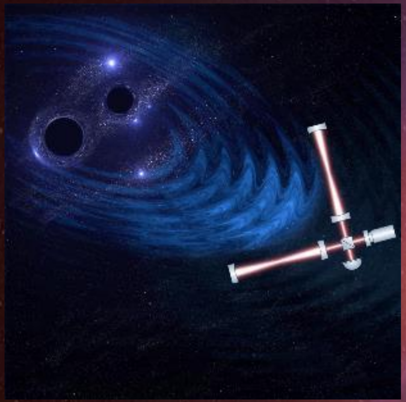
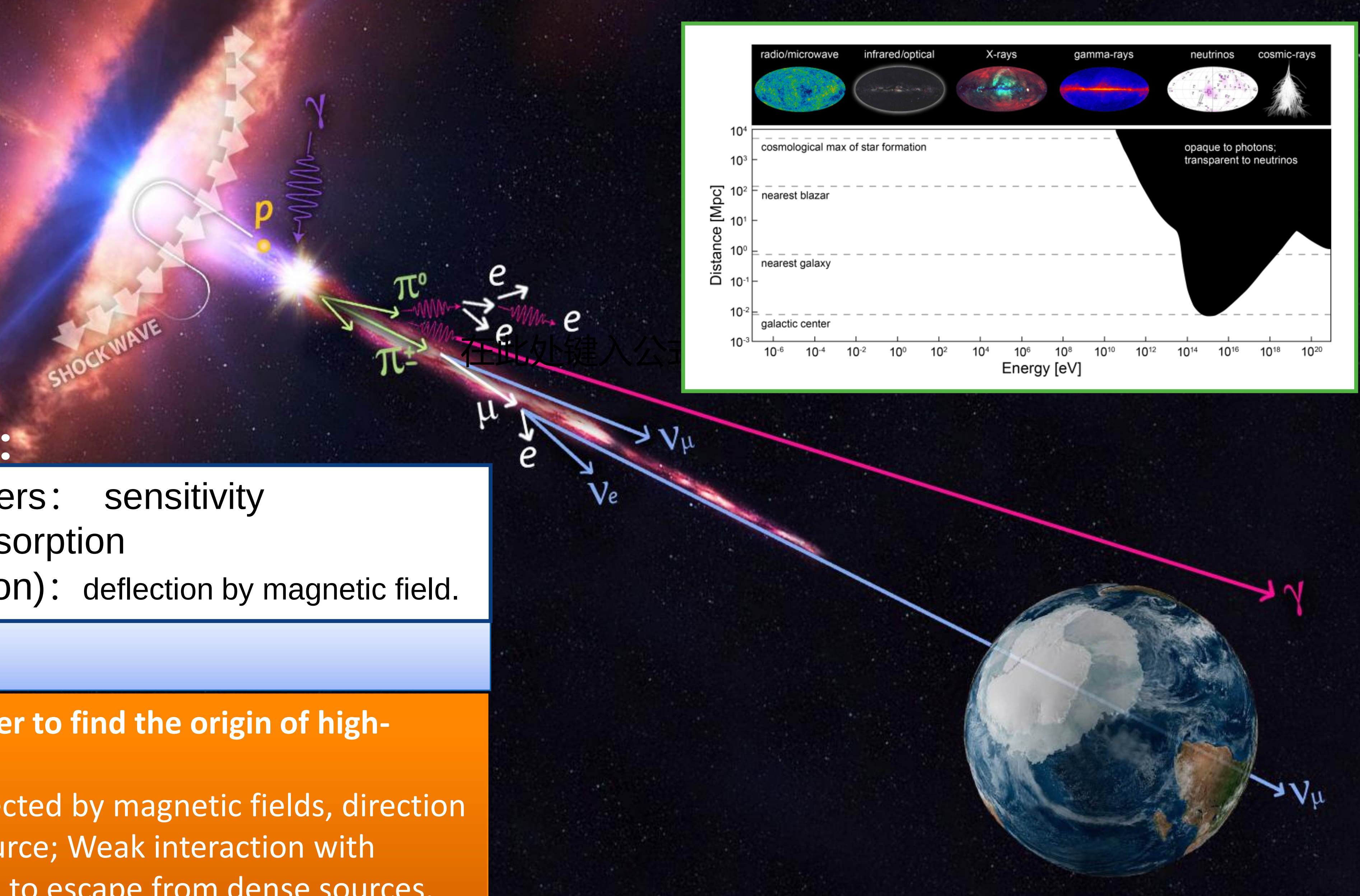
Neutrino Astronomy
—— Status and Prospects

Zhen Cao, IHEP

NOPP Workshop, IHEP, Beijing, Aug. 2026

Mutli-messager astronomy





Four Messagers:

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

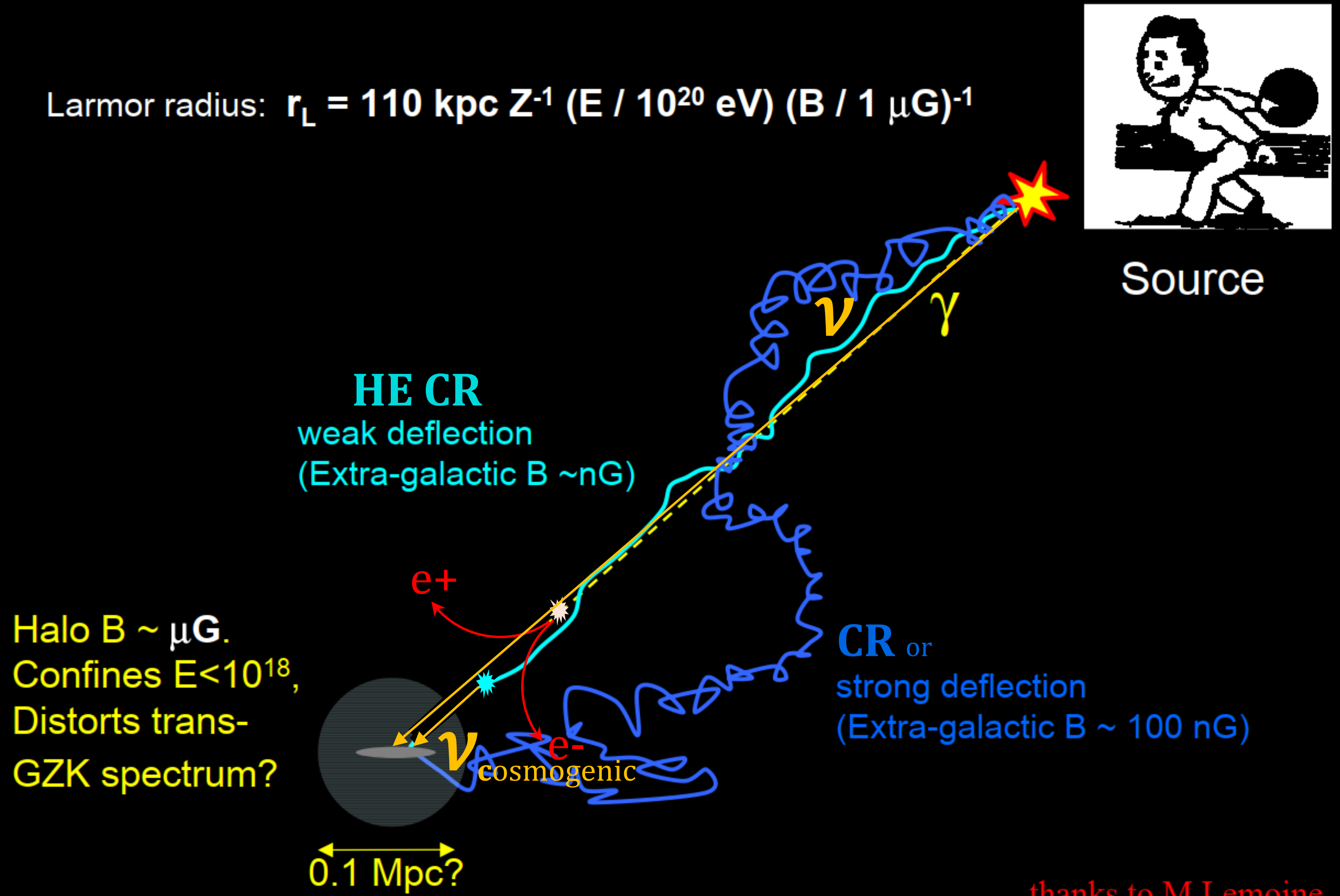
4. Neutrino

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.

Neutrinos are unique HE messengers from other galaxies

γ-rays are absorbed by CMB (E>1 PeV)

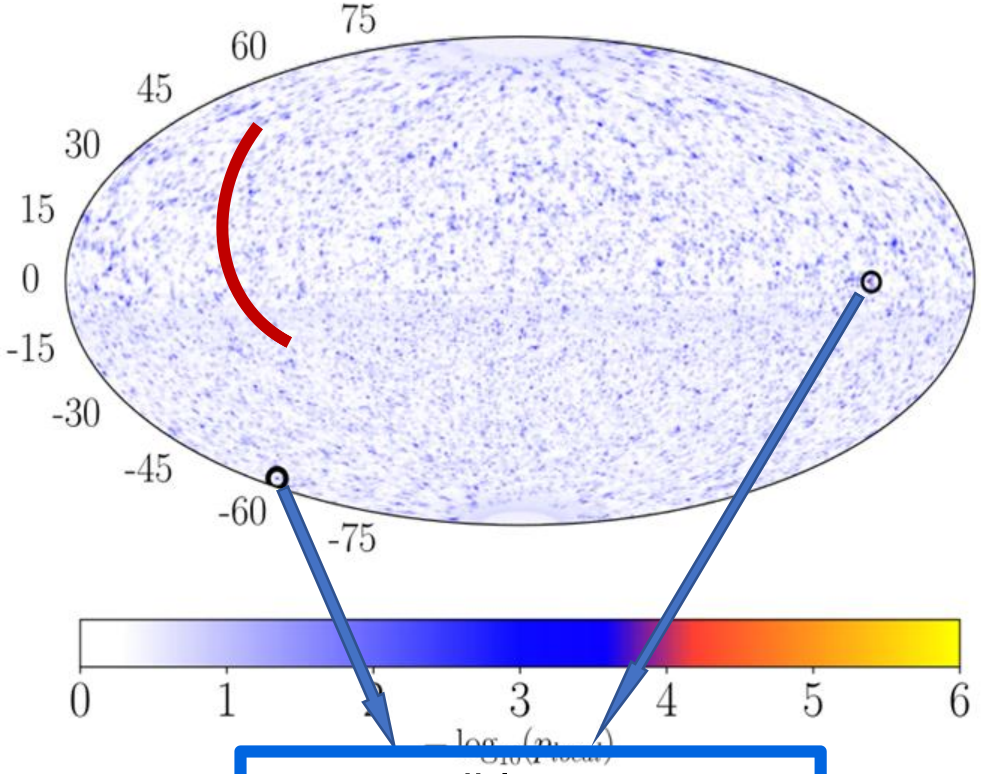
Larmor radius: r_L = 110 kpc Z^{-1} (E / 10^{20} eV) (B / 1 μG)$^{-1}$



thanks to M.Lemoine

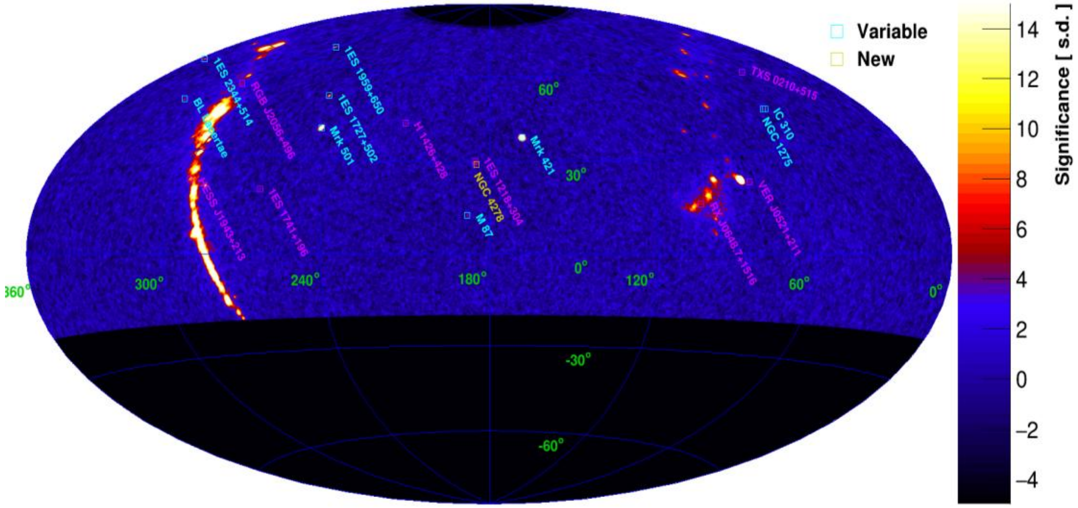
Neutrino Astronomy vs Gamma-ray Astronomy

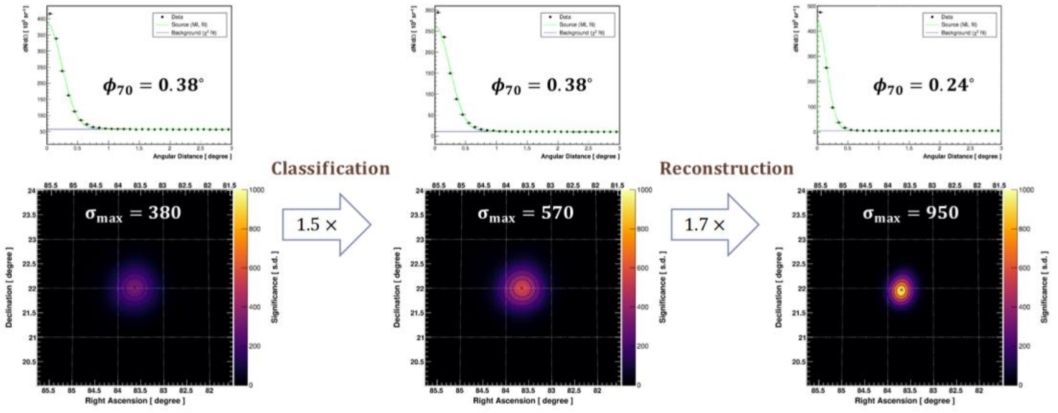
IceCube sky map with ~1M ν-**events**



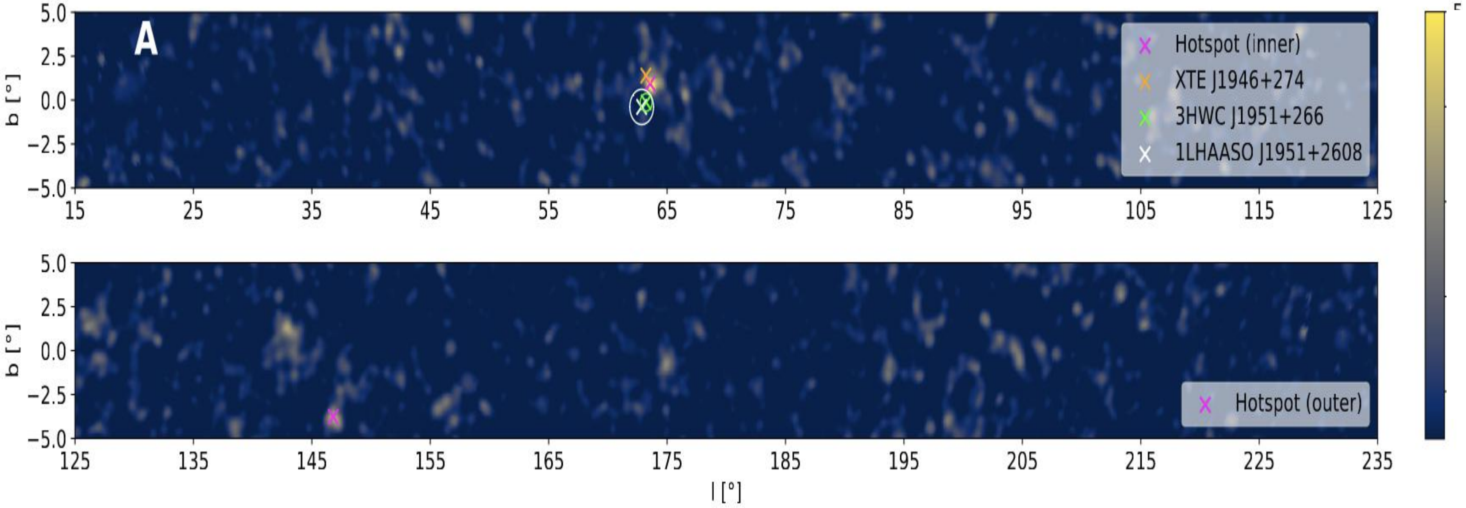
Two possible sources:
- NGC 1068 (4.2 σ)
- TXS 0506+056 (3.5 σ)

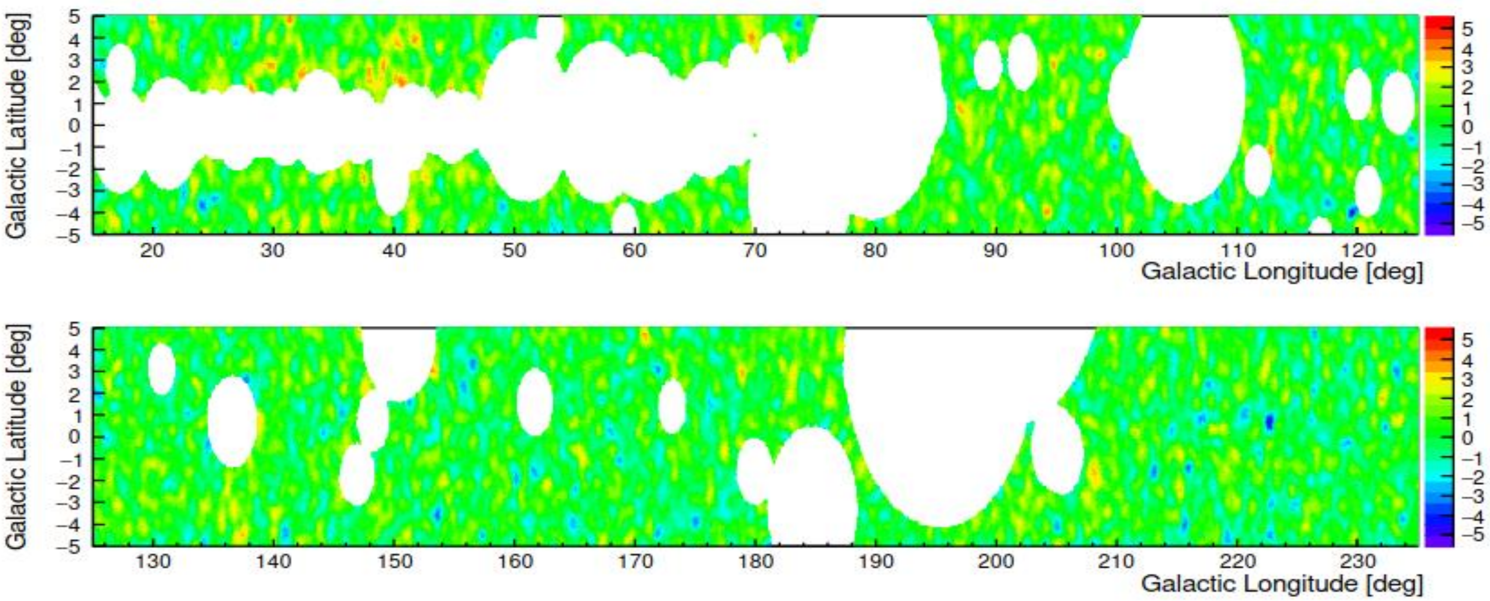
LHAASO γ-ray sky map with ~100 **sources**



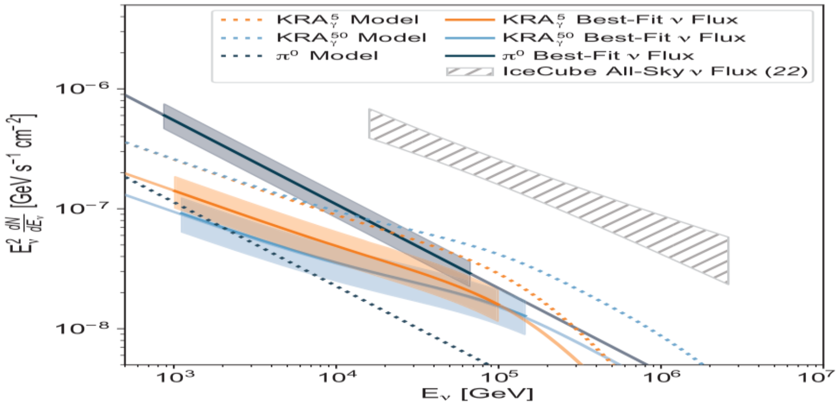


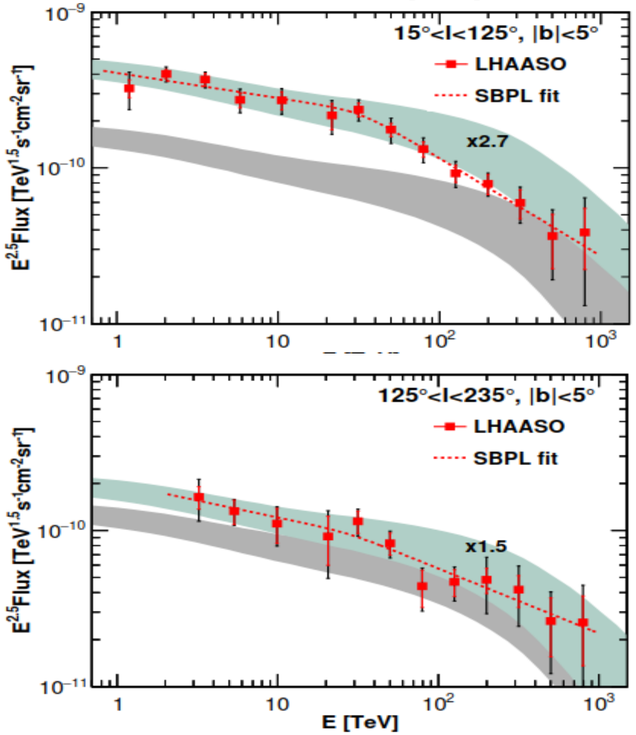
Galactic Plane





- **4.5σ by IceCube, strong model dependence**



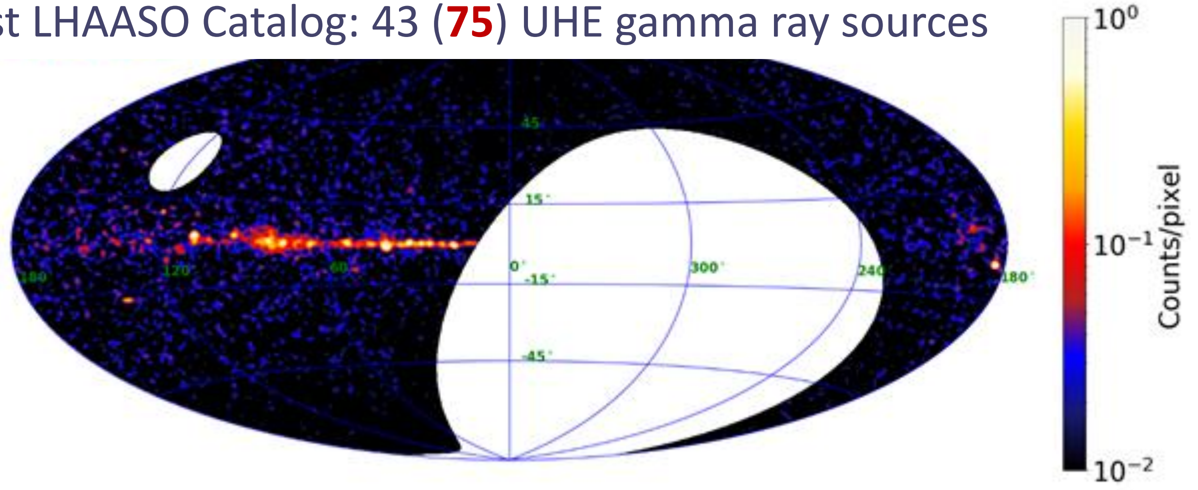


LHAASO measured γ-ray from the GP. Found big shortage if CRs assumed same as at the Earth

Strong Motivation of Detecting the Guaranteed ν-sources

LHAASO discovered ultra-high energy gamma ray sources (PeVatrons) within the Milky Way

1st LHAASO Catalog: 43 (**75**) UHE gamma ray sources



Many PeV photon sources favor hadronic origin

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

Main process:

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

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

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

$E_\gamma \approx 10\% E_p$ $\quad$ $E_\nu \approx 5\% E_p$

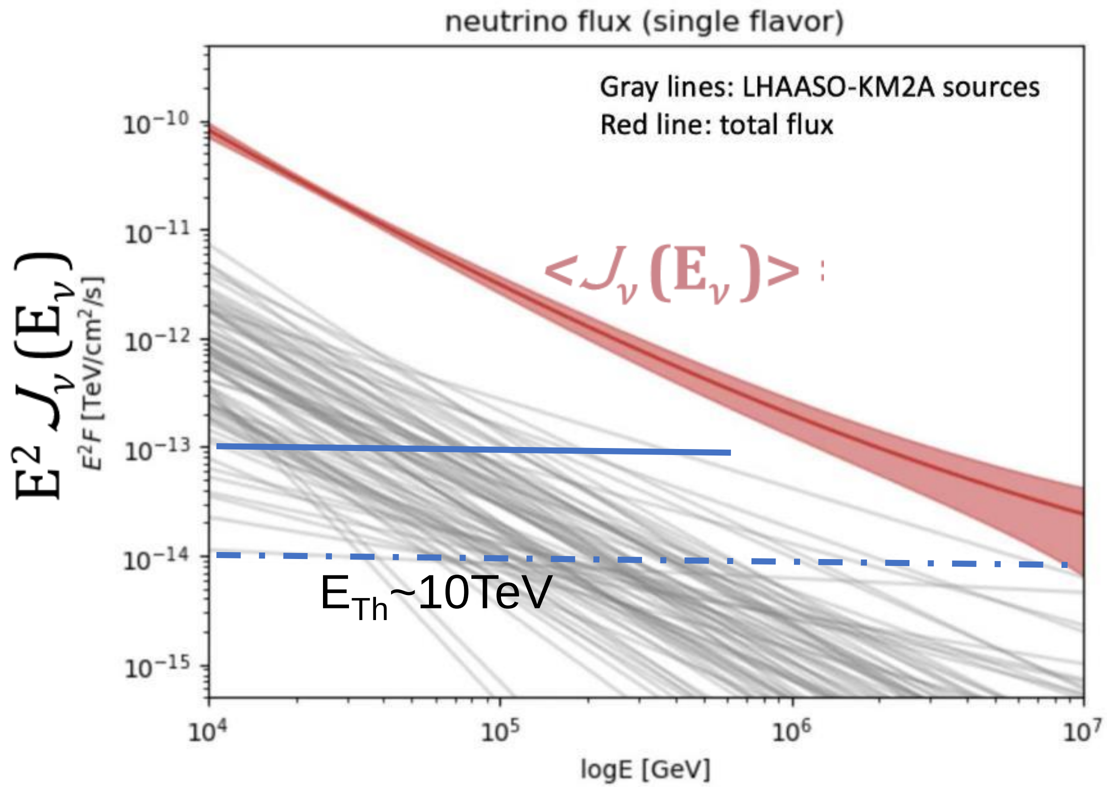
Simultaneous detection of neutrinos and photon signals, can point back to the source.

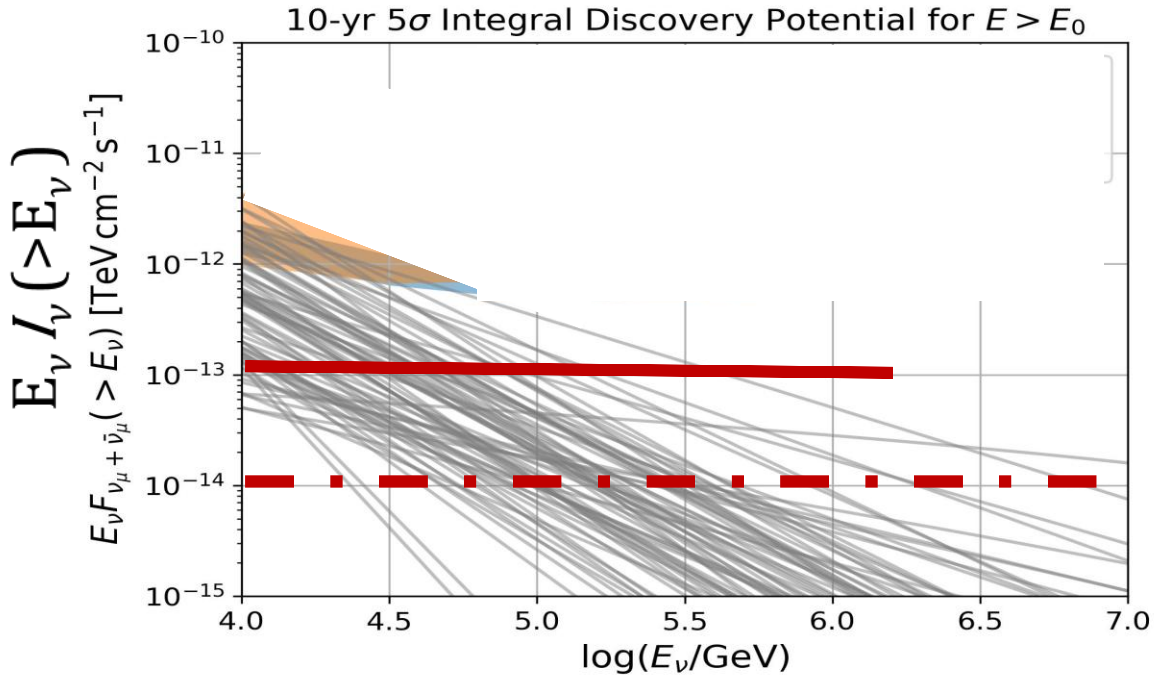
Completely solve the problem of the origin of high-energy cosmic rays!

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

Requirement for next generation NT

Discovery potential.





neutrino flux of 75 LHAASO sources:

$$J_\nu(E_\nu) = 2\, J_\gamma(2E_\nu)$$

$$\langle J_\nu(E_\nu)\rangle = \sum_{i=1}^{75} J_{\nu i}(E_\nu)/75$$

Integrated flux of 75 sources:

$$E_\nu I_\nu(>E_\nu) = \int_{E\nu} J_\nu(E_\nu)\, d\, E_\nu$$

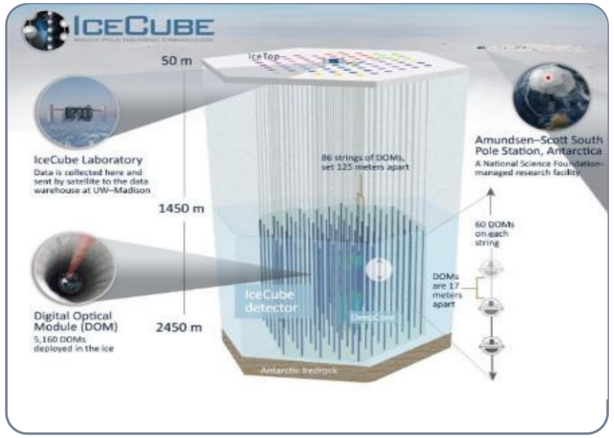
How to detect astrophysical neutrinos?

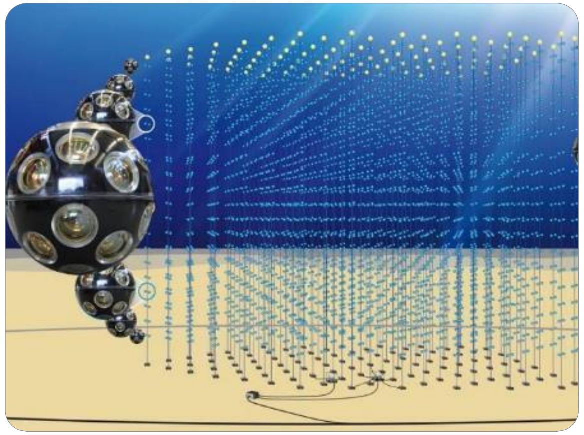
We propose to install detectors deep in a lake or in the sea and determine the direction of charged particles with the help of Cherenkov radiation.
M.A. Markov， 1960

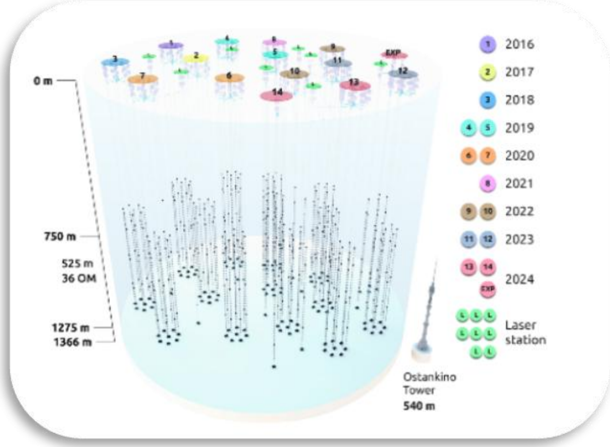
Detector’s requirement:

1) Billions of cubic meters of massive transparent medium: water or ice!
2) Detectors need to be placed under a kilometer of water. In the ocean, areas within a thousand meters underwater are easily affected by sunlight and biological influences.
3) Need to build a three-dimensional detector to measure the direction and energy information of neutrino events.

Status | international HE neutrino Telescope







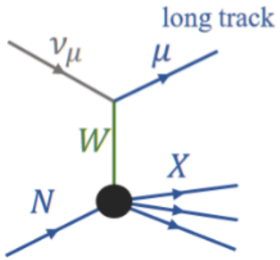
	IceCube	**KM3NeT-ARCA**	**Baikal-GVD**
	Construction from 2003 to 2010, On-working now.	28/230 strings are deployed.	14 clusters deployed.
Medium	Ice	Ocean	Lake
Volume	1 km^3	1 km^3	0.8 km^3 (phase-1)
	2500 m	3500 m	1366 m
Cost	280M Dollars	240M Euro	—

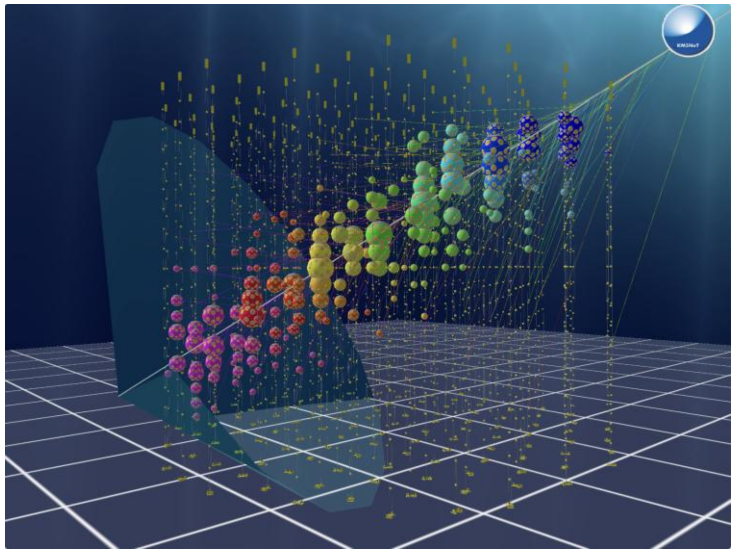
IceCube-Gen2 ~ ×8 →

But effective volume is probably still NOT sufficient to detect LHAASO sources

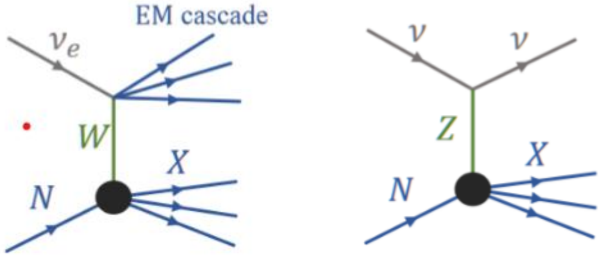
Three morphologies of neutrino events in detectors

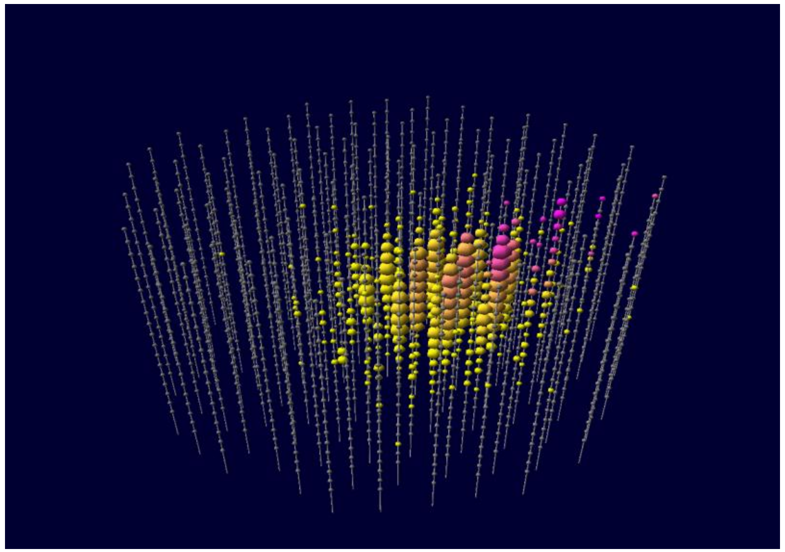
μ neutrino charged current processes



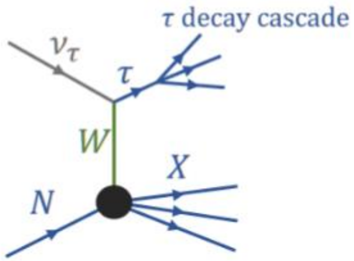


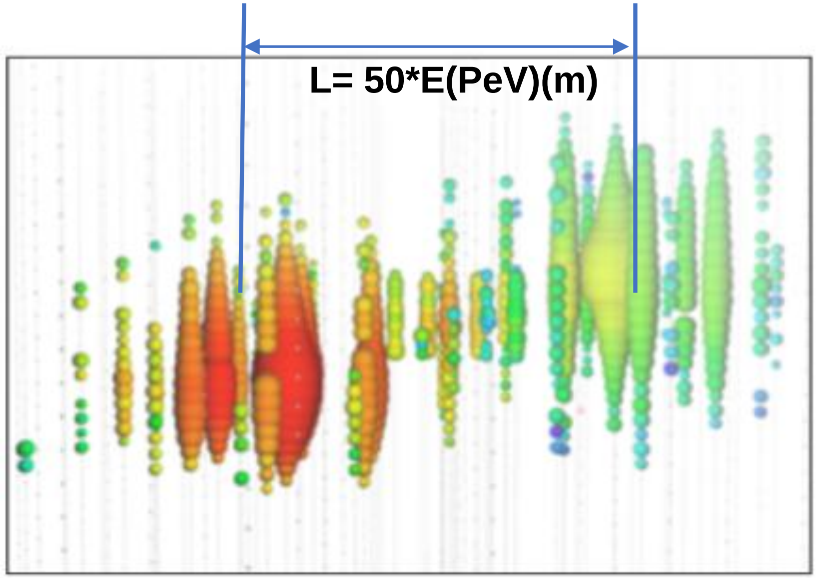
e neutrino charged current processes and neutrino neutral current processes





τ neutrino charged current processes





Track events

Cascade events

Double-bang events

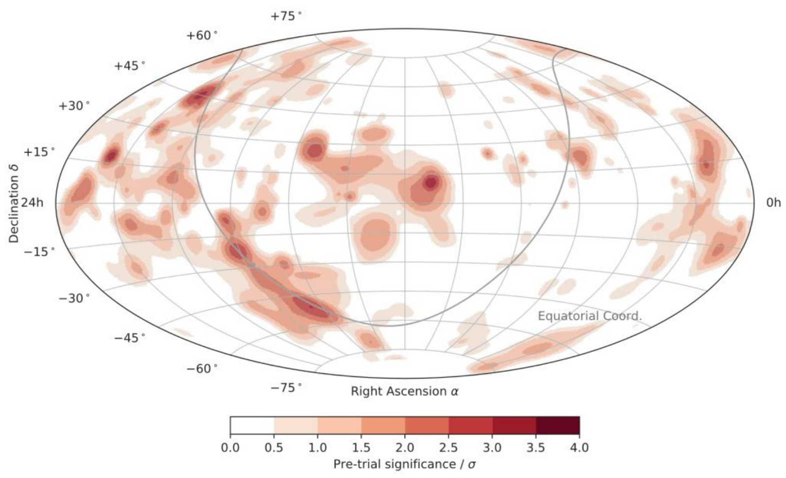
Overview of scientific progress

- **2013 The first discovery of astrophysical high-energy neutrinos.**

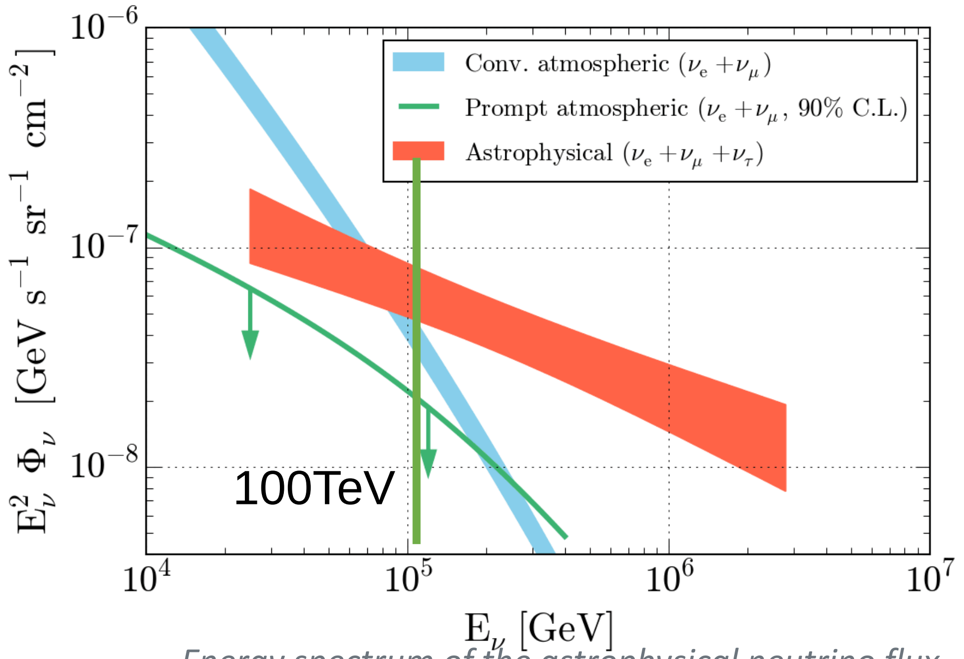
2018 First hint of association between neutrino excess and blazar TXS 0506+056 (3.5σ).

2019 The neutrinos from Seyfert II Galaxy NGC 1068 exceed the background at the level of 2.9σ.

- **2023 Signs of diffuse neutrinos in the milky way， ~4 σ**

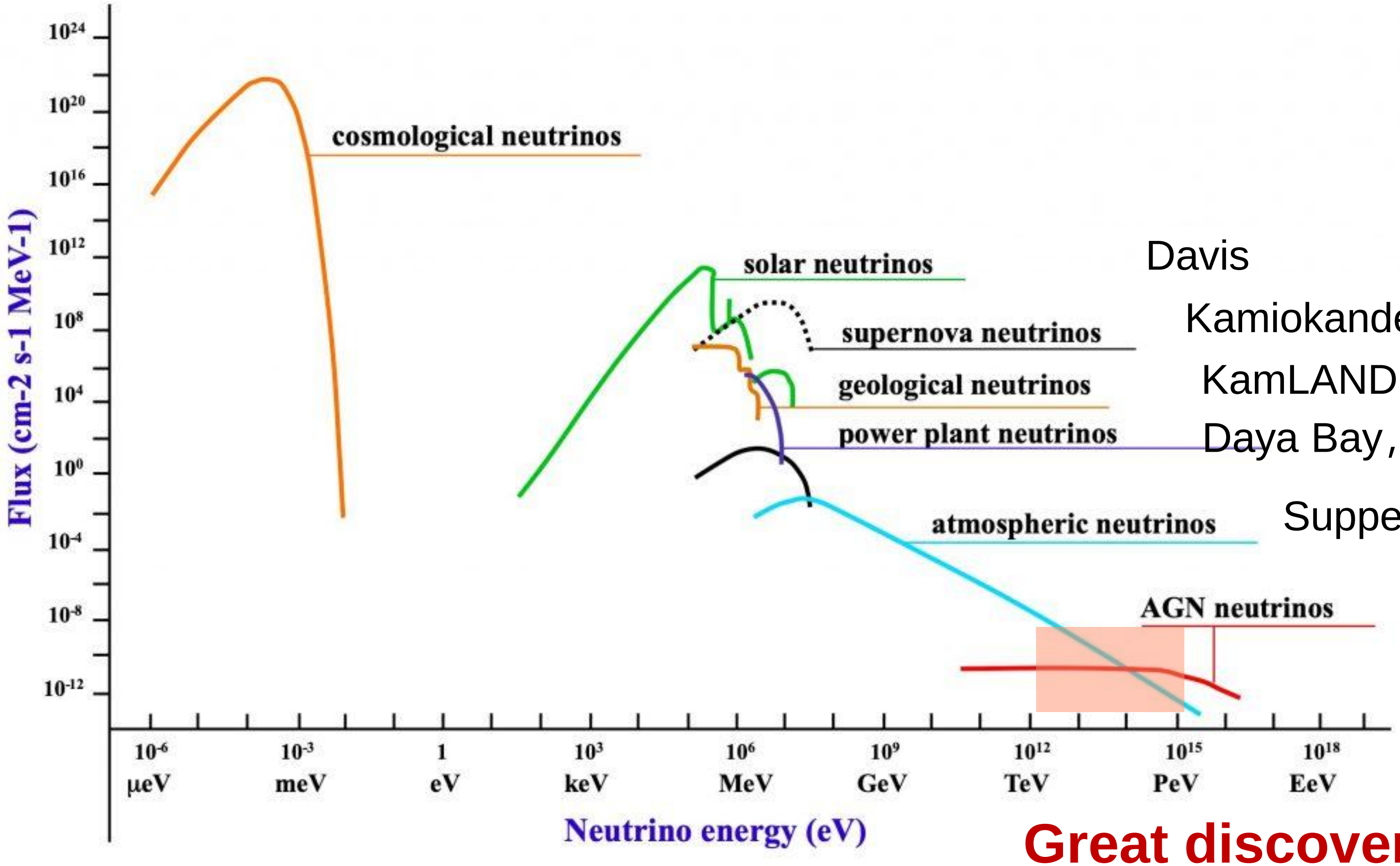


IceCube, ***SCIENCE***, Vol 380, Issue 6652



Energy spectrum of the astrophysical neutrino flux

Neutrino sources with different energy



Davis

Kamiokande, ……

KamLAND

Daya Bay, Reins & Clyde

Supper-Kamiokande, NT, IceCube …

IceCube, Baikal-GVD, KM3NeT……

Great discovery power
for extra-galactic ν-sources

Design of HUNT

Optical module with 20-inch PMT

2,220 20-inch PMTs installed in LHAASO

TTS: ~7ns; QE: >25%

P/V: >2; Q: >100C

Wide dynamic range : 1 - 2,000 P.E.

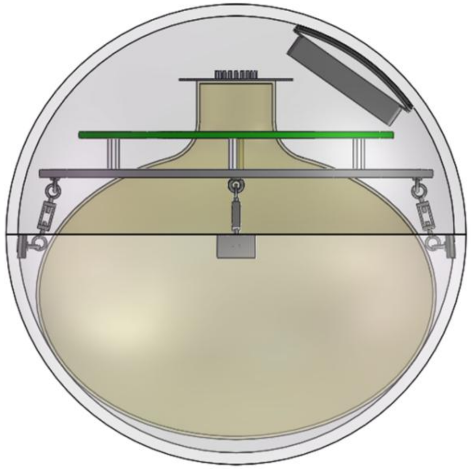
The OM uses 20-inch PMT

The PMT is sealed in a 23-inch glass sphere

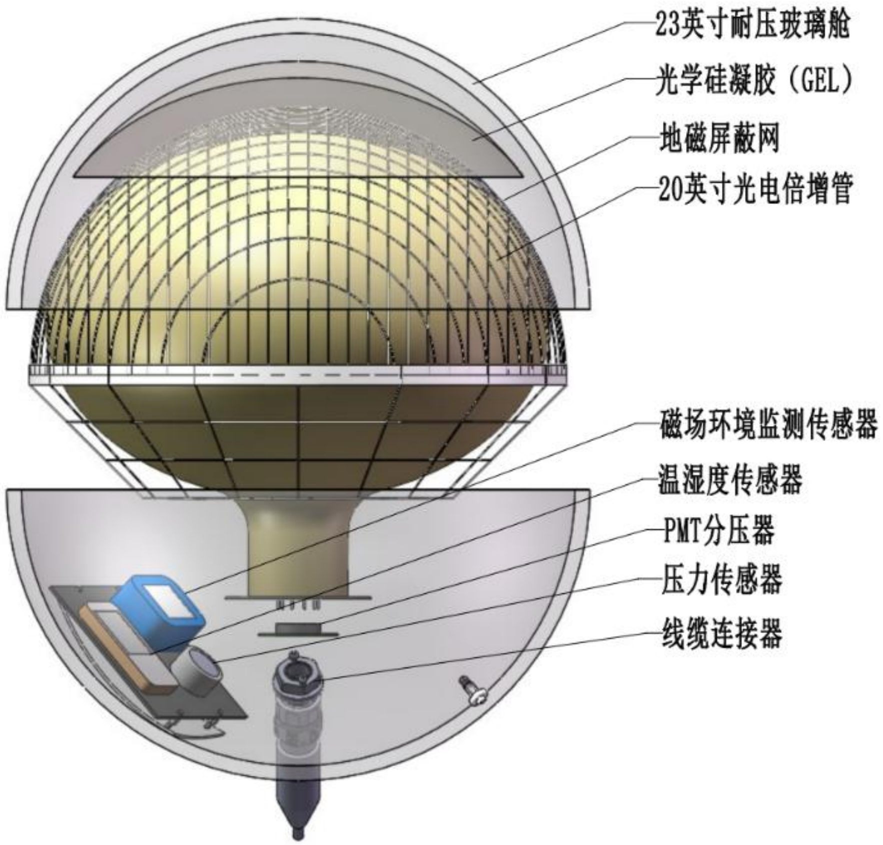
- Large photosensitive surface

  Enlarge spacing between OMs

  Enlarge volume with the same number of PMTs



Design of Optical module



20-inch PMT

Other experiments：3、8 or 10-inch

Simple, efficient and stable !

HUNT sketch map

- 2554 strings, or 864 strings with 50k OMs
- Length of string 720 m, or 1900 m
- Vertical spacing 36 m, or 30 m
- Horizontal spacing between strings ~130m
- ~30 cubic Kilometers

Specifications:

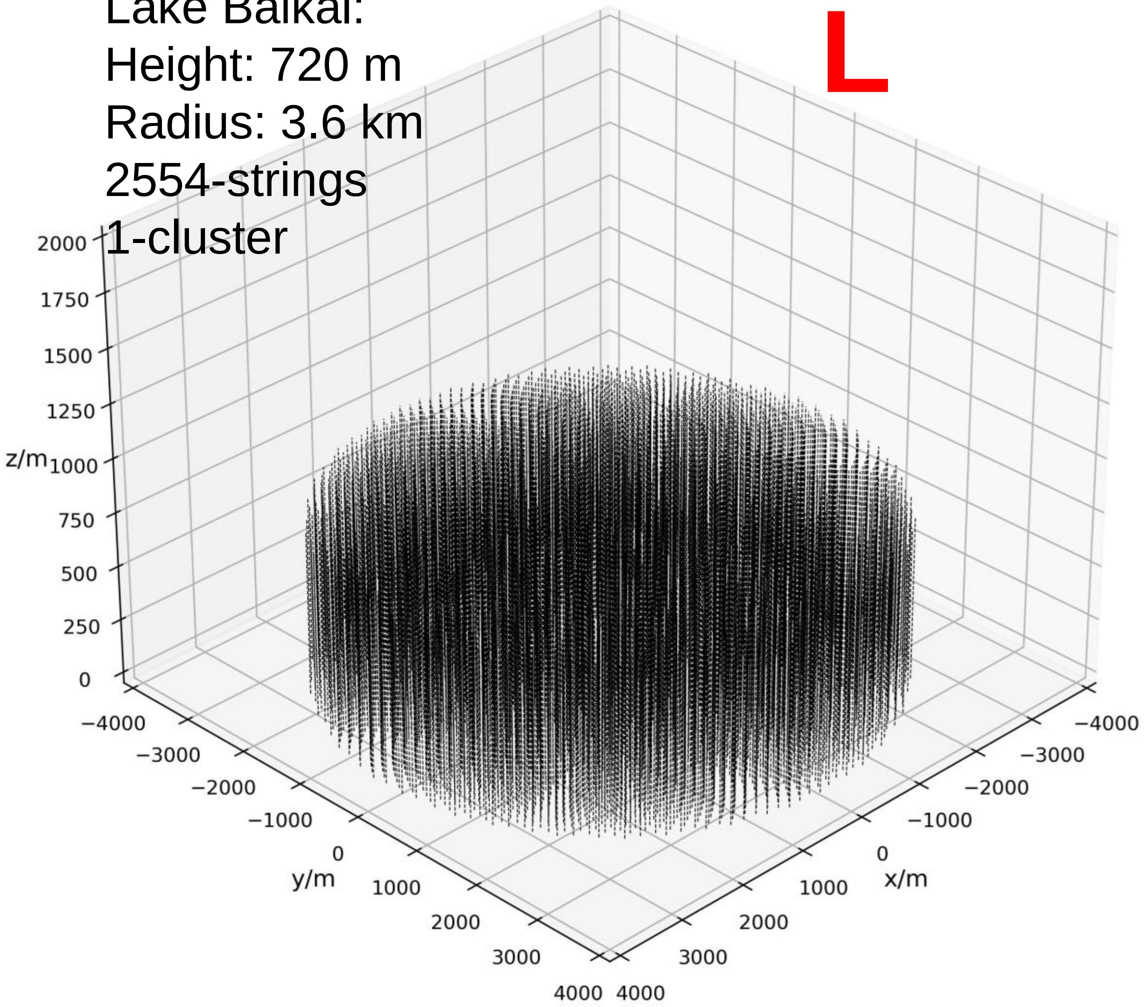
Angular resolution: ~0.1° (tracks), <3°(cascades)

Energy resolution: ΔlogE~0.3(tracks), ΔE~10-30% (cas.)

Configurations of HUNT

Lake Baikal:
Height: 720 m
Radius: 3.6 km
2554-strings
1-cluster

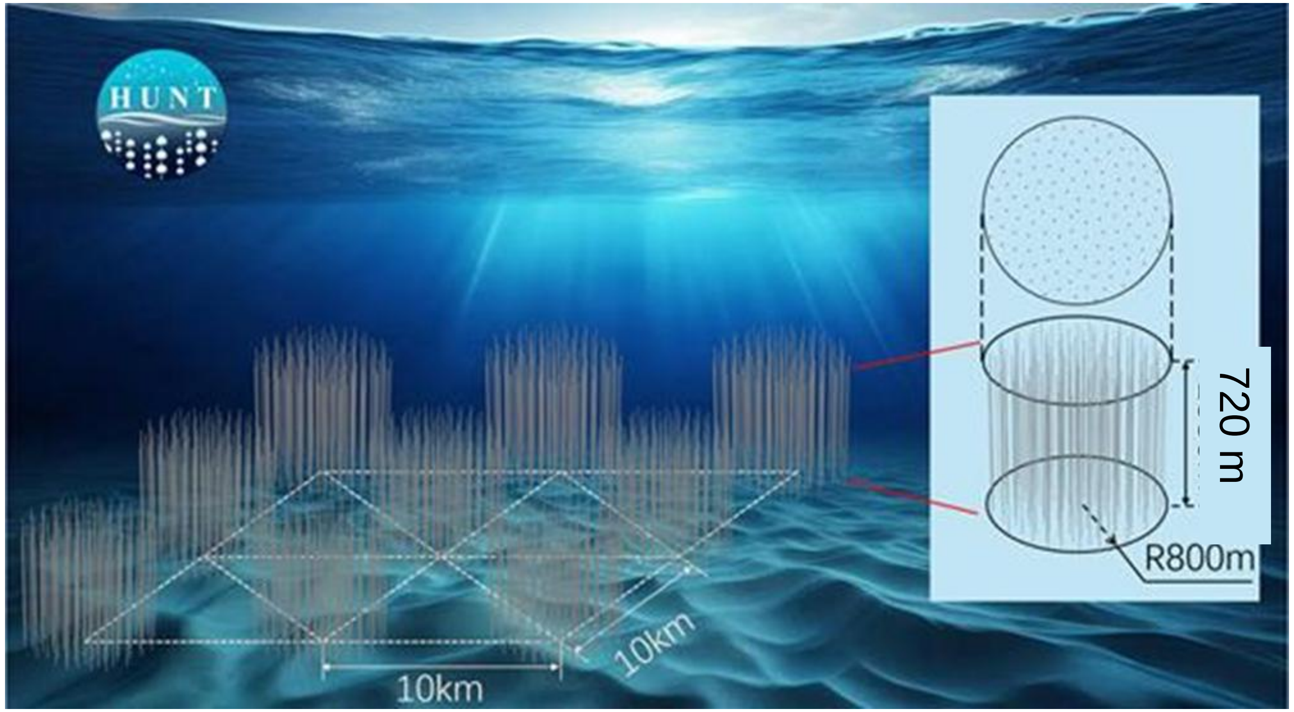
L



Alternative deployment:

9 clusters of strings
0.1° resolution is
required by each

O

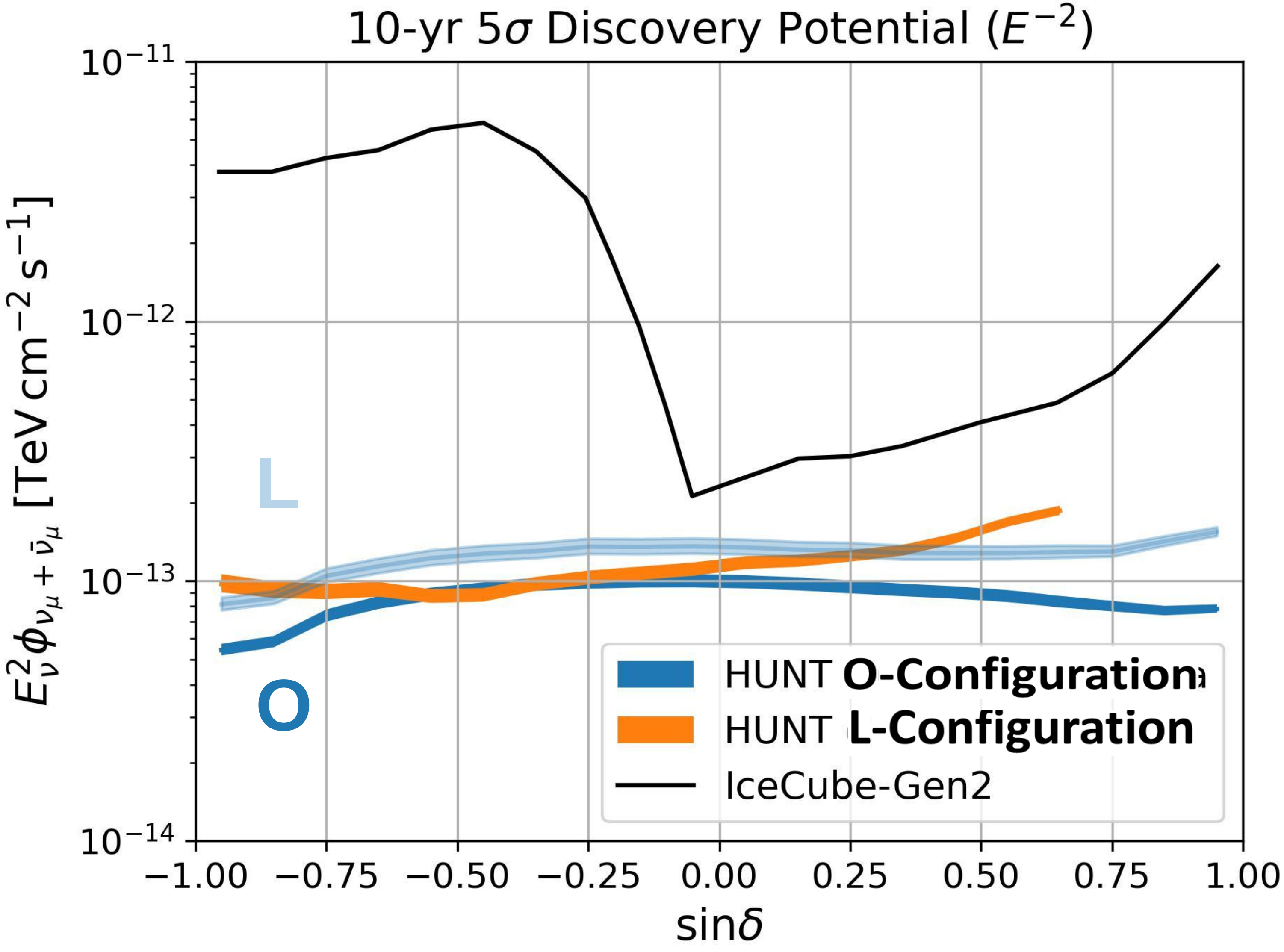


Expectation on Galactic Source Detection

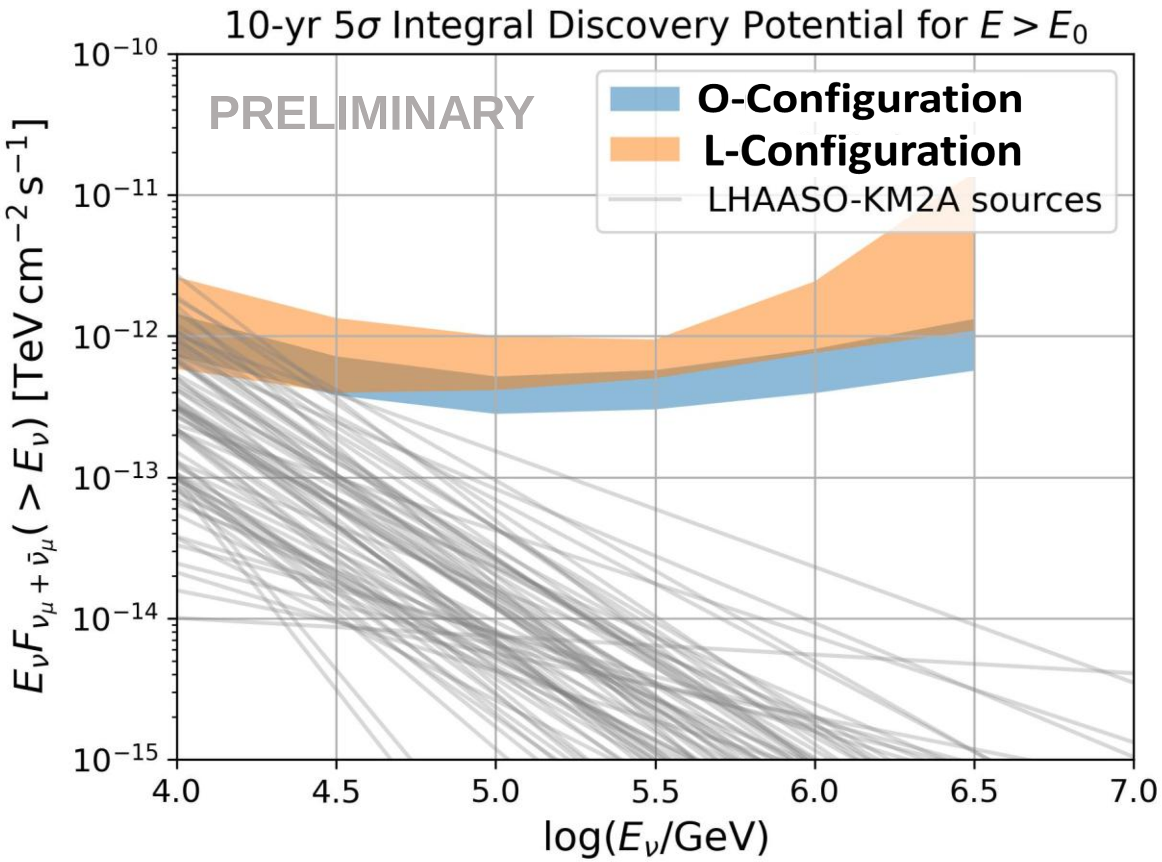
Discovery Potential for point source

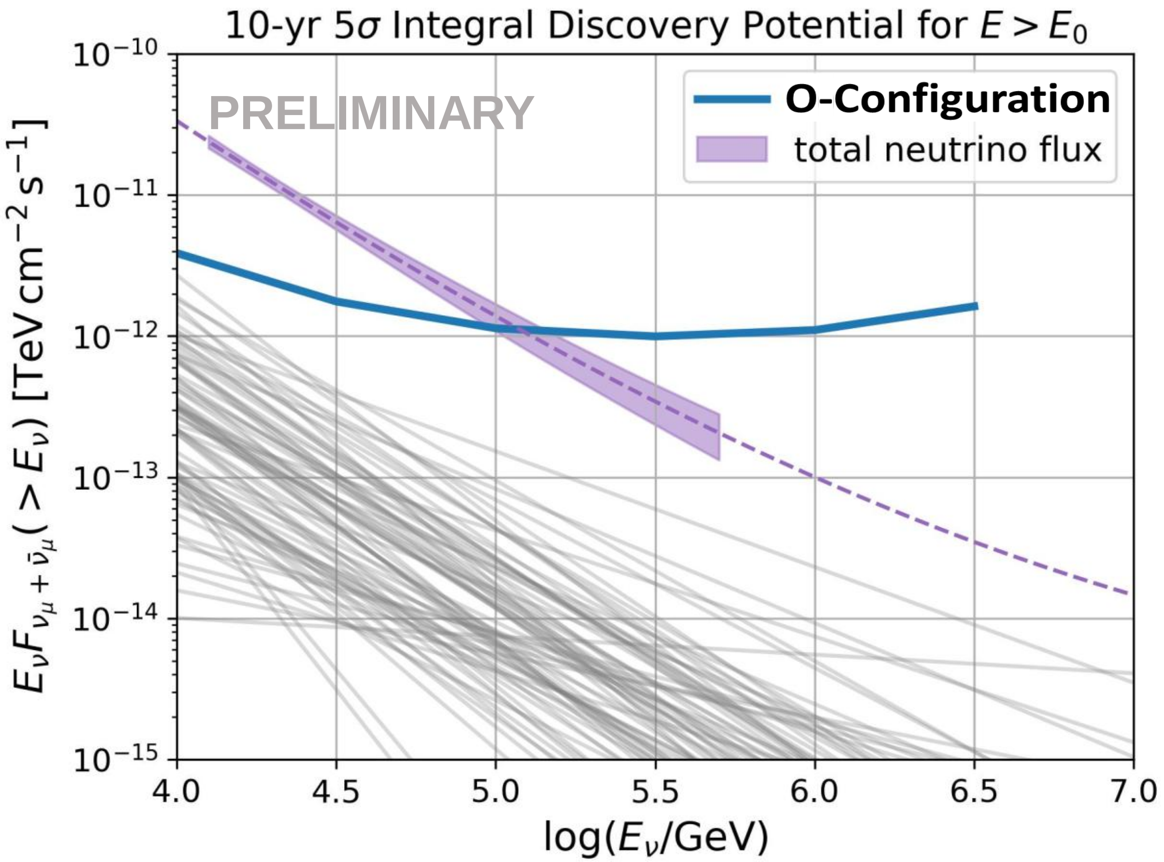
Up-going track events (zenith > 80 deg)

- angular resolution
  - similar to KM3NeT-ARCA
- energy resolution ΔlogEμ ~ 0.3
- detection efficiency
  - 10% @ Eμ = 1 TeV
  - 50% @ Eμ = 10 TeV
  - 97% @ Eμ = 100 TeV



Sensitivity estimate and Stacking LHAASO sources



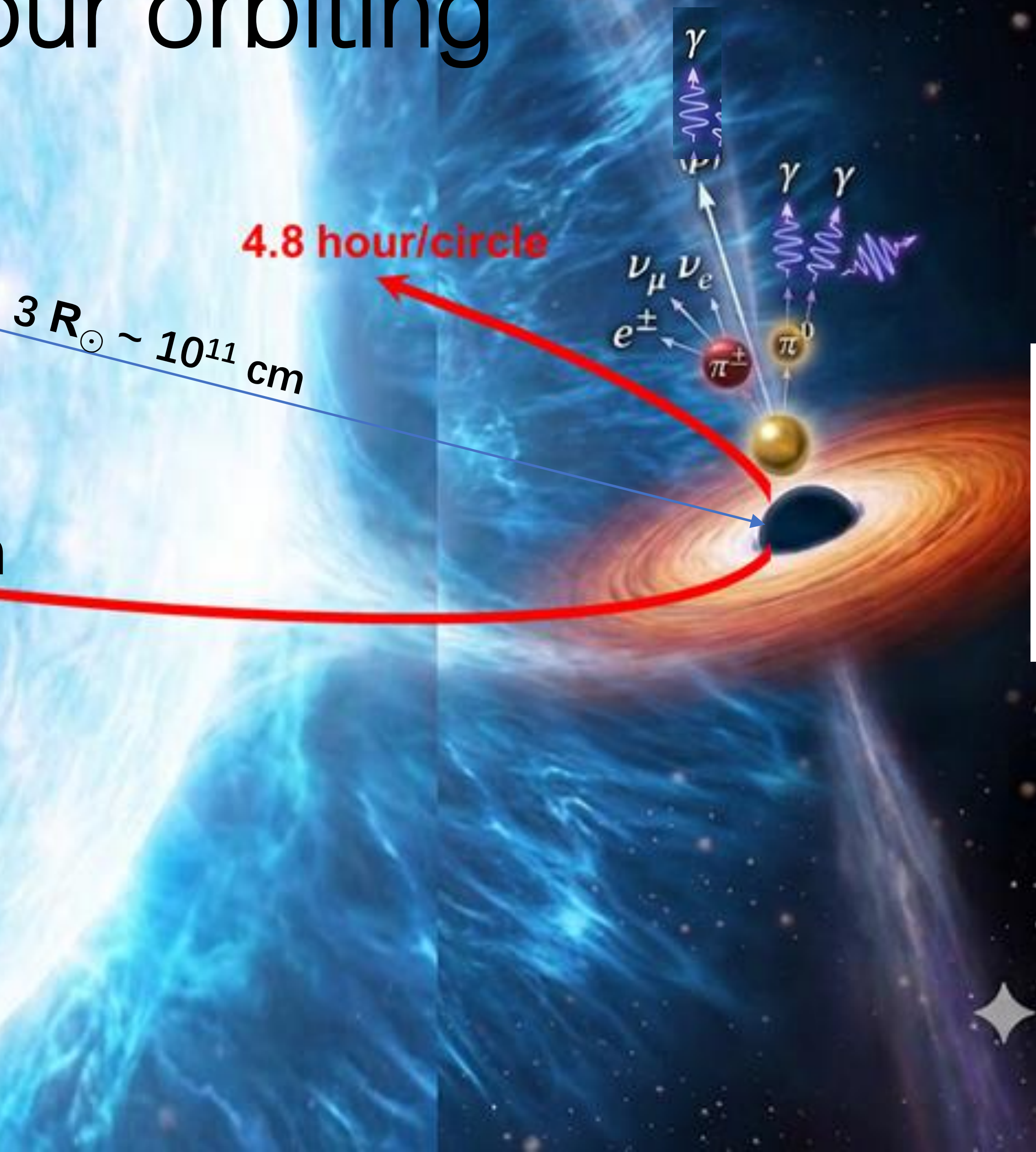


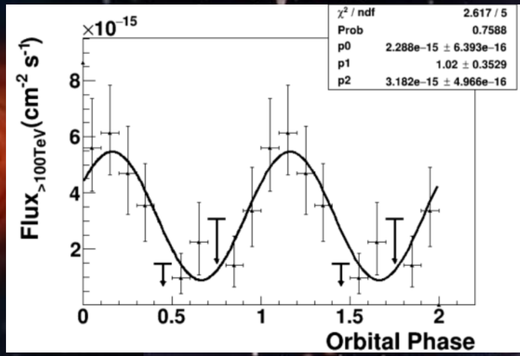
1LHAASO catalog: 75 KM2A sources
- median spectral index γ = 3.47,
- median source extension 0.26°

Cyg X-3： 4.8 hour orbiting

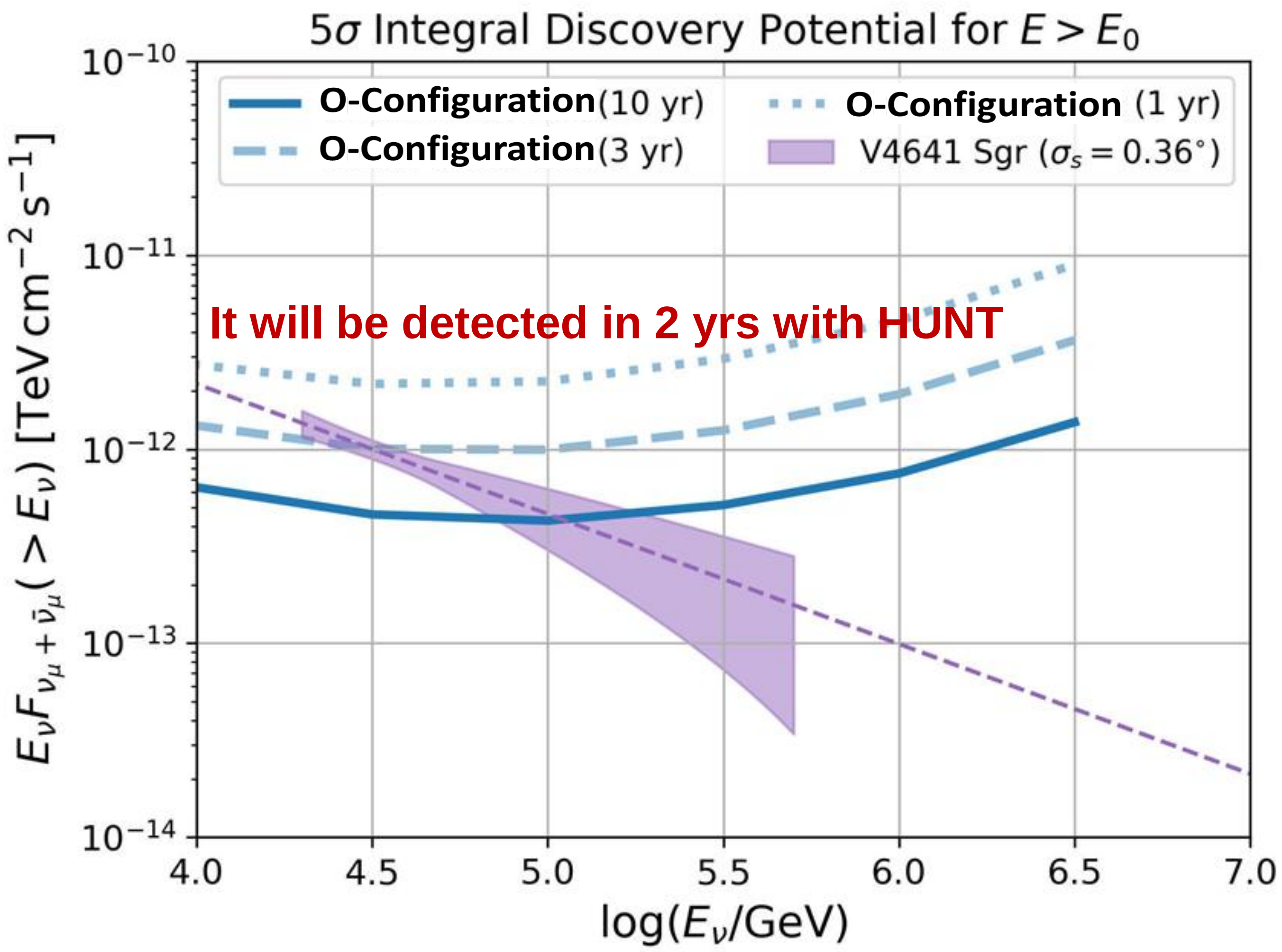
- This guarantees the proton accelerator
- ~4 PeV photons implies 40 PeV proton A super-PeVatron:
- For Protons >40 PeV, radiation mechanism:

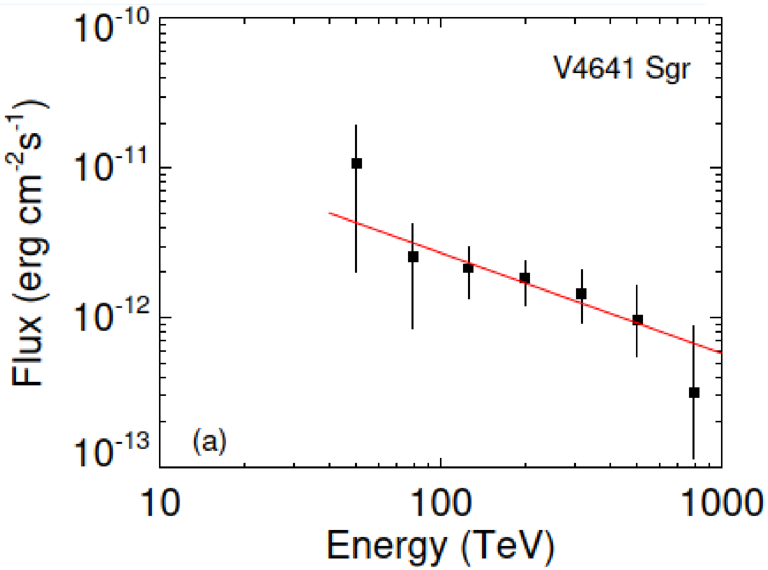
proton-γ scattering

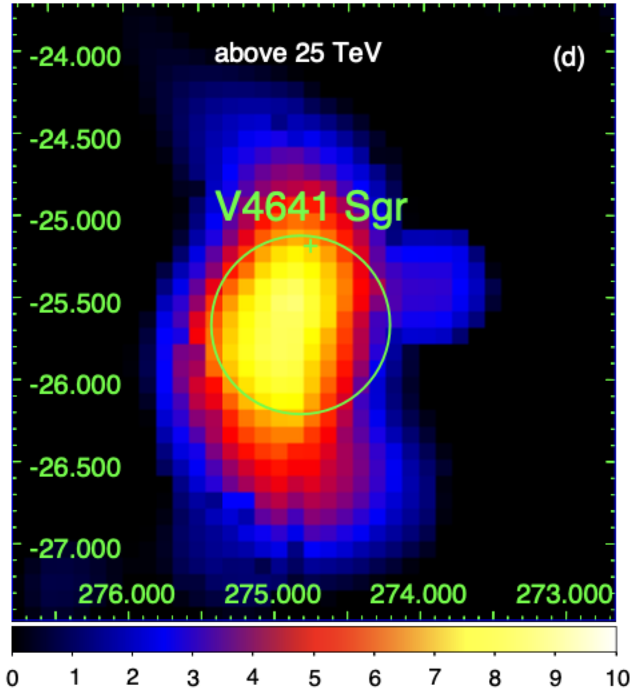




Good News: V4641 Sgr

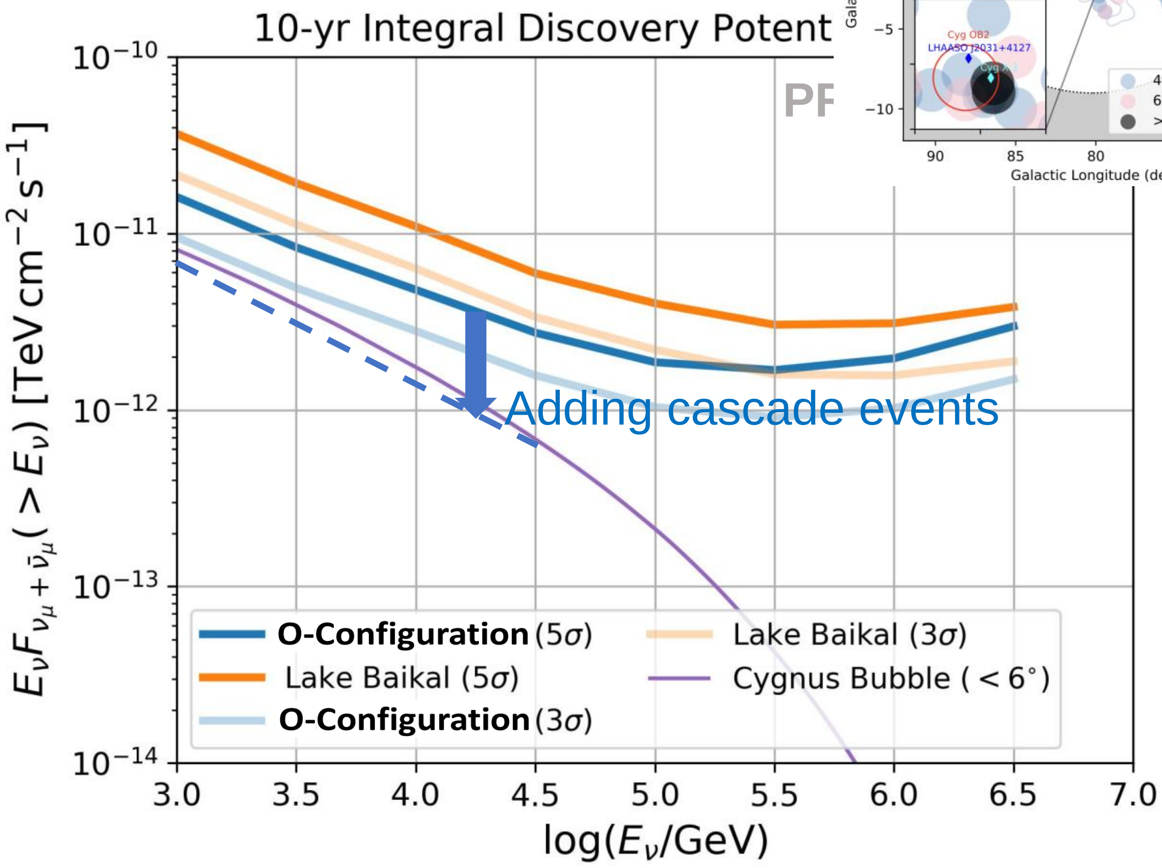


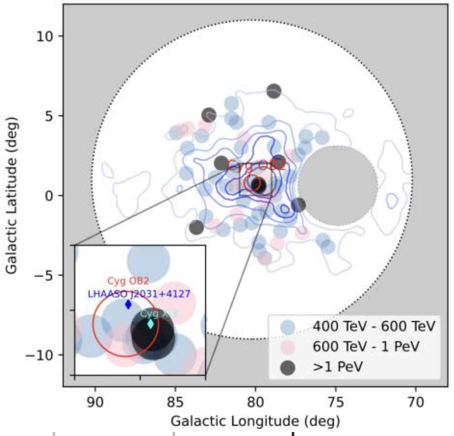


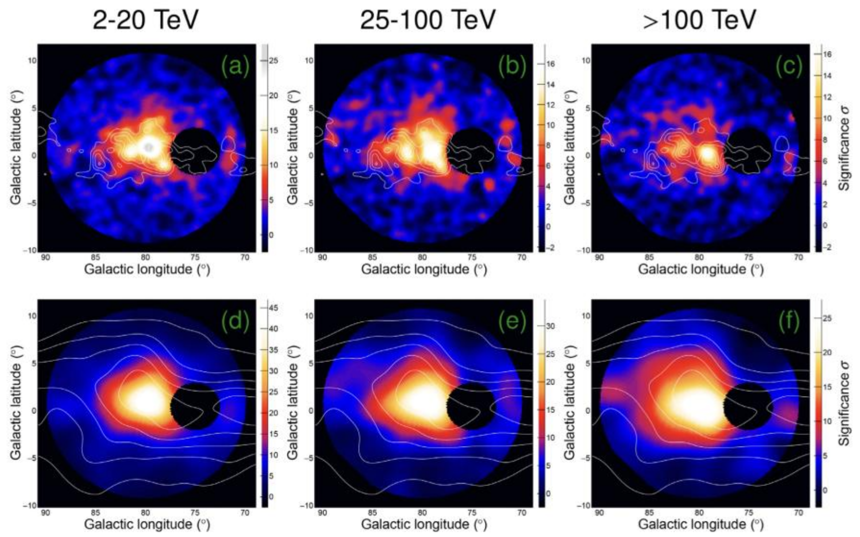


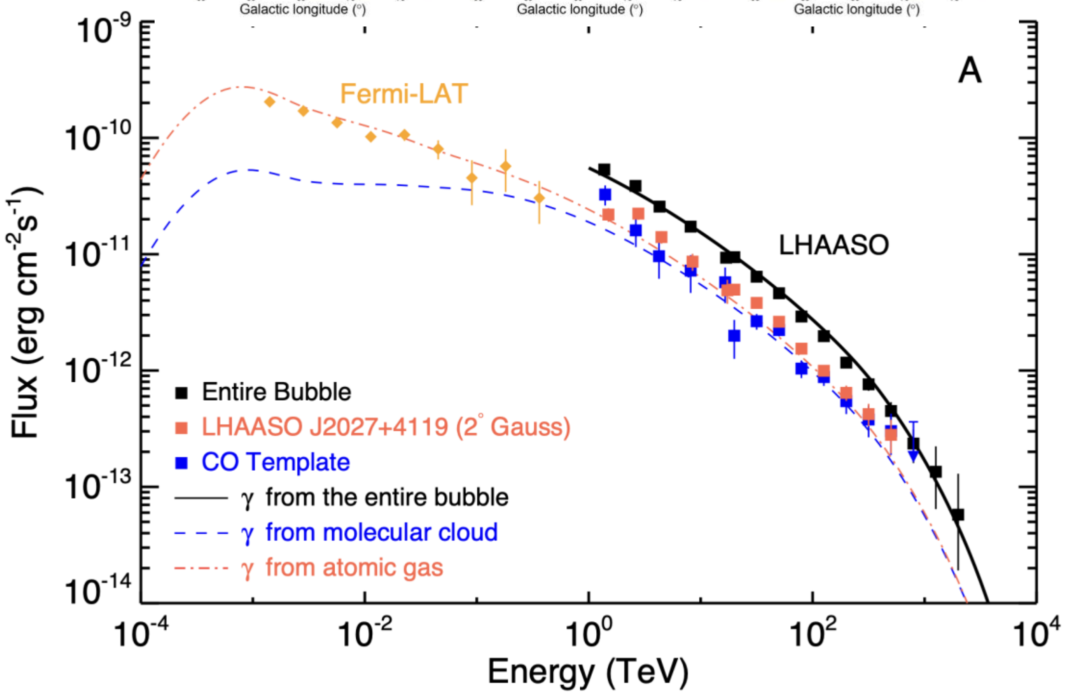
- γ-ray significance map of V4641 Sgr (LHAASO 2024, arXiv:2410.08988).

Cygnus Bubble

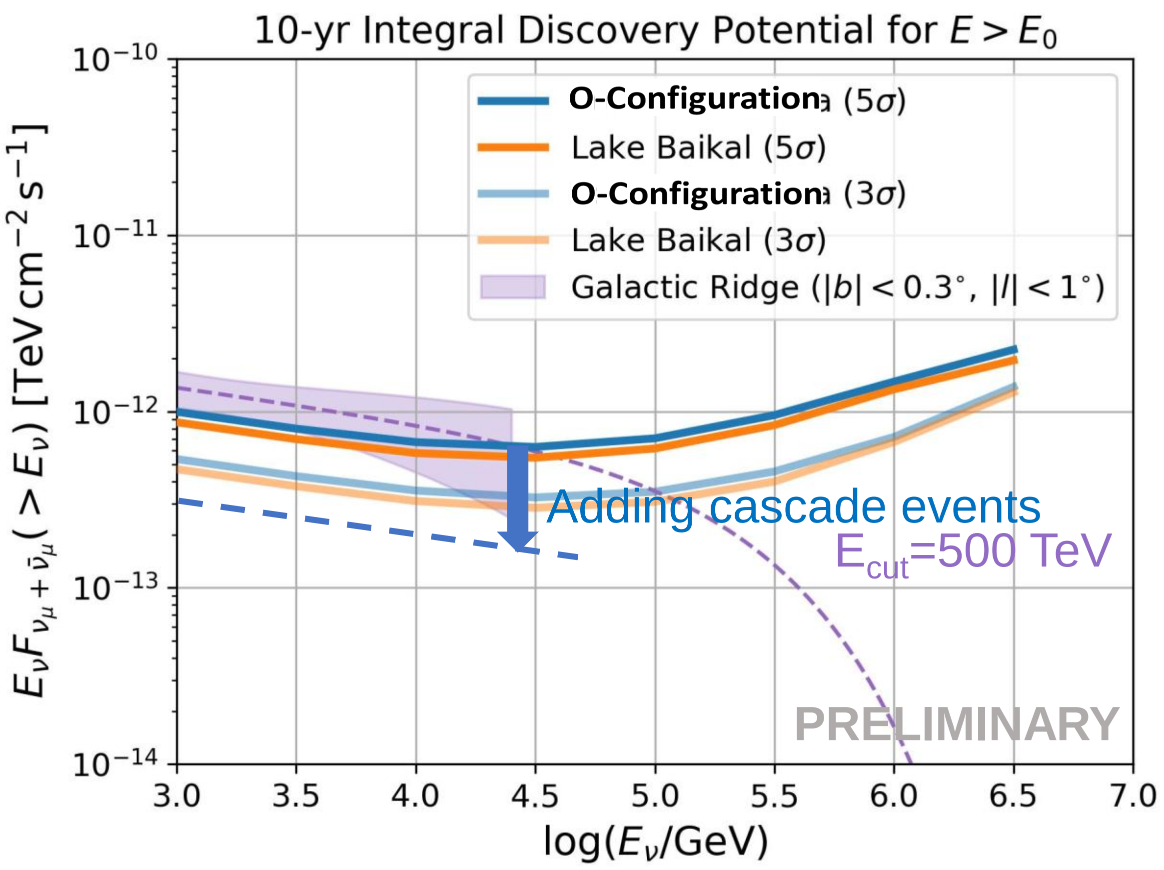




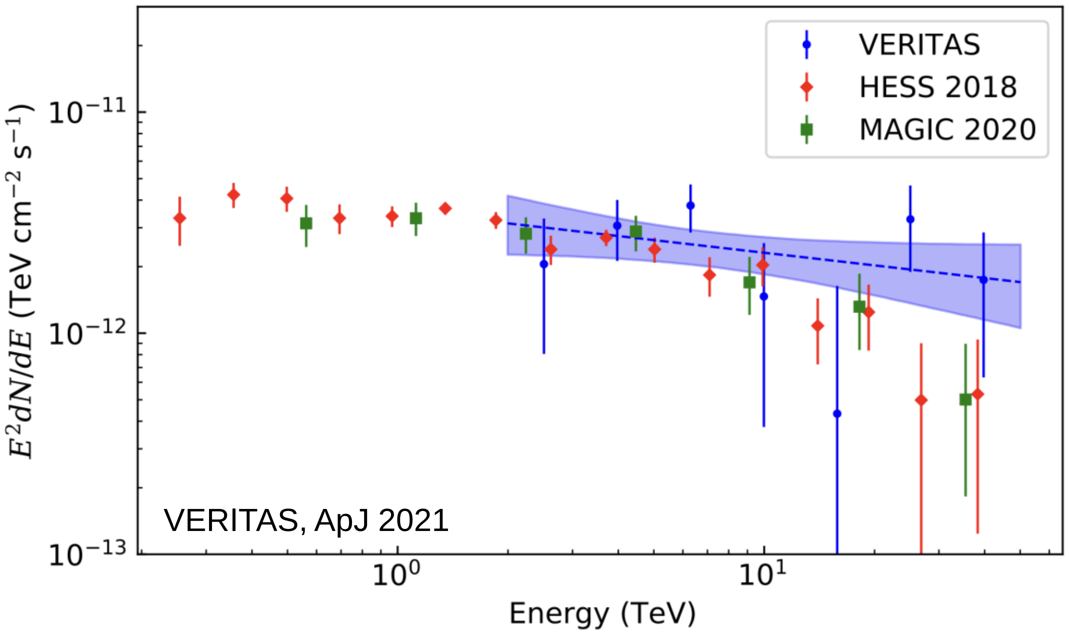




Galactic Ridge

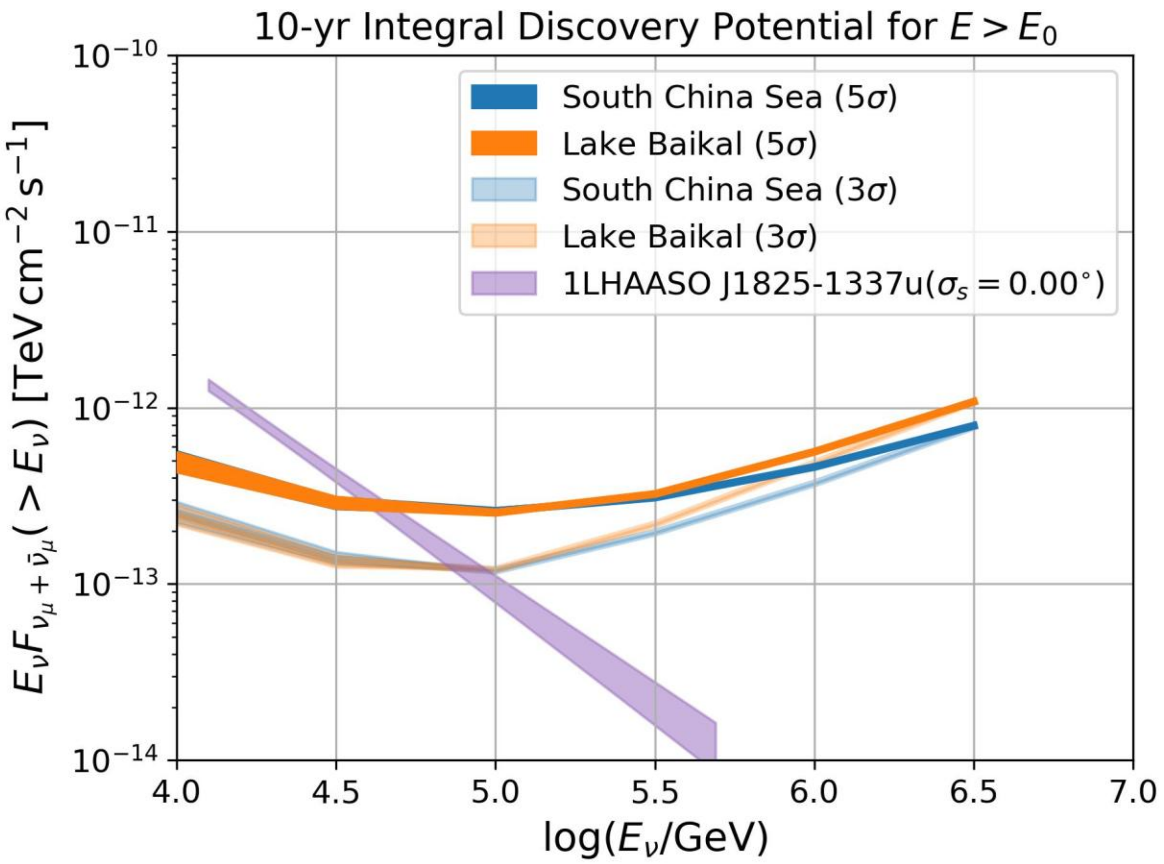


Diffuse gamma-rays from Galactic ridge

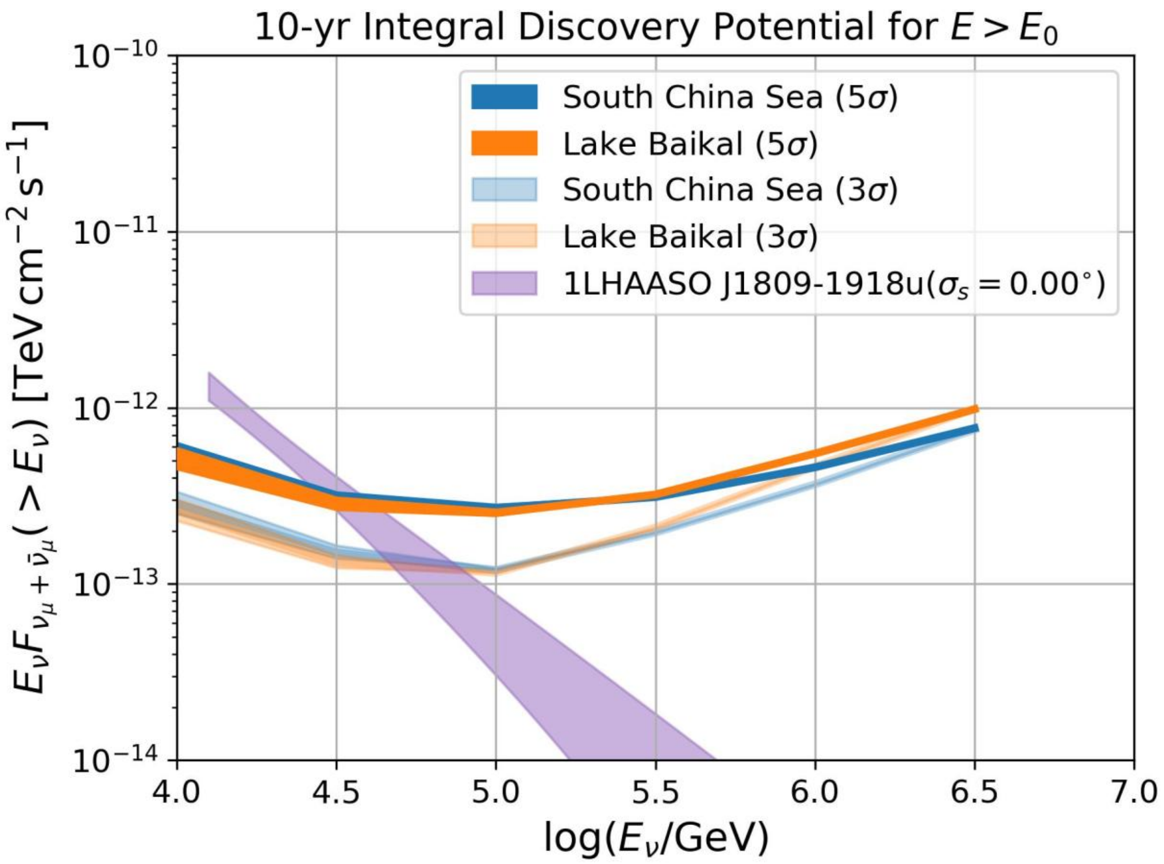


LHAASO PeVatrons

1LHAASO 1825-1337u

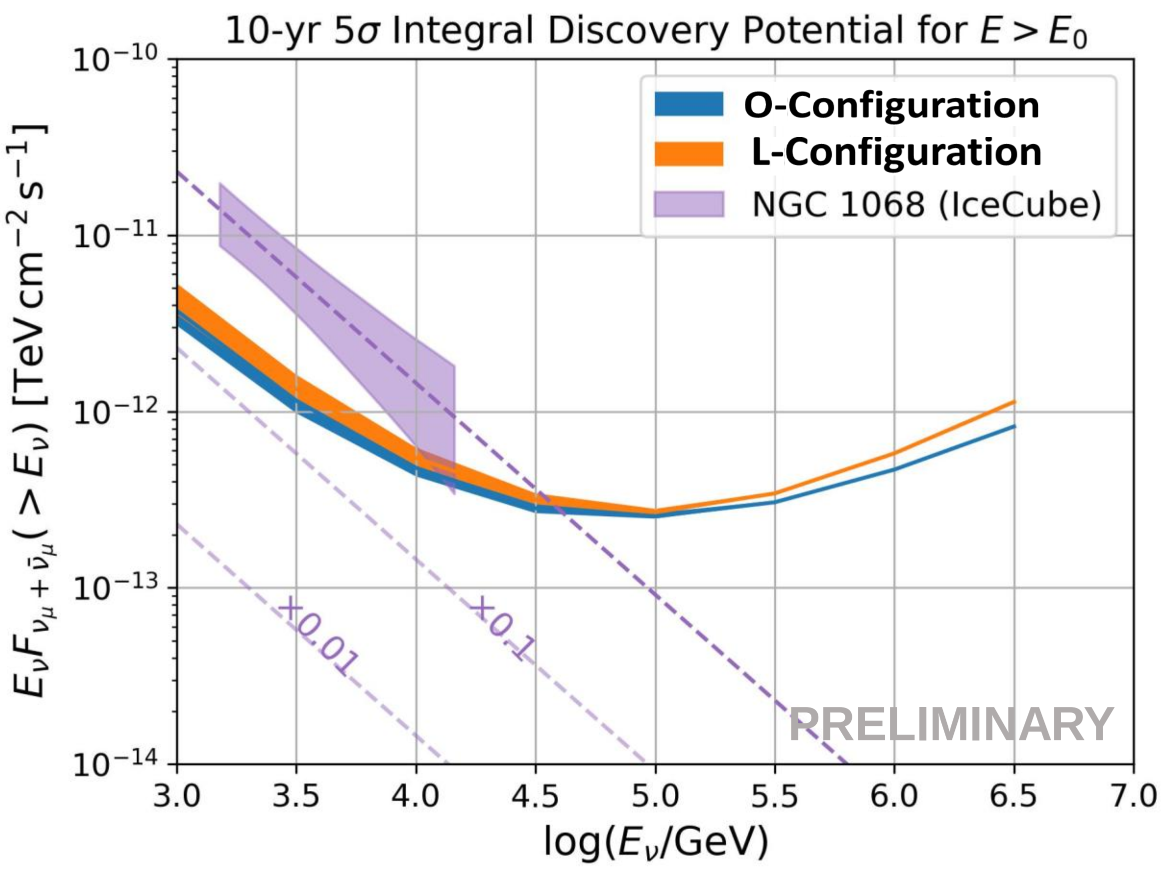


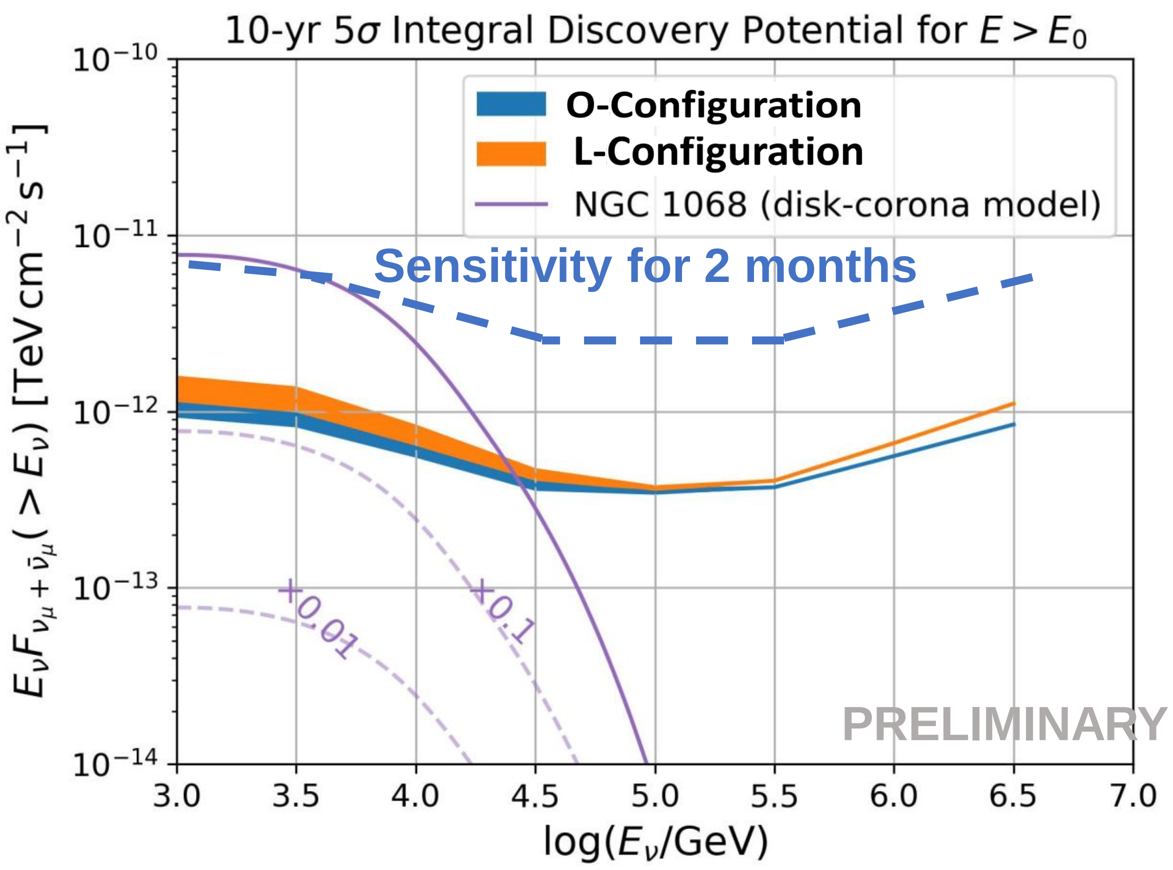
1LHAASO J1809-1918u



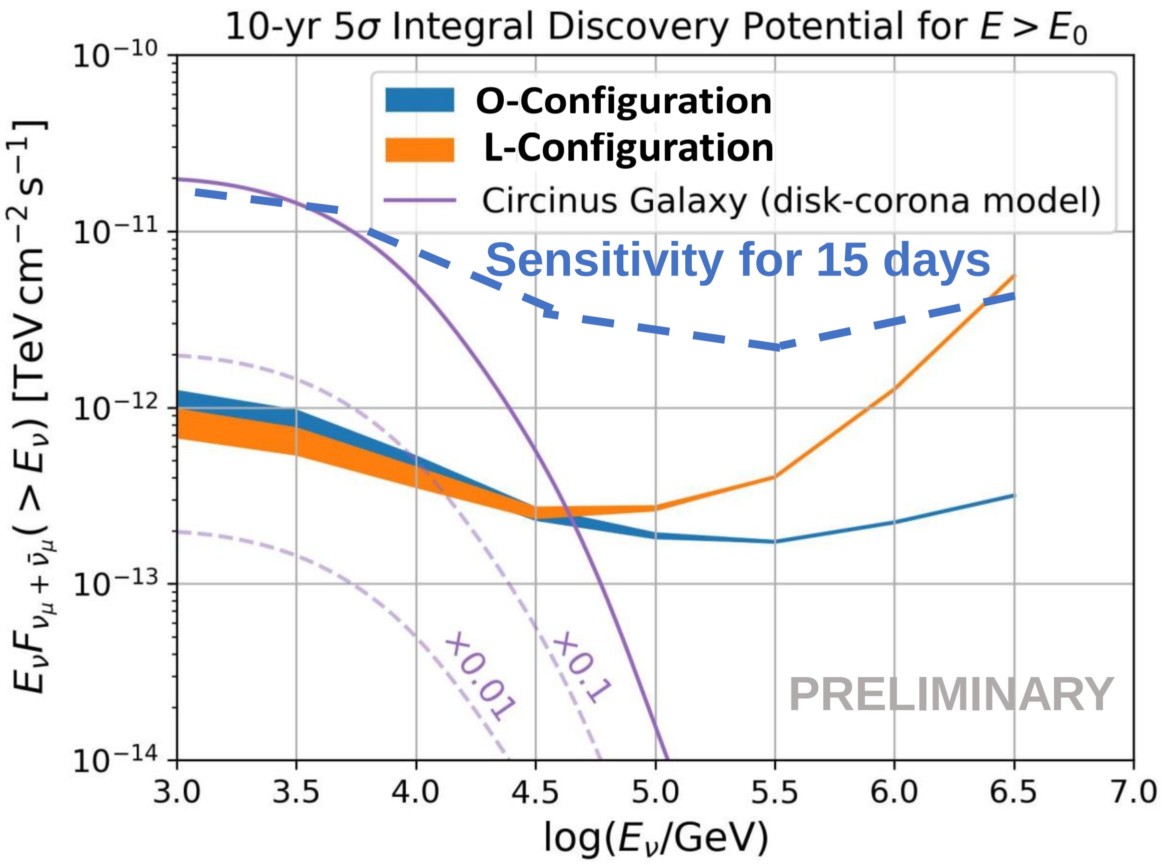
Expectation on Extra-Galactic Source Discovery — big potential

NGC 1068

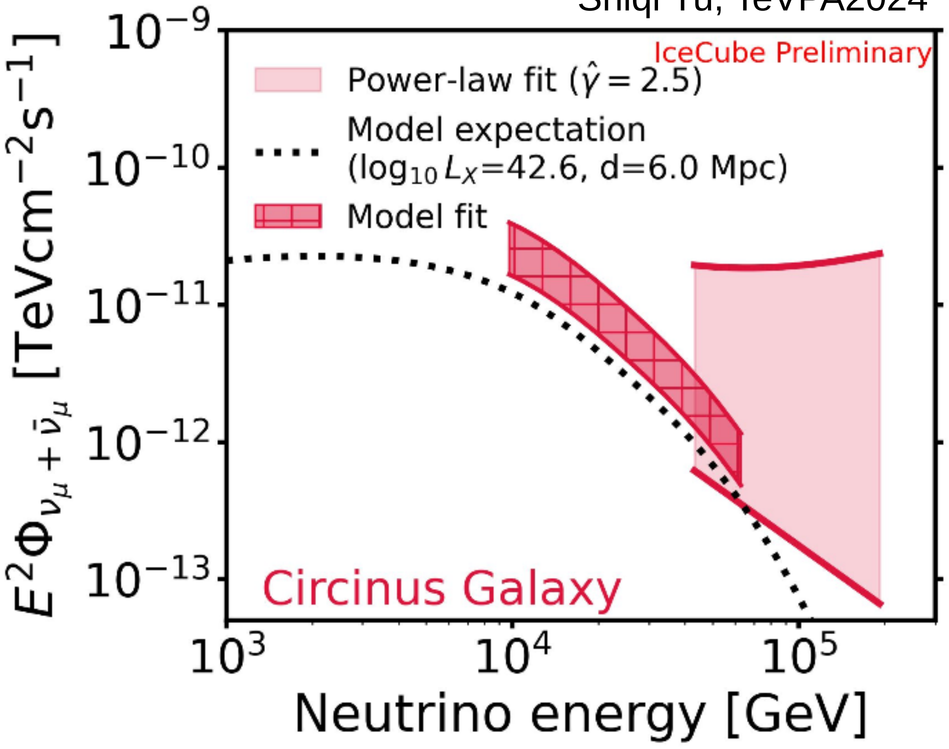

10-yr 5σ Integral Discovery Potential for $E > E_0$
O-Configuration
L-Configuration
NGC 1068 (IceCube)
×0.01
×0.1
PRELIMINARY
$E_\nu F_{\nu_\mu+\bar{\nu}_\mu}(>E_\nu)$ [TeV cm^{-2} s^{-1}]
log(E_ν/GeV)


10-yr 5σ Integral Discovery Potential for $E > E_0$
O-Configuration
L-Configuration
NGC 1068 (disk-corona model)
Sensitivity for 2 months
×0.01
×0.1
PRELIMINARY
$E_\nu F_{\nu_\mu+\bar{\nu}_\mu}(>E_\nu)$ [TeV cm^{-2} s^{-1}]
log(E_ν/GeV)

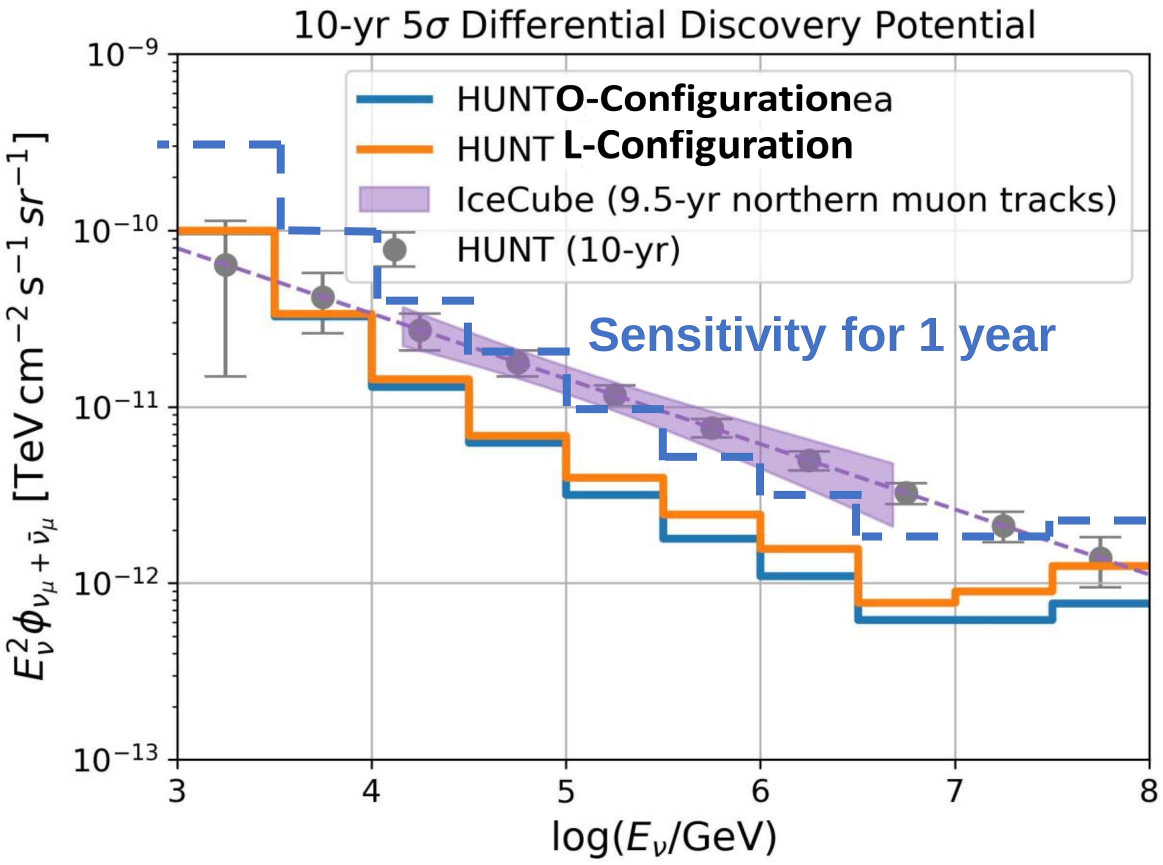
Circinus Galaxy

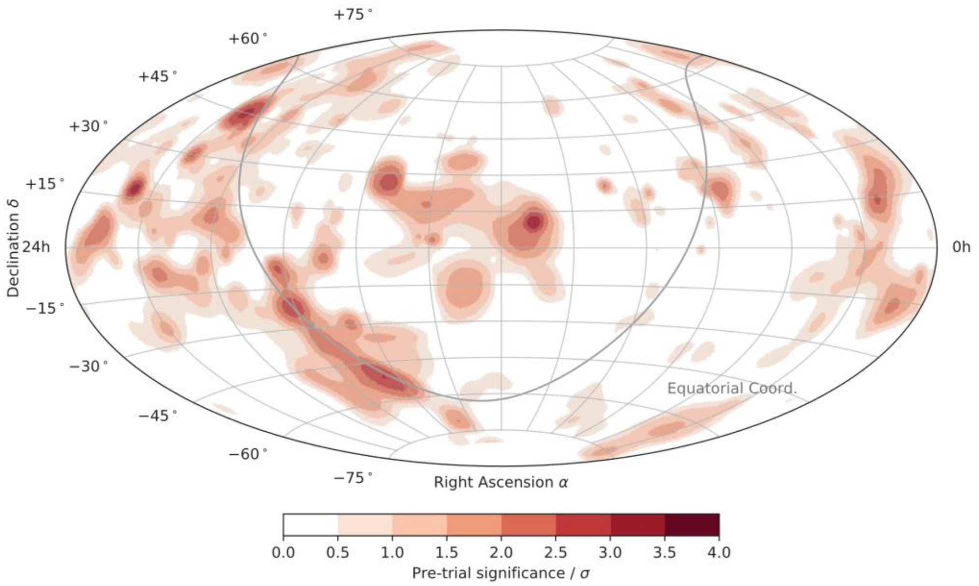


Shiqi Yu, TeVPA2024



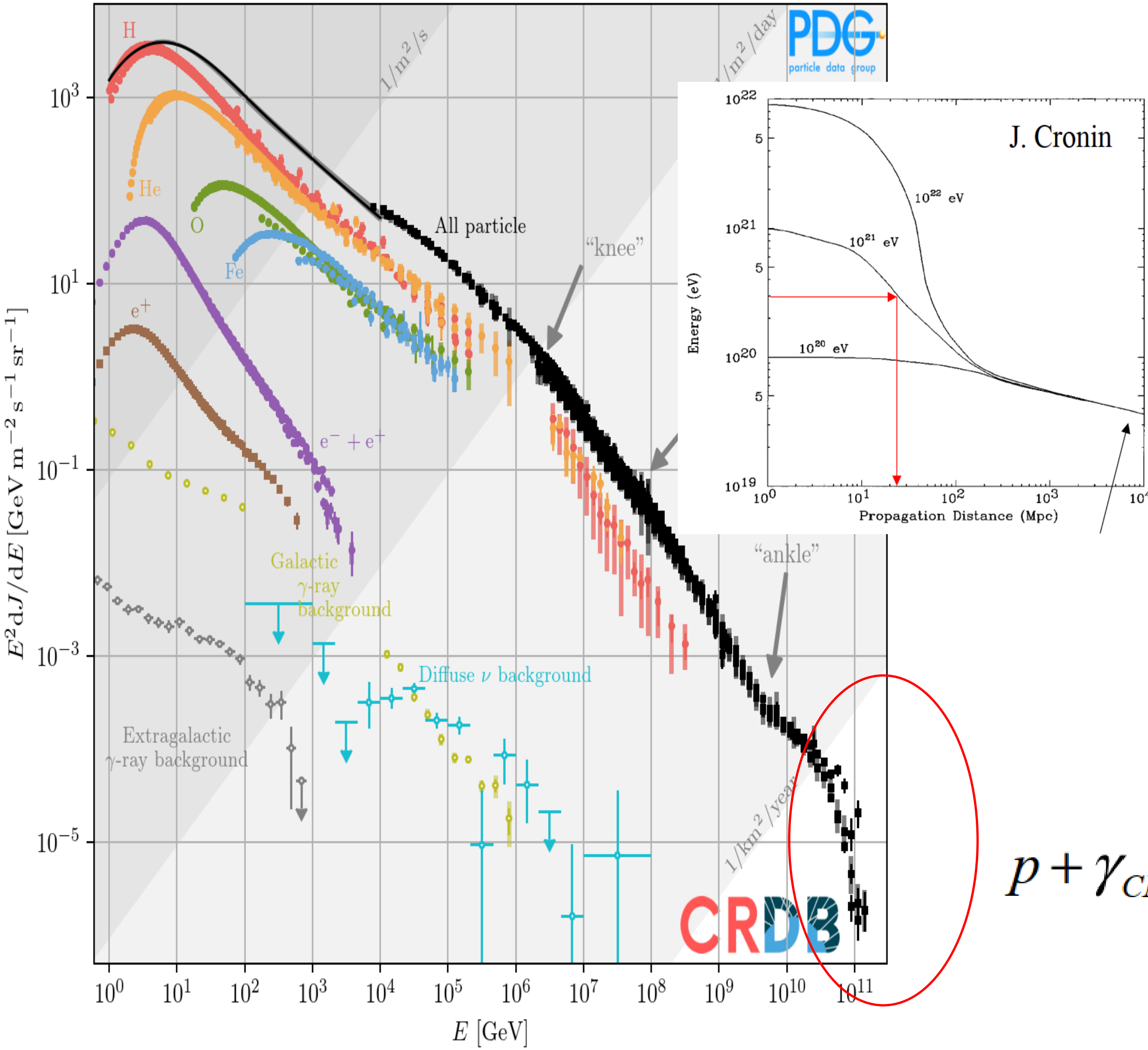
Diffuse astrophysical neutrinos

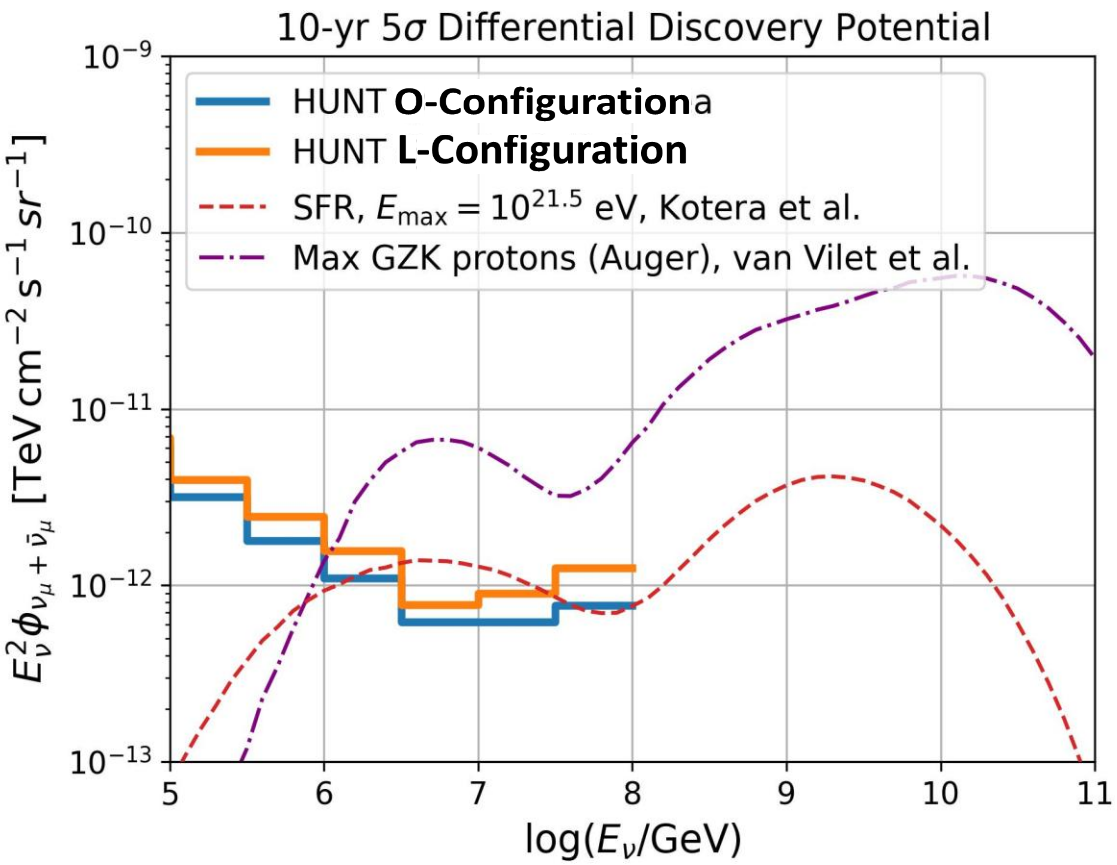




IceCube, ***SCIENCE,*** Vol 380, Issue 6652

Diffuse astrophysical neutrinos





$$p+\gamma_{CMB} \rightarrow \Delta(1232) \rightarrow p+\pi^0 \rightarrow p\gamma\gamma$$

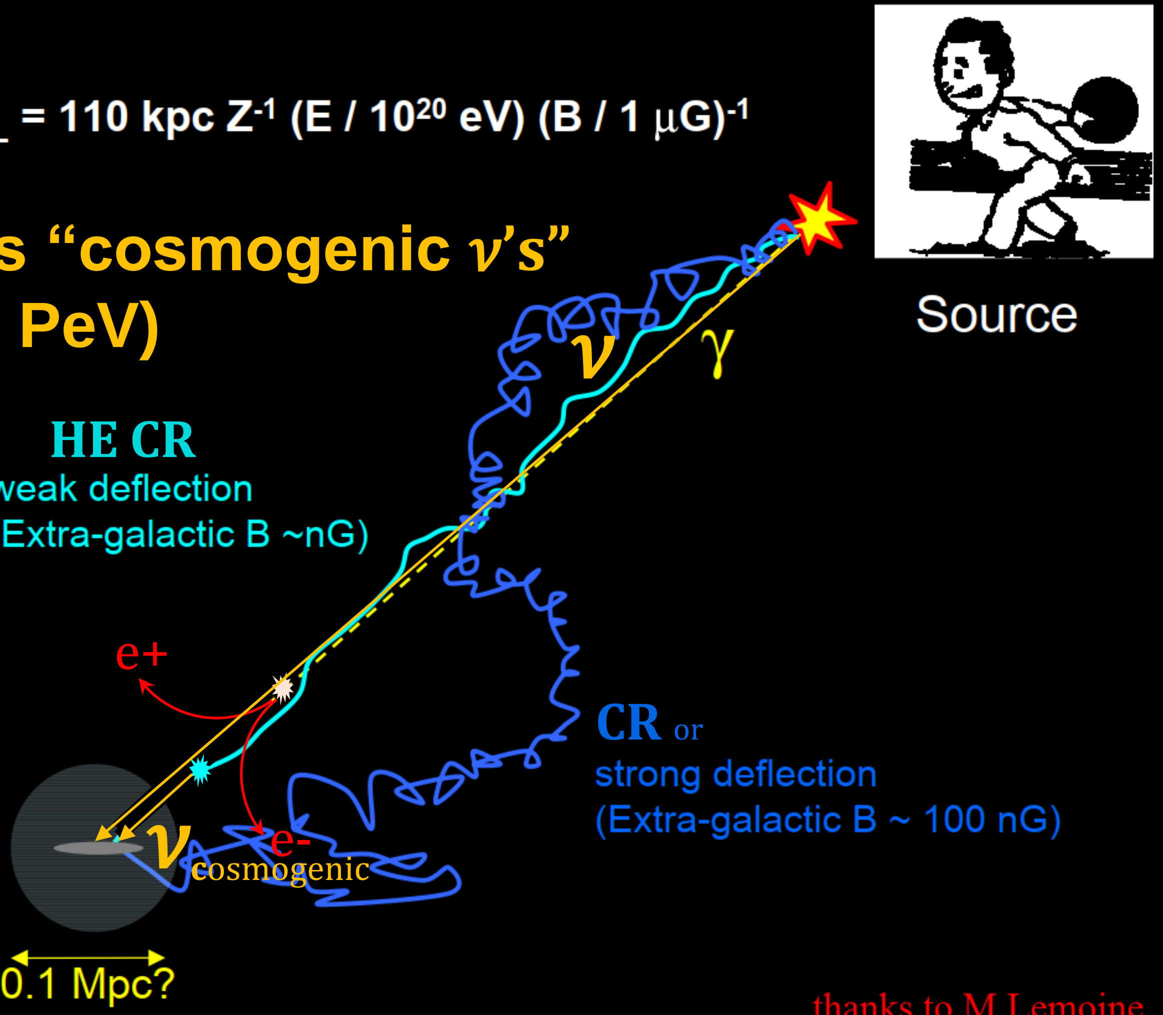
$$\rightarrow n+\pi^+ \rightarrow pe^-\overline{\nu}_e + e^+\nu_e\overline{\nu}_\mu\nu_\mu$$

Neutrinos are unique HE messengers from other galaxies

γ-rays are absorbed by CMB (E>1 PeV)

Larmor radius: r_L = 110 kpc Z^{-1} (E / 10^{20} eV) (B / 1 μG)$^{-1}$

GZK feature yields "cosmogenic ν's"
(E>100 EeV, E_ν >1 PeV)



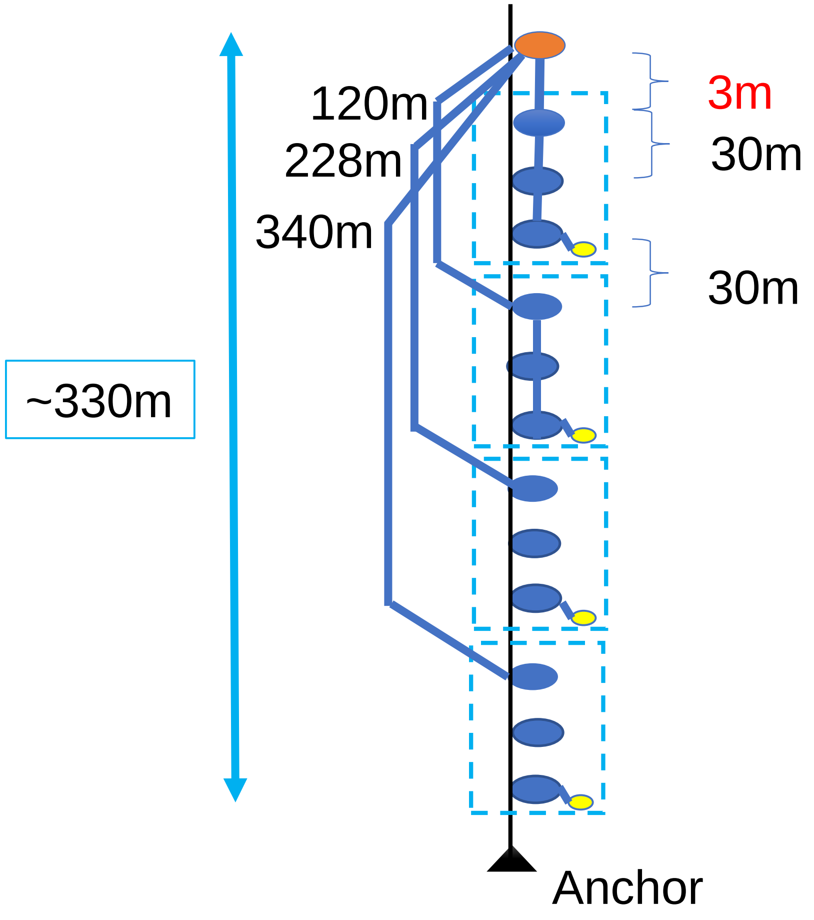
Halo B ~ μG.
Confines E<10^{18},
Distorts trans-
GZK spectrum?

thanks to M.Lemoine

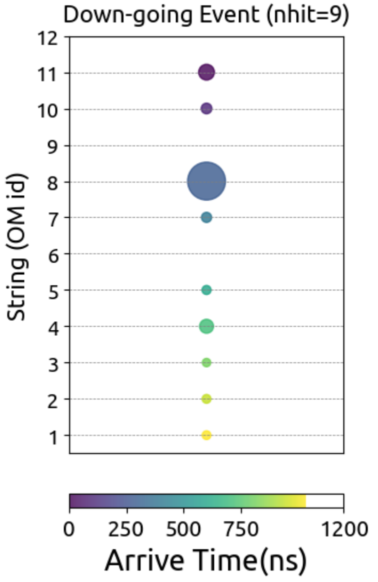
Progresses of HUNT

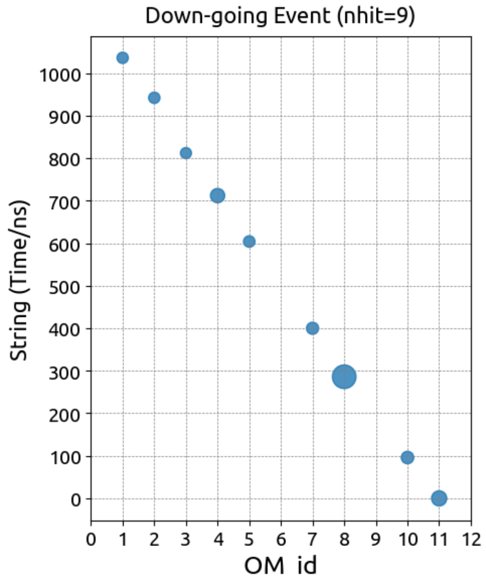
March 2024: Prototype string in Lake Baikal

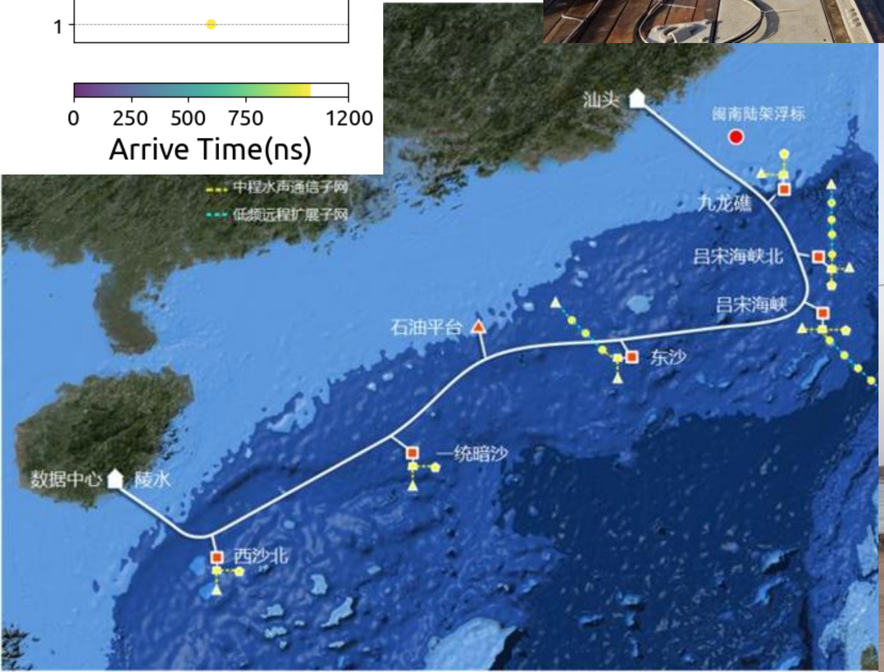
- 12 20-inch PMTs
- 4 LED calibration sources



Prototype tests at GVD at L. Baikal and in South China sea







Summary

1. Building a 30 km^3 deep-water neutrino telescope, focusing on the first confirmation of neutrino point source in the Milky Way.
2. In 2020, we proposed the project. At present, the project team has been establishing prototype detectors in GVD and the South China Sea
3. Motivated by LHAASO's PeVatron discovery, many galactic sources are investigated for their possibility of detection. MQ's could be the first identified CR origin that emitting PeV neutrinos