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

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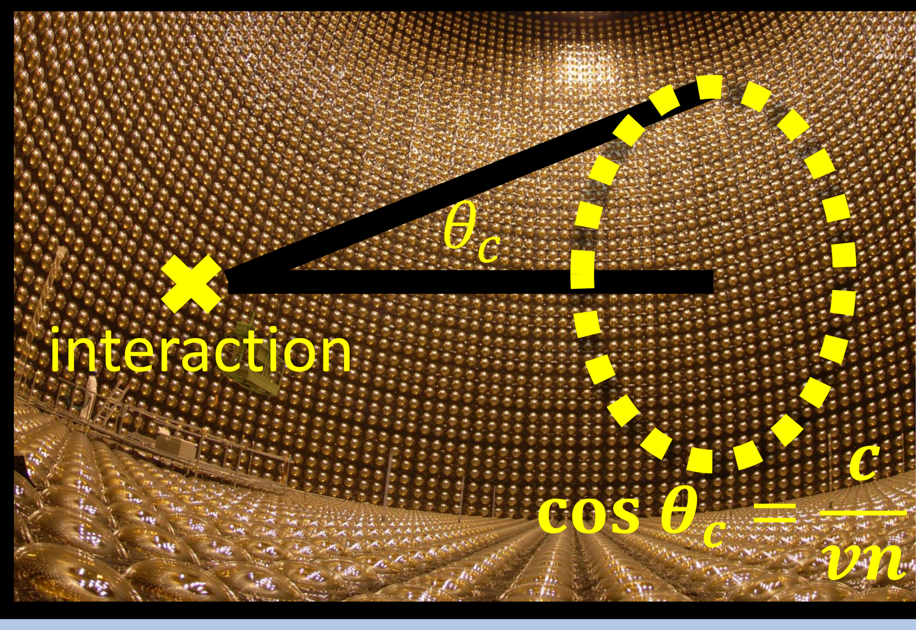
## Neutrinos from every core-collapse supernova in the universe's history form the Diffuse Supernova Neutrino Background (DSNB).

(CCSN rate) × ($\nu$ 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 neutrino spectrum.

## Super-Kamiokande is a 50-kton water Cherenkov experiment in Japan that could detect the DSNB through inverse $\beta$-decay.



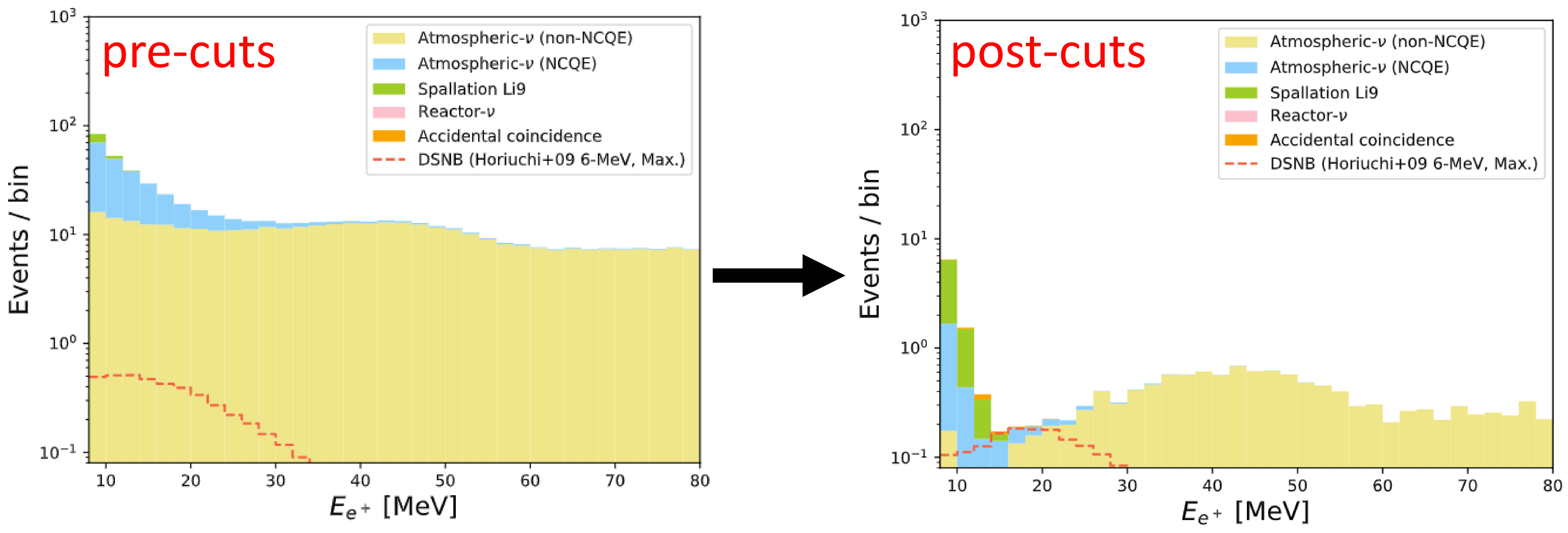

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

prompt signal — delayed capture

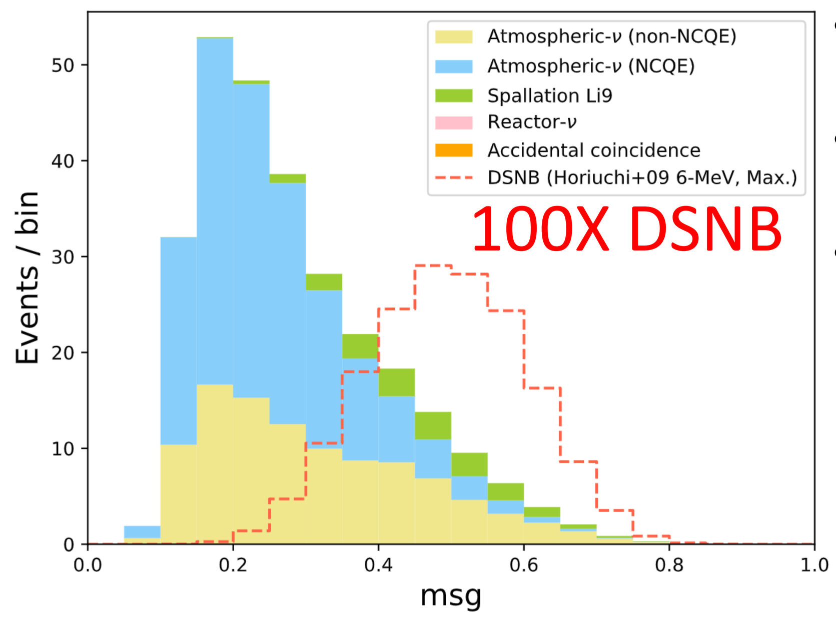
- With an analysis threshold at 8 MeV, the prompt positrons create Cherenkov radiation ($\theta_c \approx 42°$).
- Gammas released from neutron captures on either H or Gd are observed $\mathcal{O}(10\text{-}100)$ μs later.

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

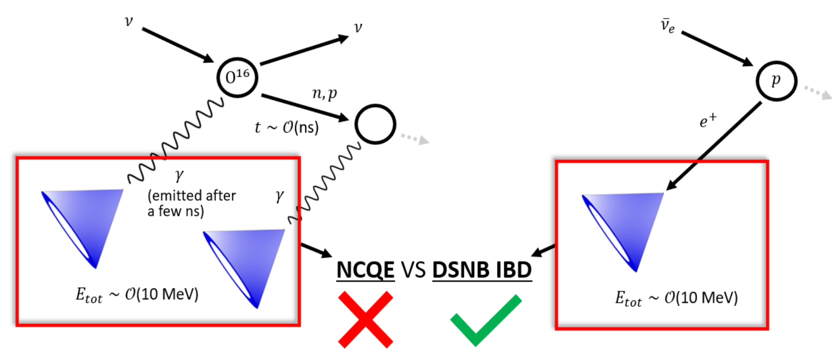
- 1st Reduction: Keep well-reconstructed events, in fiducial volume and far away from walls to reduce radioactive backgrounds.
- 2nd Reduction: Remove events associated (in time and location) with cosmic ray muons generating spallation backgrounds.
- 3rd Reduction: Target atmospheric neutrino backgrounds based on event topology, such as Cherenkov opening angle.
- 4th Reduction: Identify events having uniquely one neutron capture.



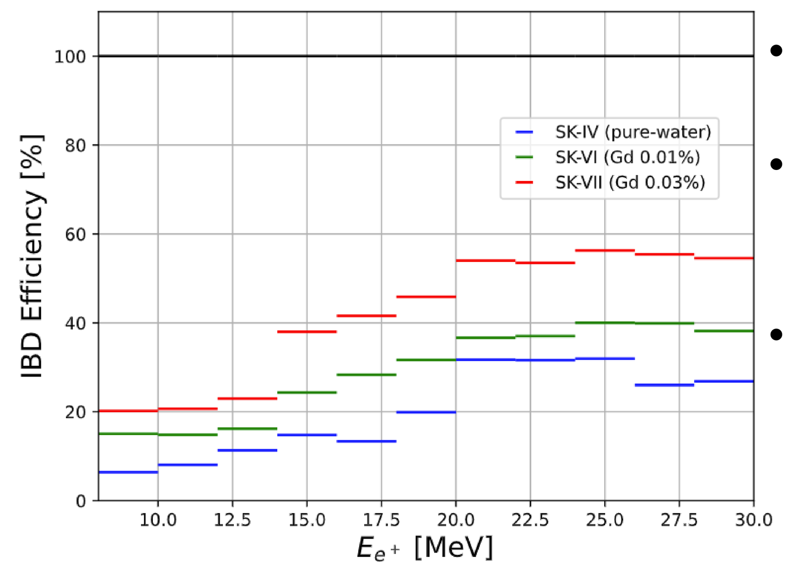

## A new cut removes multi-cone backgrounds to the DSNB.




- 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 $\nu$ analyses.
- The closer MSG is to 1, the more likely this is single-cone.

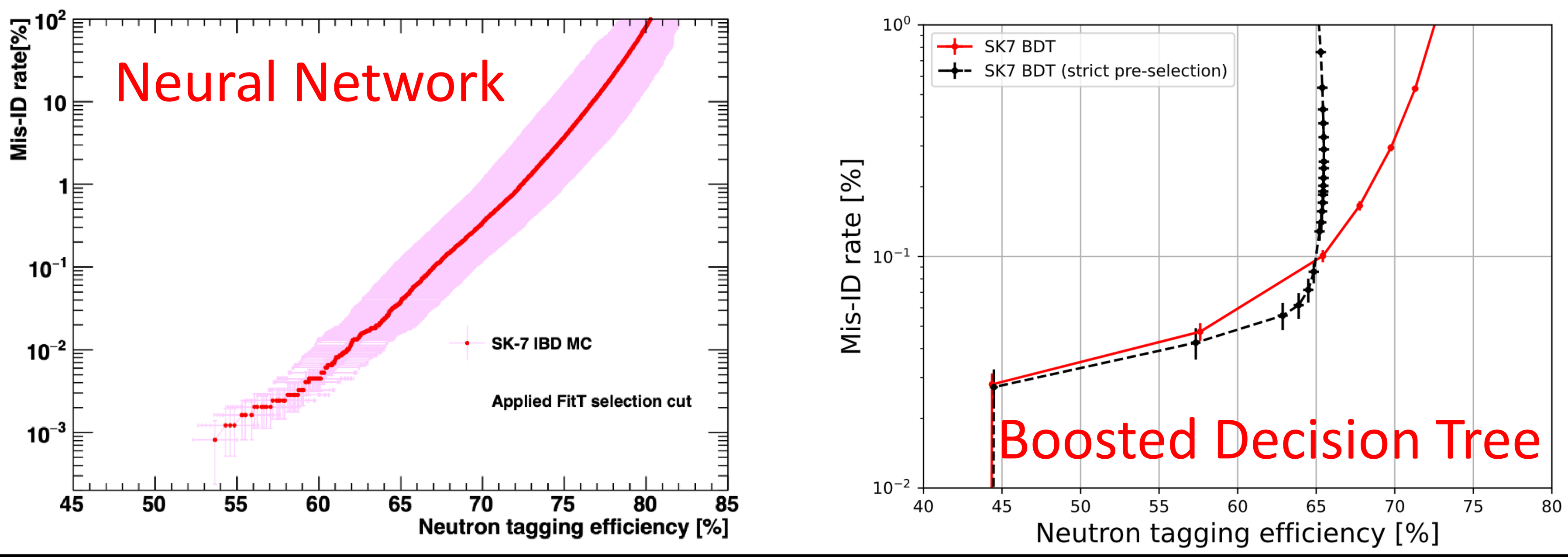



## The addition of gadolinium into the water increases IBD signal efficiency by enhancing the neutron capture signal.



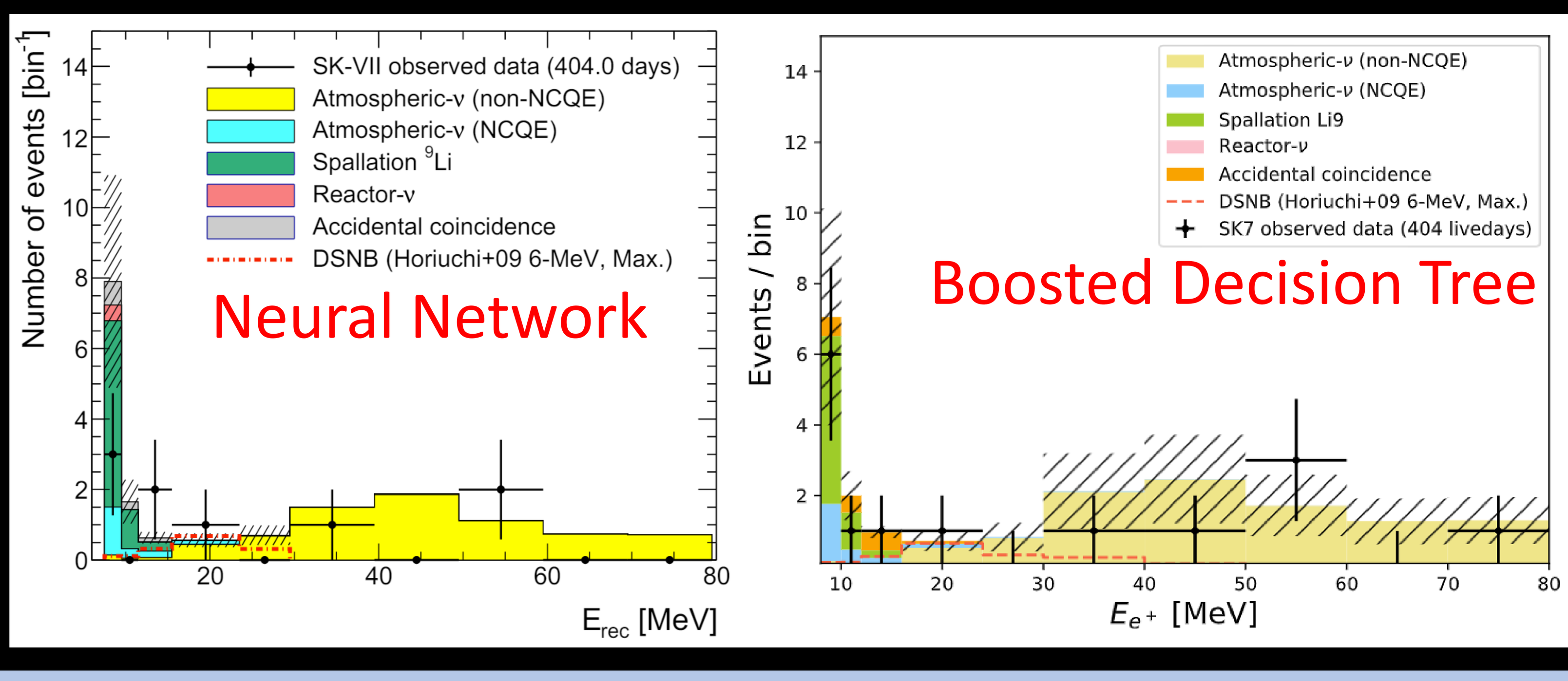

- Neutron captures on H in pure water emit one gamma at 2 MeV.
- For those on Gd, there are multiple gammas emitted with a total energy around 8 MeV.
- Captures in Gd-doped water happen faster with a capture time of about 60 μs in SK-VII (0.03% Gd).

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




- Both the Neural Network (NN) and Boosted Decision Tree (BDT) neutron tagging algorithms were trained on IBD Monte Carlo simulations.
- Both the NN and BDT can discriminate between IBD and atmospheric-$\nu$ events due to differences in event topology and neutron time-of-flight information.
- The NN is more sensitive to the angular correlations between PMT hits.
- The BDT is more sensitive 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 separately with the two techniques.

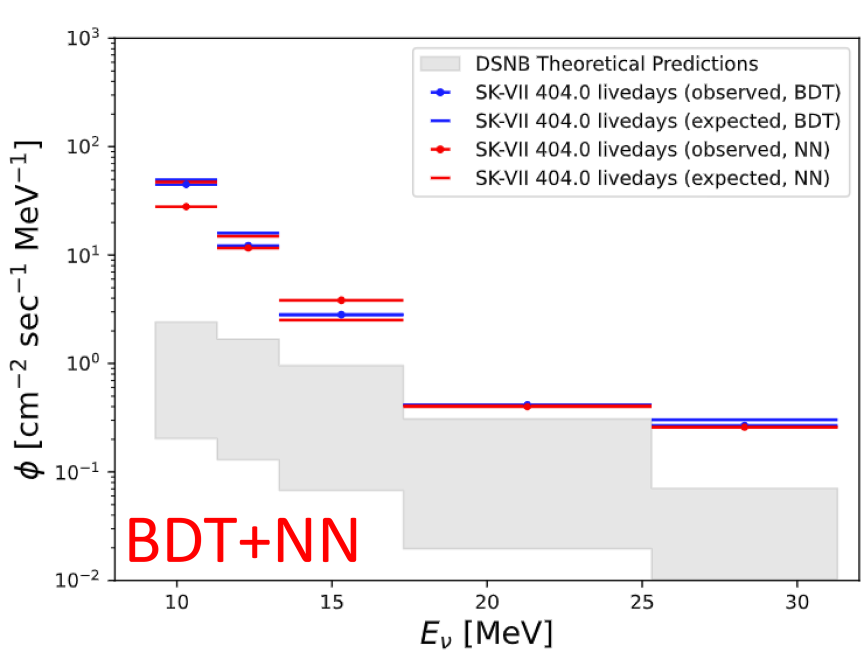
## SK-VII results: No significant excess observed above background predictions.



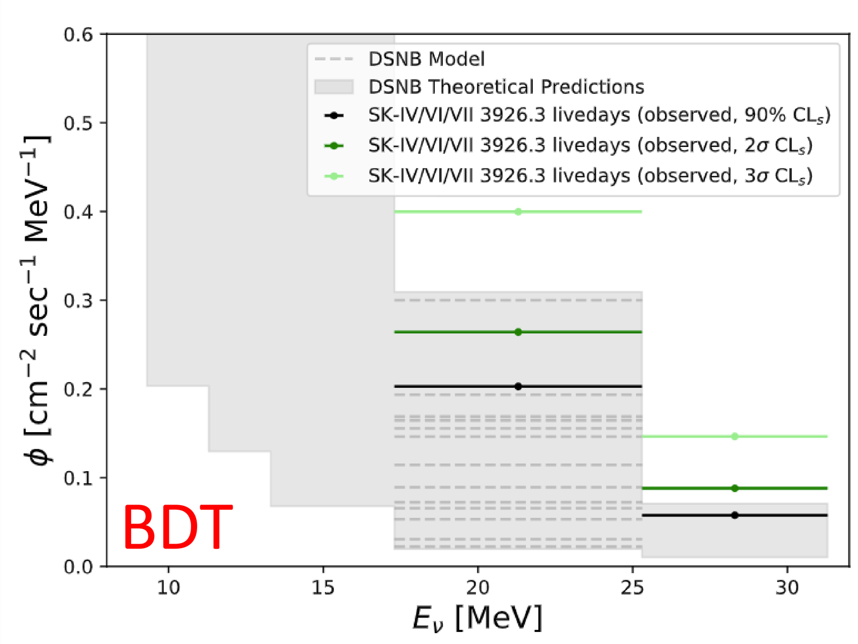

- A total of 404.0 livedays of SK-VII were analyzed.
- Background predictions with associated systematic uncertainties are shown along with observed data from the two neutron tagging approaches in SK-VII.
- Neither final sample observed a significant excess above background predictions, and the smallest 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 no significant excess observed 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.