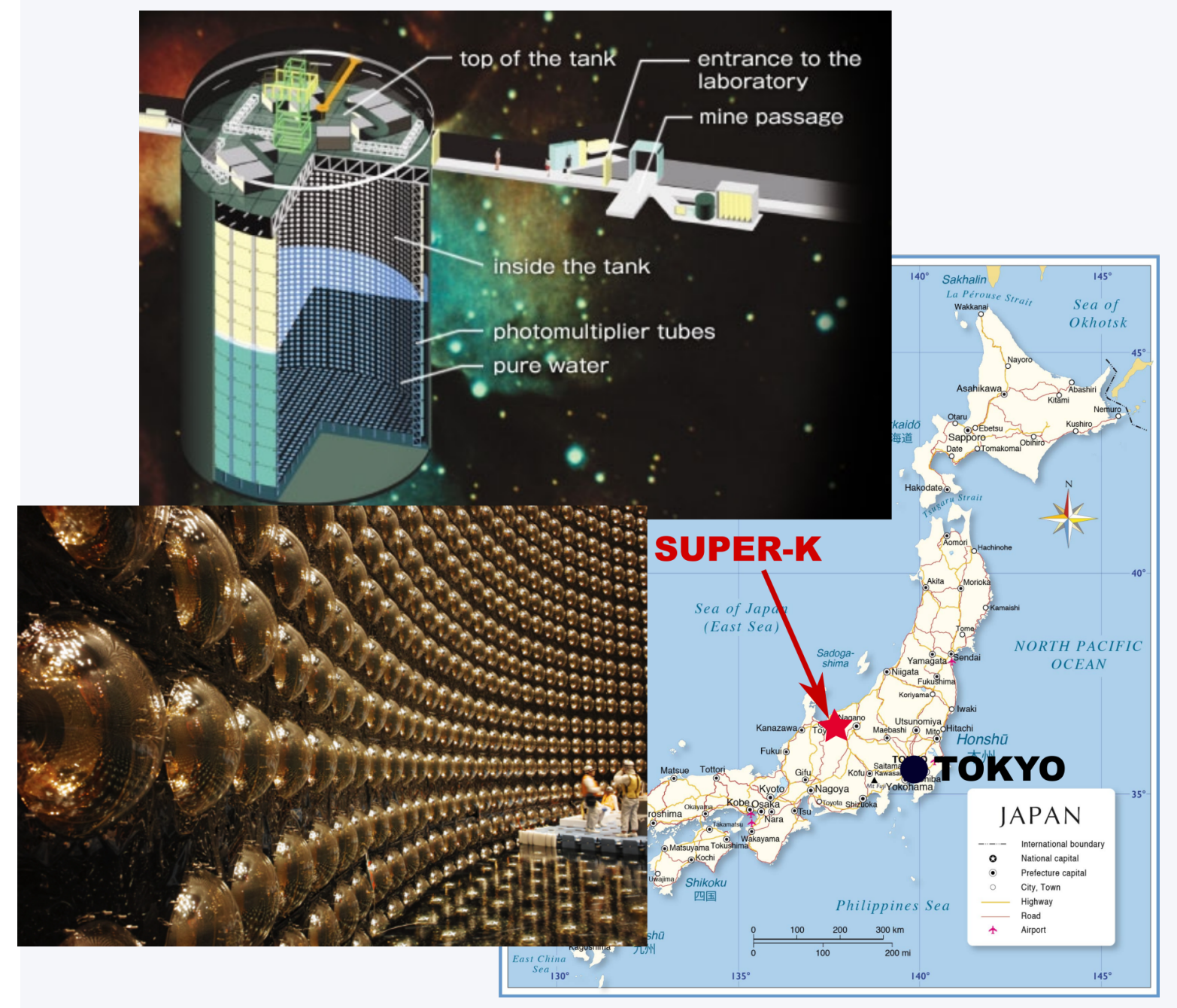
Diffuse Supernova Neutrino Background search at SK with neutron tagging

Alberto Giampaolo [1] and Sonia El Hedri [1]

[1]École Polytechnique, IN2P3-CNRS, Laboratoire Leprince Ringuet

The Super-Kamiokande Detector

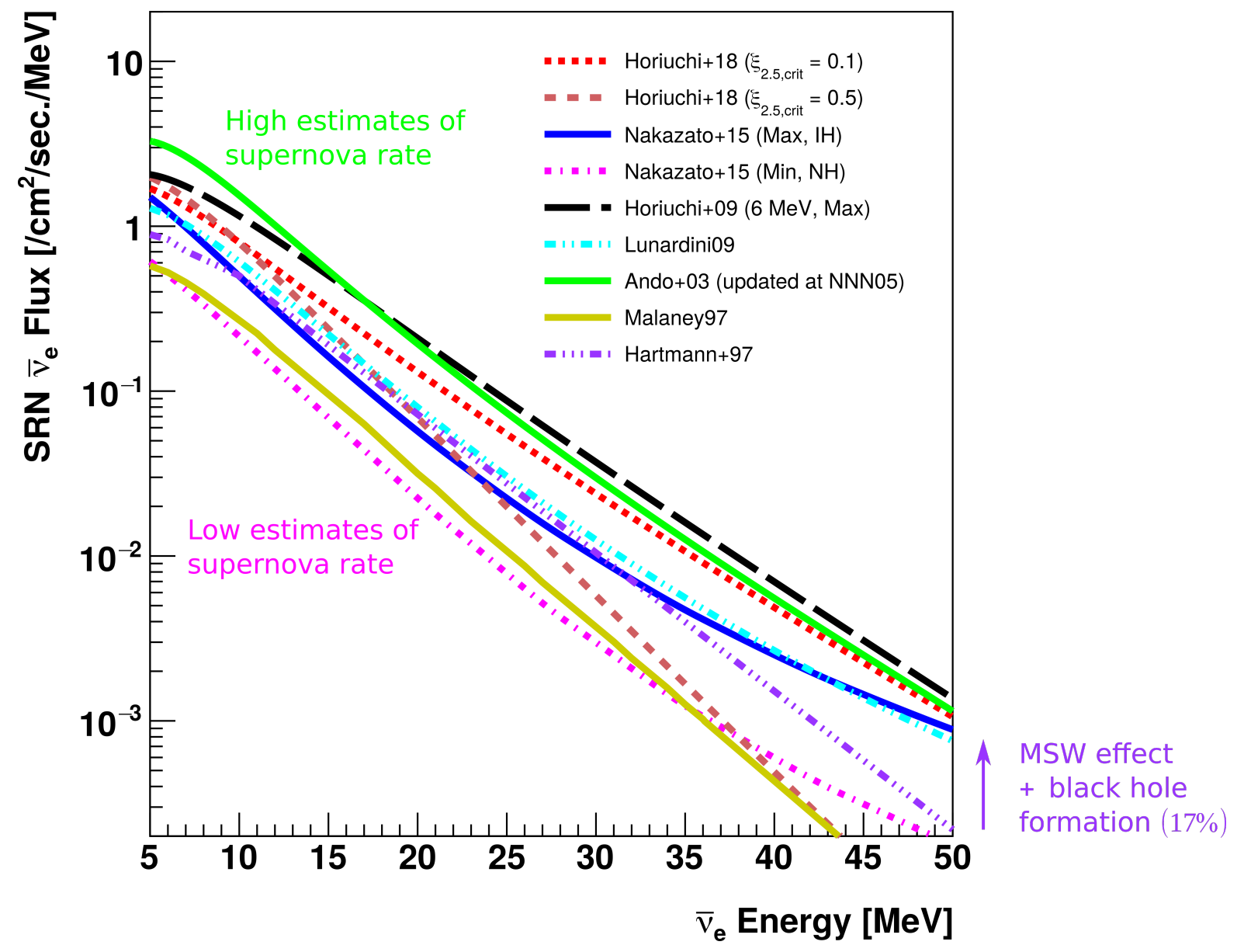


SK is a A **50-kton water Cherenkov detector** in Japan's Kamioka mine, 1 km underground, under Mt. Ikeno, which provides shielding from cosmic ray activity [1].

- Inner Detector: 11129 PMTs
- Resolution: 50cm, 3 ns
- Energy coverage: 4 MeV ↔ ~TeV
- Fiducial volume: 22.5 kton
- SK phases I-V: ultrapure water
- ⋆ SK phases VI+ (starting summer 2020): **water doped with Gadolinium** sulfate, enhancing the signature of a neutron in the detector [2]

The Diffuse Supernova Neutrino Background

The DSNB represents the **neutrino flux from all distant core-collapse supernovae**. While we only expect 2-3 galactic supernovae/century in our own galaxy, about 1 supernova/second is expected to occur in the observable Universe [3].
Detection of the DSNB and its eventual characterization would allow for the study of aggregate properties of core-collapse supernovae, while probing the history of the universe and neutrino properties. All flavors of neutrinos produced during core-collapse supernovae, reaching Earth redshifted. Expected signal is ~10s of MeVs and has so far proved elusive.



Y. Ashida

Detection channel at SK

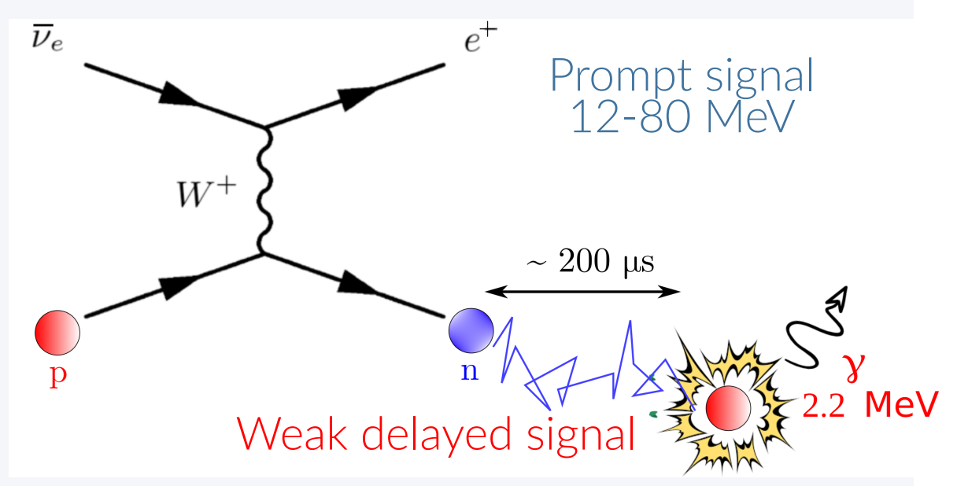
In water, we are sensitive to the DSNB through detection of a $\overline{\nu_e}$ via Inverse Beta Decay (IBD). In the SK volume, we expect 5-20 events/year, with a positron energy range of 12-80 MeV. In this range, it is crucial to remove the large amount of background from **radioactive spallation** and **atmospheric neutrino** events.
One of the tools we can use to reduce these backgrounds is to look for the **delayed coincidence signal from the IBD neutron**, which will be captured by an atomic nucleus in the water and produce a weak Cherenkov signature of their own.

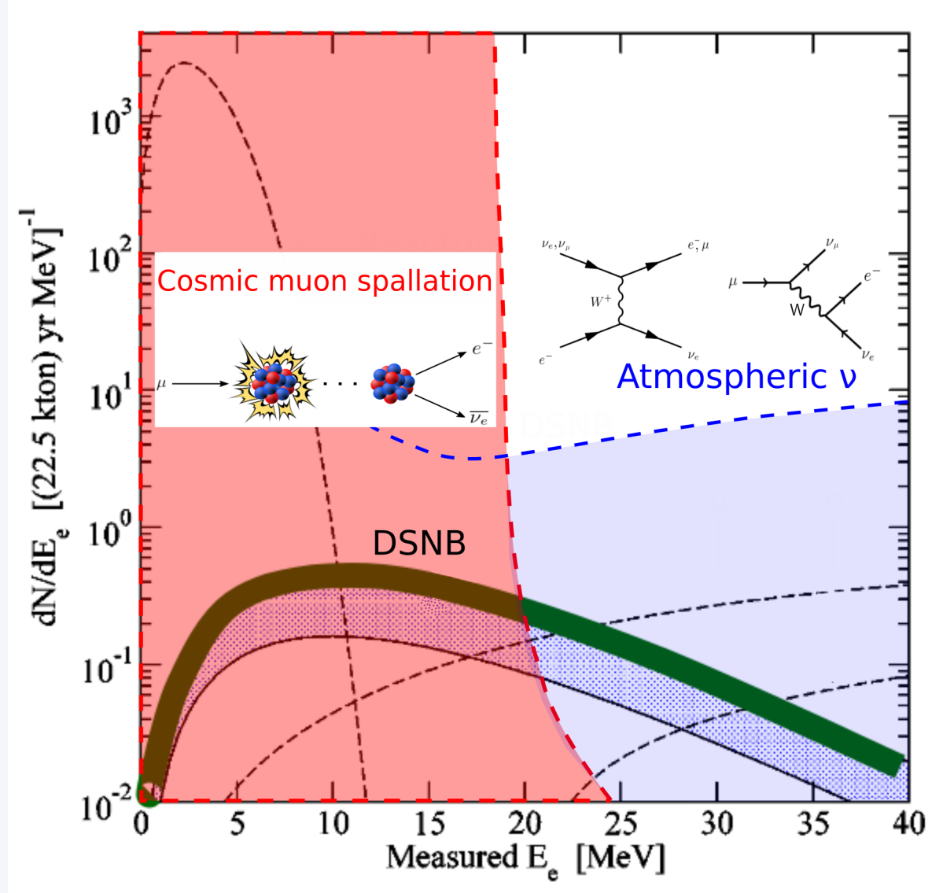
- Current analysis: uses runs from the **SK-IV** data-taking era (Sep 2008-May 2018), combined with results from previous runs (SK-I-II-III, 1996-2008)

→ neutron capture by H: 2.2 MeV signal, $\tau_{CAP} \sim 200\mu s$

- ⋆ Future analysis with SK-VI+: neutron is captured by Gd with high probability (up to 90% for nominal Gd concentration)

→ neutron capture by Gd: $\sim$ 8 MeV cascade, $\tau_{CAP} \sim\ 35\mu s$

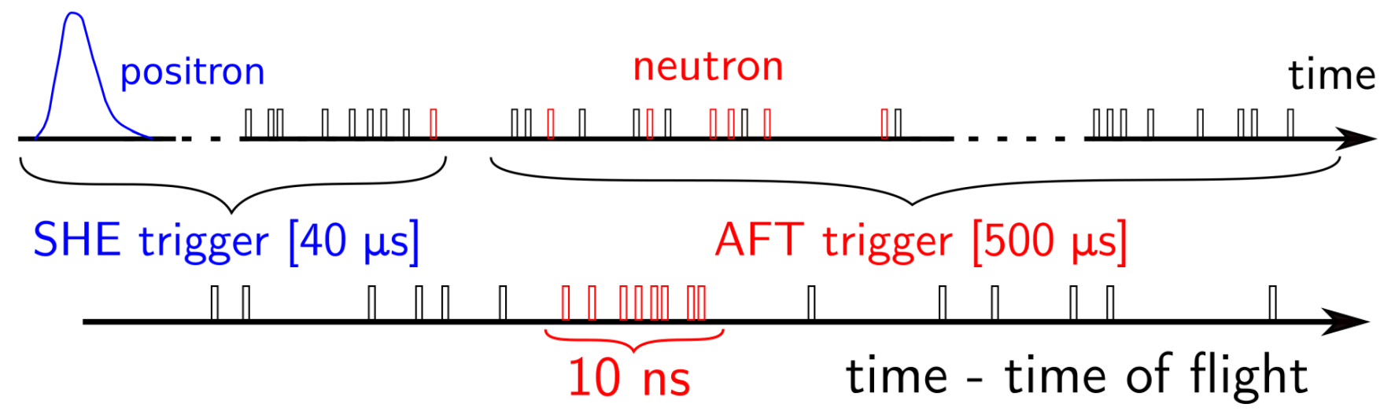




[Beacom and Vagins, Phys. Rev. Lett., 93:171101, 2004]

Neutron candidate selection

- **Wide trigger scheme** (540 μs time window), makes detection of neutron captures in water ($\tau_{CAP} \sim 200\mu$s, much larger than a typical SK event) feasible, starting with SK-IV [4].
- The **2.2 MeV neutron capture** is signal extremely weak and easily lost among abundant low-energy backgrounds (4 kHz PMT noise, radioactivity, flasher events...), causing **backgrounds from accidental coincidence**. Meanwhile, the delayed vertex cannot typically be reconstructed on its own.



- Exploit **well-reconstructed primary vertex**, which is typically within <50cm of the neutron capture vertex: look for hits clustered in 10 ns in time-t.o.f., requiring N$_{hits}$ > 5.
- This selection has efficiency: 45 %, background rate: ~11 accidentals/event

Neutron tagging MVA selection

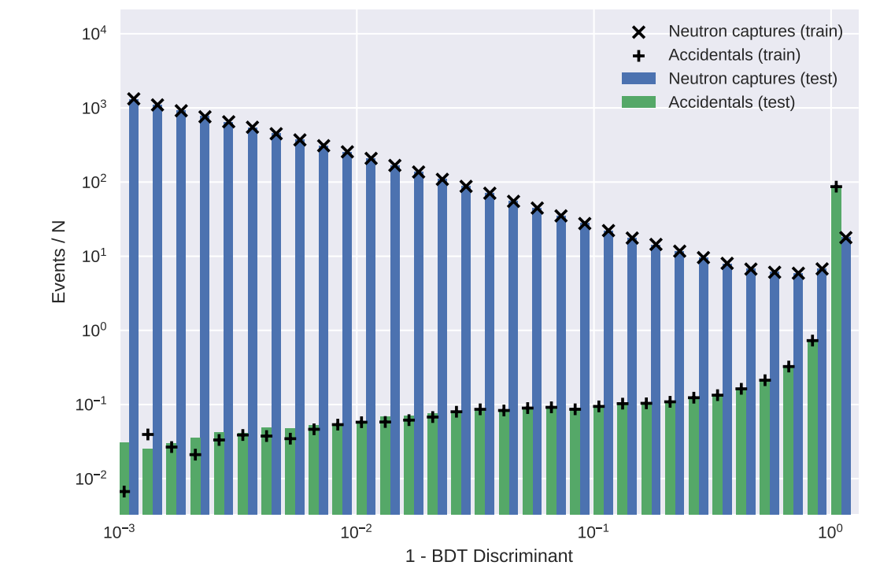
Use MVA techniques to maximally exploit correlations with well-reconstructed primary vertex

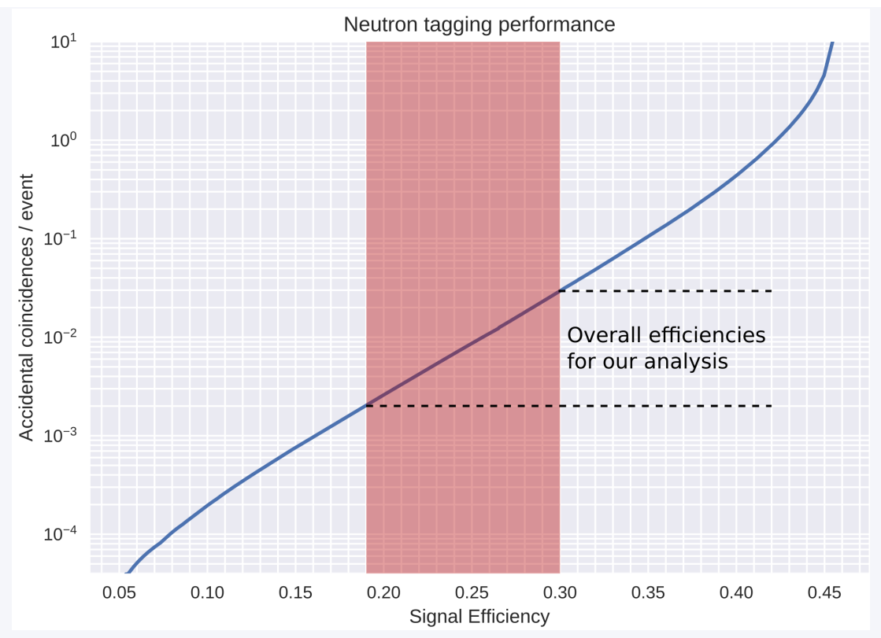
Instead of using simulated noise, **take background directly from data** triggered at random times, since the neutron tagging algorithm will be highly sensitive to the features of low-energy background.

We compute 22 observables for each neutron candidate, characterizing aspects of the neutron capture vertex, Cherenkov cone properties, and noise-likeness.

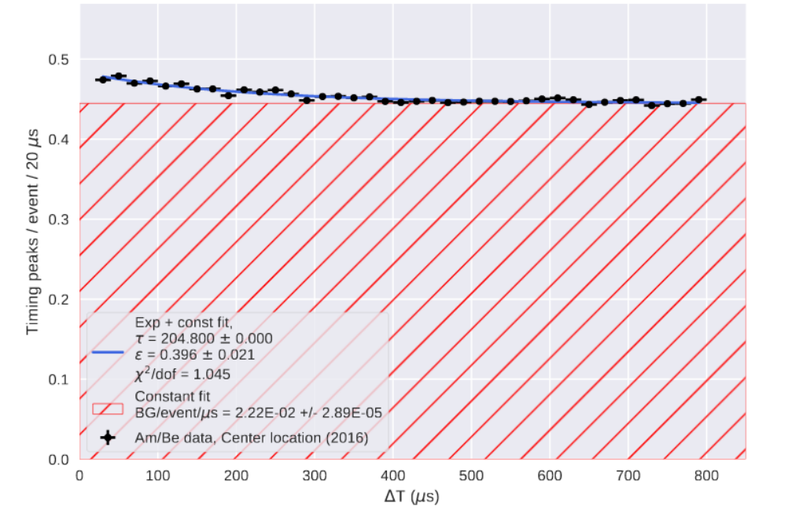
Train a Boosted Decision Tree (a Machine Learning method) to classify neutron candidates, achieving ~20%-30% overall efficiency and ~ 10^{-3}-10^{-2} accidentals/event

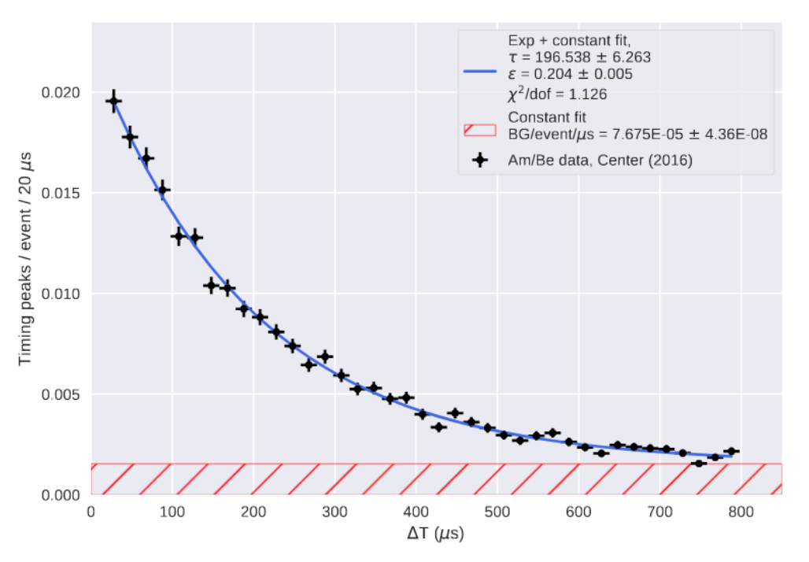
⋆ WIth the dissolution of Gd inside the tank, producing a **brighter signal associated with an 8 MeV phton cascade**, efficiency is expected to increase to >80% for future analyses using this procedure.





Validation on real neutrons





- Due to possible mismodeling of neutron capture signal, it is important to validate the performance of neutron tagging on real neutrons from data, and compare it to performance on simulation to evaluate systematic uncertainties.
- We use calibration data with Am/Be source placed in the detector, producing neutrons through radioactive decay.
- The amount of true neutrons after cuts in data, and thus the efficiency of neutron tagging, are extracted statistically, assuming neutron capture time follows a decaying exponential from IBD interaction time, with a constant background component.
- Overall systematic uncertainty of: 7%
- Top: time distribution before BDT cut. Bottom: after BDT cut.

Spectral analysis with neutron tagging

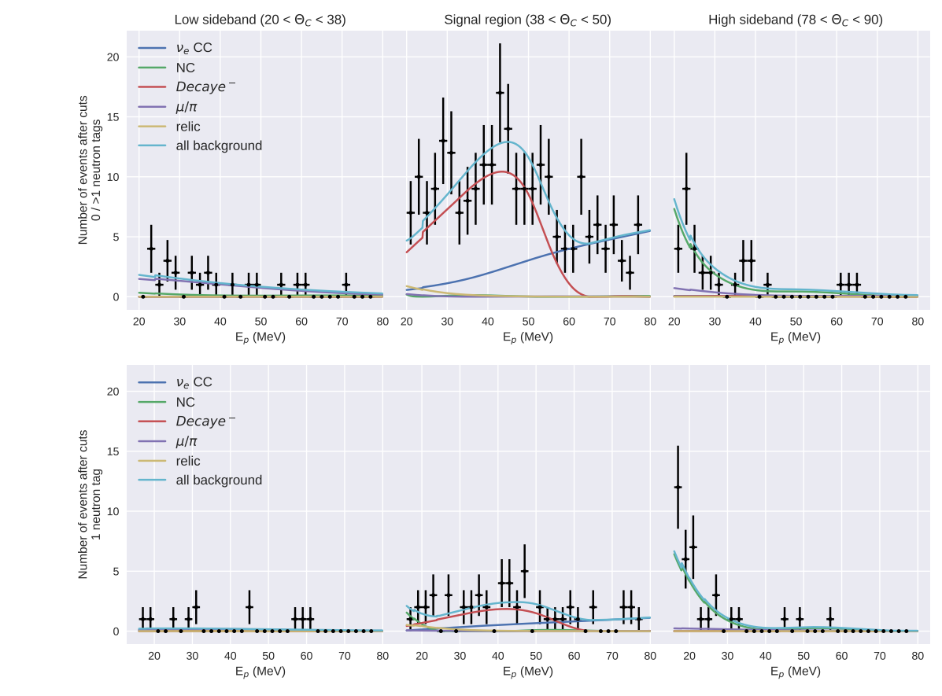
To extract upper limits on the DSNB flux, we fit the spectral shape of the data remaining after cuts against the expected irreducible background contributions (from atmospheric ν interactions) and various DSNB models and parametrizations [see Sonia el Hedri's talk]. We perform an unbinned extended maximum likelihood fit, for 6 regions simultaneously, defined according to the reconstructed Cherenkov cone angle and number of tagged neutrons, and maximize the likelihood of observing N$_j$ events for background category/signal j:

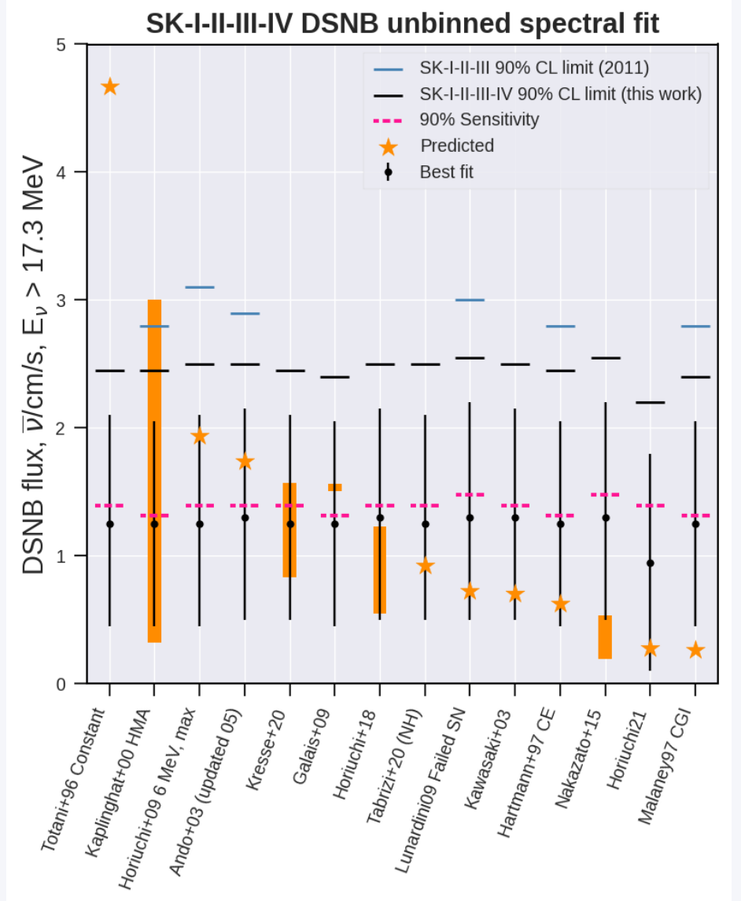
	Cherenkov angle		
Neutrons	$[20, 38]°$	$[38, 50]°$	$[78, 90]°$
1	μ/π	Signal	NC
0 or >1	μ/π	Signal	NC

$$\mathcal{L}(\{N_j\}) = e^{-\sum_{j=1}^{5} N_j} \prod_{i=1}^{N_{\text{events}}} \sum_{j=1}^{5} N_j \, \text{PDF}_j(E_i; , \theta_{c,i}, N_i^{\text{neutron}}) \qquad (1)$$

Here, **neutron tagging allows us to define a cleaner signal region**, with exactly 1 neutron identified, that will be much more sensitive to the DSNB spectrum.

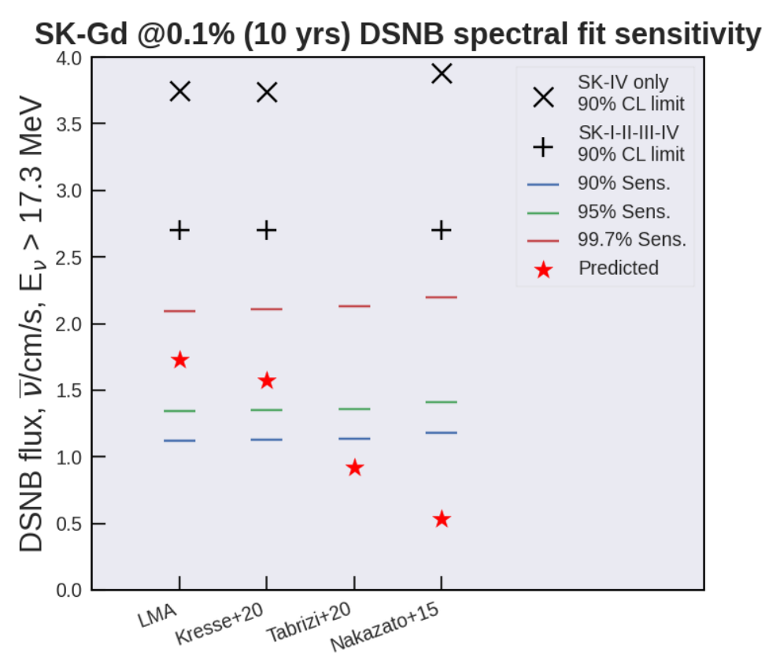
⋆ With the increased neutron tagging efficiency afforded by Gd, a much larger fraction of the signal in future analyses at SK will be contained in the clean 1-neutron region.





Sensitivity projections of current method with Gd

We make preliminary projections of the sensitivity of SK to different DSNB models with Gd-doped water. So far, we have made projections for an analysis closely following the procedure of the current search. The 90% C.L. sensitivity for 10 years of livetime of SK at nominal Gd concentration obtained is roughly 20% better than the ~20-year SK-I-II-III-IV combined runs considered by the current analysis. With such a 10-year run, before any combination with other SK runs, we would reach 2σ sensitivity to optimistic DSNB models. Further gains in sensitivity are expected, for example with improved rejection of neutron-producing backgrounds that may pass neutron tagging cuts.



Summary and outlook

- We apply an MVA-based approach to the detection of low-energy IBD neutrons from DSNB neutrinos in SK-IV.
- We use neutron tagging to improve the sensitivity of an unbinned fit of the DSNB spectrum against several theoretical models, reaching the best current experimental sensitivity to the DSNB.
- We make a first projection of the sensitivity of SK to the DSNB with Gd-doped water.
- Neutron tagging will be adapted to the detection of neutron captures on Gd to achieve higher efficiency
- Further sensitivity improvements are possible, for example through further reduction of atmospheric backgrounds contaminating the signal region of our fit.

References

[1] Christopher W. Walter. The Super-Kamiokande Experiment. 2 2008.
[2] Chenyuan Xu and. Current status of SK-gd project and EGADS. *Journal of Physics: Conference Series*, 718:062070, may 2016.
[3] John F. Beacom. The Diffuse Supernova Neutrino Background. *Ann. Rev. Nucl. Part. Sci.*, 60:439–462, 2010.
[4] S. Yamada et al. Commissioning of the new electronics and online system for the super-kamiokande experiment. *IEEE Transactions on Nuclear Science*, 57(2):428–432, 2010.

July 12th - 23rd, 2021

37th International Cosmic Ray Conference (ICRC 2021), Online - Berlin, Germany

giampaolo@llr.in2p3.fr