KamLANDにおける超新星背景ニュートリノ探索のための機械学習を用いた背景事象除去

Background reduction by machine learning
for the supernova relic neutrino search in KamLAND

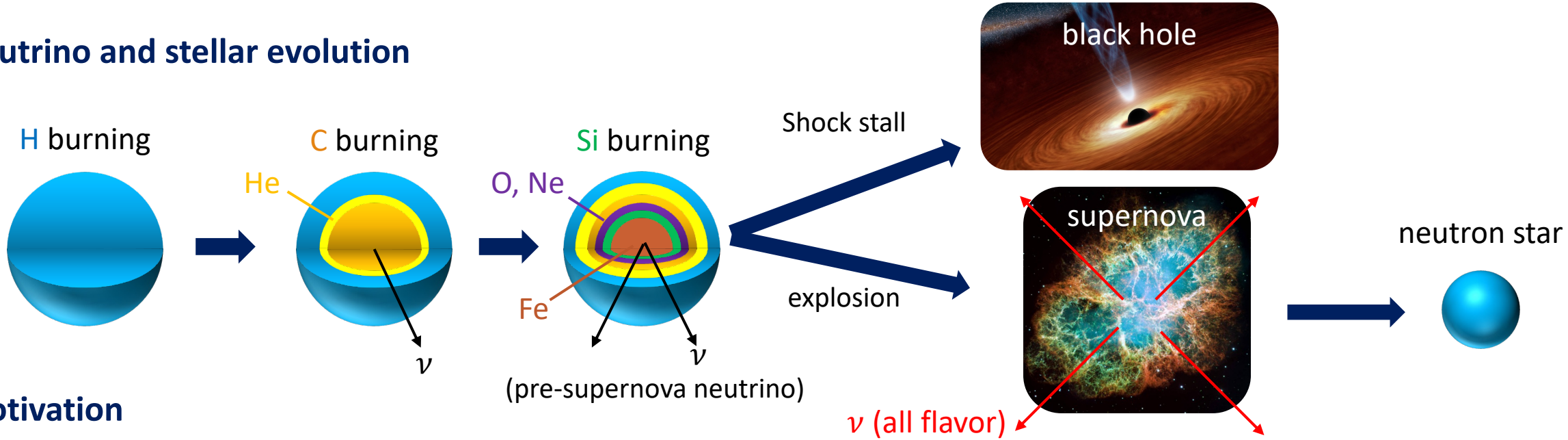
Research Center for Neutrino Science, Tohoku University

Minori Eizuka for KamLAND collaboration

(e-mail: minori@awa.tohoku.ac.jp)

Supernova Relic Neutrino (SRN)

Neutrino and stellar evolution



Motivation

SRN flux

$$\frac{d\phi(E_{\nu_i})}{dE_{\nu_i}} = c \int R_{\mathrm{ccSN}}(z) \frac{dN(E'_{\nu_i})}{dE'_{\nu_i}} (1+z) \left|\frac{dt}{dz}\right| dz$$

Supernova rate → **Star formation history**

Neutrino spectrum from each supernovae → **Mechanism of supernova**

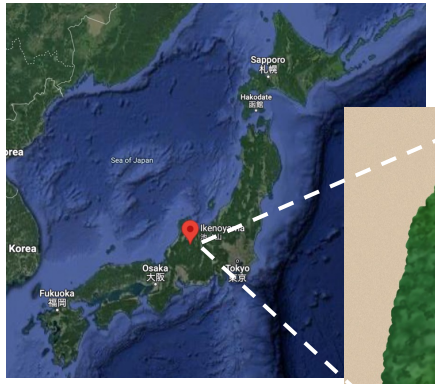
E_{ν_i}: Neutrino energy

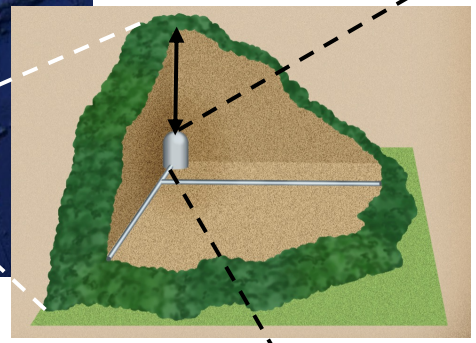
$E'_{\nu_i} = (1+z)E_{\nu_i}$

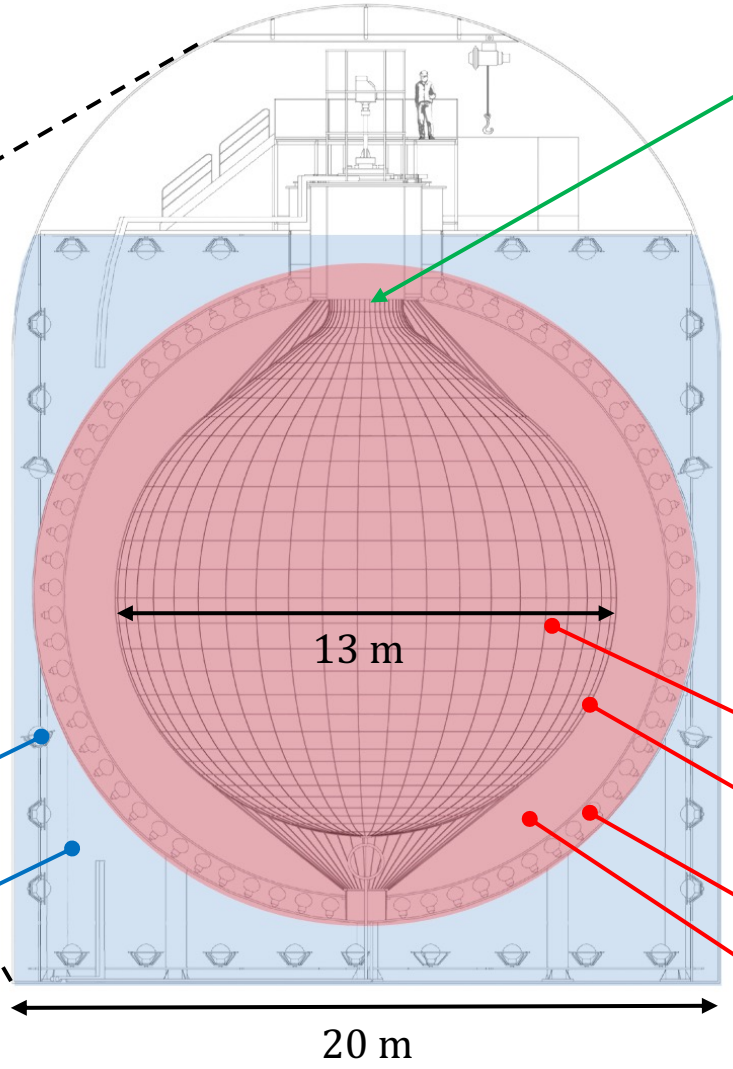
z: Redshift

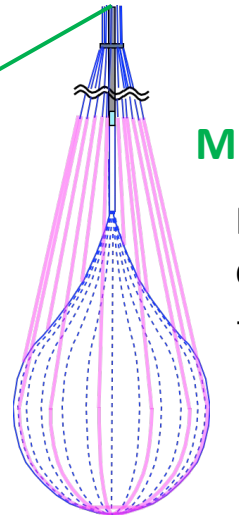
Kamioka Liquid-scintillator Anti-Neutrino Detector (KamLAND)

1000 m underground in the Kamioka mine









Miniballoon

Neutrinoless double beta decay search (KamLAND-Zen) → volume cut

Inner detector

Scintillation light → physics event

1 kt liquid scintillator

Nylon balloon

17 & 20-inch PMTs

Buffer oil

Outer detector

Cherenkov light → muon veto

20-inch PMTs

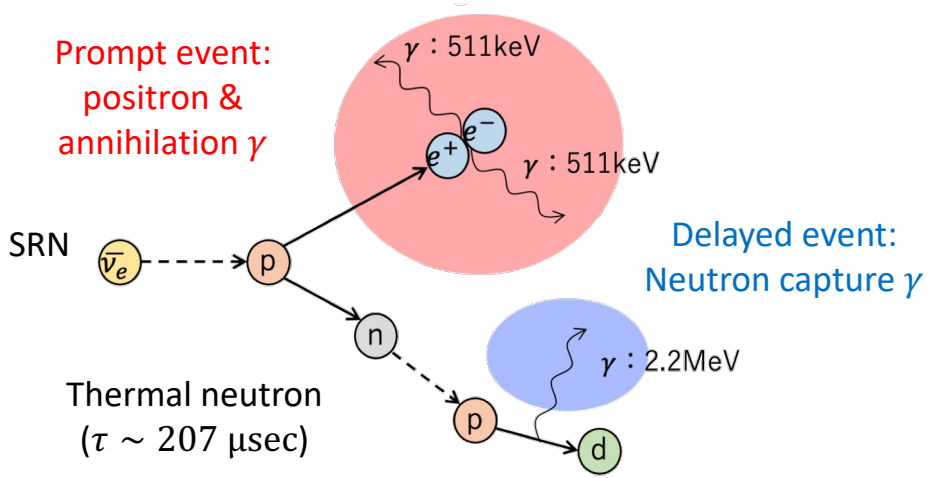
Pure water

KamLAND has significant sensitivity to MeV-energy neutrinos.

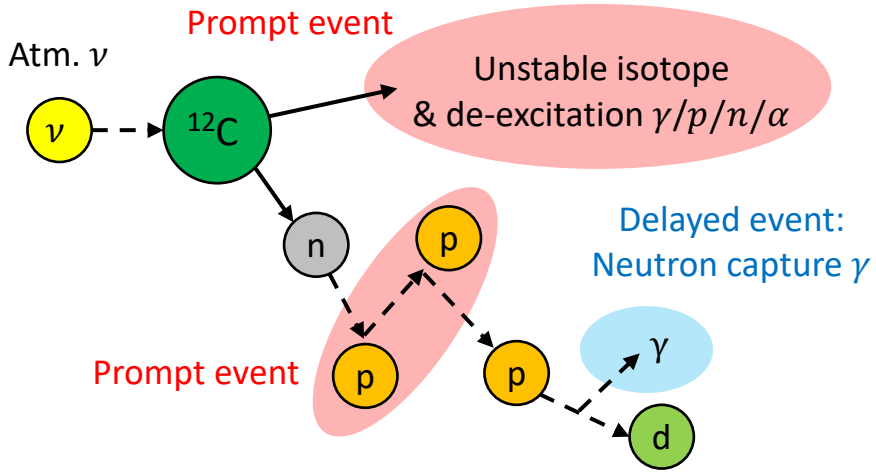
Signal and background

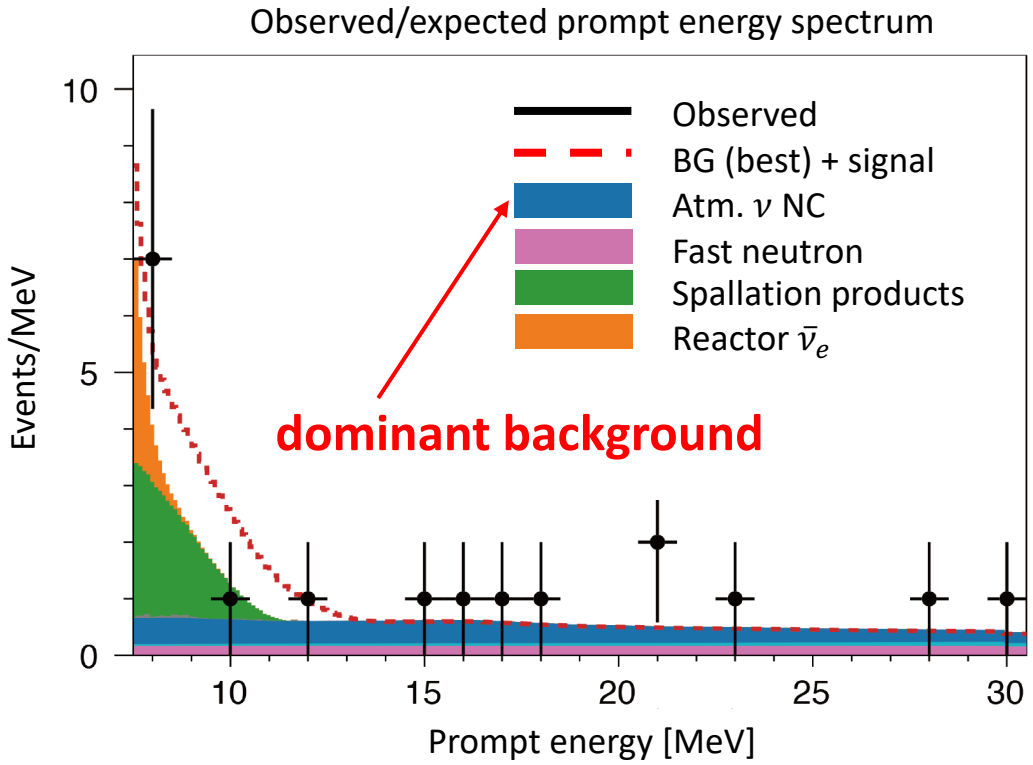
Energy region in KamLAND: $8.5 \lesssim E_{\mathrm{vis}}[\mathrm{MeV}] \lesssim 30$

Signal: Inverse Beta Decay (IBD)



Background: atmospheric neutrino neutral current



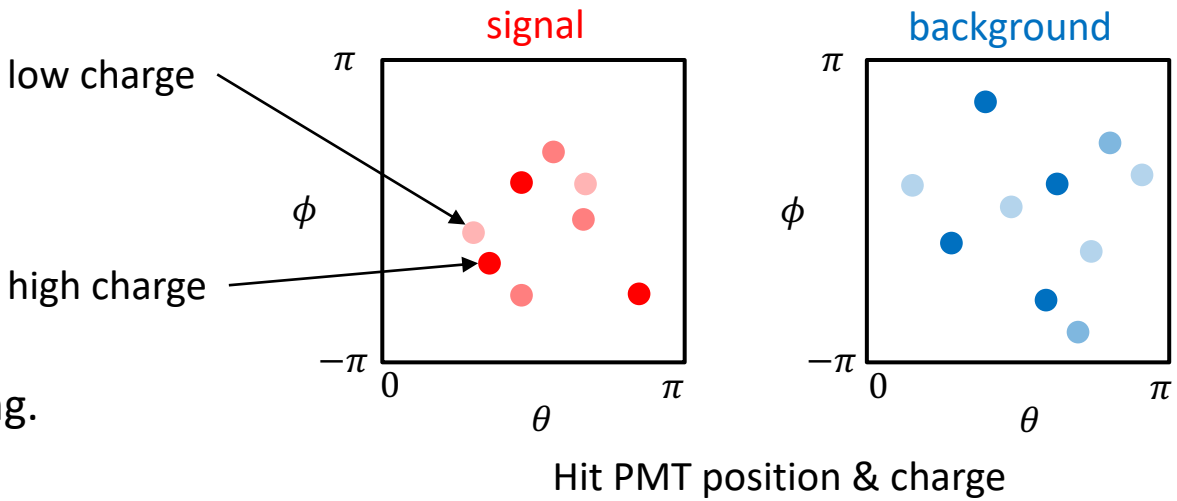


- Space-time correlation between prompt event and delayed event is used. → Delayed coincidence
- In current analysis, atmospheric neutrino events cannot be discriminated from IBD signals.

How to discriminate signal & background

Interaction topology, duration, and particles are different between SRN signal and atm. ν background.

Difference can be observed in hit position, charge, and timing.

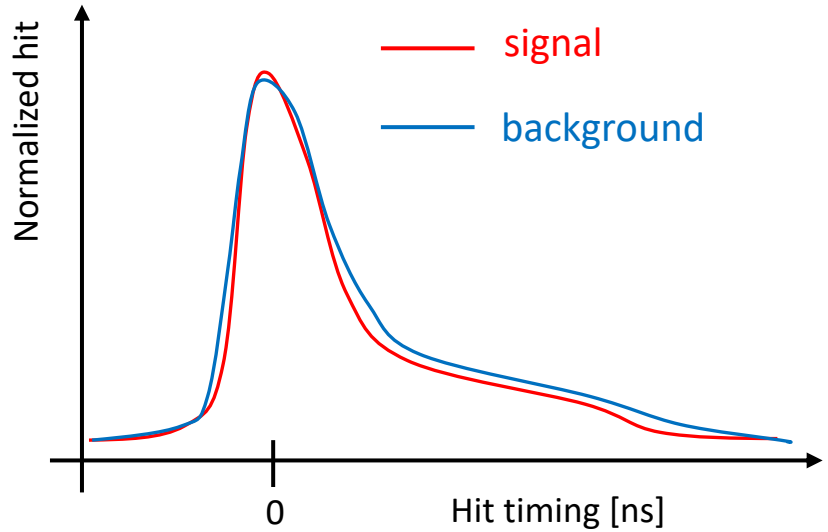


Hit PMT position & charge

Goal

Signal/background discrimination by machine learning

1. Simulation tuning
2. Simulation consistency check
3. Machine learning using simulation events
4. Performance check of the trained model



Basic concept of this analysis

real data

simulation

no candidates more than 8.5 MeV

IBD (positron)

substitute

spallation ^{12}B

consistency

positron

Step 1. simulation tuning

consistency

fast neutron

atm. ν NC

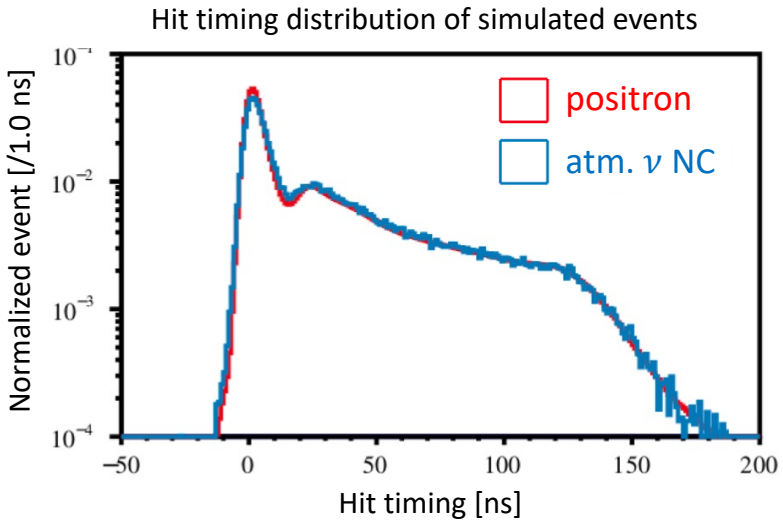
substitute

atm. ν NC

small statistics, difficult to collect

Step 2. simulation consistency check

Step 3. machine learning with simulation data



Simulation tuning

Photon simulation

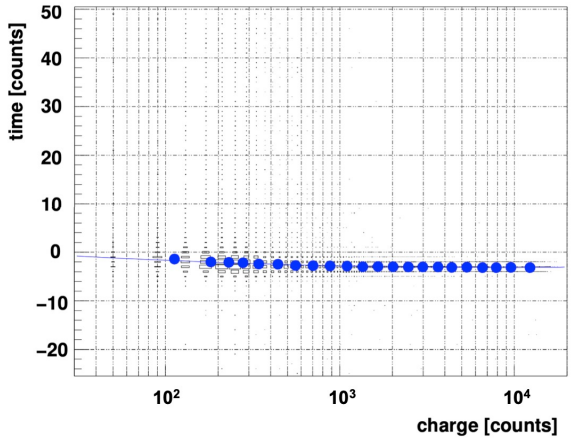
TQ correction

TDC sampling effect

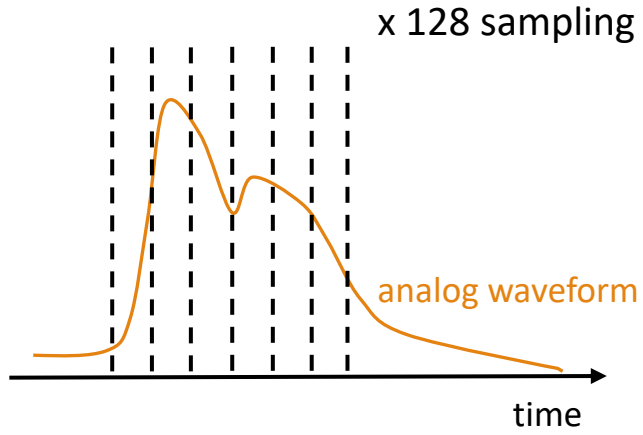
Hit position, charge, timing

Low charge event has hit timing delay.

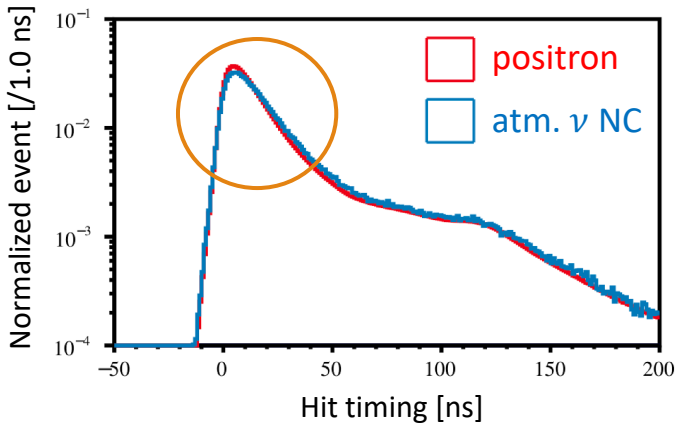
example of TQ correction



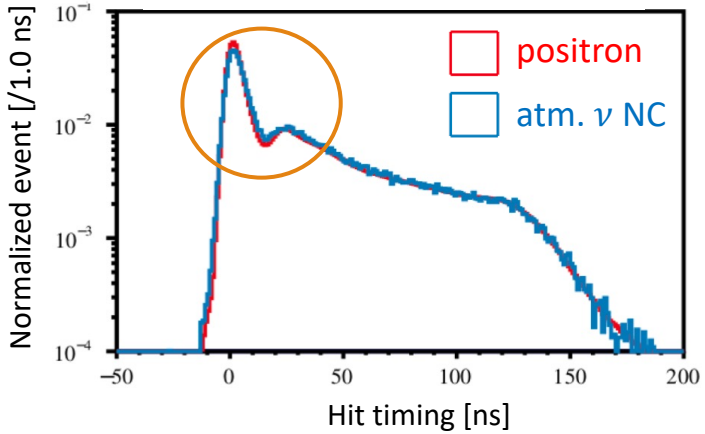
Discrete waveform sampling causes the characteristic shape in hit time distribution.



Simulation w/o TDC sampling effect



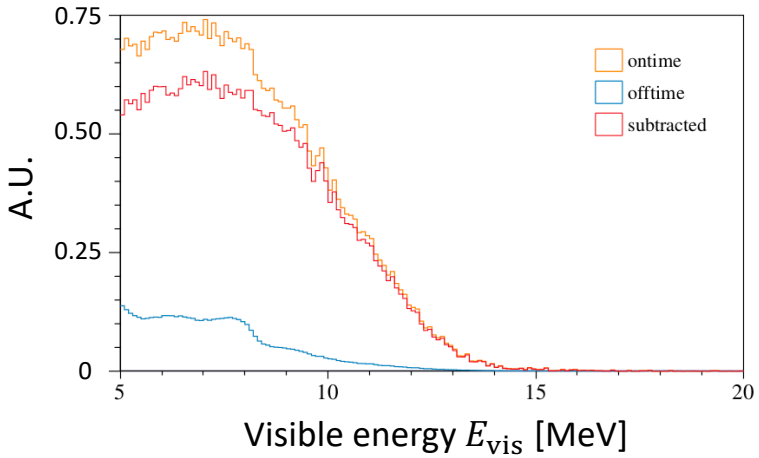
Simulation w/ TDC sampling effect



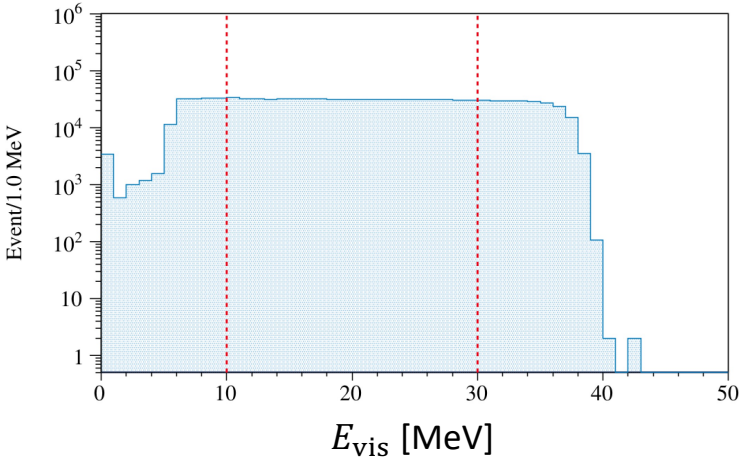
Simulation consistency check: signal

- Spallation ^{12}B is used instead of high-energy IBD candidate.
- Light particles (e^- & e^+/γ) have similar hit information.
- **Signal simulation is consistent with real data.**

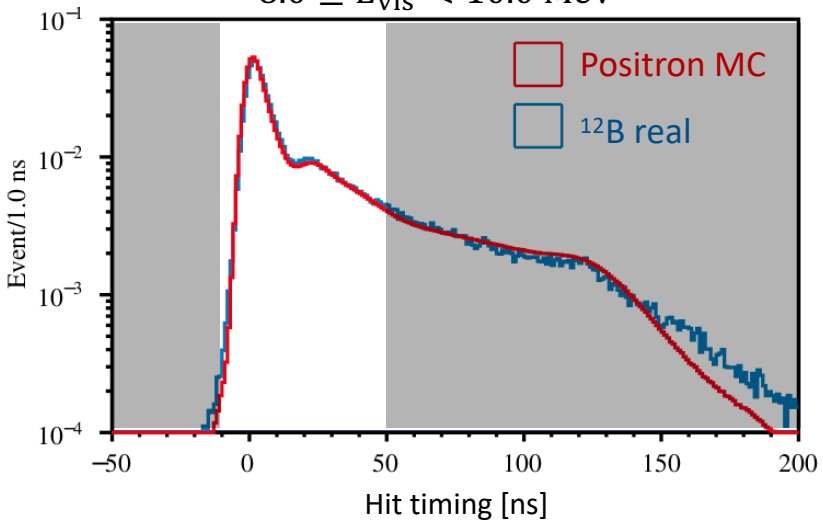
Spallation ^{12}B (e^-) in real data



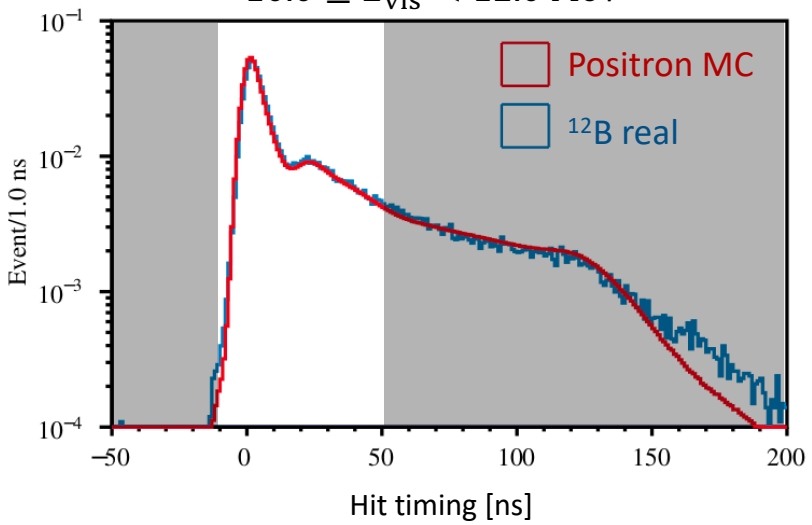
Positron MC (e^+/γ)



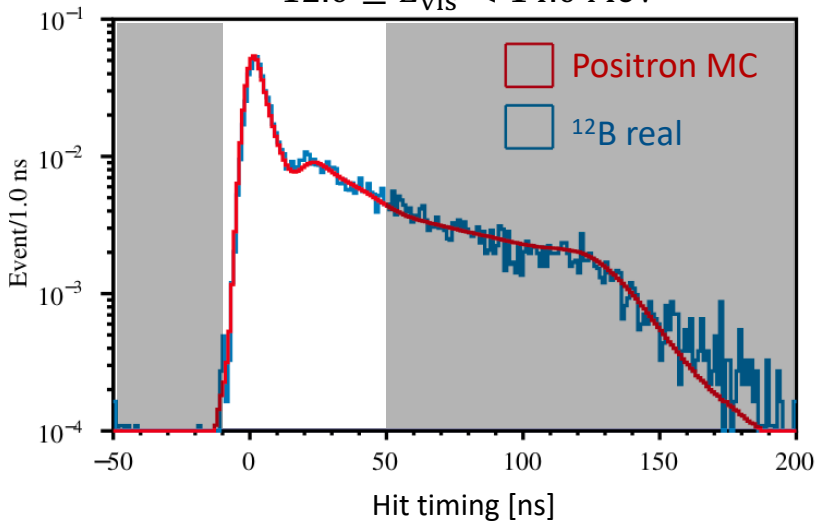
$8.0 \leq E_{\mathrm{vis}} < 10.0$ MeV



$10.0 \leq E_{\mathrm{vis}} < 12.0$ MeV

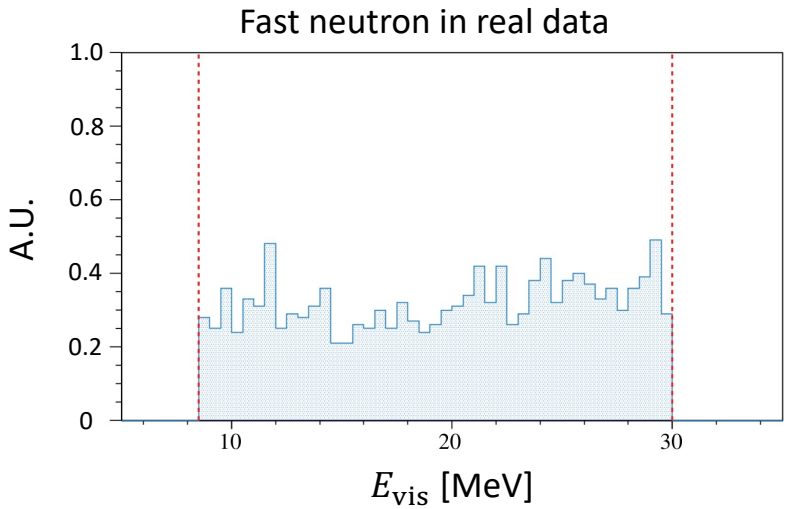


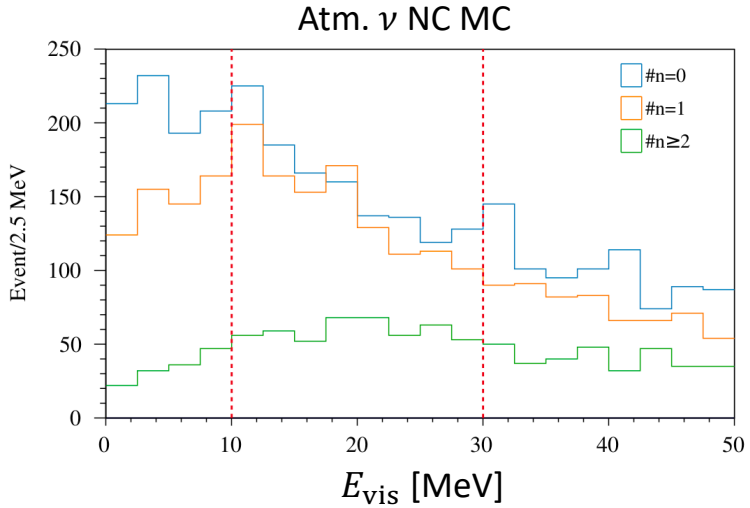
$12.0 \leq E_{\mathrm{vis}} < 14.0$ MeV

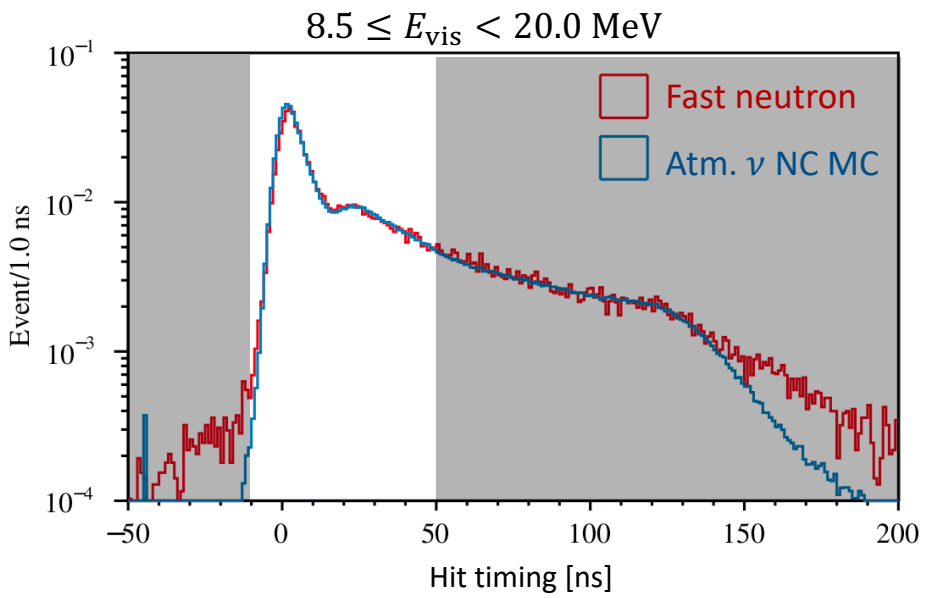


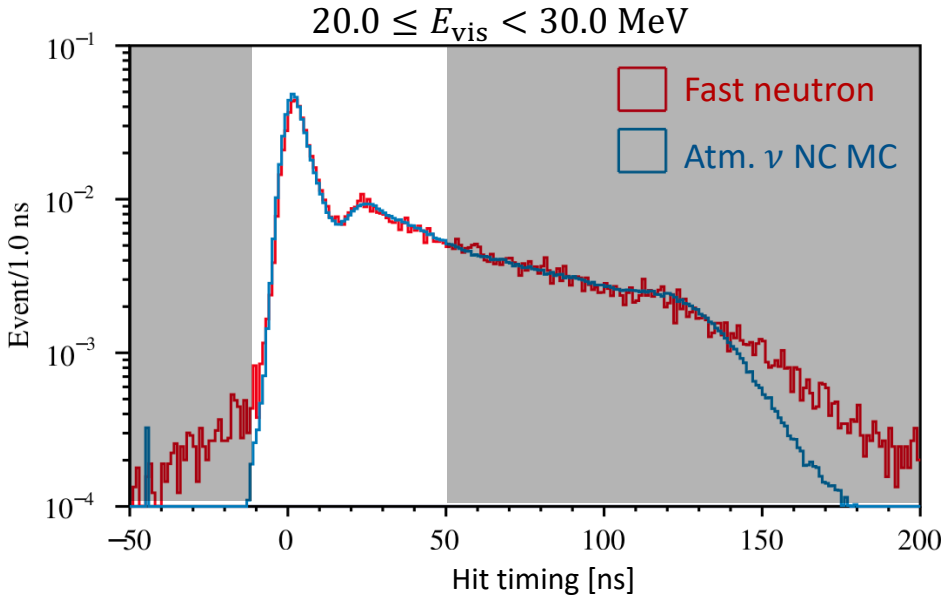
Simulation consistency check: background

- Fast neutron is used instead of atm. ν candidate.
- Fast neutrons and atm. νs have similar hit information.
- **Background simulation is consistent with real data.**









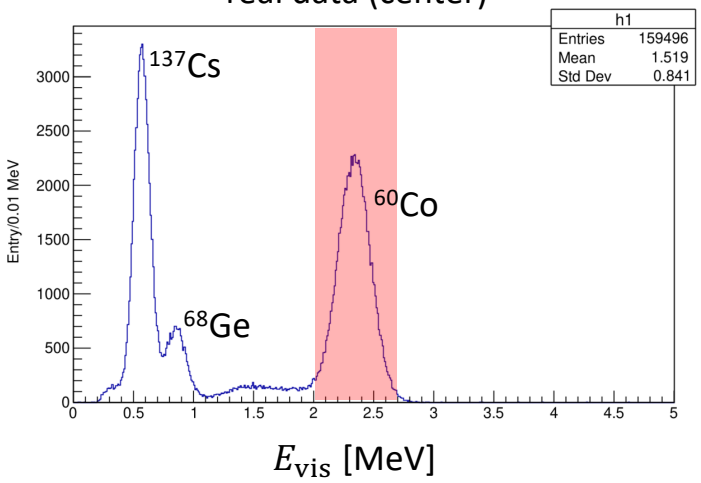
Simulation consistency check: calibration

- I used composite source runs (CoGeCs) for the low energy consistency check.

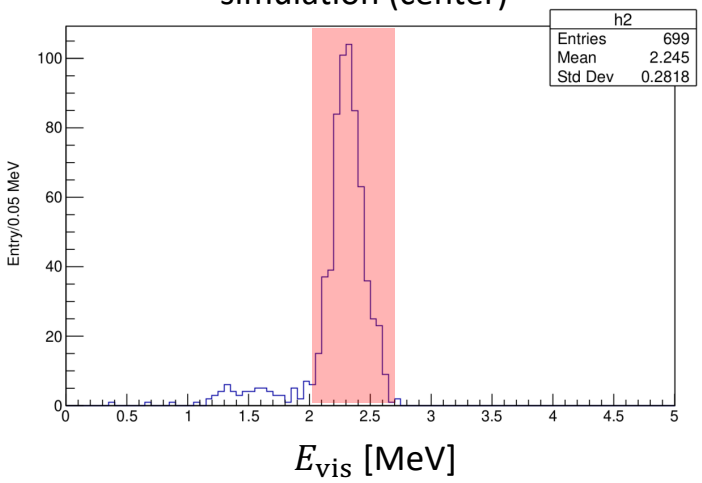
  (event position) ≤ 150 cm from the source

- **Low energy simulation is consistent with real data.**

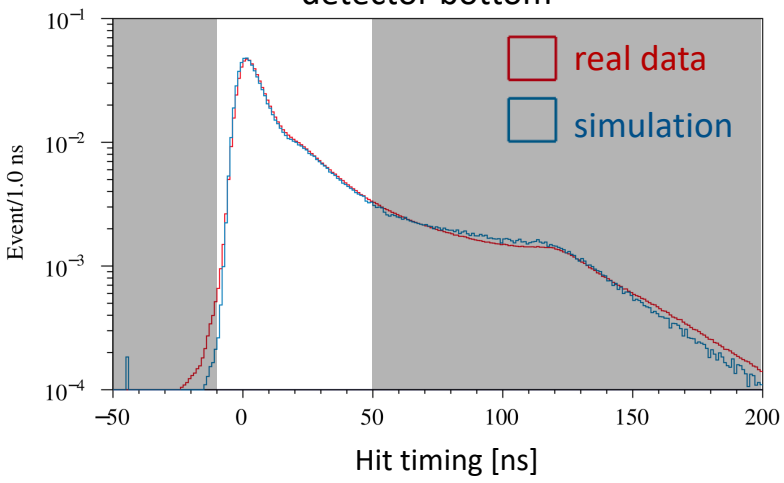
real data (center)



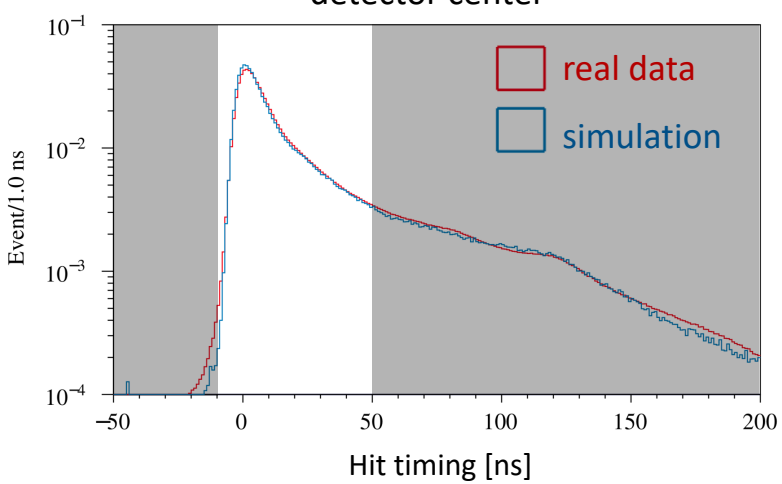
simulation (center)



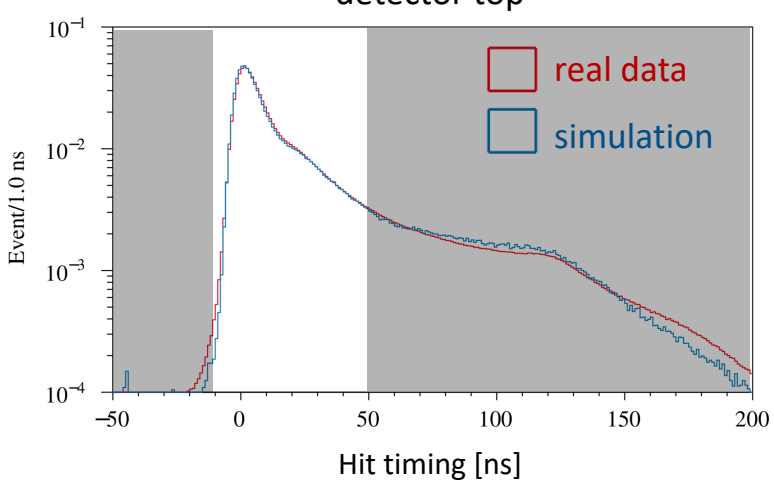
detector bottom



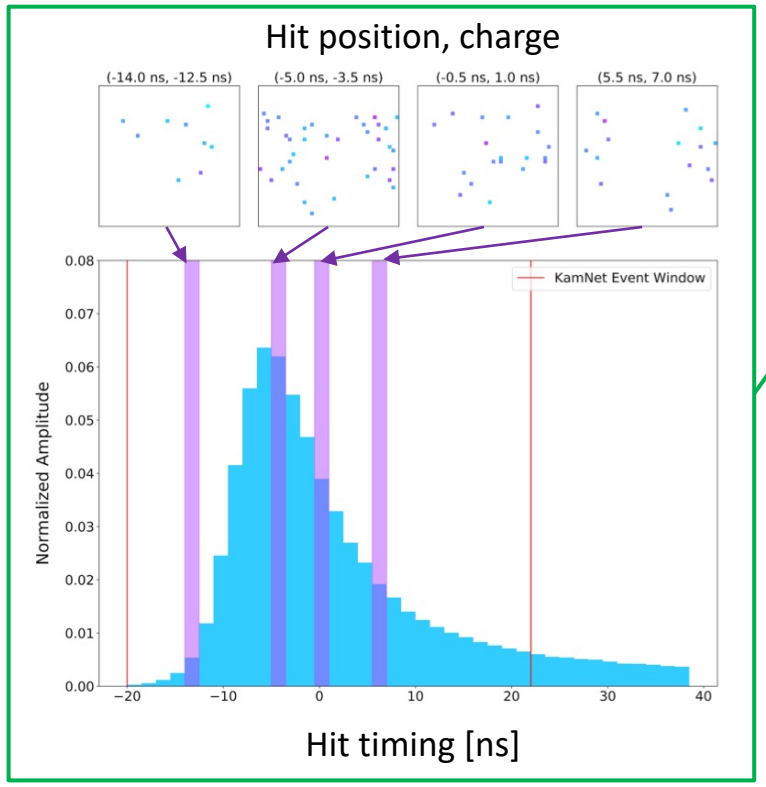
detector center



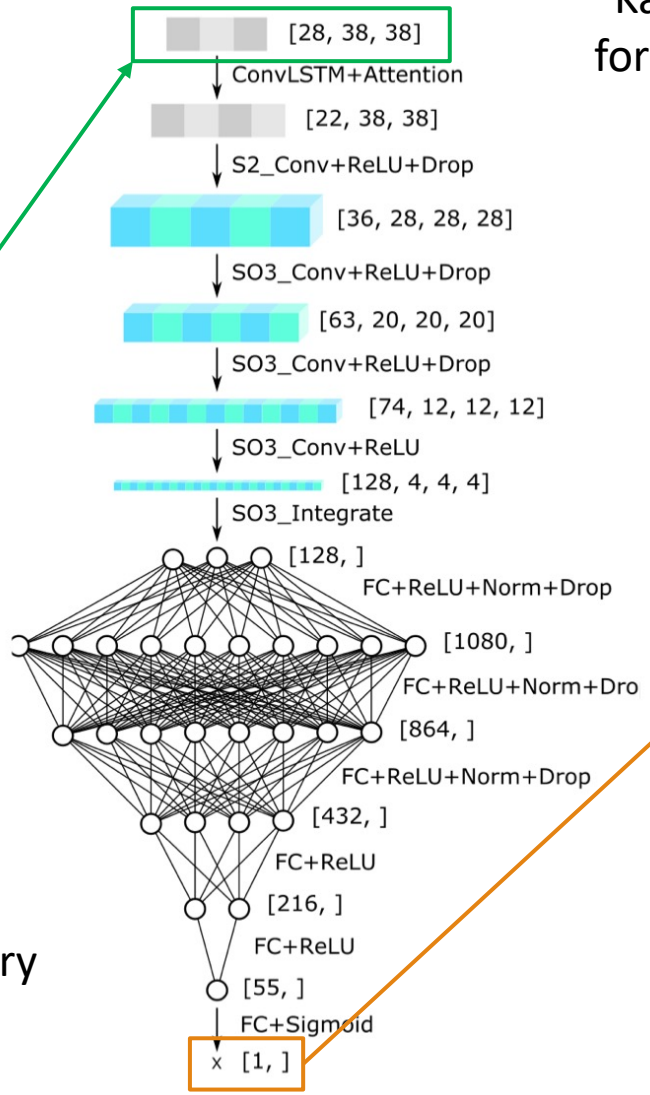
detector top



KamNet: spatiotemporal deep neural network



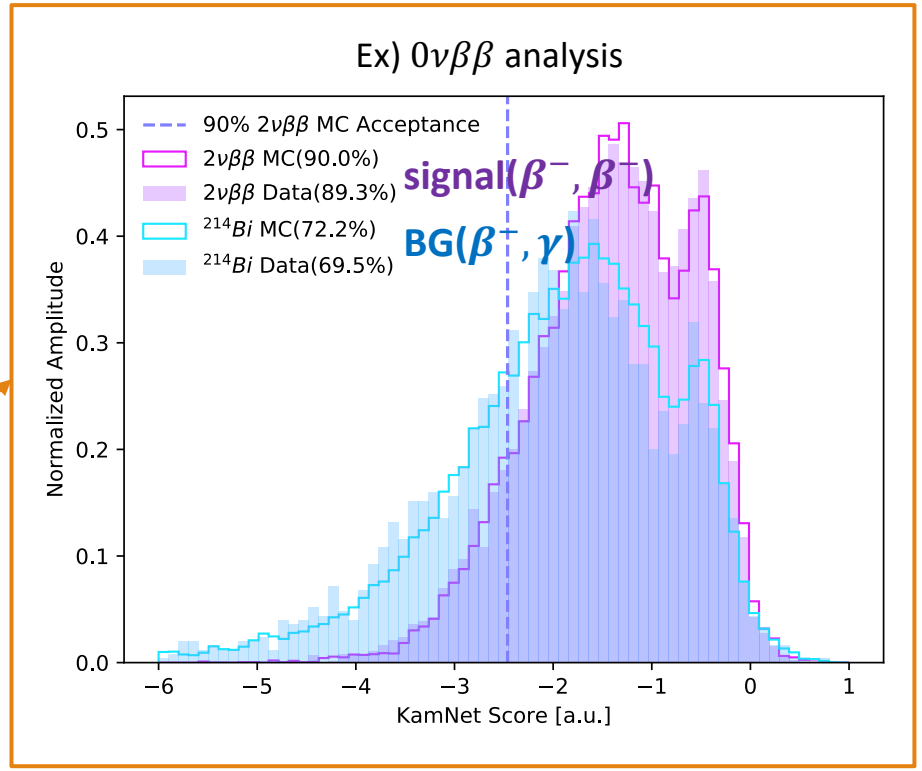
KamNet diagram



"KamNet" is a neural network originally developed for $0\nu\beta\beta$ analysis.

input: Event hit position, charge, and timing

output: KamNet score (positive→signal-like)



Characteristics of KamNet

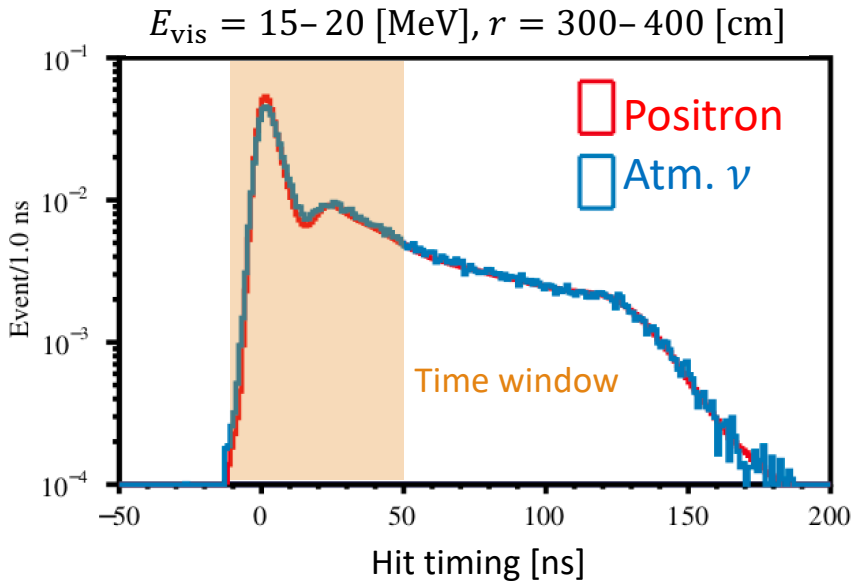
- **Spherical** neural network
- Convolutional long short-term memory
- Dropout rate

KamNet training setup

Training data

$E_{\mathrm{vis}} = 8.5\text{–}30$ [MeV], detector radius $r \leq 550$ [cm]

	training	validation
▸ Positron MC (signal)	×10,000	×3,000
▸ Atm. ν NC MC (background)	×10,000	×3,000



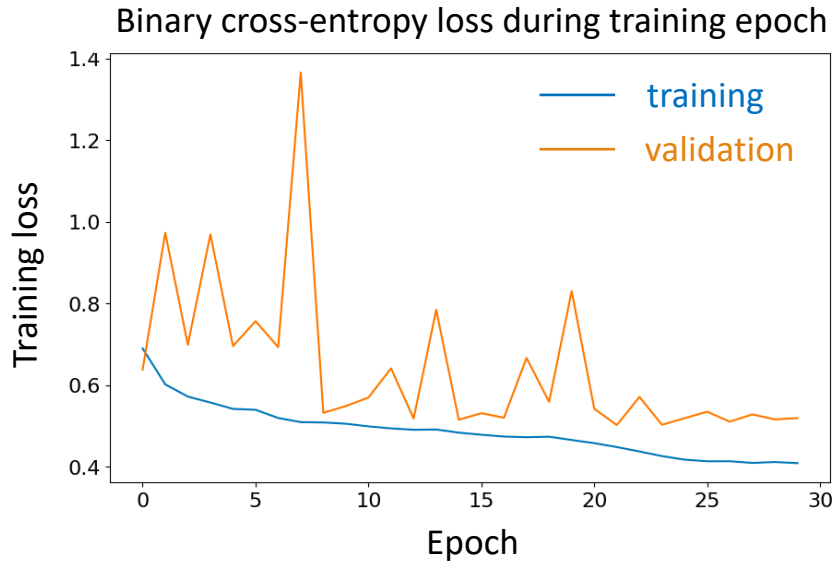
Changed point from $0\nu\beta\beta$ KamNet

- Hit information: single-hit PMT map → multi-hit PMT map
- Time window: $-20\text{–}+22$ [ns] → $-10\text{–}+50$ [ns]

Training epoch: 30

- When rejection efficiency saturates, training is enough.

Values of two lines should be small and close.



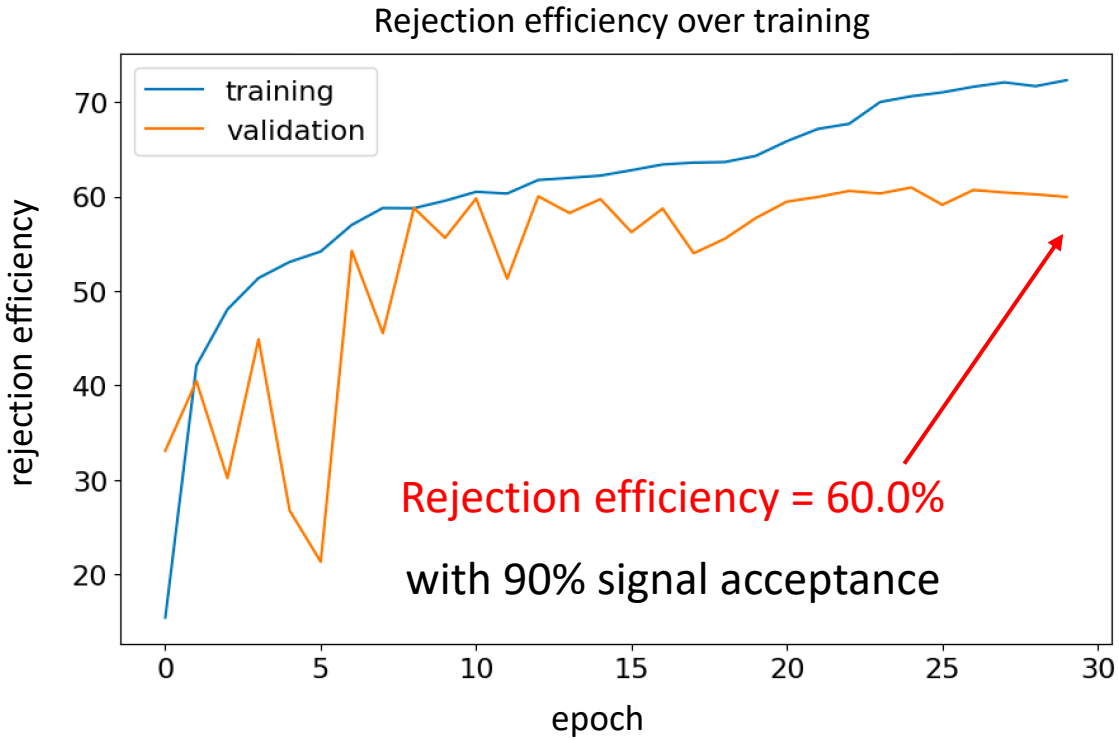
Training result & performance

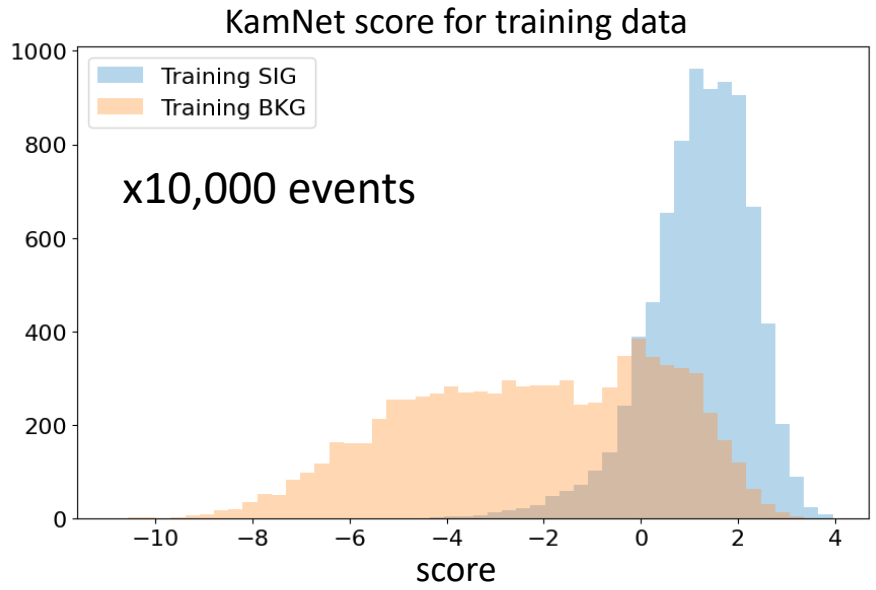
- Different signal/background score distributions

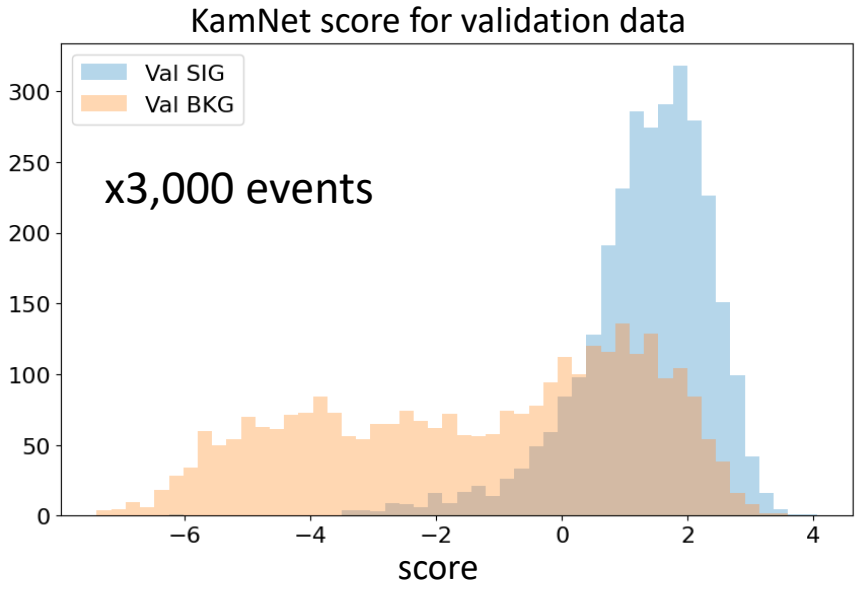
  → Event discrimination is possible.

- Rejection efficiency (validation) saturation

  → The training epoch is sufficient.







Training result & performance

*1 Area Under the ROC curve
*2 Receiver Operating Characteristic Curve

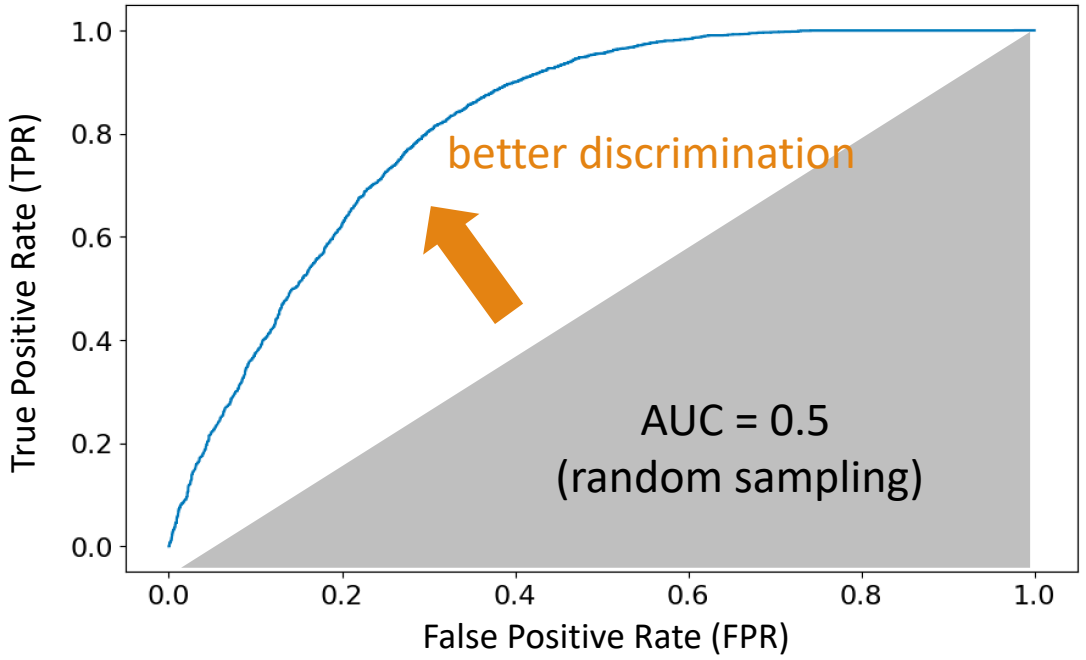
- AUC*1 = 0.818

  → Its performance is better than $0\nu\beta\beta$ KamNet model.

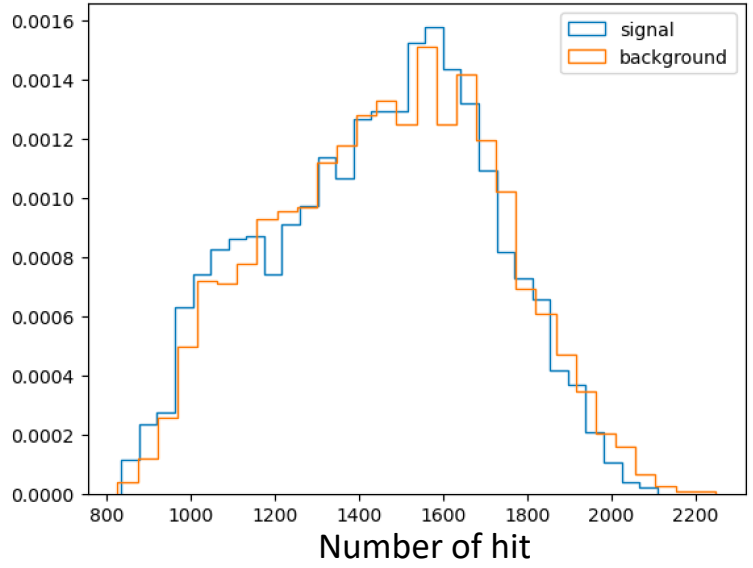
- Similar number of hit distribution between signal/background

  → KamNet do not use number of hit
  (it uses hit timing, charge, and special distribution).

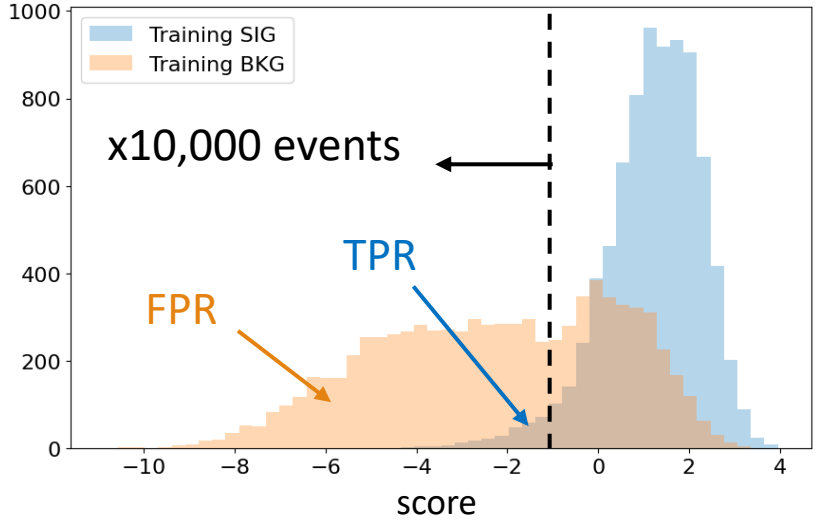
ROC*2 curve



Number of hit distribution for KamNet training



KamNet score for training data



Validation

Spallation ^{12}B and fast neutron events in real data are used for the validation of simulation events.

Validation data set

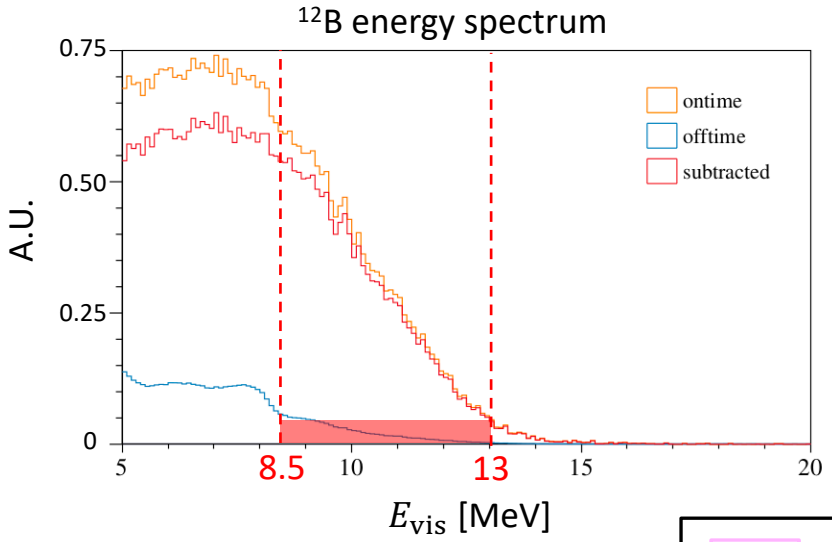
- Same energy spectrum shape (flat, $8.5-13$ MeV)
- Full fiducial volume ($r \leq 650$ cm)
- All period (only for FN)

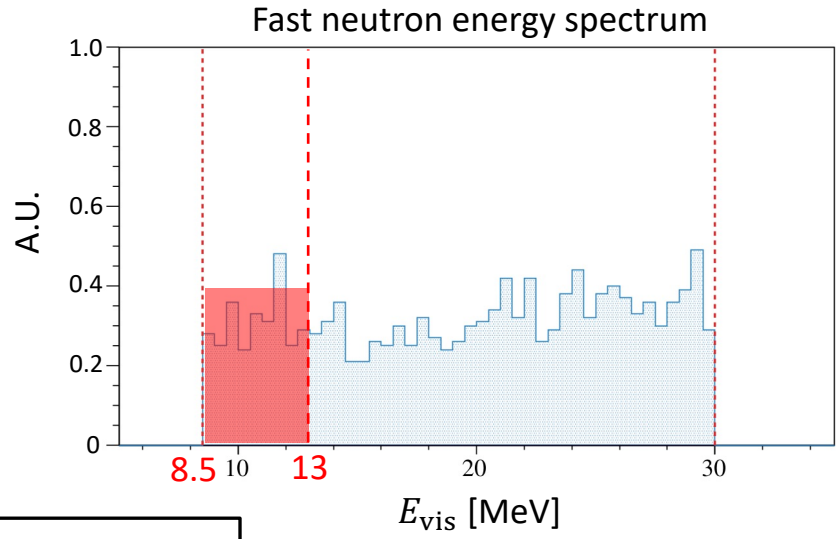
} statistics

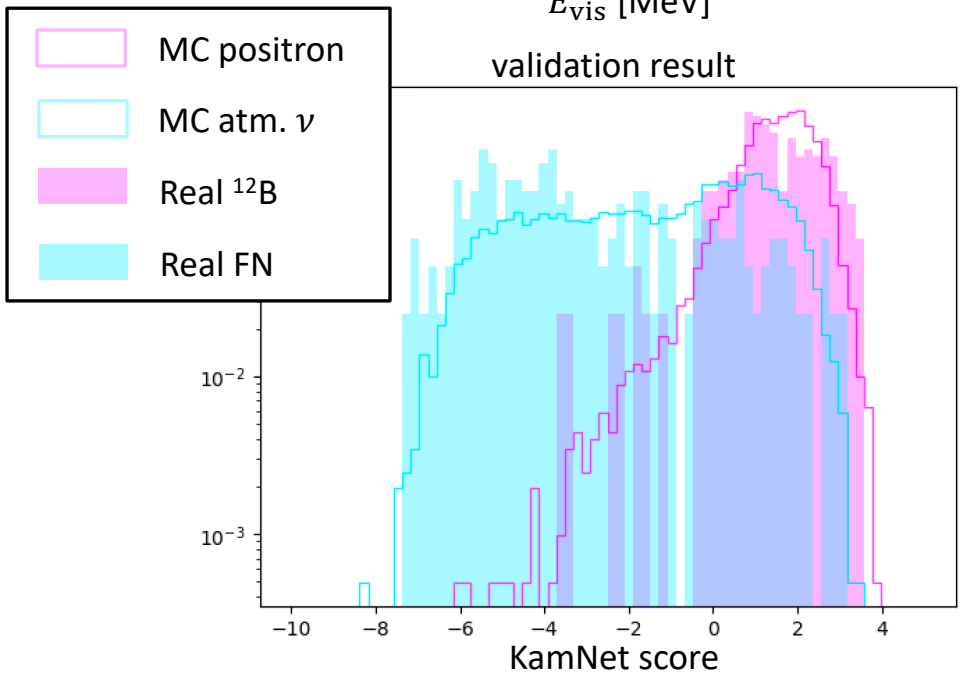
Rejection efficiency

- simulation: 69.14%
- real data: 82.50%

(with 90% signal acceptance)



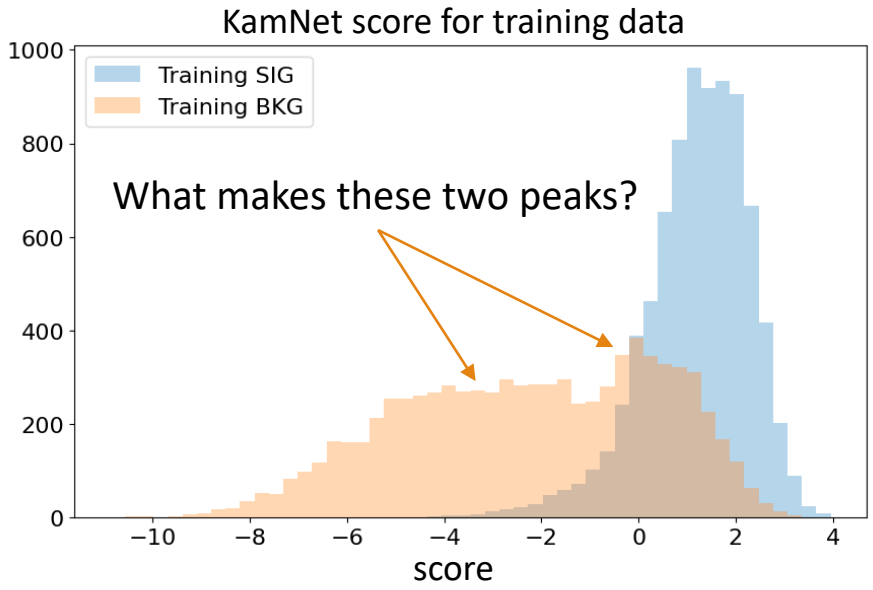




For KamNet, **real ^{12}B vs MC positron** **real FN vs MC atm. ν** **have correlations.**

Prospects

Interpretation of the score output



- Energy dependence
- Vertex dependence

} Different cut criteria?

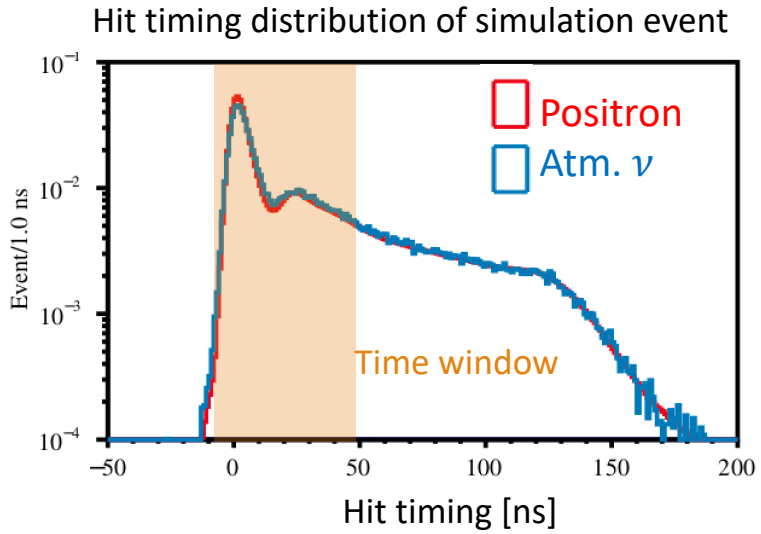
- Characteristics of simulation and real data

Sys. unc. of the rejection efficiency

1. Difference between simulation and real data
   → ~ 10%
2. Fluctuation in the trained model performance
   → estimation by about 100 times trial

Modification of KamNet structure

- Time window
  → "When" is the most important time?
- Dropout rate
- Validation weight
  → Number of ^{12}B & FN are different.



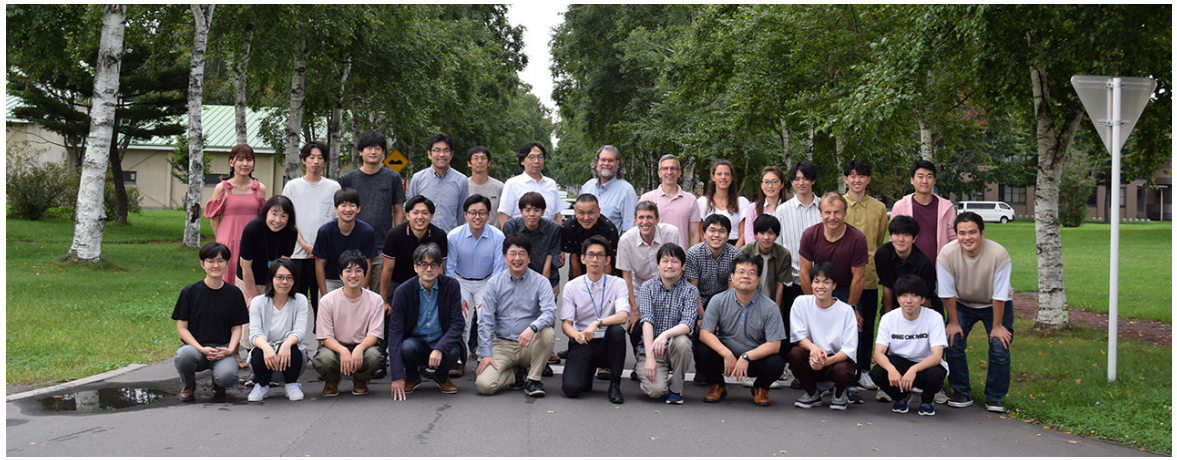
Summary

- Atmospheric neutrino interaction is the largest background for the supernova relic neutrino search in KamLAND.
- We intend to reduce this background using a neural network: KamNet.

  → To train KamNet, simulation tuning has done.

  → The preliminary trained model has a promising rejection power.
- We need additional works to interpret and polish the KamNet performance.

Thank you for listening!



KamLAND collaboration meeting in Obihiro @2023 Sep.

backup