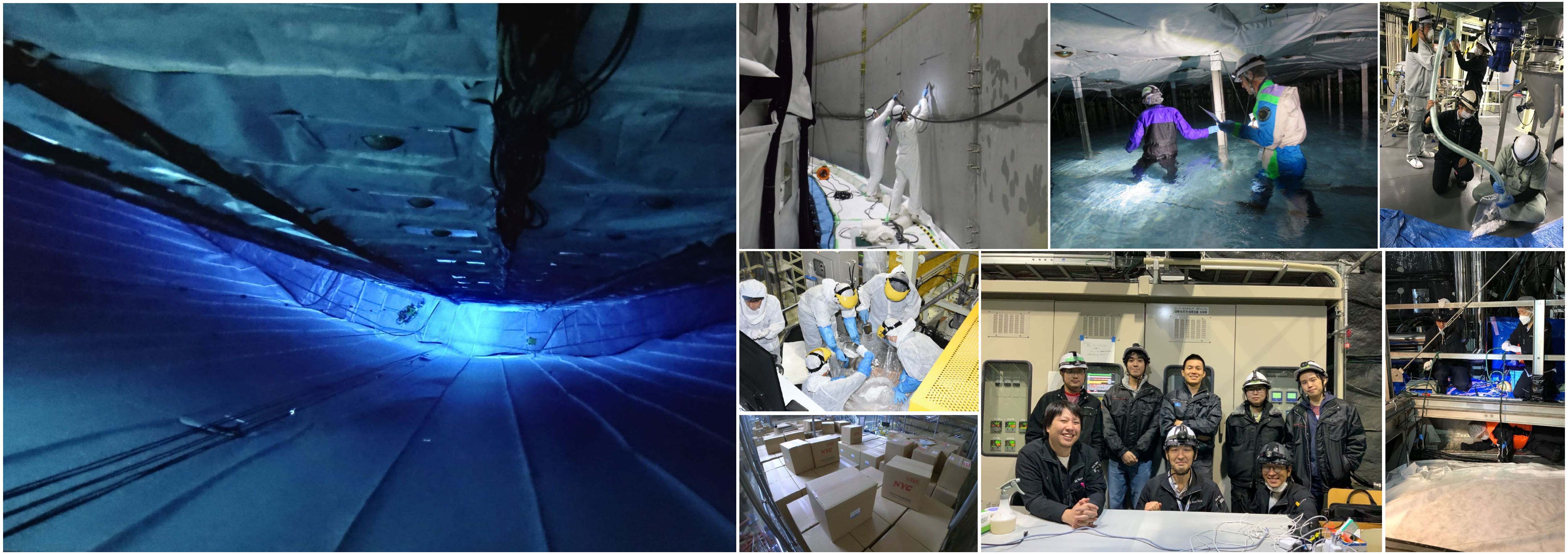


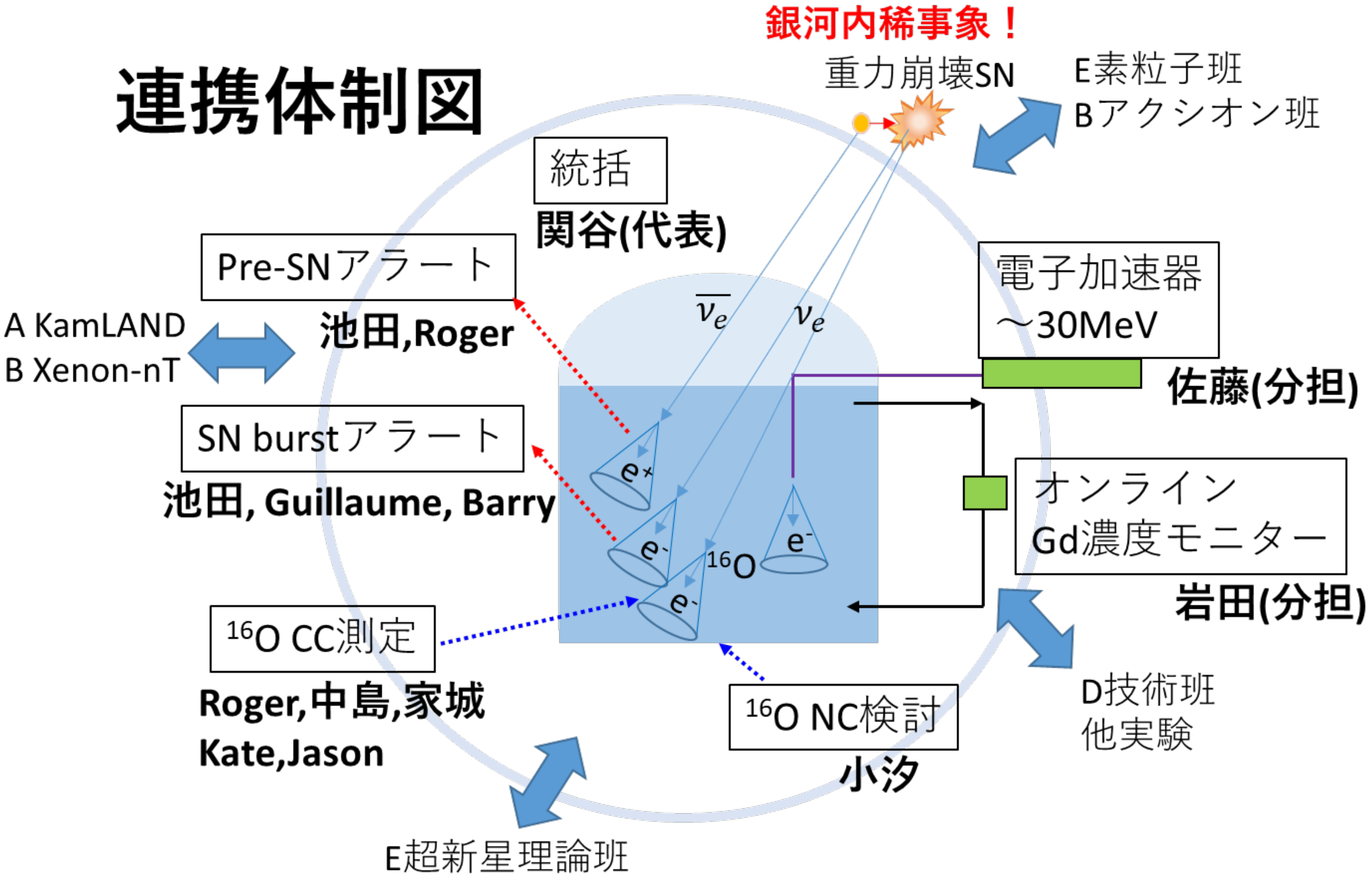
スーパーカミオカンデの万能化と超新星ニュートリノ検出にむけて

東京大学宇宙線研究所　関谷洋之

学術変革「地下稀事象」領域研究会
2024年7月6日　大阪大学

C01 Group in UGRP

- **Frontier of Rare Events in the Universe: Investigating the Origin of Elements in the Universe with the Universal Supernova Neutrino Detector**

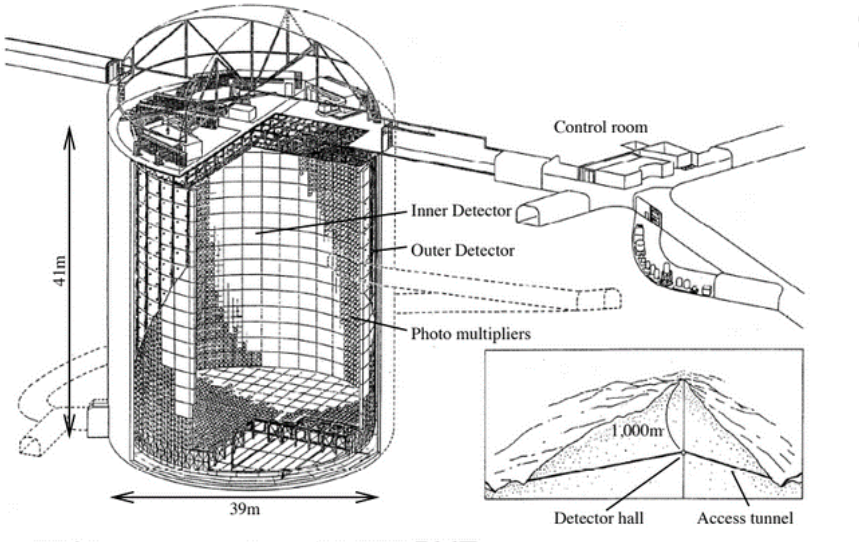


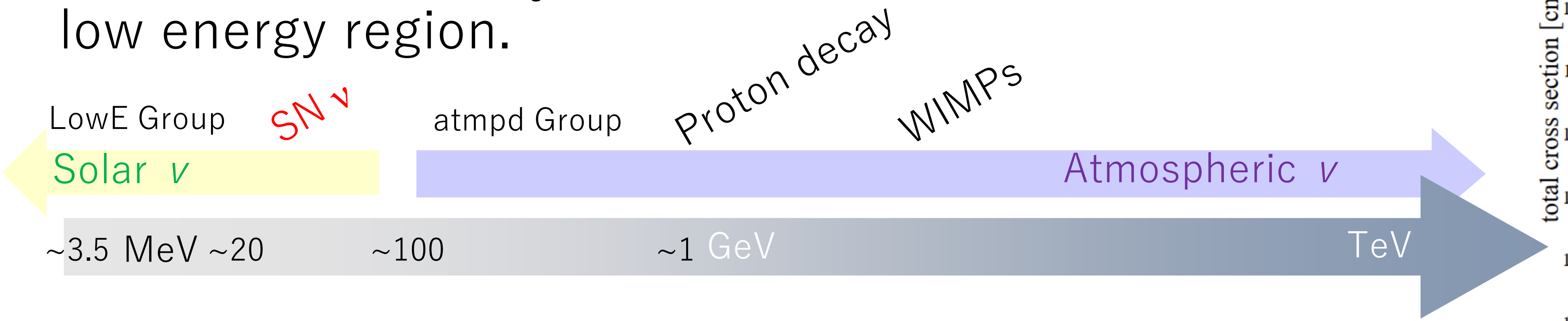
→Suzuki-san's talk in UGAP2024

→Iwata-san's talk

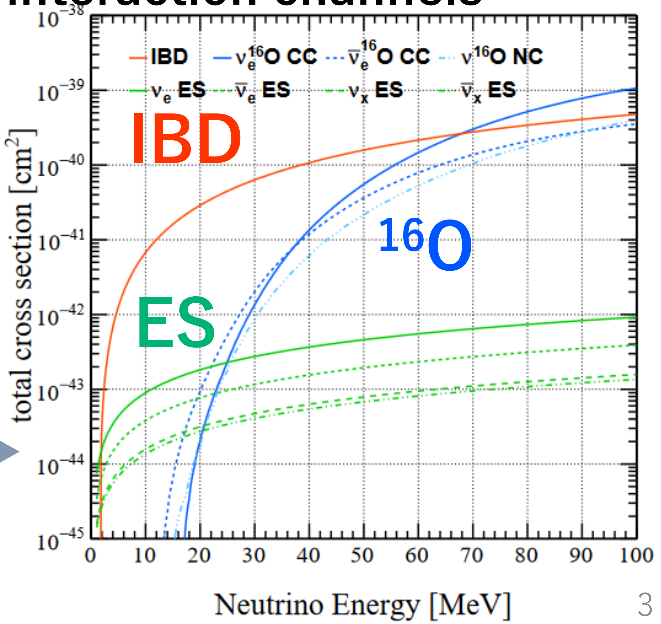
Super-Kamiokande VII (since July 5, 2022)

- **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.



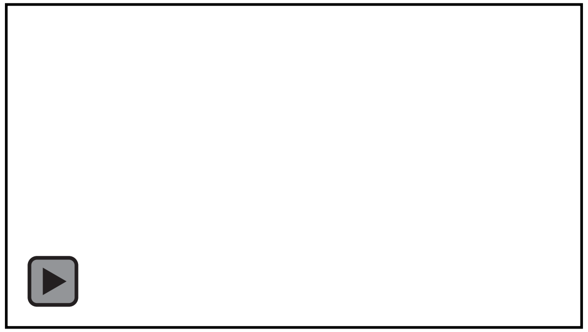


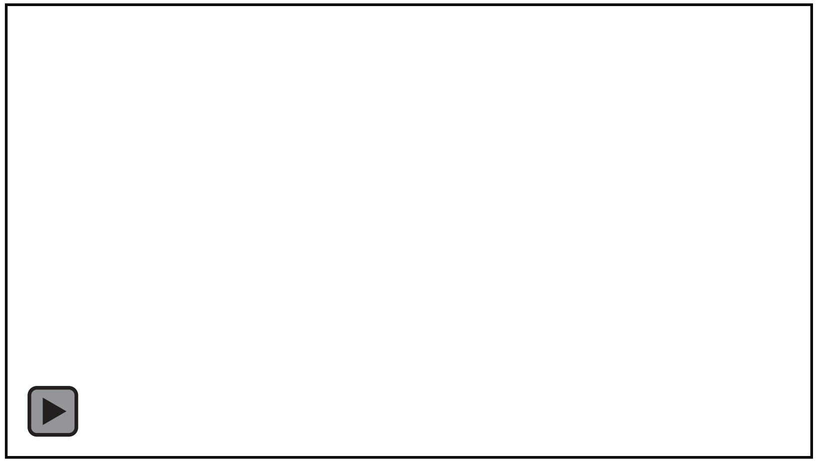
The interaction channels



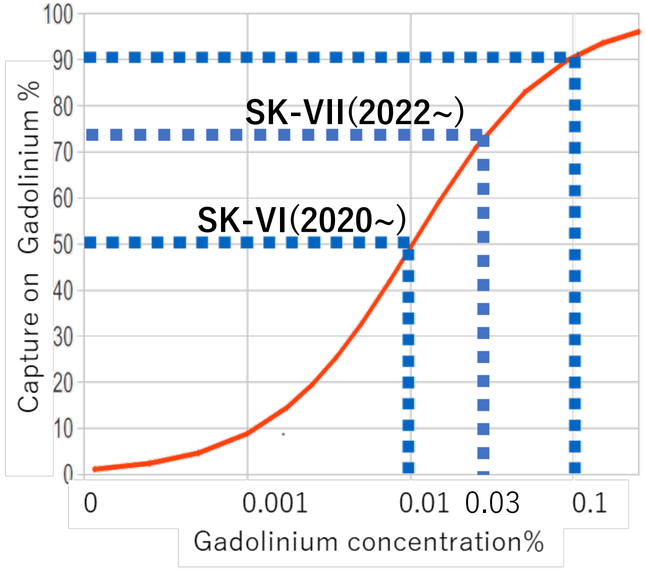
The Gd-loading

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

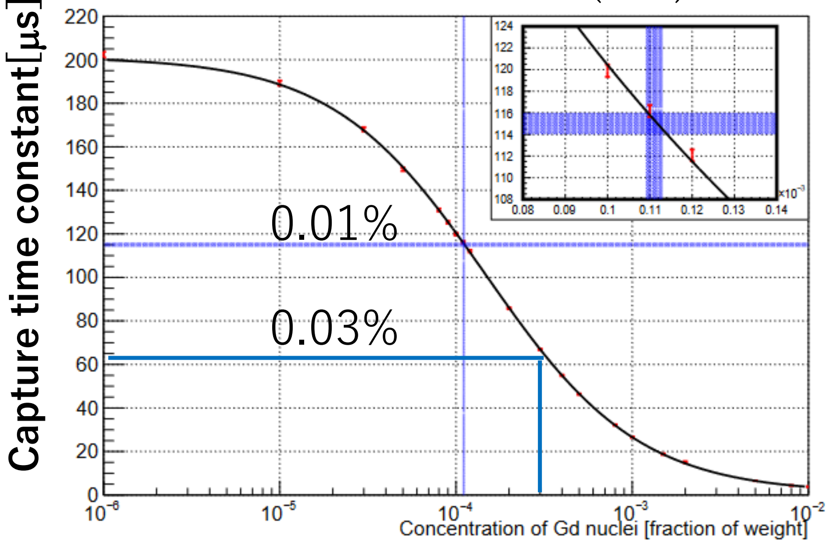


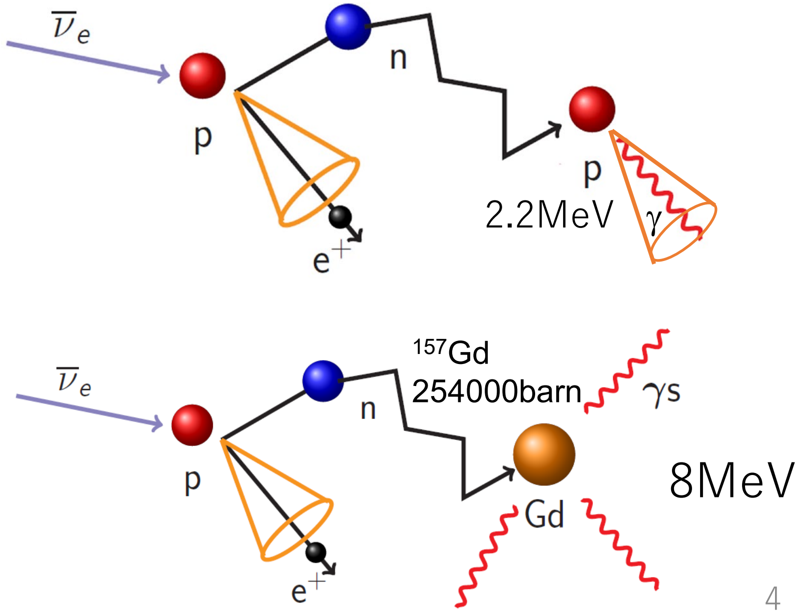


- **Neutron tagging for interaction (especially IBD) identification**
  - Originally only by delayed coincidence with 2.2MeV gamma from p-capture
  - **Gd-loading** significantly enhances its efficiency by Gd(n,γ)



NIM A 1027 (2022) 166248



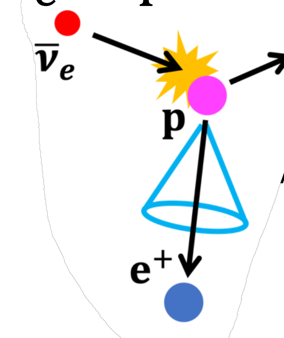


Supernova neutrino in SK

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

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

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

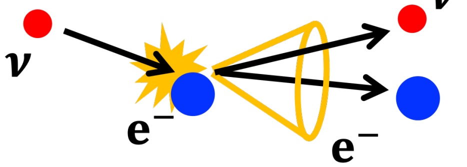


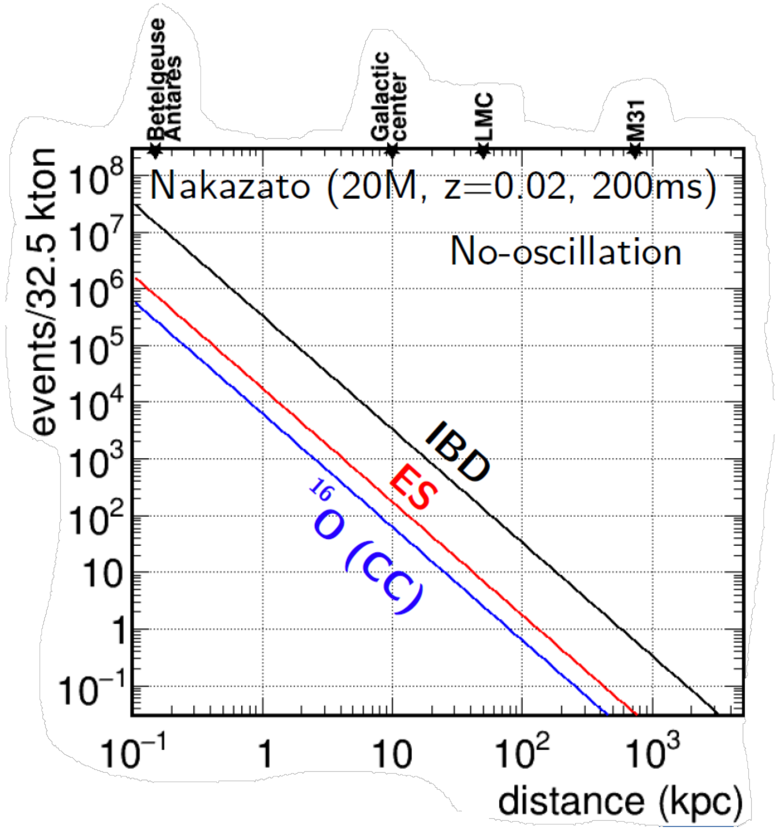
Almost uniform in MeV region

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

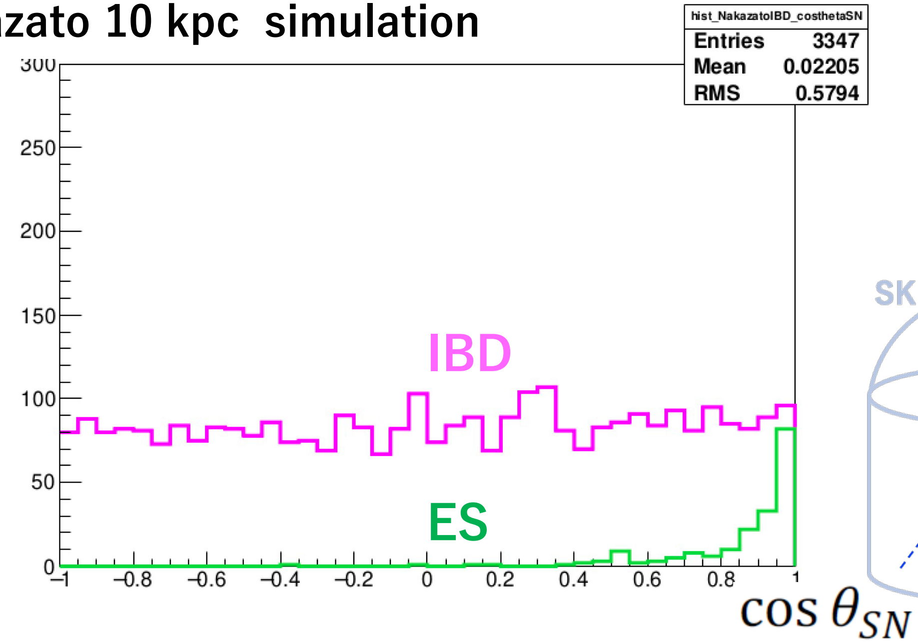
The electron keeps the neutrino direction information.

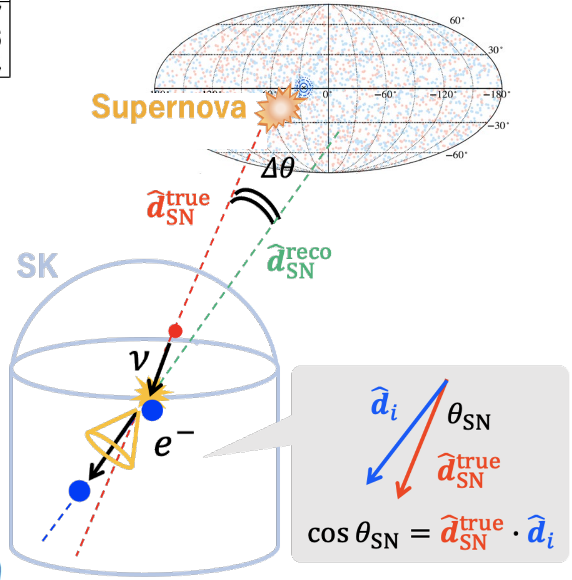
$\nu + e^- \rightarrow \nu + e^-$



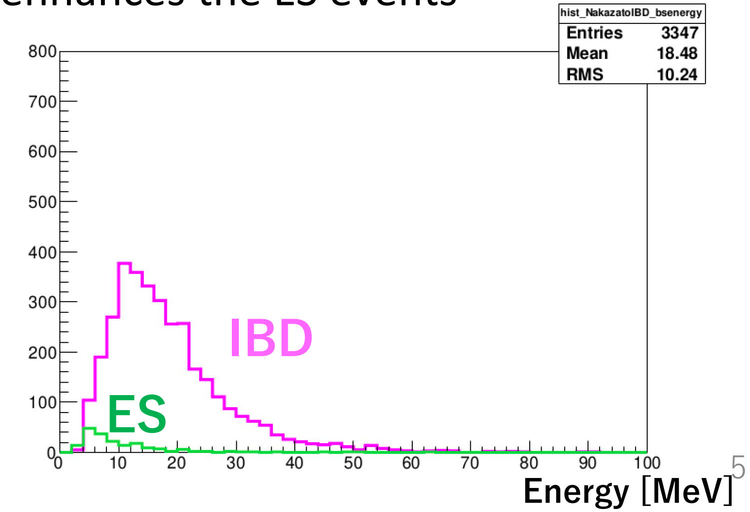


Nakazato 10 kpc simulation



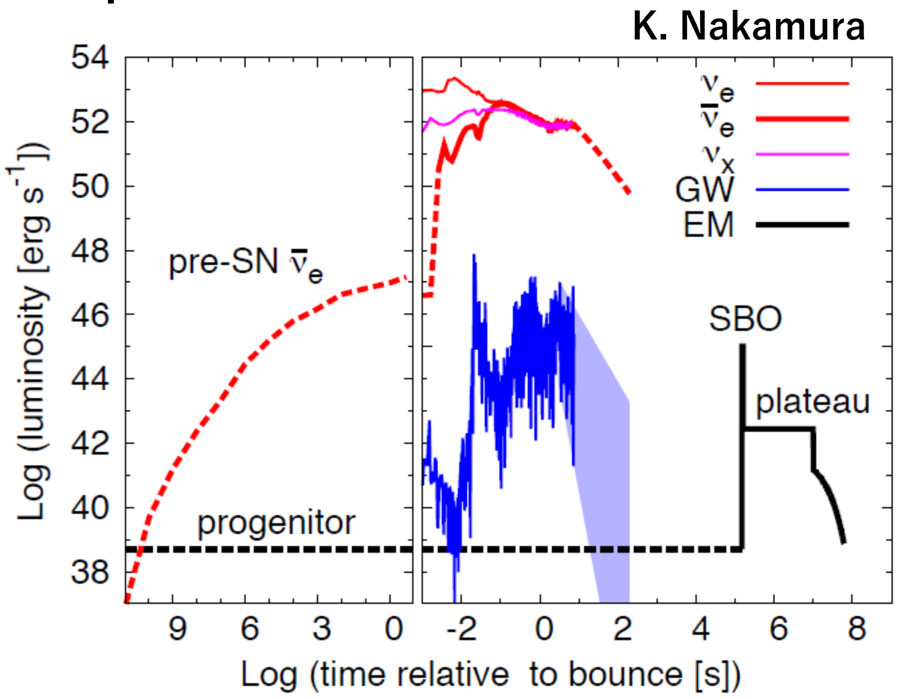


Lowering threshold enhances the ES events



"Universalization of Super-Kamiokande"

Supernova timeline



Make the most of SK for the next Galactic SN!

- $\bar{\nu}_e$ for the **per-SN alarm** and **DSNB search**
- ν_e for the **SN alarm with pointing**
- ν_x for **full information extraction** from SN

Utilize ^{16}O interaction

CC interaction: $\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}$

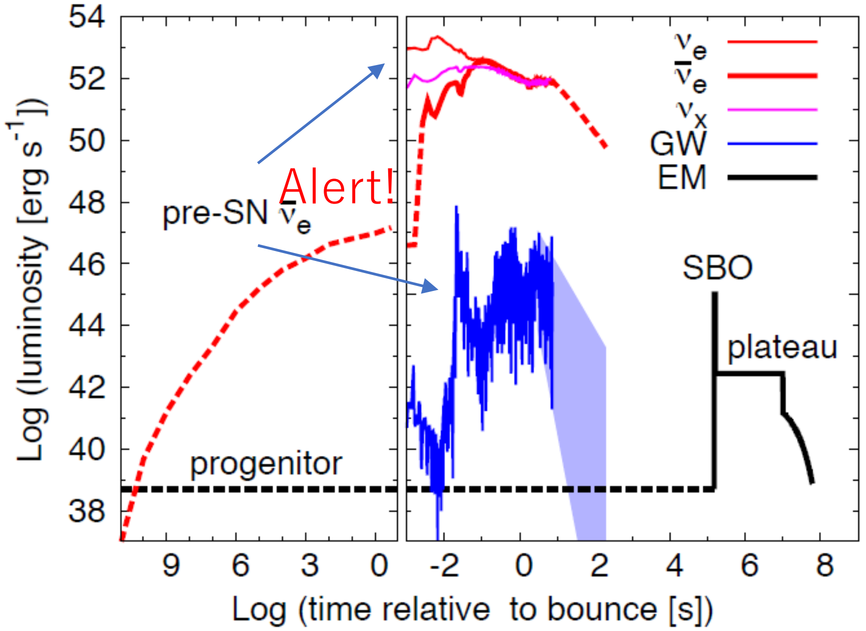
$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N},$

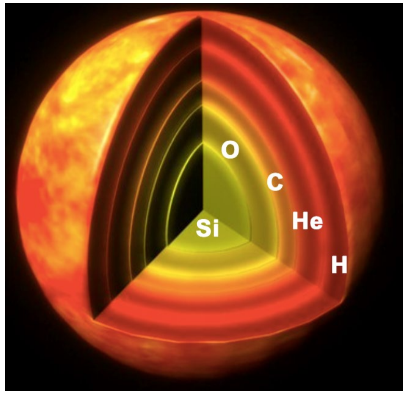
NC interaction: $\nu_x + {}^{16}\mathrm{O} \rightarrow \nu_x + \mathrm{O}^*/\mathrm{N}^*$

${}^{16}\mathrm{O}^* \rightarrow {}^{15}\mathrm{N} + p + \gamma$

${}^{16}\mathrm{O}^* \rightarrow {}^{15}\mathrm{O} + n + \gamma$

Pre-SN alarm for nearby SNe





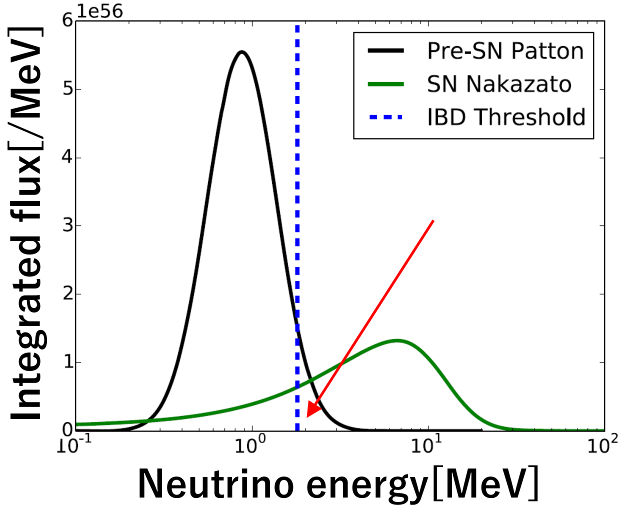
Burning Stage	Duration	Average **ν** energy
C	300 years	0.71 MeV
Ne	140 days	0.99 MeV
O	180 days	1.13 MeV
Si	**2 days**	**1.85 MeV**

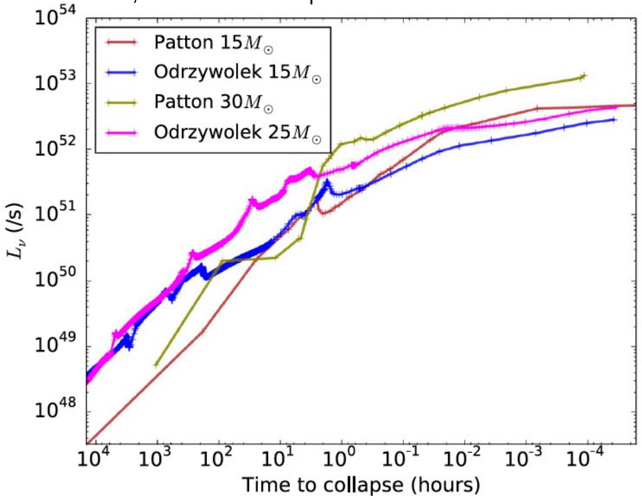
Duration of burning stages and the fraction and average energy of electron neutrinos emitted by **pair-annihilation** for a 20 M⊙ star (**Astropart.Phys. 21 (2004) 303-313**)

- and many Models・・・

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

ApJ 885:133, 2019



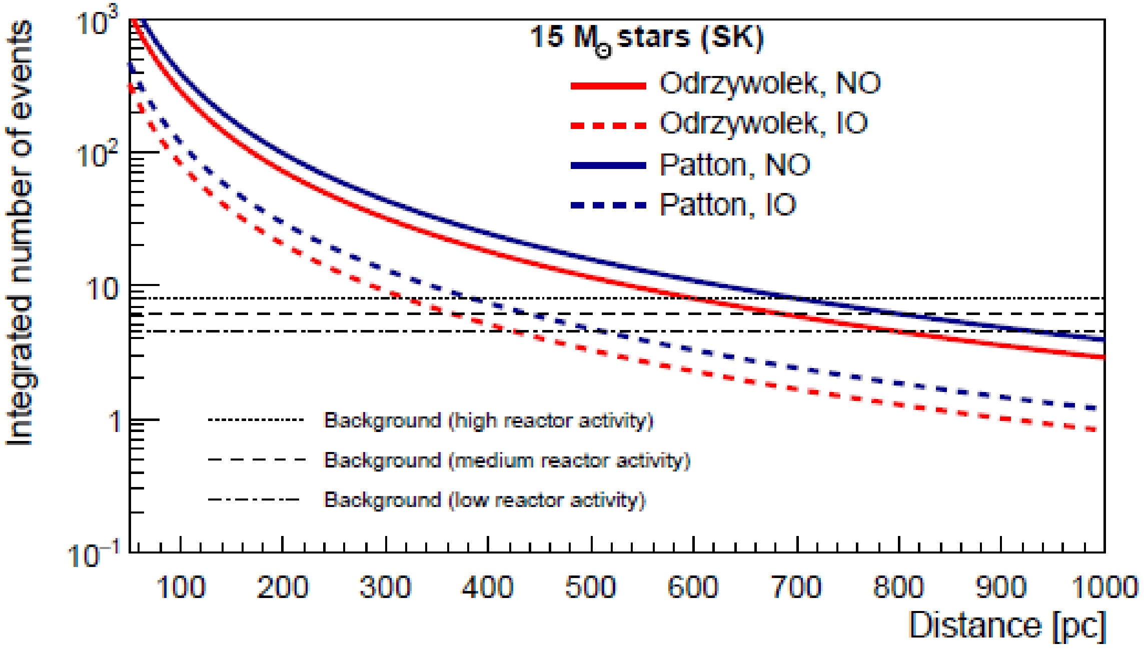


- IBD is the main channel
  - The energy threshold for IBD is 1.8 MeV
- Low-BG low-threshold required

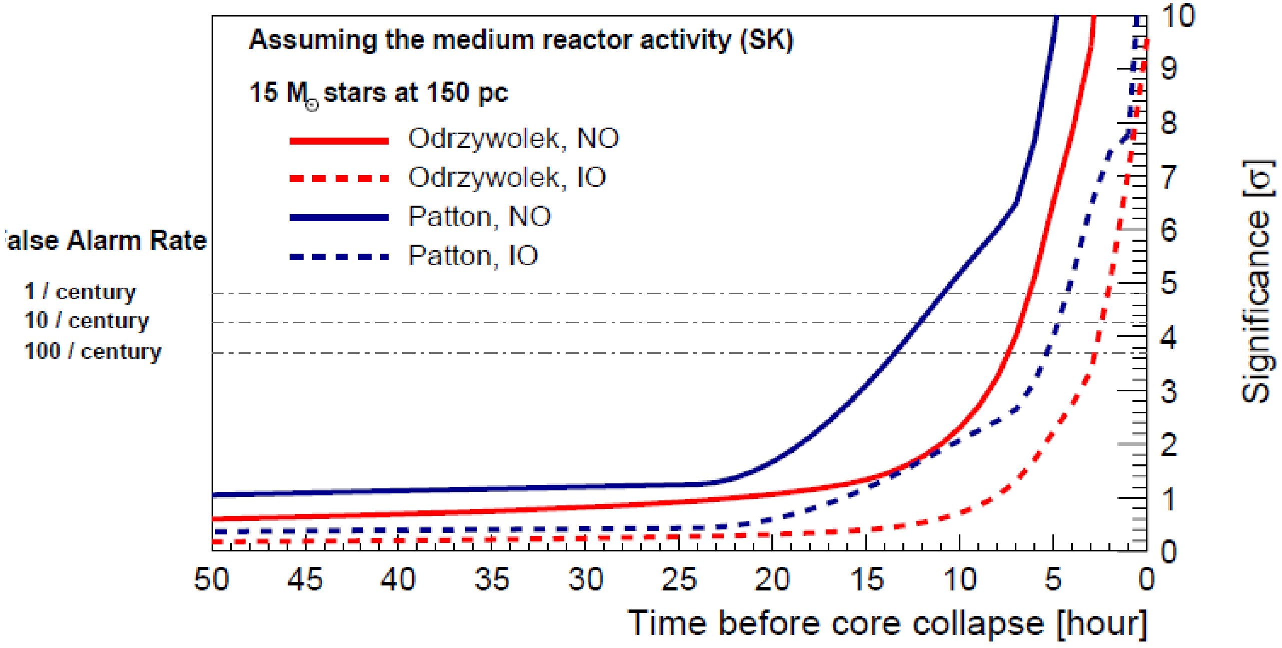
Pre-SN alarm

- During the KamLAND offline period, SK's role is important.
  - SK only GCN_circular?
  - Faster alarm system (like GCN_notice) will be tried.
    - Secure the reliability

Number of events in past 12 hours

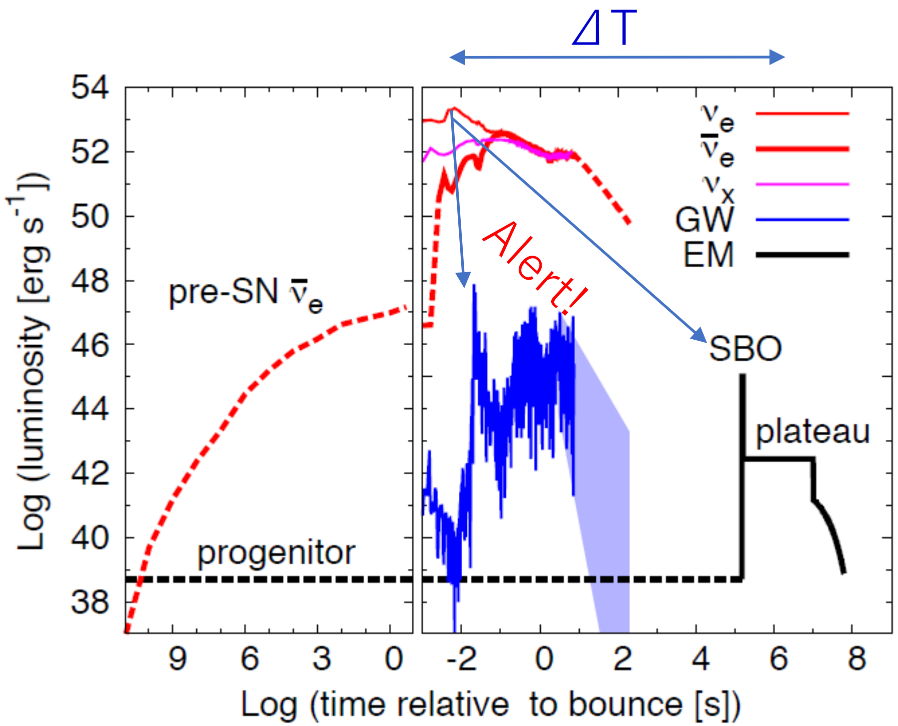


Warning significance for 150pc SN

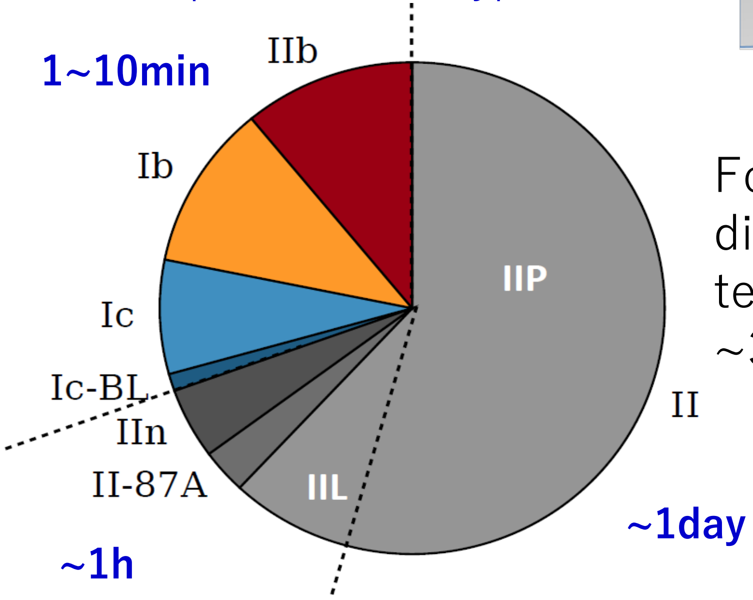


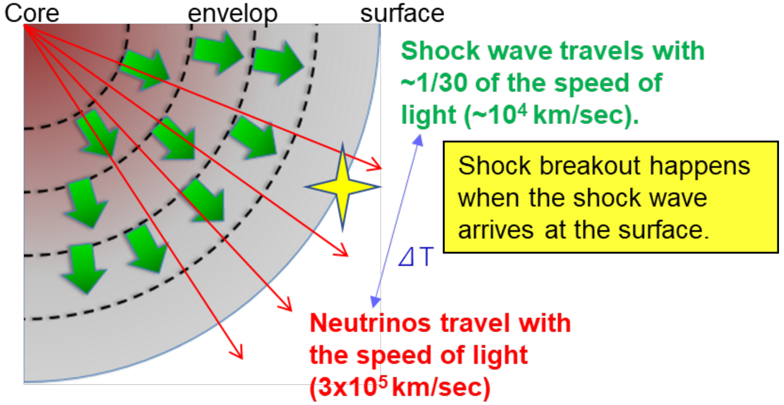
The neutrino burst alarm

The vital role for Super-Kamiokande



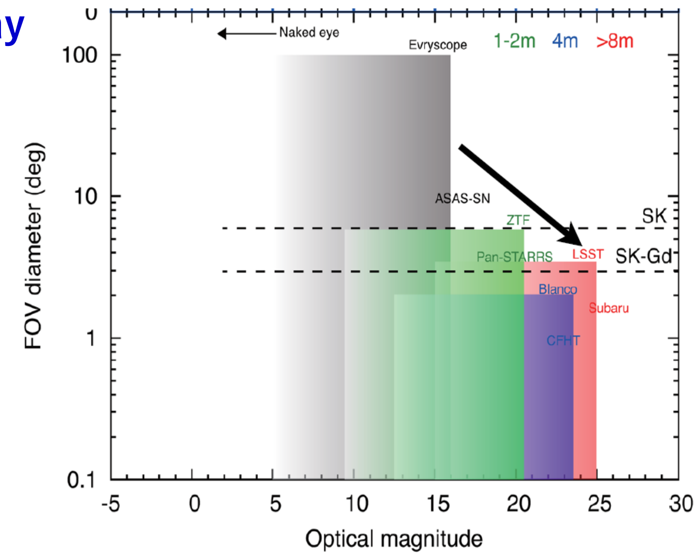
⊿T depends on the type of SN



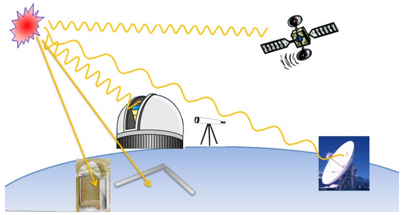


For ~70% of SNe, the time difference is several hours to tens of hours. For the remaining ~30%, that is several minutes.

K. Nakamura MNRAS, 461, 3296 (2016)



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

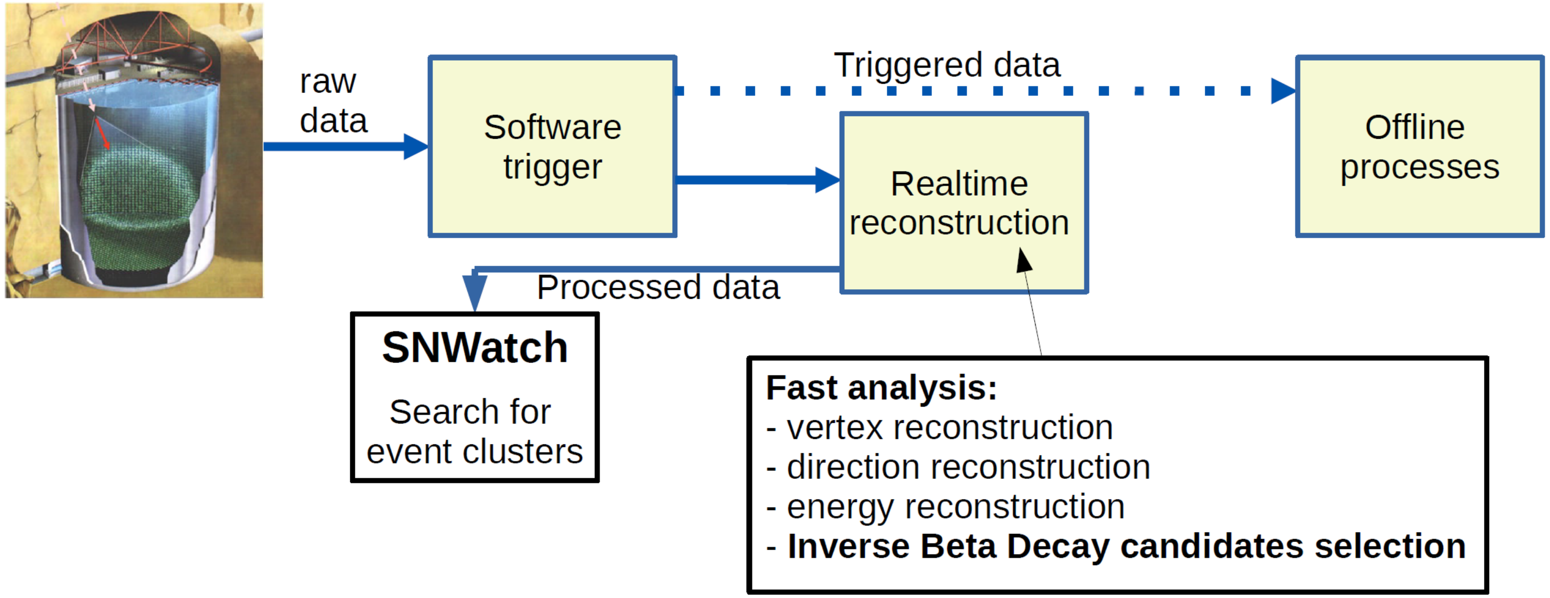


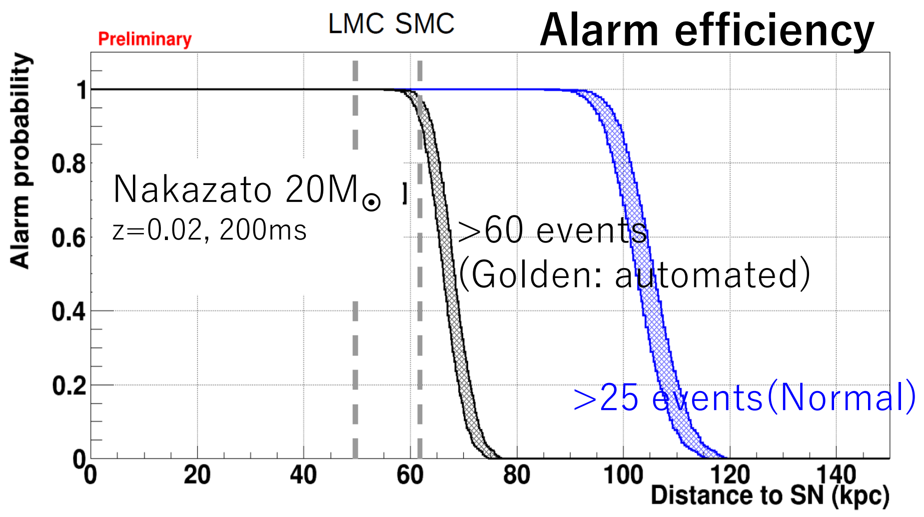
Realtime supernova monitoring of SK

SK's SN monitoring system **"SNWatch."** **arXiv:2403.06760 accepted by ApJ**

- 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.





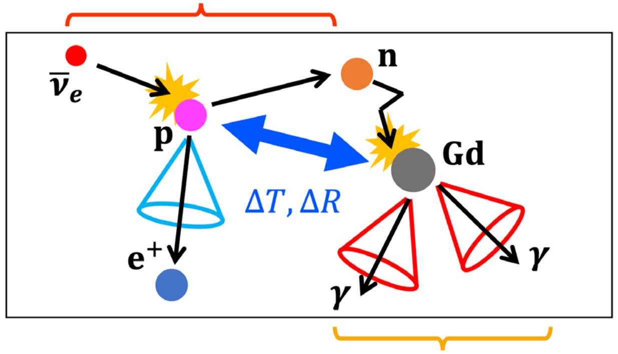
Quick IBD tagging implemented in SNwatch

0.03% Gd makes IBD tagging efficient in SN monitoring

Speed-oriented real-time simple IBD tagging algorithm

Y. Kashiwagi et al.,
Accepted by ApJ, arXiv:2403.06760

prompt candidates



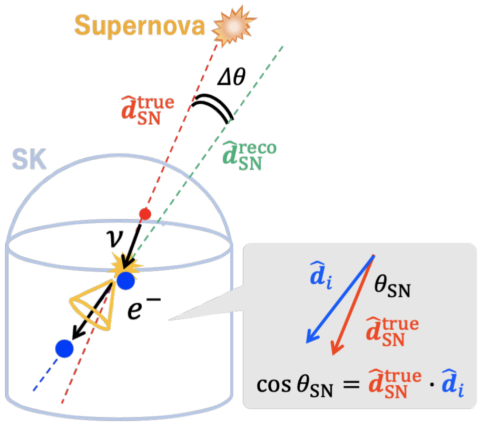
delayed candidates

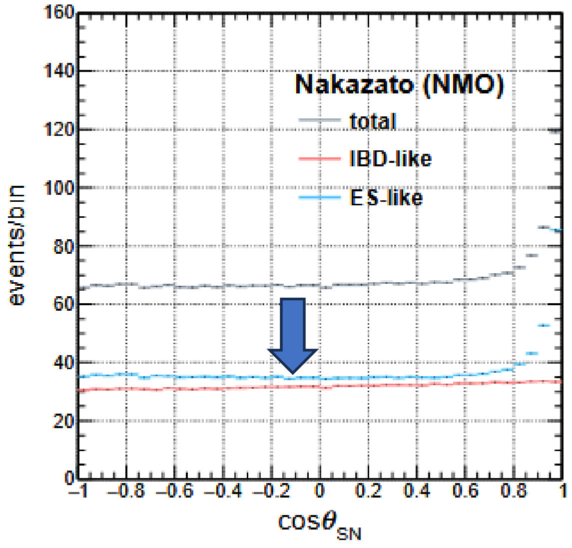
① Selection of prompt candidates ≧7MeV
② Selection of delayed candidates
③ Neutron tagging pair of events with

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

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

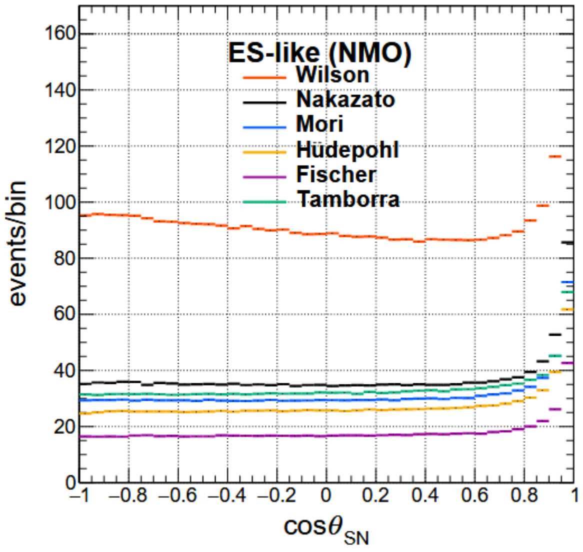
10kpc
Nakazato 20M$_\odot$
z=0.02, 200ms
NMO



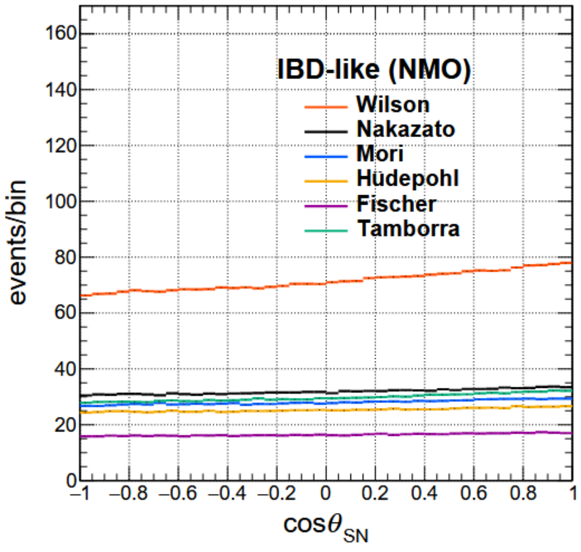


10kpc Other models

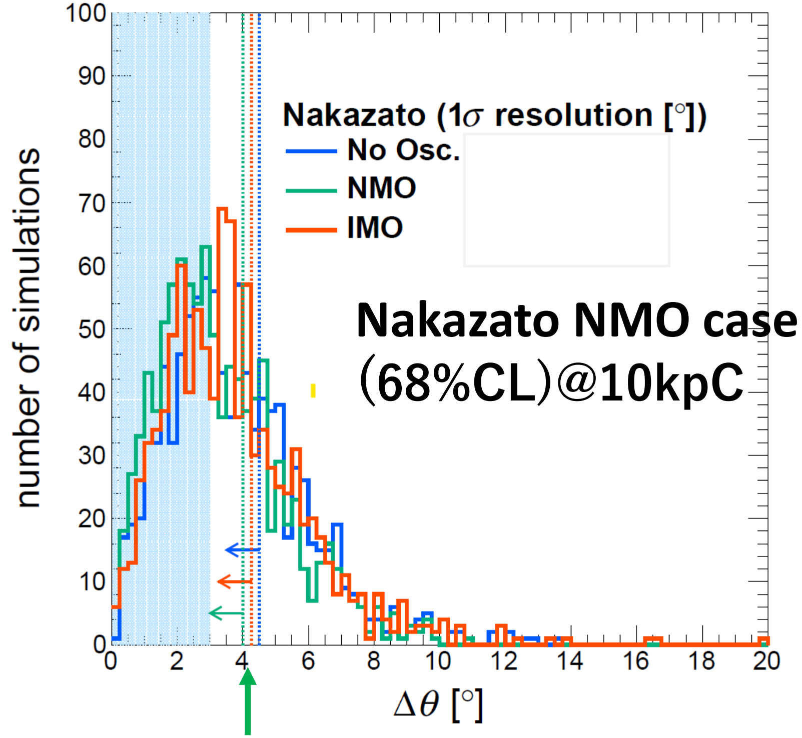
ES-like



IBD-like



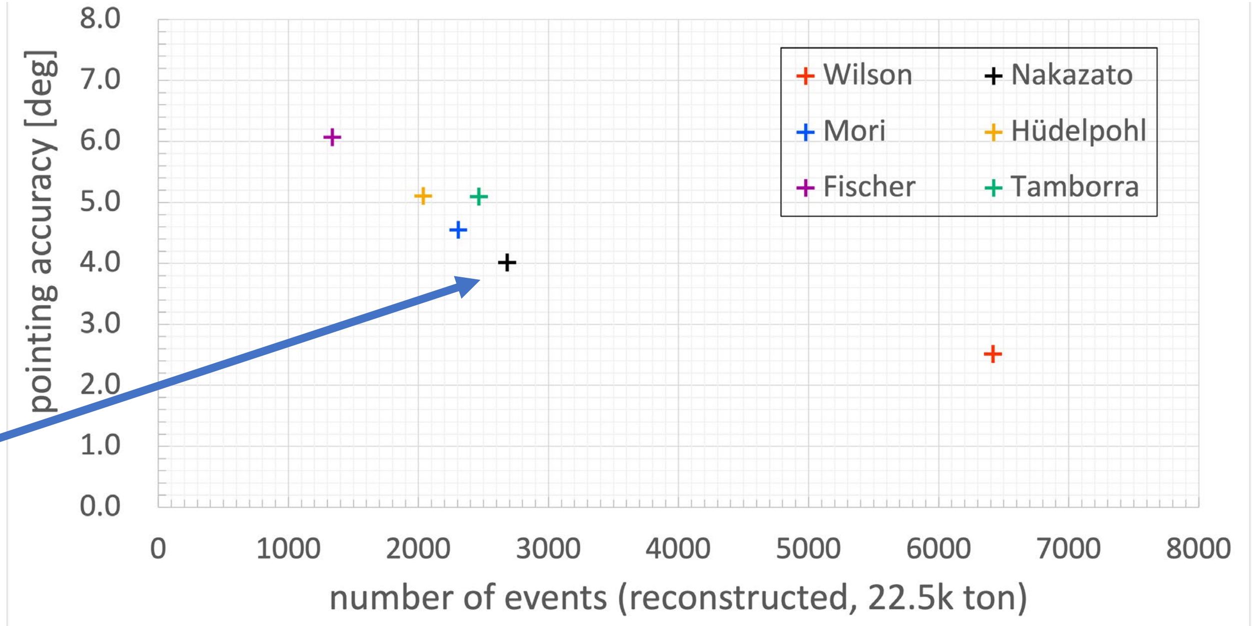
Pointing Accuracy for 10kpc SN



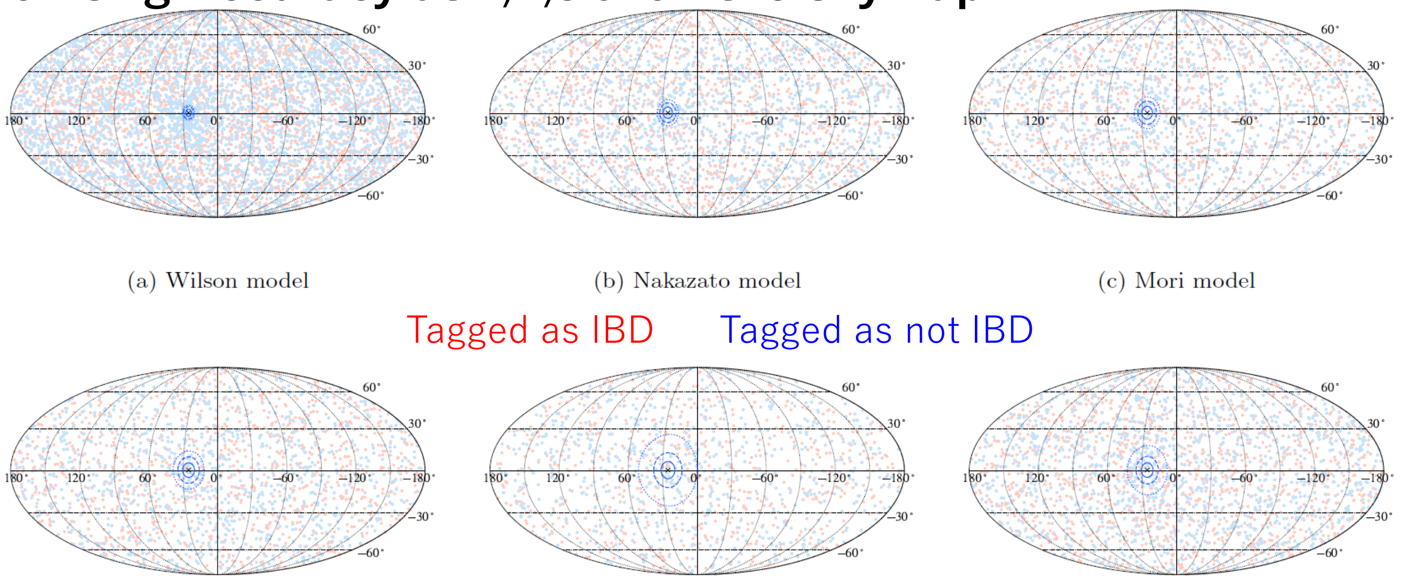
Nakazato NMO case ~4.0° (68%CL)@10kpC

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

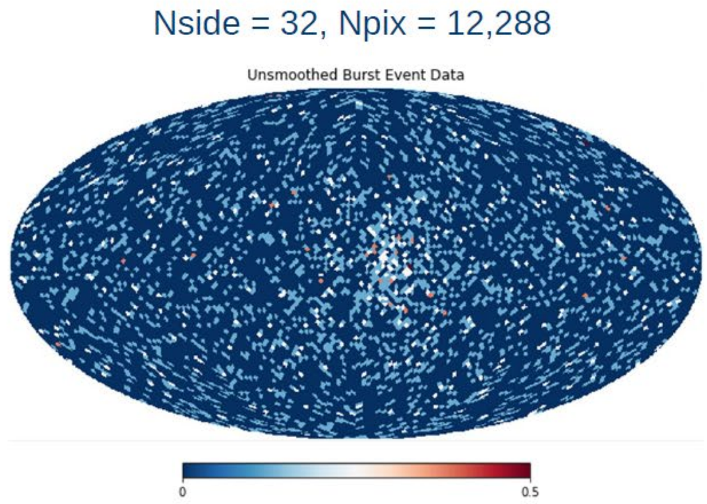


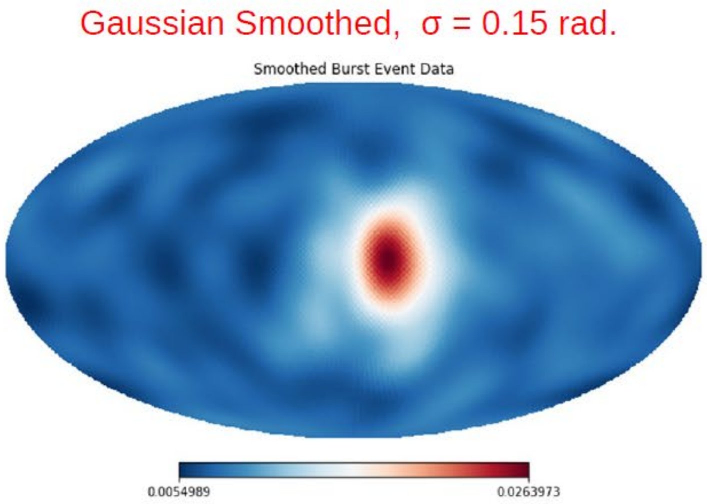
(a) Wilson model (b) Nakazato model (c) Mori model

(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

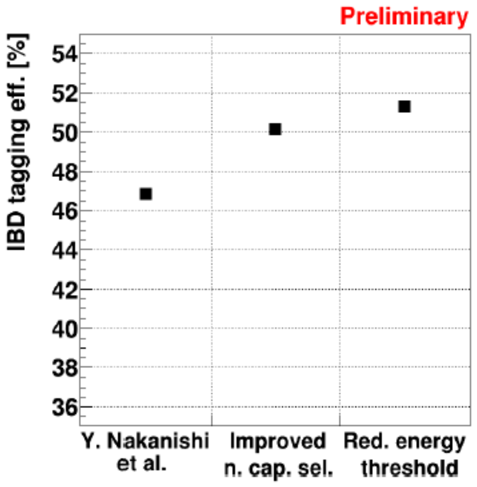


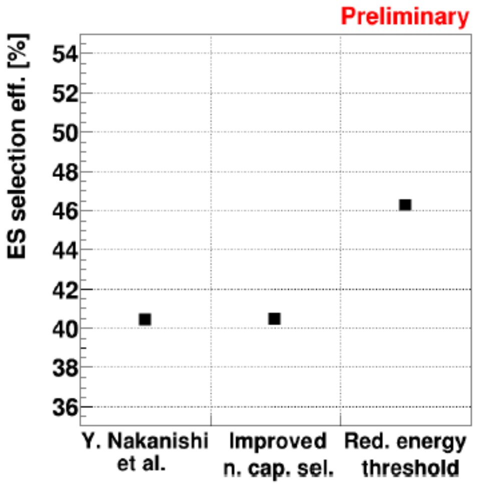


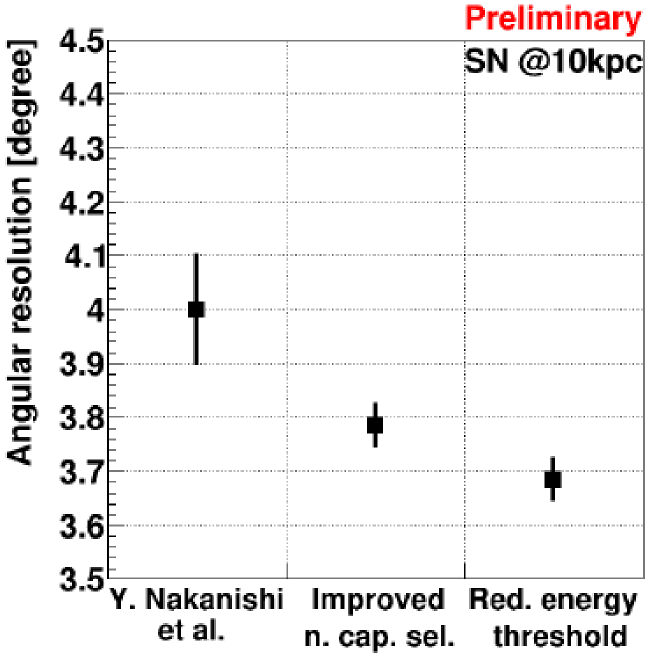
Expected further improvements

- The IBD tagging algorithm
  - Better selection of prompt/delayed events allows a better neutron capture event selection.

  → reduction of the neutron capture event contamination in the selection.
- Reduction of the analysis energy threshold
  - To improve the selection of ES events.





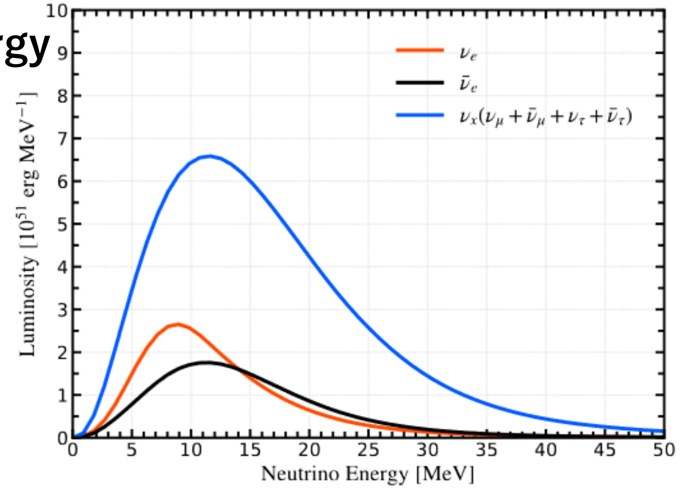


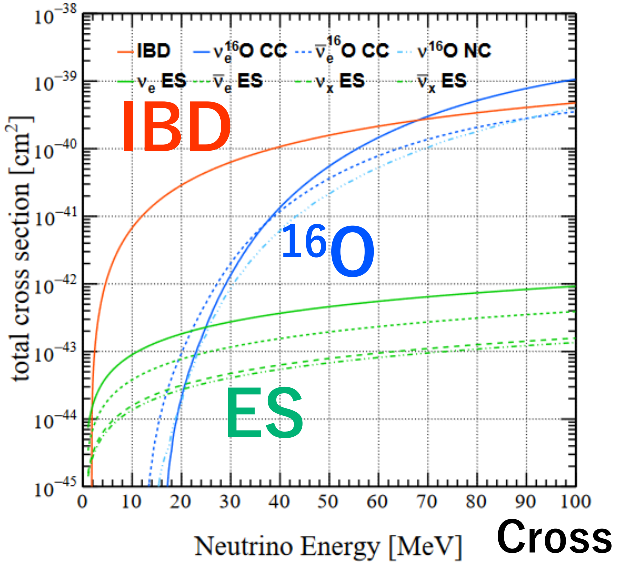
To be implemented in SNWatch

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

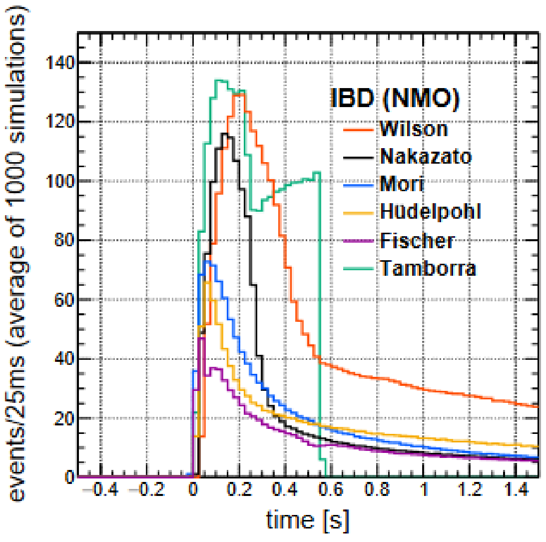
Expected number of interactions in SK for 10kpc SN

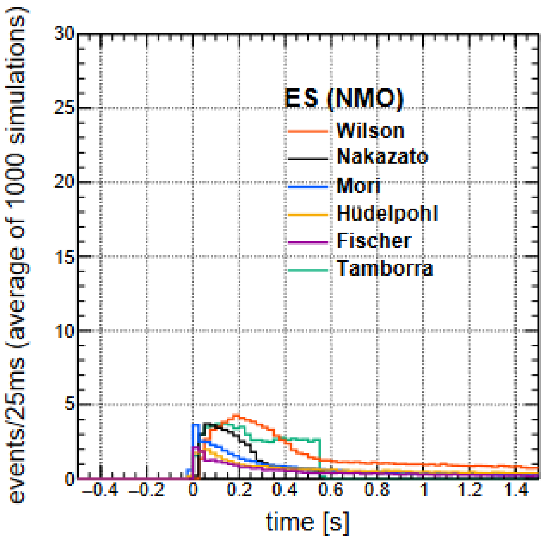
Generated by SKSNSim	Wilson No Osc.	Wilson NMO	Wilson IMO	Nakazato No Osc.	Nakazato NMO	Nakazato IMO	Mori No Osc.	Mori NMO	Mori IMO
IBD ($\bar{\nu}_e$)	7431	8207	9970	3542	3893	4693	3275	3422	3745
ES (ν_e)	223	231	229	173	172	171	177	148	156
ES ($\bar{\nu}_e$)	97	97	98	63	66	72	60	61	63
ES (ν_x)	80	79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

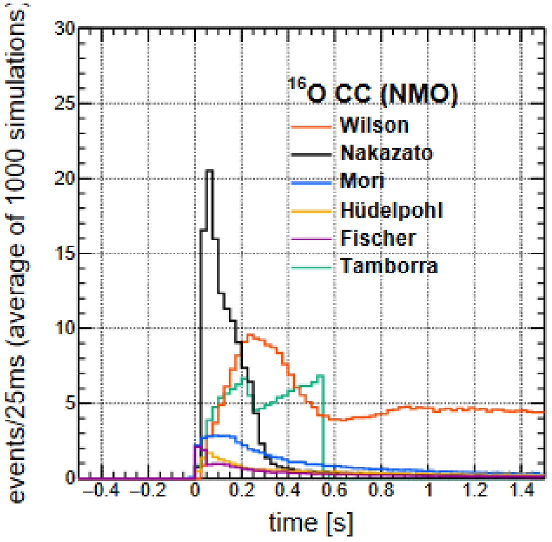
Generated by SKSNSim	Hüdelpohl No Osc.	Hüdelpohl NMO	Hüdelpohl IMO	Fischer No Osc.	Fischer NMO	Fischer IMO	Tamborra No Osc.	Tamborra NMO	Tamborra IMO
IBD ($\bar{\nu}_e$)	3048	3052	3049	1884	1990	2242	3830	3487	2718
ES (ν_e)	146	124	132	90	87	88	135	82	99
ES ($\bar{\nu}_e$)	53	53	53	35	35	37	50	45	35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

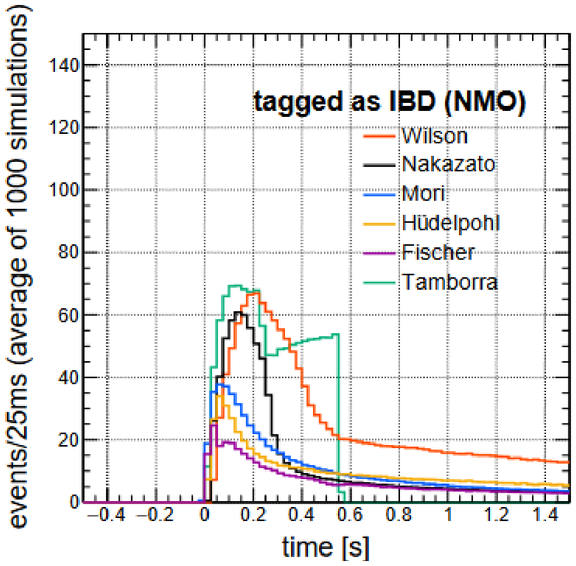




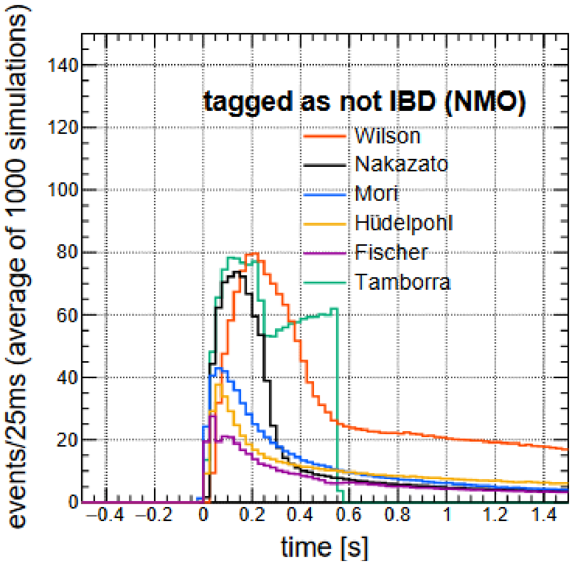


What currently can be extracted from SK (online analysis)

IBD-like



ES-like



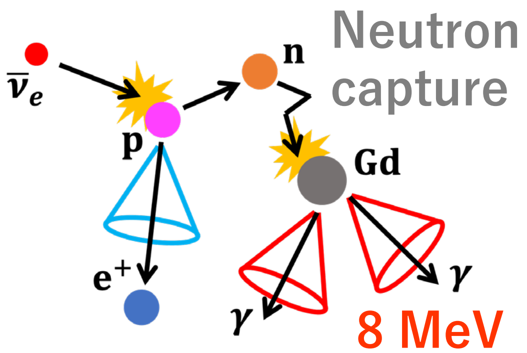
ES contaminated with IBD+^{16}O

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.

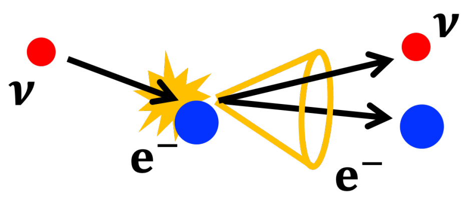
Inverse Beta Decay (IBD)

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



Elastic Scattering (ES)

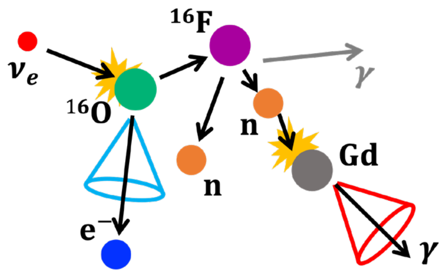
$$\nu + e^- \rightarrow \nu + e^-$$



^{16}O interactions

$$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}$$

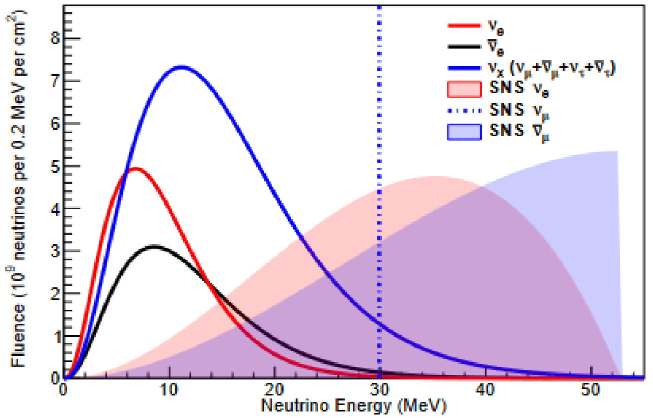
$$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N},$$



Neutrino interaction measurement at ORNL SNS

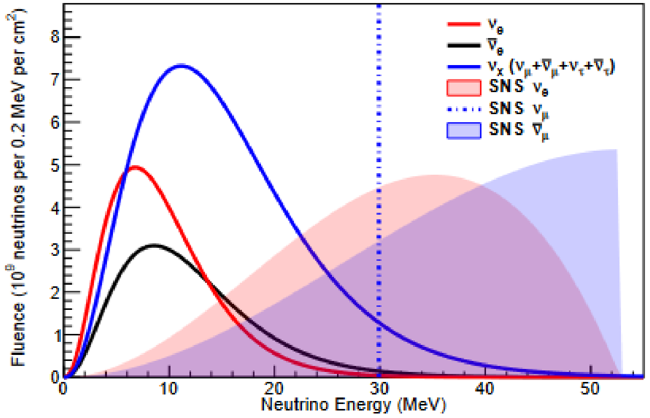
- ORNL SNS is an ideal place to measure these interactions!
- High intensity neutrino available that matches supernova neutrino energy range
- Ongoing D2O detector measurement for precise flux normalization

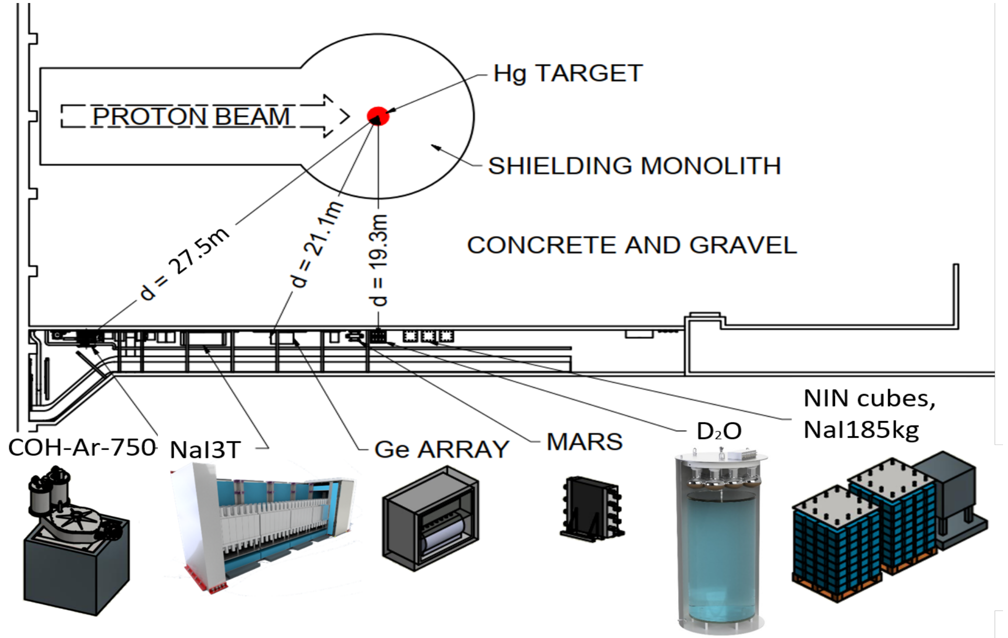
ORNL SNS neutrino spectra



COHERENT

- The COHERENT collaboration measures CEvNS (Coherent Elastic Neutrino-Nucleus Scattering) using the high-quality pion-decay-at-rest neutrino source at the Spallation Neutron Source in Oak Ridge
- Interaction with people working on the same interest but with different detector techniques

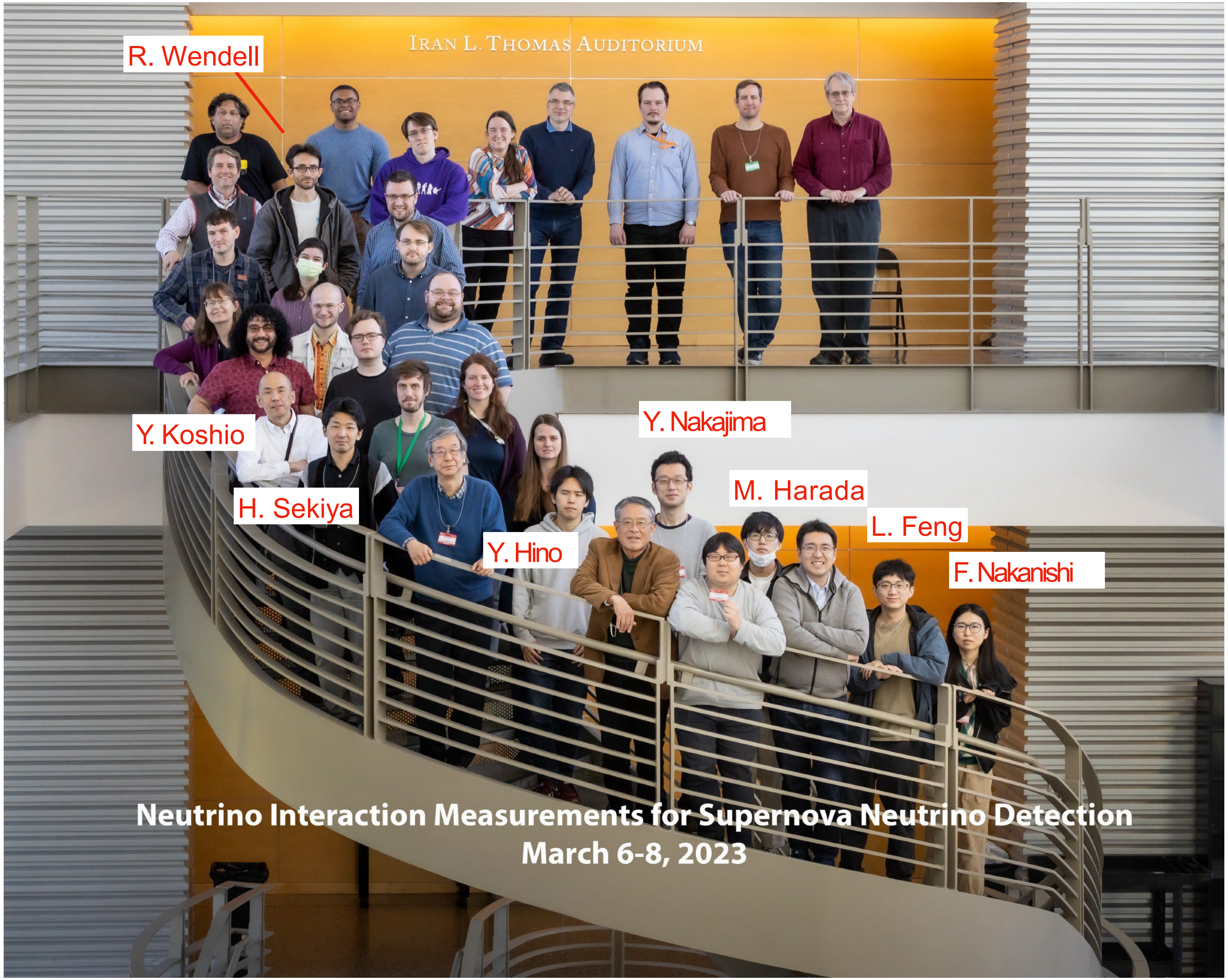




Japan group members

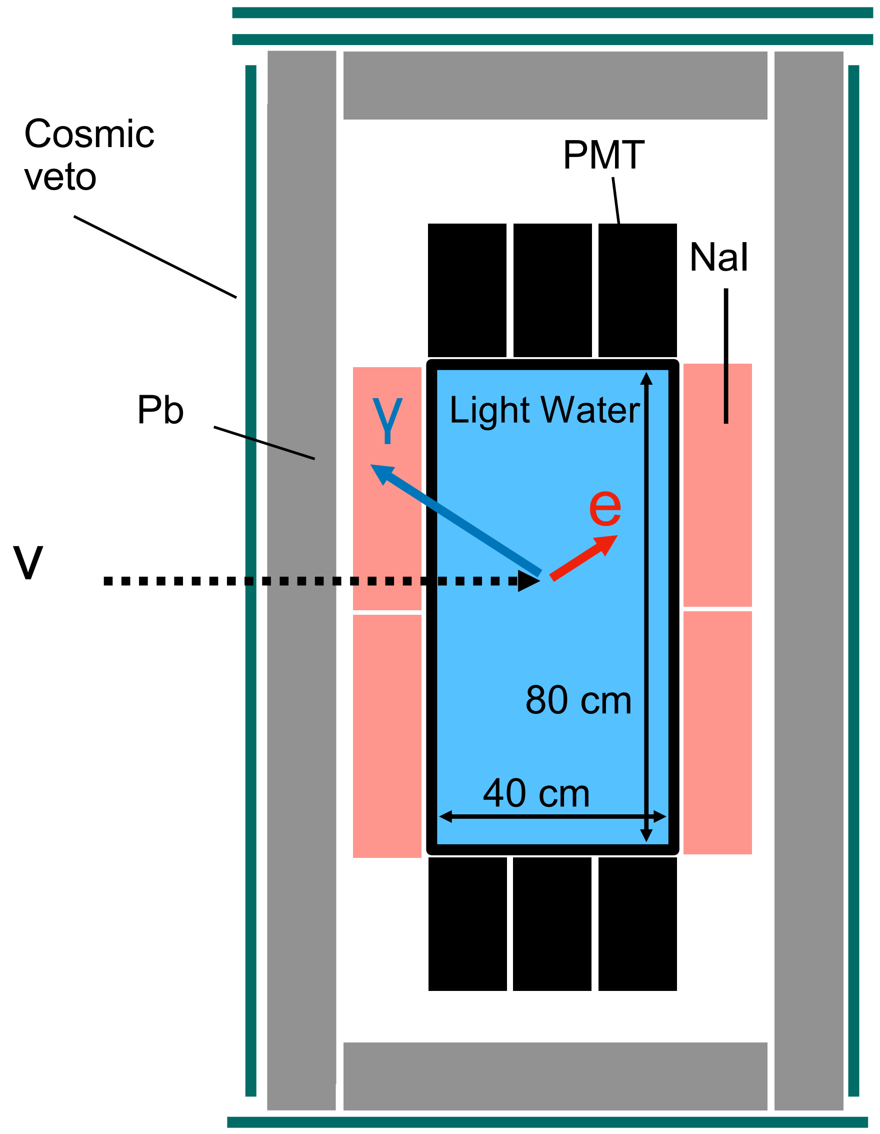
- **ICRR, University of Tokyo** Hiroyuki Sekiya (PI), Masayuki Harada (Postdoc)
- **Kyoto University** Roger Wendell (PI), LiCheng Feng (Student)
- **Okayama University** Yusuke Koshio (PI), Yota Hino (Postdoc), Fumi Nakanishi (Student)
- **University of Tokyo** Yasuhiro Nakajima (PI)

+ potential graduate students (?)

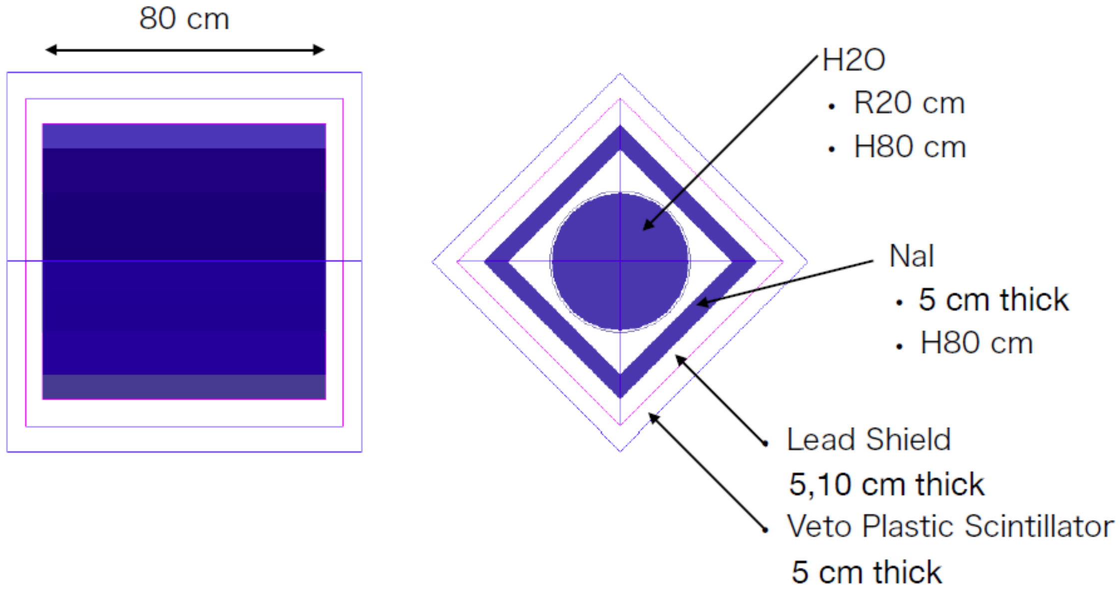


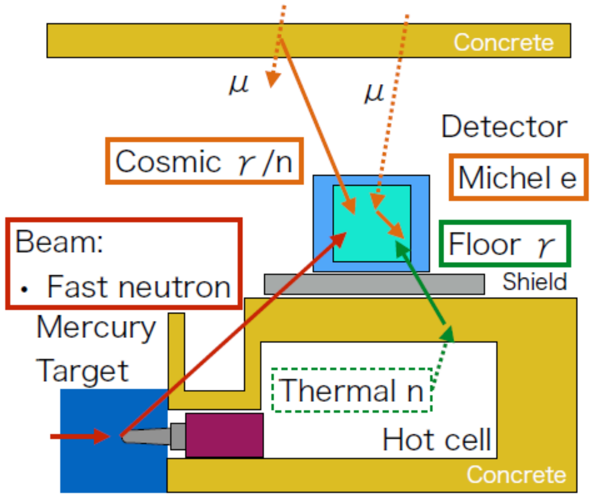
100L detector

- Study backgrounds for ν_e-O interactions
  - Most problematic backgrounds thought to be cosmic-induced photons
  - Small detector allows to place lead shield thicker than the current D_2O detector
  - NaI counters to detect both cosmic-and neutrino-induced photons
  - Movable for study background at several places
- Make initial measurement of ν_e-O CC interaction:
  $\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + \mathrm{F}^*$



100L detector simulation



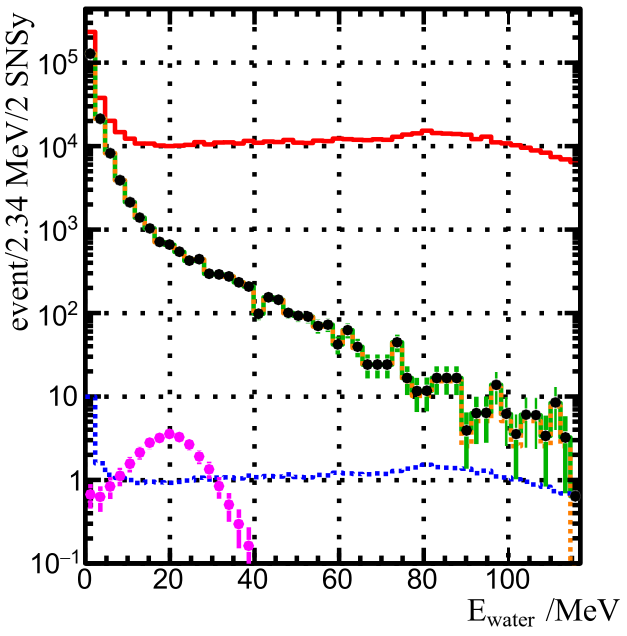


- A quick MC simulation to check signal and backgrounds with the 100L detector geometry
  - Also simulate interaction with cosmic muon and concrete ceiling (geometry based on J- PARC MLF)
- Signal rate scaled from the D_2O detector expectation
  - 390 ν_e-O CC interactions / 2 SNS-year @1.4 MW
- Cosmic background rejection due to duty factor (6×10^{-4}) and veto efficiency (1×10^{-4}) assumed

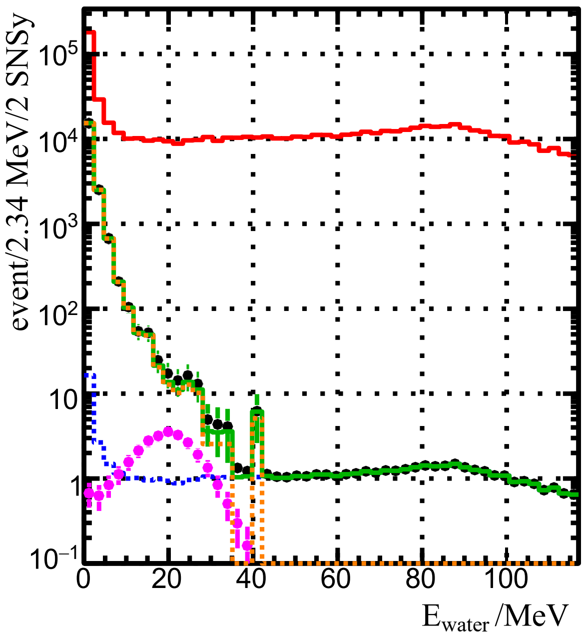
Expected signal

Y.Hino (Okayama)

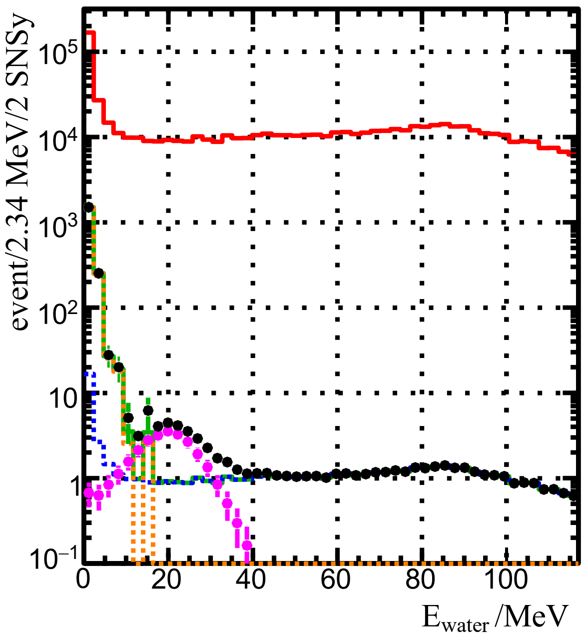
No lead shield



5 cm lead shield



10 cm lead shield



Events in 10 - 30 MeV / 2 SNS years

Total BG (Lead 0 cm)	7896
Total BG (Lead 5 cm)	282.7
Total BG (Lead 10 cm)	14.4
ν_e-O CC	34.5

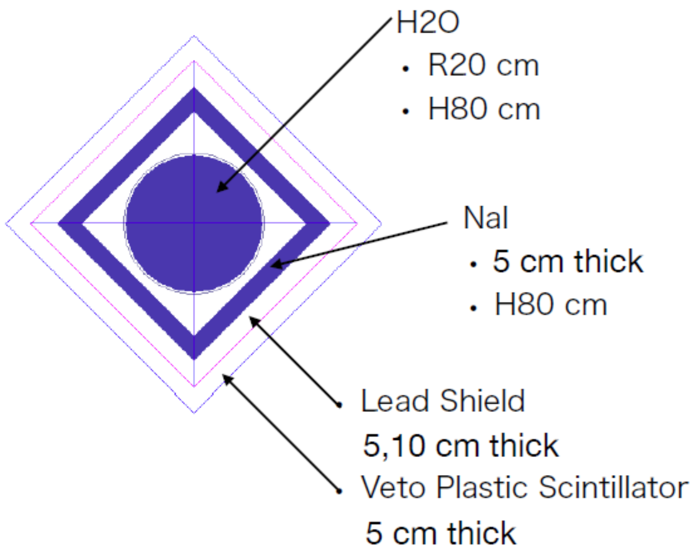
- **Could detect a few tens of events with two SNS-years of data taking!**

Gamma detection by NaIs

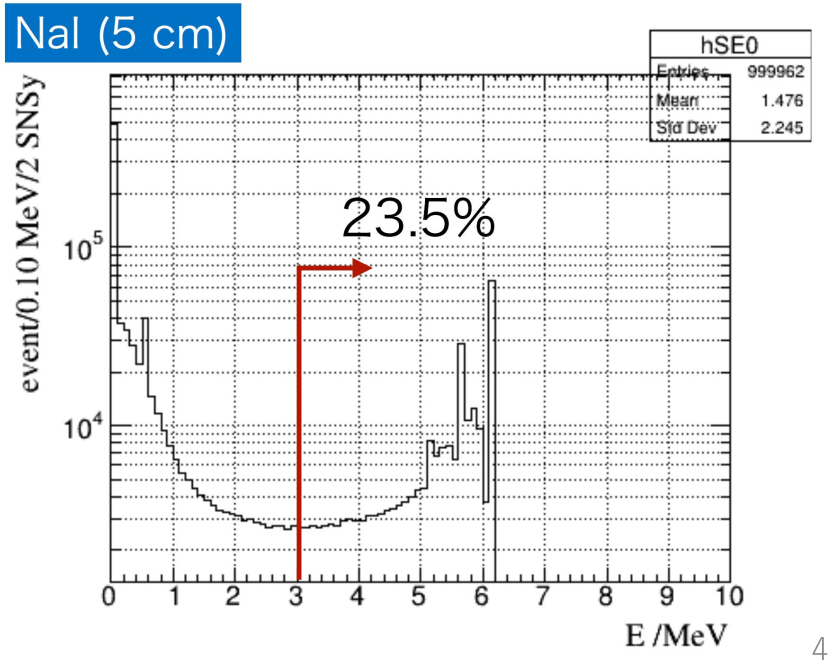
- We would also like to try to detect de-excitation gammas from

$$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + \mathrm{F}^*$$

(e.g. ${}^{16}\mathrm{F}^* \rightarrow {}^{15}\mathrm{O}^* + p, \quad {}^{15}\mathrm{O}^* \rightarrow {}^{15}\mathrm{O} + \gamma(6.18\ \mathrm{MeV})$)



- Important for understanding the interaction mechanism and discriminate against backgrounds.
- With 40 (2" x 4" x 16") crystals surrounding the side of the 100L tank, we can detect ~23% of gammas induced by neutrino interactions on ^{16}O!



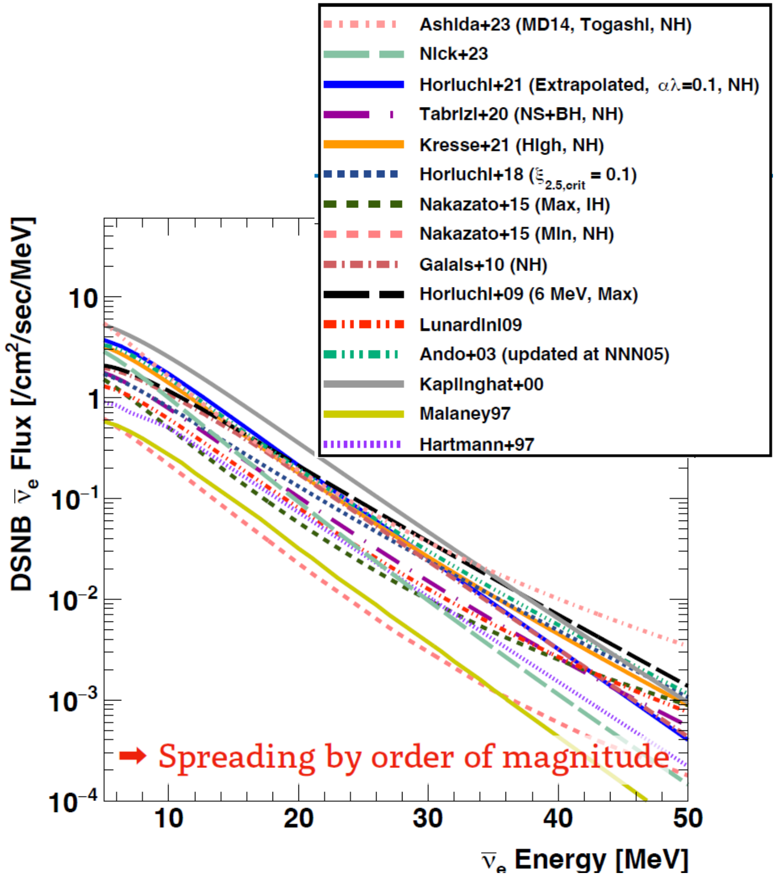
Diffuse Supernova Neutrino Background
Supernova Relic Neutrino

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

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

SN rate at z

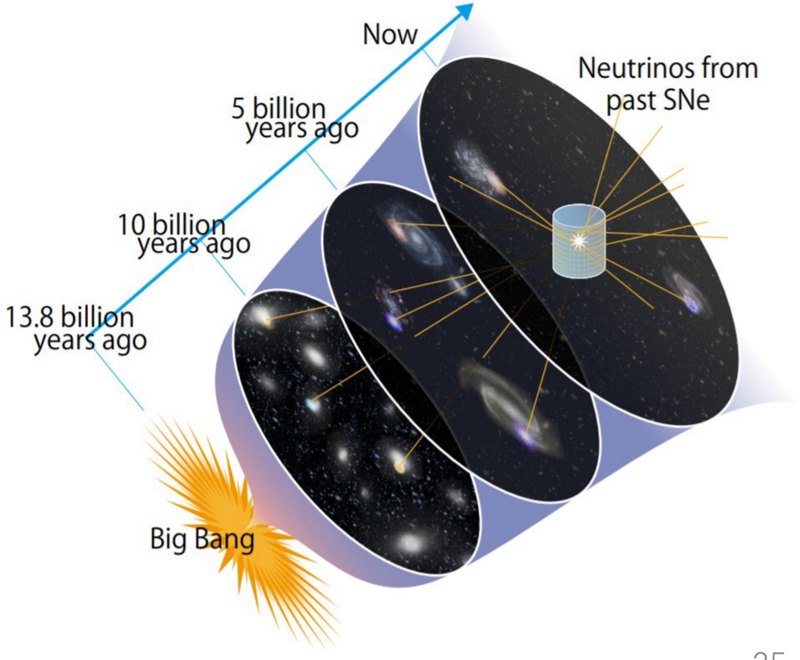
(averaged) SN spectrum



Access to

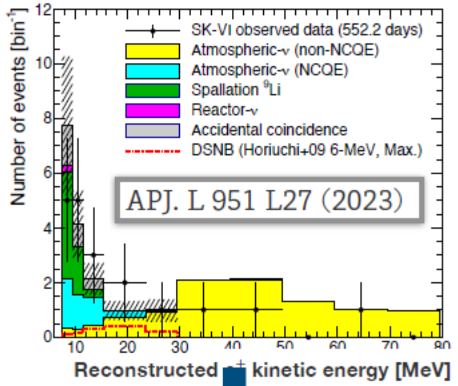
- Star formation rate
- Failed CCSNe rate;
    - BH formation rate
    - Binary star formation effect

- Typical CCSN neutrino spectrum
- Neutrino oscillation inside the star
    - Neutrino decay?, other NSI?



Results

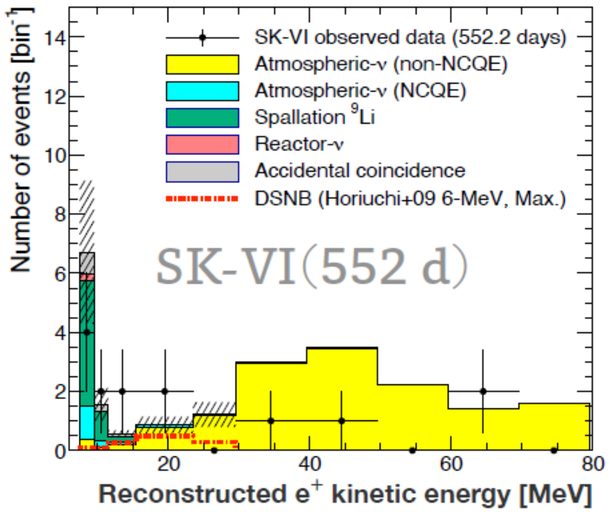
SK-Gd energy spectrum



Highlight:

- Additional 404 days with 0.03% Gd ➡ Totally 956 days SK-Gd data
  - Select only $N_n = 1$
  - New neutron ID and background reduction
- No signal obvious excess, but indicates (min. p-value=0.04)

New n-tag, NCQE reduction



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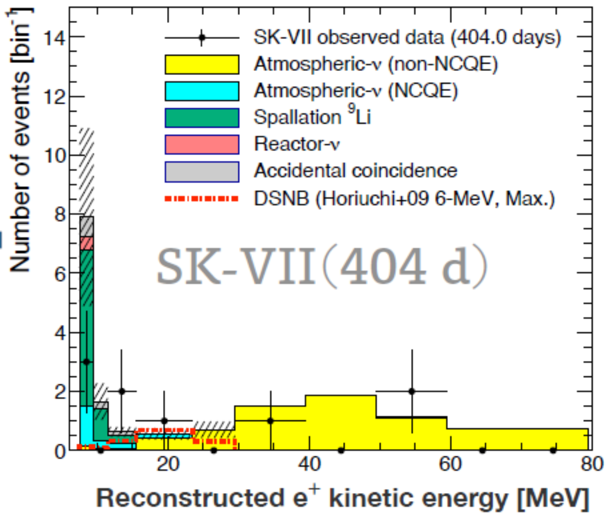

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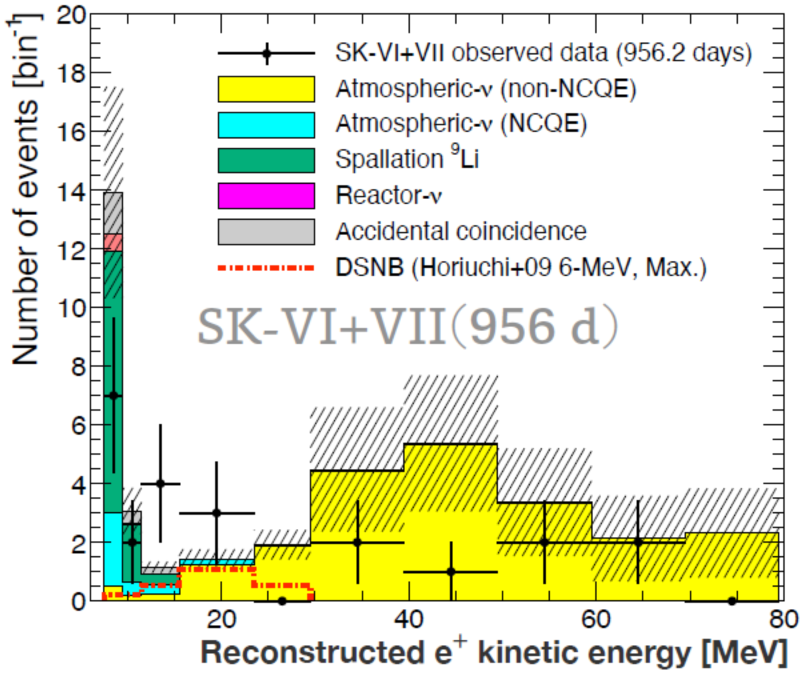

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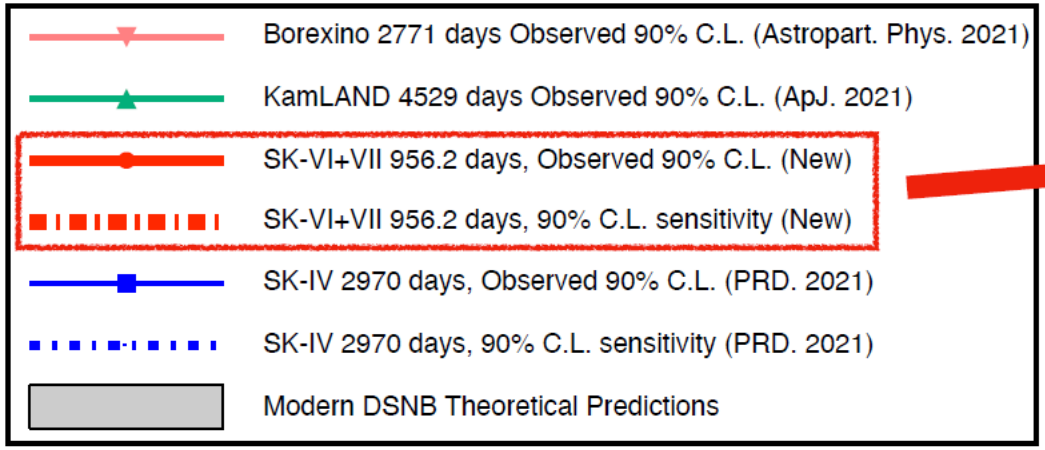
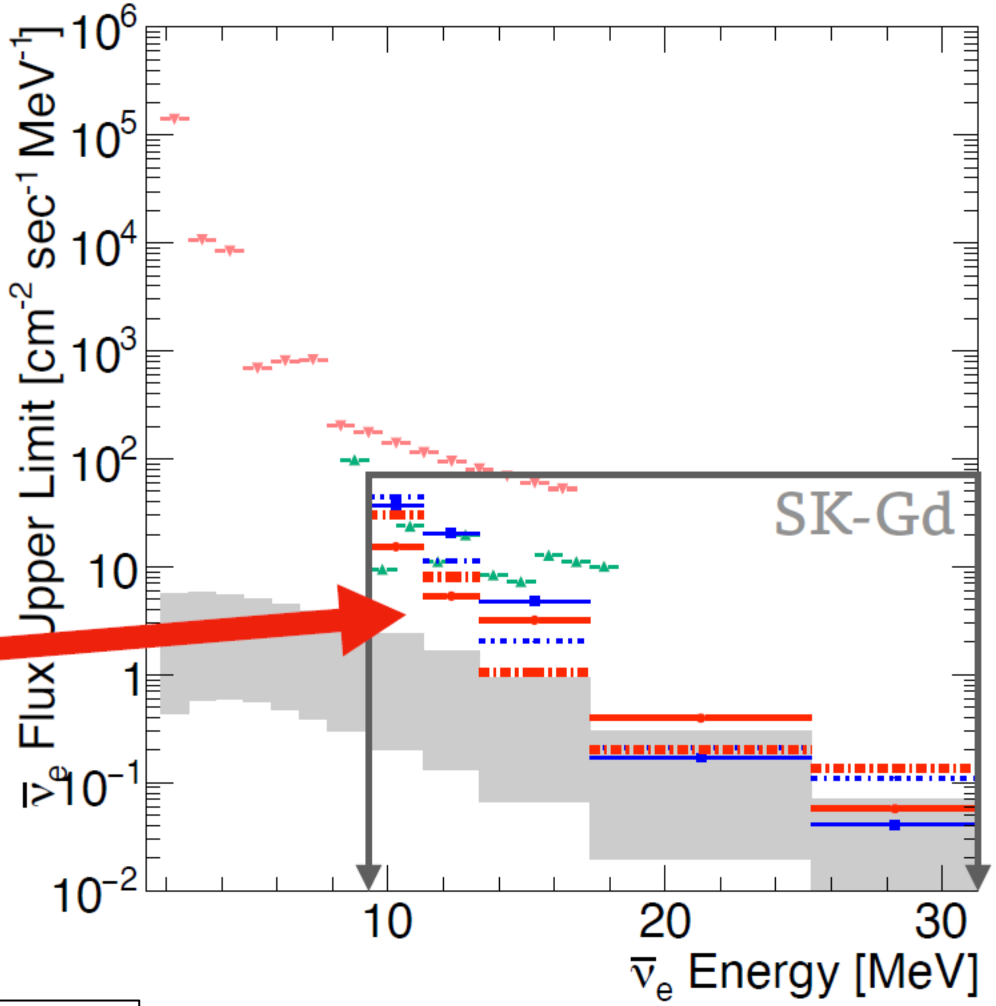
Differential flux upper limits

Spectral-independent analysis

Highlight:

- 956 days of SK-Gd with Gd 0.01%(552 d)+0.03%(404 d)
  Spectrum independent analysis
  - Only use $N_n = 1$ events
  - Differential upper limit for $9.3 < E_\nu < 31.3$ MeV
- <u>Update the world stringent sensitivity for almost all bins</u>





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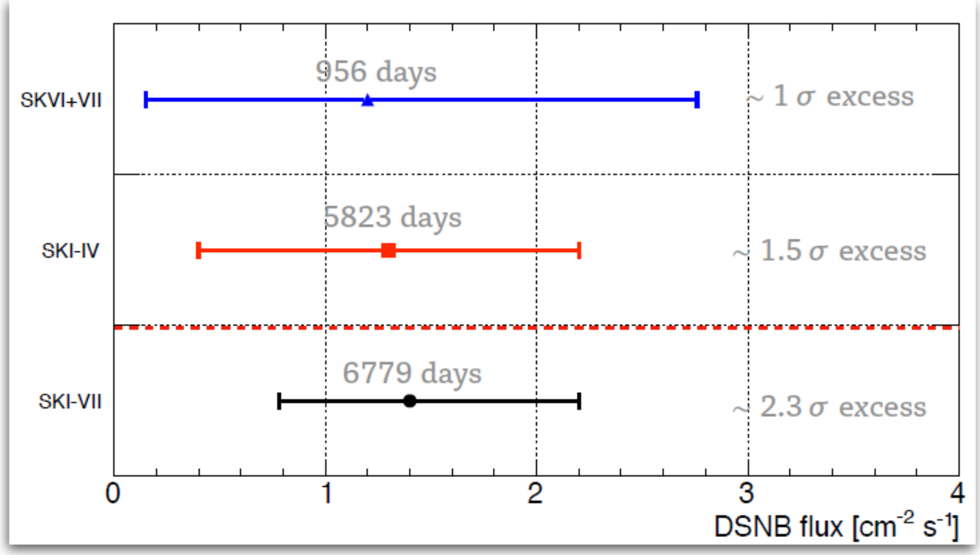
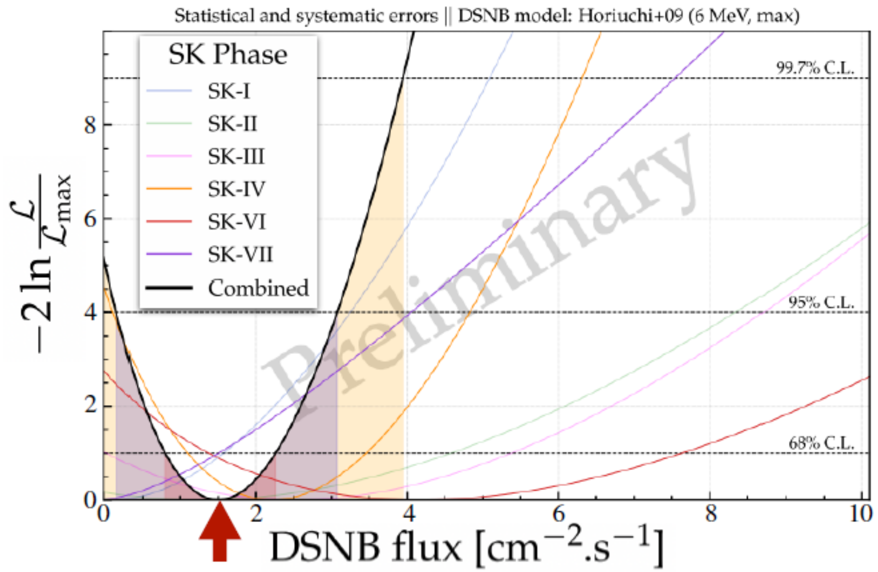
Tension from zero assumption

Spectral-fitting analysis

Spectrum fitting analysis to extract significance

- Total 6779 days of SK (5823 d pure-water and 956 d Gd-water) combined
- Analysis threshold: $E_\nu > 17.3$ MeV
- Suppress uncertainty of background prediction by fitting both $N_n=1$, $N_n \neq 1$





Best fit: 1.4

(Rogly, poste

Highlight:

- Sensitivity of SK-Gd ~1000 days exposure is already comparable level it with ~6000 days of pure-water SK
- Best fit of whole SK observation is $1.4^{+0.8}_{-0.6}$ cm^{-2} s^{-1} for $E_\nu > 17.3$ MeV

➡ **exhibit ~2.3 σ excess!!**

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Aim for 3σ in 5 years

Conclusion

UGRP C01:
Advancing Super-Kamiokande for Core-Collapse Supernovae (CCSNe)

- **Enhance Pre-SN Neutrino Alarms**:
    - Develop more reliable and faster pre-supernova neutrino alarms.
- **Improve SN Alarm Accuracy**:
    - Increase the precision and speed in determining the direction of supernova explosions and issuing supernova alarms.
- **Measure Neutrino Interactions**:
    - Conduct neutrino-^{16}O interaction measurements at ORNL for better CCSNe detection at Super-Kamiokande.
- **Pursue DSNB search**:
    - Continue efforts in detecting the Diffuse Supernova Neutrino Background (DSNB).