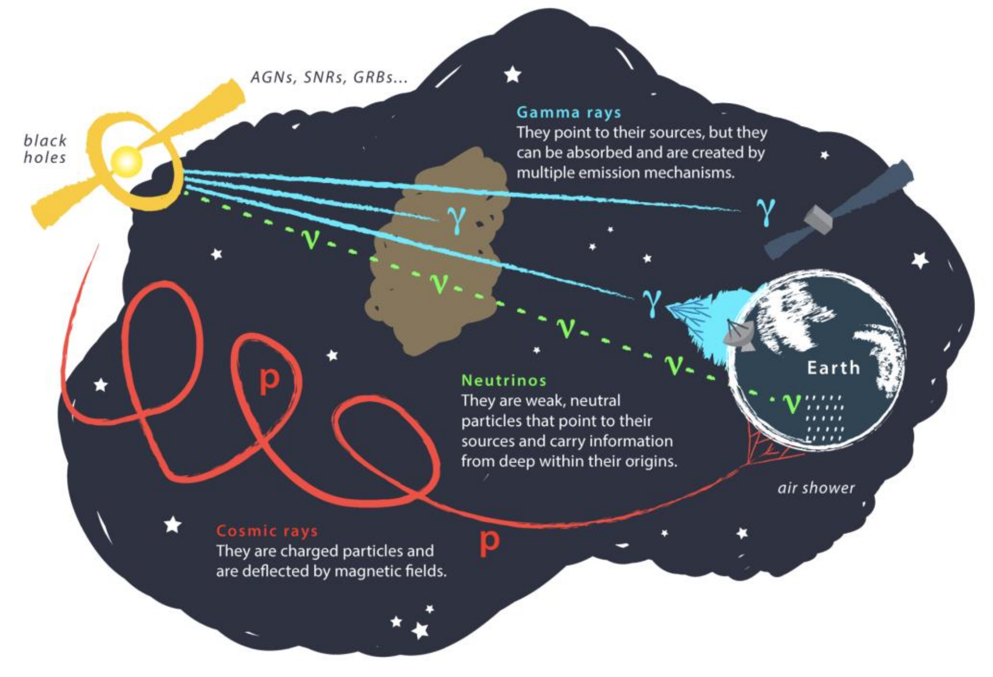
Neutrino Reconstruction in TRIDENT Based on GNN

Cen Mo (莫岑)
for the TRIDENT collaboration

Workshop on Computation in Experimental Particle Physics
17 July 2023

Neutrino Telescope

Probe origins of cosmic ray with neutrino.

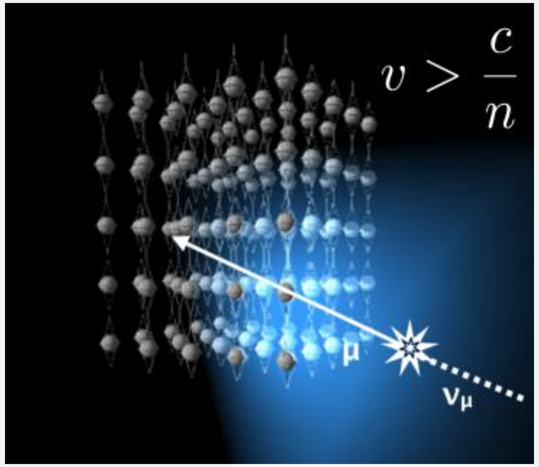


Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

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 $E_\nu \sim 10 PeV$

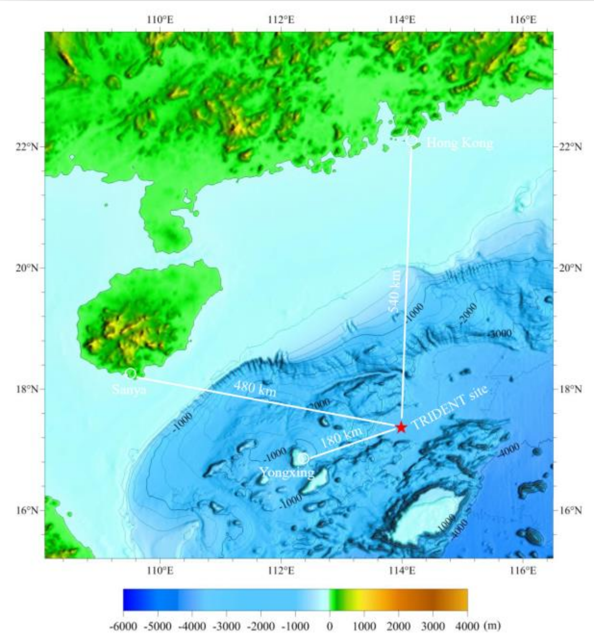
Use sea water as target



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

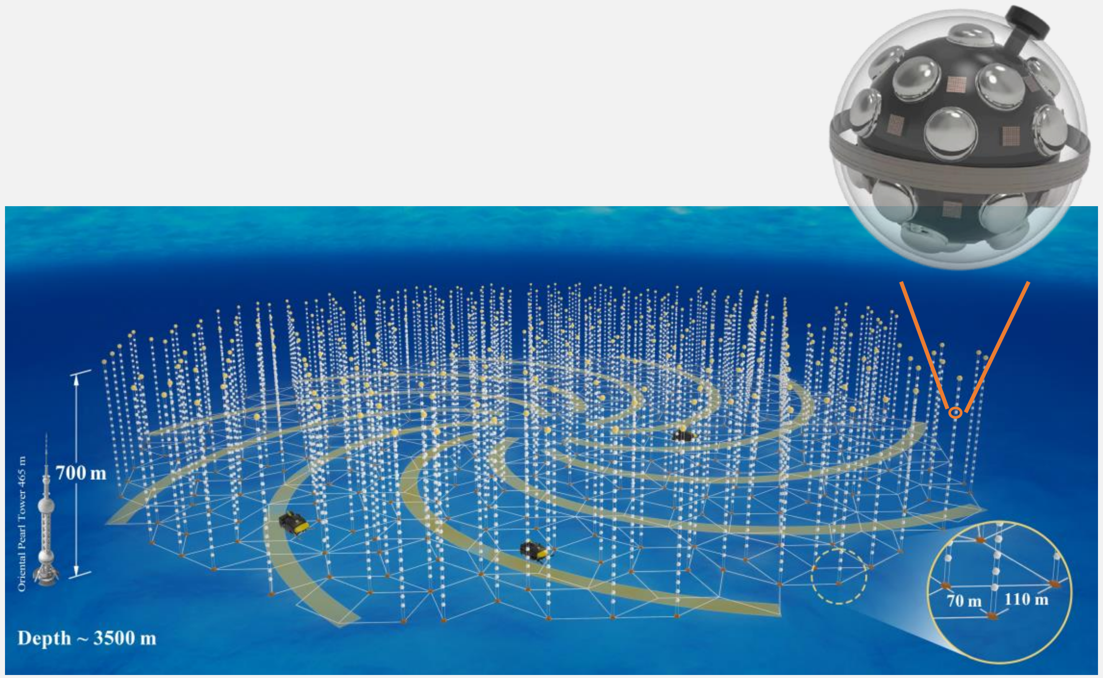
TRIDENT

- **TRIDENT**: TRoplcal DEep-sea Neutrino Telescope. arXiv:2207.04519
- To be located in the South China Sea.
- Penrose tiling structure with 2000m radius, 700m height, 3500m deep under sea level.



TRIDENT site

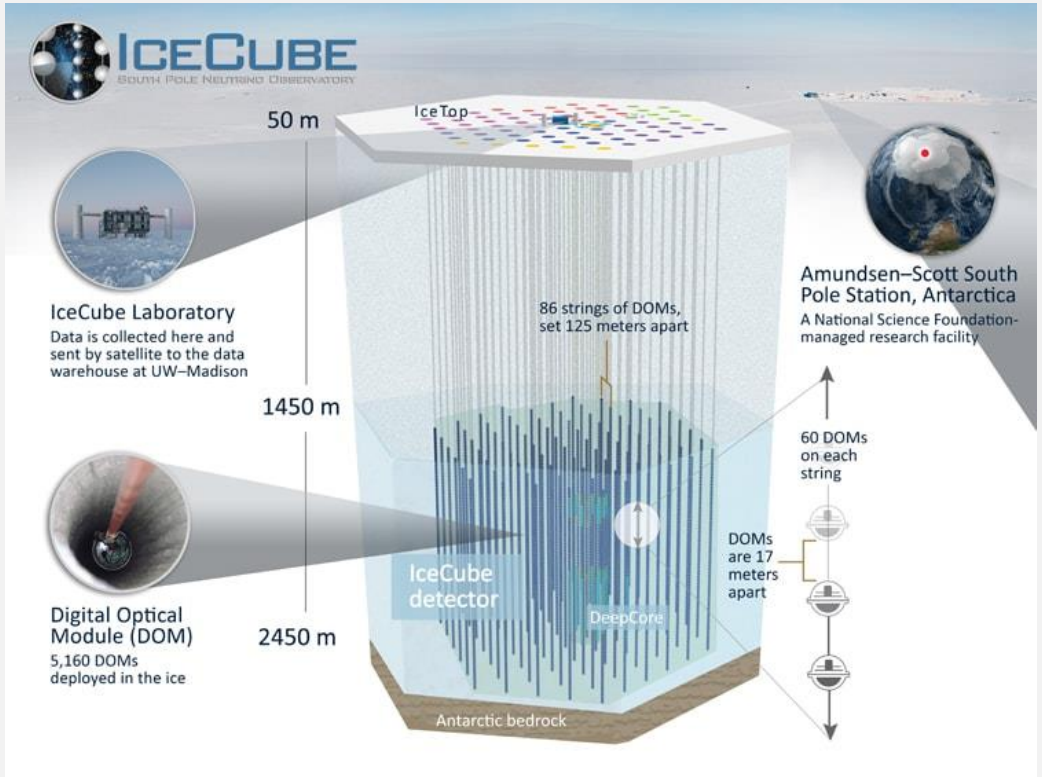
hDOM

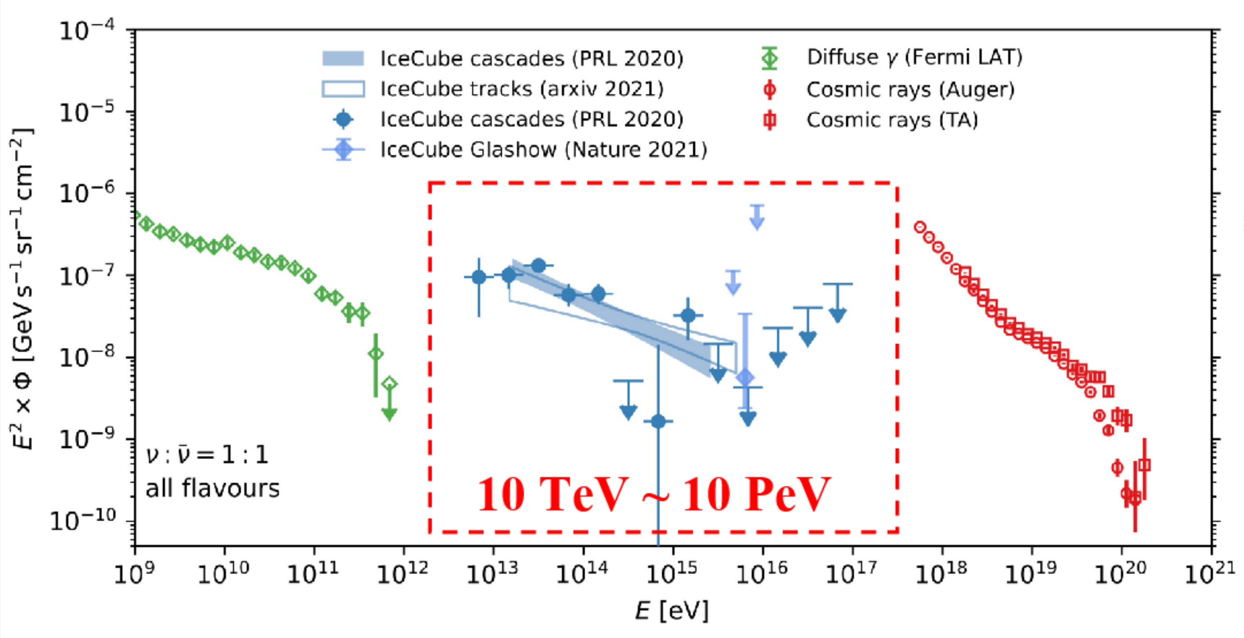


TRIDENT

IceCube

- **The largest neutrino telescope.**
- Detected astrophysical neutrinos in 2013. [Science 342,1242856(2013)]

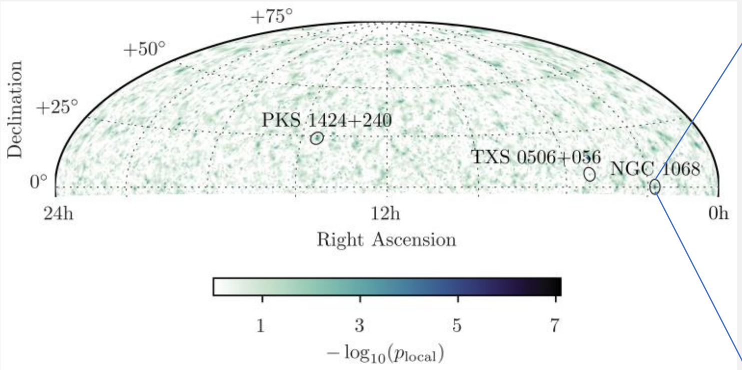


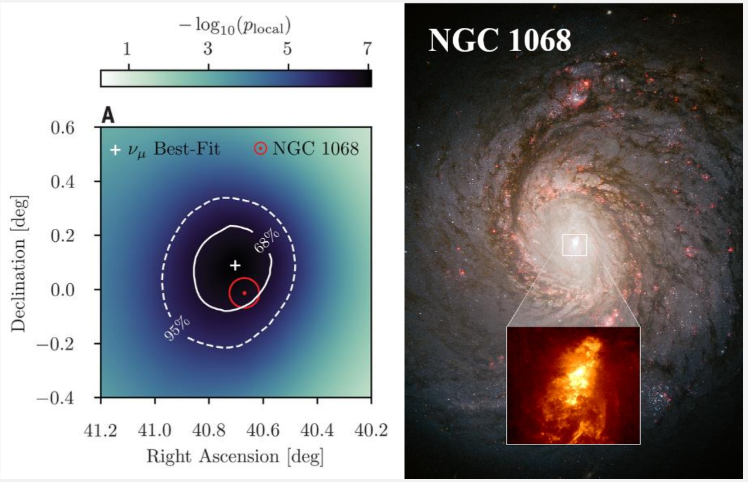


From Lu Lu, TeVPA, 2022

Detection of Neutrino Sources

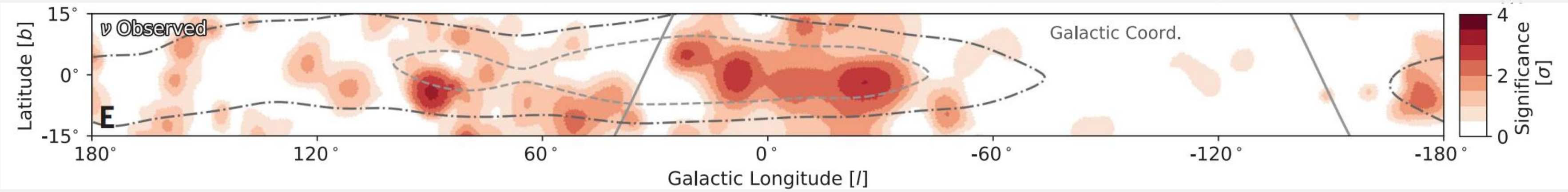
- Evidence for neutrino emission from the nearby active galaxy NGC 1068 (2022).





IceCube Collaboration, Science 378,538-543 (2022)

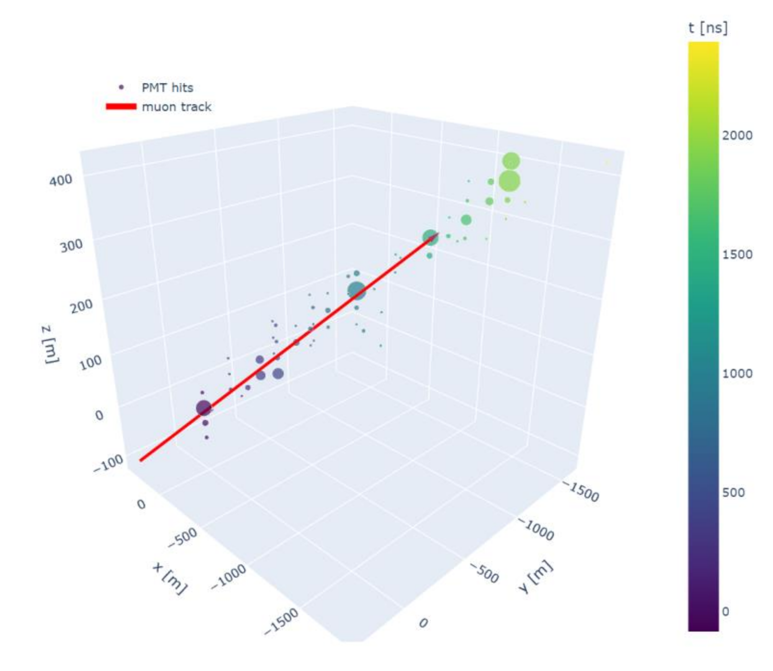
- Observation of high-energy neutrinos from the Galactic plane (2023)



IceCube Collaboration, Science 380,1338-1343(2023).

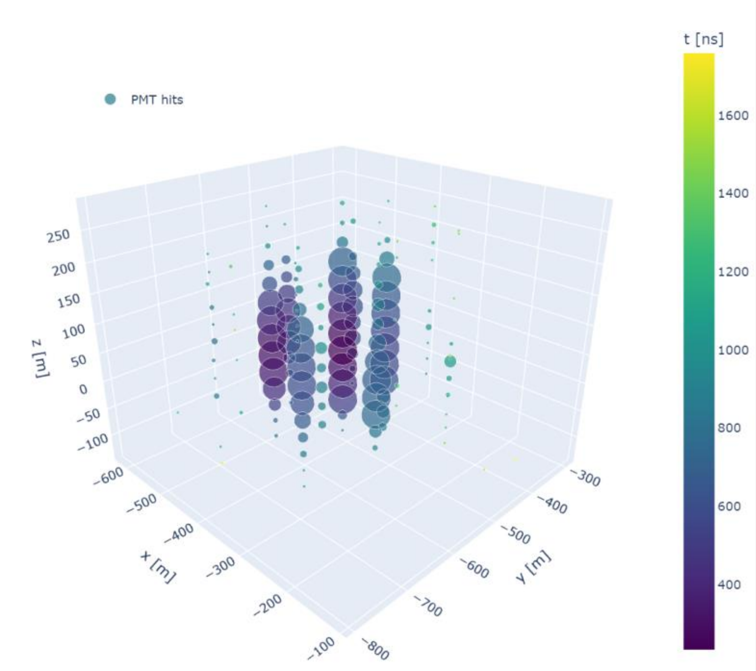
Neutrino Events

- Size of points: number of photo hits



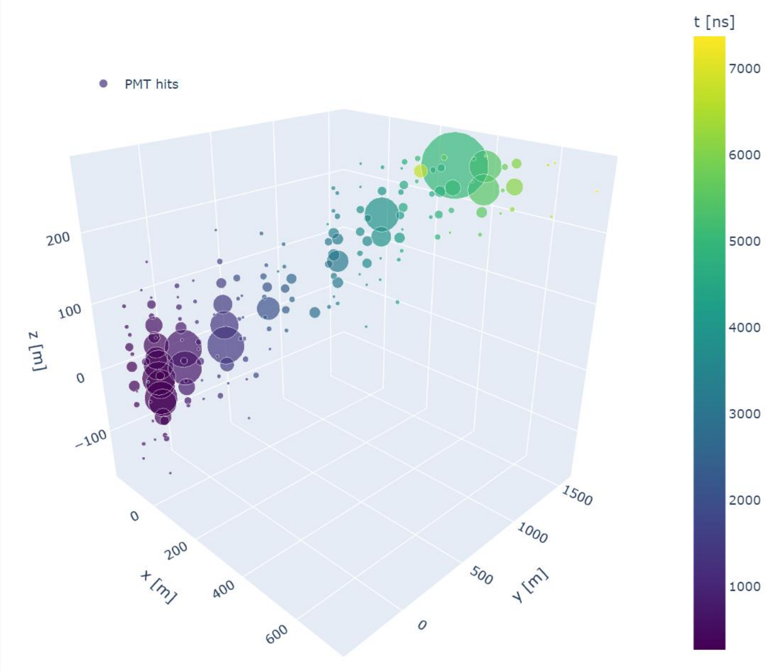
Track

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



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 of Neutrino Events

Neutrino event generator

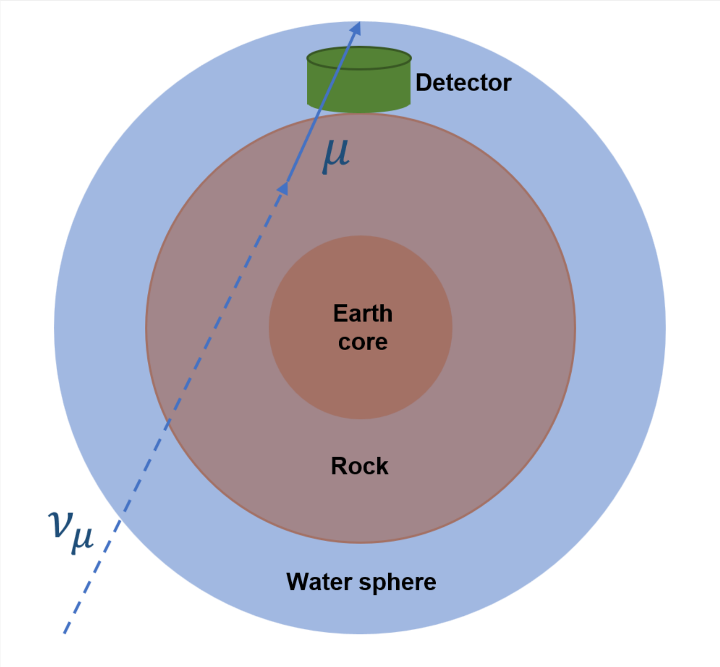
Based on CORSIKA8 (arxiv:2208.14240):

- 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

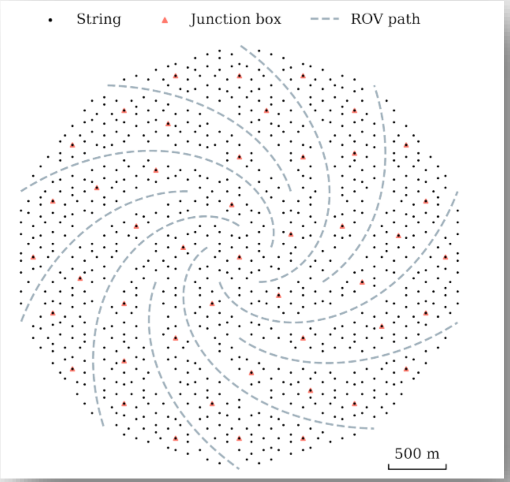
Neural Network in Neutrino Telescope

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.



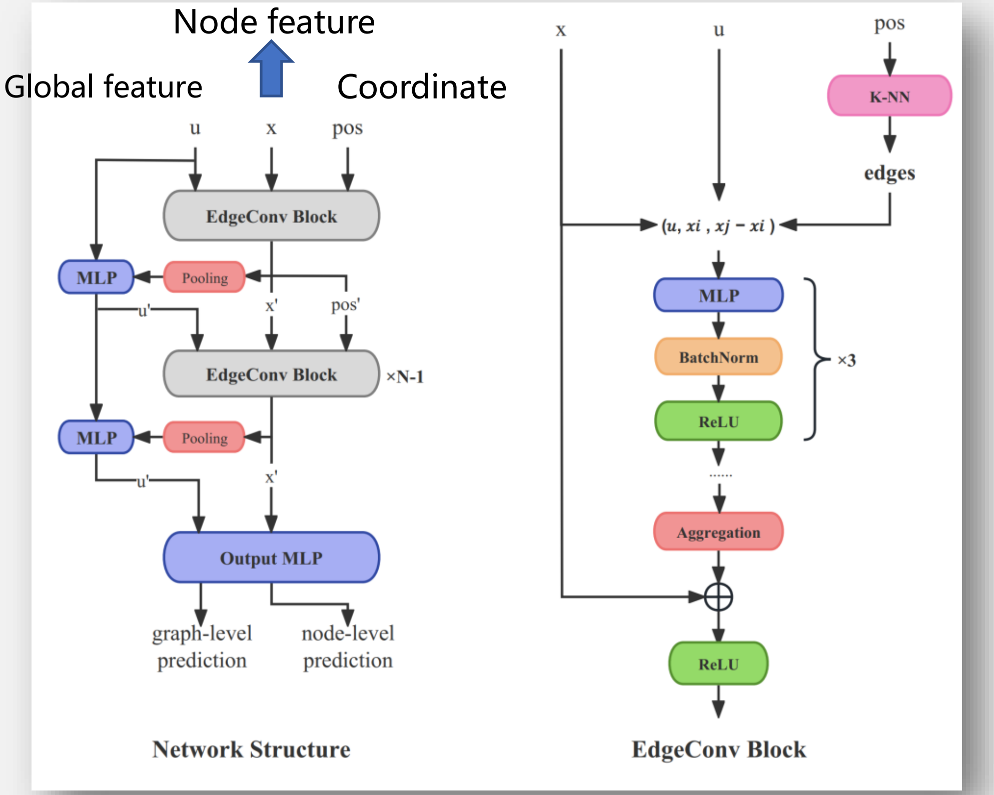
Top view of TRIDENT detectors

Use point cloud to represent neutrino events:

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

TridentNet

- TridentNet 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.



Track-like Events Reconstruction

Direction reconstruction

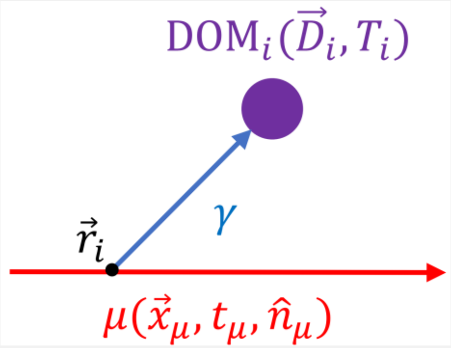
- Input features: location $\vec{D}_i$, first photon arrival time T_i and number of photo hits n_i

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

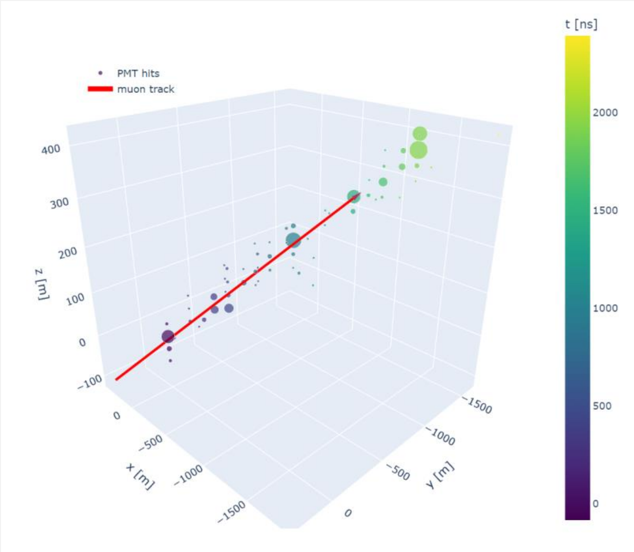
- Loss function: mean square error (MSE) with weight proportional to n_i:

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

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



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

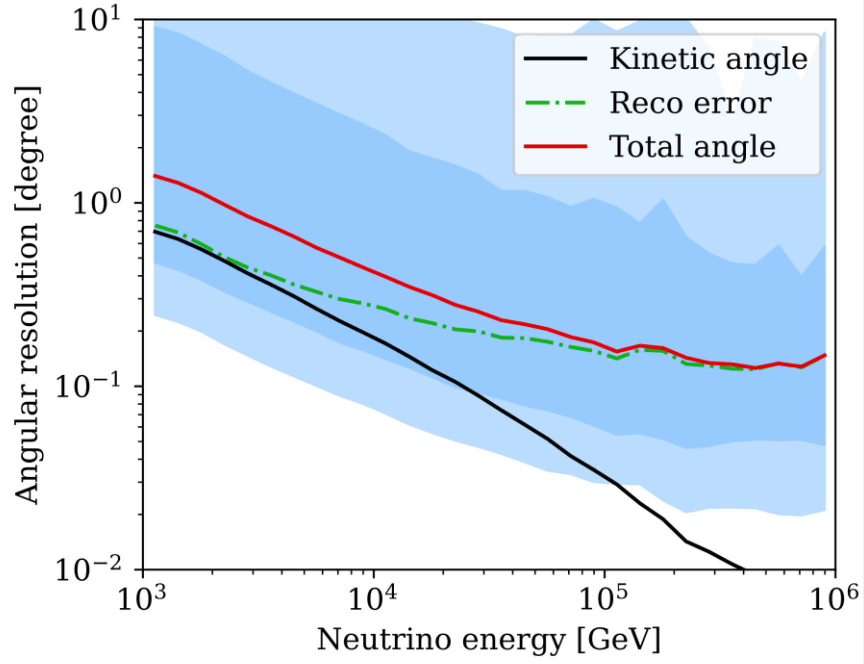


Track-like event display

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.



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

Track-like Events Reconstruction

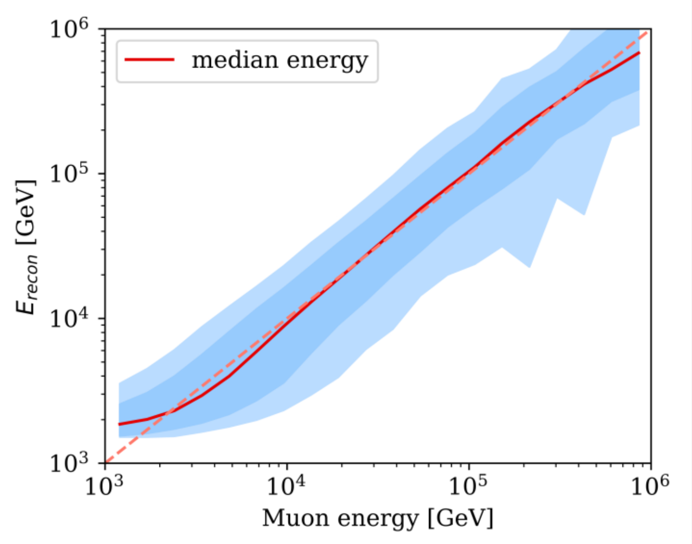
Energy reconstruction

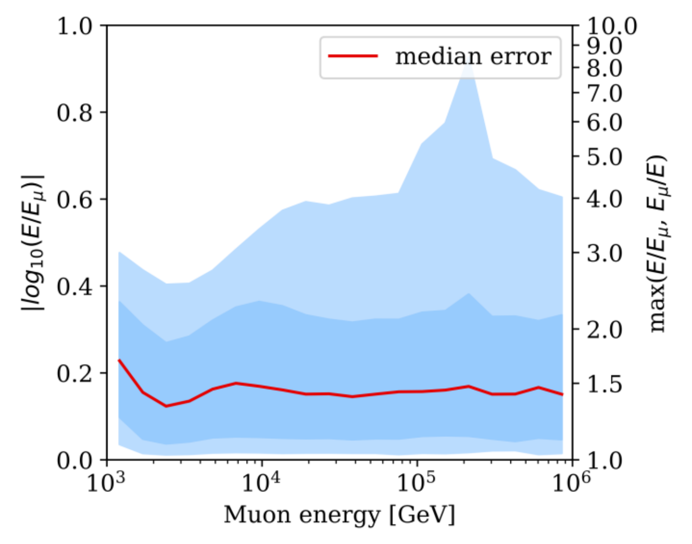
- Same input features as the direction reconstruction.
- Network is trained with MSE loss to predict $\log_{10} E_\mu$. Weight $w = \log_{10} E_\mu - 2.5$ is applied:

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

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

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

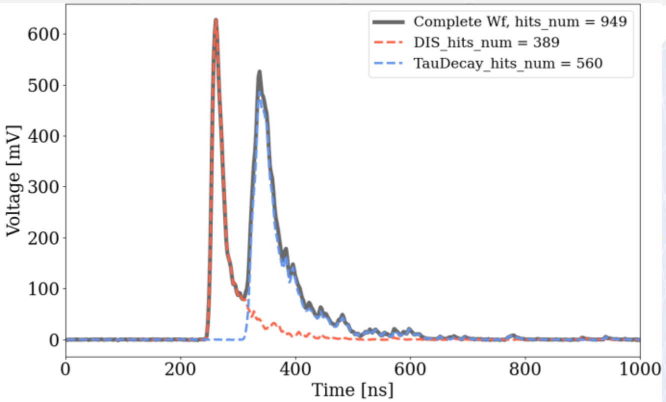




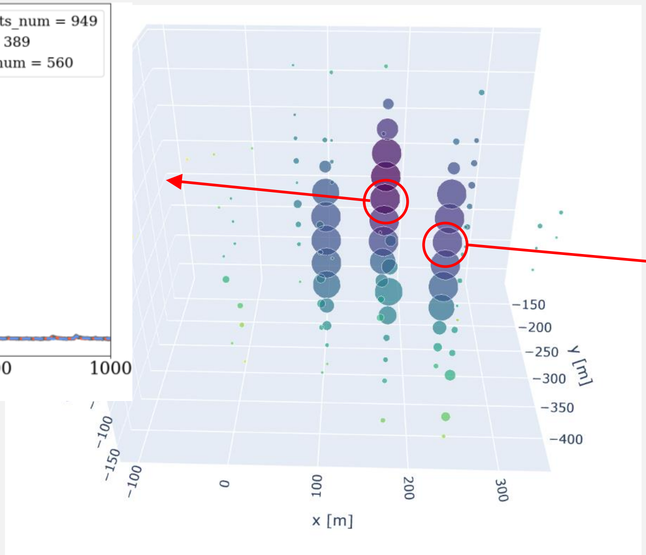
Classification of ν_τ and ν_e

- Input features:
  - 10 brightest DOMs.
  - Location of $\mathrm{DOM_i}$.
  - Waveform with time length $2000ns$.
- Network generates probabilities: $output = (p_0, p_1)$.
- Cross-entropy loss is used as the loss function:

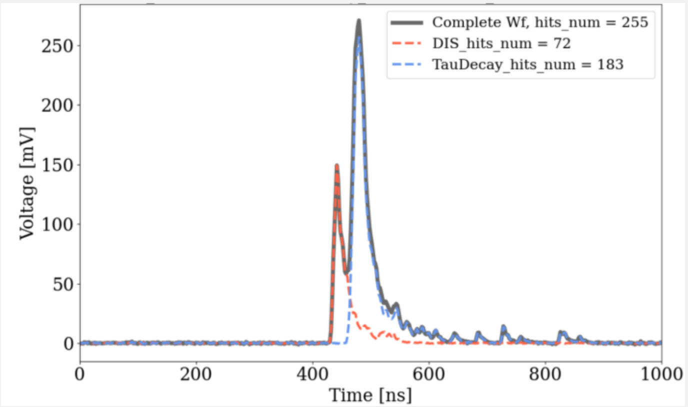
$$Loss = -y_0 \log(p_0) - y_1 \log(p_1)$$



Close to DIS vertex



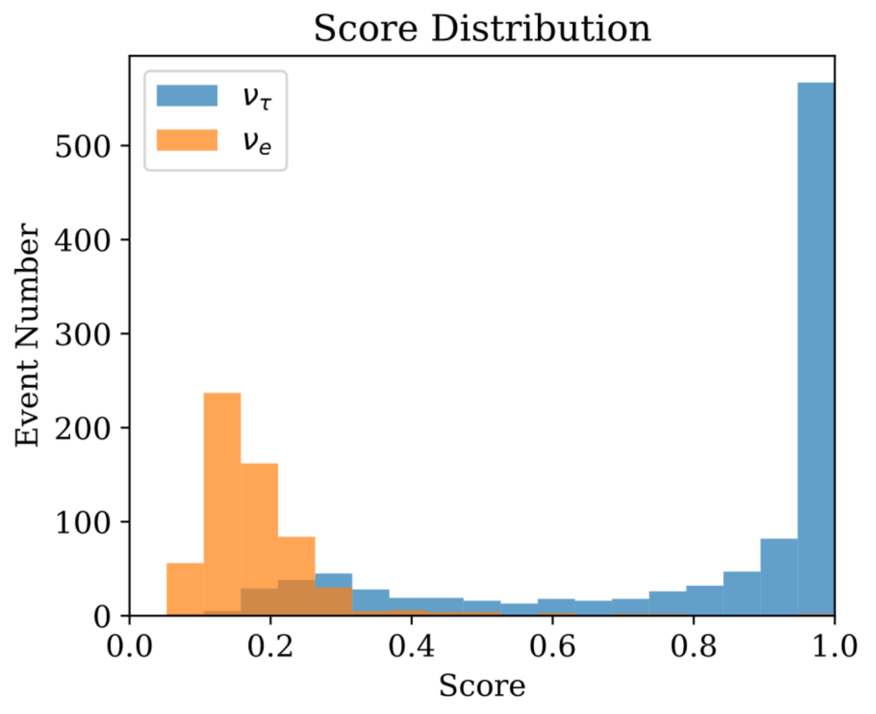
Double bang

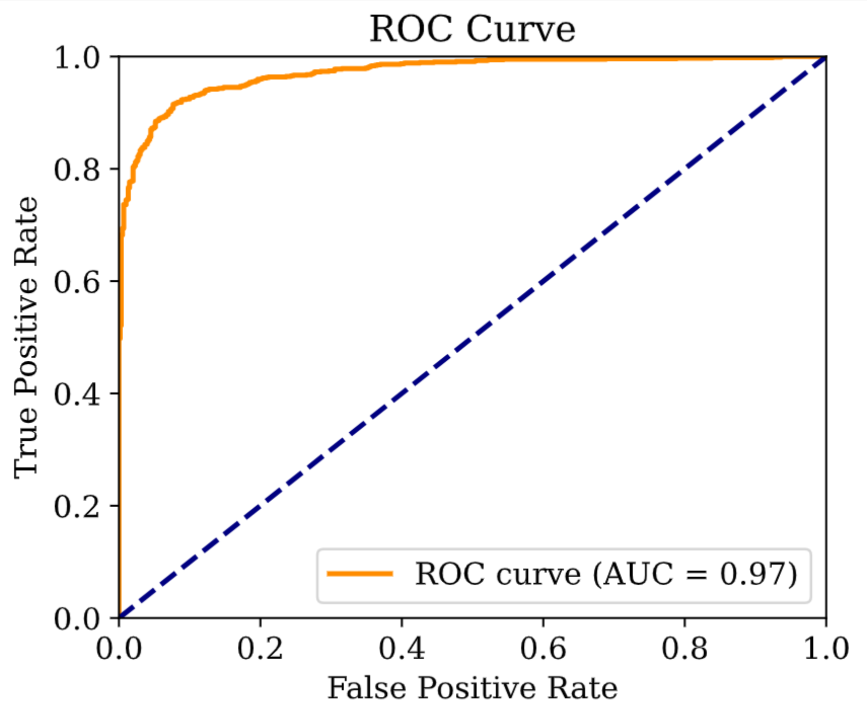


Close to decay vertex

Classification of ν_τ and ν_e

- Take label of $\nu_\tau = 1$, label of $\nu_e = 0$:





Cascade Reconstruction

ν_e direction reconstruction

- Input feature of $\mathrm{DOM_i}$:
  - Location of $\mathrm{DOM_i}$.
  - Arrival time of the earliest photon.
  - Number of photons received in time window $\left(10ns \times i, 10ns \times (i+1)\right), i \in \{0,1..99\}$
- Network is trained to predict $\hat{n}_\nu$ with MSE loss:

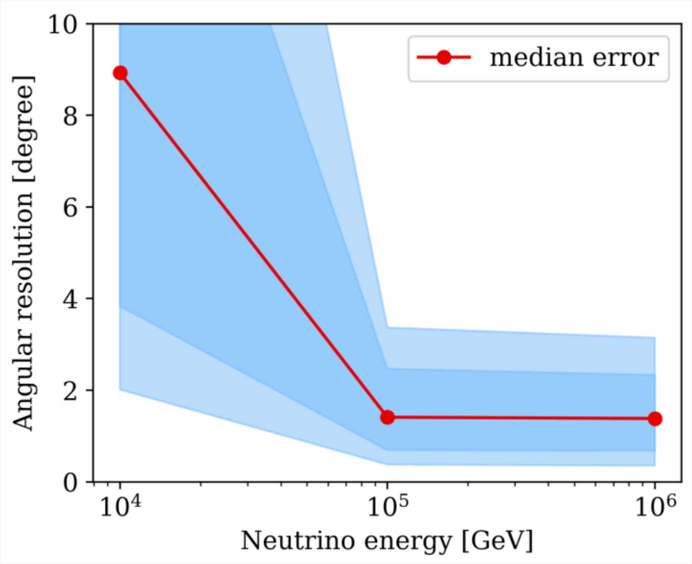
$$Loss = \left|\frac{\overrightarrow{output}}{|output|} - \hat{n}_\nu\right|^2$$

Cascade Reconstruction

ν_e direction reconstruction

- Network is only trained on ν_e events with $E_\nu = 100TeV$.
- For different E_ν, linear scaling to number of collected photons to cascade energy is applied:

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



Summary and Outlook

- Simulated neutrino events in TRIDENT are represented as point clouds and are reconstructed by TridentNet.
- GNN demonstrates high accuracy in neutrino telescope in tasks:
  - Reconstruction of direction and energy of track-like events.
  - Classification of ν_τ events and ν_e.
  - Direction reconstruction of ν_e events.

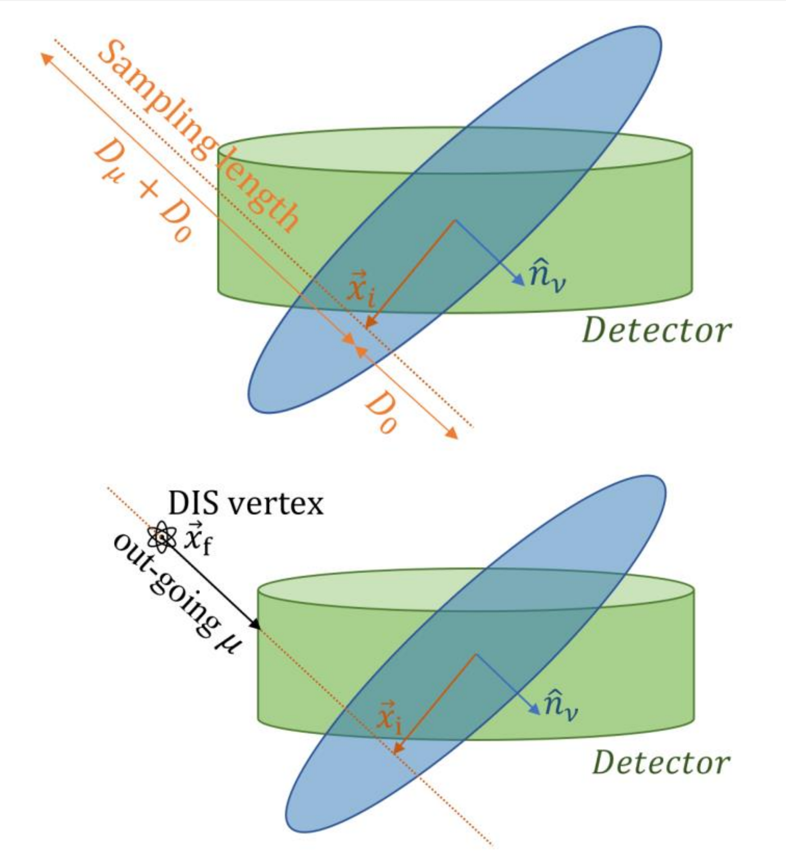
- Reconstruction of ν_τ and ν_e events will be further studied.
- Classification between neutrino events and atmospheric muon events will be investigated.

Thanks for listening!

Backup

Email: mo_cen@sjtu.edu.cn

ν_μ Vertex Sampling



Effective Area of ν_μ

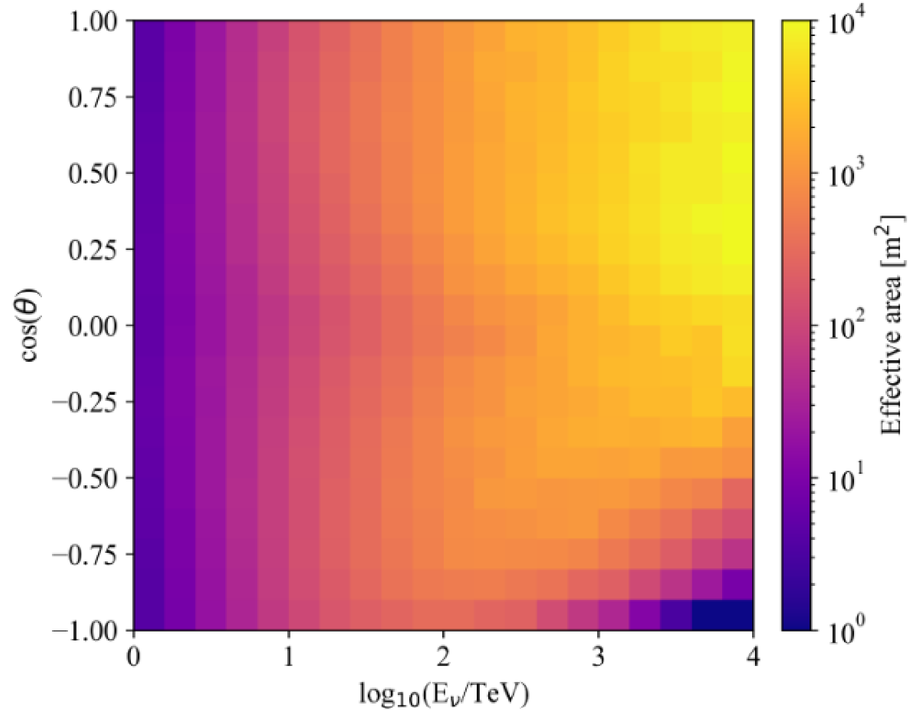
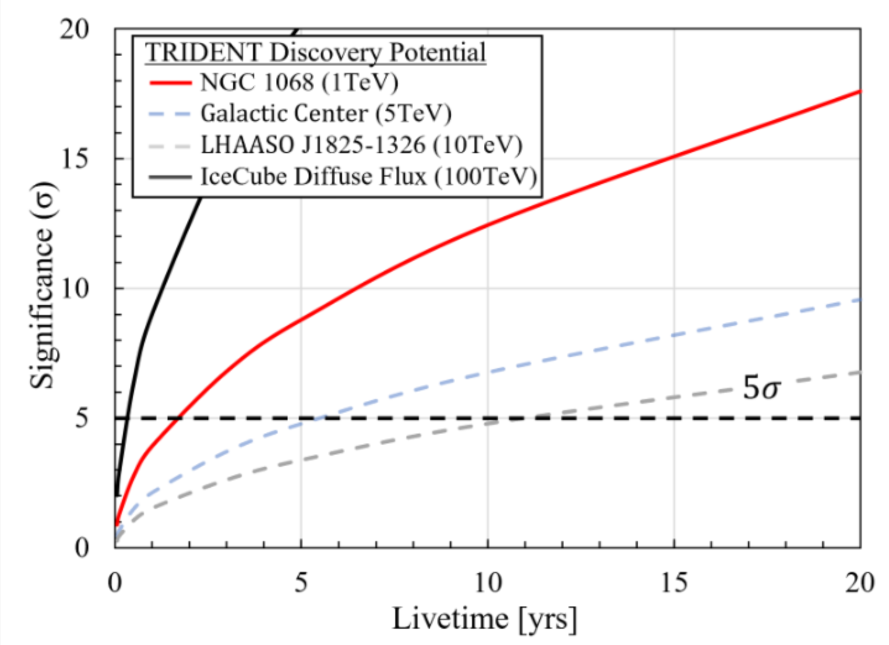


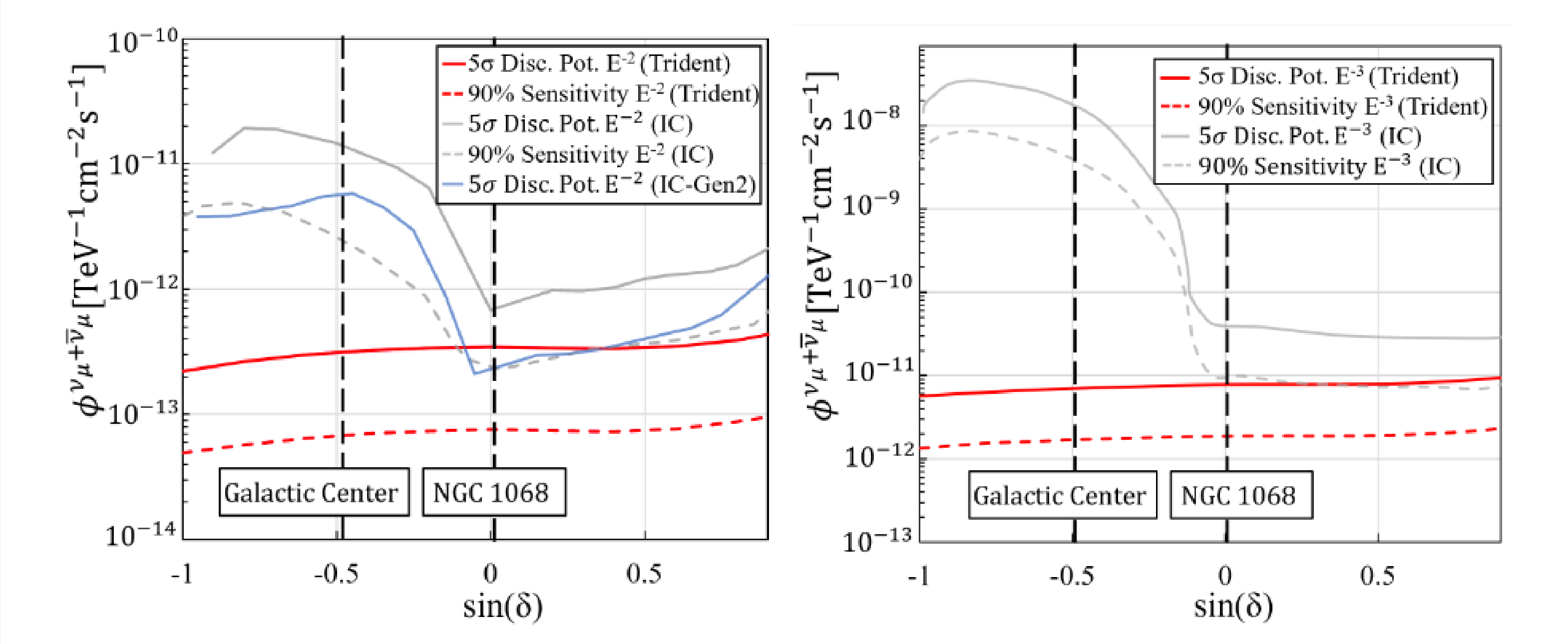
Figure 15: Effective areas at event reconstruction level for ν_μ track events as a function of primary neutrino energy and zenith angle in TRIDENT. At an energy of ~ 100 TeV, the effective area for up-going events is expected to reach 7×10^2 m^2. Only events with anglular error less than 6 degree are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

arXiv:2207.04519

Significance & Sensitivity

arXiv:2207.04519





Comparison with Likelihood Method

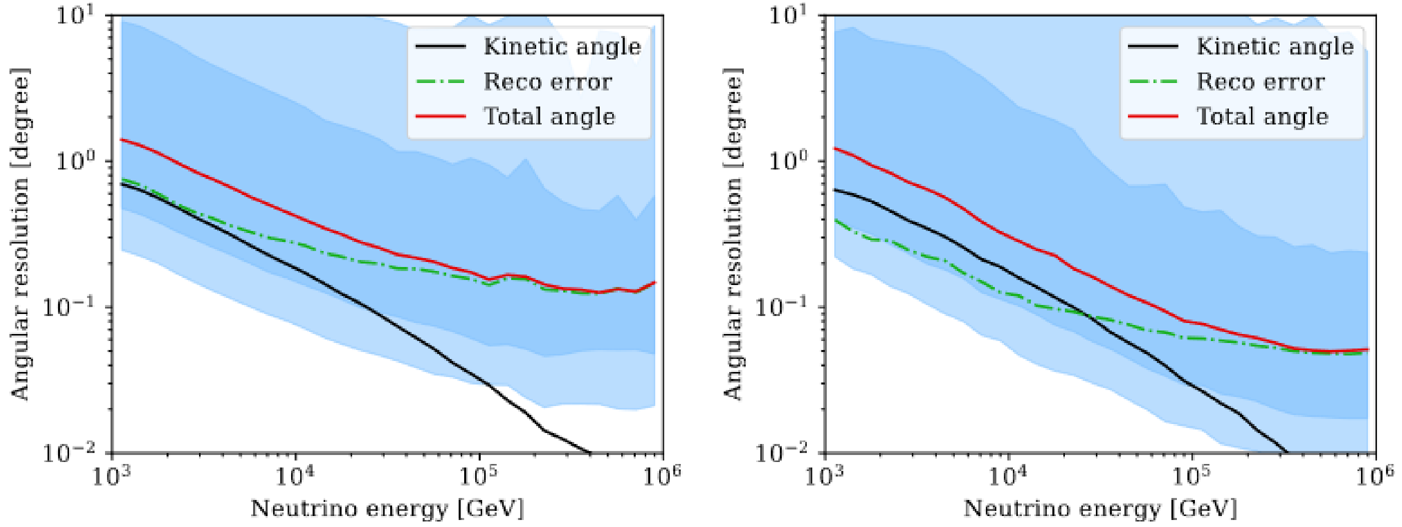


Figure 5: Median angular error of GNN (left) and likelihood method (right) depend on energy of ν_μ. The median angle between the reconstructed track and the true direction of μ and ν_μ is visualized by the green and red lines, respectively. Color bands exhibits the 68% and 90% quantiles. Black lines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