The Expected Performance of the High-energy Underwater Neutrino Telescope (HUNT)

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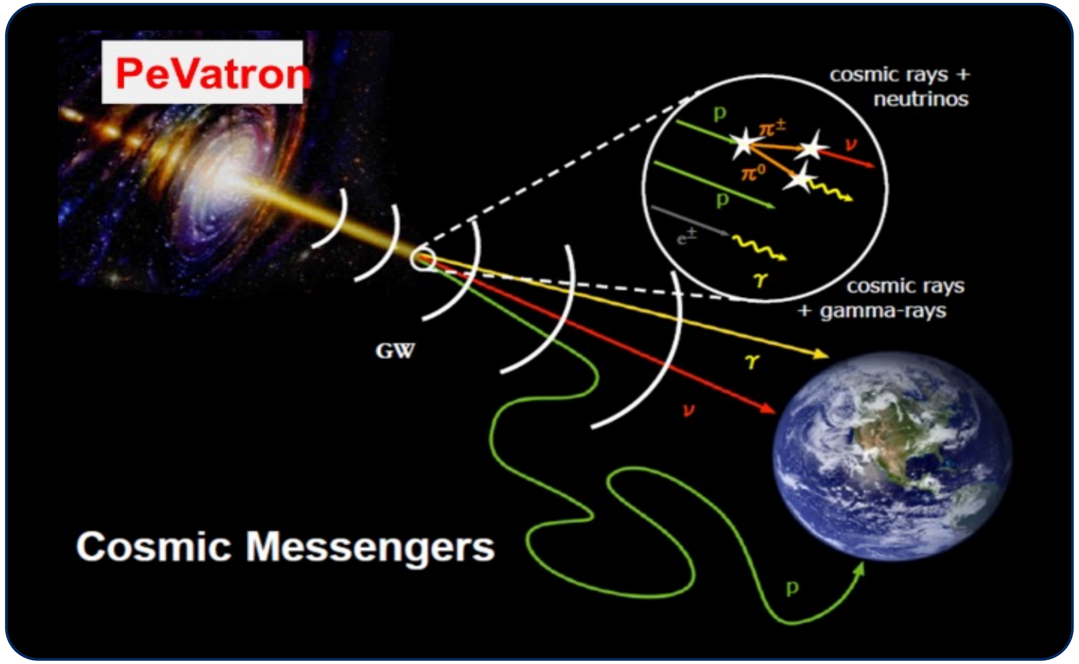
中国科学院 CHINESE ACADEMY OF SCIENCES

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

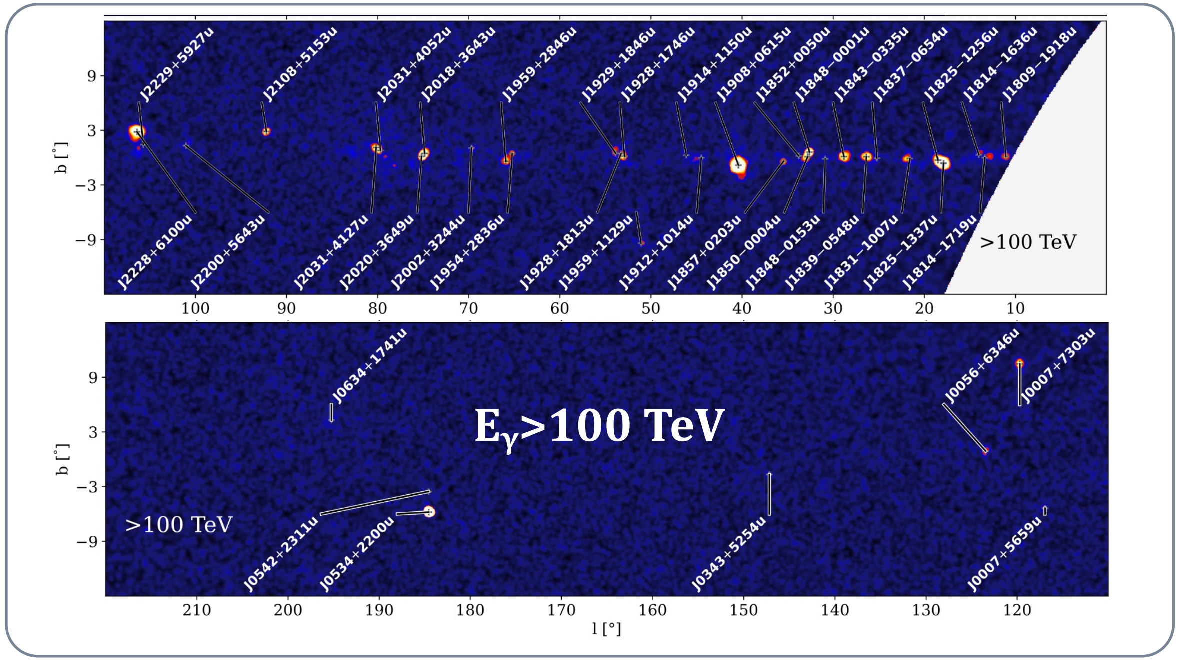
Scientific Goals

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)

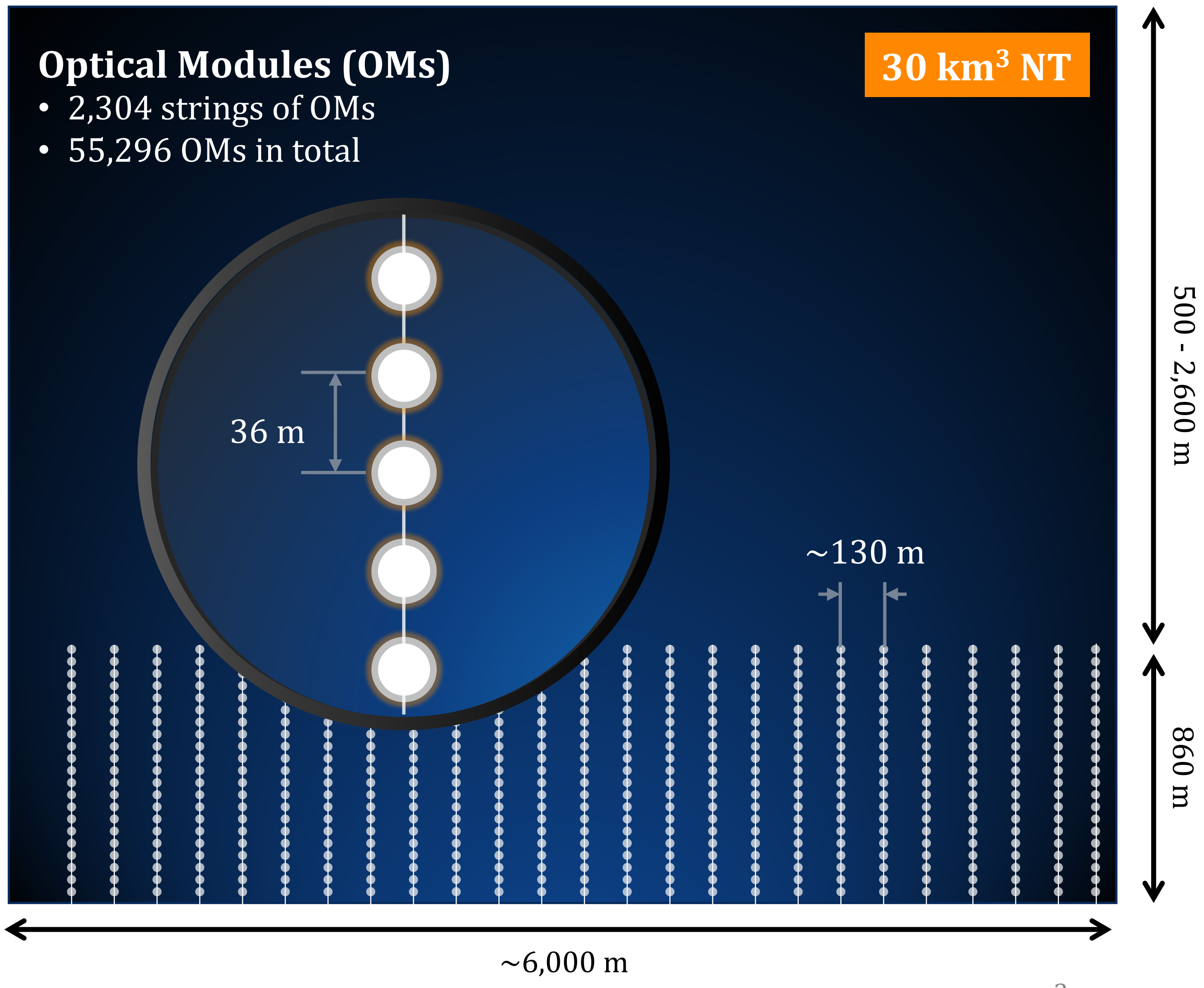


1LHAASO: 43 sources (>4σ); 22 sources (>7σ)

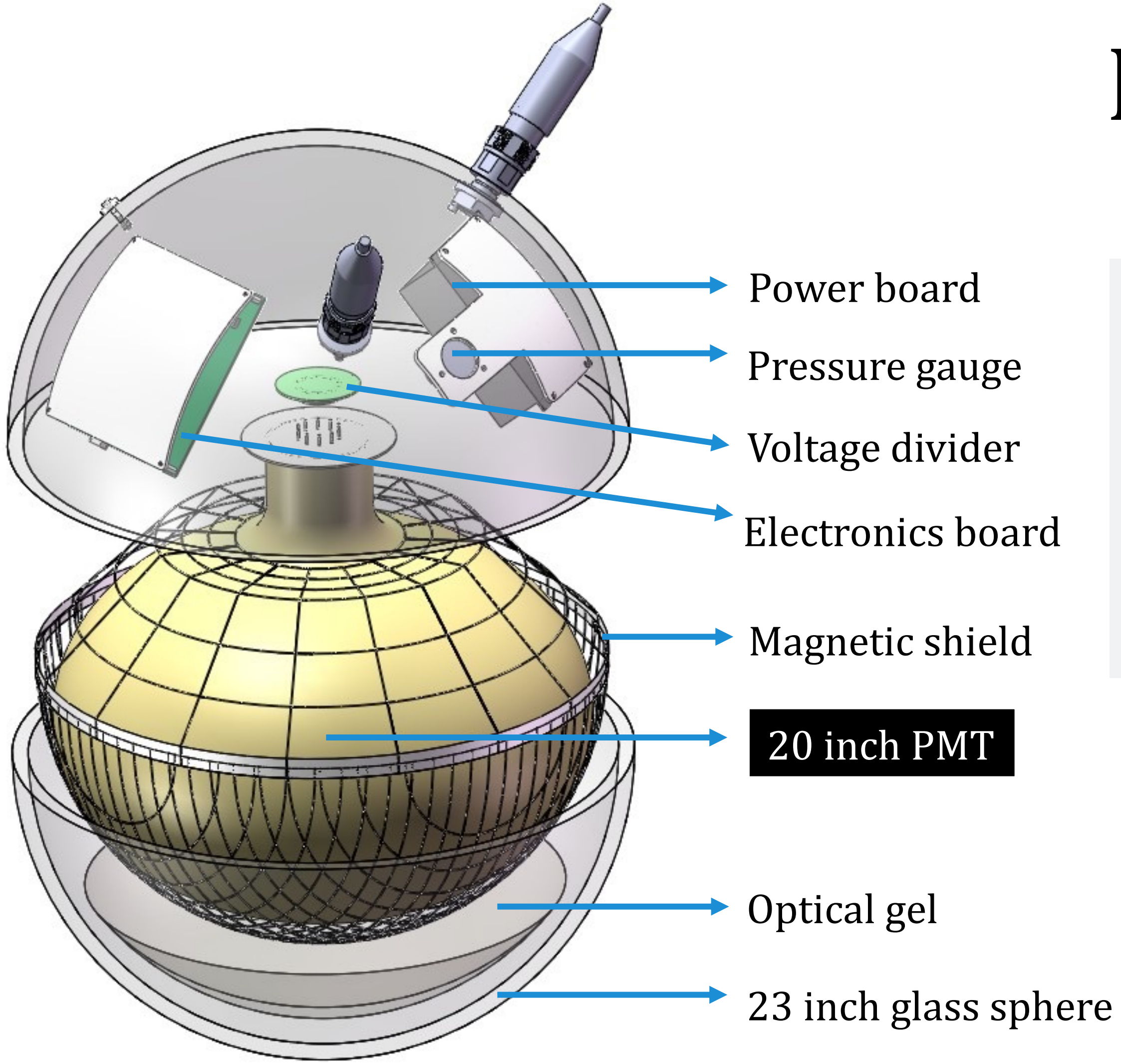
Detector Design

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

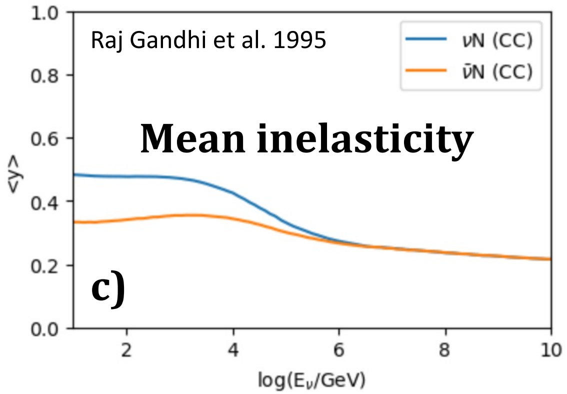


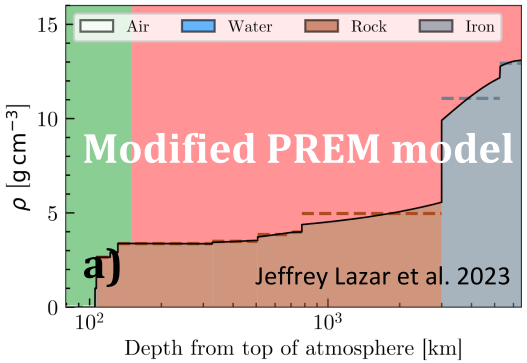
20 inch PMT

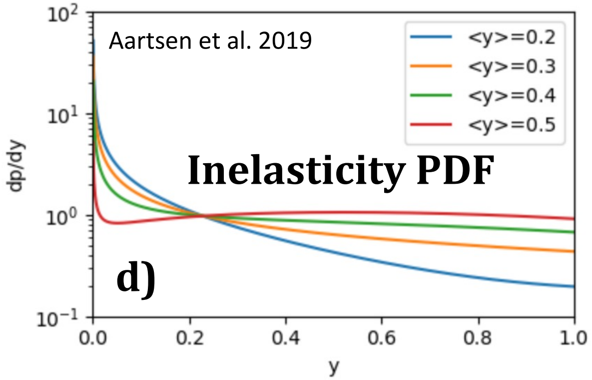
- Large photosensitive area
- Excellent time performance: TTS~7 ns
- High quantum efficiency: QE>30%

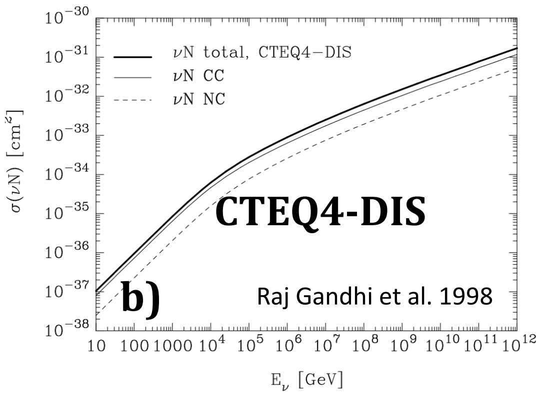
Detector Simulation

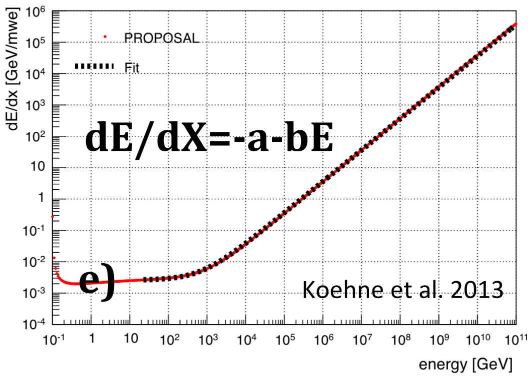
- Cylinder array
  - Lake Baikal
  - South China Sea
- Earth Model (a)
- νN cross section (b)
- Inelasticity (c, d)
- Lepton energy loss (e)



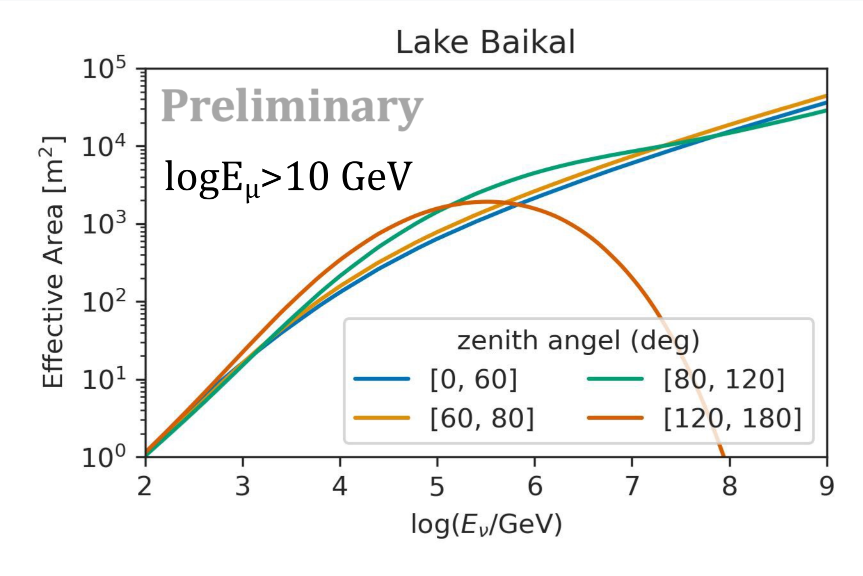




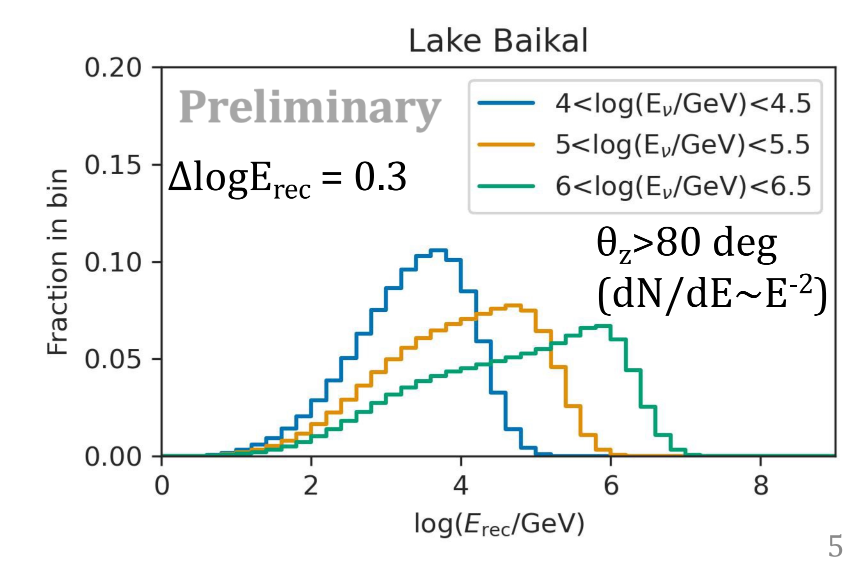




Effective Area (muon neutrino)



Reconstructed Energy (muon track)

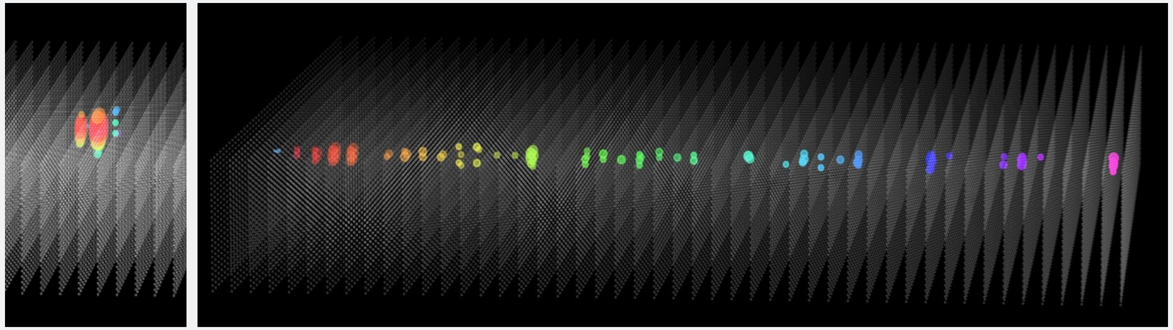


Detector Simulation

Simulation toolkits

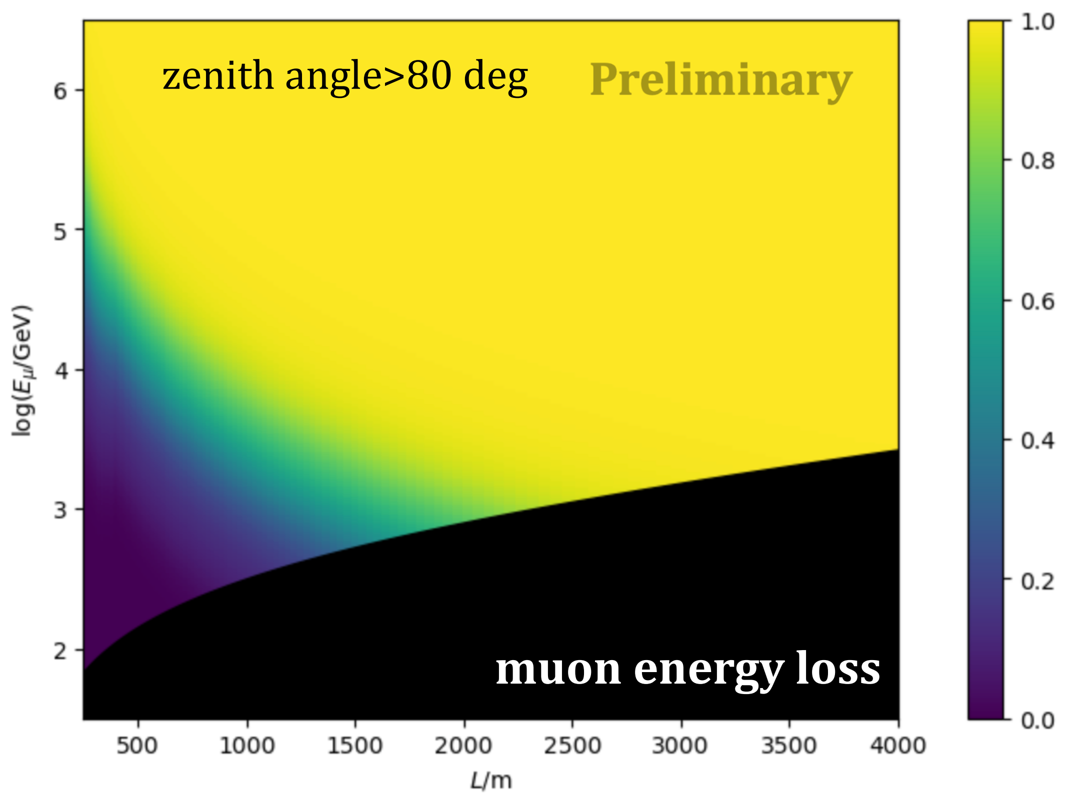
- Geant4: simulating particle interactions inside the array
- Opticks: an open source project that accelerates Geant4 based optical photon simulations
  - at least **11 times** faster than using Geant4 only
- CRMC: hadronic interactions above 100 TeV

Morphology



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

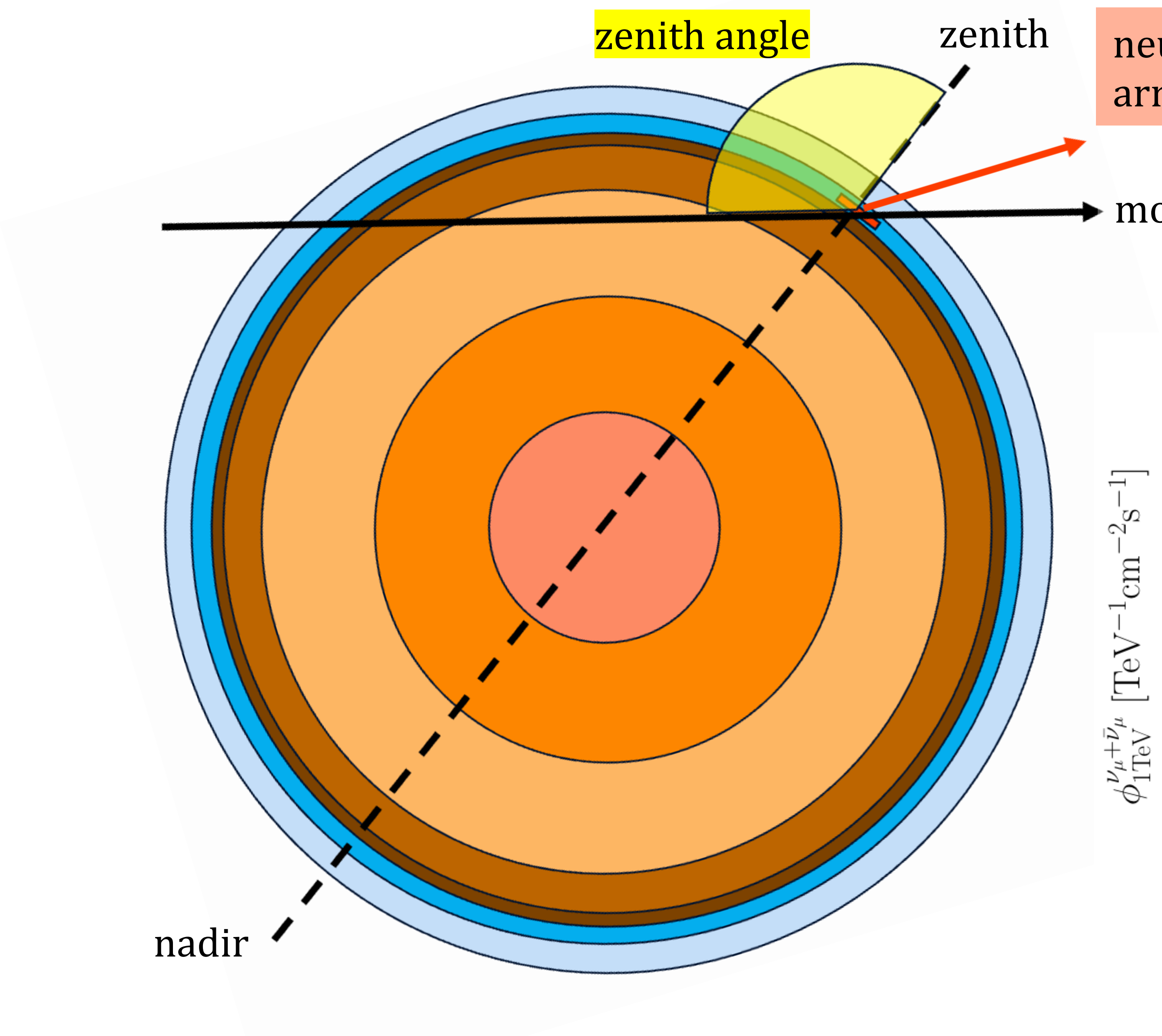
Detection Efficiency (muon-tracks)

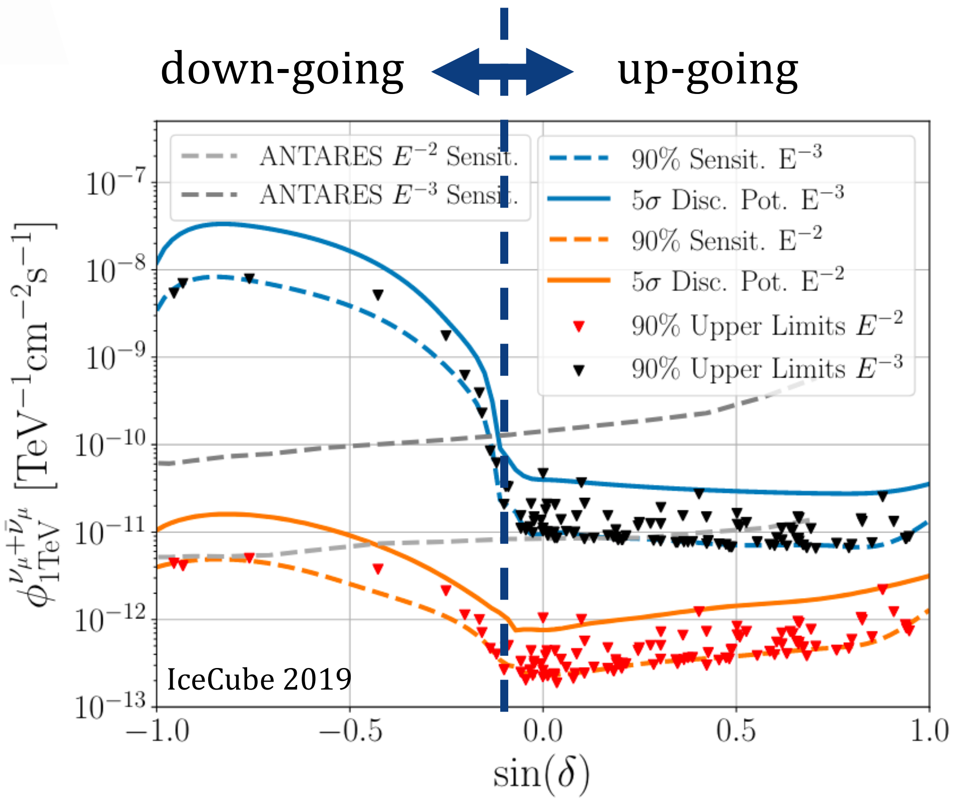


The detection efficiency for up-going muon-tracks.
We adopt the following **event selection criteria**:

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

Upgoing Tracks



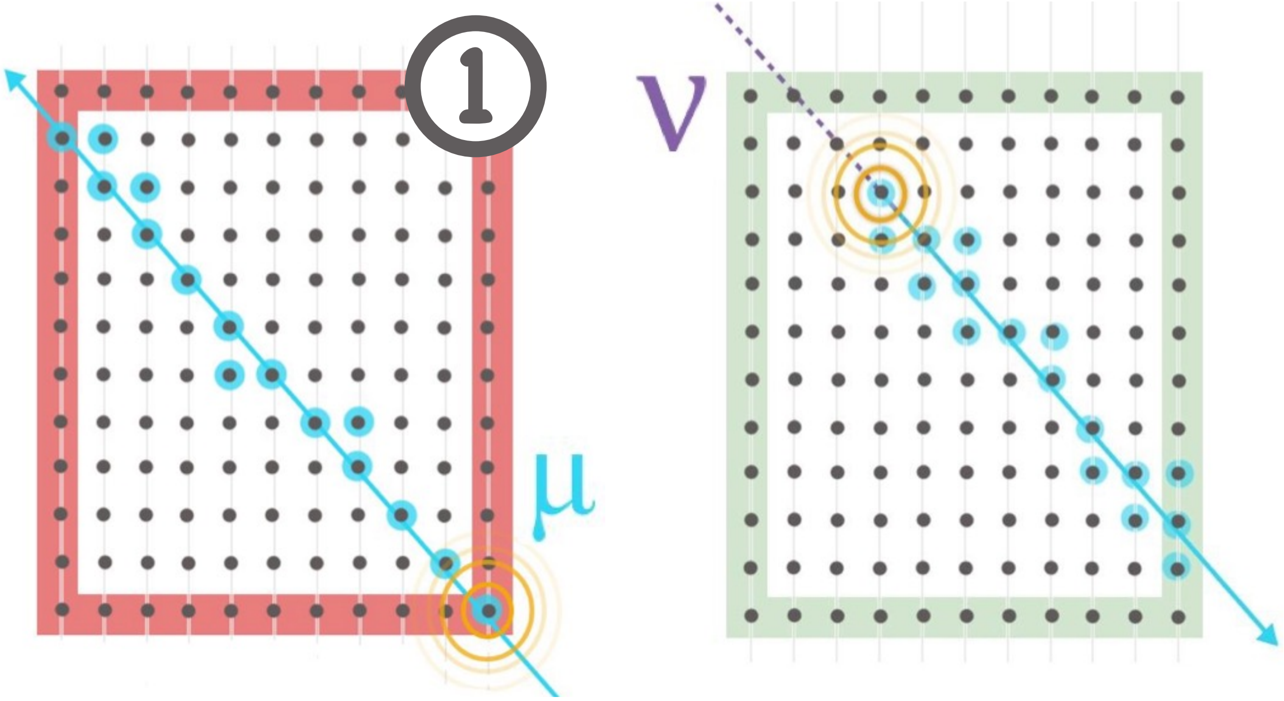


Upgoing Tracks

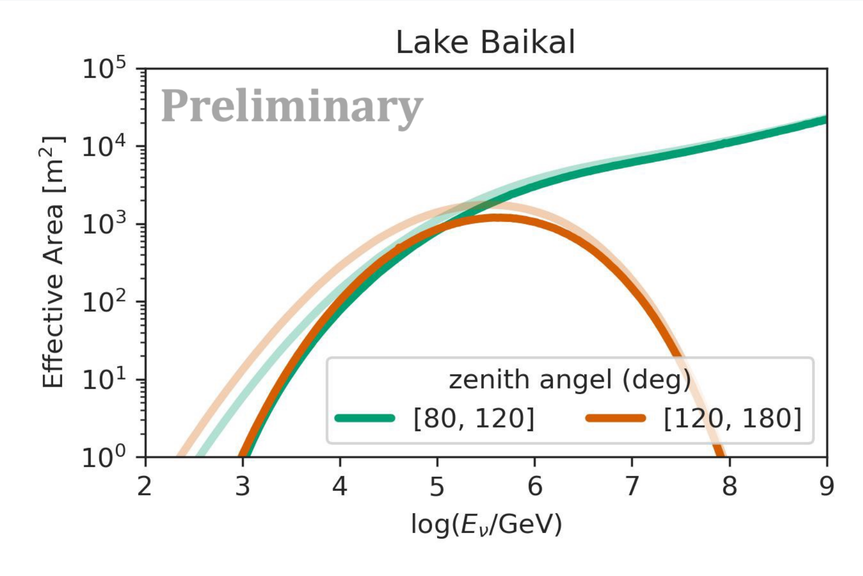
Through-going muon-tracks

Event selection criteria:

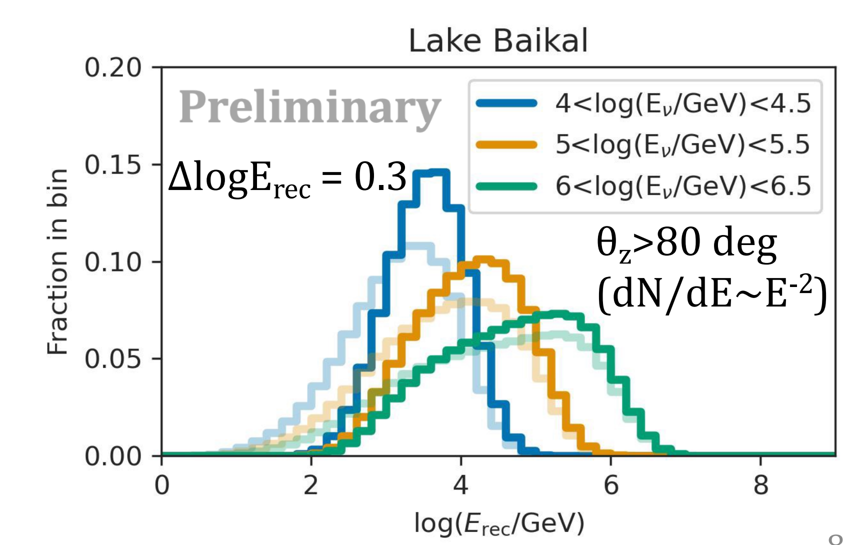
- number of PMT hit (N_{hit}) ≥ 7
- N_{PE} ≥ 1 for each hit
- total N_{PE} ≥ 21
- zenith > 80 degree
- track length > 250 m



Effective Area



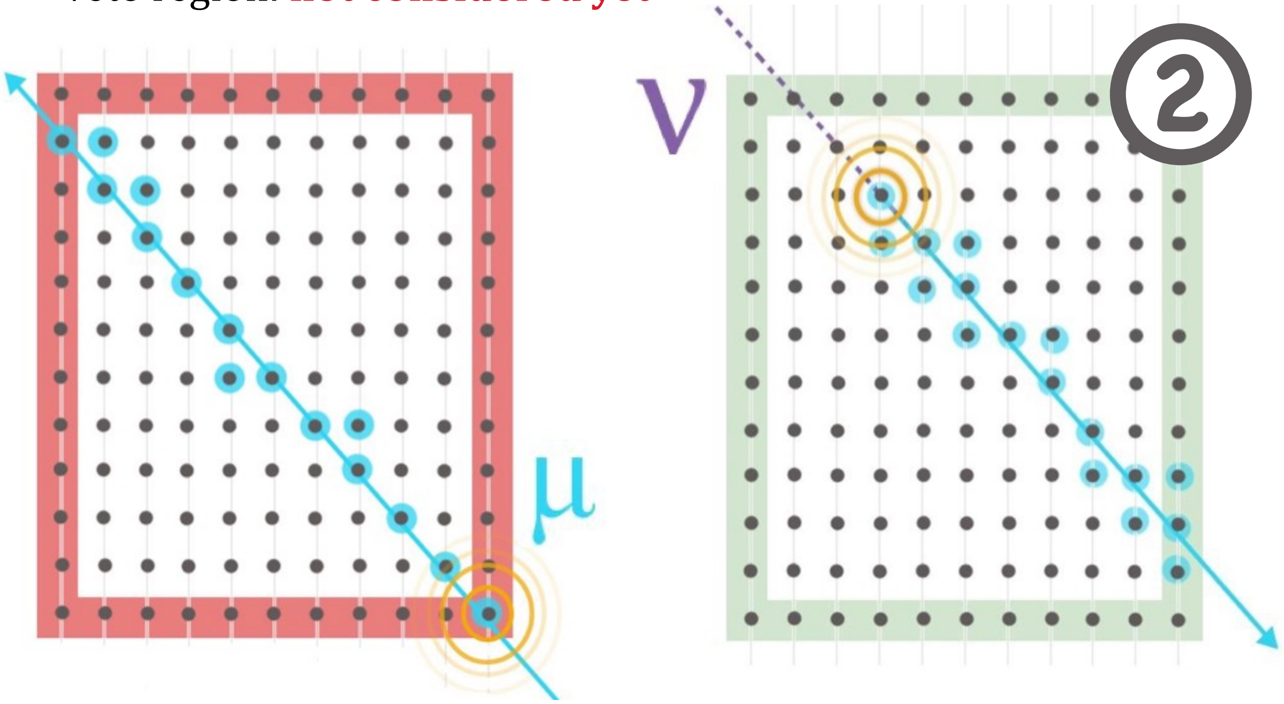
Reconstructed Energy



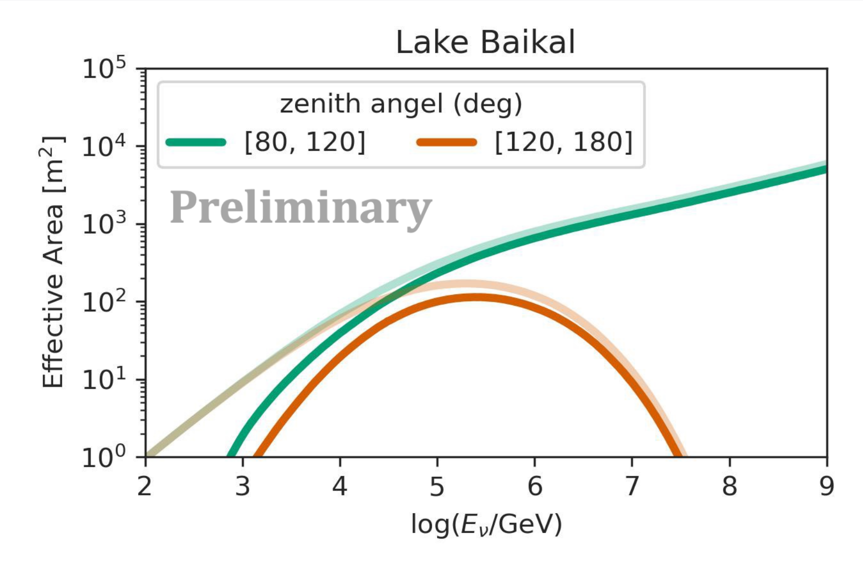
Upgoing Tracks

Starting muon-tracks

Event selection criteria:
- number of PMT hit (N_{hit}) ≥ 7
- $N_{PE} \geq 1$ for each hit
- total $N_{PE} \geq 21$
- zenith > 80 degree
- track length > 250 m
- veto region: **not considered yet**



Effective Area



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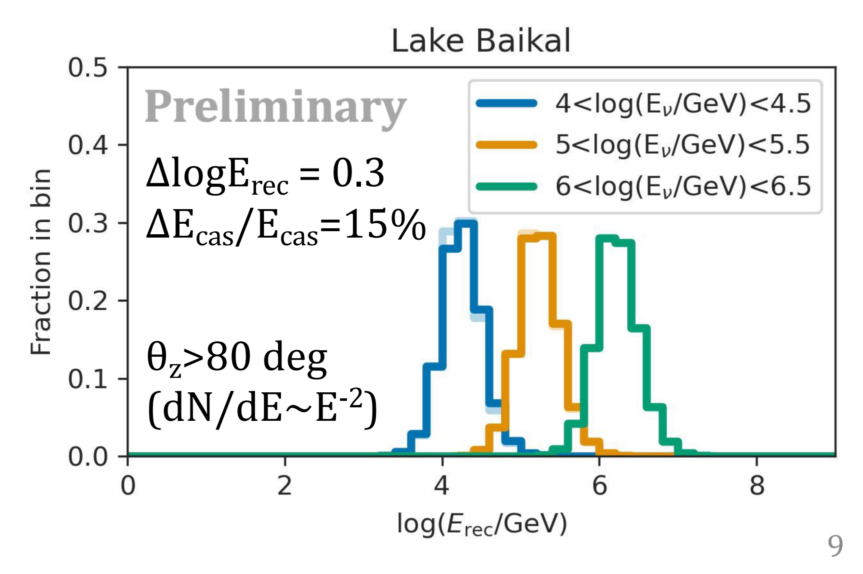


Lake Baikal vs. South China Sea

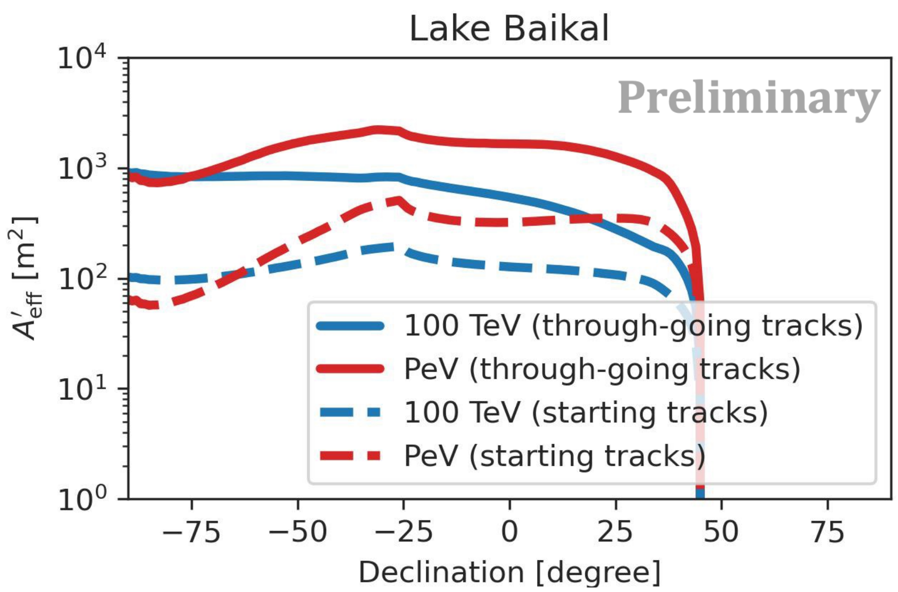
$$A'_{\text{eff}}(E_\nu, \delta_s) = \frac{1}{1\text{ day}} \int_{\theta_z > 80^\circ} A_{\text{eff}}(E_\nu, \theta_z(\delta_s, t))\text{d}t.$$

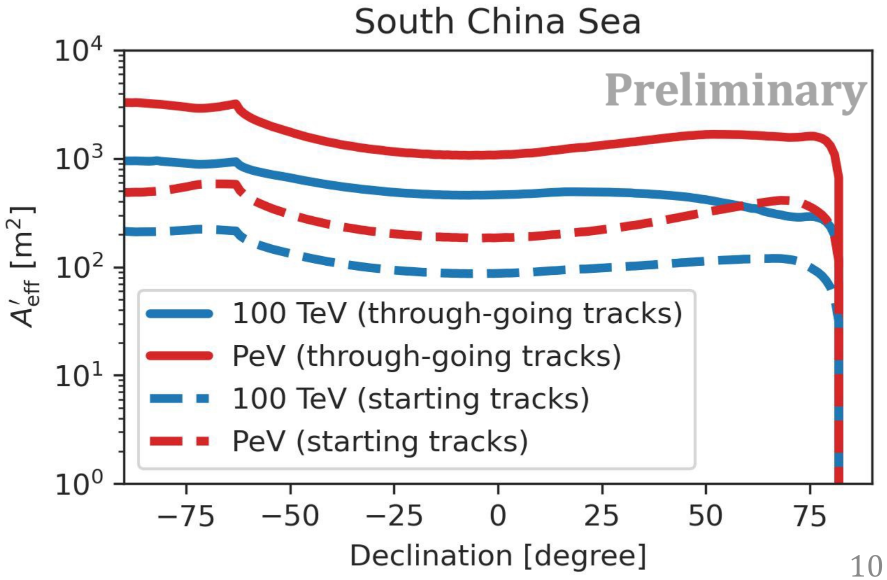
Lake Baikal

- Depth: 500-1360 m
- Larger effective area for the sources with declination angles from -50 degree to 5 degree, especially for the Galactic center.

South China Sea

- Depth: 2560-3420 m
- Larger effective area for the sources with declination angles above 20 degree.
- The observable region (for up-going events) covers most of LHAASO field of view.





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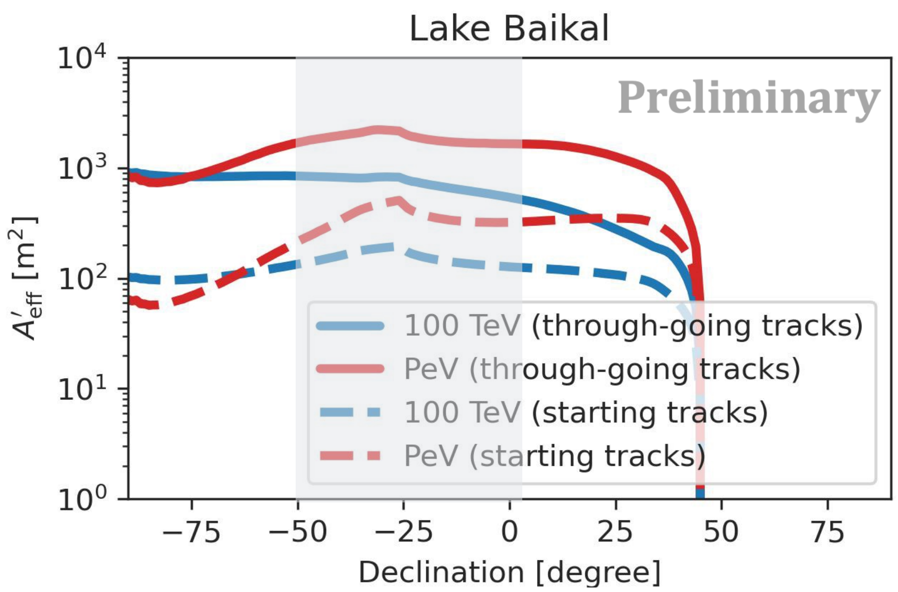
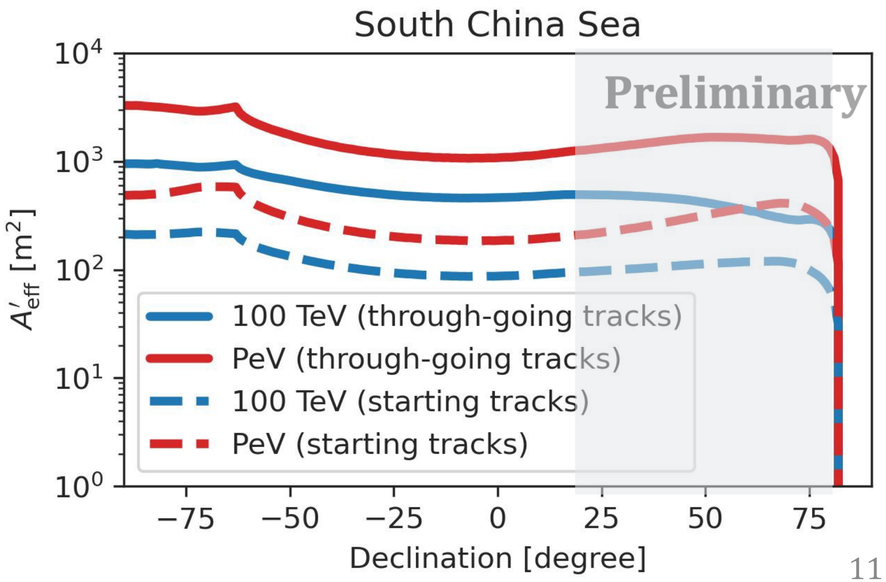




Prospects for Detecting Diffuse Neutrinos

Background

- Atmospheric muon neutrinos (MCEq)

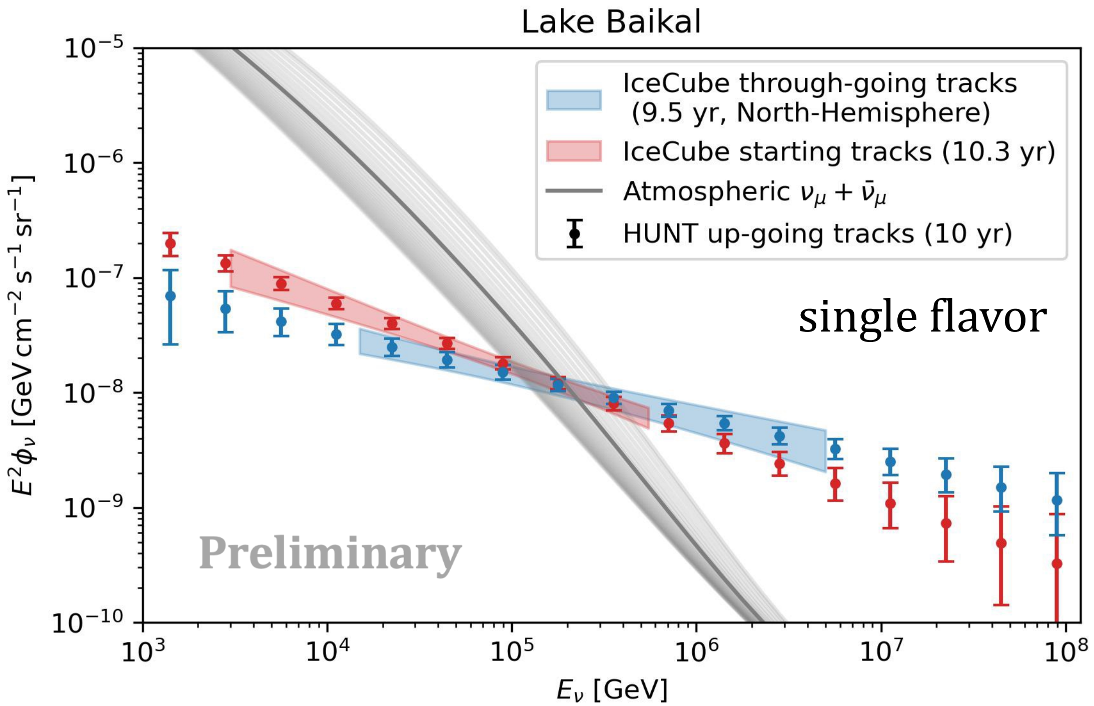
Signal

- Diffuse astrophysical muon neutrinos

Binned Likelihood

- $L = \prod e^{-n_s S_i - n_b B_i} (n_s S_i + n_b B_i)^{n_i} / n_i!$
- We approximate the median significance by replacing the data by the corresponding expectation values.

We anticipate detecting the diffuse neutrino flux above 100 TeV at 5σ level in **3 months**.



Prospects for Detecting Galactic Sources

Background

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

Signal (HESS J1702-420A)

- Neutrino energy 50 TeV – 2 PeV
- 2d Gaussian distribution $\sigma = (\sigma_s^2 + \sigma_d^2)^{0.5}$
- Intrinsic extension σ_s = 0.06 deg

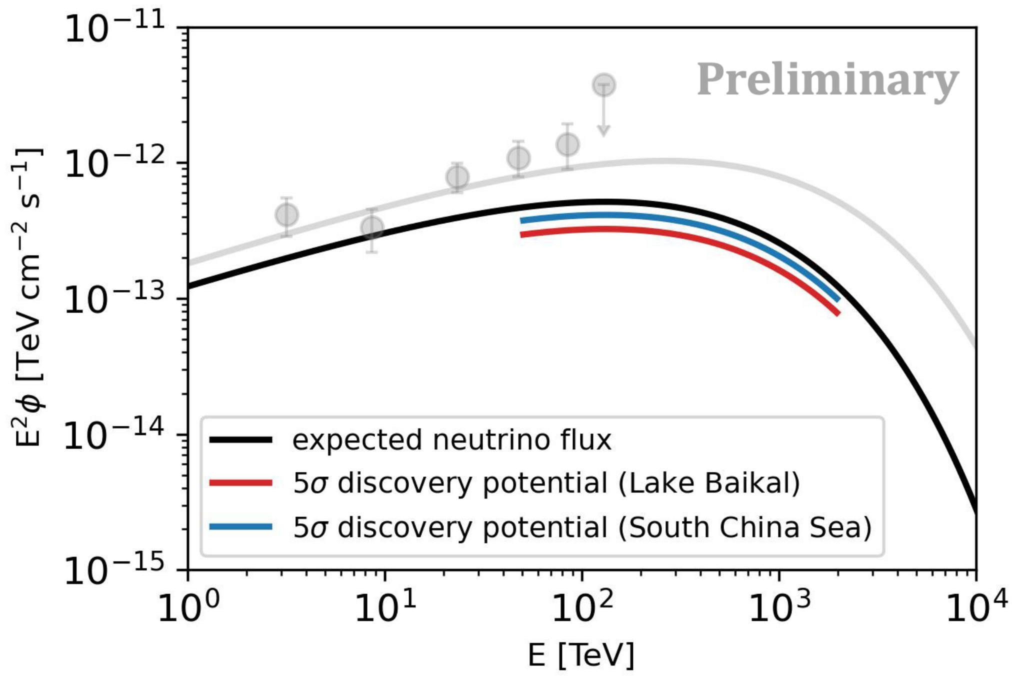
We anticipate detecting the neutrinos (50 TeV - 2 PeV) from HESS J1702-420A at 5σ level with 10 years of operation at

Lake Baikal

- if **63%** of gamma-rays (> 100 TeV) are from π^0 decay

South China Sea

- if **80%** of gamma-rays (> 100 TeV) are from π^0 decay



Detector angular resolution σ_d is assumed to be

- 0.2 deg for through-going tracks
- 0.4 deg for starting tracks

Pathfinder Experiment

Experimental Site

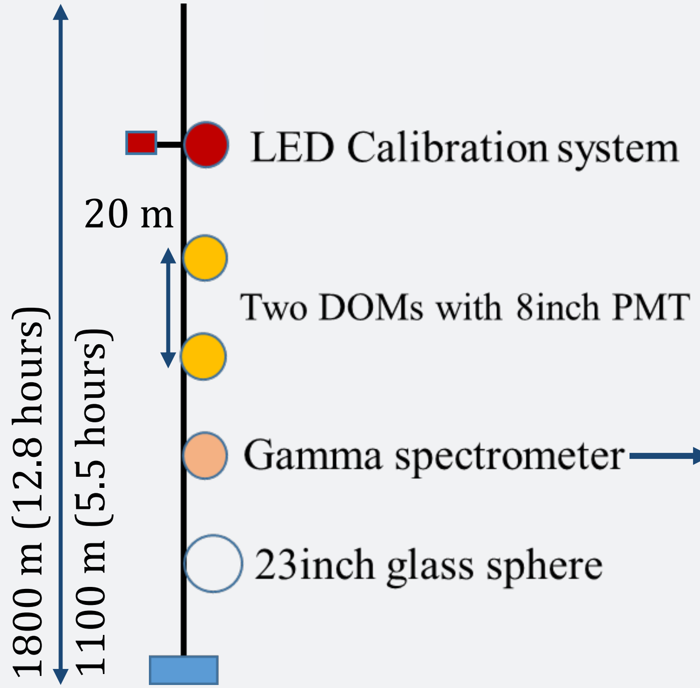
- The water of Xisha Islands in South China Sea

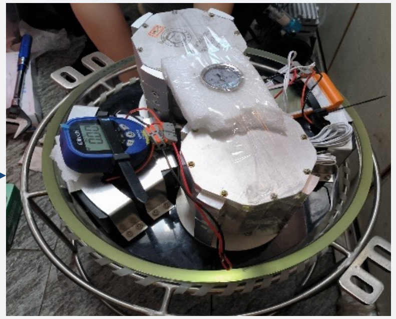
Experimental Objectives

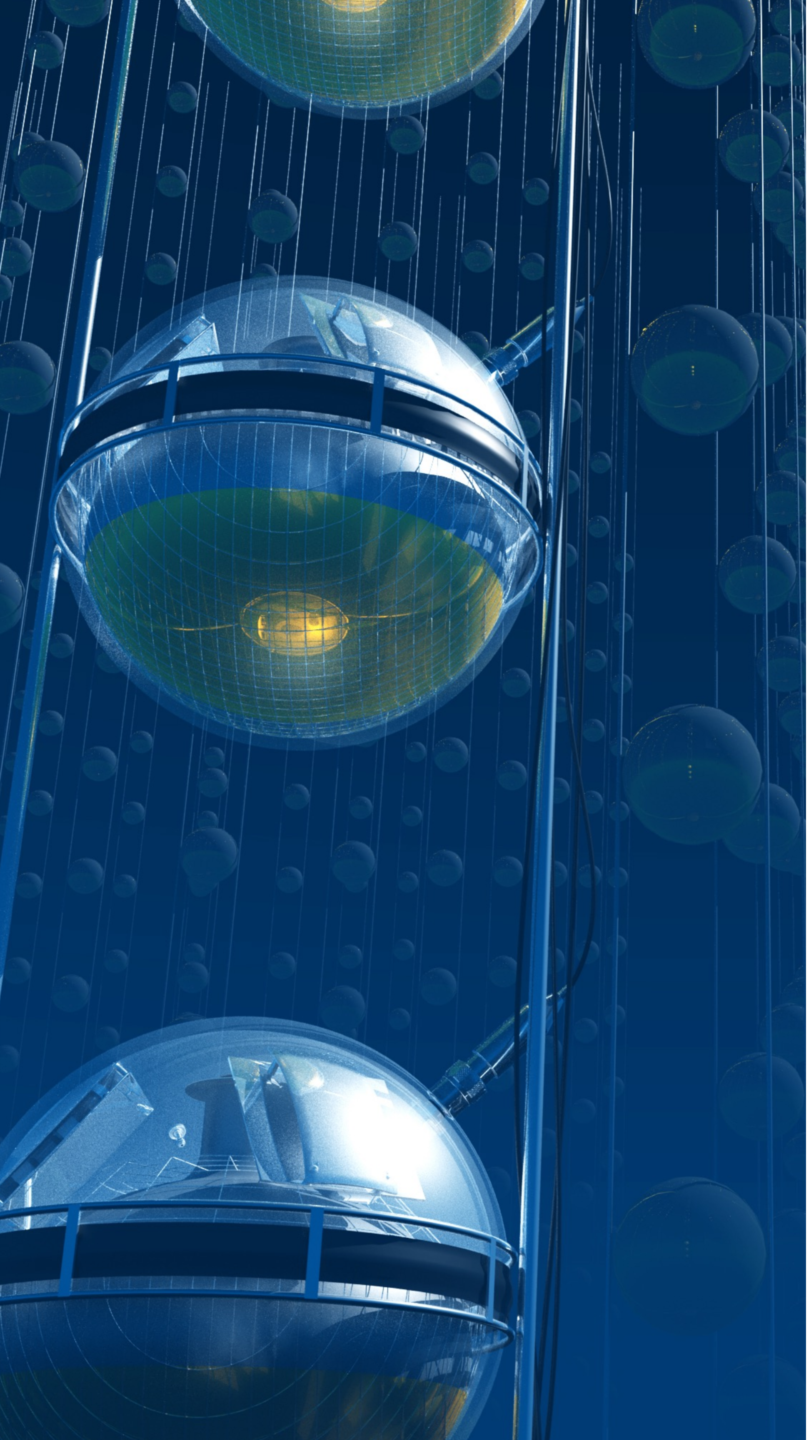
- Test of long-distance LED calibration system
  - ✓ Time resolution 0.4 ns for bright pulses
- Pressure resistance test of 23-inch glass sphere
- In-situ measurement of gamma ray background
  - ✓ The radioactivity for ^{40}K and ^{212}Pb

Scintillation Crystal Gamma Spectrometer			
Depth [m]	Radionuclide	Channel 0 [Bq/L]	Channel 6 [Bq/L]
1800	^{40}K(1460 keV)	15.1 ± 1.3	17.1 ± 0.1
1100		14.8 ± 2.8	19.4 ± 2.3
CZT Gamma-ray Spectrometer			
Depth [m]	Radionuclide	Channel 0 [Bq/L]	Channel 2 [Bq/L]
1800	^{212}Pb(238.6 keV)	1.2 ± 0.2	0.9 ± 0.2
1100		0.97 ± 0.4	1.02 ± 0.3

Pathfinder Experiment Apparatus







Summary

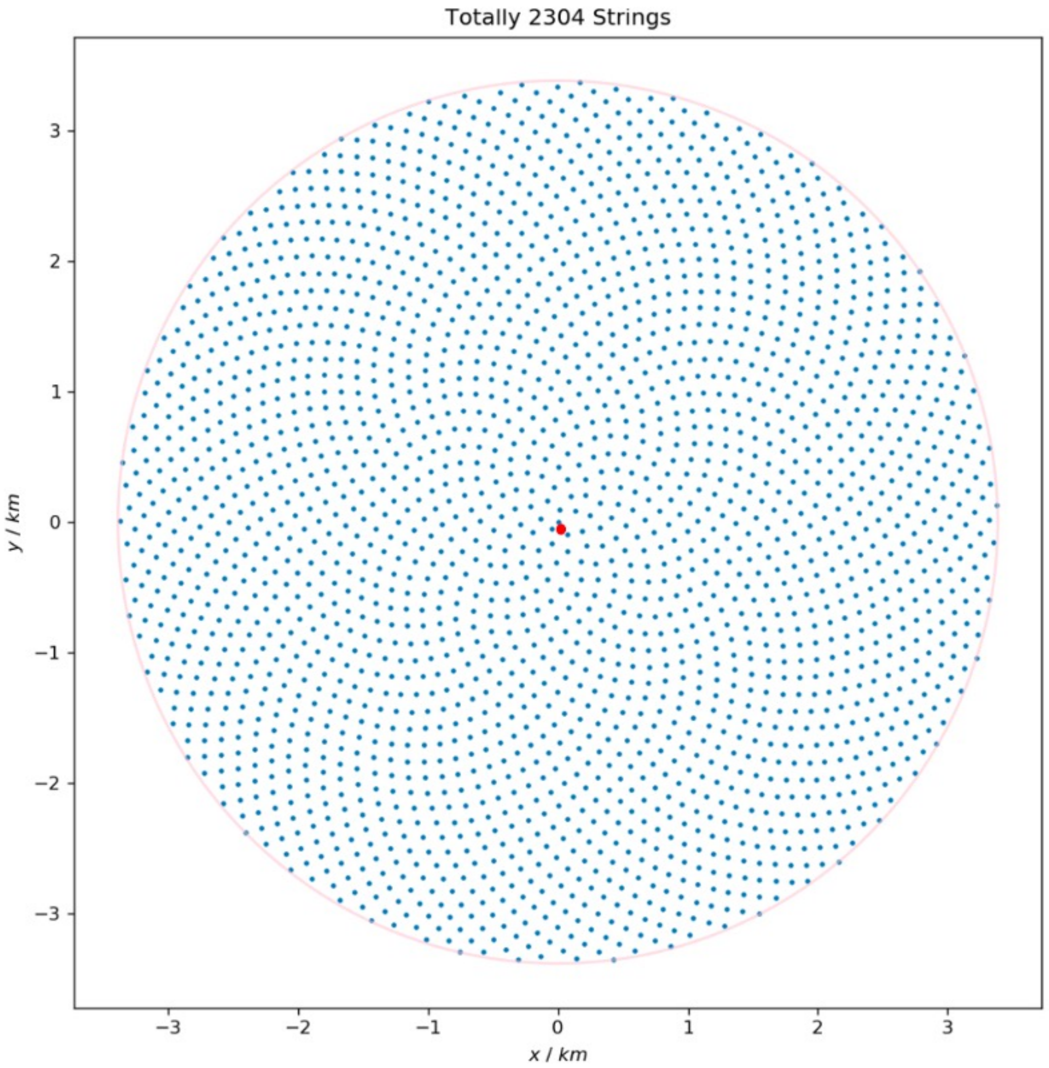
- LHAASO has discovered tens of PeVatron candidates **waiting for the identification by high energy neutrino observations.**
- **HUNT** will realize unprecedented potential in discovering single neutrino sources and precise measurement of the spectrum of the diffuse flux of astrophysical neutrinos.
- In the upcoming research, we will consider more details (e.g., noises) in the simulation and optimize the reconstruction algorithm for better performance (e.g., angular resolution).
- In the upcoming phase of the experiment, we will deploy a prototype string into the array of Baikal-GVD.

DOCX

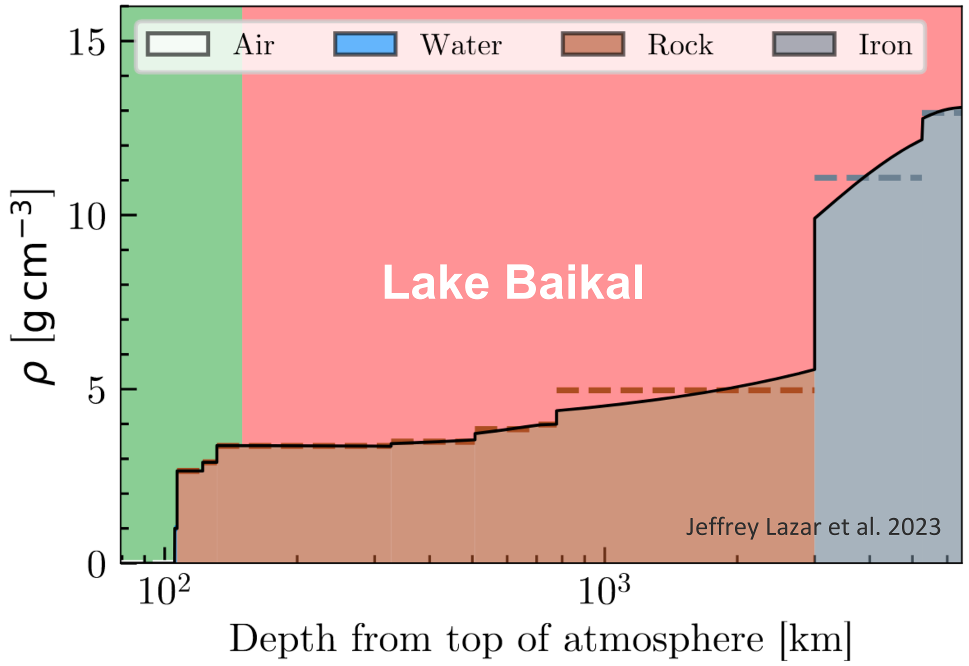
postdoc_HUNT.docx

Welcome to join our simulation and hardware groups!
huangtq@ihep.ac.cn

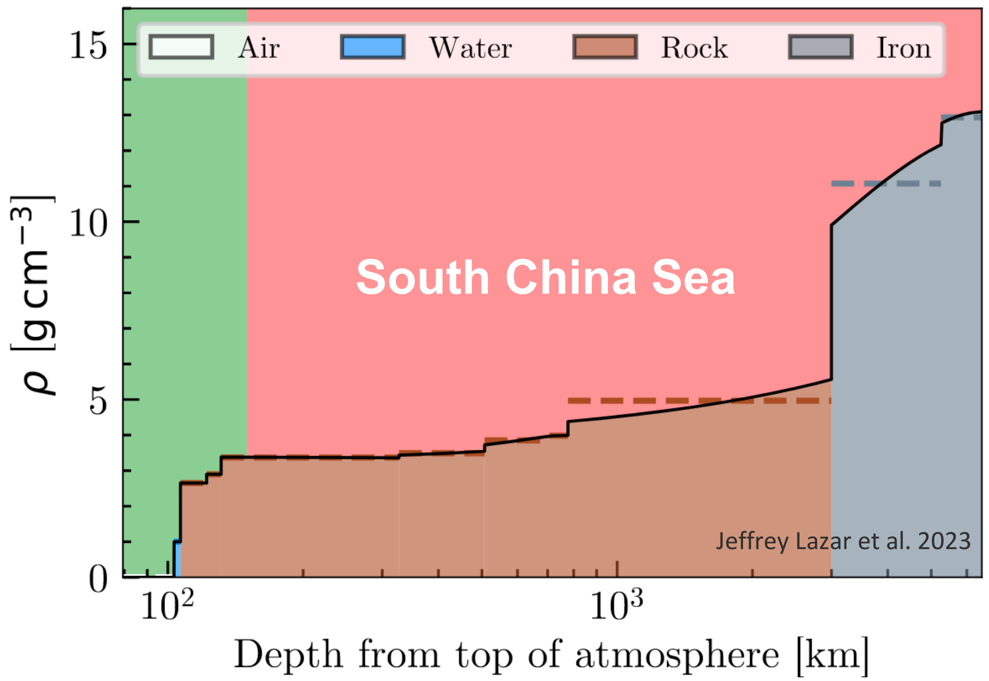
Back Up



Strings uniformly distribute on the Fibonacci lattices in a circular area (36 km^2).



Air
Water
Rock
Iron
Lake Baikal
Jeffrey Lazar et al. 2023
ρ [g cm⁻³]
0
5
10
15
10^2
10^3
Depth from top of atmosphere [km]



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Depth from top of atmosphere [km]

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.

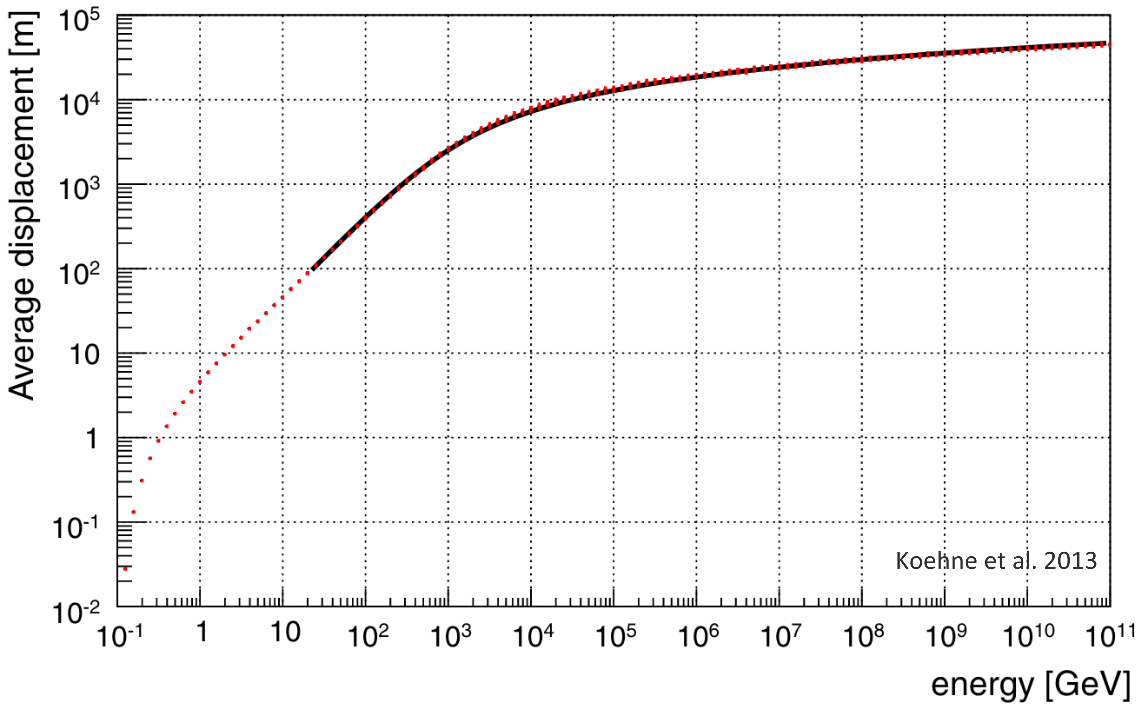
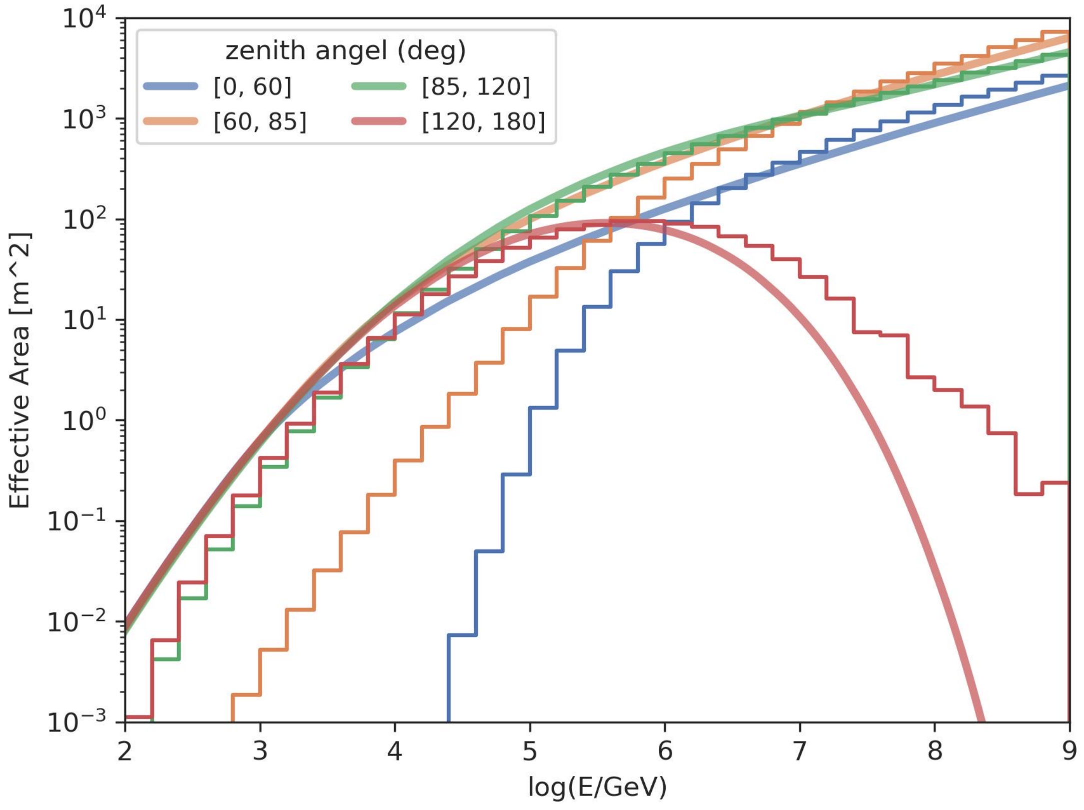
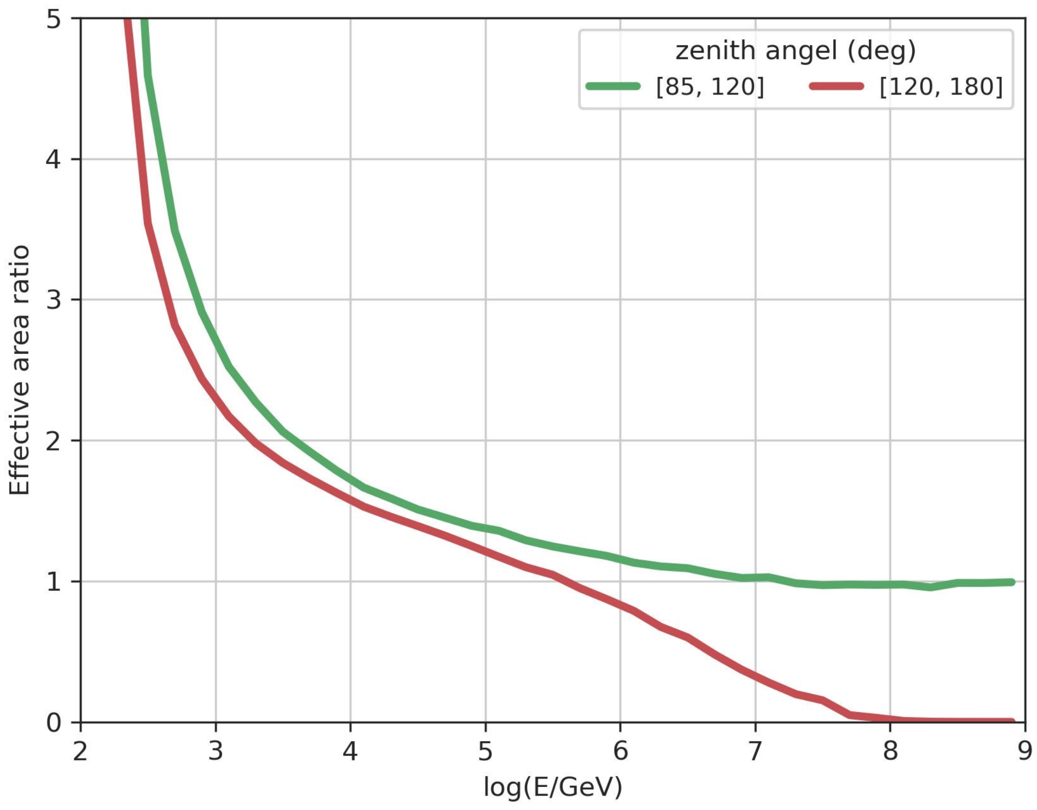


Fig. 40. Fit to the average range of a muon in ice. The range is calculated with PROPOSAL with the initial energy of the particle between 10^{-1} GeV and 10^{11} GeV.

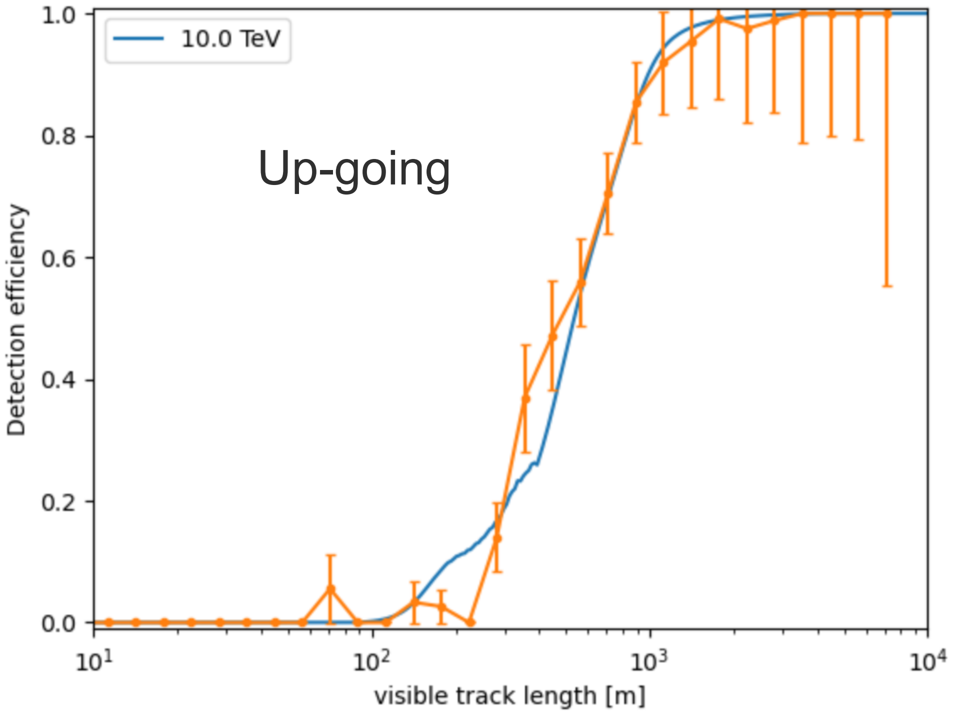
Effective area

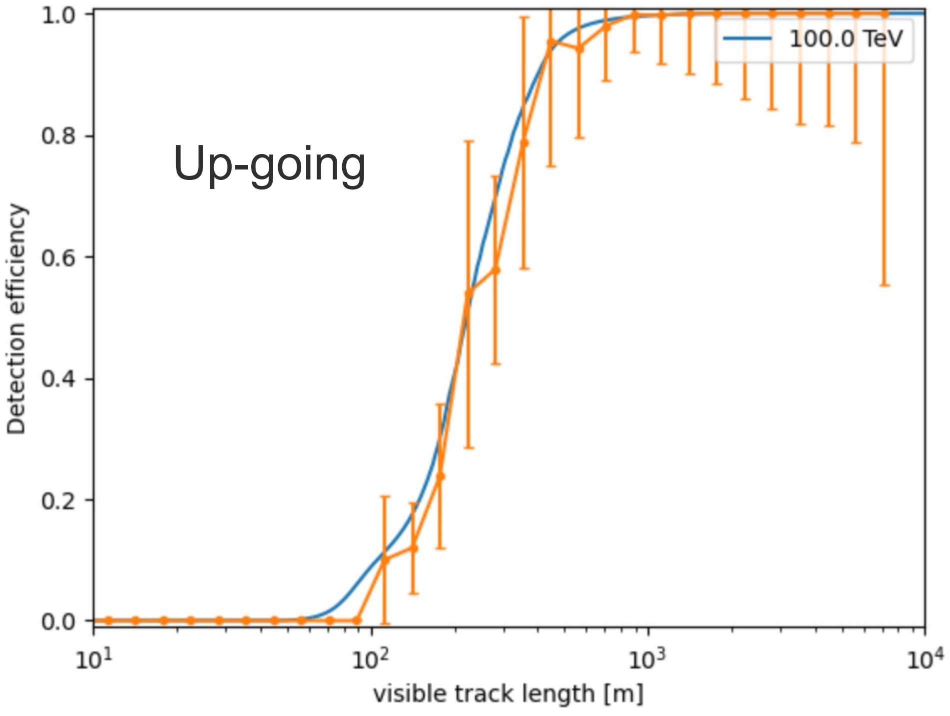
- Simulate IceCbe effective area for through-going track events
- 100% trigger rate





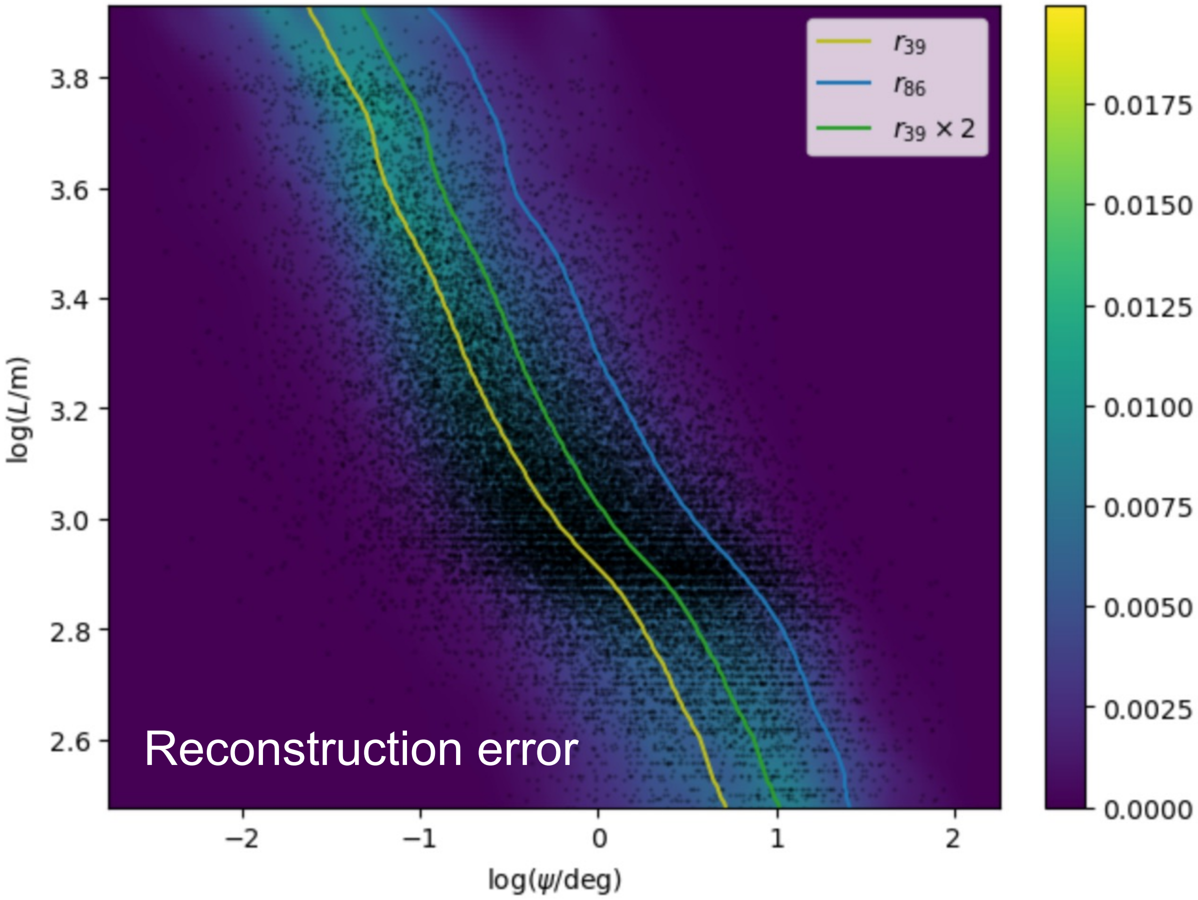
Detection efficiency





Reconstruction

Through-going track events (θ>80 deg)



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 charge number in the i-th OM;
- $t_i - T_i$ is the time residual between the theoretical expectation and the detection.

Reconstruction

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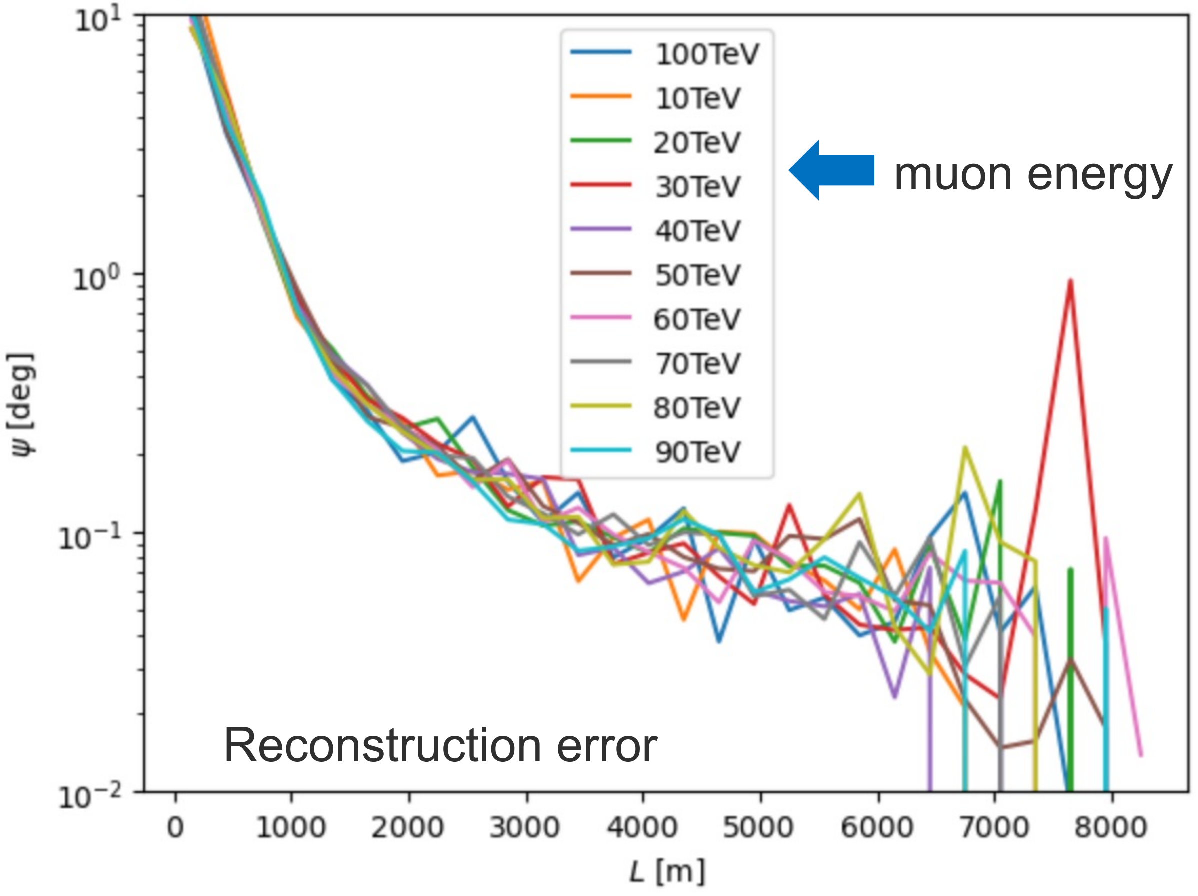

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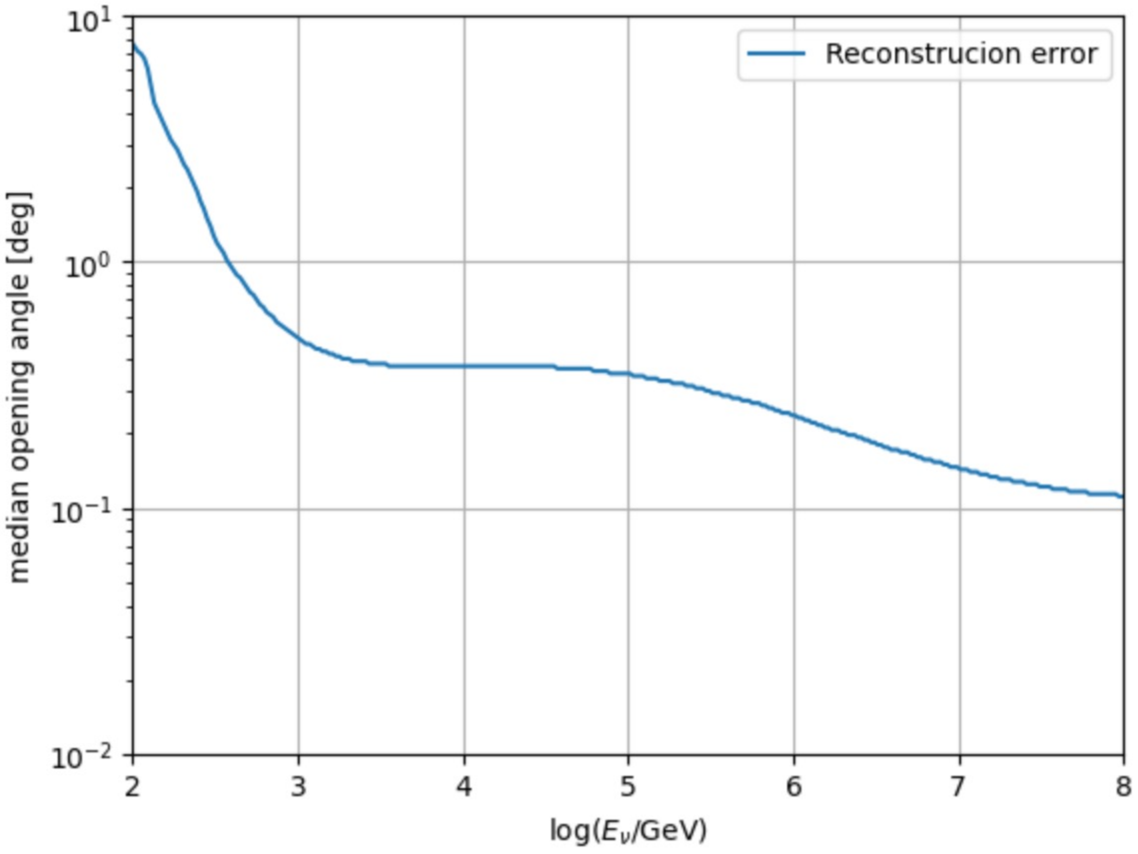

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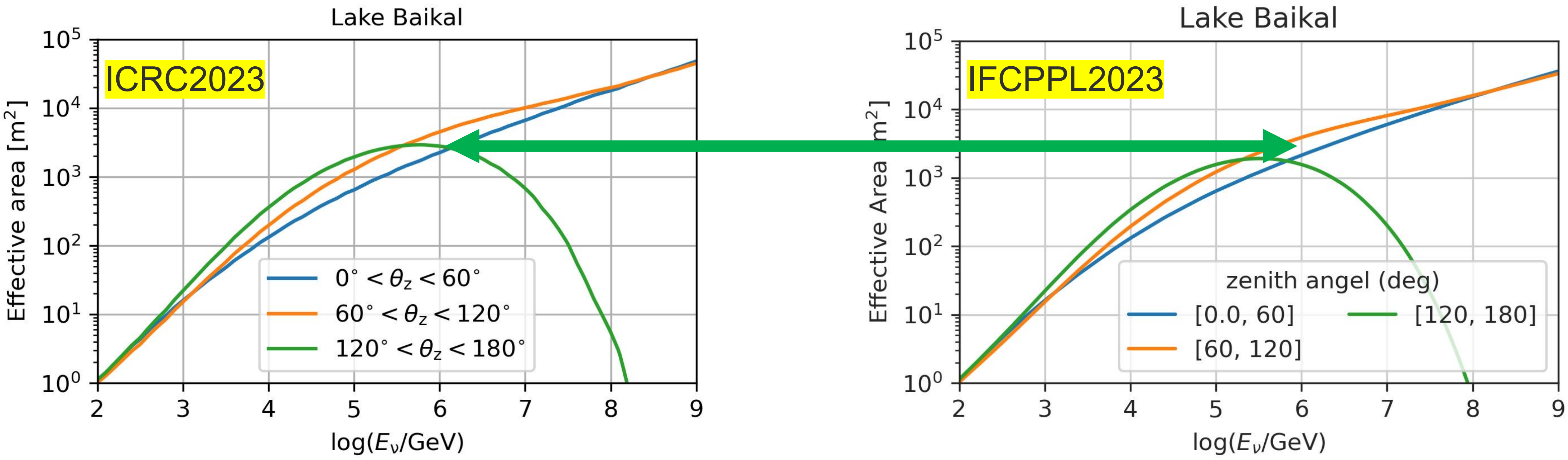
Previous results



Previous results