New limits on the low-energy astrophysical electron antineutrinos at SK-Gd experiment

Andrew Santos[1], Masayuki Harada[2], and Yuki Kanemura[2] for the Super-Kamiokande Collaboration

[1]Laboratoire Leprince-Ringuet, École Polytechnique, France (santos[at]llr.in2p3.fr)

[2]Institute for Cosmic Ray Research, University of Tokyo, Japan (mharada, kanemura[at]km.icrr.u-tokyo.ac.jp)

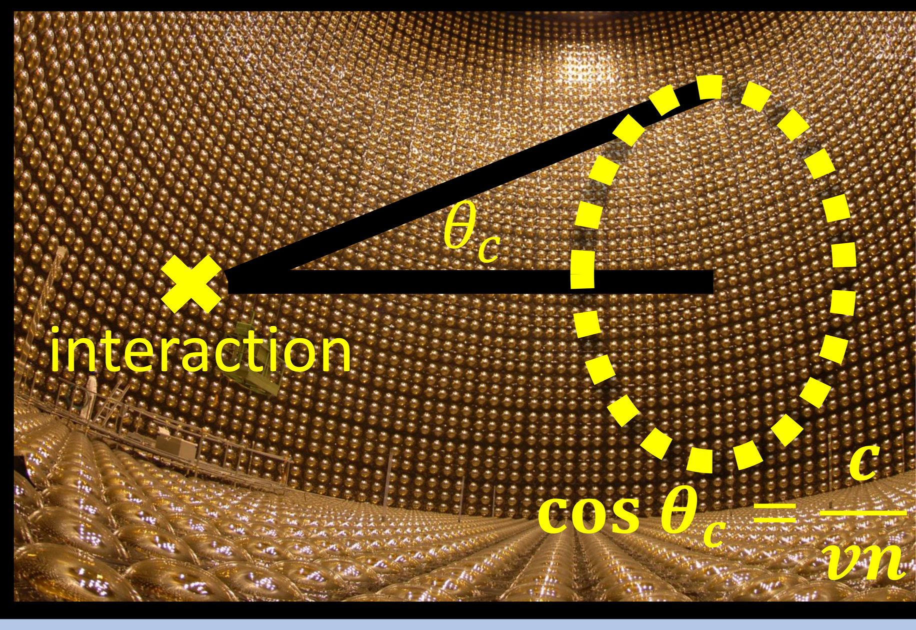
Neutrinos from every core-collapse supernova in the universe's history form the Diffuse Supernova Neutrino Background (DSNB).

(CCSN rate) × (ν flux from SN) × (expansion)

$$\frac{d\Phi_\alpha}{dE} = \int\int R_{SN}(z,M)\left[\frac{dF_\alpha(E(1+z),M)}{dM}\right]\left|c\frac{dt}{dz}\right| dz dM$$

- The three main parts are the supernova rate, the neutrino flux per supernova, and the cosmological expansion of the universe.
- The star formation history of the universe directly impacts the CCSN rate, and the fraction of CCSN forming black holes impacts the shape of the DSNB spectrum.

Super-Kamiokande is a 50-kton water Cherenkov experiment in Japan, loading Gd in 2020 and 2022 (SK-Gd) toward a DSNB discovery through inverse β-decay.



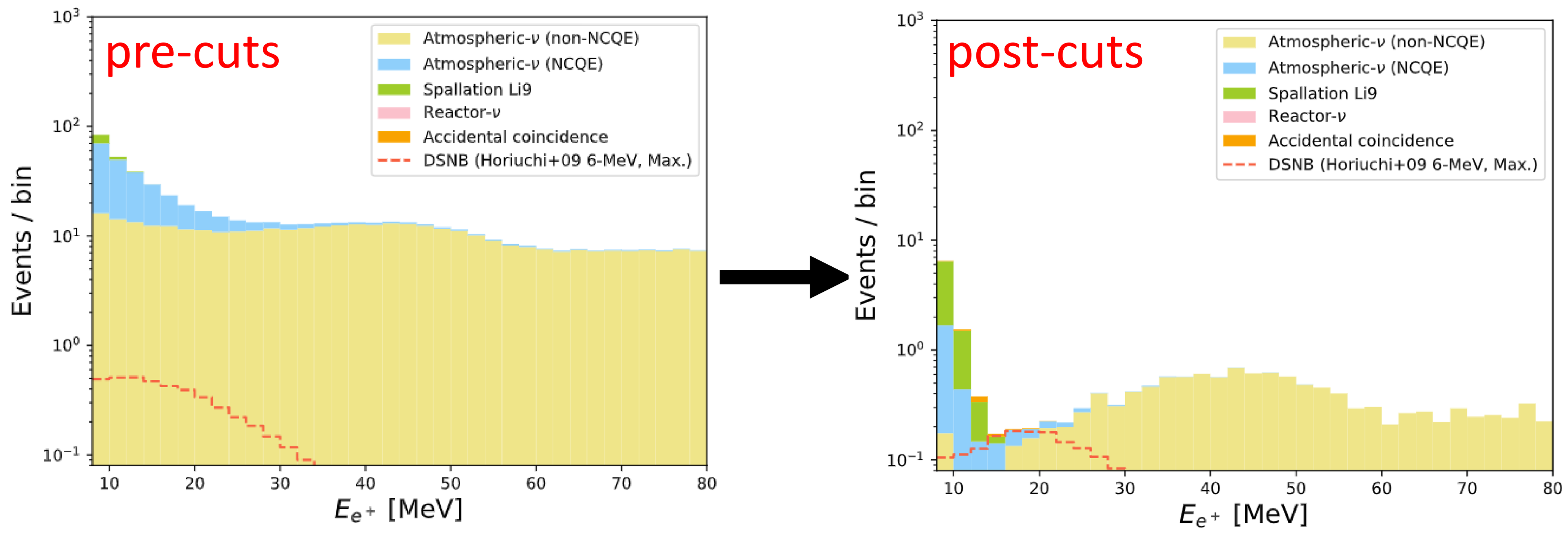
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

prompt signal (e^+) — delayed capture (n)

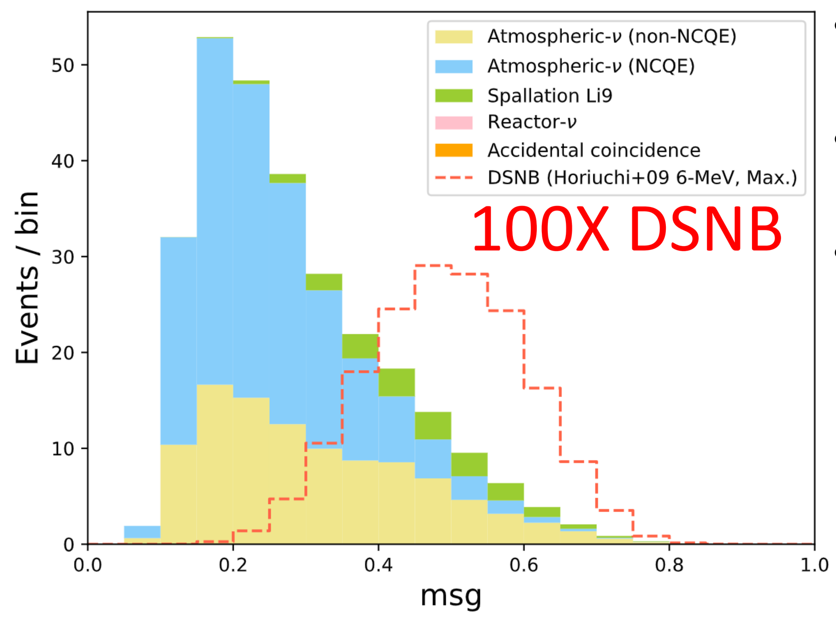
- With an analysis threshold at 8 MeV, the prompt positrons create Cherenkov radiation ($\theta_c \approx 42°$).
- Gammas released from neutron captures on either H or Gd are observed $\mathcal{O}(10\text{-}100)$ µs later.

Four main reduction steps are dedicated to select final DSNB candidate events.

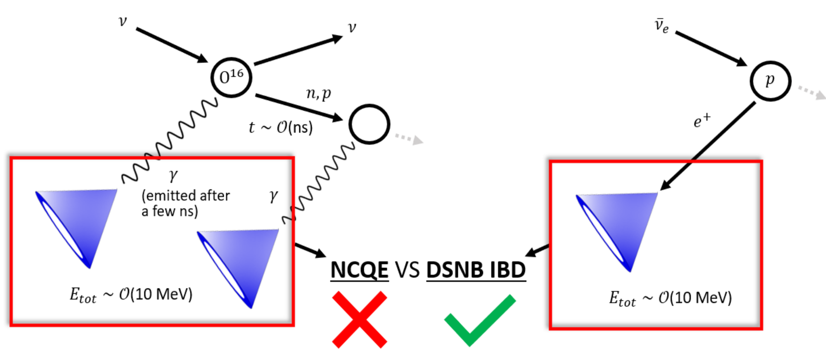
- **1st Reduction**: To reduce radioactive backgrounds (near detector walls) and keep well-reconstructed events (in fiducial volume).
- **2nd Reduction**: To remove events associated (in time and location) with cosmic ray muons generating spallation backgrounds.
- **3rd Reduction**: To target atmospheric neutrino backgrounds based on event topology, such as Cherenkov opening angle.
- **4th Reduction**: To select events having uniquely one neutron capture.



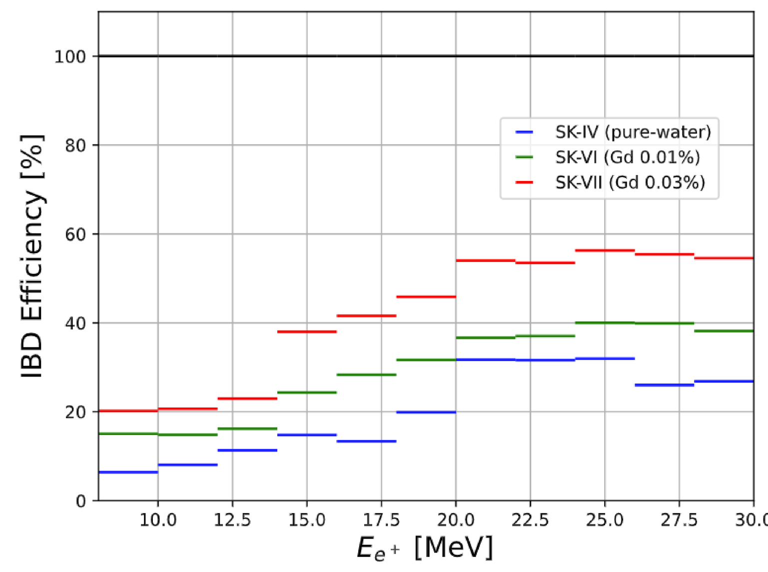
A new cut removes multi-cone backgrounds to the DSNB.



- Many atmospheric neutrino backgrounds are multi-cone events, whereas DSNB IBD is single-cone.
- A simple cut is applied using the "multiple scattering goodness" (MSG) variable from Super-K solar ν analyses.
- The closer MSG is to 1, the more likely this is single-cone.

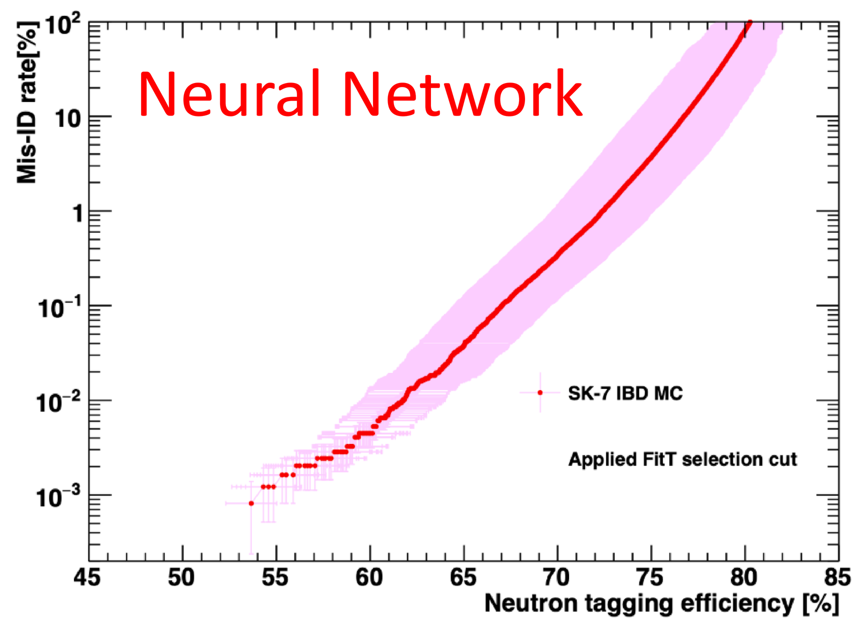


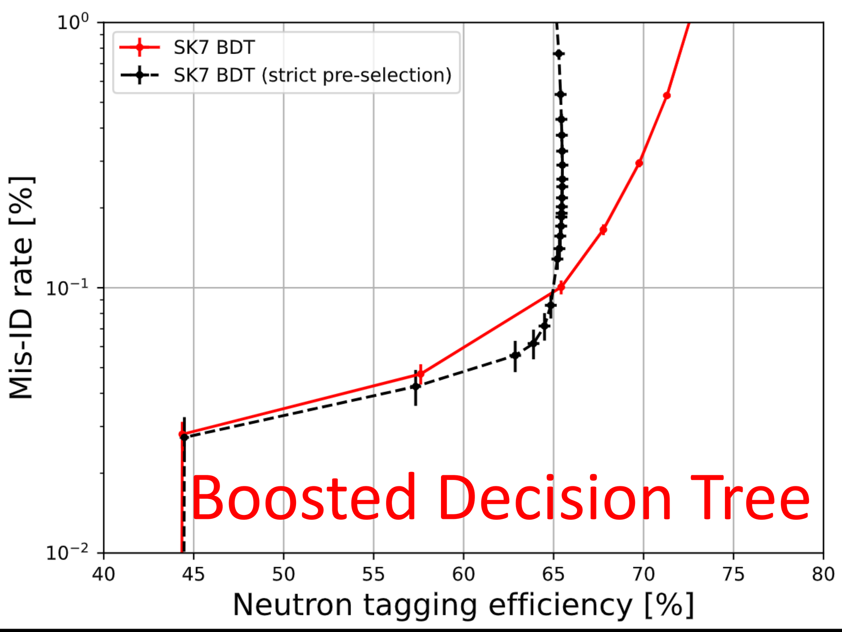
The addition of gadolinium into the water increases IBD signal efficiency by enhancing the neutron capture signal.



- Neutron captures on H in pure water emit one gamma at 2 MeV.
- For those on Gd, there are multiple gammas emitted with a total energy around 8 MeV.
- Captures in Gd-doped water happen faster with a capture time of about 60 µs in SK-VII (0.03% Gd).

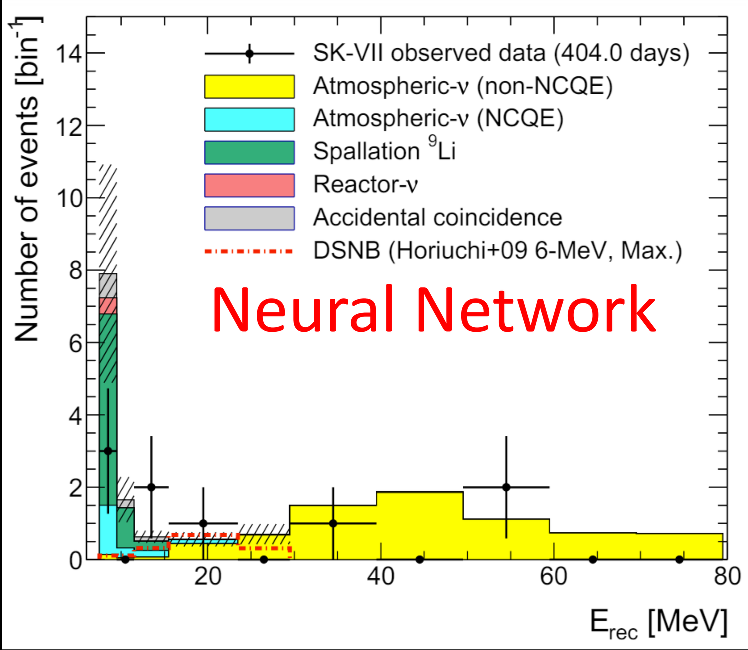
Two separate machine learning algorithms were used to identify neutron captures.

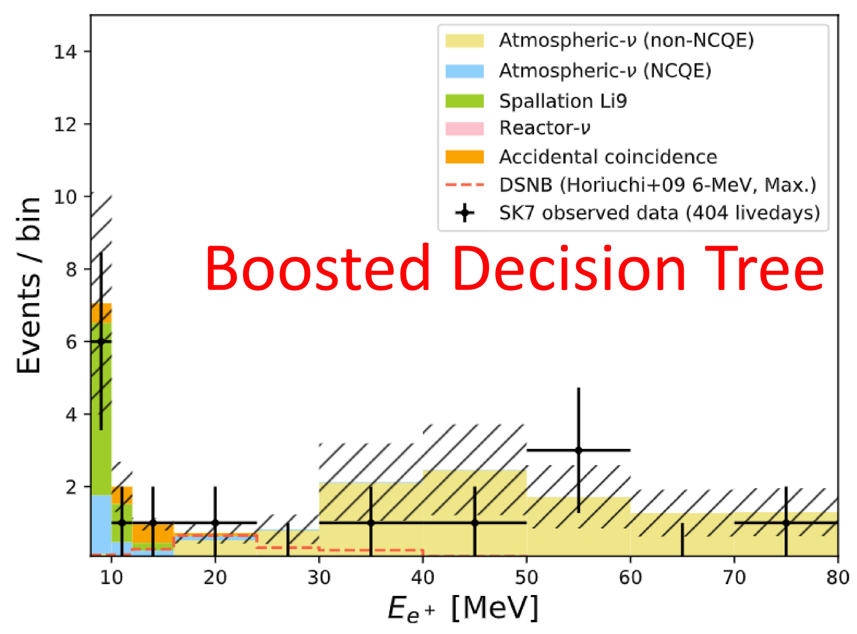




- The Neural Network (NN) was trained on 7 keV neutrons in a Monte Carlo simulation, and the Boosted Decision Tree (BDT) was trained on IBD MC simulation.
- Both the NN and BDT can discriminate between IBD and atmospheric-ν events due to differences in event topology and neutron time-of-flight information.
- The NN has many parameters related to the angular correlations between PMT hits.
- The BDT has many parameters related to overall PMT hit cluster information.
- Both the NN and BDT algorithms achieve a sub-0.1% mis-ID rate with more than 60% signal efficiency in SK-VII.
- In the SK-IV analysis, the BDT was used to look for neutron captures in pure water.
- In SK-Gd, the analysis was performed in parallel with the two techniques.

SK-VII results: No significant excess observed above background predictions.

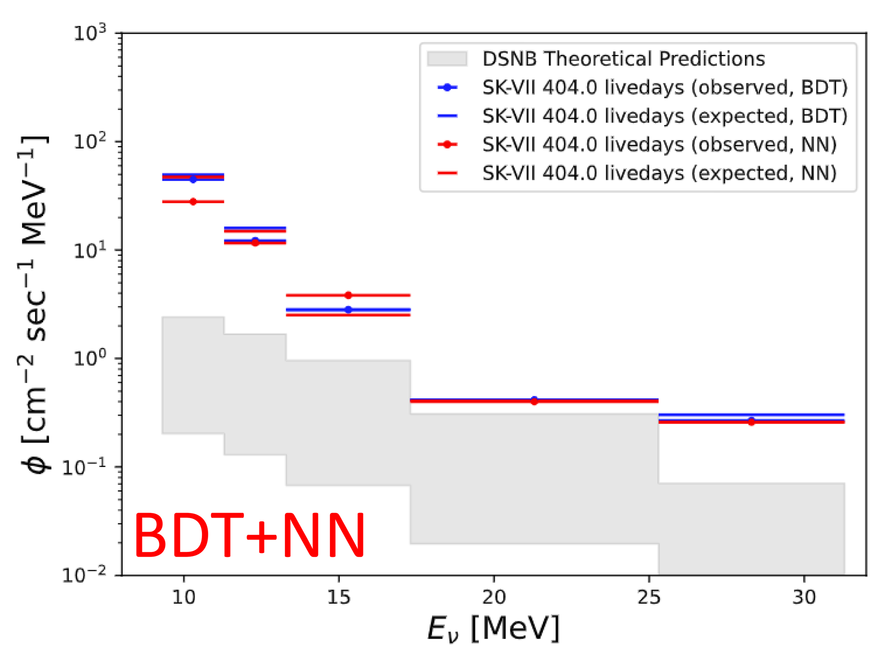




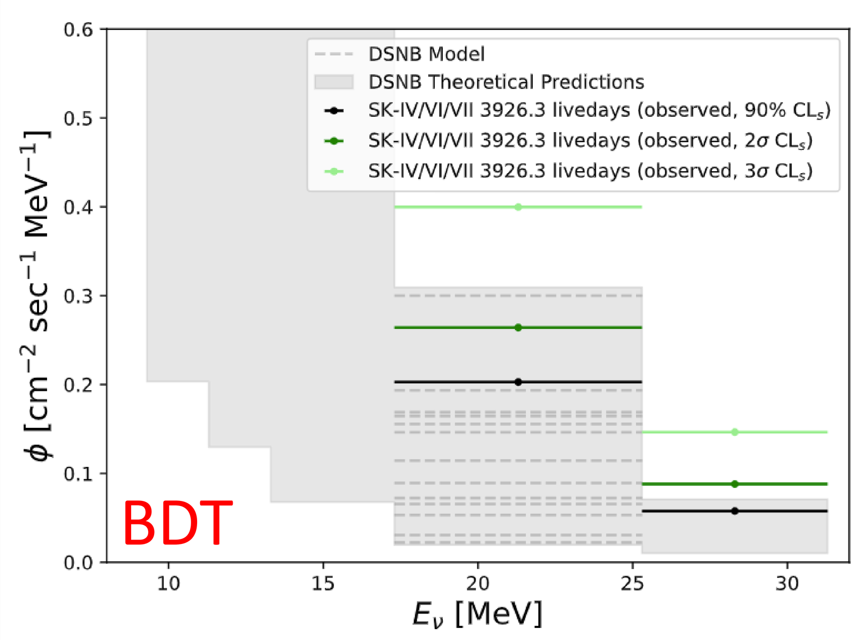
- A total of 404.0 livedays of SK-VII were analyzed.
- Background predictions with associated systematic uncertainties are shown along with observed data from the two neutron tagging approaches in SK-VII.
- Neither final sample observed a significant excess above background predictions, and the smallest p-value was 0.13 (SK-VII).
- The complete dataset for the previous SK-VI period includes 552.2 livedays, which leads to a combined sample of nearly 1000 livedays of the SK-Gd period.
- Combining both phases in the SK-Gd era results in indications of an observed excess over backgrounds with smallest p-value 0.04 (SK-VI/VII).

SK-VII results: New upper limits were set.

- Both the expected (bar) and observed (bar with point) upper limits are shown for SK-VII.
- The NN and BDT approaches had almost exactly the same expected sensitivity.
- Observed limits differ at low energies but are highly similar where we expect the highest sensitivity to the DSNB.
- With the SK-VII phase alone, we already set upper limits quickly approaching many DSNB theory predictions.



Combining SK-IV/Gd phases sets tightest upper limits to date.



- Observed upper limits for BDT samples for combined SK-IV (pure water) and SK-Gd were calculated.
- Individual DSNB theory predictions are shown in gray, dashed lines.
- Combining SK phases demonstrates world's tightest limits on DSNB.