Search for supernova relic neutrinos using machine learning techniques in KamLAND

（KamLANDにおける機械学習を用いた超新星背景ニュートリノの探索）

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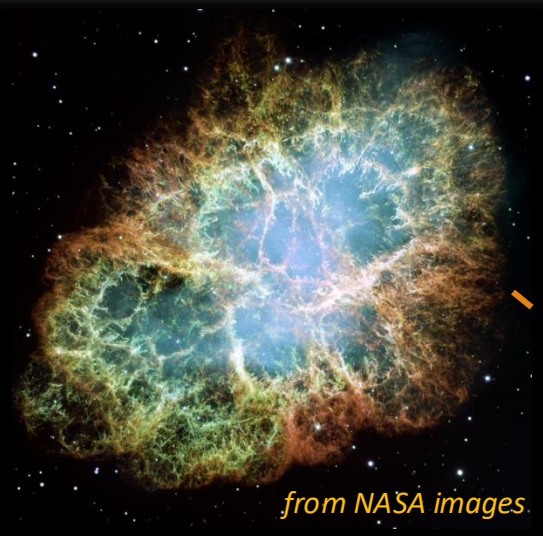
Astrophysical neutrinos



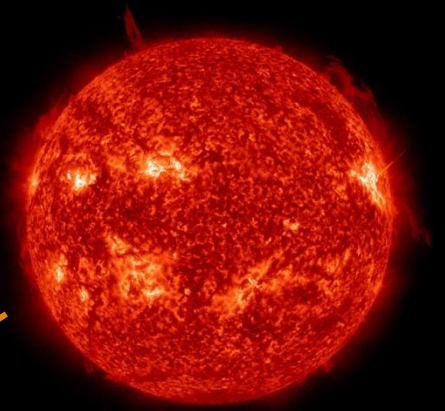
from NASA images

Supernova relic neutrinos
(supernova mechanism,
cosmological inputs)

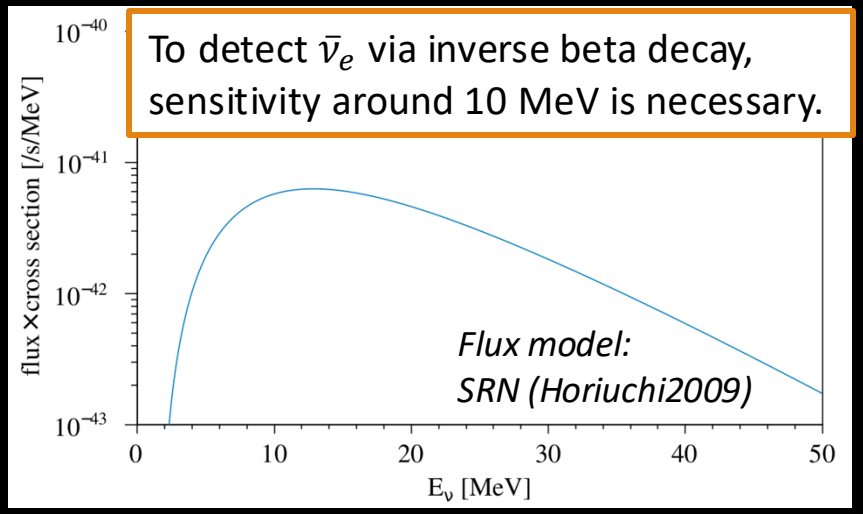
Solar antineutrinos
(beyond the standard physics)

$\nu_e \rightarrow \nu_\mu \rightarrow \bar{\nu}_e$

or $\nu_e \rightarrow \bar{\nu}_\mu \rightarrow \bar{\nu}_e$



from NASA images

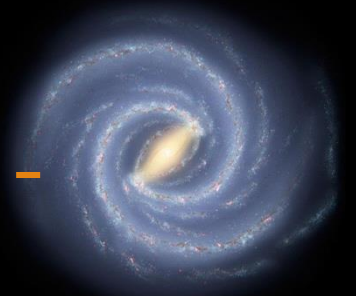


from NASA images

Light dark matter annihilation

$\chi\chi \rightarrow \nu\bar{\nu}$

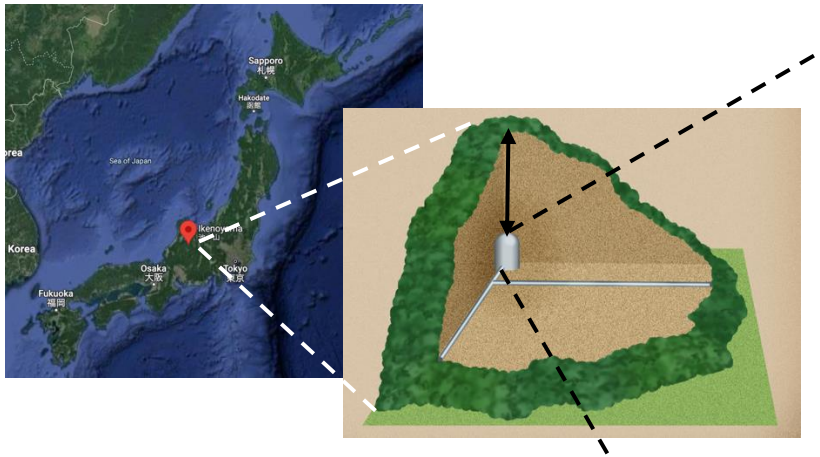
Neutrinos from
primordial black hole
(dark matter candidate)

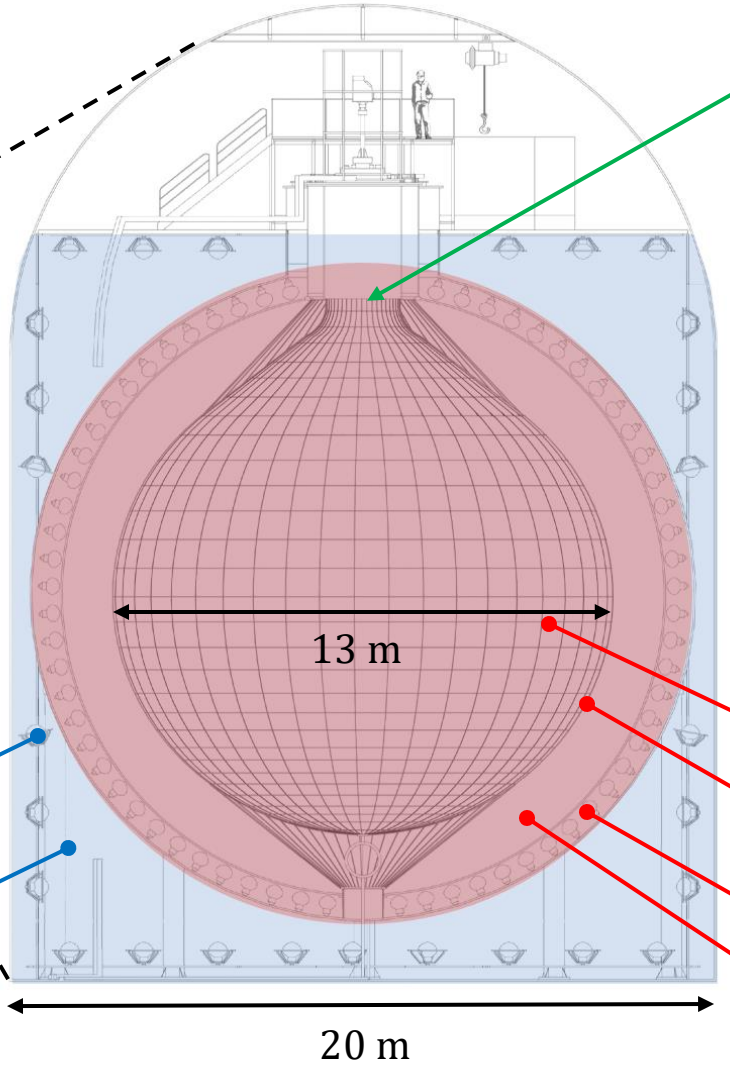


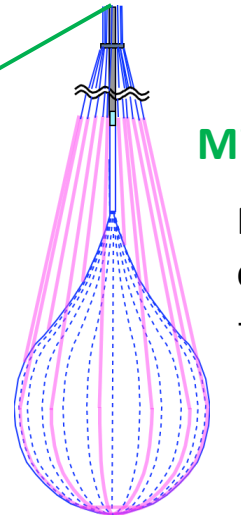
from NASA images

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

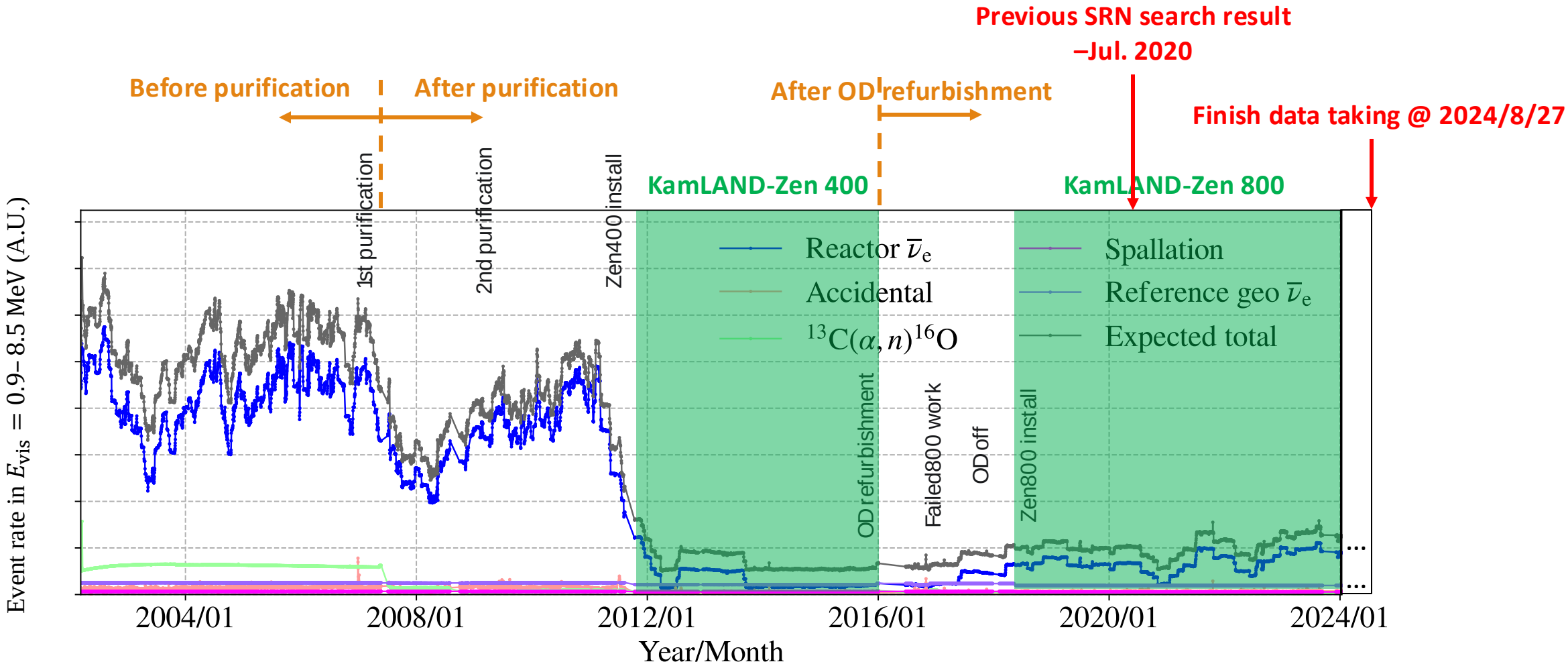
20-inch PMTs

Pure water

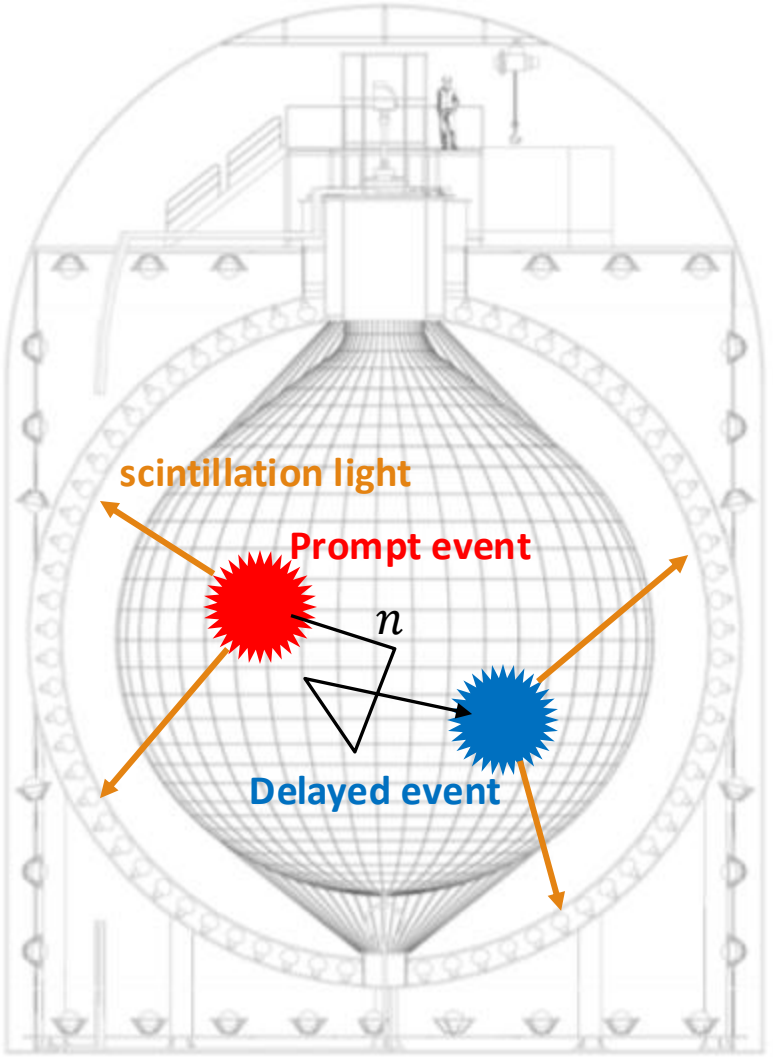
KamLAND has significant sensitivity to MeV-energy neutrinos.

Detector period of KamLAND experiment

KamLAND finished data taking in August 2024. → Full data analysis is in progress.



Event reconstruction in KamLAND



- When charged particles pass through a liquid scintillator, scintillation light is emitted isotopically.
- Scintillation light is detected by the ID 17-inch/20-inch PMTs.
  → Hit timings and charges are used for energy and vertex reconstruction.
- Astrophysical neutrino signal is detected via inverse beta decay (IBD).

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

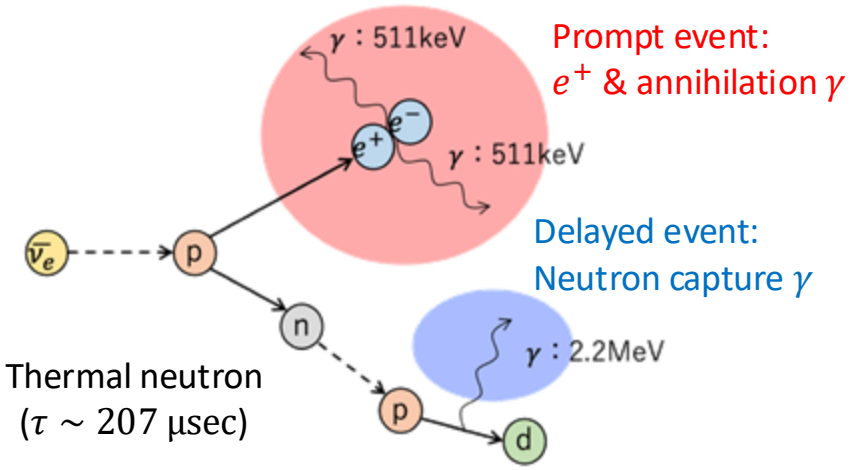
e^+ → annihilation γs → **Prompt event**

n → neutron capture on proton (and ^{12}C) → γ → **Delayed event**

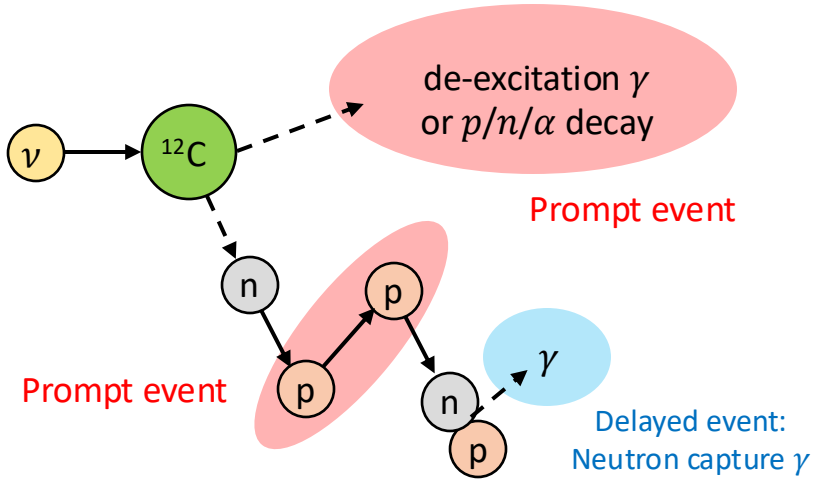
- Prompt event and delayed event have spatial-temporal correlation.
  → event identification by delayed-coincidence method

Basic concept of event discrimination

Signal: Inverse Beta Decay (IBD)



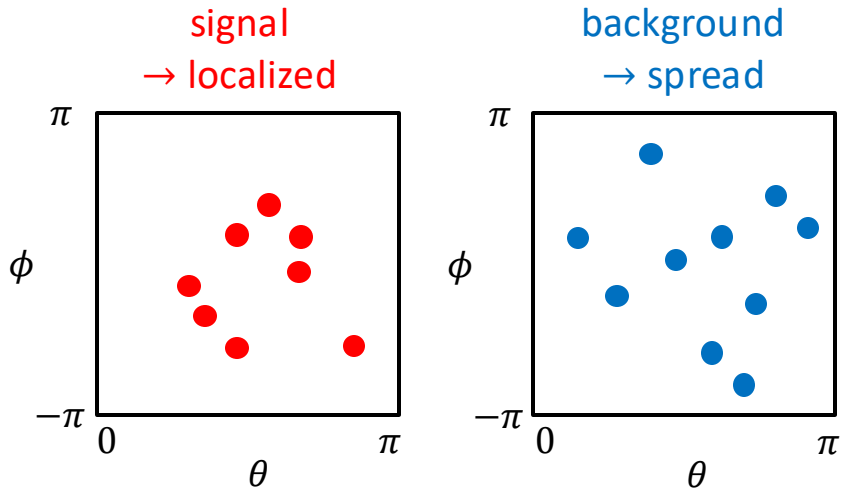
Background: atmospheric neutrino NC



Dominant background of IBD signal arises from atmospheric neutrinos.
Even though prompt events look same, prompt hit information is different.

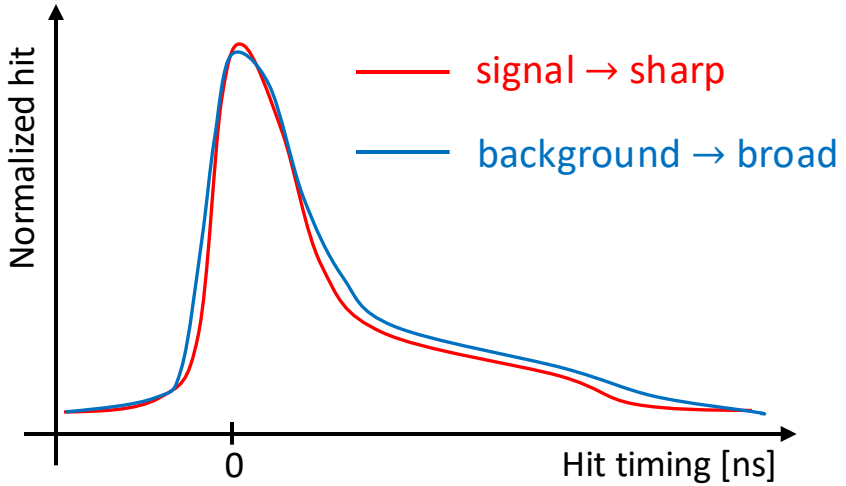
difference in the number of particles

→ difference in spherical hit map



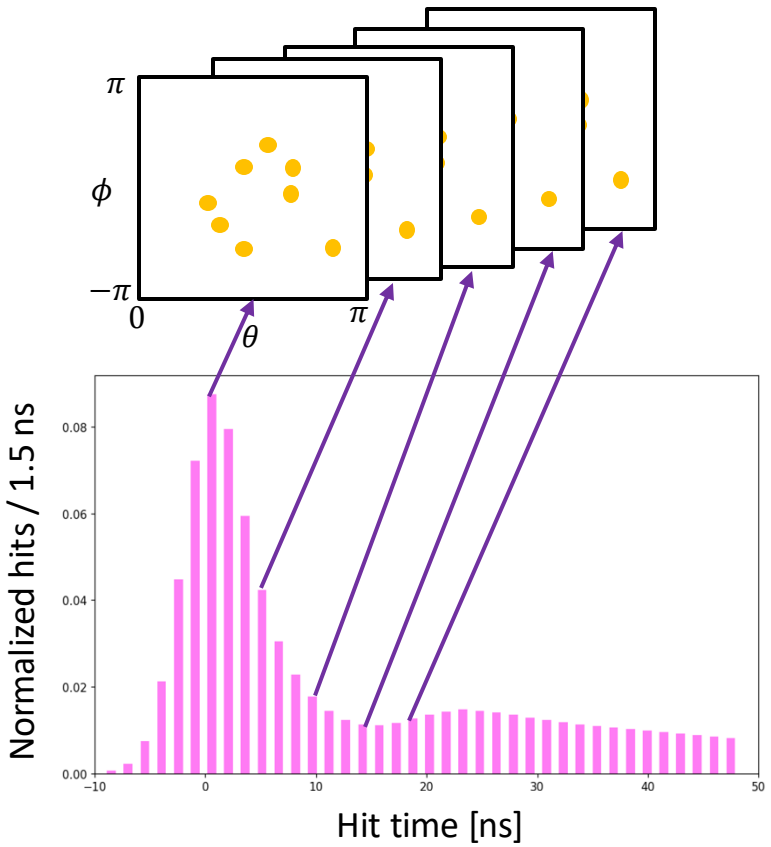
difference in the particle types

→ difference in hit timing distribution

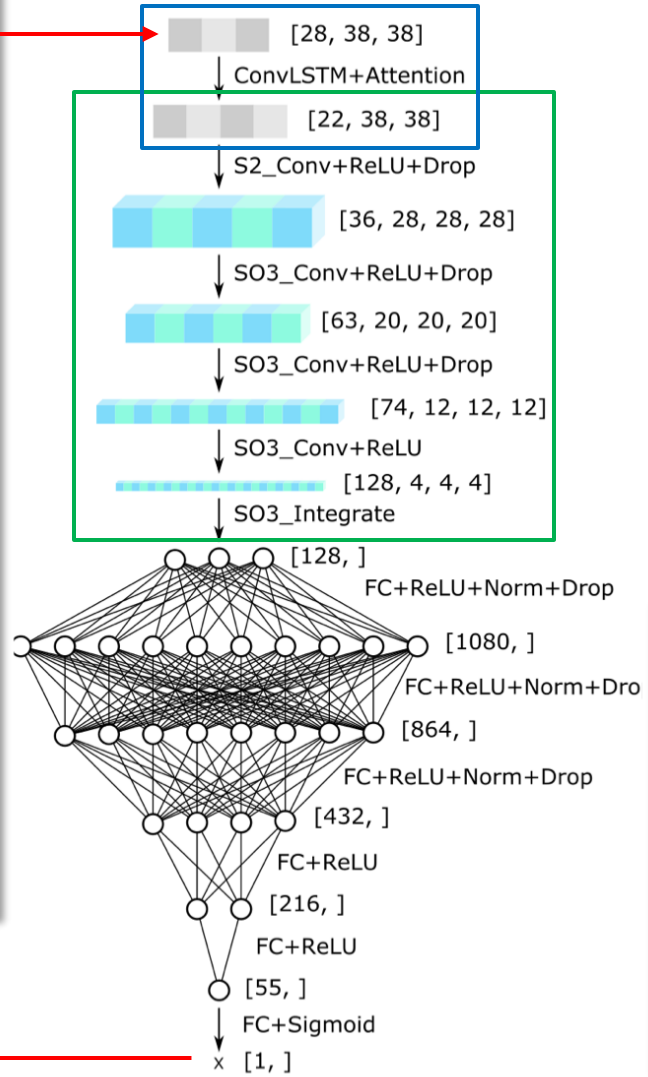


KamNet: spatiotemporal deep neural network

Input: sequential hit map

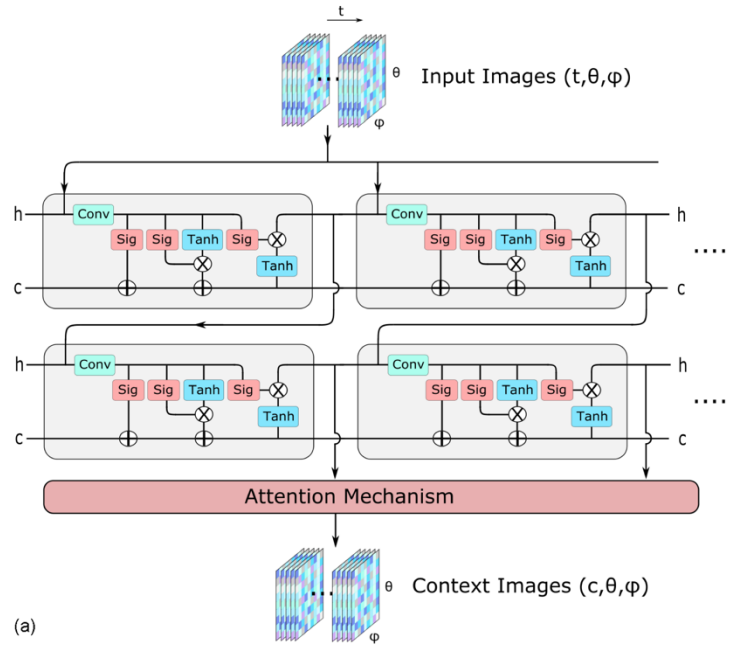


KamNet diagram

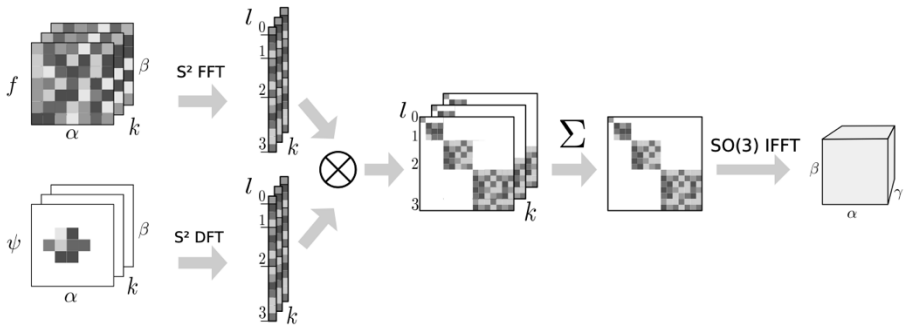


KamNet score (≃ signal likeness)

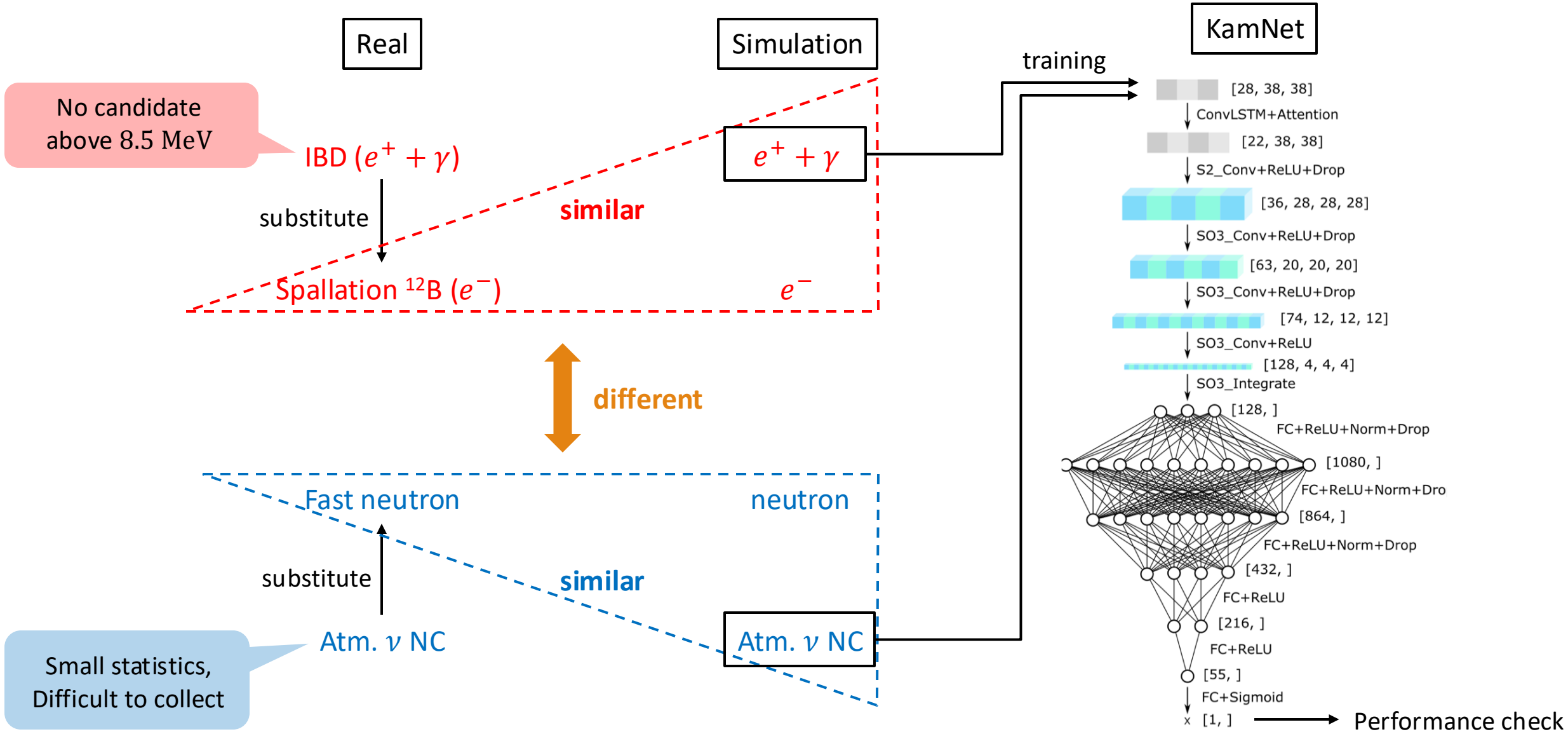
Convolutional LSTM → time correlation



"spherical" CNN → detector symmetry



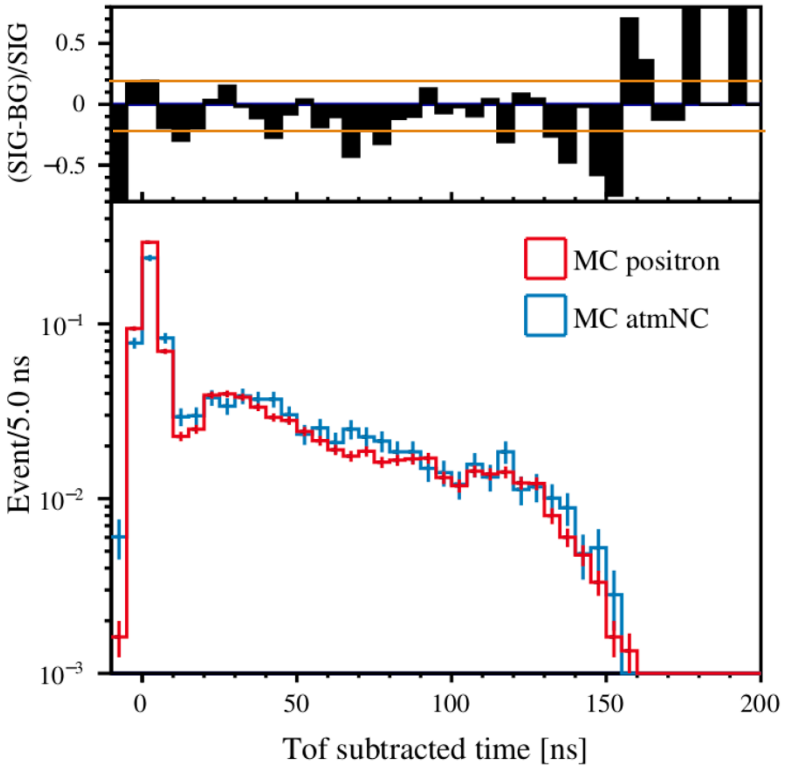
Analysis overview



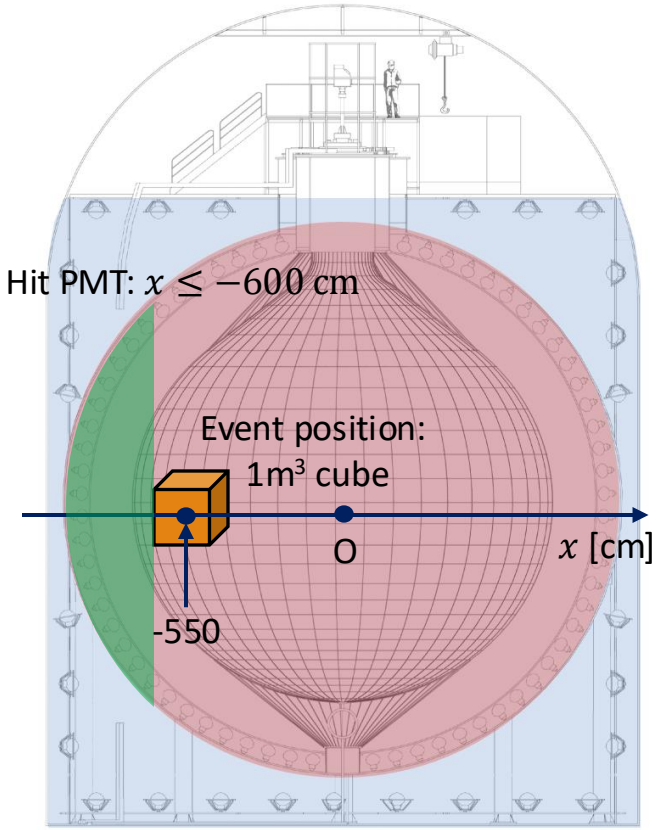
Hit timing difference

In simulation, $> 20\%$ difference is confirmed between signal and background.

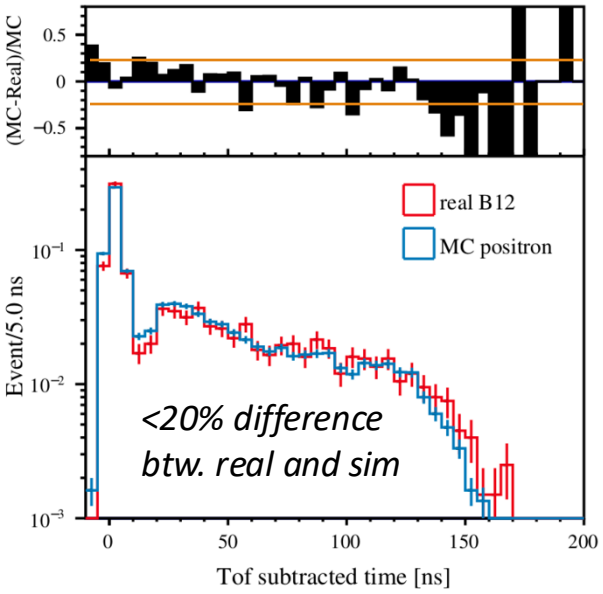
simulation $e^+ + \gamma$ vs simulation atm ν (signal vs background)



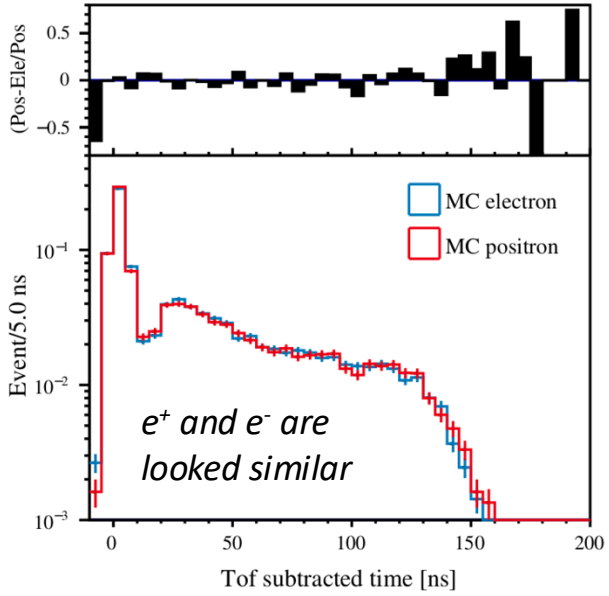
Ex) before purification



simulation $e^+ + \gamma$ vs real ^{12}B e^- decay



simulation $e^+ + \gamma$ vs simulation e^-



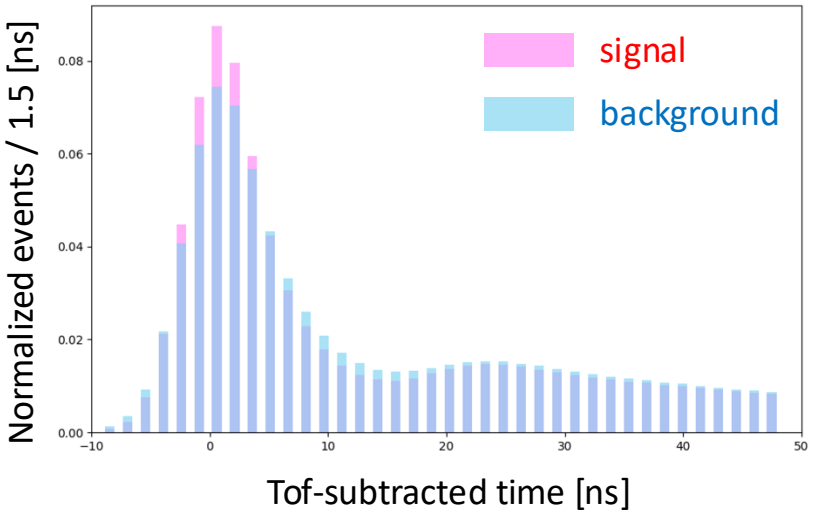
KamNet training inputs

Training data

Simulation events are used for KamNet training and test.

$e^+ + \gamma$ (signal)	$\times$ 10,000	$\times$ 3,000	$E_{\mathrm{vis}} = 8.5\text{–}30$ MeV
Atm. ν NC (background)	$\times$ 10,000	$\times$ 3,000	$r \leq 600$ cm
	for training	for test	

Hit timing distribution of training events



Hit information

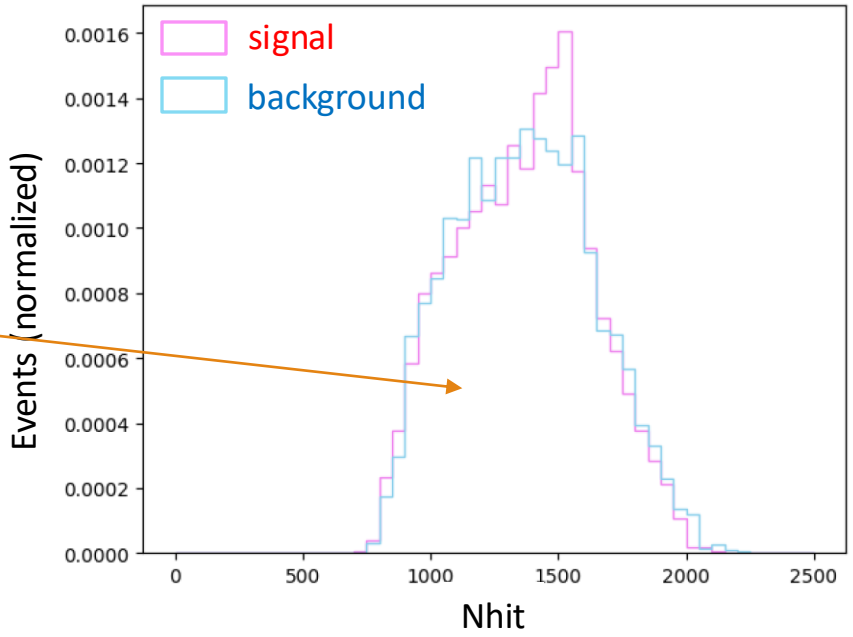
- Multi-hit PMT map
- Matching of total number of hit to avoid bias from hits

Overlap region is used for training

- Time window = $-10\text{–}+50$ [ns]

  Although time window could change KamNet performance, its effect is not so significant.

Nhit distribution before matching

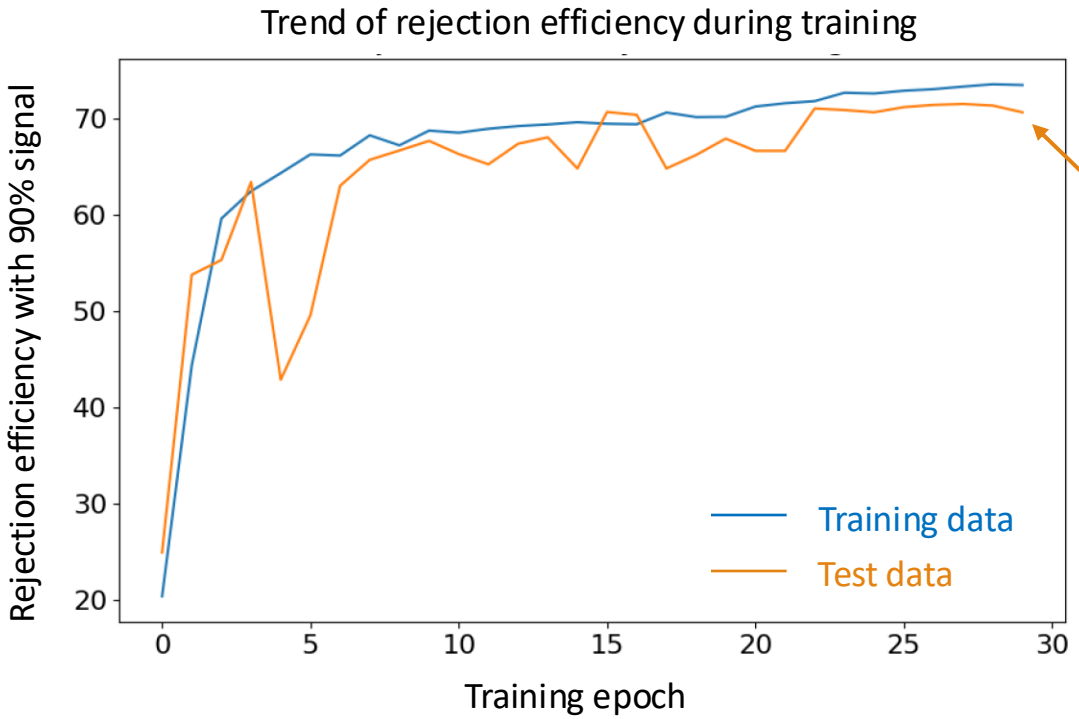


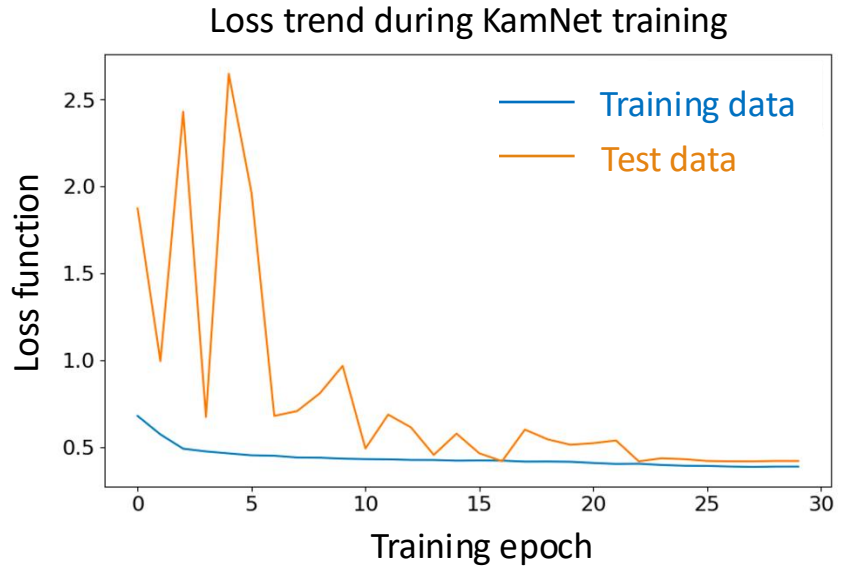
KamNet training results

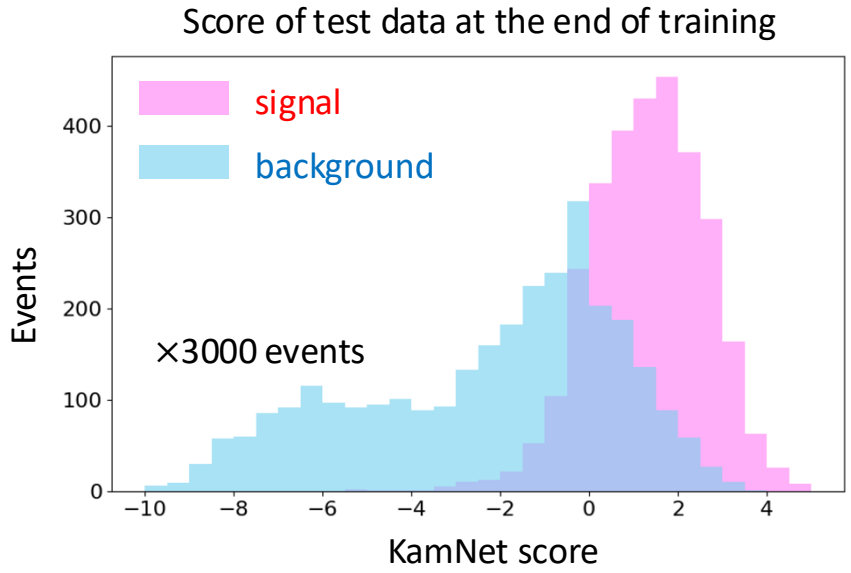
- Rejection efficiency is stabilized toward the end of training.

  → Training is succeeded (converged).

- The score distributions of training and test data are similar, and the rejection efficiencies of them are close.







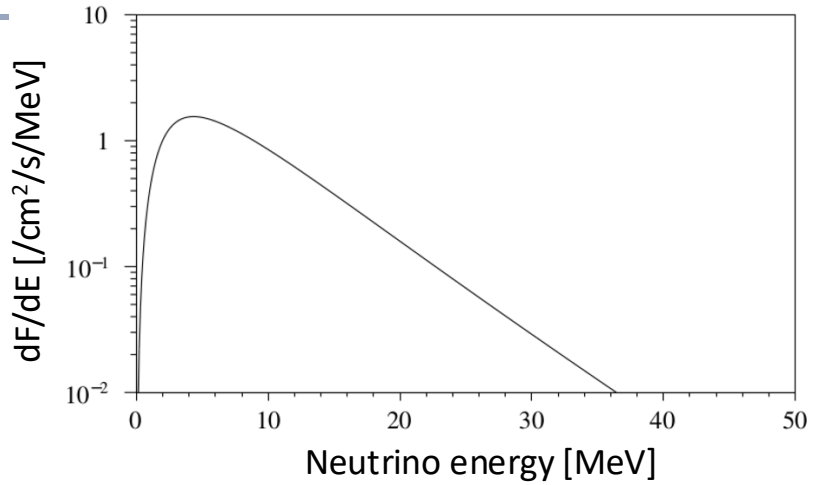
KamNet score threshold from FoM

FoM is calculated based on the test data at the end of training.

$(E_{\mathrm{vis}} = 8.5\text{–}30\ \mathrm{MeV}, r \leq 600\ \mathrm{cm})$

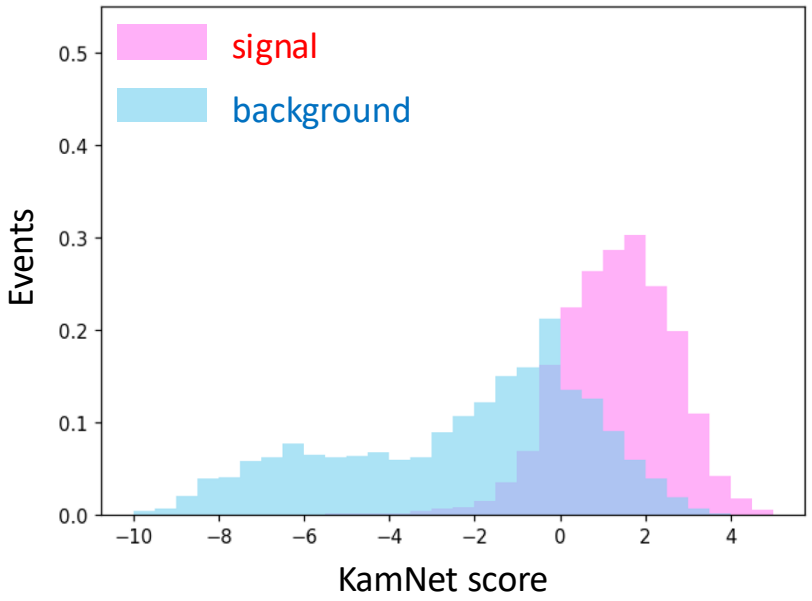
- signal: SRN model (Horiuchi2009)
- background: Expected atm. ν NC in the previous result S. Abe *et al* 2022 *ApJ* **925** 14
  → scaled by energy range, fiducial volume, livetime

Reference signal (Horiuchi2009)



ex) before purification

Score of test data at the end of training



Remaining events with KamNet threshold

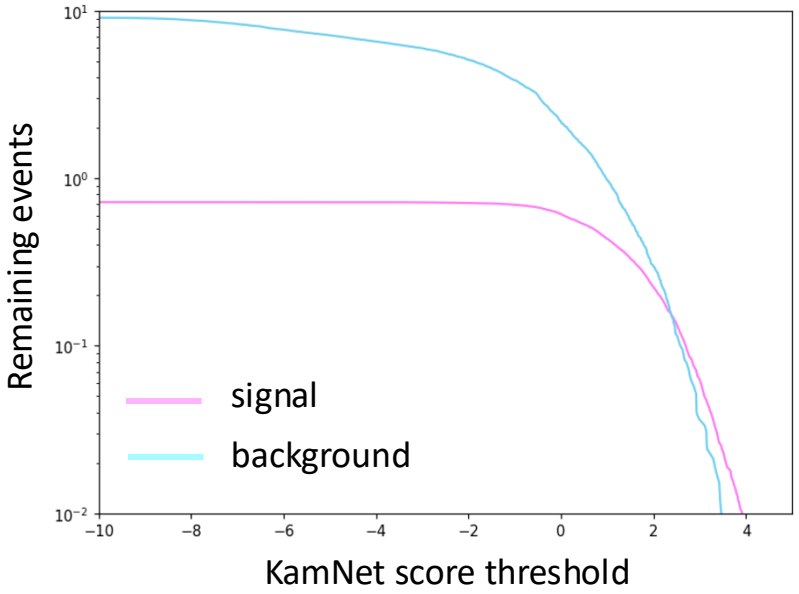
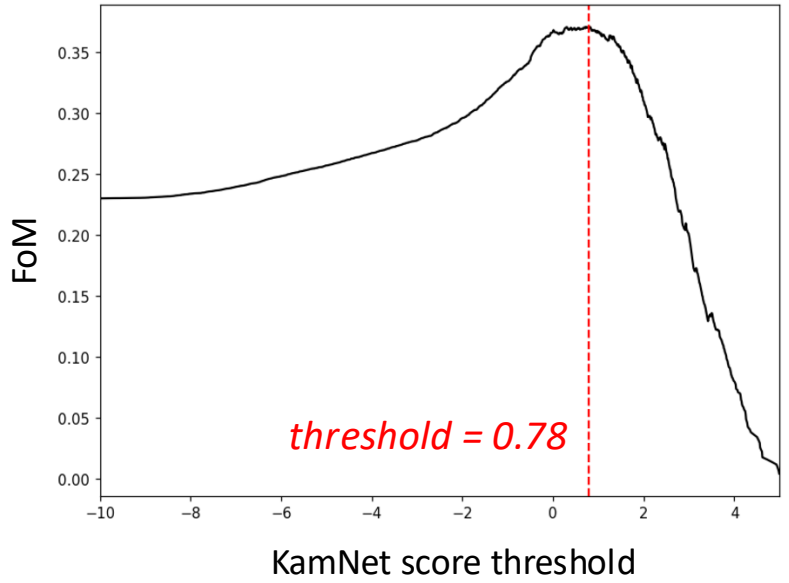


Figure of Merit for KamNet cut

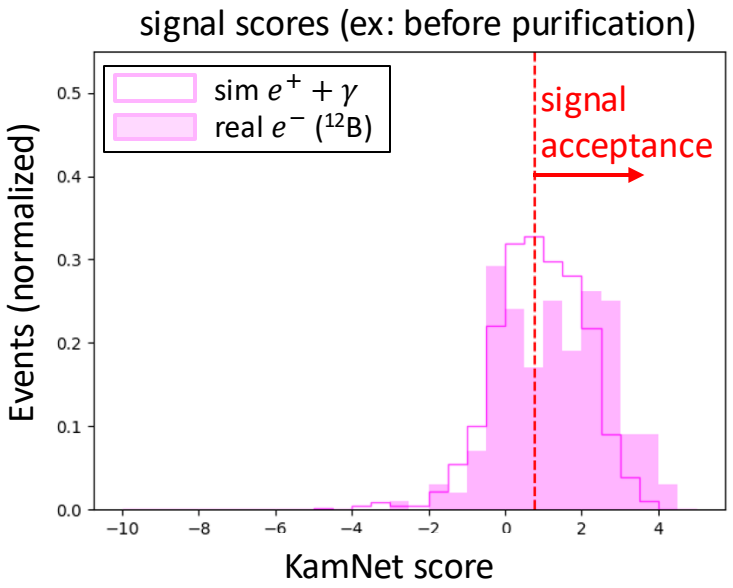


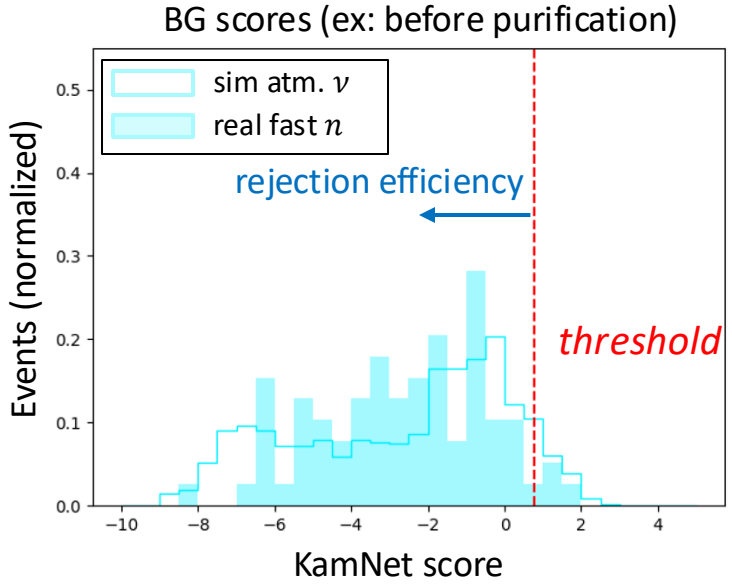
Summary of threshold and efficiency

Trained model shows ~75% background rejection with ~80% signal acceptance.

	before purification	after purification	Zen400	after OD
KamNet score threshold @ max FoM	0.78	0.59	0.31	0.25
signal acceptance	67.1%	79.0%	77.9%	79.2%
background rejection efficiency	86.6%	74.0%	74.4%	77.2%

Systematic uncertainty (difference in simulation and real)





- Difference between simulation and real data is considered as a systematic uncertainty.

  IBD (true signal) → spallation ^{12}B (similar signal)

  atmNC (true BG) → fast neutron (similar BG)

- This uncertainty is estimated based on the signal/BG efficiency at score threshold.

	before purification	after purification	Zen400	after OD
difference of signal acceptance	7.3%	1.2%	6.3%	2.0%
difference of BG rejection efficiency	2.8%	7.5%	16.3%	2.9%

preliminary

Summary

- Event arising from atmospheric neutrinos is one of the dominant background in KamLAND's SRN search.
- Deep neural network "KamNet" can discriminate events using the spatiotemporal difference in hit map.
- Trained KamNet model showed good performance:

  ~75% BG rejection efficiency with ~80% signal acceptance

- Systematic uncertainties related to the application of KamNet were estimated (~10%).

Prospects

- Fast neutron full simulation to estimate systematic uncertainty accurately

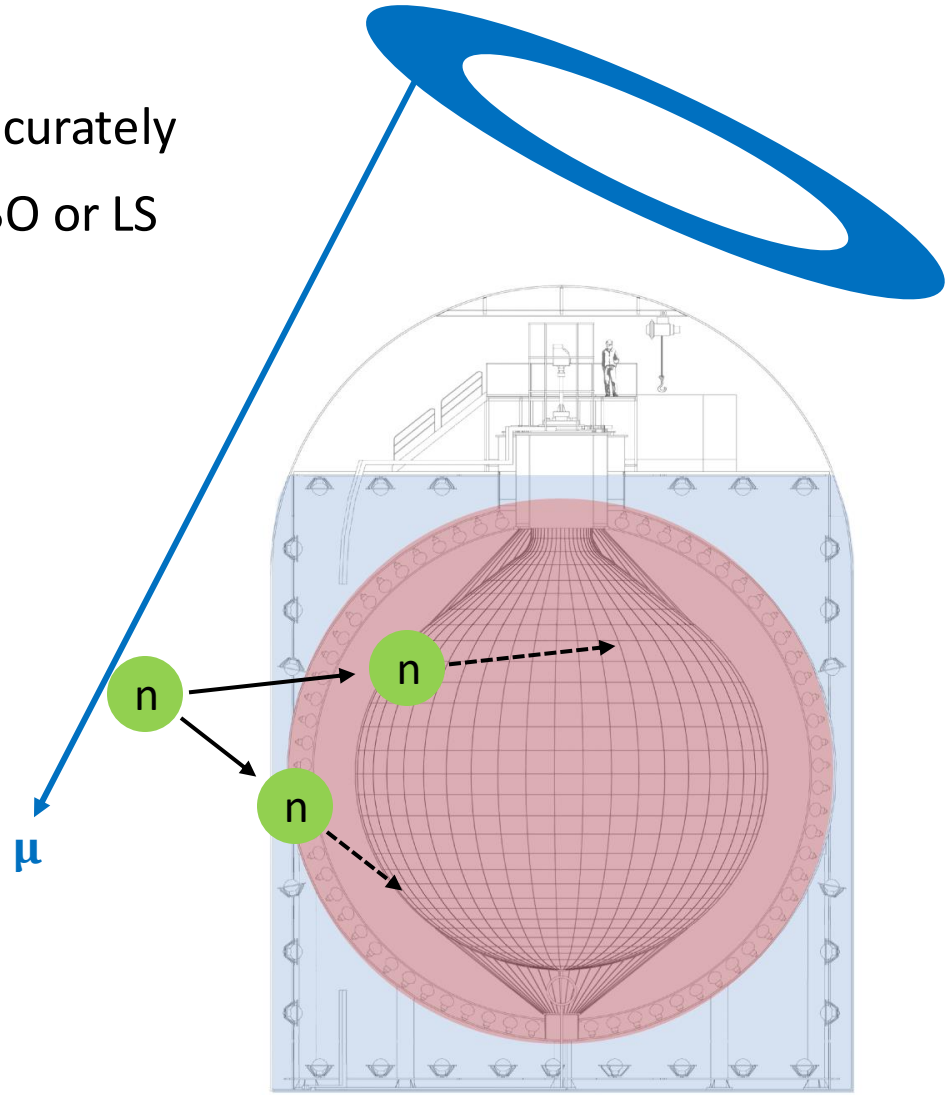
  Muon simulation → record kinematics when neutron enter the BO or LS

- KamNet model construction for during/after Zen800 period

- (KamNet model improvement to achieve better performance)

- KamNet cut for $\bar{\nu}_e$ candidate → astrophysical $\bar{\nu}_e$ search

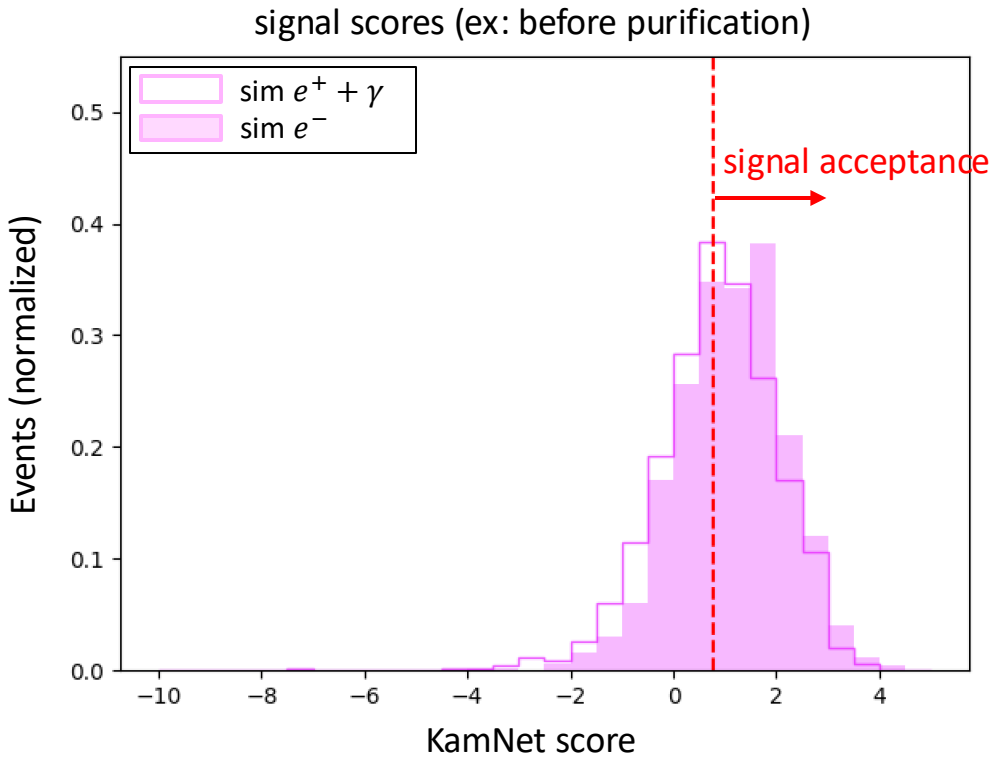
  ~1.5 times larger exposure, ~3 times better S/N from previous KamLAND result

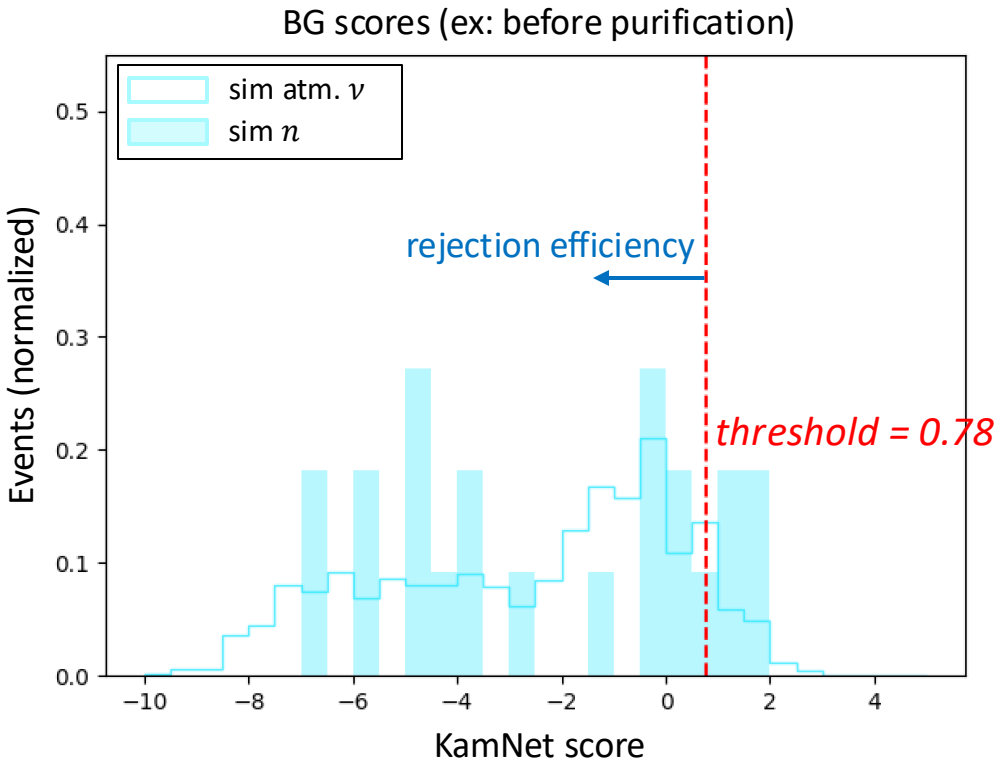


backup

KamNet performance for different particles

- $e^+ + \gamma$ and e^- are looked slightly different by KamNet. Difference of their acceptance is $< 10\%$.
- Statistics of neutron simulation is very low. It is difficult to state that atmospheric neutrinos and neutrons are similar.





Systematic uncertainty (performance fluctuation)

The fluctuation of KamNet performance in each training is considered as a systematic uncertainty.

This uncertainty is estimated from the results of 100 times trainings.

Ex) before purification