Neutrino Reconstruction in TRIDENT Based on Graph Neural Network

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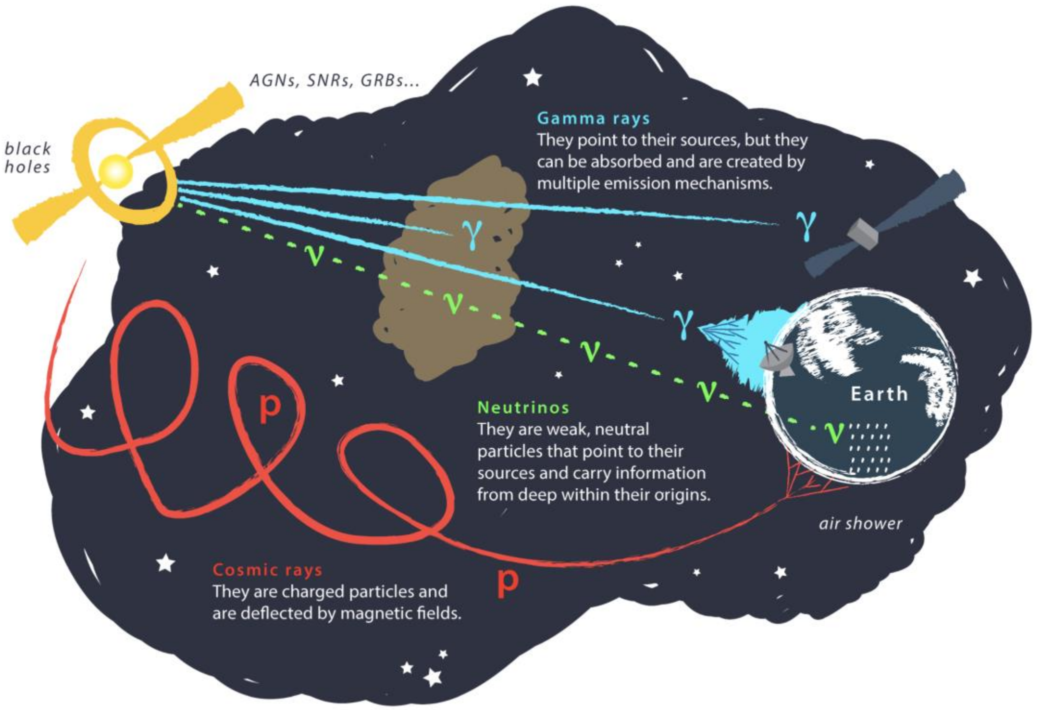
2023.12.14

Neutrino Telescope

Why do we need a neutrino telescope?

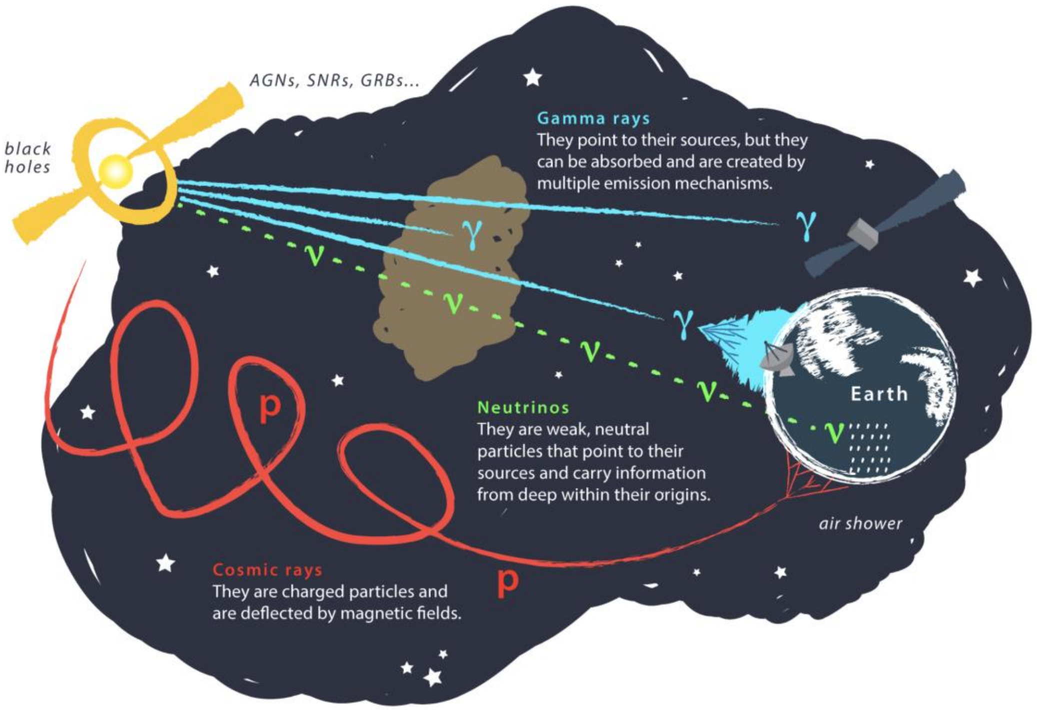
Probe origins of cosmic ray with neutrino.



Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

Neutrino Telescope

Probe origins of cosmic ray with neutrino.



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Astrophysical neutrino:

- **Small flux**

  $E_\nu \Phi_\nu < 2 \times 10^{-8} GeV cm^{-2} s^{-2} sr^{-1}$

- **Small cross section**

  $\sigma \sim 10^{-33} cm^2$ for $E_\nu \sim 10 PeV$

Neutrino Telescope

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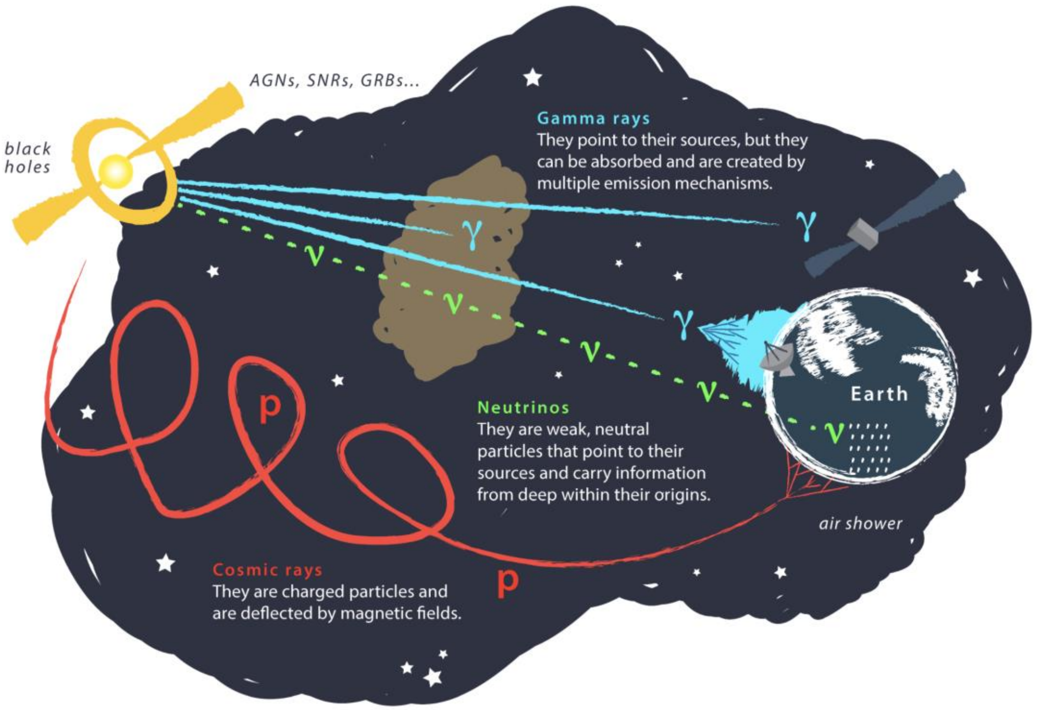

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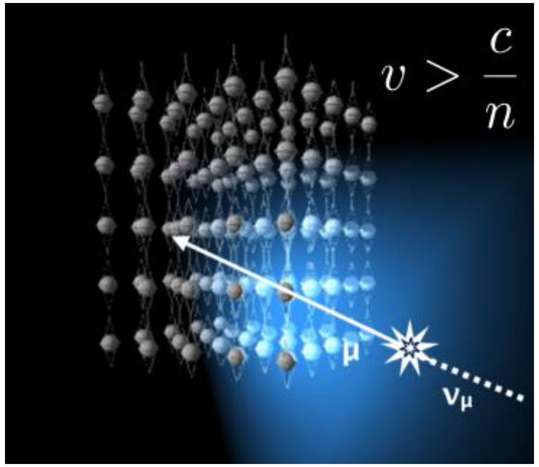
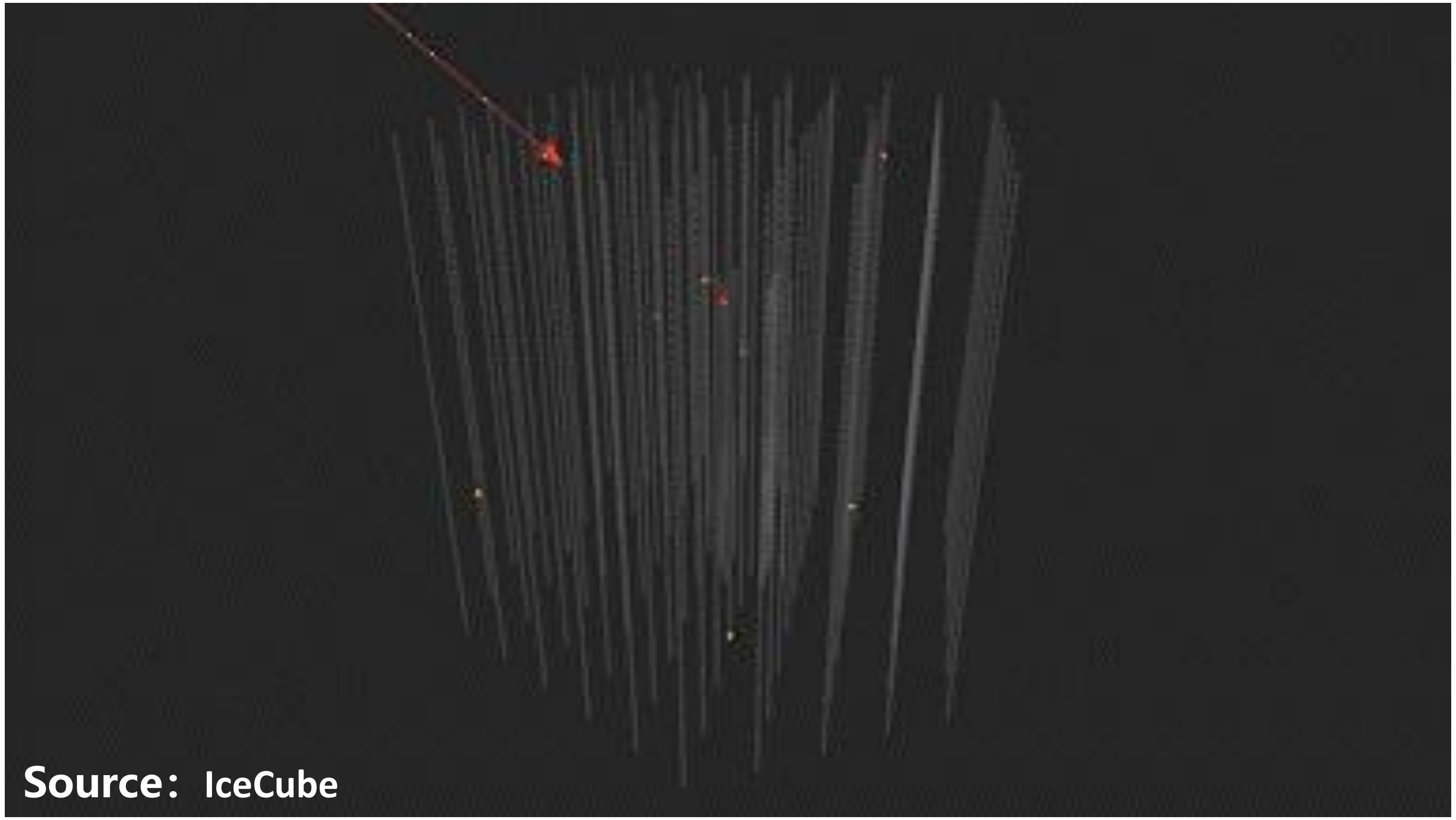
Use sea water as target



- Neutral-current interaction
  $\nu_l + N \rightarrow \nu_l + X$
- Charged-current interaction
  $\nu_l + N \rightarrow l + X$

Neutrino Telescope

Probe origins of cosmic ray with neutrino.



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Use sea water as target

- Neutral-current interaction

  $$\nu_l + N \to \nu_l + X$$

- Charged-current interaction

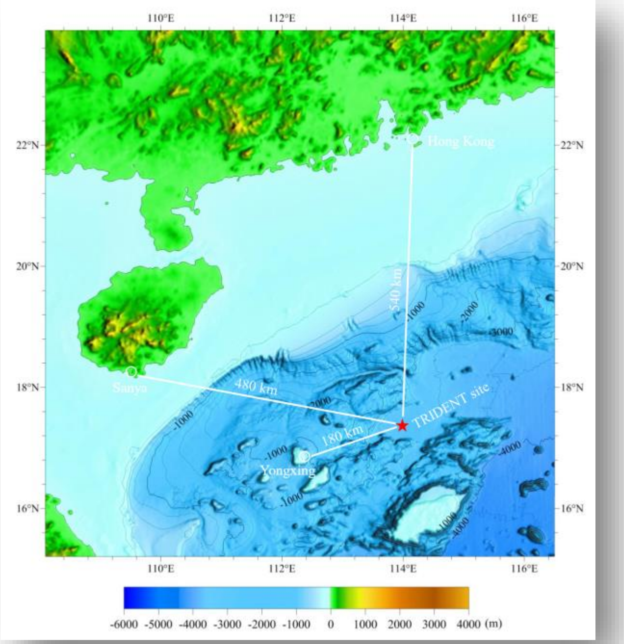
  $$\nu_l + N \to l + X$$

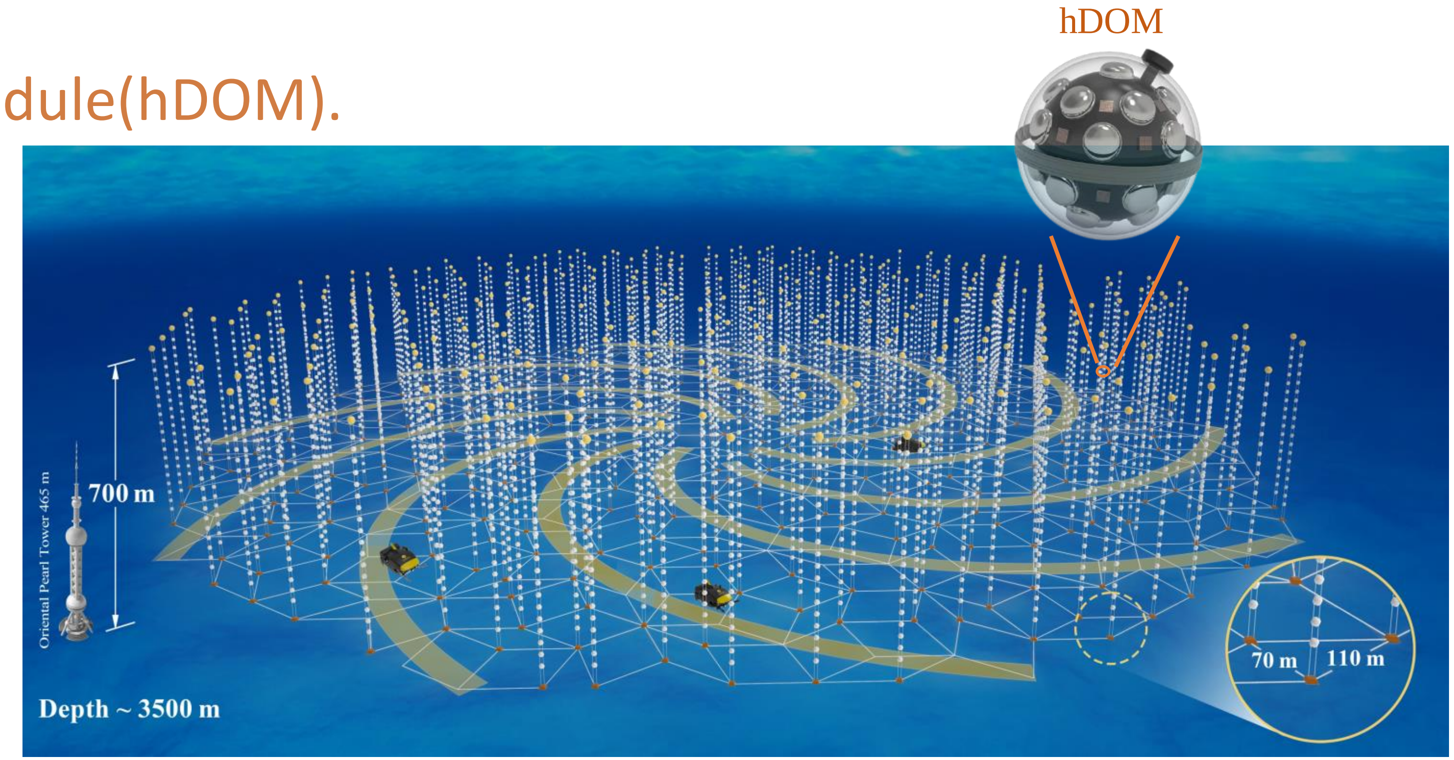
TRIDENT

- **TRIDENT**: **TR**oplcal **DE**ep-sea **N**eutrino **T**elescope.

  A multi-cubic-kilometre neutrino telescope in the western Pacific Ocean. *Nat Astron (2023).*

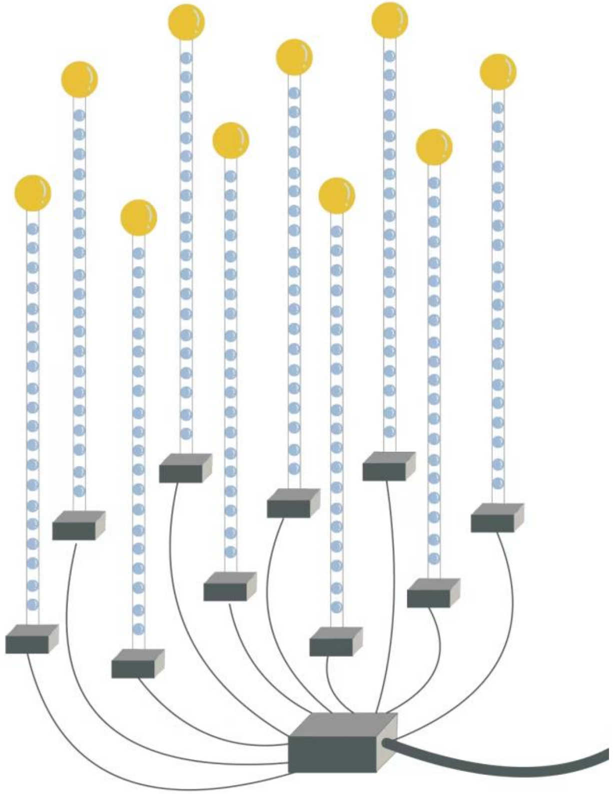
- To be located in the South China Sea.
- Penrose tiling structure with 2000m radius, 700m height (8.7 km³). 3500m deep under sea level.
- 24220 hybrid Digital Optical Module(hDOM).

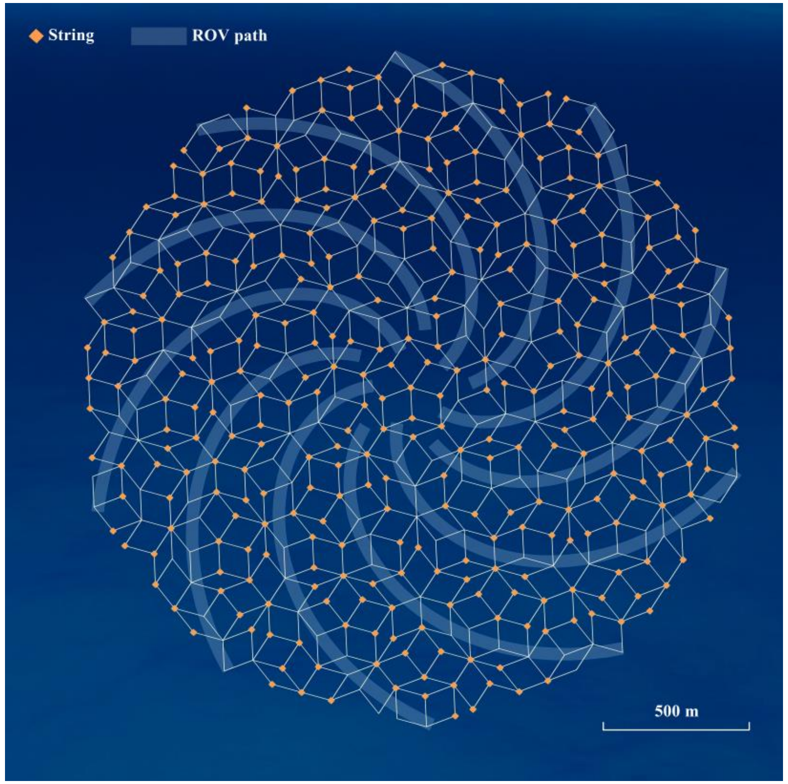




TRIDENT

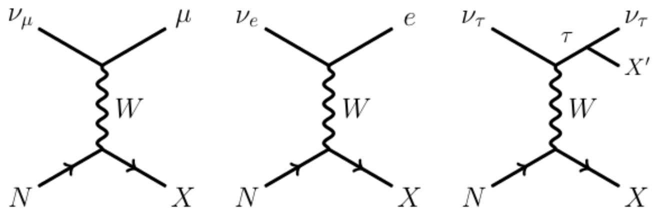
Expected Timeline



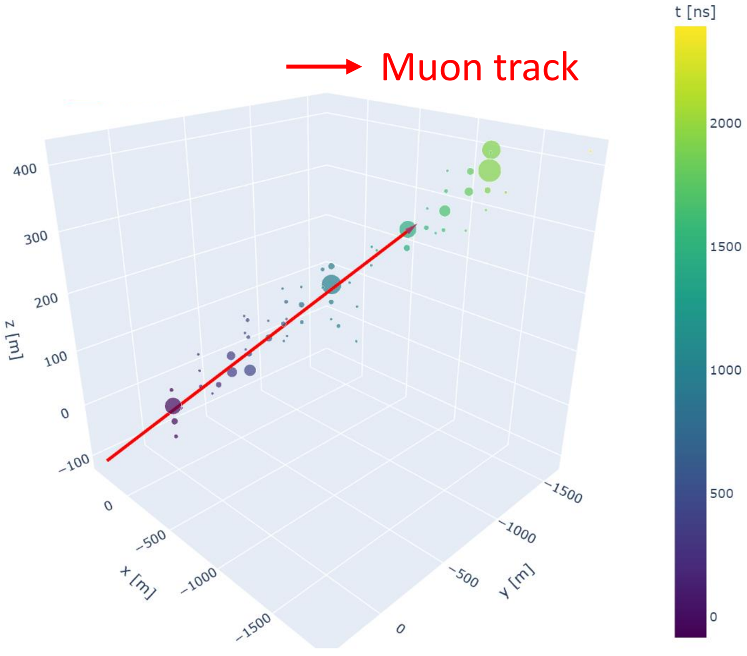


T-REX: 2019-2022 → **Phase I: 2022-2026** → **Full detector: 2026-**

Neutrino Events

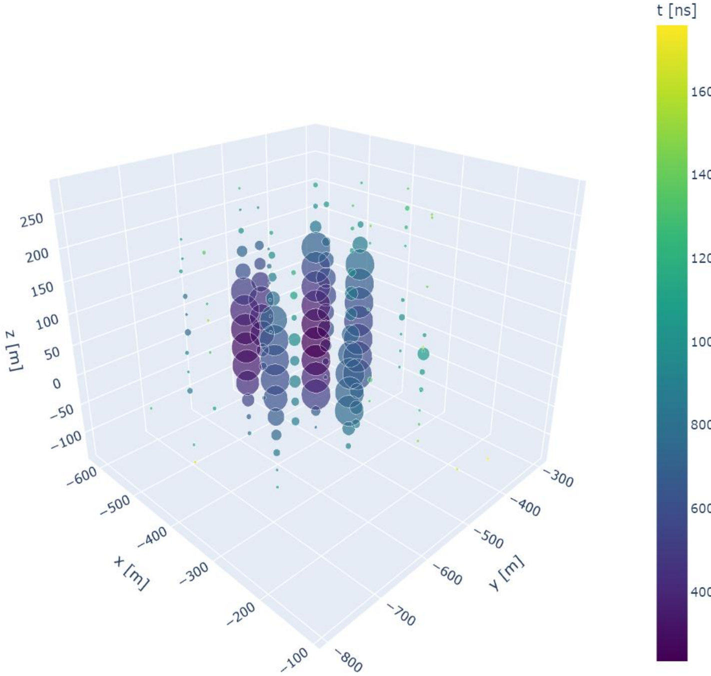


- The size of dots indicates the number of received photons.



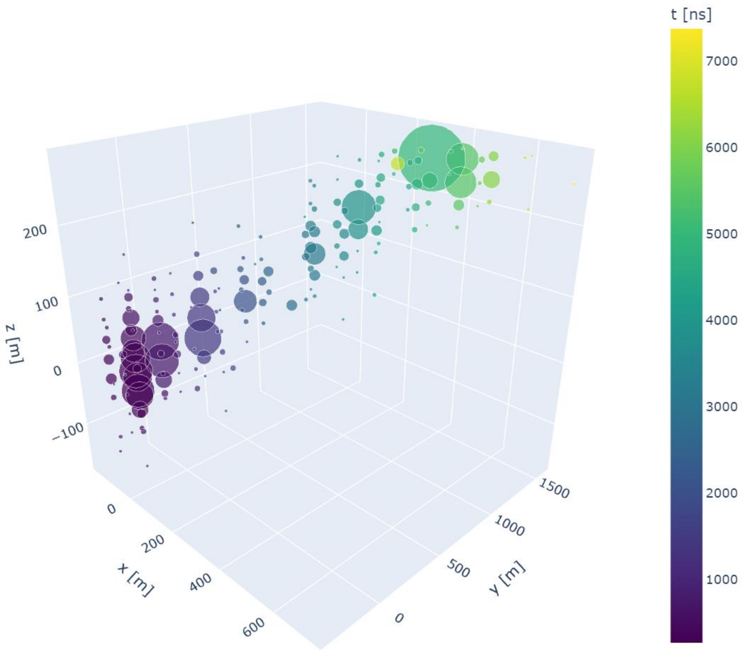
Track

$\nu_\mu + N \rightarrow \mu + X$



Cascade

$\nu_e + N \rightarrow e + X$
$or\ \nu + N \rightarrow \nu + X$



Double bang

$\nu_\tau + N \rightarrow \tau + X$
$\&\ \tau \rightarrow \nu_\tau + X'$

Simulation

Neutrino event generator

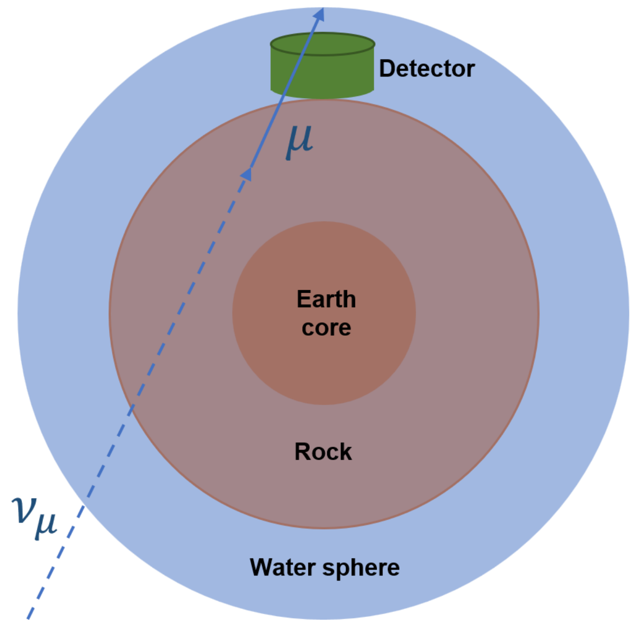
Based on **CORSIKA8** (arxiv:2208.14240):

- A preliminary earth model is built.
- Scattering of ν and p is simulated with PYTHIA8.
- Propagation of μ is simulated with PROPOSAL.

Detector simulation

Based on **Geant4**:

- Simulate the propagation of secondary particles.
- Accelerate Cherenkov photons simulation with OptiX.



Preliminary earth model

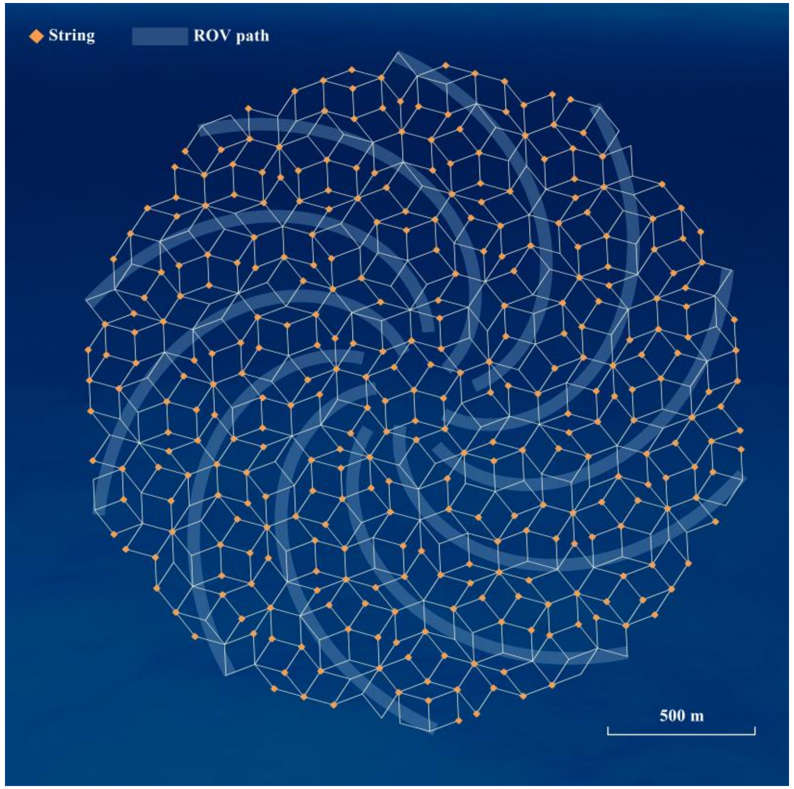
Network Architecture

Neutrino telescope:

- Irregular detector geometry
- Sparse signal

Compared GNN and SSCNN (arxiv:1706.01307) performance:

- GNN outperforms SSCNN in terms of angular resolution in track-like events.



Top view of TRIDENT

Network Architecture

Neutrino telescope:

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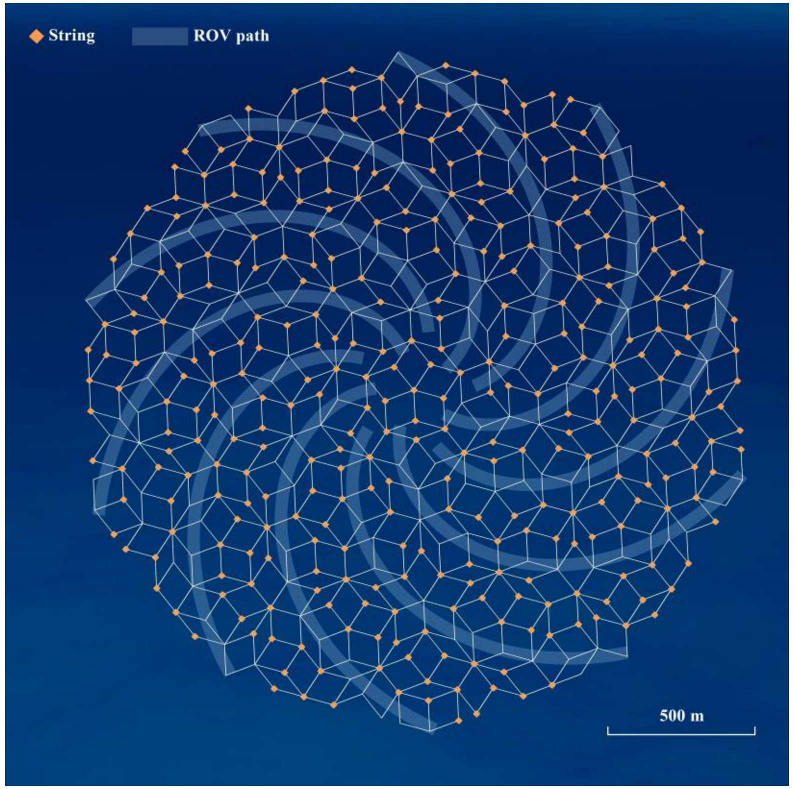
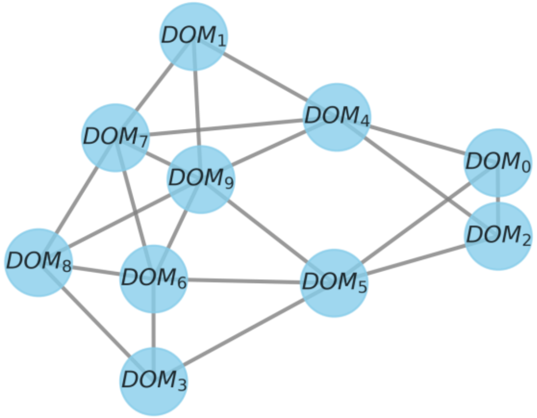


Top view of TRIDENT

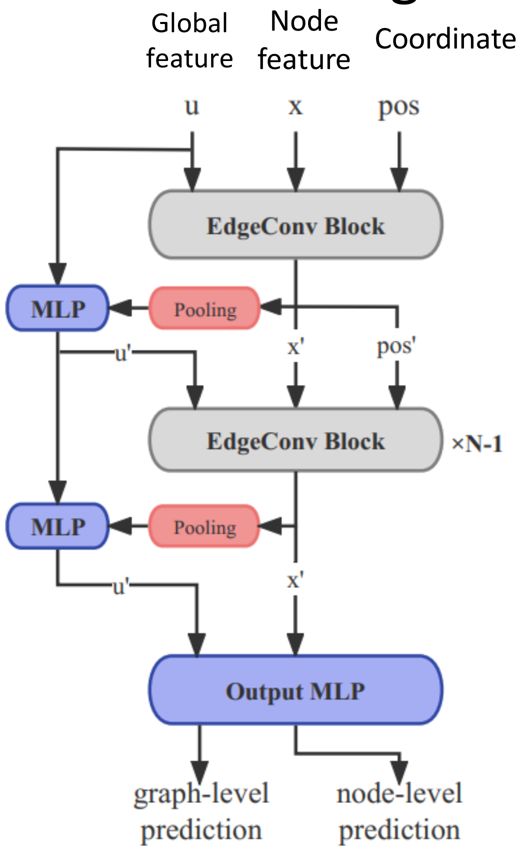


Use point cloud to represent neutrino events:

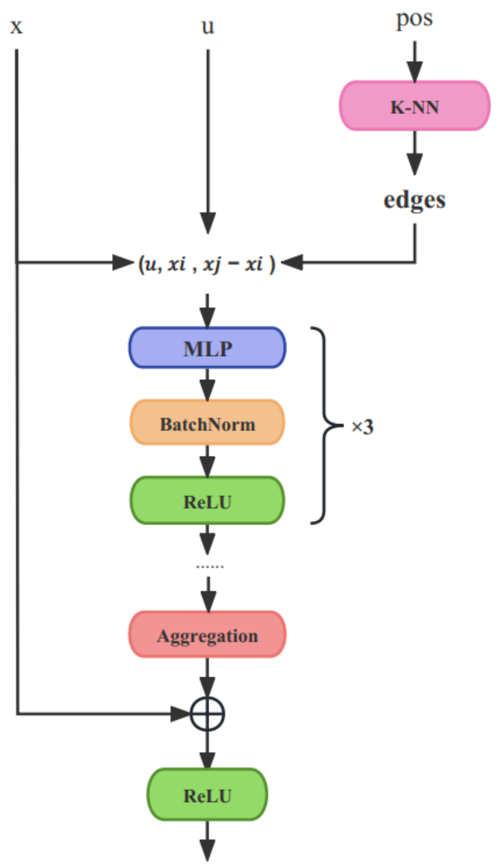
- Triggered DOMs → Nodes of point cloud
- Location of DOMs → Coordinate of nodes, pos_i.
- DOM-measured time → Features of nodes, x_i.

Network Architecture

- GNN is built based on **EdgeConv** block: modified from **EdgeConv** block used in ParticleNet (arxiv:1902.08570).
- Both graph-level and node-level target can be predicted.



Network Structure



EdgeConv Block

Cascade Reconstruction

Direction & Energy Reconstruction

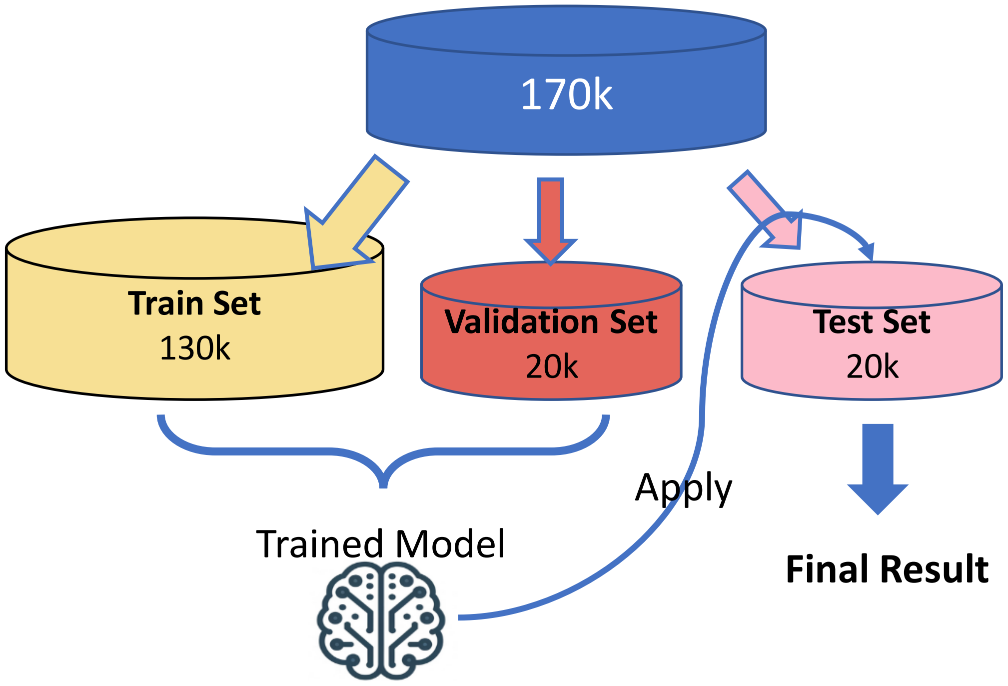
$\nu_e + N \rightarrow e + X$

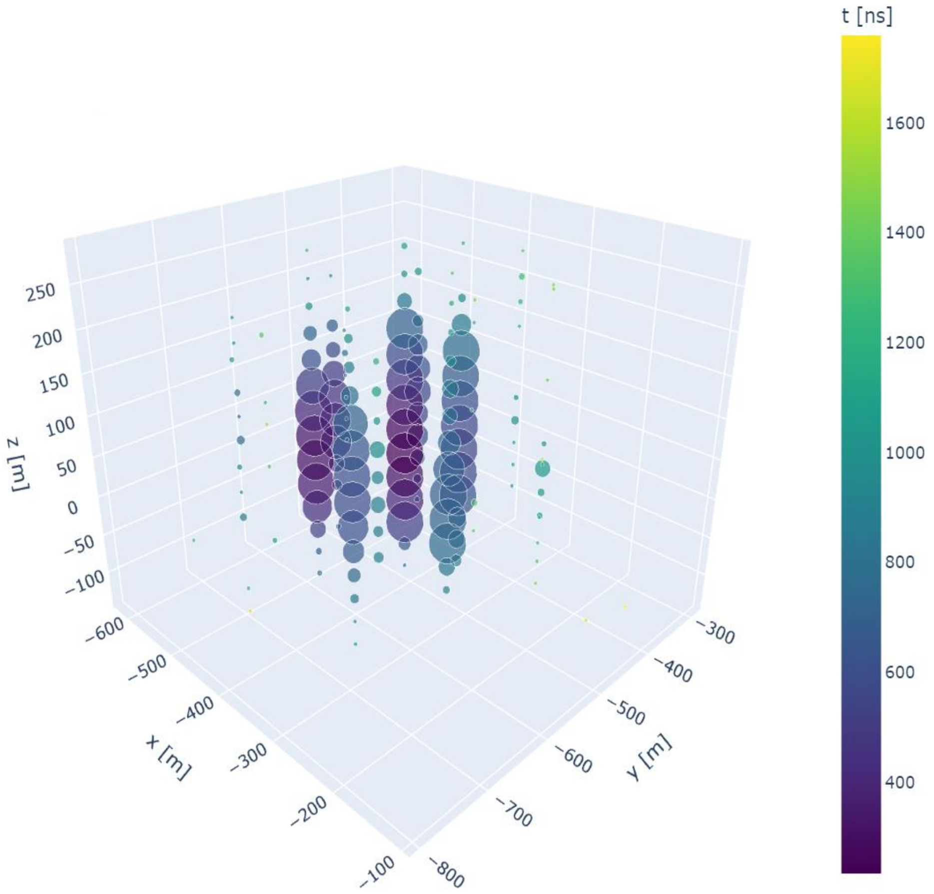
Cascade Reconstruction

ν_e direction reconstruction

Configuration for Direction Reconstruction

- ν_e energy: 100TeV
- Sample size:

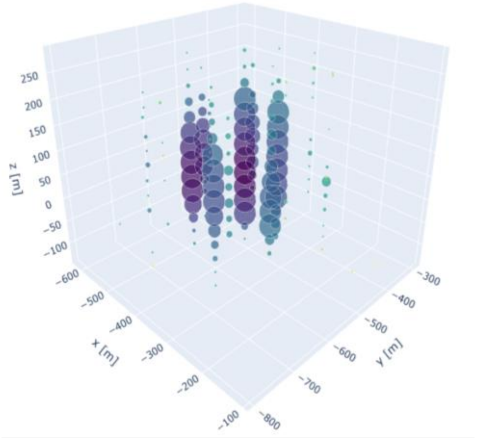




Cascade Reconstruction

ν_e direction reconstruction

- Input feature of $\mathrm{DOM_i}$:



$\mathrm{DOM_i}$: $[hit_0, hit_1 \ldots hit_N]$
$(hit_i = [x_i, y_i, z_i, n_x, n_y, n_z, t_i])$

$\Rightarrow$ $\mathrm{Node_i}$: $Histogram([t_0, t_1 \ldots t_N], bin\ width = 5ns) +$
$[x, y, z] + [n_x, n_y, n_z]$

Average

- Histogram is further modified (**normalization**):

$$\mathrm{Node_i} = [x, y, z, n_x, n_y, n_z, \ln(Histogram + 1)]$$

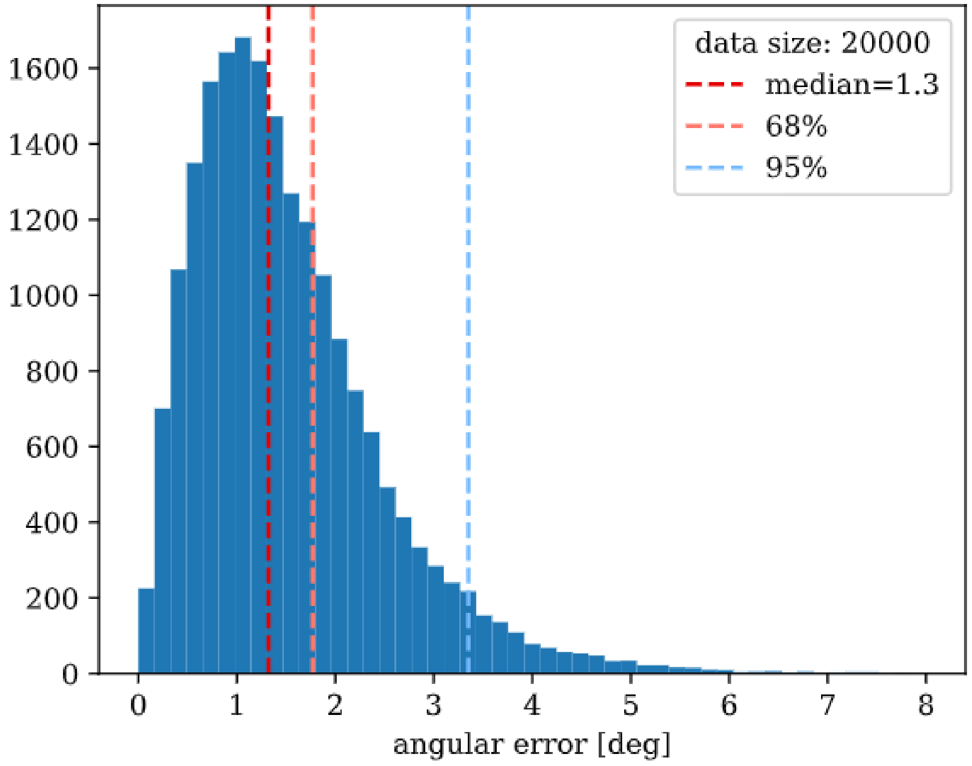
- Network is trained to predict $\hat{n}_\nu$ with MSE loss:

$$Loss = \left| \frac{\overrightarrow{output}}{|output|} - \hat{n}_{truth} \right|^2$$

Cascade Reconstruction

ν_e direction reconstruction

- **Angular error**: angle between **recon_direction** and **truth_direction**
- Resolution reaches **1.3 degrees**. As a comparison: likelihood method: ~1.7 degrees (DOI: 10.22323/1.301.0950)



Angular resolution Improvement: 25%

Cascade Reconstruction

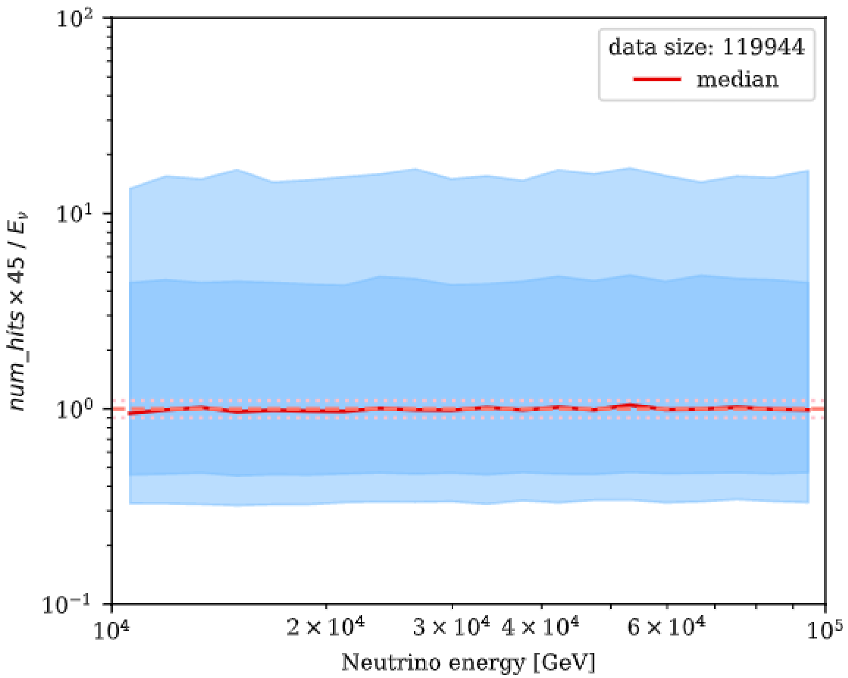
- **ν_e energy reconstruction**

Configuration for Energy Reconstruction

- ν_e energy: 10TeV ~ 100TeV
- Sample size: 150k samples are splitted into:

$$train : validation : test = 120k : 15k : 15k$$

Linearity between num_hits & Energy

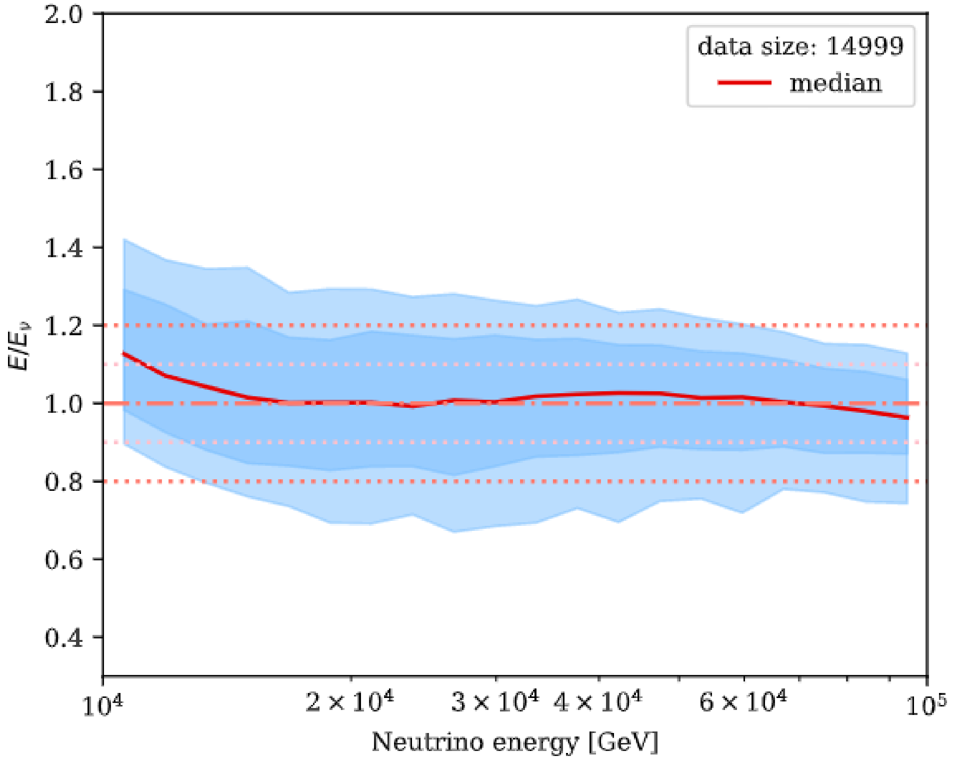


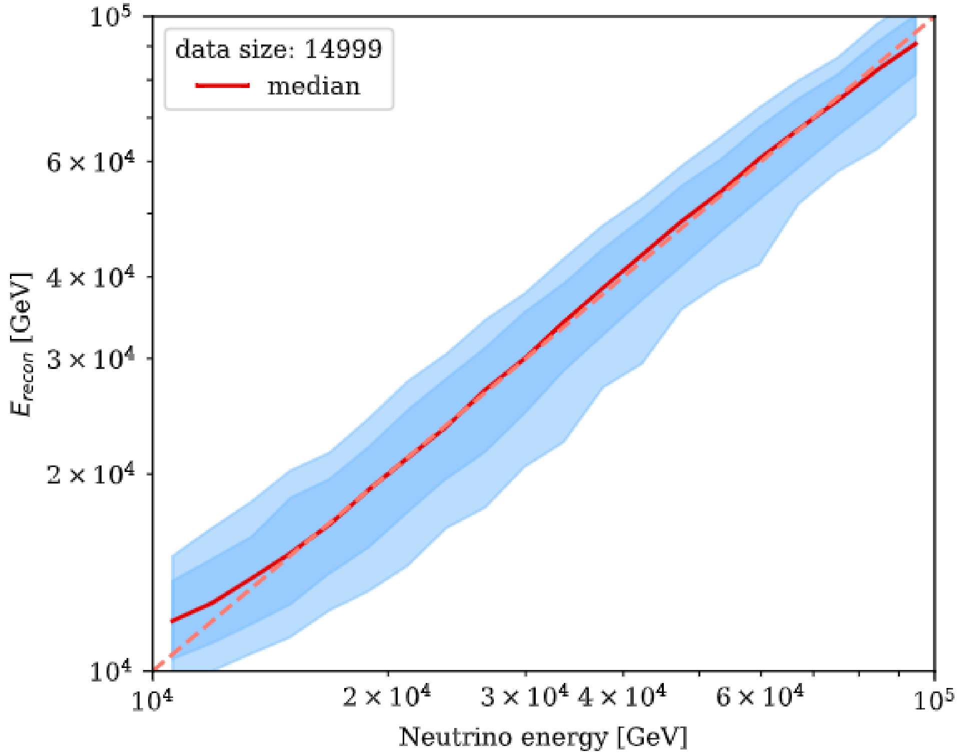
Cascade Reconstruction

- Train GNN with:

$$\log_{10} E = \boldsymbol{GNN(graph)} + \log_{10}(\text{num\_hits} \times 45)$$
$$Loss = (\log_{10} E - \log_{10} E_{truth})^2$$

- Energy resolution is around 10% for high energy event – comparable results with the traditional likelihood method.





Track Reconstruction

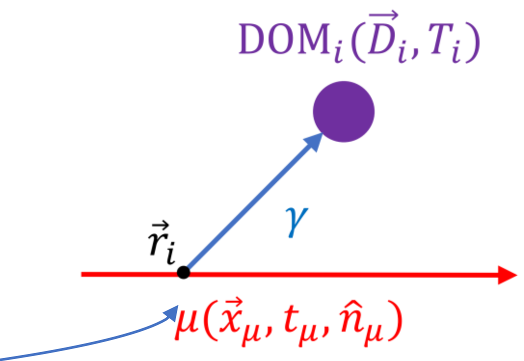
Direction Reconstruction

$\nu_\mu + N \rightarrow \mu + X$

ν_μ Direction reconstruction

$train : validation : test = 900k : 70k : 100k$

- **Input features**: location $\vec{D}_i$, first photon arrival time T_i and number of photo hits n_i.



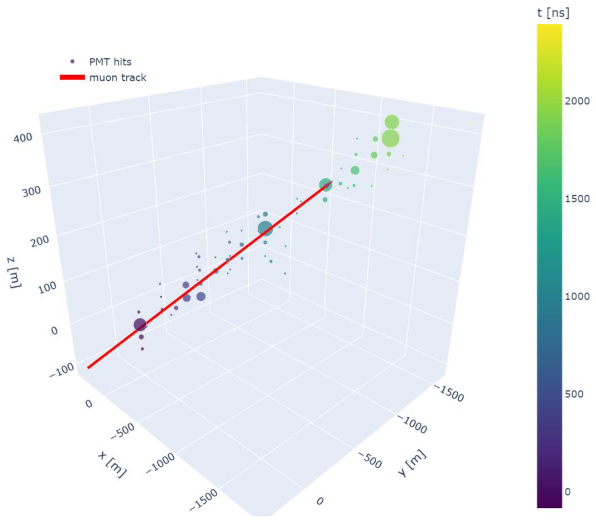
μ emits photon and triggers $\mathrm{DOM_i}$

- To make full use of the geometric feature of track-like events, the network is trained to predict $\vec{r}_i$ for each $\mathrm{DOM_i}$.

- **Linear fit** on the predicted $\vec{r}_i'$ to reconstructs $\hat{n}_\mu$.

- **Loss function**: mean square error (MSE) with weight proportional to n_i:

$$Loss = \Sigma_i n_i \times \left|\overrightarrow{output}_i - \vec{r}_i\right|^2 / \Sigma_i n_i$$



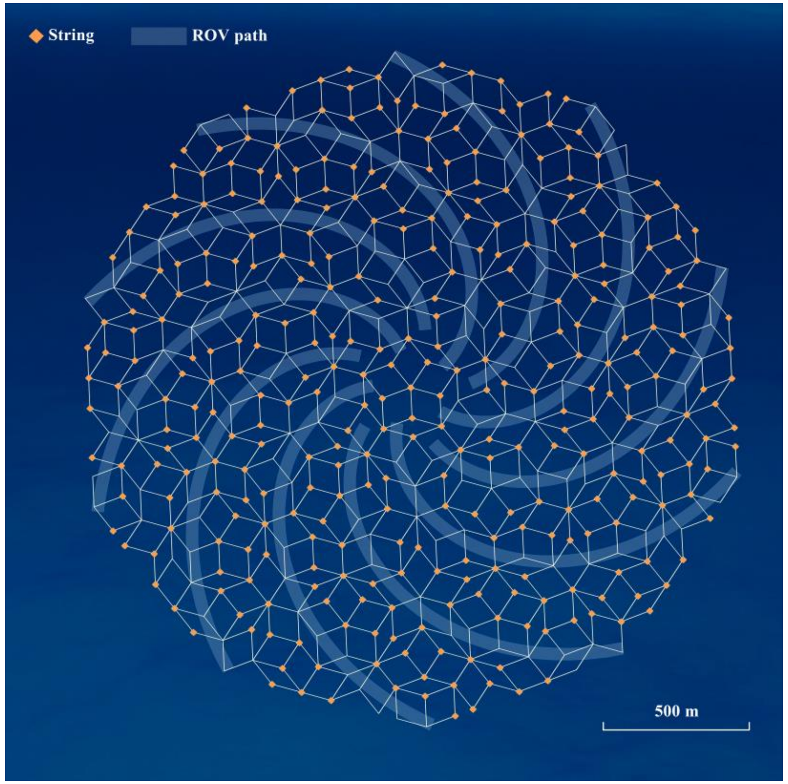
Track-like event display

Track Reconstruction

- **Data Augmentation:** based on symmetry of TRIDENT.

5-fold Rotational Symmetry

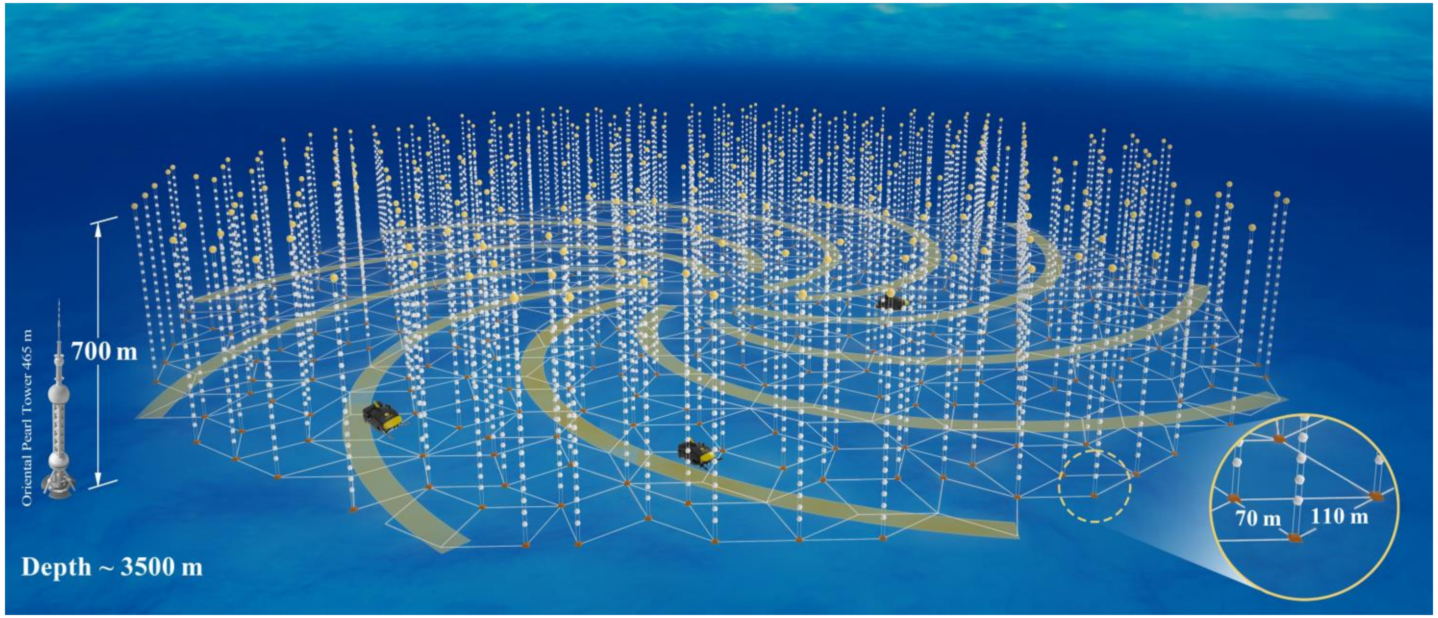
Invariant under 36° rotation around z-axis



Data size × 5

Reflection Symmetry

Invariant under $x \to -x$ and $z \to -z$

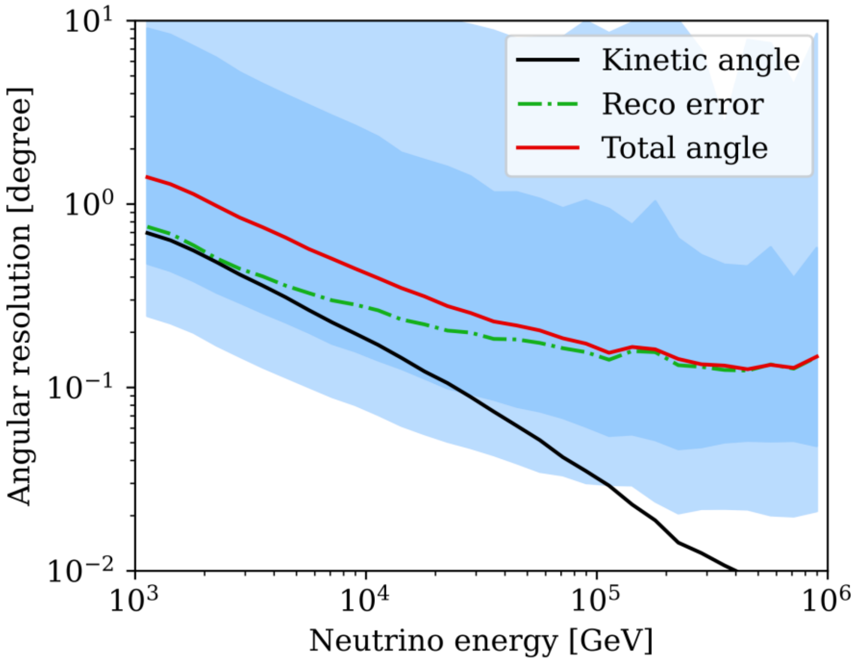


Data size ×4

Track Reconstruction

ν_μ Direction **reconstruction**

- Model is trained on events with **track length > 500m**.
- Median angular error decreases from 1 degree to **0.1 degree** as the energy of ν_μ increases – competitive to the result of likelihood method.



- Kinetic angle = $< \vec{n}_\mu, \quad \vec{n}_\nu >$
- Reco error = $< \vec{n}_\mu, \vec{n}_{recon} >$
- Total angle = $< \vec{n}_\nu, \vec{n}_{recon} >$

Summary and Outlook

- Simulated neutrino events in TRIDENT are represented as point clouds and are reconstructed by Graph Neural Network.
- GNN demonstrates high accuracy in reconstructing ν_e and ν_μ events in neutrino telescope:

Task	Resolution (GNN)	Resolution (Traditional method)
Cascade direction	**1.3 degrees**	1.7 degrees
Cascade energy	**10% (>50 TeV)**	5~20%
Track direction	**~0.1 (>50 TeV)**	0.1 (>50 TeV)

Summary and Outlook

- Simulated neutrino events in TRIDENT are represented as point clouds and are reconstructed by Graph Neural Network.
- GNN demonstrates high accuracy in reconstructing ν_e and ν_μ events in neutrino telescope:
  - **25% improvement** for ν_e direction reconstruction.
  - **10% energy resolution** for ν_e & **0.1 angular resolution** for ν_μ: competitive to traditional method.
- Reconstruction **speed** achieved by GNN (~1 ms/event) significantly outperforms the speed of likelihood method (~1 s/event).

- Improvement of neutrino reconstruction will be further studied.
- Future research will try to enhance the method's robustness against experimental uncertainties and noise.

Thanks for listening!

Email: mo_cen@sjtu.edu.cn

Neutrino Telescope

Hyper-Parameters

- **Learning rate**:

Initial learning Rate = 0.003

lr scheduler: ReduceLROnPlateau(factor=0.5, patience=5)

- **optimizer**:

Adam(betas=(0.9, 0.999), eps=1e-8, weight_decay=0)

Likelihood Reconstruction of ν_e

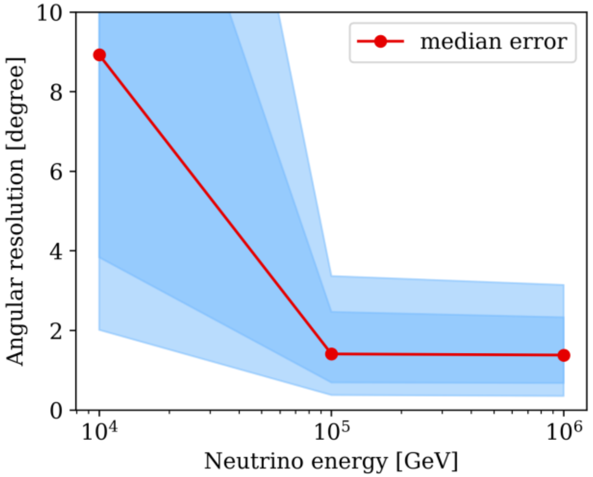
$$\log \mathscr{L} = \sum_{empties} \log[P_i^{nohit}] + \sum_{hitPMTs} \log[1 - P_i^{nohit}]$$

$$P_i^{nohit} = \exp[-\mu_{sig}(r_i, z_i, a_i, E_S) - R_{bg} \cdot T]$$

(equation 5.2) are considered. The expected number of hits from the shower μ_{sig} is evaluated using interpolation of a three-dimensional histogram depending on r_i, z_i and a_i at a shower energy of 1 PeV (figure 8). The expected number of hits at different shower energies is calculated using the fact that the number of emitted photons scales linearly with the shower energy E_S.

- Former GNN result on samples with other energy (by linear scaling num_photons):

$$n' = n \times \frac{100TeV}{E_\nu}$$



Track-like Events Reconstruction

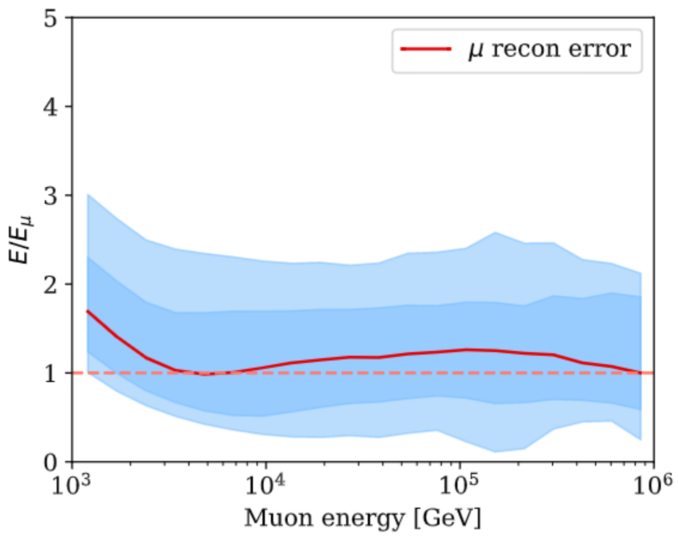
Energy reconstruction

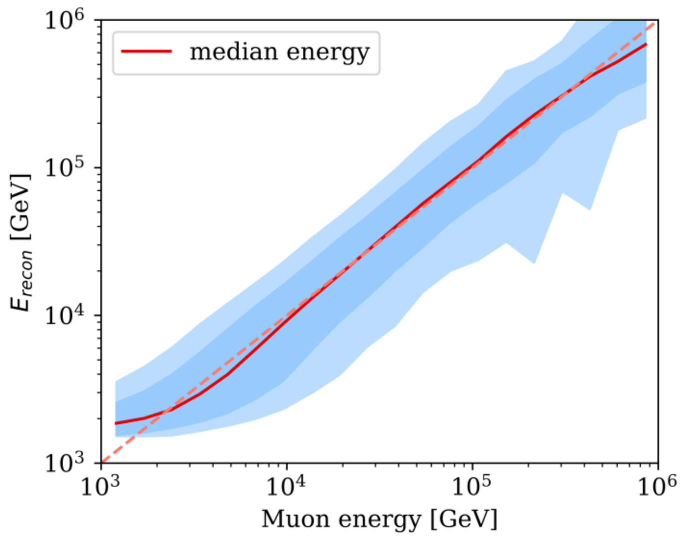
- Same input features as the direction reconstruction.
- Network is trained with MSE loss to predict $\log_{10} E_\mu$. Weight $w = \log_{10} E_\mu - 2.5$ is applied:

$$Loss = w\left(output - \log_{10} E_\mu\right)^2$$

- A shift term, $b = 0.15$ is added to outputs of the model:

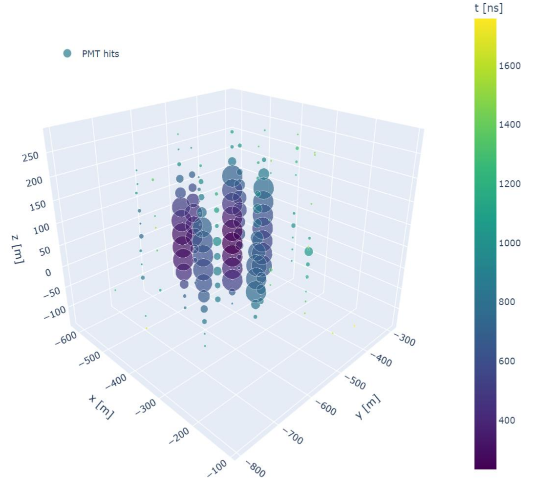
$$E_{recon} = 10^{\mathrm{output+b}}$$



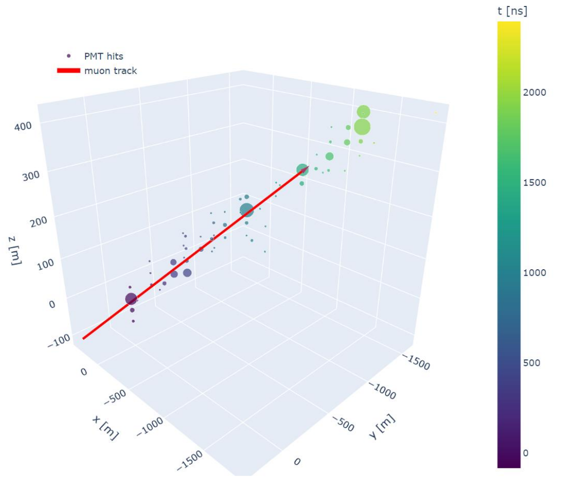


Contents of Tasks

- Reconstruction of ν_e/**cascade** events
  - Direction Reconstruction
  - Energy Reconstruction

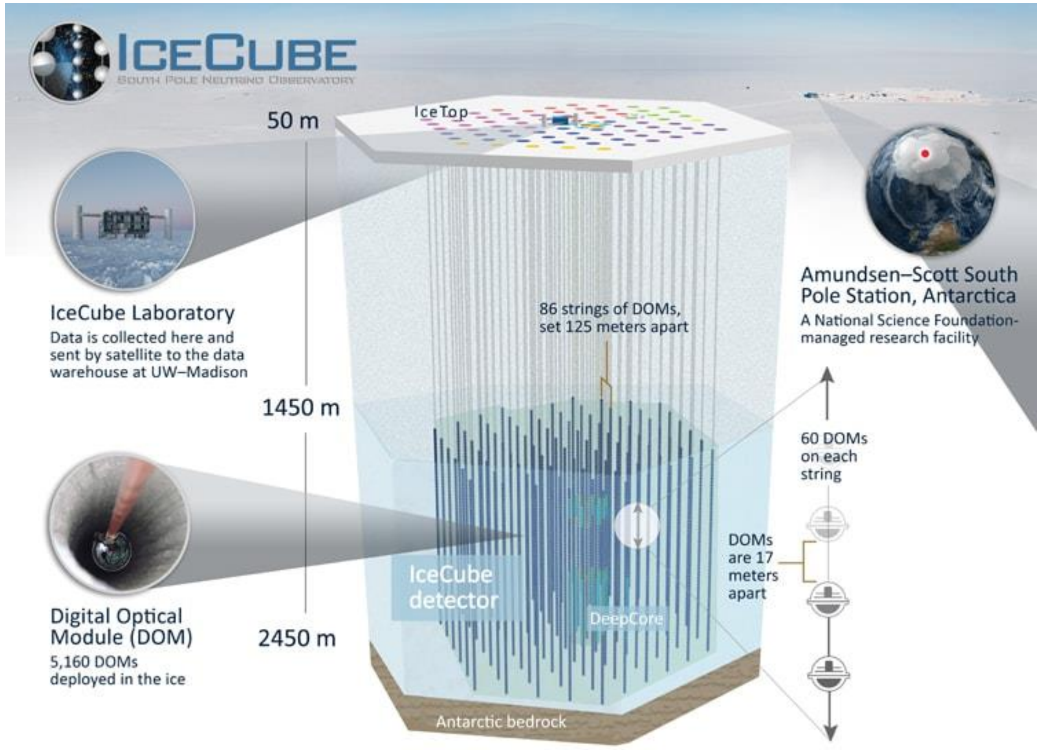


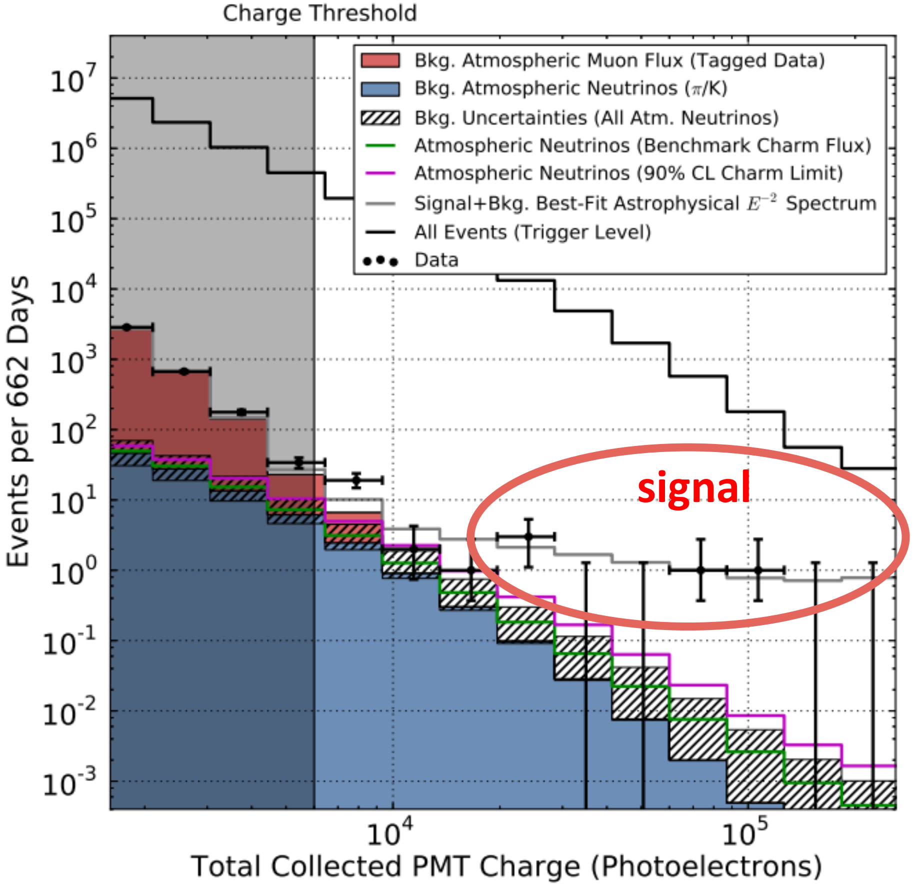
- Reconstruction of ν_μ/**track** events
  - Direction Reconstruction



IceCube

- **Currently the largest neutrino telescope.**
- Detected astrophysical neutrinos in 2013. Science 342,1242856(2013)

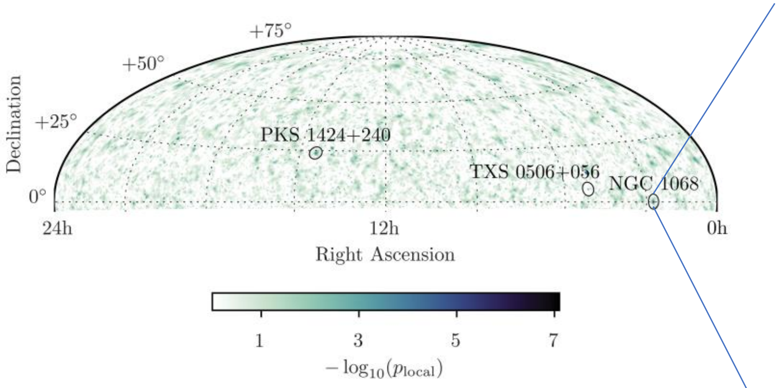




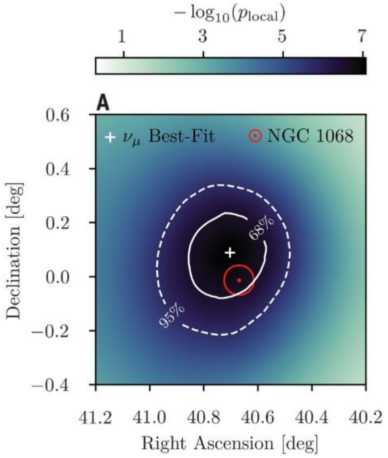
Science,342:6161(2013)

Detection of Neutrino Sources

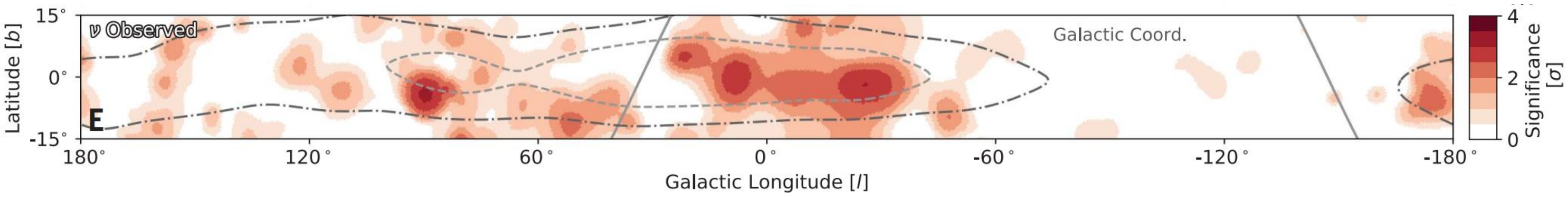
- Evidence for neutrino emission from the nearby active galaxy NGC 1068 (2022).



Science 378,538-543 (2022)

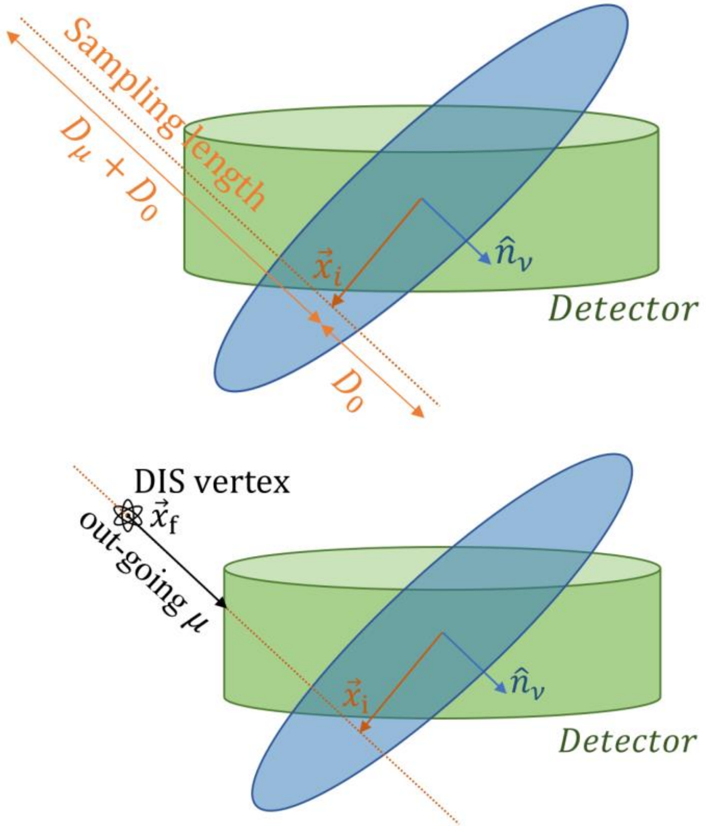


- Observation of high-energy neutrinos from the Galactic plane (2023)



Science 380,1338-1343(2023).

ν_μ Vertex Sampling



Effective Area of ν_μ

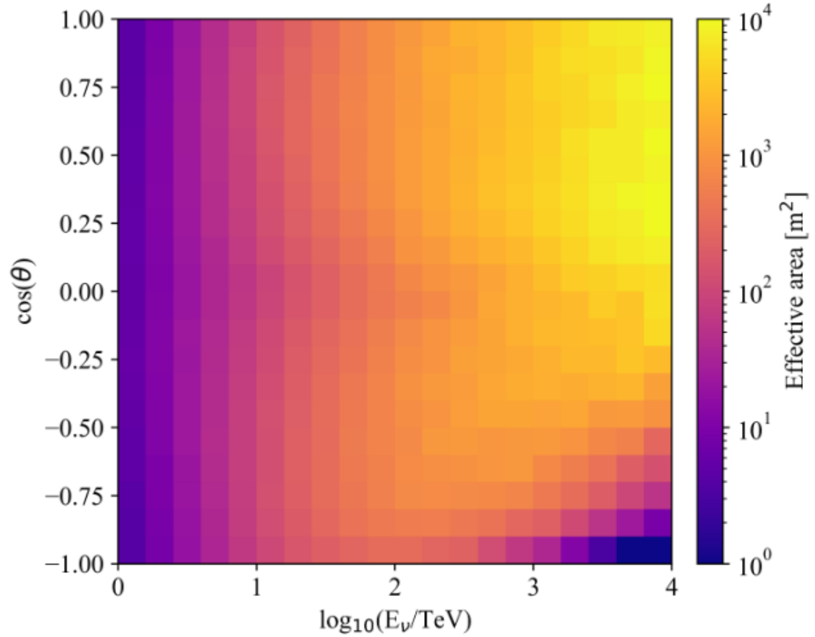
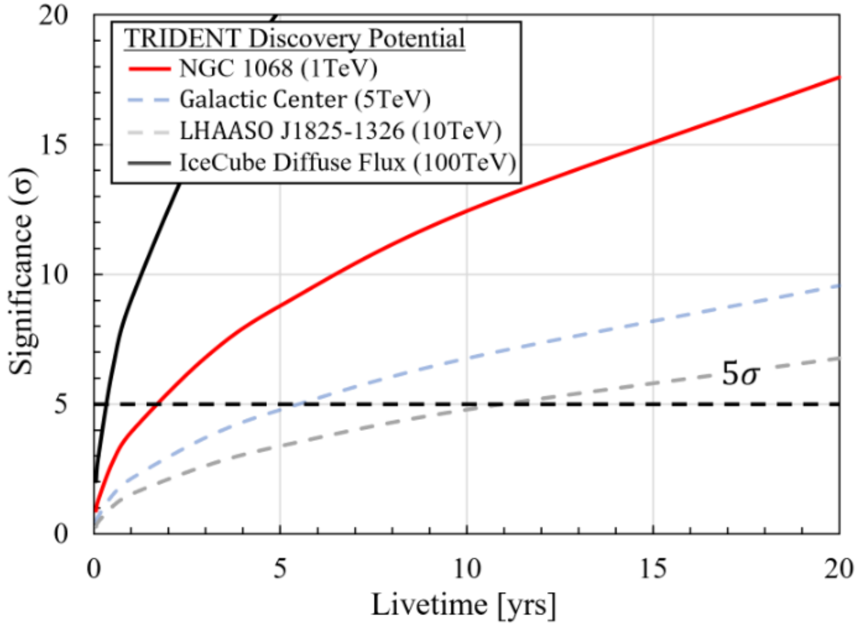


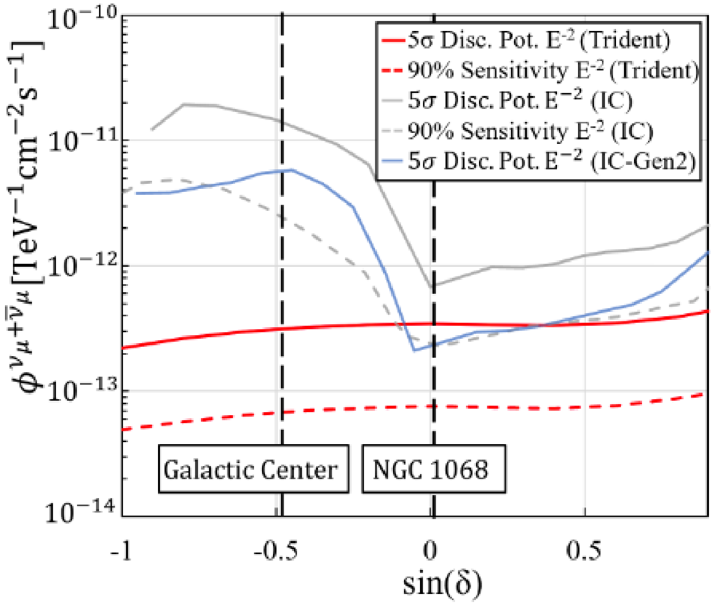
Figure 15: Effective areas at event reconstruction level for ν_μ track events as a function of primary neutrino energy and zenith angle in TRIDENT. At an energy of ~ 100 TeV, the effective area for up-going events is expected to reach 7×10^2 m^2. Only events with anglular error less than 6 degree are selected to evaluate the effective area.

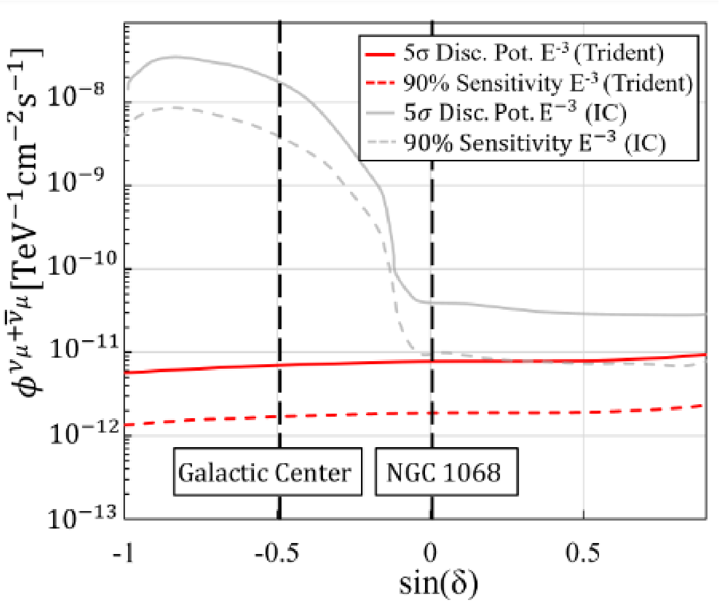
arXiv:2207.04519

Significance & Sensitivity

arXiv:2207.04519







Comparison with Likelihood Method

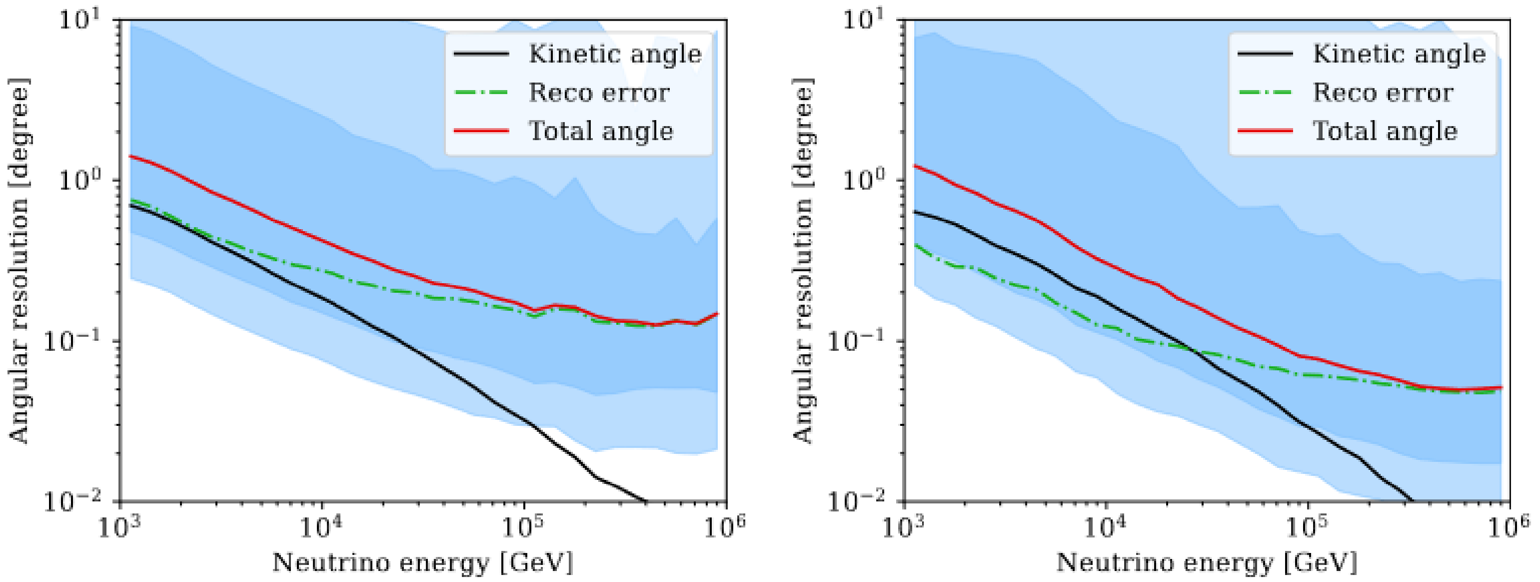
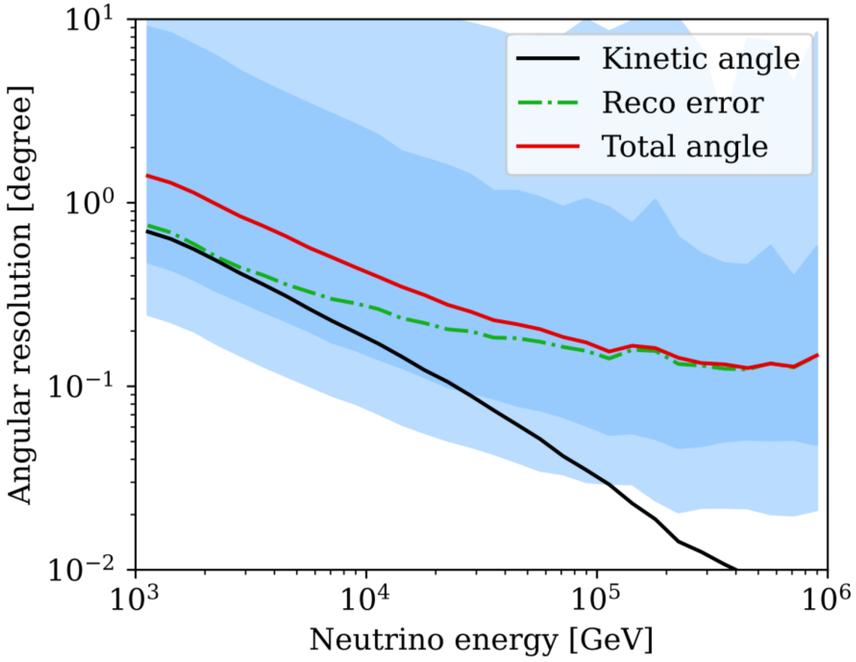


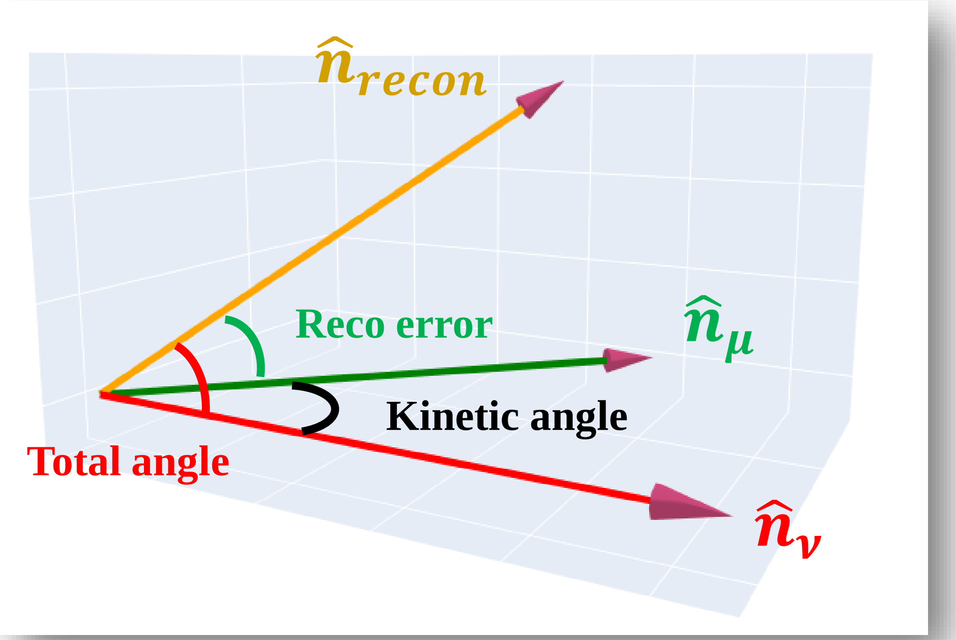
Figure 5: Median angular error of GNN (left) and likelihood method (right) depend on energy of ν_μ. The median angle between the reconstructed track and the true direction of μ and ν_μ is visualized by the green and red lines, respectively. Color bands exhibits the 68% and 90% quantiles. Black lines are the median angle between direction of μ and ν_μ.

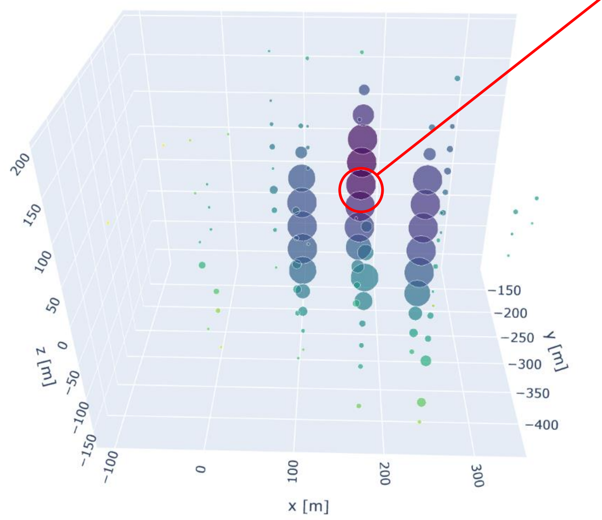
Track-like Events Reconstruction

Direction reconstruction

- Model is trained on events with track length > 500m.
- Median angular error decreases from 1 degree to 0.1 degree as the energy of ν_μ increases.







$$[x, y, z]_{DOM} \;\&\; [t_{hit1}, t_{hit2} \ldots t_{hitn}]$$

$$[x, y, z]_{DOM} \;\&\; \min(t_{hit1}, t_{hit2} \ldots t_{hitn})$$

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