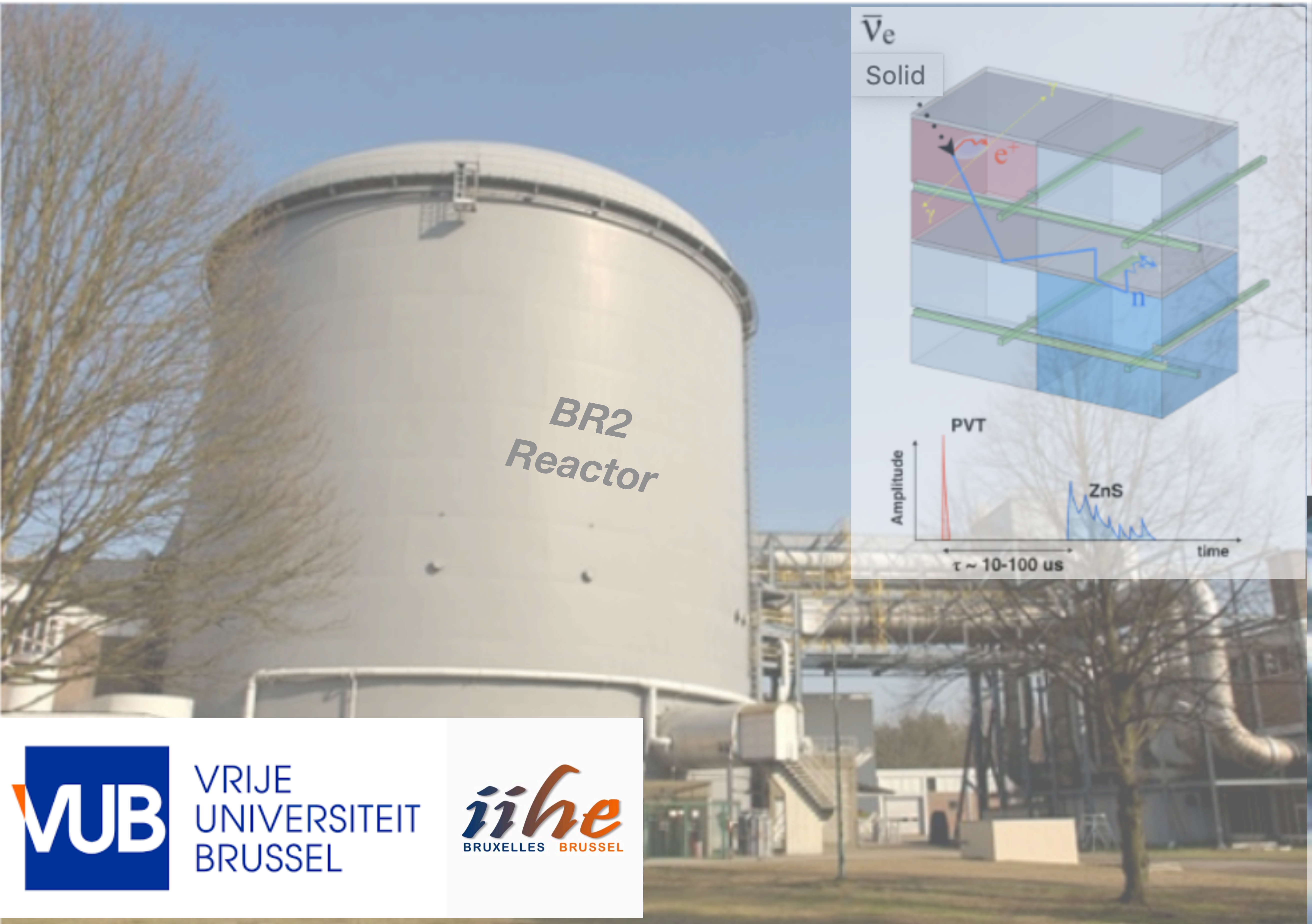
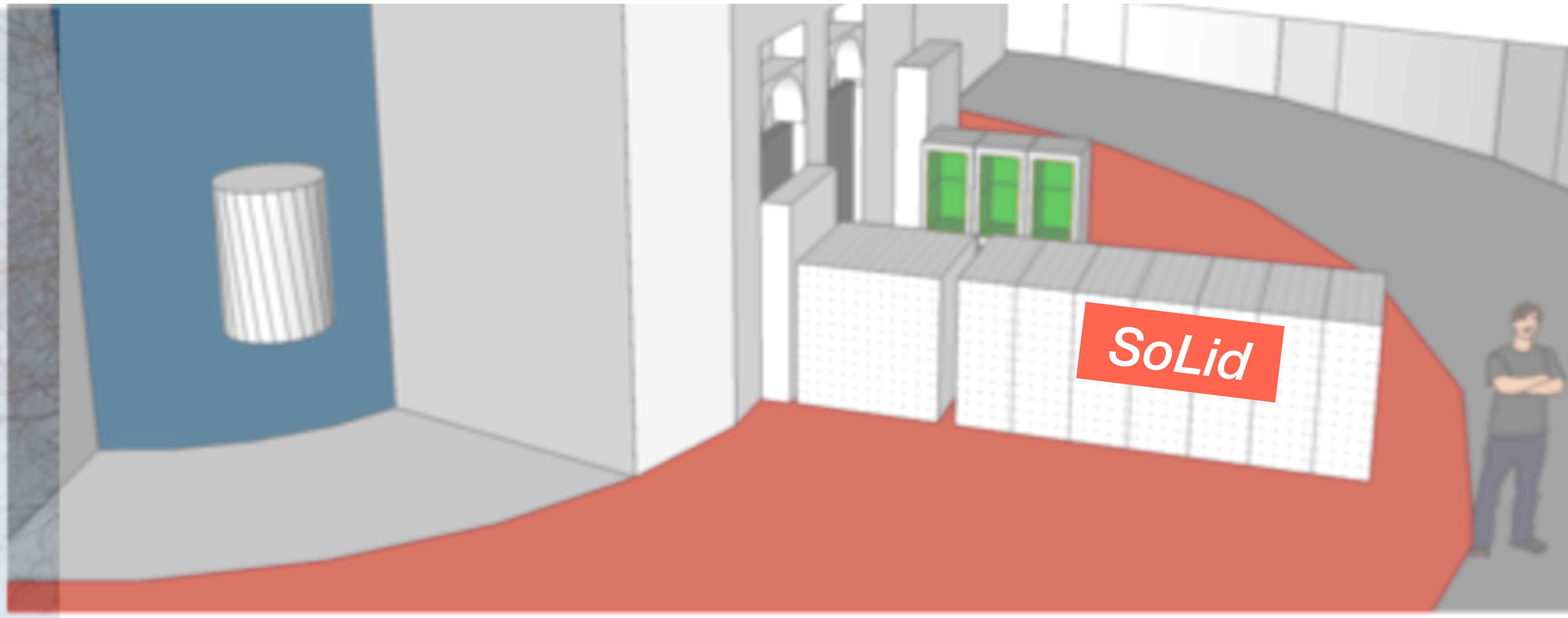
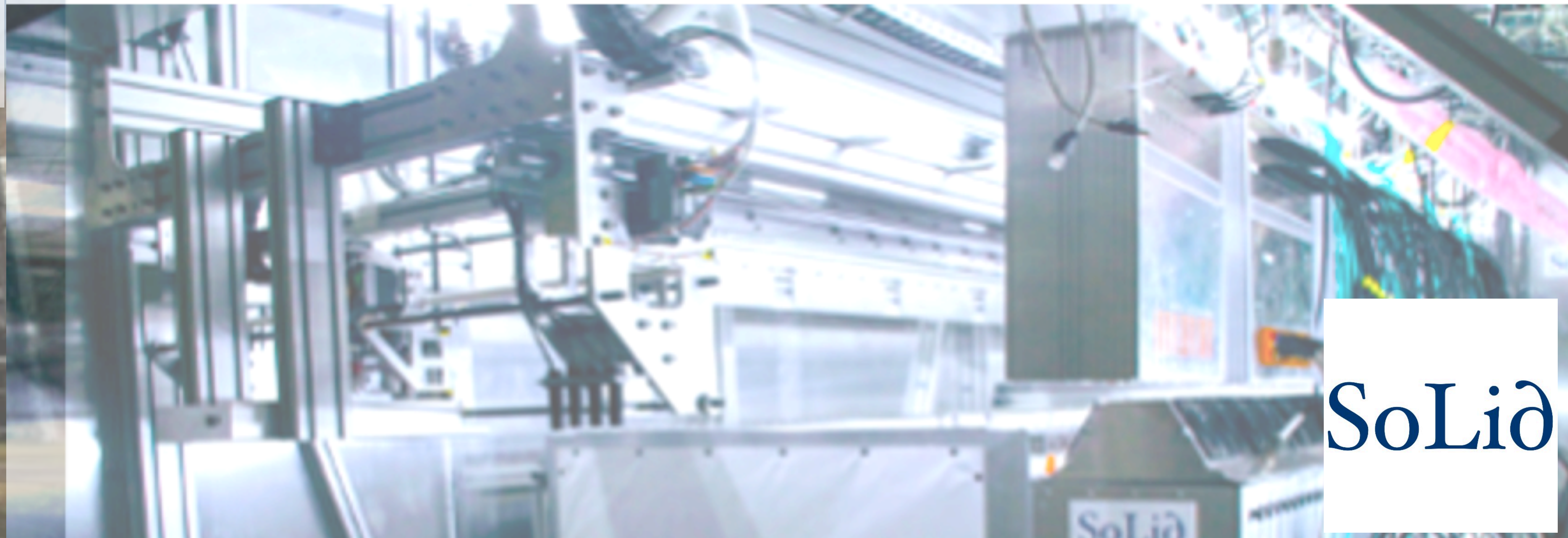
Neutrino Searches @ SoLid Experiment

Rijeesh KELOTH | 23 November 2021 | IIHE/HEP@VUB Colloquium







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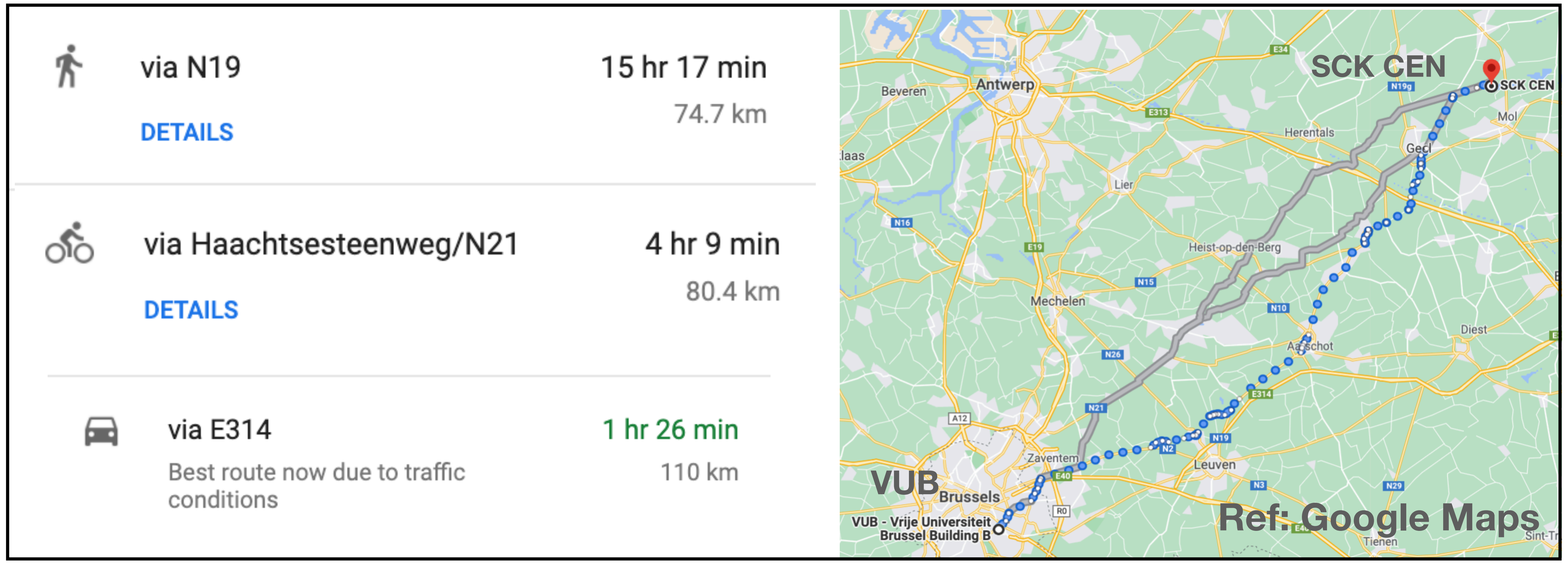
SoLid

Introduction

- **Search** for **oscillations** with **Lithium-6 detector** (**SoLid**) is located in **BR2** nuclear reactor of the SCK· CEN @ Mol
- SCK· CEN is the Belgian National Nuclear Lab with ~1000 employees

Collaborators from IIHE/VUB:

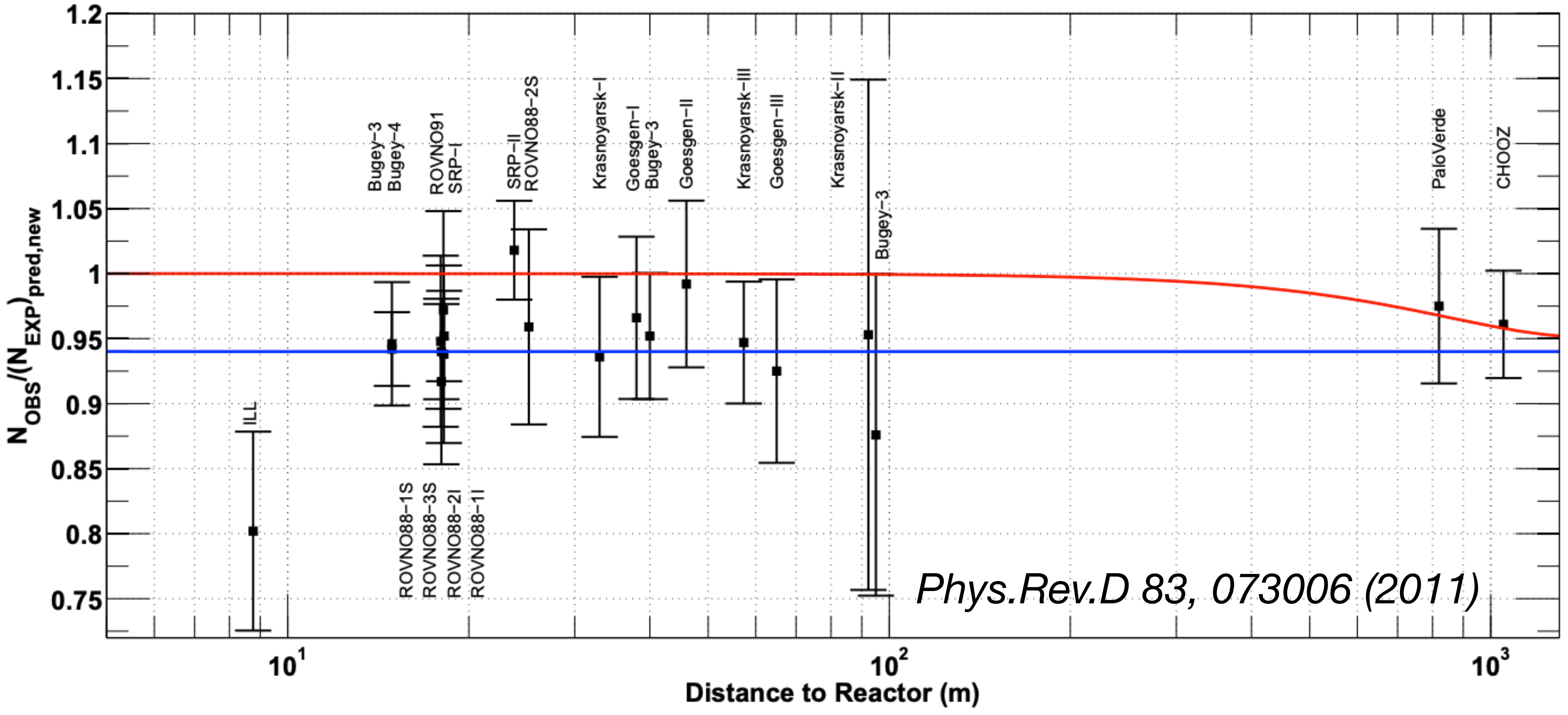
- Jorgen D'Hondt (Supervisor)
- Rijeesh Keloth (Post-doc)



- **The primary goal:**
  - precisely measure the electron antineutrino energy spectrum and flux.
  - search for very short distance neutrino oscillations as a probe of eV-scale sterile neutrinos.

Experiment Goals

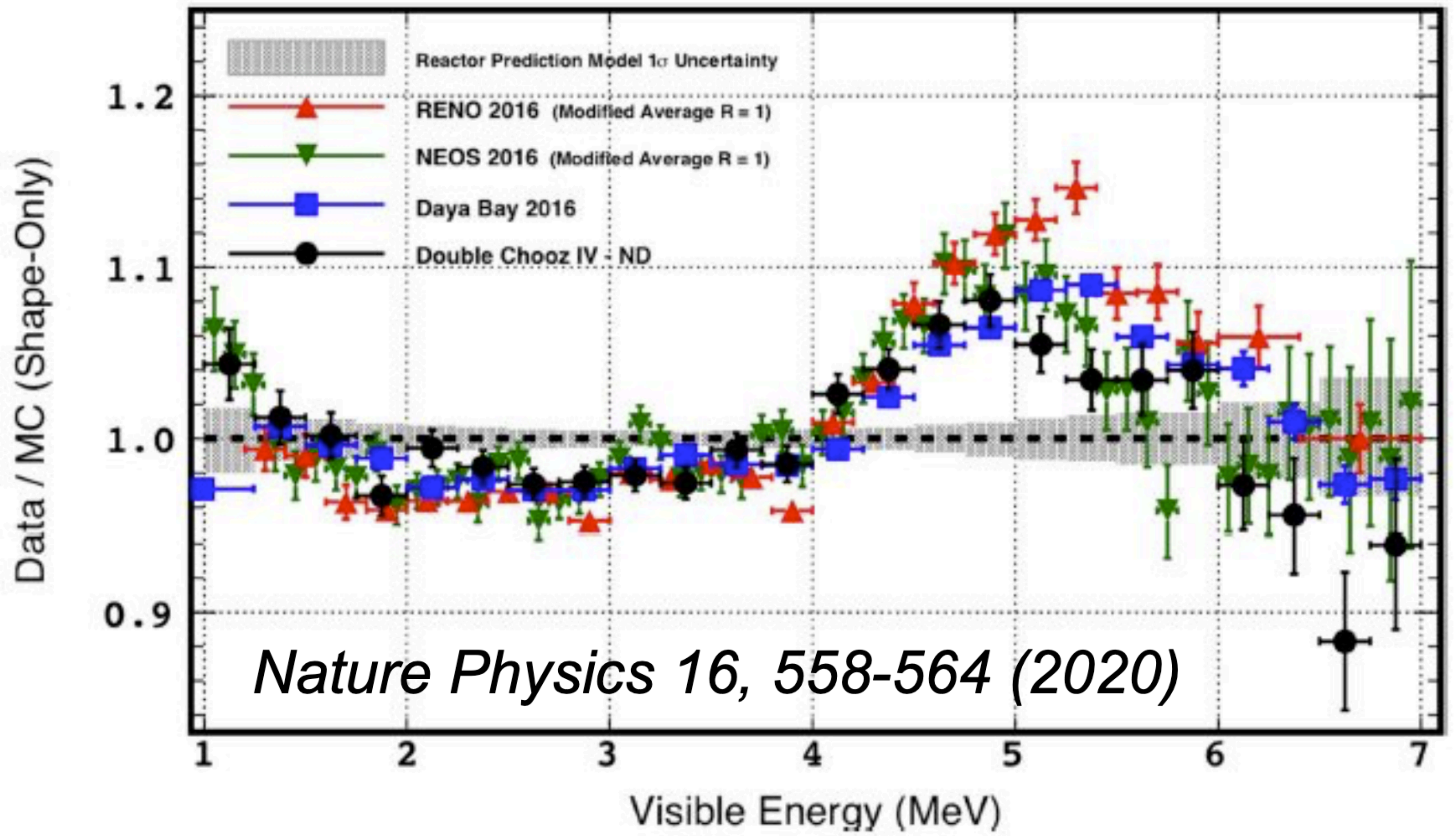
- Probe the reactor anomaly (RAA)



Phys.Rev.D 83, 073006 (2011)

$$P_{ee} = 1 - \cos^4\theta_{\text{new}} \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E_{\bar{\nu}_e}}\right) - \sin^2(2\theta_{\text{new}}) \sin^2\left(\frac{\Delta m^2_{\text{new}} L}{4E_{\bar{\nu}_e}}\right).$$

- Measure precisely the U-235 antineutrino spectrum



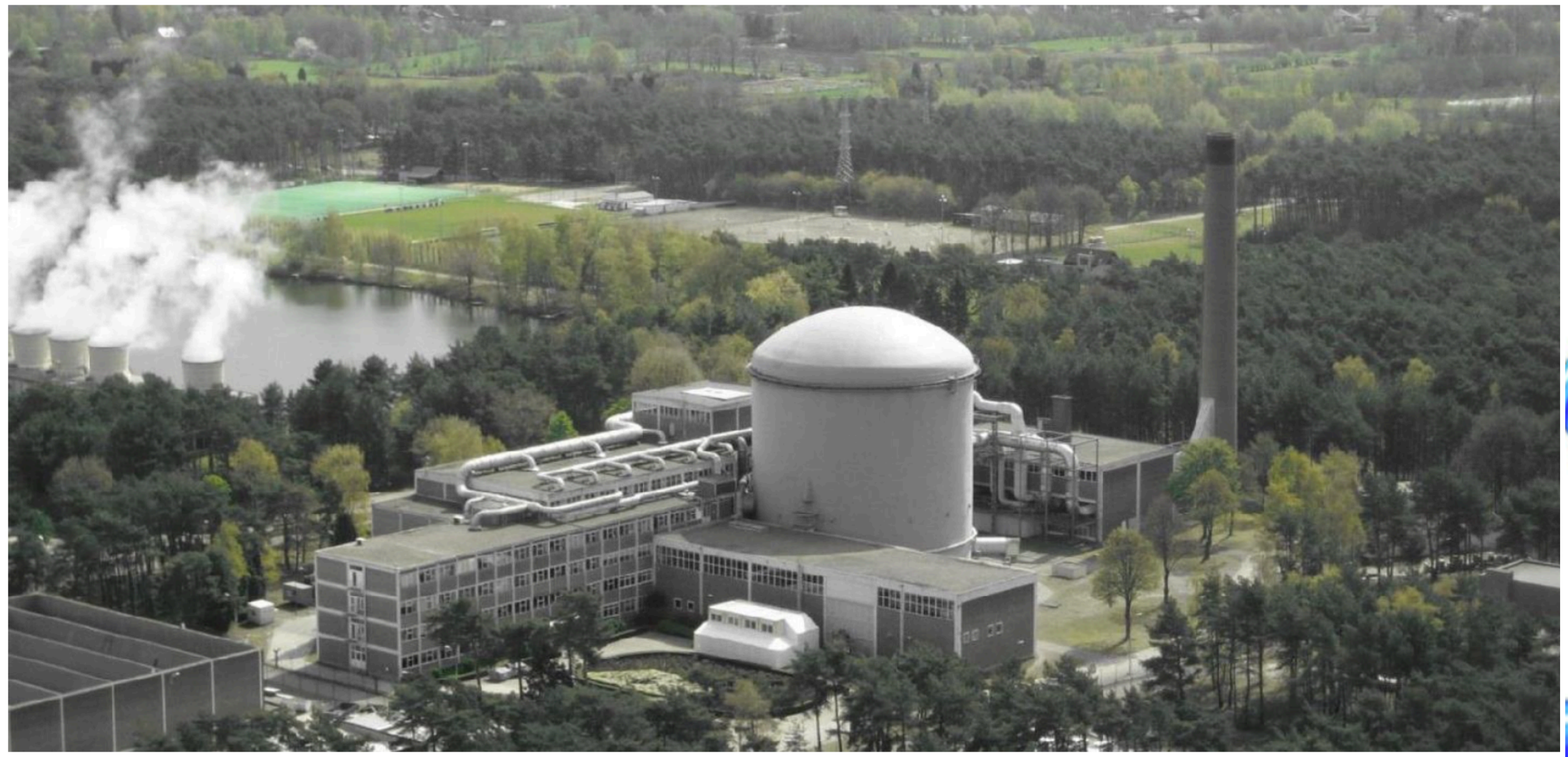
Nature Physics 16, 558-564 (2020)

- Unexpected bump at ~5 MeV reported by antineutrino experiments at power (LEU) reactors (**^{235}U**, ^{239}Pu, ^{241}Pu and ^{238}U isotopes).
- Recent indication from short-baseline liquid scintillator experiments at **^{235}U** research (HEU) reactors. arXiv:2107.03371 [nucl-ex]

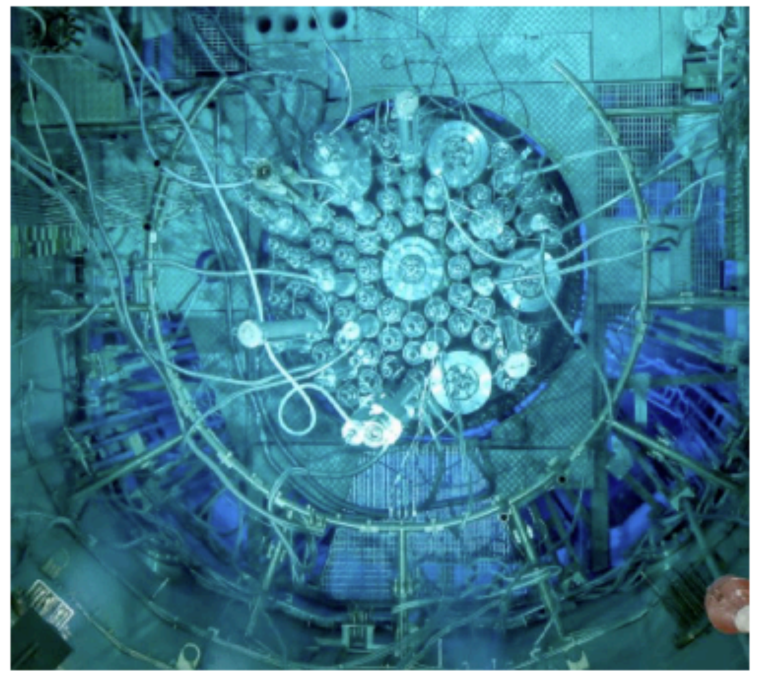
BR2 Reactor

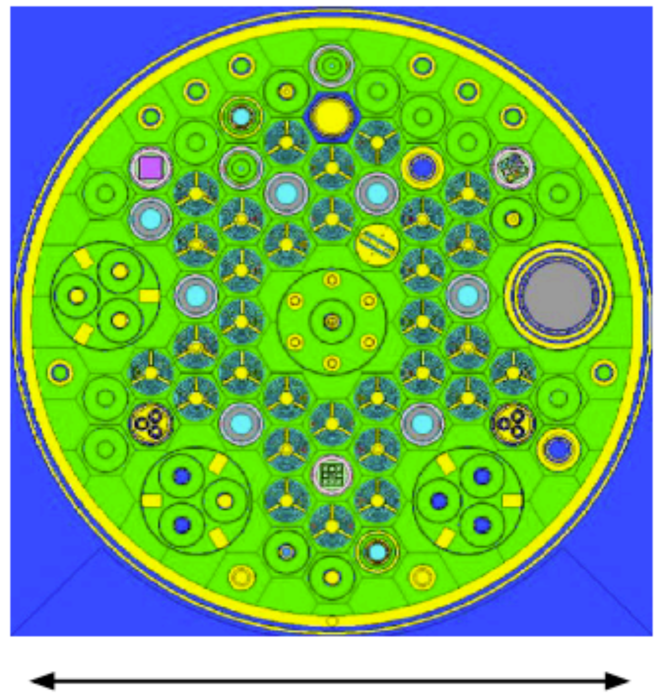
- Compact core (50 cm effective diameter)
- Highly enriched ^{235}U (> 93.5%) nuclear fuel
- Variable operating power (45-80 MW) for an average of 6 cycles per year (140 days)
- Low-level reactor background (gamma, neutron)

- Reactor off period data is essential for better understanding of other backgrounds as well
- Detector calibration is performed in R-off period using calibration sources like Na-22, AmBe etc.

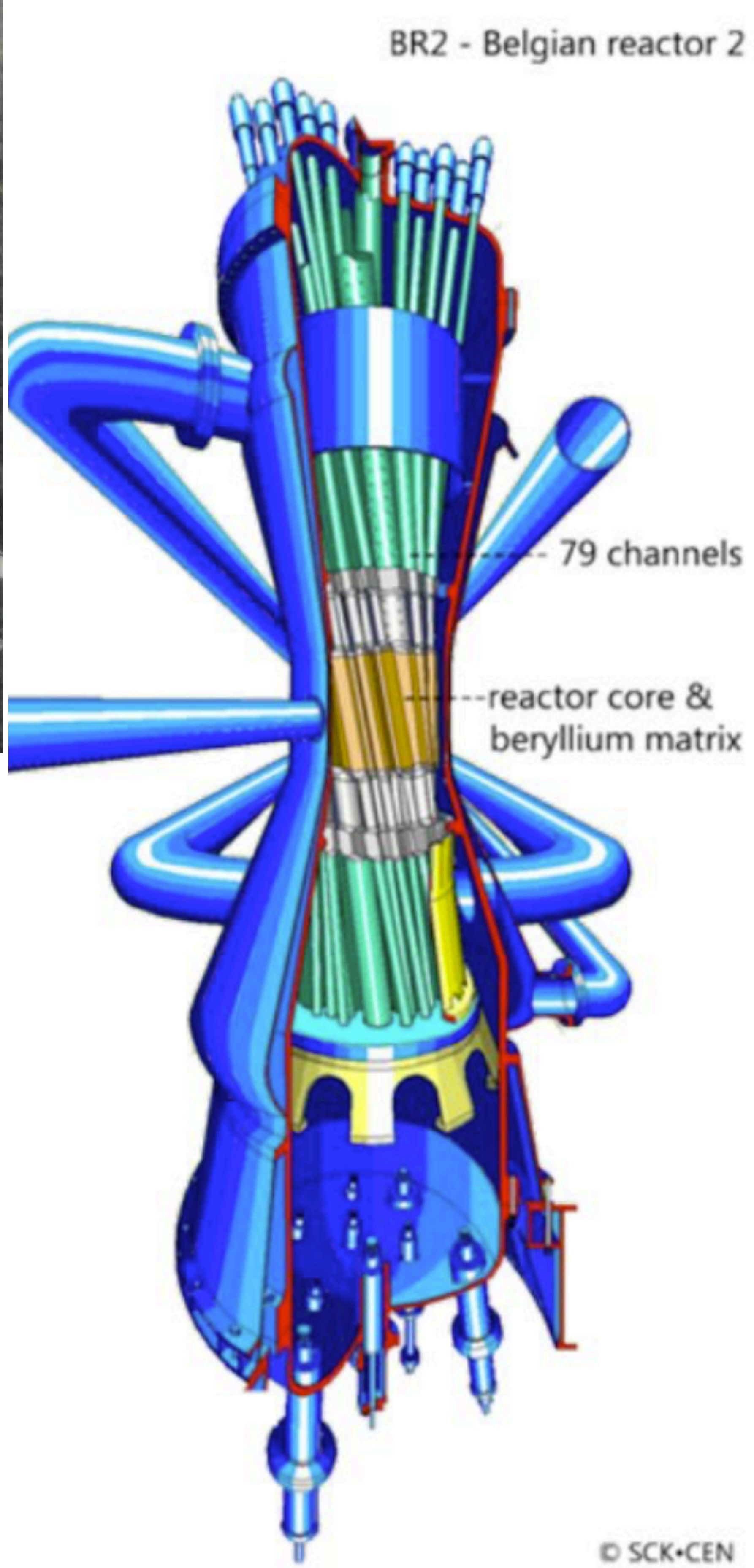


SCK CEN BR2 research reactor at Mol, Belgium





~ 1.1 m



Antineutrino Detection Principle

- **Inverse beta decay** (IBD) interaction of electron antineutrinos detected using combination of two scintillators:

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

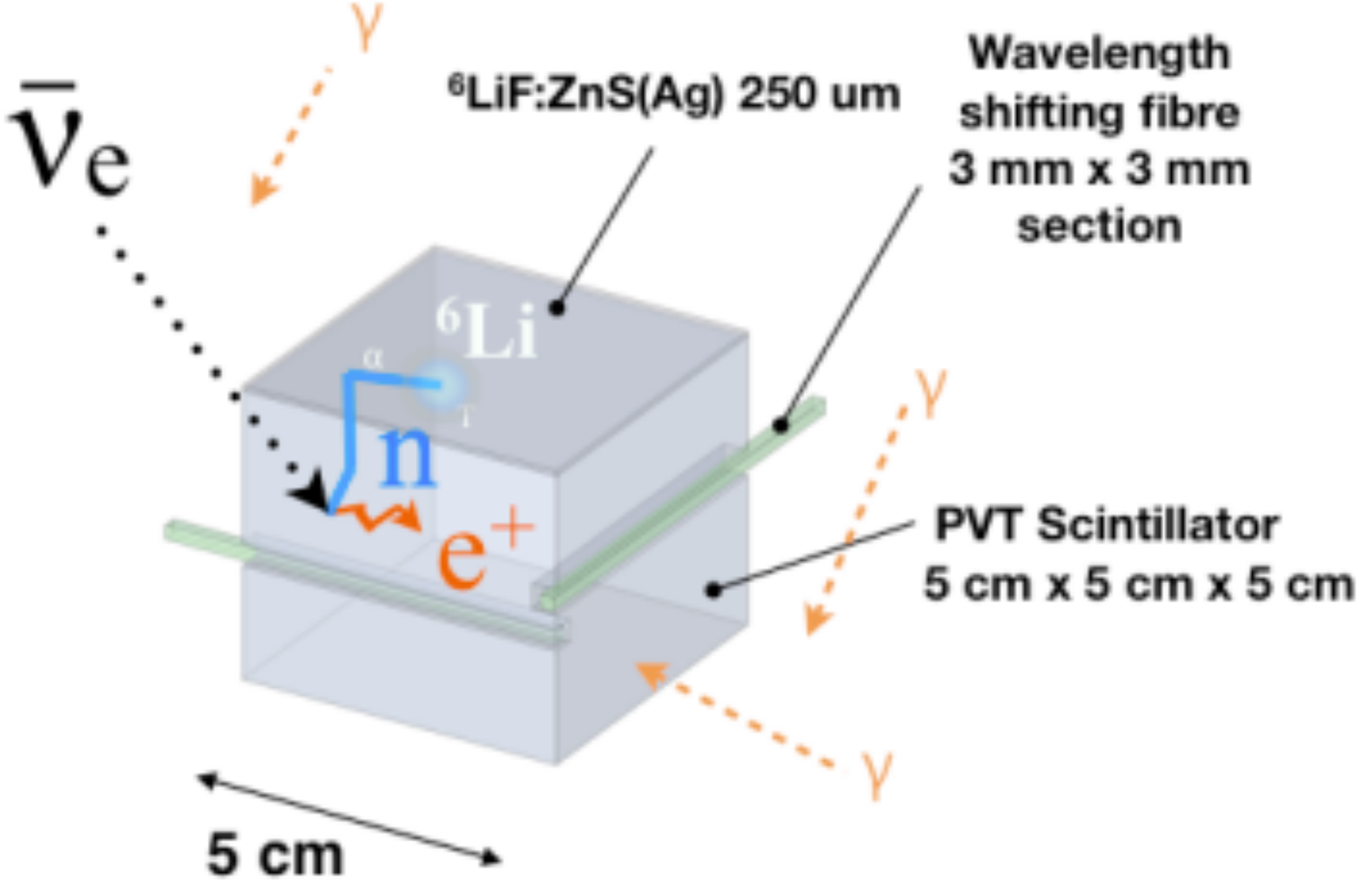
PVT cube (5 cm) for prompt signal: ES (electromagnetic scintillation)

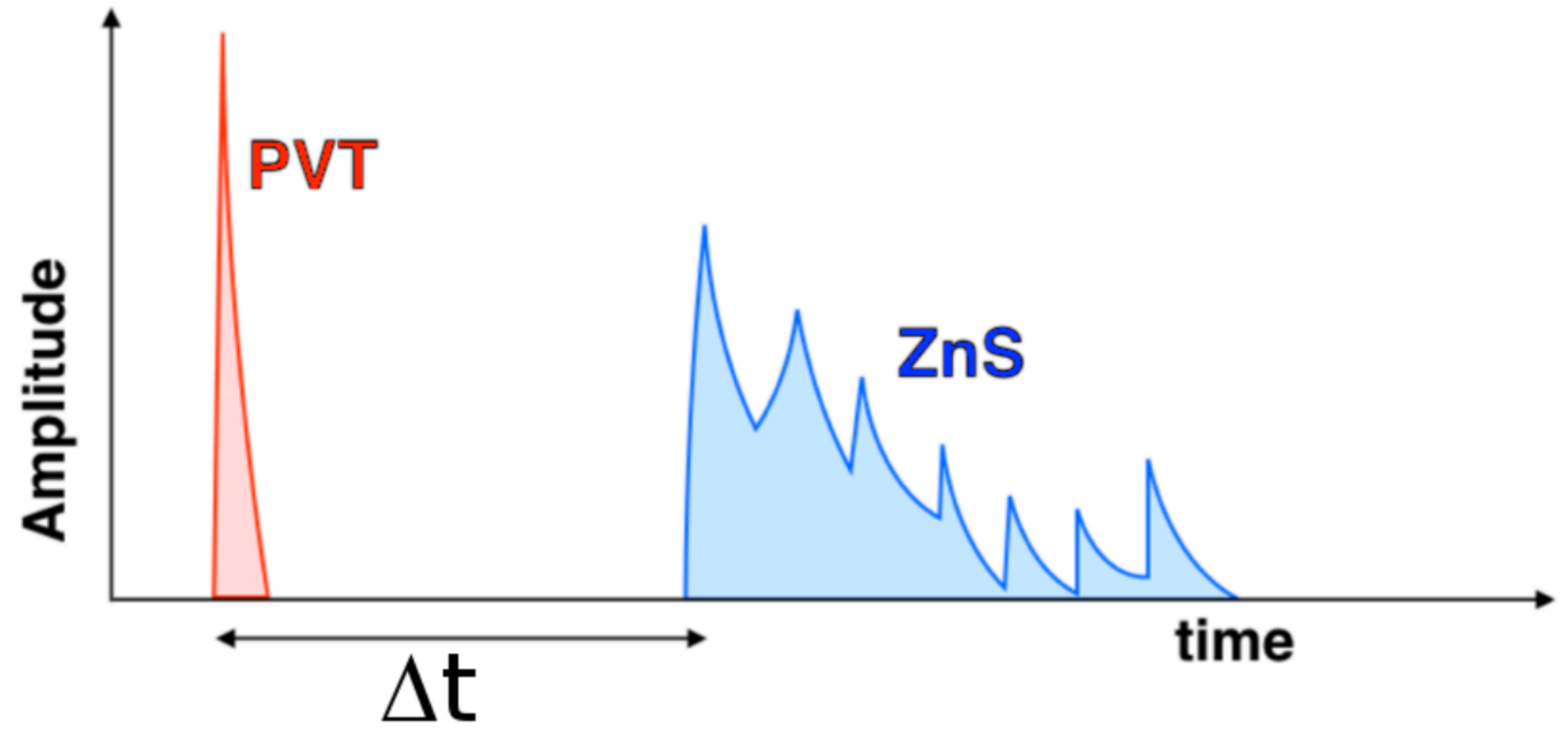
- Energy deposit by positron carrying the antineutrino energy
- 2 annihilation gammas (511 keV) are emitted

^{6}LiF:ZnS(Ag) sheets for delayed signal: NS (nuclear scintillation)

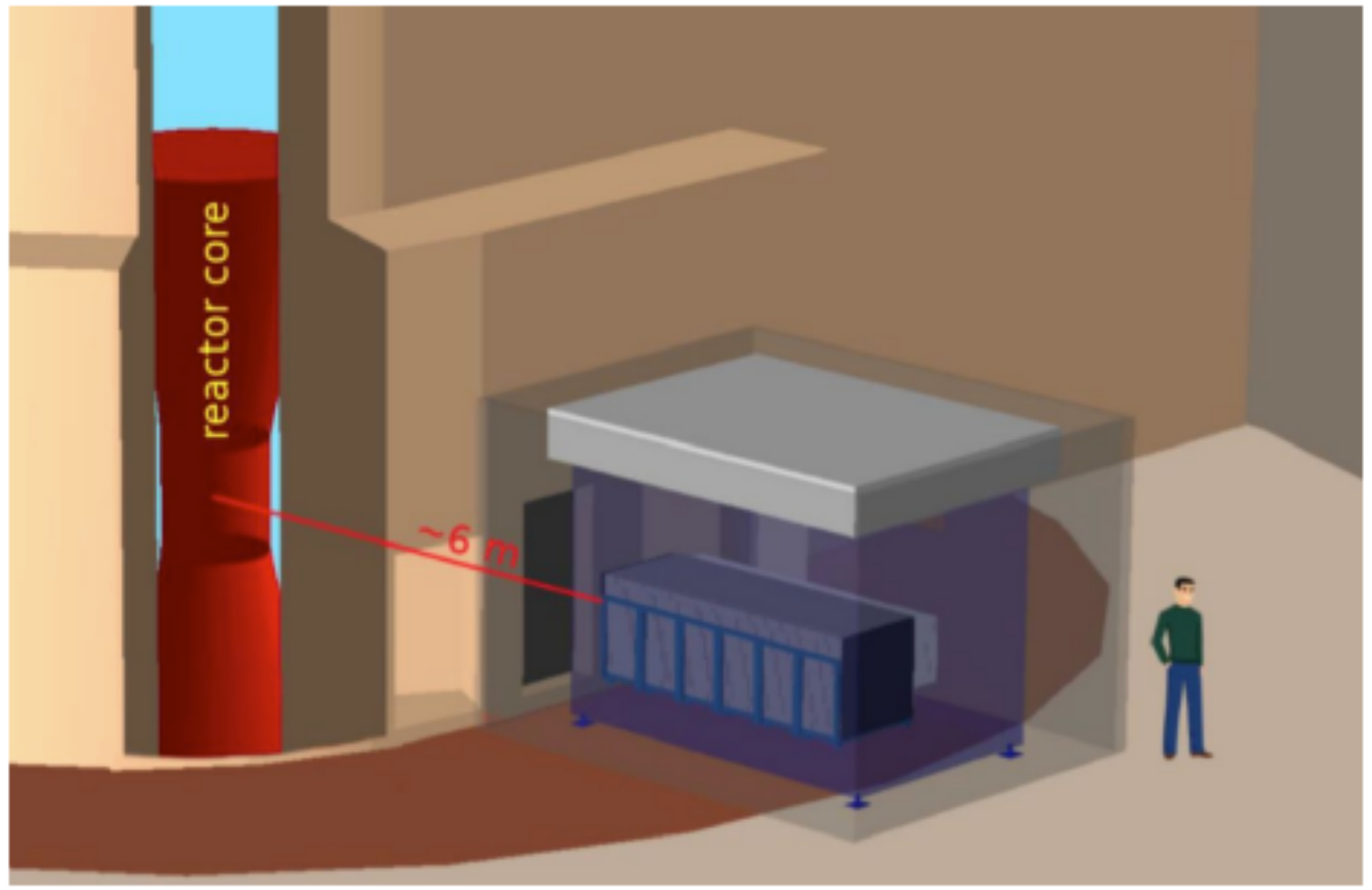
- Sheets cover two faces of each cube
- A thermal neutron is captured ~64 μs after the prompt signal

Use the **delayed coincidence** between ES and NS signals to tag IBD interactions

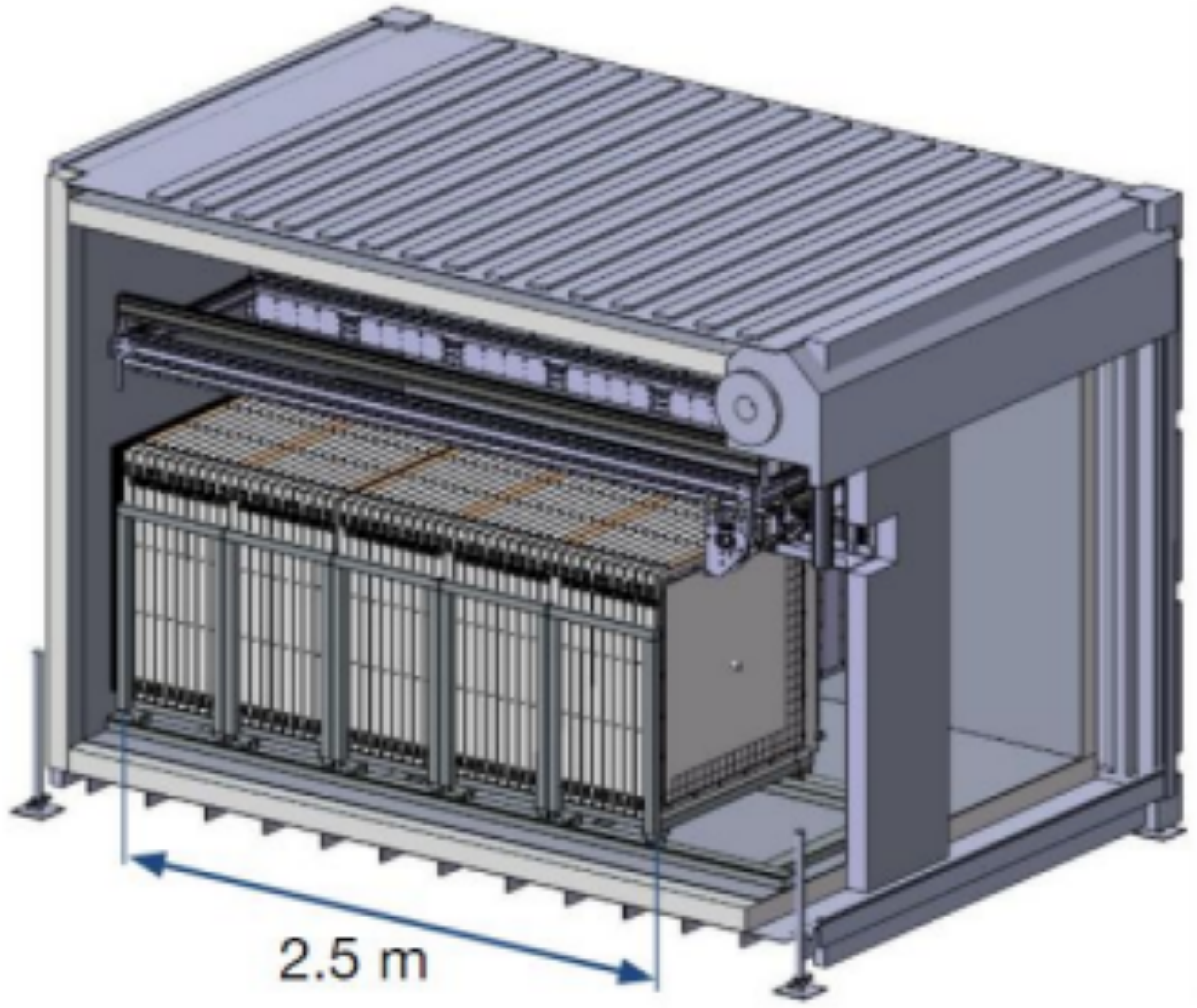




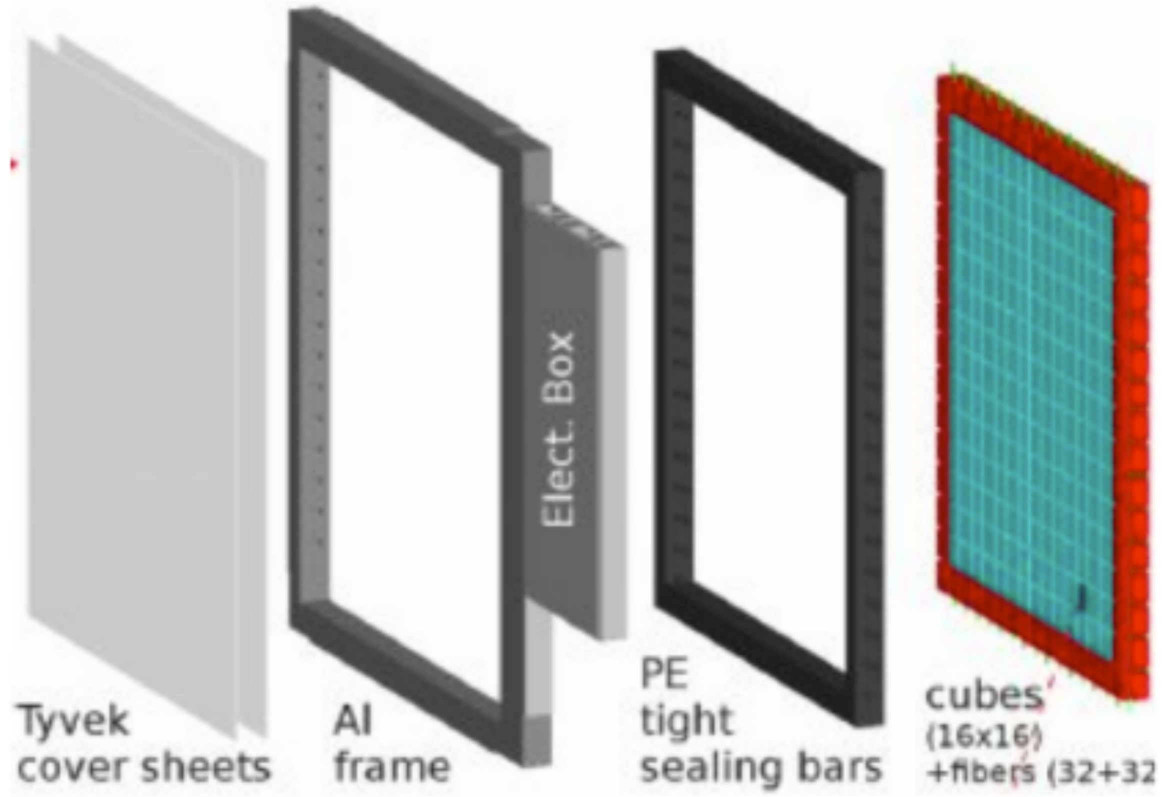
SoLid Detector Layout and Design



SoLi∂ detector model

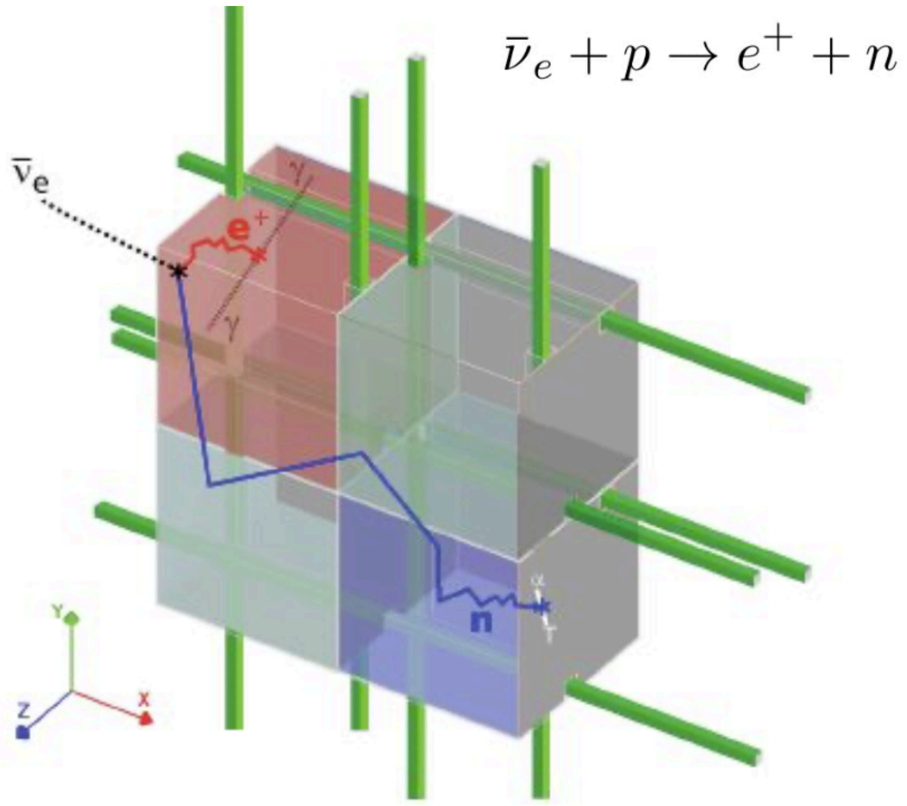


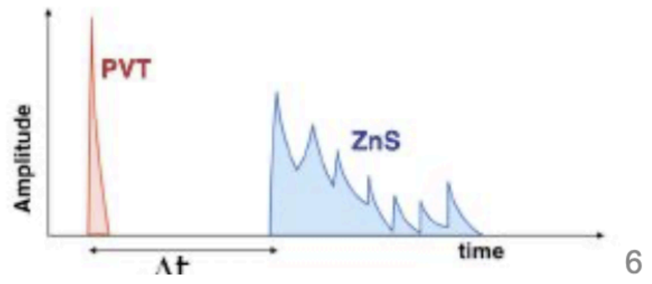
SoLi∂ container



Split view of a layer

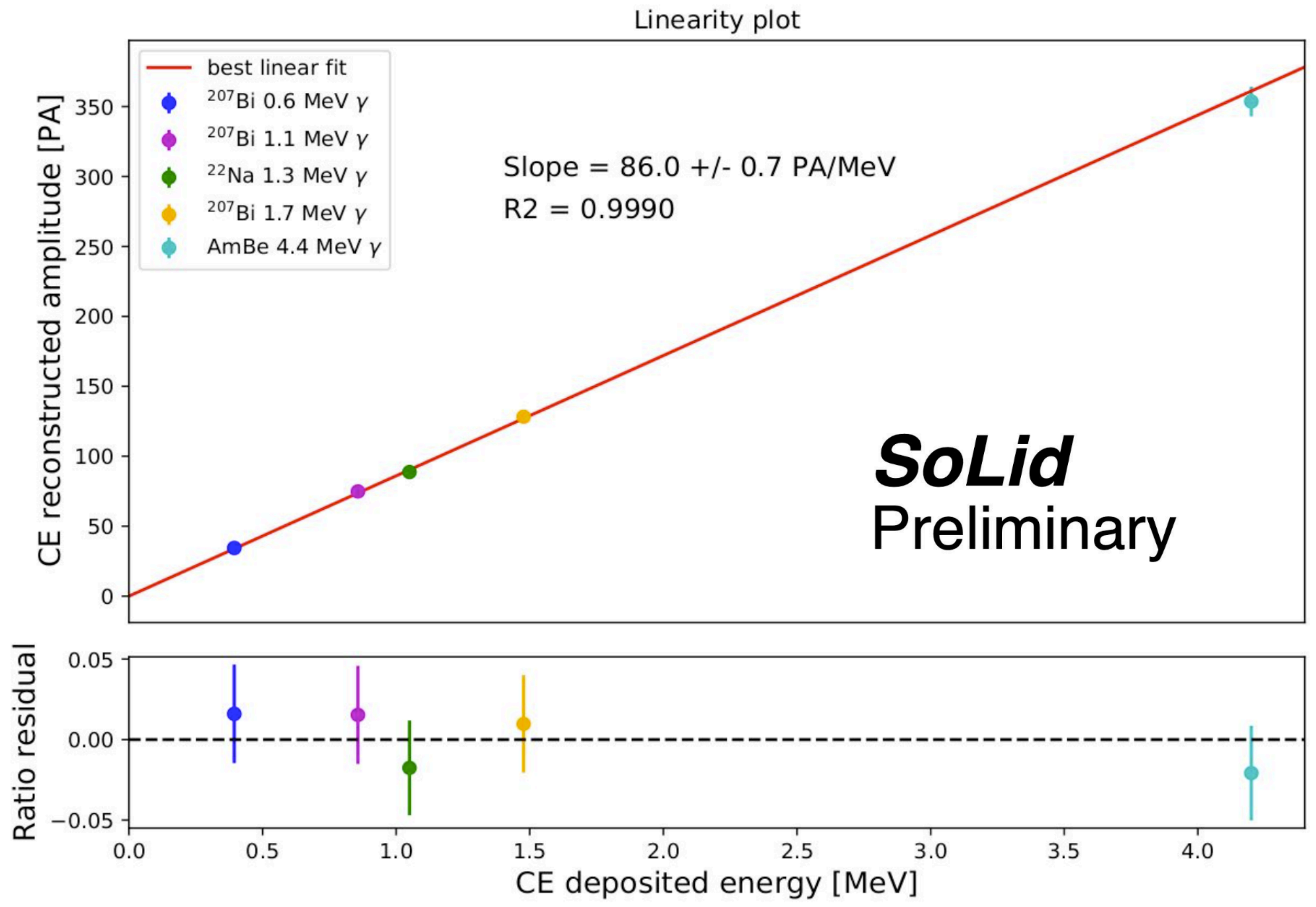
- ~6 m from reactor core, 2.5 m long
- 12,800 (5 cm x 5cm x 5cm) PVT cubes (1.6 ton fiducial volume)
- **3,200** readout channels
- Wavelength shifting fibers (WLS) in X-Y directions
- Signals detected by Multi-Pixel Photon Counter (MPPC)s (Silicon Photomultipliers)





SoLid Technology

- Plastic scintillator (ELJEN EJ-200) provides alternative technology for antineutrino measurement
- Very good **linearity** of response



- Highly segmented detector allows direct access to the positron energy and identification of annihilation gammas
- Event topologies allow classification of signal and background

Challenges

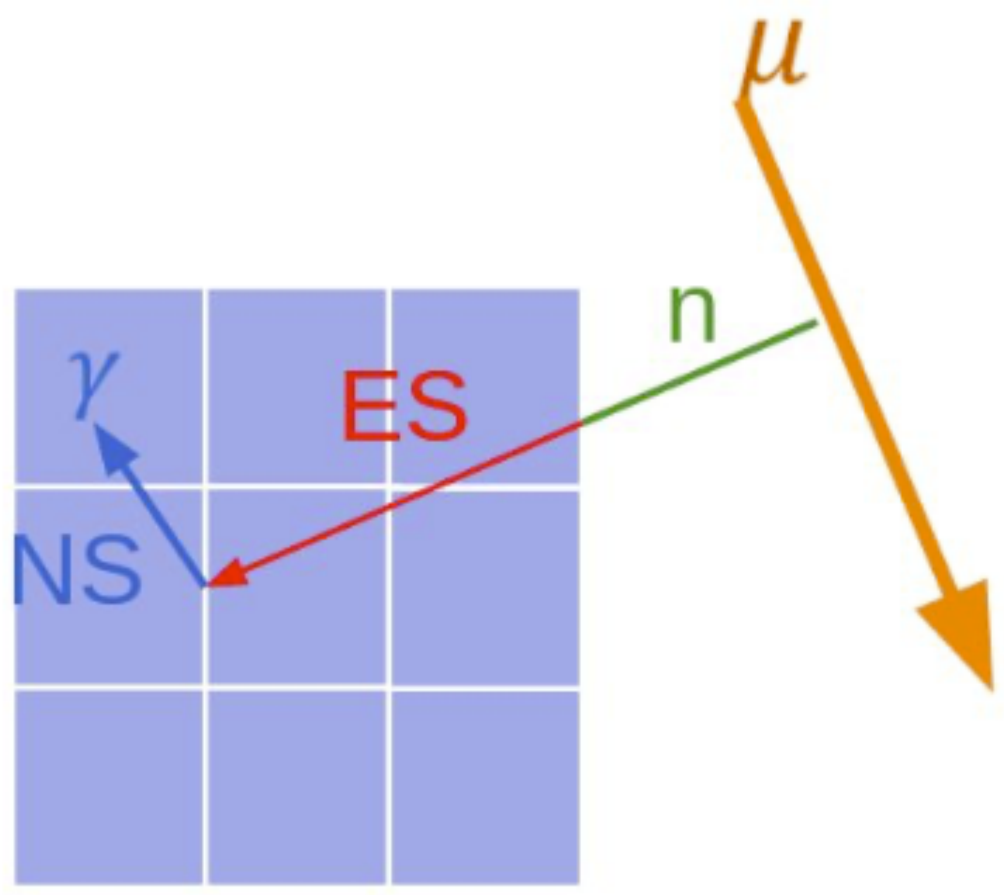
- No direct gamma-neutron PSD
- Reduction of high backgrounds requires multivariate ML techniques
- Need detailed understanding of complex detector
- Large number of readout channels and parameters to calibrate

Background Sources

Background sources:

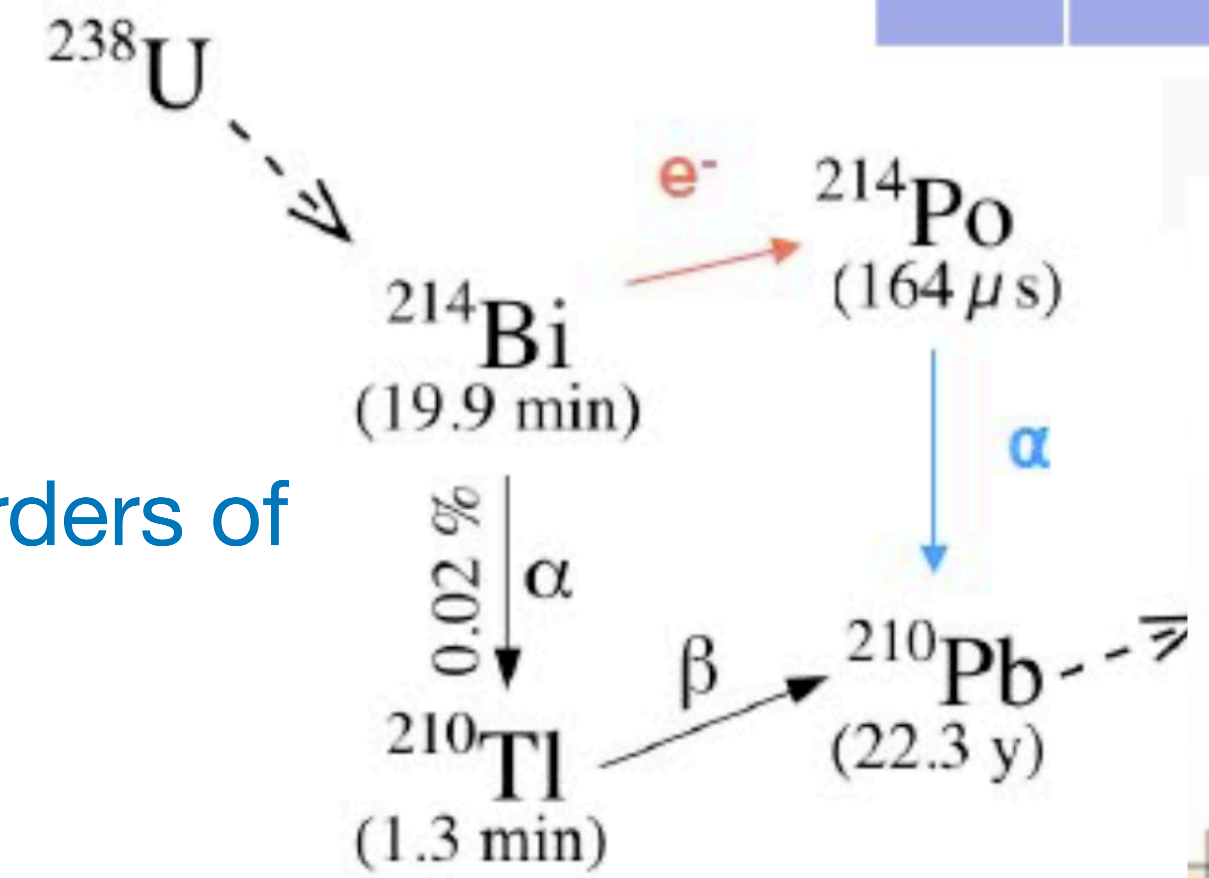
Fast neutrons (external)

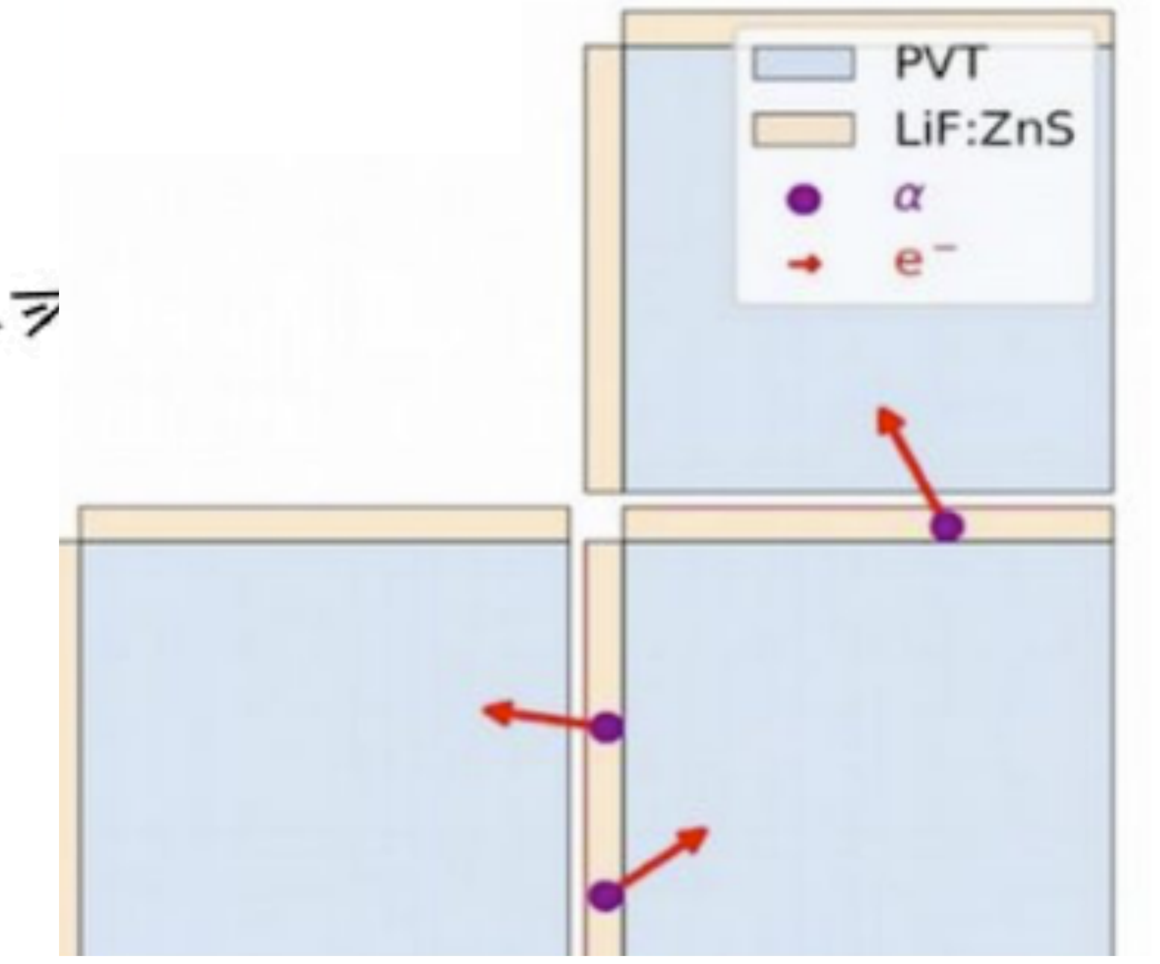
- Fast neutrons induced by cosmic-ray shower & spallation
- Neutron recoil events: Electromagnetic scintillation (ES)
- Neutron capture: Nuclear scintillation (NS)



BiPo (internal)

- Derived from ^{238}U/^{230}Th series • ^{214}Bi decay (e-, γ): ES
- ^{214}Po decay (α): NS
- Unexpectedly high contaminant in LiF:ZnS(Ag) sheets • ~2 orders of magnitude above IBDs before selection



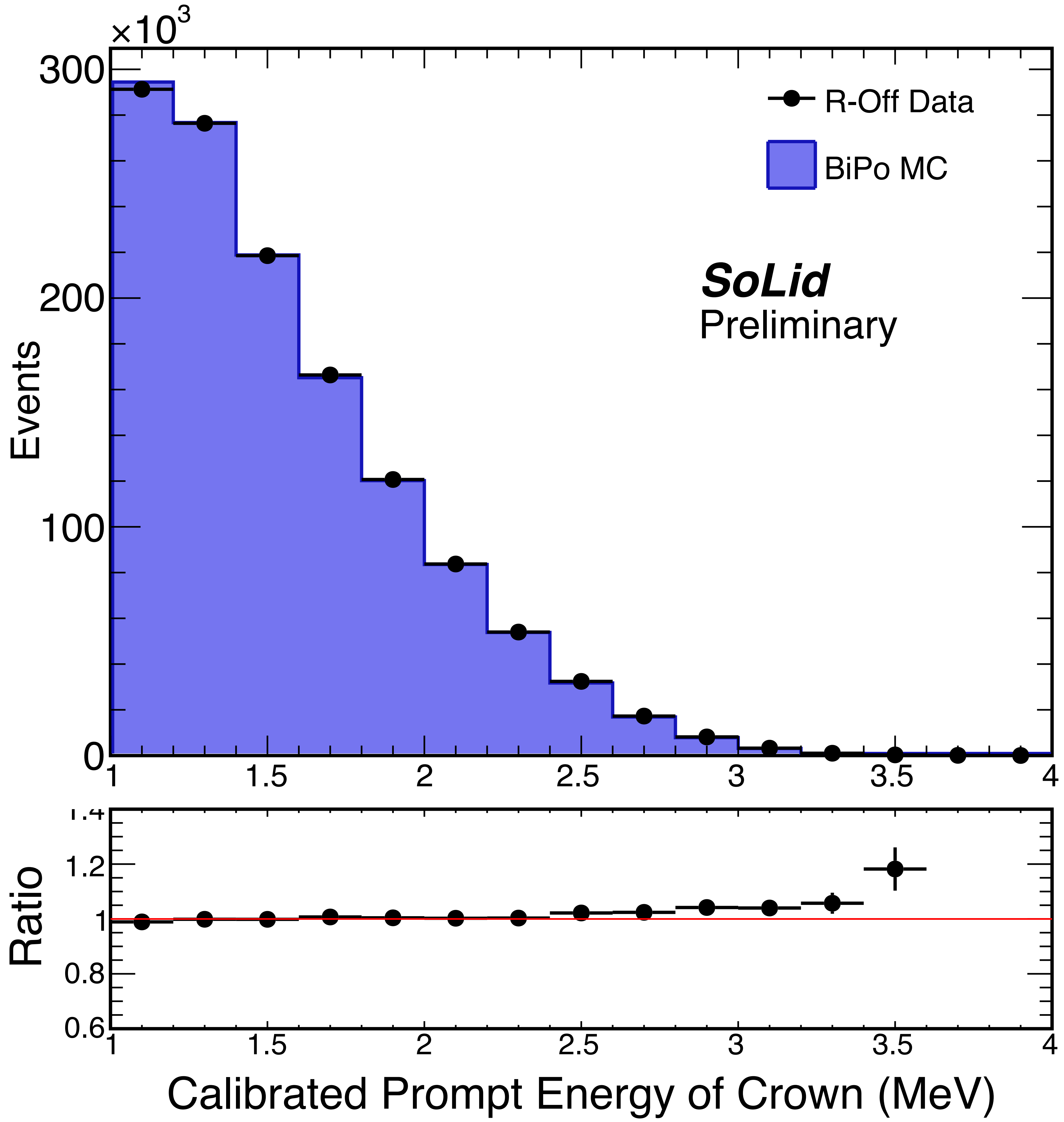


Accidental (external)

- Gamma rays from ^{41}Ar decay (reactor)
- Radon emanation from the building

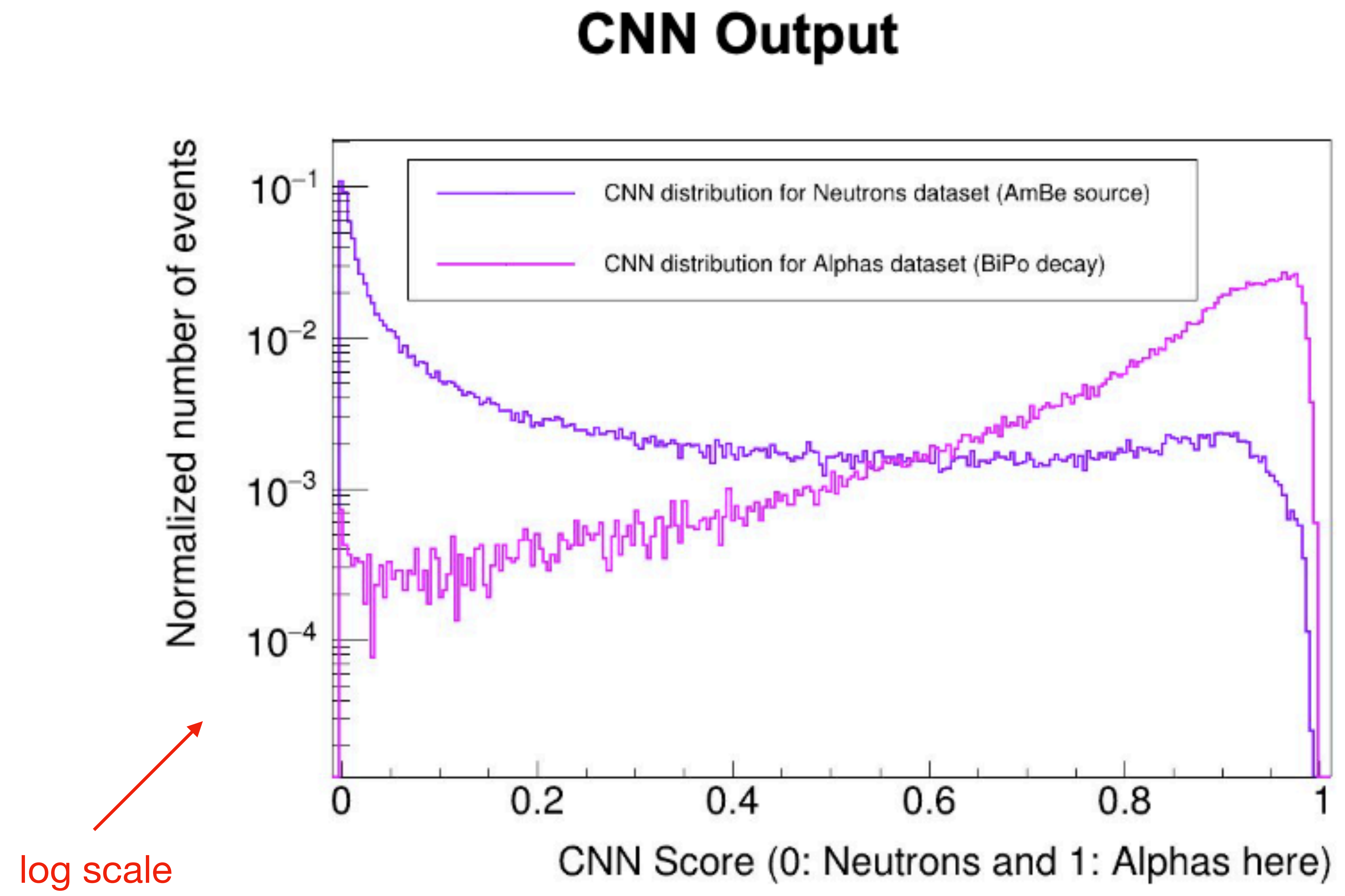
BiPo for Detector Response Model

- Utilize BiPo background to verify the detector response model.
- Select a high-purity BiPo sample close to the signal region.
- ~187 days of Phase-I reactor-off data used for comparison with MC simulation.
- Very good data-MC agreement ⇒ prompt energy at the percent-level up to ~3 MeV
- **Probes simulation's ability to describe complex topologies**
- **Systematic uncertainties** derived from disagreement between data and MC.



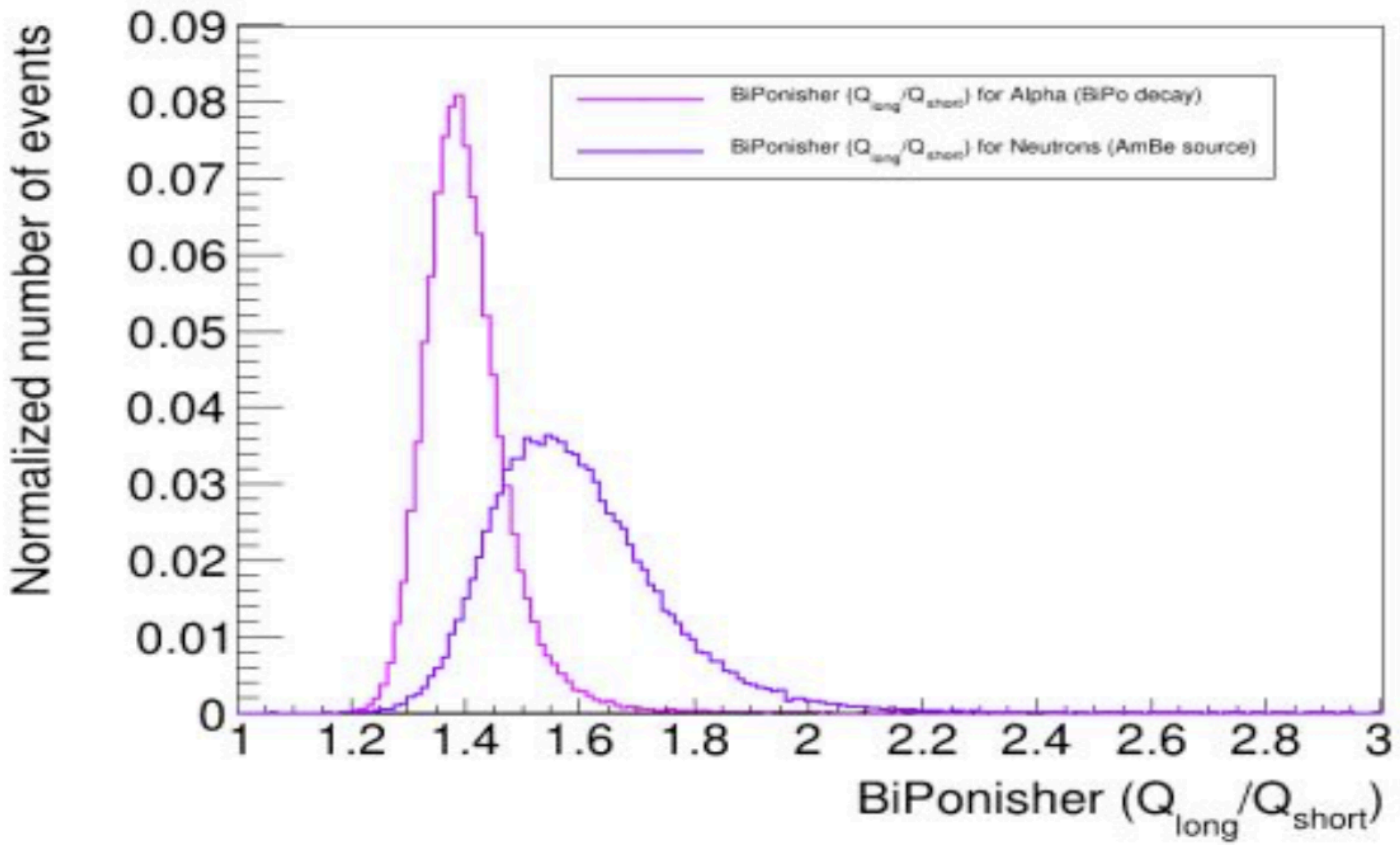
Biponator : ML Method

- Alpha / Neutron discrimination with convolutional neutral net (CNN) to reduce BiPo background.
- At 80% neutron efficiency, the CNN rejects 94% of alphas ⇒ big improvement over previous method.
- Results in an extra order of magnitude reduction in reactor-off events, after timing and spatial cuts.
- Overall reduction factor of ~85 (after energy range selection)



BiPonisher: Previous α/n discriminant

- Charge integration (CI) ratio



Event Selection for IBD Analysis

1. Pre-selection
- for signal and BiPo

2. Correlation between ES and NS

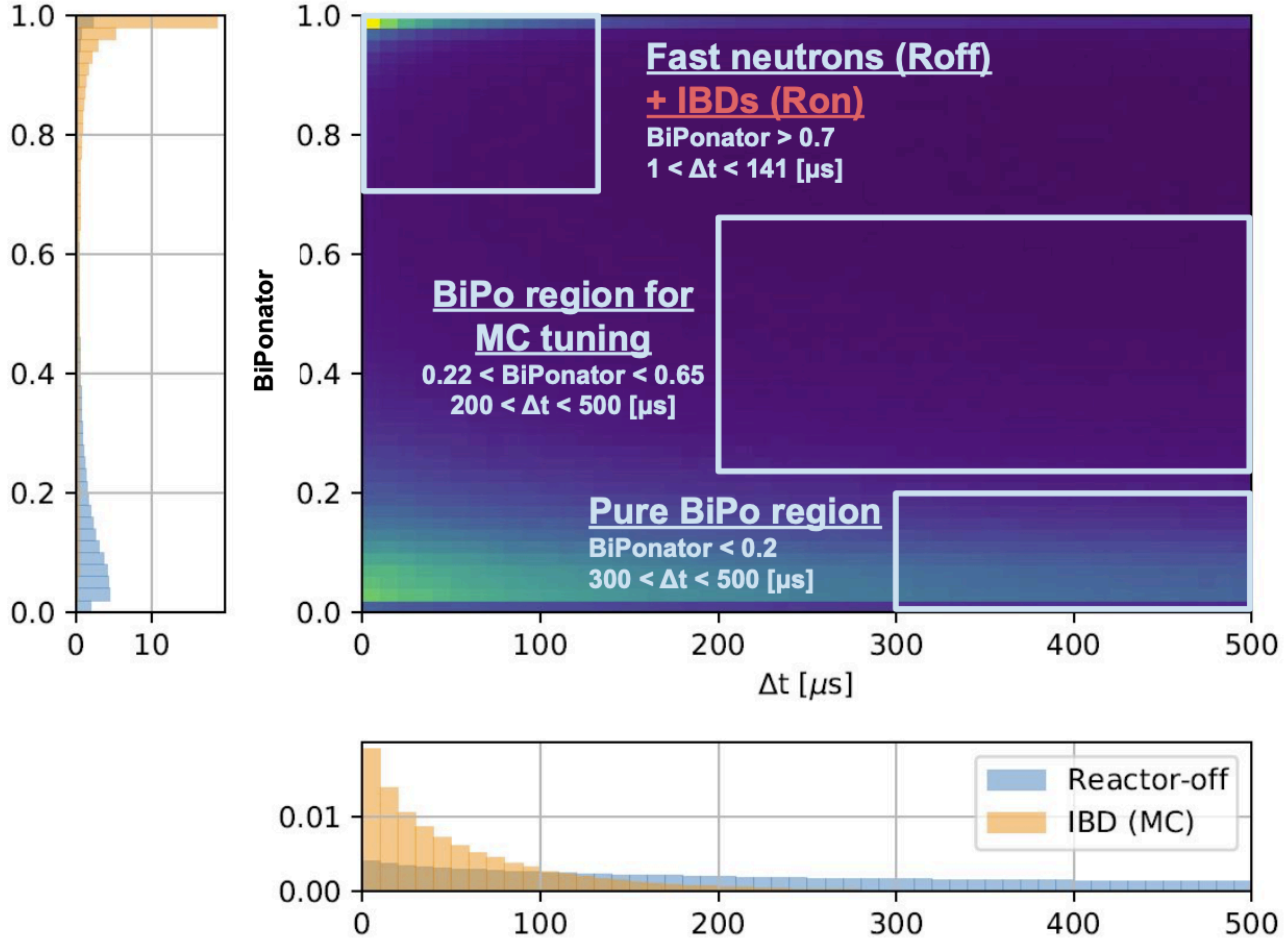
- $\Delta_{NS\text{-}ES}$X,Y : [-3, 3]
- $\Delta_{NS\text{-}ES}$Z : [-2, 3]
- $\Delta_{NS\text{-}ES}$R : [0, 4]

Spatial correlation in cube position of NS and ES

3. Energy information of ES
- Eprompt: [1.5, 7] MeV

4. Topological information
presence of the *annihilation gammas*, also very useful for event classification.

5. Subtraction of background components



Extraction of Signal Rate

- The reactor-off and reactor-on coincidence rates are the sum of several components

$$R_{\text{Reactor-on}}(t) = R_{IBD}(t) + R_{Cosmic}(t) + R_{BiPo}(t) + R_{Acc}(t)$$

$$R_{\text{Reactor-off}}(t) = R_{Cosmic}(t) + R_{BiPo}(t) + R_{Acc}(t)$$

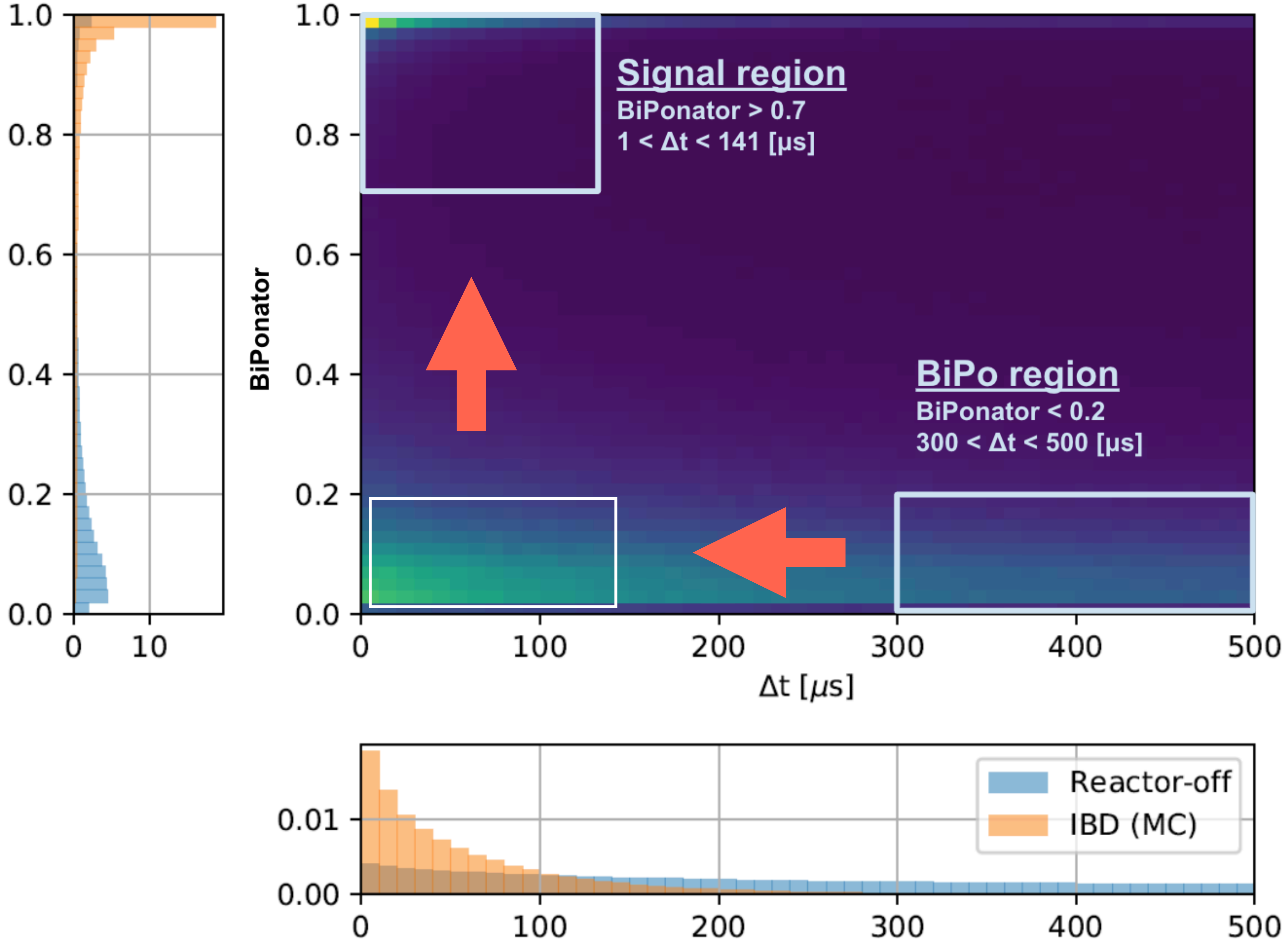
- Accidental components are (atm. neutron, gamma from ^{41}Ar) flat in ΔT_{ES-NS}
  - Accidental subtracted Signal:

$$R_{Signa-Acc} = R_{Signal} - c_{Acc\to Signal} \times R^{Acc}_{Signal}.$$

  - Accidental subtracted BiPo:

$$R_{BiPo-Acc} = R_{BiPo} - c_{Acc\to Signal} \times R^{Acc}_{BiPo}$$

- Derive the scale factors for BiPo to go from high ΔT to low ΔT then low Biponator to high Biponator score regions



- **Accidental and BiPo subtracted signal:**

$$R_{Signal-BiPo-Acc} = R_{Signal-Acc} - R^{BiPo}_{Signal}$$

Extraction of Signal Rate

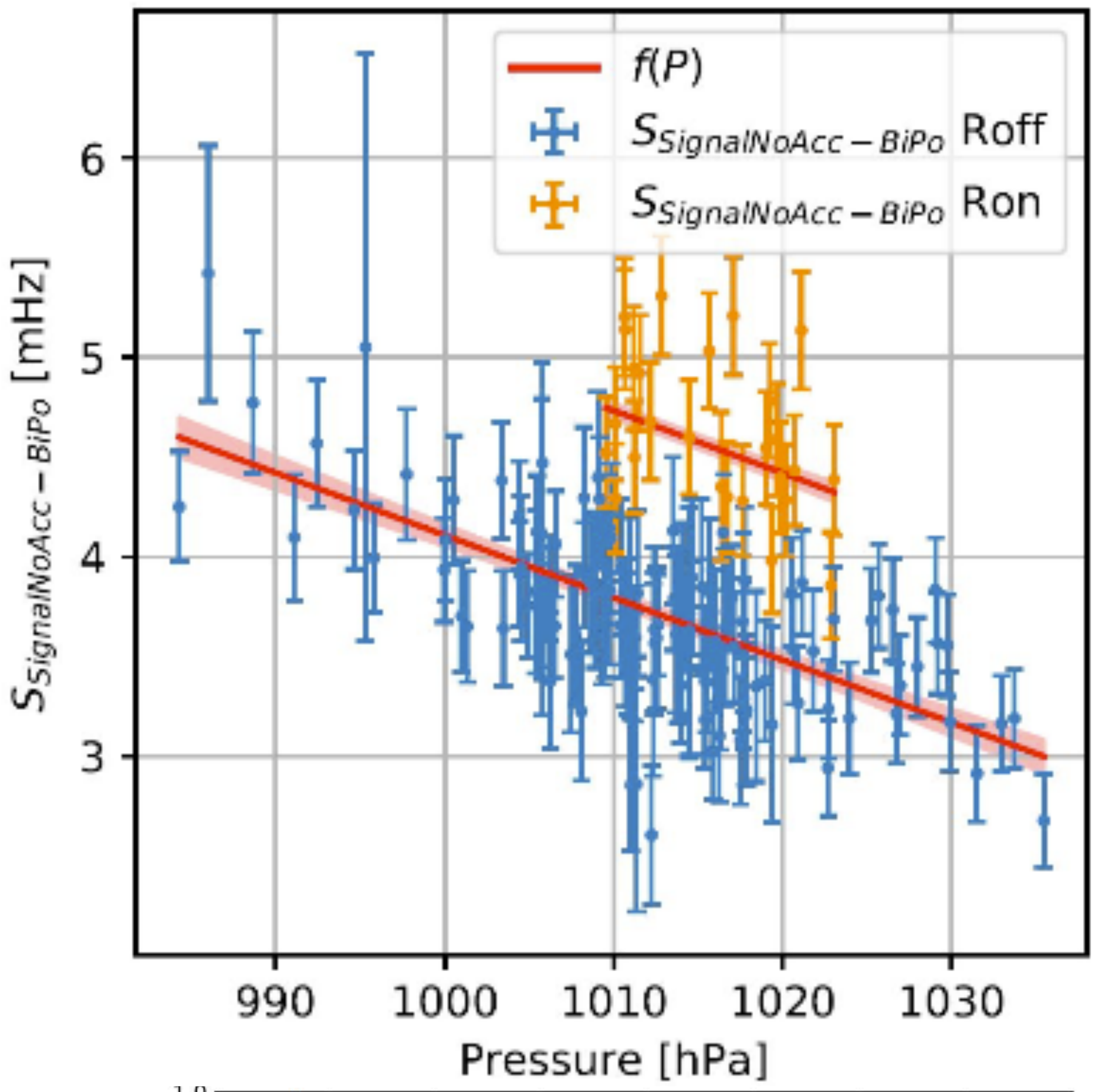
- **Subtraction of cosmic induced component:**

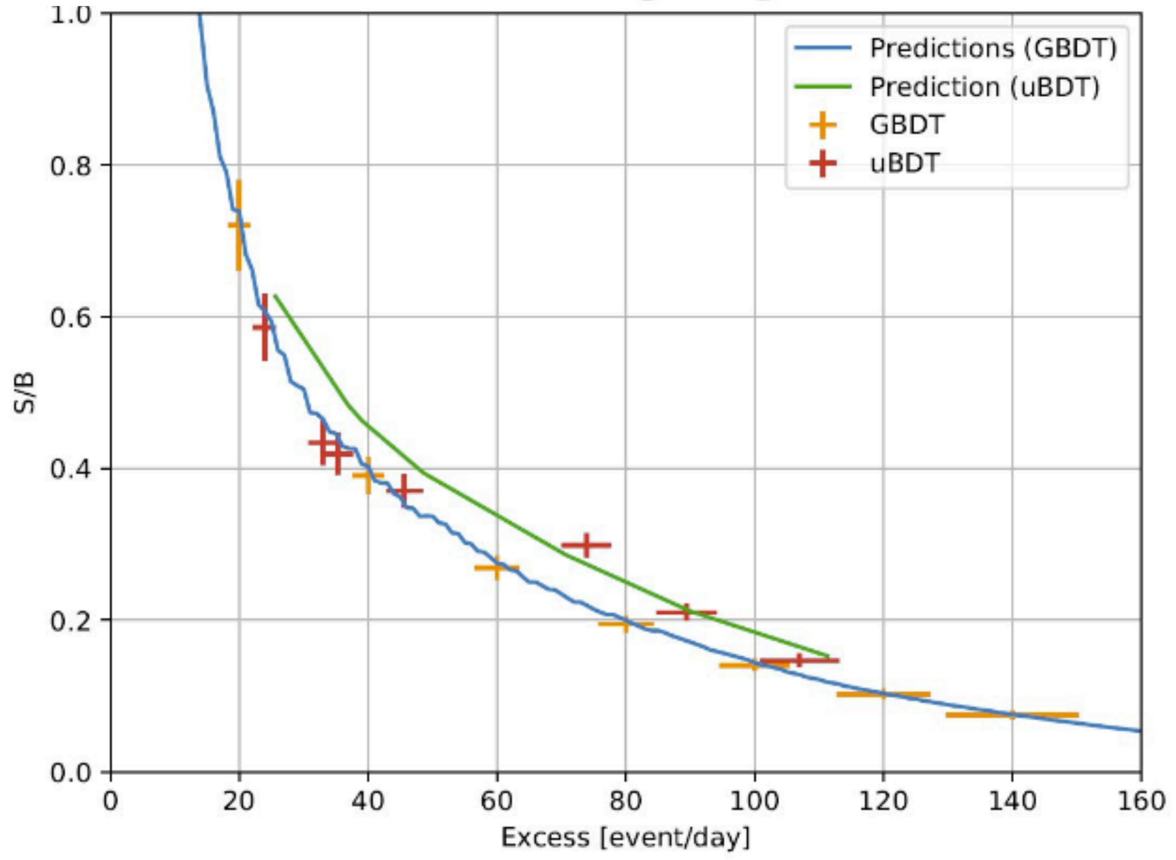
$$f\left(P_{Atm}\right) = a \times P_{Atm} + b$$

- Compute the excess rate for each day in Reactor off

- Compute the excess rate for each day in Reactor on:

$$R_{Excess} = R_{Signal-BiPo-Acc} - R^{model}_{Cosmic}$$

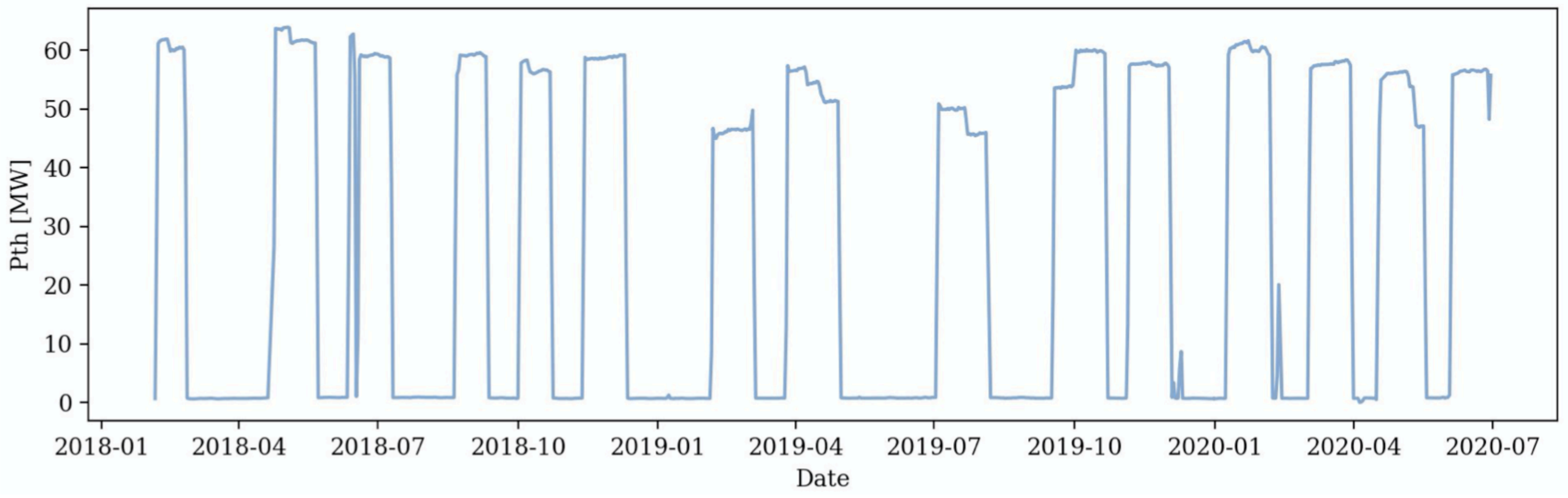




Phase I Data Set

Phase I Data on tape

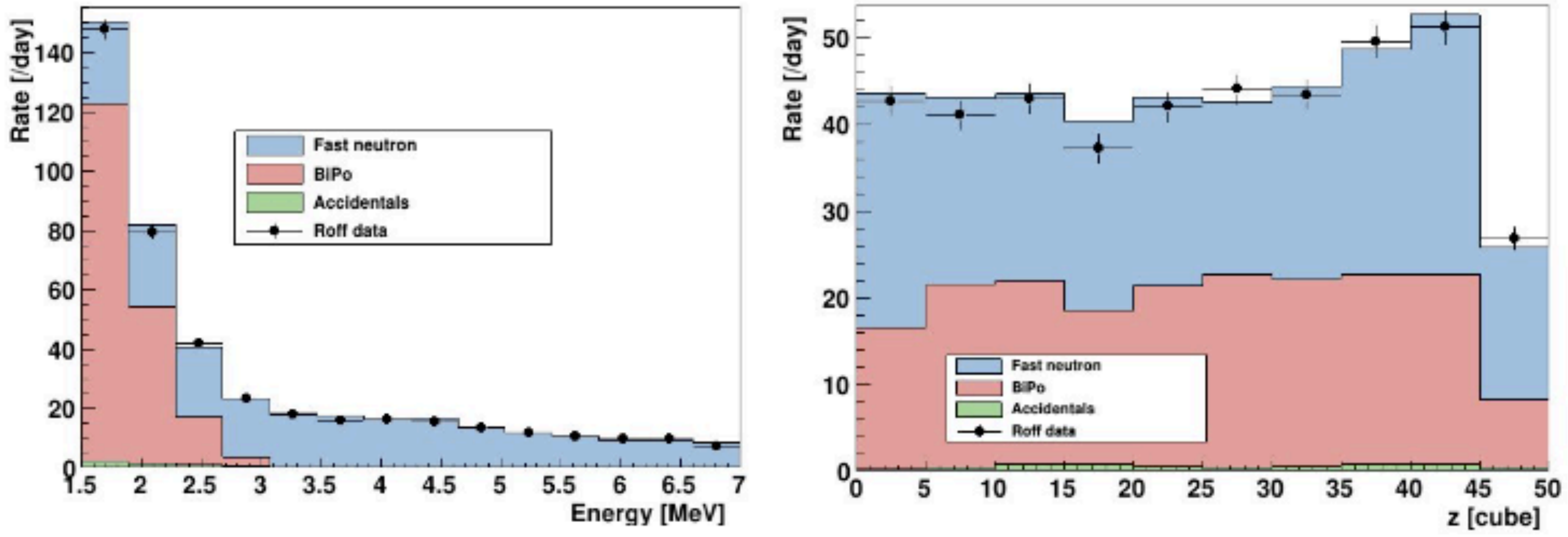
- Two years of data **(April 2018 - July 2020).**
- **14 reactor cycles** during this time.
- Physics-quality data is collected only during ideal conditions with **chilled container, sufficiently low humidity in the container and full shielding**.
- Pass the data through multiple data quality criteria to find and reject faulty data.
- Selected respectively ~300 days and ~180 days of sufficiently high quality reactor-on (ron) and reactor-off (roff) data for an oscillation analysis.



Multivariate Analyses

Gradient Boosted Decision Tree (BDTG)

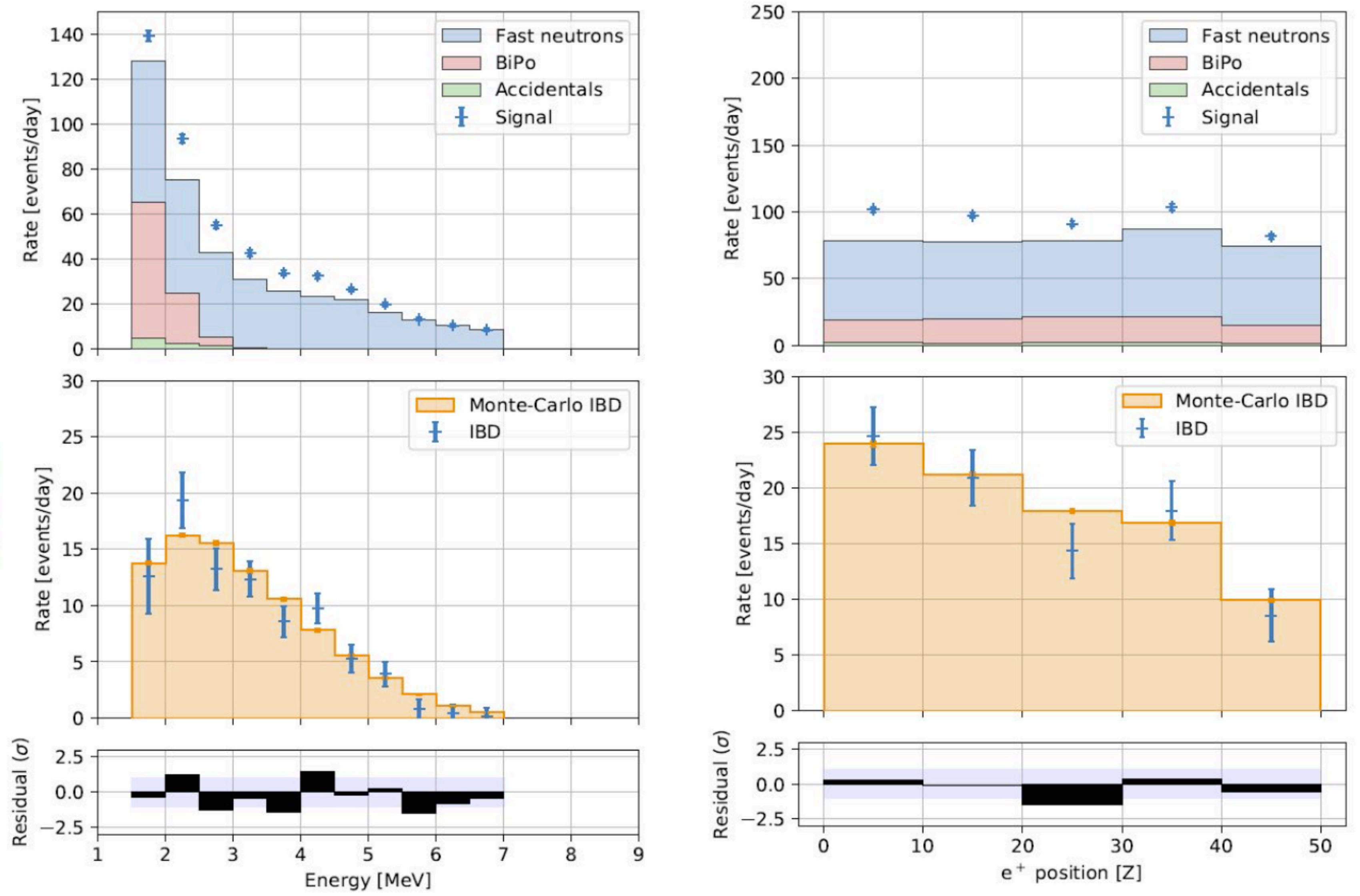
- TMVA BDT trained by evaluating the gradient of the objective function

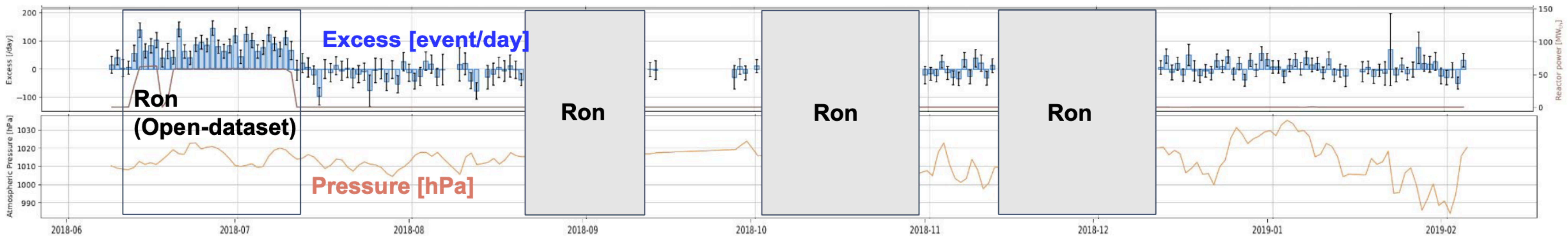


Uniform Boosted Decision Tree (uBDT)

arXiv:1305.7248

- Optimize discrimination whilst ensuring uniform efficiency for specific variables.





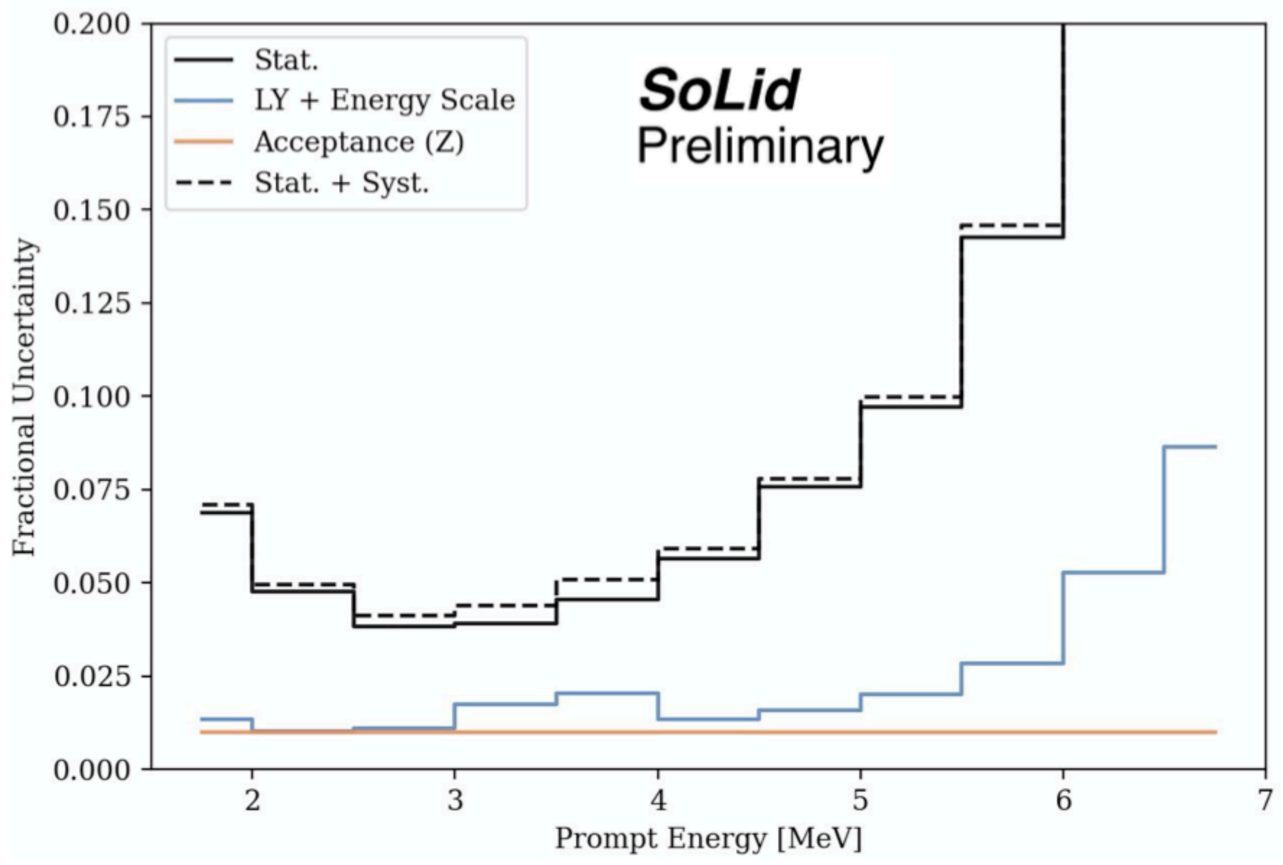
- A comparison between background model and Roff are in good agreement
- Additionally we looked at the open R-on data set to see the excess events (90 events/day in uBDT analysis)

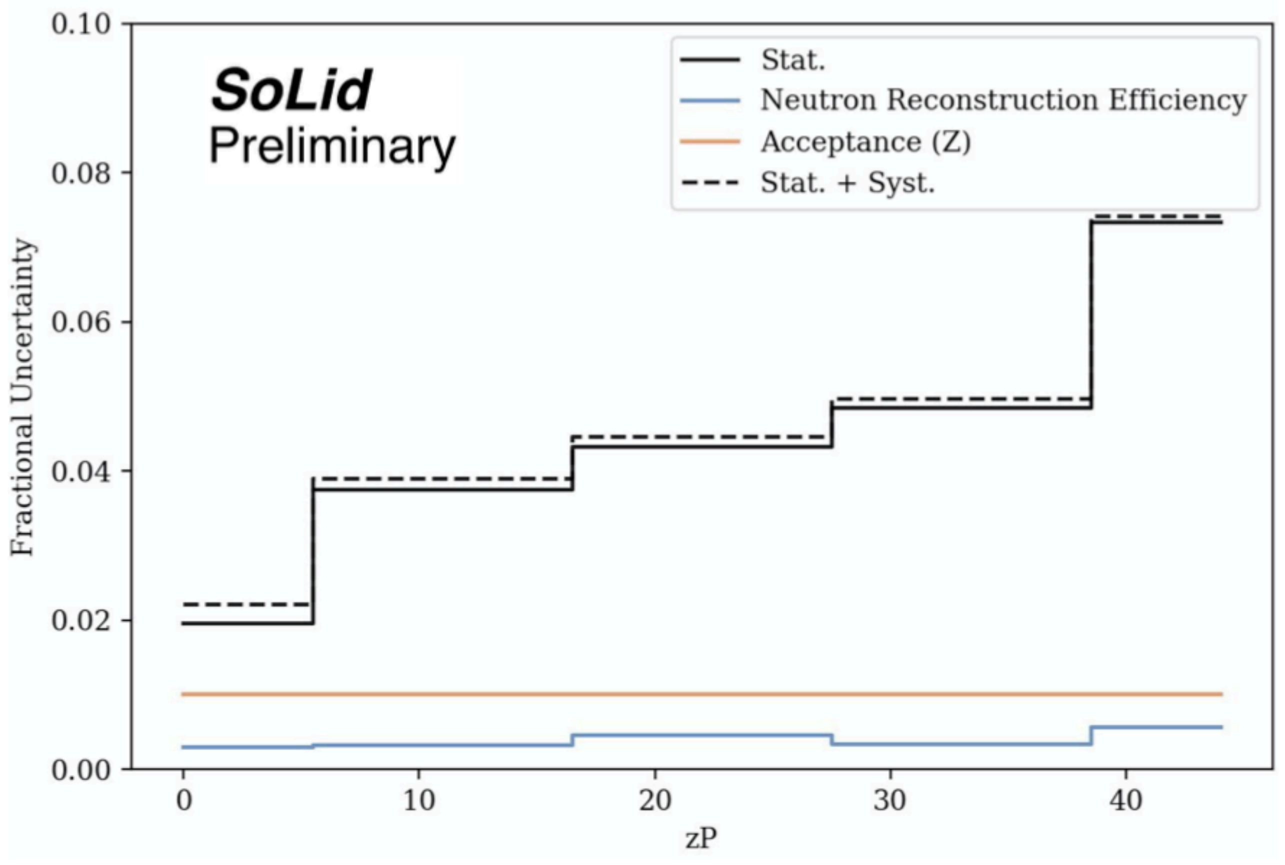
Phase I Oscillation Sensitivity

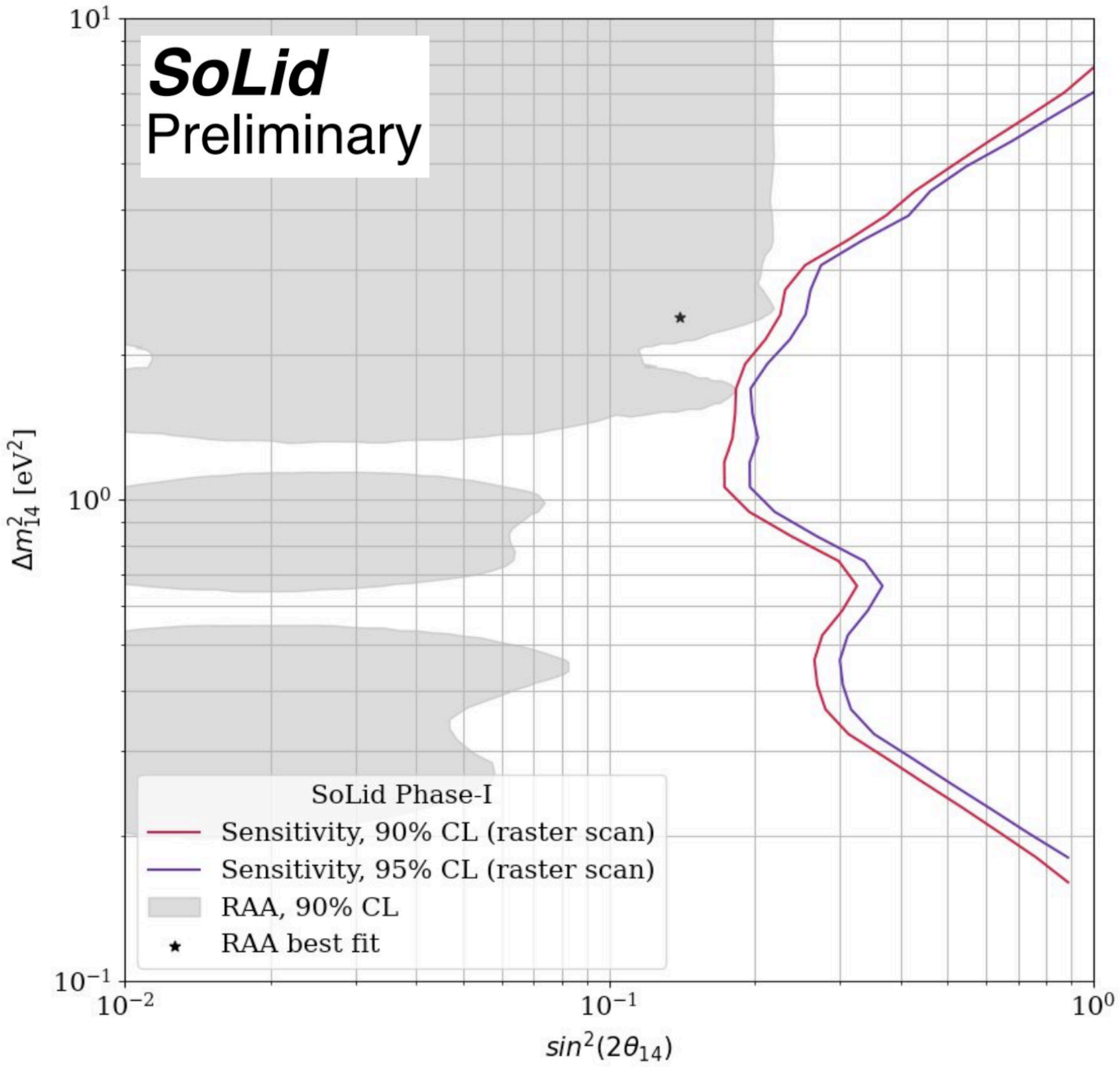
- **Feldman-Cousins** construction to estimate sensitivity to sterile neutrino oscillations.

- **Systematic uncertainties** related to the light yield (LY), energy scale and neutron capture efficiency are taken into account ⇒ statistically dominated.

- **Ongoing effort** to assess impact of remaining systematics and improve sensitivity with new analysis techniques!



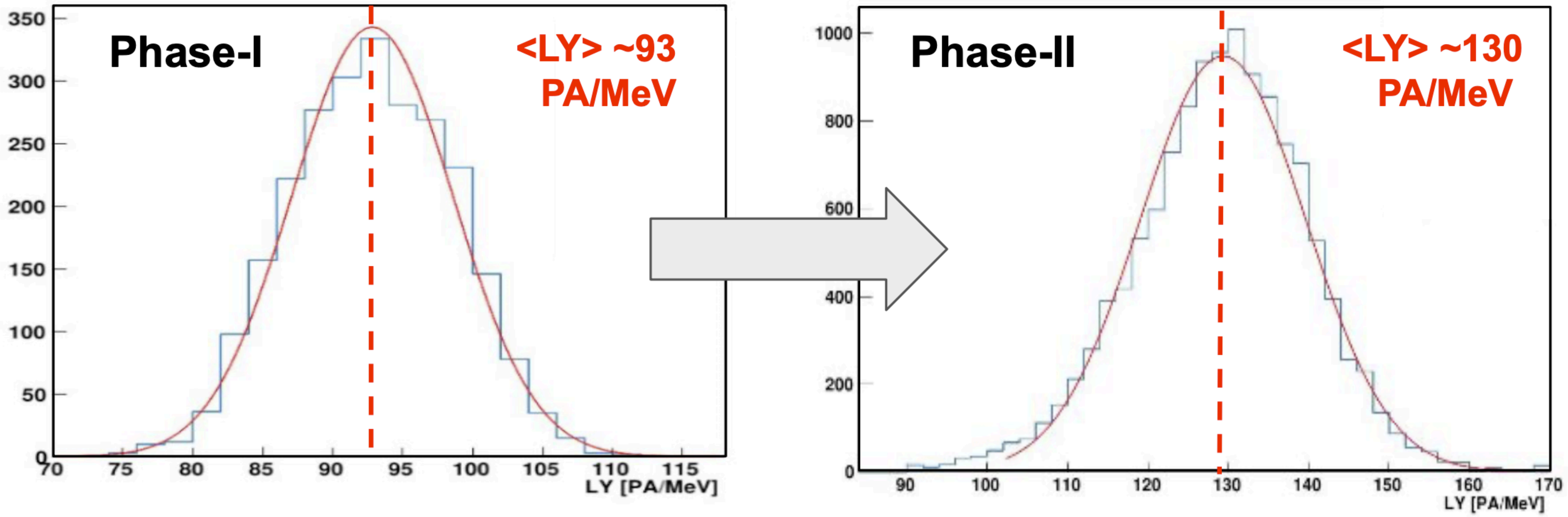




SoLid Phase-II: Detector Upgrade

Upgraded the detector with new MPPCs (S14 series)

- Better photon detection efficiency compared to S12 series ⇒ translates to a 40% increase in light yield
- Cross-talk reduced by a factor of two
- Improved energy resolution
- Expected improvement of annihilation gamma reconstruction
- Taking data with Phase-II detector since late 2020



Conclusions

- SoLid has approximately 2 years of data with the Phase-I detector
- Alternative technology complements other experiments
- Detector response well understood
- MVA and ML techniques used to reduce high rates of background
- Atmospheric neutrons and BiPo Dedicated analysis based on 2-gamma topologies very promising
- Successful detector upgrade and data-taking underway with Phase-II

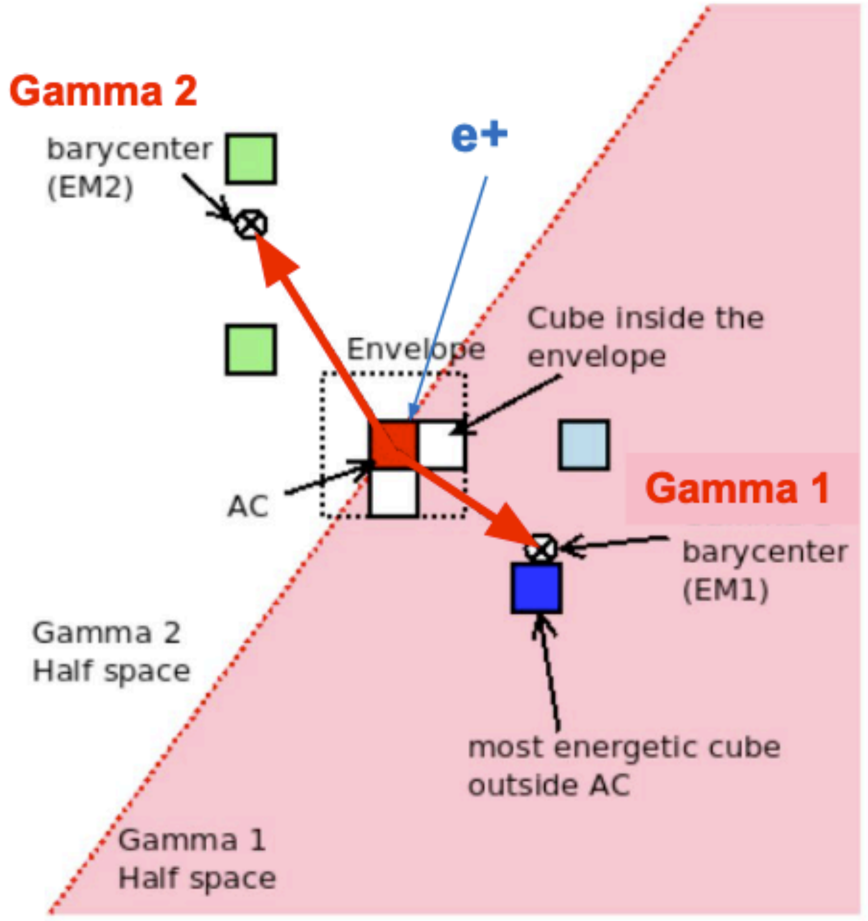
https://iopscience.iop.org/article/10.1088/1748-0221/16/02/P02025
https://iopscience.iop.org/article/10.1088/1748-0221/14/11/P11003

Oscillation results of Phase-I dataset coming soon!

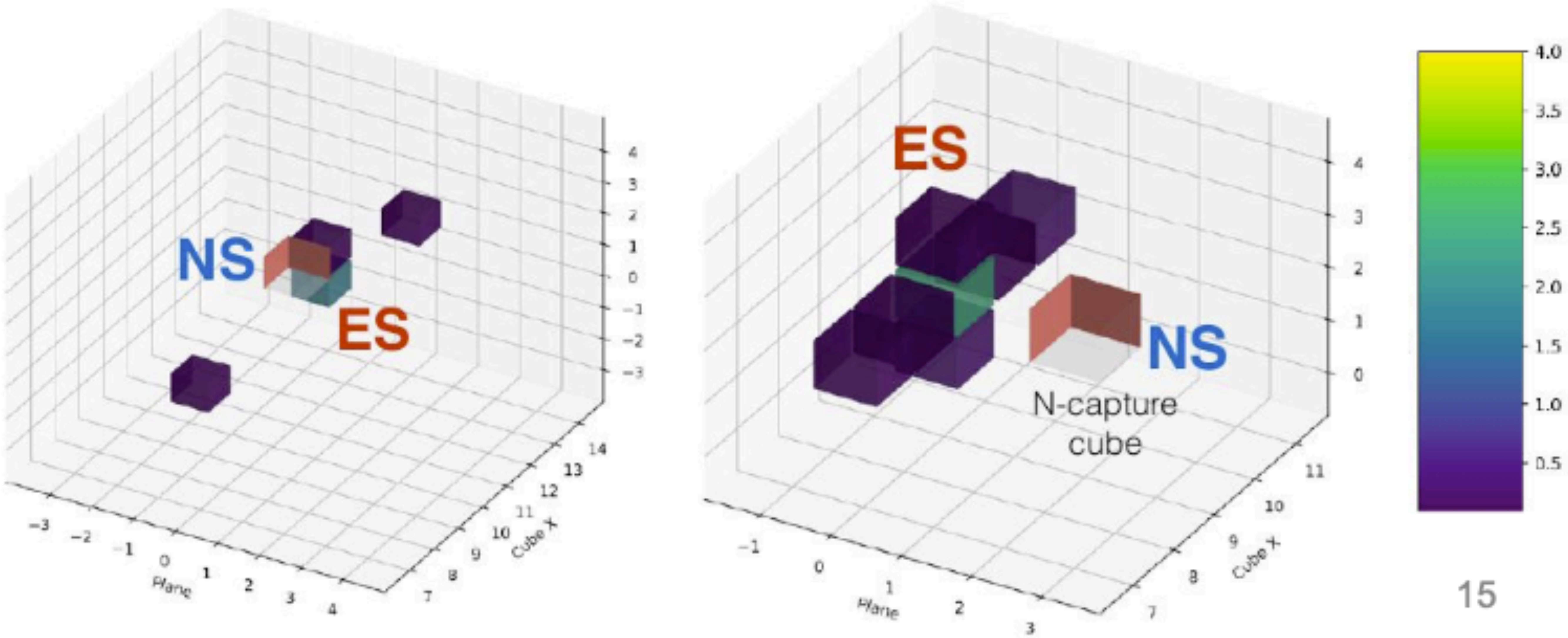
Backups

Event Topology Classification

Annihilation gammas reconstruction

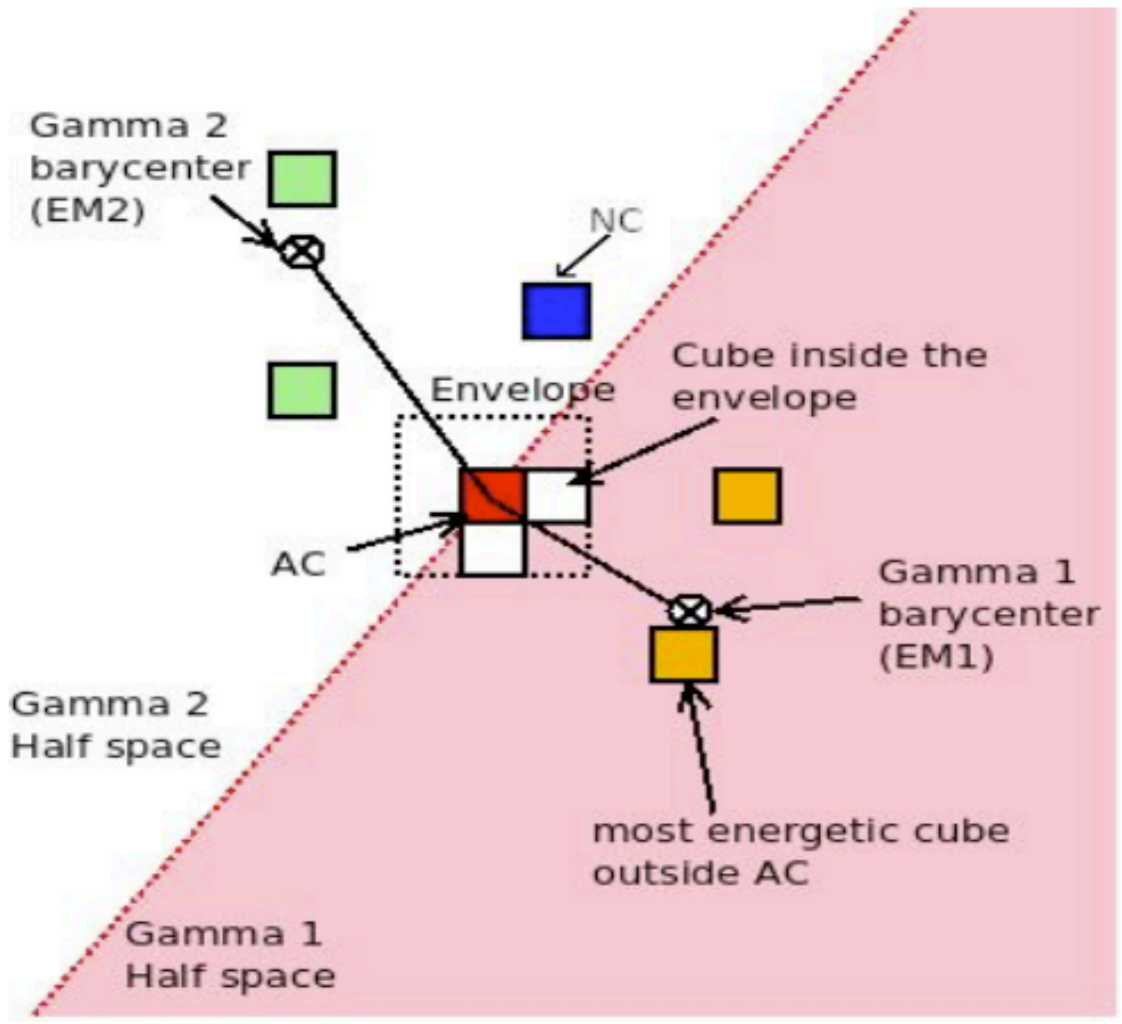


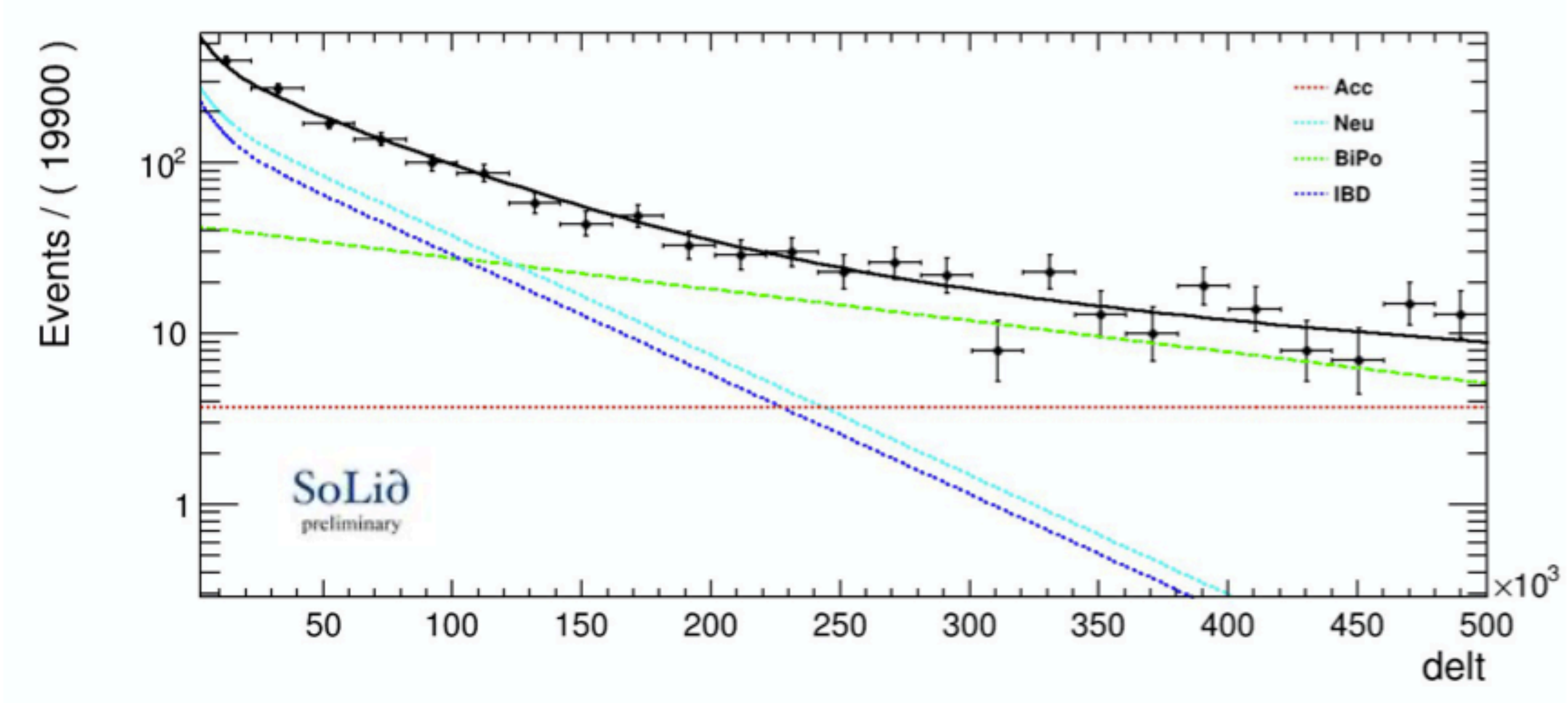
- Method 1: Locate first gamma cluster then split the detector into two hemispheres and search for second detached cluster.
- Method 2: Track gammas by minimizing likelihood function of cubes position according to Compton scattering cross sections
- Classification based on 0, 1, 2 gamma cluster in event

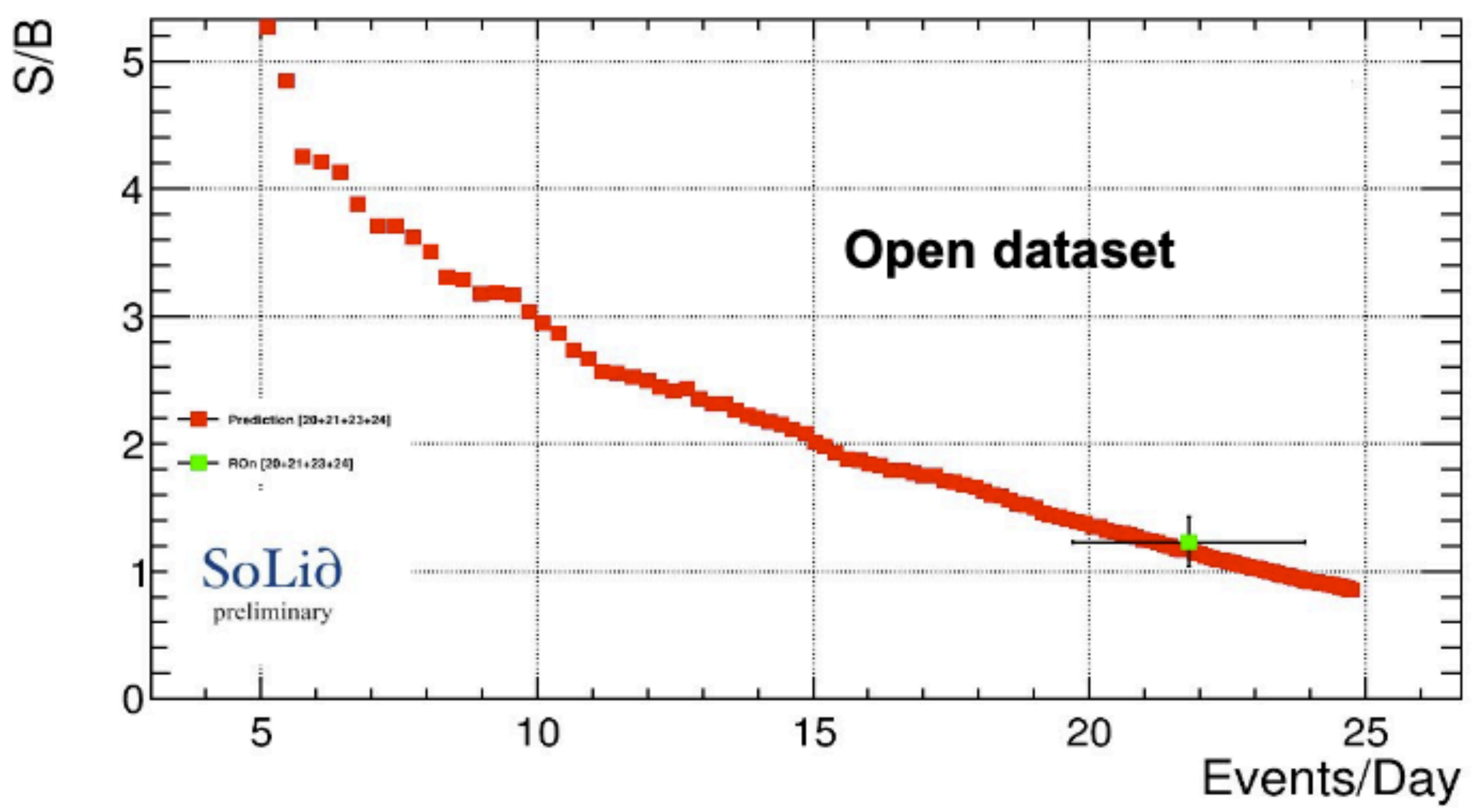


Two Gamma Antineutrino Topological Selection

- **New analysis** based on event topologies (taking maximal advantage of detector segmentation).
- Preliminary analysis of events with **both annihilation gammas**.
- **Multivariate analysis** for remaining background rejection
- a. Each background component determined with **multi-dimensional (Δt , Δr) simultaneous fit**.
- Good agreement between excess and predicted excess, with S/B larger than one:
- Beyond Phase-I this approach will benefit from **detector upgrade** features

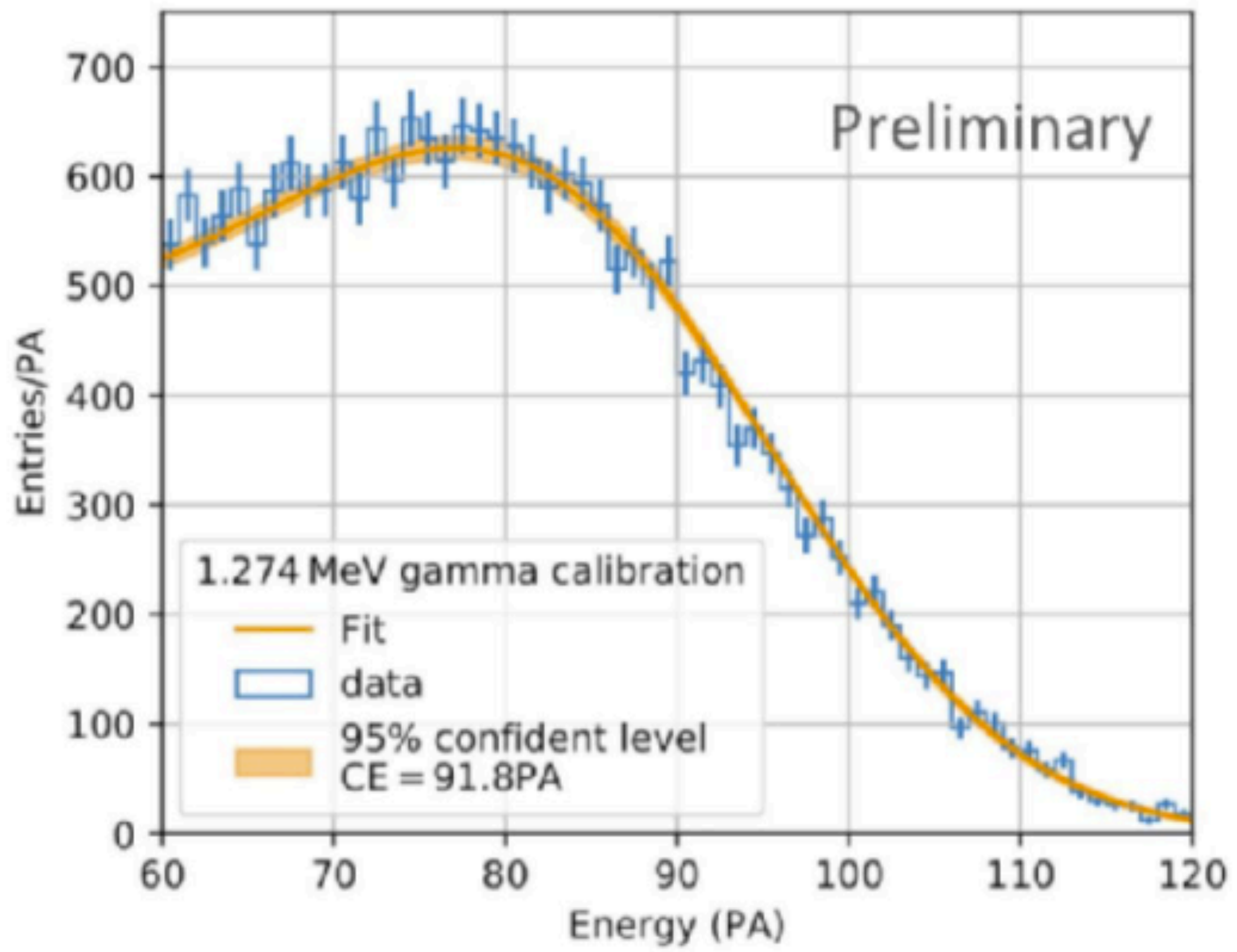


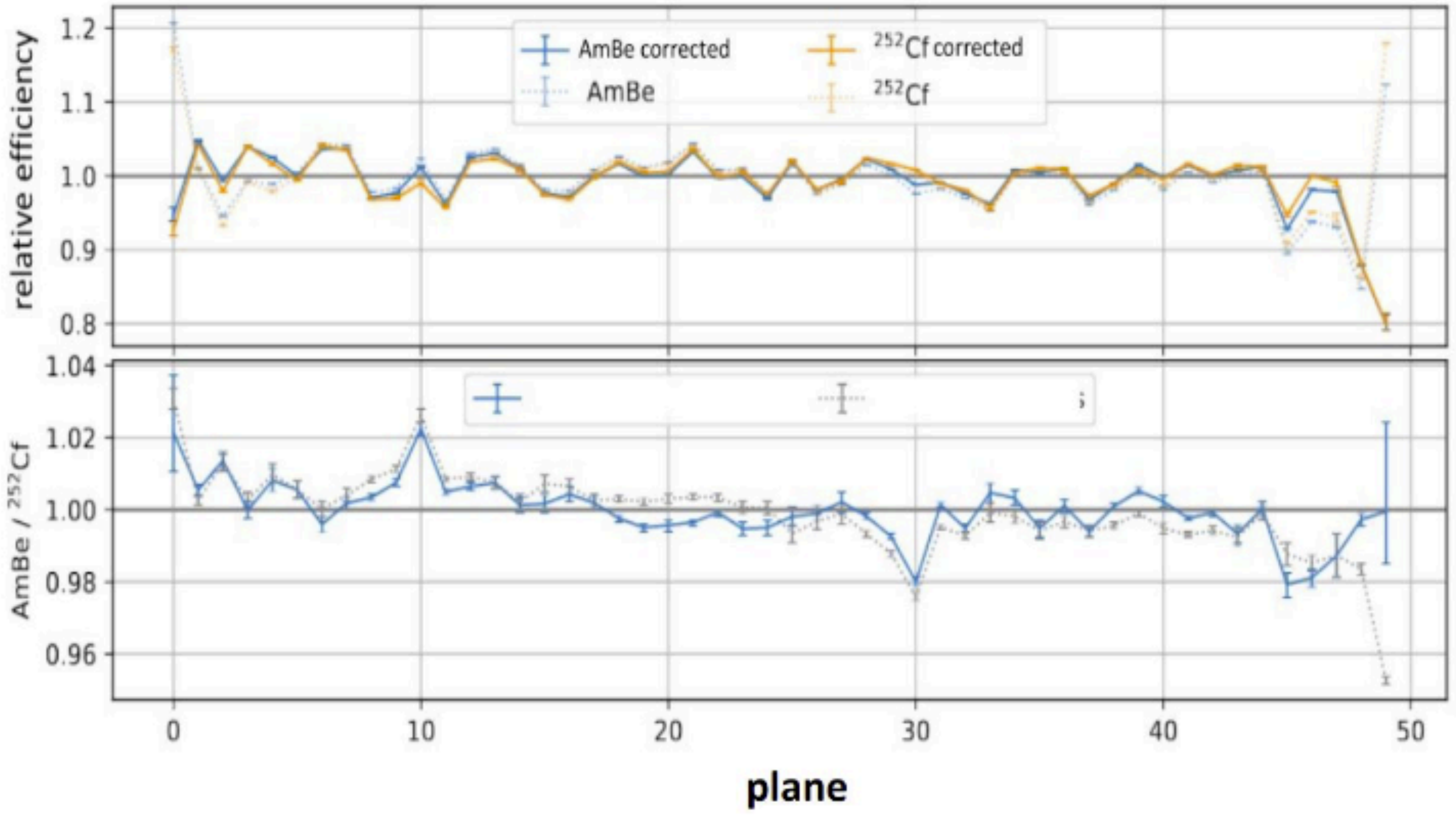


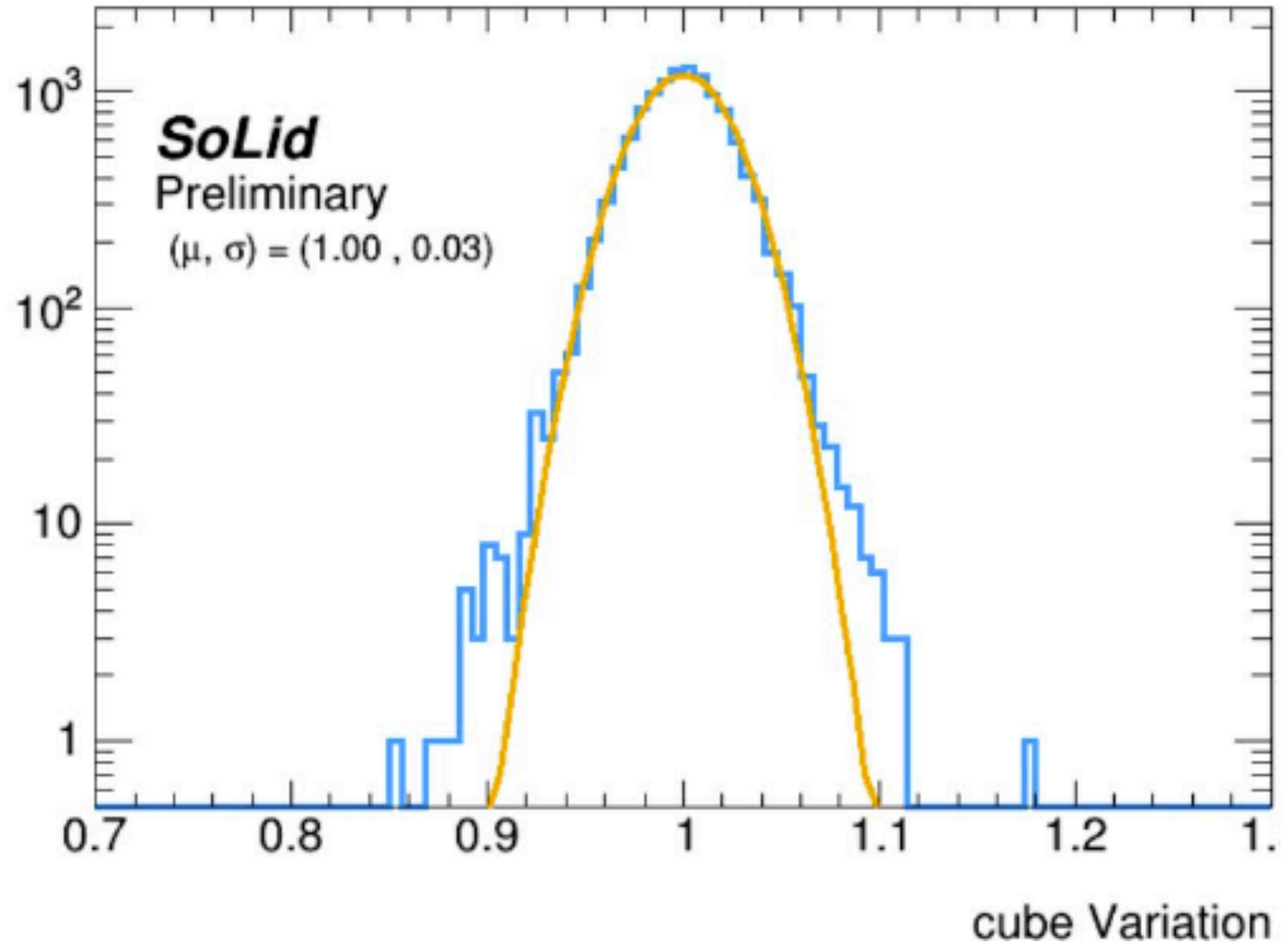


Detector Calibration

- Gamma sources used for energy calibration of the detector.
- Linearity and homogeneity of the detector energy response tested at the percent level
- AmBe and Cf neutron sources to measure neutron efficiency

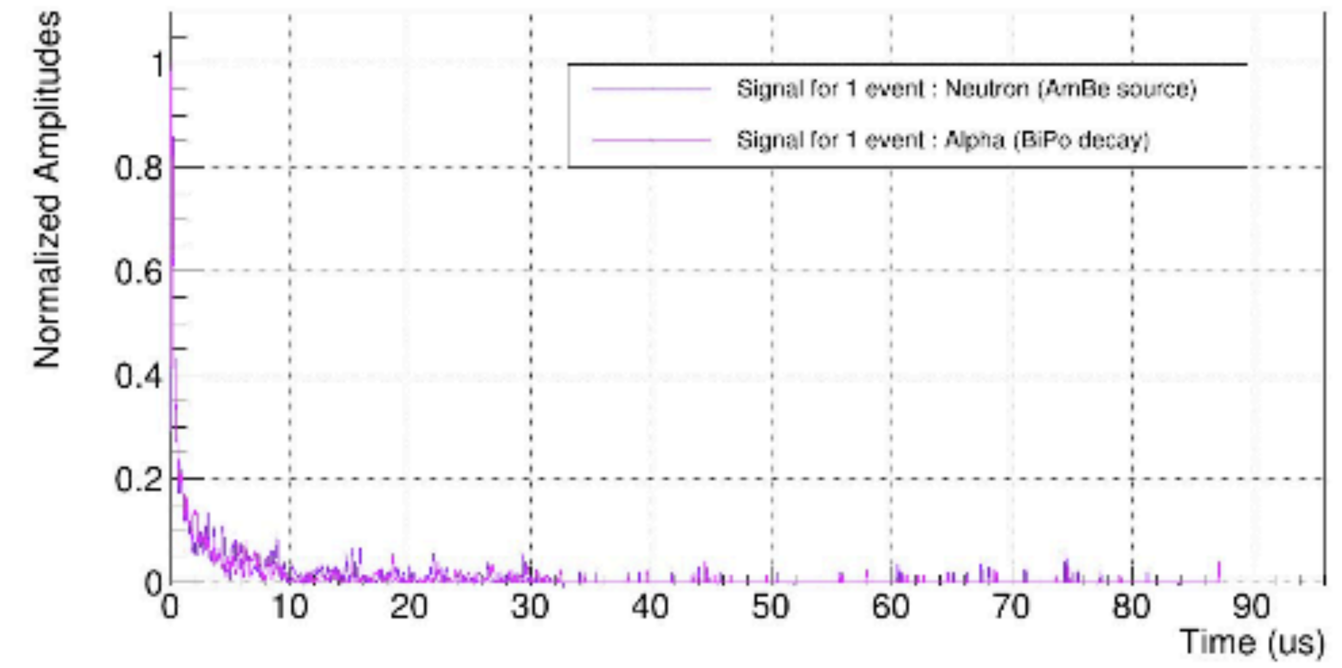






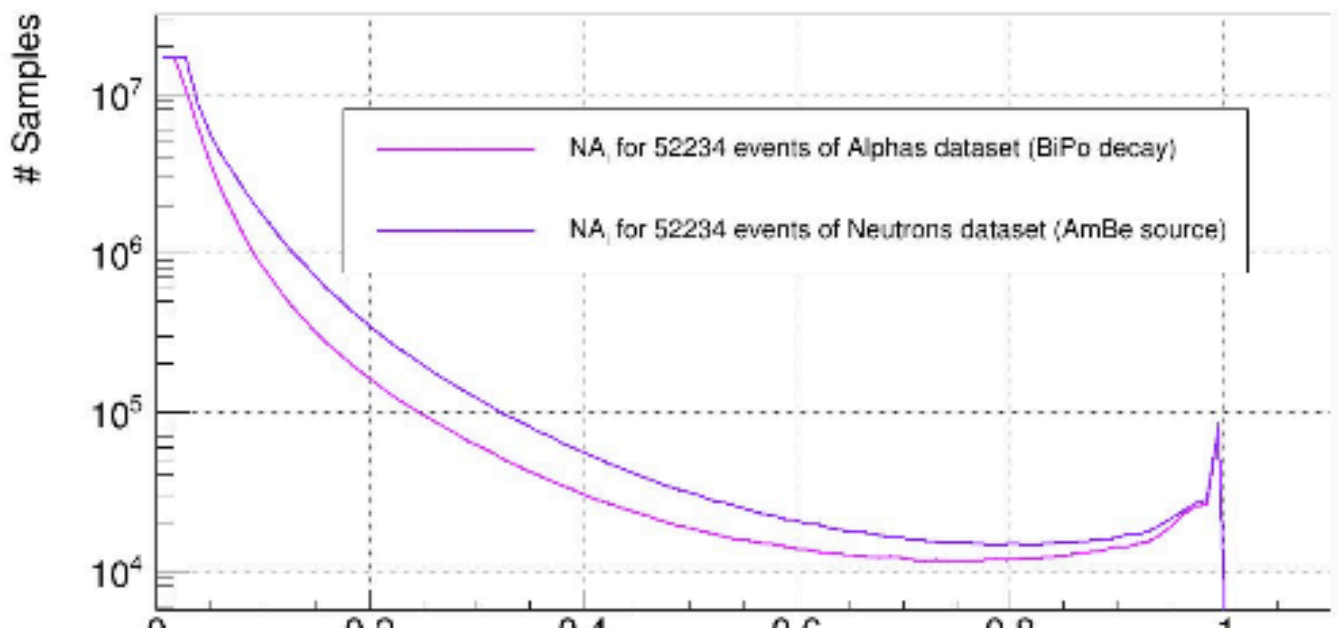
BiPonator : ML PSD Method

CNN Input

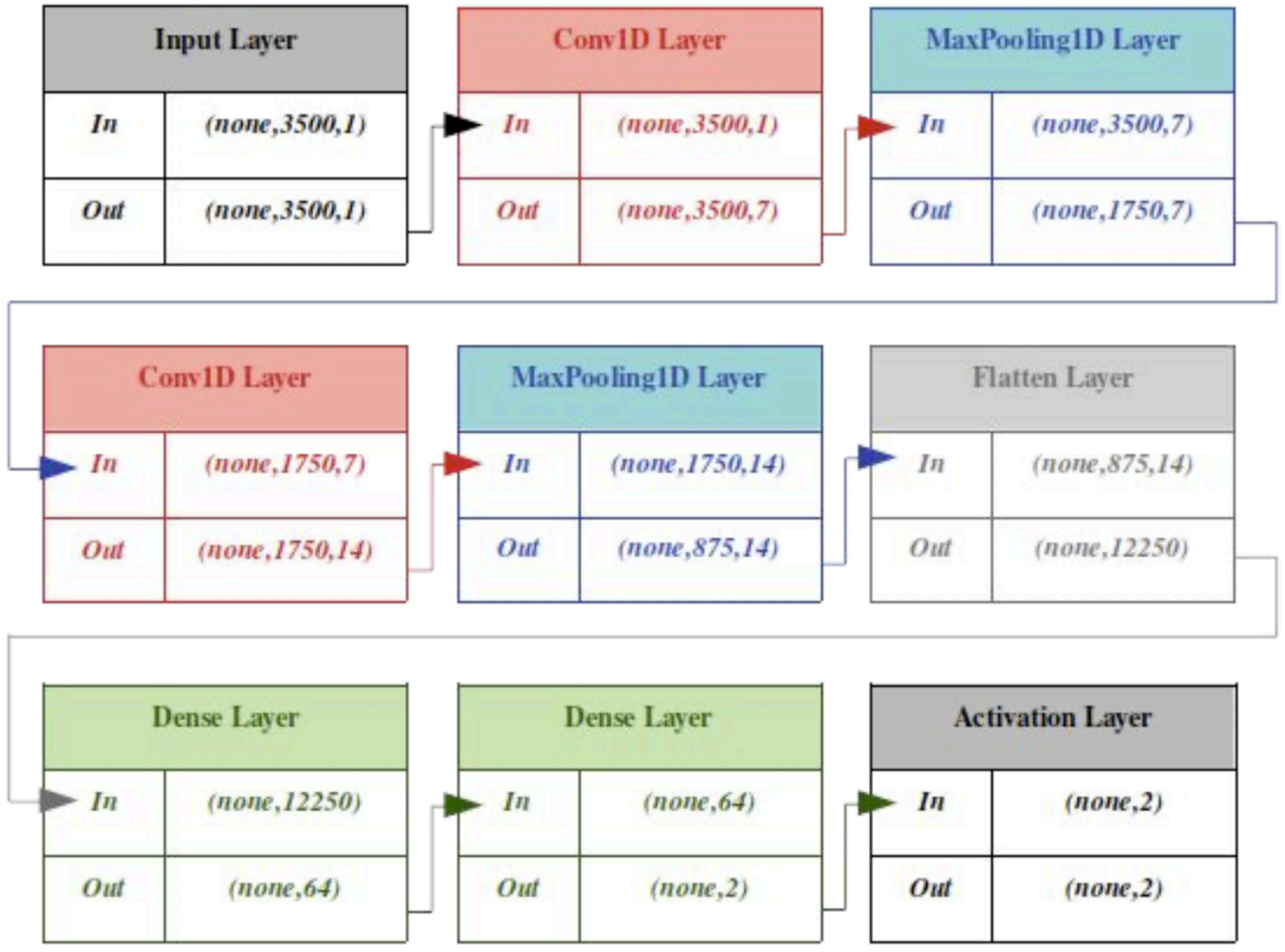


For each event,

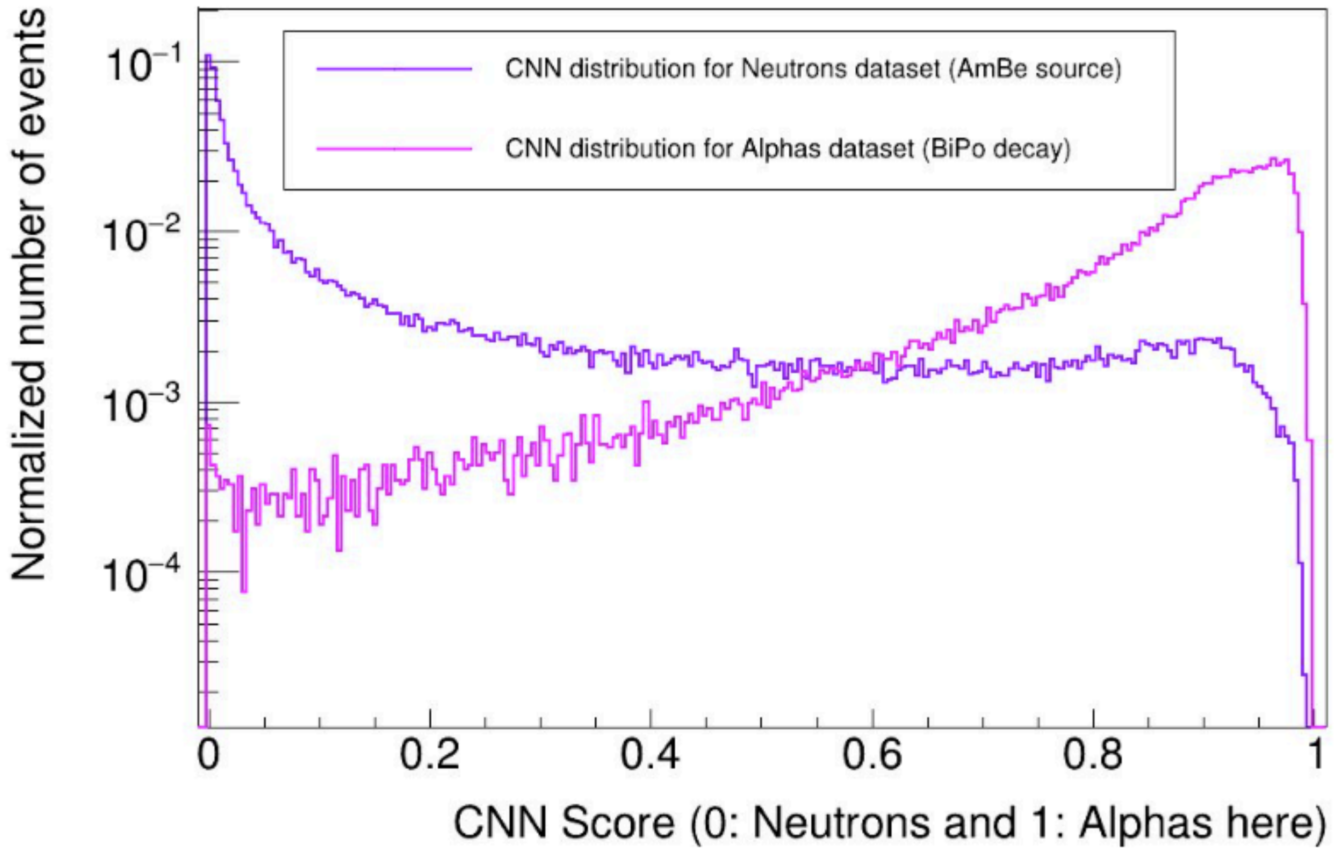
$$NA_i = \frac{(A_i - A_{min})}{(A_{max} - A_{min})}$$



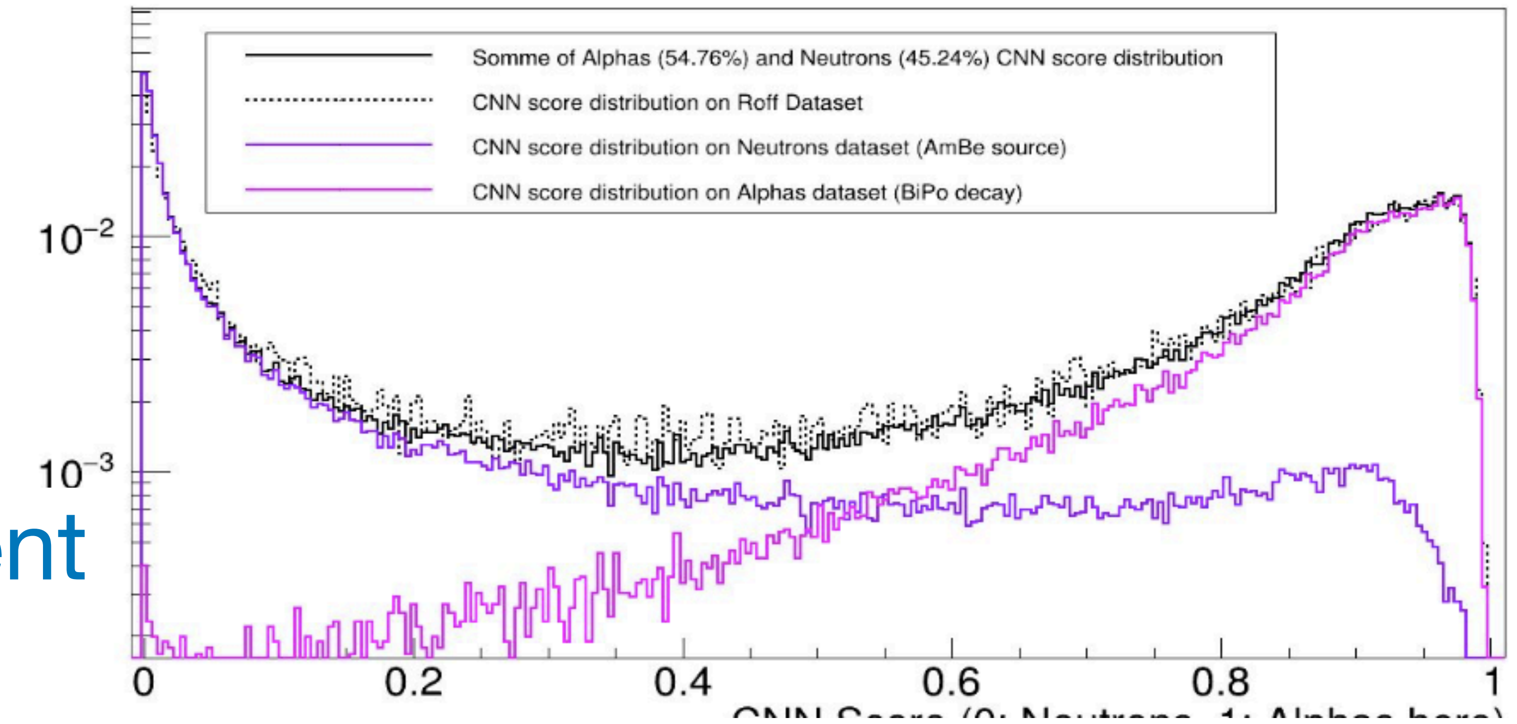
CNN Factory



CNN Output



Ex : inference on Roff dataset (54.76% of alphas and 45.24% of neutrons)



- Alpha / Neutron discrimination improvement to reduce more BiPo background
- Pulse Shape Discrimination (PSD)