Astrophysical neutrino search in KamLAND

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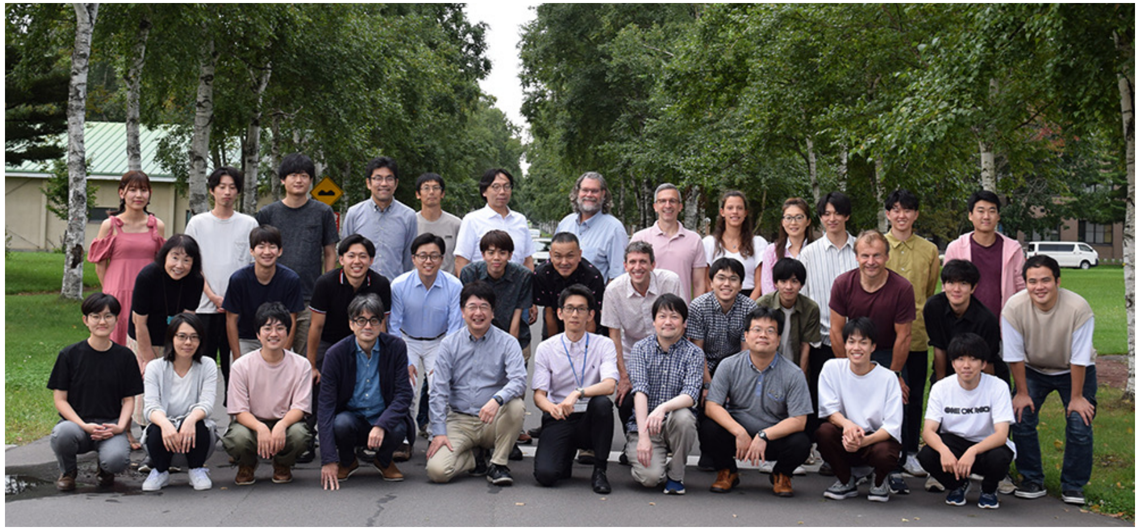
The KamLAND collaboration

~50 researchers from US, Netherlands, and Japan



2023 collaboration meeting @Obihiro

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大阪大学 OSAKA UNIVERSITY

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TOKUSHIMA UNIVERSITY

UNIVERSITY of HAWAIʻI

Nikhef

BERKELEY LAB

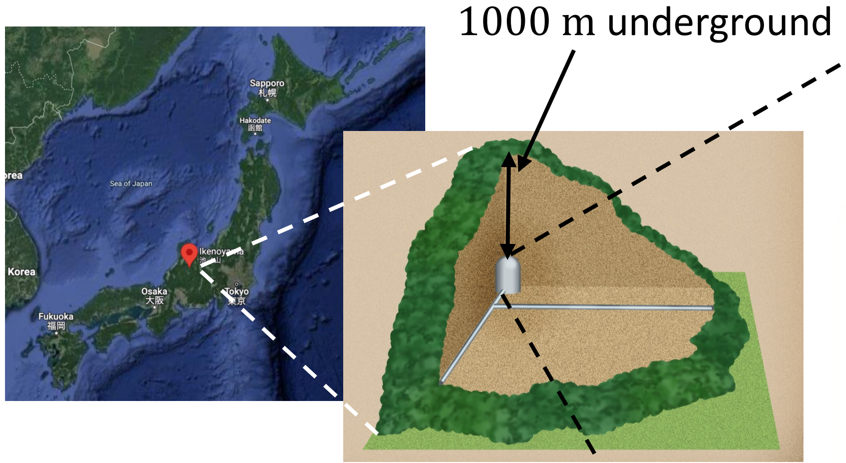
THE UNIVERSITY OF TENNESSEE KNOXVILLE

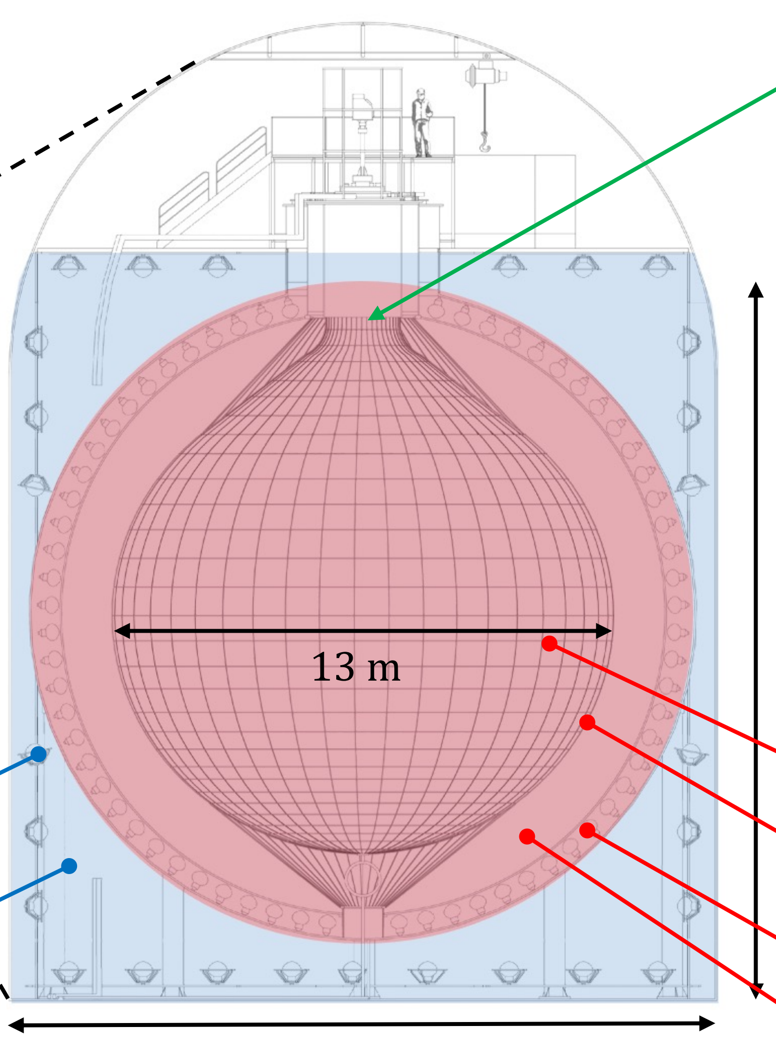
TUNL

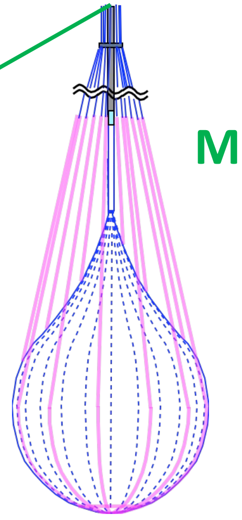
BOSTON UNIVERSITY

Kamioka Liquid-scintillator Anti-Neutrino Detector (KamLAND)

Located in Kamioka @Japan







Miniballoon

($0\nu\beta\beta$ search has been performed during KamLAND-Zen period.)

Inner detector

Scintillation light → physics event observation

1 kton Liquid Scintillator (LS)

Nylon/EVOH balloon

17 & 20-inch PMTs

Buffer oil

Outer detector

Cherenkov light → muon veto

20-inch PMTs

Purified water

KamLAND has a significant sensitivity to MeV-energy neutrinos.

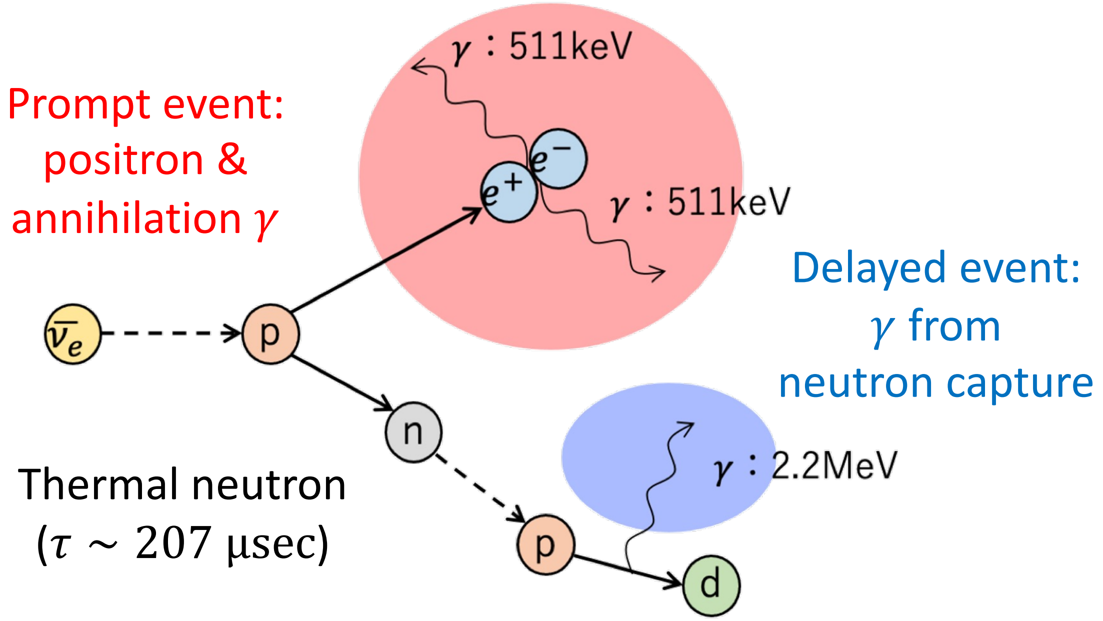
Astro-ν detection channel

Inverse Beta Decay (IBD) $\bar{\nu}_e + p \rightarrow n + e^+$

- Neutrino energy is reconstructed from observed energy.

$$E_\nu \simeq E_{\text{prompt}} + T_n + 0.78\ [\text{MeV}]$$

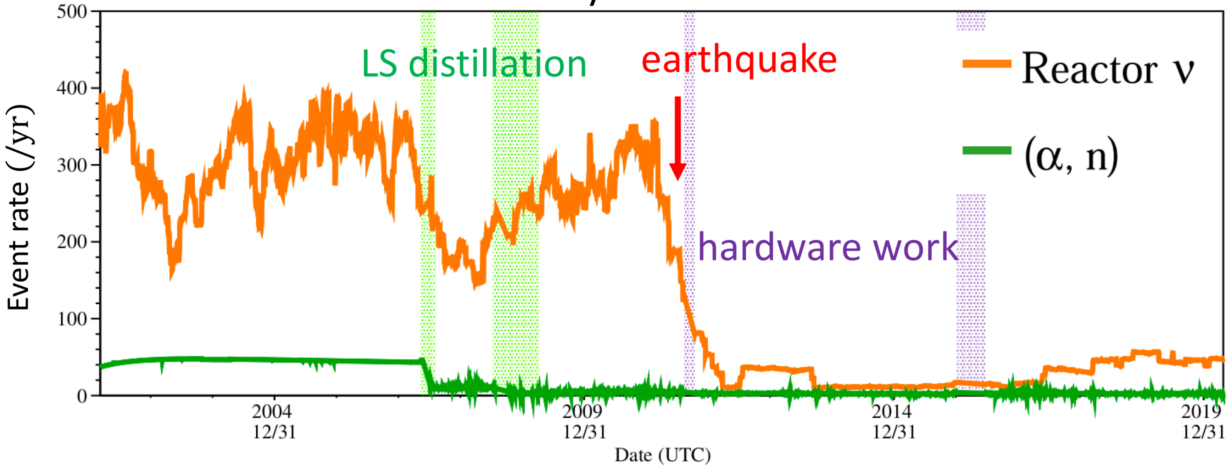
- Space-time correlations are used for this observation (***delayed coincidence***).



Backgrounds

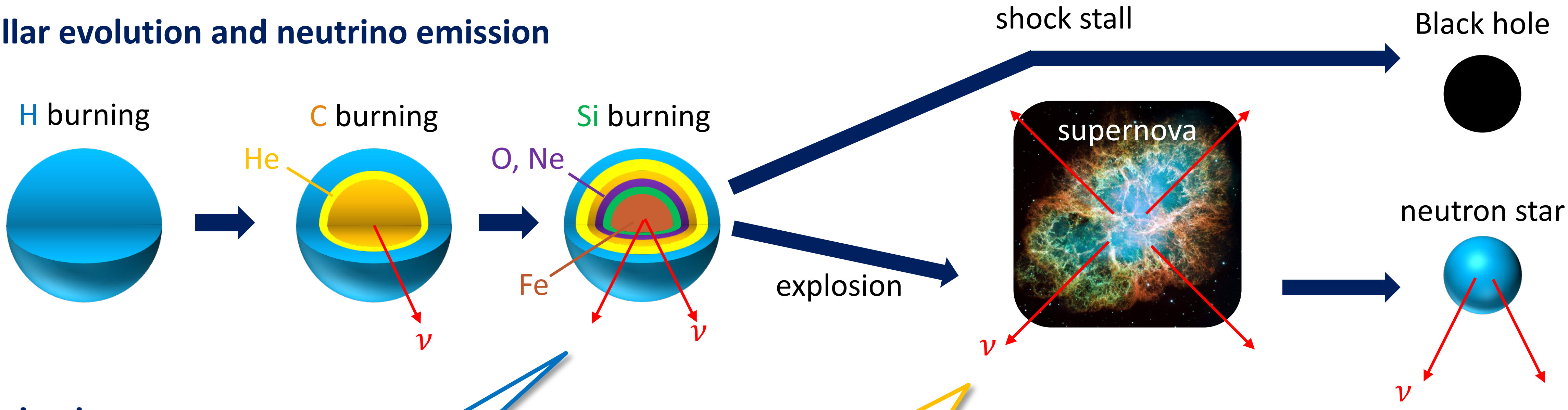
Reactor $\bar{\nu}_e$	Indistinguishable from astro-ν events
Geo $\bar{\nu}_e$	
Accidental coincidence	likelihood cut
Spallation products (9Li)	muon veto, shower tag
$(\alpha$, n) interaction	LS distillation
Atmospheric neutrino	hard to distinguish
Fast neutron	

Time variation of delayed coincidence event rate



Supernova and neutrinos

Stellar evolution and neutrino emission



Motivations

Pre-supernova neutrino (pre-SNν)
- Later phase of stellar evolution

Supernova neutrino (SNν)
- Explosion mechanism
- Neutrino mass hierarchy
- (Galactic) star formation rate

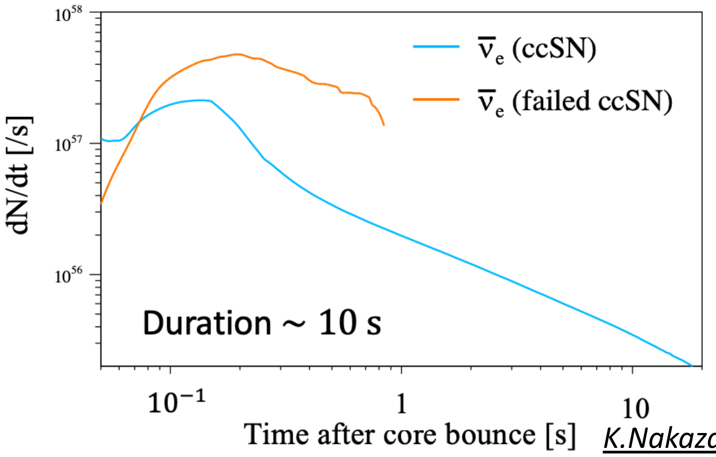
Supernova relic neutrino (SRN)
← integration of past SNνs
- Explosion mechanism
- Cosmic history

<u>Important information can be obtained from above neutrino observations.</u>

SNν Supernova neutrino burst search

Period: Mar. 2002–Apr. 2020
(livetime ~ 13.7 yr)

Time distribution of SNν($\bar{\nu}_e$)



K.Nakazato, et al, ApJS, **205** 2 (2013)

Selection criteria

Event rate of IBD candidates is low.
~ 1 event/day (~2011)
~ 0.1 event/day (2011~)

Energy range: $0.9 \leq E_{\mathrm{prompt}}\ [\mathrm{MeV}] \leq 100$

Requirement: two IBD candidates (cluster) within 10 s time window

Search result

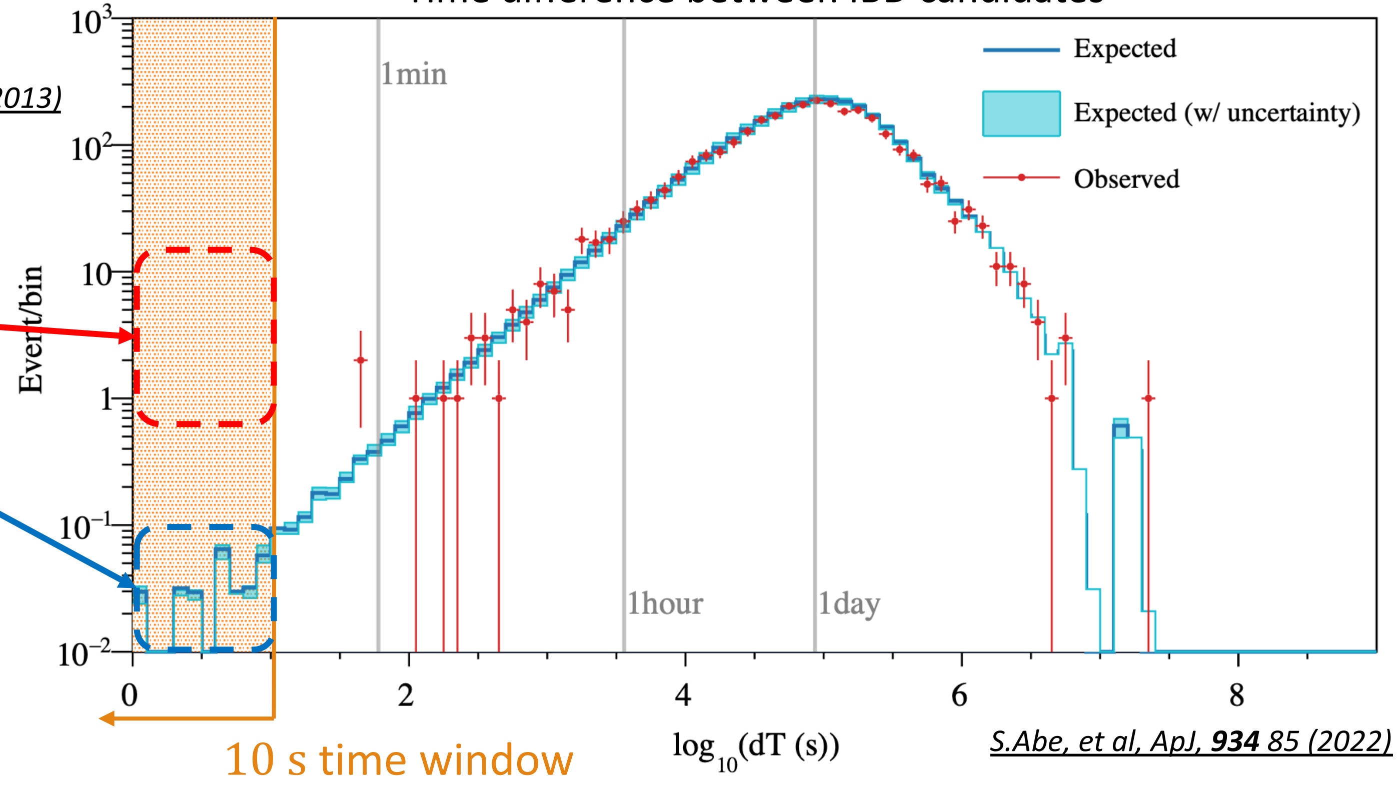
There are no SNν candidates.

"Background" of the burst search

Observed cluster rate $< 0.15\ \mathrm{yr}^{-1}$ *(90% U.L.)*

To interpret this result as a supernova rate,
it is necessary to estimate the detectable range.

Time difference between IBD candidates



S.Abe, et al, ApJ, **934** 85 (2022)

SNν Interpretation of search result

Model by Nakazato *(K.Nakazato, et al, ApJS, **205** 2 (2013))*
is used for this numerical calculation.

Detectable range

SNνs are observed with $\geq 95\%$ detection probability

$\leq 40\text{–}58$ kpc (ccSN)
$\leq 62\text{–}77$ kpc (failed ccSN)

with model & neutrino
mass hierarchy uncertainties

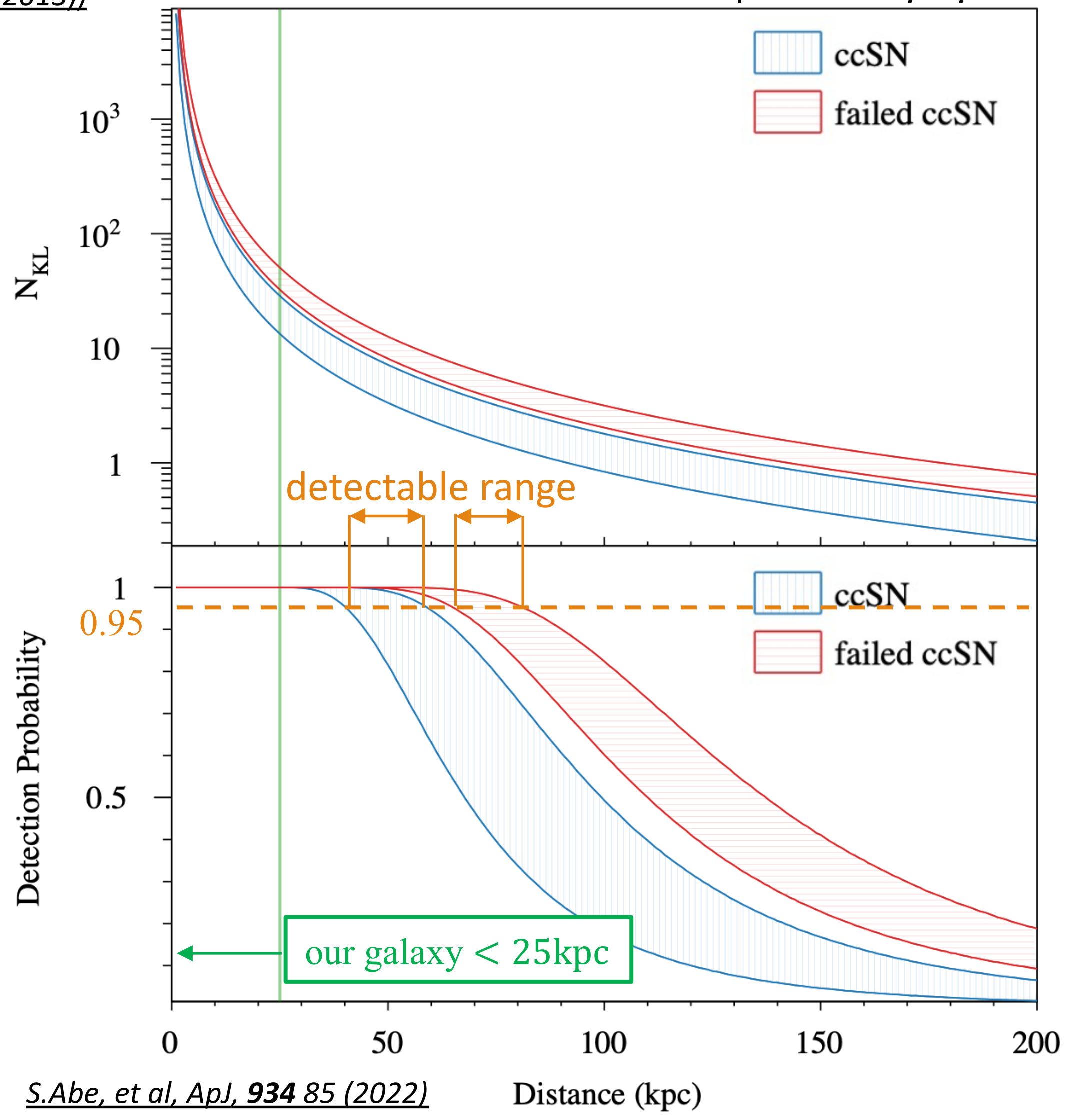
SNνs from our Galaxy can be observed with $> 99\%$ probability

Supernova rate

Observed cluster rate = supernova rate in our Galaxy

Galactic supernova rate $< 0.15\ \mathrm{yr}^{-1}$ (90% U.L.)

Number of events and detection probability by IBD



*S.Abe, et al, ApJ, **934** 85 (2022)*

Constraint on the Galactic Star Formation Rate (SFR)

We attempted to constrain the Galactic SFR, which is important to understand our Galaxy.

Relation between supernova rate and SFR

$$R_{\mathrm{SN}}^{\mathrm{gal}} = k_{\mathrm{SN}}\psi_{\mathrm{SFR}}^{\mathrm{gal}}$$

$R_{\mathrm{SN}}^{\mathrm{gal}} = 0.15\ \mathrm{yr}^{-1}\ [\mathrm{yr}^{-1}]$: Galactic supernova rate (burst search result)

$\psi_{\mathrm{SFR}}^{\mathrm{gal}}\ [M_{\odot}\mathrm{yr}^{-1}]$: Galactic SFR

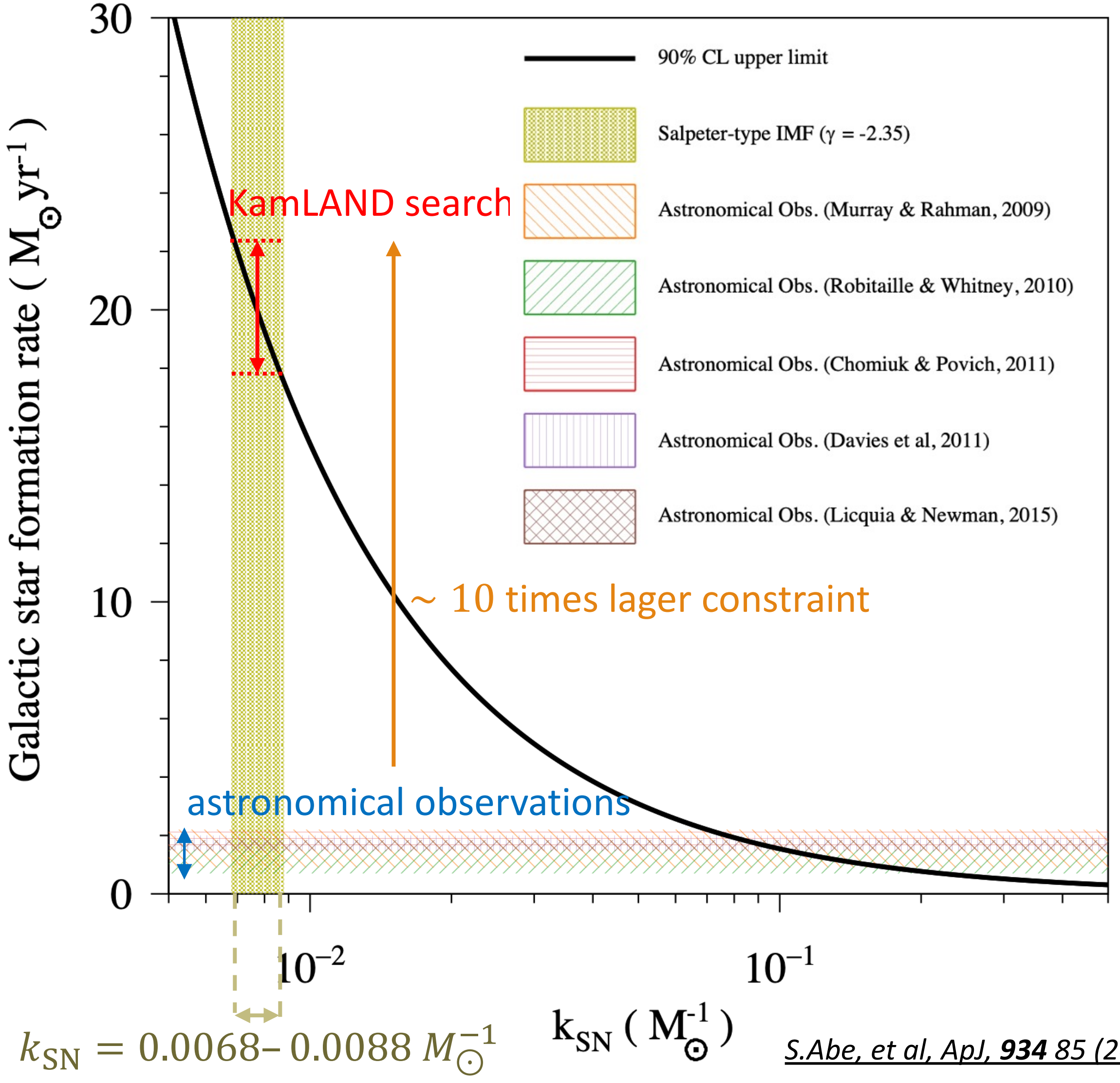
$k_{\mathrm{SN}} = 0.0068\text{–}0.0088\ [M_{\odot}^{-1}]$: scale factor
with information of mass distribution of stars
(Initial Mass Function)

Result

$\psi_{\mathrm{SFR}}^{\mathrm{gal}} < 17.5\text{–}22.7\ M_{\odot}\mathrm{yr}^{-1}$ ***(90% U.L.)***

First constraint from neutrino experiments

Galactic SFR from this work and astronomical observations



*S.Abe, et al, ApJ, **934** 85 (2022)*

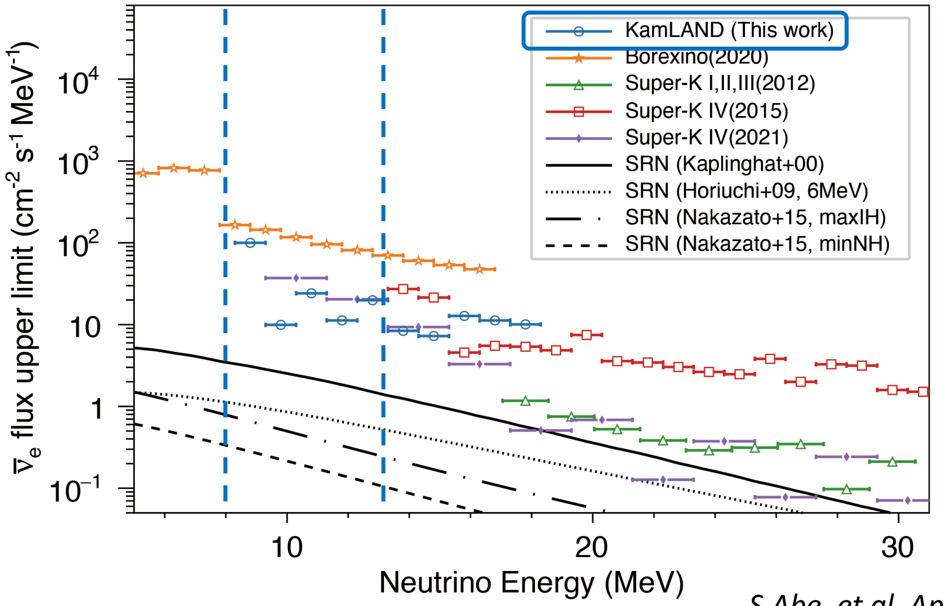
SRN Supernova relic neutrino search

Period: Mar. 2002–Jul. 2020
(livetime ~ 12.4 yr)

Latest results $E_{\text{prompt}} = 7.5\text{–}30\ \text{MeV}$

- Fitting of energy & radius distributions
  → zero event best fit for all models
- Model independent flux upper limit
  → most stringent limit for 8– 13 MeV

Model independent neutrino flux upper limit



*S.Abe, et al, ApJ, **925** 14 (2022)*

Plans for improvements

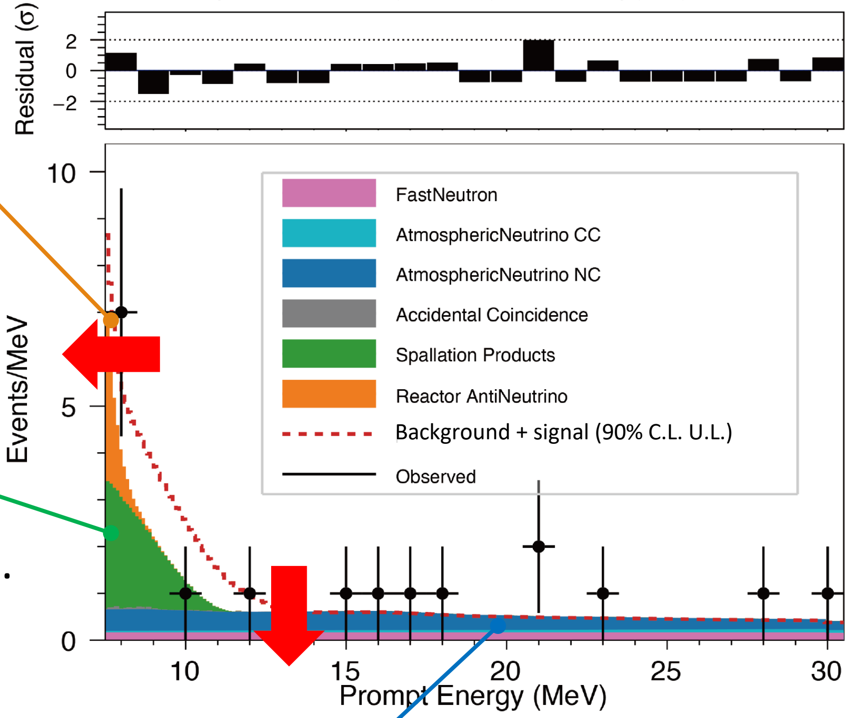
Reactor $\bar{\nu}_e$

Extended livetime of reactor-off period
→ lower energy threshold

Spallation products

Likelihood cut with muon-induced shower info.

Fitting result of prompt energy spectrum



*S.Abe, et al, ApJ, **925** 14 (2022)*

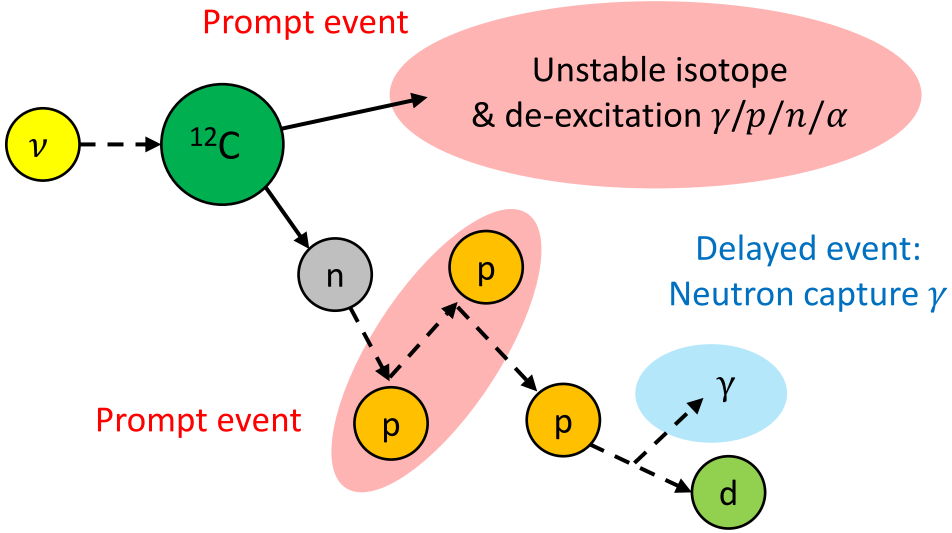
Main topic

Atmospheric neutrinos

Event discrimination using machine learning techniques

SRN Atmospheric neutrino background

- Atm. ν neutral current makes sequential events.
  - "Same" features as IBD for the delayed-coincidence method
  - Largest background in $E_{\mathrm{prompt}} \gtrsim 10\ \mathrm{MeV}$

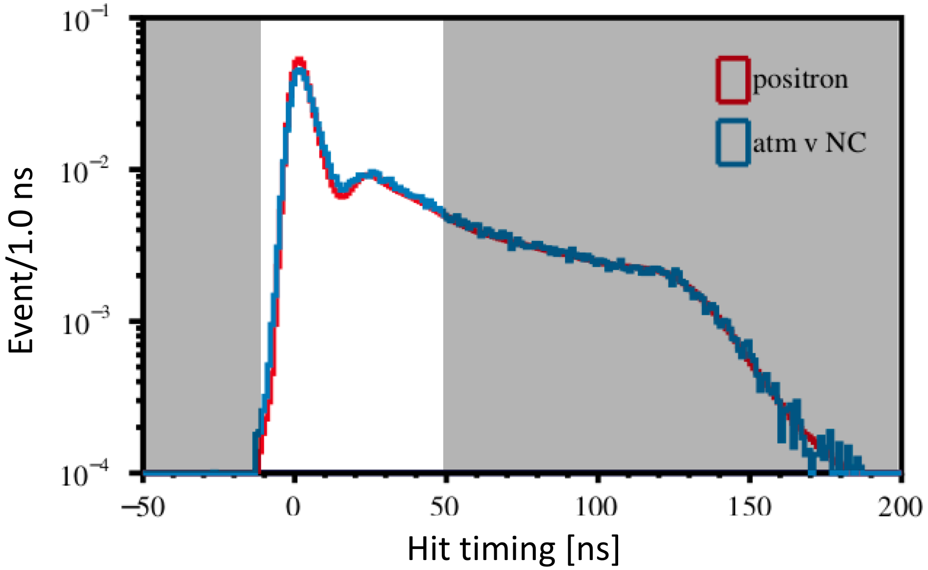


- Differences should appear in the prompt hit pattern.
  - Hit timing
  - Hit charge
  - Hit position

Event discrimination using a neural network

- Given the lack of high-energy ($E_{\mathrm{prompt}} \gtrsim 10\ \mathrm{MeV}$) IBD and atm. ν candidates, a well tuned simulation is developed.

Hit timing distribution of simulation events

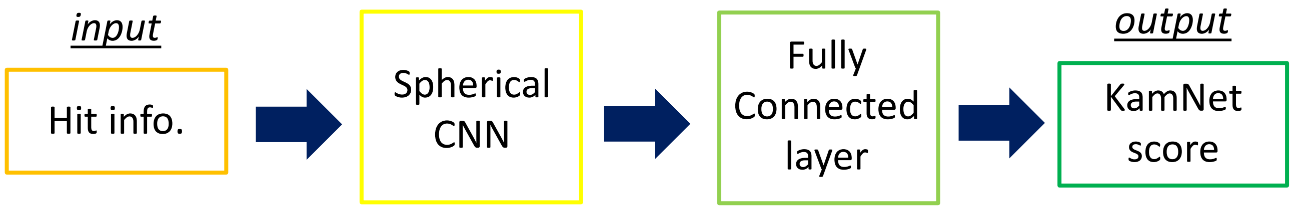


Event discrimination using a neural network: KamNet

- KamNet is a spatiotemporal NN developed by KamLAND group.

  A. Li, et al, Phys. Rev. C, **107** 014323 (2023)

  - Spherical neural network to **conserve detector's symmetry**
  - Convolutional long short-term memory to **incorporate time correlation**
  - Dropout to **avoid over training**

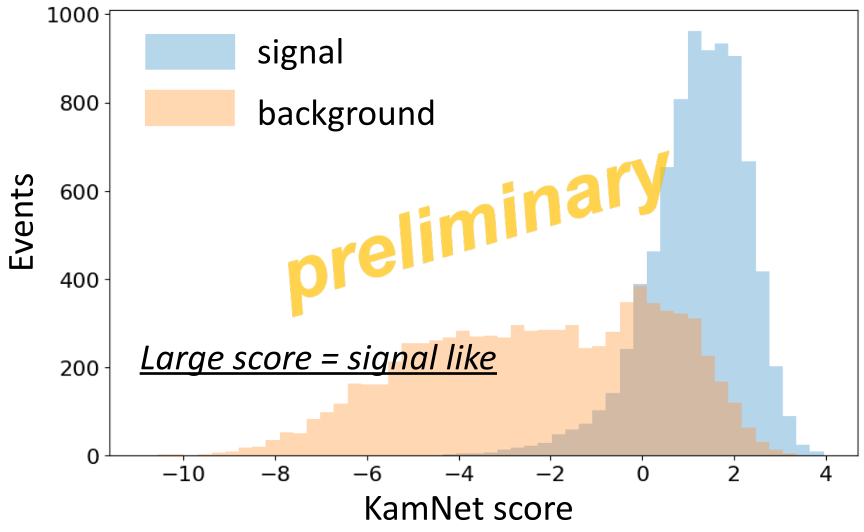


- Training have been done with tuned simulation events.
  - Separated KamNet score distribution (upper right)

    → **Event discrimination is successful.**
  - Rejection efficiency saturation (lower right)

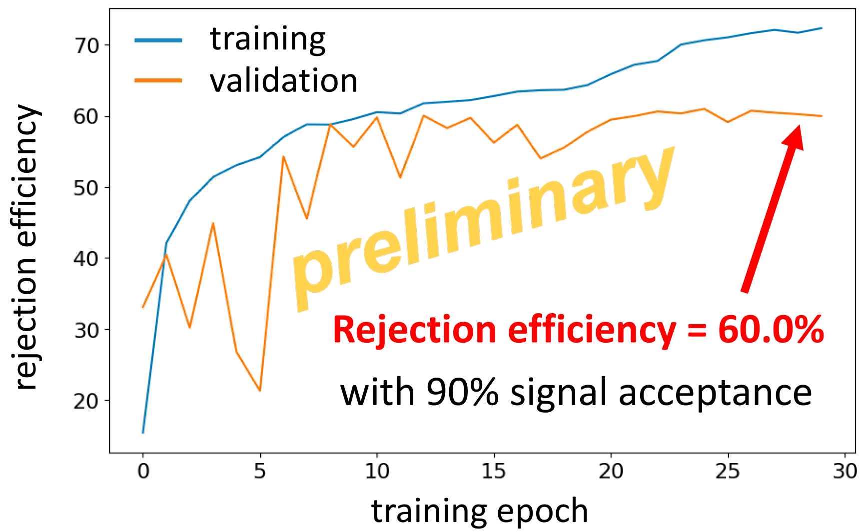
    → **Training of KamNet is sufficient.**

KamNet score for training data



Large score = signal like

Rejection efficiency over training

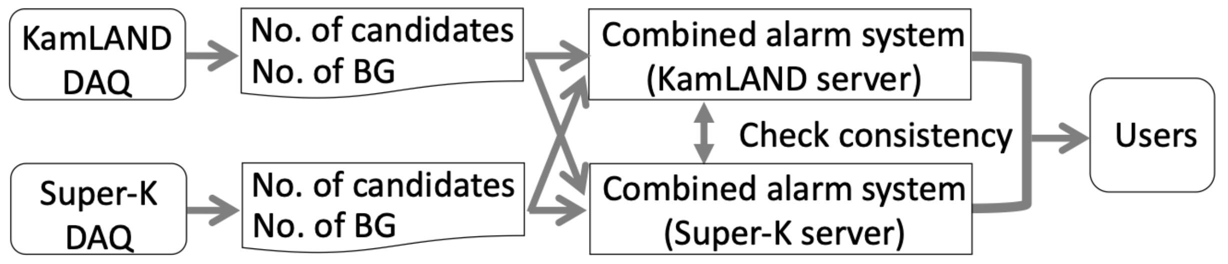


Rejection efficiency = 60.0%

with 90% signal acceptance

Combined pre-SN alarm

Combined pre-SN alarm system by KamLAND & Super-Kamiokande (SK-Gd) has been launched.



KamLAND DAQ → No. of candidates No. of BG → Combined alarm system (KamLAND server)

Super-K DAQ → No. of candidates No. of BG → Combined alarm system (Super-K server)

Check consistency → Users

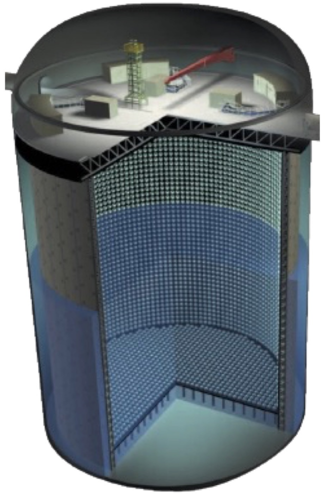
KamLAND

Low background condition → **early alarm**

SK-Gd

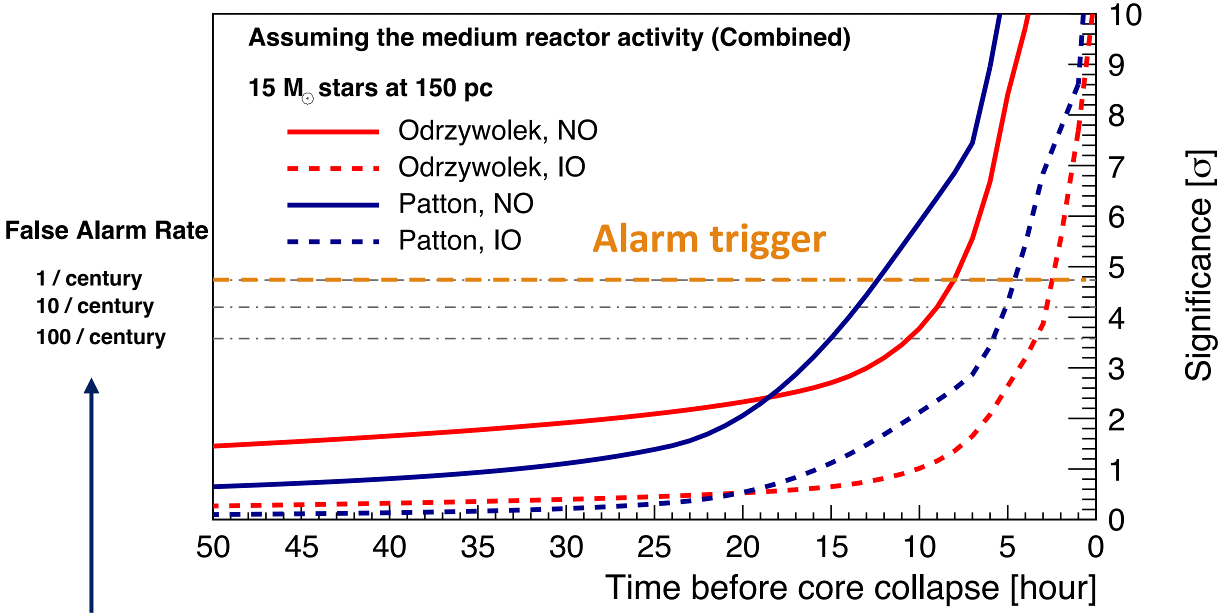
Large fiducial volume

→ **rapid increase of significance**



- 22.5 kt water Cherenkov detector
- Neutron capture gamma-ray by Gd

Time evolution of significance by the combined alarm system



Frequency of false-positive alarm calculated by MC (BG only)

arXiv:2404.09920

Alarm with time profile

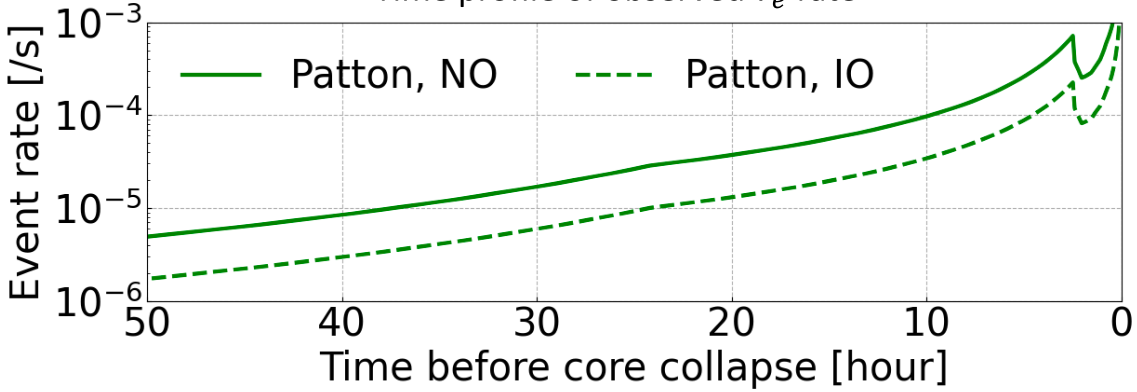
To improve the alarm sensitivity, time profile (shape) is incorporated with the number of event.

$$likelihood =$$

$$\underbrace{PDF(\text{\# of evt in time window})}_{\text{“Rate term”}} \times \underbrace{PDF(\text{time profile})}_{\text{“shape term”}}$$

$$likelihood\ ratio = \frac{likelihood(\text{BG} + \text{signal})}{likelihood(\text{BG only})}$$

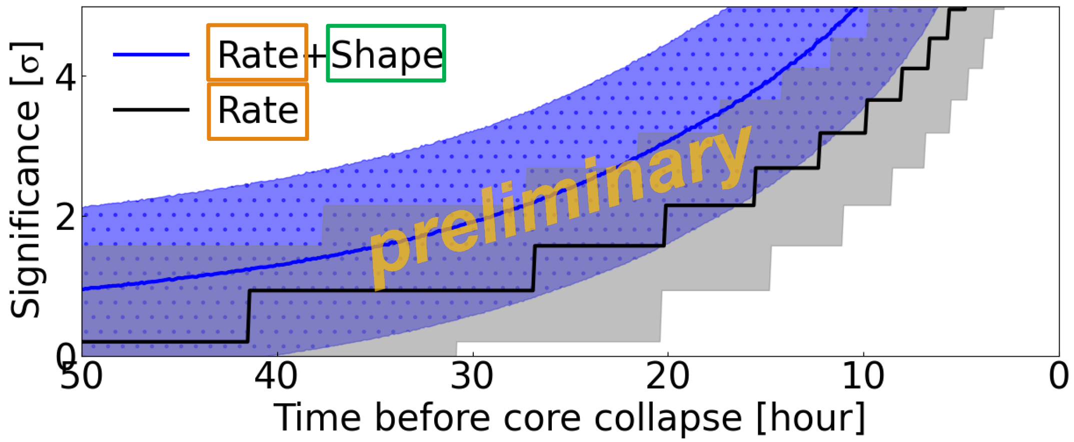
Time profile of observed $\bar{\nu}_e$ rate



Warning time (significance> 3σ)

		Rate+Shape Reference model		**Rate**
		Patton NO	Patton IO	
Observed model	Patton NO	**20.4**	**20.2**	12.2
	Patton IO	**7.3**	**7.3**	2.4

Comparison of two analysis method



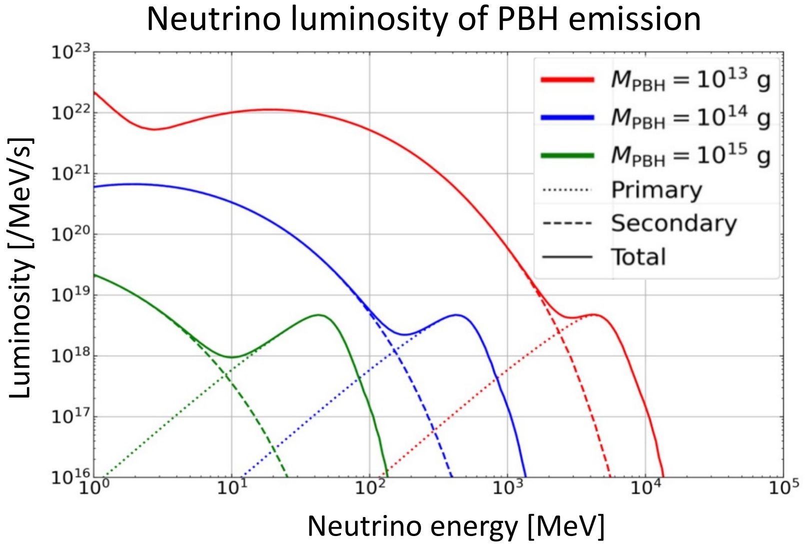
$15\text{M}_\odot$, 150 pc, Patton model with NO

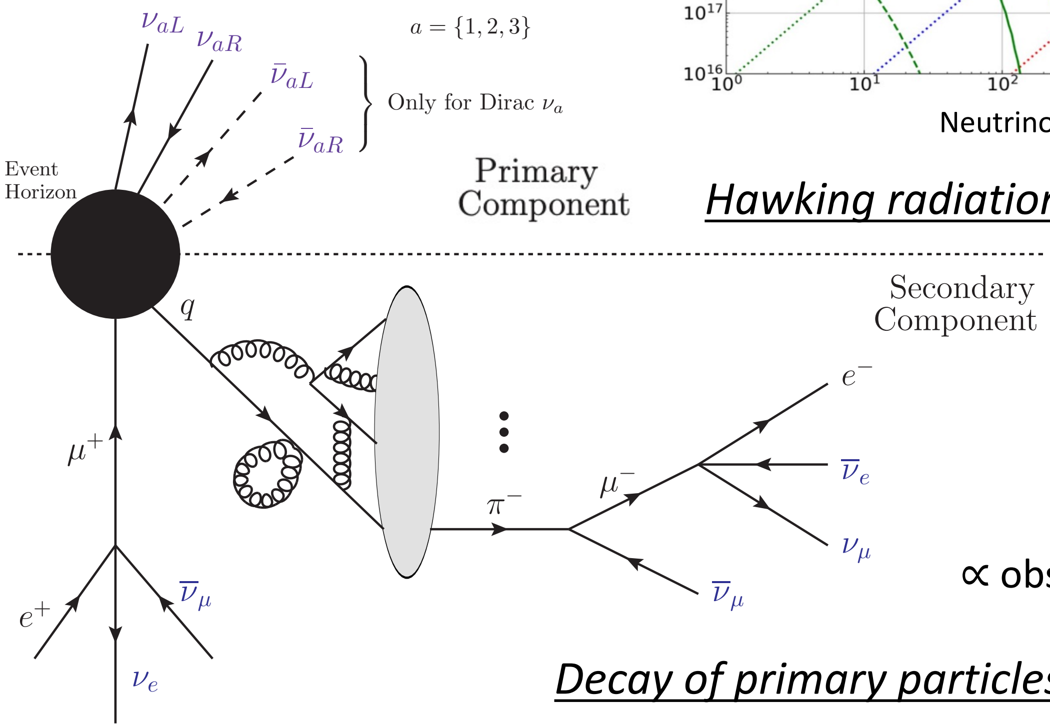
Alarm sensitivity is improved due to the shape term.

PBH Neutrinos from Primordial Black Hole

Primordial Black Hole

- Hypothetical black hole formed by gravitational collapse in the early universe
- Dark matter candidate





Hawking radiation

Decay of primary particles

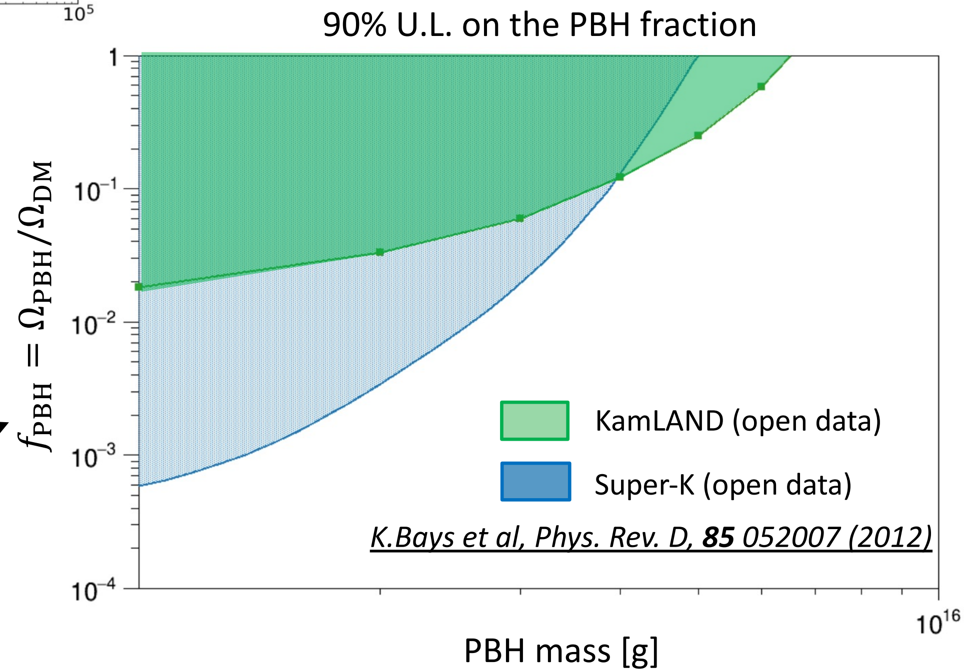
PBH neutrino search

- Constraint on the PBH fraction f_{PBH} from the KamLAND's open data

*S.Abe, et al, ApJ, **925** 14 (2022)*

- Rejection of $f_{\mathrm{PBH}} = 1$
  → **evidence of other dark matters**

∝ observed events



*K.Bays et al, Phys. Rev. D, **85** 052007 (2012)*

Summary

- KamLAND, which is a 1 kt liquid scintillator, can search astrophysical neutrinos via inverse beta decay.
- There are no supernova neutrino candidates. We set upper limit on the Galactic supernova rate and Galactic star formation rate.
- For supernova relic neutrino search, a neural network analysis is in progress.
- Combined pre-supernova alarm system is running. Alarm with time profile is under development.
- KamLAND can also search neutrinos from primordial black hole. This study is ongoing.

backup

Previous studies of SN burst search

KamLAND

🟩 Liquid scintillator 🟦 Cherenkov

Search period : Mar. 2002–Apr. 2020

Livetime : 5011.51 day

volume : 1 kt

Energy region : $0.9 \leq E\ [\mathrm{MeV}] \leq 100$

UL on the supernova rate : $0.15\ \mathrm{yr}^{-1}$

Detectable range : $\lesssim 41\text{–}59\ \mathrm{kpc}\ (\mathrm{ccSN})/\lesssim 64\text{–}79\ \mathrm{kpc}\ (\text{failed ccSN})$

	SK	LVD	Baksan	SNO	MiniBooNE	IMB
Search period	1996年4月 –2018年5月	1992年6月 –2021年	1980年6月 –2018年12月	1999年11月 –2003年8月	2004年12月 –2008年7月	1986年5月 –1991年3月
Livetime	2589.2 day（SK-I, II） 3318.41 day（SK-IV）	∼ 29 yr	33.02 yr	241.4 day（Phase I） 388.4 day（Phase II）	1221.44 day	863 day
Fiducial volume	22.5 kt	300 t/1000 t	240 t	1 kt	800 t	8 kt
Observed energy region	≥ 6.5–7.0 MeV $\gtrsim 5.5$ MeV	≥ 4–7 MeV	≥ 8 MeV	≥ 4.5 MeV	11–45 MeV	20–60 MeV
U.L. of SN rate	0.32 /yr 0.29 /yr	0.08 /yr	0.070 /yr	–	0.69 /yr	0.71 /yr
Detectable range (detection probability)	$\lesssim$ 100 kpc（∼ 100%）	$\lesssim$ 25 kpc（$\geq$ 95%）	$\lesssim$ 25 kpc	$\lesssim$ 10 kpc（∼ 100%） $\lesssim$ 30 kpc（∼ 100%）	$\lesssim$ 13.4 kpc（$\geq$ 95%）	Our galaxy

Component of delayed coincidence events

spallation

^{12}C spallation by cosmic muon
(mainly by ^{9}Li $\beta^- + n$ decay)

accidental coincidence

decay of radioactive isotopes in detector
components or rock（mainly by ^{208}Tl $2.6\ \mathrm{MeV}\ \gamma$）

atmospheric neutrino

prompt: charged lepton or de-excitation γ,
delayed: neutron capture

reactor $\bar{\nu}_e$ geo $\bar{\nu}_e$

inverse beta decay

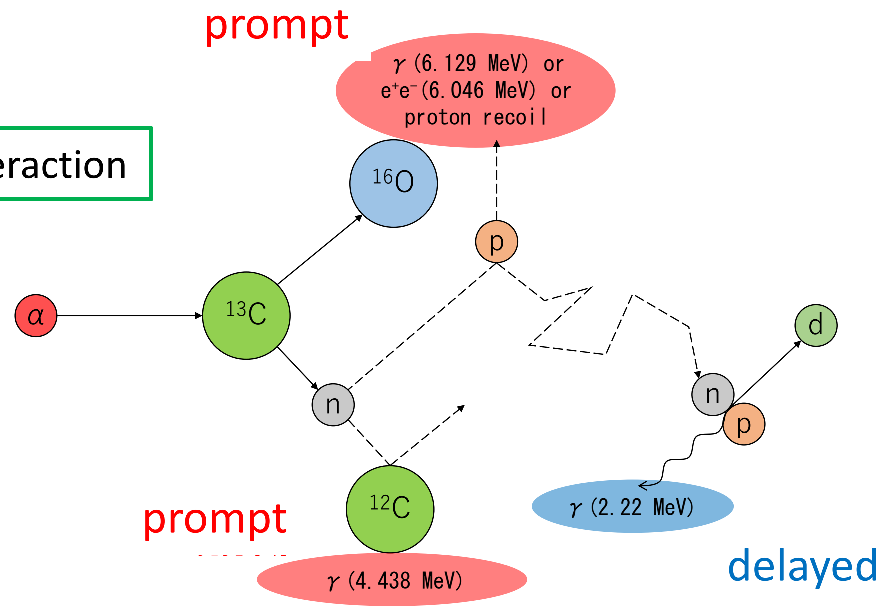
(α, n) interaction

reaction of α-ray from ^{210}Po (radioactive impurity) and ^{13}C
prompt: ^{16}O de-excitation or proton scatter, delayed: neutron capture

fast neutron

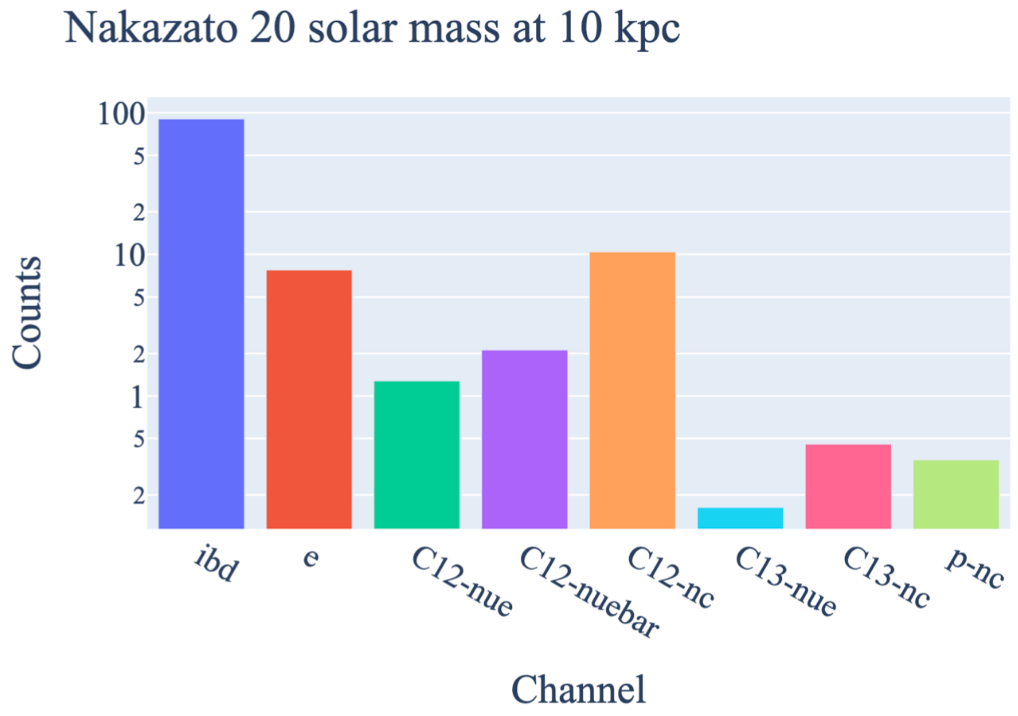
prompt: scattered proton by high-energy neutron
delayed: neutron capture

$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ interaction



Number of expected events/ detection probability with some models

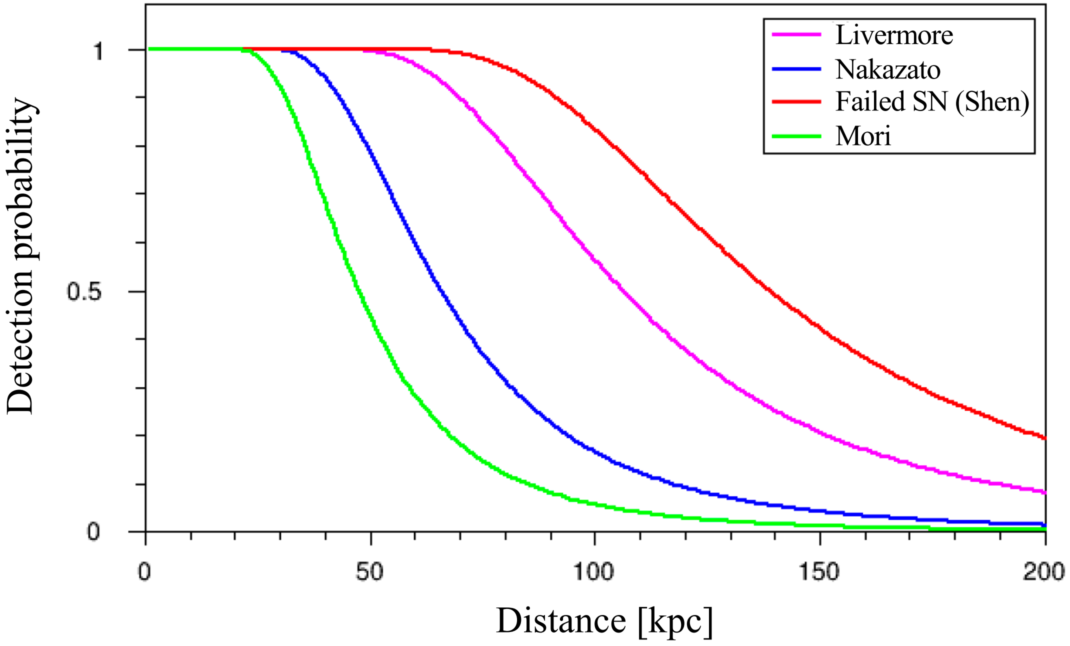
Number of expected events by different neutrino detection channels



Model dependence of detection probability

IBD only, time distribution is not considered

Livermore model is within Nakazato model uncertainty



Galactic supernova distribution

- SN distribution is used for detection probability calculation by NC only analysis.

Radial distribution

$$\sigma_{\mathrm{cc}}(r) \propto r^{\xi} \exp\left(-\frac{r}{u}\right)$$

$$\begin{cases} \xi = 4 \\ u = 1.25\ \mathrm{kpc} \end{cases}$$

This corresponds to the NS distribution

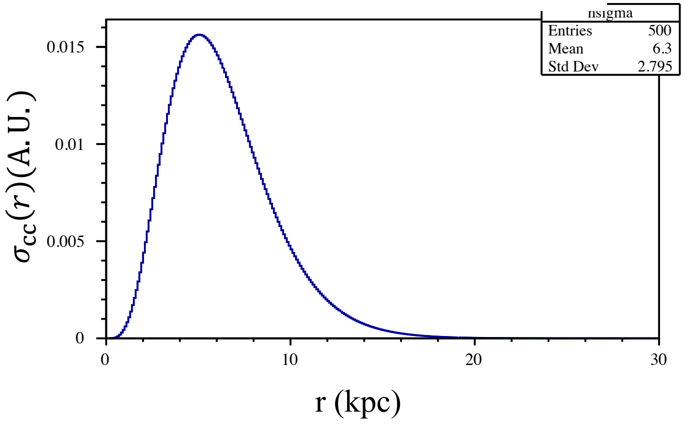
r : radius from the Galactic center

$$\longrightarrow \quad d(r, z, \theta) = \left[r^2 + z^2 + d_{\odot}^2 - 2 r d_{\odot} \cos\theta\right]^{1/2}$$

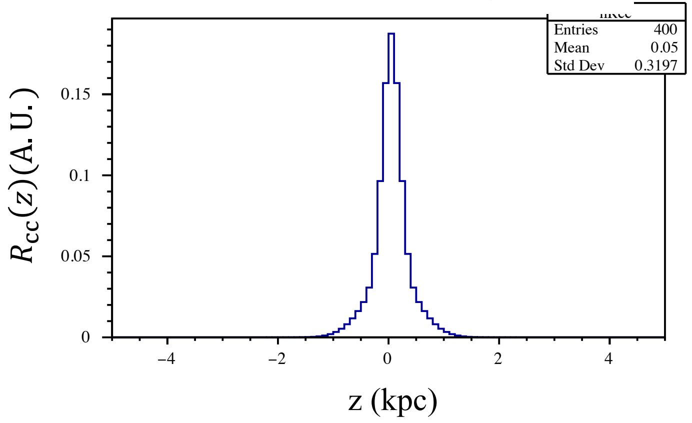
$d_{\odot} \sim 8.5\ \mathrm{kpc}$: solar distance from the Galactic center

d: distance from the solar

Radial distribution of supernova



Vertical distribution of supernova



Vertical distribution

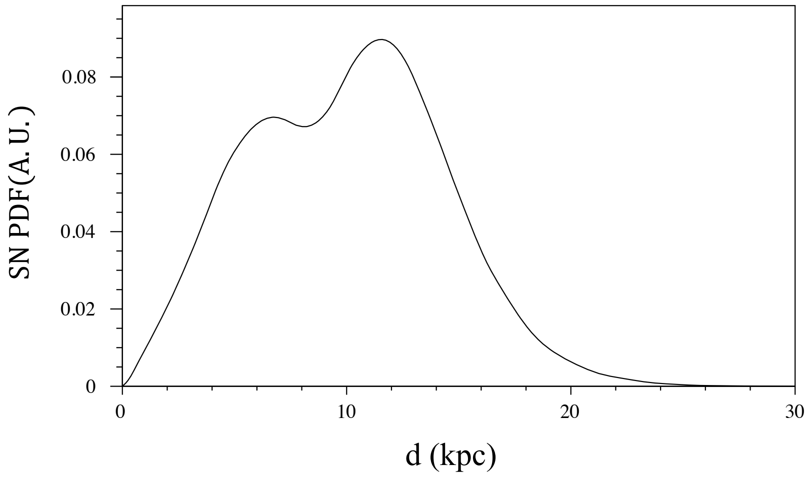
$$R_{\mathrm{cc}}(z) \propto 0.79 \exp\left[-\left(\frac{z}{212\ \mathrm{pc}}\right)^2\right] + 0.21 \exp\left[-\left(\frac{z}{636\ \mathrm{pc}}\right)^2\right]$$

z : distance from galactic plane

Three-dimensional distribution

$$n_{\mathrm{cc}}(r, z) \propto \sigma_{\mathrm{cc}}(r) R_{\mathrm{cc}}(z)$$

Three-dimensional distribution of supernova



Calculation of star formation rate

- Supernova rate R_{SN} and star formation rate ψ_{SFR} are linked by following equation.

$$R_{\mathrm{SN}}(z) = \frac{\int_{m_{\mathrm{l}}^{\mathrm{SN}}}^{m_{\mathrm{u}}^{\mathrm{SN}}} \phi_{\mathrm{IMF}}(m)\mathrm{d}m}{\int_{m_{\mathrm{l}}}^{m_{\mathrm{u}}} m\phi_{\mathrm{IMF}}(m)\mathrm{d}m} \times \psi_{\mathrm{SFR}}(z) \equiv k_{\mathrm{SN}} \times \psi_{\mathrm{SFR}}(z)$$

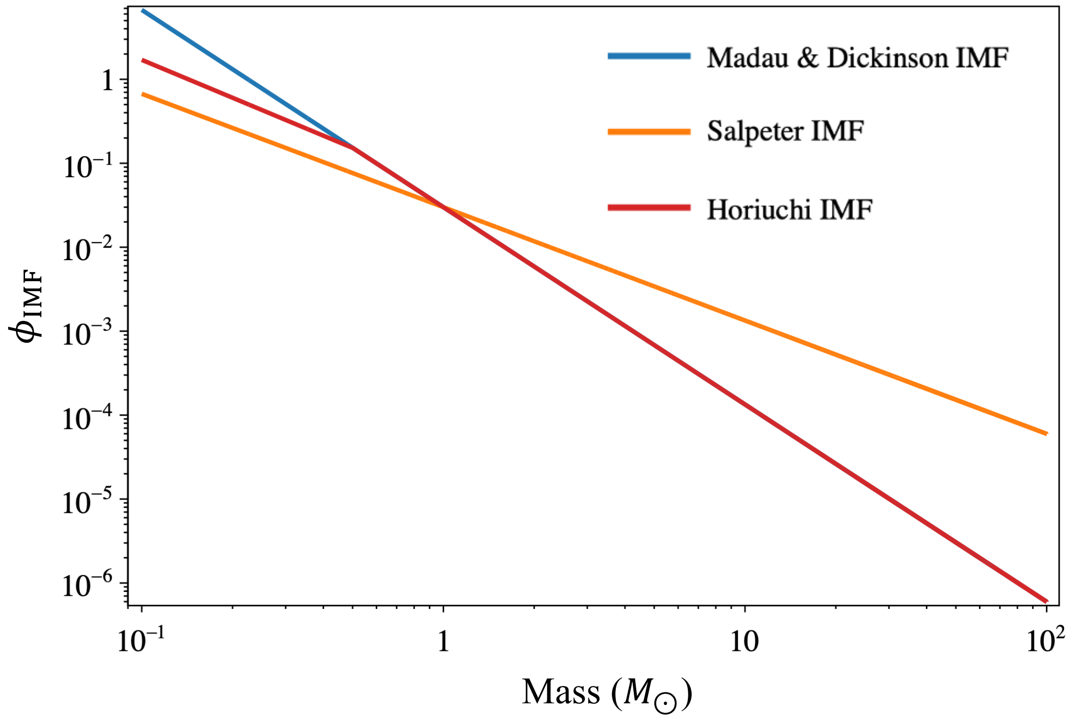
- ☐ ϕ_{IMF} : Initial Mass Function, IMF
  number distribution of star as a function of mass

$$\phi_{\mathrm{IMF}} = 0.03\left(\frac{m}{M_\odot}\right)^{-\gamma}$$

- ☐ $m_u^{\mathrm{SN}}/m_l^{\mathrm{SN}}$: upper/lower limit of SN mass, $8\text{–}40\ M_\odot$
- ☐ m_u/m_l : upper/lower limit of stellar mass, $0.1\text{–}100\ M_\odot$

$$\longrightarrow\ k_{\mathrm{SN}} = 0.0068\text{–}0.0088\ M_\odot^{-1}$$

Salpeter-type initial mass function



Original salpeter IMF : $\gamma = -1.35$

Madau & Dickinson IMF : $\gamma = -2.35$

Horiuchi IMF : $\gamma = -1.5$ for $0.1\text{–}0.5\ M_\odot$
$\gamma = -2.35$ for $0.5\text{–}100\ M_\odot$

Constraints on the SFR from astronomical observation

Murray & Rahman (2009) $0.9 < \psi_{\mathrm{SFR}}^{\mathrm{gal}}\ [M_{\odot}\mathrm{yr}^{-1}] < 2.2$

frequency of free-free radiation observed by WMAP (micro wave)

Robitaille & Whitney (2010) $0.68 < \psi_{\mathrm{SFR}}^{\mathrm{gal}}\ [M_{\odot}\mathrm{yr}^{-1}] < 1.45$

SFR set to reproduce observation result of Spitzer survey (infrared)

Chomiuk & Povich (2011) $\psi_{\mathrm{SFR}}^{\mathrm{gal}} = 1.9 \pm 0.4\ M_{\odot}\mathrm{yr}^{-1}$

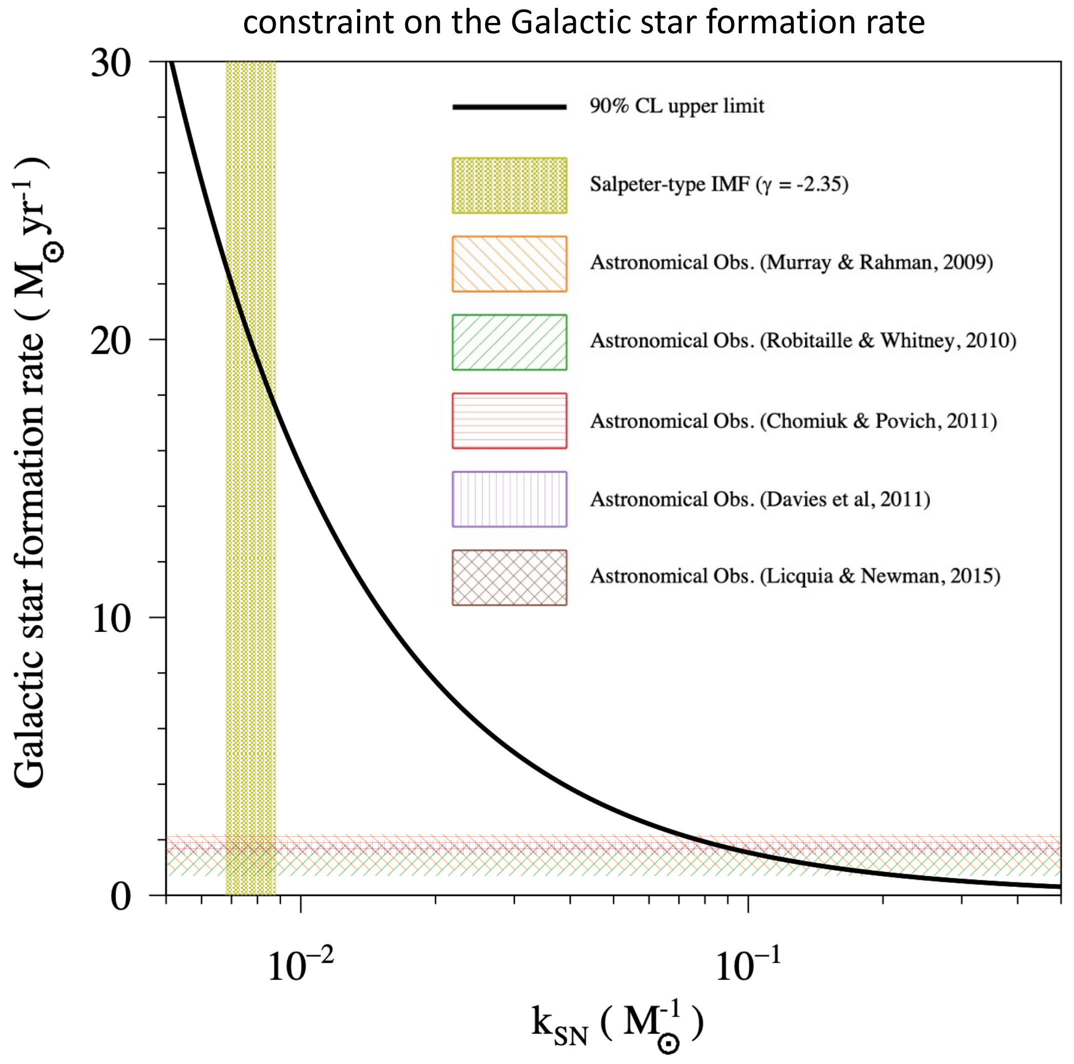
combined result of previous SFR estimations by normalizing with same initial mass function

Davis, et al (2011) $1.5 < \psi_{\mathrm{SFR}}^{\mathrm{gal}}\ [M_{\odot}\mathrm{yr}^{-1}] < 2.0$

SFR obtained by comparing simulation result and observed data of Midcourse Space Experiment

Licquia & Newman (2015) $\psi_{\mathrm{SFR}}^{\mathrm{gal}} = 1.65 \pm 0.19\ M_{\odot}\mathrm{yr}^{-1}$

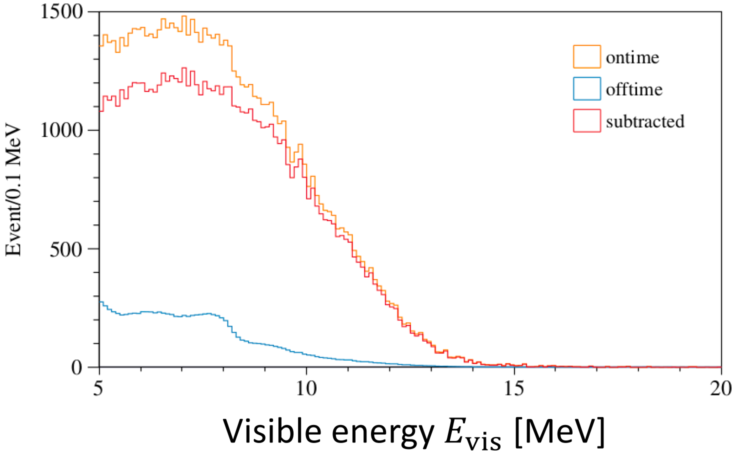
combined result of previous SFR estimations by Hierarchical Bayesian method



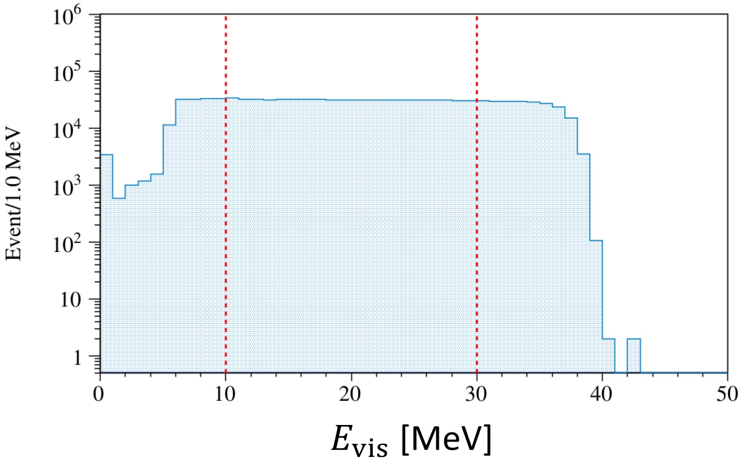
Simulation consistency check: signal

- Spallation ^{12}B is used instead of high-energy IBD candidate ($r \leq 600$ cm).
- Light particles (e^- & e^+/γ) have similar hit information.
- **Signal simulation is consistent with real data.**

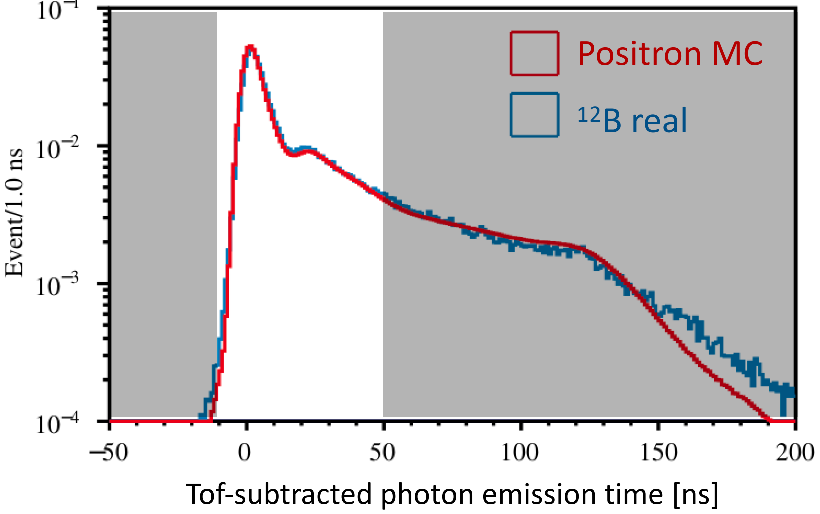
Spallation ^{12}B (e^-) in real data



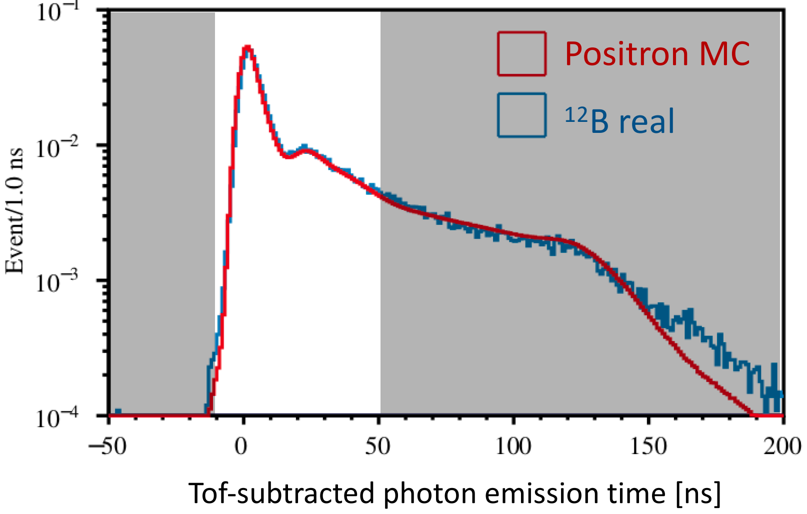
Positron MC (e^+/γ)



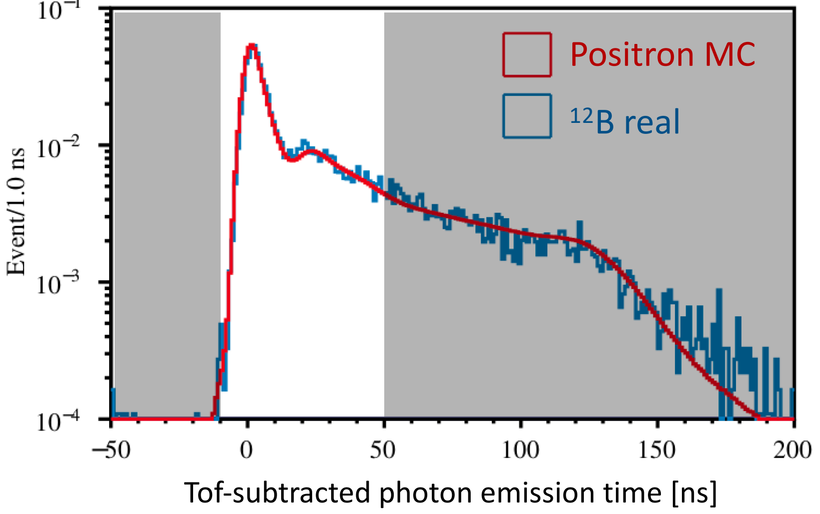
$8.0 \leq E_{\mathrm{vis}} < 10.0$ MeV



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

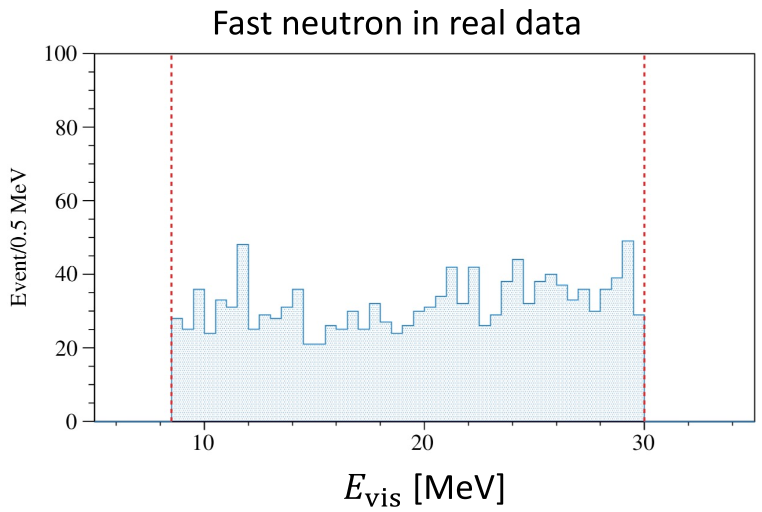


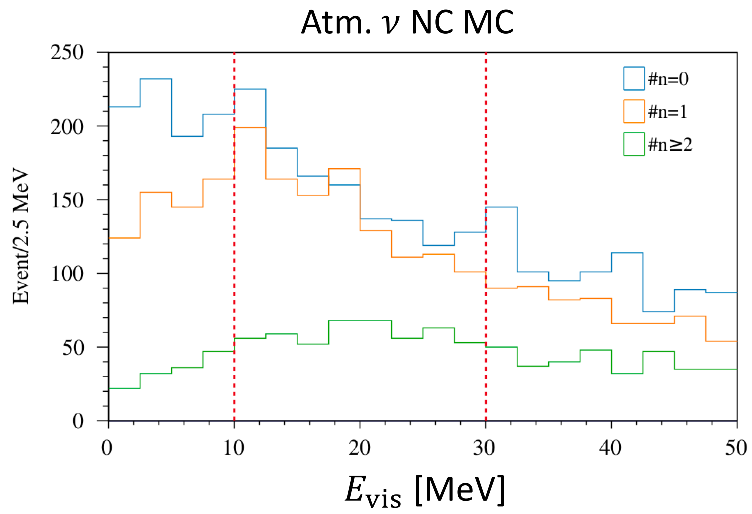
$12.0 \leq E_{\mathrm{vis}} < 14.0$ MeV

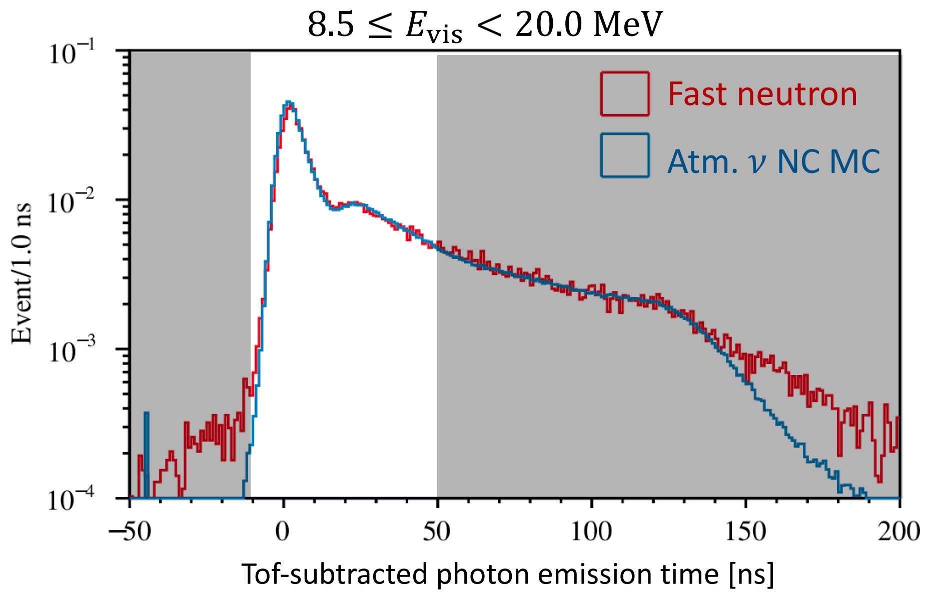


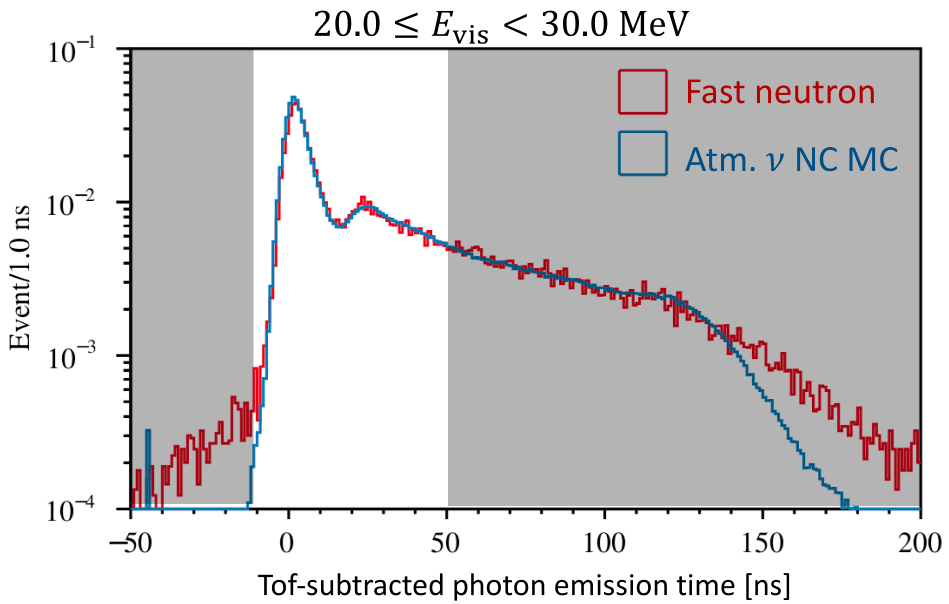
Simulation consistency check: background

- Fast neutron is used instead of atm. ν candidate ($r \leq 650$ cm).
- Fast neutrons and atm. νs have similar hit information.
- **Background simulation is consistent with real data.**

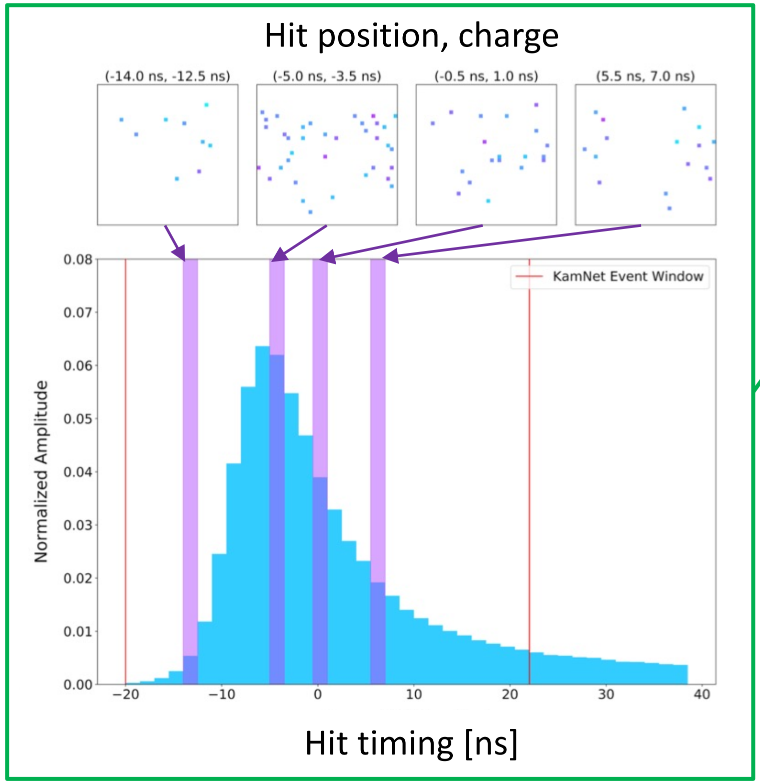




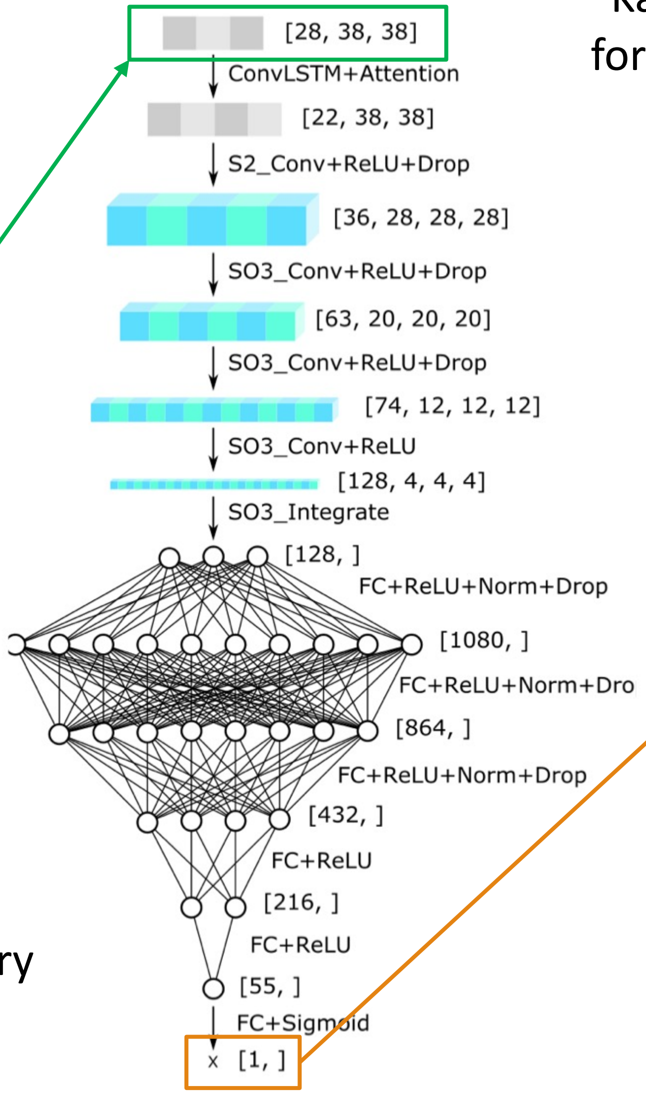




KamNet: spatiotemporal deep neural network



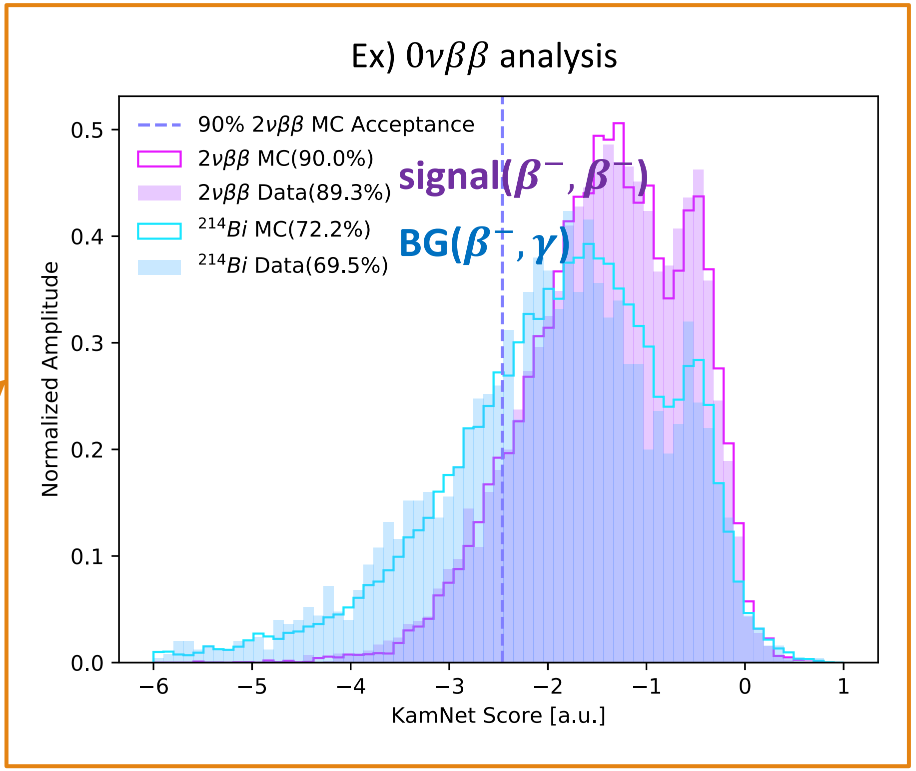
KamNet diagram



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

input: Event hit position, charge, and timing

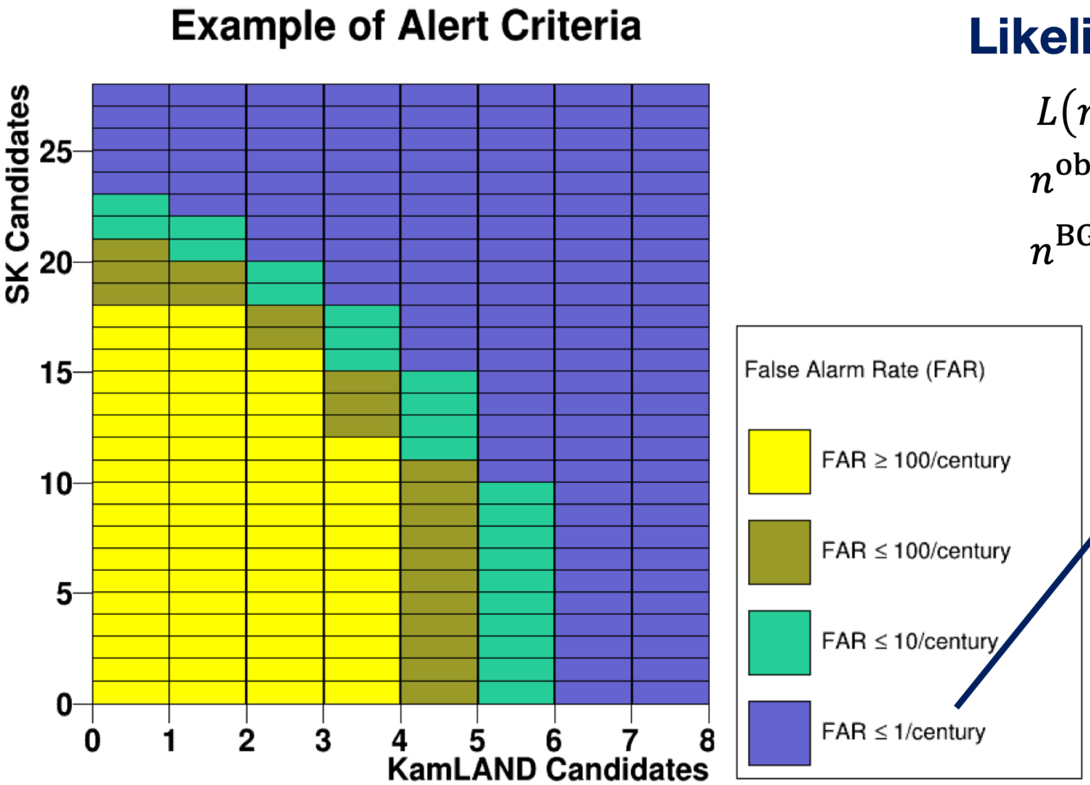
output: KamNet score (positive→signal-like)



Characteristics of KamNet

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

Combined alarm system



Likelihood function

$$L\left(n_{\mathrm{KL}}^{\mathrm{obs}}, n_{\mathrm{SK}}^{\mathrm{obs}}\right) = \mathrm{Pois}(n_{\mathrm{KL}}^{\mathrm{obs}}, n_{\mathrm{KL}}^{\mathrm{BG}}) \times \mathrm{Pois}(n_{\mathrm{SK}}^{\mathrm{obs}}, n_{\mathrm{SK}}^{\mathrm{BG}})$$

n^{obs}: number of candidates

n^{BG}: number of expected BG

The system provides warning when the combinations of $n_{\mathrm{KL}}^{\mathrm{obs}}$ and $n_{\mathrm{SK}}^{\mathrm{obs}}$ are in **blue region** (≦ 1 FAR/century).

- Combined alarm system is **running in both KamLAND and SK side.** **(redundancy system)**
- BG number is average one over a past period. (KamLAND: 90 days, SK: 30 days)
- The system outputs **every 5 minutes**.
- If FAR ≦ 1/century, an alarm will be sent **GCN circular**.

PBHν flux on the Earth

Contributions from the Galaxy and outer Galaxy

$$\Phi_{\mathrm{tot}} = \Phi_{\mathrm{EG}} + \Phi_{\mathrm{Gal}}$$

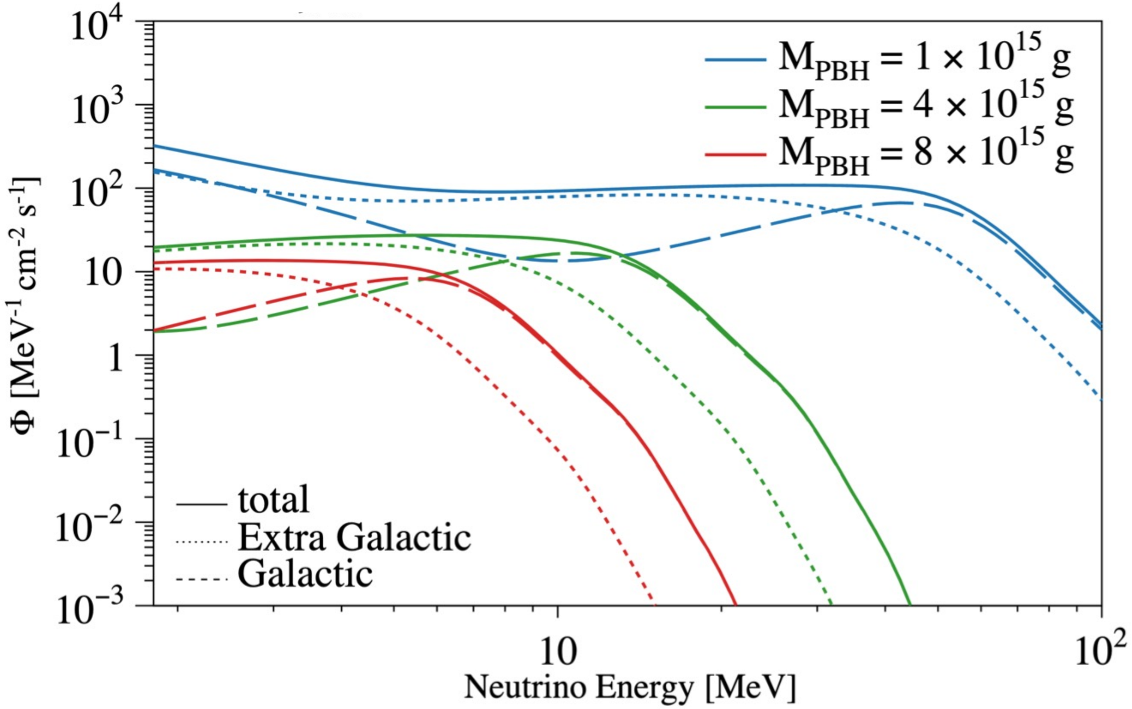
Φ_{Gal} Flux from the Galaxy

- Ignore redshift
- PBH distribution is assumed to be same as dark matter

Φ_{EG} Flux from out of the Galaxy

- Consider redshift
- PBH distribution is assumed to be uniform

PBHν flux on the Earth ($f_{\mathrm{PBH}} = 1$)



Neutrino oscillation

- Primary component (Hawking radiation) All flavors of neutrinos are same amount → ignore oscillation
- Secondary component (decay of particles) Considering the oscillation, its effect on the PBH flux is $\leq 2\%$