Supernova neutrino detection in KamLAND

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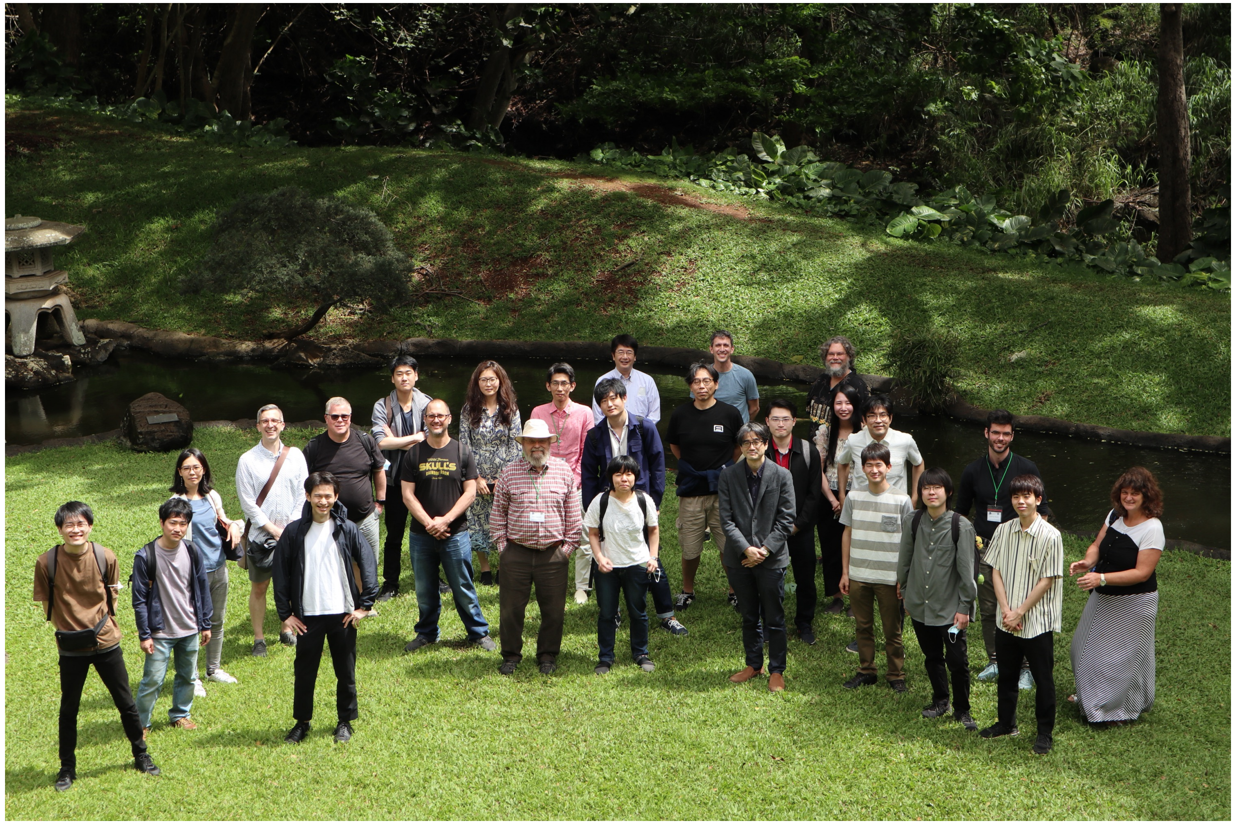
The KamLAND collaboration

~50 researchers from US, Netherlands, and Japan



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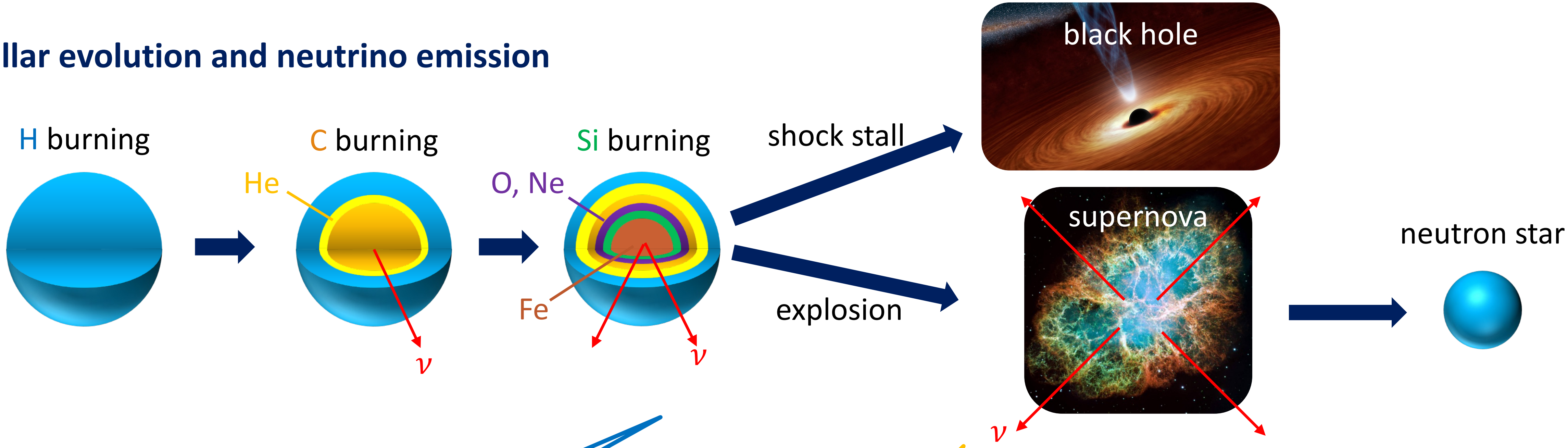
Introduction (1)

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)
- ✓ Explosion mechanism
- ✓ Cosmic history

integration of past SNνs

Important information can be obtained from above neutrino observations.

Introduction (2)

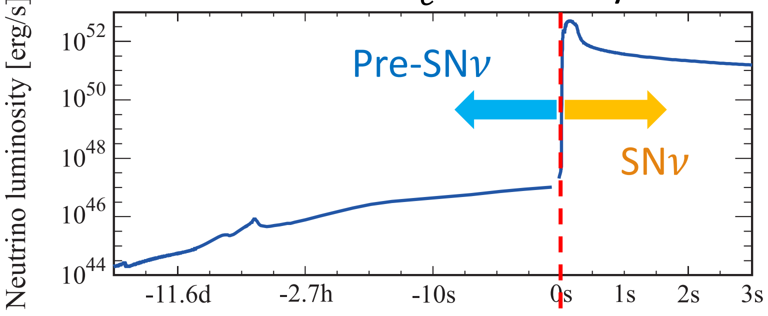
Properties of various types of SNνs

Pre-SNν
- ✓ Increasing number of events
  → Alarm of the explosion
- ✓ Average energy ~ 1 MeV

SNν
- ✓ Burst events
- ✓ Only once observed (from SN1987A)
- ✓ Average energy ~ 10 MeV

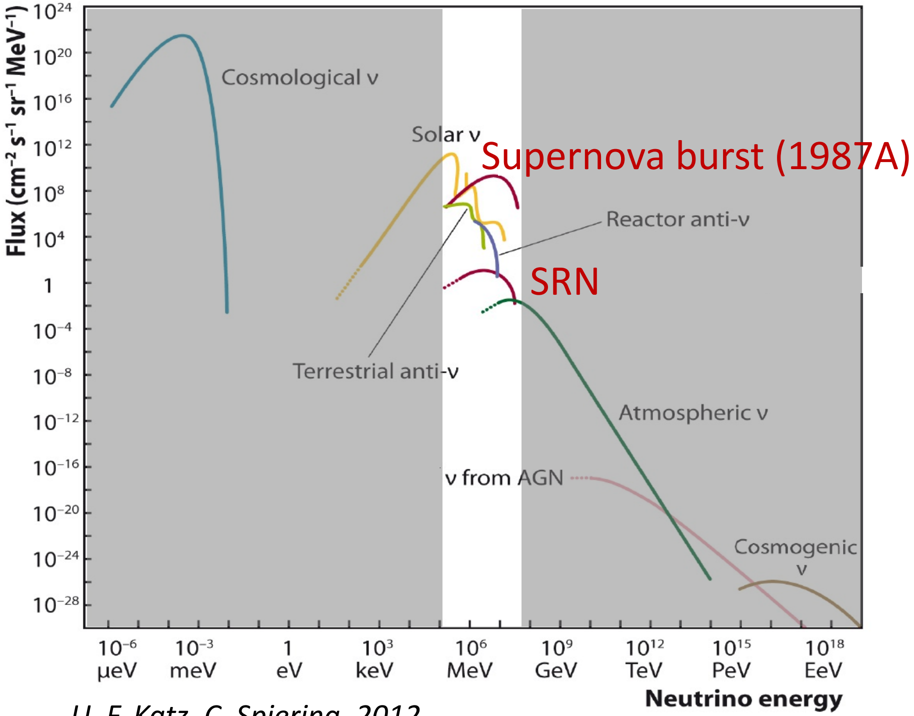
SRN
- ✓ Exist constantly in the universe
- ✓ No observation
- ✓ "Golden window" 10– 30 MeV

Evolution of $\bar{\nu}_e$ luminosity

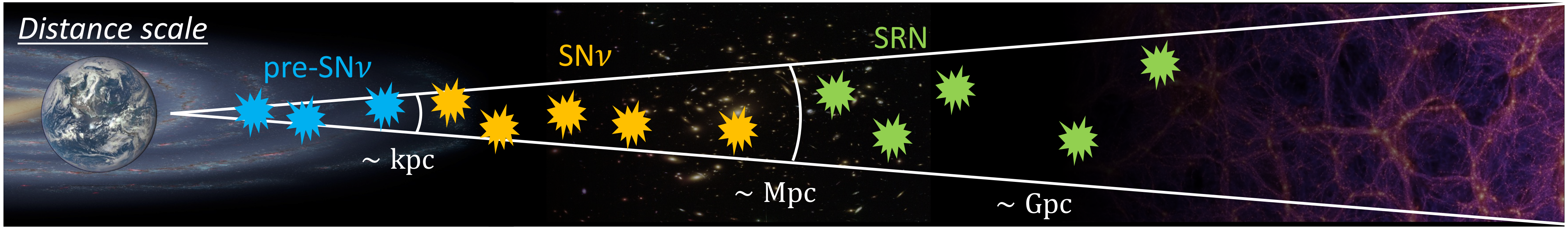


K. Asakura, et al, 2016

Unified neutrino fluxes

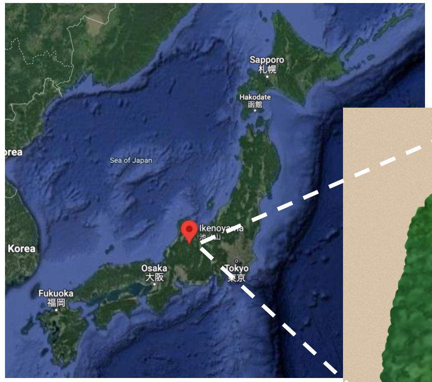


U. F. Katz, C. Spiering, 2012

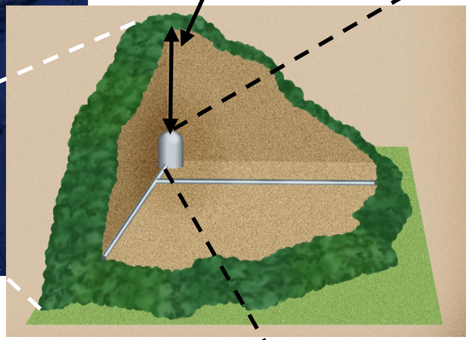


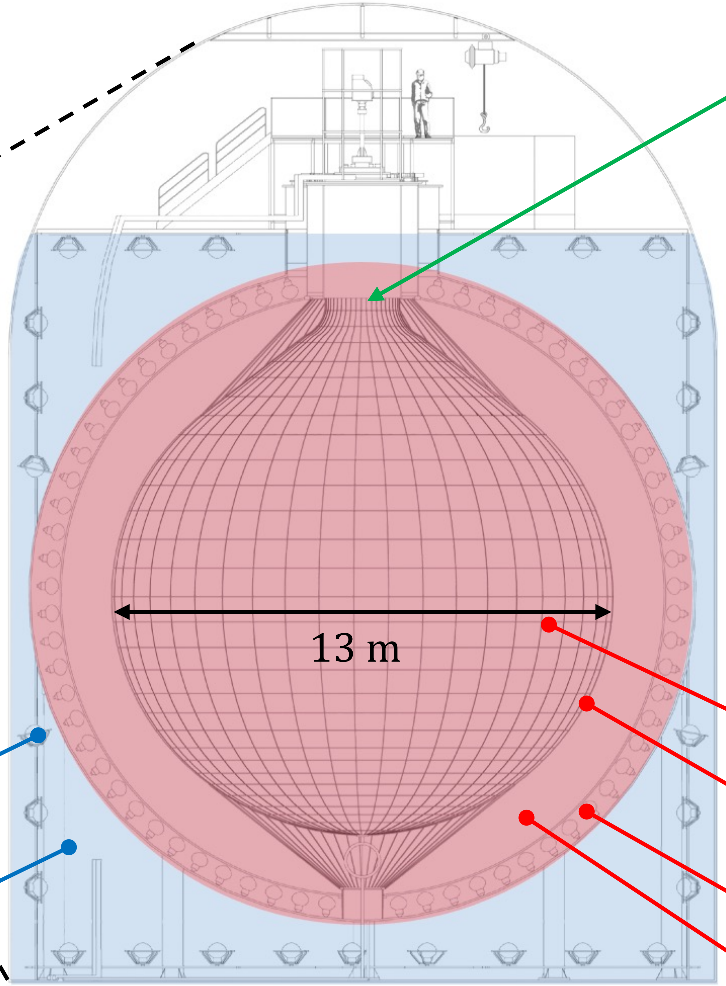
Kamioka Liquid-scintillator Anti-Neutrino Detector (KamLAND)

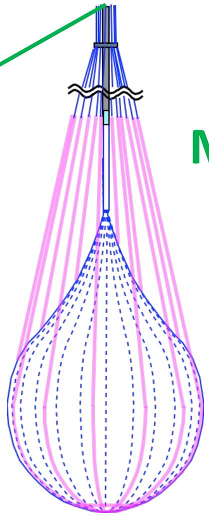
Located in Kamioka @Japan



1000 m underground







Miniballoon

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

Inner detector

Scintillation light is used for the physics event observation.

- 1 kton Liquid Scintillator (LS)
- Nylon/EVOH balloon
- 17 & 20-inch PMTs
- Buffer oil

Outer detector

Cherenkov light is used for the muon veto.

- 20-inch PMTs
- Purified water

KamLAND has a significant sensitivity to MeV-energy neutrinos.

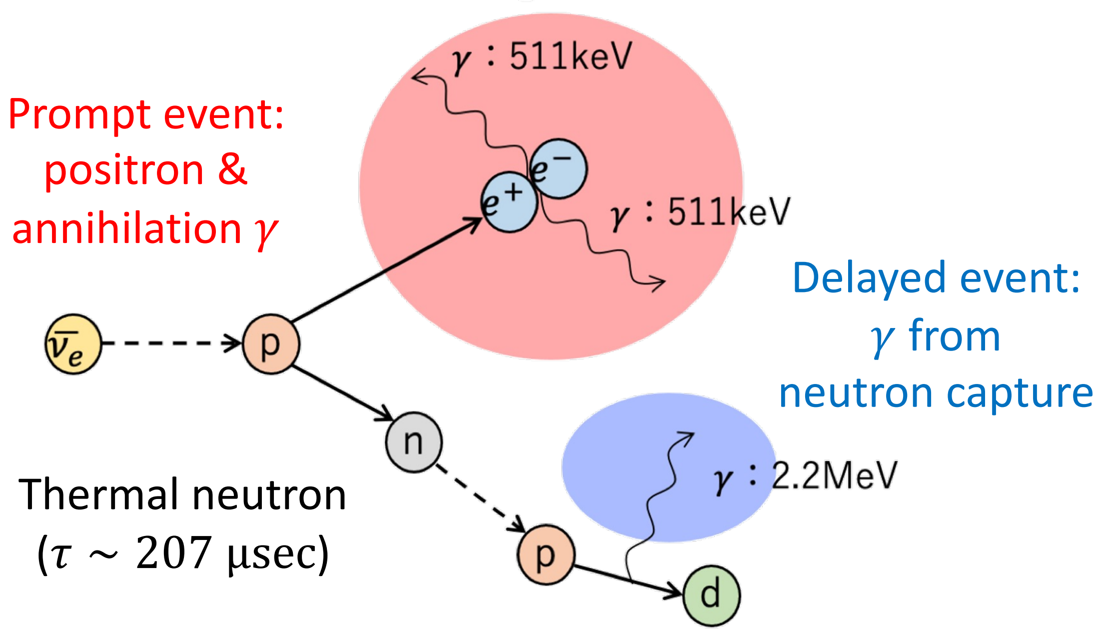
SNν detection channel

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

- Neutrino energy can be reconstructed from the observed energy.

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

- Space-time correlations of sequential events are used for background reduction (***delayed coincidence***).



Delayed coincidence events (except for SNν event)

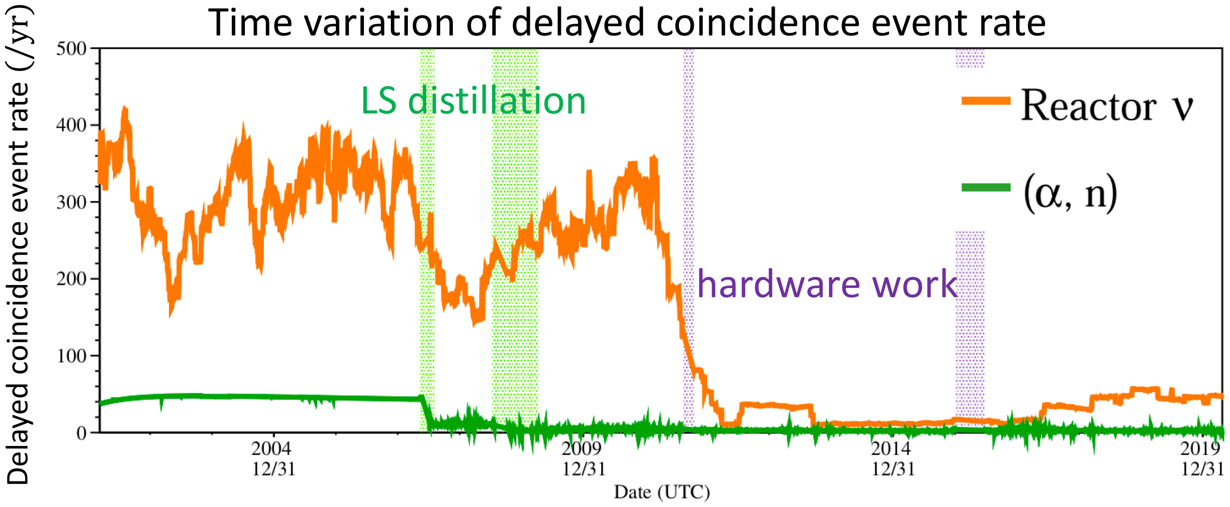
- Reactor $\bar{\nu}_e$
- Geo $\bar{\nu}_e$

Indistinguishable from SNν events

- Accidental coincidence → likelihood cut
- Spallation products (^{9}Li) → muon veto, shower tag
- (α, n) interaction → LS distillation

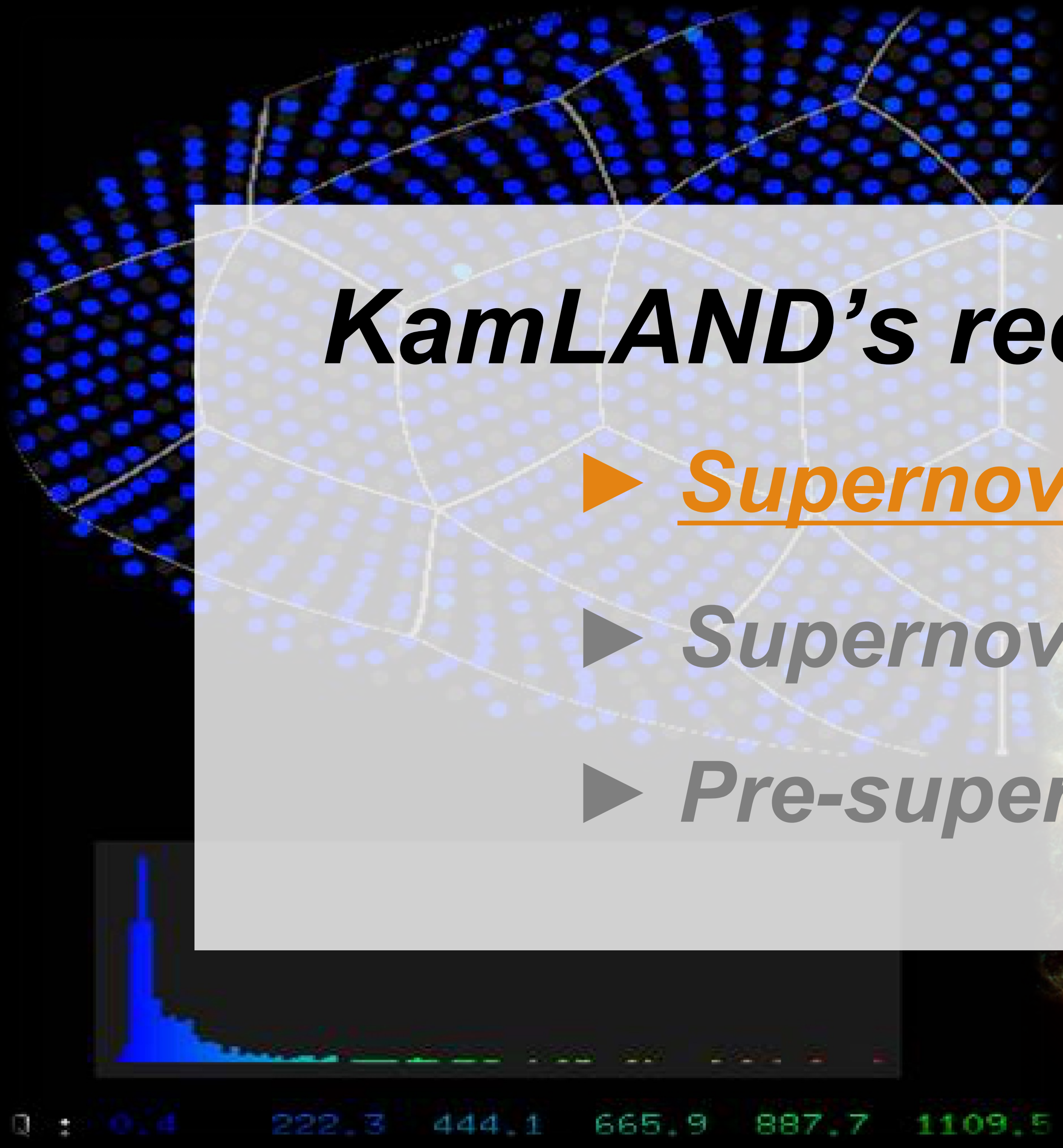
- Atmospheric neutrino
- Fast neutron

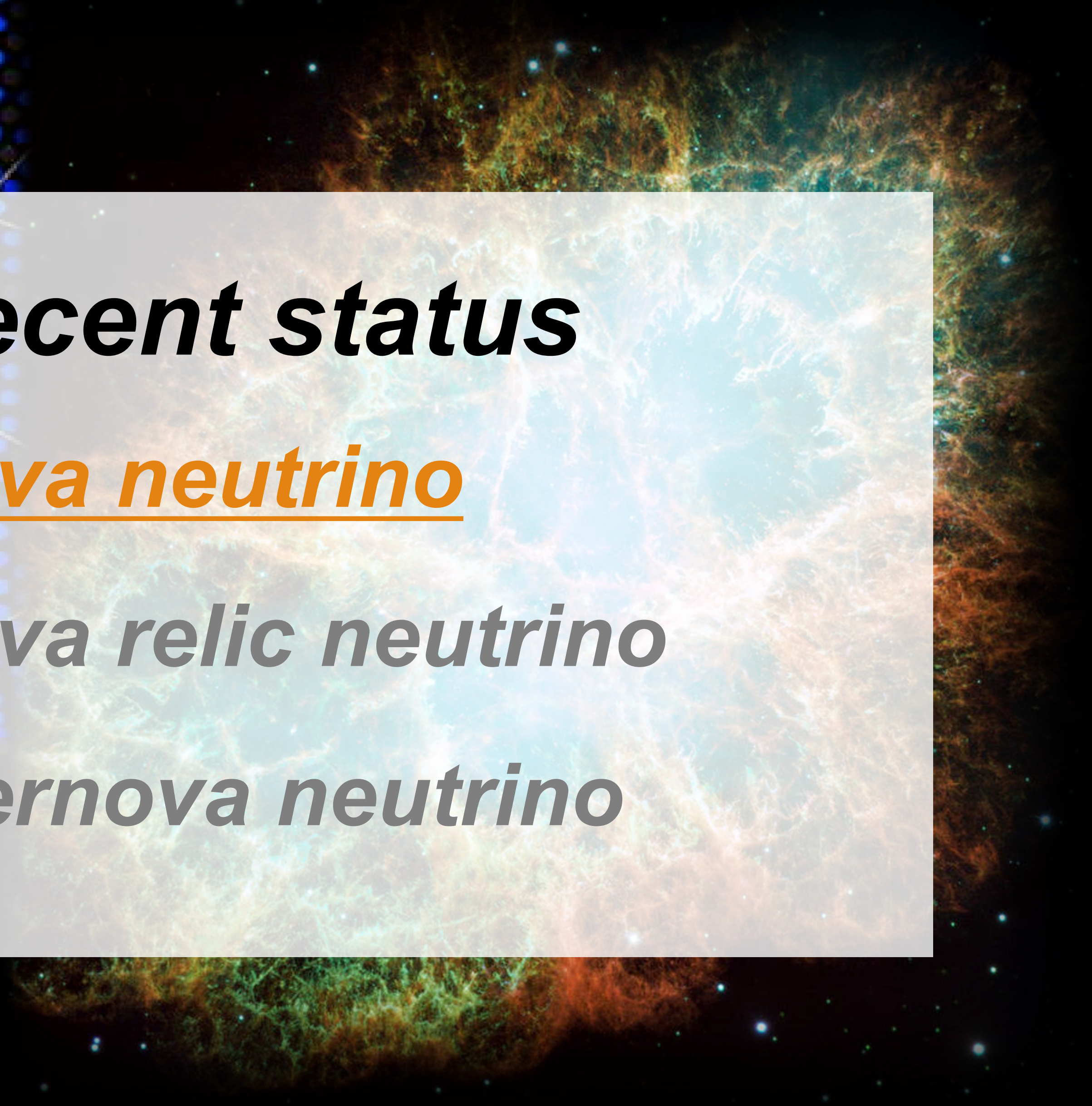
Proton scatter, hard to reduce



KamLAND's recent status

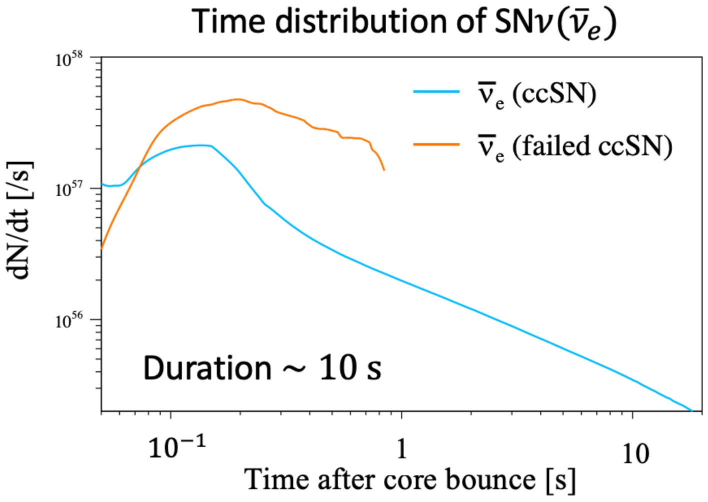
- ► **Supernova neutrino**
- ► Supernova relic neutrino
- ► Pre-supernova neutrino





SNν Supernova neutrino burst search

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

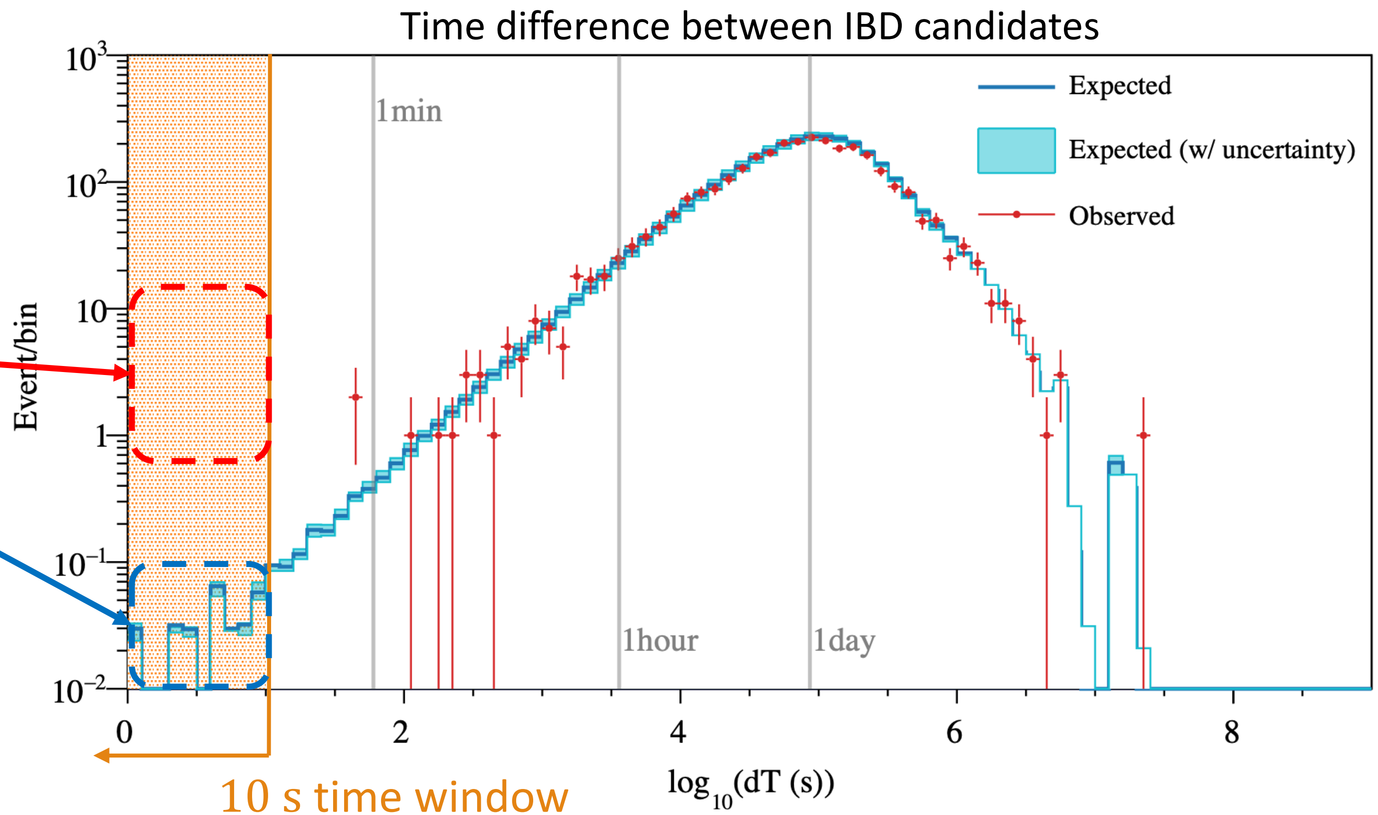


Selection criteria

Energy range: $0.9 \le E_{\text{prompt}}$ [MeV] ≤ 100

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

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



Search result

There are no SNν candidates.

"Background" of the burst search

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

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

Interpretation of search result

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

Detectable range

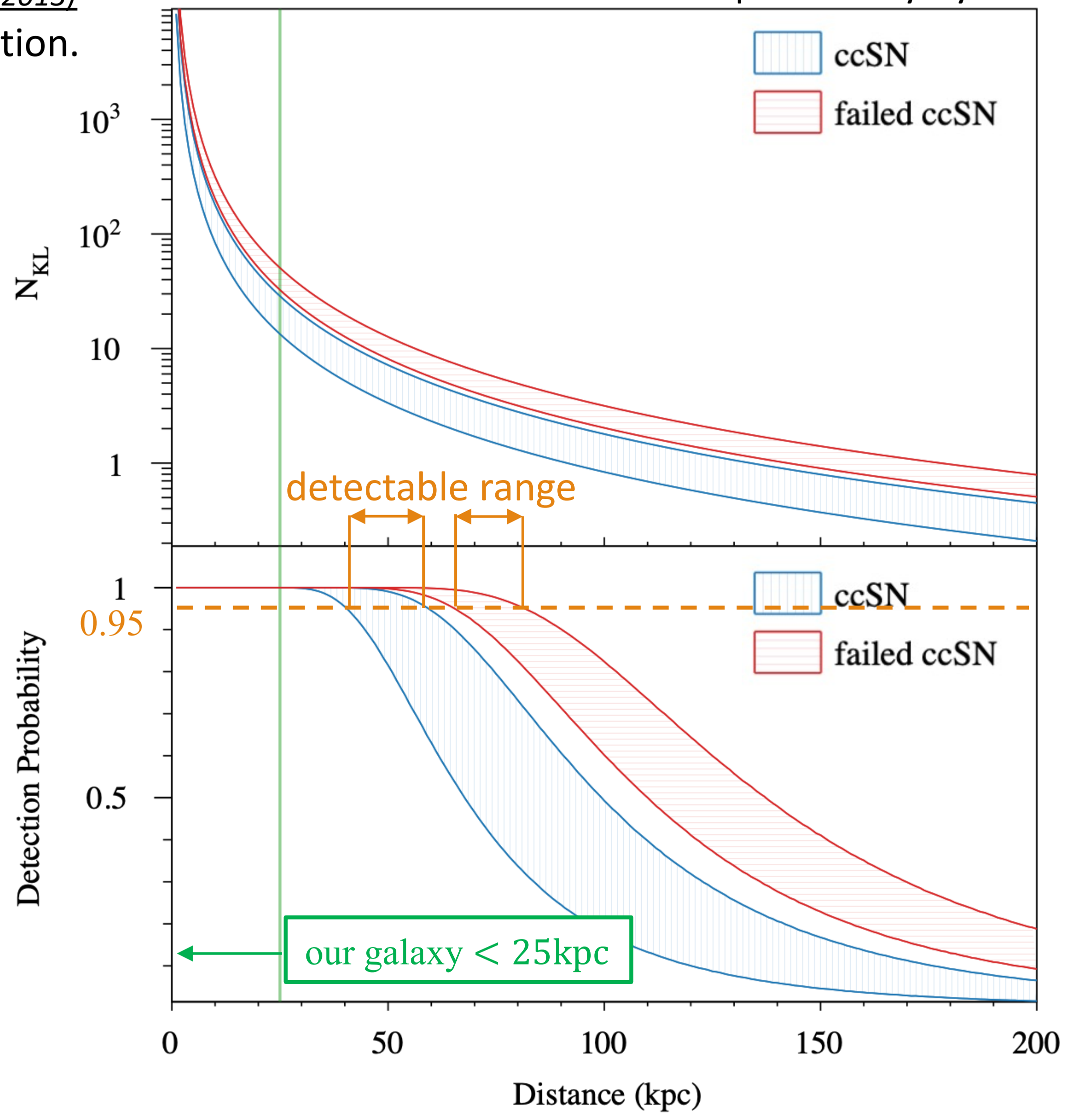
SNνs are observed with $\geq 95\%$ detection probability

$\leq 40\text{–}58$ 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

Number of events and detection probability by IBD



Supernova rate

Observed cluster rate = supernova rate in our Galaxy

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

SNν 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

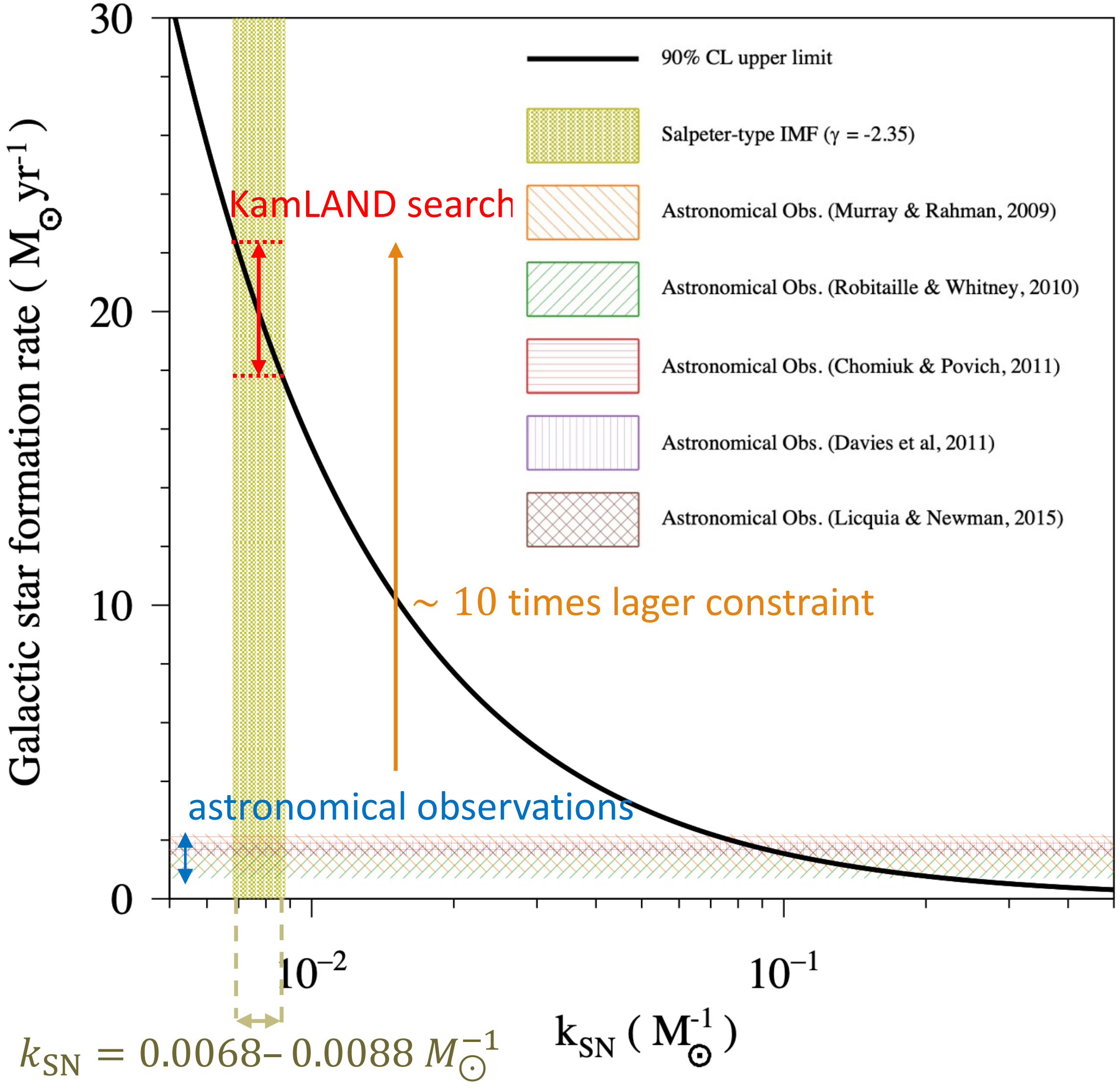
$k_{\mathrm{SN}} = 0.0068\text{–}0.0088$ $[M_\odot^{-1}]$: scale factor
with information of mass distribution of stars (Initial Mass Function)

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

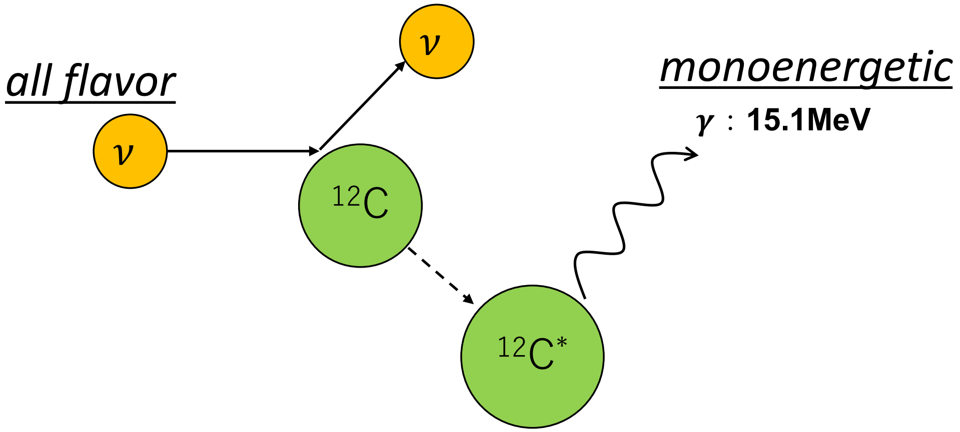


SNν

Another detection channel — ^{12}C neutral current

ν– ^{12}C Neutral Current (NC)

$$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$$



- ✓ Sensitive to $\nu_{e\mu\tau}, \bar{\nu}_{e\mu\tau}$
- ✓ Easy to search

! Delayed coincidence is not available.
! NC has never been used in KamLAND experiment.

→ Estimation of energy scale uncertainties is necessary.

NC event candidates (except for SNν events)

- Solar ν_e (hep NC)
- Atm. ν (NC)

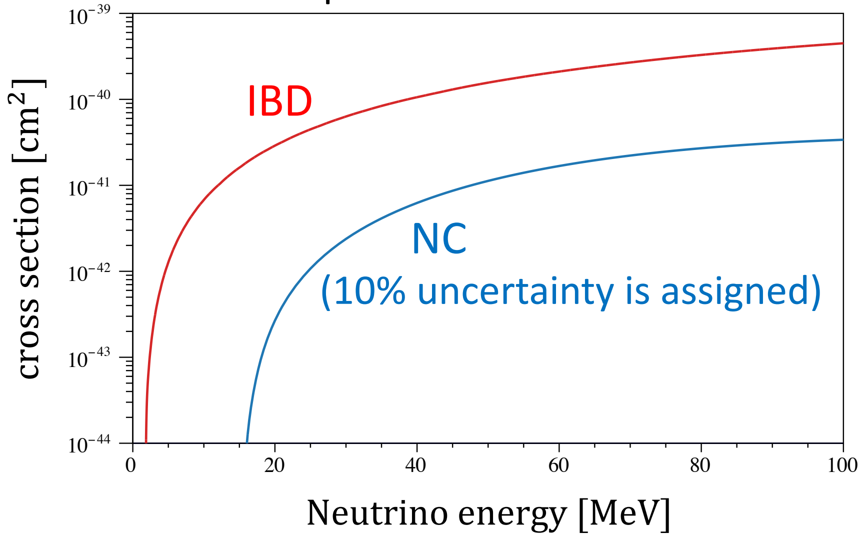
Indistinguishable from SNν events

- Solar ν_e (^{8}B, hep ES)
- Spallation products
- Atm. ν (NCQE, CCQE etc.)
- Fast neutron

Unrelated to NC, observed in the energy region

Significantly reduced by burst event search

Comparison of cross sections



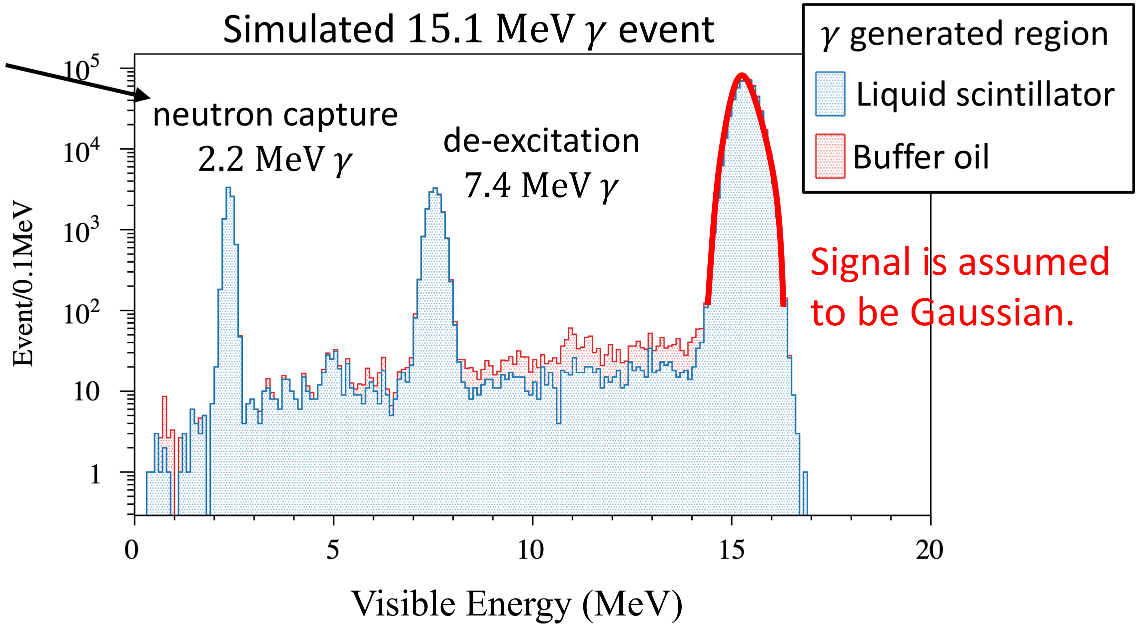
SNν Energy scale uncertainty

Signal simulation

→ Signal energy region w/o energy scale uncertainty

Uncertainty estimation

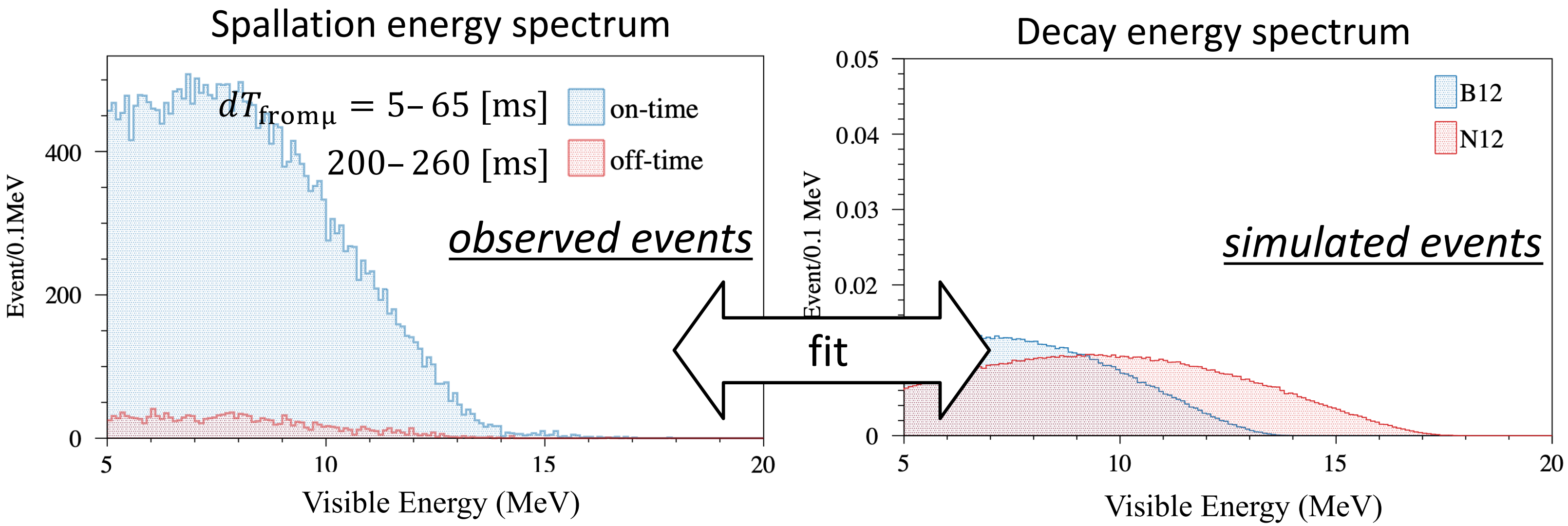
- Dominant uncertainty comes from the difference of observed/simulated energy scale.
- ***Decay events of unstable isotopes are used.***



β^- decay	β^+ decay
^{12}B $Q = 13.4$ MeV, $\tau = 29.1$ ms	^{12}N $Q = 17.3$ MeV, $\tau = 15.9$ ms

Energy region is chosen to satisfy

Signal efficiency > 99%



IBD+NC combined SNν search

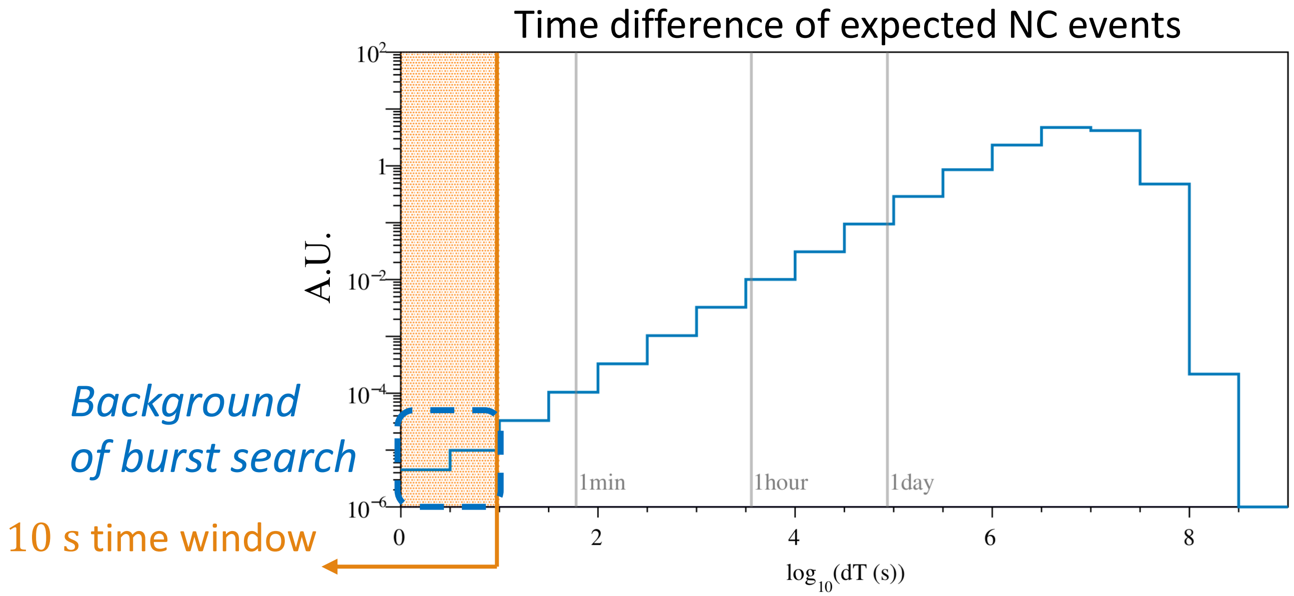
Detectable range improvement

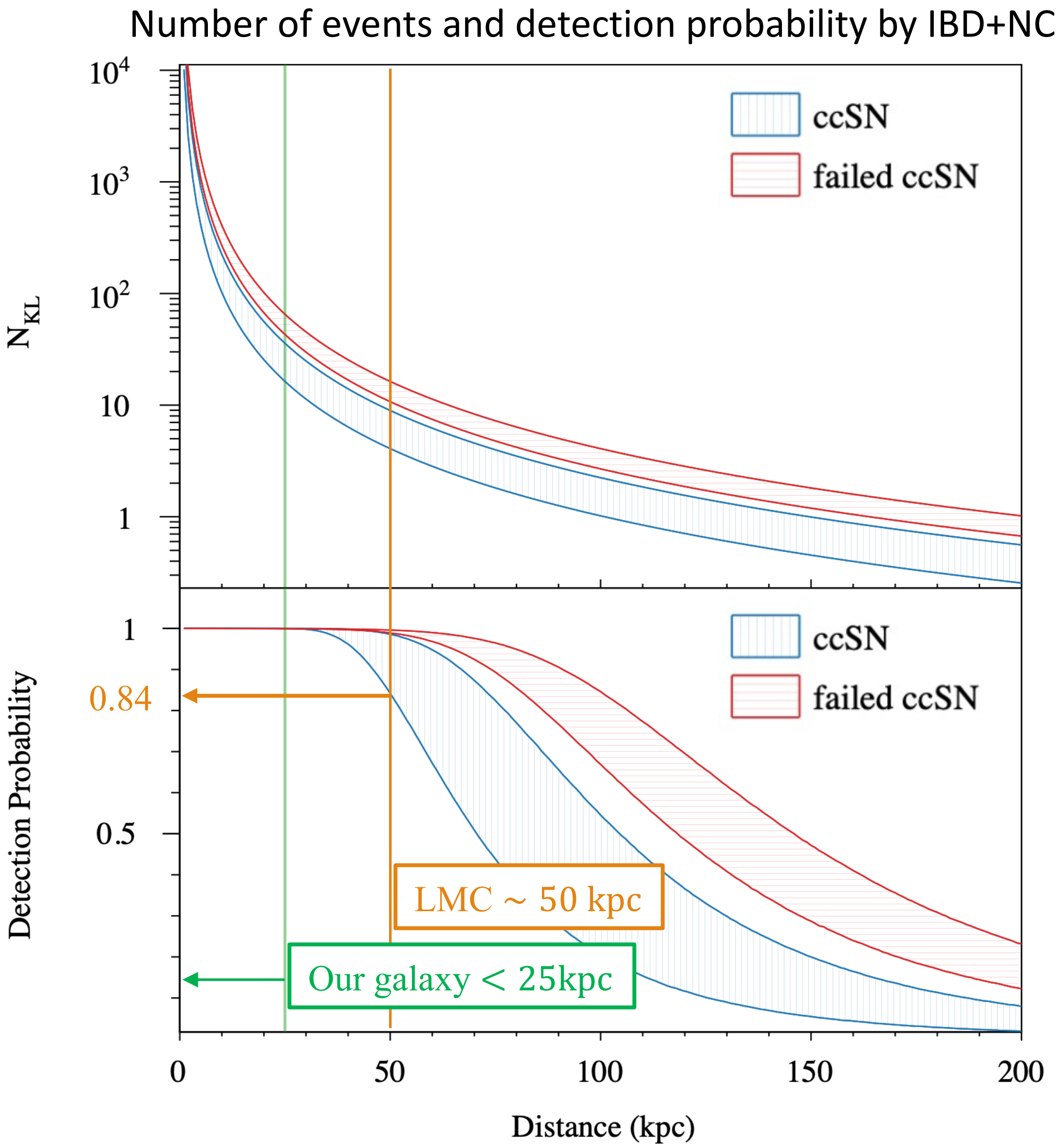
≥ 95% detection range: **2 kpc↑**
≥ 50% detection range: **6 kpc↑**

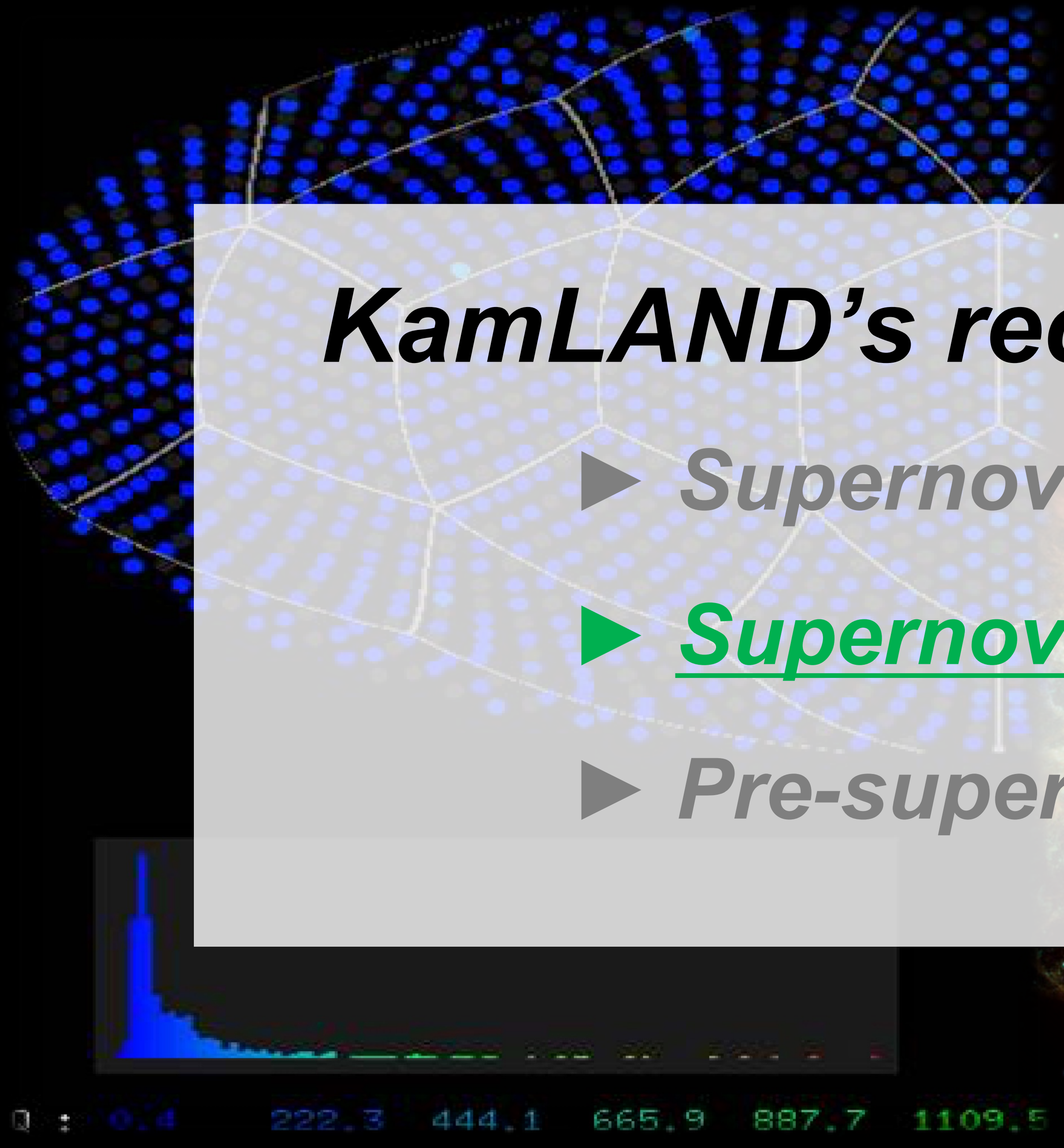
High detection probability to SNν from LMC

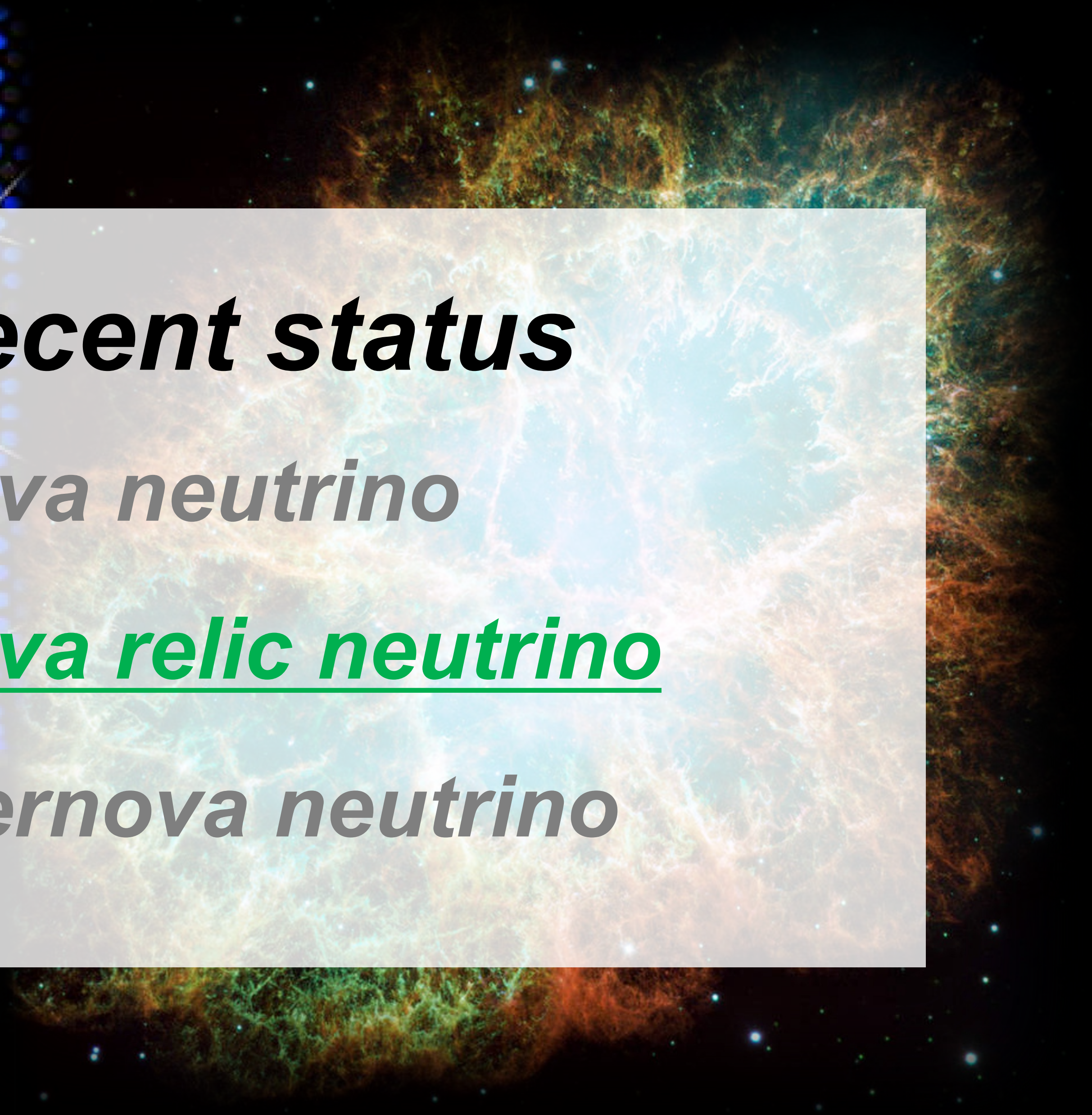
Data analysis

Real data analysis is currently under development.









KamLAND's recent status

- ► Supernova neutrino
- ► **<u>Supernova relic neutrino</u>**
- ► Pre-supernova neutrino

Latest result of SRN search

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

SRN search $E_{\mathrm{prompt}} = 7.5\text{– }30\ \mathrm{MeV}$

- ✓ Simultaneous fitting of energy & radius
  ← To constrain fast neutron background
- ✓ Fitting parameter:
  number of SRN events and atm. ν events

Zero-event best fit for all cases

SRN theoretical model	Fit result 90% C.L. U.L. (best fit)		Expected
	# of events	Flux $(\mathrm{cm^{-2}s^{-1}})$	Flux $(\mathrm{cm^{-2}s^{-1}})$
Kaplinghat (2000)	9.4 (0)	74.5	19.9
Horiuchi (2009) (6 MeV effective temp.)	10.2 (0)	61.6	5.8
Nakazato (2015) (max, IH)	9.3 (0)	108	5.1
Nakazato (2015) (min, NH)	8.9 (0)	105	2.2

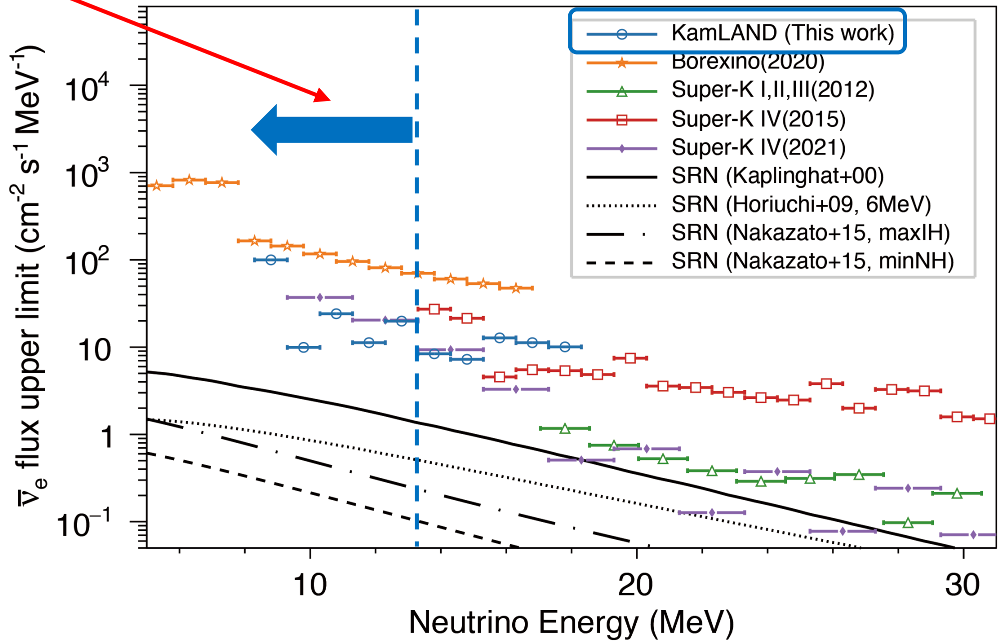
Model independent neutrino flux

Other astrophysical $\bar{\nu}_e$ sources

- 8B solar ν_e conversion
- Dark matter annihilation
- $\bar{\nu}_e$ from primordial black holes

Most stringent limit for 8– 13 MeV

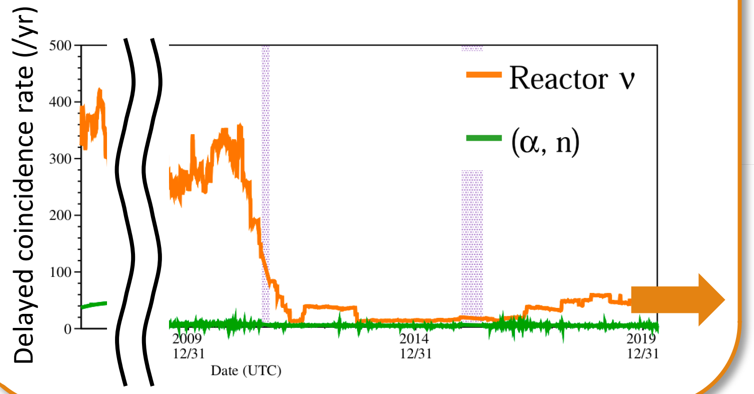
Model independent neutrino flux upper limit



SRN Prospects for updating the result

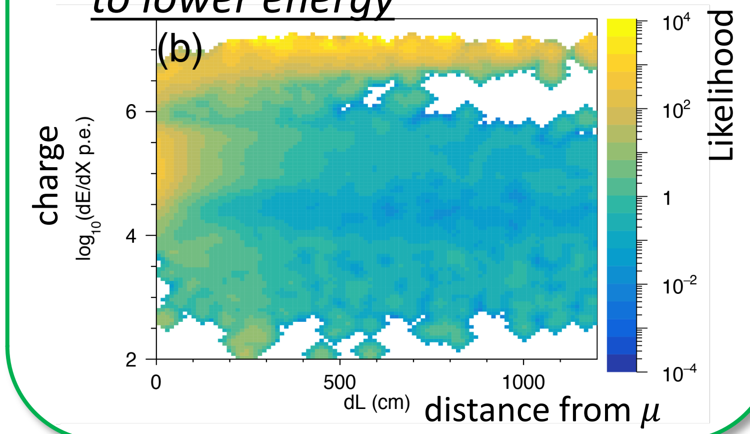
Reactor $\overline{\nu}_e$

Expansion of the reactor-off period



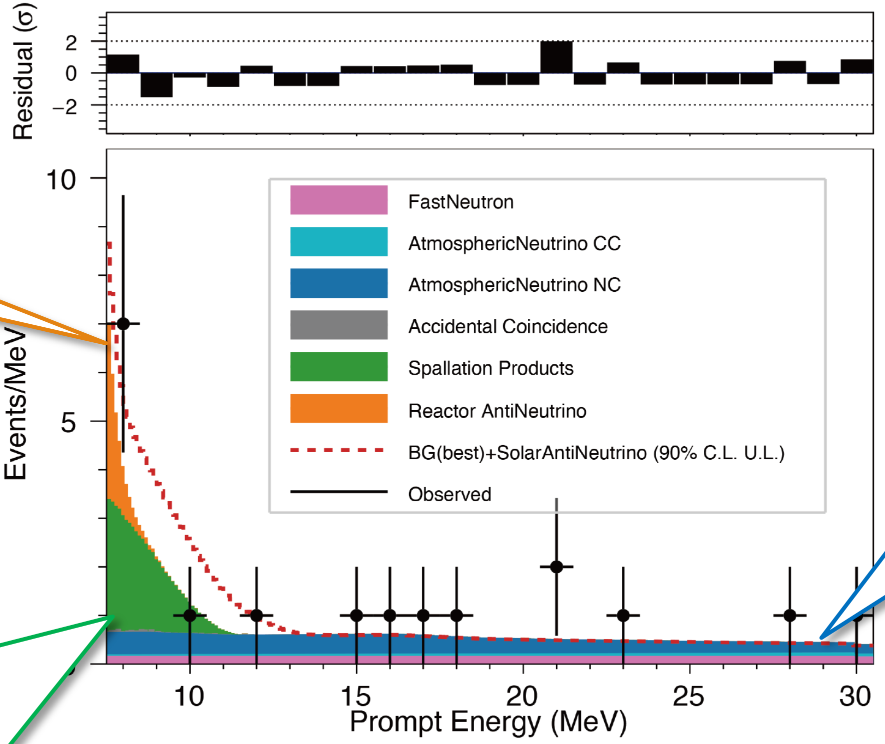
Spallation products

Application of the shower tool to lower energy



✓ Lower energy threshold
✓ Background reduction

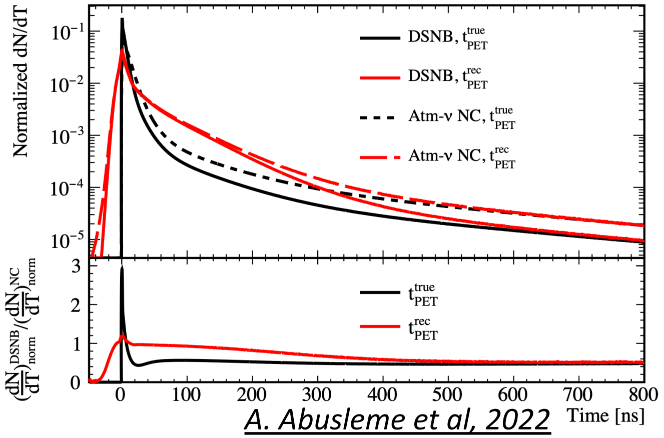
Fitting result of prompt energy spectrum



Atm. ν NC

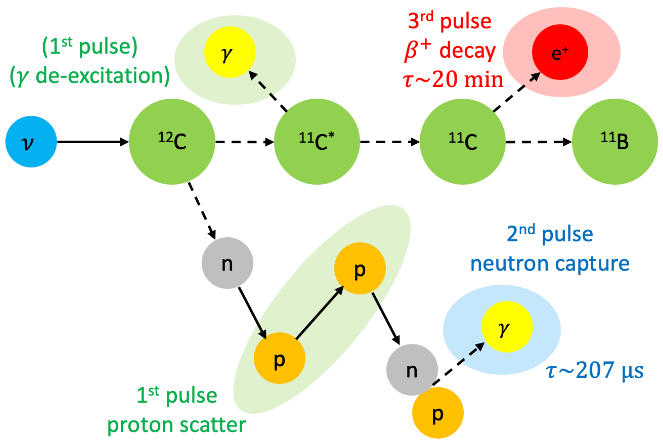
Pulse shape discrimination

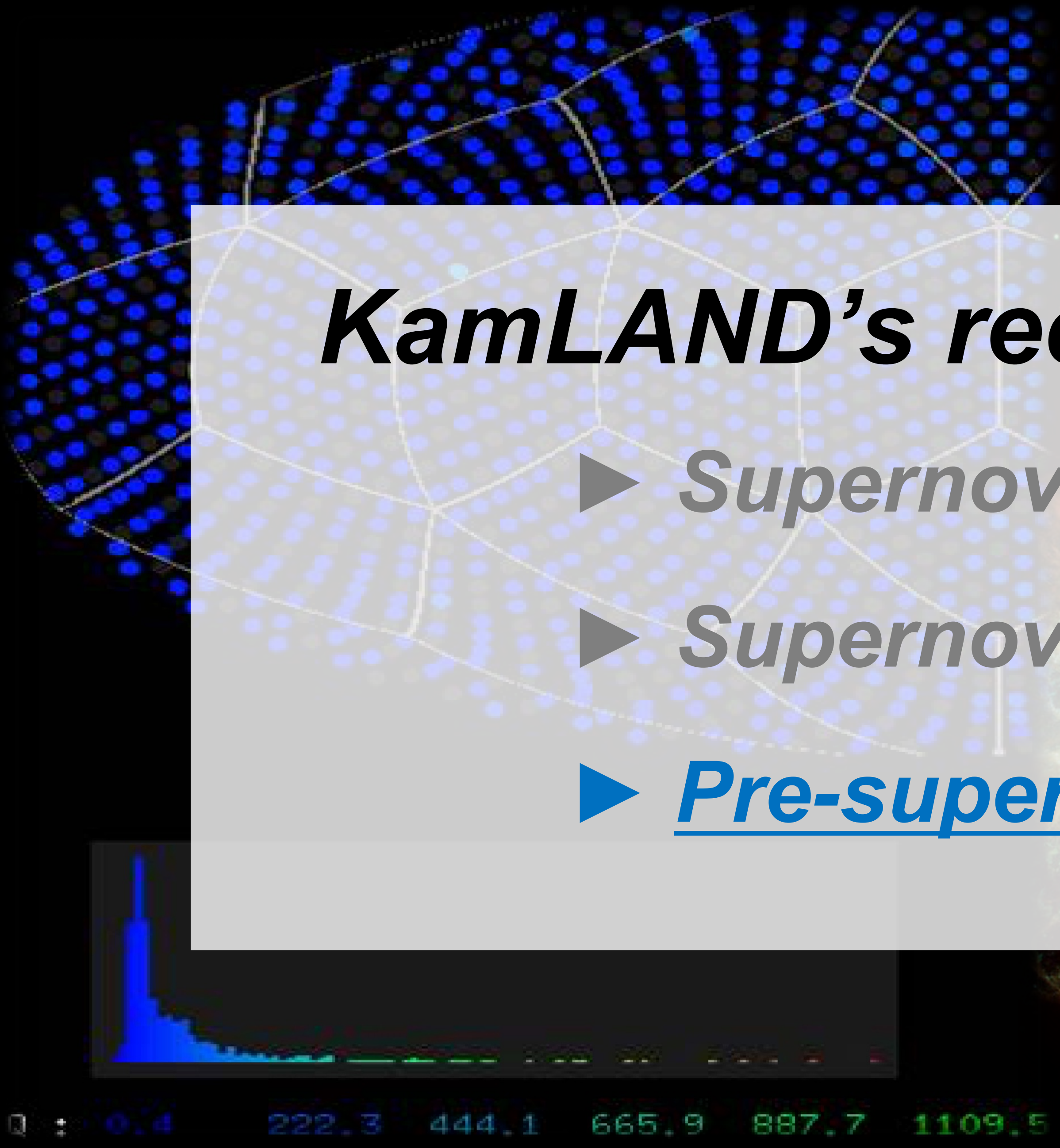
Photon emission time spectrum

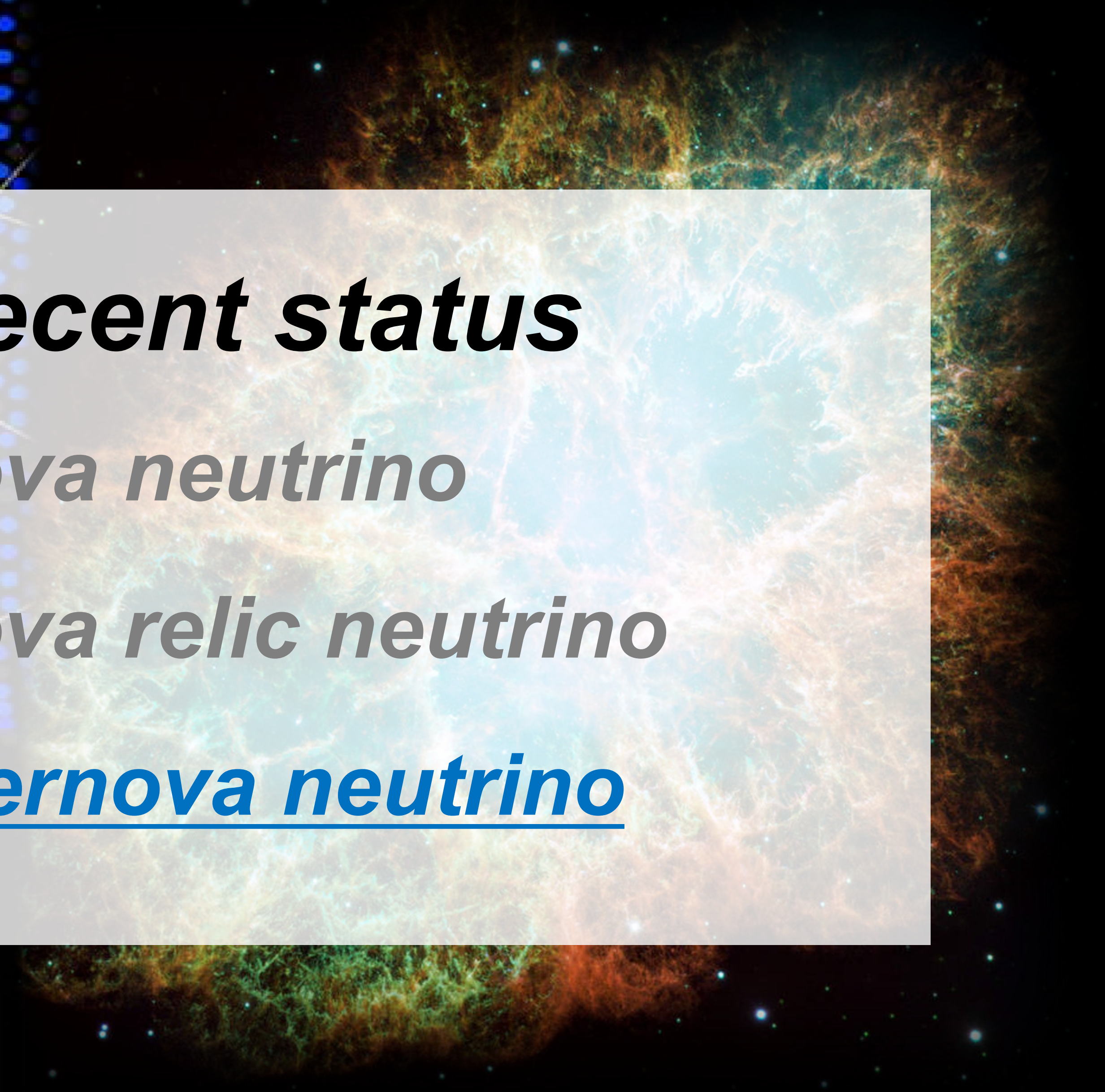


A. Abusleme et al, 2022

^{11}C triple coincidence







KamLAND's recent status

- ► *Supernova neutrino*
- ► *Supernova relic neutrino*
- ► ***Pre-supernova neutrino***

Pre-SN alarm

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

Combined search by Poisson likelihood

$$\mathcal{L} = Poisson\left(n_{KL}^{obs} \middle| S_{KL} + B_{KL}\right) \times Poisson\left(n_{SK}^{obs} \middle| S_{SK} + B_{SK}\right)$$

KL for KamLAND, SK for Super-Kamiokande

- n^{obs}: observed number of candidates
- S: parameters represent signal contributions
- B: parameters represent background contributions

KamLAND

Low background condition

→ It is possible to issue the alarm early.

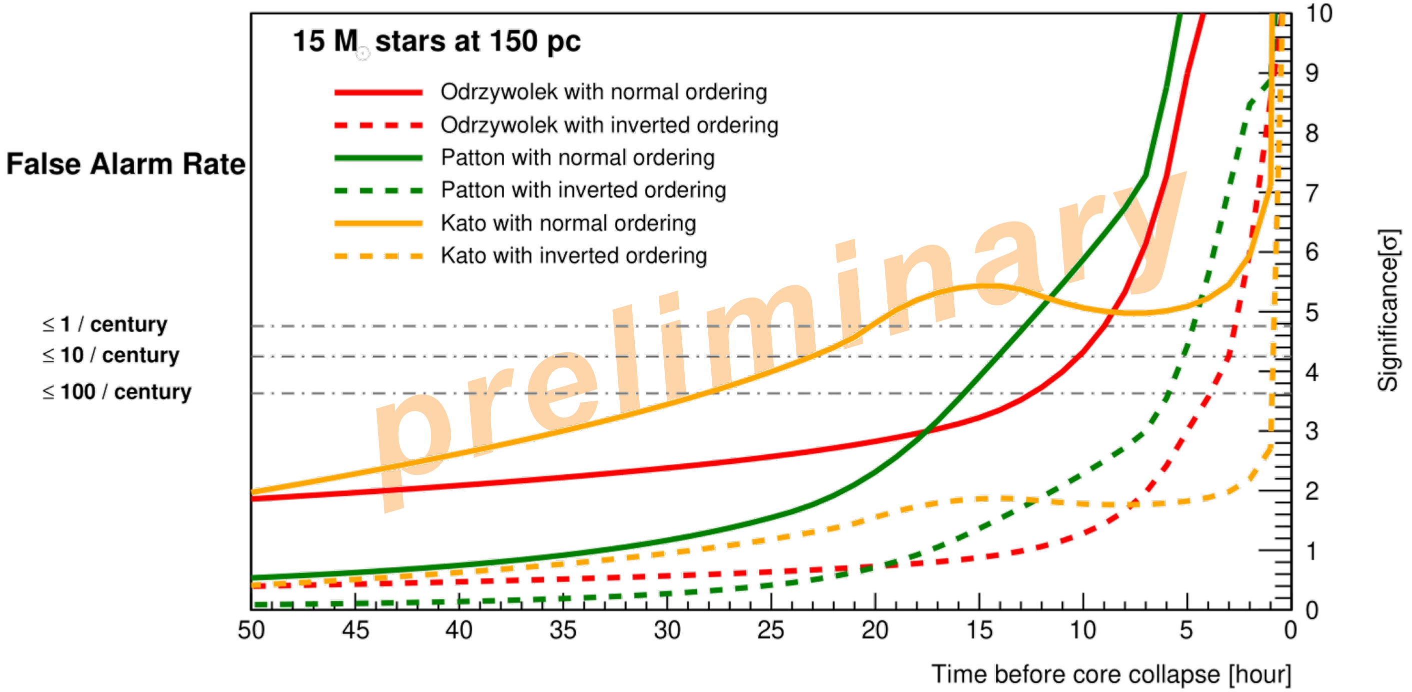
SK-Gd

Large fiducial volume

→ It helps increasing significance.

We can derive benefits from both detectors.

Time evolution of significance by the combined alarm system



Summary

- We searched neutrino bursts by supernovae. *S. Abe, et al, 2022, Apj, **934**, 85* (IBD only)
  - ✓ There were no supernova neutrino ($\bar{\nu}_e$) candidates.
  - ✓ Supernova neutrinos from our Galaxy can certainly be observed ($\geq 99\%$).
  - ✓ We set a constraint on the Galactic Star Formation Rate.
  - ✓ The study of new detection channel ($\nu - 12\mathrm{C}$ NC) is under development.

- We also searched supernova relic neutrinos. *S. Abe, et al, 2022, Apj, **925**, 14*
  - ✓ There were no significant excesses over the background model.
  - ✓ The most stringent upper limit was set on the model-independent flux ($8 - 13\ \mathrm{MeV}$).

- We are preparing for pre-supernova neutrino events. *K. Asakura, et, al, 2016, Apj, **818**, 91* (KamLAND sensitivity)

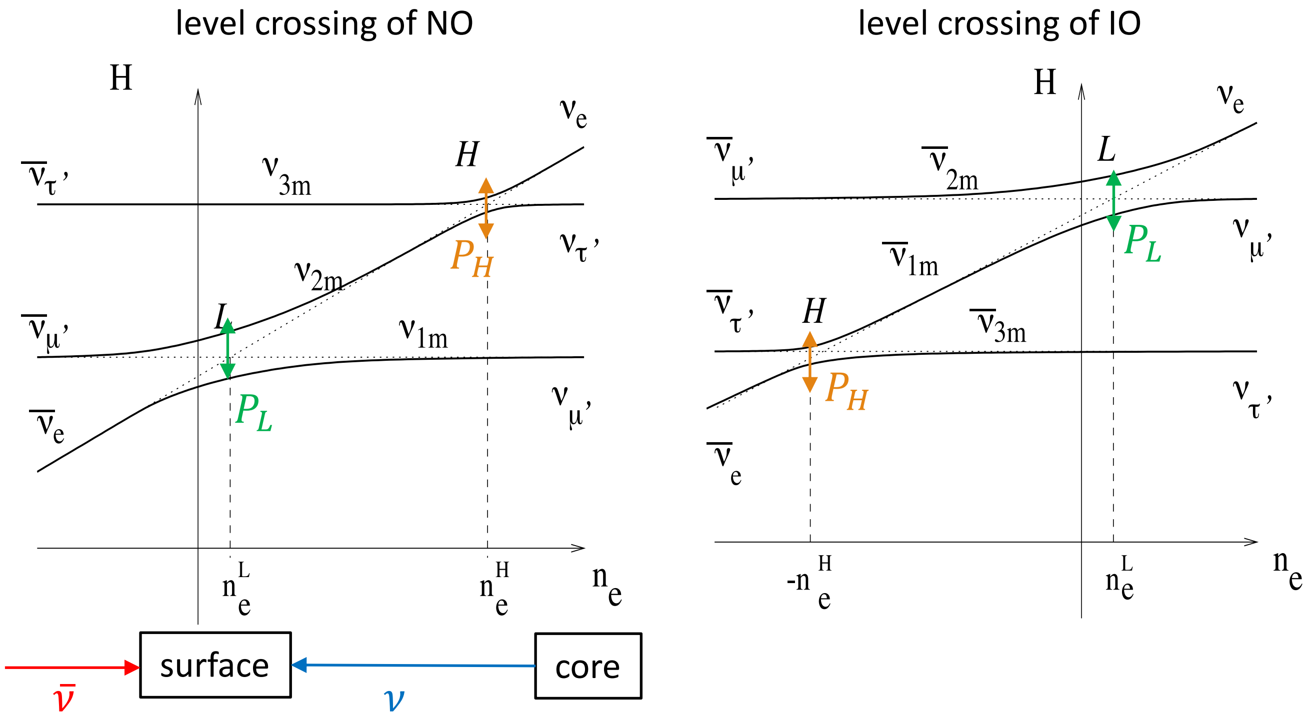
backup

Matter effect of supernova neutrino

- Matter effect by CC potential occur in following region:

$$\rho \sim 1.4\times10^6\ [\mathrm{g/cm^3}] \left(\frac{\Delta m^2}{1\ \mathrm{eV}^2}\right)\left(\frac{10\ \mathrm{MeV}}{E}\right)\left(\frac{0.5}{Y_e}\right)\cos 2\theta$$

  - H resonance（$\sim 10^2 – 10^3\ \mathrm{g/cm^3}$）
  - L resonance（ $\sim 40\ \mathrm{g/cm^3}$ ）



- Flux of observed mass eigenstate $\bar{F}_i$ is described using flip probability.

Flip probability P :”jumping“ probability of mass eigenstates in matter

Ex) in the case of electron-anti neutrino

$$\bar{F}_i = \bar{a}_i F_{\bar{e}}^0 + (1-\bar{a}_i)F_x^0 \longrightarrow F_{\bar{e}} = \sum |U_{ei}|^2\, \bar{F}_i = \bar{p}F_{\bar{e}}^0 + (1-\bar{p})F_x^0$$

$$\bar{a}_1 = 1 - P_L, \bar{a}_2 = P_L, \bar{a}_3 = 0 \qquad \bar{p} = \sum |U_{ei}|^2\, \bar{a}_i = |U_{ei}|^2(1-P_L) + |U_{e2}|^2 P_L$$

“survival probability”

Previous studies of SN burst search

Liquid scintillator | Cherenkov

KamLAND

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: $\leq 41\text{–}59$ kpc (ccSN)/$\leq 64\text{–}79$ kpc (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 ≳ 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)	≤ 100 kpc（∼ 100%）	≤ 25 kpc（≥ 95%）	≤ 25 kpc	≤ 10 kpc（∼ 100%） ≤ 30 kpc（∼ 100%）	≤ 13.4 kpc（≥ 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 MeV γ)

atmospheric neutrino

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

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

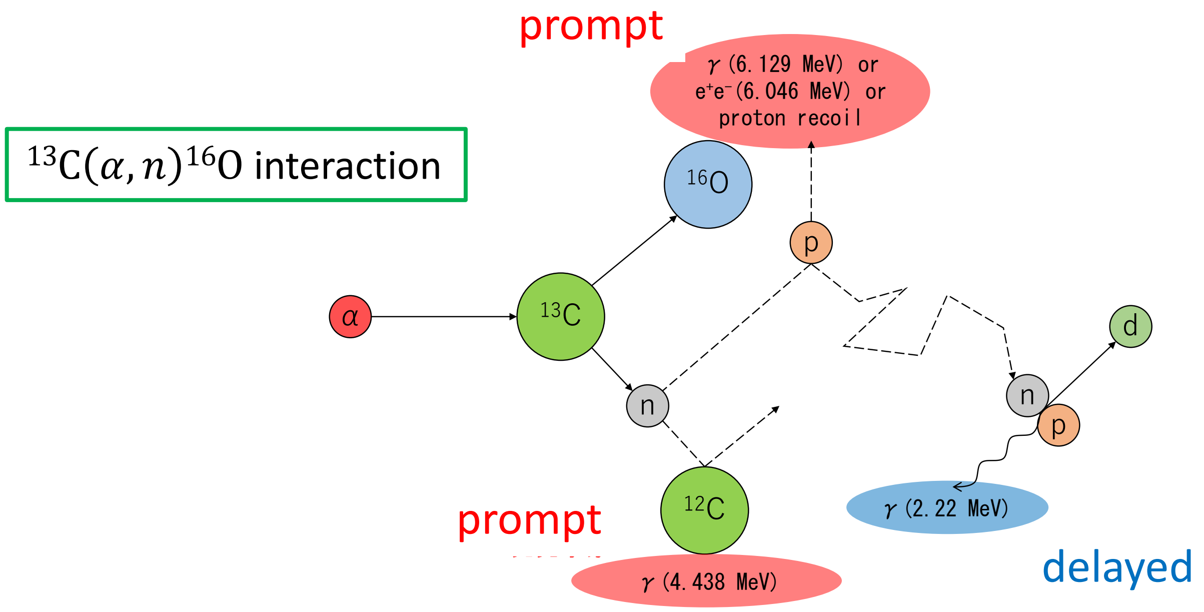
inverse beta decay

(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

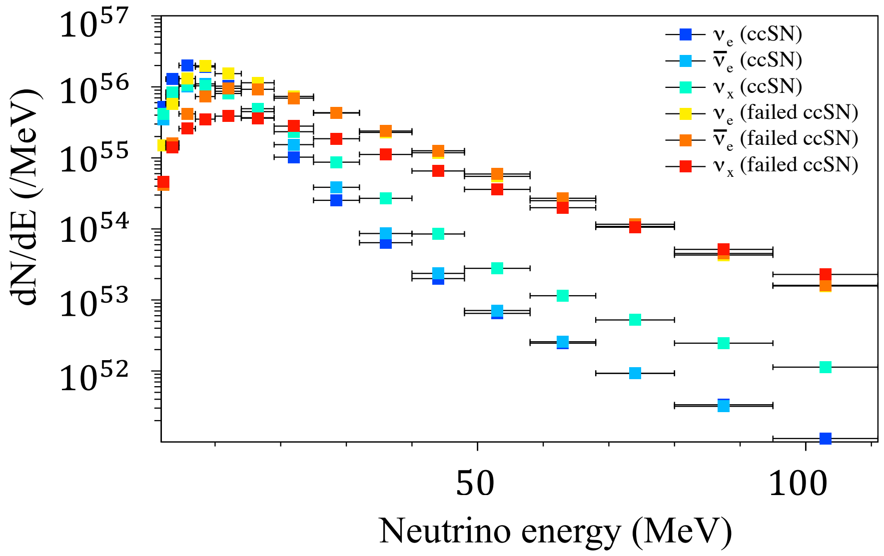
prompt: scattered proton by high-energy neutron
delayed: neutron capture



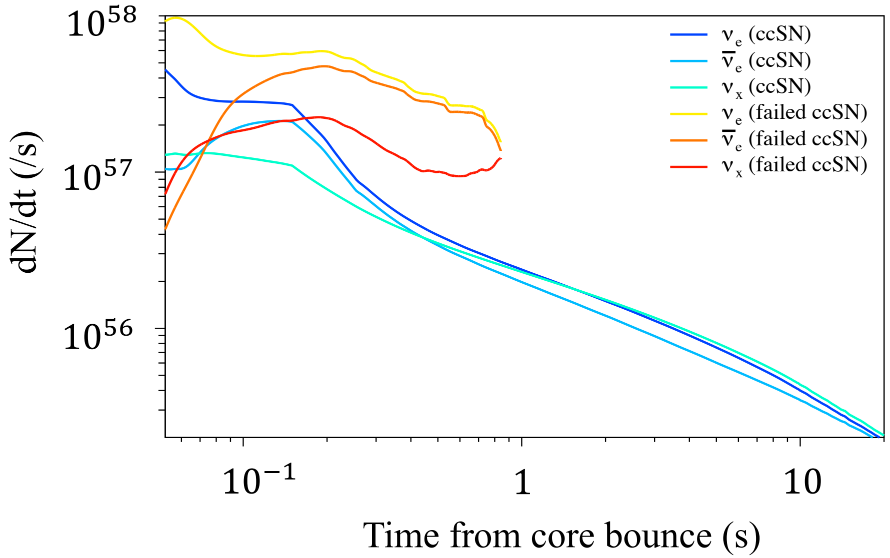
Supernova neutrino model

- Nakazato model Nakazato, K., et al, 2013
  - ➢ Early phase : neutrino-radiation hydrodynamic simulation
  - ➢ Late phase : quasi-static evolutionary calculations of proto-neutron star cooling

Spherical symmetry



- Right figures: energy and time distribution of neutrinos emitted from core collapse SN (ccSN)



- I checked all parameter combination.
  - ➢ Progenitor mass

$$M_{\mathrm{init}} = 13\ M_{\odot}, 20\ M_{\odot}, 30\ M_{\odot}, 50\ M_{\odot}$$

  - ➢ Metallicity

$$Z = 0.02\ (\mathrm{solar}), 0.004\ (\mathrm{Small\ Magelanic\ Cloud})$$

  - ➢ Shock revival time

$$t_{\mathrm{revive}} = 100\ \mathrm{ms}, 200\ \mathrm{ms}, 300\ \mathrm{ms}$$

Calculation of number of expected events

- $\bar{\nu}_e$ flux at the Earth $F_{\bar{e}Earth}(r,t)$

$$F_{\bar{e}\mathrm{Earth}}(r,t) = \frac{1}{4\pi r^2}\left\{\bar{p}\frac{d^2N_{\bar{e}0}}{dE\mathrm{d}t} + (1-\bar{p})\frac{d^2N_{x0}}{dE\mathrm{d}t}\right\}$$

- □ r : distance from the Earth
- □ $\frac{d^2N_{i0}}{dE\mathrm{d}t}$: number of ν_i emitted from SN
  ← obtained from Nakazato model
- □ $\bar{p}$: survival probability of $\bar{\nu}_e$
  ← consider matter effect in SN

$$\bar{p} = \cos^2\theta_{12}\cos^2\theta_{13}\ (\mathrm{NH}), \sin^2\theta_{13}\ \ (\mathrm{IH})$$

$$\sin^2\theta_{12} = 0.320$$
$$\sin^2\theta_{13} = 0.0216$$

de Salas, P., et al, 2018

Earth matter effect is ignored.

- Number of observed events in KamLAND N_{KL}

$$N_{KL}(r) = \mathcal{N}_{\mathrm{target}} \times \int \mathrm{d}t\mathrm{d}E\, F_{\bar{e}\mathrm{Earth}}(r,t)\sigma_{\mathrm{IBD}}(E)\epsilon_{\mathrm{eff}}(E)$$

- □ $\mathcal{N}_{\mathrm{target}}$: number of target proton $(r = 600\ \mathrm{cm})$
  $= (5.98 \pm 0.13)\times 10^{31}$
- □ $\sigma_{\mathrm{IBD}}(E)$: IBD cross section
- □ $\epsilon_{\mathrm{eff}}(E)$: IBD detection efficiency in KamLAND

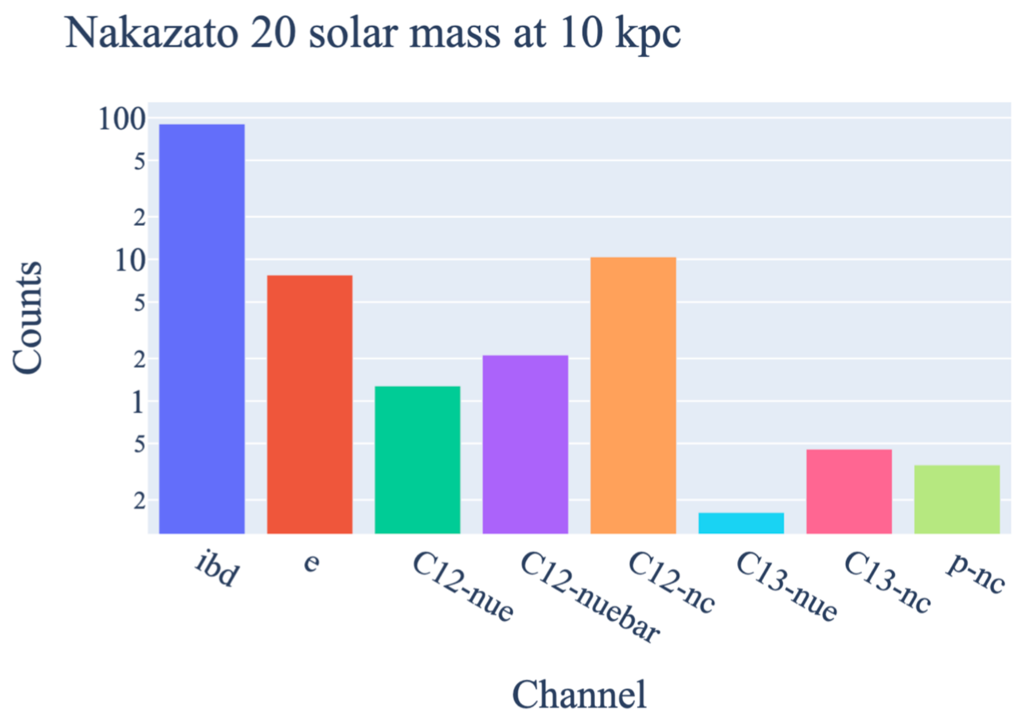
Range of integration

$$1.8\ \mathrm{MeV} \le E \le 111\ \mathrm{MeV}$$
$$0\ \mathrm{s} \le t \le 20\ \mathrm{s}$$

Livetime effect is considered as deadtimes after muon events.

Number of expected events/ detection probability with some models

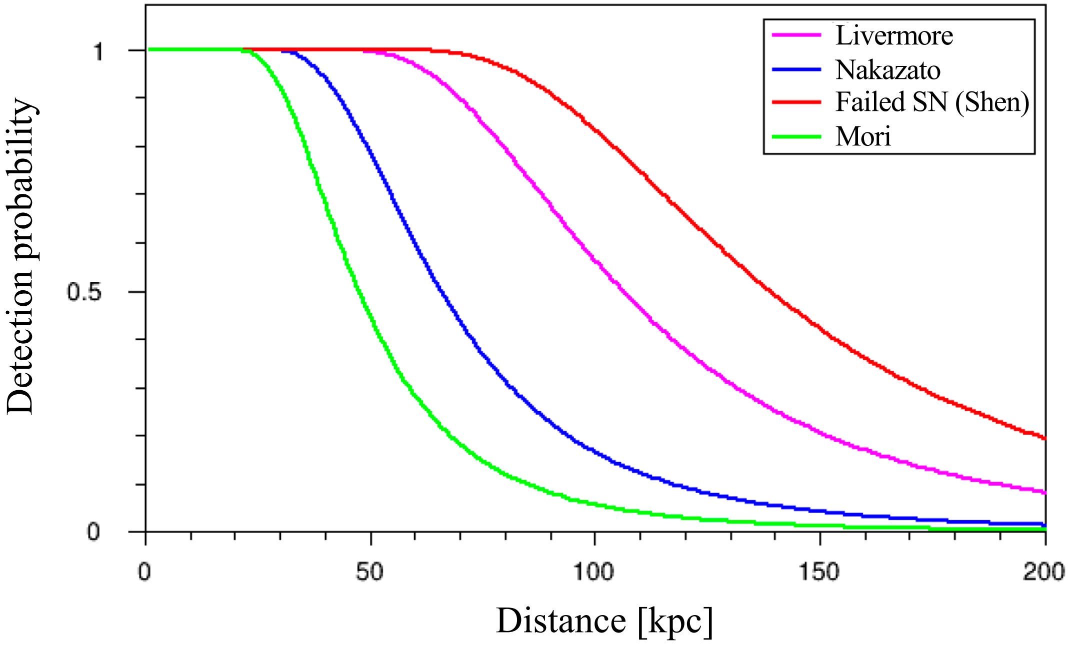
Number of expected events by different neutrino detection channels



Model dependence of detection probability

IBD only, time distribution is not considered

Livermore model is within Nakazato model uncertainty



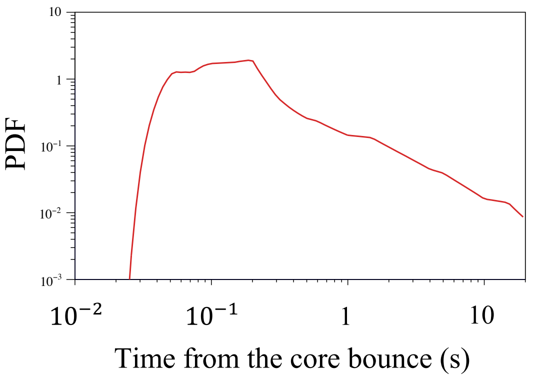
Detectable range (IBD only)

To convert observed cluster rate to supernova rate,
detectable range of SNν is need to be known.

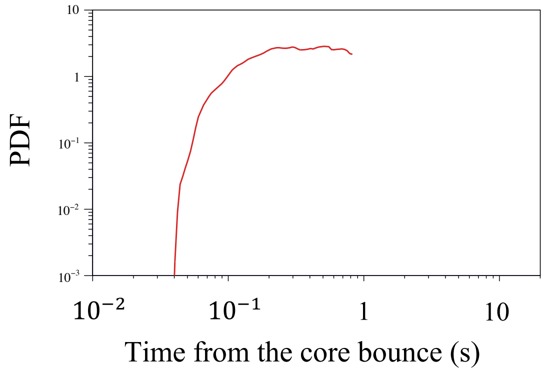
K. Nakazato, et al., ApJS (2013)

1. Numerical calculation of N_{KL} by Nakazato model (upper right figure) — widely used long time simulation
2. MC simulation of expected event time distribution in KamLAND

SNν event PDF in KamLAND（ccSN）



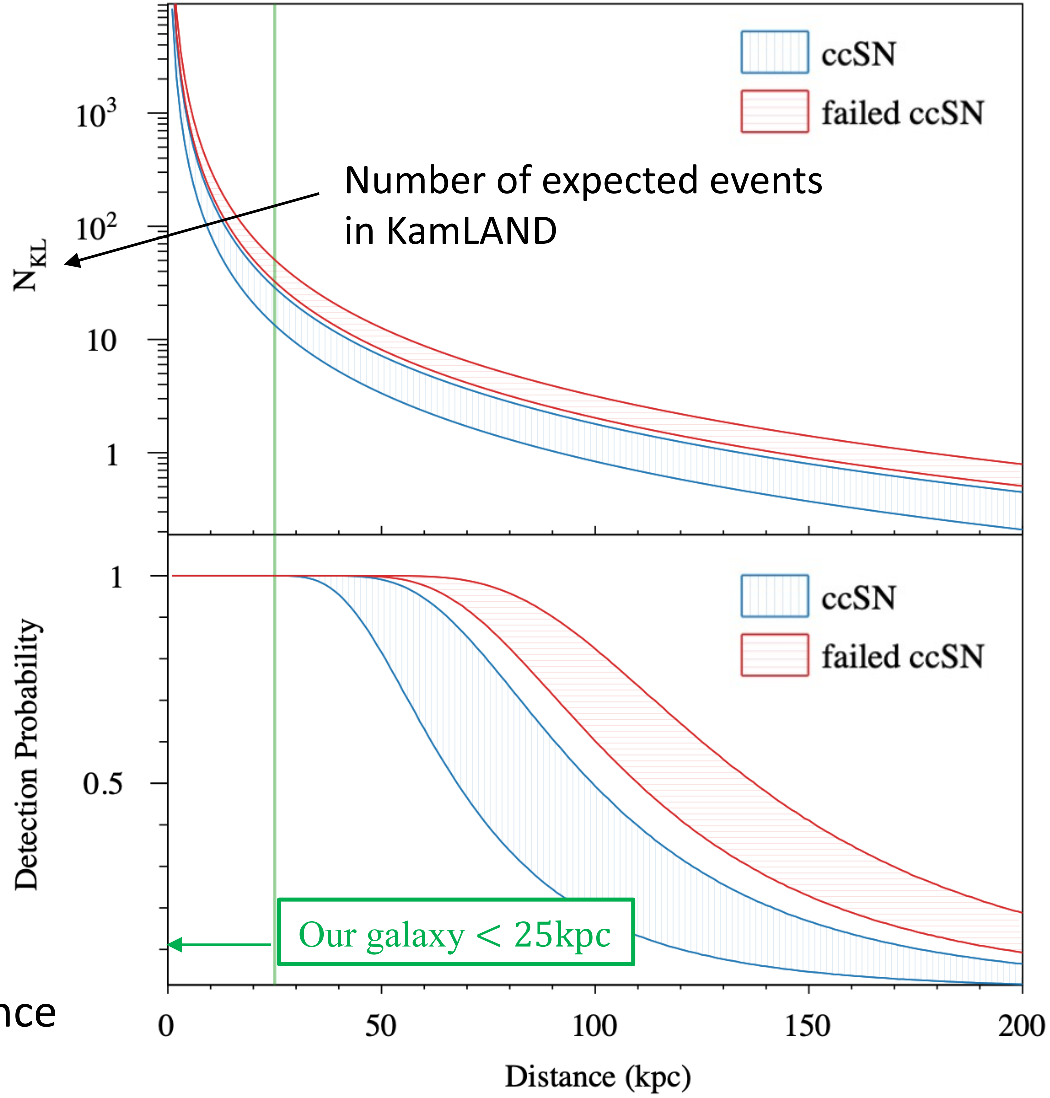
SNν event PDF in KamLAND（failed ccSN）



3. Calculation of time difference of expected events (SNν candidate? Or not?)

Repeating 1. to 3., detection probability is calculated for each distance (lower right figure).

Number of expected events and detection probability by IBD



Detectable range (NC only)

- Detectable range cannot cover our Galaxy.

Detectable range

$\lesssim 7\text{–}10$ kpc (ccSN)
$\lesssim 10\text{–}11$ kpc (failed ccSN)

With model & NC cross section uncertainty

- I calculated detection probability by considering Galactic supernova distribution.

Detection probability in our Galaxy

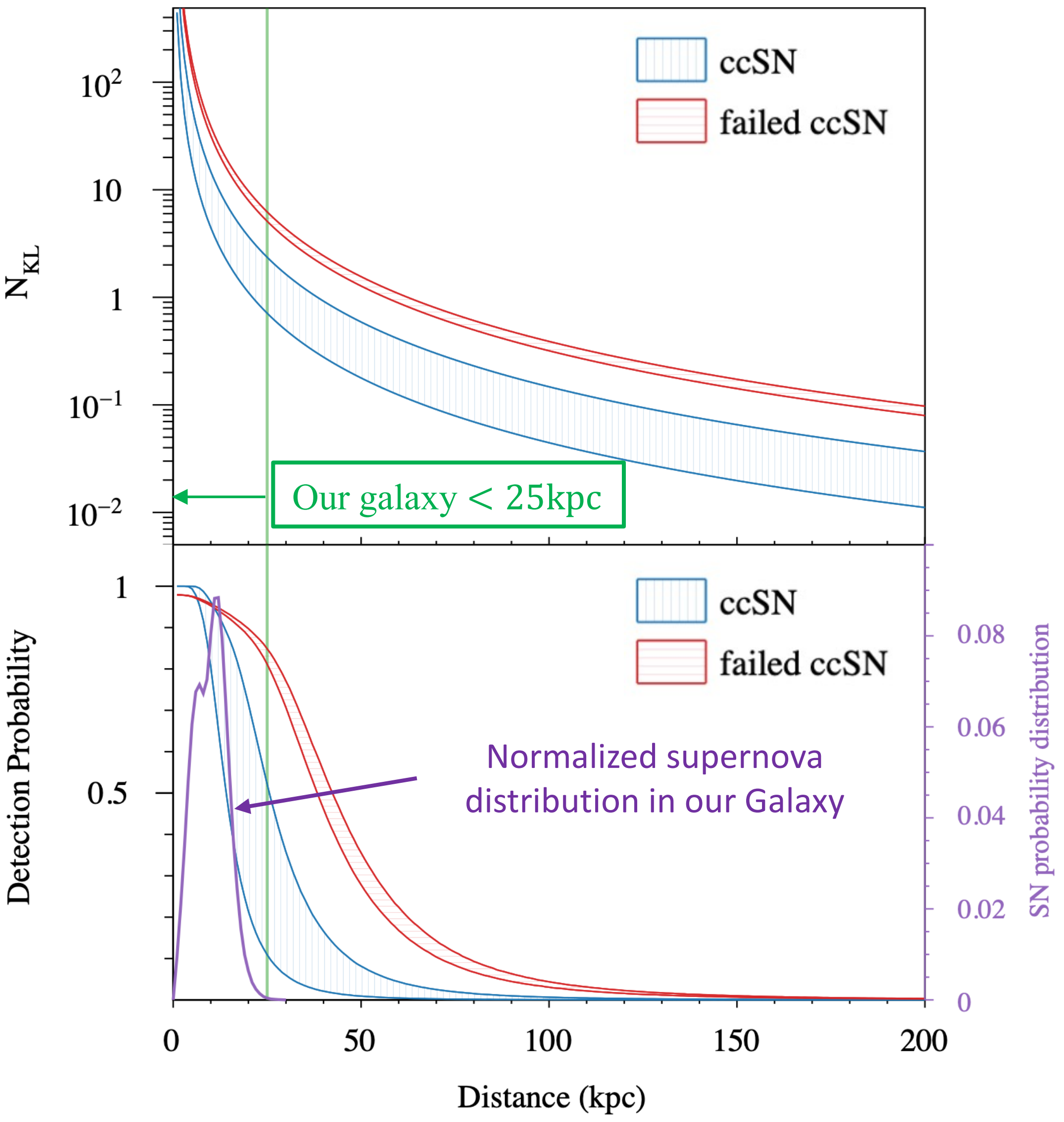
(detection probability × SN PDF)

$\lesssim 74.7\text{–}94.1\%$ (ccSN)
$\lesssim 94.8\text{–}95.4\%$ (failed ccSN)

Upper limit on the galactic supernova rate

$\lesssim 0.45\text{–}0.56\ \mathrm{yr}^{-1}$ (ccSN)
$\lesssim 0.44\ \mathrm{yr}^{-1}$ (failed ccSN)

Number of expected events and detection probability by NC



Galactic supernova distribution

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

Radial distribution

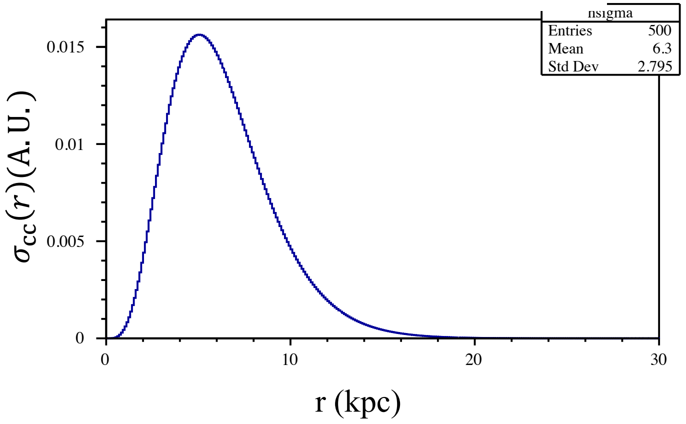
$$\sigma_{cc}(r) \propto r^{\xi} \exp\left(-\frac{r}{u}\right)$$

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

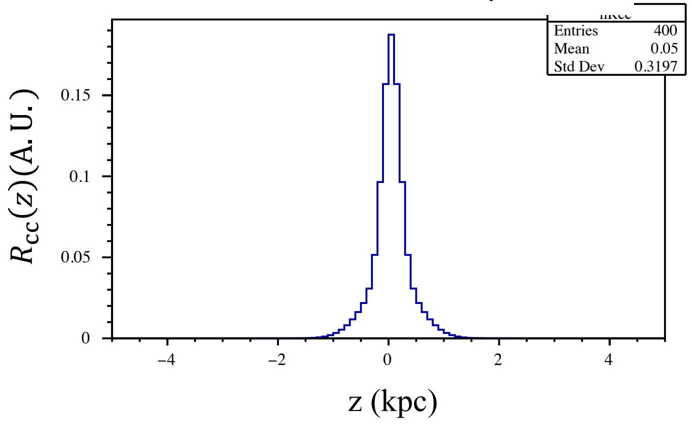
This corresponds to the NS distribution

r : radius from the Galactic center

Radial distribution of supernova



Vertical distribution of supernova



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

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

d: distance from the solar

Vertical distribution

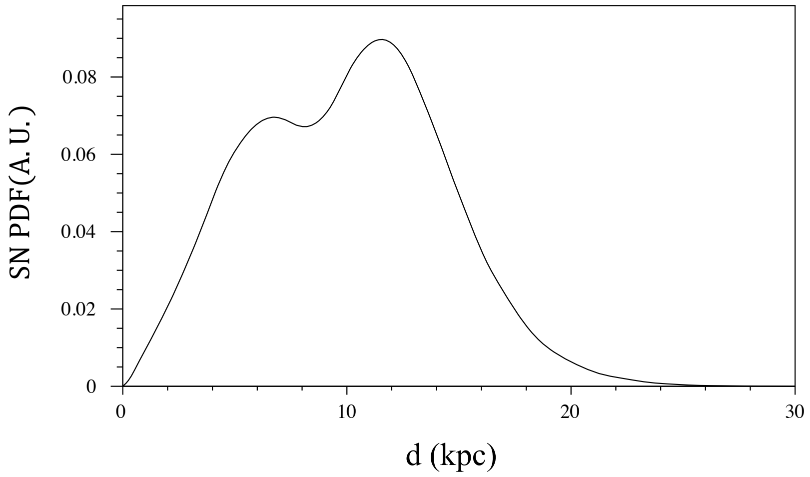
$$R_{cc}(z) \propto 0.79 \exp\left[-\left(\frac{z}{212\ \mathrm{pc}}\right)^2\right] + 0.21 \exp\left[-\left(\frac{z}{636\ \mathrm{pc}}\right)^2\right]$$

z : distance from galactic plane

Three-dimensional distribution

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

Three-dimensional distribution of supernova



Estimation of energy scale uncertainty（1）

Scale uncertainty between observed and simulated events

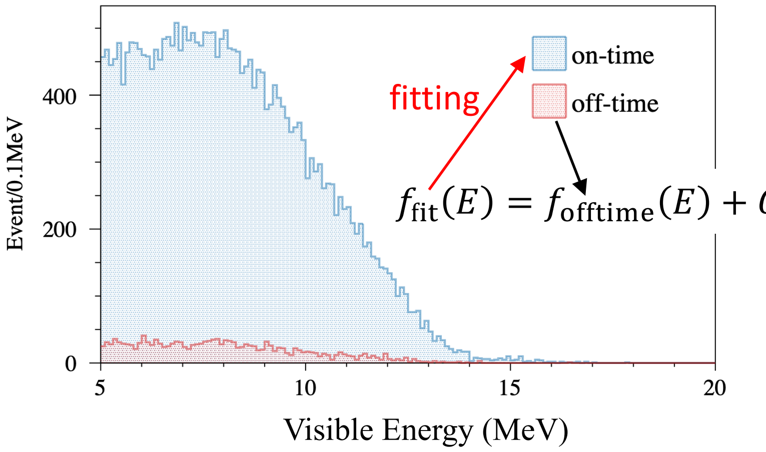
- Reference: ^{12}B, ^{12}N decay events

$$Q = 13.4, 17.3\ \text{MeV (around 15.1 MeV)}$$

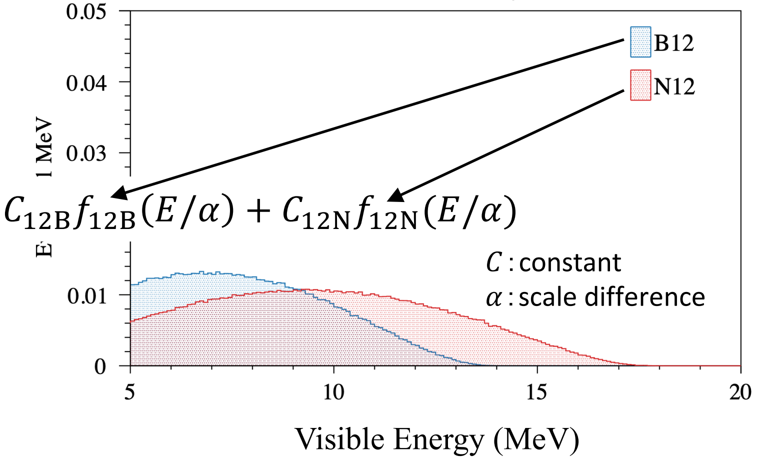
- Fitting result

3.9%（before purification）
9.6%（after purification）
8.8%（after Zen 400）

Observed spallation events after cosmic muons



Simulation of decay events



$$f_{\text{fit}}(E) = f_{\text{offtime}}(E) + C_{12\text{B}} f_{12\text{B}}(E/\alpha) + C_{12\text{N}} f_{12\text{N}}(E/\alpha)$$

C : constant
α : scale difference

Quenching effect on the energy scale uncertainty

- Quenching effect:
  a part of dE/dx in LS is lost in the process of scintillation emission dL/dx

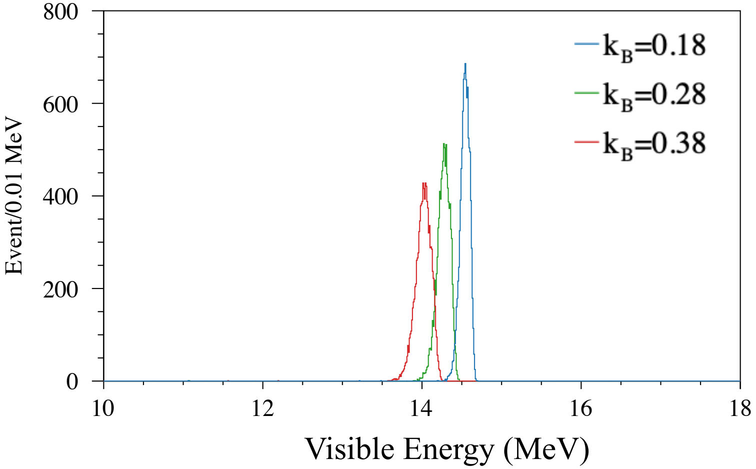
  → Birks formula

$$\frac{dL}{dx} = \frac{L_0\left(\frac{dE}{dx}\right)}{1 + k_B\left(\frac{dE}{dx}\right)}$$

k_B is LS specific value
KamLAND previous study: $k_b \sim 0.3 \pm 0.1\ \text{mm/MeV}$

- The effect of k_B uncertainty is 1.9%

Visible energy with different k_B



Estimation of energy scale uncertainty (2)

Summary of energy scale uncertainties

4.3% (before purification) / 9.8% (after purification) / 9.0% (after Zen 400)

Energy selection should be set to obtain enough signal efficiency.

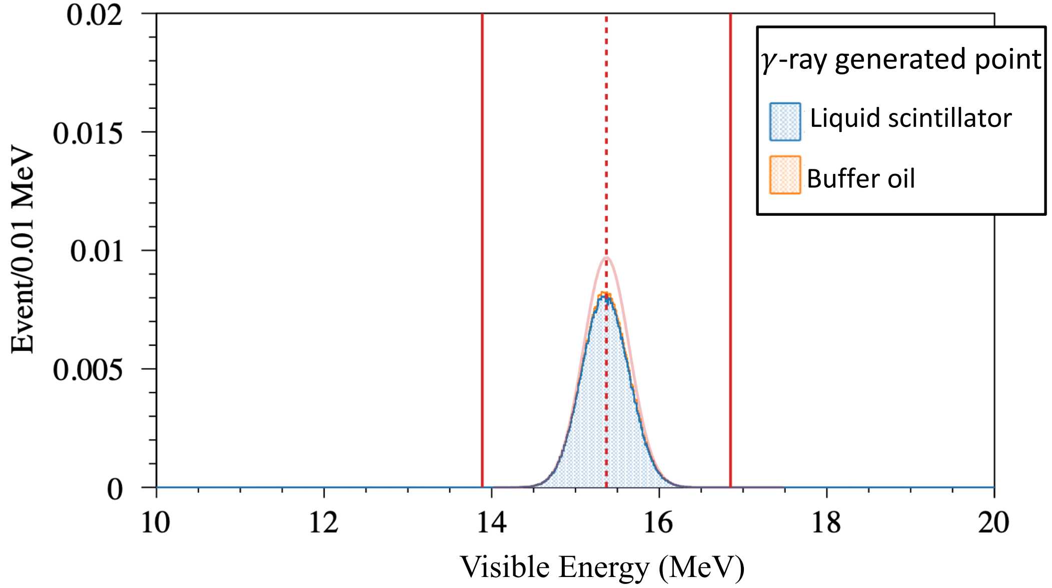
Energy selection criteria

- Fit reconstructed 15.1 MeV γ spectrum
- Set energy range as $\pm 3\sigma$ in addition to mean$\times$(uncertainty)

Before purification: $13.89 \leq E\ [\mathrm{MeV}] \leq 16.85$
After purification: $13.16 \leq E\ [\mathrm{MeV}] \leq 17.95$
After Zen 400: $13.53 \leq E\ [\mathrm{MeV}] \leq 18.32$

- Under this selection, signal efficiency is >99%

Simulated signal and energy region



Conversion from observed cluster rate to SN rate

Tamman, G. A., et al, 1994

- Supernova rate is estimated from the observed historical supernovae.

- Contribution from type-II supernova at LMC, SMC is… ~ 0.5 /100 yr

TABLE 2
ABSOLUTE FREQUENCIES (in SNu) OF SUPERNOVAE OF DIFFERENT TYPES IN DIFFERENT TYPES OF GALAXIES

Supernova Type	Galaxy Type: E-S0	S0/a-Sa	Sab-Sb	Sbc-Sd	Sdm-Im
All types	0.25	0.17	0.53	1.29	1.40
Ia	0.25	0.12	0.12	0.12	0.12
Ib	…	0.01	0.07	0.19	0.23
II	…	0.04	0.34	0.98	1.05

TABLE 4
SN FREQUENCIES IN LOCAL GROUP GALAXIES

Parameter	Galaxy and Type: LMC Sm	SMC Im	M31 Sb	M33 Sc
n (Ia)[a]	0.04	0.01	0.38	0.06
n (II + Ib)[a]	0.45	0.11	0.83	0.62
τ (yr)	204	833	83	147

Calculation of star formation rate

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

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

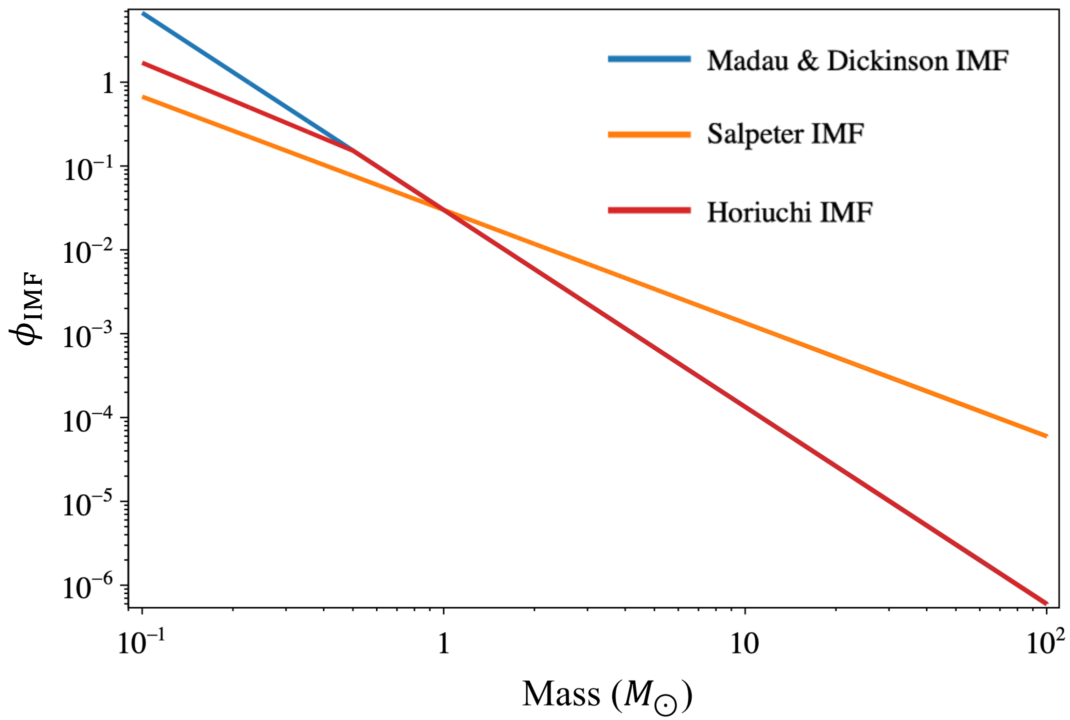
- ϕ_{IMF} : Initial Mass Function, IMF
  number distribution of star as a function of mass

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

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

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

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) $0.9 < \psi_{\rm SFR}^{\rm gal}\ [M_{\odot}{\rm yr}^{-1}] < 2.2$

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

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

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

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

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

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

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

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

combined result of previous SFR estimations by Hierarchical Bayesian method

constraint on the Galactic star formation rate