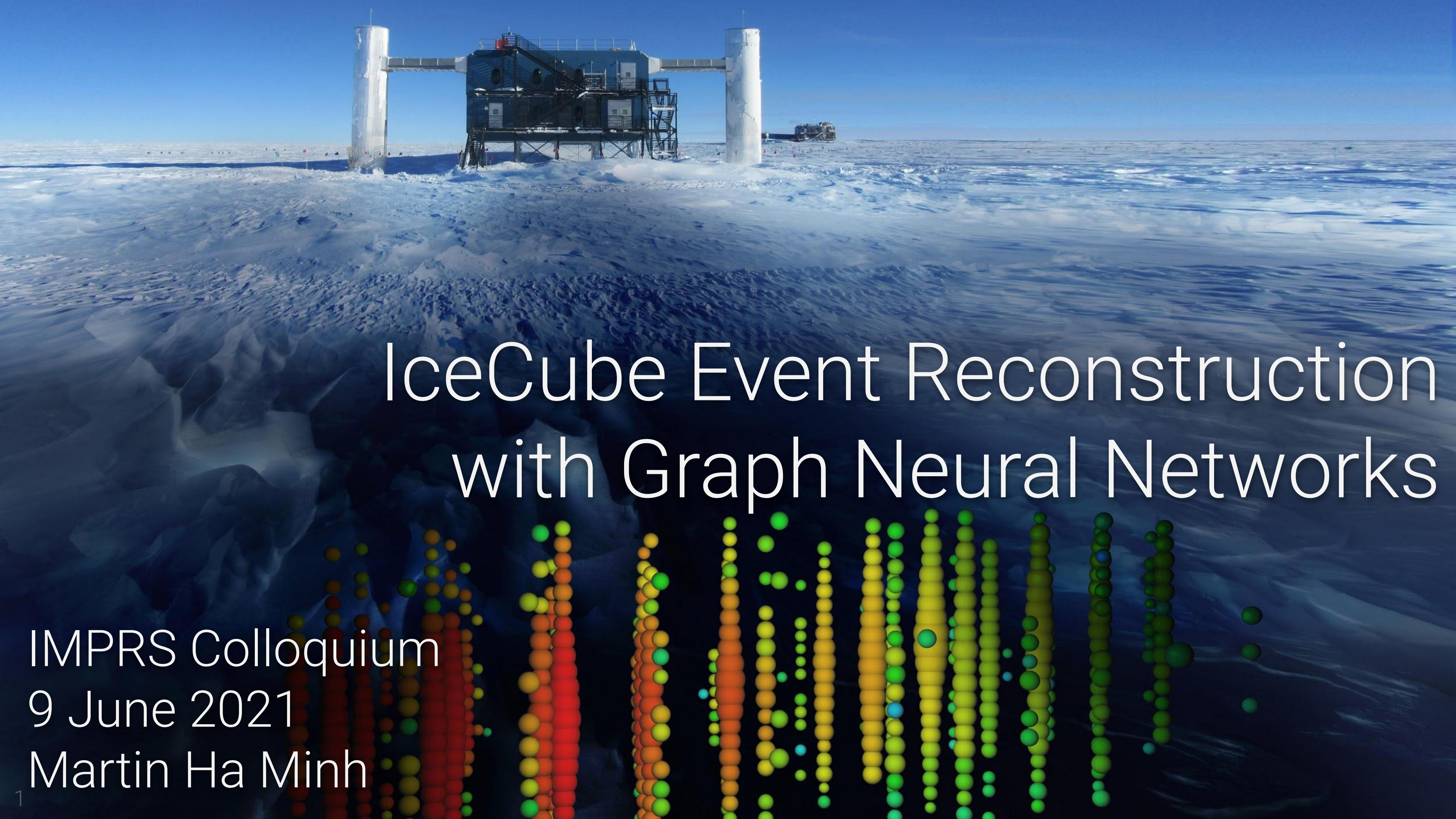
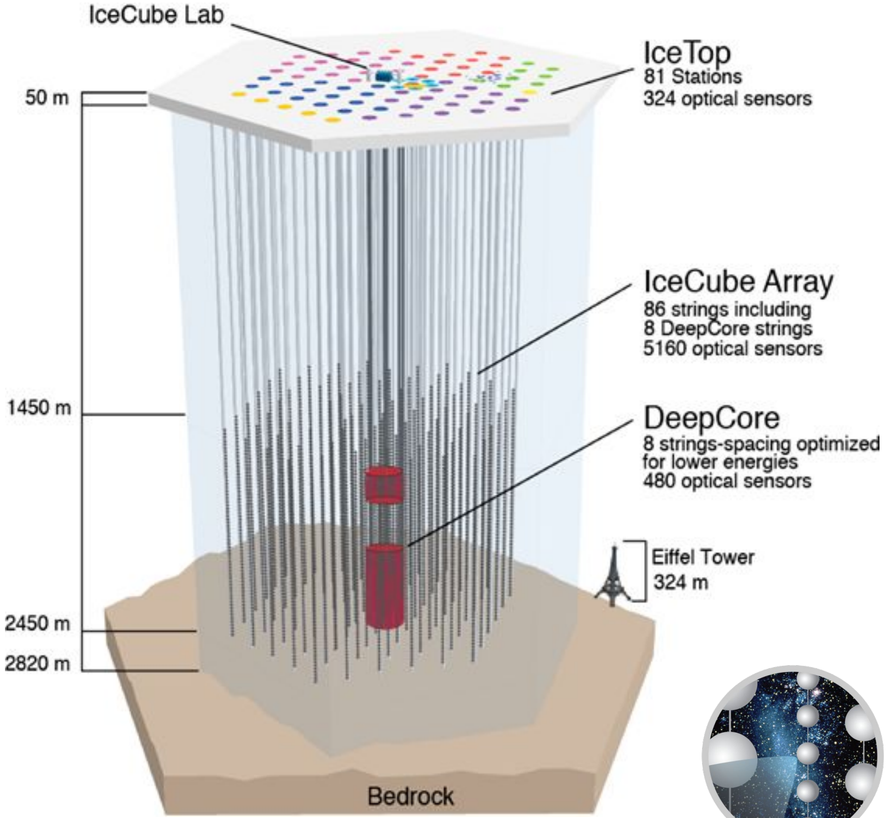
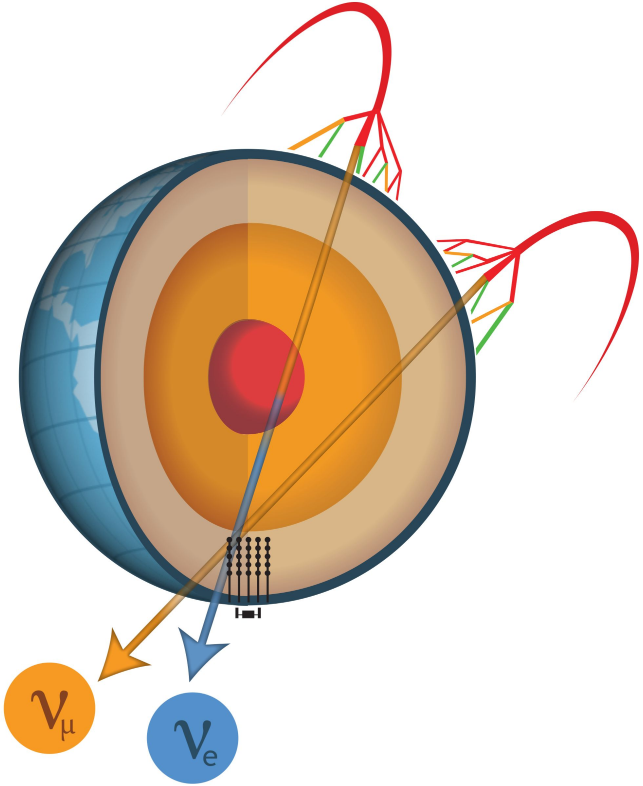


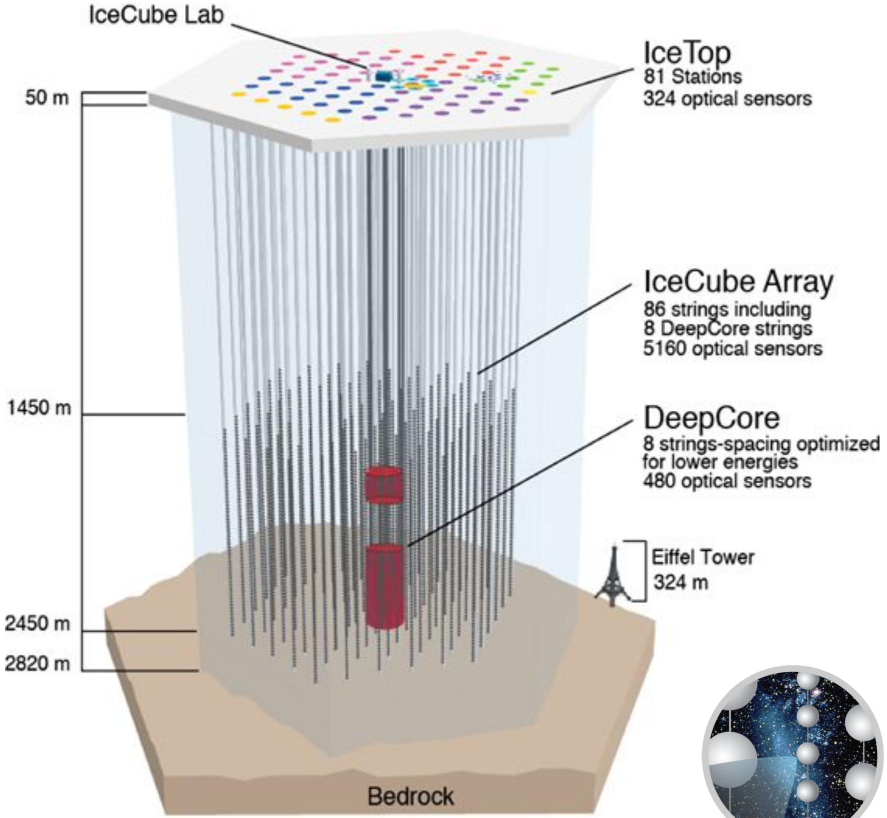
IceCube Event Reconstruction with Graph Neural Networks

IMPRS Colloquium
9 June 2021
Martin Ha Minh


IceCube Lab
IceTop
81 Stations
324 optical sensors
50 m
IceCube Array
86 strings including
8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized
for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock



ν_μ
ν_e



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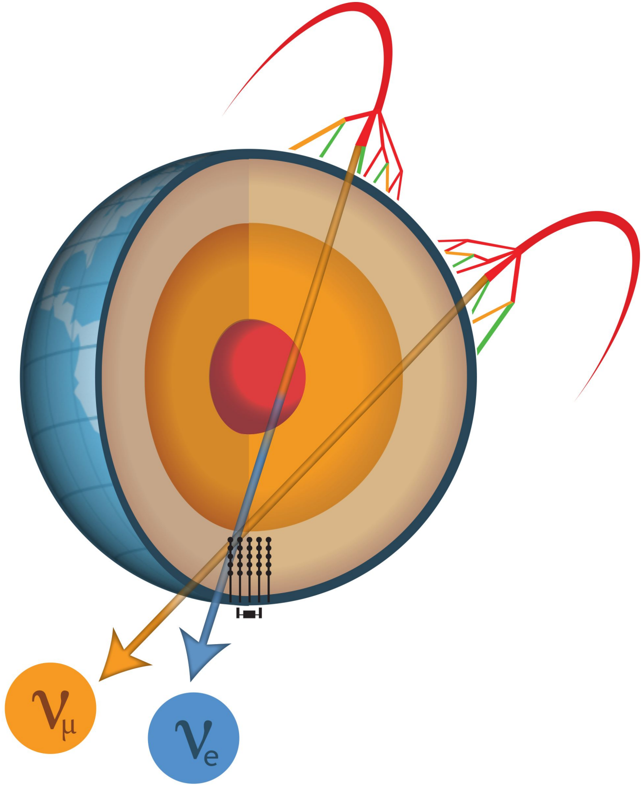
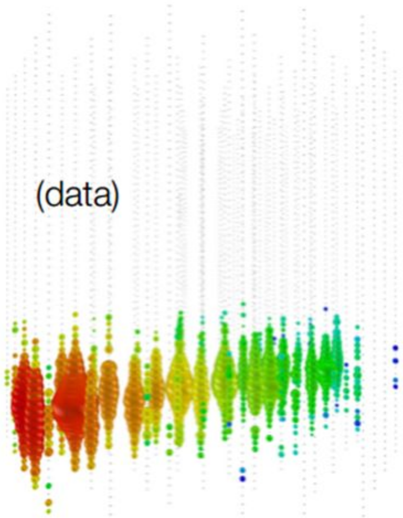
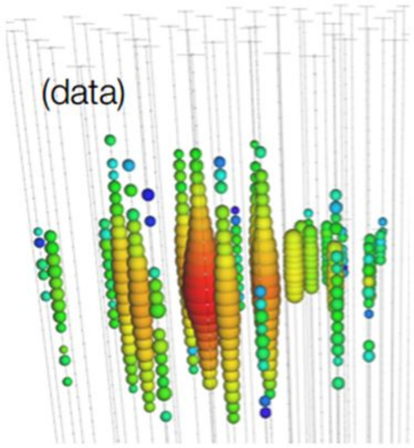


Charged-current ν_μ



Up-going track

Neutral-current / ν_e



Isolated energy deposition (cascade)


IceCube Lab at the South pole

Neutrino astronomy

IceCube Lab at the South pole

Neutrino astronomy

BSM physics

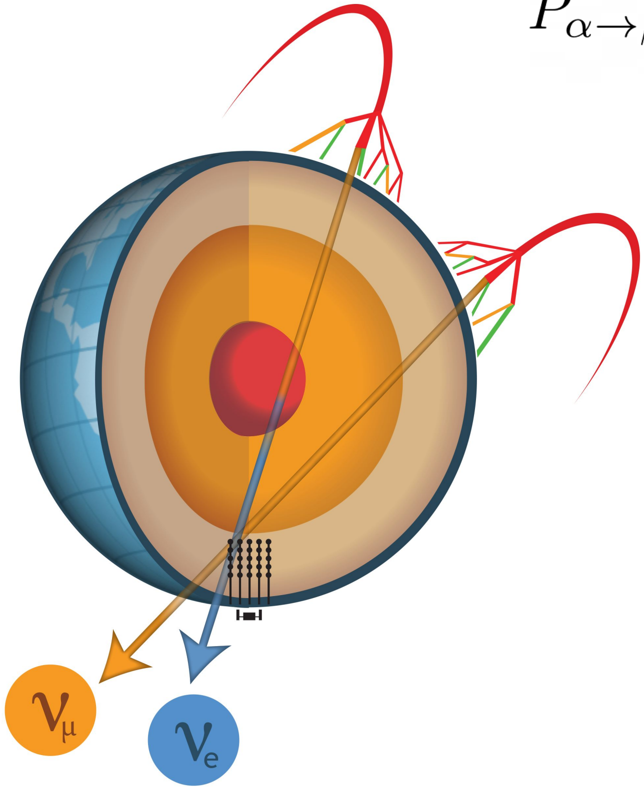
IceCube Lab at the South pole

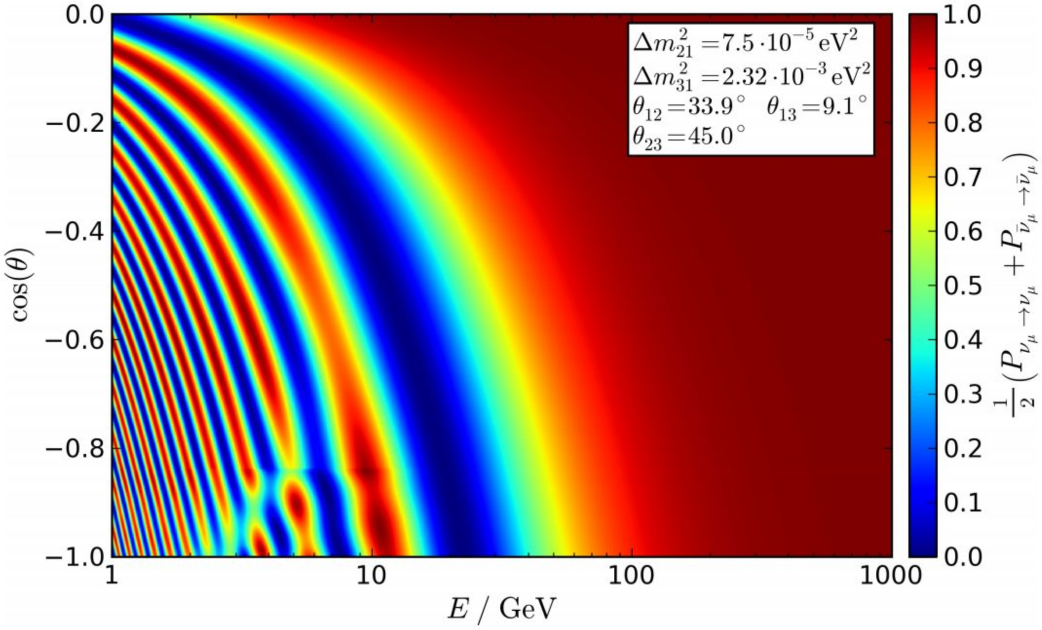
IceCube Lab at the South pole

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta_{\alpha\beta})\sin^2\left(\frac{\Delta m^2_{\alpha\beta} L}{4E}\right)$$

Physical parameters

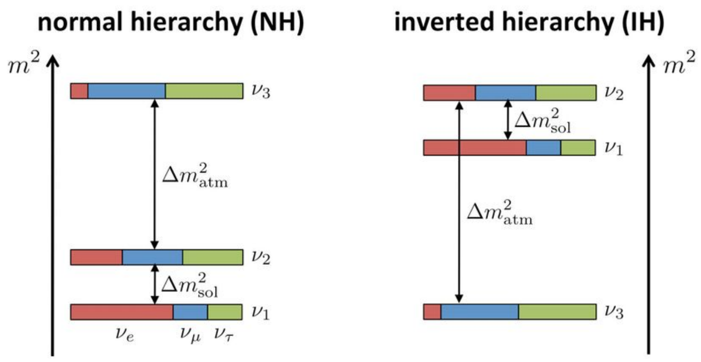
Experimental properties





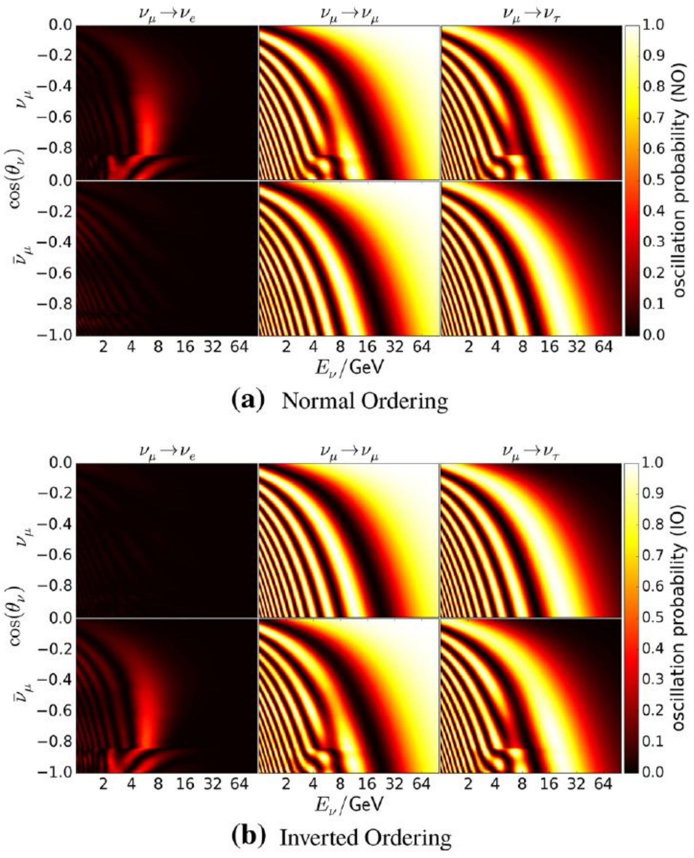
Survival probability of a atmoshperhic muon neutrino at IceCube

Neutrino mass hierarchy



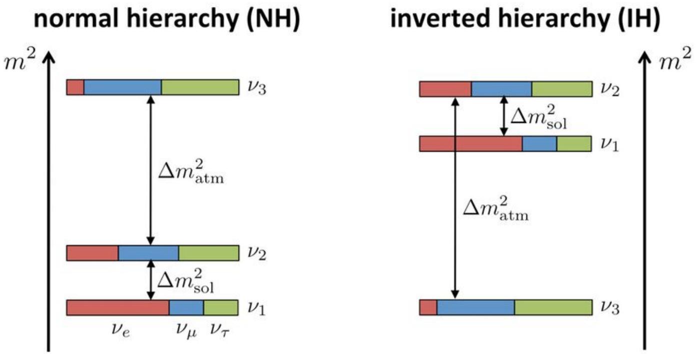
arXiv:1902.07771

Neutrino mass hierarchy

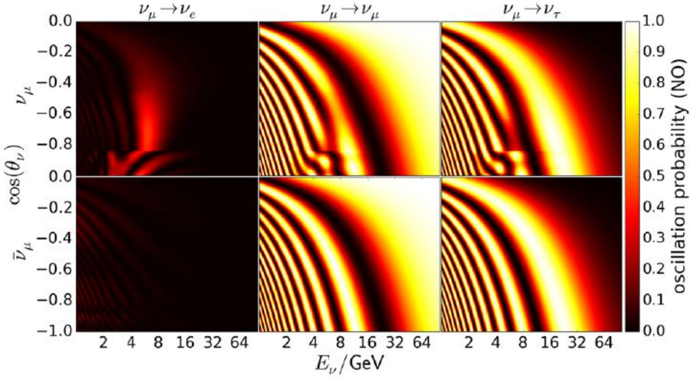


(a) Normal Ordering

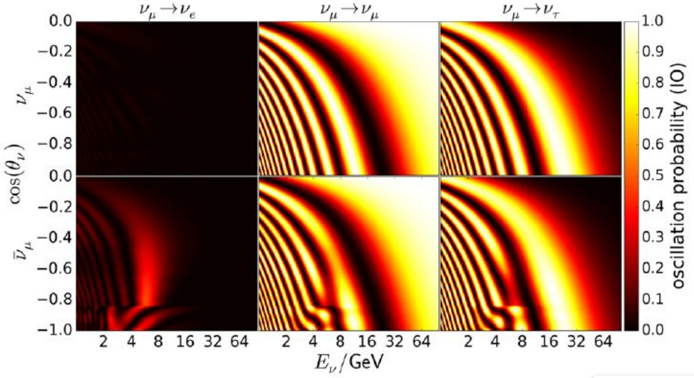
(b) Inverted Ordering



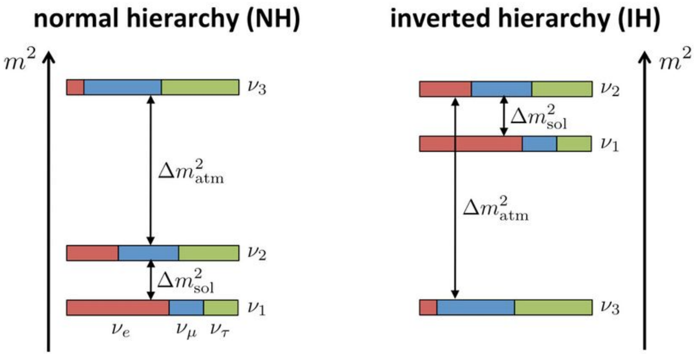
Neutrino mass hierarchy

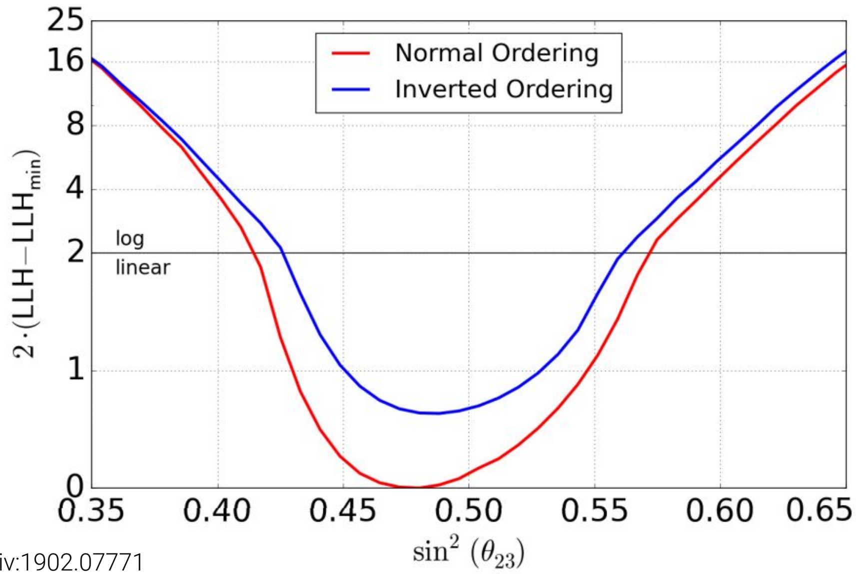


(a) Normal Ordering



(b) Inverted Ordering





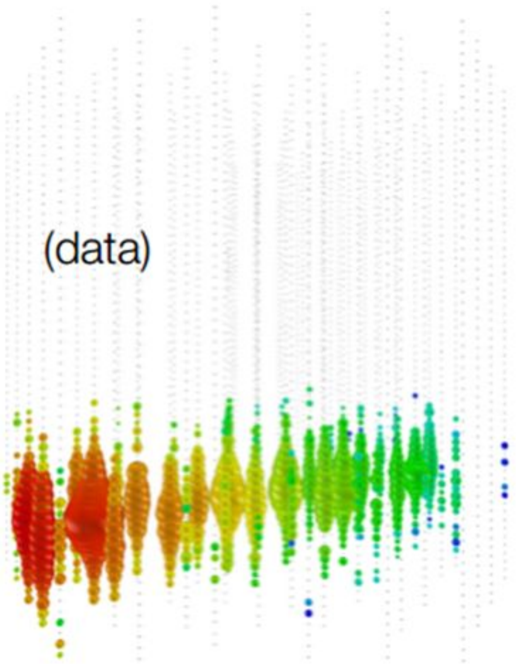
arXiv:1902.07771

MSW effects shows different signatures!

However: effect only visible < 10GeV !

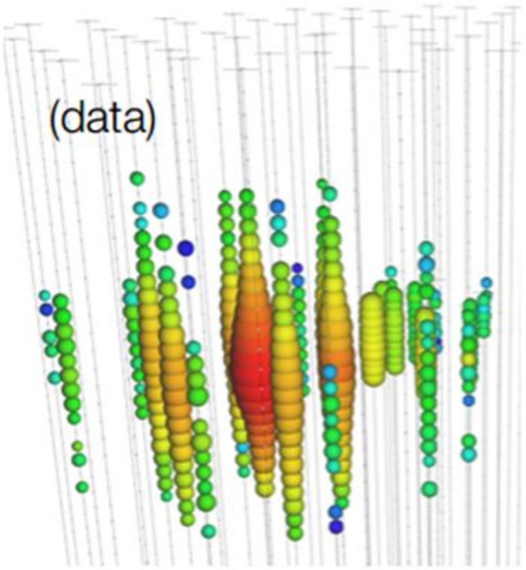
Need for lower energies!

Charged-current ν_μ



Up-going track

Neutral-current / ν_e



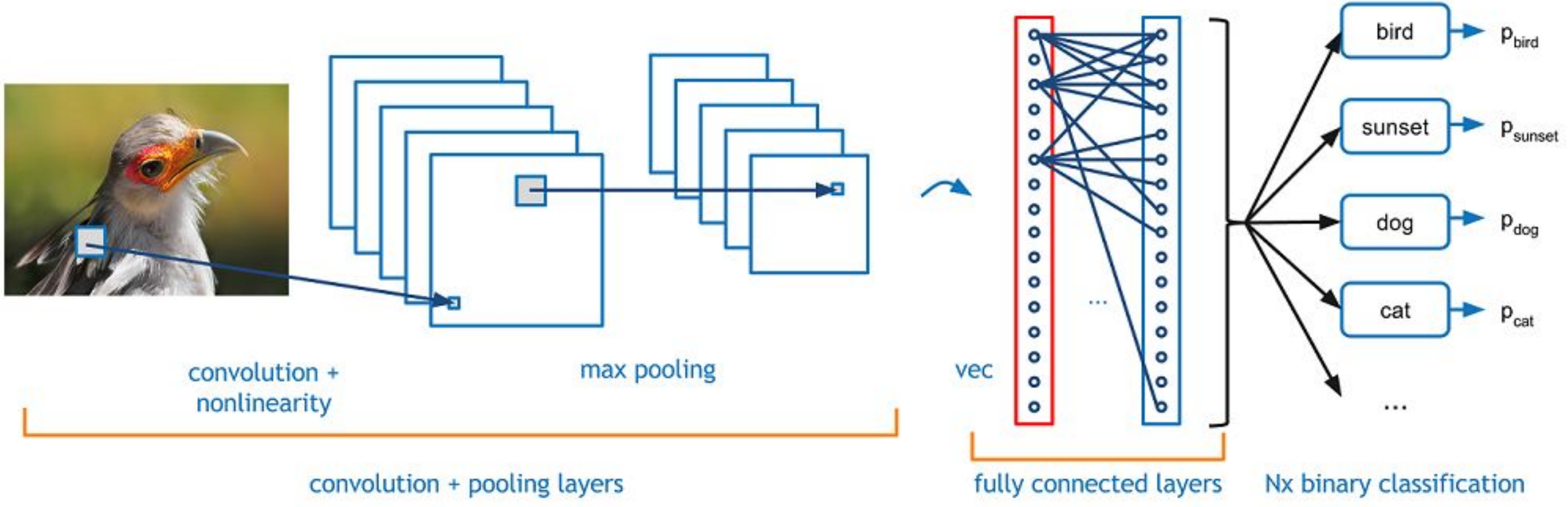
Isolated energy deposition (cascade)

Quantities necessary for analysis:

- Neutrino direction
- Neutrino energy
- Interaction type (track vs data)

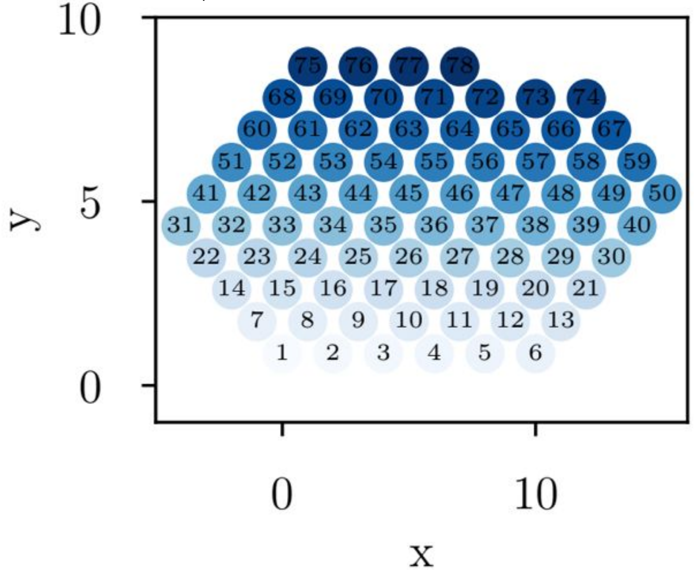
How do we get to those?

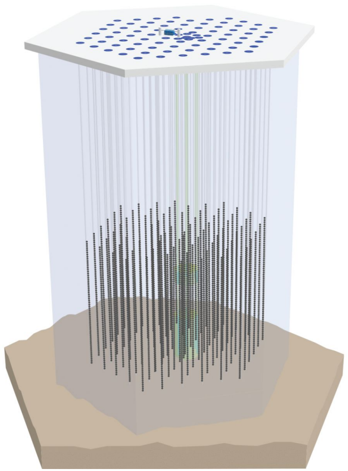
Convolutional neural networks

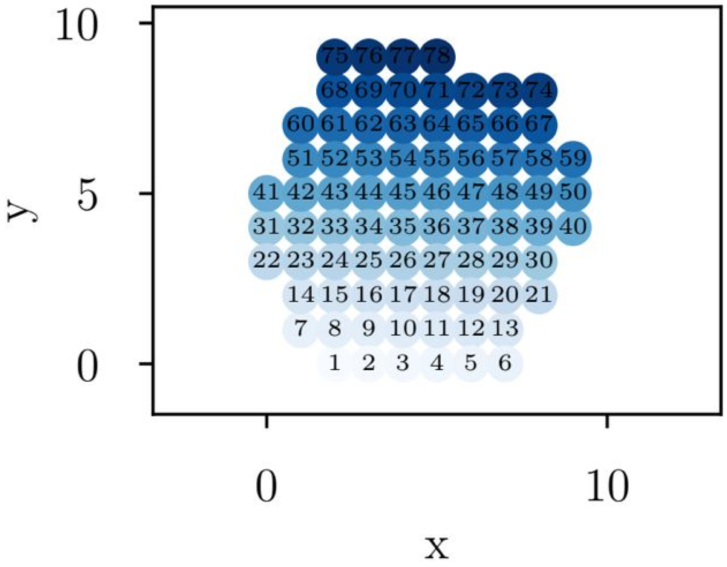


CNNs often used for image processing
→ Adaptation of IceCube detector

"Top down" view of detector



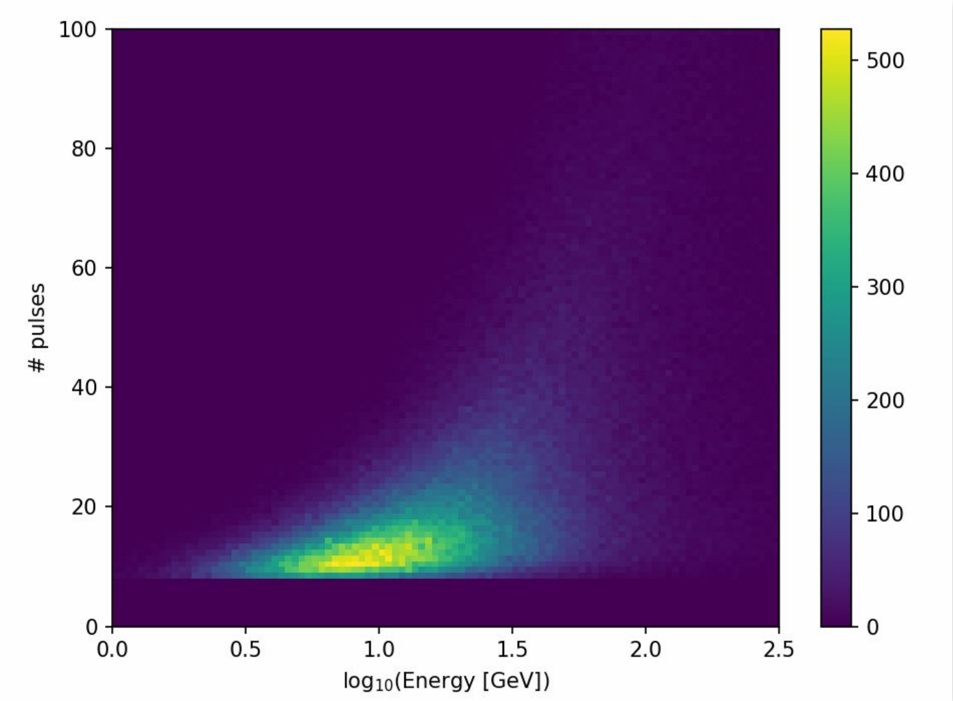




Convolutional neural networks

Caveats:

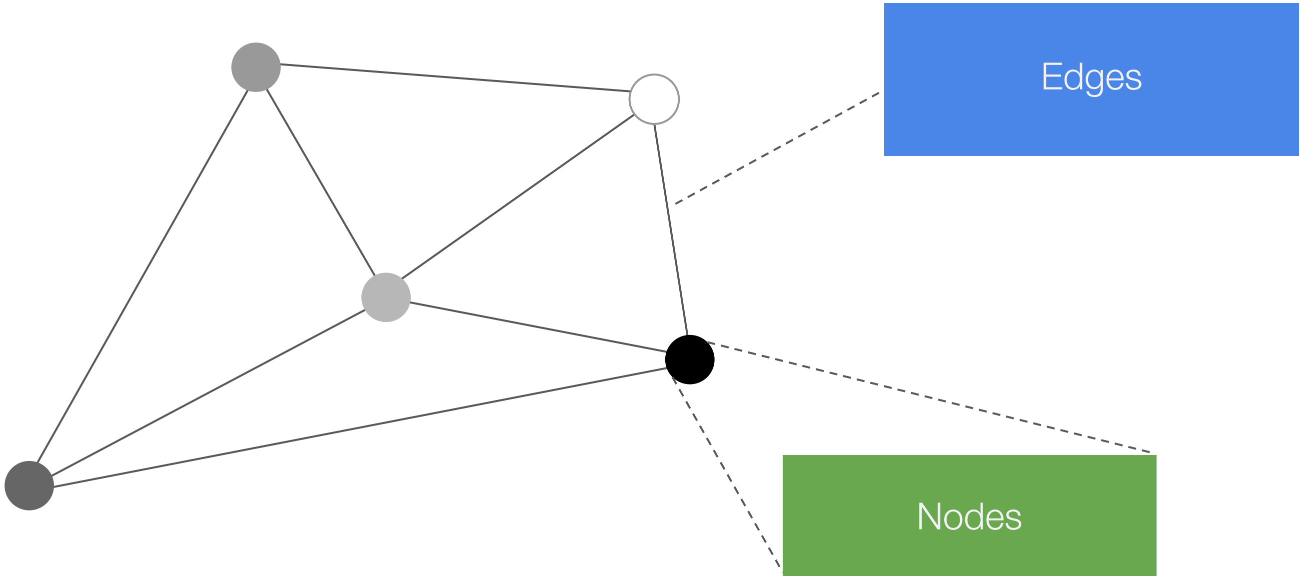
- **Detector geometry gets changed** for neural network
- Symmetric convolution kernel **assumes symmetry and regularity**
- Per-DOM (digital optical module) summary of pulse information **omits already sparse information**



Pulse - energy distribution in oscillation analysis

Can we do without?

Convolutional neural networks

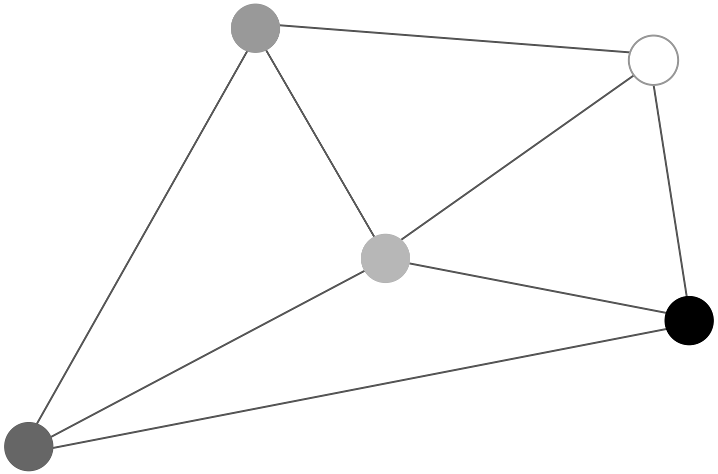


Graph neural networks

$$H^{(l+1)} = \sigma\left(\tilde{D}^{-\frac{1}{2}}\tilde{A}\tilde{D}^{-\frac{1}{2}}H^{(l)}W^{(l)}\right)$$

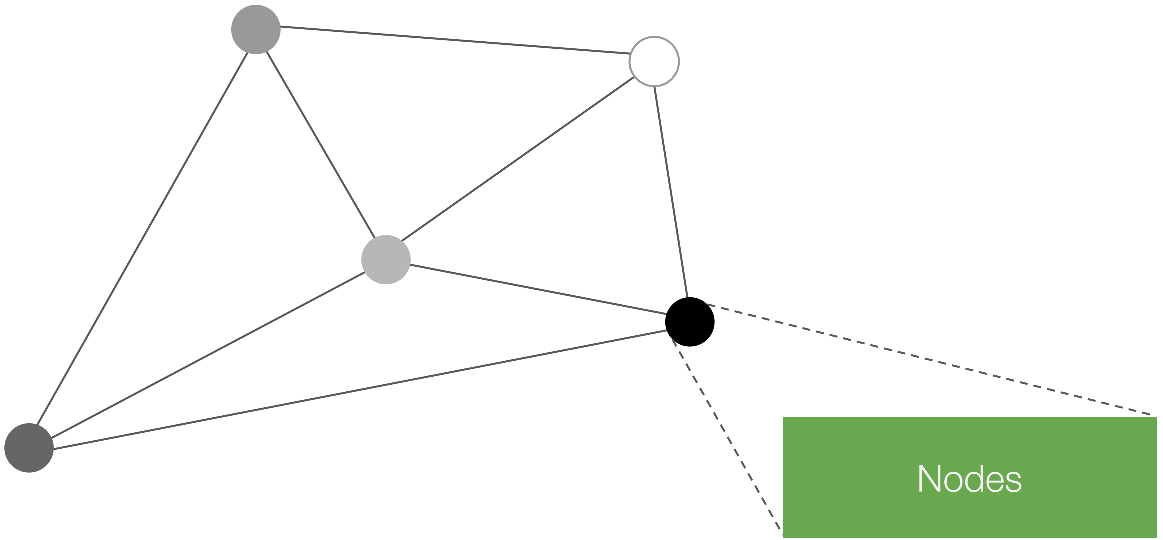
Equation for a layer step

Example: GCNConv from arXiv:1609.02907v4



Graph neural networks

$$H^{(l+1)} = \sigma\left(\tilde{D}^{-\frac{1}{2}}\tilde{A}\tilde{D}^{-\frac{1}{2}}\boxed{H^{(l)}}W^{(l)}\right)$$



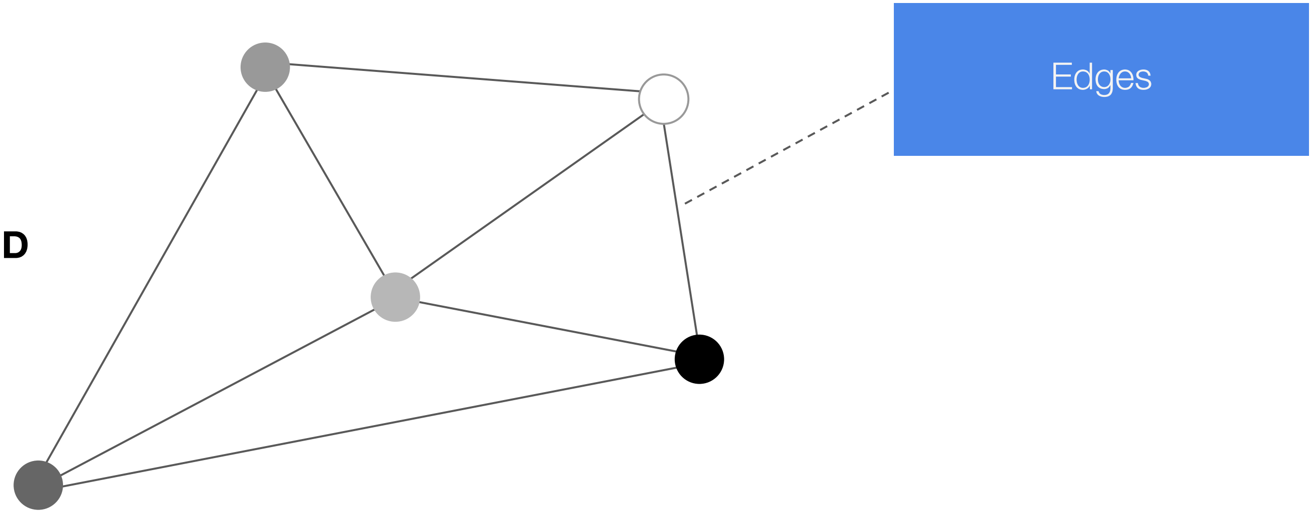
Graph neural networks

$$H^{(l+1)} = \sigma\left(\tilde{D}^{-\frac{1}{2}}\tilde{A}\tilde{D}^{-\frac{1}{2}}H^{(l)}W^{(l)}\right)$$

Connections are described in **adjacency matrix A**

Diagonal node degree **D** of A for normalization

$$\tilde{D}_{ii} = \sum_j \tilde{A}_{ij}$$



Graph neural networks

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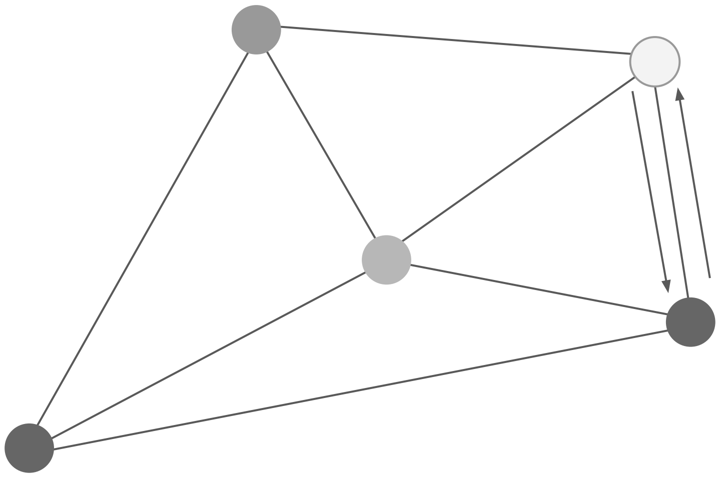


Message Passing

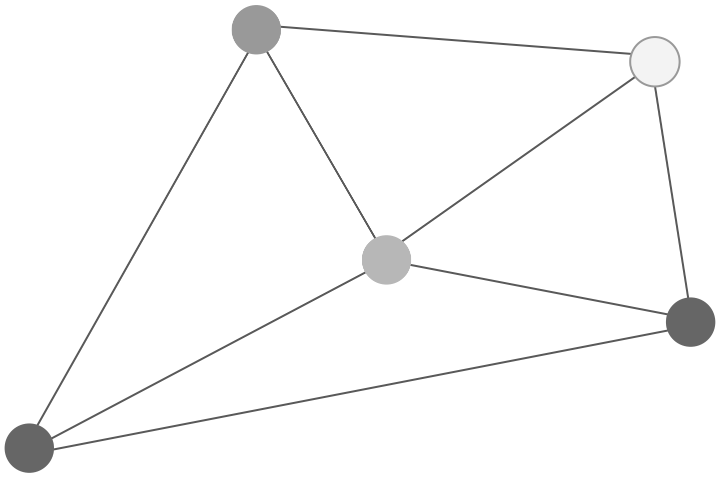
Convolutional
kernel in CNNs

Graph neural networks

$$H^{(l+1)} = \sigma\left(\tilde{D}^{-\frac{1}{2}}\tilde{A}\tilde{D}^{-\frac{1}{2}}H^{(l)}W^{(l)}\right)$$

Trainable layer weights

Activation function



Various functions exist for message passing;
see also in PyTorch Geometric

Graph neural networks

- Very similar in nature to **CNNs**
- Can represent information despite **irregular configuration** of problem
- Accepts **variable input lengths**
- **PyTorch Geometric** library has many GNN related layers and tools

Fast and flexible compared to traditional methods!

PyTorch geometric

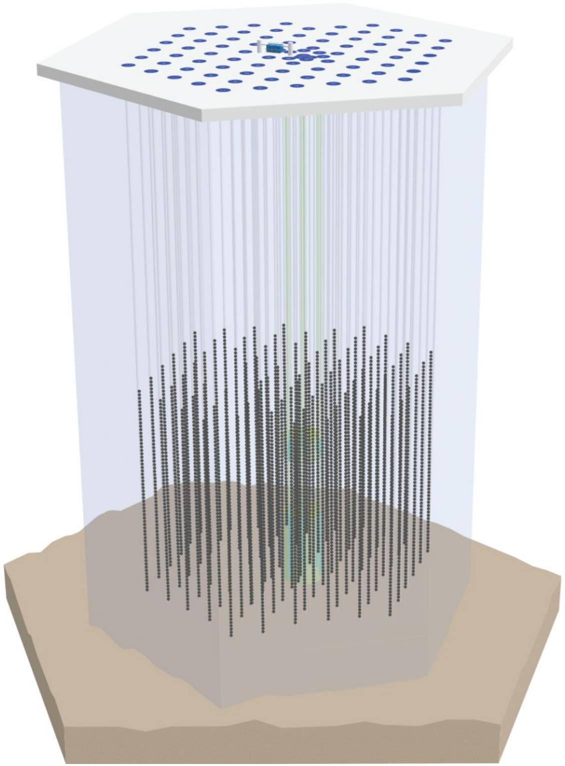
Graph neural networks

First intuition: Translate IceCube architecture into graph structure: **DOMs as nodes, spatial distance as edges**

What do with DOMs with **multiple pulses**?

How to encode time differences?

→ **Pulse-based GNN**



Events are graphs in abstract space with

x-, y-, z-positions, time, charge

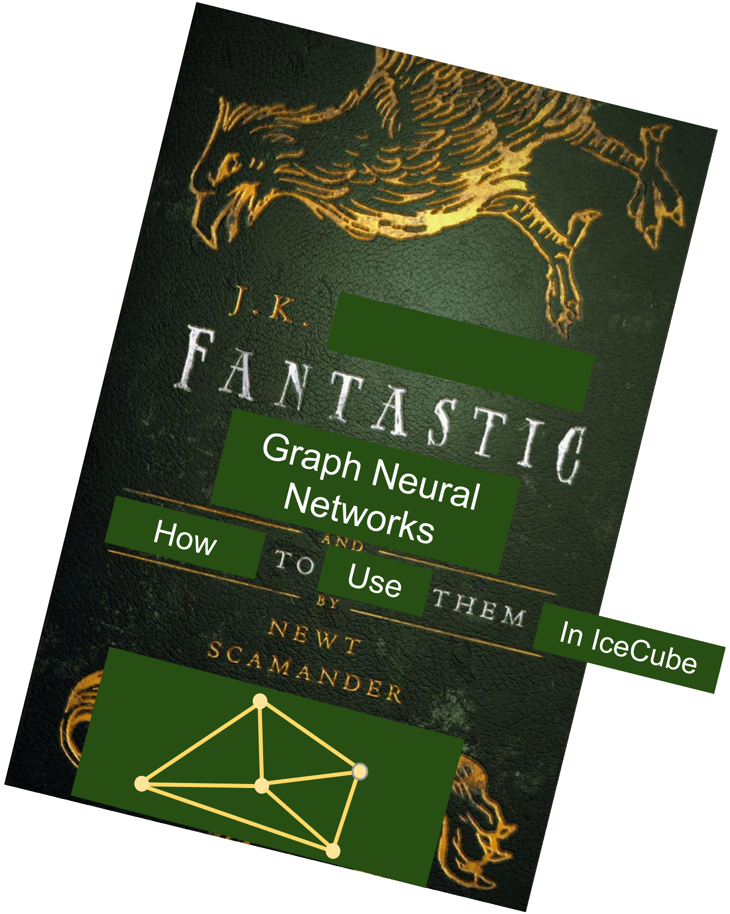
of each registered pulse

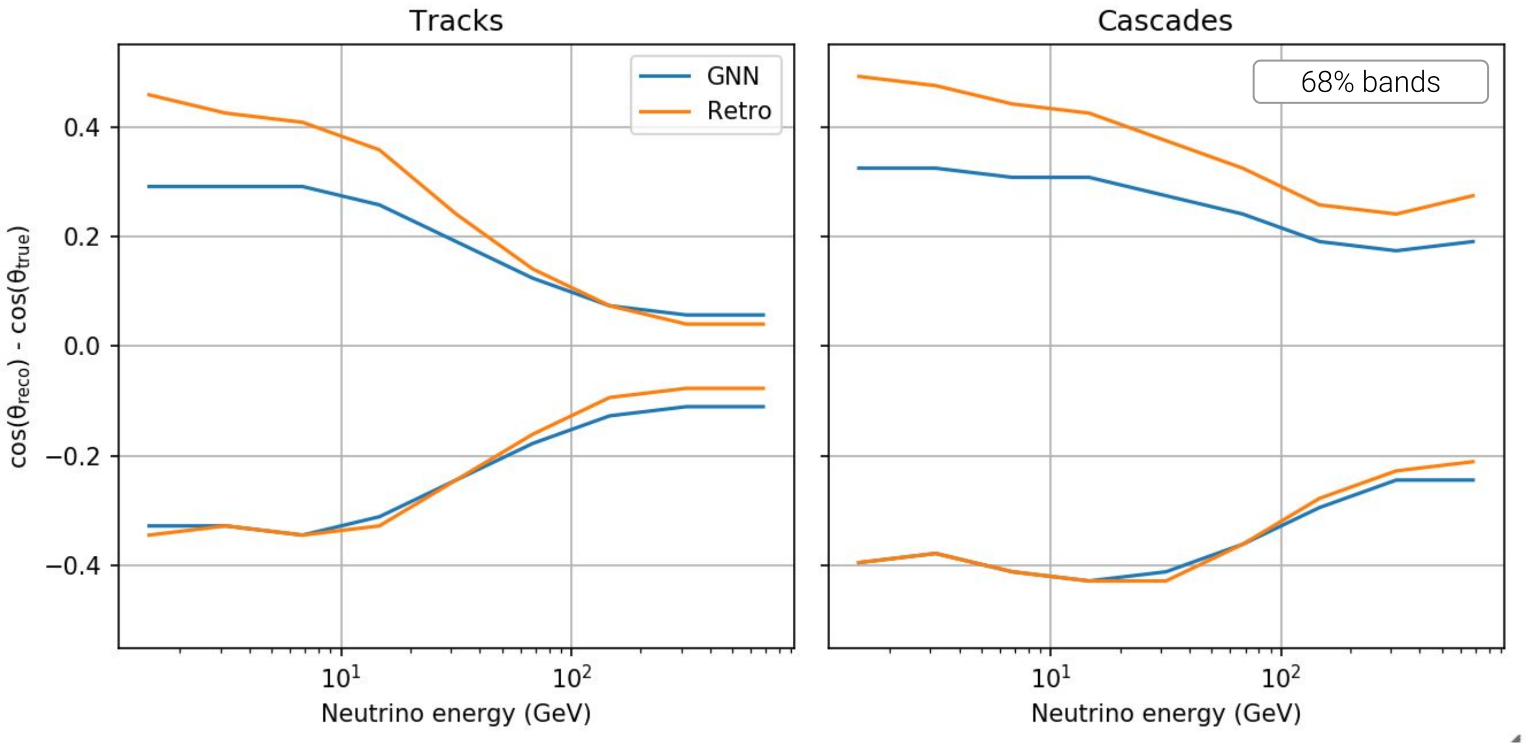
→ Uses **complete pulse information**

Network implicitly correlation between pulses

→ **Highly flexible, usable for current detector and IceCube Upgrade!**

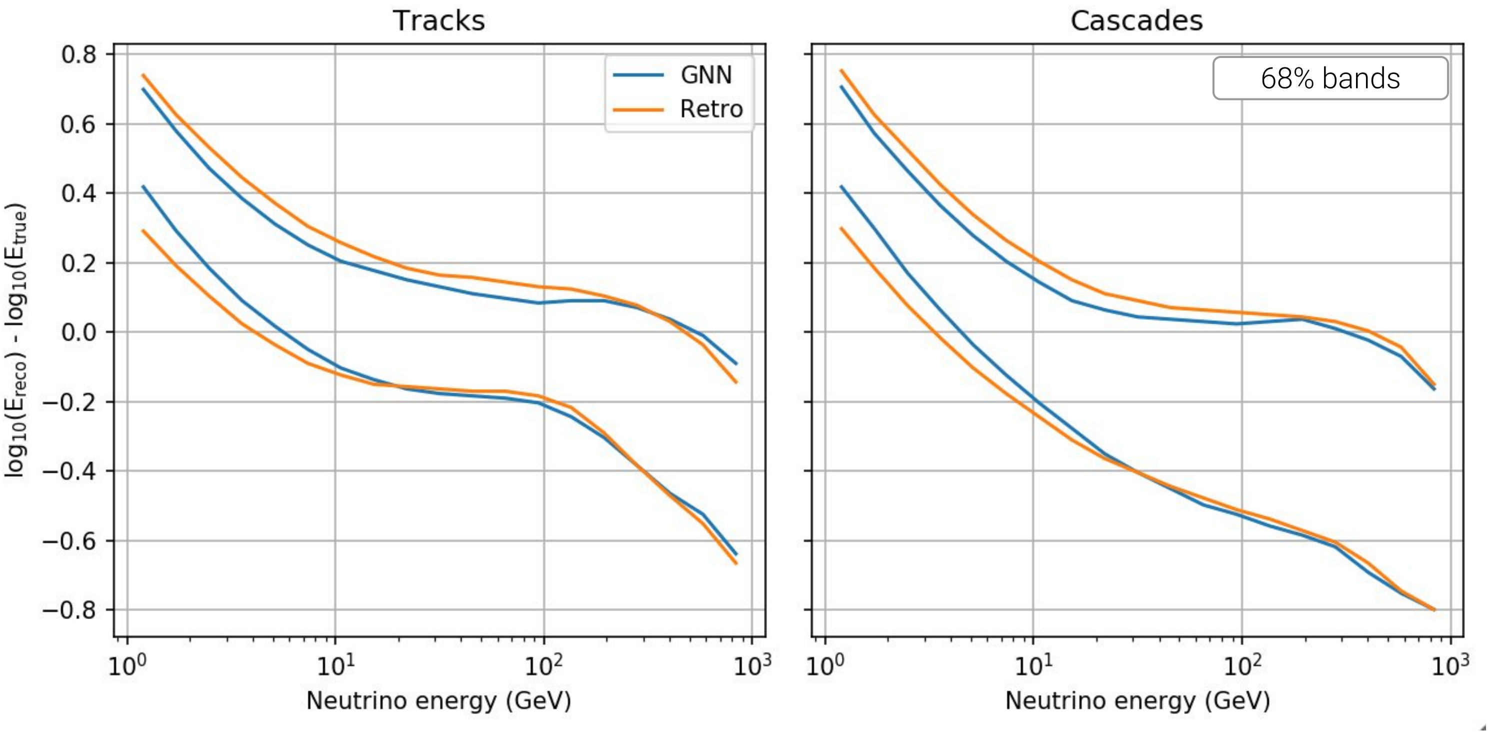
→ Apply on simulations and compare to baseline





Retro: Baseline reconstruction algorithm

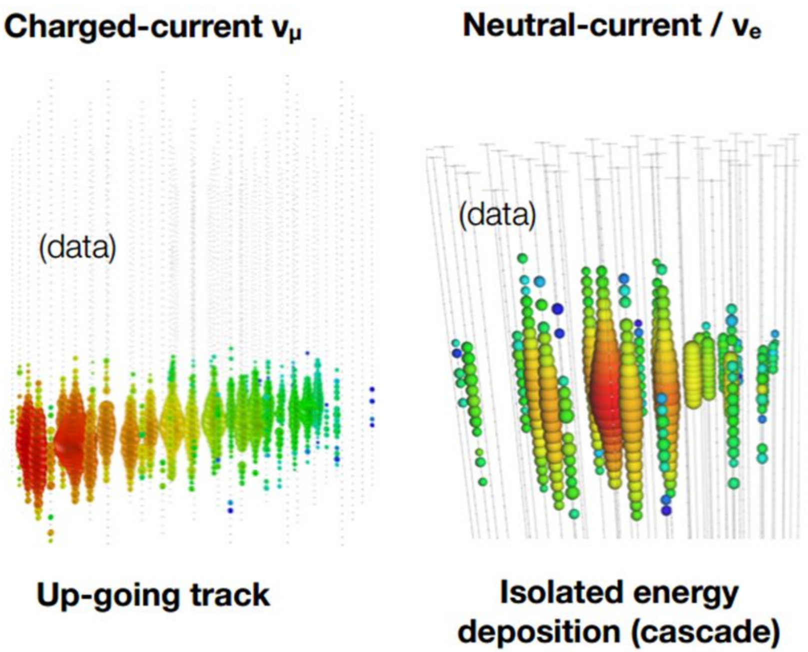
Outperforming, especially in low-energy region!



Retro: Baseline reconstruction algorithm

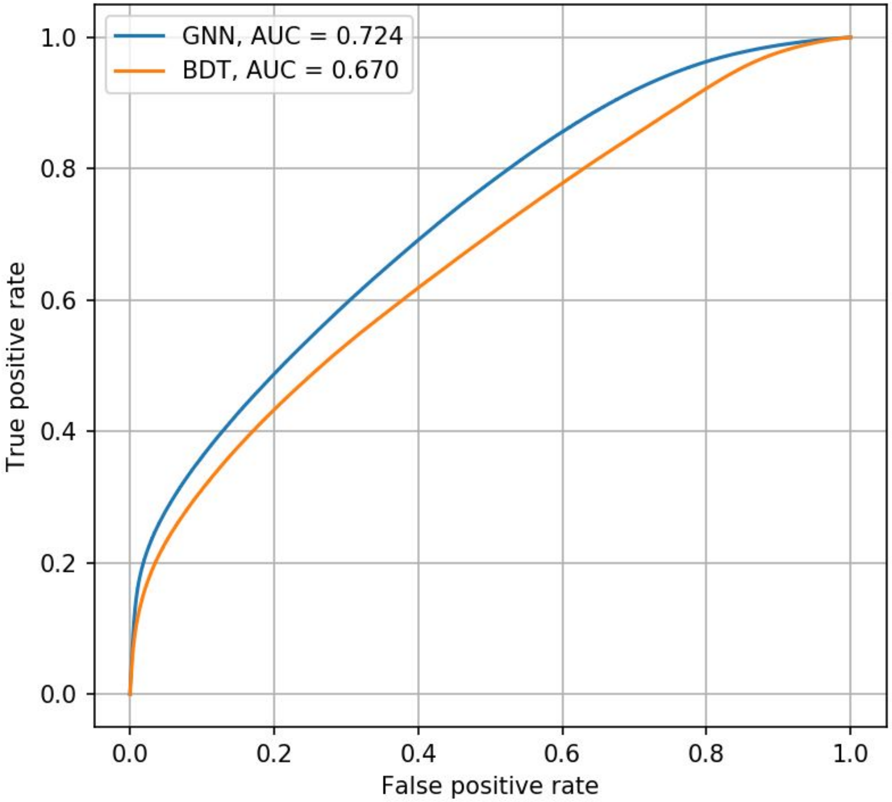
Outperforming, especially in low-energy region!

Track identification

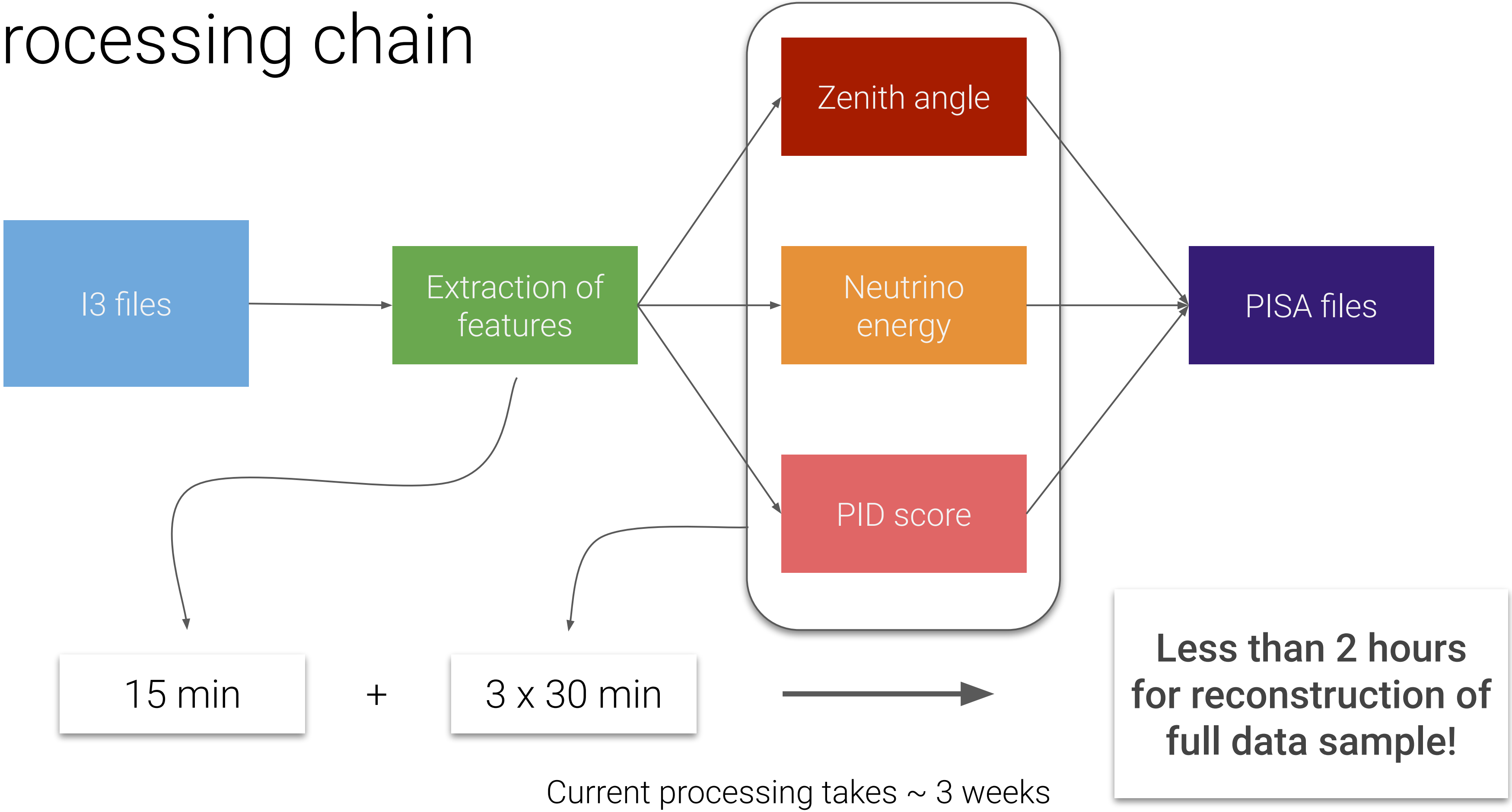


Current identification algorithm is based on boosted decision tree (BDT)

Track identification ROC curve

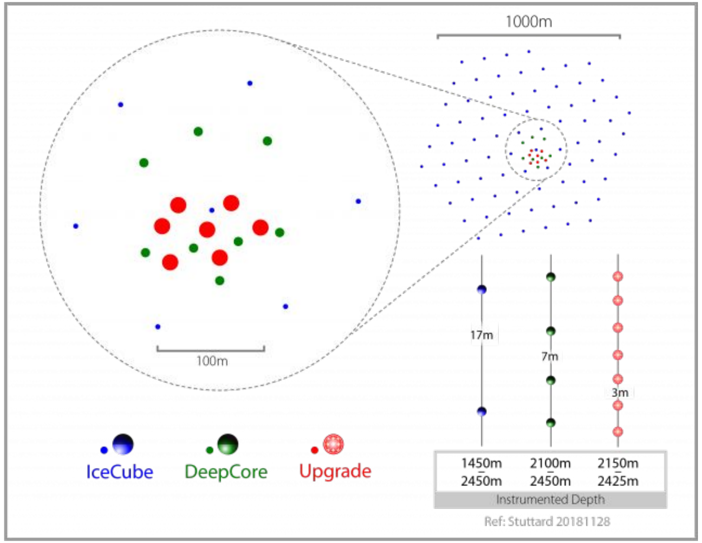


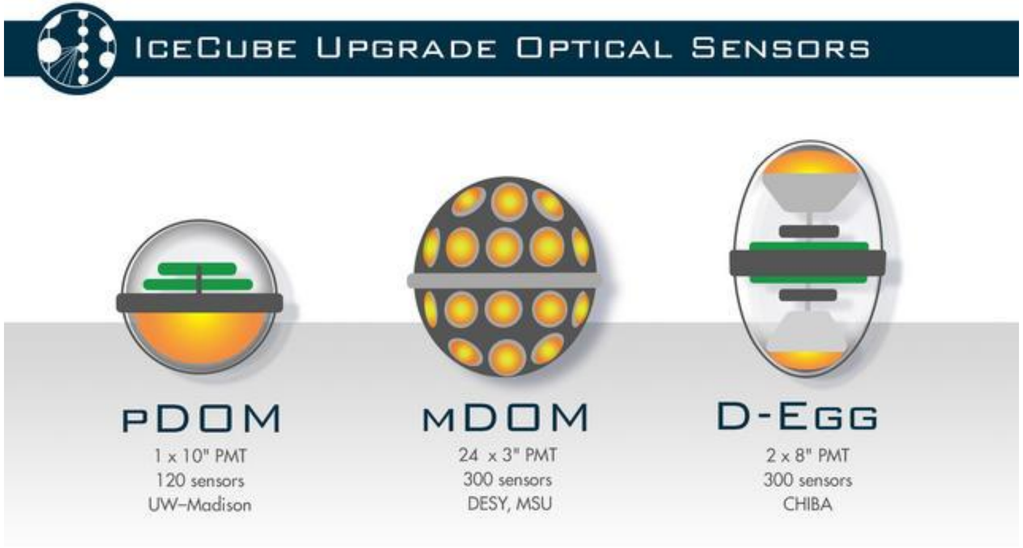
Processing chain



- IceCube Upgrade in construction!
- New strings and modules present challenges
- Graph neural network already compatible

ICECUBE UPGRADE





- IceCube neutrino oscillation physics can probe **neutrino mass ordering** and the **unitarity of the PMNS matrix**
- Development of **reconstruction and classification algorithm with GNNs** in full speed
- Can compete with traditional methods, but at **speeds magnitudes higher**

Outlook:

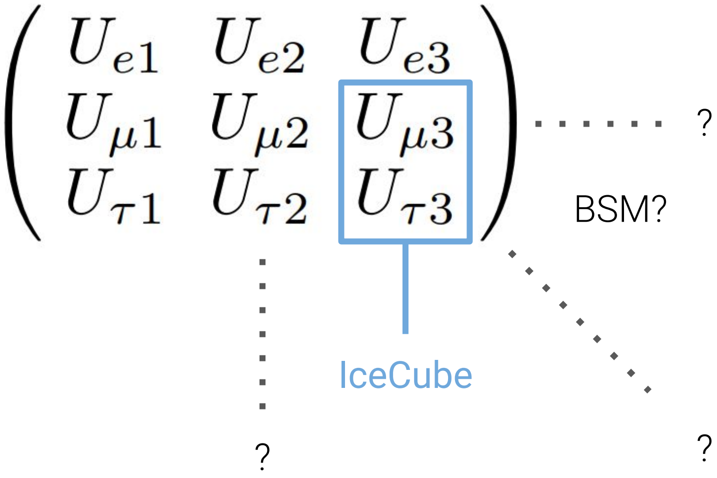
- **Sensitivity studies, oscillation analysis** with existing IceCube data
- Explore **event selection** possibilities
- IceCube Upgrade

Conclusion

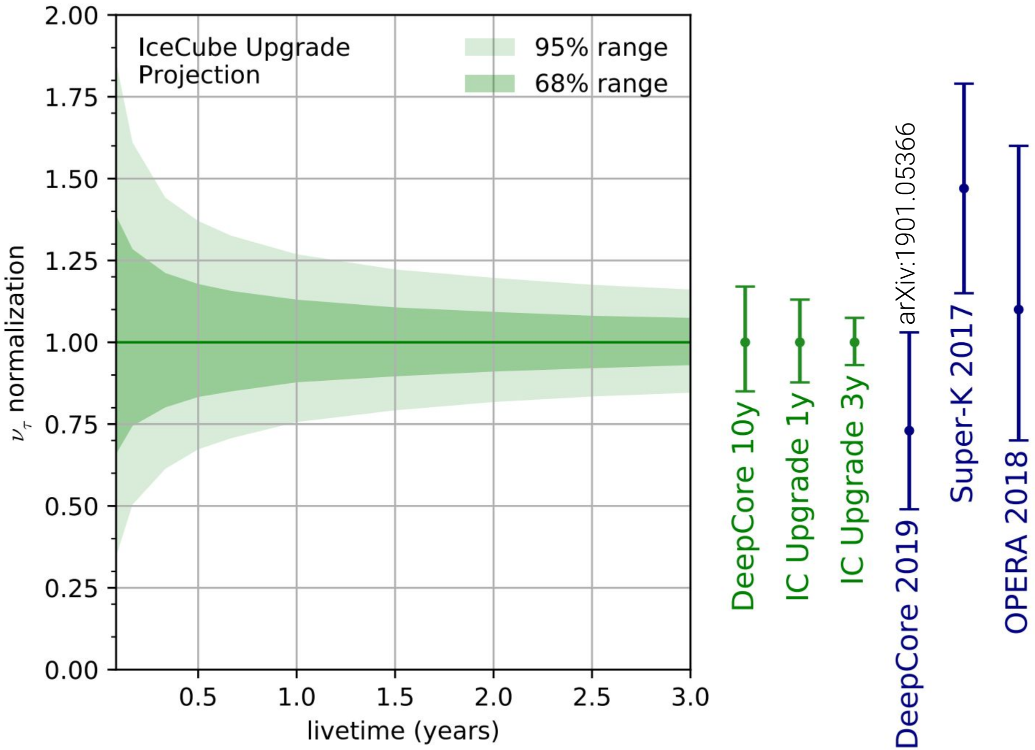
Thanks for your attention!

Backup

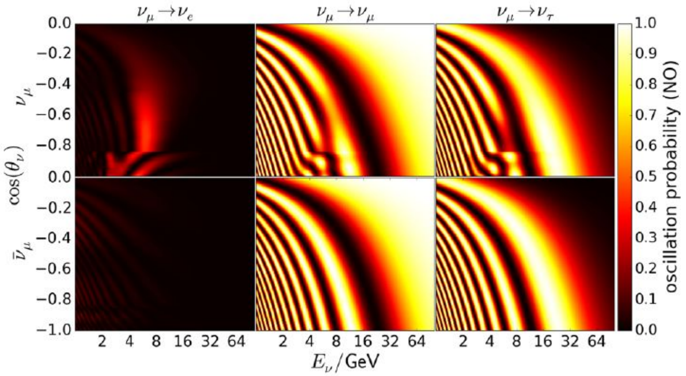
Measuring **nu tau appearance** allows for probing the **unitarity of the PMNS matrix**:



Inconsistencies can be direct hint for BSM physics!



Nutau appearance rate, 1 sigma bars



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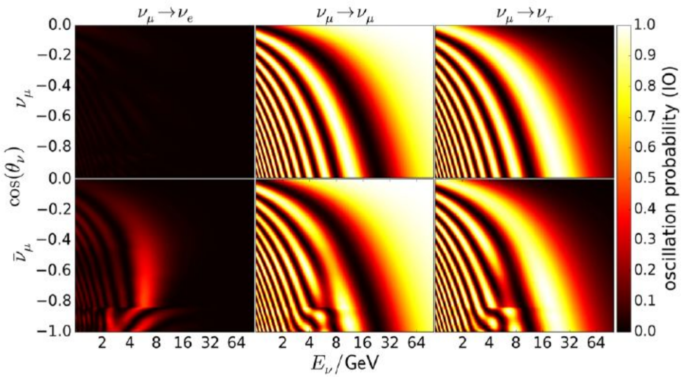

(b) Inverted Ordering