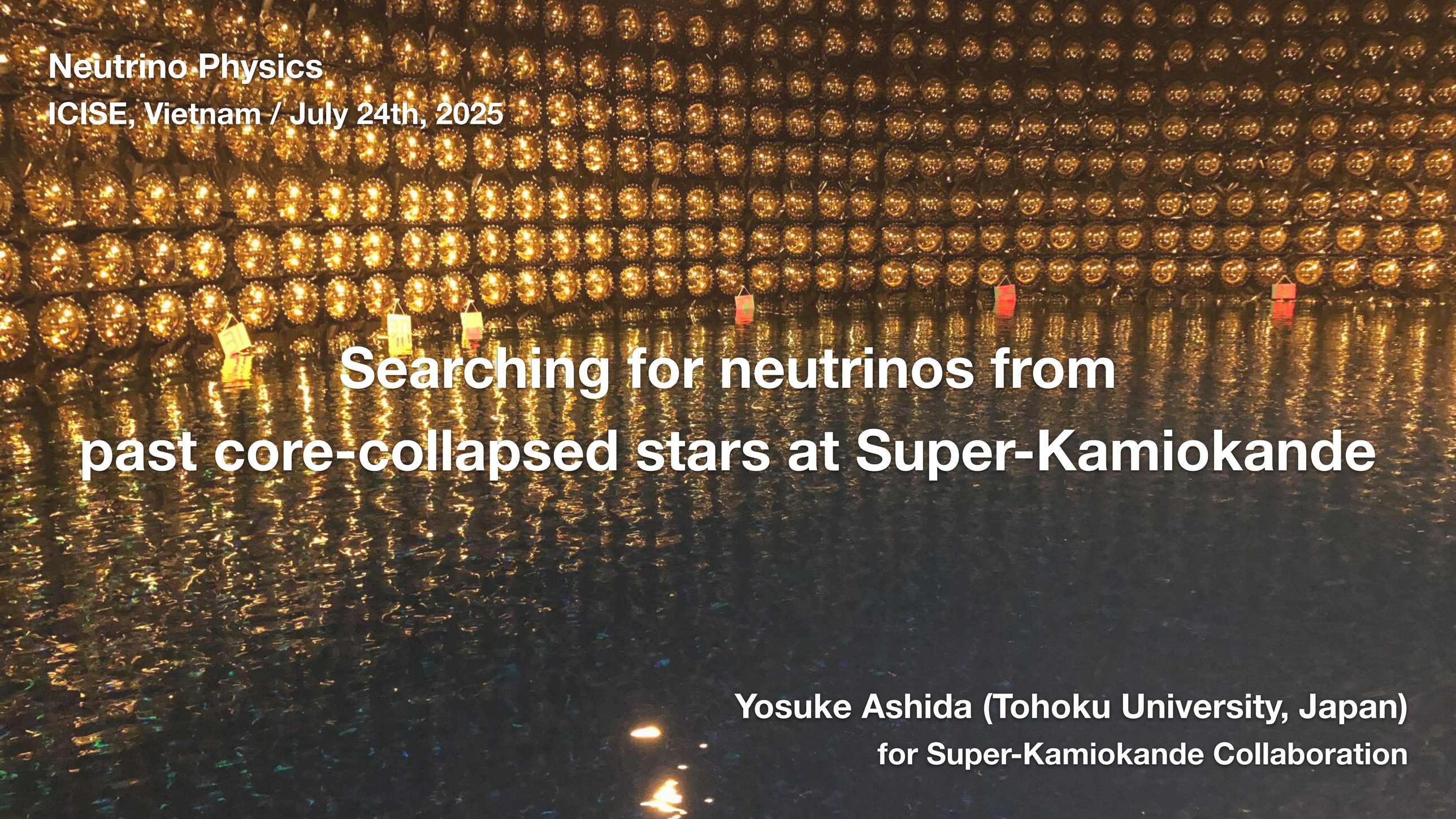
Neutrino Physics

ICISE, Vietnam / July 24th, 2025



Searching for neutrinos from past core-collapsed stars at Super-Kamiokande

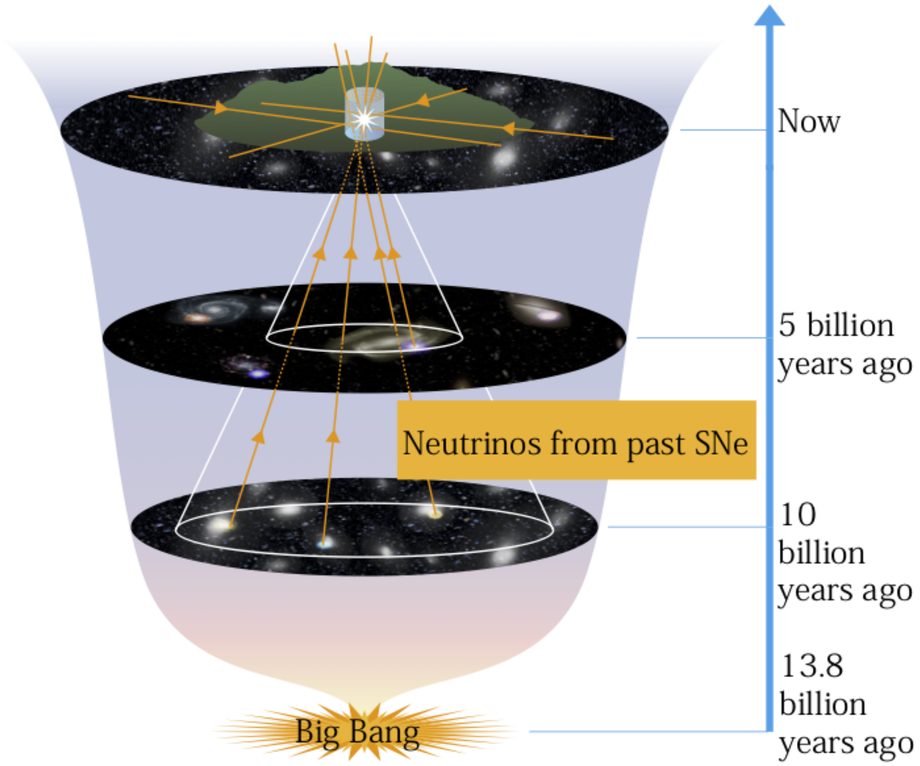
Yosuke Ashida (Tohoku University, Japan)

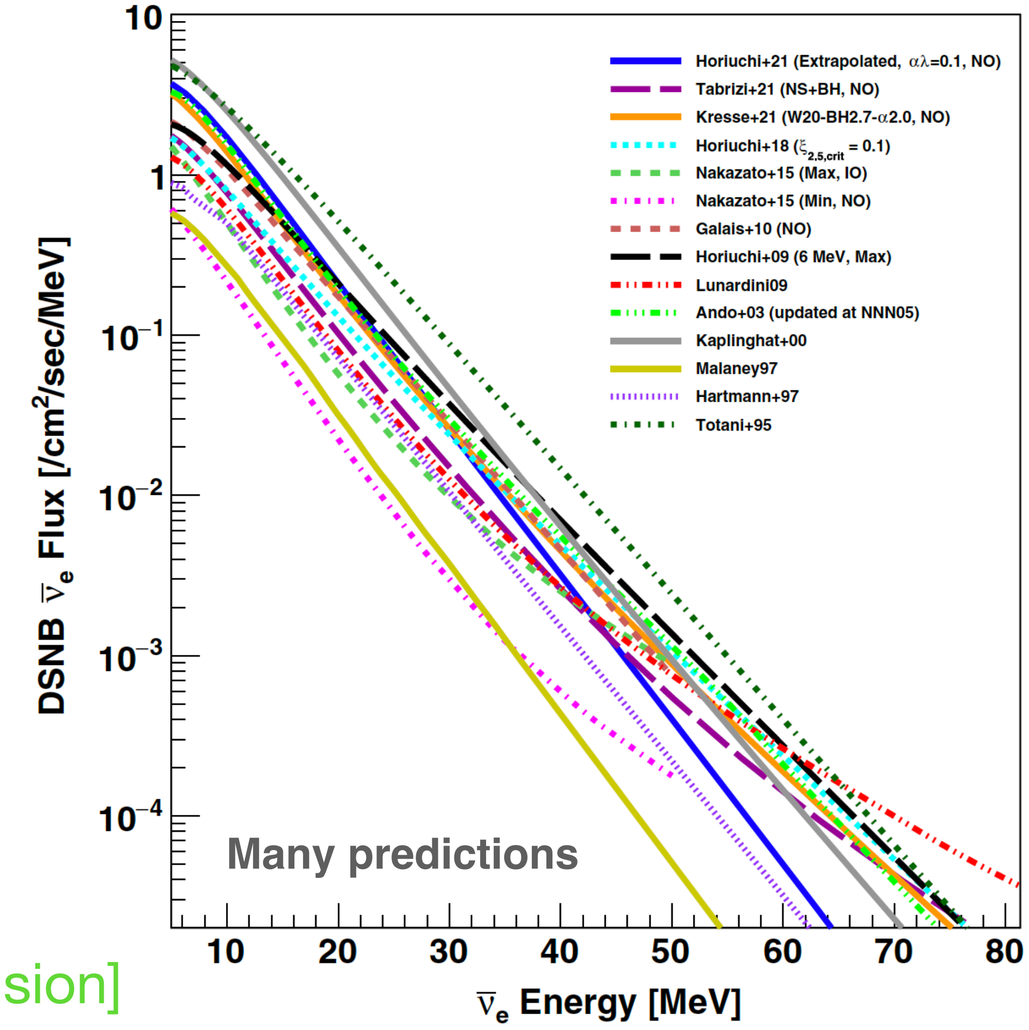
for Super-Kamiokande Collaboration

Message from Stars in the Past

The accumulated flux of neutrinos released from stellar core collapse over the cosmic history

= **Diffuse Supernova Neutrino Background; DSNB**





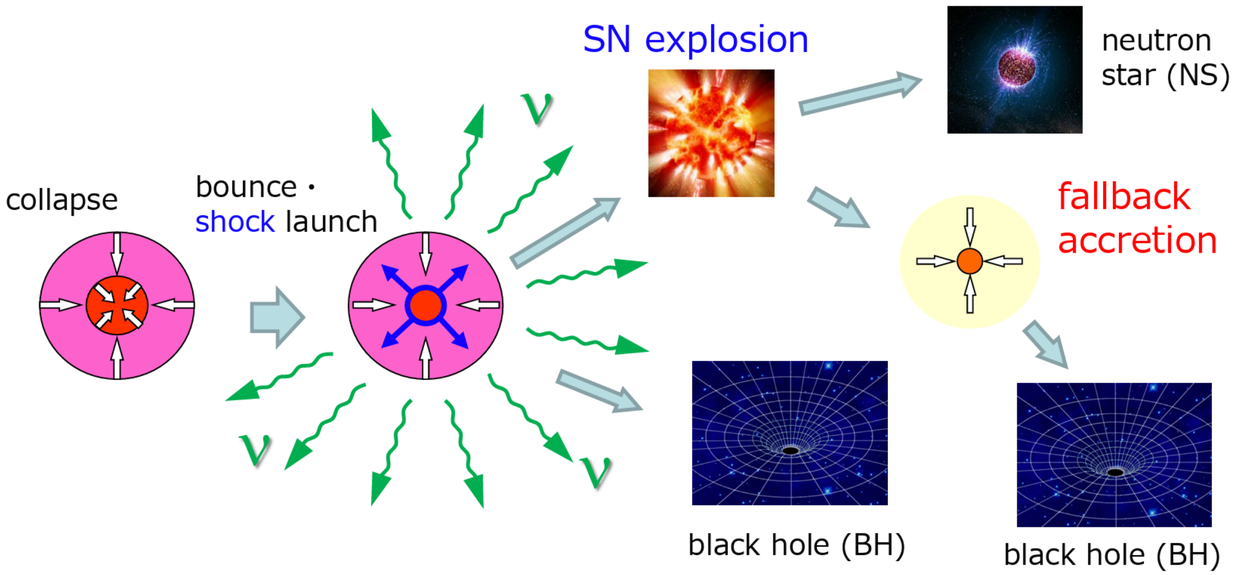
$\Phi = \int$ [ν emission] ⊗ [Star formation] ⊗ [Universe expansion]

DSNB in Neutrino Astronomy

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)

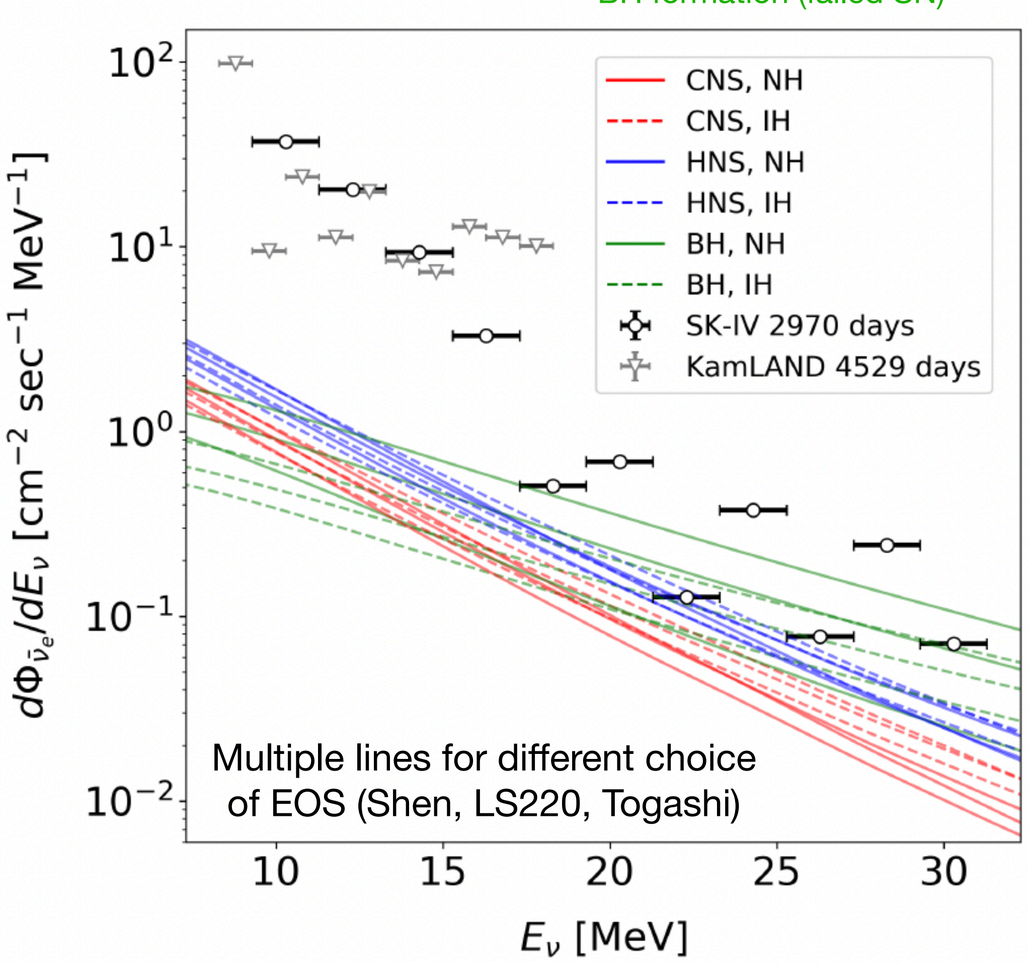
- Recent studies suggest DSNB as a probe of the *fate* of stellar core collapse.
- Fraction of black hole formation is tied with galactic chemical evolution.
- These can connect to optical/GW surveys, i.e.,

  multi-messenger astronomy is possible.

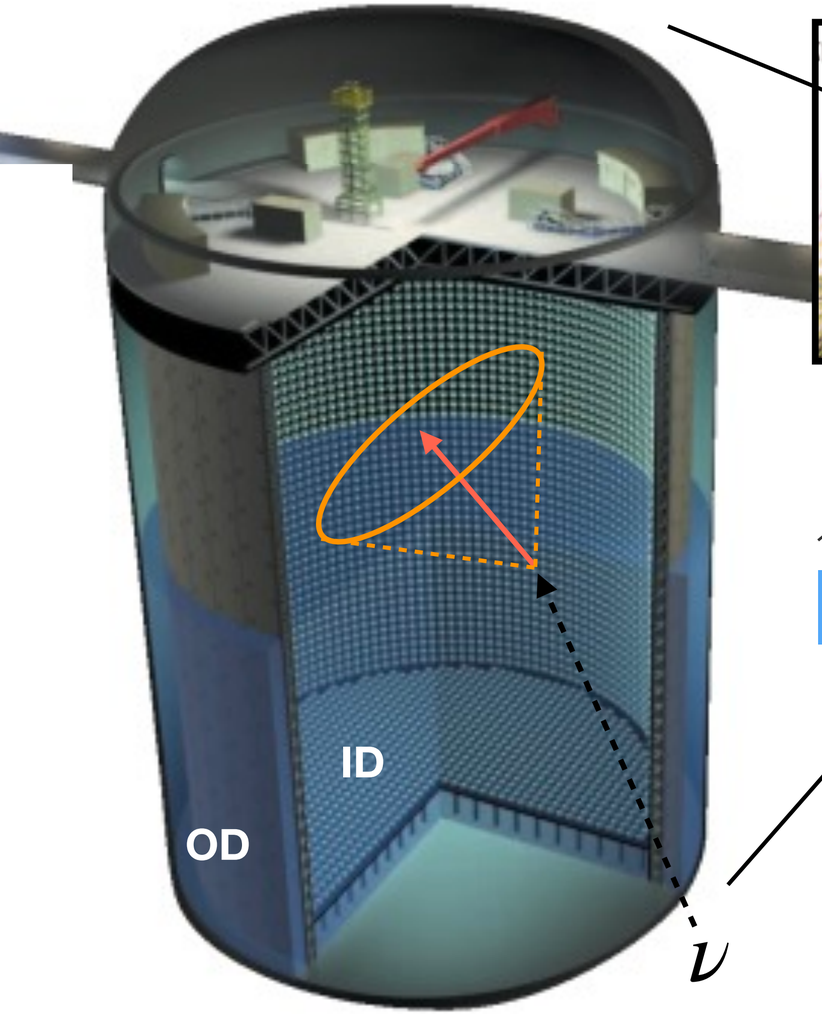


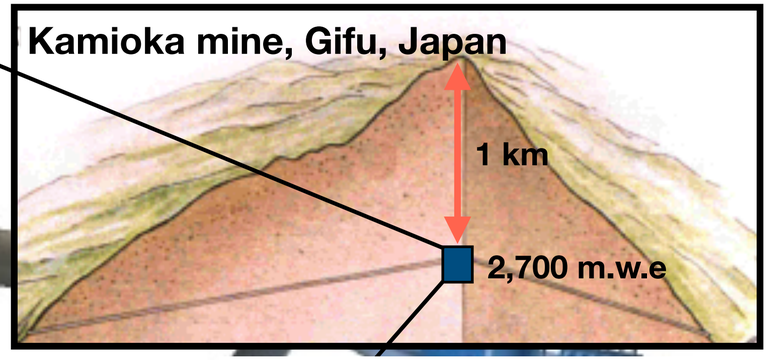
from K. Nakazato

Typical mass NS (~1.4Msun)
Heavier mass NS (~1.7Msun)
BH formation (failed SN)



Super-Kamiokande





Atmospheric muon rate ~2 Hz

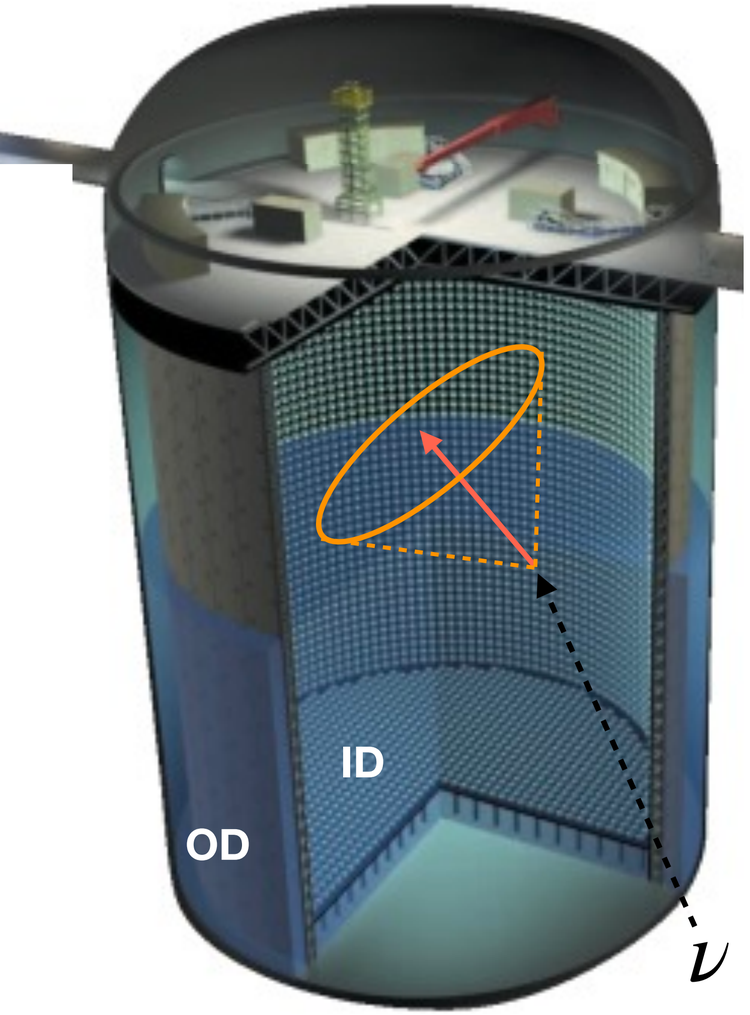
- 50 kton water (**22.5 kton** for analysis)
- **11,129** 20-inch PMTs (Inner Detector)
  → Physics event of interest
- **1,885** 8-inch PMTs (Outer Detector)
  → Background veto (muon etc)

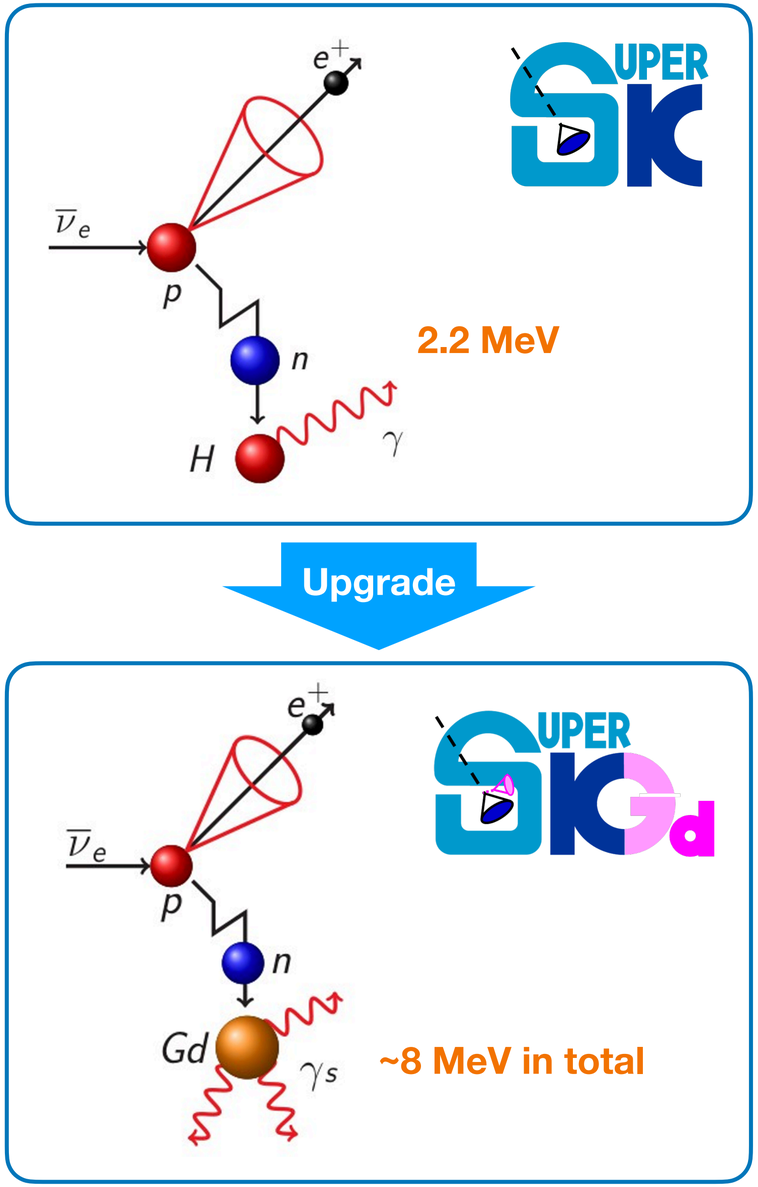
- 7 phases completed so far, and SK-VIII is on-going now.
- DSNB search performed multiple times.
  - SK-I to IV: published in Physical Review D 104, 122002 (2021)
  - SK-VI & VII: presented at NEUTRINO 2024 (paper in prep)
  - SK-I through VIII: study in progress

Today

Super-Kamiokande with Gadolinium

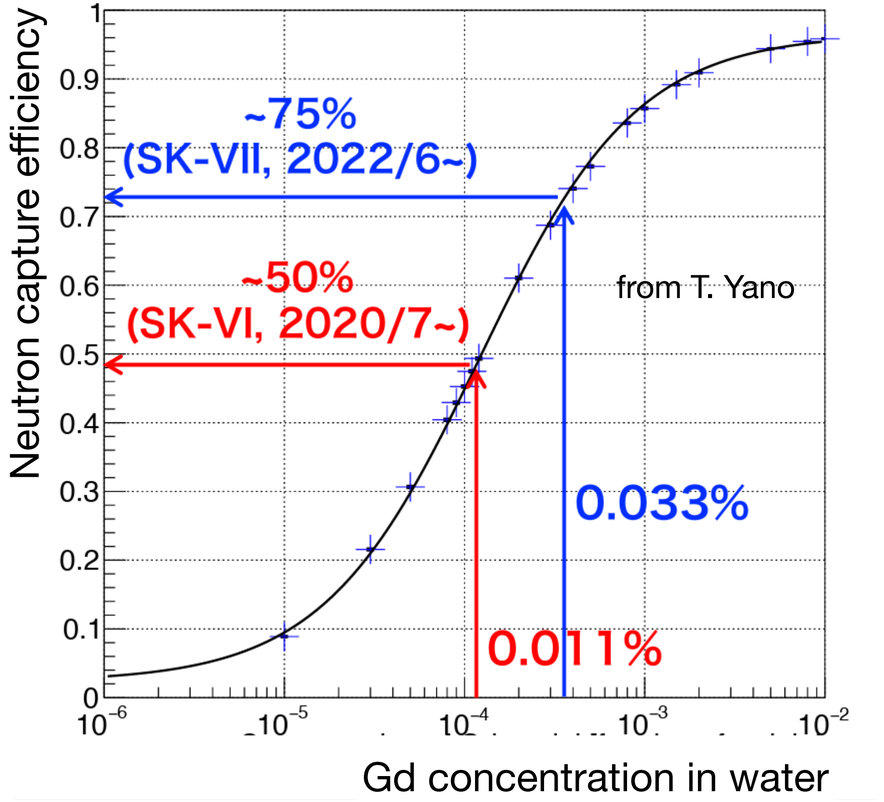
K. Abe et al. (SK Collaboration), NIMA 1027, 166248 (2022)
M. Harada et al. (SK Collaboration), ApJL 951, L27 (2023)
K. Abe et al. (SK Collaboration), NIMA 1065, 169480 (2024)





Gd loaded to improve neutron detection.

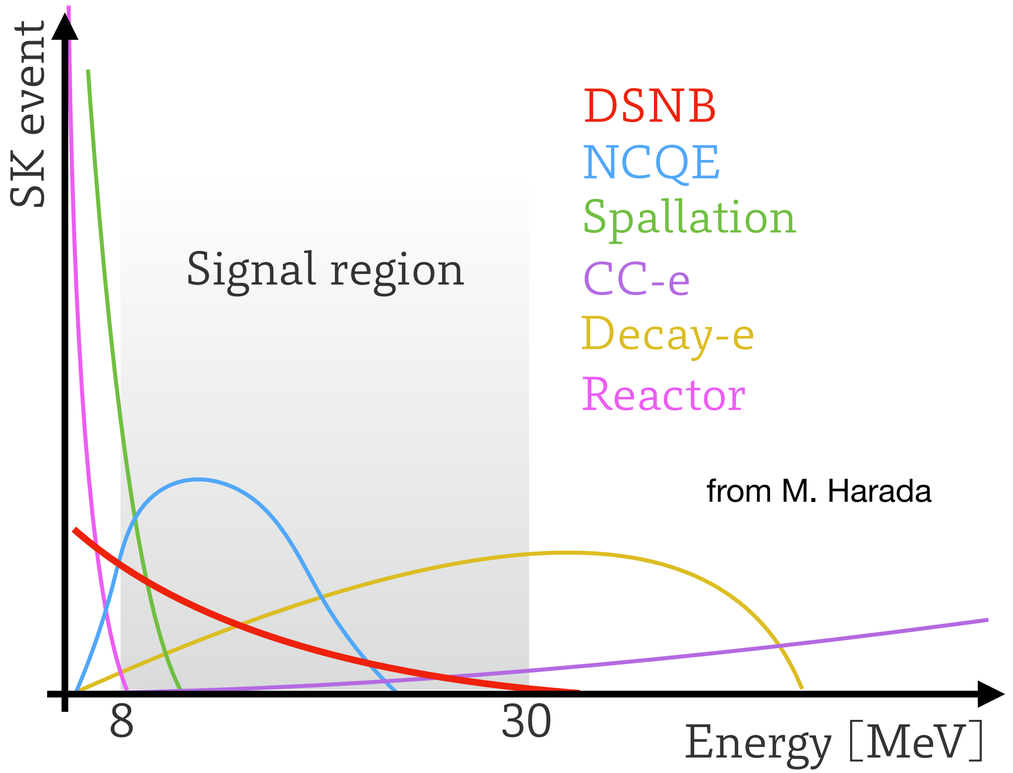
- Capture Xsec: 0.33 barn → **~49 kbarn**
- γ energy: 2.2 MeV → **~8 MeV**
- 0.011% (SK-VI), 0.033% (SK-VII~)



Signal and Background

- Signal = **inverse beta decay (IBD)**, $\bar{\nu}_e + p \rightarrow e^+ + n$ (dominant channel)
  - **e^+** = "*prompt*" signal (main energy range: **8~30 MeV**)
  - **n** = "*delayed*" signal via **γ-ray(s)** from thermal capture on hydrogen or gadolinium

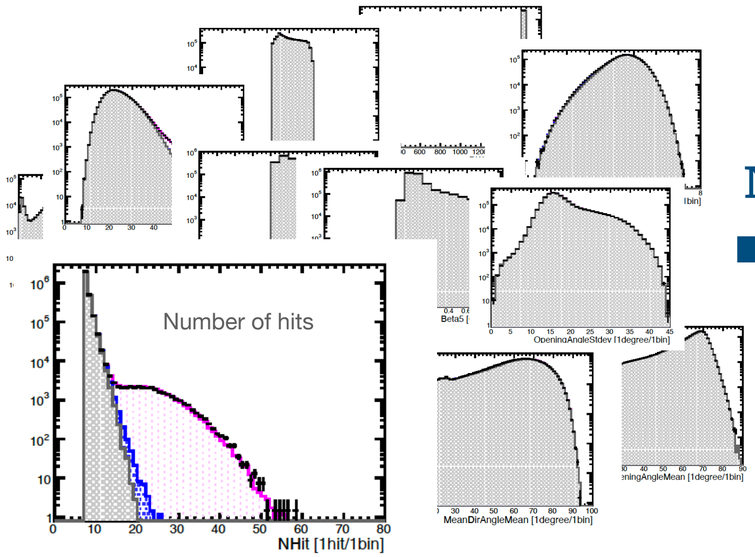
- Many types of backgrounds mimicking this signature.
  - Atmospheric neutrinos (NCQE, CC)
  - Radioactive isotopes produced by atmospheric muons
  - Solar neutrinos
  - Reactor neutrinos



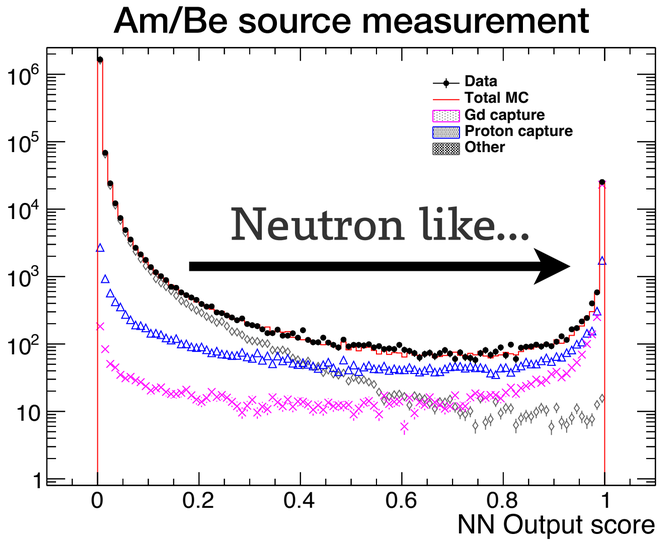
from M. Harada

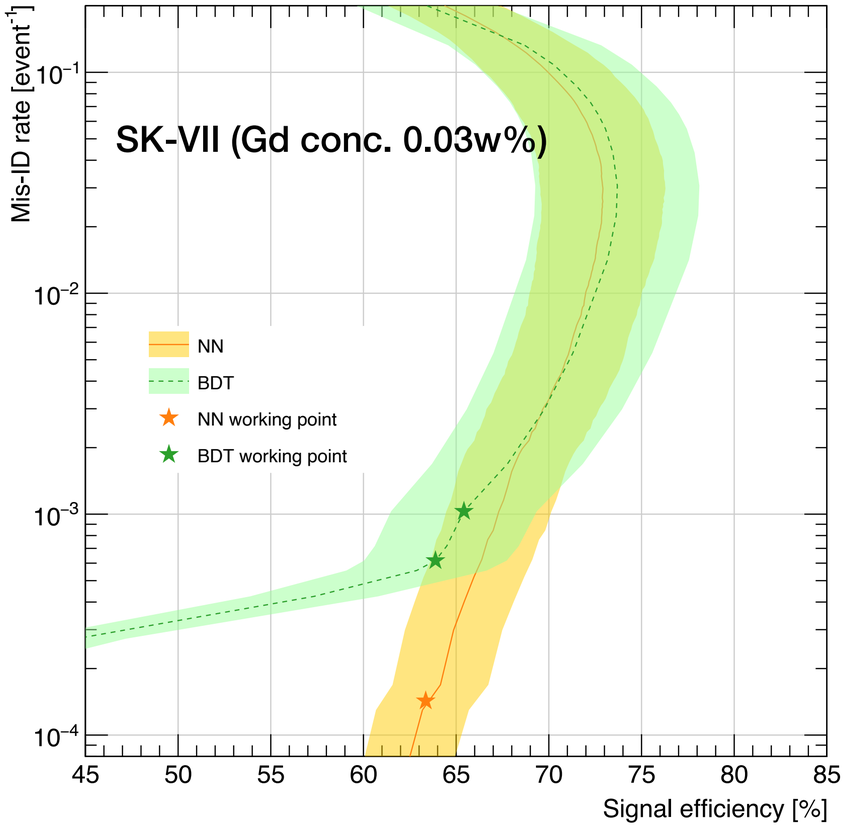
Neutron Tagging

- 12 (NN) or 22 (BDT) variables about spacial and temporal hit patterns are employed.
- **~60%** signal efficiency for the non-neutron rejection at **O(10^{-4})** is achieved (depending on working point).
- Am/Be neutron source is used to validate the employed method.

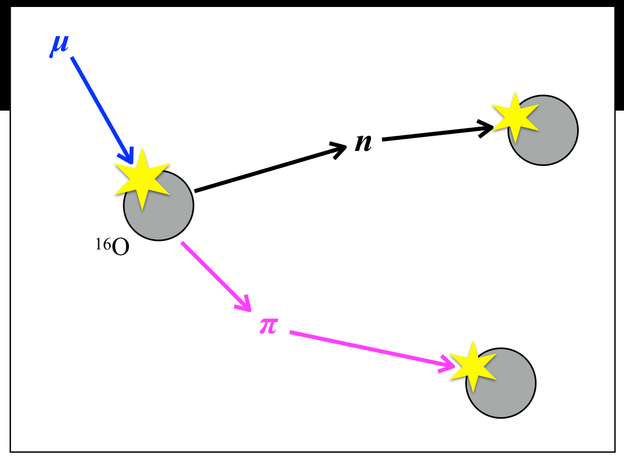


NN

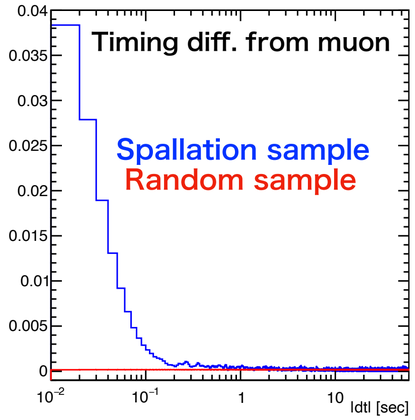


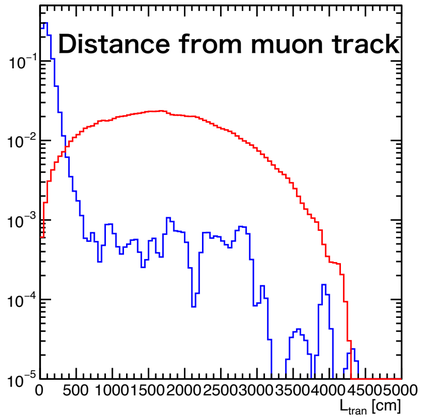


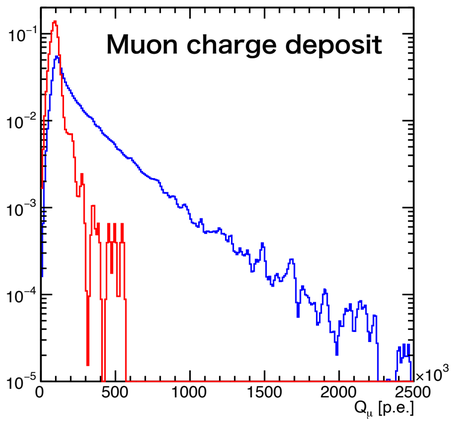
Spallation Reduction (<16 MeV)

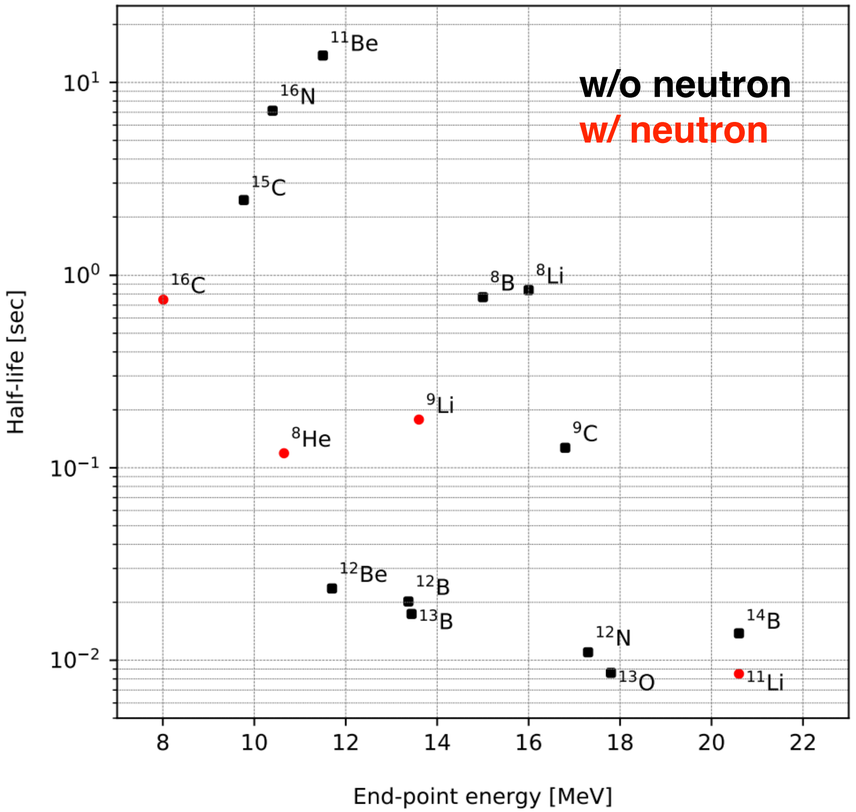


- Radioactive isotopes created by atmospheric muons are troublesome.
- A dedicated reduction technique based on spacial and temporal correlations between signal candidates and muons is used.
- **~50%** signal efficiency for the spallation reduction to **~1%** is achieved.
- Isotopes that decay with a neutron (**^{9}Li**) are more difficult to reduce.





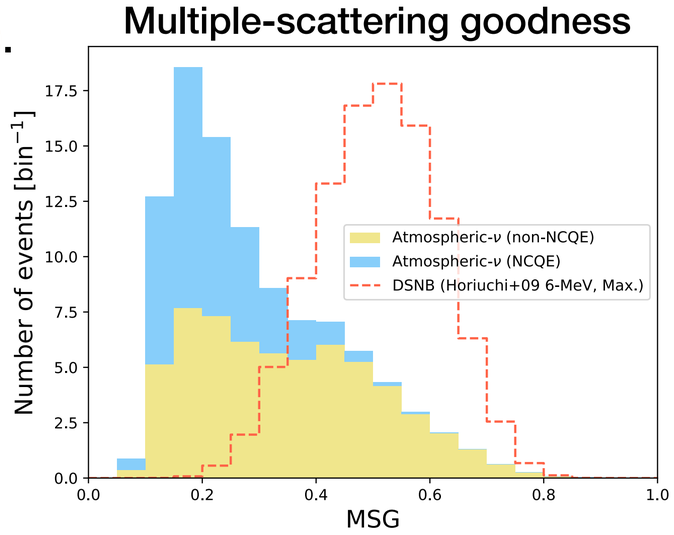


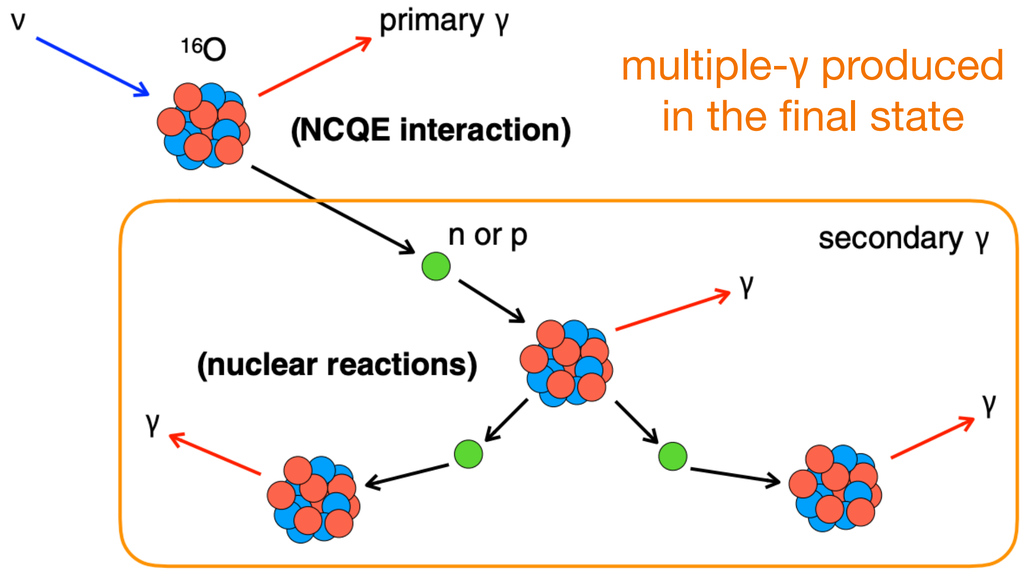


Atmospheric Neutrinos: NCQE (<16 MeV)

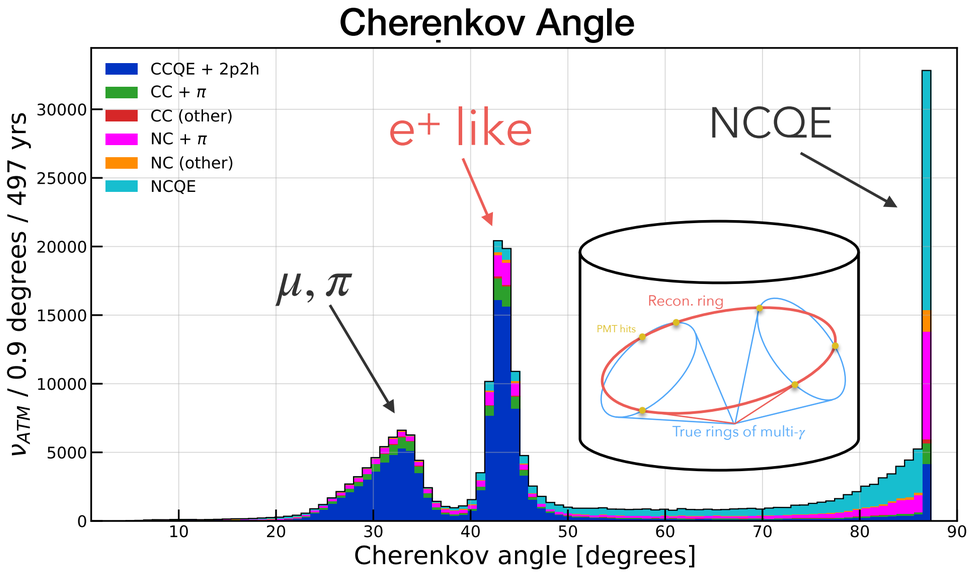
- Neutral-current quasielastic interactions can involve nuclear deexcitation γ-ray(s).
- Multiple gamma-rays produce different PMT hit patterns than single electrons.
  - Cherenkov angle
  - Multiple scattering goodness (MSG)
- Absolute intensity is estimated by referring to the T2K measurement result.

K. Abe et al. (T2K Collaboration), PRD 100, 112009 (2019)



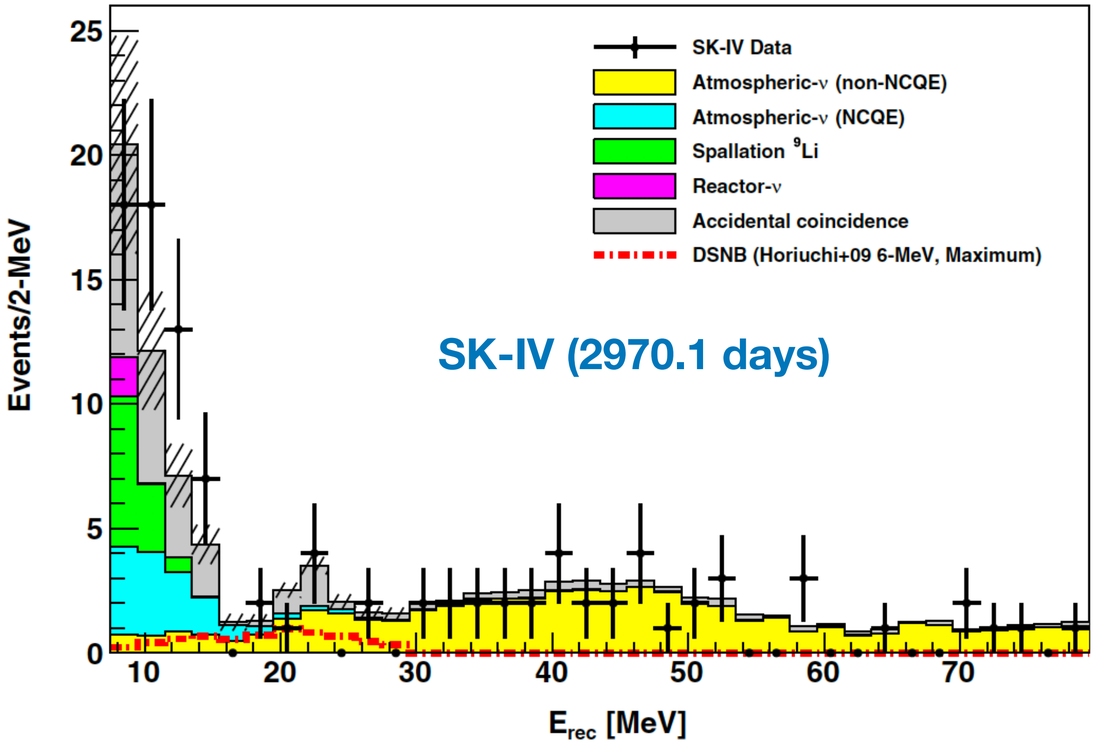


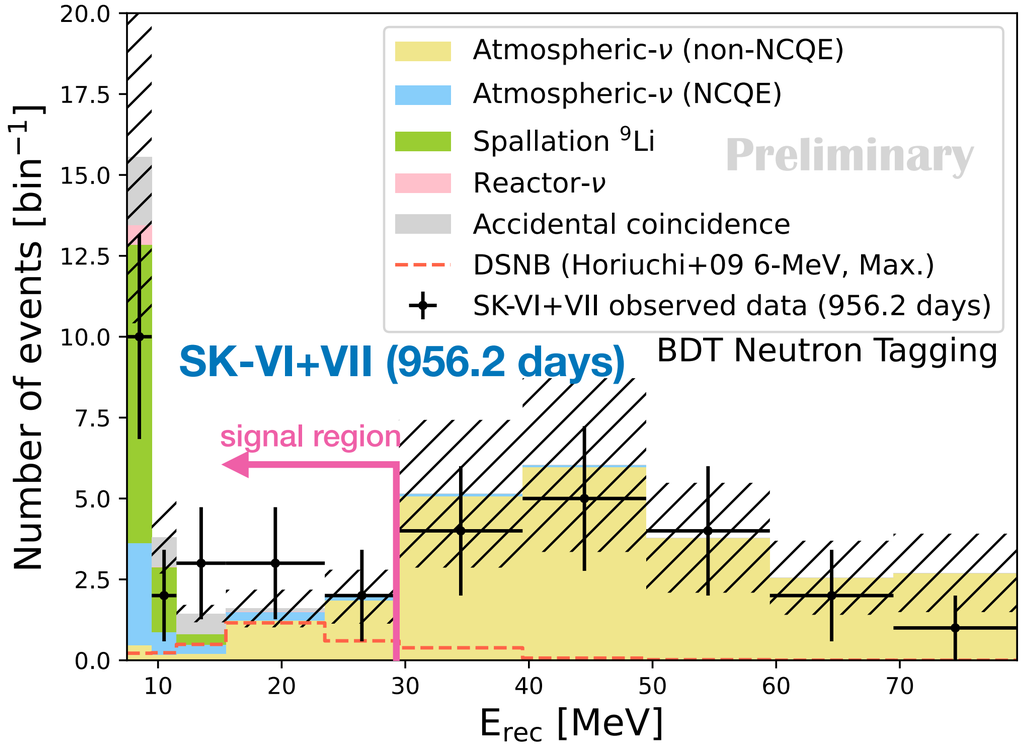
multiple-γ produced in the final state



Energy Spectrum of Selected Events

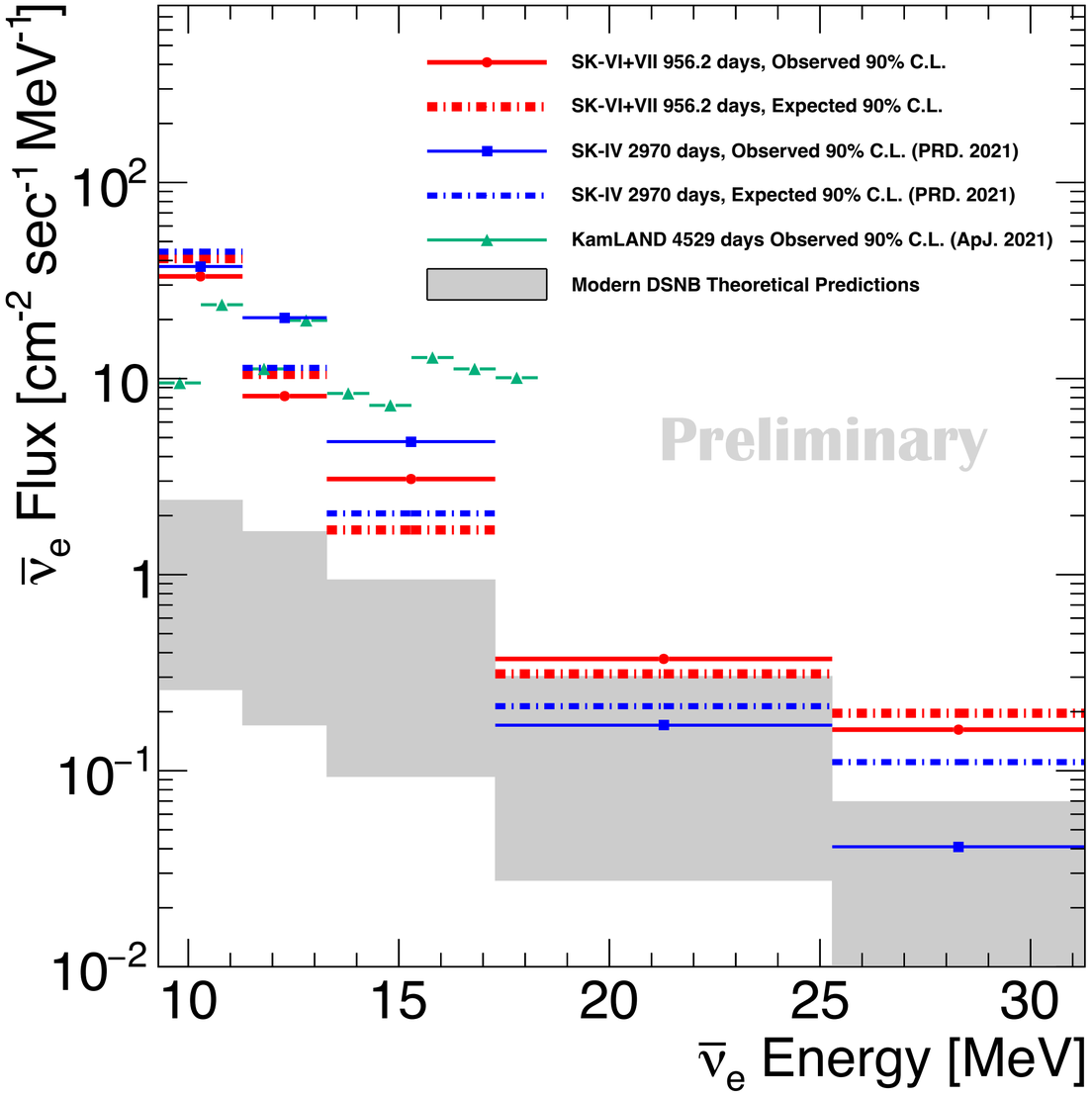
- SK-VI+VII search improves neutron tagging efficiency (up to ×2) and NCQE rejection (mainly by MSG).
- No significant excess was observed over the search energy range in SK-IV (smallest p-value = 0.05) nor SK-VI+VII (smallest p-value = 0.04).





Upper Limits on Extraterrestrial Electron Antineutrinos

- Super-K sensitivity reaches the theoretical band.
- The new upper limit by SK-VI+VII is better than previous limits by SK-IV and KamLAND at low energies.
- The best limit is still given by SK-IV at higher energies due to its larger statistics.



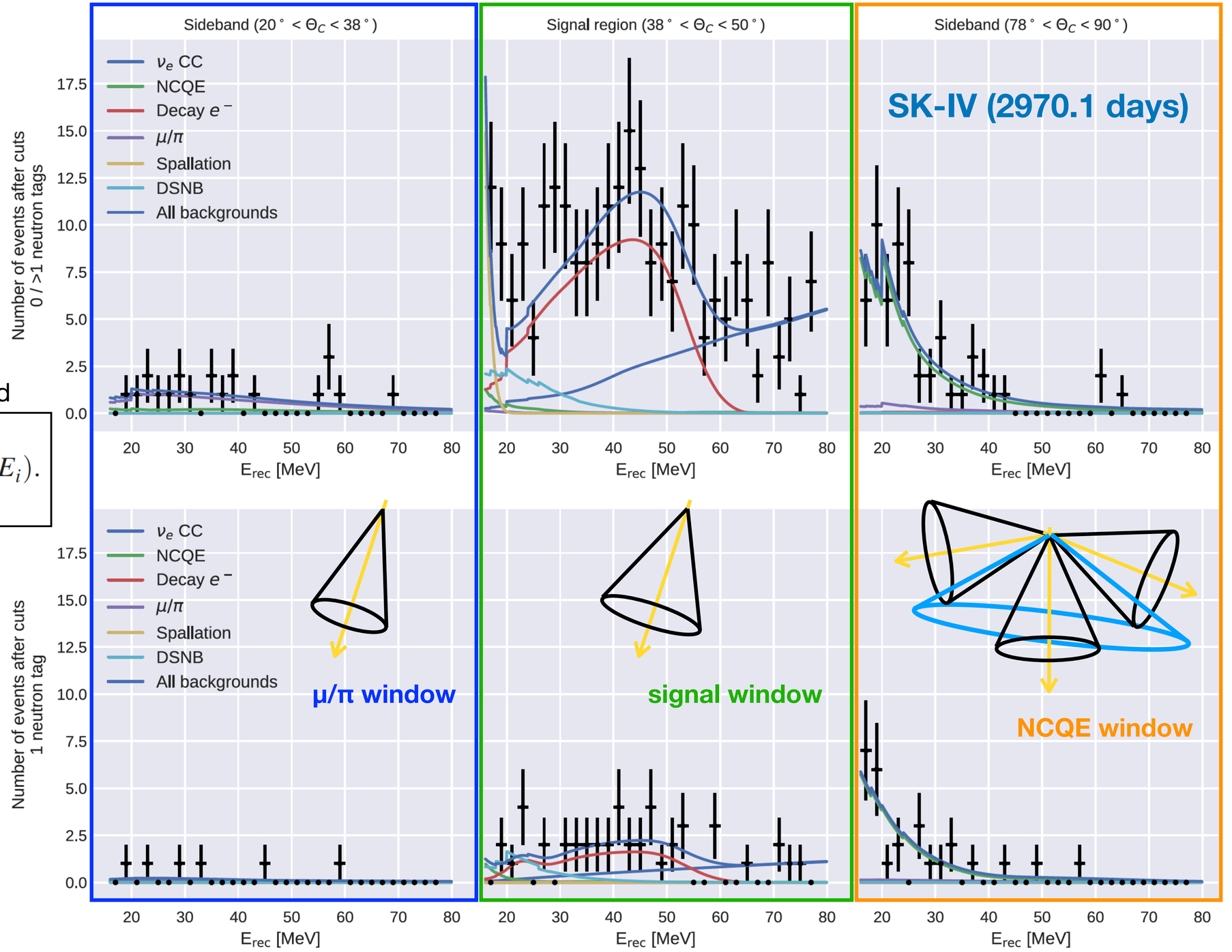
Spectral Fit

$N_n \neq 1$

Extended unbinned maximum likelihood

$$\mathcal{L}(\{N_j\}) = e^{-\sum_{j=0}^{5} N_j} \prod_{i=1}^{N_{\text{events}}} \sum_{j=0}^{5} N_j \text{PDF}_j^{(r)}(E_i).$$

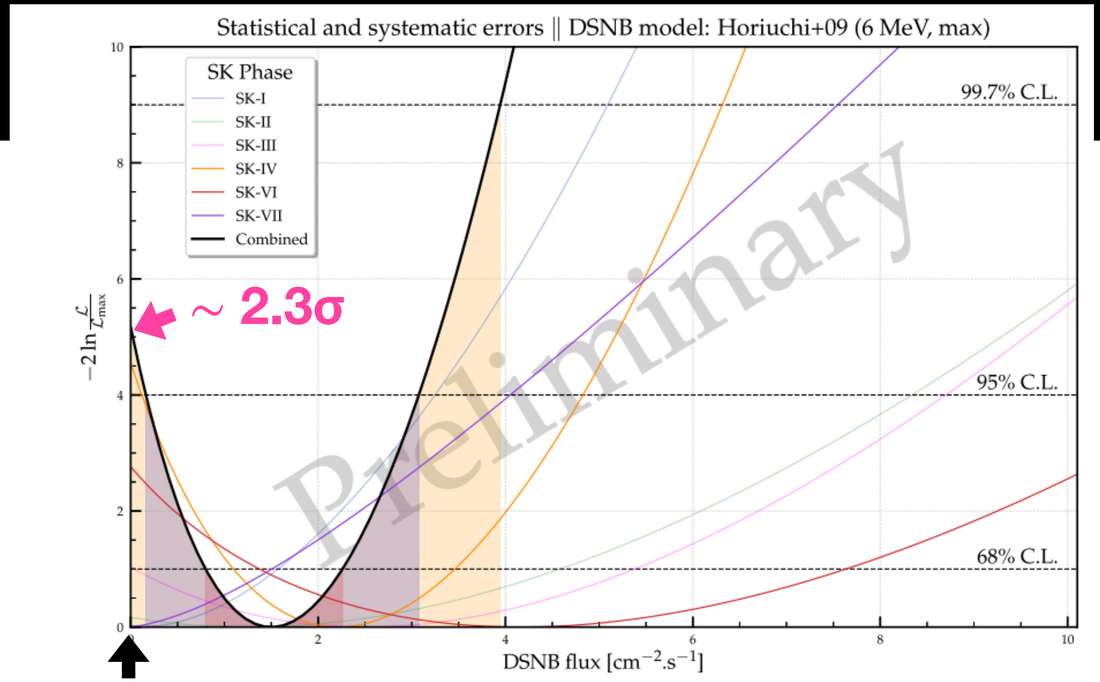
$N_n = 1$



Fitting Result

- Best-fit DSNB ν_e flux is **~1.4 cm^{-2} sec^{-1}**.
- Null DSNB hypothesis is disfavored in both pure-water and Gd-water phases and is rejected at **2.3σ** from the combined analysis.

We might catch the first hint of DSNB??



Zero-DSNB assumption

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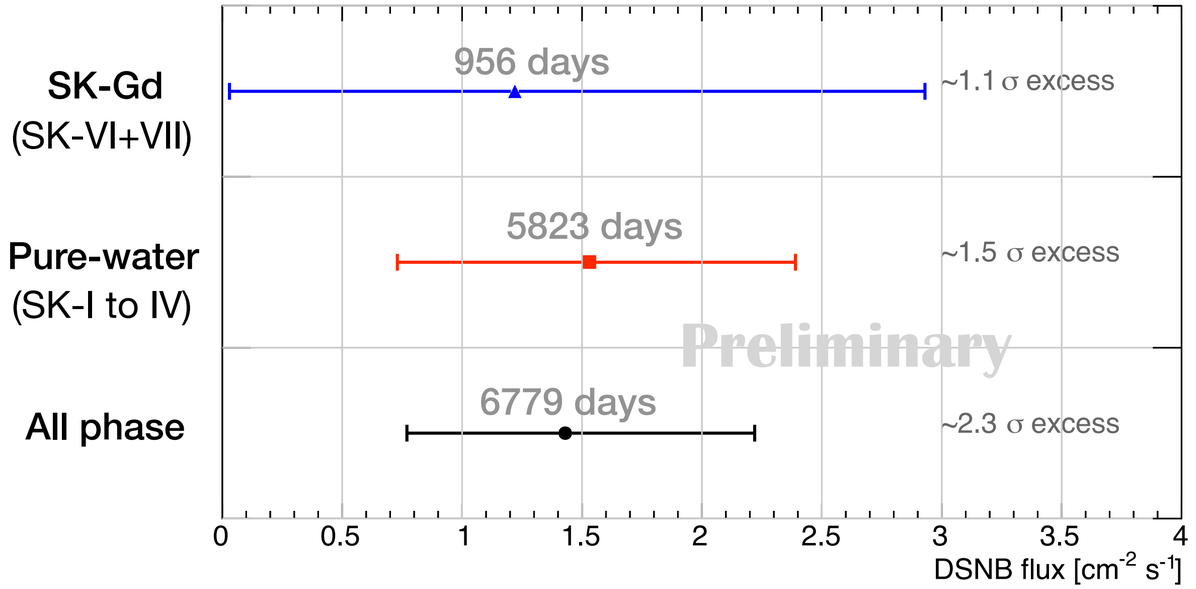
NEWS | 09 July 2024

Huge neutrino detector sees first hints of particles from exploding stars

Japan's Super-Kamiokande observatory could be seeing evidence of neutrinos from supernovae across cosmic history.



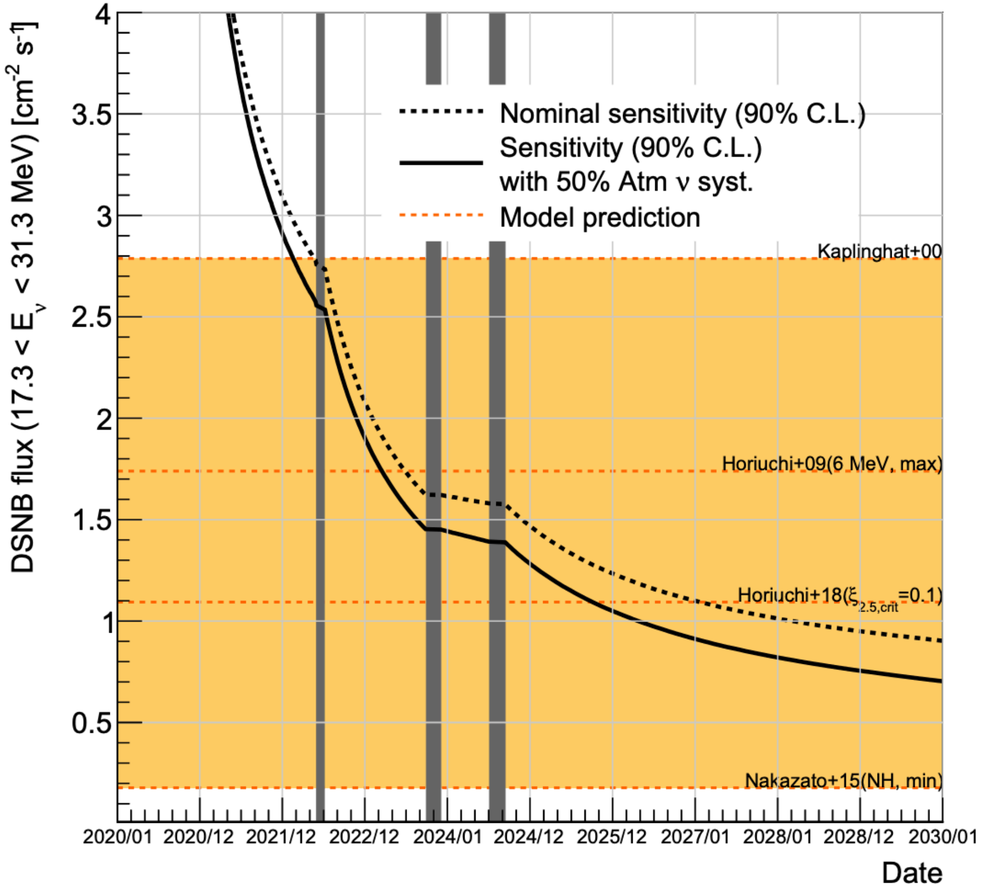
Future Prospects

We are now actively working towards releasing the new result!

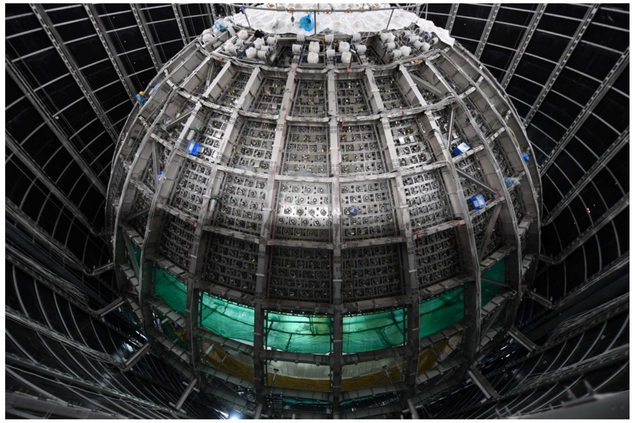
- More statistics for SK-I through the latest SK-VIII.
- More precise estimation of atmospheric neutrino background relying on T2K and Super-K **neutron** measurements.
- Further improved NCQE reduction using **CNN**.
- Better understanding of spallation background.

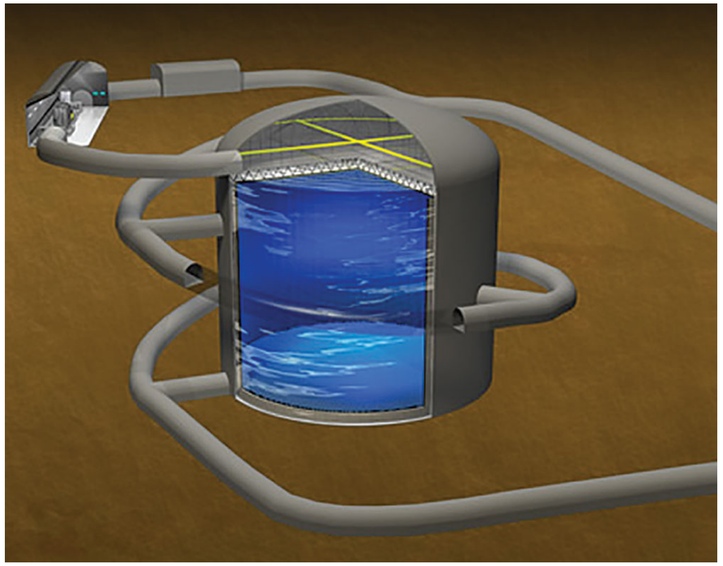
S. Han et al. (SK Collaboration), PRD 112, 012004 (2025)

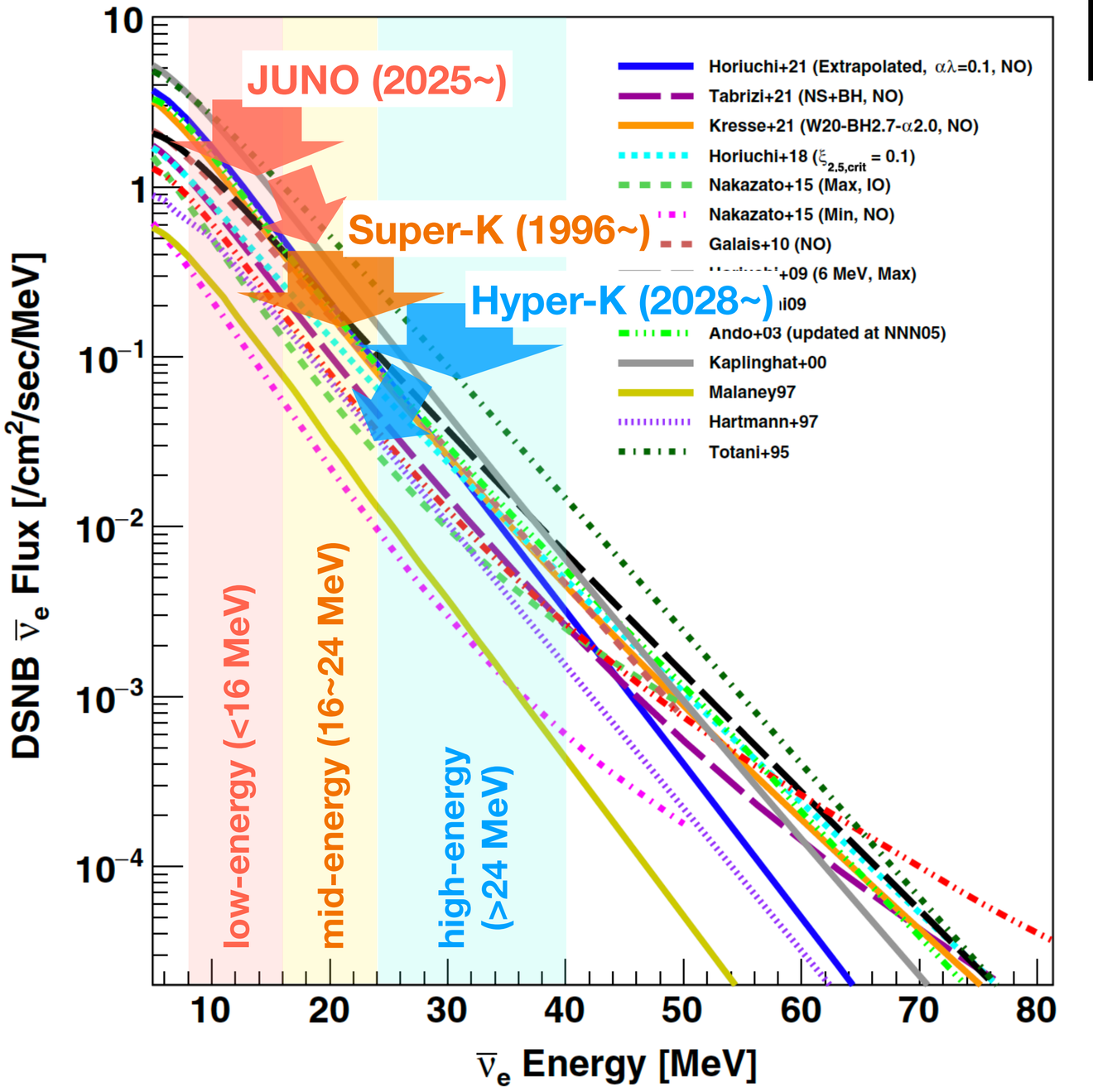
K. Abe et al. (T2K Collaboration), accepted by PRD



and Next Era…



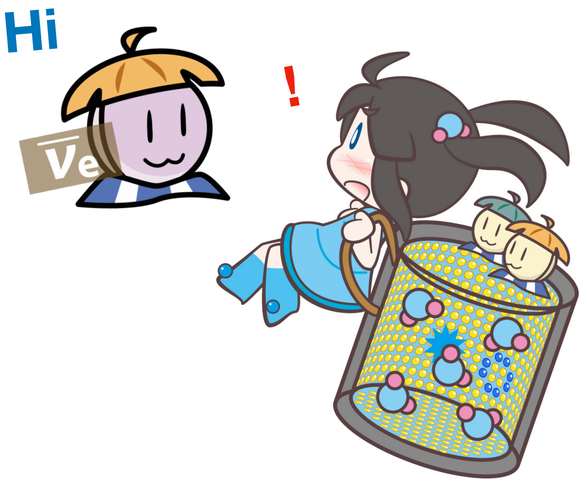



JUNO (2025~)
Super-K (1996~)
Hyper-K (2028~)
low-energy (<16 MeV)
mid-energy (16~24 MeV)
high-energy (>24 MeV)
DSNB $\bar{\nu}_e$ Flux [/cm^2/sec/MeV]
$\bar{\nu}_e$ Energy [MeV]
Horiuchi+21 (Extrapolated, $\alpha\lambda$=0.1, NO)
Tabrizi+21 (NS+BH, NO)
Kresse+21 (W20-BH2.7-α2.0, NO)
Horiuchi+18 ($\xi_{2.5,crit}$ = 0.1)
Nakazato+15 (Max, IO)
Nakazato+15 (Min, NO)
Galais+10 (NO)
+09 (6 MeV, Max)
il09
Ando+03 (updated at NNN05)
Kaplinghat+00
Malaney97
Hartmann+97
Totani+95

Summary

- Super-K has been searching for the flux of neutrinos released from core collapse of massive stars.
- The latest search improves over the previous search about signal capture and background rejection, achieving the world's best sensitivity.
- Null DSNB hypothesis is rejected at 2.3σ from the SK-I to VII combined fit.
- We have many items to improve for the next search using more data from the Gd phase!

DSNB is probably dim, but our future is bright!



Supplements