

**Exploring anti-neutrino event selection  
and  
background reduction techniques for  
ISMARAN**

# Indian Scintillator Matrix for Reactor Anti-Neutrino detection- ISMРАН

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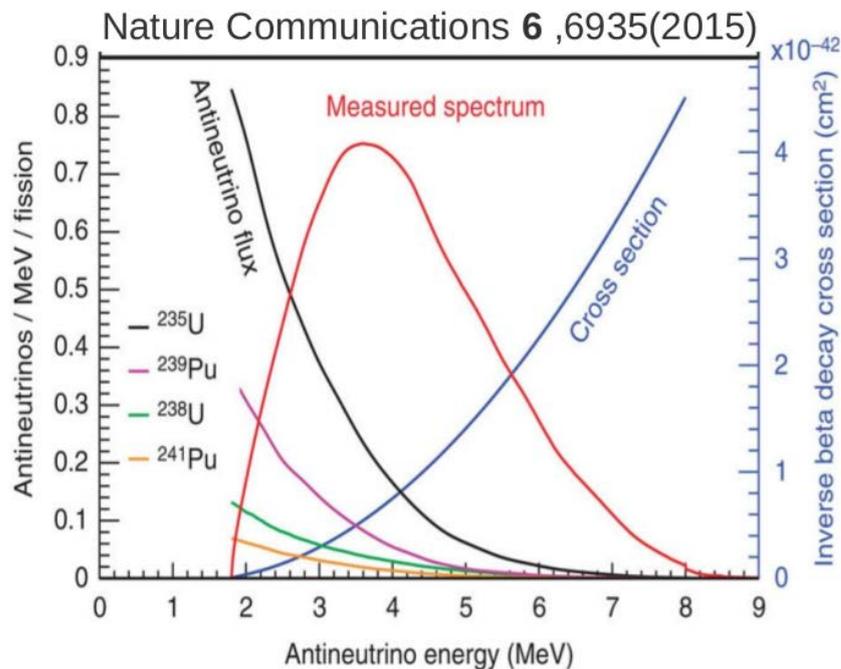


# Outline

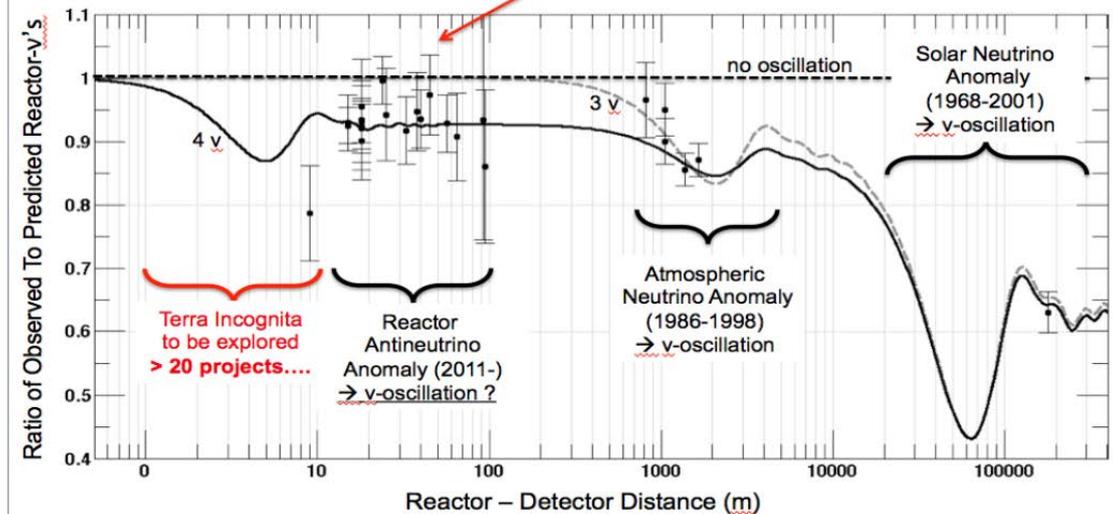
- ✦ **Introduction**
- ✦ **Dhruva reactor and experimental site**
- ✦ **Proposed ISMRAN at Dhruva**
- ✦ **Simulations for ISMRAN**
- ✦ **Measurements with mini-ISMRAN**
- ✦ **Summary and outlook**

# Introduction: Physics Motivation

- Anti-neutrinos from reactor provide an excellent non-intrusive probe for monitoring reactor power and its core composition.
- The detection of anti-neutrino through the inverse beta decay at closer distances ( $\sim 10$  m) would be interesting for the sterile neutrino searches.



Observed to predicted ratio  $\sim 0.943 \pm (0.023)$



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# Dhruva Reactor

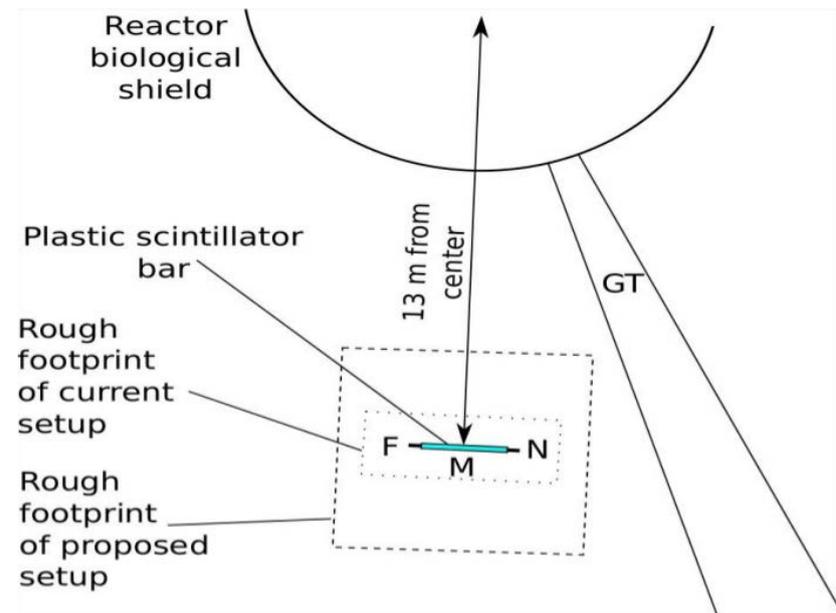
**Reactor Type : Vertical Tank / Thermal Reactor**

- ✦ **Date of Criticality : August 8, 1985**
- ✦ **Reactor Power : 100 MW (Maximum)**
- ✦ **Fuel Material : Natural Uranium Metal**
- ✦ **Fuel Element : Clusters**
- ✦ **Fuel Cladding : Aluminum**
- ✦ **Total weight of fuel : 6.35 T**
- ✦ **Core size : 3.72m(D) x 3.87m(H)**
- ✦ **Max. neutron flux :  $1.8 \times 10^{14}$  n/cm<sup>2</sup> /sec**
- ✦ **Moderator : Heavy water**
- ✦ **Coolant : Heavy water**
- ✦ **Shut off Rods : Cadmium**
- ✦ **Uses : Basic research, isotope production, manpower training, neutron activation analysis and testing neutron detectors.**



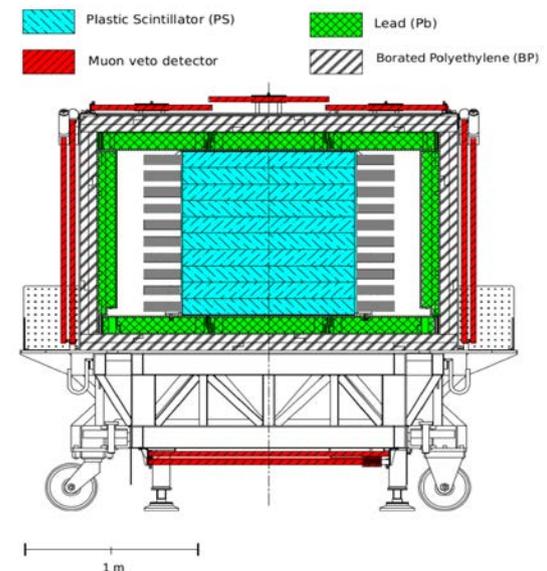
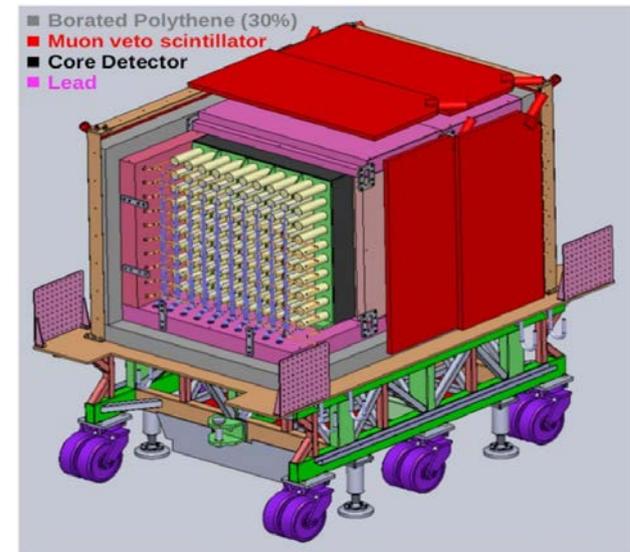
# Proposed detector (ISMARAN)

- Plastic scintillator (PS) bars of 100cm x 10cm x 10cm directly coupled to 3" PMTs at both ends
- Each bar wrapped with a reflective aluminized mylar film coated with 4.8 mg/cm<sup>2</sup> density Gadolinium (Gd) paint for neutron capture.
- Proposed distance from reactor core : ~ 13 m from center.

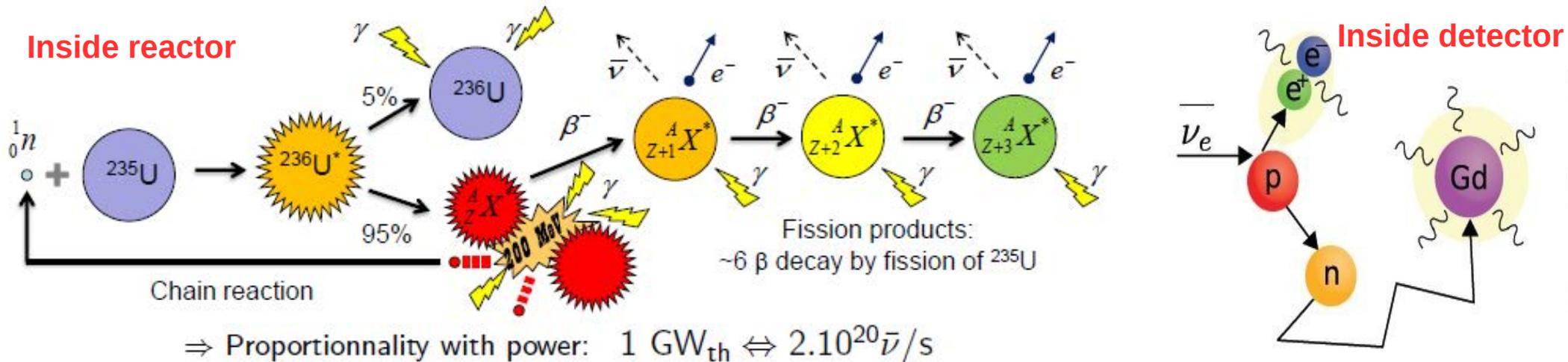


# Proposed detector (ISMARAN)

- ✦ **Segmented geometry : 10 x 10 array, total of 100 PS bars.**  
**1m<sup>3</sup> volume**  
**1 ton by weight**  
**~13 m from center of reactor core.**
- ✦ **Core detector will be in shielded enclosure of**  
**10 cm thick Lead (Pb) : Gamma shielding**  
**10 cm thick Borated polyethylene (BP) : thermal neutron shielding**
- ✦ **Muon veto scintillators :3 cm thick covering all the six planes of the detector**



# Anti-neutrino detection rate with ISMRAN at Dhruva



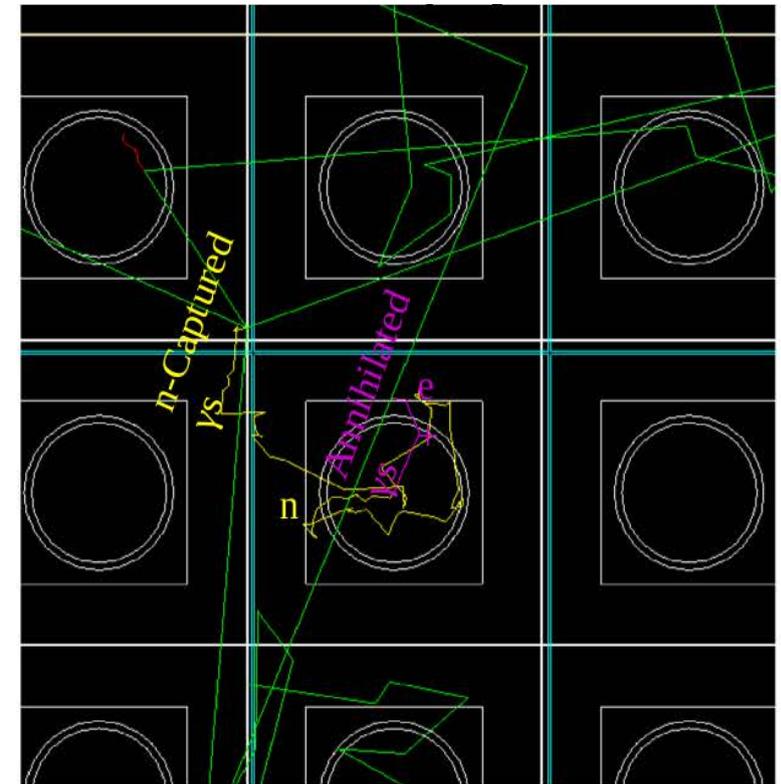
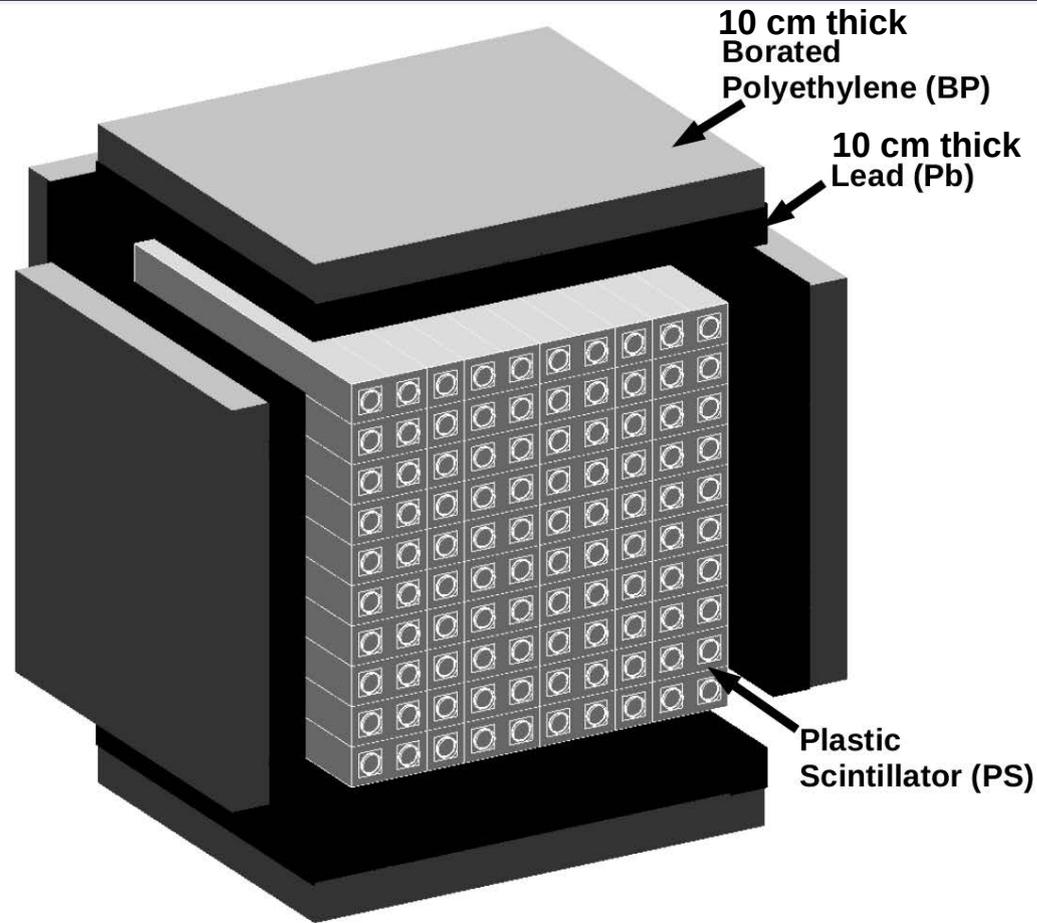
Number of reactor anti-neutrinos detected by a scintillator detector is given by,

$$N_{\bar{\nu}_e} = \frac{N_p \cdot \eta \cdot t \cdot P_{\text{th}} \cdot \bar{\sigma}_f}{4 \cdot \pi \cdot D^2 \cdot \bar{E}_f}$$

$N_p$  = Number of free protons =  $5.23 \times 10^{28} / \text{m}^3$ ; Detector Efficiency  $\eta = 15\%$ ; Duration  $t = 86400\text{s}$ ; Source to detector distance  $D = 13 \text{ m}$ ; Reactor Thermal Power  $P_{\text{th}} = 100 \text{ MW}$ ; Flux averaged cross-section  $\bar{\sigma}_f = 5.91 \times 10^{-43} \text{ cm}^2$ ; Average energy per fission  $\bar{E}_f = 204.7 \text{ MeV}$

**The detected neutrino rate (ISMRAN) is  $\sim 60 \text{ day}^{-1}$**   
 Point source has been assumed.

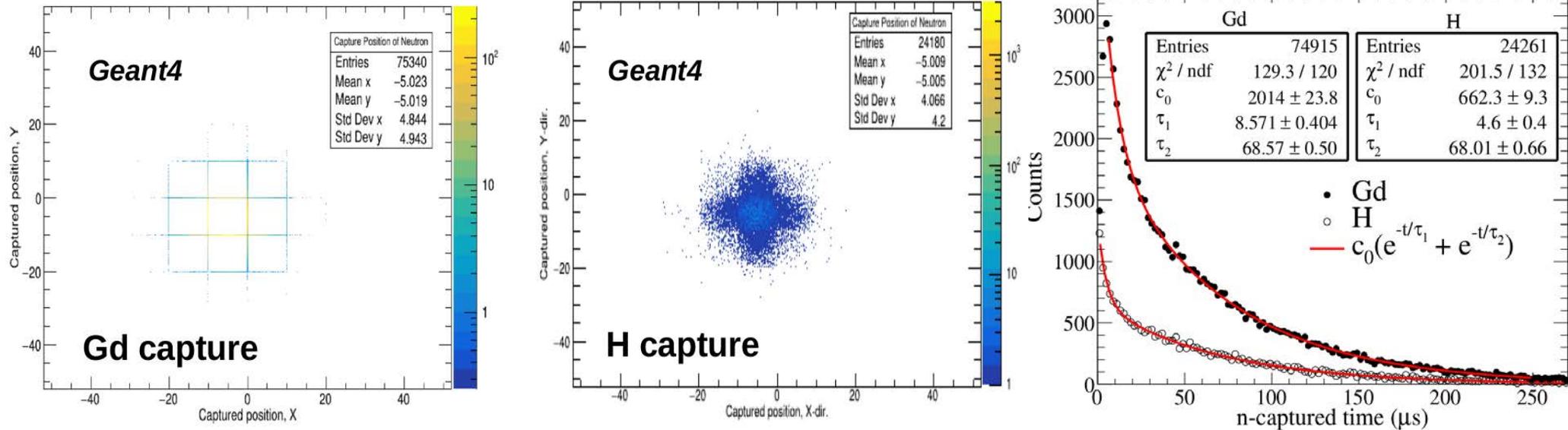
# Simulations for ISMRAN



Simulated IBD Event in ISMRAN

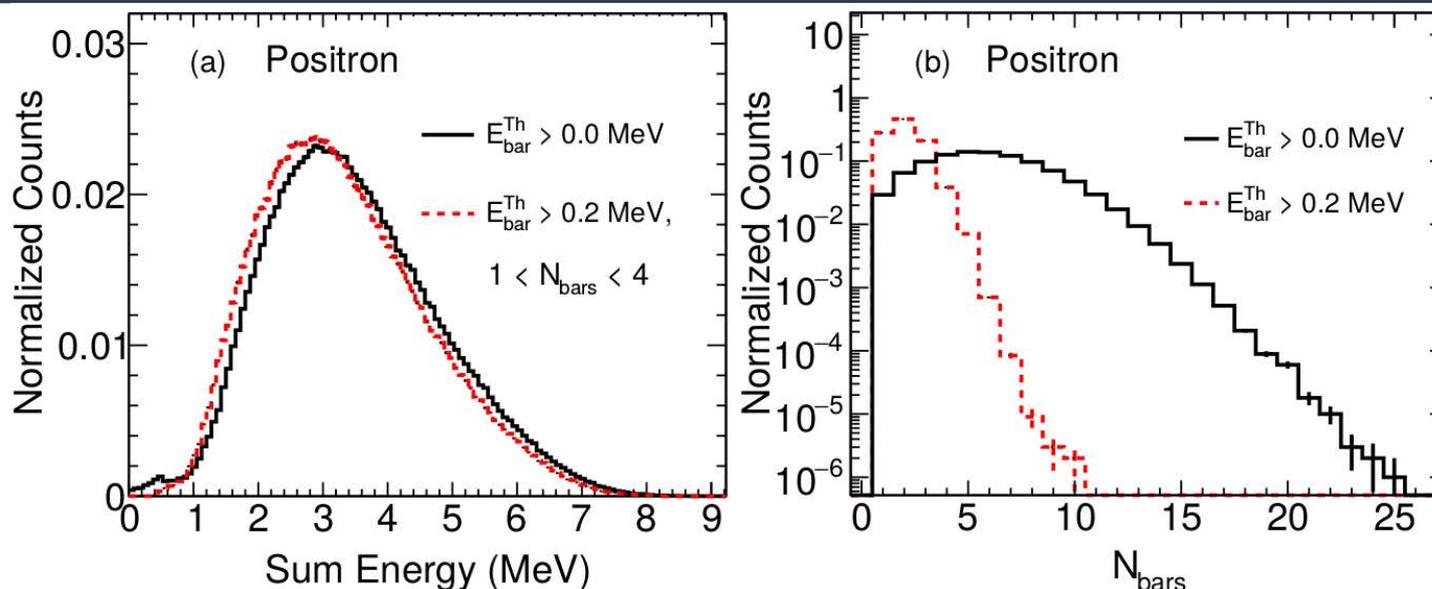
A threshold  $E_{\text{bar}}^{\text{Th}} = 0.2 \text{ MeV}$  on energy deposited in each PS bar is used in simulation similar to one used in data to achieve spectral uniformity among bars

# Neutron capture simulations



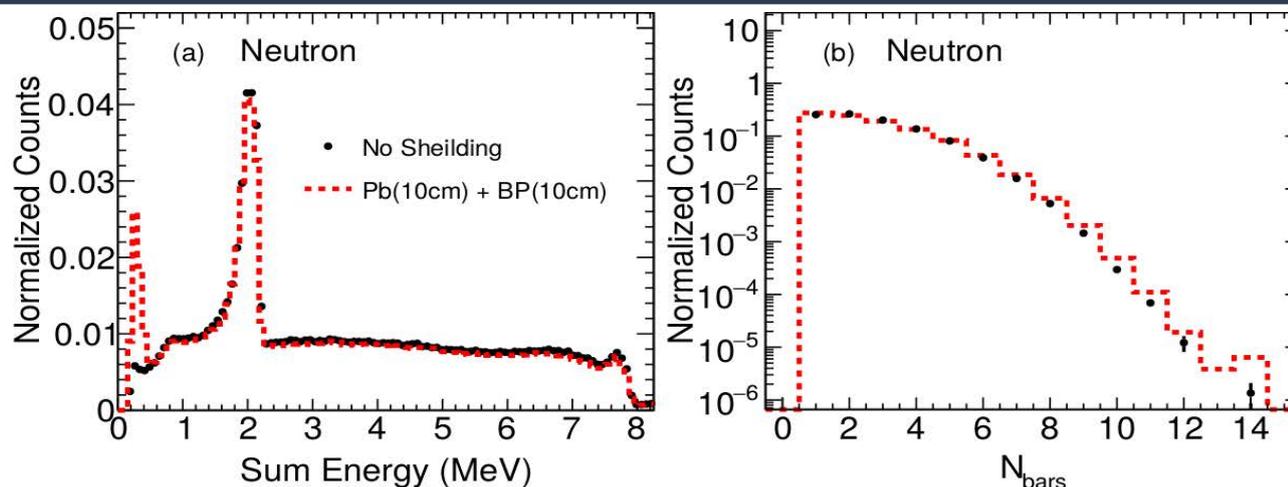
- With few keV neutrons generated near center the capture event profile shows majority captures, either on Gd or H, happening within the central 9-10 bars.
- Capture time distribution shows decay time constant of  $\sim 68 \mu\text{s}$  (on top right).
- $\sim 75\%$  captures occur on Gd and  $\sim 25\%$  on H while a small fraction of neutrons get captured on other materials e.g. Carbon and Lead etc.

# Sum Energy and Multiplicity simulations for pure IBD events



- A 'prompt event' in ISMRAN is defined as the energy deposited by the positron and the two 511 keV  $\gamma$ -rays produced from its annihilation with an electron. This can be studied in terms of the sum energy and multiplicity ( $N_{\text{bars}}$ ) variables as shown in figure above.
- The sum energy distribution in PS bars, for these prompt events, closely follows the  $\bar{\nu}_e$  energy spectrum for no threshold on PS bars and shifts to lower values with 0.2 MeV threshold and  $1 < N_{\text{bars}} < 4$  cut.
- The multiplicity distribution peaks at around 2-3 bars with 0.2 MeV threshold and provides a possible selection criteria for choosing prompt event.

# Sum Energy and Multiplicity simulations for pure IBD events



- A 'delayed event' in ISMRAN is defined as the energy deposited by the cascade  $\gamma$ -rays from neutron capture on Gd in the wrapped foil. Although capture on H is also studied in simulation, the energy cuts in data to reduce background may not allow efficient reconstruction of these events.
- A prominent peak corresponding to neutron capture on H nuclei at  $\sim 2$  MeV is visible.
- The incomplete containment of the  $\sim 8$  MeV cascade from Gd capture leads to a energy continuum-like feature with a substantially suppressed peaky structure at the end.
- The low energy peak at  $\sim 0.3$  MeV is Compton scattered energy from shielding in a capture event
- Multiplicities ranging from 1 to 14 are seen.  $N_{bars} > 3$  cut for delayed event is being considered with the advantage of no overlap with prompt selection but a reduced delay event detection efficiency

# Anti-neutrino detection efficiency estimates

Estimation of anti-neutrino detection efficiency ' $\epsilon$ ' based on the sum energy and  $N_{\text{bars}}$  variables was performed in simulation considering a 'loose' and a 'tight' cut on the sum energy variable as tabulated below

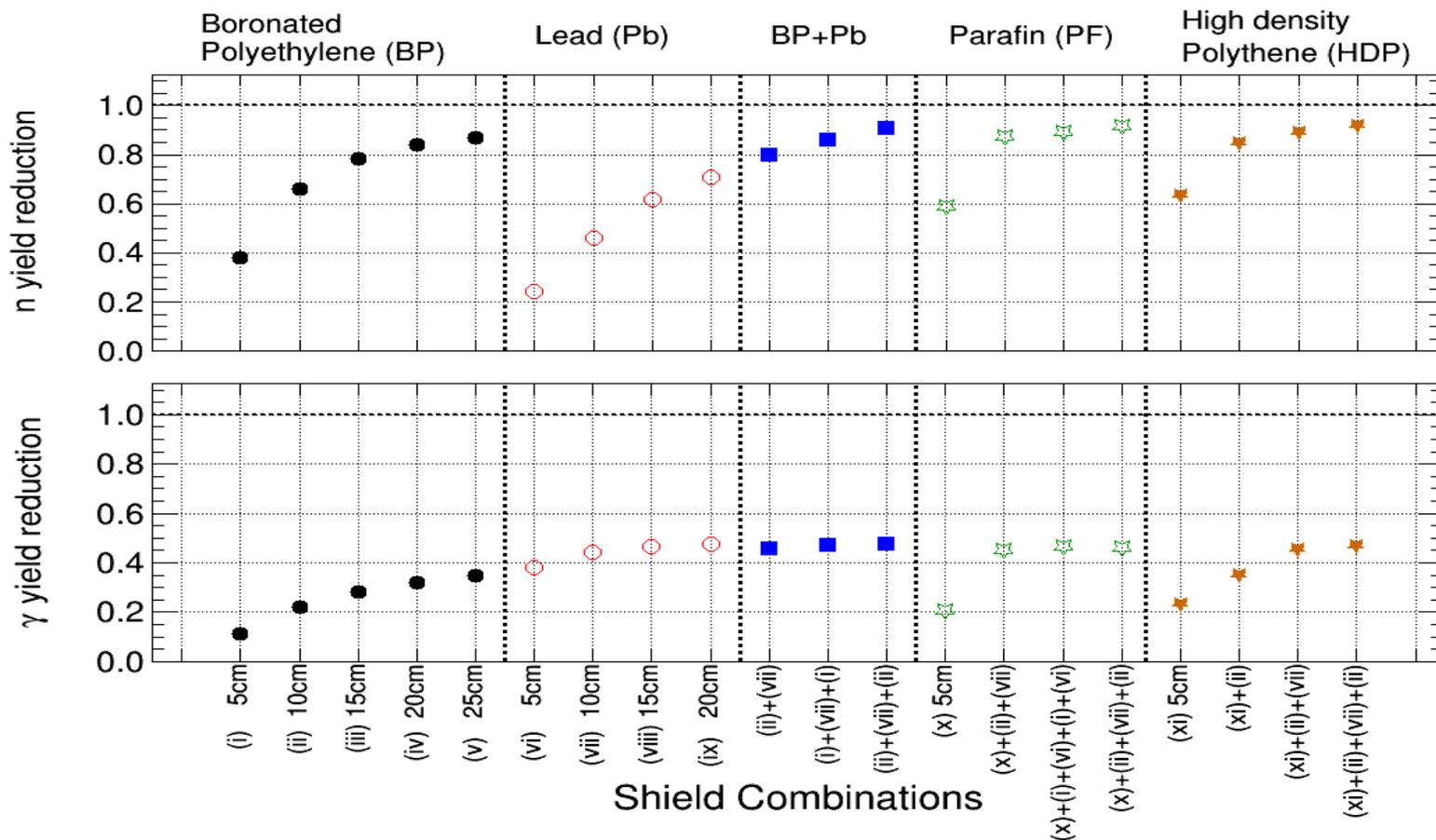
'Loose cut'	$\epsilon(\%)$	'Tight Cut'	$\epsilon(\%)$
$1.8 < E^{\text{prompt}} \text{ (MeV)} < 8.0,$ $1 < N_{\text{bars}}^{\text{prompt}} < 4$ $0.8 < E^{\text{delayed}} \text{ (MeV)} < 8.0,$ $N_{\text{bars}}^{\text{delayed}} > 3$	20	$2.2 < E^{\text{prompt}} \text{ (MeV)} < 8.0,$ $1 < N_{\text{bars}}^{\text{prompt}} < 4$ $3.0 < E^{\text{delayed}} \text{ (MeV)} < 8.0,$ $N_{\text{bars}}^{\text{delayed}} > 3$	18
$1.8 < E^{\text{prompt}} \text{ (MeV)} < 8.0,$ $1 < N_{\text{bars}}^{\text{prompt}} < 4$ $0.8 < E^{\text{delayed}} \text{ (MeV)} < 8.0,$ $N_{\text{bars}}^{\text{delayed}} > 3$ $4.0 < \Delta T \text{ } (\mu\text{s}) < 200.0$	19	$2.2 < E^{\text{prompt}} \text{ (MeV)} < 8.0,$ $1 < N_{\text{bars}}^{\text{prompt}} < 4$ $3.0 < E^{\text{delayed}} \text{ (MeV)} < 8.0,$ $N_{\text{bars}}^{\text{delayed}} > 3$ $8.0 < \Delta T \text{ } (\mu\text{s}) < 200.0$	16

- With the minimum threshold requirement of 0.2 MeV energy deposit in a single PS bar and no multiplicity cut the anti-neutrino detection efficiency estimate is about 98%.
- The above values are obtained without the incorporation of background in the simulation. With the inclusion of background these are expected to reduce further.

# Shielding study with 5 inch Liquid scintillator in lab environment

Different shielding configurations tested using a 5 inch liquid scintillator with Am-Be (neutron and gamma) source.

CAEN Pulse shape discrimination firmware (for V1730) utilized for the study



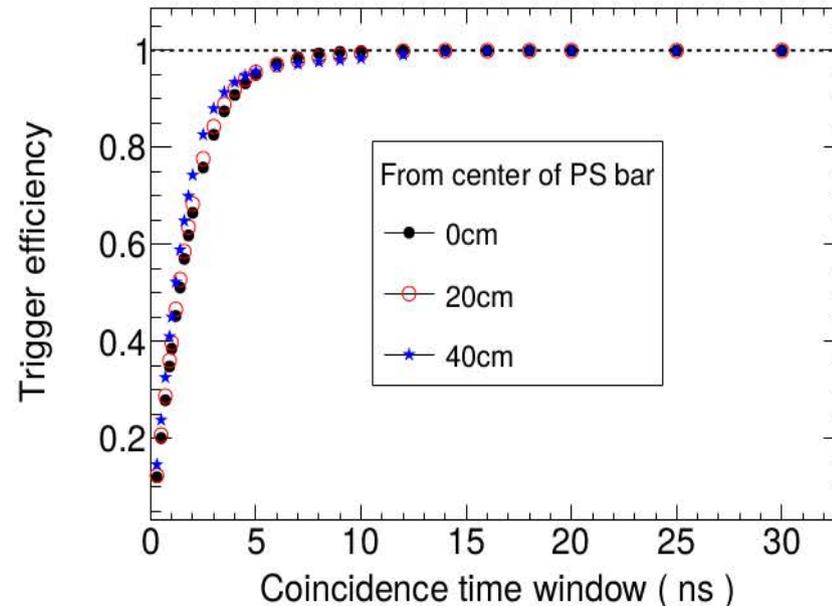
# Mini-ISMIRAN (4 x 4) matrix

- ✦ **16 PS bars arranged in a 4 X 4 matrix form the mini-ISMIRAN setup**
- ✦ **32 PMT channels being read out using a digital DAQ system comprising of high sampling rate CAEN V1730 (500 MS/s) digitizers**
- ✦ **Initial data taking is done in triggerless mode. Offline reconstruction of events.**



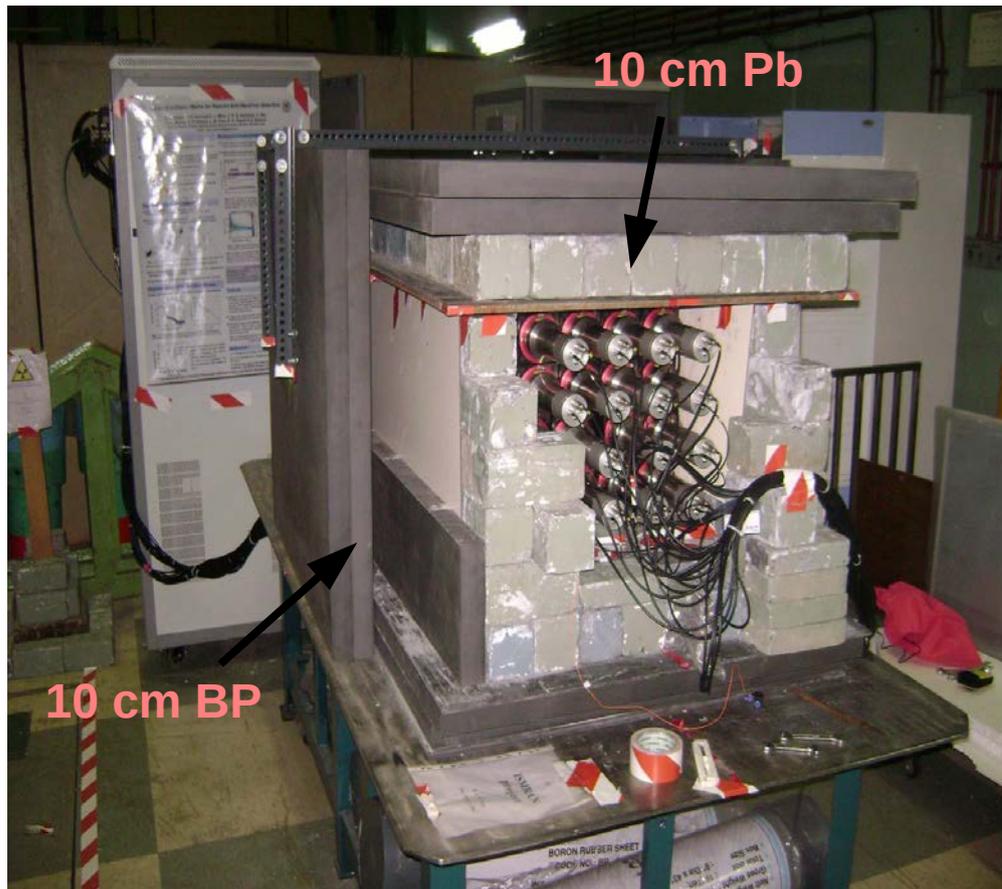
# Event triggering efficiency

Optimum coincidence window for triggering event from two PMTs in a single PS bar studied for different  $^{137}\text{Cs}$  source positions representing different event locations inside the bar



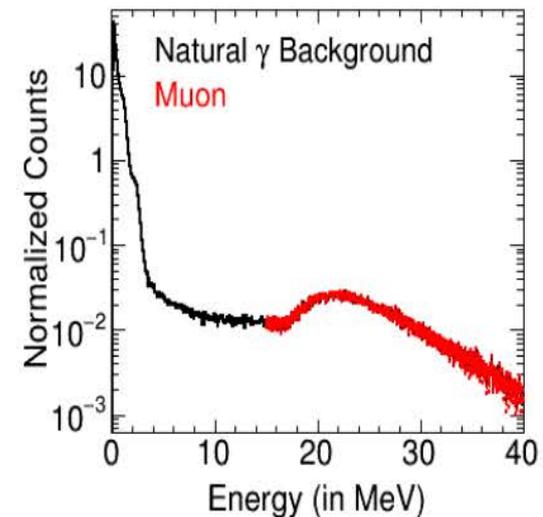
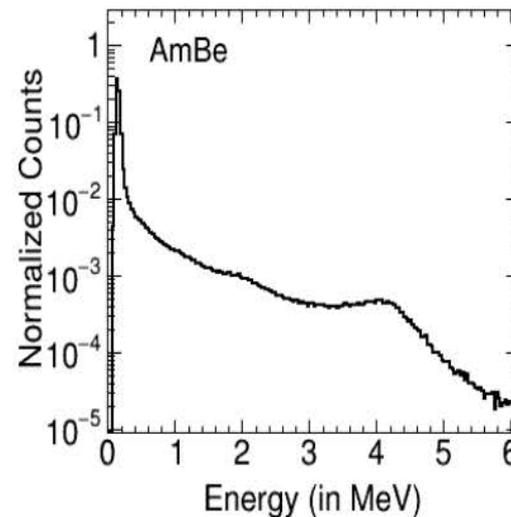
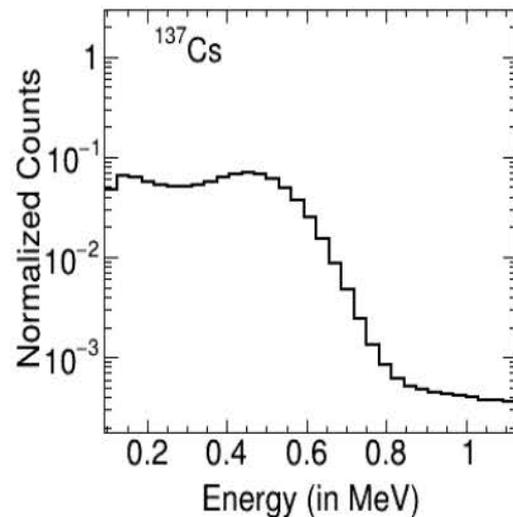
Although the efficiency curve reaches 100% at  $\sim 10$  ns a coincidence window of 16 ns is chosen due to digitizer clock constraints.

# Mini-ISMRRAN at Dhruva reactor hall



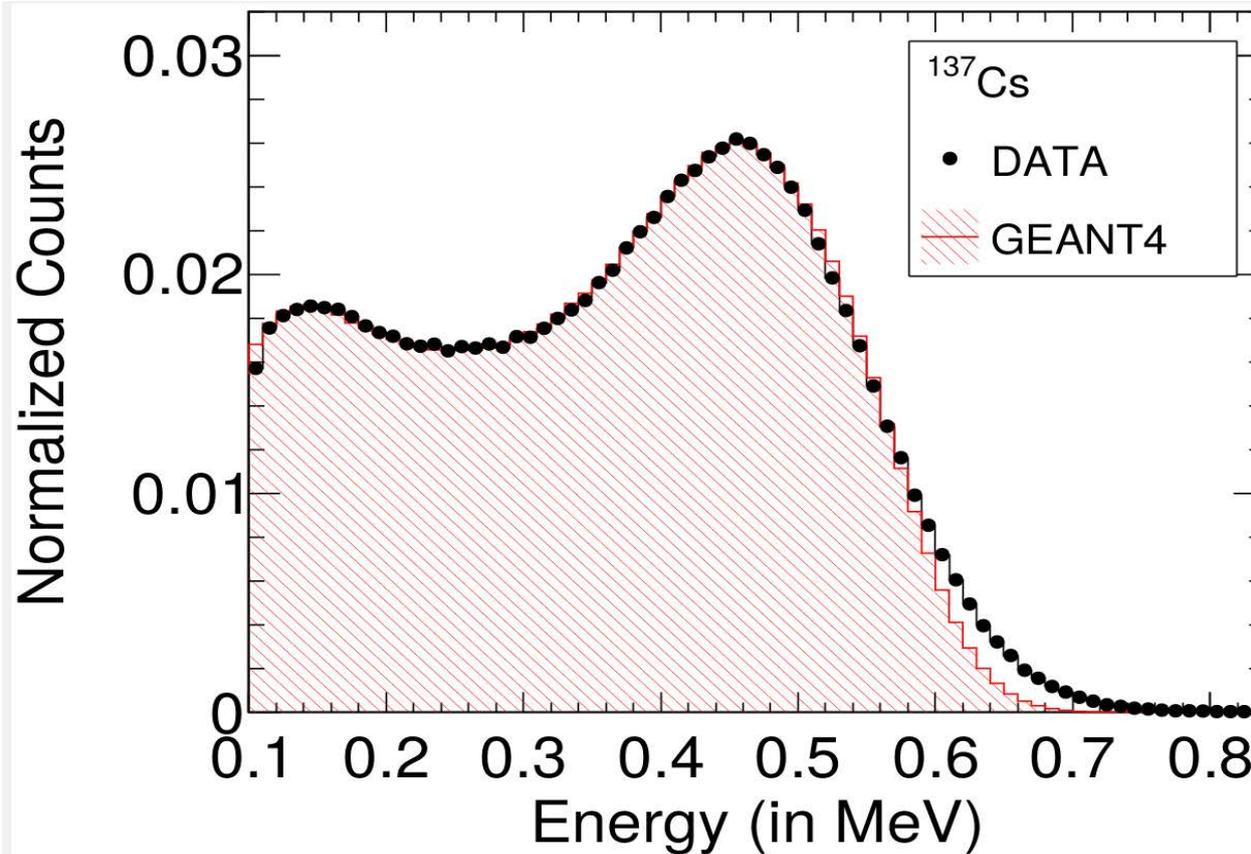
# Energy calibration

- Energy calibration was done using Compton edges from different radioactive sources.



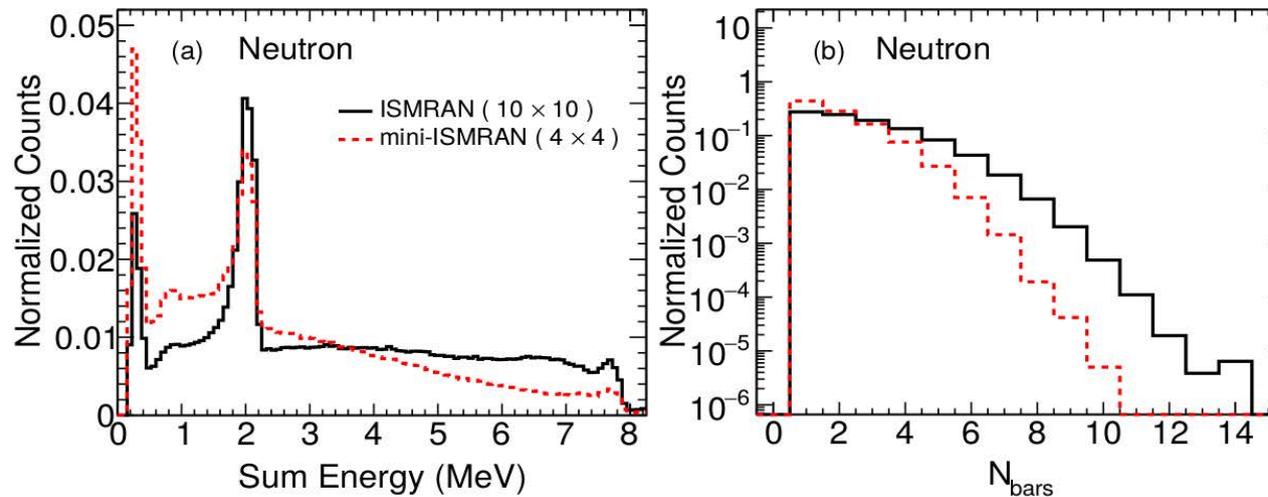
Energy response for gamma, neutron and muons in PS bar in laboratory

# Data and simulation (Geant4)



**$^{137}\text{Cs}$  source spectrum in one plastic scintillator bar.  
reasonable agreement between data and  
simulation. Energy resolution function  $\sim 20\%/\sqrt{E}$**

# Neutron sum energy and multiplicity simulations in mini-ISMRAN

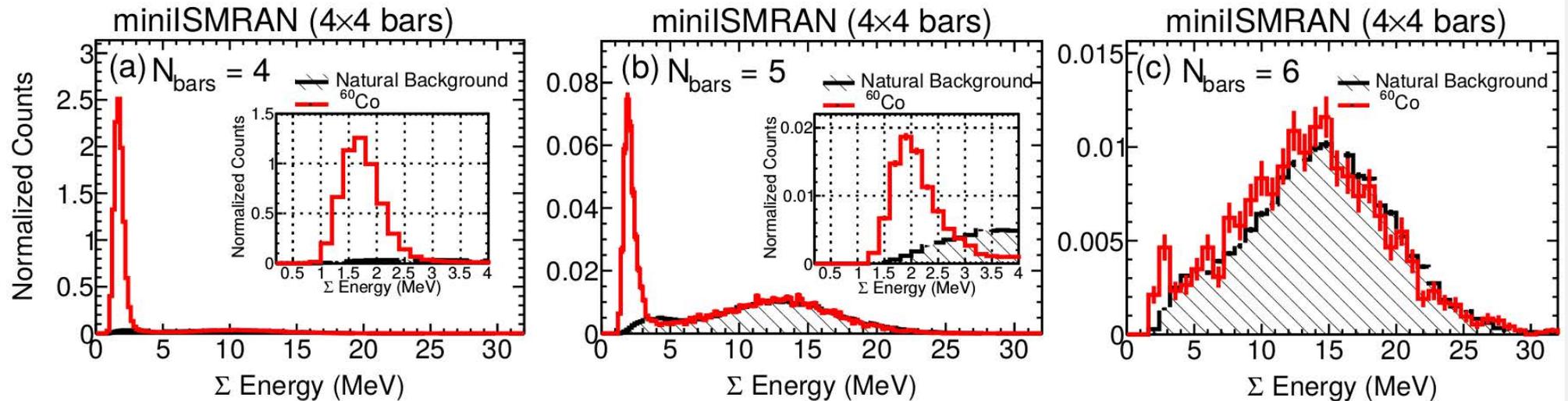


**Figure: (Left) Comparison of sum energy distribution of delayed neutron events in ISMRAN (10 x 10) and mini-ISMRAN (4 x 4) matrix with 'proposed' shielding and 0.2 MeV threshold . (Right) shows the  $N_{\text{bars}}$  distribution for the two cases.**

✦ The shift in the sum energy distribution of neutron capture events due to reconstruction of capture energies to lower values can be seen as we go from 100 PS bar ISMRAN setup to the 16 PS bar mini-ISMRAN setup. Most of the capture events are reconstructed below 4 MeV.

✦ Multiplicities also get restricted due to the restricted volume of the prototype detector with maximum multiplicity reaching around 10.

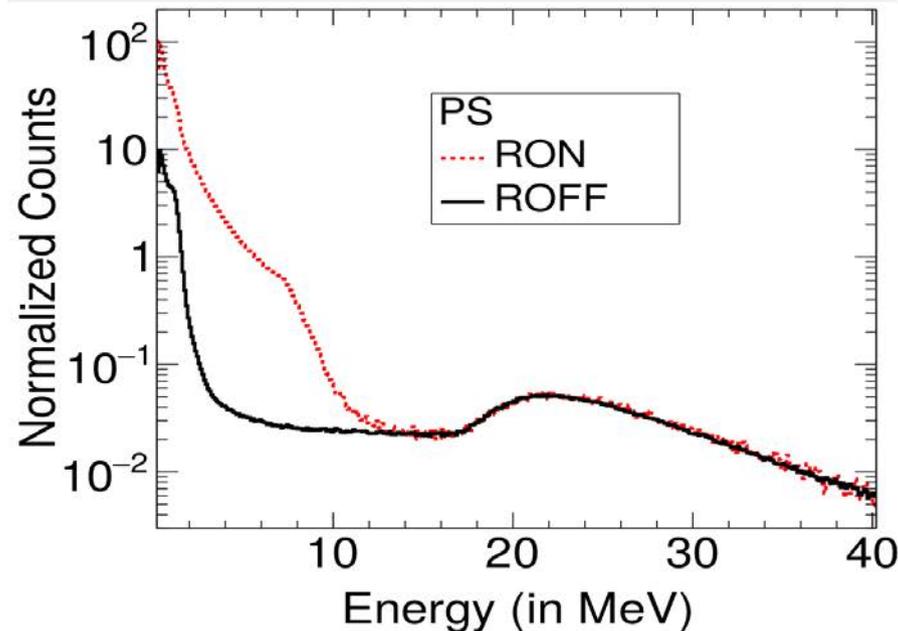
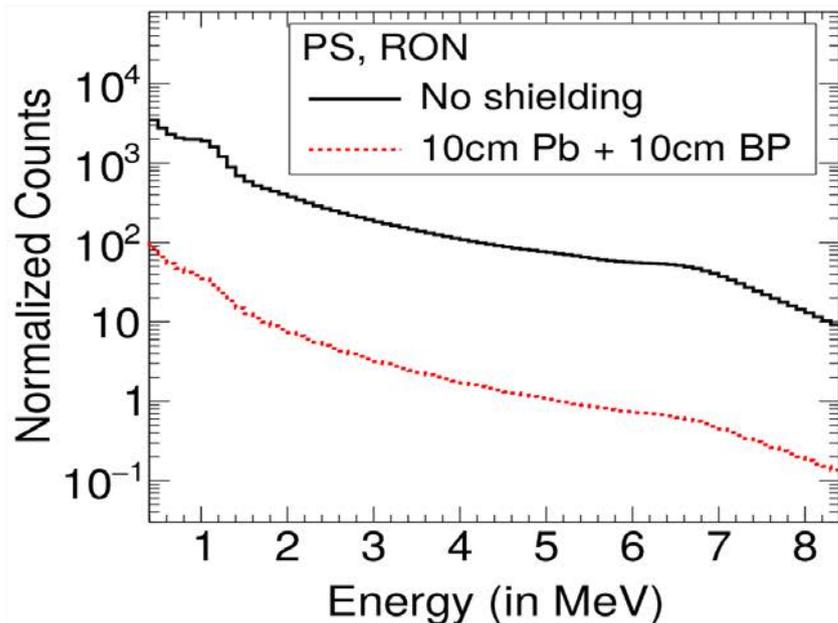
# $^{60}\text{Co}$ event selection in mini-ISMARAN using sum energy technique



Sum energy distribution for a  $^{60}\text{Co}$  source which has two co-incident gamma-rays of 1.17 MeV and 1.33 MeV was obtained in laboratory measurement and compared alongside that for natural background. The summing was done progressively for events with signals above threshold of 0.2 MeV and multiplicity  $N_{\text{bars}} = 2$  bars, 3 bars and so on, triggered within a time window of 40 ns. Figure panels (a), (b) and (c) show comparison for 3 important cases of  $N_{\text{bars}} = 4$ ,  $N_{\text{bars}} = 5$  and  $N_{\text{bars}} = 6$  firing within 40 ns.

A peak at  $\sim 2$  MeV in the sum energy signifying the faithful selection of coincident  $\gamma$ -ray events is visible in  $N_{\text{bars}} = 5$  case since the reconstructed sum energy of the coincident event improves as compared to  $N_{\text{bars}} = 4$  case. However, the sum energy distribution for  $N_{\text{bars}} = 6$  shows that the fraction of coincident events reconstructed are reduced significantly as compared to the natural background i.e. poorer S/B ratio.

# Measurements from the shielded setup



Energy plots of a single PS bar under 10 cm Pb + 10 cm BP shielding and no shielding in reactor ON is shown. Two orders of magnitude reduction of background with the 10 cm BP + 10 Pb shielding is observed

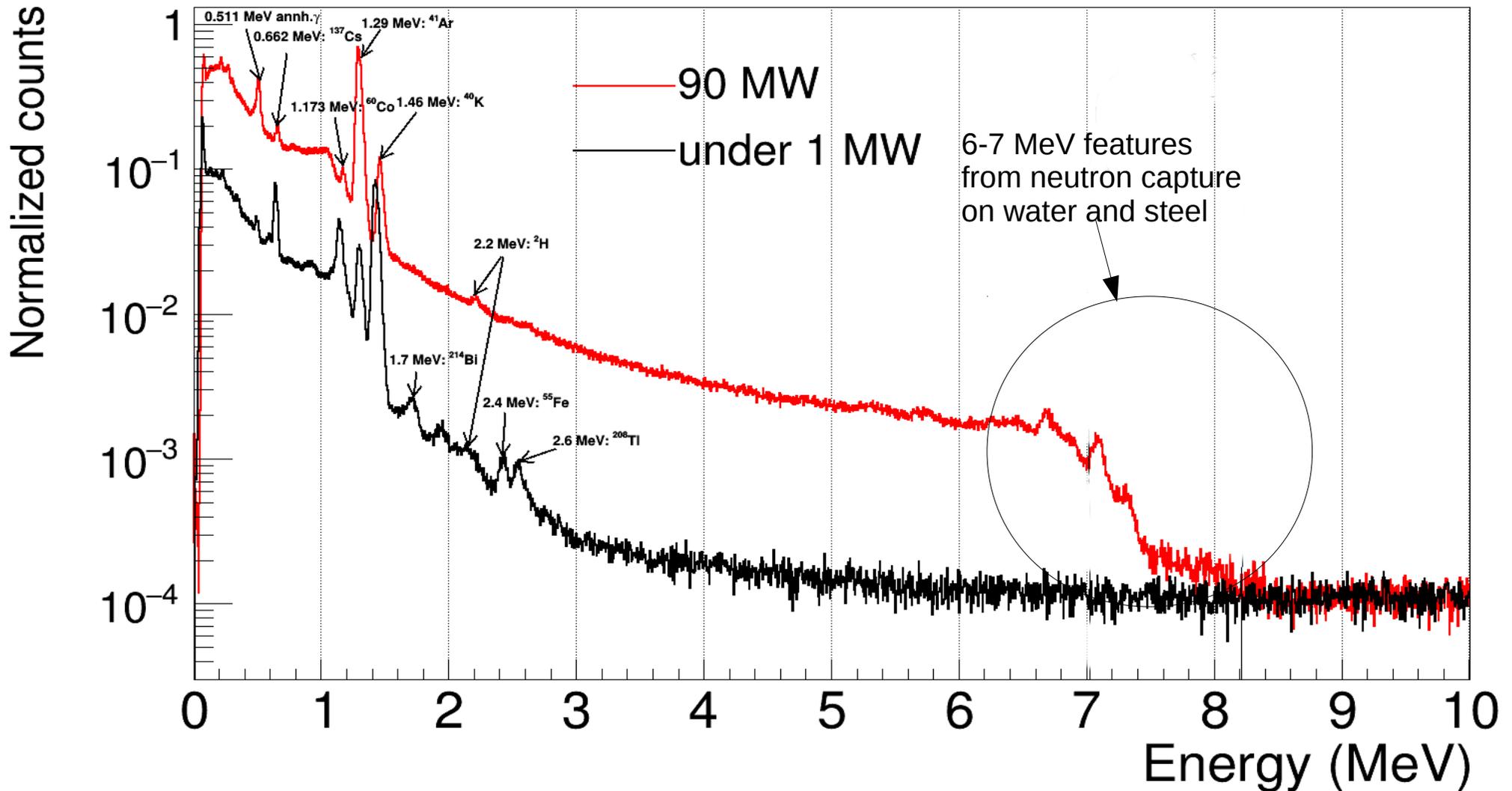
Also coincidence condition among two bars representing the positron annihilation or neutron capture like event further reduces background by an order of 10.

Need to identify and quantify uncorrelated and correlated backgrounds giving signal in PS bar under reactor ON.

Detector configurations	Count Rates (Hz)
No Shielding (Single PS bar)	~ 24,000
10 cm thick lead shield	~ 2,000
10 cm thick lead + 10 cm thick B.P.	~ 500
10 cm thick lead + 10 cm thick B.P.	~ 10

( $N_{\text{bars}} = 2$ , time window < 40 ns)

# Reactor background study with $\text{CeBr}_3$ scintillator (2 inch crystal) detector



Different  $\gamma$ -ray activities present in reactor ON and OFF conditions measured using  $\text{CeBr}_3$

# Current progress for the mini-ISM-RAN setup



- Additional 5 cm High Density polyethylene (HDPE) being assembled for suppressing outside neutron background
- Measurement of neutron background inside HDPE using 5 inch Liquid scintillator in progress.
- A paper on the detector development and simulations for the ISMRAN and mini-ISM-RAN setup has been accepted in Nucl. Instr. & Meth. Section A and in process of getting published. First version available with ArXiv id [arXiv:1806.04421v1](https://arxiv.org/abs/1806.04421v1)

# Summary and Outlook

- **ISMARAN experiment is proposed to study the reactor anti-neutrinos at DHRUVA.**
- **A prototype detector array of 4x4 matrix, mini-ISMARAN, of plastic scintillator bars is tested and commissioned at DHRUVA reactor hall.**
- **Lead (10cm) and Boronated Polyethylene structure has been constructed for mini-ISMARAN. Further shielding of 5 cm HDPE being assembled.**
- **Background measurements with mini-ISMARAN are in progress with reactor ON and OFF conditions.**
- **Working on incorporating background in simulations and studying its impact on anti-neutrino detection efficiency.**
- **Data acquired inside shielding being analysed for anti-neutrino like events.**
- **Design and fabrication of the support structure for shielding in progress.**
- **The purchase of the remaining PS bars, V1730 digitizers, HV cables, connectors, Lead and BP shielding for full ISMARAN detector is already being processed and the setup is expected to be ready for installation in next 6-8 months.**

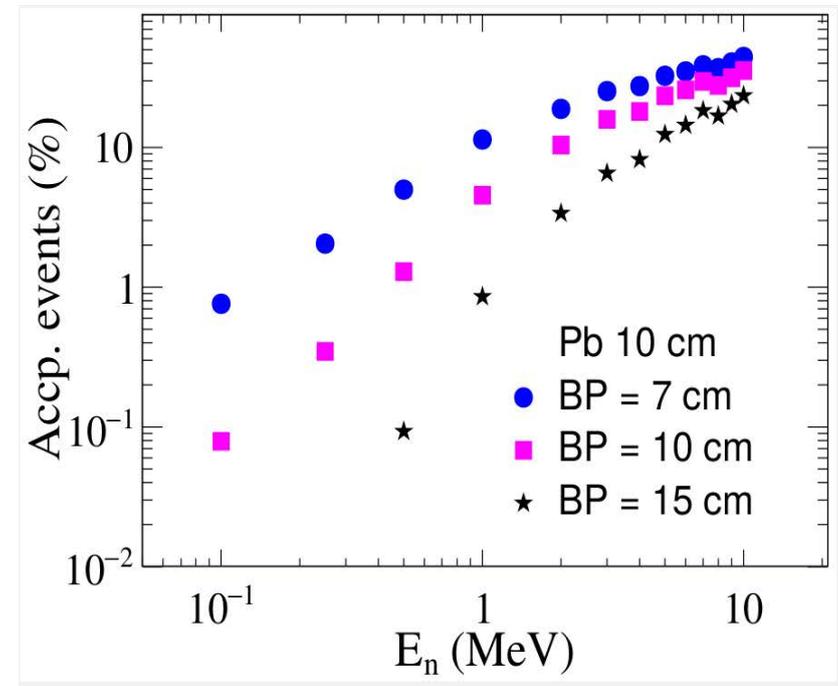
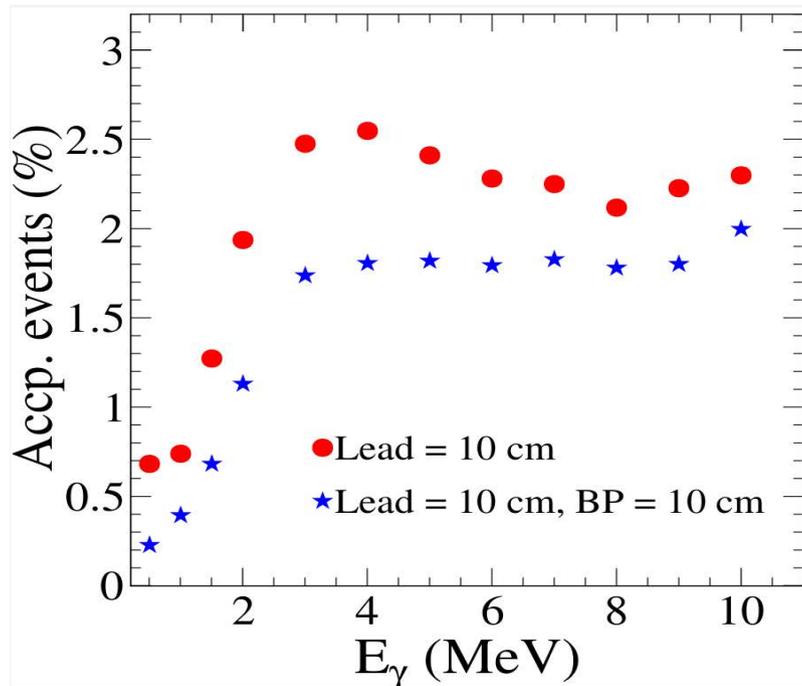
# Acknowledgements

- ✦ **Centre for Design and Manufacture, BARC**
- ✦ **Crystal Technology Laboratory, BARC**
- ✦ **Reactor Operations Division, DHRUVA**
- ✦ **Lawrence Livermore National Laboratory, USA**

**Thank you for your attention!**

**Backup Slides...**

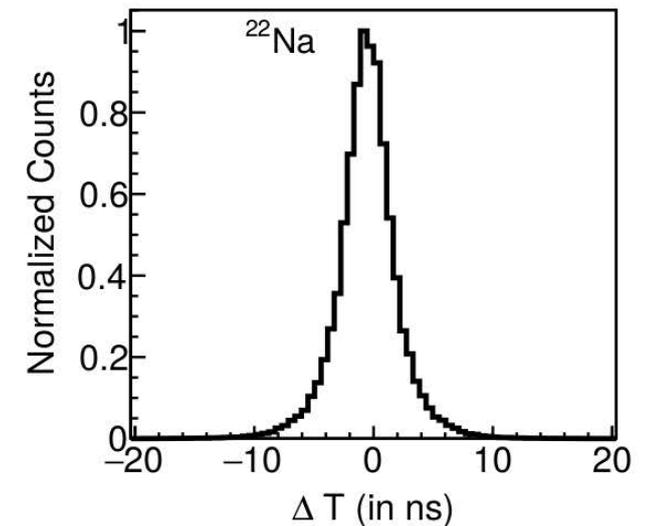
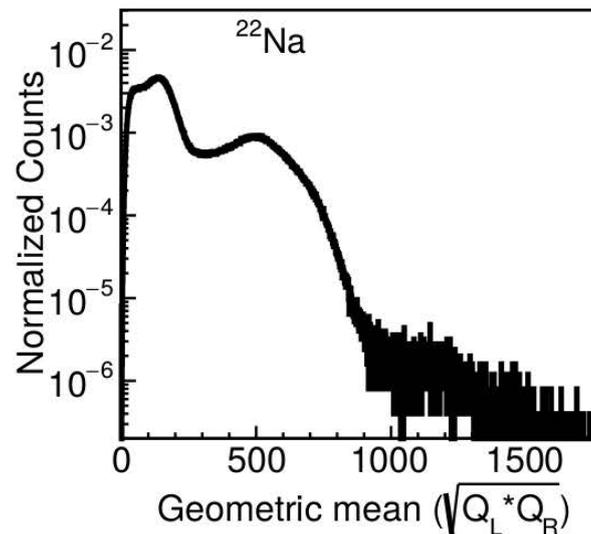
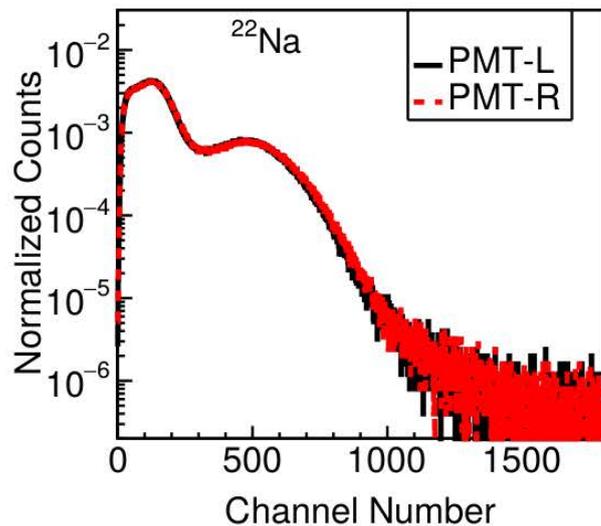
# Shielding simulations for ISMRAN



- ✦ Simulations were performed to test the effectiveness of the proposed 10 cm Pb and 10 cm BP shield
- ✦ Gamma and neutrons in energy ranges as expected in the reactor hall setup were generated and acceptance of the different configurations of shield was tested
- ✦ Only ~2% gammas are accepted for up to 10 MeV range (on left) while neutrons below 10 MeV show ~5% reduction when coupled with 10 cm BP (on right). But beyond 10 MeV energy BP is less effective.

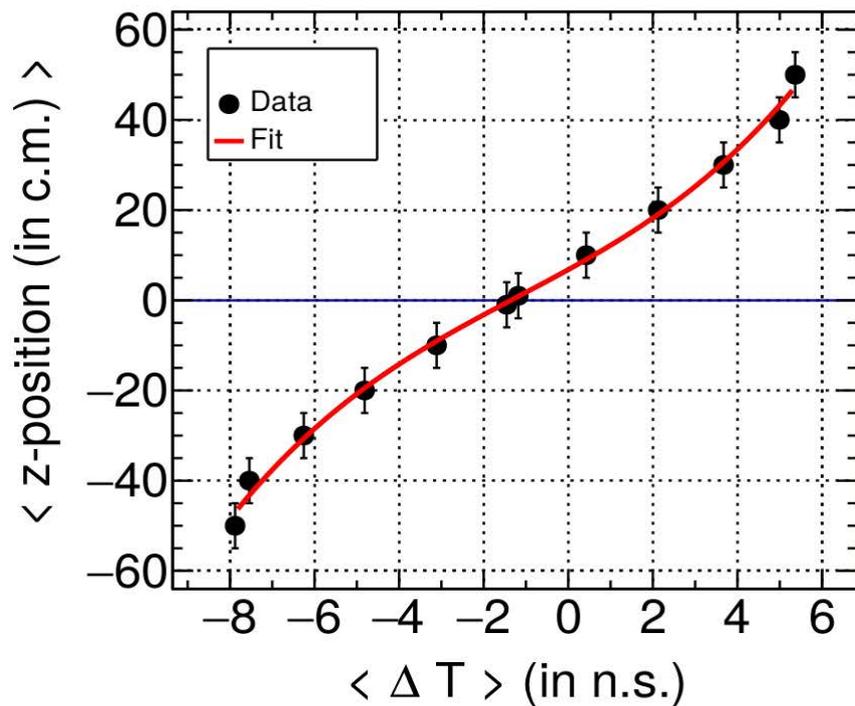
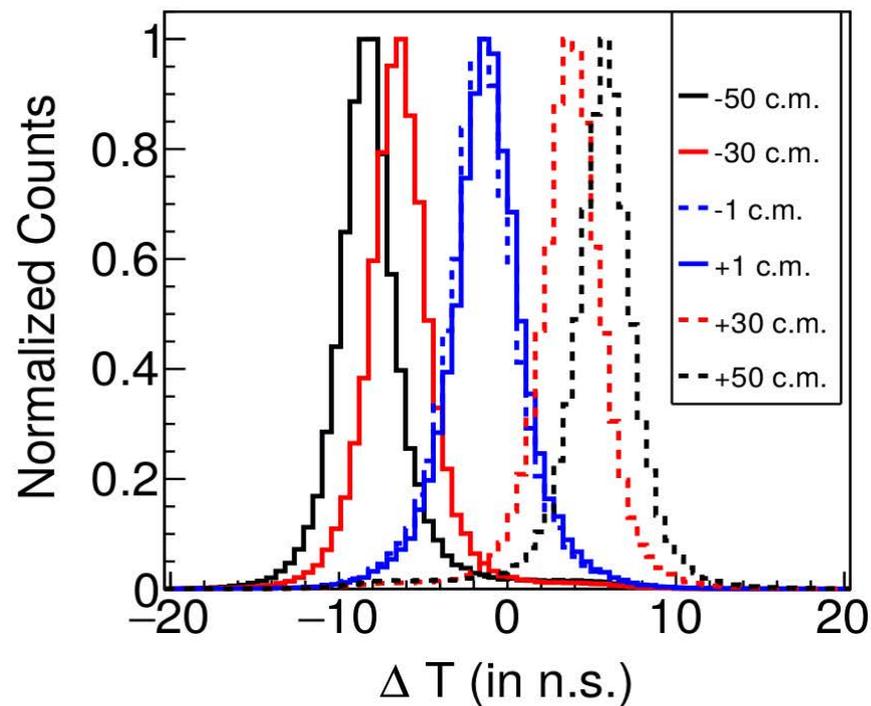
# Plastic scintillator bars

- **Plastic scintillator bar characteristics :**
  - a) Charge from both side PMT == > Geometric Mean**
  - b) Timestamp of each event in PMTs**
  - c) From time difference can determine position.**



# Timing and Position in PS bar

- Time difference between both PMT's used to determine average position using known radioactive source.



# Natural background (gamma and muon)

Dominant contribution of background is from :

a) Gamma from  $^{40}\text{K}$  (1.46 MeV)

b) Gamma from  $^{208}\text{Tl}$  (2.614 MeV)

c) Cosmic muons inducing spallation neutrons

