GraphNeT: Graph neural networks for neutrino telescope event reconstruction

Roberto Cappuccio

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- Neutrino Physics
- Neutrino Detection
- Neutrino Experiments
- IceCube drilldown and data analysis
- GrapNet neural networks

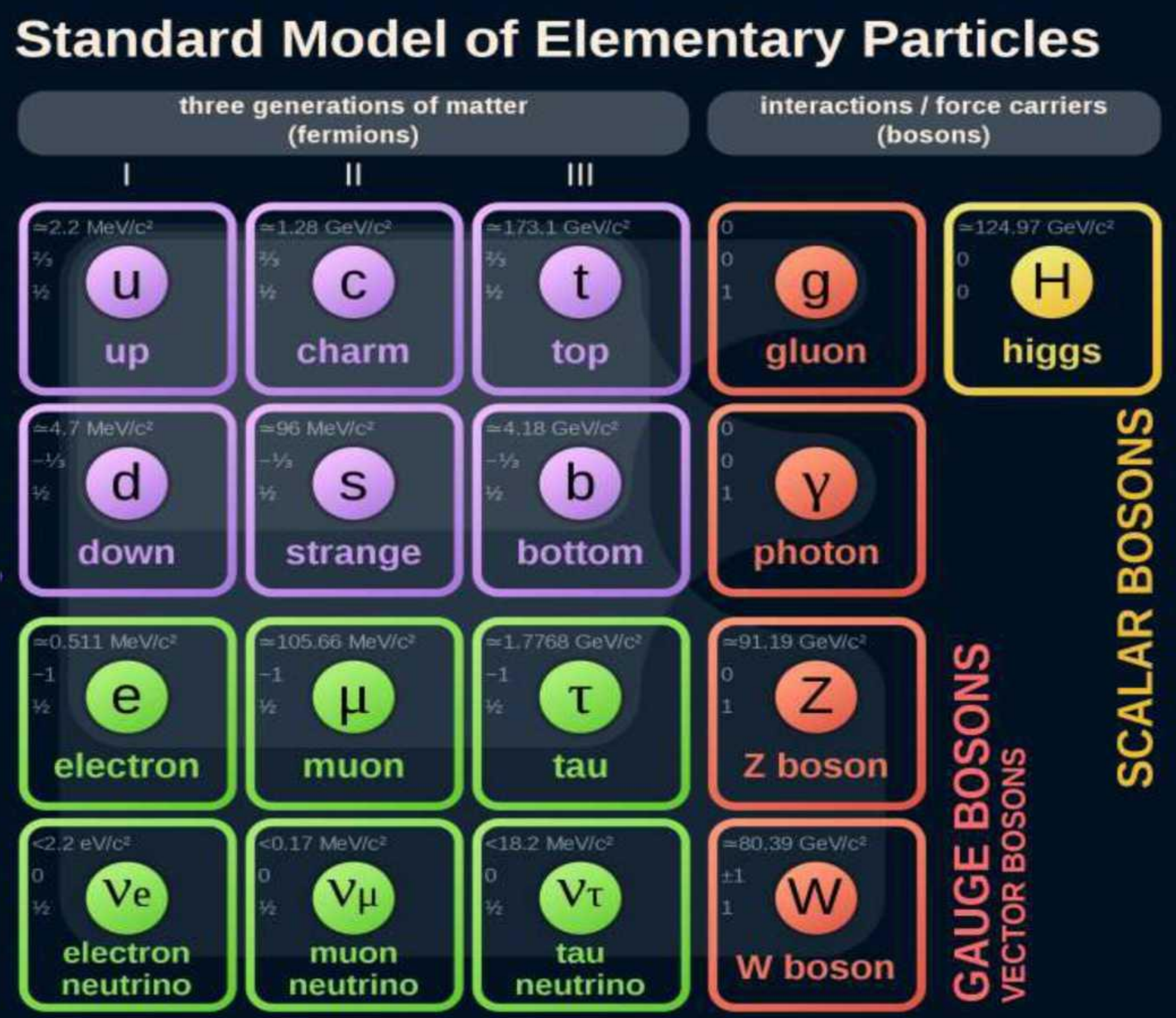
Introduction to Neutrinos

Introduction

- Neutrinos are subatomic particles that play a crucial role in our understanding of the universe.

- Studying neutrinos can help us learn more about fundamental forces, particle physics, and astrophysics.

- This presentation will cover the basic properties of neutrinos, their detections and the experiment IceCube. Then a new neural-network-based methodology will be presented for the event classification tasks.



QUARKS

LEPTONS

Charged Current Interaction Lagrangians

quarks

$$\mathcal{L}_{\rm cc} = \frac{g}{\sqrt{2}} \overline{(u\ c\ t)_{\rm L}}\ \gamma^\mu U \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\rm L} W_\mu^+ + \text{h.c.}$$

Cabibbo-Kobayashi-Maskawa Matrix

leptons

$$\mathcal{L}_{\rm cc} = \frac{g}{\sqrt{2}} \overline{(e\ \mu\ \tau)_{\rm L}}\ \gamma^\mu V \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_{\rm L} W_\mu^- + \text{h.c.}$$

Maki-Nakagawa-Sakata-Pontecorvo Matrix

V-Matrix Parametrization

$$O_1(\theta_1, \alpha_1, \beta_1, \gamma_1) = \begin{pmatrix} c_1 e^{i\alpha_1} & s_1 e^{-i\beta_1} & 0 \\ -s_1 e^{i\beta_1} & c_1 e^{-i\alpha_1} & 0 \\ 0 & 0 & e^{i\gamma_1} \end{pmatrix}$$

$$O_2(\theta_2, \alpha_2, \beta_2, \gamma_2) = \begin{pmatrix} e^{i\gamma_2} & 0 & 0 \\ 0 & c_2 e^{i\alpha_2} & s_2 e^{-i\beta_2} \\ 0 & -s_2 e^{i\beta_2} & c_2 e^{-i\alpha_2} \end{pmatrix}$$

$$O_3(\theta_3, \alpha_3, \beta_3, \gamma_3) = \begin{pmatrix} c_3 e^{i\alpha_3} & 0 & s_3 e^{-i\beta_3} \\ 0 & e^{i\gamma_3} & 0 \\ -s_3 e^{i\beta_3} & 0 & c_3 e^{-i\alpha_3} \end{pmatrix}$$

where $s_i \equiv \sin\theta_i$ and $c_i \equiv \cos\theta_i$ (for $i = 1, 2, 3$)

Dirac Neutrinos

$$V = O_i O_j O_i \quad (i \neq j)$$

MajoranaNeutrinos

$$V = O_i O_j O_k \quad (i \neq j \neq k)$$

Dirac or Majorana Neutrinos?

If neutrinos are Dirac particles, the phases *x*, *y* and *z* can be removed. Then the neutrino mixing matrix is

Dirac neutrino mixing matrix

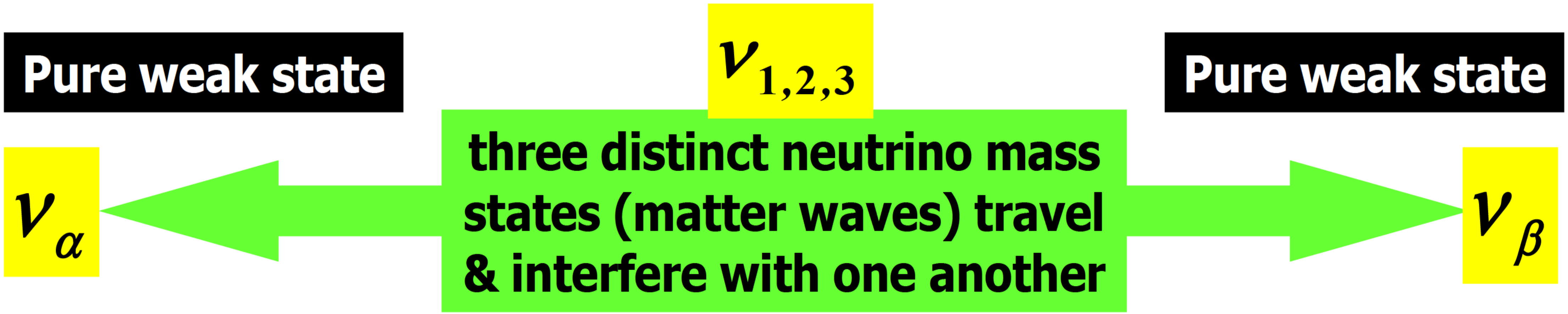
$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

If neutrinos are Majorana particles, left- and right-handed fields are correlated. Hence only a common phase of three left-handed fields can be redefined (e.g., $z = 0$). Then

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

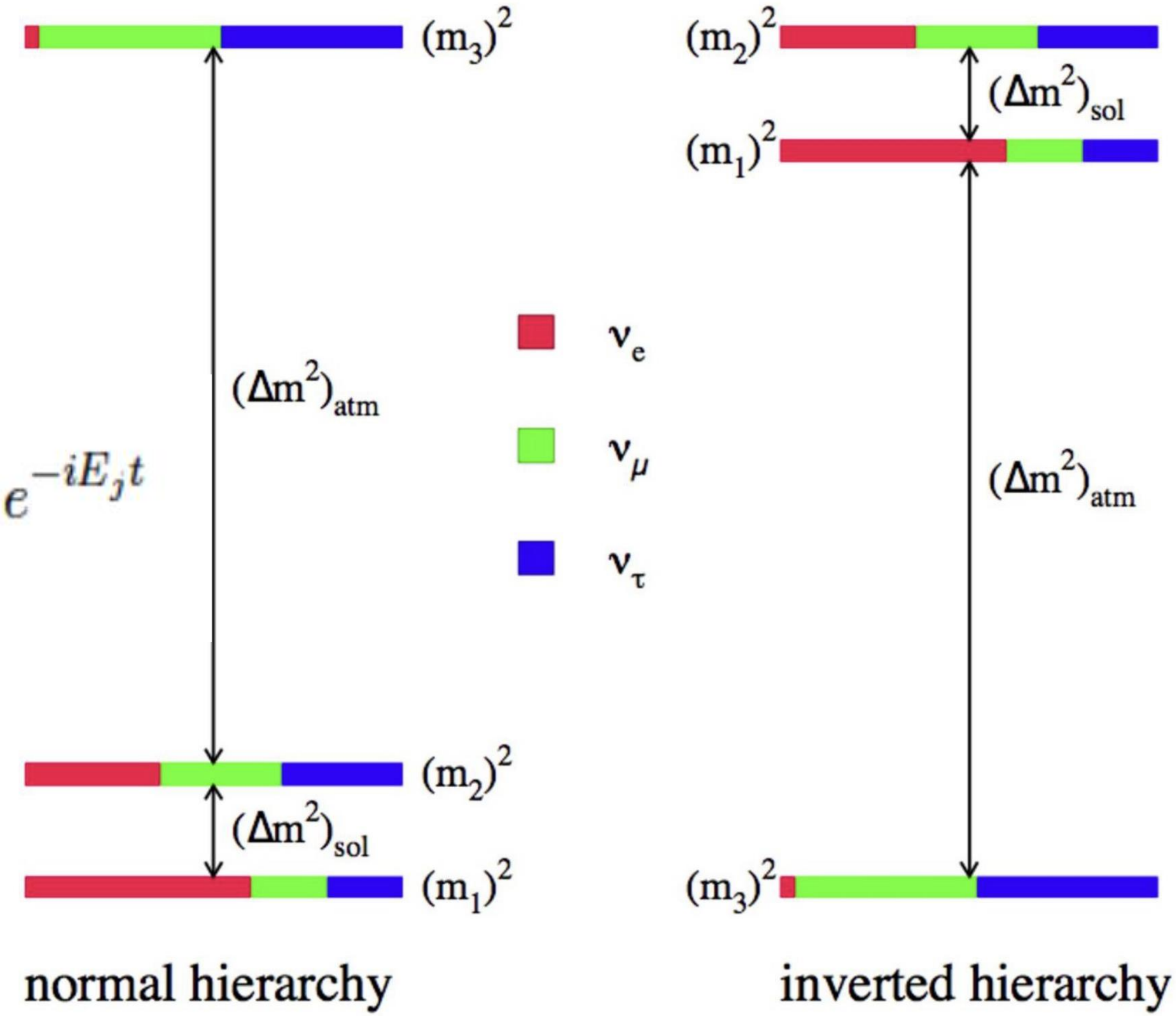
Neutrino Oscillations

- Neutrino oscillation is a spontaneous periodic change from one neutrino flavor state to another.
- It is a specific quantum phenomenon and it occurs as a natural consequence of neutrino mixing.



Neutrino Mass Hyerarchy

$$|\nu_\ell, t\rangle = \sum_{j=1}^{n} U^*_{\ell j} |\nu_j, t\rangle \quad \text{where} \quad |\nu_j, t\rangle = |\nu_j, 0\rangle\, e^{-iE_j t}$$



2-Flavor Oscillation

The oscillation probability for appearance ν experiments:

$$P\left(\nu_\mu \to \nu_e\right) = \left|\langle \nu_e | \nu_\mu(t) \rangle\right|^2 = \left|\left(\cos\theta\langle\nu_1| + \sin\theta\langle\nu_2|\right)\left(-\sin\theta|\nu_1\rangle + \cos\theta e^{-i\Delta E t}|\nu_2\rangle\right)\right|^2$$

$$= \left|\sin\theta\cos\theta\left(1 - e^{-i\Delta E t}\right)\right|^2 = 2\left(\sin\theta\cos\theta\right)^2\left(1 - \cos\frac{\Delta m^2 t}{2E}\right)$$

$$= \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

The conversion and survival probabilities in realistic units:

$$P\left(\nu_\mu \to \nu_e\right) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2 L}{E}$$

$$P\left(\nu_\mu \to \nu_\mu\right) = 1 - \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2 L}{E}$$

Due to the smallness of (1,3) mixing, both solar & atmospheric neutrino oscillations are roughly the 2-flavor oscillation.

Δm^2 in unit of eV^2 , L in unit of km , E in unit of GeV

1.27 ?

	Natural units	Realistic units
Phase factors	$\exp\left(-iE_{1,2}t\right)$	$\exp\left(-i\frac{E_{1,2}}{\hbar}t\right)$
Energies and momentum	$E_{1,2}=\sqrt{p^2+m_{1,2}^2}$	$E_{1,2}=\sqrt{p^2c^2+m_{1,2}^2c^4}$
Energy difference	$\Delta E=\frac{\Delta m^2}{2E}$	$\Delta E=\frac{\Delta m^2c^3}{2p}=\frac{\Delta m^2c^4}{2E}$
Time and distance	$t=L$	$t=\frac{L}{c}$
Oscillation argument	$\frac{1}{2}\Delta Et=\frac{\Delta m^2L}{4E}$	$\frac{1}{2}\frac{\Delta E}{\hbar}t=\frac{c^3}{\hbar}\cdot\frac{\Delta m^2L}{4E}$

$$c = 2.998\times10^{5}\ \text{km s}^{-1}$$
$$\hbar = 6.582\times10^{-25}\ \text{GeV s}$$

$$\frac{c^3}{4\hbar} \Rightarrow \frac{1}{4\times0.1973}=1.267\approx1.27$$

$$c=1 \quad\Rightarrow\quad \hbar=6.582\times10^{-25}\ \text{GeV}\times2.998\times10^{5}\ \text{km}$$
$$=1.973\times10^{-19}\ \text{GeV km}=0.1973\,\text{eV}^2\ \text{GeV}^{-1}\ \text{km}$$

3-Flavor Oscillation

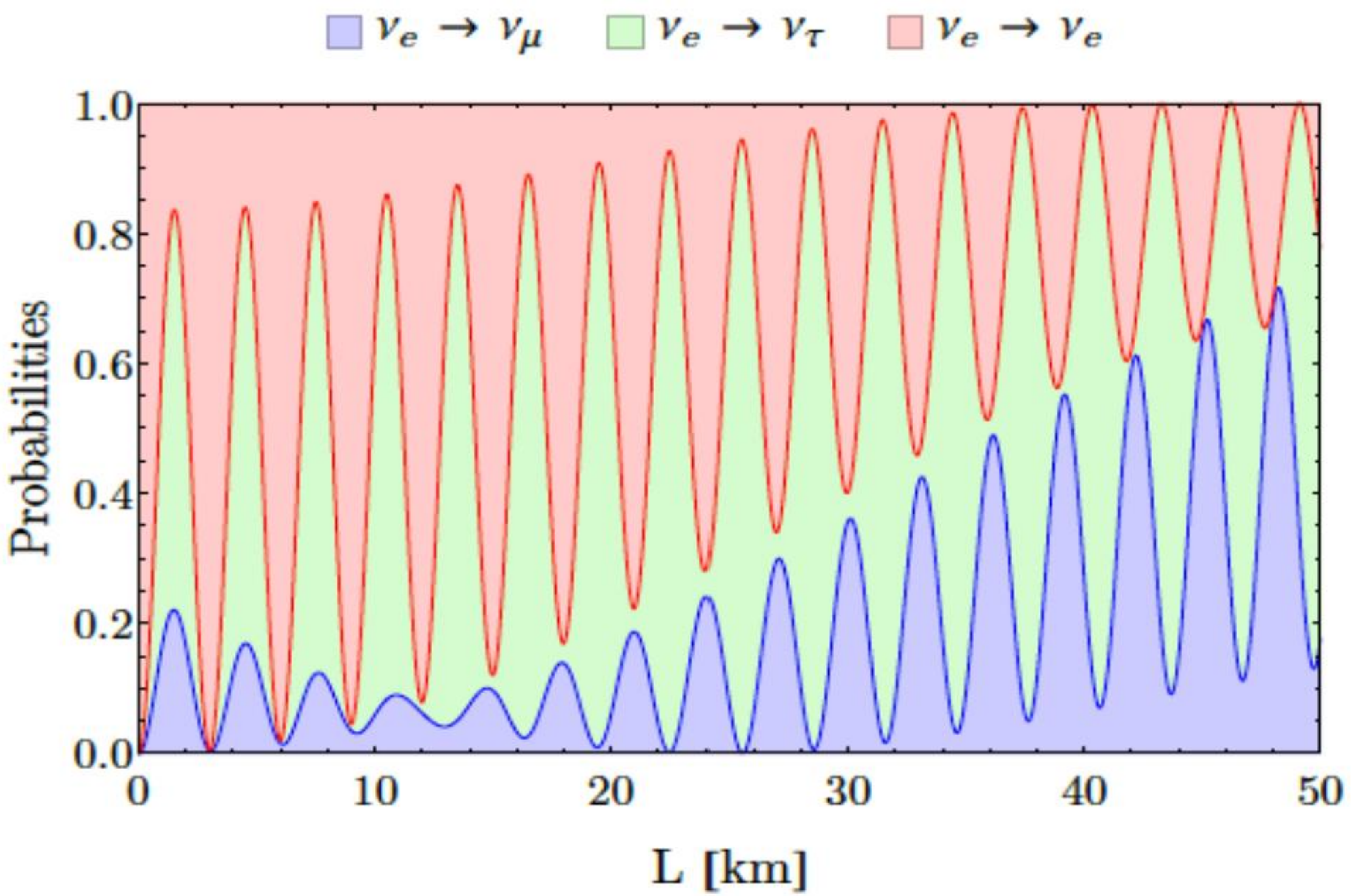
The final formula of 3-flavor oscillation probabilities with CP violation:

$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) = \delta_{\alpha\beta} - 4\sum_{i<j}^{3} \mathrm{Re}\left(V_{\alpha i}V_{\beta j}V^*_{\alpha j}V^*_{\beta i}\right)\sin^2\frac{\Delta m^2_{ji}L}{4E}$$

$$+ 8\mathcal{J}\sum_{\gamma}\epsilon_{\alpha\beta\gamma}\sin\frac{\Delta m^2_{21}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{32}L}{4E}$$

The 1st oscillating term: CP conserving; and the 2nd term: CP violating!

Neutrino Oscillation Probabilities



Neutrino Oscillation Studies

$\nu_\mu \rightarrow \nu_\tau$ oscillations (Δm_{23}, θ_{23})

Atmospheric: Super-K, Soudan-2, MACRO IceCube/Deepcore, …

LBL: K2K, MINOS, OPERA, T2K, NOvA, …

$\nu_e \rightarrow (\nu_\mu + \nu_\tau)$ oscillations (Δm_{12}, θ_{12})

Solar: SNO, Super-K, Borexino, …

Reactor: KamLAND

θ_{13} experiments

LBL: MINOS, T2K, NOvA, …

Reactor: Daya Bay, Reno, Double Chooz

Status (before Neutrino 2016)

Parameter	best-fit ($\pm 1\sigma$)
Δm^2_{21} $[10^{-5}$ eV $^2]$	$7.54^{+0.26}_{-0.22}$
$\|\Delta m^2\|$ $[10^{-3}$ eV $^2]$	2.43 ± 0.06 (2.38 ± 0.06)
$\sin^2\theta_{12}$	0.308 ± 0.017
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ $(1.31^{+0.29}_{-0.33})$

K. Nakamura and S.T. Petcov, “14. Neutrino mass, mixing and oscillations”

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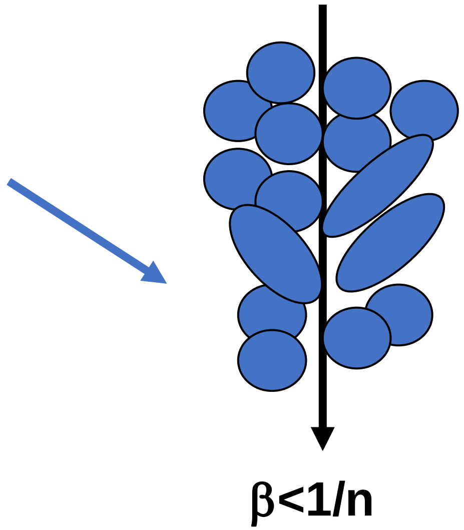
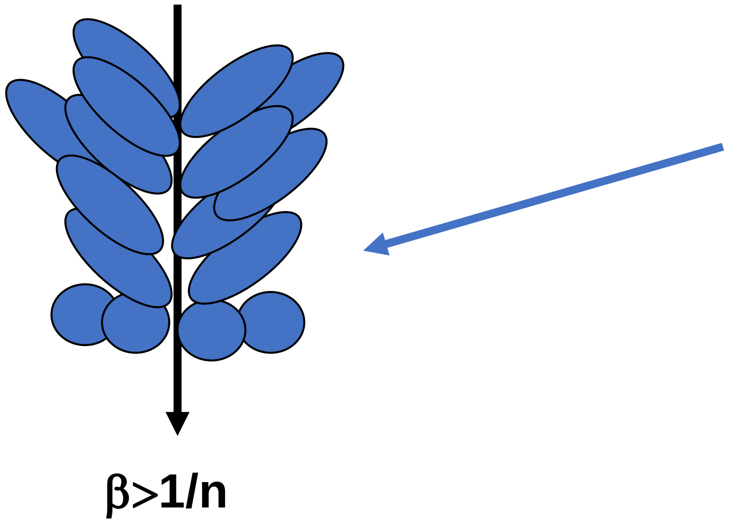
How to Detect Neutrinos: Cerenkow Light

- Cerenkov radiation is emitted whenever a charged particle passes through a (dielectric) medium with velocity $\beta c = v > c/n$, where v is the velocity of the particle and n the refractive index of the medium.
- Incoming particle polarizes atoms in the medium which, in turn, become electric dipoles:

No radiation Emission

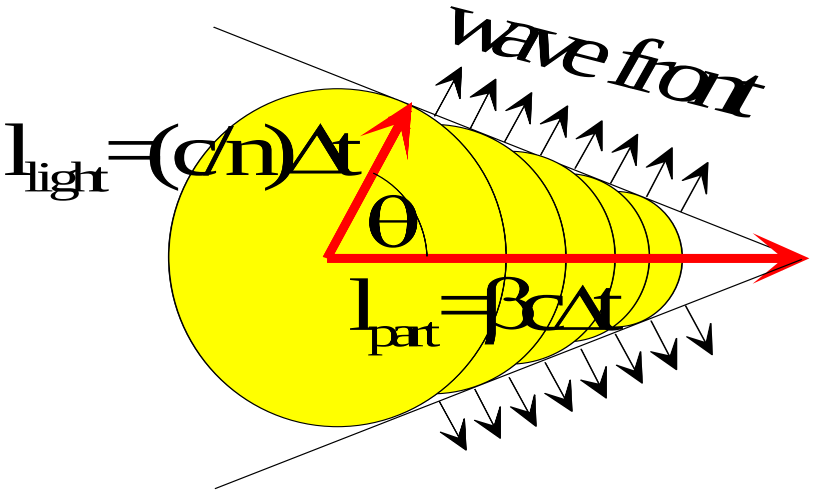




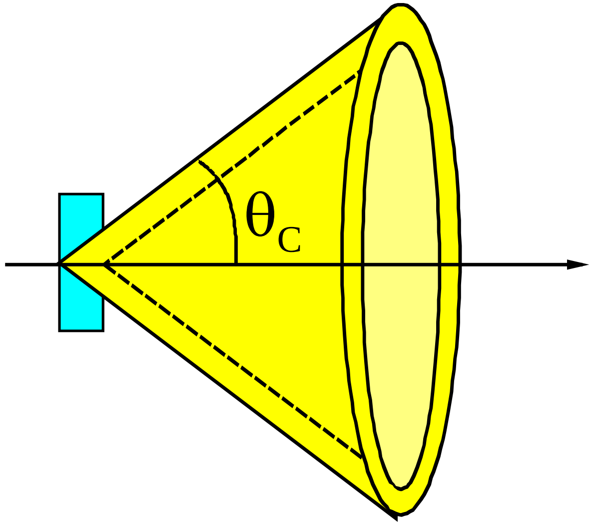
Radiation Emission

Cerenkon Light

- The emission angle θ_c can be qualitatively interpreted as a shock wave as happens for a boat or a supersonic plane.



$$\cos\theta_C = \frac{1}{n\beta} \quad \text{with} \quad n = n(\lambda) \geq 1$$



- Threshold velocity: $\beta_s = 1/n \rightarrow \theta_c \sim 0$
- Maximum angle: $\theta_{max} = \arccos(1/n)$
- In water n = 1.33 and θc = 41°

The above equation are valid in L>>λ where L is the length of the medium and λ is the wavelength of emitted light

Cerenkov Spectrum

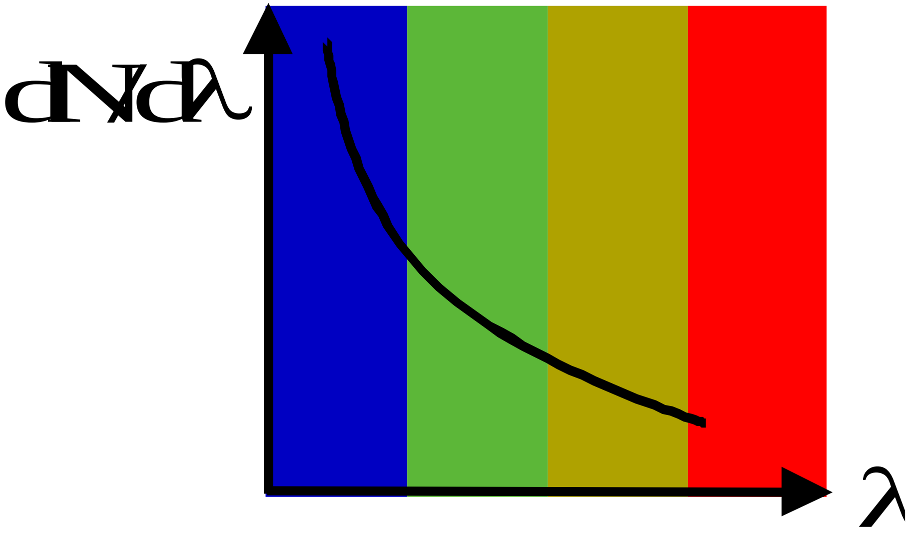
Number of photons emitted per unit length and unit wavelength range. We observe that it decreases as λ increases.

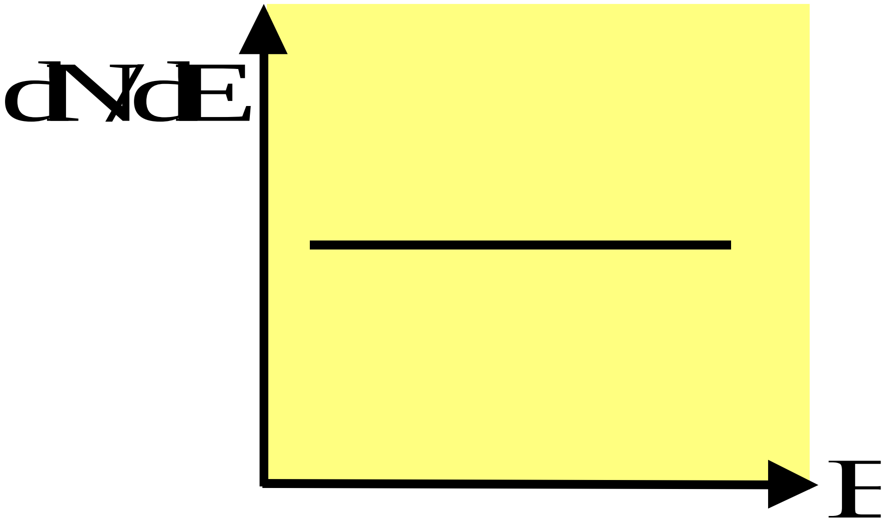
$$\frac{d^2N}{dxd\lambda} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1-\frac{1}{\beta^2 n^2}\right) = \frac{2\pi z^2\alpha}{\lambda^2}\sin^2\theta_C$$

$$\frac{d^2N}{dxd\lambda} \propto \frac{1}{\lambda^2} \quad \text{with } \lambda = \frac{c}{\nu} = \frac{hc}{E} \quad \frac{d^2N}{dxdE} = const.$$

$$\alpha = \frac{2\pi e^2}{hc} = \frac{1}{137} \quad \frac{1}{4\pi\epsilon_0} = 1$$

The number of photons emitted per unit of Length does not depend on energy.





Cerenkon Light Energy Loss

- The energy lost by Cerenkov radiation increases with β. However even with β -> 1 it is very small, and generally smaller than Bethe Block energy loss:

$$-\frac{dE}{dx} = z^2 \alpha \frac{\hbar}{c} \int \omega \left(1 - \frac{1}{\beta^2 n^2(\omega)} \right) d\omega$$

medium	n	θ_{max} (β=1)	N_{ph} (eV^{-1} cm^{-1})
air	1.000283	1.36	0.208
isobutane	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

How much light?

Let us consider:

- a 1 cm thick radiator
- an angle θc = 30º
- a DE = 1 eV
- a particle of charge = 1

$$\frac{dN}{dEdx} = \frac{z^2\alpha}{\hbar c}\sin^2\vartheta_c$$

$$\Rightarrow \quad N_{ph} = 370 \cdot \sin^2\vartheta_c \cdot L \cdot \Delta E = 370 \times 0.25 = 92.5$$

Considering, also, that the quantum efficiency of a photomultiplier is around 20% then:

$$\Rightarrow \quad N_{ph} = 18$$

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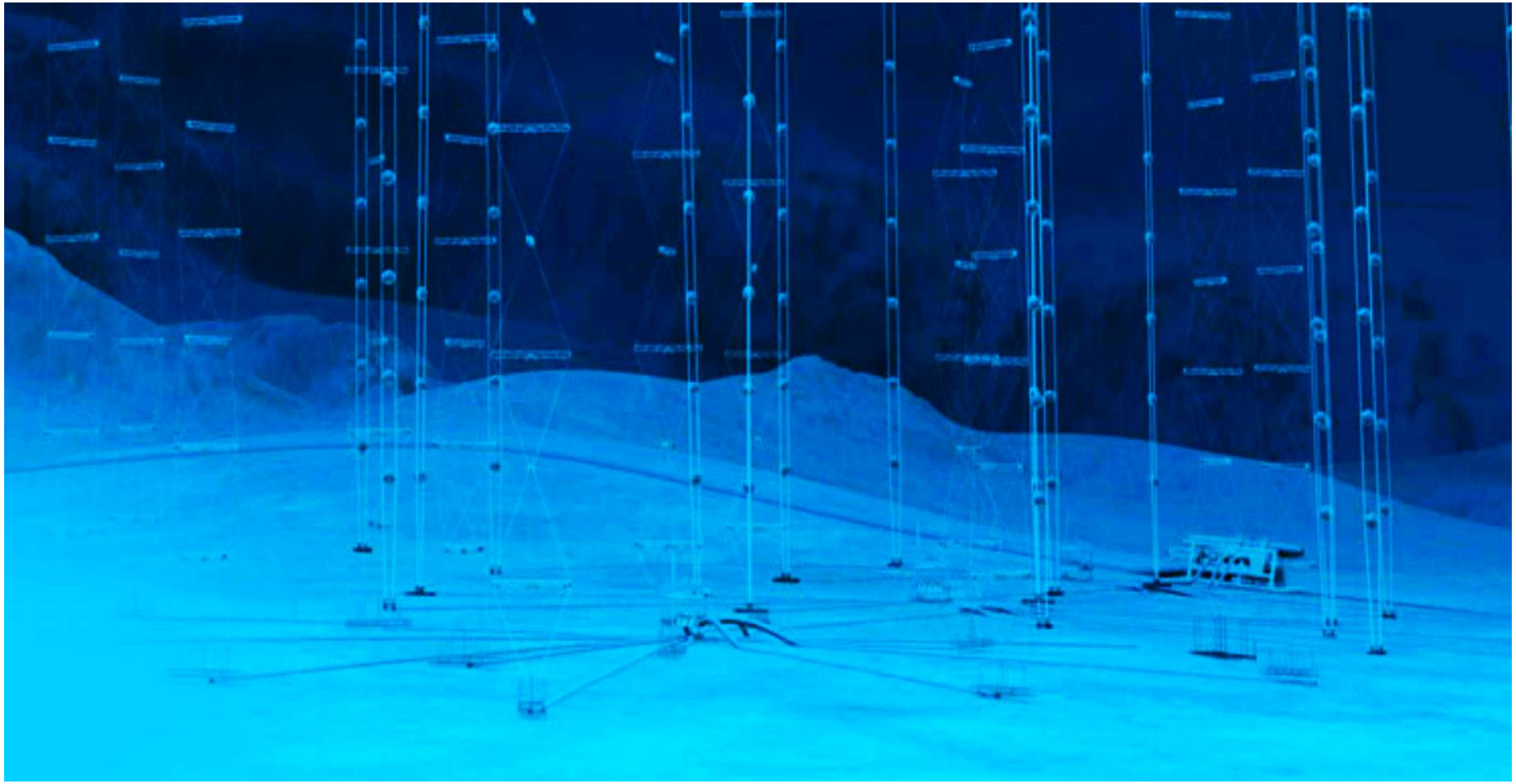
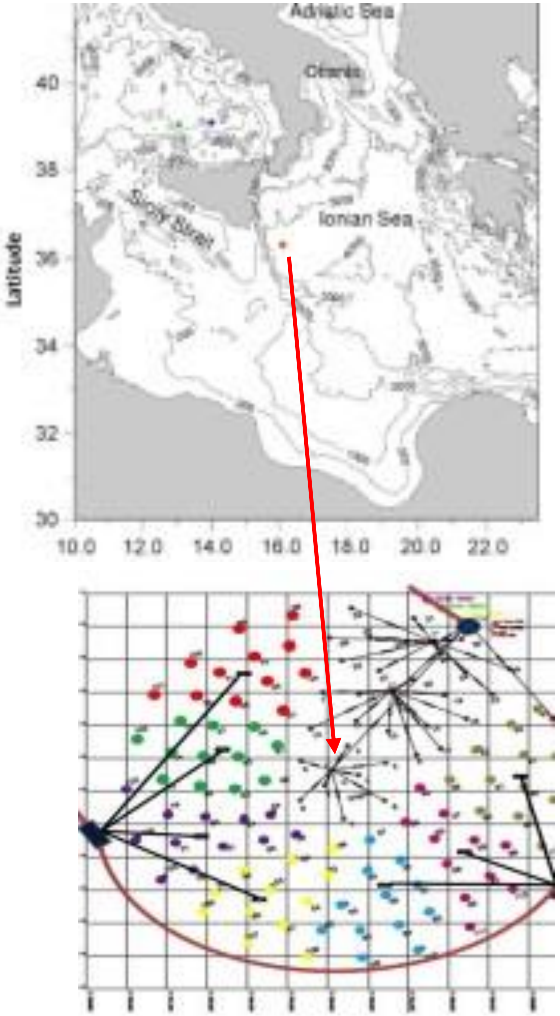
Cherenkov Neutrino Experiment Timeline

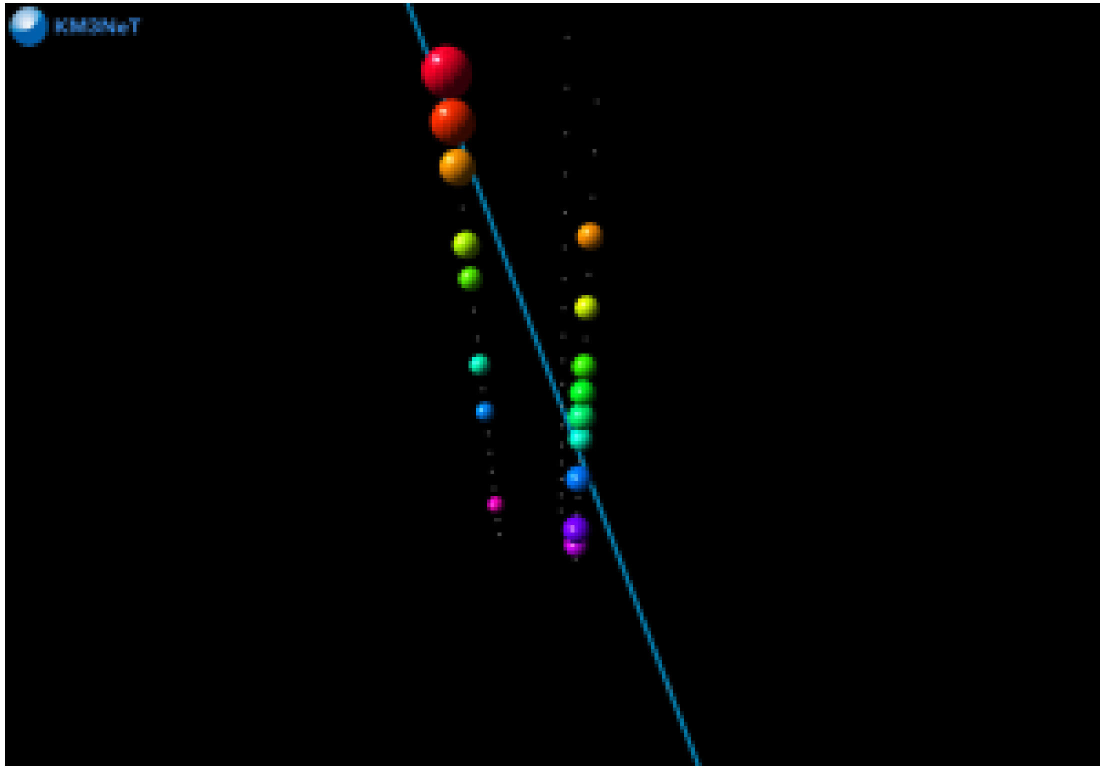
- DUMAND: Deep Underwater Muon and Neutrino Detector - proposed by F. Reynes on 1975 (9 strings and 216 OMs, 4.6 Km deep of bottom level).
- BAIKAL - Bezrukov, Domogatsky, Berezinsky, Zatsepin - 1981 First site exploration and R&D, 1.3 Km depth, Baikal lake, from NT36 (36 OMs) to NT200 (200 OMs)
- NESTOR - Pylos island, Greece - 3.8 Km deep. Survey started in the 90's (12 floors with 14 OMs per floor, 168 in total)
- AMANDA - South Pole - 1996 started (19 strings and 677 OMs)
- ANTARES - R&D started in 1997, off-shore of Toulon, 2.5 Km deep (12 strings, 75 OMs
- each string)
- NEMO - R&D start in 1998 - first site exploration in 2002, off-shore of Capopassero, 33.5 Km deep, phase 1 (4 floors 16 OMs), phase 2 (8 floors 32 OMs)
- IceCube - construction 2005-2010, South Pole, 86 strings, 5160 OMs
- KM3NeT/ARCA - construction started on Dec 2015, off-shore Capopassero, 2 building blocks with 115 strings per block and 18 Doms each string.

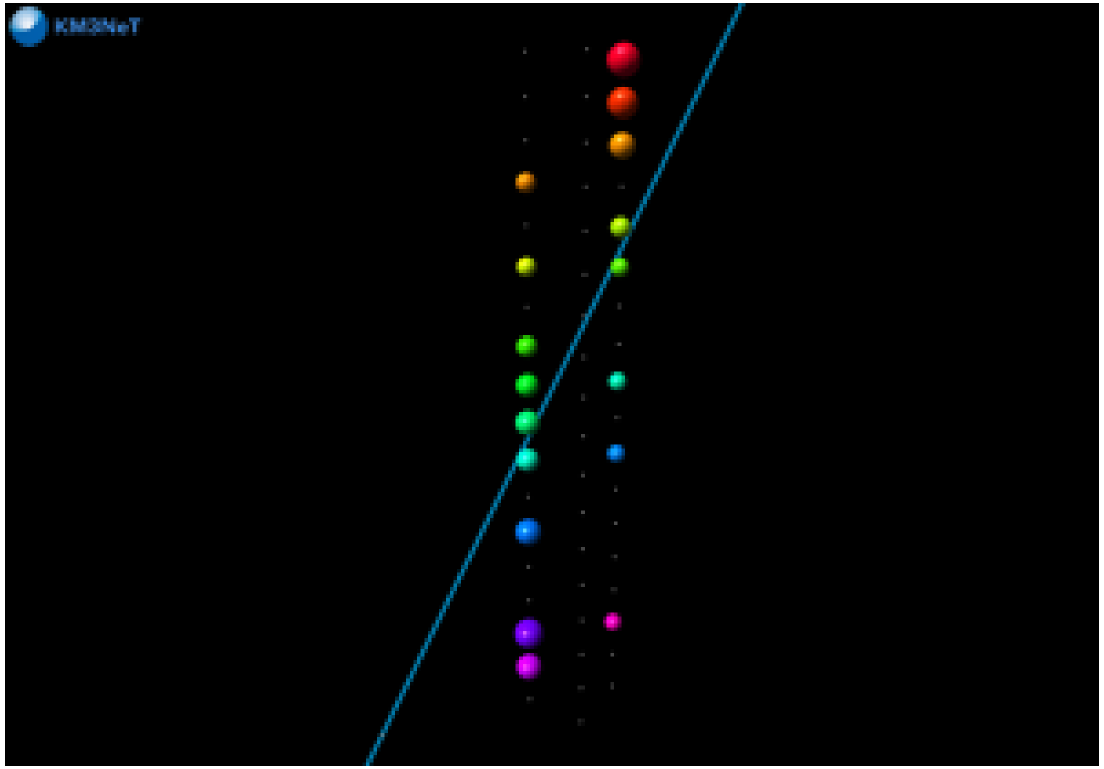
KM3NeT/ARCA Overview





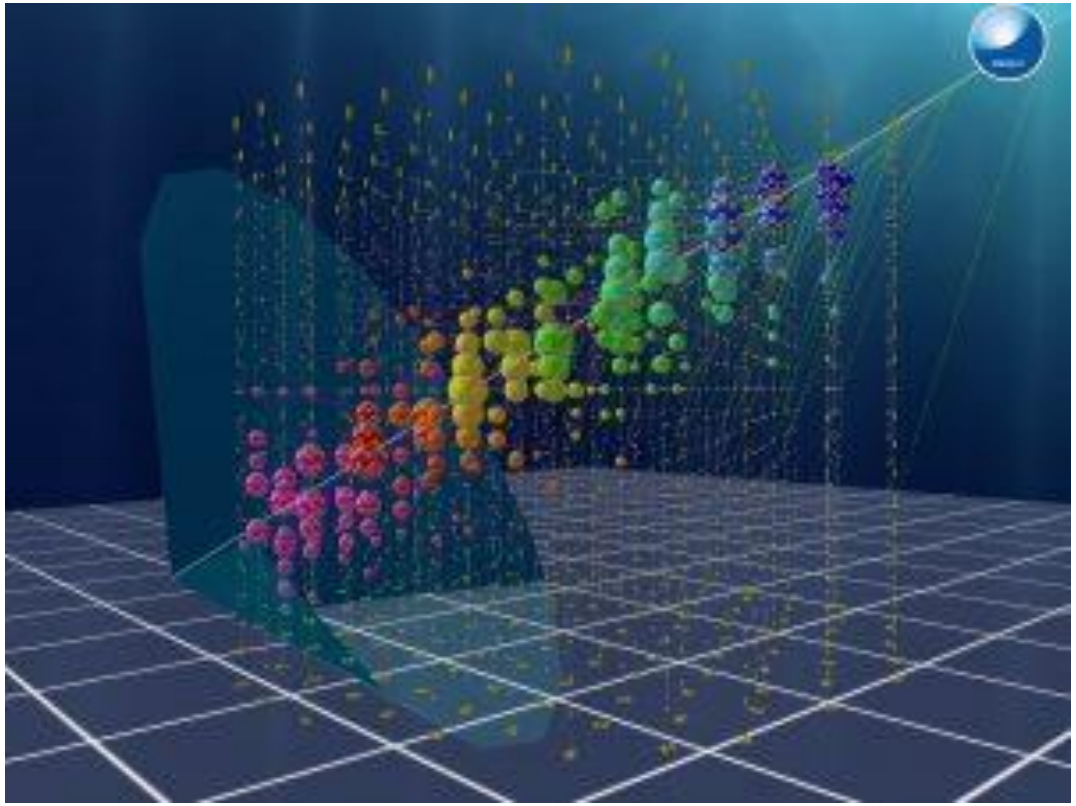
ARCA Reconstructed Events (muon)

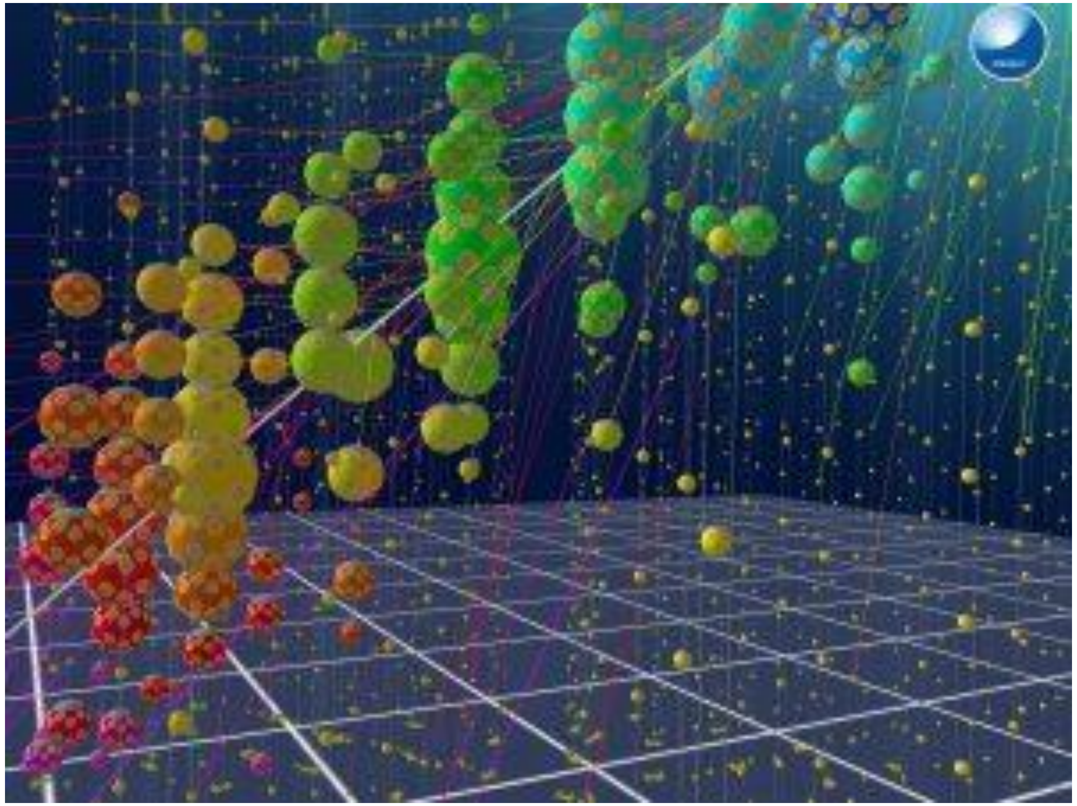




- The size of the spheres reflects the amount of light collected and their colour represents the arrival time of the light on the module: red is earlier than blue.
- The path of the muon particle that travels from above is reconstructed from this information and is made visible as the blue line.

ARCA Simulated Events





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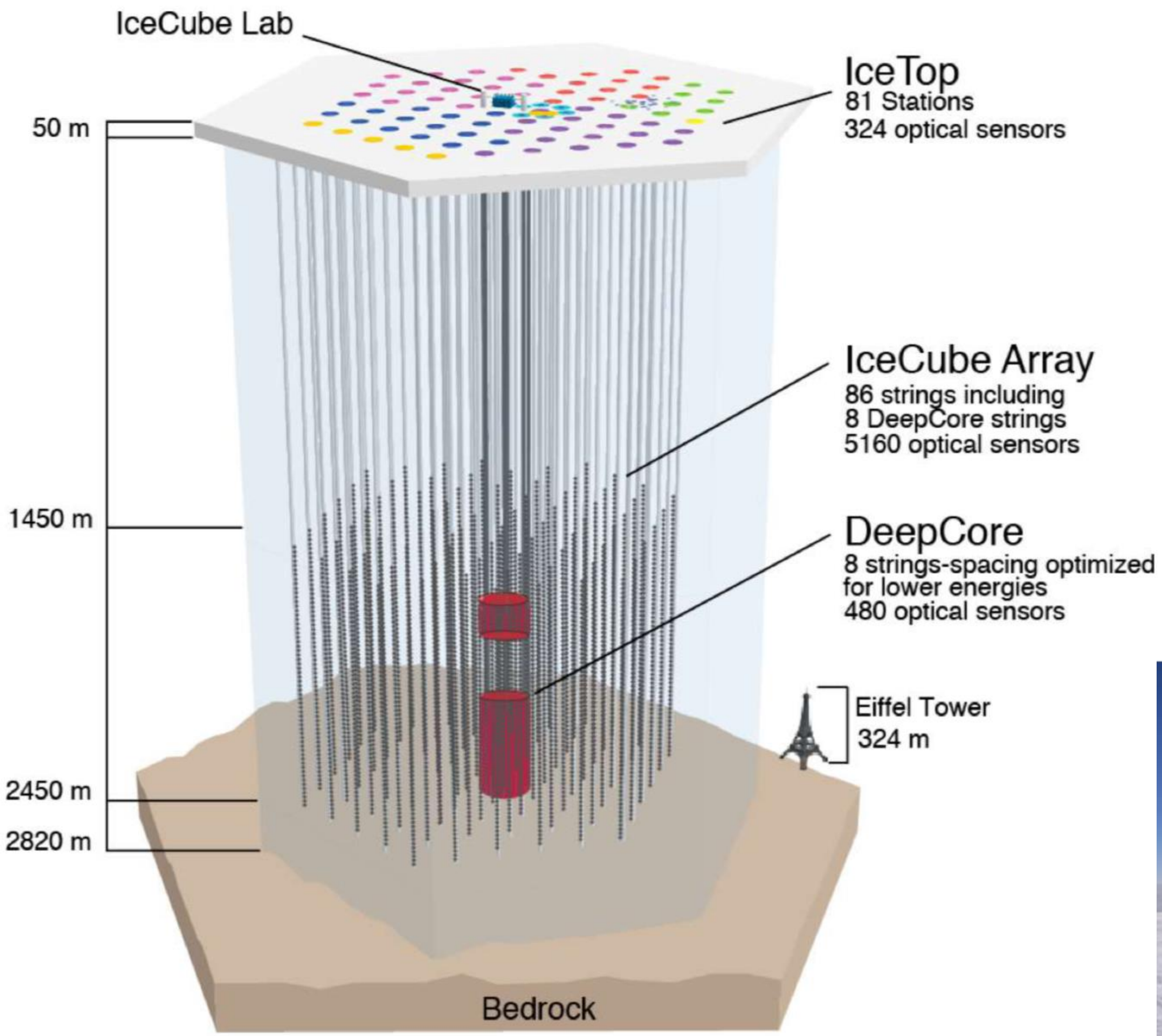
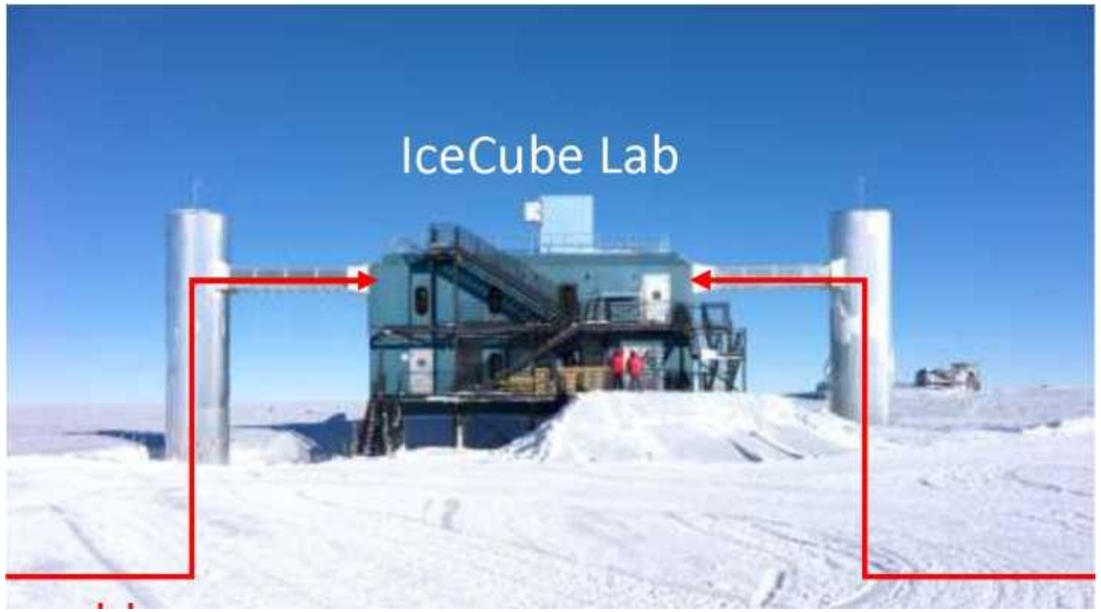
IceCube Overview



IceCube Overview

- The cables of all 86 strings run together in the IceCube Lab
- On-line processing and filtering
- Detector uptime of 99.8% (!)
- Data transfer to North:
  - High priority data (e.g. alerts) can be sent 24/7 over IRIDIUM connections (very low bandwidth), Starlink in testing phase
  - Usually, a couple hours per day satellites with higher bandwidth are in reach, can transfer up to ~100 GB/day
- Rest of data is literally “shipped” out on disk



Events in IceCube

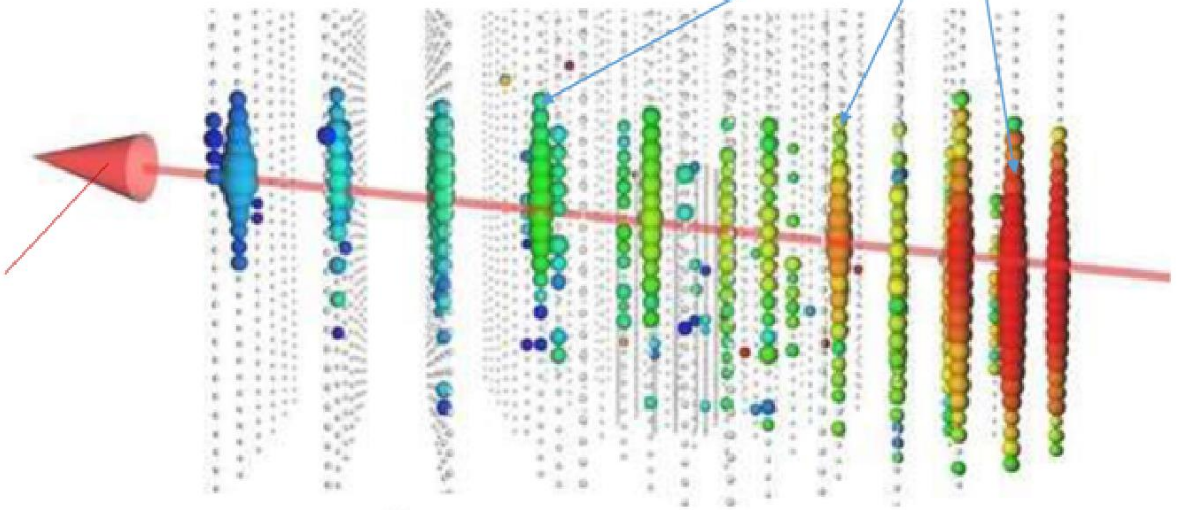
- Every DOM gets around ~500-800 hits per second, mainly from dark noise
- Hits from physics events are ~1 order of magnitude fewer
- Most of this is suppressed by trigger conditions
- Per year, we read out roughly:
  - 10^{10} events caused by atmospheric muons
  - 10^{9} events caused by noise
  - 100.000 events from atmospheric neutrinos
- "A handful of very high energy events likely to be of astrophysical origin"

- Special triggers exist for example looking for supernovae, they monitor the overall hit rate, where a correlated increase could indicate a nearby supernova

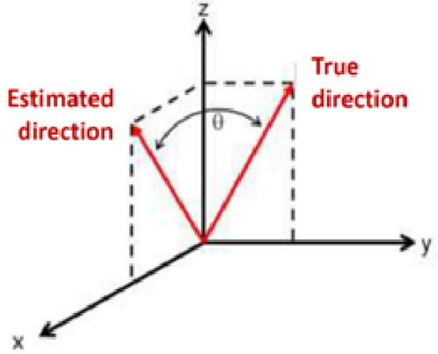
IceCube Event Reconstruction

Features: variable length series of so-called "pulses"
- time, charge, sensor ID / position

Label / regression target:
Neutrino Direction (zenith, azimuth)



Scoring Metric: Angle between true and estimated direction:



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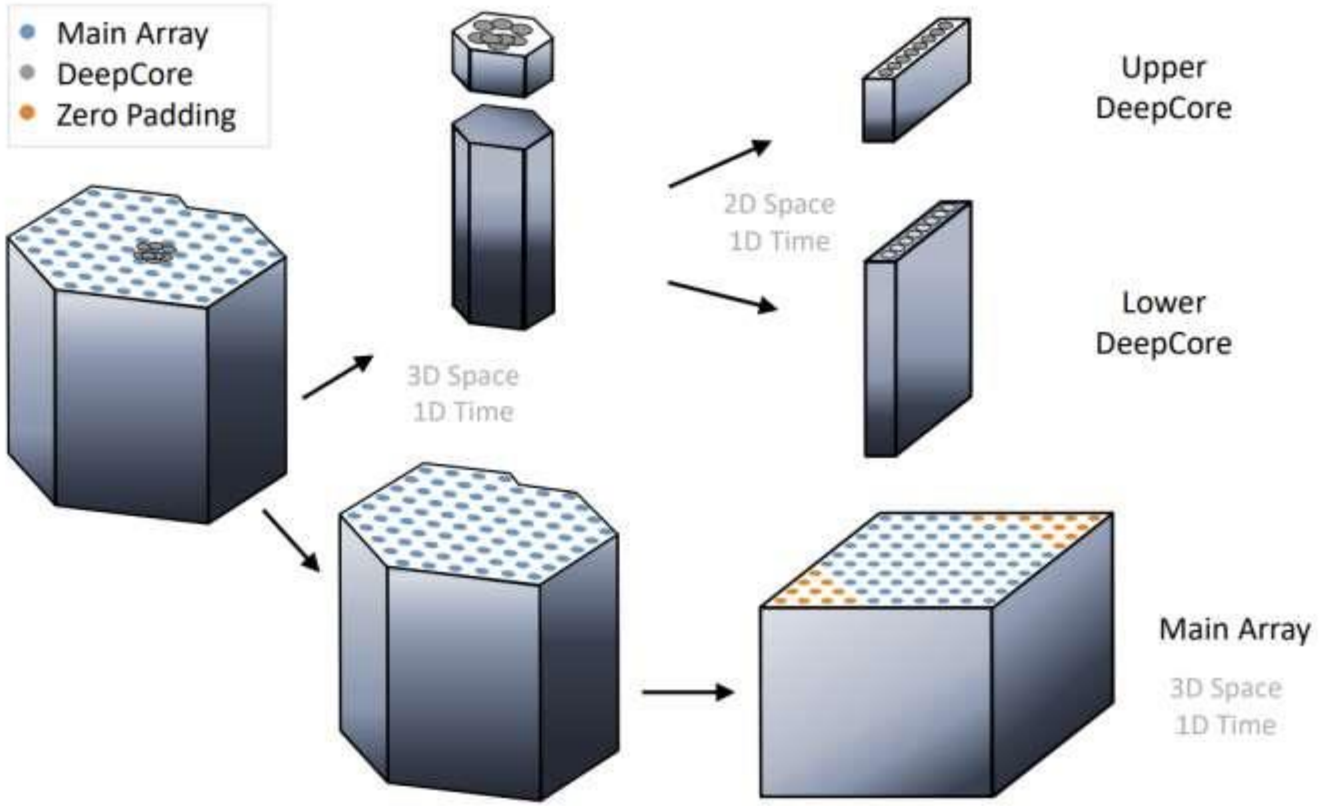
CNNs in Neutrino Telescopes

- Transform the raw data into 3d images



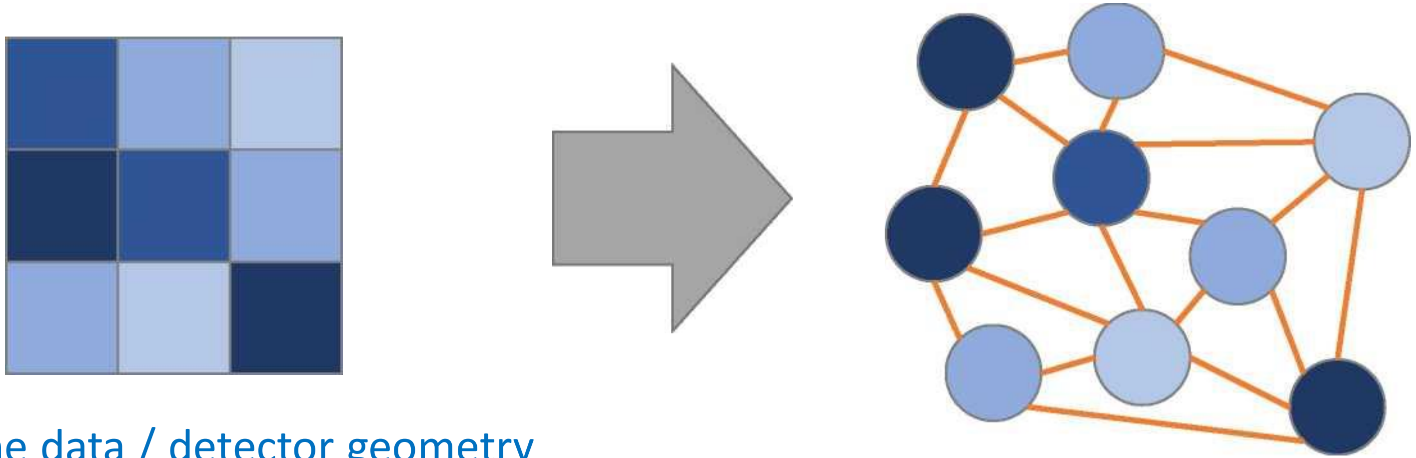
- A convolutional neural network based cascade reconstruction for the IceCube Neutrino Observatory
- https://doi.org/10.1088/1748-0221/16/07/P07041

→One big limitation: transformation onto rigid 3d "image"
→ Especially for DeepCore

Graph Neural Networks

CNN: fixed, rigid correlation structure:

GGN: Representation of data as a mathematical graph:



But, the data / detector geometry may deviate from this regularity

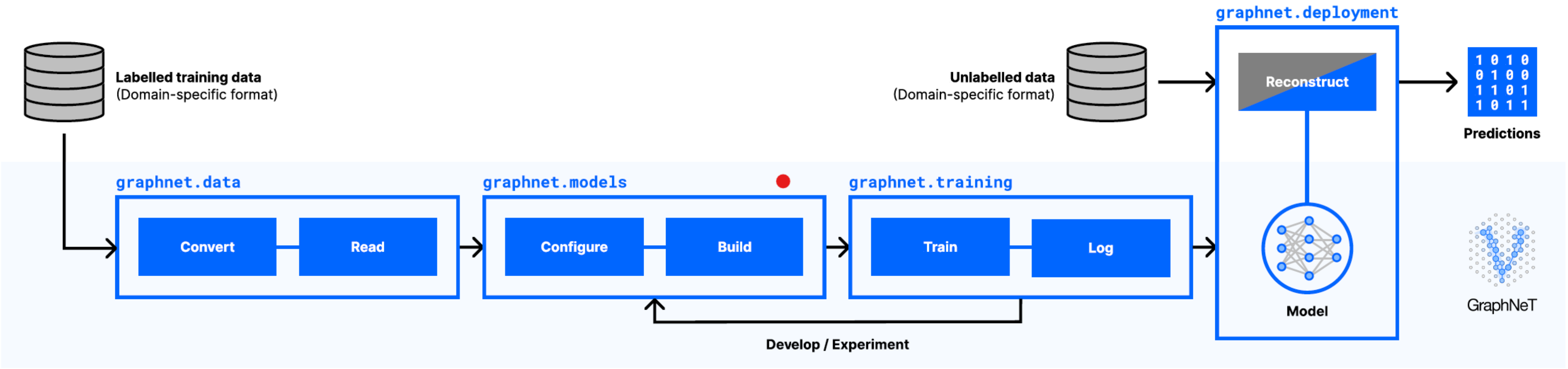
- **Node** features can be exactly the same as pixels in CNNs
- **Edges** representing the pair-wise relation between nodes (e.g. spatial distance)

- **G**raph **N**eural **N**etworks (**GNN**s):
  - generalization of NNs to arbitrary geometries
  - can define “graph convolutions“ similar to CNNs

GraphNeT
Graph Neural Networks for Neutrino Telescope Event Reconstruction

[graphnet-team/graphnet: Graph neural networks for neutrino telescope event reconstruction (github.com)]

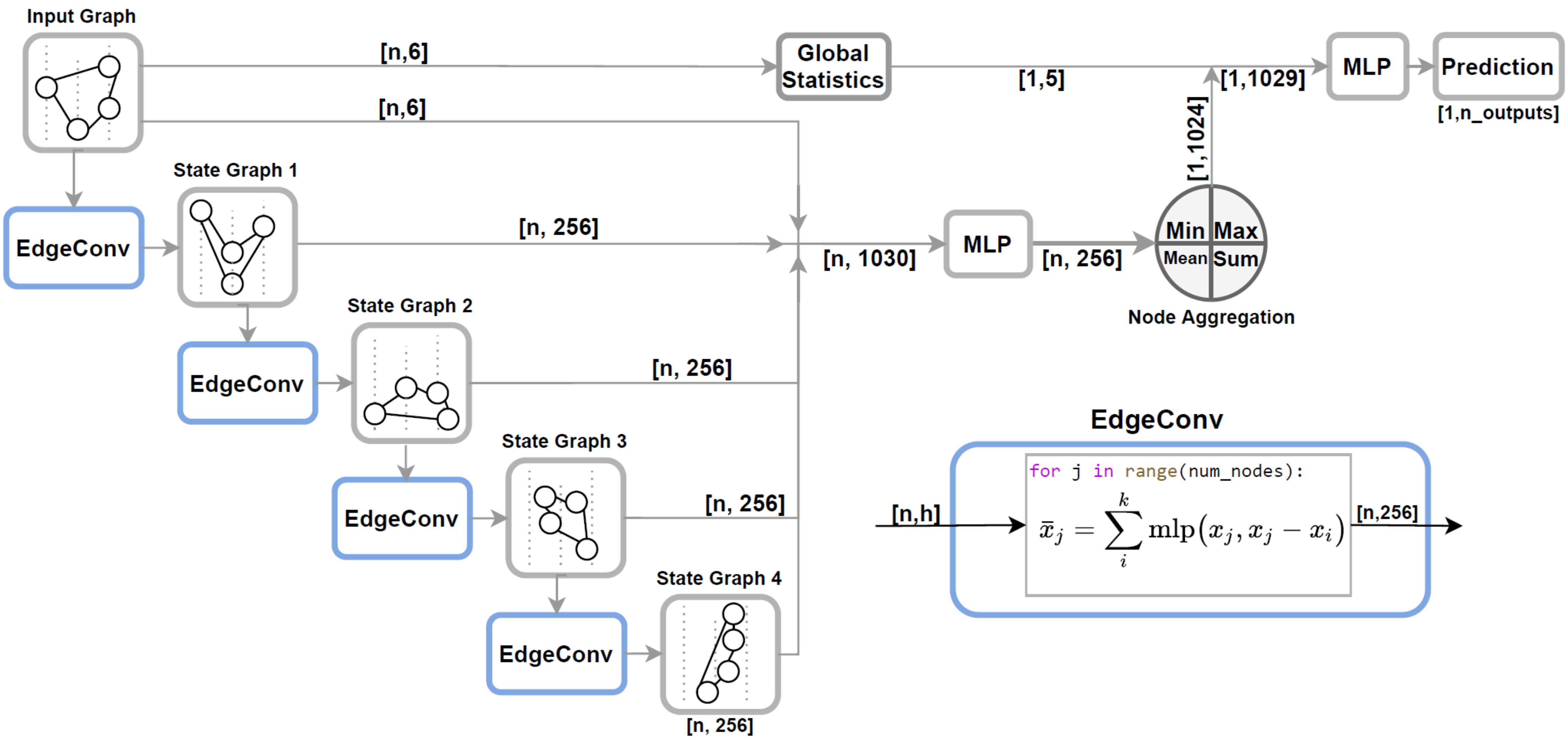
GraphNet Workflow



High-level overview of a typical workflow using GraphNeT:

1. *graphnet.data* enables converting domain-specific data to industry-standard, intermediate file formats and reading this data;
2. *graphnet.models* allows for configuring and building complex GNN models using simple, physicsoriented components;
3. *graphnet.training* manages model training and experiment logging;
4. *graphnet.deployment* allows for using trained models for inference in domain-specific reconstruction chains.

DynEdge: the Heart of GraphNet

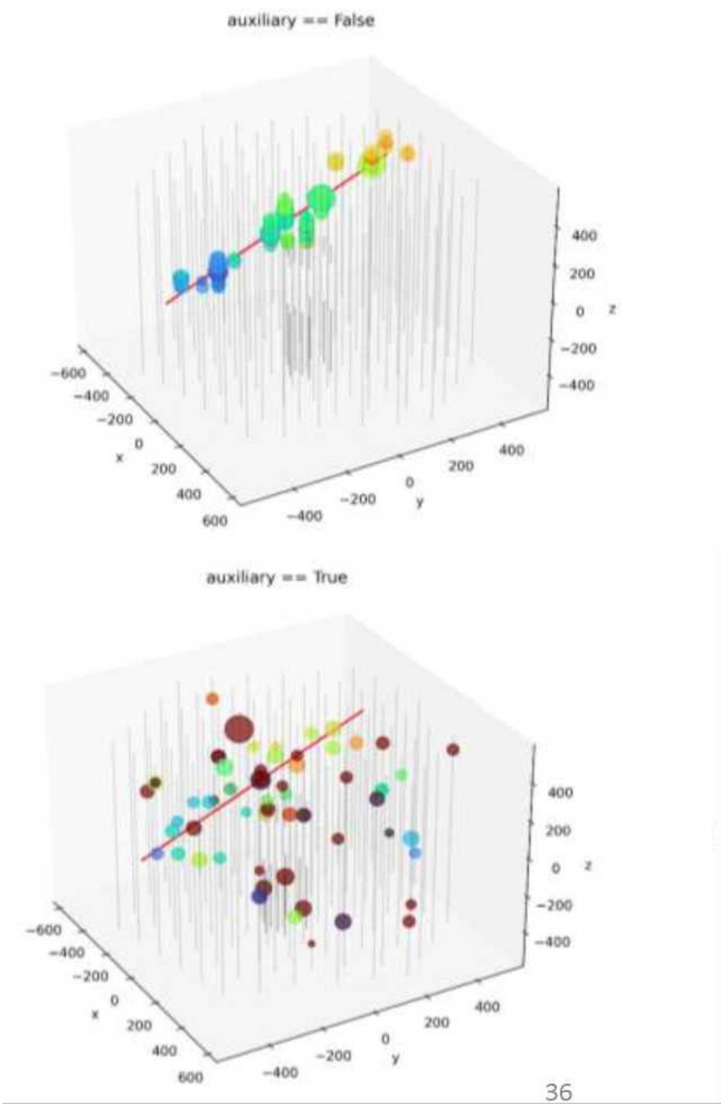


DynEdge Train & Test

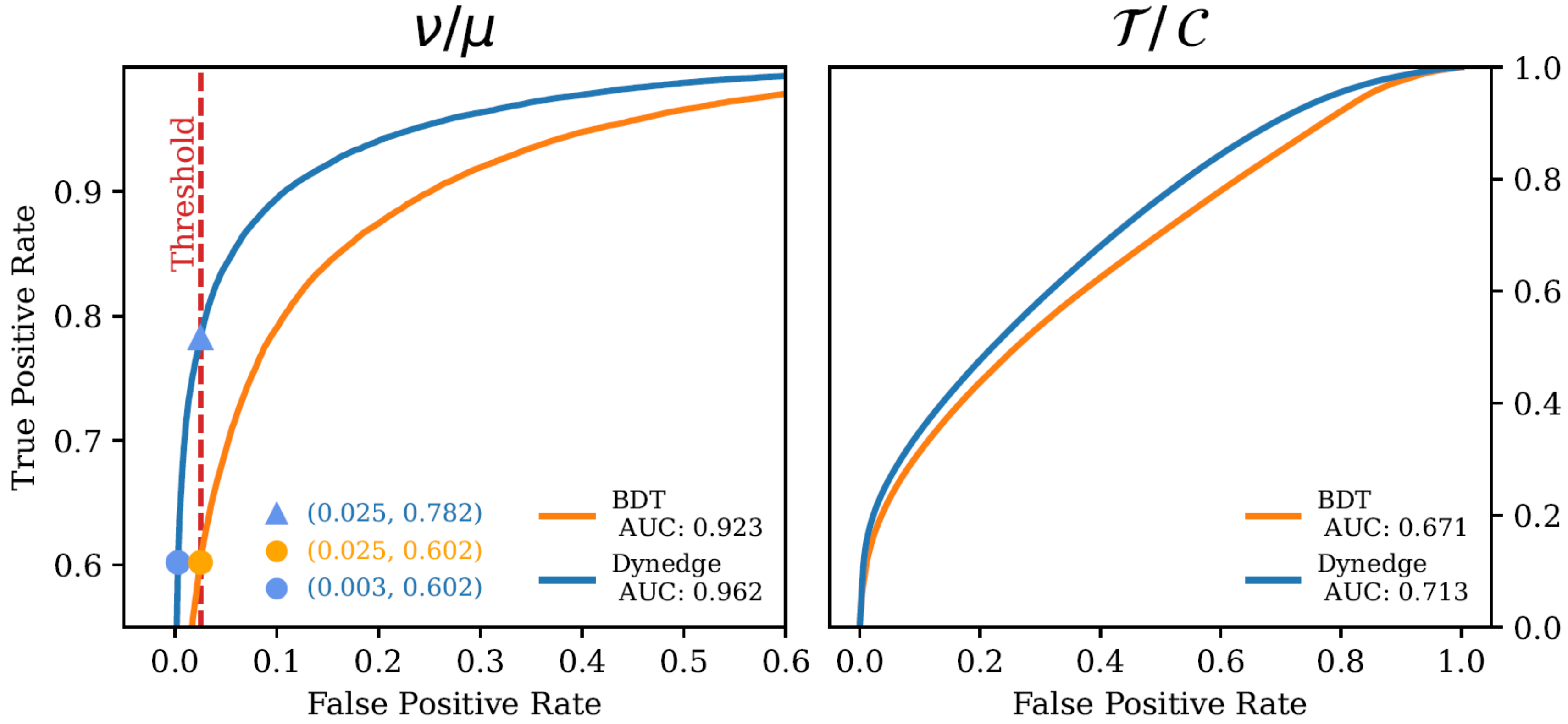
- Low energy neutrino dataset from 1GeV to 1000GeV simulated with GENIE https://doi.org/10.1016/j.nima.2009.12.009
- Training on the simulated dataser with separation of “track-like” events from “cascade-like” ones.

- IceCube detector has 5160 sensors at fixed, known locations
- Per event each sensor receives zero - many "pulses", i.e. variable-length time series

- Comparison of results with RETRO algorithm https://doi.org/10.1140/epjc/s10052-022-10721-2



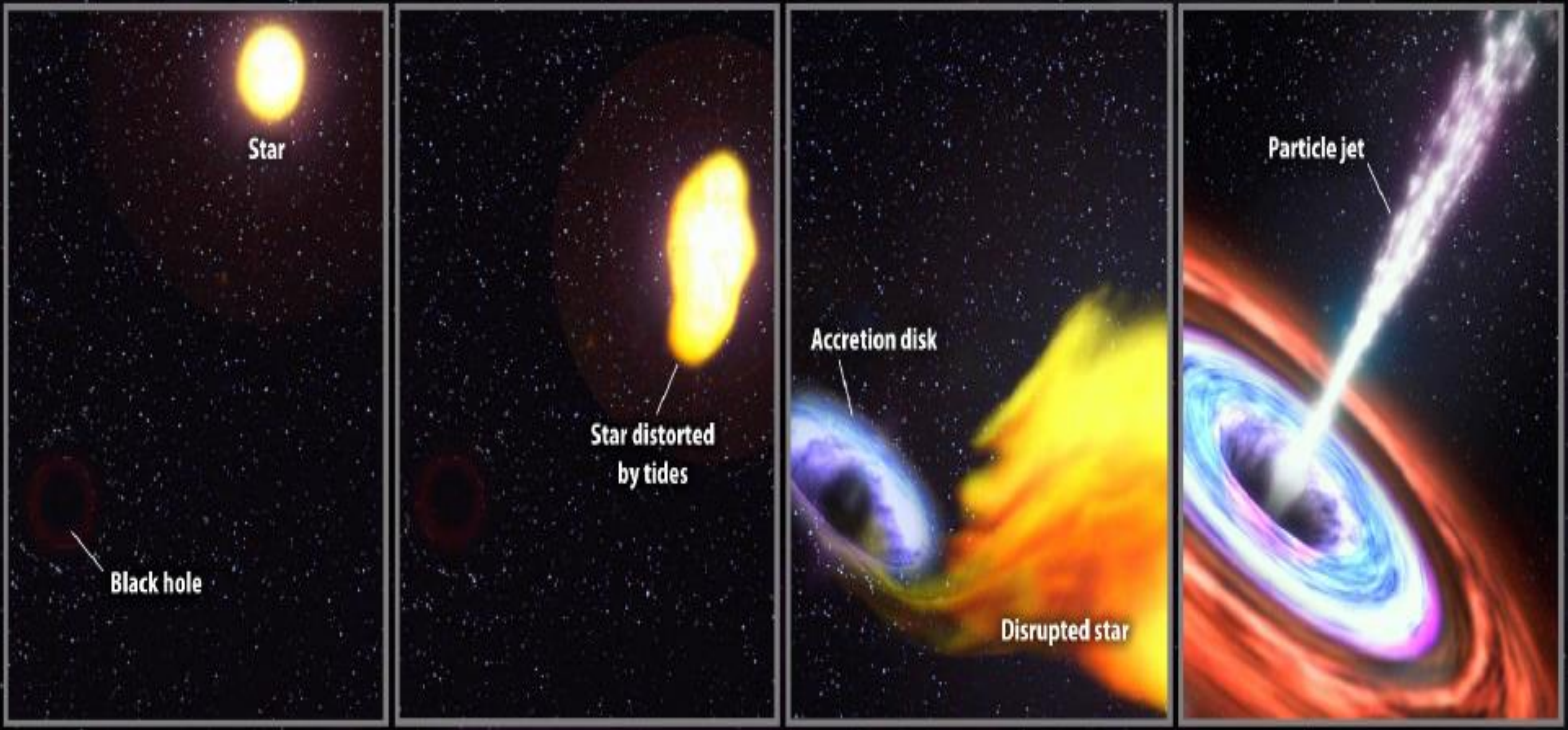
IceCube Event Reconstruction Sample



DYNEDGE classifier vs Boosted Decision Tree performance

- 18% increase in ν/μ classification task
- 6% increase in AUC score in $\mathcal{T}/\mathcal{C}$ classification task

The End


Star
Black hole
Star distorted
by tides
Accretion disk
Disrupted star
Particle jet