ConvNets for enhanced background discrimination in the Diffuse Supernova Neutrino Background (DSNB) search

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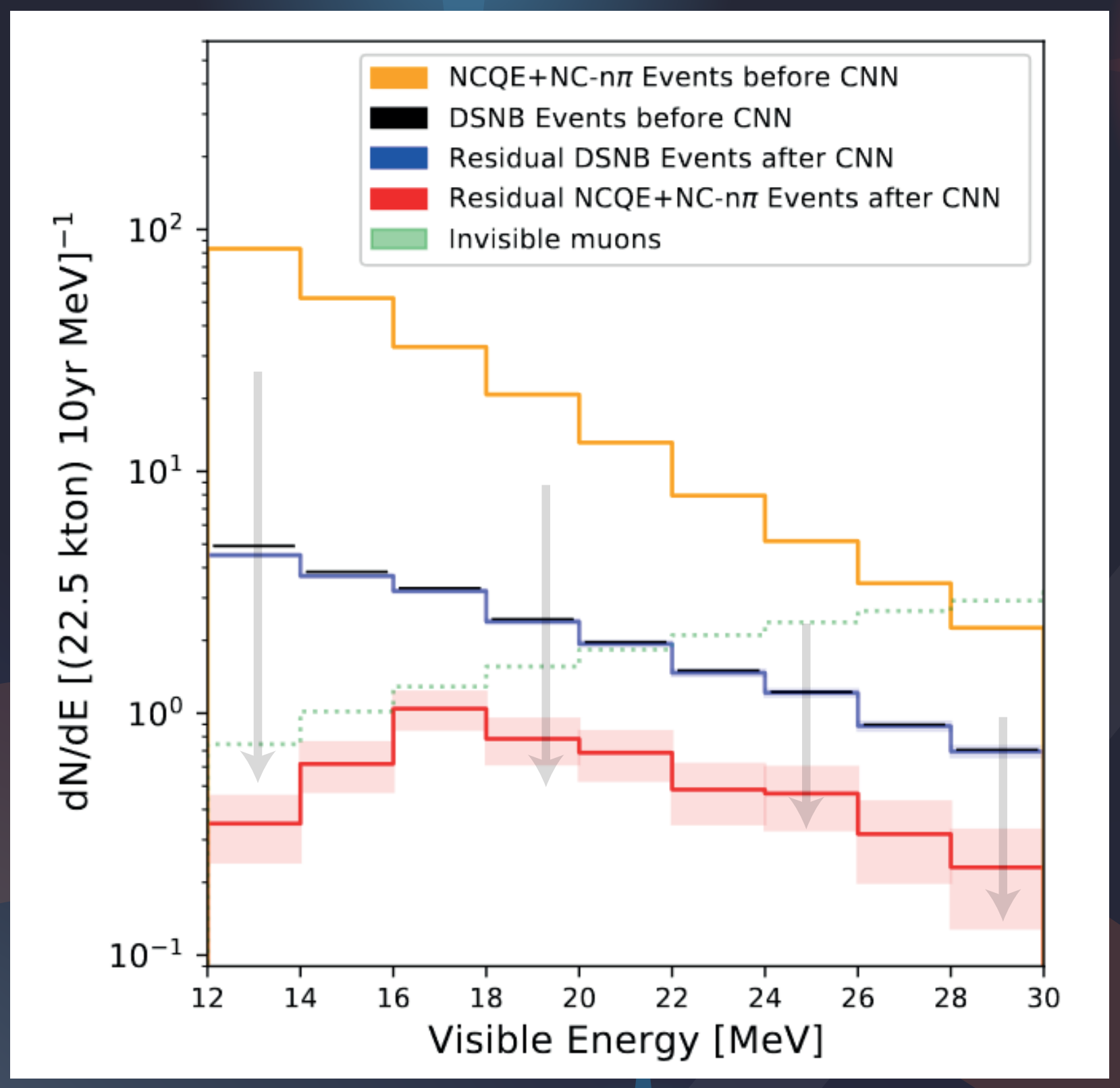
Overview

The Diffuse Supernova Neutrino Background (DSNB) is the faint signal of all core-collapse supernovae explosions on cosmic scales. A prime method for detecting the DSNB is finding its IBD signatures in Gadolinium-loaded large water Cherenkov detectors like Super-Kamiokande (SK-GD). While the enhanced neutron tagging capability of Gadolinium greatly reduces single-event backgrounds, correlated events mimicking the IBD coincidence signature remain a potentially harmful background.



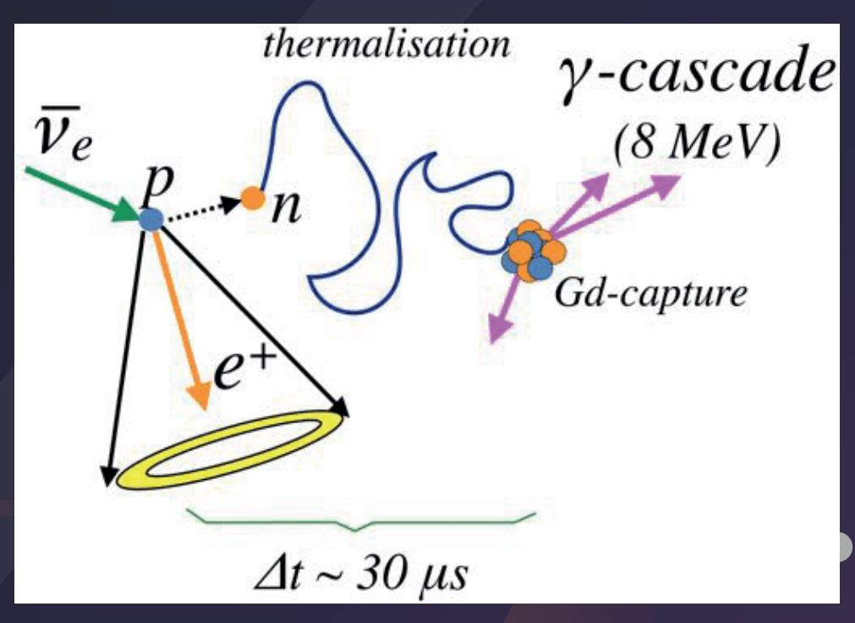
Especially in the low-energy range of the observation window, Neutral-Current (NC) interactions of atmospheric neutrinos dominate the DSNB signal, which leads to an initial signal-to-background (S:B) ratio inside the observation window of about **1:10.**

C(CNNs) that offer the possibility for a

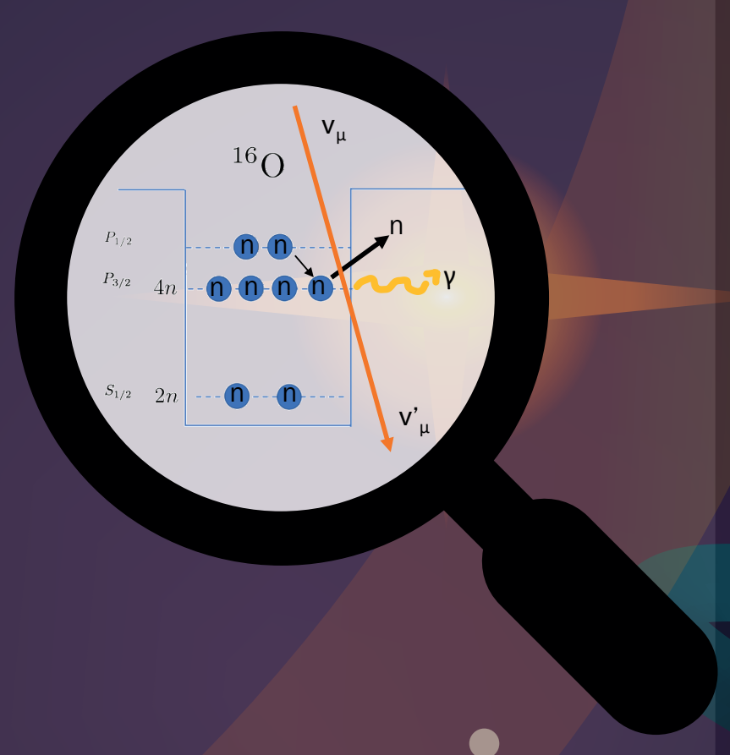
Here, we report on a novel machine learning method based on Convolutional Neural Networks (CNNs) that offer the possibility for a direct classification of the PMT hit patterns of the prompt events. Based on the events generated in a simplified SK-GD-like detector setup, we find that a trained CNN can maintain a signal efficiency of 96 % while reducing the residual NC background to 2 % of the original rate, corresponding to a **final signal-to-background ratio of about 4:1**. This provides excellent conditions for a DSNB discovery.

Detection and Background

One of the most promising methods of detecting the DSNB is **inverse beta decay** in a gadolinium-enriched water Cherenkov detector. Neutron tagging with Gadoli-



Gadolinium is a great experimental method to suppress every single-event background. . The signal window therefore contains reduced background which can produce either an IBD-like coincidence



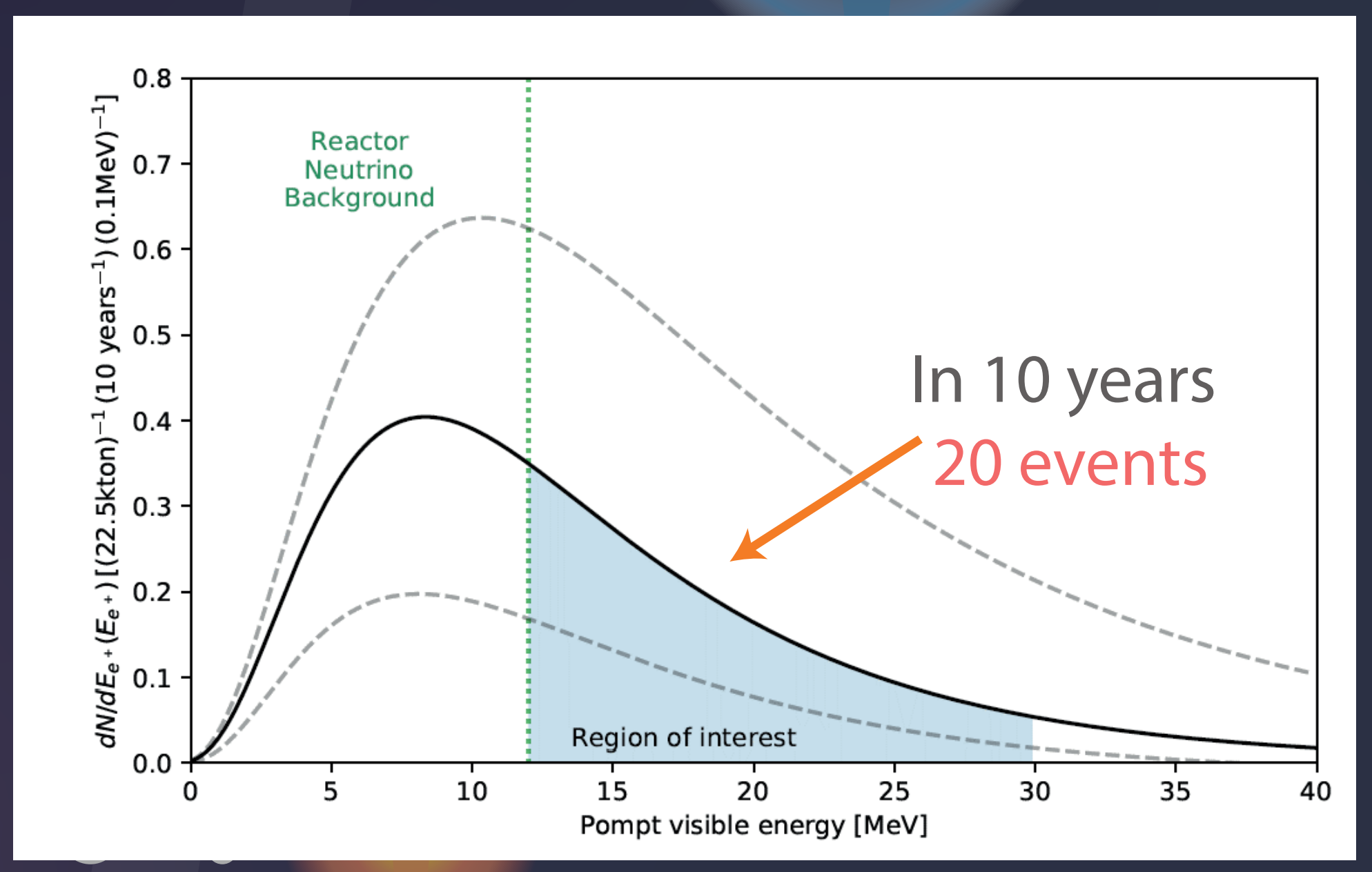
IBD-like coincidence signal or in some cases a true IBD signal. IBDs induced by reactor and atmospheric antielectron-neutrinos define a narrow detection window from roughly 12 MeV to 30 MeV. Within this observation window, the most prominent background is posed background is posed by Neutral-Current (NC) interactions of atmospheric neutrinos on oxygen in the water that are able to mimic the IBD coincidence signature. The coincidence signature is created by emitting one or several gammas and one or more neutrons in nuclear breakup reactions. While the hadronic fragments of an NC interactions are mostly below Cherenkov threshold, the gammas produced in de-excitation processes of the remnant nucleus are identified as the prompt event within the expected visible energy window.

ν_x $\bar{\nu}_e$

Diffuse Supernova Neutrino Background

Massive stars ($M > 8\ M_\odot$) undergo a core-collapse supernova (CCSNe) at the end of their burning phase. The released gravitational binding energy caused by the gravitational collapse of the star cannot be successfully liberated in the dense core regions by photons, but only through neutrinos due to their weakly interacting nature.
The DSNB is an proposed background composed of neutrinos (and anti-neutrinos) emitted by all the CCSNe throughout the Universe.
The role played by the emerging neutrinos in CCSN is versatile and their direct study and detection of a galactic CCSN can give insight in the condition of the collapsing core and the explosion mechanism, whereas detecting the DSNB can also reveal additionally the fraction of hidden/failed SN events and an average Supernova neutrino-spectrum. Current estimates regarding the number of emitted neutrinos during a supernova explosion amount to around 10^58 particles with equal partition between flavours due to eigenstates mixing through pair production during the proto-neutron star cooling [1].

While not yet observed, the DSNB signal can be predicted based on our current understanding of CCSNe and cosmology. We use the estimate for the DSNB flux estimated by Kresse et al. [2]. We show the fiducial model (solid black line) along with upper and lower bounds for the prediction (grey dashed lines).



In SK-Gd, the DSNB signal is dominated by the reactor neutrino background at energies below 12 MeV [3]. In the region of interest (12–30 MeV), the fiducial model predicts 20 events in 10 years for a fiducial volume of 22.5 kt and a delayed neutron detection efficiency of 67 %.

Sources:

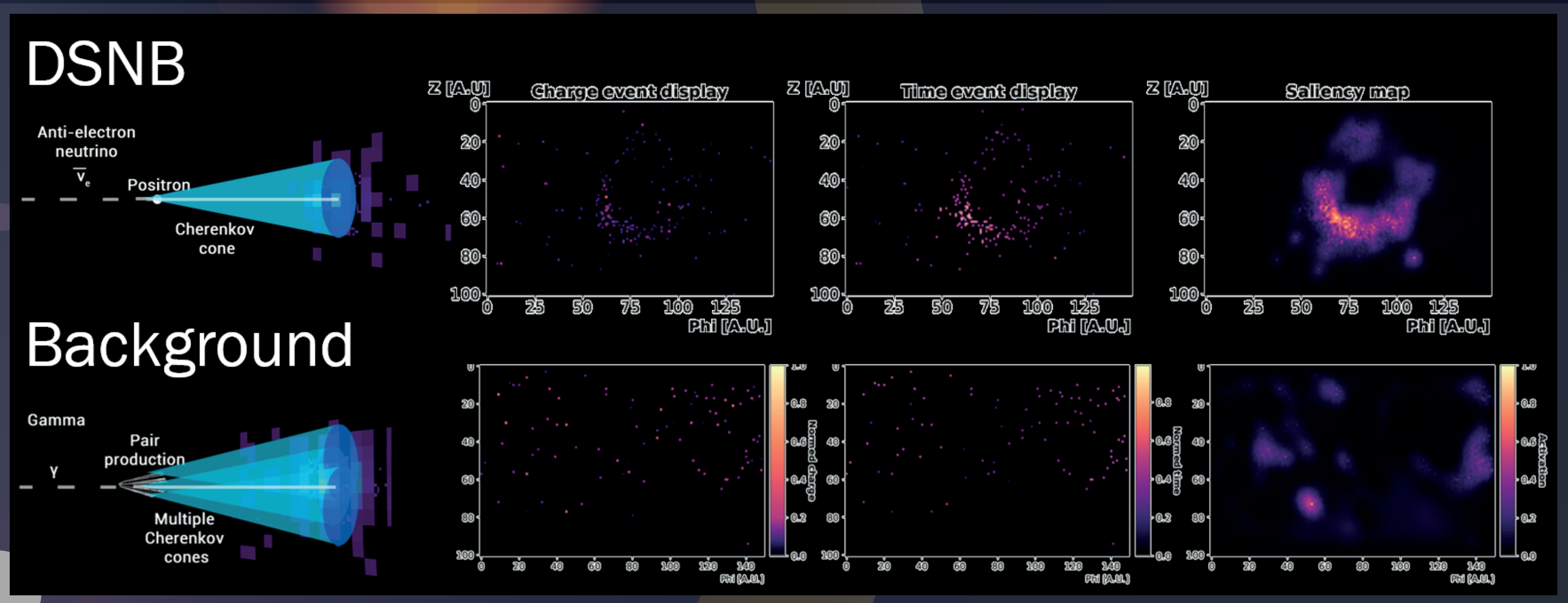
[1] T. Yoshida, T. Kajino, et. al. "Neutrino Oscillation Effects on Supernova Light Element Synthesis," Astrophys.J.649:319-331,2006, 2 6 2006.

[2] D. Kresse, T. Ertl and H.-T. Janka, Stellar Collapse Diversity and the Diffuse Supernova Neutrino Background, Astrophys. J.909 (2021) 169 [arXiv:2010.04728].

[3] J.F. Beacom and M.R. Vagins, GADZOOKS! Anti-neutrino spectroscopy with large water Cherenkov detectors, Phys. Rev. Lett. 93 (2004) 171101 [hep-ph/0309300]

[4] Ilmage of SK-GD: https://www-sk.icrr.u-tokyo.ac.jp/sk/news/2020/08/sk-gd-e.html

ConvNet



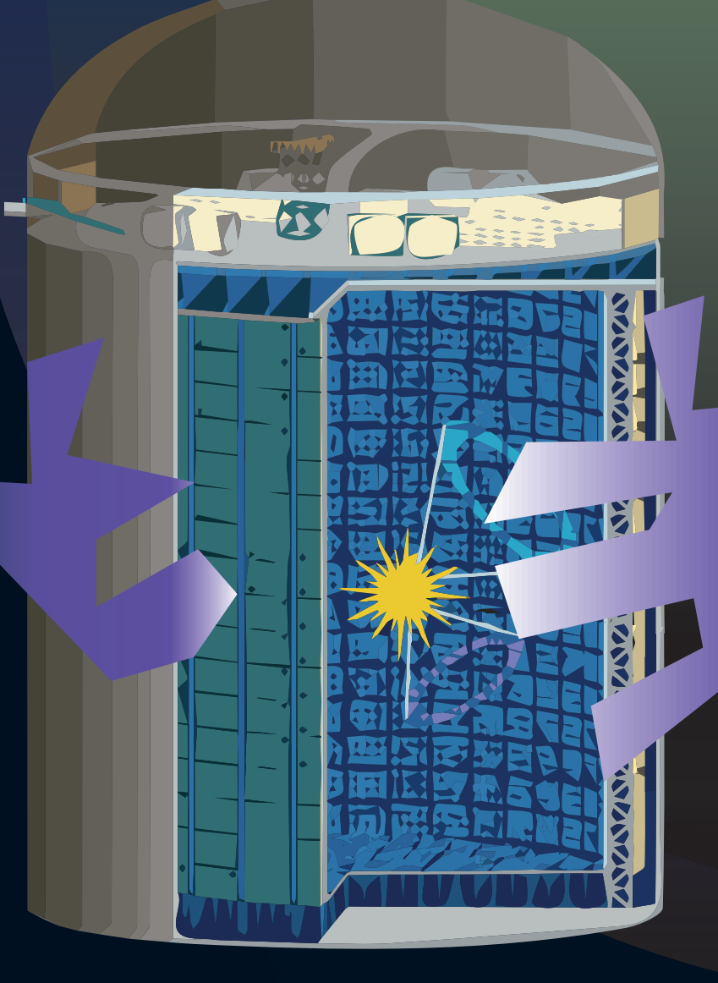
The DSNB and NCQE data, which was generated in MC simulations, is converted into a pixelized image we call a "hit map", conceptually close to a conventional event display. The collected charge (photo electrons, p.e.) per PMT and first photon arrival time are translated into two hit maps in which each PMT is assorted to a specific pixel. Pixels in both hit maps are normalized to a range from 0 to 1. In the case of charge information, the case of charge information, the normalization is the number detected in the present event. This prevents the CNN from picking up on the absolute scale of the observed charge signal and thus largely prevents an energy bias in the classification.

Training data
185.000 Images
Class balanced

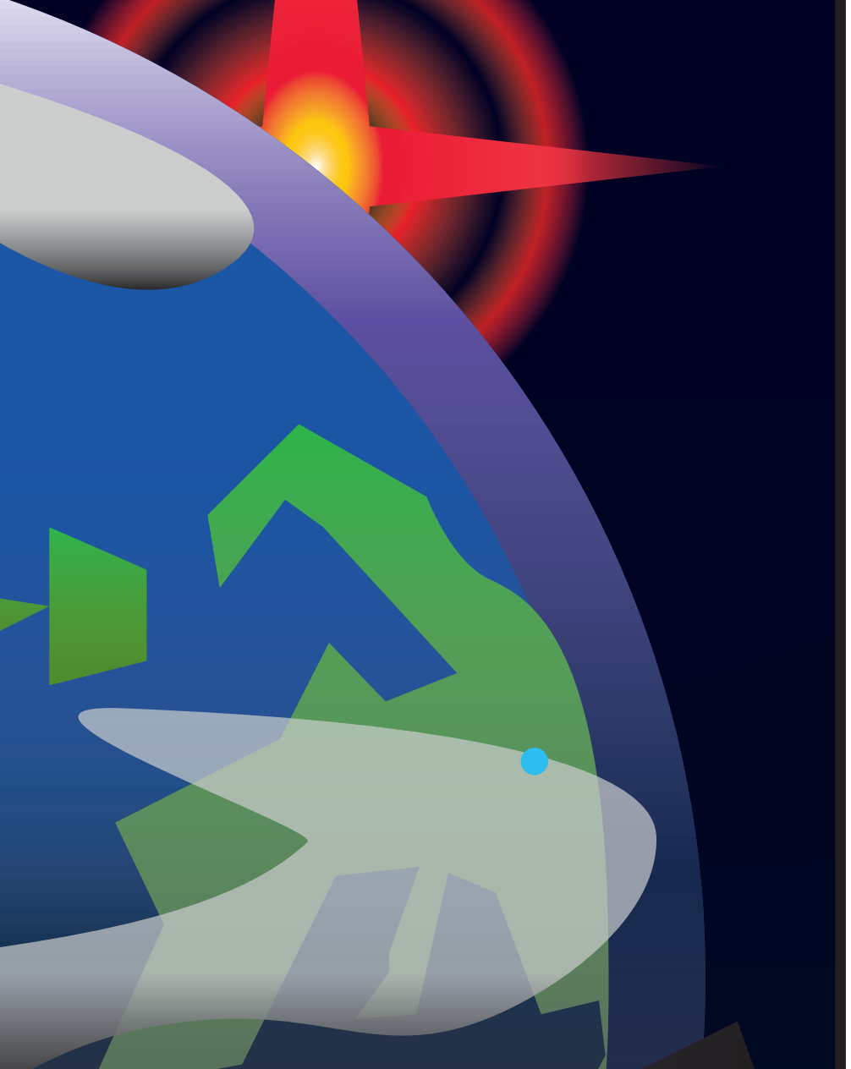
Validation data
15.000 images
Class balanced
Used to monitor training progress and tune hyperparamters

Test data
20.000 images
Class balanced
Used only once in the end to evaluate the networks performance

To build and train the CNN the Keras libraries and the Tensorflow framework in Python. The CNN features a total of 726k trainable and 1.2k non-trainable parameters and consists of six consecutive "64-double convolutional packages". Each package consists of two successive convolutional layers with 64 kernels each, followed by a 2-dimensional (2,2)-Maxpooling layer, a BatchNormalisation layer and a final Dropout layer in four of the six packages which is set to 20 %. The classification result for the two categories DSNB and NCQE is One-Hot encoded in a two-dimensional target vector.



SK-GD-like Detector
h ~36m ~11 k PMTs
r ~ 17m 22.5 kton fiducial volume
[4]



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