

Supernova Neutrinos in Super-Kamiokande



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 on behalf of the Super-Kamiokande Collaboration
 NEUTRINO Conference 2026@UCI
 June 25, 2026



The Super-Kamiokande Collaboration

~250 collaborators
from 59 institutes
in 11 countries

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
BMCC/CUNY, USA
University of California, Irvine, USA
California State University, USA
University of Chinese Academy of Sciences, China
Chonnam National University, Korea
Duke University, USA
Gifu University, Japan
GIST, Korea
University of Glasgow, UK
University of Hawaii, USA
Hiroshima University, Japan
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK

ILANCE, France/Japan
INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Institute of Science Tokyo, Japan
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
Kyungpook National University, Korea
University of Liverpool, UK
LLR, Ecole polytechnique, France
University of Minnesota, USA
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland

NIT, Nihama college, Japan
NIT, Numazu college, Japan
Okayama University, Japan
Osaka Electro-Communication Univ., Japan
University of Oxford, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
University of Silesia in Katowice, Poland
Sungkyunkwan University, Korea
Tohoku University, Japan
The University of Tokyo, Japan
Tokyo University of Science, Japan
University of Toyama, Japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan





Apr. 1, 2026

Super-Kamiokande 30th Anniversary

1996 – 2026

Contents

- Upgrade of SK with Gadolinium
- The Role of SK for Core-Collapse Supernova Explosion in Multi-Messenger and Time-Domain Astronomy
- New results of the Diffuse Supernova Neutrino Background (DSNB) search in SK

MC & Data analysis and slide materials by S. Fujita, Y. Ashida, M. Harada, A. Santos, G. Pronost, and many collaborators



Details in Posters

#38 Yota Hino

“Modification on thermal motion in Geant4 for neutron capture simulation in Gadolinium loaded water”

#84 Guillaume Pronost

“Super-Kamiokande's Supernova monitoring: A trigger for multi-messenger research”

#102 Mao Nishigami

“Neutron Tagging Efficiency Evaluation in the Super-Kamiokande Gd Phases”

#228 Fumi Nakanishi

“Search for Neutrinos Associated with a Failed Supernova Candidate in M31 with Super-Kamiokande”

#342 Masayuki Harada

“Evaluation of spallation background for DSNB search in SK-Gd”

#360 Saki Fujita

“New Results from the Diffuse Supernova Neutrino Background Search at Super-Kamiokande”

#424 Bin Zhang

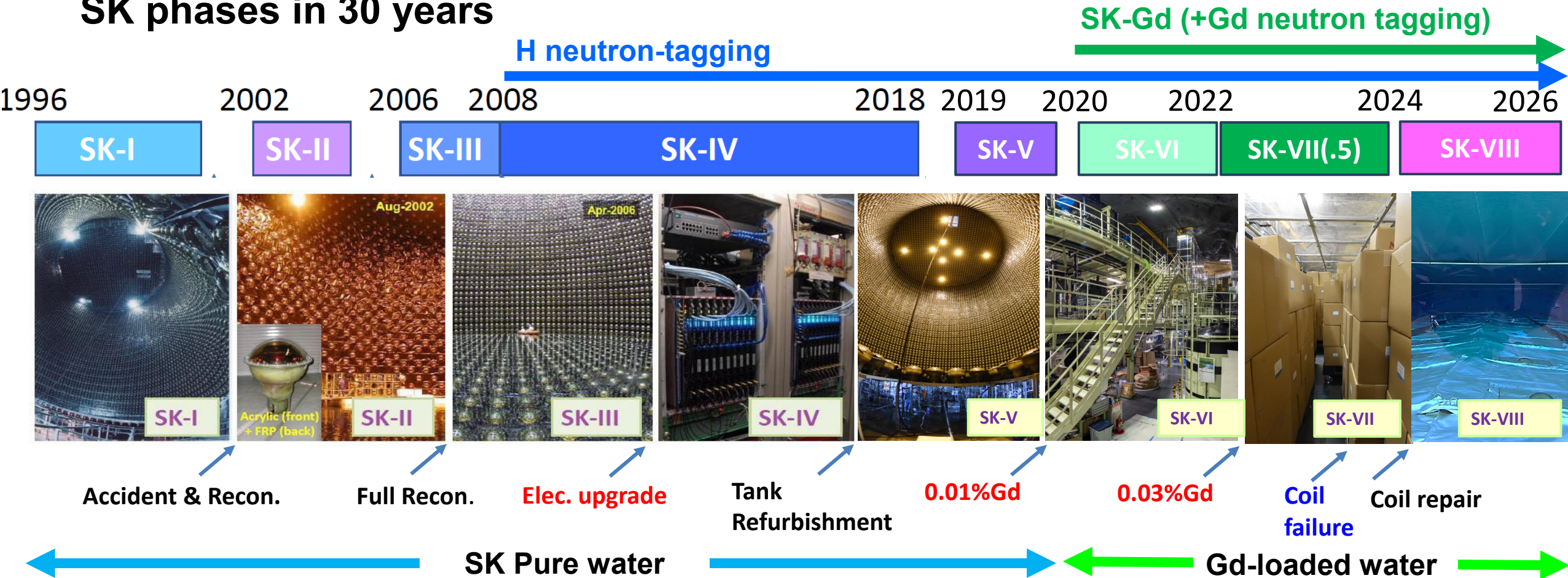
“SRN Search with an Expanded Time Window at Super-Kamiokande-IV”

#502 Licheng Feng

“Constraining Atmospheric NCQE Backgrounds for Super-Kamiokande DSNB Searches using T2K Data”

Super-Kamiokande History

SK phases in 30 years



Total live time for current analysis:

- Solar neutrino: 5805 days (SK-I~IV)
- Atmospheric neutrino: 6511 days (SK-I~V) + 564 days (SK-VI)
- Neutron tagging DSNB search: 3349 days (SK-IV~V) + 1653 days (SK-VI~VIII)

Supernova neutrino in SK

The main channel

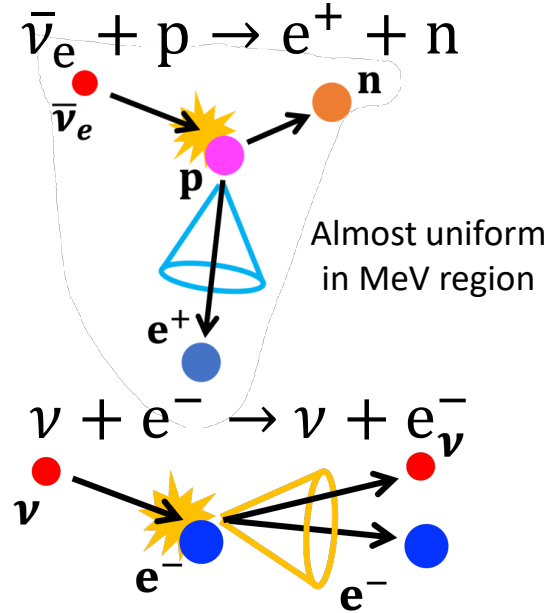
Inverse Beta Decay reaction (IBD) ~90%

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

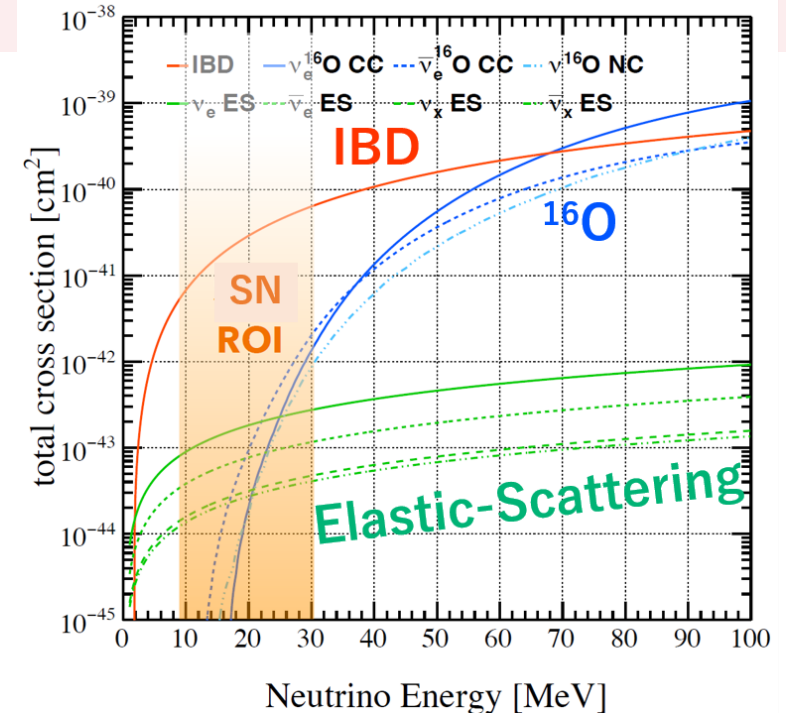
As the neutrino telescope

Elastic Scattering interactions (ES) ~5%

The electron keeps the neutrino direction information.

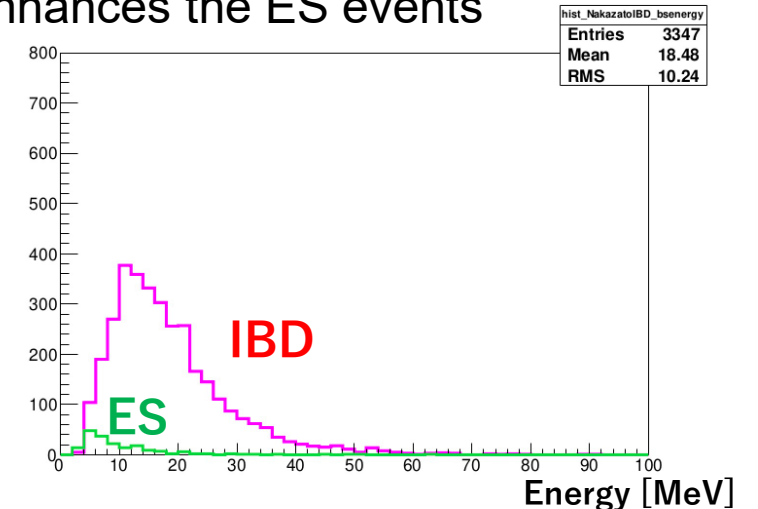
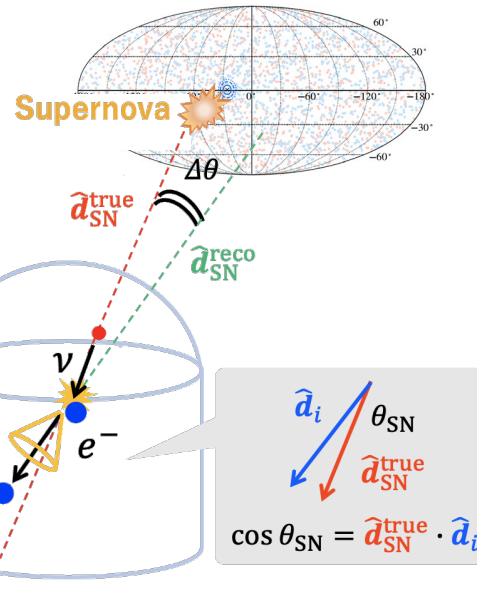
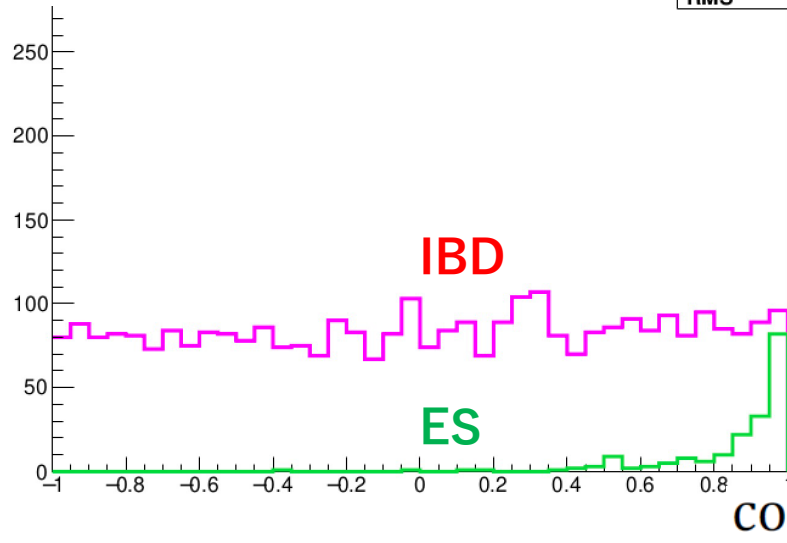


The interaction channels



Lowering threshold enhances the ES events

Nakazato $20M_{\odot}$ $z=0.02$ 200ms
10 kpc simulation

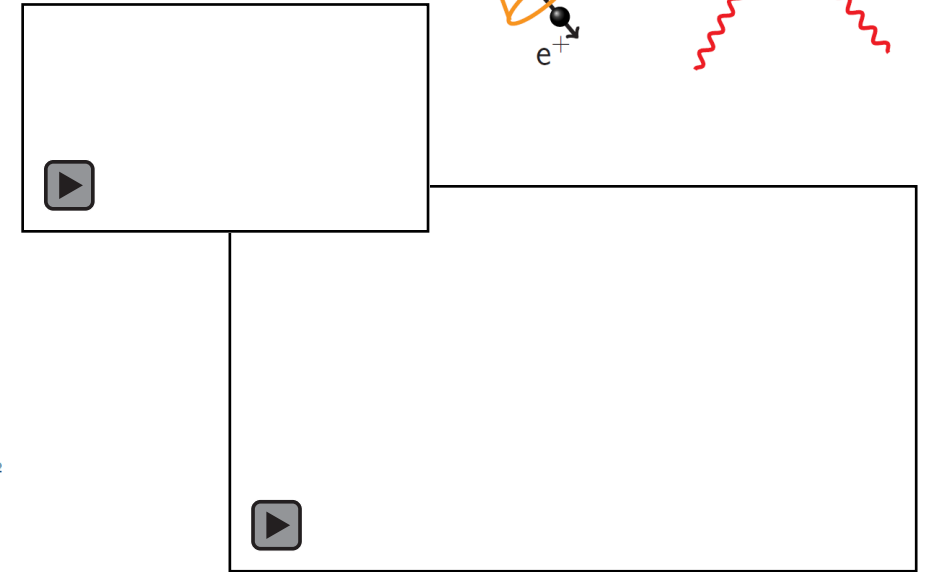
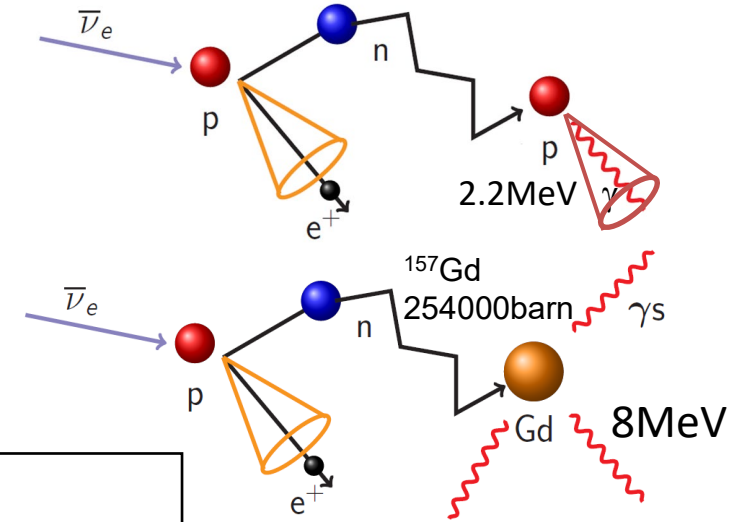
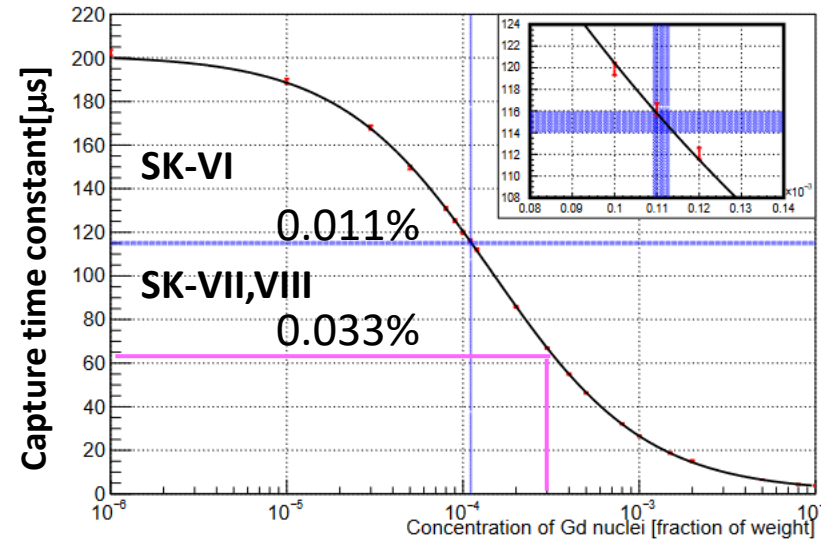
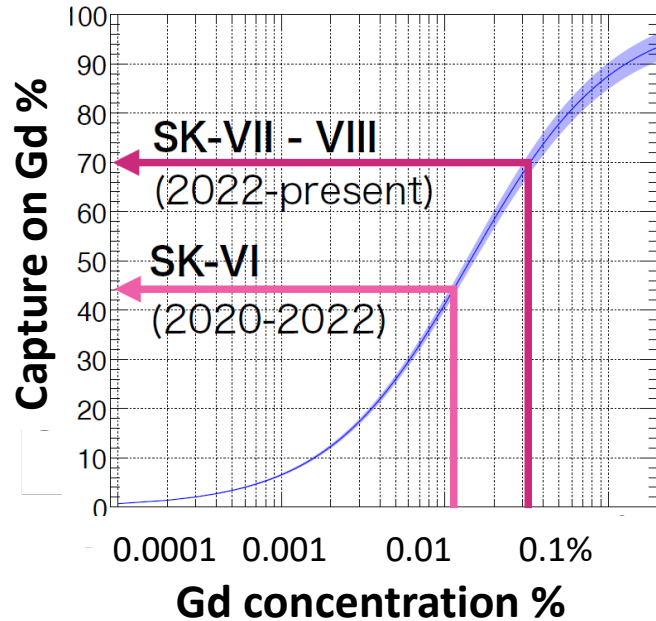


The Gd-loading to SK

- **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 $Gd(n,g)$

Since July 5, 2022, 39 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$ in SK
= 16.2 tons of Gd(0.033 w%)
→ ~70% Gd neutron capture efficiency



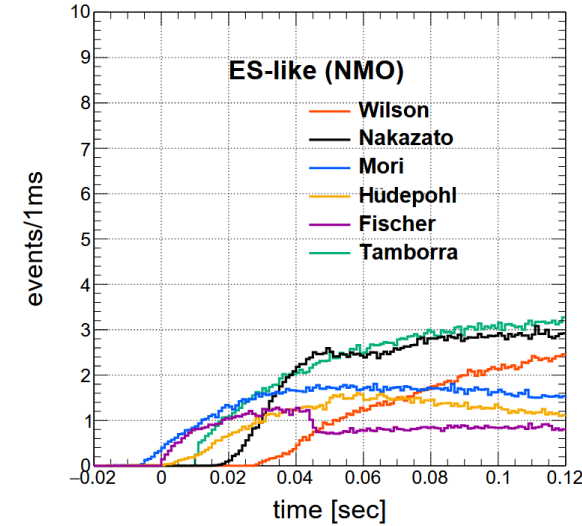
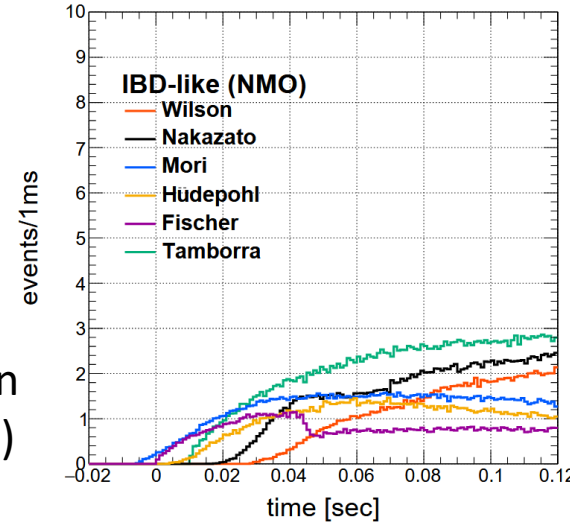
Separating IBD from BG improves sensitivity to low-energy signals such as DSNB.
Separating ES from IBD improves the SN direction-pointing accuracy.

SK's vital role of neutrino observation in CCSN

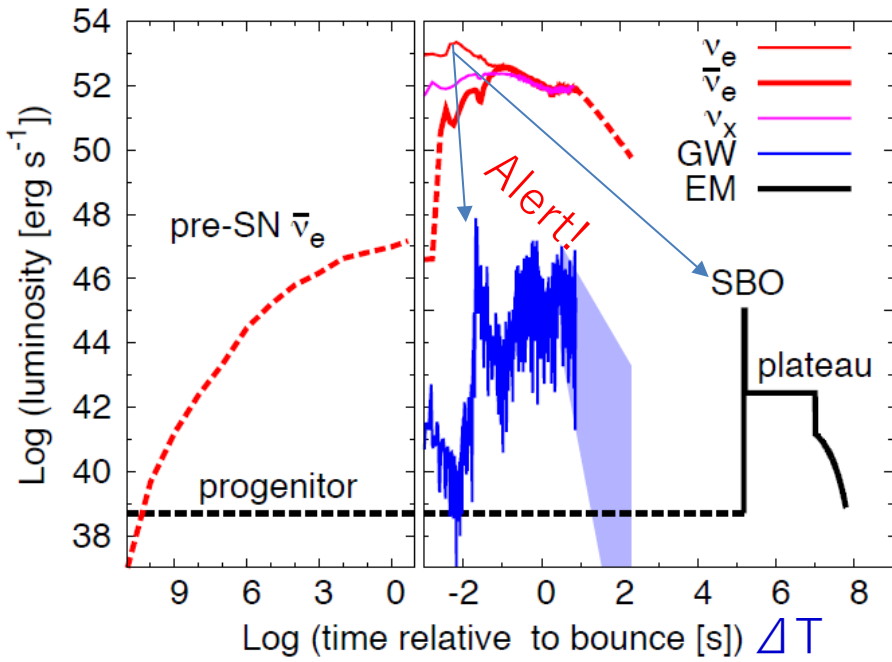
1. Understand the explosion mechanism:

Detecting SN neutrinos allows us to directly probe and understand the core-collapse supernova explosion mechanism.

Model-Dependent Time Evolution of Expected Events in SK (22.5 kt)

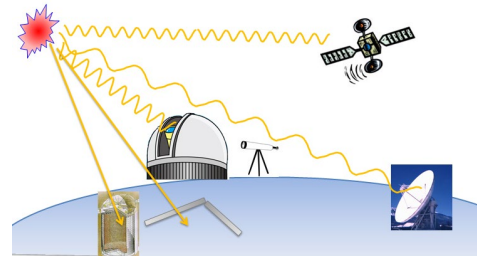


K. Nakamura MNRAS, 461, 3296 (2016)



2. Multi-messenger trigger:

Issuing prompt alerts based on the first-arriving neutrinos to notify electromagnetic (EM) observatories.



Speed, pointing accuracy, and distance estimation are crucial for EM follow-up observations.

SK-alert's distance coverage

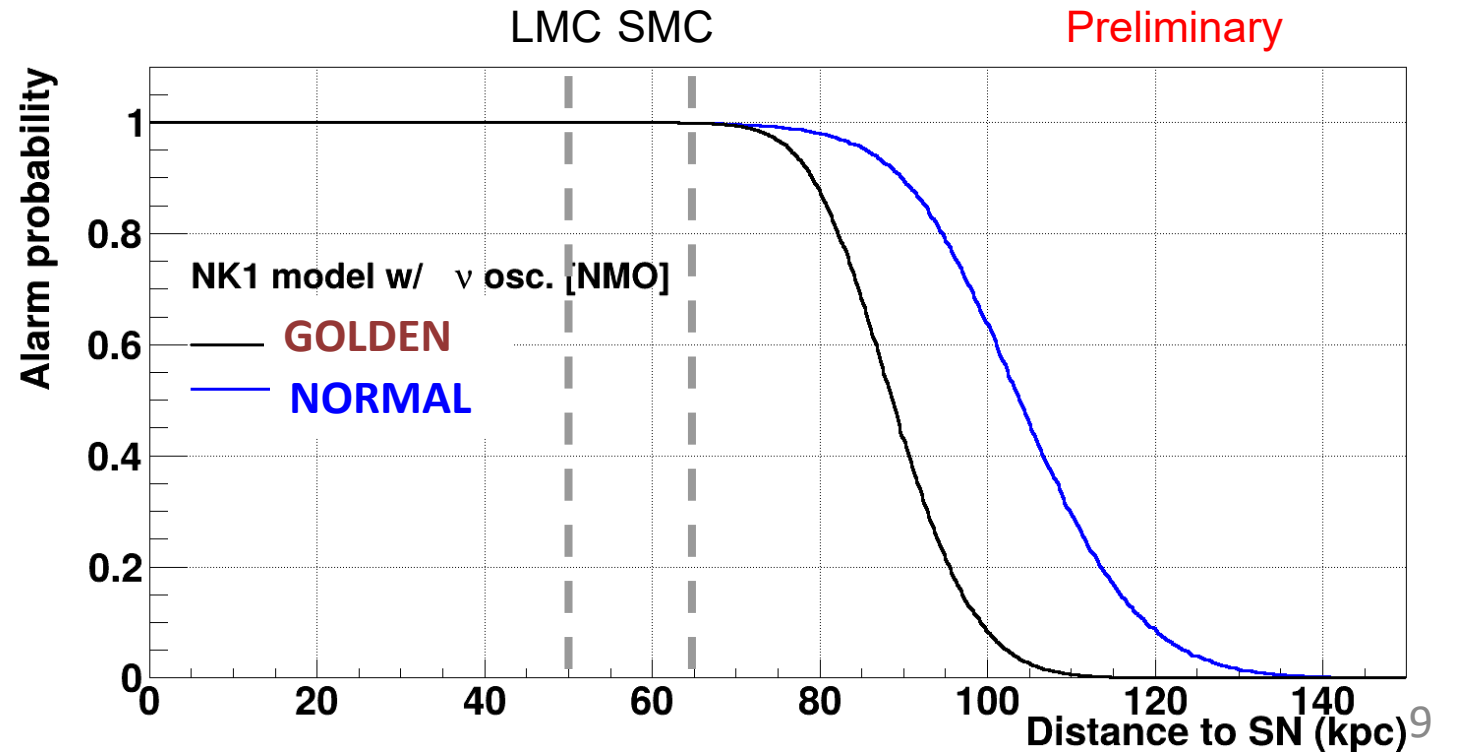
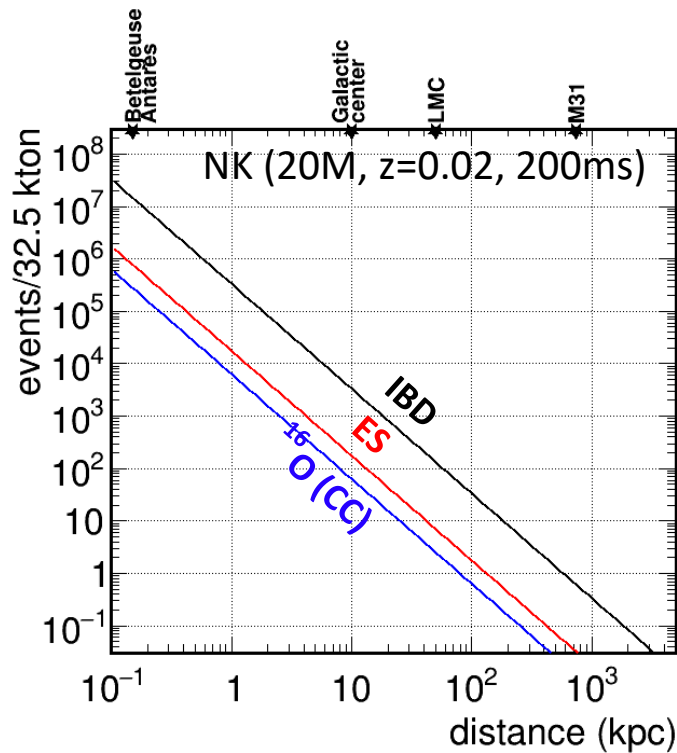
SK can detect a burst of events up to ~ 100 kpc (depending on the models).
The thresholds for the alerts are defined as

GOLDEN alert: total events >35 with IBD events >10

NORMAL alert: total events >25 with IBD events >10

The LMC is covered by the GOLDEN alarm.

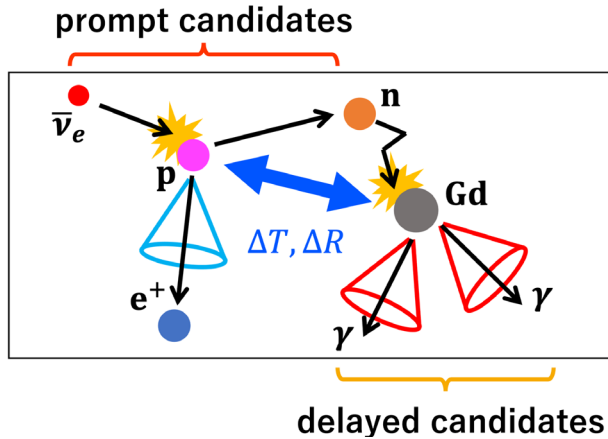
The SMC is also covered by the GOLDEN alarm with a $\sim 99.81\%$ probability at 65 kpc.



How quick? Within ~90 sec for 10kpc SN

Speed-oriented online analysis pipeline: SN_Watch Reconstructing the events and fitting SN direction

1. Real-time simple IBD tagging algorithm

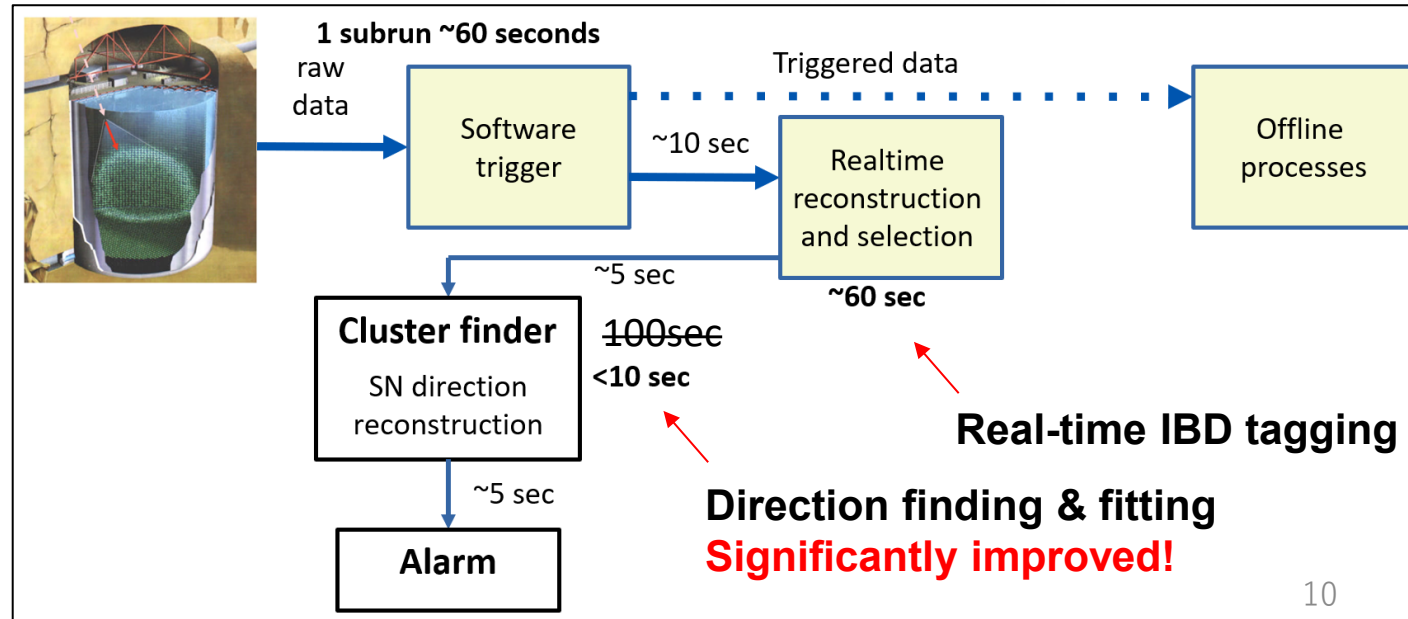
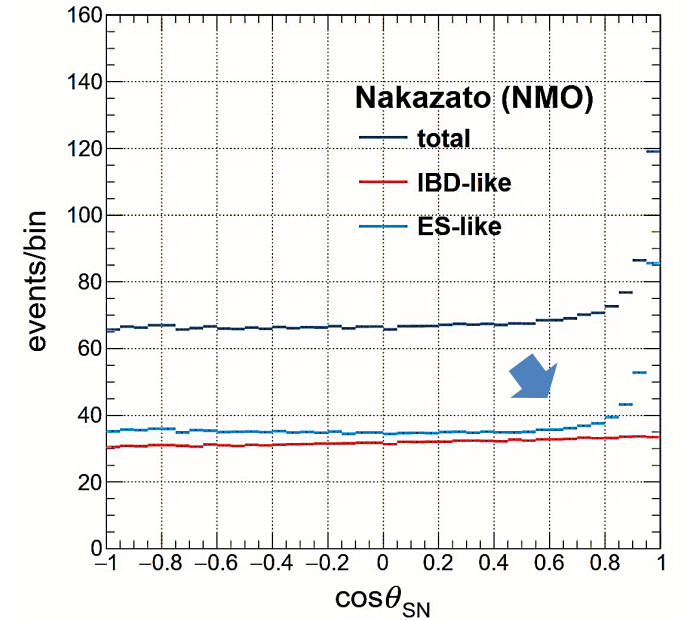
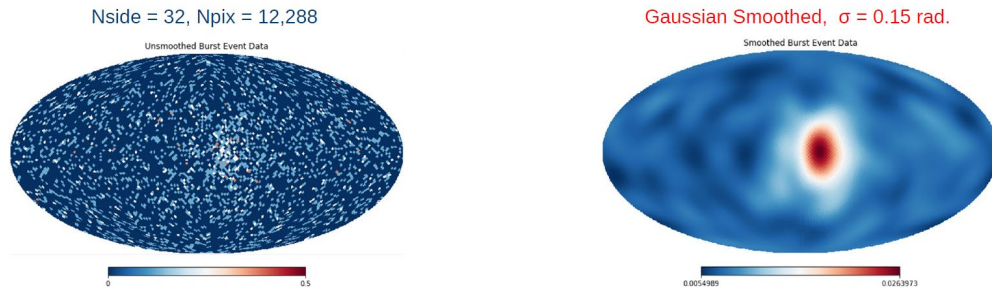


- ① Selection of prompt candidates $\geq 6\text{MeV}$
- ② Selection of delayed candidates
- ③ Neutron tagging pair of events with $\Delta T < 500 \mu\text{s}$ & $\Delta R < 300 \text{ cm}$

This selection algorithm tags ~50% IBD events

2. HEALPix-based initial direction finder → Full likelihood fitting

Hierarchical Equal Area isoLatitude Pixelation of a sphere:



SK's default alert channel: GCN(Kafka)

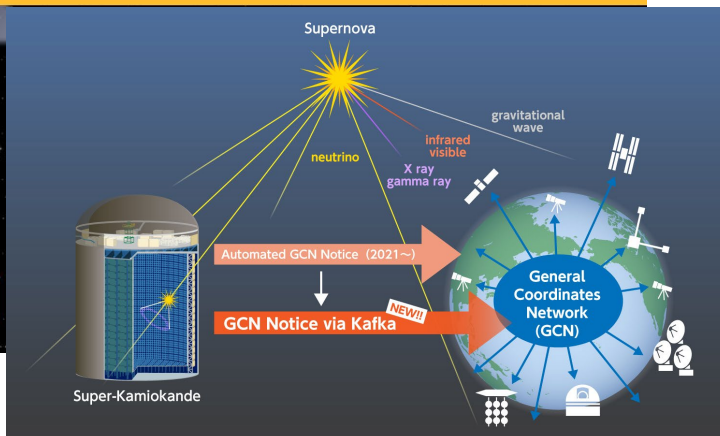
Since Aug 26, 2025

NASA's streaming alert system with minimum latency

GCN: NASA's Time-Domain and Multimessenger Alert System

GCN distributes alerts between space- and ground-based observatories, physics experiments, and thousands of astronomers around the world.

Buttons: Start streaming GCN Notices, Post a GCN Circular

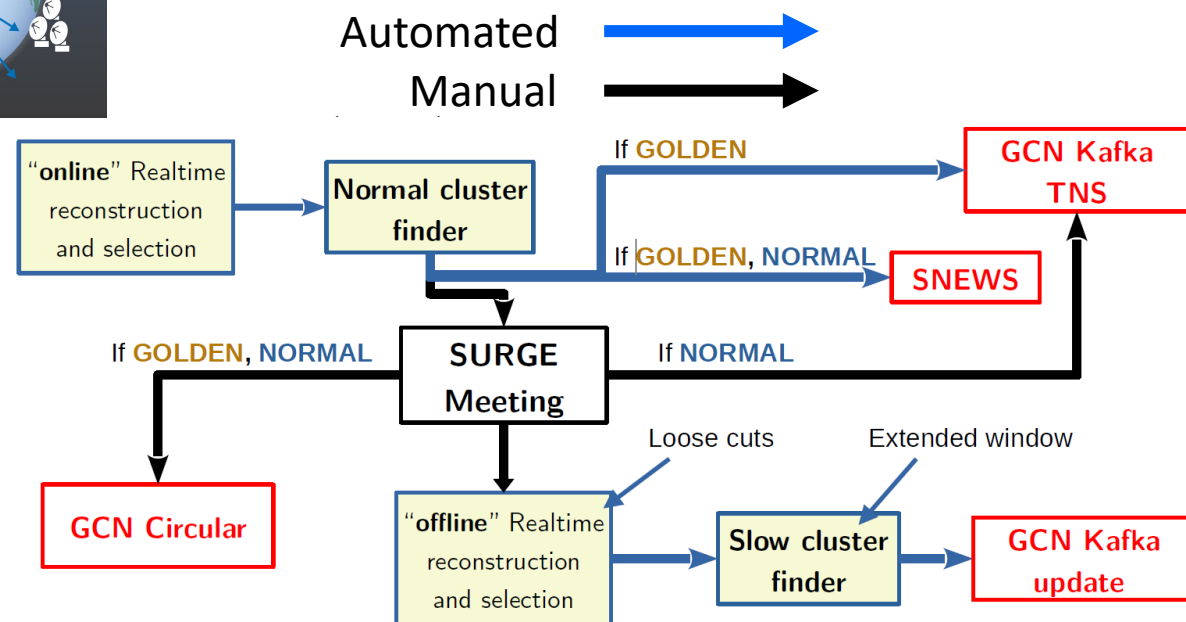


<https://gcn.nasa.gov/missions/sksn>

```
ex) sn_alert.schema.json
"trigger_time": "2023-08-01T00:00:01.000000Z",
"n_events": 64176,
"n_ibd_events": 6310,
"detection_interval": 10,
"rate_energy_range": [6000, 100000],
"ra": 270.82,
"dec": 31.46,
"ra_dec_error": 0.91,
"luminosity_distance": 0.0025,
"luminosity_distance_error": 0.0004,
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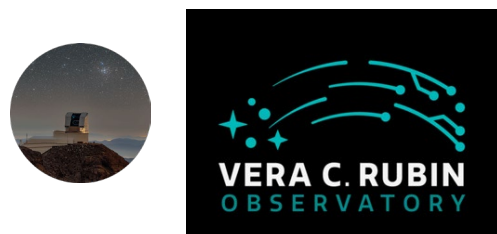
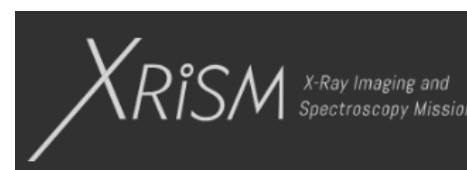
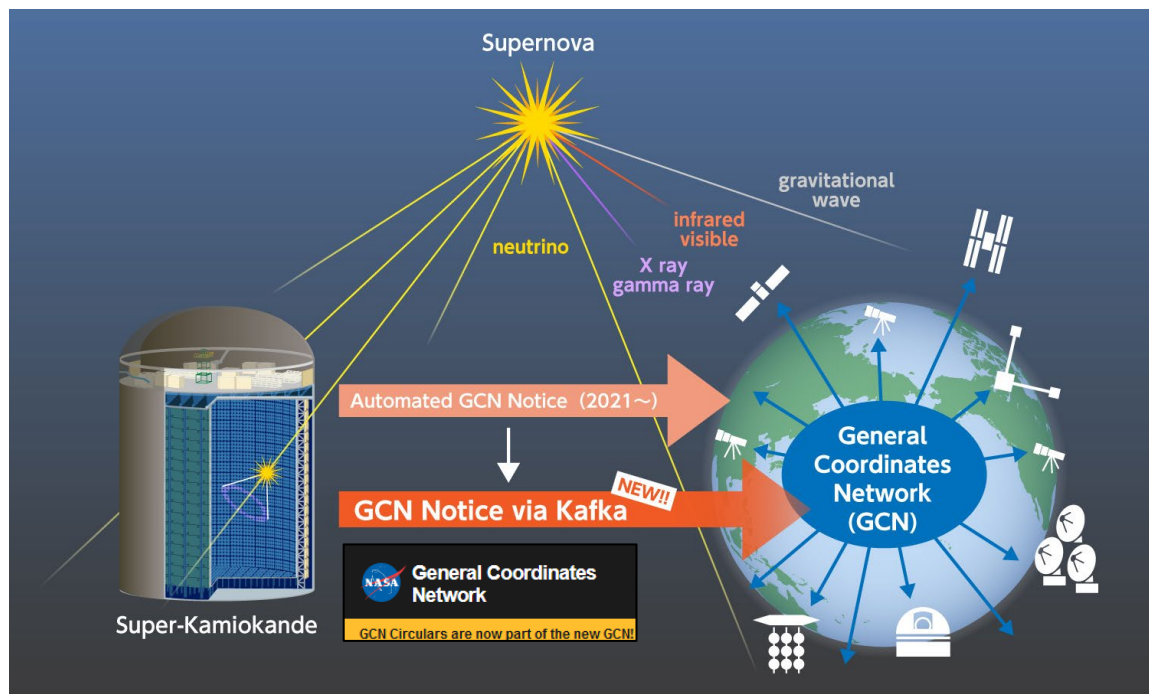
Other channels

Channel	Timestamp	Direction	Distance	Latency	Note
GCN (Kafka)	✓	✓	✓	~ 1 sec	Automated
GCN (Classic)	✓	✓	✓	~ 40 sec	Automated
TNS	✓	✓	✓	< 5sec	Automated
SNEWS (1.0, 2.0)	✓	×	×	< 5sec	Automated
Atel	✓	✓	✓	~ 1h	Manual
GCN Circular	✓	✓	✓	~ 1h	Manual



Our direct communication channels

- ✓ Test alert for training via GCN(Kafka)
- ✓ Custom low-level alert (silver, bronze, ...) with FAR

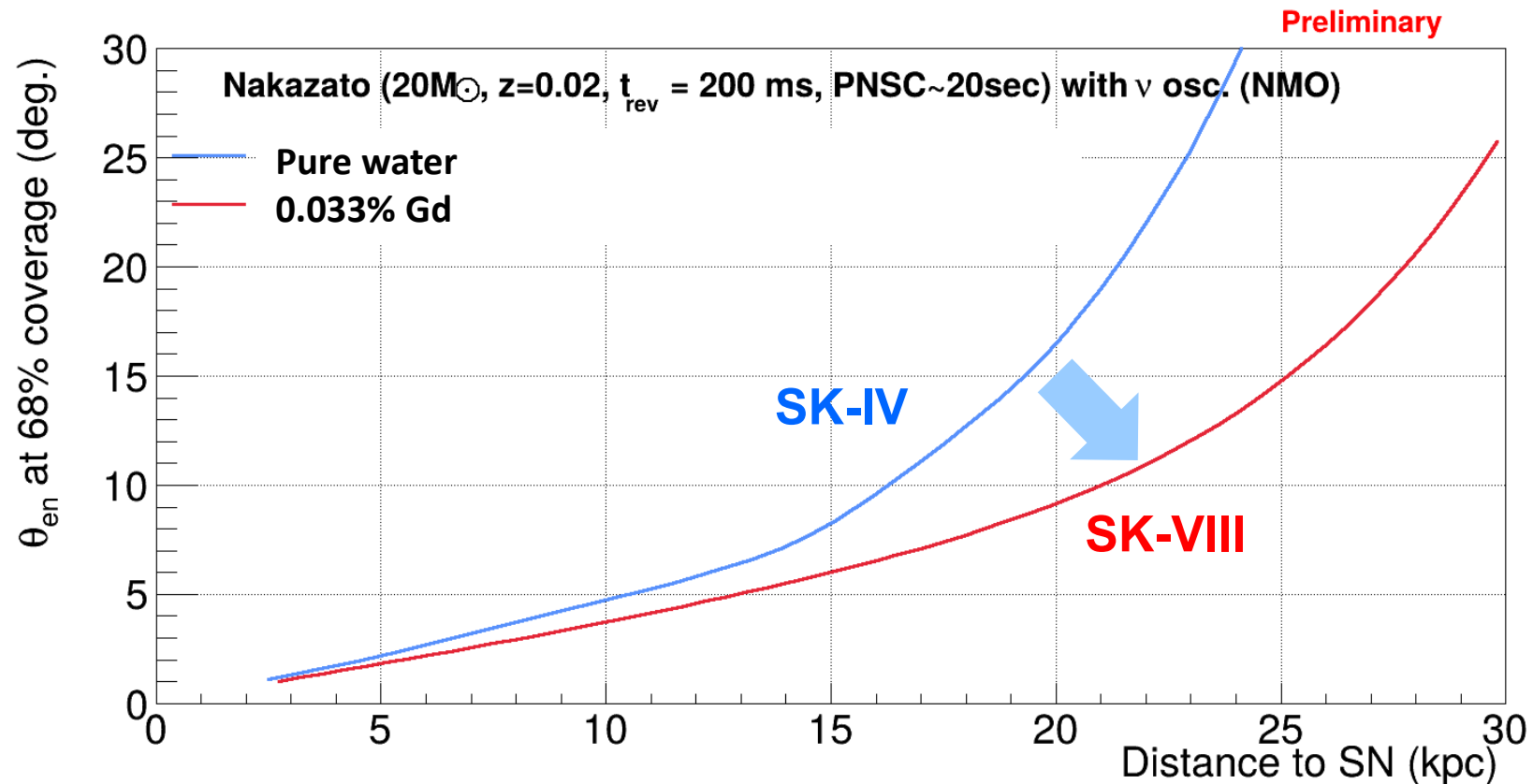


The pointing accuracy

@10kpc (Nakazato $20M_{\odot}$, PNSC 20sec)

$3.78 \pm 0.04^{\circ}$ (1σ)

$5.52 \pm 0.06^{\circ}$ (90%C.L.)



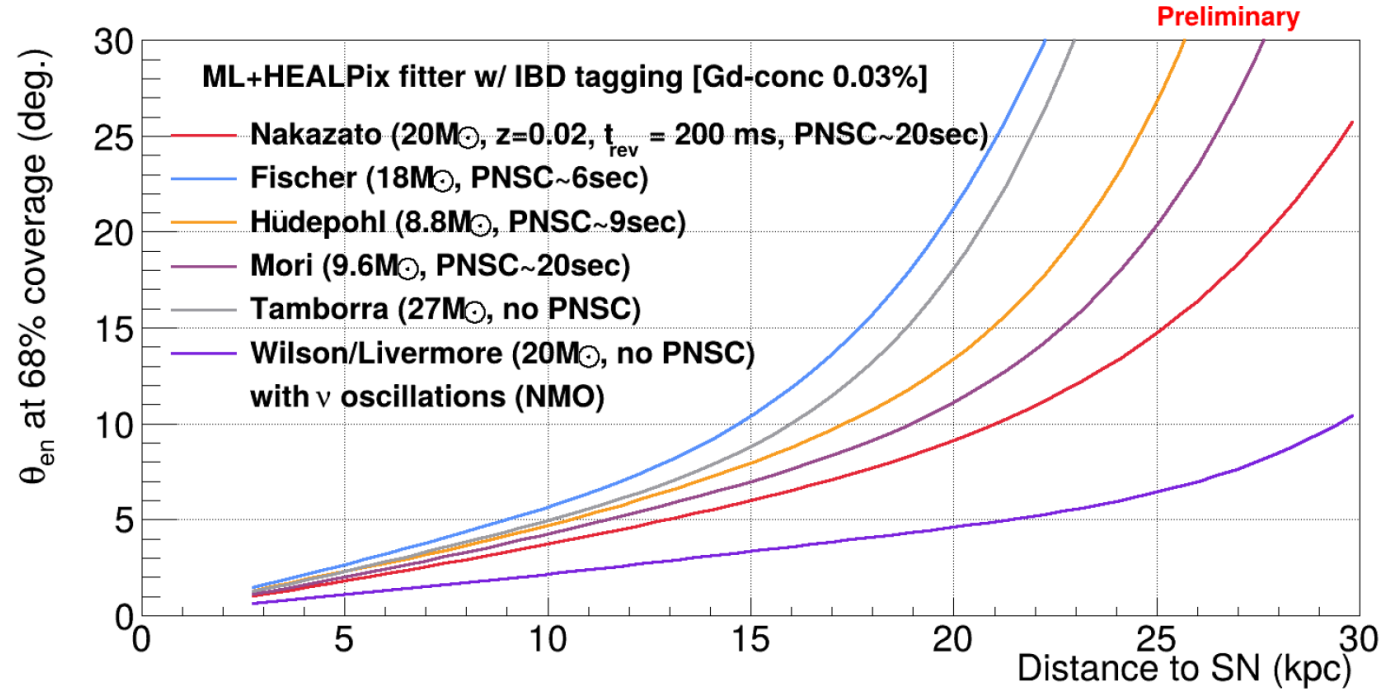
Model dependence of pointing accuracy

Poster #84 Guillaume Pronost

@10kpc 2.2 - 5.6° (1σ)

Preliminary

Model	Total events in SK	Pointing (1σCL)	Pointing (90%CL)
Nakazato	2681	3.78 ± 0.04°	5.52 ± 0.06°
Fischer (8M)	1338	5.62 ± 0.18°	8.78 ± 0.28°
Hüdepohl	2037	4.93 ± 0.16°	7.38 ± 0.24°
Mori	2307	4.09 ± 0.13°	5.99 ± 0.19°
Tamborra	2463	4.87 ± 0.16°	7.67 ± 0.25°
Wilson	6418	2.17 ± 0.07°	3.30 ± 0.11°



Upgrading distance estimation for focusing

The current distance estimate in the GCN SK notice is based on **scaling the observed 1987A events**.
→ Substantial statistical and systematic uncertainties.

Suwa et al. (ApJ 980 (2025) 117) provided a new method, based on **Proto Neutron Star Cooling (PNSC) ν production** (where the physics process is model-independent).
Relies on event rates and average energy information from the cooling stage (~ 20 sec).

Average energy in our sample

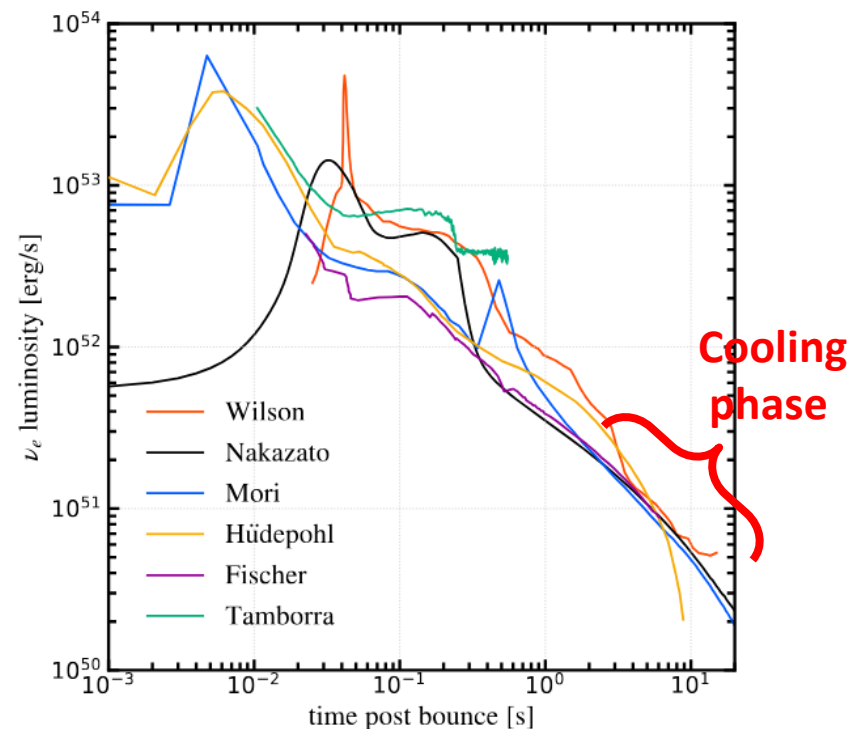
$$E_{e^+} = 25.3 \text{ MeV} \left(\frac{M_{\text{PNs}}}{1.4 M_{\odot}} \right)^{3/2} \left(\frac{R_{\text{PNs}}}{10 \text{ km}} \right)^{-2} \left(\frac{g\beta}{3} \right) \left(\frac{t + t_0}{100 \text{ s}} \right)^{-3/2}$$

Rate of events in our sample

$$\mathcal{R} = 720 \text{ s}^{-1} \left(\frac{M_{\text{det}}}{32.5 \text{ kton}} \right) \left(\frac{D}{10 \text{ kpc}} \right)^{-2} \left(\frac{E_{e^+}}{25.3 \text{ MeV}} \right)^5 \left(\frac{R_{\text{PNs}}}{10.0 \text{ km}} \right)^2$$

$$\begin{aligned} \rightarrow D &= 10 \text{ kpc} \left(\frac{\mathcal{R}}{720 \text{ s}^{-1}} \right)^{-1/2} \left(\frac{E_{e^+}}{25.3 \text{ MeV}} \right)^{5/2} \\ &\times \left(\frac{M_{\text{det}}}{32.5 \text{ kton}} \right)^{1/2} \left(\frac{R_{\text{PNs}}}{10 \text{ km}} \right). \end{aligned}$$

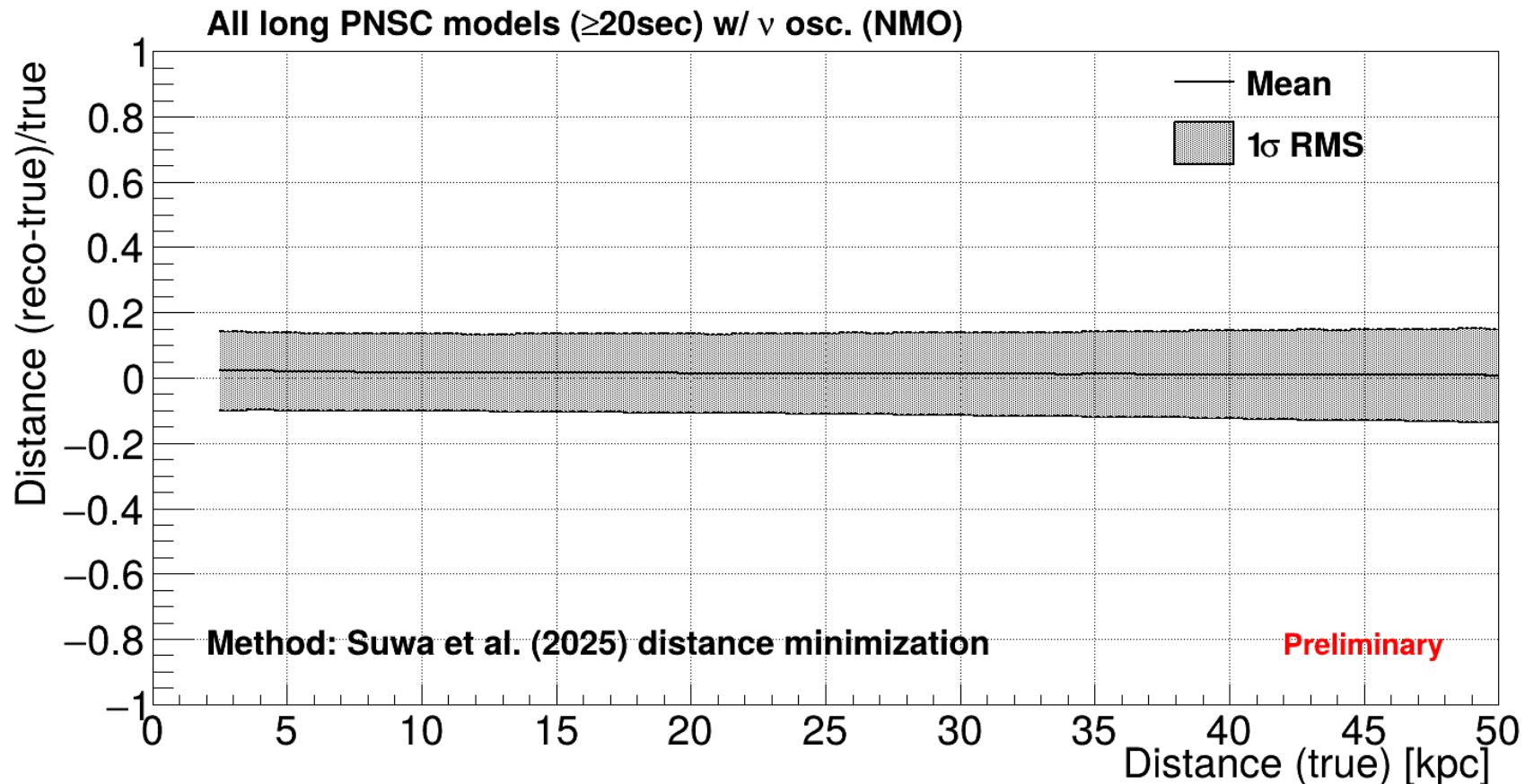
R_{PNs} = theoretically model-dependent, assumed 12.4 km \sim 10 km



Error on distance estimation

Few models cover the cooling phase up to 20 seconds. Therefore, we used the long-term Nakazato (5 PNSC variations) and Mori models to evaluate the distance estimation errors. The 1σ error for a supernova at 10 kpc is approximately +12% / -12%

→ Will be implemented in the alert

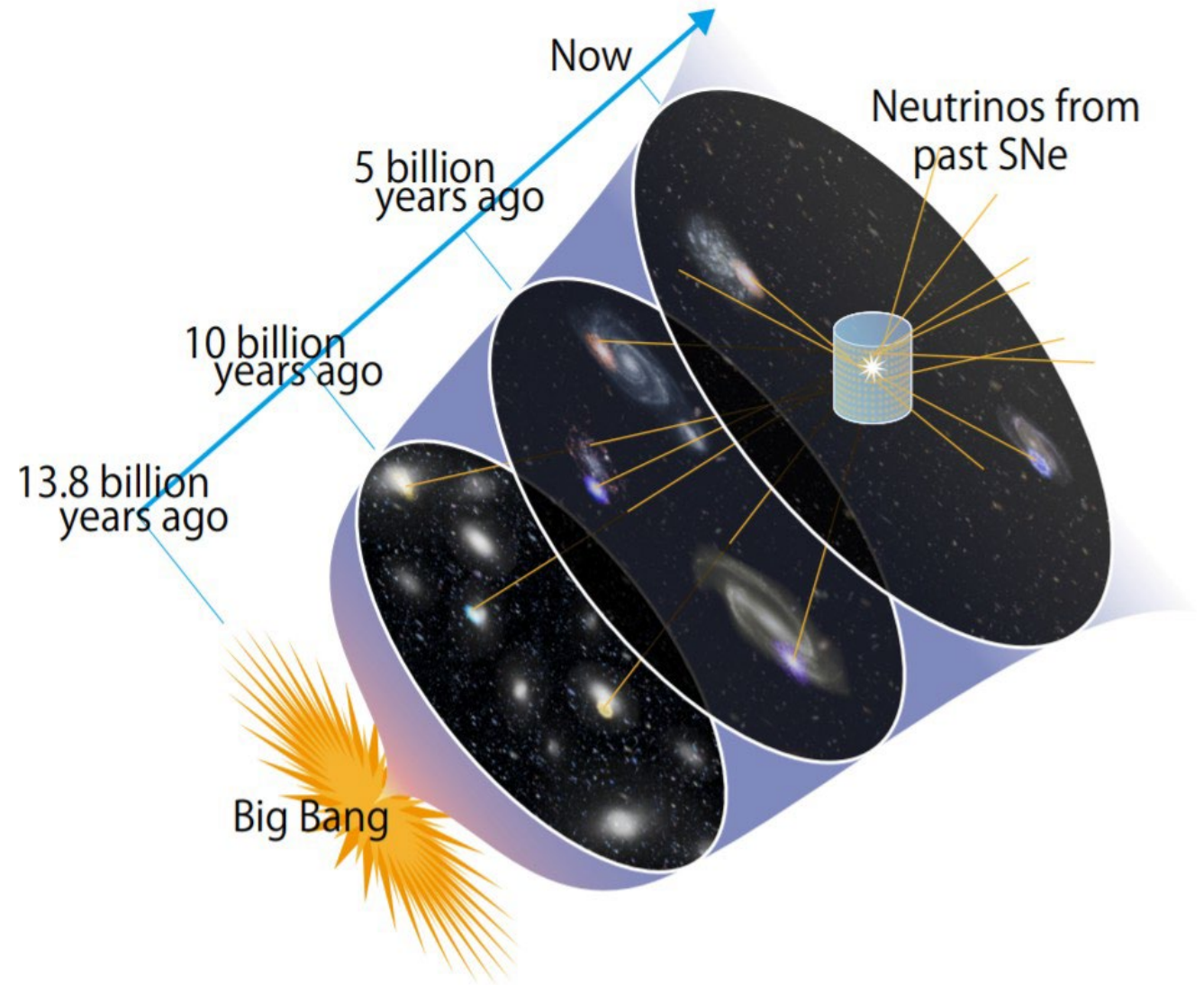


Diffuse Supernova Neutrino Background

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

Promising extra-galactic ν

There must have been $O(10^{18})$ explosions in the history of the universe.



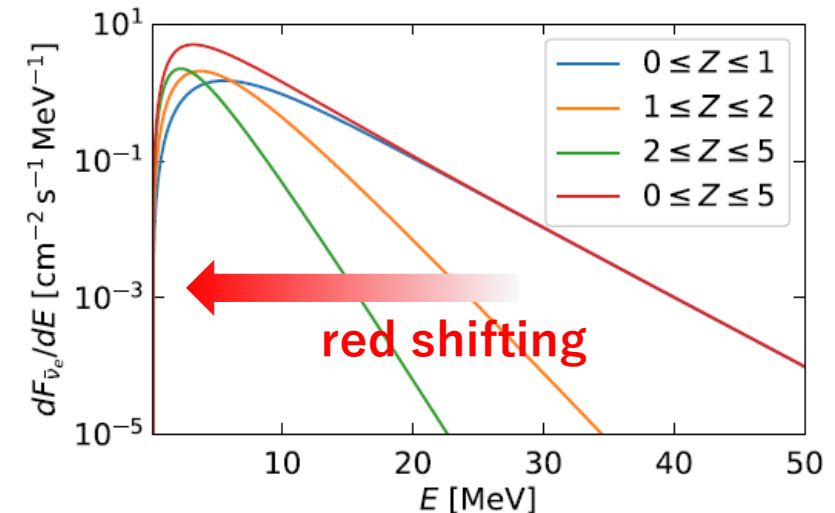
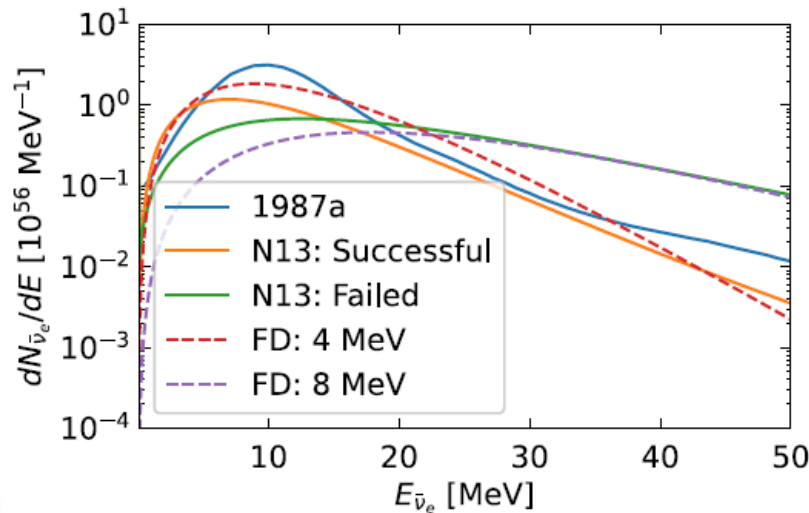
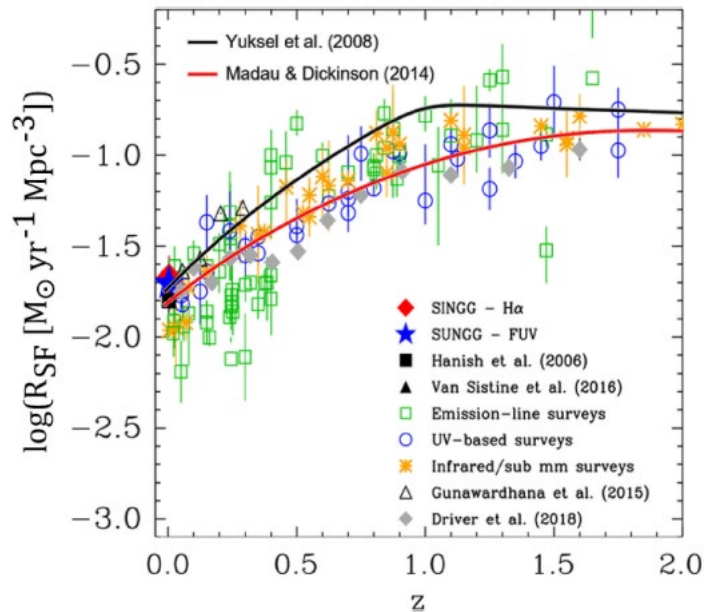
Diffuse Supernova Neutrino Background

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

SN rate at z

(averaged) SN spectrum

Red shift



S.Ando et al., Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10

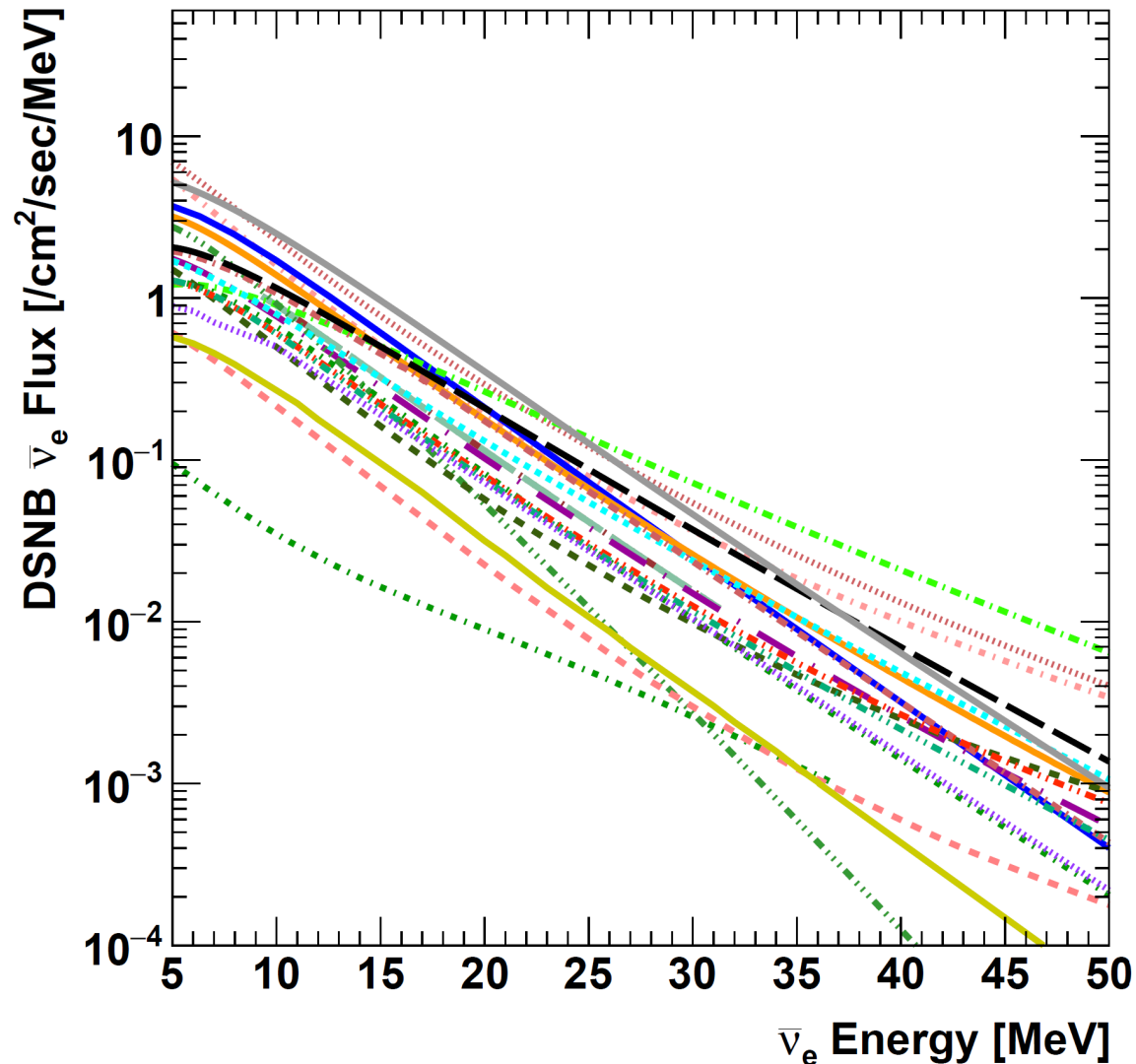
Access to

- ✓ Star formation rate
- ✓ BH formation rate
- ✓ Binary interaction effect
- ✓ Mechanism of the supernova explosion

- + Particle physics
 - ✓ ν Mass Ordering
 - ✓ exotic process (ex ν -decay)

DSNB models

Comprehensive list of available DSNB models



- ✓ Star formation rate
- ✓ BH formation rate
- ✓ Binary interaction effect
- ✓ Mechanism of the supernova explosion

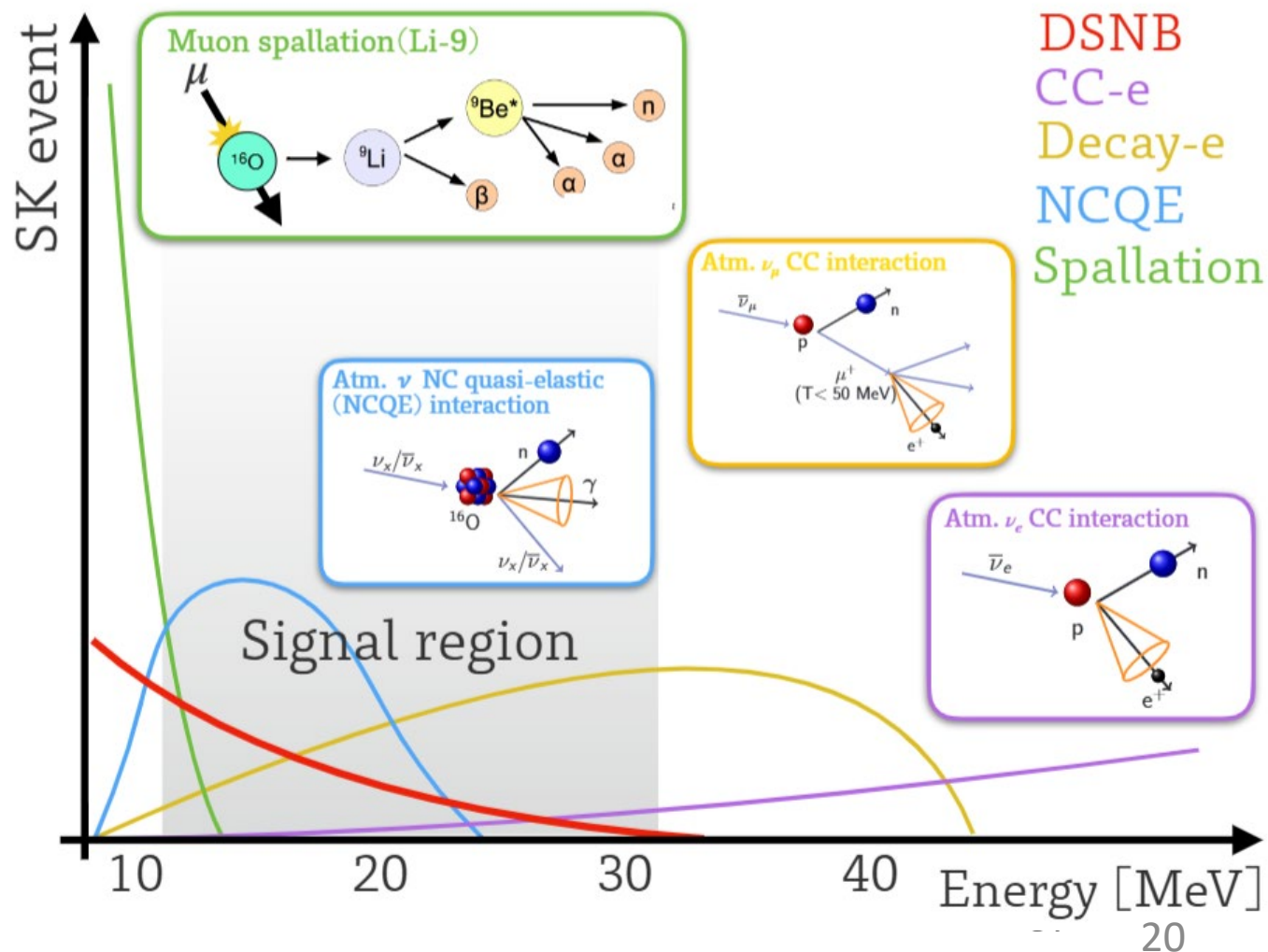
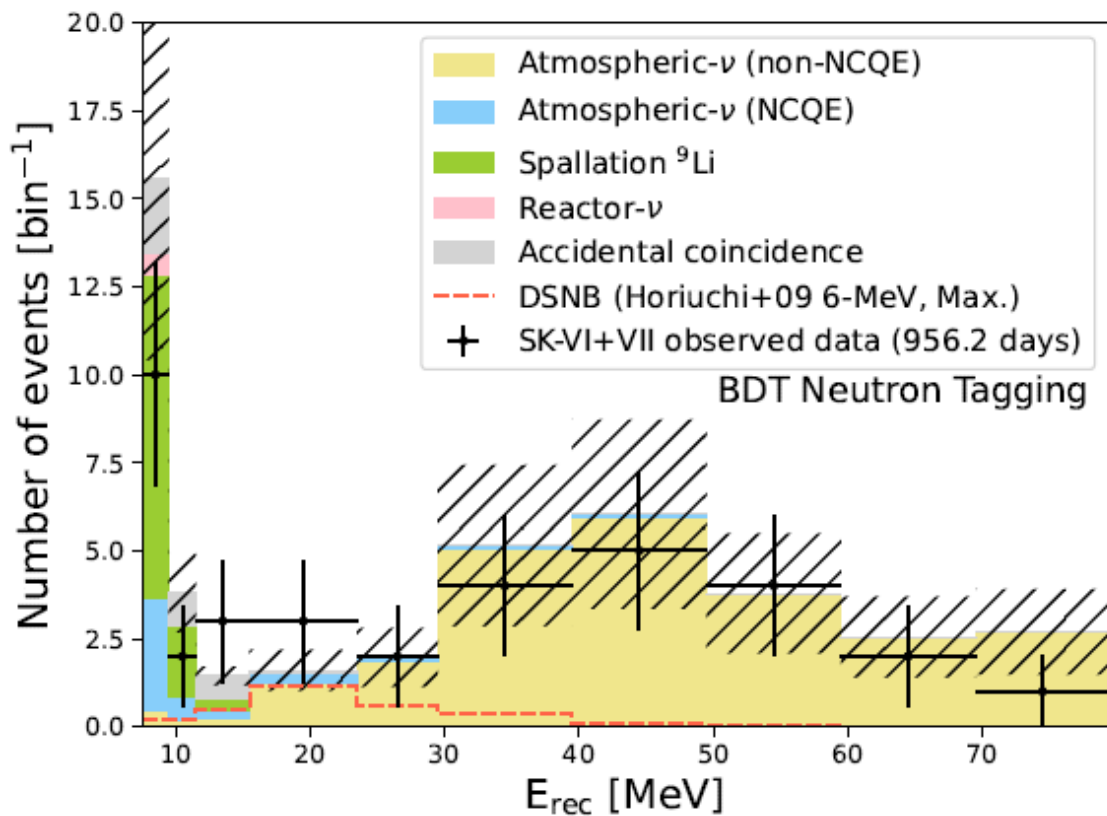
- ⋯ Nakazato+24 (HB06, Fallback50%, NH)
- ⋯ Martinez-Mirave+24 ($f_{\text{MR}}=0.2$)
- Ekanger+24 NH, $f=0.236$
- ⋯ Ashida+23 (MD14, Togashi, NH)
- ⋯ Ivanez+23 (SH, Togashi, IH)
- Horiuchi+21 (Extrapolated, $\alpha\lambda=0.1$, NH)
- Kresse+21 (High, NH)
- Tabrizi+20 (NS+BH, NH)
- ⋯ De Gauvea+20 (max, NH)
- ⋯ Barranco+18 (Λ CDM, leptonic, fiducial)
- ⋯ Horiuchi+18 ($\xi_{2.5, \text{crit}} = 0.1$)
- ⋯ Priya+17 (Fiducial)
- ⋯ Nakazato+15 (Max, IH)
- ⋯ Nakazato+15 (Min, NH)
- ⋯ Galais+10 (NH)
- Horiuchi+09 (6 MeV, Max)
- ⋯ Lunardini09
- ⋯ Ando+03 (updated at NNN05)
- Kaplinghat+00
- Malaney97
- ⋯ Hartmann+97

Background of DSNB search in SK

$\bar{\nu}_e$ BG and those mimic the IBD event topology

Latest publication
SK-VI+VII

arXiv:2511.02222
Accepted for ApJ



DSNB Spectral fitting analysis

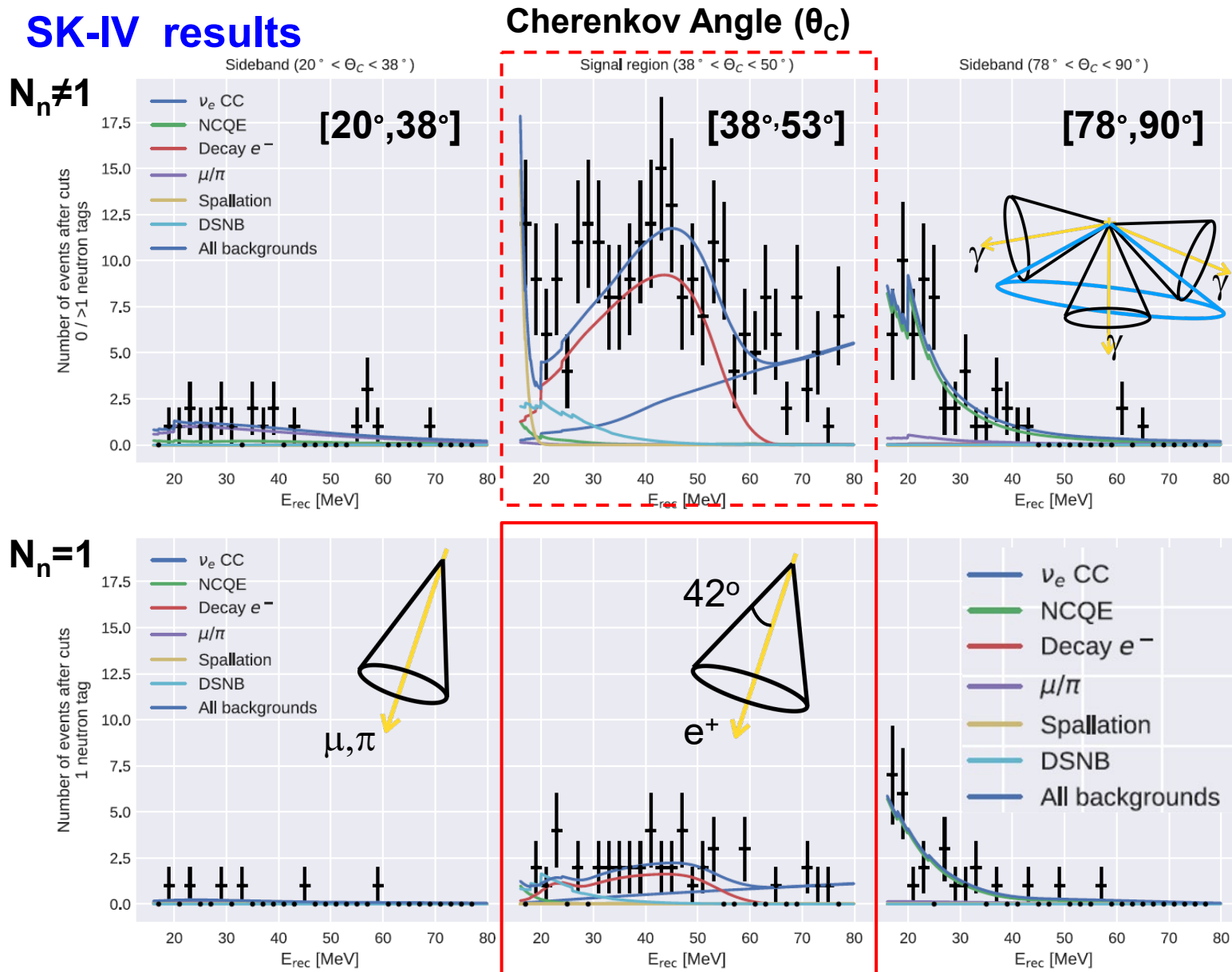
PRD 104, 122002 (2021)

Extended unbinned maximum likelihood fit based on energy: Simultaneously extract the signal and background strengths using PDFs.

6-Window Strategy:

Instead of applying hard cuts to remove background-like events, sideband windows are used to constrain the background scale and shape, enhancing sensitivity to the DSNB in the main window.

SK-IV results



New analysis with a 5000-day dataset

= ~3350-day pure water + ~1650-day Gd water

Phase	Period	Livetime [days]	Water Status
SK-IV	Oct. 2008 - Feb. 2018	2970.1	Pure-water
SK-V	Feb. 2019 - Jul. 2020	379.2	Pure-water
SK-VI	Aug. 2020 - Jun. 2022	552.2	Gd-water (0.01w%)
SK-VII	Jul. 2022 - Oct. 2023	404.0	Gd-water (0.03w%)
SK-VII.5	Dec. 2023 - Jul. 2024	191.8	Gd-water (0.03w%)
SK-VIII	Sep. 2024 - Mar. 2026	505.7	Gd-water (0.03w%)

- **Additional datasets:** SK-V (379 days), SK-VII.5 (192 days), SK-VIII (506 days)
- **Refined event selections:** Neutron tagging, spallation cut, NC γ cut, etc
- **Lowered energy threshold** in the main window ($N_n=1$, $\theta_C = [38^\circ, 53^\circ]$):

$$E_{rec} = 15.5 \text{ MeV} \rightarrow 11.5 \text{ MeV} \quad (E_\nu = 17.3 \text{ MeV} \rightarrow 13.3 \text{ MeV})$$

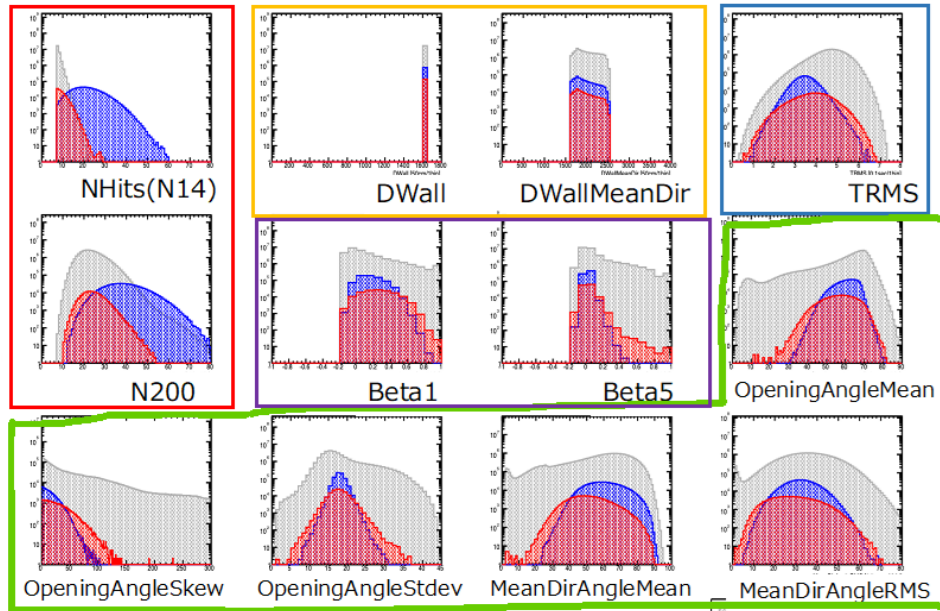
- **Improvements on background modeling and systematics:** ${}^9\text{Li}$, N_n , NCQE, etc
- **Combined result with all Ntag-enabled SK phases (SK-IV+V+VI+VII+VII.5+VIII)**

IBD Neutron tagging

Neural Network (TMVA-MLP) as introduced in SK-VI+VII paper

A pre-selection requires hit clusters above 5(SK-IV,V) or 7(SK-VI,VII,VIII) hits in 14ns window

12 variables representing the number of PMT hits, spatial features of PMT hits, the RMS of the hit timing peak, and the distance from the ID wall.



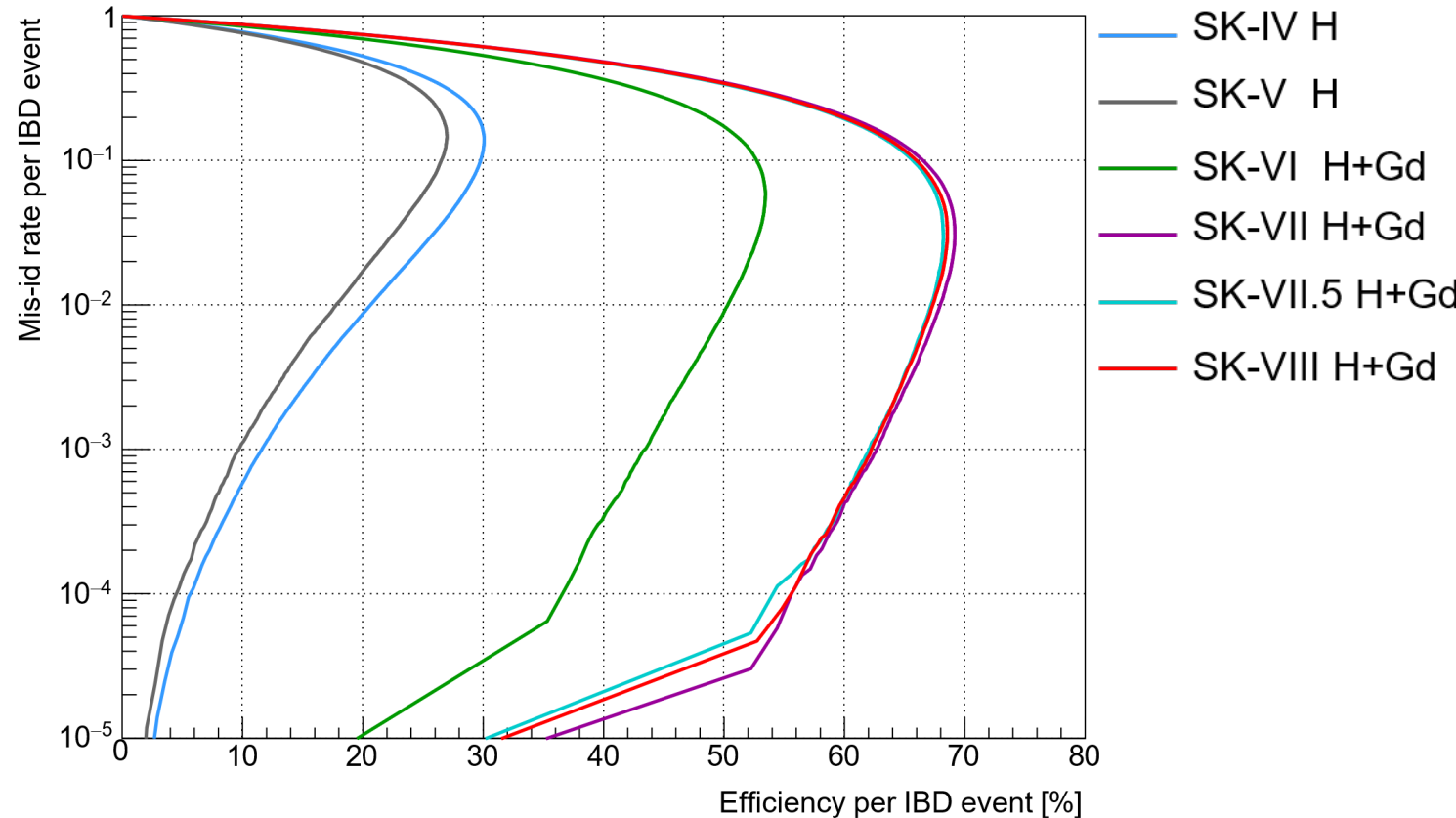
PMT hits

Mean direction/Distance from SK ID

Timing info

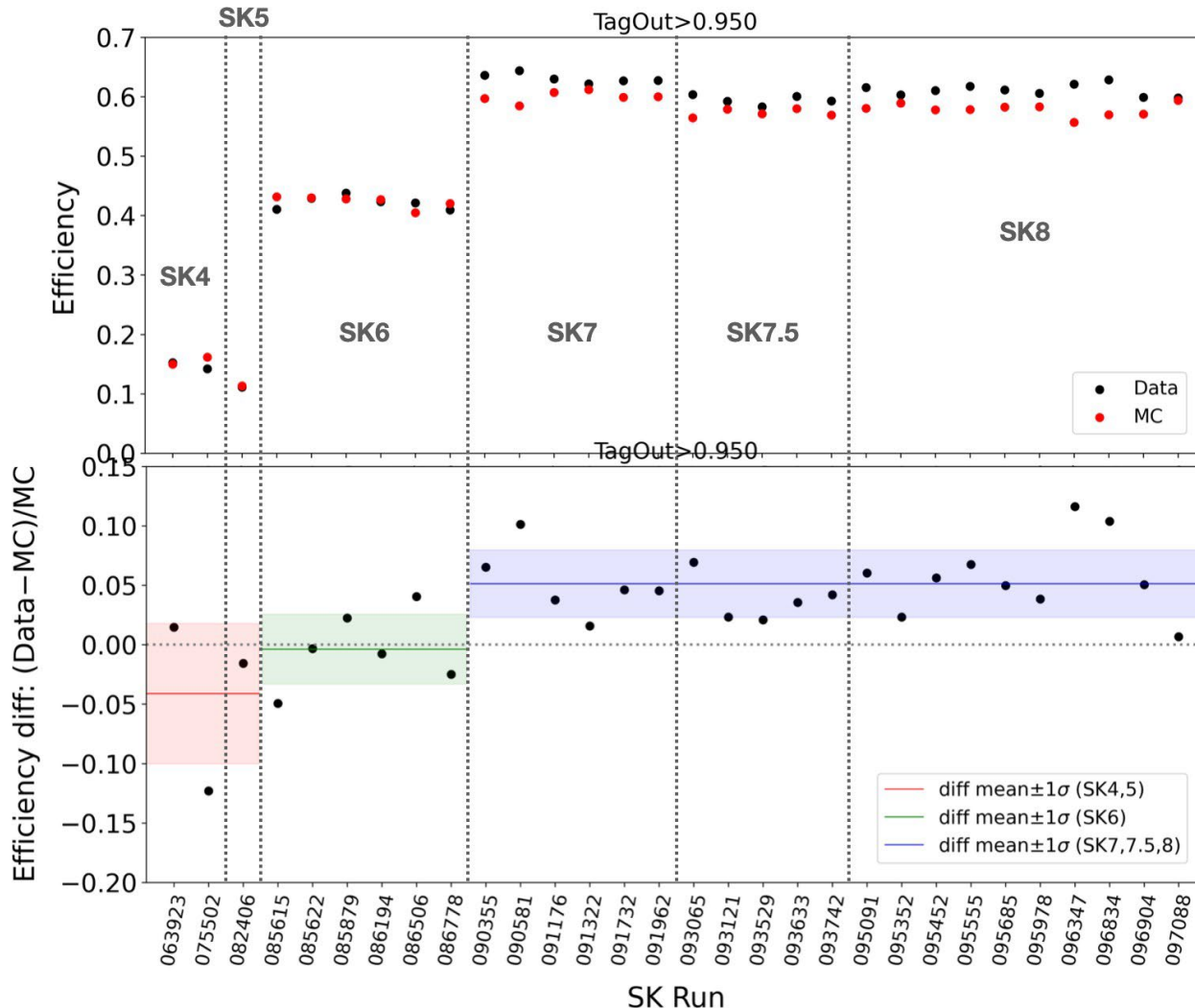
Harmonic Beta parameters

Hit patterns



Validation with Am/Be calibration

Am/Be neutron source calibration and MC tuning ${}^9\text{Be} + \alpha(\text{from } {}^{241}\text{Am}) \rightarrow {}^{12}\text{C}^* + \gamma(4.4\text{MeV}) + n$
Data-MC mismatch is used to evaluate systematic uncertainty.



Performance @expected working point

- SK-IV,V: ~10% signal efficiency
- SK-VI: ~40% signal efficiency
- SK-VII,VII.5,VIII: ~60% signal efficiency

Data-MC mismatch

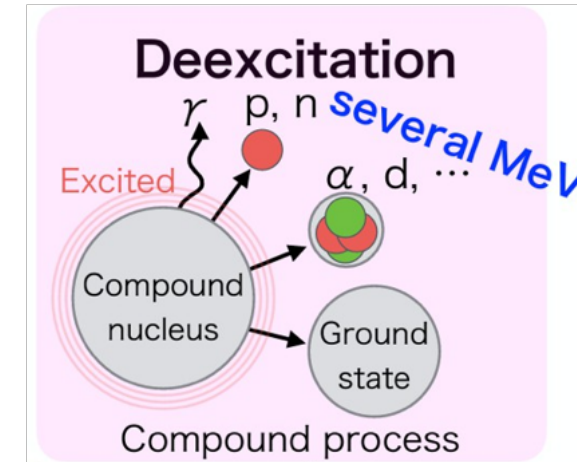
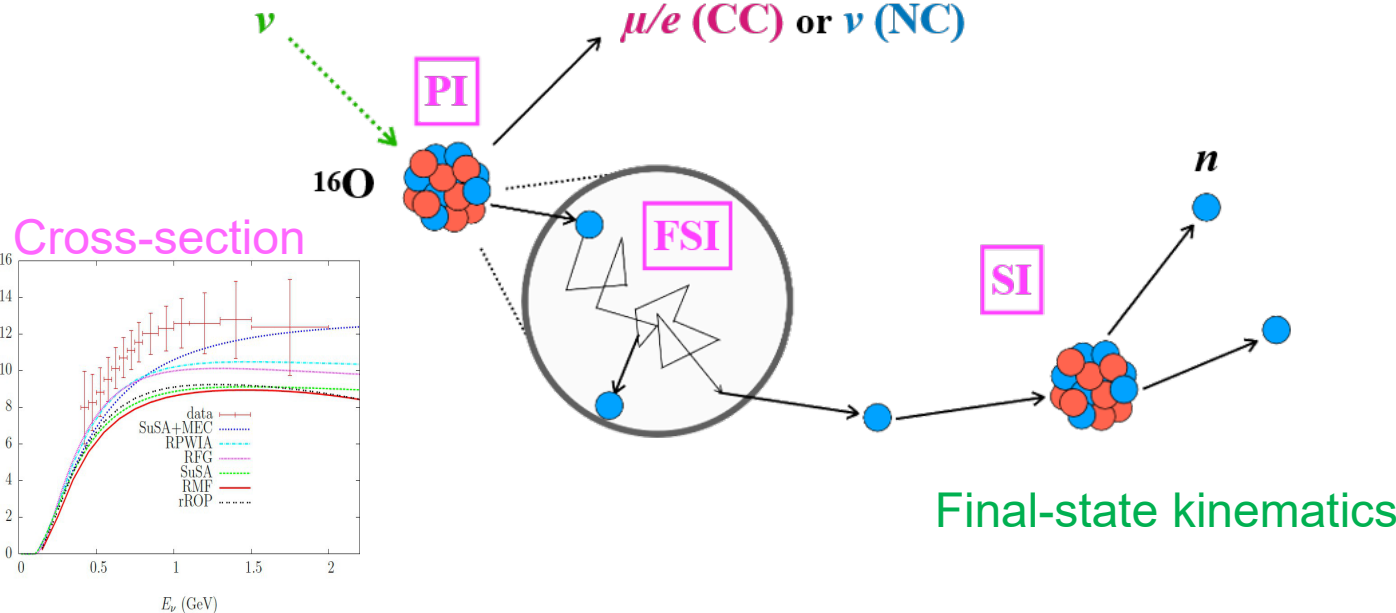
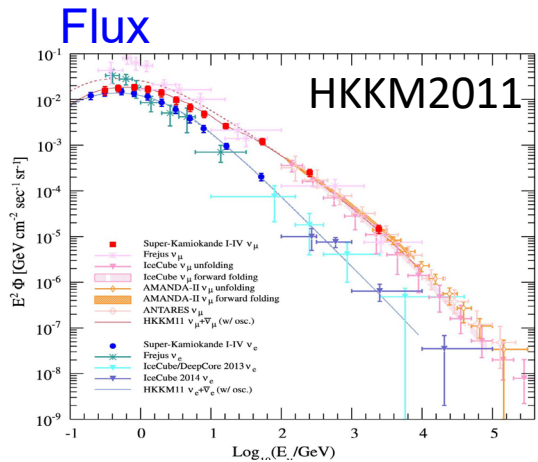
(systematics regarding ntag efficiency)

- SK-IV,V: 10% (SK-IV paper: 12.5%)
- SK-VI: 3% (SK-VI+VII paper: 8.4%)
- SK-VII,VII.5,VIII: 5% (SK-VI+VII paper: 3.4%)

Atmospheric neutrino backgrounds

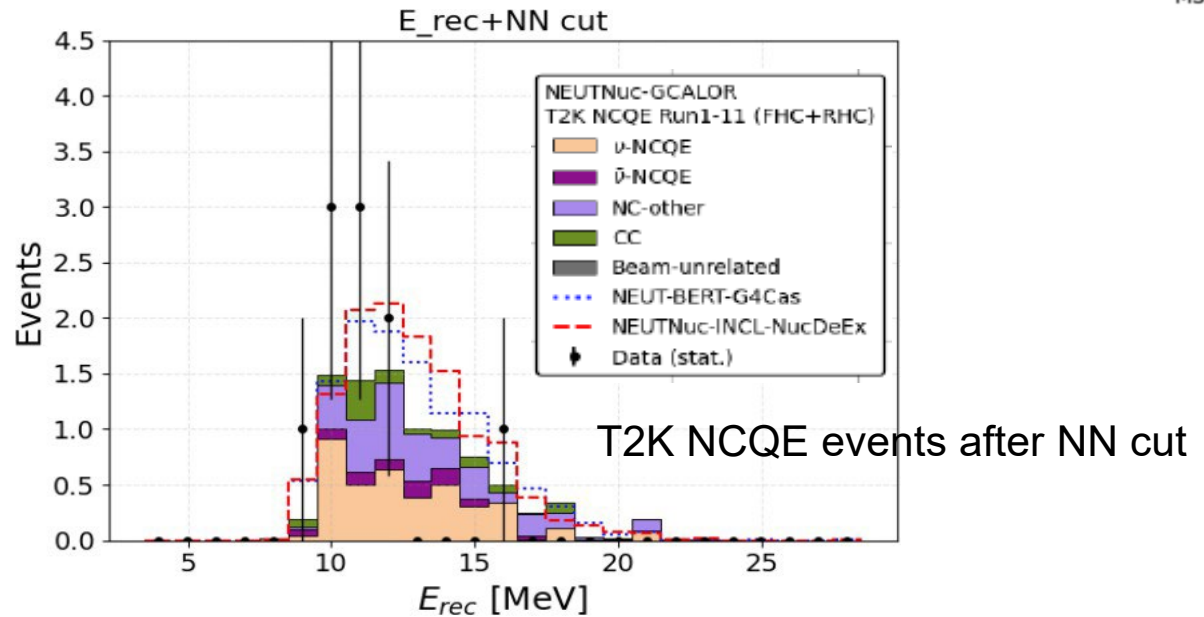
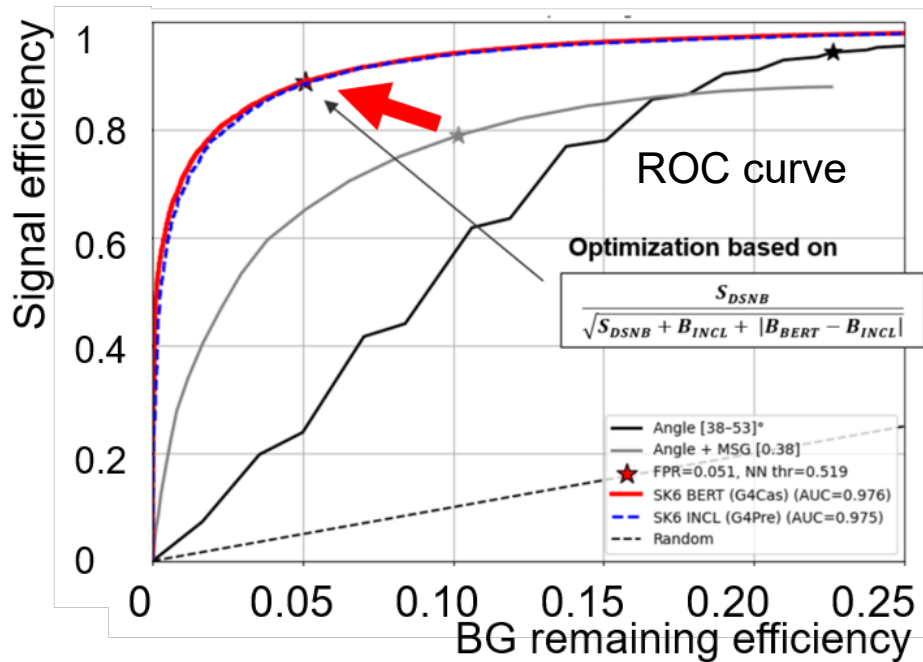
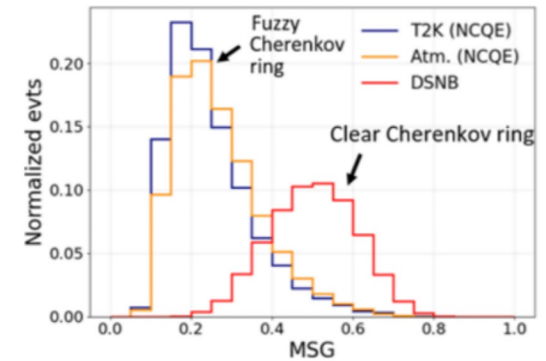
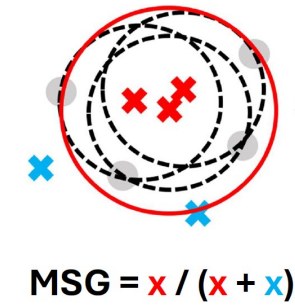
Atmospheric neutrino BG estimation involves systematic uncertainties regarding **flux**, **cross-section**, and **final-state kinematics**. → T2K and SK atm ν programs help!

- For **CC**: neutrino flux (**~20%**) and interaction cross-sections (**~30%**).
- For **NC γ** : systematics on its nominal prediction (\sim flux + xsec + final-state γ) are directly evaluated and constrained **by referring to the T2K result**.
- **Neutron multiplicity** is affected by every stage of Primary Interaction (**PI**) + Final State Interaction (**FSI**) + Secondary Interaction (**SI**). Its systematics is **estimated by an independent SK analysis**.



arXiv:1110.4739v1

- Developed a new NN classifier to discriminate IBD and NCy.
 - Based on θ_c , MSG, and N50
- The NN framework was validated using T2K NCQE samples.
 - Now directly relies on the Data-MC comparison in T2K.



[sig eff., bkg eff.] =
 [~0.8, ~0.1] → [~0.9, ~0.05]

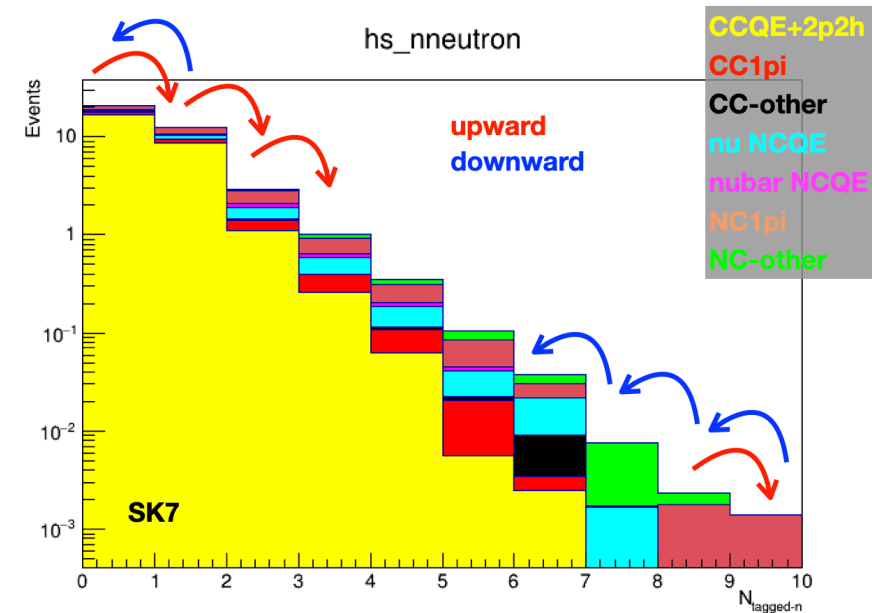
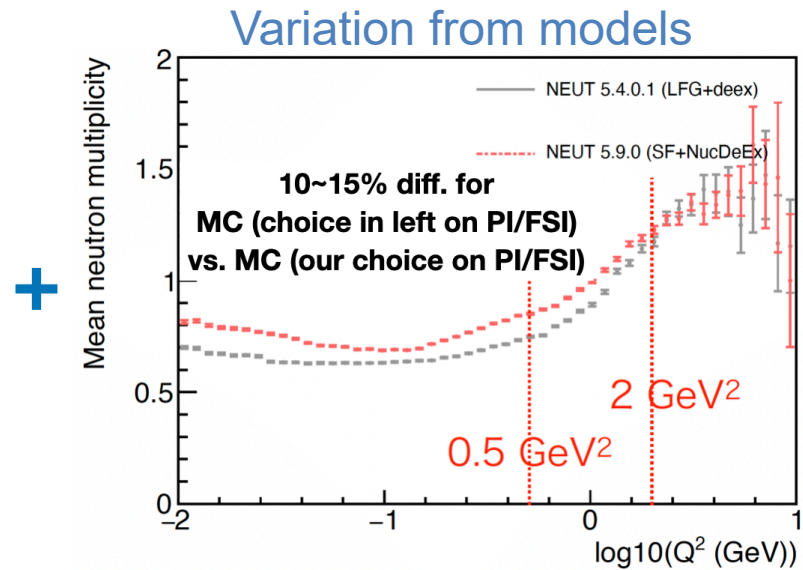
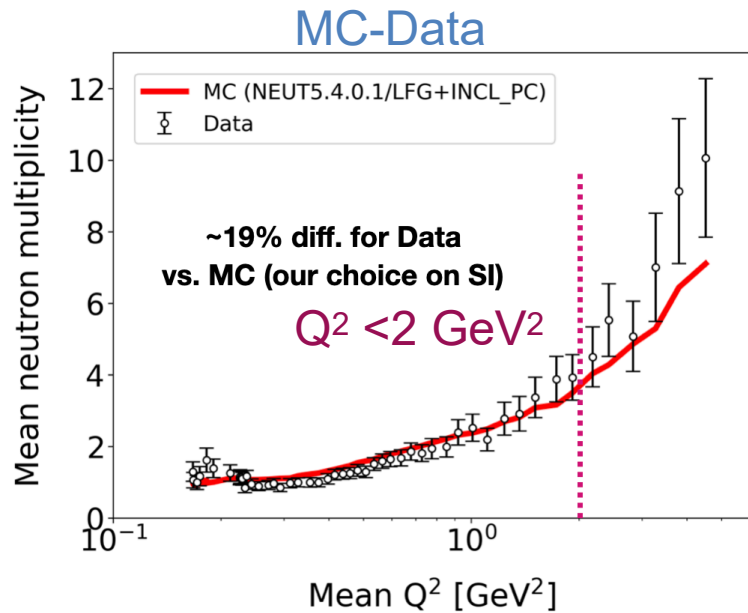
10% signal gain + 1/2 background!

- Smaller systematics for remaining NCQE background: **71% → 45%**
- (Currently limited by statistics, but improvement expected with more data.)

Neutron multiplicity uncertainty from SK atm. ν

PRD 112, 012004 (2025)

- Mean neutron multiplicity with atmospheric neutrinos in SK is compared between Data and our choice of models in MC, providing a $\sim 30\%$ uncertainty.
- Evaluated the impact of this mismatch on the neutron multiplicity bins using MC.
- Higher tagging efficiency (\sim Gd amount) improves the upward systematic uncertainty.



= 30% uncertainty on “mean” multiplicity in $Q^2 < \text{GeV}^2$

Previously All phases: **-40%/+40%**

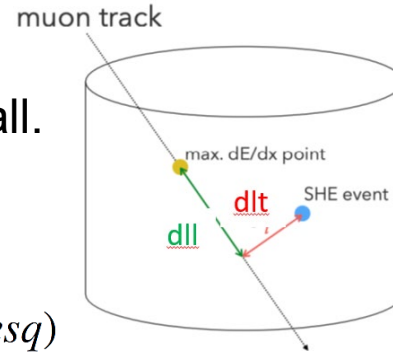
Now SK-IV,V: **-30%/+27%** SK-VI: **-31%/+18%** SK-VII,VII.5,VIII: **-32%/+12%**

Treatment of Spallation BG

Reliable spallation full MC is not ready now.
 Instead, we use a data-driven approach to cut spall.

Log-likelihood to remove spallation:

$$\mathcal{L} = \log \prod_{i \in \text{vars}} \frac{\text{PDF}_i^{\text{spall}}(x)}{\text{PDF}_i^{\text{random}}(x)} \quad (\text{vars} = dt, dlt, dll, qtot, resq)$$



$N_n=1$: ${}^9\text{Li}$, accidental coincidence

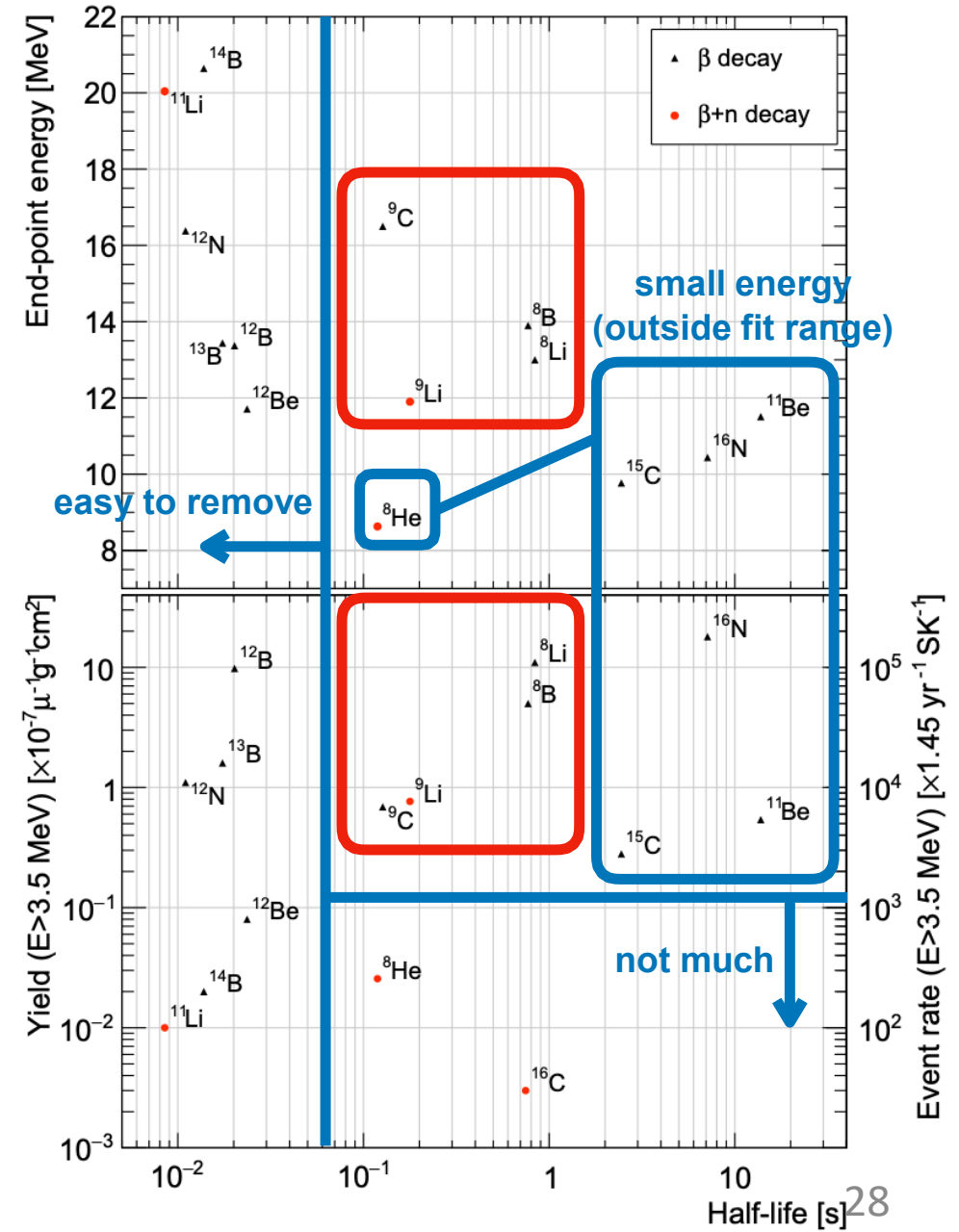
- To lower the analysis threshold down to $E_{rec}=11.5$ MeV in the $N_n=1$ panel

Previously: Assigned a conservative 50% systematic error (considering only dt).

Update: Reduced the uncertainty to 30% after confirming that the effect of dlt is subdominant.

$N_n \neq 1$: ${}^8\text{B}$, ${}^8\text{Li}$, ${}^9\text{C}$ (mixed)

- The exact treatment and evaluation of the cut efficiency of this mixed background require further investigation.
- This time, we conservatively exclude events in the $N_n \neq 1$ panel with $E_{rec} < 22$ MeV from the spectral fitting in this analysis.

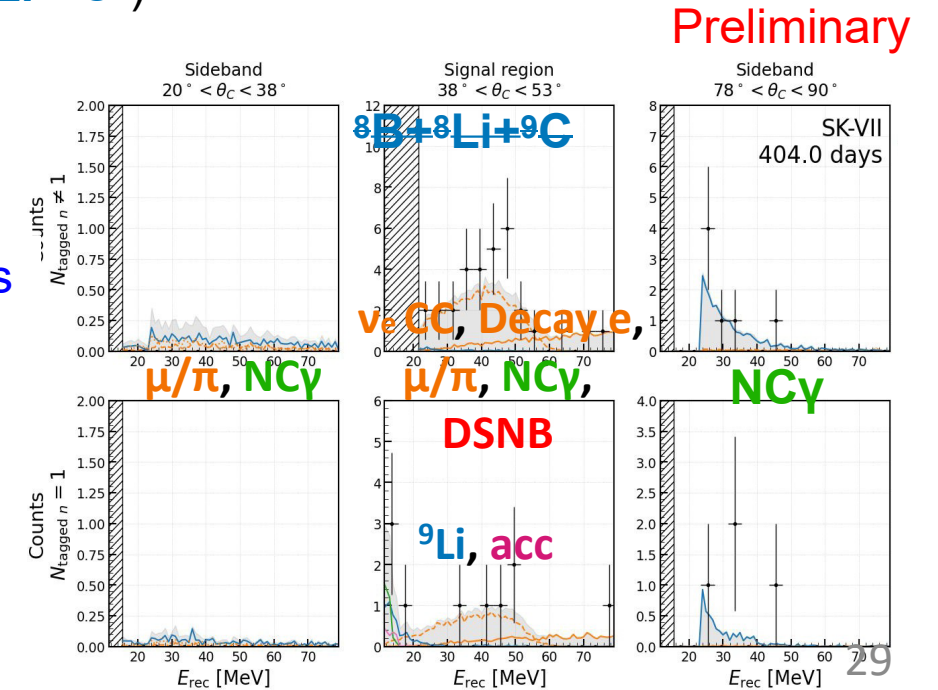


Components in the Spectral Fit

- 1 signal + 7 background components
- **Signal**: Horiuchi+09, 6 MeV Max, Kresse+21, Ashida+23 (“**DSNB**”)
- **Background**
 - atmospheric ν_e CC (“ **ν_e CC**”)
 - invisible muon/pion from atmospheric ν_μ CC, NC1 π etc (“**Decay e**”)
 - visible muon/pion from atmospheric ν CC, NC1 π etc (“ **μ/π** ”)
 - nuclear deexcitation gamma rays from atmospheric ν NCQE, NC1 π etc (“**NC γ** ”)
 - ~~muon spallation induced isotopes with no neutron (“**spall $^8\text{B}+^8\text{Li}+^9\text{C}$** ”)~~
 - muon spallation induced isotope with neutron (“**spall ^9Li** ”)
 - accidental coincidental events (“**acc**”)

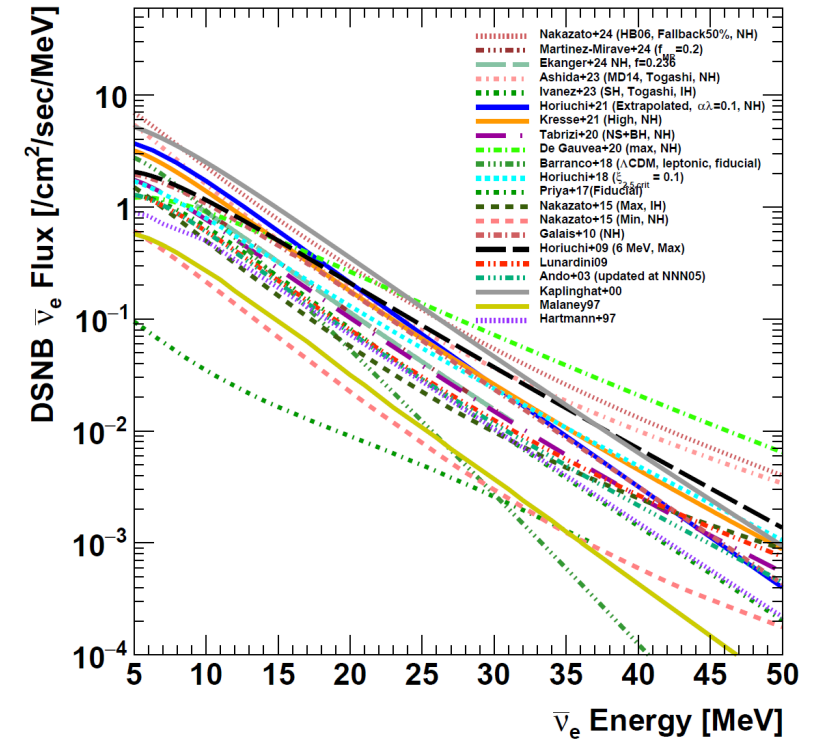
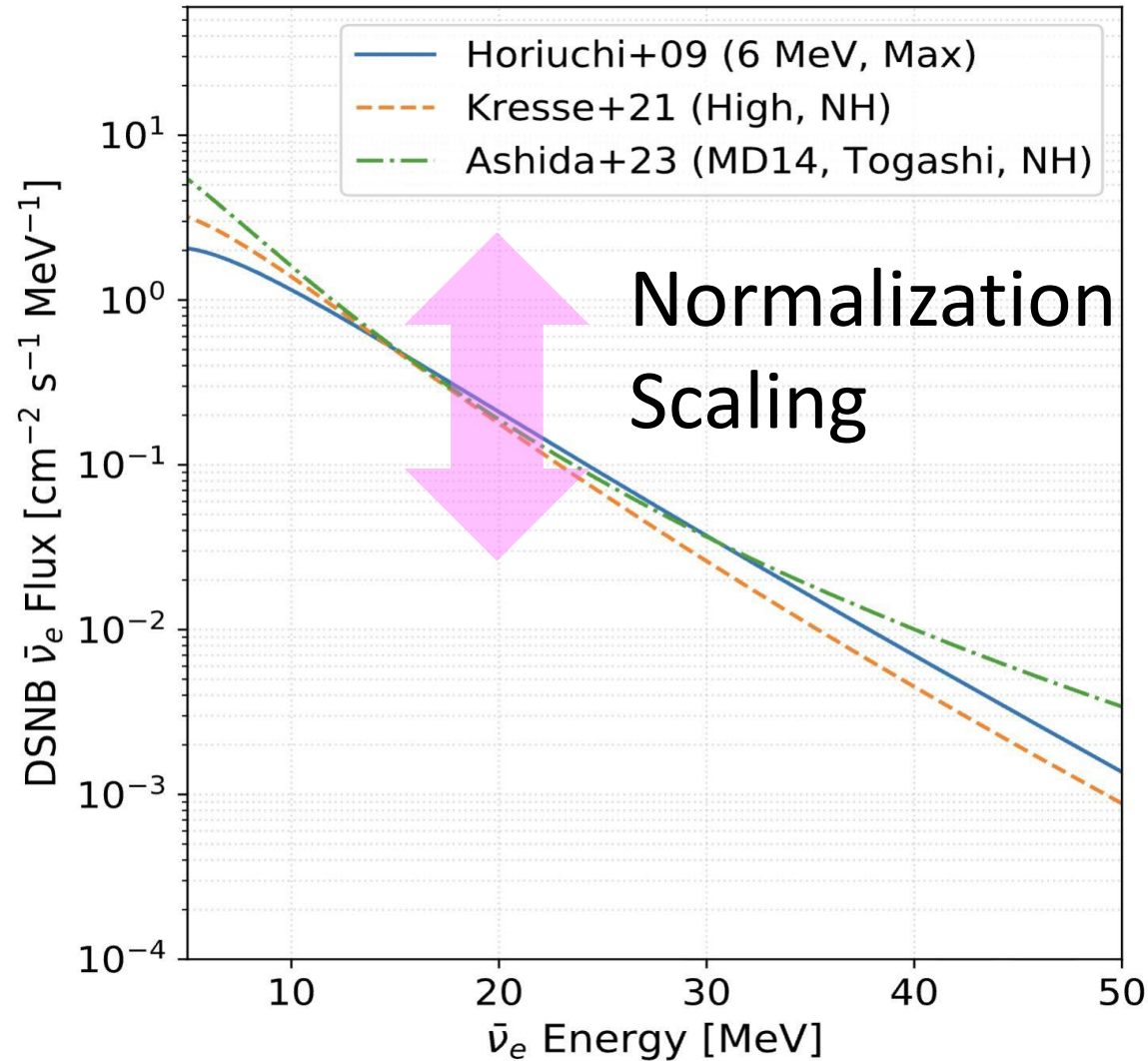
atmospheric ν

$$\mathcal{L}(\text{Data} | N_s, \vec{N}_b, \eta_s, \vec{\eta}_b) = \mathcal{L}(\vec{0} | \eta_s, \vec{\eta}_b) \leftarrow \text{pull term for nuisance parameters} \right. \\
\times e^{-(\varepsilon_s(\eta_s)N_s + \sum_{j \in \vec{b}} N_j)} \\
\times \prod_{i=1}^{N_{\text{data}}} \left[\varepsilon_s(\eta_s)N_s \cdot \text{PDF}_s(E^i, \theta_C^i, N_n^i) \right. \\
\left. + \sum_{j \in \vec{b}} N_j \cdot \text{PDF}_j(E^i, \theta_C^i, N_n^i | \vec{\eta}_b) \right] \left. \begin{array}{l} \times \\ \text{Signal-related PDF} \\ + \\ \text{BG-related PDFs} \\ \text{Shape depending on} \\ \text{nuisance parameters.} \end{array} \right.$$



Signal DSNB Models for fitting

3 models assessed this time



The shape is
model-dependent

SK-IV, V, VI, VII, VII.5, VIII joint fit

One likelihood, one minimization over all phases simultaneously

Shared parameters:

- DSNB signal normalization
- Background MC scaling:
atmospherics (ν_e CC, decay-e, NC γ , μ/π),
spallation ${}^9\text{Li}$
- Correlated nuisances:
atmospheric CC / NC neutron multiplicity,
spallation ${}^9\text{Li}$ remaining rate

Per-phase parameters:

- Accidental coincidence normalization
- Uncorrected nuisances:
neutron tagging efficiency uncertainty,
signal detection efficiency uncertainty

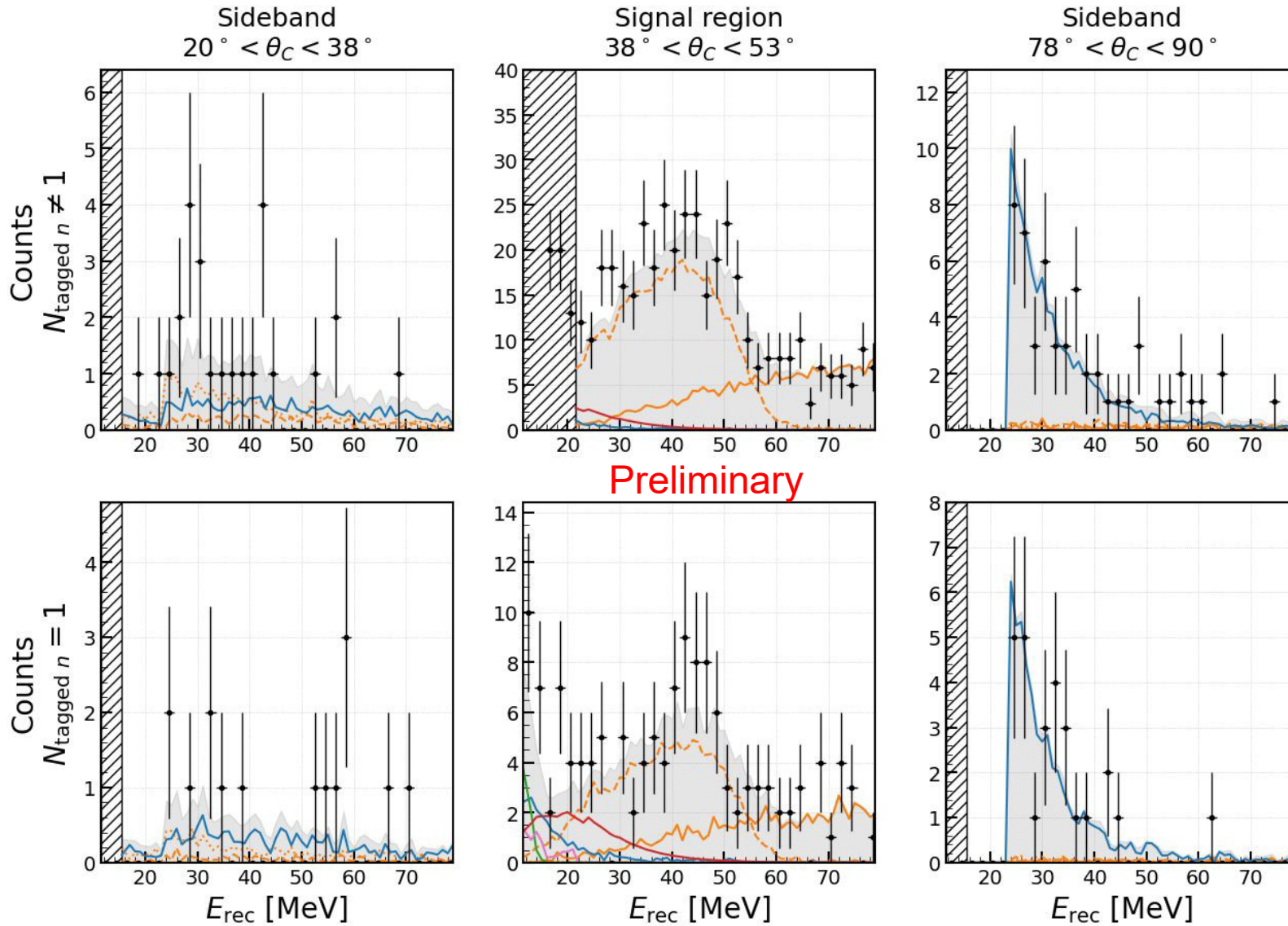
**12 + (3 x 6 phases)
= 30 parameters**

	Parameters	Sharing
Signal	DSNB signal rate	Shared
Backgrounds	atmospheric ν_e CC scale on MC	Shared
	atmospheric decay-e scale on MC	Shared
	atmospheric NC γ scale on MC	Shared
	atmospheric μ/π scale on MC	Shared
	other spallation (${}^8\text{B}+{}^8\text{Li}+{}^9\text{C}$) scale on MC	Shared
	${}^9\text{Li}$ spallation scale on MC	Shared
	accidental coincidence rate	Per-phase
Nuisances	atmospheric bkg ntag migration (CC)	Shared
	atmospheric bkg ntag migration (NC γ)	Shared
	ntag efficiency uncertainty	Per-phase
	signal efficiency uncertainty	Per-phase
	${}^9\text{C}$ fraction	Shared
	${}^8\text{B}$ fraction	Shared
	${}^9\text{Li}$ spectral shape	Shared

**Joint Fit Results for SK-Ntag era
(SK-IV+V+VI+VII+VII.5+VIII)**

Horiuchi+09, 6MeV case

SK-IV, V, VI, VII, VII.5, VIII joint best-fit (signal unstacked)



- + Data (SK-IV + V + VI + VII + VII.5 + VIII)
- DSNB (Horiuchi+09, 6 MeV, max)
- All backgrounds
- Atmos ν_e CC
- - - Atmos decay e
- ⋯ Atmos μ/π
- Atmos NC γ
- Spall ${}^9\text{Li}$
- Accidental coincidence

IBD event rate for $E_\nu > 13.3$ MeV
($E_{\text{rec}} > 11.5$ MeV)

Best-fit: $4.8^{+2.2}_{-2.0}$ events/yr

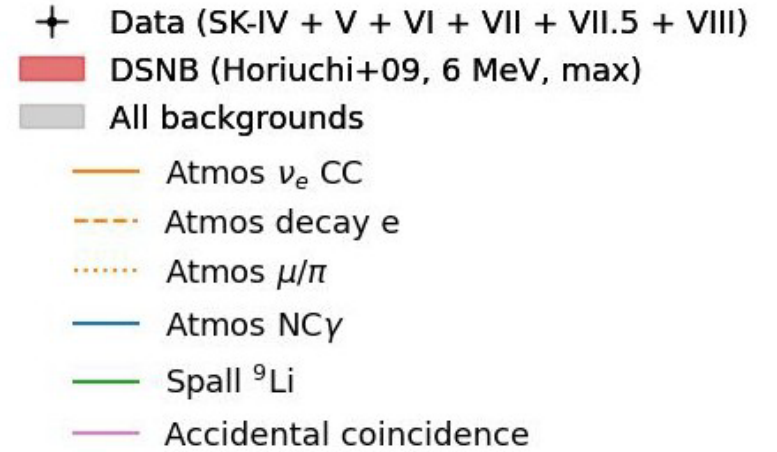
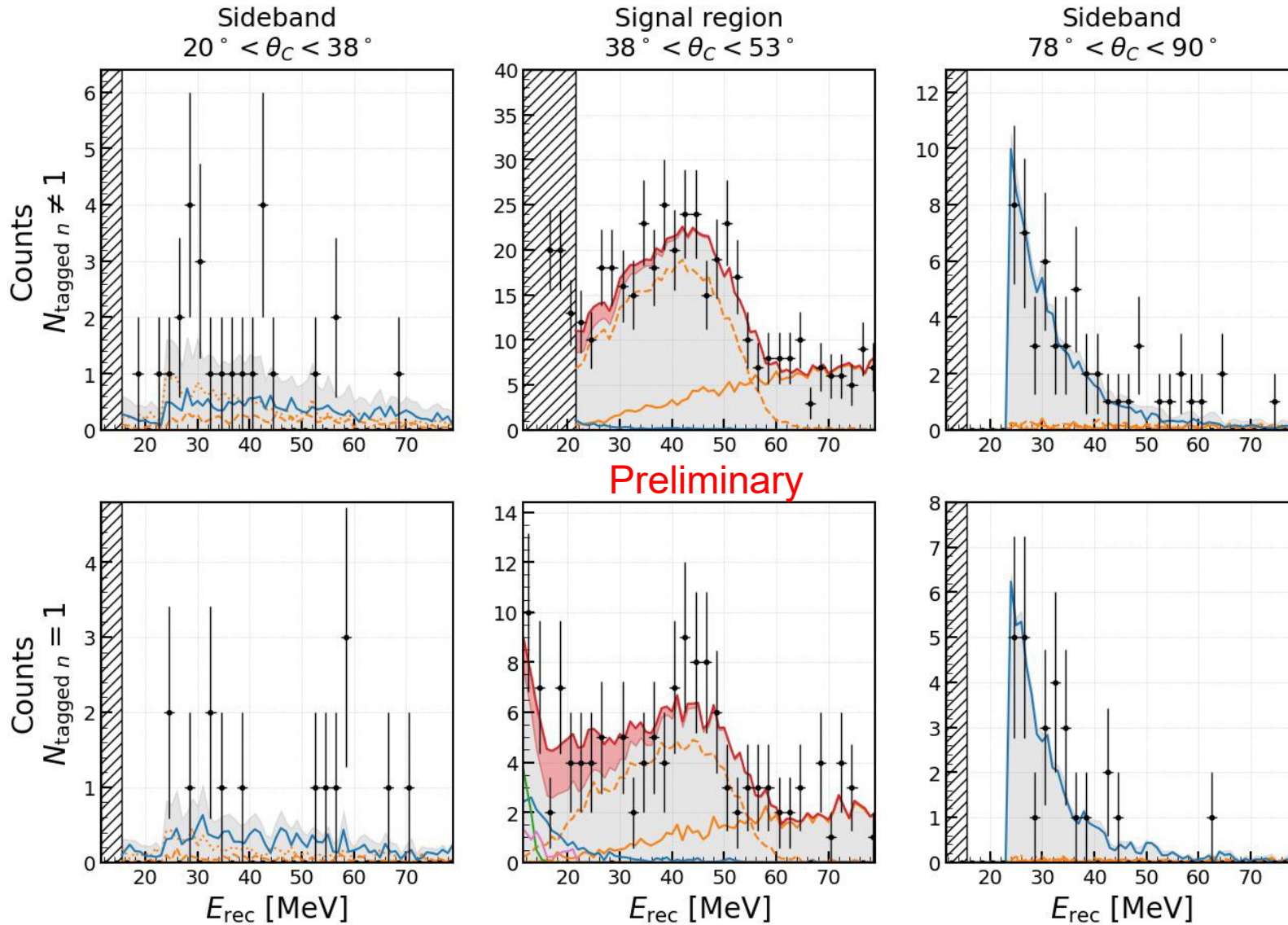
Predicted: 2.9 - 5.2 events/yr
 (Horiuchi+09, 6MeV, min - max)

DSNB flux for $E_\nu > 13.3$
($E_{\text{rec}} > 11.5$ MeV)

Best-fit: $3.6^{+1.6}_{-1.5}$ $\text{cm}^{-2} \text{s}^{-1}$

Predicted: 2.1 - 3.9 $\text{cm}^{-2} \text{s}^{-1}$
 (Horiuchi+09, 6MeV, min - max)

SK-IV, V, VI, VII, VII.5, VIII joint best-fit (signal stacked)



IBD event rate for $E_\nu > 13.3$ MeV
($E_{\text{rec}} > 11.5$ MeV)

Best-fit: $4.8^{+2.2/-2.0}$ events/yr

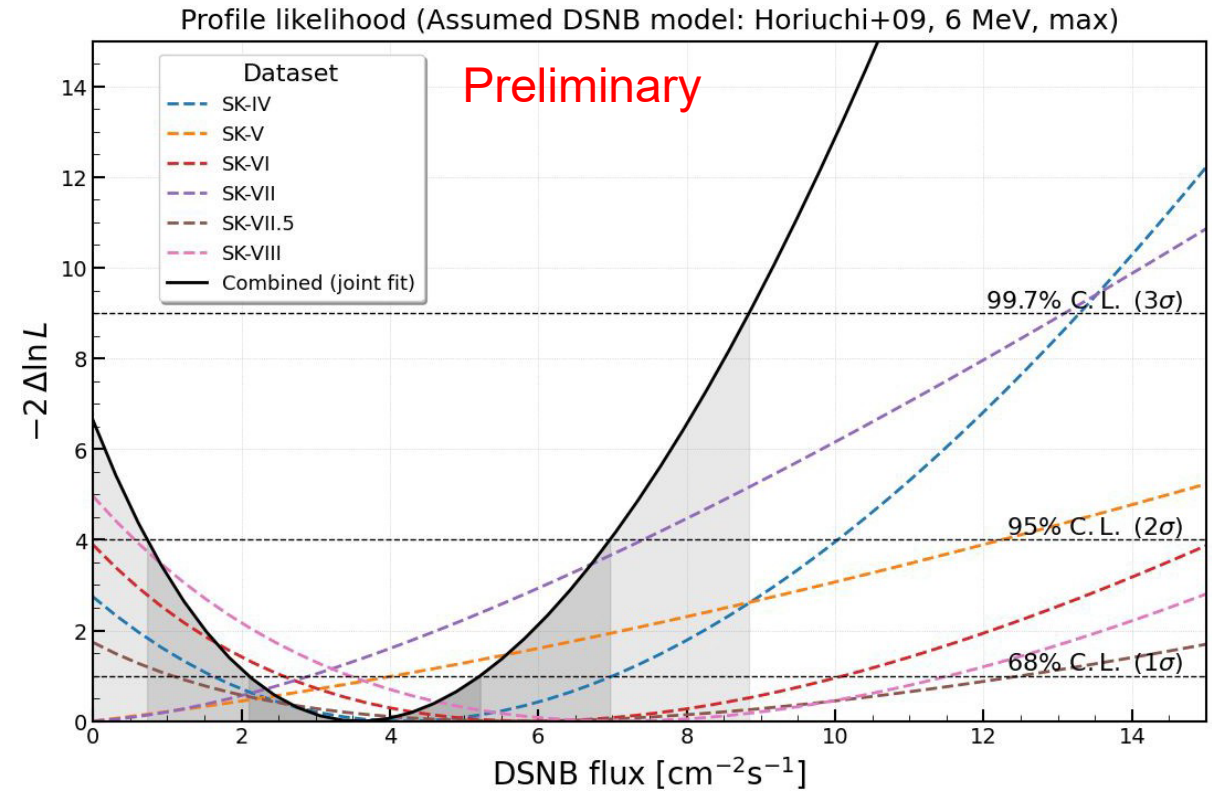
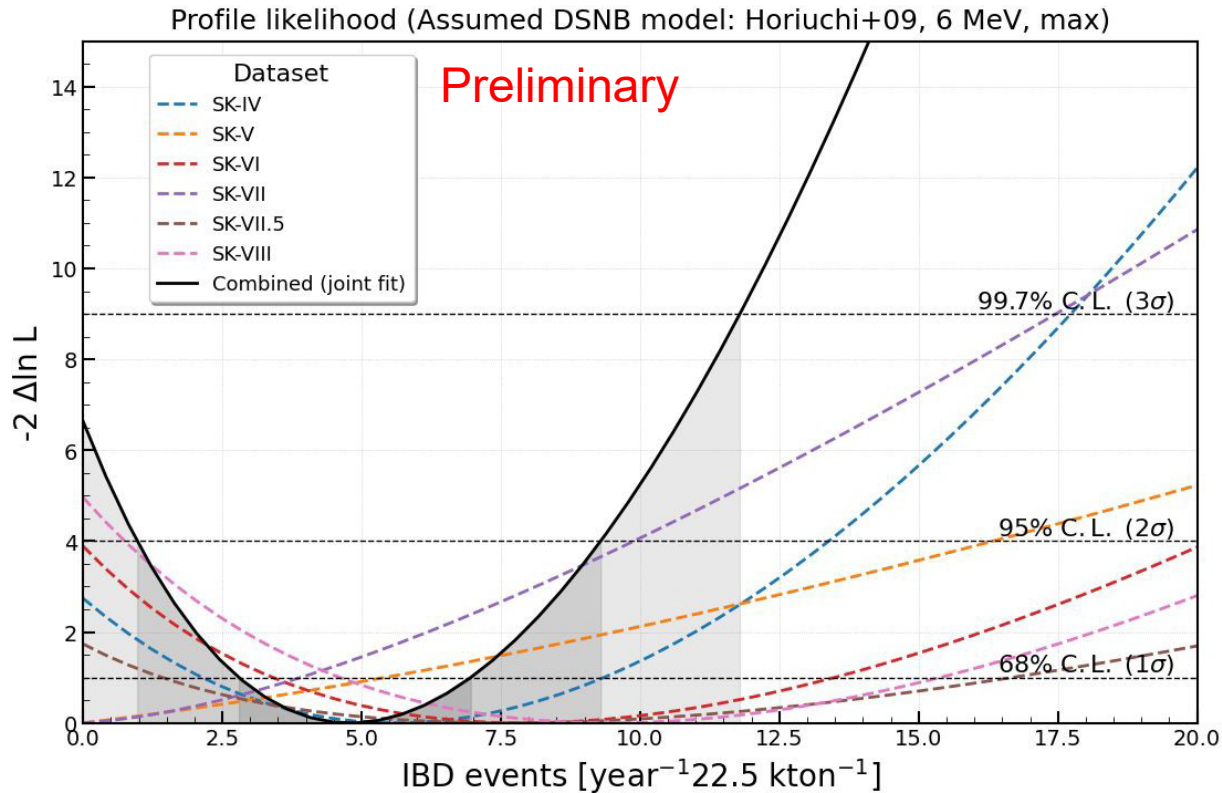
Predicted: 2.9 - 5.2 events/yr
 (Horiuchi+09, 6MeV, min - max)

DSNB flux for $E_\nu > 13.3$
($E_{\text{rec}} > 11.5$ MeV)

Best-fit: $3.6^{+1.6/-1.5}$ $\text{cm}^{-2} \text{s}^{-1}$

Predicted: 2.1 - 3.9 $\text{cm}^{-2} \text{s}^{-1}$
 (Horiuchi+09, 6MeV, min - max)

Profile likelihood curves



Joint fit significance = 2.6σ

99.5% CL

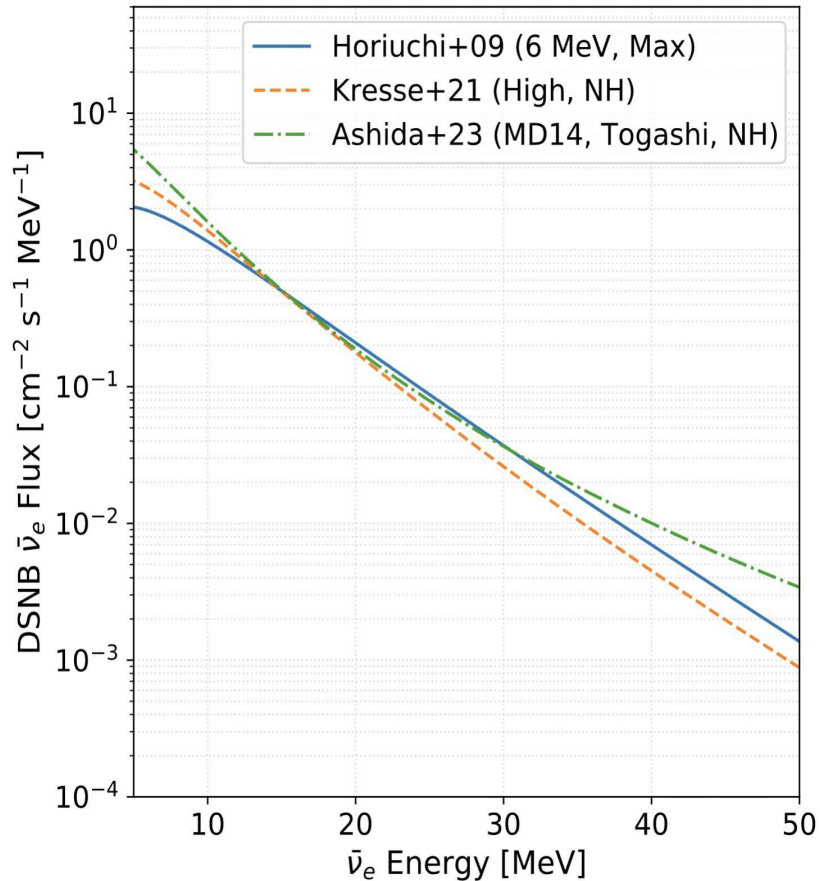
Under the null DSNB hypothesis, the one-sided p-value is 5×10^{-3} .

(Note that the per-phase curves are from the individual phase fits.)

Results for Different DSNB Models

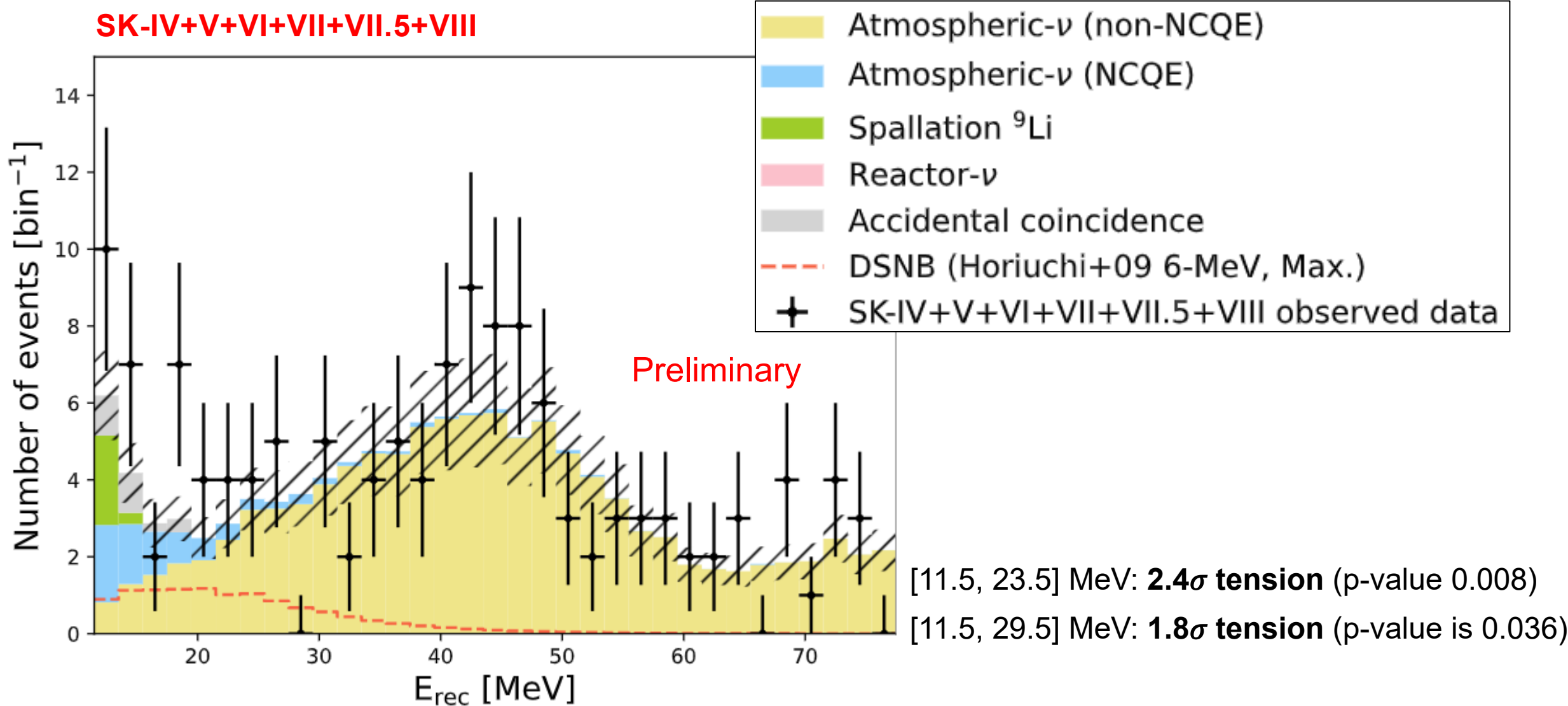
- We assessed three DSNB models that vary in shape
 - Horiuchi+09 6 MeV max, Kresse+21, and Ashida+23

Preliminary



	IBD event rate [events/year]		DSNB flux [$\text{cm}^{-2} \text{s}^{-1}$]		Significance (SK-IV ~ VIII joint fit)	Maximum Likelihood Value
	Best-fit	Pred	Best-fit	Pred		
Horiuchi+09 6 MeV, max	4.8 +2.2/-2.0	5.2	3.6 +1.6/-1.5	3.9	2.6σ	1226.1
Kresse+21	5.1 +2.2/2.0	4.3	4.1 +1.8/-1.6	3.5	2.7σ	1225.3
Ashida+23	5.7 +2.5/-2.3	5.5	4.0 +1.8/-1.6	3.9	2.6σ	1225.9

Model-independent binned analysis result



General tension with a BG-only hypothesis, with greater tension at lower energies.

Summary

- Since the introduction of Gadolinium, Super-Kamiokande has successfully accumulated over **1,650 days** of continuous observation data.
- We are fully prepared for the next galactic supernova. We have upgraded our real-time alert infrastructure using GCN Kafka and are advancing collaborations with electromagnetic telescopes to catch the Shock Breakout signals.
- Our real-time reconstruction capabilities are highly robust. For a typical supernova at 10 kpc, based on the Nakazato model, we can achieve a **pointing accuracy of $3.8^\circ(1\sigma)$** and a **distance-estimation precision of $\pm 12\%$ (1σ)**
- **SK observed the first indication of the DSNB.** The best-fit DSNB signal flux obtained from a joint fit of SK-Ntag era phases (SK-IV, V, VI, VII, VII.5, VIII) is **$3.6 +1.6/-1.5 \text{ cm}^{-2} \text{ s}^{-1}$ ($4.8 +2.2/-2.0 \text{ events yr}^{-1}$) for $E > 13.3 \text{ MeV}$** , assuming the Horiuchi+09, 6 MeV, max model. This corresponds to a **2.6σ tension with a null hypothesis (5×10^{-3} one-sided p-value)**. Similar significance was obtained for two other DSNB models with varying spectral shapes.
- Similar conclusions we can draw from the binned analysis. Depending on the binning, **the binned analysis shows tension with the BG-only hypothesis at the $1.8- 2.4\sigma$ level.**

A reminder when comparing to Neutrino 2024 presentation

A 2.3σ excess was reported at Neutrino 2024

(https://agenda.infn.it/event/37867/contributions/233922/attachments/122065/178295/20240620_v9.pdf)

- This number was obtained from a post-fit likelihood summation of SK-1, 2, 3, 4, 6, and 7 phases, **not from a joint fit.**
- The energy threshold was $E_{\text{tot}} = 16$ MeV for all panels.
- This number was driven by previous SK-4 results (**not re-analyzed at that time.**)
- This number has **not been published.**

A reminder when comparing to Neutrino 2024 presentation

Our current results are obtained from

- A joint fit of SK-4, 5, 6, 7, 7.5, and 8 phases (all re-analyzed).
- We lowered the energy threshold of $N_n = 1$ panel to 12 MeV (“signal golden” panel).
- We increased the energy threshold of $N_n \neq 1$ panel to 22 MeV.
 - **Rationale:** With updated systematics constraining the backgrounds, we are now obliged to be extremely confident that the 16-22 MeV region in $N_n \neq 1$ is spallation-free, which at the moment, we are not. Therefore, we increased the energy threshold.
 - Of course, the real solution is to understand backgrounds in that region.
- However, our message is that, with increasing SK-Gd statistics and lowering of the energy threshold in the “signal golden panel”, **we can obtain strong results even if we do not include the potentially worrisome energy region** in our analysis.