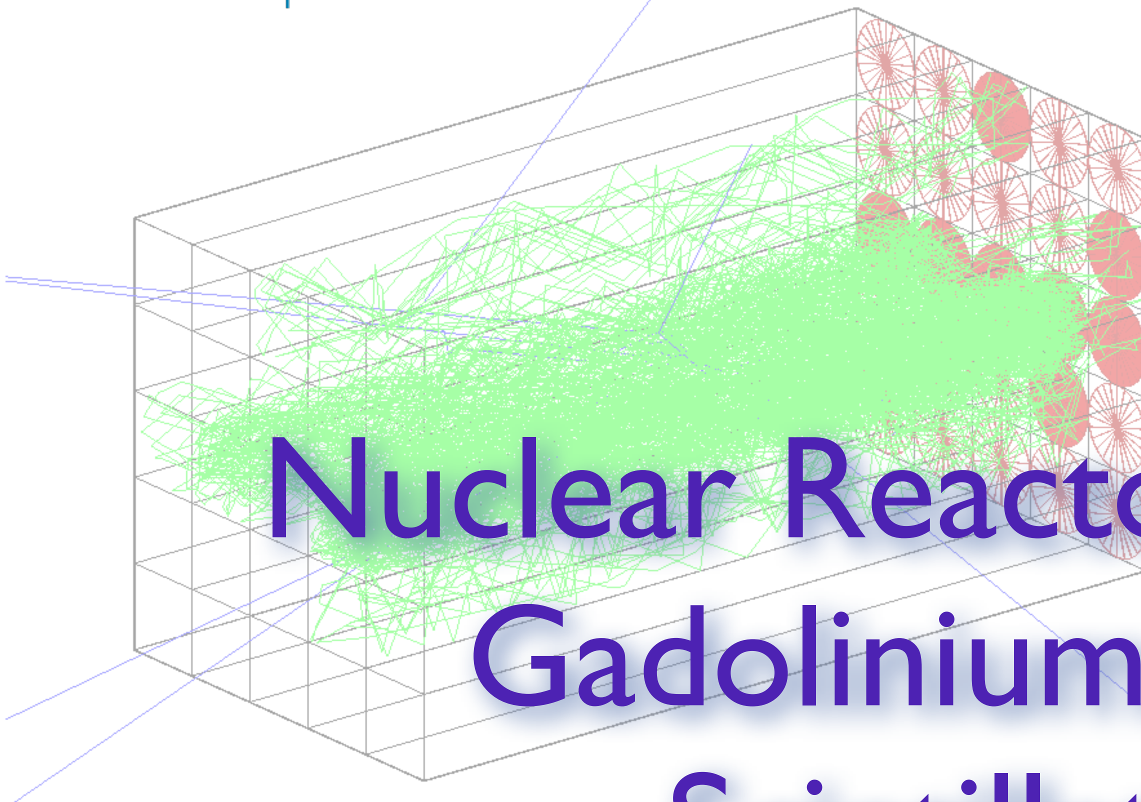

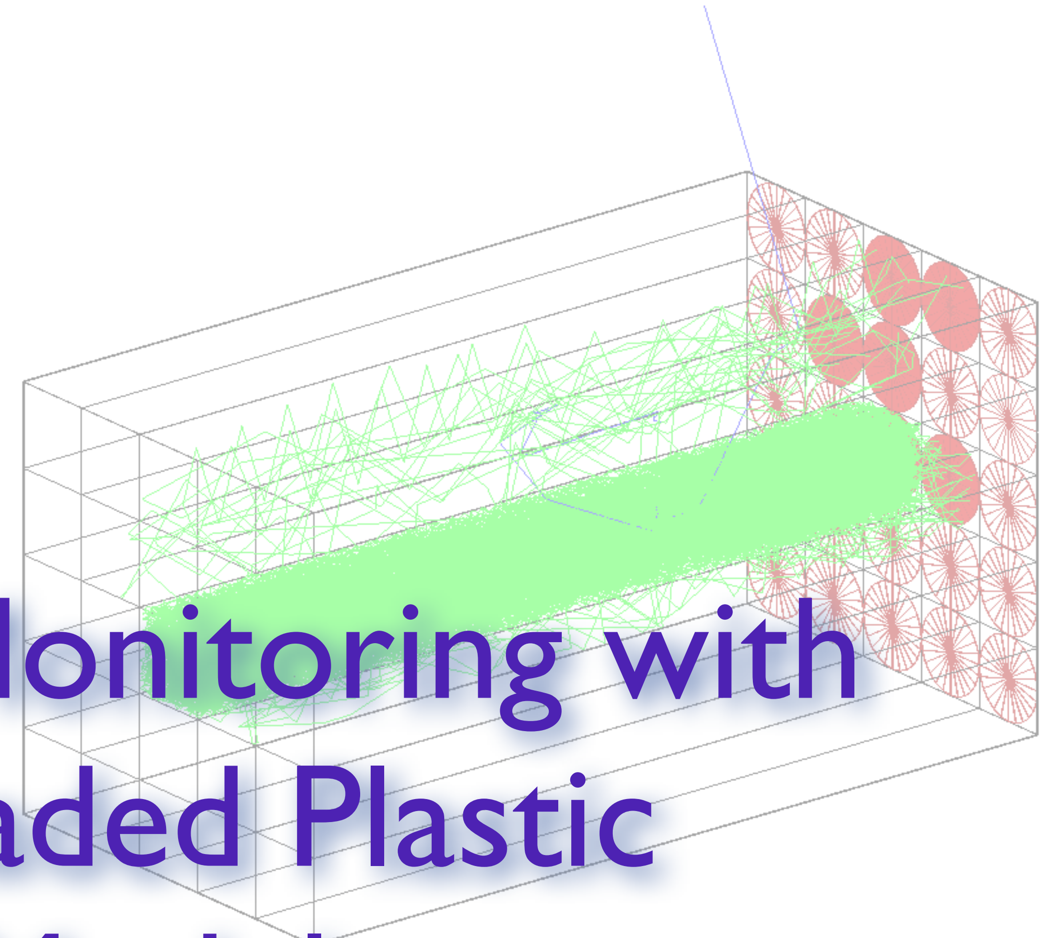

Nuclear Reactor Monitoring with Gadolinium-Loaded Plastic Scintillator Modules

Sertaç Öztürk

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Applied Antineutrino Physics Workshop 2023 18-21 September, York

Nuclear Reactors in Turkey

- The first NPP construction has been recently started at Akkuyu.
  - It is planed to start operations in 2024.
  - There will be 4 power units with capacity of 1200 MWe (P_{th} = 3200 MWt) each.
  - Enriched uranium dioxide is the fuel.
- Construction of additional NPP in Sinop and İgneada is being planned near future.
- National and independent safeguard application is very crucial .
- Monitoring NPP with a compact particle detector is possible.

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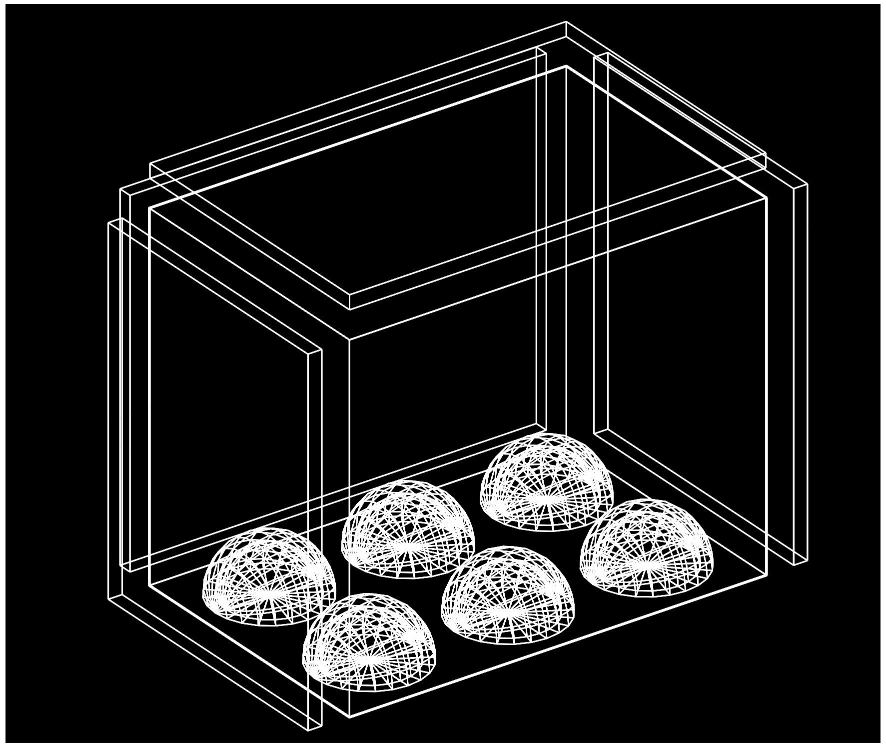
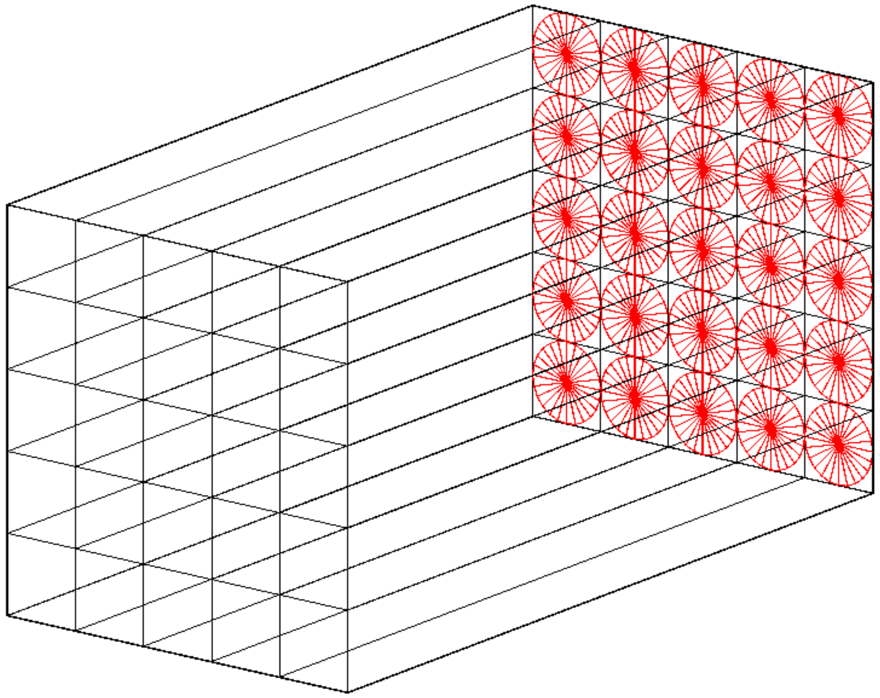
Detector Designs

- Two different antineutrino detector design approaches are considered.
  - ✓ Water Cherenkov detector (Liquid-state)
    - Published in TJP and presented in Applied Antineutrino Physics 2016
  - ✓ Segmented plastic scintillator detector (Solid-state)



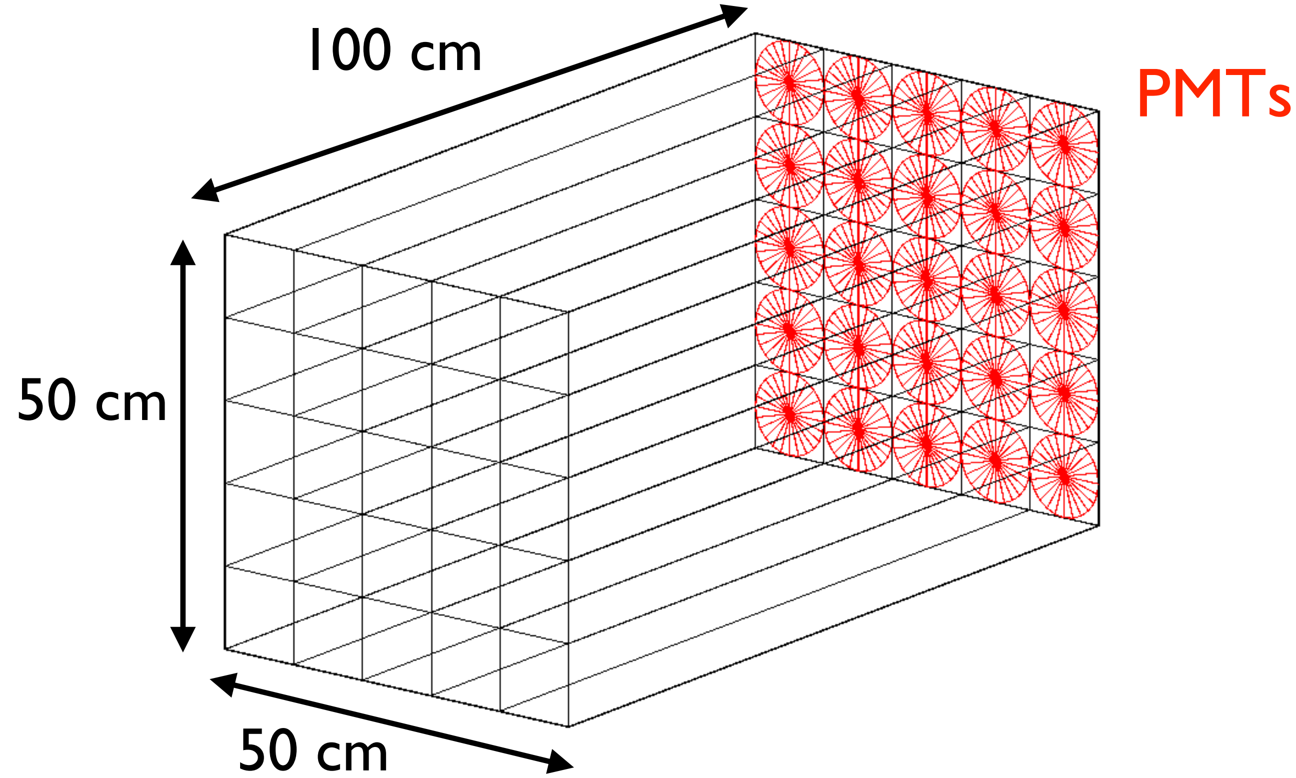
- Easier to construct
- Cheaper

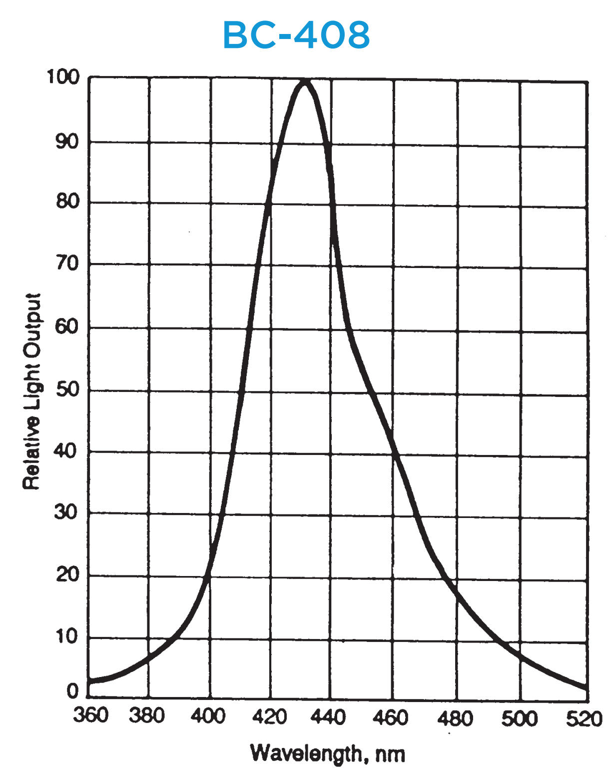


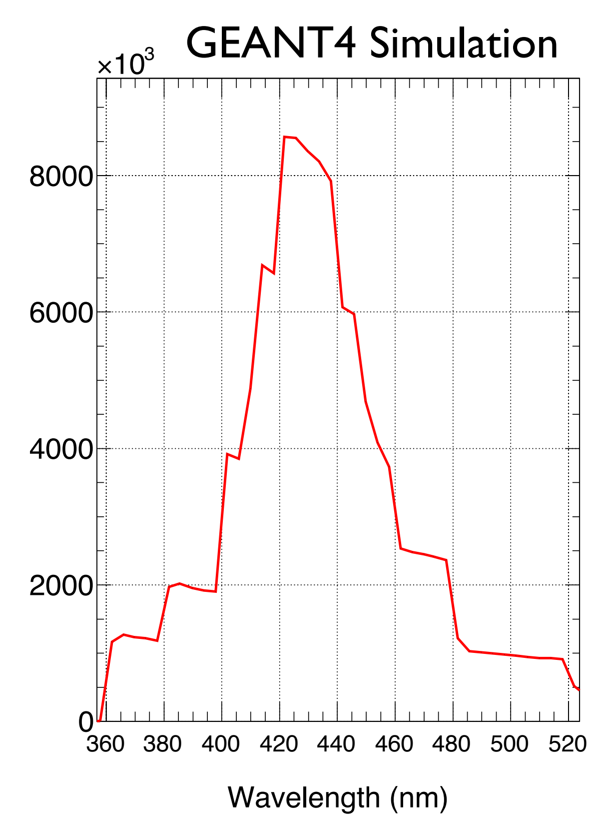
- Better mobility
- Great background suppression

Segmented Plastic Scintillator Detector

- Gadolinium-loaded segmented plastic scintillator modules for antineutrino detection.
- There are 25 identical 10x10x100 cm gadolinium-loaded polyvinyltoluene based (BC-408) plastic scintillators.
- Each plastic scintillator is wrapped in 20 µm thick aluminium sheet to obtain a segmented structure.
- It is about **250 kg** and about **1185 antineutrino events** can be observed per a day when it is placed **50 m** away from the 3.2 GWt reactor core.







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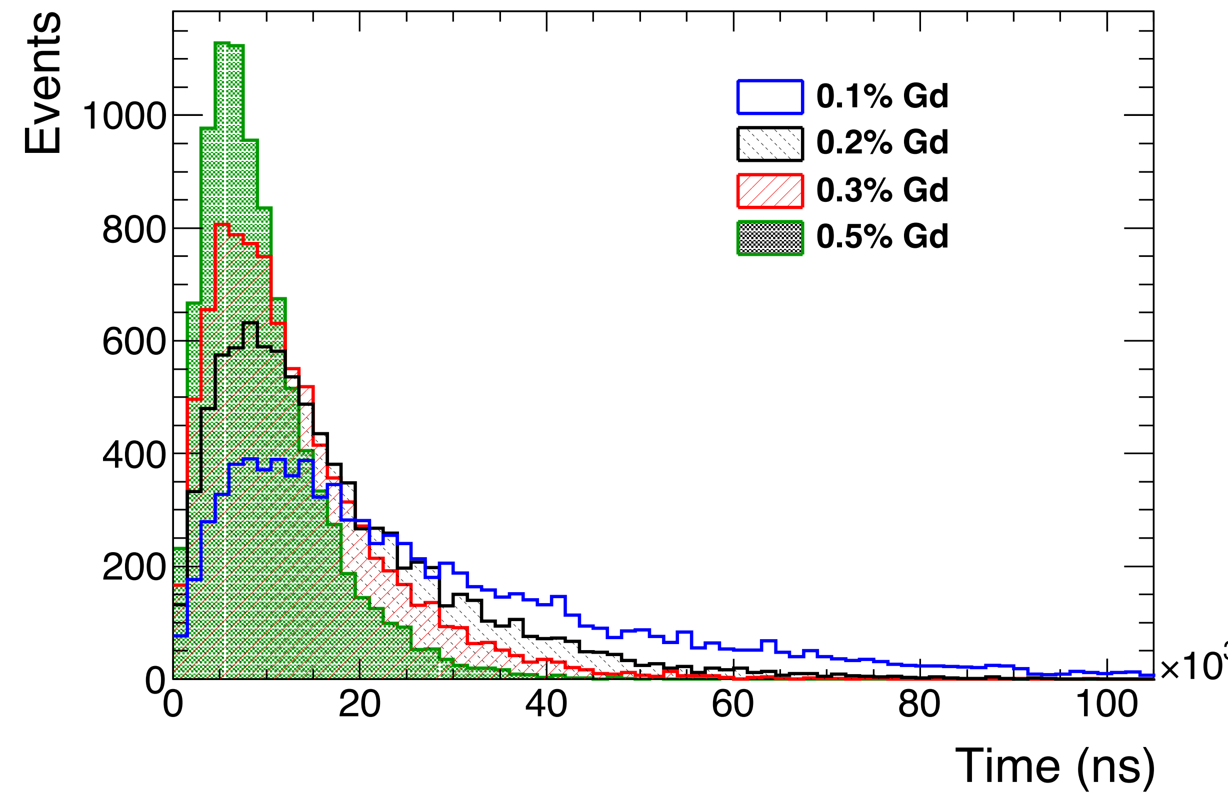
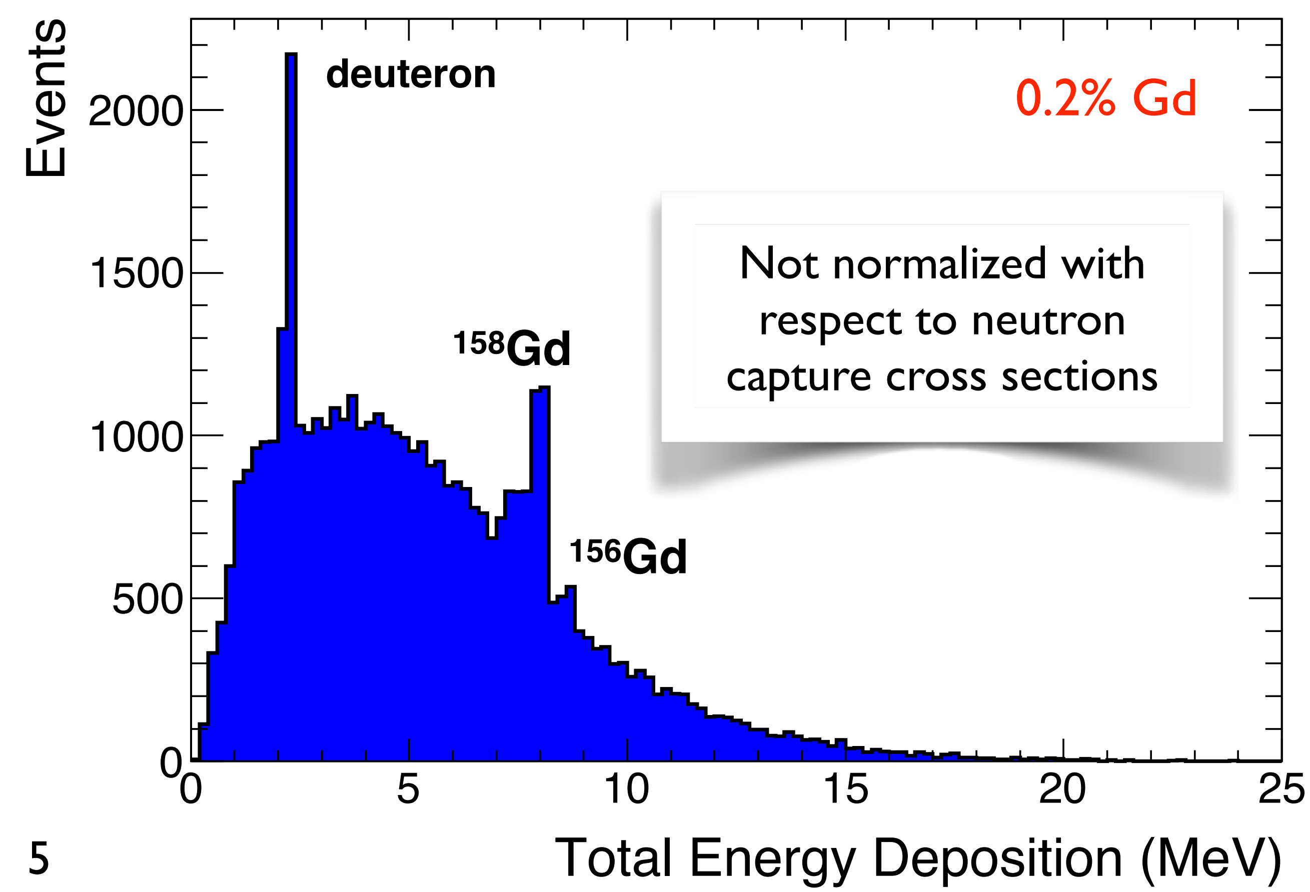
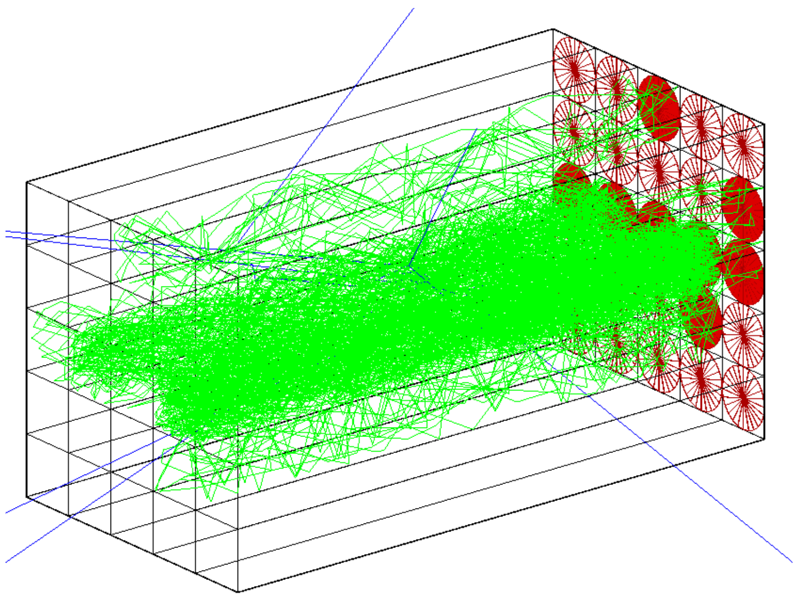
Gadolinium-loaded Plastic Scintillators

- Synthesis of Gd-loaded plastic scintillators were reported.
  - ✓ Transparency and the other optical properties of Gd-loaded scintillator with 1%-3% loading were almost the same as unloaded case.
- The amount of loaded Gd concentration in the scintillator directly effects the delayed signal, which is generated by thermal neutron capture.
- Plastic scintillator blocks with 0.2%-0.3% amount of Gd was optimum, which gave a prompt-delayed time difference between 4 and 50 µs.

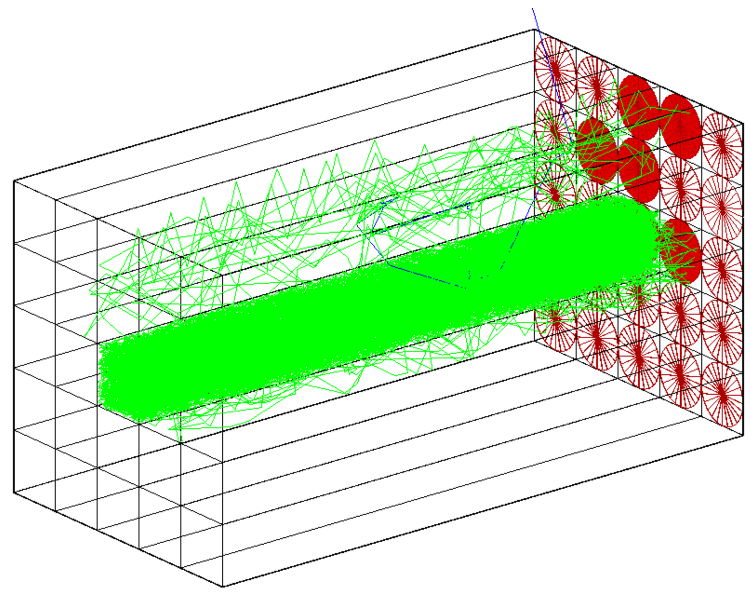




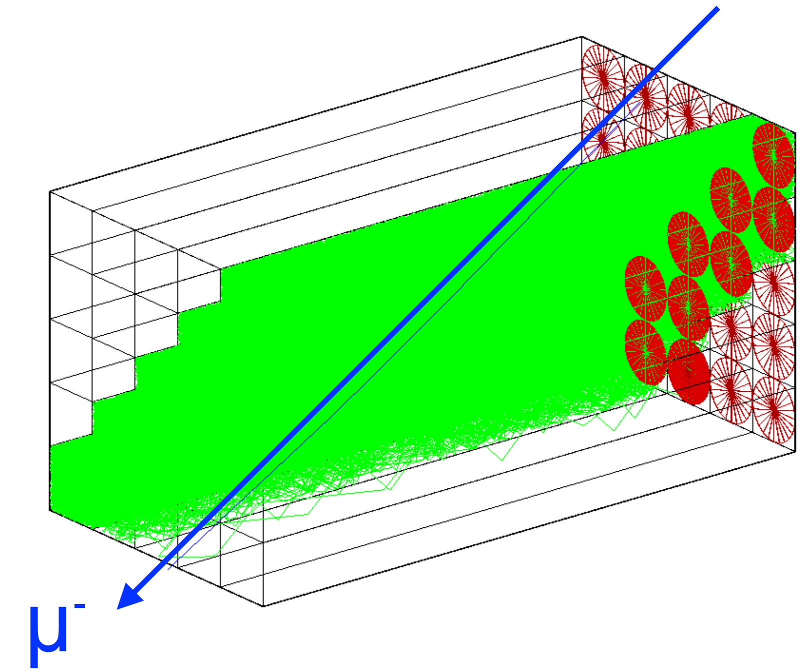
Event Topologies



10 keV neutron



3 MeV positron

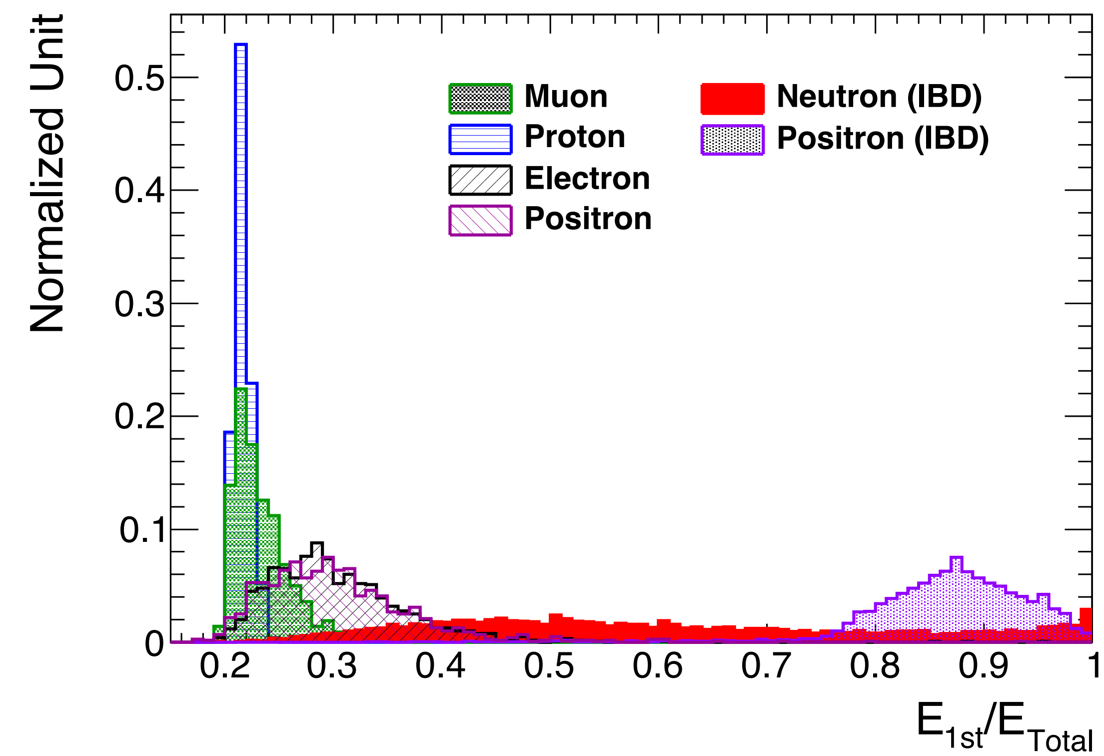


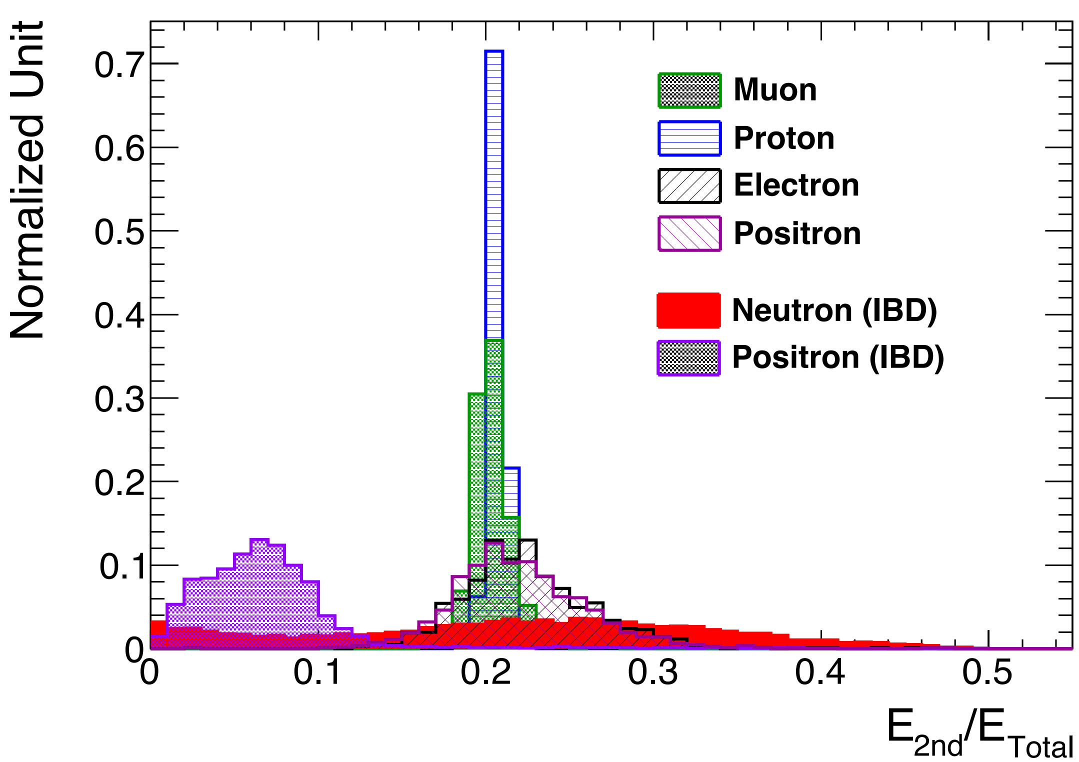
1 GeV/c muon

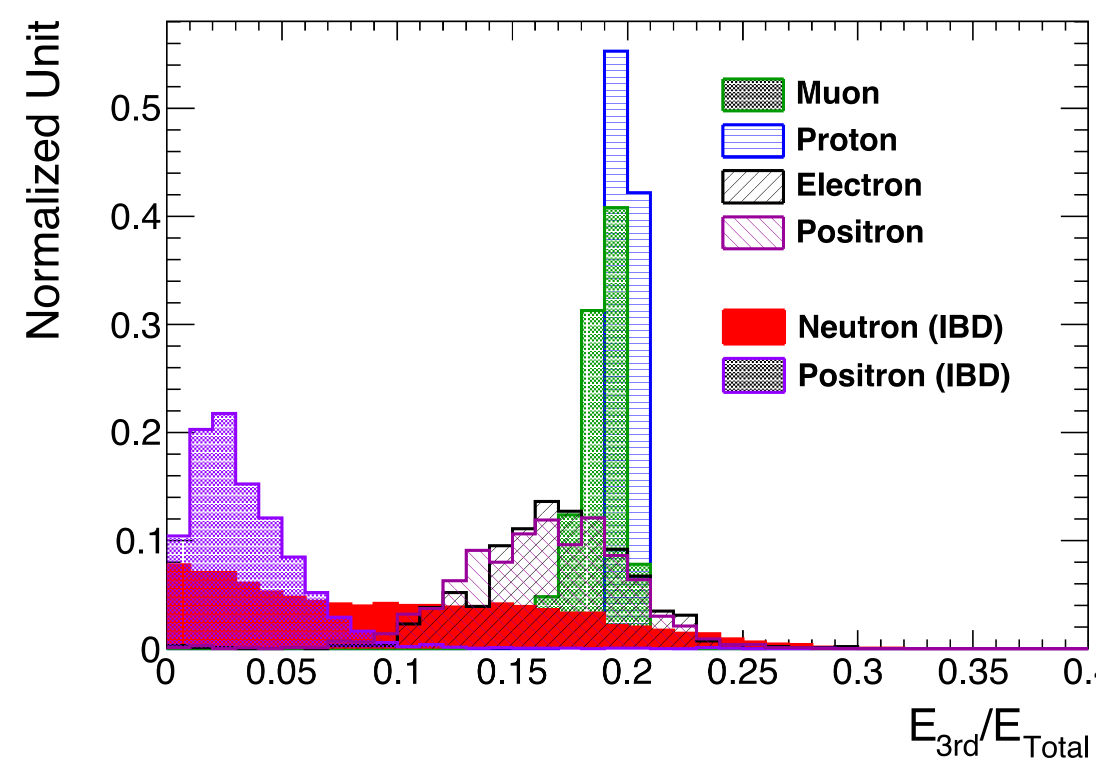
- ☑ Segmented structure of the detector gives great separation between IBD candidate events and cosmic background
- ☑ Antineutrino events and cosmic ray events have different event topology
- ☑ The energy correlation between PMT signals might be used for selecting the antineutrino events
- ☑ Number of photoelectron (PE) correlations between PMTs are expected quite to be different.

Cosmic Background Suppression

- E_{1st}/E_{Total}, E_{2nd}/E_{Total} and E_{3rd}/E_{Total} distributions of antineutrino events and cosmic rays events are shown
  - E_{1st}, E_{2nd} and E_{3rd} are the highest, the second highest and the third highest energy deposits among the all modules. E_{Total} is the total energy deposit.
- IBD event and cosmic background events show quite different distributions.

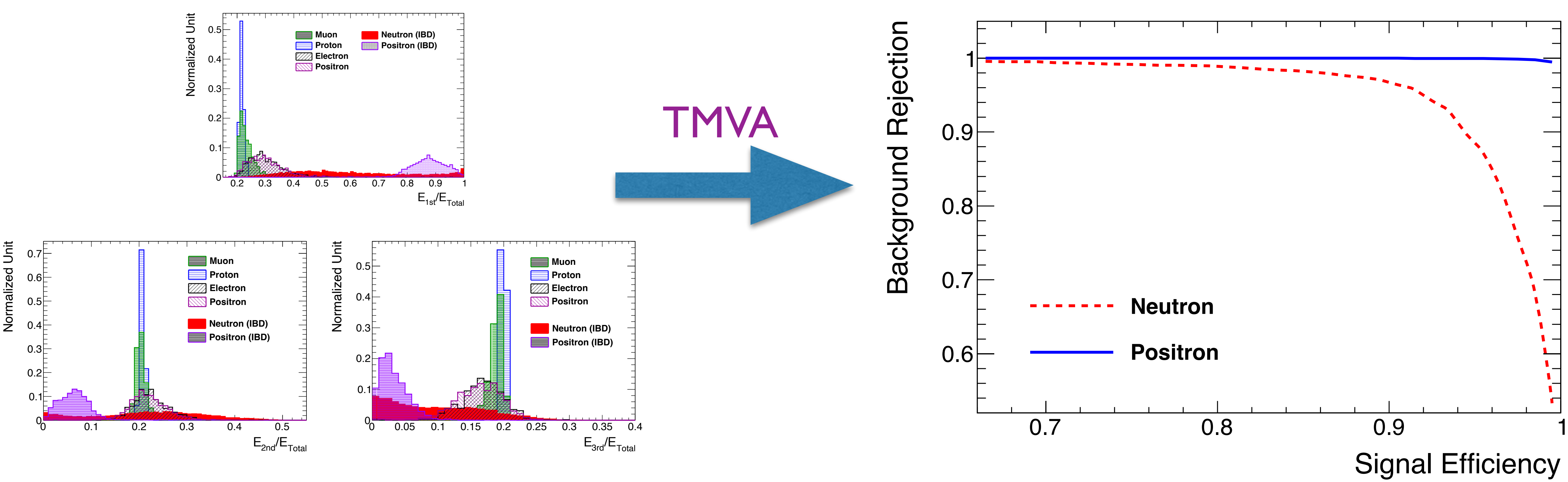






Multivariate Analysis

- Generally, using several variables at the same time could improve background rejection significantly.
- TMVA is used to combine E_{1st}/E_{Total}, E_{2nd}/E_{Total} and E_{3rd}/E_{Total} distributions.
- Signal comes from thermal neutron capture, background is taken as the sum of all considered cosmic particles.
- Boosted Decision Tree is chosen as a multivariate discriminant.
  - ✓ Likelihood or Artificial Neural Networks methods could also be used.



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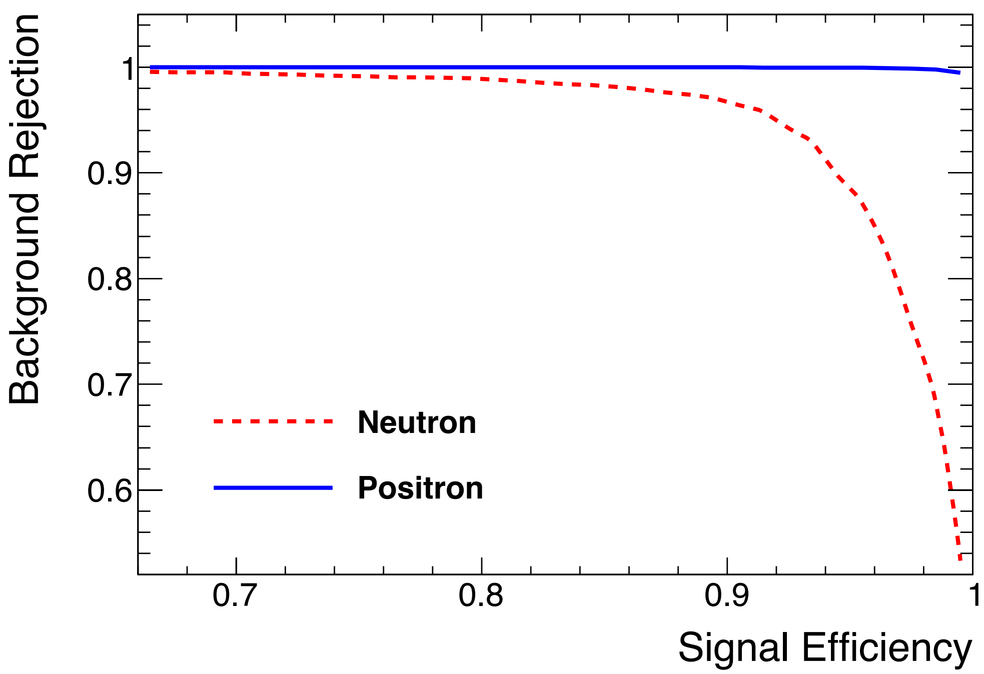
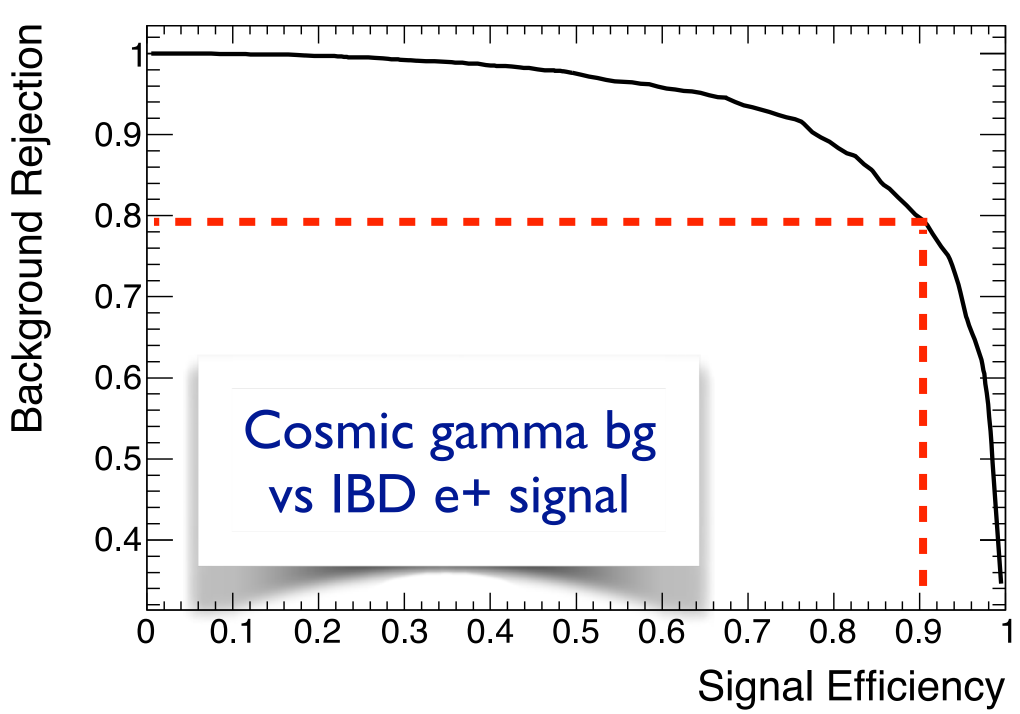
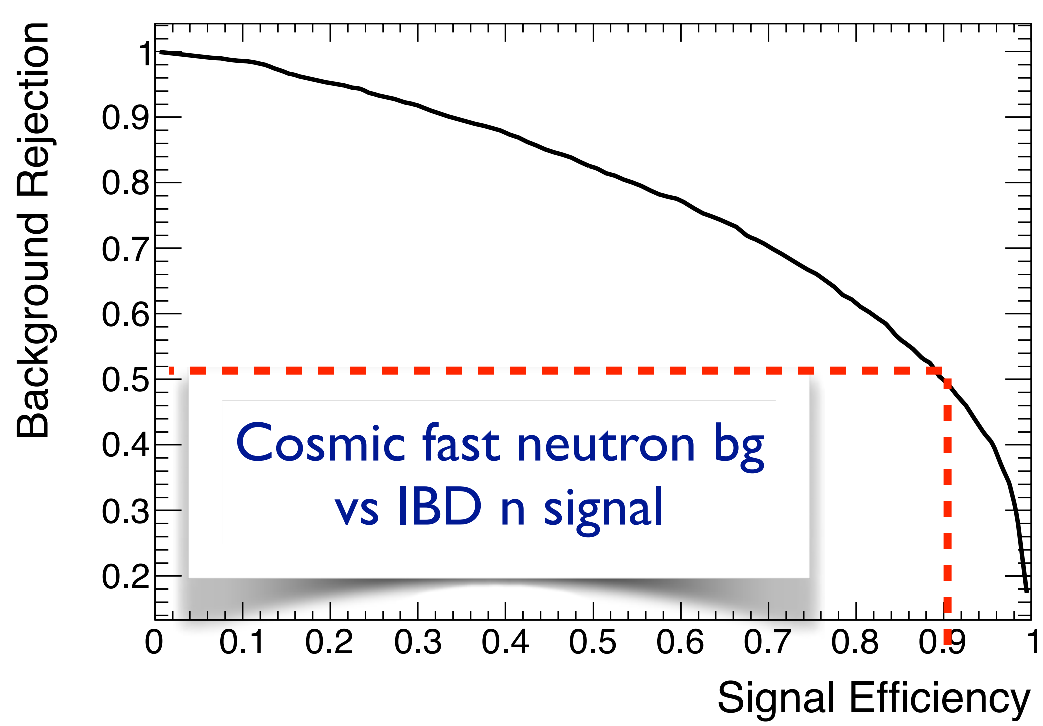
Multivariate Analysis (II)

- It was found that about 95% of charged cosmic background rejection appears to be achievable while keeping 95% of the antineutrino events.
  - ✓ Not requiring any active shielding parts.
- The same approach is used for fast neutron and gamma background rejection.
  - ✓ It is not efficient as charged cosmic bg rejection, but still improves bg suppression







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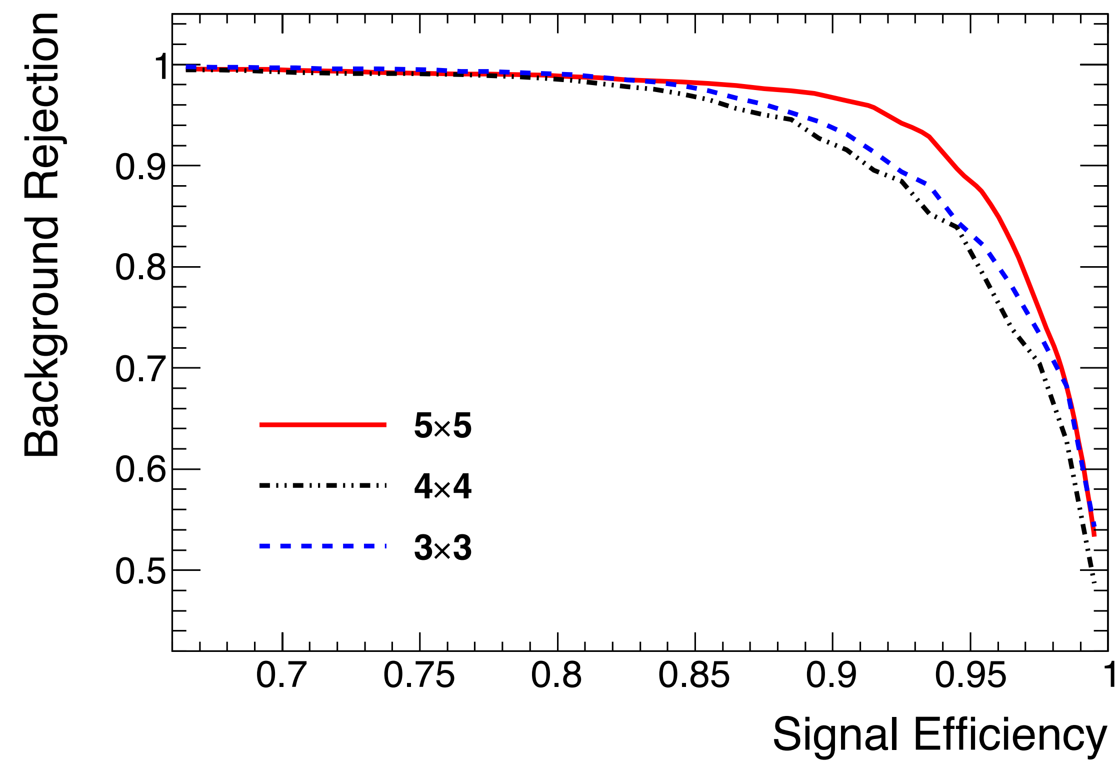
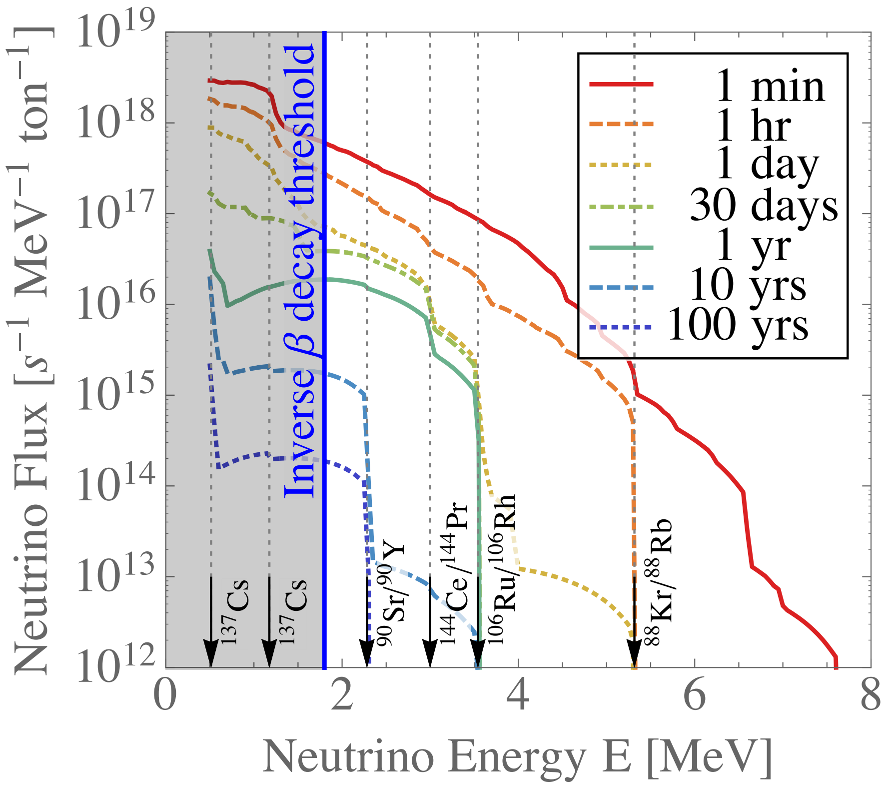
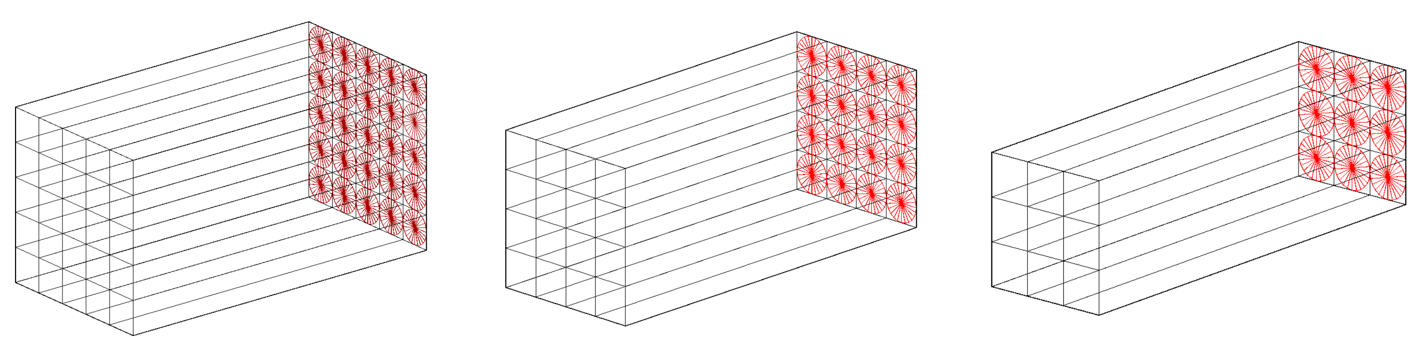
Module Number Dependency

- The effect of detector size and module numbers have also been investigated.
  - MVA technique is also can be used with lower number od modules.
  - Nuclear waste monitoring as well.







5x5
25 modules

4x4
16 modules

3x3
9 modules

Documentation

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Nuclear reactor monitoring with gadolinium-loaded plastic scintillator modules

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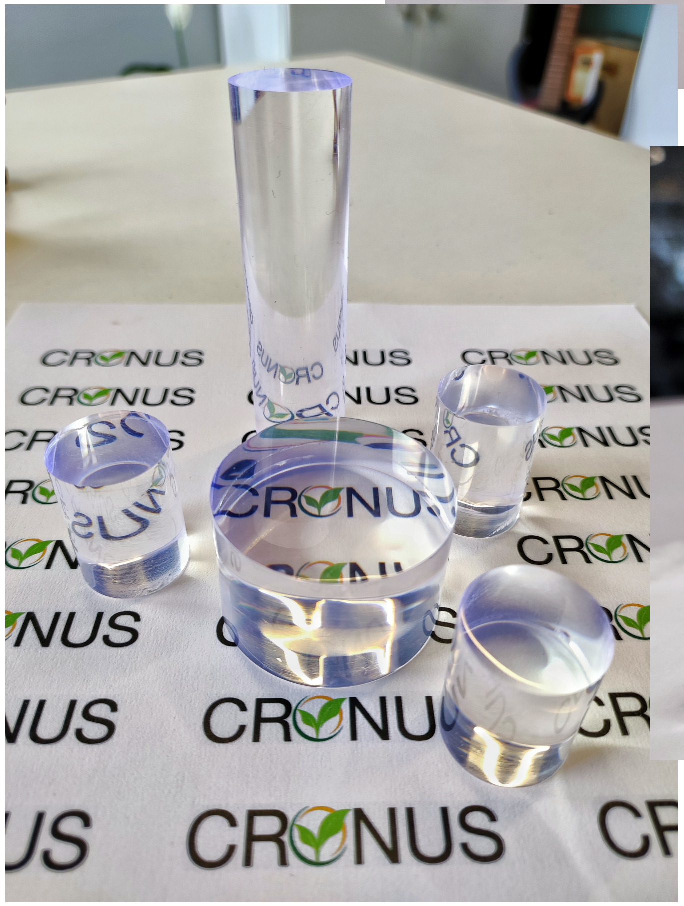
ABSTRACT

In this study, simulation-based design and optimization studies of a gadolinium-loaded segmented plastic scintillator detector are presented for monitoring applications of nuclear reactors in Turkey using antineutrinos. For the first time in the literature, a multivariate analysis technique is introduced to suppress cosmic background for such a reactor antineutrino detector.

- Published in Nim A.
  - ✓ https://doi.org/10.1016/j.nima.2019.163314
- There are no commercial Gd-loaded plastic scintillator sale.
- Gd-loaded plastic scintillator synthesis is the key point.

Synthesis of Plastic Scintillators

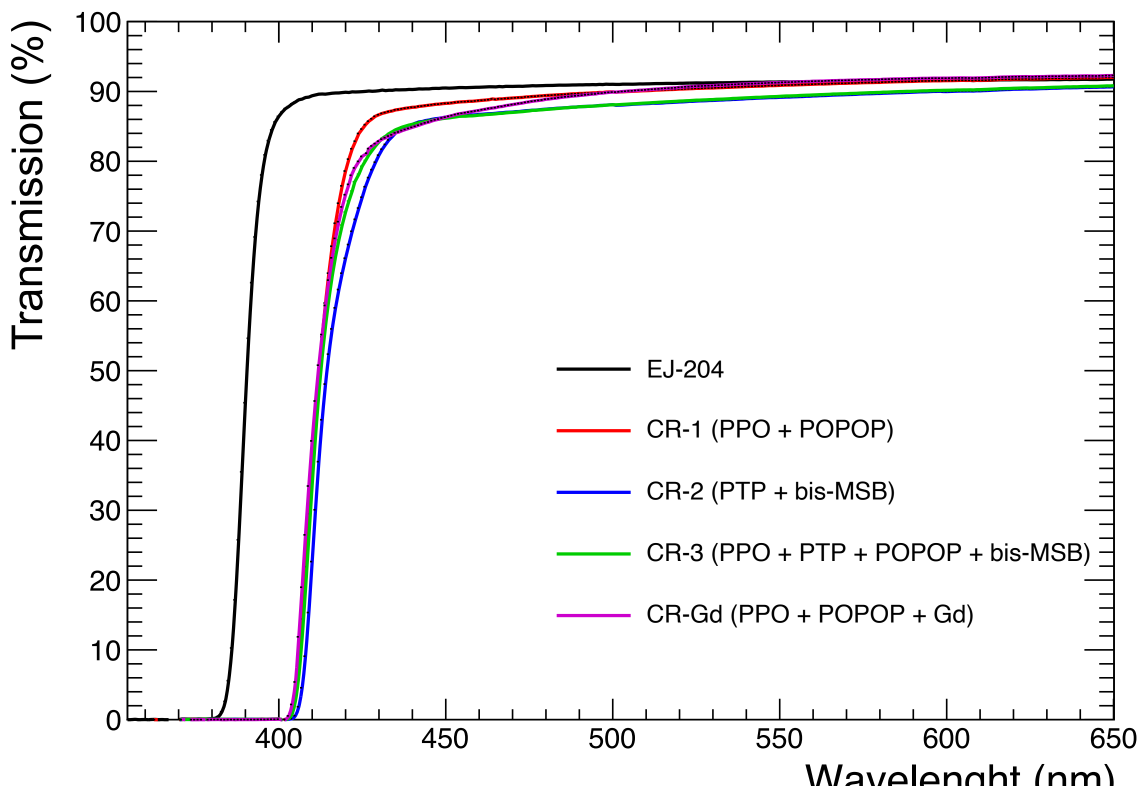
- Synthesis of regular and Gd-loaded plastic scintillator synthesis have been done.
- A typical plastic scintillator consists of three components:
  - polymer base, primary fluor (first additive), and wavelength shifter (second additive).
- Gd additive could be salt, organometallic or nanoparticles.
  - Transparency problem for nanoparticles
- The plastic scintillator samples are produced using the thermal bulk polymerization technique.
  - Size and shape limitation
- CRONUS Technology Comp. in Turkey

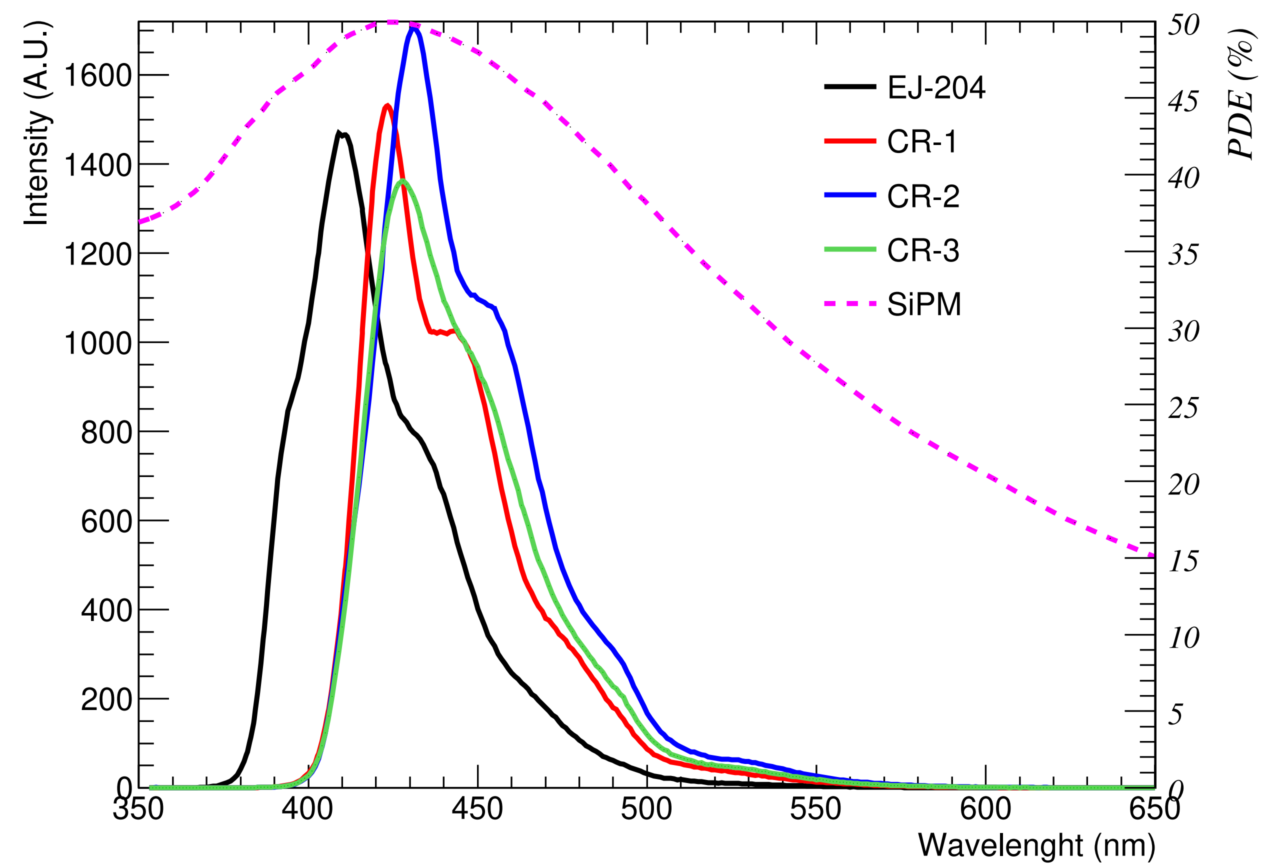


Plastic Scintillator Samples

- 4 different types plastic scintillator samples are produced.
  - Polyvinyltoulene as polimer base
  - PPO and PTP as primary flour
  - POPOP and bis-MSB as secondary flour
  - Gd(TMHD)3 as Gd additive
- Transmission rates in 1 cm length are around 85%.
- Photo detection efficiency at the emission peak values of the scintillator samples vary maximum 1%.

Sample	Primary Flour	Wavelenght Shifter
CR-1	1.5% PPO	0.08% POPOP
CR-2	1.5% PTP	0.08% bis-MSB
CR-3	0.75% PPO + 0.75% PTP	0.04% POPOP + 0.04% bis-MSB
CR-Gd	1.5% PPO	0.08% POPOP + 0.2% Gd(TMHD)3





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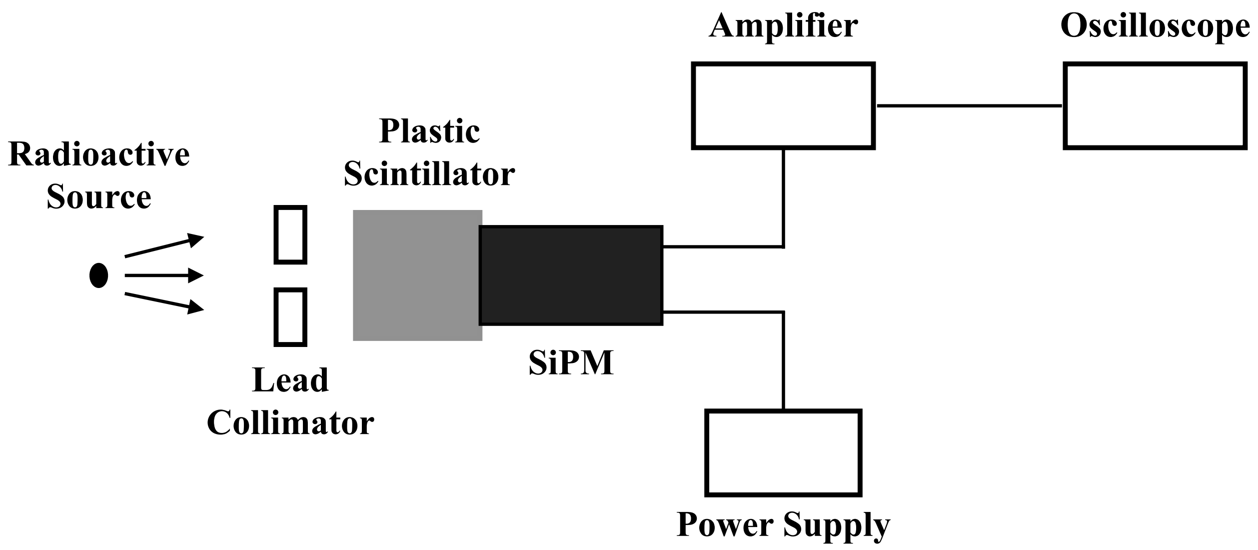
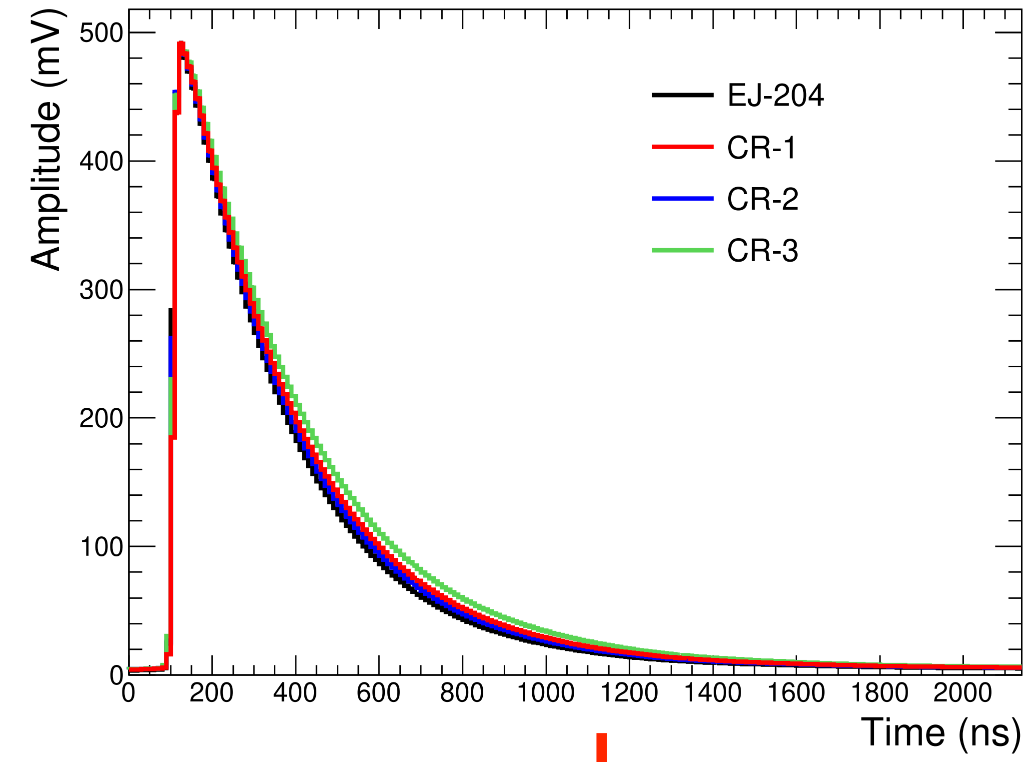
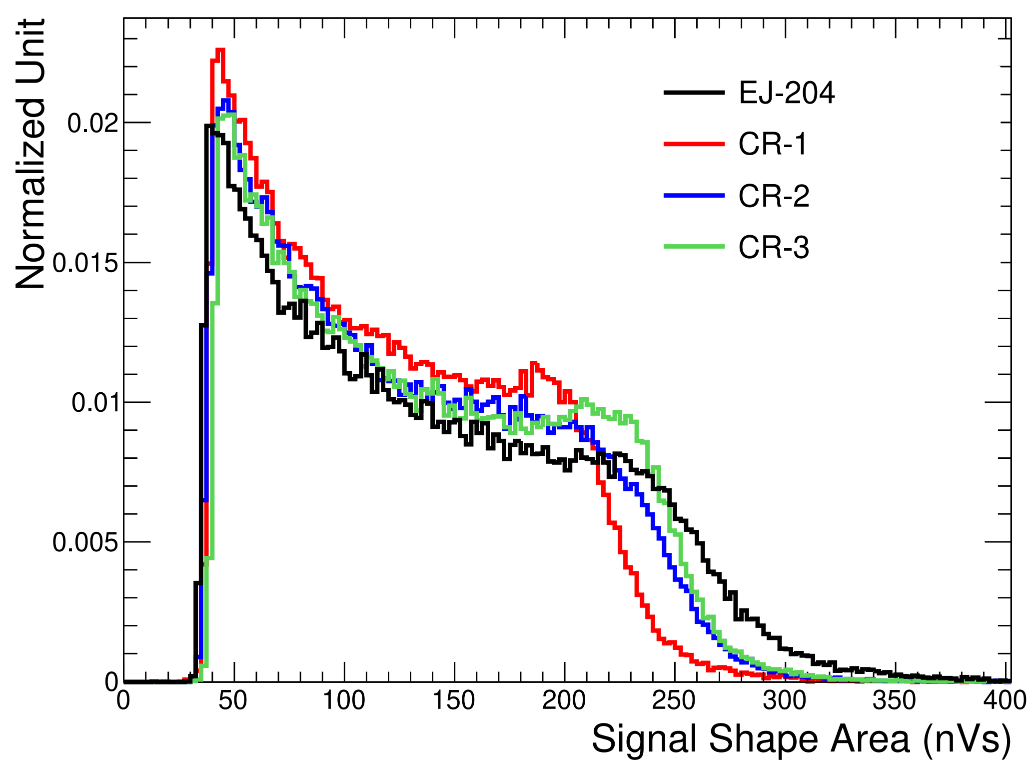
Light Yield Measurement

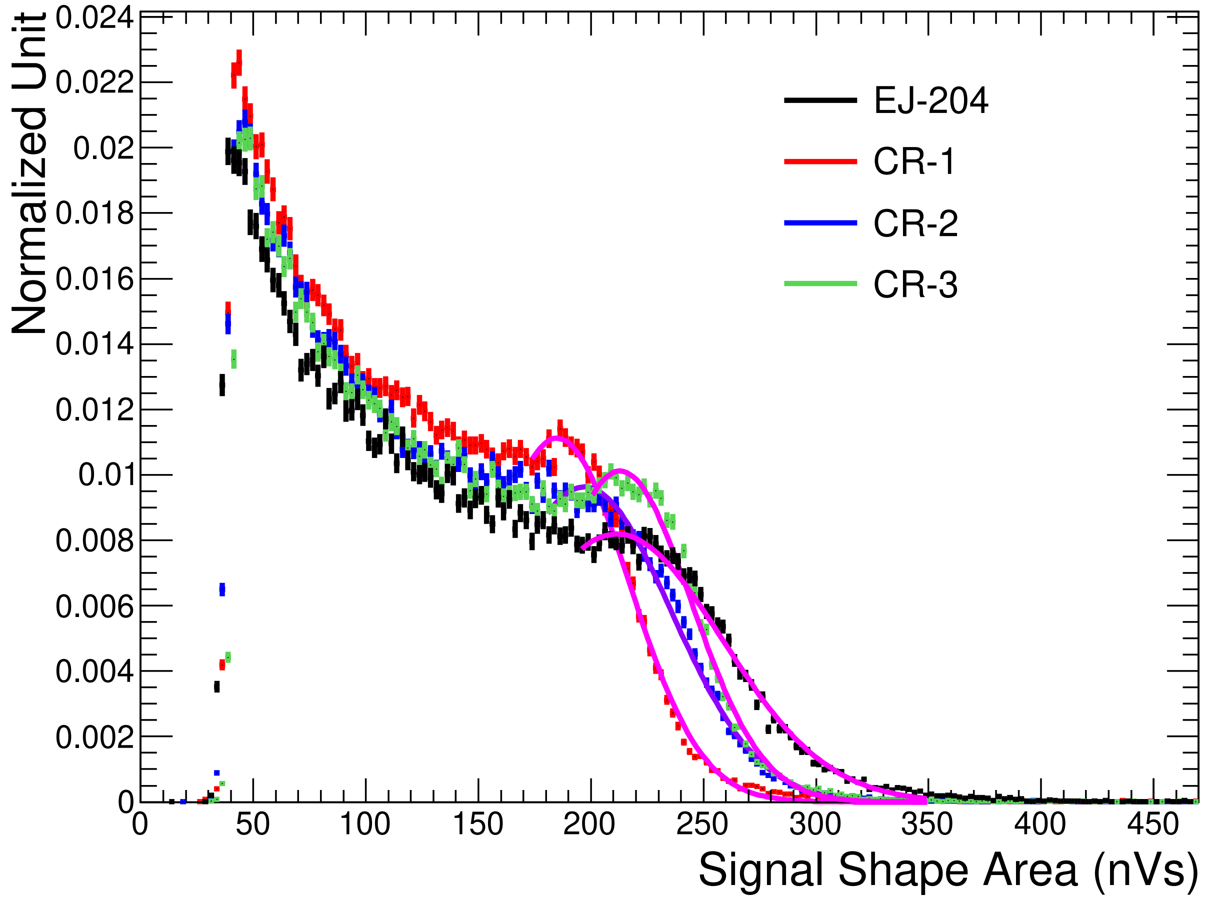


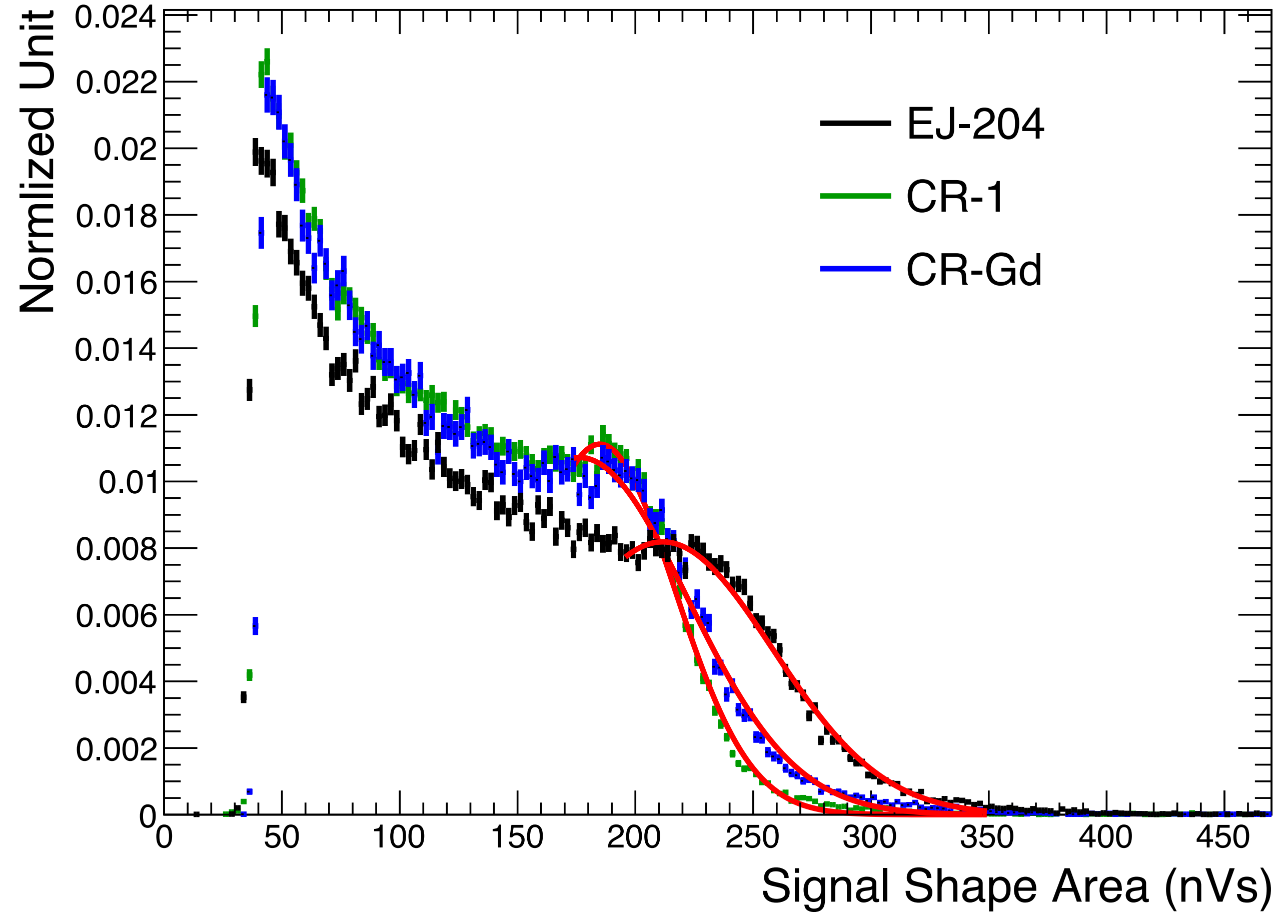




- 10x10x10 mm^3 cube size
- Onsemi J-series SiPM with the size of 6×6 mm (MICROFJ-60035-TSV)
- Cs-137 as a radioactive source
  - ✓ Clear shape of compton-edge
- The compton- edge region in the energy distribution is fit with the Gaussian function and specific % values in the energy tail of the peak are taken.

Light Yield Results





Samples	Rel. LY @ 90%	Rel. LY @ 80%	Rel. LY @ 70%	Rel. LY @ 60%	Rel. LY @ 50%	LY
EJ-204	100	100	100	100	100	10400
CR-1	85.73	85.08	84.40	83.88	83.43	8788 ± 38
CR-2	92.23	91.73	91.41	91.27	90.97	9518 ± 20
CR-3	97.77	96.42	95.35	94.72	93.74	9943 ± 65
CR-Gd	84.63	85.27	85.57	85.98	86.22	8895 ± 26

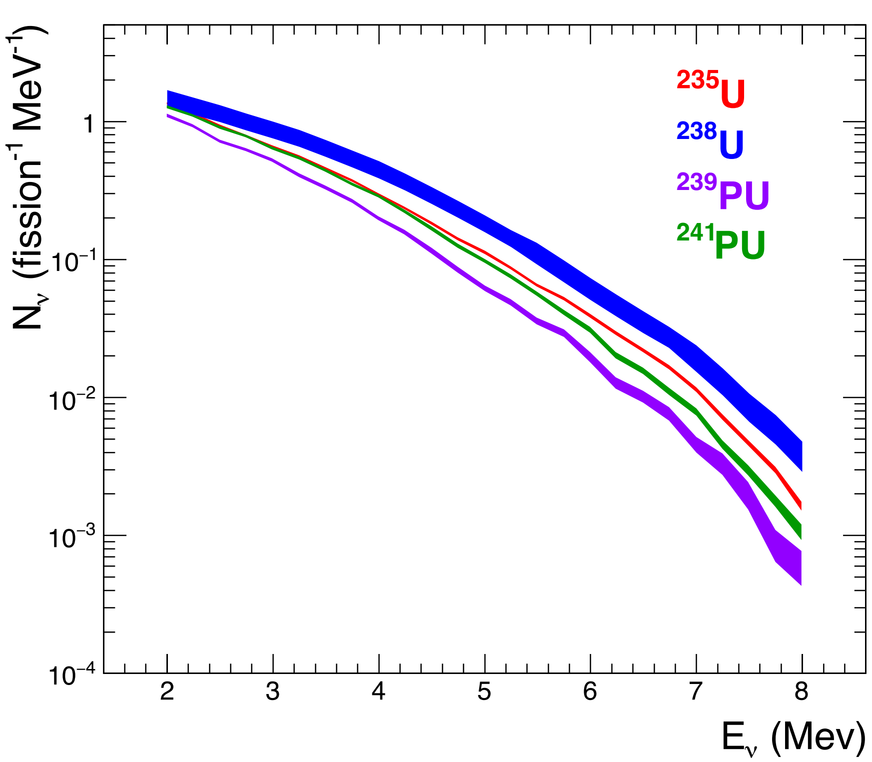
Prospects and Conclusion

- Nuclear reactors and nuclear technology will be active in Turkey in the next years.
- Monitoring these reactors independently and reactor antineutrino energy spectrum measurements are the main purposes.
- The effort for production and characterization of gadolinium loaded plastic scintillator has been started.
  - ✓ Gd-loaded plastic scintillator samples with CR-3 content (PPO + PTP + POPOP + bis-MSB)
  - ✓ Neutron radioactive source
- It is planned to submit projects funding to produce a demonstration module.
  - ✓ 25 segments with the each size of 5x5x40 cm
  - ✓ GEANT4 simulation using ERNIE: A reactor antineutrino inverse beta decay event generator (https://doi.org/10.17632/grk8256yr6.1)
  - ✓ Machine learning using PyTorch

Backup

Reactor Neutrinos

- A nuclear reactor is an intense source of antineutrinos.
  - ✓ 6 ν_e / fission
  - ✓ ~$2\times10^{20}\nu_e$/s for P_{th} = 1 GW
- Measuring antineutrino flux from a nuclear reactor can provide real time information of the status of the reactor and its thermal power.
- The thermal power produced in the fission process is directly related with emitted antineutrino flux.

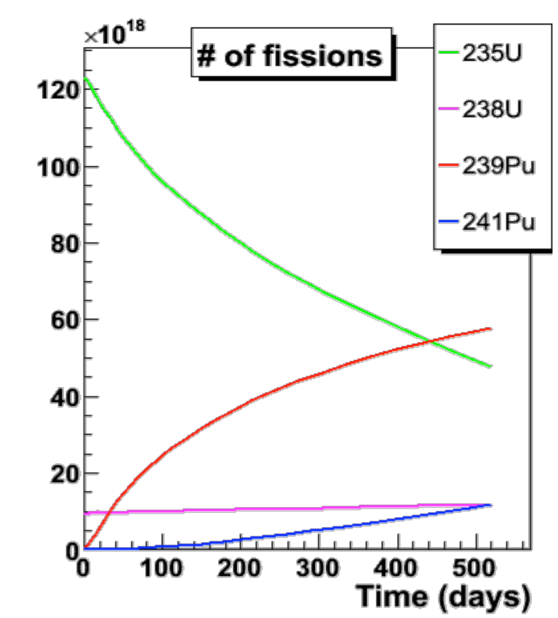


Average fission rate

$$N_f = 6.24\times10^{18}\left(\frac{P_{th}}{MW}\right)\left(\frac{MeV}{W_e}\right)s^{-1}$$

$$N_\nu = \gamma(1+k)P_{th}$$

- N_ν: measured neutrino rate
- γ: a constant depending on detector
- P_{th}: reactor thermal power



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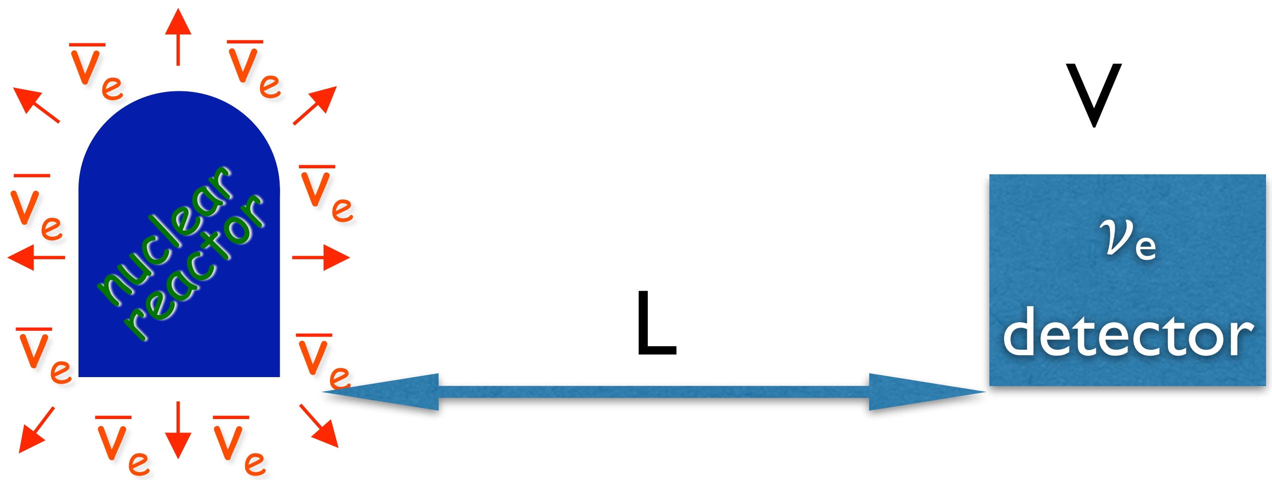
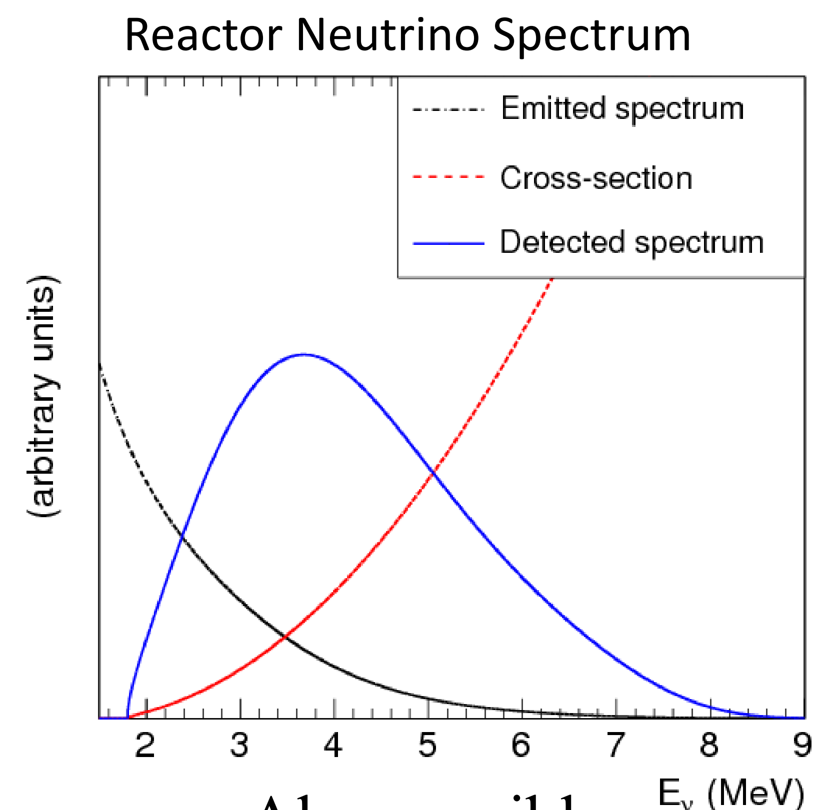
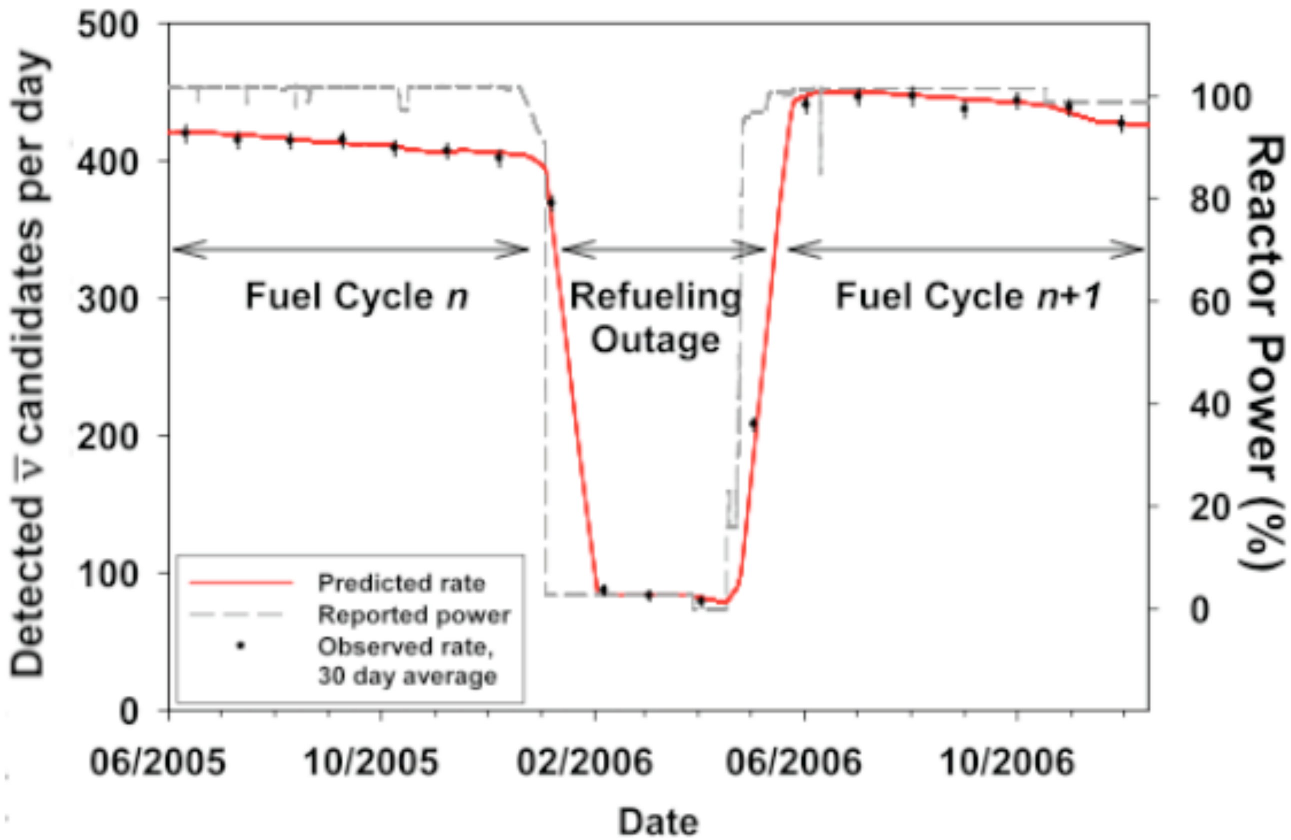
Reactor Neutrinos (II)



Inverse β Decay: $\bar{\nu}_e + p \rightarrow e^+ + n$





$$R_\nu = \frac{N_f N_p \langle \sigma \rangle}{4\pi L^2}$$

Also possible:

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

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$

- P_{th} = 3200 MWt and W_e=203 MeV for Akkuyu NPP.

  ✓ Average cross section

  $$\sigma = 5.82 \times 10^{-43}\, cm^2$$