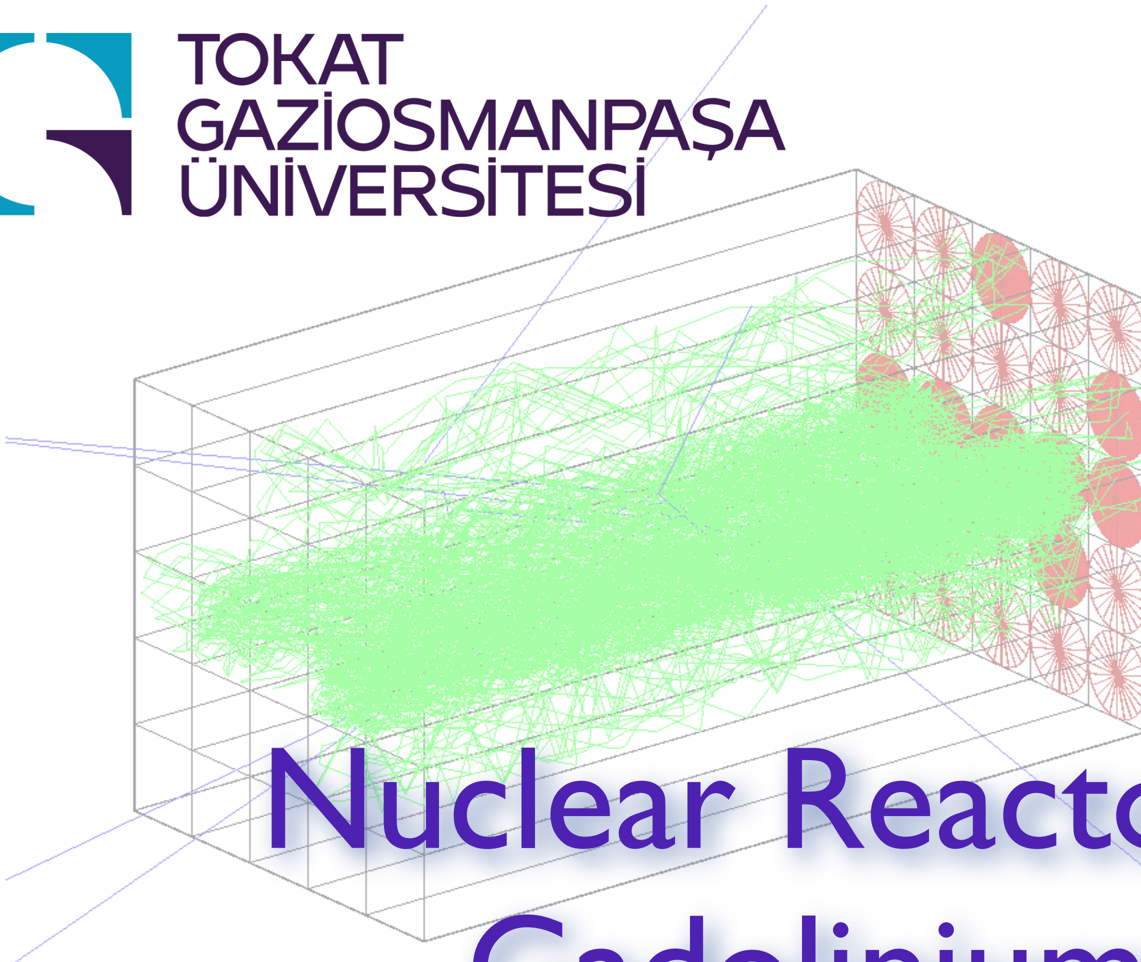
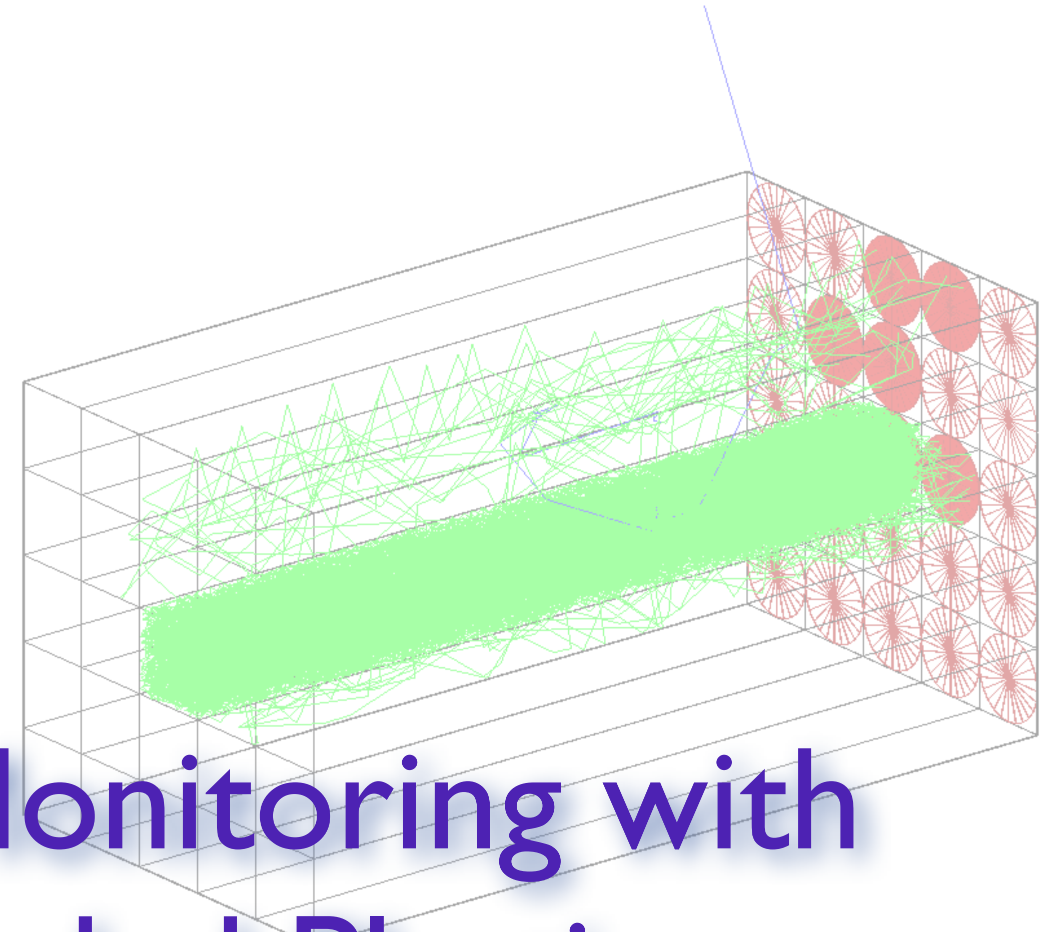
TOKAT GAZİOSMANPAŞA ÜNİVERSİTESİ





Nuclear Reactor Monitoring with Gadolinium-Loaded Plastic Scintillator Modules

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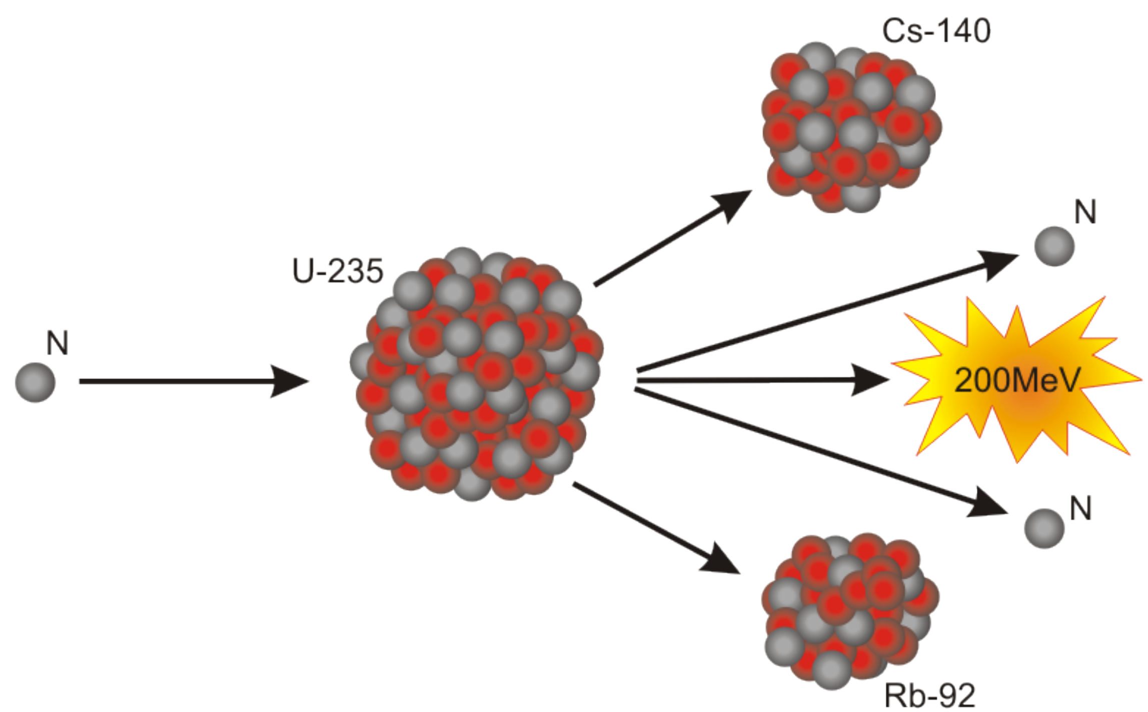
Outline

- Motivation
- Detector Design and Simulation Results
- Future Plans
- Conclusion

Nuclear Reactors in Turkey

- The first NPP construction has been recently started at Akkuyu.
  - ✓ It is planed to start operations in 2023.
  - ✓ There will be 4 power units with capacity of 1200 MWe 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.

Nuclear Fission



$$n + {}^{235}U \rightarrow {}^{140}Ba + {}^{94}Kr + 2n + 200MeV$$

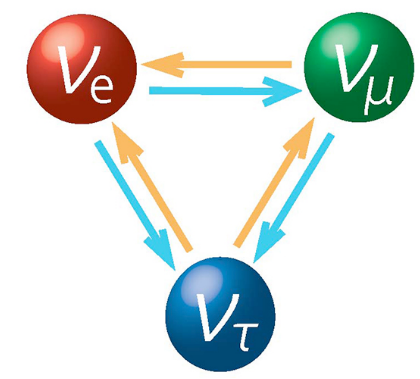
$$^{140}Ba \underset{13gün}{\overset{\beta(1MeV)}{\longrightarrow}} {}^{140}La \underset{40saat}{\overset{\beta(2.2MeV)}{\longrightarrow}} {}^{140}Ce$$

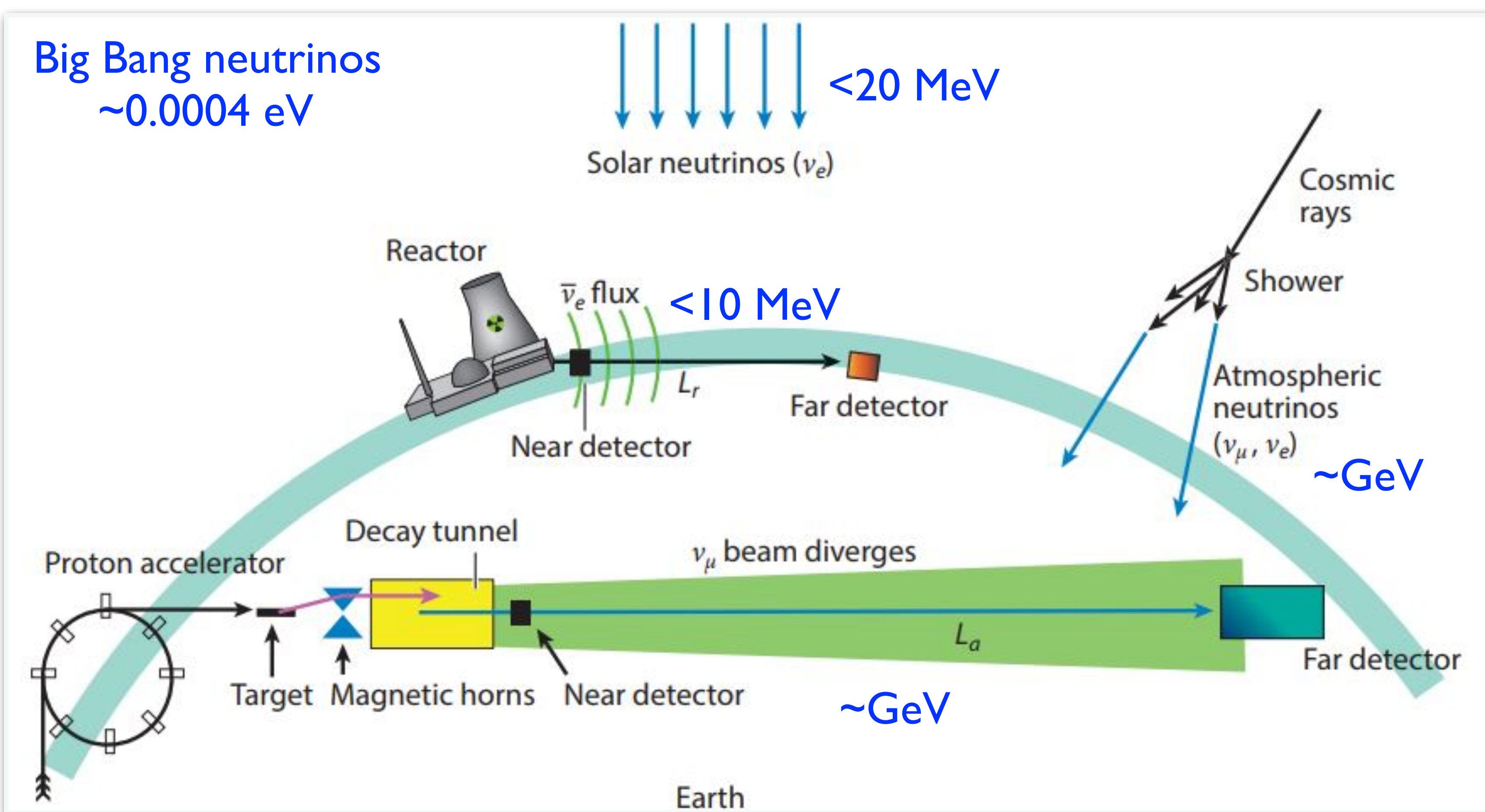
$$^{94}Kr \underset{0.2saniye}{\overset{\beta(7.5MeV)}{\longrightarrow}} {}^{94}Rb \underset{2.7saniye}{\overset{\beta(10MeV)}{\longrightarrow}} {}^{94}Sr \underset{75saniye}{\overset{\beta(3.4MeV)}{\longrightarrow}} {}^{94}Y \underset{19dakika}{\overset{\beta(4.9MeV)}{\longrightarrow}} {}^{94}Zr$$

- A NPP produce energy with nuclear fission process.
  - Splitting a nucleus into several smaller fragments.
  - The missing mass is converted into energy.
- Controlled chain reaction.
- Uranium and Plutonium as the fuel.
- In each fission chain:
  - ~ 200 MeV / fission
  - 6 ν_e / fission
- Nuclear reactors are intense sources of antineutrinos.
  - First neutrino detection from Savannah River NP was recorded by Cowan and Reines in 1956.

Neutrinos

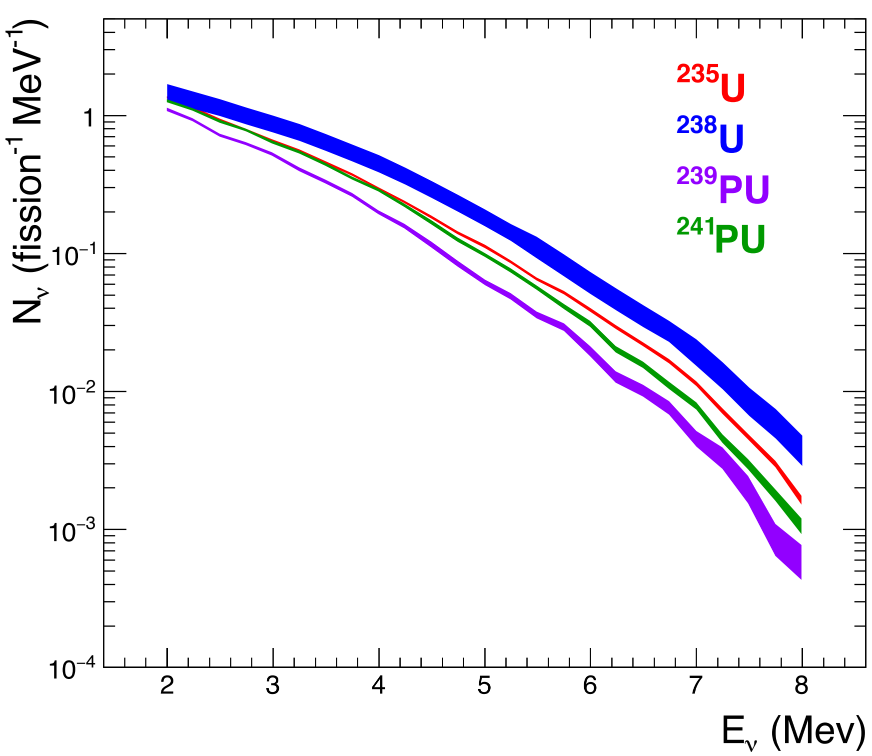
- Neutrinos are fundamental, almost massless, weak interacting particles.
  - passing though earth without any interaction.
- Neutrinos come in three flavors.
  - change its flavor (neutrino oscillation).
- Neutrinos are everywhere.
  - Coming from big bang, stars, supernovas, upper atmosphere, center of earth, nuclear reactors, …
- Each second there are about 100 billion neutrinos passing through the tip of your finger.





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

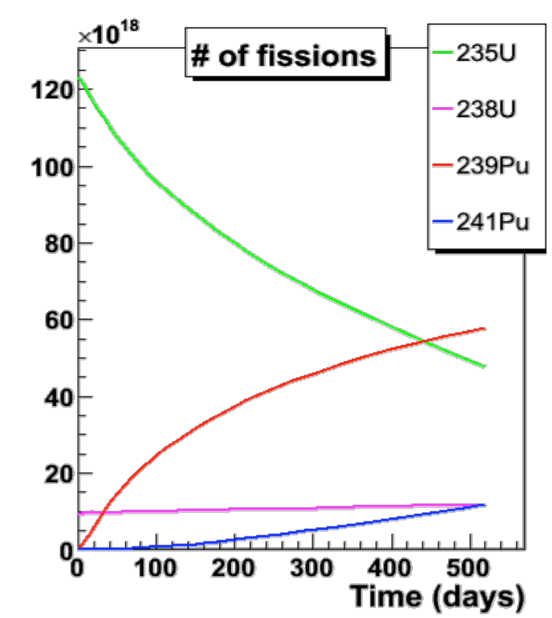
$$N_f = 6.24 \times 10^{18} (\frac{P_{th}}{MW})(\frac{MeV}{W_e}) s^{-1}$$

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

a constant depending on detector

reactor thermal power

measured neutrino rate



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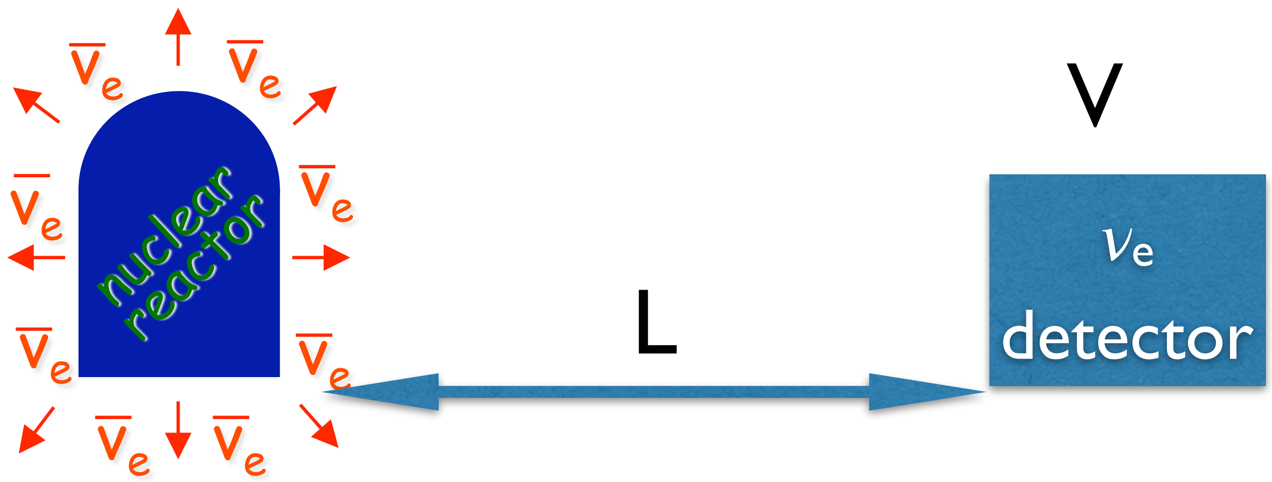
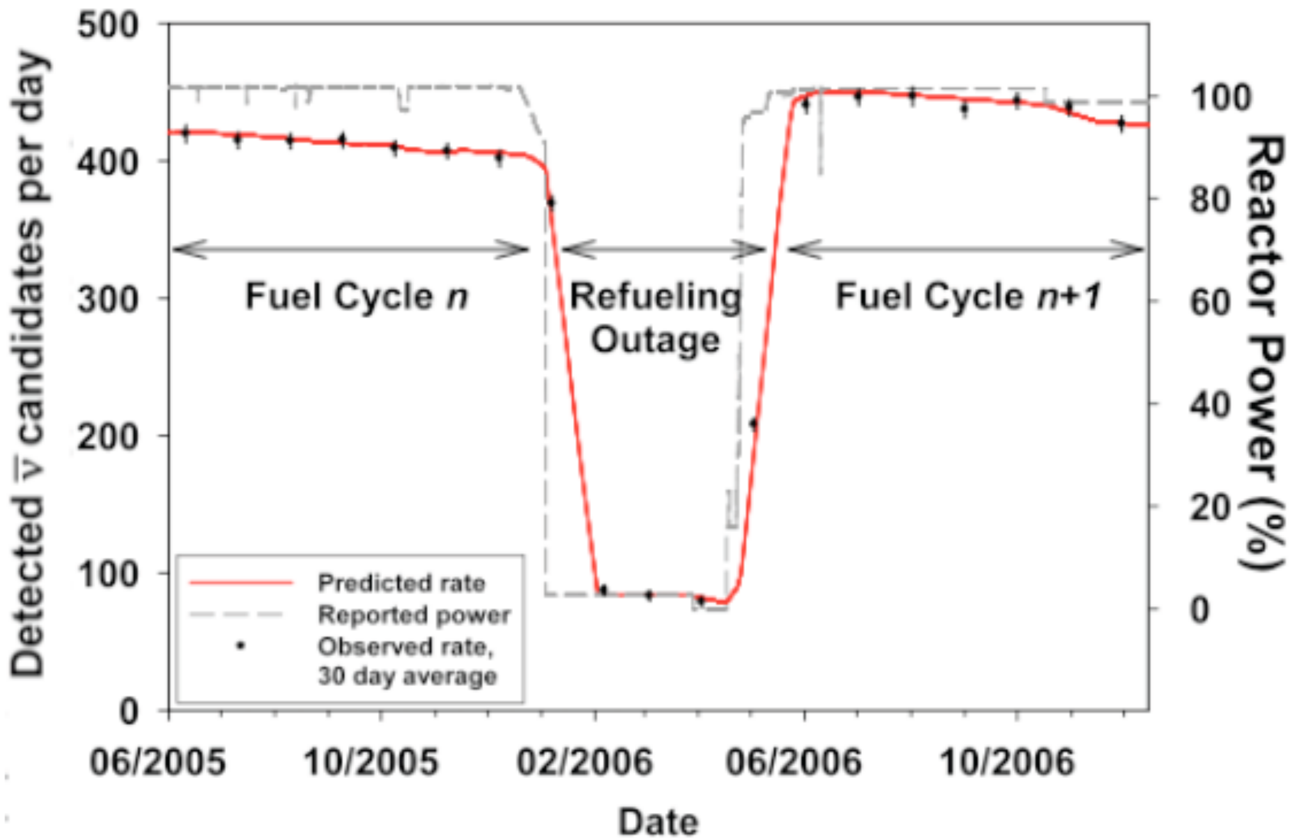
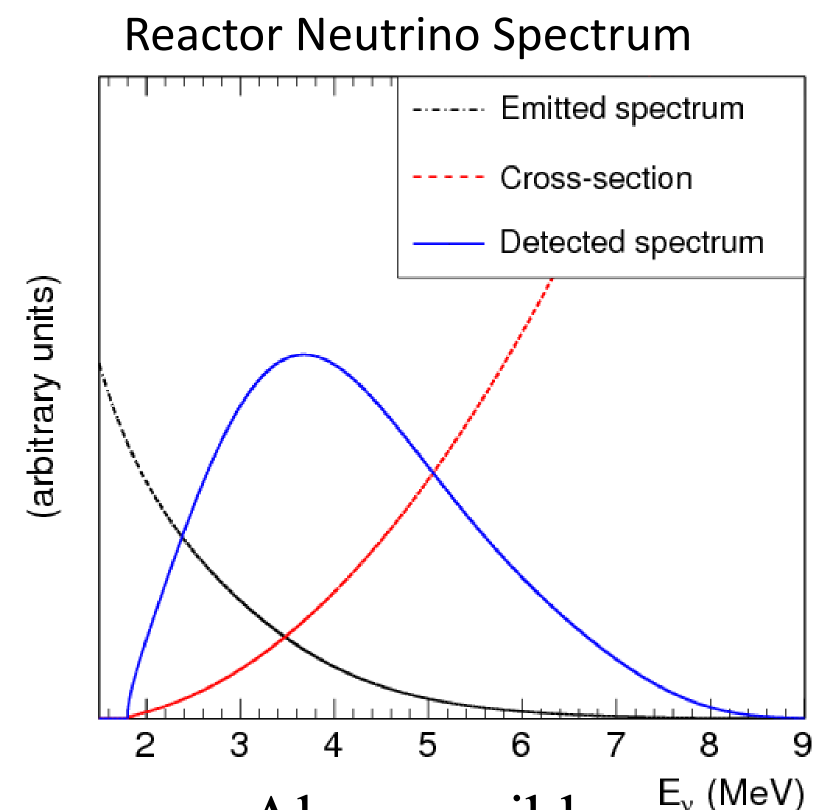
Reactor Neutrinos (II)





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

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



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

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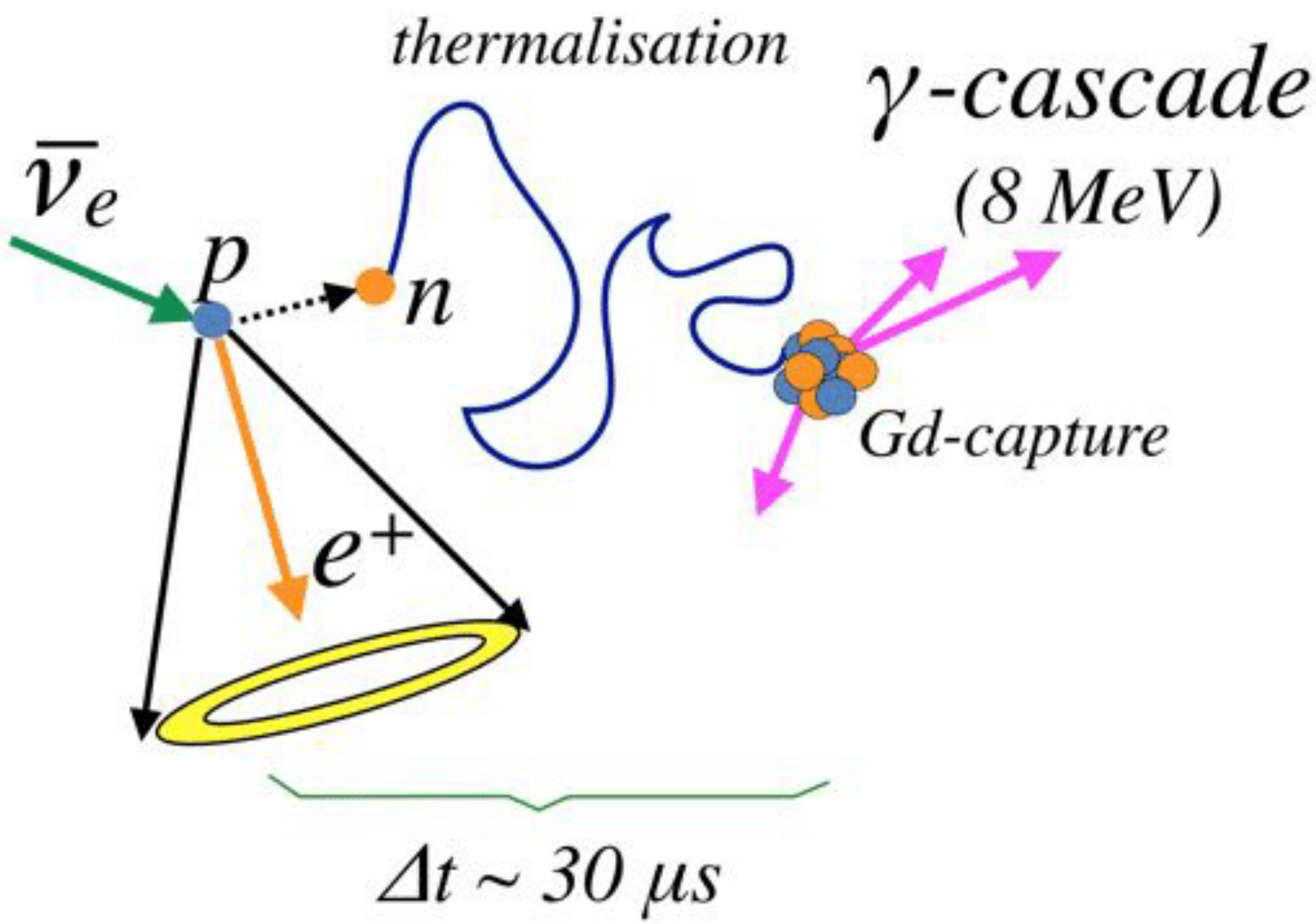
Signal Reconstruction

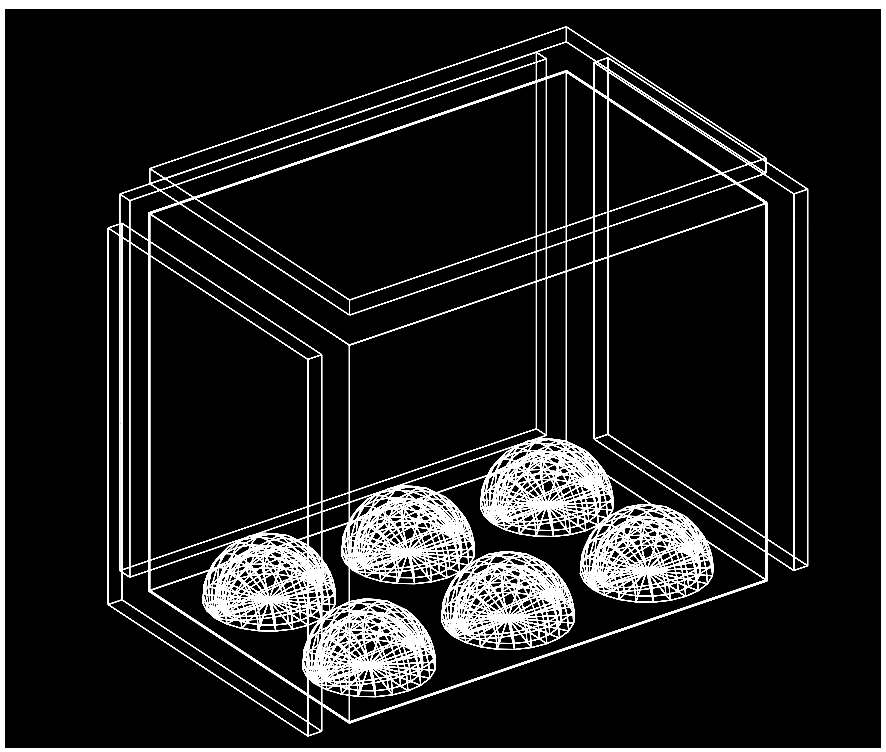


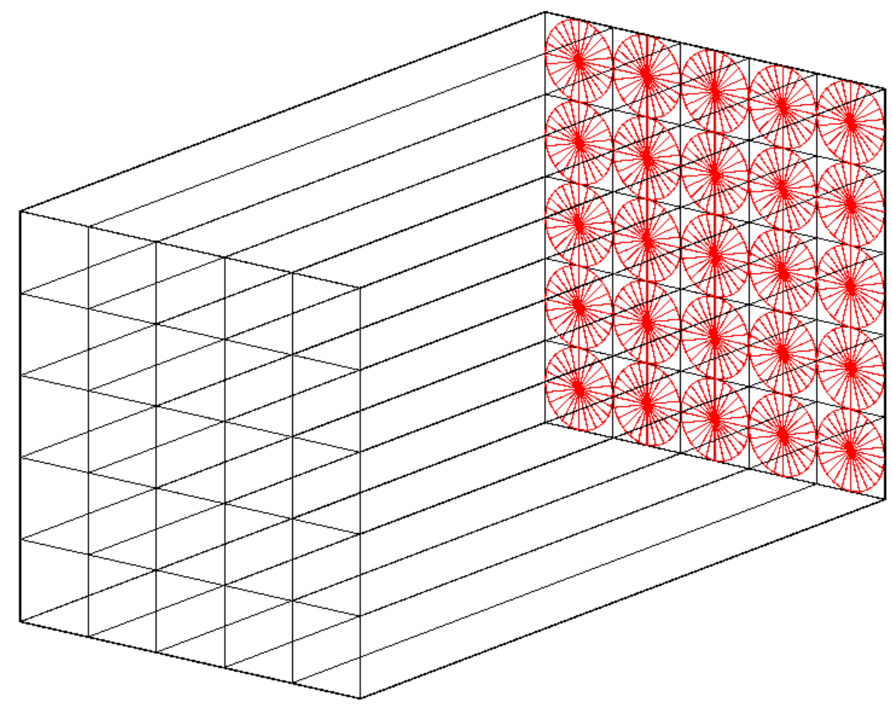
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

- Prompt signal positron 1~12 MeV
- Delayed signal γ cascade from thermal neutron capture ~8 MeV
- Time delay 20-80 μs.

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)



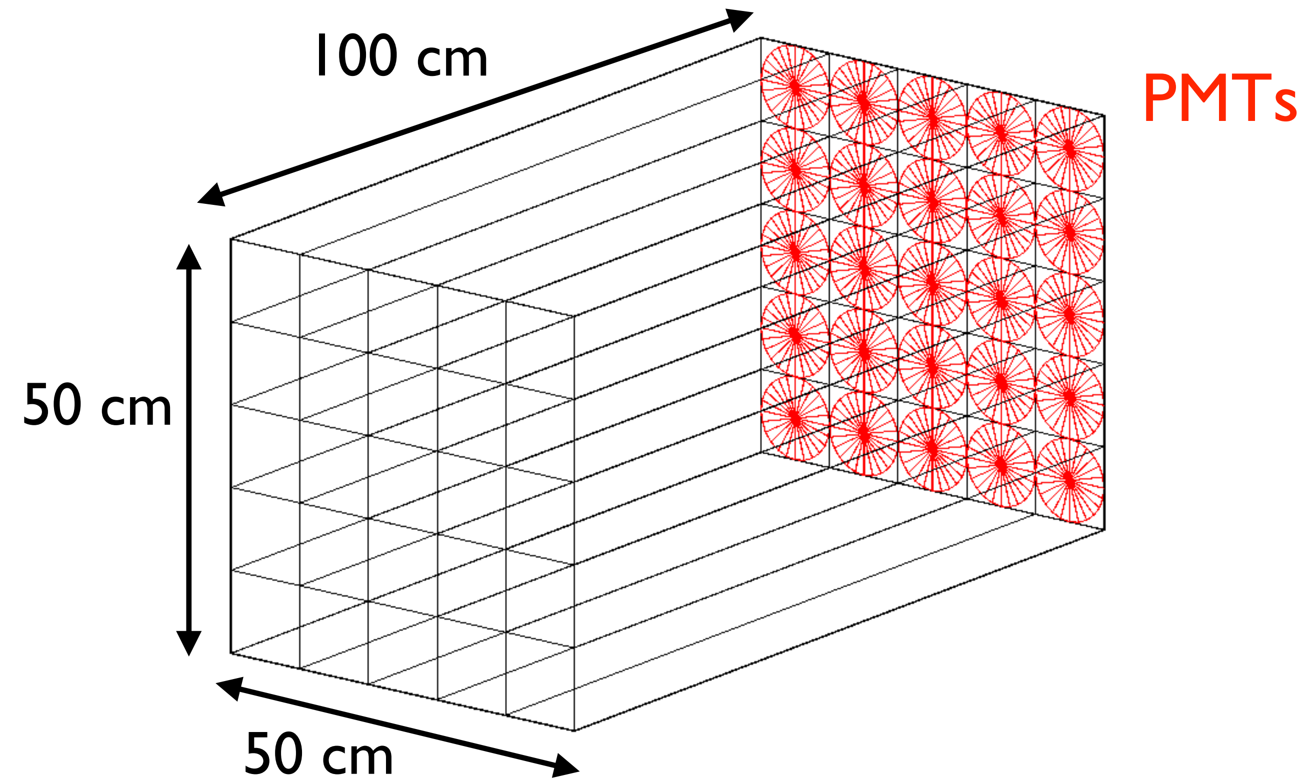


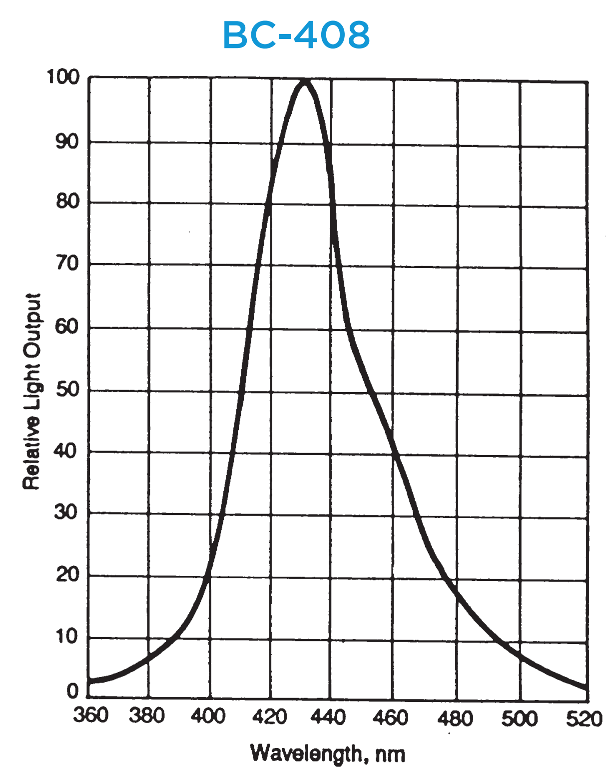
- Easier to construct
- Cheaper

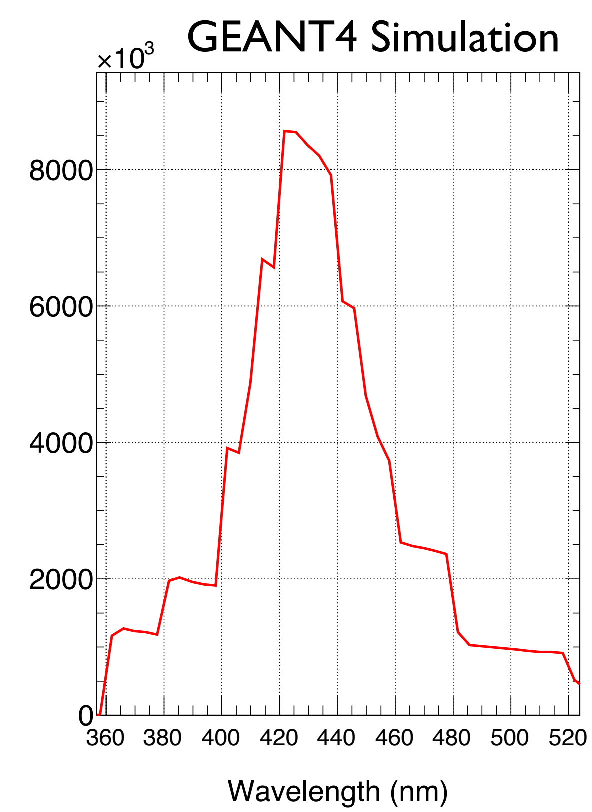
- Better mobility
- Great background suppression

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.

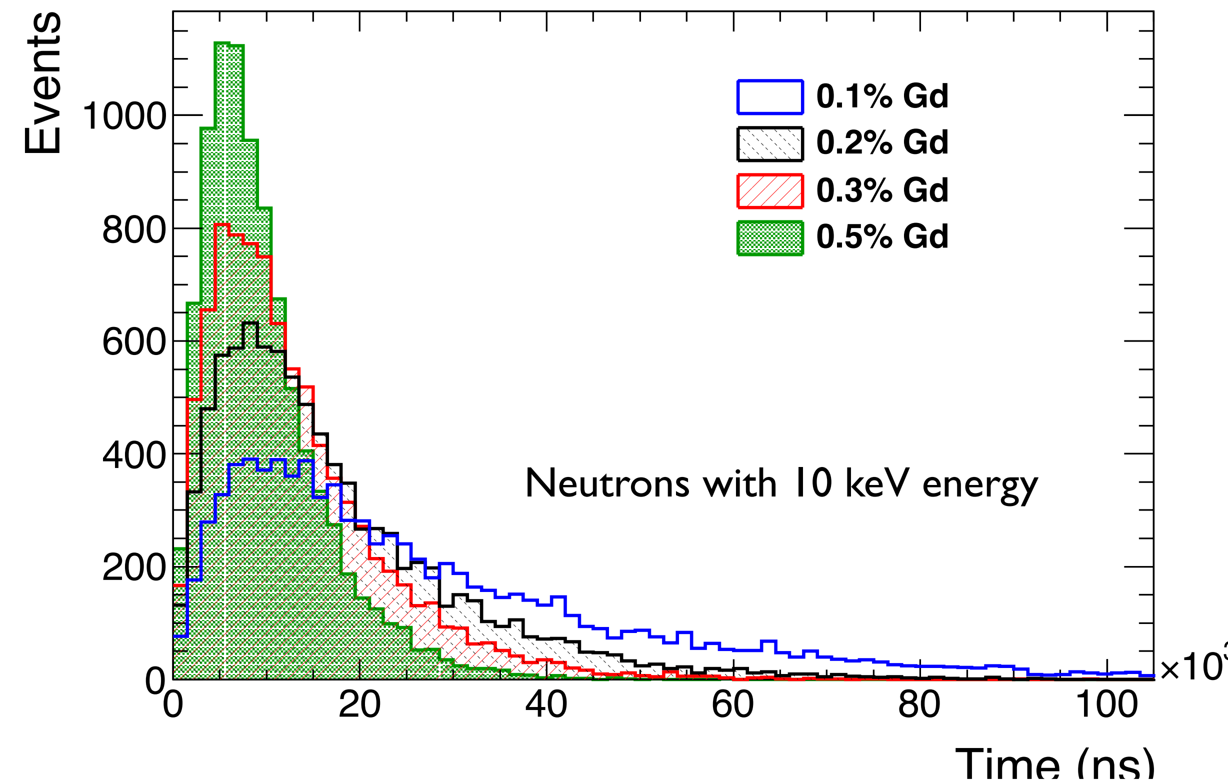


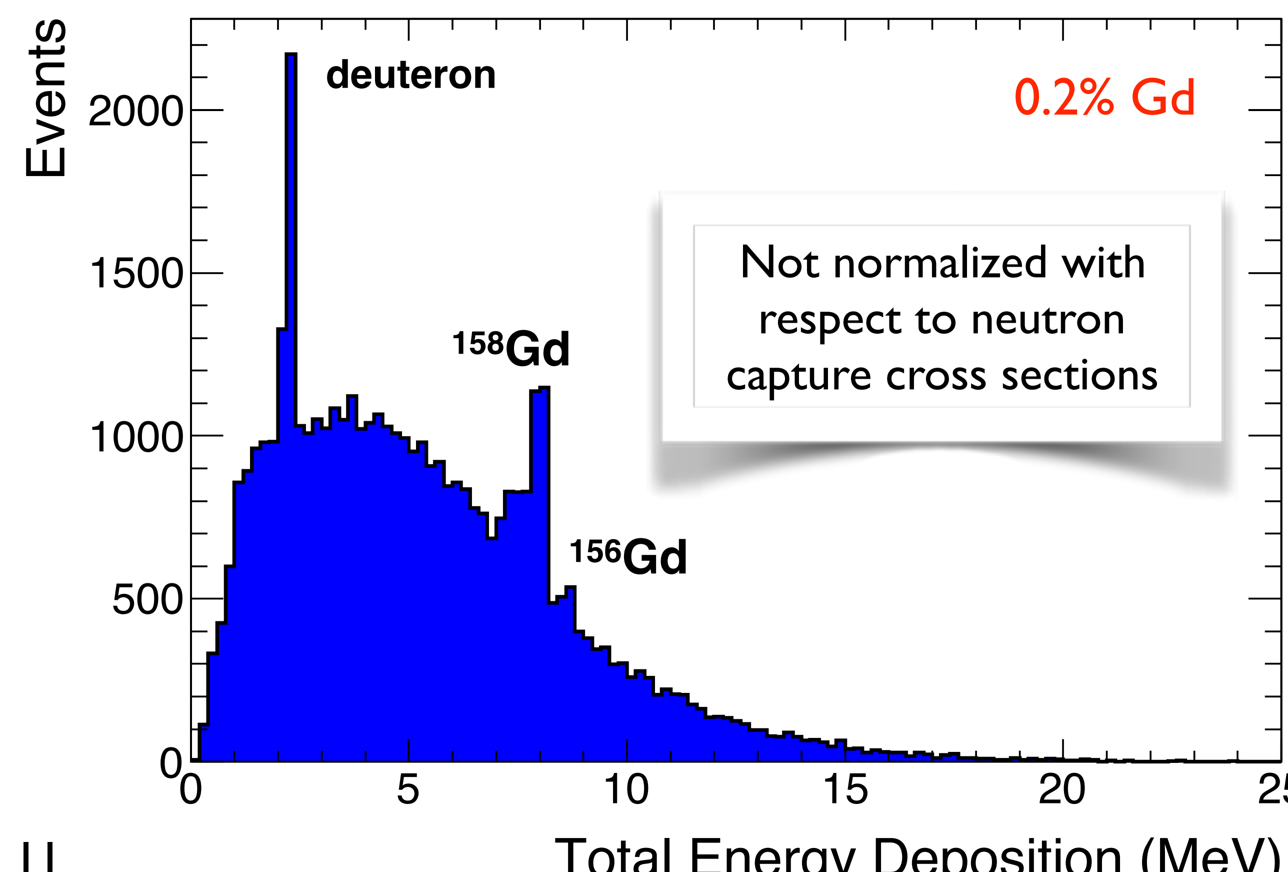




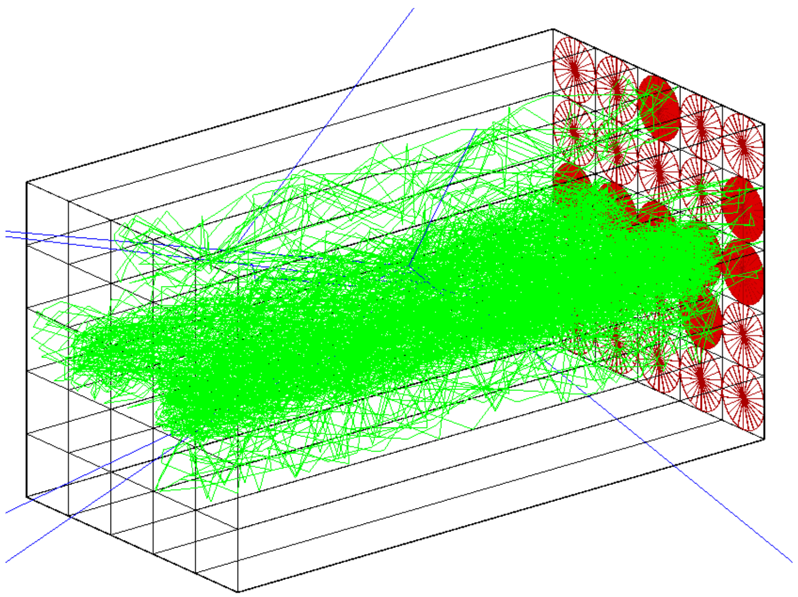
Gadolinium-loaded Plastic Scintillators

- Gd-loaded plastic scintillators were successfully synthesized and produced.
- 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.

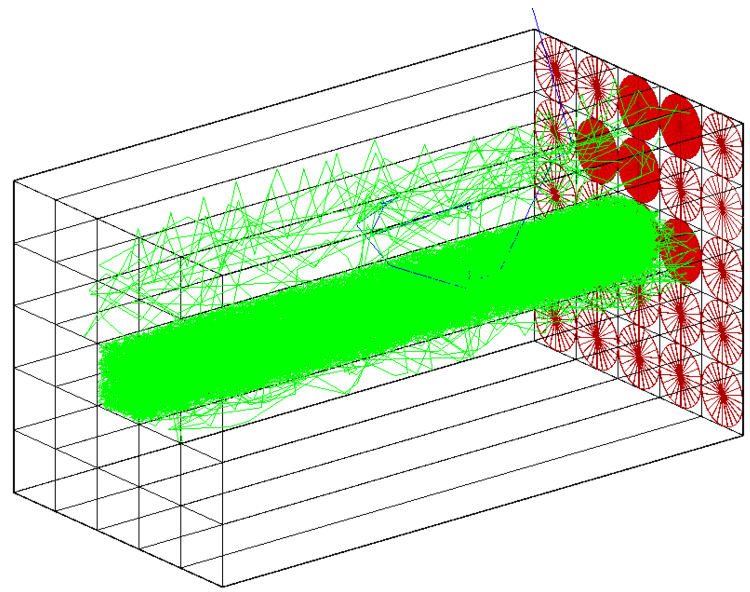




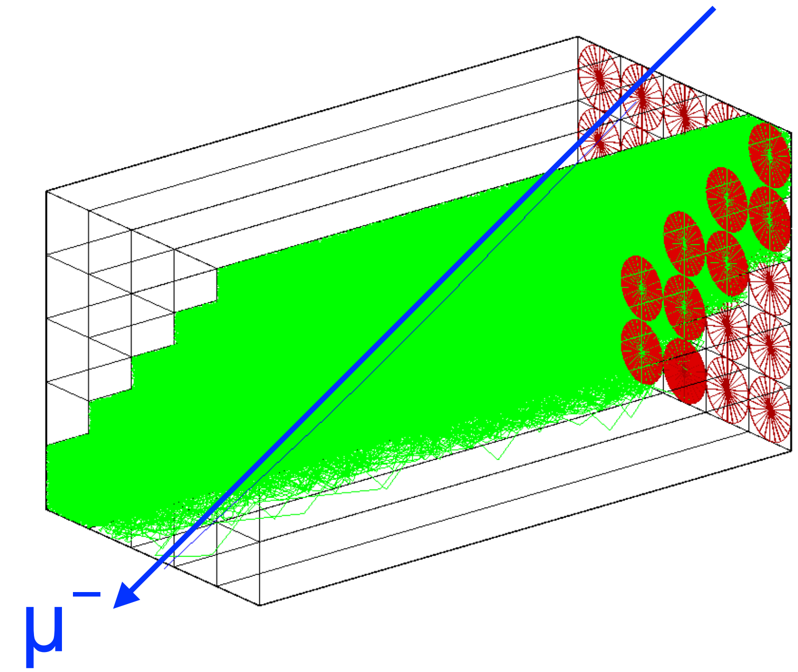
Event Topologies



10 keV neutron



5 MeV positron

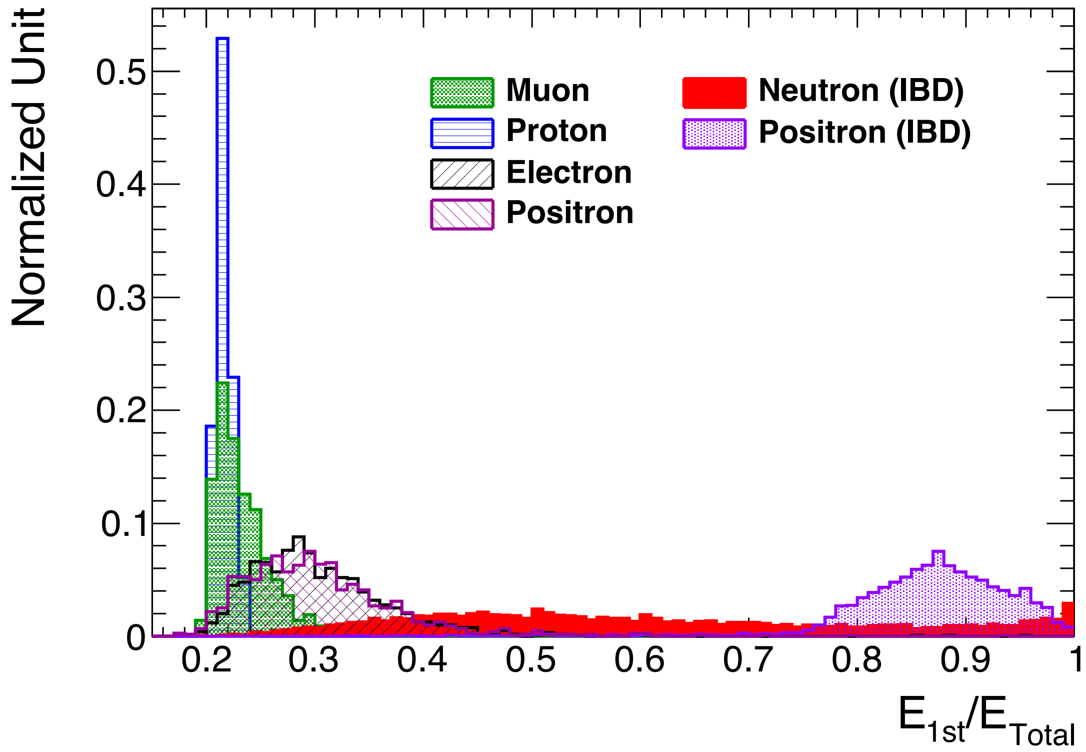


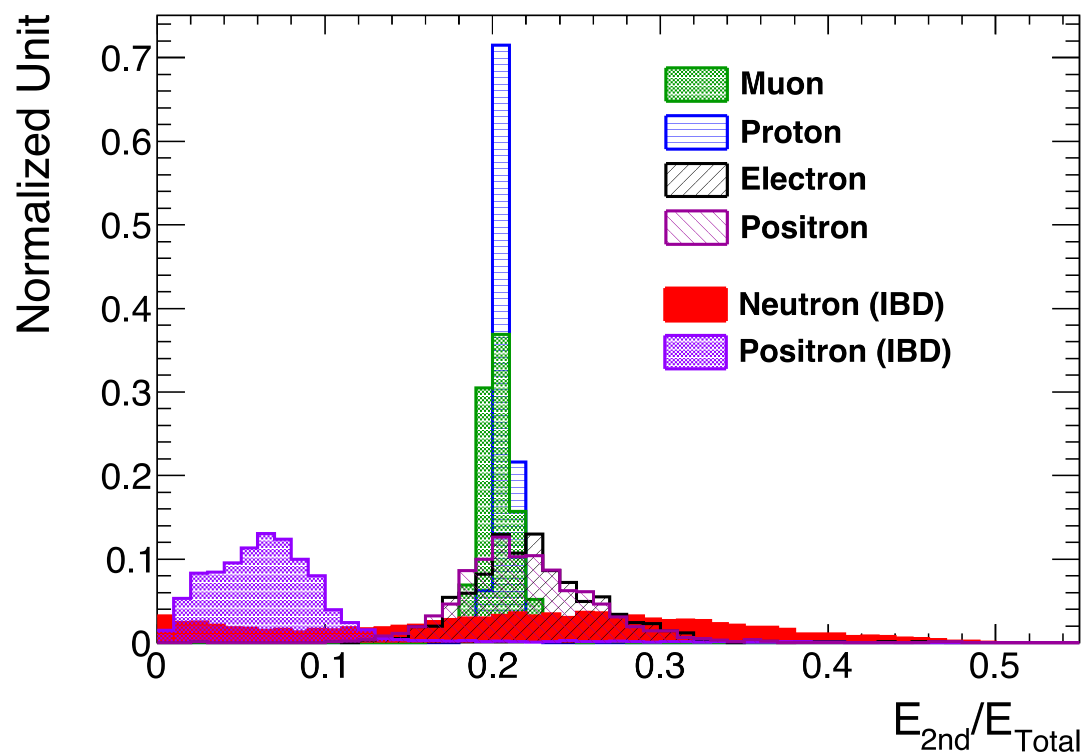
1 GeV/c muon

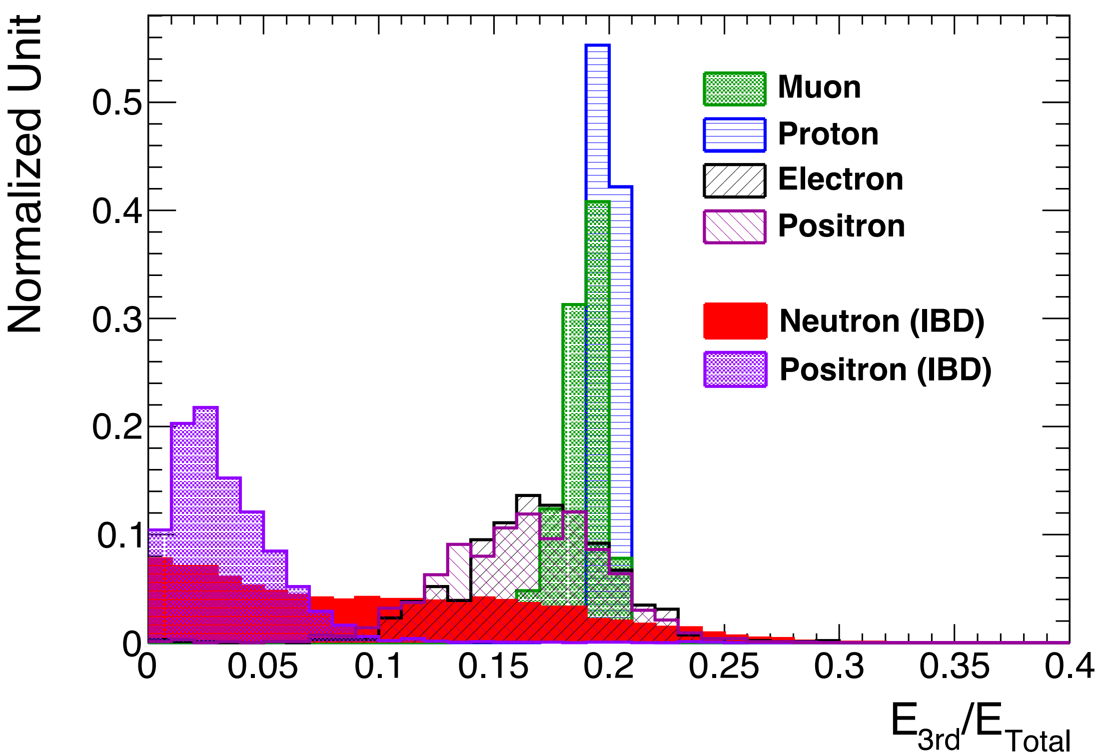
- Segmented structure of the detector gives great separation between IBD candidate events and cosmic background
- Antineutrino events and cosmic ray events have different event topology
- The energy correlation between PMT signals might be used for selecting the antineutrino events
- Number of photoelectron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

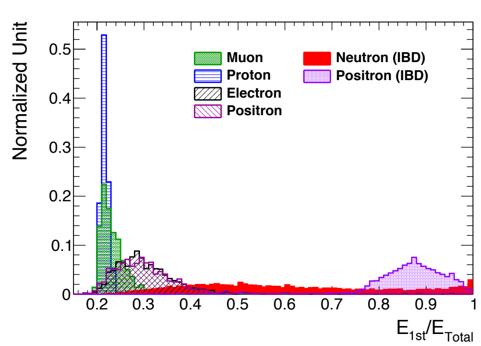


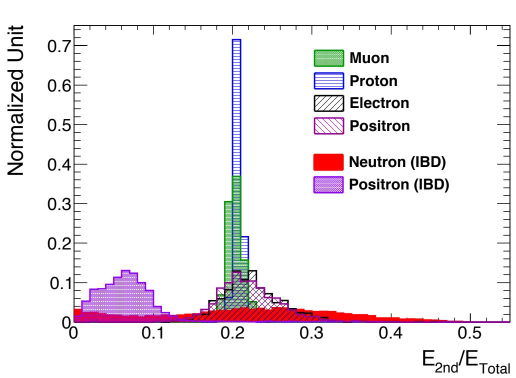


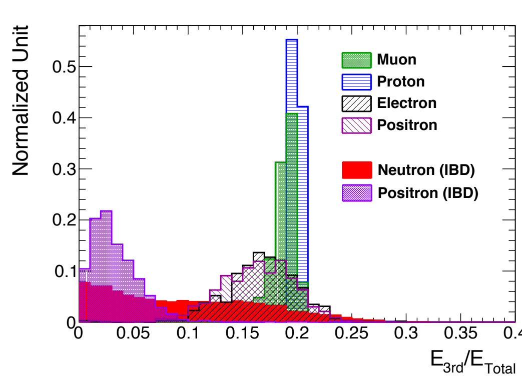


Multivariate Analysis

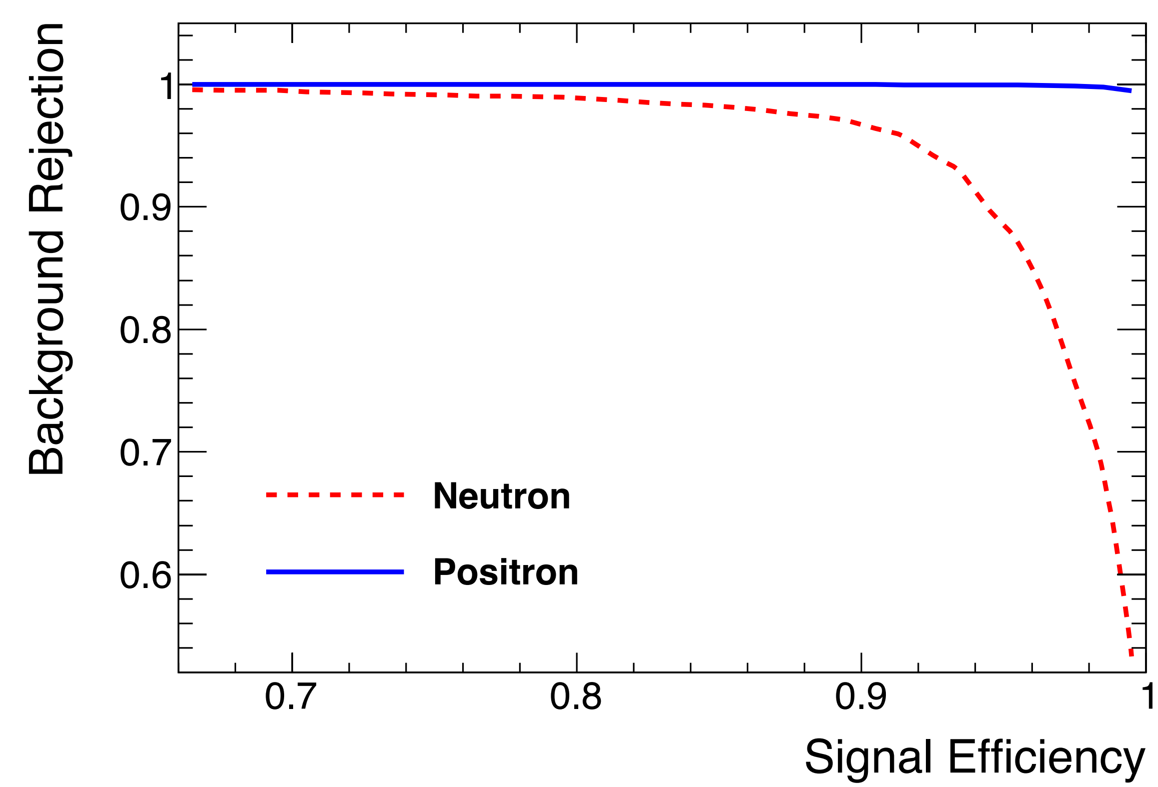
- Generally, using several variables at the same time could improve background rejection significantly.
- TMVA is used to combine E_{1st}/E_{Total}, E_{2nd}/E_{Total} and E_{3rd}/E_{Total} distributions.
- Signal comes from thermal neutron capture, background is taken as the sum of all considered cosmic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





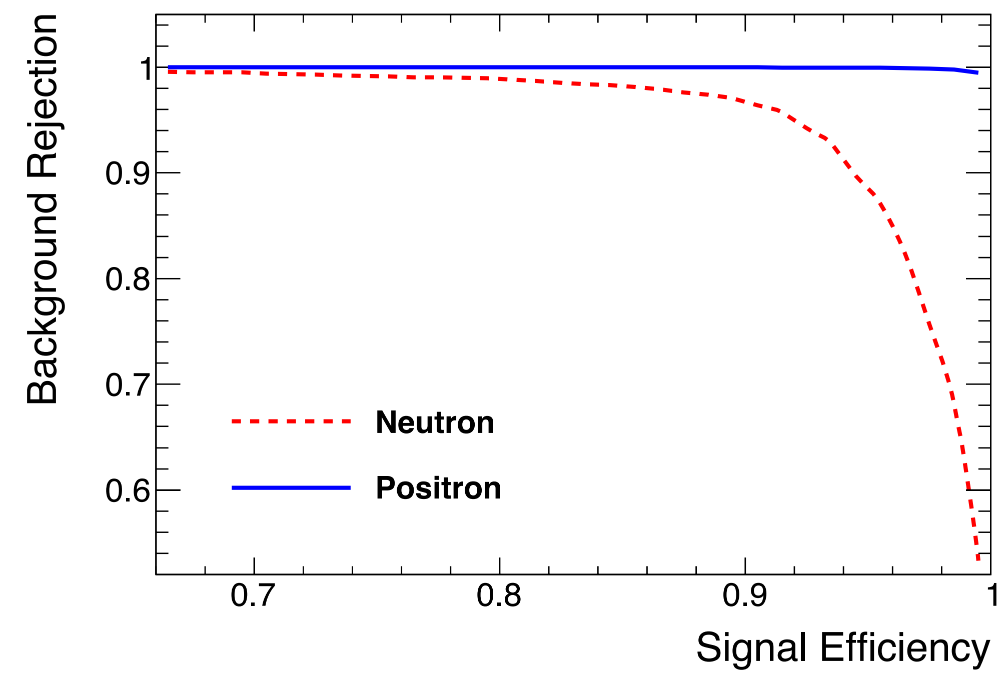


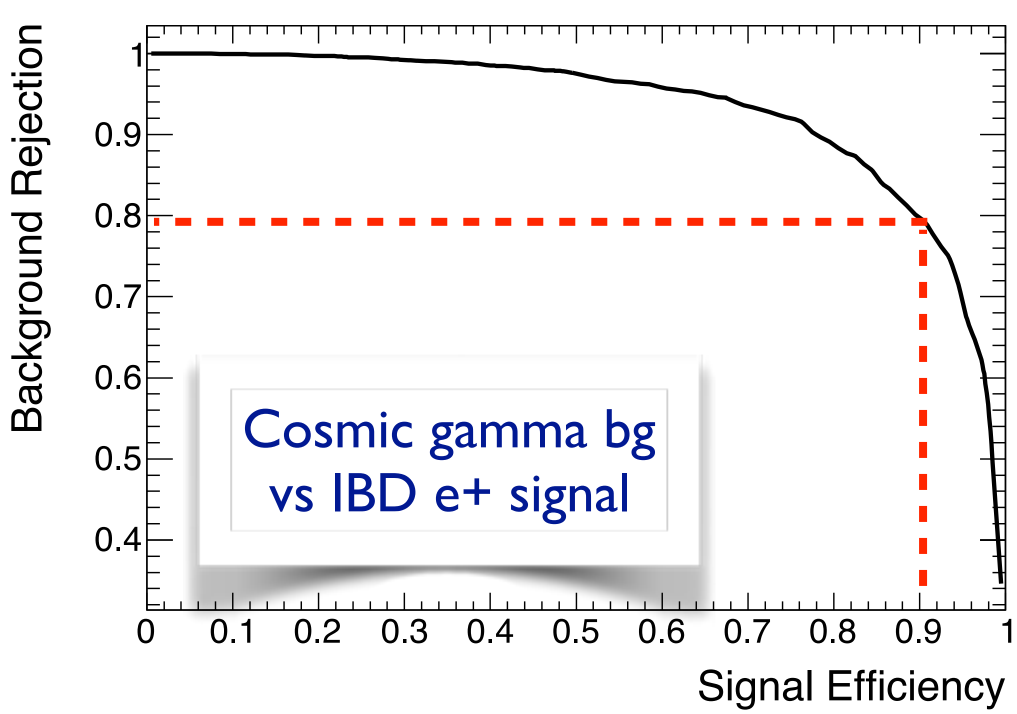
TMVA

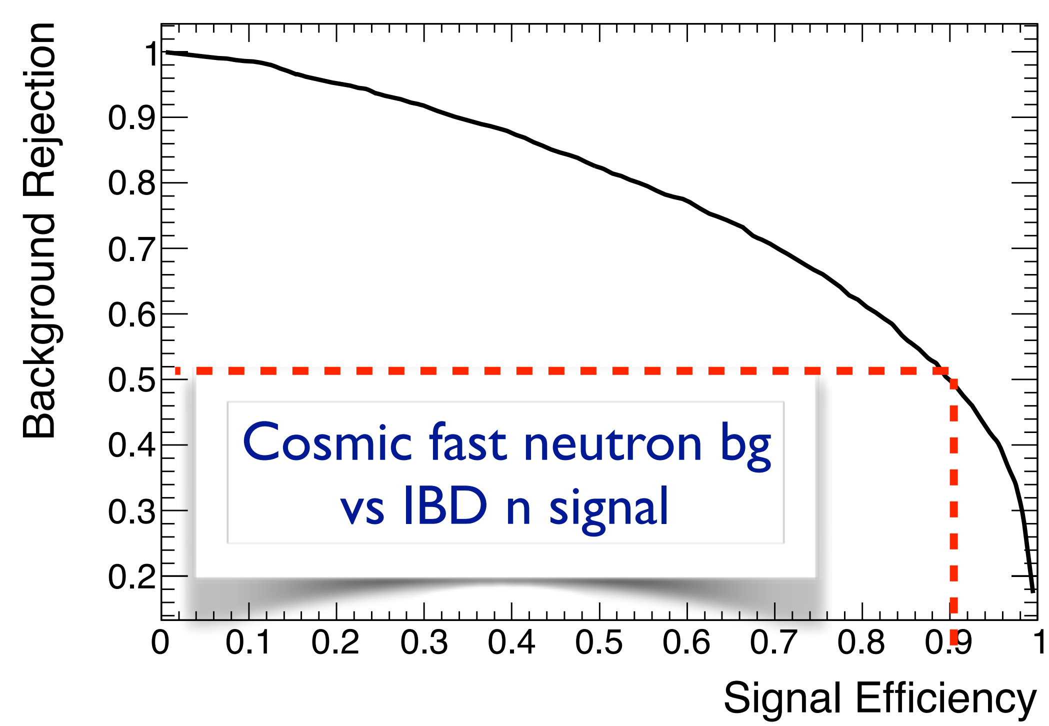


Multivariate Analysis (II)

- 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

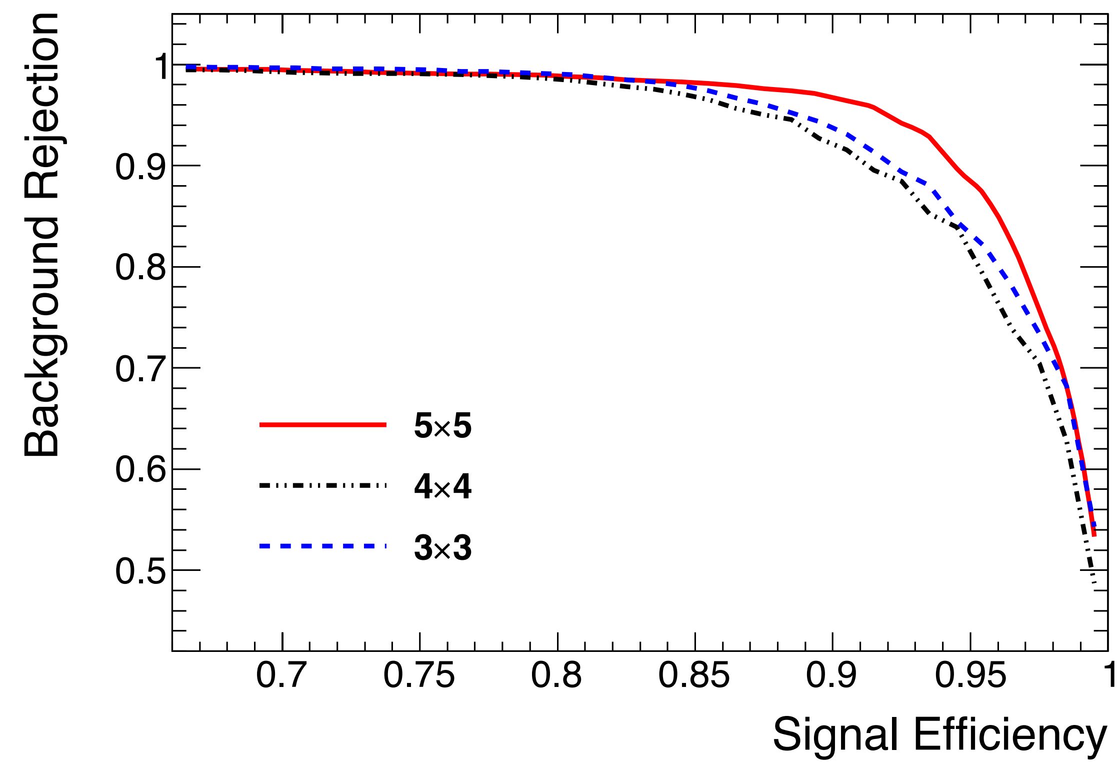


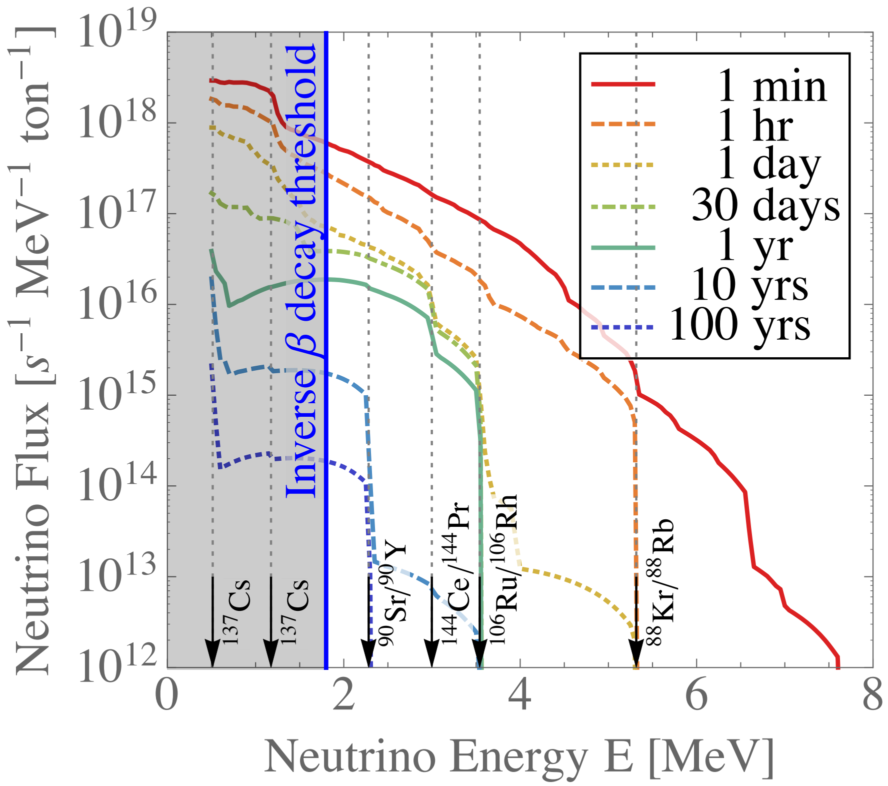


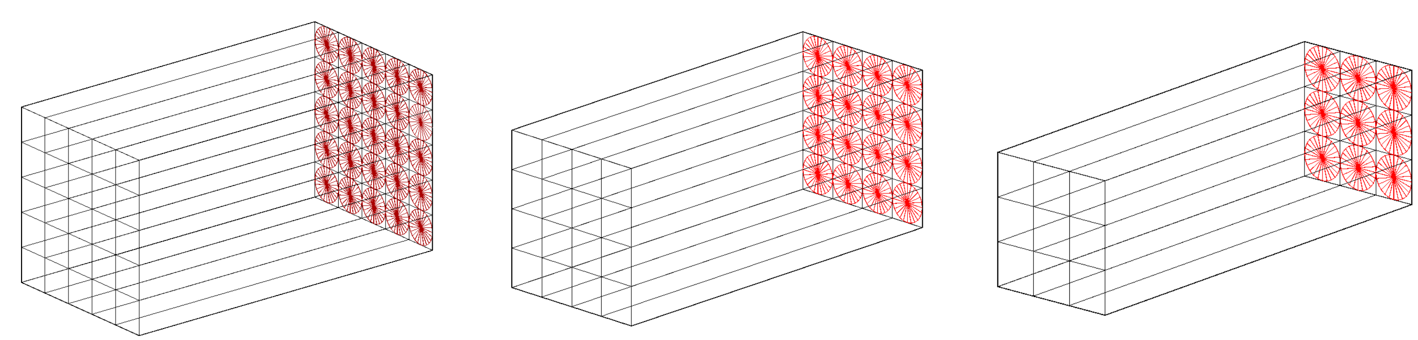


Module Number Dependency

- 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

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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.

4. Prospect

Nuclear technology is a new area for Turkey. The first nuclear reactor in Turkey is going to start operation in 2023, in Akkuyu. Construction of additional nuclear power plants in Sinop and gneada are being planned in the near future. These reactors will provide a great opportunity for development of new national (and also international) neutrino physics projects.

A kind of segmented detector made of gadolinium loaded plastic scintillators for monitoring nuclear reactors discussed in this paper must be one of the highest priority project for nuclear safety in Turkey. Such a neutrino detector could be used for monitoring of nuclear reactors and nuclear wastes [20] in Turkey. In addition, reactor antineutrino energy spectrum measurements could be performed with scientific purposes, and it would be the first step towards development of a new reactor neutrino oscillation experiment in Turkey.

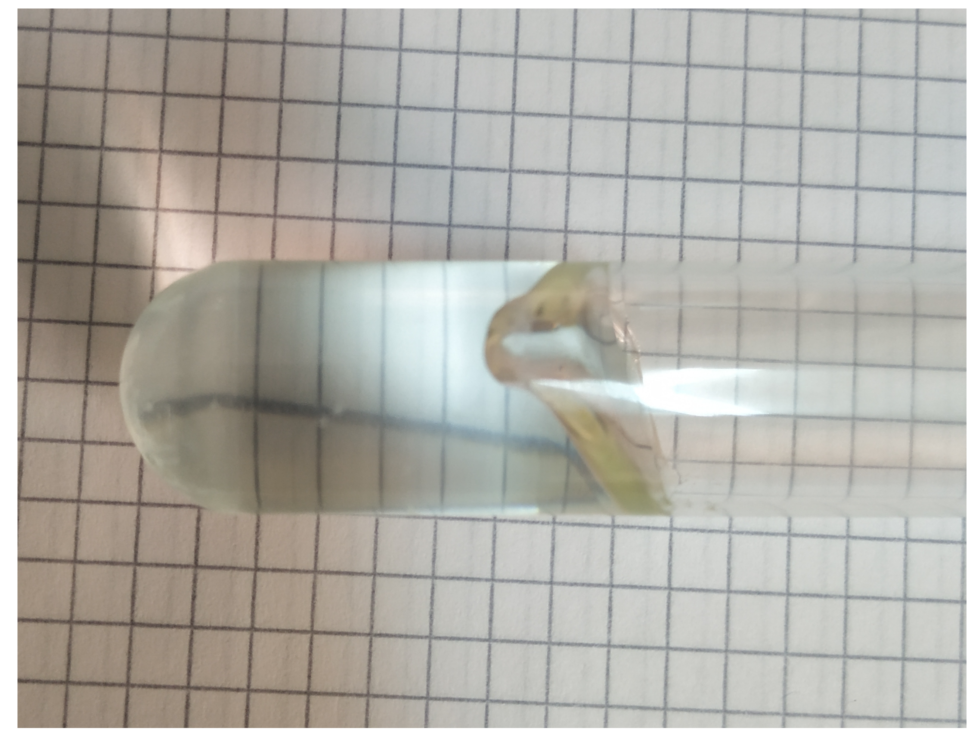
For that reason, it is planned to submit a project for funding to produce a demonstration module. Production and tests of gadolinium loaded plastic scintillator blocks can be done in Turkish Atomic Energy Authority, Sarayköy Nuclear Research and Training Center (SANAEM). High quality plastic scintillators have been produced in SANAEM in the past and there is necessary technological know how to synthesize new types of element loaded scintillator blocks with desired volumes and shapes.

The final design with some form of passive shielding, the construction and test are expected to take up to 2 years, before the first nuclear reactor core becomes active.

- ☑ Published in Nim A.
  - ✓ https://doi.org/10.1016/j.nima.2019.163314
- ☑ A presentation based on "Nuclear Reactor monitoring effort in Turkey" was given in NuTools Mini-Workshop for Applied Antineutrino Technology Community.
- ☑ Gd-loaded plastic scintillator synthesis is the key point.

Synthesis of Gd-Loaded Plastic Scintillators

- Gd-loaded plastic scintillators production and characterization studies has been started.
  - A plastic scintillator sample has been manufactured using thermal bulk polymerization technique.
  - Polystyrene + PPO (+ POPOP)
    - PPO %3, POPOP %0.1
- Gd dopant has just been delivered.
- No project budget for the preliminary study.
- A research project is being prepared.



Prospects and Conclusion

- Nuclear reactors and nuclear technology will be active in Turkey in the coming years.
- Monitoring these reactors independently is very important.
- In addition, reactor antineutrino energy spectrum measurements could be performed with scientific purposes, and it would be the first step towards development of a new reactor neutrino oscillation experiment in Turkey.
- The effort for production and characterization of gadolinium loaded plastic scintillator has been started.
- It is planned to submit projects funding to produce a demonstration module.
- The final design with some form of of passive shielding, the construction and test are expected to take up to 2 years, before the first nuclear reactor core becomes active.