清華大學
Tsinghua University

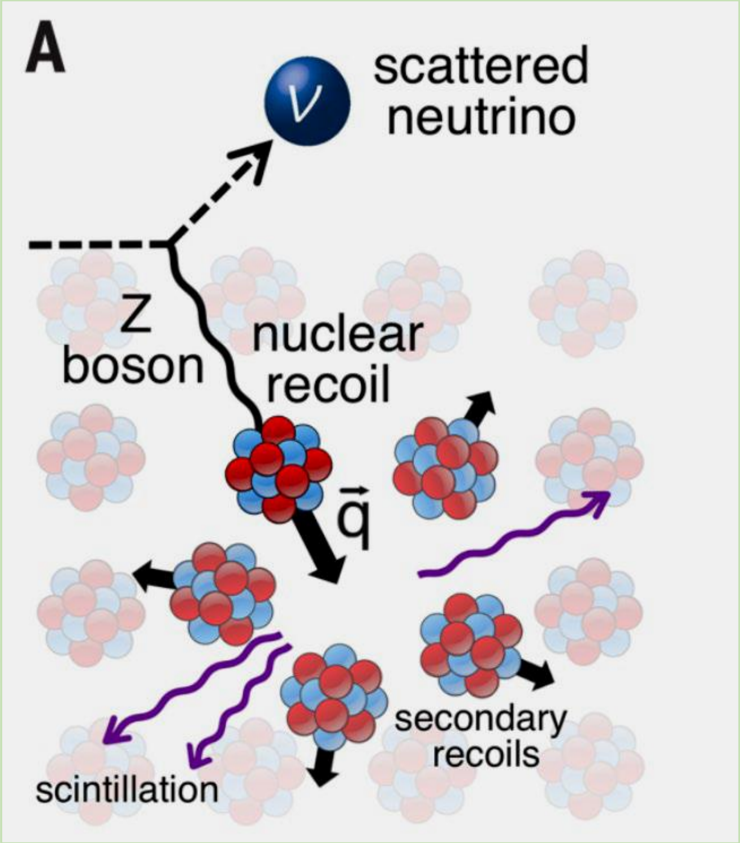
Projected Backgrounds in the RELICS Experiment

Kaihang Li Tsinghua University
On behalf of the RELICS Collaboration
likh23@mails.tsinghua.edu.cn

VIEWS24, Vienna, Austria
Apr 25–27, 2024

The RELICS Experiment

REactor neutrino LIquid xenon Coherent Scattering experiment



$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2)^2.$$

$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

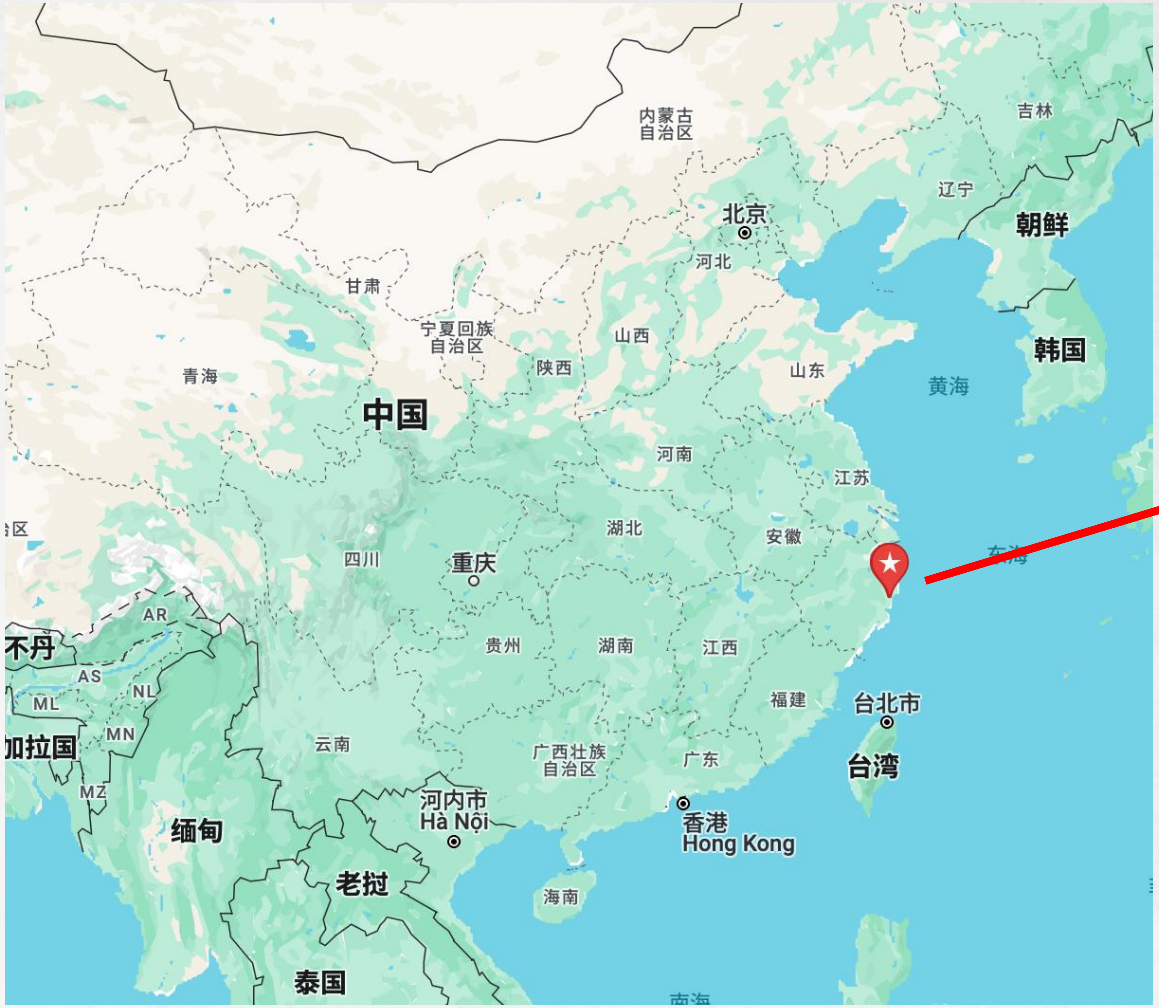
$$Q_W \propto N \implies \boxed{\frac{d\sigma}{dT} \propto N^2}$$

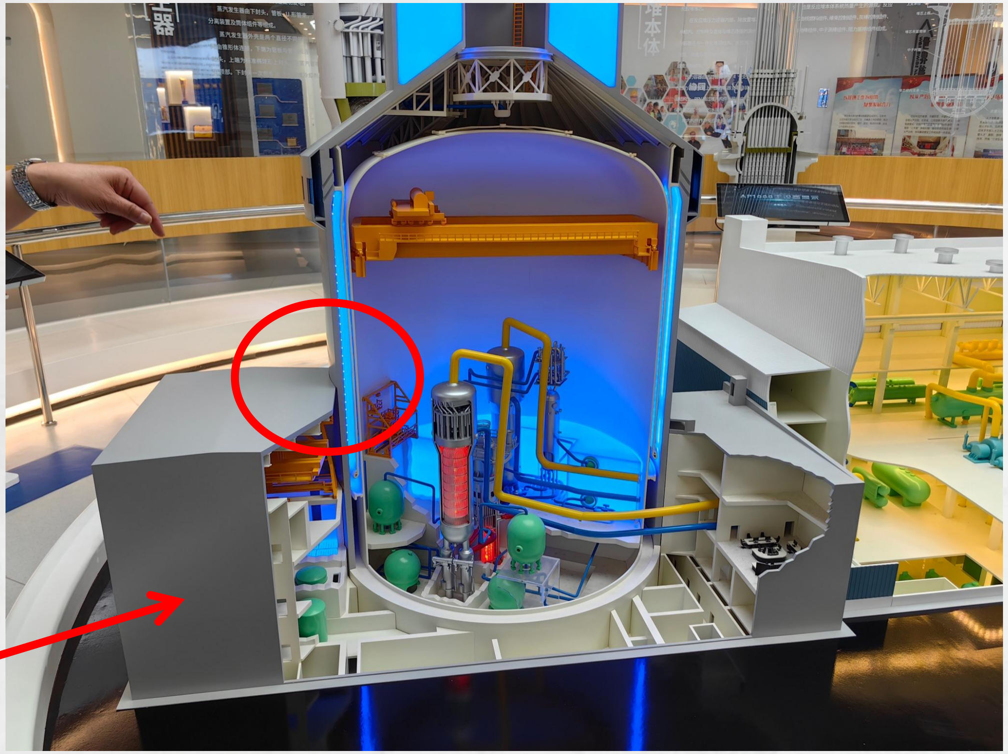
Z-exchange of a neutrino with nucleus:

- Z_boson wavelength larger than size of nucleus
- nucleus recoils as whole
- coherent up to $E_\nu \sim 50\text{MeV}$
- The reaction cross section $\sigma \sim N^2$

arXiv:1708.01294

The RELICS Experiment





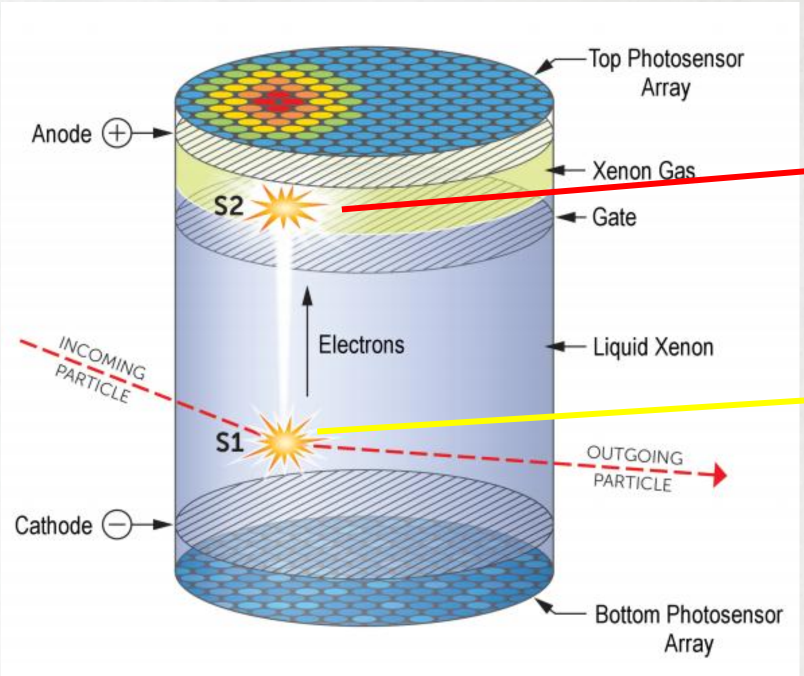
Reactor parameters

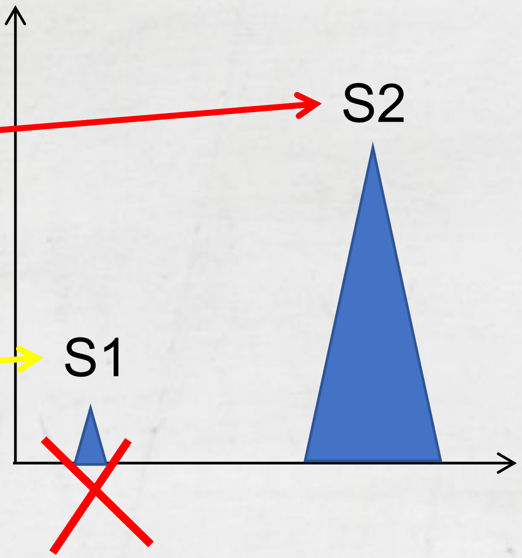
- Power ~ 3GW
- Distance to Core ~ 25m
- Expected ν flux ~ $10^{13}\nu/cm^2/s$

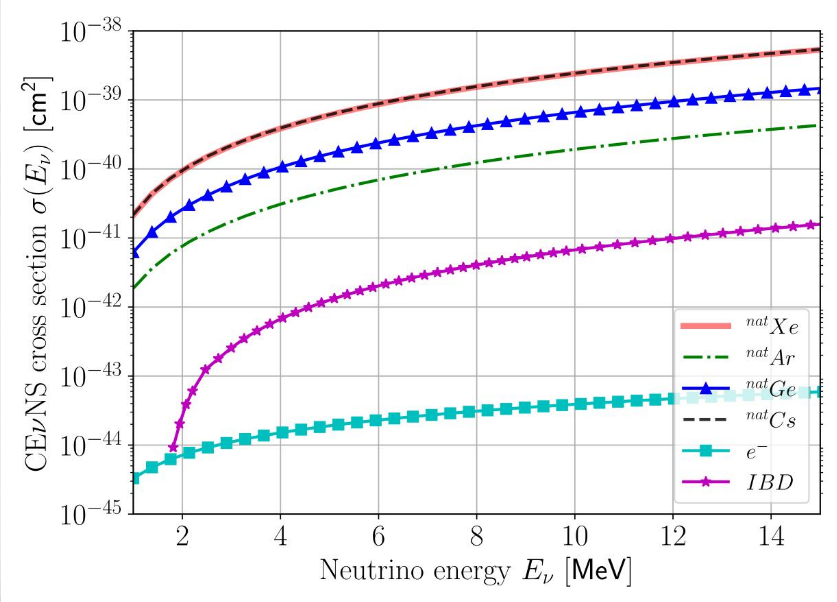
Credit: Google Map

Principle of detection

Liquid xenon Time Projection Chamber (LXeTPC)







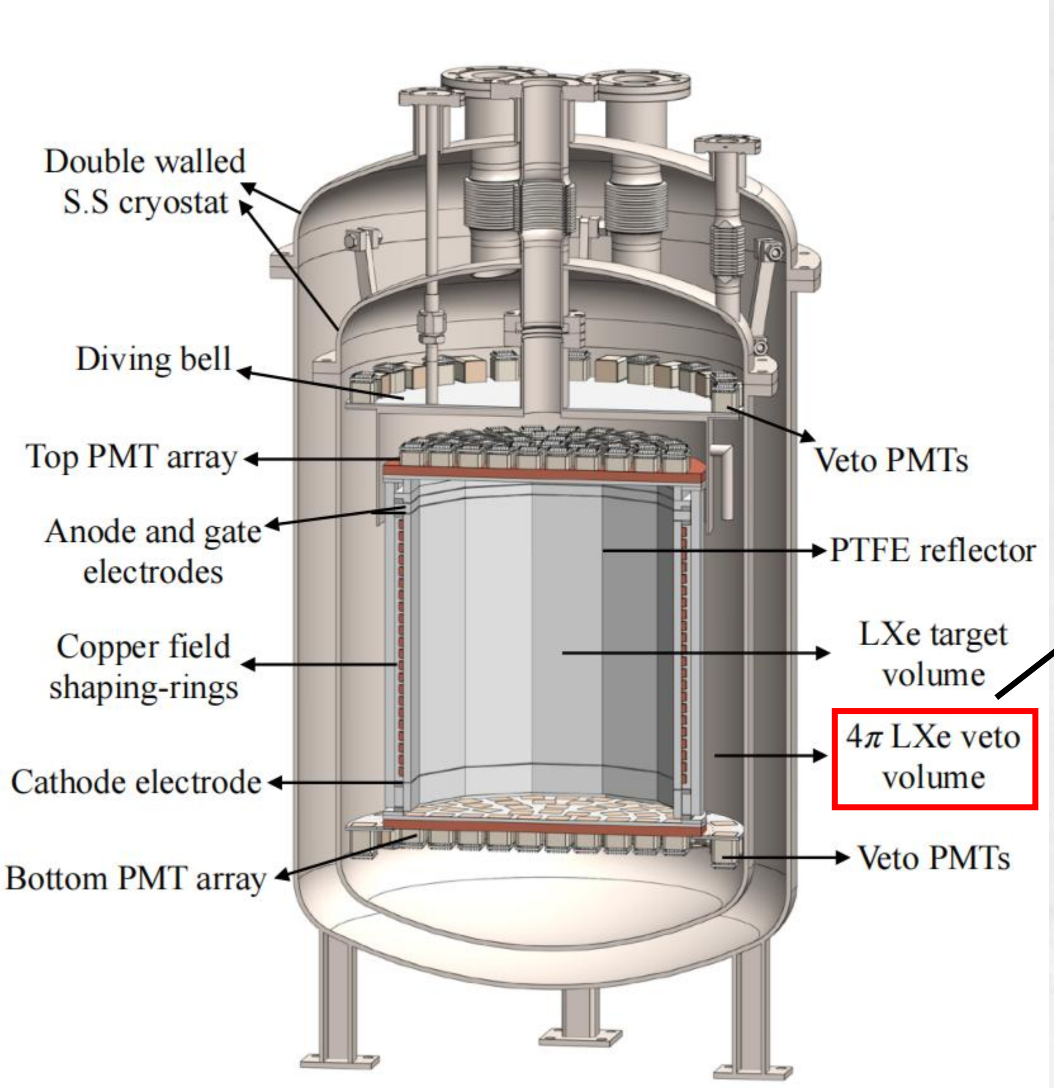
For reactor neutrino, Energy ~ MeV

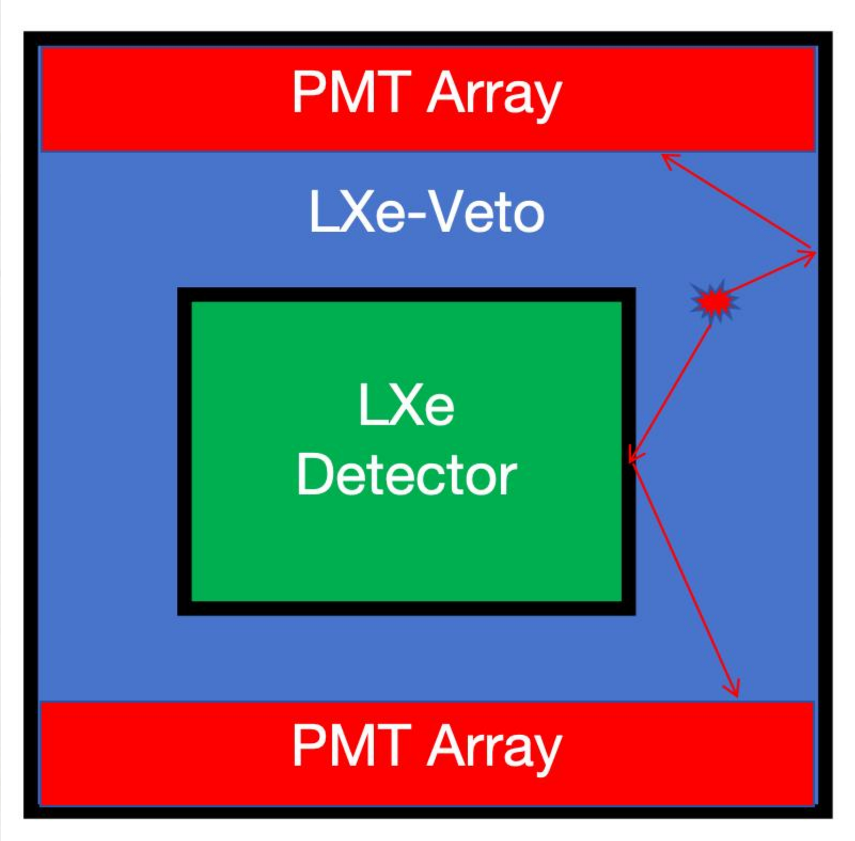
- Recoil Energy $\sim 0.3 - 1\mathrm{keV}$
- S1 single too small to observe
- S2-only analysis

- High reaction cross section
- Low threshold
- Low background
- Signal screening function
- Location reconstruction

Credit: PandaX Collaboration

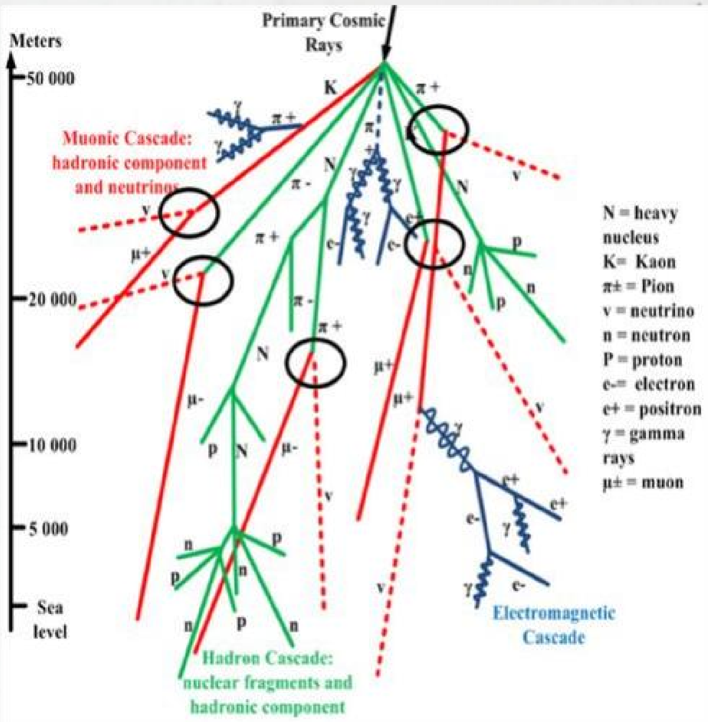
Detector Design





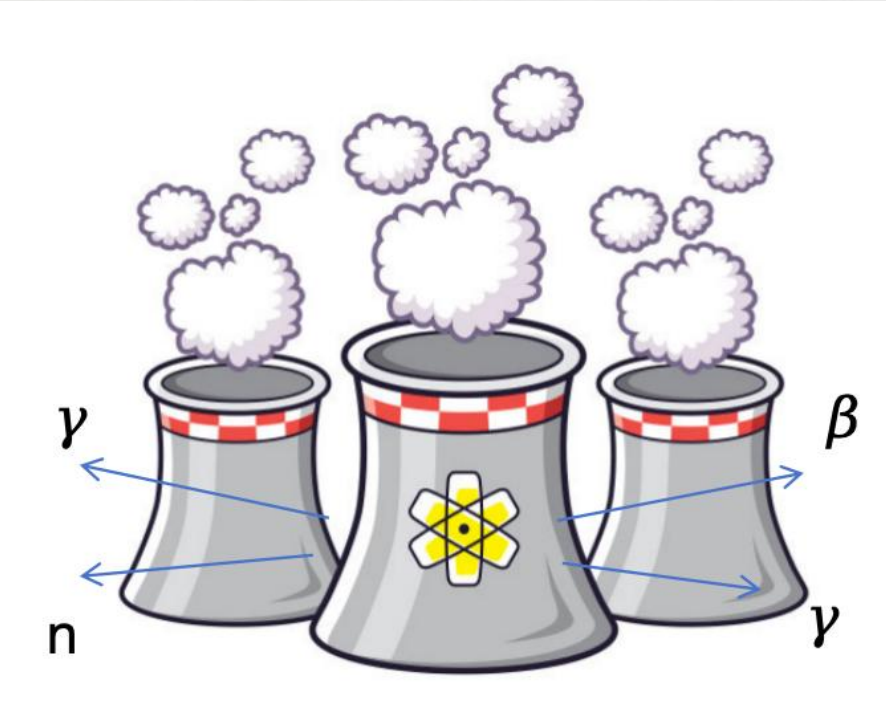
- All particles need to go through the veto to reach the detector.
- Black part: Teflon can reflect photons.

Background



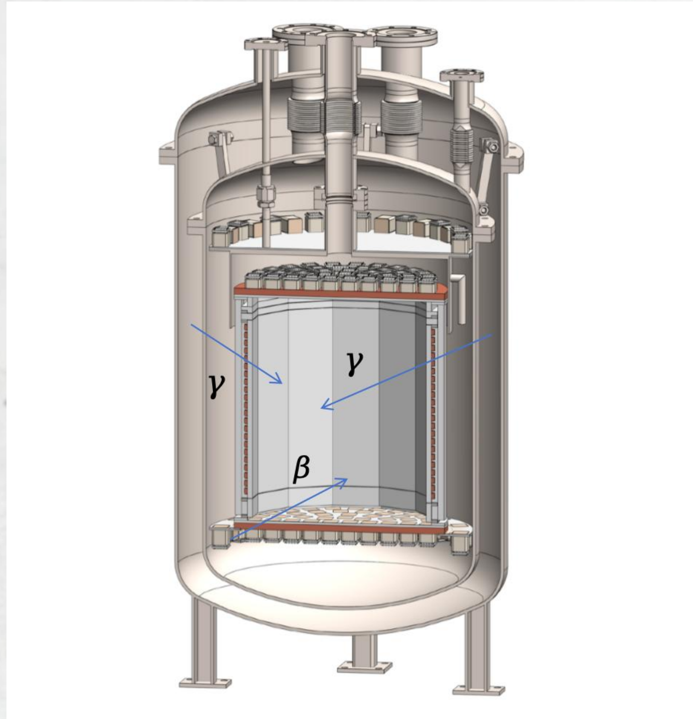
Cosmic ray

- Cosmic muon
- Cosmic ray neutron
- Cosmic ray proton
- ...



Reactor

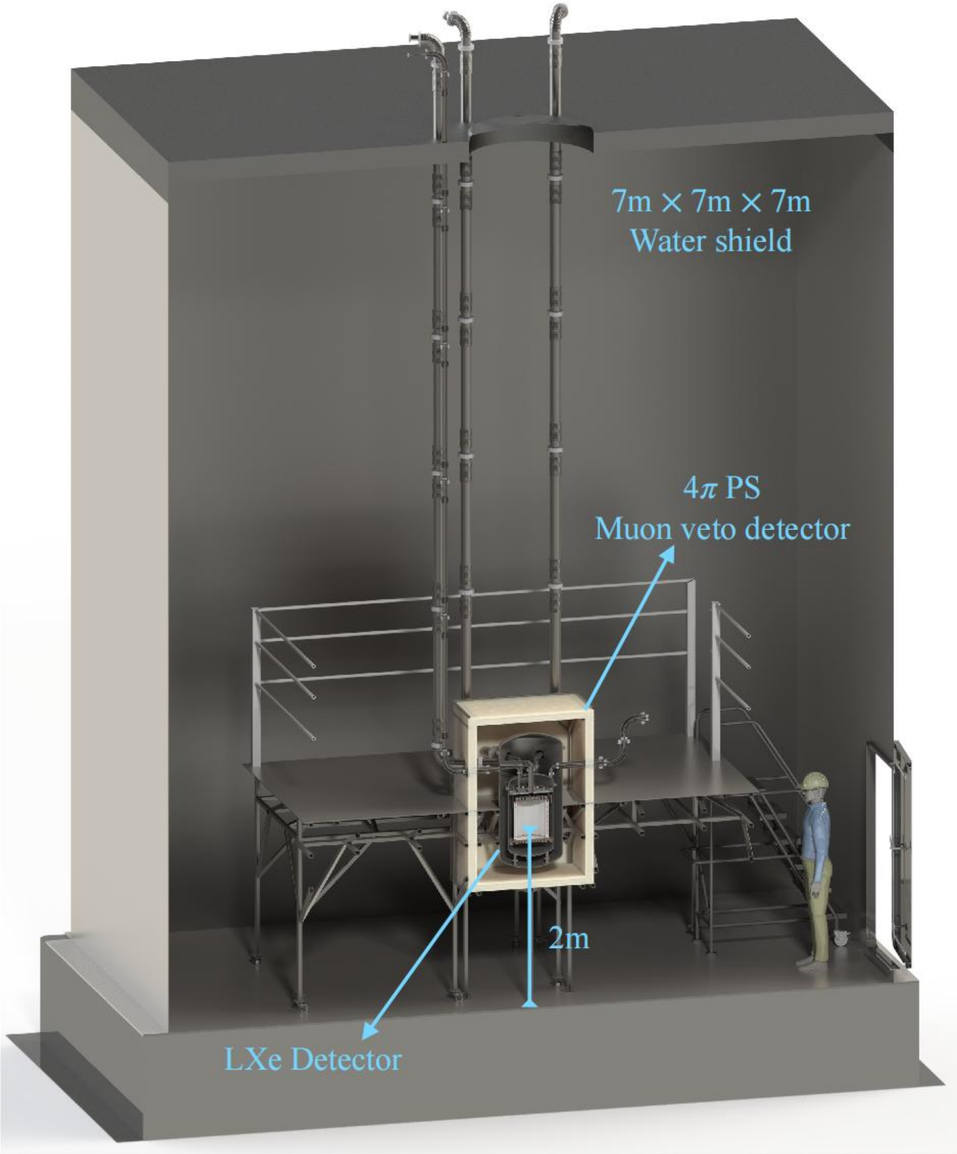
- Neutron
- Gamma
- ...



Detector itself

- Steel
- PMT
- Material...
- LXe

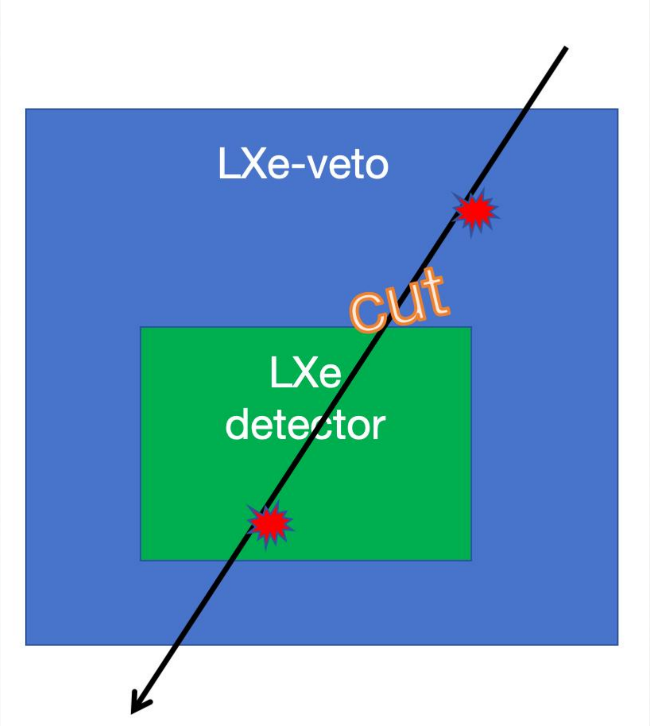
Shield overview



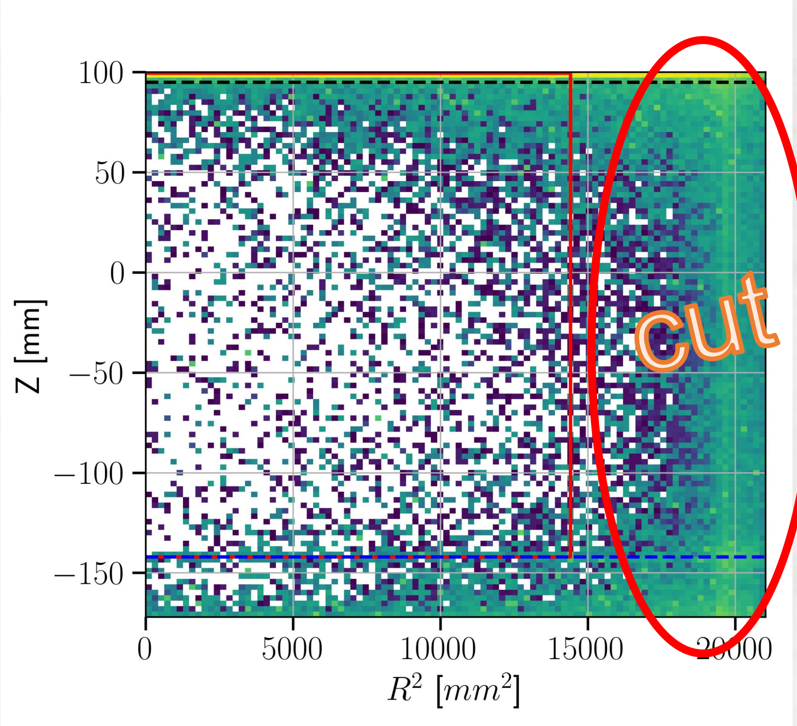
- Water shield. Length, width and height 7 meters.
- Considered the source of background at the bottom.The detector is located 1.5 meters below the center.
- 4π PS Muon veto detector.Assuming 99% muon veto efficiency.
- The detector materials were screened and required to have low radioactivity.

Event Selection

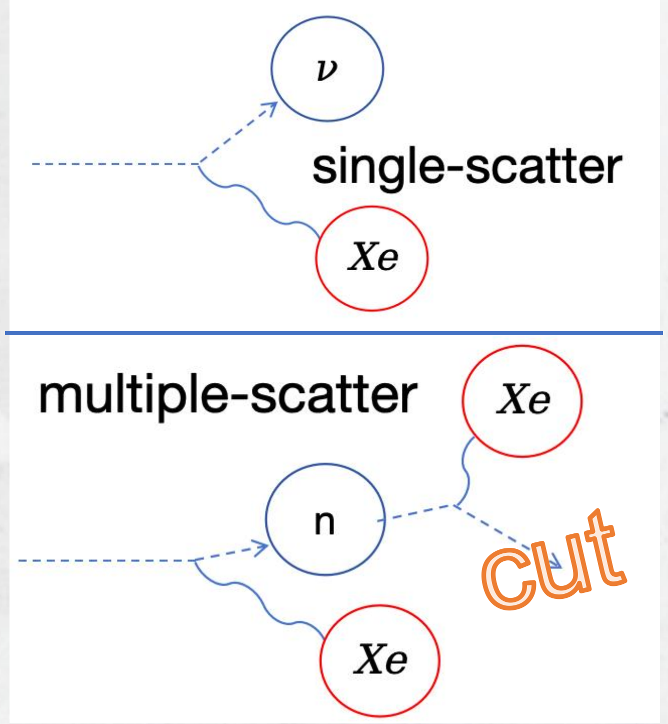
The event selection will be applied on all background



I. LXe-veto: Remove events that deposit energy in both LXe detector and LXe veto.



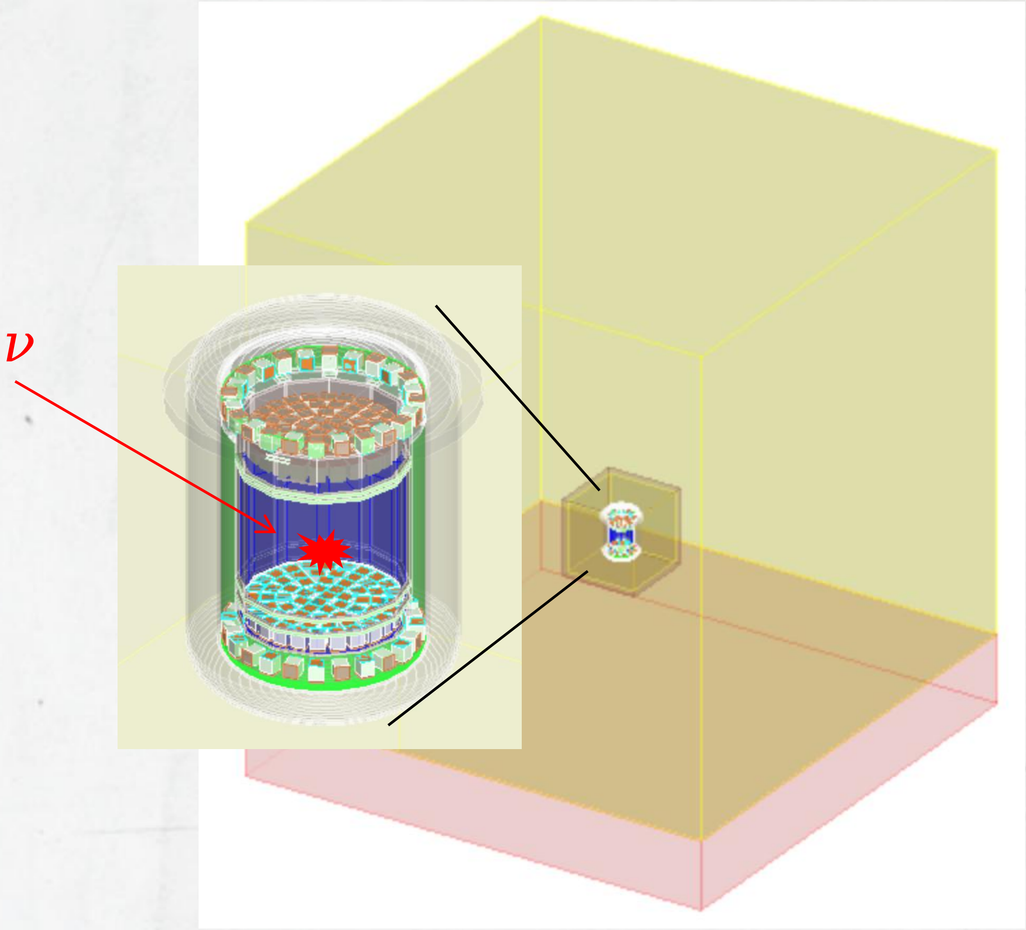
II. Fiducial Volume: A cylinder with a height of 24.2cm and a radius of 12cm.



III. Single-scatter: Remove events that scatter multiple times in sensitive LXe.

Simulation Framework

Geant4,BambooMC,RelicsSim,Relicsapt,Gitlab,Wiki

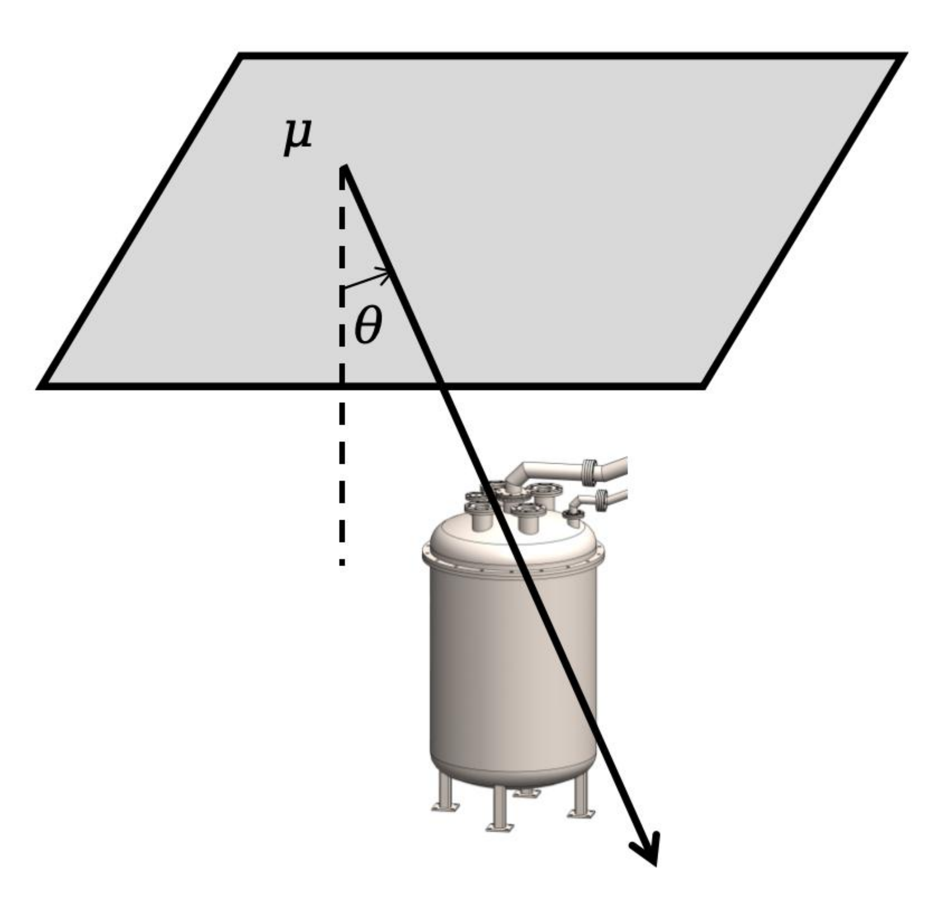


physics list

- EM Physics --- G4EmLivermorePhysics
- Decays --- G4DecayPhysics
  G4RadioactiveDecayPhysics
- hadron physics --- G4HadronElasticPhysicsHP
- shielding --- G4HadronPhysicsShielding
- stopping physics ---- G4StoppingPhysics
- ion physics----- G4IonQMDPhysics

Cosmic muon

The energy and angular distributions of muons follow the Shukla model



- Energy is related to angle
- Muon generator
  - Emission plane: 5m*5m
  - Muon energy range: 0.5 - 1000GeV
  - Muon type: μ^{+} and μ^{-}
  - ….

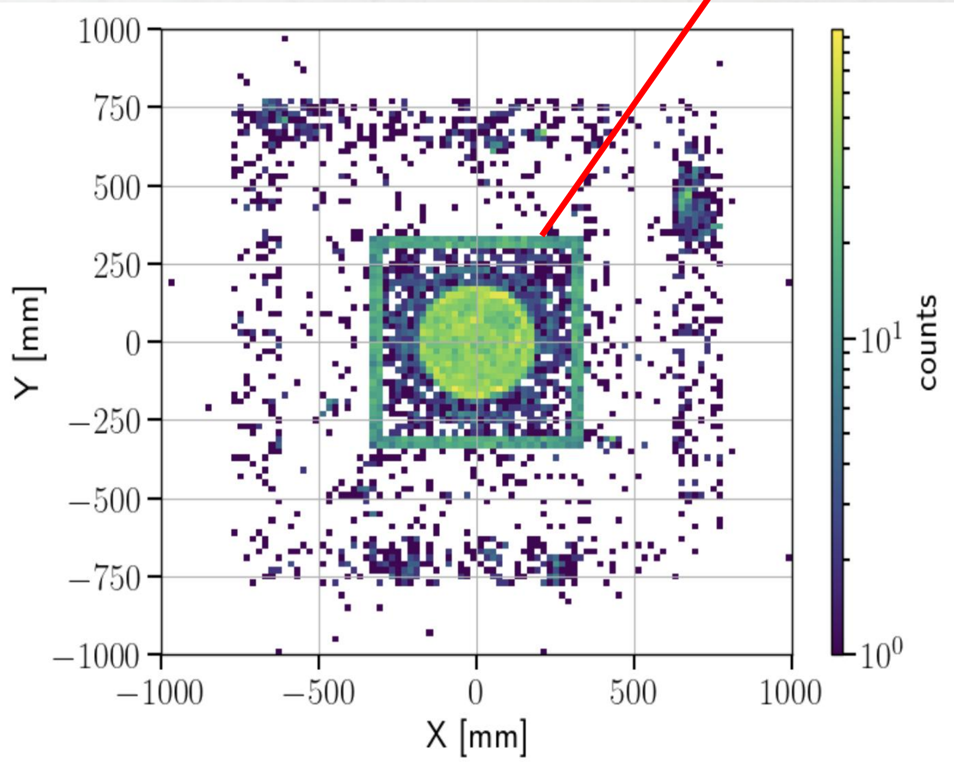
- Too much computational pressure
- Filter energy deposition message
  - Message in LXe-veto and LXe detector
  - Nuclear recoil(NR) and Electronic recoil(ER)

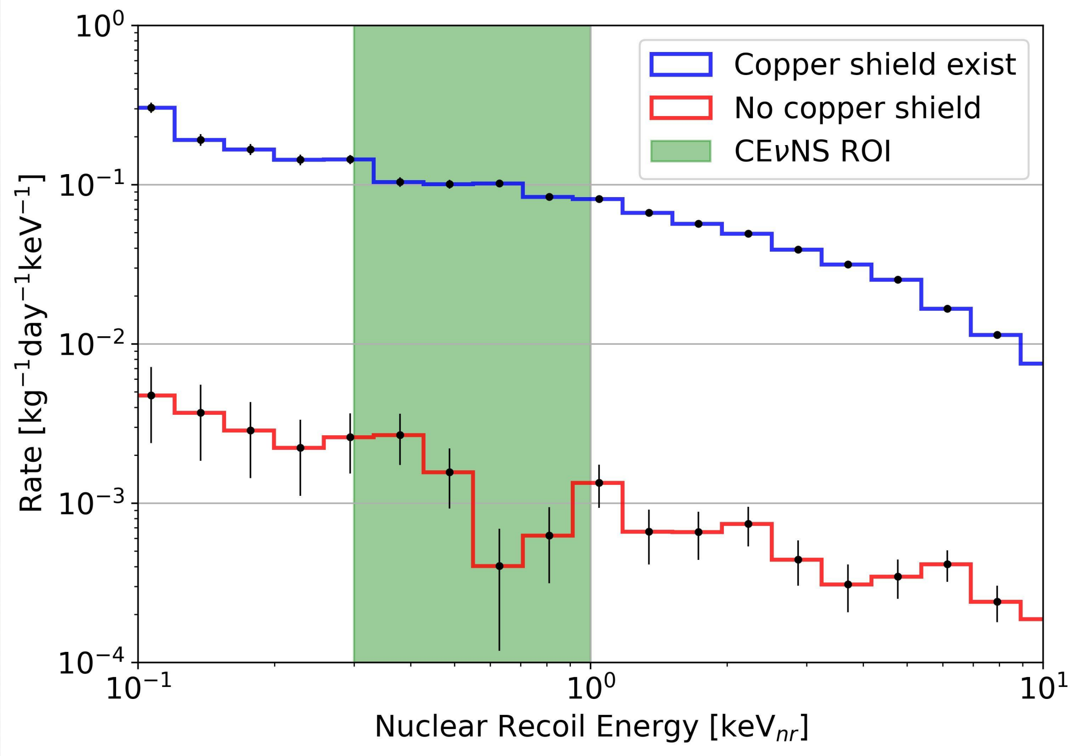
Cosmic muon

Cosmic muon makes it easier to knock neutrons out of heavy nucleus

Primary shield,we set copper shield.

Copper position





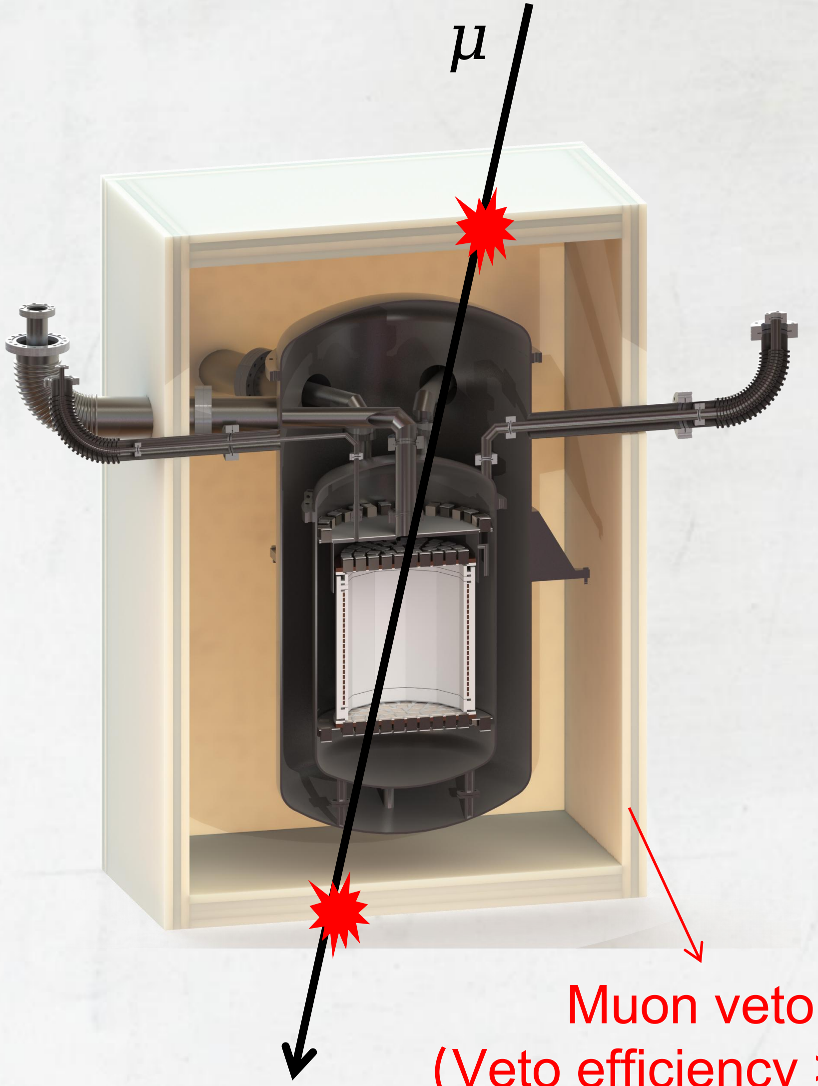
Remove copper shield:

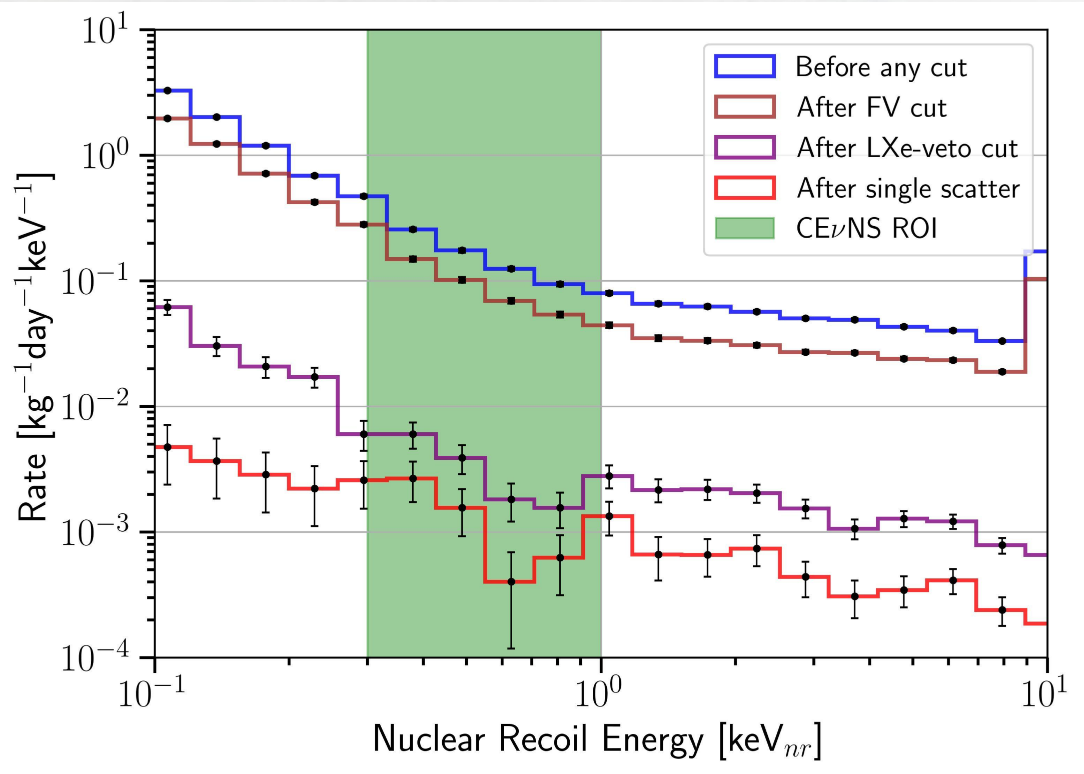
- Reduce background
- Event rate:$(0.08\pm0.01)\times10^{-2}\cdot kg^{-1}\cdot day^{-1}$ in 0.3-1keV

CEvNS event :$110\times10^{-2}\cdot kg^{-1}\cdot day^{-1}$

Cosmic muon

Assuming 99% muon veto efficiency with PS muon veto detector

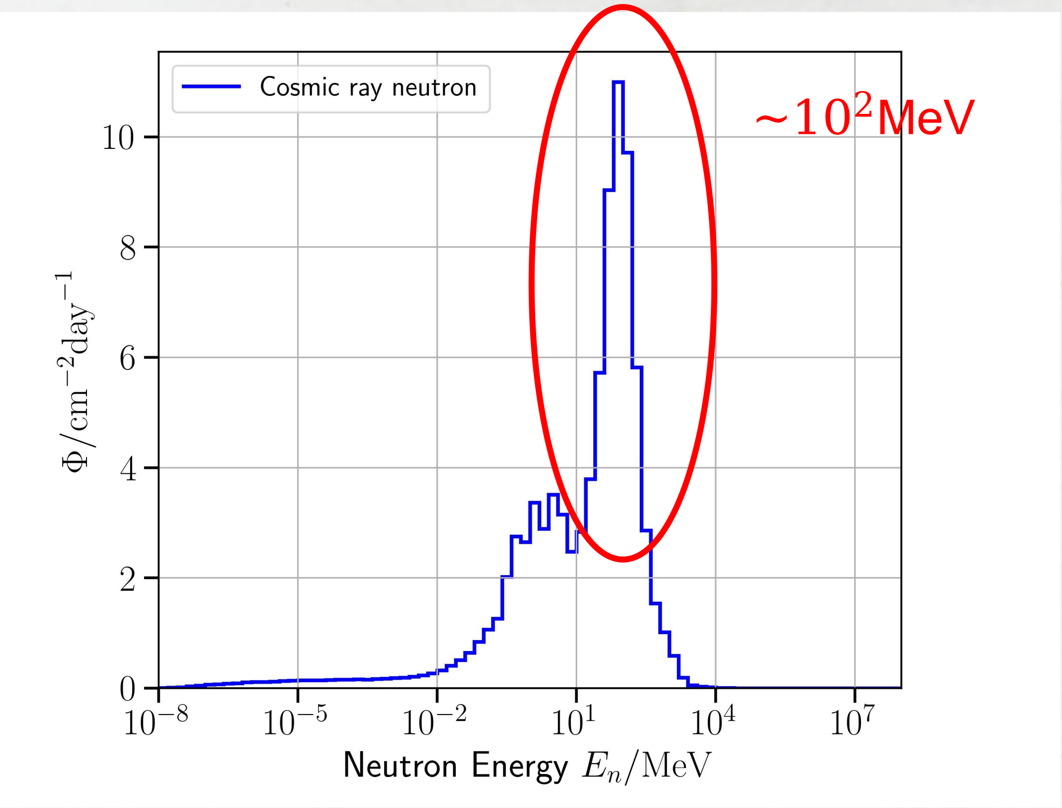




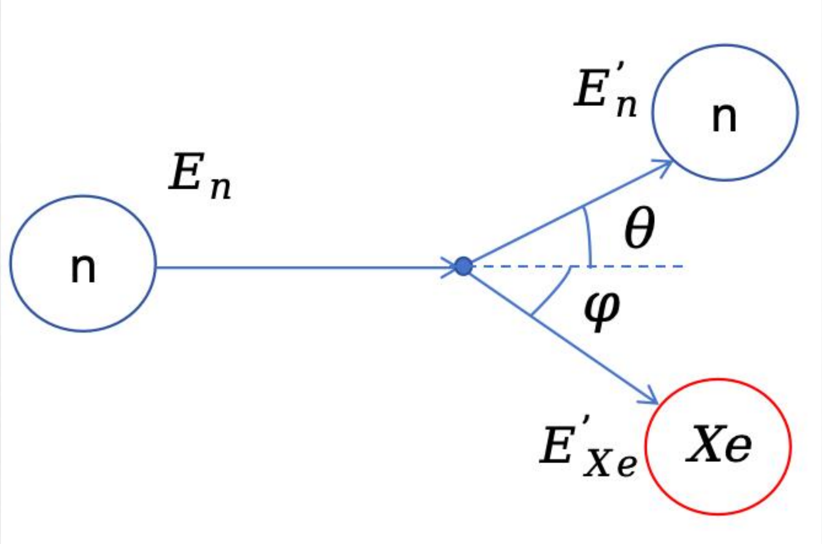
- Taking into account the Muon veto effect
- LXe-veto cut works very well

Cosmic ray neutrons

The energy and angular distributions of cosmic neutorn comes from the Cosmic-Ray Shower Generator (CRY)



Total rate: $85.91 \cdot cm^{-2} \cdot day^{-1}$



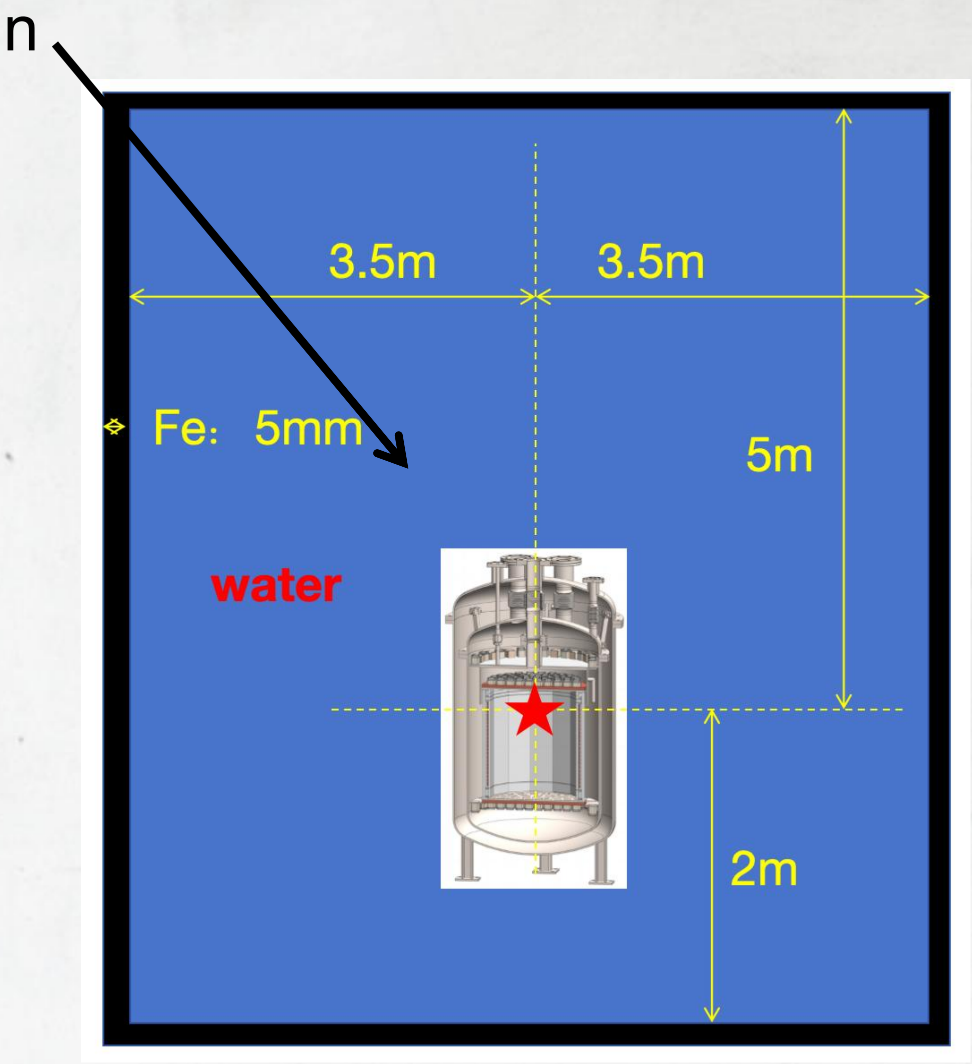
$$E'_{Xe} = \mathrm{E_n}\frac{4m_n M}{(m_n + M)^2}cos^2\varphi$$

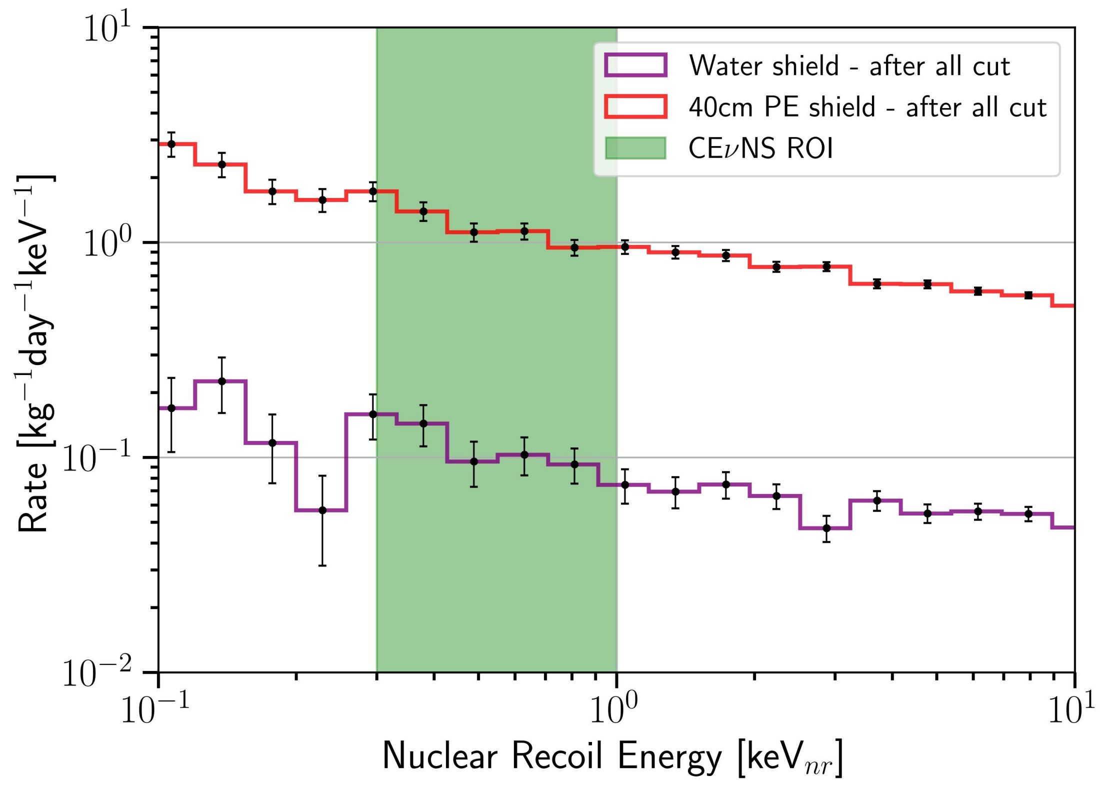
$$\approx 0.03\mathrm{E_n}cos^2\varphi$$

- Neutron's energy greater than 30keV can deposit NR energy similar to CEvNS events.
- Need to design shield for cosmic ray neutron.

Cosmic ray neutrons

Add water shield to shield cosmic ray neutrons

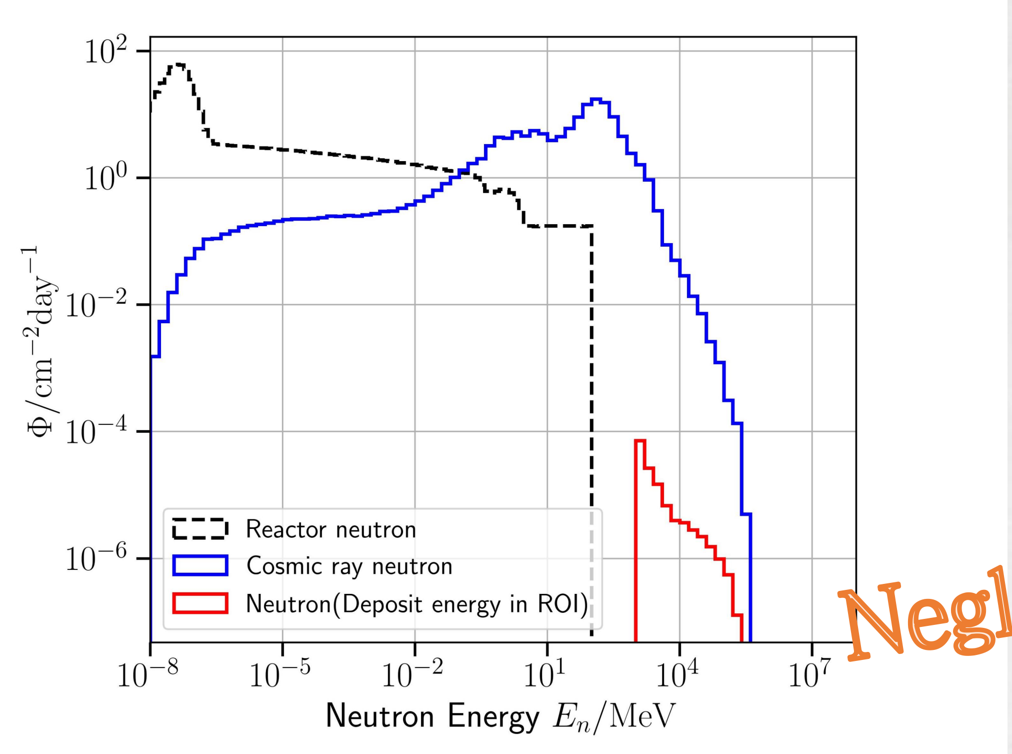




- Water shield has better shielding effect;
- NR background caused by cosmic ray neutron has reached a level we can accept;

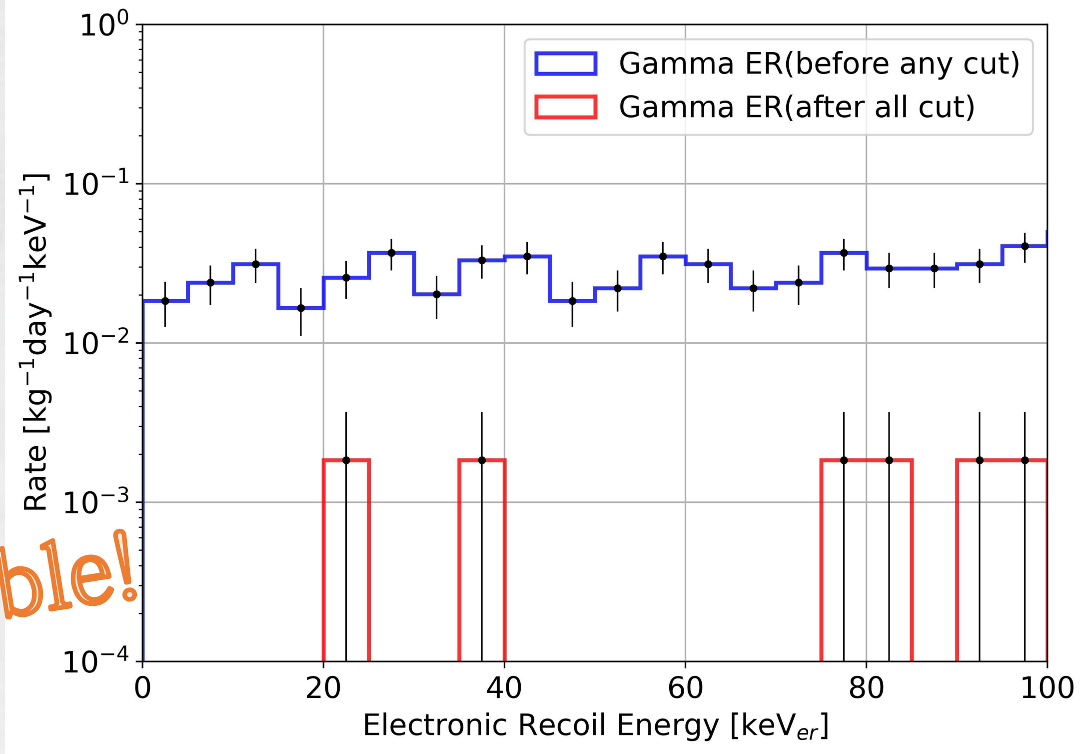
Neutrons and gamma from reactor

Neutron NR



Negligible!

Gamma ER

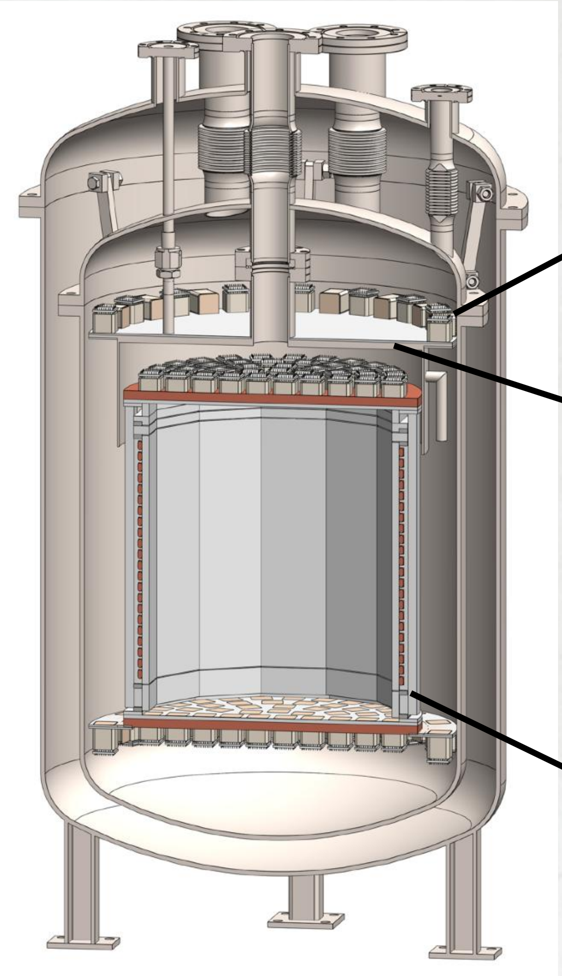


- Black: Energy spectrum of reactor neutron;
- Blue: Energy spectrum of cosmic neutron;
- Red: Cosmic neutron that deposits energy;

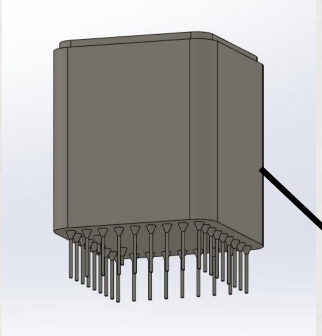
$(0.5\pm0.2)\times10^{-3}\cdot\mathrm{keV}^{-1}\cdot\mathrm{kg}^{-1}\cdot\mathrm{day}^{-1}$

$[0,100]\mathrm{keV}_{ER}$

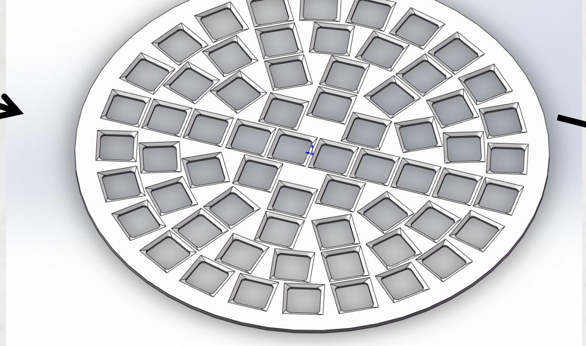
Detector materials



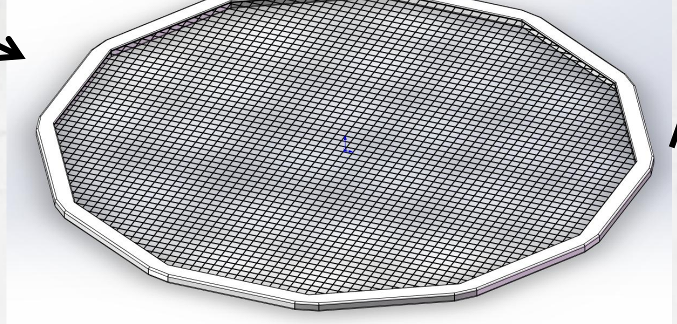
PMT



Teflon

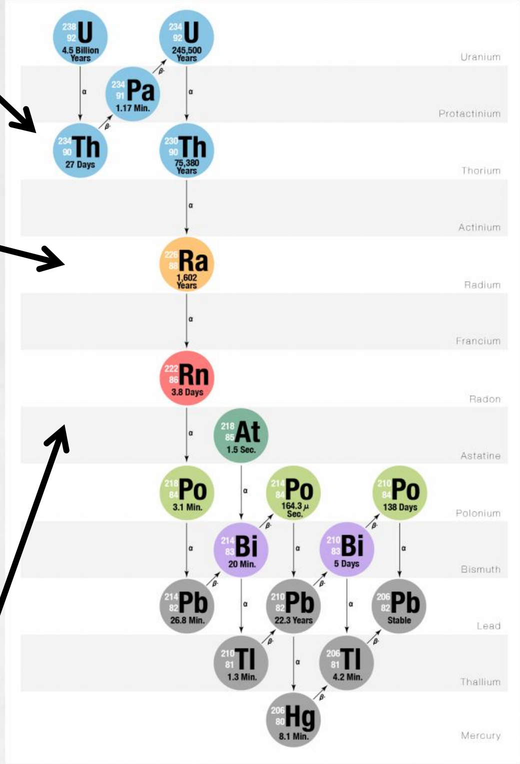


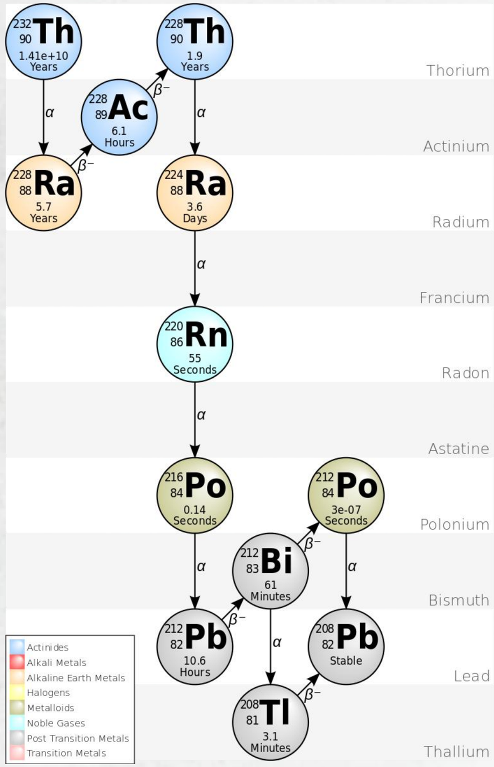
electrode



Nuclide	Copper	S.S	Teflon	PMT window	PMT base
^{238}U	0.08	1.8	0.059	0.14	0.16
^{232}Th	0.01	1.9	0.1	0.17	0.07
^{60}Co	0.04	5.4	0.03	0.62	0.01
^{40}K	0.03	9	0.75	11.1	0.16
^{137}Cs	0	0	0	0.79	0

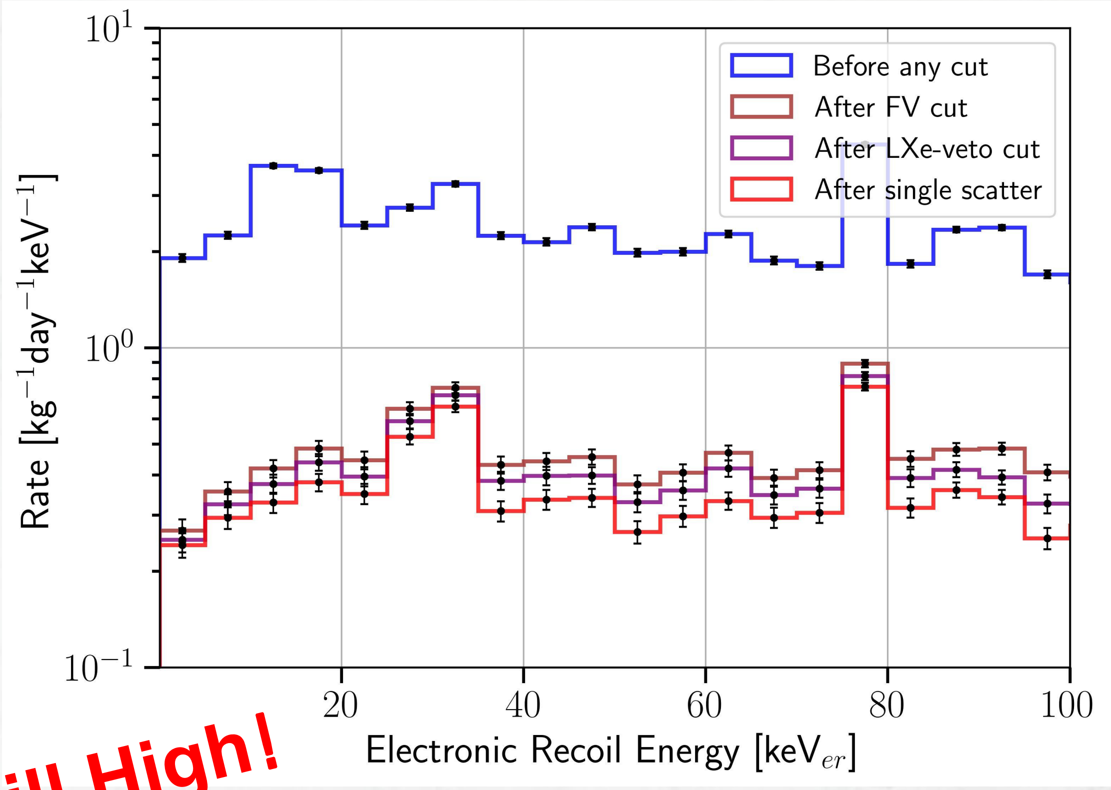
XENON100 Reference Values





Detector materials

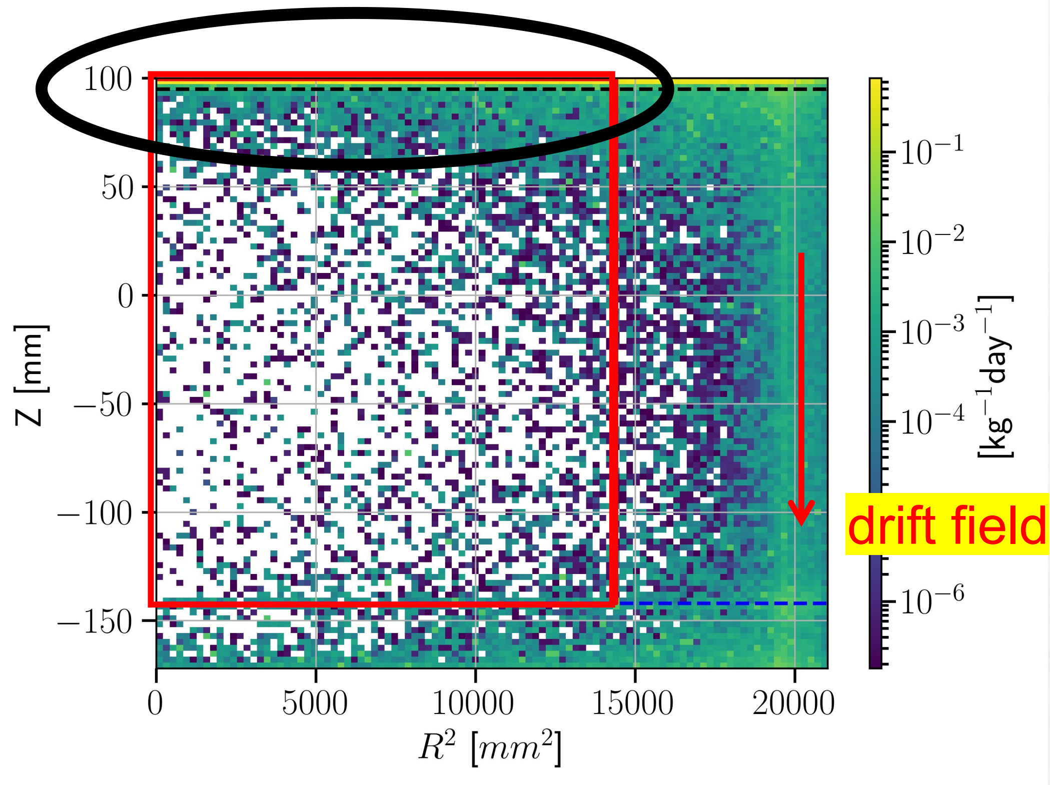
FV cut works very well



Still High!

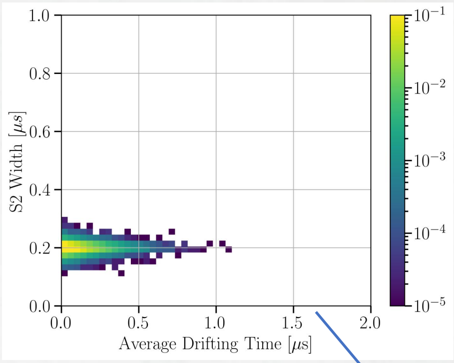
(364 ± 5)×10^{-3}·keV^{-1}·kg^{-1}·day^{-1}

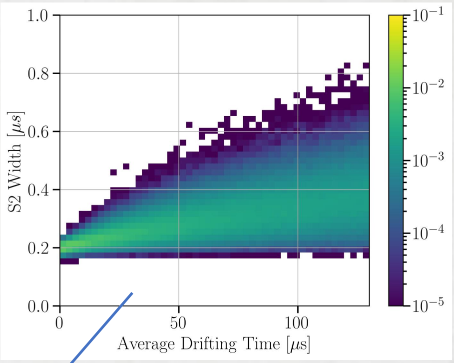
[0,100]keV_{ER}



- Event locations are concentrated at the top
- Different drift times will have different S2 widths

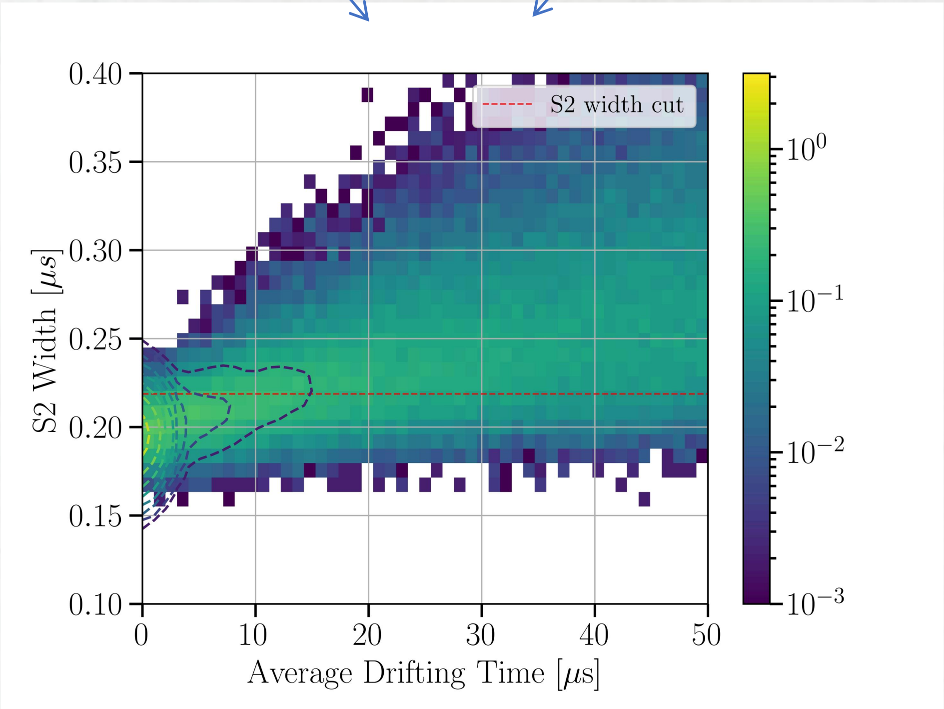
S2 width selection

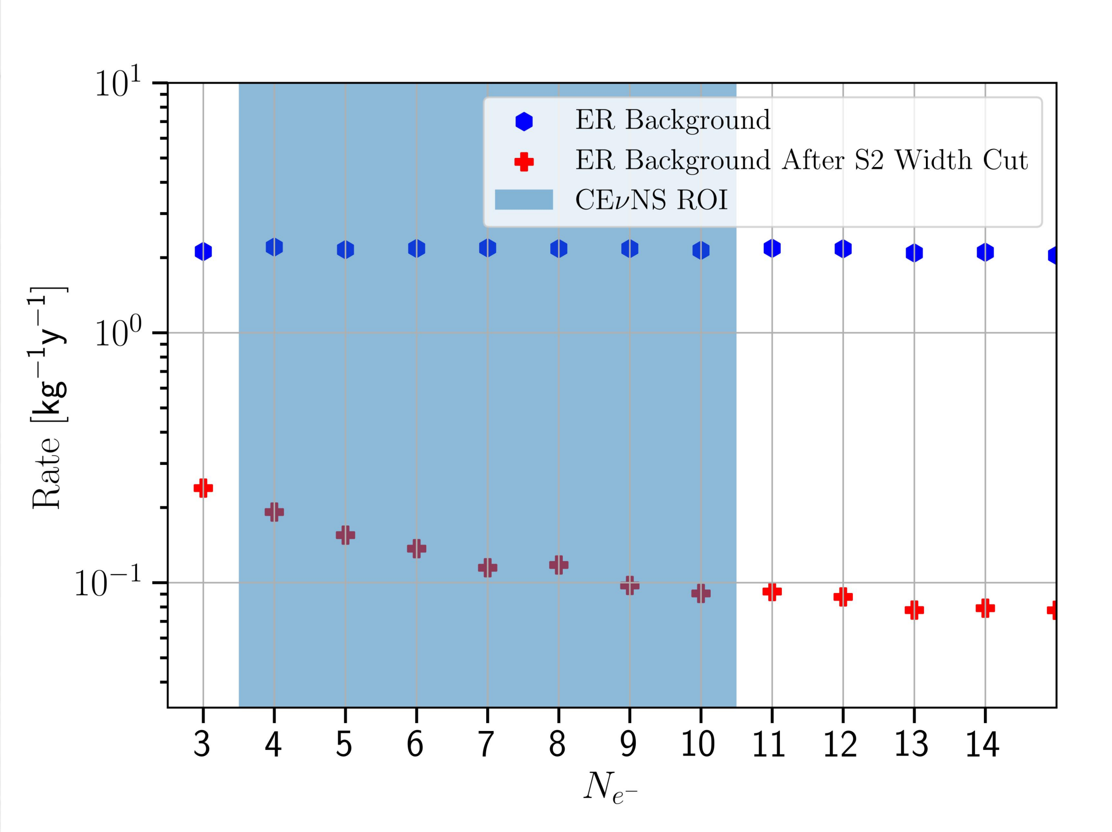




ER background

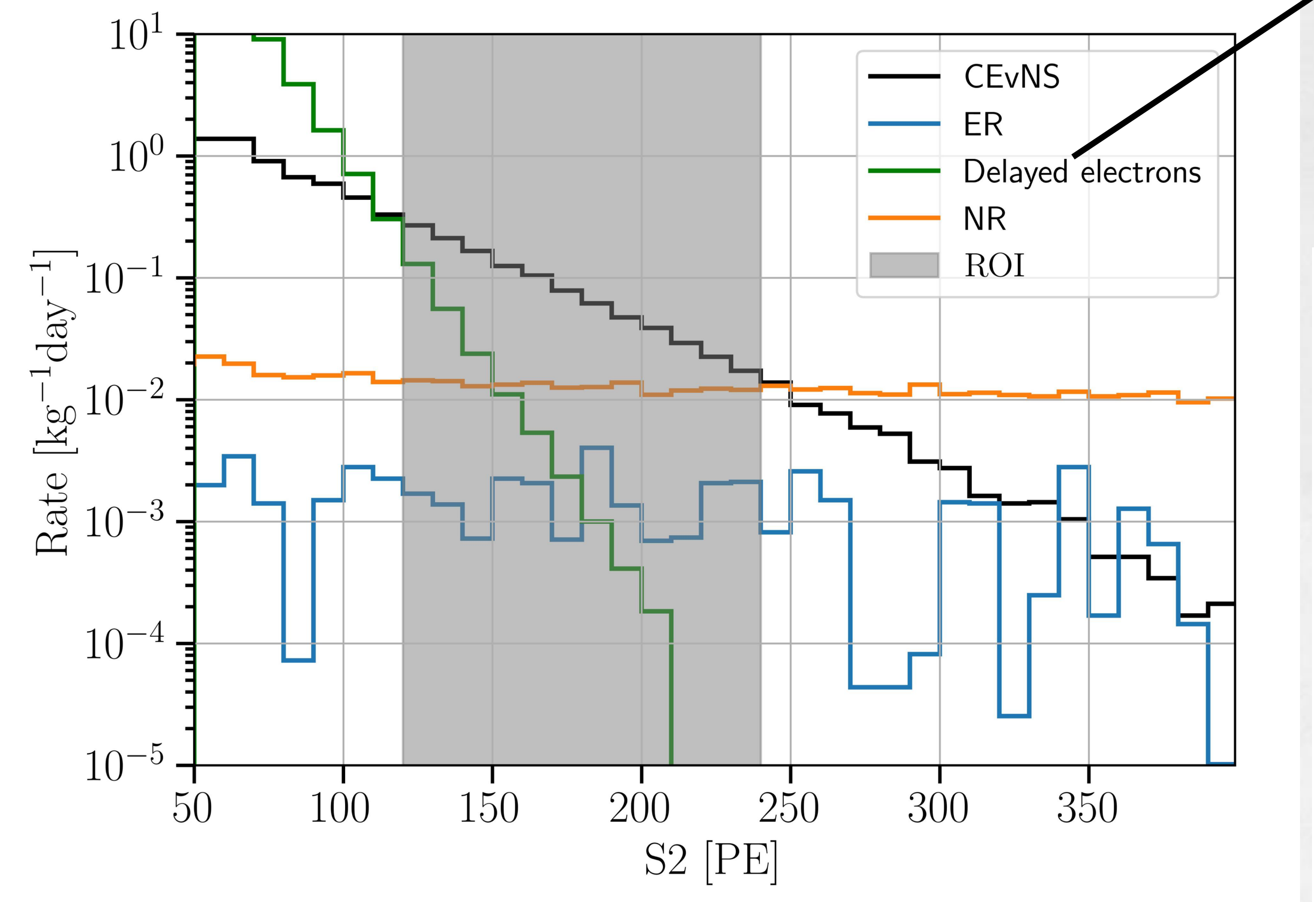
CEvNS

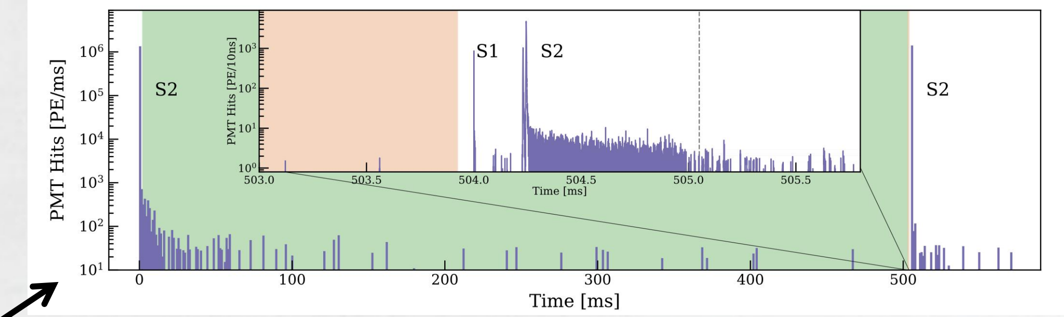




- Drifting time threshold of 0.22us
- Background rejection power: ~96%
- CEvNS signal acceptance: >80%

Total background





Credit: the XENON Collaboration

CEvNS ROI: [120, 240] PE

	Events / (32kg・year)
CEvNS	12874.8
NR	1862
ER	215.2
Delay electrons	1154

Summary

- Background simulation of RELICS Experiment.
  - RelicsSim framework.
  - Cosmic ray neutron is the dominant NR background.
  - Detector material is the dominant ER background.
  - Single-to-background ratio of 4:1 in CEvNS ROI.
- Shield and events cut method are designed to suppress background.
  - Water shield with length, width and height of 7 meters.
  - Muon veto with 99% veto efficiency.
  - Low-background detector material and S2-width selection.

The RELICS Collaboration

香 港 中 文 大 學（深 圳）
The Chinese University of Hong Kong, Shenzhen

西湖大學
WESTLAKE UNIVERSITY

Thanks

Kaihang Li   Tsinghua University
likh23@mails.tsinghua.edu.cn

Reactor neutrino

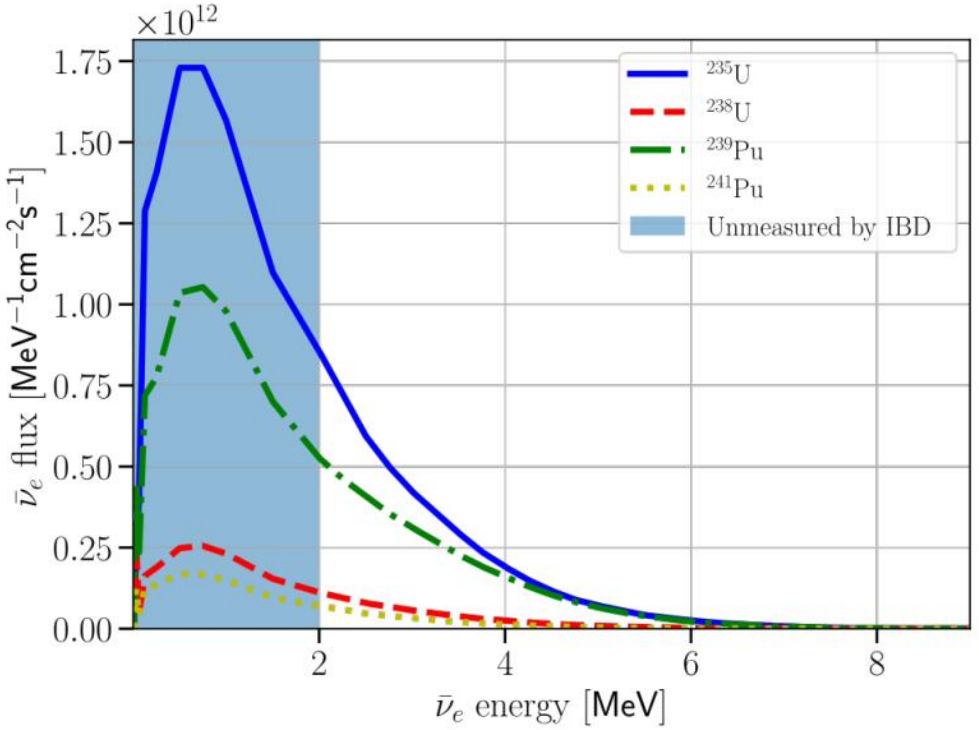


Figure 6. The $\overline{\nu}_e$ energy spectra of ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu with a 3 GW reactor core at 25 m distance.

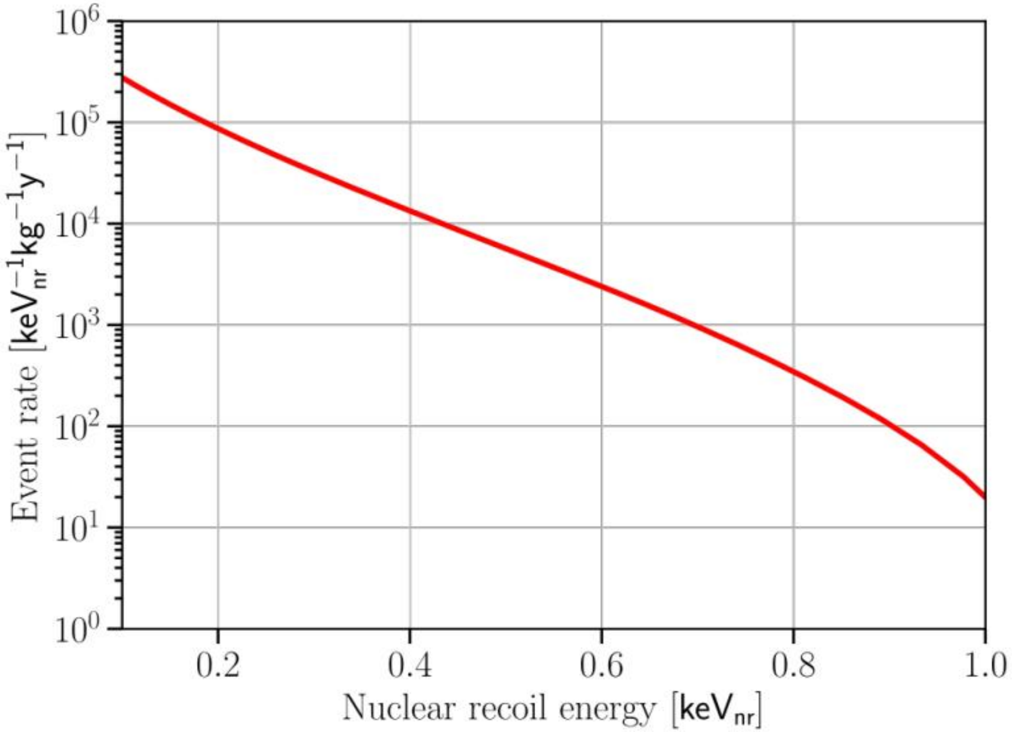
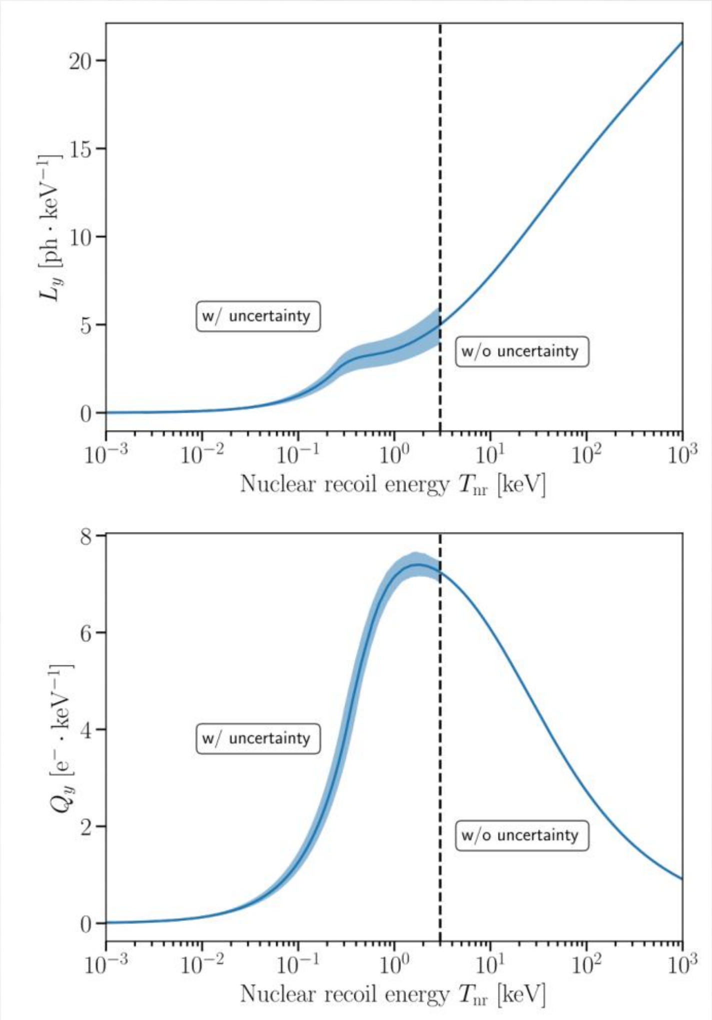
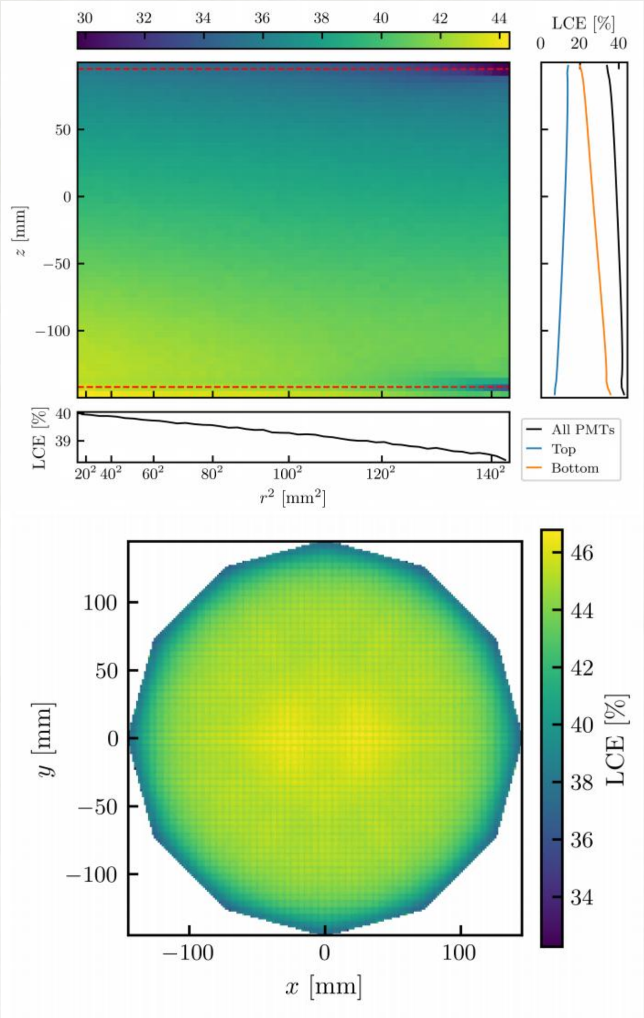


Figure 7. The expected CEνNS event rate in xenon medium from reactor neutrino with a flux of 10^{13}cm^{-2}s^{-1}.

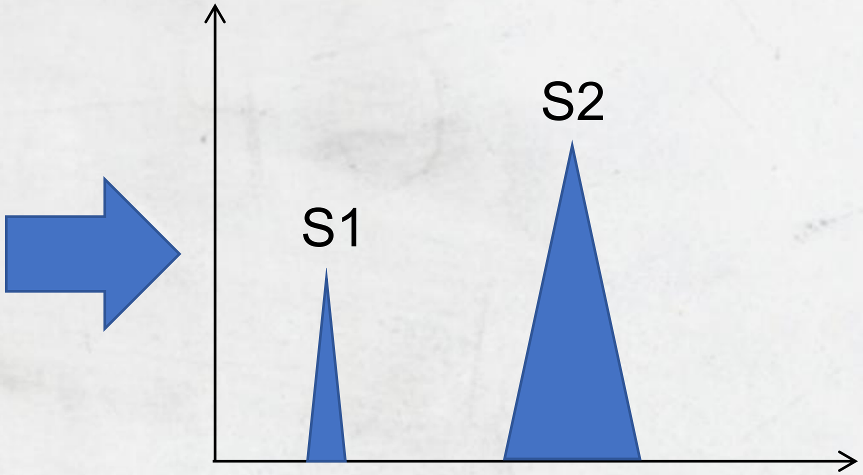
Simulation Framework（Appletree,RelicsAPT）



LXe response



light collection efficiency (LCE)



Observable S1, S2 signals

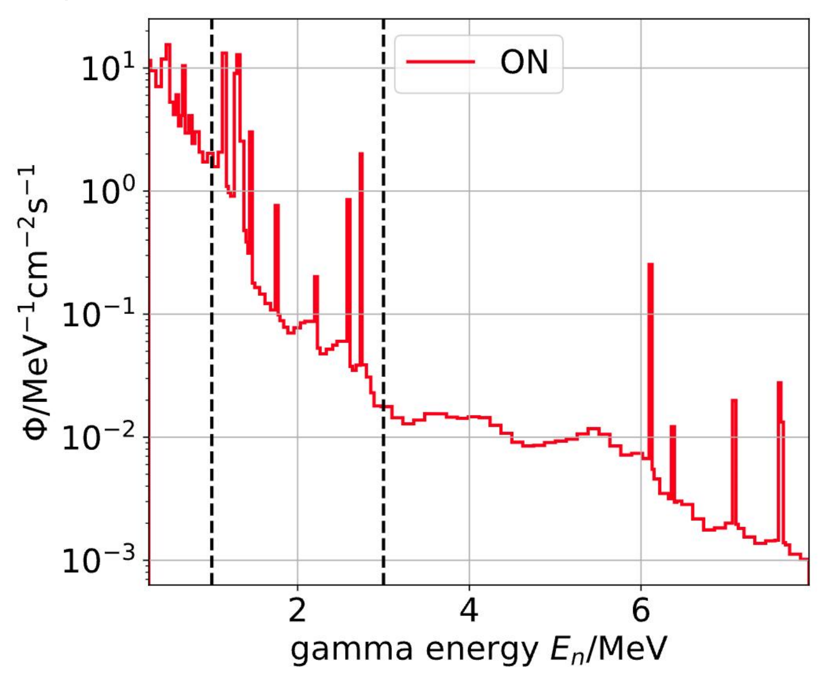
Simulation Framework（Appletree,RelicsAPT）

Table 1. The detector related parameters.

Optical parameters		
PTFE reflectivity (LXe & GXe)	99%	(Aprile et al. 2020)
LXe Rayleigh scattering length	30 cm	(Aprile et al. 2020)
LXe absorption length	10 m	50 m in (Aprile et al. 2020)
Signal generation		
PMT quantum efficiency (ϵ_{QE})	30%	3% in (Aprile et al. 2020)
PMT collection efficiency (ϵ_{CE})	70%	90% in (Aprile et al. 2020)
Double PE probability (p_{DPE})	20%	21.9% in (Aprile et al. 2020)
g_1	0.099 PE/ph	()
g_2	30 PE/e$^-$	()
Detector operation		
Drift field	500 V/cm	
Electron lifetime	12 *ms*	(Plante et al. 2022)

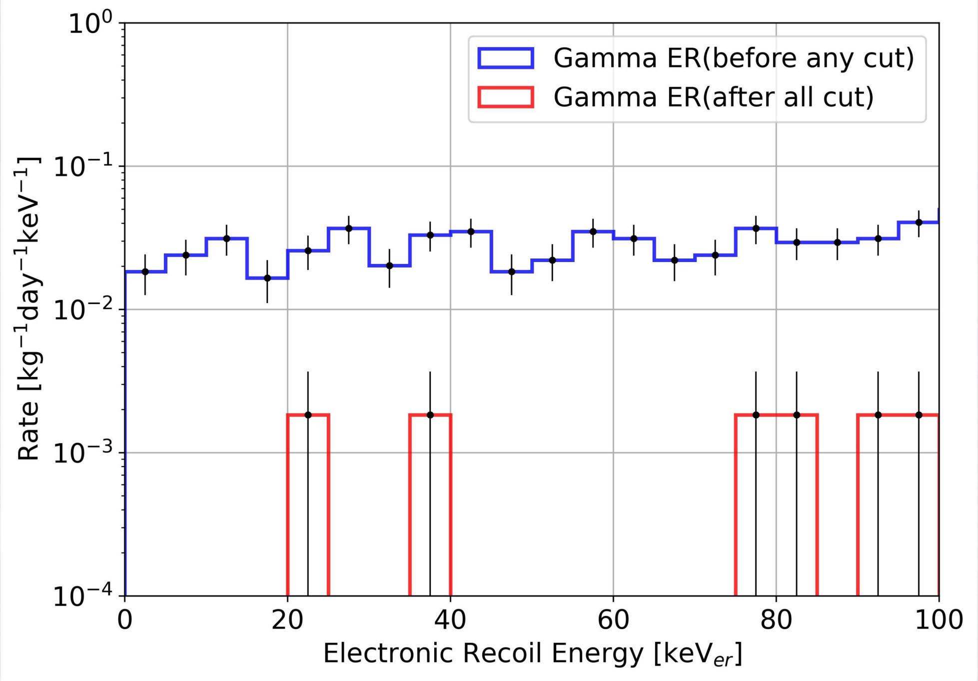
Gamma from reactor and environment

Energy Spectrum



Total rate: 18.45·cm^{-2}·s^{-1}

ER



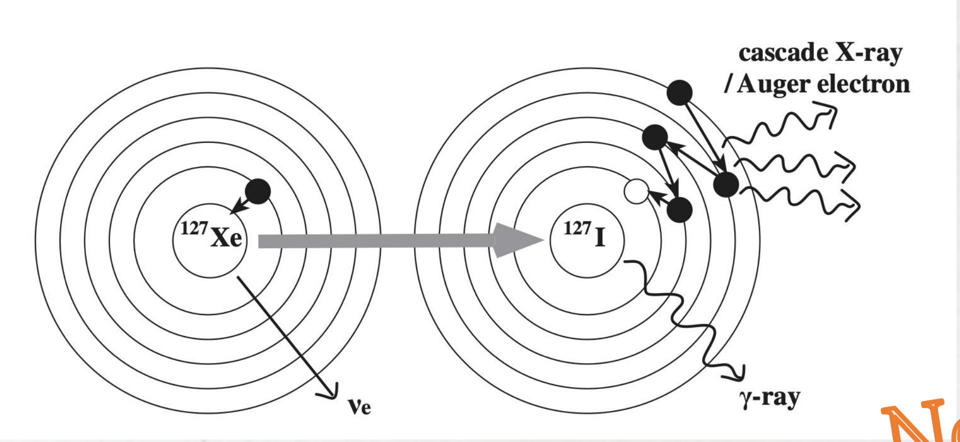
$(0.5\pm0.2)\times10^{-3}$·keV^{-1}·kg^{-1}·day^{-1}

[0,100]keV$_{ER}$

Xe127 and Ar37

I. Xe127: (36.4days)

- Muon bombard
- Neutron capture



	Events	Amplitude	Expected (%)	Observed (%)
K 33.2 keV	2067	18200 ± 400	83.37	82.7 ± 2.4
L 5.2 keV	542	3090 ± 130	13.09	14.1 ± 0.7
M 1.1 keV	164	580 ± 50	2.88	2.6 ± 0.2
N 186 eV	31	133 ± 23	0.66	0.6 ± 0.1

II. Ar37: (35days)

- Proton bombard
- Neutron bombard
- Neutron capture

Decay mode	Energy release (keV)	Branching ratio (%)
K-capture	2.8224	90.2
L-capture	0.2702	8.9
M-capture	0.0175	0.9

Negligible!

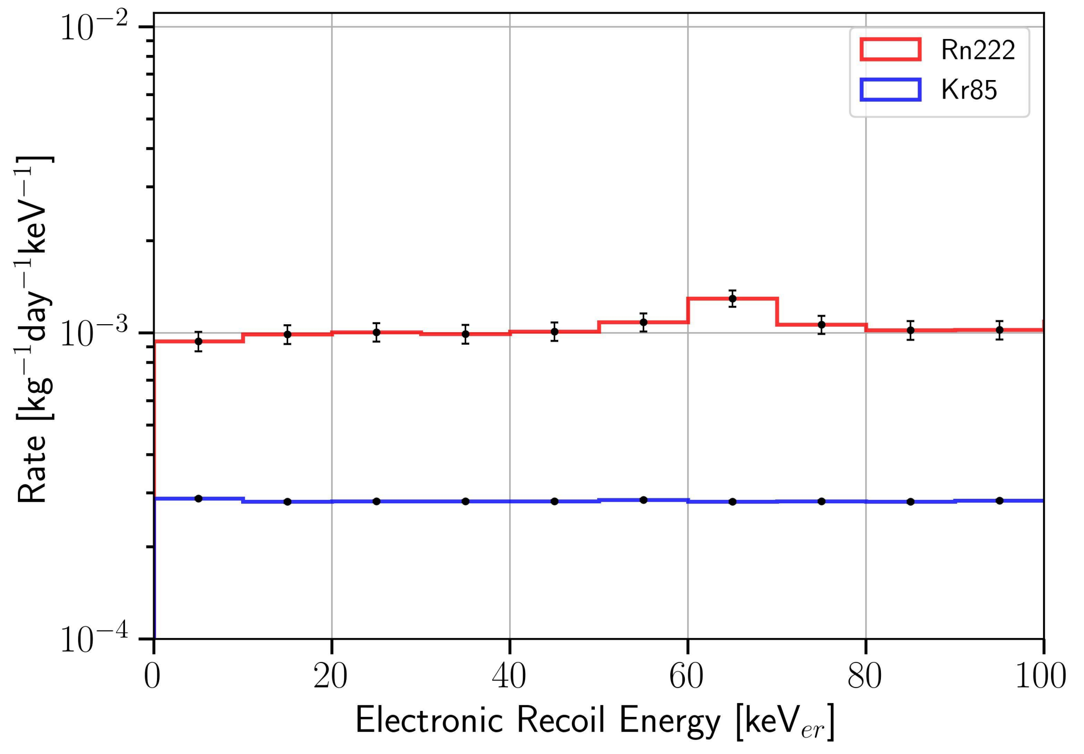
Tatal ER background $< 10^{-4} \cdot kg^{-1} \cdot day^{-1}$

Intrinsic Rn222 and Kr85

- Rn222 and Kr85 are intrinsic in LXe
- Cannot be removed by recycling purification

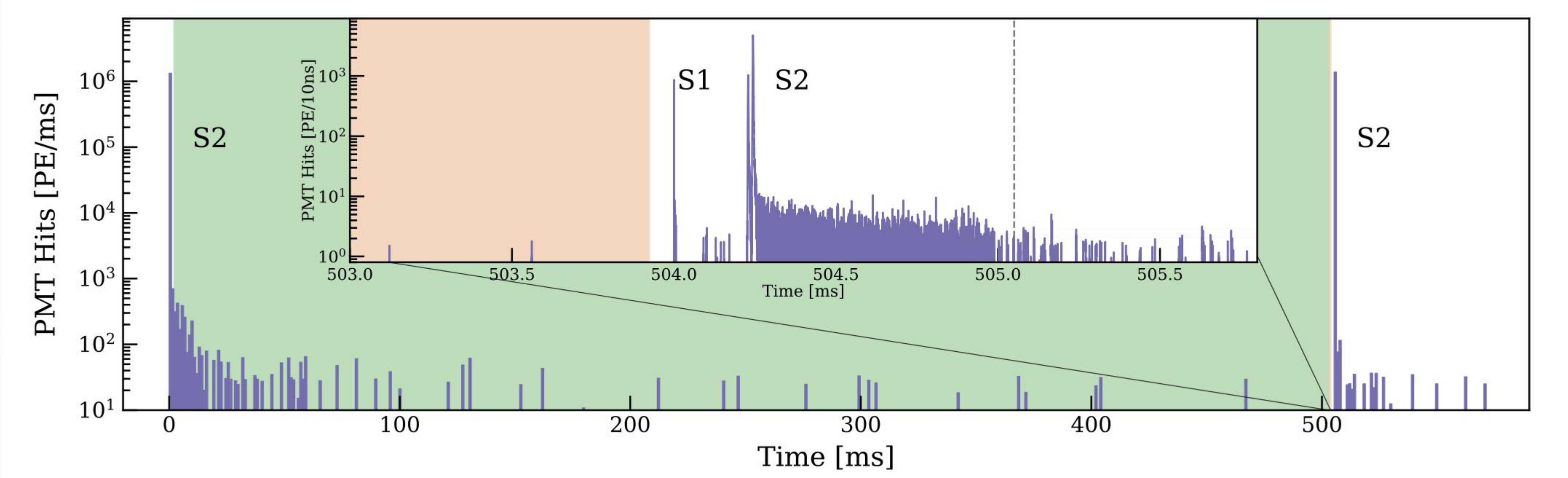
	LXe	Comment
^{85}Kr	10 ppt $^{nat}Kr/Xe$	$^{85}Kr/^{nat}Kr=1.7\times10^{-11}$, $T_{1/2}$=10.76y
^{222}Rn	40 μBq/kg	

	ER background ($10^{-3}\cdot keV^{-1}\cdot kg^{-1}\cdot day^{-1}$)
^{85}Kr	0.39 ± 0.01
^{222}Rn	1.02 ± 0.01



Subdominant!

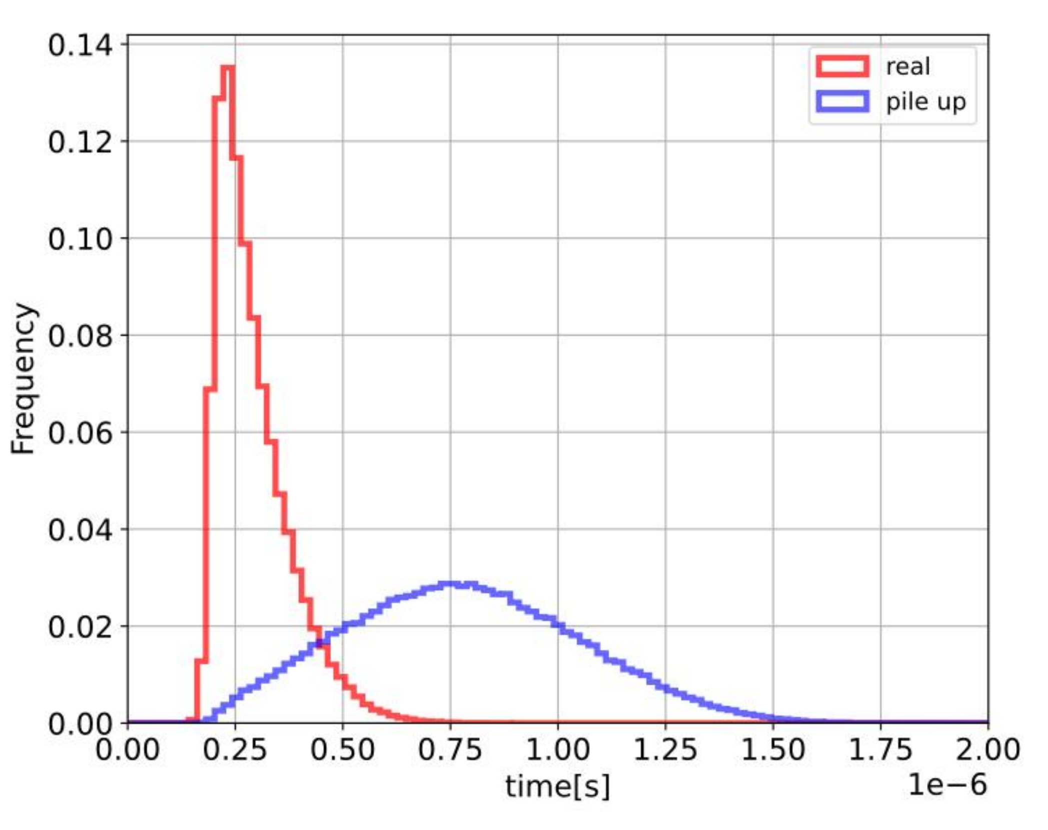
Delayed electrons



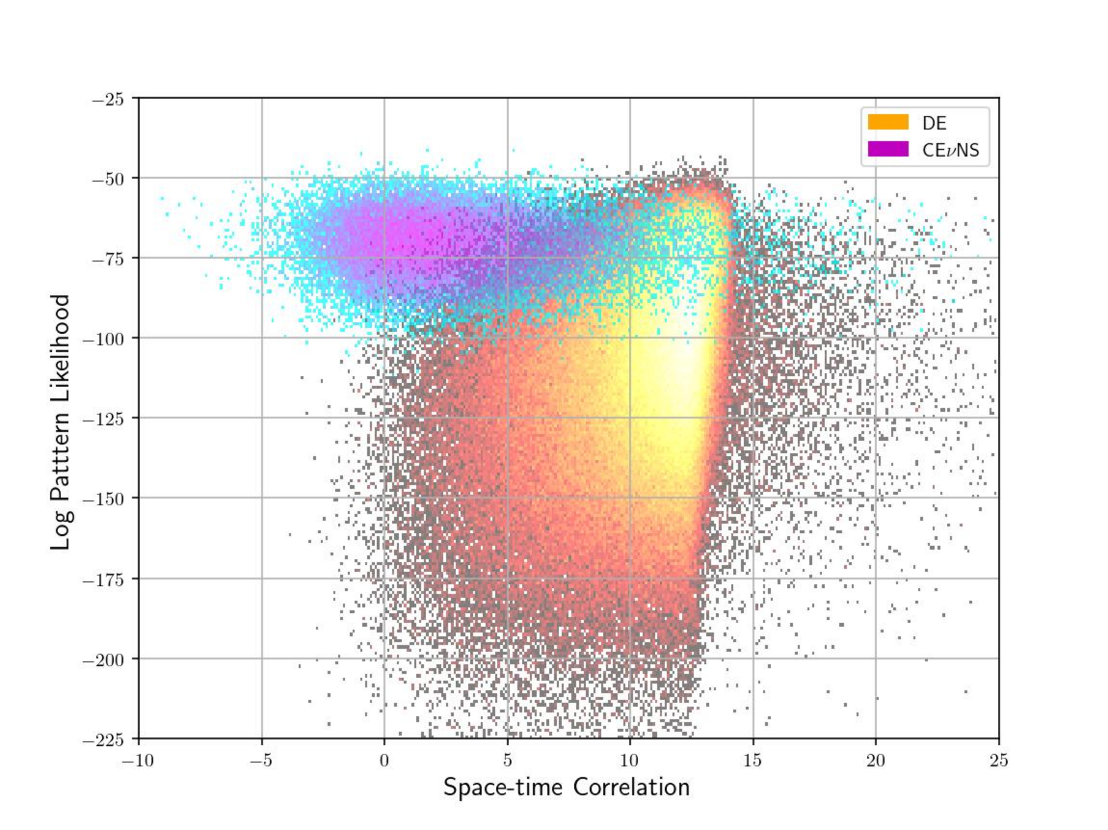
- This background has been observed by large LXeTPC searching for dark matter particles ;
- After a larger signal, such as muon, there will be some electrons inside LXe that gradually escape from the gas-liquid interface after a time delay.
    1. The waveform of the delayed electrons will differ from the real signal;
    2. The signal distribution of delayed electrons may be related to the muon track;

Delayed electrons

1、Waveform Classifier

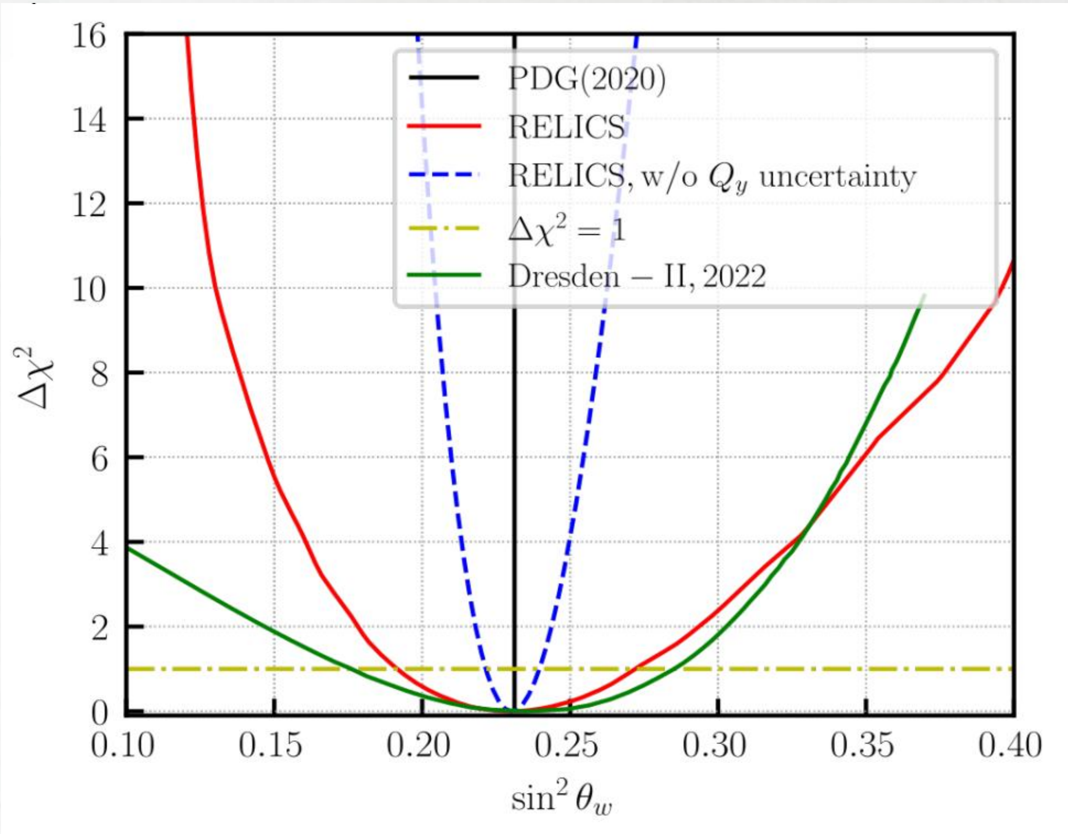


2、Pattern Classifier



Sensitivity

Weak mixing angle θ_W



Nonstandard neutrino interaction (NSI)