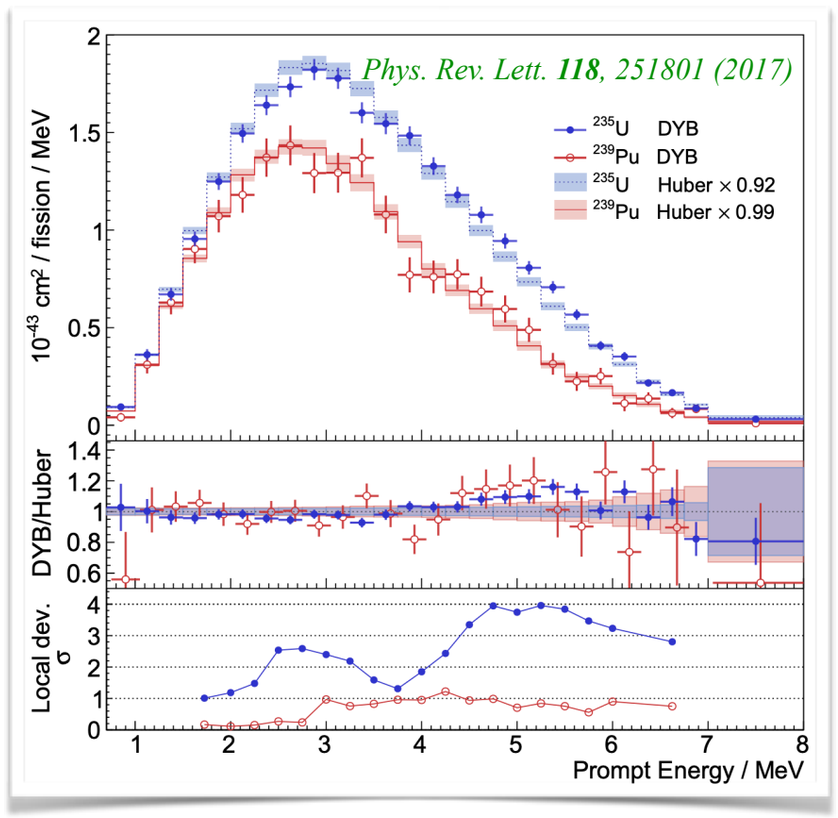

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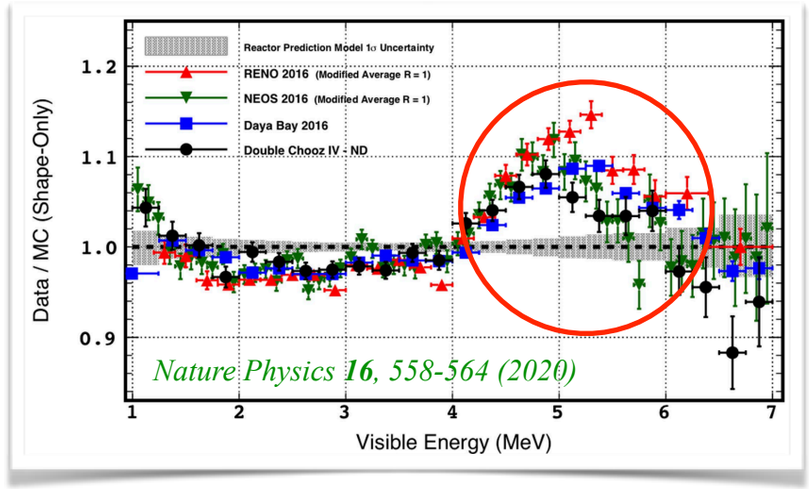

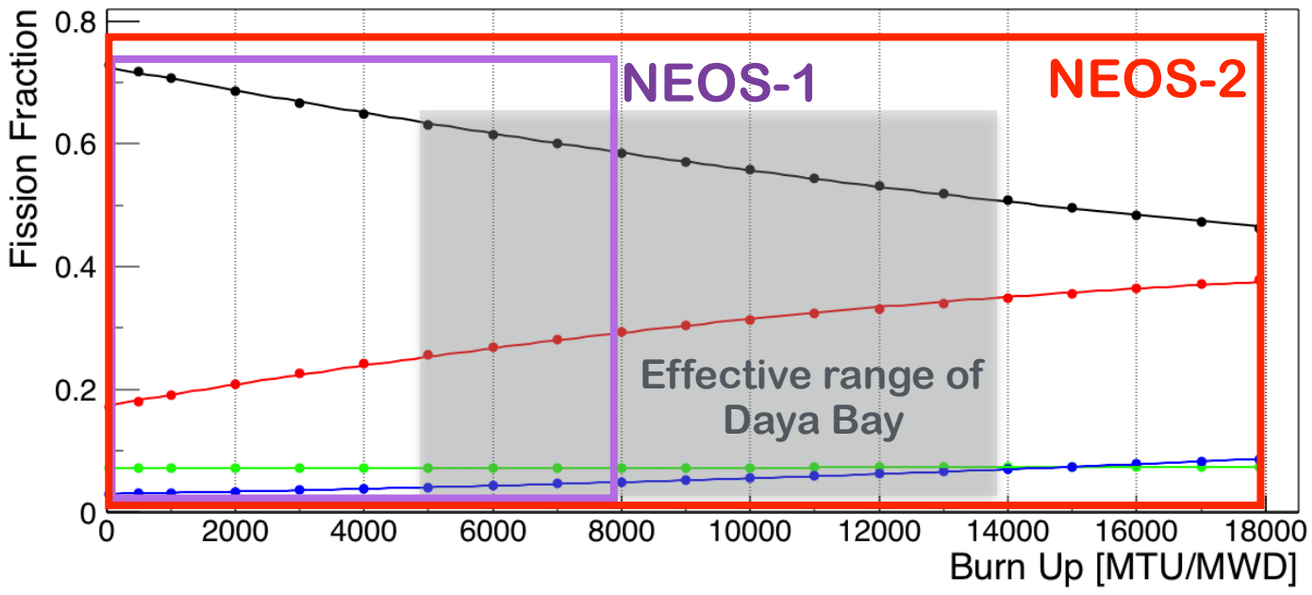

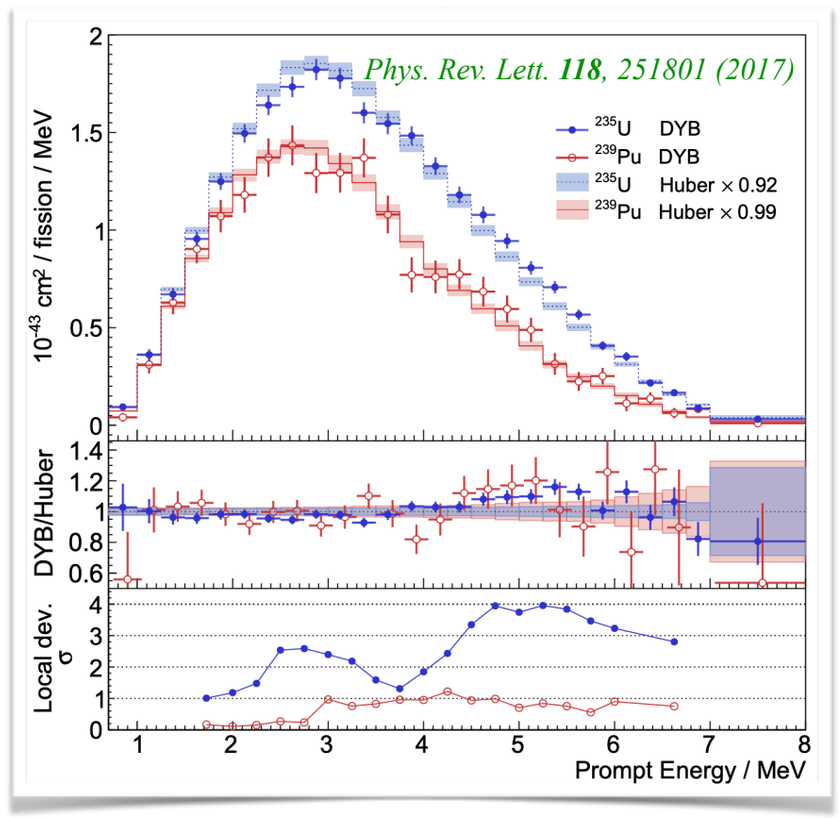

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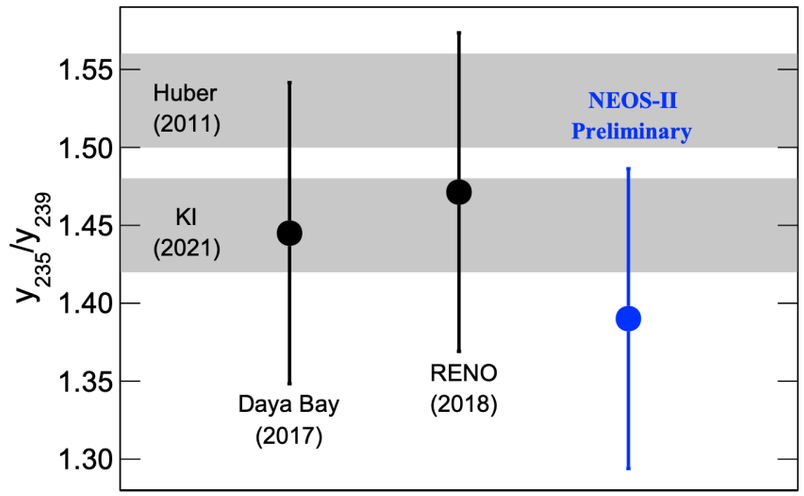
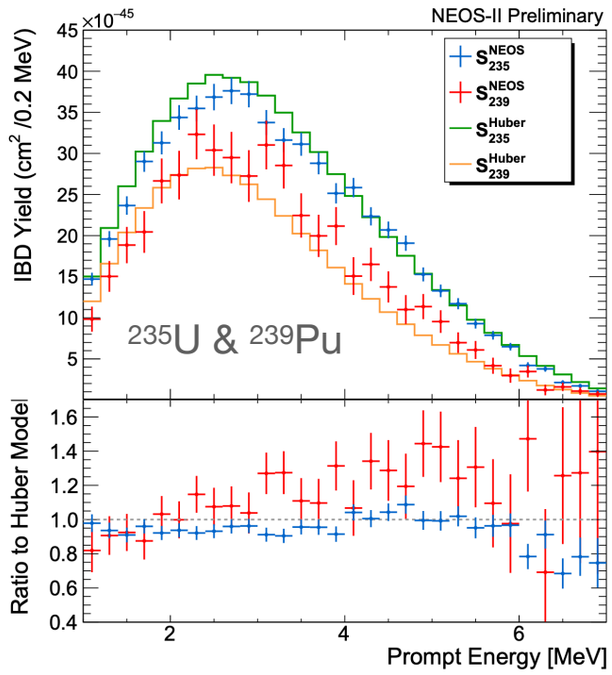
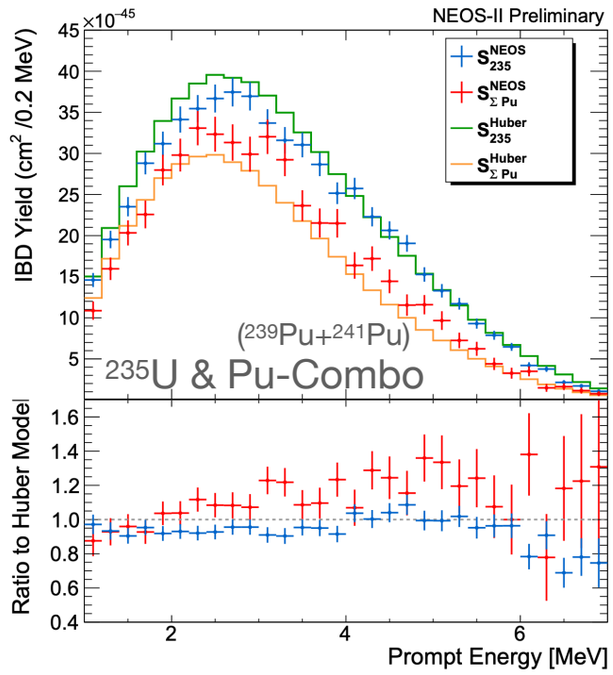


- Spectra decomposition
  - Extraction of ^{235}U & $^{(239)}$Pu spectra
  - Deficit & 5-MeV excess in ^{235}U
  - Not conclusive for $^{(239)}$Pu





Deep Learning in NEOS

Inverse β-decay

- NEOS detector is a calorimeter w/ Gd-LS to measure the electron antineutrino spectra.
- Neutrino detection through inverse β-decay (IBD) in the active target

  $\bar{\nu}_e + p \rightarrow e^+ + n$ (IBD)

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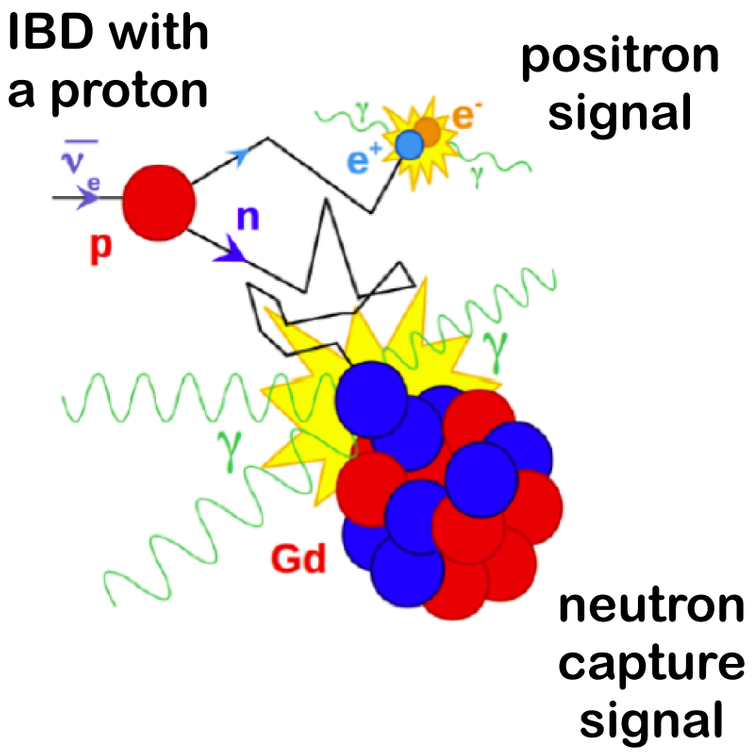

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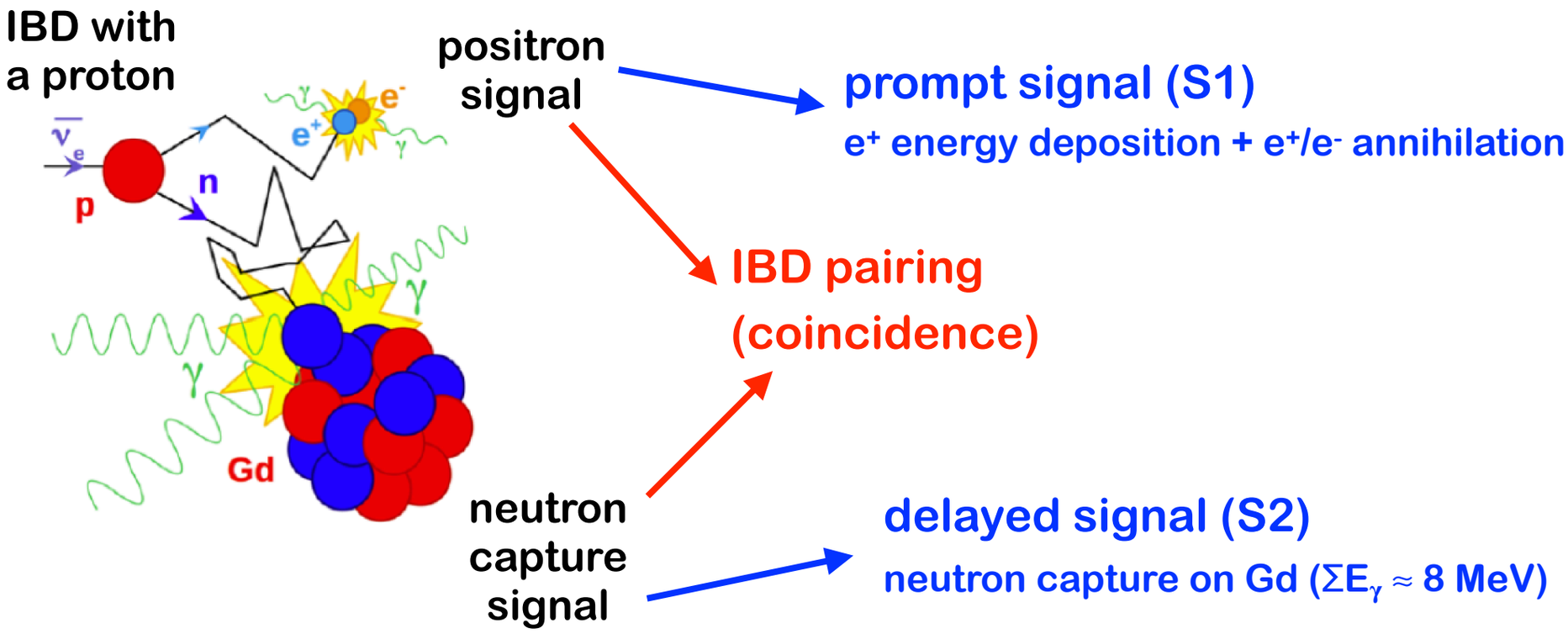
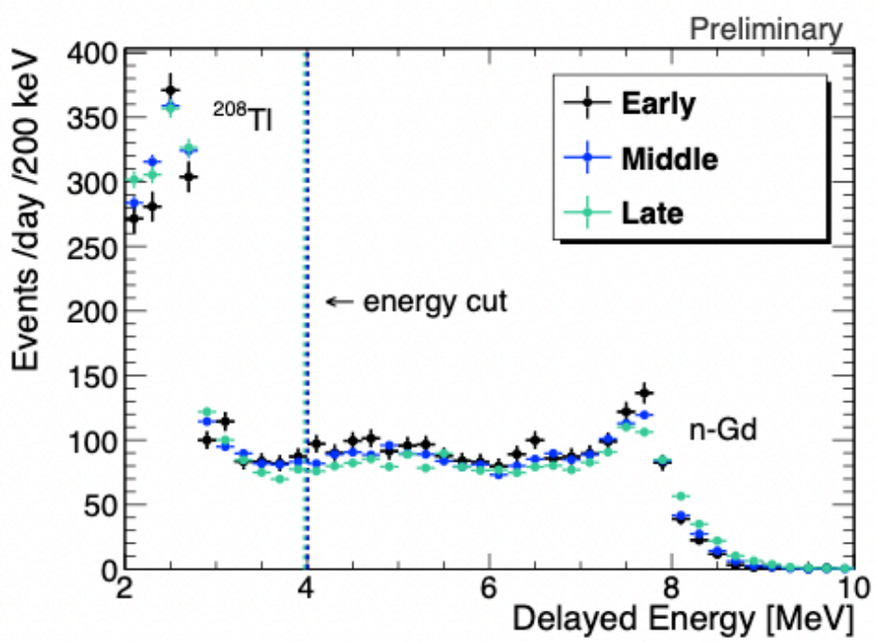
- IBD in the Gd-LS

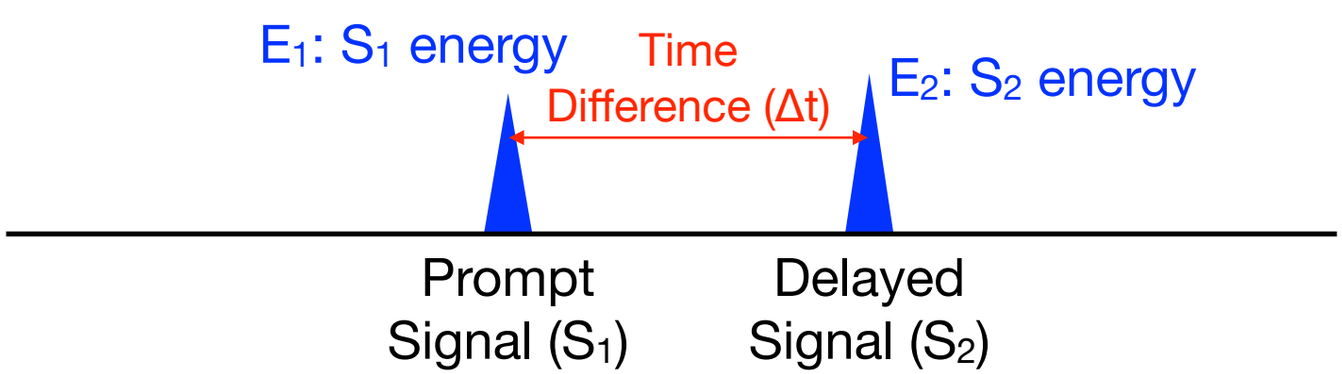


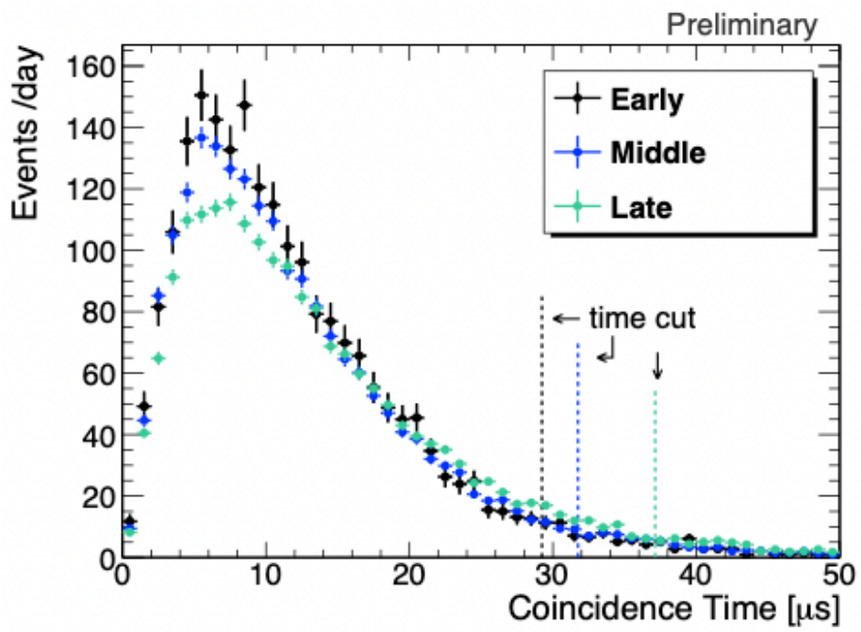
Deep Learning in NEOS

IBD Selection Criteria

- Criteria for IBD selection
  - Delayed energy & coincidence time



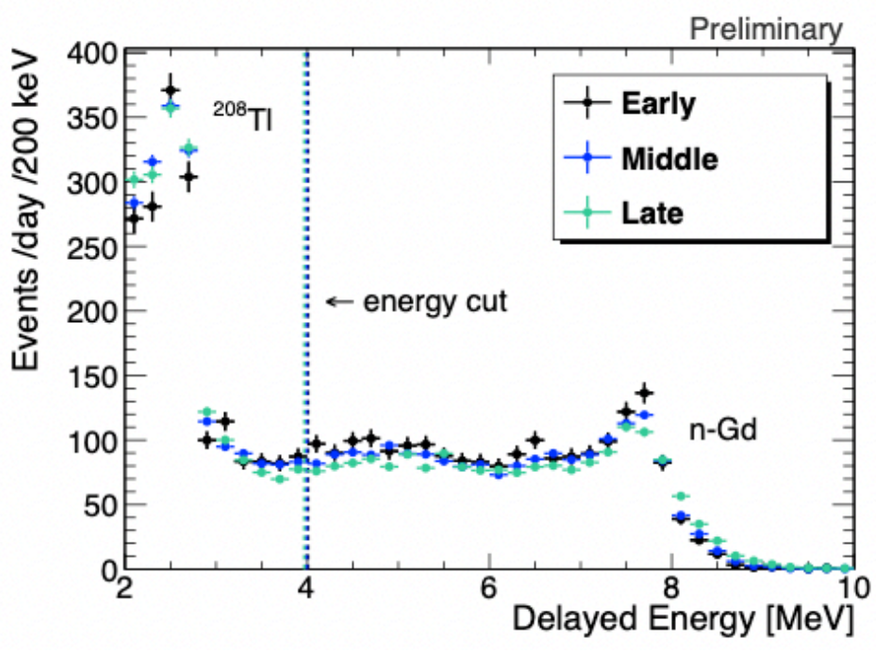


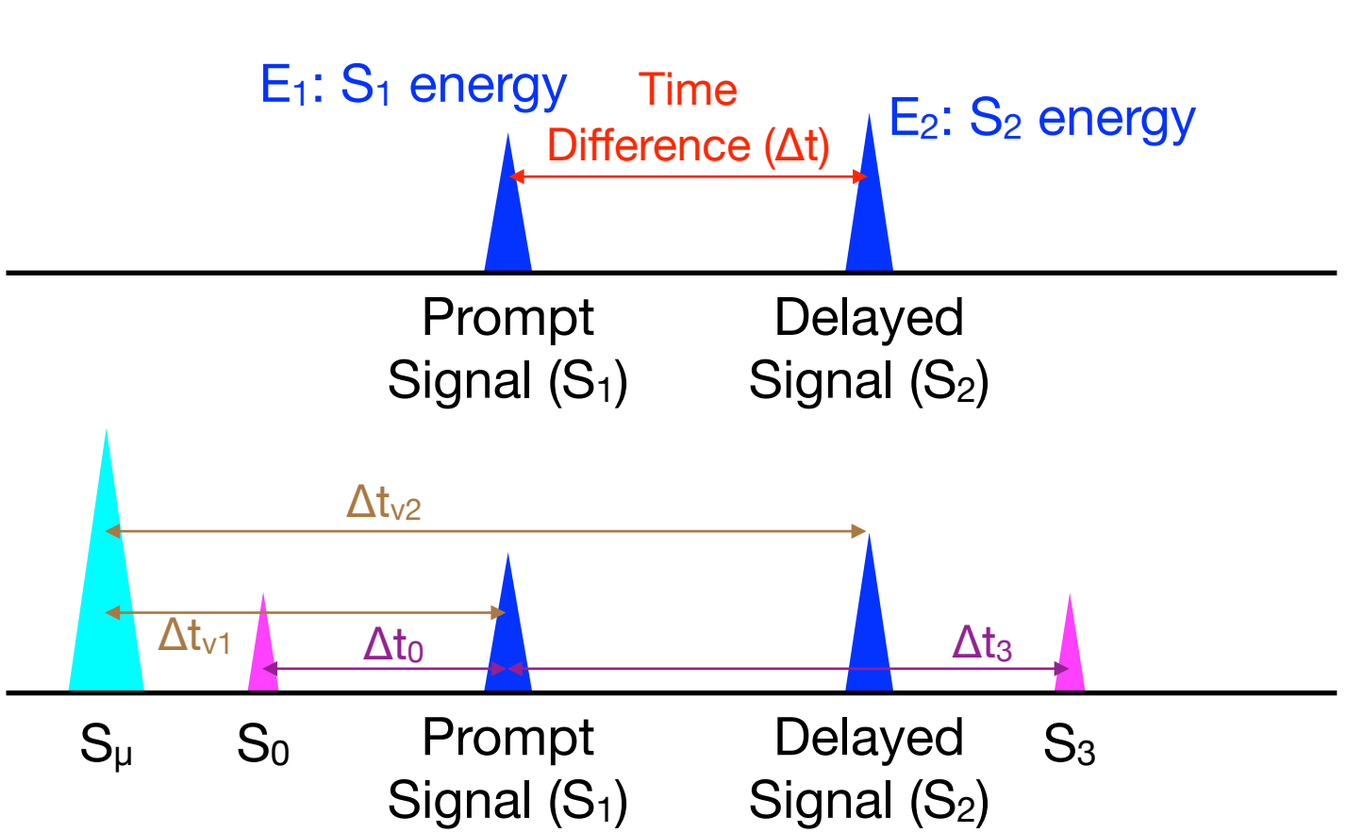


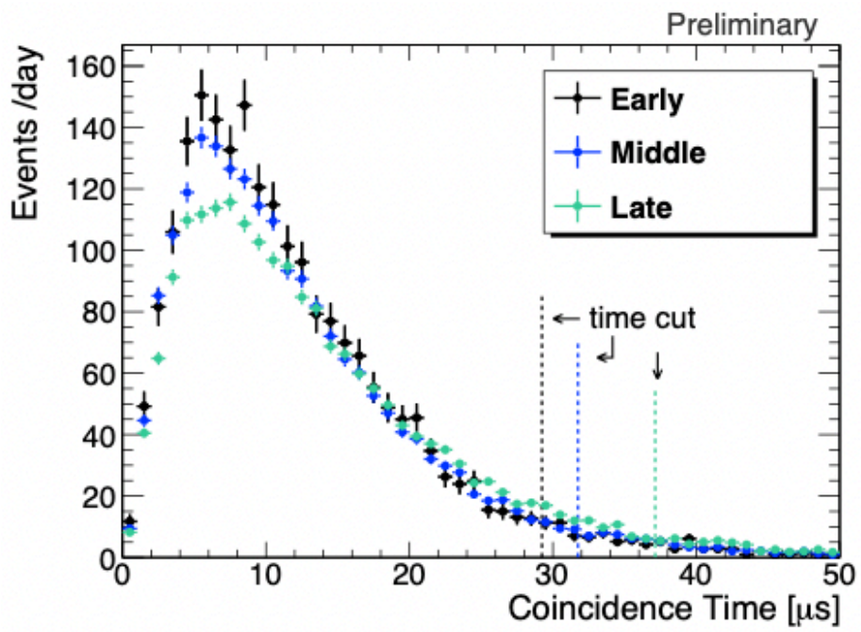
Deep Learning in NEOS

IBD Selection Criteria

- Criteria for IBD selection
  - Delayed energy & coincidence time
- Criteria for background rejection
  - Muon veto
  - Multiplicity against the multiple neutrons
  - Pulse shape discrimination (PSD)
    - To remove the fast-neutron backgrounds



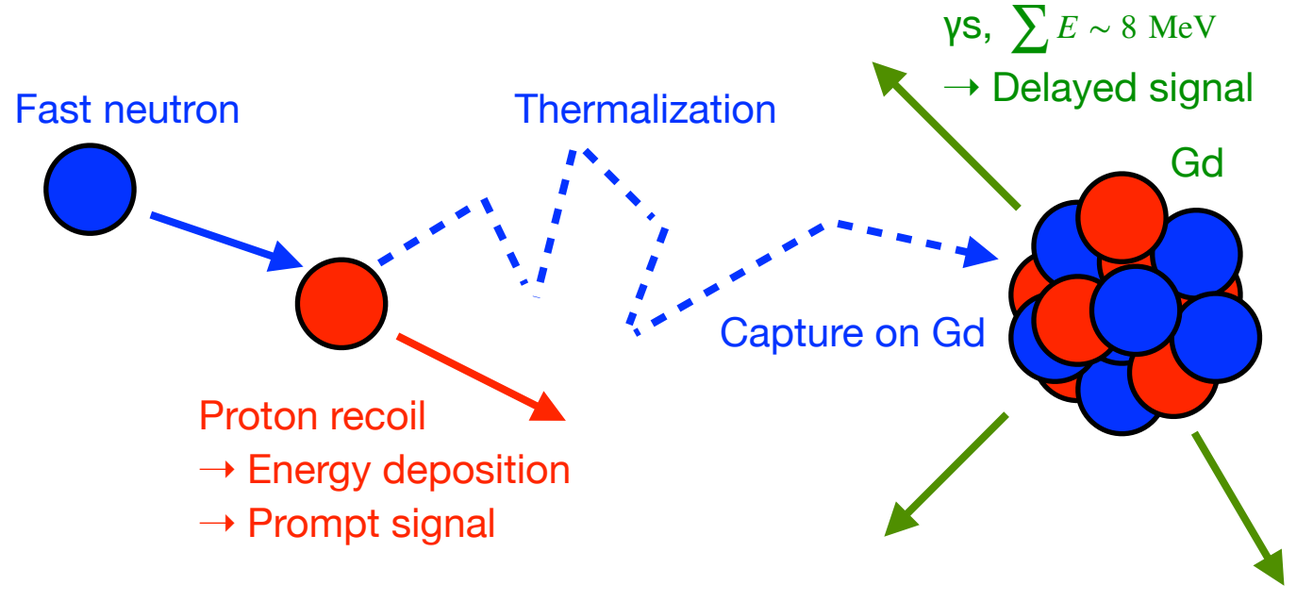




Deep Learning in NEOS

Pulse Shape Discrimination

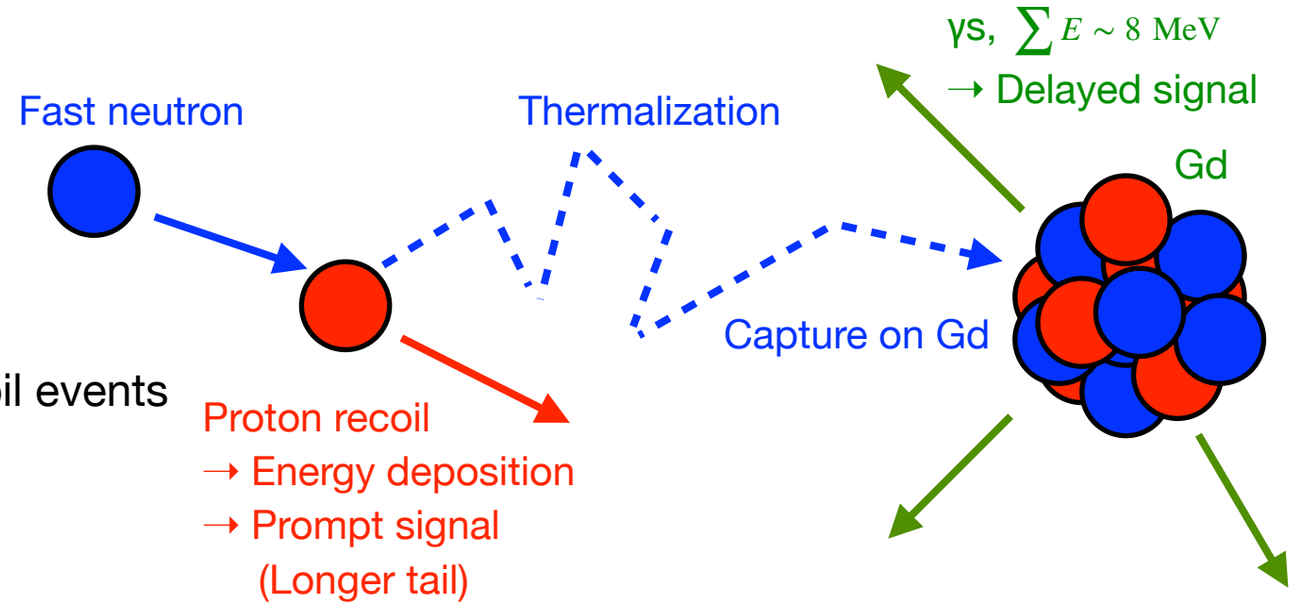
- Fast neutron background
  - Most dominant background

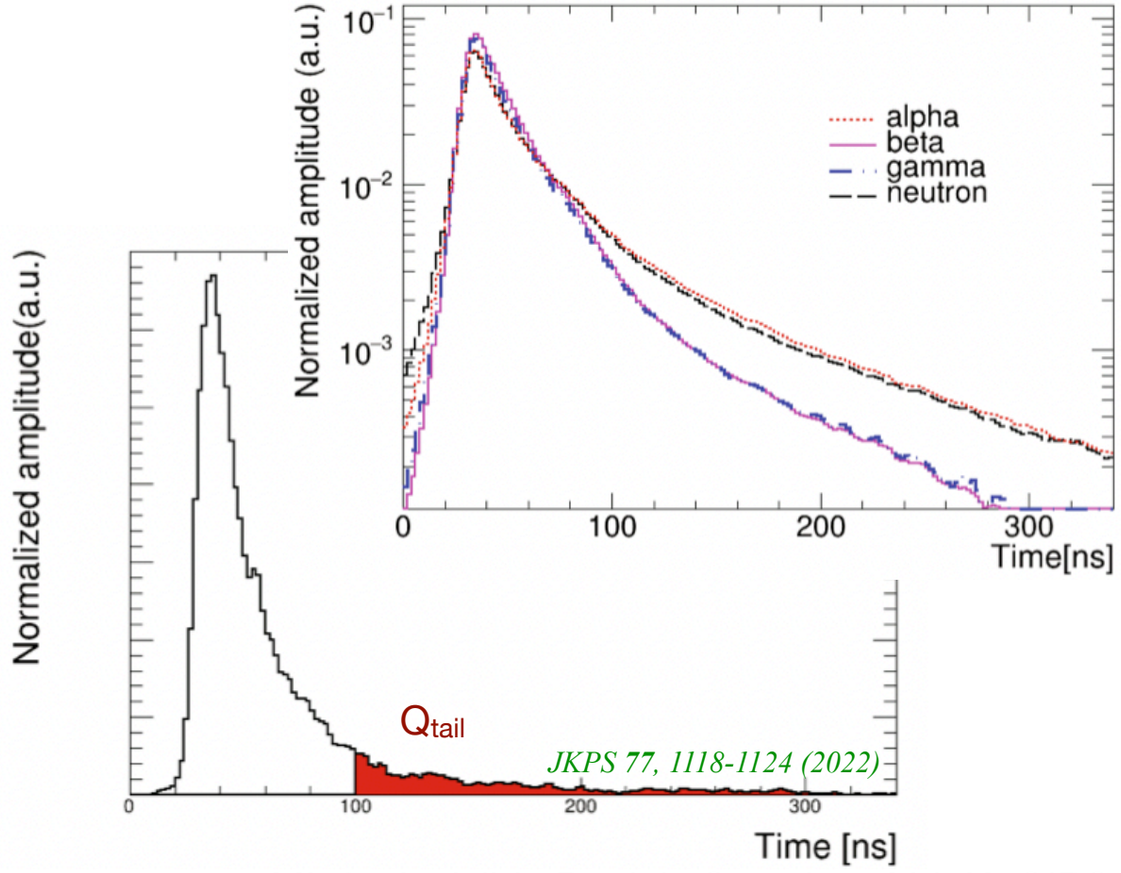


Deep Learning in NEOS

Pulse Shape Discrimination

- Fast neutron background
  - Most dominant background
  - Pulse shape discrimination (PSD)
    - Using different pulse shapes b/w e^- & p^+ recoil events
    - Conventional method: Q_{tail}/Q_{total}





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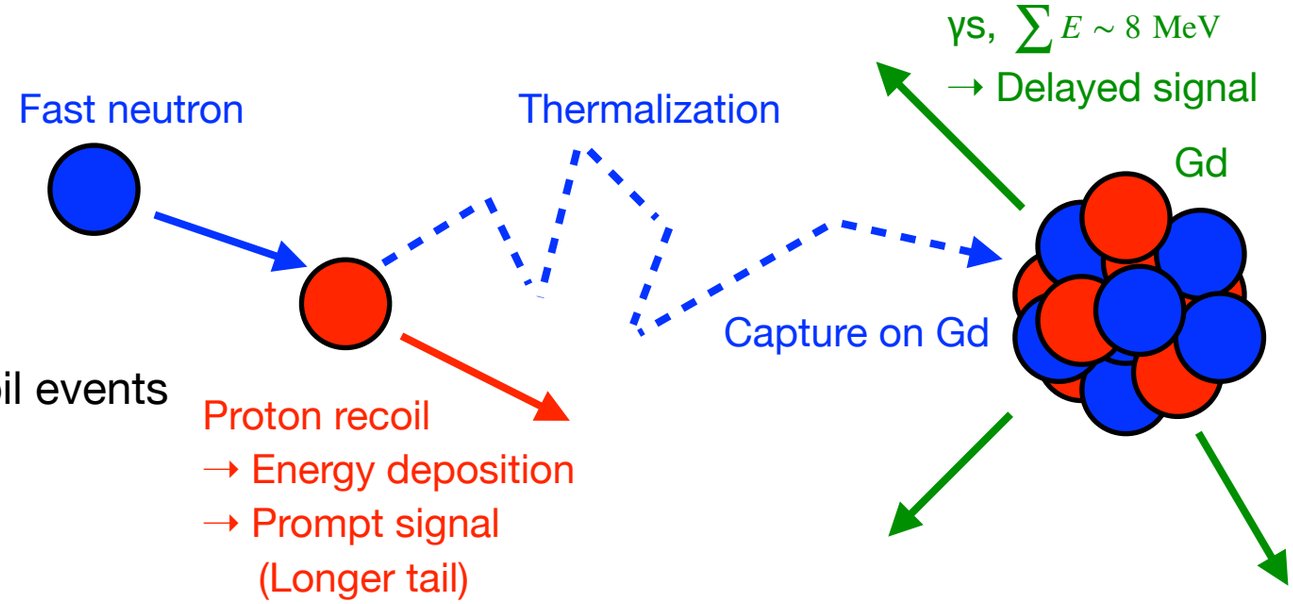
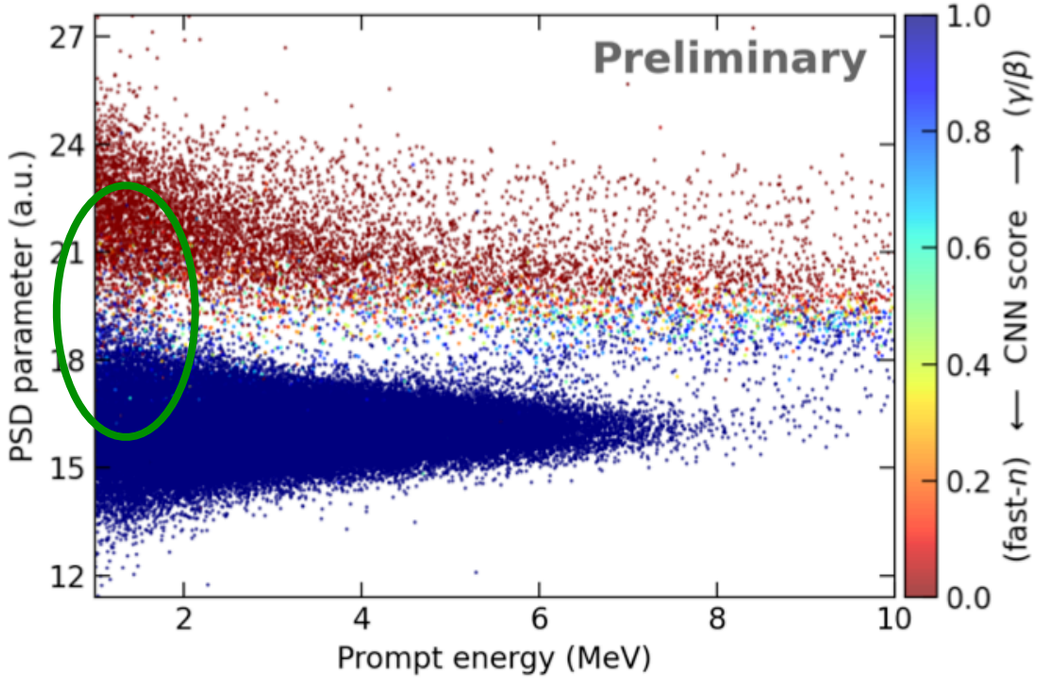
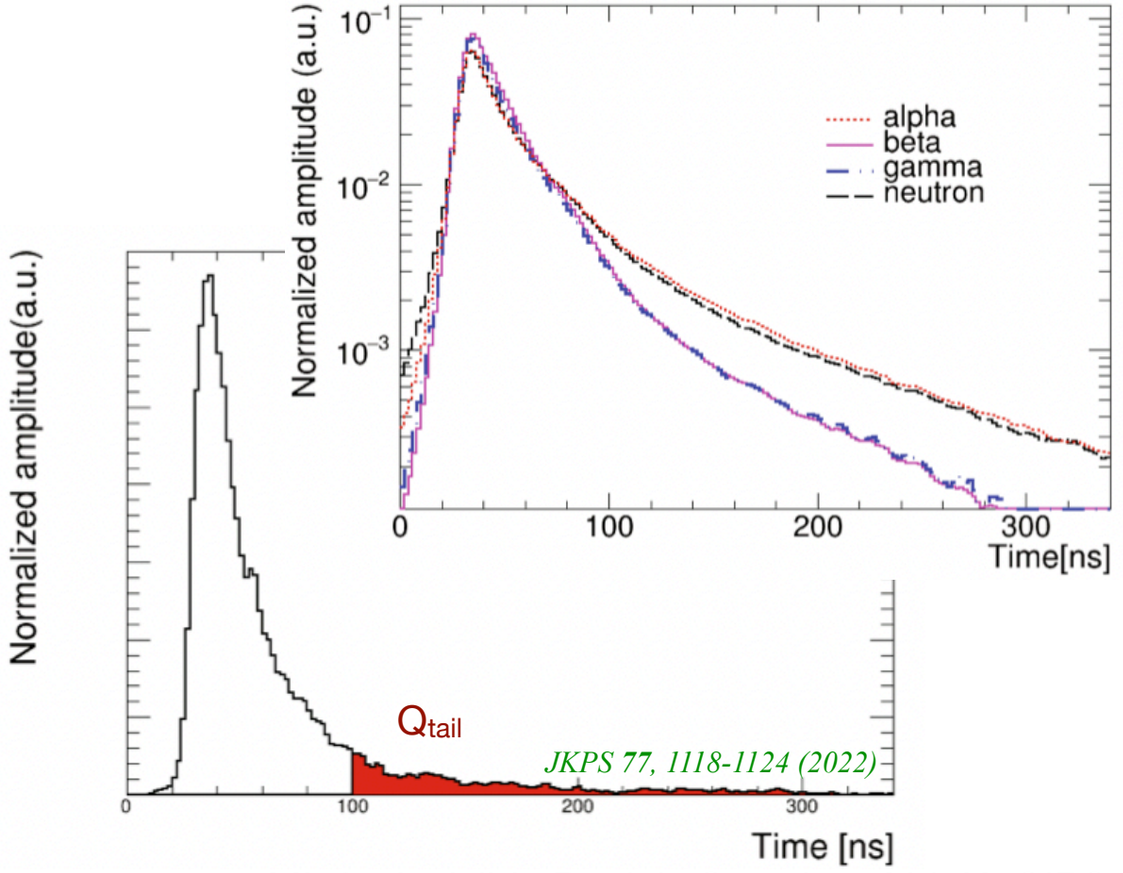
    - Overlapped region in low energy





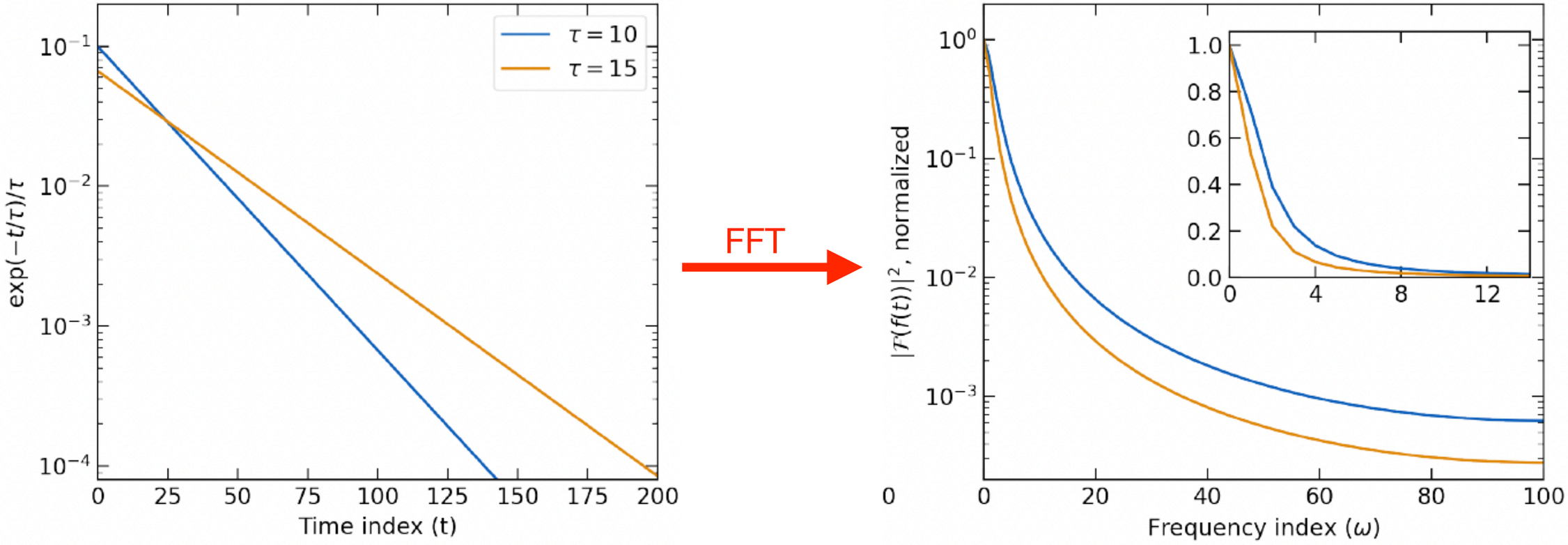


Deep Learning in NEOS

Power Spectrum of Waveform

- Fast-Fourier transformed (FFT) waveform
  - Large & small decay time can be discriminated by FFT.
  - Using power spectrum in the frequency domain

$$\mathscr{P}(\omega) = \sum_{i=1}^{38} \left| \mathscr{F}\left[w_i(t)\right] \right|^2$$



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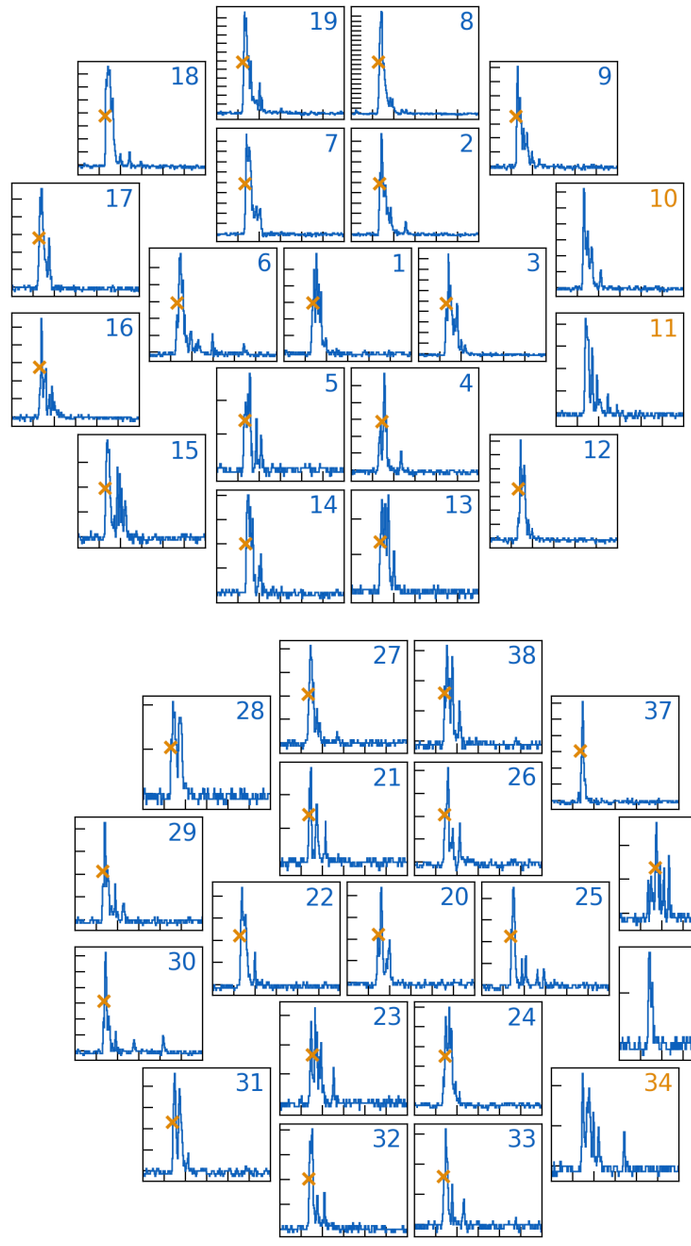
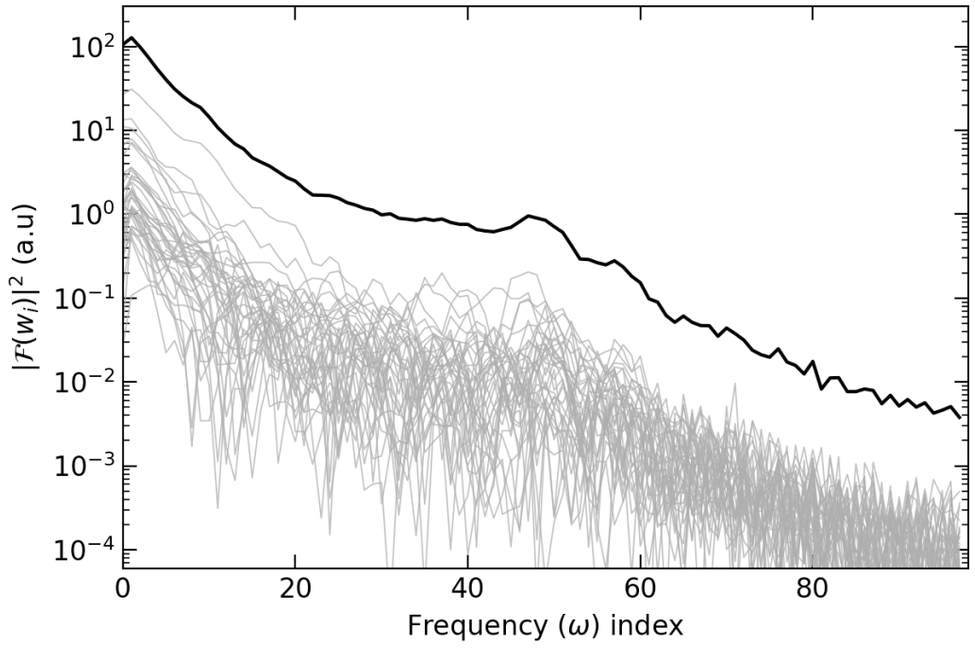
    - Neglecting the phase terms → Reducing a half of # of time bins
    - The power spectrum is used as an input for CNN.





Deep Learning in NEOS

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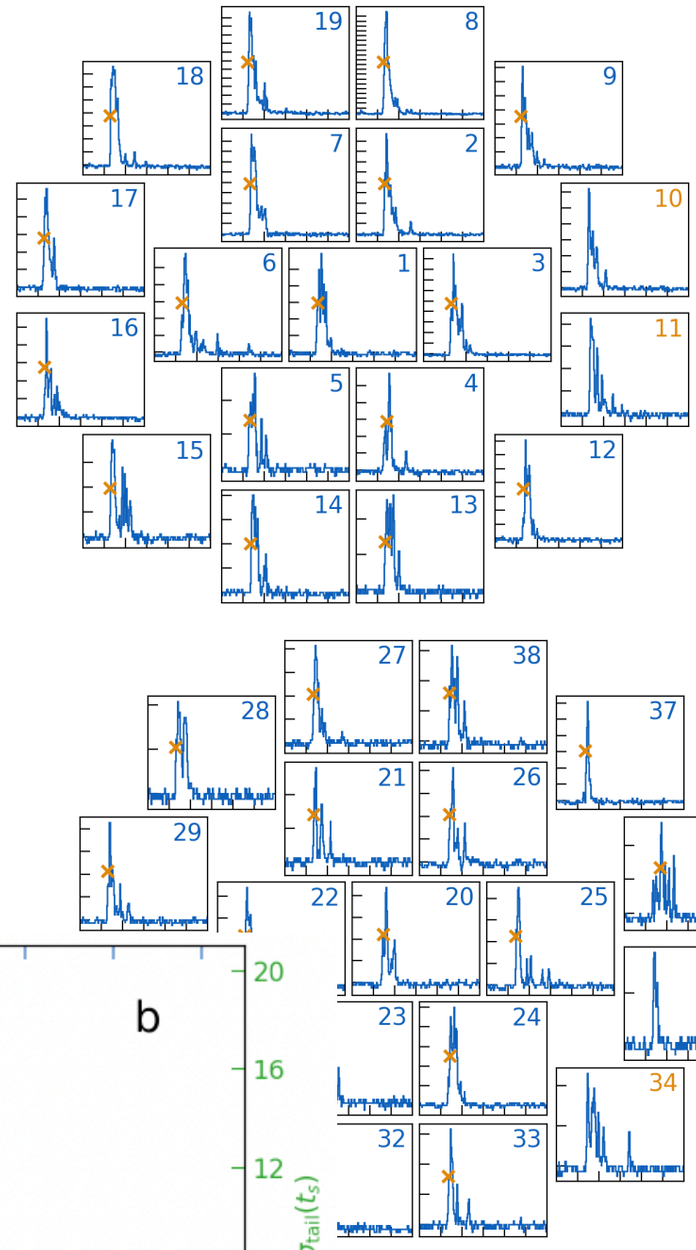
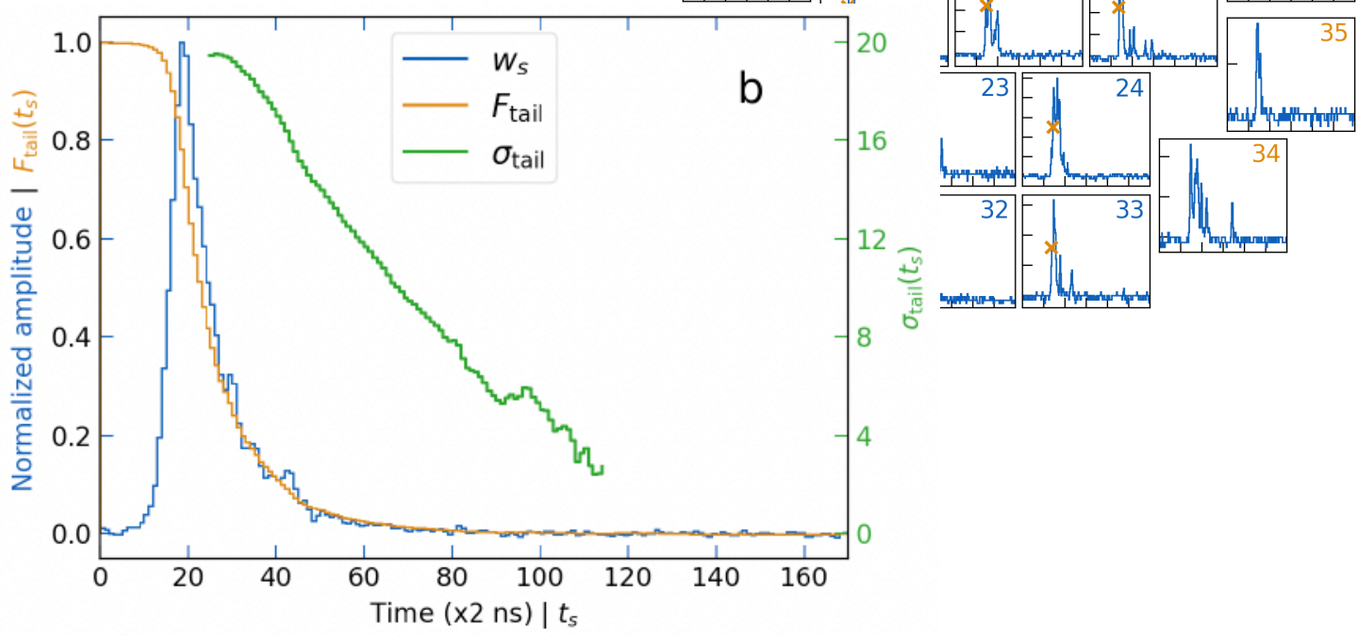
  - Data reduction
    - Neglecting the phase terms → Reducing a half of # of time bins
    - The power spectrum is used as an input for CNN.
  - Synchronized waveform for conventional PSD
    - Errors to find pulse times to synchronize
    - Cannot use some PMTs' information



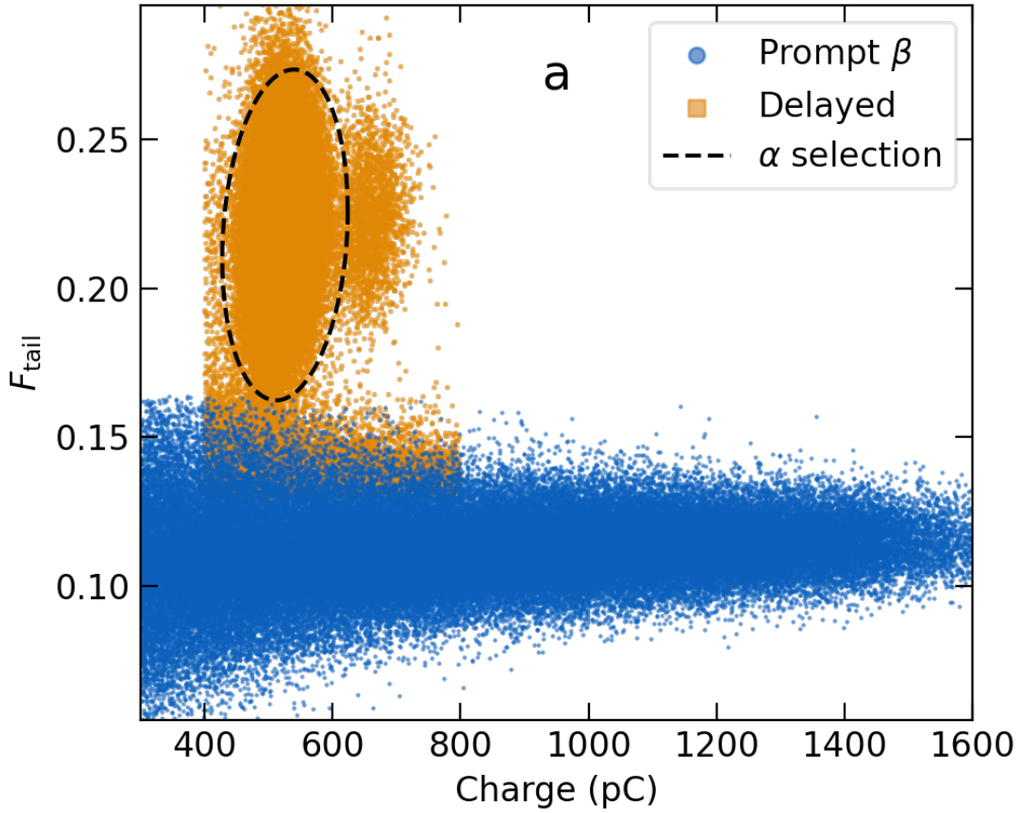


Deep Learning in NEOS

Sampling for e^-/p^+ Recoil Events

- Bi-Po pair events
  - Originated from the radon contamination in the LS

    $^{214}Bi \rightarrow e^- + {}^{214}Po \rightarrow \alpha + {}^{210}Pb$
  - Short half-life ~164 μs → 300-μs time window



Deep Learning in NEOS

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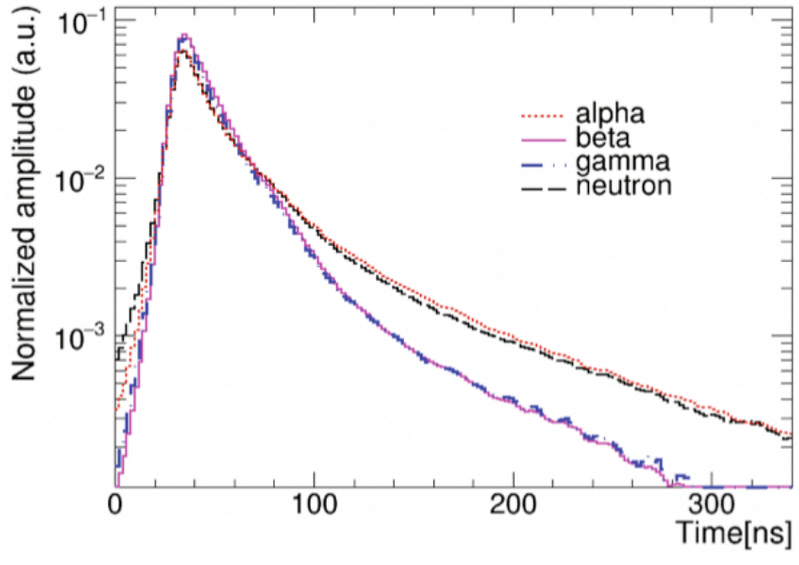
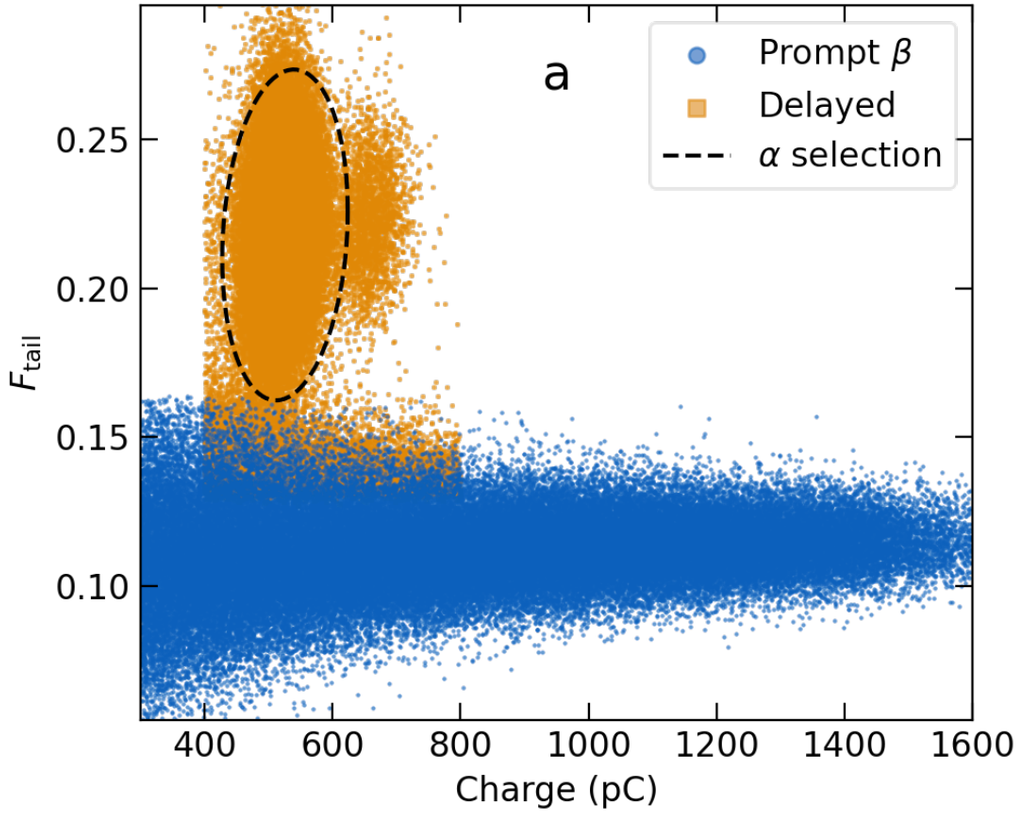
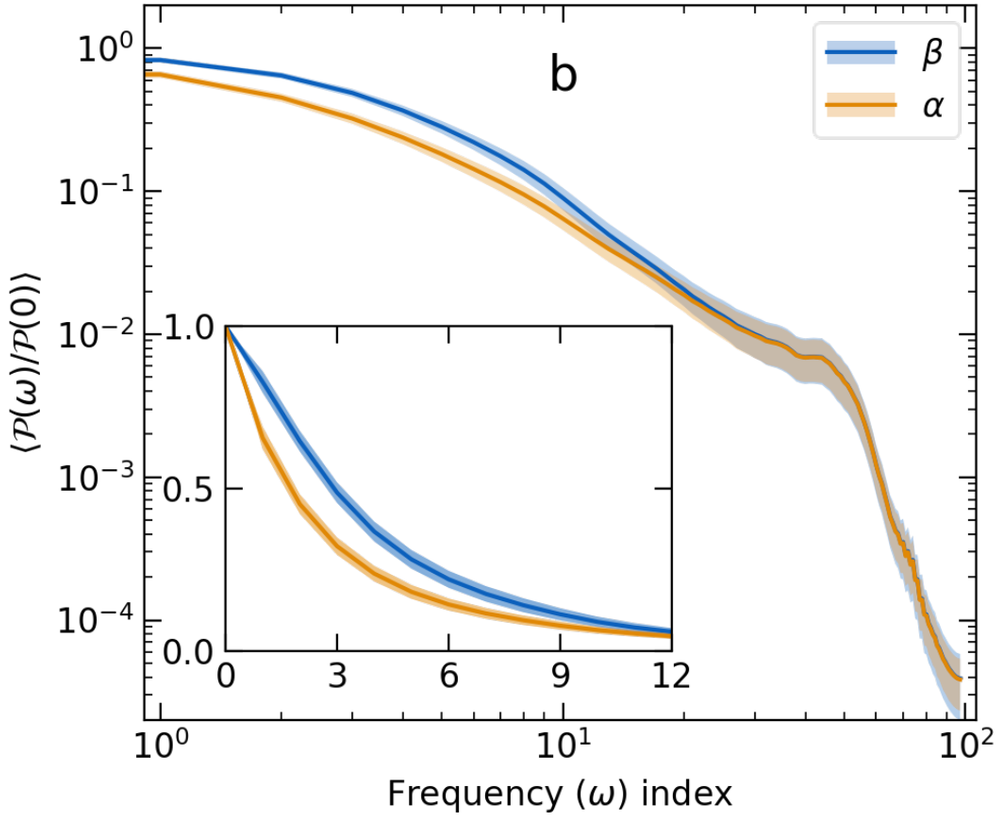
- Bi-Po pair events
  - Originated from the radon contamination in the LS

    $^{214}Bi \rightarrow e^- + {}^{214}Po \rightarrow \alpha + {}^{210}Pb$
  - Short half-life ~164 μs → 300-μs time window
  - Pulse shape of α is similar to that of p^+ recoil
    - α events are used as samples for p^+ recoil events.



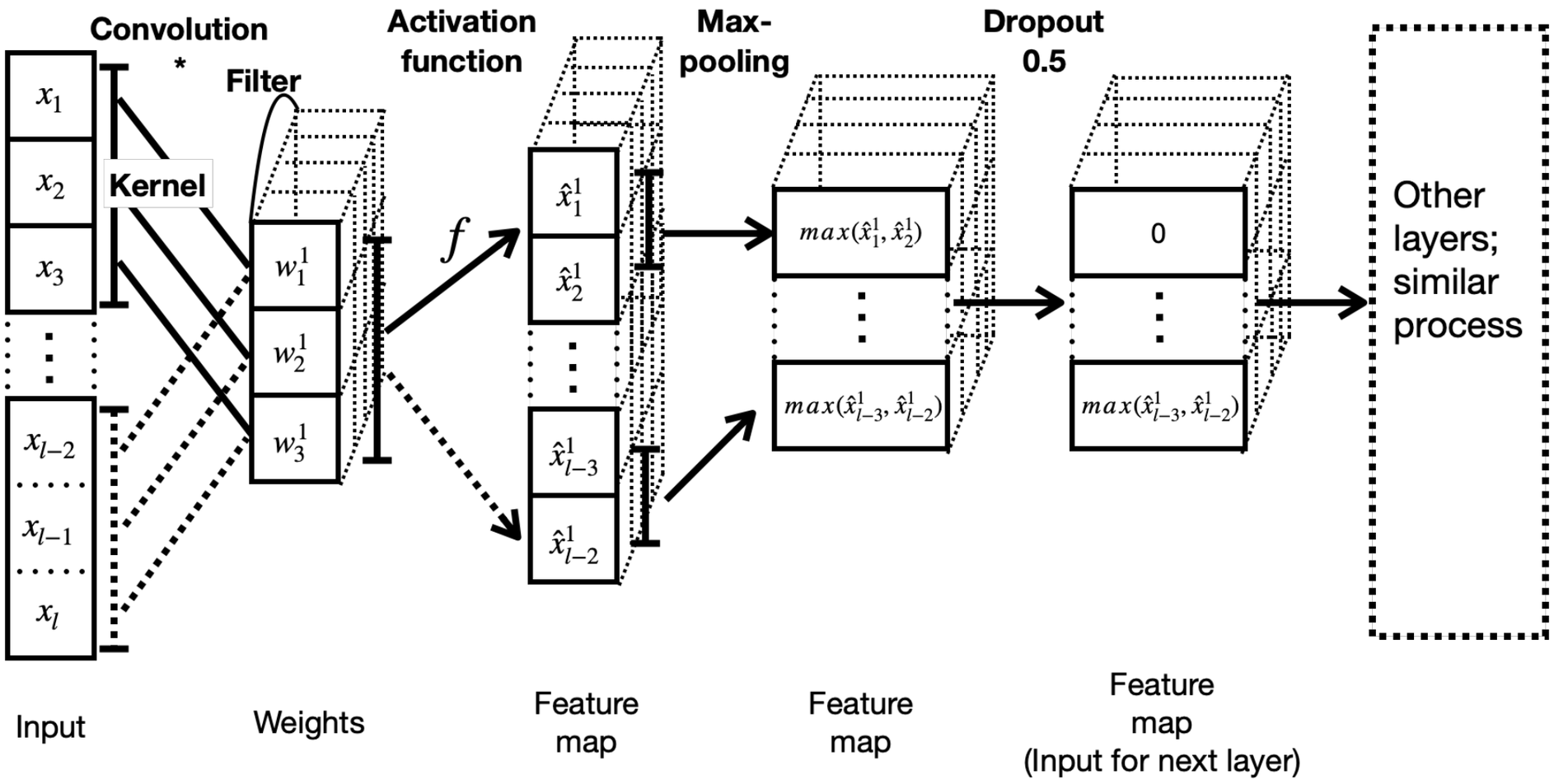




Deep Learning in NEOS

Convolutional Neural Network

- Convolutional Neural Network (CNN)
  - Avoiding an overfitting
  - Improving the generalization

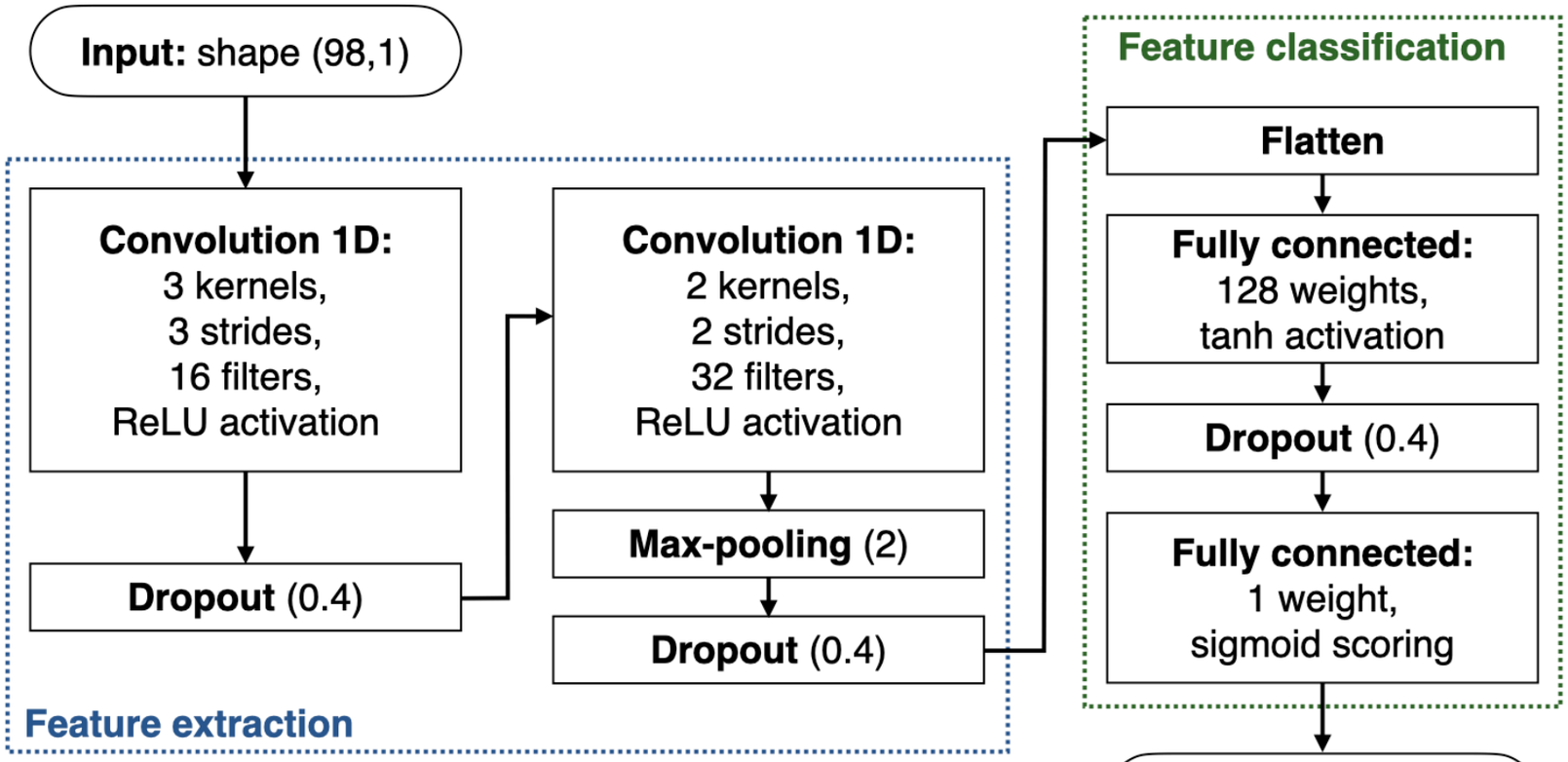


An example of CNN framework

Deep Learning in NEOS

Convolutional Neural Network

- Convolutional Neural Network (CNN)
  - Avoiding an overfitting
  - Improving the generalization
- CNN architecture
  - We tried to construct CNN architectures as simple as possible
  - The appropriate architectures are found by trial and error.

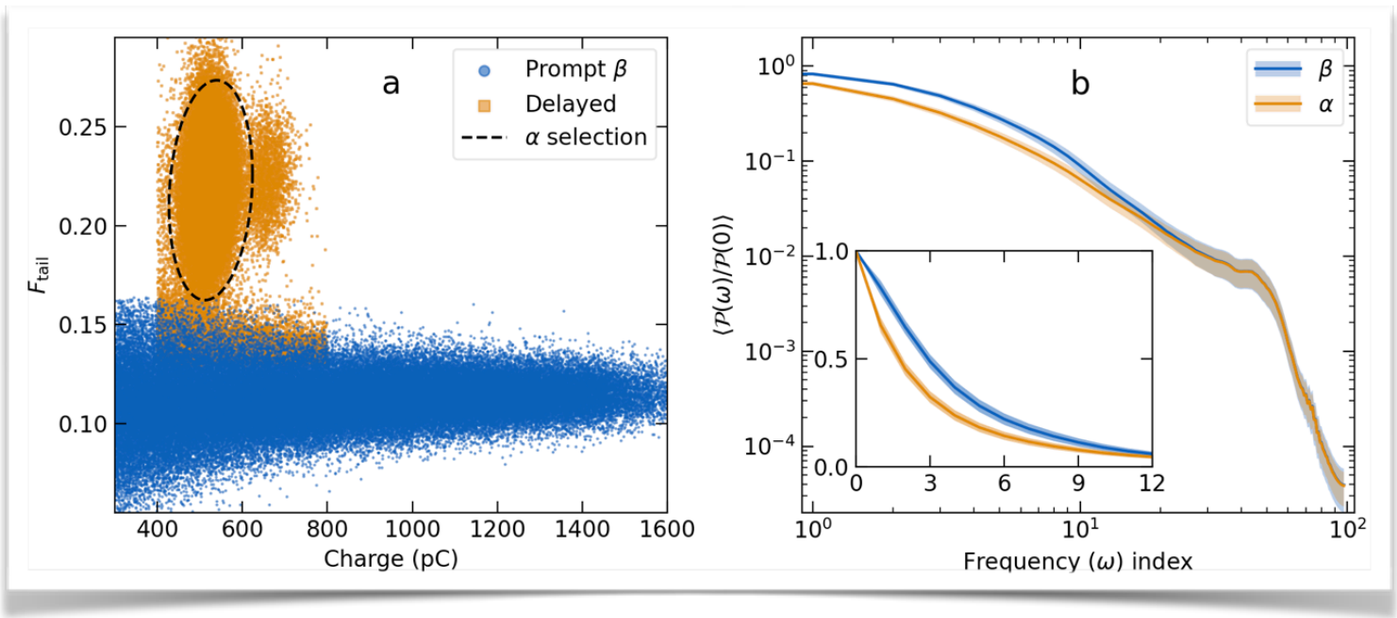


CNN architecture design

Deep Learning in NEOS

Convolutional Neural Network

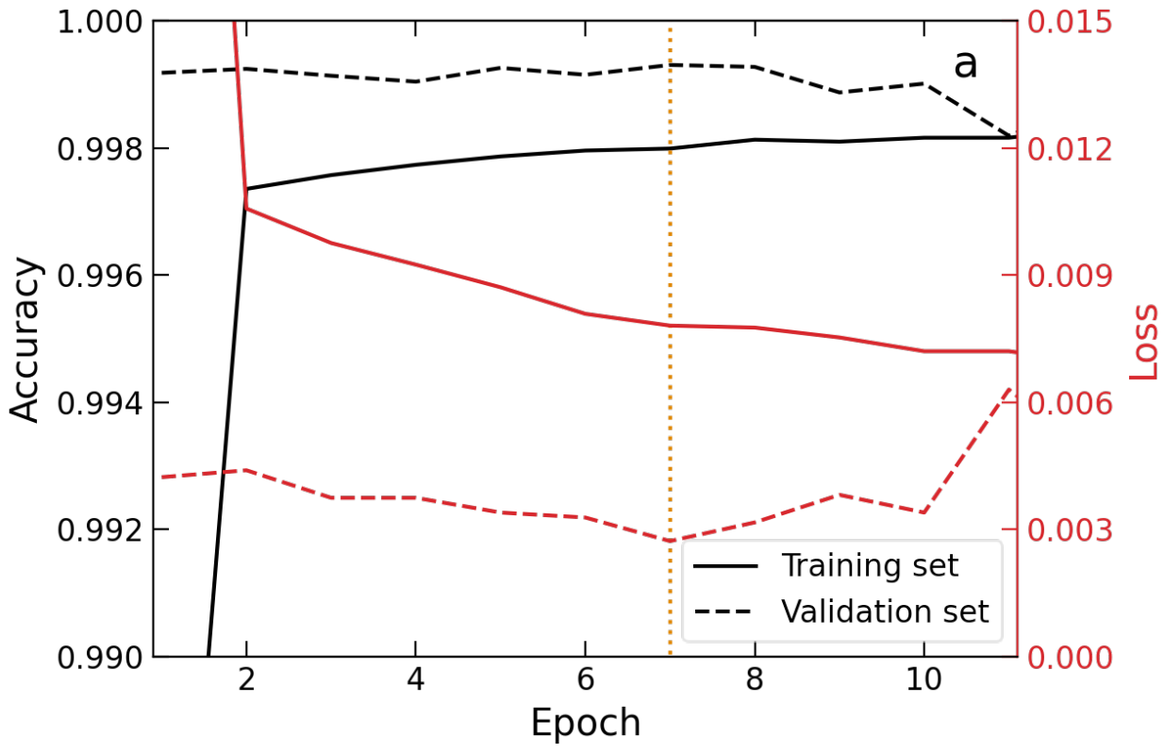
- Convolutional Neural Network (CNN)
  - Avoiding an overfitting
  - Improving the generalization
- CNN architecture
  - We tried to construct CNN architectures as simple as possible
  - The appropriate architectures are found by trial and error.
- Training sample & loss function
  - Power spectra of Bi-Po events
  - 80% of training set & 20% of validation set
  - Binary cross entropy

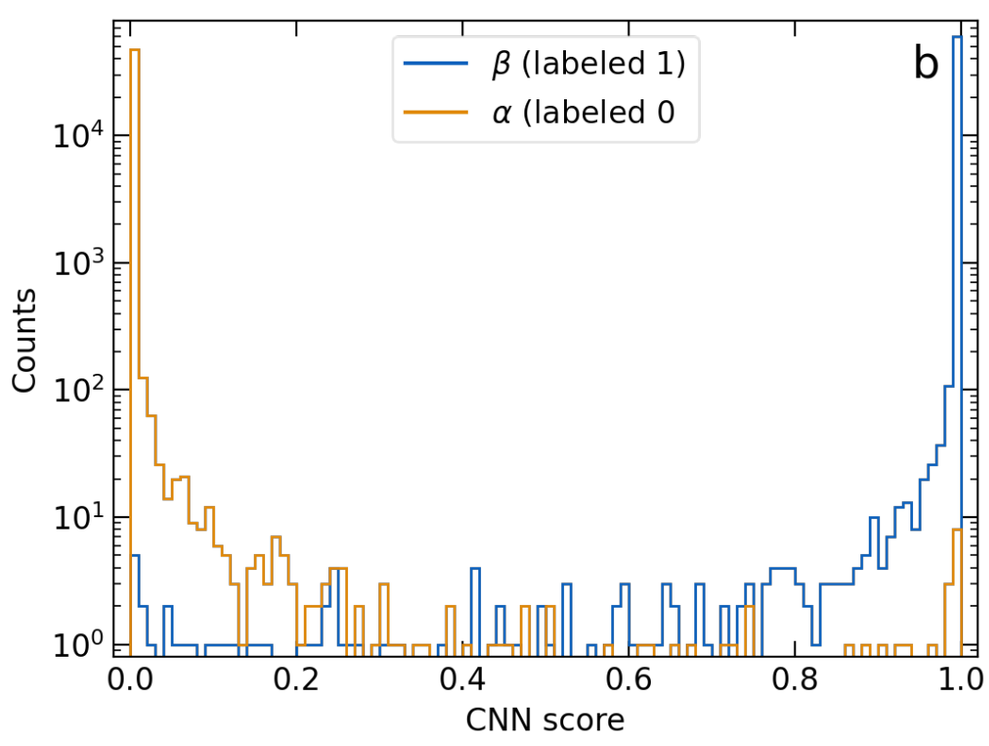


Deep Learning in NEOS

Background Reduction via CNN

- Training results
  - Stop condition
    - Training loss decreases while validation loss grows → overfitting
    - Validation loss does not decrease within 5 epochs.
  - After 7th epoch, the training does not improved the validation loss.
    - 99.93% accuracy for the validation data set at epoch 7.
  - Most of events are separated out at the given label.

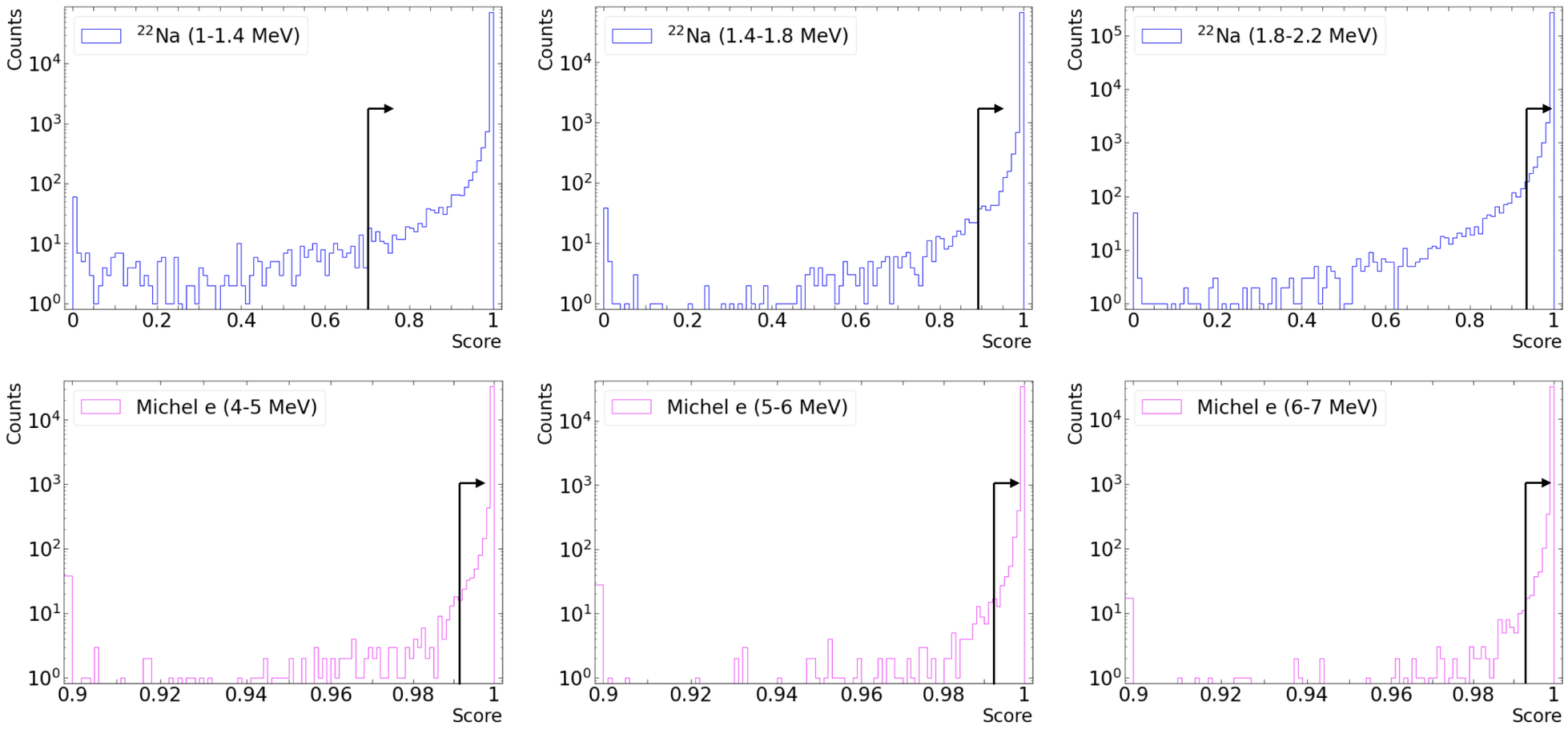




Deep Learning in NEOS

Background Reduction via CNN

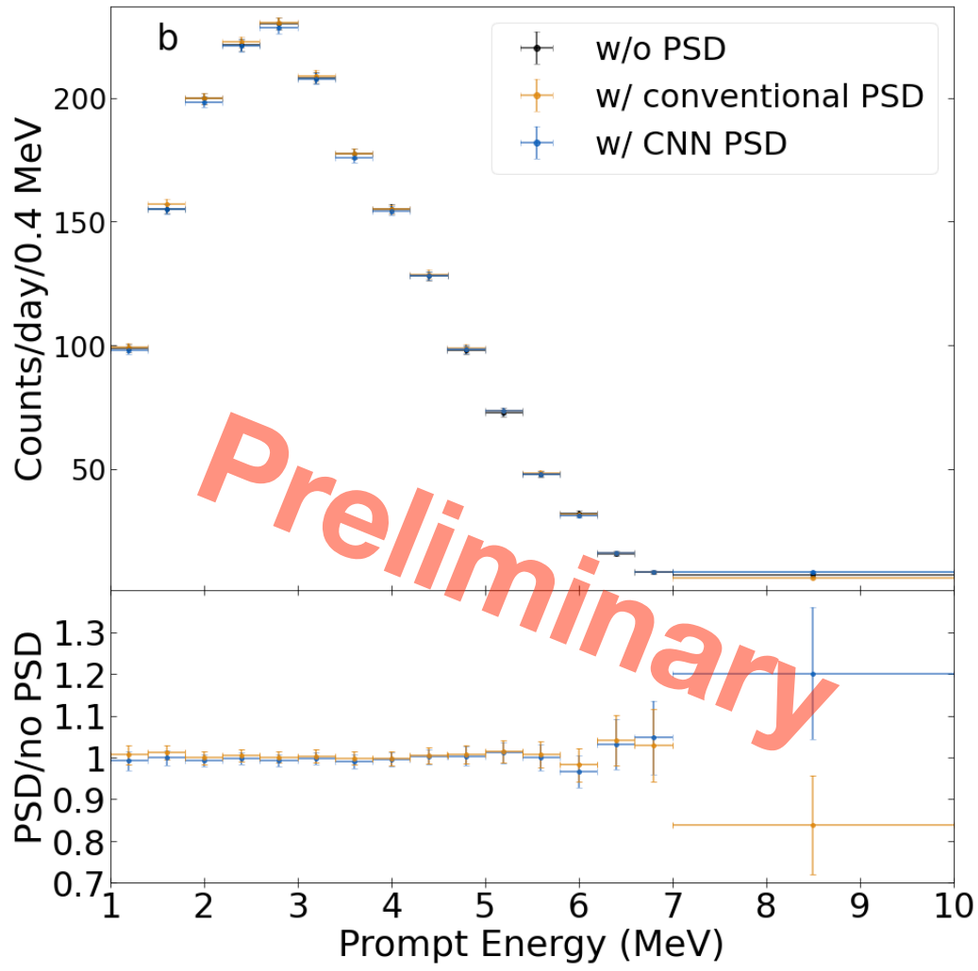
- Selection cut for CNN score
  - Pure sample for electron recoil events
    - ^{22}Na calibration source data for low energy
    - Michel electron data for high energy
  - 99.5% acceptance for each energy window



Deep Learning in NEOS

Background Reduction via CNN

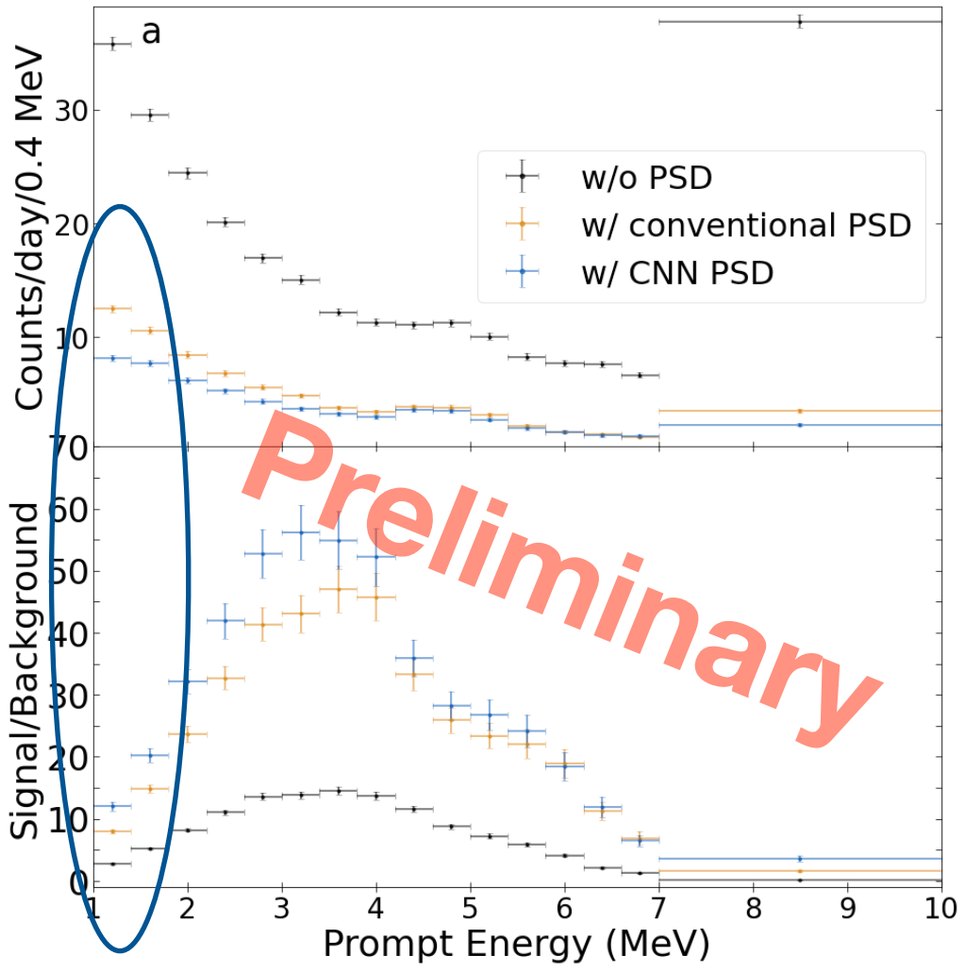
- IBD events w/ CNN PSD, w/ conventional PSD & w/o PSD
  - Signal rates (on - off) for all cases are consistent.

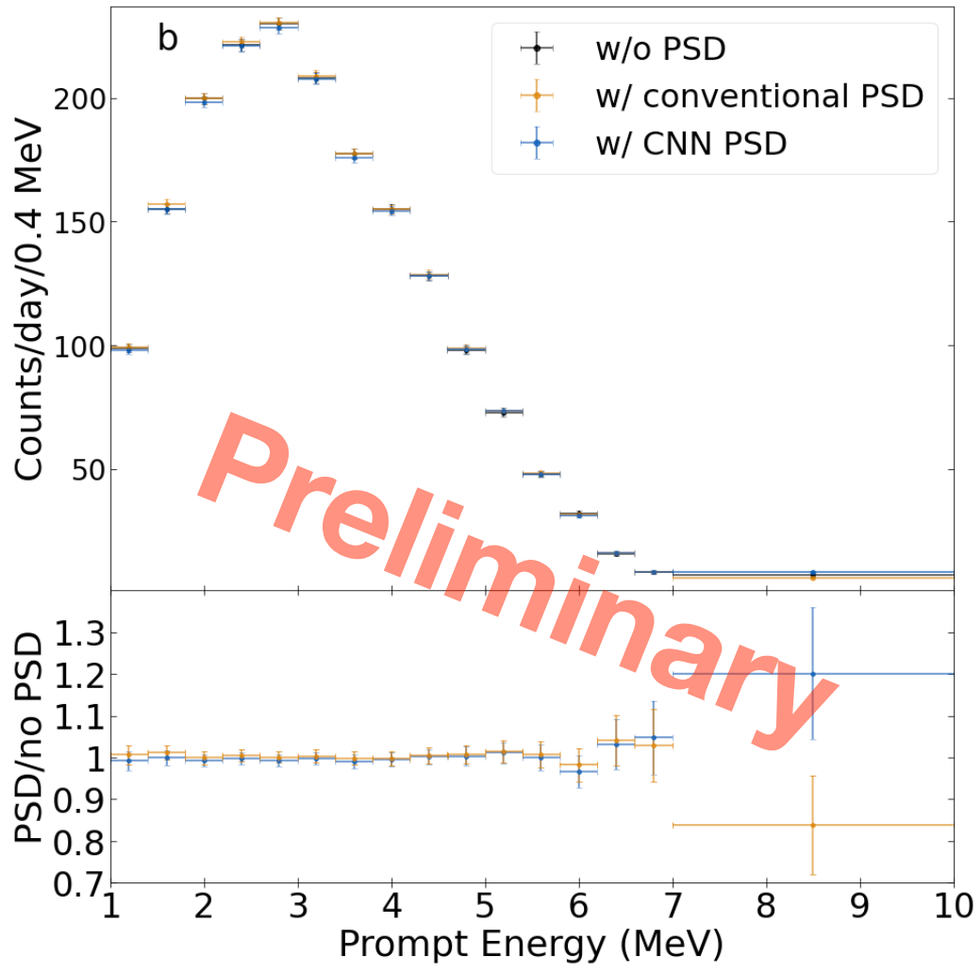


Deep Learning in NEOS

Background Reduction via CNN

- IBD events w/ CNN PSD, w/ conventional PSD & w/o PSD
  - Signal rates (on - off) for all cases are consistent.
  - S/B ratio: 24 (conventional PSD) → 31 (CNN PSD)
  - Significant improvement in the low energy region



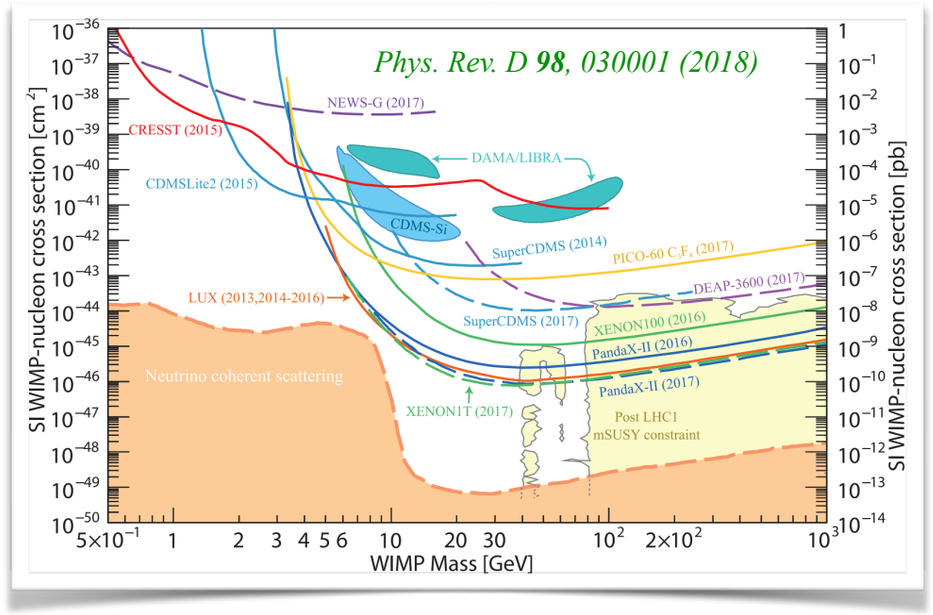


COSINE-100 Experiment
for Dark Matter Search

COSINE-100

DAMA/LIBRA Experiment

- No experiments have succeeded in direct detection of dark matter (DM), except DAMA/LIBRA.

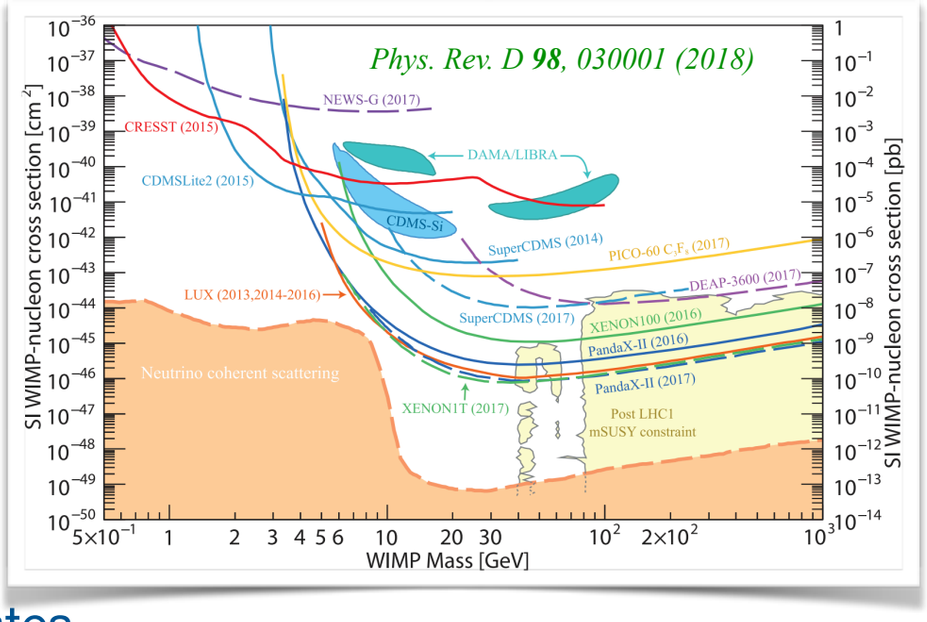


COSINE-100

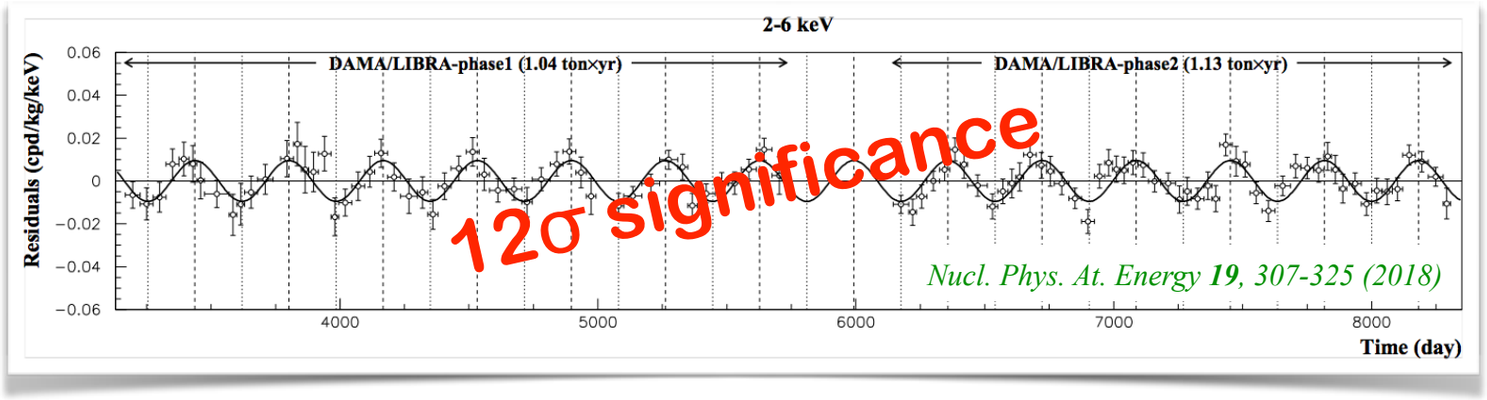
DAMA/LIBRA Experiment

- No experiments have succeeded in direct detection of dark matter (DM), except DAMA/LIBRA.
- DAMA/LIBRA experiment
  - Search for annual modulation signature by DM
  - Claim an observation of the DM at 12σ C.L

    (2-6 keV, 2.17-ton·yr exposure)
  - The results are compatible with the nature of DM candidates.



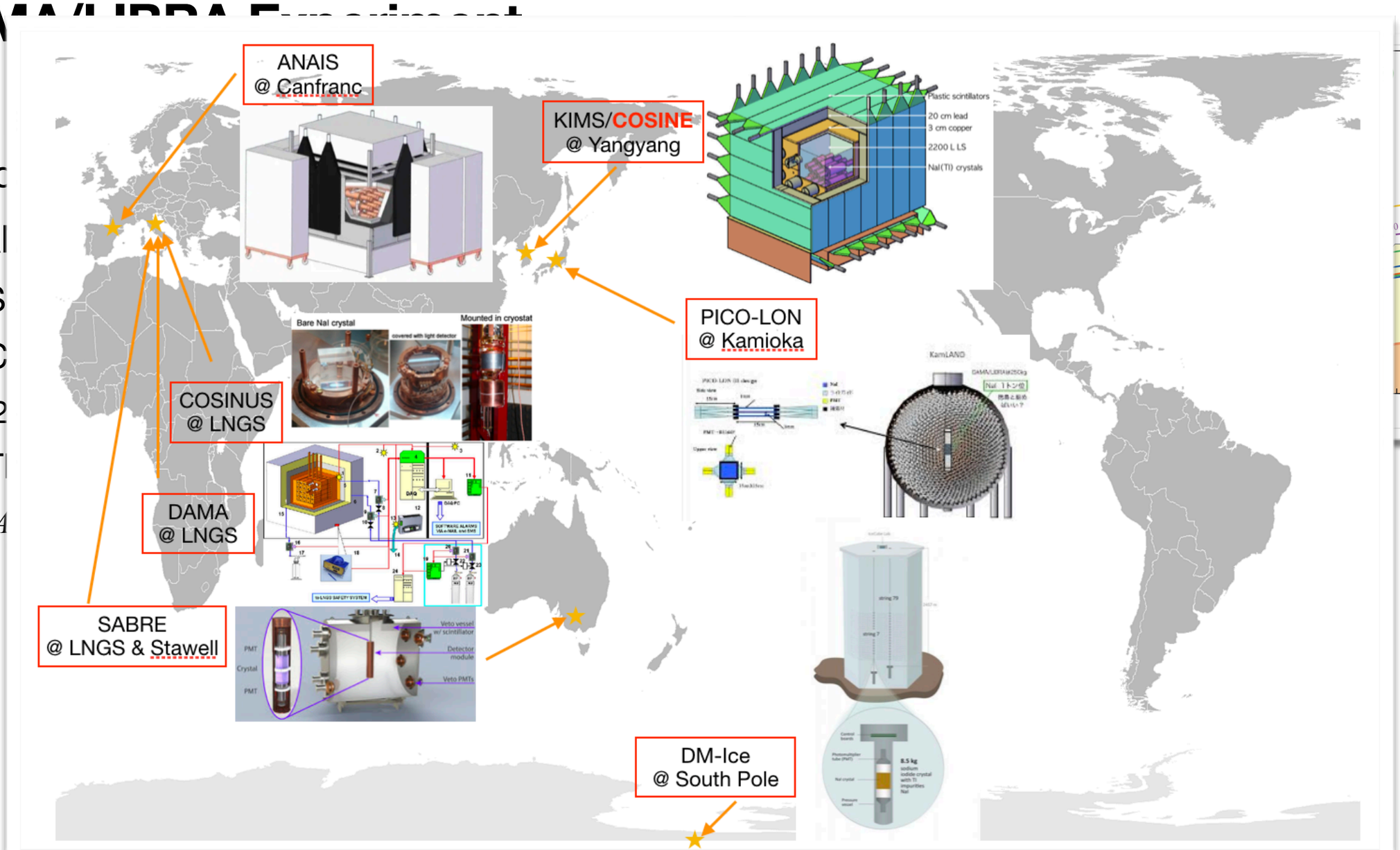
($A = 0.0096 \pm 0.0008$ counts/day/kg/keV, $\varphi = 145 \pm 5$ days, $T = 0.9987 \pm 0.0008$ yr)



COSINE-100

DAM

- No
  of c
- DAI
  - S
  - C
    (2
  - T
    (*A*



- Only observe in DAMA/LIBRA
  - NaI(Tl) crystal is special for DM interaction?
  - There are many efforts to test DAMA/LIBRA's signal, using NaI(Tl) crystal.

COSINE-100

Collaboration

- DM-Ice and KIMS joint effort to search for dark matter interactions
  - ~50 collaborators in 17 institutes
  - To verify the DAMA/LIBRA's claim via the same target material

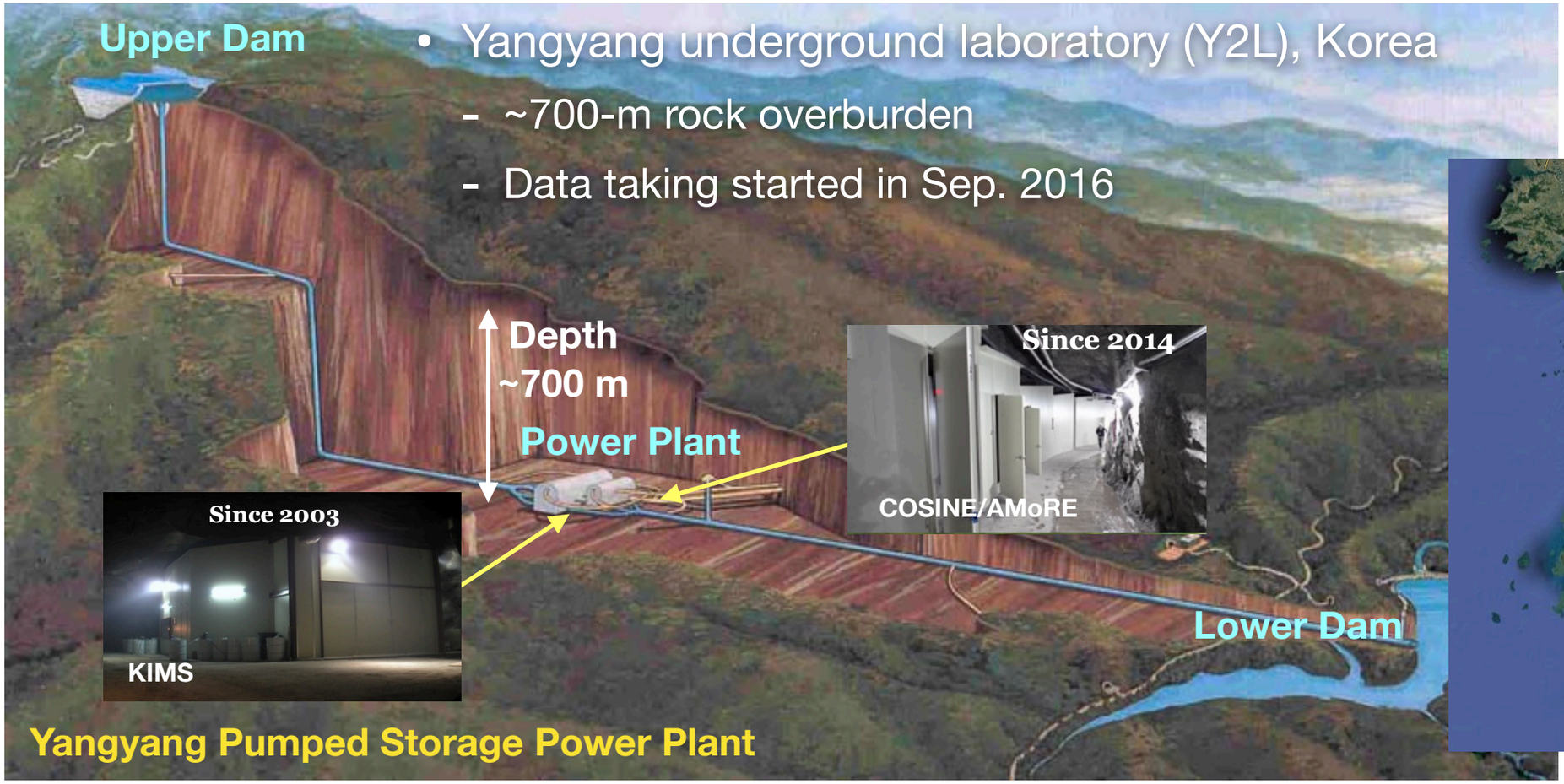
COSINE-100

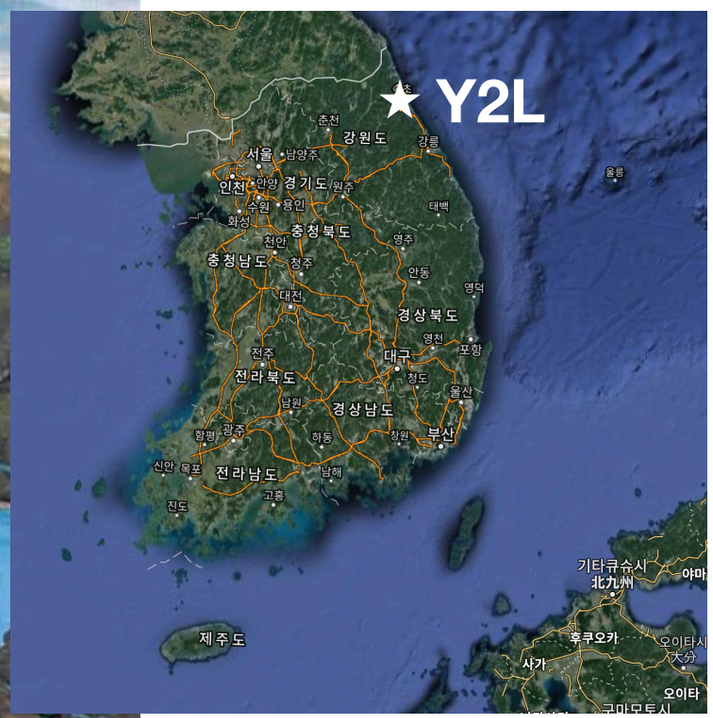
Collaboration & Experimental Site

DM-ICE + KIMS (Korea Invisible Mass Search Experiment) = COSINE

- DM-Ice and KIMS joint effort to search for dark matter interactions
  - ~50 collaborators in 17 institutes
  - To verify the DAMA/LIBRA's claim via the same target material

- Yangyang underground laboratory (Y2L), Korea
  - ~700-m rock overburden
  - Data taking started in Sep. 2016

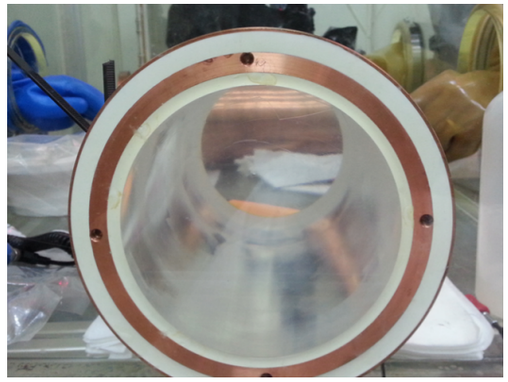


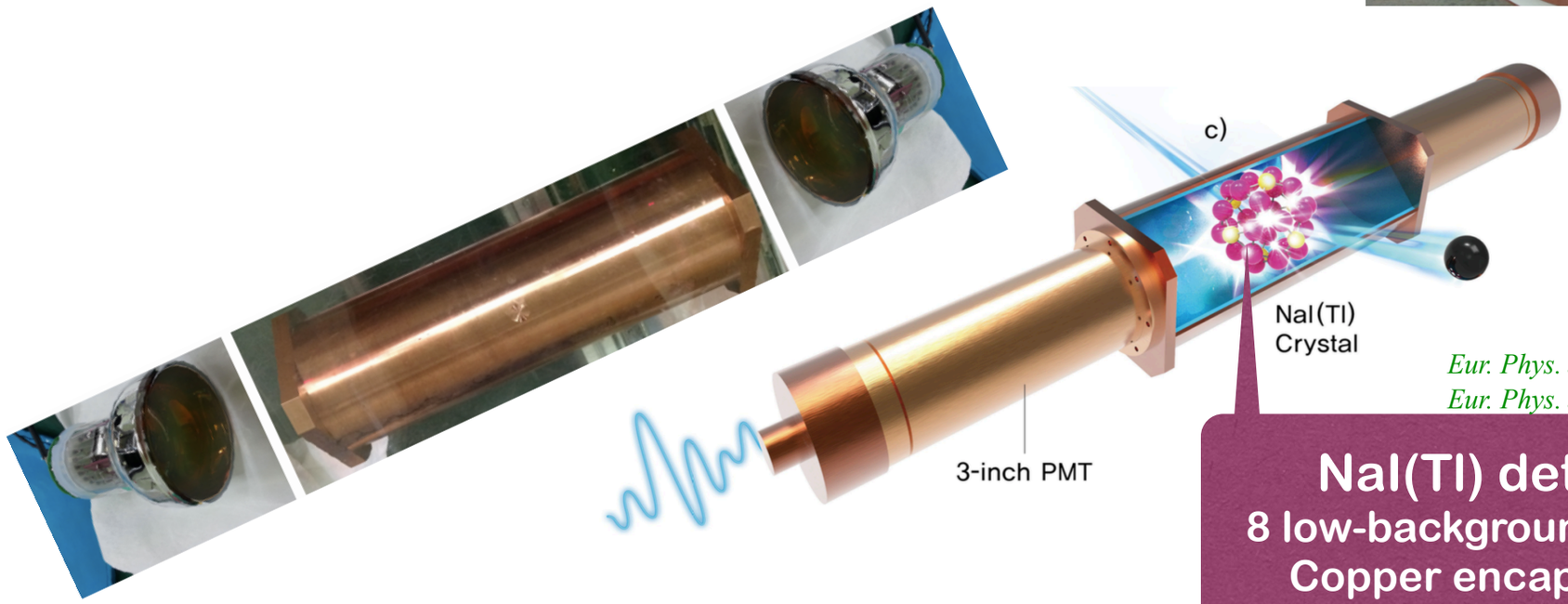


COSINE-100

Detector Configuration

- 8 low-background NaI(Tl) crystals w/ 106 kg in total
  - U/Th/K levels are less than DAMA, but total α (~^{210}Pb) are higher than DAMA.
  - Total background is 2-3 times that of DAMA.
  - Higher light yield (15 p.e/keV) than DAMA (5-10 p.e/keV)
- Each crystal is encapsulated in copper
- Two 3” PMTs (R12669SEL) are attached to each crystal.





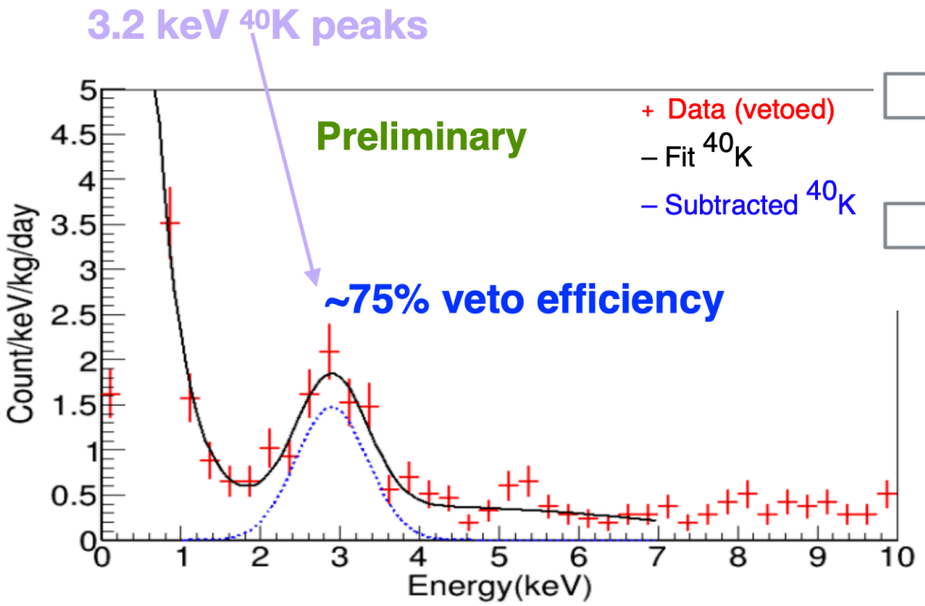
Eur. Phys. J. C ***78****, 107 (2018)*
Eur. Phys. J. C ***78****, 490 (2018)*

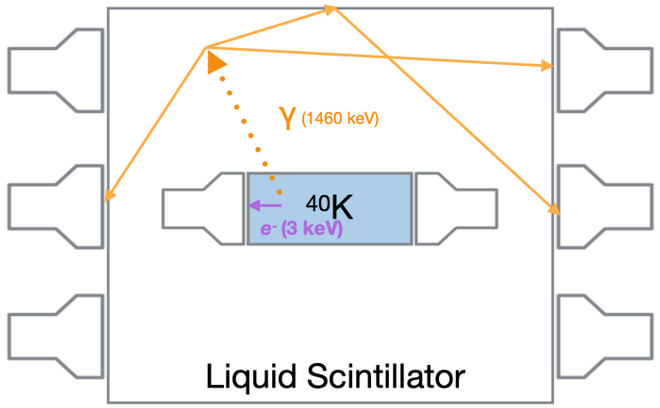
NaI(Tl) detector
8 low-background crystals
Copper encapsulation
Two 3” PMTs

COSINE-100

Detector Configuration

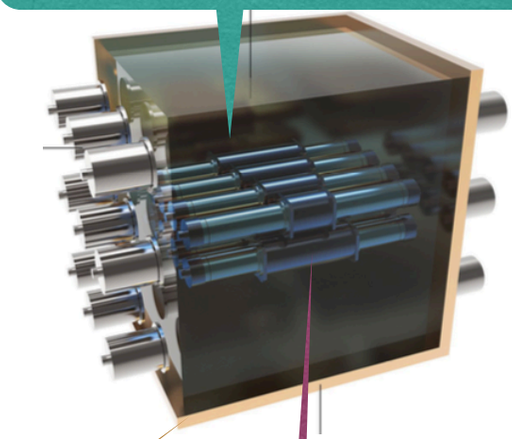
- Liquid scintillator (LS) as an active veto
  - 2200-L LAB-based LS & 5” PMTs (R877)
  - Designed to accommodate twice as many crystals
    - Upgradable to COSINE-200

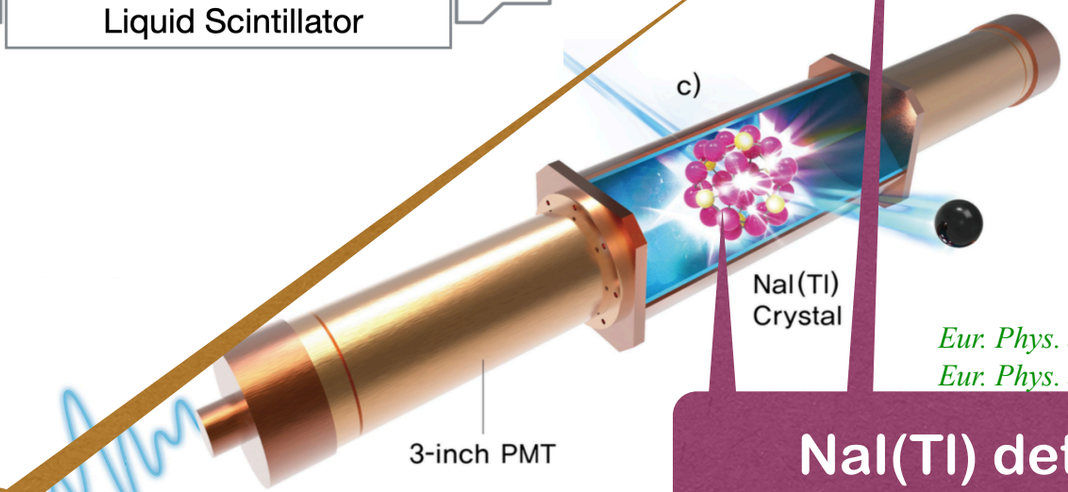




Nucl. Instrum. Meth. A ***851***, 103 (2017)
Nucl. Instrum. Meth. A ***106***, 165431 (2021)

Liquid Scintillator
2200-L LAB-based LS for veto
5” PMTs for LS detector





Eur. Phys. J. C. ***78***, 107 (2018)
Eur. Phys. J. C. ***78***, 490 (2018)

NaI(Tl) detector
8 low-background crystals
Copper encapsulation
Two 3” PMTs

Eur. Phys. J. C. ***78***, 107 (2018)

Passive Shields
3-cm thick copper box
20-cm thick lead shielding

COSINE-100

Detector Configuration

*JINST **13**, T02007 (2018), JCAP **02**, 013 (2021)*

4π Muon Counter
37 plastic scintillator panels
2” PMTs (H7195) for muon counter

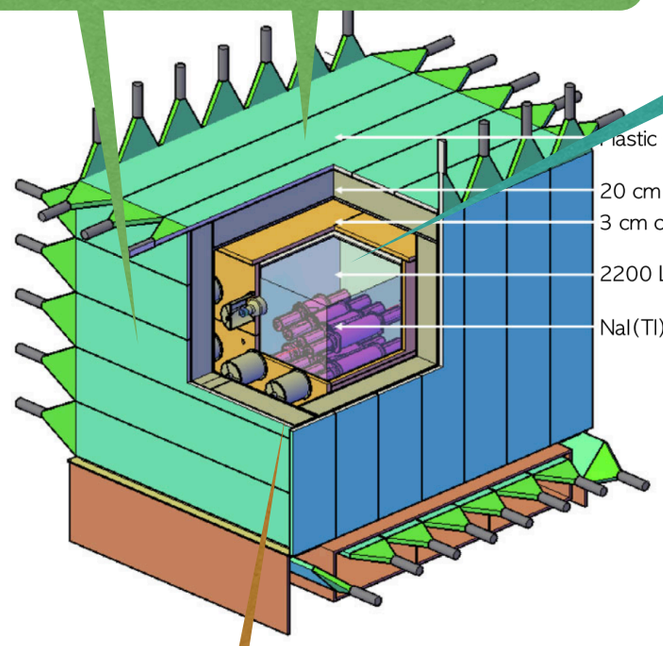
*Nucl. Instrum. Meth. A **851**, 103 (2017)*
*Nucl. Instrum. Meth. A **106**, 165431 (2021)*

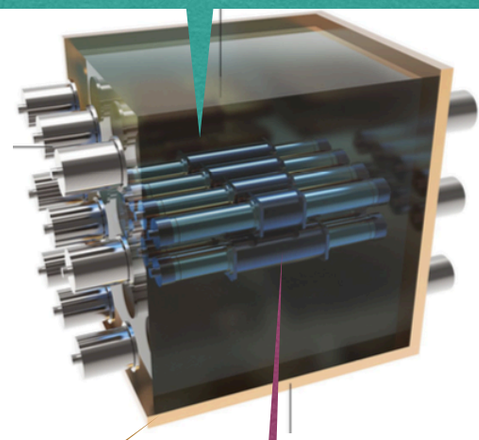
Liquid Scintillator
2200-L LAB-based LS for veto
5” PMTs for LS detector

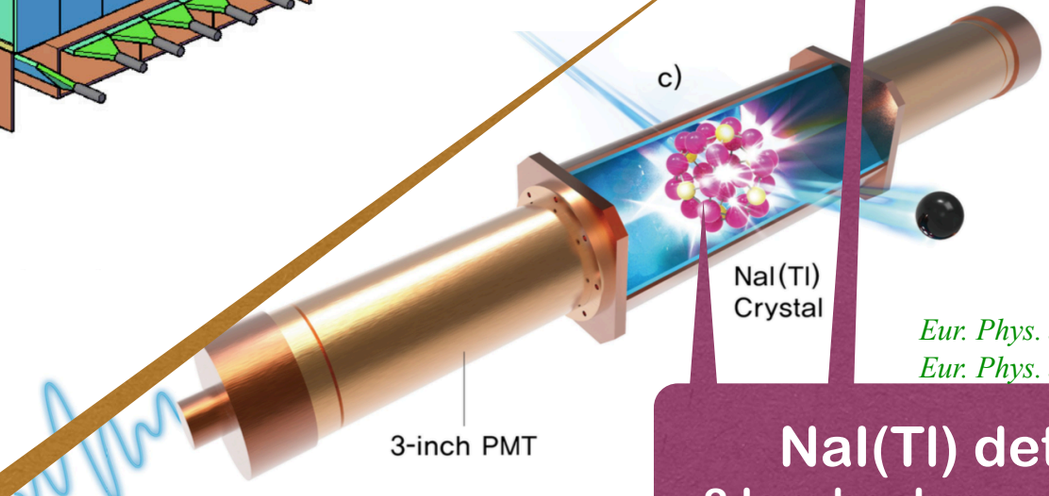
*JINST **13**, T06005 (2018)*

Neutron Monitoring
Fast neutron detector
(Liquid scintillator)

Thermal neutron detector
(^{3}He gas detector)







*Eur. Phys. J. C. **78**, 107 (2018)*

Passive Shields
3-cm thick copper box
20-cm thick lead shielding

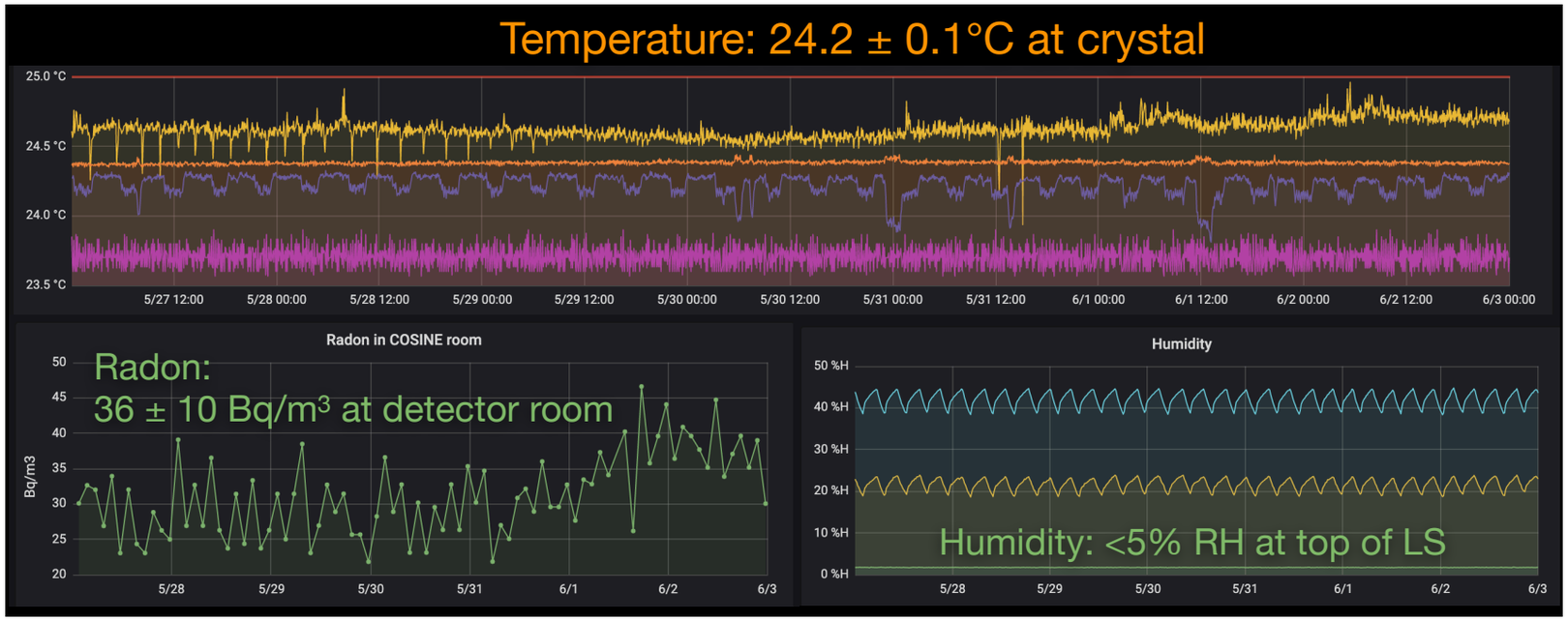
*Eur. Phys. J. C. **78**, 107 (2018)*
*Eur. Phys. J. C. **78**, 490 (2018)*

NaI(TI) detector
8 low-background crystals
Copper encapsulation
Two 3” PMTs

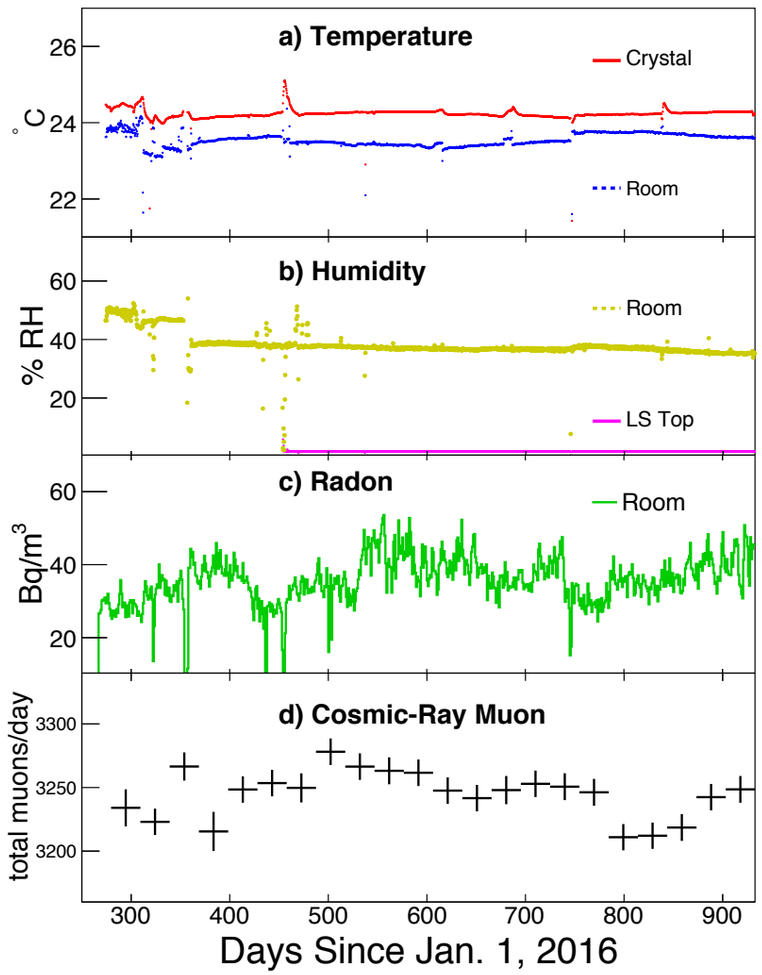
COSINE-100

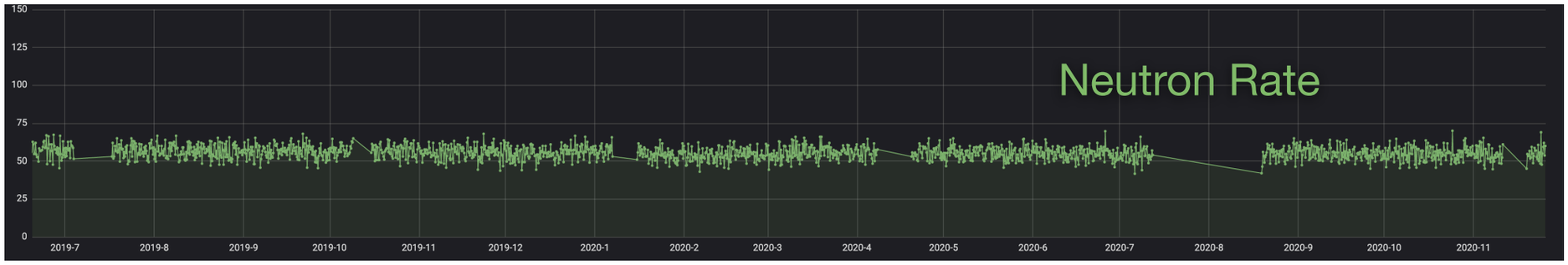
Monitoring

- Monitoring system has >200 parameters.
  - DAQ system: trigger rate, electronics status
  - Environmental parameters are stable.
  - Neutron rates are also monitored.



Phys. Rev. Lett. ***123***, 031302 (2019)

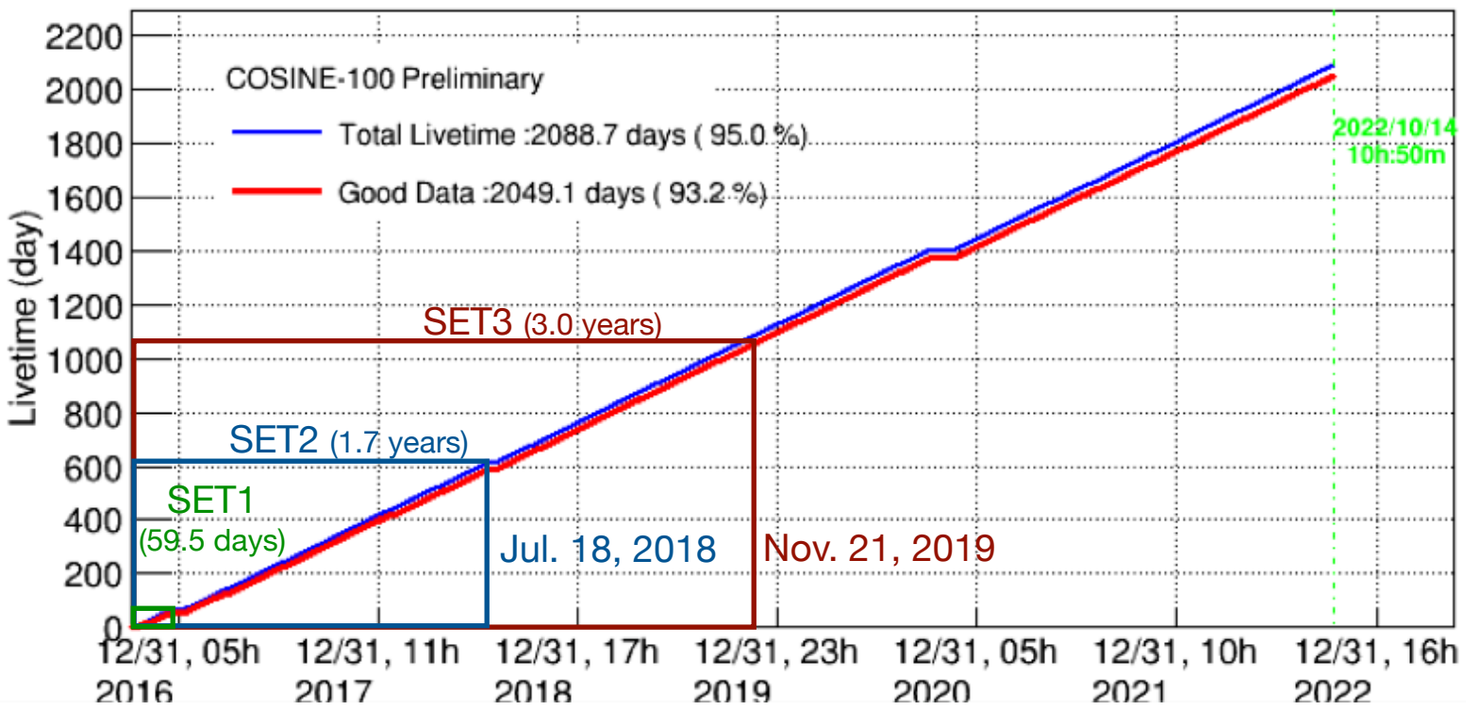




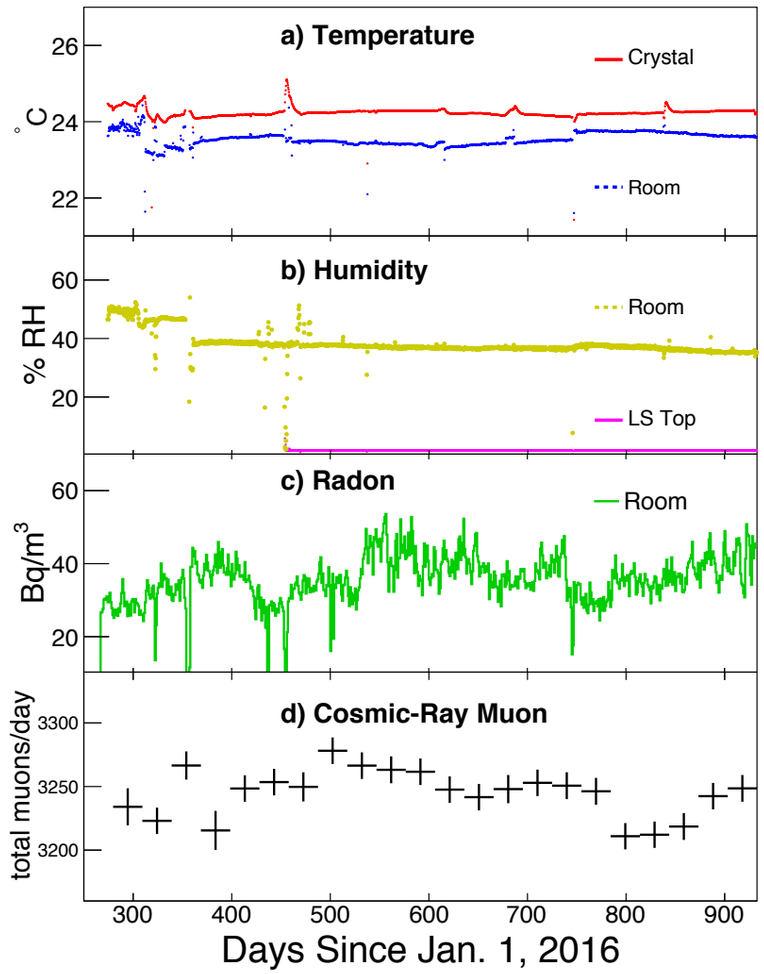
COSINE-100

Monitoring & Operation

- Monitoring system has >200 parameters.
  - DAQ system: trigger rate, electronics status
  - Environmental parameters are stable.
  - Neutron rates are also monitored.
- Stable running from Sep. 30, 2016 (6 years)
  - DAQ efficiency ~93% (calibration runs, power outage)
  - Exposure time: ~2050 days



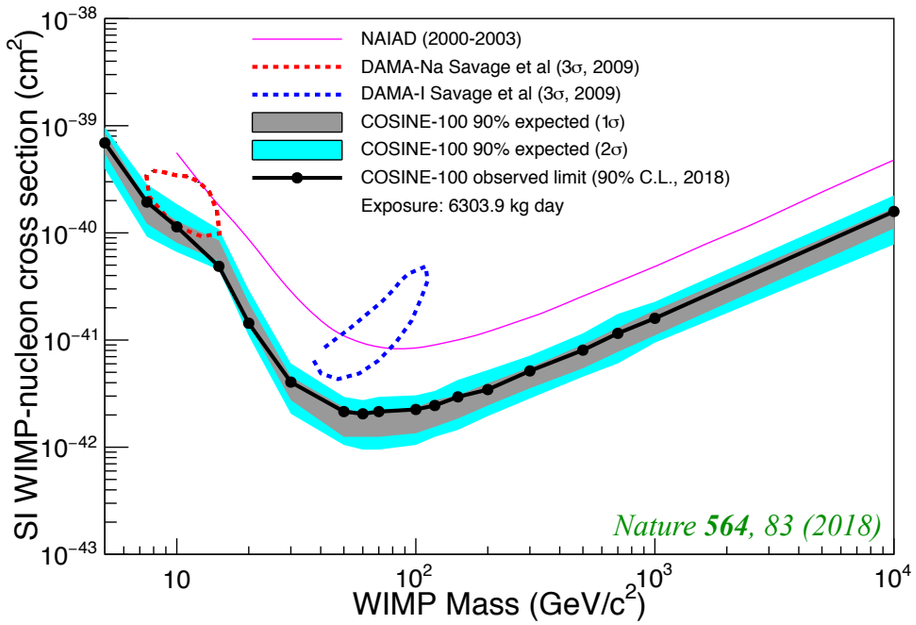
Phys. Rev. Lett. ***123****, 031302 (2019)*



COSINE-100

WIMP Extraction Analysis

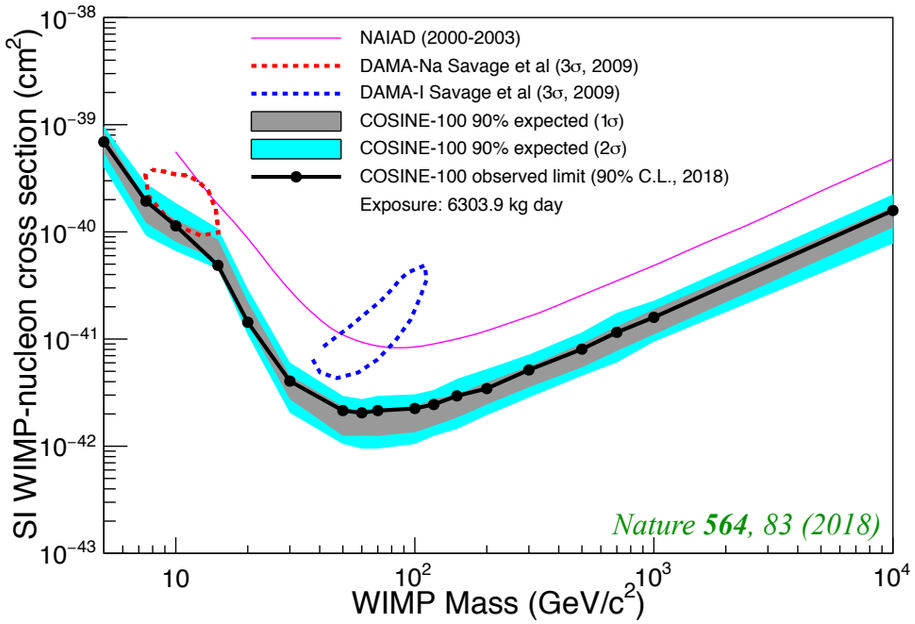
- First physics analysis (SET1; 59.5 days)
  - WIMP extraction analysis: SI WIMP & SHM
  - Excluding DAMA/LIBRA w/ the same target material

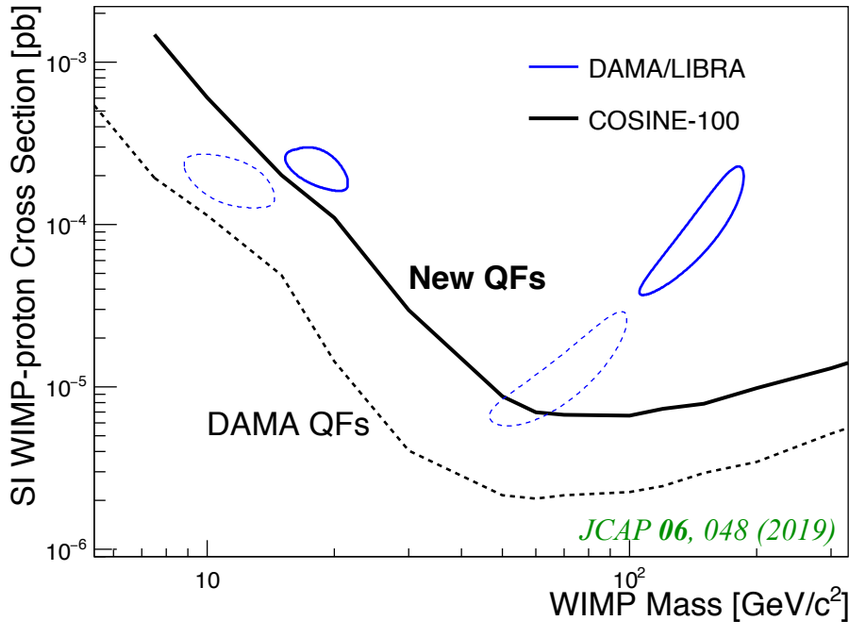


COSINE-100

WIMP Extraction Analysis

- First physics analysis (SET1; 59.5 days)
  - WIMP extraction analysis: SI WIMP & SHM
  - Excluding DAMA/LIBRA w/ the same target material
- Various model & quenching factor (QF)
  - SI & SD WIMP
  - Assuming different QF → cannot exclude DAMA/LIBRA

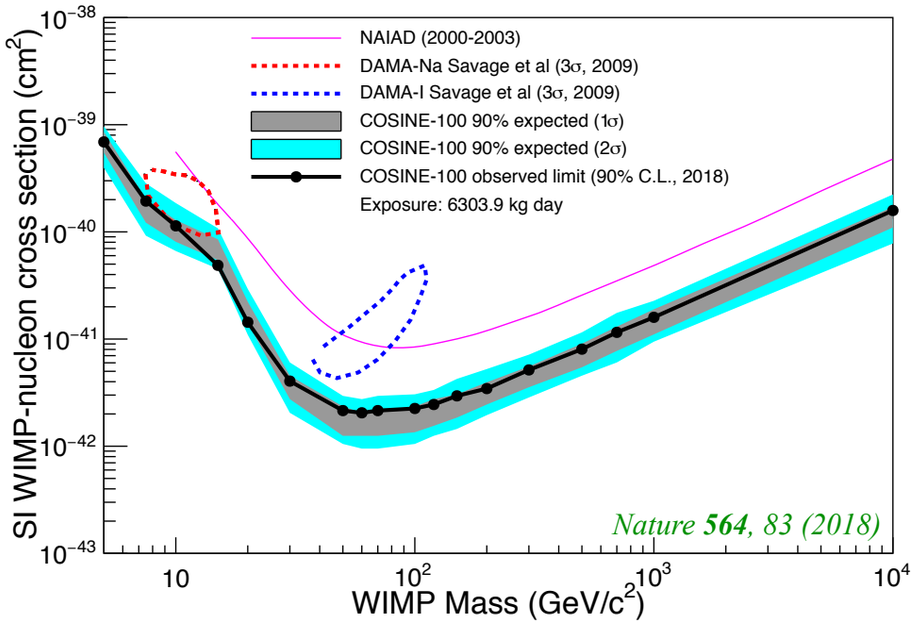


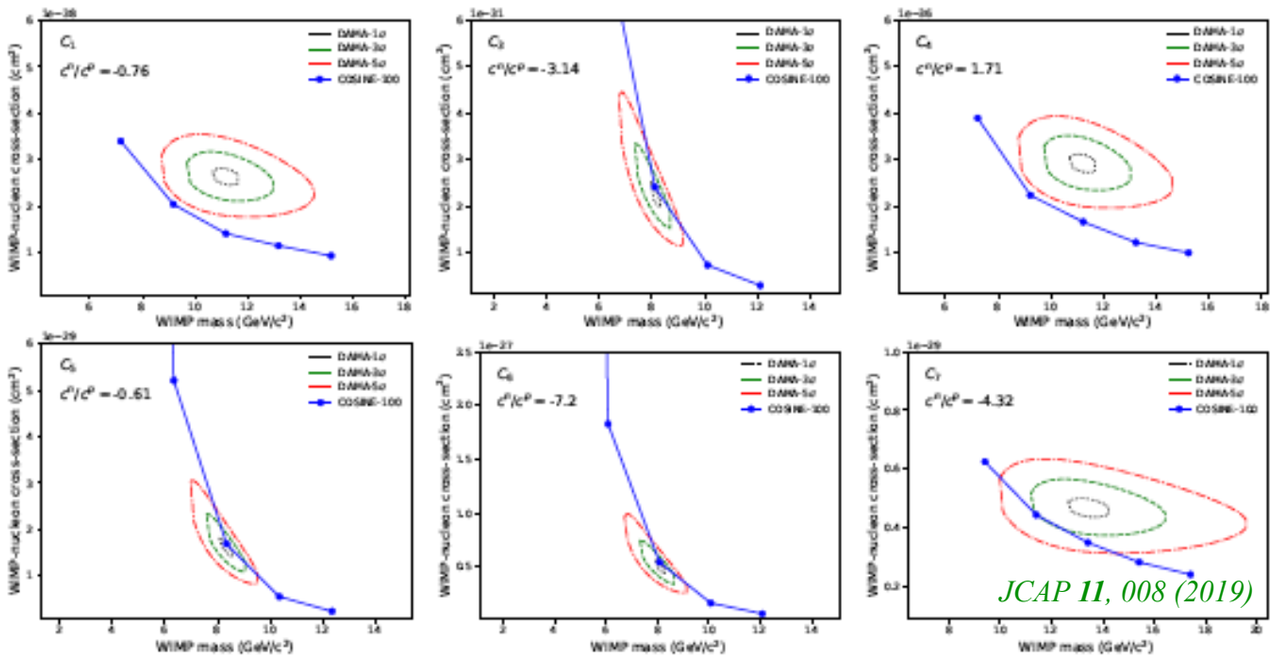


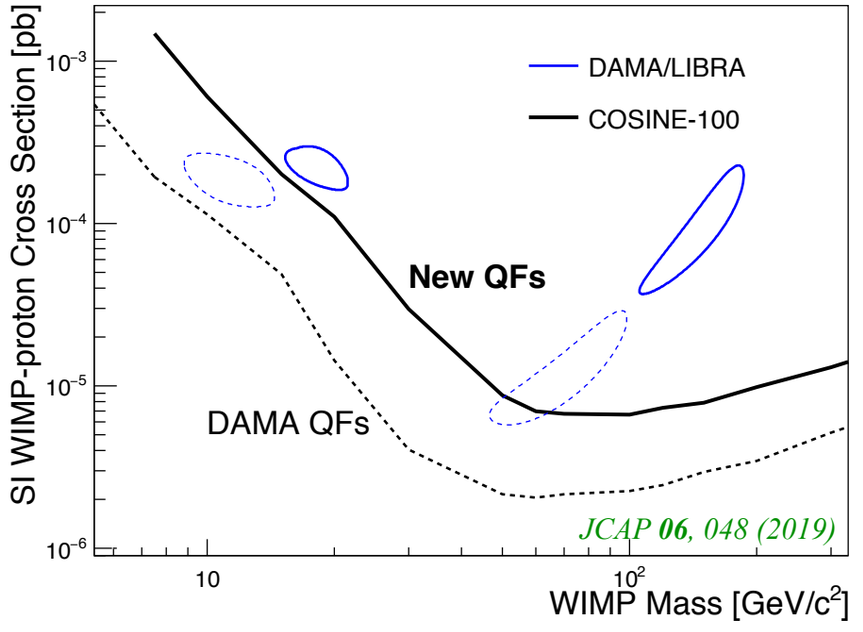
COSINE-100

WIMP Extraction Analysis

- First physics analysis (SET1; 59.5 days)
  - WIMP extraction analysis: SI WIMP & SHM
  - Excluding DAMA/LIBRA w/ the same target material
- Various model & quenching factor (QF)
  - SI & SD WIMP
  - Assuming different QF → cannot exclude DAMA/LIBRA
- Effective field theory (EFT) operators
  - Cannot cover DAMA/LIBRA for several operators



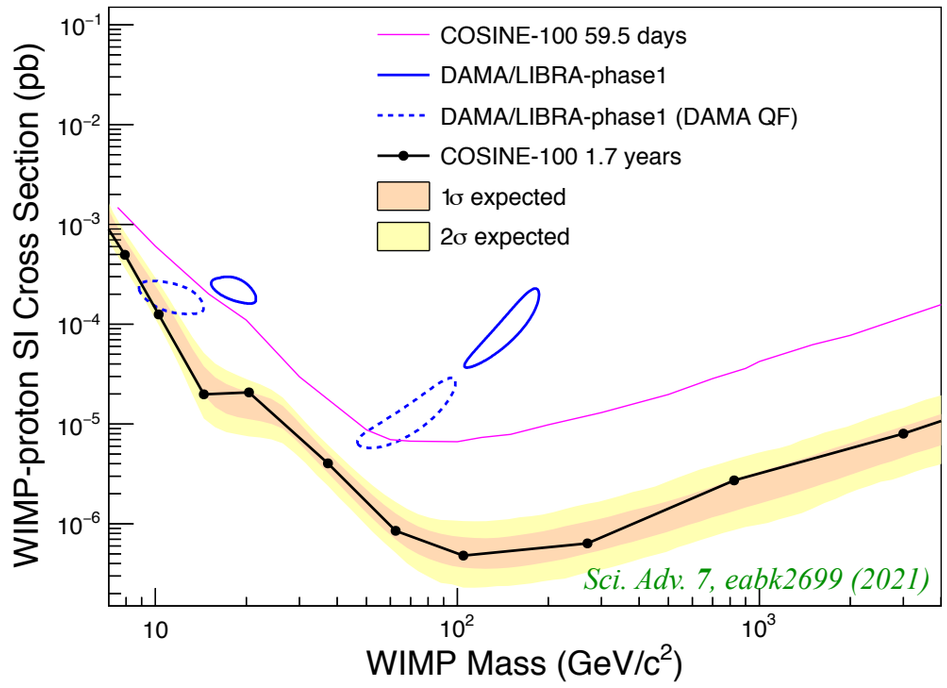


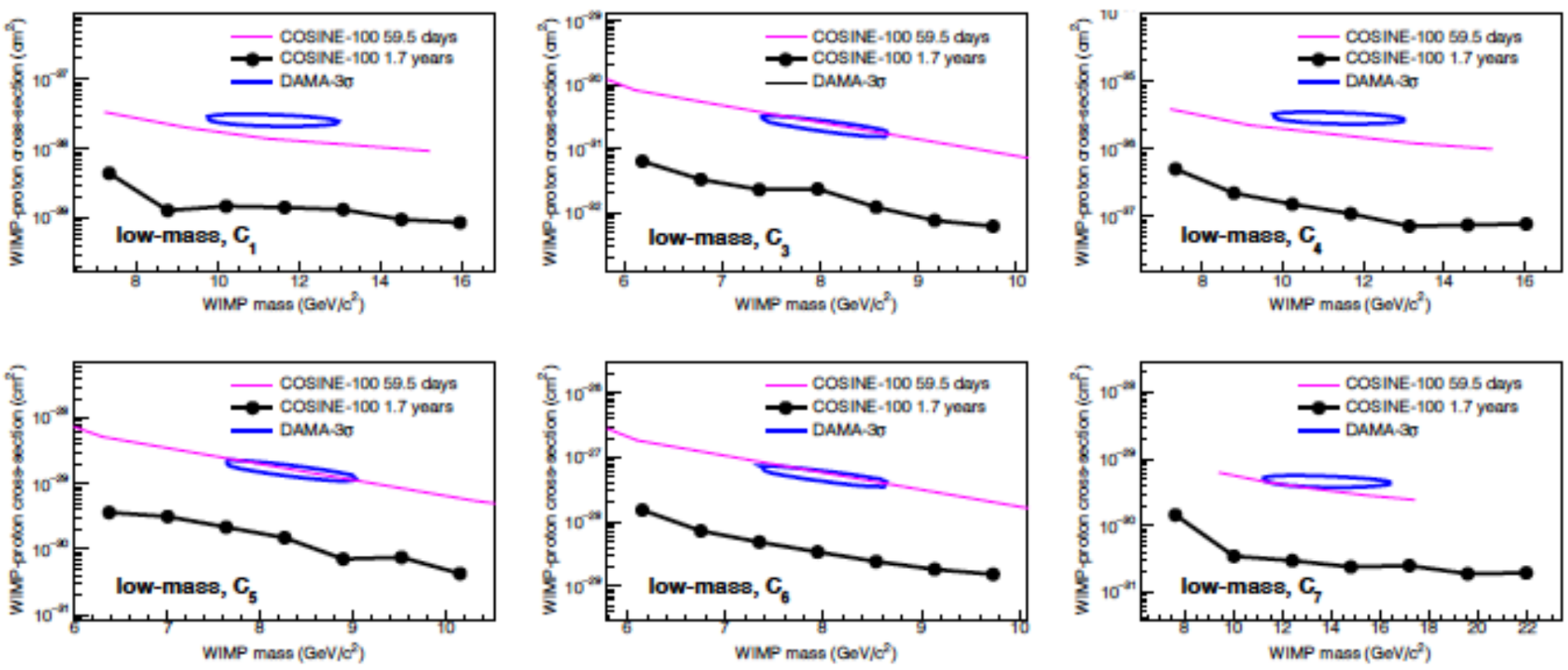


COSINE-100

WIMP Extraction Analysis

- SET2 data analysis (1.7 years)
  - SI WIMP & different QF
  - EFT operators
  - Fully cover the alternative scenarios for QF & EFT

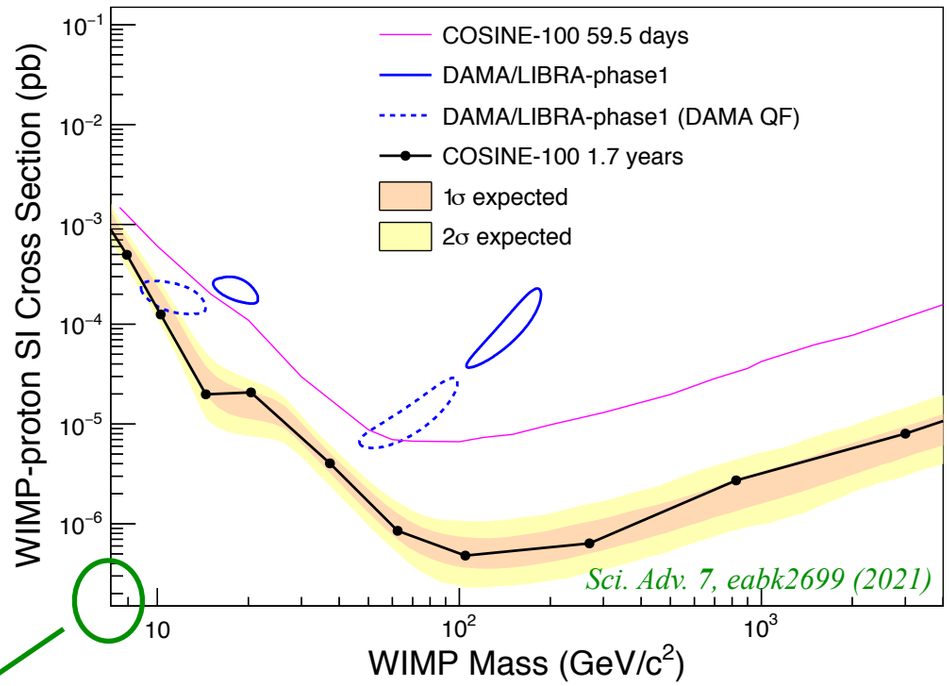


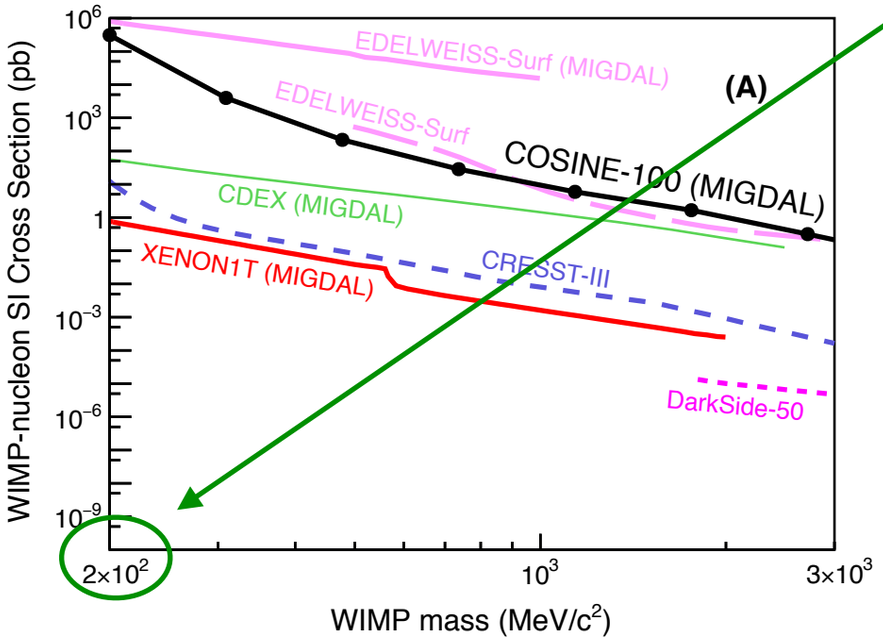


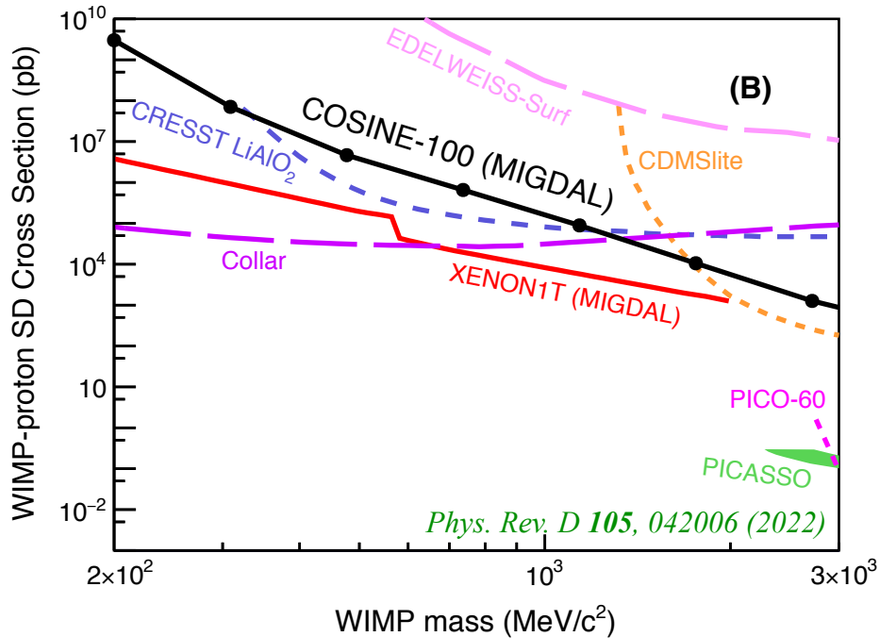
COSINE-100

WIMP Extraction Analysis

- SET2 data analysis (1.7 years)
  - SI WIMP & different QF
  - EFT operators
  - Fully cover the alternative scenarios for QF & EFT
- WIMP search via Migdal effect
  - Sub-GeV DM search (from 7 to 0.2 GeV/c²)
- SET3 data analysis is ongoing.



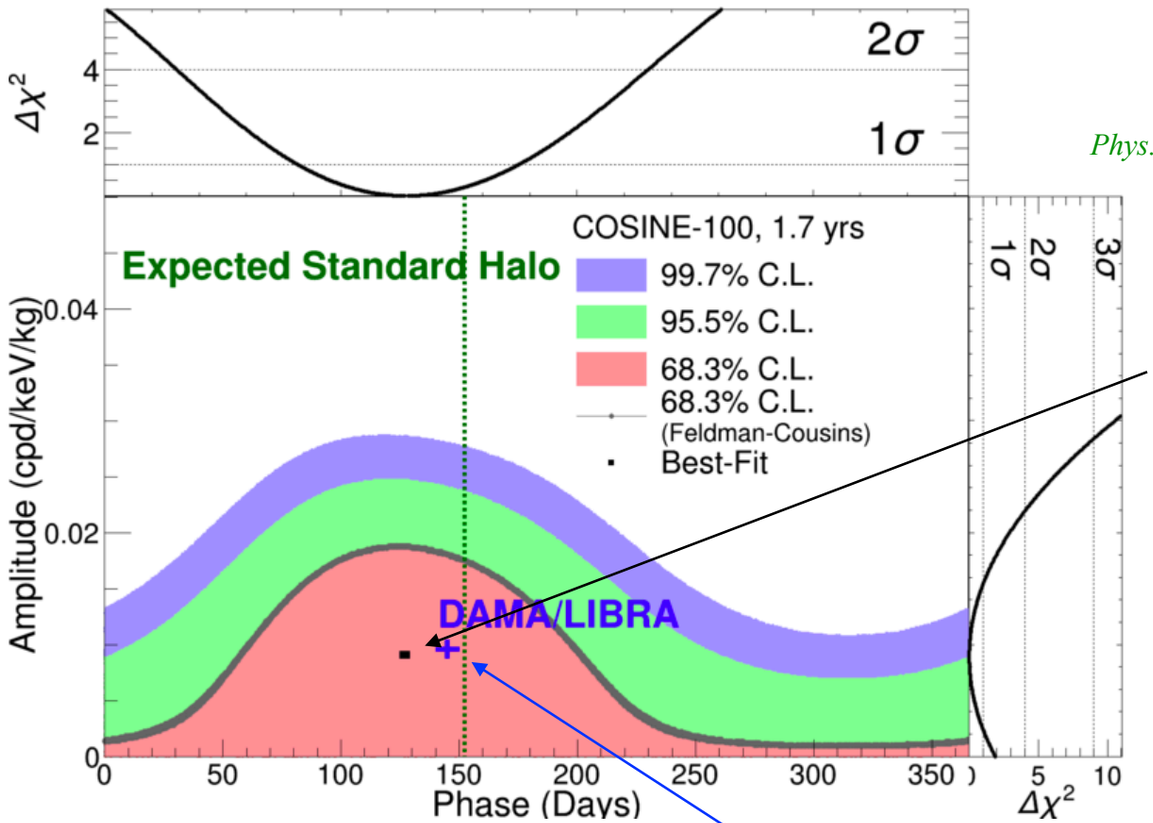




COSINE-100

Modulation Analysis

- First modulation analysis (SET2; 1.7 years)
  - Model-independent DM search
  - The results agree both of DAMA/LIBRA and null hypothesis.



Phys. Rev. Lett. ***123***, 031302 (2019)

COSINE-100 data-SET2
Amp. = 0.0092 ± 0.0067 cpd/keV/kg
Phase = 127.2 ± 45.9 days

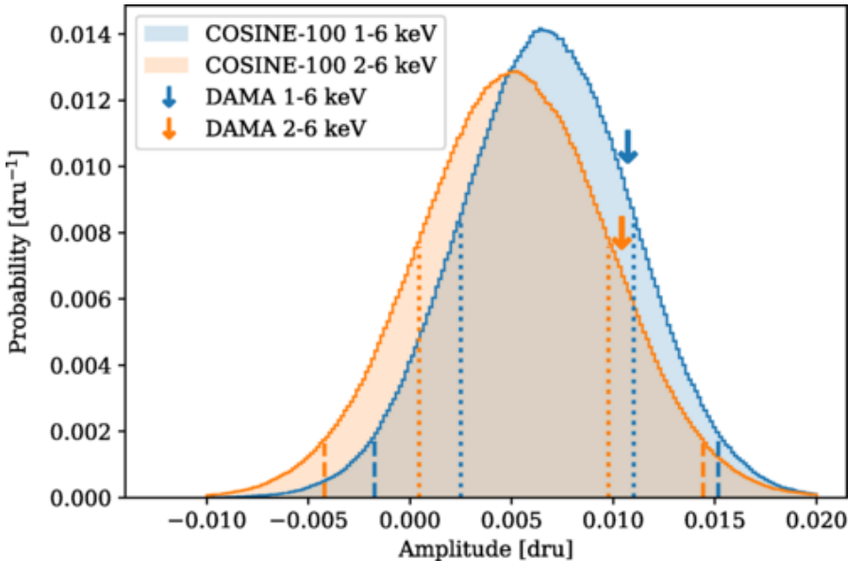
Configuration	Amplitude [cpd/kg/keV]	Phase (Days)
COSINE-100	0.0092 ± 0.0067	127.2 ± 45.9
DAMA/LIBRA (Phase1 + Phase2)	0.0096 ± 0.0008	145 ± 5
COSINE-100	0.0083 ± 0.0068	152.5 (fixed)
COSINE-100 (Without LS)	0.0024 ± 0.0071	152.5 (fixed)
ANAIS-112	-0.0044 ± 0.0058	152.5 (fixed)
DAMA/LIBRA (Phase1 + Phase2)	0.0095 ± 0.0008	152.5 (fixed)

DAMA/LIBRA-phase1+2
Amp. = 0.0096 ± 0.0008 cpd/keV/kg
Phase = 145 ± 5 days

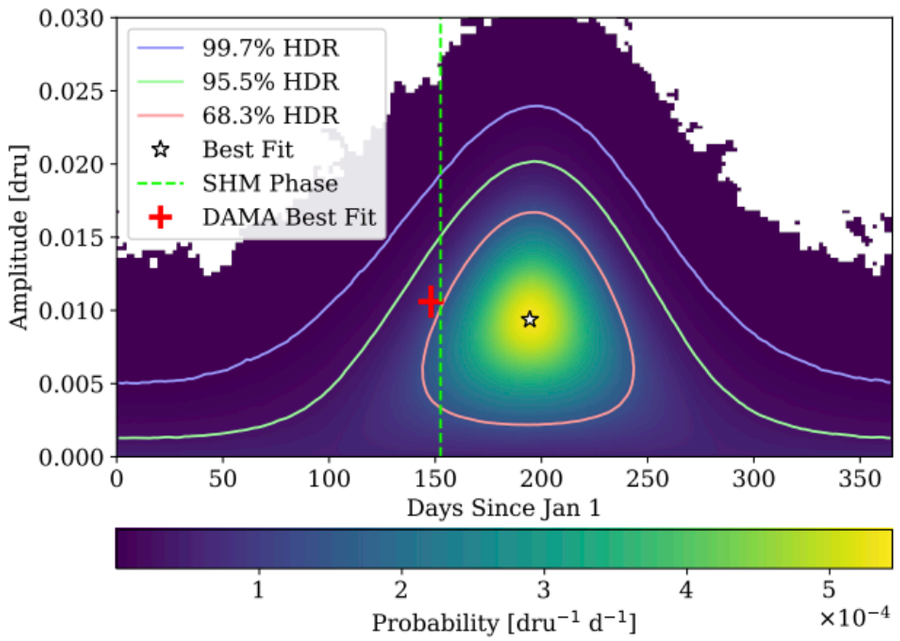
COSINE-100

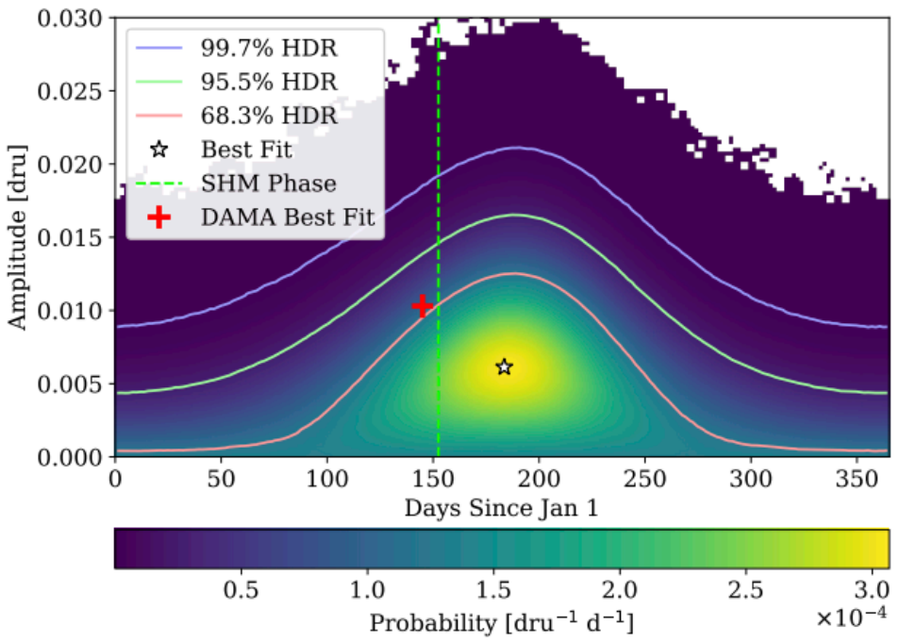
Modulation Analysis

- First modulation analysis (SET2; 1.7 years)
  - Model-independent DM search
  - The results agree both of DAMA/LIBRA and null hypothesis.
- SET3 data analysis (3 years)
  - Still cannot rule out any of DAMA/LIBRA & null hypothesis
- 5-years data (SET4) analysis is ongoing.



*Phys. Rev. D **106**, 052005 (2022)*

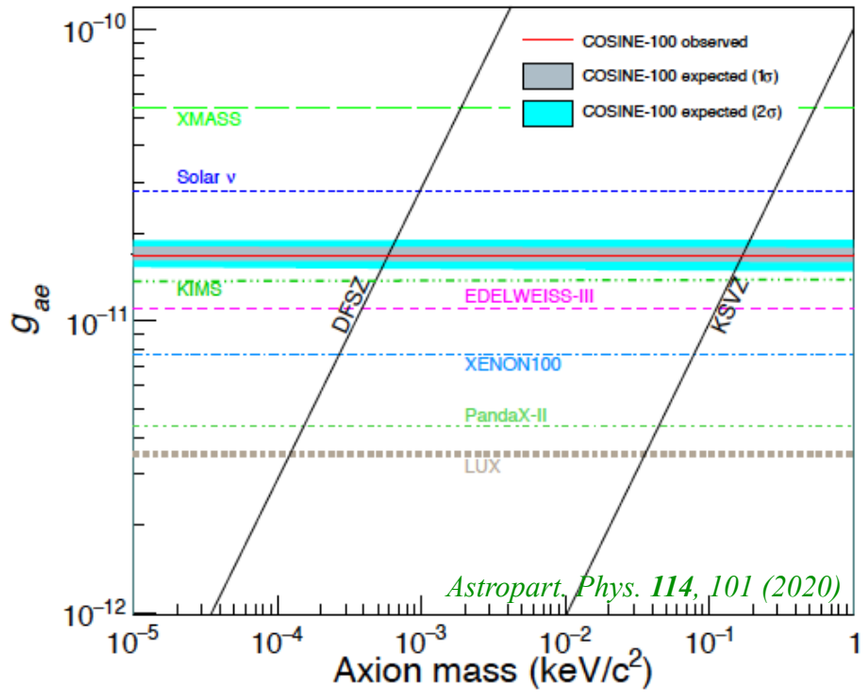




COSINE-100

Other Scenarios

- Published Results
  - Solar axion

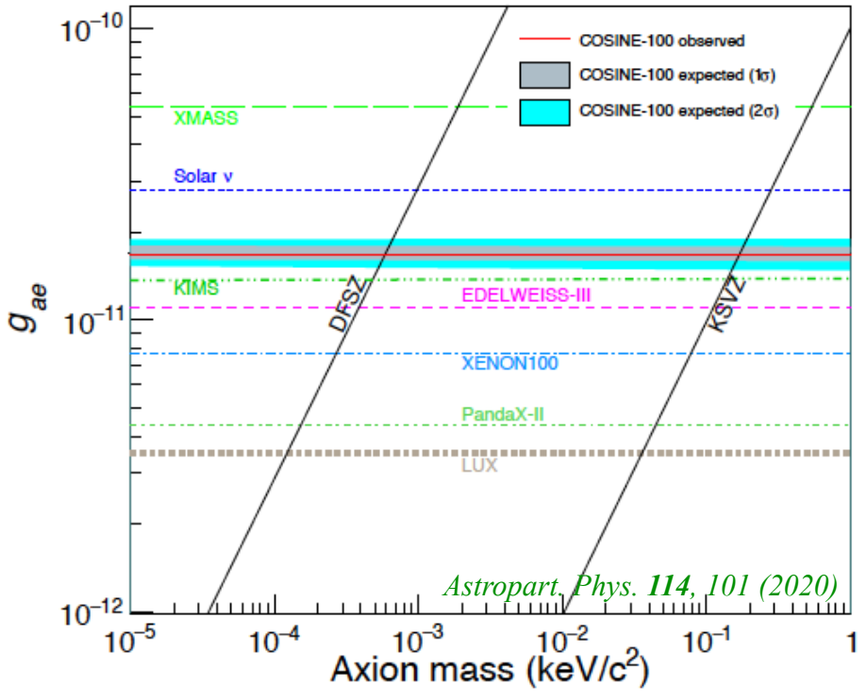


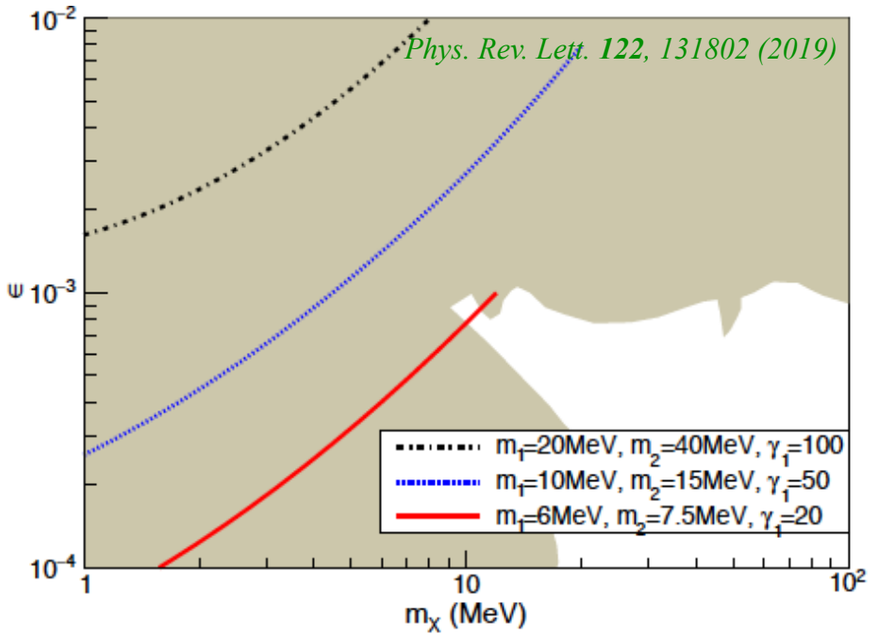
Astropart. Phys. ***114****, 101 (2020)*

COSINE-100

Other Scenarios

- Published Results
  - Solar axion
  - Inelastic boosted dark matter

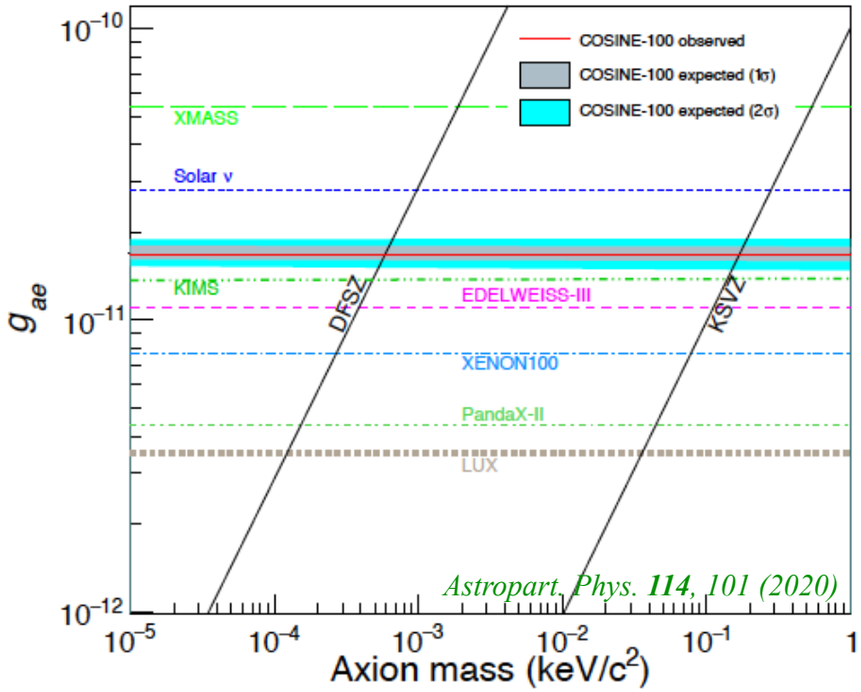




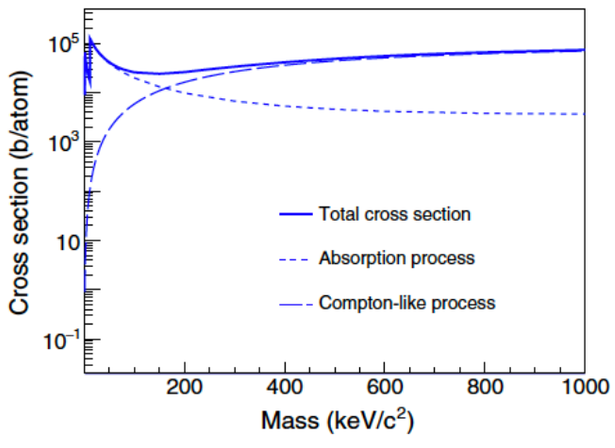
COSINE-100

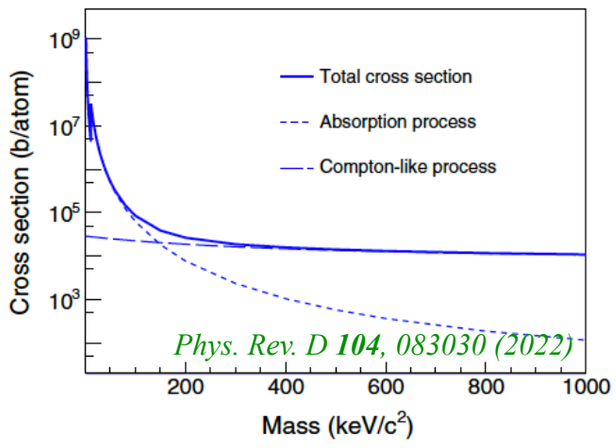
Other Scenarios

- Published Results
  - Solar axion
  - Inelastic boosted dark matter
- Bosonic super-WIMP search
  - Adding Compton-like process
  - Work in progress

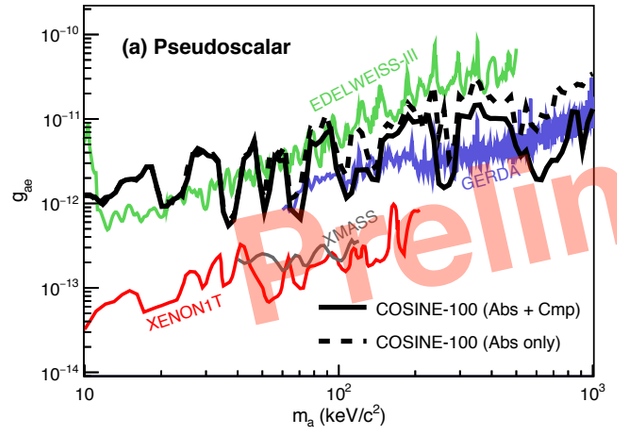


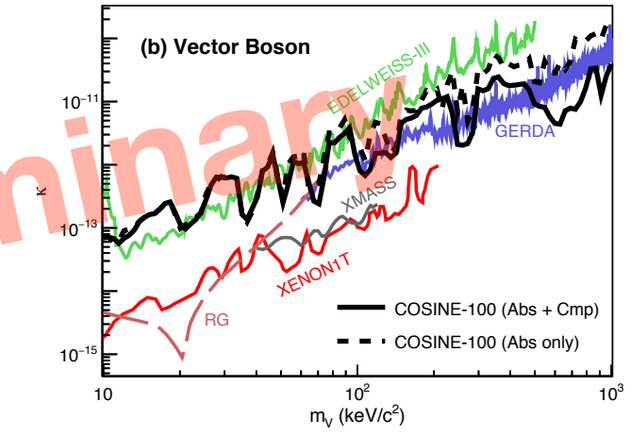
Astropart. Phys. ***114***, *101 (2020)*

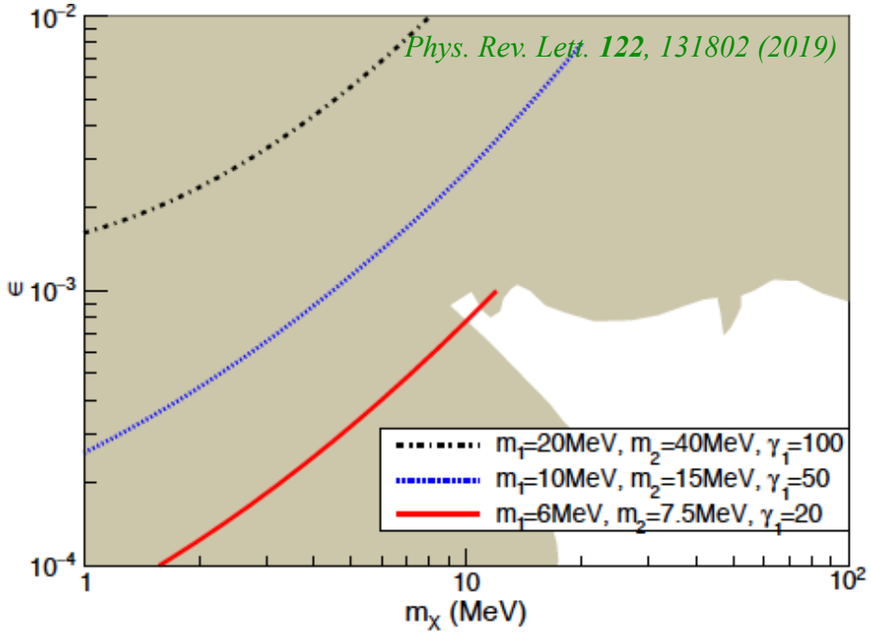




Phys. Rev. D ***104***, *083030 (2022)*





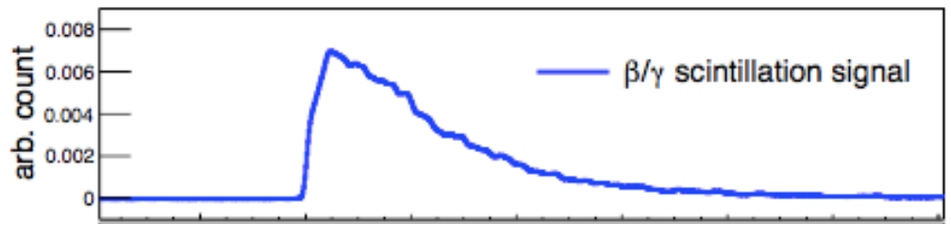


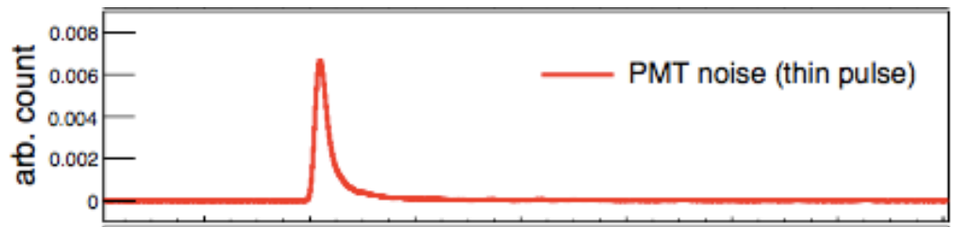
Phys. Rev. Lett. ***122***, *131802 (2019)*

Machine Learning in COSINE-100

Event Selection — Scintillation VS Noise

- Waveform
  - 500-MHz sampling — 2-ns time bin
  - Sharp shape of PMT-noise waveform





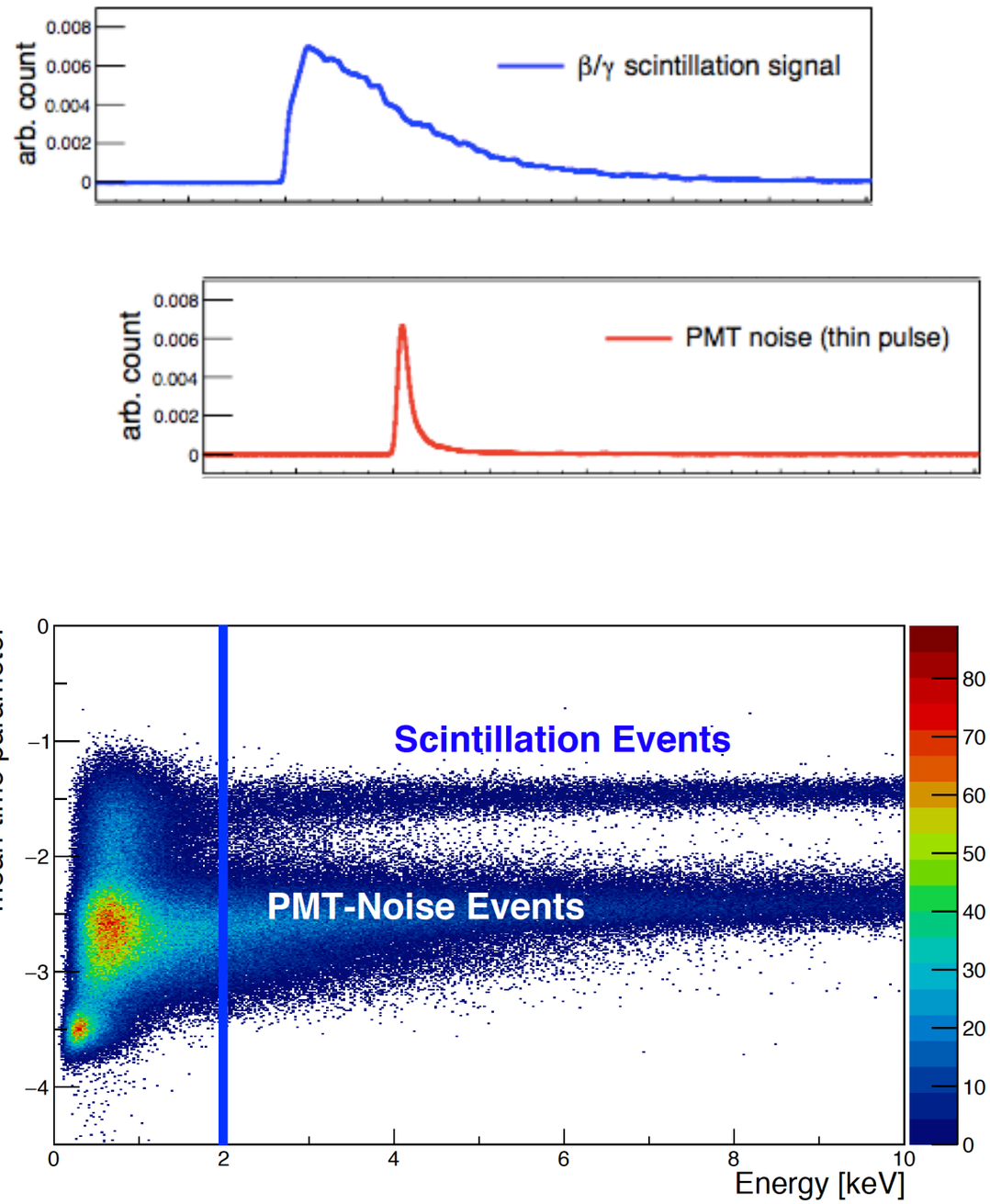
Machine Learning in COSINE-100

Event Selection — Scintillation VS Noise

- Waveform
  - 500-MHz sampling — 2-ns time bin
  - Sharp shape of PMT-noise waveform
- Mean-time parameter p_m
  - Definition

    $p_m = \ln\left(\langle t\rangle_1 + \langle t\rangle_2\right)$

    $\langle t\rangle_i$: charge weighted mean time of PMT i
  - Smaller values of PMT-noise events due to sharp shape
  - Separating scintillation events from PMT-noise events above 2 keV



Machine Learning in COSINE-100

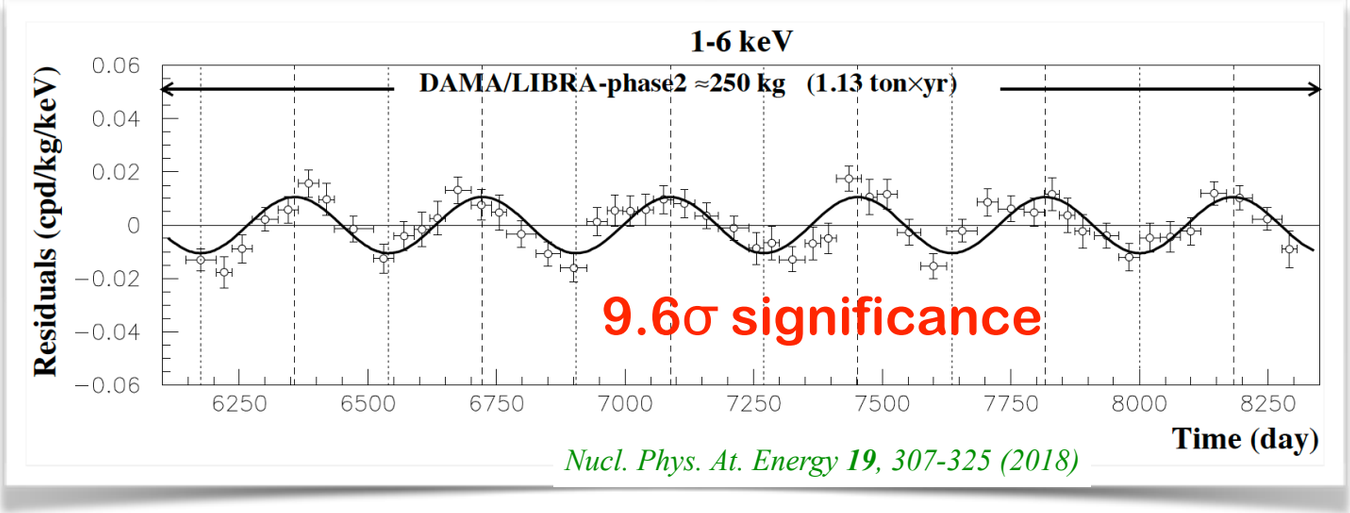
Event Selection — Scintillation VS Noise

- Waveform
  - 500-MHz sampling — 2-ns time bin
  - Sharp shape of PMT-noise waveform
- Mean-time parameter p_m
  - Definition

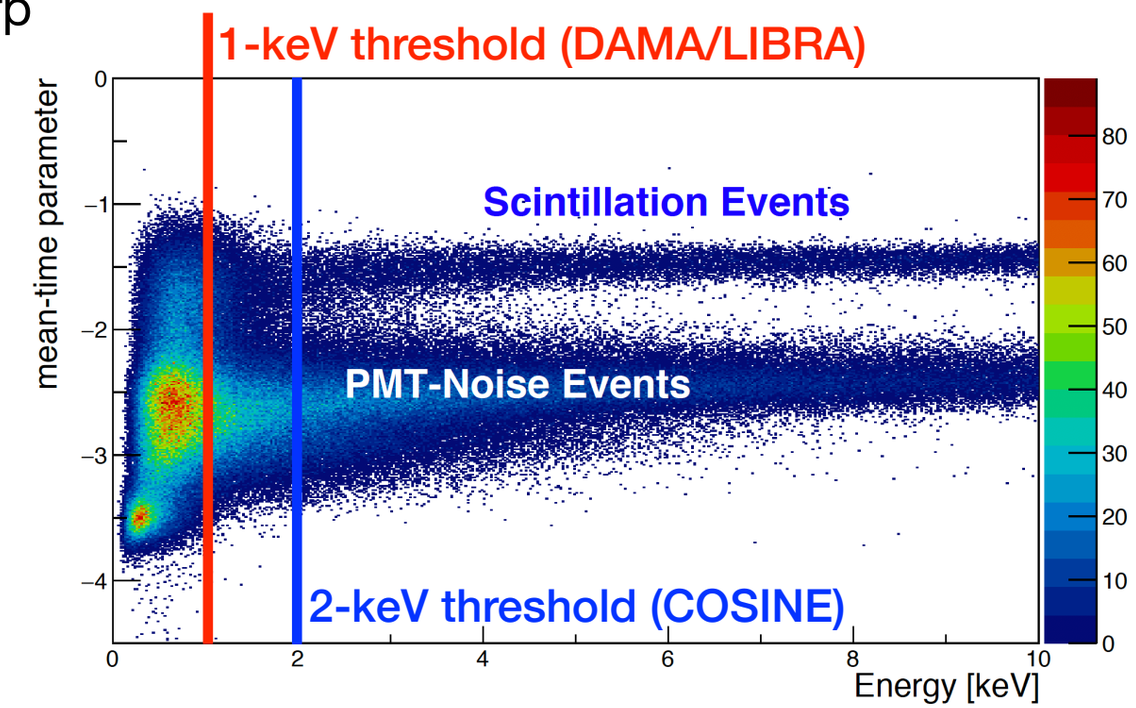
$$p_m = \ln\left(\langle t\rangle_1 + \langle t\rangle_2\right)$$

$\langle t\rangle_i$: charge weighted mean time of PMT i

  - Smaller values of PMT-noise events due to sharp shape
  - Separating scintillation events from PMT-noise events above 2 keV
- 2-keV threshold in SET1 analysis
  - Using mean-time parameter
  - DAMA/LIBRA-phase2
    - Lowering the threshold to 1 keV from 2 keV.
    - Need to lower the threshold to 1 keV



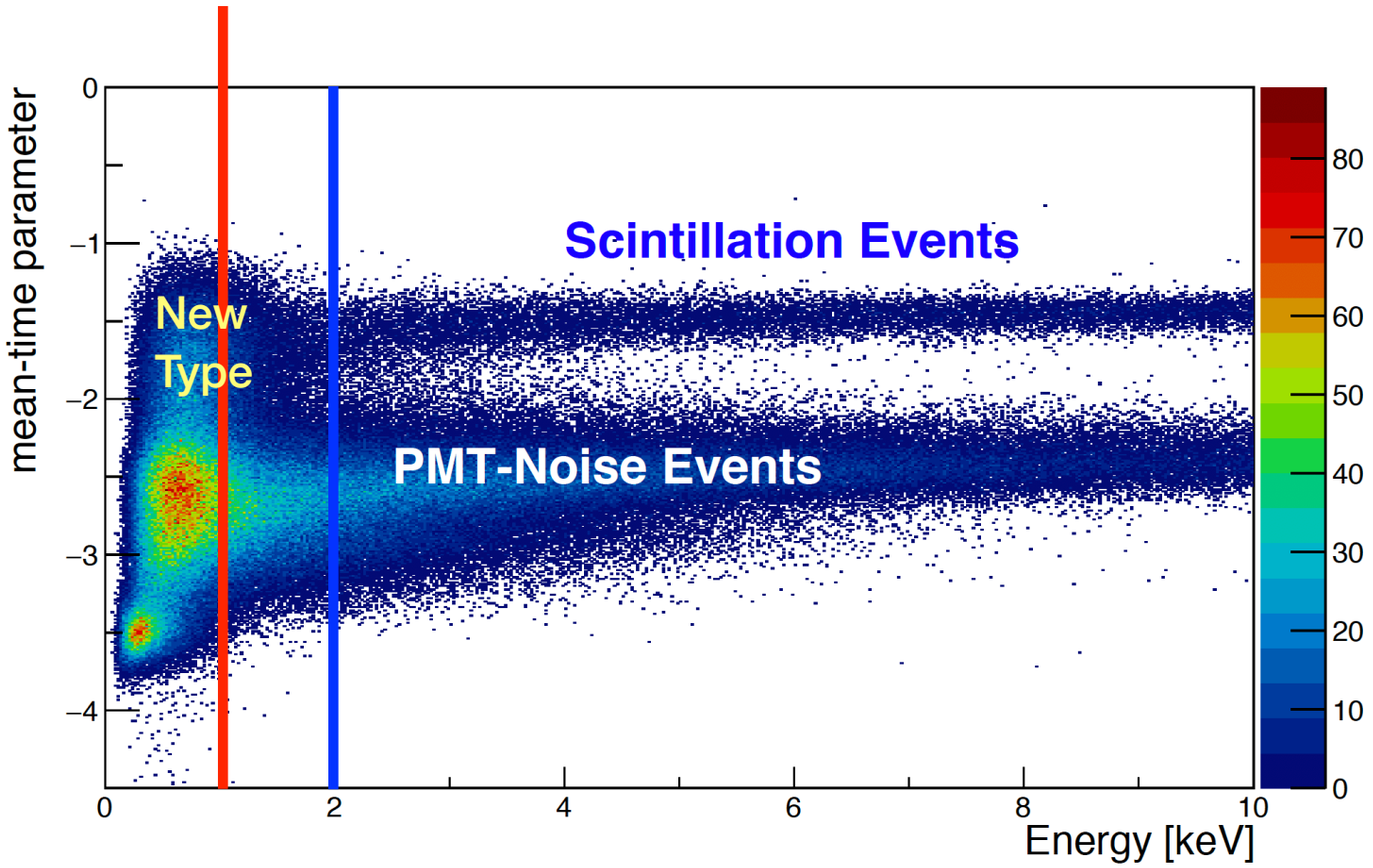
Nucl. Phys. At. Energy ***19****, 307-325 (2018)*



Machine Learning in COSINE-100

Parameter Development

- There is new type of noise events below 2 keV
  - Cannot be discriminated from scintillation events via mean-time parameter
  - Need to develop new parameters



Machine Learning in COSINE-100

Parameter Development

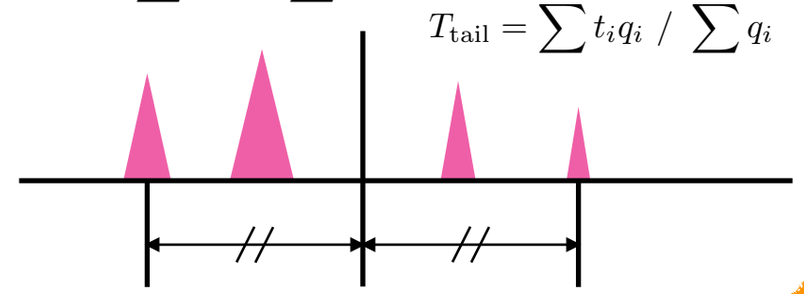
- There is new type of noise events below 2 keV
  - Cannot be discriminated from scintillation events via mean-time parameter
  - Need to develop new parameters
- Pulse-shape parameter p_d
  - Simplified decay time for characterizing waveforms
  - Definition

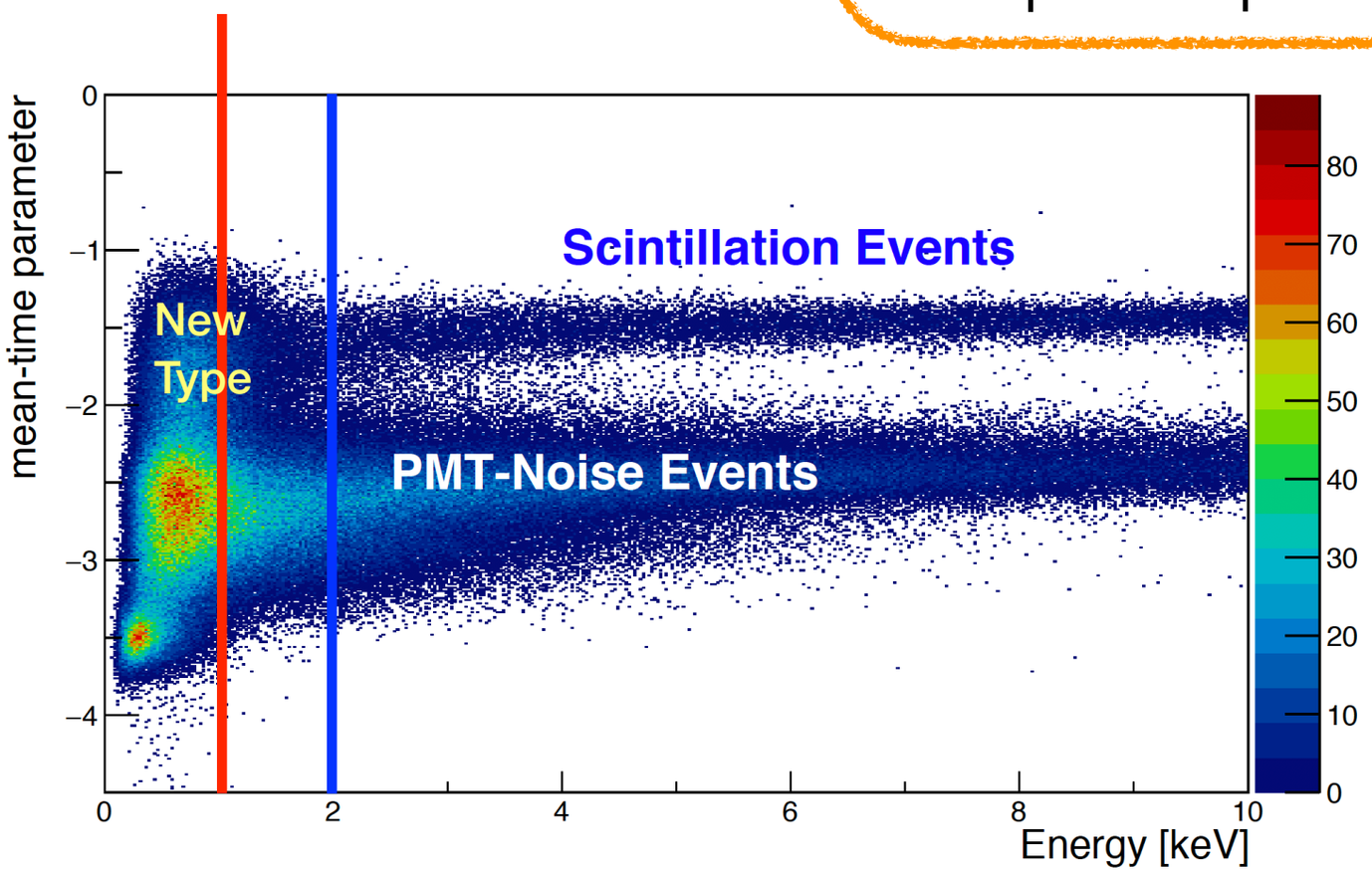
$$p_d = \ln\left(t_{d,1} + t_{d,2}\right)$$

$$t_d = -\frac{\ln\left(Q_{\text{tail}}/Q_{\text{head}}\right)}{T_{\text{tail}} - T_{\text{head}}}$$

$$Q_{\text{head}} = \sum q_i \qquad T_{\text{head}} = \sum t_i q_i \;/\; \sum q_i$$

$$Q_{\text{tail}} = \sum q_i \qquad T_{\text{tail}} = \sum t_i q_i \;/\; \sum q_i$$





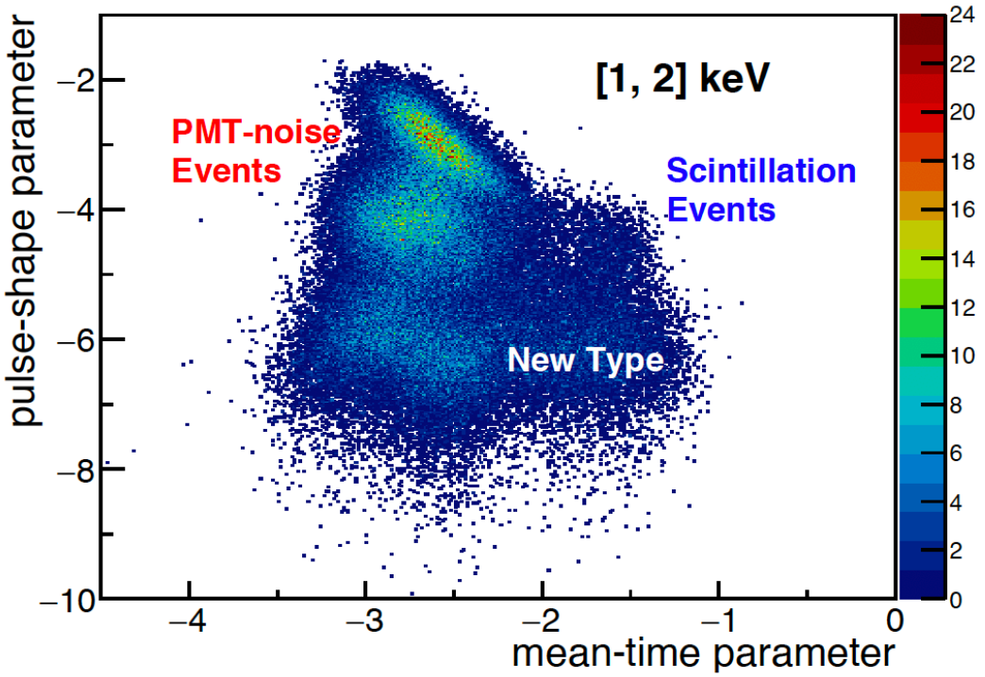
Machine Learning in COSINE-100

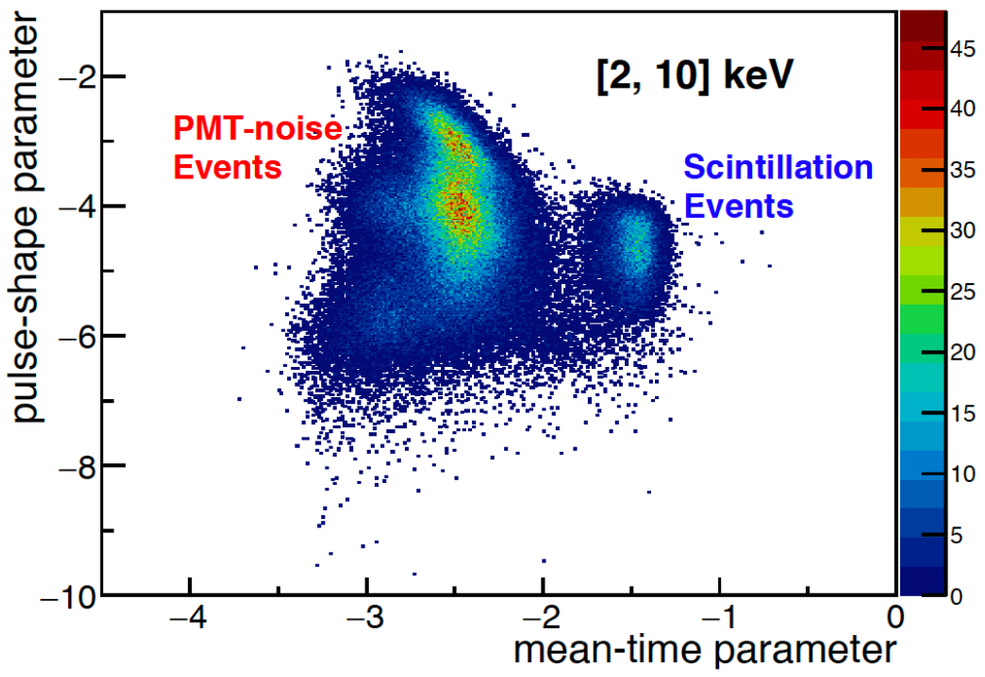
Parameter Development

Astropart. Phys. ***130****, 102581 (2021)*

- There is new type of noise events below 2 keV
  - Cannot be discriminated from scintillation events via mean-time parameter
  - Need to develop new parameters
- Pulse-shape parameter p_d
  - Simplified decay time for characterizing waveforms
  - Definition

    $p_d = \ln\left(t_{d,1} + t_{d,2}\right)$
  - New type noise
    - Visible only via the new parameter for events below 2 keV
    - p_m values are similar to those for scintillation events.





Machine Learning in COSINE-100

Parameter Development

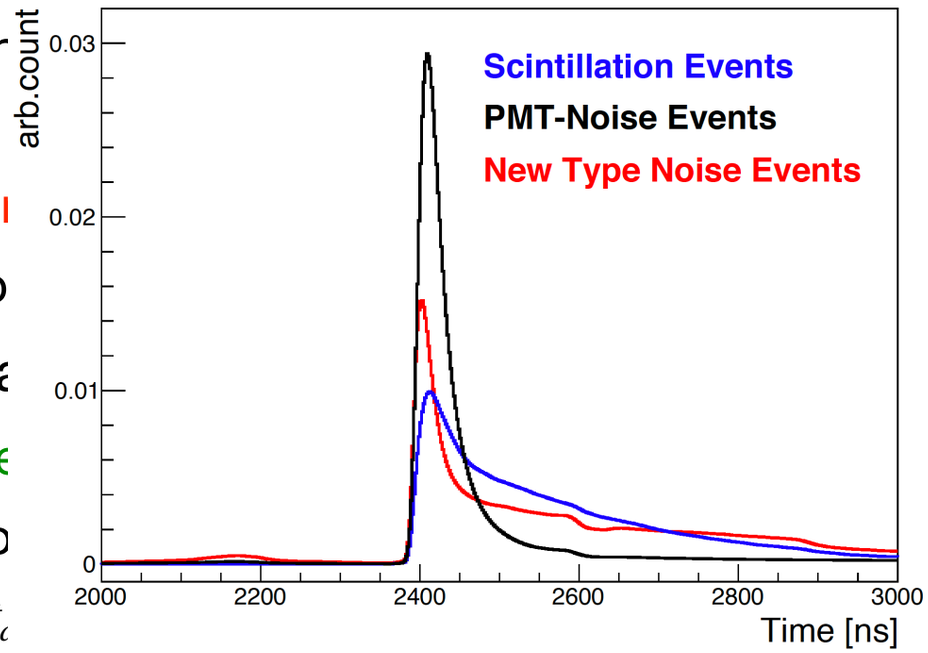
Astropart. Phys. ***130****, 102581 (2021)*

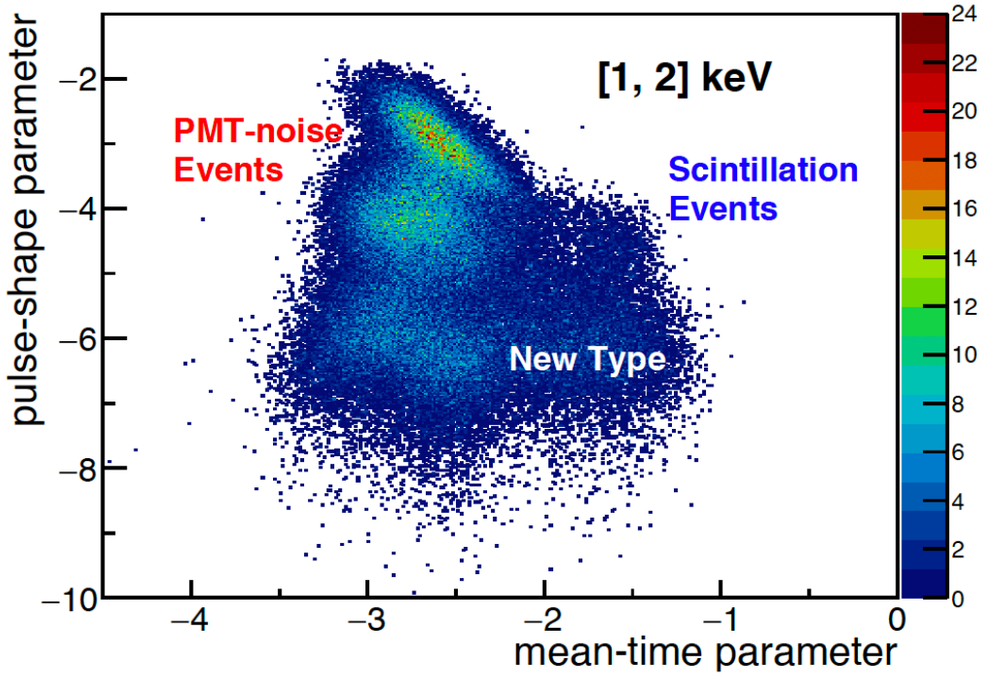
- There is r
  - Cannot
    mean-ti
  - Need to
- Pulse-sha
  - Simplifie
  - Definitio

$$p_d = \ln\left(t_c\right.$$

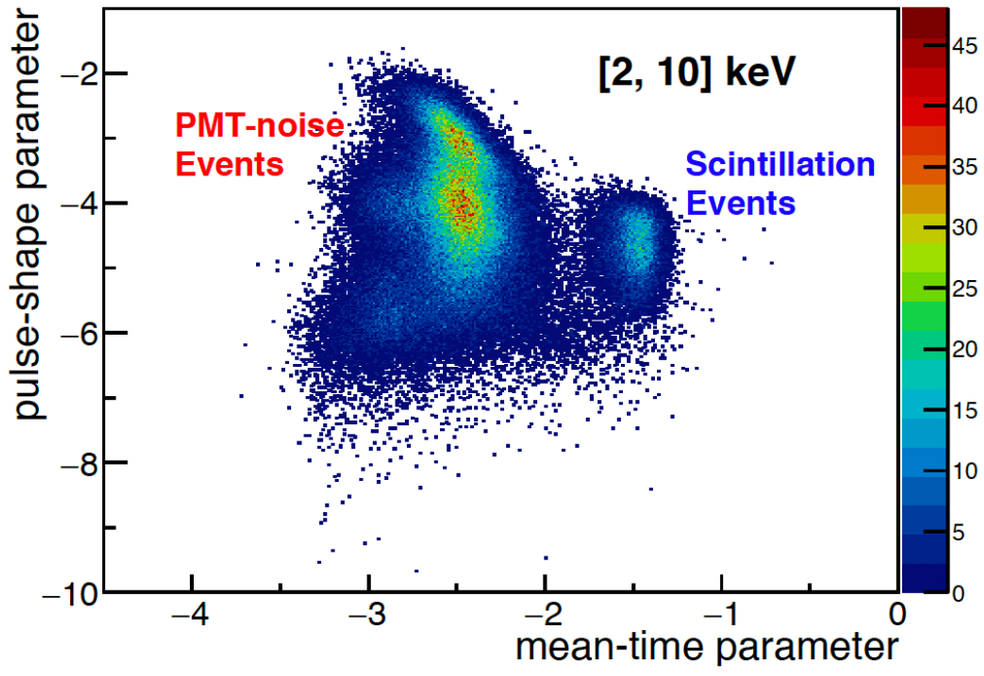
via

ns





- New type noise
  - Visible only via the new parameter for events below 2 keV
  - p_m values are similar to those for scintillation events.
  - Sharp head + long tail



Machine Learning in COSINE-100

Parameter Development

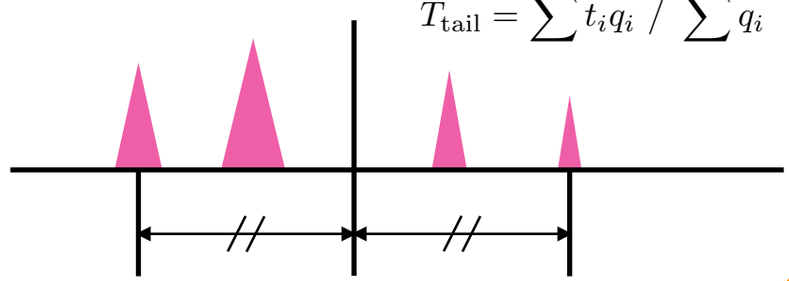
Astropart. Phys. ***130****, 102581 (2021)*

- Issue for pulse-shape parameter
  - Dividing into first & second half
    - Four or more pulse (SPE) hits are needed.
    - It can make inefficiency of scintillation events in very low energy region.

$$t_d = -\frac{\ln\left(Q_{\text{tail}}/Q_{\text{head}}\right)}{T_{\text{tail}} - T_{\text{head}}}$$

$$Q_{\text{head}} = \sum q_i \qquad T_{\text{head}} = \sum t_i q_i \;/\; \sum q_i$$

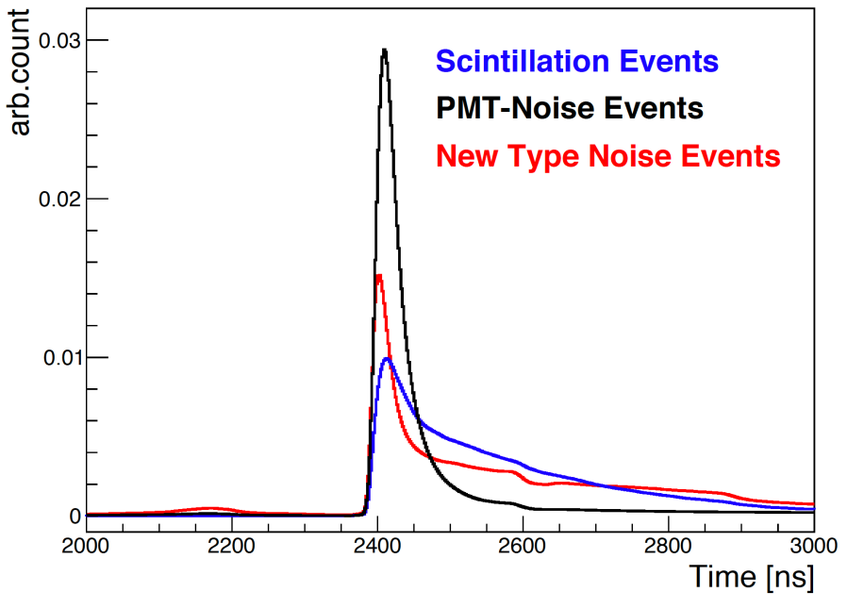
$$Q_{\text{tail}} = \sum q_i \qquad T_{\text{tail}} = \sum t_i q_i \;/\; \sum q_i$$



Machine Learning in COSINE-100

Parameter Development

Astropart. Phys. ***130****, 102581 (2021)*



- Issue for pulse-shape parameter
  - Dividing into first & second half
    - Four or more pulse (SPE) hits are needed.
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- Likelihood parameter p_l
  - Reference waveform
    - Using p_m & p_d to select scintillation/PMT-noise events
    - Accumulating PMT pulses
  - Definition: a score of log-likelihood values b/w waveform of each event & scintillation/PMT-noise references

$$p_l = \frac{\ln \mathscr{L}_n - \ln \mathscr{L}_s}{\ln \mathscr{L}_n + \ln \mathscr{L}_s}$$

$\mathscr{L}_n$: likelihood for PMT-noise reference

$\mathscr{L}_s$: likelihood for scintillation reference

Machine Learning in COSINE-100

Parameter Development

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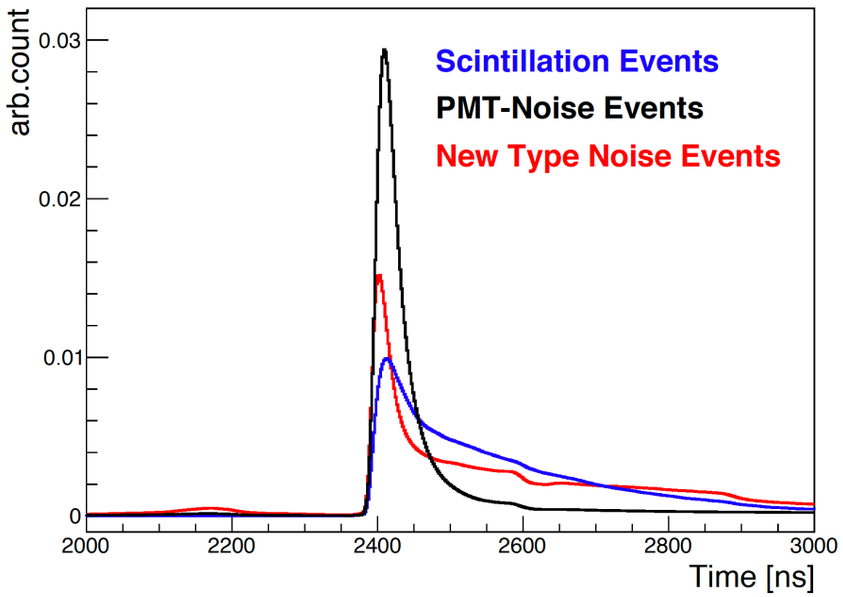
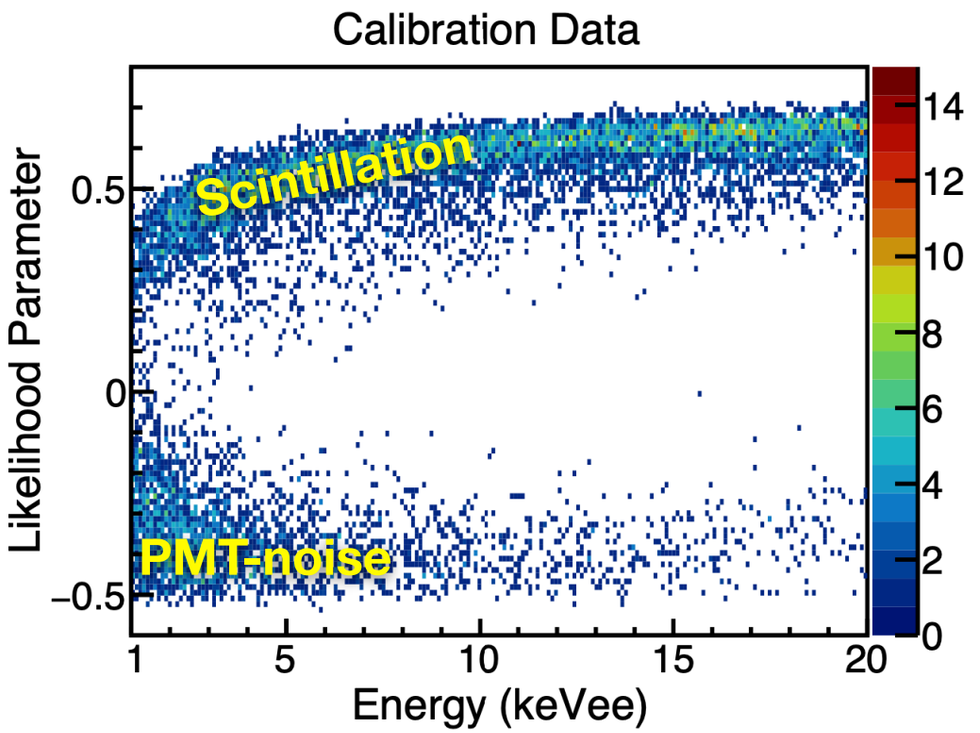
$\mathscr{L}_n$: likelihood for PMT-noise reference

$\mathscr{L}_s$: likelihood for scintillation reference

  - Likelihood parameter shows good discrimination power above 1 keV region



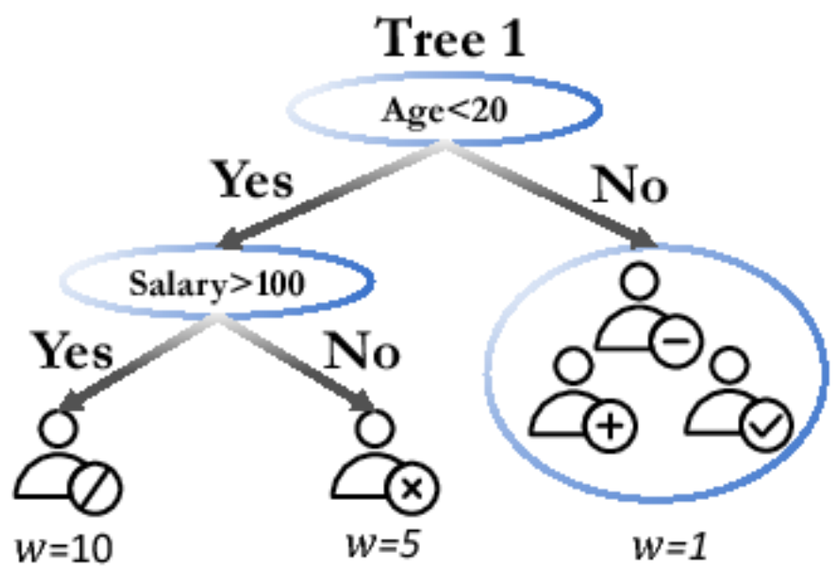


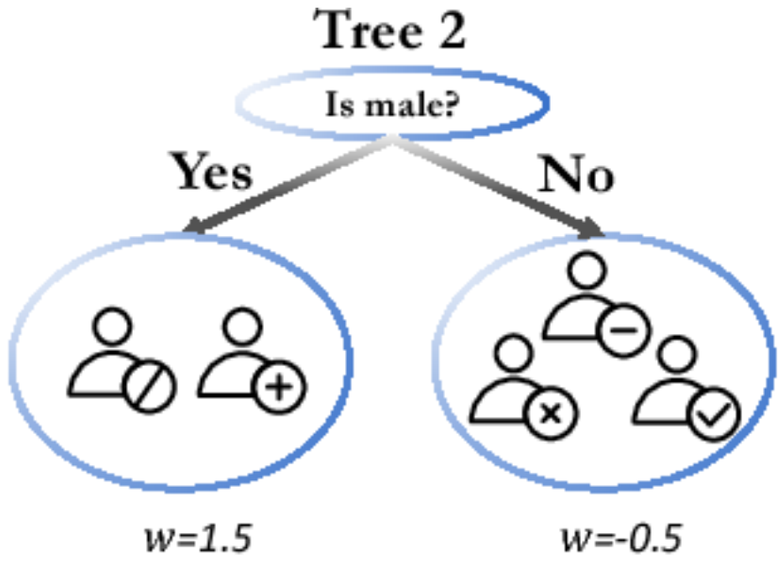
Machine Learning in COSINE-100

Boosted Decision Tree (BDT)

Astropart. Phys. ***130****, 102581 (2021)*

- Decision tree
  - Splitting data recursively based on input parameters
  - Accounting correlations b/w individual parameters
- Boosting
  - Combining many weak trees into a strong classifier.
  - Using adaptive boosting
- Combining several parameters into a single powerful discriminator
- Fast, easy to use and good performance
- Sensitive to overfitting
  - Cross validation via test samples
  - Comparing energy spectra to MC
  - Low energy peak (^{22}Na, ^{40}K)



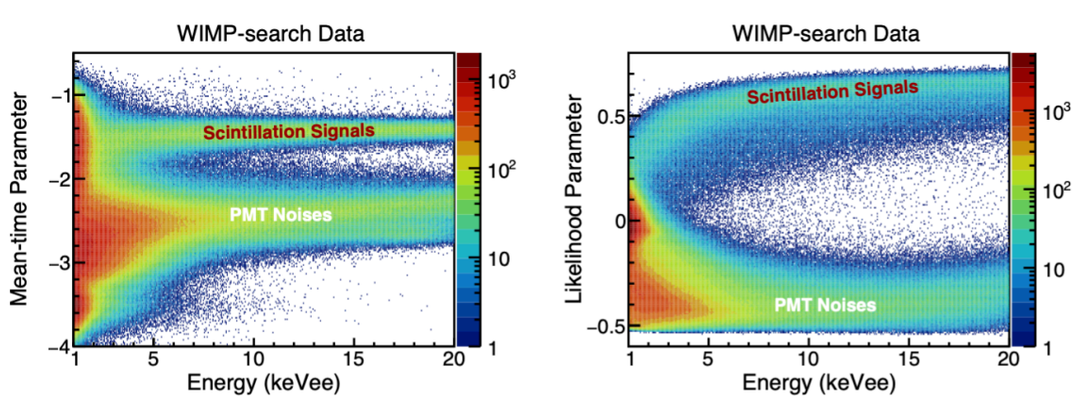


Machine Learning in COSINE-100

Boosted Decision Tree (BDT)

Astropart. Phys. ***130***, *102581 (2021)*
Phys. Rev. D ***105***, *042006 (2022)*

Noise Samples
Physics data
(Including signals)



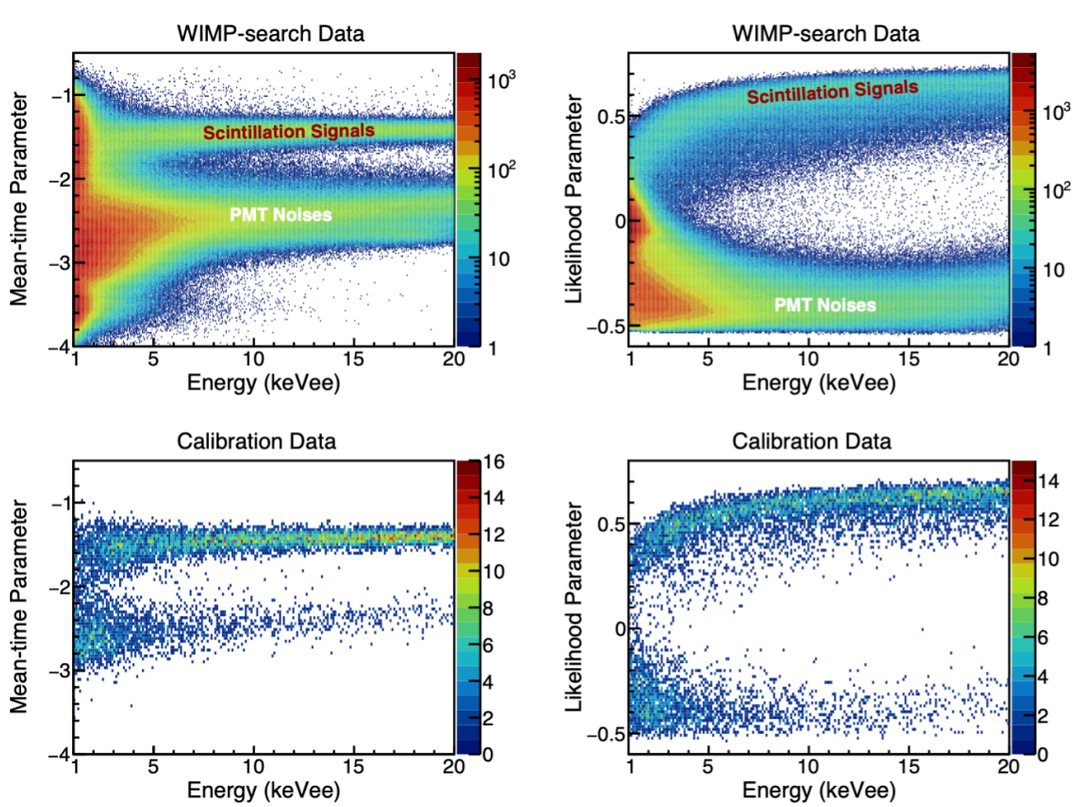
Machine Learning in COSINE-100

Boosted Decision Tree (BDT)

Astropart. Phys. ***130***, *102581 (2021)*
Phys. Rev. D ***105***, *042006 (2022)*

Noise Samples
Physics data
(Including signals)

Signal Samples
Calibration data
(cut via p_l)



Machine Learning in COSINE-100

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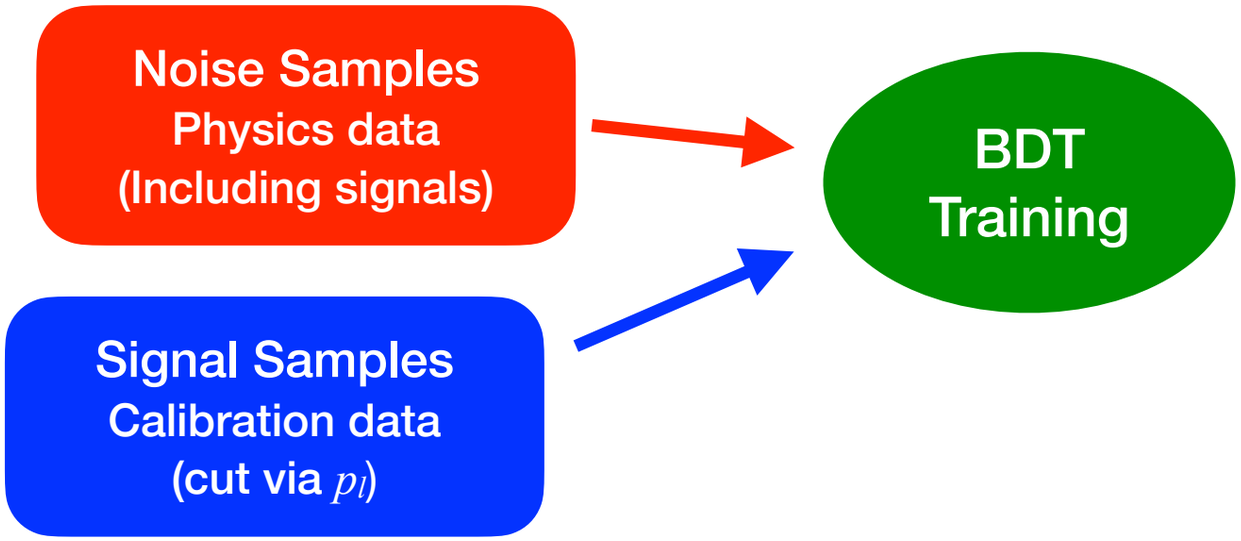
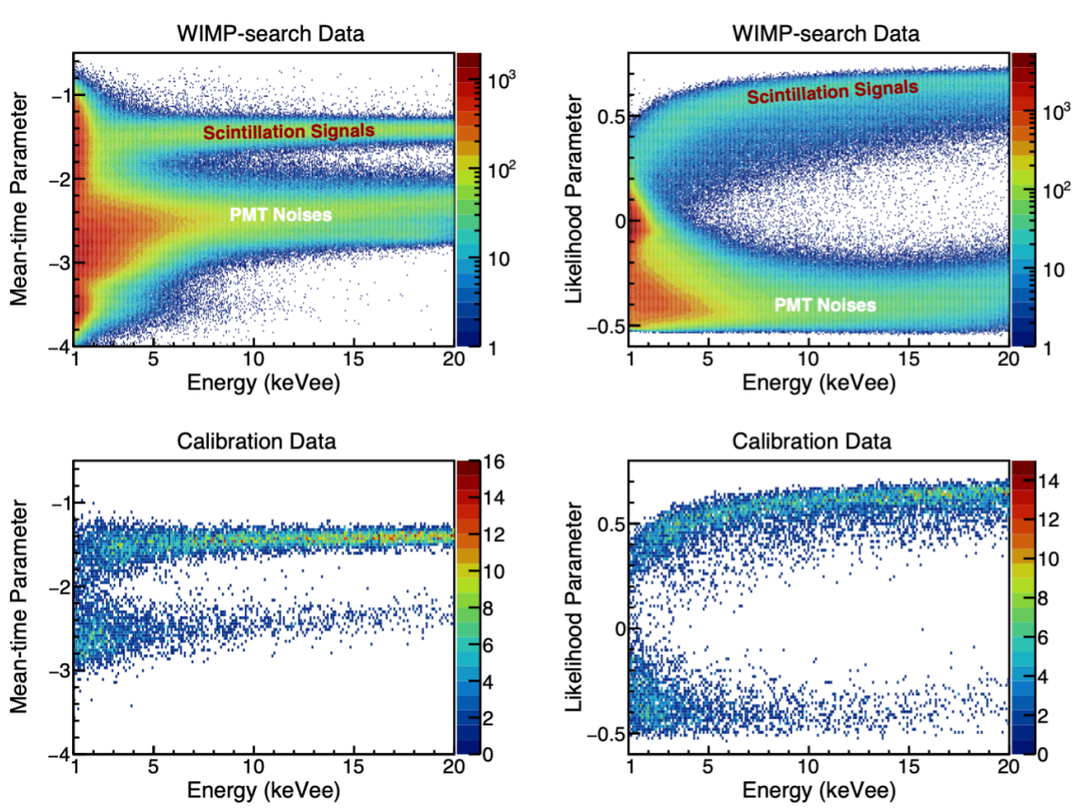
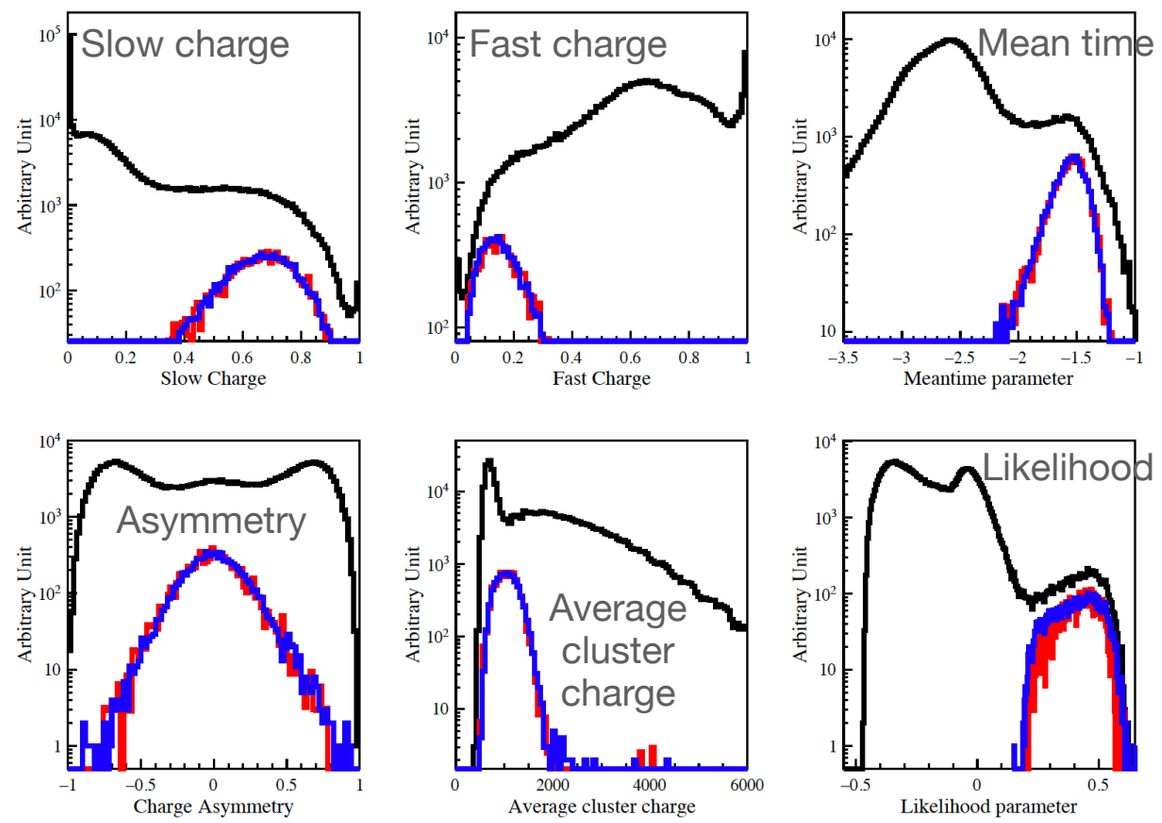




Input parameters
Noise Sample Signal Sample
Decision as signal in noise sample



Machine Learning in COSINE-100

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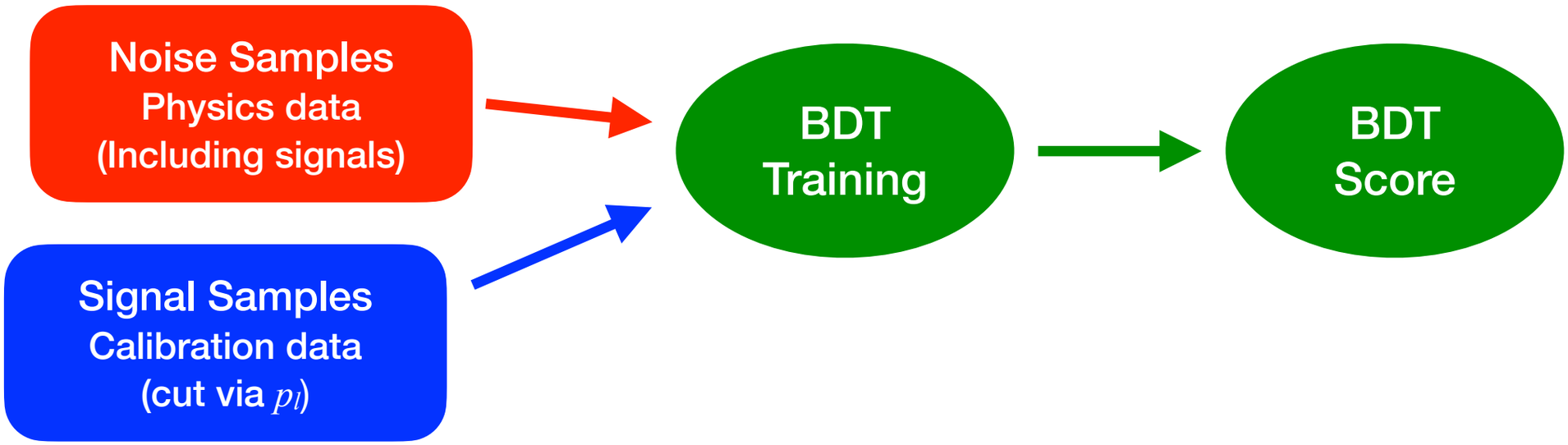
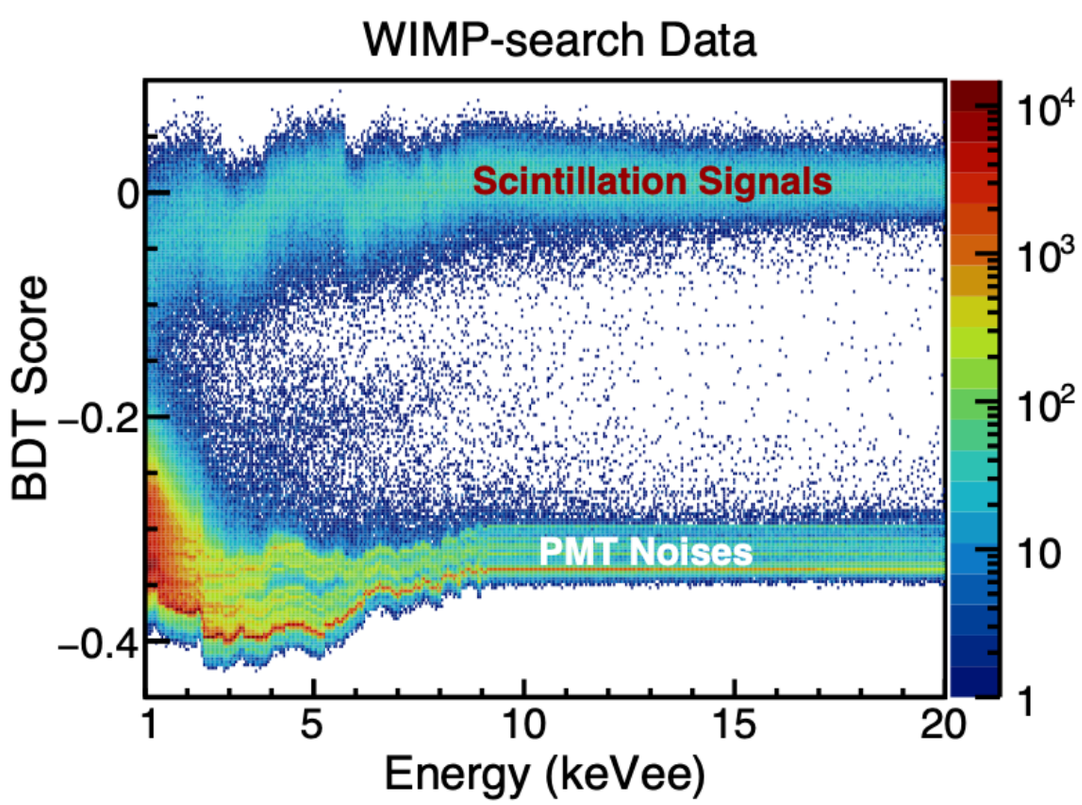
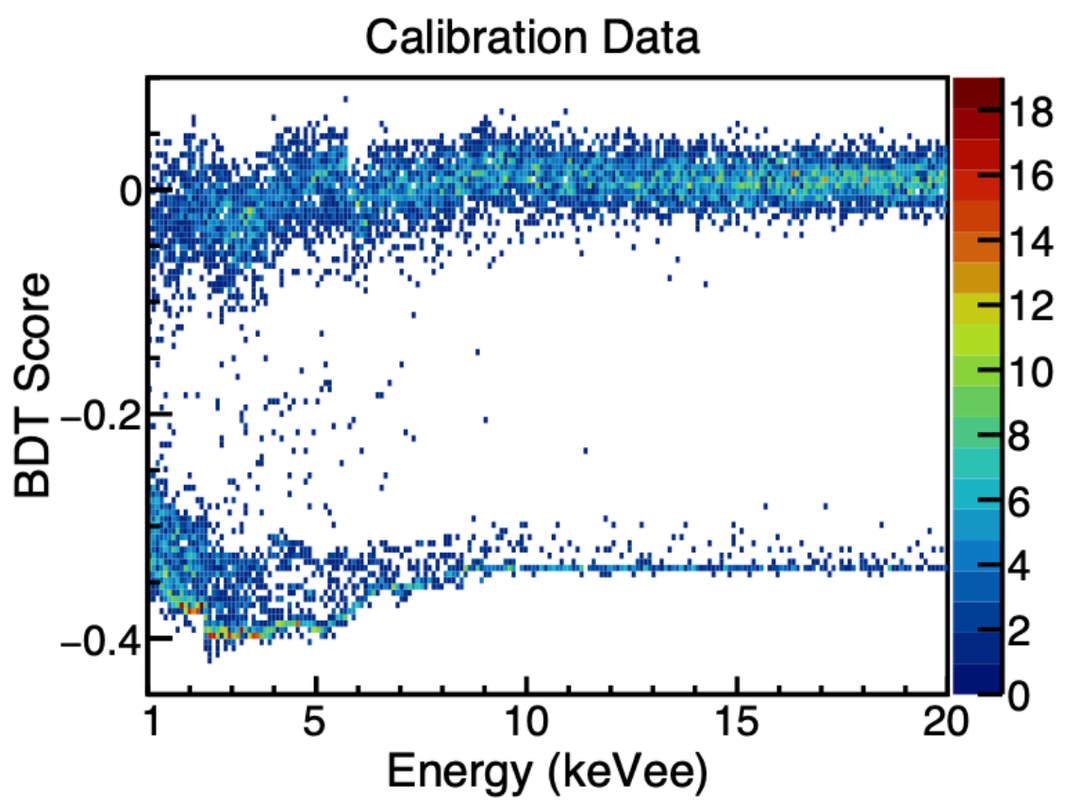




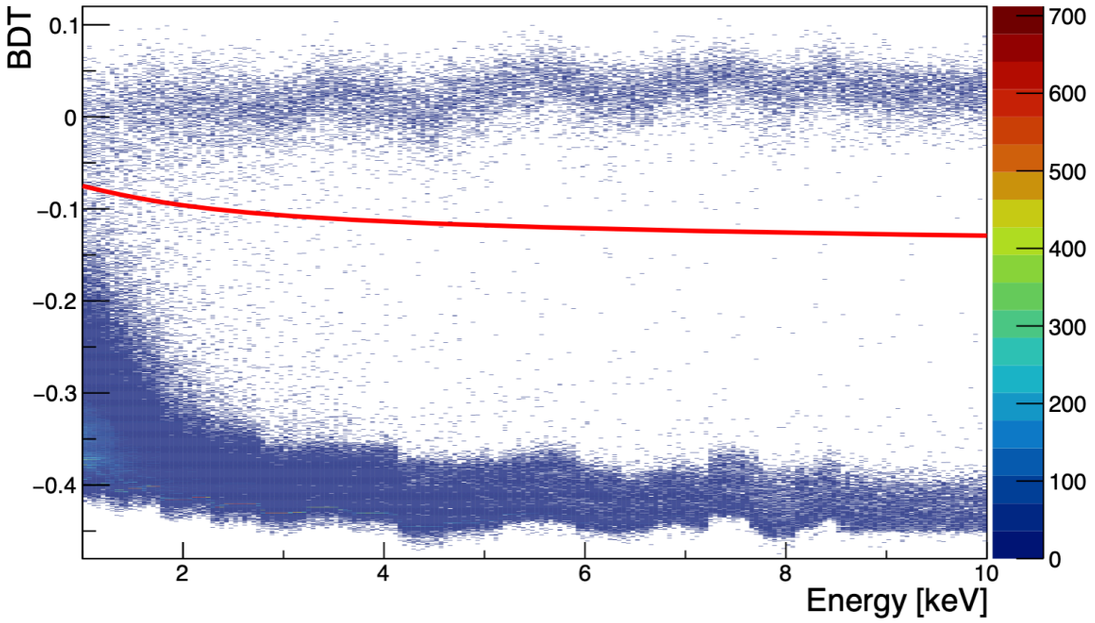


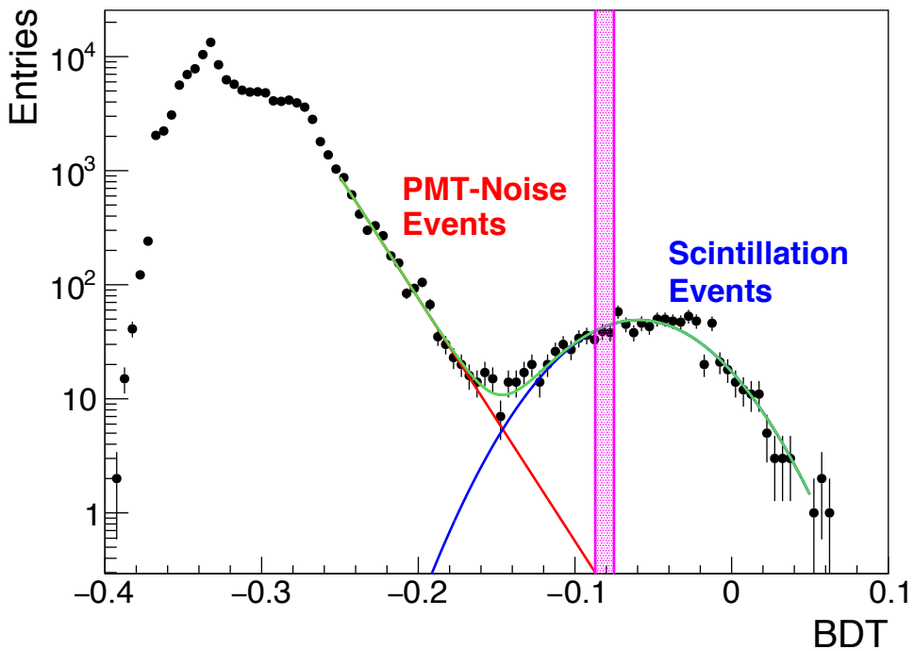
Machine Learning in COSINE-100

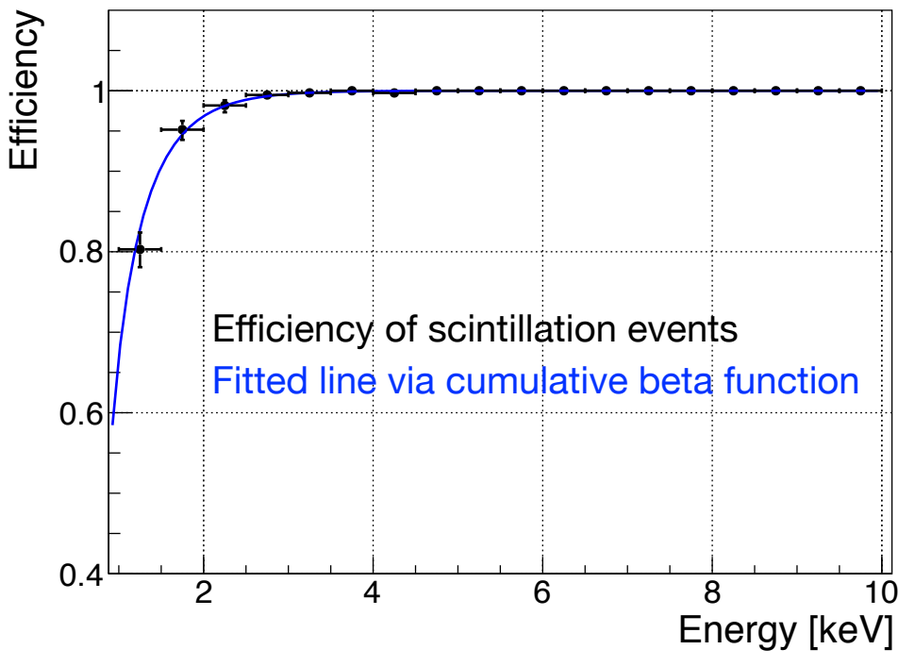
Boosted Decision Tree (BDT)

Astropart. Phys. ***130****, 102581 (2021)*

- Criteria to select scintillation events
  - Cut for S/N ratio > 99
  - Efficiency estimation by modeling
    - 70-80% efficiency in [1, 1.5] keV
- Achieving the 1-keV threshold via BDT
  - Direct comparison w/ DAMA/LIBRA



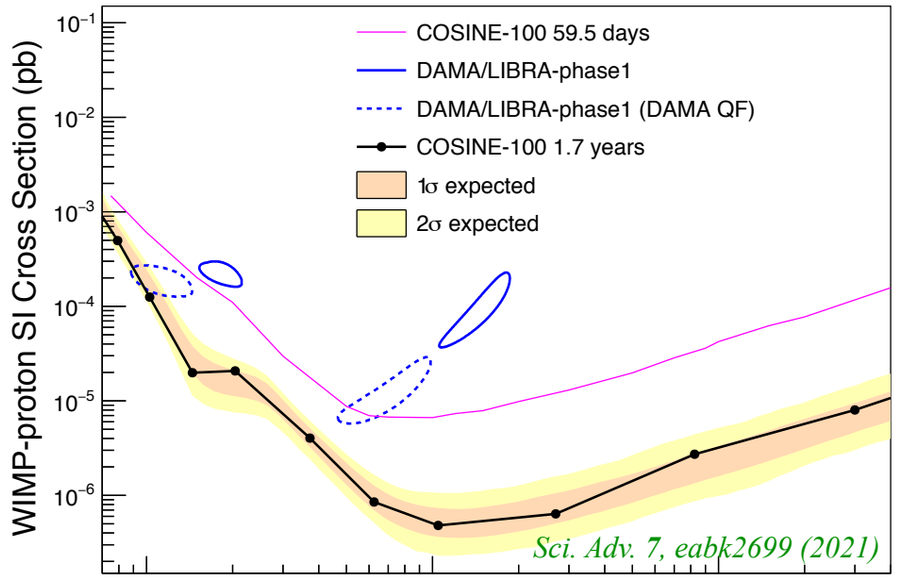


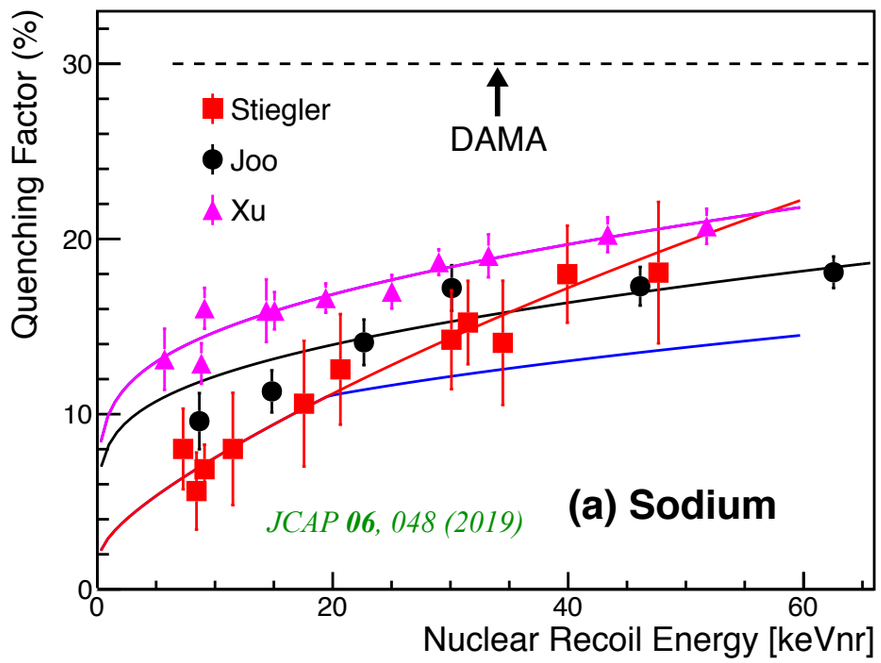


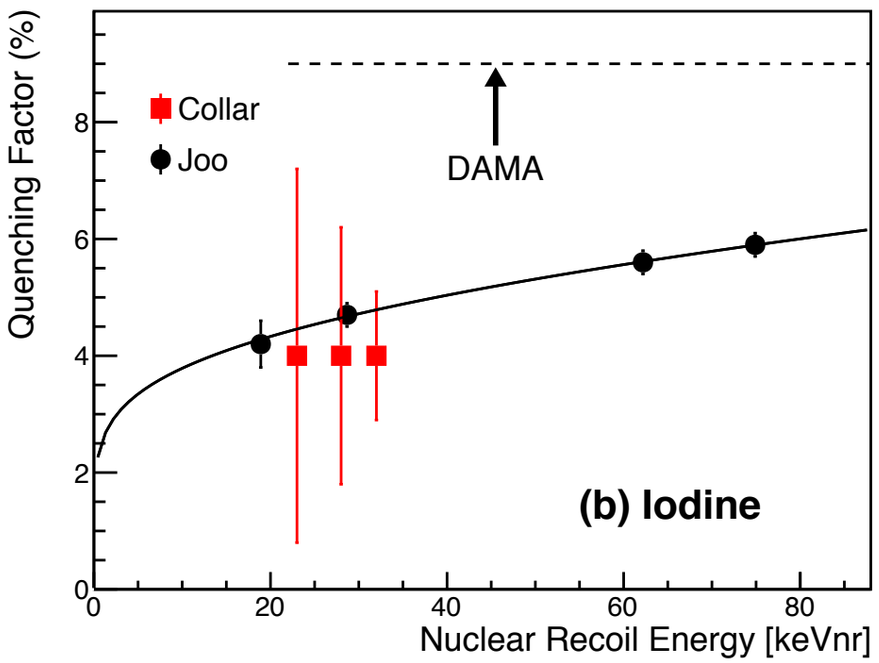
Machine Learning in COSINE-100

Current Status

- Issue for quenching factor (QF)
  - The ratio of E_{nr} to E_{ee}
  - Measurement of DAMA is different from recent measurements.
  - It became clear in extraction analysis.
  - If DAMA crystals have larger QFs, we need lower threshold for direct comparison in modulation analysis.







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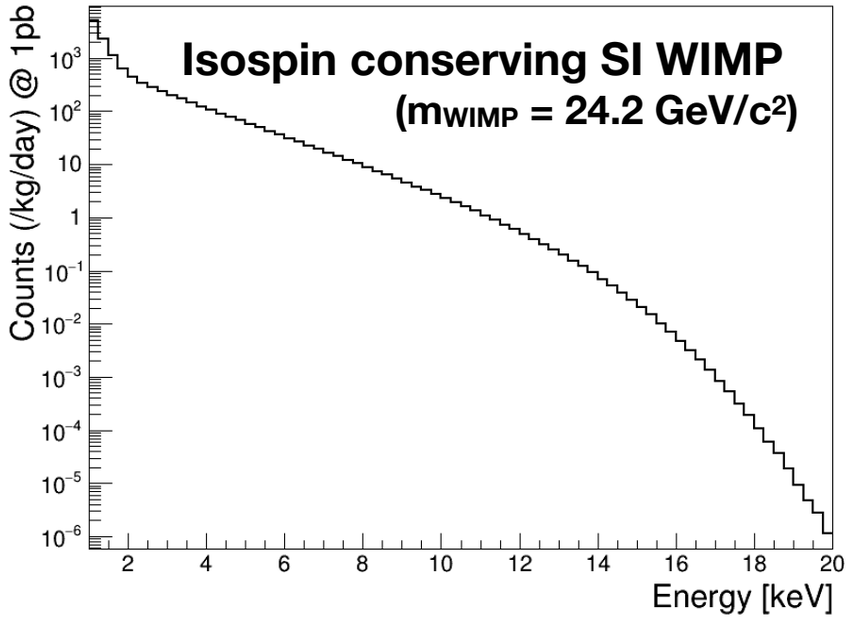
- E_{nr} by WIMPs is mainly distributed in low energy.
  - Lower threshold results in a very large sensitivity improvement in low mass region.
- Below 1 keV?



Machine Learning in COSINE-100

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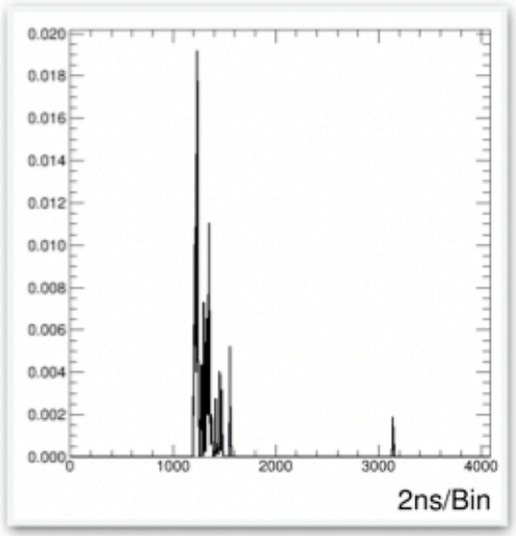
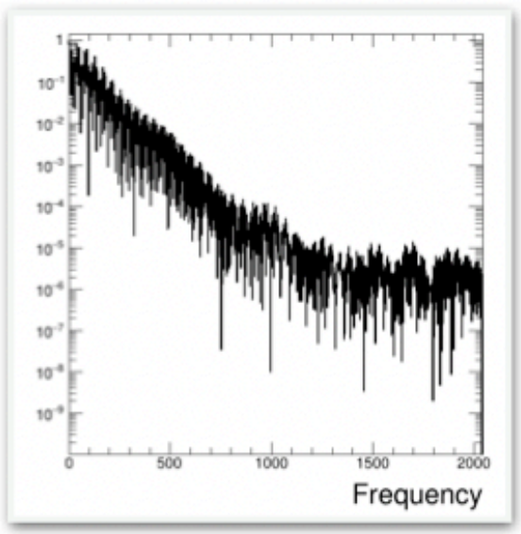


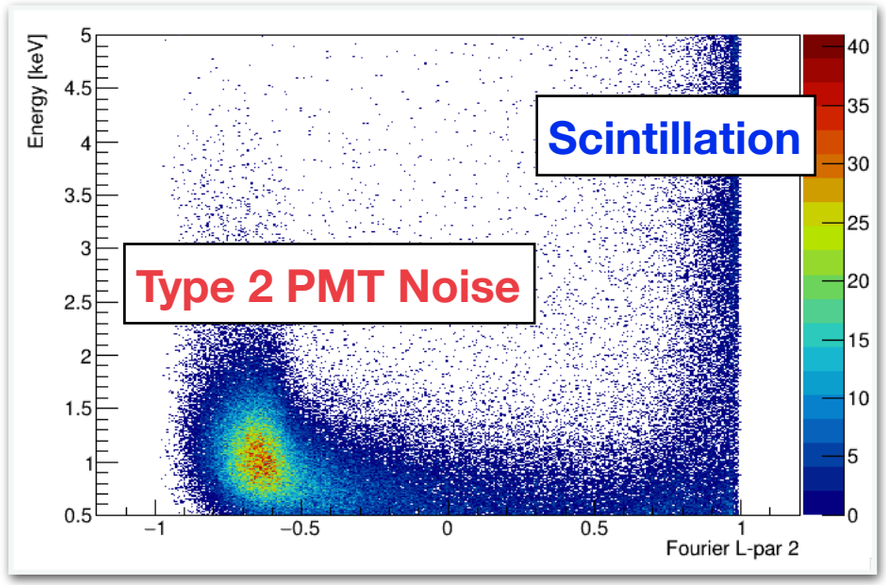
Waveform example of COSINE-100 data

FFT



Fourier transformed waveform

Preliminary



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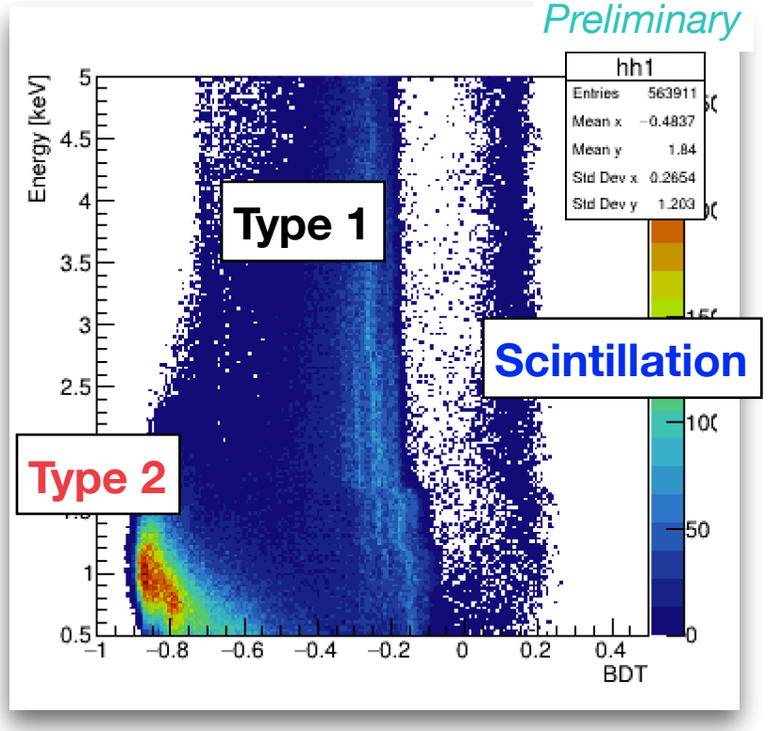
  - New type noise (type-2) cannot discriminated below 1 keV.
  - Adding a newly developed parameter based on FFT

Preliminary



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- Below 1 keV?
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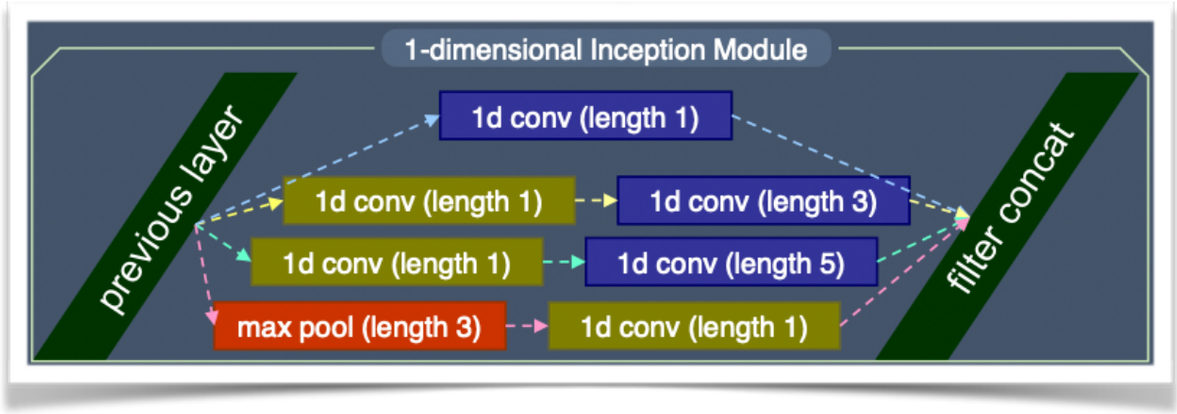
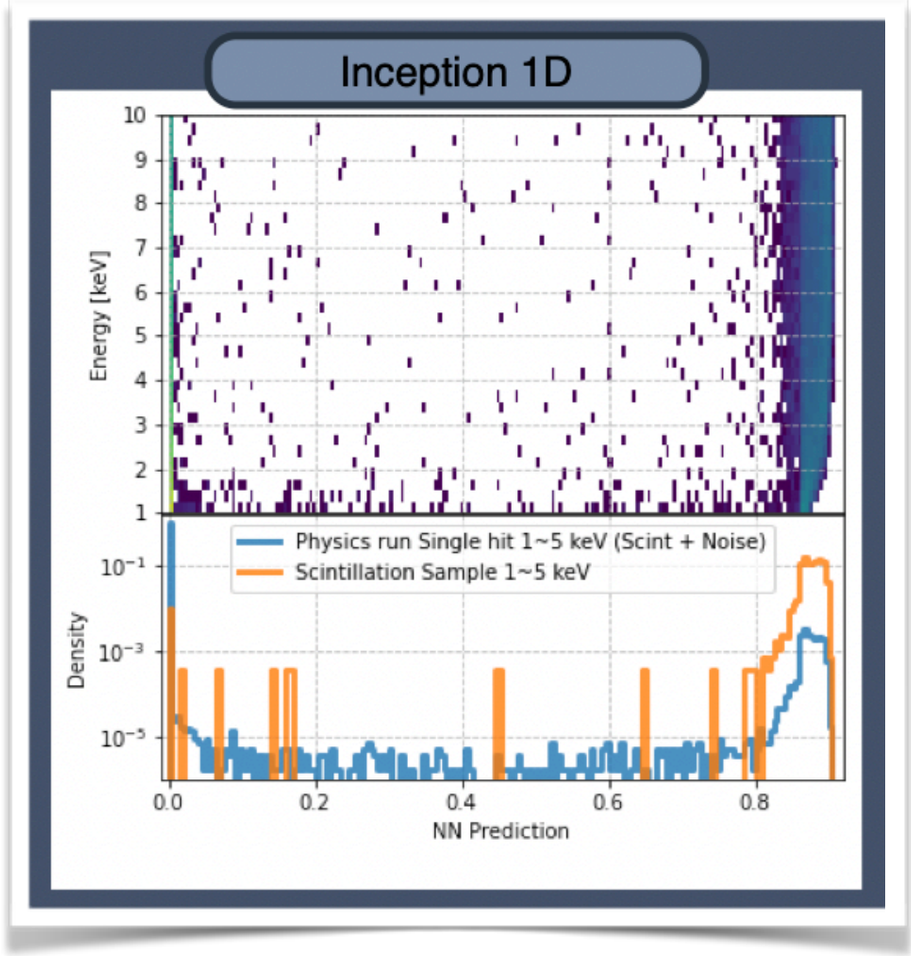
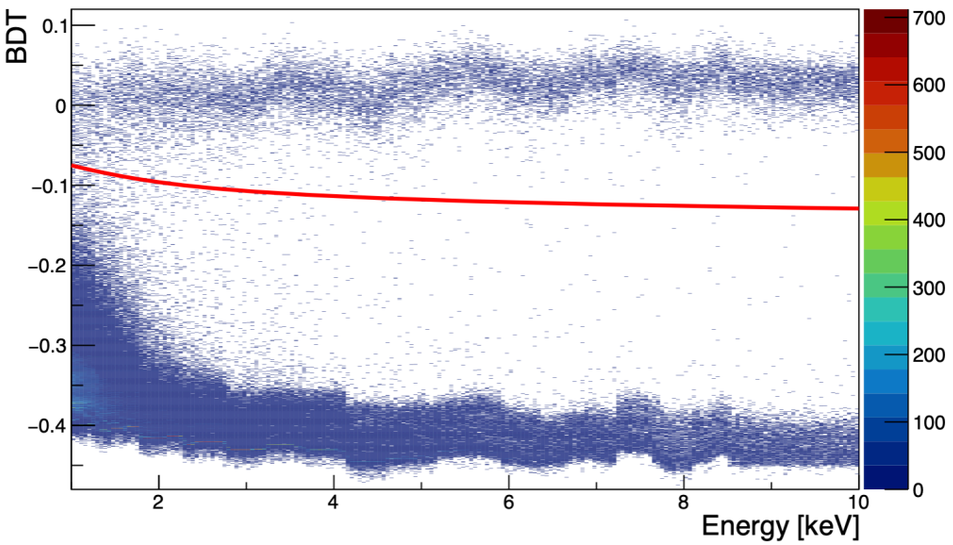
  - Study on deep learning is also ongoing.

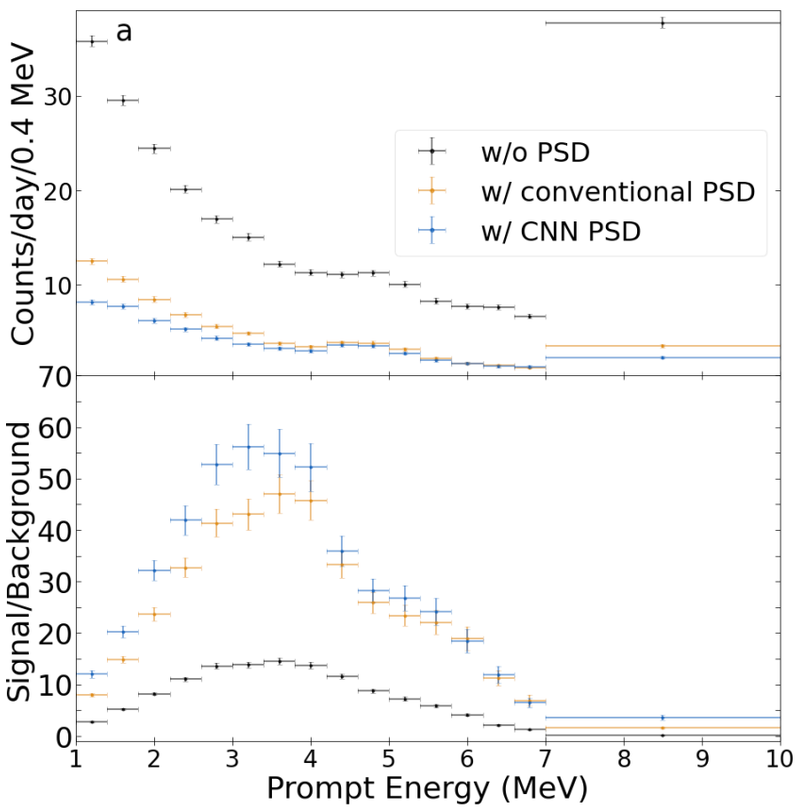




Summary

- NEOS
  - Identification of e^- and p^+ recoil events using CNN
  - CNN has improved PSD performance, especially in the low-energy domain.
- COSINE-100
  - Separating scintillation signals from PMT-noise events using BDT
  - 1-keV threshold achieved thanks to BDT
  - Studies are underway to lower the threshold below 1 keV.





Thank You for Your Attention !!!

Backup