BACKGROUND AT JUSL AND SIMULATION OF NUCLEAR RECOILS IN LIQUID XENON DETECTORS

Sayan Ghosh

Saha Institute of Nuclear Physics, HBNI,
1/AF, Bidhannagar, Kolkata 700064,
West Bengal, INDIA.

RAPID 2021

Outline

- Measurements and Simulation of different backgrounds at JUSL
  - Motivation
  - Gamma background measurement
  - Cosmic muon measurement and simulation
  - Neutron measurements
  - Radiogenic and Cosmogenic neutron Simulation
  - Comparisons
- Simulation of nuclear recoil due to SN neutrino-induced neutrons in liq. Xenon detectors
  - Introduction
  - Supernova neutrinos and CEνNS recoil spectrum
  - Neutrino induced neutrons (νI*n*) in liquid Xenon
  - GEANT4 simulation
  - S1 and S2 signal generation and analysis
  - Conclusion and Outlook

Background at JUSL

S. Ghosh, S. Dutta, N. K. Mondal and S. Saha.

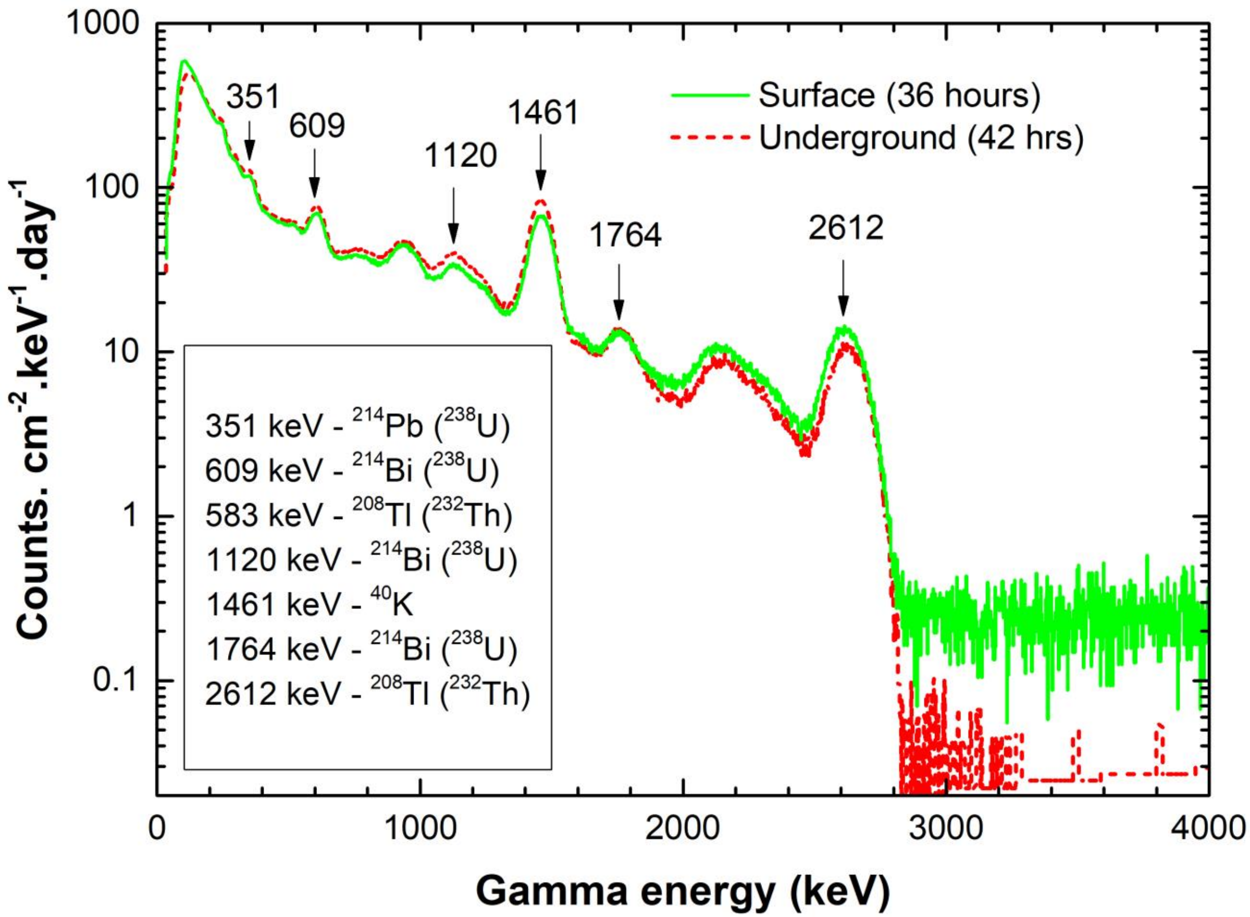
Motivation

- Rare event searches, like direct Dark Matter (DM) searches, neutrino-less double beta decay (NDBD), etc., look for extremely small signals ⟶ extremely low events rates.
- Accurate determination and mitigation of background radiation forms a very important aspects for setting up such experiments.
- Reduction of charged cosmic ray background is done by setting up these experiments in underground laboratories.
- The gamma ray and neutron background are artefacts of the radioactivity of the surrounding rock ⟶ irreducible and specific to the site.
- In an attempt to setup a rare event search experiment in India, an underground laboratory, named as Jaduguda Underground Science Laboratory (JUSL) has been set up at a vertical depth of 555 m (~ 1.6 kmwe) in the Jharkhand state of India.

Gamma Background

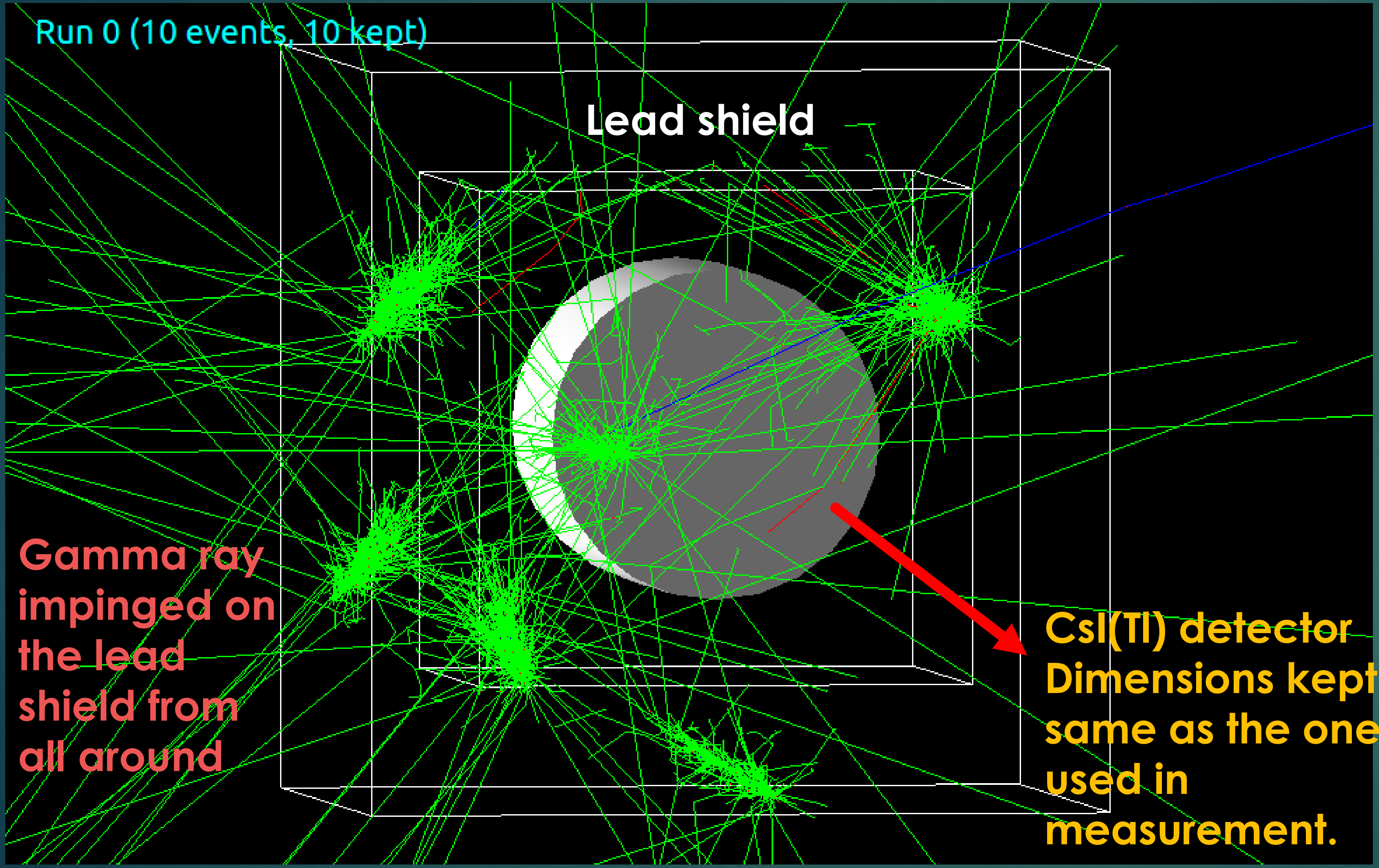
- Gamma ray background in the underground laboratory generally arises from the radioactive decay of ^{238}U and ^{232}Th, along with the elements in their nuclear decay chain, and ^{40}K present in the surrounding rock.
- The measurement was done using a CsI(Tl) scintillator of 50 mm diameter and 1:1 (height:diameter) aspect ratio.
- The scintillator was manufactured by the Crystal Technology Section of Bhabha Atomic Research Centre (BARC), Mumbai and it was directly optically coupled to a Hamamatsu photomultiplier (PMT).
- Calibration was done using various known gamma ray sources.
- Measurements were done both at the surface and at JUSL.

Contd…



- The gamma ray spectrum as measured by the CsI(Tl) detector in both the surface and underground laboratories.
- Flux at both the surface and underground sites are comparable in the range $E_\gamma \leq 2.6$ MeV.
  - Suppression (~10) of gamma ray flux seen in the region $E_\gamma \geq 3$ MeV at JUSL.

Contd…

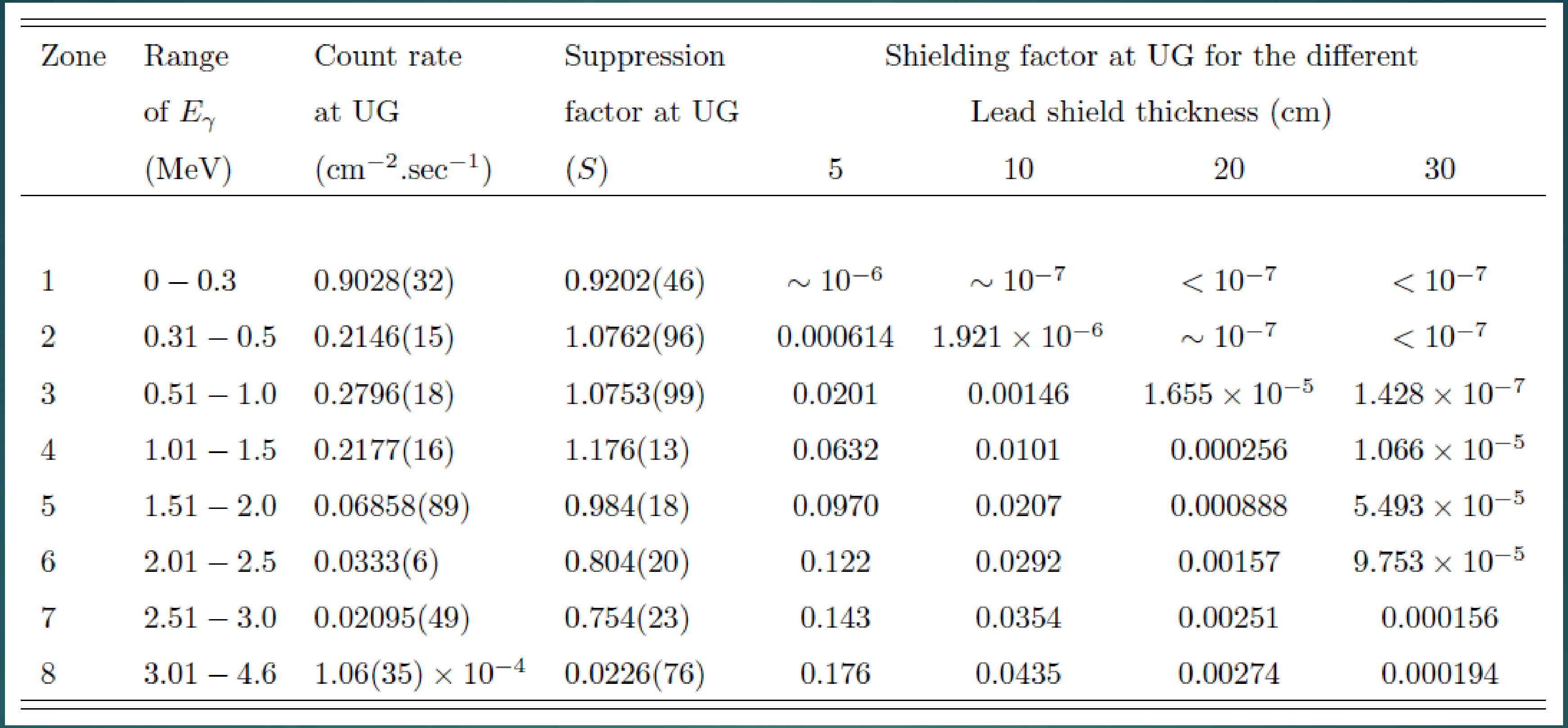


Gamma ray impinged on the lead shield from all around

CsI(Tl) detector Dimensions kept same as the one used in measurement.

- In order to carry out DM direct detection experiment, the gamma ray background is reduced by passive shielding methods using high *Z* elements like Lead (Pb).
- We investigate the thickness of lead required to shield the gamma ray for different zones of the background spectrum using GEANT4 simulation.

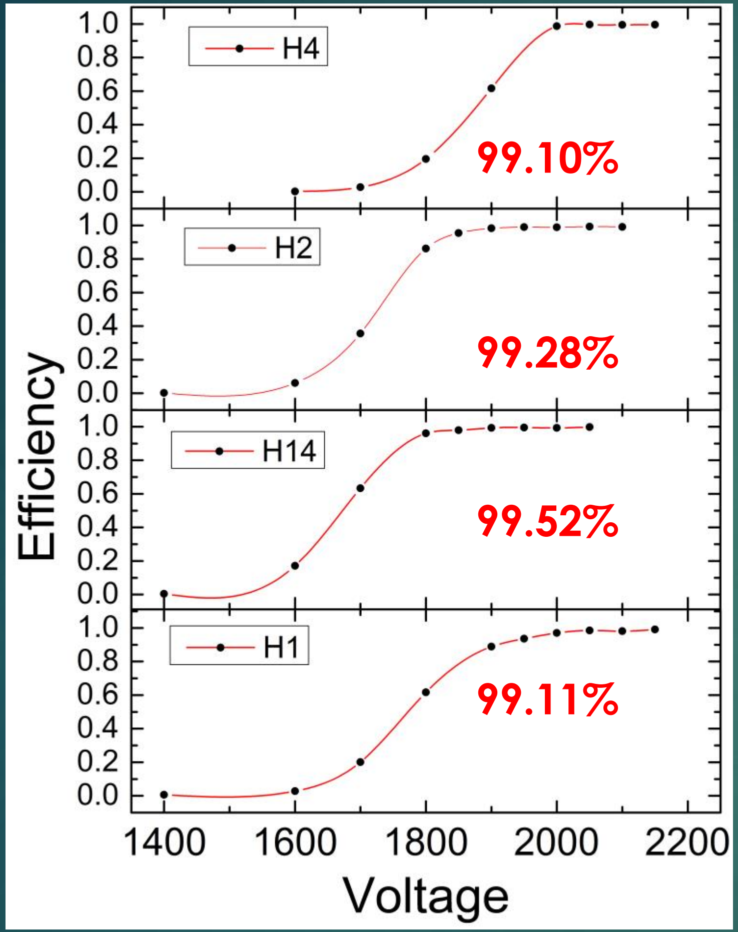
Contd…



Zone	Range of E_γ (MeV)	Count rate at UG ($\mathrm{cm}^{-2}.\mathrm{sec}^{-1}$)	Suppression factor at UG (S)	Shielding factor at UG for the different Lead shield thickness (cm)			
				5	10	20	30
1	$0 - 0.3$	0.9028(32)	0.9202(46)	$\sim 10^{-6}$	$\sim 10^{-7}$	$< 10^{-7}$	$< 10^{-7}$
2	$0.31 - 0.5$	0.2146(15)	1.0762(96)	0.000614	1.921×10^{-6}	$\sim 10^{-7}$	$< 10^{-7}$
3	$0.51 - 1.0$	0.2796(18)	1.0753(99)	0.0201	0.00146	1.655×10^{-5}	1.428×10^{-7}
4	$1.01 - 1.5$	0.2177(16)	1.176(13)	0.0632	0.0101	0.000256	1.066×10^{-5}
5	$1.51 - 2.0$	0.06858(89)	0.984(18)	0.0970	0.0207	0.000888	5.493×10^{-5}
6	$2.01 - 2.5$	0.0333(6)	0.804(20)	0.122	0.0292	0.00157	9.753×10^{-5}
7	$2.51 - 3.0$	0.02095(49)	0.754(23)	0.143	0.0354	0.00251	0.000156
8	$3.01 - 4.6$	$1.06(35) \times 10^{-4}$	0.0226(76)	0.176	0.0435	0.00274	0.000194

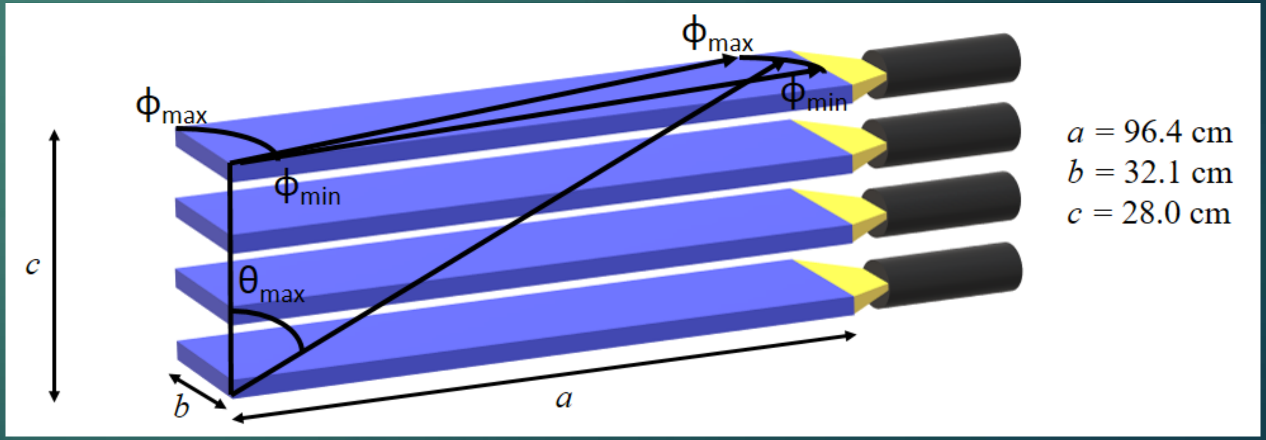
- 30 cm Lead shield successfully shields gamma background of energies even in the range $E_\gamma \geq 3$ MeV.
- Suppression factor ~ 10^4 for $E_\gamma \geq 3$ MeV.

Muon Background:- Experimental Measurements



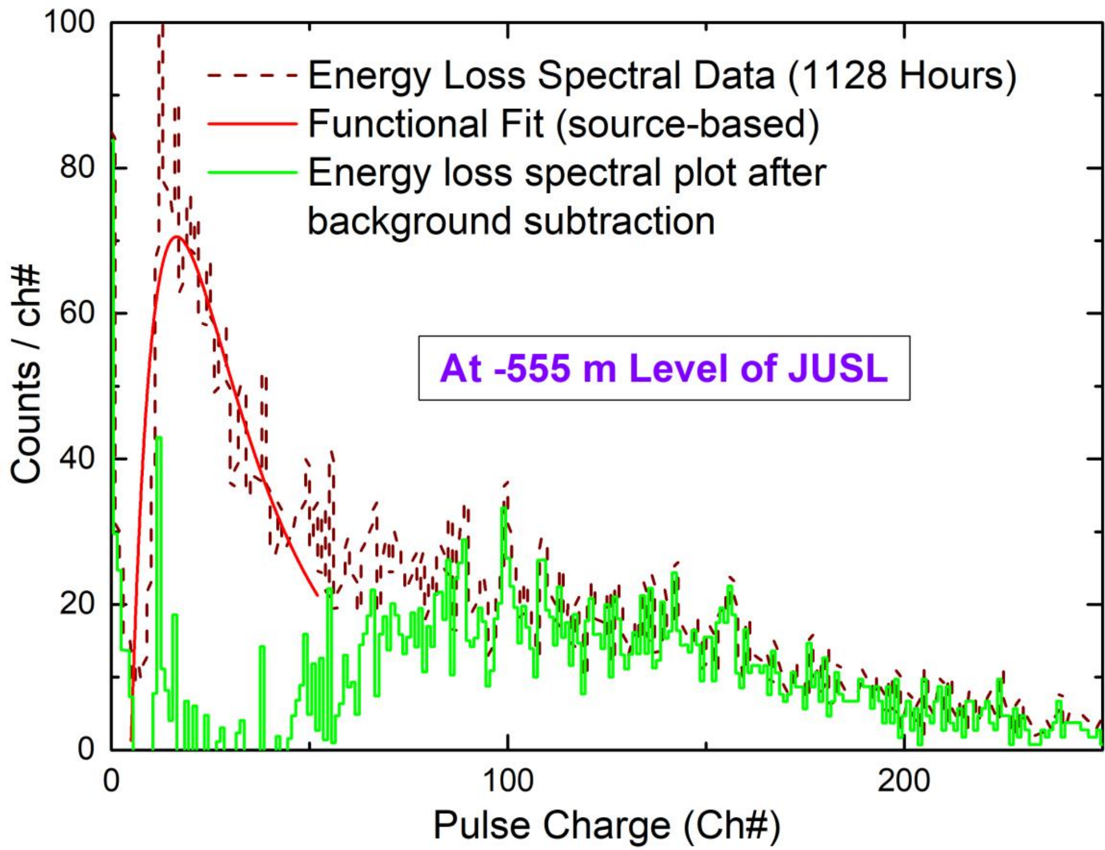
- Total effective efficiency is **(97.04±1.17)%**

- Cosmic muons can penetrate large depths of Earth and give rise to considerable background at experimental sites.
- Interaction of muons with the surrounding rock can produce neutrons (cosmogenic) in the energy range of a few MeV to 100s of GeV ⟶ mimic DM like signals in the detector.

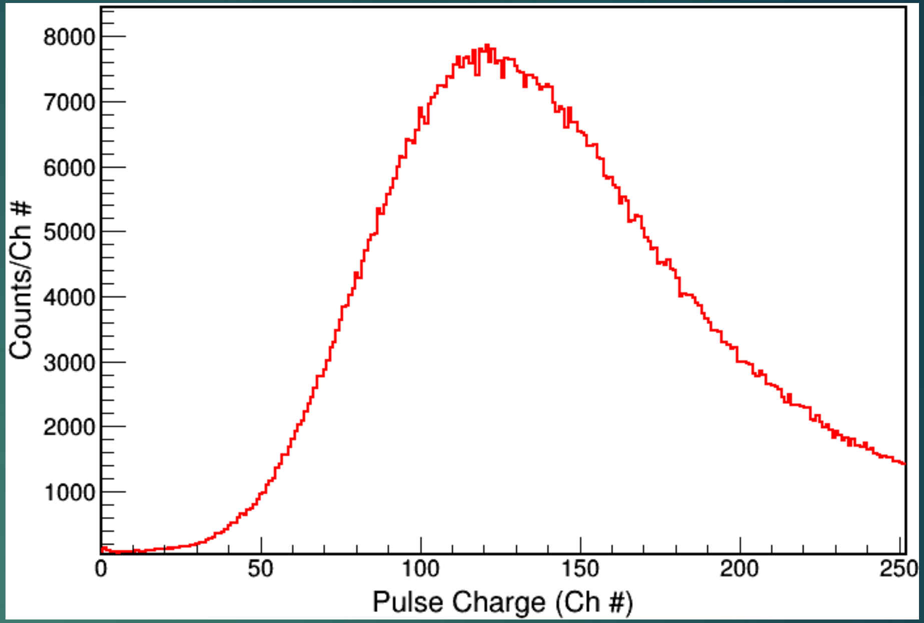


a = 96.4 cm
b = 32.1 cm
c = 28.0 cm

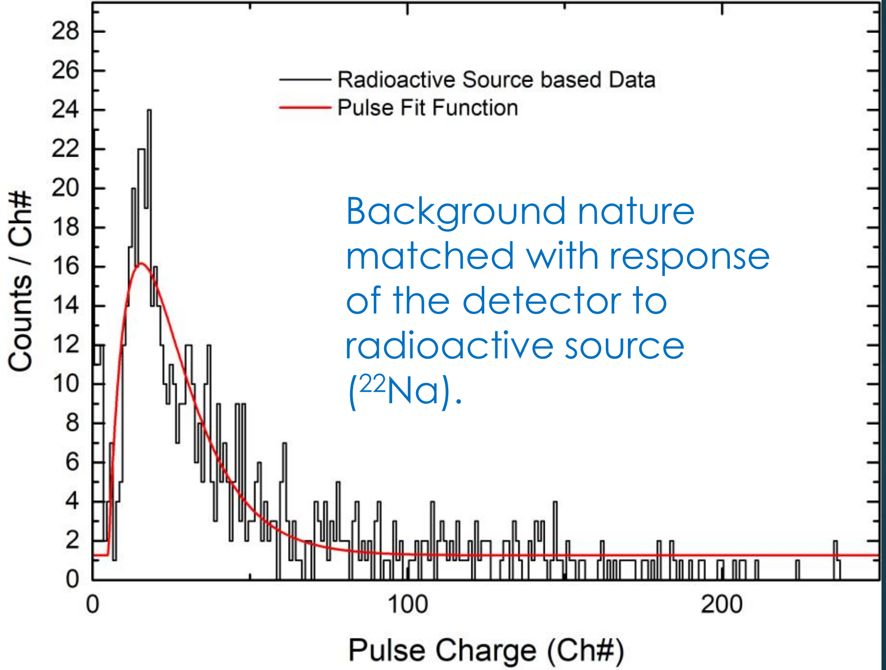
Contd…



- Energy spectrum of muons at the underground site.
- Total spectrum has a background riding over the landau distribution.
- Muon flux after background subtraction is $(\mathbf{2.257 \pm 0.261 \pm 0.042}) \times \mathbf{10^{-7}}$ **cm^{-2} sec^{-1}**.

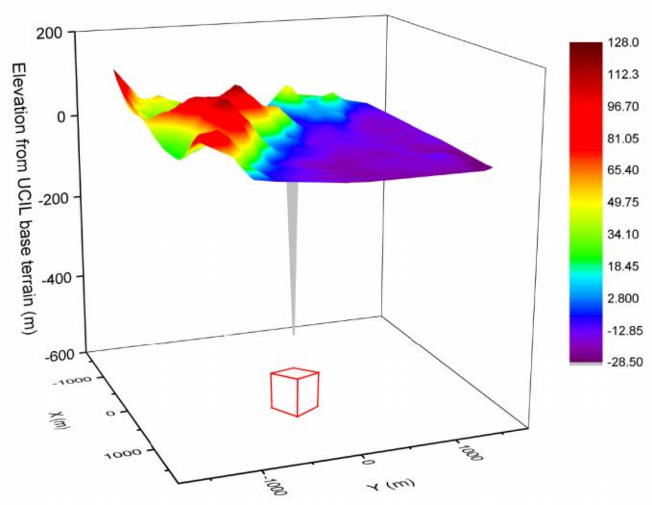


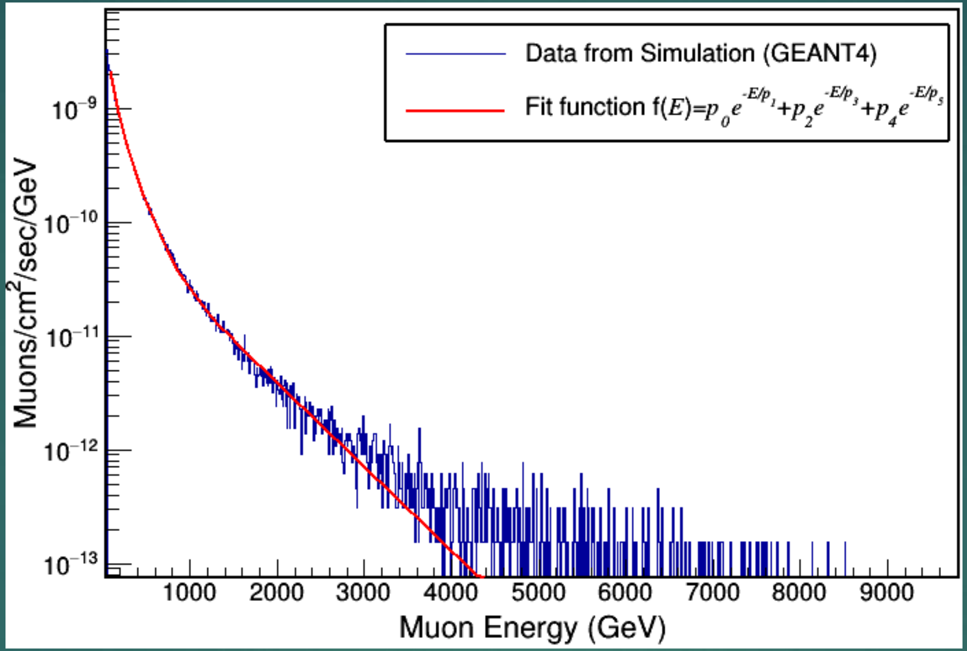
Muon Energy deposition (ΔE) spectrum at the surface (14 hours)

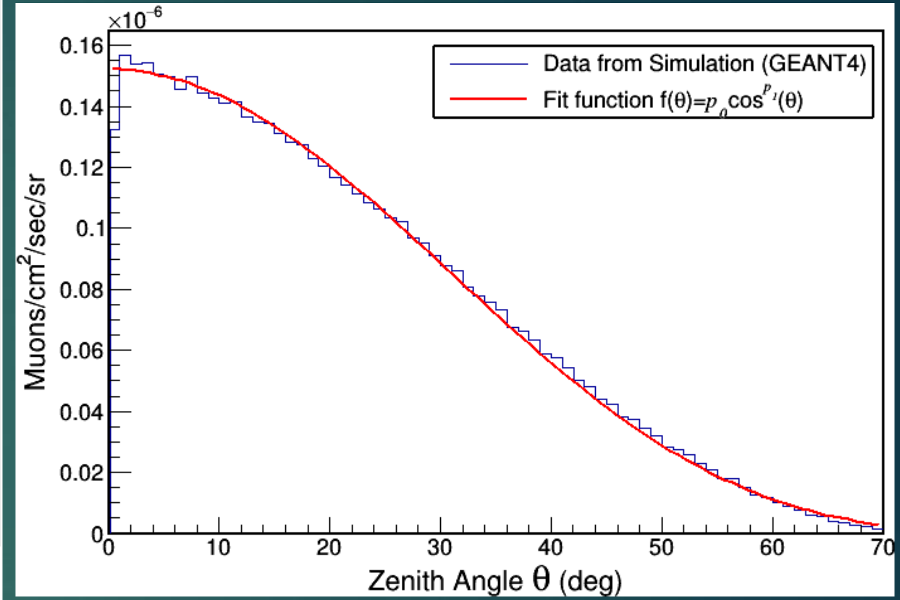


Background nature matched with response of the detector to radioactive source (^{22}Na).

Muon Background:- Simulation

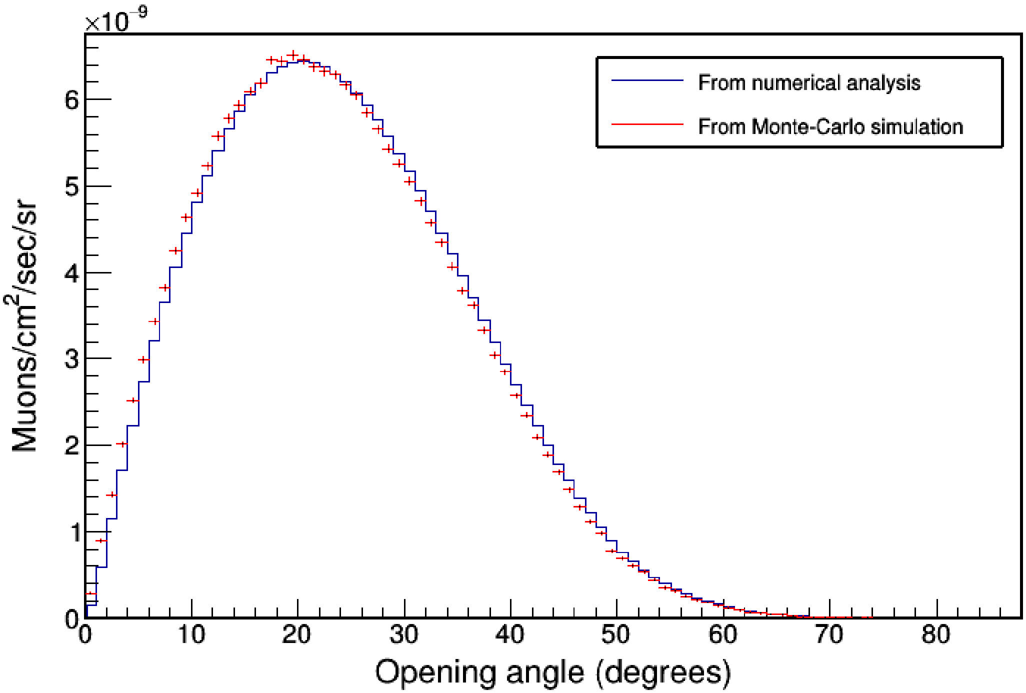






- Energy spectrum and zenith angle distribution of muons at the underground site.
- $E_{\mu}^{\text{avg}} = 186.45 \pm 0.51$ GeV. Exponent of Zenith angle variation $n = 3.756 \pm 0.047 \pm 0.009$.
- Vertical muon intensity $I_0 = (1.558 \pm 0.099 \pm 0.002) \times 10^{-7}$ cm^{-2} sec^{-1} sr^{-1}.

Contd...



$$\Phi_\mu^{\text{detector}} = \frac{4I_0}{a\times b}\times\int_0^{\theta_{\max}}\int_{\phi_{\min}}^{\phi_{\max}}(a-c\tan\theta\cos\phi)(b-c\tan\theta\sin\phi)\cos^{n+1}\theta\sin\theta\,d\theta\,d\phi$$

Resultant muon flux obtained from simulation :-

$(2.051 \pm 0.142 \pm 0.009)\times 10^{-7}$ cm^{-2} sec^{-1}.

- The detector (muon telescope) is not symmetrical and does not have full solid angle coverage ⟶ Aperture like effect.
- Estimate of muon flux observed by the telescope done by numerical and Monte-Carlo (MC) simulation.
- MC simulation done by generating muons on the top surface of the detector stack and recording the number of successful 4-fold coincidences for each zenith angle bin.

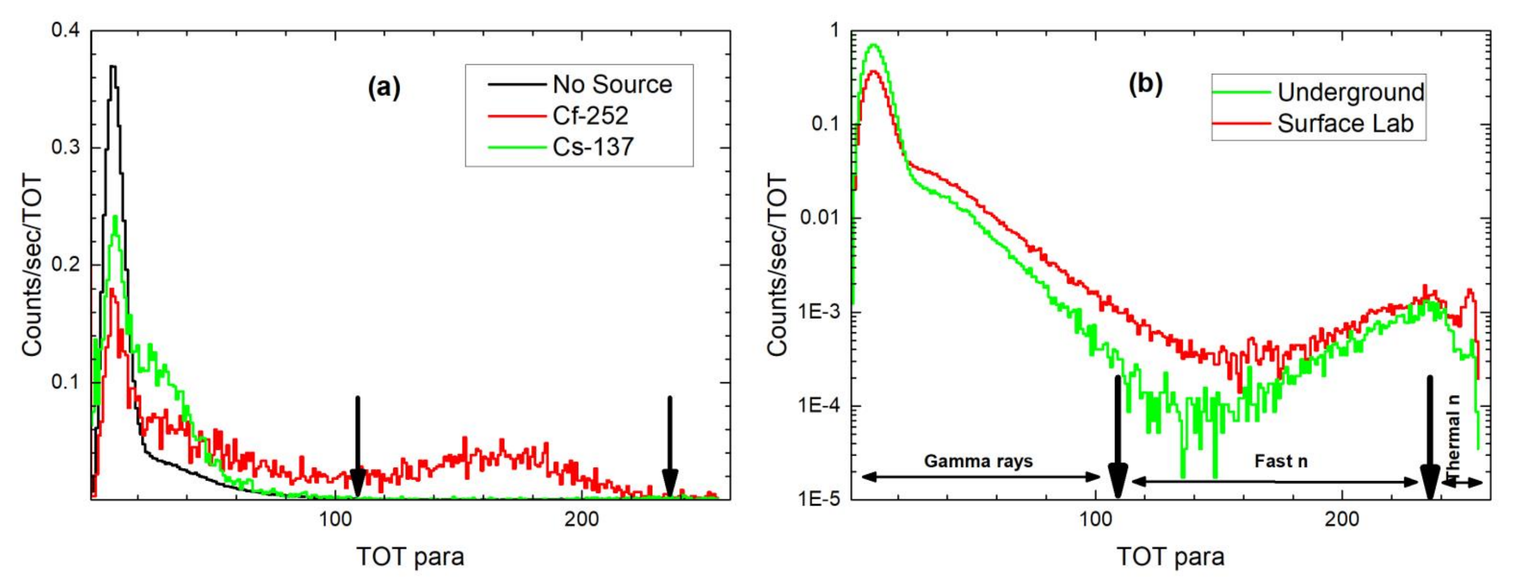
Neutron Background:- Experimental Determination

- Neutrons are generated from the (α, n) reactions from decay of ^{238}U, ^{232}Th and their decay remnants and their spontaneous fission in the surrounding rock.
- The experimental measurement was done using a pressurized ^{4}He detector manufactured by Arktis Radiation Detectors, Switzerland ⟶ 600 mm long cylinder with an inner diameter of 65 mm with ^{4}He kept at 150-180 bar.[1]
- Fast neutrons give rise to nuclear recoils and these recoils deposit energy into the medium giving rise to scintillation.[2]
- Lithium coating along the inner walls of the detector imparts thermal neutron sensitivity.
- Low number of electrons in ^{4}He decreases sensitivity to gamma rays.[3]
- n-γ and thermal-fast neutron discrimination done by pulse shape discrimination (PSD) based on a time over threshold (ToT) analysis. Electronics board and discrimination algorithm already incorporated into the system.

---

[1] R. Chandra, et. al., Jour. Instrum. 7 (2012) C03035.
[2] R. Kelley, et. al., AIP Advances 5 (2015) 037144.
[3] R. Kelley, et. al., Nucl. Instrum. Meth. A 830 (2016) 44-52.

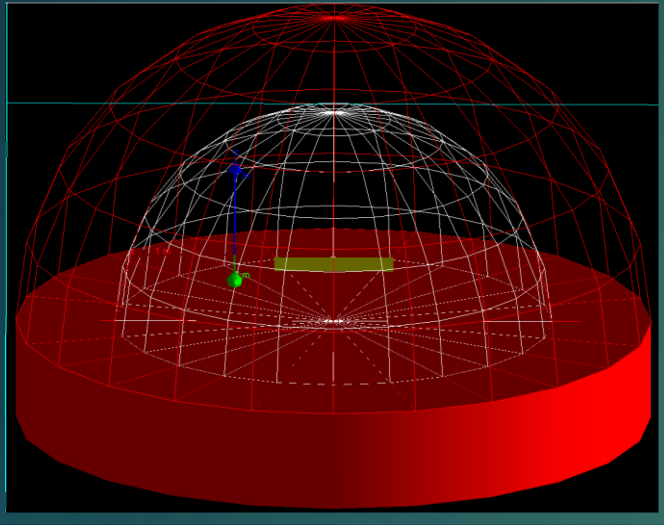
Contd…

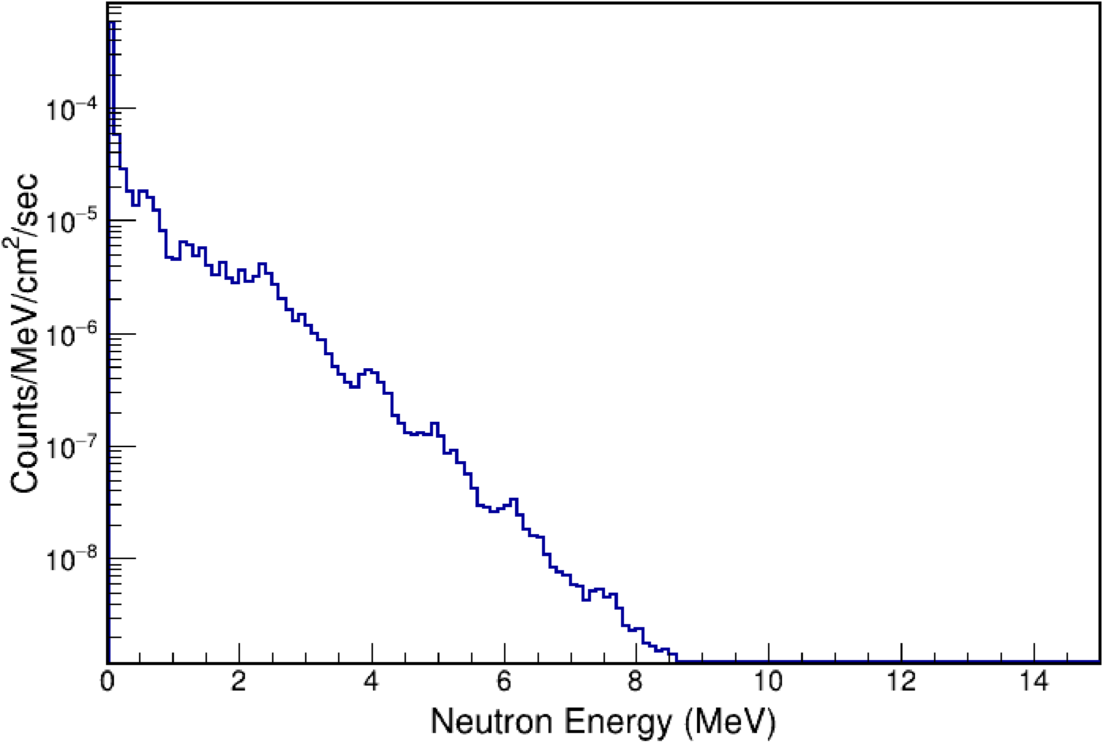


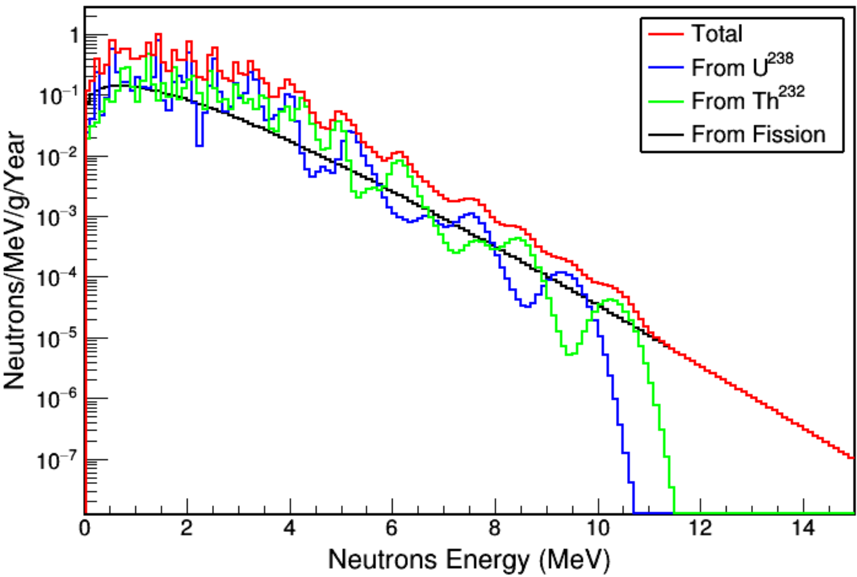
- Flux of neutrons in the energy range $E_n \leq 10$ MeV was found to be $(\mathbf{1.63} \pm \mathbf{0.03}) \times \mathbf{10^{-4}}$ **cm^{-2} sec^{-1}**.

Neutron Background:- Radiogenic

Neutron Simulation







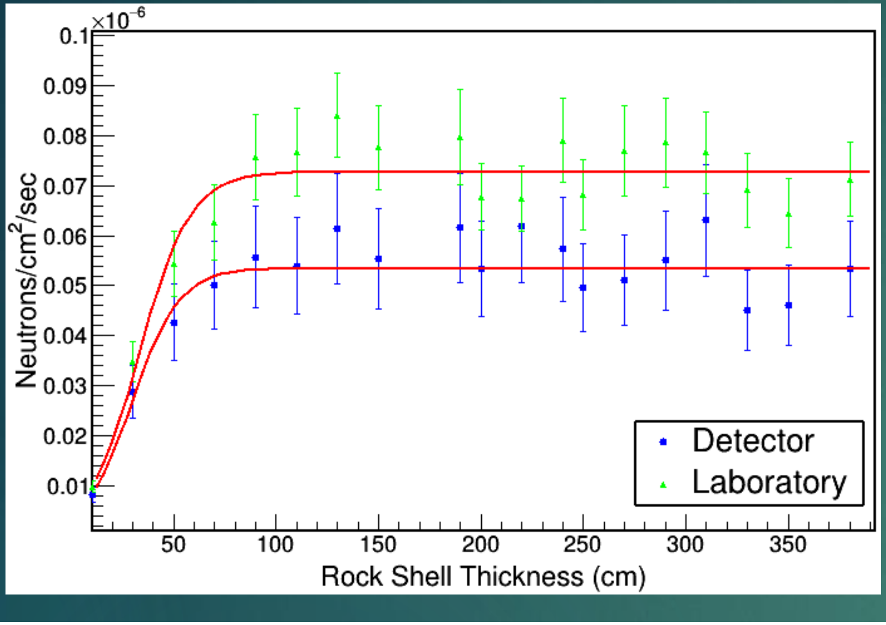
- The underground laboratory is a room that of dimensions (4.5 × 4.5 ×

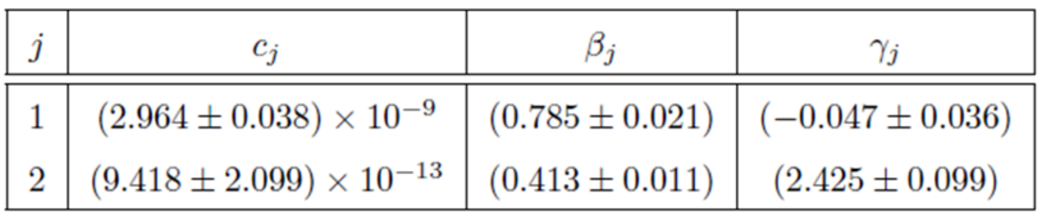
Neutron Background:- Cosmogenic

Neutron Simulation

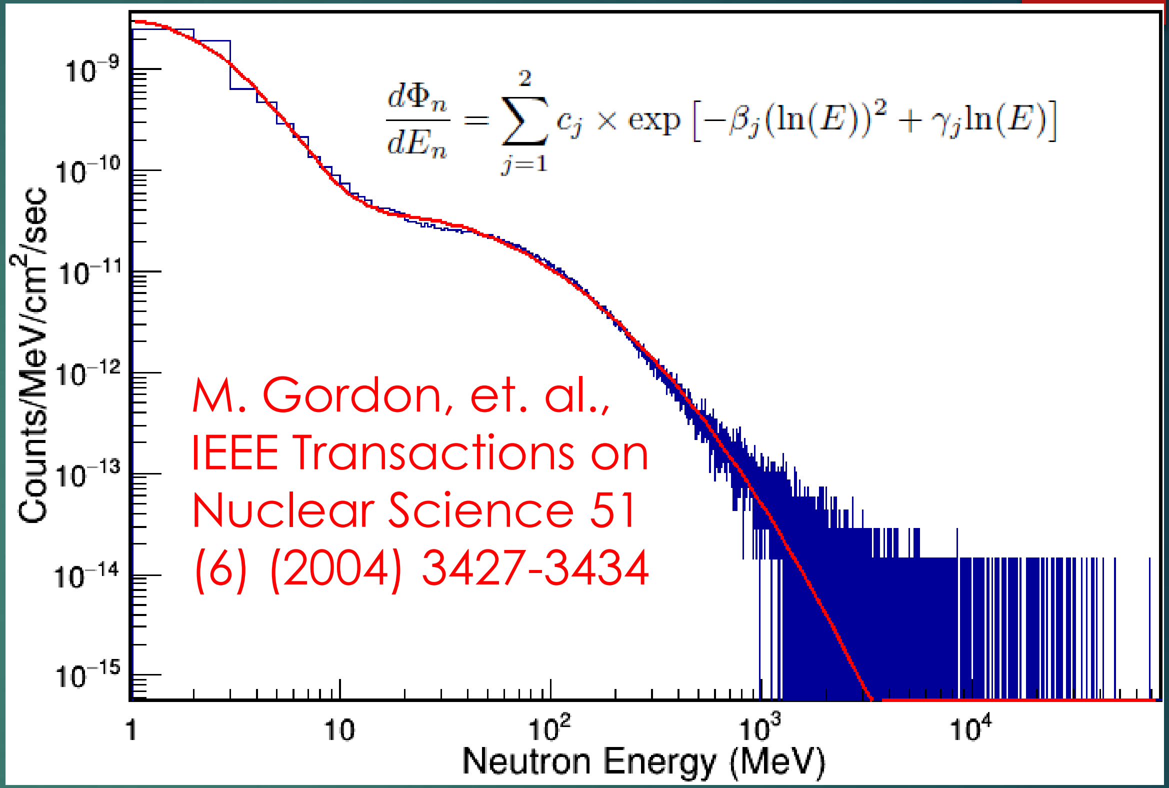
- These neutrons are produced due to the interaction of muons with the surrounding rock ⟶ dependence on penetration depth of muons.
- Typically in the energy range of a few MeV to few 100s of GeV. Therefore they can mimic the DM signal.
- Muons following the energy and zenith angle distribution obtained from simulation are generated on outer surface of the hemispherical rock shell of varying thicknesses.
- Neutrons produced will be scattered in all directions and some will reach the detector geometry kept in the middle ⟶ Backscattering also accounted for.

Contd...





j	c_j	β_j	γ_j
1	$(2.964 \pm 0.038) \times 10^{-9}$	(0.785 ± 0.021)	(-0.047 ± 0.036)
2	$(9.418 \pm 2.099) \times 10^{-13}$	(0.413 ± 0.011)	(2.425 ± 0.099)

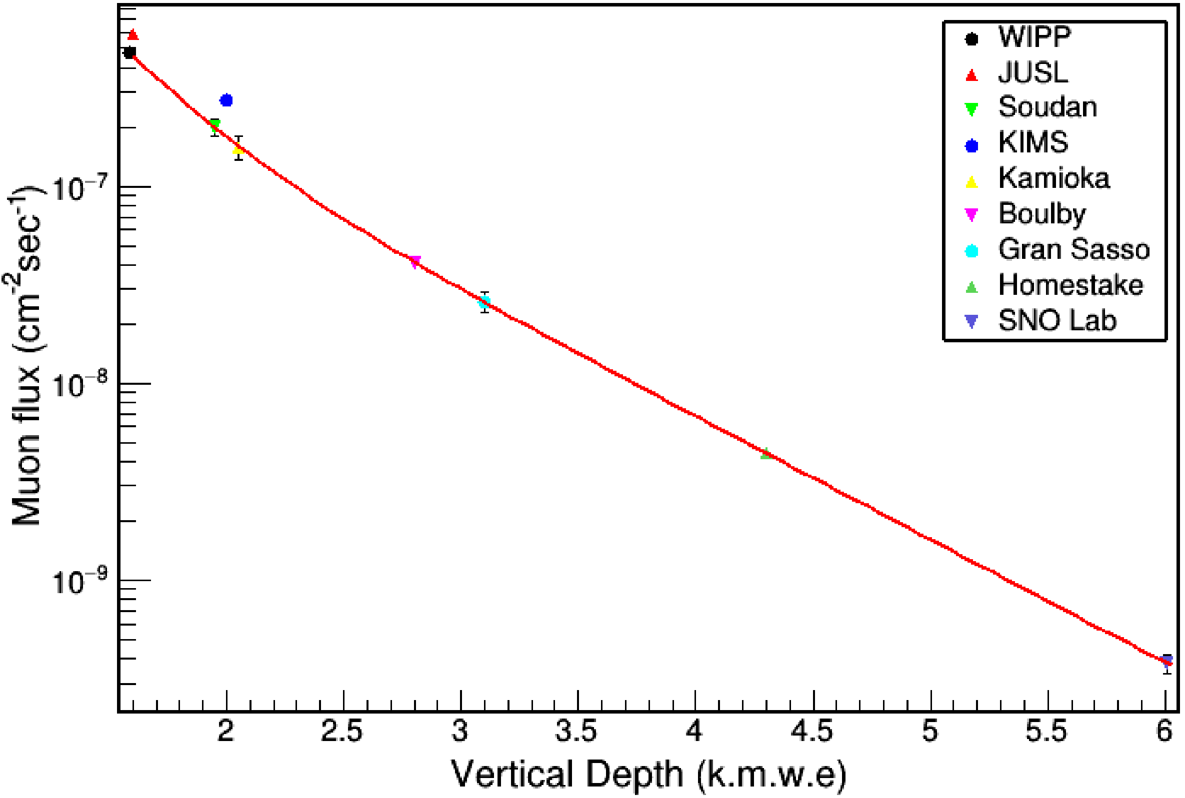


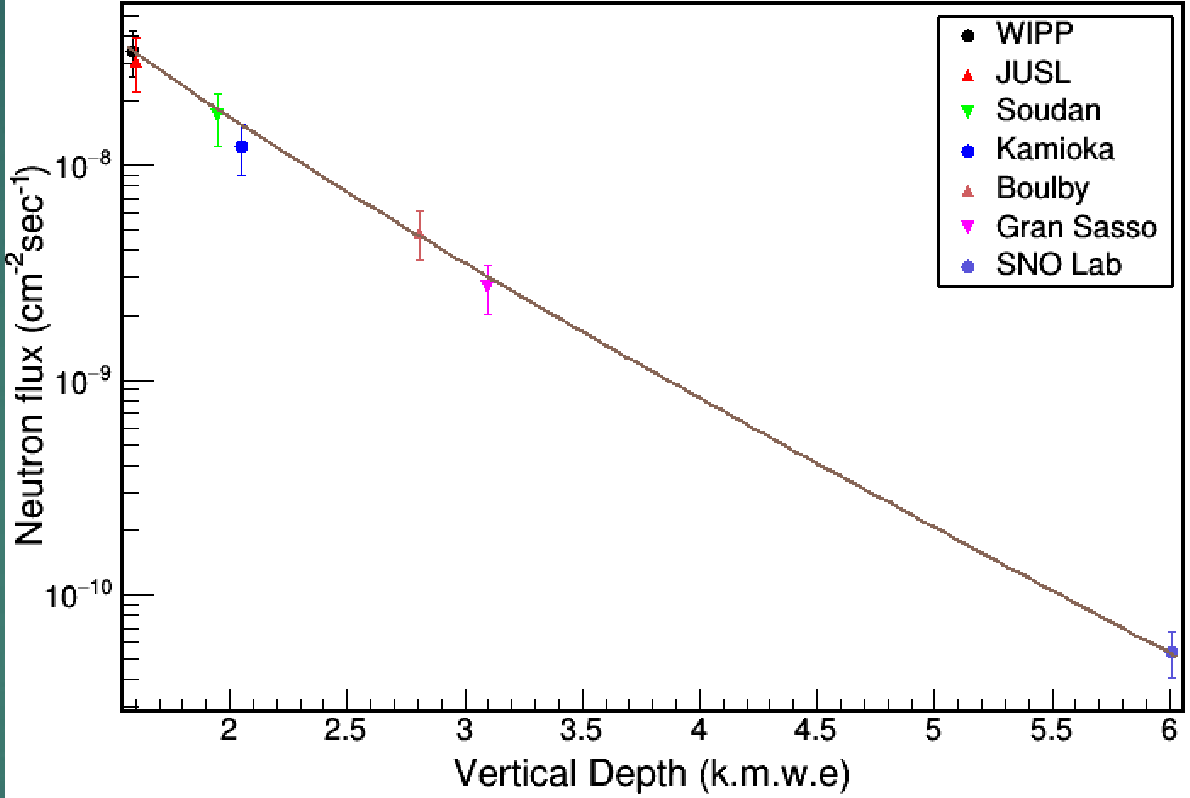
$$\frac{d\Phi_n}{dE_n} = \sum_{j=1}^{2} c_j \times \exp\left[-\beta_j(\ln(E))^2 + \gamma_j \ln(E)\right]$$

M. Gordon, et. al., IEEE Transactions on Nuclear Science 51 (6) (2004) 3427-3434

- 2 m of rock shell thickness found to be the optimum choice again. Floor thickness 100 cm not found to cause any difference in the cosmogenic neutron flux.
- Flux of cosmogenic neutrons at the detector was found to be $(\mathbf{5.661 \pm 0.103}) \times \mathbf{10^{-8}}$ **cm^{-2} sec^{-1}**.

Comparison with other labs





- Global Fit functions :- D. Mei, A. Hime, Phys. Rev. D 73 (2006) 053004.
- Simulation results from both the cosmic ray muon flux and cosmogenic neutron fluxes match well with data from other underground sites.

Simulation of nuclear recoil due to SN neutrino-induced neutrons in liq. Xenon detectors

P. Bhattacharjee, A. Bandopadhyay, S. Chakraborty, **S. Ghosh**, K. Kar, and S. Saha

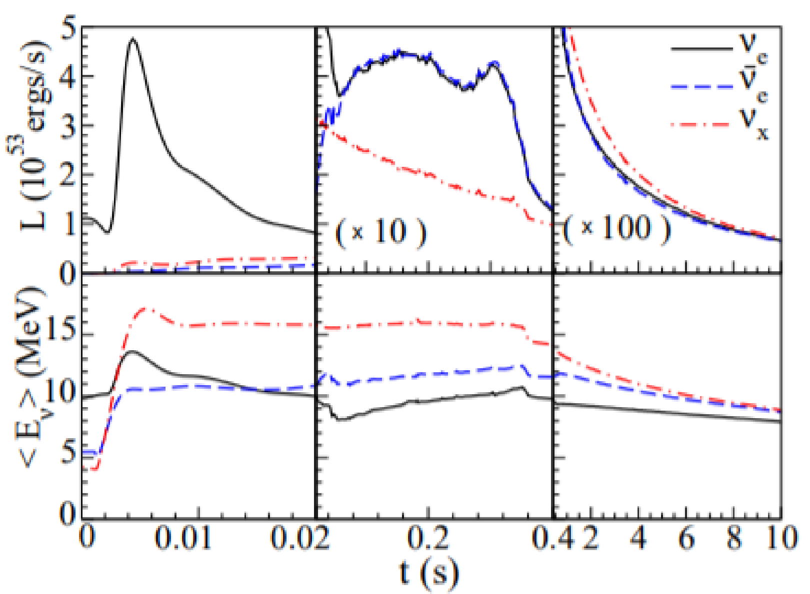
Introduction

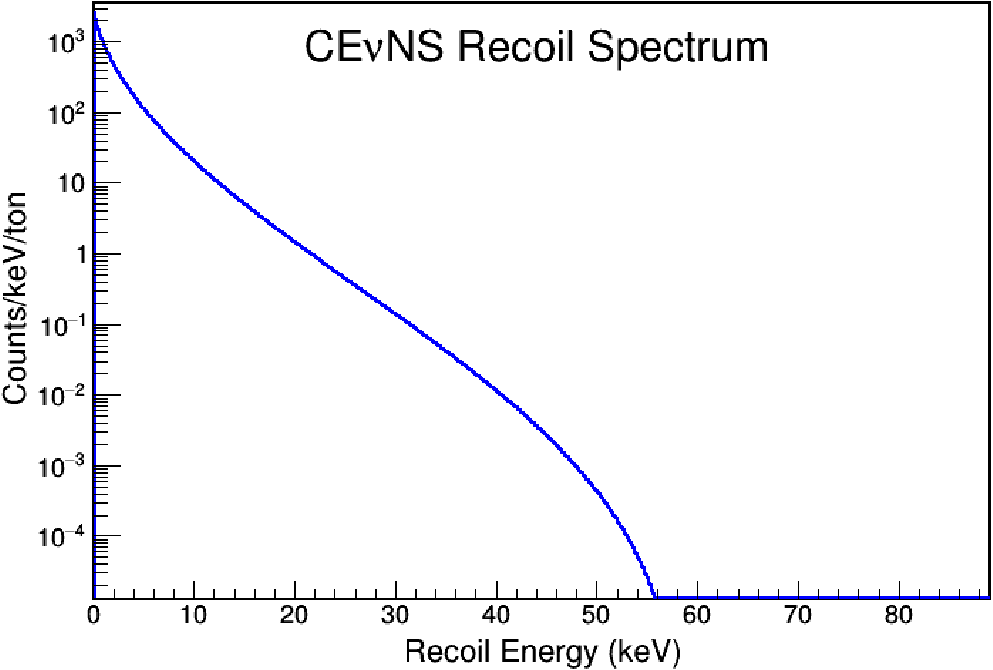
- Core collapse supernovae (SNe) produce huge flux of neutrinos of all flavours with E_ν up to a few tens of MeV over a time scale of about 10 s.
- These neutrinos can be detected via their Charged Current (CC) and Neutral Current (NC) interactions with the detector material.
- In large volume liquid Xenon based dark matter detectors these neutrinos can give rise to detectable signals due to neutrino induced nuclear recoils (NR) via Coherent Elastic neutrino-Nucleus Scattering (CEνNS).
- In addition to CEνNS, the neutrinos can produce neutrons inside the liquid Xenon tank through inelastic CC interactions, and these neutrons can generate additional NR ⟶ an additional channel for SN detection.
- It is found that neutrino-induced neutrons can give the dominant contribution to the NR spectrum at recoil energies of $E_R \geq 30$ keV, over that due to CEνNS alone.

Supernova neutrinos and xenon NR spectrum due to CEνNS spectrum

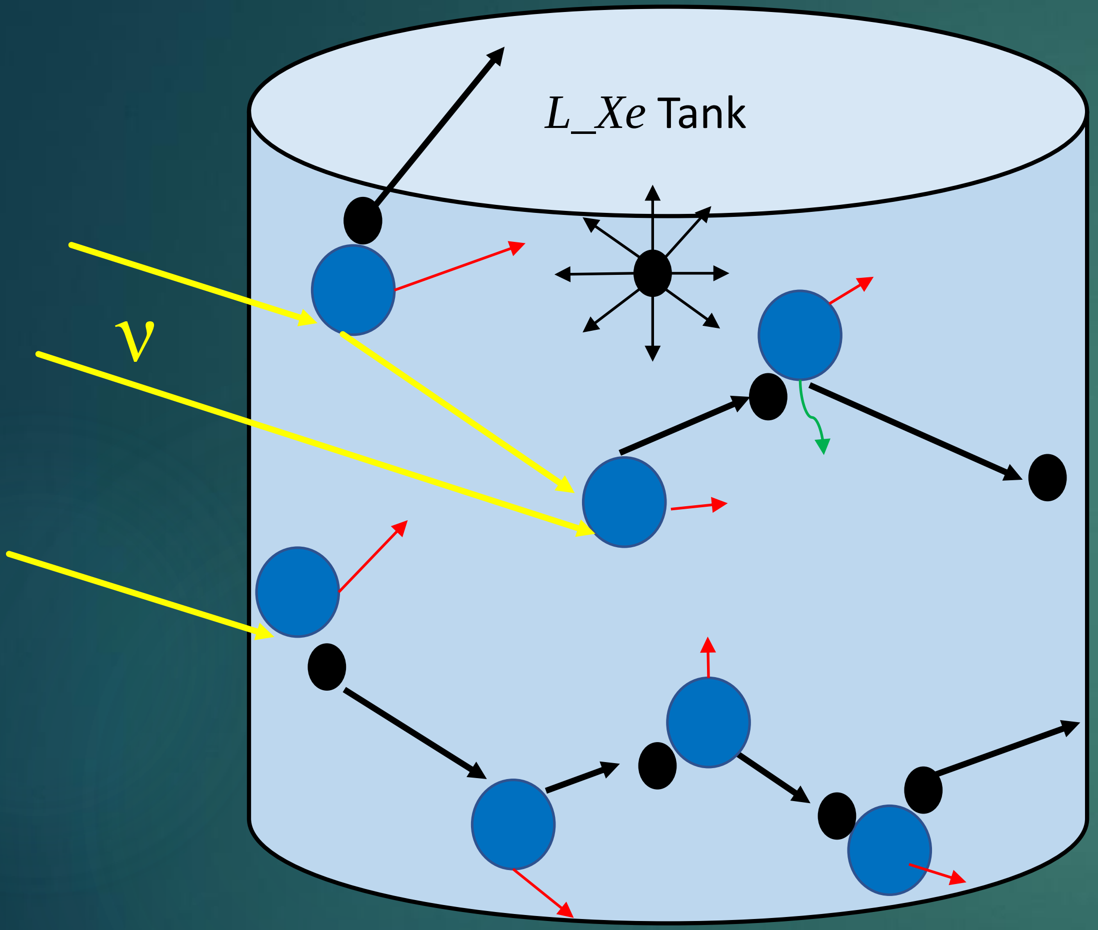
- In this work consider the SN due to the collapse of a 18 $M_\odot$ progenitor star at 1 kpc distance from the Earth.
- 1 tonne liquid Xenon detector (consider ^{132}Xe for illustration).
- The temporal profiles of the average energy and luminosity of different neutrino species are taken from **T. Fischer, S. C. Whitehouse, *et. al.*, Astron. Astrophys. 517, A80 (2010)**.

S. Chakroborty, P. Bhattacharjee and K. Kar Phys. Rev. D **89**, 013011 (2014)





Neutrino-induced Neutrons

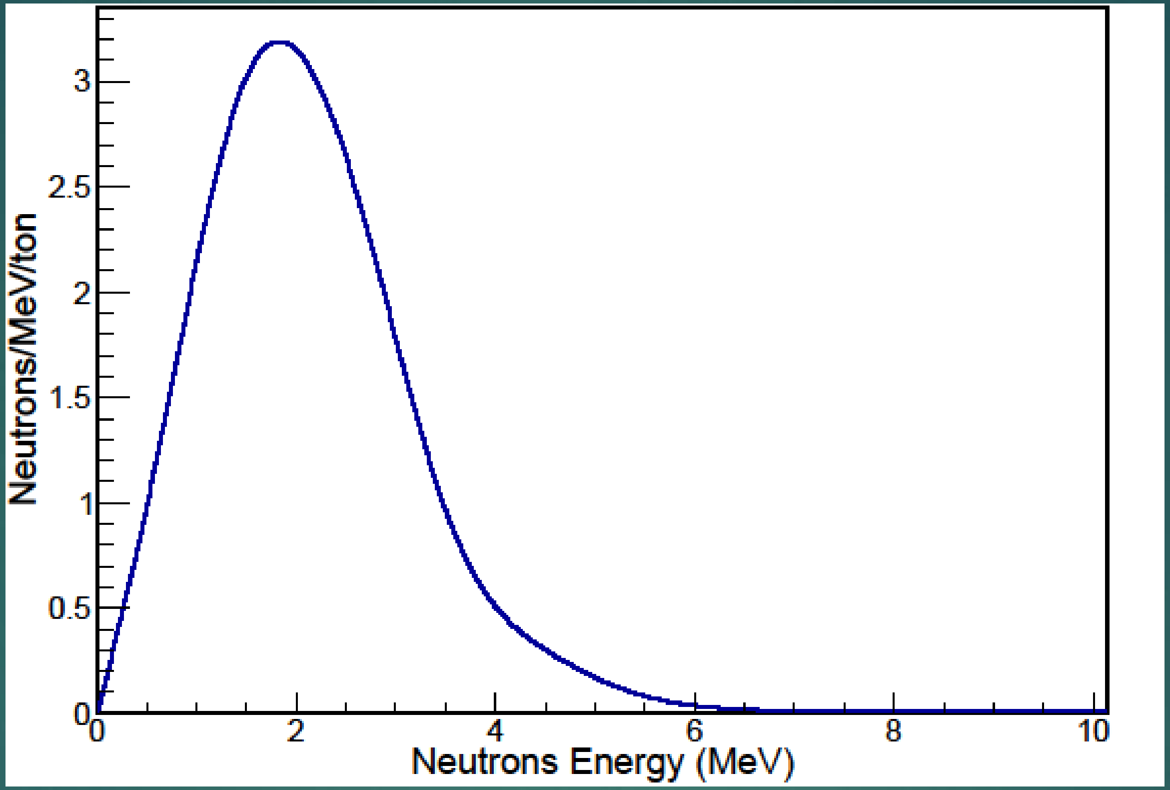


- Inelastic CC interaction of SN neutrinos with ^{132}Xe can produce ^{132}Cs nuclei in excited states which can de-excite through emission of neutrons.
- These neutrino induced neutrons (ν*In*) can undergo elastic and inelastic scattering on xenon nuclei and produce recoiling xenon nuclei.
  - The small black circles represent neutrons.
  - The Big blue circles represent ^{132}Xe nuclei.
  - The black lines represent neutron scattering lines or production lines.
  - The small red lines represent Xenon nuclear recoils.
  - The curly green lines represent photons being produced in association with neutrons.
- Single or multiple recoils may be generated due to elastic and in-elastic interactions of the neutrons with the Xenon nuclei.

$$\nu_e + {}^{132}_{54}\mathrm{Xe} \rightarrow e^- + {}^{132}_{55}\mathrm{Cs}^*$$

$$^{132}\mathrm{Cs}^* \rightarrow {}^{132-X}\mathrm{Cs} + Xn$$

Contd…



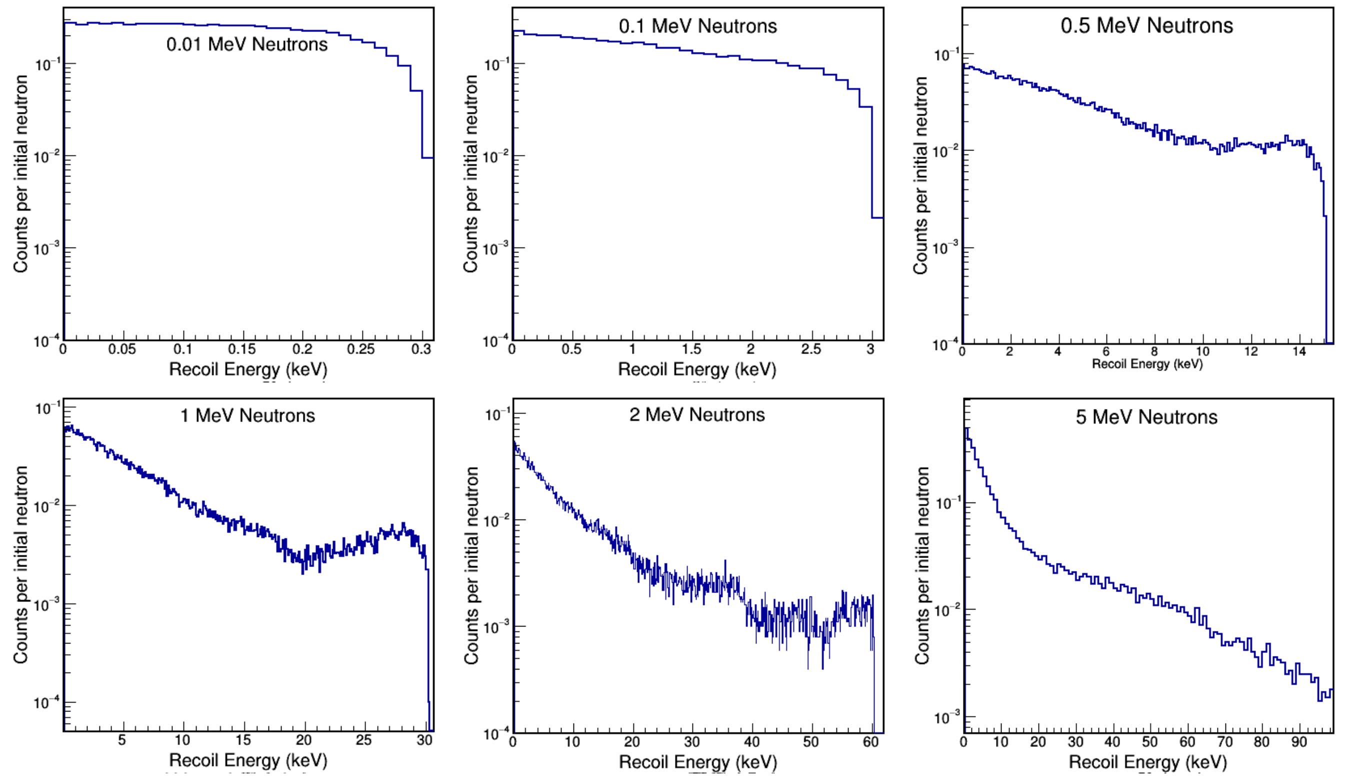
Back

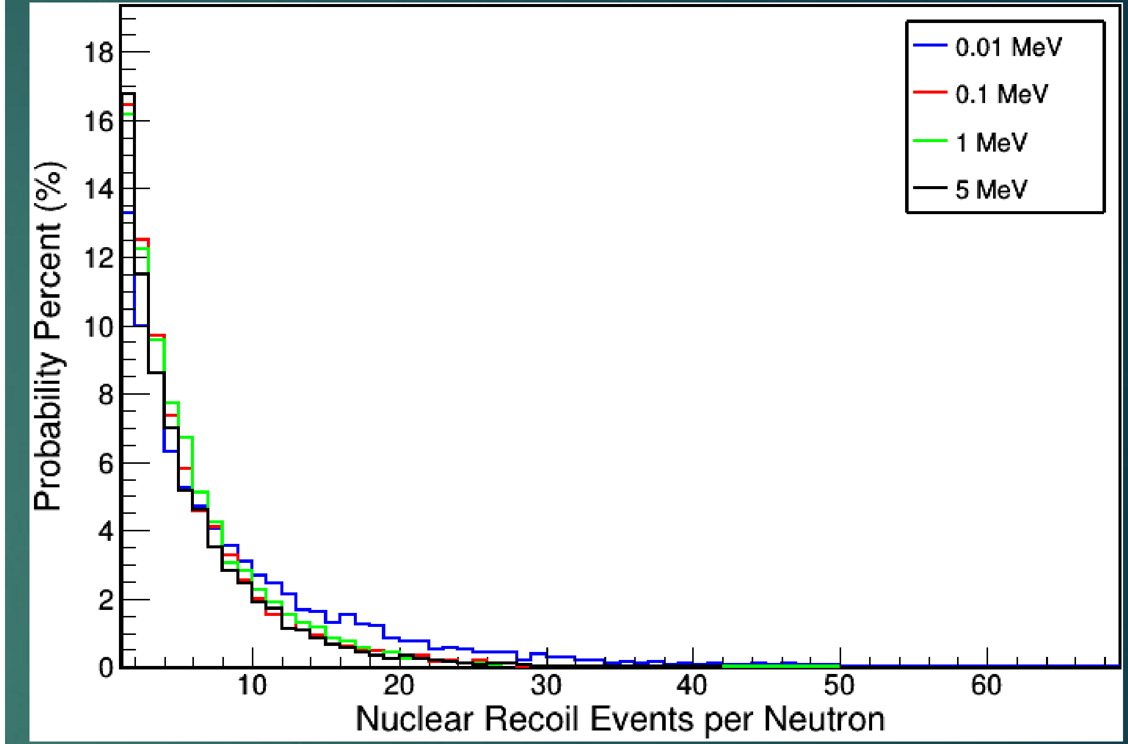
- Spectrum of neutrons produced from inelastic CC interaction of SN neutrinos with ^{132}Xe nuclei for a 18 $M_{\odot}$ progenitor SN at 1 kpc distance from the Earth for the case of normal ordering (NO) of neutrino mass hierarchy.
- Total number of neutrons generated is ~ 8.

GEANT4 simulation

- We take a 1 ton liquid Xenon tank with 1:1 (height:diameter) aspect ratio with the diameter being ~ 75.4 cm.
- Detector material ⟶ liquid Xenon (^{132}Xe) with density ~ 2.953 g/cm^3.
- We start with mono-energetic neutrons.
  - Mono-energetic neutrons were generated homogenously inside the liq. Xenon tank and propagated isotropically.
  - Neutrons can generate nuclear recoils by elastically scattering off the stationary Xe nuclei in the tank.
  - In-elastic processes can also take place ⟶ Xe nucleus absorbs a neutron, resulting in an excited nucleus which decays by emission of neutrons and γ rays.
  - These new neutrons can further undergo elastic and/or in-elastic processes to produce further nuclear recoils.

Contd...

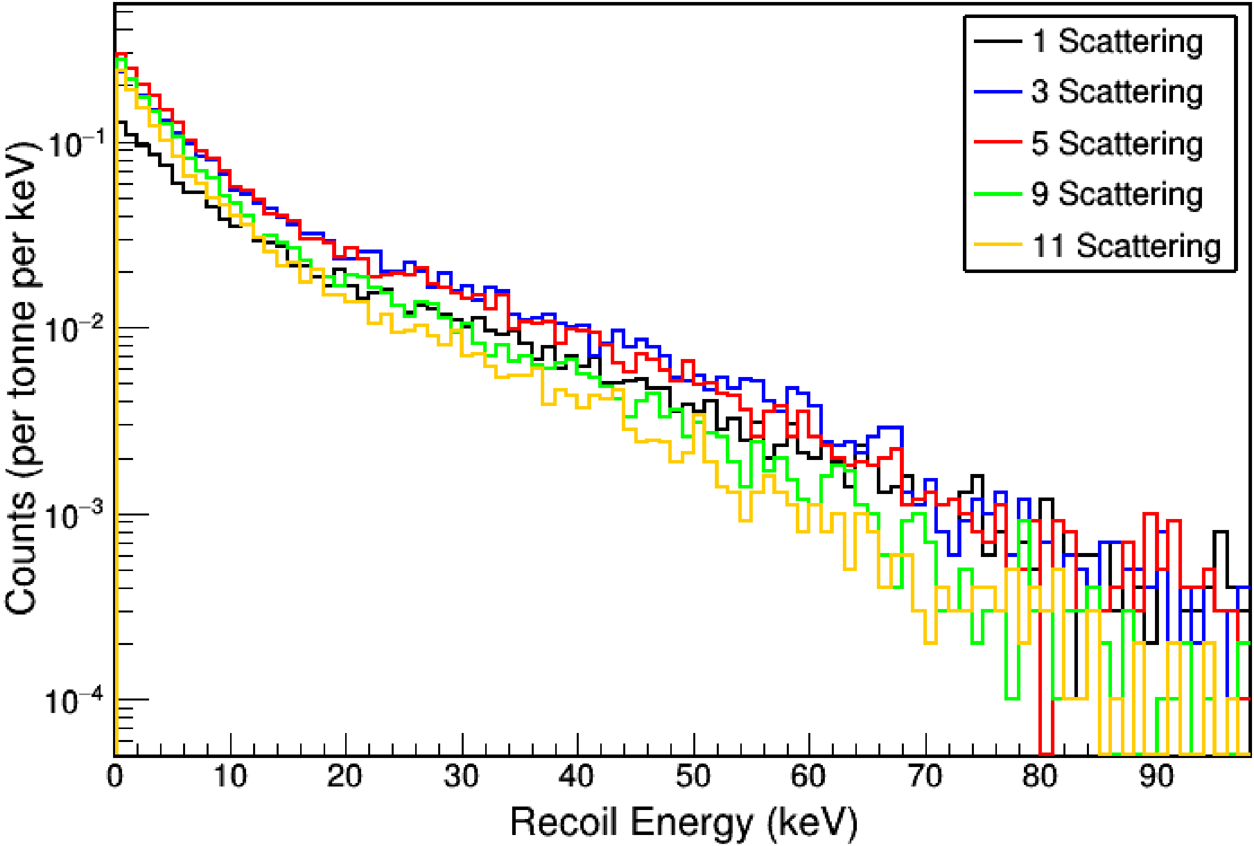




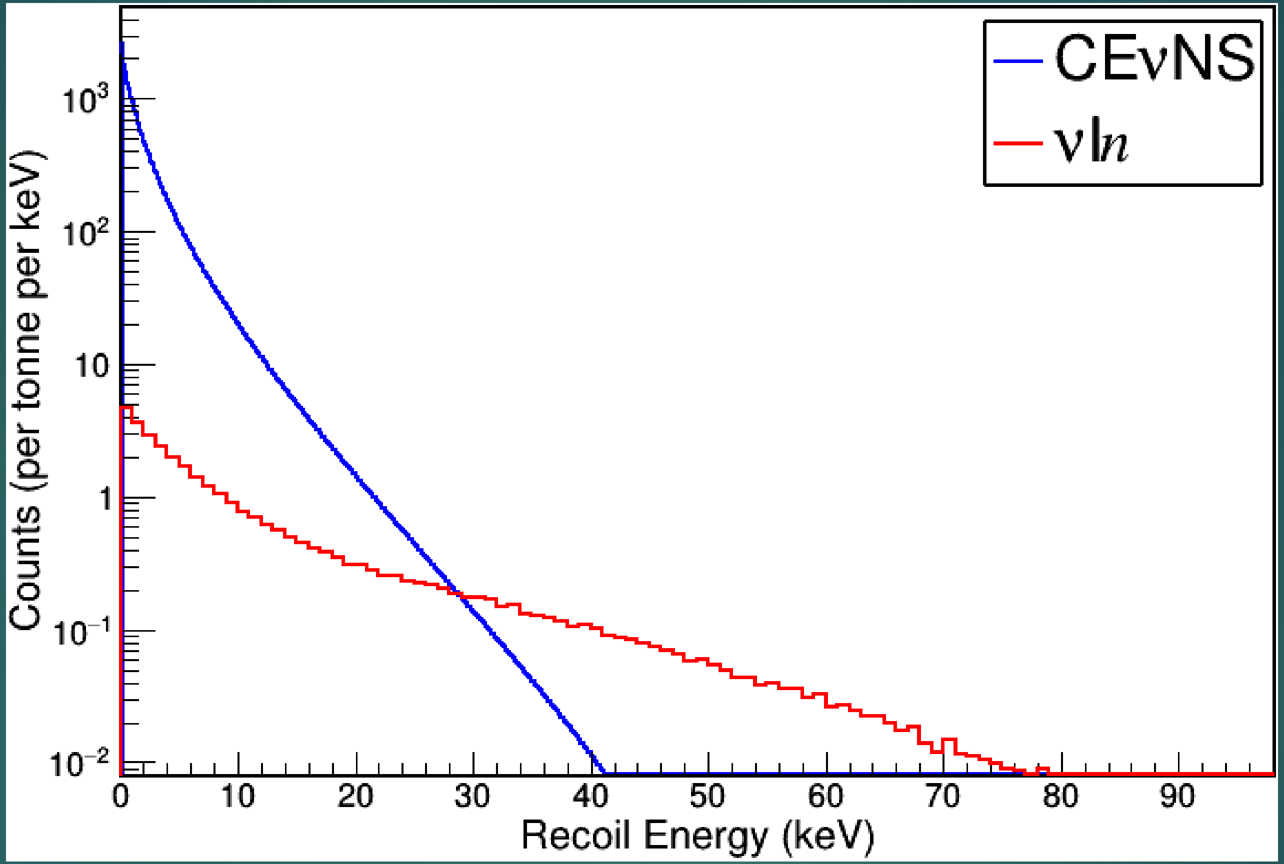
- At low energies of initial neutrons all scattering angles are equally probable → Flat recoil spectra.
- For more energetic initial neutrons, low scattering angles are more probable → Low energy recoils are more abundant.
- Probability of multiple nuclear recoil generation decreases with increasing energy of initial neutron.

Contd…

- Finally we use the neutron spectrum obtained from CC interactions of the SN neutrinos. Neutron Spectrum



Differential Rate Spectrum



- At recoil energies $E_R \geq 30$ keV dominant contribution from νIn events.

S1and S2 signal generation

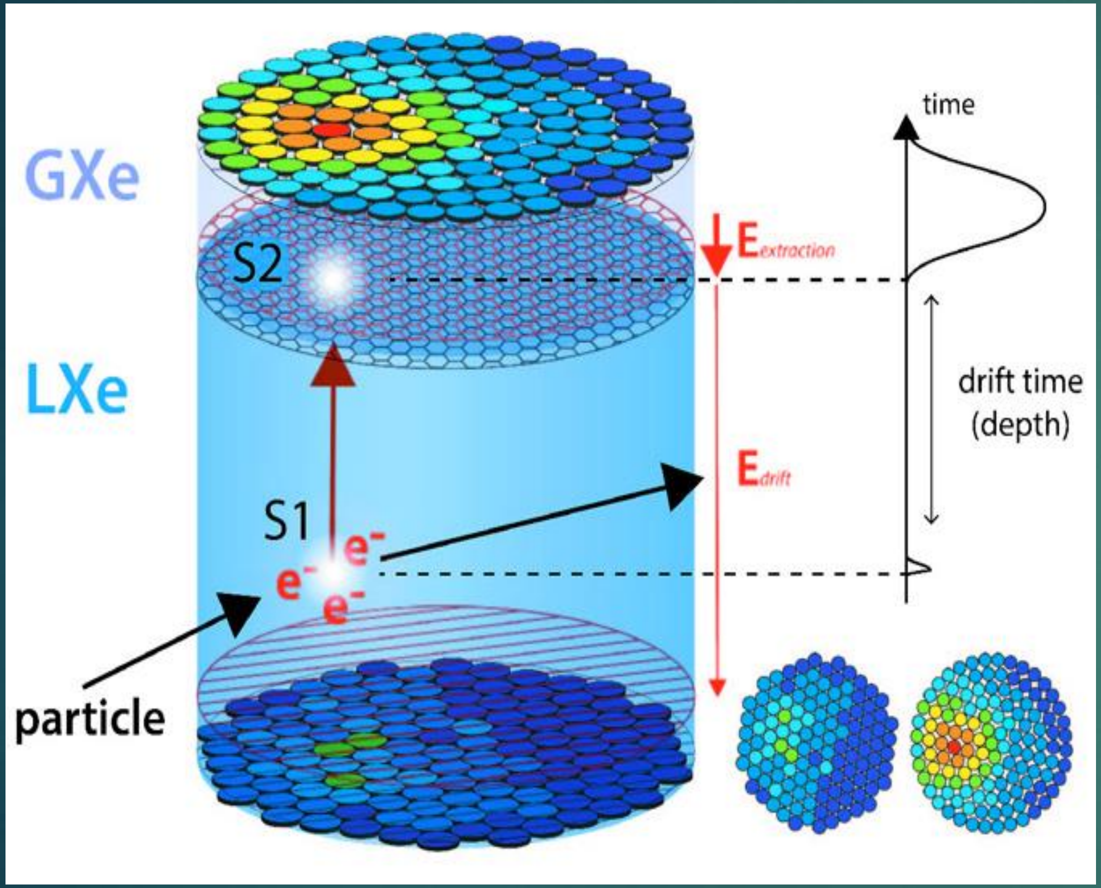
- The final observable signals in liquid Xenon TPC based DM detectors are the S1 and S2 signals.
  - S1 from scintillation and S2 due to ionization
- S1 and S2 signals in this work have been computed using MC simulations based on the model described in **E. Aprile, *et. al.*, (XENON), J. Cosmol. Astropart. Phys. 04 (2016) 027** and **R. F. Lang, C. McCabe, *et. al.*, PRD 94, 103009 (2016)**.

$$\mathrm{S1} = \mathrm{Gauss}(N_{\mathrm{PE}}, 0.4\sqrt{N_{\mathrm{PE}}})$$

$$\mathrm{S2} = \mathrm{Gauss}(20\ \tilde{N}_{\mathrm{el}}, 7\sqrt{\tilde{N}_{\mathrm{el}}})$$

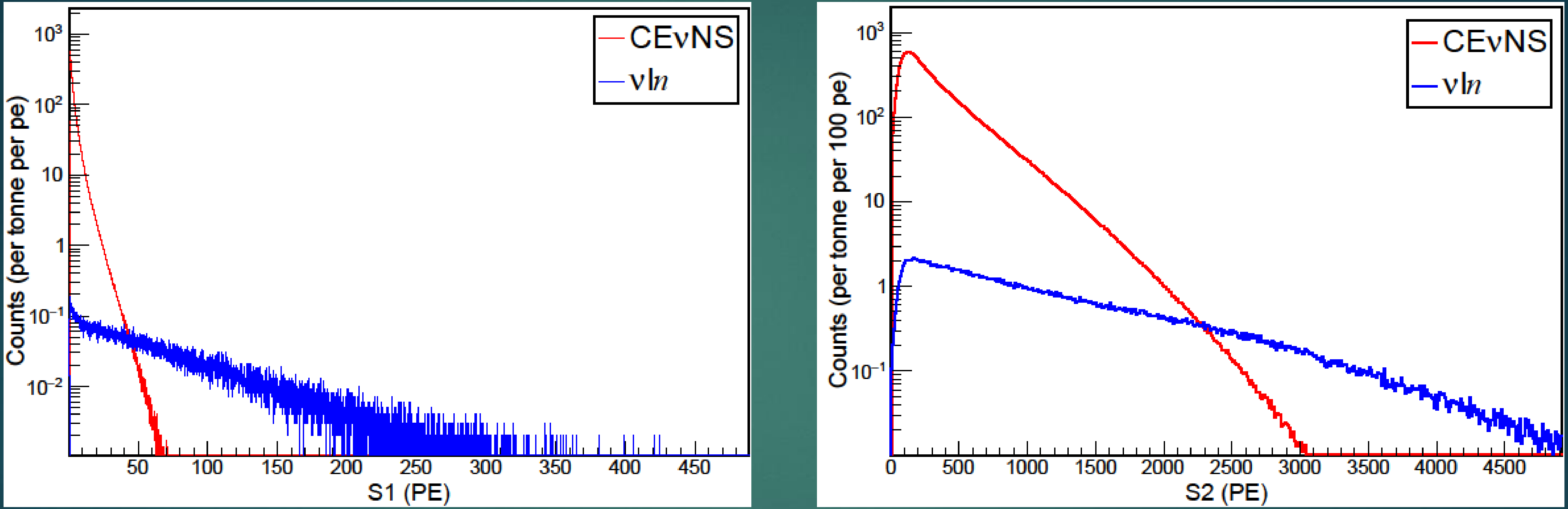
- N_{PE} and $\widetilde{N}_{\mathrm{el}}$ are the number of detected photoelectrons and ionization electrons reaching the liquid-gas interface respectively.
  - They are dependent on the recoil energy.
  - Also depend on various other quantities and properties of the liquid Xenon detector.

Contd.



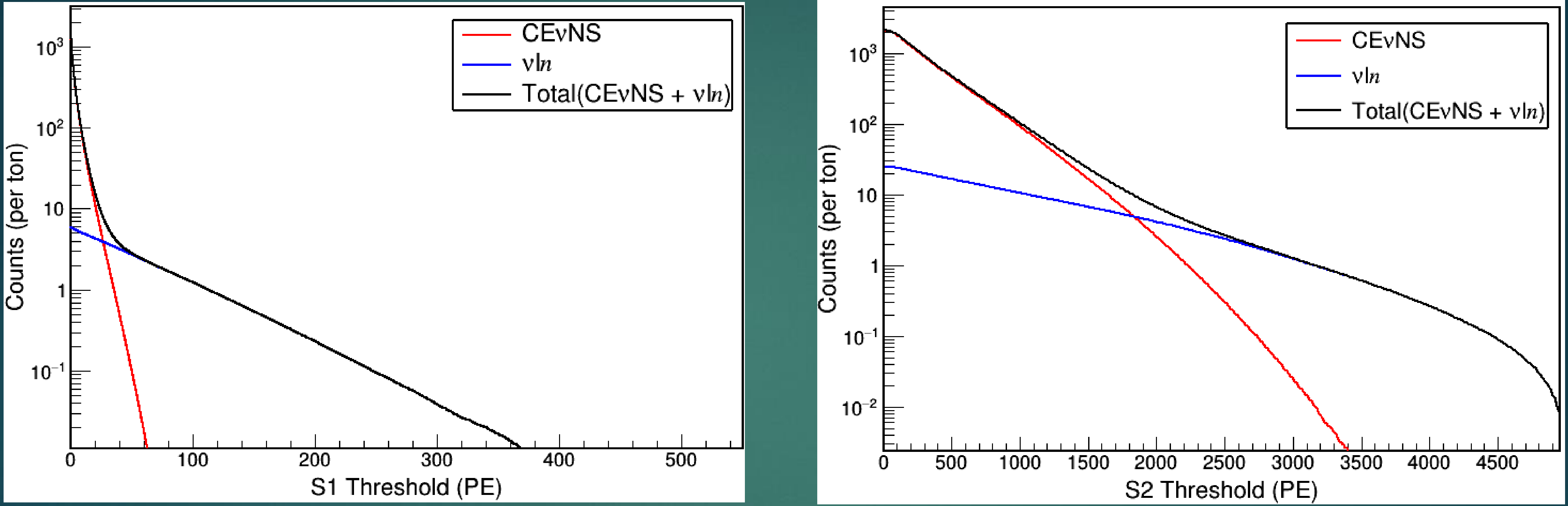
- S2 width is typically 1.5-2 μs.
  - For multiple recoil from same neutrons, drift time of electrons is a determining factor.
  - S2 signals due to two consecutive electrons arriving at the gas phase boundary > 2 μs apart in time are treated as two separate S2 signals..
  - S2 signals due to electrons arriving within 2 μs of each other are merged into one S2 signal..
  - S2 signals arising from two recoils separated by more than 3 mm in z-direction are treated as separate signals
- S1 signals are generated from scintillation photons.
  - Light travel time across the entire detector height < S1 pulse width.
  - S1 generated from multiple NR from the same neutron is summed into a single S1.
- CEνNS events give rise to single NR ⟶ single S1 and single S2 for each CEνNS interaction.

Contd…



- At sufficiently large signals (S1 or S2) the νI*n* contribution is dominates over the CEνNS contribution.

Contd…



- At high thresholds, S1>30 PE and S2>1900 PE, recoil events due to νIn events dominate.
  - CEνNS events alone would not give significant number of recoil events at high thresholds.
- Total effective signal gets a tail like extension due to the contribution of νIn events.

Conclusion and Outlook

- The neutrino-induced neutrons present an extra handle for SN neutrino detection in addition to the CEνNS process.
- At higher thresholds $\nu\mathrm{I}n$ events contribution is dominant $\longrightarrow$ tail like feature of the total S1 and S2 signal.
- Future multi-ton scale liquid Xenon TPC based dark matter detectors like LZ (7 tonnes) and DARWIN (40 tonnes) may offer good opportunities to look for the SN $\nu\mathrm{I}n$ signals since total number of neutrons produced will be higher.
- CEνNS contribution comes from all flavours of neutrinos whereas $\nu\mathrm{I}n$ events get dominant contribution from ν_e.
  - Identification of the $\nu\mathrm{I}n$ events can give an observational handle on the flavour composition of the total SN neutrino flux.

Thank You