My journey through research in dark matter

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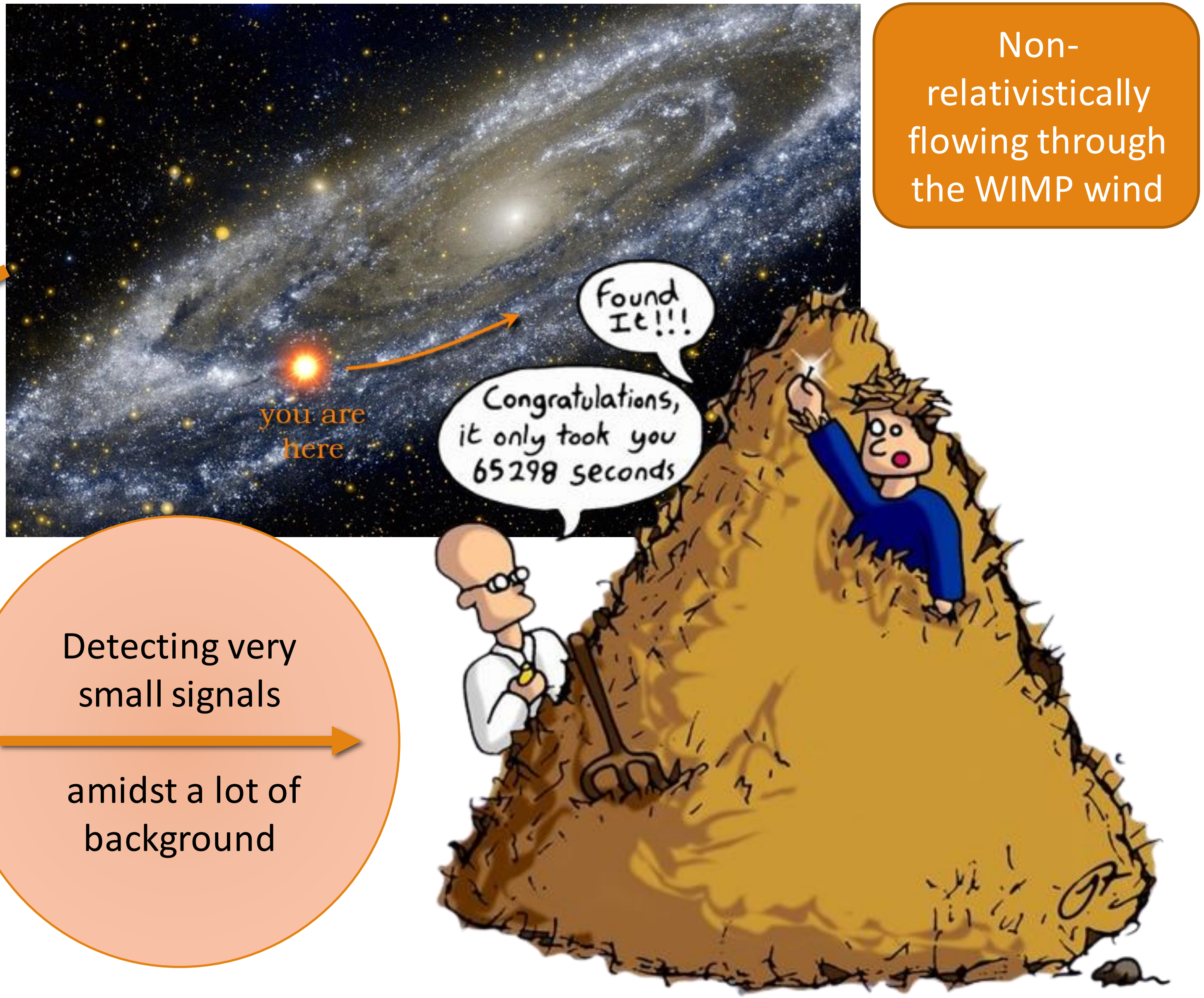
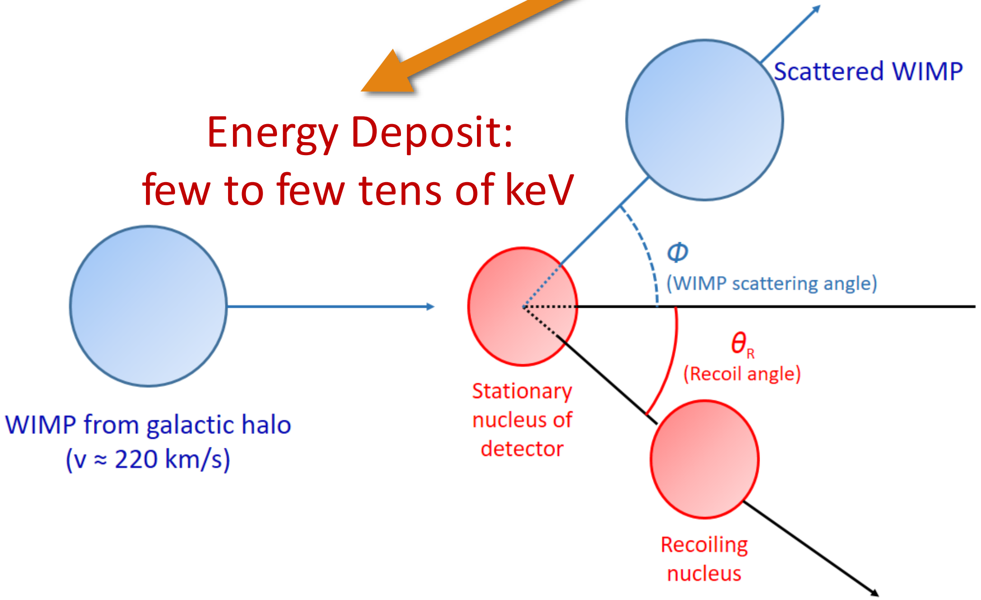
Dark Matter Detection :- Finding a needle in a haystack

Our very own spaceship



Non-relativistically flowing through the WIMP wind

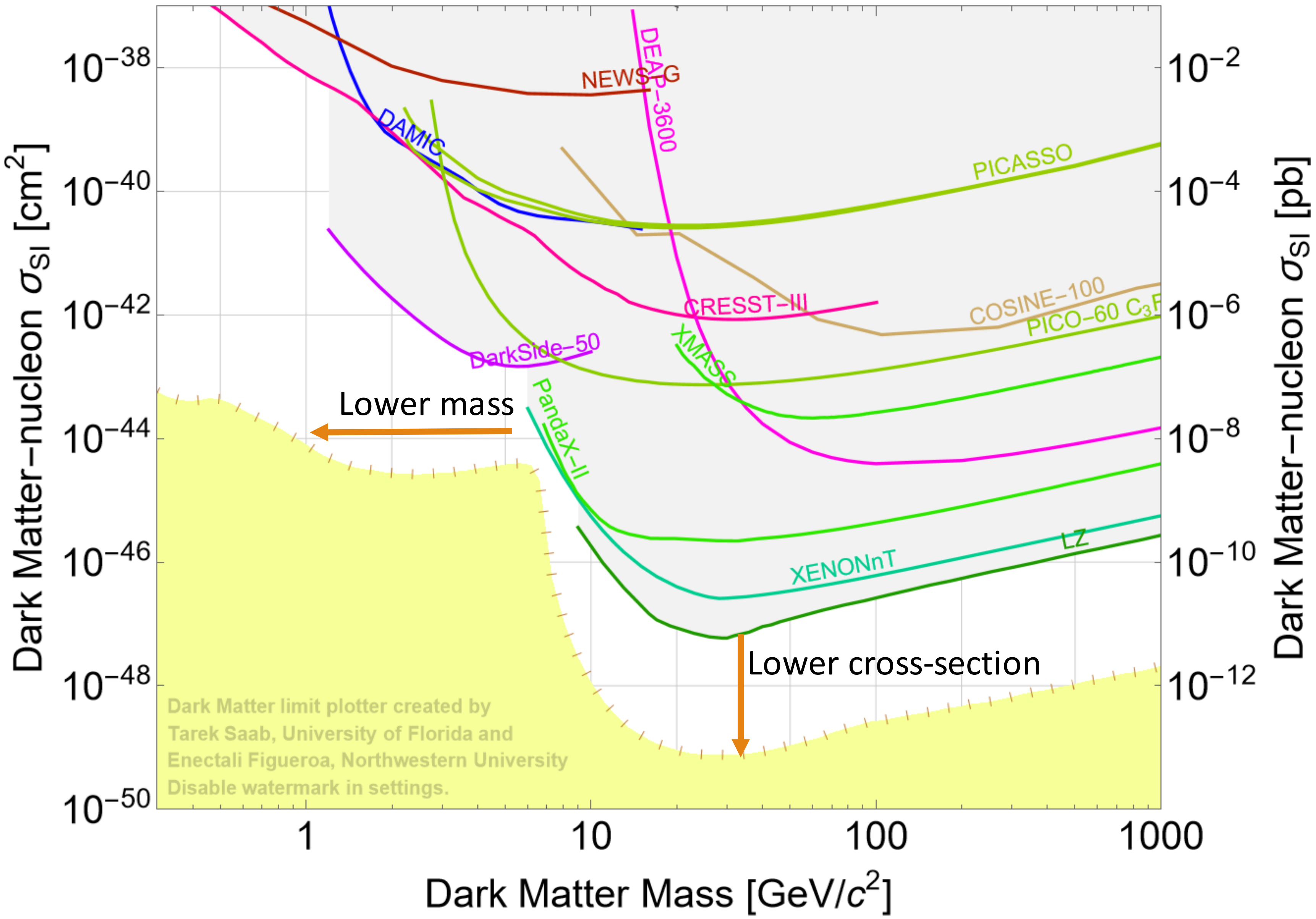
Energy Deposit:
few to few tens of keV



Detecting very small signals

amidst a lot of background

Status of direct DM search



Lower mass

Lower cross-section

- ➢ Understand, reduce and quantify background
- ➢ Model detector response at low energies

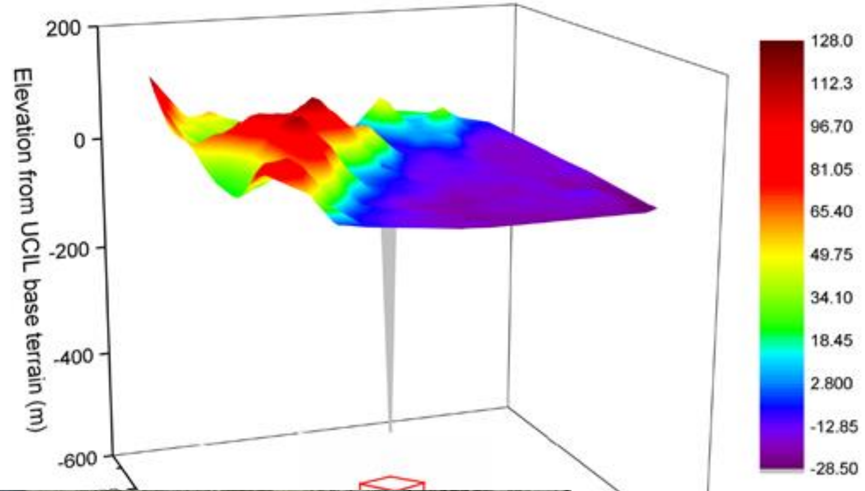
- ➢ Increase detector size and reduce background by an order of magnitude (XLZD)

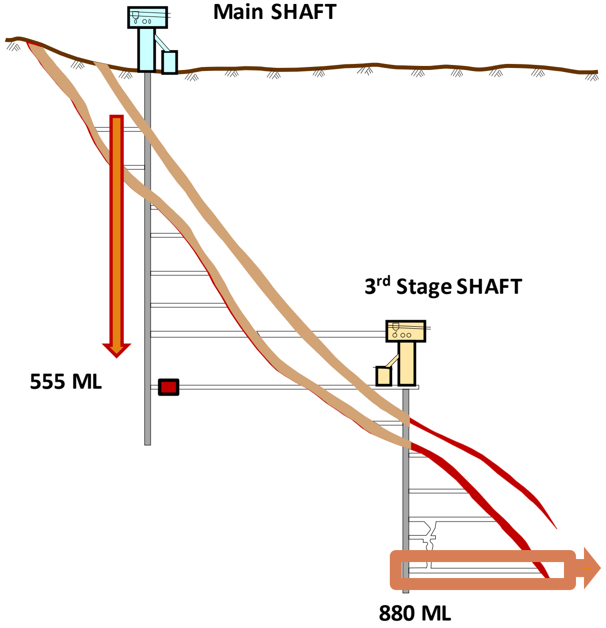
Image created using
[Dark Matter Limit Plotter]

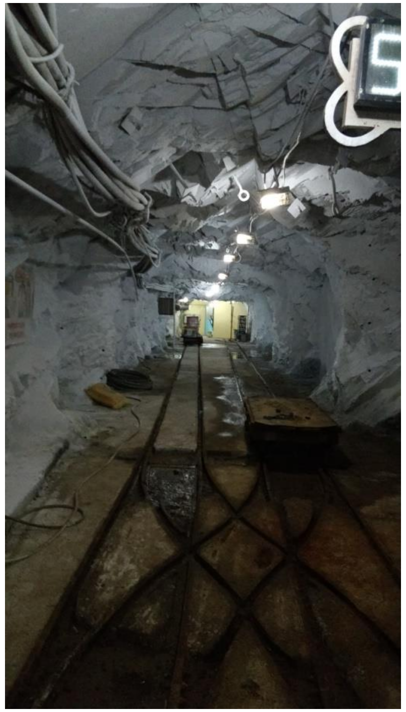
Setting up a direct DM detection experiment in India

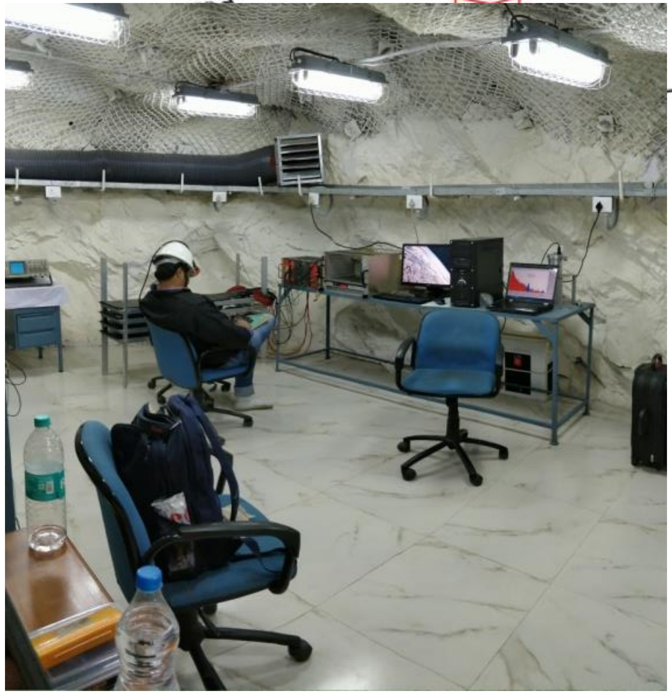
- New proposed cryogenic scintillator-based direct dark matter search experiment in India
  - Scintillator and SiPM studies at low temperature

- Prototype experiment at 555 m initially to understand background
  - Measurement and simulation of cosmogenic and radiogenic backgrounds at the site





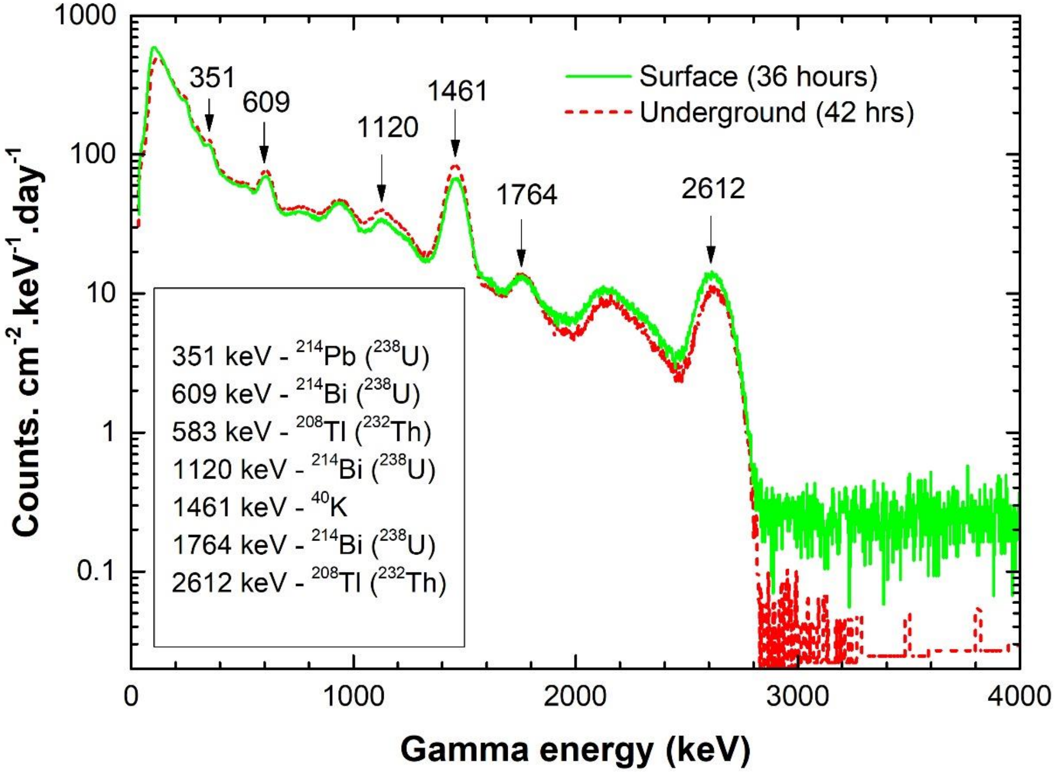


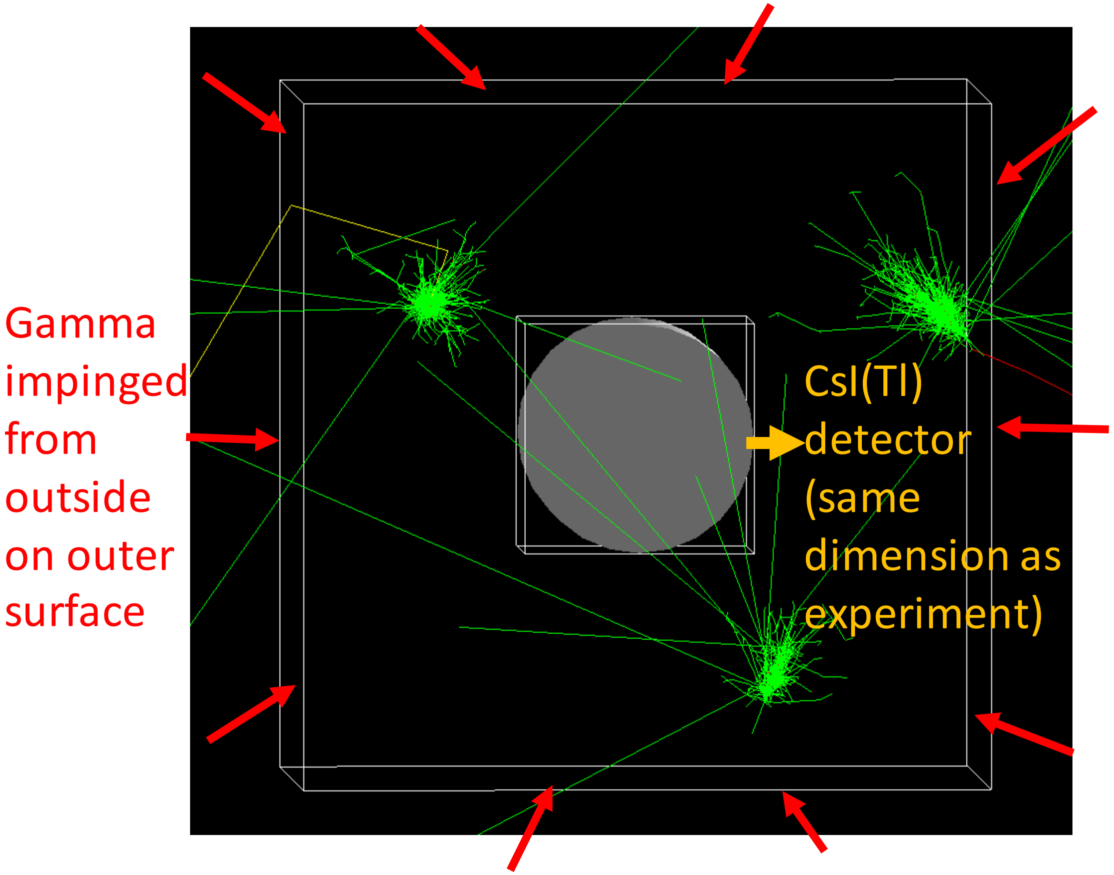


Backgrounds at underground site

Gamma Background

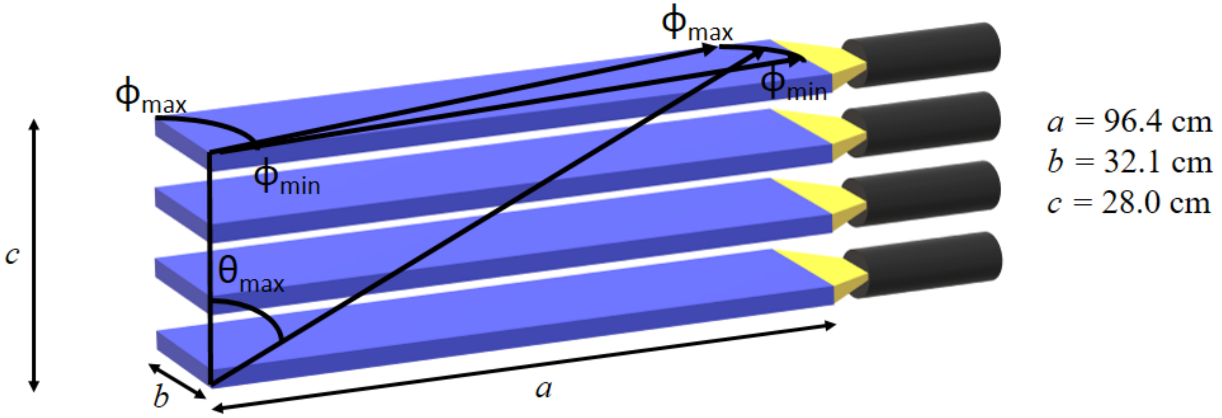
Gamma spectrum measured with CsI(Tl) detector



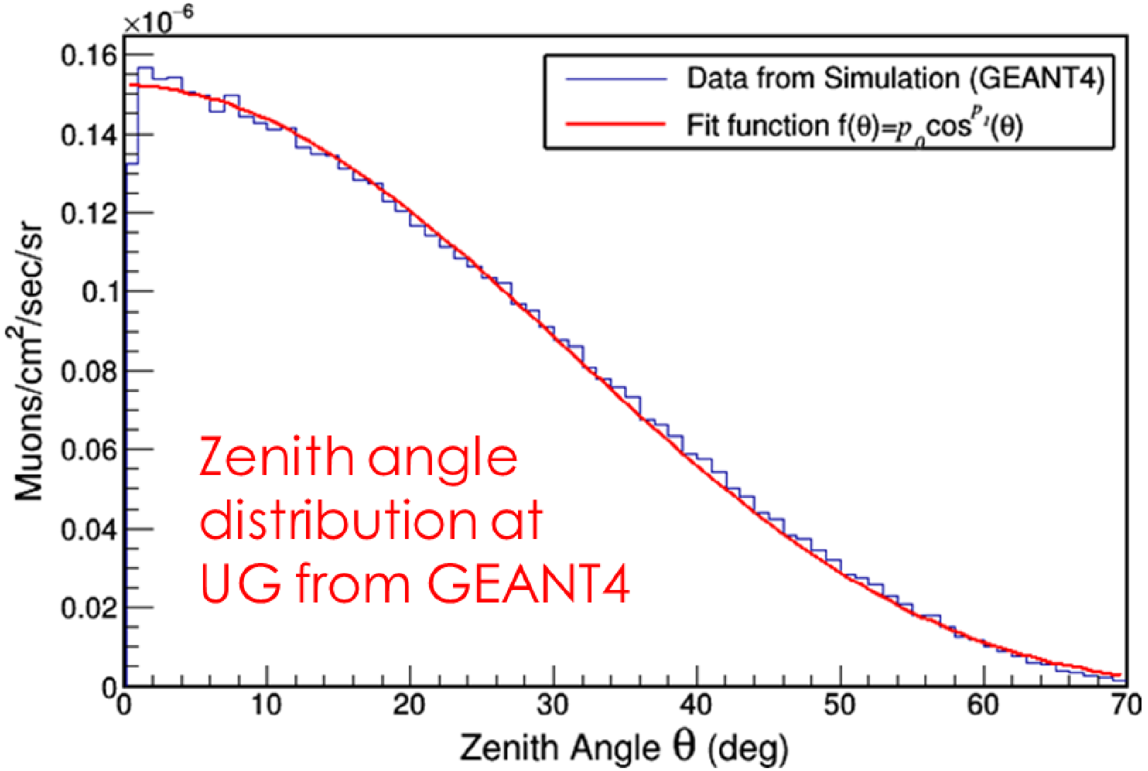


- Shielding with Lead investigated with GEANT4.
- 30 cm Pb $\longrightarrow$ Shielding of 4.36×10^5 for $E_\gamma \geq 3$ MeV.

Muon Background



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



Zenith angle distribution at UG from GEANT4

- Muon flux after background subtraction is $(2.257 \pm 0.261 \pm 0.042) \times 10^{-7}$ **cm^{-2} sec^{-1}**.

$$\varphi = \frac{I_0}{a \times b} \int_{\theta_{min}}^{\theta_{max}} \int_{\emptyset_{min}}^{\emptyset_{max}} f(a, b, c, \theta, \emptyset)\, d\emptyset\, d\theta$$

Resultant muon flux obtained from simulation :- $(2.051 \pm 0.142 \pm 0.009) \times 10^{-7}$ **cm^{-2} sec^{-1}**.

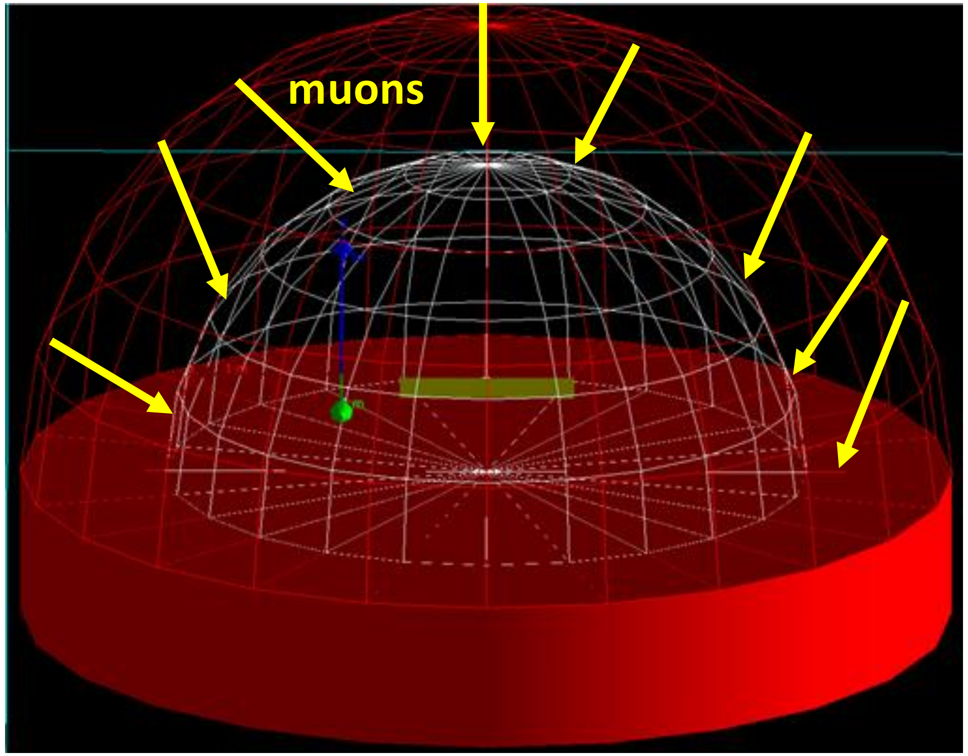
Neutron Flux

- The experimental measurement was done using a pressurized ^{4}He detector
  - 600 mm long cylinder with an inner diameter of 65 mm with ^{4}He kept at 150-180 bar ⟶ fast neutrons.
  - Inner wall lined with Lithium compound ⟶ thermal neutrons

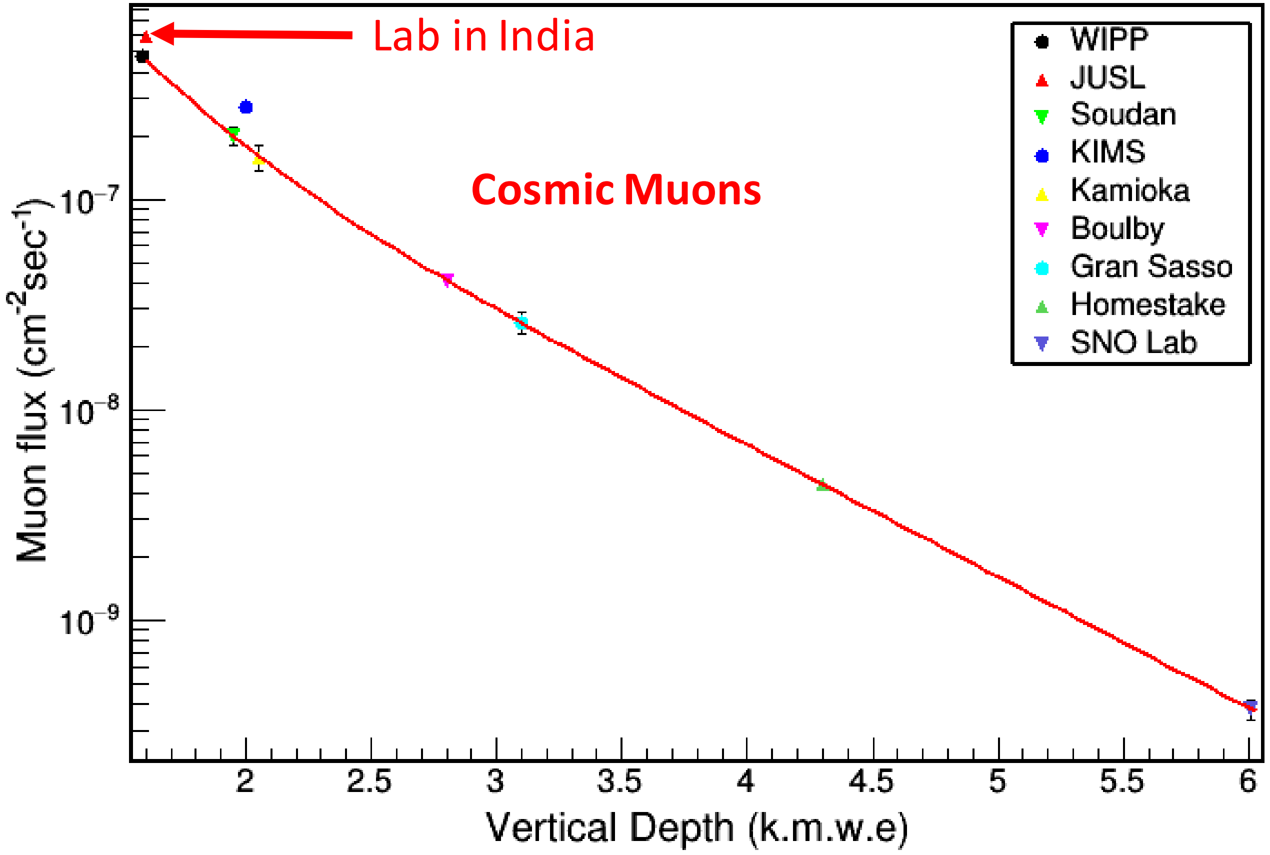
- Flux of neutrons in the energy range $E_n \leq 10$ MeV was found to be $(\mathbf{1.63 \pm 0.03}) \times \mathbf{10^{-4}}$ **cm^{-2} sec^{-1}**

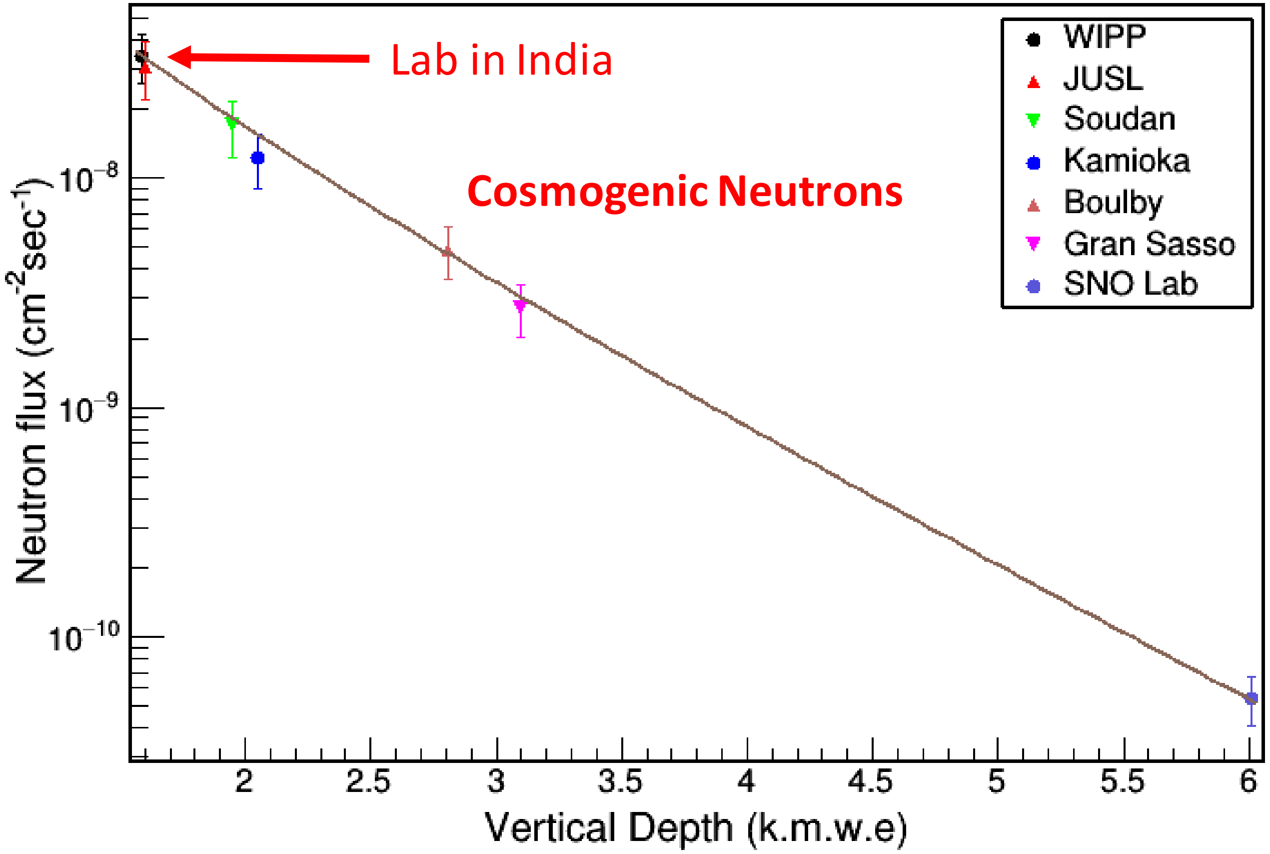
- Neutron flux including the backscattering from GEANT4 simulation obtained as $(\mathbf{2.61 \pm 0.17}) \times \mathbf{10^{-4}}$ **cm^{-2} sec^{-1}**

- 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



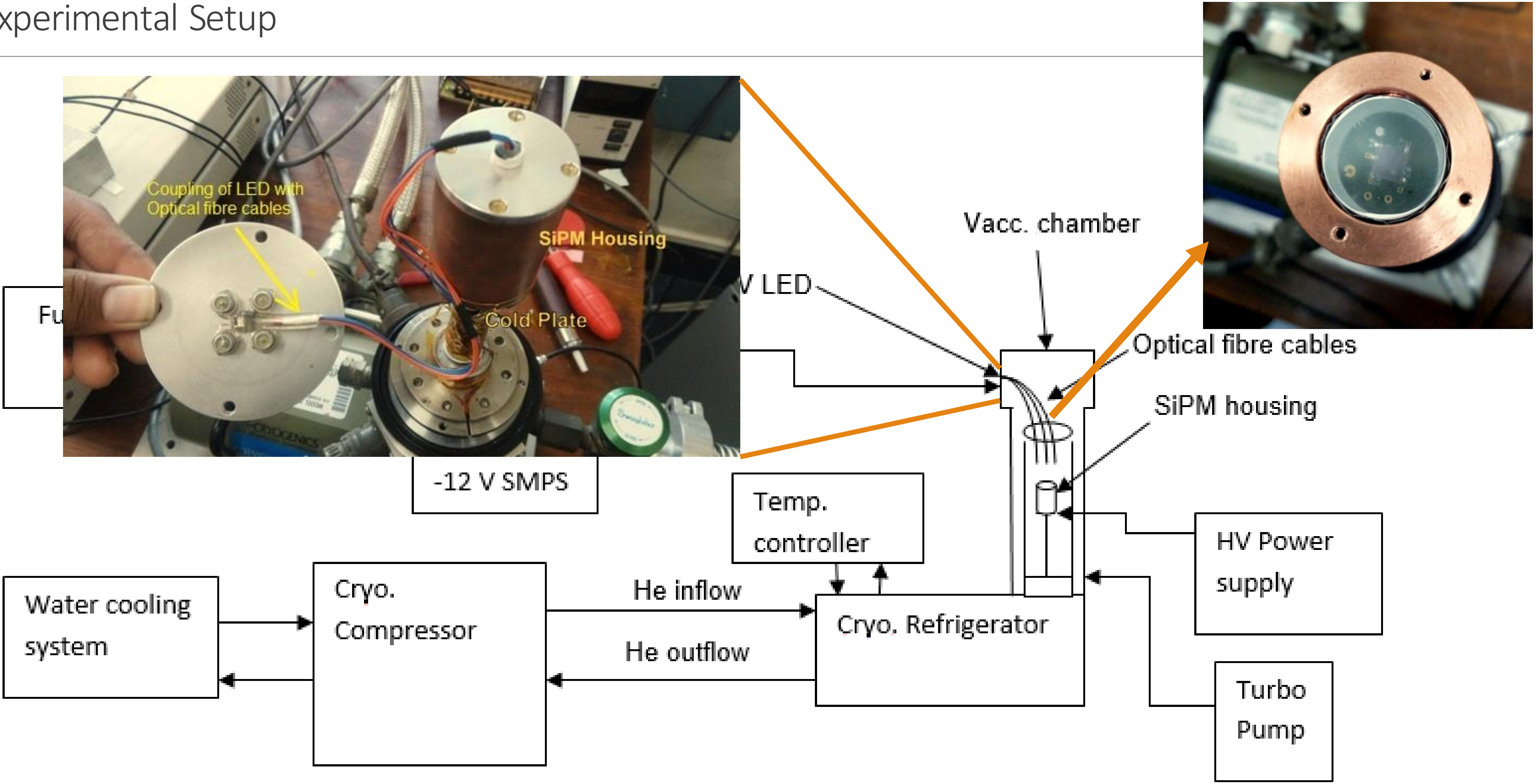


Global Fit functions :- D. Mei, A. Hime, Phys. Rev. D 73 (2006) 053004

S. Banik, V. K. S. Kashyap, S. Ghosh, *et. al.* JINST 16 P06022 (2021) and S. Ghosh, *et. al.*, Astropart. Phys. 139, 102700 (2022)

Scintillators and SiPMs at low temperature

Experimental Setup



Fu

V LED

Vacc. chamber

Optical fibre cables

SiPM housing

-12 V SMPS

Temp. controller

HV Power supply

Water cooling system

Cryo. Compressor

He inflow

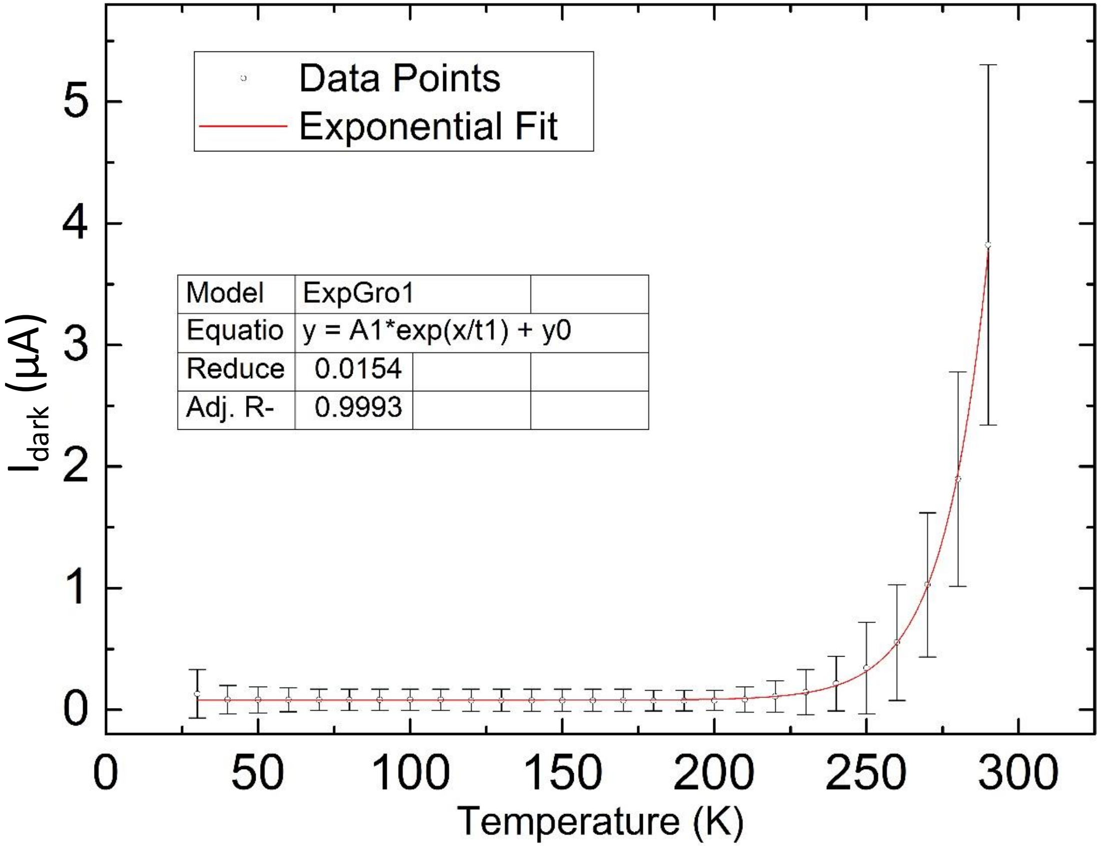
He outflow

Cryo. Refrigerator

Turbo Pump

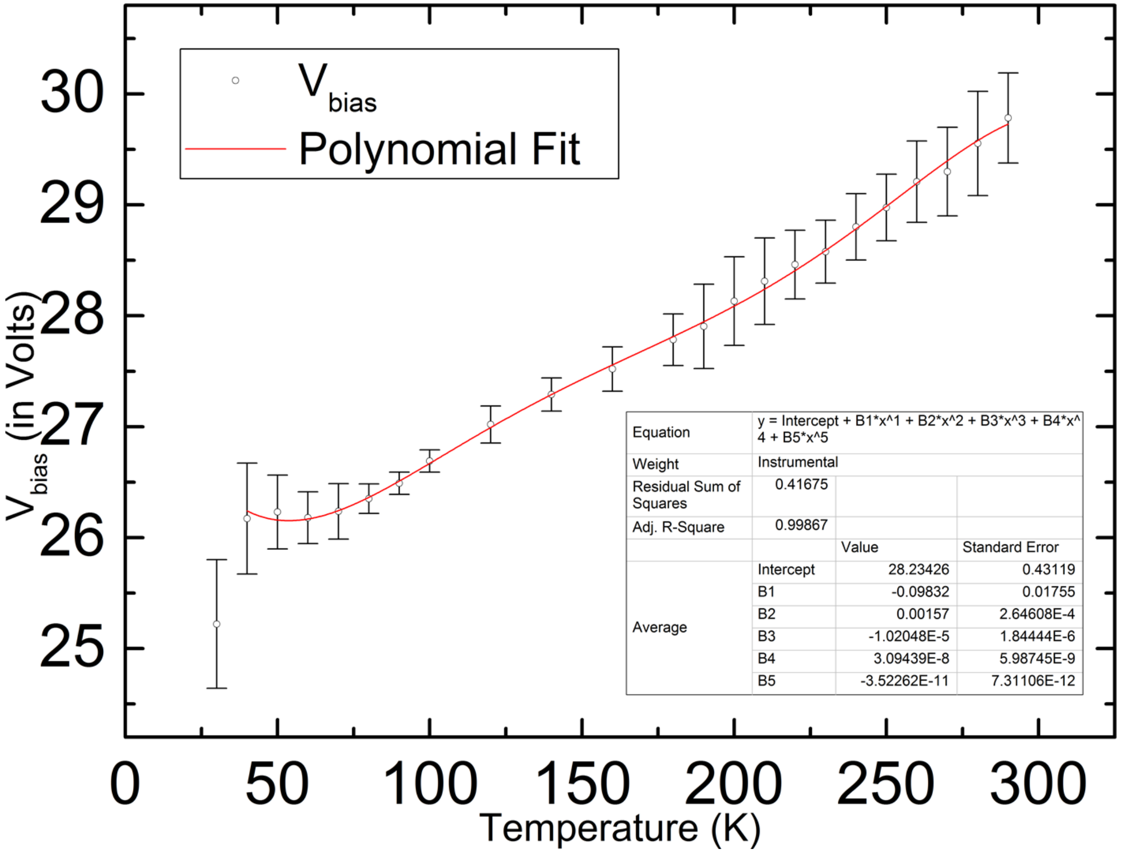
SiPM studies at low temperature

SiPM was kept in dark condition



Model	ExpGro1	
Equatio	y = A1*exp(x/t1) + y0	
Reduce	0.0154	
Adj. R-	0.9993	

SiPM was directly irradiated with blue LED



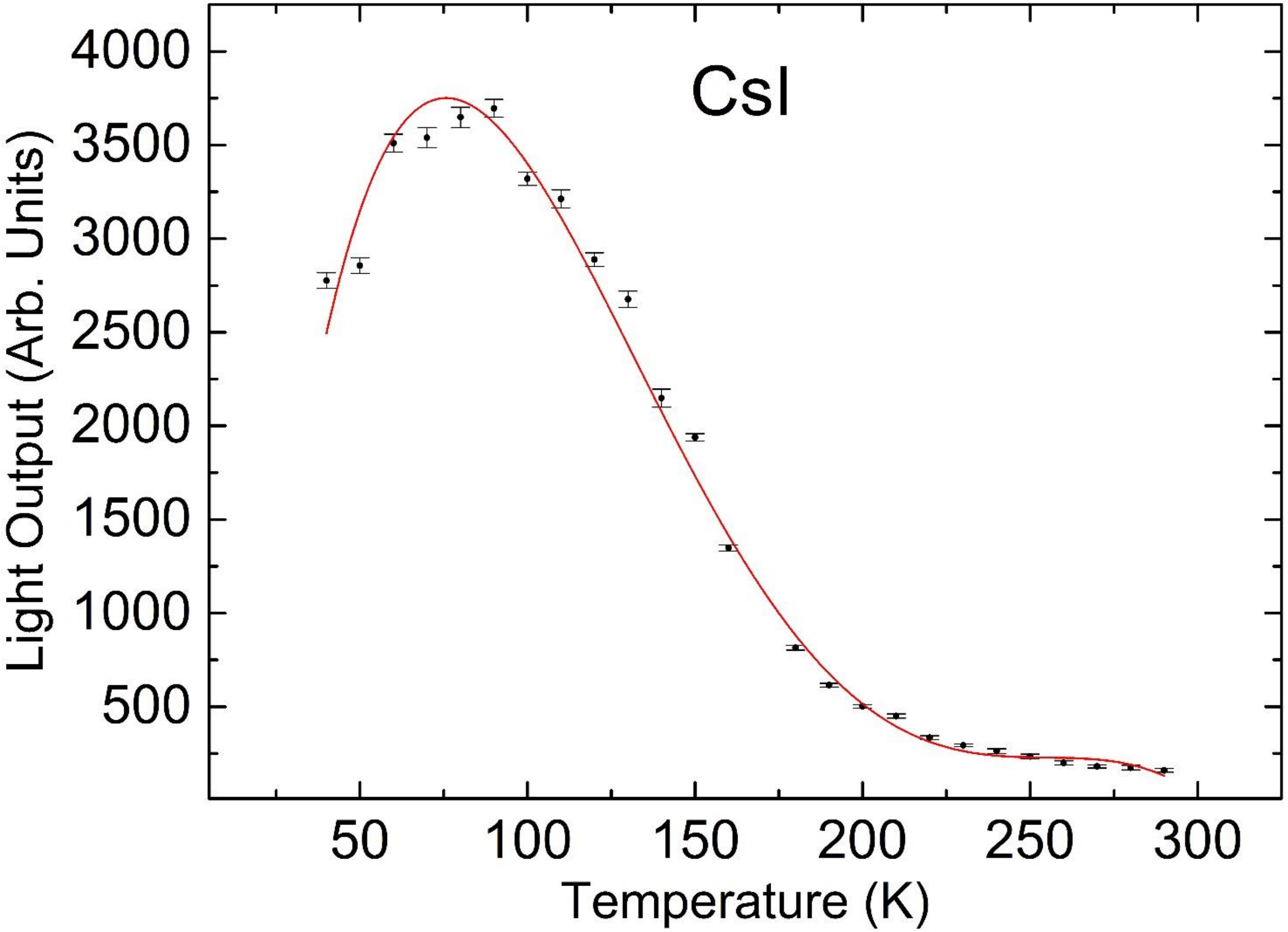
Equation	y = Intercept + B1*x^1 + B2*x^2 + B3*x^3 + B4*x^4 + B5*x^5		
Weight	Instrumental		
Residual Sum of Squares	0.41675		
Adj. R-Square	0.99867		
		Value	Standard Error
Average	Intercept	28.23426	0.43119
	B1	-0.09832	0.01755
	B2	0.00157	2.64608E-4
	B3	-1.02048E-5	1.84444E-6
	B4	3.09439E-8	5.98745E-9
	B5	-3.52262E-11	7.31106E-12

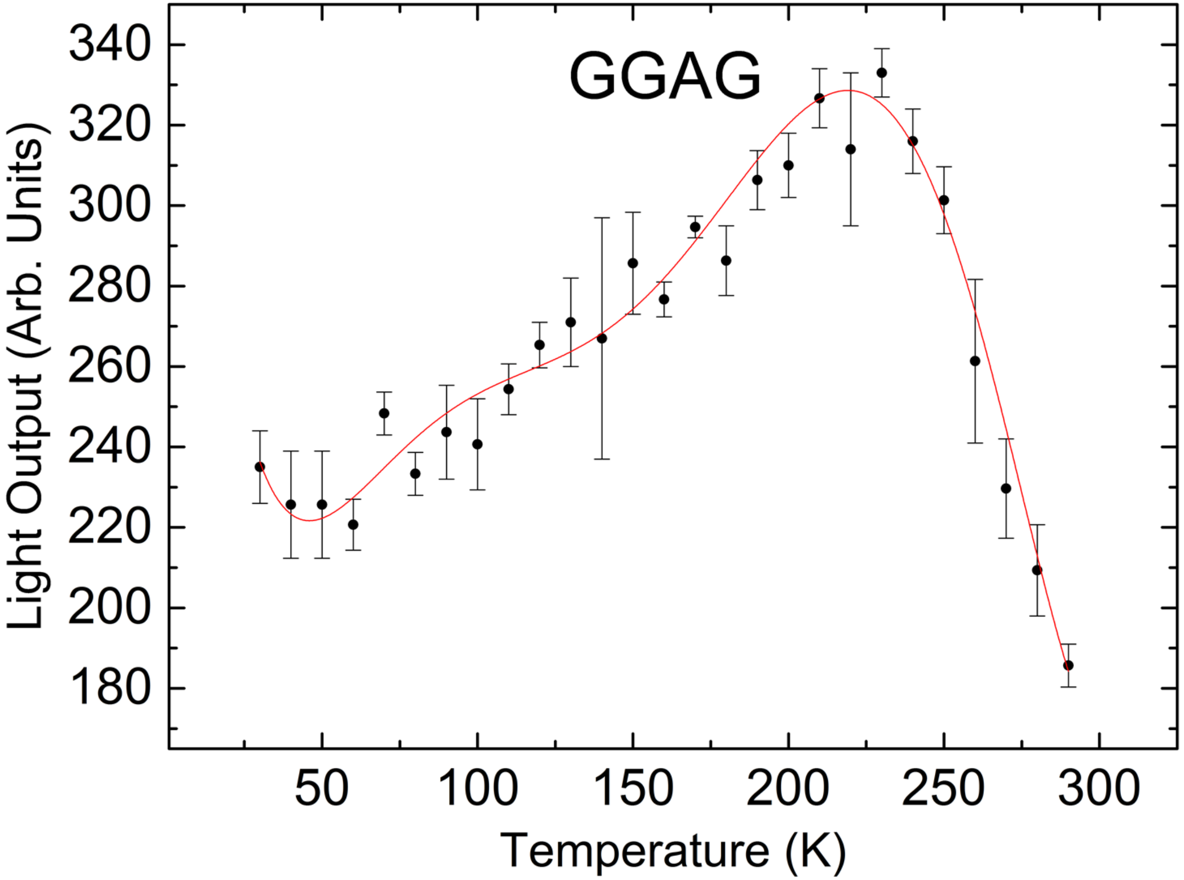
- Dark current and bias voltage behaved as expected till 40 K.
- At lower temperatures, it showed very high non-linearity and very high dark currents.

Scintillator light output variation

CsI and GGAG ($Gd_3Ga_3Al_2O_{12}$)

Scintillators irradiated with Cs^{137} source
(662 keV gamma energy)



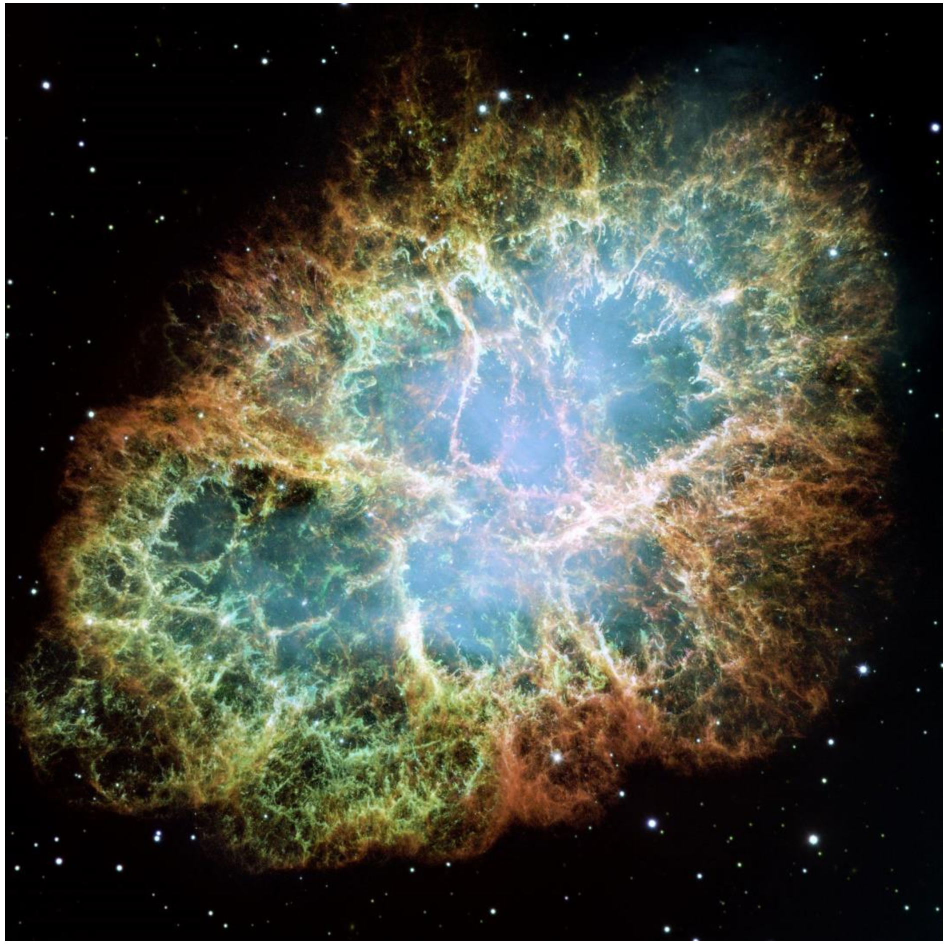


CsI Data in agreement with **C. Amsler, *et. al.*,
NIM A 480 (2002) 494-500**

Supernova neutrino interactions in xenon TPCs

Why are supernova neutrinos interesting?

- Neutrinos from very early phases of supernova reach us: other particles are trapped due to high density.
- Through neutrinos, we can learn a lot about the supernova, such as mass, type, etc.
- Neutrinos arrive much earlier than the photons.
- Network of neutrino detectors can form a **S**upernova **E**arly **W**arning **S**ystem (SNEWS2.0) to inform the multimessenger community.



Crab Nebulla. Credits :- NASA, ESA, J. Hester, A. Loll (ASU)

How are dark matter detectors relevant here?

ν of all flavours
Energies ≈ few to few tens of MeV

All flavors

Coherent Elastic Neutrino Nucleus Scattering (CEνNS)

(Nuclear Recoils)

Recoil Energies ≈ 1 – 20 keV

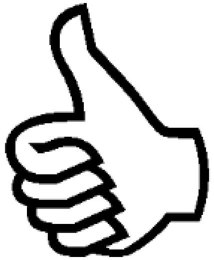
ν_es only

Inverse Beta decay
↓
High thresholds

Traditional neutrino detectors

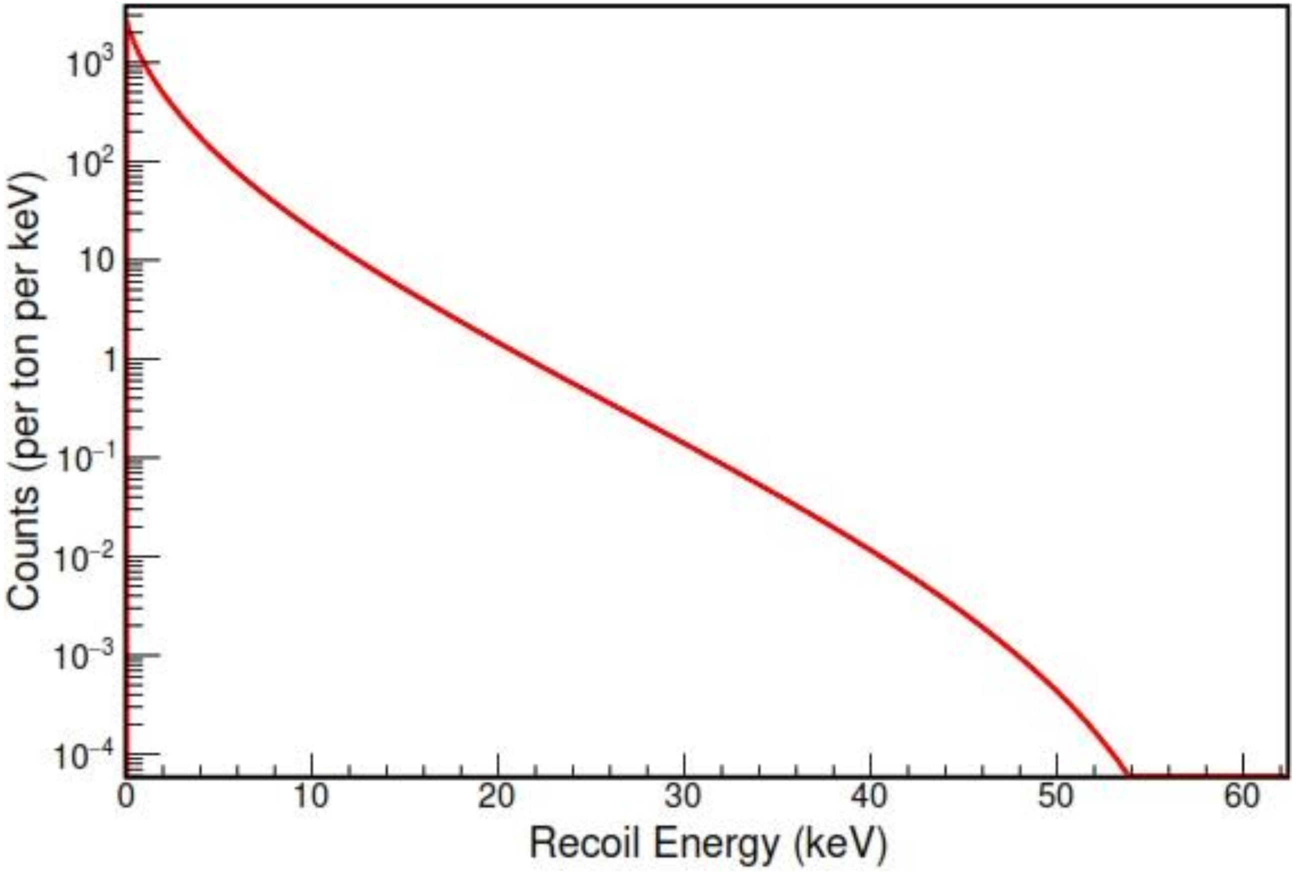
High threshold!!!!

Large volume
Dark Matter Detectors
with
super low thresholds
and ultra-low
backgrounds



Supernova neutrino CEvNS and CC interactions

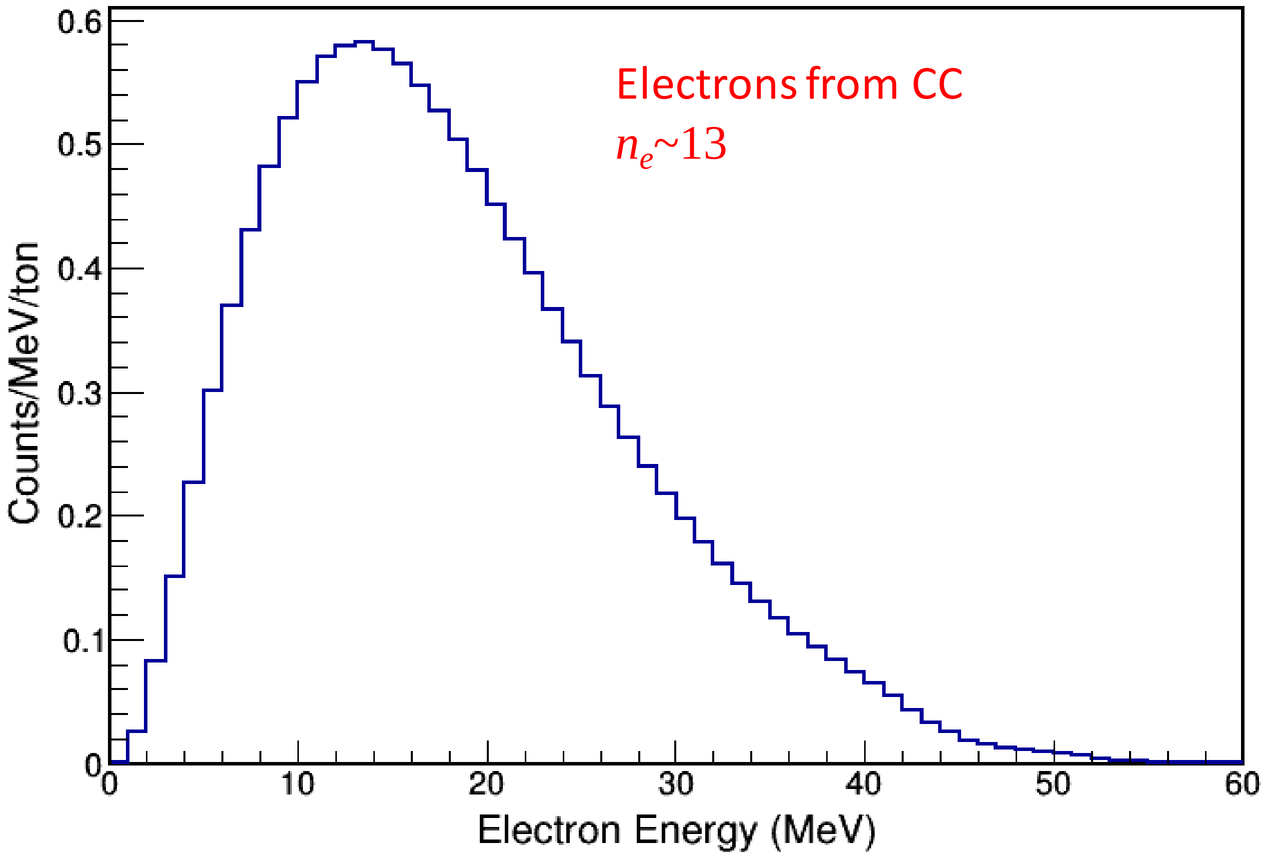
- In this work consider the SN due to the collapse of a 18 $M_\odot$ progenitor star at 1 kpc distance from the Earth.
- For target we took 1 tonne of liquid xenon (^{132}Xe isotope only)
- Neutrinos will undergo CEνNS and charged current interactions

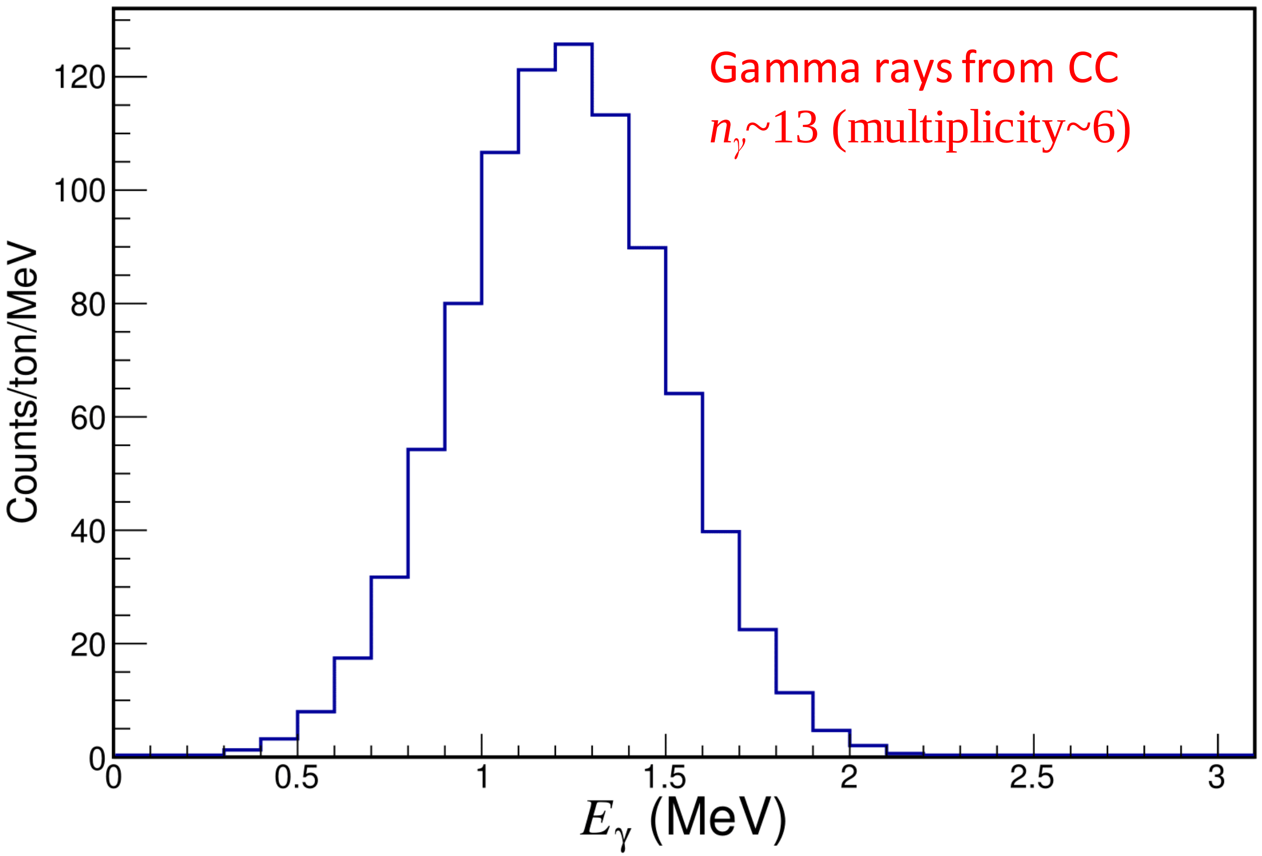


$$\nu_e + {}^{132}_{54}\mathrm{Xe} \rightarrow e^- + {}^{132}_{55}\mathrm{Cs}^*$$

$$^{132}\mathrm{Cs}^* \rightarrow {}^{132-X}\mathrm{Cs} + Xn \longrightarrow$$ Neutrino-induced neutrons (νIn) (Energies ~ 2 MeV)

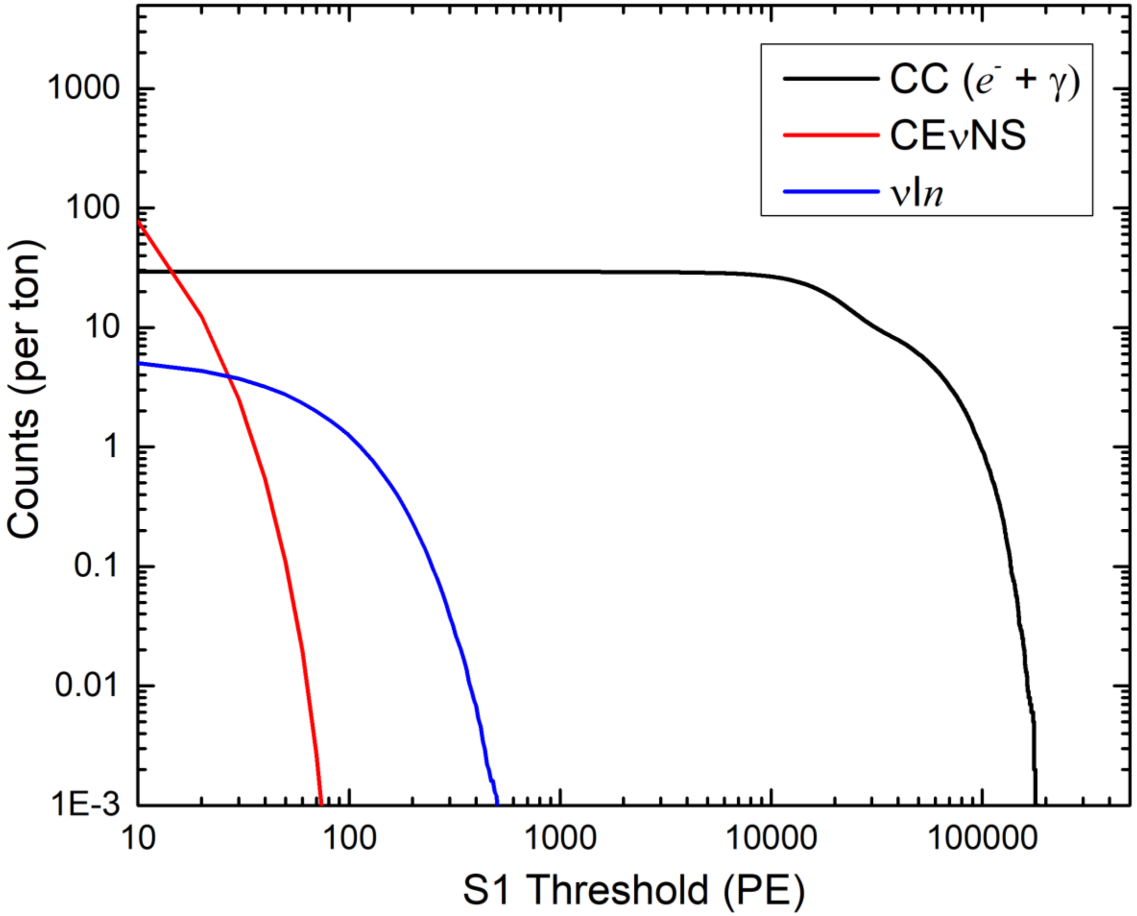
Electrons and gamma from CC interactions

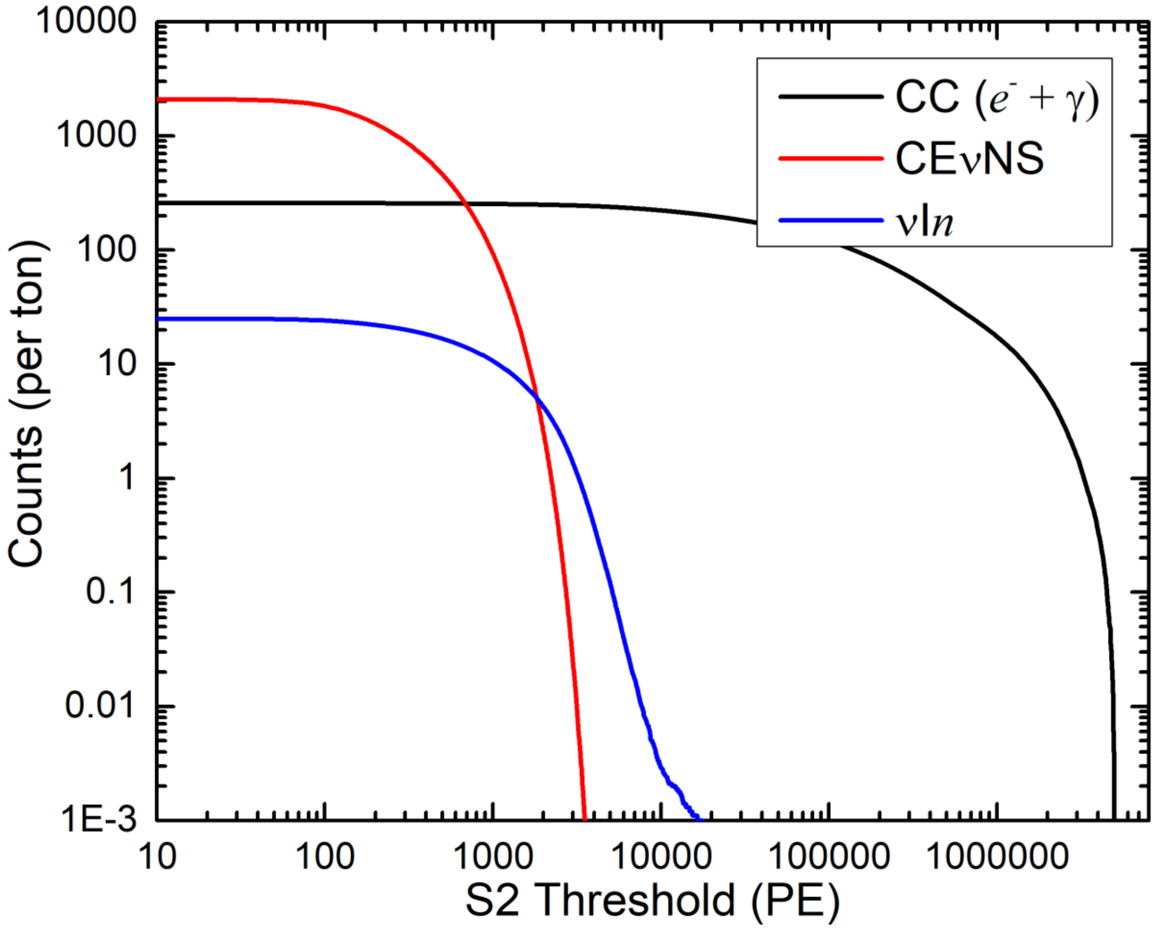




- Interaction of neutrons, electrons and gamma rays following their energy spectra in GEANT4
- Multiple scattering accounted for signal generation

Integrated S1 and S2 spectra





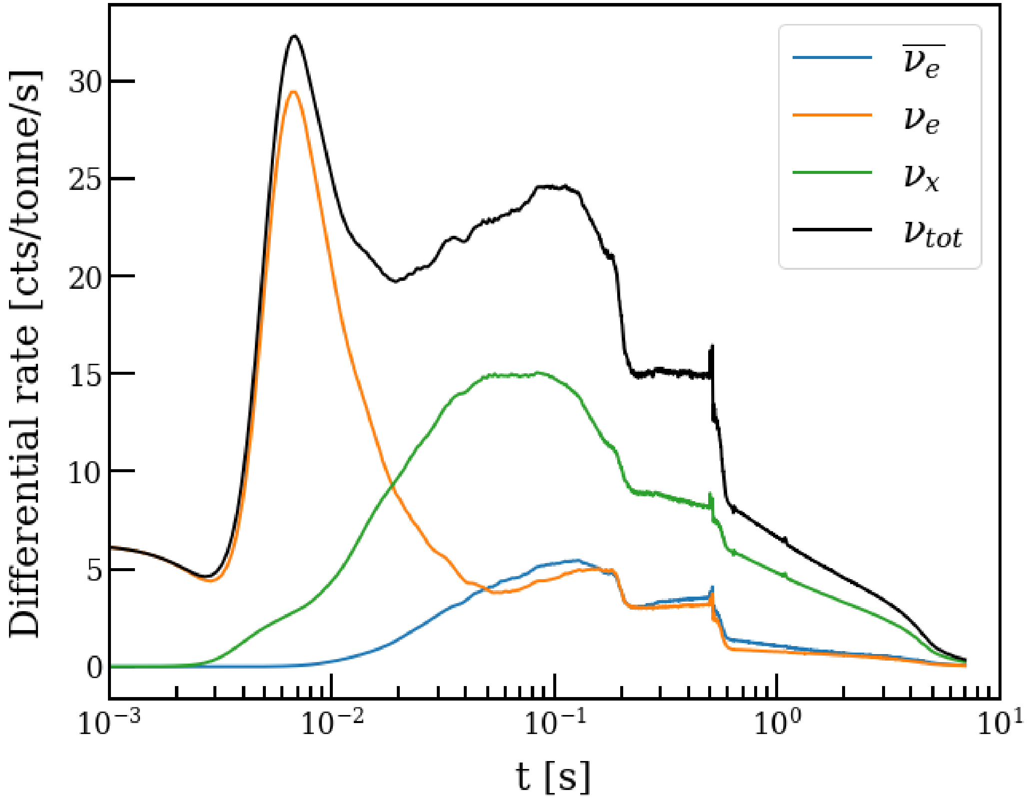
- ➢ Implications of such large signals to detector?
- ➢ Would it be possible to detect the CC and CEνNS signals together :- May lead to flavour composition studies of SN neutrinos.

P. Bhattacharjee, A. Bandopadhyay, S. Chakroborty, S. Ghosh, et. al., *Phys.Rev.D* 106 (2022) 4, 043029.

Works in XENON collaboration

Supernova at 10 kpc

- Reference supernova model :- 11 $M_\odot$ at a distance of 10 kpc (Bollig 2016, Mirizzi, et. al., arXiv:1508.00785)



- At a distance of 10 kpc, a typical SN can generate ~70 CEνNS interactions in XENONnT (~700 interactions in XLZD (40 t)).

GitHub
SNAX

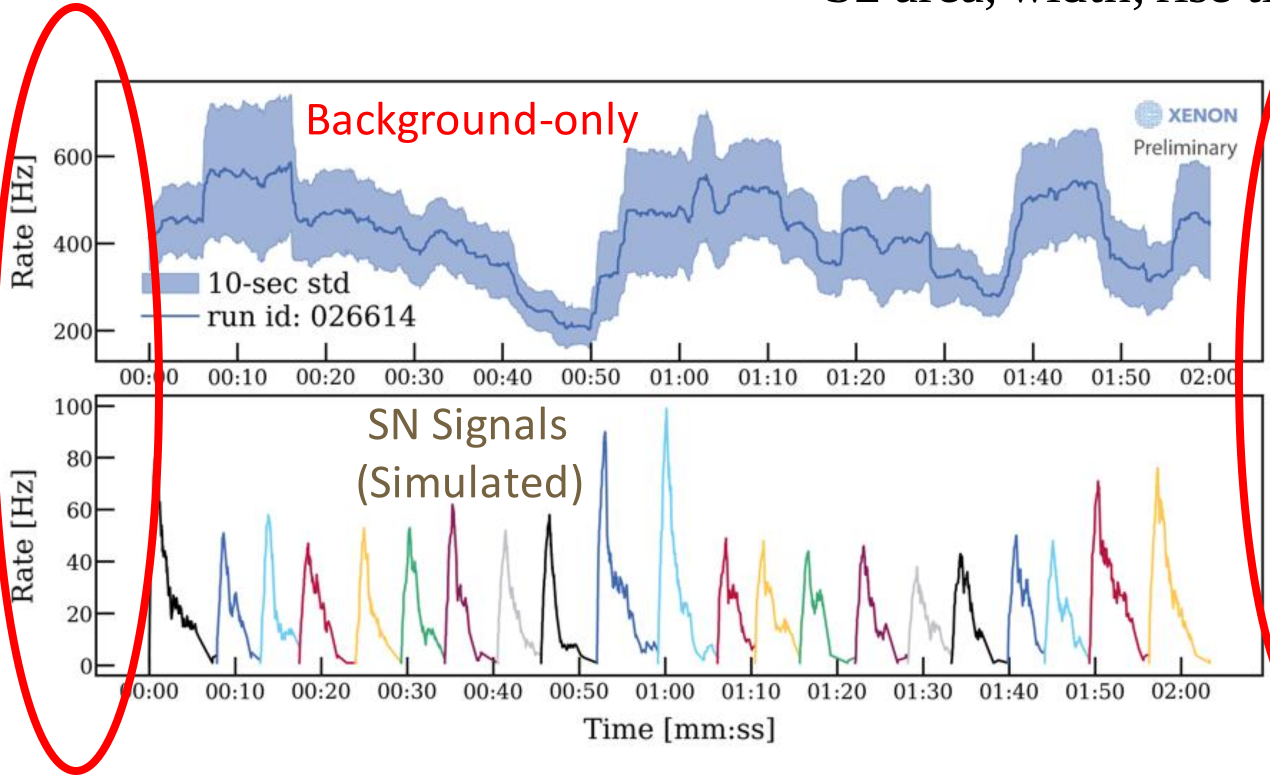
GitHub
snewpy

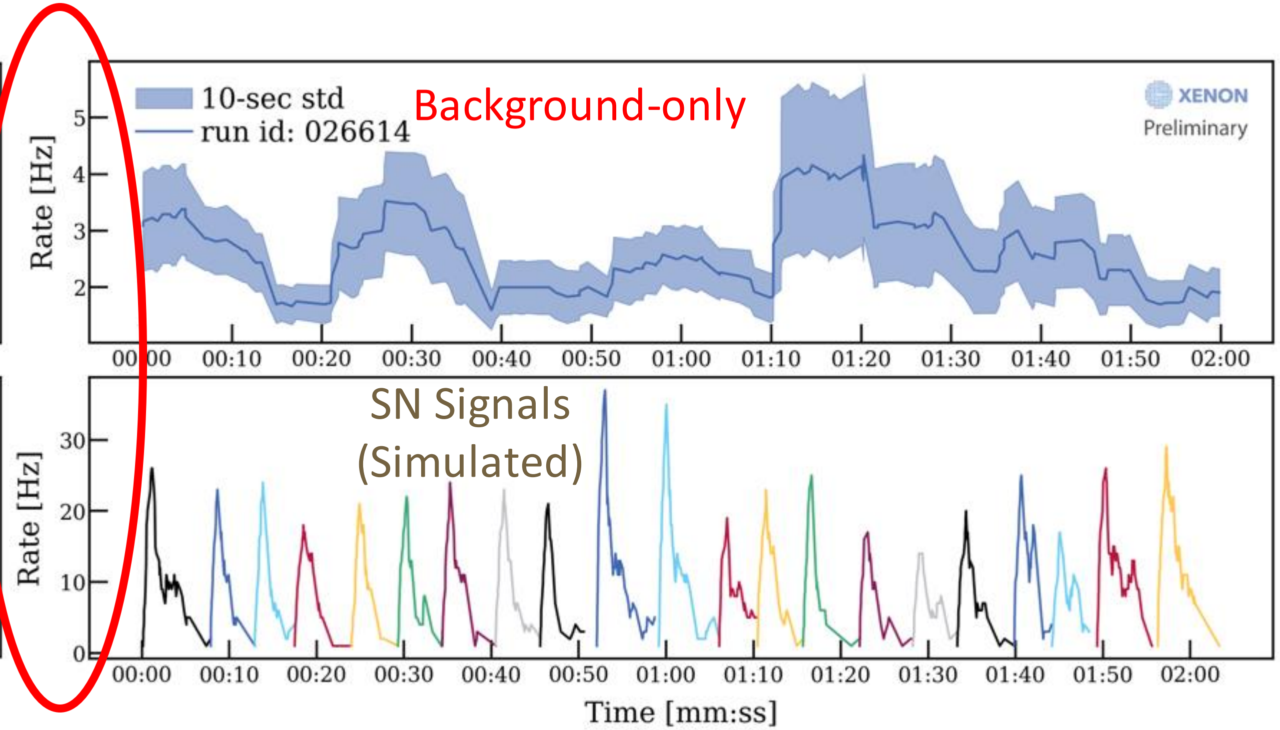
Signal and background in detector

SIGNALS AND BACKGROUND WITHOUT CUTS

SIGNALS AND BACKGROUND AFTER CUTS

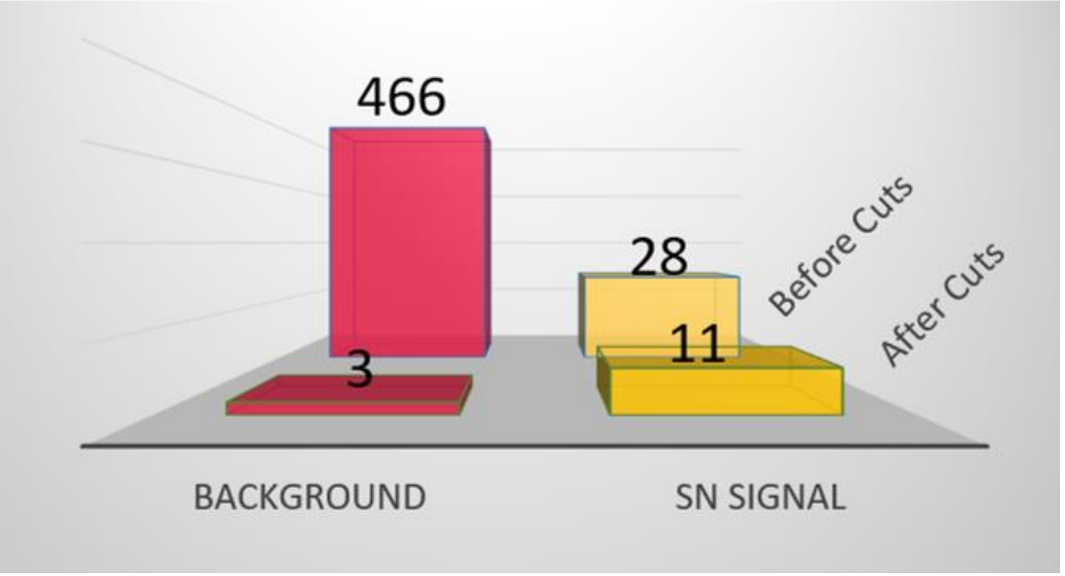
We put cuts on features like
S2 area, width, rise time, x-y position, etc.



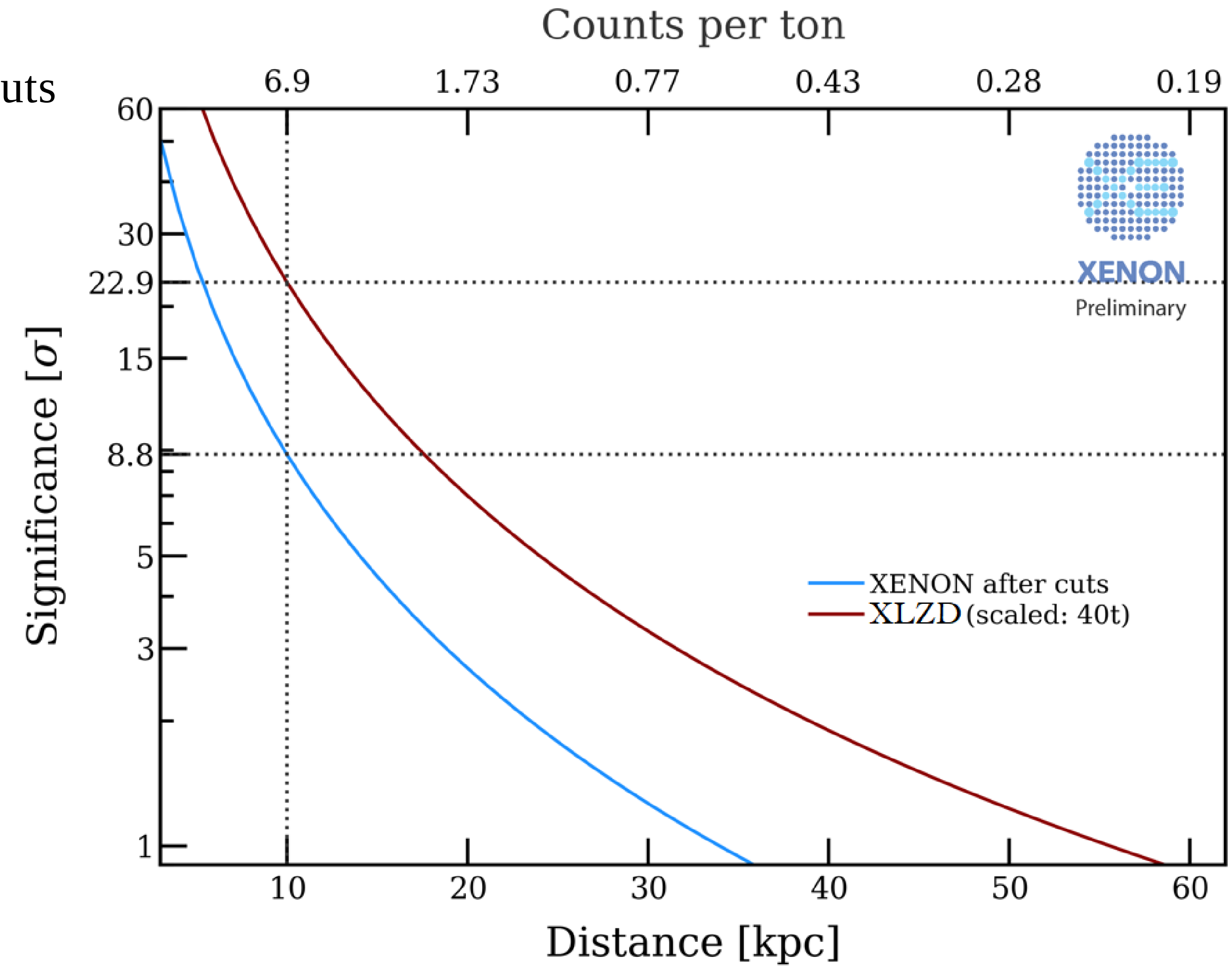


Detection Significance

Background and signal counts before and after cuts



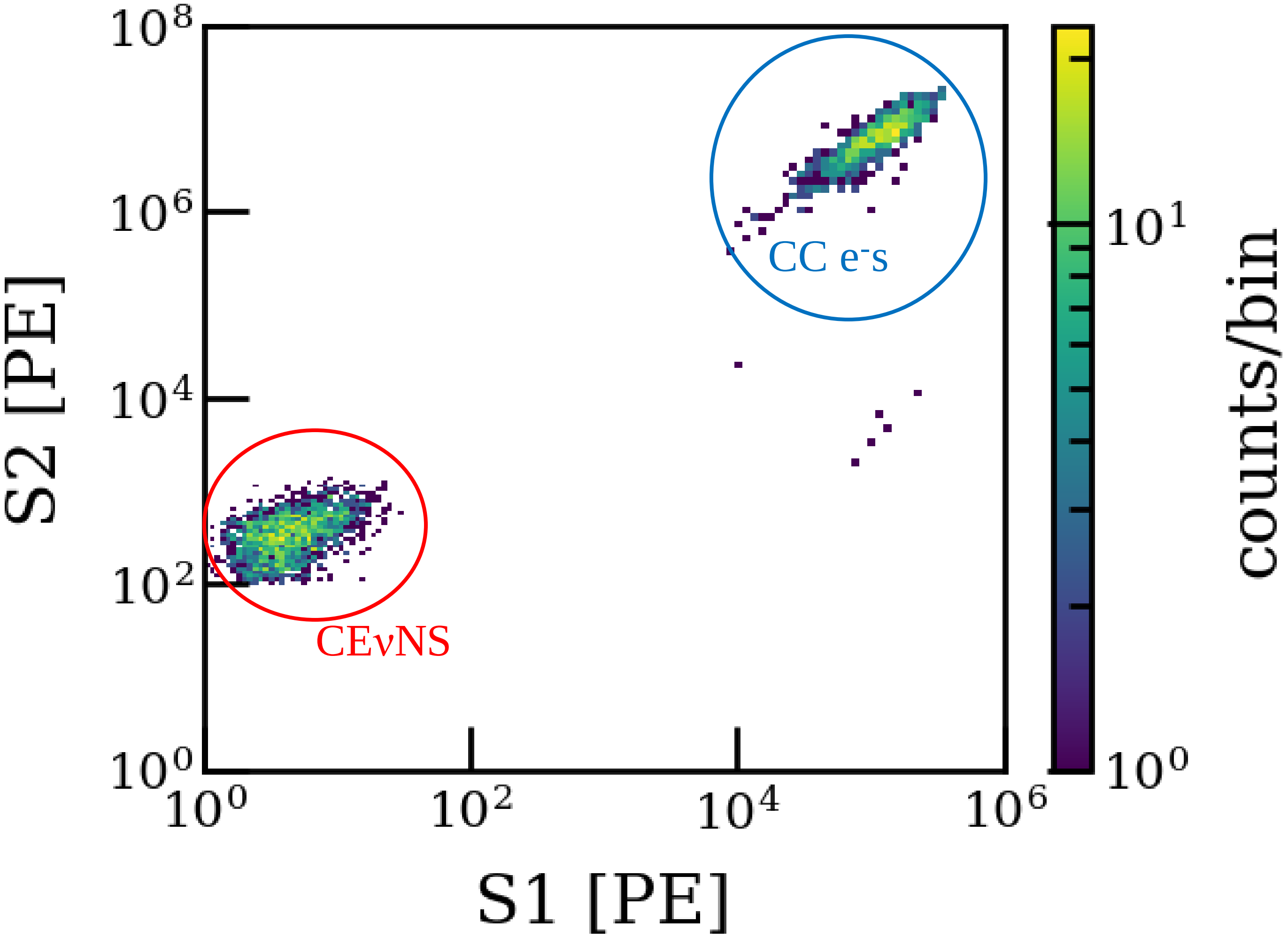
Melih Kara
(SNvD 2023@LNGS: International Conference on Supernova Neutrino Detection)



Signal sizes for CC electrons

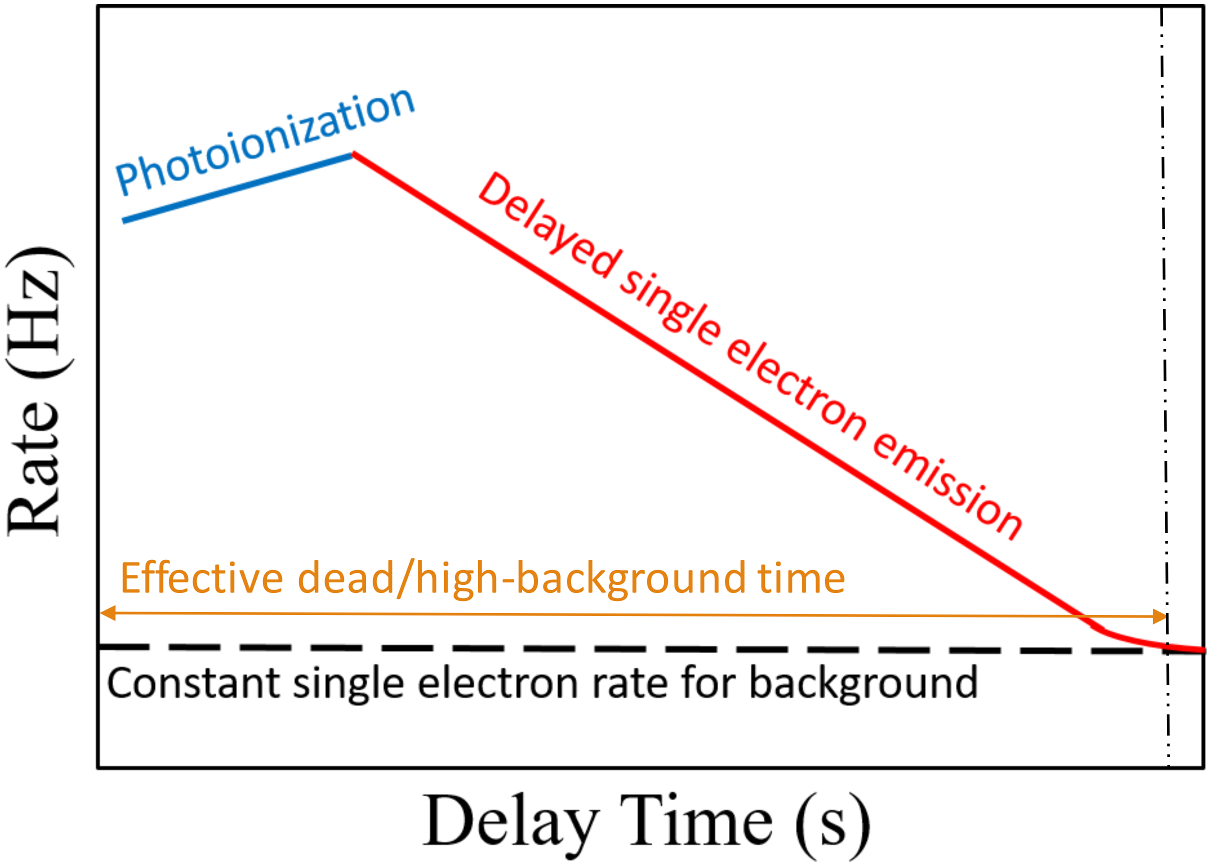
- For XENONnT/LZ < 1 CC electrons for SN at 10 kpc.

- With XLZD (40 t) we can expect ~ 4 CC electrons.
  - Distance for at least 1 CC electron ~21 kpc.



Limitations to CEvNS detection

- Saturation in PMTs and dead times in DAQ systems (~ms).
- Enhanced photo-ionization rate due to large S2s.
- Enhanced delayed few electron signal rate.
- Effective dead time for muon signals is ~ seconds



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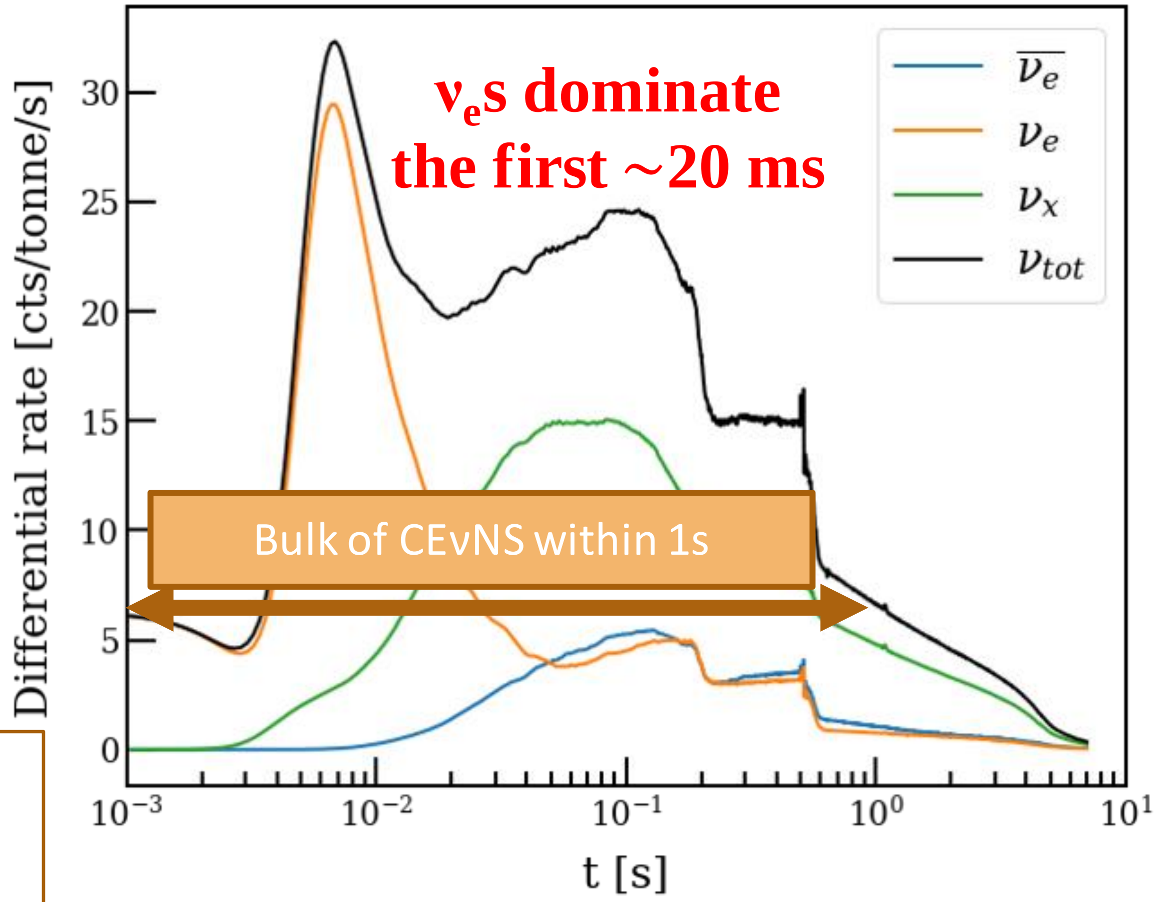


ν_es dominate the first ~20 ms

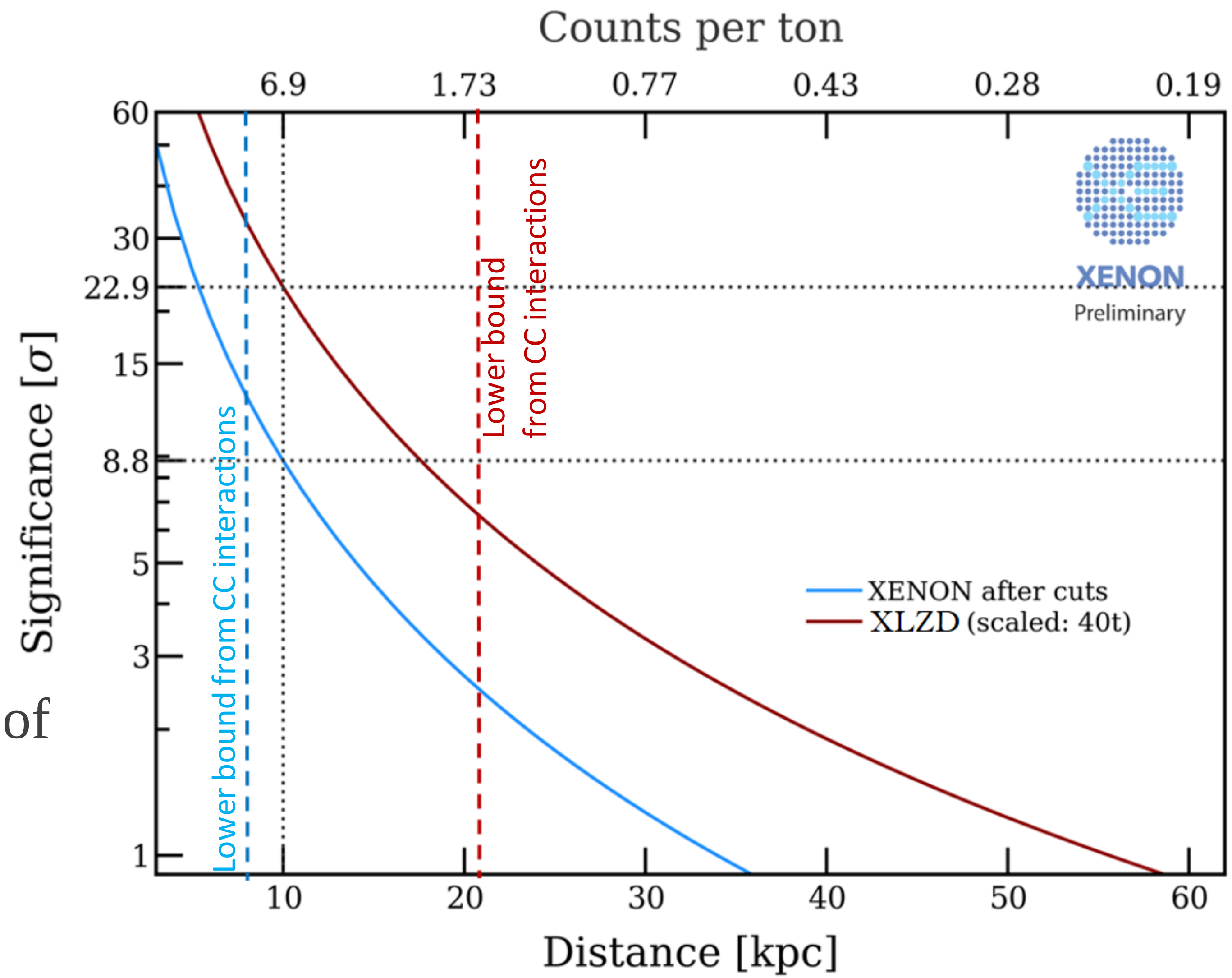
Bulk of CEvNS within 1s

The first CC interaction may submerge the later CEvNS upto the next ~1s

Implications on future detectors

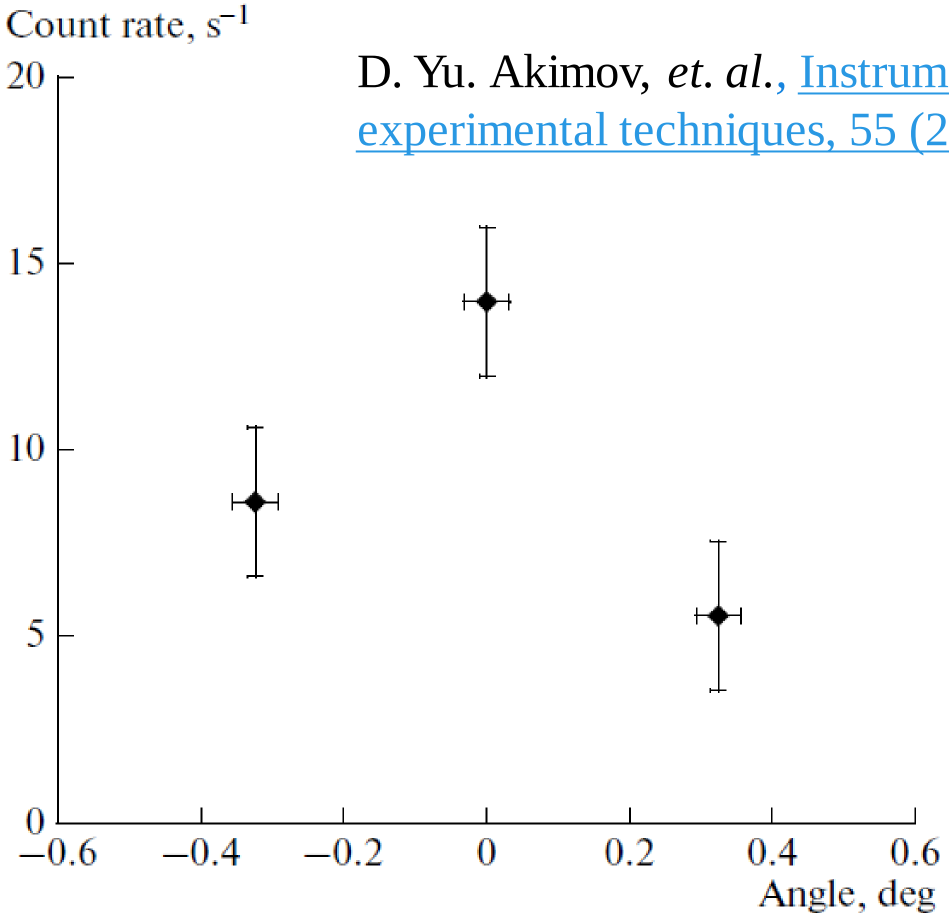
- ➢Lower bound on the supernova distance due to the CC electrons?

- ➢Implications on design of future generation detectors like DARWIN/XLZD.
  - Enable detection of signals from $\mathcal{O}(1\text{ keV}) - \mathcal{O}(100\text{ MeV})$
  - Methods to suppress enhanced photoionization.
  - Understanding the origin and suppression of delayed few electrons signals



What I look forward to

- These implementations help us in lowering Dark Matter search thresholds with S2-only analysis.
- Lowering delayed electron emission ⟶ significantly lowers accidental backgrounds for current and future detectors.



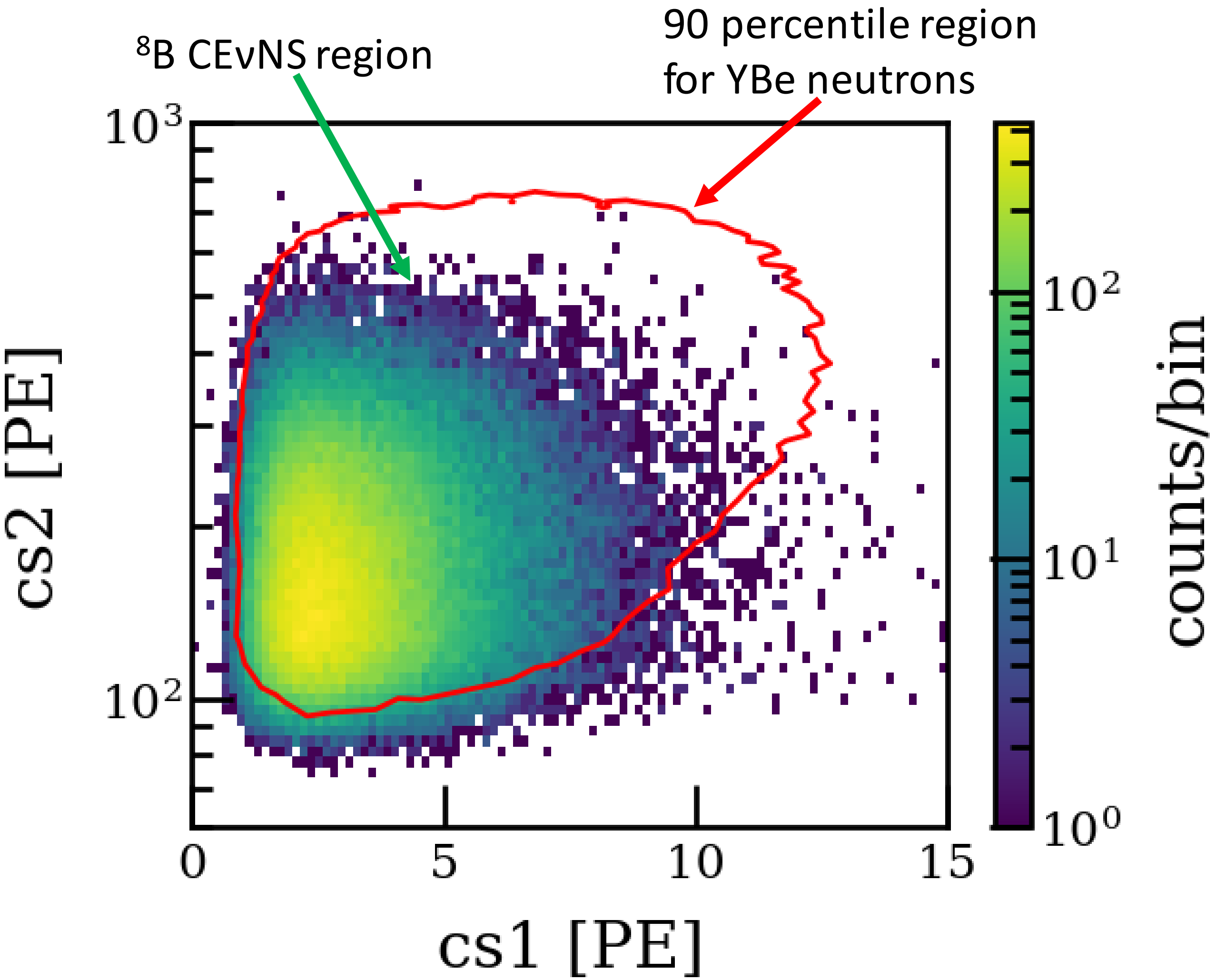
D. Yu. Akimov, *et. al.*, [Instruments and experimental techniques, 55 (2012) 4](#).

- Sources of delayed electron emission
  - Fluorescence from Teflon?
  - Trapping of electrons near the liquid-gas interface?
  - Correlation with isolated single photons?

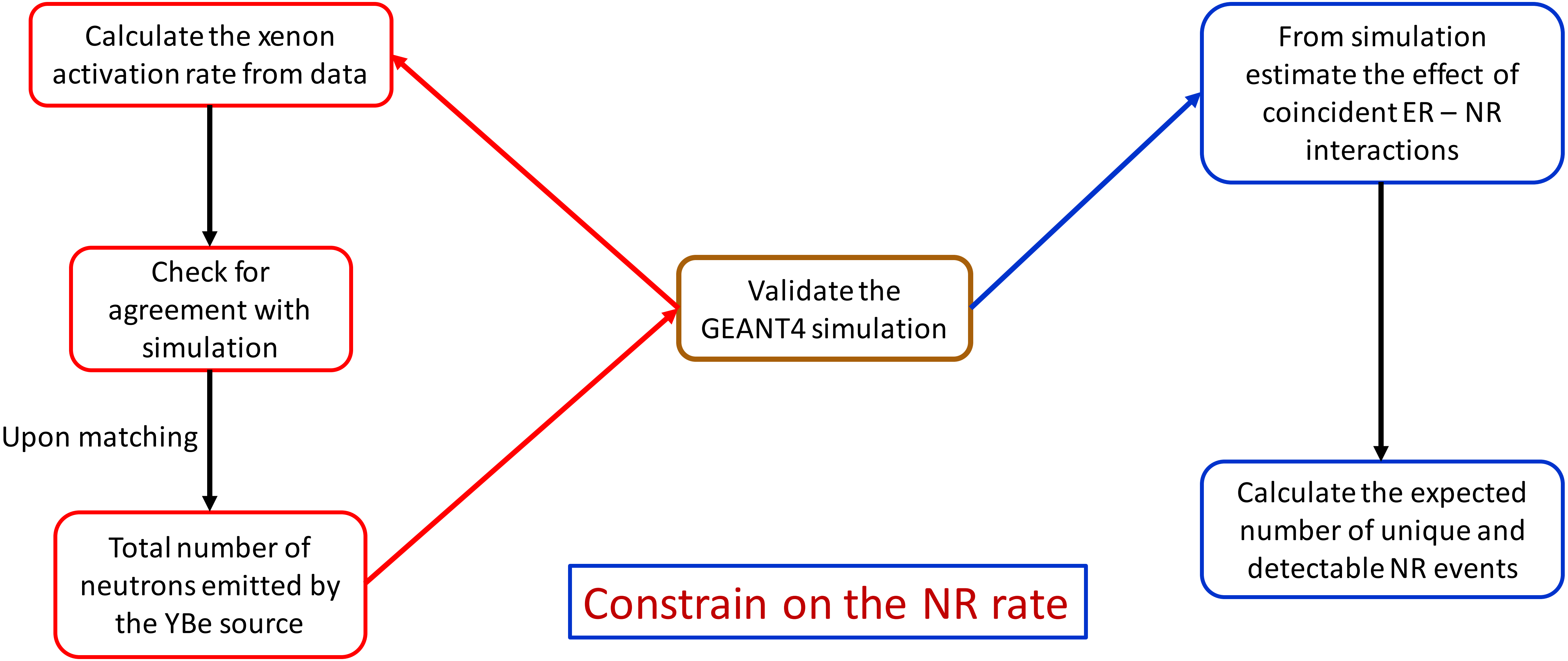
Low Energy neutron Calibration of XENONnT

The YBe calibration

- Light and charge yield at very low NR energies (^{8}B CEvNS region) :- Low energy neutron calibration.
- YBe source produces neutrons at ~152 keV.
- Worked out the expected neutron rate in the detector for the calibration.



Calculating the neutron rate



Calculate the xenon activation rate from data

Check for agreement with simulation

Upon matching

Total number of neutrons emitted by the YBe source

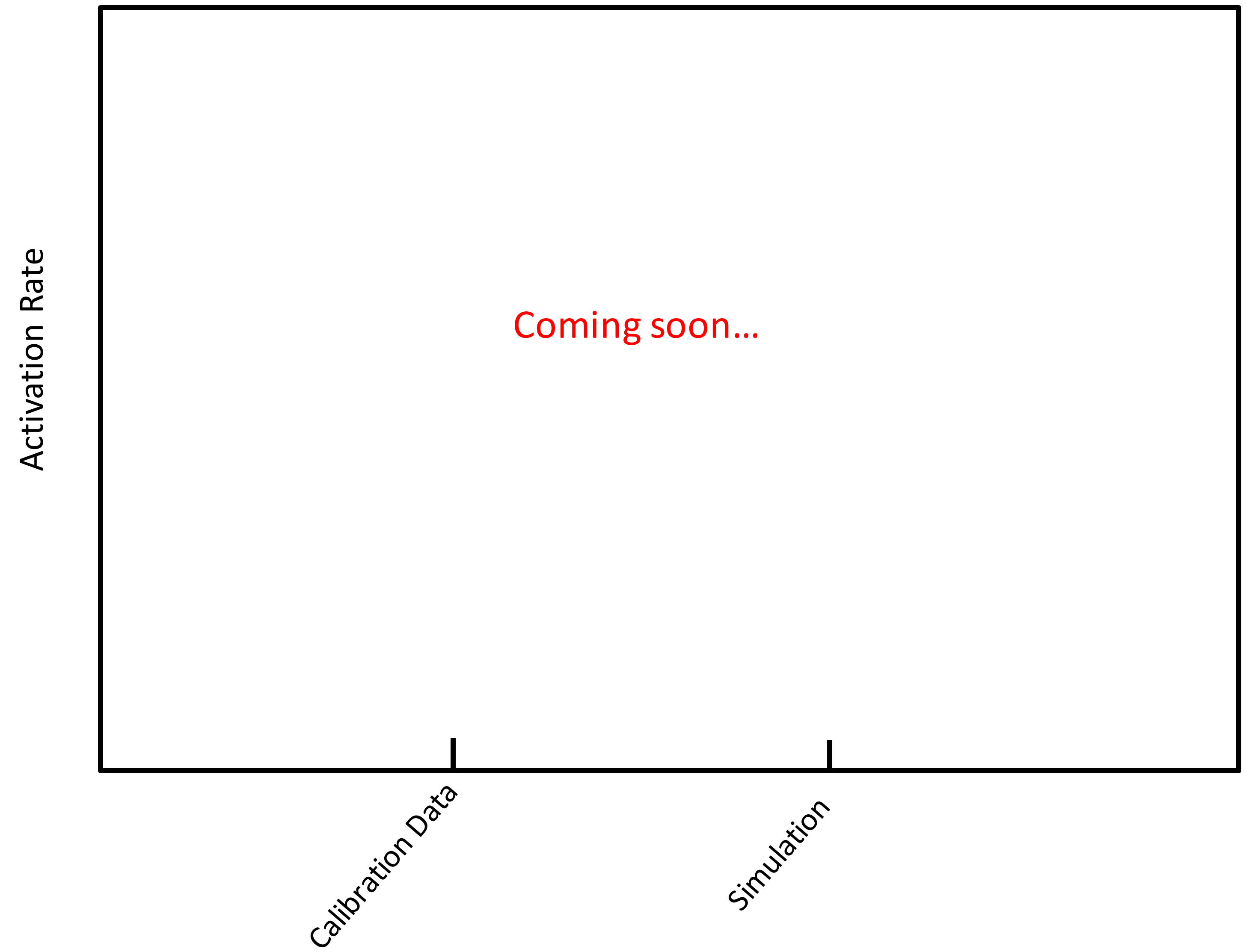
Validate the GEANT4 simulation

From simulation estimate the effect of coincident ER – NR interactions

Calculate the expected number of unique and detectable NR events

Constrain on the NR rate

Results…



Nuclear Recoil Rate :- Coming soon…

Survival probability of electron neutrinos using solar pp neutrino in XLZD

The future of xenon community

XENON

Currently operating with 8.5 tonnes of liquid Xenon at Gran Sasso in Italy

LUX-ZEPLIN

Currently operating with 10 tonnes of liquid Xenon at SURF in South Dakota

DARWIN

Leading many R&D projects designing a future 50 tonnes liquid Xenon detector

The XLZD consortium

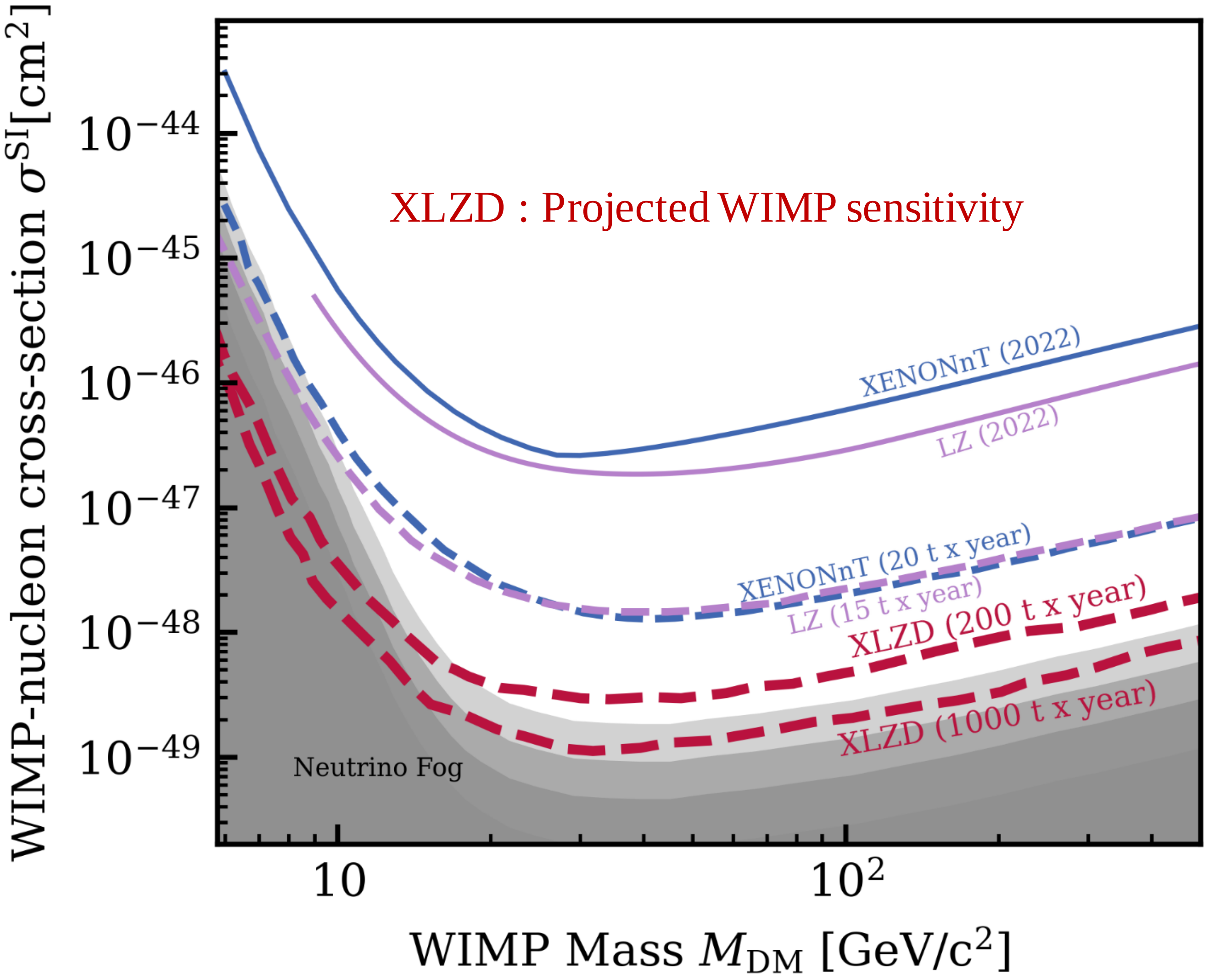
xzld.org

World leading DM search experiments joining hands for the next generation xenon observatory

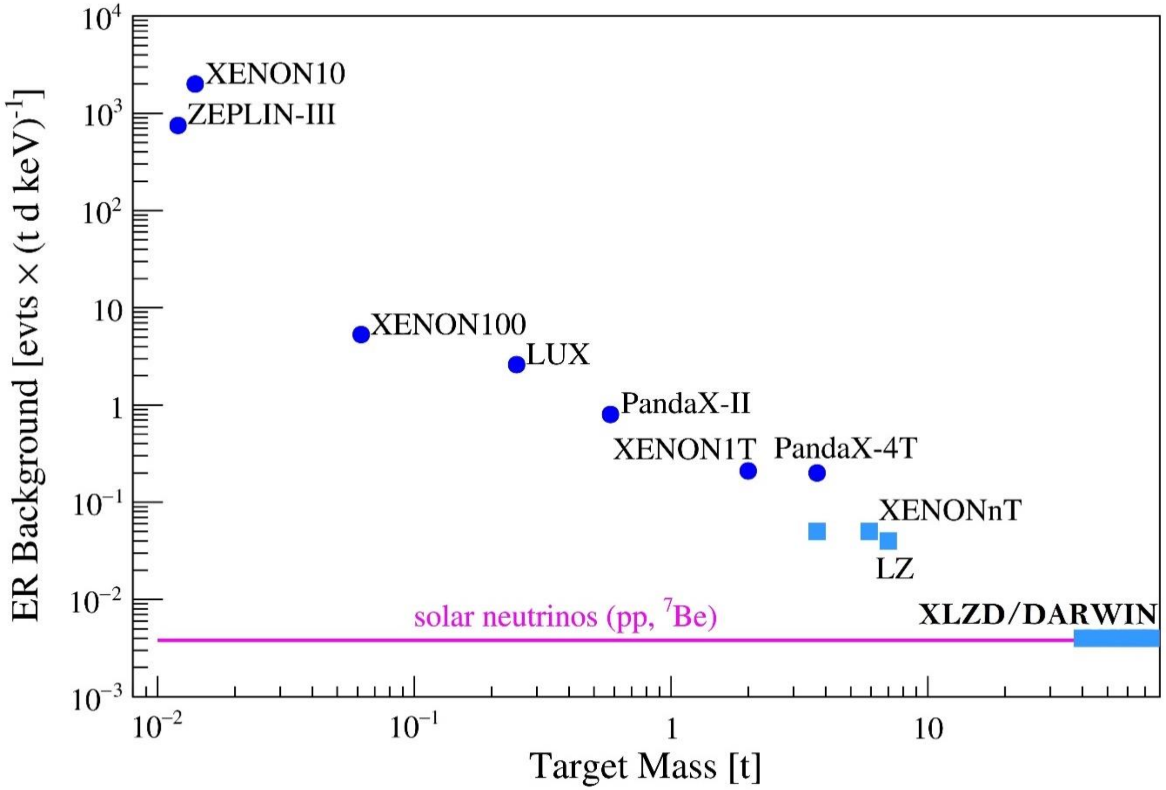
Whitepaper:- J. Aalbers, et. al., *J. Phys. G: Nucl. Part. Phys.* **50** 013001 (2022)

MOU signed in July 2022

XLZD : Ultimate WIMP hunter

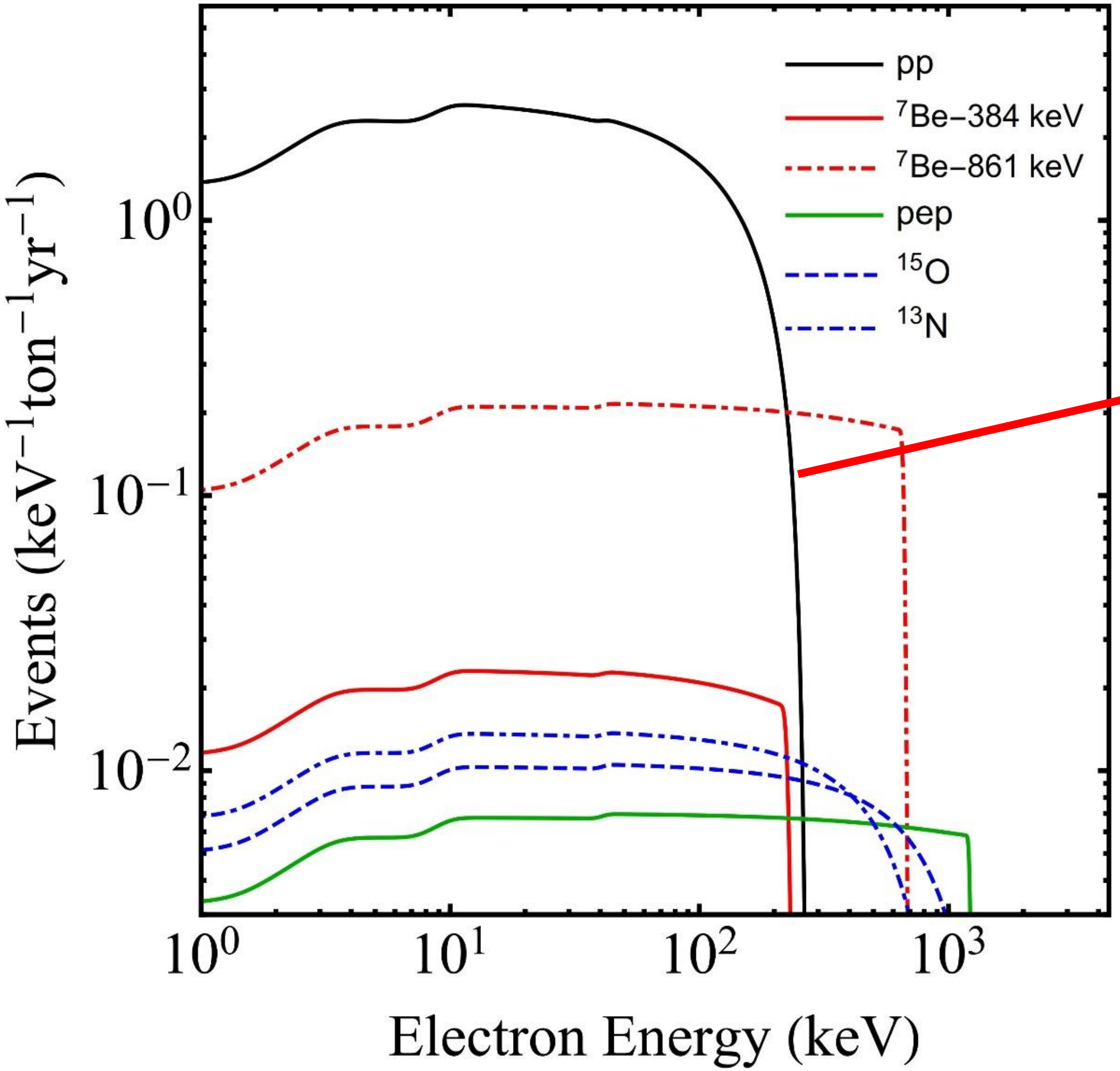


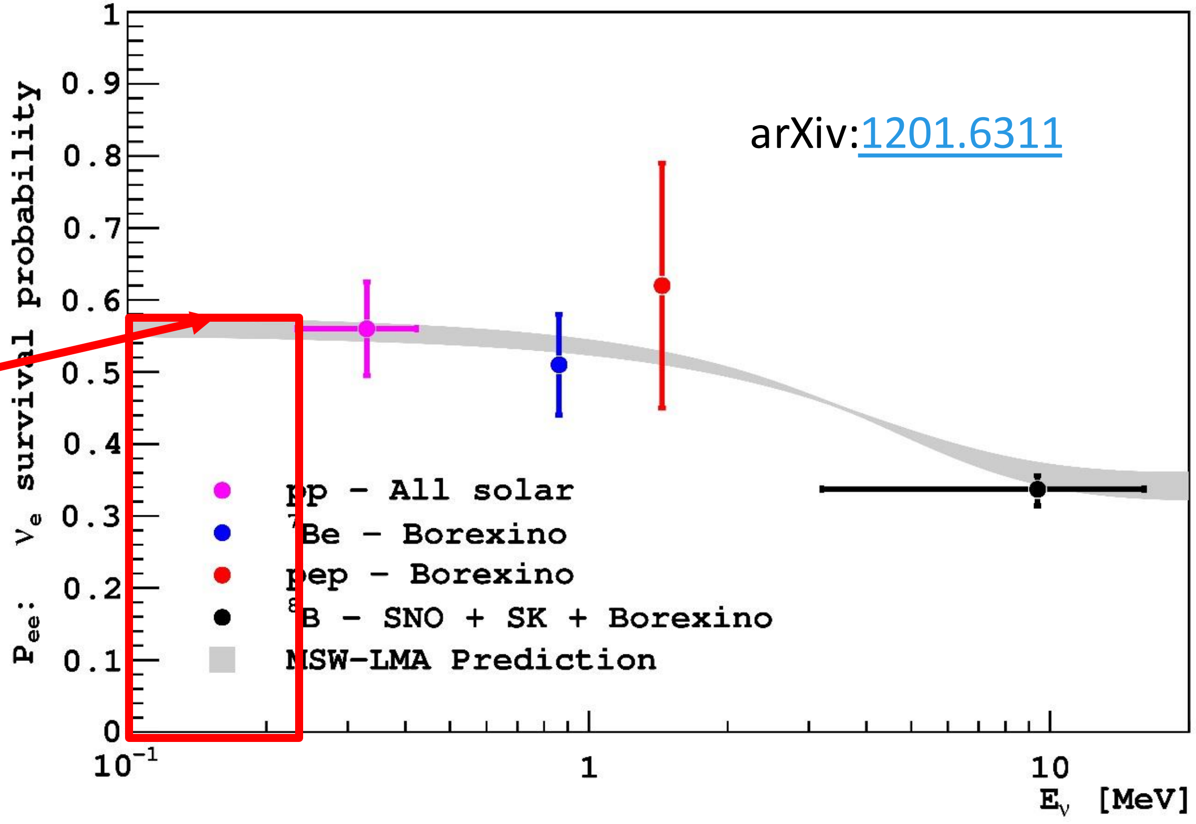
J. Aalbers, et. al., *J. Phys. G: Nucl. Part. Phys.* **50** 013001 (2022)



- ➢ Realistic target mass :- 60 tonnes of LXe
- ➢ Global Xenon market will be one of the challenges

XLZD : Solar pp neutrinos



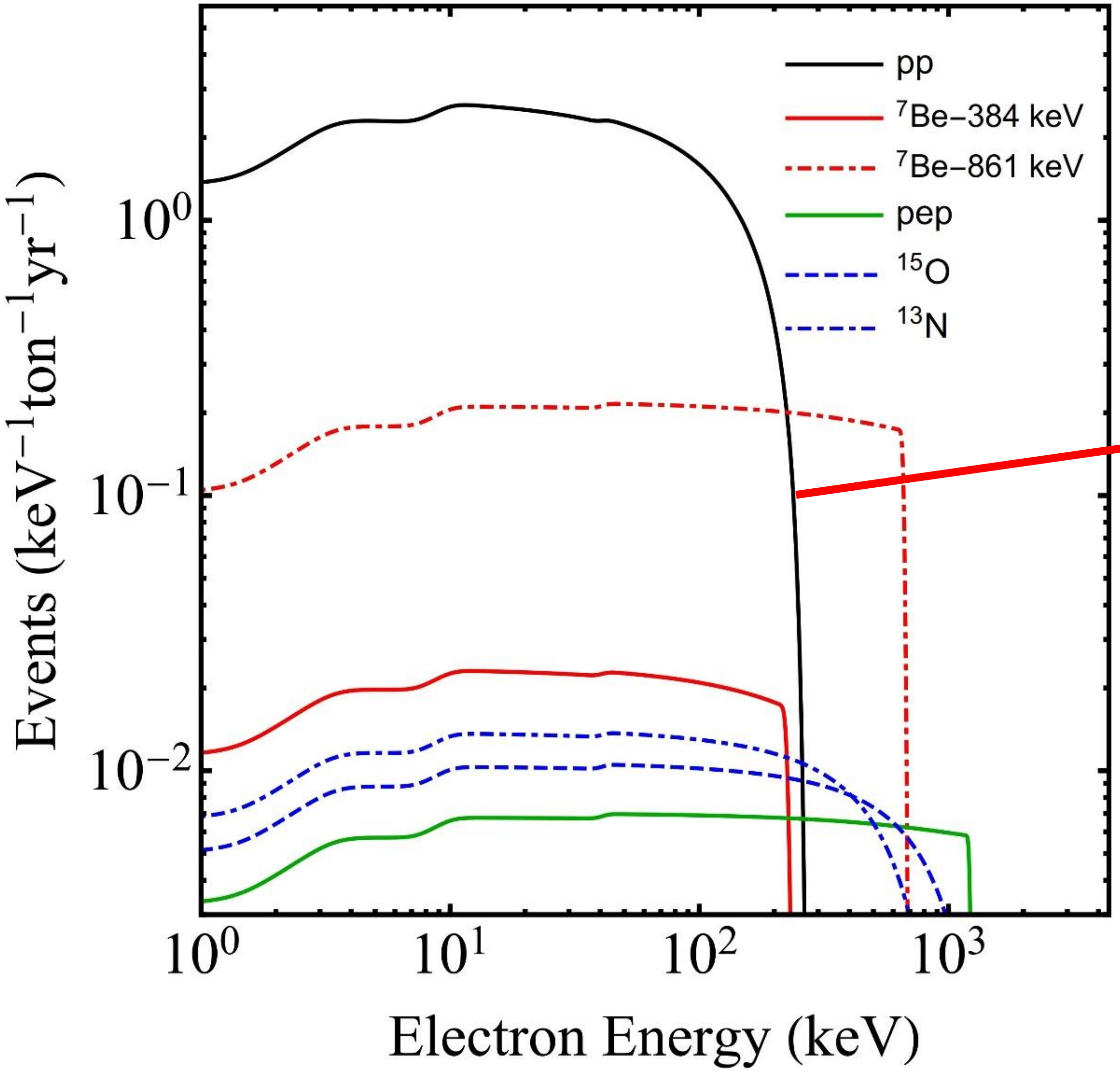


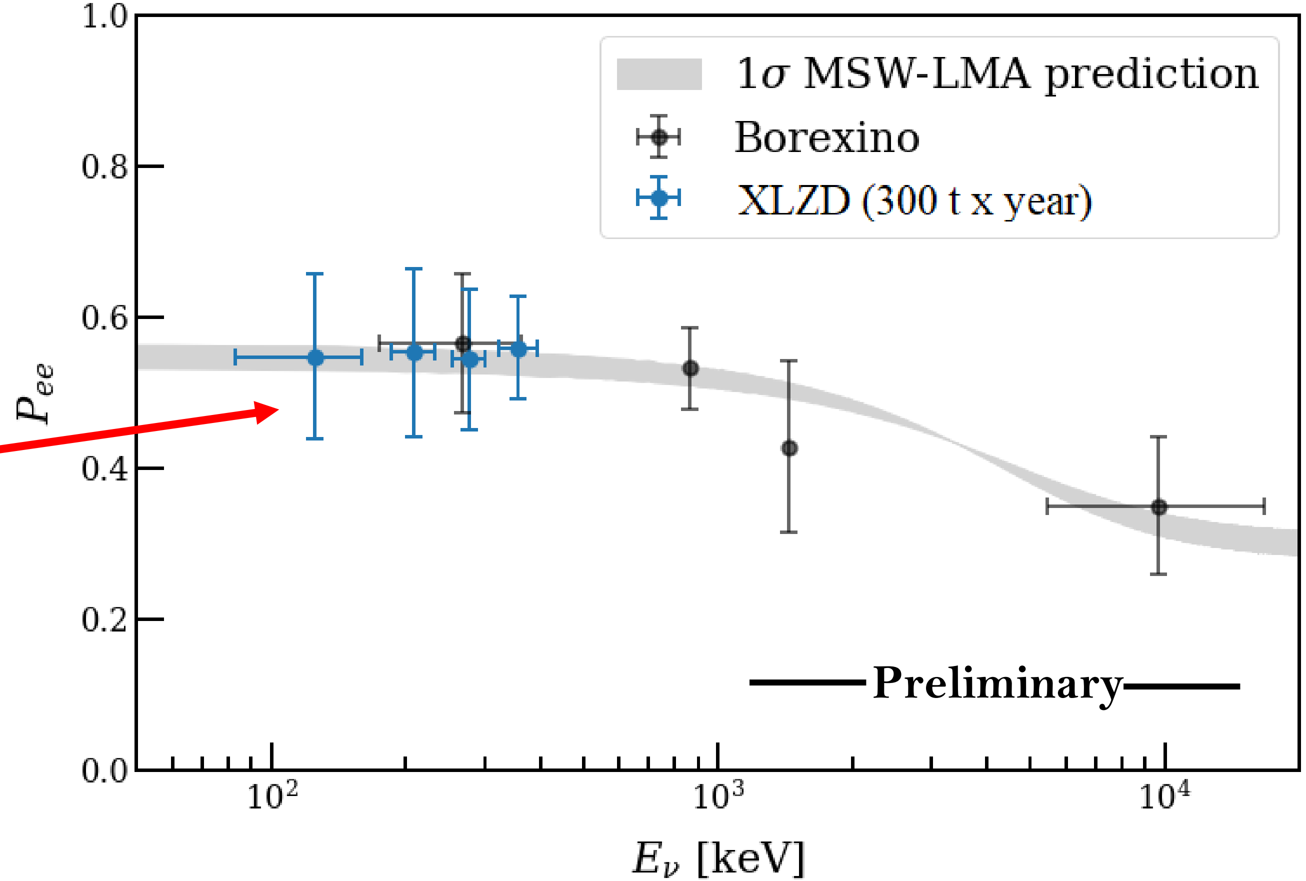
arXiv:1201.6311

- Precision measurement of *pp* solar neutrino flux

J. Aalbers, et. al., *J. Phys. G: Nucl. Part. Phys.* **50** 013001 (2022)

XLZD : Solar neutrinos (ER)





- Precision measurement of *pp* solar neutrino flux
- Multiple measurement of P_{ee} at energies lower than Borexino measurement

J. Aalbers, et. al., *J. Phys. G: Nucl. Part. Phys.* **50** 013001 (2022)

Summary

- Role in setting up a new direct DM detection experiment in India
  - Background measurement and simulation
  - Characterization of SiPMs and Scintillators

→ GEANT4, detector R&D, staying underground

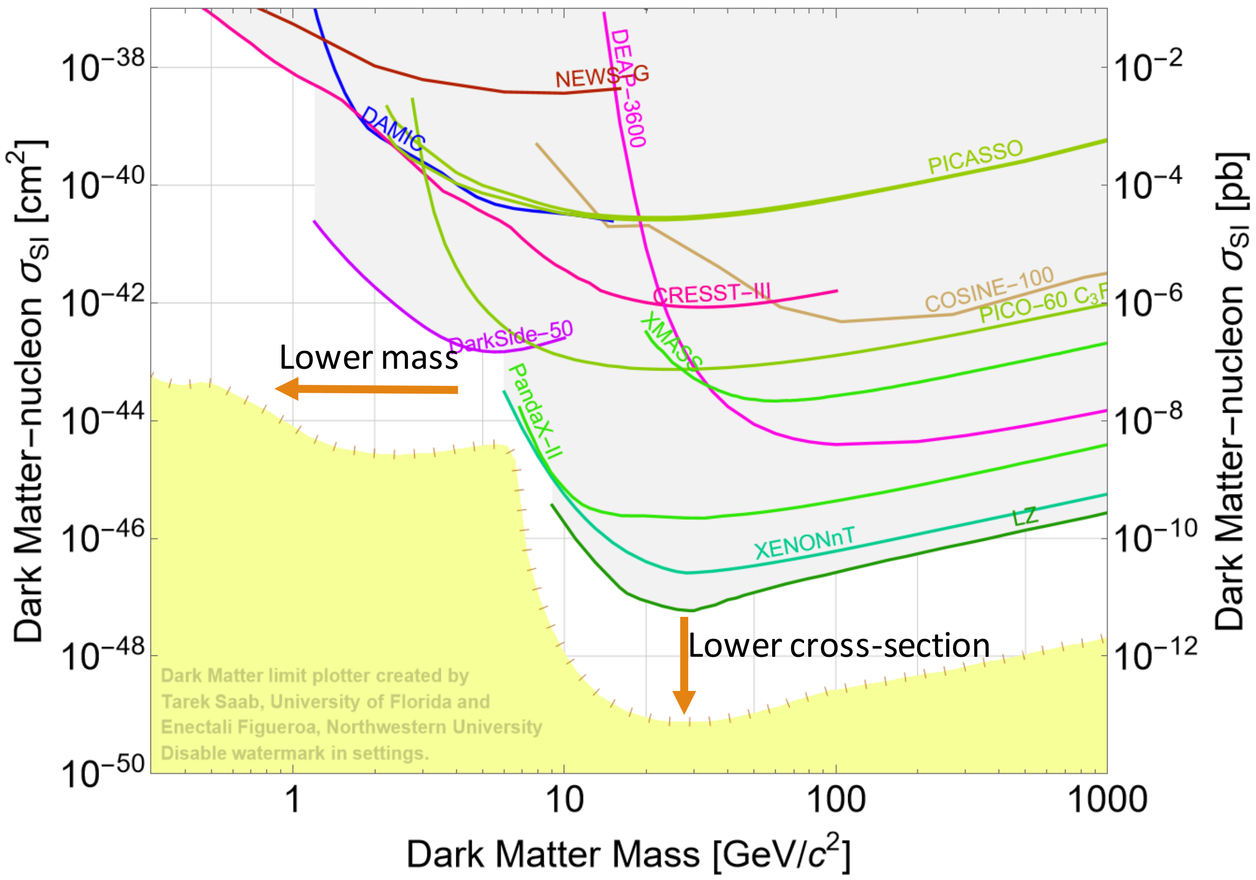
- Supernova neutrino detection with dual-phase xenon TPCs
  - Optimizing cuts and CEνNS detection significance. → S2-only analysis, detector cuts, interest in single electrons
  - Effect and implication of CC interaction in current and future detectors

- Low energy nuclear recoil calibration with XENONnT
  - MC validation
  - Nuclear recoil rate calculation

→ Data analysis, event selection

- Solar pp neutrino detection with XLZD. → Supervision

Looking forward



Lower mass

Lower cross-section

Understanding of :-

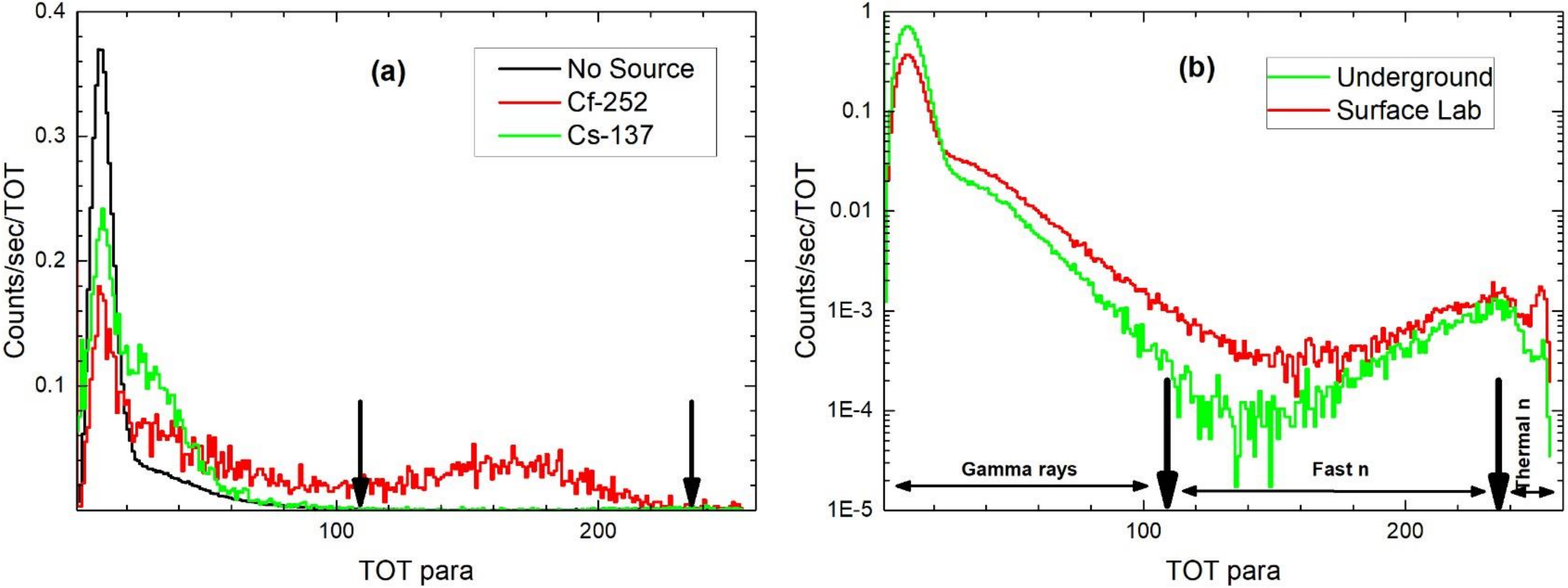
i. intrinsic background and its reduction

ii. low energy detector response

- ➢ Source of delayed electron emission
  - ➢ Fluorescence
  - ➢ Correlation with isolated single photons
  - ➢ Trapping at liquid interface
- ➢ S2-only analysis
- ➢ Low energy NR calibrations
- ➢ Supernova neutrino detection
- ➢ Low energy region in XLZD (solar pp, and others…)

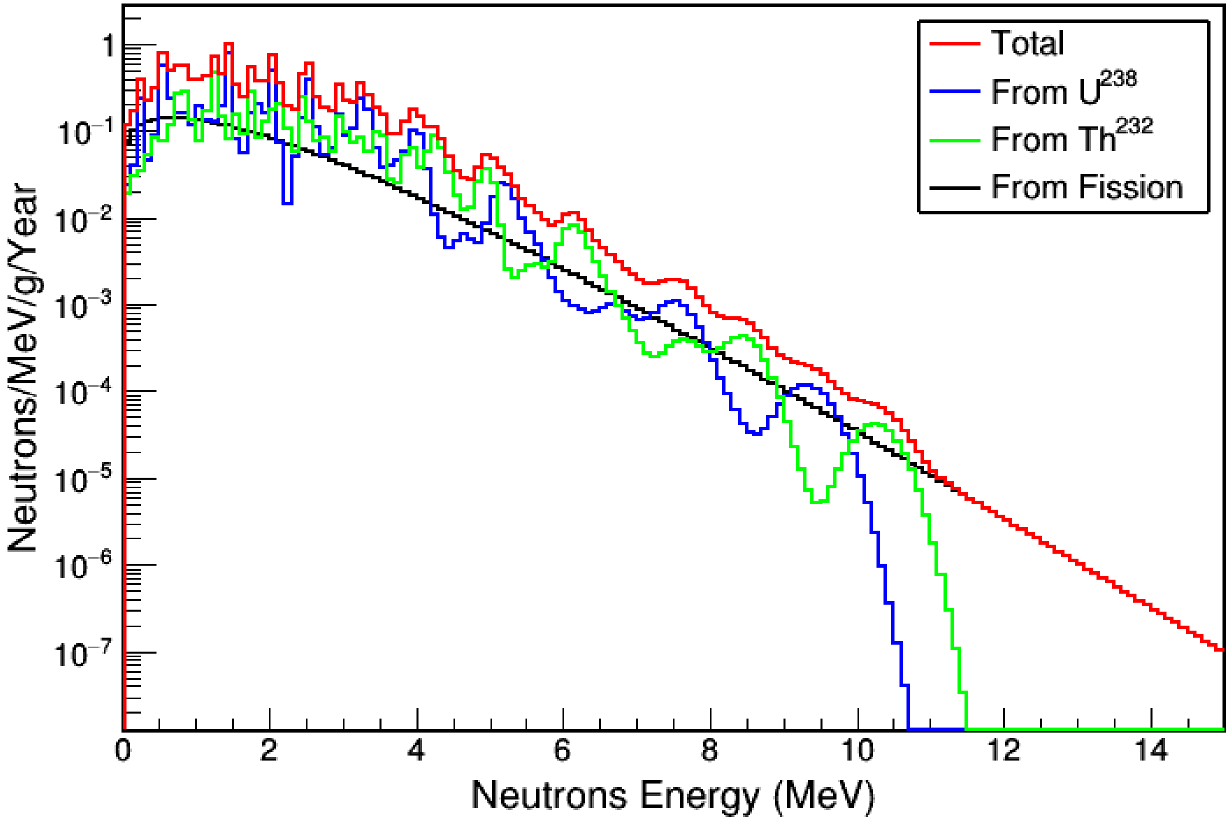
Backups…

He Neutron detector



S. Ghosh, *et. al.*, Astropart. Phys. 139, 102700 (2022)

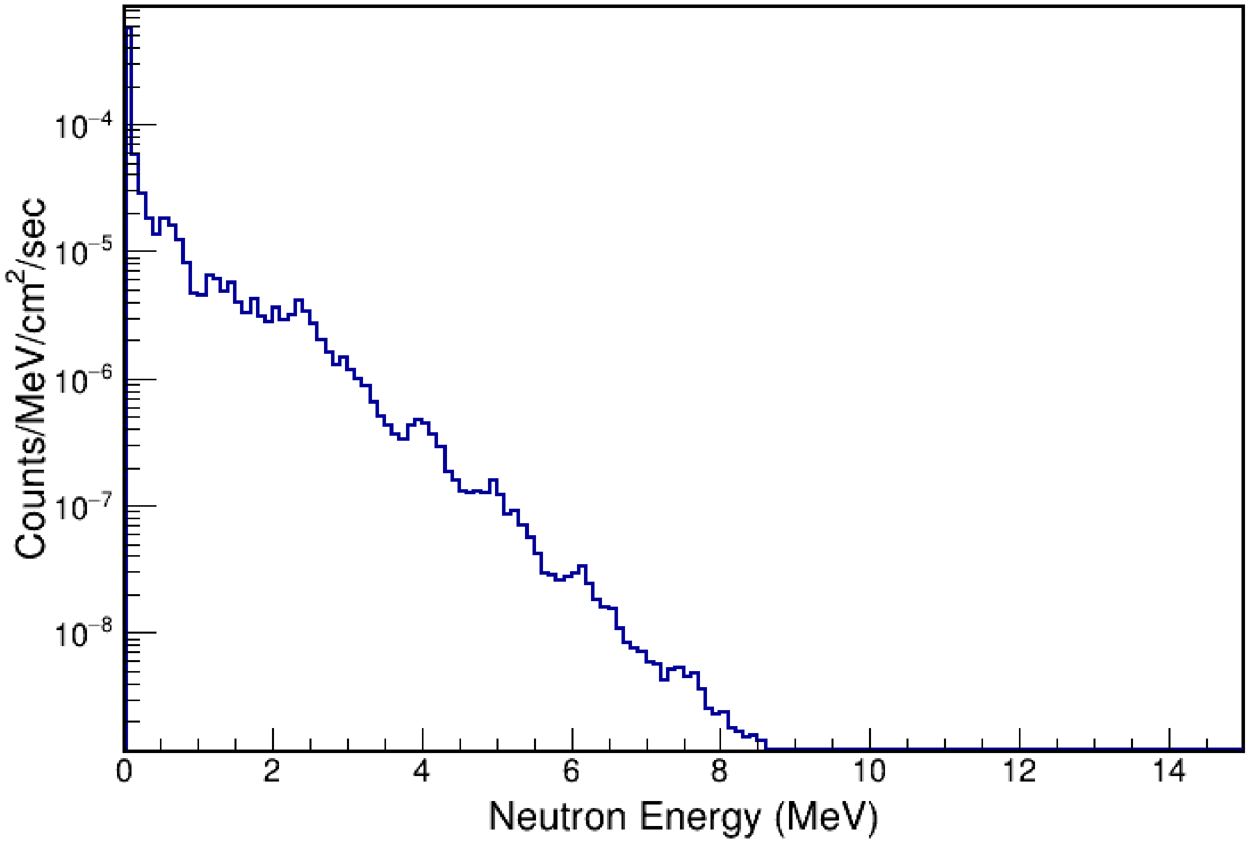
Radiogenic neutrons



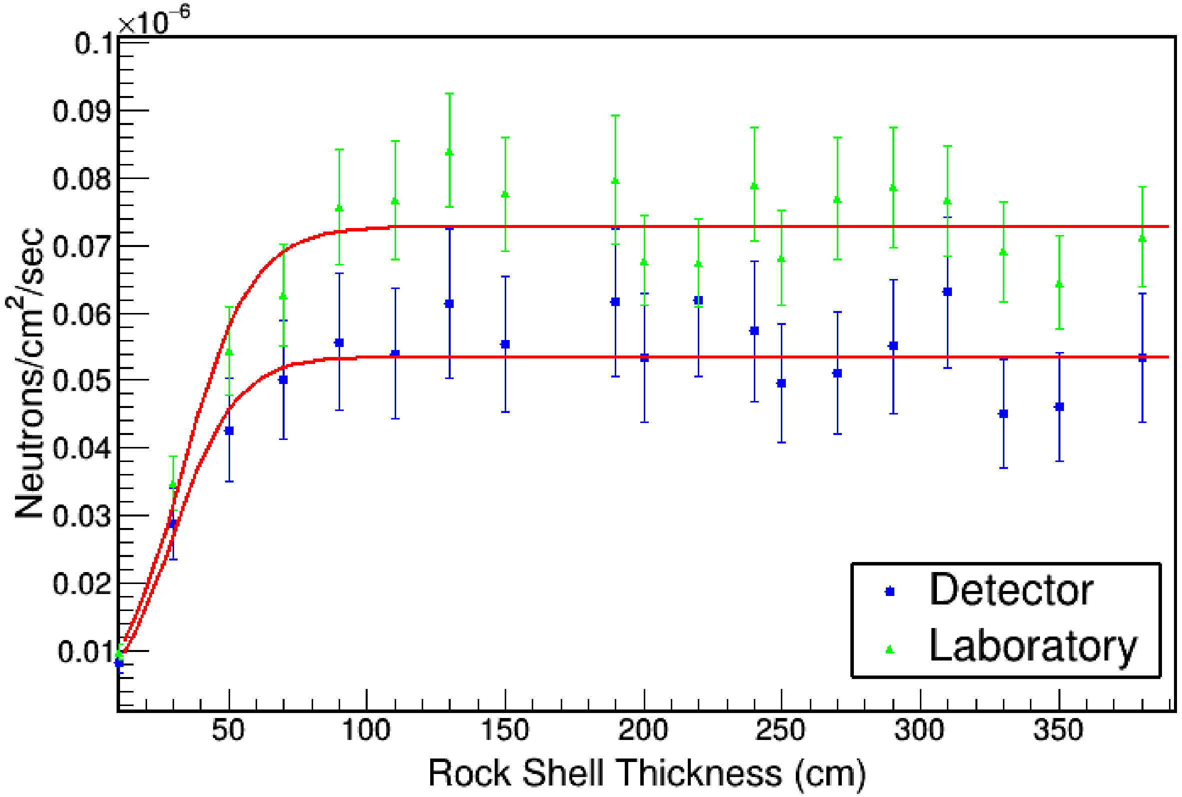
Spectrum neutrons produced inside the rock

http://neutronyield.usd.edu/,
Zhang-Mei-Hime [NIM A606, 651 (2009)](NIM A606, 651 (2009)) .

Spectrum neutrons at the detector

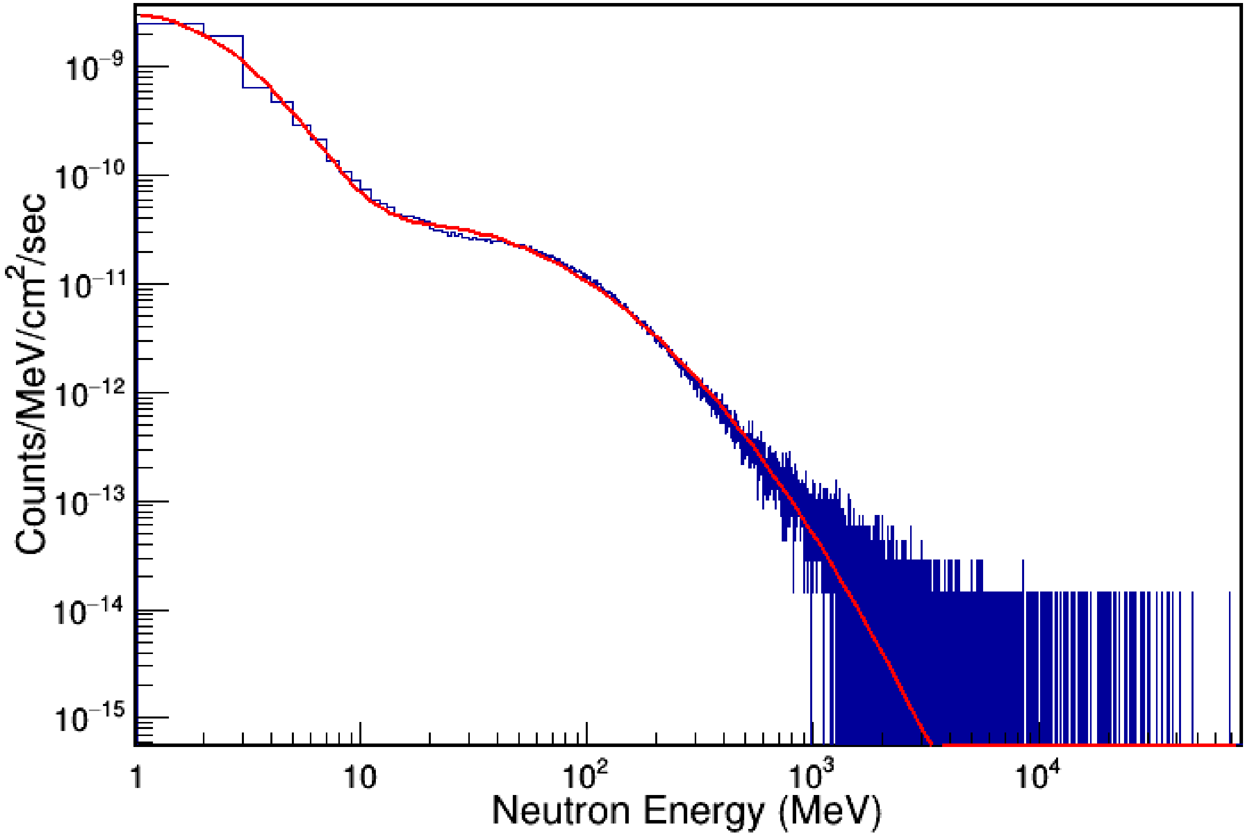


Cosmogenic neutrons

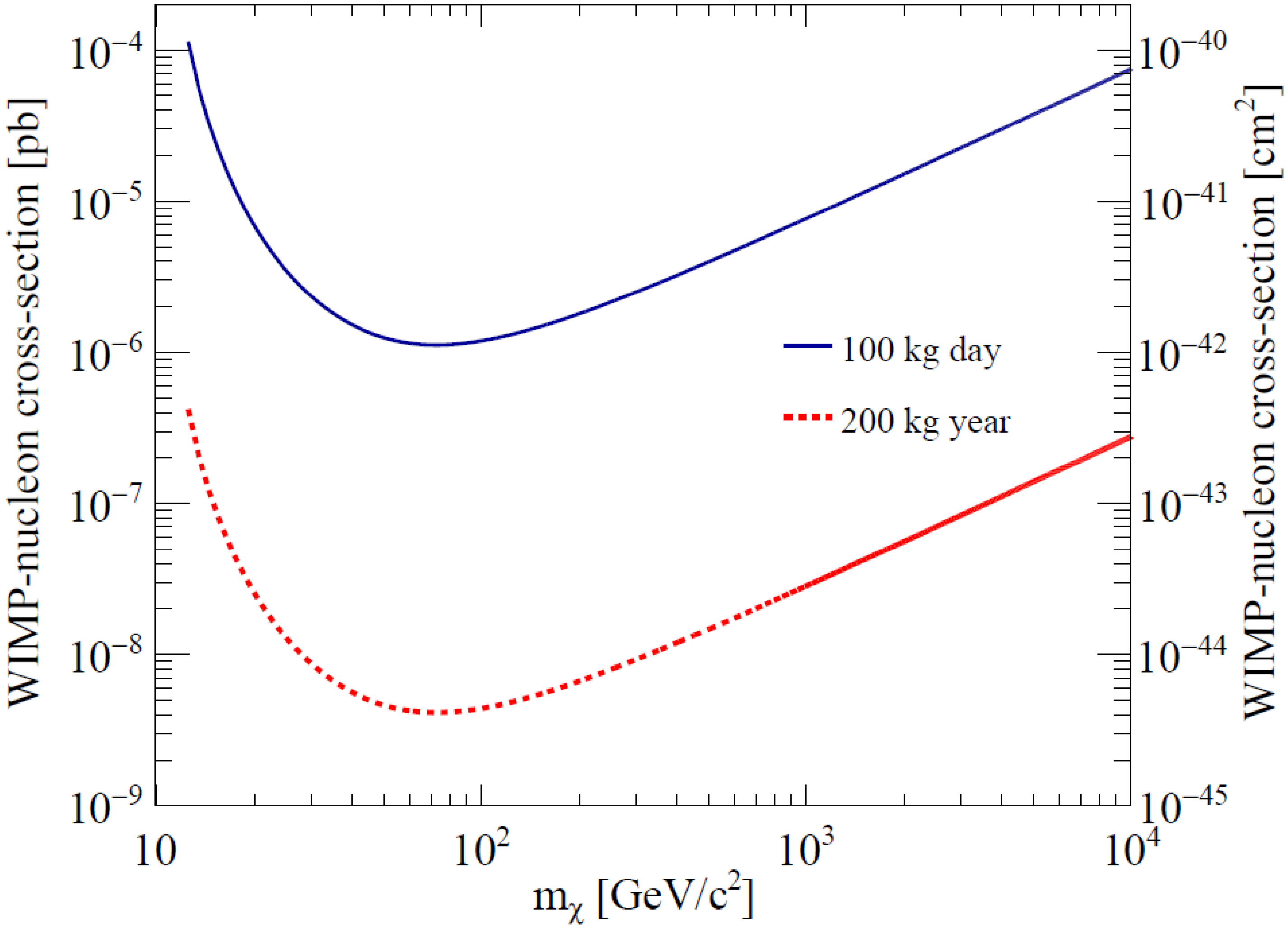


Optimization of rock shell thickness

Cosmogenic neutron spectrum at the detector



Preliminary DM sensitivity



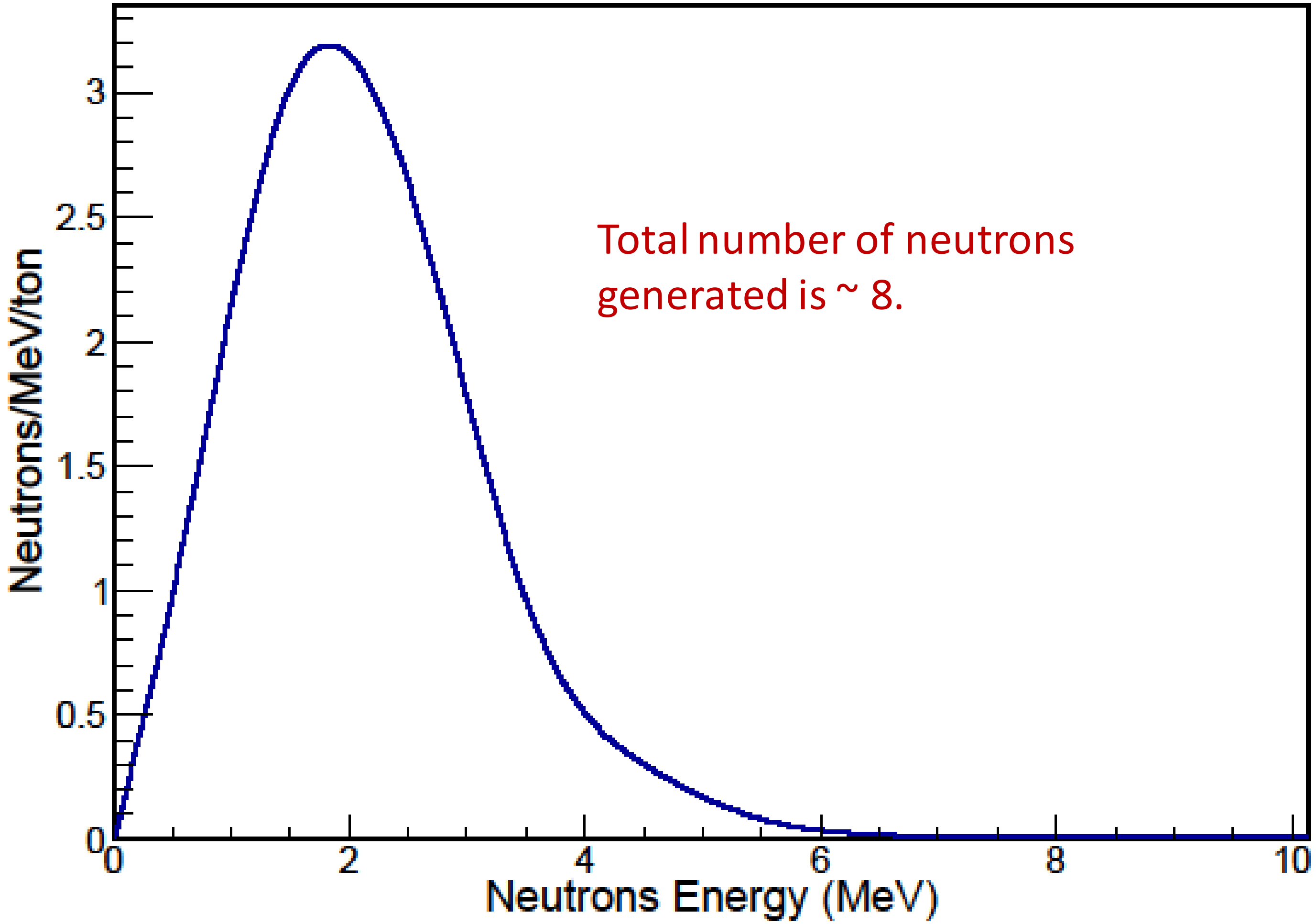
S. Banik, V. K. S. Kashyap, S. Ghosh, *et. al*. JINST 16 P06022 (2021)

Intrinsic Scintillator Light Increase

- Two processes, exciton-exciton annihilation (Birk’s mechanism) and electron-hole recombination (Onsager mechanism). Former causes reduction in light due to annihilation of Self Trapped Excitons (STE) and latter gives scintillation.
- Birk’s mechanism is much less efficient for alkali halides because of high electron mobility.
- Electron thermalizes in intrinsic scintillators mainly through electron-phonon interaction.
- Thermalization distance increases with decrease in temperature.
- Recombination probability $p = 1 - \exp(-\frac{r_{ONS}}{r})$, where $r_{ONS} = e^2/4\pi\varepsilon_0\varepsilon kT$.

Neutrons from CC interactions

$$^{132}\mathrm{Cs}^* \rightarrow {}^{132-X}\mathrm{Cs} + Xn$$ → Neutrino-induced neutrons (νIn)

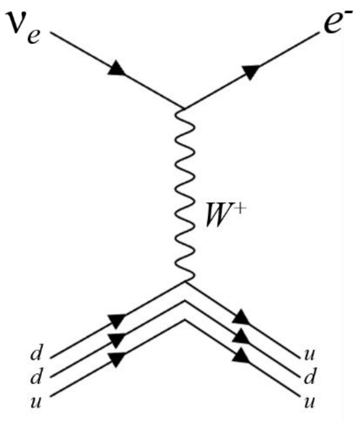


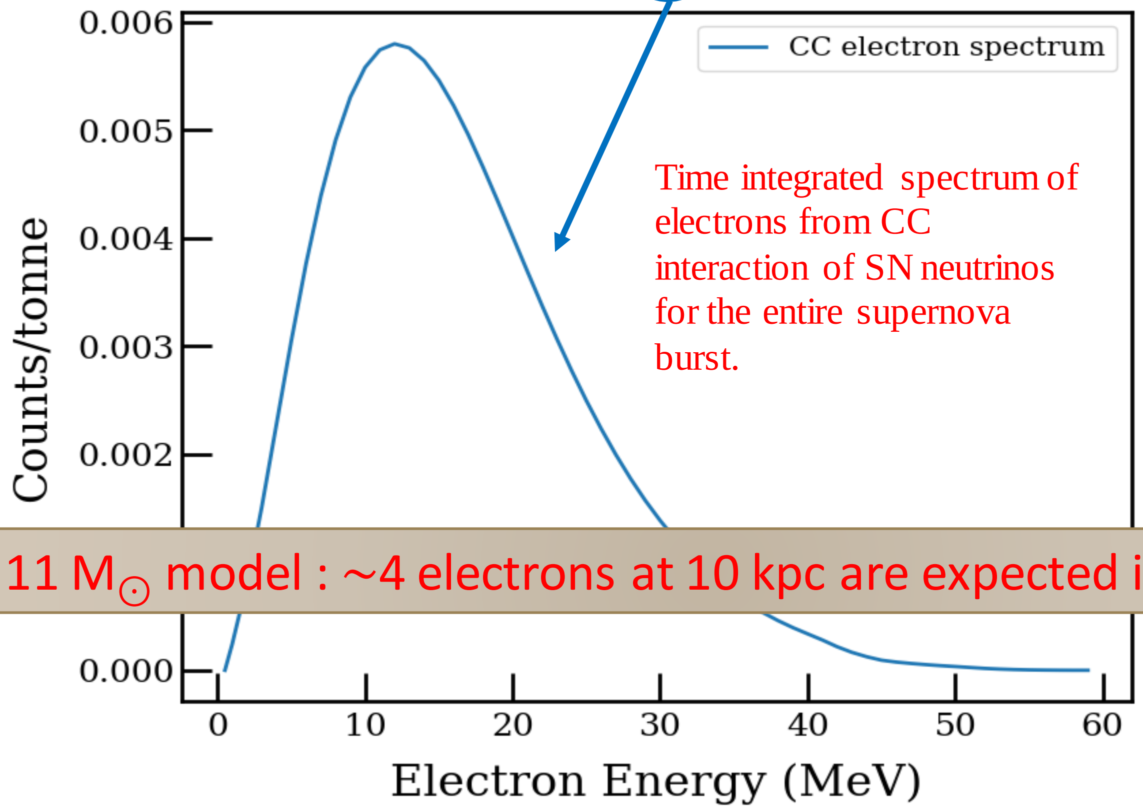
Total number of neutrons generated is ~ 8.

CC interactions of SN neutrinos (a limitation?)

- The CC interactions lead to emission of electrons and a daughter nucleus in an excited state (^{132}Cs* in case of ^{132}Xe).

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





Time integrated spectrum of electrons from CC interaction of SN neutrinos for the entire supernova burst.

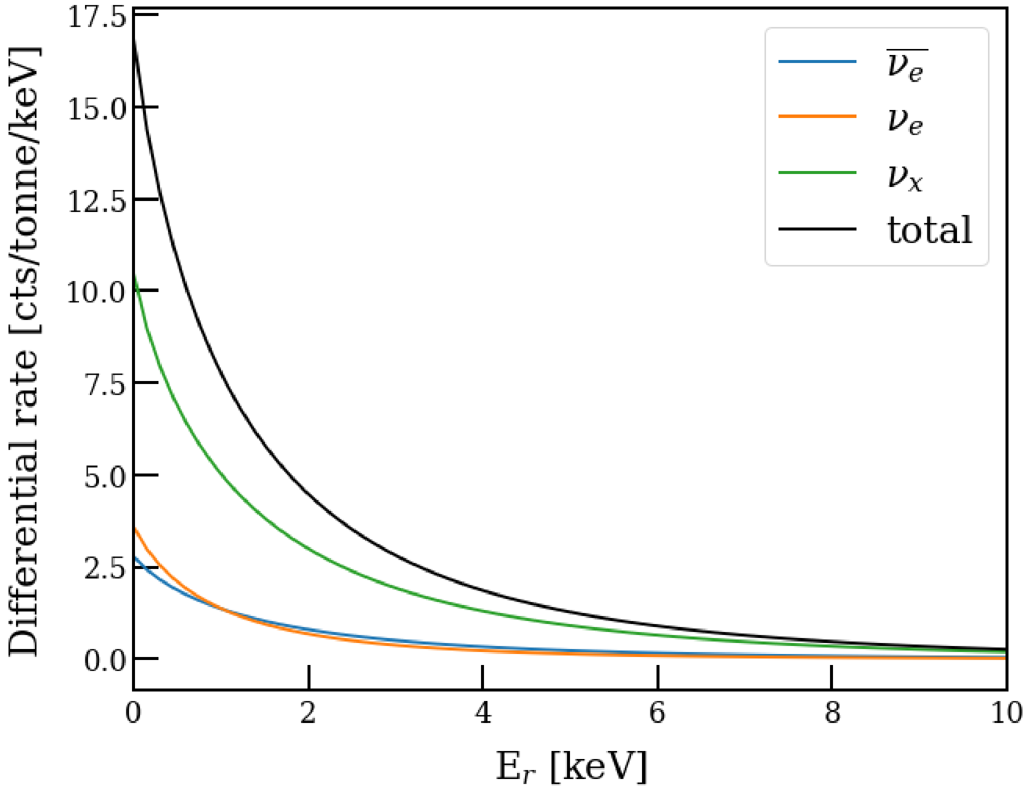
For 11 $M_\odot$ model : ~4 electrons at 10 kpc are expected in XLZD (40 t).

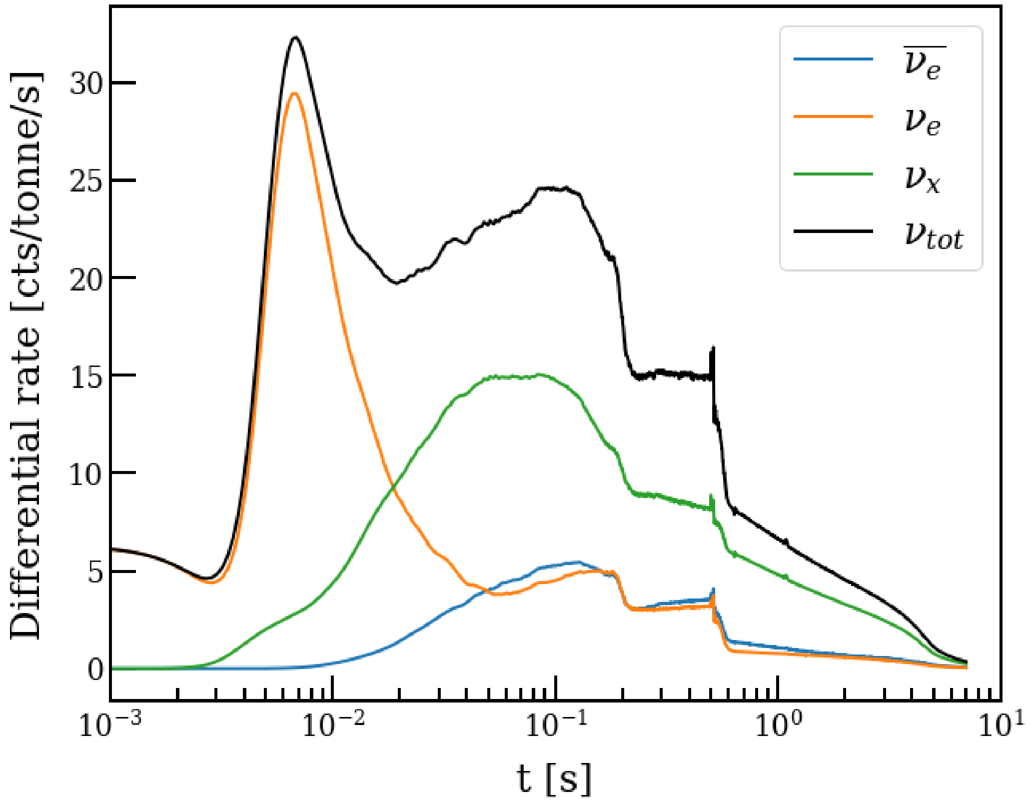
Supernova at 10 kpc

GitHub
SNAX

GitHub
snewpy

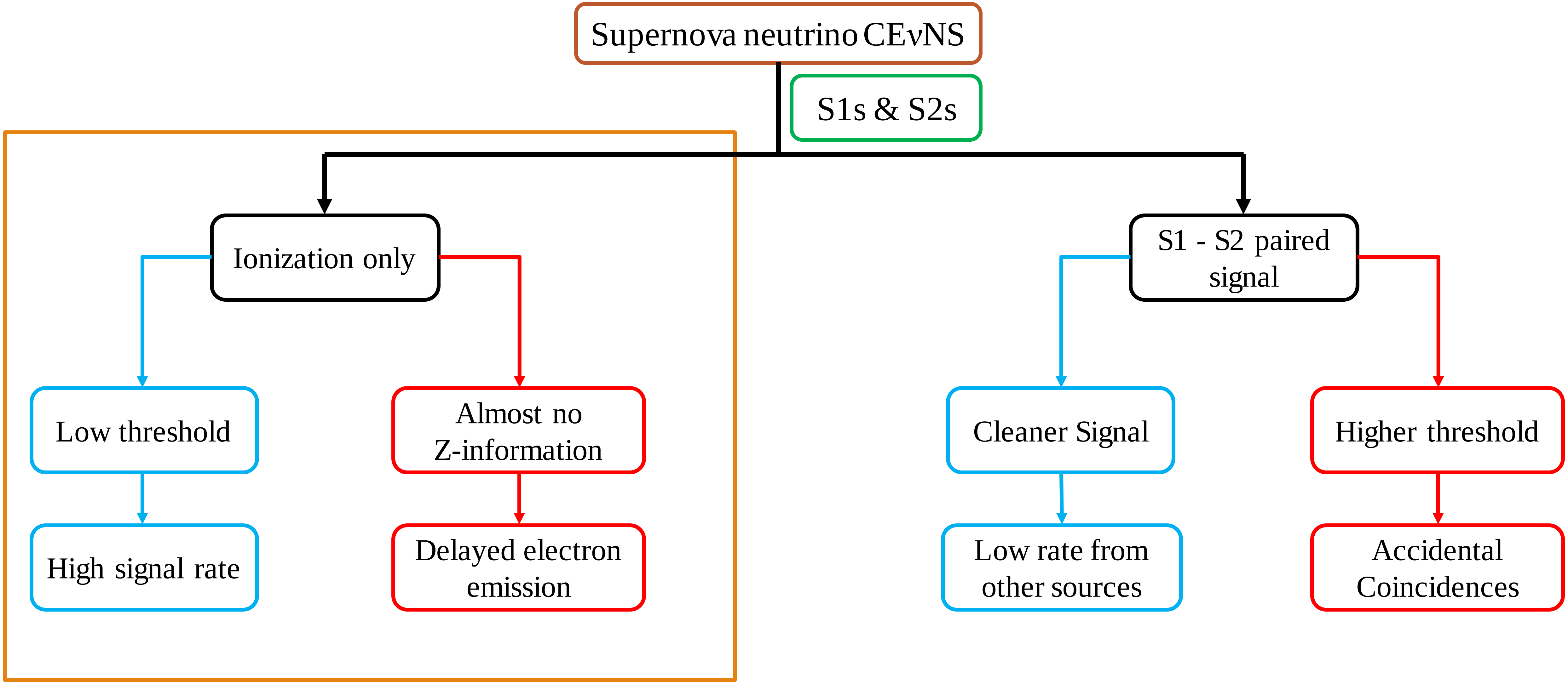
- Reference supernova model :- 11 $M_\odot$ at a distance of 10 kpc (Bollig 2016, Mirizzi, et. al., arXiv:1508.00785)





- At a distance of 10 kpc, a typical SN can generate ~70 CEνNS interactions in XENONnT (~700 interactions in XLZD (40 t)).

Analysis pathways



Supernova neutrino CEvNS

S1s & S2s

Ionization only

Low threshold

High signal rate

Almost no Z-information

Delayed electron emission

S1 - S2 paired signal

Cleaner Signal

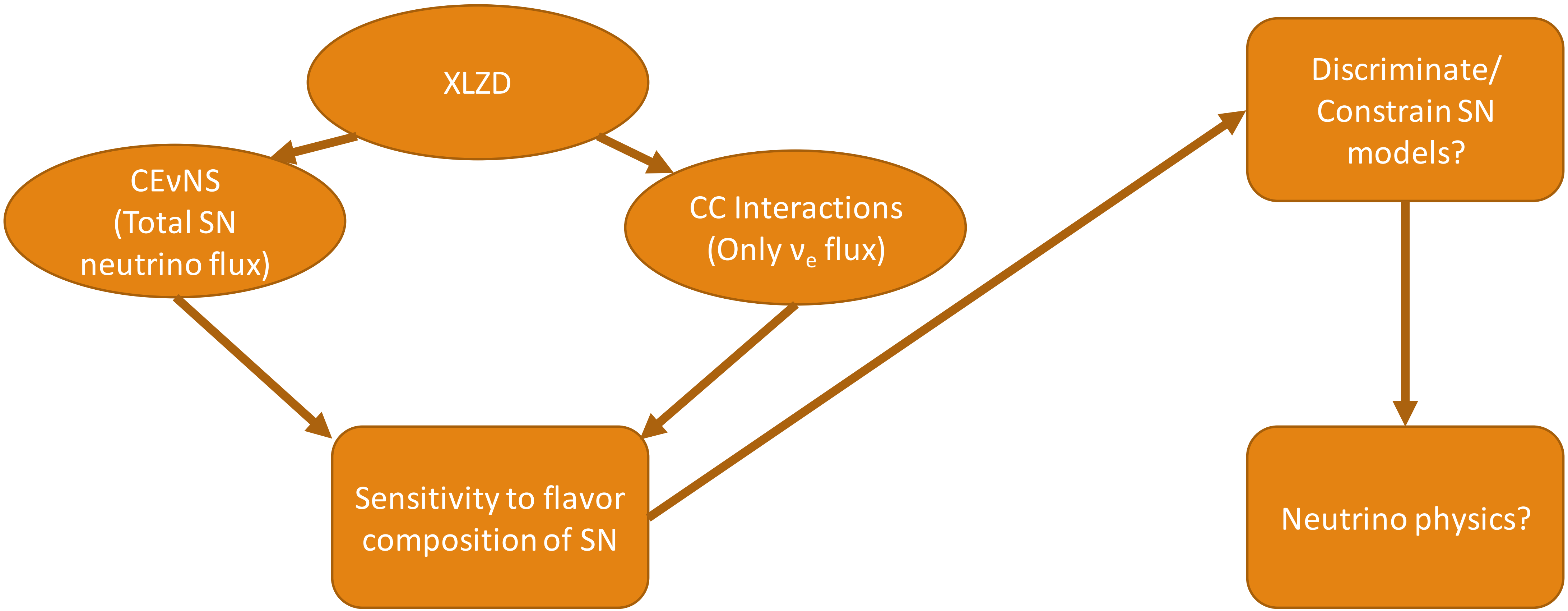
Low rate from other sources

Higher threshold

Accidental Coincidences

What if we managed to implement the design?

- These implementations help us in lowering Dark Matter search thresholds with S2-only analysis.
- Lowering delayed electron emission ⟶ significantly lowers accidental backgrounds for XLZD.


XLZD

CEvNS
(Total SN
neutrino flux)

CC Interactions
(Only ν_e flux)

Sensitivity to flavor composition of SN

Discriminate/
Constrain SN
models?

Neutrino physics?

Plans for the position at SLAC

Reducing ACs :- Understand Delayed electron emission

- Understand the origin of delayed few-electron emission
  - Explore and understand the source of uncorrelated electrons first
  - Ideas :- Fluorescence or trapped impurities at the liquid-gas interface
  - Possible strategies to suppress the signal
  - Direct importance to LZ and to future detector design of XLZD.
- This will lower ACs and lower the analysis threshold for low-mass DM searches.
- Reduction of delayed electron emission also enhances supernova sensitivity of LZ and in future for XLZD.

Other plans with detector R&D

- I wish to work on HydroX.
  - Study the dependence of hydrogen doping on S2-signals in gas mode
  - Finally understand the change in signal shapes in the dual-phase mode
- Explore ideas for simultaneous detection of CEνNS and CC signals from supernova neutrinos with XLZD.

Signals in dual-phase xenon TPC