Super-Kamiokande Gadolinium project (SK-Gd) for supernova neutrino hunting

Fermilab Neutrino Seminar on Mar. 31, 2022

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Super-Kamiokande

Since July 2020

Super-Kamiokande Gd

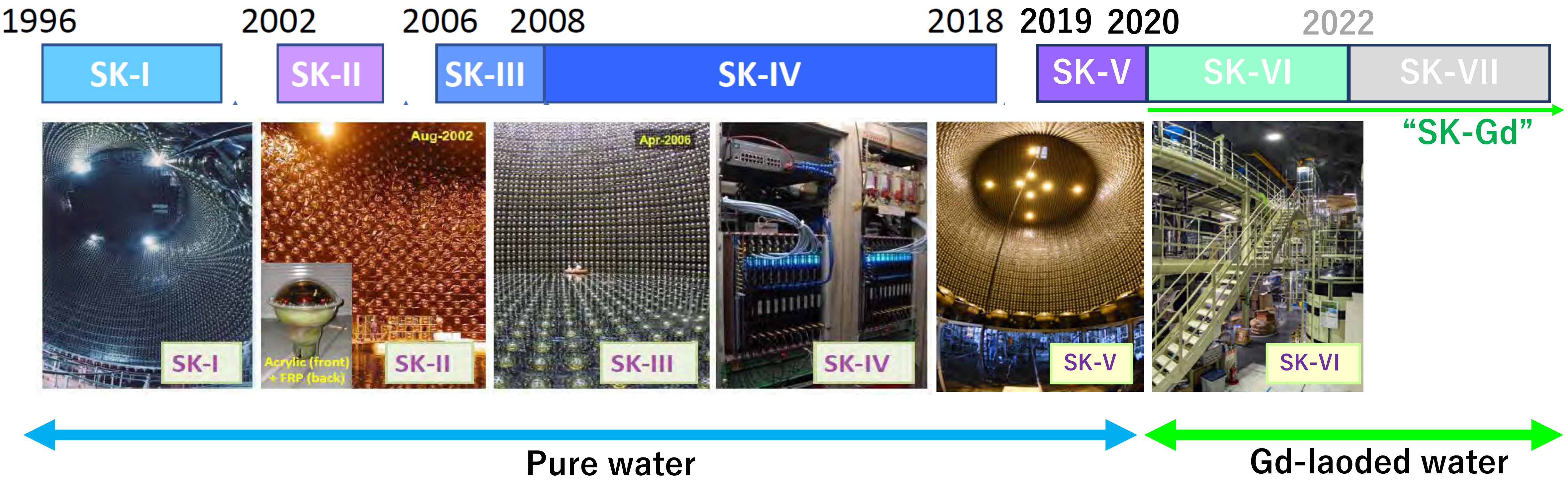
The most significant upgrade in SK history
While the look inside the inner detector hasn't changed.

Super-Kamiokande

Super-Kamiokande Gd

Complete replacement of the water system

Super-Kamiokande experimental phases



1996 SK-I
2002 SK-II
2006 SK-III
2008 SK-IV
2018
2019 SK-V
2020 SK-VI
2022 SK-VII

“SK-Gd”

Pure water

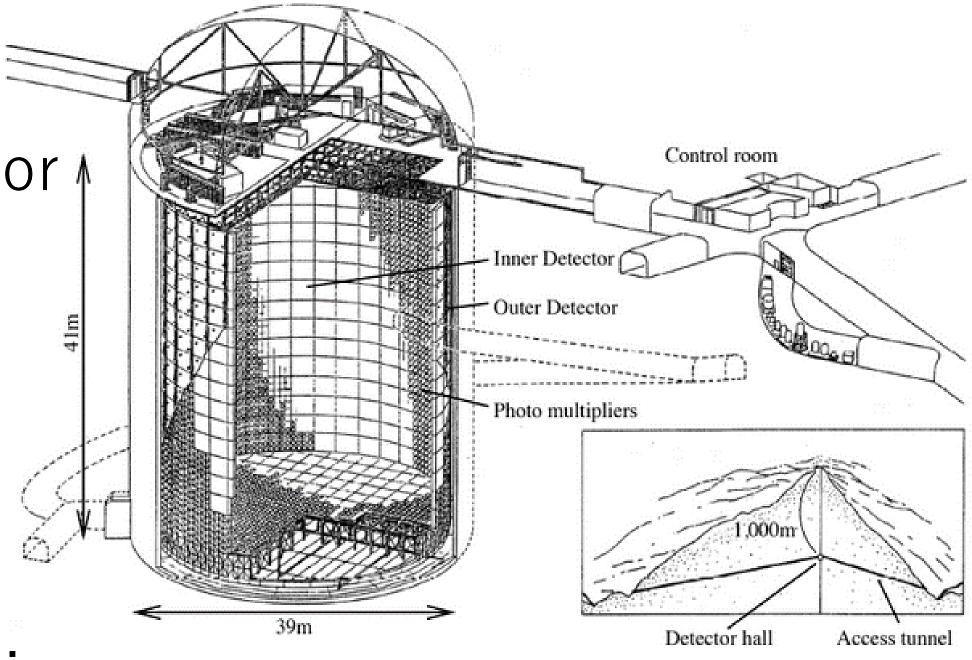
Gd-laoded water

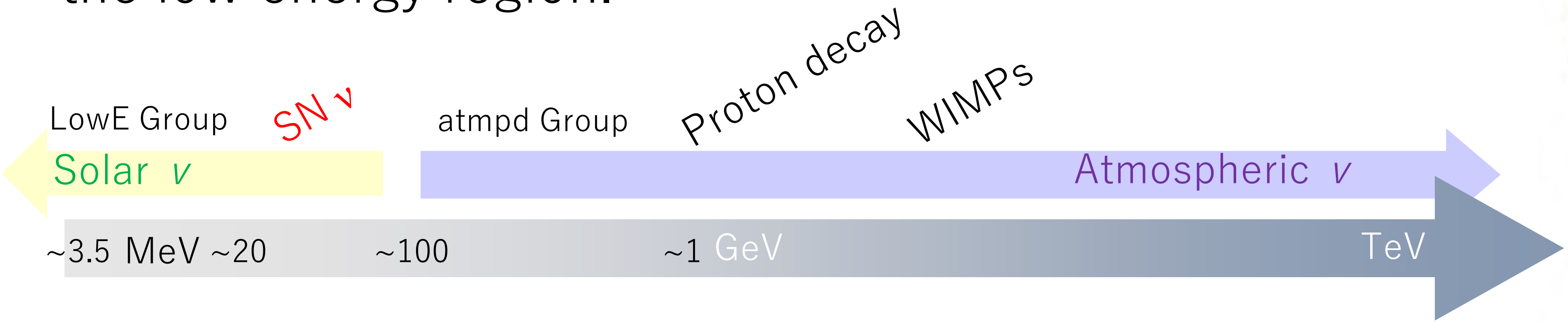
“SK-Gd is a broad and general term for the experiment after the start of the Gd-loading.”

- **The phase of the experiment is still called SK-VI, SK-VII,…**

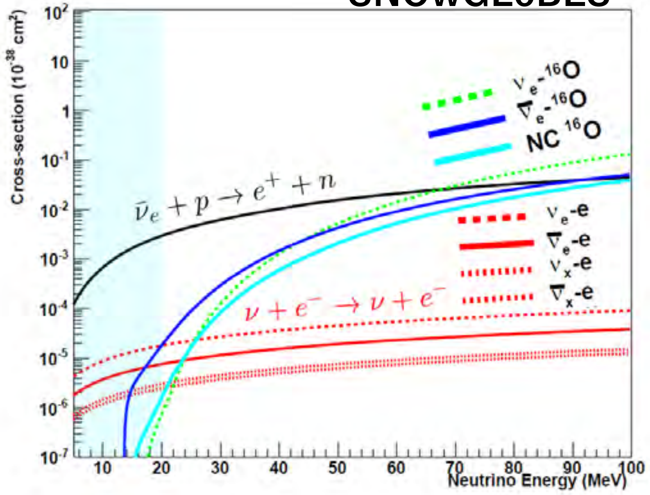
Super-Kamiokande VI

- Ring imaging Gd-doped water Cherenkov detector
  - **49.5k m^3 of pure water with 5.4 tons of Gd （0.011 w%)**
    - **~50% 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.





SNOwGLoBES

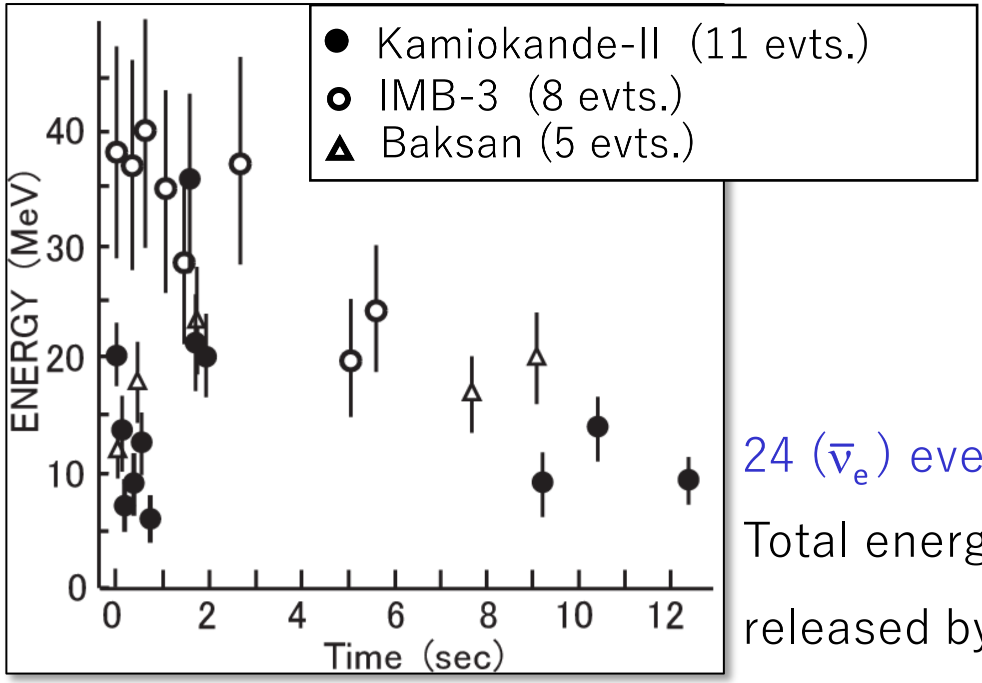


Contents

- Supernova and Diffuse Supernova neutrino Background
- DSNB search in SK-IV(pure water phase)
- The SK-Gd Project
  - R&Ds had been pursued.
  - Gd-loading to Super-Kamioknade (SK-Gd)
- SK-Gd status and the next step
- Enhanced SN burst alert system of SK-Gd
- New SN burst early warning system

Supernova neutrinos

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

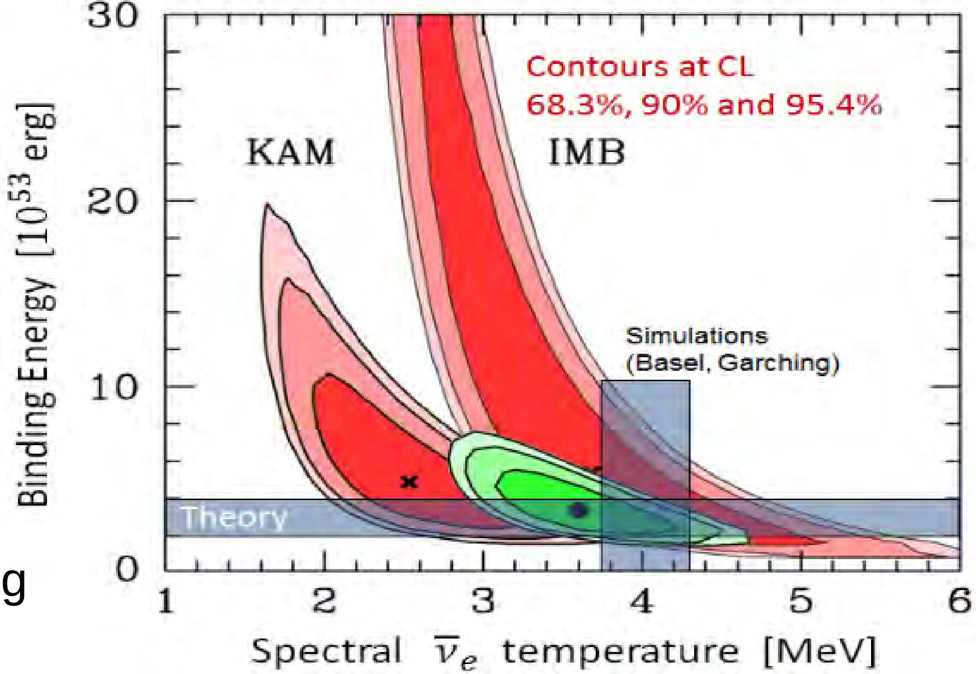


24 ($\bar{\nu}_e$) events in total.

Total energy

released by $\bar{\nu}_e$: ~5x10^{52} erg

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



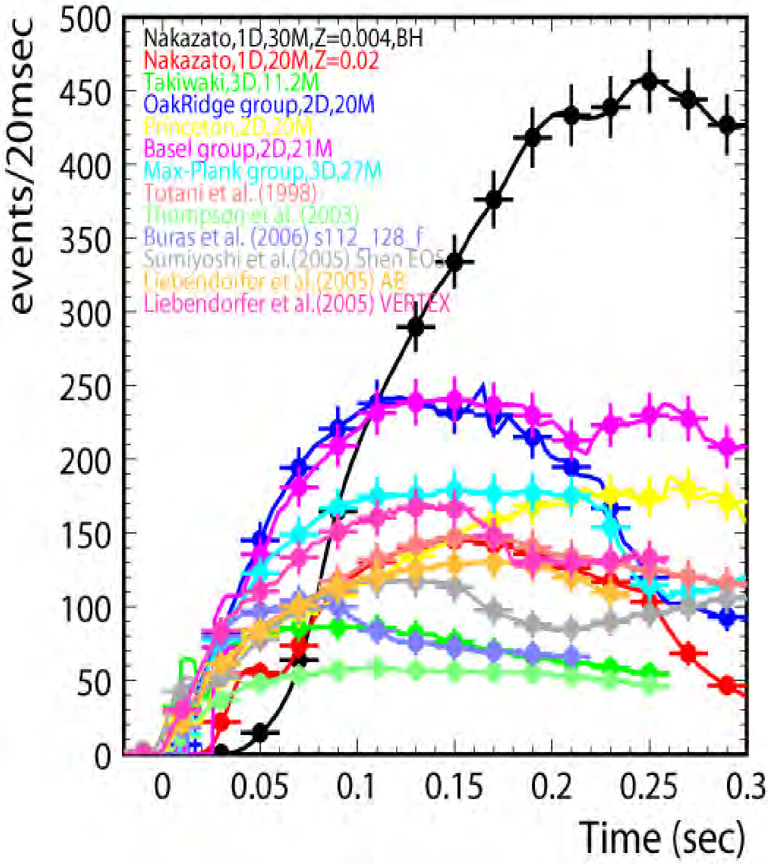
- The obtained binding energy is almost as expected, but large error in neutrino mean energy. No detailed information of burst process.
- We need energy, flavor and time structure.

If SN happens in our Galaxy

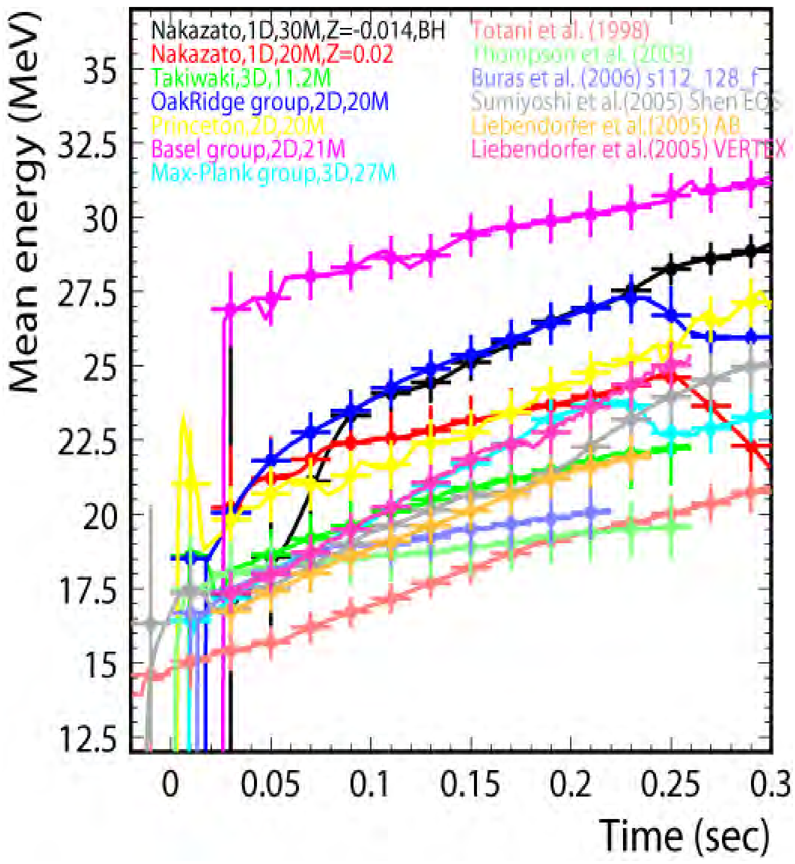
- SK should get enough statistics to discriminate models!

For SN at 10 kpc

Time variation of event rate



Time variation of mean energy



Total expected events in SK

	Totani 1998	**Nakazato 20Msun, z=0.02**
$\bar{\nu}_e p \rightarrow e^+ n$	7300	3100
$\nu + e^- \rightarrow \nu + e^-$	320	170
^{16}O CC	110	57

Can’t wait!
Let's take another approach!

Diffuse Supernova Neutrino Background

Supernova Relic Neutrino

Neutrinos emitted in past supernova explosions and stored in the current universe

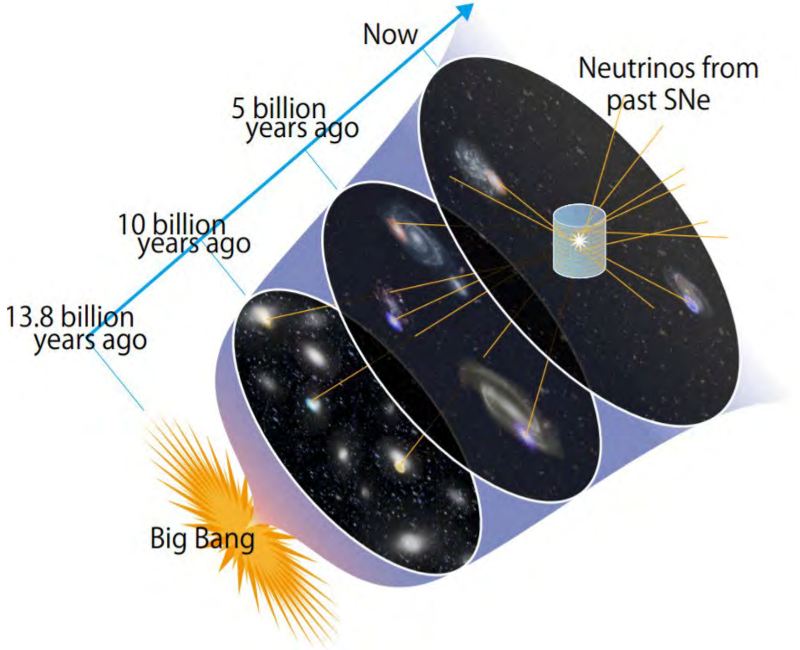
- In the entire universe, several supernova explosions occur every second.
- There must have been O(10^{18}) explosions in the history of the universe.

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

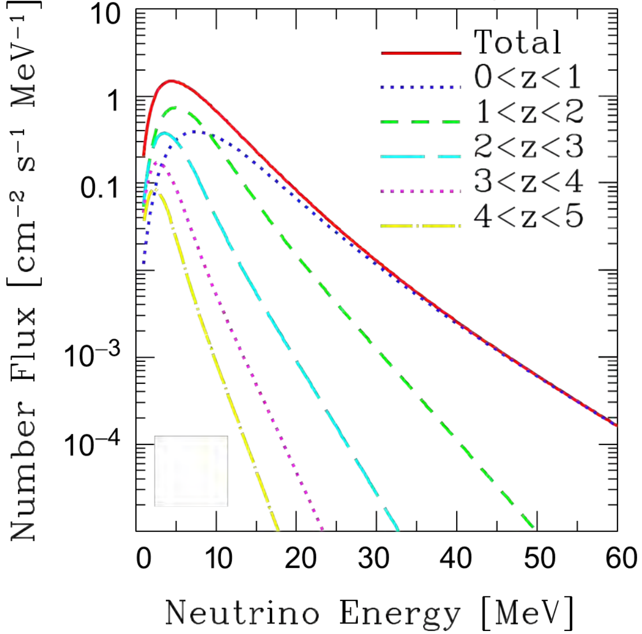
SN rate at z

(averaged) SN spectrum

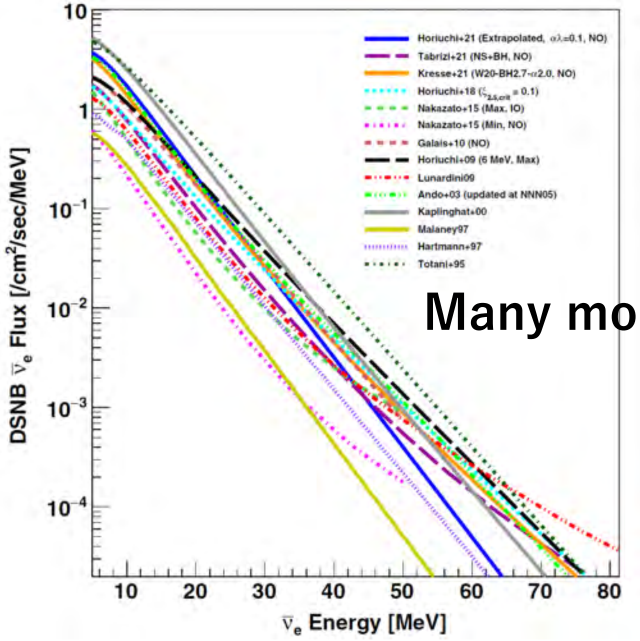
Access to
- ✓ **History of Star Formation**
- ✓ **Mechanism of supernova explosion**



S. Ando 2004 *ApJ* **607** 20

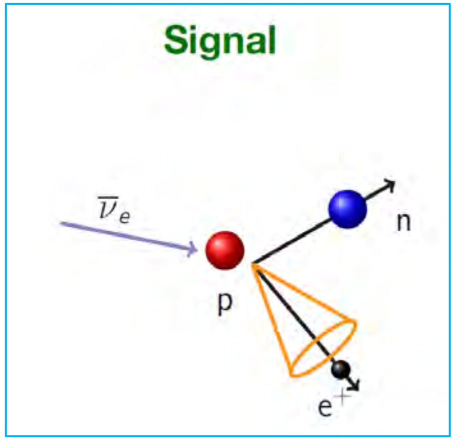


PRD **104**, 122002 (2021)

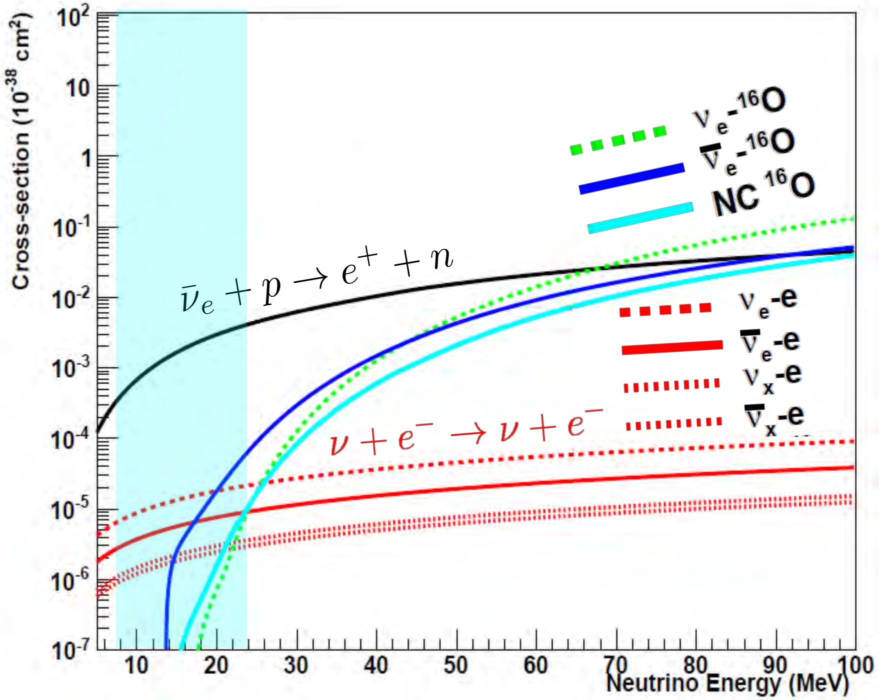


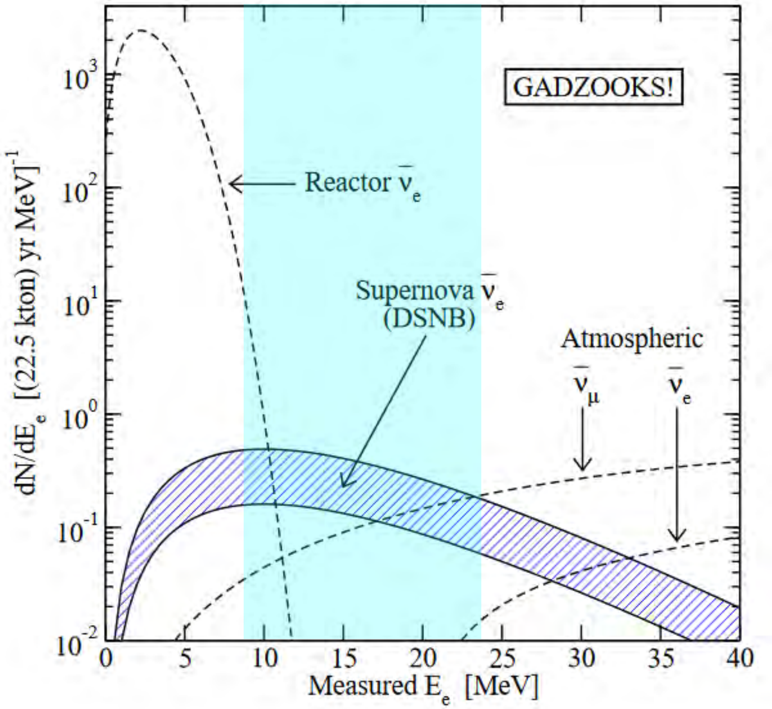
Many models

DSNB signal in Super-Kamiokande

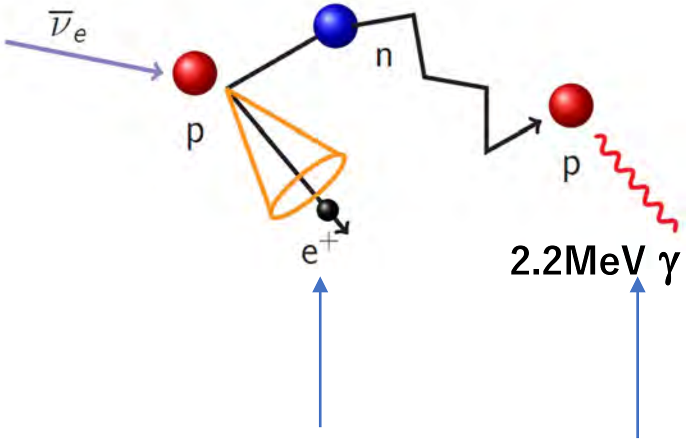


- **Main channel:** Inverse beta decay $(\bar{\nu}_e + p \rightarrow e^+ + n)$.
- **Signal window:** Between reactor neutrinos and atmospheric neutrinos.
- **Event rate:** A few interactions/year/SK





Neutron-tag in pure water



Delayed coincidence

…Low efficiency

The spallation background

Spallation products of oxygen nuclei induced by the ~2Hz muons

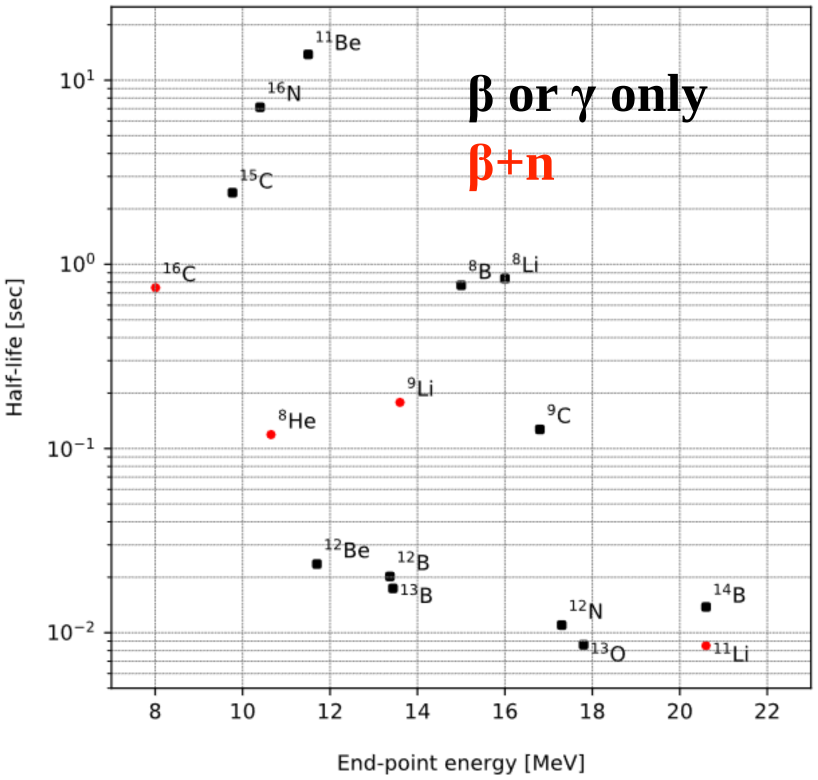
- Below 20 MeV, the associated background is 10^6 times higher than the DSNB flux prediction.

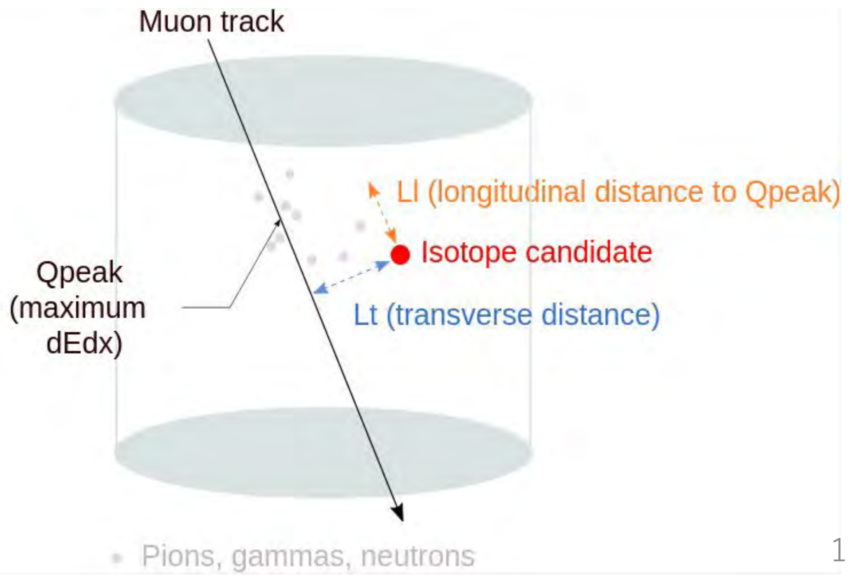
BG reduction is essential

- Nuclei that decay without neutrons(>99%)
  - Correlation with muons and **the neutron tagging**
- Nuclei that decay with neutrons (e.g., ^{9}Li, < 1%)
  - Correlation with muons is the only useful information

Cuts-based reduction uses distance and time difference from muons, etc.

- Removal efficiency: > 90%
- Signal efficiency: 50-90% (depending on energy)



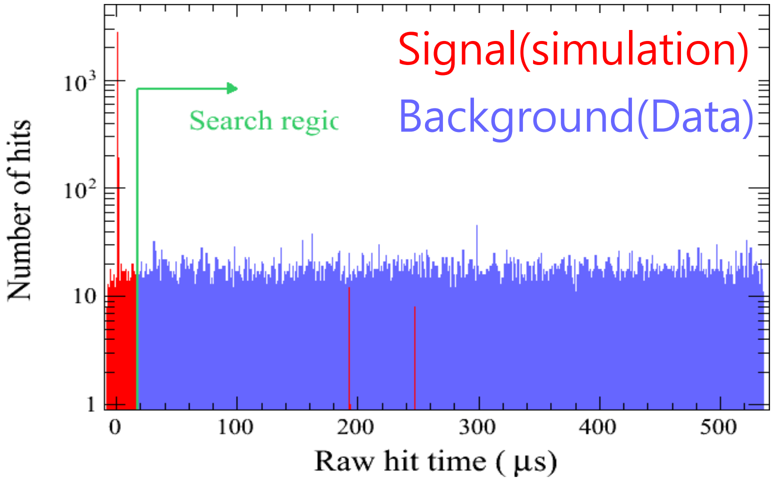


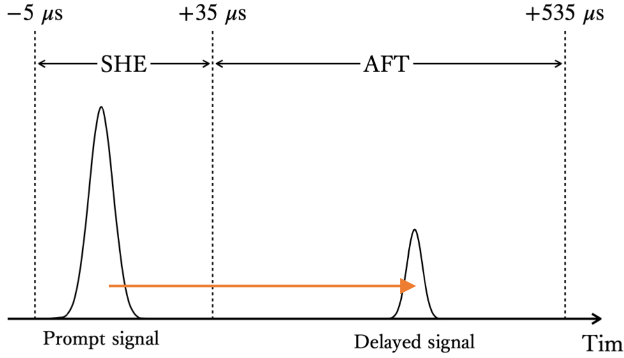
Neutron-tagging in pure water

$n + H \rightarrow D + \gamma\,(2.2\ \mathrm{MeV})$

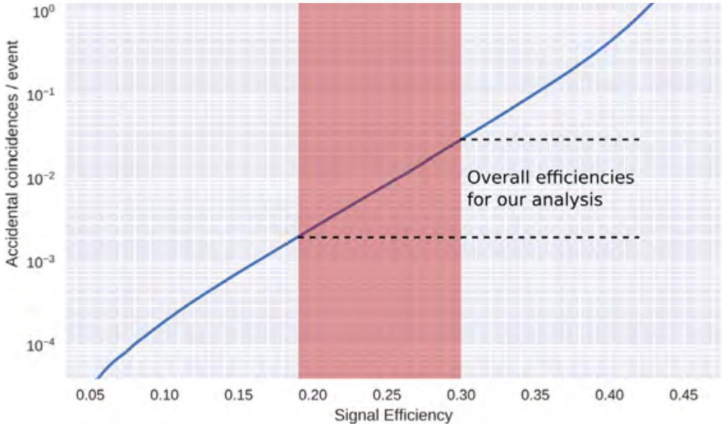
- **Neutron capture by H （τ ~200μsec)**
  - 2.2MeV →~7PMT hits (out of 11000PMTs)
  - Buried in the low energy background events (dark noise in PMT, RIs, radon, etc.)
- **Trigger scheme in DAQ**
  - If ~9 MeV or higher events exist (Super High Energy trigger), all hits for the next 500 us are recorded (AFTer trigger).
- **Machine learning-based neutron selection algorithm**
  - 22 parameters used in BDT.
    - PMT hit pattern, cluster hits, the distance between the primary and delayed events, etc.
  - Trained for 2.8×10^{8} neutron candidates.
    - With 2×10^{6} simulated neutron captures and accidental coincidence events
  - Efficiency: 18~30% with 0.2~3% mis-tagging.
  - Systematic uncertainty: 12.5% checked by Am/Be calibration.

R. Akutsu Ph. D Thesis



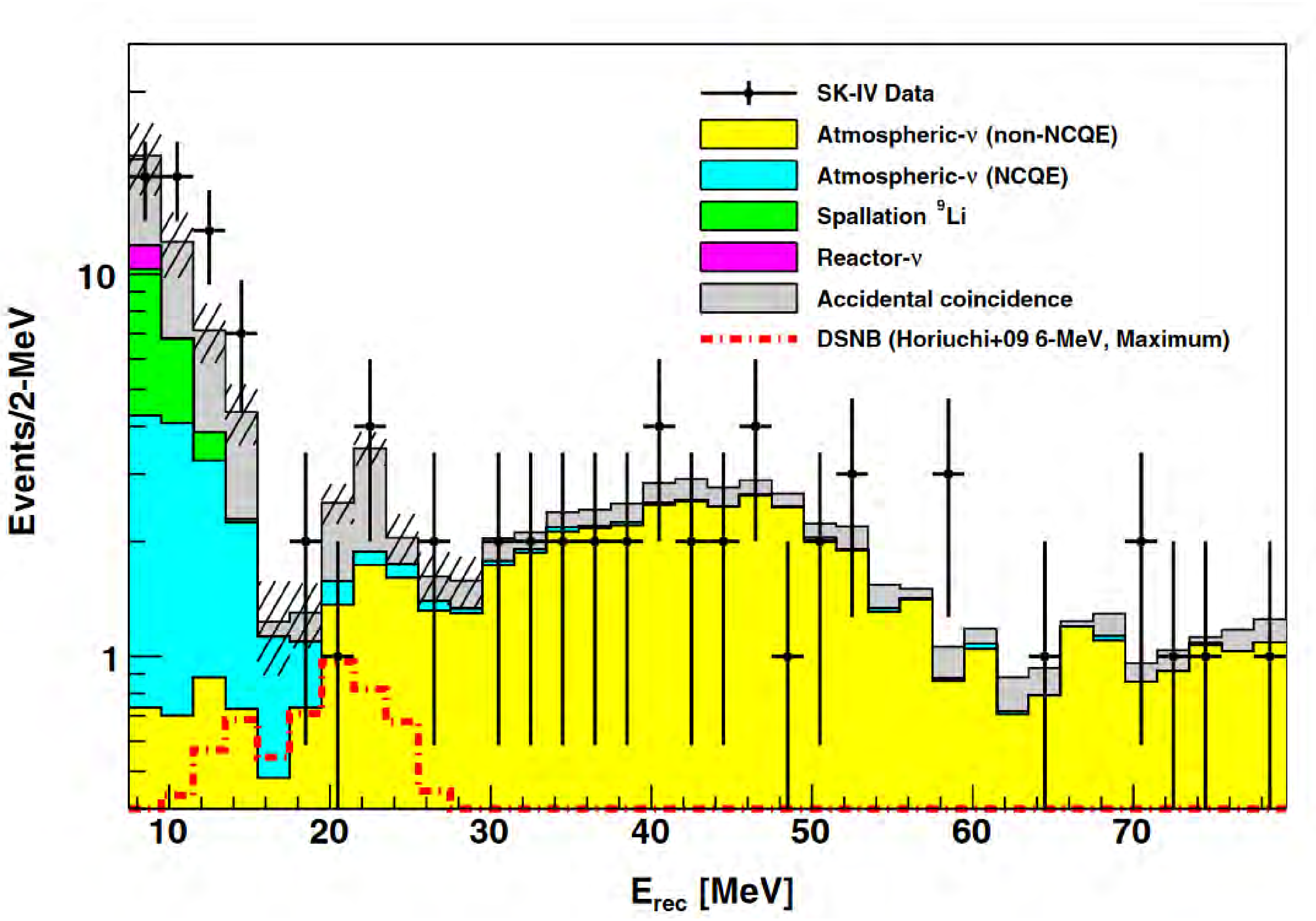


ROC (BDT performance)

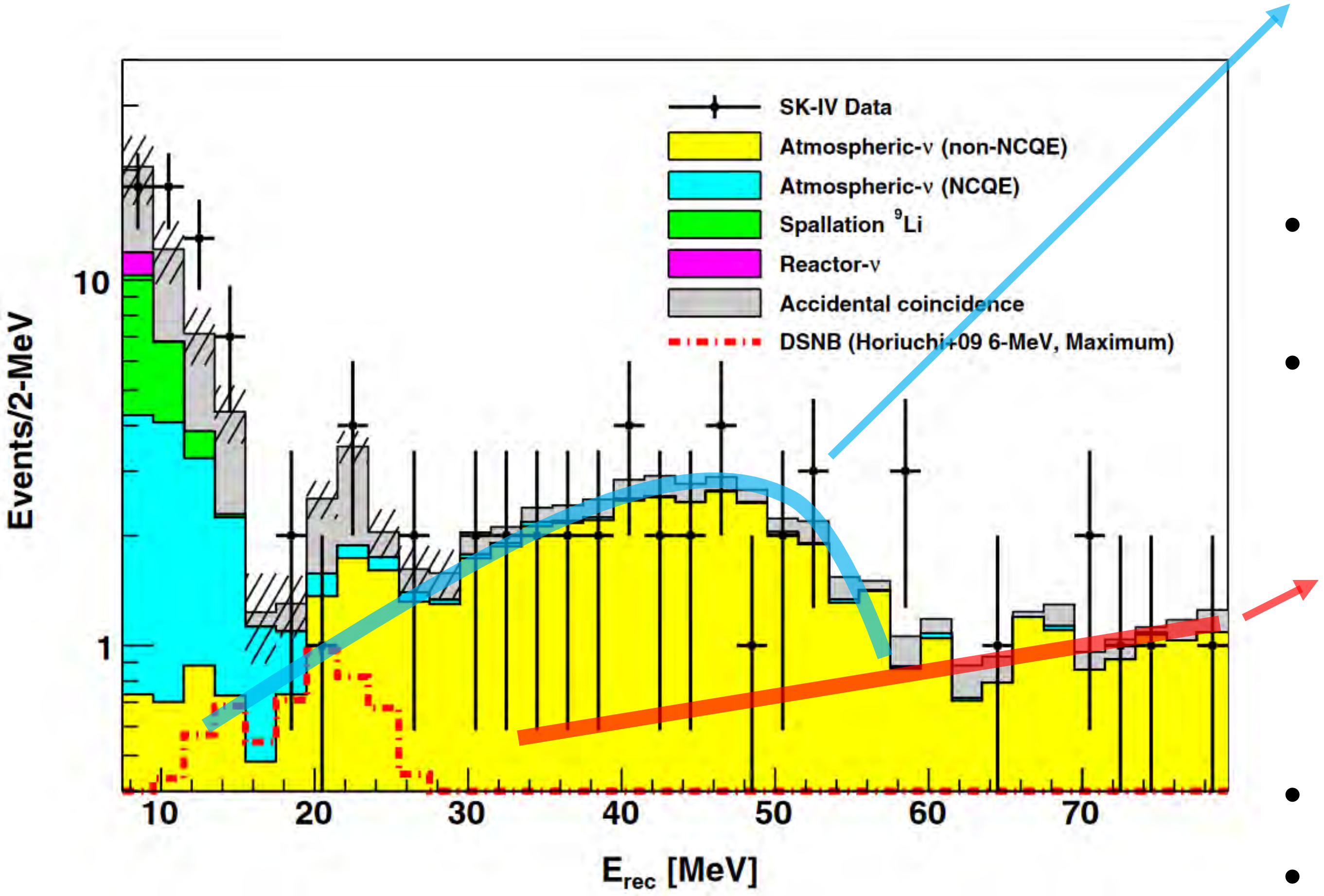


The Results form SK-IV

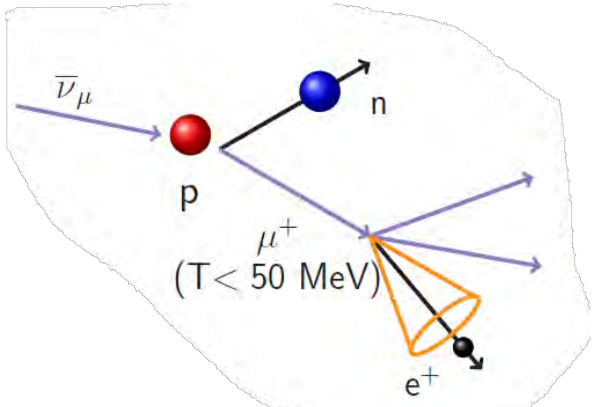
Phys. Rev. D 104, (2021) 122002



Background : Atmospheric ν CC

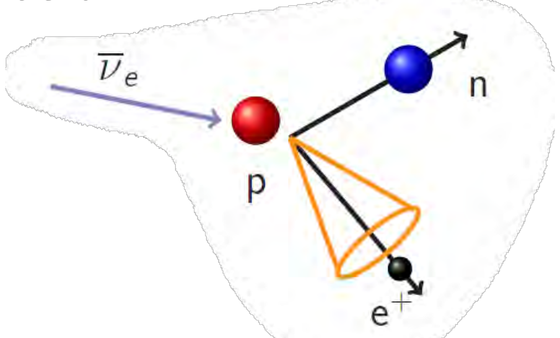


ν_μ CC



- When muons are not visible (below Cherenkov threshold), and only electrons are observed
- The energy distribution is the well-known Michael spectrum

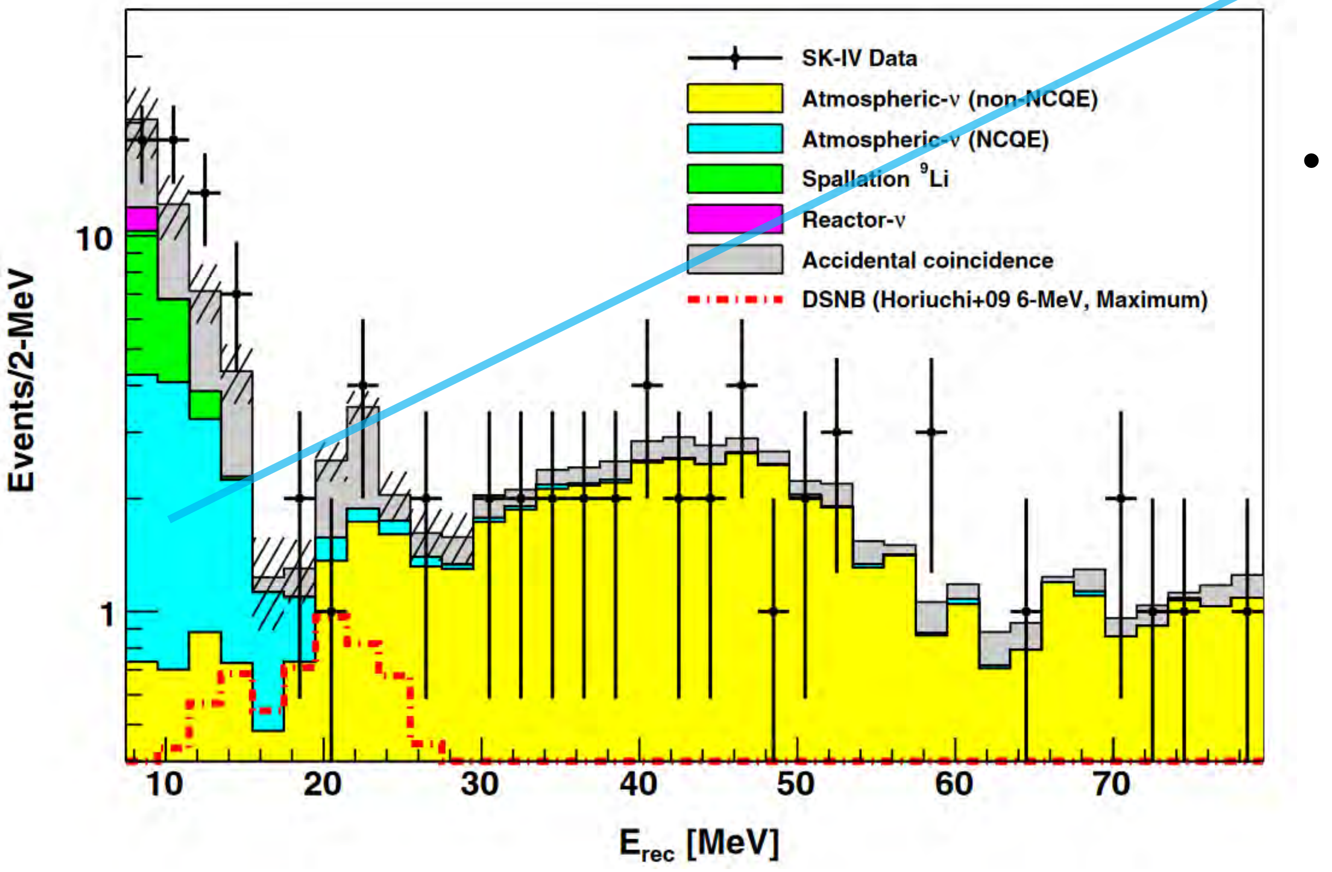
ν_e CC



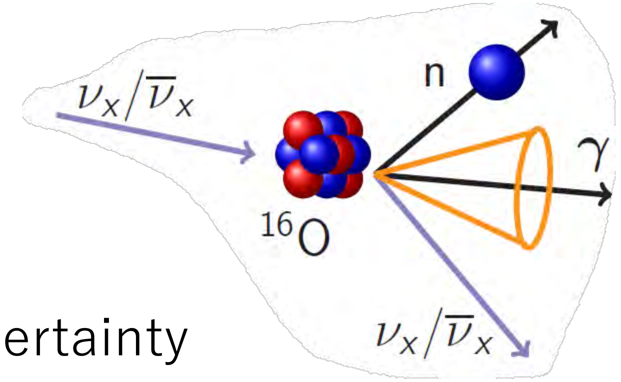
- Major components above 50 MeV
- Small contribution to DSNB region

- These BGs (using >30MeV region) are subtracted with 20% systematic uncertainty

Background : Atmospheric ν NC



NC(QE)



- Largest uncertainty

  Systematic error: 60-80% (energy-dependent)

Atm. ν flux

× **NCQE cross-section**

(←**T2K measurement**)

× **Number of generated neutrons**

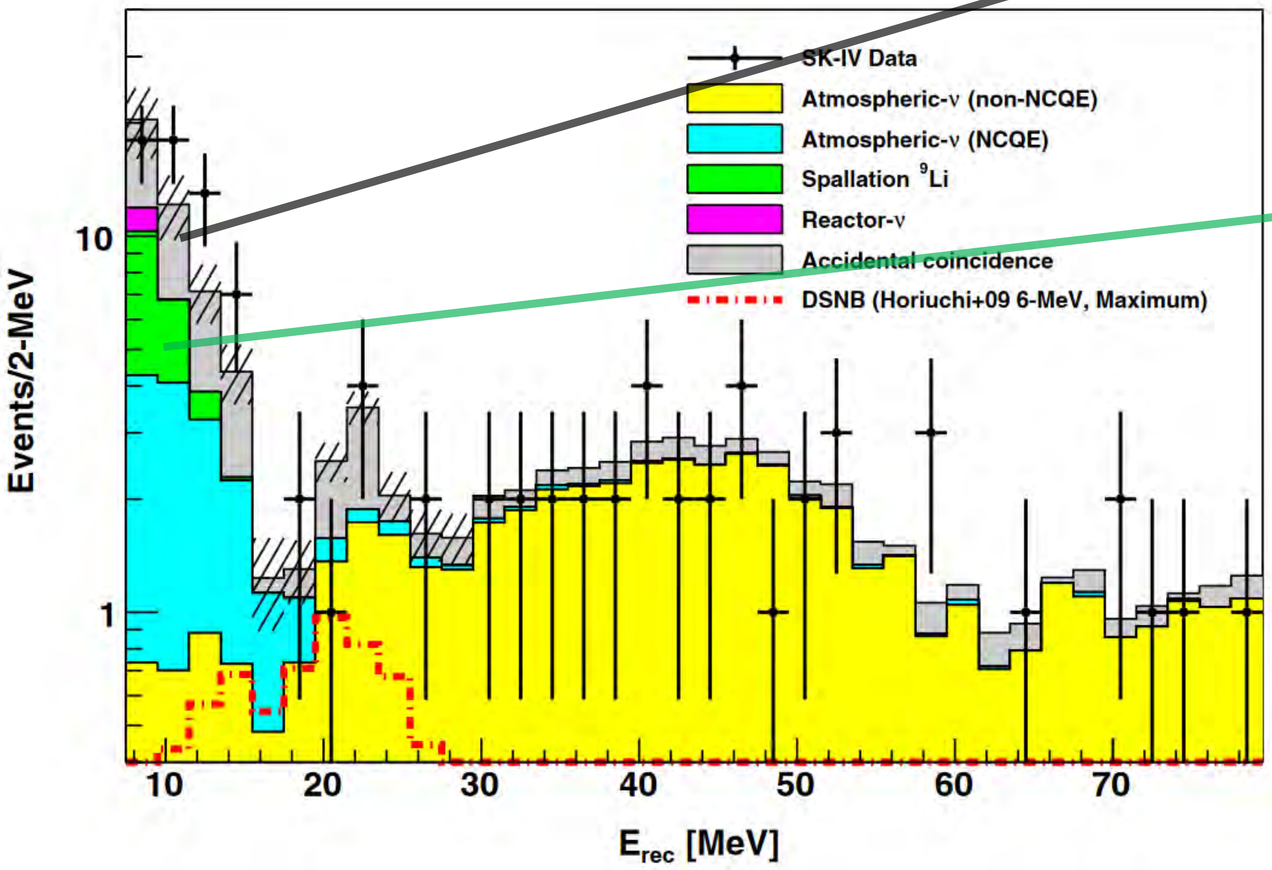
(←**T2K CC measurement**)

× **Neutron detection efficiency**

(←**Am/Be calibration**)

Understanding and reducing this uncertainty is essential!

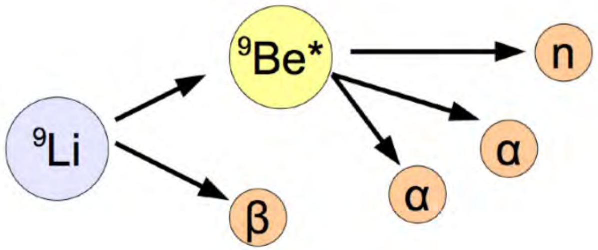
Background : Accidental and Spallation



Accidental

- Spallation events without neutrons
  + fake neutron

^{9}Li



- Beta decay + n: same topology as IBD

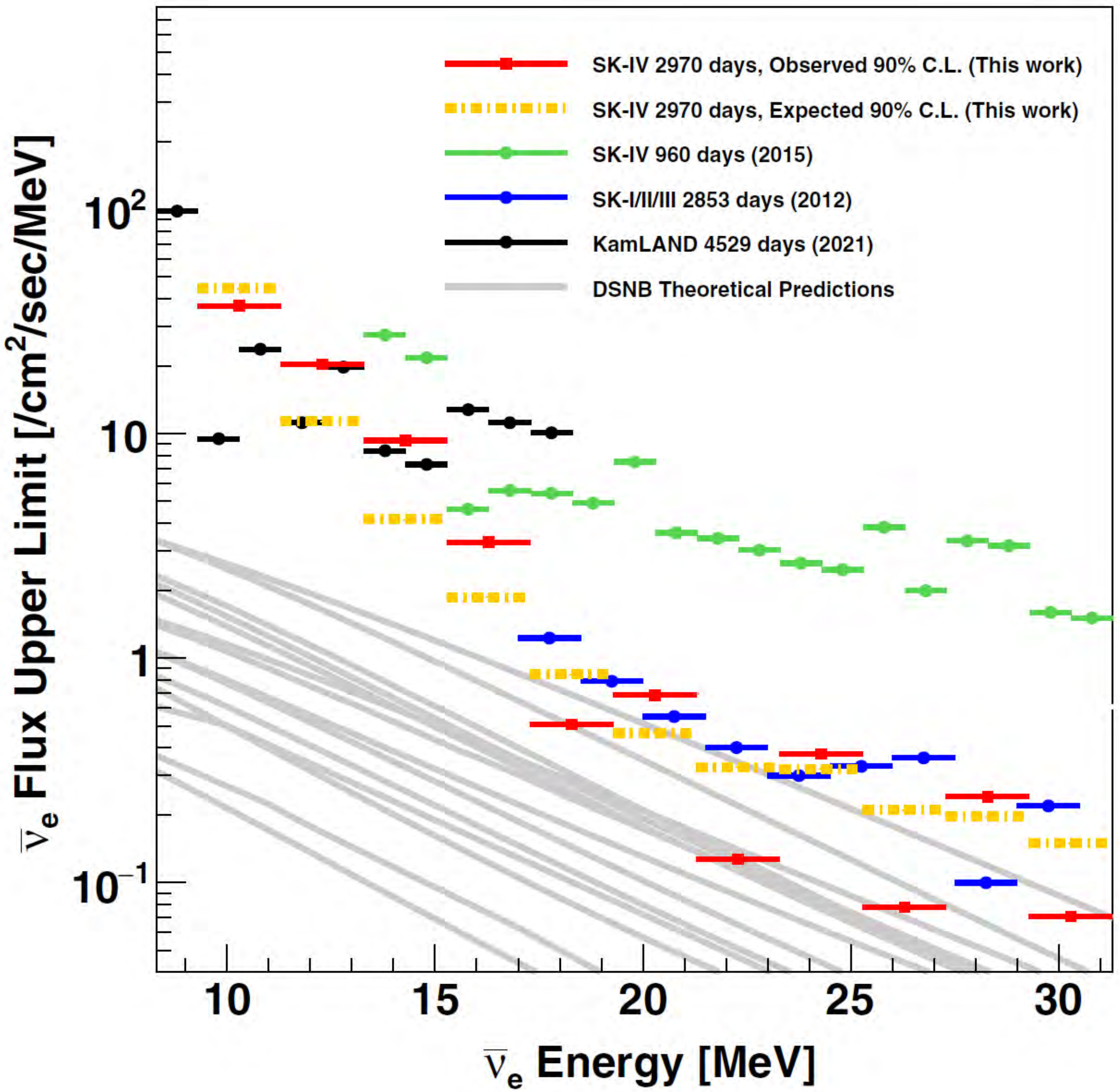
Both can be reduced using the spallation cut and strict neutron selection, but there is a tradeoff with the efficiency of detecting signal events.
→Optimize cut conditions for each energy

Model-independent limit

- Strongest limit

  above 15 MeV

- Already reached some model prediction regions



Spectral shape fitting

For each DSNB model, the obtained energy spectra were fitted with expected BG above 15.5MeV region.

- Side-band regions separated by Cherenkov angles were fitted simultaneously.

  Low angle region:

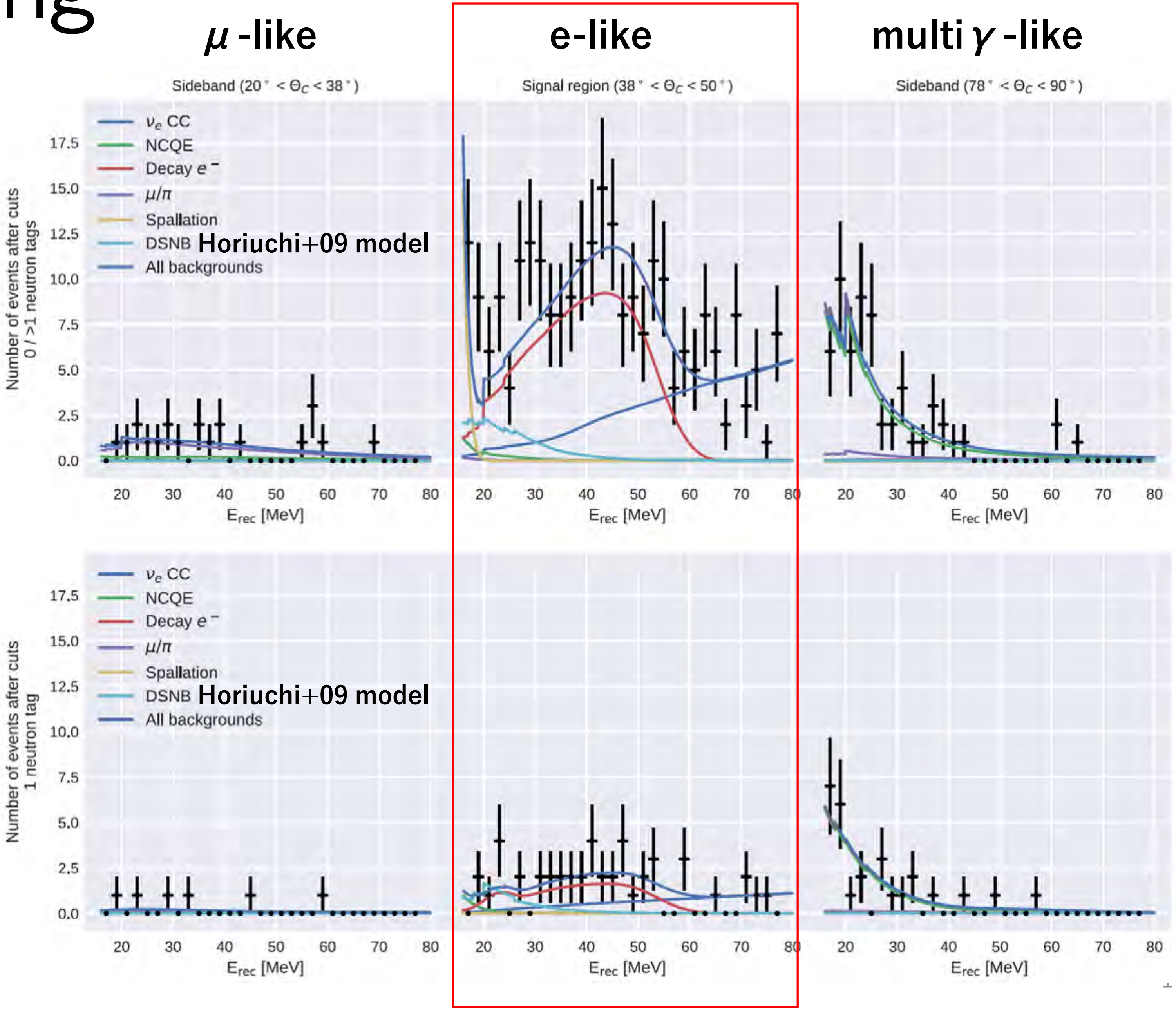
  Atmospheric backgrounds involving visible μ and p.

  High angle region:

  NCQE events with multiple γ-rays.

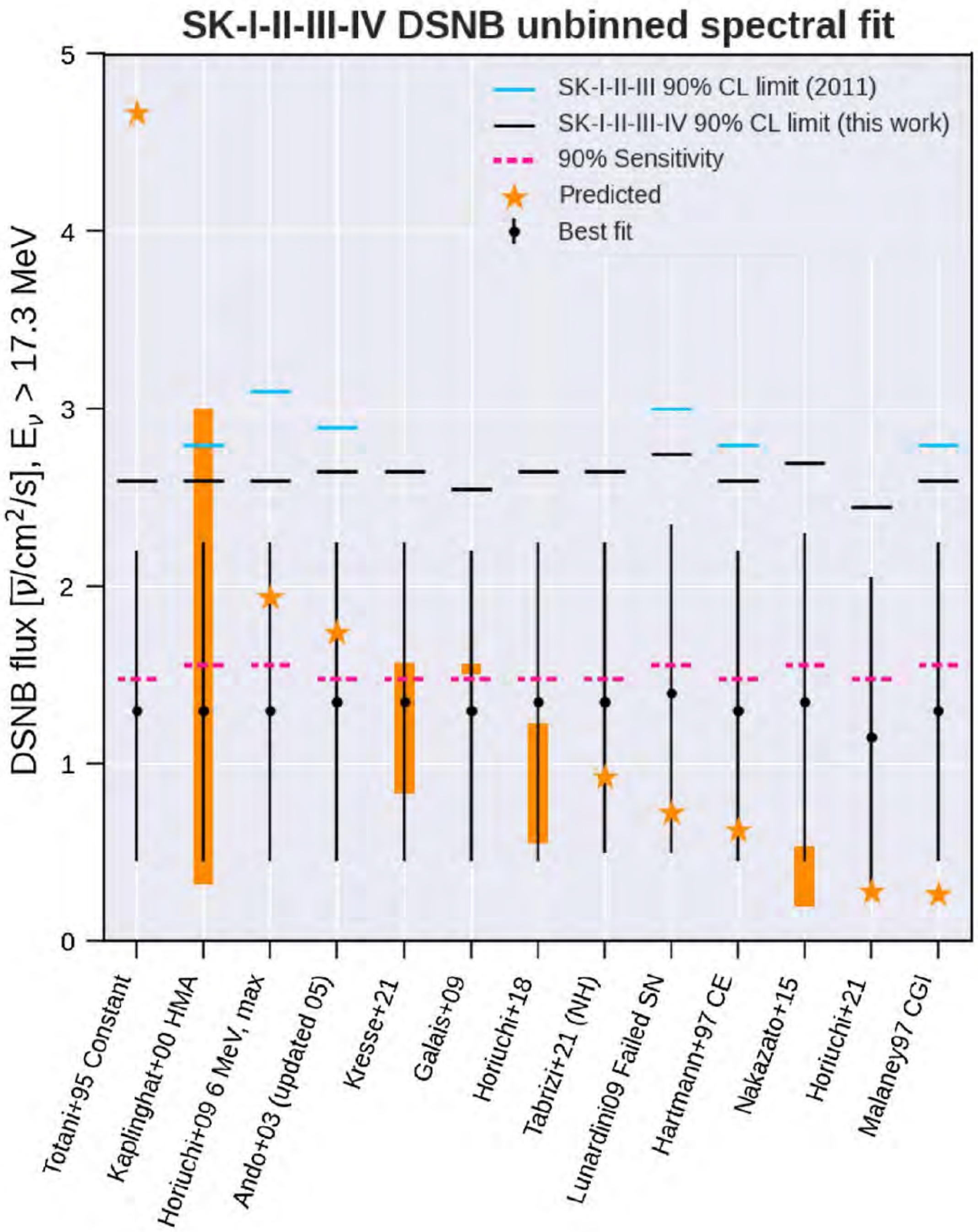
“IBD-like” events (exactly one identified neutron) and “non-IBD-like” events are also separated.

- Due to the low efficiencies of the neutron tagging cuts, the non-IBD-like events still contain a sizable signal.



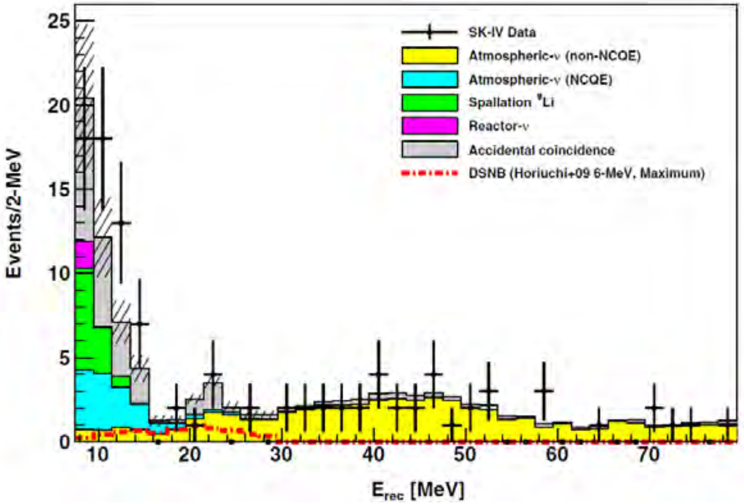
Limits to Models

- The number of observations is about 1 σ larger than the background, and the limit is worse than the sensitivity.
- 90% CL sensitivity reached the region below some model predictions.
- Future SK-Gd observations will validate most models.
- Aiming for the world's first observation of supernova background neutrinos



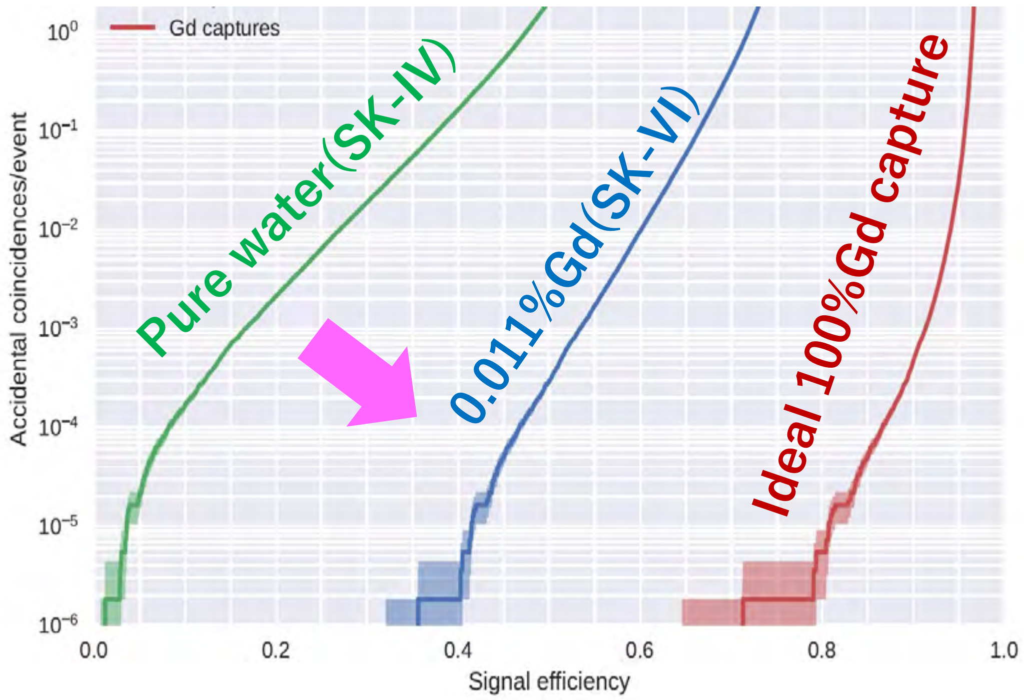
How Gd-loading helps?

In SK-IV(pure water), accidental coincidence remains due to low neutron tagging efficiency

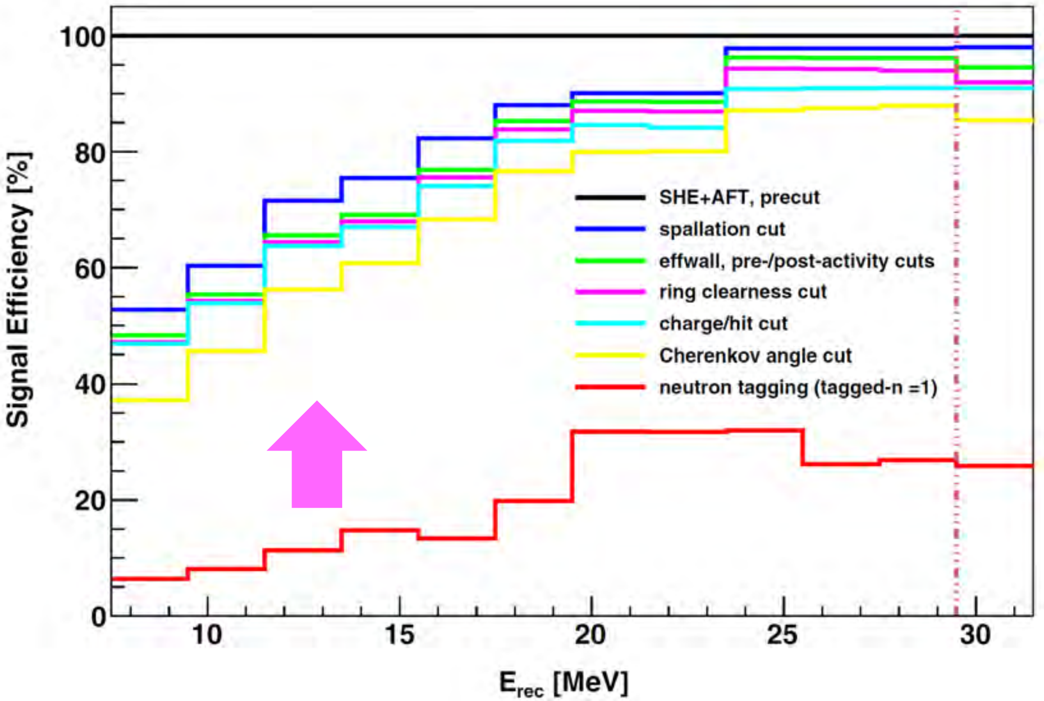


- Reduction of accidental BG (approx. 1/10) with high neutron detection efficiency.
- Also signal statistics increases (2~3 times)

ROC curve (n tagging BDT performance)

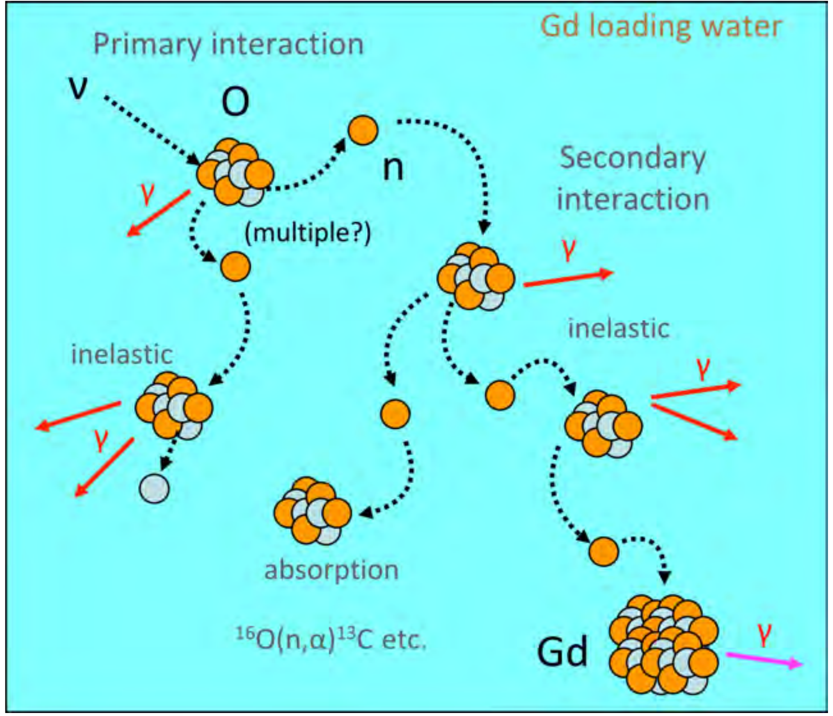


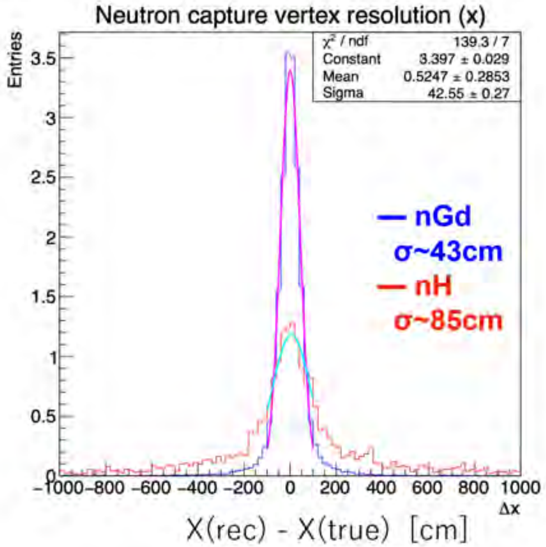
Pure water(SK-IV)

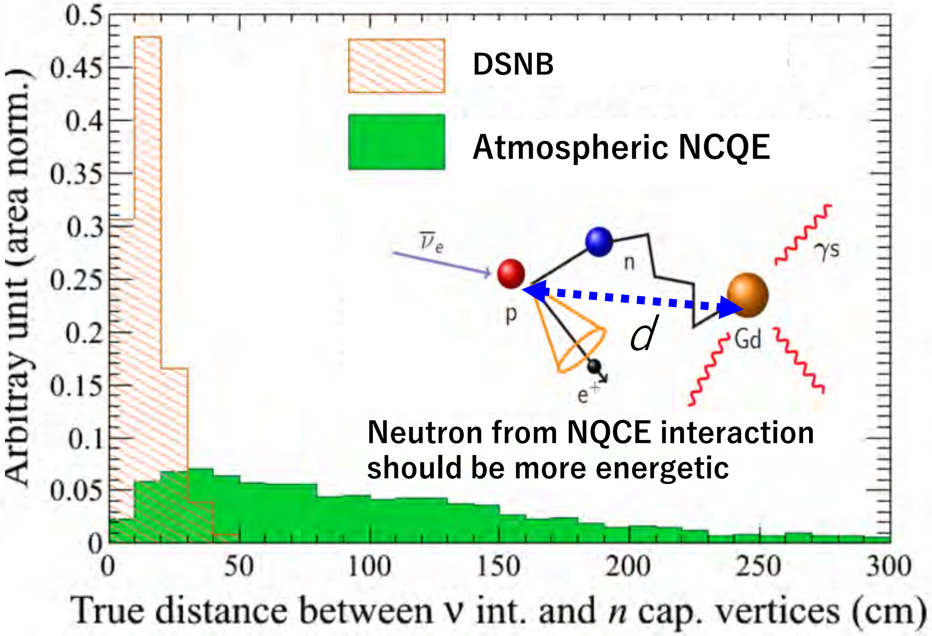


Further improvements expected (understudy)

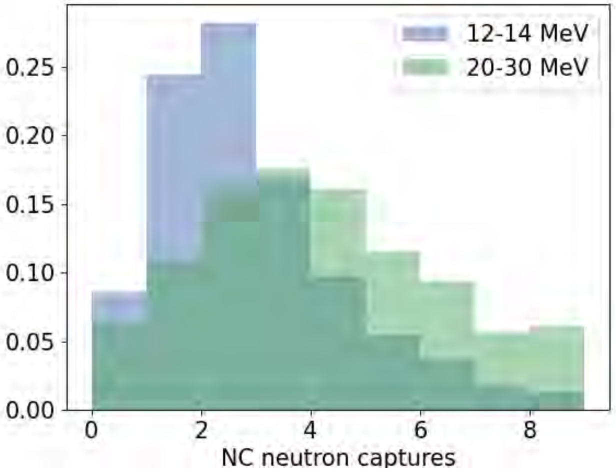
- The next largest BG that should be reduced is the atmospheric NCQE.
- Gd also helps to reject the NCQE BG.
  - Neutron multiplicity counting
  - The neutron capture vertex resolution



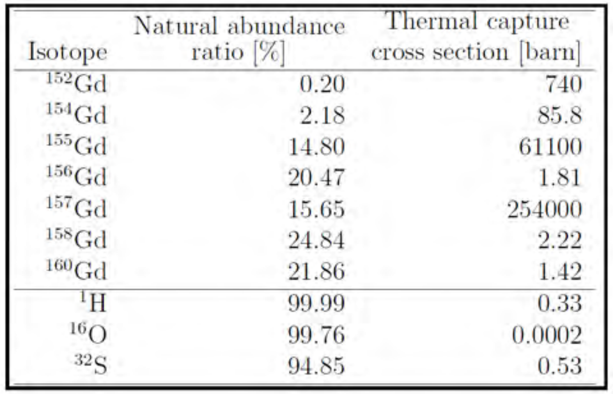




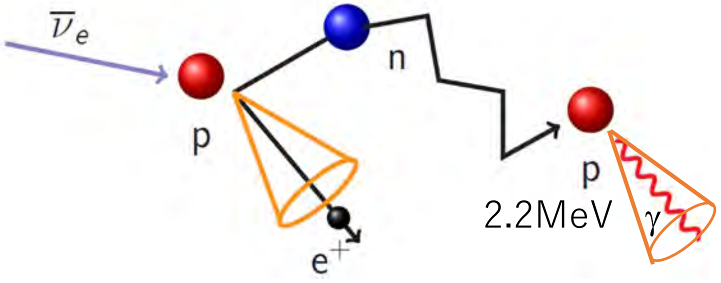
Neutron from NQCE interaction should be more energetic

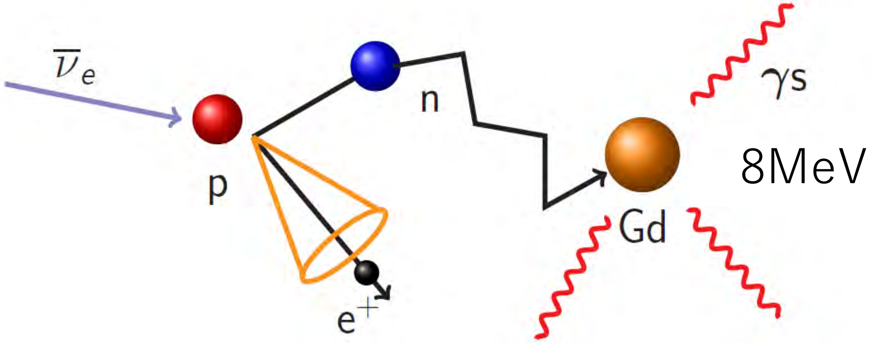


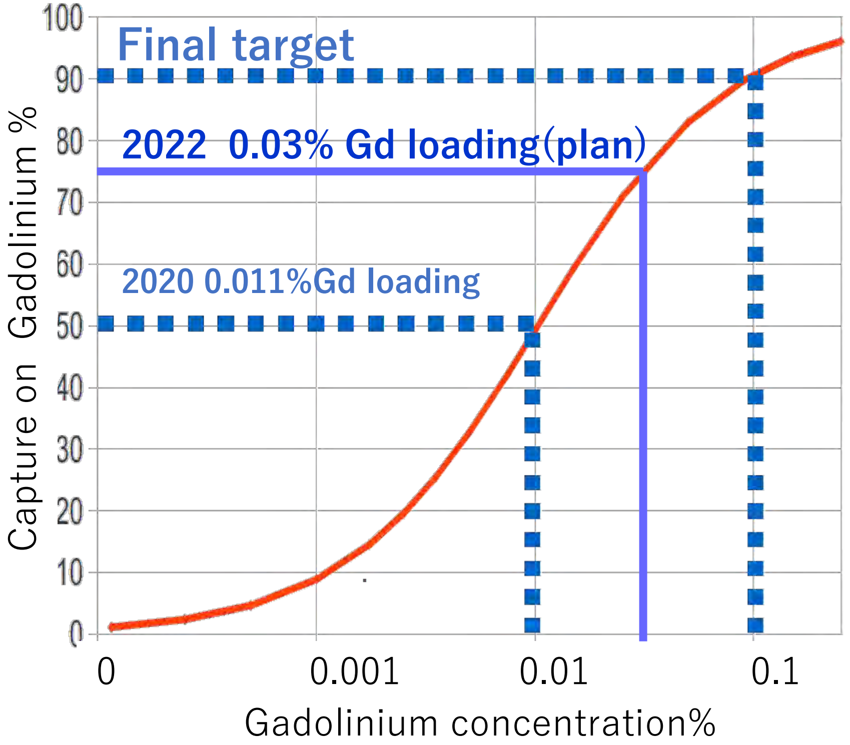
SK-Gd (2020-)



Isotope	Natural abundance ratio [%]	Thermal capture cross section [barn]
^{152}Gd	0.20	740
^{154}Gd	2.18	85.8
^{155}Gd	14.80	61100
^{156}Gd	20.47	1.81
^{157}Gd	15.65	254000
^{158}Gd	24.84	2.22
^{160}Gd	21.86	1.42
^{1}H	99.99	0.33
^{16}O	99.76	0.0002
^{32}S	94.85	0.53





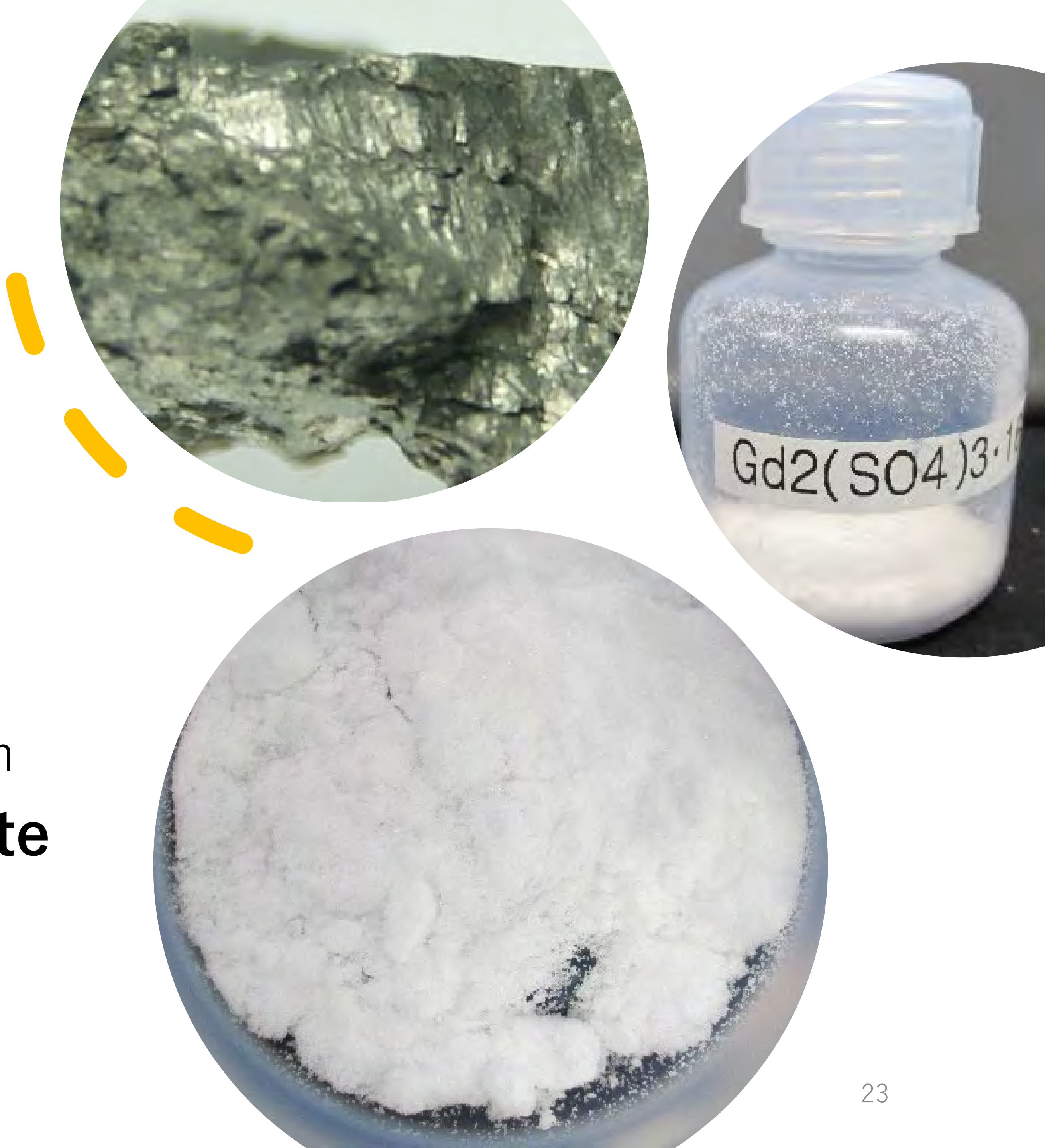


Gd-loading to SK

- Significantly enhances detection capability of neutrons from $\overline{\nu}$ interactions
- Initial loading was conducted in July-August 2020. 0.011% Gd concentration was achieved, about 50% of neutron would be captured by Gd

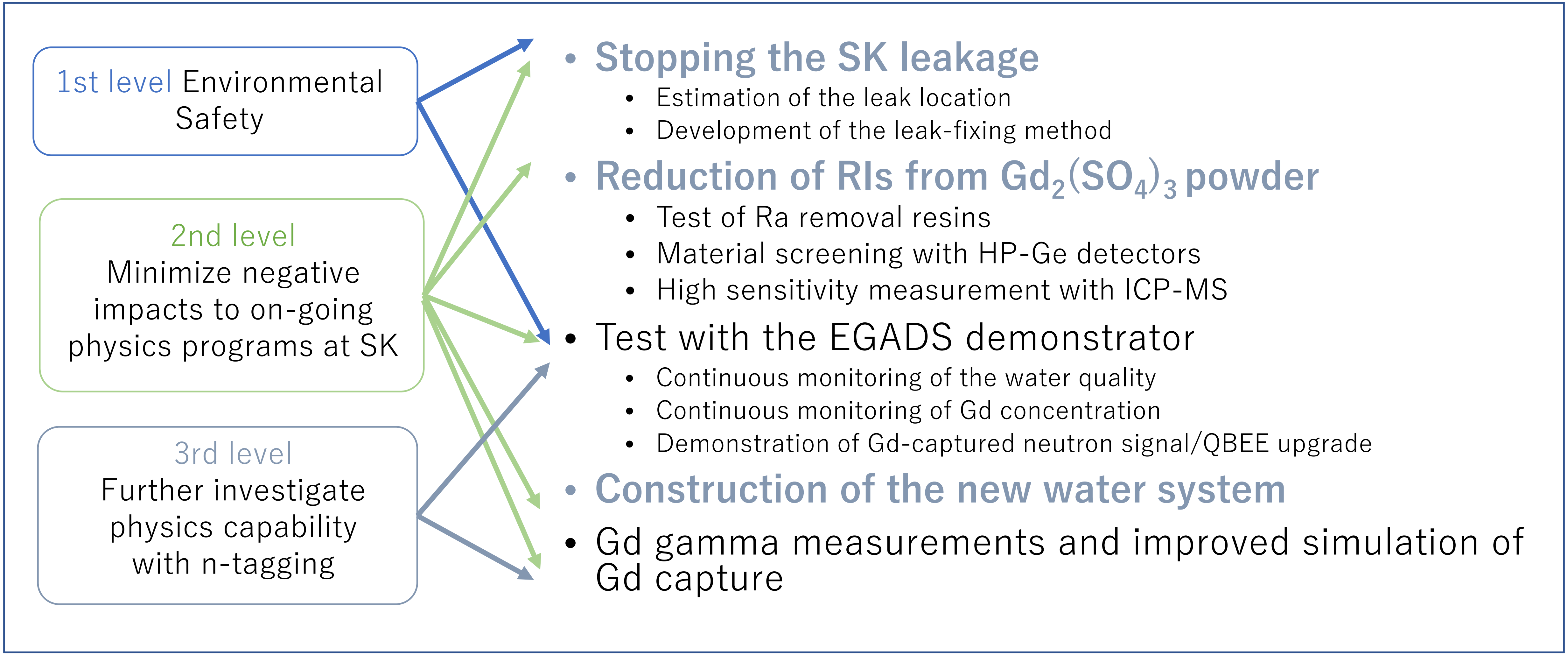
Gd-loading is not trivial!
It's Chemistry!

- Gd metal is not soluble in water. A compound must have been selected.
  - Gadolinium chloride solution rusts even SUS tanks
  - Cherenkov light does not pass through gadolinium nitrate solution
- **Gadolinium sulfate octa-hydrate** $Gd_2(SO_4)_3 \cdot 8H_2O$ was chosen.



Other difficulties we have overcome

R&D items in 2016



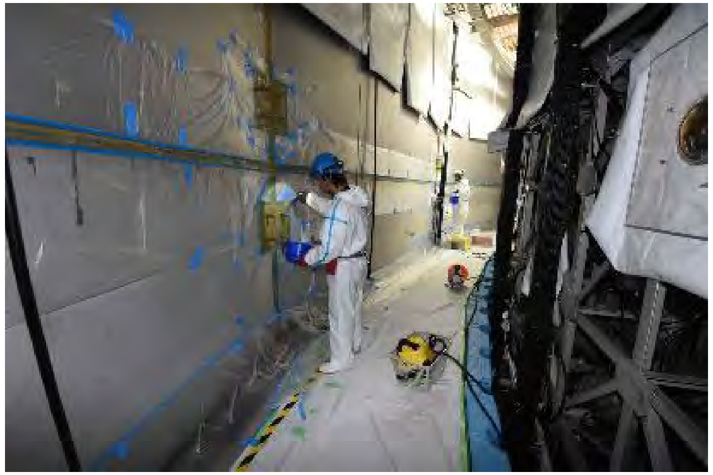
1st level Environmental Safety

2nd level
Minimize negative impacts to on-going physics programs at SK

3rd level
Further investigate physics capability with n-tagging

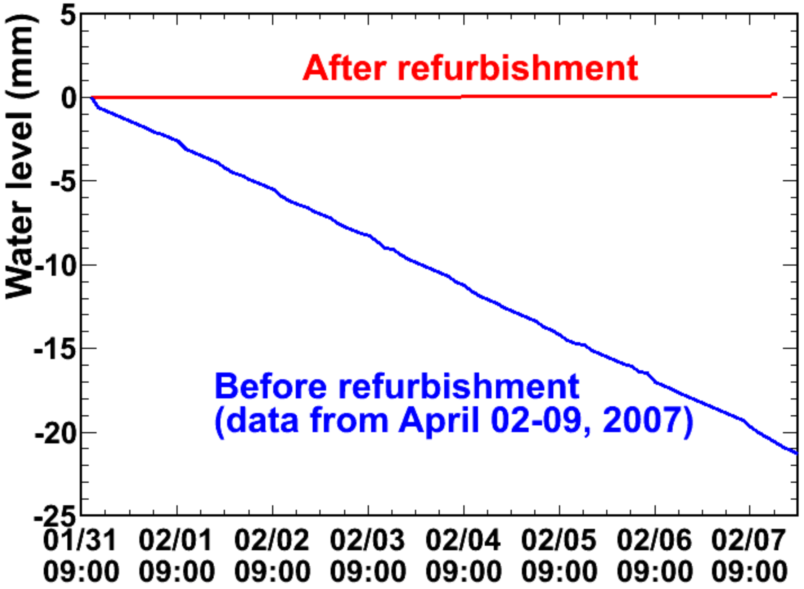
- **Stopping the SK leakage**
  - Estimation of the leak location
  - Development of the leak-fixing method
- **Reduction of RIs from $Gd_2(SO_4)_3$ powder**
  - Test of Ra removal resins
  - Material screening with HP-Ge detectors
  - High sensitivity measurement with ICP-MS
- Test with the EGADS demonstrator
  - Continuous monitoring of the water quality
  - Continuous monitoring of Gd concentration
  - Demonstration of Gd-captured neutron signal/QBEE upgrade
- **Construction of the new water system**
- Gd gamma measurements and improved simulation of Gd capture

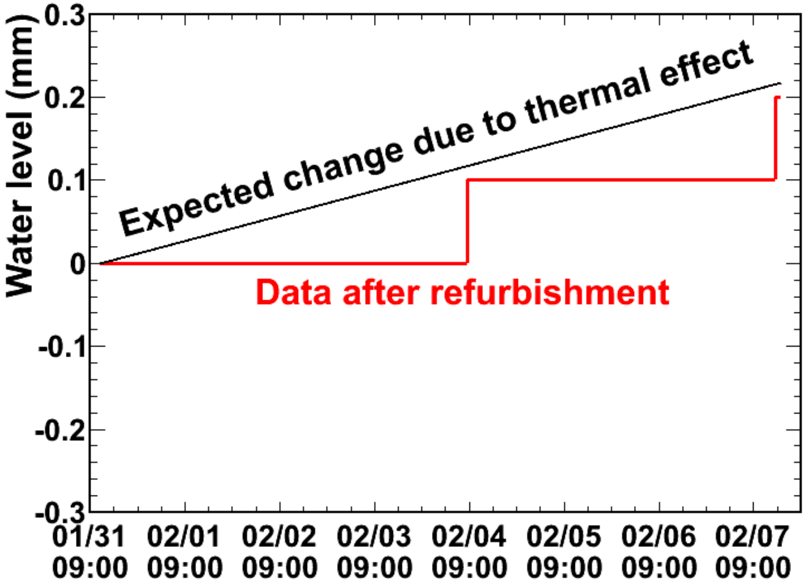
Stopping the SK leakage



The tank was refurbished with water sealing by painting resin on all the welding line from May 31, 2018, to January 29, 2019.

- After the work, ultrapure water was filled in the tank. A leak test was conducted; the change in water level in the tank was measured from 11:30 on January 31, 2019, to 15:52 on February 7, 2019.





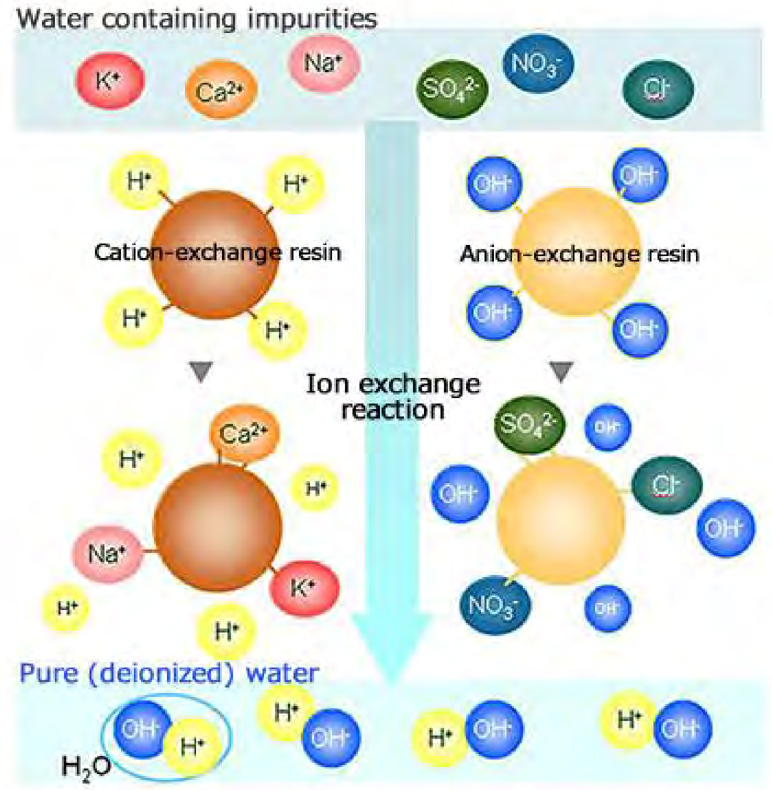
No significant water leakage was observed (less than 17 liters per day).

→Gd-loading ready!

Water purification

Gd sulfate could not be introduced with the original SK water system designed to remove all the impurities other than H_2O.

Key technology:
Ion exchange resin

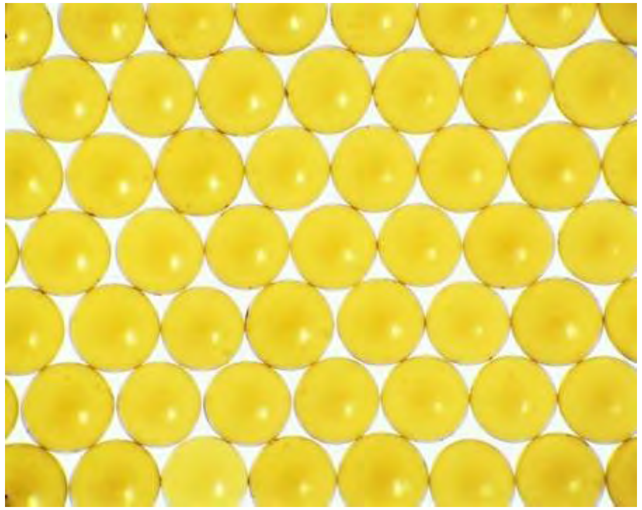


Development of special ion exchange resins

Anion exchange resin $OH^- \rightarrow SO_4^{2-}$

Cation exchange resin $H^+ \rightarrow Gd^{3+}$

RI impurities (Ra^{2+}, $UO_2(SO_4)_3^{4-}$ etc.) are also removed.



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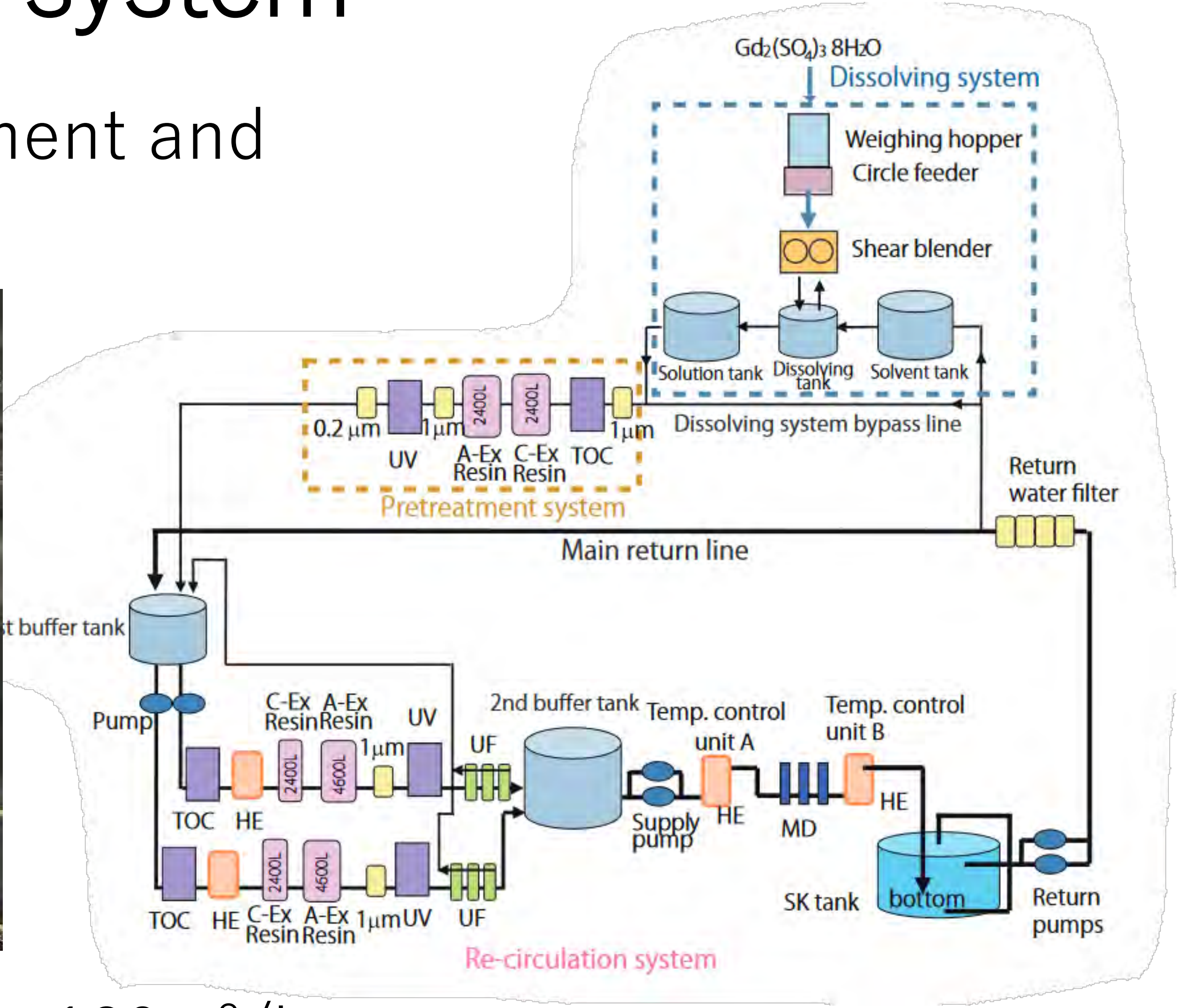
Pretreat + Recirculation system

- The resins are used for pretreatment and circulatory purification



- The flow rate has been doubled to 120m^3/h

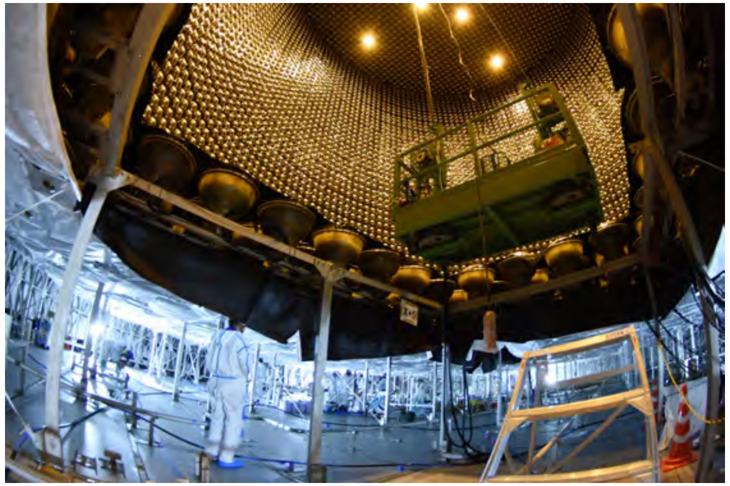
2 x 60m^3/h for maintenance

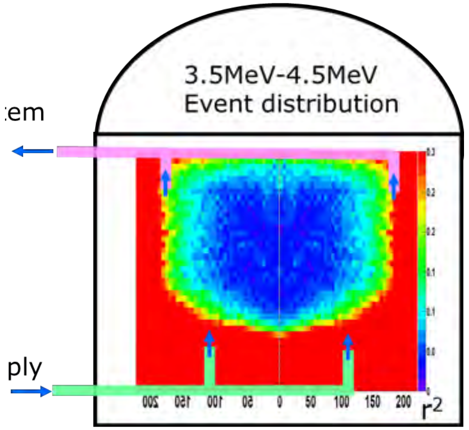
Piping upgrade and modification of outlets

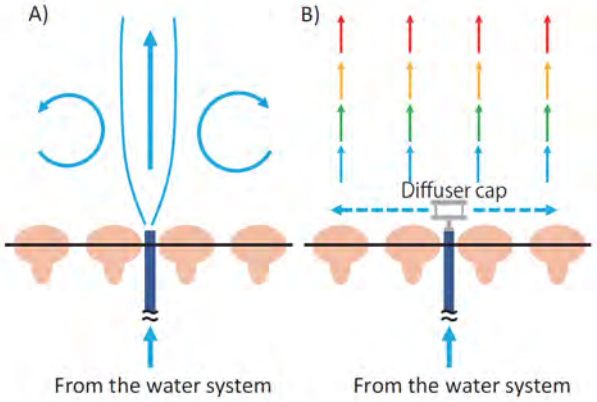
For doubling the circulation flow rate

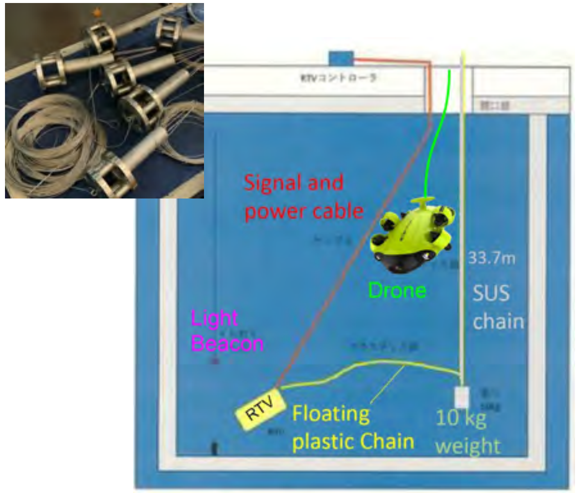
To avoid convection currents rolling up the Rn at the bottom of the tank.

Pipe upgrade in 2018



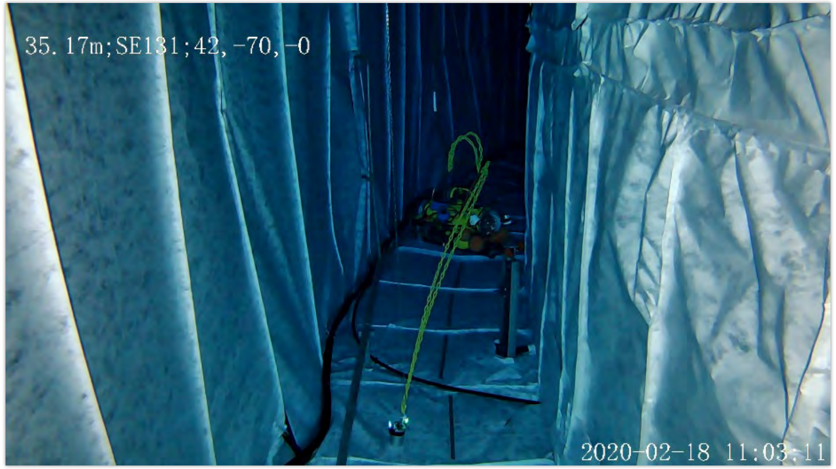






Outlet modification in 2020

Caps were put by RTV

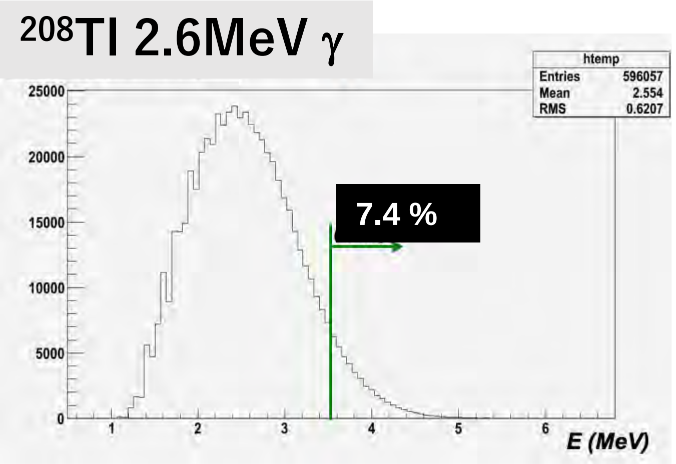


Required purity of $Gd_2(SO_4)_3{\cdot}8H_2O$

- Radioactive impurities (^{238}U, ^{232}Th, etc.) affect SK's solar neutrino observations above 3.5MeV due to energy resolution.
- 99.999% high purity products contain 50~100 mBq/kg of RIs.

RI levels of Typical 5N $Gd_2(SO_4)_3{\cdot}8H_2O$ → Simulated energy spectra

Chain	Main sub-chain isotope	Radioactive concentration (mBq/kg)
^{238}U	^{238}U	50
	^{226}Ra	5
^{232}Th	^{228}Ra	10
	^{228}Th	100
^{235}U	^{235}U	32
	^{227}Ac/ ^{227}Th	300



→ After cuts applied

~3 x 10 ^{5} events/day/ FV

SK-IV Rn BG for solar neutrino analysis ~200events/day/FV

→ 3 orders reduction

The difficulty;

- Homogeneous production of more than 10 tons
- Evaluation methods

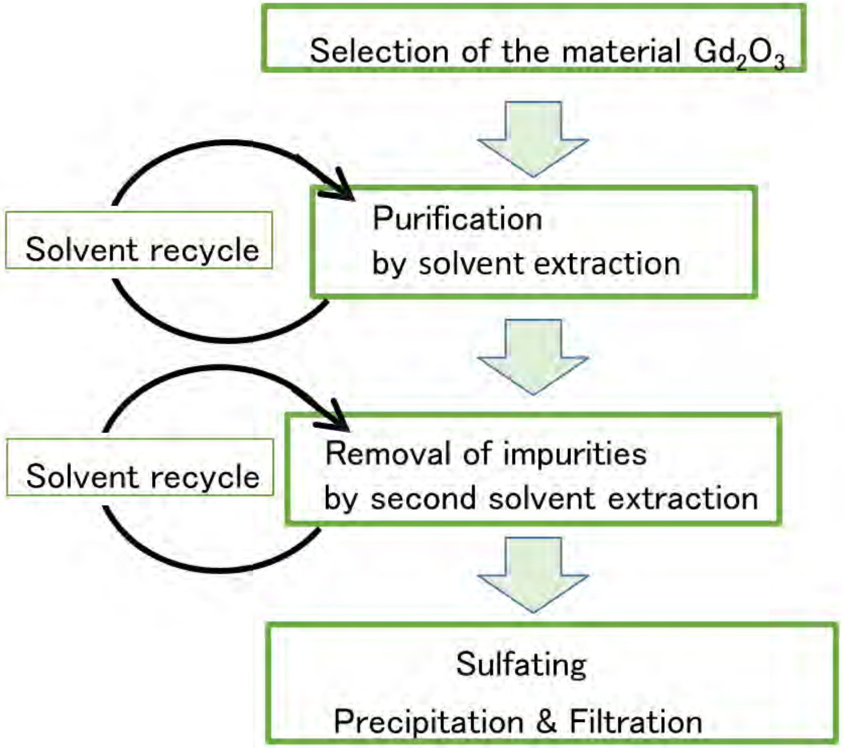
Required RI levels

^{238}U < 5mBq/kg = 400 ppt

^{232}Th < 0.05mBq/kg = 13ppt

Preparation of 13 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$

- Development with a rare earth company (Nippon Yttrium Co., Ltd.)
- Dedicated solvent extraction process line
  - 13 tons production in 7 months = 2 tons/month
- Evaluation of raw materials and batch-by-batch screening



Selection of the material Gd_2O_3

Solvent recycle

Purification by solvent extraction

Solvent recycle

Removal of impurities by second solvent extraction

Sulfating

Precipitation & Filtration

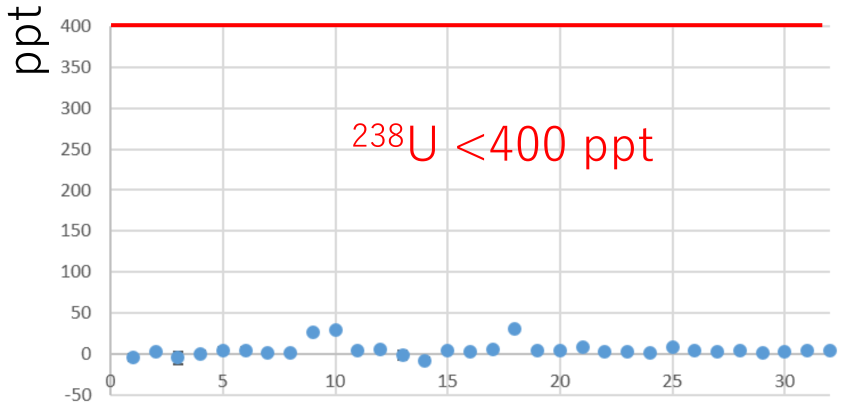
Evaluation of 13 tons of $Gd_2(SO_4)_3{\cdot}8H_2O$

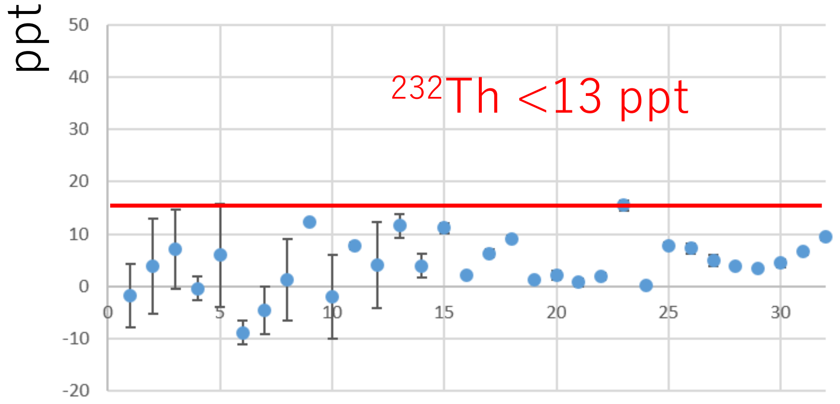
- All the 26 batches are evaluated with **ICP-MS** and **Ge detectors**

ICP-MS: For long lifetime isotopes

Established the method of separation and extraction of U/Th from high Gd concentration solution using resin to evaluate at ppt level

PTEP 2017 11 113H01
PTEP 2019 6 063H03





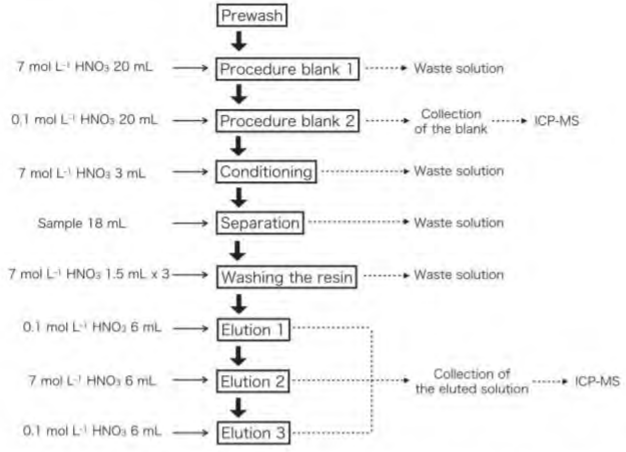
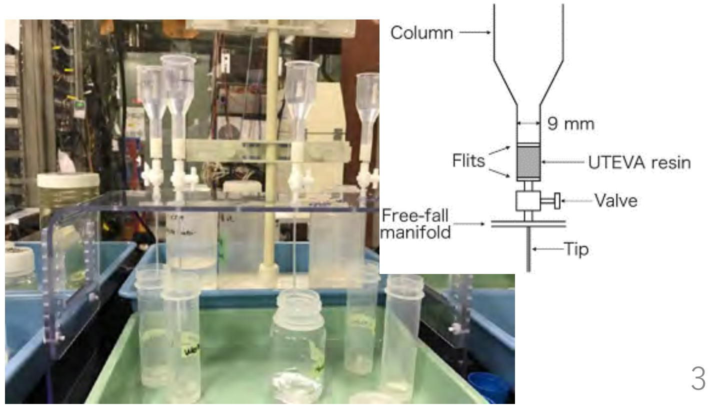


Fig. 6. Diagram of the whole procedure for the solid-phase extraction.



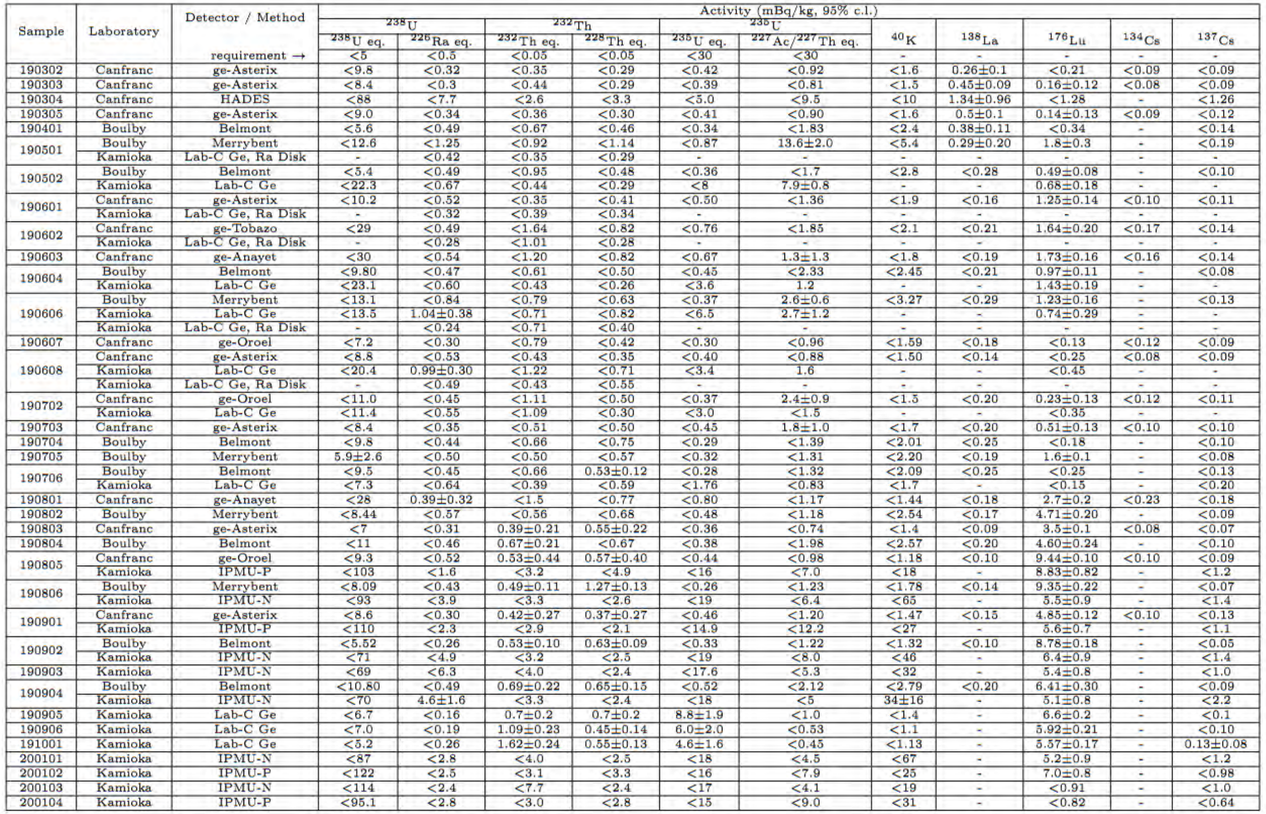
Evaluation of 13 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$

- All the batches are evaluated with ICP-MS and Ge detectors

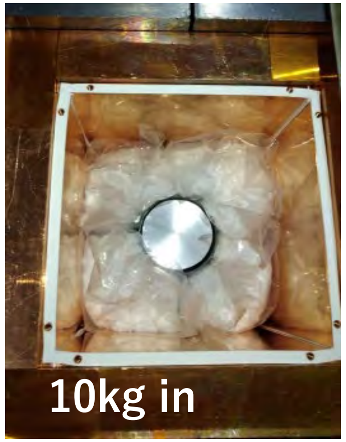
Ge: For short lifetime isotopes

The highest sensitivity (lowest BG Ge) detectors in the world shared the work (Canfranc, Boulby, and Kamioka collaboration)

PTEP under preparation



Sample	Laboratory	Detector / Method	Activity (mBq/kg, 95% c.l.)										
			^{238}U		^{232}Th		^{235}U		^{40}K	^{138}La	^{176}Lu	^{134}Cs	^{137}Cs
			^{238}U eq.	^{226}Ra eq.	^{232}Th eq.	^{228}Th eq.	^{235}U eq.	$^{227}Ac/^{227}Th$ eq.					
		requirement →	<5	<0.5	<0.05	<0.05	<30	<30	-	-	-	-	-
190302	Canfranc	ge-Asterix	<9.8	<0.32	<0.35	<0.29	<0.42	<0.92	<1.6	0.26±0.1	<0.21	<0.09	<0.09
190303	Canfranc	ge-Asterix	<8.4	<0.3	<0.44	<0.29	<0.39	<0.81	<1.5	0.45±0.09	0.16±0.12	<0.08	<0.09
190304	Canfranc	HADES	<88	<7.7	<2.6	<3.3	<5.0	<9.5	<10	1.34±0.96	<1.28	-	<1.26
190305	Canfranc	ge-Asterix	<9.0	<0.34	<0.36	<0.30	<0.41	<0.90	<1.6	0.5±0.1	0.14±0.13	<0.09	<0.12
190401	Boulby	Belmont	<5.6	<0.49	<0.67	<0.46	<0.34	<1.83	<2.4	0.38±0.11	<0.34	-	<0.14
190501	Boulby	Merrybent	<12.6	<1.25	<0.92	<1.14	<0.87	13.6±2.0	<5.4	0.29±0.20	1.8±0.3	-	<0.19
	Kamioka	Lab-C Ge, Ra Disk	-	<0.42	<0.35	<0.29	-	-	-	-	-	-	-
190502	Boulby	Belmont	<5.4	<0.49	<0.95	<0.48	<0.36	<1.7	<2.8	<0.28	0.49±0.08	-	<0.10
	Kamioka	Lab-C Ge	<22.3	<0.67	<0.44	<0.29	<8	7.9±0.8	-	-	0.68±0.18	-	-
190601	Canfranc	ge-Asterix	<10.2	<0.52	<0.35	<0.41	<0.50	<1.36	<1.9	<0.16	1.25±0.14	<0.10	<0.11
	Kamioka	Lab-C Ge, Ra Disk	-	<0.32	<0.39	<0.34	-	-	-	-	-	-	-
190602	Canfranc	ge-Tobazo	<29	<0.49	<1.64	<0.82	<0.76	<1.85	<2.1	<0.21	1.64±0.20	<0.17	<0.14
	Kamioka	Lab-C Ge, Ra Disk	-	<0.28	<1.01	<0.28	-	-	-	-	-	-	-
190603	Canfranc	ge-Anayet	<30	<0.54	<1.20	<0.82	<0.67	1.3±1.3	<1.8	<0.19	1.73±0.16	<0.16	<0.14
190604	Boulby	Belmont	<9.80	<0.47	<0.61	<0.50	<0.45	<2.33	<2.45	<0.21	0.97±0.11	-	<0.08
	Kamioka	Lab-C Ge	<23.1	<0.60	<0.43	<0.26	<3.6	1.2	-	-	1.43±0.19	-	-
190606	Boulby	Merrybent	<13.1	<0.84	<0.79	<0.63	<0.37	2.6±0.6	<3.27	<0.29	1.23±0.16	-	<0.13
	Kamioka	Lab-C Ge	<13.5	1.04±0.38	<0.71	<0.82	<6.5	2.7±1.2	-	-	0.74±0.29	-	-
	Kamioka	Lab-C Ge, Ra Disk	-	<0.24	<0.71	<0.40	-	-	-	-	-	-	-
190607	Canfranc	ge-Oroel	<7.2	<0.30	<0.79	<0.42	<0.30	<0.96	<1.59	<0.18	<0.13	<0.12	<0.09
190608	Canfranc	ge-Asterix	<8.8	<0.53	<0.43	<0.35	<0.40	<0.88	<1.50	<0.14	<0.25	<0.08	<0.09
	Kamioka	Lab-C Ge	<20.4	0.99±0.30	<1.22	<0.71	<3.4	1.6	-	-	<0.45	-	-
	Kamioka	Lab-C Ge, Ra Disk	-	<0.49	<0.43	<0.55	-	-	-	-	-	-	-
190702	Canfranc	ge-Oroel	<11.0	<0.45	<1.11	<0.50	<0.37	2.4±0.9	<1.5	<0.20	0.23±0.13	<0.12	<0.11
	Kamioka	Lab-C Ge	<11.4	<0.55	<1.09	<0.30	<3.0	<1.5	-	-	<0.35	-	-
190703	Canfranc	ge-Asterix	<8.4	<0.35	<0.51	<0.50	<0.45	1.8±1.0	<1.7	<0.20	0.51±0.13	<0.10	<0.10
190704	Boulby	Belmont	<9.8	<0.44	<0.66	<0.75	<0.29	<1.39	<2.01	<0.25	<0.18	-	<0.10
190705	Boulby	Merrybent	5.9±2.6	<0.50	<0.50	<0.57	<0.32	<1.31	<2.20	<0.19	1.6±0.1	-	<0.08
190706	Boulby	Belmont	<9.5	<0.45	<0.66	0.53±0.12	<0.28	<1.32	<2.09	<0.25	<0.25	-	<0.13
	Kamioka	Lab-C Ge	<7.3	<0.64	<0.39	<0.59	<1.76	<0.83	<1.7	-	<0.15	-	<0.20
190801	Canfranc	ge-Anayet	<28	0.39±0.32	<1.5	<0.77	<0.80	<1.17	<1.44	<0.18	2.7±0.2	<0.23	<0.18
190802	Boulby	Merrybent	<8.44	<0.57	<0.56	<0.68	<0.48	<1.18	<2.54	<0.17	4.71±0.20	-	<0.09
190803	Canfranc	ge-Asterix	<7	<0.31	0.39±0.21	0.55±0.22	<0.36	<0.74	<1.4	<0.09	3.5±0.1	<0.08	<0.07
190804	Boulby	Belmont	<11	<0.46	0.67±0.21	<0.67	<0.38	<1.98	<2.57	<0.20	4.60±0.24	-	<0.10
190805	Canfranc	ge-Oroel	<9.3	<0.52	0.53±0.44	0.57±0.40	<0.44	<0.98	<1.18	<0.10	9.44±0.10	<0.10	<0.09
	Kamioka	IPMU-P	<103	<1.6	<3.2	<4.9	<16	<7.0	<18	-	8.83±0.82	-	<1.2
190806	Boulby	Merrybent	<8.09	<0.43	0.49±0.11	1.27±0.13	<0.26	<1.23	<1.78	<0.14	9.35±0.22	-	<0.07
	Kamioka	IPMU-N	<93	<3.9	<3.3	<2.6	<19	<6.4	<65	-	5.5±0.9	-	<1.4
190901	Canfranc	ge-Asterix	<8.6	<0.30	0.42±0.27	0.37±0.27	<0.46	<1.20	<1.47	<0.15	4.85±0.12	<0.10	<0.13
	Kamioka	IPMU-P	<110	<2.3	<2.9	<2.1	<14.9	<12.2	<27	-	5.6±0.7	-	<1.1
190902	Boulby	Belmont	<5.52	<0.26	0.53±0.10	0.63±0.09	<0.33	<1.22	<1.32	<0.10	8.78±0.18	-	<0.05
	Kamioka	IPMU-N	<71	<4.9	<3.2	<2.5	<19	<8.0	<46	-	6.4±0.9	-	<1.4
190903	Kamioka	IPMU-N	<69	<6.3	<4.0	<2.4	<17.6	<5.3	<32	-	5.4±0.8	-	<1.0
190904	Boulby	Belmont	<10.80	<0.49	0.69±0.22	0.65±0.15	<0.52	<2.12	<2.79	<0.20	6.41±0.30	-	<0.09
	Kamioka	IPMU-N	<70	4.6±1.6	<3.3	<2.4	<18	<5	34±16	-	5.1±0.8	-	<2.2
190905	Kamioka	Lab-C Ge	<6.7	<0.16	0.7±0.2	0.7±0.2	8.8±1.9	<1.0	<1.4	-	6.6±0.2	-	<0.1
190906	Kamioka	Lab-C Ge	<7.0	<0.19	1.09±0.23	0.45±0.14	6.0±2.0	<0.53	<1.1	-	5.92±0.21	-	<0.10
191001	Kamioka	Lab-C Ge	<5.2	<0.26	1.62±0.24	0.55±0.13	4.6±1.6	<0.45	<1.13	-	5.57±0.17	-	0.13±0.08
200101	Kamioka	IPMU-N	<87	<2.8	<4.0	<2.5	<18	<4.5	<67	-	5.2±0.9	-	<1.2
200102	Kamioka	IPMU-P	<122	<2.5	<3.1	<3.3	<16	<7.9	<25	-	7.0±0.8	-	<0.98
200103	Kamioka	IPMU-N	<114	<2.4	<7.7	<2.4	<17	<4.1	<19	-	<0.91	-	<1.0
200104	Kamioka	IPMU-P	<95.1	<2.8	<3.0	<2.8	<15	<9.0	<31	-	<0.82	-	<0.64



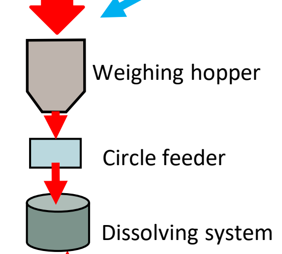
Ra-disk method

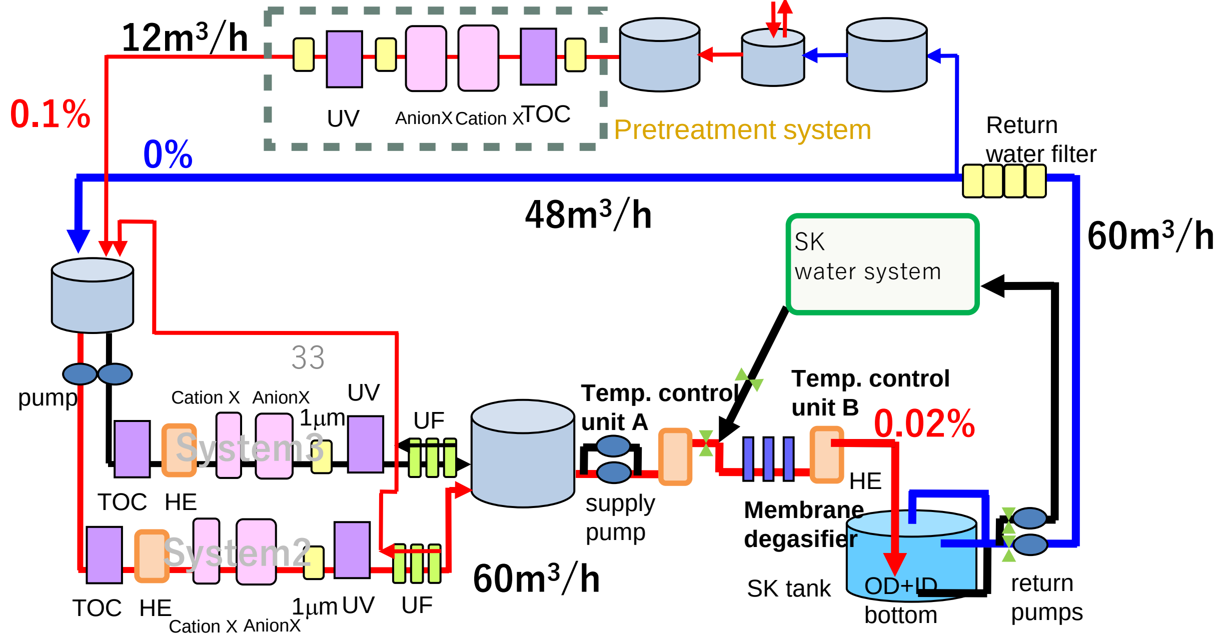
The Gd-loading Jul. 14 – Aug. 18, 2020

The pure water in the SK tank was taken from the top and returned from the bottom in **0.02% $Gd_2(SO_4)_3$** solution **(=0.01% Gd = 0.026% $Gd_2(SO_4)_3 \cdot 8H_2O$**)
It took 35 days to replace 50,000 tons of water at 60 m^3/h

One batch:
8.2 kg of $Gd_2(SO_4)_3 \cdot 8H_2O$
＋ 768 L of SK water

Repeated every 30 minutes for 24 hours for 35 consecutive days





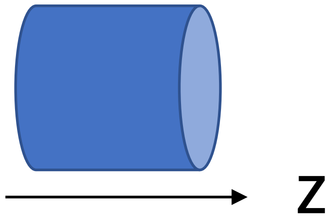
Just after mixing

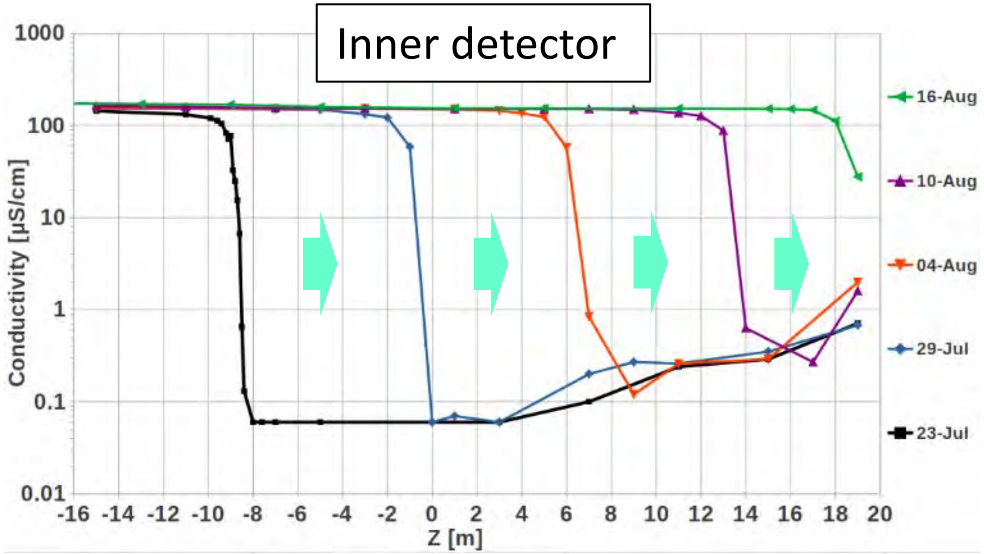
10minutes later

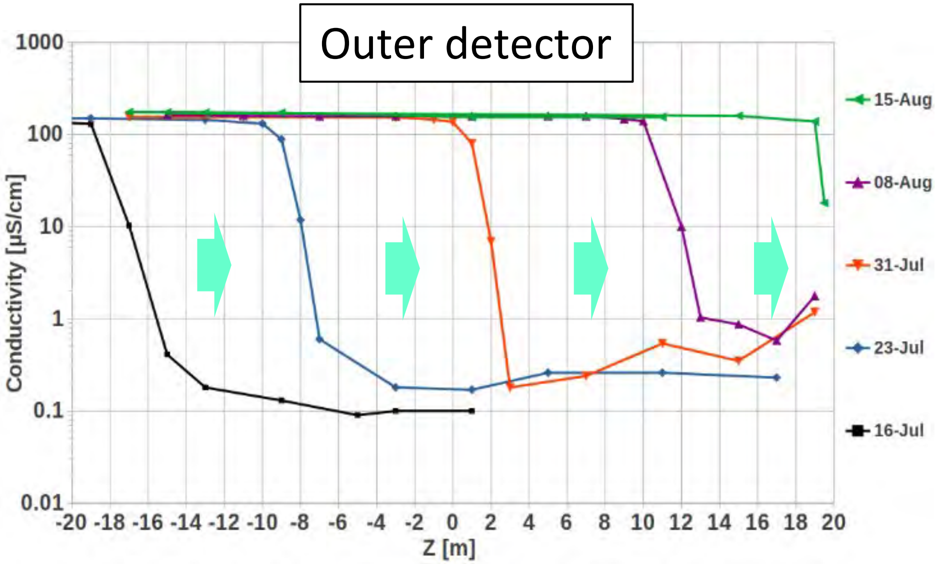
Gd concentration check during the loading

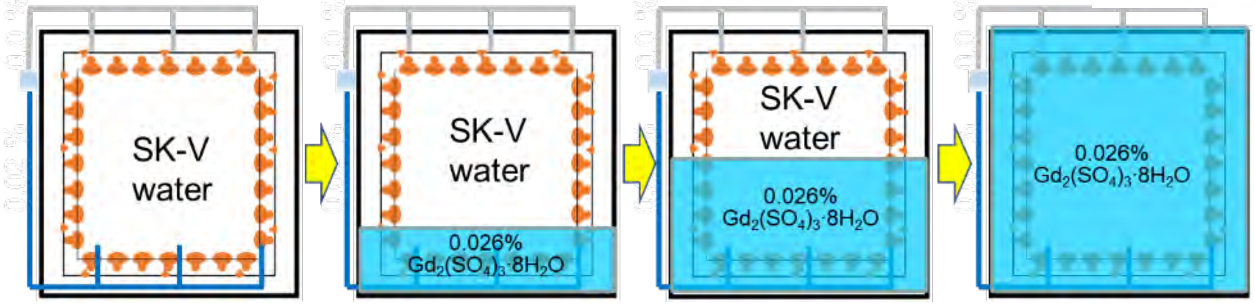
Sampled water directly from various positions in the tank, and its conductivity was measured

Aug.15
Aug.10
Aug. 4
Jul.29
Jul. 23





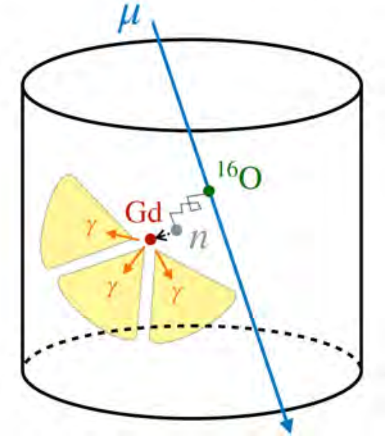


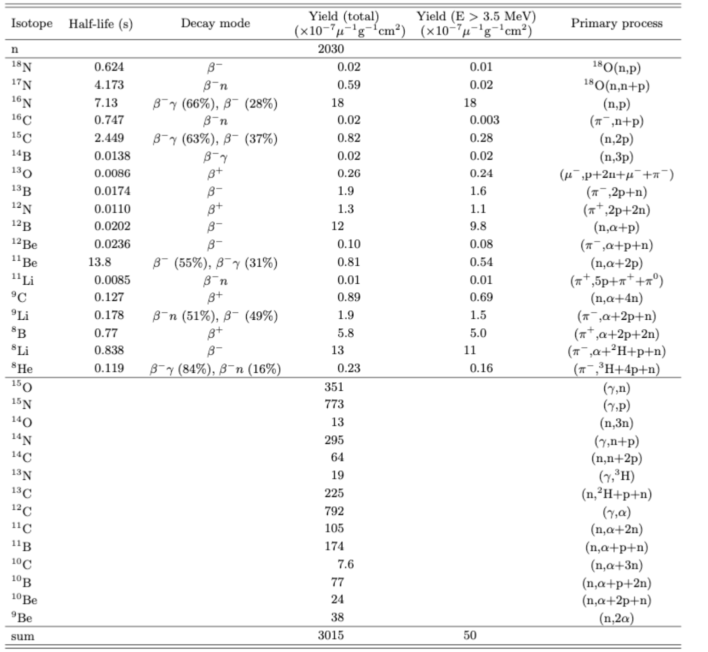


Confirmed Gd built up from the bottom of the tank

Spallation neutron for Gd check

- **Simply selected μ-induced spallation neutrons were used for Gd concentration monitoring**



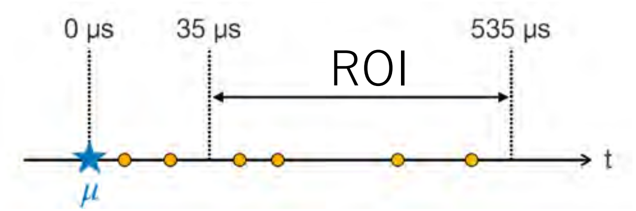


Isotope	Half-life (s)	Decay mode	Yield (total) ($\times10^{-7}\mu^{-1}g^{-1}cm^2$)	Yield (E > 3.5 MeV) ($\times10^{-7}\mu^{-1}g^{-1}cm^2$)	Primary process
n			2030		
^{18}N	0.624	β^-	0.02	0.01	^{18}O(n,p)
^{17}N	4.173	$\beta^- n$	0.59	0.02	^{18}O(n,n+p)
^{16}N	7.13	$\beta^-\gamma$ (66%), β^- (28%)	18	18	(n,p)
^{16}C	0.747	$\beta^- n$	0.02	0.003	(π^-,n+p)
^{15}C	2.449	$\beta^-\gamma$ (63%), β^- (37%)	0.82	0.28	(n,2p)
^{14}B	0.0138	$\beta^-\gamma$	0.02	0.02	(n,3p)
^{13}O	0.0086	β^+	0.26	0.24	(μ^-,p+2n+μ^-+π^-)
^{13}B	0.0174	β^-	1.9	1.6	(π^-,2p+n)
^{12}N	0.0110	β^+	1.3	1.1	(π^+,2p+2n)
^{12}B	0.0202	β^-	12	9.8	(n,α+p)
^{12}Be	0.0236	β^-	0.10	0.08	(π^-,α+p+n)
^{11}Be	13.8	β^- (55%), $\beta^-\gamma$ (31%)	0.81	0.54	(n,α+2p)
^{11}Li	0.0085	$\beta^- n$	0.01	0.01	(π^+,5p+π^++π^0)
^{9}C	0.127	β^+	0.89	0.69	(n,α+4n)
^{9}Li	0.178	$\beta^- n$ (51%), β^- (49%)	1.9	1.5	(π^-,α+2p+n)
^{8}B	0.77	β^+	5.8	5.0	(π^+,α+2p+2n)
^{8}Li	0.838	β^-	13	11	(π^-,α+^{2}H+p+n)
^{8}He	0.119	$\beta^-\gamma$ (84%), $\beta^- n$ (16%)	0.23	0.16	(π^-,^{3}H+4p+n)
^{15}O			351		(γ,n)
^{15}N			773		(γ,p)
^{14}O			13		(n,3n)
^{14}N			295		(γ,n+p)
^{14}C			64		(n,n+2p)
^{13}N			19		(γ,^{3}H)
^{13}C			225		(n,^{2}H+p+n)
^{12}C			792		(γ,α)
^{11}C			105		(n,α+2n)
^{11}B			174		(n,α+p+n)
^{10}C			7.6		(n,α+3n)
^{10}B			77		(n,α+p+2n)
^{10}Be			24		(n,α+2p+n)
^{9}Be			38		(n,2α)
sum			3015	50	

List of spallation products

S.Li and J.Beacom,
Phys. Rev. C 89, 045801 (2014)

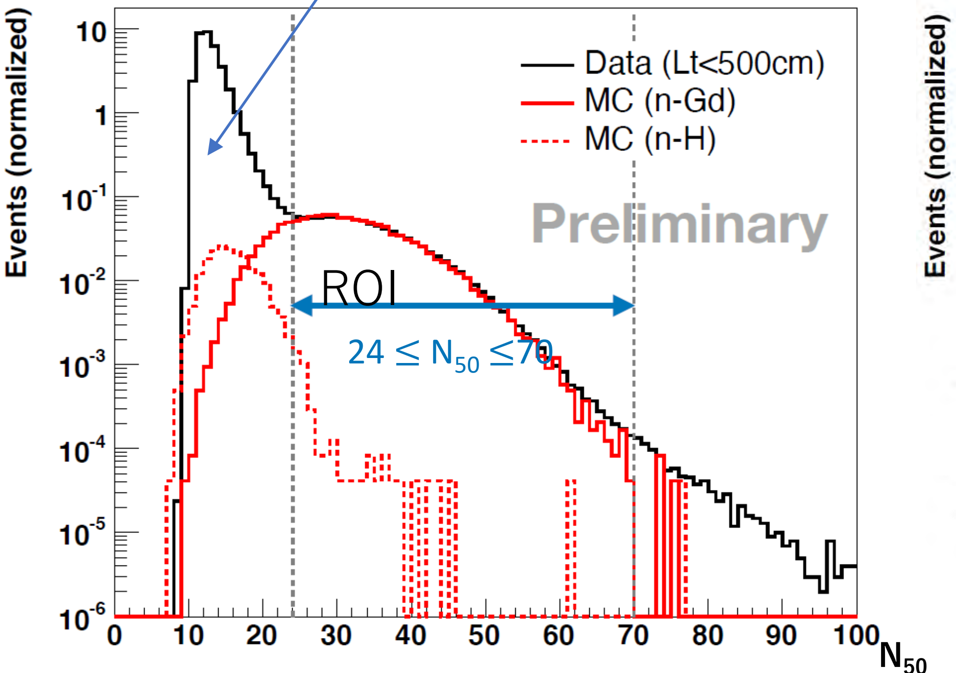
Timing selection



- Michel decay-e ~2.2μs
- Neutron thermalization ~4.3μs
- PMT after pulses 10~20μs

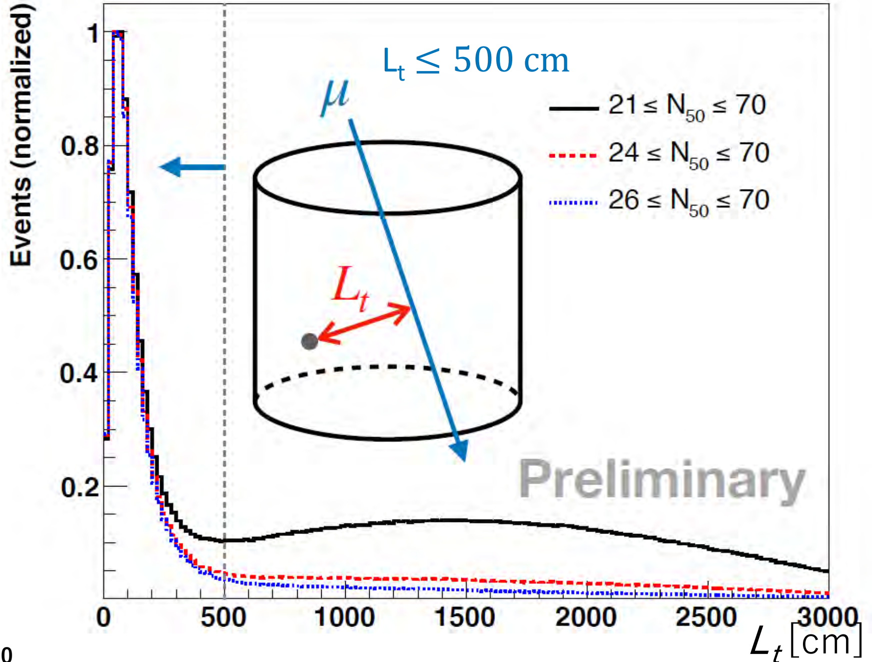
N_{50} selection

RI events etc

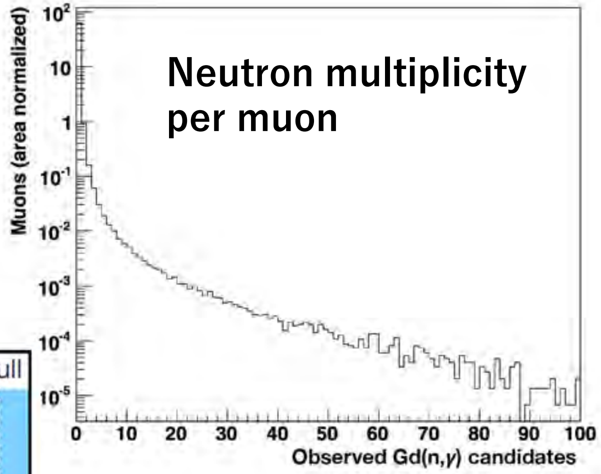


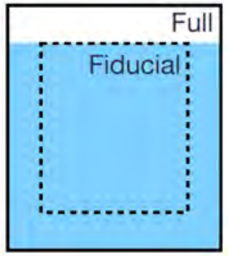
Distance to μ track selection

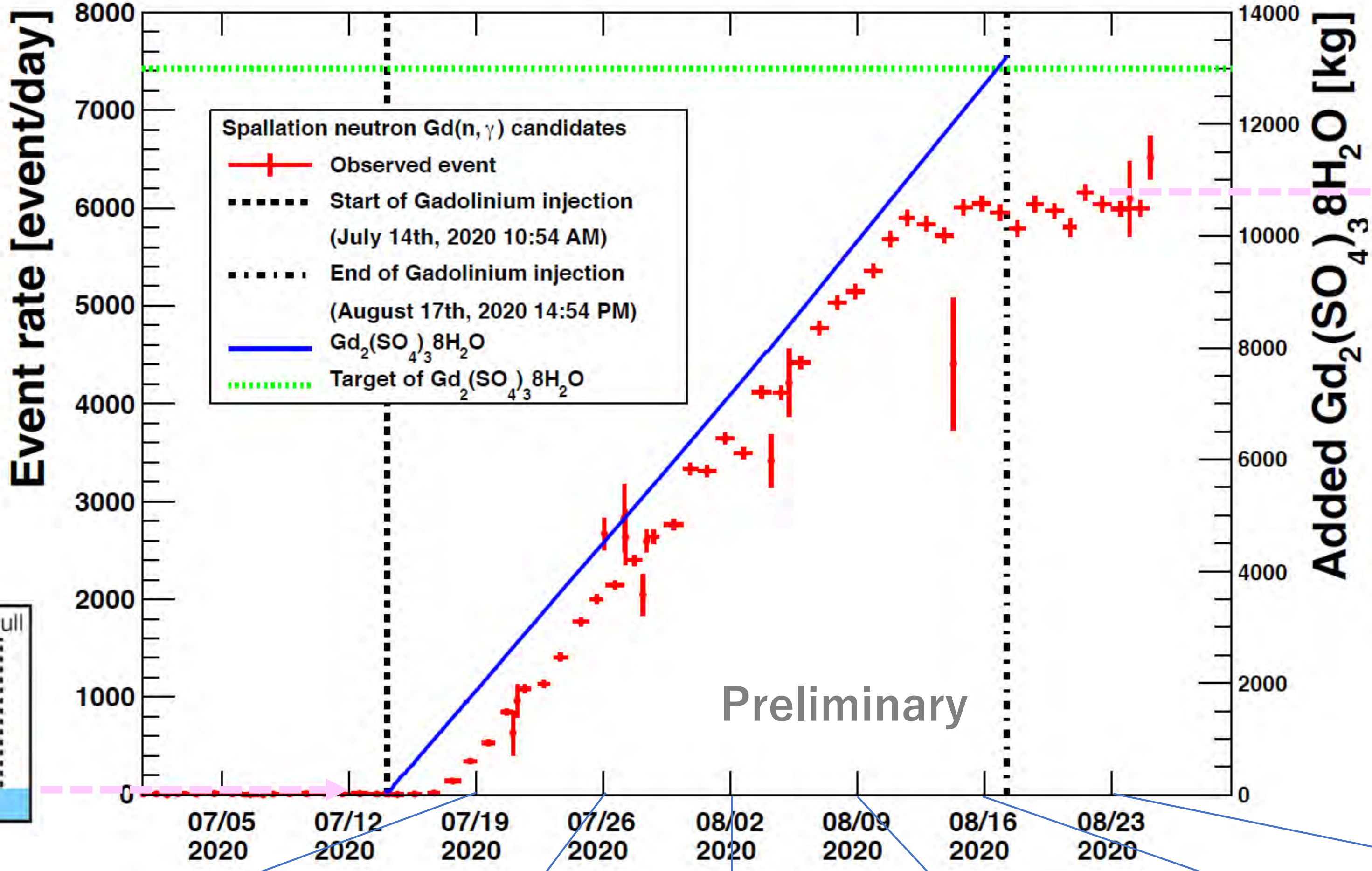
Neutron capture occurs near the muon track.

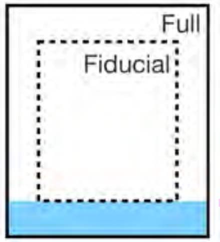


Neutron event rates vs. Gd-loading

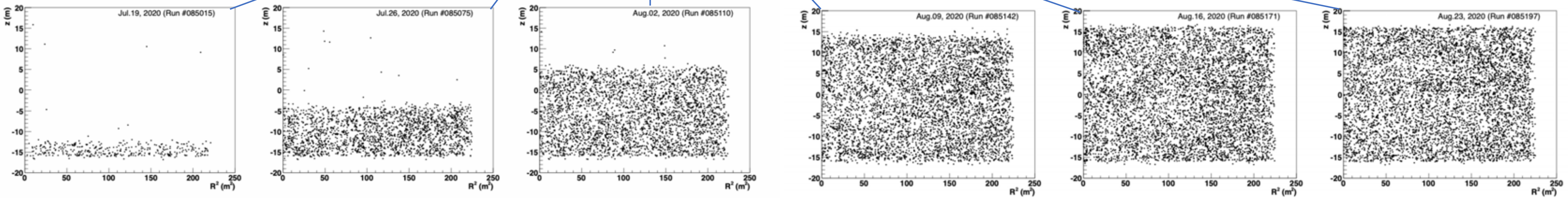








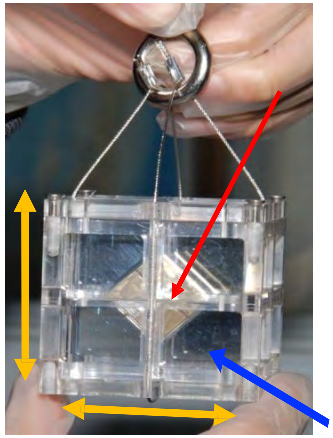
Confirmed Gd built up from the bottom of the tank



Gd concentration check after loading

- Neutron capture time is sensitive to Gd concentration.

Am/Be neutron source was deployed in SK



8 BGO Crystals

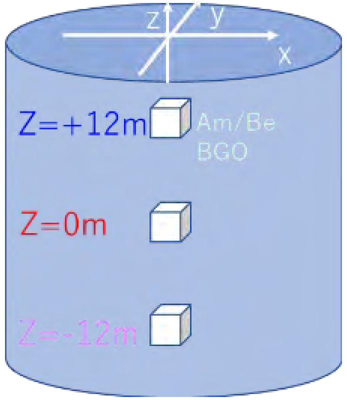
Am/Be neutron source

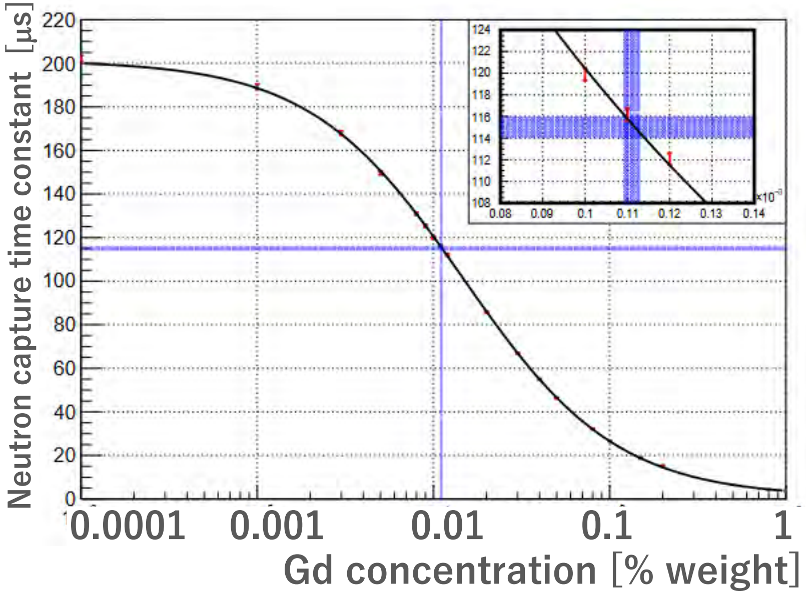
100~200 neutrons/s

$^{241}\mathrm{Am} \rightarrow {}^{237}\mathrm{Np} + \alpha$

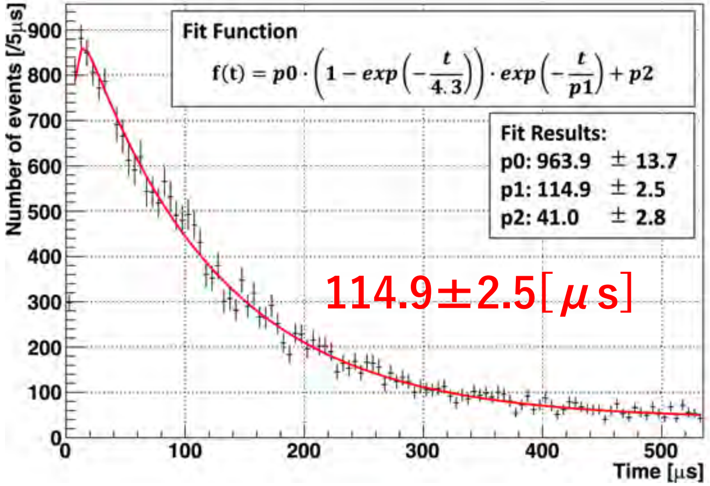
$^{9}\mathrm{Be} + \alpha \rightarrow {}^{13}\mathrm{C}^{*} + \mathrm{n}\ (2\text{-}6\ \mathrm{MeV})$

$^{13}\mathrm{C}^{*} \rightarrow {}^{12}\mathrm{C} + \gamma\ (4.43\ \mathrm{MeV})$





Time difference between scintillation and neutron capture γ-rays as of September 29, 2020



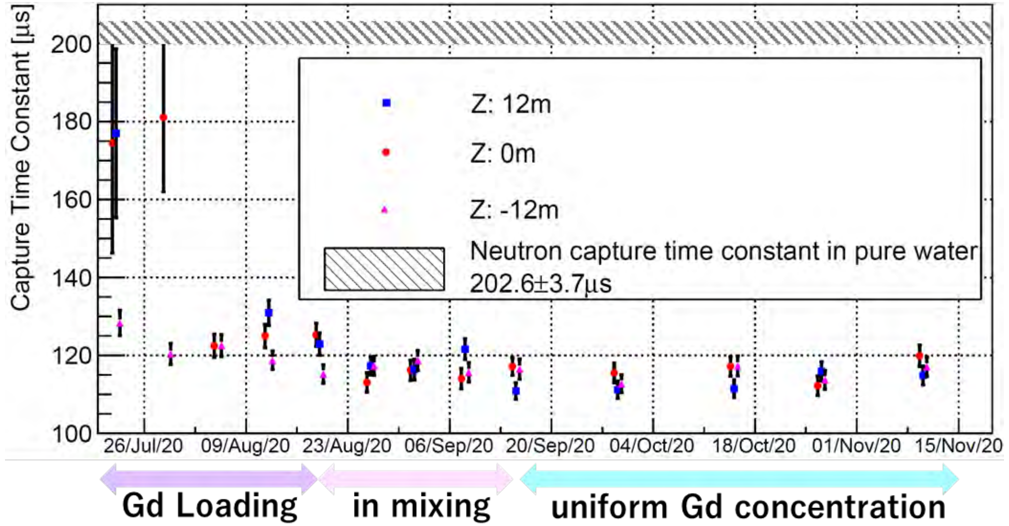
Fit Function

$$f(t) = p0 \cdot \left(1 - exp\left(-\frac{t}{4.3}\right)\right) \cdot exp\left(-\frac{t}{p1}\right) + p2$$

Fit Results:
p0: 963.9 ± 13.7
p1: 114.9 ± 2.5
p2: 41.0 ± 2.8

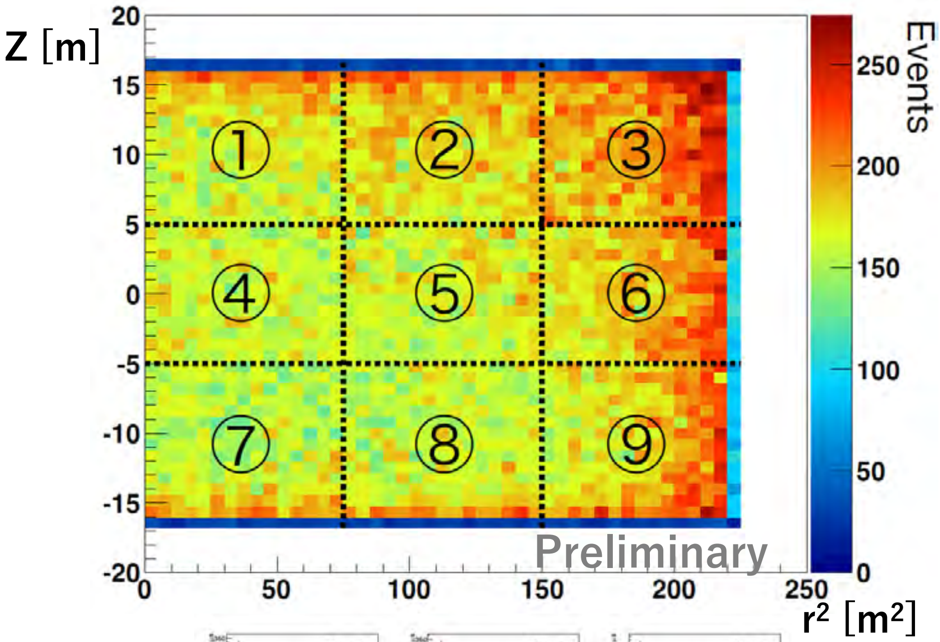
114.9±2.5[μs]

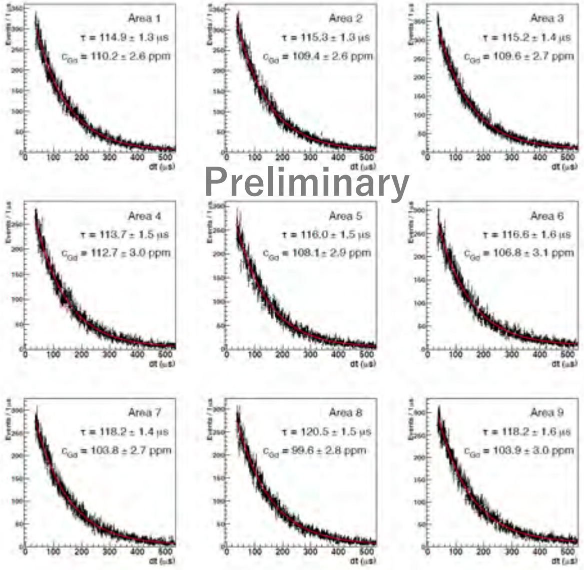
Every two weeks

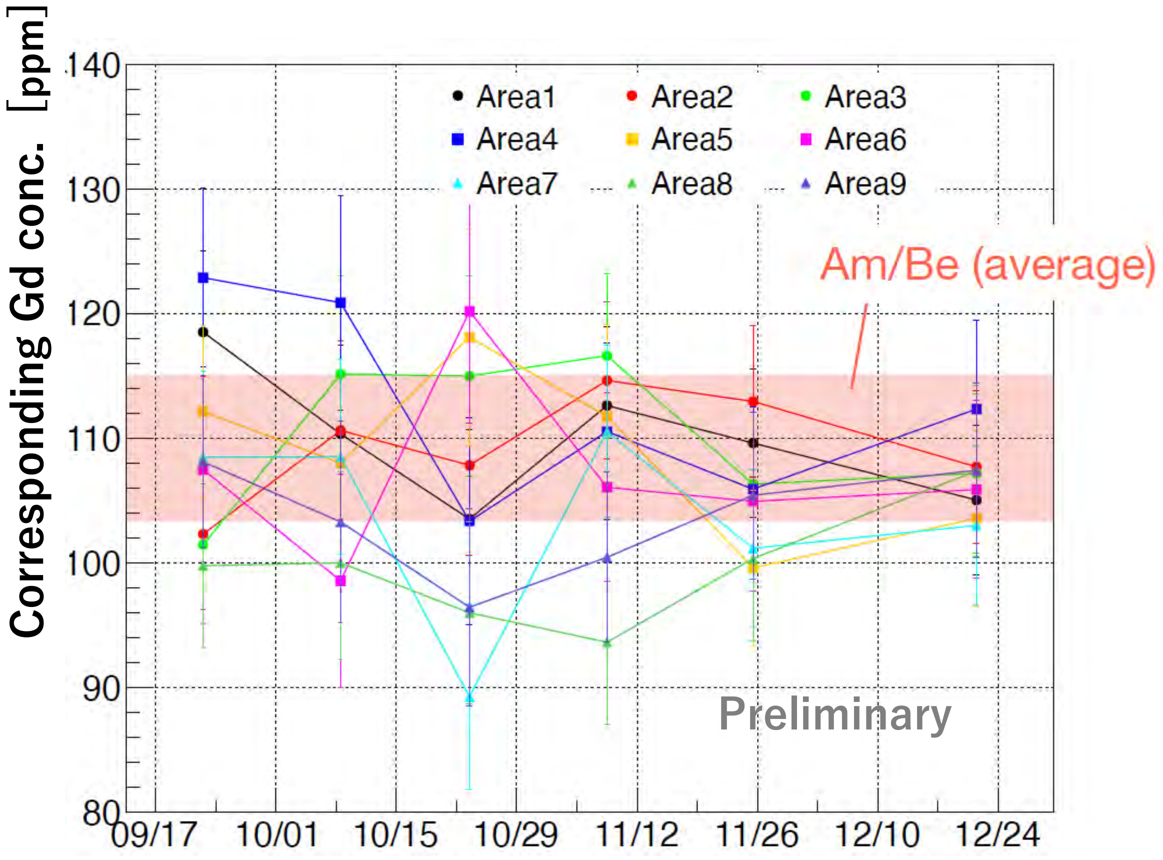


Since September 2020:
The average capture time
115.6±0.6 μs
=>Gd concentration
110.9±1.4 ppm

Uniformity check by spallation neutron





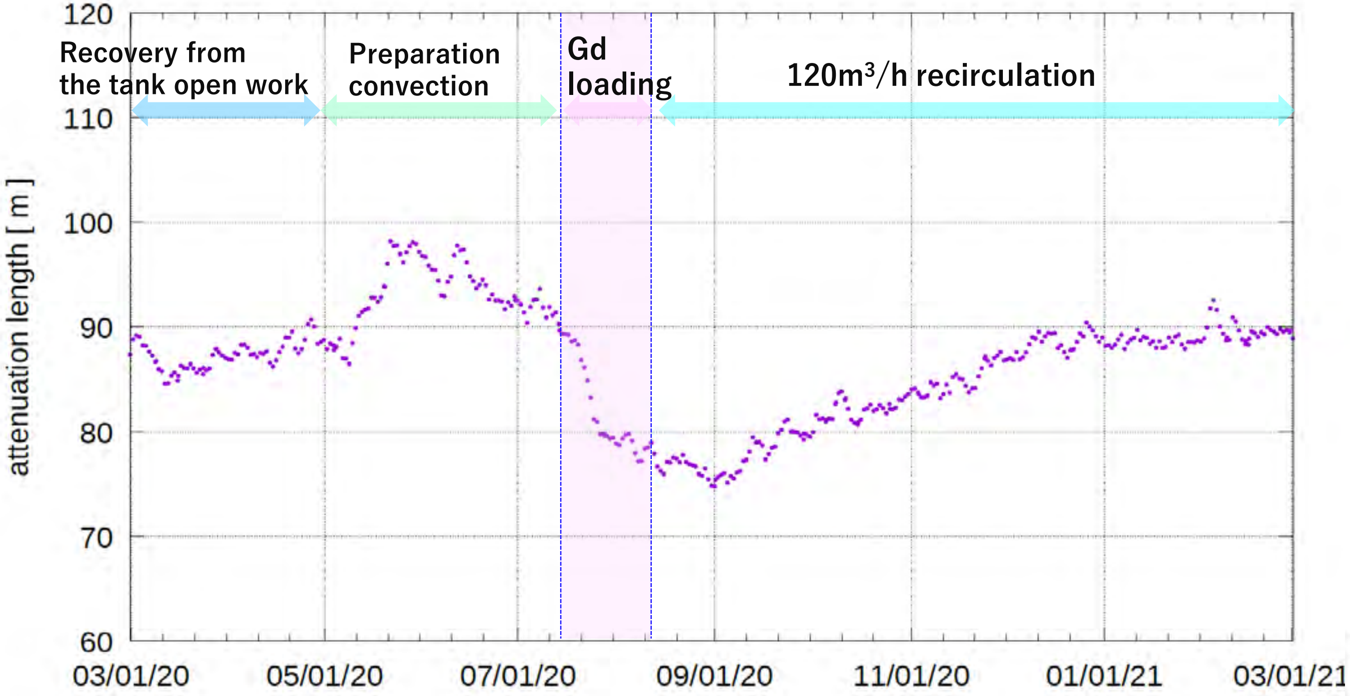


The position dependence has been decreased.

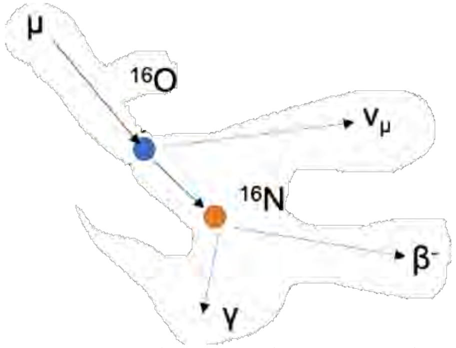
The Gd concentration has become uniform throughout the tank.

Water transparency and energy scale

- The same level of transparency as that of pure water phase

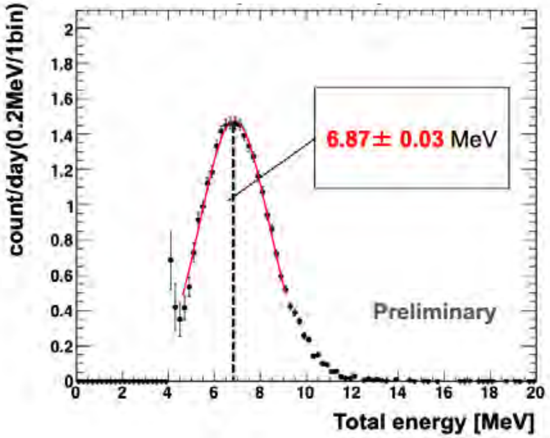


- Energy scale compared between SK-IV and SK-VI using ^{16}N decay events from cosmic μ captured ^{16}O

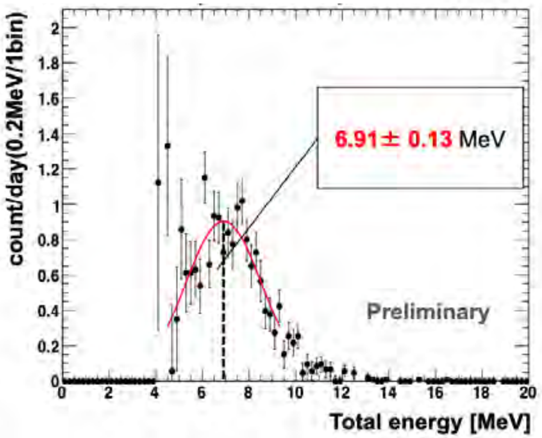


$^{16}N \rightarrow \beta^-(Q\ 4.3\text{MeV}) + \gamma(6.1\text{MeV})$ BR: 66.2%
$\beta^-(Q\ 10.4\text{MeV})$ BR:28.0%
$\beta^-(Q\ 3.3\text{MeV}) + \gamma(7.1\text{MeV})$ BR: 4.8%

SK-IV 2970days (before Gd)



SK-VI 106days (after Gd)



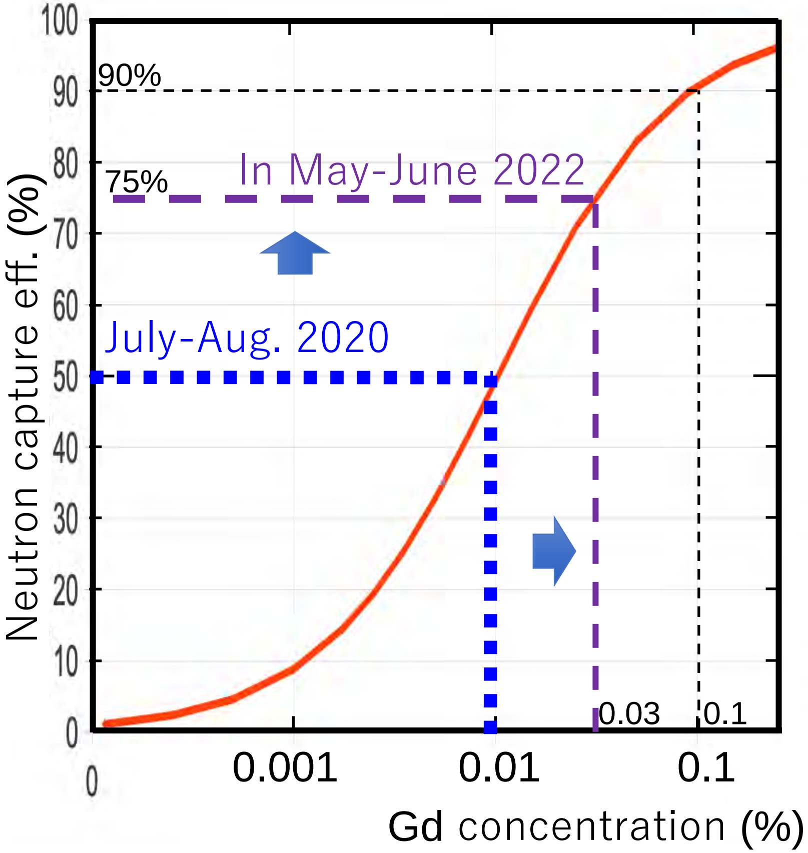
There is no significant change in water transparency or energy scale before and after the Gd-loading, allowing for the same physics studies to date.

N.B. Cut efficiencies are not optimized yet (especially for SK-VI)

Next Step

As the initial Gd-loading looks fine!

- Increase Gd concentration to 0.03%
    - Planned in May-June 2022.
    - Neutron capture efficiency will increase to 75%.
    - 26 tons of ultra-pure $Gd_2(SO_4)_3 \cdot 8H_2O$ are being produced.
    - 18tons are ready to go
- Long term observation
    - Planned from 2022 to 2027.
    - Expected number of SRN events is 5~13 for the five years.



NYC

Gadolinium Sulfate

Ultra High Purity

LOT.NO P-GDSO-220242

NET 20.0kg

DATE 2022.03.25

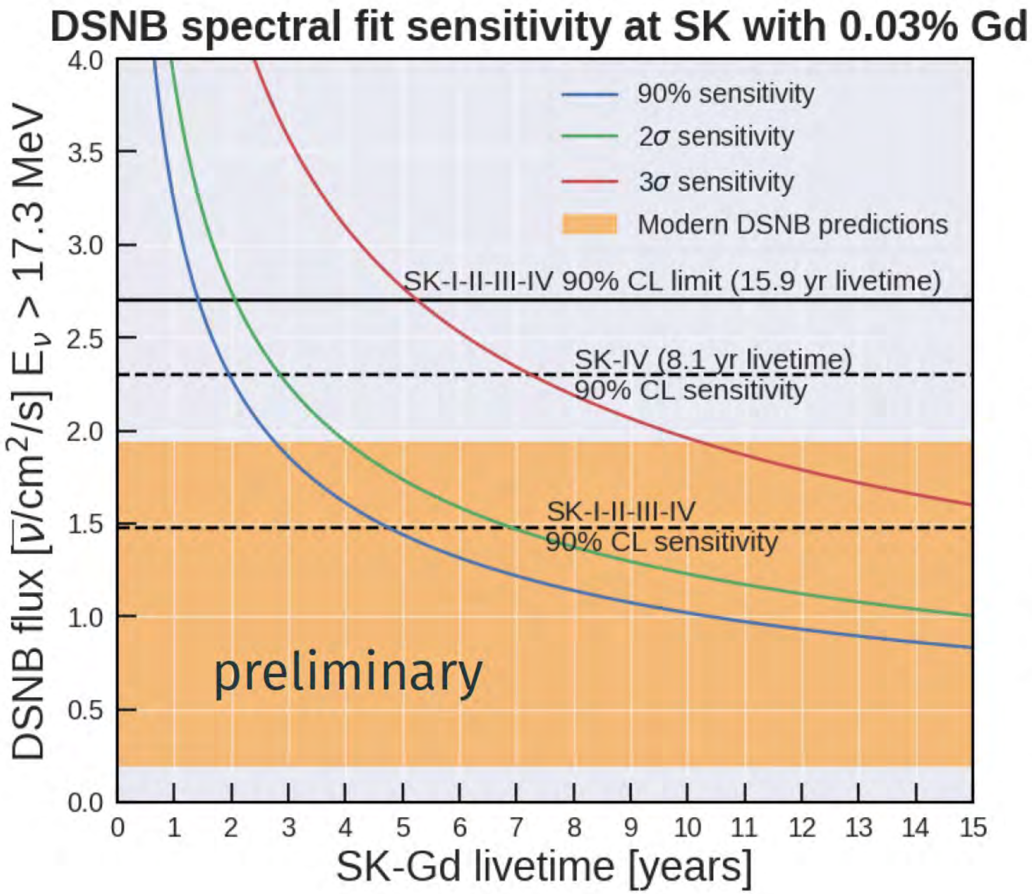
日本イットリウム㈱

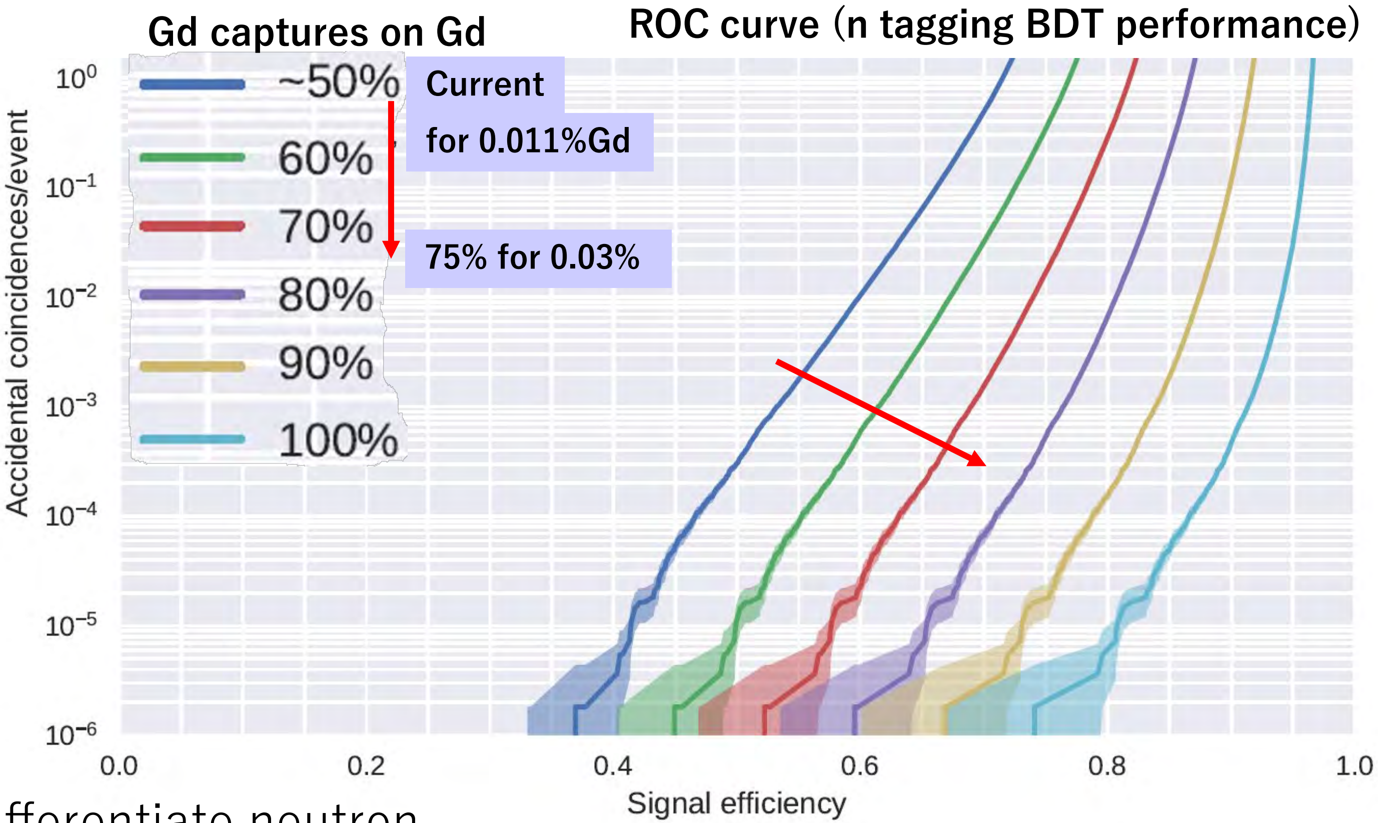
福岡県大牟田市唐船2081-398

☎0944-53-8546

Expected sensitivity of SK-Gd with 0.03%

- Assume atmospheric background is the same as in SK-IV(conservative)
- Ntag efficiency at 0.03% Gd concentration





Further improvement: To what extent can we differentiate neutron capture signals from atmospheric interactions?

Supernova burst neutrino

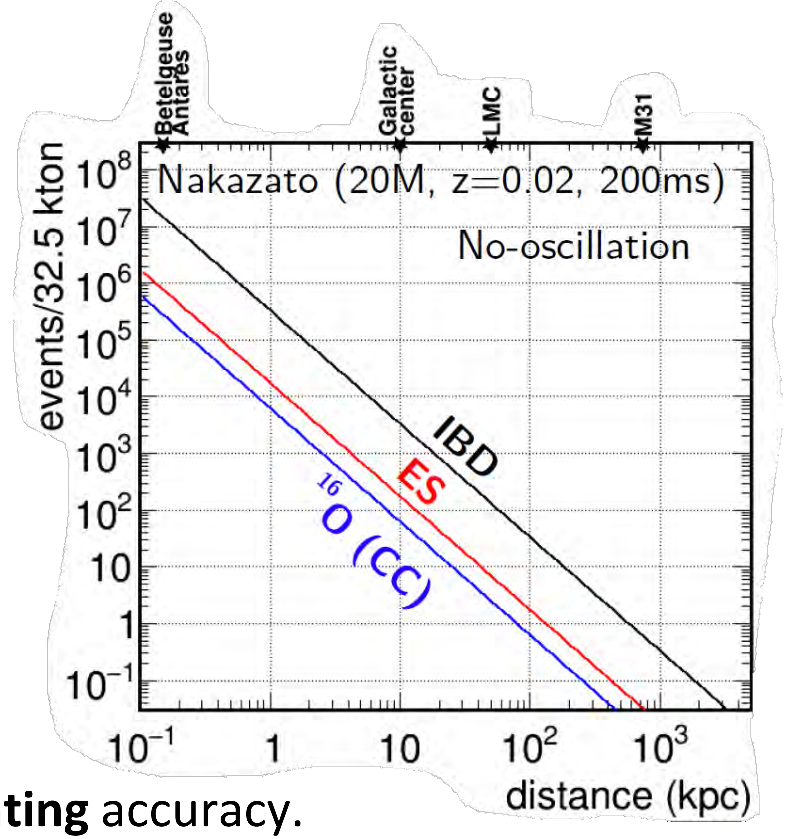
Super-Kamiokande can point the galactic SN direction via ES

Inverse Beta Decay reaction (IBD) ~90% $\bar{\nu}_e + p \to e^+ + n$

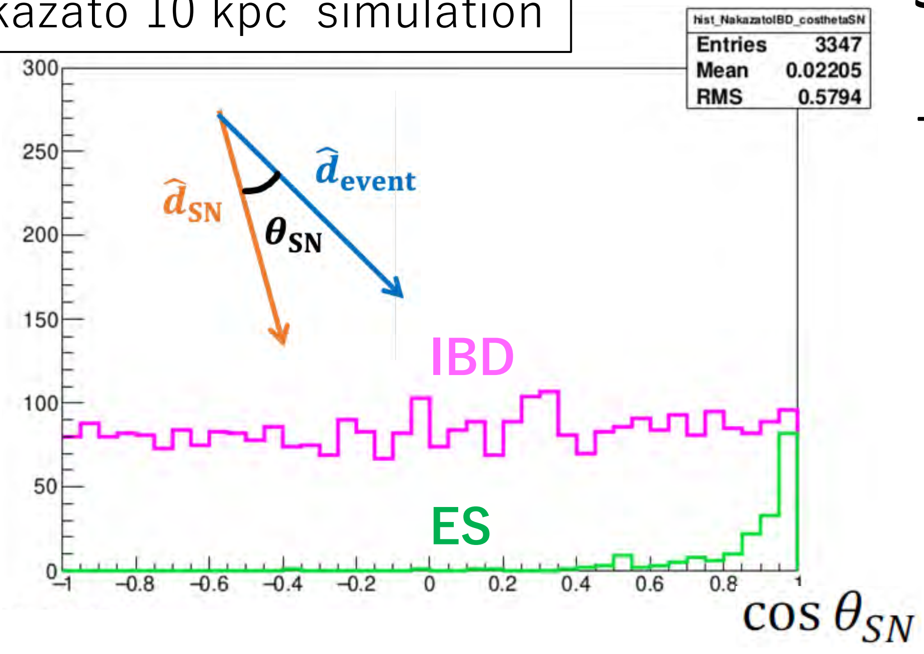
The direction of positron does not reflect the direction of the neutrino

Elastic Scattering interactions (ES) ~5% $\boldsymbol{\nu + e^- \to \nu + e^-}$

The electron keeps the neutrino direction information.

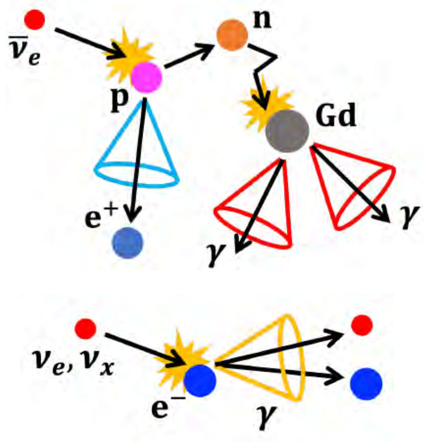


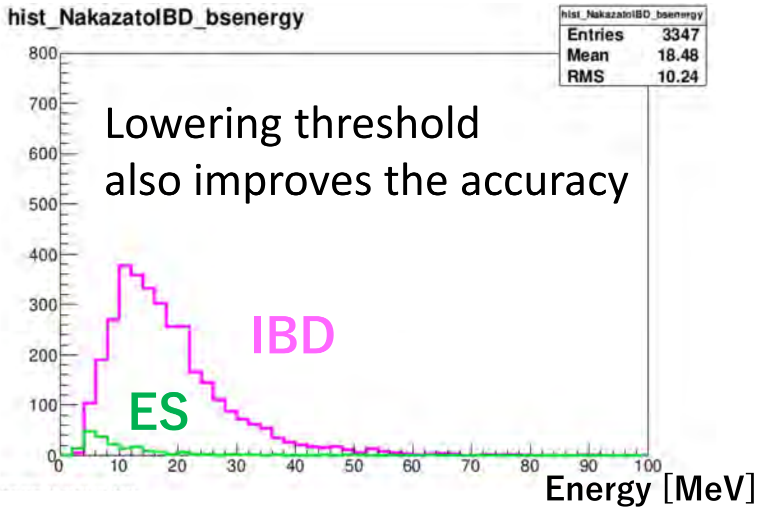
Nakazato 10 kpc simulation



Separating ES from **IBD** allows improving the **SN direction pointing** accuracy.

→ Gd enhances the IBS tagging





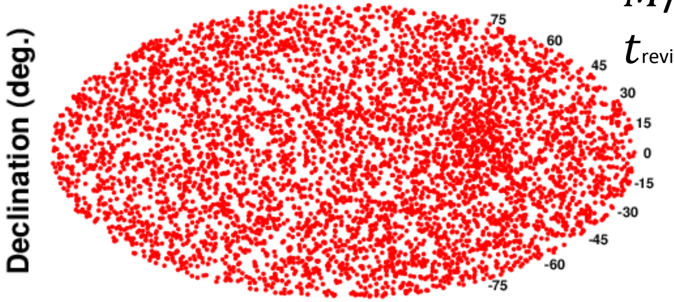
Lowering threshold also improves the accuracy

Expected pointing accuracy

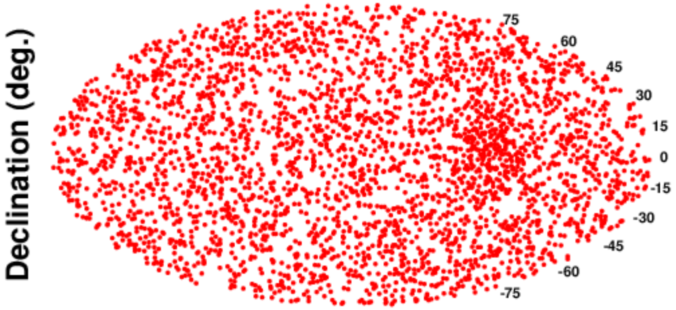
Extracted ES events (10kpc SN Nakazato)

$M/M_\odot = 20$, $Z = 0.02 \sim Z_\odot$,
$t_{\mathrm{revive}} = 200\mathrm{ms}$

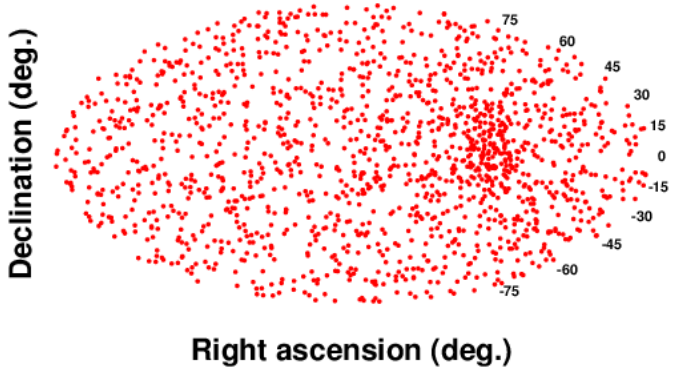
No Gd, SK-IV
Pointing accuracy
4deg (N.O. case)

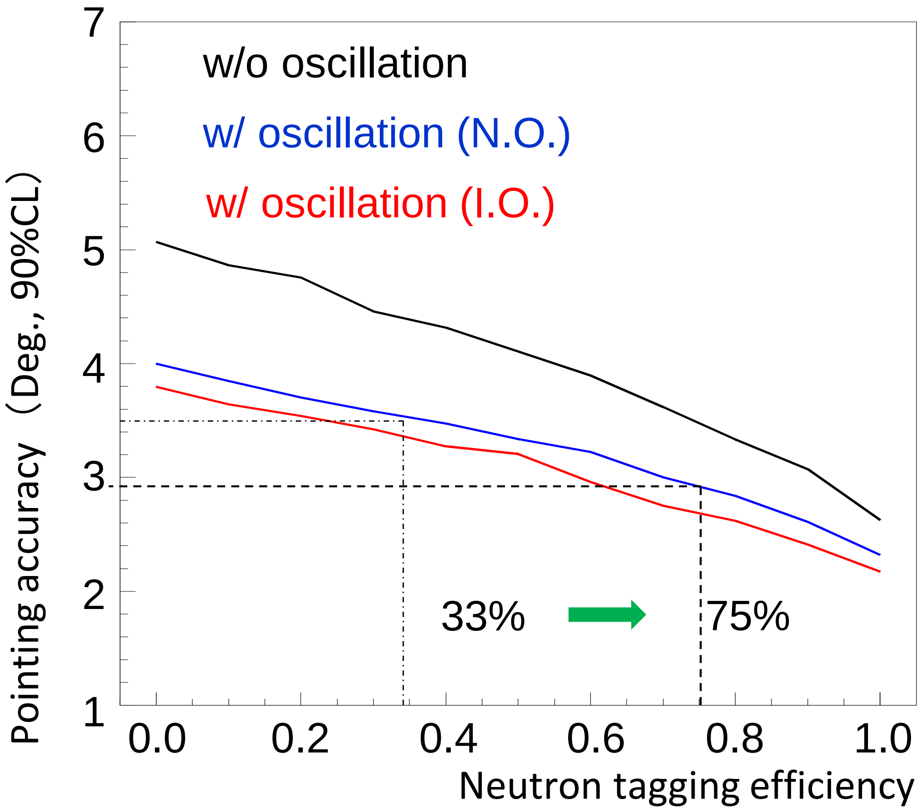


Current SK-VI 0.01%Gd
3.5 deg (N.O. case)
Search for the delayed sig.
with current threshold

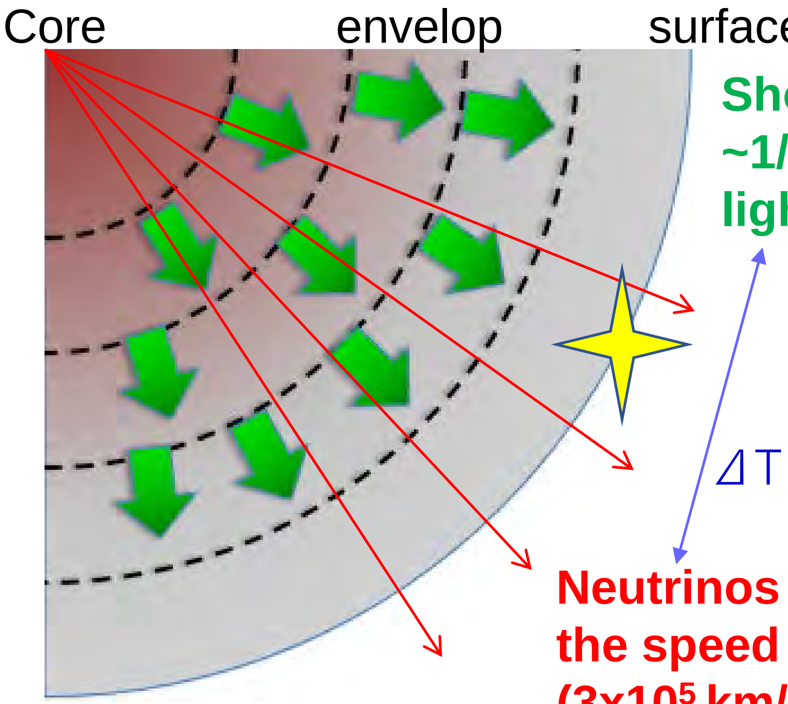


Next phase 0.03% Gd
2.9 deg (N.O. case)
w/ Lowering threshold





Role of SK in Multi-messenger astronomy

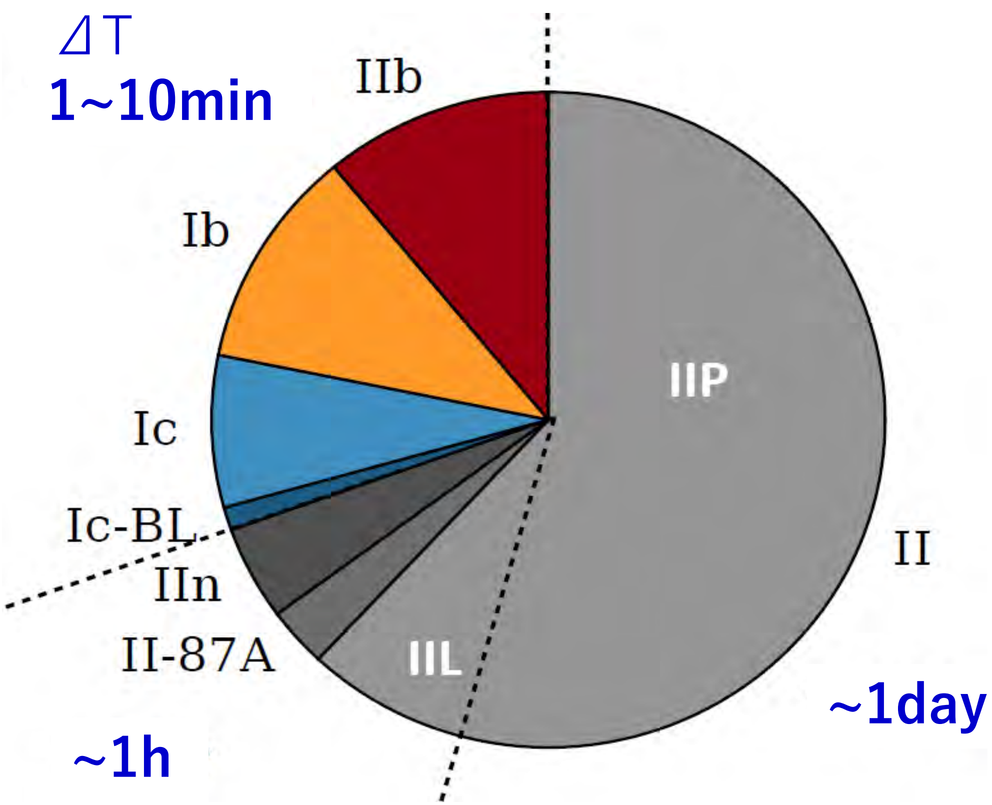


Shock wave travels with ~1/30 of the speed of light (~10^4 km/sec).

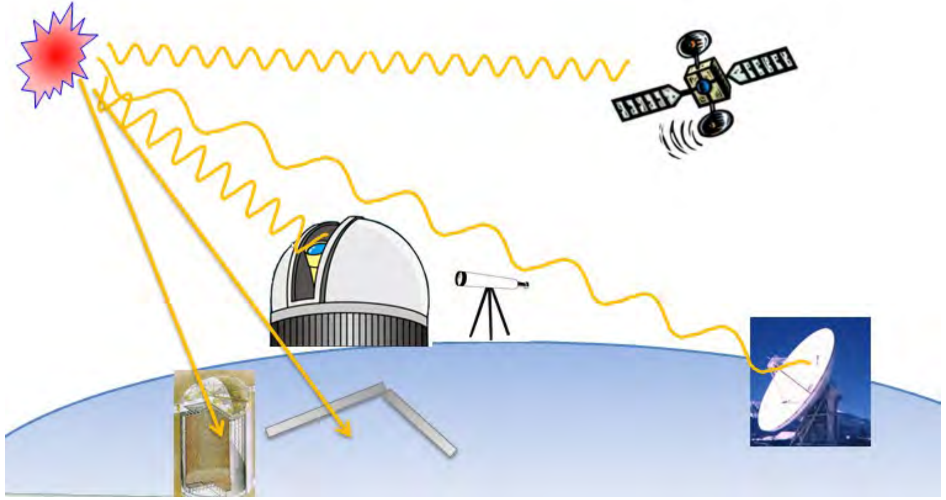
Shock breakout happens when the shock wave arrives at the surface.

Neutrinos travel with the speed of light (3×10^5 km/sec)

I. Shivvers et al., 2017 PASP



The time difference is several hours to tens of hours for ~70% of SNe and several minutes for others.



SK can send alerts to optical telescopes.

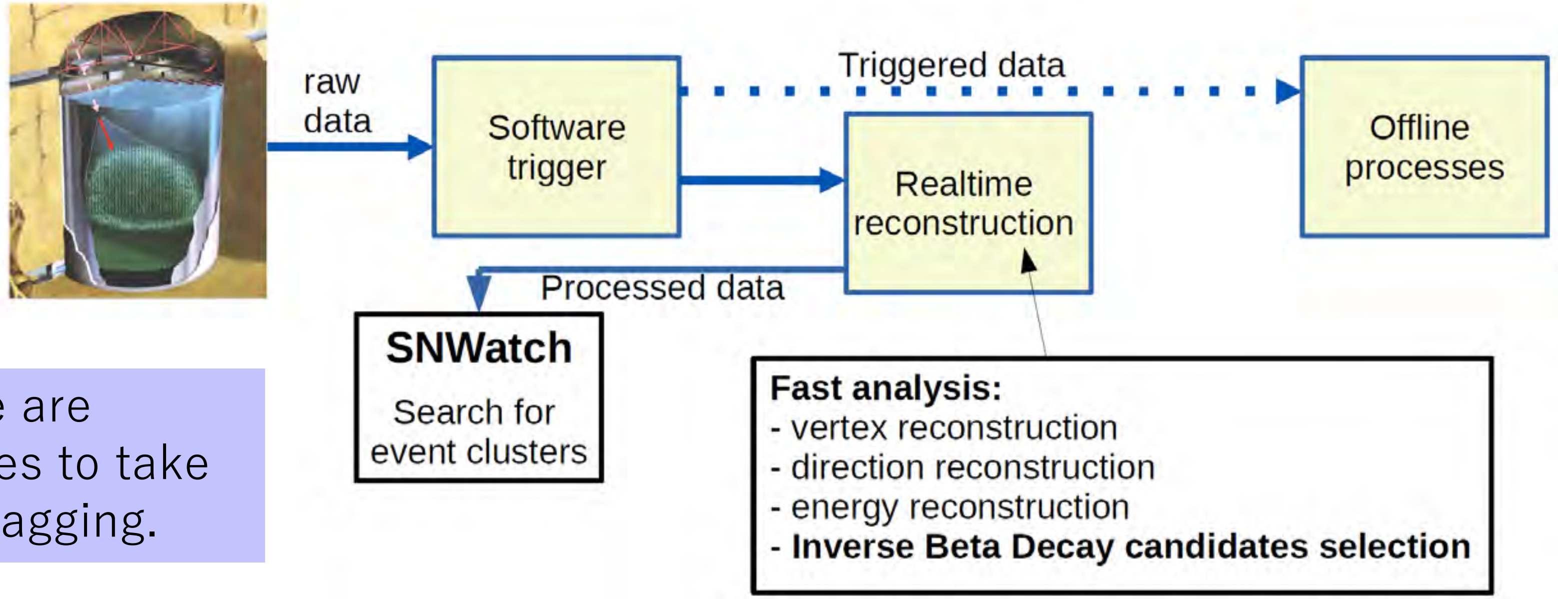
< 3 degrees is required
for FOV of Subaru, Simonyi Survey Telescope, etc.

Realtime supernova monitoring

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 alarm is sent to Super-Kamiokande SN experts.
  - The criteria are determined so that we would have 100% SN detection efficiency at the Large Magellanic Cloud.



raw data

Software trigger

Triggered data

Offline processes

Realtime reconstruction

Processed data

SNWatch

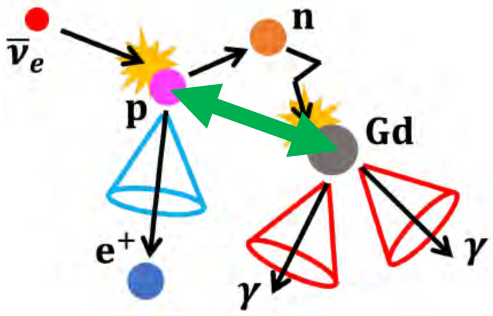
Search for event clusters

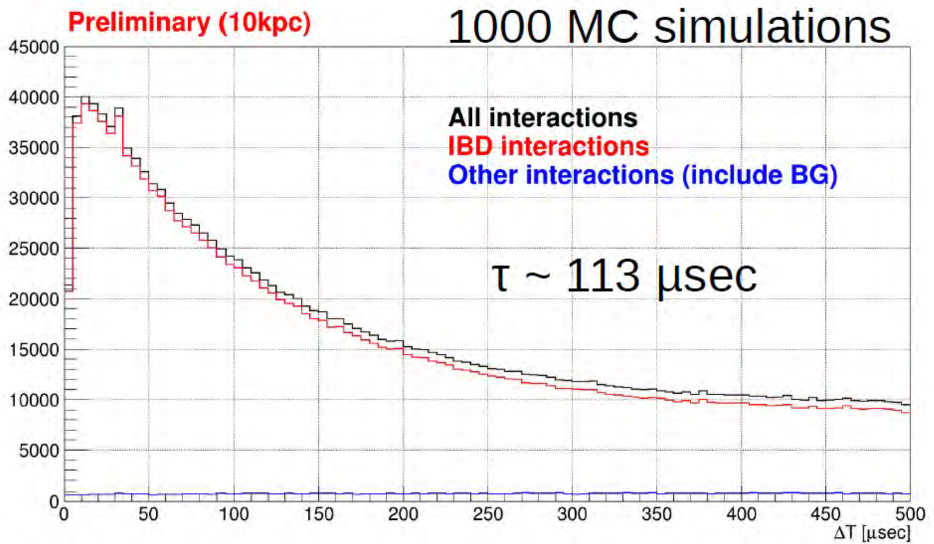
Fast analysis:
- vertex reconstruction
- direction reconstruction
- energy reconstruction
- **Inverse Beta Decay candidates selection**

Since the Gd loading in 2020, we are modifying the SNWatch processes to take advantage of the improved IBD tagging.

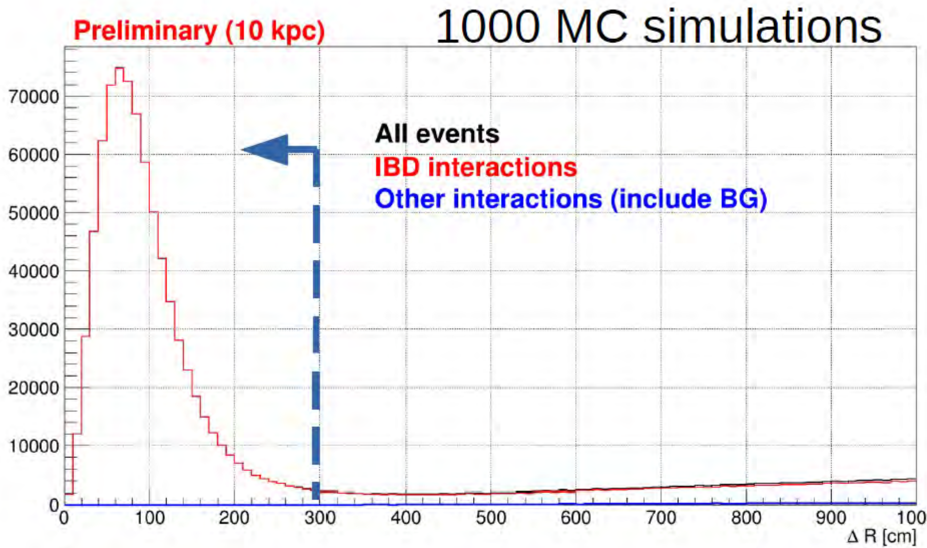
Quick IBD tagging in SNwatch

- From the reconstructed events, “prompt-like” candidates (events with E > 7 MeV) and “delayed-like” candidates (events with E < 7 MeV) are separated.
- Only the time and space correlation between “prompt-like” and “delayed-like” candidates an IBD candidate selection can be built:
  - **Pair of events with $\Delta T < 500\ \mu$sec, and $\Delta R < 300$ cm**





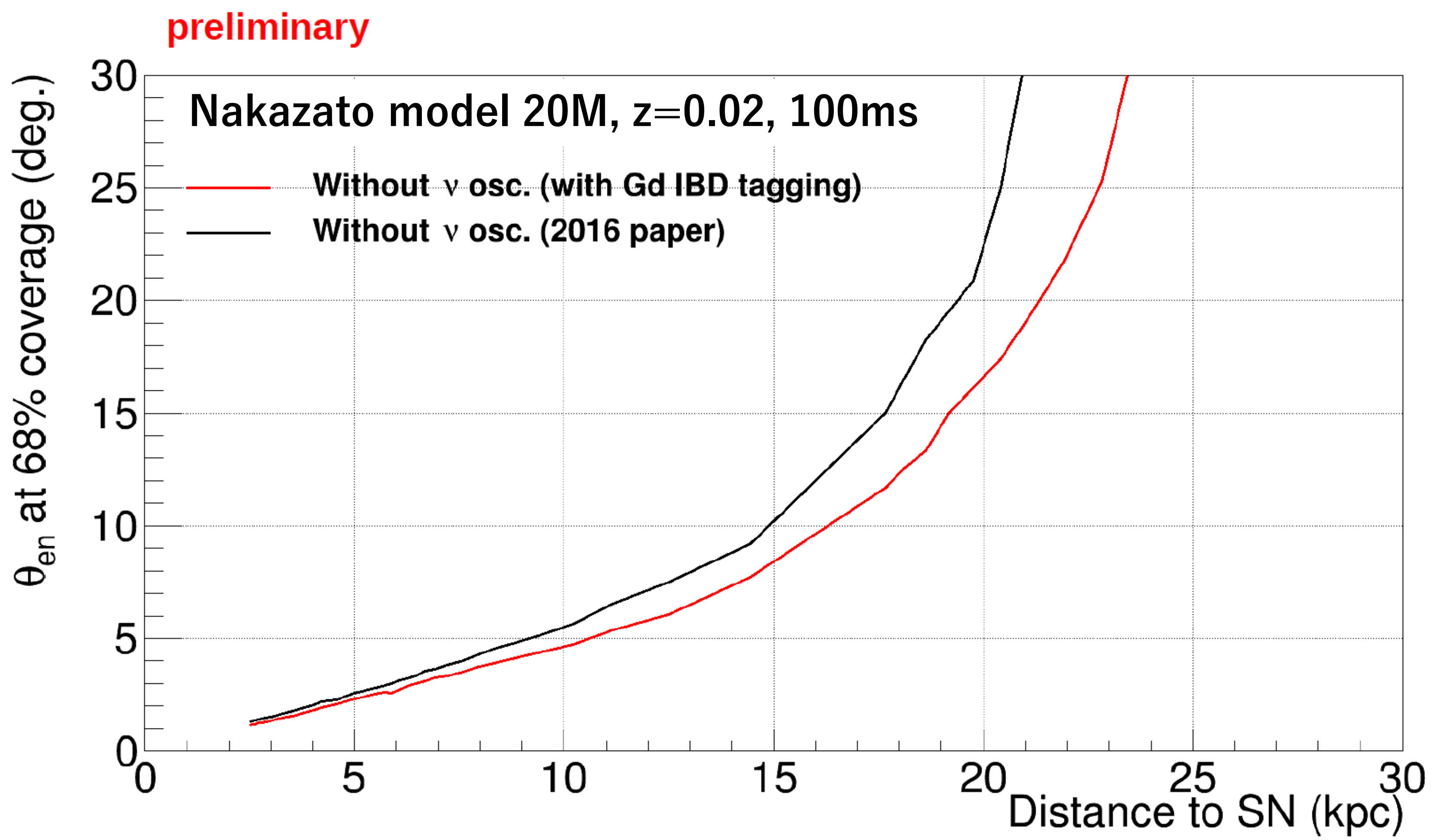
ΔT μsec



ΔR cm

This selection algorithm tags ~33% IBD events with the current Gd loading.

SNwatch pointing accuracy with 0.01% Gd



- **The preliminary results show 10~30% improvement between 2.5 and 25 kpc thanks to the Gd-loading.**

Alert release time

Fast alarm is critical to observe the SN burst light.

- Up to recently, it was taking a long time for SK to release an alarm;
  - Event reconstruction ~3 min for 10 kpc SN (~10 min for 3 kpc)
  - Experts meeting to decide to release an alarm and send the alarm.

→ On average, ~1h was needed to send the alarm(and miss 30% of optical SNe.)

⬇

- Software and algorithm upgrades using multi-threading
  - Event reconstruction: **<1 min for 10 kpc SN** (~5 min for 3 kpc SN)
    - Further quick Healpix-based (from WMAP, Plank) SN direction finder is under investigation.

      → Preliminary results indicate ~2 sec for 10 kpc SN (<5 sec for any SN)
  - **Automated alarm** shortly after the SN direction reconstruction

→ The alarm is expected to be released in about 1 minute following the Galactic SN. (Preliminary)

SK Supernova alert on GCN Notice

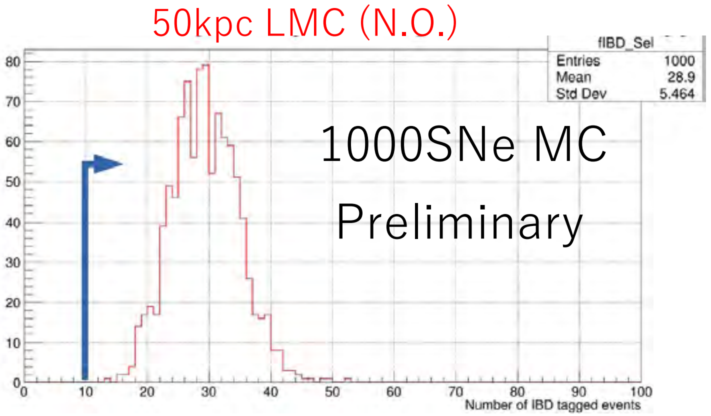
IBD tagging has a low BG contamination
Any burst of IBD uniformly distributed in the detector should be a clear SN signal.

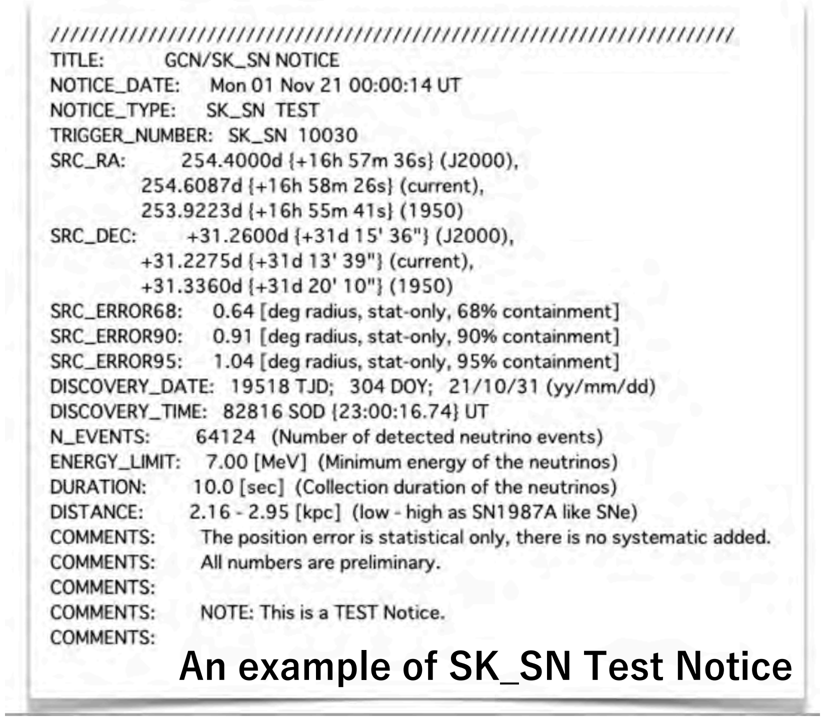
- Since December 13th, 2021, an automated notice process activated in SNwatch.
- In addition to the usual SNwatch criteria, if the number of IBD tagged events is > 10, the notice is distributed automatically to the astronomer community.
- **The alert can be received on GCN (The Gamma-ray Coordinates Network)** with the same framework as other GCN notices; GRB, GW, and high energy neutrino alerts.

A dummy (test) alert is published for the test every month (on 1st day of the month).

For more details about SK_SN Notice, refer to https://gcn.gsfc.nasa.gov/sk_sn.html

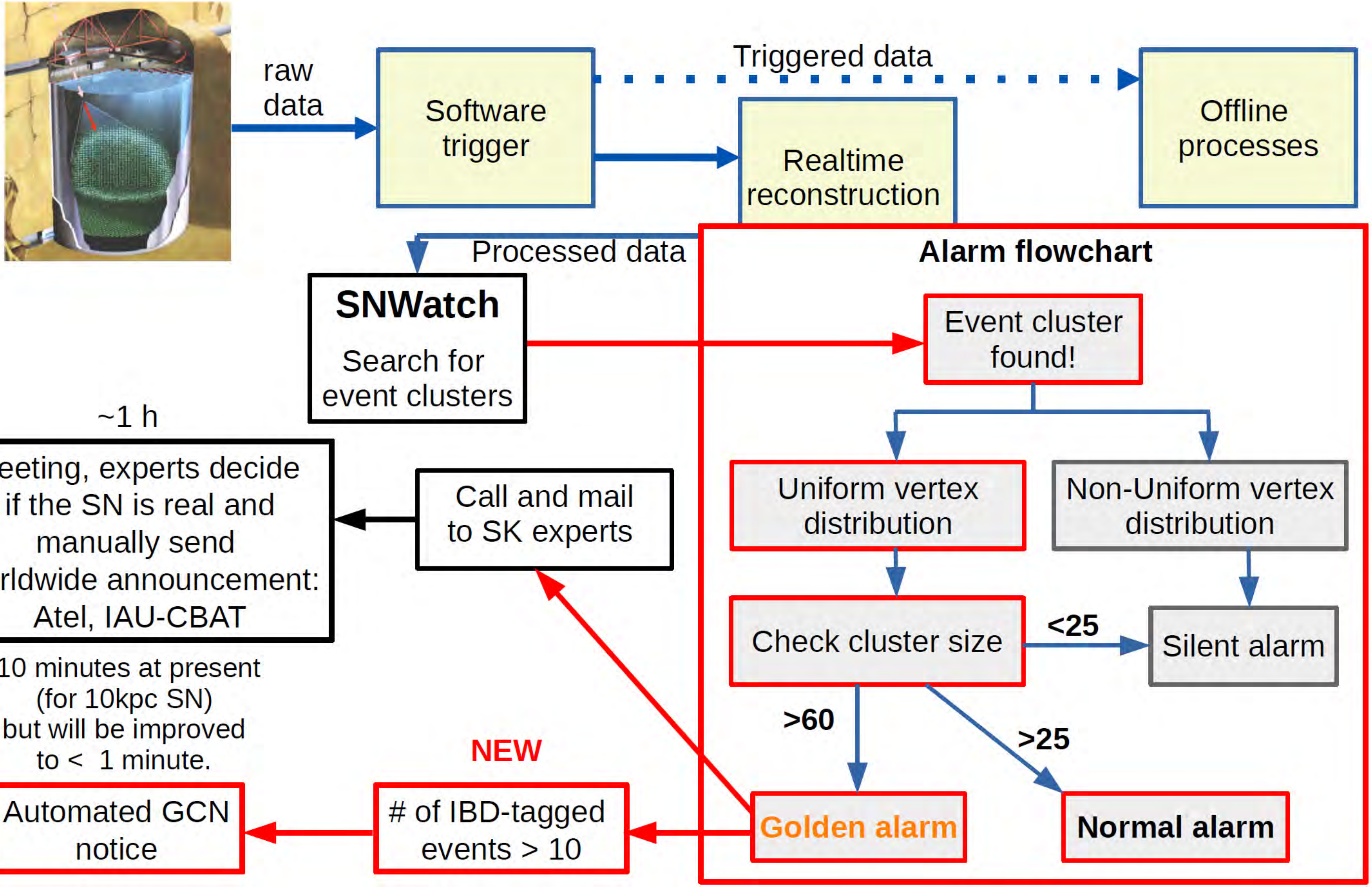
The 10 IBD threshold was selected to ensure100% detection efficiency for core-collapse SNe up to LMC





```
//////////////////////////////////////////////////////////////////////
TITLE:          GCN/SK_SN NOTICE
NOTICE_DATE:     Mon 01 Nov 21 00:00:14 UT
NOTICE_TYPE:     SK_SN  TEST
TRIGGER_NUMBER:  SK_SN  10030
SRC_RA:         254.4000d {+16h 57m 36s} (J2000),
                254.6087d {+16h 58m 26s} (current),
                253.9223d {+16h 55m 41s} (1950)
SRC_DEC:        +31.2600d {+31d 15' 36"} (J2000),
                +31.2275d {+31d 13' 39"} (current),
                +31.3360d {+31d 20' 10"} (1950)
SRC_ERROR68:     0.64 [deg radius, stat-only, 68% containment]
SRC_ERROR90:     0.91 [deg radius, stat-only, 90% containment]
SRC_ERROR95:     1.04 [deg radius, stat-only, 95% containment]
DISCOVERY_DATE:  19518 TJD;  304 DOY;  21/10/31 (yy/mm/dd)
DISCOVERY_TIME:  82816 SOD {23:00:16.74} UT
N_EVENTS:        64124  (Number of detected neutrino events)
ENERGY_LIMIT:    7.00 [MeV]  (Minimum energy of the neutrinos)
DURATION:        10.0 [sec]  (Collection duration of the neutrinos)
DISTANCE:        2.16 - 2.95 [kpc]  (low - high as SN1987A like SNe)
COMMENTS:        The position error is statistical only, there is no systematic added.
COMMENTS:        All numbers are preliminary.
COMMENTS:
COMMENTS:        NOTE: This is a TEST Notice.
COMMENTS:
```

An example of SK_SN Test Notice



raw data

Software trigger

Triggered data

Offline processes

Realtime reconstruction

Processed data

SNWatch

Search for event clusters

Alarm flowchart

Event cluster found!

Uniform vertex distribution

Non-Uniform vertex distribution

Check cluster size

<25

Silent alarm

>60

>25

Golden alarm

Normal alarm

Call and mail to SK experts

~1 h

Meeting, experts decide if the SN is real and manually send worldwide announcement: Atel, IAU-CBAT

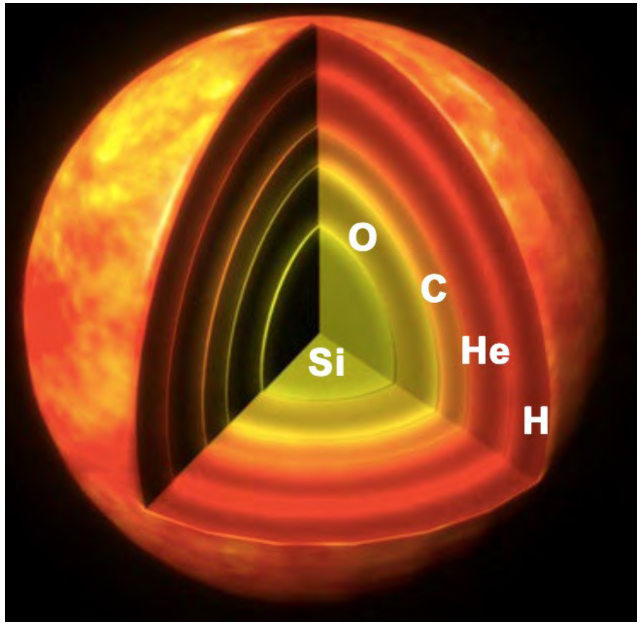
~10 minutes at present (for 10kpc SN) but will be improved to < 1 minute.

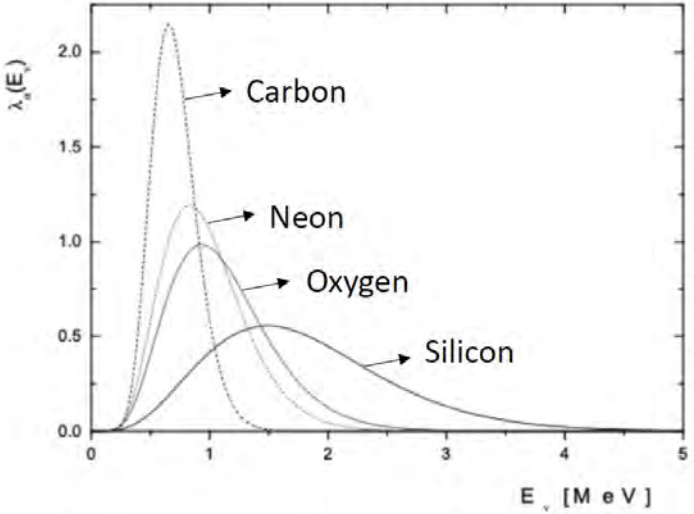
NEW

\# of IBD-tagged events > 10

Automated GCN notice

Even earlier alarm: Si burning signal





Pre-Supernova $\bar{\nu}_e$ spectrum for a a 20 $M_\odot$ star

Pre-Supernova Stars

The neutrino emission increases significantly as a massive star approaches the core-collapse Supernova.
After the ignition of Carbon burning starts, the electron-positron annihilation process generating thermal neutrinos becomes the star's dominant form of cooling.

$$e^+ + e^- \rightarrow \nu_x + \bar{\nu}_x$$

The last stage of these stars before the core-collapse is the **Si-burning**. Neutrinos emitted at this stage have an average energy of 1.85 MeV.

Although the pre-Supernova neutrinos have lower energies than Supernova neutrinos, Si-burning neutrinos exceeding the IBD threshold could be detected in SK-Gd.

→possibility of creating an alternative Supernova alarm

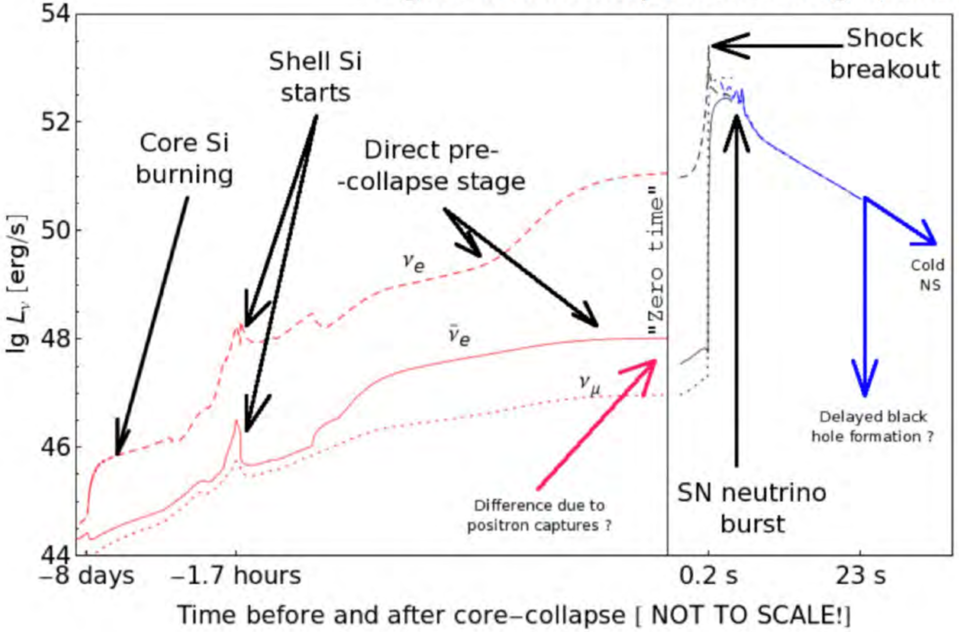
A. Odrzywolek et al., Astropart.Phys.21 (2004) 303

Si burning models

- **Odrzywolek et. al.**

Pair $e^+ + e^- \rightarrow \nu_\alpha + \overline{\nu}_\alpha$

Odrzywolek & Heger Acta Phys. Polon. B 41 (2010) 1611

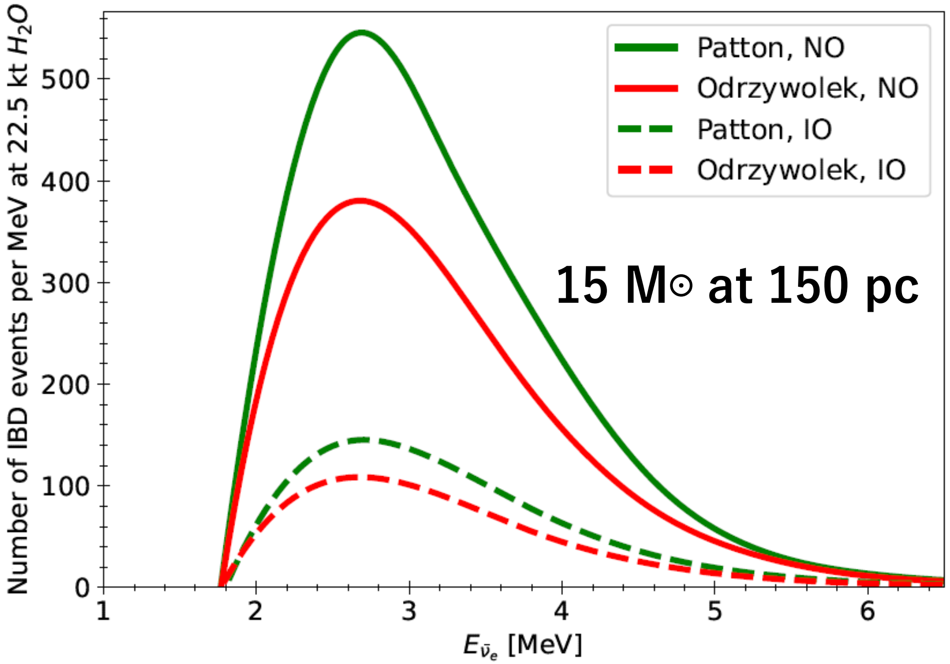


- **Patton et. al.**

Patton et al. 2017 ApJ 840 2

$\beta^\pm$ decay	$A(N,Z) \rightarrow A(N-1, Z+1) + e^- + \overline{\nu}_e$ $A(N,Z) \rightarrow A(N+1, Z-1) + e^+ + \nu_e$
e^+/e^- capture	$A(N,Z) + e^- \rightarrow A(N+1, Z-1) + \nu_e$ $A(N,Z) + e^+ \rightarrow A(N-1, Z+1) + \overline{\nu}_e$
Plasma	$\gamma^* \rightarrow \nu_\alpha + \overline{\nu}_\alpha$
Photoneutrino	$e^\pm + \gamma \rightarrow e^\pm + \nu_\alpha + \overline{\nu}_\alpha$
Pair	$e^+ + e^- \rightarrow \nu_\alpha + \overline{\nu}_\alpha$

E$\bar{\nu}_e$ spectra in SK
over the last 10 hours prior to the CCSN→

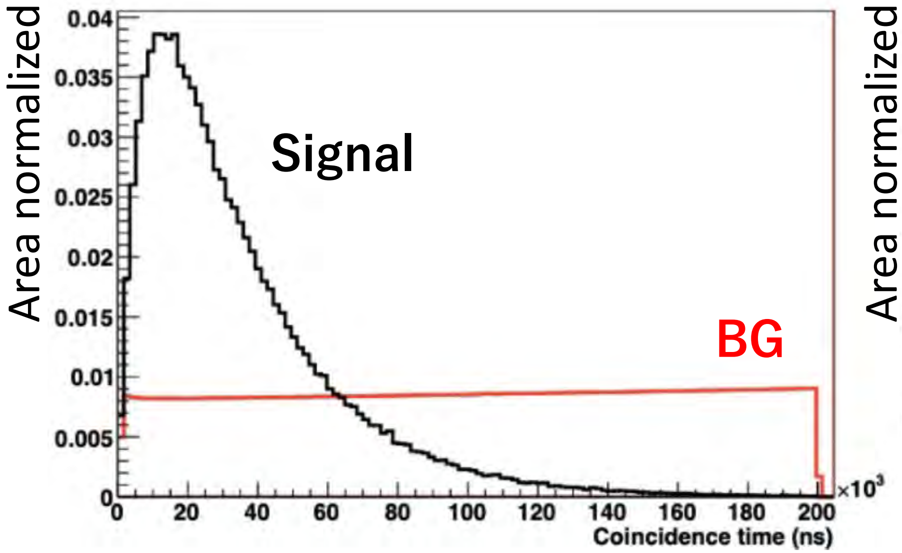


Backgrounds

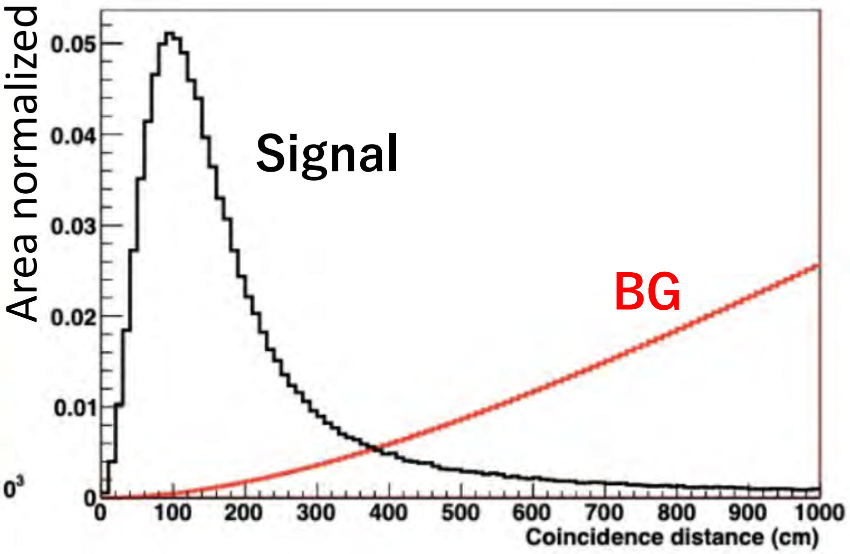
Accidental coincidences:
The primary BG. Intrinsic background comes from radioactive decays, dark noise, and uncorrelated events close in time and distance.

Reactor and geoneutrinos:
Background due to active Japanese nuclear reactors

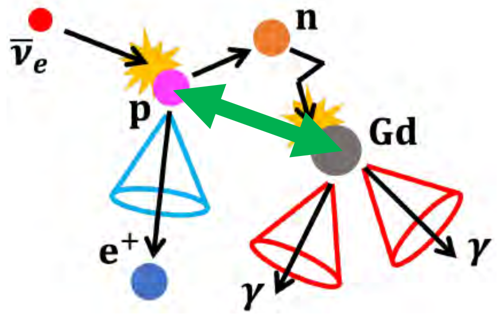
Radioactive Contaminations:
With the Gd-loading, radioactive impurities are distributed in the detector. ^{238}U, ^{232}Th, and ^{235}U contribute $^{18}O(\alpha,n)^{21}Ne^{*}$ and $^{17}O(\alpha,n)^{20}Ne^{*}$



$\Delta T\ \mu sec$



$\Delta R\ cm$



Event selection with WIT

- The pre-supernova alert system is integrated into an independent trigger in SK called **Wide-band Intelligent Trigger**. WIT is a system designed to extend the sensitivity of SK to low energy events using parallel computing to **reconstruct vertices in realtime,** discarding events that are not well reconstructed or very close to the walls of the detector.

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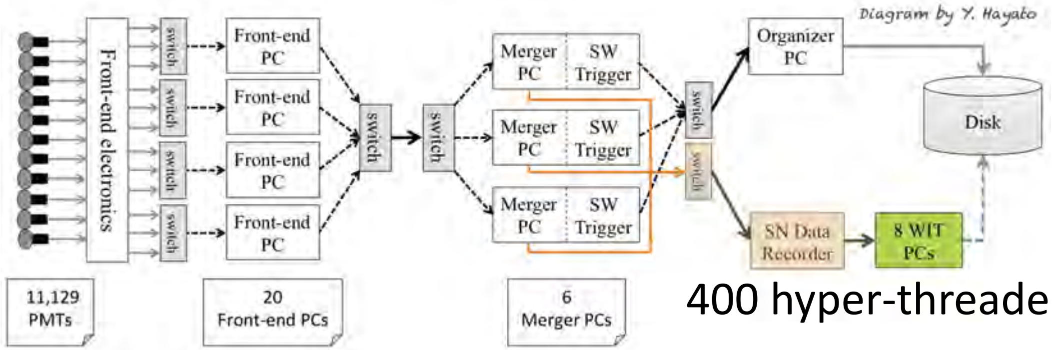
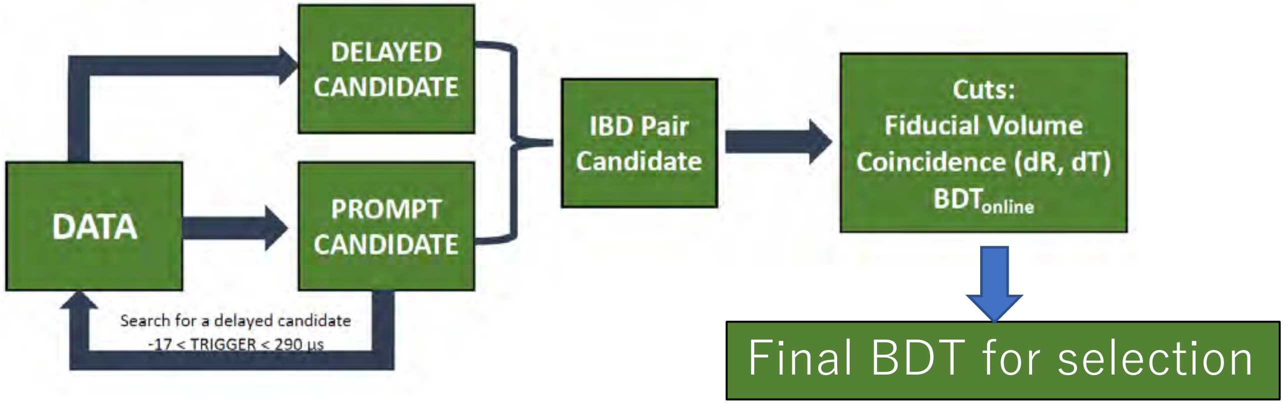


400 hyper-threaded cores

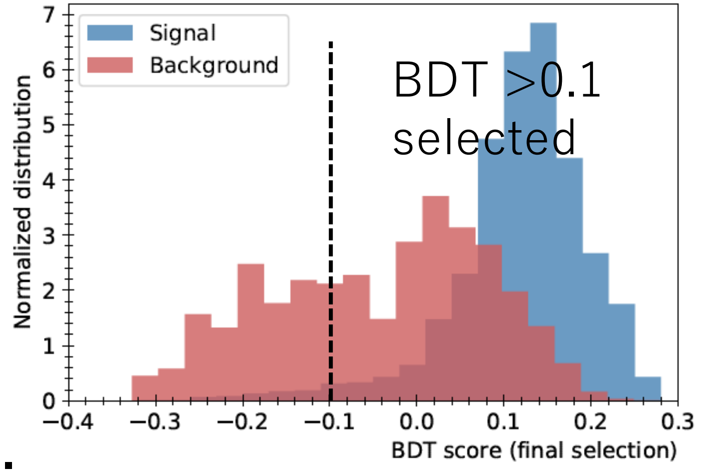
Search for Coincidence Events:



Process time (latency) ~ 10 min.

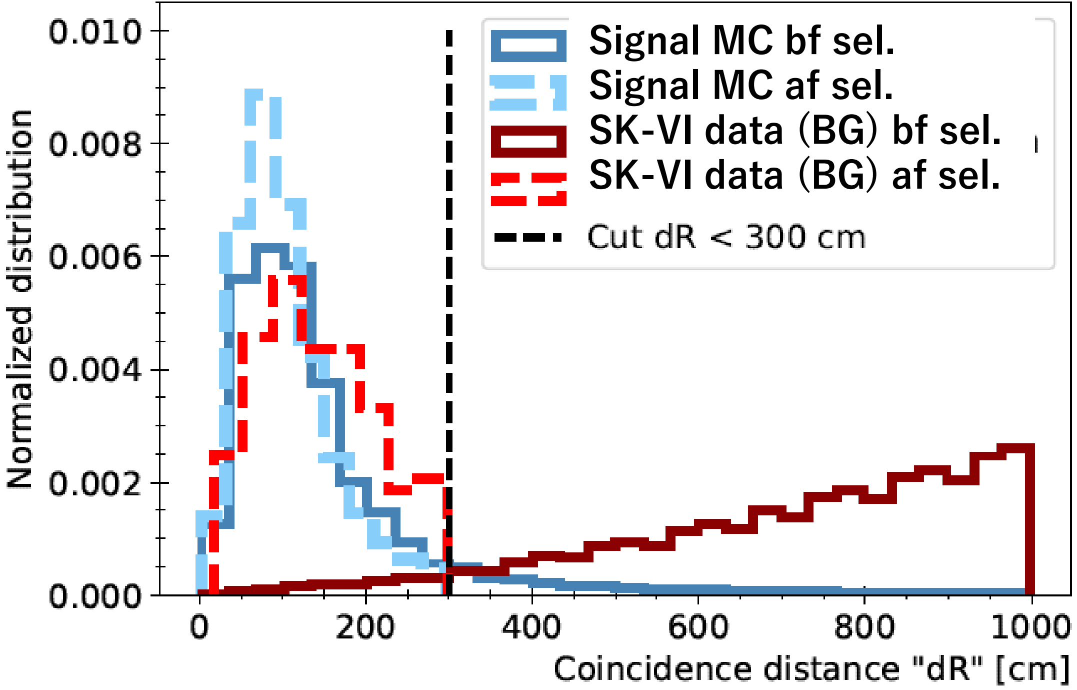
2 BDTs for event selection

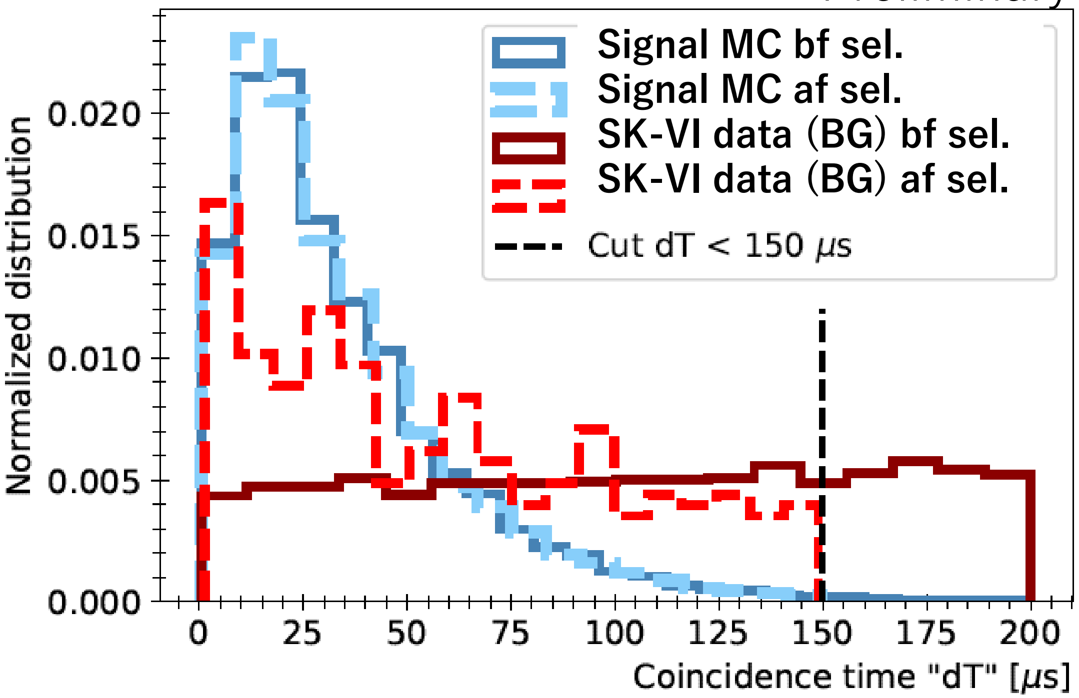
At first, BDT$_{online}$ is created as a pre-selection using only ΔR and ΔT in order to carry less events through the data processing, then final BDT using angular distribution of hits, reconstructed energy and quality, and distance from detector wall is created.



Sensitivity calculation for SK-VI

Final selection $\Delta R < 300$ cm, $\Delta T < 150\ \mu s$, and BDT score > -0.1


Preliminary

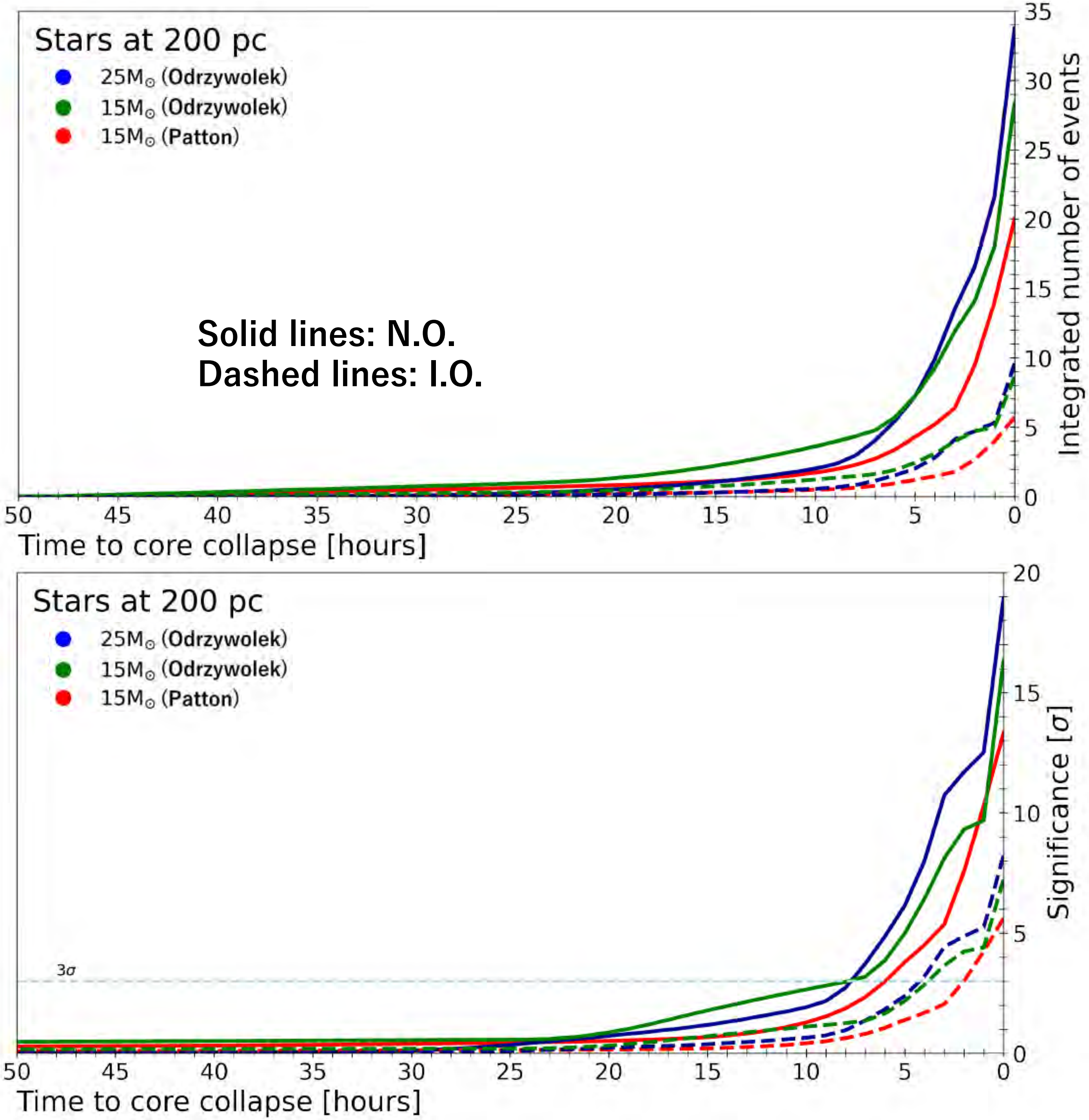

Preliminary

- Remaining BG after selection ~ 0.1 events/hour
- Significance are evaluated $p = P(N_{events} \geq N_{BG}) = \sum_{n=N_{events}}^{\infty} Pois(n; N_{BG})$

3 σ significance alarm (to SK collaboration) for an 8hours window was activated on Oct. 21, 2021.

SK-VI sensitivity to Betelgeuse

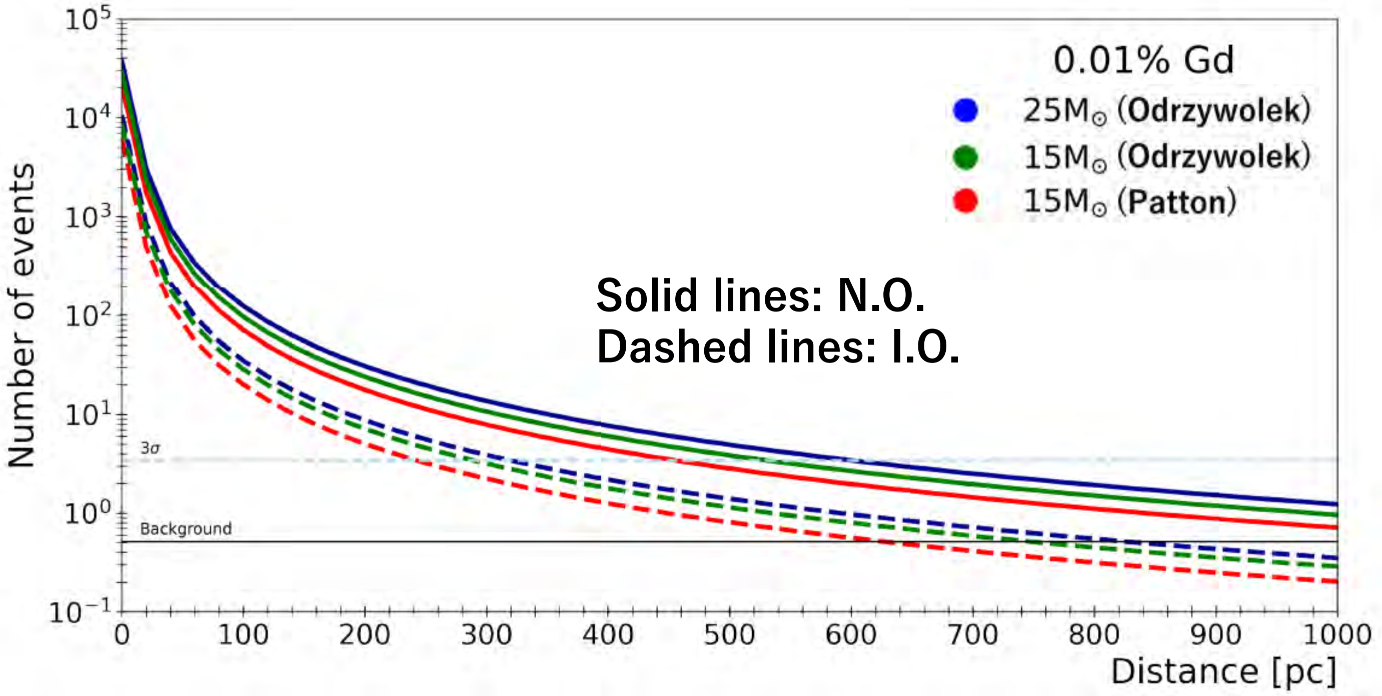
https://commons.wikimedia.org/wiki/File:Orion_3008_huge.jpg



Solid lines: N.O.
Dashed lines: I.O.

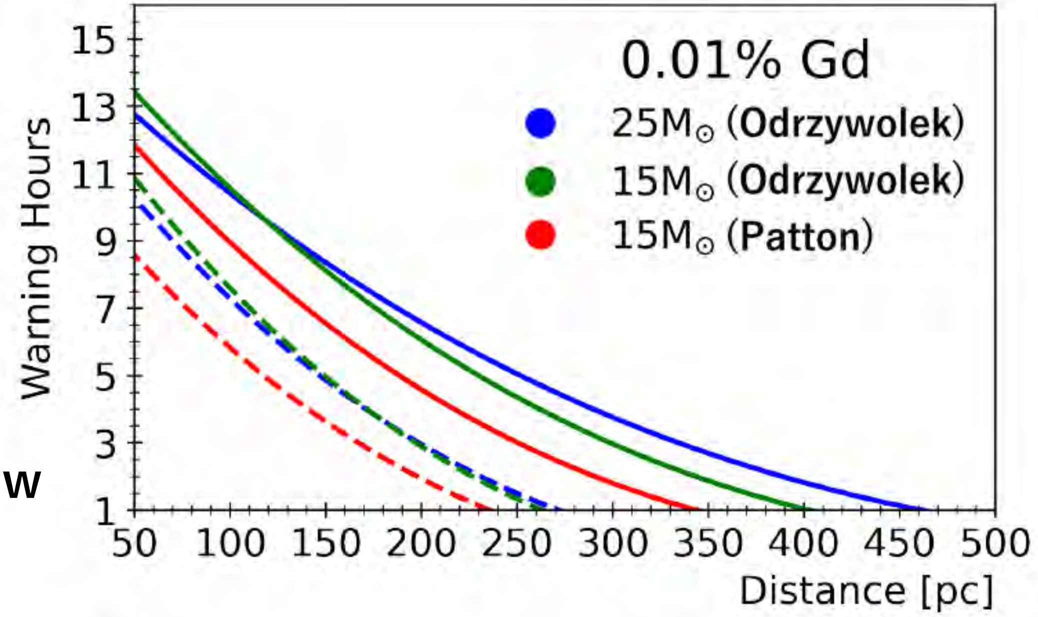
Evolution of the number of IBD (Top) and the significance level (Bottom) in SK-IV (with 0.01% Gd) over the last 50 hours before the core-collapse for massive stars at d = 200 pc.

SK-VI's monitoring range



Solid lines: N.O.
Dashed lines: I.O.

Expected number of IBD events integrated over 8 hours before the core-collapse in SK-VI as a function of distance



Warning hours before the core collapse with the past 8 hours integration window for a 3 σ detection by the alert system

- SK-VI observe pre-supernova neutrinos with a 3 σ detection for stars up to 0.5~0.6kpc

SK is watching…

THE ASTROPHYSICAL JOURNAL, 899:153 (12pp), 2020 August 20 Mukhopadhyay et al.

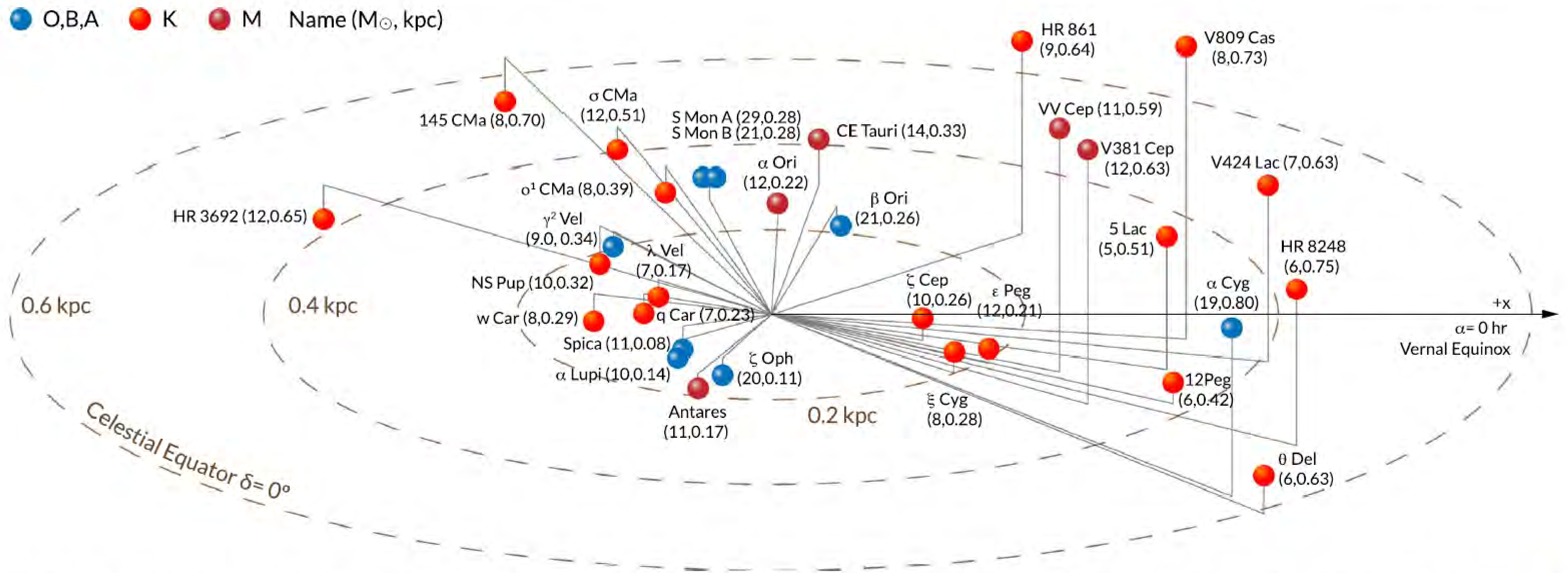


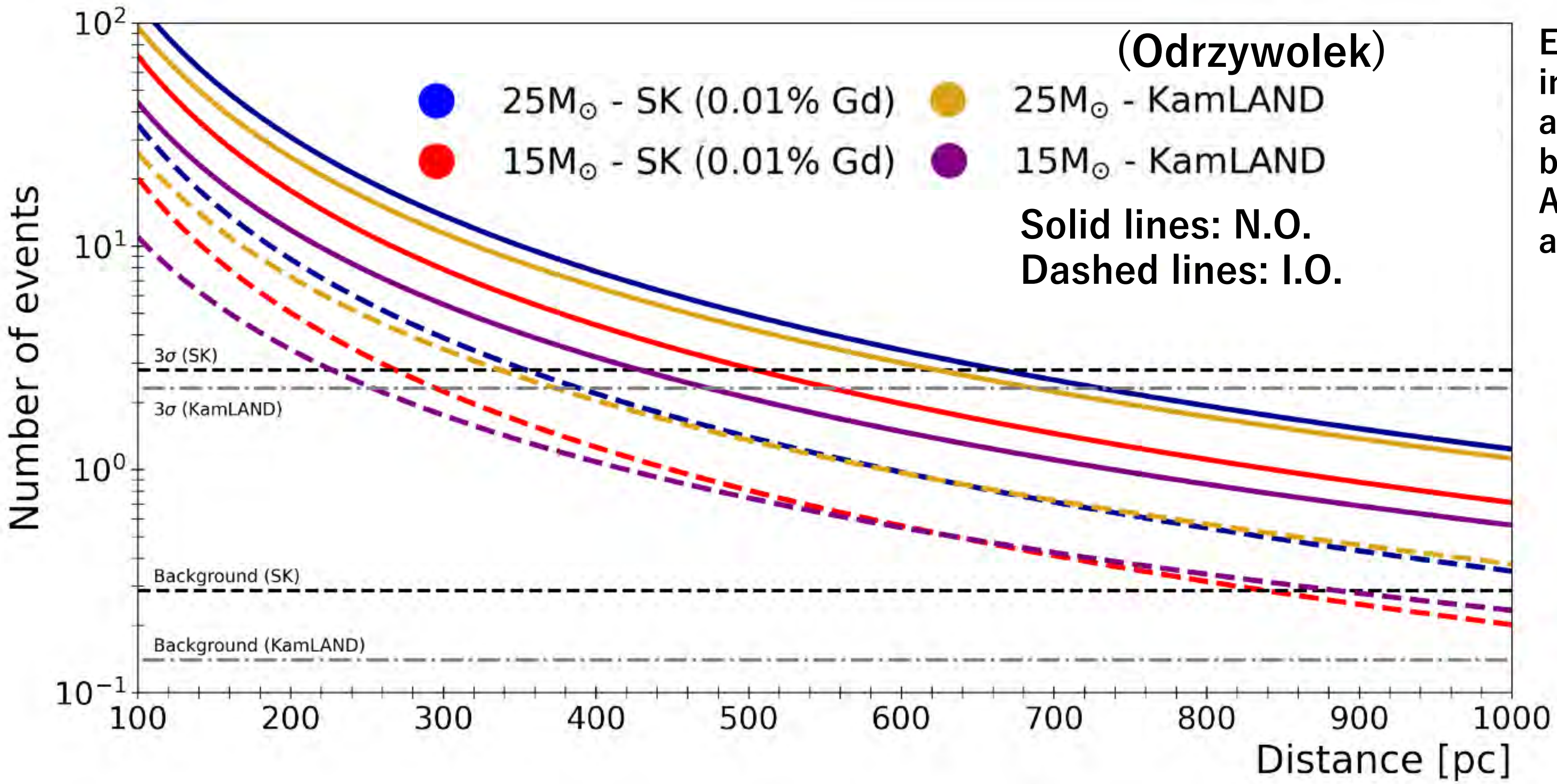
Figure 2. Illustration of nearby ($D \leqslant 1$ kpc) core collapse supernova candidates. Each star's spectral type, name, mass, and distance is shown in labels. See Table A1 for details and references.

Comparison with KamLAND

K. Asakura et al 2016 ApJ 818 91

Lower energy thresholds and lower background than SK
Fewer events than SK, as it is 20 times smaller than SK

➡ Similar sensitivity



Expected number of IBD events integrated over 8 hours(SK) and 48 hours(KamLAND) before the core-collapse Assuming all Japanese reactors are off

The pre-supernova alert system in KamLAND works with a fixed background rate of 0.071–0.355 events/day, depending on the reactor activity in Japan, and integrates selected events over a 48 hours time window.

SK+KamLAND alert in preparation

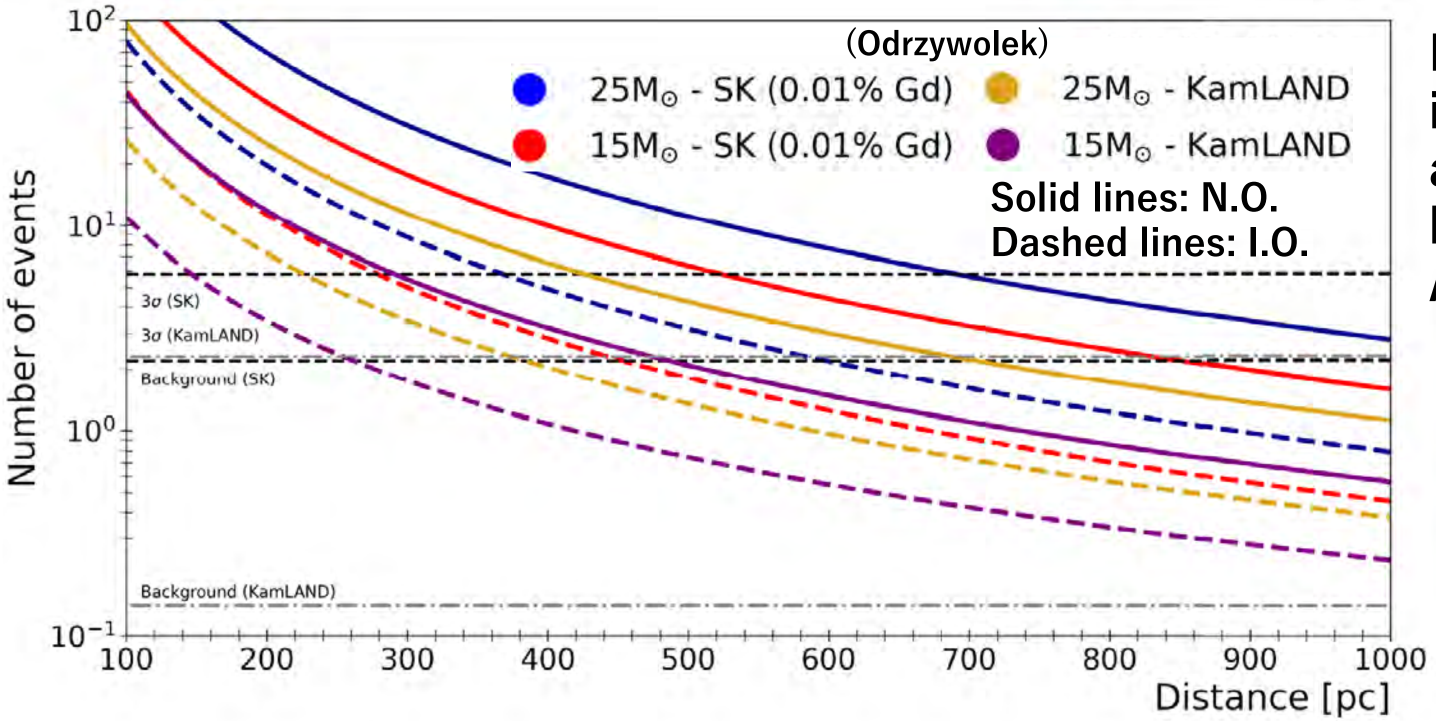
- A combination of results of both detectors could extend detection ranges and early warnings for the alarms. At least, coincidence alert increases the significance.

→**MOU among KamLAND and SK on pre-SN alarm is in preparation.**

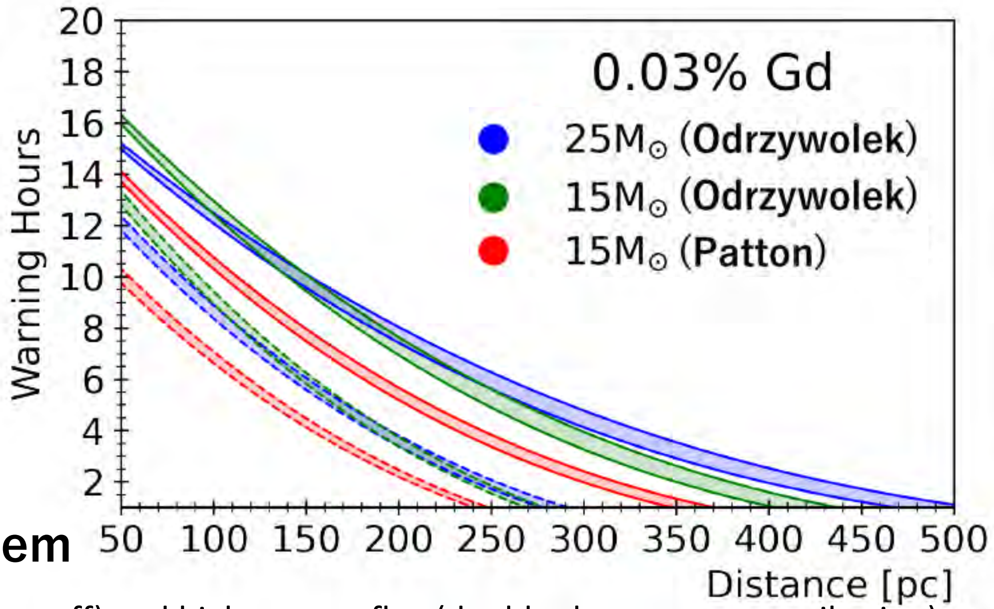
“If a significant number of anti-neutrinos candidates are seen in both KL and SK, and if they are consistent with expectations from pre-SN, KL and SK will try to make an announcement to the community via such publicly accessible services such as GCN.”

SK+KamLAND coincidence alert will be sent to GCN soon.

SK-VII (0.03% Gd) sensitivity



Expected number of IBD events integrated over 8 hours(SK) and 48 hours(KamLAND) before the core-collapse
Assuming all Japanese reactors are off



Expected Warning hours before the core collapse with the past 8 hours integration window for a 3σ detection by the alert system

The bands show BG cases between low reactor flux (Japanese reactors off) and high reactor flux (double the current contribution)

Conclusion

- Super-Kamiokande has been running since 1996 and achieved a world-leading sensitivity to the DSNB flux at 90% CL, comparable to the fluxes of several realistic models.
- SK has recently moved to the SK-Gd phase, achieving a concentration of 0.01%, and to be upgraded to 0.03% soon. The enhanced neutron tagging capabilities will allow us to set meaningful constraints on astrophysical observables with the realistic prospect of a ground-breaking discovery.
- SK continuously monitors the detector events to probe any burst indicating a supernova. The 0.01% Gd neutron tagging improved SN pointing accuracy by 0.6 deg at 10 kpc (Nakazato model). Thanks to the automated GCN notice system implementation, the delay before sending an alarm to astronomers is expected to be ~1 minute for the SNe in our galaxy.

Conclusion (cont'd)

- Neutrinos from pre-Supernova stars, with an average energy of 1.85 MeV in the Si-burning phase can be detected in SK-Gd for the ranges of about 600 parsecs;
- Their detection can also give early warnings for potential Supernova events. Betelgeuse, for example, would have a warning notice of 8 hours before the explosion. The Pre-Supernova alert system has been running in Super-Kamiokande since October 22nd. Future phases of Gd loading will extend the detection ranges and increase alert hours.