The Status of High-energy Underwater Neutrino Telescope (HUNT)

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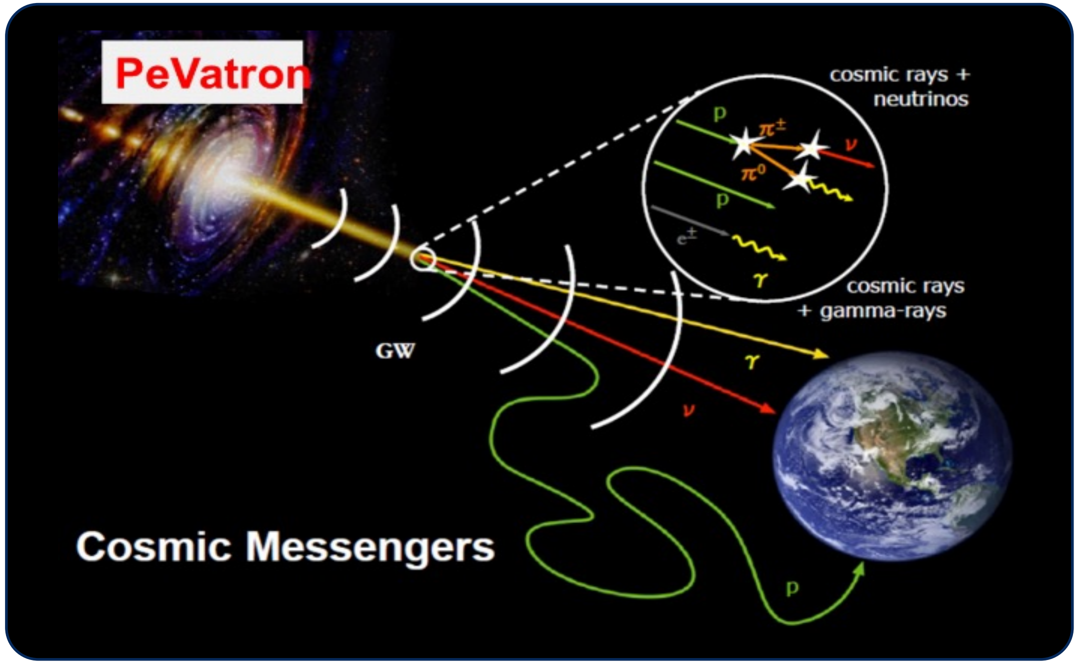
中国科学院 CHINESE ACADEMY OF SCIENCES

中国科学院高能物理研究所 Institute of High Energy Physics Chinese Academy of Sciences

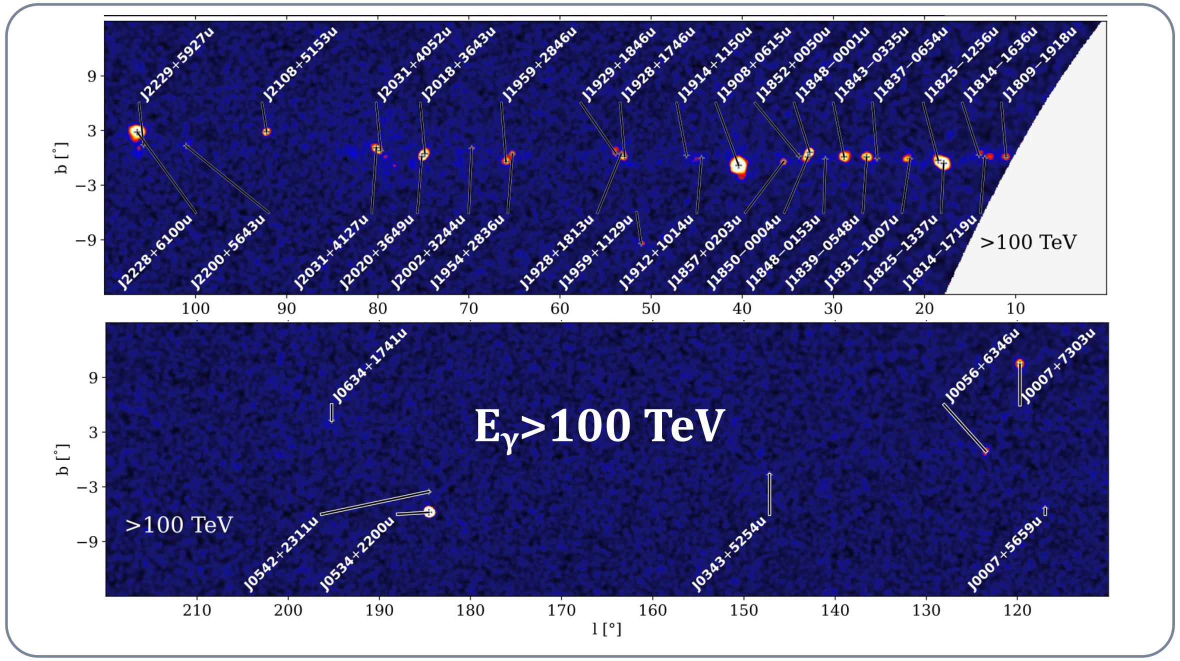
Scientific Goals

High-energy Underwater Neutrino Telescope (HUNT)

- Identifying the **hadronic PeVatrons** in our Galaxy
- Resolving the high energy neutrino sky above 100 TeV
- Understanding the origin, acceleration and propagation of high energy cosmic-rays



PeVatrons: accelerator of PeV cosmic-rays (e.g., electrons, protons)

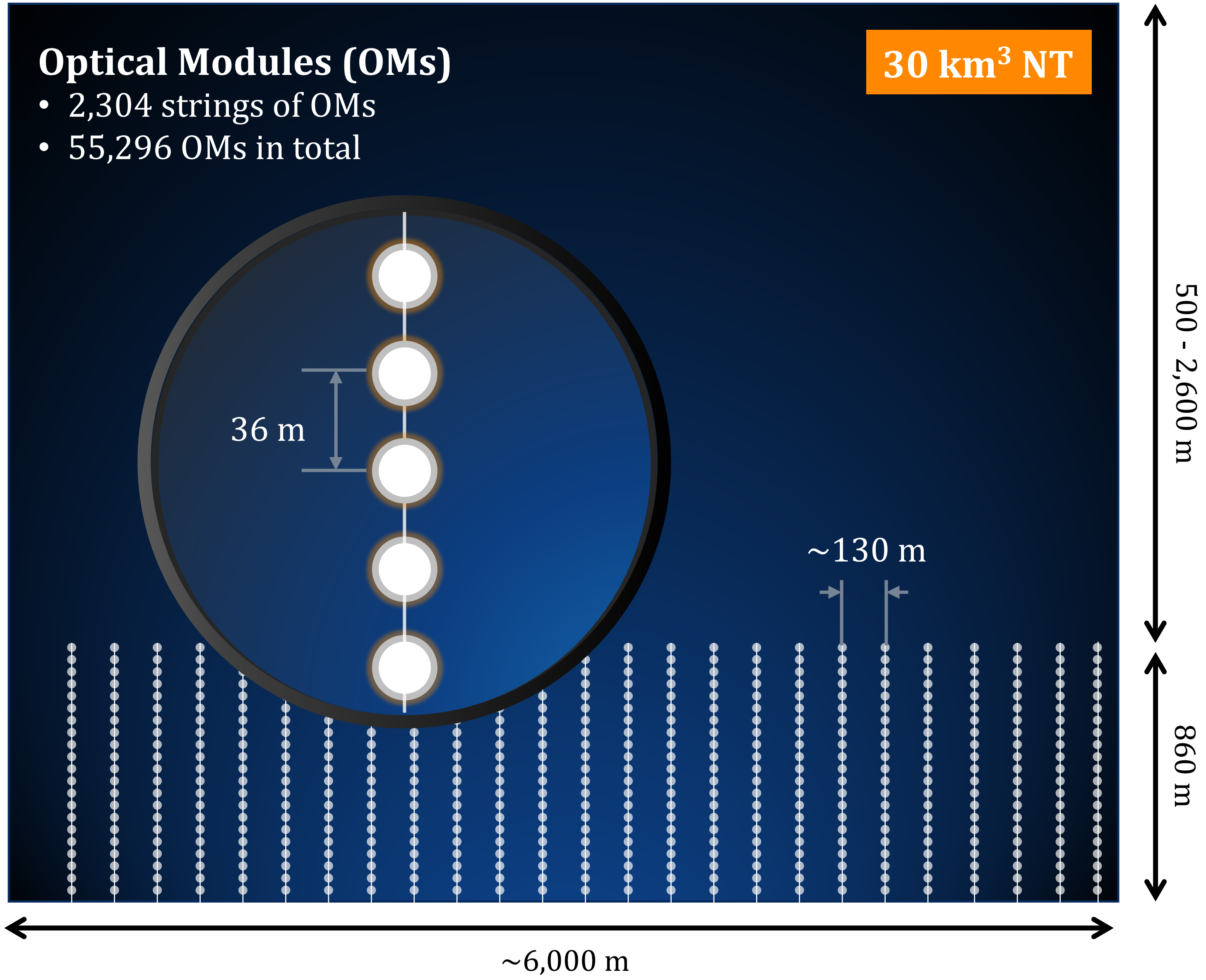


1LHAASO: 43 sources (>4σ); 22 sources (>7σ)

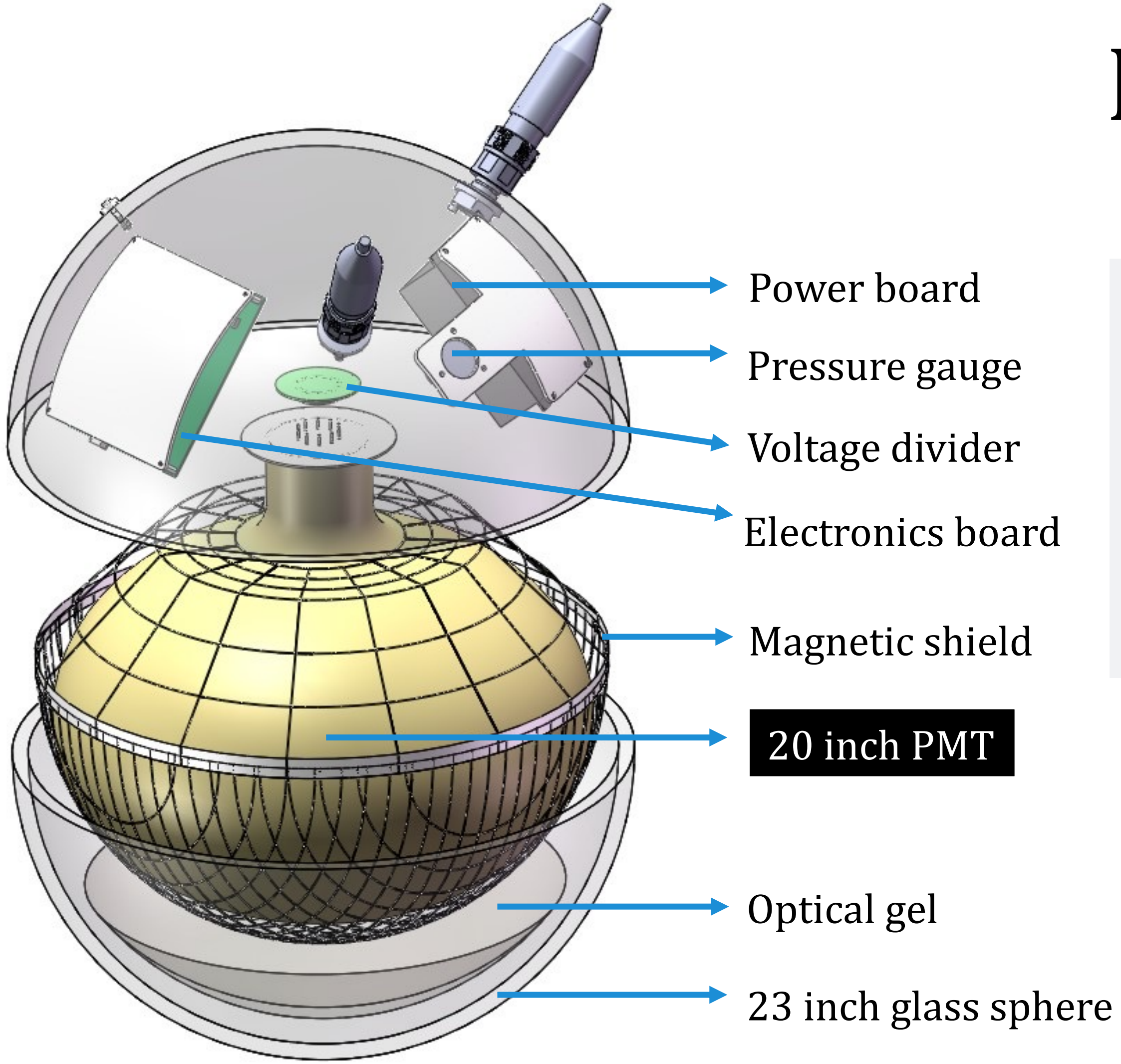
Detector Design

Requirements for HUNT

- Angular resolution: ~0.1° (tracks), <3°(cascades)
- Energy resolution: ΔlogE~0.3(tracks), ΔE~10-30% (cascades)
- Discovering the neutrino sources (>100 TeV)



Detector Design

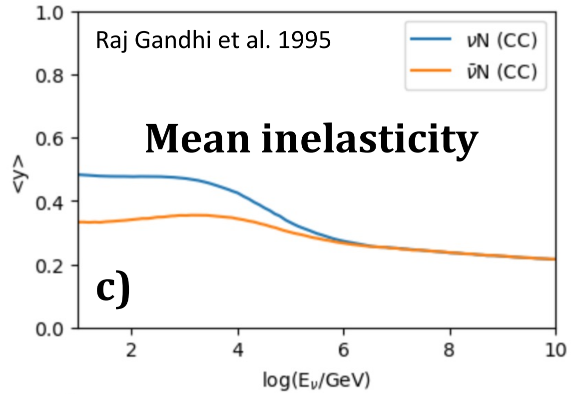


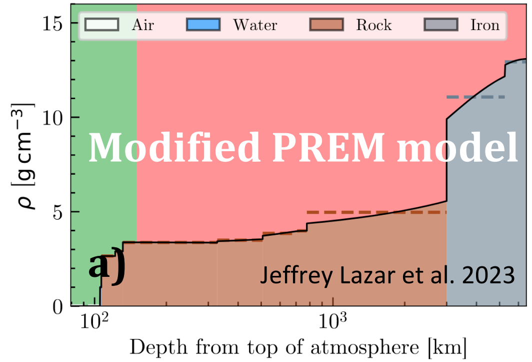
20 inch PMT

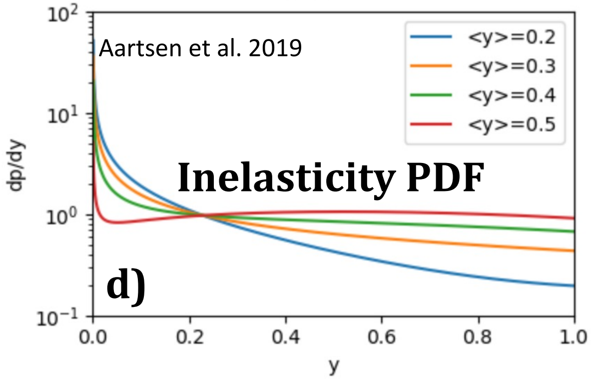
- Large photosensitive area
- Excellent time performance: TTS~7 ns
- High quantum efficiency: QE>30%

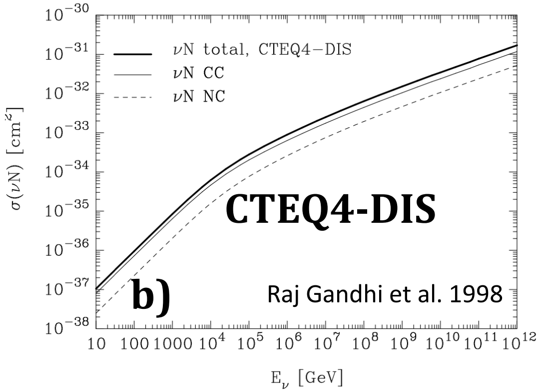
Detector Simulation

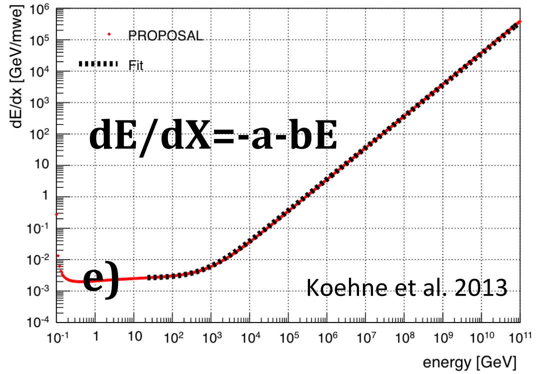
- Cylinder array
  - Lake Baikal
  - South China Sea
- Earth Model (a)
- νN cross section (b)
- Inelasticity (c, d)
- Lepton energy loss (e)





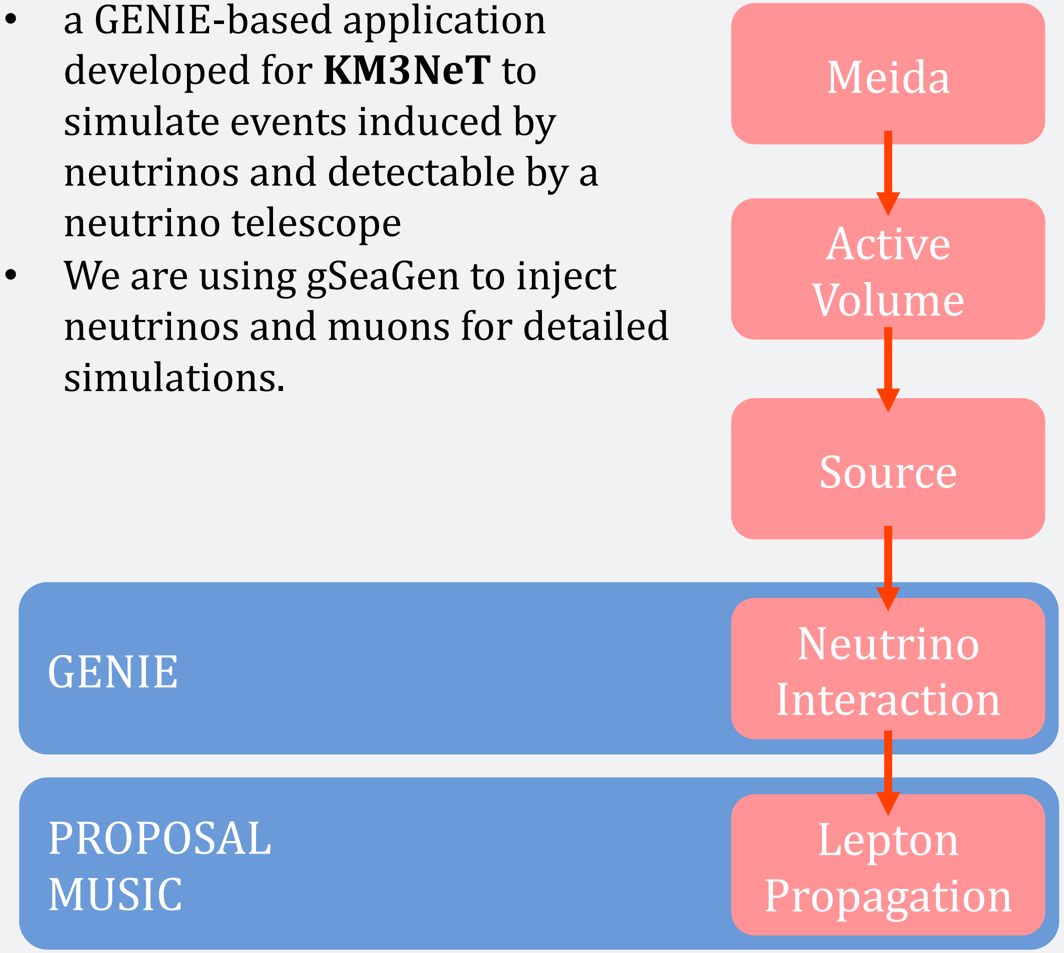






gSeaGen

- a GENIE-based application developed for **KM3NeT** to simulate events induced by neutrinos and detectable by a neutrino telescope
- We are using gSeaGen to inject neutrinos and muons for detailed simulations.

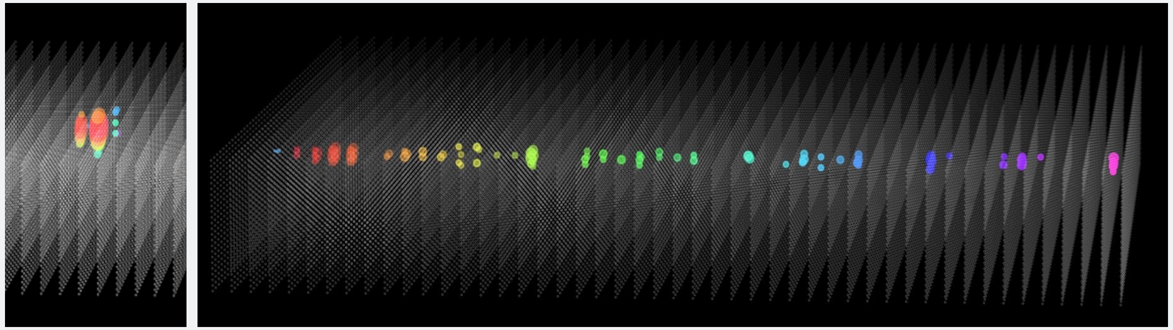


Detector Simulation

Simulation toolkits

- Geant4: simulating particle interactions inside the array
- CRMC: hadronic interactions above 100 TeV
- Two libraries, G4ART and G4DMT, are developed to accelerate the simulation above 100 TeV.

Morphology



Left: Cascade event induced by an 1 PeV electron;
Right: Track event induced by an 100 TeV muon

G4DMT & G4ART

G4DMT: Geant4 Distributed Multiple Threads
- fine-grained and multi-level parallelism on the particle tracking tasks generated by a single primary particle

G4ART: Geant4 Accelerated Ray Tracing
- heterogeneous parallel acceleration of optical process calculations

One electron (1 PeV)
- default Geant4 takes **137 hours**
  - 1-core CPU
- G4DMT + G4ART takes **410 seconds**
  - 32-core CPU, 4 GPUs
- **1200 times faster**

Xu et al. in prep

Detector Simulation

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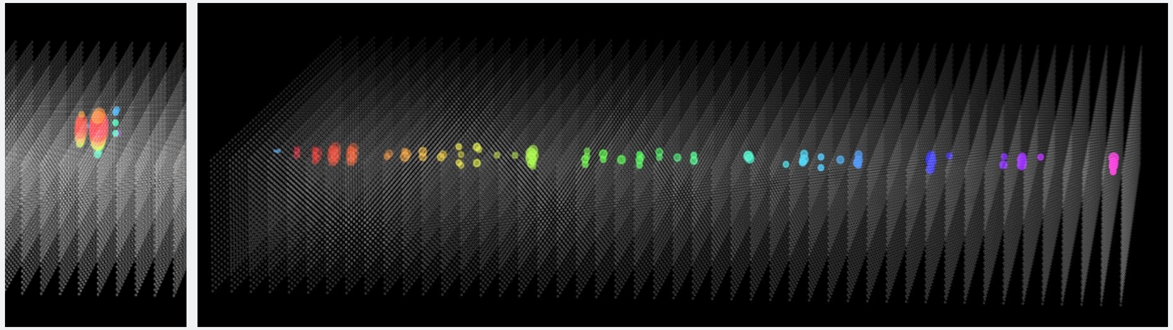
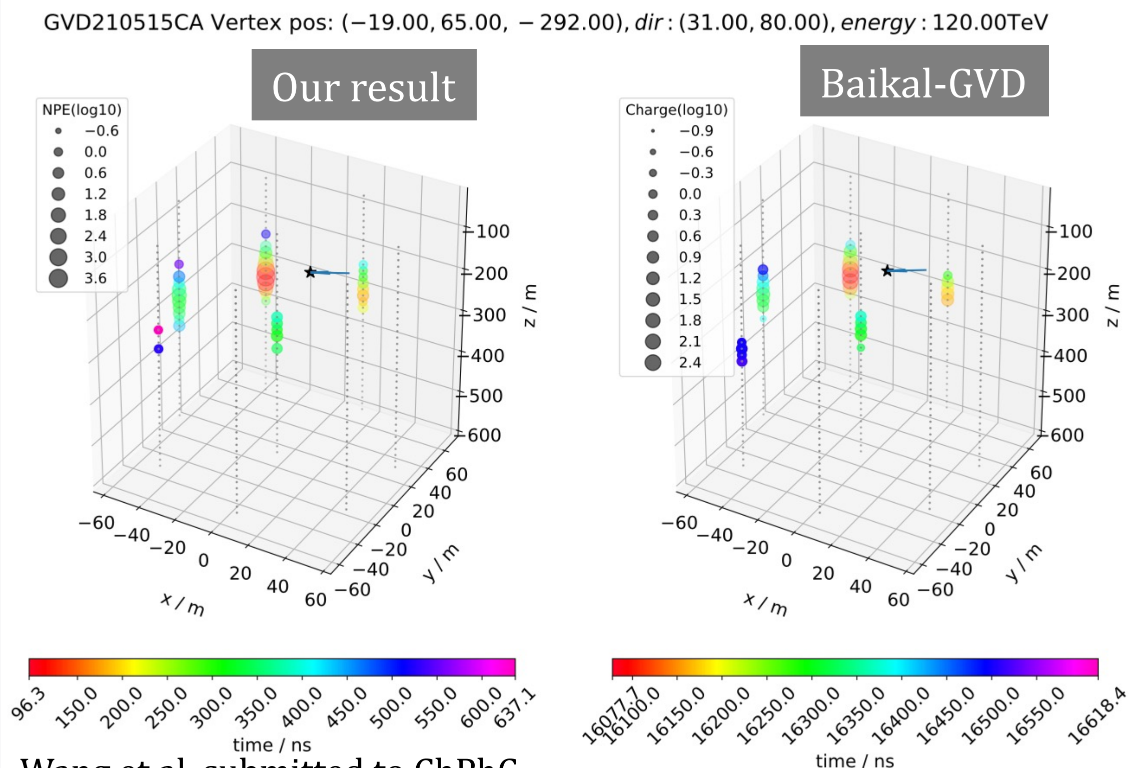


Left: Cascade event induced by an 1 PeV electron;
Right: Track event induced by an 100 TeV muon

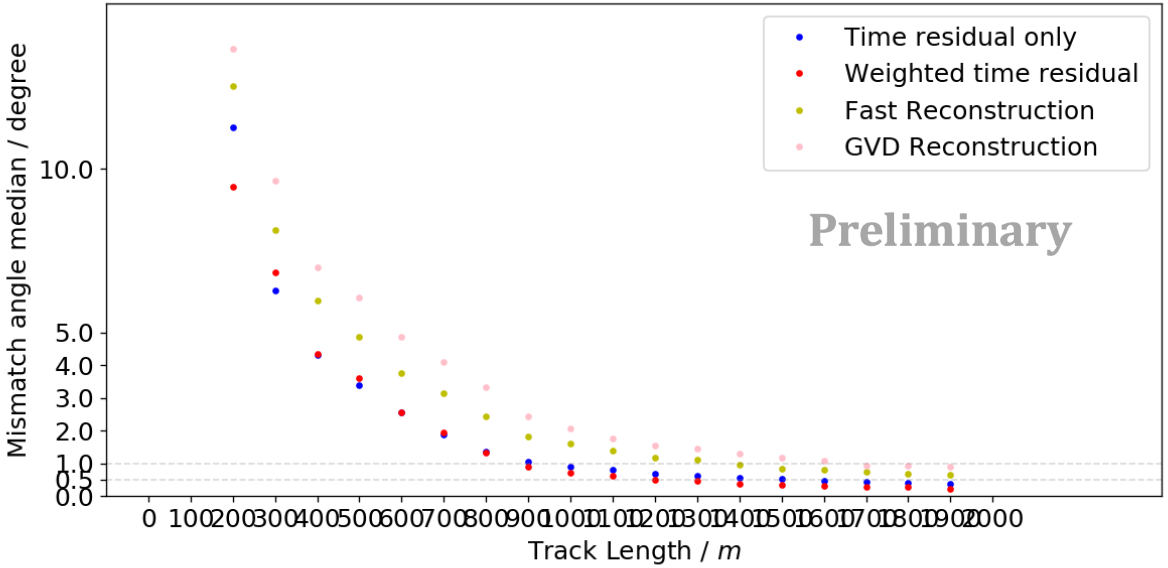
Simulating Baikal-GVD observations

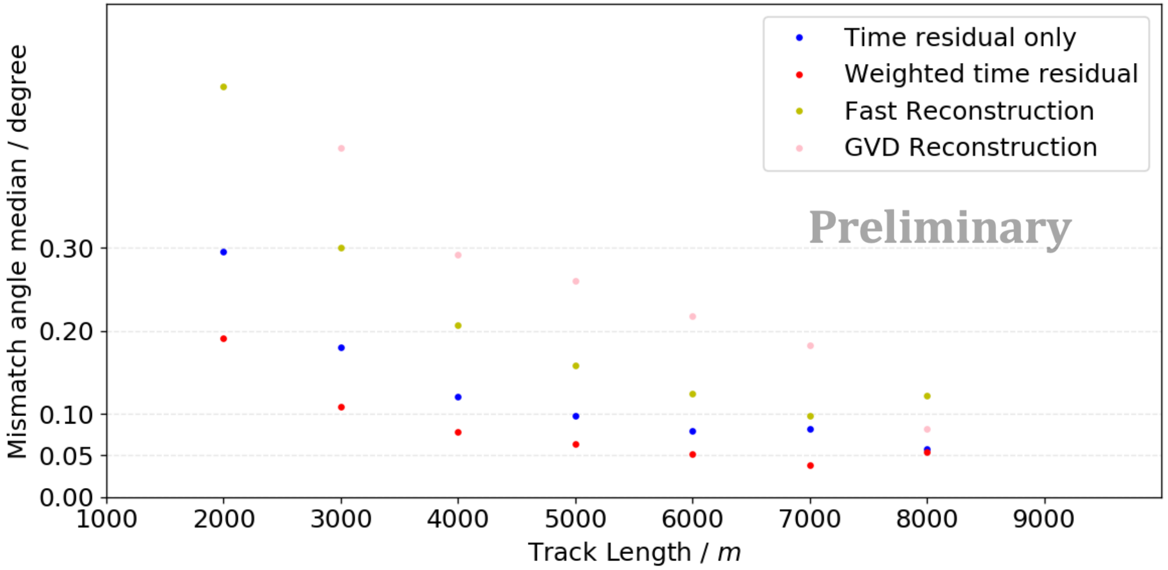
- Baikal-GVD observed 16 cascade events.
- We simulate the GVD observation (e.g., NPE) using the reconstructed parameters of these events.
- Our simulations are consistent with the GVD observations considering the systematic uncertainty.



Wang et al. submitted to ChPhC

Reconstruction





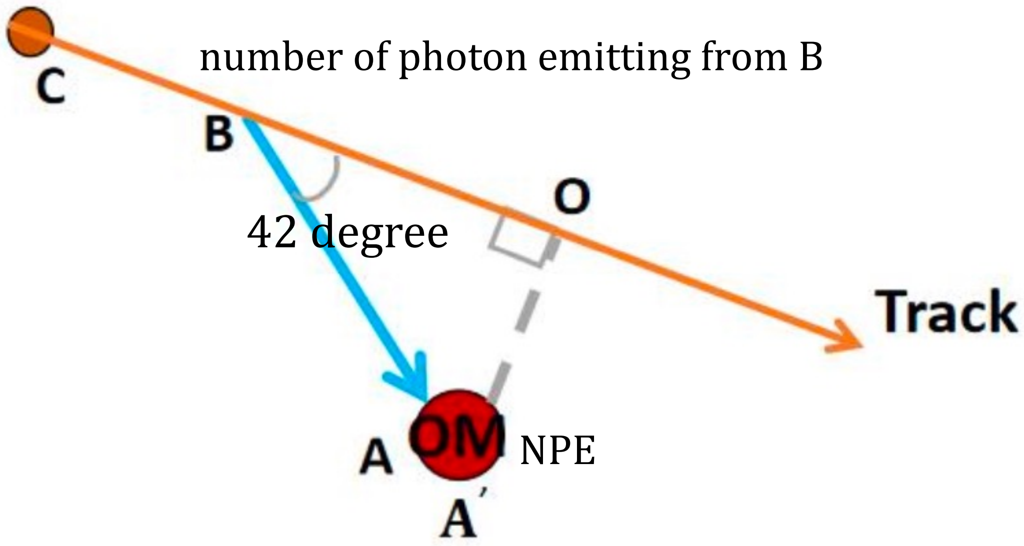
Weighted time-residual method.

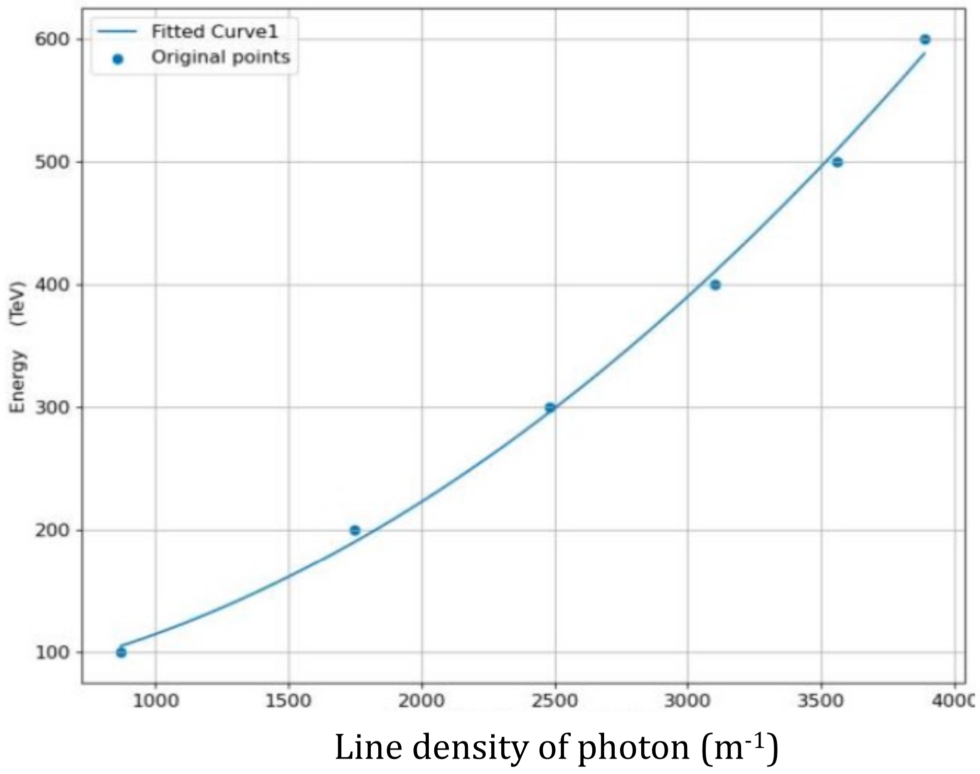
$$\chi^2_{\mathrm{WTR}} = \sum_i^N w_i \left(\frac{t_i(X,\theta) - T_i}{\sigma_i} \right)^2$$

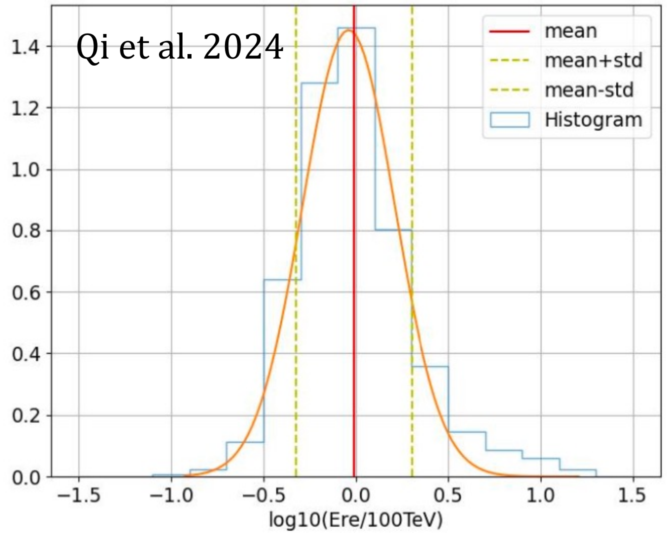
- σ_i is the time detection error of the i-th OM;
- $w_i=q_i/\Sigma q_j$ is the fraction of NPE in the i-th OM;
- t_i-T_i is the time residual between the theoretical expectation and the detection.

The median opening angle for track length of 3000 m is around **0.1°**.

Reconstruction

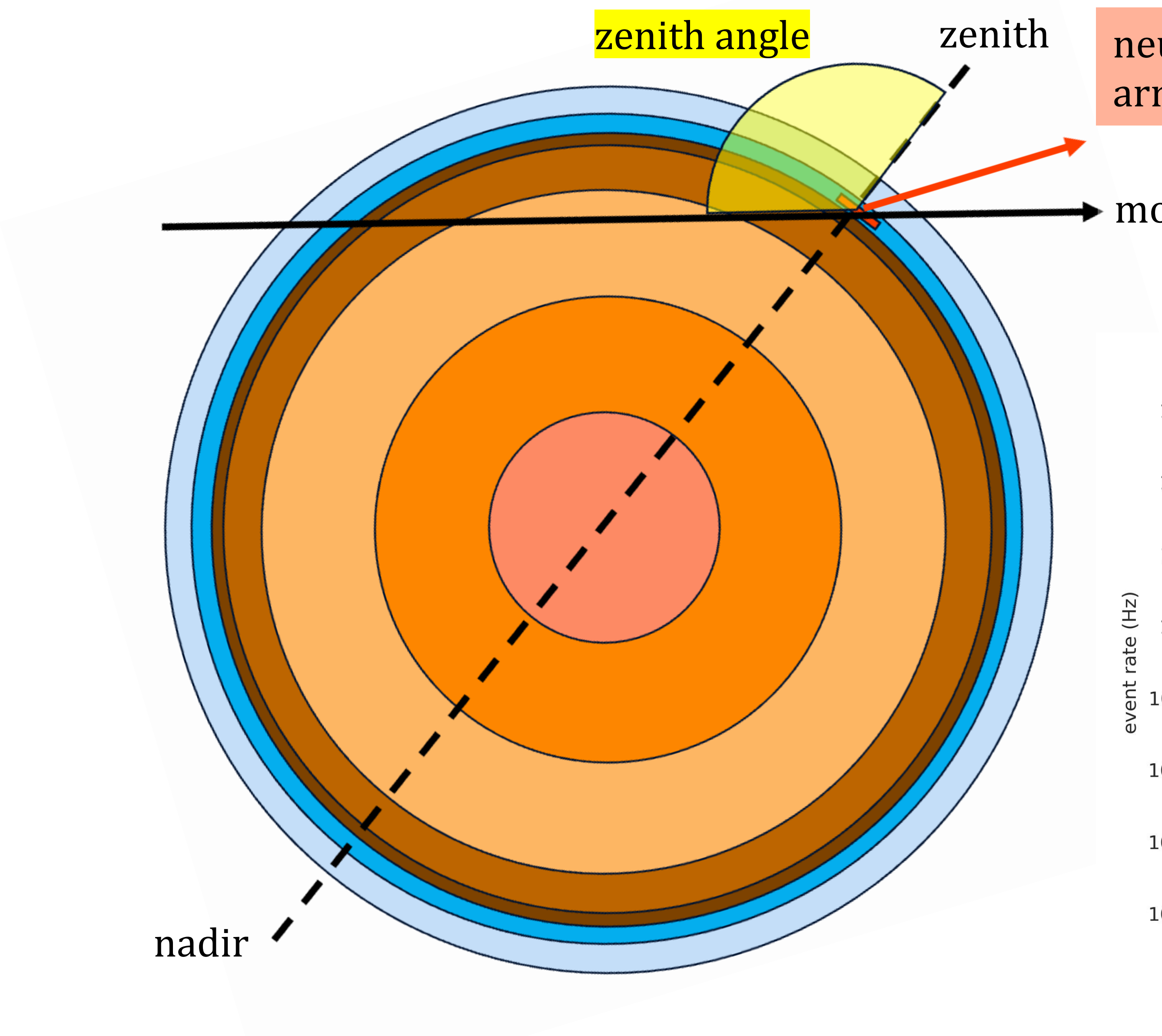


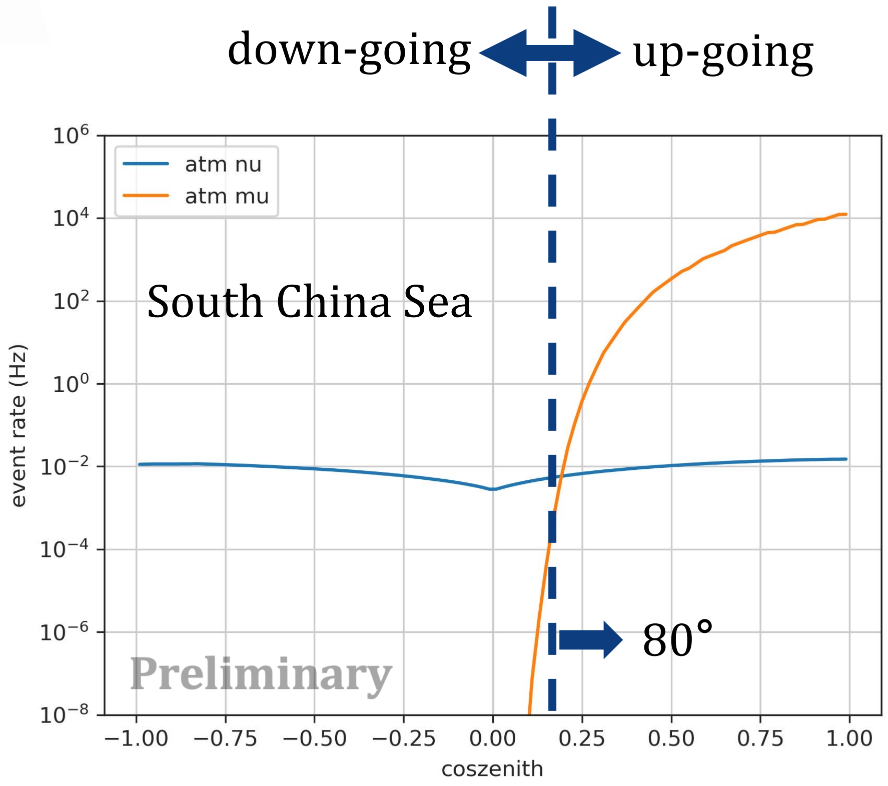




- The connection between the line density of photons along the track and the muon initial energy
- The energy resolution is around **$\Delta \log(E_{rec}) = 0.27$**

Upgoing Tracks





Lake Baikal vs. South China Sea

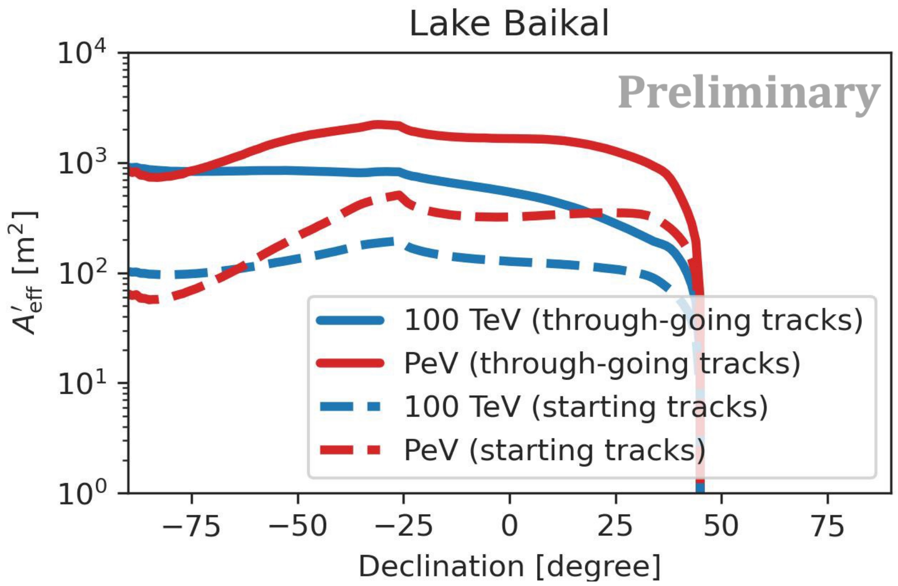
$$A'_{\rm eff}(E_\nu, \delta_s) = \frac{1}{1\,\rm day}\int_{\theta_z > 80^\circ} A_{\rm eff}(E_\nu, \theta_z(\delta_s, t))\mathrm{d}t.$$

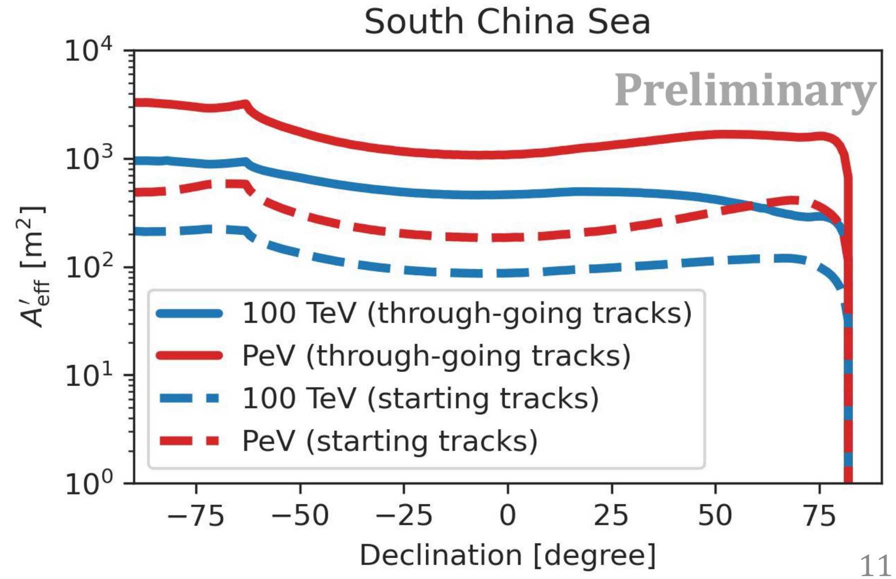
Lake Baikal

- Depth: 500-1360 m
- Larger effective area for the sources with declination angles from -50° to 5°, especially for the **Galactic center** (decl. = -29°).

South China Sea

- Depth: 2560-3420 m
- Larger effective area for the sources with declination angles above 20°.
- The observable region overlaps with the LHAASO's coverage, with declination ranging from -21° to 79°.





Discovery Potential

Background

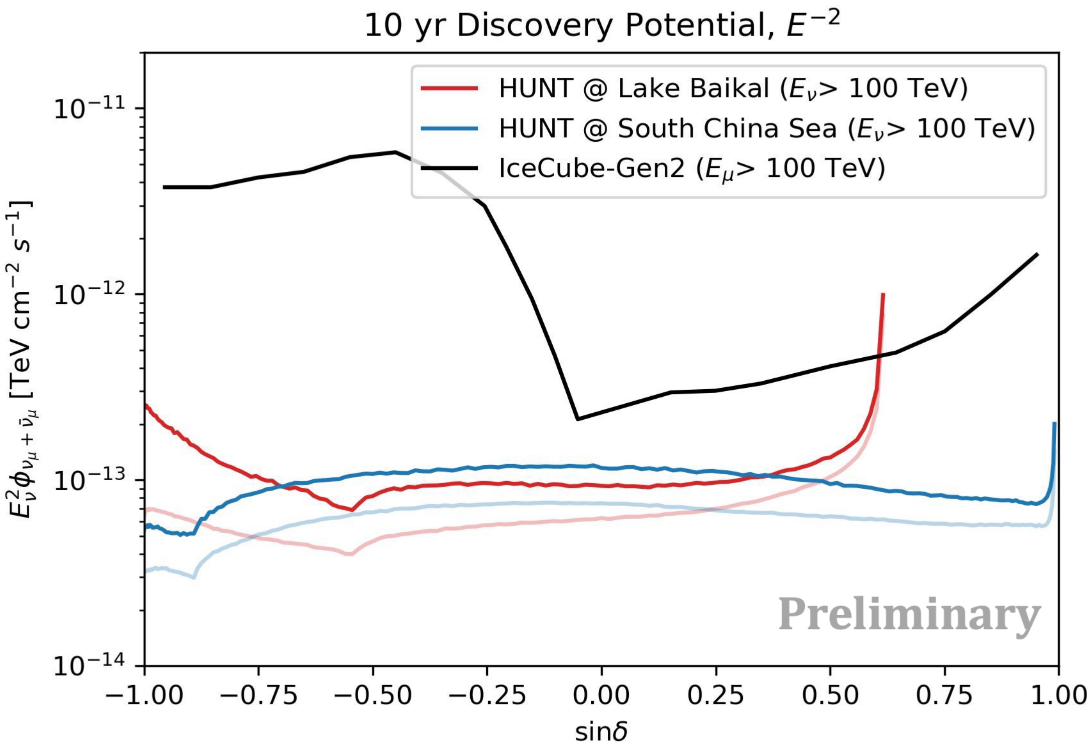
- Atmospheric muon neutrinos (MCEq)
- Diffuse astrophysical muon neutrinos (9.5 yr, tracks)

Signal

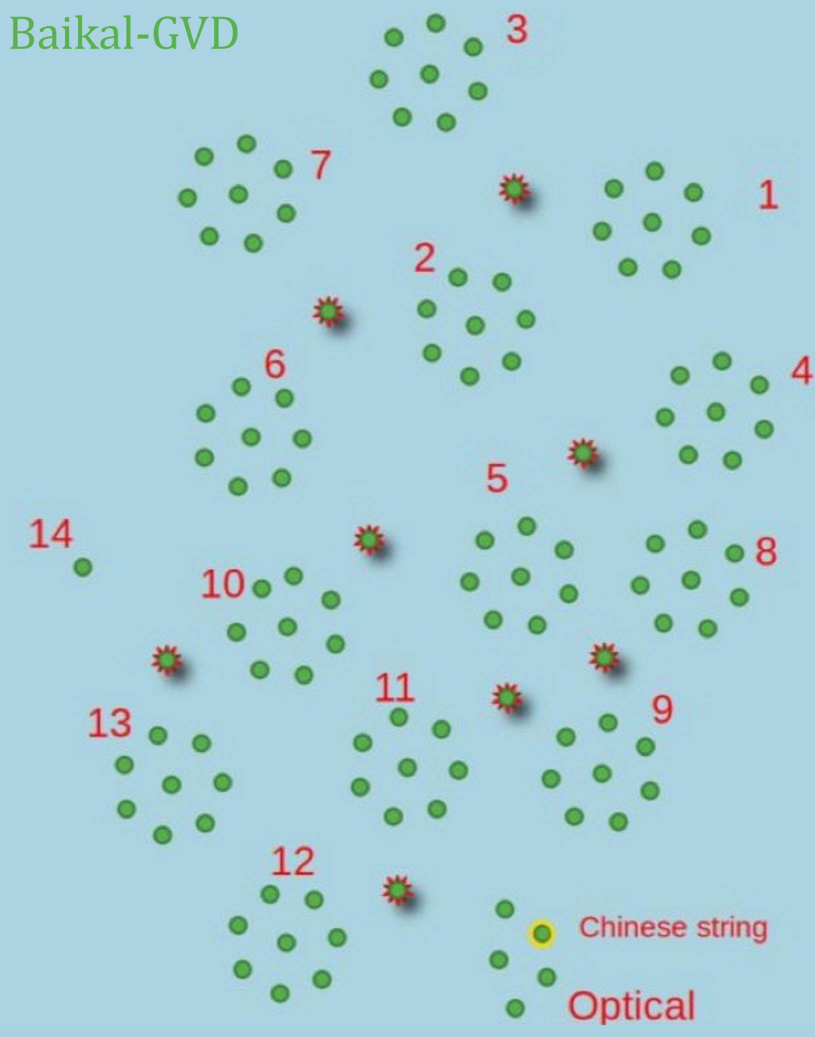
- Point-like sources following E^{-2} spectrum

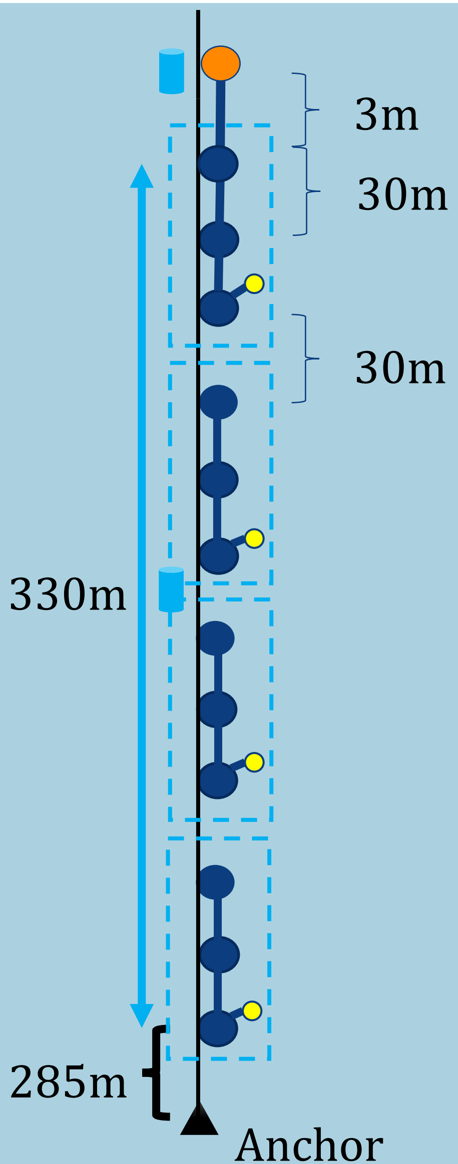
Sensitivity to sources (Ambrogi et al. 2018)

- $\Omega = \pi R_{ROI}^2 = \pi(\sigma_{PSF}^2 + R_{src}^2)$
- 5σ discovery potential: $N_s/\sqrt{N_b} = 5$
- $N_s > 1$
- $N_s/N_b > 0.75$

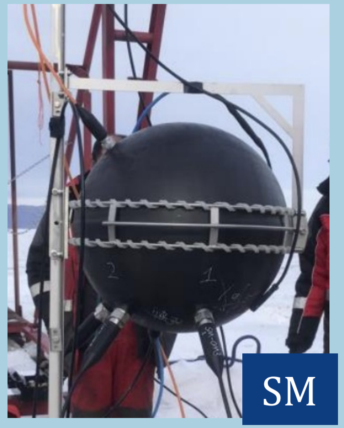


Pathfinder Experiment

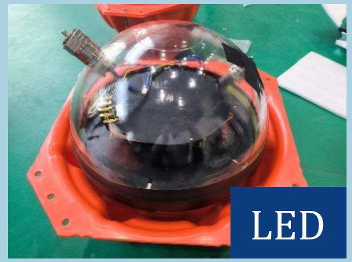




String module



LED module



Acoustics positioning system

Optical module

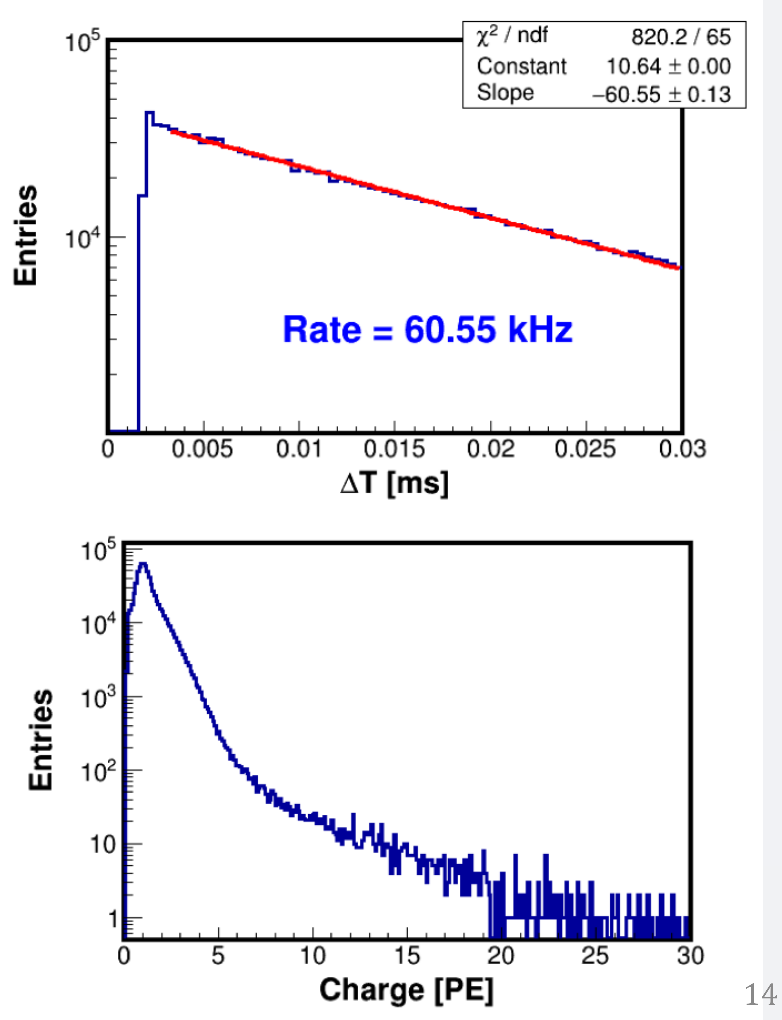
Pathfinder Experiment

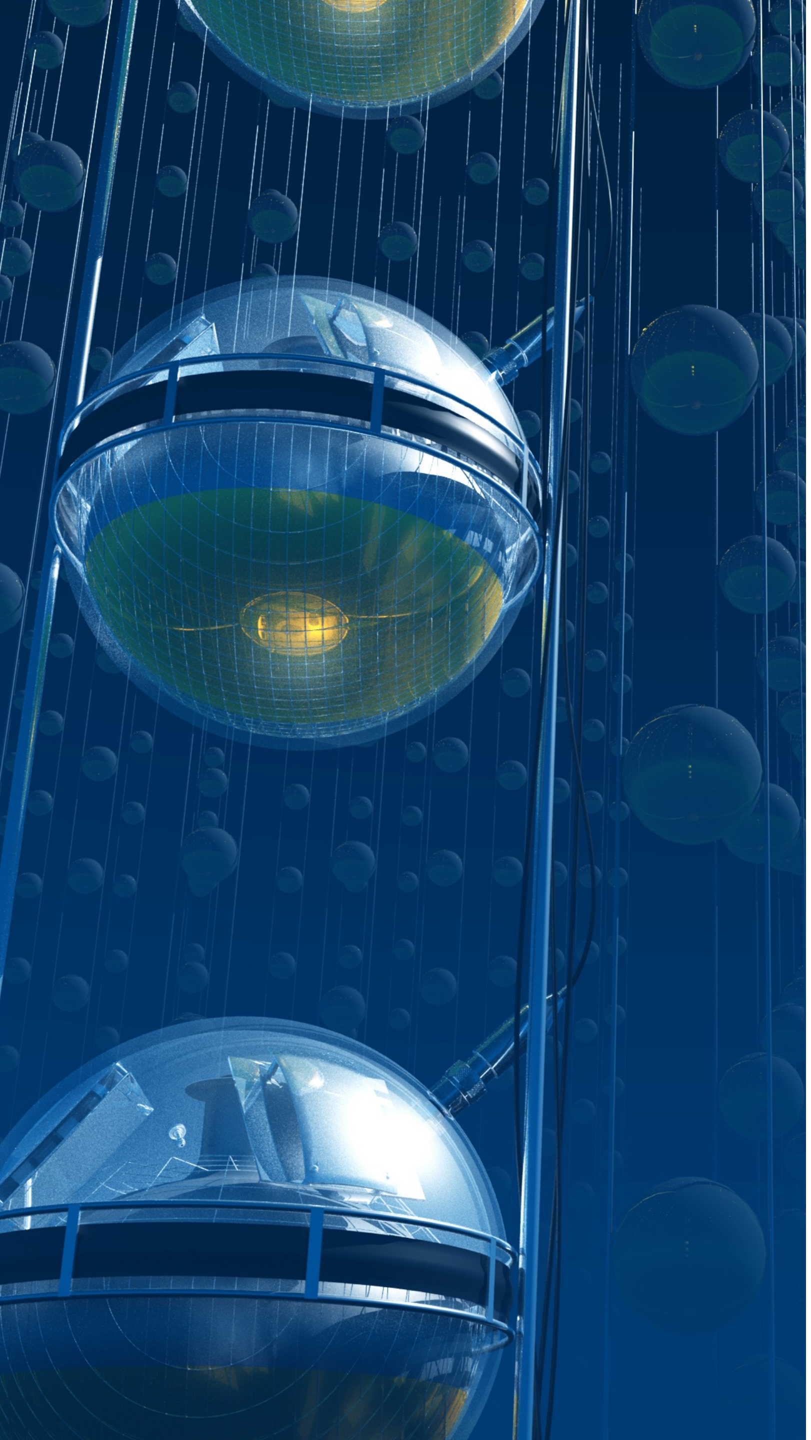
Experimental Objectives

- To accumulate experience for deployment and operation
- To study the operational status of the ultra-large aperture optical modules in the environment of Lake Baikal

First impressions

Single-channel distribution of hit time differences (top)
Amplitude spectrum for a typical OM (bottom)



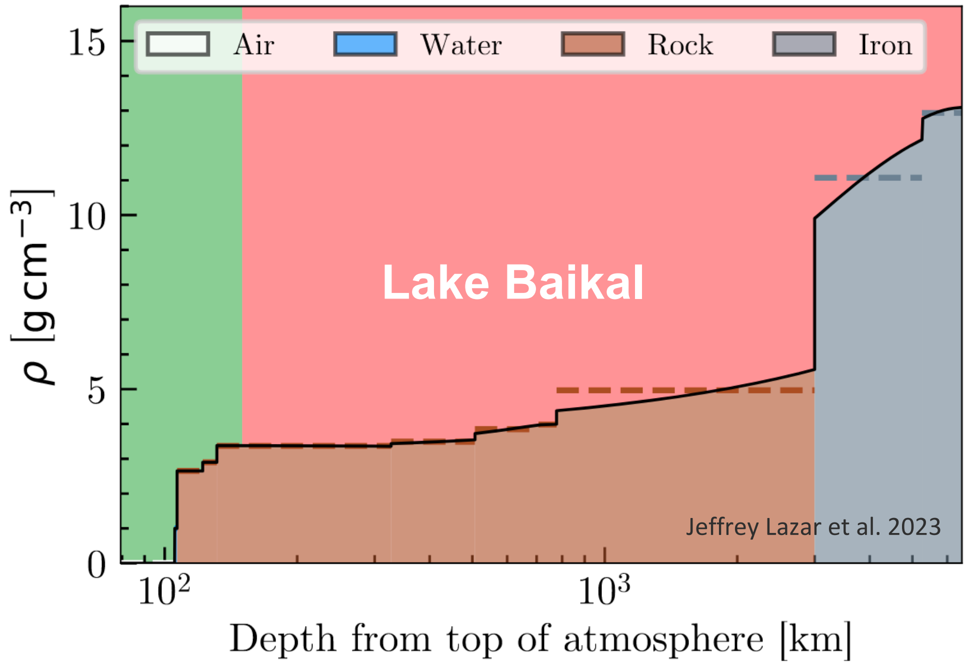


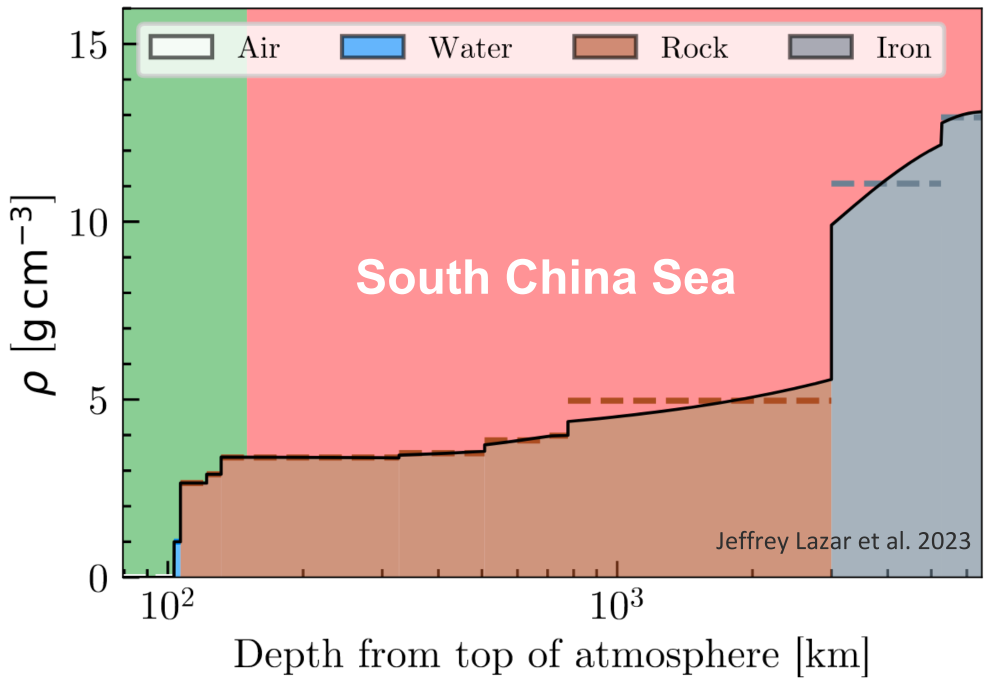
Summary

- LHAASO has discovered tens of PeVatron candidates waiting for the identification by high energy neutrino observations.
- We have developed the toolkits that can greatly speed up the simulation of primary particles (e.g., muon, electron) above 100 TeV.
- The reliability of simulating particles inside the array has been validated.
- HUNT will realize unprecedented potential in discovering single neutrino sources, especially for the Galactic center.
- A prototype string has been deployed in Lake Baikal and connected to the GVD array in March 2024. **The prototype strings will be deployed in the South China Sea this year and operate long-term.**
- **We will release the conceptual design report this year.**

Back Up

Modified PREM model





Muon energy loss

Medium	α, [10^{-3} GeV cm^2 g^{-1}]	β, [10^{-6} cm^2 g^{-1}]
Air	2.81	3.58
Water	2.49	4.22
Rock	2.21	5.31

Table 1: The parameters for muon energy loss in different media.

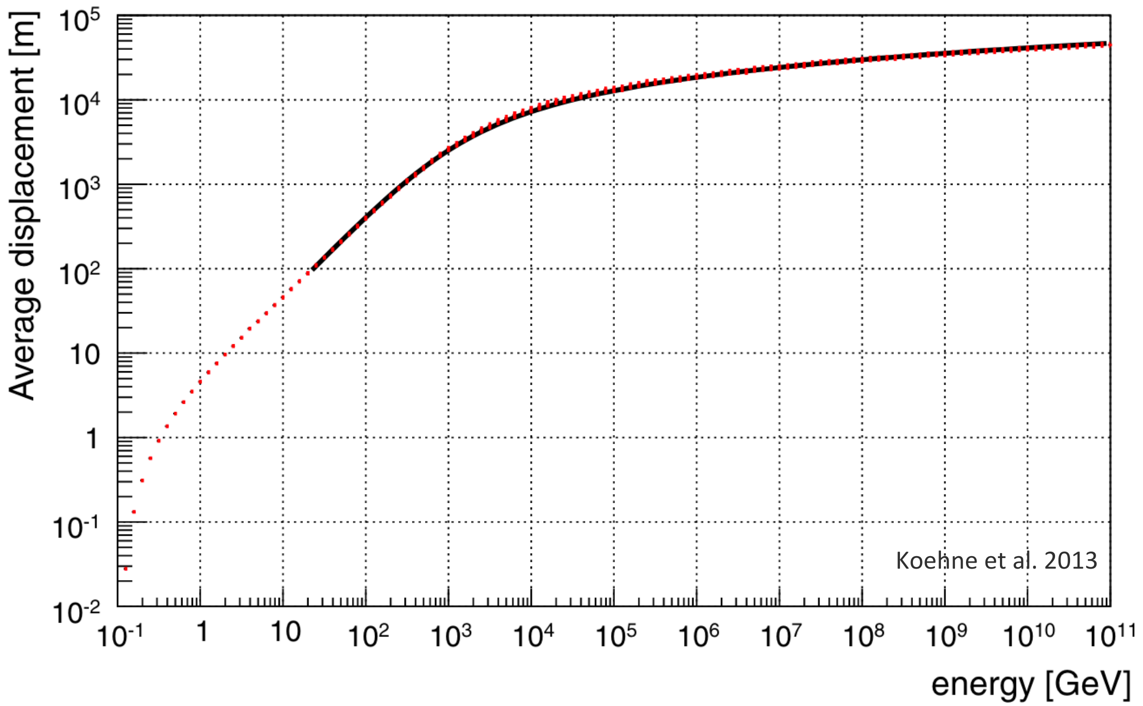
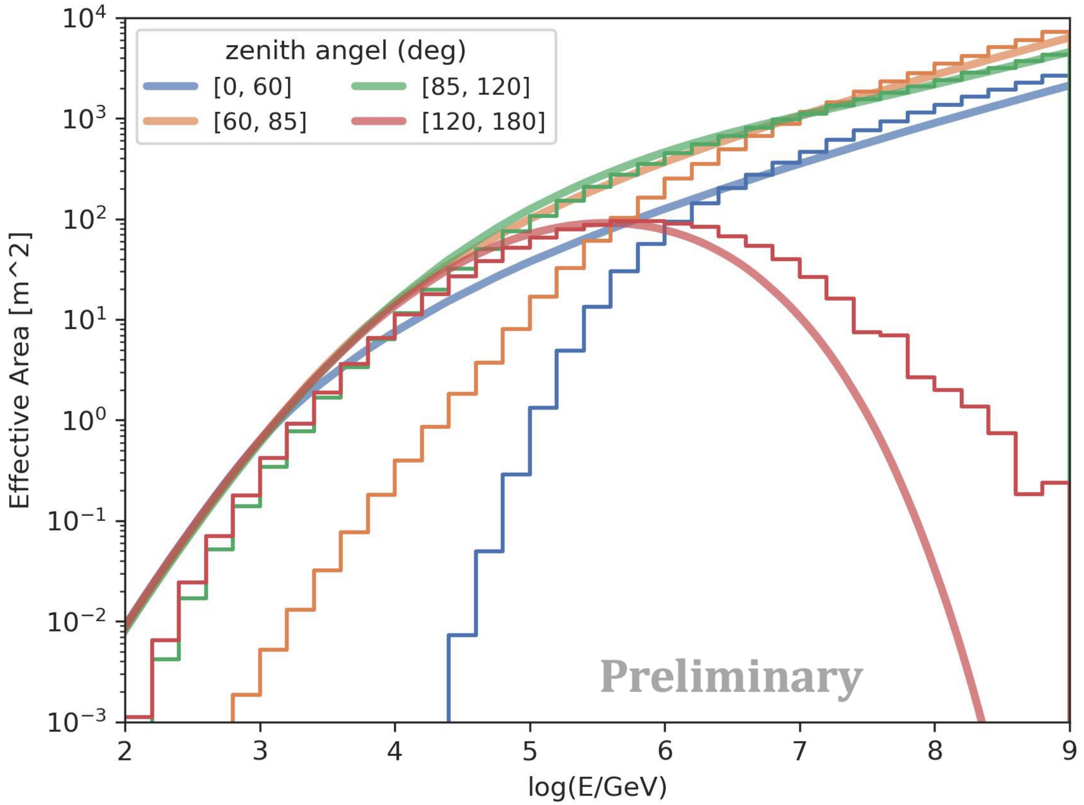
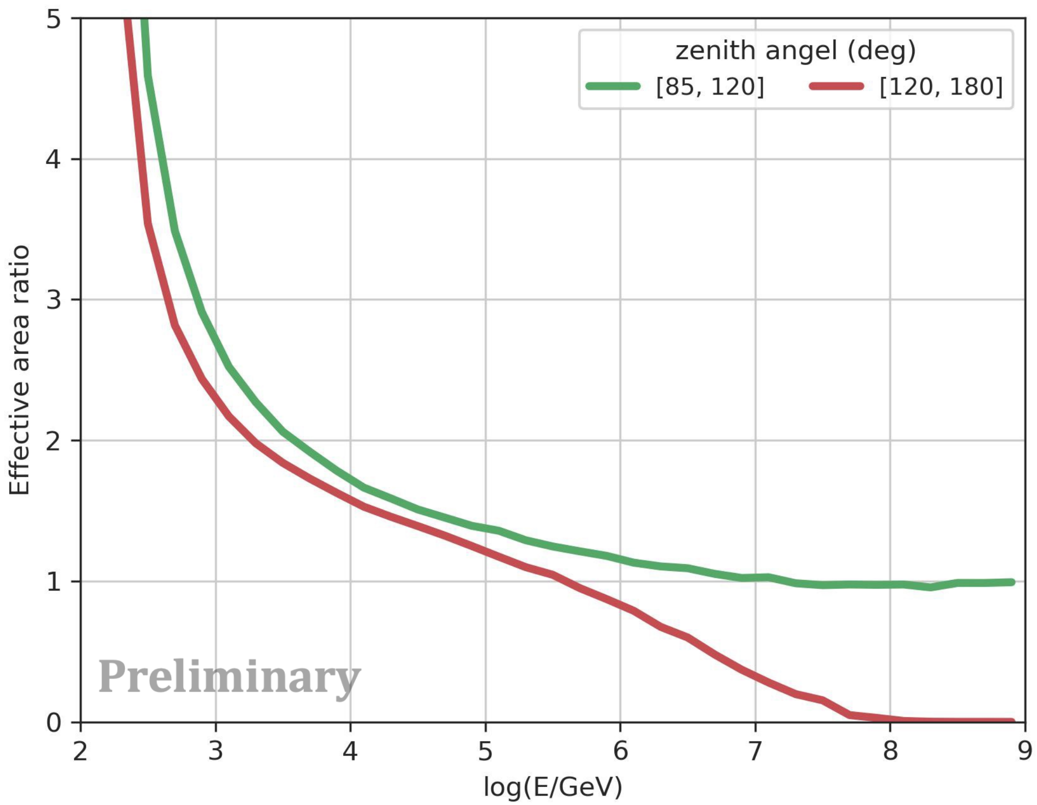


Fig. 40. Fit to the average range of a muon in ice. The range is calculated with PROPOSAL with the initial energy of the particle between 10^{-1} GeV and 10^{11} GeV.

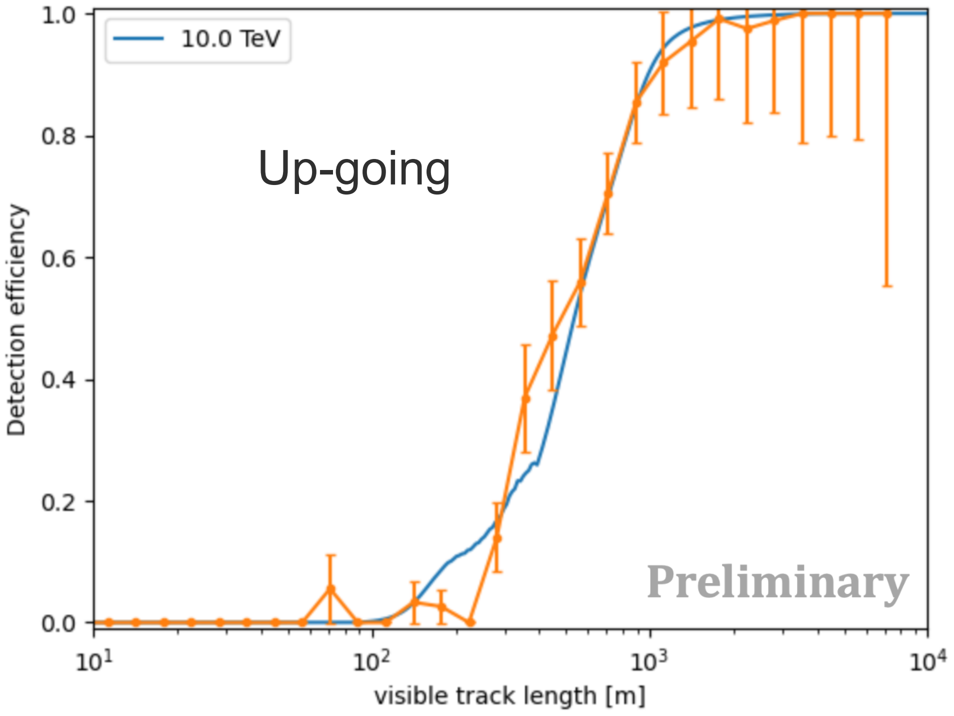
Effective area

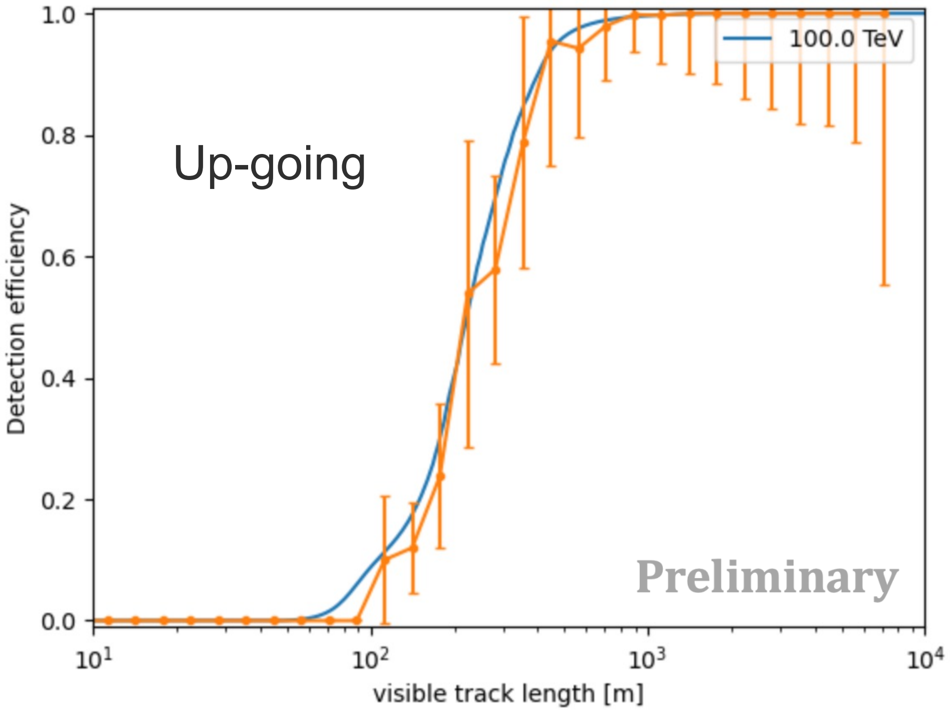
- Simulate IceCbe effective area for through-going track events
- 100% trigger rate





Detection efficiency

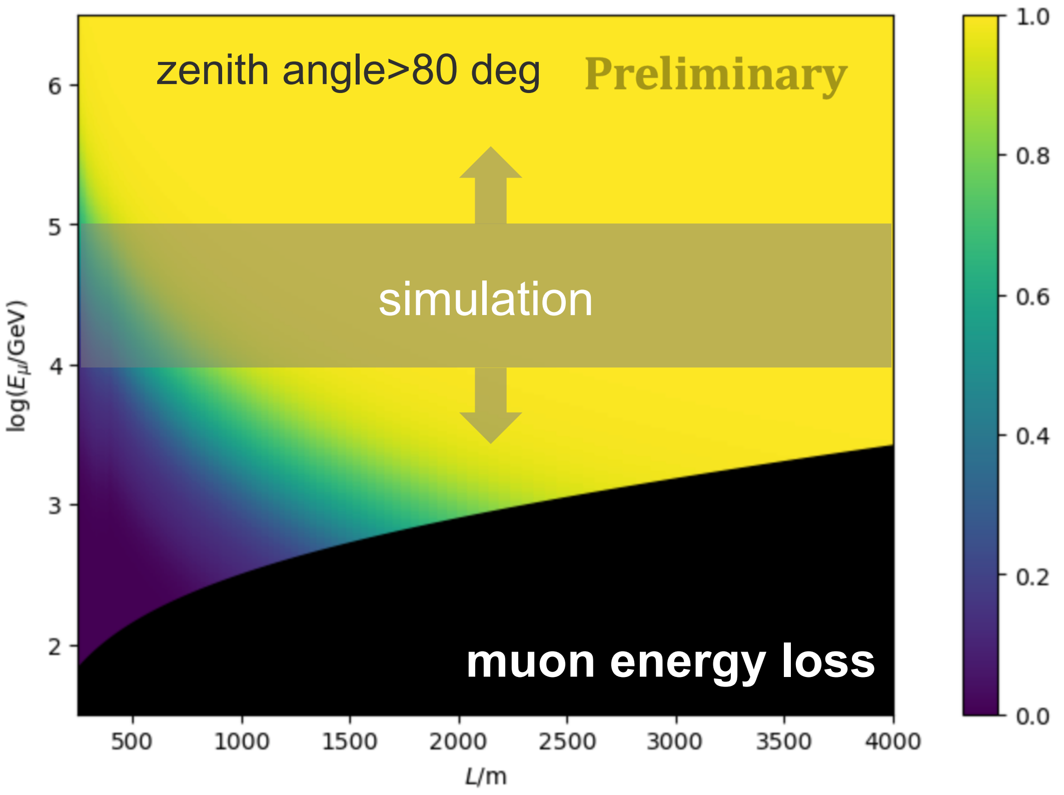




Detection efficiency

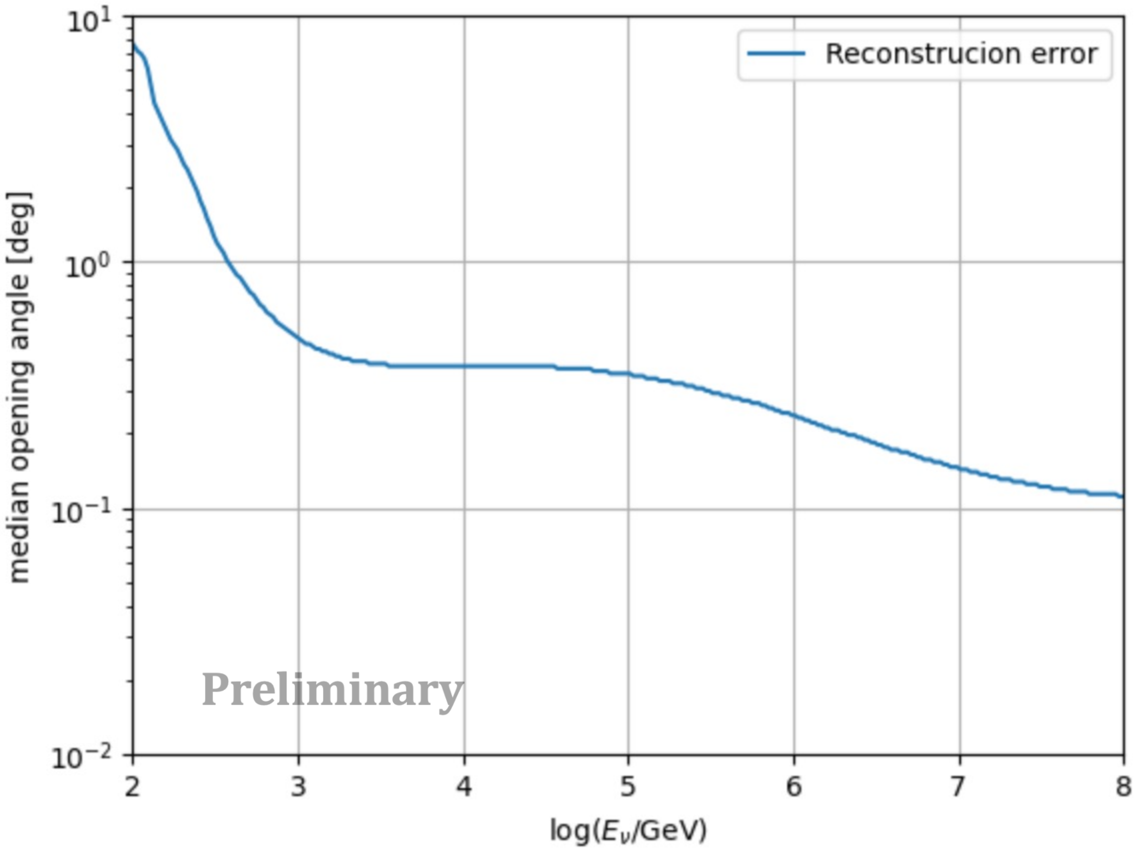
The detection efficiency for up-going muon-tracks.
We adopt the following **event selection criteria**:

- number of PMT hit (N_{hit}) ≥ 7
- number of photoelectrons (N_{PE}) ≥ 1 for each hit
- total $N_{PE} \geq 21$
- track length > 250 m



Reconstruction

Through-going track events (θ>80 deg)



Weighted time-residual method.

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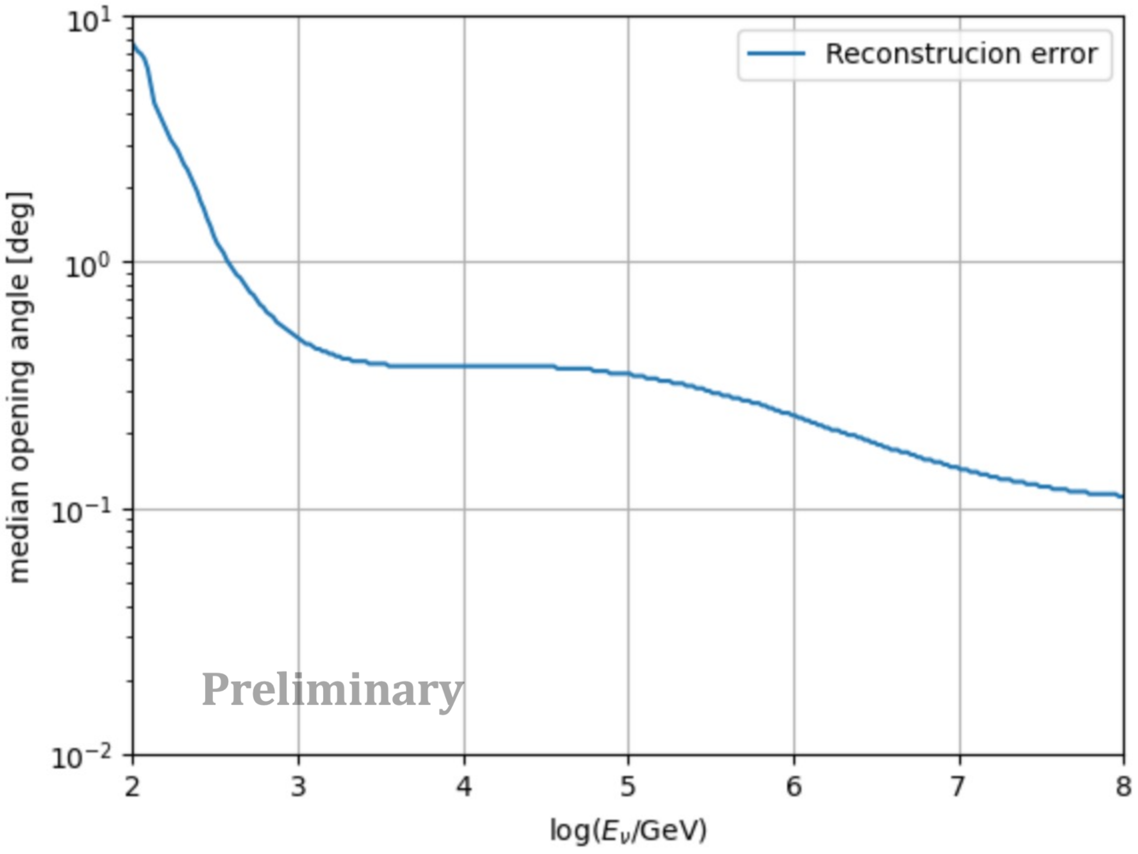

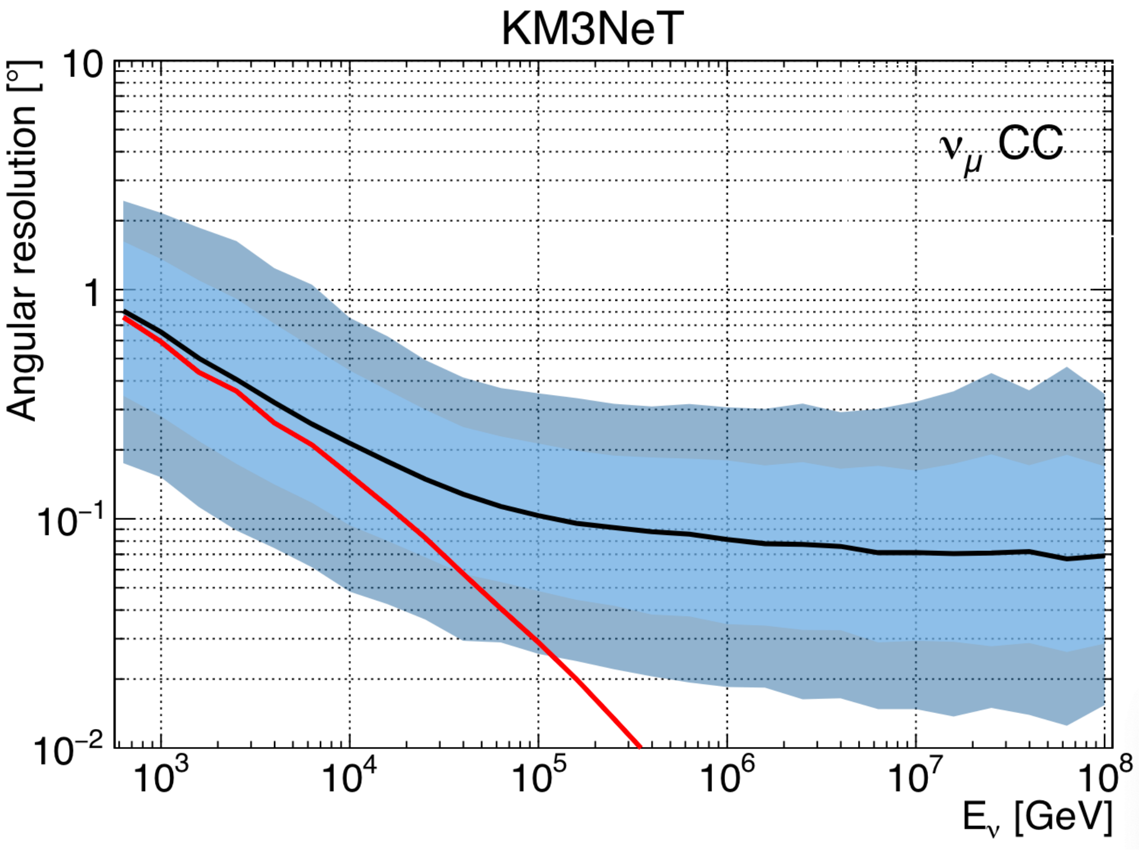

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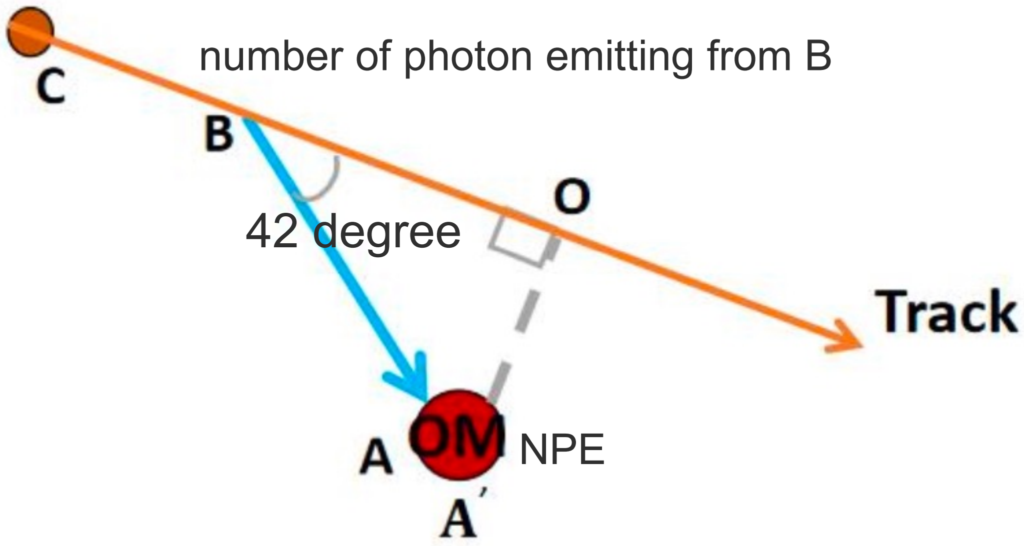
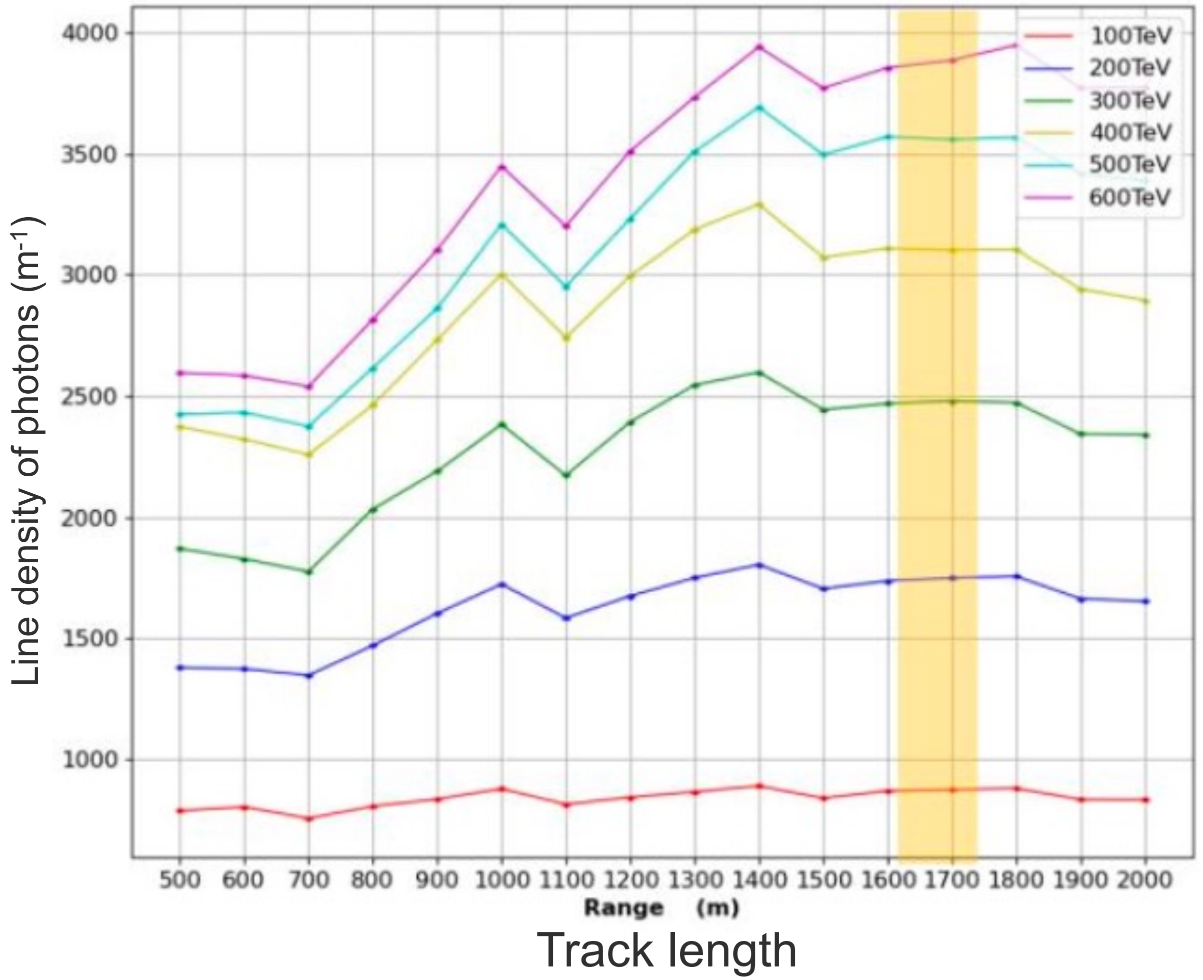
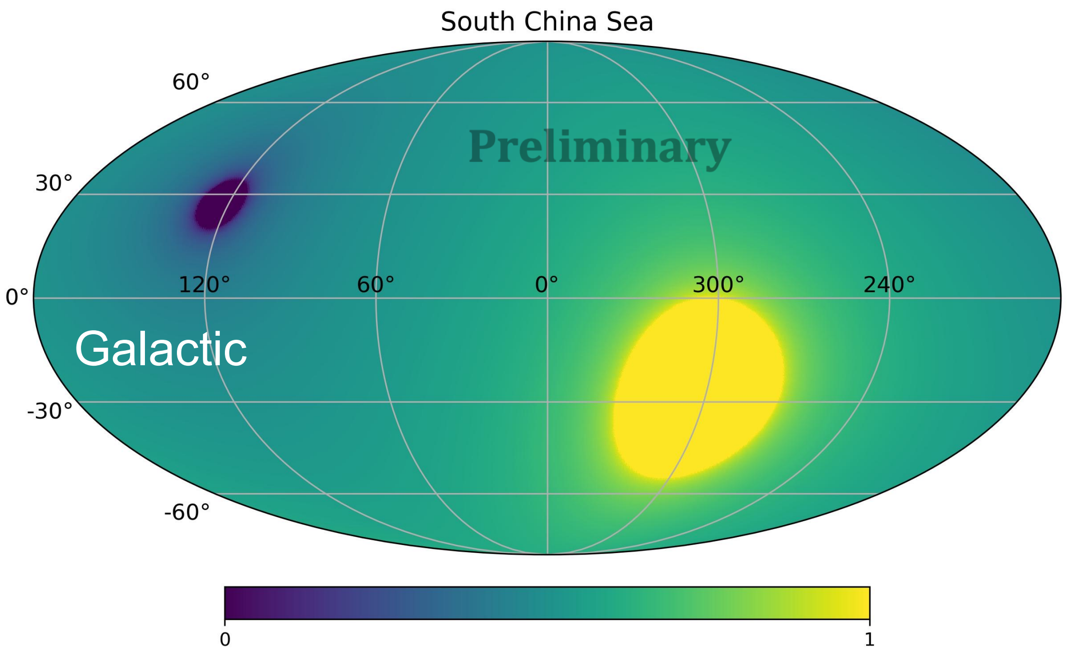
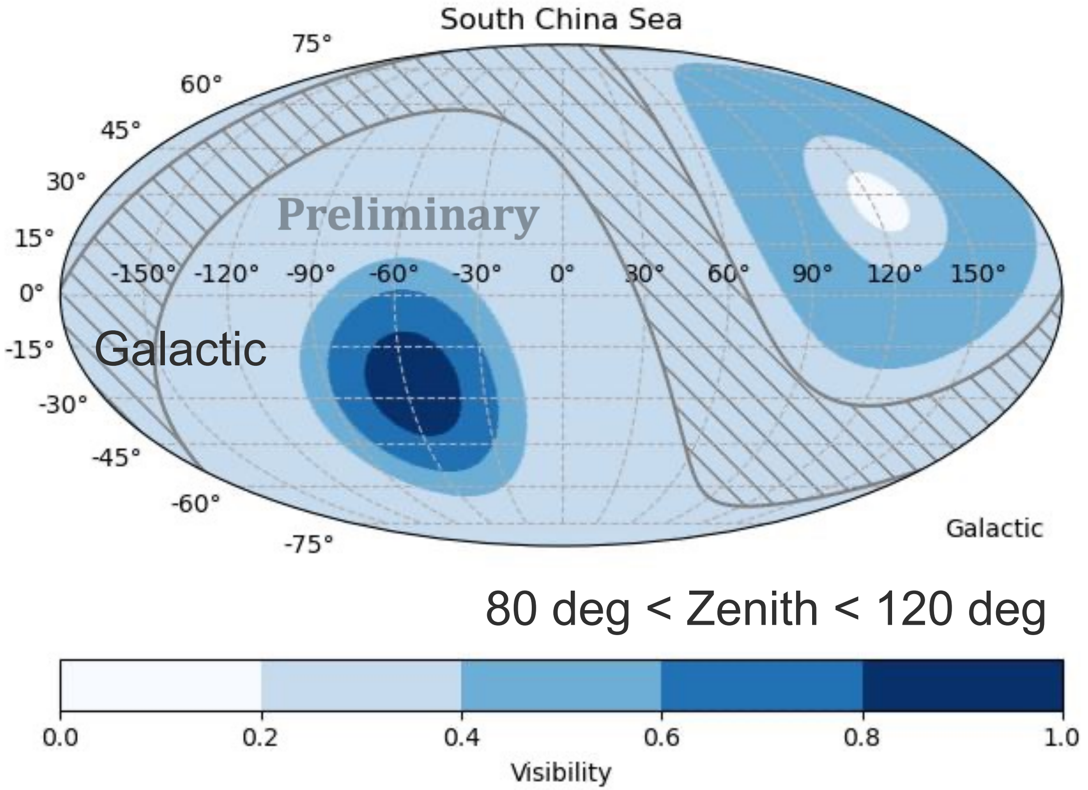




Visibility

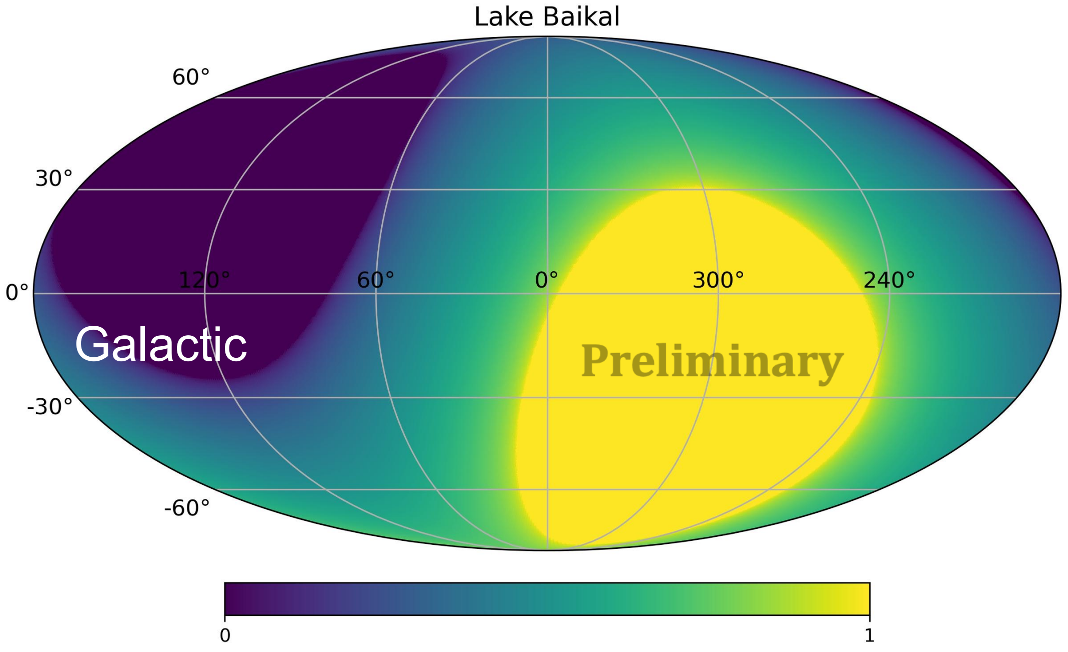


Zenith > 80 deg

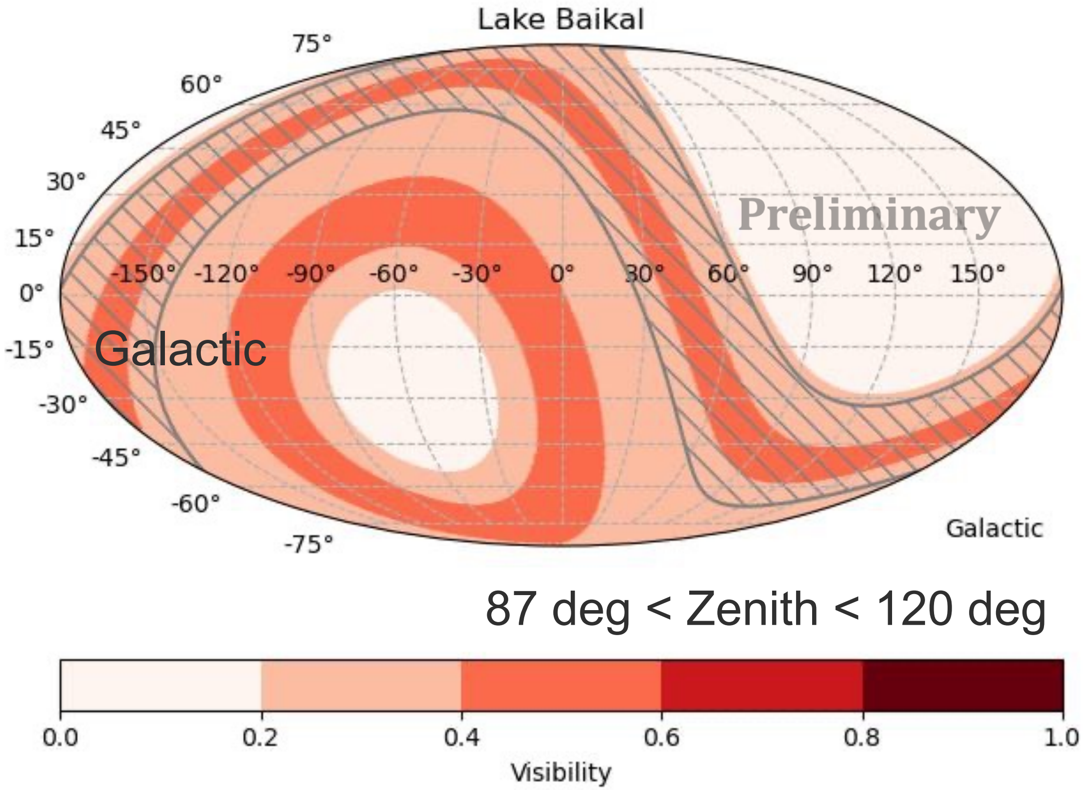


80 deg < Zenith < 120 deg

Visibility



Zenith > 87 deg



87 deg < Zenith < 120 deg