The 12th Supernova Neutrino Workshop / 第12回 超新星ニュートリノ研究会

Numazu / 沼津

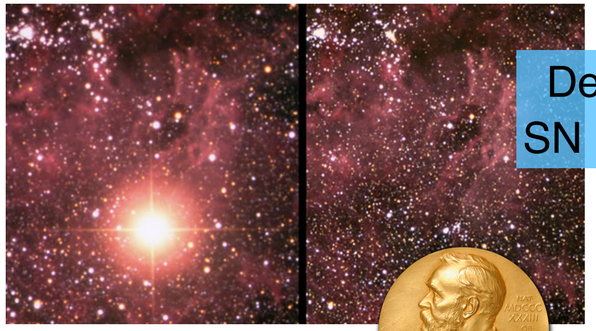
March 9th, 10th / 3月9日, 10日

Development of an analysis method for the diffuse supernova neutrino background measurement at multiple telescopes

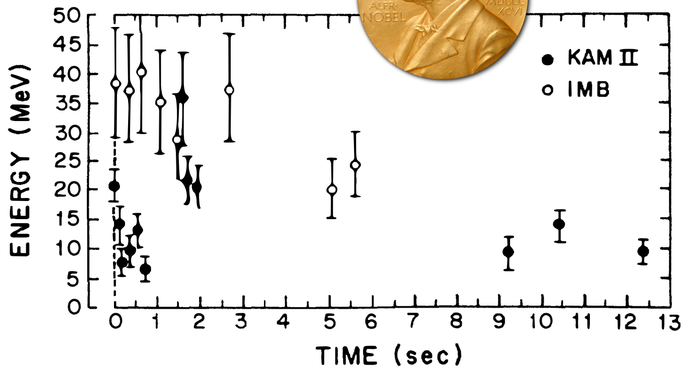
複数検出器での超新星背景ニュートリノスペクトル測定のための解析手法の開発

ASHIDA, Yosuke / 芦田 洋輔

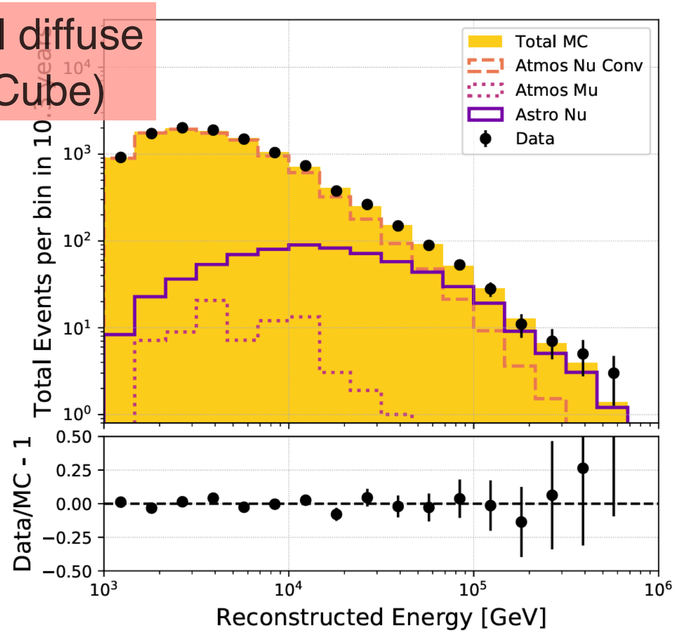
Tohoku University / 東北大学

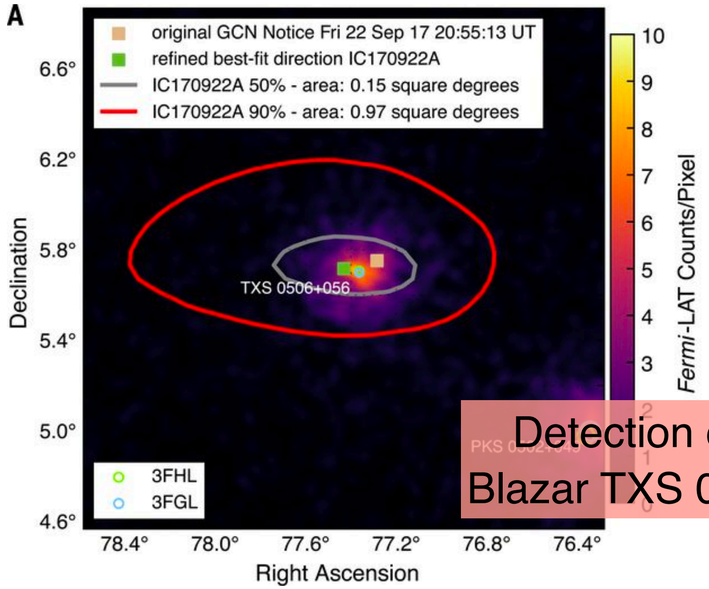


Detection of neutrinos from SN 1987A (Kamiokande else)



Confirmation of astrophysical diffuse high-energy neutrinos (IceCube)

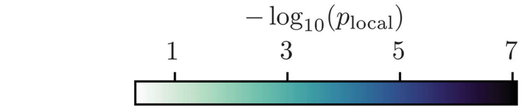


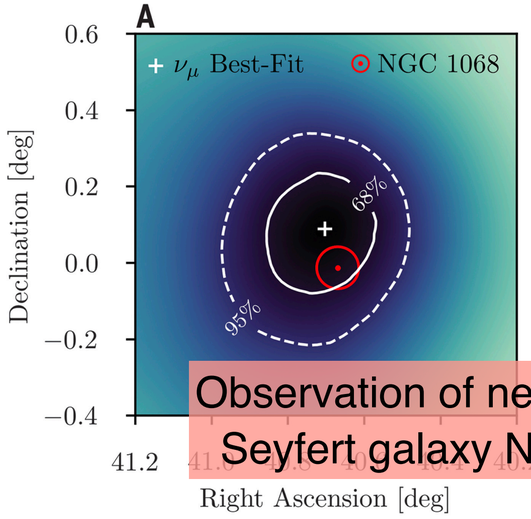


Detection of a neutrino from Blazar TXS 0506+056 (IceCube)

thermal

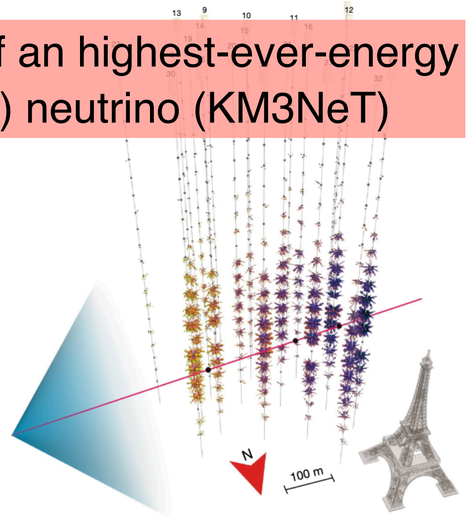
non-thermal

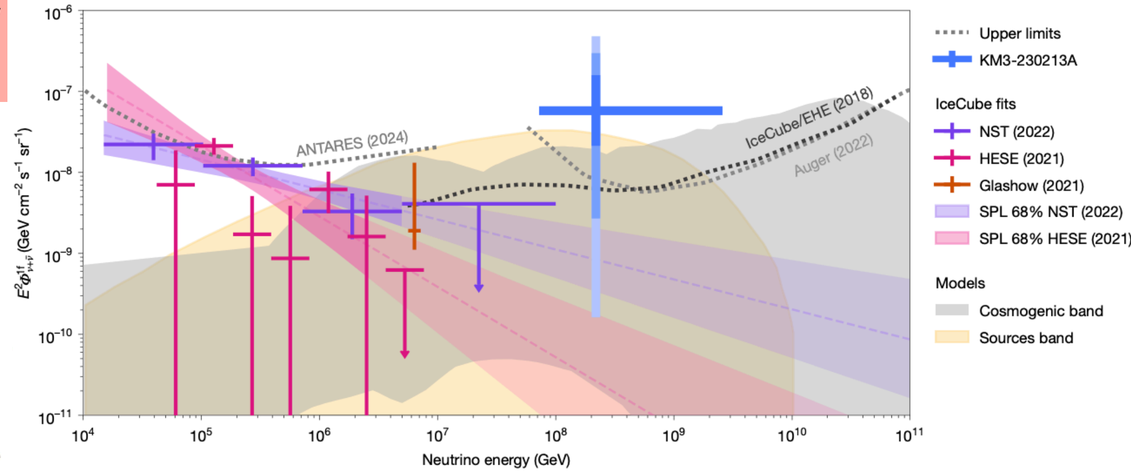




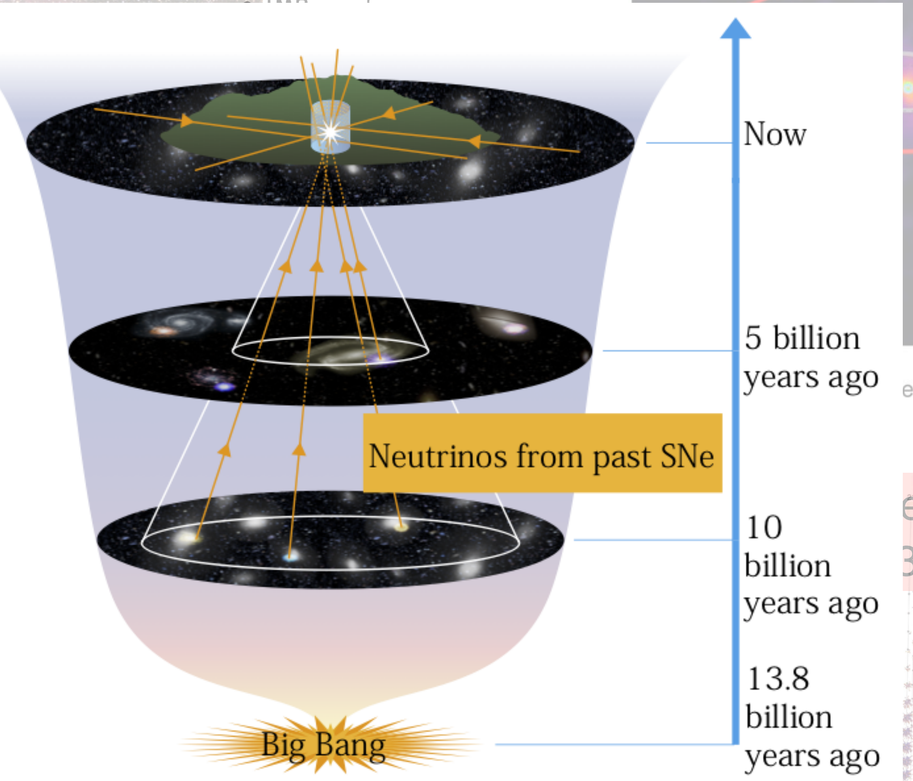
Observation of neutrino emission from Seyfert galaxy NGC 1068 (IceCube)

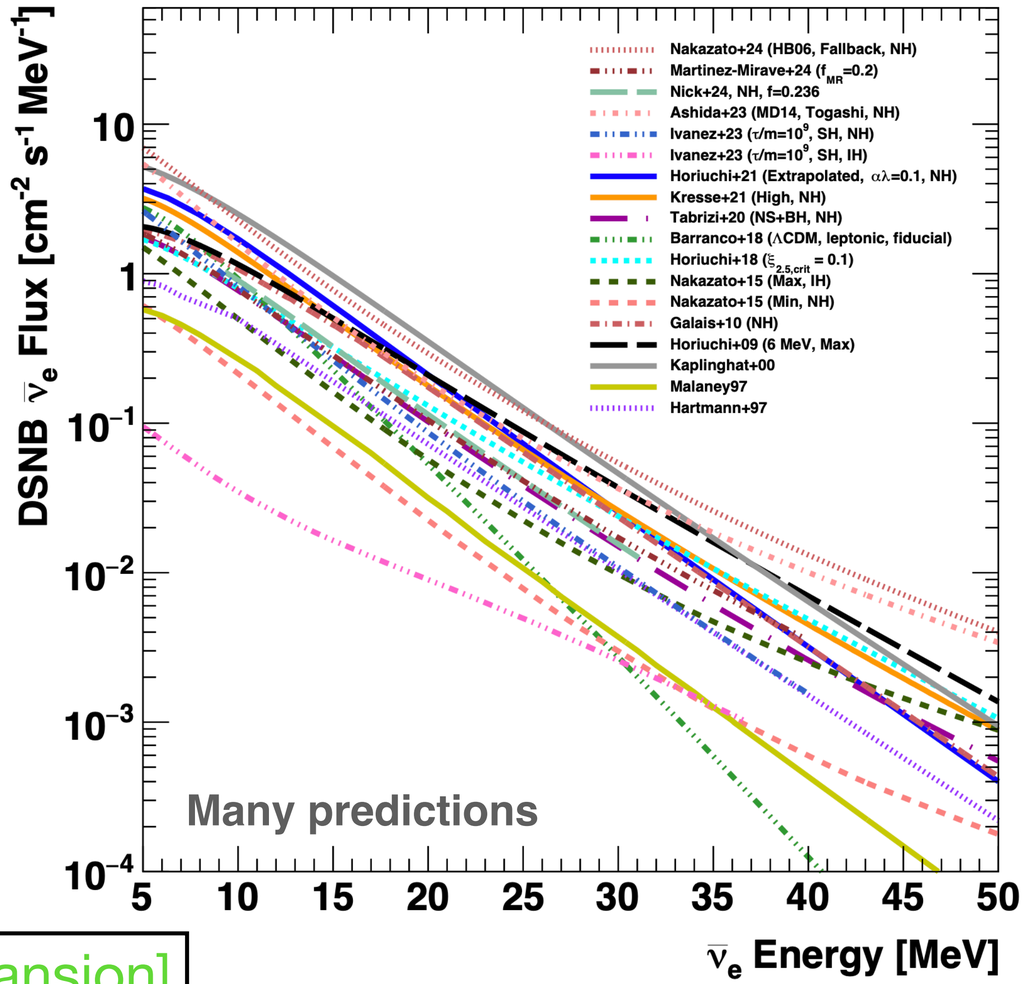
Observation of an highest-ever-energy (~220 PeV) neutrino (KM3NeT)





DSNB will be a new, unique probe in a neutrino astronomy program in the next decade!!



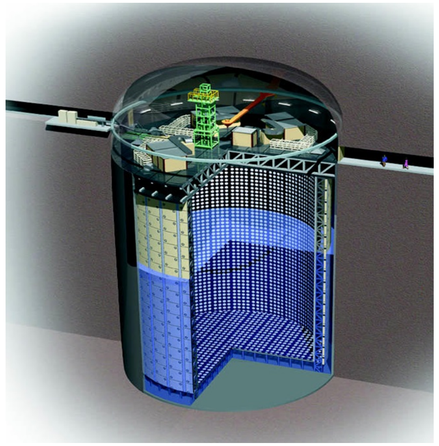


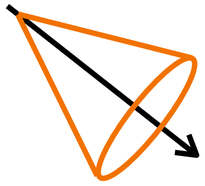
$\Phi = \int$ [ν emission] ⊗ [Star formation] ⊗ [Universe expansion]

Neutrino Detectors for DSNB

Water Cherenkov

- Good scalability (O(10) kton → O(100) kton)
- Small light yield
  - higher energy threshold
  - worse reconstruction performance
- Background modeling
  - Insensitive to low energy hadronic particles
  - More chains for muon spallation isotopes
  - Smaller reference dataset for neutrino interactions

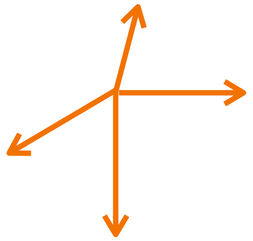




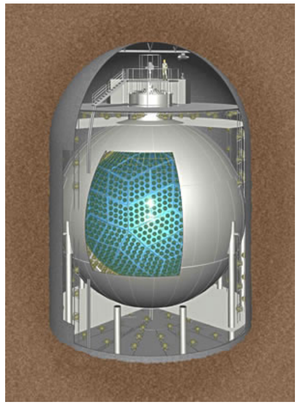
Directional emission
(42 deg opening angle in water)

Liquid Scintillator

- Worse scalability (O(1) kton → O(10) kton)
- Large light yield
  - lower energy threshold
  - good reconstruction performance
- Background modeling
  - Sensitive to almost any particles
  - Less chains for muon spallation isotopes
  - A lot of scintillation-based neutrino cross section measurement results available



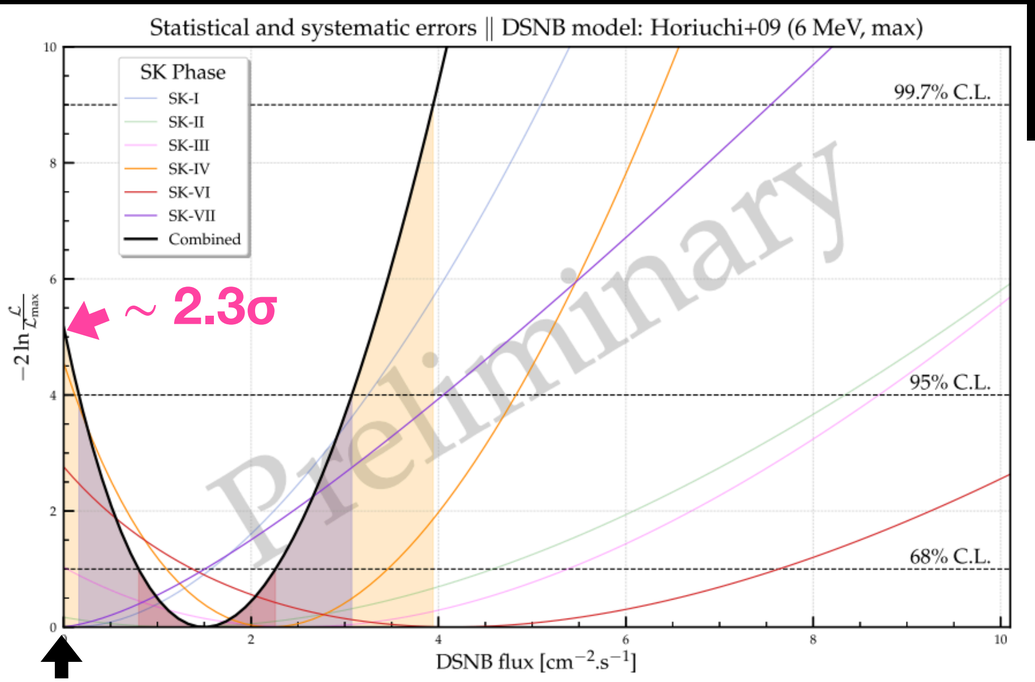
Isotropic emission



First Hint from Super-K??

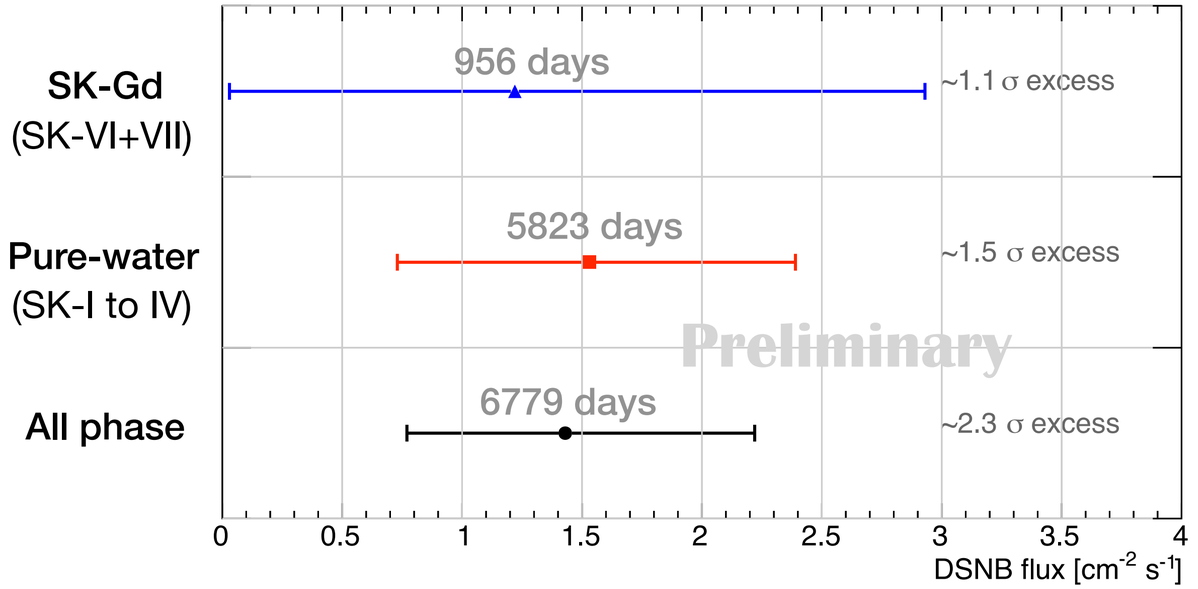
- Best-fit DSNB $\overline{\nu}_e$ flux is **~1.4 cm^{-2} sec^{-1}** (>17.3 MeV).
- Null DSNB hypothesis is disfavored in both pure-water and Gd-water phases and is rejected at **2.3σ** from the combined analysis.

Stay tuned for the latest result to be released this summer!

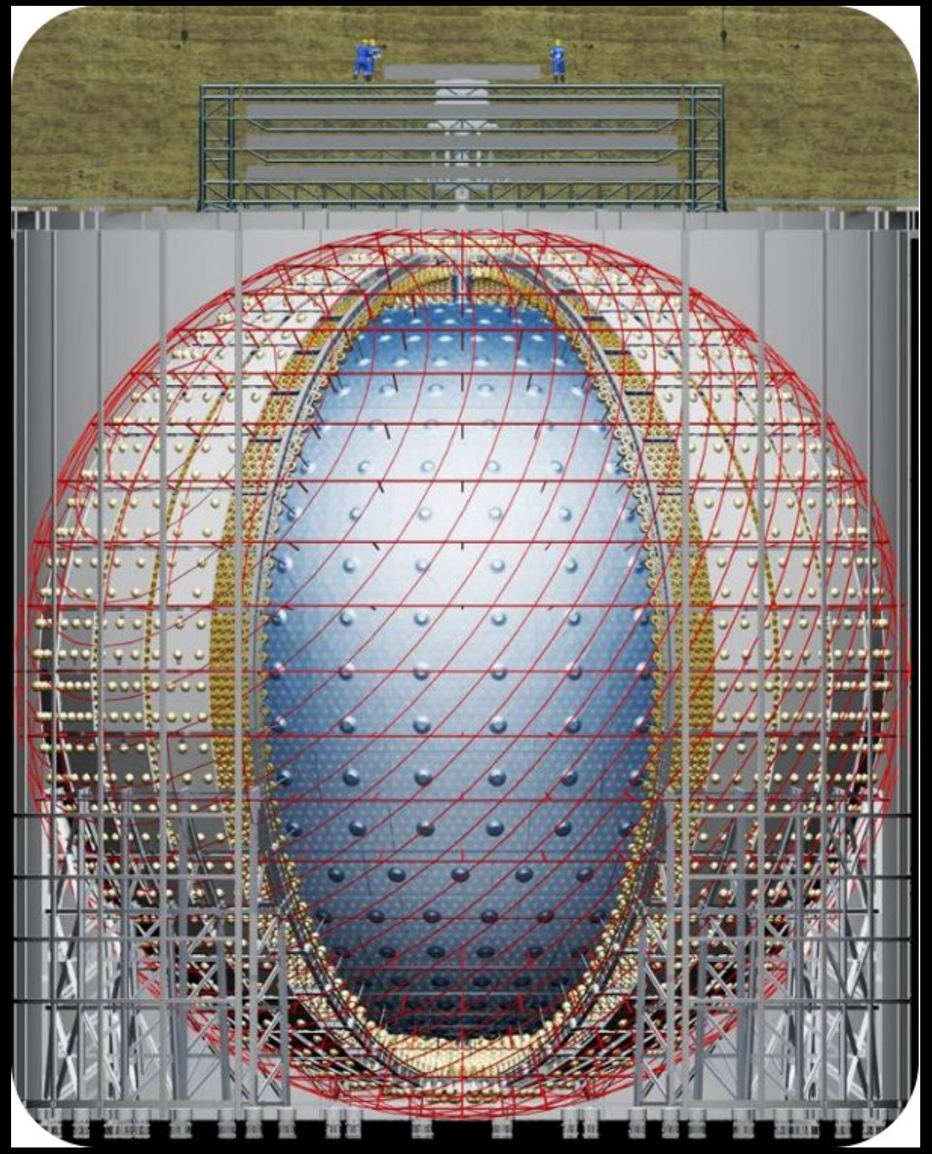


Zero-DSNB assumption

M. Harada at NEUTRINO2024



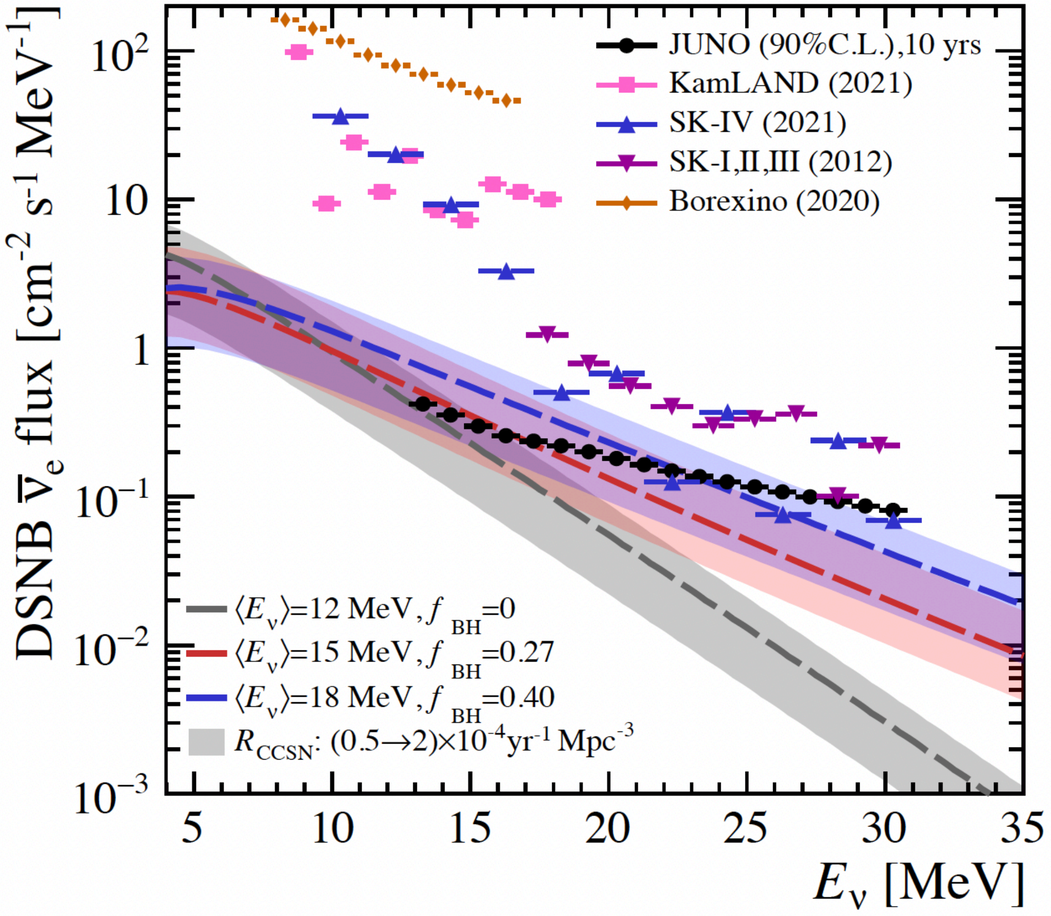
JUNO just kicked off last summer!

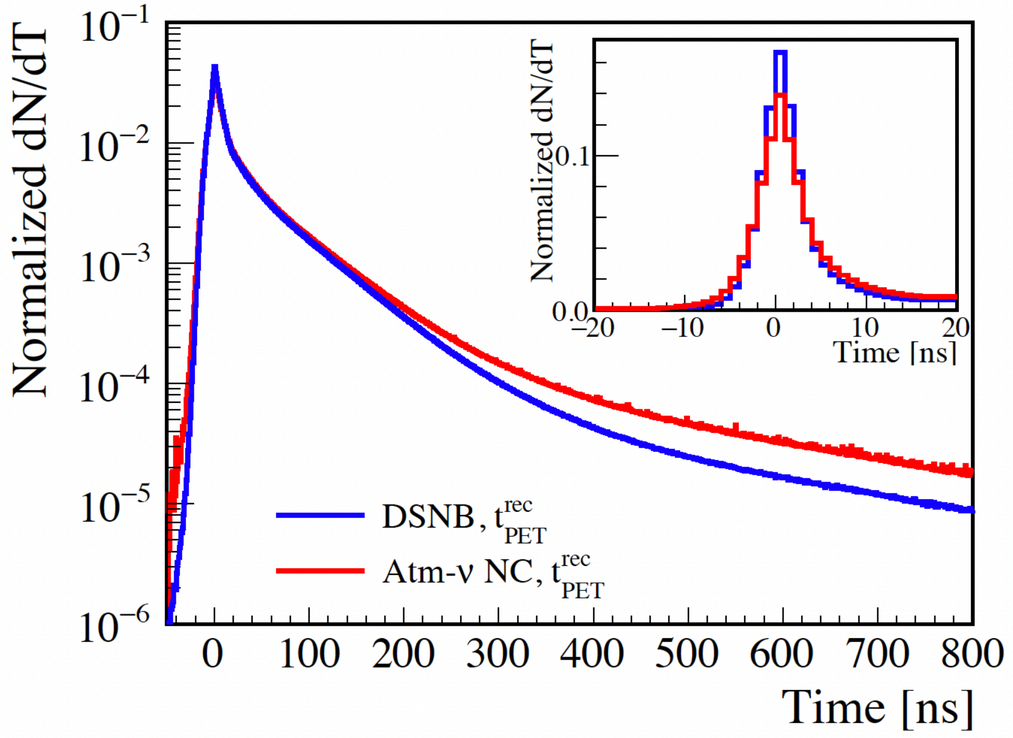


from I. Morton-Blake

JUNO's Prospect

With benefits of their large volume (~14.7 kton) + strong background rejection based on the pulse shape, they expect to achieve good reach to DSNB models after 10 years.





A. Abusleme et al. (JUNO Collaboration), JCAP 10, 033 (2022)
J. Cheng et al., arXiv:2311.16550 [hep-ex]

A Bigger Monster is Coming…

NIKKEN SEKKEI

Hyper-Kamiokande, under Construction

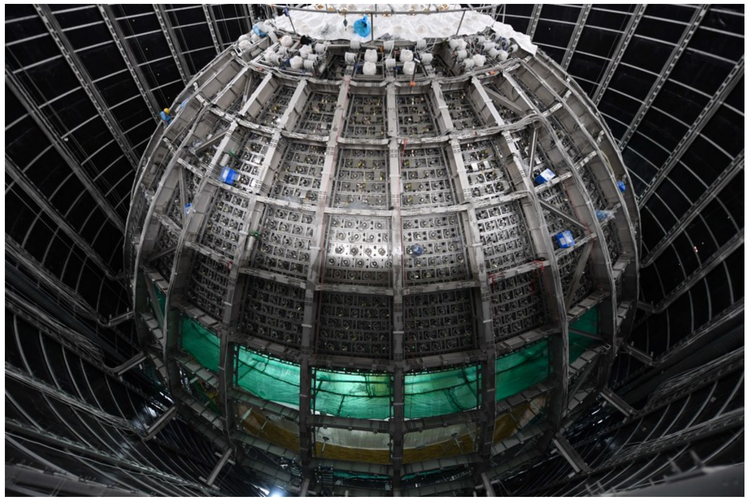
A successor of the greatest *parent* and *grandparent* (**8.4× Super-K**)

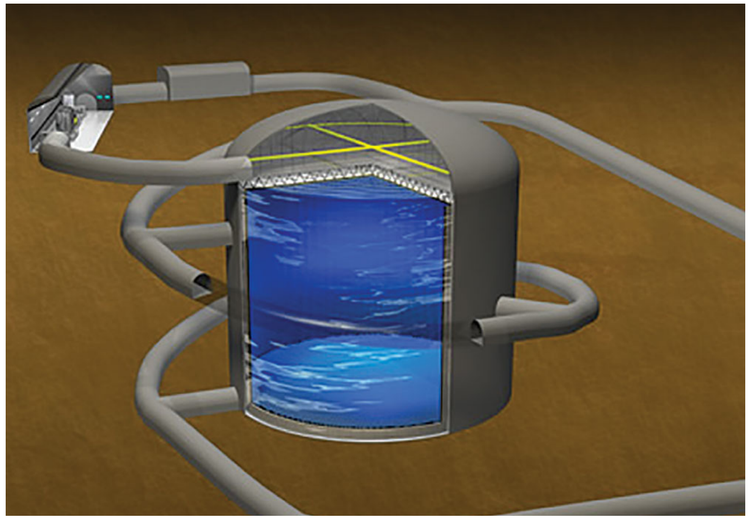
- While with plenty of physics goals, **MeV to TeV astrophysics** is among the most important missions.
- Plays a key role in the DSNB study to cover the wide energy range.

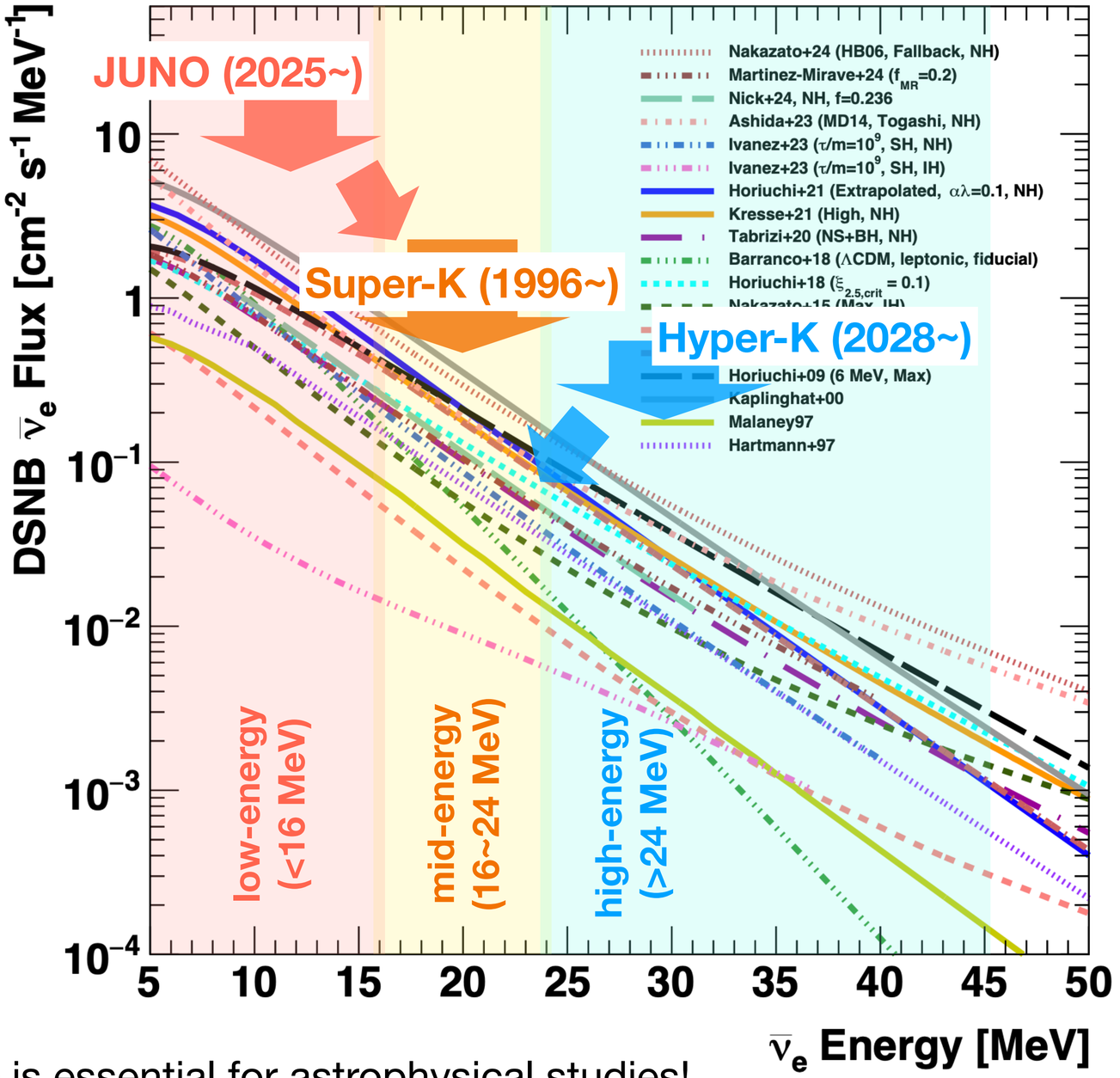
Construction status

- Excavation has been completed in **July 2025**.
- Many groups are rushing in parallel towards the operation start in **June 2028**.

Next Era







DSNB observation over the wide energy range is essential for astrophysical studies!

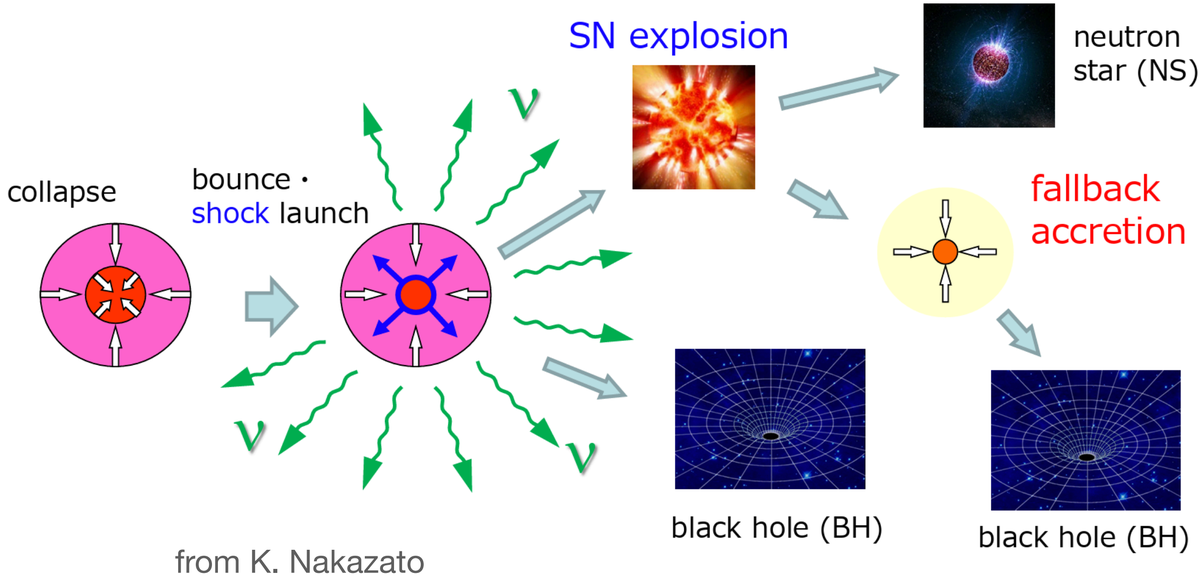
Core Collapse Fate and DSNB

新学術 / 学変 publications

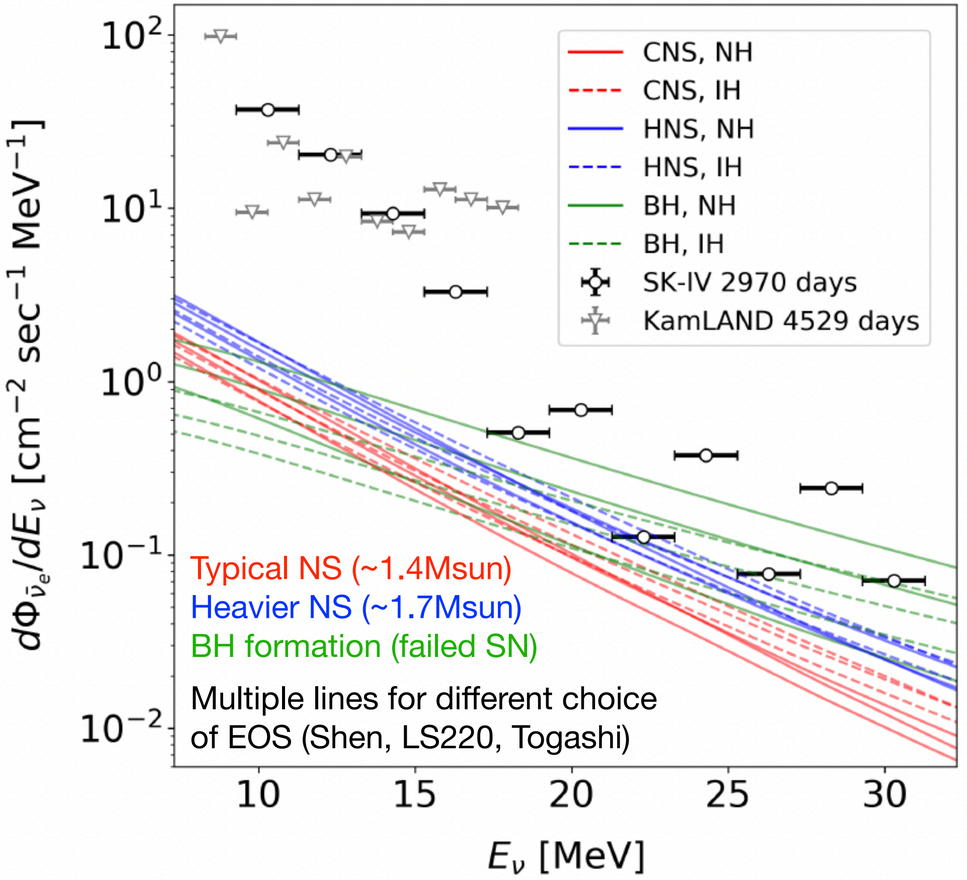
Y. Ashida, K. Nakazato, ApJ 937, 1 (2022)
Y. Ashida, K. Nakazato, T. Tsujimoto, ApJ 953, 2 (2023)
K. Nakazato, R. Akaho, Y. Ashida, T. Tsujimoto, ApJ 975, 1 (2024)

- Emitted ν spectrum is expected to depend on the remnant after core collapse ("*fate*").
  - Information about the fate are accessible by other observations (pulser, failed SN monitoring, GW etc).

- Consider three major cases as a fate and calculate DSNB flux for each.
  - Canonical mass neutron stars (~1.4M_{sun})
  - High mass neutron stars (~1.7M_{sun})
  - Black holes (failed SNe)



from K. Nakazato



CARNE

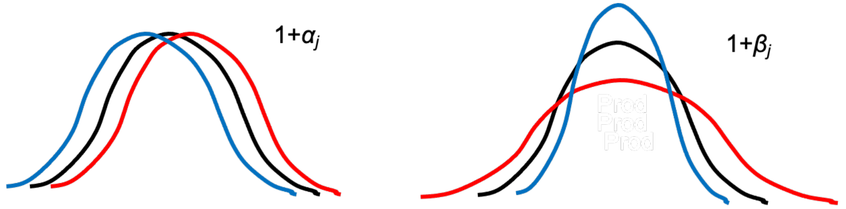
- Need to get prepared for making full use of available dataset from multiple future detectors.
- Another demand comes from the theoretical field as they would like to investigate their models with realistic experimental assumptions.

  → We are developing a dedicated spectral fitting code, *Code for Analyzing Relic NEutrinos* (**CARNE**).

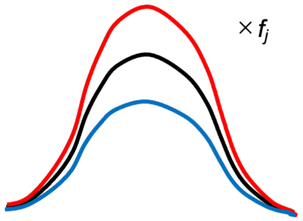
- Philosophy
  - Detector type: water Cherenkov & liquid scintillator (primarily assume Hyper-K and JUNO)
  - Signal: inverse beta decay of electron antineutrinos
  - Background: realistic background incorporated from each group
  - Code access: public use for a wide use in the community; feedback reflected for improvement, making the code more matured to be referred as a basis for the actual use in future
  - Extension possibility: flexible design for potential extension, e.g., detector, observable

Scheme

- Statistical model: an extended unbinned likelihood
- Observable: detection energy
- Flow:



1. Prepare probability density functions (PDFs) of each signal and background; apply shift (energy scale) and shape (energy resolution) systematics here.
2. Produce N_{obs} events based on PDF, detector size, operation time, and analysis efficiency etc (as a toy dataset); in background-only hypothesis, $N_{obs} = N_{bkg,nom}$.
3. Calculate likelihood for each toy dataset by scanning N_{sig} and N_{bkg}, and normalize each likelihood by the maximum likelihood to obtain Test Statistic (TS).
4. From each toy dataset, obtain upper limits at different confidence levels (1σ: TS ≤ 1.00, 2σ: TS ≤ 3.84, 3σ: TS ≤ 6.63 based on Wilks' theorem).



$$L(E_i; N_{sig}, N_{bkg}) = \frac{e^{-(N_{sig}+N_{bkg})}}{N_{obs}!} \prod_{i=1}^{N_{obs}} \{N_{sig} P_{sig}(E_i) + N_{bkg} P_{bkg}(E_i)\} \times \prod_{\theta} exp\left\{-\frac{1}{2}\left(\frac{\theta - \theta_0}{\sigma_\theta}\right)^2\right\}$$

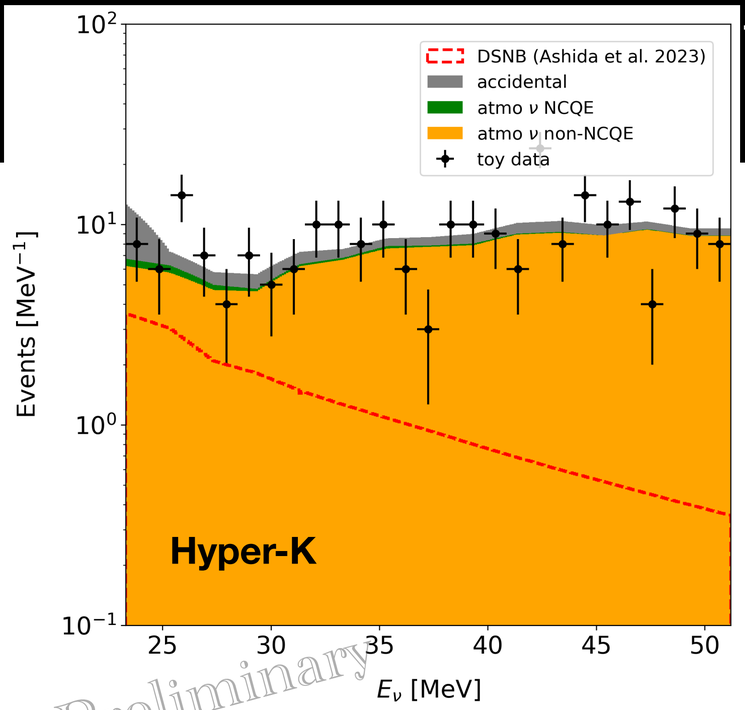
Poisson term for statistics
(*i*: event ID)

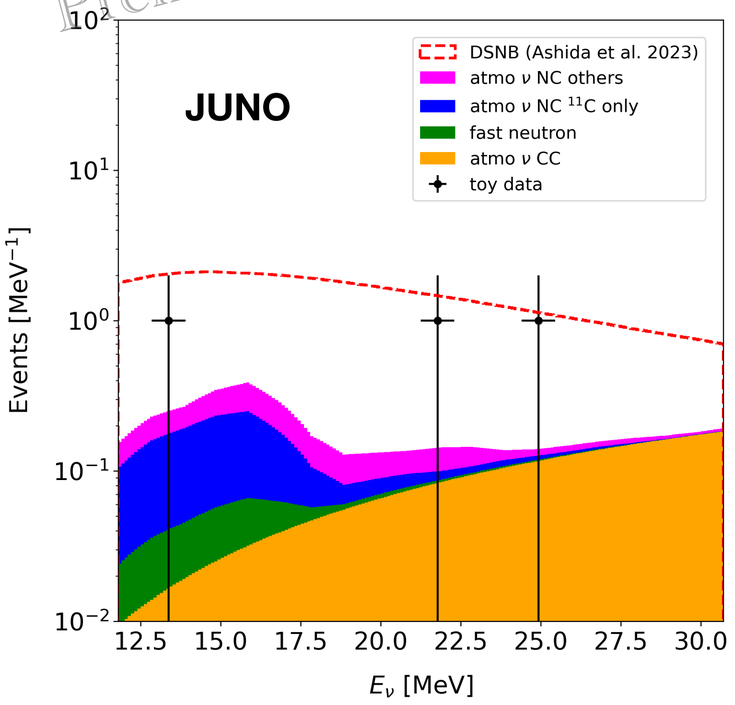
pull term for systematics
($\theta \sim \alpha_j, \beta_j, f_j$: PDF shift/shape, bkg norm etc)

$$TS = -2 \ln\left(\frac{L}{\hat{L}}\right)$$

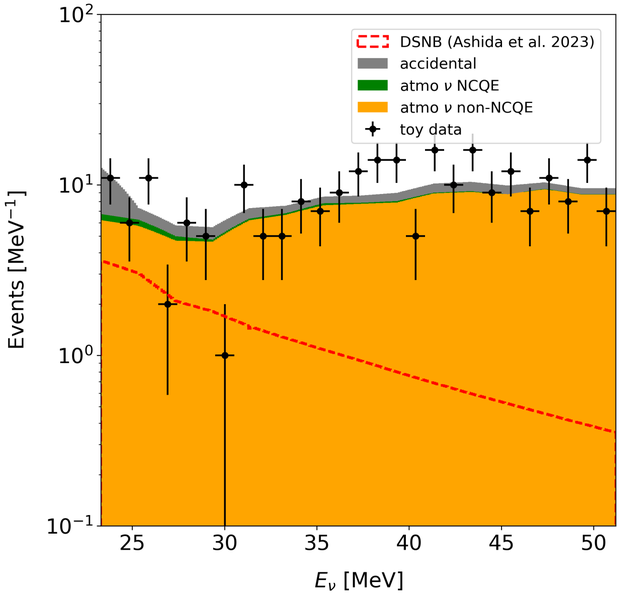
Demonstration Setup

- DSNB model: [Y. Ashida et al., ApJ 953, 2 (2023)]
- **Hyper-K**, extrapolated from SK-IV [K. Abe et al., PRD 104, 122002 (2021)]
  - Volume: 187 kton
  - Operation time: 7 years (2028~2035)
  - Background: non-NCQE (mainly CCQE), NCQE, accidental coincidence
  - Neutrino energy range: 23.3~51.3 MeV
- **JUNO**, taken from JUNO [A. Abusleme et al., JCAP 10, 033 (2022)]
  - Volume: 14.7 kton (FV1)
  - Operation time: 10 years (2025~2035)
  - Background: CC, NC, fast neutron, ^{9}Li/^{8}He, reactor
  - Neutrino energy range: 11.8~30.8 MeV
- Systematics
  - 20% on total background scale (no others for now)

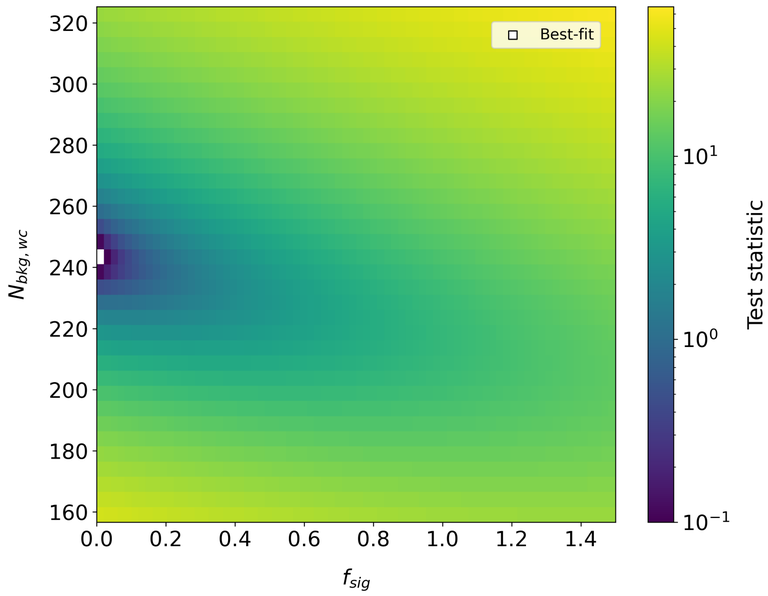




Example Trials



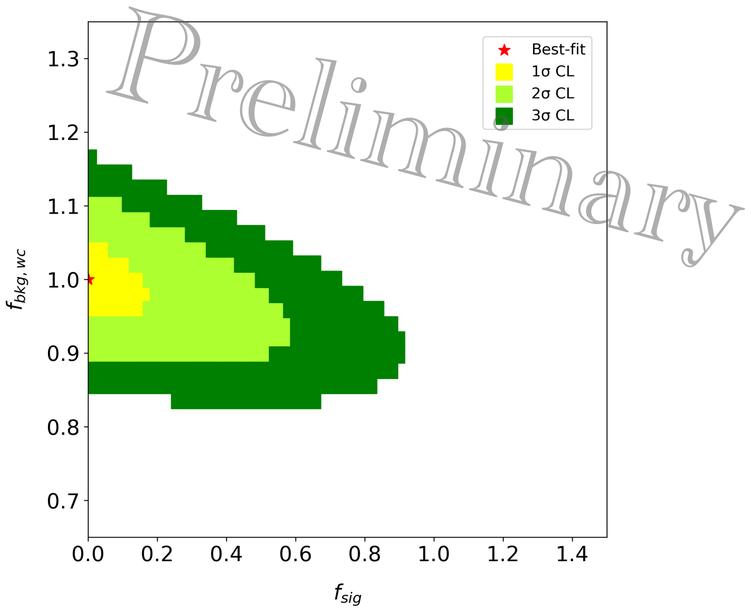
A certain toy sample with expectations



Test Statistic along scans

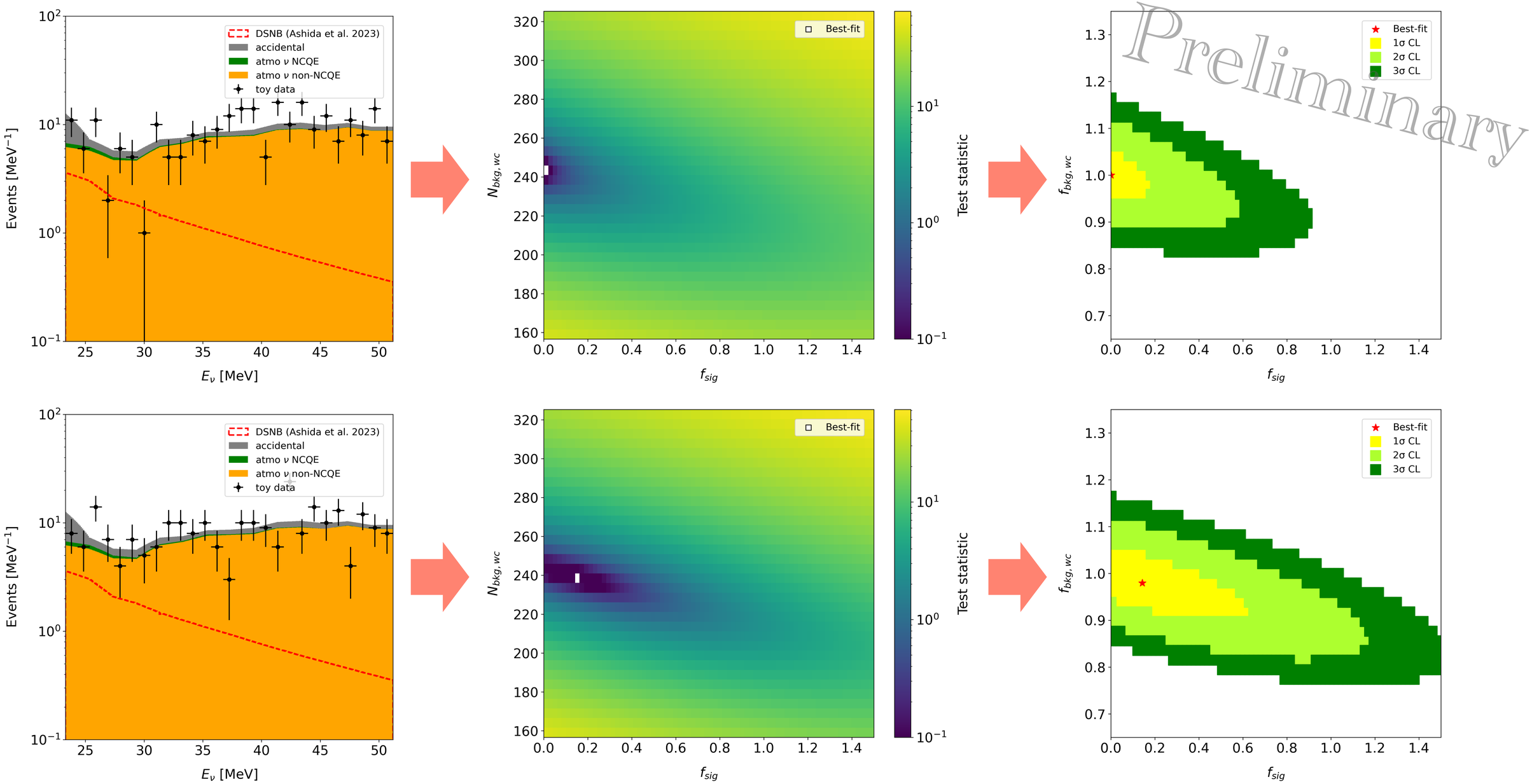
f_{sig}: scaling to nominal DSNB

$N_{\mathrm{bkg,wc}}$: background at Hyper-K



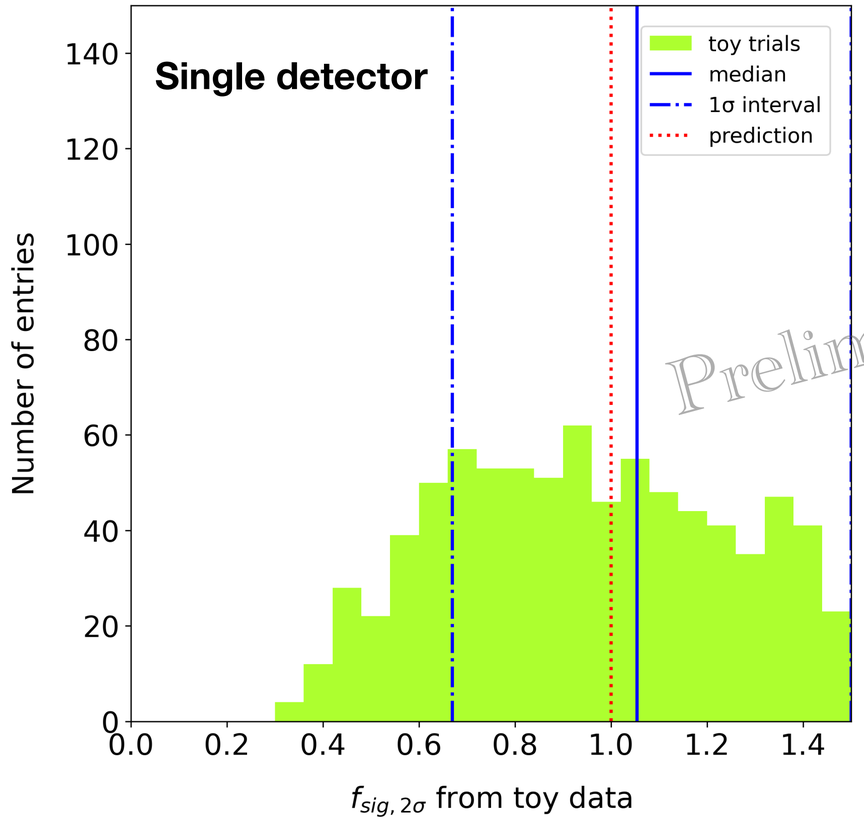
Allowed region based on TS

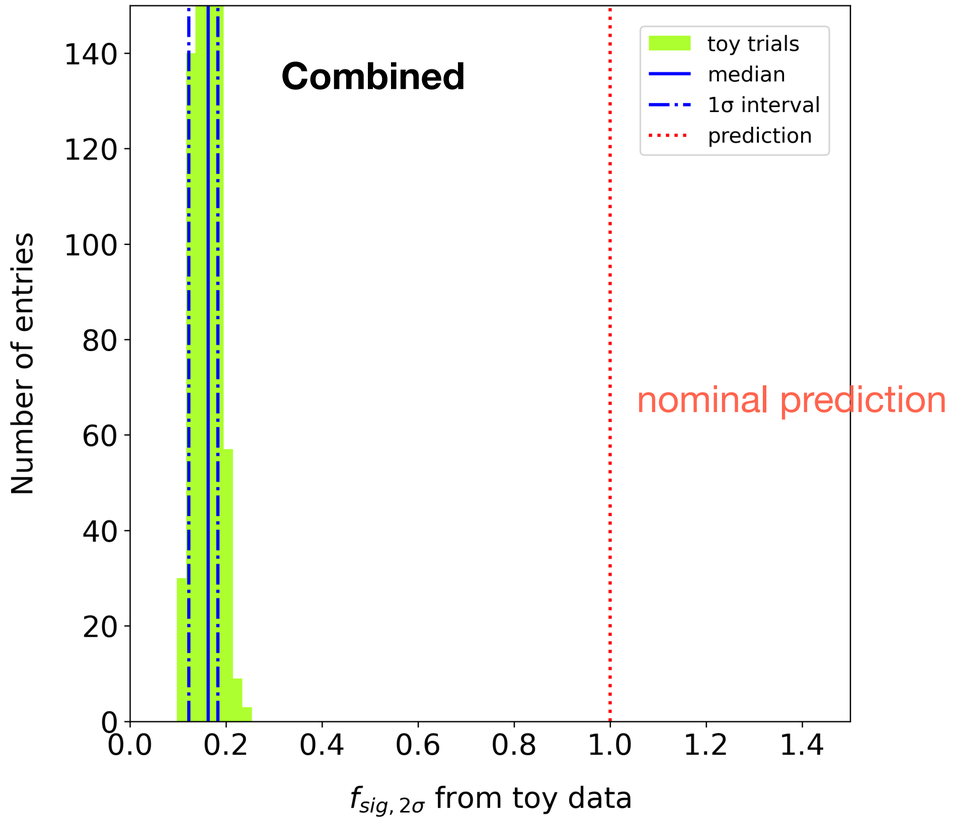
Example Trials



Demonstration Result

- Single detector cases are compared with a combined detector case.
- Multiple detector utilization provides a better sensitivity as expected.





NOTE: This is one test case. Please do not take them as official sensitivities from these detectors! We will check more on quantity!

Toward Public Release: *Usability*

run_carne.ipynb → carne.py

In [ ]:
```
## import libraries

import math
import numpy as np

from carne import carne
from carne import utils
```

load source codes

In [ ]:
```
## load and tailor data

enu = np.linspace(50, 0, 50)  # MeV

xsec = utils.load_ibd_xsec(enu)  # cm^2
flux = utils.load_dsnb_flux(enu)  # cm^-2 s^-1 MeV^-1

sig_wc, sigeff_wc = utils.load_sig("wc")
bkg_wc = utils.load_bkg("wc")

sig_ls, sigeff_ls = utils.load_sig("ls")
bkg_ls = utils.load_bkg("ls")
```

load input data

In [ ]:
```
## setup carne

hk = carne.wc(size=189., runtime=10., sig_wc, sigeff_wc, bkg_wc)
toy_hk = hk.create_toy(ntoy=10000, mode="bkgonly")

juno = carne.ls(size=14.7, runtime=10., sig_ls, sigeff_ls, bkg_ls)
toy_juno = juno.create_toy(ntoy=10000, mode="bkgonly")
```

setup detector objects → produce toy MC samples

In [ ]:
```
## perform fit

scan_fsig = np.linspace(100, 0, 1)
scan_fbkg = np.linspace(100, 0, 1)
scan_set = [scan_fsig, scan_fbkg]

loglikeli_hk, teststat_hk = utils.calc_likelihood(hk, toy_hk, scan_set)
loglikeli_juno, teststat_juno = utils.calc_likelihood(juno, toy_juno, scan_set)
loglikeli_comb, teststat_comb = utils.calc_likelihood(hk, toy_hk, juno, toy_juno, scan_set)
```

scan over signal and background scales to calculate TS

Summary

***CARNE* under development for the future DSNB spectroscopy**

- DSNB is a unique probe of astrophysics and its discovery has been awaited for long.
- Super-K may lie very close to the first observation.
- Next-generation detectors are operating soon with their own search window.
- Making full use of available data from multiple detectors is essential for astrophysical studies.
- An initial demonstration result from CARNE is shown.

***Plans*: public release before summer**

- Improve code structure for a better usability and realistic speed.
- Perform validation with publicly released data from Super-K.
- Apply analysis with CARNE on the latest public data from Super-K + KamLAND.

Thanks for your attention!

Supplements

Achievements in 新学術 & 学術変革

The Astrophysical Journal, 937:30 (11pp), 2022 September 20

2022

https://doi.org/10.3847/1538-4357/ac8a46

Exploring the Fate of Stellar Core Collapse with Supernova Relic Neutrinos

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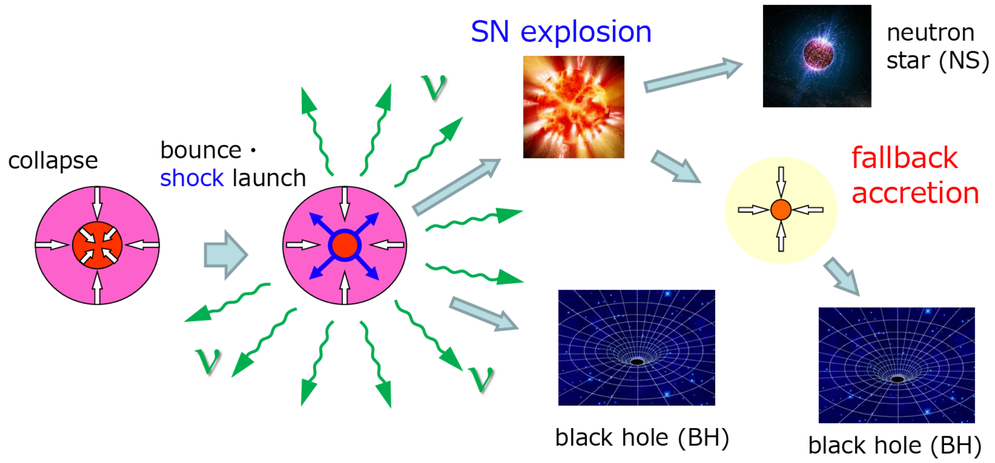
Particularly focused on **BH-forming CCSNe** and **chemical evolution of galaxy**



from K. Nakazato

The Astrophysical Journal, 953:151 (9pp), 2023 August 20

2023

https://doi.org/10.3847/1538-4357/ace3ba

Diffuse Neutrino Flux Based on the Rates of Core-collapse Supernovae and Black Hole Formation Deduced from a Novel Galactic Chemical Evolution Model

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2024

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Impacts of Black-hole-forming Supernova Explosions on the Diffuse Neutrino Background

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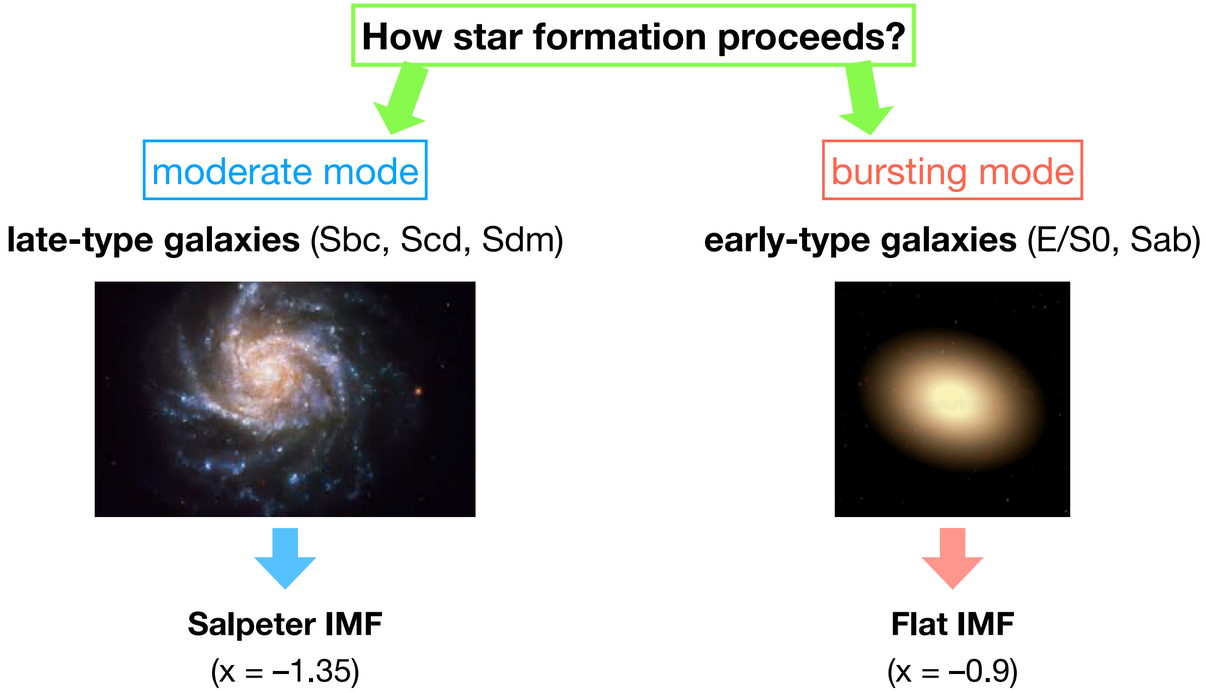
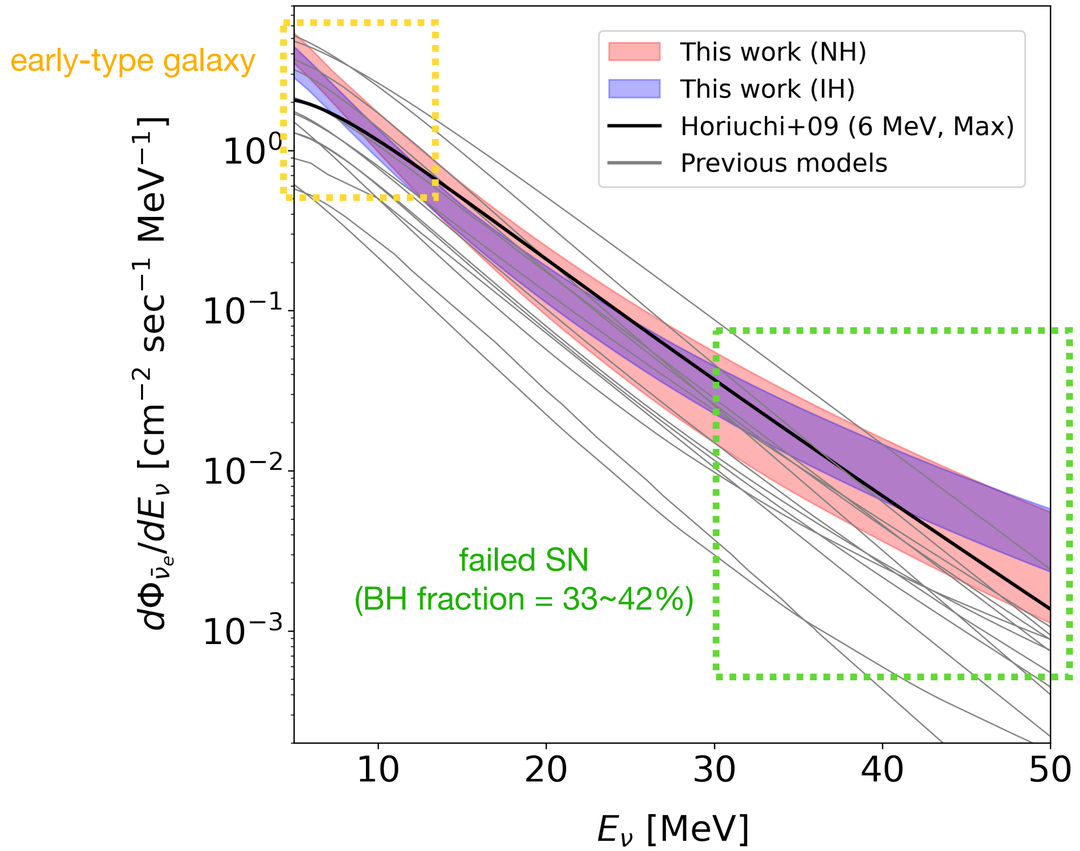
Galactic Chemical Evolution and DSNB

Y. Ashida et al., ApJ 953, 2 (2023)

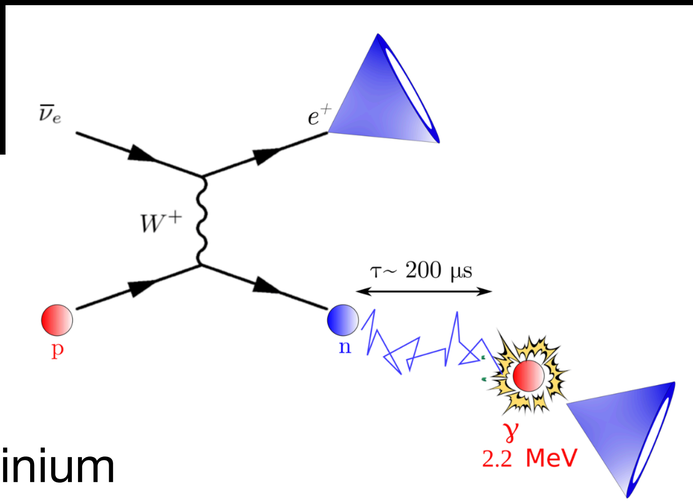
- Set the maximum mass of progenitors for successful explosions to **$18M_{sun}$** from both observational and theoretical findings.
- Proposed a new evolution model to compensate for the discrepancy in chemical abundance; categorize galaxies into five and assume different initial mass functions (IMF) depending types.



T. Tsujimoto, MNRAS 518, 3475 (2023)

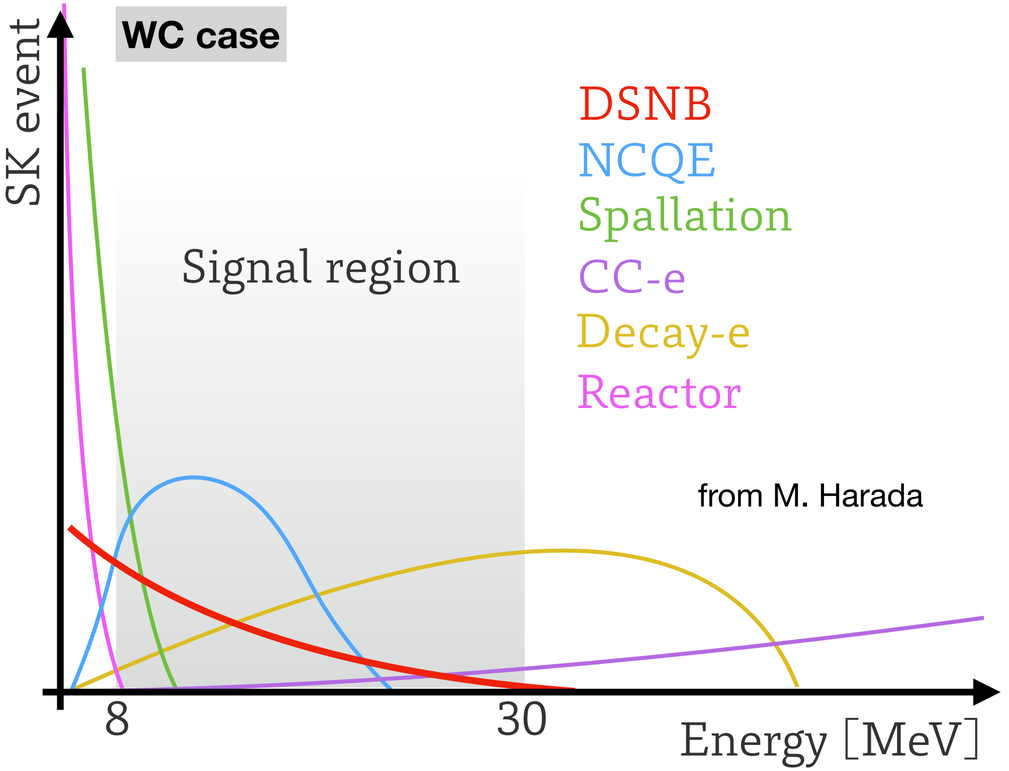


Experimental Search

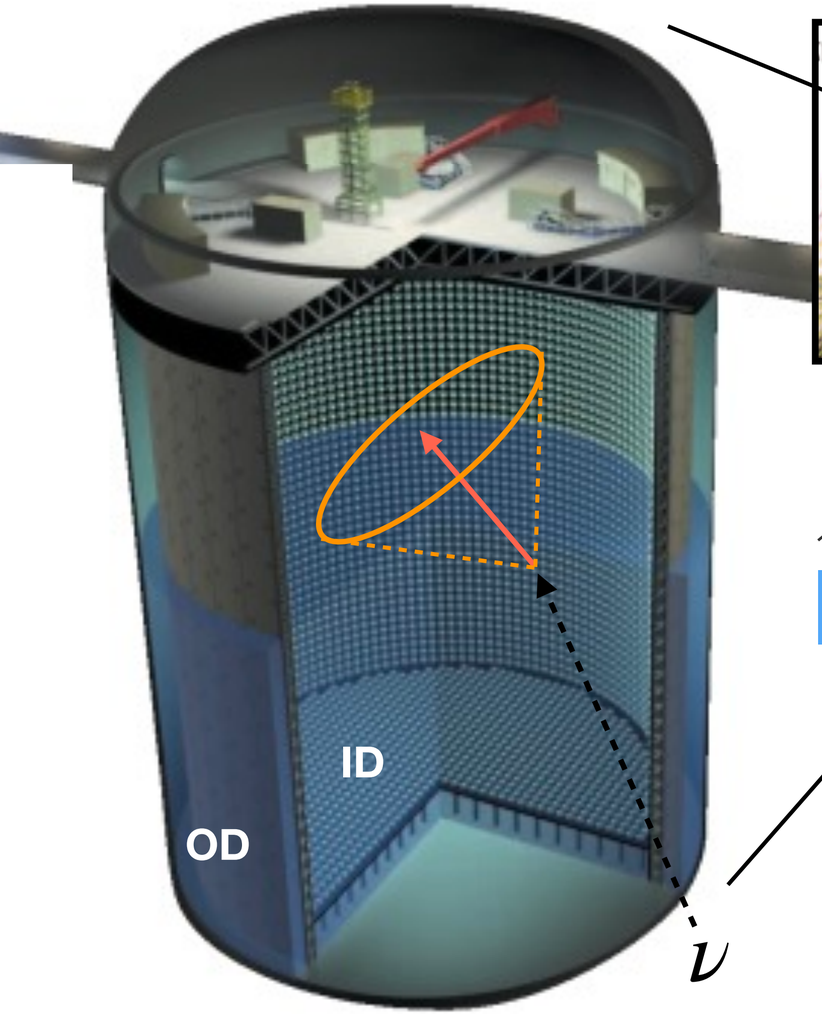


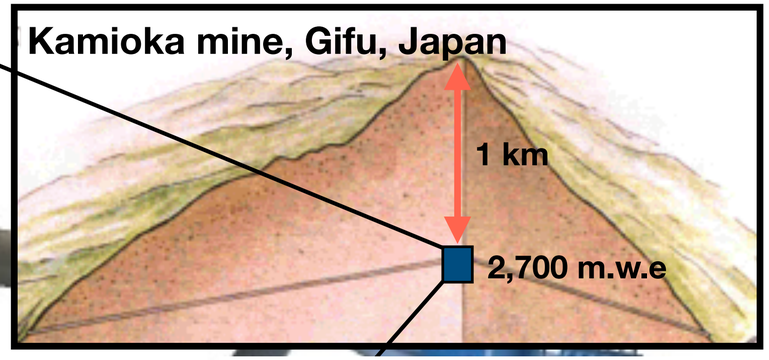
- Signal = **inverse beta decay (IBD)**, $\bar{\nu}_e + p \rightarrow e^+ + n$ (dominant channel)
  - **e^+** = "*prompt*" signal (main energy range: **O(1–10) MeV**)
  - **n** = "*delayed*" signal via **γ-ray(s)** from thermal capture on hydrogen or gadolinium

- Many types of backgrounds mimicking this signature.
  - Atmospheric neutrinos (charged / neutral current)
  - Radioactive isotopes and neutrons by atmospheric muons
  - Solar neutrinos
  - Reactor neutrinos



Super-Kamiokande





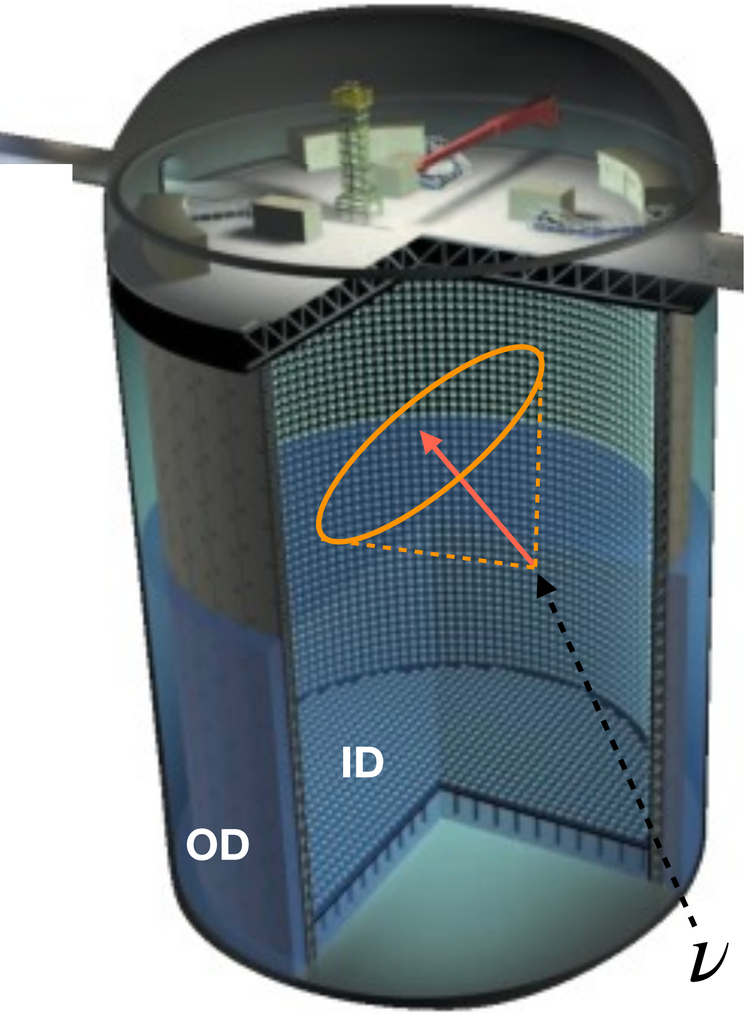
Atmospheric muon rate ~2 Hz

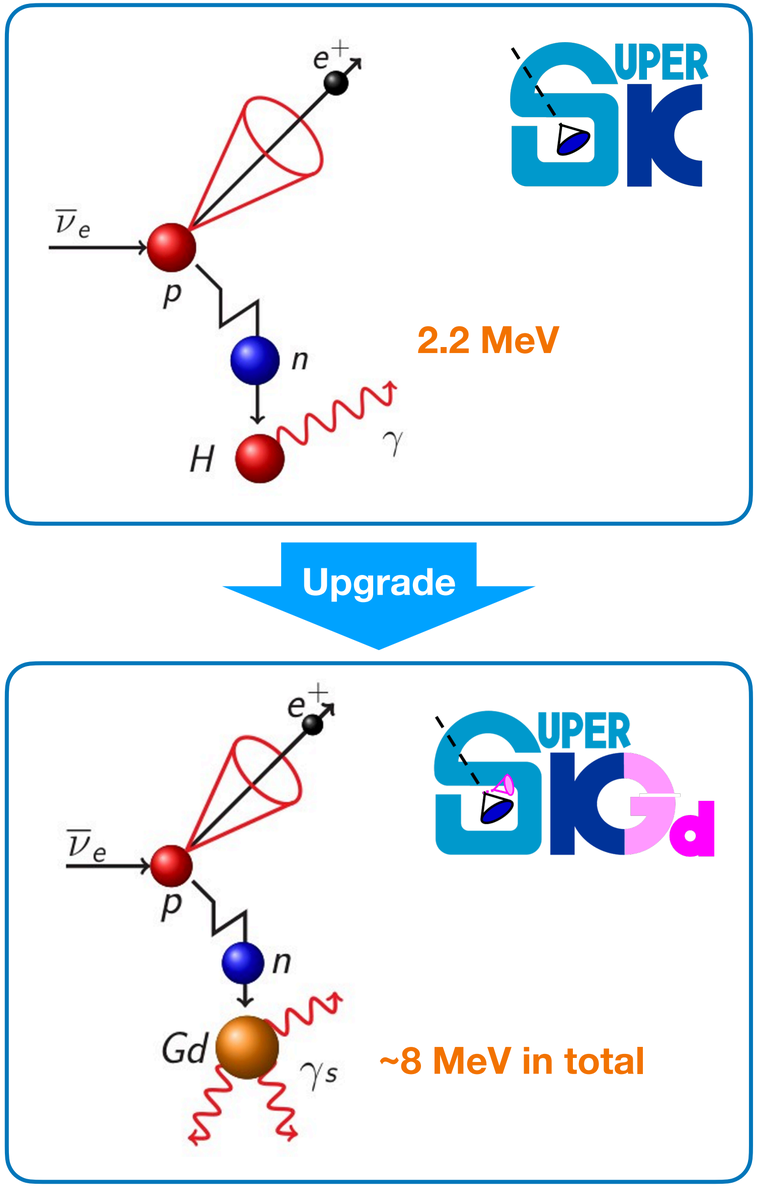
- 50 kton water (**22.5 kton** for analysis)
- **11,129** 20-inch PMTs (Inner Detector)
  → Physics event of interest
- **1,885** 8-inch PMTs (Outer Detector)
  → Background veto (muon etc)

- 7 phases completed so far, and SK-VIII is on-going now.
- DSNB search performed multiple times.
  - SK-I to IV: published in Physical Review D 104, 122002 (2021)
  - SK-VI & VII: presented at NEUTRINO 2024 (paper in prep)
  - SK-I through VIII: study in progress

Super-Kamiokande with Gadolinium

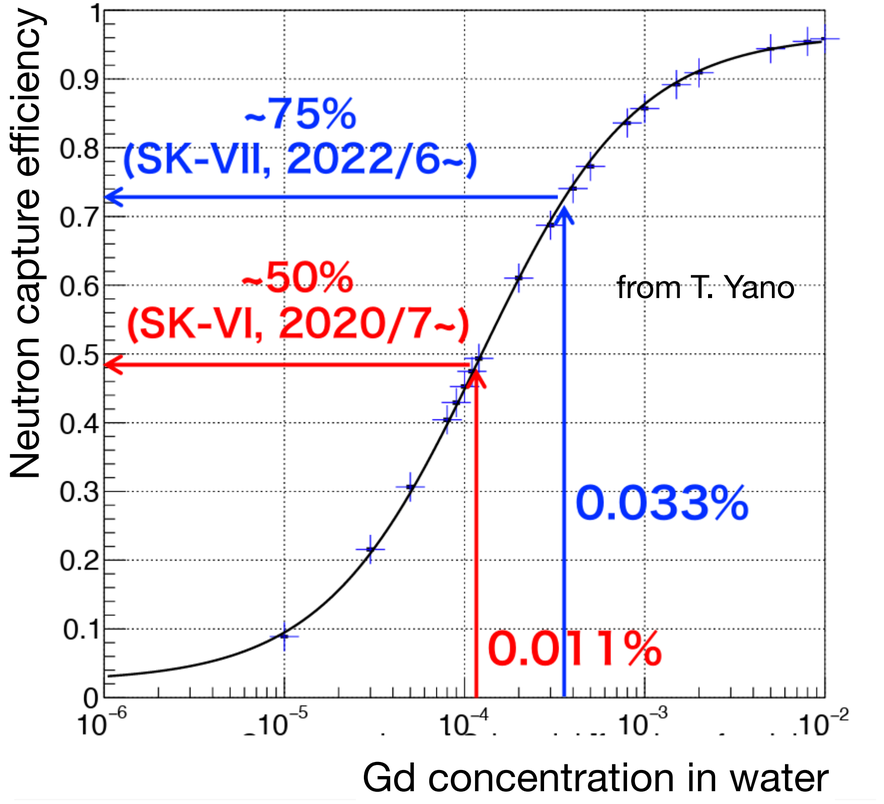
K. Abe et al. (SK Collaboration), NIMA 1027, 166248 (2022)
M. Harada et al. (SK Collaboration), ApJL 951, L27 (2023)
K. Abe et al. (SK Collaboration), NIMA 1065, 169480 (2024)





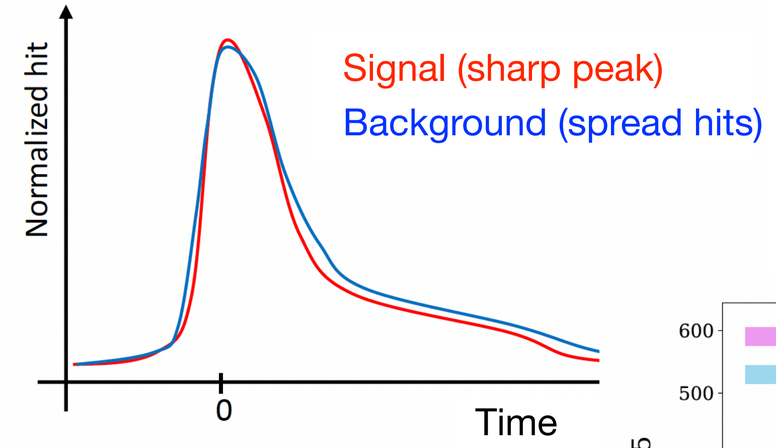
Gd loaded to improve neutron detection.

- Capture Xsec: 0.33 barn → **~49 kbarn**
- γ energy: 2.2 MeV → **~8 MeV**
- 0.011% (SK-VI), 0.033% (SK-VII~)

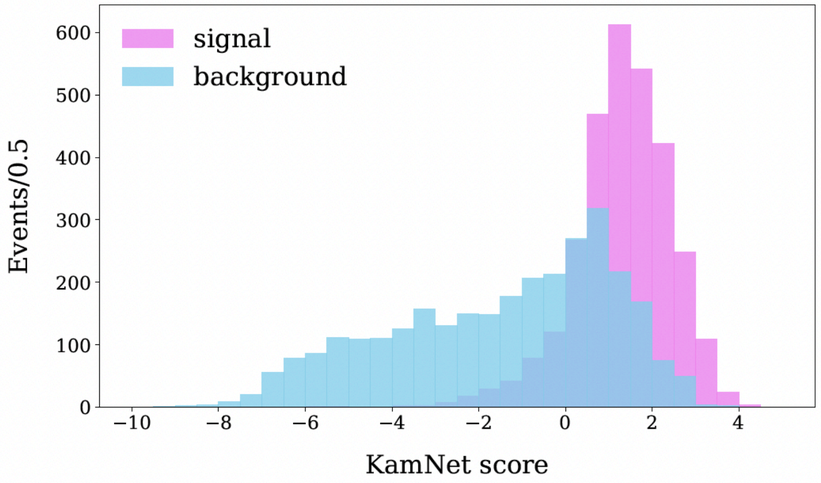


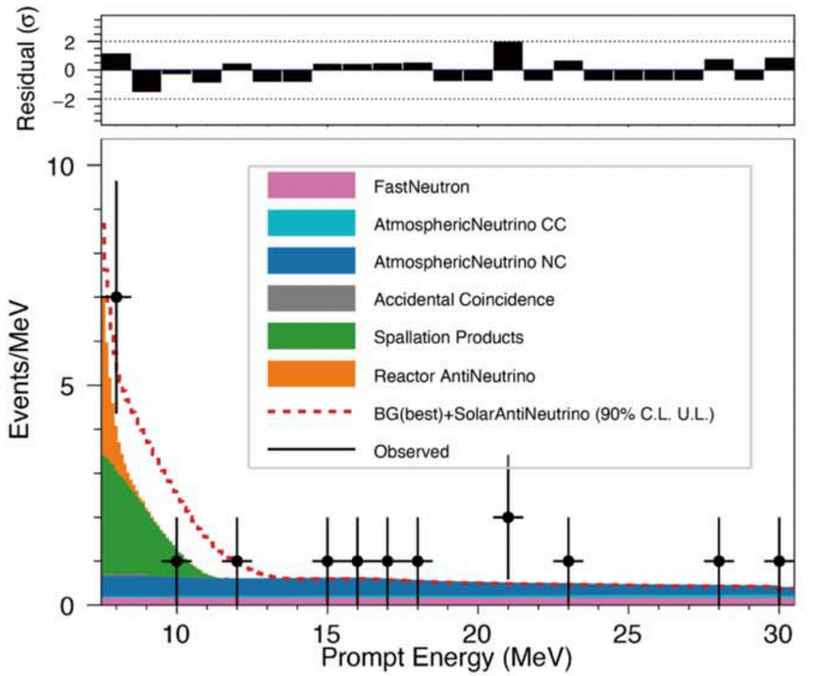
Search at KamLAND

- KamLAND performed a search in 2022 using its reactor-off period.
- They are now introducing DNN to capture signal/background difference in *space* and *time* distributions — a new result with this discriminator will be shown soon!



M. Eizuka, PoS (ICRC2025) 1036





S. Abe et al. (KamLAND Collaboration), ApJ 925, 14 (2022)