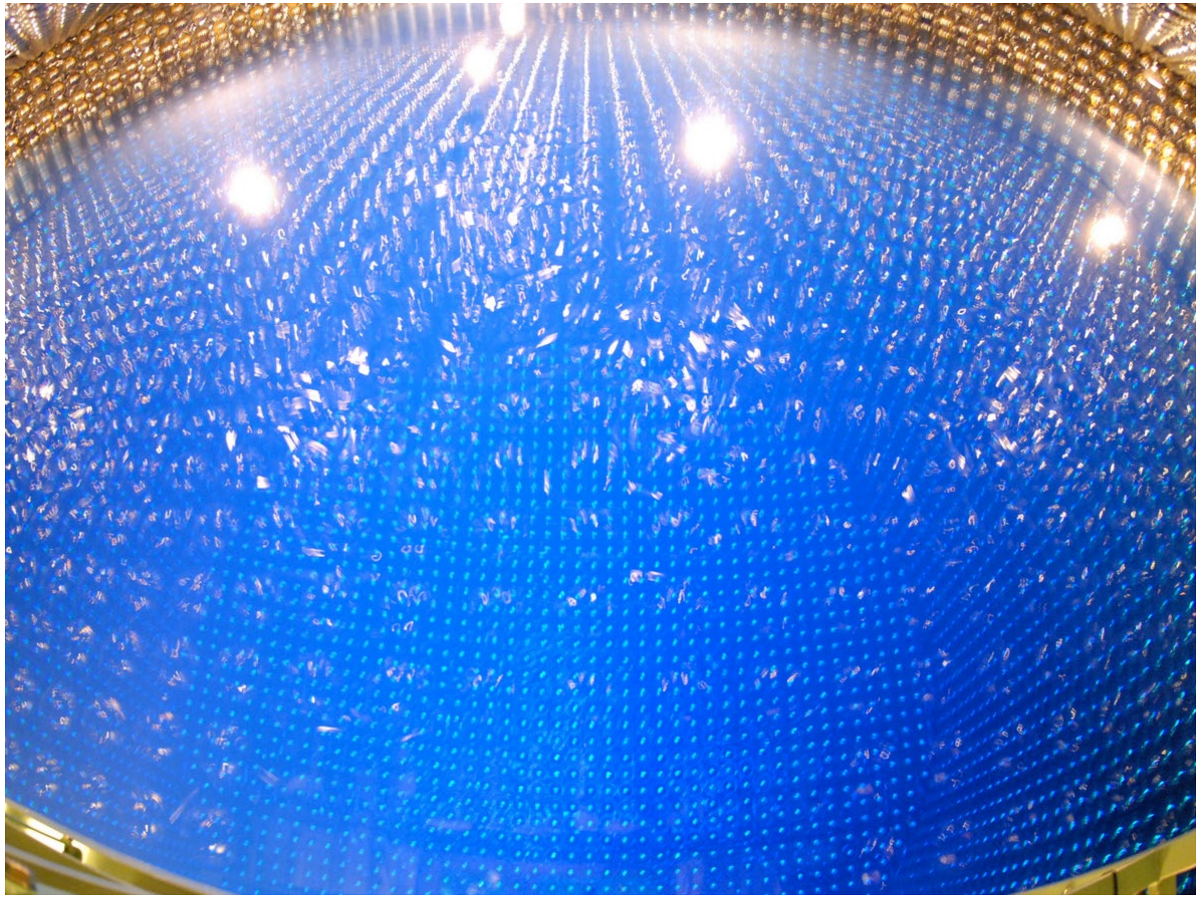
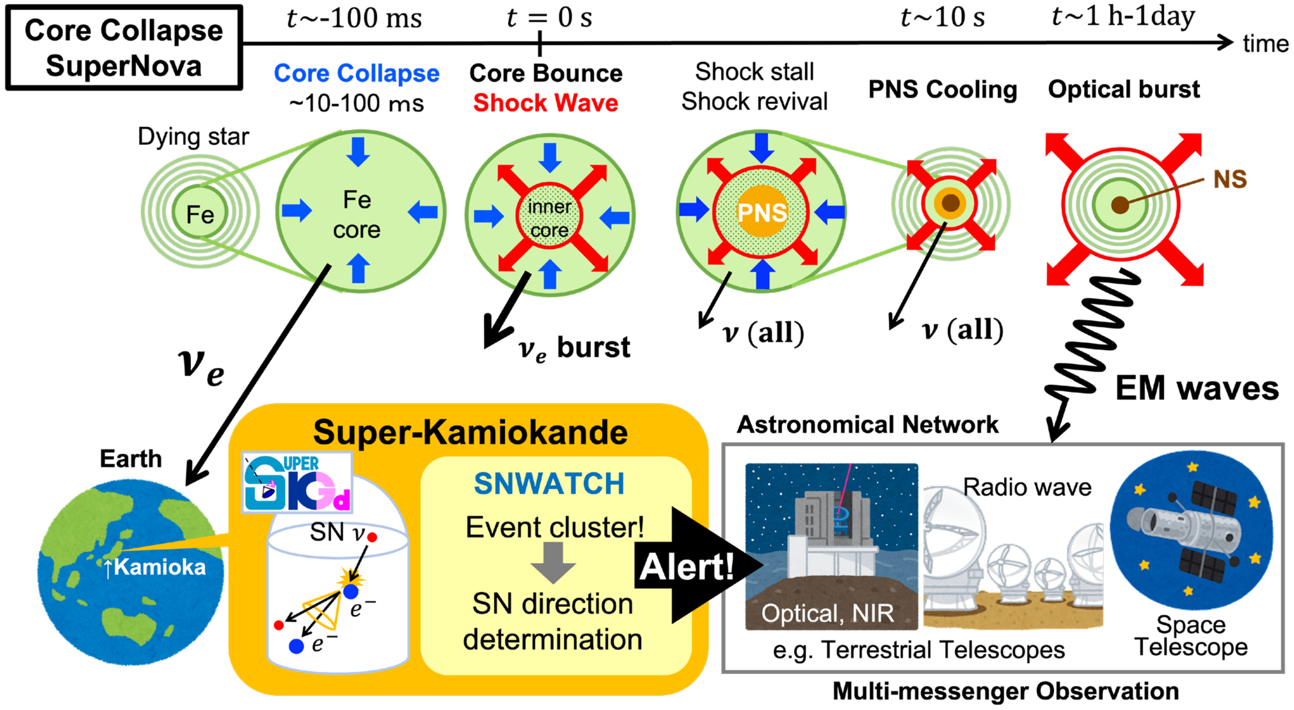




Super-Kamioaknde -MM through CCSN bursts-

「マルチメッセンジャー天文学の展開」研究会
東京大学柏キャンパス図書館メディアホール

関谷洋之

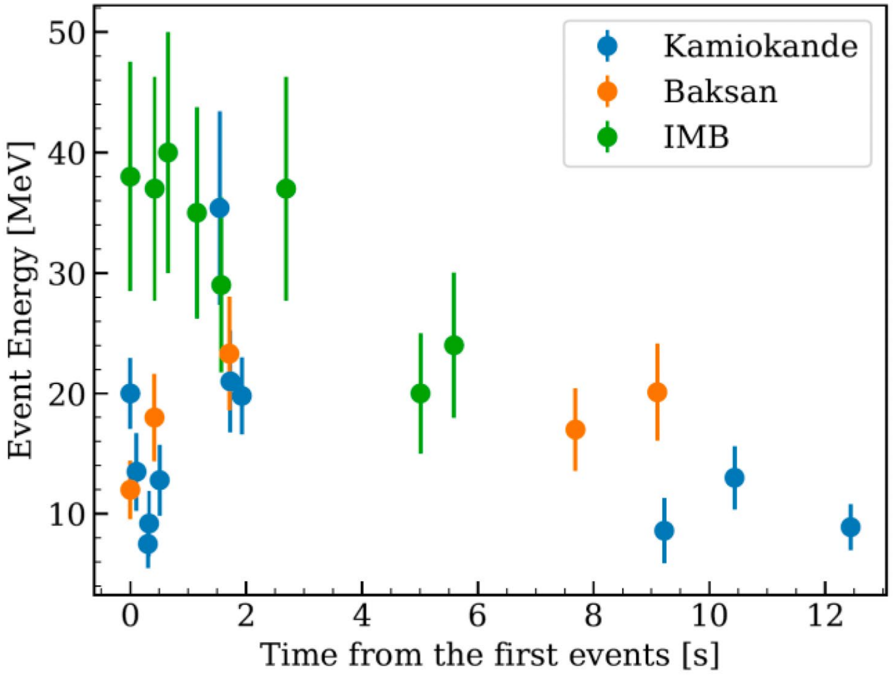
2023年11月1日

次世代ニュートリノ科学・
マルチメッセンジャー天文学連携研究機構
Next-generation Neutrino Science and Multi-messenger Astronomy Organization

Supernova neutrinos

- The only detected SN neutrinos are from LMC(50kpc) in 1987.

M. Mori



11 events
5 events
8events

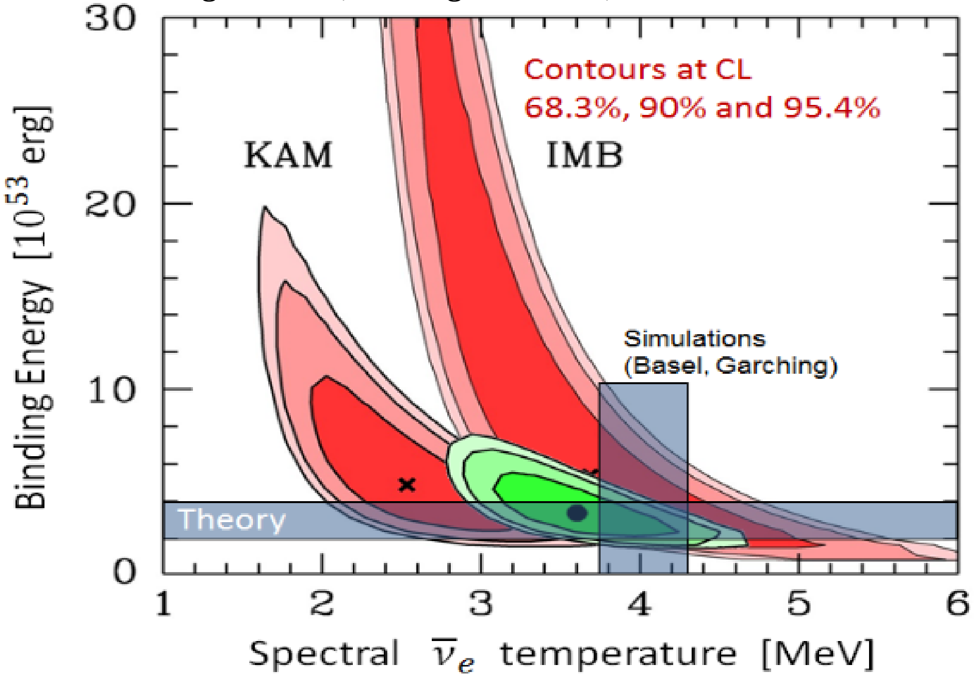
In total
24 ($\overline{\nu}_e$) events

Total energy

released by $\overline{\nu}_e$:

~5x10^{52} erg

Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

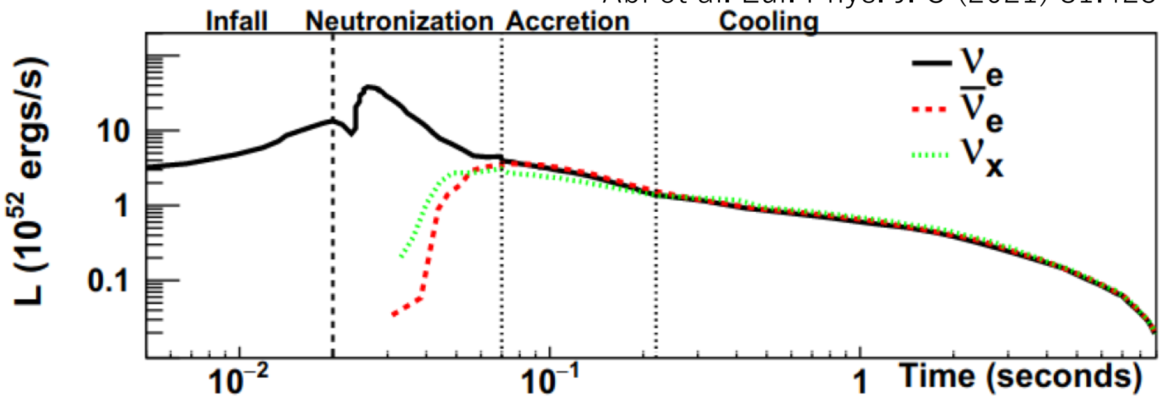


- The obtained binding energy is almost as expected, but there is a large error in neutrino mean energy. There is no detailed information on the burst process.

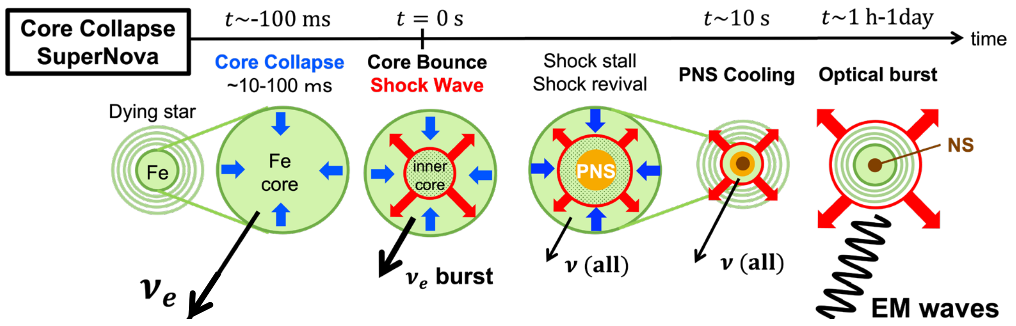
Core-collapse supernova (>8M$_\odot$)

- The basic mechanism of core-collapse supernovae explosions (CCNS) was established by detecting 24 neutrinos from 1987A. Neutrinos play a key role in the explosion.

Abi et al. Eur. Phys. J. C (2021) 81:423



Luminosity vs. time



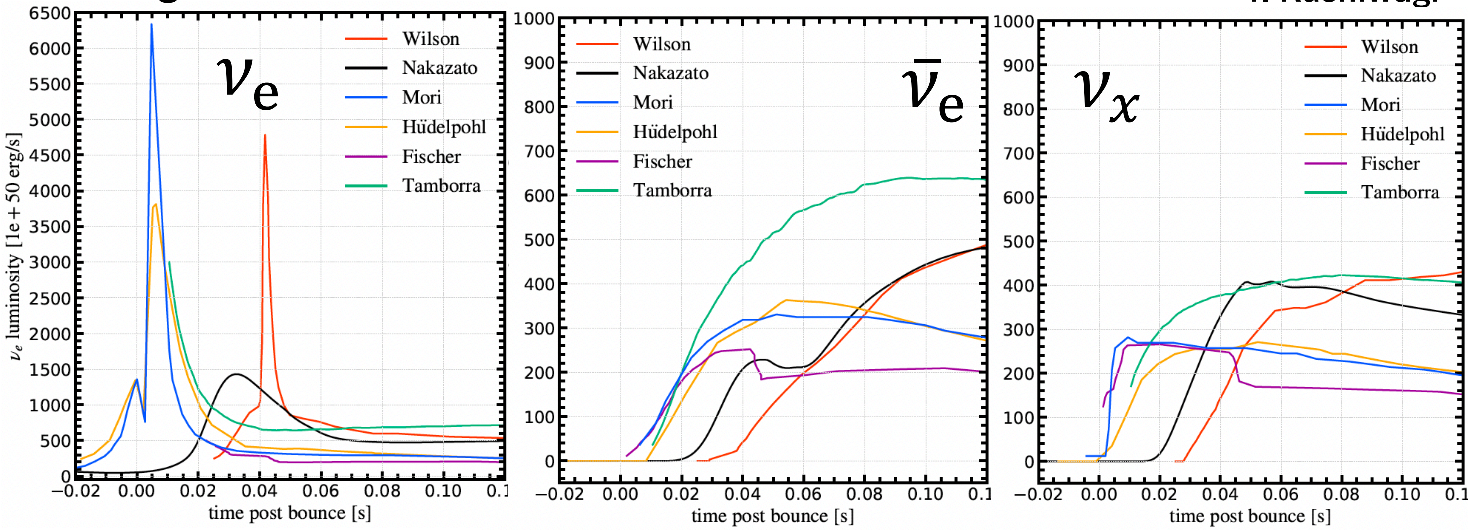
However, details are largely unknown

- Shock revival mechanism, equation of state, PNS formation
- Convection, SASI, …
- Fail and BH formation,…
- Many unknowns, models, and predictions

Ex) Wilson, Nakazato, Mori, Hüdelpohl, Fischer, Tamborra

Light curves ~0.1 sec

Y. Kashiwagi



- We must prepare for the next nearby SN
- Explore the time, energy, and flavor structure to get at the details of the explosion mechanism

Supernova Models

- Five 1D models + one 3D model

*Shen, et al. *Nucl. Phys. A* **637** (1998) 435–450.
Shen, et al. *PTEP* **100** (1998) 1013–1031.
Mori *et al.*, *PTEP* **2021 (2021) 023E01
***Lattimer & Swesty, *Nucl. Phys. A* **535** (1991) 331–376.

Summary of Supernova models. Core bounce occurs at 0 s.

Model Name	Wilson[1]	Nakazato[2]	Mori[3]	Hüdelpohl[4]	Fischer[5]	Tamborra[6]
Dimension	1D	1D	1D	1D	1D	3D
progenitor mass [$M_\odot$]	20	20	9.6	8.8	8.8	27
start time [s]	0.03	-0.05	-0.256	-0.02	0.0	0.011
duration [s]	14.96	20.05	19.95	8.98	6.10	0.54
Equation of State	-	Shen*	DD2**	Shen*	Shen*	LS***

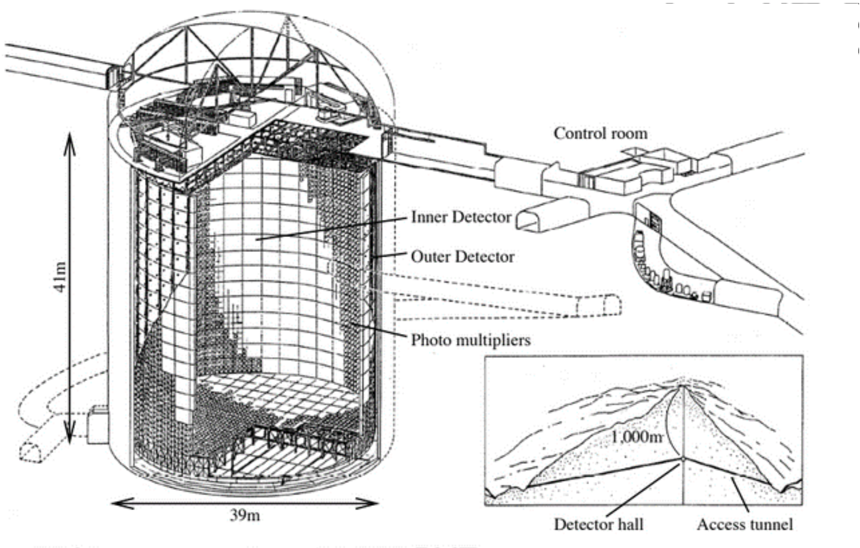
Reference [1] Totani, T., et al. *ApJ* 496.1 (1998): 216
[2] Nakazato, K., et al. *ApJS* 205.1 (2013): 2
[3] Mori, M., et al. *PTEP* 2021.2 (2021): 023E01
[4] Hüdepohl, L., et al. *PhRvL* 104.25 (2010): 251101
[5] Fischer, T., et al. *A&A* 517 (2010): A80
[6] Tamborra et al. *PRD* 90.4 (2014): 045032.

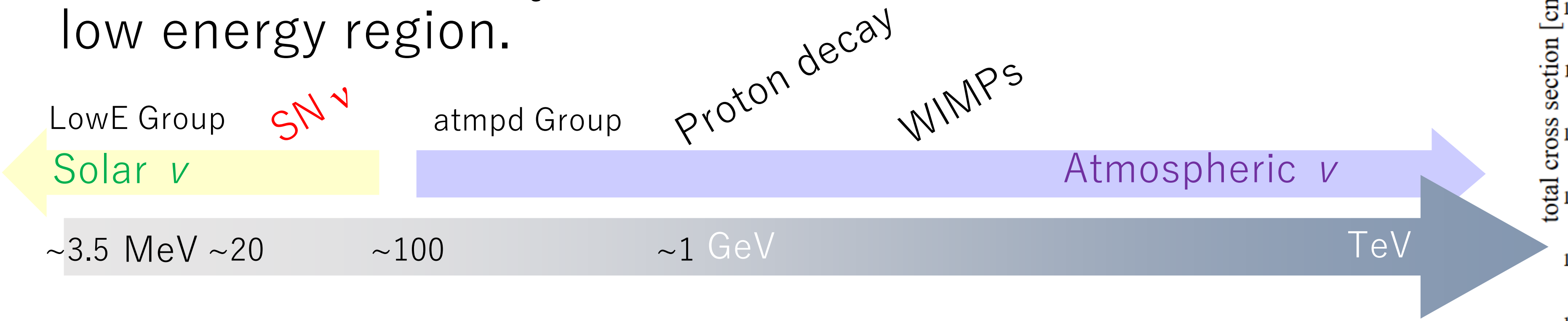
Electron capture Supernova (O-Ne-Mg core)

SASI (Standing Accretion-Shock Instability)

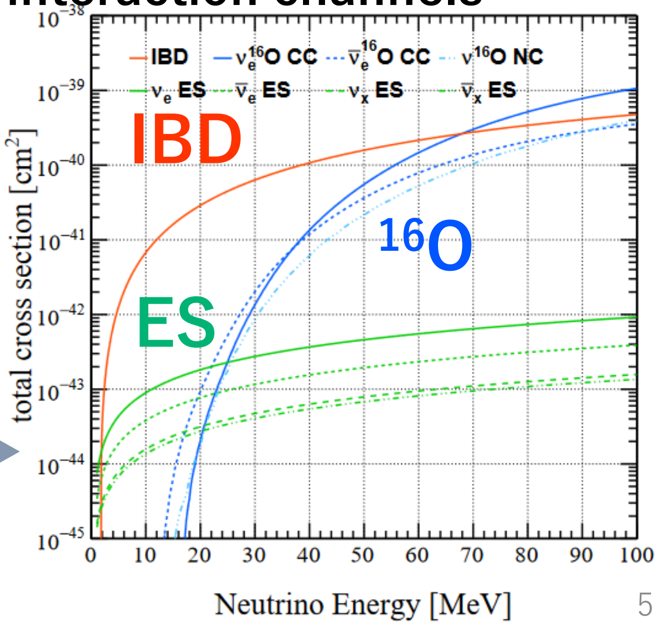
Super-Kamiokande VII (since July 5, 2022)

- **Ring imaging Gd-doped water Cherenkov detector**
  - **49.5k m^3 of pure water with 16.2 tons of Gd(0.03 w%)**
    - **39 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$**
    - **~75% Neutron capture efficiency**
  - **Target volume 32k m^3 for SN ν**
  - 11129 50cm PMTs for Inner detector
  - 1885 20cm PMTs for outer detector
- 1km (2700 mwe) underground in Kamioka
- Measurable： Energy, neutrino types, and direction
- Most sensitive to $\bar{\nu}_e$ through inverse beta decay in the low energy region.





The interaction channels

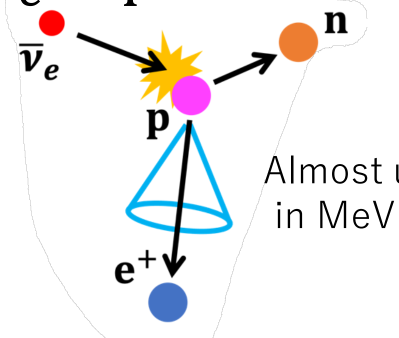


Supernova neutrino in SK

The main channel
Inverse Beta Decay reaction (IBD) ~90%

The direction of the positron does not reflect the direction of the neutrino

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

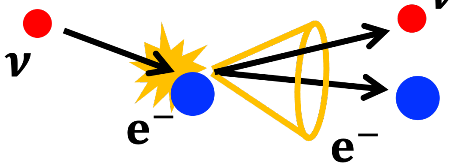


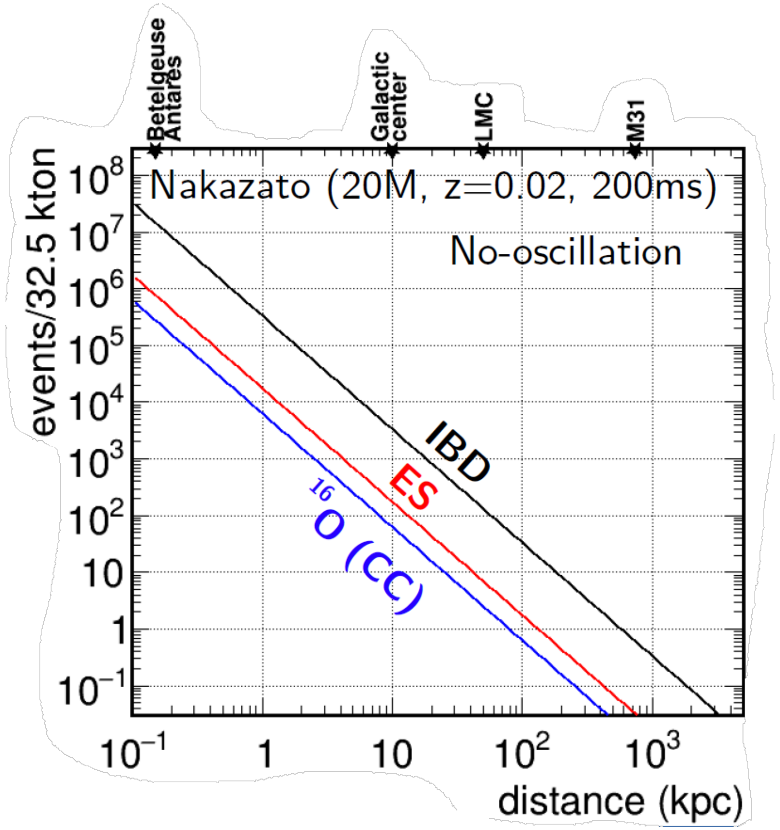
Almost uniform in MeV region

As the neutrino telescope
Elastic Scattering interactions (ES) ~5%

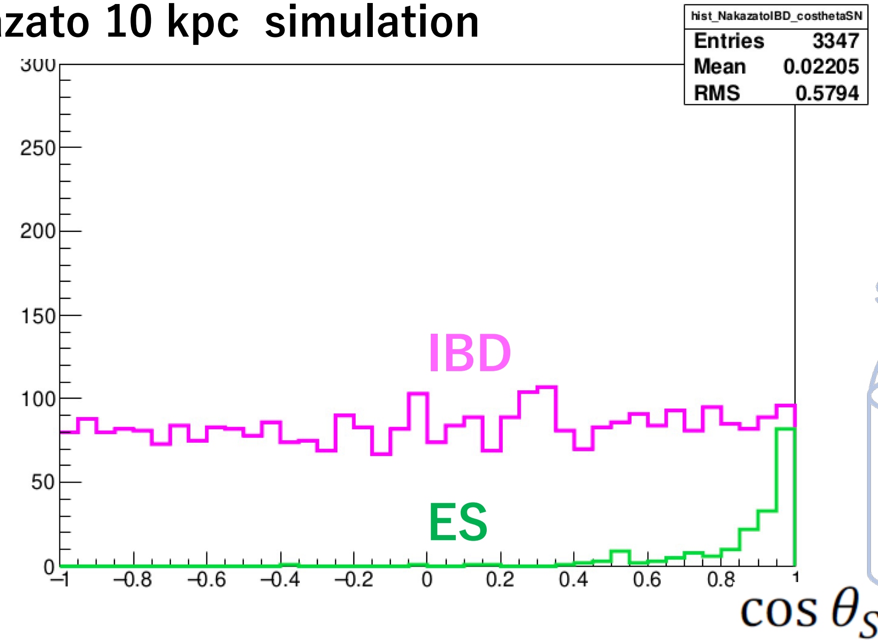
The electron keeps the neutrino direction information.

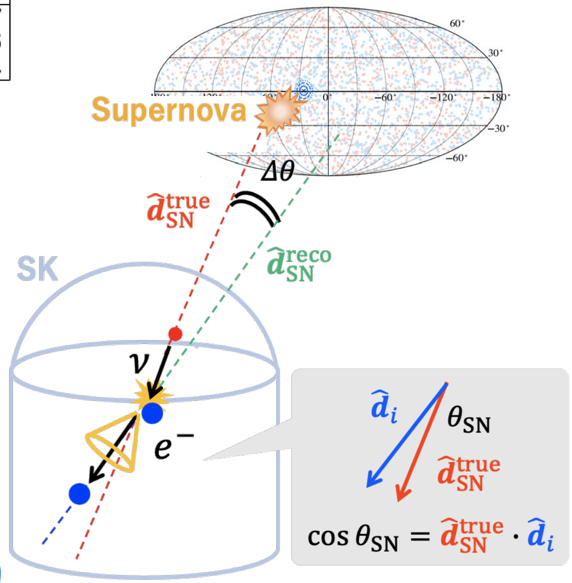
$$\nu + e^- \rightarrow \nu + e^-$$



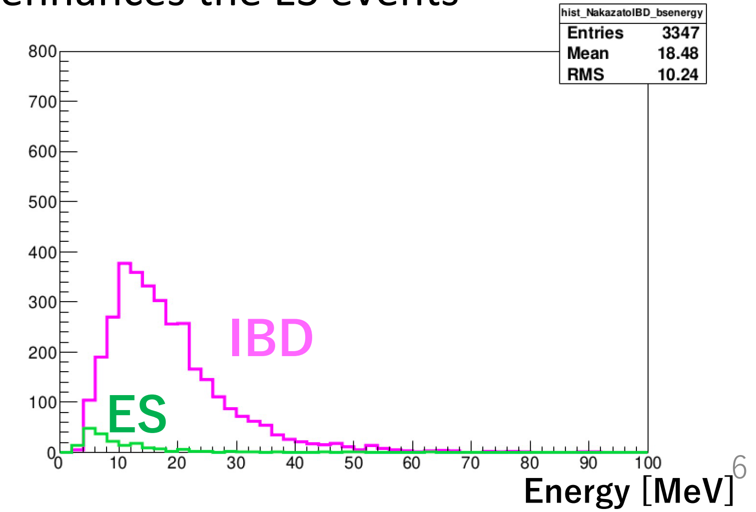


Nakazato 10 kpc simulation



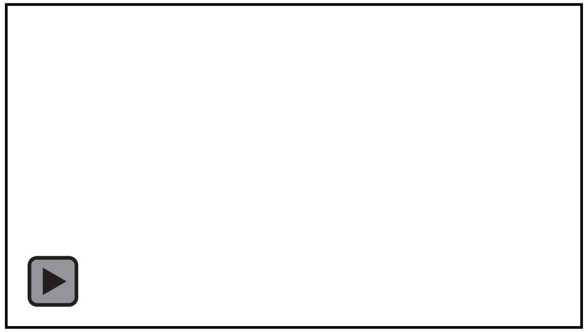


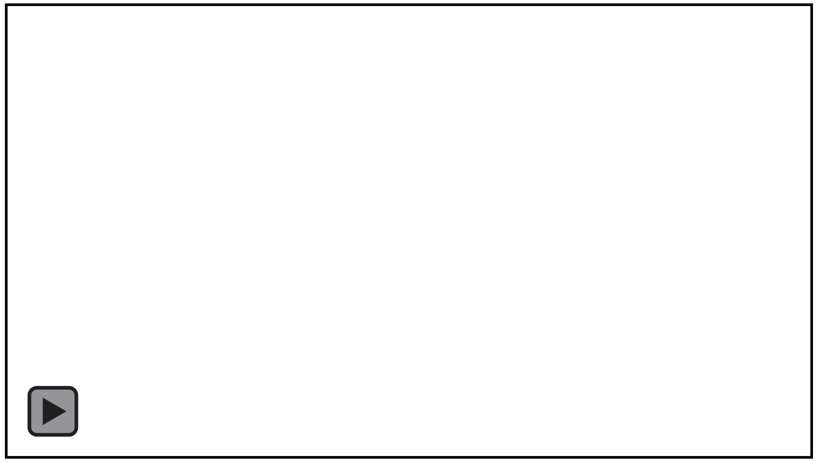
Lowering threshold enhances the ES events



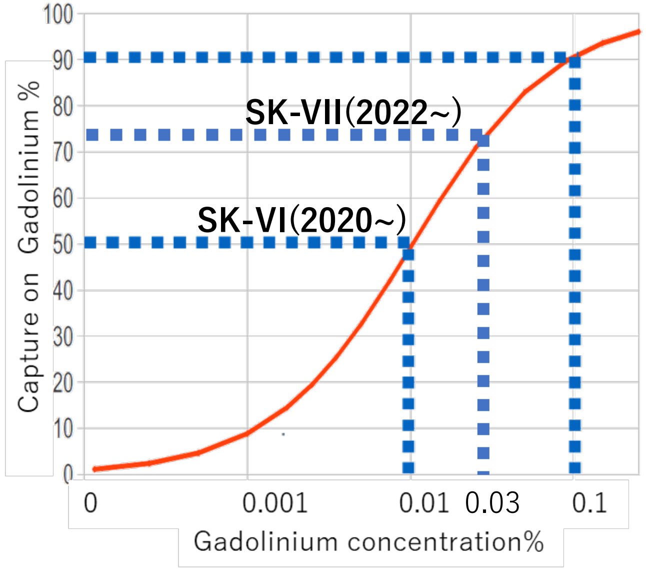
The Gd-loading

Separating ES from **IBD** allows
improving the **SN direction pointing** accuracy.
→ Gd enhances the IBS tagging

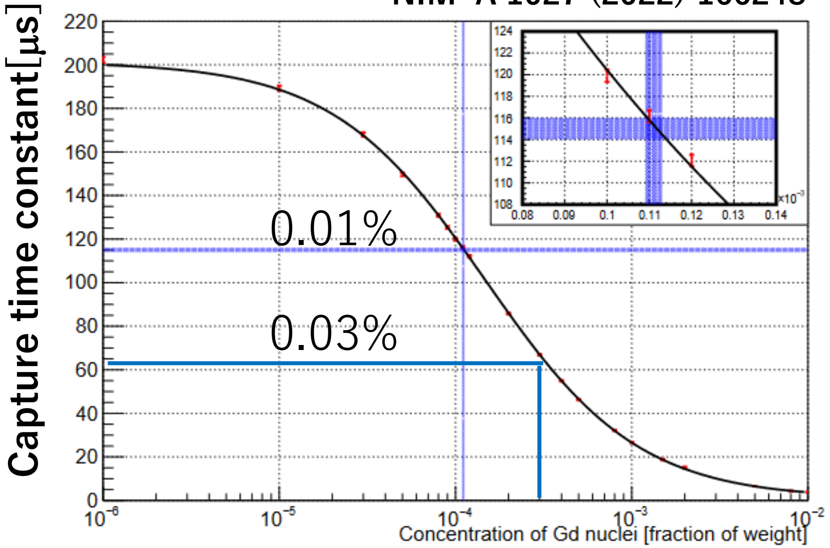


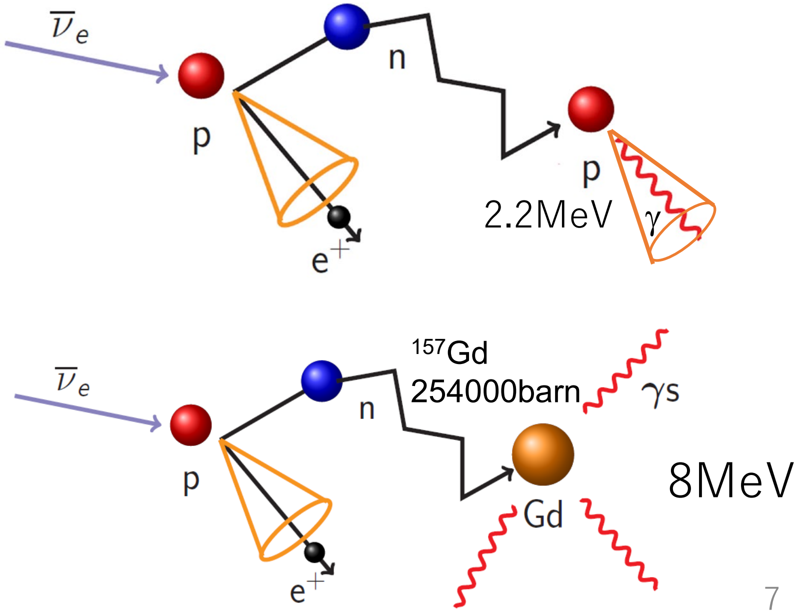


- **Neutron tagging for interaction (especially IBD) identification**
  - By delayed coincidence with 2.2MeV gamma from p-capture
  - **Gd-loading** significantly enhances its efficiency by Gd(n,γ)



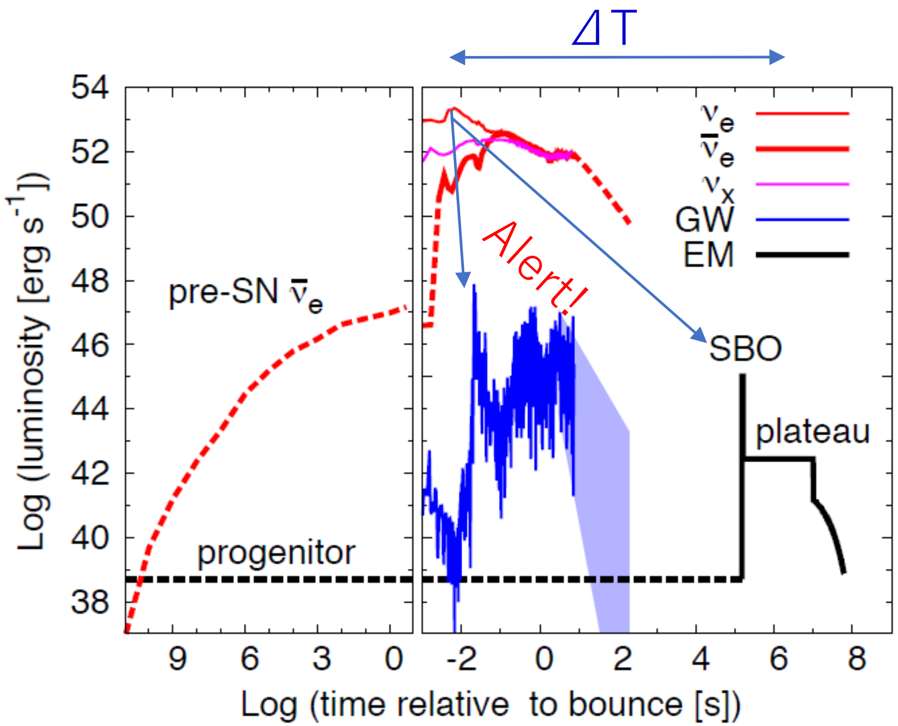
NIM A 1027 (2022) 166248

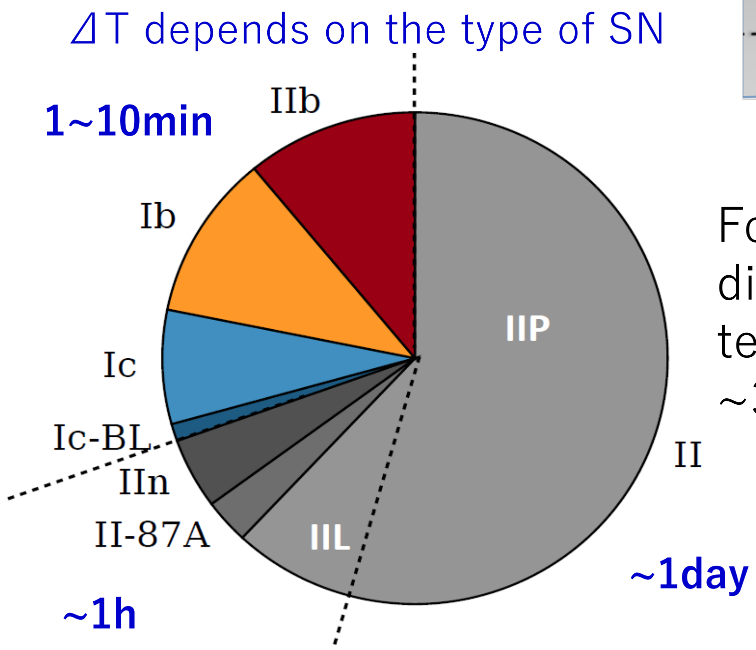


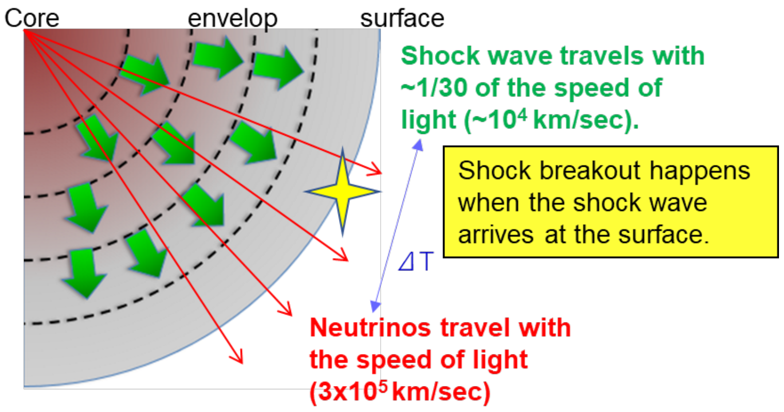


For multi-messenger astronomy

The vital role for Super-Kamiokande →**Neutrino burst alarm**



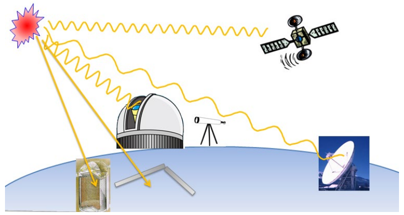


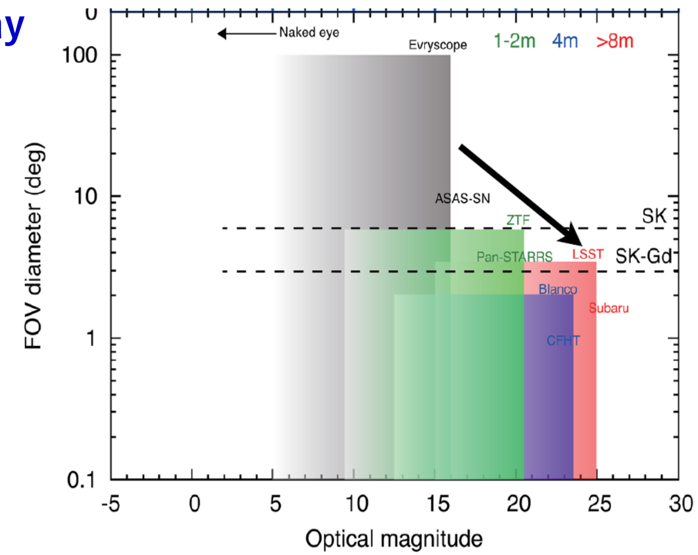


For ~70% of SNe, the time difference is several hours to tens of hours. For the remaining ~30%, that is several minutes.

K. Nakamura MNRAS, 461, 3296 (2016)

- **Neutrino burst alarm <~1 min. with the DIRECTION INFORMATION <~3° must help the pointing of EM telescopes**



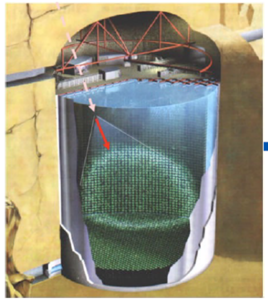


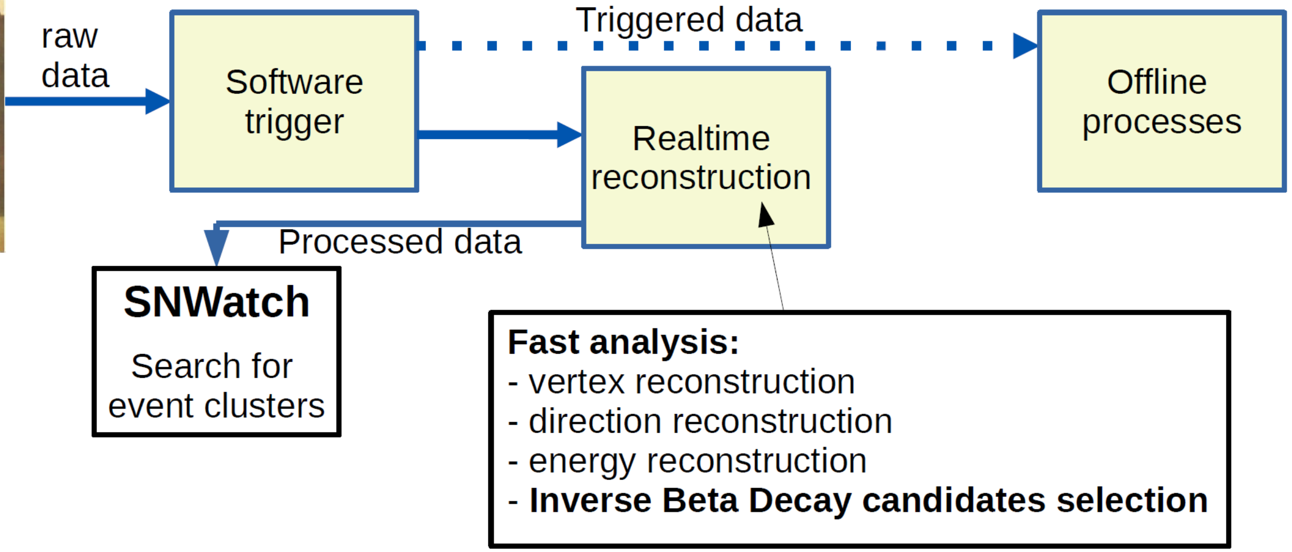
Realtime supernova monitoring of SK

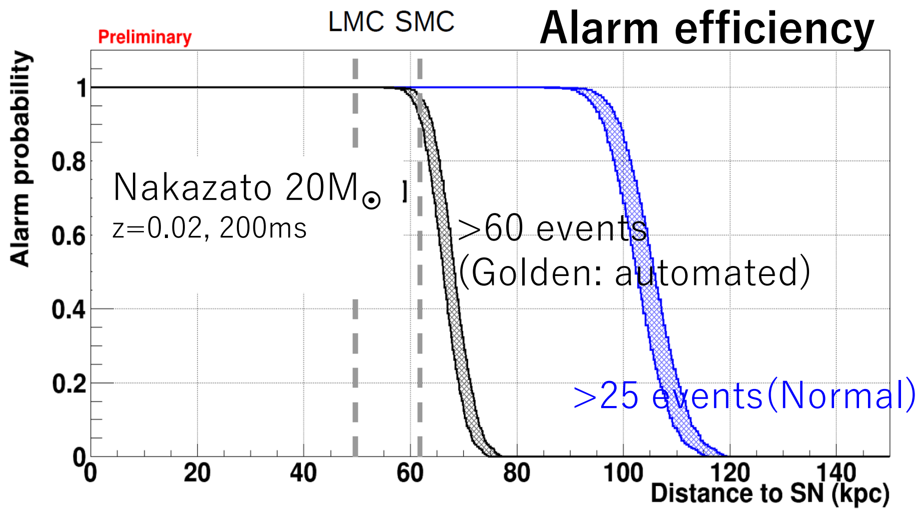
SK's SN monitoring system **"SNWatch."** Astropart. Phys. 81 (2016)

- Quick online analysis code, reconstructing the events and fitting SN direction

- In case the event burst matches the criteria (uniformity of the events in the detector, number of events), an automatic alarm is sent
  - The criteria are determined so that we would have 100% SN detection efficiency at the Large Magellanic Cloud.



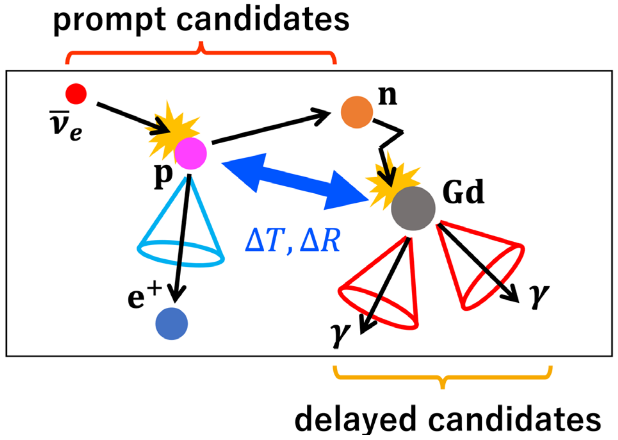




Quick IBD tagging implemented in SNwatch

0.03% Gd makes IBD tagging efficient in SN monitoring

Speed-oriented real-time simple IBD tagging algorithm



① Selection of prompt candidates ≧7MeV

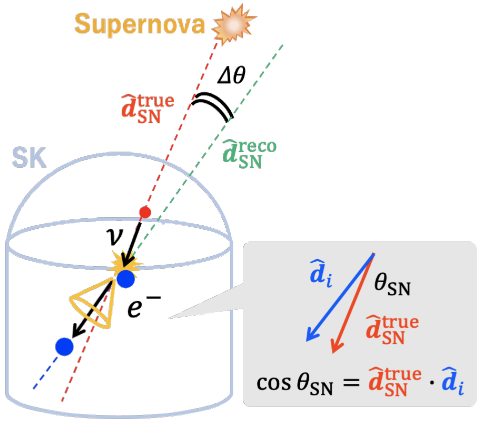
② Selection of delayed candidates

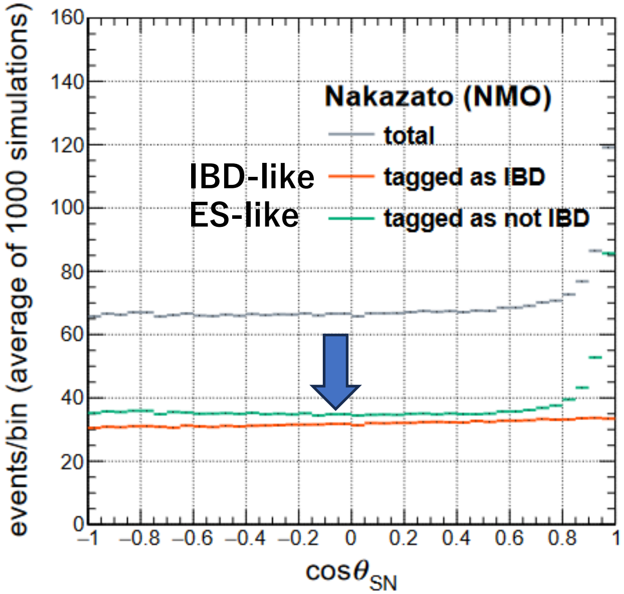
③ Neutron tagging pair of events with

$$\Delta T < 500\ \mu s\ \&\ \Delta R < 300\ \text{cm}$$

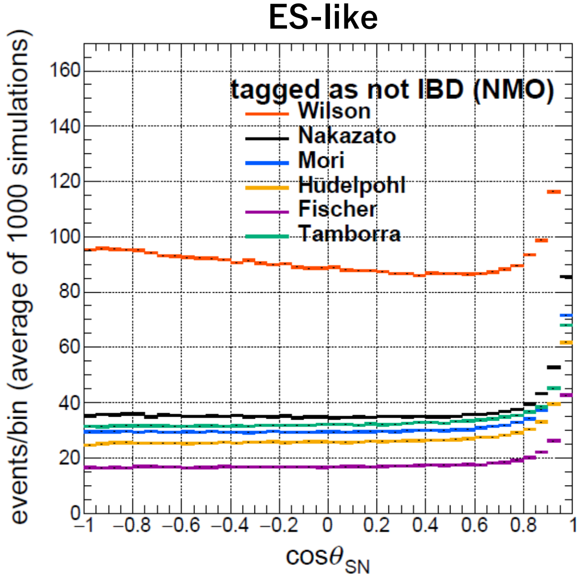
This selection algorithm tags ~50% IBD events

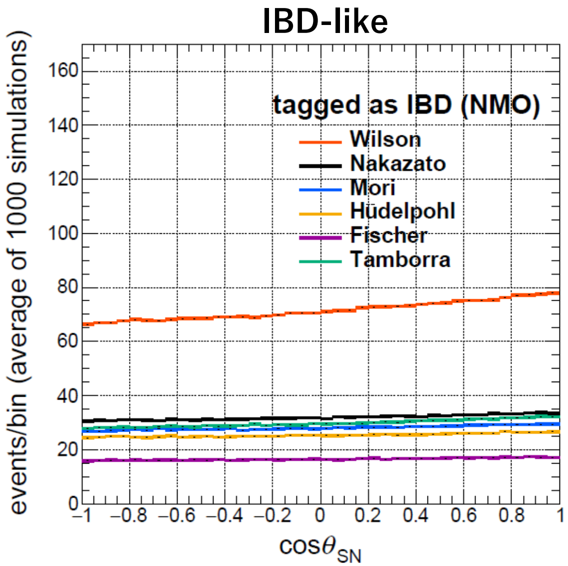
10kpc
Nakazato 20M$_\odot$
z=0.02, 200ms
NMO



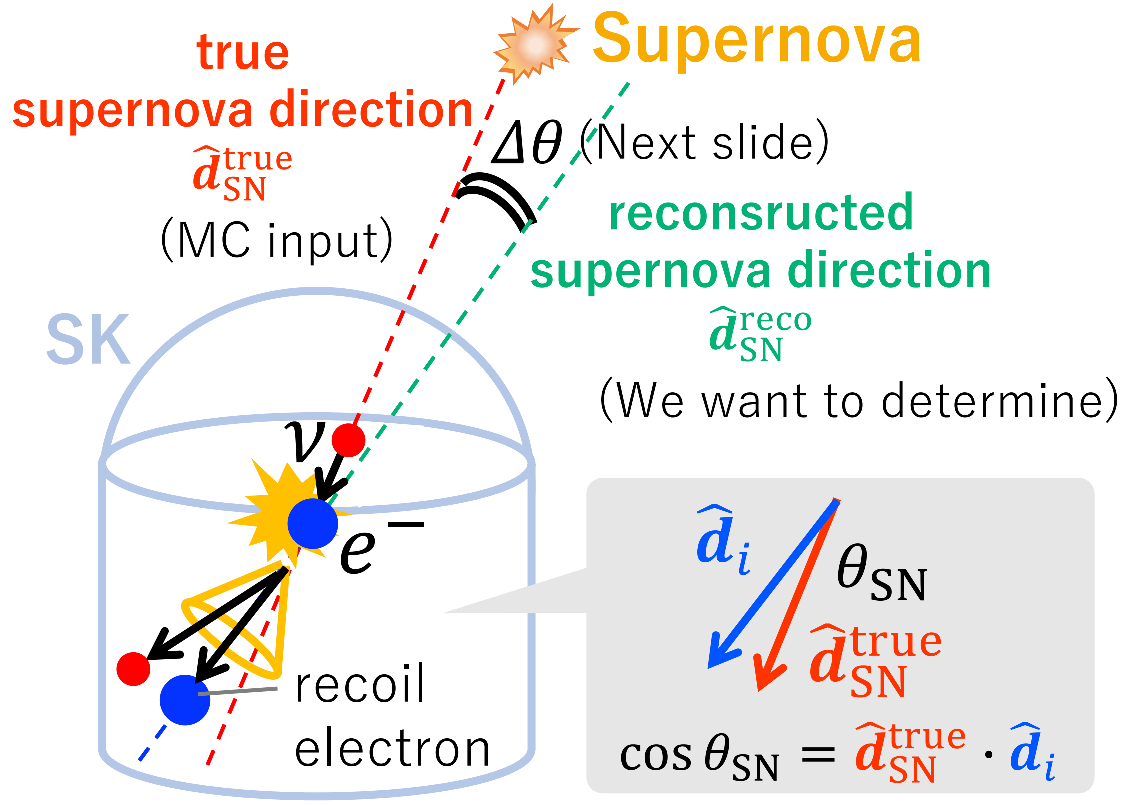


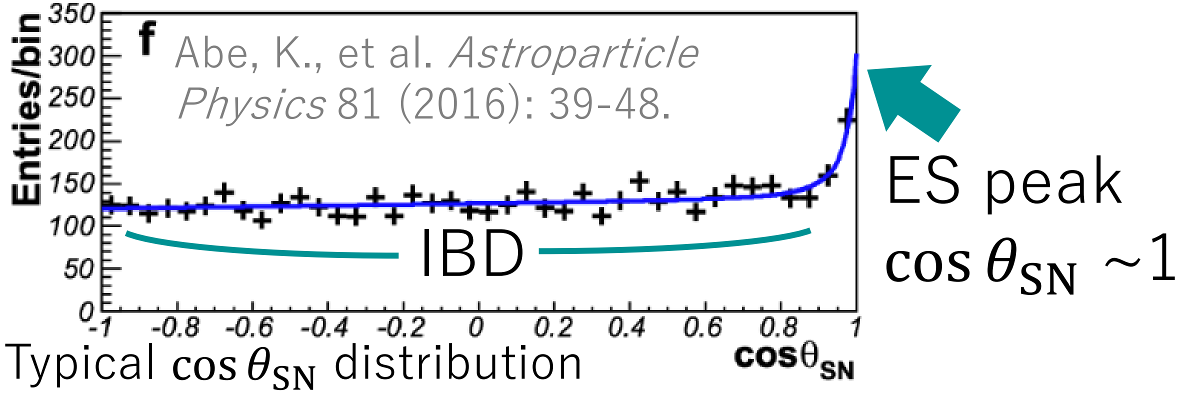
10kpc Other models





Determination of SN direction





Typical $\cos\theta_{\text{SN}}$ distribution

- Maximum Likelihood Fit
  - The likelihood function for the i-th event

$$L_i = \sum_r N_{r,k}\, t_r(f_i)\, p_r(E_i, \hat{d}_i; \hat{d}^{\text{reco}}_{\text{SN}})$$

# of event; tagging efficiency term; reaction (IBD, ES, ^{16}O CC); energy bin; energy; PDF function (determined by SK MC)

  - Likelihood

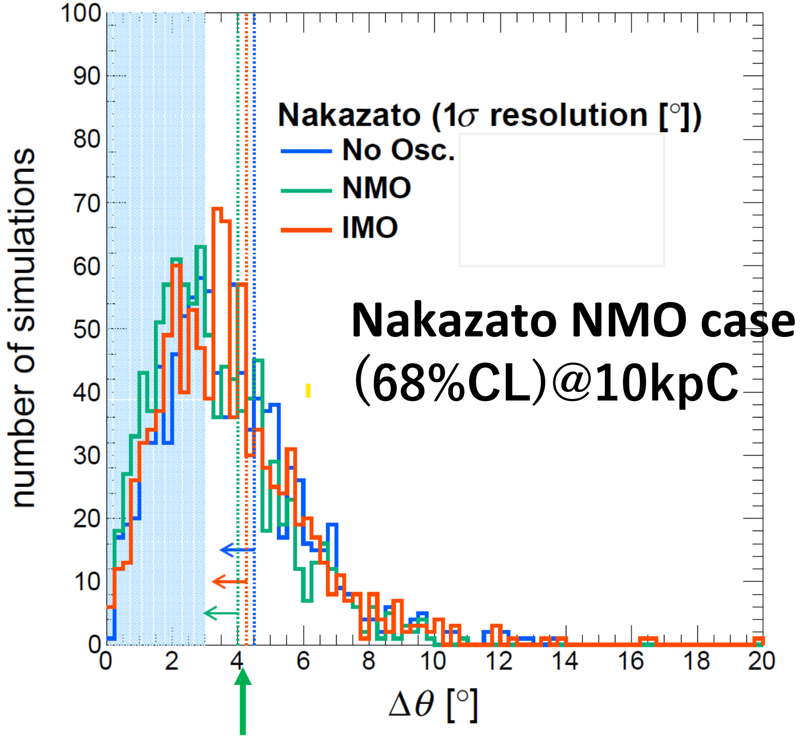
$$\mathcal{L} = \exp\left\{\sum_{k,r} N_{r,k}\right\} \prod_i L_i$$

  - Maximized by

$$\frac{\partial \mathcal{L}}{\partial N_{r,k}} = \frac{\partial \mathcal{L}}{\partial \hat{d}^{\text{reco}}_{\text{SN}}} = 0$$

This process takes time…

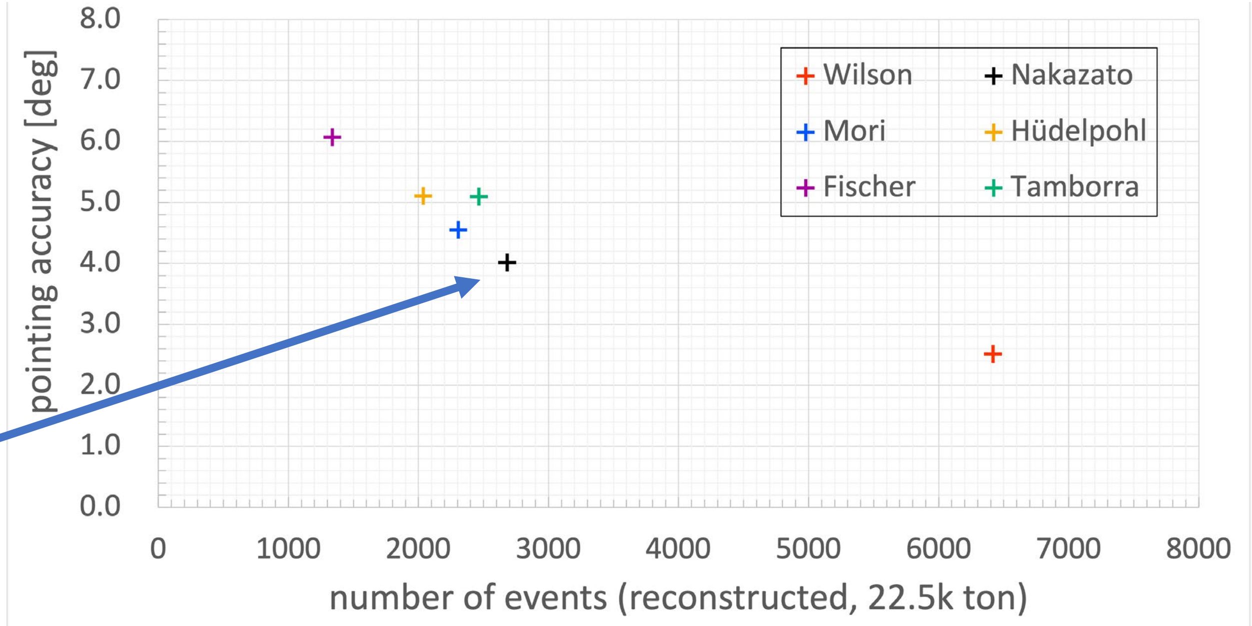
Pointing Accuracy for 10kpc SN



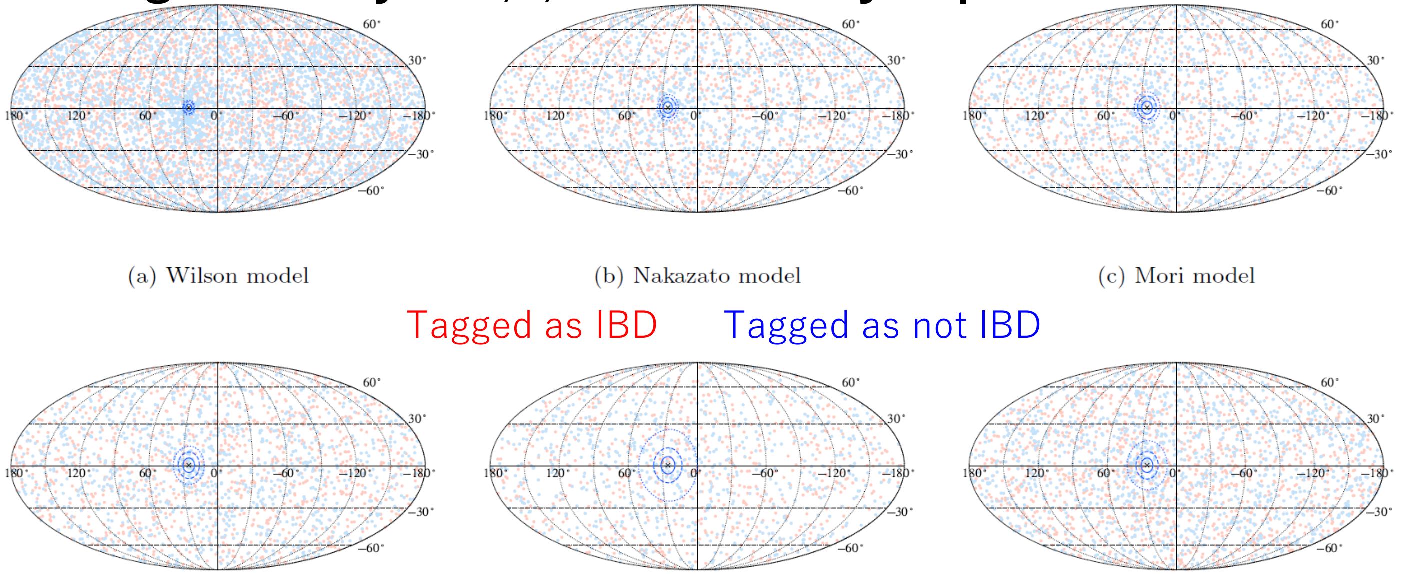
Nakazato NMO case 4.0°
(68%CL)@10kpC

Pointing accuracy at 1σ is the value of $\Delta\theta$ at which the integral of the histogram includes 68% of the 1000 MC samples

Pointing accuracy vs. # of total events



Pointing Accuracy at 1,2,3 σ on the skymap



(a) Wilson model

(b) Nakazato model

(c) Mori model

Tagged as IBD   Tagged as not IBD

(d) Hüdelpohl model

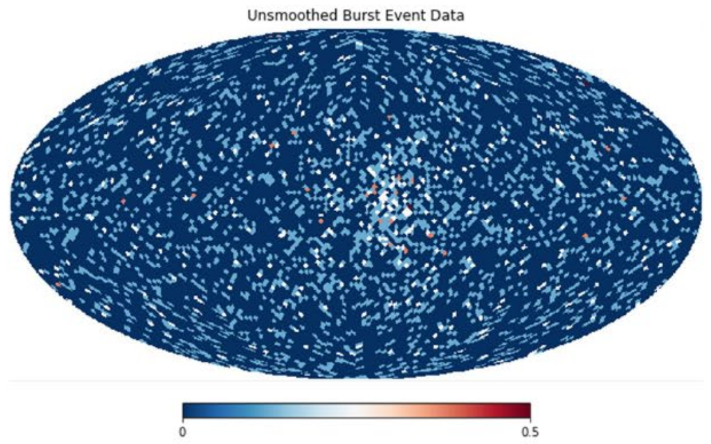
(e) Fischer model

(f) Tamborra model

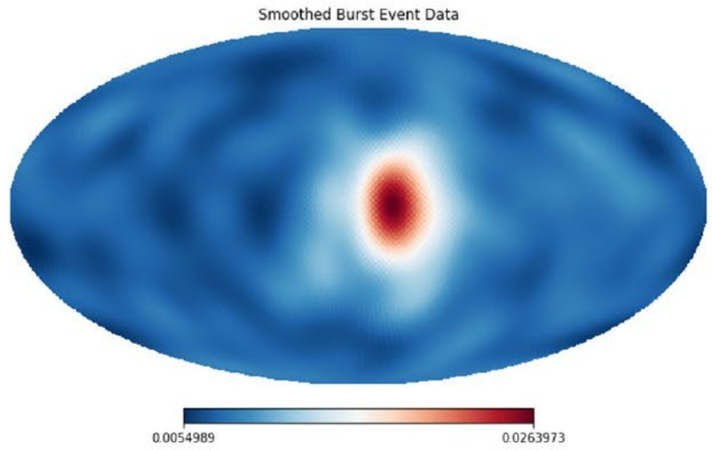
Upgrading with HealPix direction estimation

- HEALPix-based fitter (**H**ierarchical **E**qual **A**rea isoLatitude **Pix**elation of a sphere):
  - A sphere of the sky is made and divided in pixels of equal area
  - The pixels are populated with the projection of each event's reconstructed direction on the sphere.
  - The sphere is then smoothed with a Gaussian function
  - The pixel with the maximum number of events is then selected as the initial SN direction → Maximum Likelihood fitting

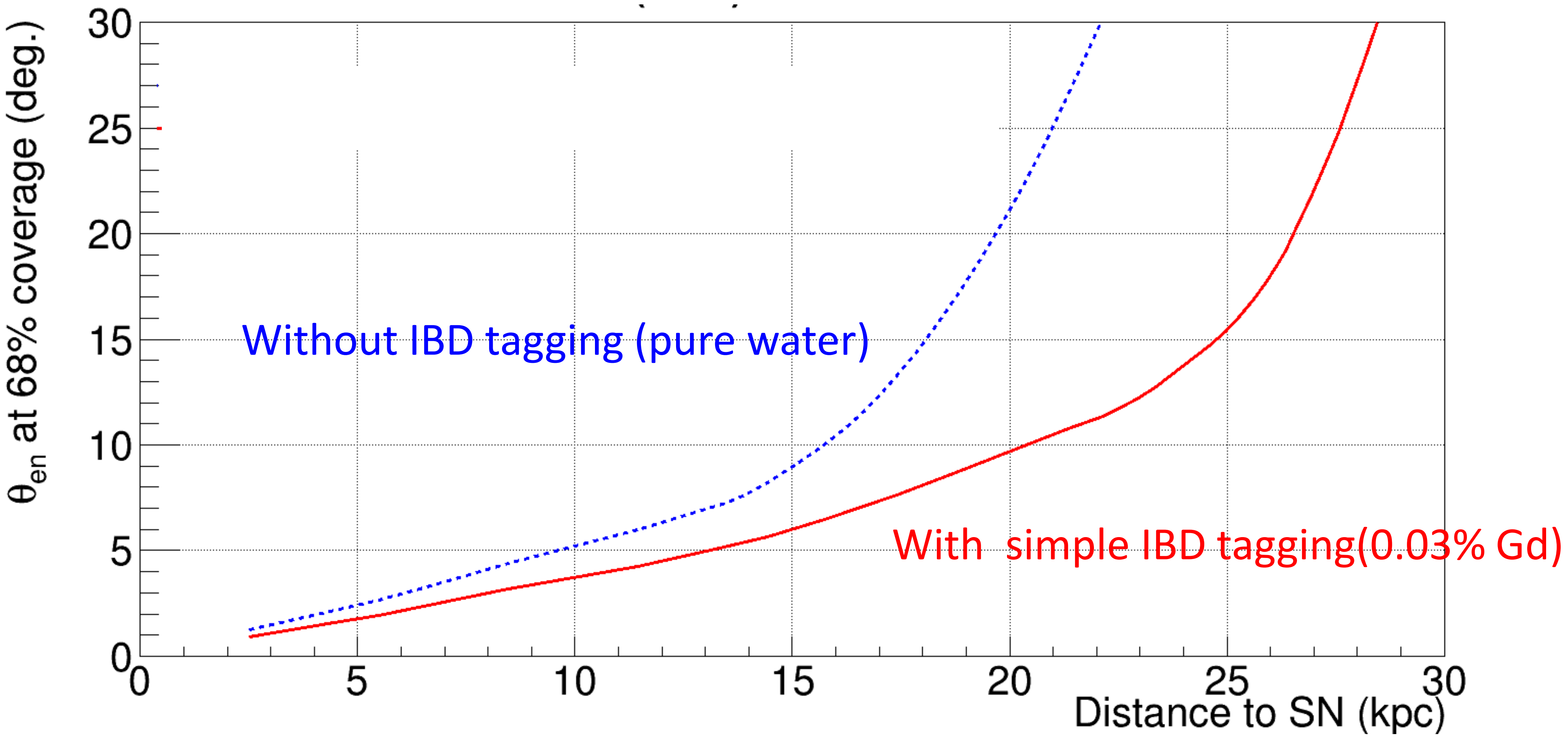
Nside = 32, Npix = 12,288



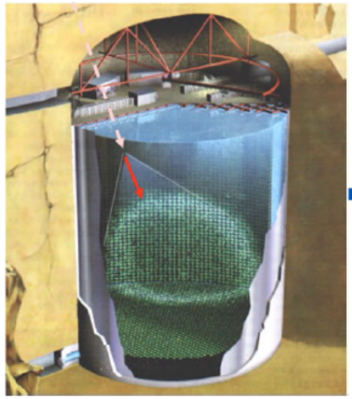
Gaussian Smoothed, σ = 0.15 rad.



How much improved by 0.03% Gd?



How much is boosted by HealPix?



1 subrun ~60 seconds

raw data → Software trigger

Software trigger → ~10 sec → Realtime reconstruction and selection

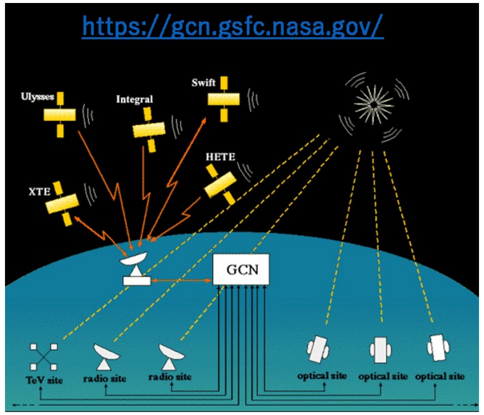
Triggered data ⇢ Offline processes

~60 sec

Realtime reconstruction and selection → ~5 sec → Cluster finder: SN direction reconstruction

~~90–110 sec~~ → ~10 sec

Cluster finder → ~5 sec → Alarm

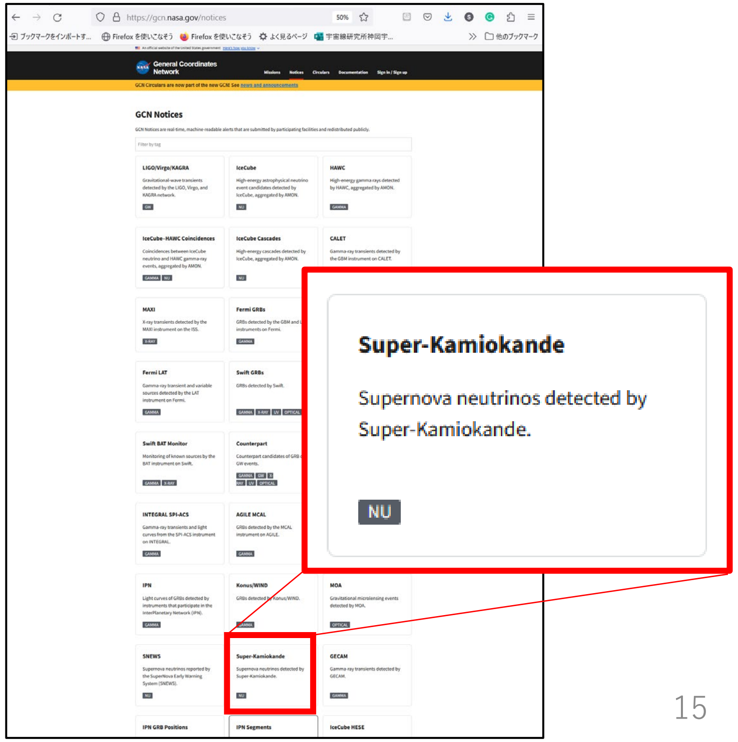


General Coordinates Network

GCN Circulars are now part of the new GCN!

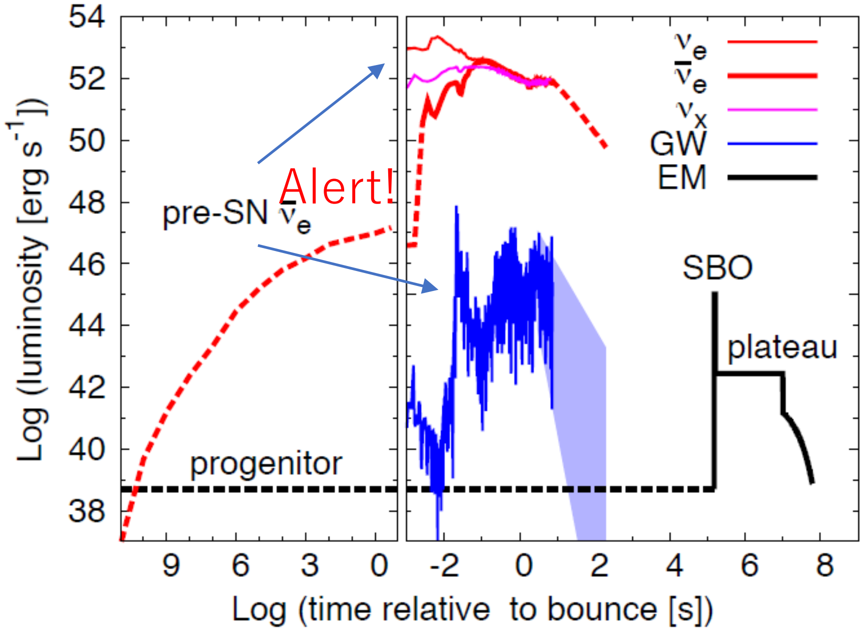
→ ASAS-SN All-Sky Automated Survey for Supernovae

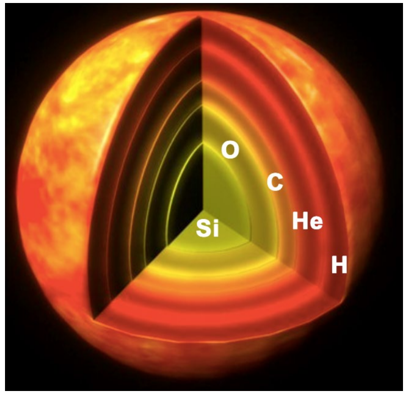
SK_SN Notice on GCN



- **Within 1.5min, SK_SN notice will be sent through GCN Notice**

Pre-SN alarm for nearby SNe





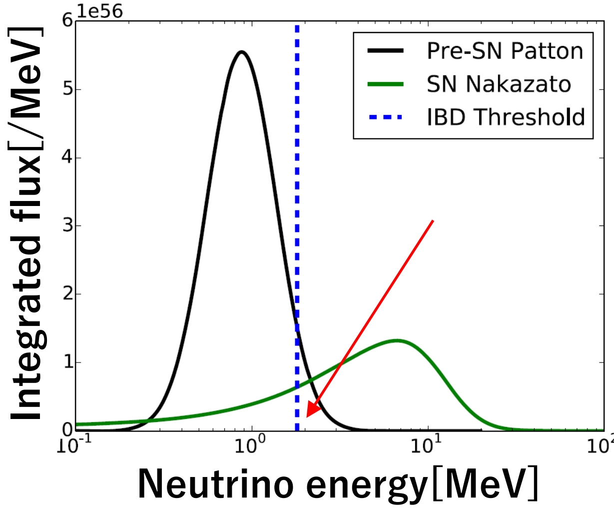
Burning Stage	Duration	Average ν energy
C	300 years	0.71 MeV
Ne	140 days	0.99 MeV
O	180 days	1.13 MeV
Si	**2 days**	**1.85 MeV**

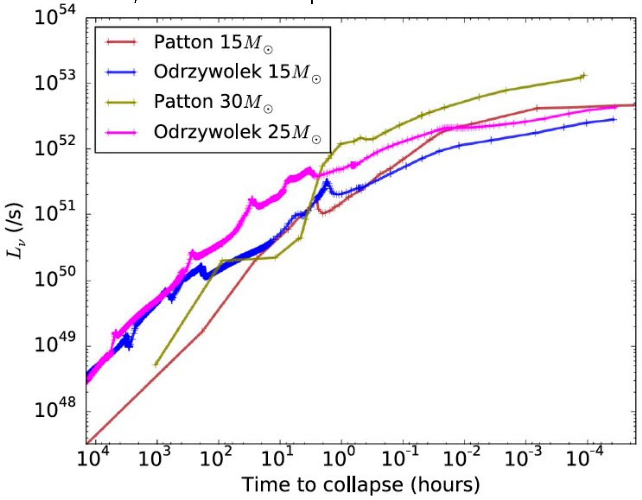
Duration of burning stages and the fraction and average energy of electron neutrinos emitted by **pair-annihilation** for a 20 M⊙ star (**Astropart.Phys. 21 (2004) 303-313**)

- and many Models･･･

Odrzywolek, et al 2010 Acta Phys. Pol. B 41, 1611
Patton, et al 2017 ApJ 851 6

ApJ 885:133, 2019

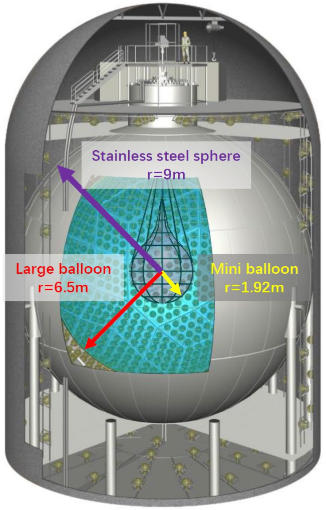




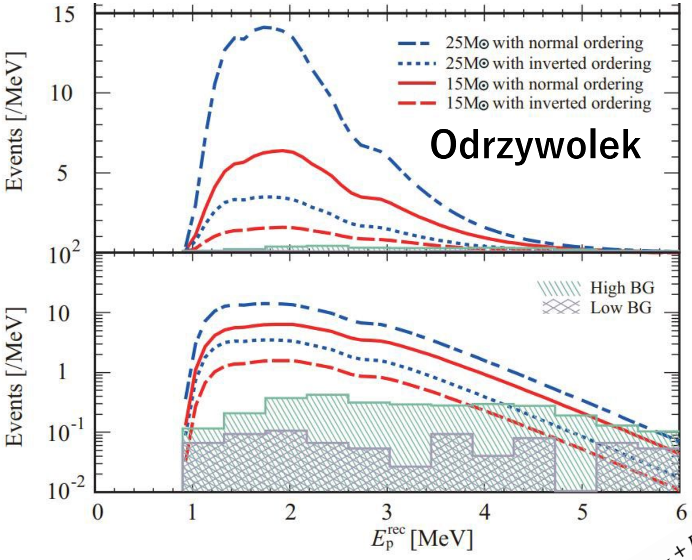
- Low-BG low-threshold required
  - Liquid scintillators/ Gd-Water Cherenkov
- IBD is the main channel
  - The energy threshold for IBD is 1.8 MeV
  - Large volume is needed.

Pre-SN alarm

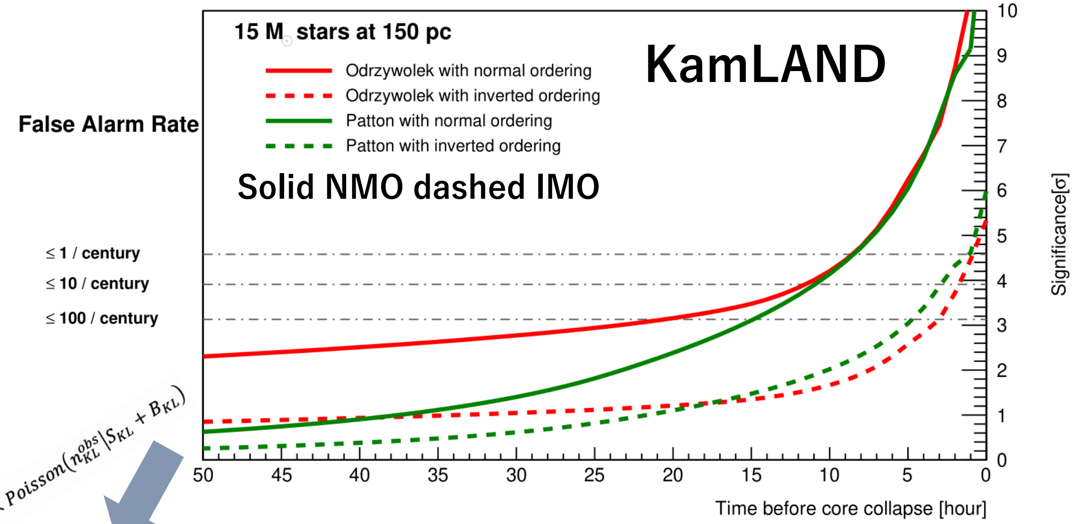
ApJ Journal, 818:91 (8pp), 2016



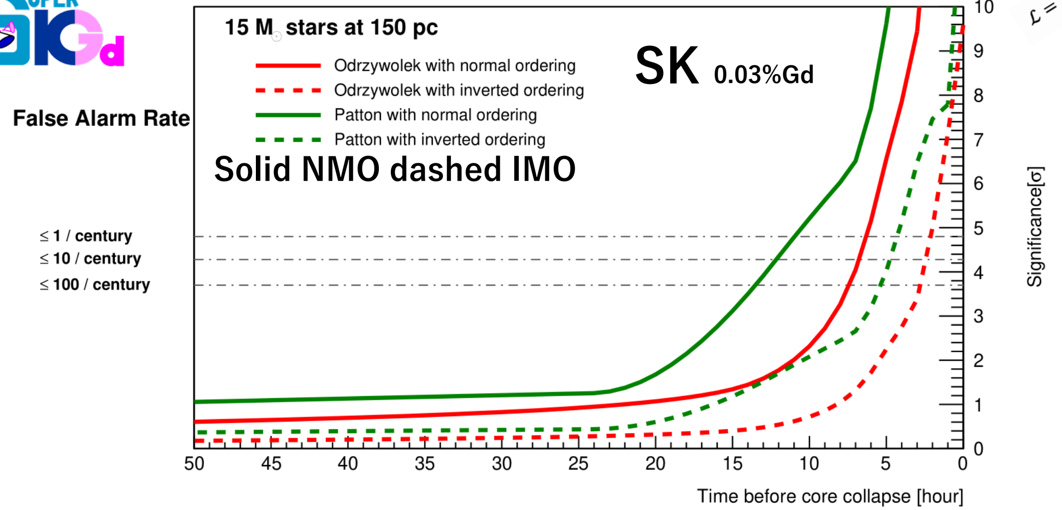
1kt LS



The significance of detection based on the number of accumulated events for Betelgeuse

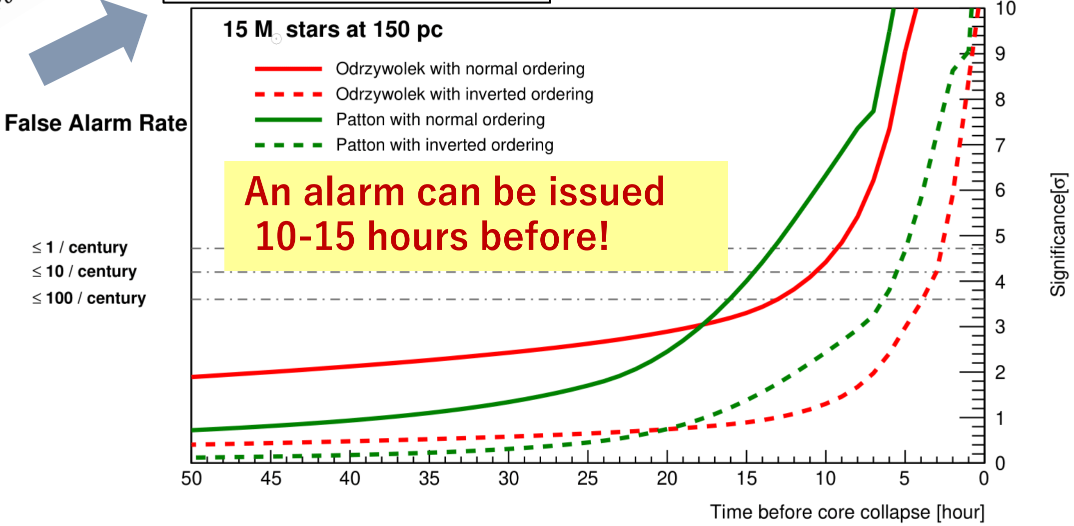


$\mathcal{L} = Poisson(n_{SK}^{obs}|S_{SK} + B_{SK}) \times Poisson(n_{KL}^{obs}|S_{KL} + B_{KL})$



SK+KamLAND

https://www.lowbg.org/presnalarm/



An alarm can be issued 10-15 hours before!

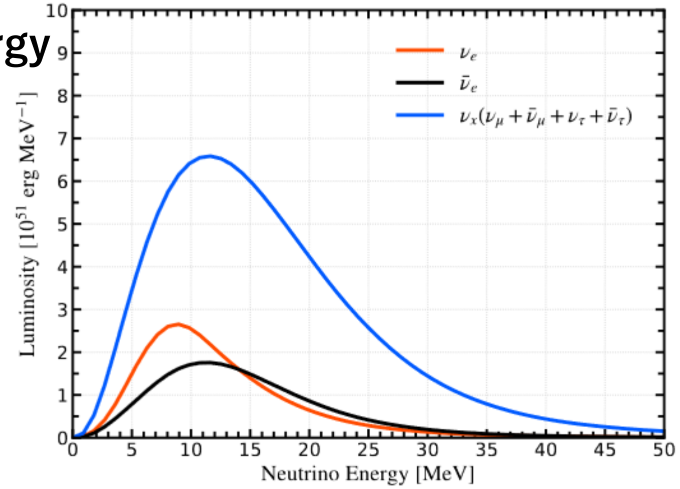
A combined alarm with SK and KL has been available since May 2022 (MoUed)

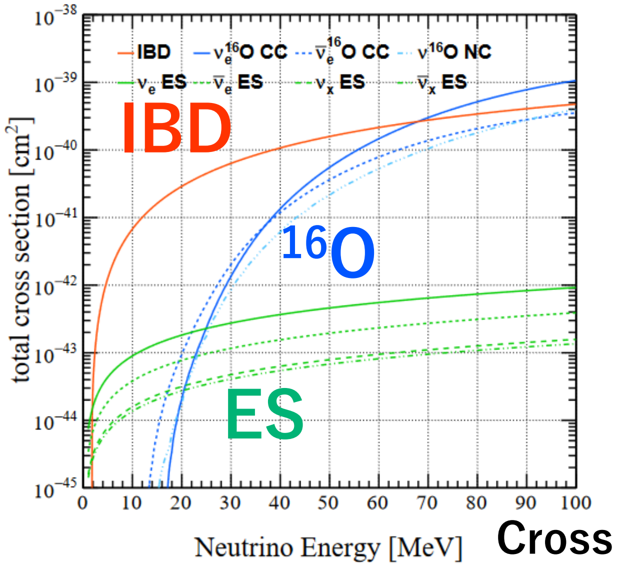
GCN circular is also available

Make the most of SK

- The number of ^{16}O interactions in SK is still larger than the number of all interactions in other detectors.

Nakazato model neutrino energy





Cross section vs. Neutrino energy

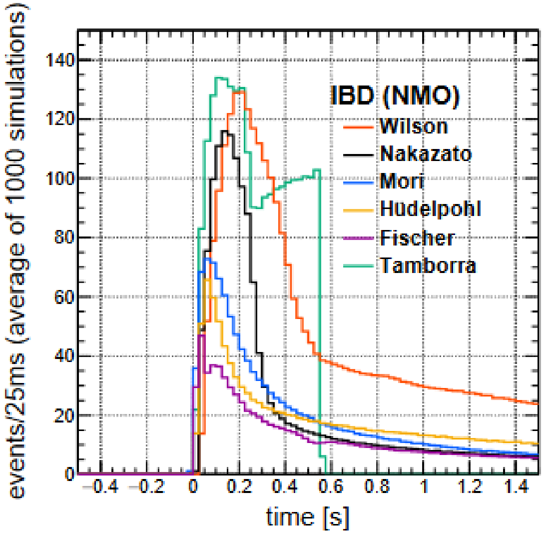
Expected number of interactions in SK for 10kpc SN

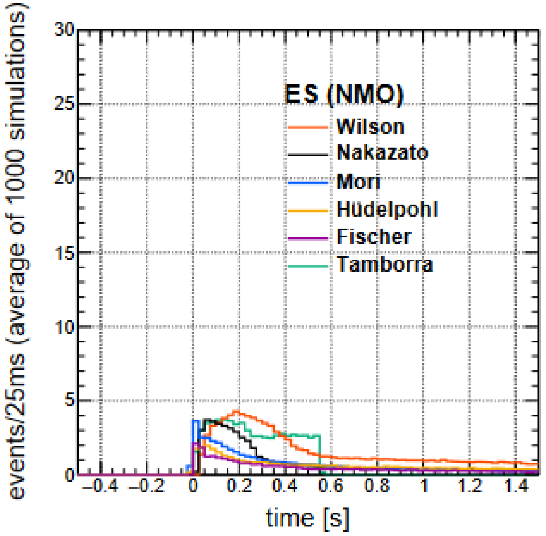
Generated by SKSNSim	Wilson No Osc.	Wilson NMO	Wilson IMO	Nakazato No Osc.	Nakazato NMO	Nakazato IMO	Mori No Osc.	Mori NMO	Mori IMO
IBD ($\bar{\nu}_e$)	7431	8207	9970	3542	3893	4693	3275	3422	3745
ES (ν_e)	223	231	229	173	172	171	177	148	156
ES ($\bar{\nu}_e$)	97	97	98	63	66	72	60	61	63
ES (ν_x)	80	79	80	60	60	60	52	57	56
ES ($\bar{\nu}_x$)	69	69	69	52	51	48	45	45	44
^{16}O CC (ν_e)	44	1034	729	48	180	139	8	86	62
^{16}O CC ($\bar{\nu}_e$)	195	329	633	46	68	116	30	42	71
^{16}O NC (ν_e, ^{15}N)	4	89	63	4	15	12	1	8	5
^{16}O NC ($\bar{\nu}_e$, ^{15}N)	22	43	89	5	8	16	3	4	8
^{16}O NC (ν_x, ^{15}N)	177	93	119	31	20	23	15	8	10
^{16}O NC ($\bar{\nu}_x$, ^{15}N)	177	156	112	31	28	21	15	14	10
^{16}O NC (ν_e, ^{15}O)	1	24	17	1	4	3	0	2	1
^{16}O NC ($\bar{\nu}_e$, ^{15}O)	6	12	24	1	2	4	1	1	2
^{16}O NC (ν_x, ^{15}O)	48	25	32	9	5	6	4	2	3
^{16}O NC ($\bar{\nu}_x$, ^{15}O)	48	42	30	8	8	5	4	4	3
total	8622	10530	12294	4074	4580	5389	3690	3904	4239

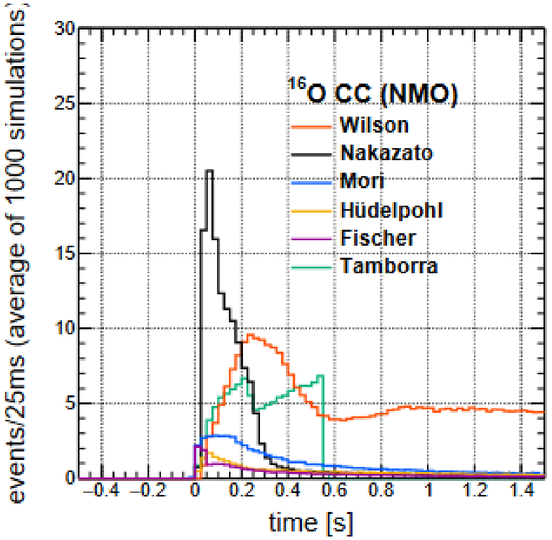
Generated by SKSNSim	Hüdelpohl No Osc.	Hüdelpohl NMO	Hüdelpohl IMO	Fischer No Osc.	Fischer NMO	Fischer IMO	Tamborra No Osc.	Tamborra NMO	Tamborra IMO
IBD ($\bar{\nu}_e$)	3048	3052	3049	1884	1990	2242	3830	3487	2718
ES (ν_e)	146	124	132	90	87	88	135	82	99
ES ($\bar{\nu}_e$)	53	53	53	35	35	37	50	45	35
ES (ν_x)	43	47	46	31	31	31	28	38	35
ES ($\bar{\nu}_x$)	38	38	38	27	26	25	25	26	30
^{16}O CC (ν_e)	12	32	26	5	27	21	55	90	80
^{16}O CC ($\bar{\nu}_e$)	30	31	33	15	18	27	97	90	77
^{16}O NC (ν_e, ^{15}N)	1	3	2	0	2	2	5	8	7
^{16}O NC ($\bar{\nu}_e$, ^{15}N)	3	3	3	1	2	2	11	10	8
^{16}O NC (ν_x, ^{15}N)	6	4	4	5	3	4	16	13	14
^{16}O NC ($\bar{\nu}_x$, ^{15}N)	6	6	6	5	4	4	16	17	19
^{16}O NC (ν_e, ^{15}O)	0	1	1	0	1	1	1	2	2
^{16}O NC ($\bar{\nu}_e$, ^{15}O)	1	1	1	0	0	1	3	3	2
^{16}O NC (ν_x, ^{15}O)	1	1	1	1	1	1	4	3	4
^{16}O NC ($\bar{\nu}_x$, ^{15}O)	2	2	1	1	1	1	4	5	5
total	3390	3398	3396	2100	2228	2487	4280	3919	3135

Current limitation

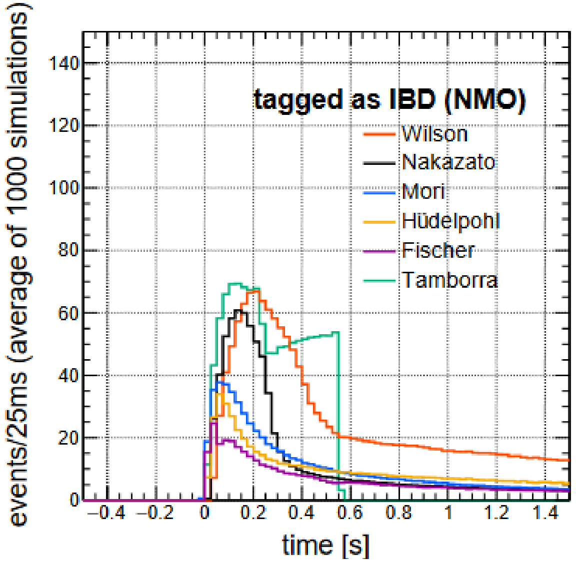
True interactions in SK



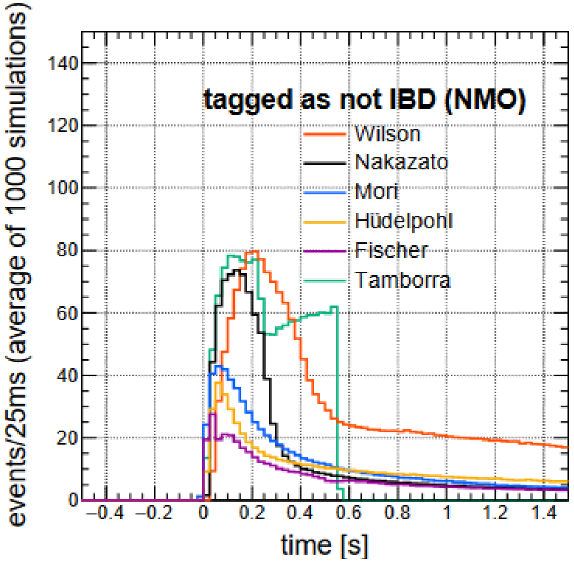




What currently can be extracted from SK (online analysis)



IBD-like



ES-like

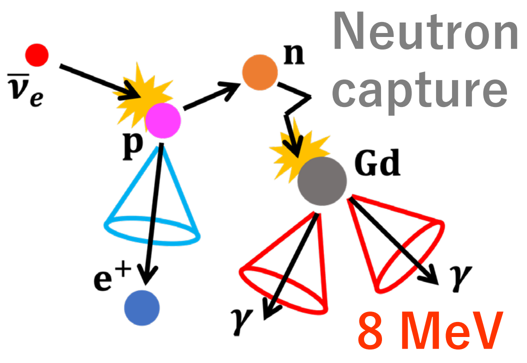
ES+IBD+^{16}O

Plans to make use of ^{16}O channel in SK

- They are more complicated topologies than IBD's and ES's.
- All final state particles should be investigated.

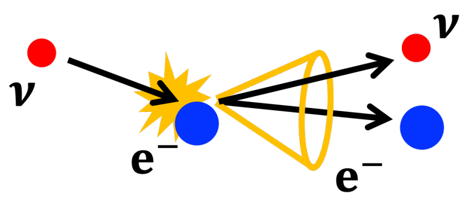
Inverse Beta Decay (IBD)

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



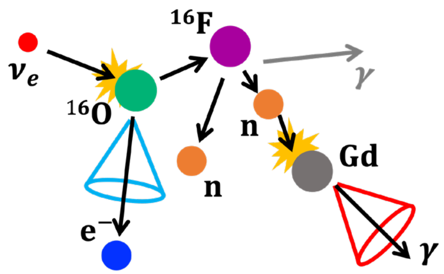
Elastic Scattering (ES)

$$\nu + e^- \rightarrow \nu + e^-$$

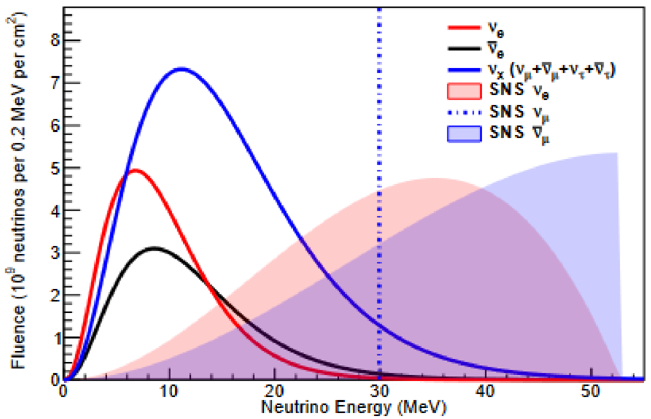


^{16}O interactions

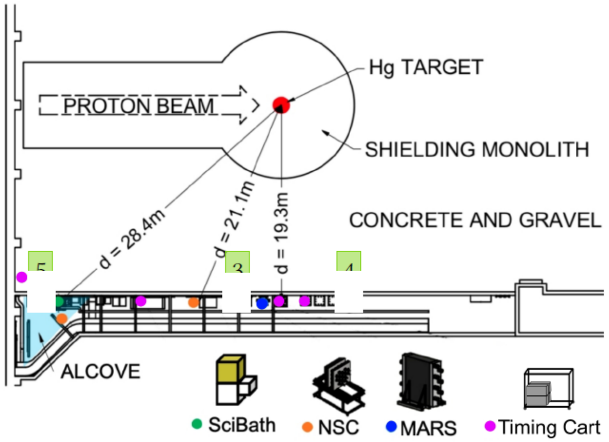
$$\nu_e + {}^{16}O \rightarrow e^- + {}^{16}F$$
$$\bar{\nu}_e + {}^{16}O \rightarrow e^+ + {}^{16}N,$$



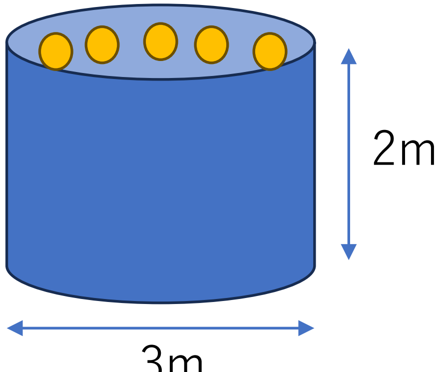
ORNL SNS neutrino spectra

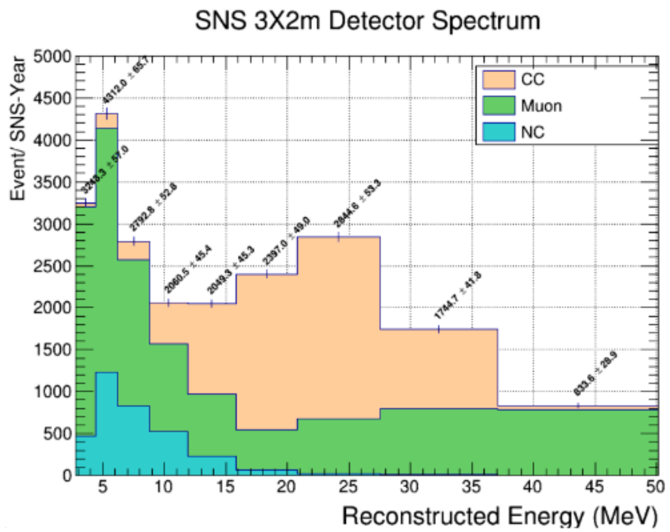


With COHERENT detectors, a dedicated experiment is planned at ORNL



8% photo coverage





Summary

- **Enhancing Supernova Understanding:** A multi-messenger astronomy approach combining neutrinos, gravitational waves, and electromagnetic waves plays a pivotal role in comprehending supernova explosions.
- **SK's Unique Role, Warning with direction info:** The Super-Kamiokande detector is a distinctive and vital instrument for studying supernova explosions within our galaxy.
- **Gd Introduction Advantages:** The incorporation of Gd has significantly enhanced directional accuracy and reduced warning issuance time, improving our ability to study these phenomena. We are advancing alert for the Si-Burning period, working closely with KamLAND.
- **Information Extraction Efforts:** Our ongoing efforts include extracting more information from ^{16}O interactions in water. (Suwa-san’s talk)
- **Towards More Distant and Statistically Significant Events:** For insights into more distant supernova explosions, higher statistical significance, and other ν sources, Hyper-Kamiokande is under preparation (Asaoka-san’ talk)