Applications of GraphNeT

In IceCube Neutrino Observatory

3rd GraphNeT Workshop / 3rd of May. 2023

Rasmus Ørsøe

Technical University of Munich

In parallel to Development …

Commits on Apr 19, 2023

Merge pull request #485 from asogaard/labels … Verified 62eb86c
asogaard committed last week

Add more intuitive key for Direction label 59386cc
asogaard committed last week

Merge pull request #489 from JostMigenda/typos … Verified b331367
asogaard committed last week

2000+ Commits in 240+ Pull Requests

Commits on Sep 22, 2021

Addressed most of Andreas comments 2b20e95
Rasmus Ørsøe committed on Sep 22, 2021

Commits on Sep 21, 2021

Added sqlite_converter that creates a database ala I3ToSQLite. Notice… … c5b573a
Rasmus Ørsøe committed on Sep 21, 2021

Added i3 extractor and general … 06b3c11
Rasmus Ørsøe committed on Sep 21, 2021

Commits on Apr 12, 2021

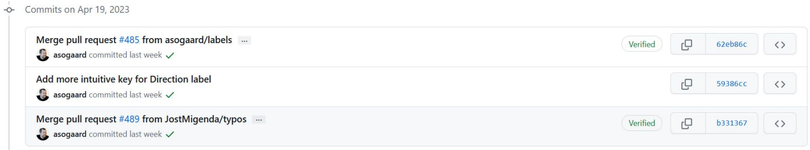
Initial commit Verified a243f7a
philippeller committed on Apr 12, 2021

Today

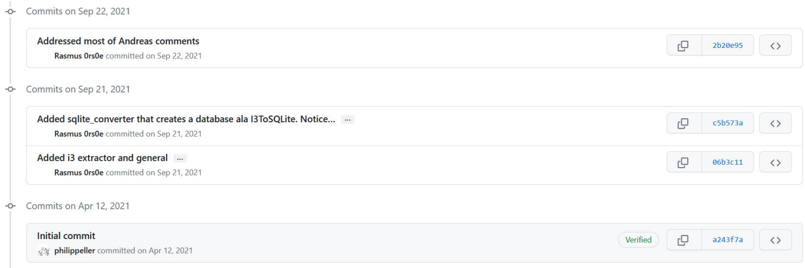
First Commit

In parallel to Development …

We’ve been investigating Applications in IceCube



2000+ Commits in 240+ Pull Requests



Today

First Commit

2 Papers,
4+ Posters,
~20 talks,

ML4Astro, A3D3, Neutrino22,
ML4LatticeQCD, NOW2022, ACAT,..

Applications in IceCube

Today

DynEdge Paper

Presents DynEdge and shows performance & robustness on oscillation dataset in IceCube

First Commit

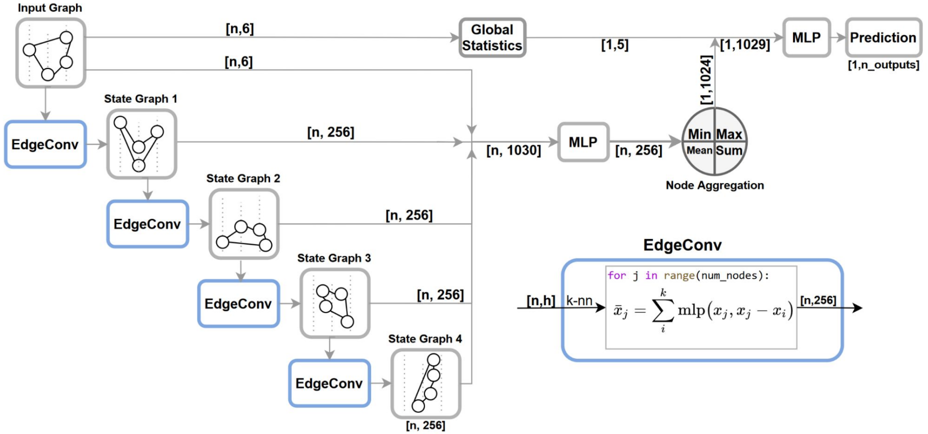


Diagram of DynEdge, from the paper.

Applications in IceCube

Today

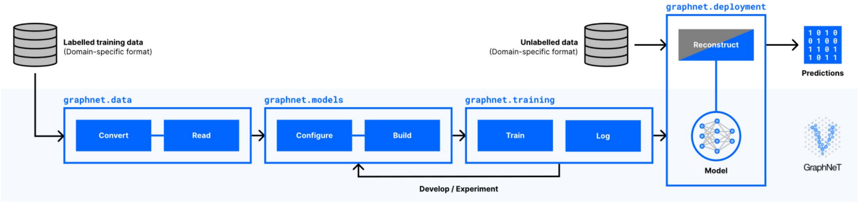
JOSS Paper

Presents GraphNeT, workflow and usage

DynEdge Paper

Presents DynEdge and shows performance & robustness on oscillation dataset in IceCube

First Commit



Overview of GraphNeT, from JOSS paper

Drop-in Replacement

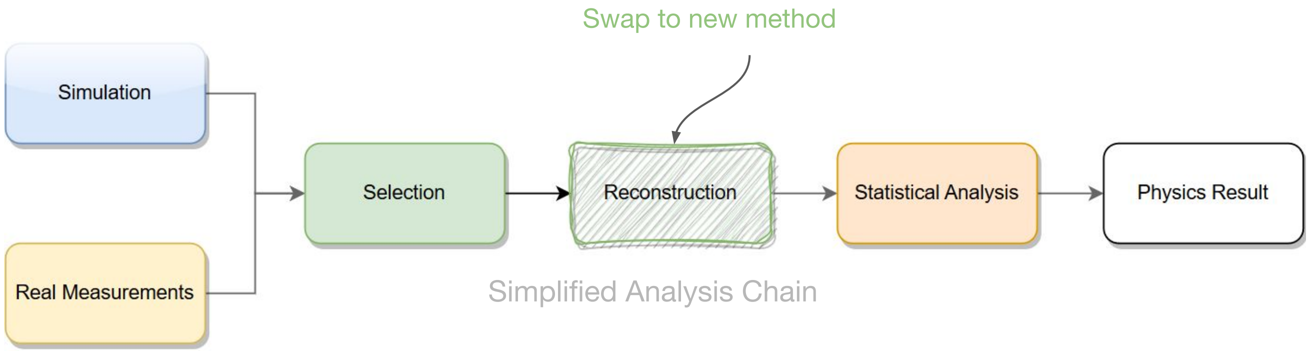
In Existing Analyses

Drop-in replacement
(Low hanging fruits)

Physics results depend highly on the sensitivity, reliability and speed of reconstruction methods

Pro
Improved reconstructions likely to improve results in existing analyses.
Little overhead for analysis owners.

Con
The existing data selection is not always optimal for ML.
Potential improvement in selection not taken into account.



Simplified Analysis Chain

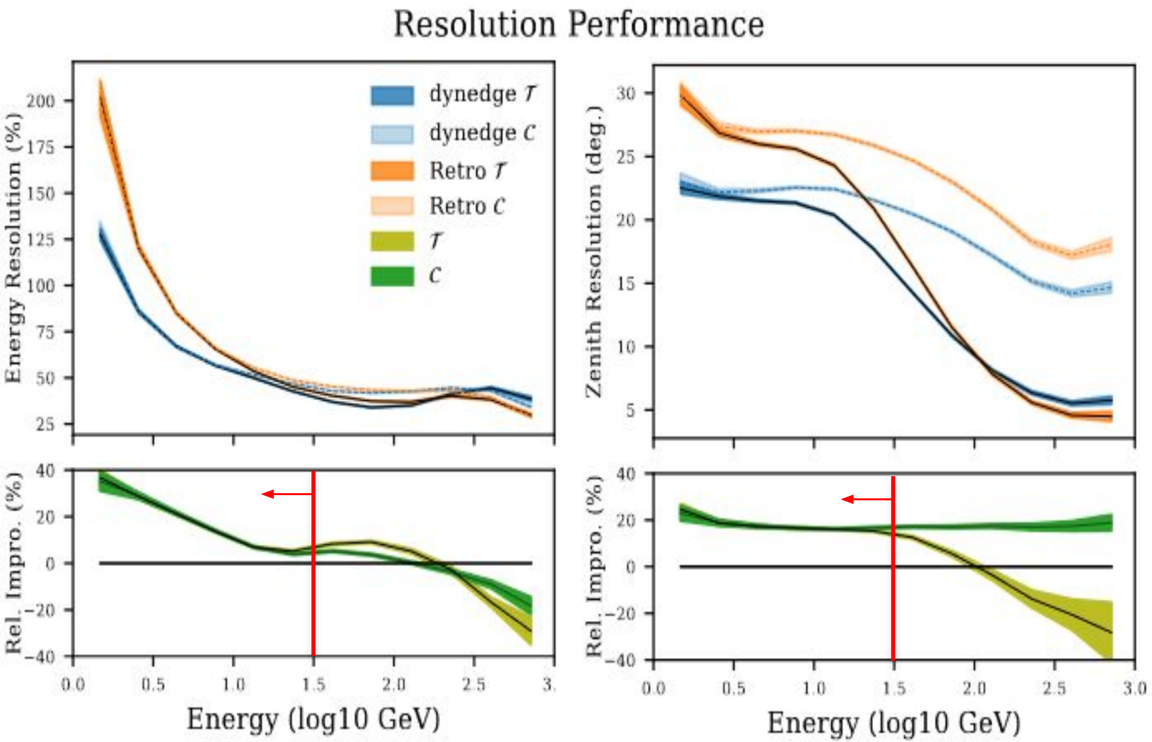
Drop-in replacement

Oscillation Analysis in IceCube

Comparing current method with DynEdge:

Around 20% improvement in variables in relevant energy range used in the oscillation measurement

But what could that mean for the final result?



Drop-in replacement

Oscillation Analysis in IceCube

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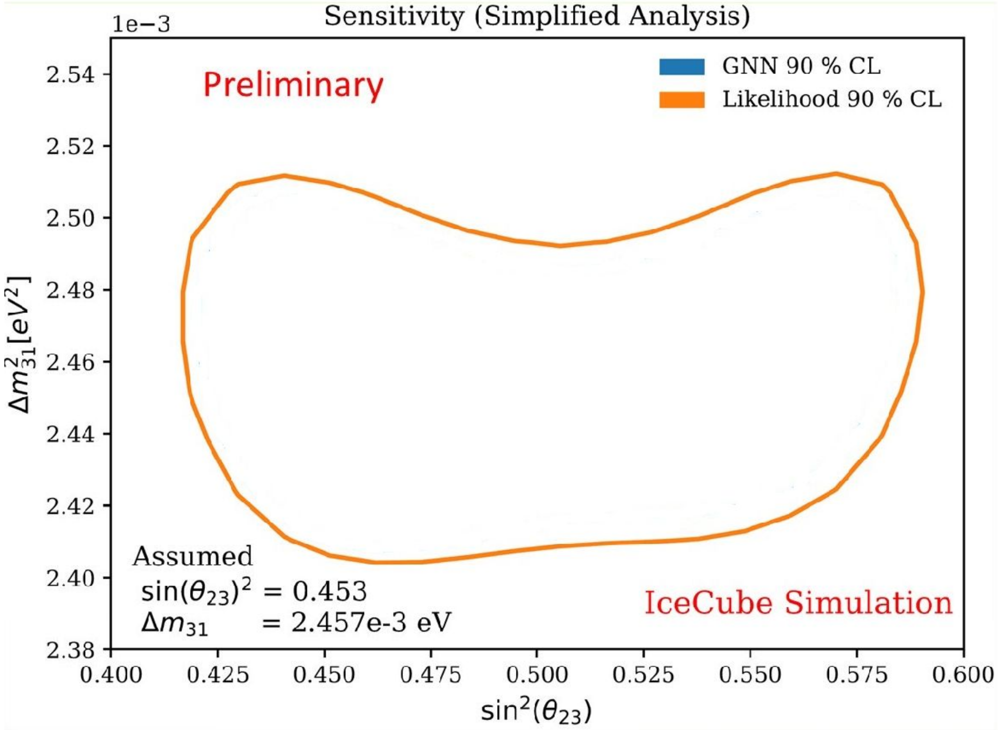
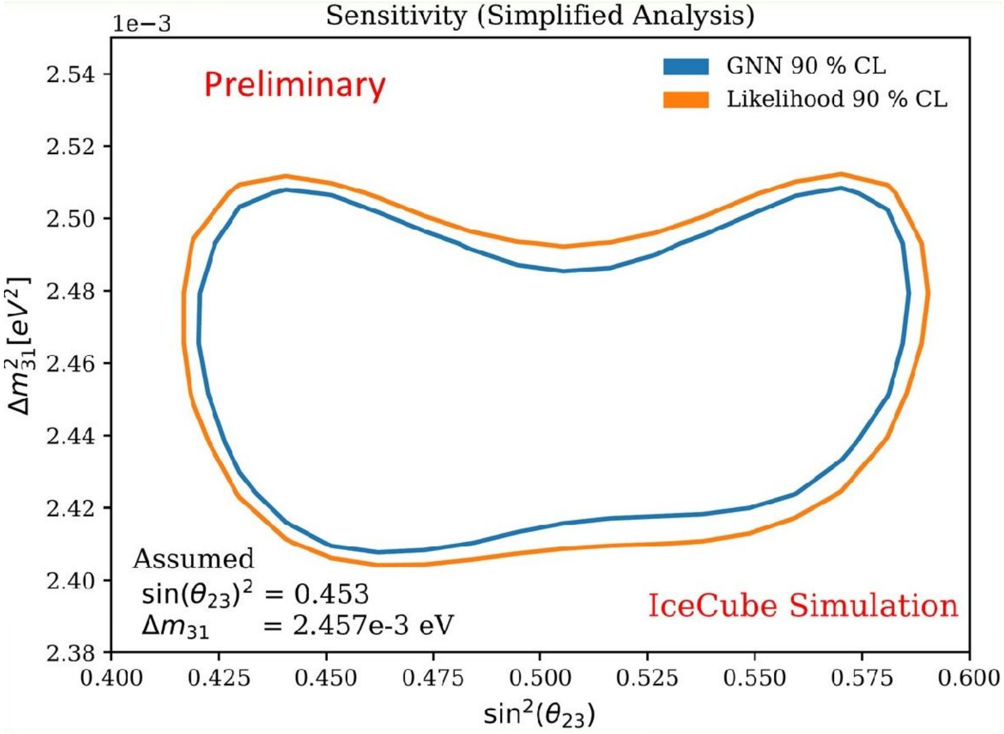


Drop-in replacement

Oscillation Analysis in IceCube

But what could that mean for the final result?

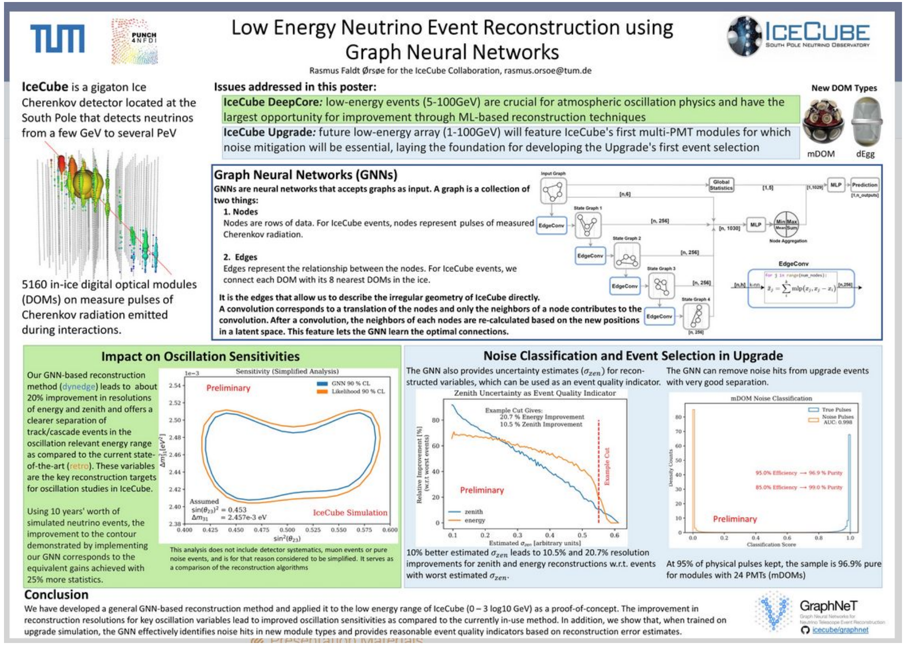
The comparison suggests improvements equivalent to an additional **25%** statistics.



Drop-in replacement

Oscillation Analysis in IceCube

These results were shown in a poster for **Neutrino2022**



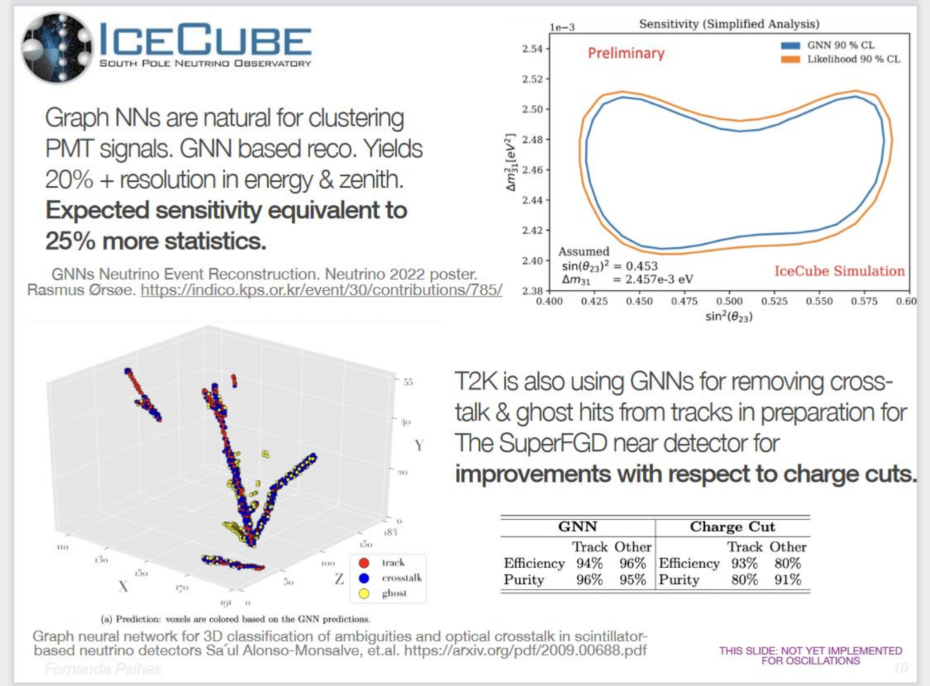
"*Low Energy Neutrino Event Reconstruction using Graph neural Networks*", Neutrino2022

Drop-in replacement

Oscillation Analysis in IceCube

.. and they were mentioned at **NOW2022**

in a talk given by Fernanda Psihas



"*The Role of Machine Learning in Neutrino Physics*", NOW2022

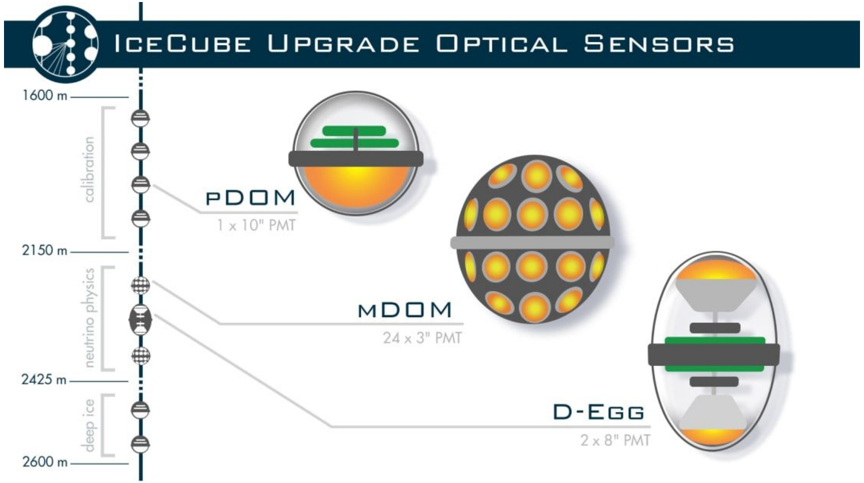
Unlocking New Physics Analyses

Unlocking New Physics Analyses:

IceCube Upgrade Oscillation Sensitivity Projections

"The goal of IceCube Upgrade is to provide world-leading sensitivity to neutrino oscillations and to take unique measurements of tau neutrino appearance with high precision. It also serves as a R&D platform for the future IceCube-Gen2 experiment."

Physics Potential of the IceCube Upgrade



IceCube Press Release

Around 700 new modules

Unlocking New Physics Analyses:

IceCube Upgrade Oscillation Sensitivity Projections

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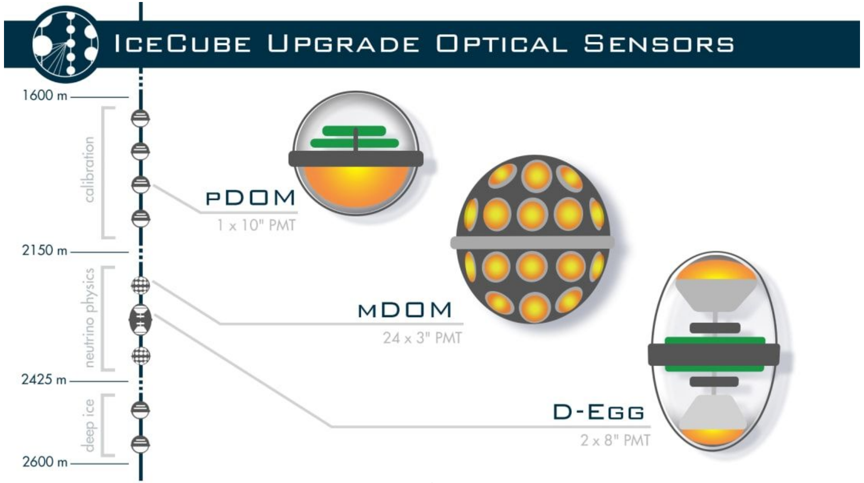
Physics Potential of the IceCube Upgrade



IceCube Press Release

Challenges (From a Data Science Perspective)

1) Current reconstruction methods not compatible with new modules

2) Cleaning algorithms doesn’t work on new modules

Around 700 new modules

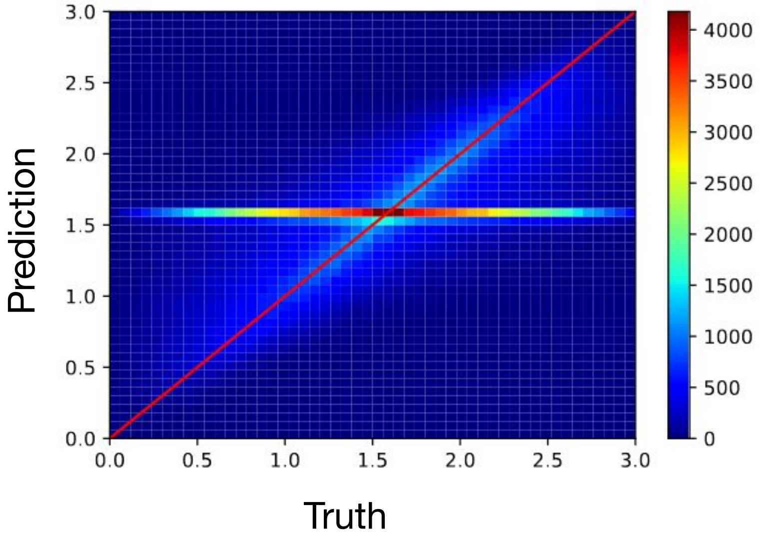
Unlocking New Physics Analyses:

IceCube Upgrade Oscillation Sensitivity Projections

Challenges (From a Data Science Perspective)

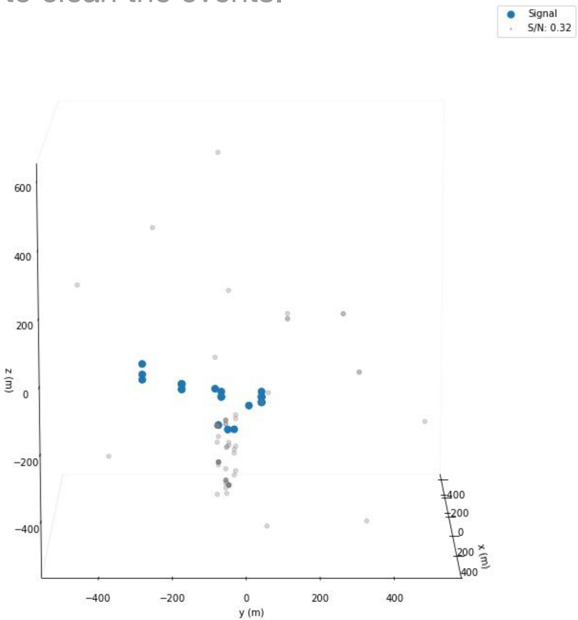
1) Current reconstruction methods not compatible with new modules, but DynEdge is!

2) **Cleaning algorithms doesn't work on new modules**

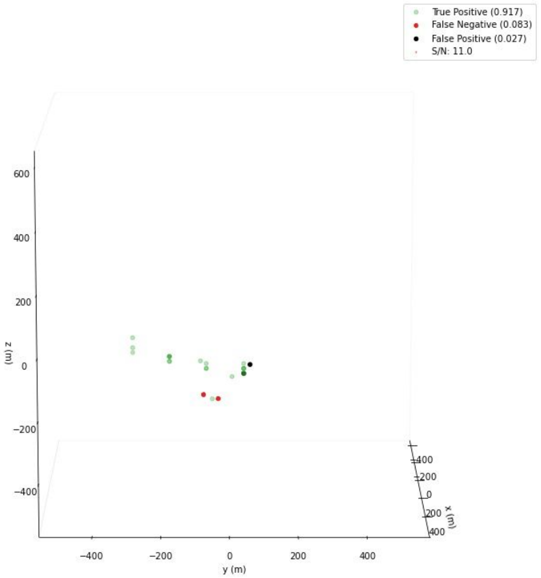


Unlocking New Physics Analyses:
IceCube Upgrade Oscillation Sensitivity Projections

We phrased noise cleaning as a node classification problem, and used DynEdge to clean the events.



Uncleaned Event

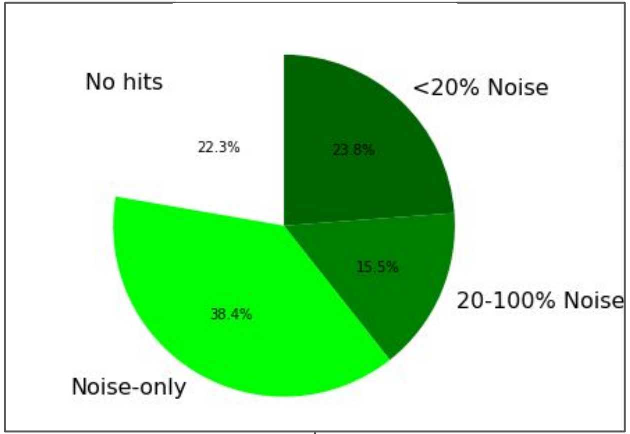


Cleaned by DynEdge

Unlocking New Physics Analyses:

IceCube Upgrade Oscillation Sensitivity Projections

“Classical” Cleaning algorithm

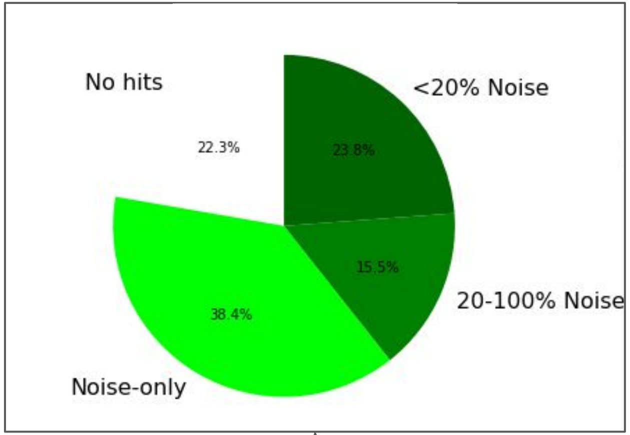


Only 24% of examples have reasonable noise pollution after cleaning

Unlocking New Physics Analyses:

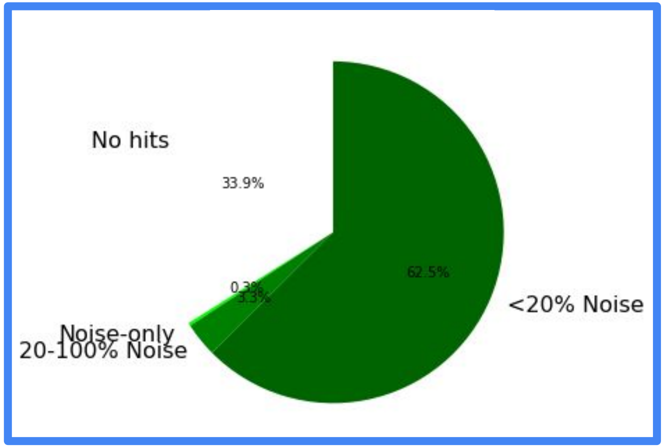
IceCube Upgrade Oscillation Sensitivity Projections

“Classical” Cleaning algorithm



Only 24% of examples have reasonable noise pollution after cleaning

GraphNeT:DynEdge

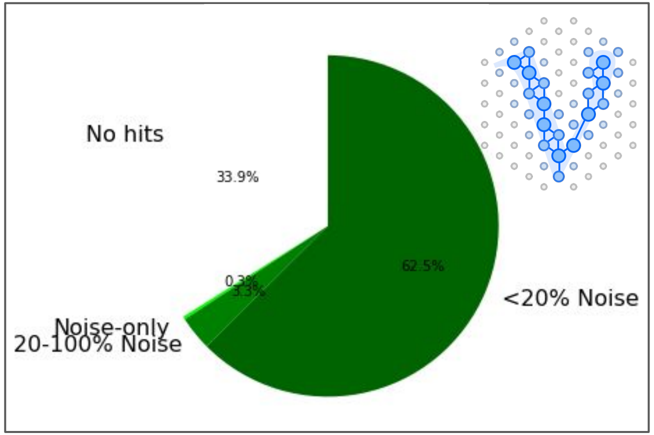


63% of examples have reasonable noise pollution after cleaning

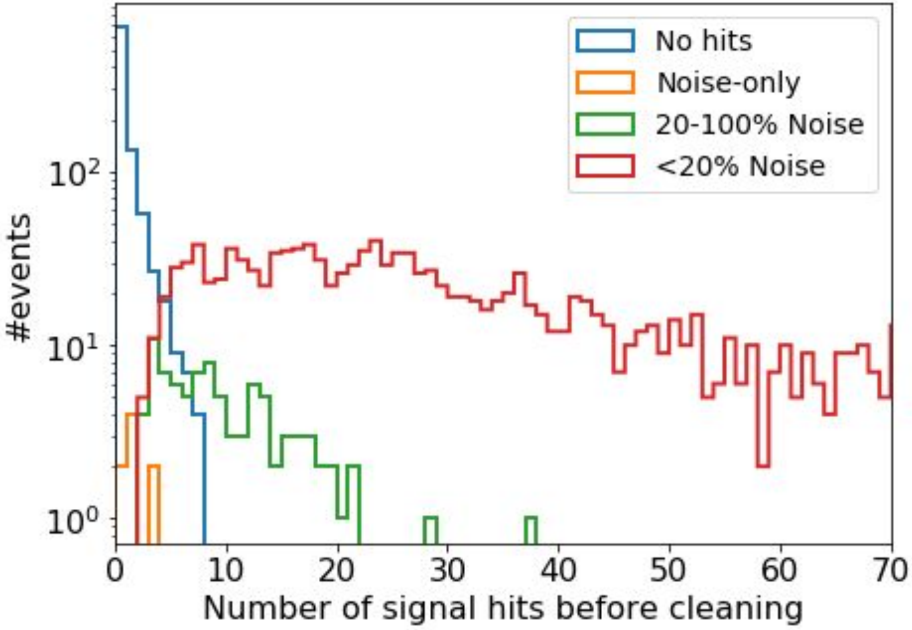
Unlocking New Physics Analyses:

IceCube Upgrade Oscillation Sensitivity Projections

GraphNeT:DynEdge



Distribution of signal hits before cleaning
(in categories from pie-chart)

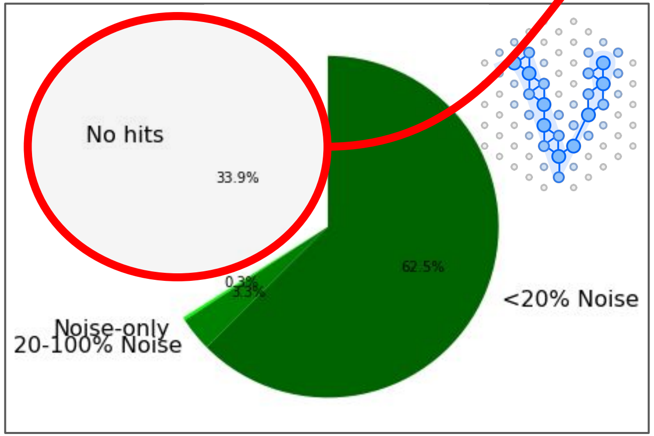


(Plot made by Jan Weldert)

Unlocking New Physics Analyses:

IceCube Upgrade Oscillation Sensitivity Projections

GraphNeT:DynEdge



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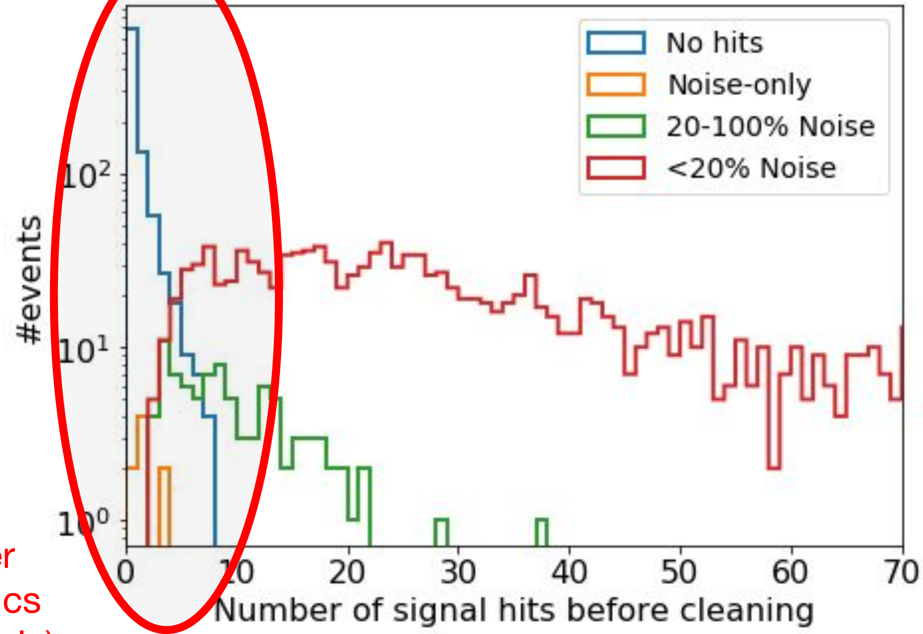


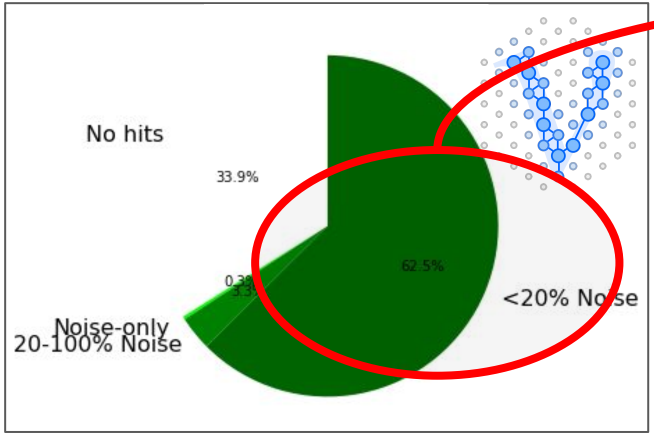
All events with 0 pulses after cleaning had 9 or less physics pulses; most have 0 (log-scale)

(Plot made by Jan Weldert)

Unlocking New Physics Analyses:

IceCube Upgrade Oscillation Sensitivity Projections

GraphNeT:DynEdge



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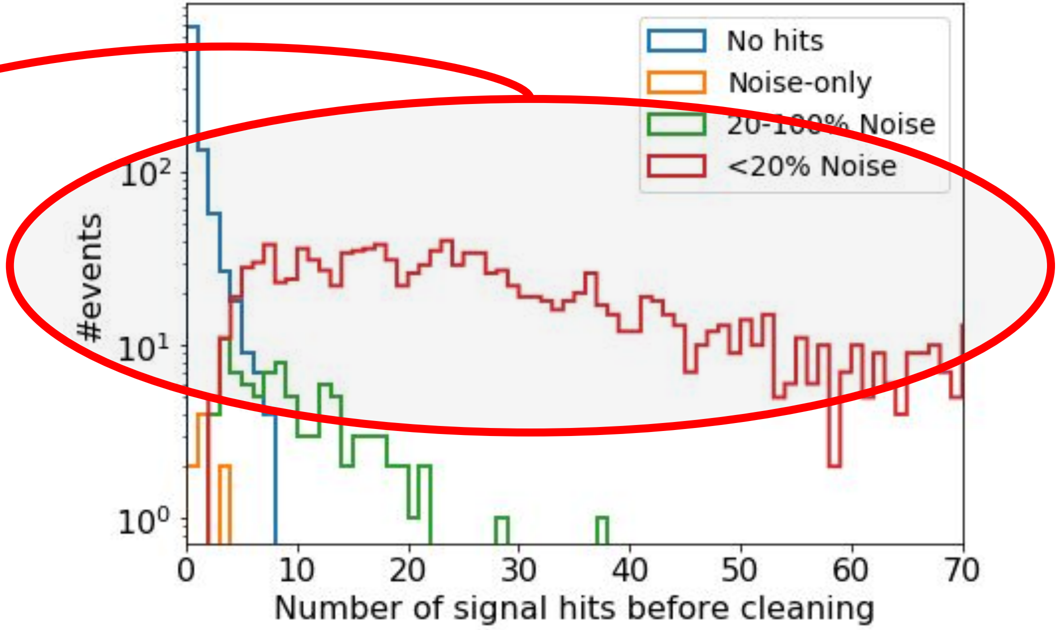
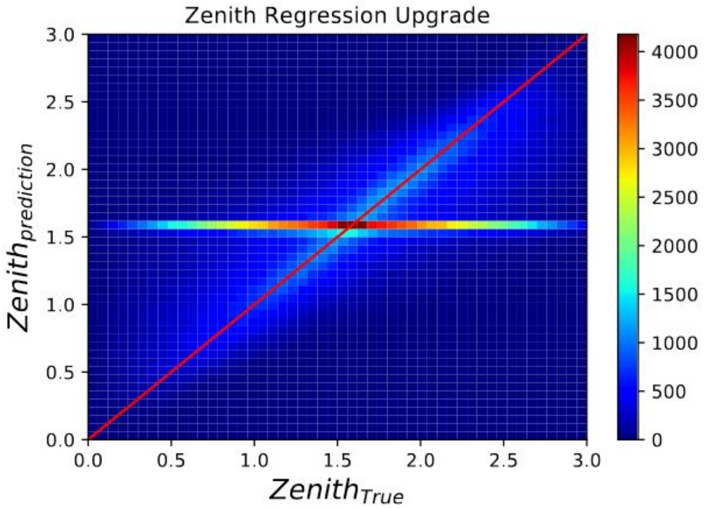


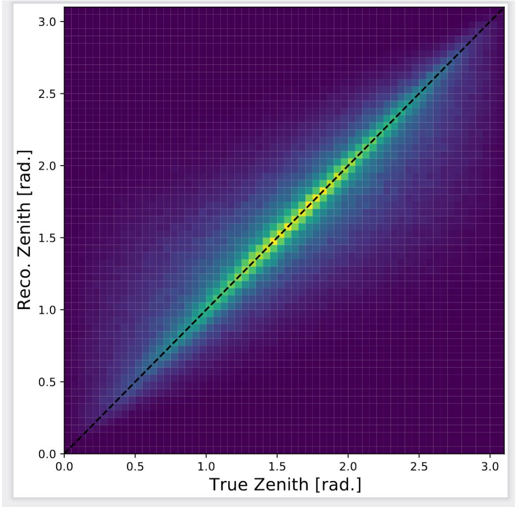
(Plot made by Jan Weldert)

Unlocking New Physics Analyses:

IceCube Upgrade Oscillation Sensitivity Projections



“Classically” cleaned events



GNN cleaned events

Unlocking New Physics Analyses:

IceCube Upgrade Oscillation Sensitivity Projections

Deploy pre-trained models with a minimal technical threshold:

```
from graphnet.deployment.i3modules import GraphNeTI3Deployer
```

```
# Construct I3 deployer
deployer = GraphNeTI3Deployer(
    graphnet_modules=[deployment_module],
    n_workers=1,
    gcd_file=gcd_file,
)

# Start deployment - files will be written to output_folder
deployer.run(
    input_files=input_files,
    output_folder=output_folder,
)
```

Unlocking New Physics Analyses:

IceCube Upgrade Oscillation Sensitivity Projections

Conclusion:

The pulse cleaning & reconstruction paved the way for Kayla and Jan to project sensitivities for multiple oscillation measurements, and the results will be shown at ICRC2023 this summer, and likely followed up by an IceCube paper.

Other groups within IceCube studying different physics will use their work as a stepping stone for new analyses.

Steps are being taken to compare the GNN cleaning with methods on other datasets..

Penn State University

Kayla DeHolton

Jan Weldert

On-Going Studies

On-Going Studies:

Simulation / Data Disagreement at Low Energies

Because of it's speed and similar response to systematic uncertainties, DynEdge has been used frequently to help probe causes of MC/Data disagreement in the low energy range of IceCube.

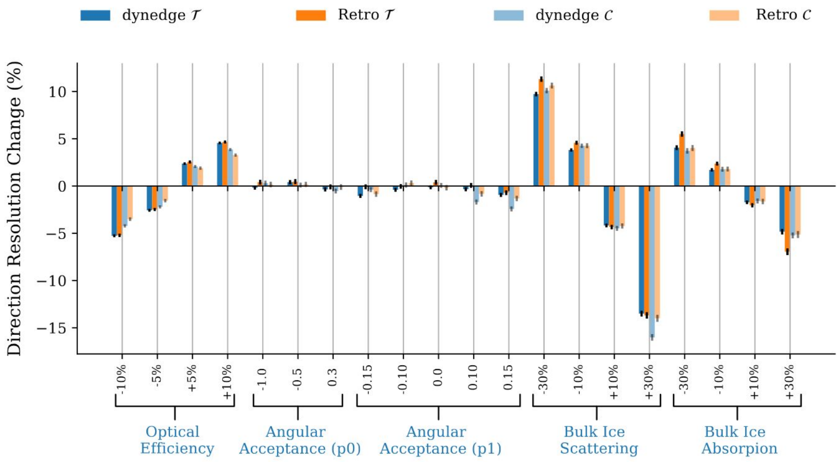
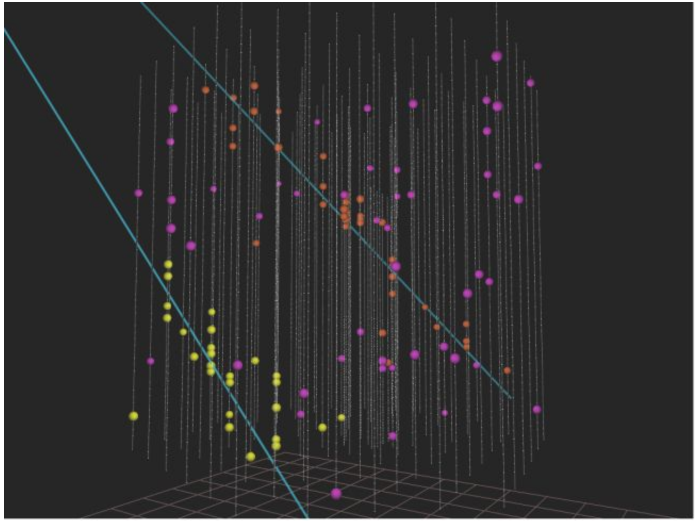


Figure 10. The variation in resolution for DYNEDGE and RETRO on the 20 different systematic sets for reconstruction targets energy, zenith, and direction.

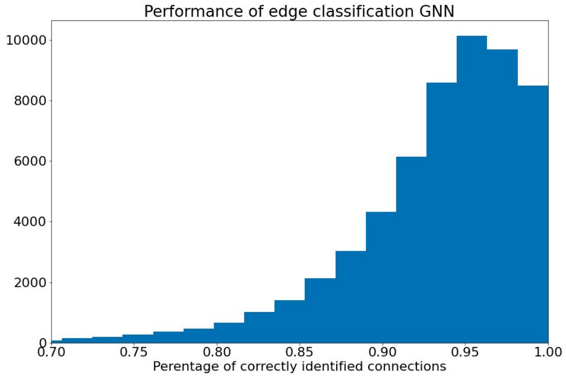
(DynEdge paper)

On-Going Studies:
Event Splitting

Patrick Hatch, PhD Student at Queen's University is phrasing the splitting of coincidental events as an *edge classification* problem in GraphNeT.



Example of coincidental event



Early results from Patrick, suggesting that the method is working. Further studies in progress.

Patrick Hatch

On-Going Studies:

Event Selection for Low Energy Range

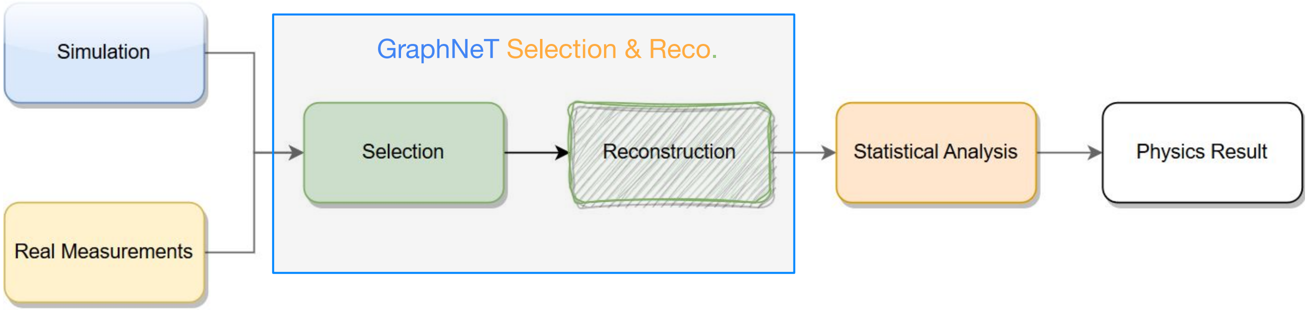
Morten, Peter & Andreas, MSc Students at Niels Bohr Institute
Are working on an event selection using GraphNeT at the energy range typically used for neutrino oscillations in IceCube.

Early results suggest that a significant improvement in signal retention is possible, which is likely to improve the contours shown at Neutrino2022 even further.

Morten Holm

Peter Andresen

Andreas Mogensen



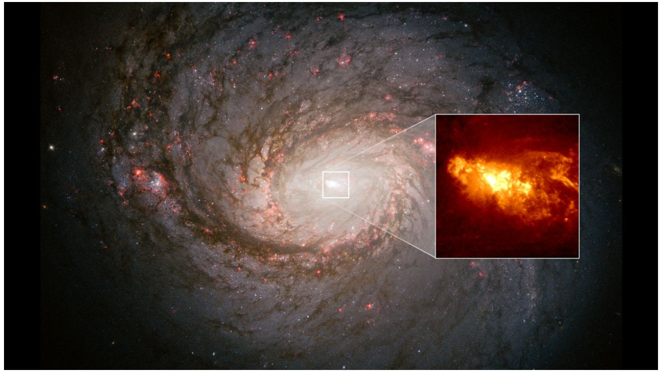
On-Going Studies:

Neutrino Emissions from NGC1068 - Extended Analysis

IceCube telescope: High-energy neutrinos discovered in galaxy NGC 1068

First neutrino image of an active galaxy

For over ten years the IceCube Observatory in the Antarctic has been monitoring the light traces of extragalactic neutrinos. While evaluating the observatory's data, an international research team led by the Technical University of Munich (TUM) discovered a high-energy neutrino radiation source in the active galaxy NGC 1068, also known as Messier 77.



(NGC1068 by Hubble Space Telescope)

Published in Science - at 4.2 sigma - teasingly close to discovery

Extended analysis underway with more statistics

On-Going Studies:

Neutrino Emissions from NGC1068 - Extended Analysis

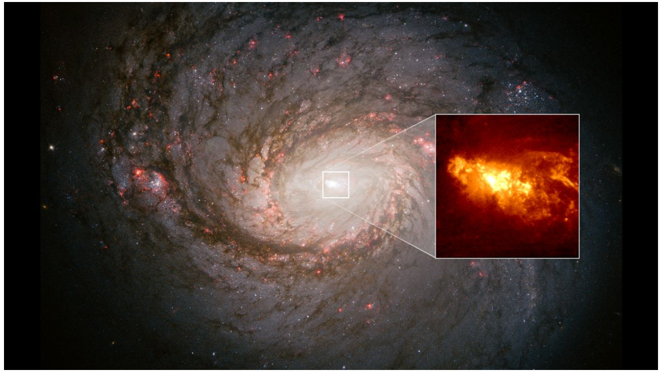
Include data taken while IceCube was still under construction

Datasets with a different number of deployed strings:

- Requires retraining of existing energy reconstruction (CNN)
- Will introduce multiple estimators instead of a single

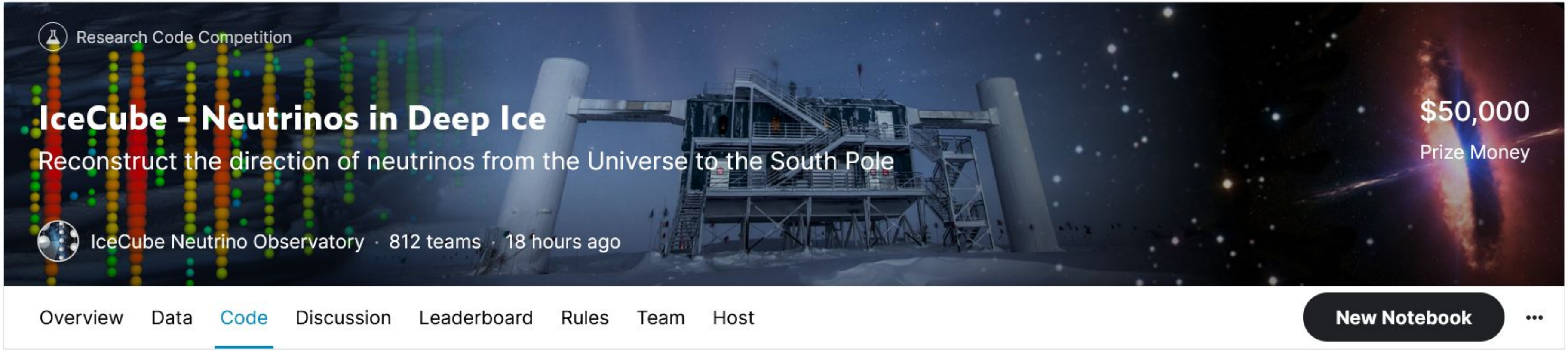
Early results suggests **20 - 40% improvement** in reco. energy.

Will be part of ICRC2023 proceeding



(NGC1068 by Hubble Space Telescope)

Lessons from kaggle



For the past months, an IceCube reconstruction challenge has been ongoing, and yesterday it was concluded!

Lessons from kaggle

Early on we shared a pre-trained DynEdge with the competitors, along with an example notebook introducing GraphNeT.

Many have played around with GraphNeT, made their own GNNs or modified DynEdge.

Solutions in the top 30 is still being shared, but a general picture is emerging

Graph Neural Networks on Competition Data

Graph Neural Networks (GNNs) are a class of neural networks that work on graph representation of data. In recent years, development and application of GNNs have been of high interest in the machine learning community, and includes areas of research such as protein folding, computer vision and knowledge graphs. Part of the appeal of GNNs is the data representation itself - the graphs - as they provide an abstract and flexible format to represent a wide range of issues as GNN problems. Specifically for IceCube, GNNs are interesting because graphs allow us to naturally represent the irregular geometry.

GraphNeT
Graph Neural Networks for
Neutrino Telescope Event Reconstruction

(Snapshot of example notebook)

Lessons from kaggle

My model has a simple structure with EdgeConv and Transformer connected.

in several of our models, we incorporated GraphNet feature extractor.

combining GraphNet and Transformer

GNN and Transformer part

I used VonMisesFisher3DLoss

I focused on fine-tuning the baseline GraphNet solution

GNNs Ensemble

I used the `DirectionReconstructionWithKappa` task directly from GraphNet

Lessons from kaggle

8 solutions in the top 10 has been made public:

Ensembling	7/8
GNN + Transformer	6/8 (4/6 is DynEdge)
VonMisesFisherLoss	6/8 (2/8 is cross entropy)
Pure Transformer	1/8
Pure GNN	1/8

Most solutions used functionality from GraphNeT.

One solution ensemble many RNN-based models, where one of the ensemble members used 1D CNN layers.

The internet has spoken

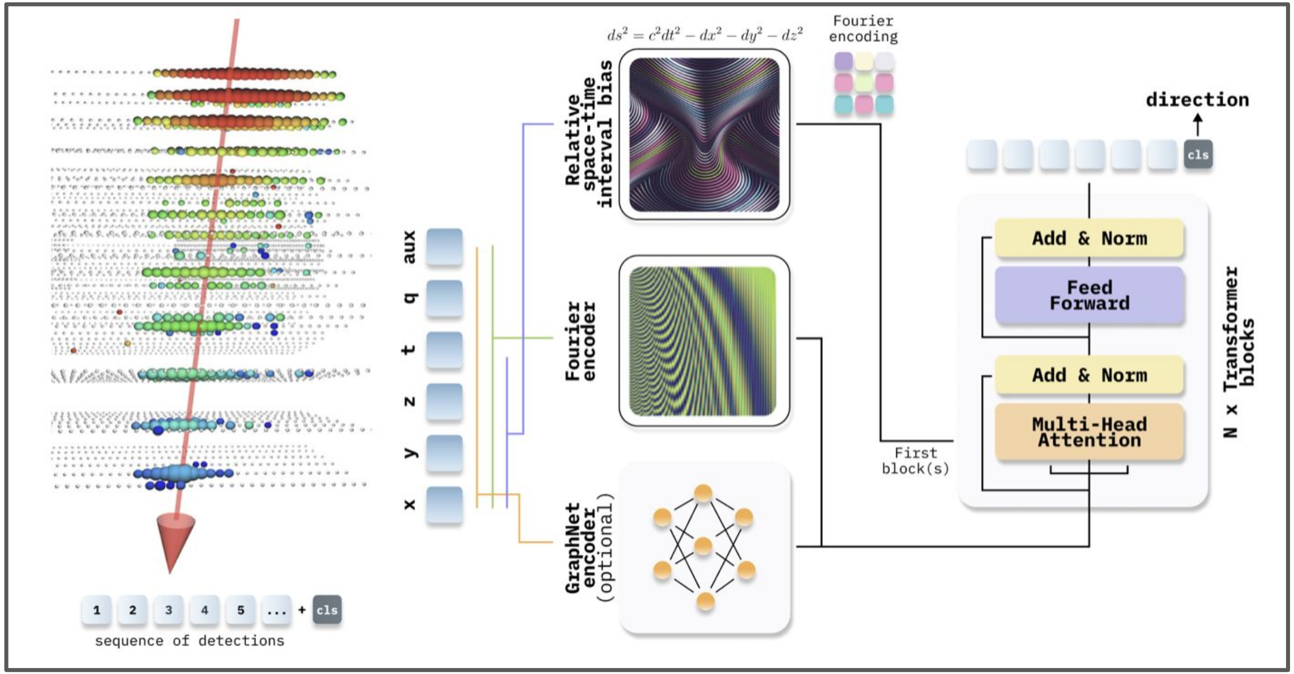
GNN + Transformer trained w. VonMisesFisher3DLoss in ensemble

But how?

Lessons from kaggle

(1st place architecture)

(2nd place architecture)



Thank you for listening!

GraphNeT
Graph Neural Networks for
Neutrino Telescope Event Reconstruction

icecube/graphnet