IMPROVING THE SENSITIVITY OF KM3NET TO MEV-GEV NEUTRINOS FROM SOLAR FLARES

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KM3NeT: searching for neutrinos in the Mediterranean sea

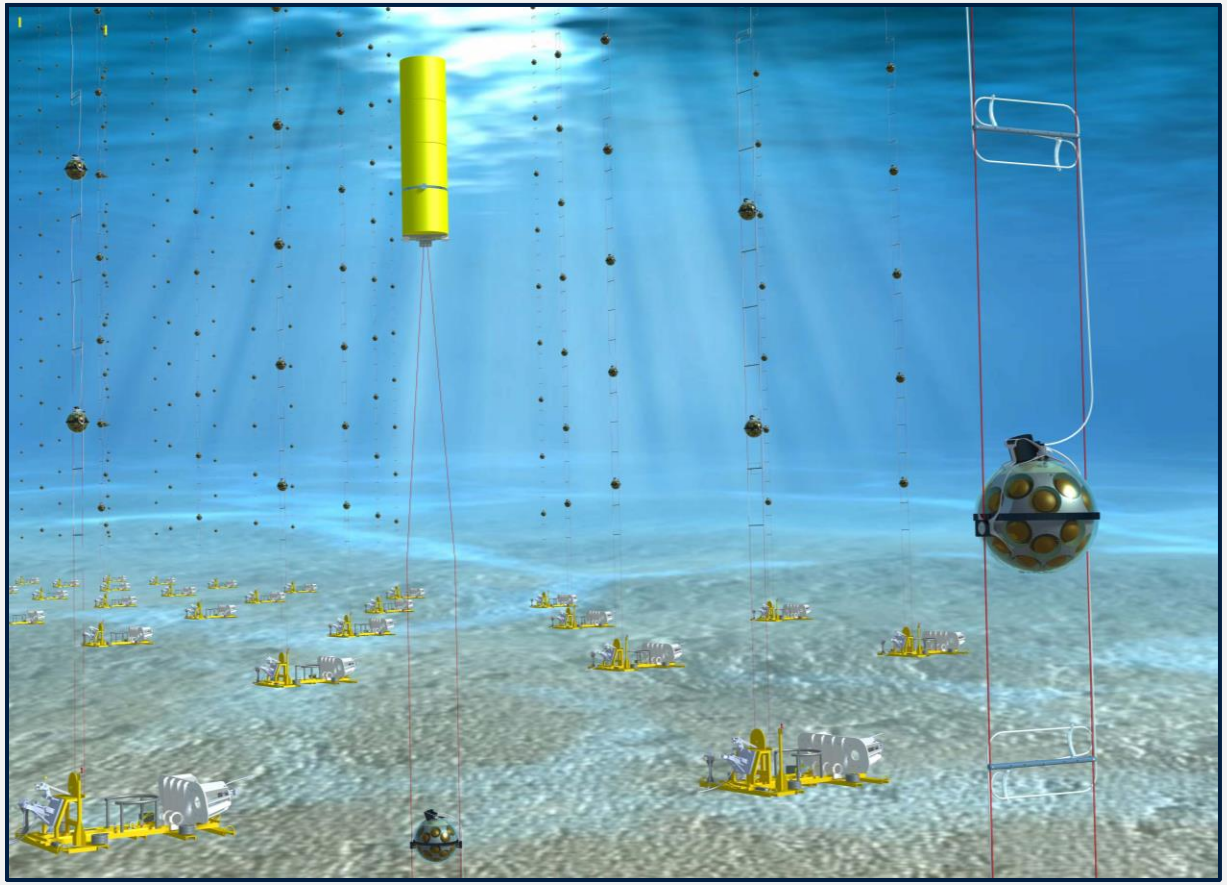
KM3NeT is a Cherenkov neutrino telescope currently being deployed at the bottom of the Mediterranean sea

It consists of two discrete detector arrays:

KM3NeT/ORCA situated at a depth of 2.5 km off the coast of Toulon, France, and

KM3NeT/ARCA situated at a depth of 3.5 km off the coast of Sicily, Italy.

In its final configuration, KM3NeT will result in an **instrumented volume of a cubic kilometre**.

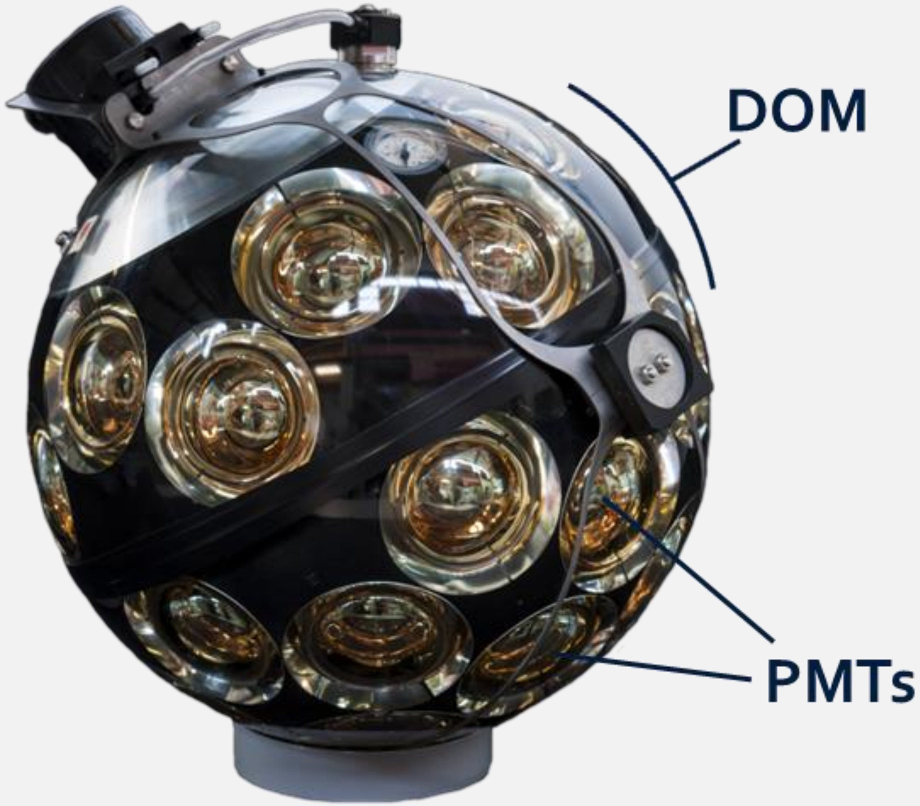


Artist's rendition of the KM3NeT/ORCA array

KM3NeT Collaboration, "Letter of intent for KM3NeT 2.0", J. Phys. G: Nucl. Part. Phys. **43** (2016)

KM3NeT's multi-PMT optical module

KM3NeT Collaboration, "The KM3NeT multi-PMT optical module", JINST **17** (2022)



KM3NeT's Digital Optical Module (DOM) is made of **31 3" PMTs** enclosed in a pressurized glass sphere.

KM3NeT's unique DOM design allows for better reconstruction at high energies, as well as for better noise rejection at the single-DOM level.

Low-level data stored by KM3NeT is filtered requiring at least two-hits coincidences on the same DOM.

Low-level data originates mostly from ^{40}K decay and bioluminescence, and can be modelled well by random coincidences.

Low energies in KM3NeT

KM3NeT's current detection methods rely on **multi-DOM coincidences**.

This limits the sensitivity of the detector to a **few GeV** in **ORCA** and **tens of GeV** in **ARCA**.

SN searches target O(MeV) neutrinos and are performed by looking at an excess of luminosity in the detection volume

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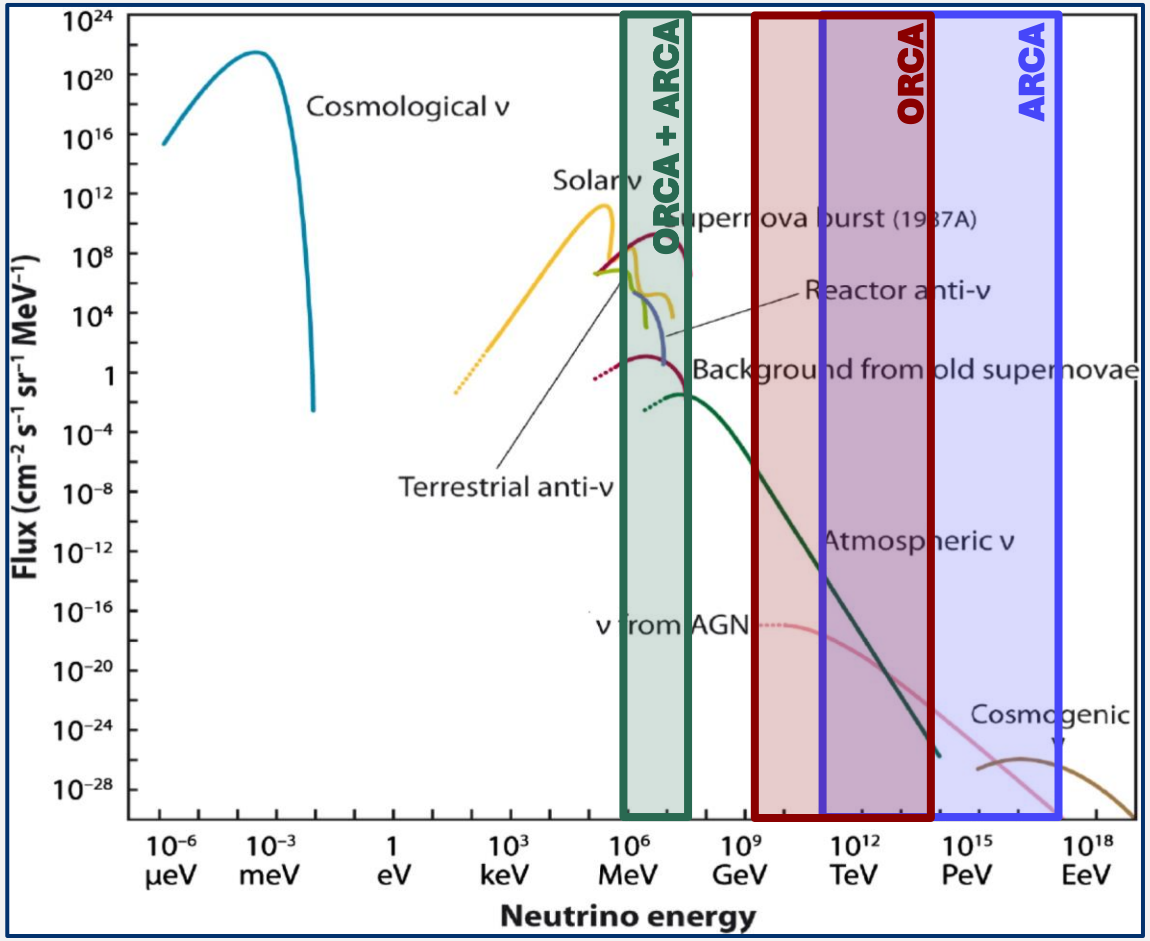
The MeV-GeV neutrino signature is coherent at the single-DOM level allowing for an **improvement of the current sensitivities**.

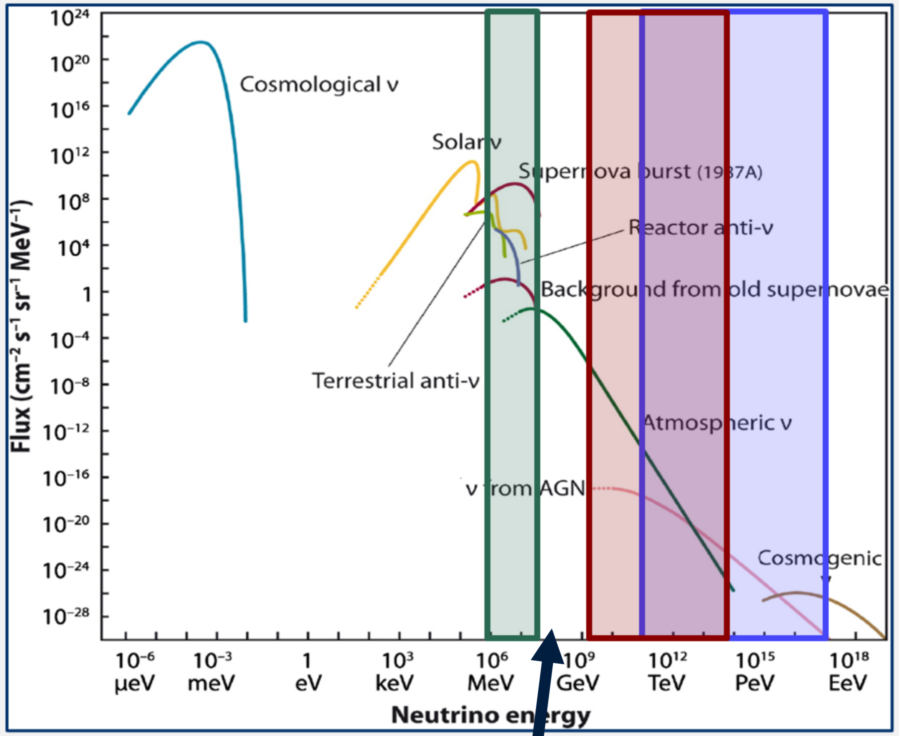


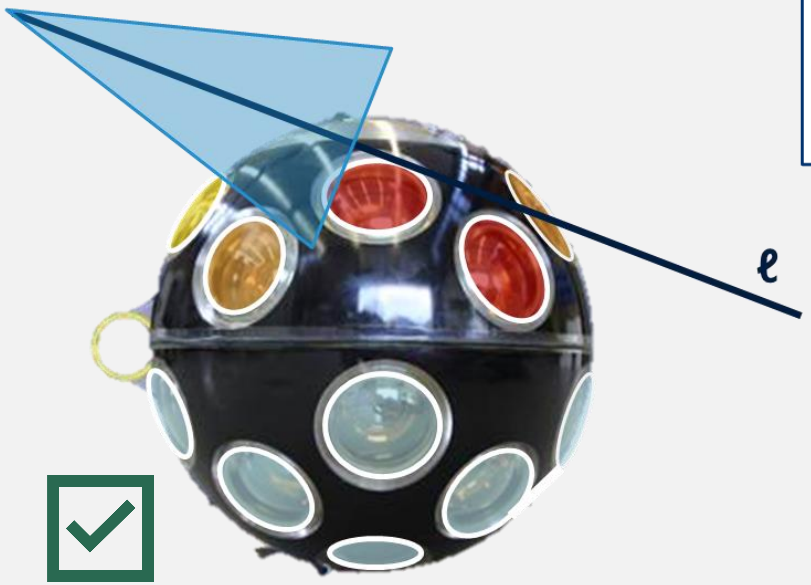
Adapted from U. F. Katz, C. Spiering, "High-energy neutrino astrophysics: Status and perspectives", Prog. Part. Nucl. Phys. **67** (2011).

MeV-GeV neutrino signatures

The products of the interaction of MeV-GeV neutrinos with water don't travel long-enough distances to trigger multiple DOMs.

Nonetheless, <u>the hits' distribution on a single DOM can help distinguish neutrinos from environmental noise.</u>



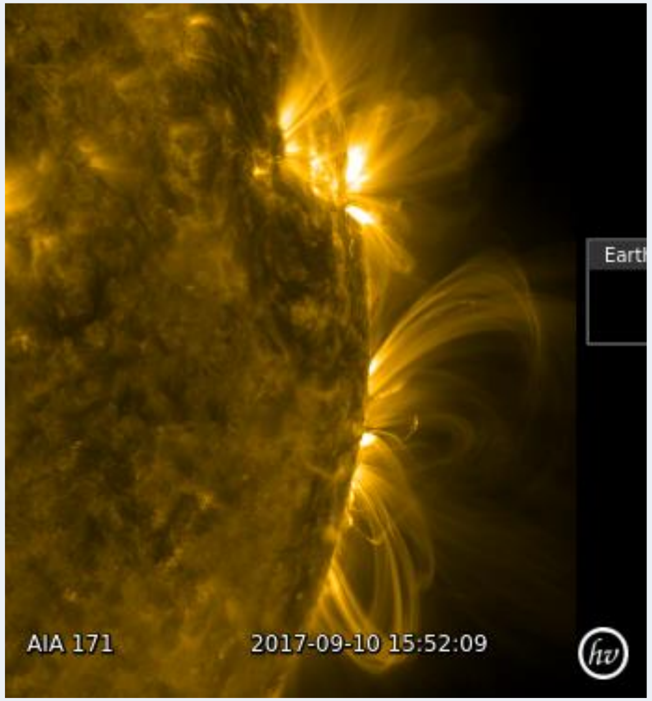


Currently there is no selection that targets MeV-GeV neutrinos

MeV-GeV neutrino sources

Single-DOM events can be used to search for transient sources in the MeV-GeV range:

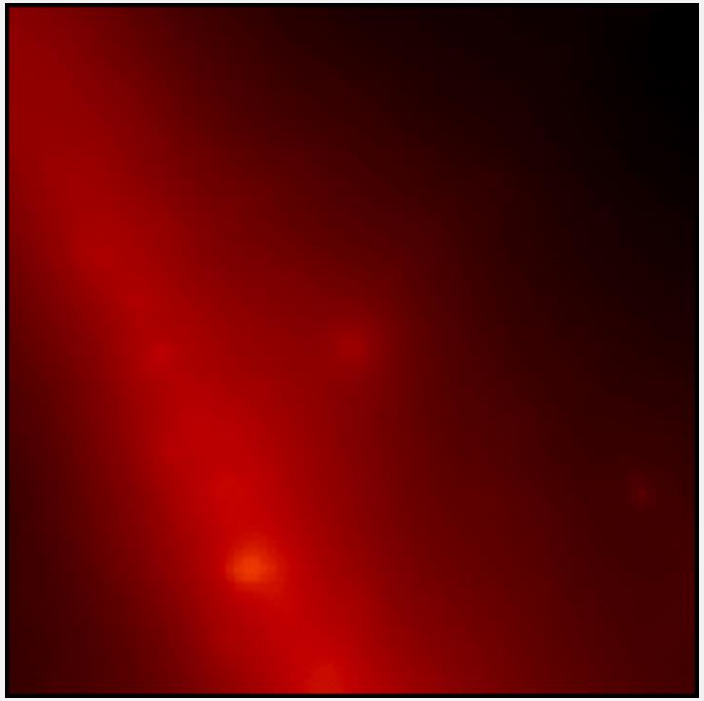
Solar Flares



Credit: NASA/SDO

G. de Wasseige, "*Solar Flare Neutrinos in the Multi-Messenger Era: Flux Calculations and a Search with the IceCube Neutrino observatory*", *PhD thesis Vrije Universiteit Brussel (2018)*

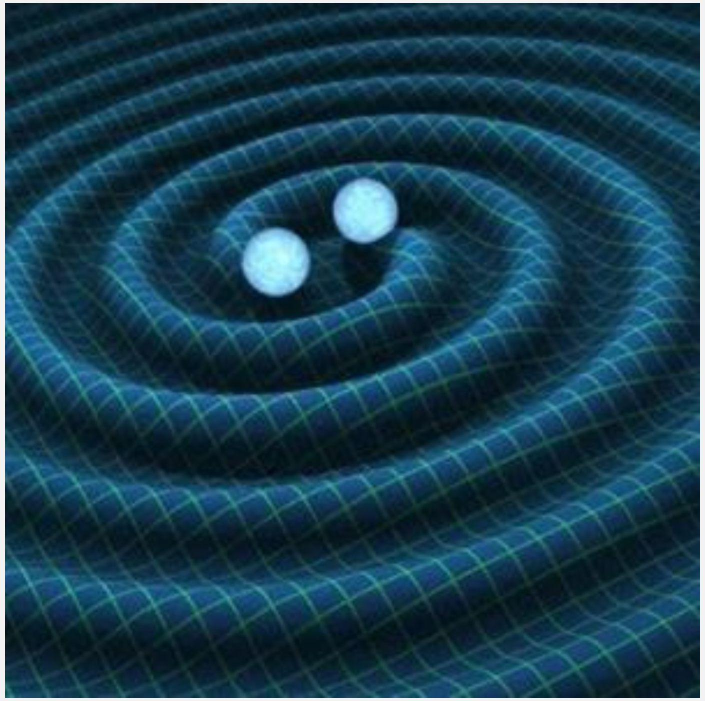
GRBs



Credit: NASA/DOE/Fermi LAT Collaboration

K.Murase, et al., "Subphotospheric Neutrinos from Gamma-Ray Bursts: The Role of Neutrons", *Phys. Rev. Lett.* ***111*** *(2013)*

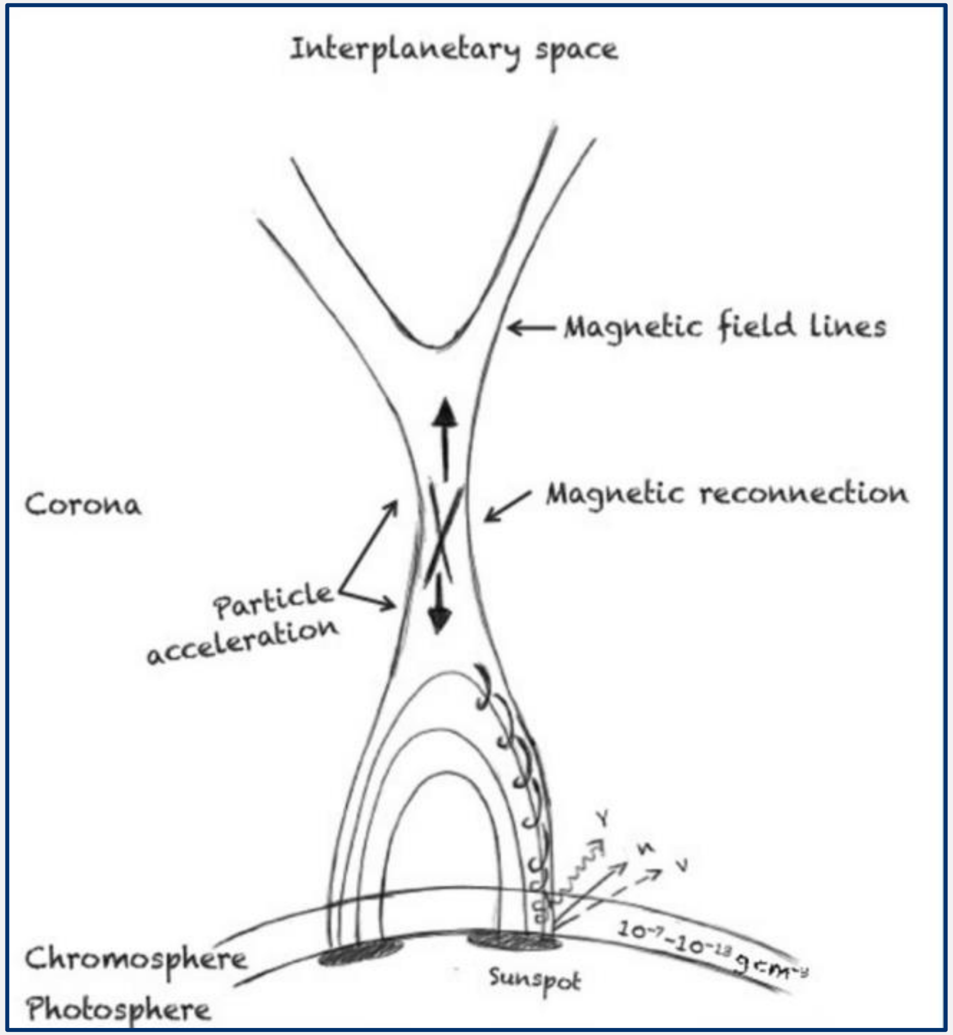
GWs



Credit: R. Hurt/Caltech-JPL

T. Pradier, "Coincidences between Gravitational Wave Interferometers and High Energy Neutrino Telescopes", *Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip.*, ***602 (1)****(2009)*

Neutrinos from solar flares



G. de Wasseige, *"Solar Flare Neutrinos in the Multi-Messenger Era: Flux Calculations and a Search with the IceCube Neutrino observatory", PhD thesis Vrije Universiteit Brussel (2018)*

Solar flares are known sites of **hadronic acceleration**,

Following magnetic reconnection, ions can be accelerated **up to several GeV**.

They are either launched towards interplanetary space (SEPs), or injected into the Chromosphere

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In highly-energetic flares, the proton-proton collision produces pions, that then decay into **gamma-ray** and **neutrinos**.

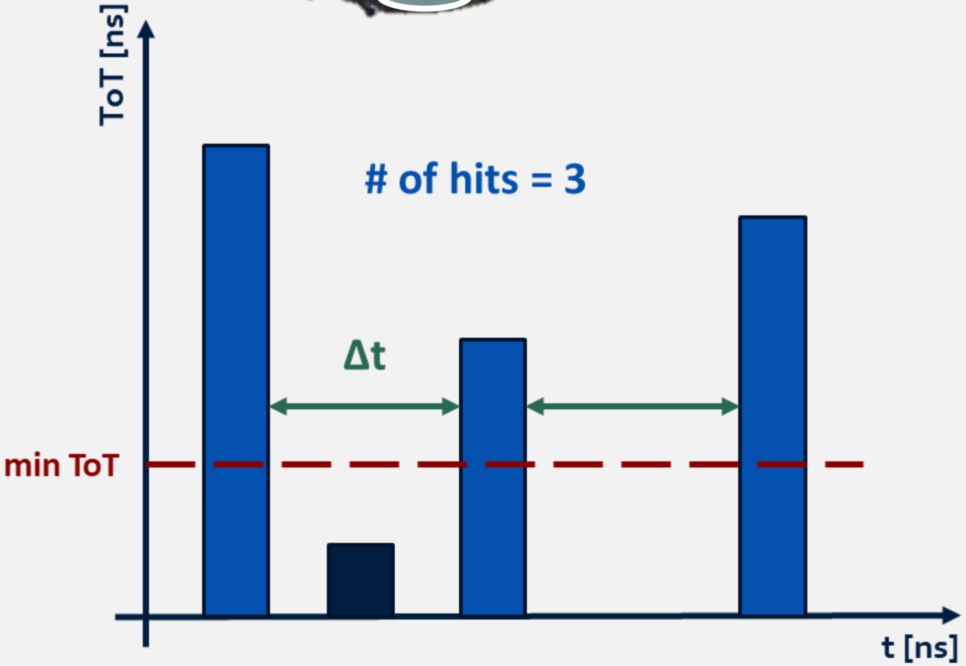
Single-DOM events

ToT = Time over Threshold

Single-DOM events are defined as group of PMT hits, that are recorded on the same DOM with a time offset **Δt < 30 ns**.

Only hits with **ToT > 5 ns** are used, and

Only events with **number of hits > 2** are kept.



By comparing data (background) with neutrino simulations (signal), we optimise the cuts on Δt, min ToT, and min # of hits by looking at fractional increments in the percentage of survived ToT.

Graph dataset

DOM Graph

Each PMT is a node

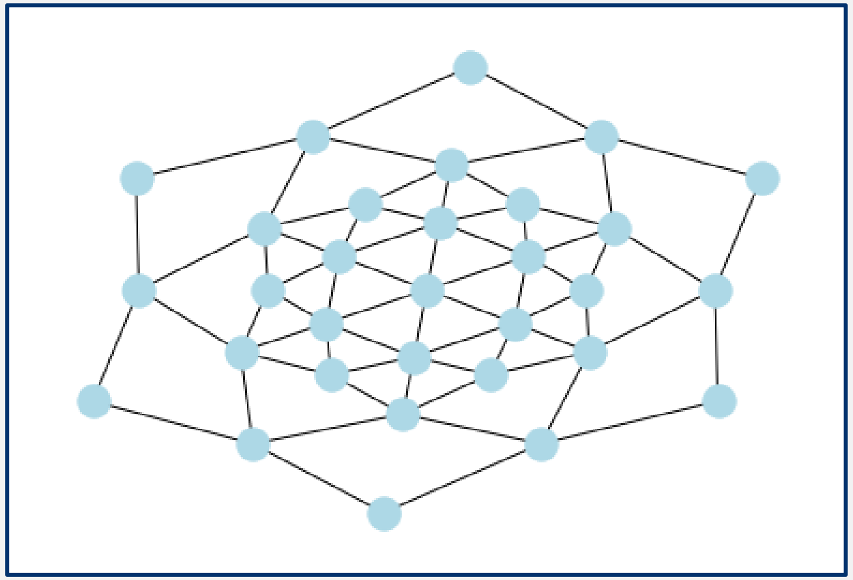
Optimise for PMT density to draw edges

ToT is a node attribute

Hit/no hit is a node label

Weighted std of Dt is a graph attribute

Signal/backgroud are graph labels



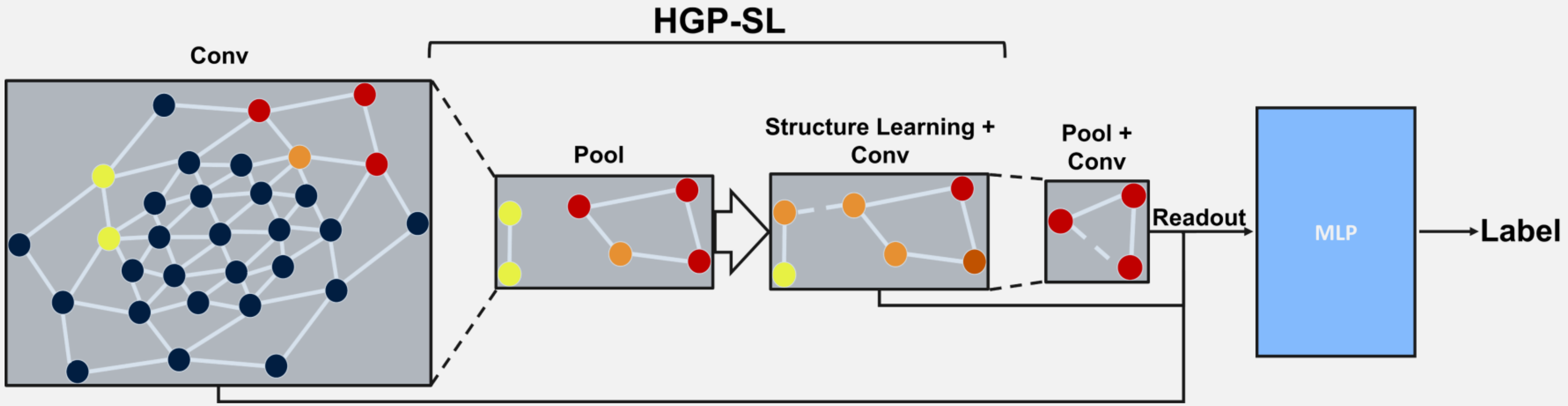
Model architecture

Z. Zhang, et al., *"Hierarchical Graph Pooling with Structure Learning", arXiv preprint (2019)*

This GNN is made of three graph-convolutional layers alternated with hierarchical pooling layers and structure learning (**HGP-SL**).

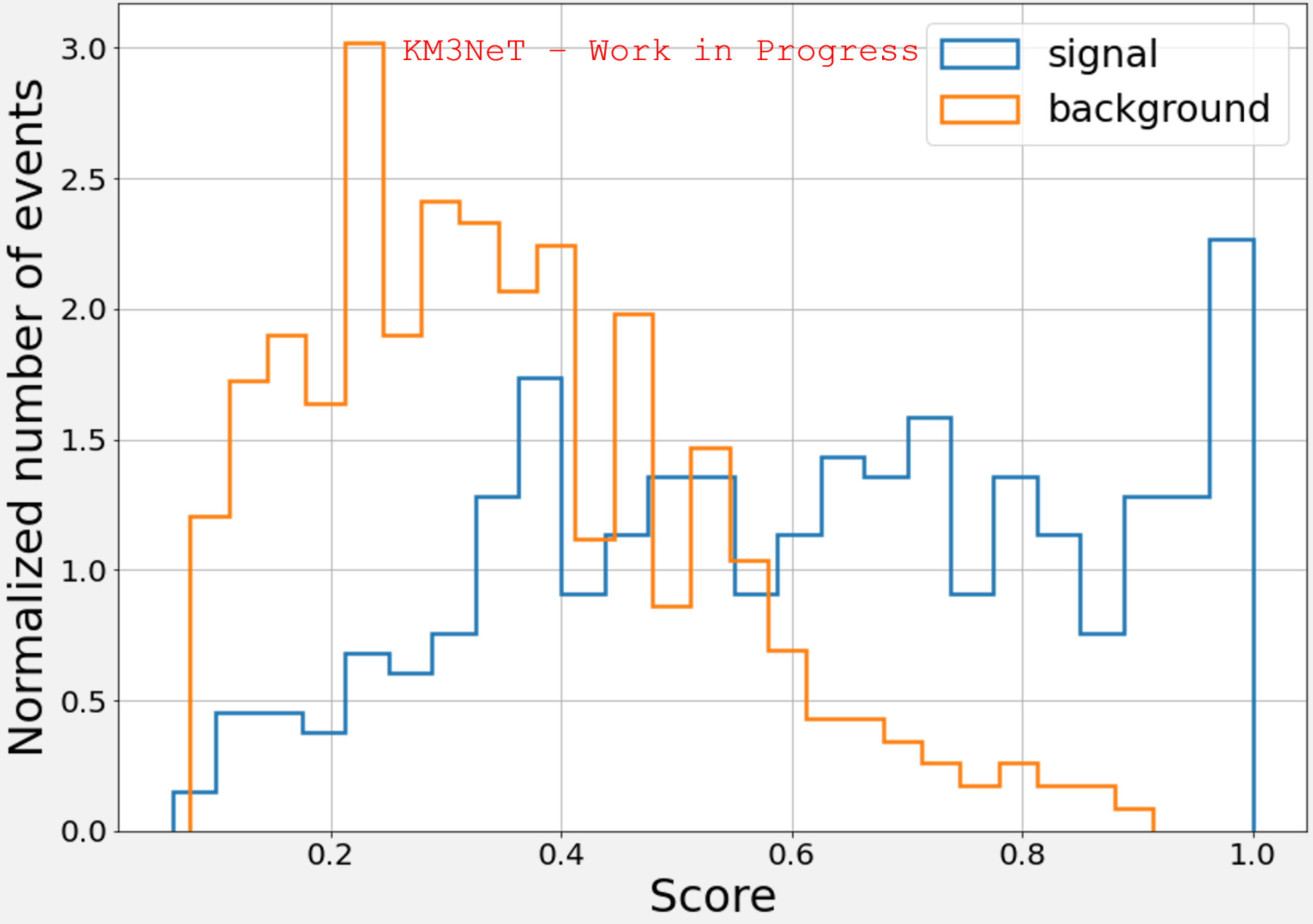
The representations obtained after convolution are merged through a readout function and fed into an MLP for binary classification.

Hierarchical Graph Pooling	**Structure Learning**
It selects the subset of most representative nodes to produce a lower dimensional representation of the graph.	It learns a refined structure of the graph by computing a similarity between nodes. It allows to avoid highly disconnected graphs after pooling.



Score distribution

Best epoch of 100 on the validation sample:



875 background events (data),
and 875 signal events (simulations)

Dataset split into **50% training**, **10% validation**, and **40% test**

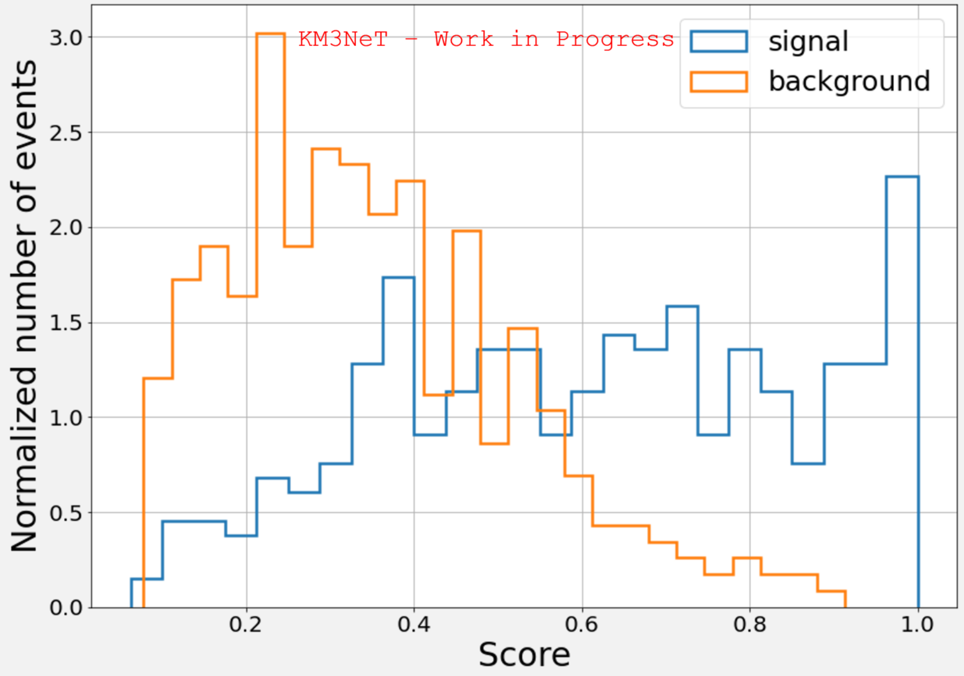
Summary and prospects

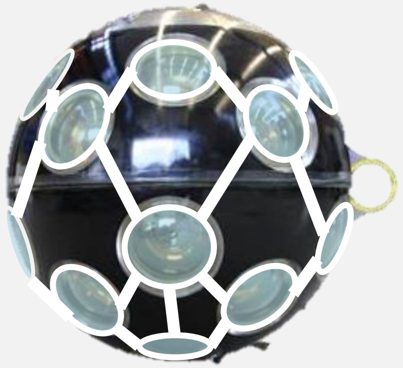
We are developing a new event selection using single-DOM events.

We build the events from low-level data, and we are using hard-cuts to reject a large portion of background.

We train a GNN with data and neutrino simulations for binary classification.

We will use this selection to perform a solar-flare neutrino search.

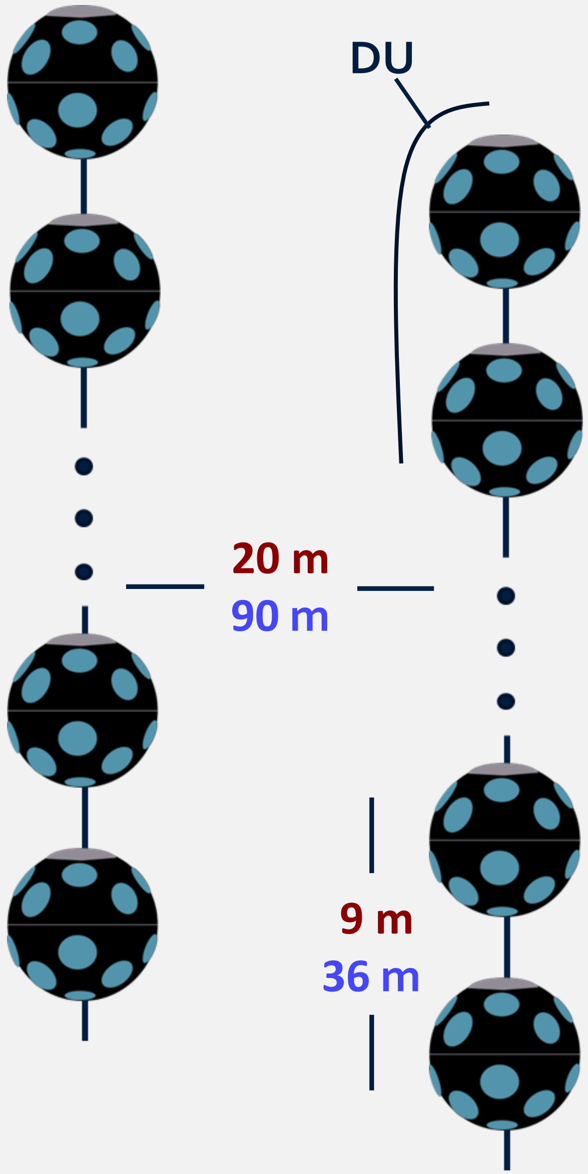




Thanks for your attention!

BACKUP SLIDES

KM3NeT: searching for neutrinos in the Mediterranean sea



With a higher density of instrumentation, **ORCA** is optimised for lower energies and oscillation studies

With a larger instrumented volume, **ARCA** is optimised for high-energy astrophysical searches

KM3NeT Collaboration, "Letter of intent for KM3NeT 2.0", J. Phys. G: Nucl. Part. Phys. **43** (2016)

115 DUs in ORCA
115 × 2 DUs in ARCA

18 DOMs per DU

31 PMTs per DOM

There are currently
19 active DUs in ORCA, and
21 active DUs in ARCA

Searching for transient sources

Training set

Bkg (Transientless Data)

Signal (Simulations)

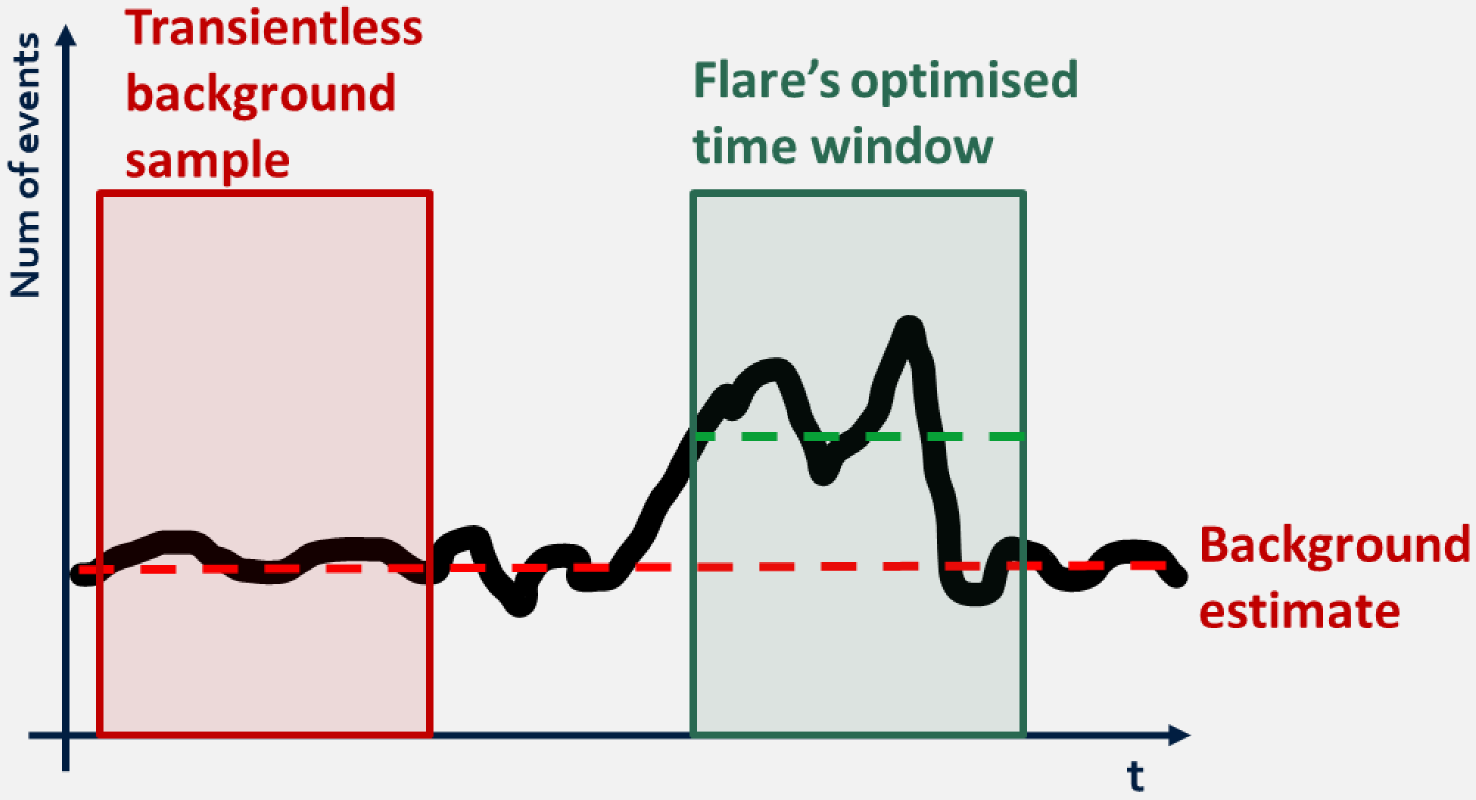
↓

GNN

↓

Prediction

Data after event Selection

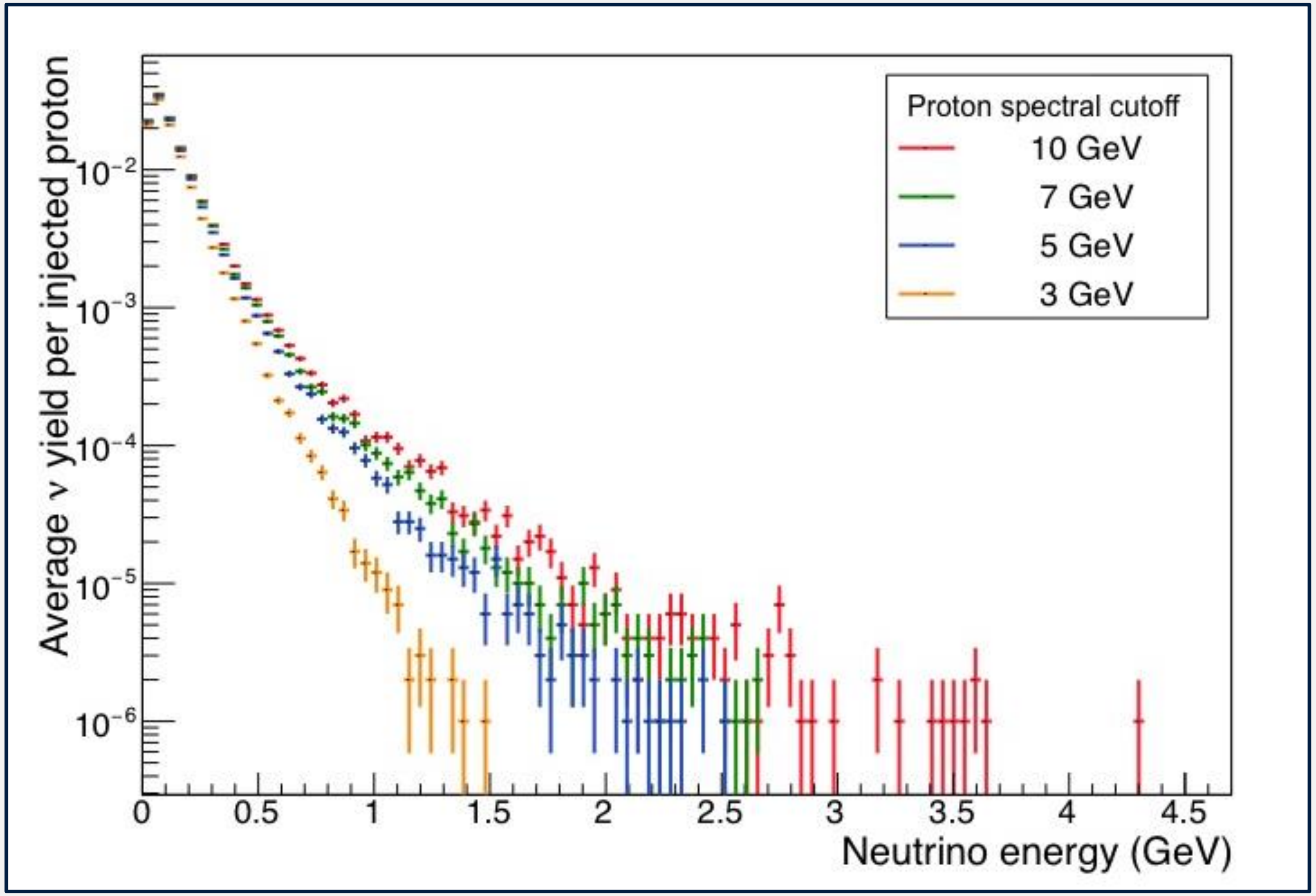


Solar-flare neutrinos predictions

$$F(E) = A\,E^{-\delta}\,H(E_{max} - E)$$

Constant A and spectral index δ derived from observations

Neutrino energies can reach up to a few GeV



G. de Wasseige, *“Solar Flare Neutrinos in the Multi-Messenger Era: Flux Calculations and a Search with the IceCube Neutrino observatory”, PhD thesis Vrije Universiteit Brussel (2018)*

Model architecture: layers

Z. Zhang, et al., *"Hierarchical Graph Pooling with Structure Learning", arXiv preprint (2019)*

Conv → **Pooling** → **Structure Learning** → **Conv** → **Pooling** → **Conv** → **3x Linear**

to perform **pooling** nodes are ranked using an **information score**, i.e., a measure of the distance between the node's representation and its neighbours'

Structure learning is performed by computing **similarity score** between nodes. similarity is high between connected nodes, while disconnected nodes with high similarity get virtually connected before performing convolution.