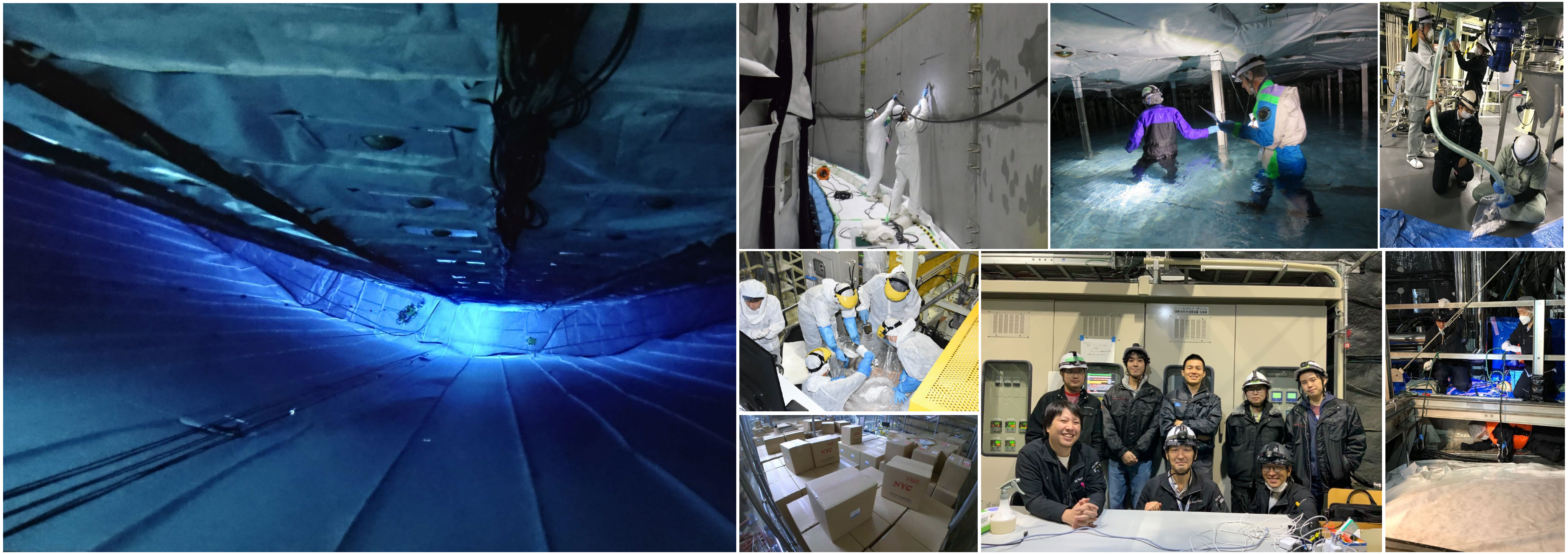


2018-2023 Super-Kamioaknde Gadolinium Project

Hiroyuki Sekiya

Unraveling the History of the Universe and Matter Evolution
with Underground Physics(UGAP2024) @Tohoku University

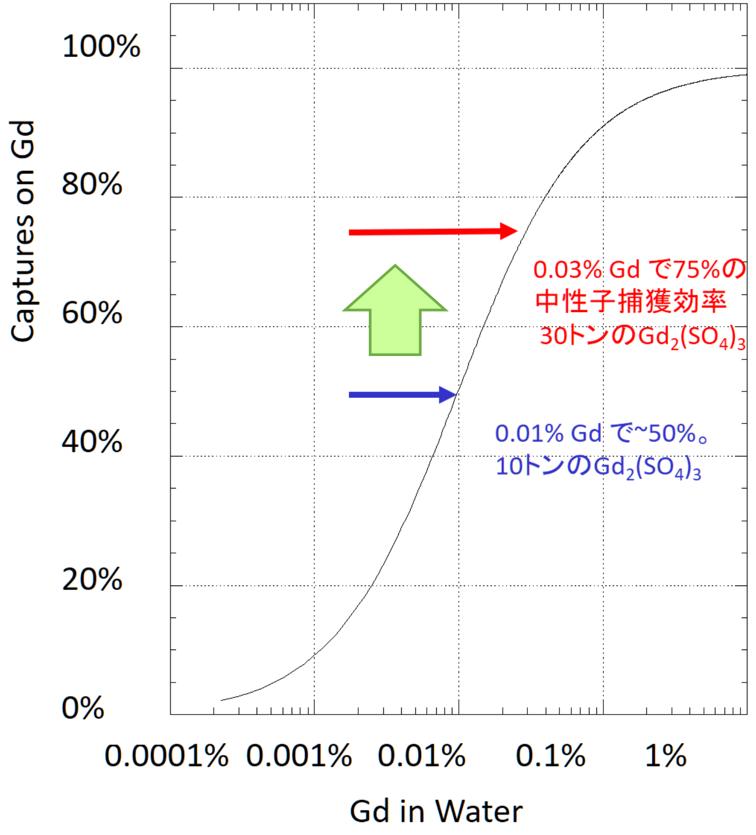
Mar. 6, 2024

C01 Group in UGAP

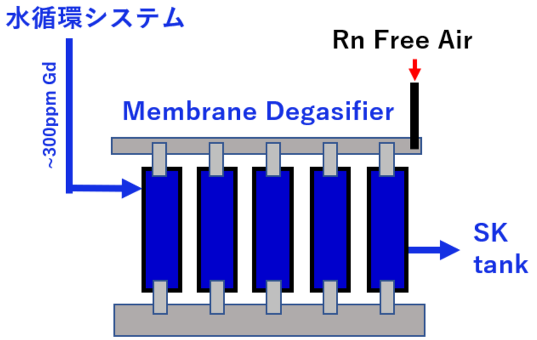
- **Unraveling the History of the Universe and Matter Evolution by SN neutrinos with Upgraded Super-Kamiokande**

Sekiya: Increase neutron tagging efficiency

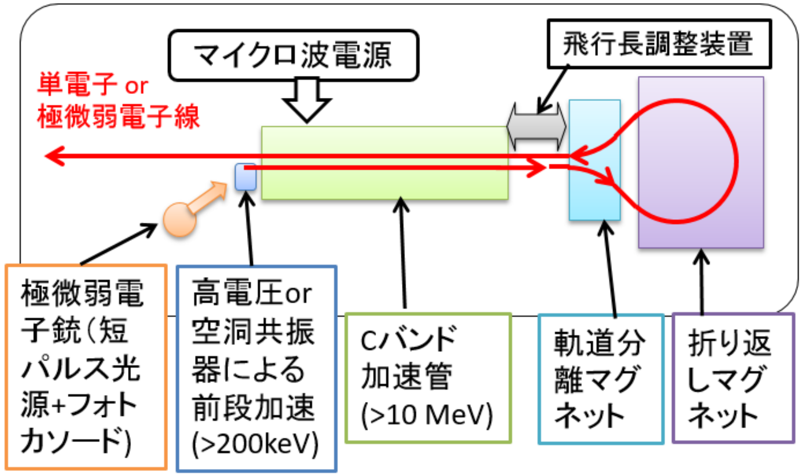
Takaku+Sakaguchi: Gd screening ←D01



Takeuchi:
Further reduction of Rn



Suzuki:
Development of Linac for calibration up to 20MeV



2018-2024 Paper (SK-Gd Physics)

- Performance of SK-Gd's Upgraded Real-time Supernova Monitoring System, **Y. Kashiwagi** et al. (The Super-Kamiokande Collaboration),To be Submited to A,stro. Phys. J., arXiv:24XX.XXXX
- Solar neutrino measurements using the full data period of Super-Kamiokande IV, The Super-Kamiokande Collaboration, accepted by Phys. Rev. D, arXiv:2312.12907
- Measurement of the neutrino-oxygen neutral-current quasielastic cross section using atmospheric neutrinos in the SK-Gd experiment, **S. Sakai** et al. (The Super-Kamiokande Collaboration), Phys. Rev. D 109, L011101 arXiv:2311.03842
- Search for astrophysical electron antineutrinos in Super-Kamiokande with 0.01wt% gadolinium-loaded water **M. Harada** et al. (The Super-Kamiokande Collaboration),The Astrophysical Journal Letters, 951:L27 arXiv:2305.05135
- Measurement of the cosmogenic neutron yield in Super-Kamiokande with gadolinium loaded water, **M. Shinoki** et al. (The Super-Kamiokande Collaboration), Phys. Rev. D 107, 092009 (2023) arXiv:2212.10801
- Search for Cosmic-Ray Boosted Sub-GeV Dark Matter Using Recoil Protons at Super-Kamiokande, The Super-Kamiokande Collaboration, Phys. Rev. Lett. 130, 031802 (2023) arXiv:2209.14968
- Neutron tagging following atmospheric neutrino events in a water Cherenkov detector, The Super-Kamiokande Collaboration, Journal of Instrumentation, Volume 17, October 2022 arXiv:2209.08609
- Searching for Supernova Bursts in Super-Kamiokande IV, **M. Mori** et al. (The Super-Kamiokande Collaboration), The Astrophysical Journal, 938, 35 (2022) arXiv:2206.01380
- Pre-supernova Alert System for Super-Kamiokande**, L. N. Machado** et al. (The Super-Kamiokande Collaboration), The Astrophysical Journal, 935, 40 (2022) arXiv:2205.09881

2018-2024 Paper (Cont’d SK-Gd Physics)

- Search for solar electron anti-neutrinos due to spin-flavor precession in the Sun with Super-Kamiokande-IV, The Super-Kamiokande Collaboration, Astroparticle Physics Volume 139, June 2022, 102702 arXiv:2012.03807
- Diffuse supernova neutrino background search at Super-Kamiokande,The Super-Kamiokande Collaboration, Phys. Rev. D 104, 122002 (2021) arXiv:2109.11174
- Search for Tens of MeV Neutrinos associated with Gamma-Ray Bursts in Super-Kamiokande, The Super-Kamiokande Collaboration, Prog. Theor. Exp. Phys. 2021, 103F01 arXiv:2101.03480
- Search for neutrinos in coincidence with gravitational wave events from the LIGO-Virgo O3a Observing Run with the Super-Kamiokande detector, The Super-Kamiokande Collaboration, Astrophys. J. 918 78 (2021) arXiv:2104.09196
- Indirect search for dark matter from the Galactic Center and halo with the Super-Kamiokande detector,The Super-Kamiokande Collaboration, Phys. Rev. D 102, 072002 (2020), arXiv:2005.05109
- Search for Astronomical Neutrinos from Blazar TXS0506+056 in Super-Kamiokande,**K. Hagiwara** et al. (The Super-Kamiokande Collaboration), Astrophysical Journal Letters, 887 (2019) L6, arXiv:1910.07680
- Sensitivity of Super-Kamiokande with Gadolinium to Low Energy Antineutrinos from Pre-supernova Emission, **C. Simpson** et al. (The Super-Kamiokande Collaboration), Astrophysical Journal 885, (2019) 133, arXiv:1908.07551
- Measurement of the neutrino-oxygen neutral-current quasielastic cross section using atmospheric neutrinos at Super-Kamiokande, **L. Wan** et al. (Super-Kamiokande Collaboration), Phys. Rev. D 99, 032005 (2019), arXiv:1901.05281

2018-2024 Paper (Low BG technical)

- **K. Ichimura** et al., Development of a low-background HPGe detector at Kamioka Observatory, Progress of Theoretical and Experimental Physics, ptad136,
- **Y. Sakakieda** et al., "Rapid Analysis of 226Ra in Ultrapure Gadolinium Sulfate Octahydrate" Progress of Theoretical and Experimental Physics, ptad117
- **H. Hosokawa** et al., "Development of ultra-pure gadolinium sulfate for the Super-Kamiokande gadolinium project" Progress of Theoretical and Experimental Physics, Volume 2023, Issue 1, January 2023, 013H01
- **Y. Iwata** et al., Emission characteristics of gadolinium ions in a water Cherenkov detector Progress of Theoretical and Experimental Physics, Volume 2022, Issue 12, December 2022, 123H01
- **S. Ito** et al., Improved method for measuring low-concentration radium and its application to the Super-Kamiokande Gadolinium project, Progress of Theoretical and Experimental Physics, Volume 2020, Issue 11, November 2020,113H01
- **Y. Nakano** et al., Measurement of the radon concentration in purified water in the Super-Kamiokande IV detector, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment Volume 977, 11 October 2020, 164297
- **S. Ito** et al., Development of a method for measuring rare earth elements in the environment for future experiments with gadolinium-loaded detectors, Progress of Theoretical and Experimental Physics, Volume 2019, Issue 6, June 2019, 063H03
- Evaluation of gadolinium's action on water Cherenkov detector systems with EGADS, **Ll. Marti** et al., Nuclear Instruments and Methods in Physics Research Section A 959 (2020), 163549 arXiv:1908.11532

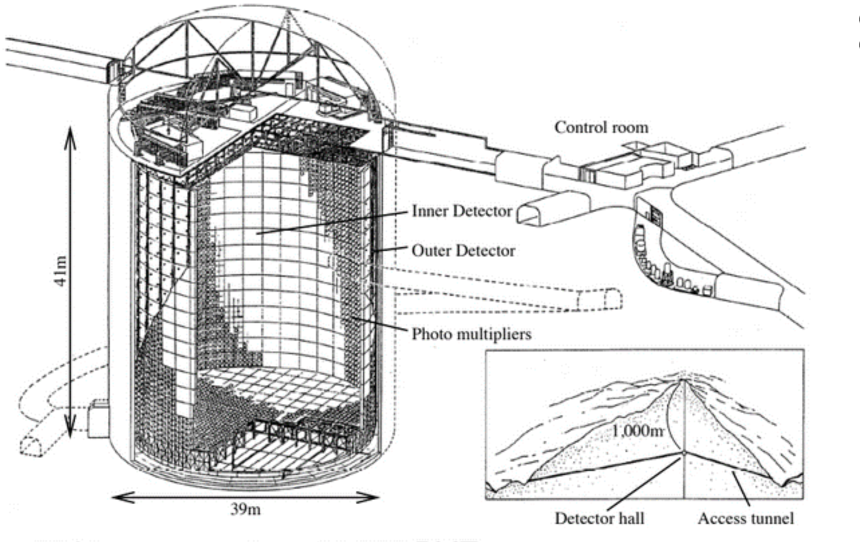
2018-2024 Paper (Gd-loadings)

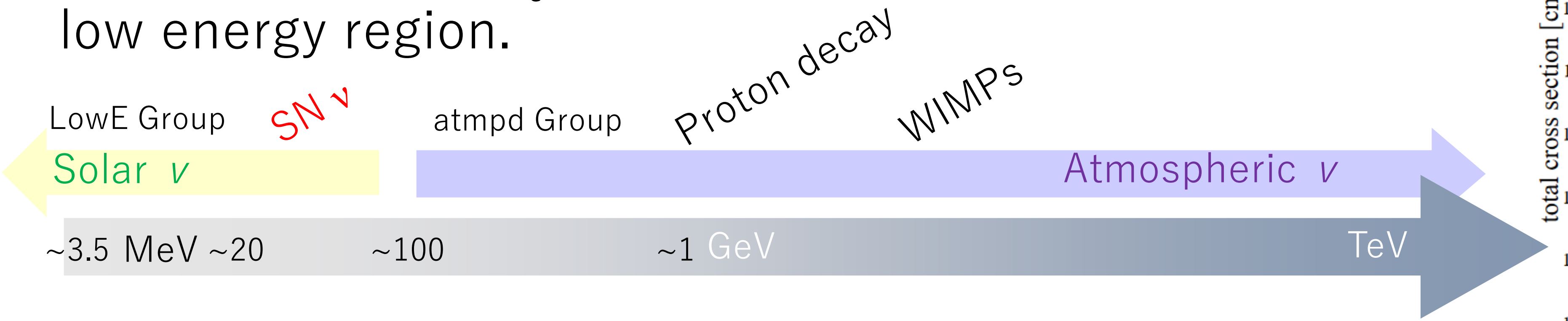
- Second Gadolinium Loading to Super-Kamiokande, The Super-Kamiokande Collaboration, To be submited to NIMA in a week, arXiv:24XX.XXXX
- First Gadolinium Loading to Super-Kamiokande, The Super-Kamiokande Collaboration, Nuclear Inst. and Methods in Physics Research, A 1027 (2022) 166248 arXiv:2109.00360

In the last 5 years, through SK-Gd Project**, 9 students** and **6 young researchers** wrote significant physics and cutting-edge technical papers.

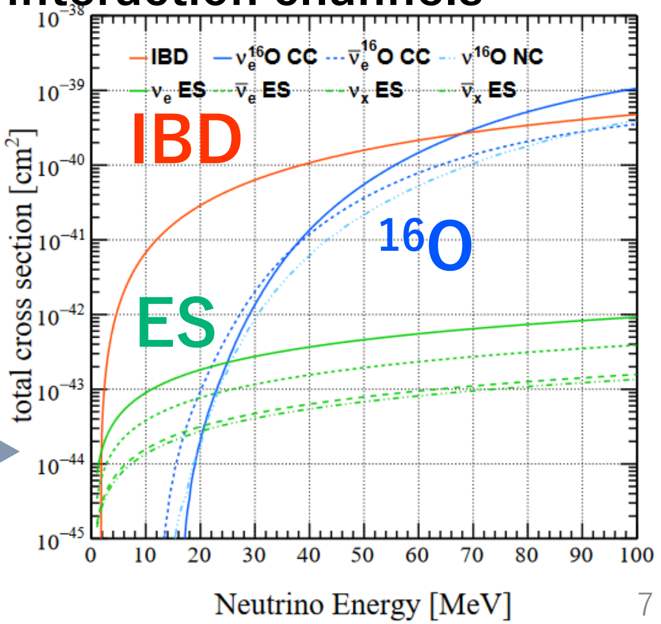
Super-Kamiokande VII (since July 5, 2022)

- **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

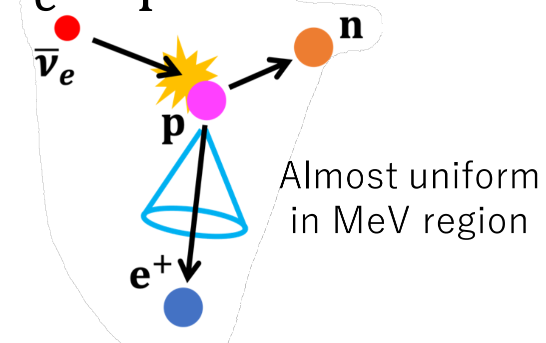


Supernova neutrino in SK

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

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

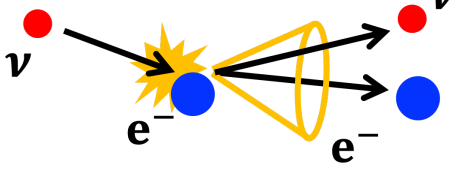
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

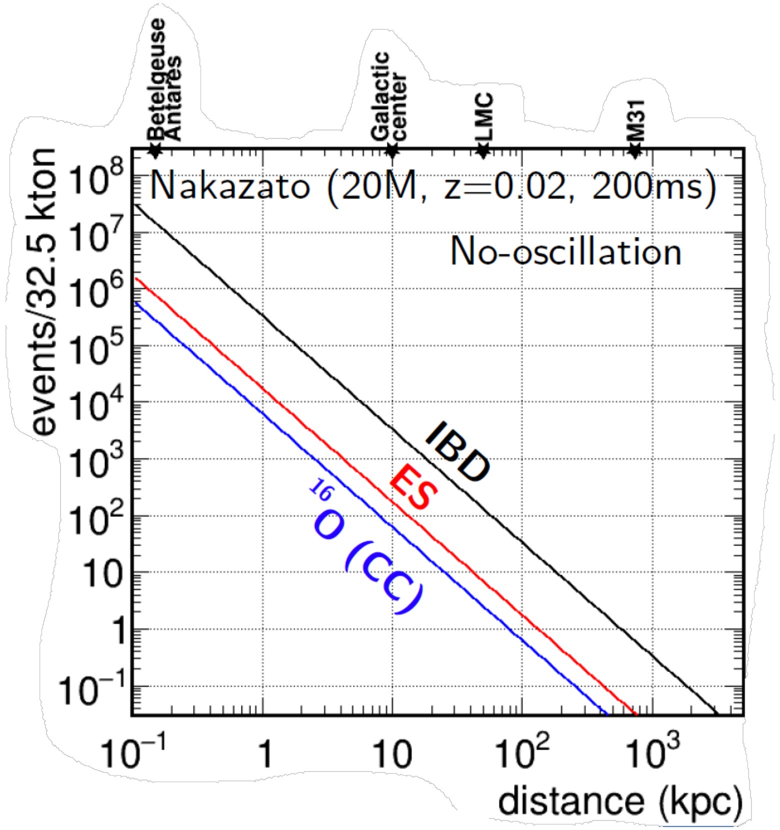


As the neutrino telescope
Elastic Scattering interactions (ES) ~5%

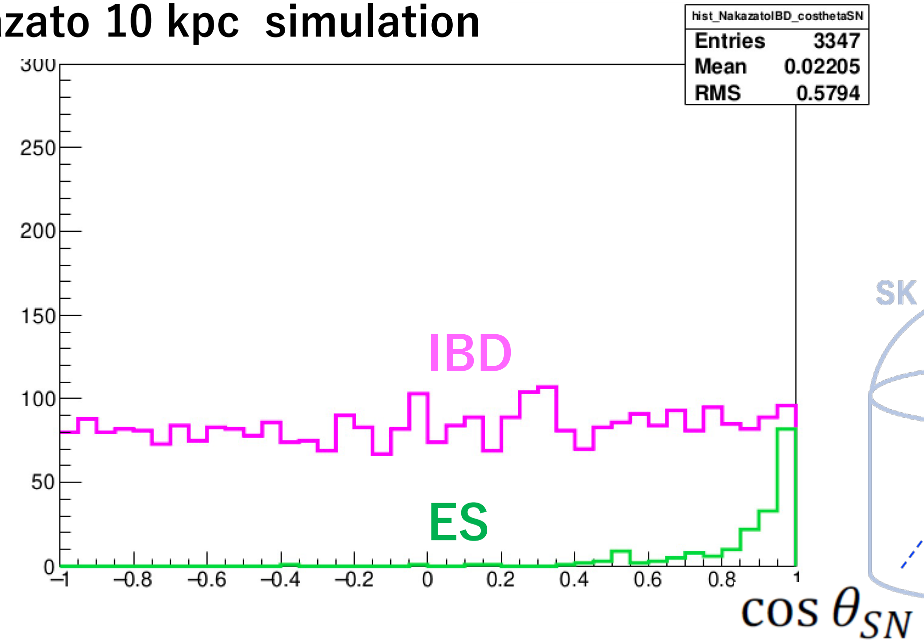
The electron keeps the neutrino direction information.

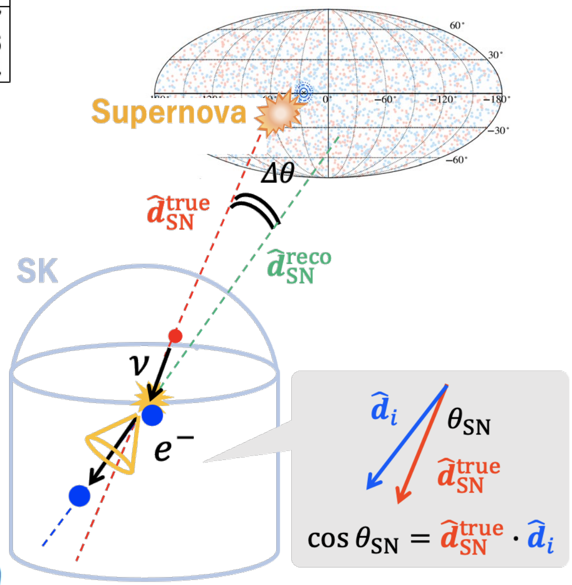
$$\nu + e^- \rightarrow \nu + e^-_\nu$$



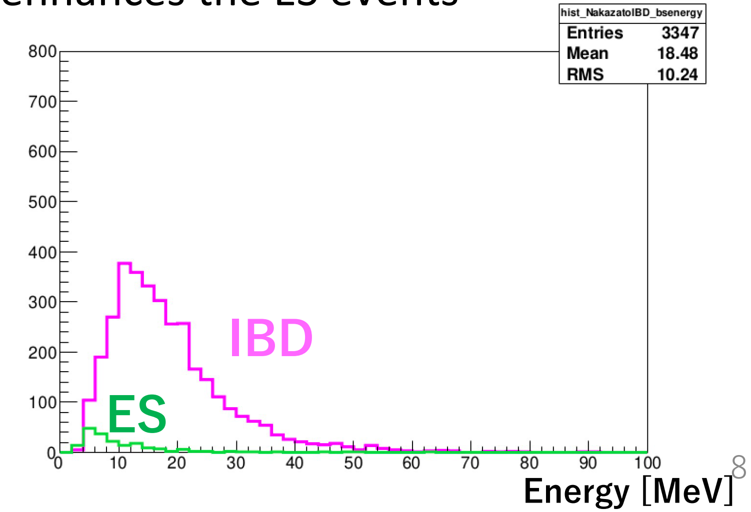


Nakazato 10 kpc simulation





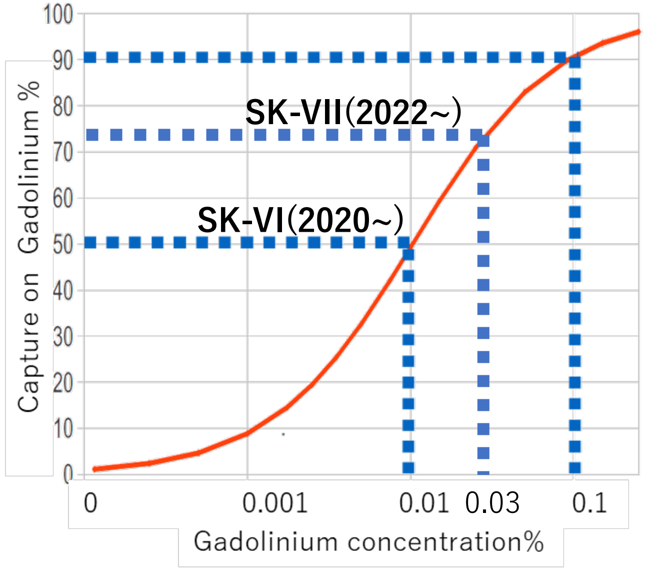
Lowering threshold enhances the ES events



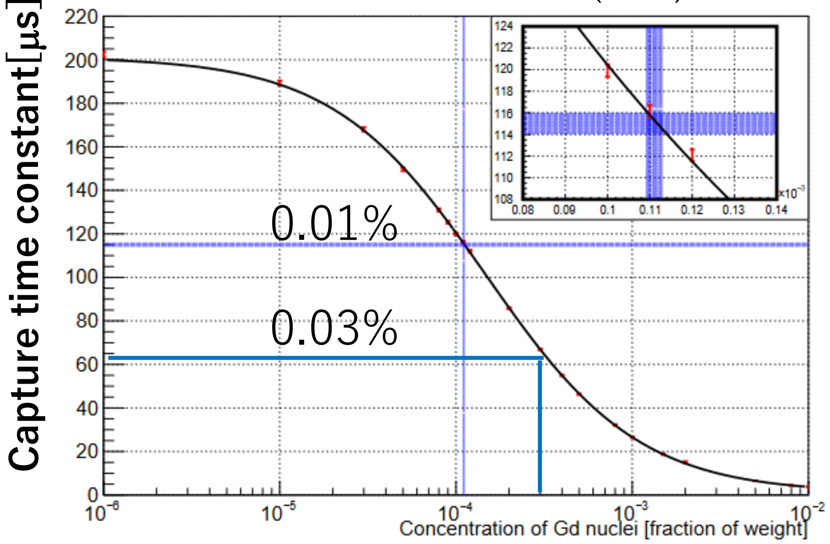
The Gd-loading

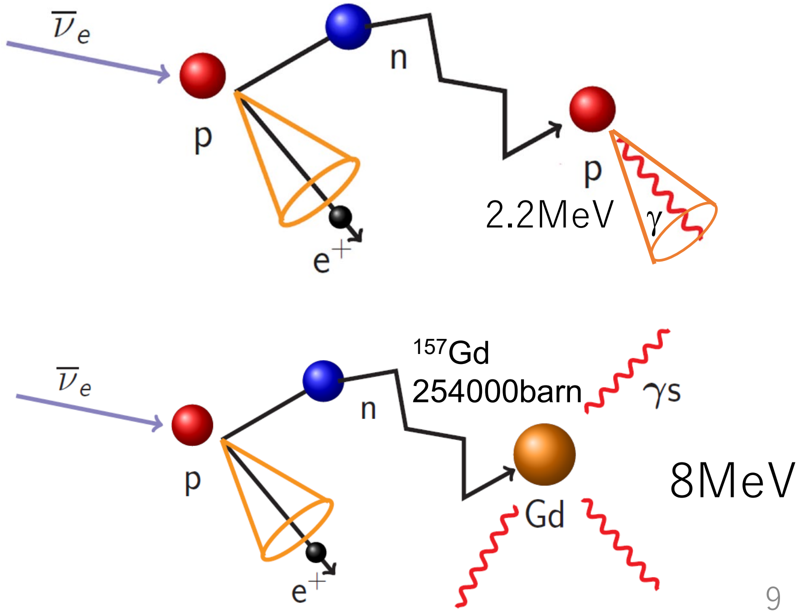
Separating ES from **IBD** allows
improving the **SN direction pointing** accuracy.
→ Gd enhances the IBS tagging

- **Neutron tagging for interaction (especially IBD) identification**
  - Originally only 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



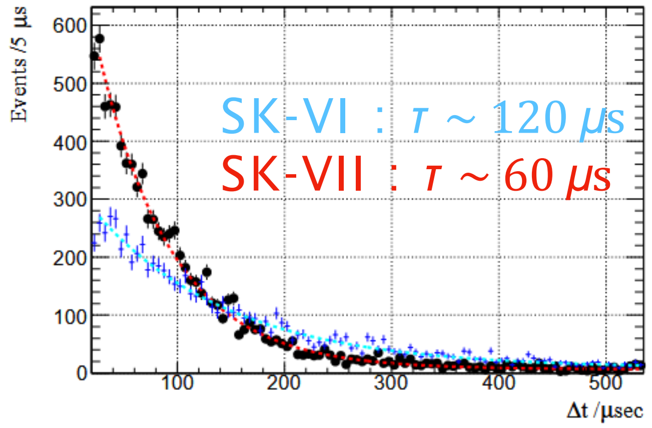


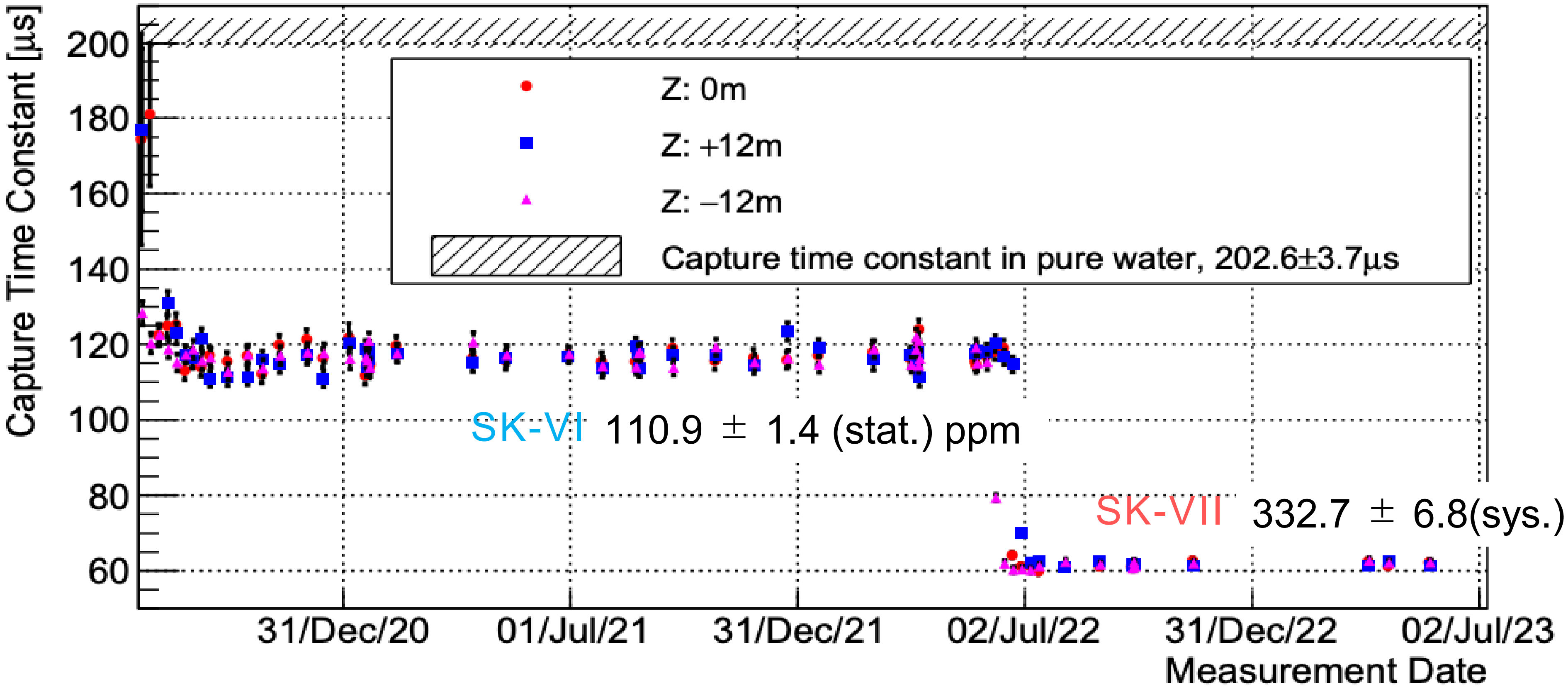
Gd concentration

Measured by neutron capture time (Am/Be source)

- **Perfectly in agreement with the expected value from the amount of loaded Gd.**

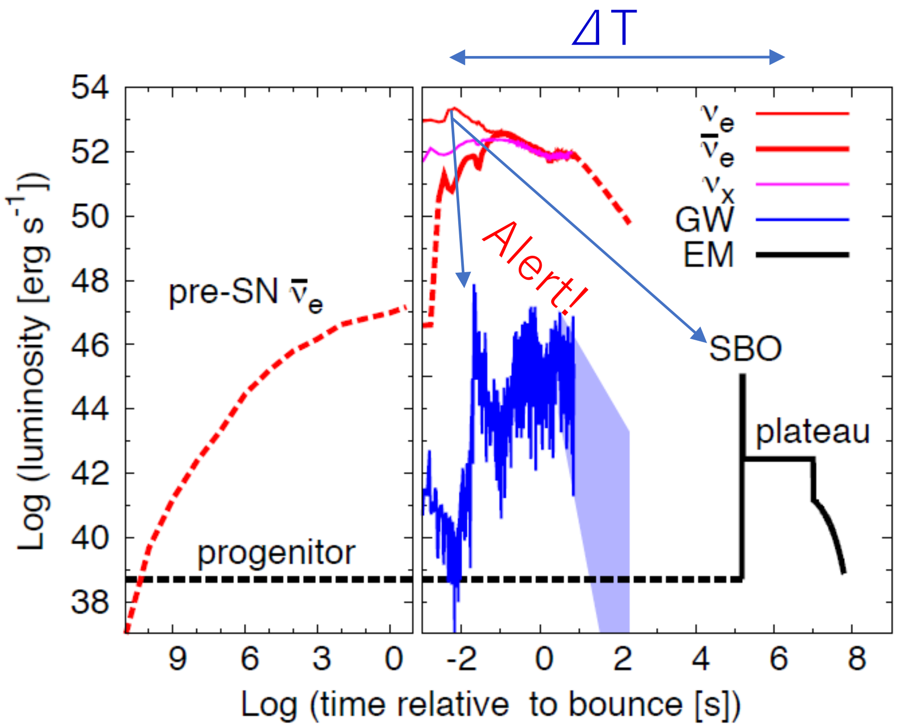
Spallation neutron case



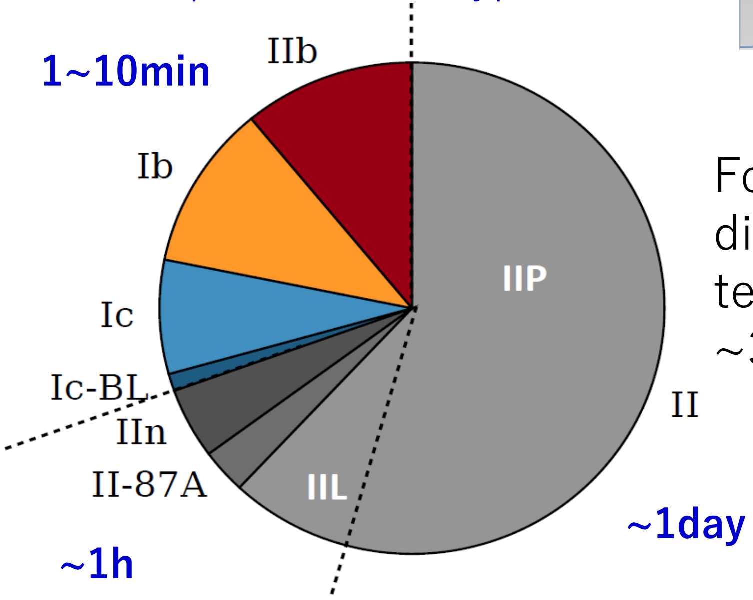


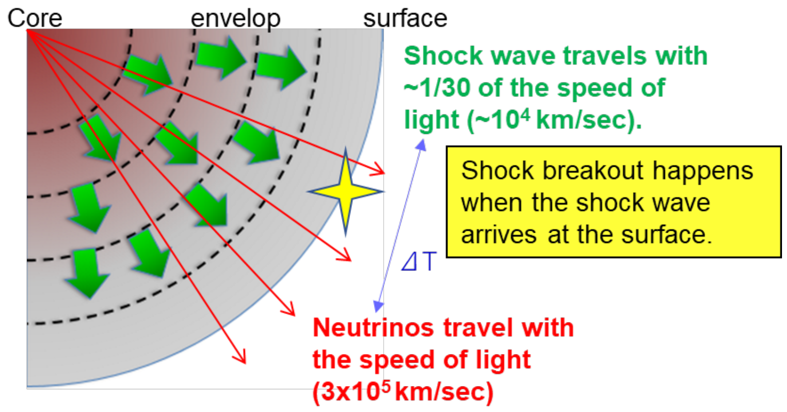
For multi-messenger astronomy

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



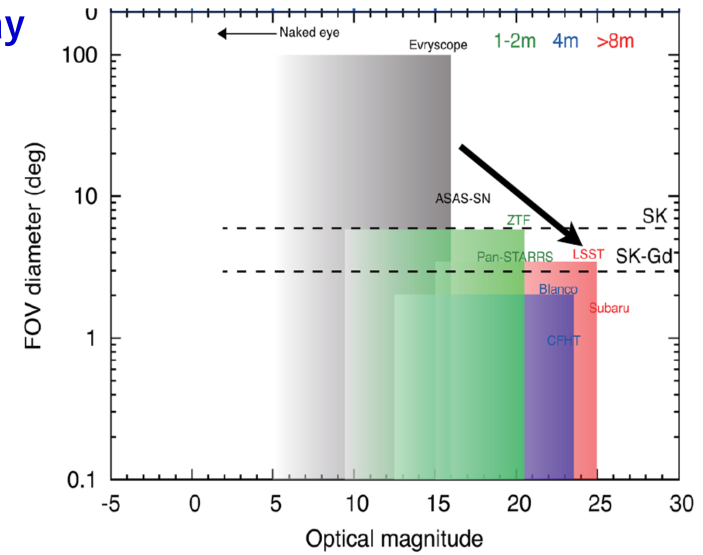
⊿T depends on the type of SN



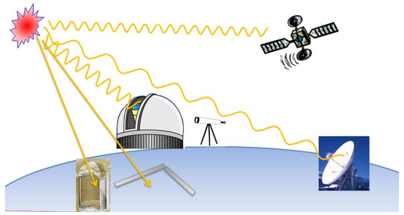


For ~70% of SNe, the time difference is several hours to tens of hours. For the remaining ~30%, that is several minutes.

K. Nakamura MNRAS, 461, 3296 (2016)



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

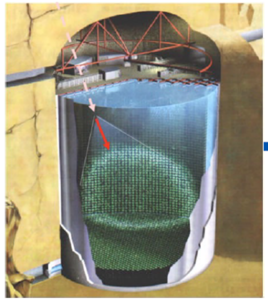


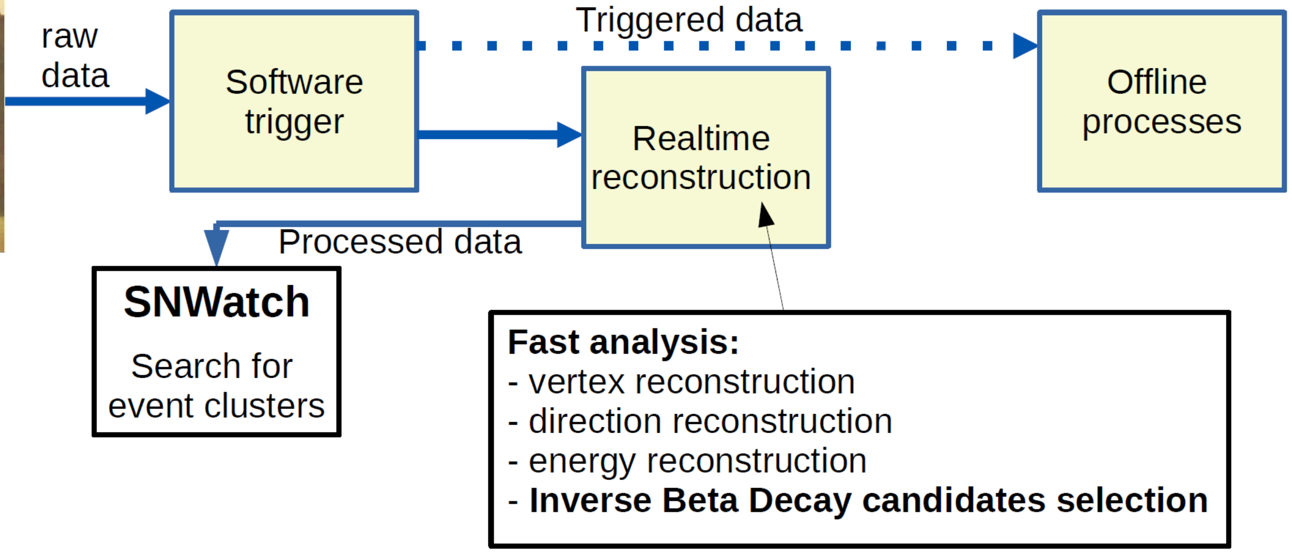
Realtime supernova monitoring of SK

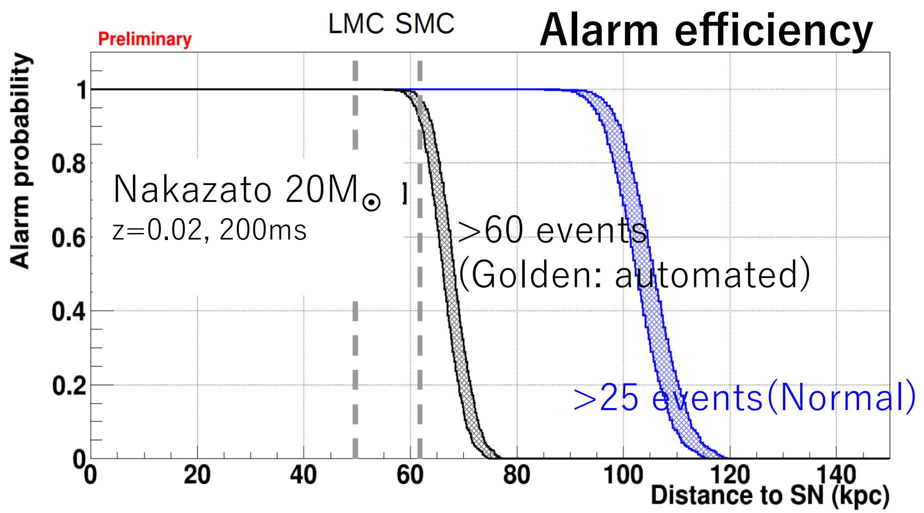
SK's SN monitoring system **"SNWatch."** Astropart. Phys. 81 (2016)

- 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.





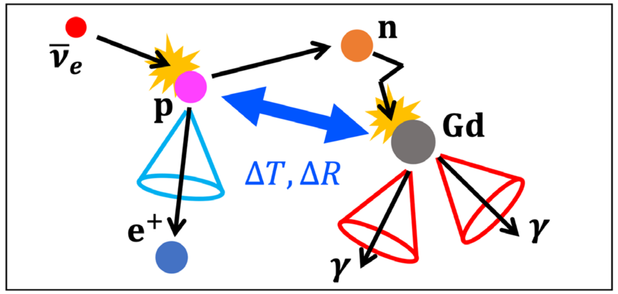


Quick IBD tagging implemented in SNwatch

0.03% Gd makes IBD tagging efficient in SN monitoring

Speed-oriented real-time simple IBD tagging algorithm

prompt candidates



delayed candidates

① Selection of prompt candidates ≧7MeV

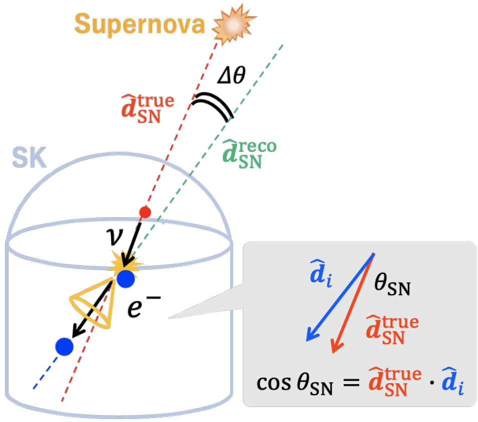
② Selection of delayed candidates

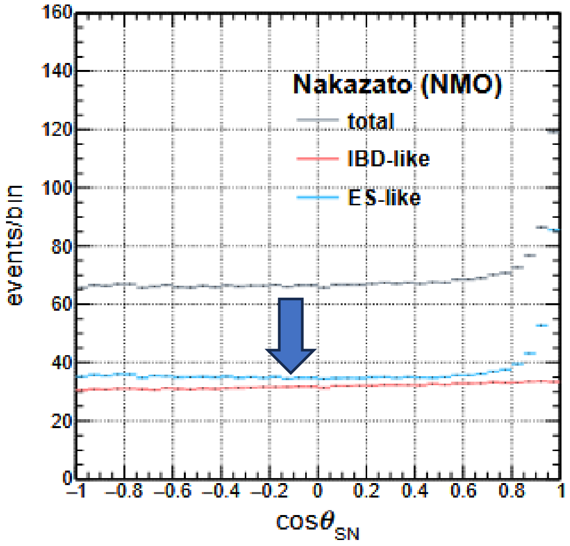
③ Neutron tagging pair of events with

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

This selection algorithm tags ~50% IBD events { **IBD-like**, **ES-like** }

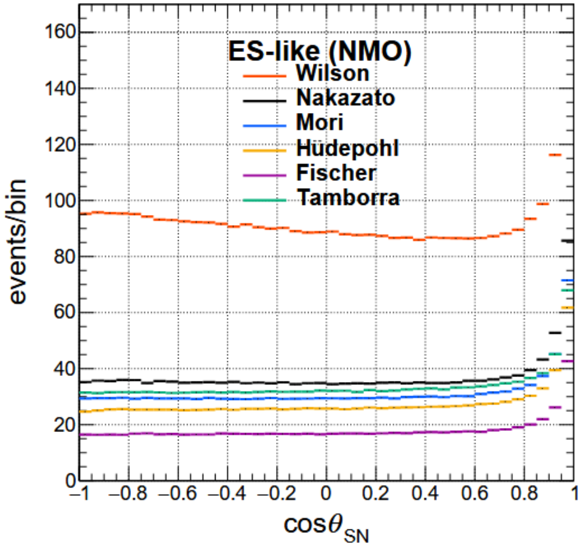
10kpc
Nakazato 20M$_\odot$
z=0.02, 200ms
NMO



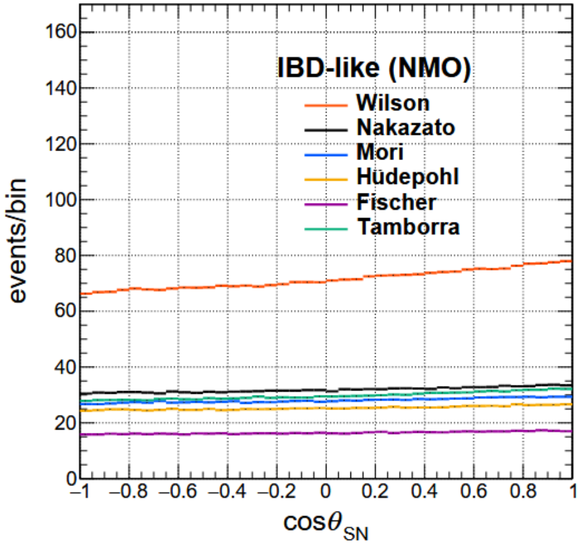


10kpc Other models

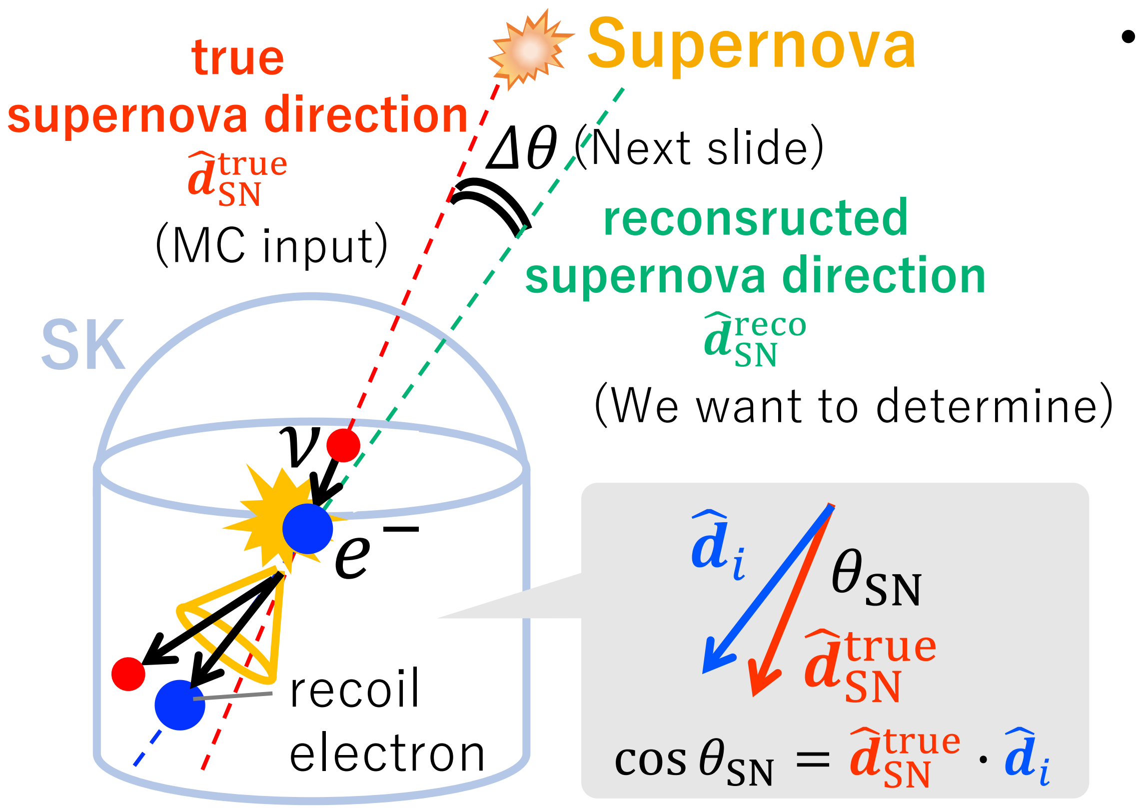
ES-like

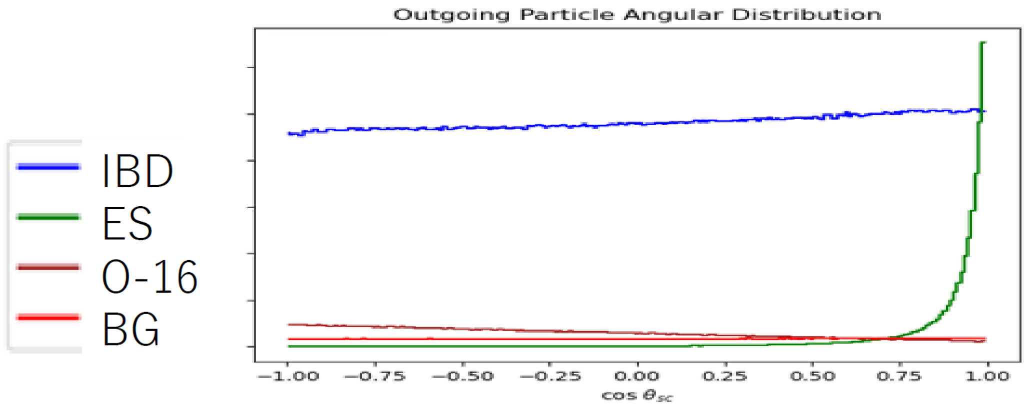


IBD-like



Determination of SN direction





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

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

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

  - Likelihood

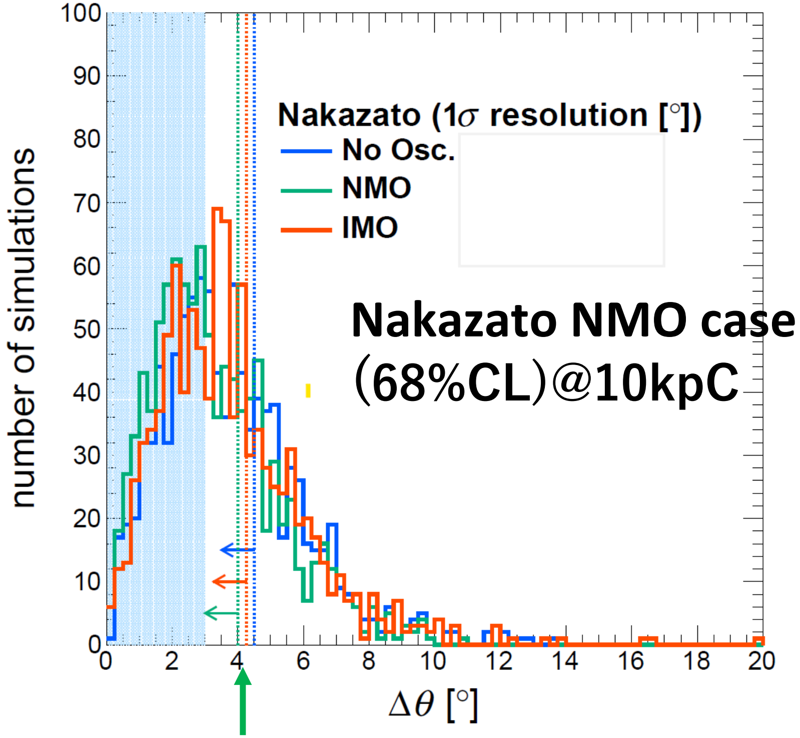
$$\mathcal{L} = \exp\left\{\sum_{k,r} N_{r,k}\right\} \prod_i L_i$$

  - Maximized by

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

This is powerful, but the initial grid search and the loop process to get difference between a trial SN direction and each event direction take time…

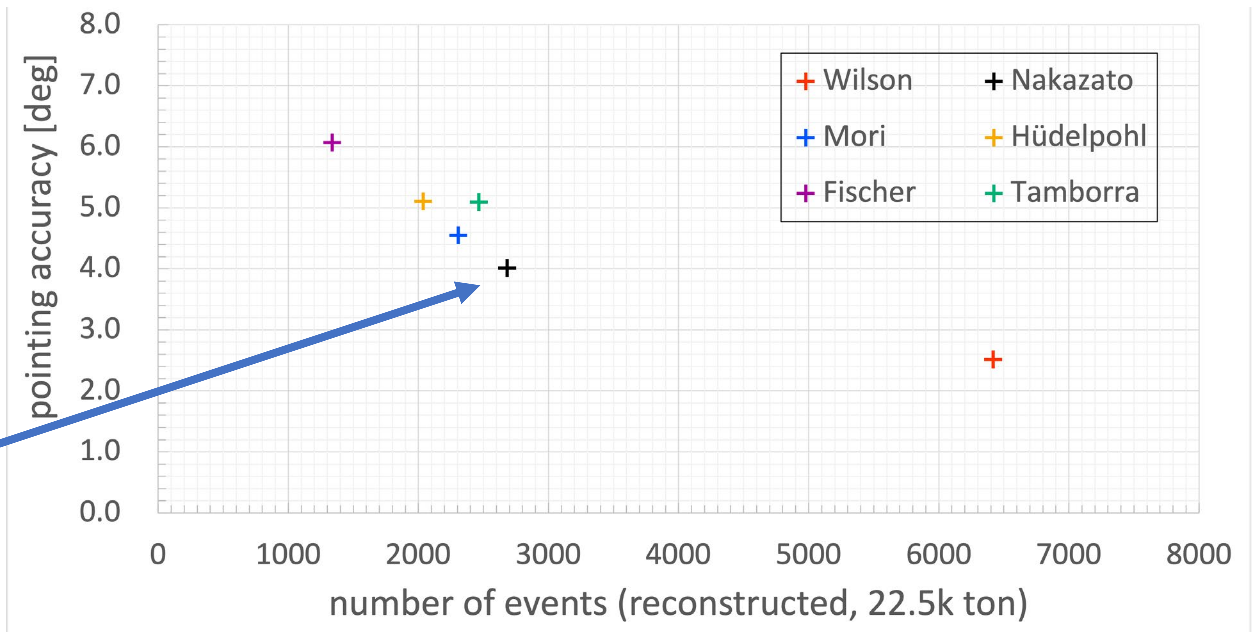
Pointing Accuracy for 10kpc SN



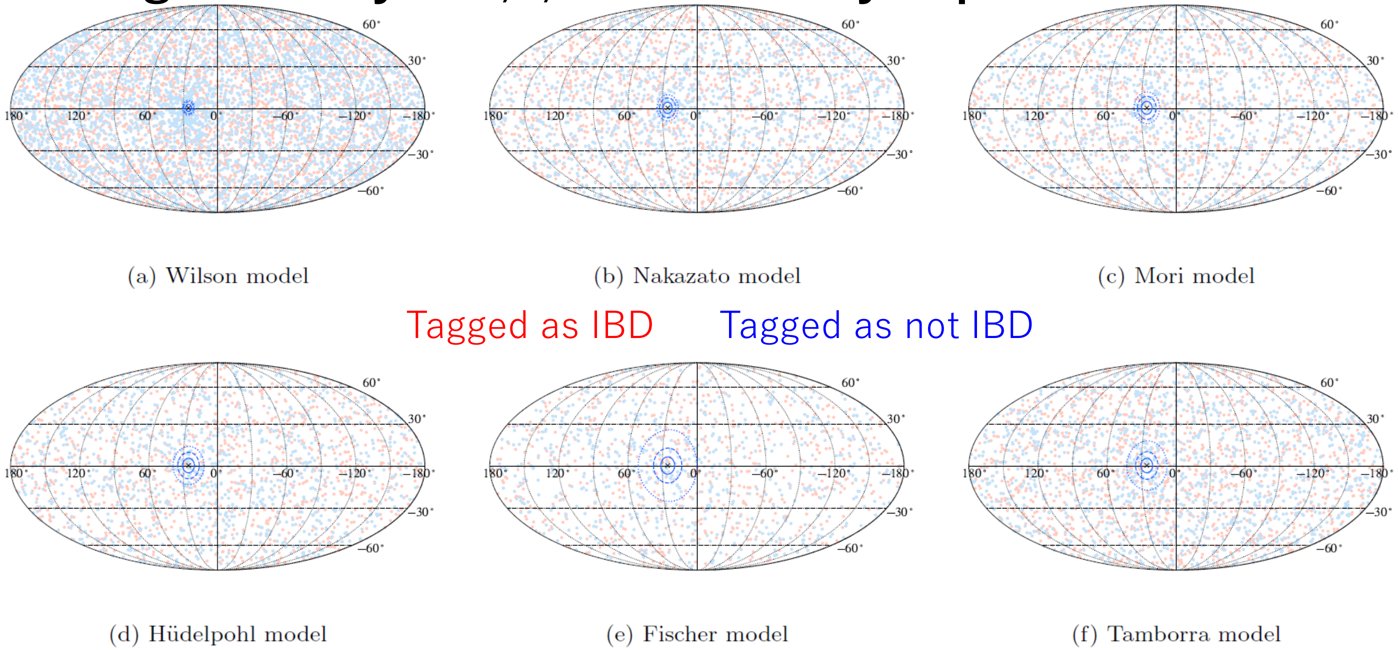
Nakazato NMO case ~4.0°
(68%CL)@10kpC

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

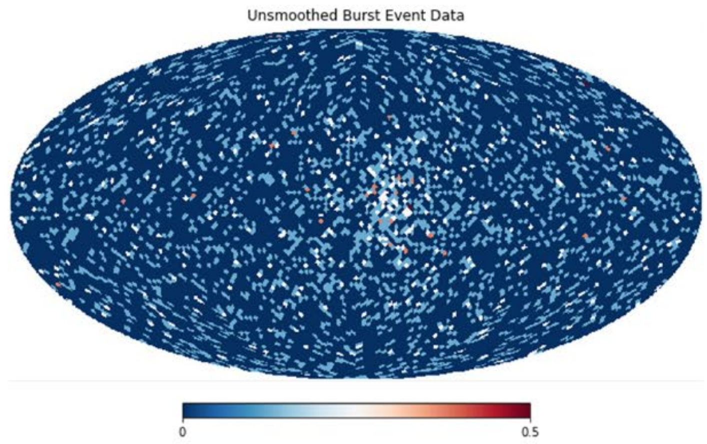
Tagged as IBD Tagged as not IBD

(d) Hüdelpohl model (e) Fischer model (f) Tamborra model

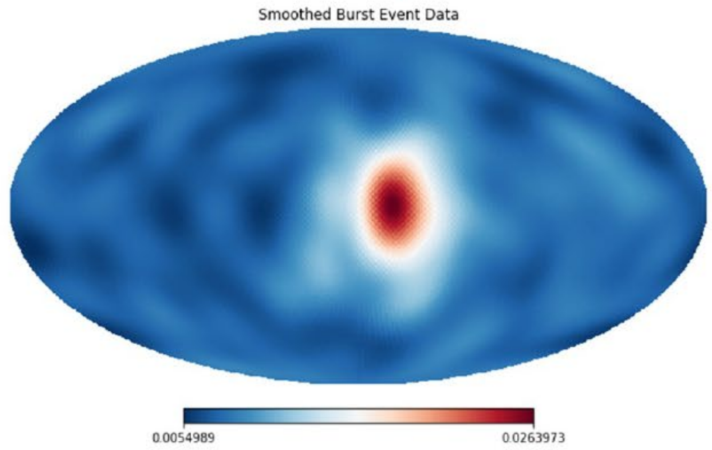
Upgrading with HealPix direction estimation

- 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

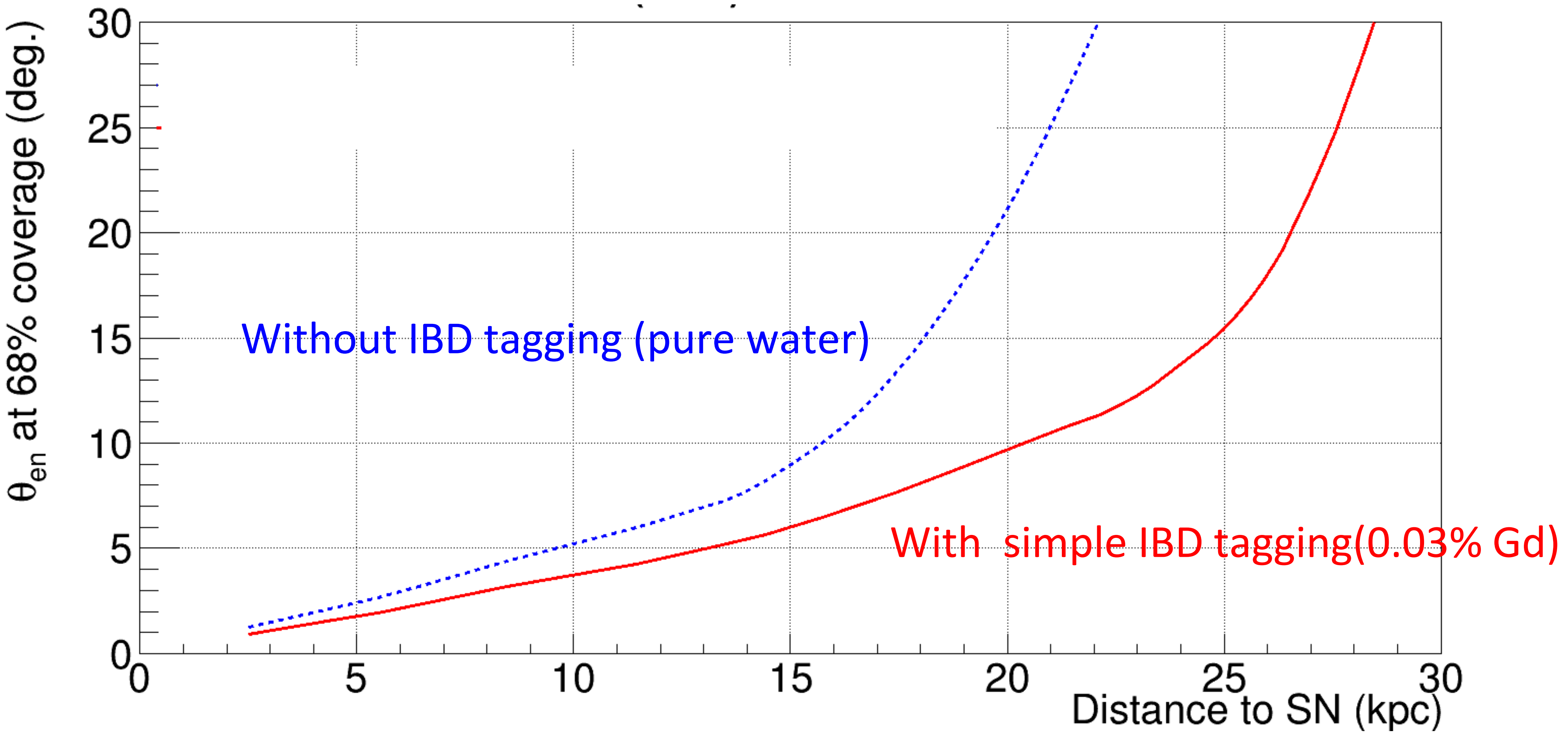
Nside = 32, Npix = 12,288



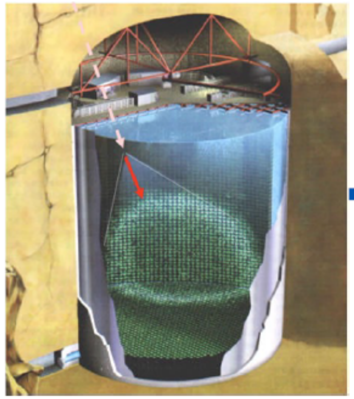
Gaussian Smoothed, σ = 0.15 rad.



How much improved by 0.03% Gd?



How much is boosted by HealPix?



1 subrun ~60 seconds

raw data → Software trigger

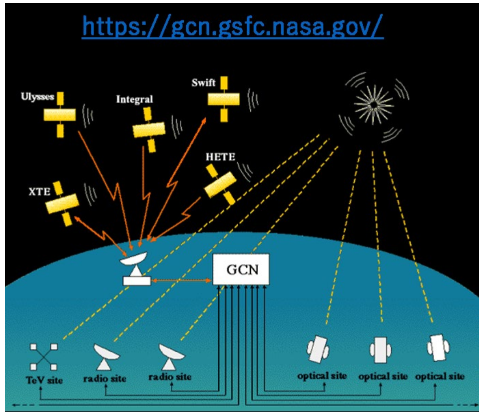
Triggered data ⇢ Offline processes

Software trigger → ~10 sec → Realtime reconstruction and selection (~60 sec)

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

~~90–110 sec~~ → ~10 sec

Cluster finder → ~5 sec → Alarm

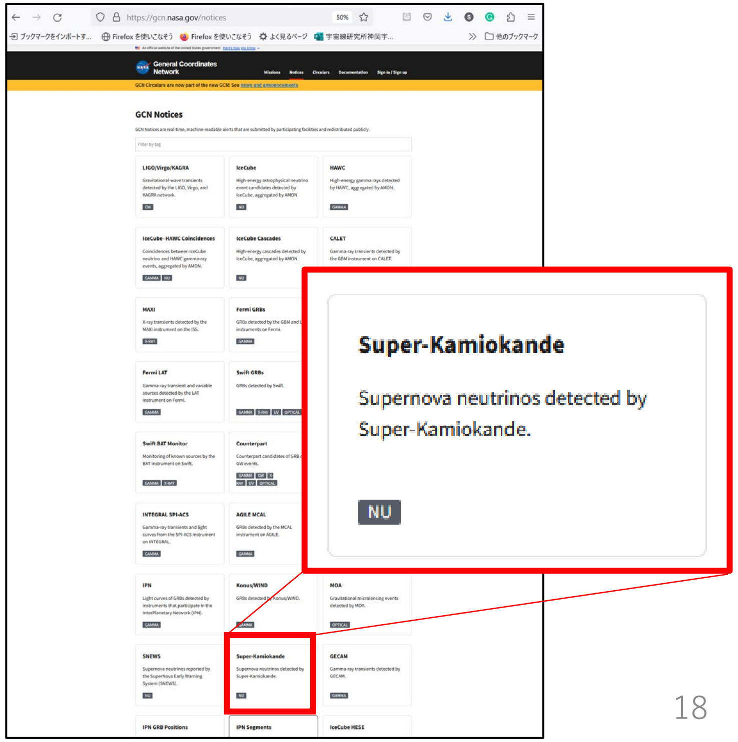


General Coordinates Network

GCN Circulars are now part of the new GCN!

ASAS-SN All-Sky Automated Survey for Supernovae

SK_SN Notice on GCN



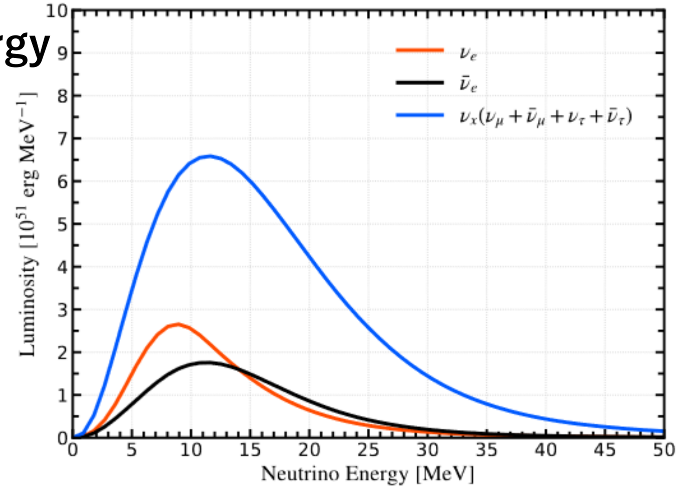
- **Within 2min, SK_SN notice will be sent through GCN Notice**

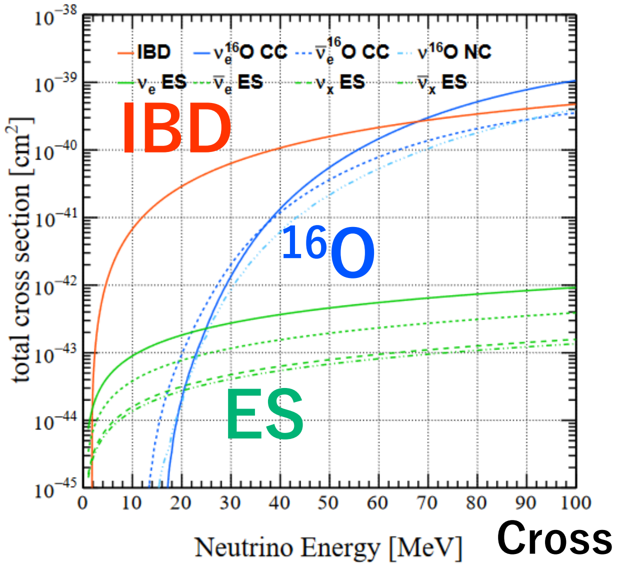
For the next

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

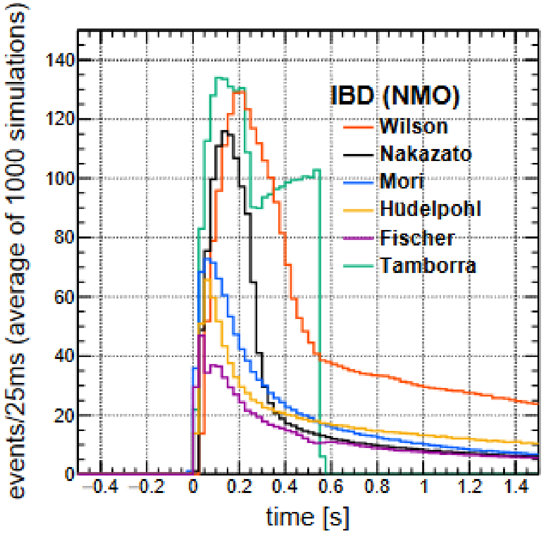
Expected number of interactions in SK for 10kpc SN

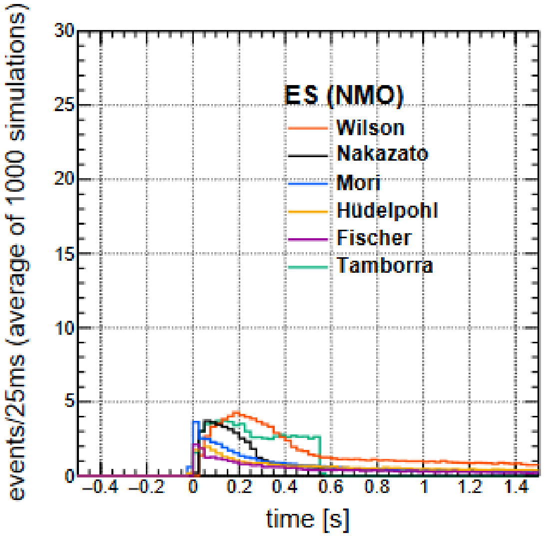
Generated by	Wilson			Nakazato			Mori		
SKSNSim	No Osc.	NMO	IMO	No Osc.	NMO	IMO	No Osc.	NMO	IMO
IBD ($\bar{\nu}_e$)	7431	8207	9970	3542	3893	4693	3275	3422	3745
ES (ν_e)	223	231	229	173	172	171	177	148	156
ES ($\bar{\nu}_e$)	97	97	98	63	66	72	60	61	63
ES (ν_x)	80	79	80	60	60	60	52	57	56
ES ($\bar{\nu}_x$)	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

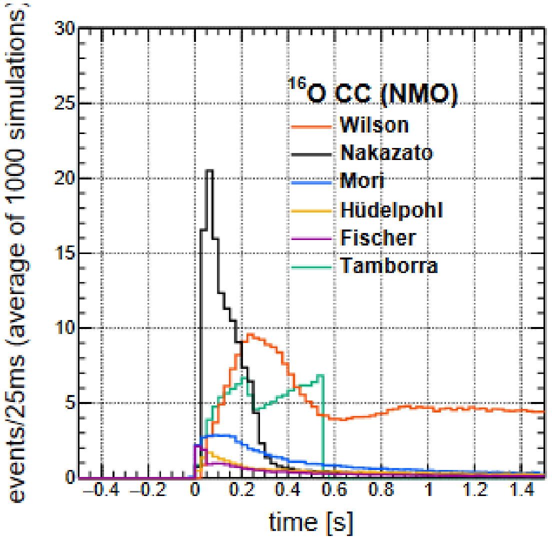
Generated by	Hüdelpohl			Fischer			Tamborra		
SKSNSim	No Osc.	NMO	IMO	No Osc.	NMO	IMO	No Osc.	NMO	IMO
IBD ($\bar{\nu}_e$)	3048	3052	3049	1884	1990	2242	3830	3487	2718
ES (ν_e)	146	124	132	90	87	88	135	82	99
ES ($\bar{\nu}_e$)	53	53	53	35	35	37	50	45	35
ES (ν_x)	43	47	46	31	31	31	28	38	35
ES ($\bar{\nu}_x$)	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

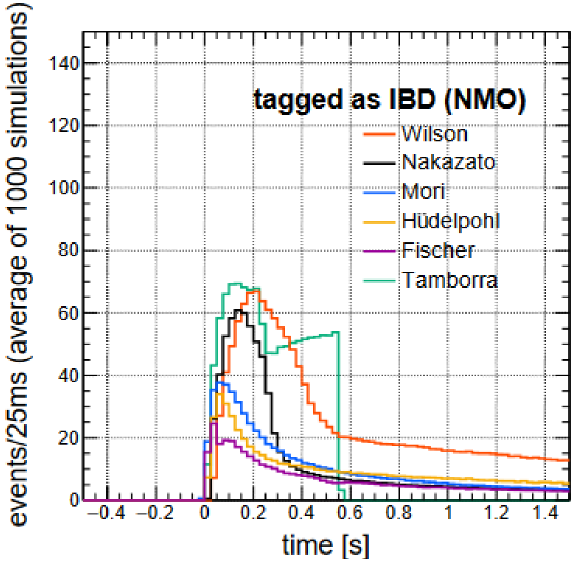




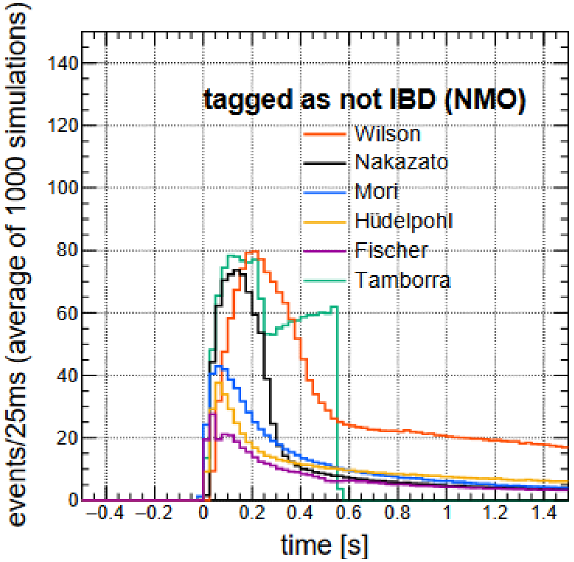


What currently can be extracted from SK (online analysis)

IBD-like



ES-like



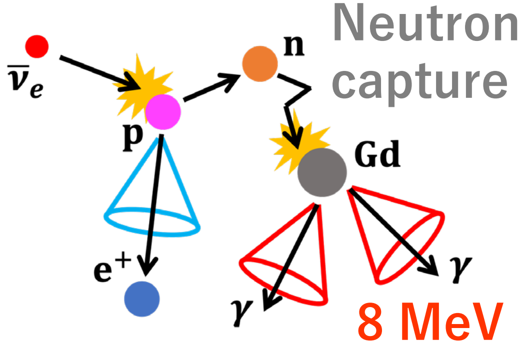
ES contaminated with IBD+^{16}O

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.

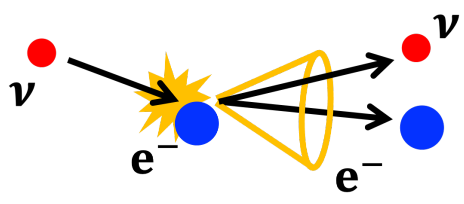
Inverse Beta Decay (IBD)

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



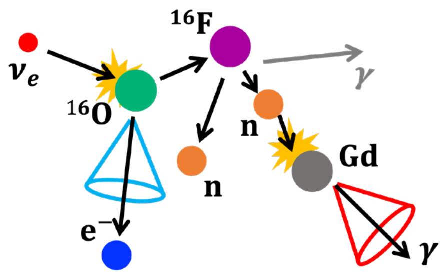
Elastic Scattering (ES)

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

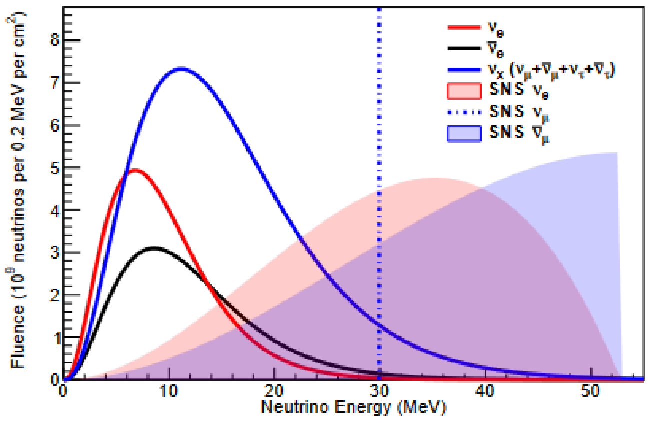


^{16}O interactions

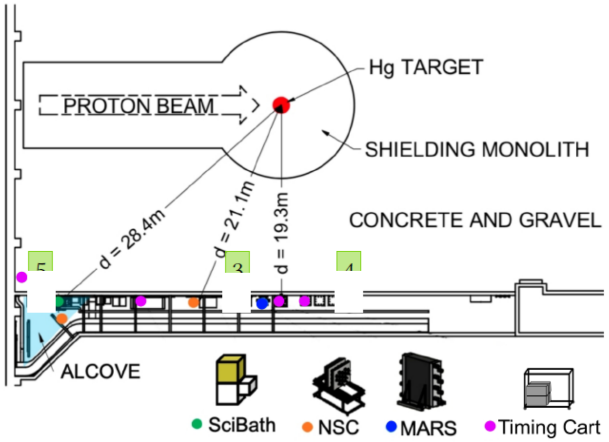
$$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}$$
$$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N},$$



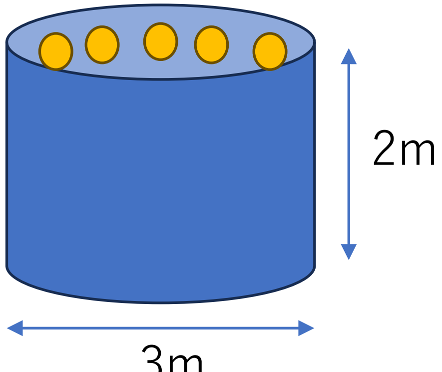
ORNL SNS neutrino spectra



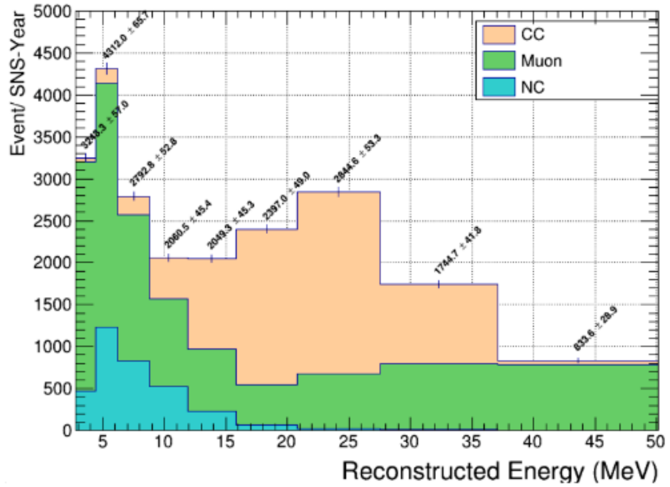
With COHERENT detectors, a dedicated experiment is planned at ORNL



8% photo coverage



SNS 3X2m Detector Spectrum



Status of DNSB analysis

Diffuse Supernova Neutrino Background

Supernova Relic Neutrino

Neutrinos emitted in past supernova explosions and stored in the current universe → **promising extra-galactic ν**

- In the entire universe, several supernova explosions occur every second.
- There must have been O(10^{18}) explosions in the history of the universe.

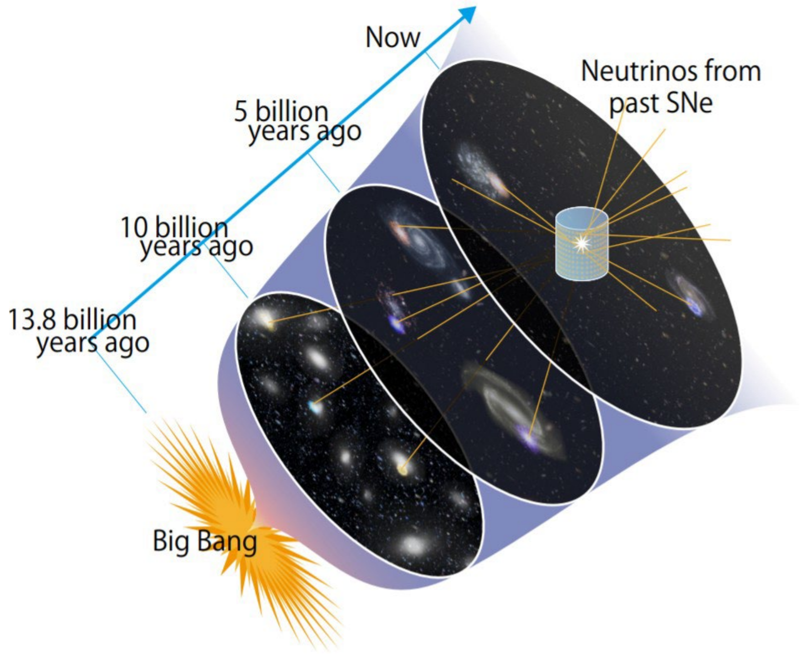
$$\frac{dF_\nu}{dE_\nu} = c \int_0^{z_{max}} R_{SN}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu} (1+z) \frac{dt}{dz} dz$$

SN rate at z

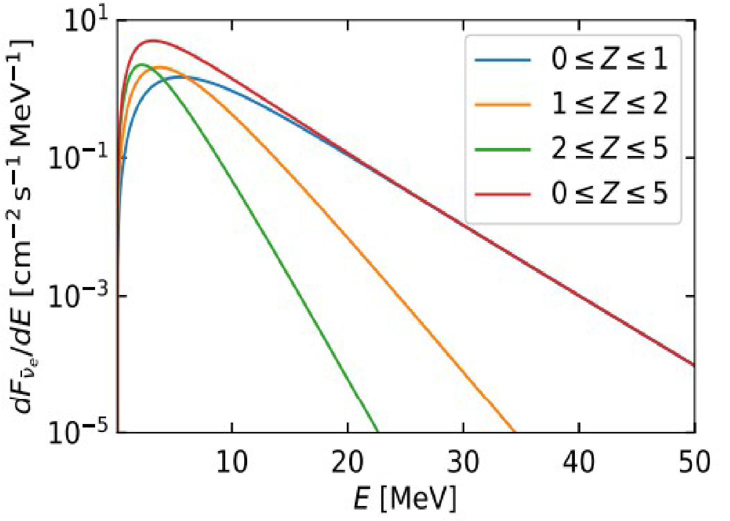
(averaged) SN spectrum

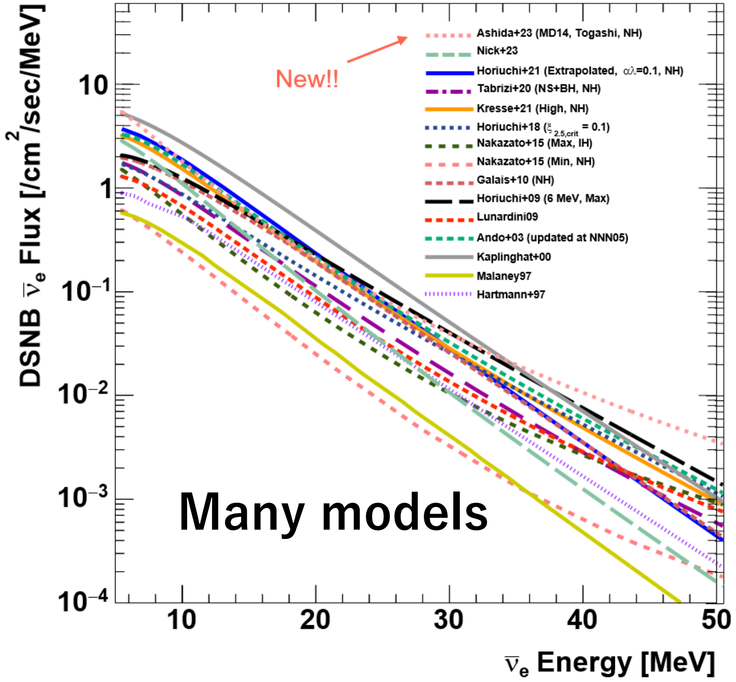
Access to

- ✓ **History of Star Formation**
- ✓ **BH formation**
- ✓ **Mechanism of the supernova explosion**



Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10



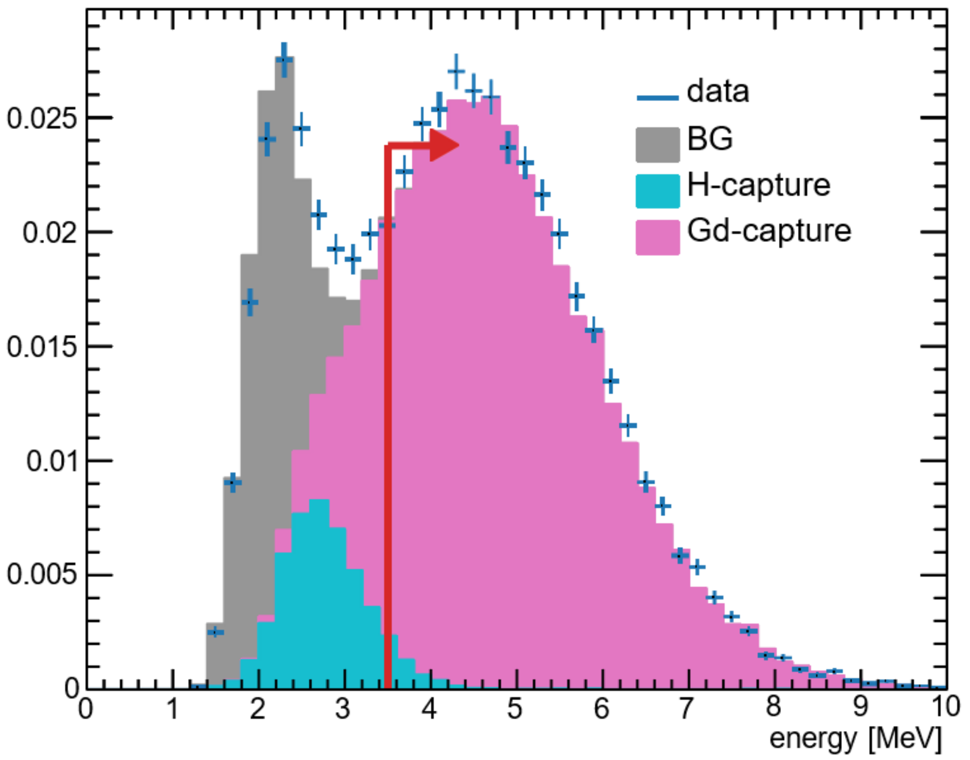


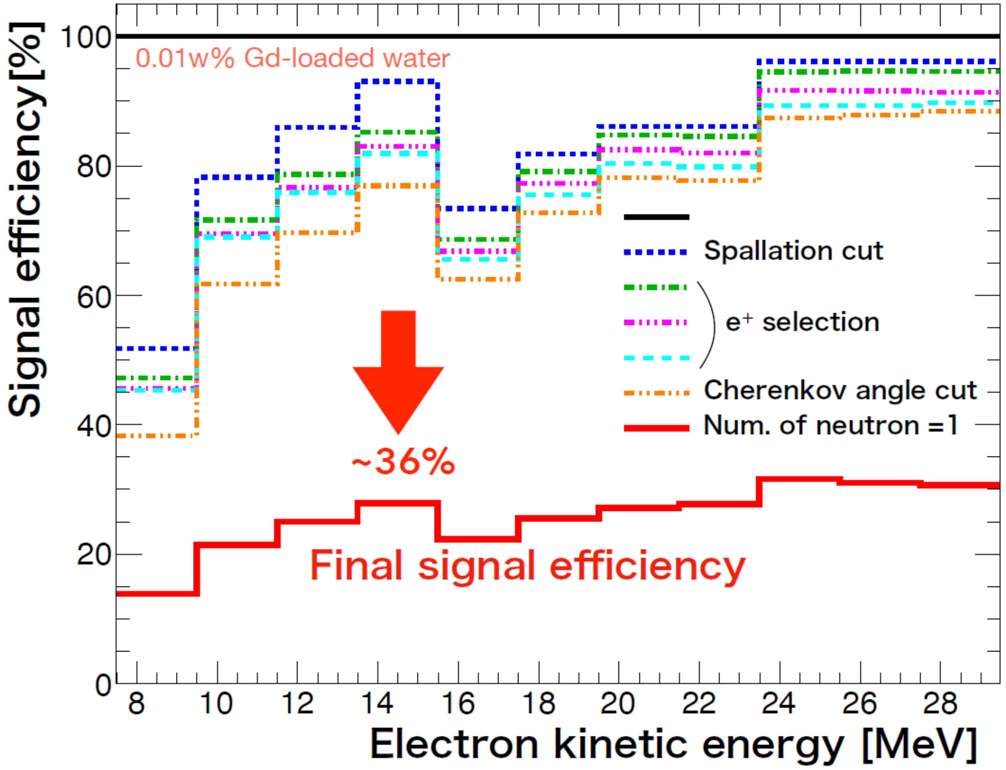
Published DSNB search results @0.01%Gd

M. Harada et al., ApJL 951, L27 (2023)

- Neutron detection with cut-based method (Efficiency ~ 35.6%)

Neutron selection in Am/Be calibration





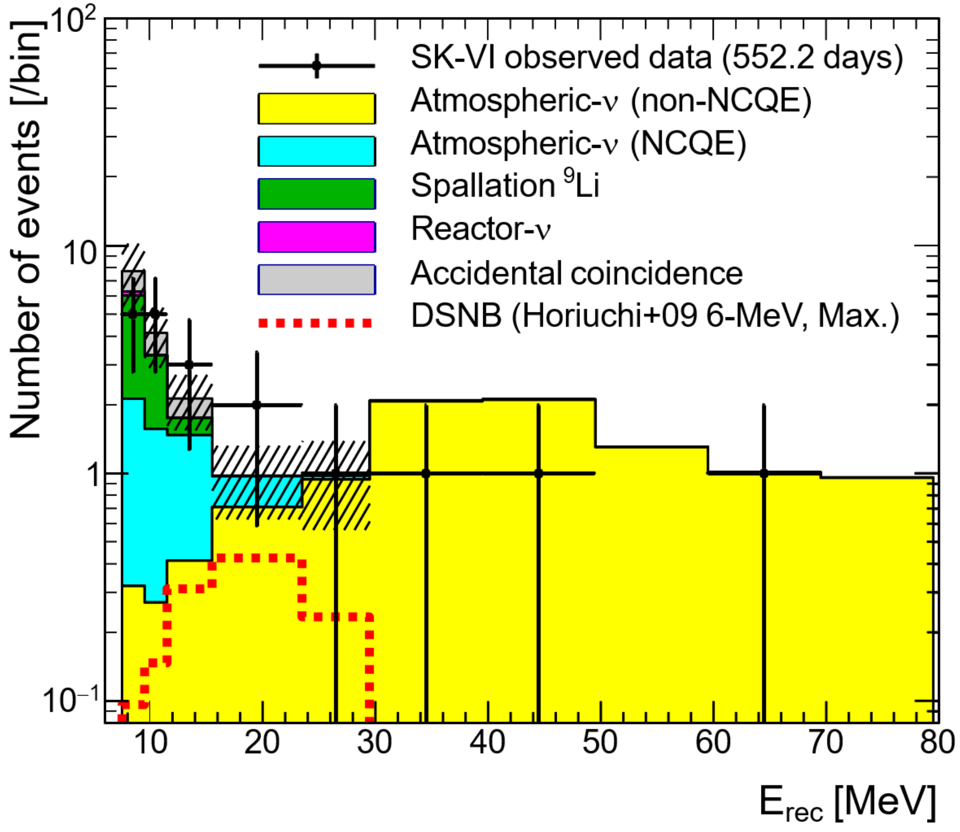
Published DSNB search results @0.01%Gd

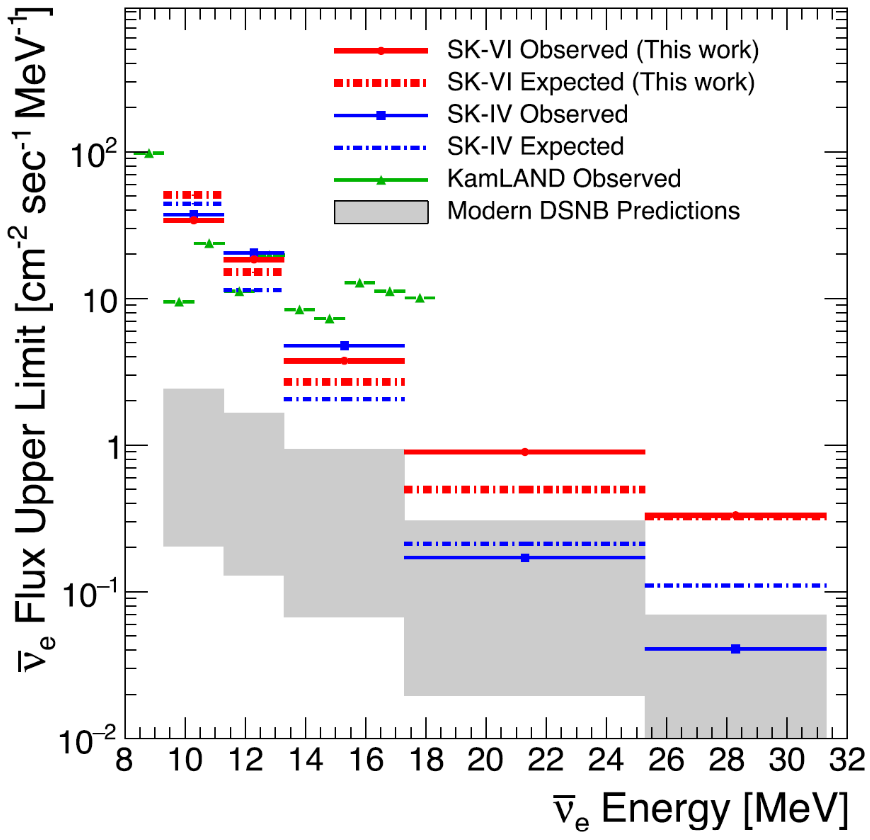
- SK-VI 552 days data
  - 16 events were observed

  → consistent with background

M. Harada et al., ApJL 951, L27 (2023)

Flux upper limit comparable with the results from pure-water phase which has 5 times of live-time



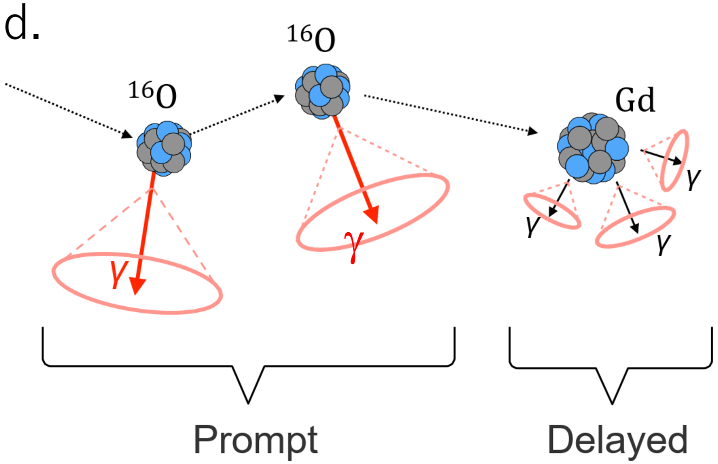


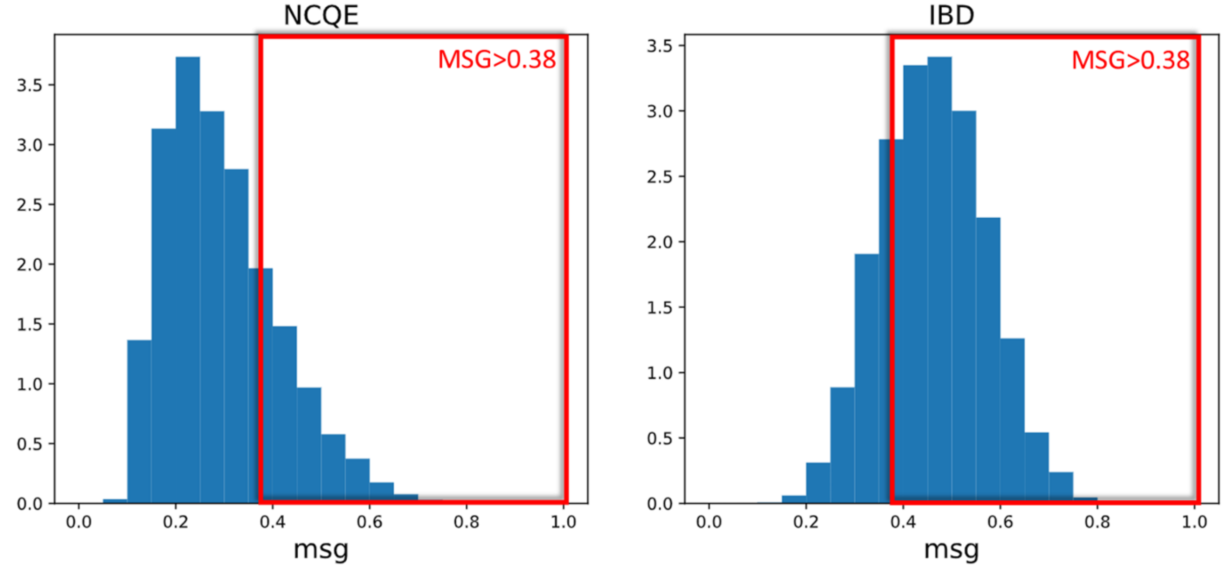
SK-Gd is world's most sensitive for SRN above 13 MeV

Updated DSNB search@0.01%Gd NCQE BG reduction

The most problematic BG

can be reduced if the prompt multiple γs are identified.



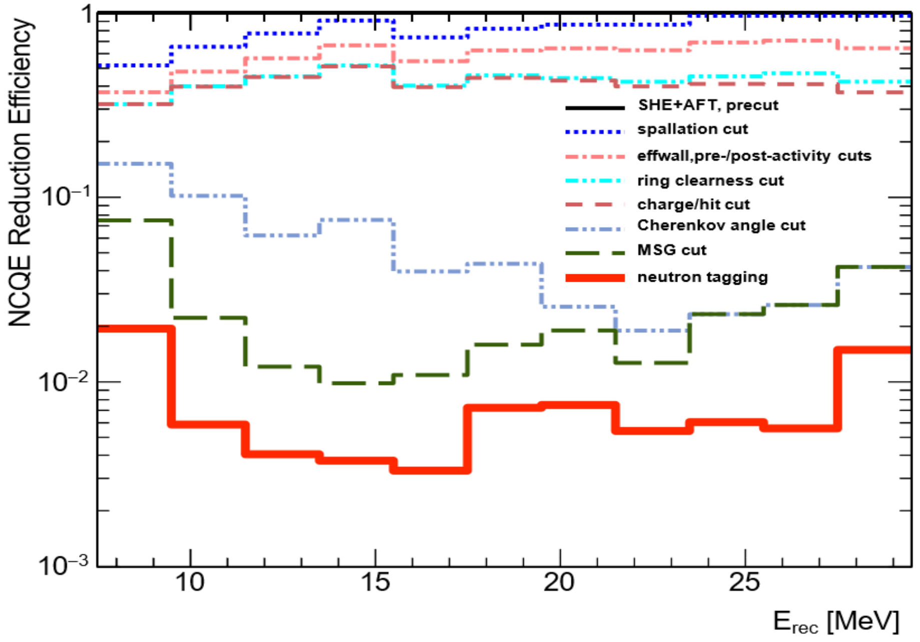


Multiple-scattering goodness (MSG)

originally for solar ν to reject low energy electron scattering BG events

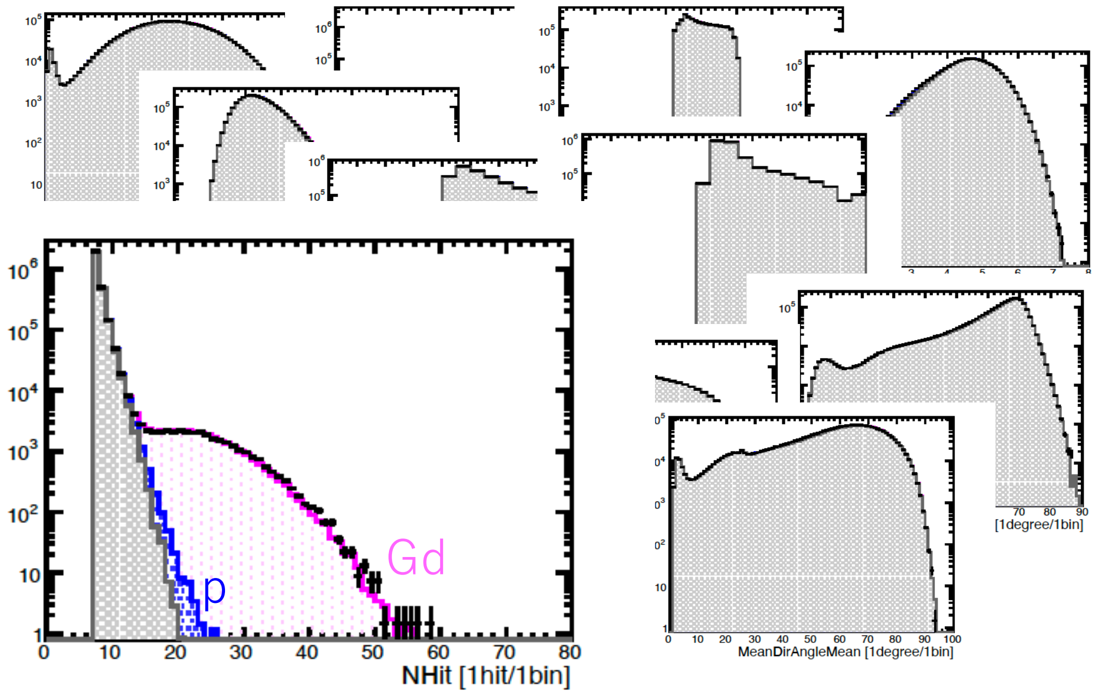
Small MSG:
more isotropic hit pattern: more NCQE-like

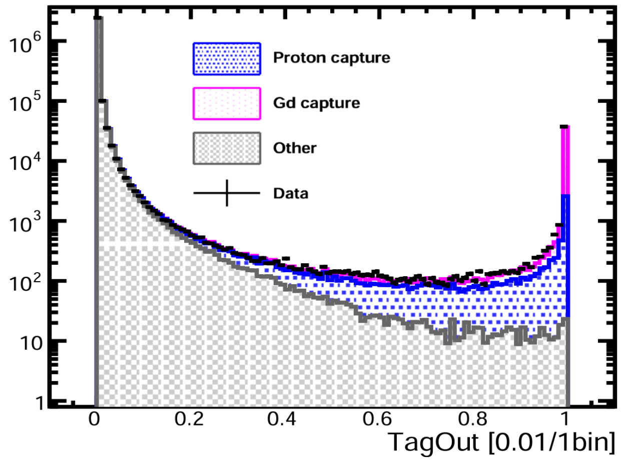
Large MSG:
more forward hit pattern: more IBD-like

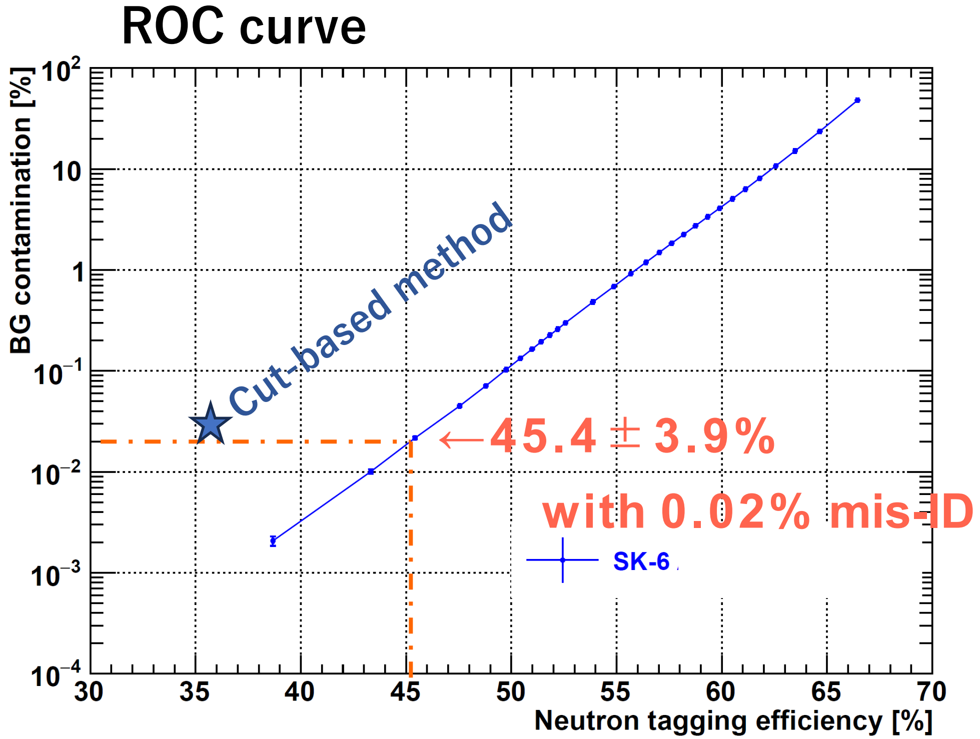


Updated DSNB search@0.01%Gd Neutron tagging with NN

- 12 feature input variables
  - Nhit, hit timing, β–parameters,..



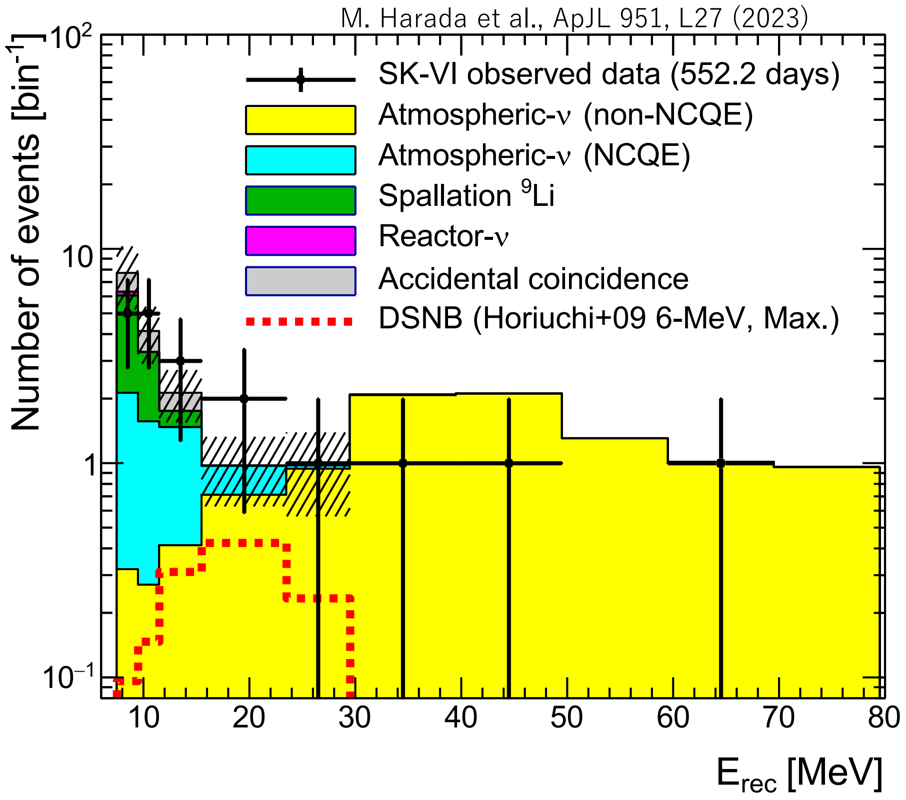


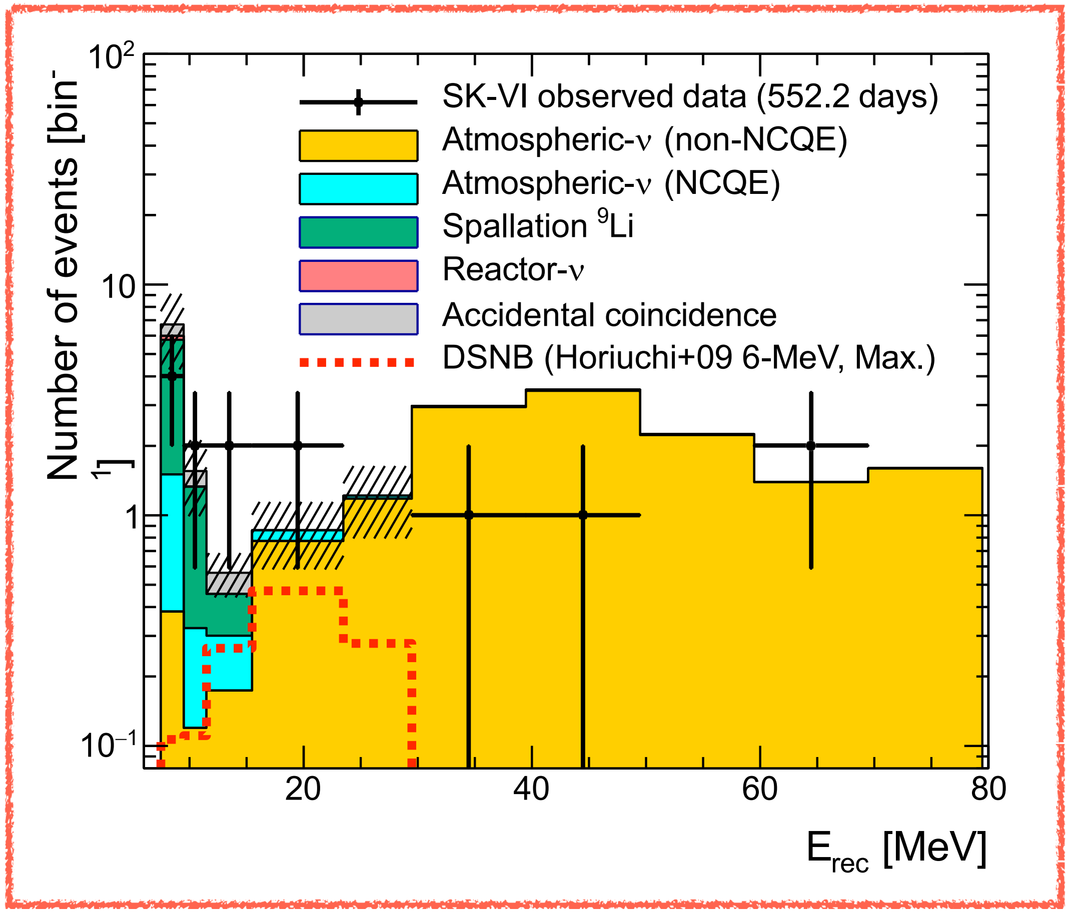


1.3 times improvement of Ntag efficiency!

Updated DSNB search@0.01%Gd

M. Harada





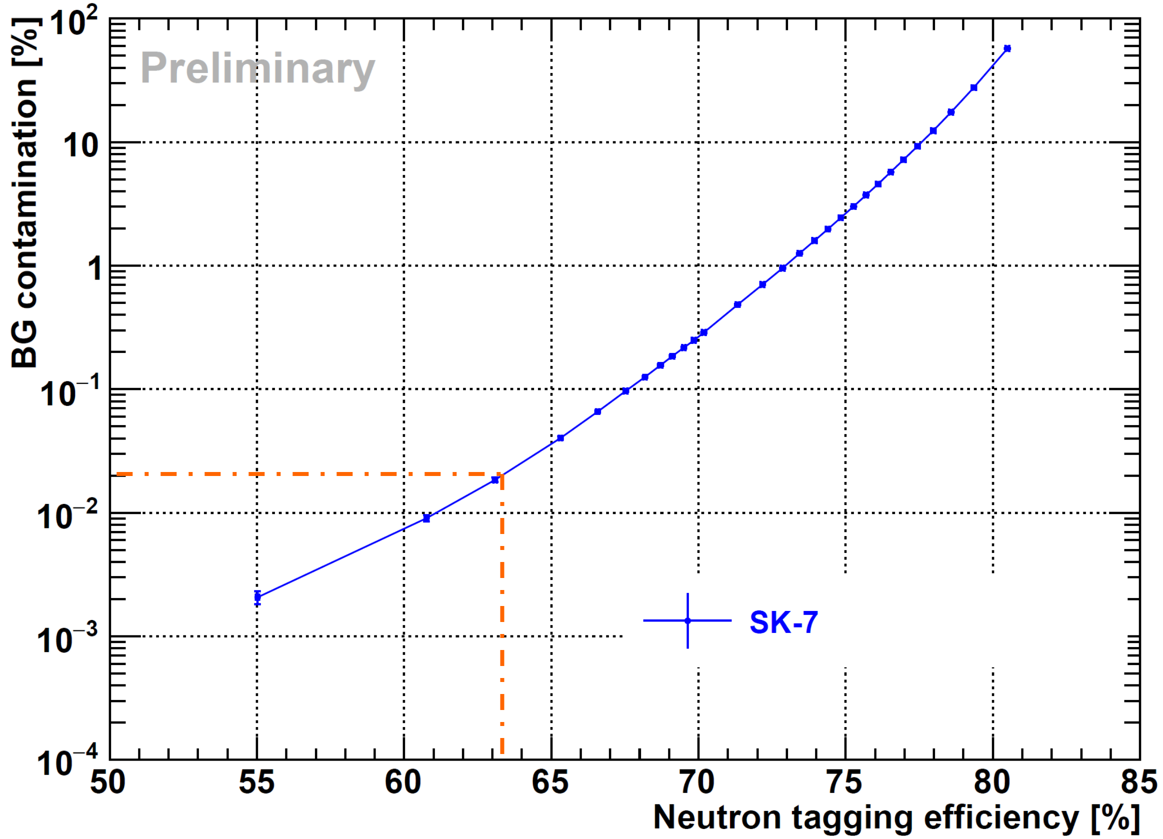
- Significantly improved NCQE reduction
- x1.3 better neutron tagging

Flux limit is coming soon!

DSNB search@0.03%Gd

- NN neutron tagging is ready for DSNB analysis

Y. Kanemura



✓ **63.1±1.1% with 0.02% mis-ID**
→Further 1.4 times improvement expected

- Stay tuned for SK-Gd's DSNB search results!

Summary

- From 2018 to 2024, significant advancements have been made in SK's capability to differentiate between IBD and ES by incorporating Gd.
- The lataset SK-Gd with 0.03% Gd concentration can promptly detect supernova explosions at 10 kpc, providing alerts with an angular resolution as fine as 4 degrees in under 2 minutes.
- Analysis of data obtained with 0.01% Gd concentration has yielded the world's most sensitive search for diffuse supernova neutrino background neutrinos.
- Please stay tuned for the results of the DSNB search at 0.03% Gd concentration.