HUNT

BAIKAL-GVD

Proposal for a next generation neutrino telescope

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Moscow, ISCRA 2025

Outline

1, Motivation

2, HUNT and its potential

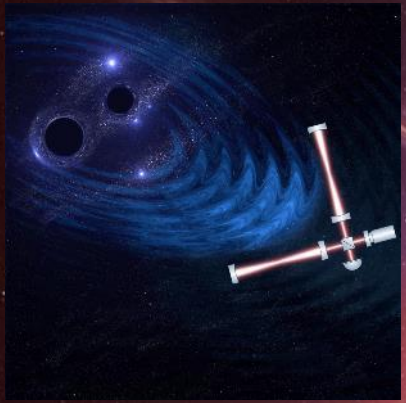
3, R&D of detector

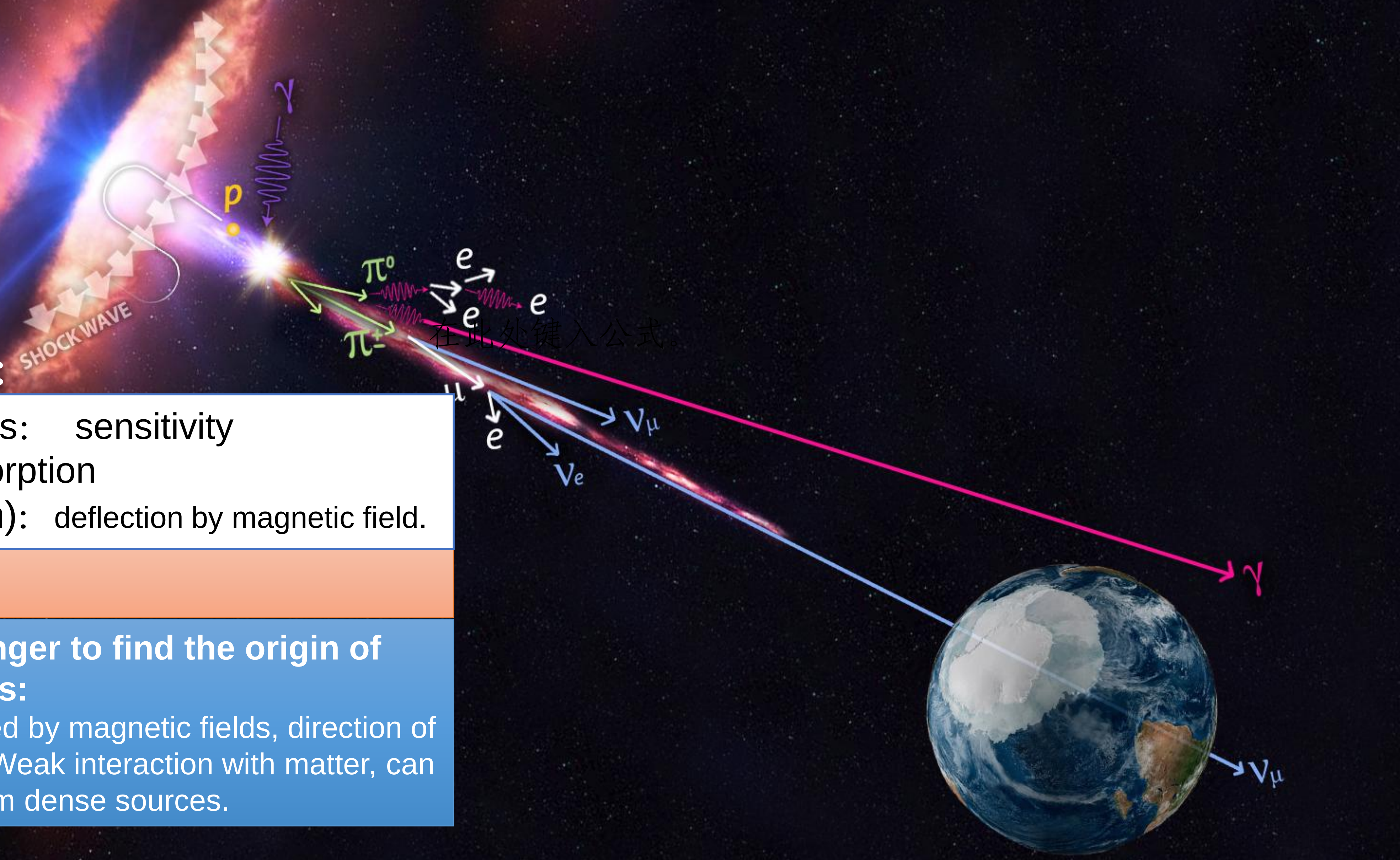
4, Prototype strings

5, Summary

Motivation

Multi-messenger astronomy





Four Messengers:

1. Gravitational wavers: sensitivity
2. **Gamma-ray**: absorption
3. **Cosmic ray**(proton): deflection by magnetic field.

4. Neutrino

Almost the only messenger to find the origin of high-energy cosmic rays:

Electrically neutral, unaffected by magnetic fields, direction of arrival points to the source; Weak interaction with matter, can travel far, able to escape from dense sources.

Status | Multi-messenger Astronomy

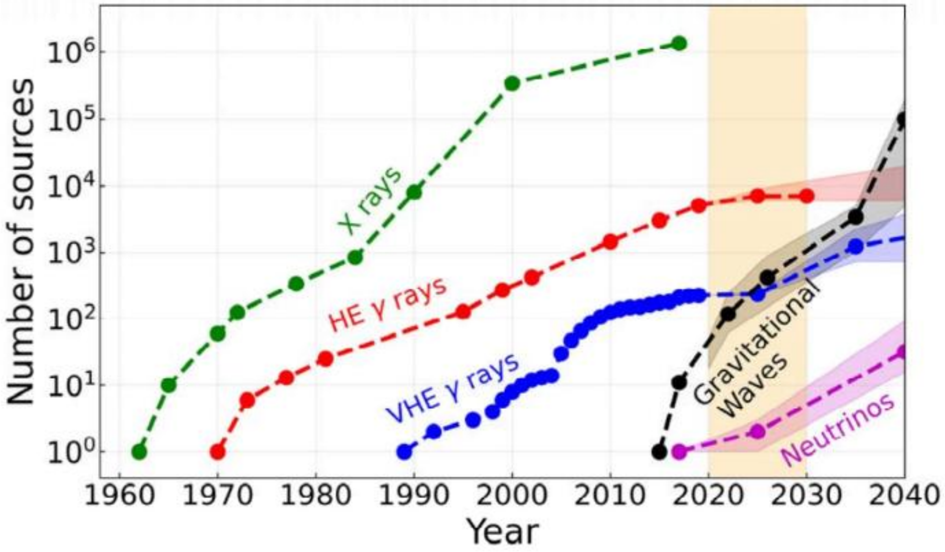
Gravitational Waves nHz mHz kHz

Neutrinos VHE UHE

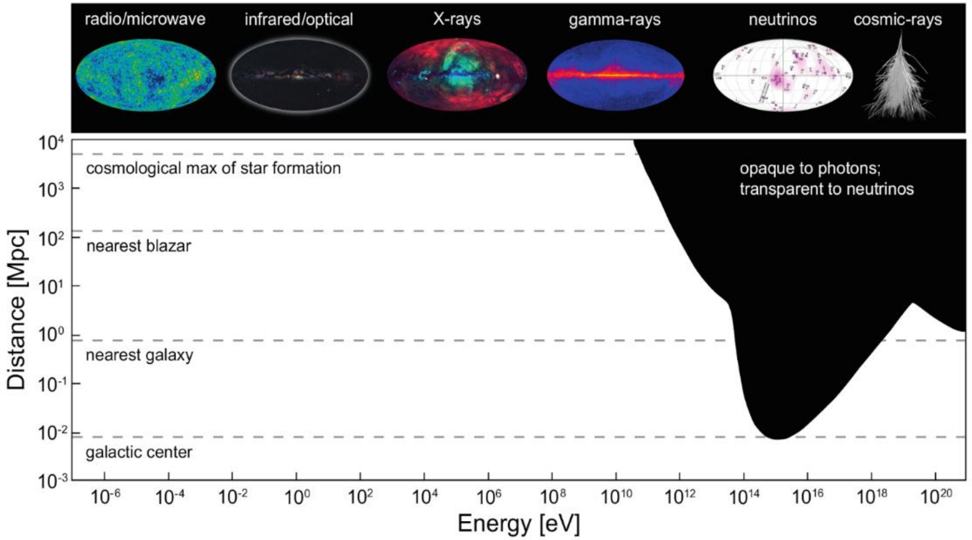
Gamma Rays

Cosmic Rays VHE UHE

- GW and **neutrino** astronomies are just starting and hold the promise of similar growth.



- Opaque to photons, transparent to neutrinos



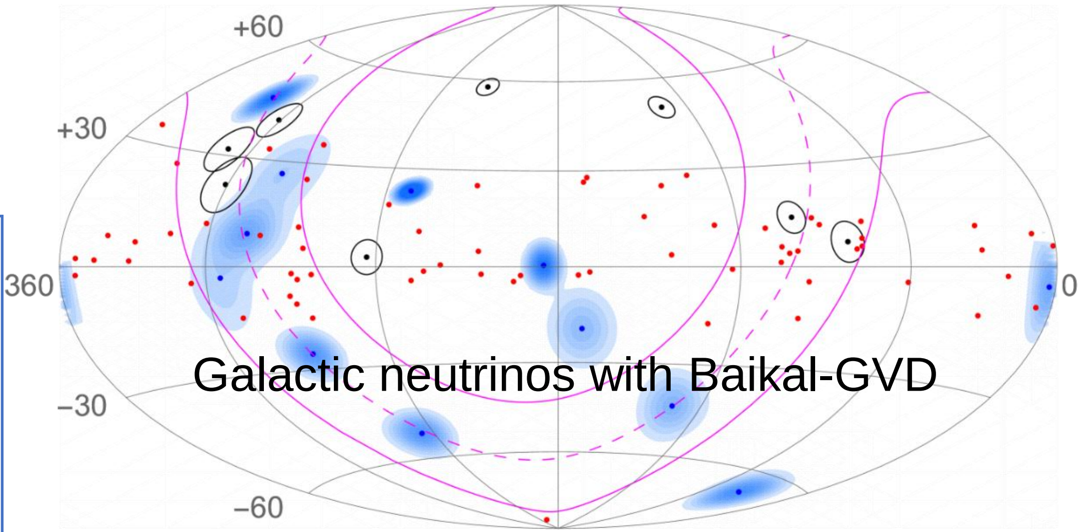
Status | Neutrino Astronomy

M.A. Markov, Seminar at JINR, Dubna in the middle of the 50th

1960: deep underground and deep underwater detection of high-energy cosmic neutrinos were firstly suggested by **Moisey Markov.**

1976 - Now
- Hawaii（4,500m）: DUMAND
- Mediterranean（3,000m）: ANTARES, KM3NeT
- South Pole（2,500m）: AMANDA, IceCube
- Lake Baikal（1,300m）: NT series, Baikal-GVD ……

1998-2003: **NT200**, Detection principle was verify for the first time.
2013: First high energy neutrino event (290 TeV).
2018 - Now
- Blazar TXS 0506+056(3.5σ)
- NCG1068 (2.9σ – 4.2 σ)
- Diffuse neutrino source in the Milky Way，~4σ.

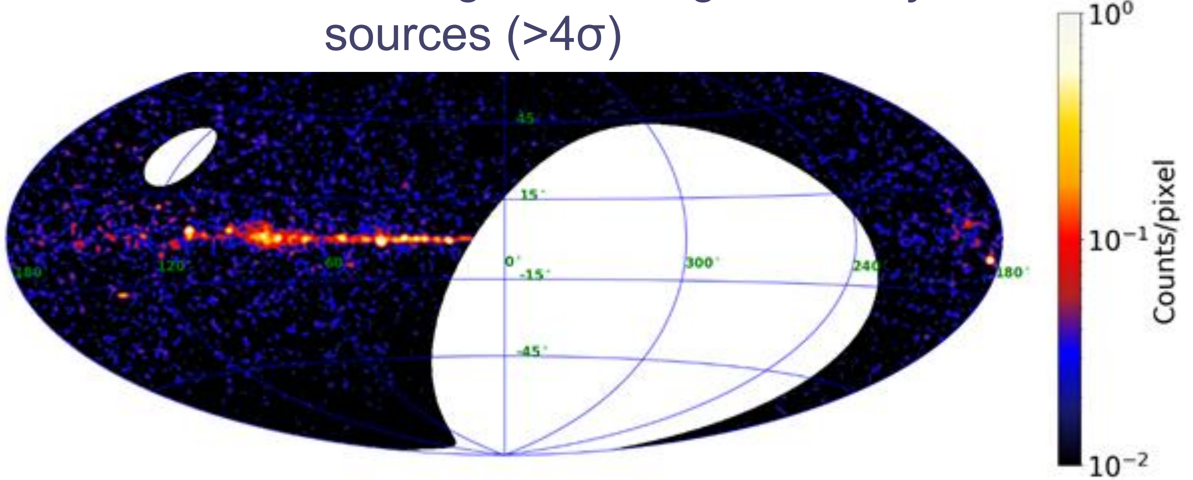


Baikal-GVD Collaboration, Astrophys. J. 982 (2025) 73

5σ is not reached, and the neutrino source is not confirmed!

LHAASO discovered UHE γ sources in the Milky Way

1st LHAASO Catalog: 43 UHE gamma ray sources (>4σ)



Main process:

$$p + p \longrightarrow N(\pi^+ + \pi^- + \pi^0) + X$$

$$p + \gamma \longrightarrow n + \pi^+$$

$$\pi^+ \longrightarrow \nu_\mu + \mu^+ \longrightarrow \nu_\mu + (e^+ + \bar{\nu}_\mu + \nu_e)$$
$$\pi^- \longrightarrow \bar{\nu}_\mu + \mu^- \longrightarrow \bar{\nu}_\mu + (e^- + \nu_\mu + \bar{\nu}_e)$$
$$\pi^0 \longrightarrow 2\gamma$$

$$E_\gamma \approx 10\% E_p$$

$$E_\nu \approx 5\% E_p$$

Two sources of PeV photons:

Leptonic origin Synchrotron radiation produced by relativistic electrons and inverse Compton scattering of low-energy photons No neutrinos

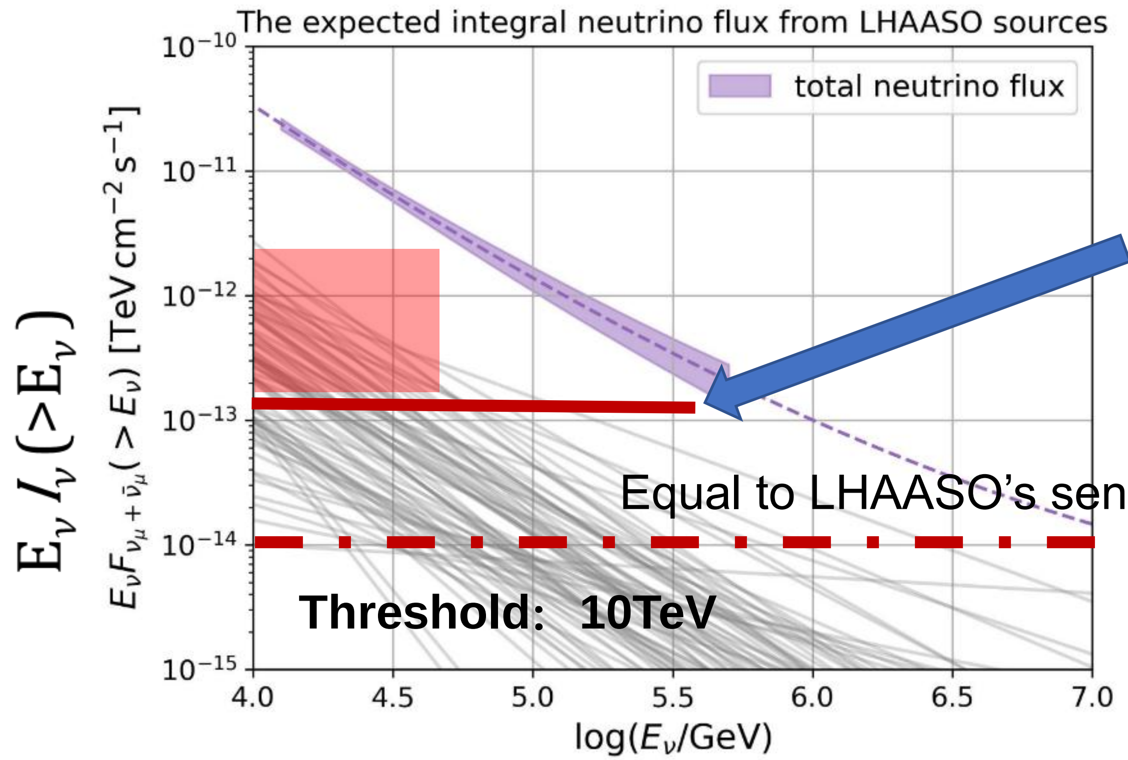
Hadronic origin Interaction of PeV energy cosmic rays with source region matter or photon fields
a large number of neutrinos

- Simultaneous detection: neutrinos and photon signals, can point back to the source.
- Solve the problem of the origin of high-energy cosmic rays!

- LHAASO Collaboration, 2021, Nature, 594, 33.
- LHAASO Collaboration, 2024, ApJS, 271, 25.

HUNT and its potential

Requirement for next generation NT



Integral Sensitivity($E_\nu I_\nu(>E_\nu) = \int_{E_\nu} J_\nu(E_\nu)\, dE_\nu$:

better than 10^{-13} TeV/cm^2/s @10TeV

To observe the neutrino sources in the Milky Way, then we can combine with photon and other data (such as LHAASO)

Grey lines: neutrino flux of 43 LHAASO gamma ray sources.

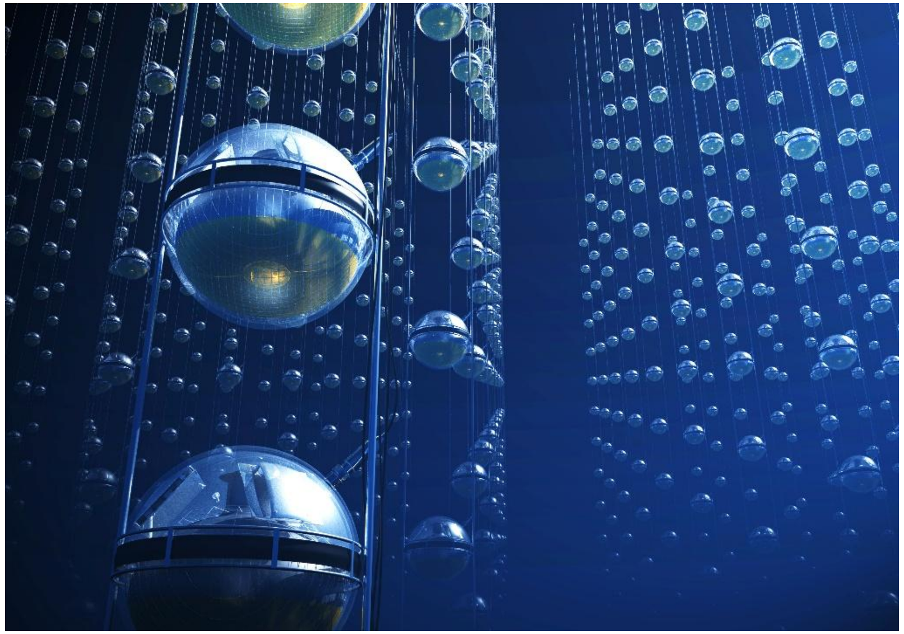
30 times volume of IC！

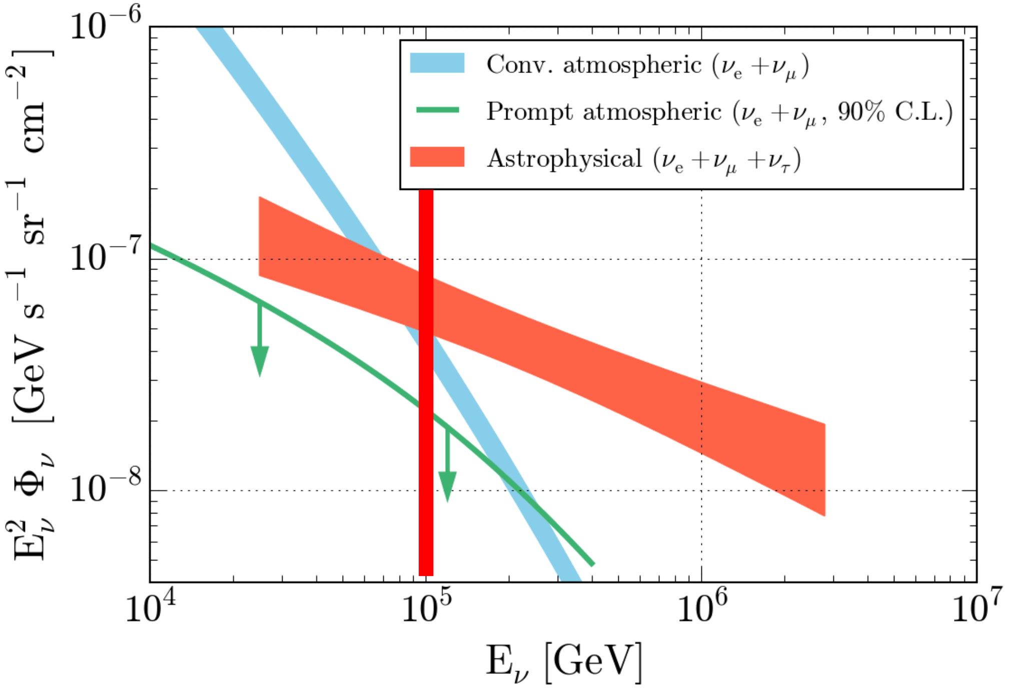
- Candidates of PeV cosmic ray in the Milky Way;
- Lots of neutrino sources in the extragalactic space.

Scientific Goals

High-energy Underwater Neutrino Telescope

- Identifying the **hadronic PeVatrons** in our Galaxy(>100TeV)
- Resolving the high energy neutrino sky
- Understanding the propagation mechanism of high energy cosmic-rays
- Exploring the frontiers of neutrino physics and new physics





Energy spectrum of the astrophysical neutrino flux

Lake Baikal: Unique site for HUNT

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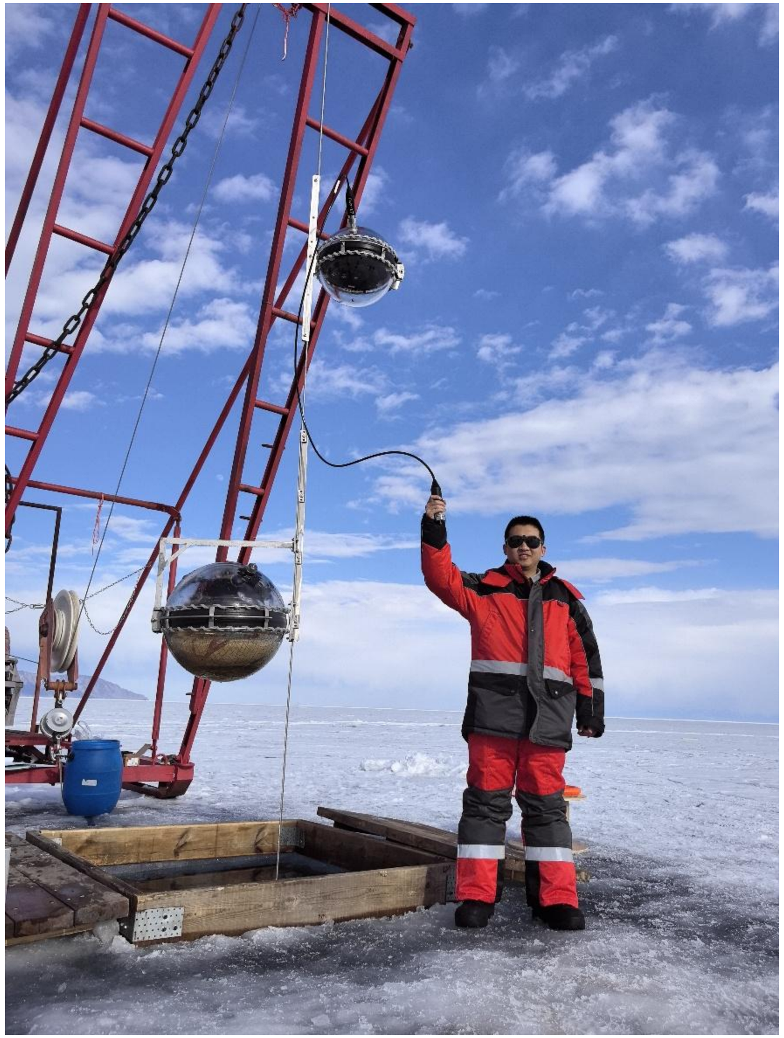
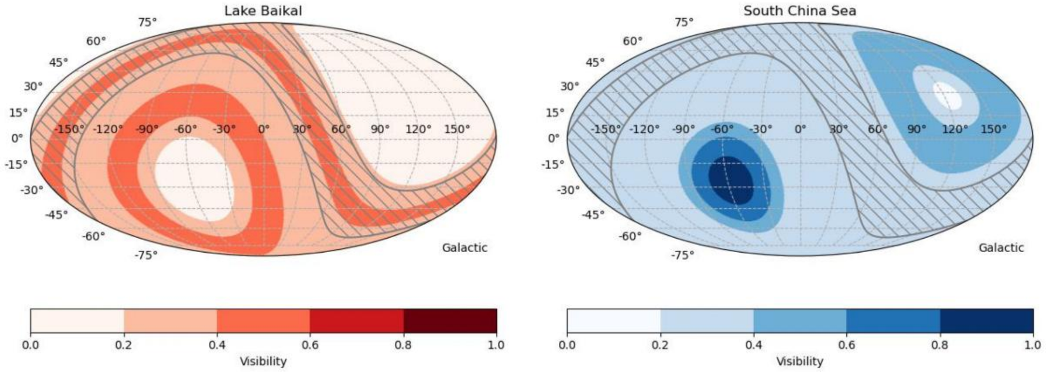


- Very flat lakebed within 100km^2: 1366 $\pm$ 1 m
- Very transparent water
- Very close to shore station: ~4 km
- No high light background.
- Stable ice cover for 7 weeks a year:

Extreme low deployment cost!



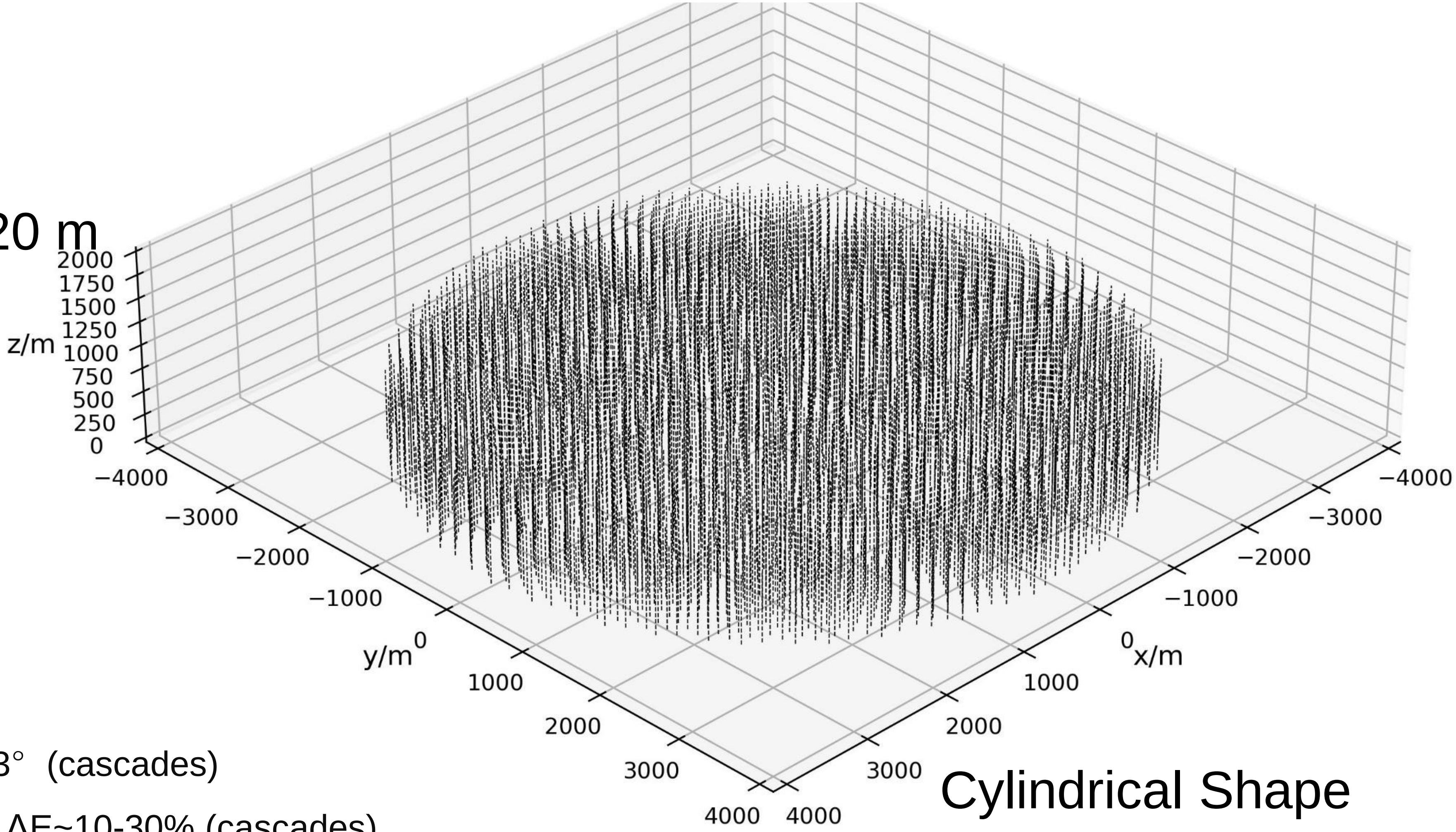
Lake Baikal has better FOV for the center of the Milky Way.

Configuration

HUNT at Lake Baikal (water depth ~ 1300 m)

- 30 km^3
- 2,212 strings

- Height of string: ~720 m
- Radius: ~3.8 km

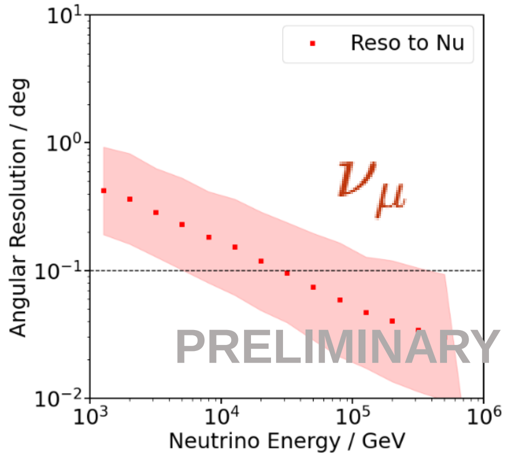


Cylindrical Shape

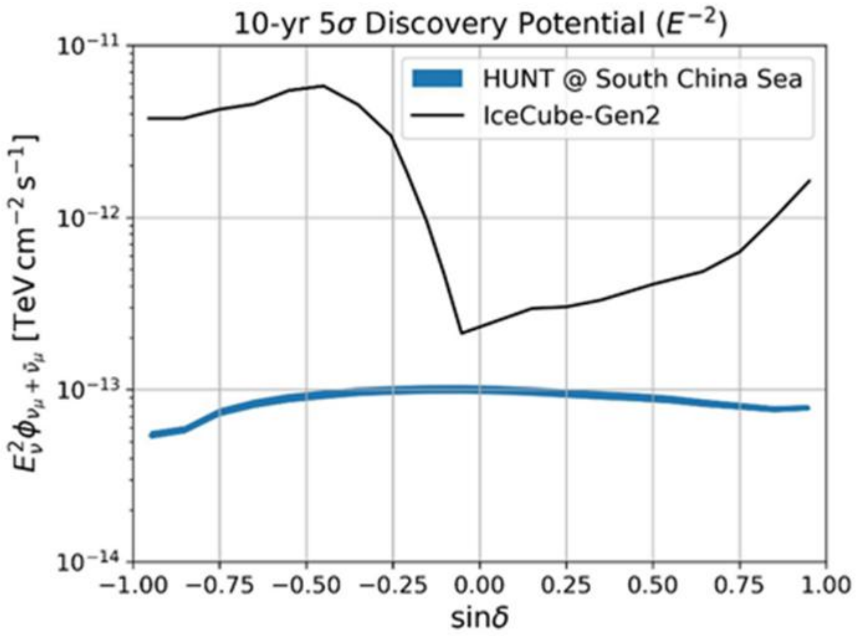
Specifications:

- Angular resolution: ~0.1° (tracks), <3° (cascades)
- Energy resolution: ΔlogE~0.3(tracks), ΔE~10-30% (cascades)

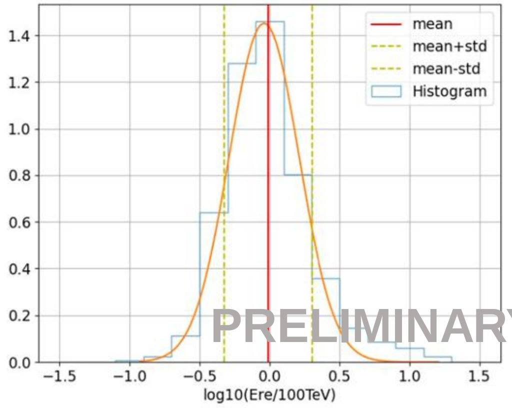
Performance expectation



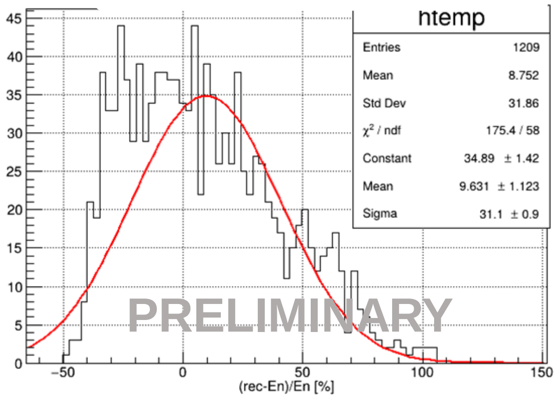
Angle resolution
~0.1⁰@>100TeV



Sensitivity compared with IC2

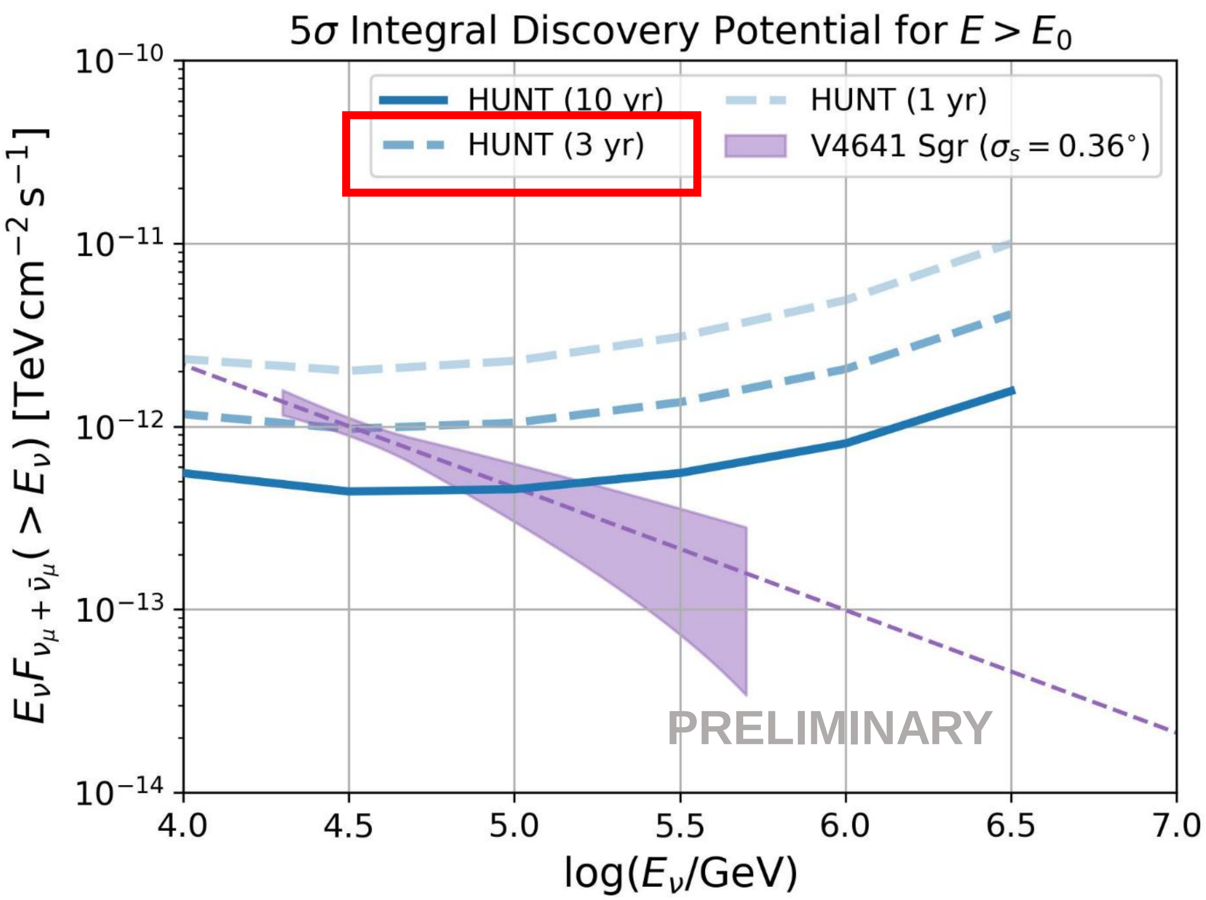


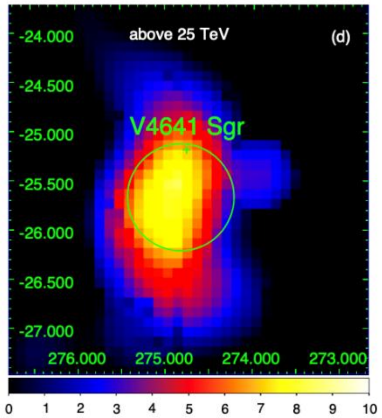
Energy resolution(track)
Δlog(Erec) = 0.27



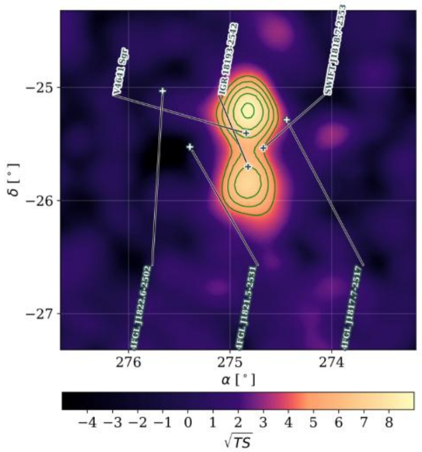
Energy resolution(cascade):
~31%(100-300TeV)

Discovery Potential | Microquasar

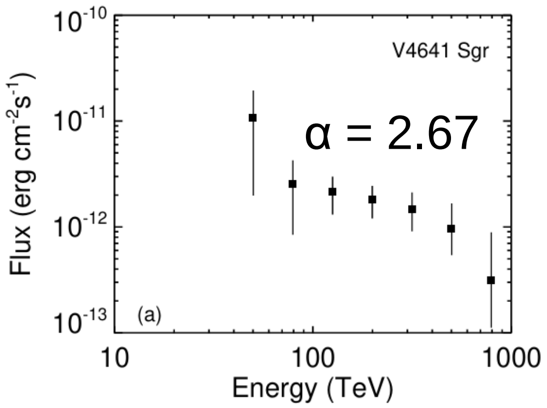


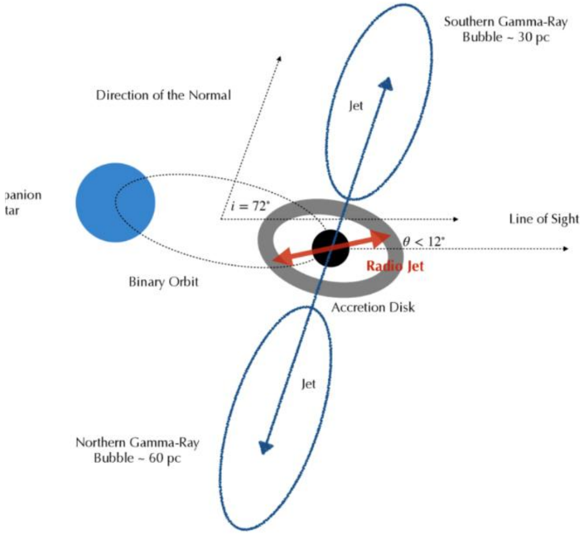


LHAASO, 2024, arXiv:2410.08988

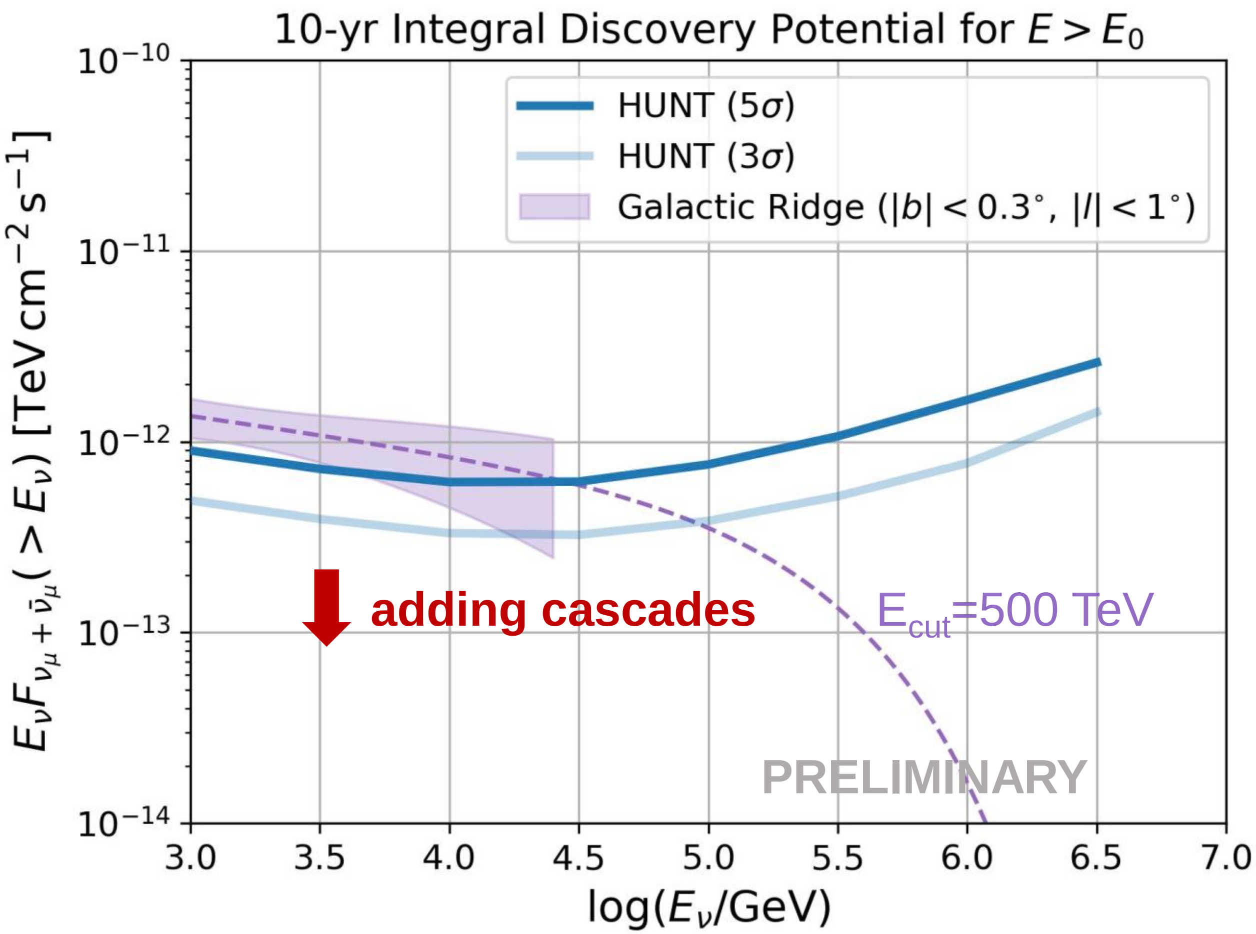


Alfaro R., et al., 2024, Nature

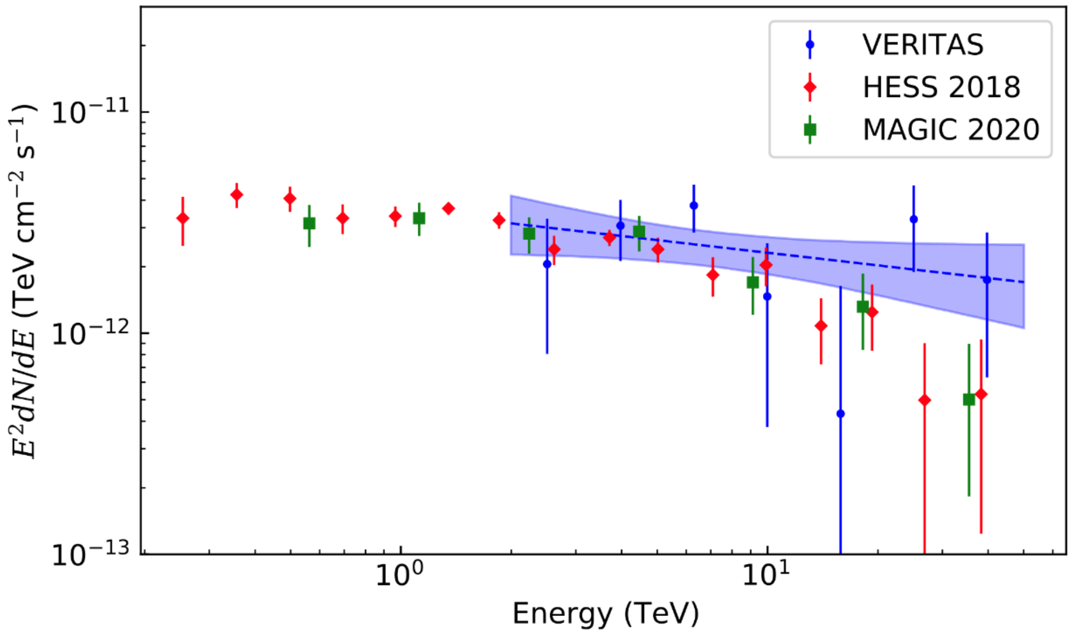




Discovery Potential | Galactic Ridge

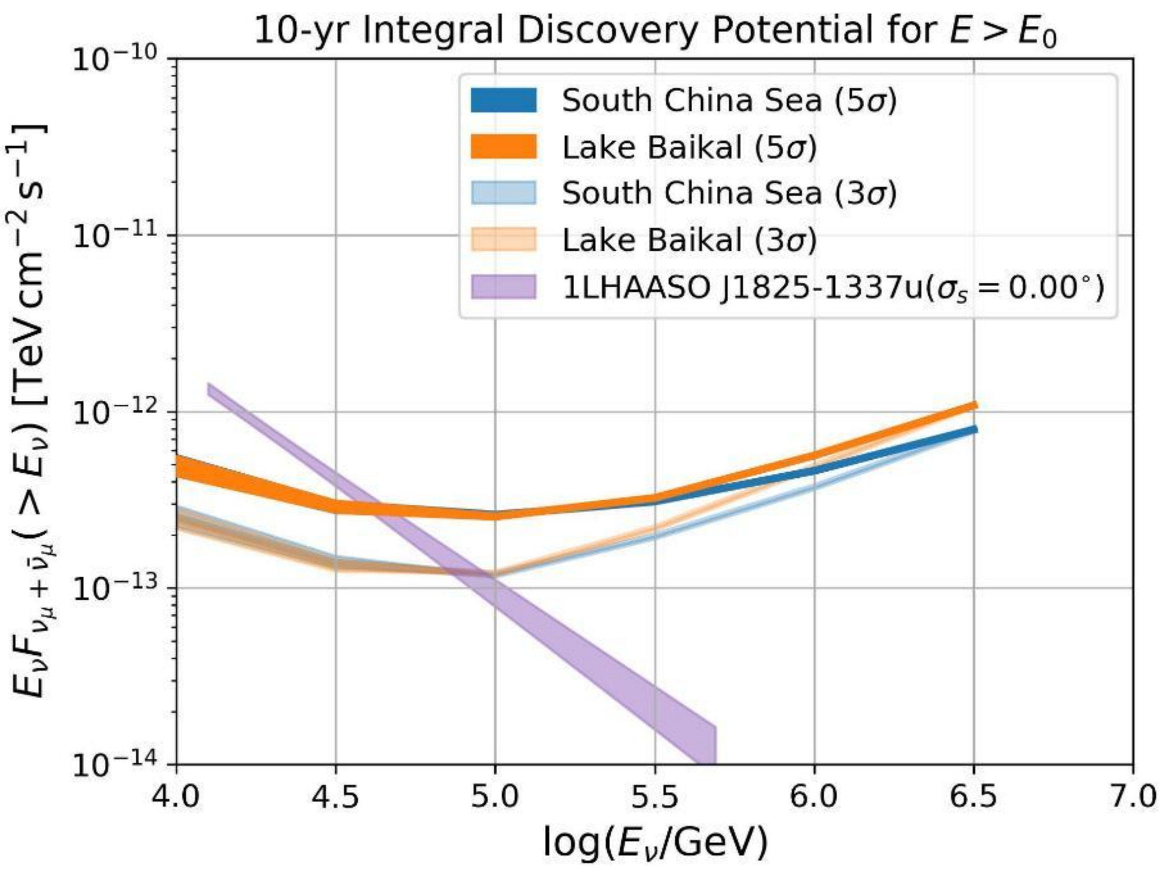


Diffuse gamma-rays from Galactic ridge

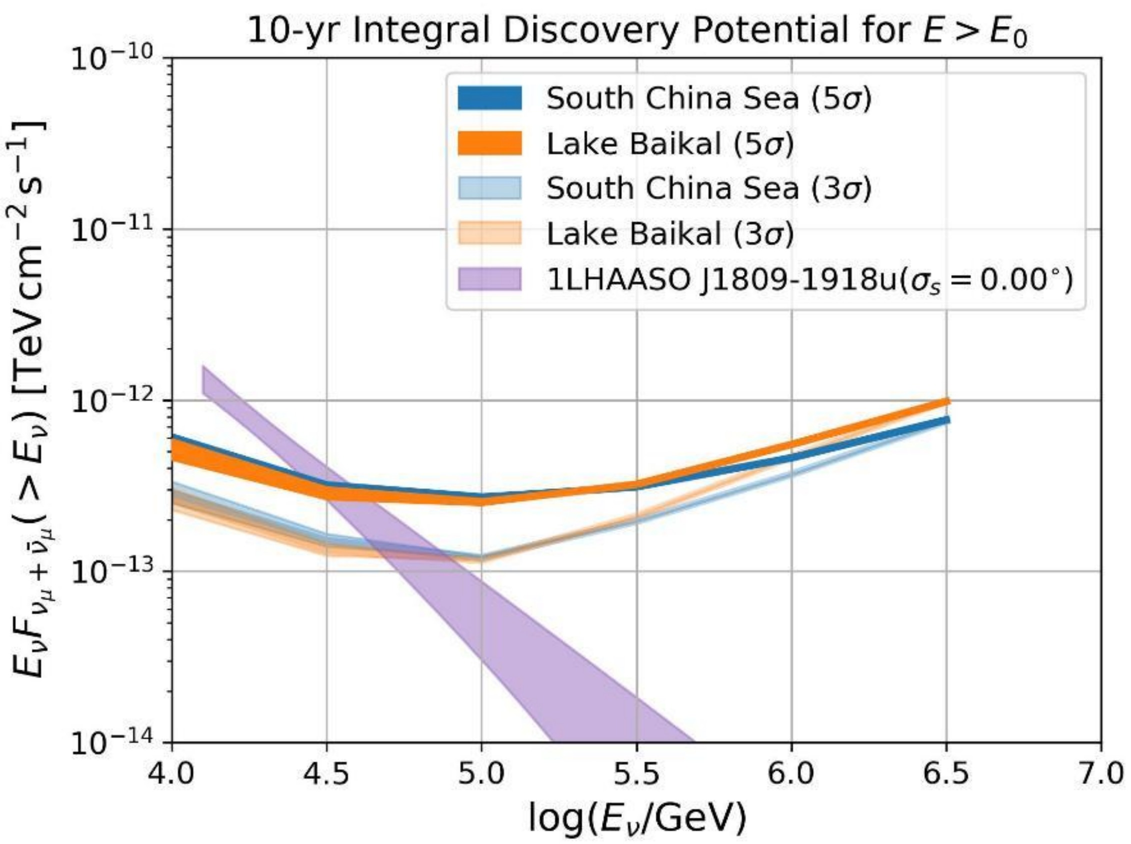


Discovery Potential | LHAASO's UHE γ sources.

1LHAASO 1825-1337u

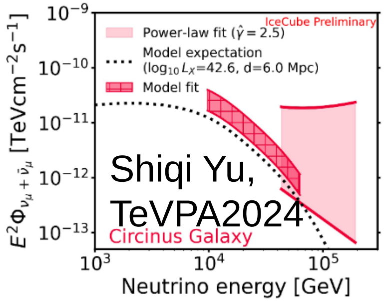


1LHAASO J1809-1918u

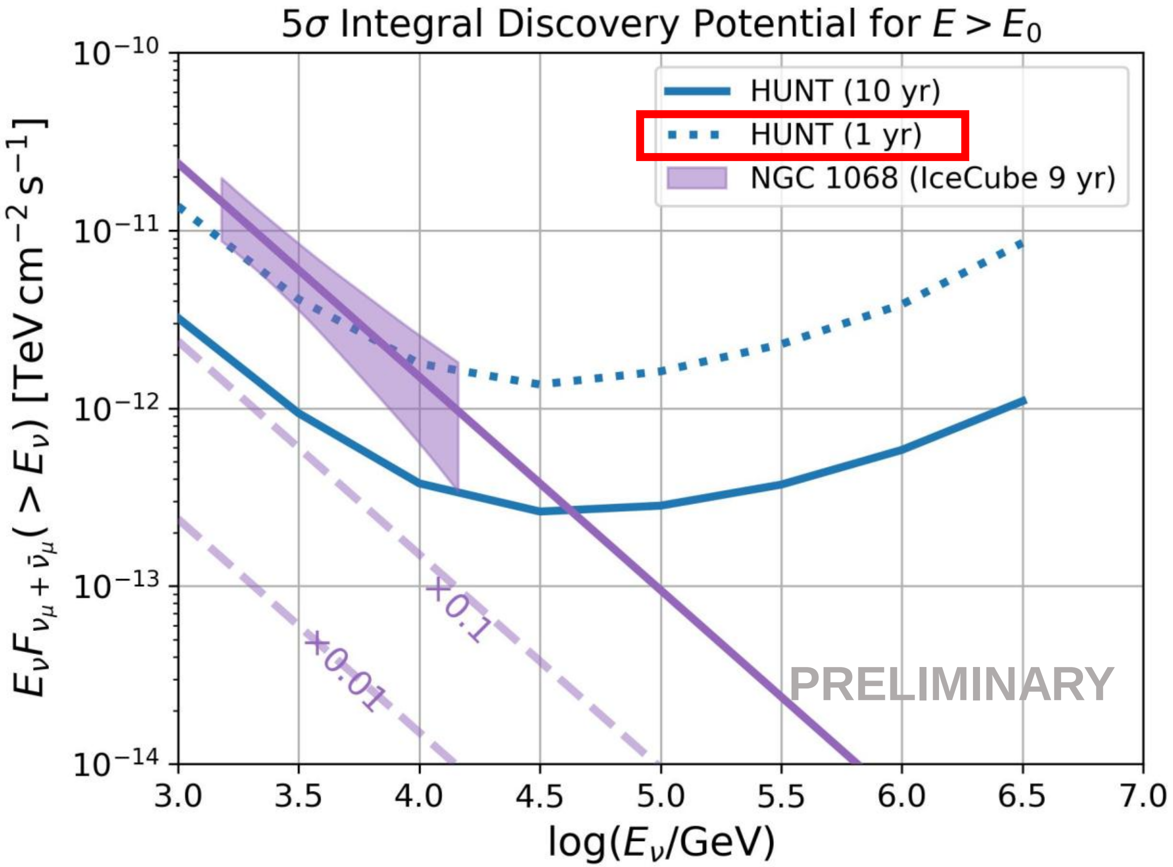


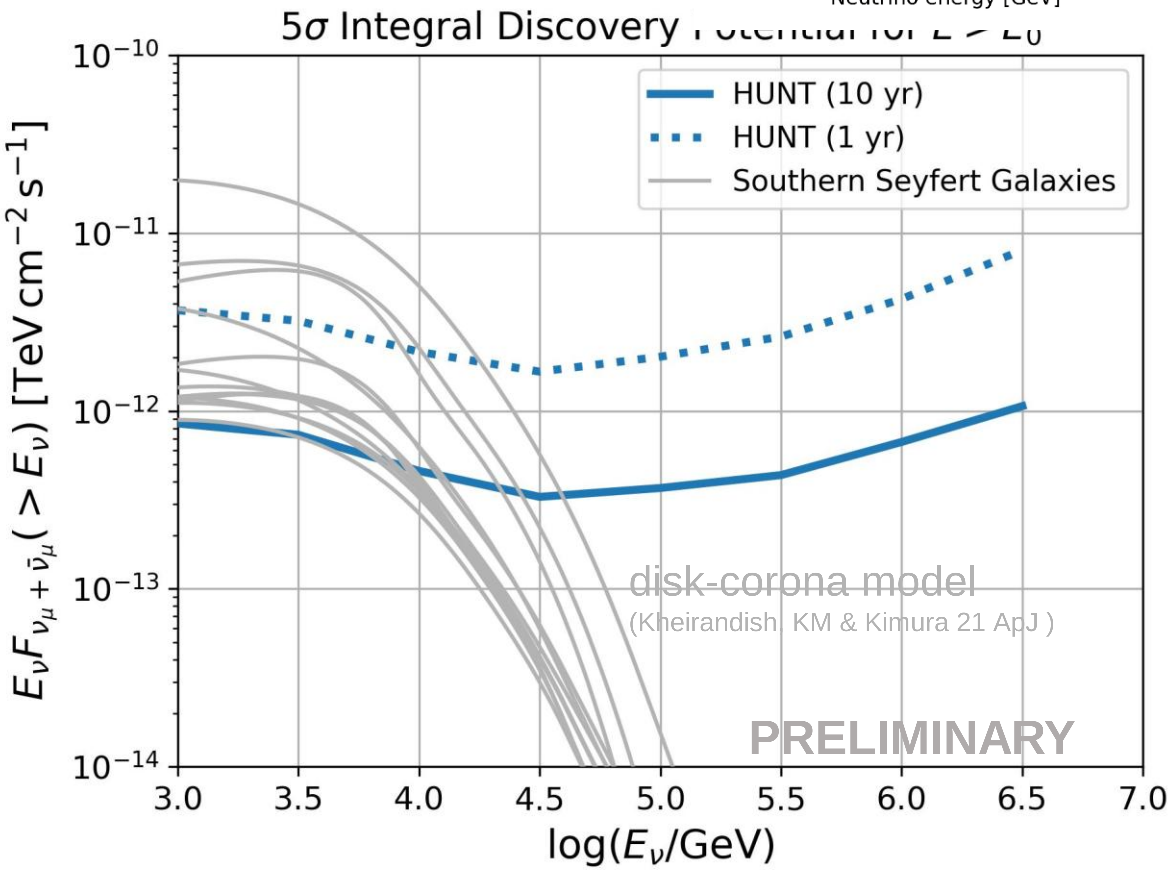
Discovery Potential | Seyfert Galaxies

Circinus Galaxy



Shiqi Yu, TeVPA2024





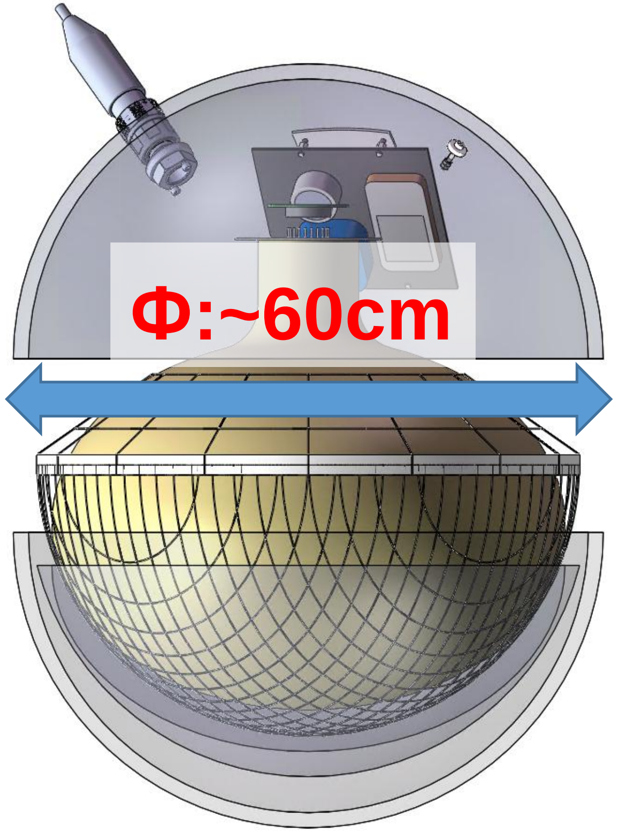
HUNT will discover tens of neutrino sources.

中国科学院高能物理研究所

R&D of detector

NEW super-scale Optical Module

Much simpler, Lower cost and better stability.



20-inch PMT

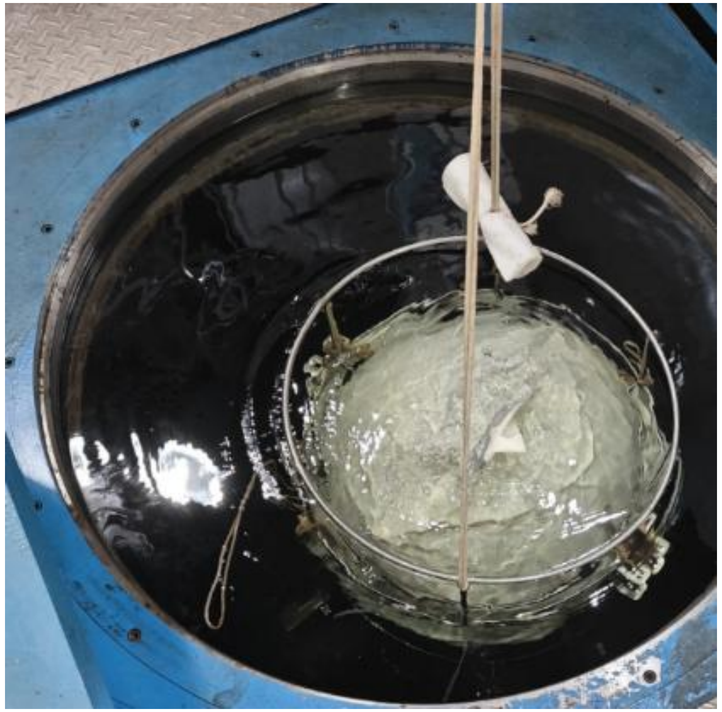
20-inch PMTs in LHAASO.

The number of detected signals is 1.6 times that of GVD’s OM
This makes the arrangement of OM very sparse(Density of OMs is smaller).

Largest pressure-resistant glass sphere

- Super-large: the outer diameter ~23 inches

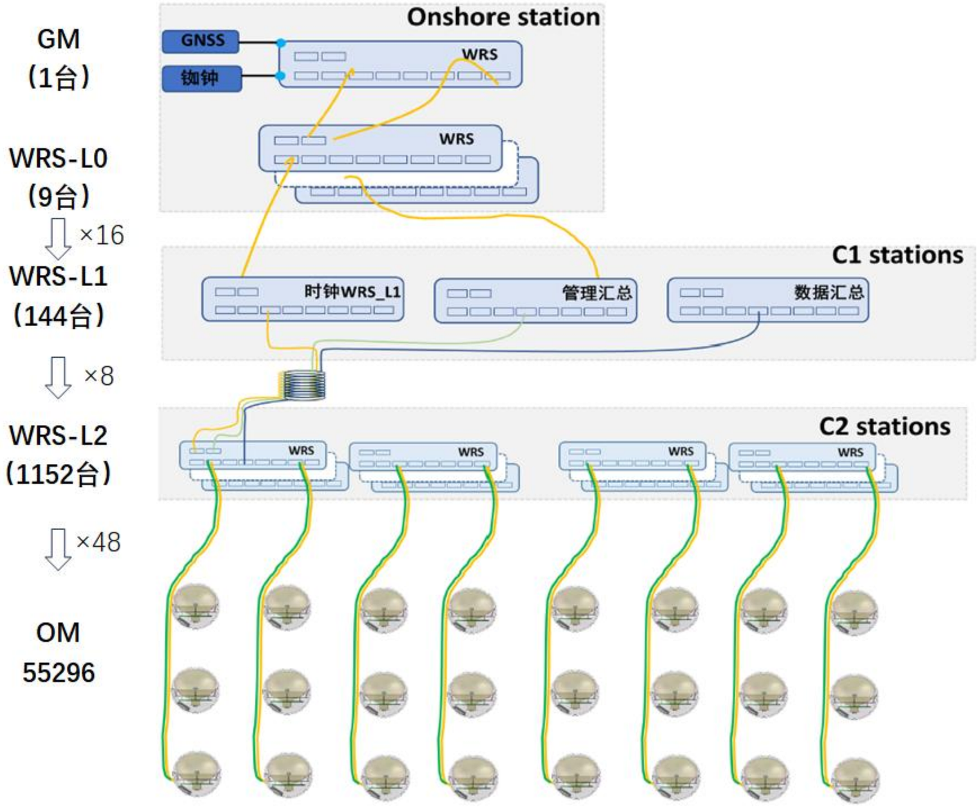
- Light transmittance: ~ 90%;
- Pressure resistance: > 3000m;



The sample passed the pressure test of 50Mpa.

White rabbit clock synchronization technology

✓High precision clock synchronization



1,300 WR switches in LHAASO

Successfully applied in LHAASO （**<0.2ns**）**a**nd Baikal-GVD prototypes.

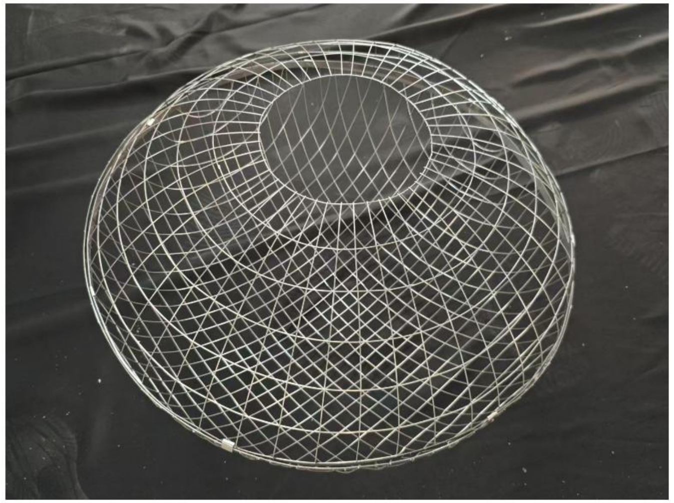
Instruments | Geomagnetic shielding

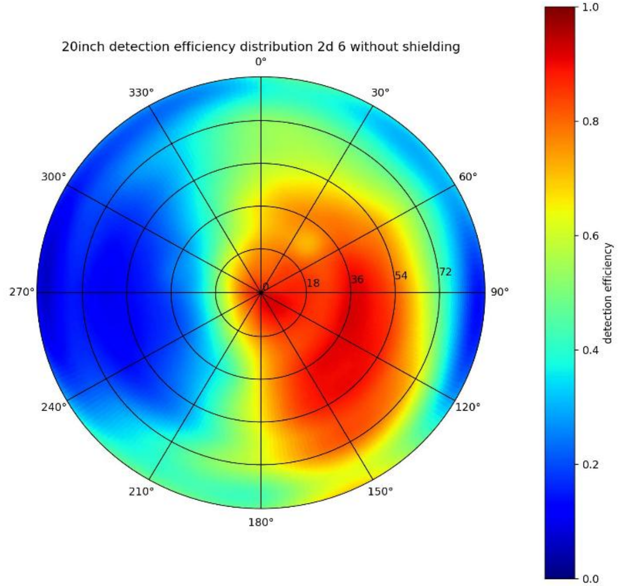
Improve PMT's performance with Geomagnetic fielding

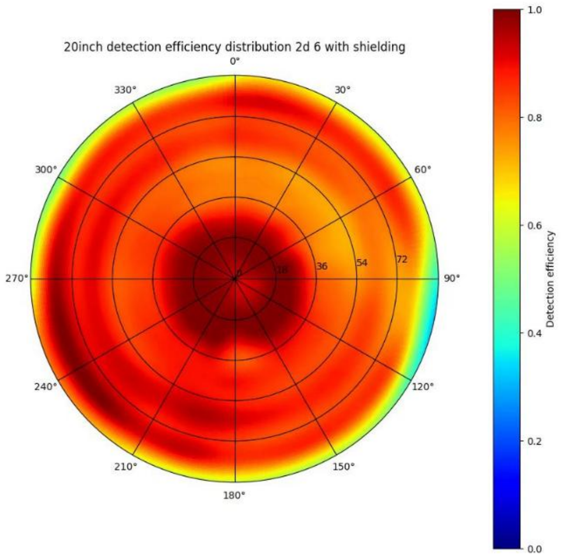
1. Relative Transit time & TTS
2. Charge distribution
3. Detection efficiency

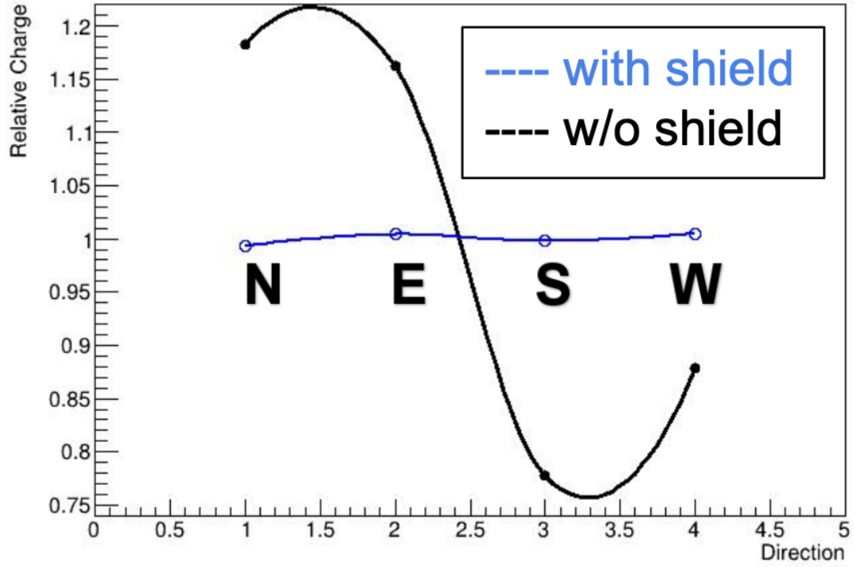
Geomagnetic shielding produced in China recently.

- ➢ high-permeability materials: Permalloy
- ➢ Modeling and design via COSMOL software







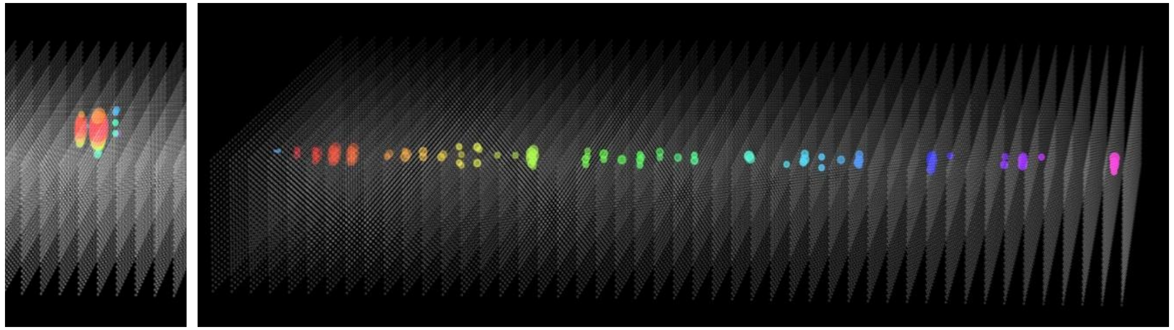


Simulation program

HUNTSimNeT

- **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.

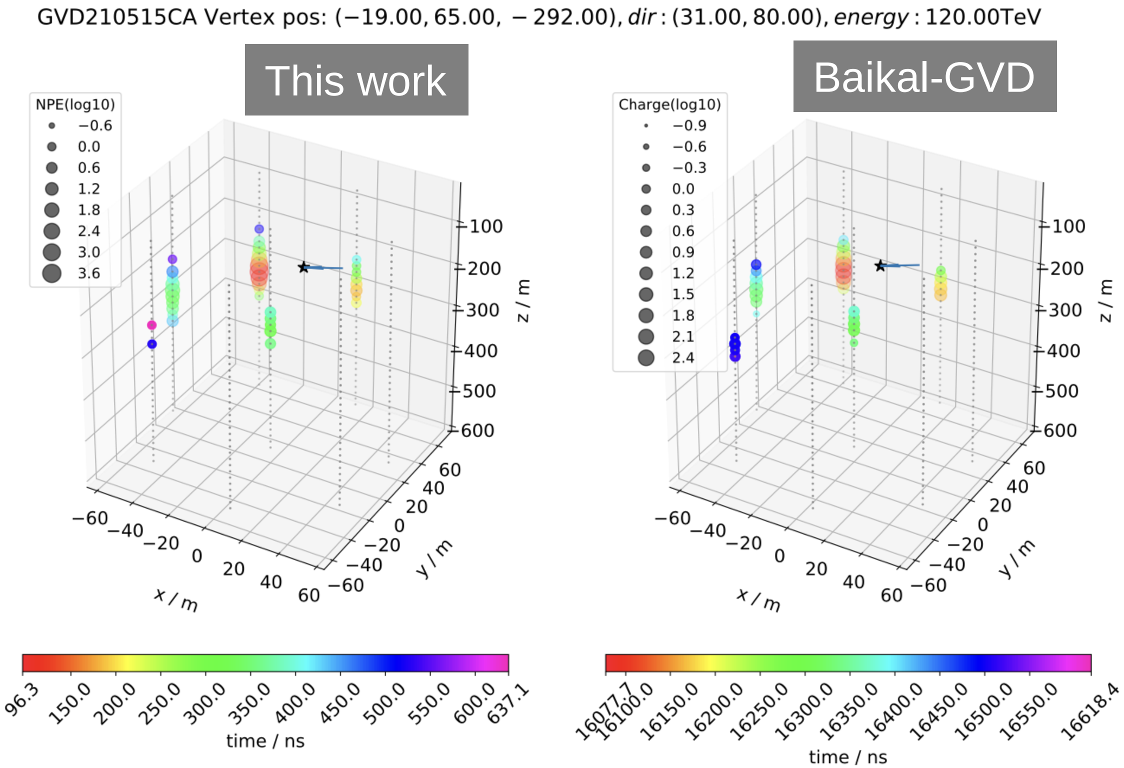
Morphology



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

Simulating Baikal-GVD observations

- 16 Baikal-GVD cascade events observed.
- 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**



Wang, et al., 2024, CPC

Simulation | Parallel algorithm

Full simulation need deal with the transport process of billions of photons generated by neutrino.

G4DMT: Geant4 Distributed Multiple Threads（**CPU Parall**）
- Call all CPUs to simulate a primary particle.

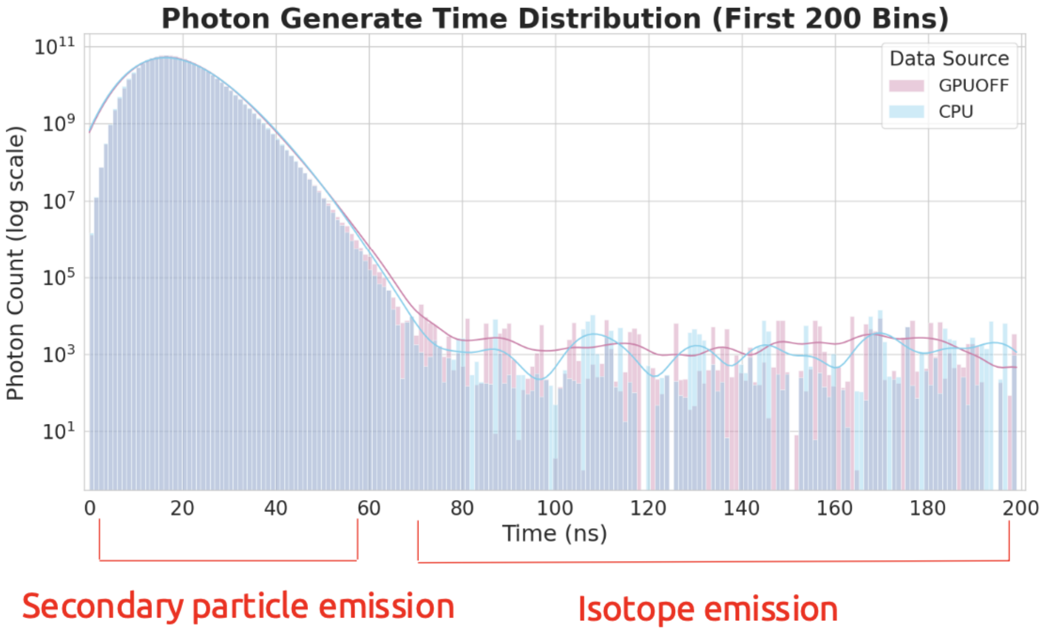
G4ART: Geant4 Accelerated Ray Tracing（**GPU parall**）
- Speeds up optical photon simulation.

One electron (1 PeV)
- CPU: AMD 7950X
- GPU: Nvidia 4090D 24G
- default Geant4: **40 hours**
- G4ART only: **4 hours**
- G4ART + G4DMT: **2000 s**
  - number of threads: 4

50X speedup

Validation
- Start time, Photon absorption length, arrival time and energy.

| Photon generation time

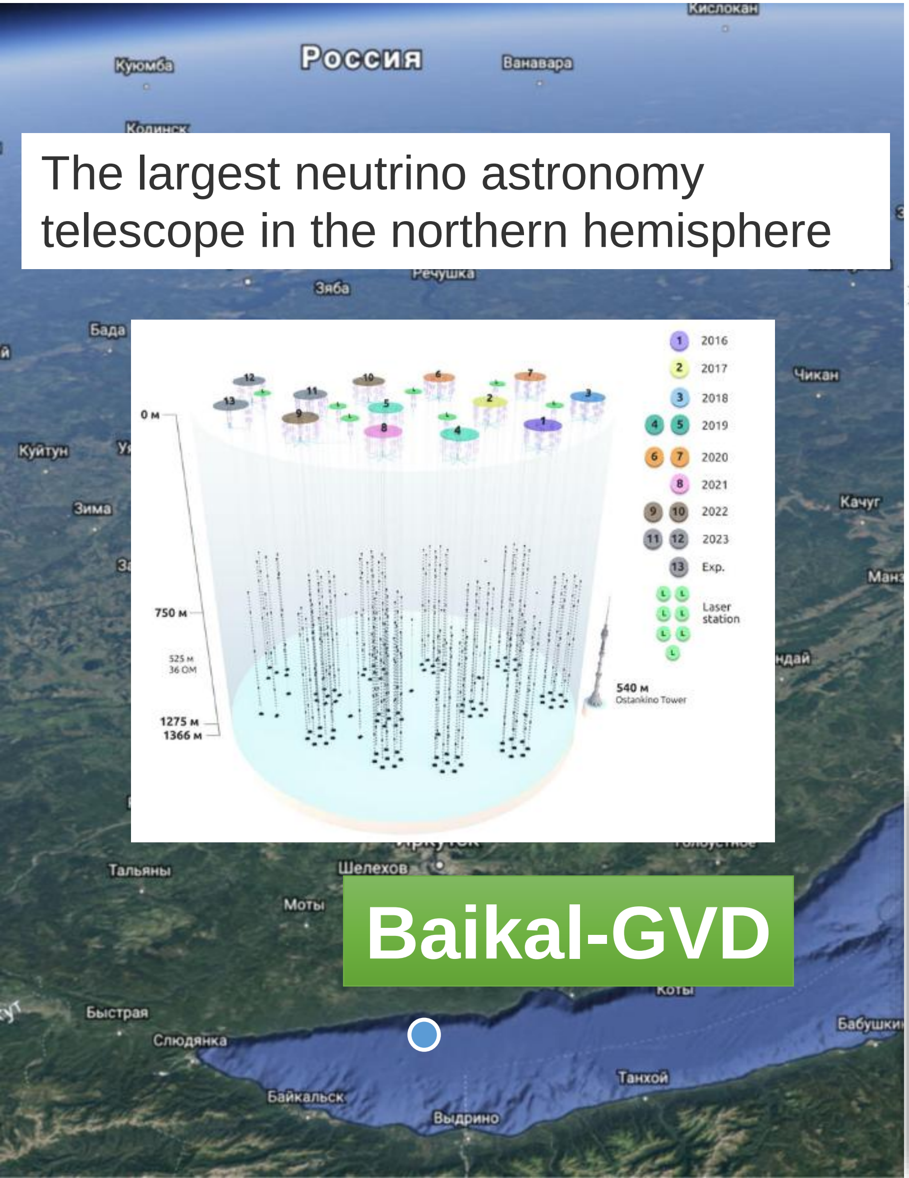


the difference between W/ and W/O G4ART is within 10%.

Prototype strings

Collaboration of two experiments

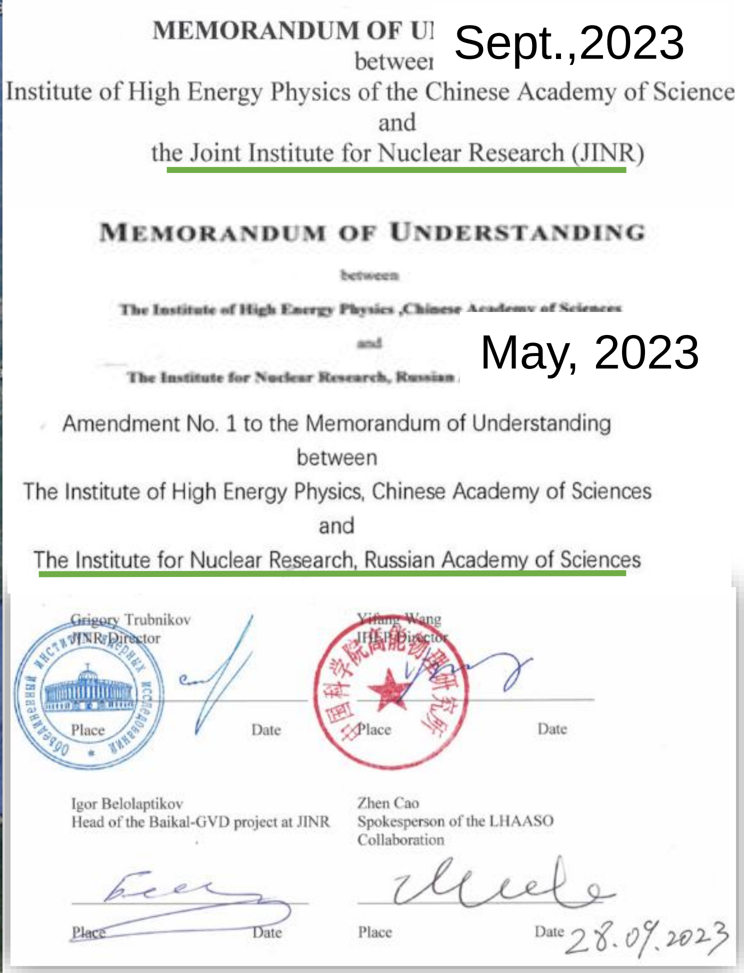
The largest neutrino astronomy telescope in the northern hemisphere



Baikal-GVD

Two MOUs with INR and JINR to promote the R&D of the next generation NT.

Sept.,2023



MEMORANDUM OF U[illegible]
between
Institute of High Energy Physics of the Chinese Academy of Science
and
the Joint Institute for Nuclear Research (JINR)

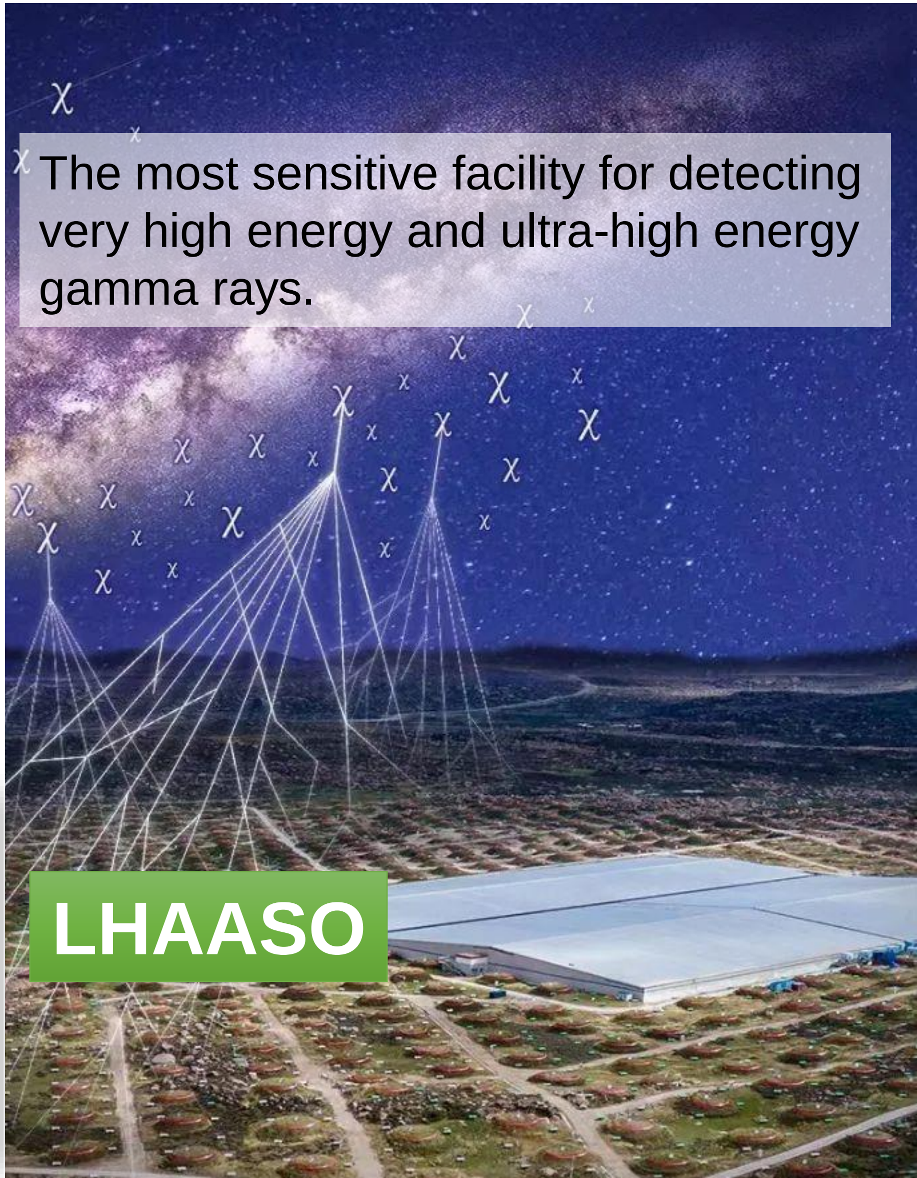
MEMORANDUM OF UNDERSTANDING
between
The Institute of High Energy Physics, Chinese Academy of Sciences
and
The Institute for Nuclear Research, Russian

Amendment No. 1 to the Memorandum of Understanding
between
The Institute of High Energy Physics, Chinese Academy of Sciences
and
The Institute for Nuclear Research, Russian Academy of Sciences

Grigory Trubnikov JINR Director	Yifang Wang IHEP Director
Place Date	Place Date
Igor Belolaptikov Head of the Baikal-GVD project at JINR	Zhen Cao Spokesperson of the LHAASO Collaboration
Place Date	Place Date 28.09.2023

May, 2023

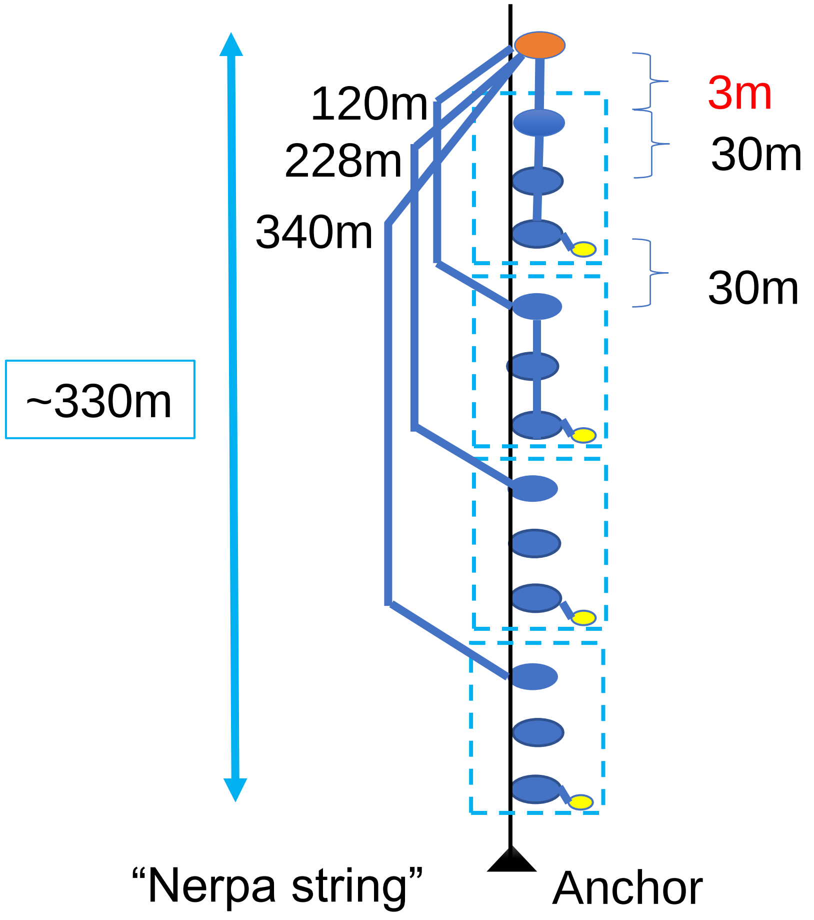
The most sensitive facility for detecting very high energy and ultra-high energy gamma rays.



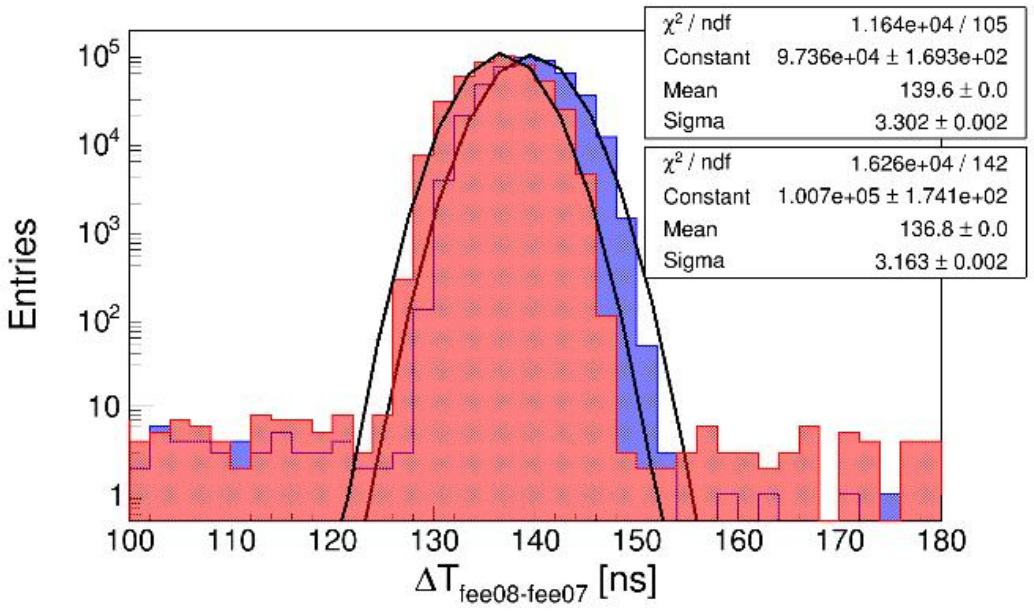
LHAASO

1st Prototype String @ Lake Baikal

- 12 OMs with 20-inch PMTs
- 4 LED calibration modules

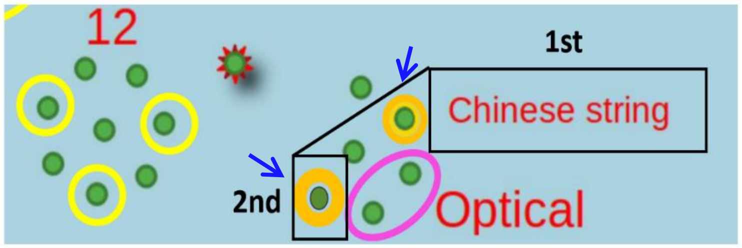


1^{st} Prototype String @ Lake Baikal



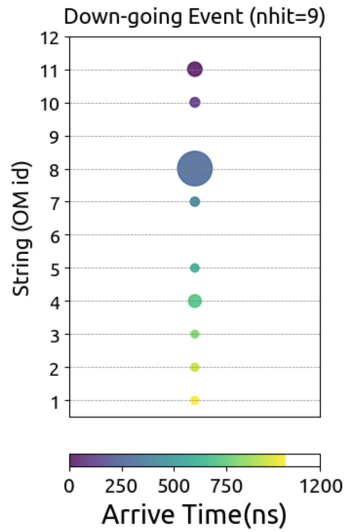
- Q-T correction -> Same Light intensity : ~0.4ns
- PMT calibration : ~0.5ns
- Module shape correction : ~1ns

418nm: 137.5ns @ 30m -> 1.374 [refractive index]
460nm: 135.2ns @ 30m -> 1.351 [refractive index]

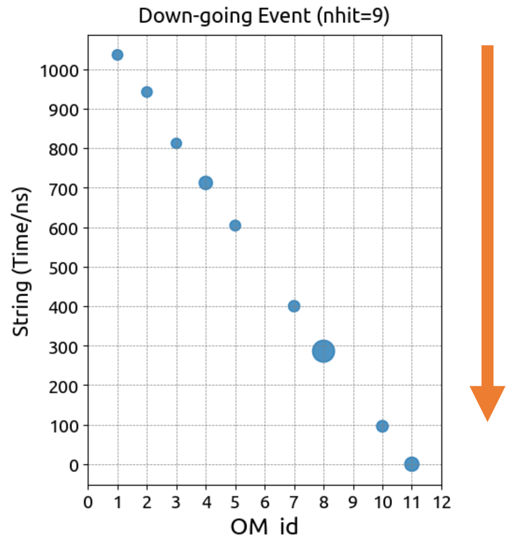


1st & 2nd string located in GVD

Size of signal



Arrival time

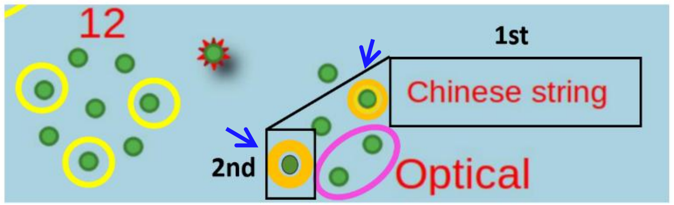


- Around 10 muon-like events (>=4 hits) per day.

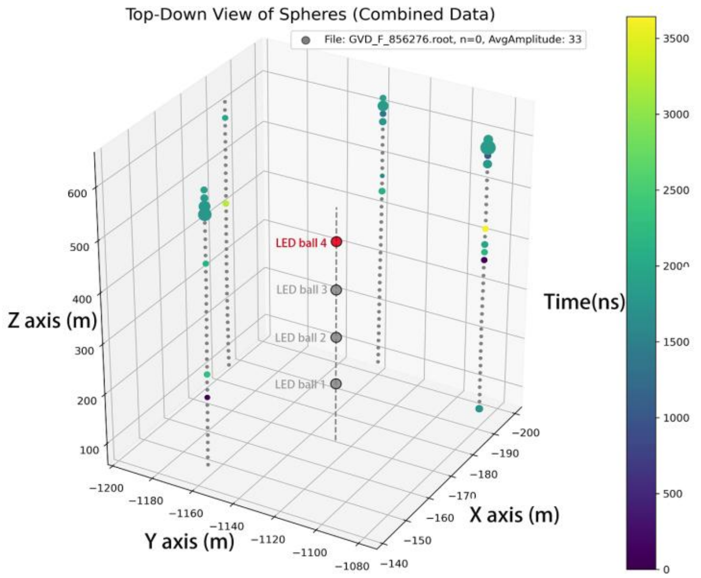
Joint analysis of 1st String and GVD

Dataset: LED calibration on April 7, 2024.

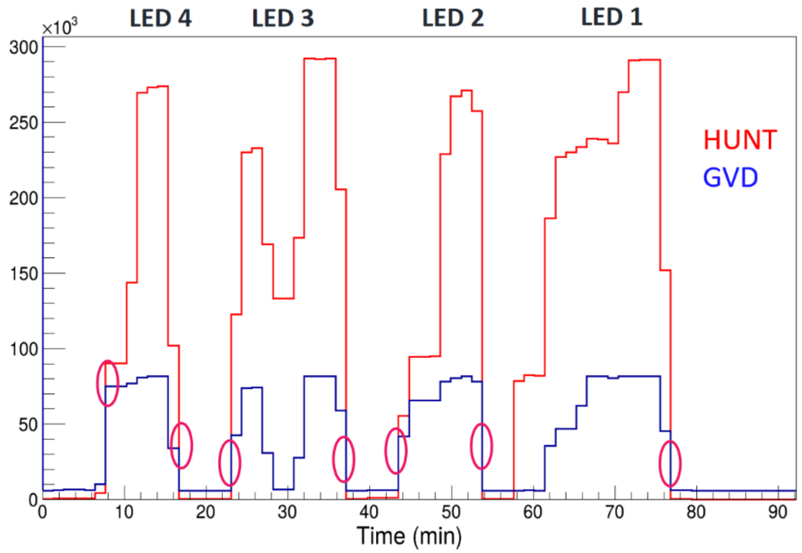
- LED light No.4, 3, 2 and 1 were turn on in order;
- The nearby GVD OMs can detect the LED signals ;
- Can be used to calibrate the time delay between two types of OM, and detection efficiency lately;



1st & 2nd string located in GVD



HUNT LED lighting nearby GVD strings

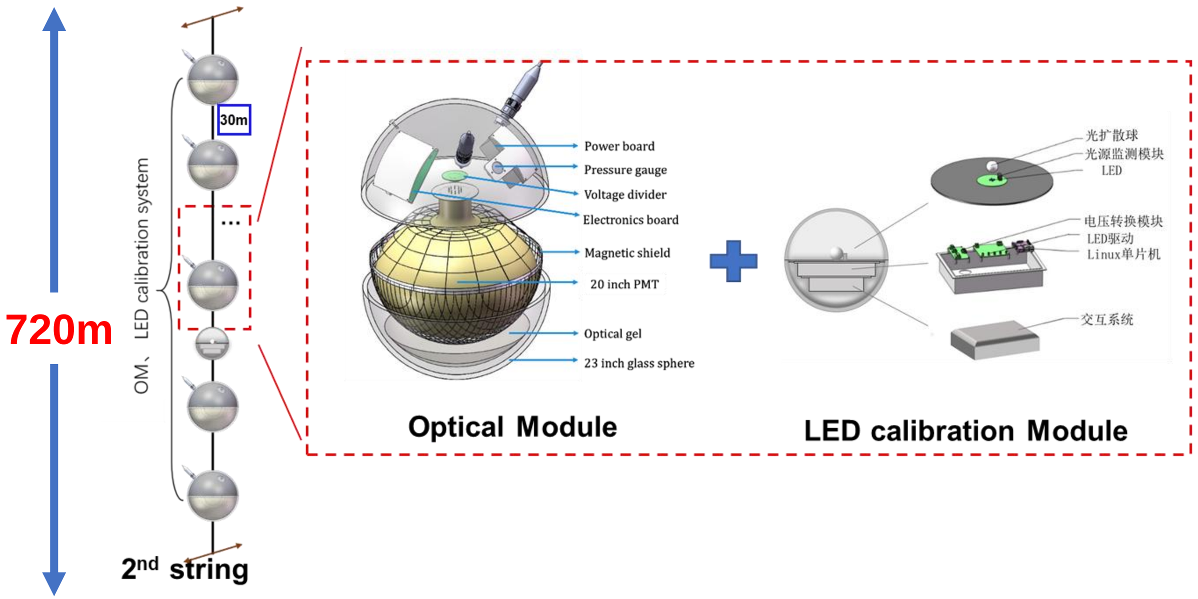


Calibration Time delay by event by events
GVD-HUNT= -38s - 488510850ns

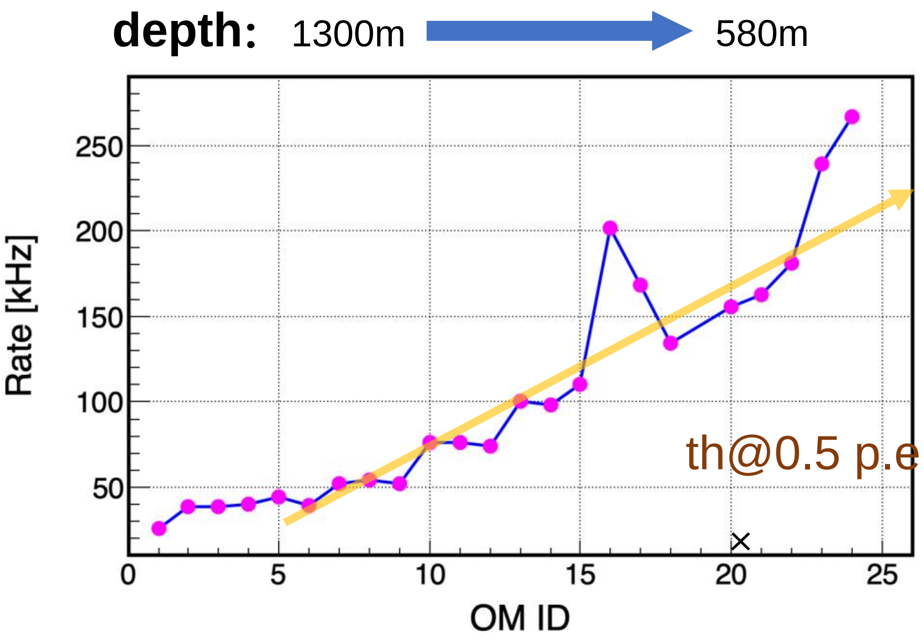
Status of 2nd prototype string

- The **2nd** prototype string, including **24 Optical Modules(OMs)** + **4 LED calibration modules**, was installed in this March.

- **Operation Mode 1:** Gain at 1E7 with a threshold of ~0.5 p.e.
- **Operation Mode 2:** Gain at 1E5 with a threshold of ~1.6 p.e.
- For short of disk storage, operation **Mode 2** since April 15.
- To today, all of OMs without any waterproof issues.



The relationship between single-channel noise rate vs different water depth.

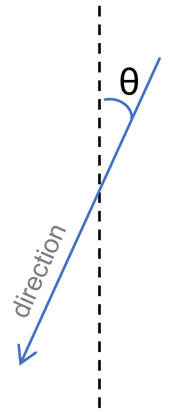


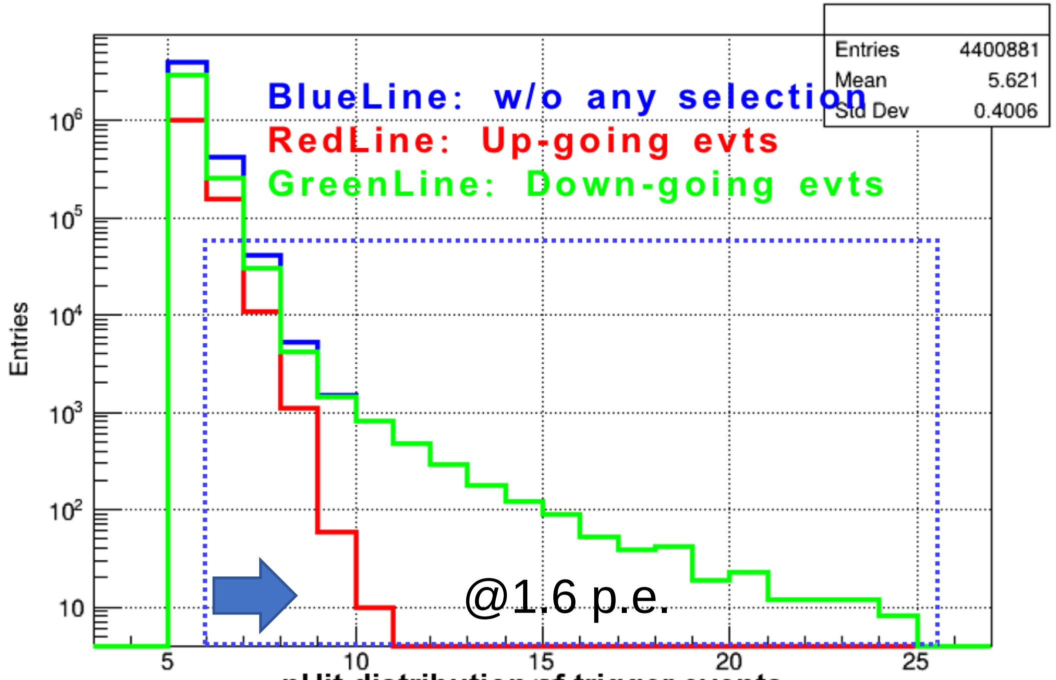
- **the deeper the water depth, the lower the noise rate.**

Data analysis of 2nd Prototype string

Preliminary Results:

- Dataset: 30/04 - 05/05/2025 with **Operation Mode 2.**
- Number of down-going events > up-going events.
  - nHit > 6, down-going events(muon-like), 0.07Hz.
  - nHit > 6, up-going events(neutrino-like), 0.02Hz.





nHit distribution of trigger events
(6 days' raw data)

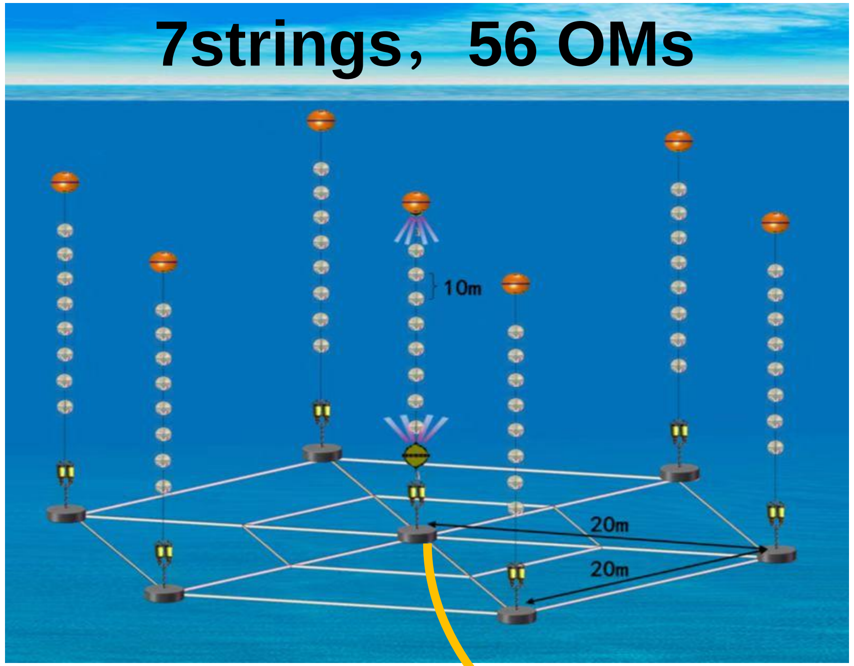
Next:

Develop MC Geant4 simulation program to check the charge and time distribution with experimental data, and study the detection eff. Of OM detailedly.

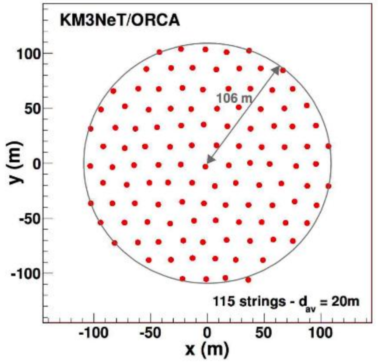
Prototype strings @ South China Sea

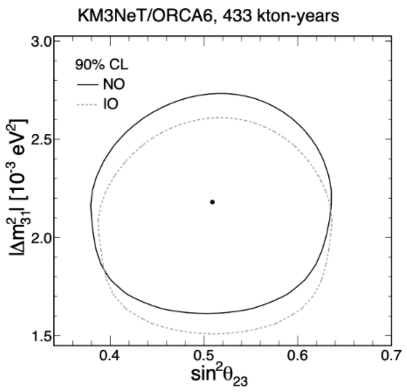
Phase I: Long-term monitor string (Jan 2025)
- 4 OMs, vertical spacing ~10 m

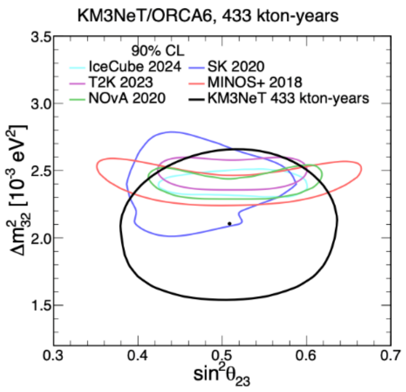
Phase II: Seven-string array (2025-2026)
- R&D of OM, APS, waterproof connectors, deployments,…….
- Measure the atmosphere neutrinos.

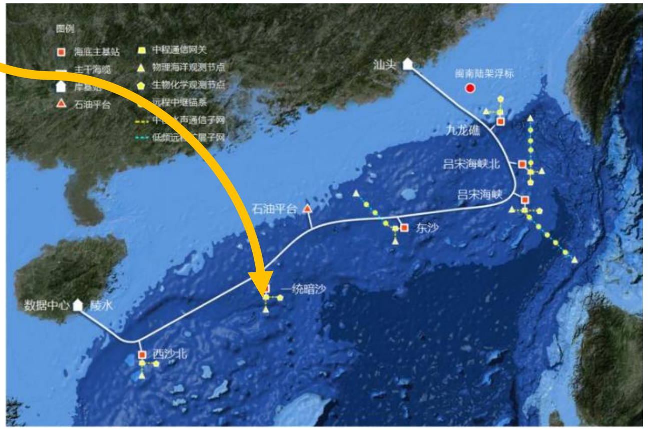


KM3NeT-ORCA6 (510 days, 433 kton-years)

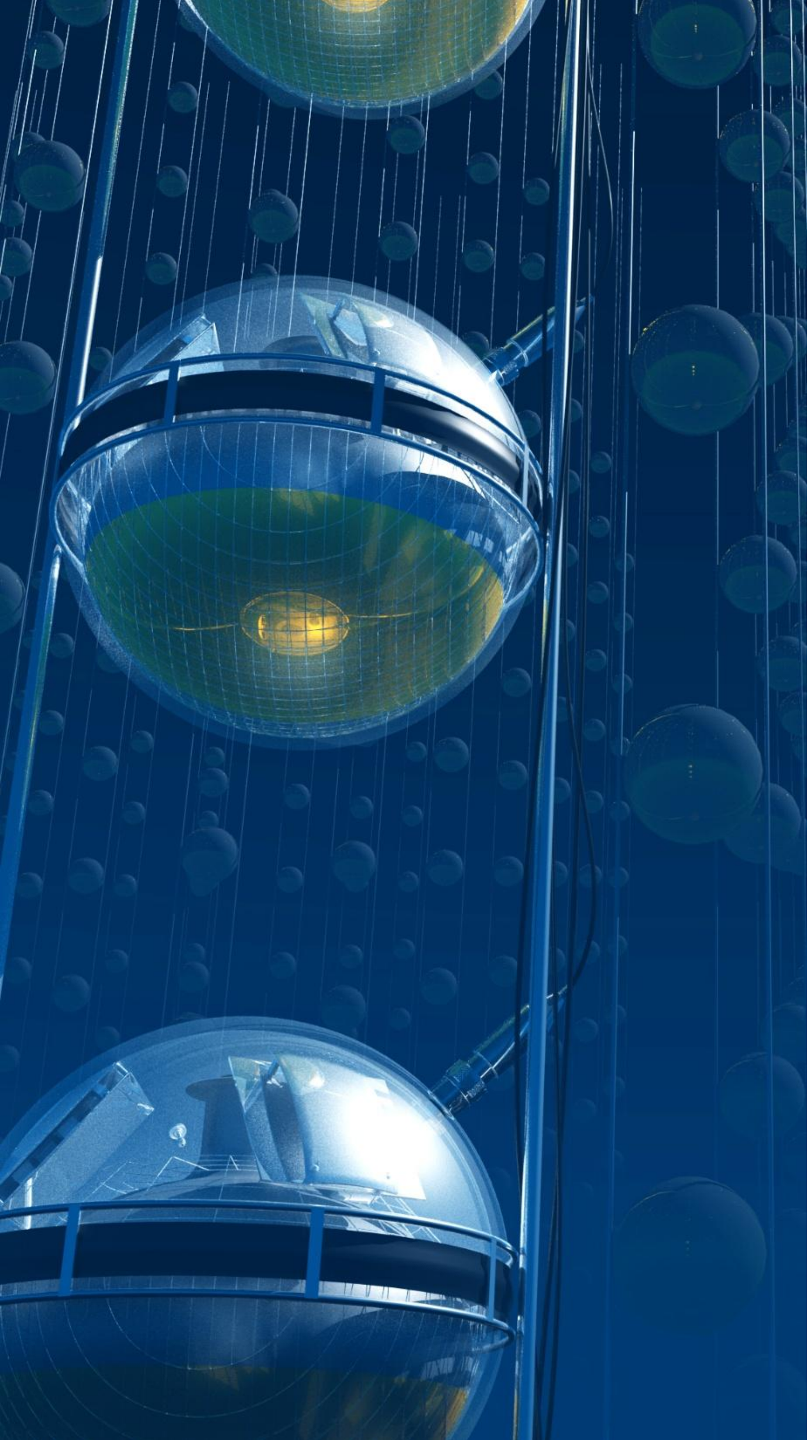








Supported by Deepsea Network China.



Summary

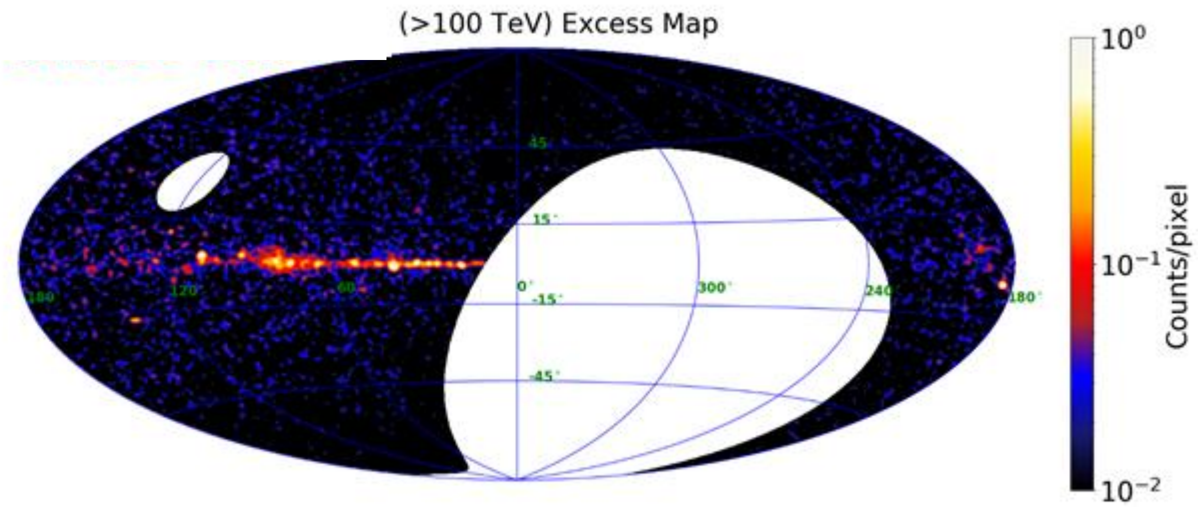
- LHAASO has discovered tens of Galactic PeVatron candidates which are good candidates for high-energy neutrino sources.
- HUNT will realize unprecedented potential in discovering the neutrino counterparts of Galactic PeVatrons and resolving the high-energy neutrino sky.
- Prototype string in Lake Baikal has observed muon-like events. We are going to deploy another string in 2026. The seven-string array in South China Sea is coming.
- We hope HUNT project will be built in Lake Baikal.

Thanks.

PeVatrons discovered in the Milky Way

Neutrino observation will decisively solve the problem of the origin of cosmic rays!

- PeVatrons ⟶ neutrinos above 50 TeV & gamma-rays above 100 TeV.
- LHAASO observed tens of gamma-ray sources above 100 TeV.
- Gamma-rays above 100 TeV can be produced in both leptonic and hadronic scenarios.



1st LHAASO Catalog: 43 UHE gamma-ray sources (>4σ).

Main process:

$$p + p \longrightarrow N(\pi^+ + \pi^- + \pi^0) + X$$

$$p + \gamma \longrightarrow n + \pi^+$$

$$\pi^+ \longrightarrow \nu_\mu + \mu^+ \longrightarrow \nu_\mu + (e^+ + \bar{\nu}_\mu + \nu_e)$$
$$\pi^- \longrightarrow \bar{\nu}_\mu + \mu^- \longrightarrow \bar{\nu}_\mu + (e^- + \nu_\mu + \bar{\nu}_e)$$
$$\pi^0 \longrightarrow 2\gamma$$

* LHAASO Collaboration, 2021, Nature, 594, 33.
* LHAASO Collaboration, 2024, ApJS, 271, 25.

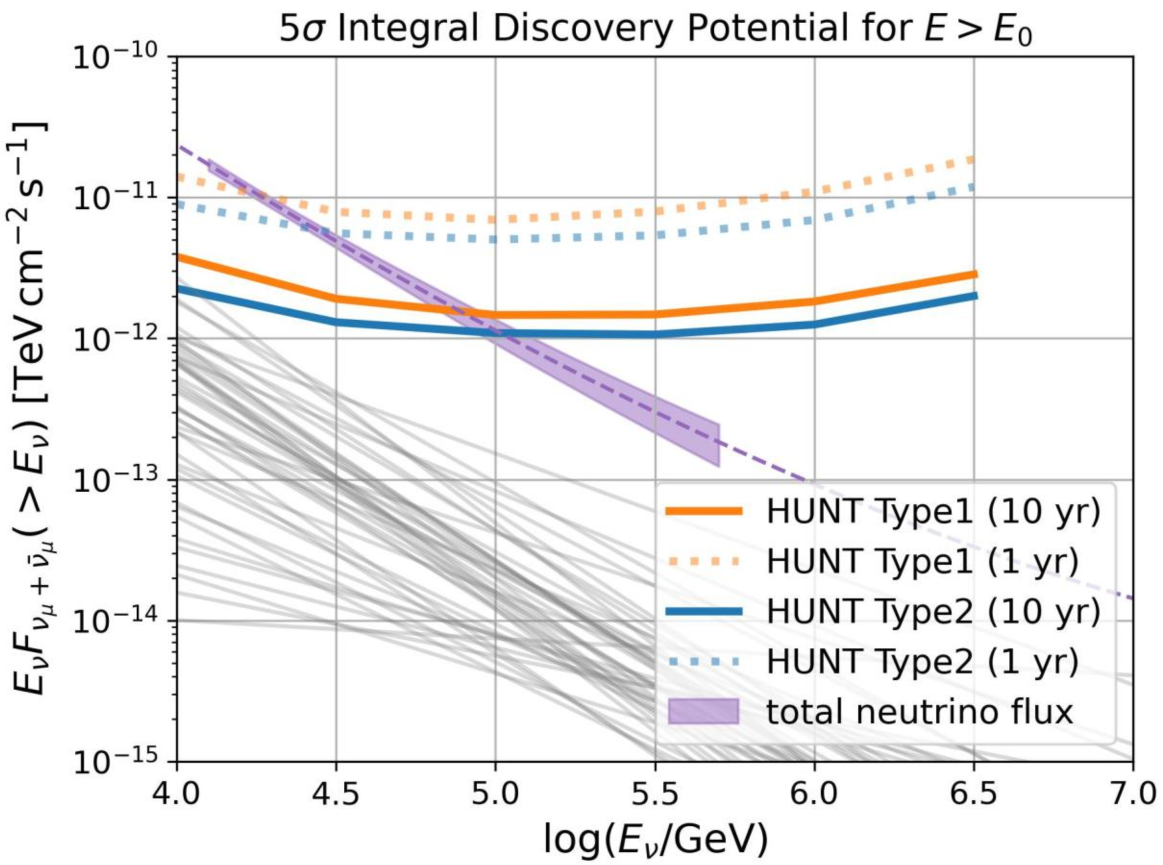
Discovery Potential | Stacking LHAASO sources

1LHAASO catalog

- 43 sources with significant (>4σ) emission above 100 TeV
- median spectral index 3.28
- median source extension 0.21°

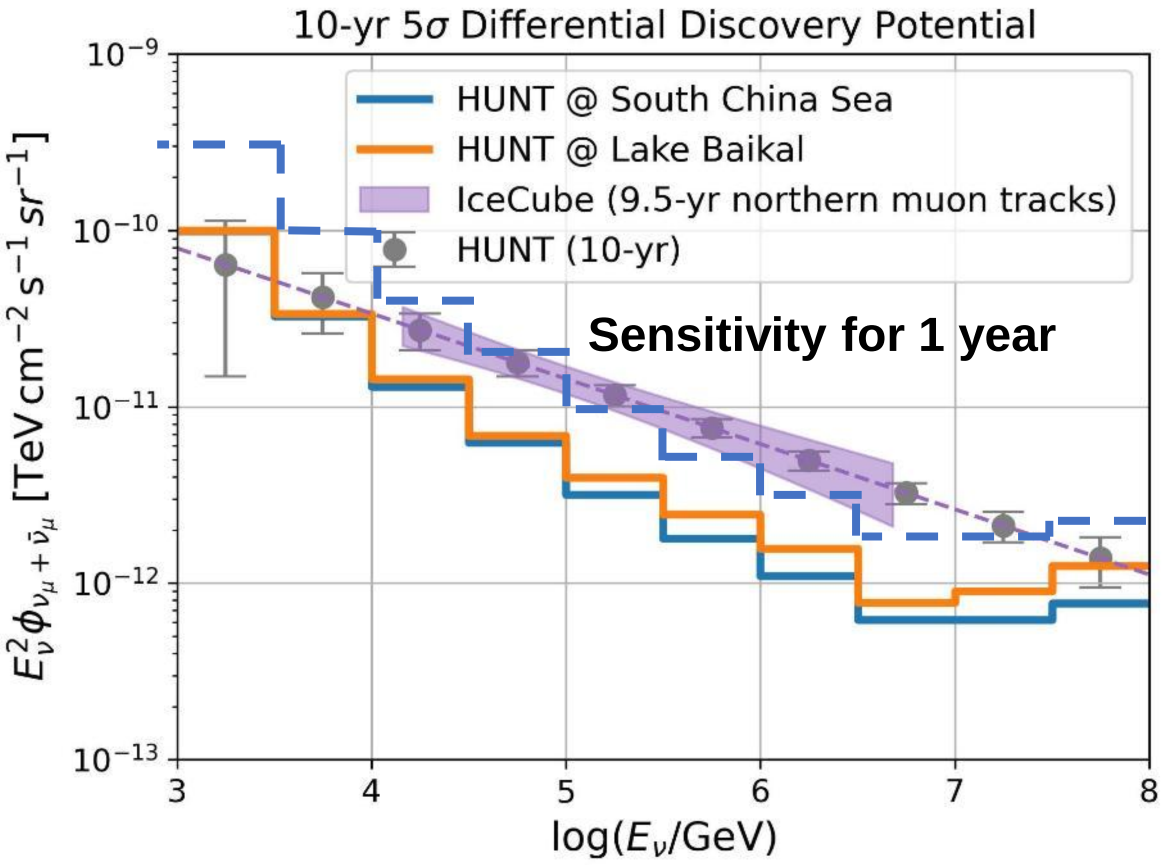
Neutrino & Gamma-ray Relation

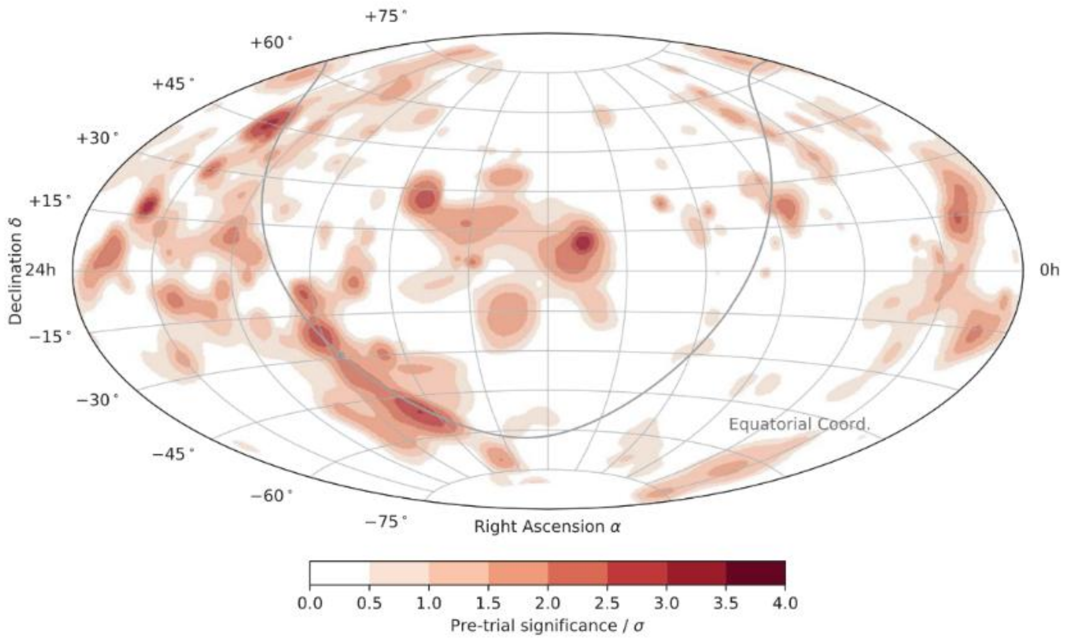
- $E_\gamma = 2E_\nu$
- $N_\nu = 3N_\gamma$
- $\nu_e : \nu_\mu : \nu_\tau$ = 1:1:1
- $J_\nu(E_\nu) = 2J_\gamma(2E_\nu)$



中国科学院高能物理研究所

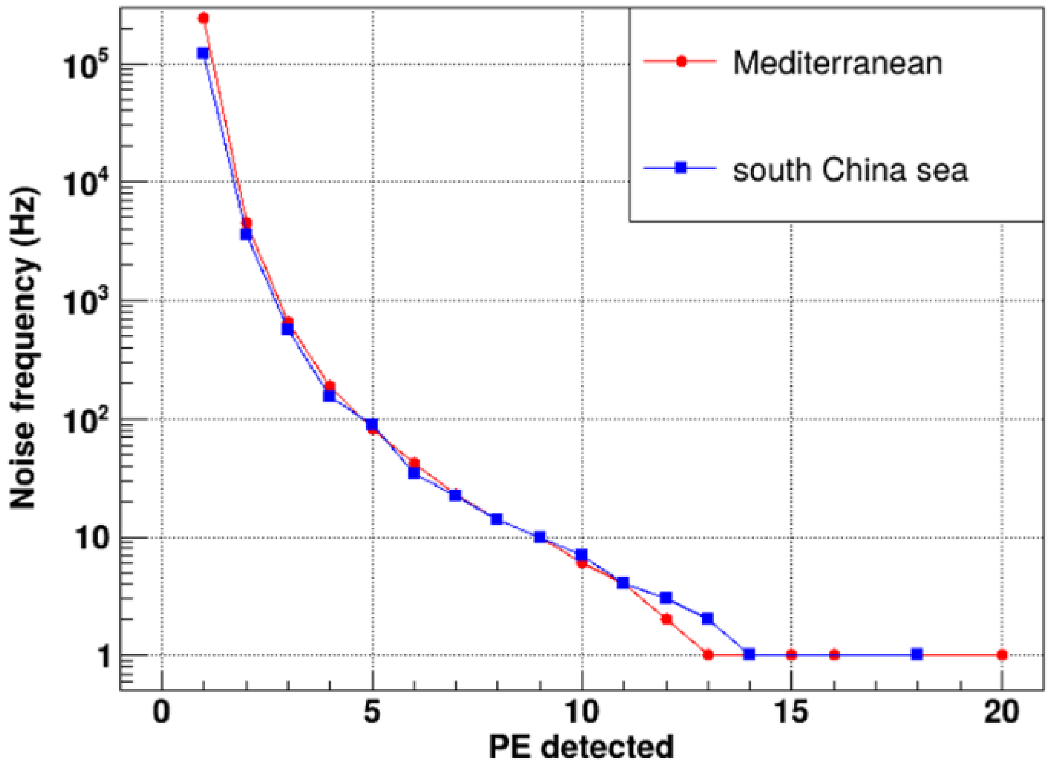
Discovery Potential | diffuse neutrinos

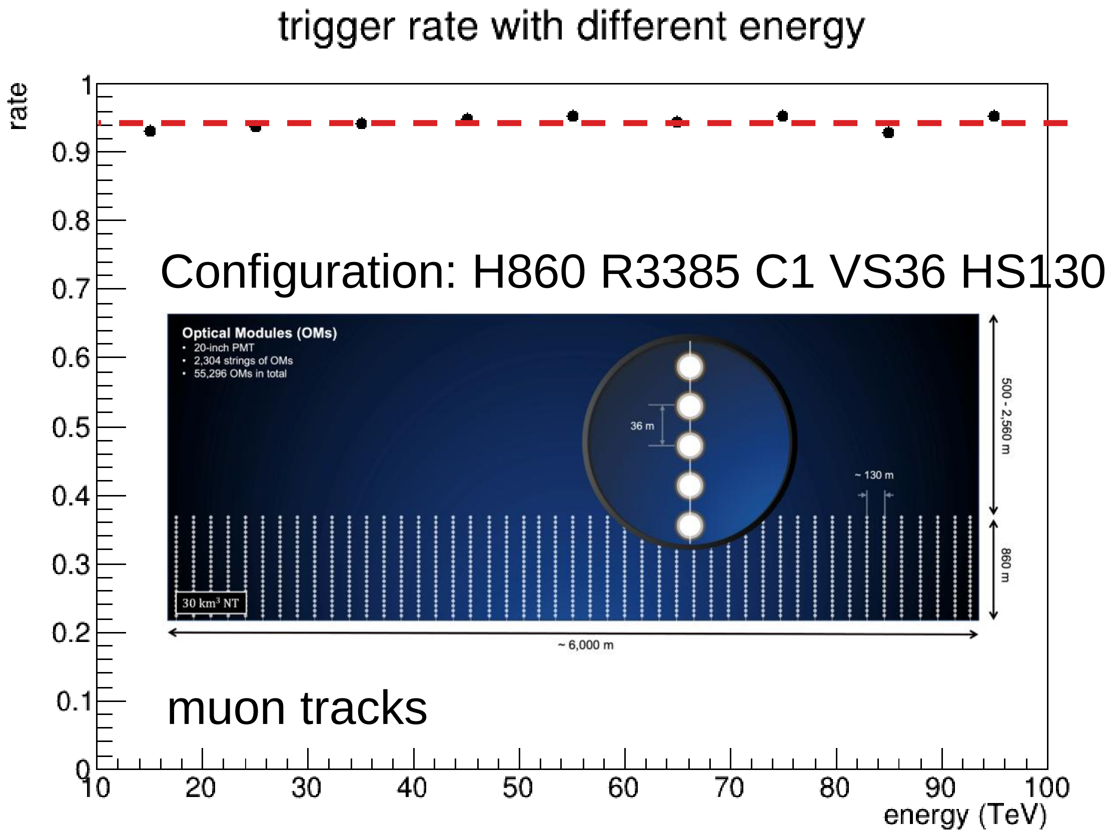




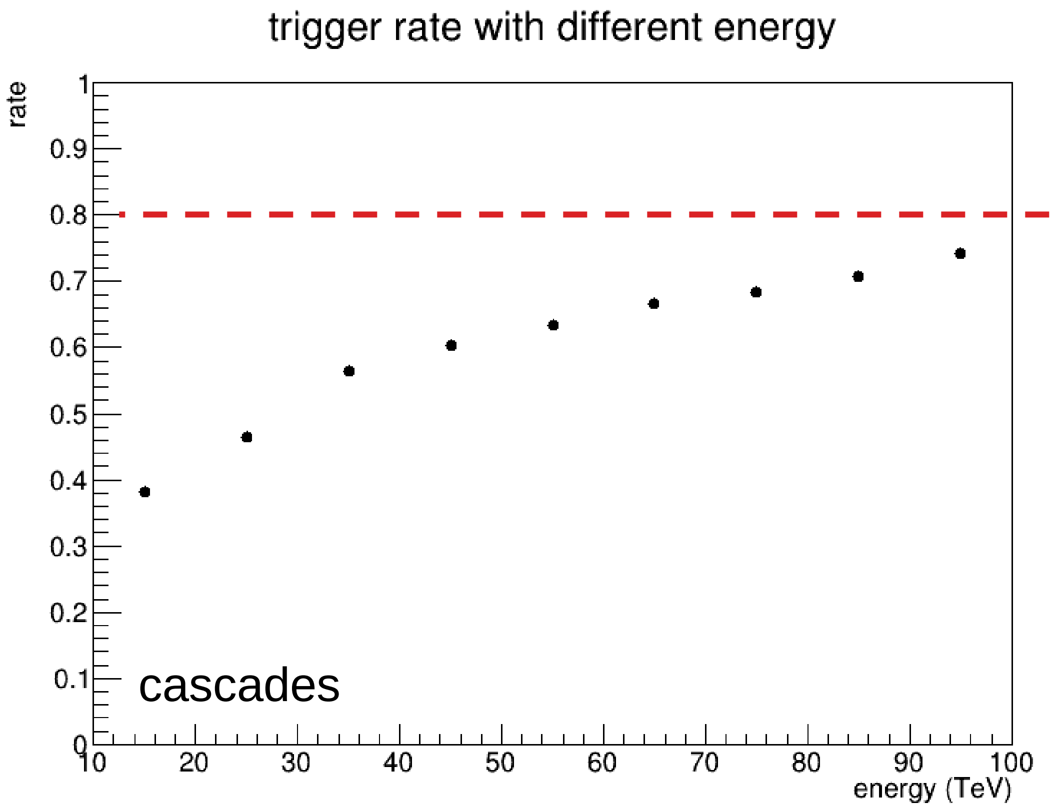
IceCube, ***SCIENCE,*** Vol 380, Issue 6652

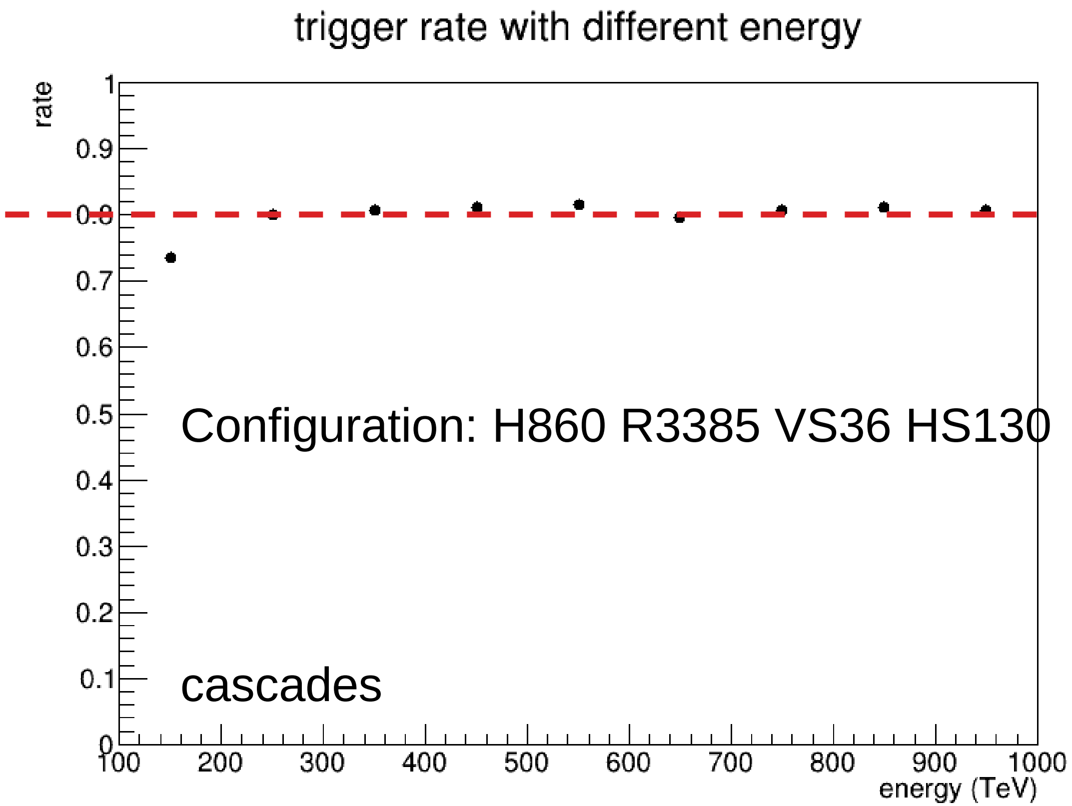
Trigger | track events

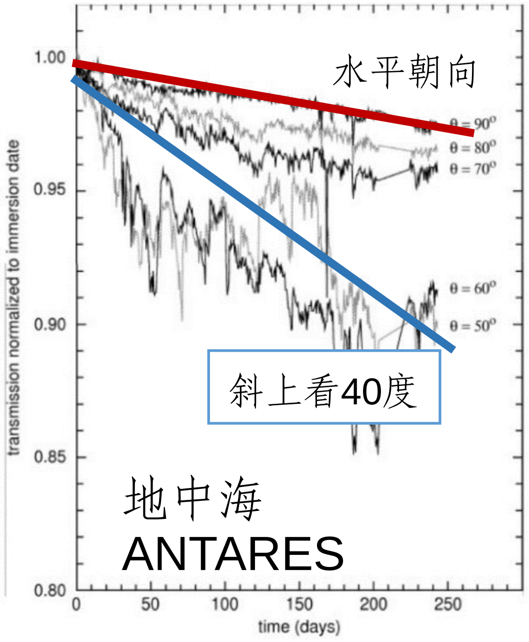


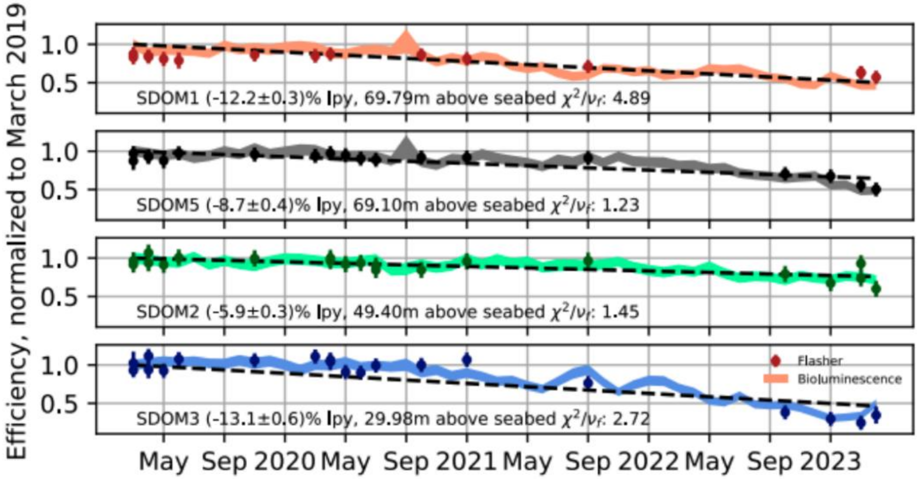


Trigger | cascade events



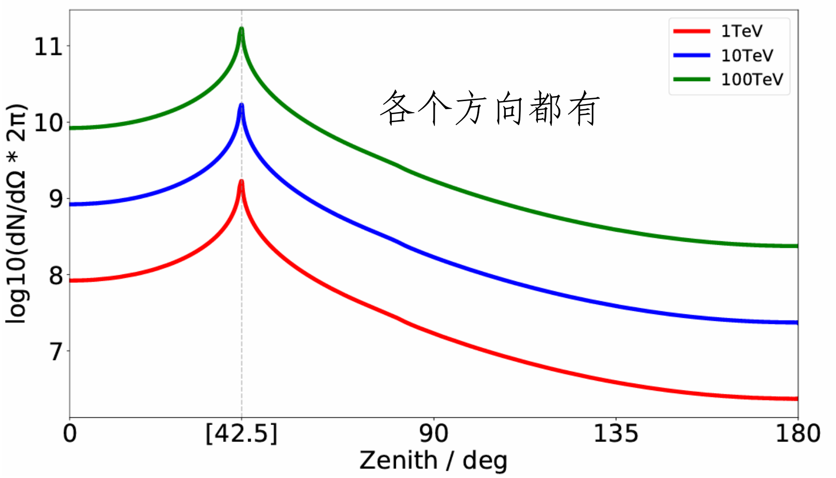




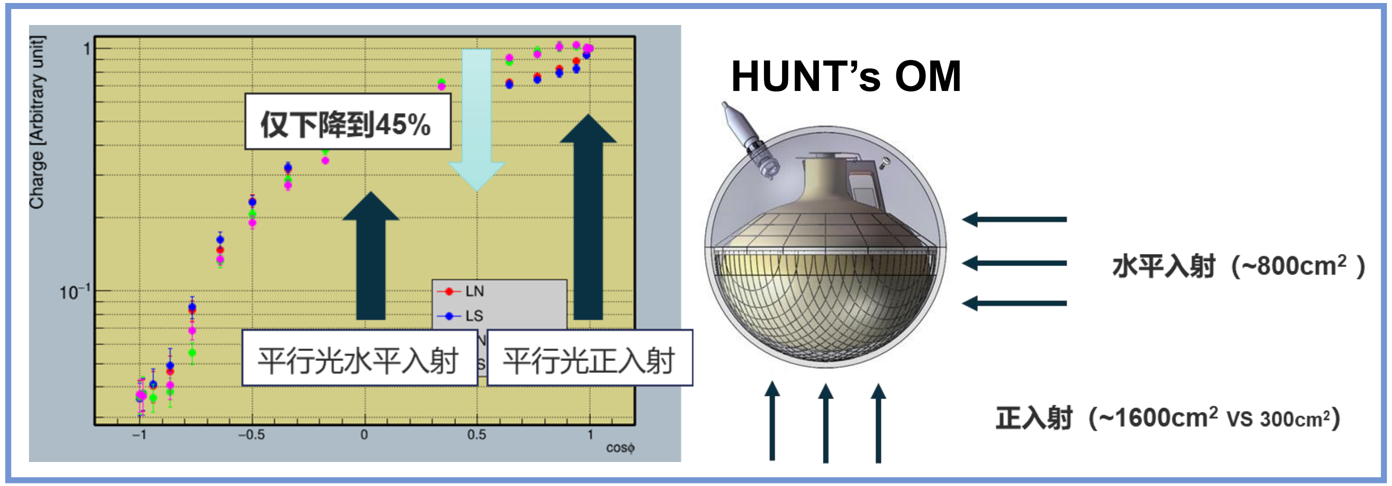


加拿大P-one（探头朝上看）

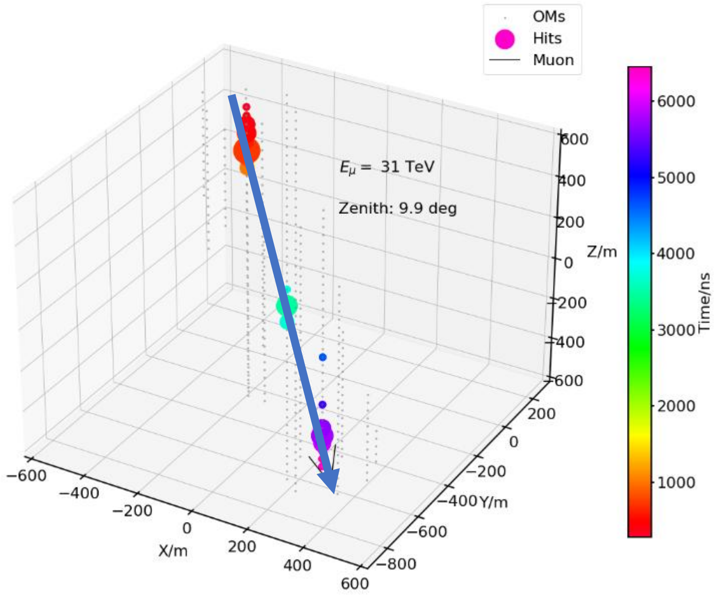
- ➢ 地中海ANTARES和加拿大P-one实验均观测到朝上看探头的探测效率：**~10%/year**下降（**由于表面污染**）
- ➢ 俄罗斯Baikal-GVD，**1年**朝上看的探头就失效。



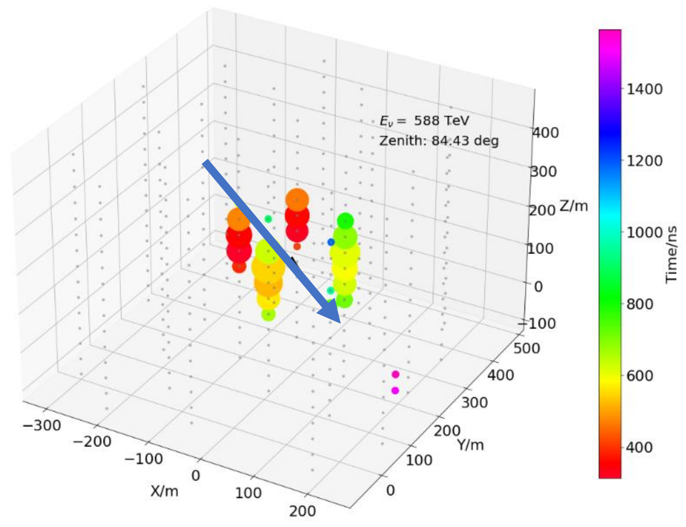
中微子簇射过程的光子角度分布



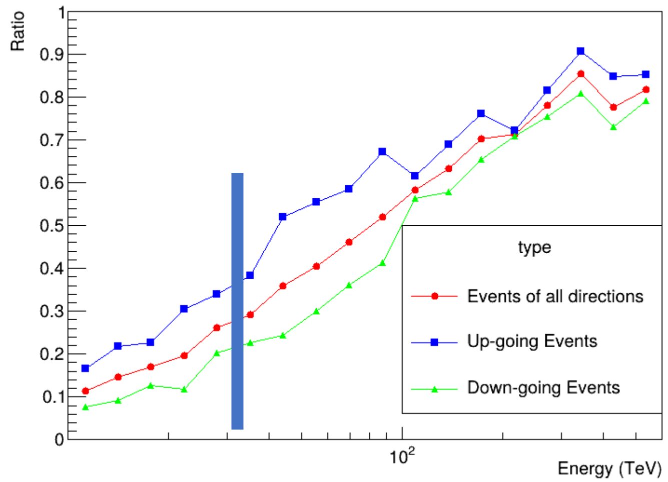
Sensitive to the neutrino events with all directions



向下的径迹型事例
（20多个单元着火）

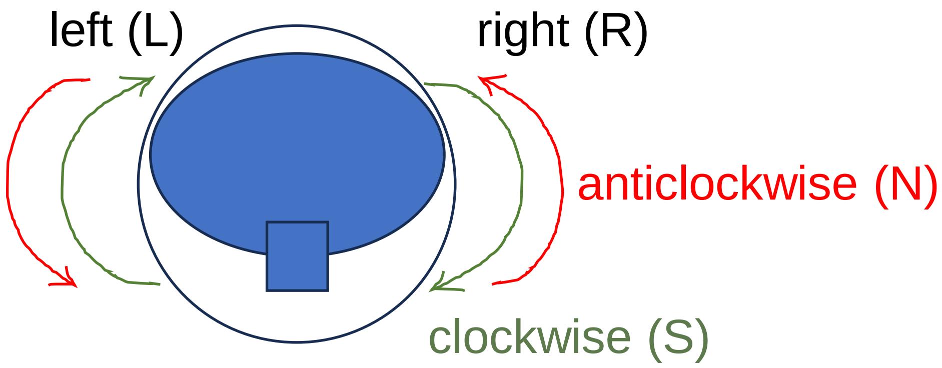


水平 簇射事例

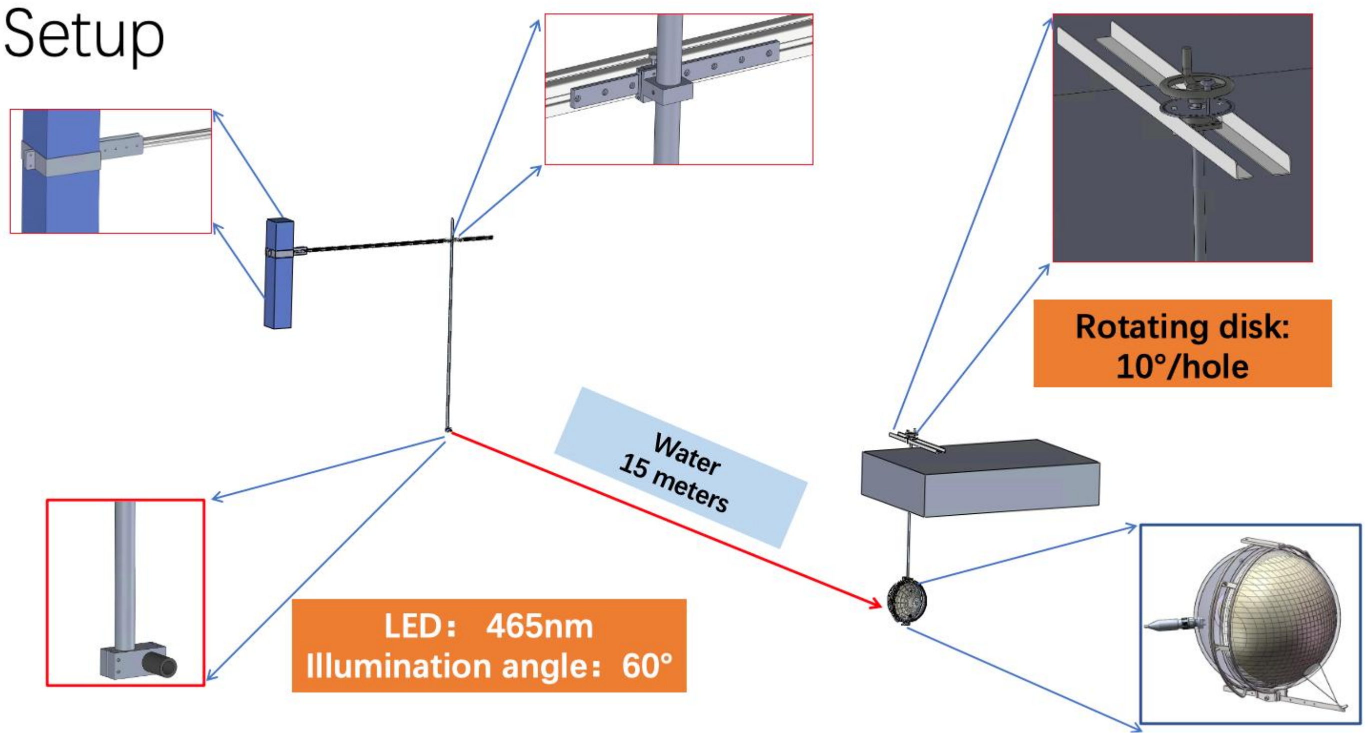


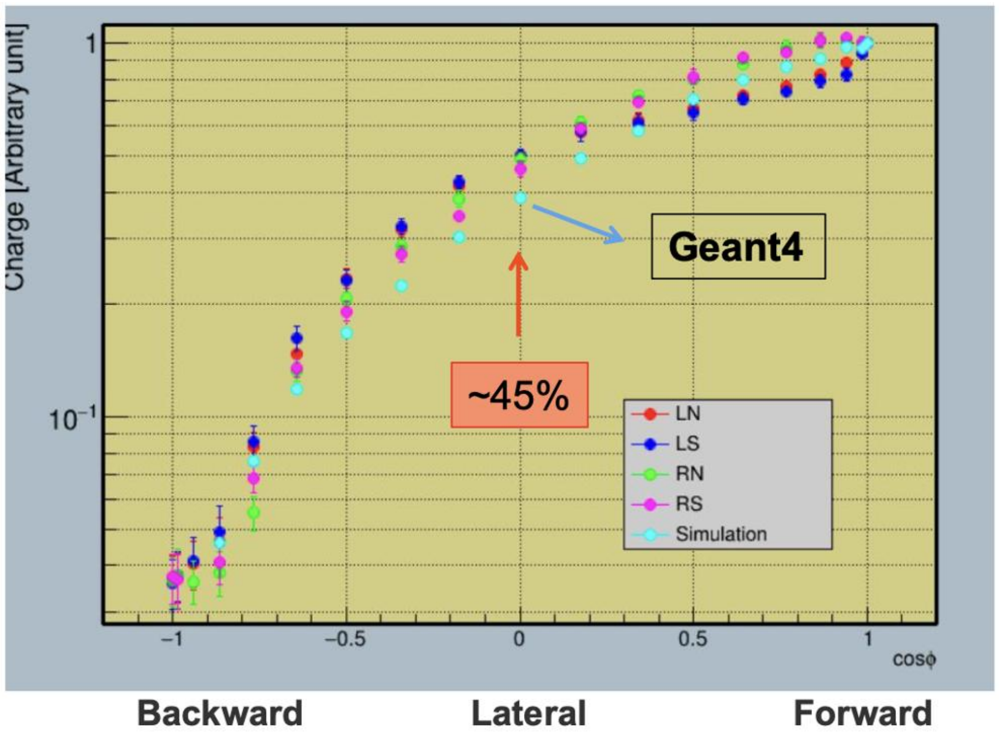
10-600TeV的全向ν_e事例探测效率
（反应顶点包含探测器内和探测器外）

Simulation | in-OM



Setup





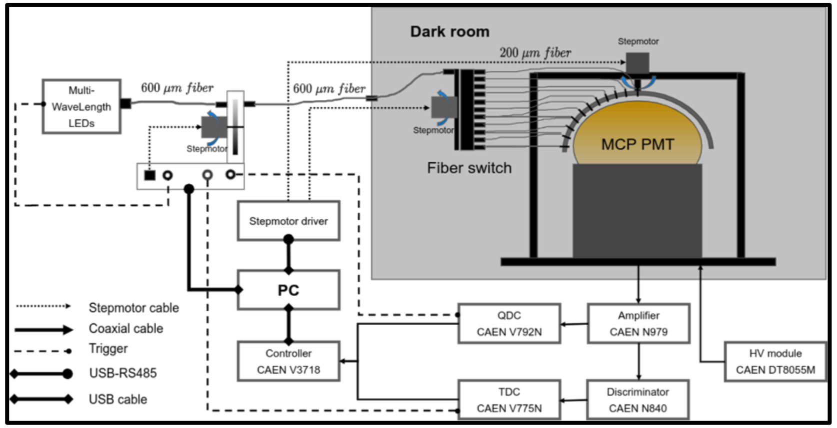
- Forward: 100%
- Lateral: 45%
- Backward: 3%

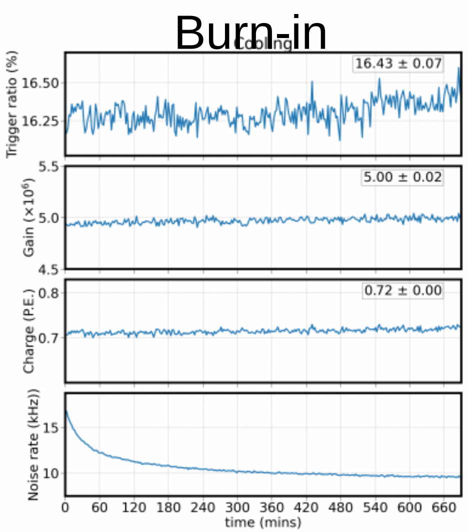
PMT tested in the lab.

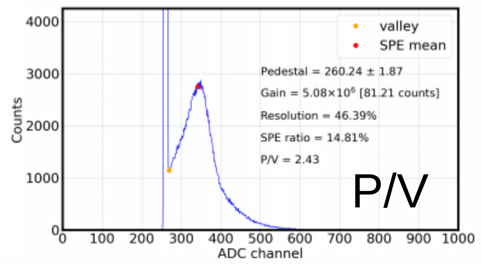
No. PAB2309-9035

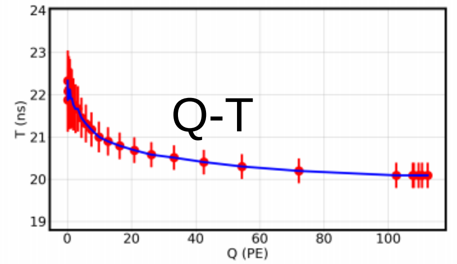
PMT type	20 SN MCP
Testing time	20231114_0919
Channel	
Tester	
Appearance	
Weight/kg	

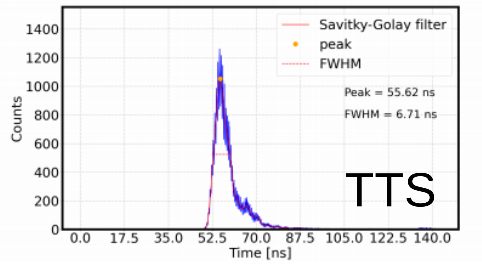
Item	IHEP	NVT
HV (V)	-1715	
Gain (1E6)	5.1	
SPE Ratio	14.8%	
SPE Resolution	0.5	
P/V	2.4	
RTT (ns)	55.6	
TTS (ns)	6.7	
Noise rate (kHz)	9.6	
Nonlinearity @ -2% @ 1khz (P.E.)	3095	
Nonlinearity @ -2% @ 2khz (P.E.)	1561	
Nonlinearity @ -2% @ 5khz (P.E.)	556	
Nonlinearity @ -5% @ 1khz (P.E.)	None	
Nonlinearity @ -5% @ 2khz (P.E.)	2103	
Nonlinearity @ -5% @ 5khz (P.E.)	795	

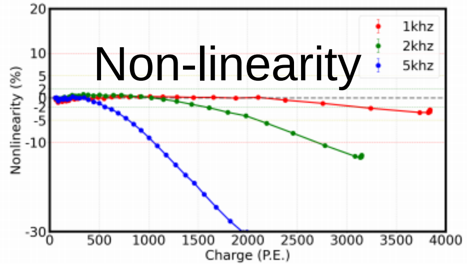


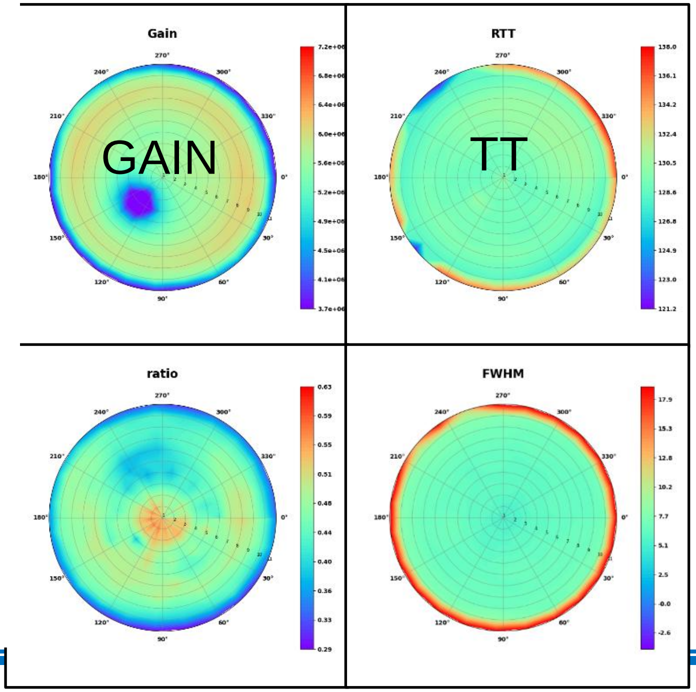












2D Scan