Overview on Recent Progress of High-energy Neutrino Astronomy

Donglian Xu (TDLI)

Neutrino Scattering: Theory, Experiment, Phenomenology (**ν**STEP2024)

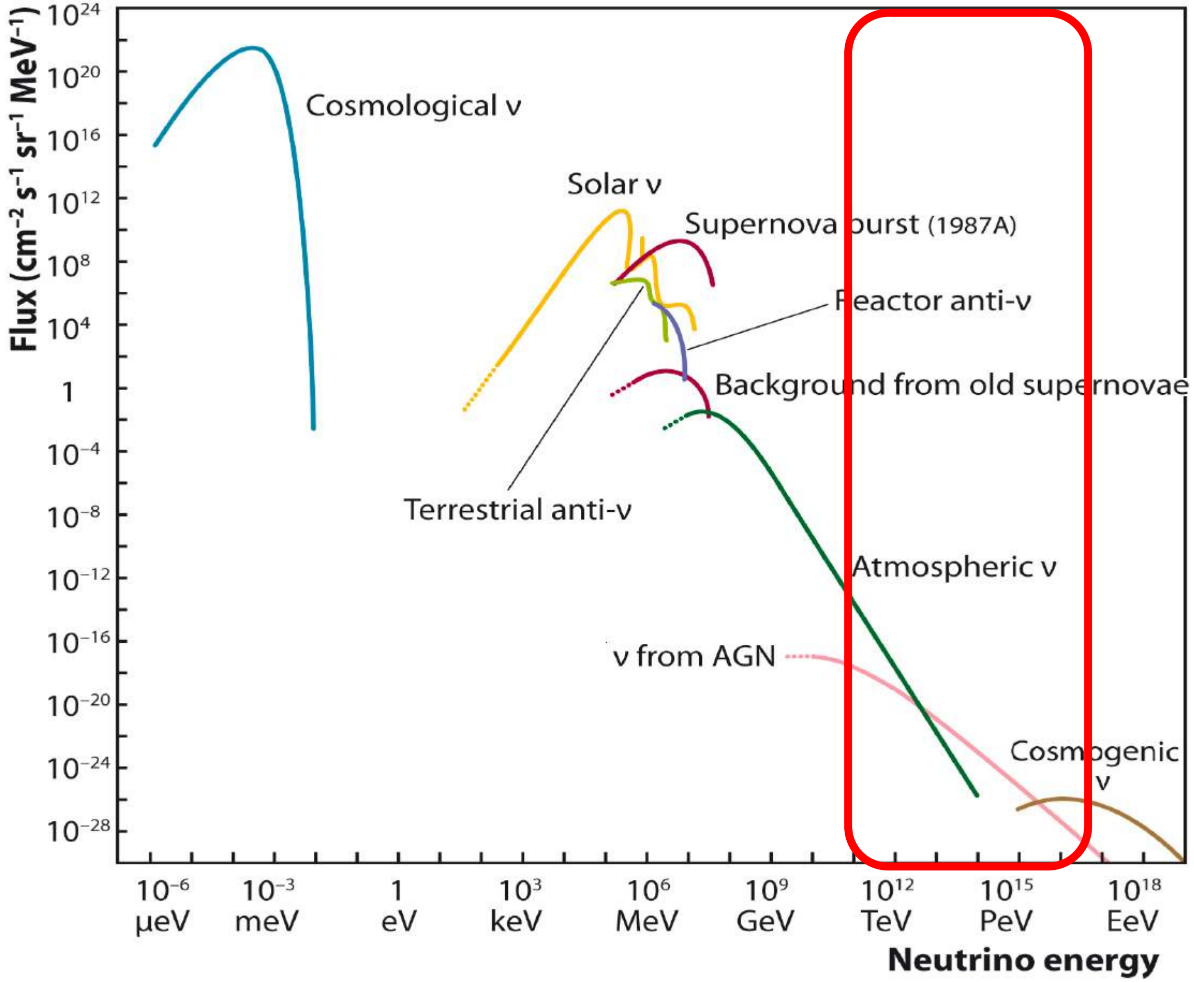
2024.05.17-20, Hangzhou

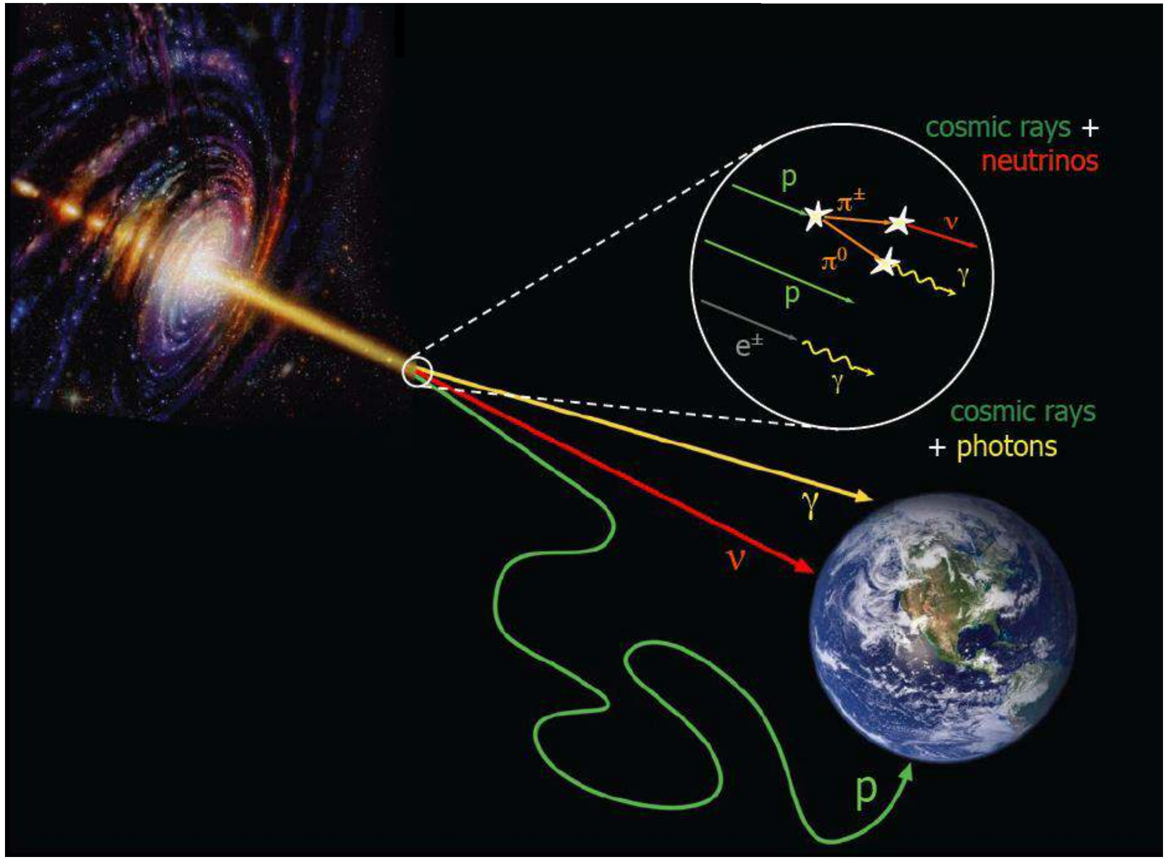
Outline

- **Recent results from existing detectors**
  - IceCube
  - KM3NeT / Antares
  - Baikal-GVD
- **(Next-gen) neutrino telescopes under planning**
  - IceCube-Gen2 (South Pole)
  - KM3NeT (Mediterranean)
  - Baikal-GVD (Lake Baikal)
  - P-One (East Pacific)
  - TRIDENT / HUNT / NEON (South China Sea)

Neutrino: a unique cosmic messenger

Century-old puzzle: **what's the origin of cosmic rays?**

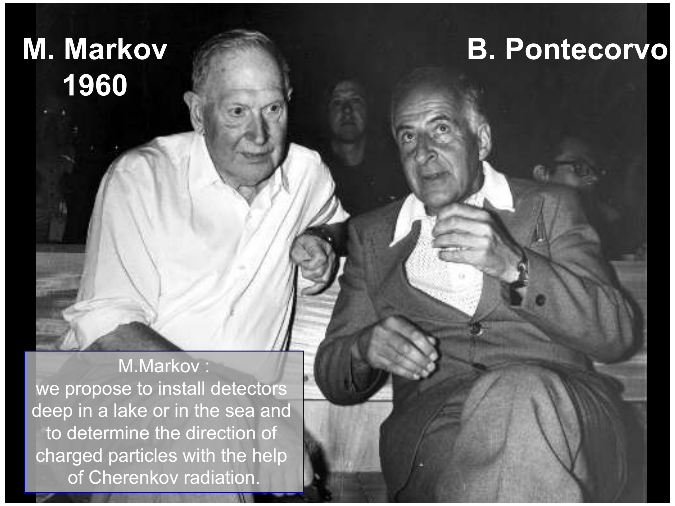


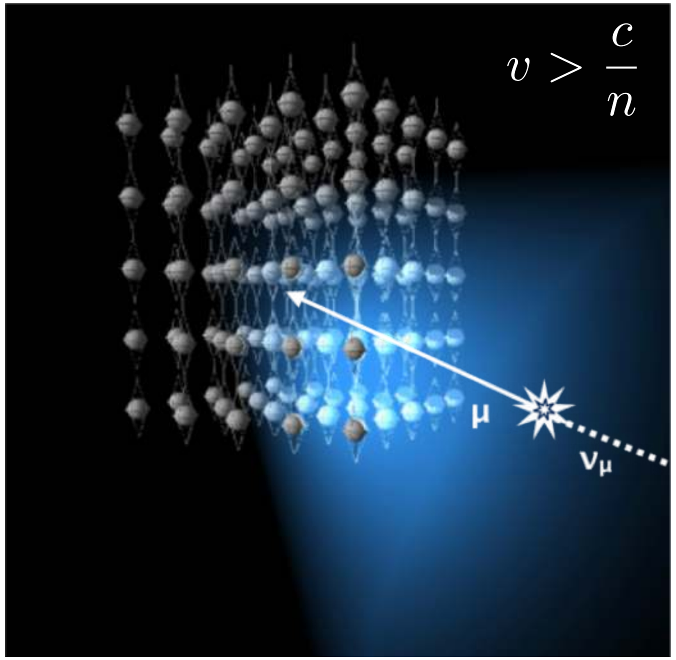


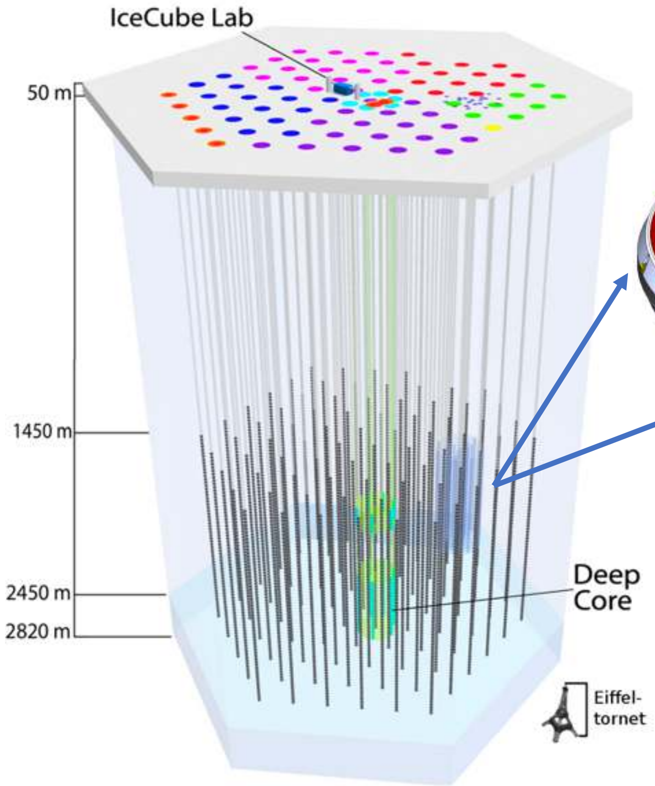
Detection of high-E astrophysical neutrinos would be smoking evidence for the origins of cosmic rays!

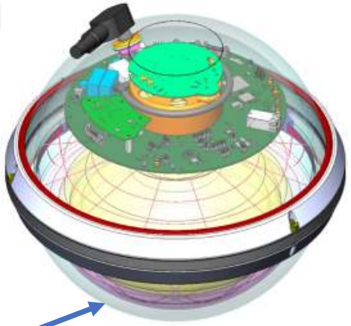
Neutrino telescopes

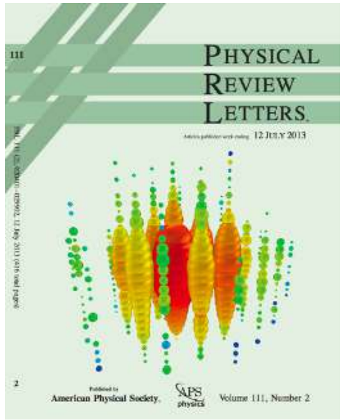
IceCube: world's largest neutrino telescope

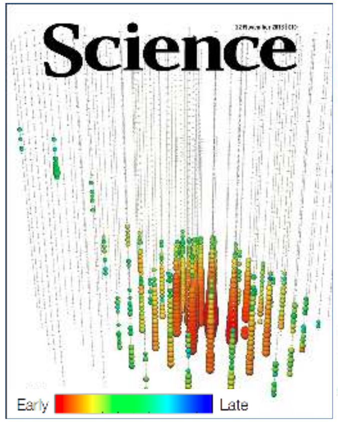


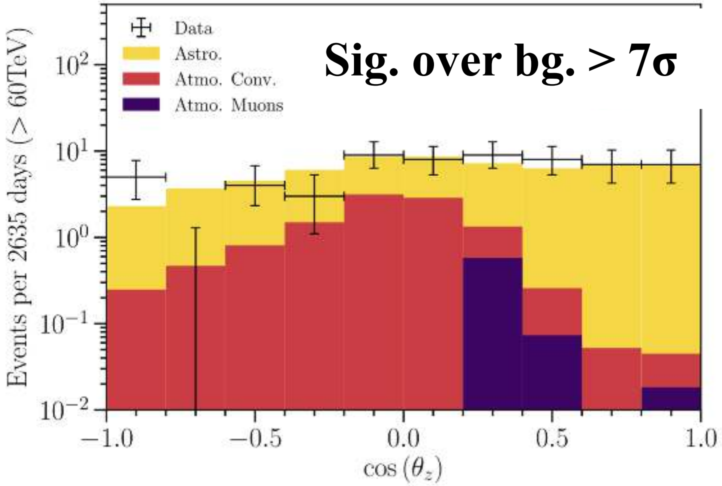










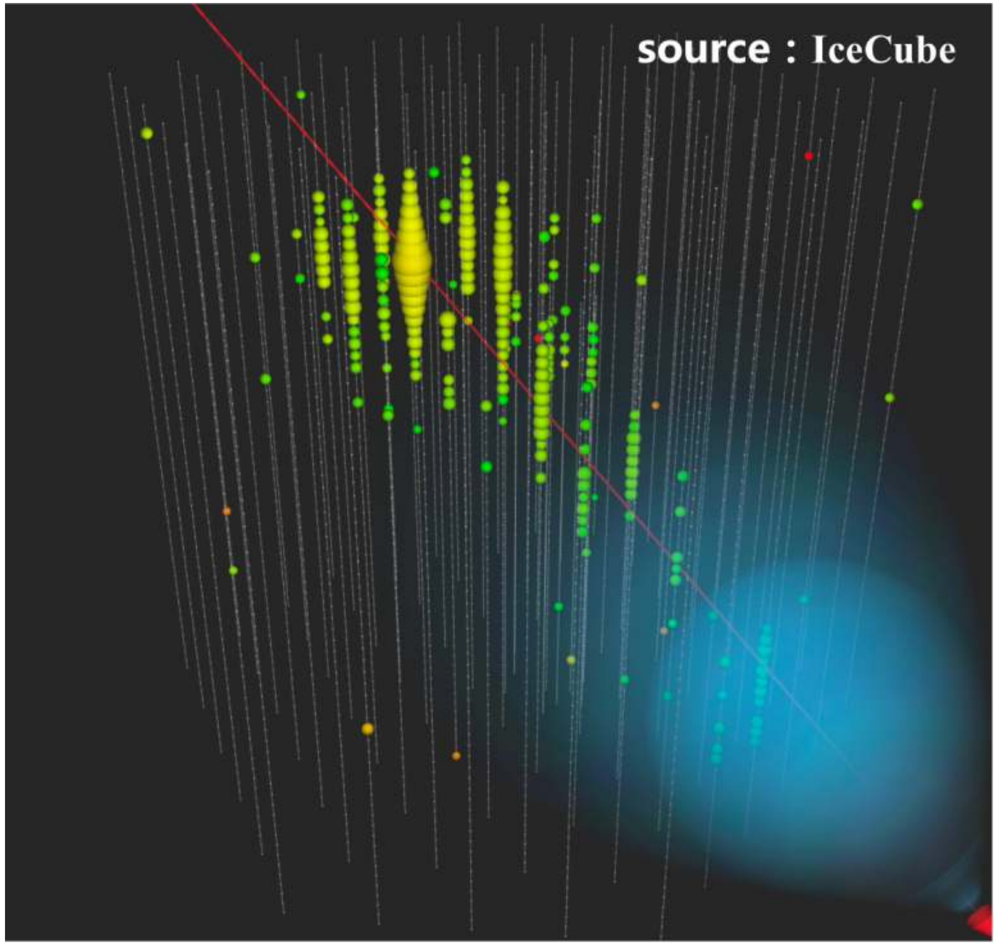


- **86** strings, **5160** DOMs
  → a cubic-kilometer array
- Fully operating since 2010

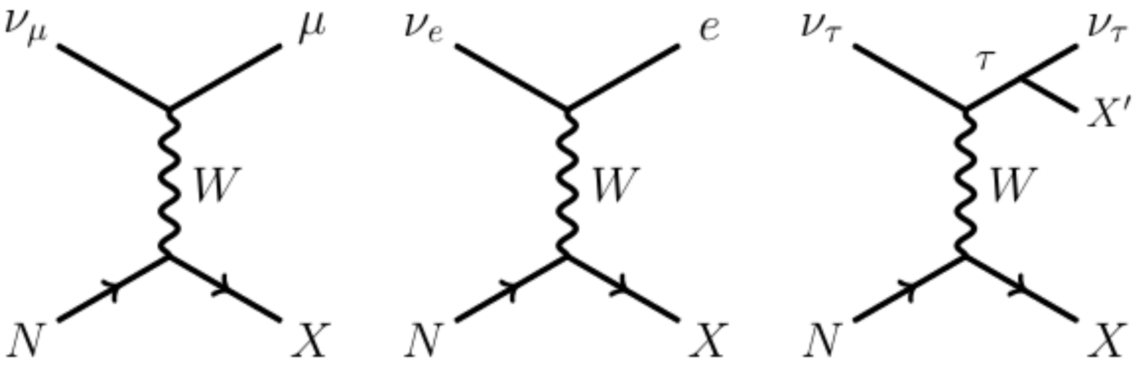
Phys. Rev. D 104, 022002 (2021) (7.5-yr)
Phys. Rev. Lett. 113, 101101 (2014) (3-yr)
Science 342, 6161 (2013) (2-yr)

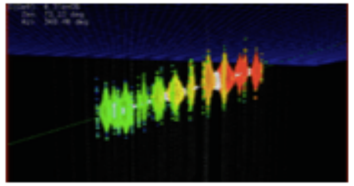
Neutrino telescope events

Tracks: relied primarily on for pointing

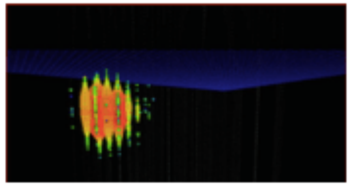


IceCube event topologies

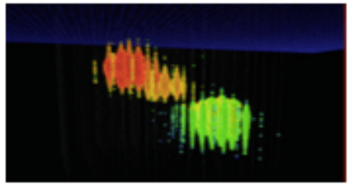




Track
~ 1°

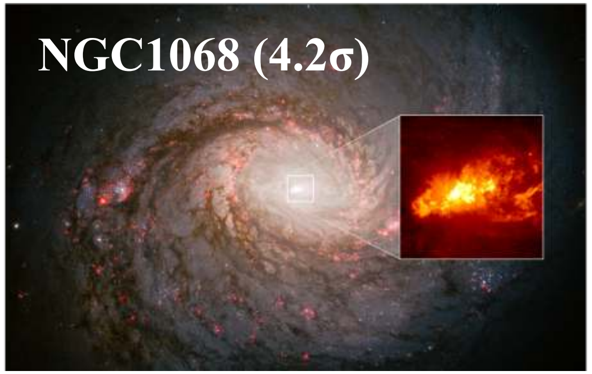


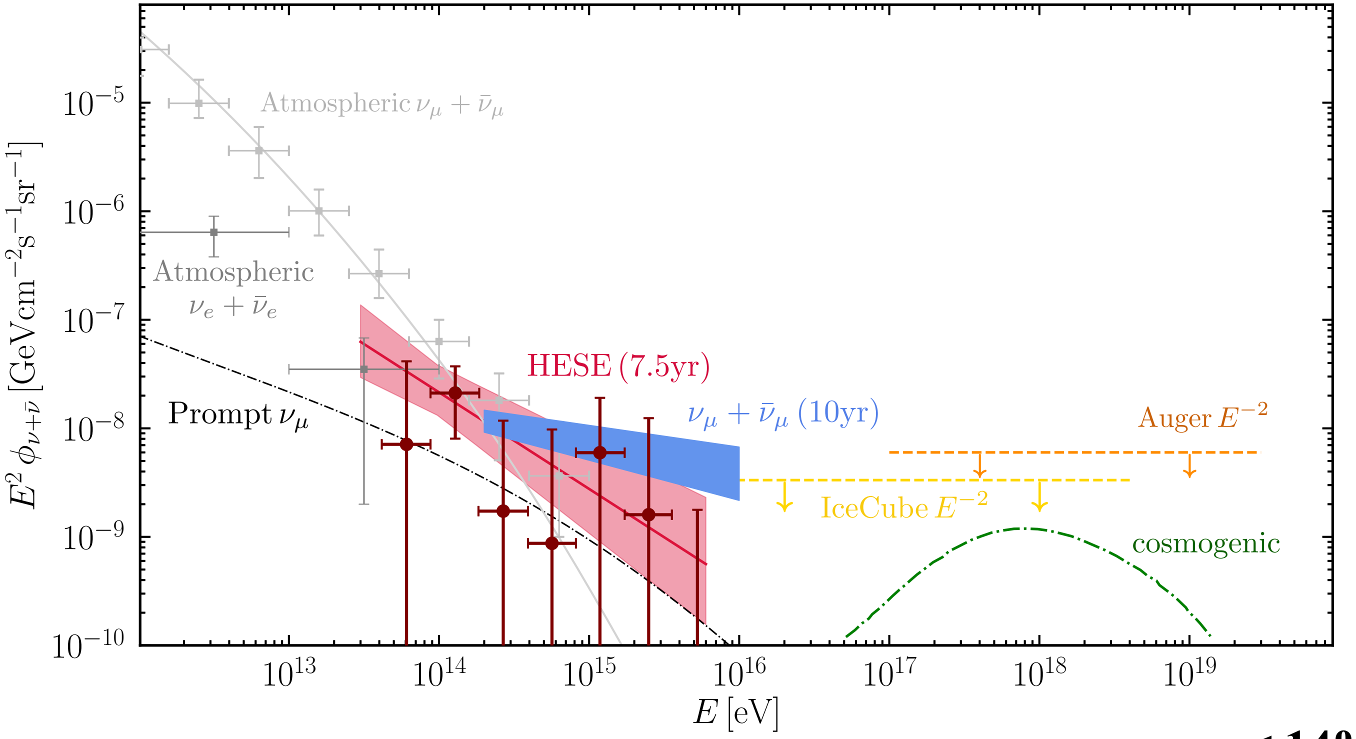
Cascade
~ 10°



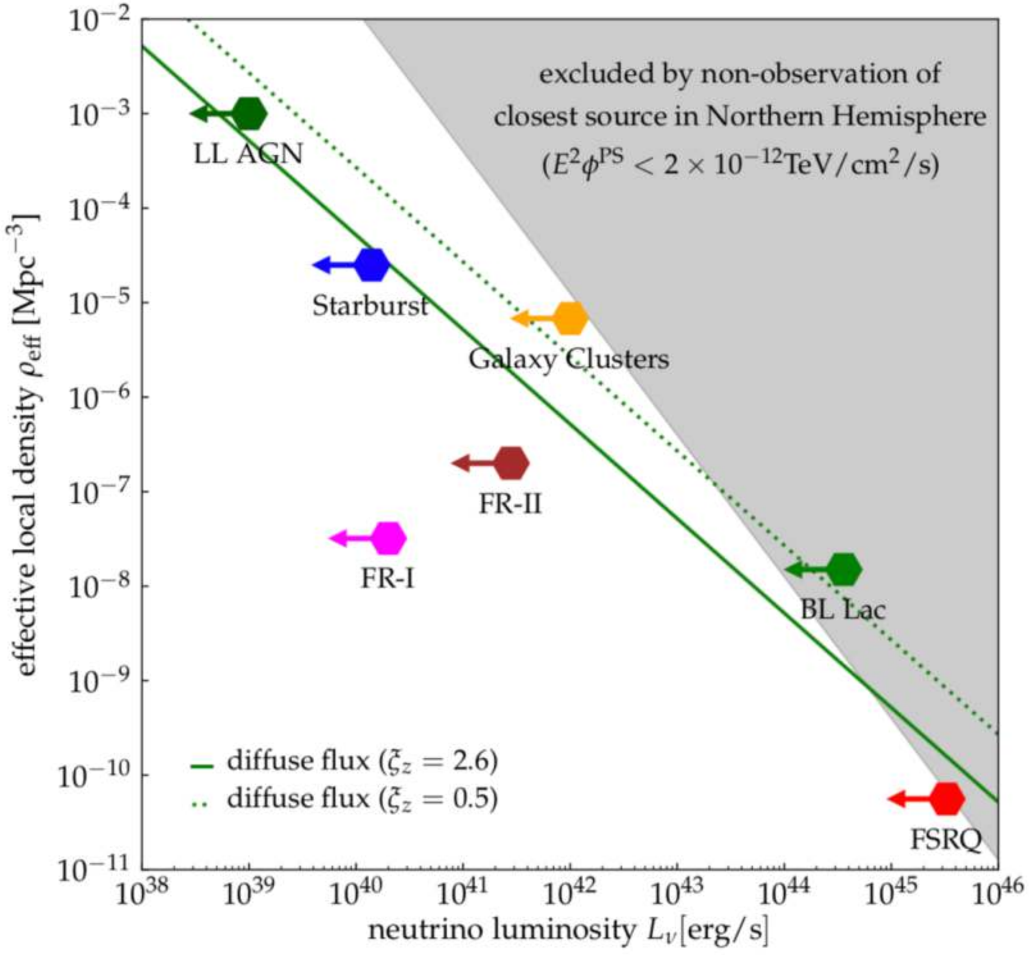
Double Cascade

A new era of neutrino astronomy





Halzen & Khierandish, arXiv:2202.00694

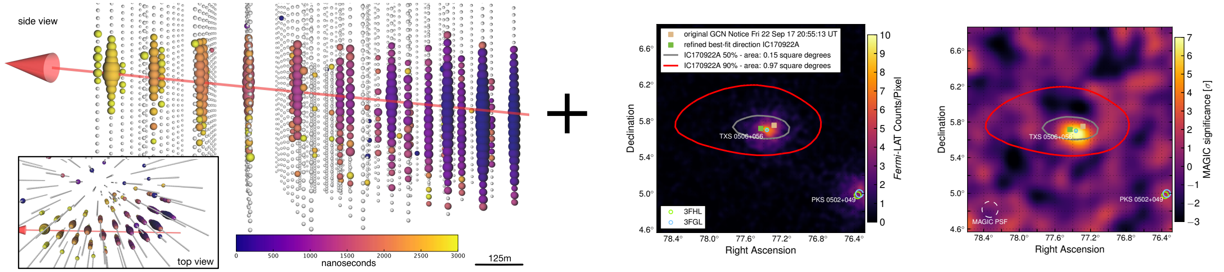


< 14% of the diffuse flux can come from the Galaxy

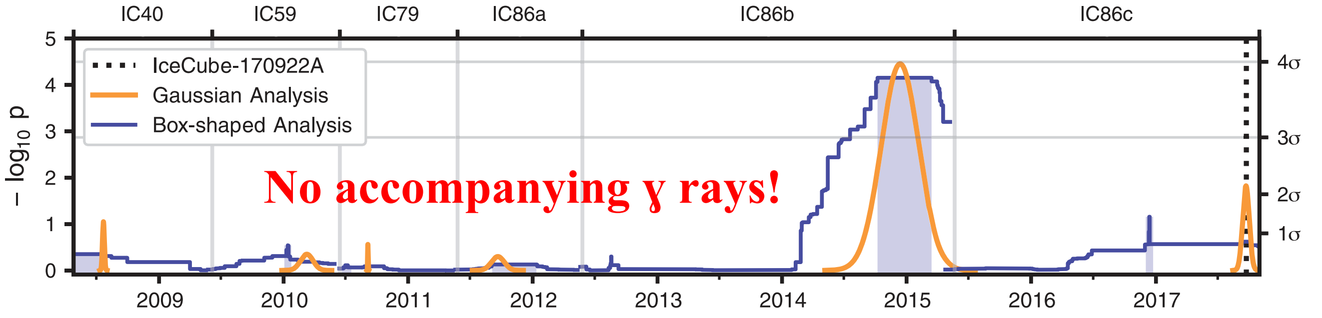
A new era of neutrino astronomy

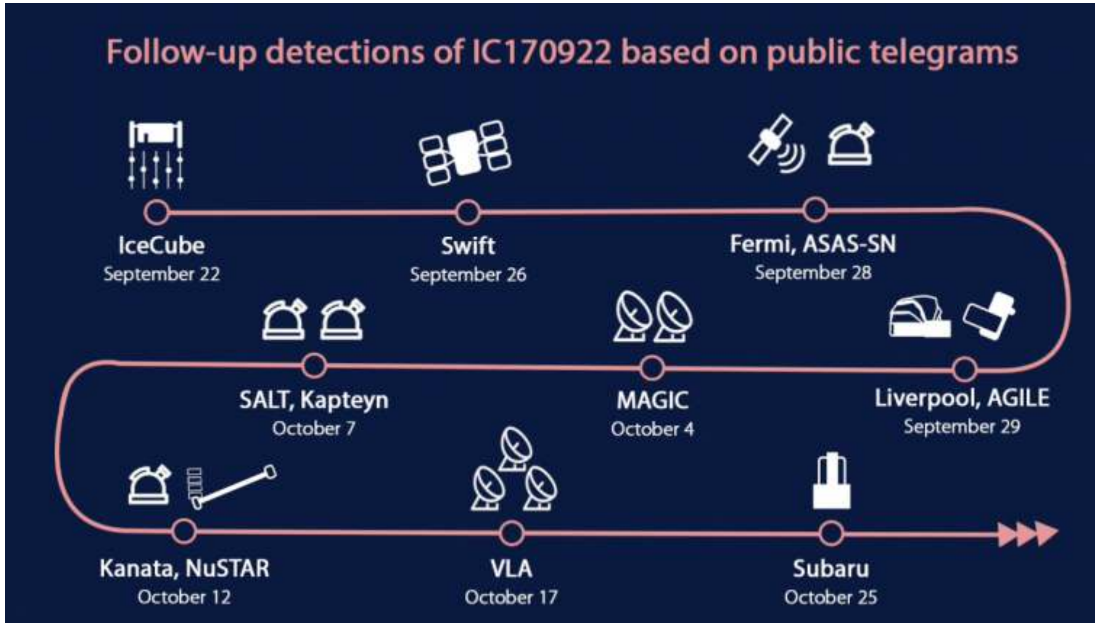
IC170922 (290 TeV) coincided with TXS0506+056

- IC170922 + Multi-messenger: chance probability: **3σ**



- In archival data: 19 (6 exp. bg) events ; **3.5σ**





Science 361, eaat1378 (2018); **Science** 361, eaat2890 (2018)

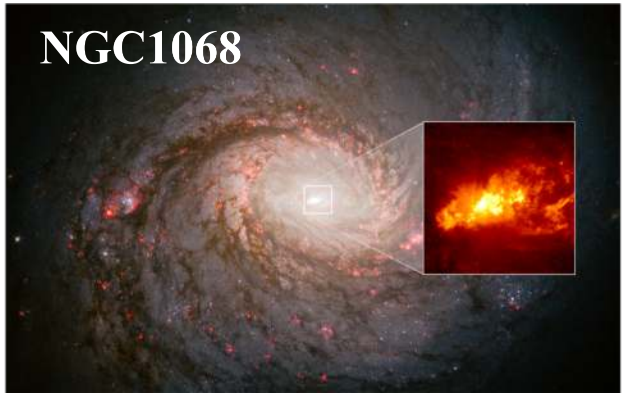
A new era of neutrino astronomy

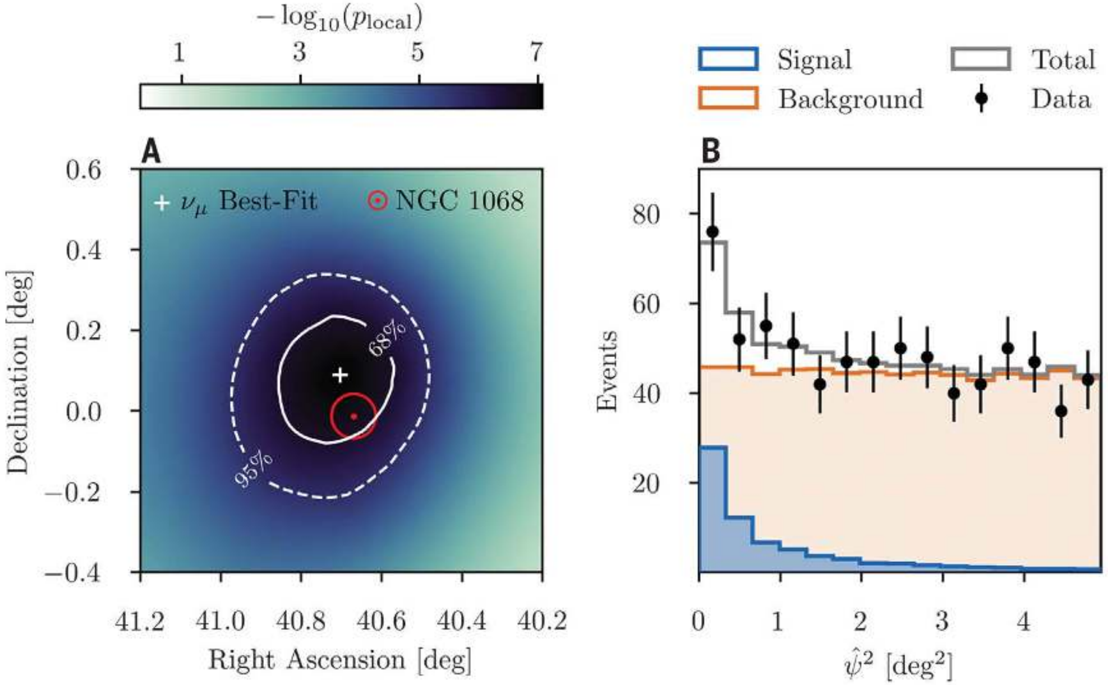
IceCube Collaboration, **Science 378, 538 (2022)**

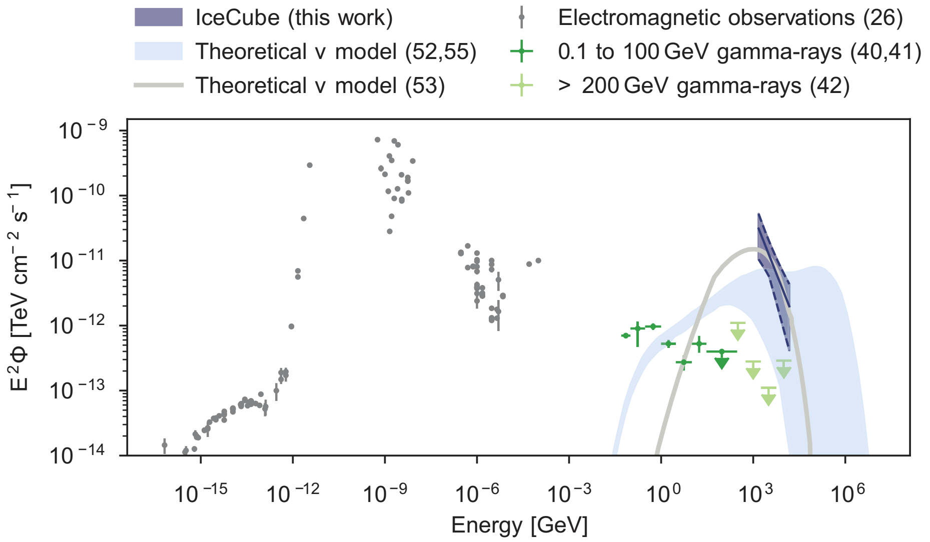
Event excess: **79 $^{+22}_{-20}$**

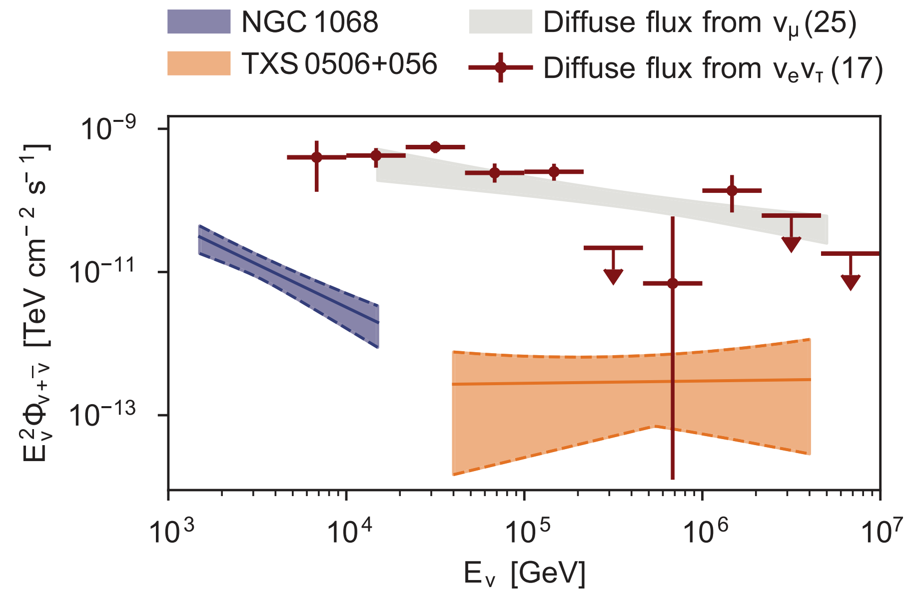
Global significance: **4.2σ**

Data collected: 2011.05 – 2020.05









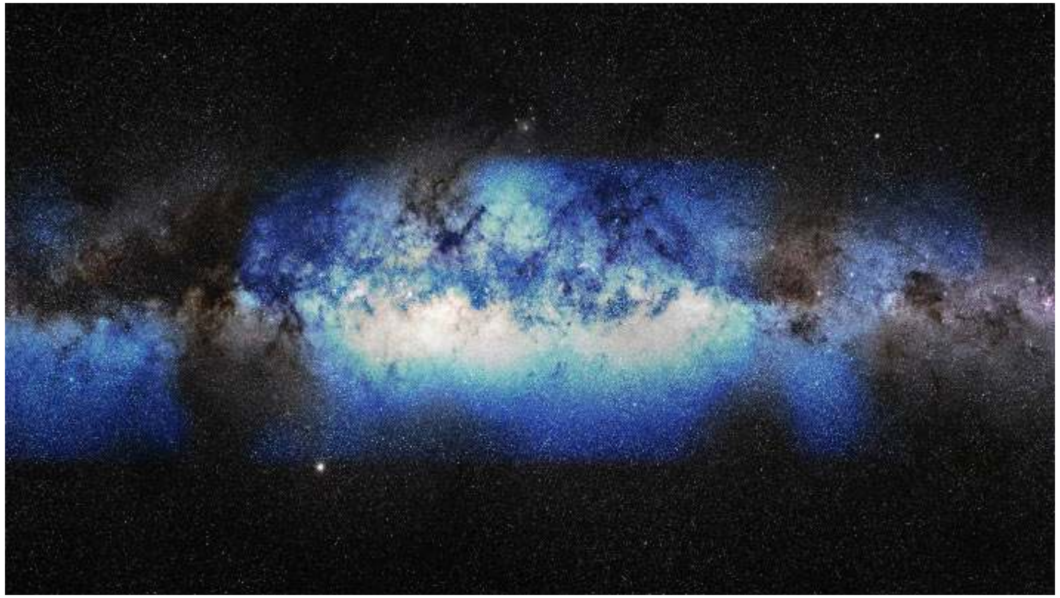
Most significant astrophysical neutrino source to date !

Galactic diffuse neutrinos

Global significance: **4.5σ**

Data collected (**10 yrs**): 2011.05 – 2021.05

Consistent with **Galactic plane diffuse emission** model or **a class of unresolved sources.**

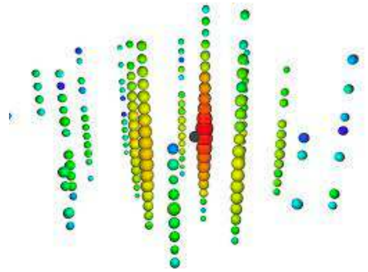


RESEARCH ARTICLE

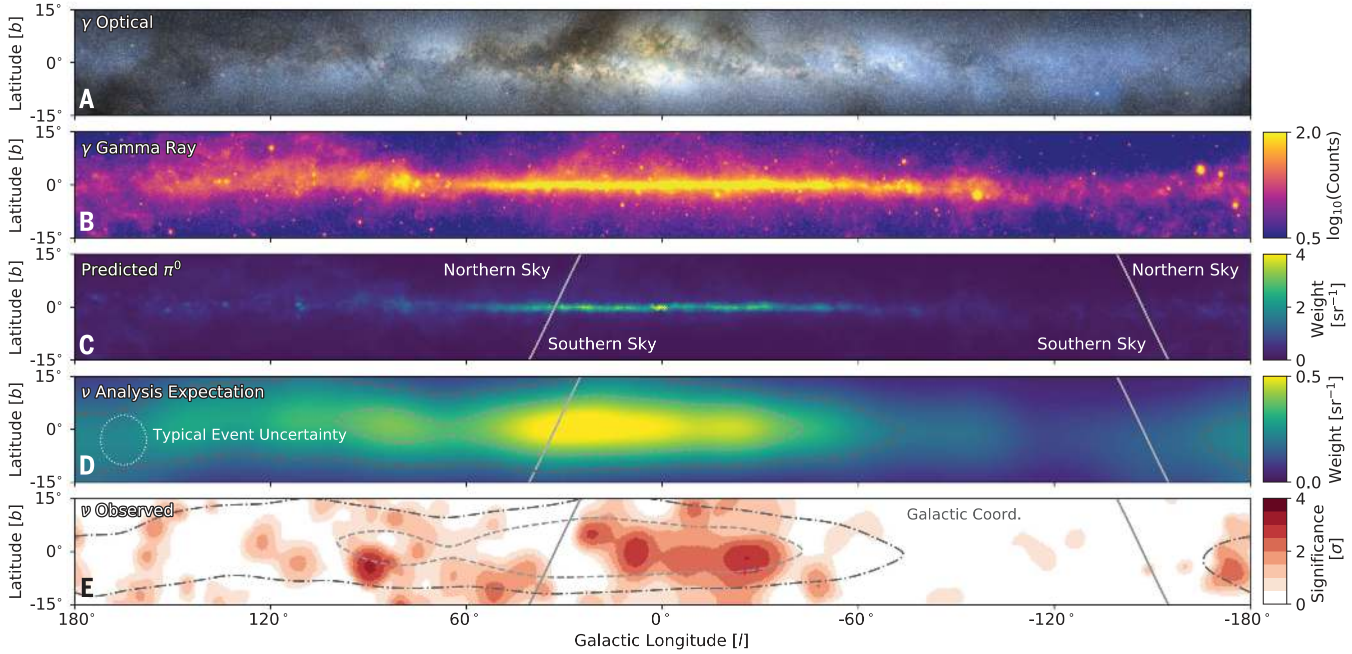
NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane

IceCube Collaboration*†

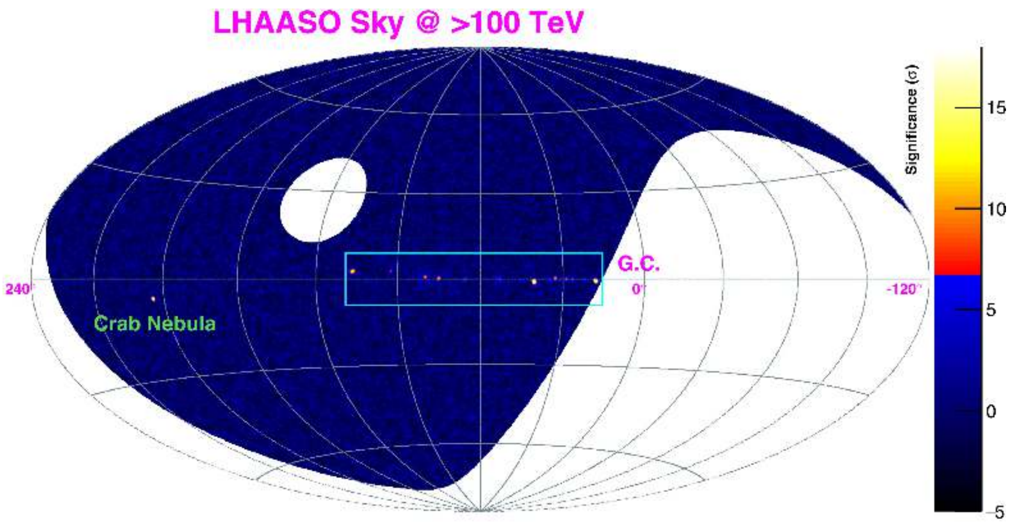


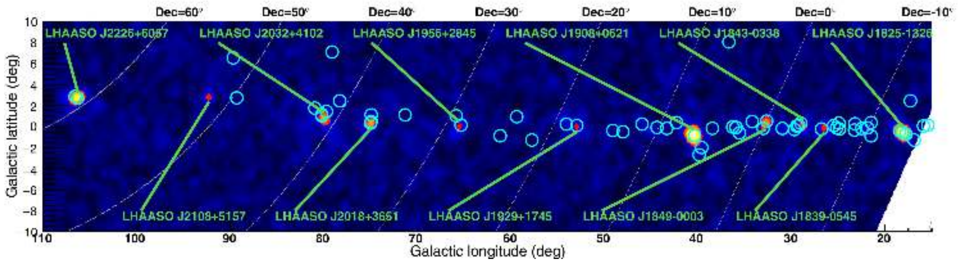
IceCube Collaboration, Science 380, 1338–1343 (2023)



Galactic neutrino sources?

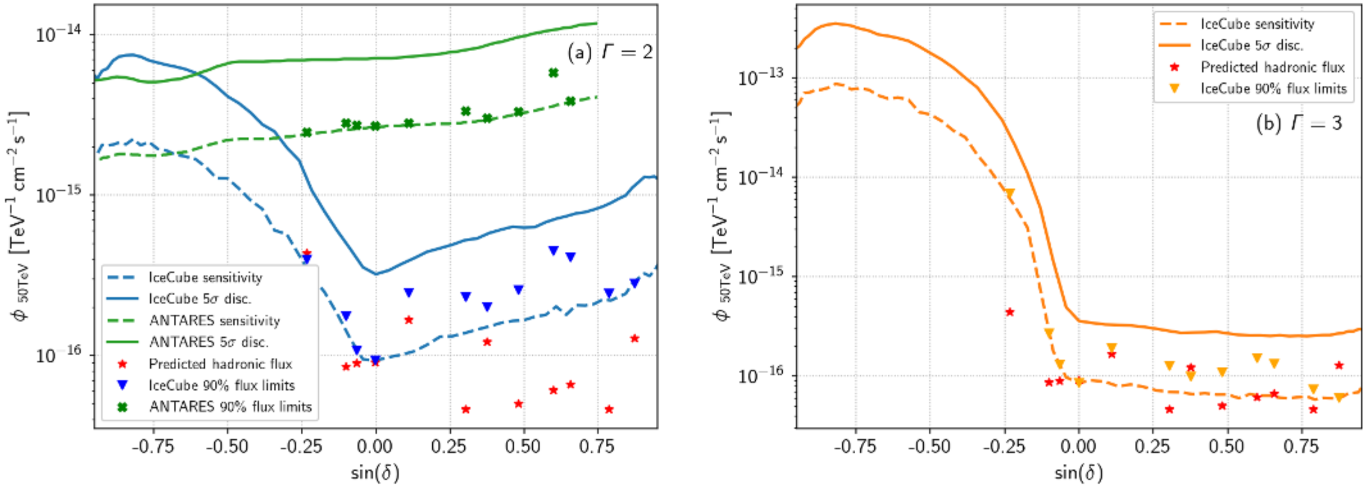
LHAASO detected 12 sources > 100 TeV, highest energy photon detected ~ **1.4 PeV from the Cygnus region** !





Cao. Z., et al, Nature **594**, 33–36 (2021)

IceCube-LHAASO joint analysis (12 sources)



Hadronic component constraints:

- **< 59%** of the Crab gamma flux could be of hadronic origin
- **< 47%** hadronic emission for J2226+6057

IceCube Collaboration, *ApJL,* 945 (2023) 1, L8

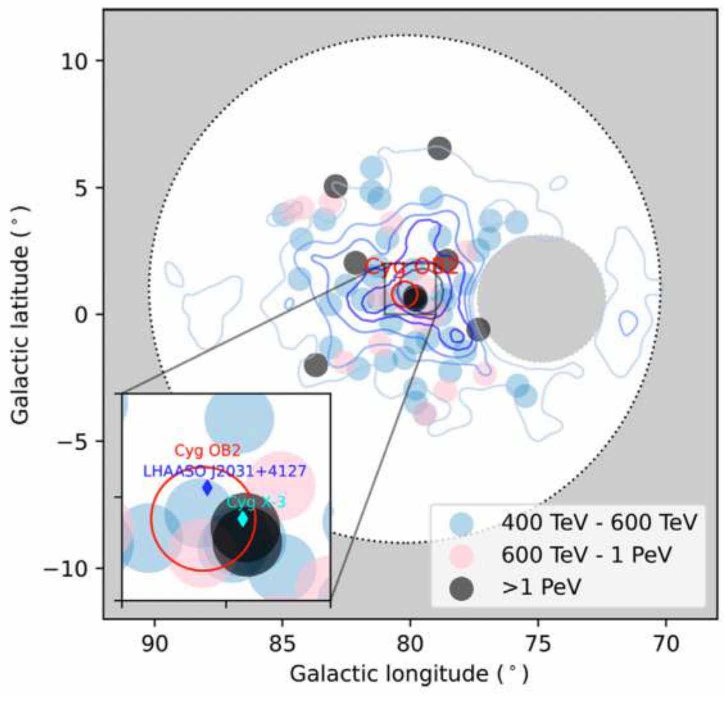
Galactic neutrino sources?

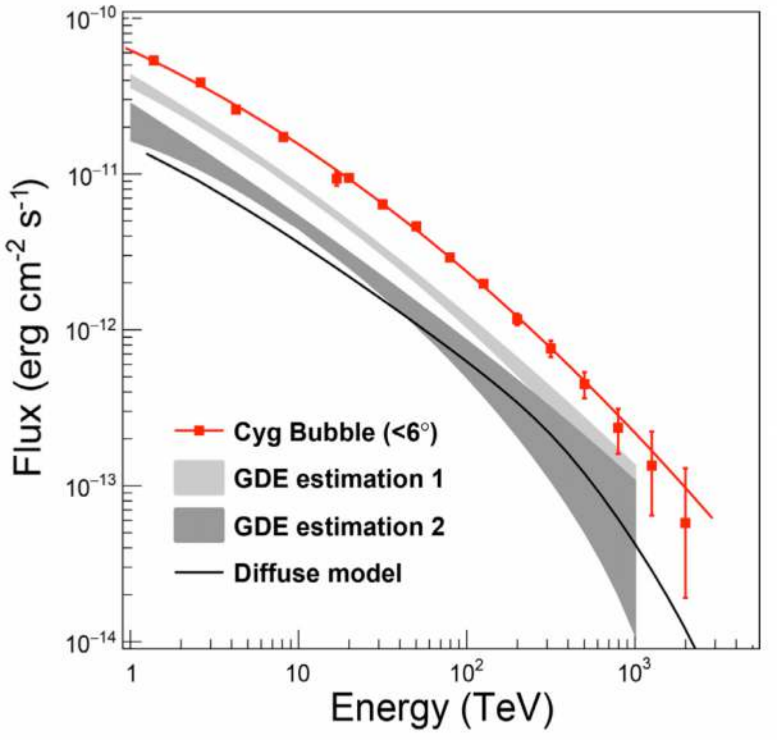
LHAASO detected **8 photons above 1PeV** from the massive star-forming Cygnus X region (at least 6° bubble)

→ indicating presence of **Super PeVatrons !**

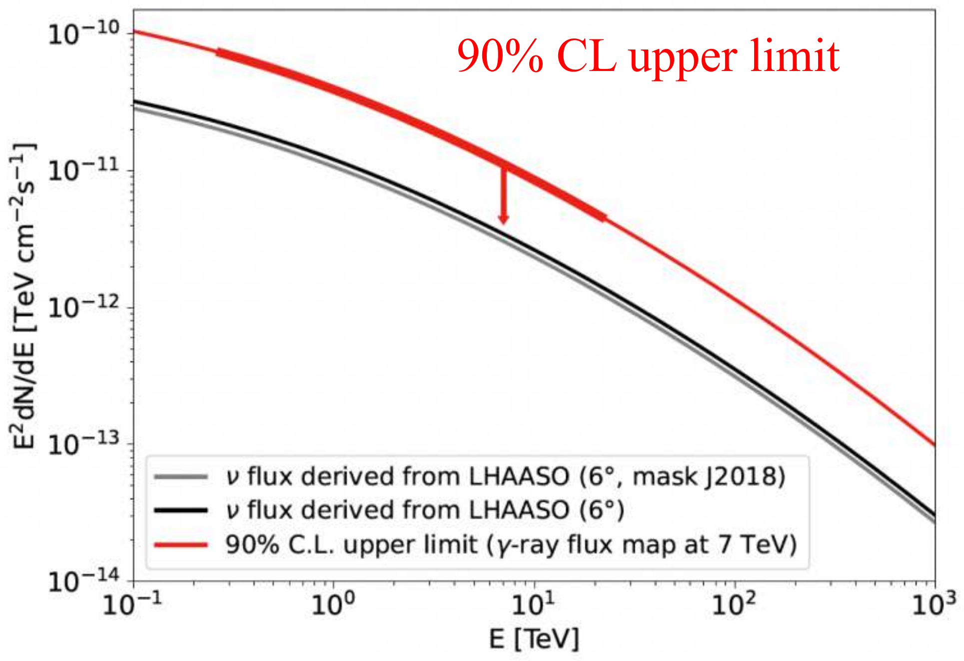
IceCube-LHAASO joint analysis (Cygnus bubble)

- Template search with 7-year IceCube public tracks, no significant signals found
- Neutrino flux limit <5.7×10^{-13} TeV^{-1}cm^{-2}s^{-1} at 5 TeV





LHAASO Collaboration, Sci. Bull. 69 (2024) 4, 449-457



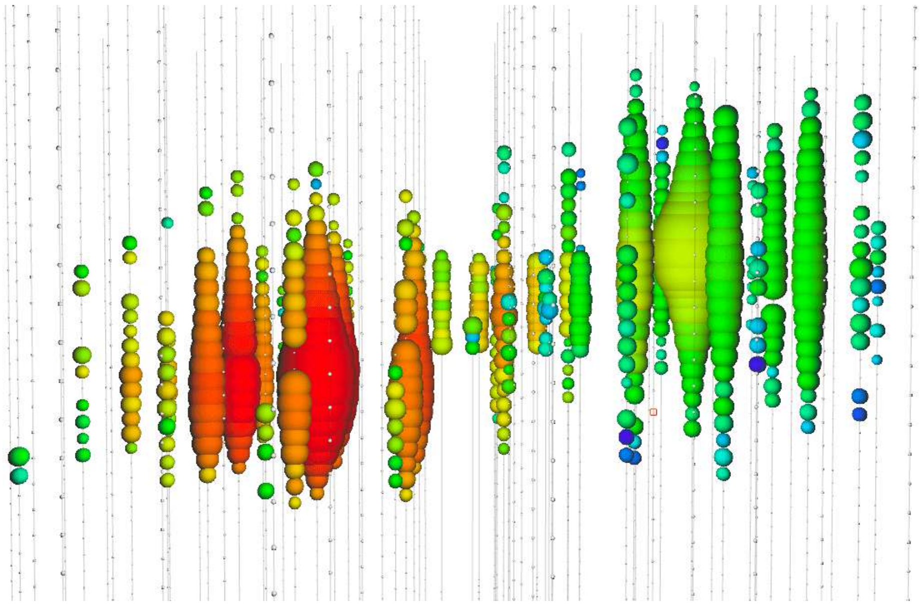
W.-L. Li, T.-Q. Huang, D.-L. Xu, and H.-H. He

arXiv:2402.17352 (ApJ accepted)

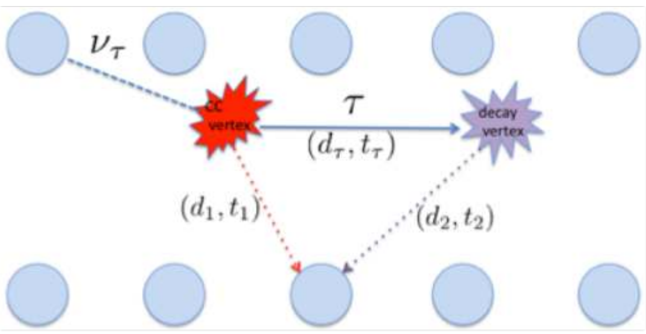
Identifying astrophysical tau neutrinos

“The Tau Double-Bang Signal”

Learned and Pakvasa, 1994



Schematic ν_τ CC interaction in IceCube

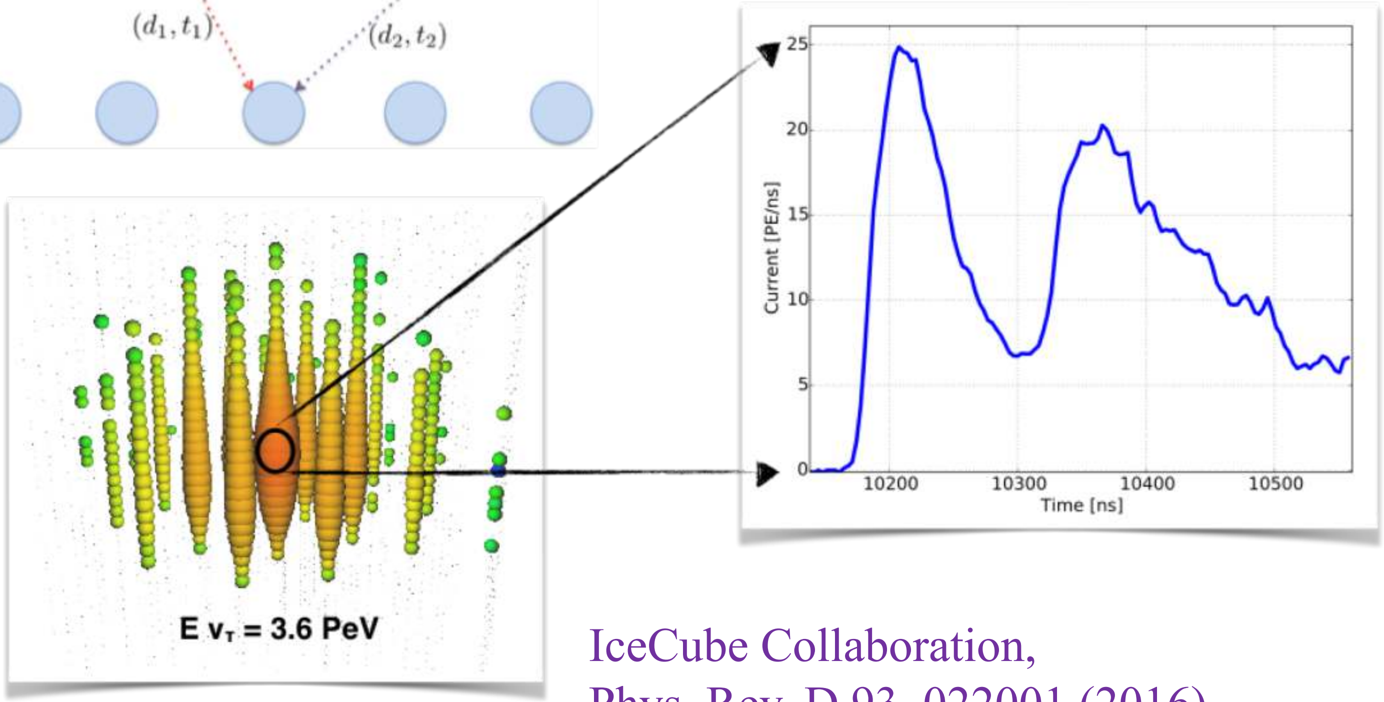


$\nu_\tau + N \rightarrow \tau^- + X$ ➡

$\tau^- \rightarrow \nu_\tau + hadrons$ (64.8%) ✓

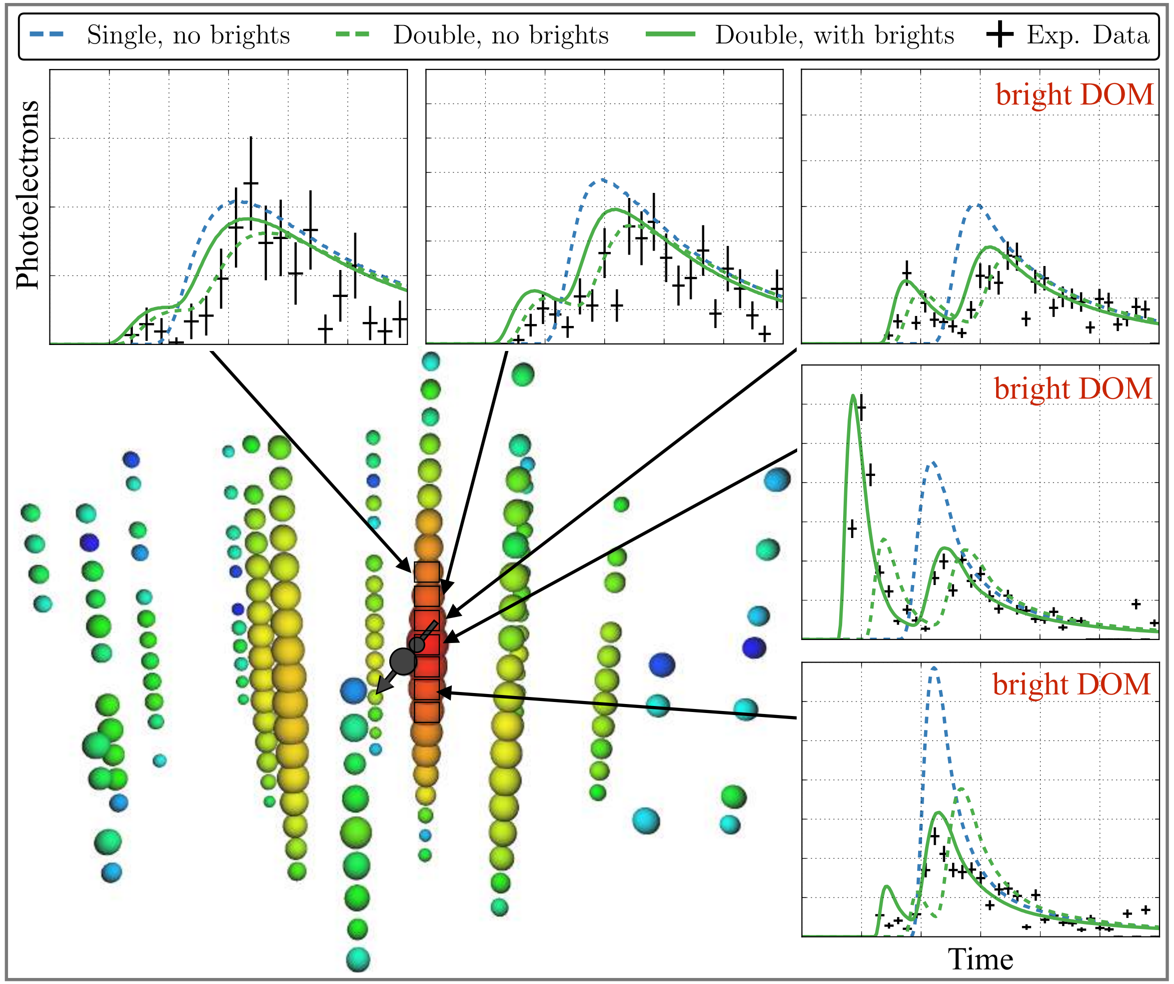
$\tau^- \rightarrow \nu_\tau + \bar{\nu}_e + e^-$ (17.8%) ✓

$\tau^- \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^-$ (17.4%)



IceCube Collaboration,
Phys. Rev. D 93, 022001 (2016)
Corresponding authors: D. Williams, D.-L. Xu

IceCube tau neutrino event candidates



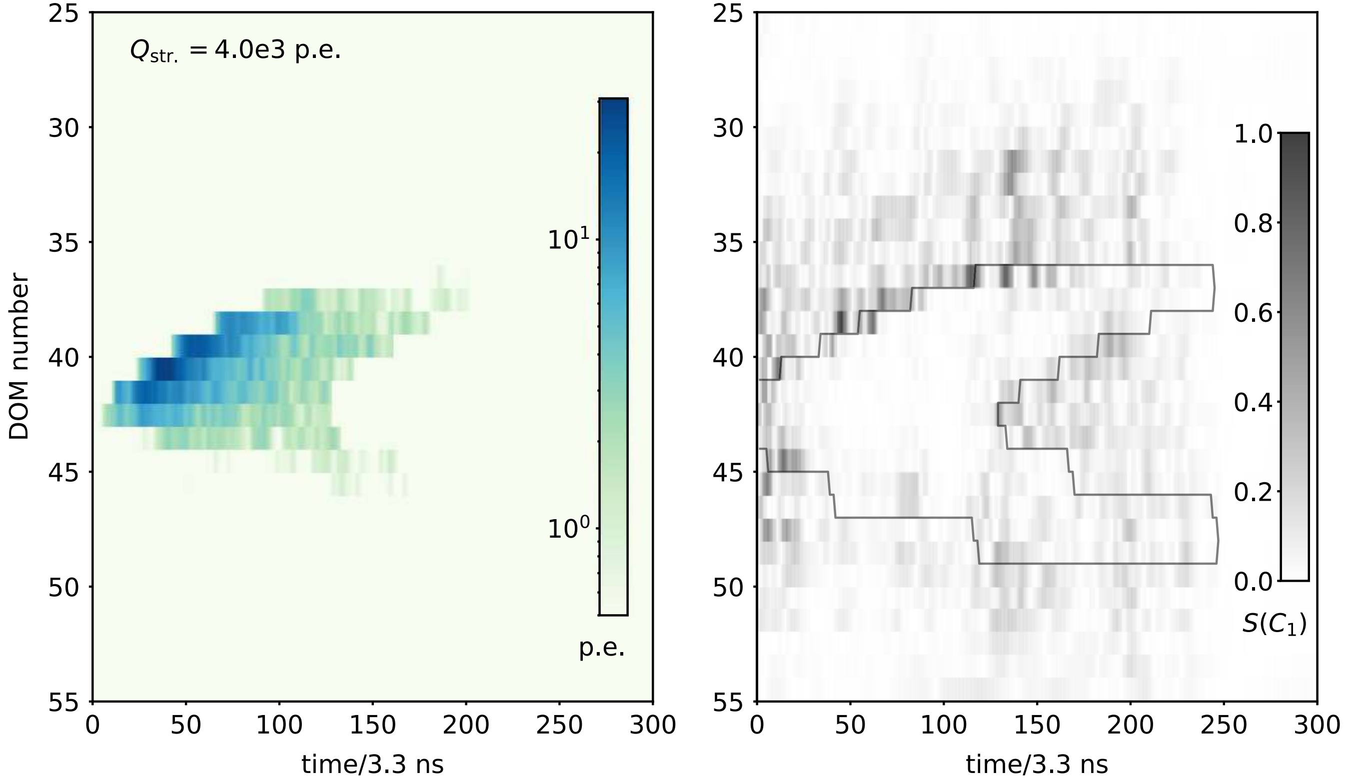
- **Analyzed 7 yr of collected data**
- **Most promising tau neutrino candidate identified up to 2022**
- **Three independent analyses found this same event – one with reconstruction method, two with waveform methods**

IceCube Collaboration, *Eur. Phys. J. C* **82**, 1031 (2022)

M. Meier, J. Soedingrekso, PoS (ICRC2019) 960

L. Wille, D.-L. Xu, PoS (ICRC2019) 1036

IceCube tau neutrino event candidates

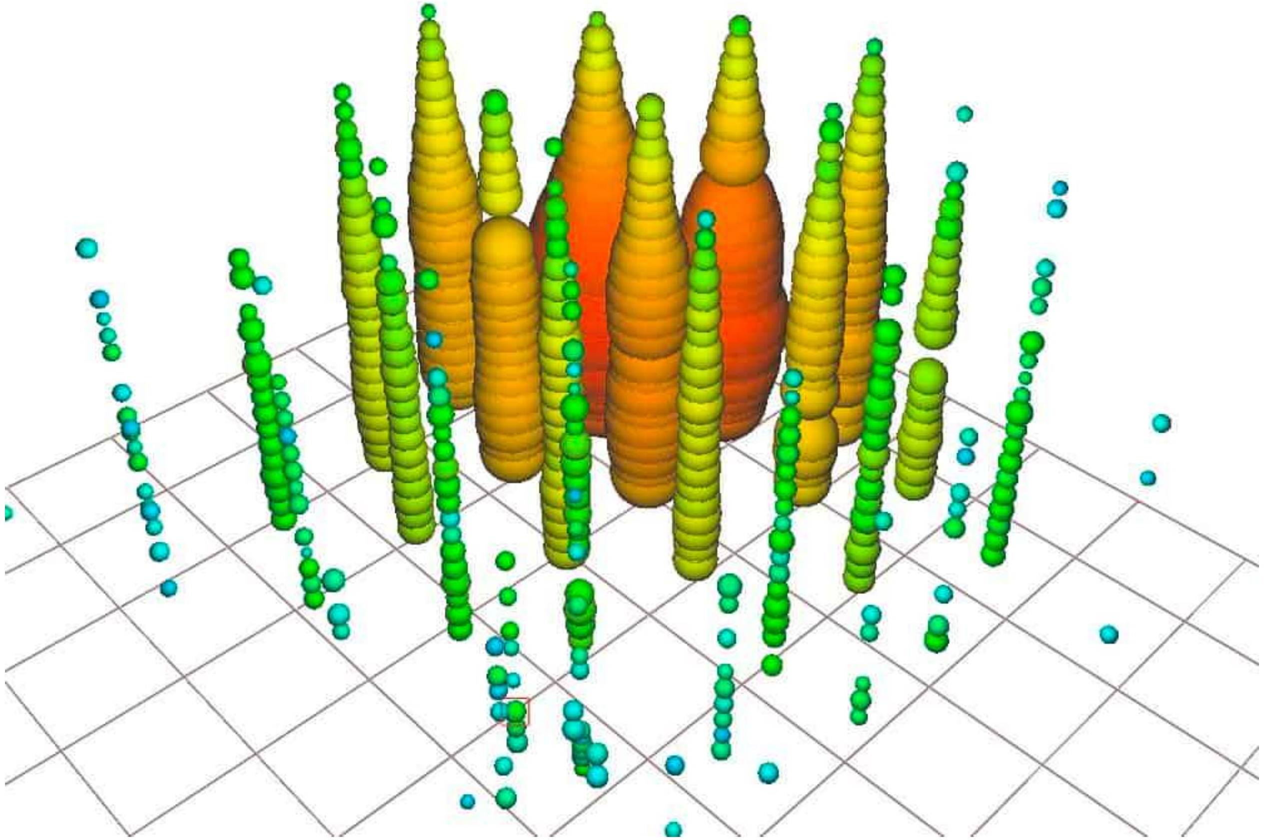


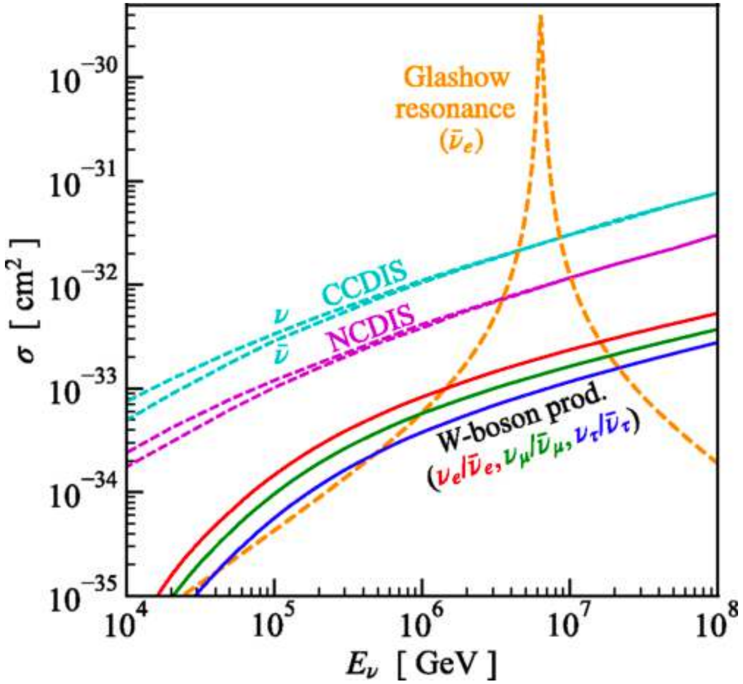
A candidate astrophysical tau neutrino detected in September 2015

- **Analyzed 9.7 yr of collected data from 2011 to 2020**
- **Using CNN trained on images derived from simulated events**
- **7 candidate tau events over an estimated bg of 0.5 events**
- **Ruled out no astrophysical tau hypothesis at 5σ level**

IceCube Collaboration, Phys. Rev. Lett. 132, 151001 (2024)

IceCube Glashow resonance events

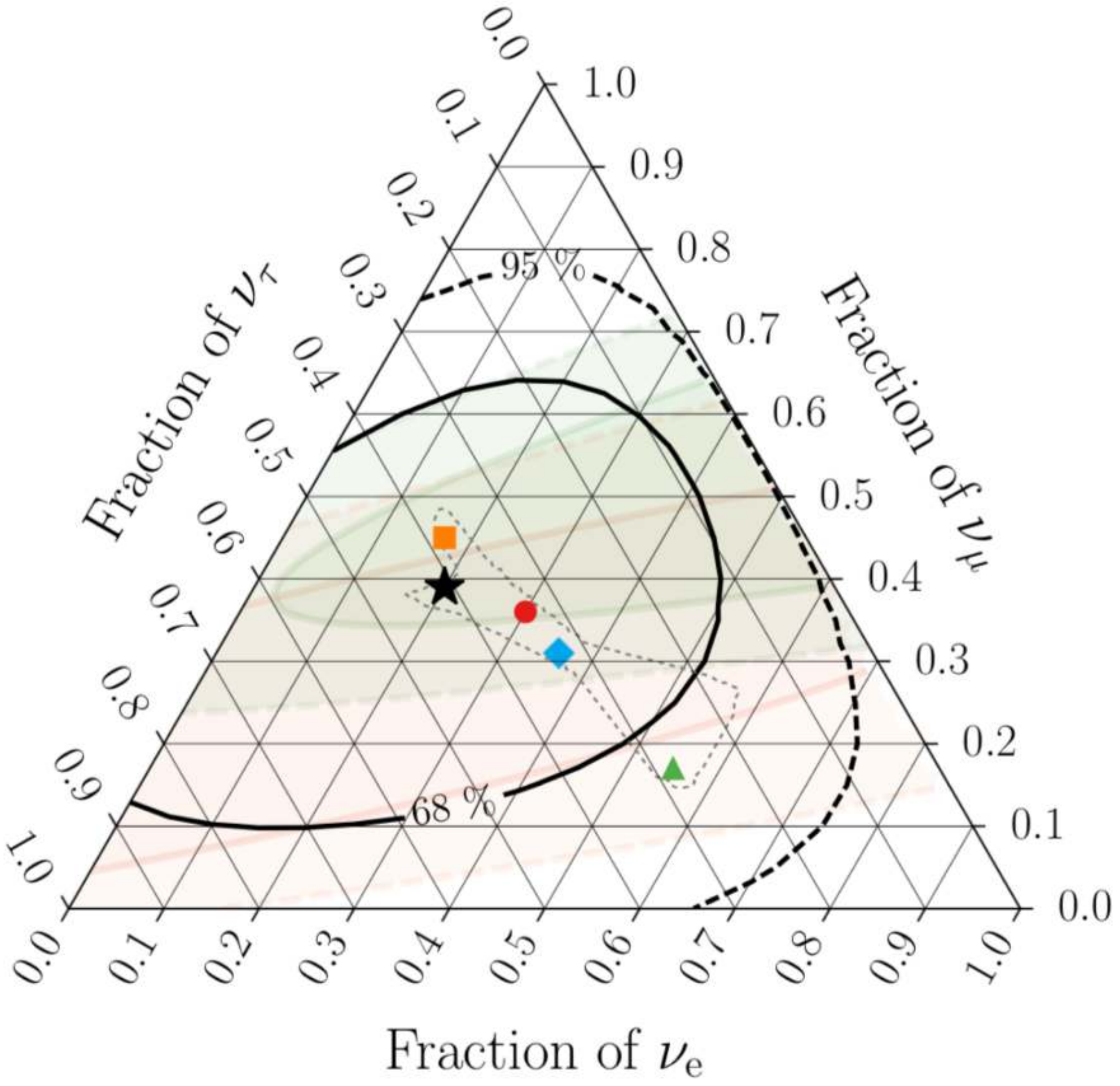




Glashow resonance events enable the identification of the astrophysical anti-electron neutrino flux

IceCube Collaboration, Nature 591, 220–224 (2021)

IceCube neutrino flavor composition



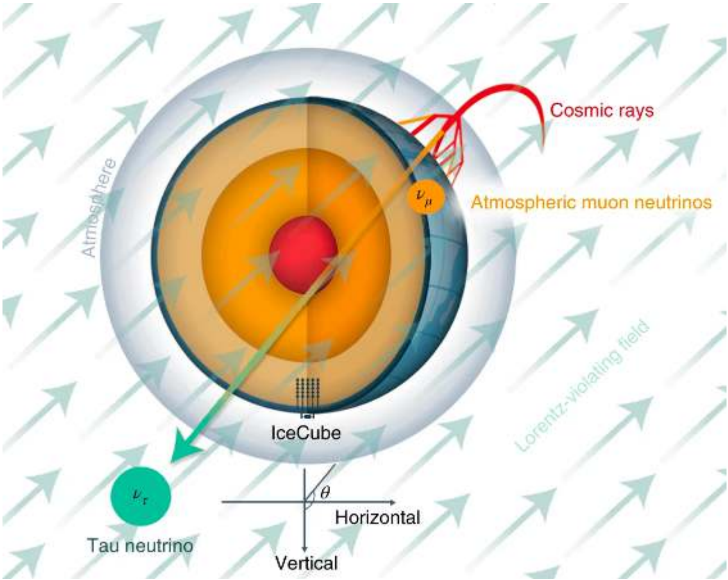
$\nu_e : \nu_\mu : \nu_\tau$ at source $\rightarrow$ on Earth:

■ (orange square)	0:1:0 $\rightarrow$ 0.17 : 0.45 : 0.37
● (red circle)	1:2:0 $\rightarrow$ 0.30 : 0.36 : 0.34
▲ (green triangle)	1:0:0 $\rightarrow$ 0.55 : 0.17 : 0.28
◆ (blue diamond)	1:1:0 $\rightarrow$ 0.36 : 0.31 : 0.33

IceCube Collaboration, *Eur. Phys. J. C* **82**, 1031 (2022)

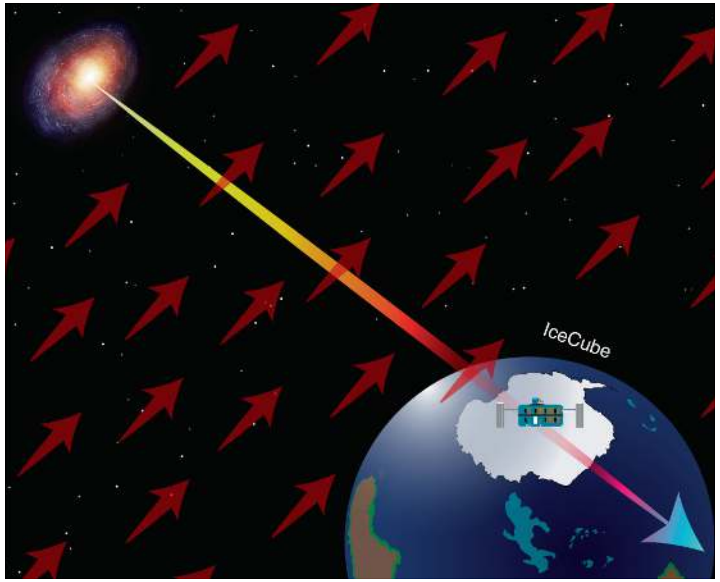
(New) physics with IceCube neutrino flavor ratios

Precision test of Lorentz symmetry



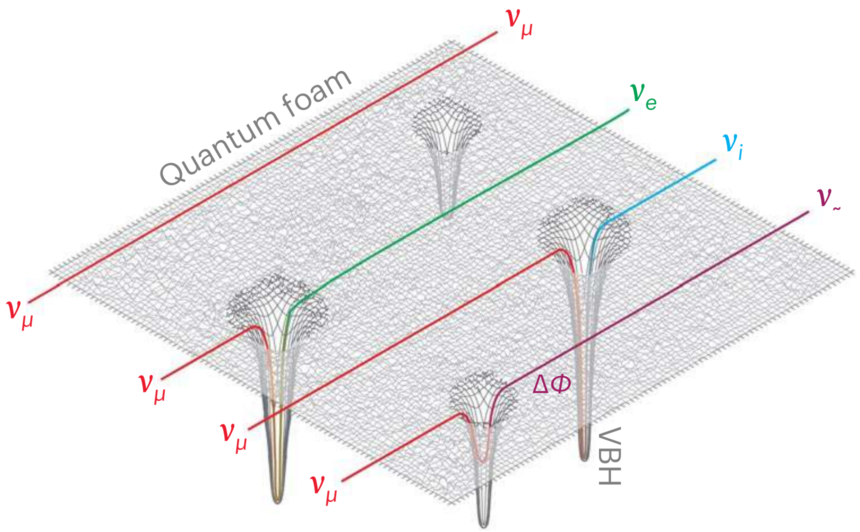
IceCube Collaboration,
Nat. Phys. 14, 961-966 (2018)

Search for quantum gravity



IceCube Collaboration,
Nat. Phys. 18, 1287-1292 (2022)

Decoherence from quantum gravity



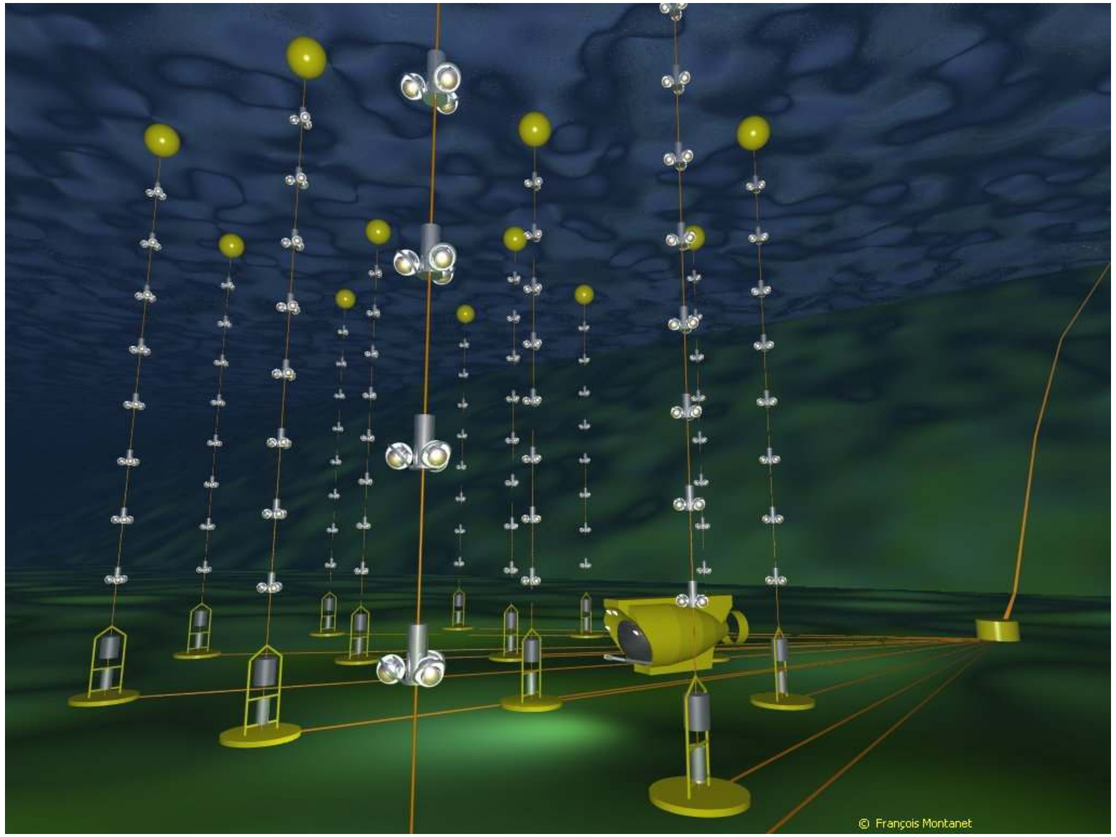
IceCube Collaboration,
Nat. Phys. (2024)

See Aaron Vincent and Carlos Arguelles' talks at this conference

Results from Antares

12 lines, 885 PMTs (~0.01 km^3) at Toulon, France

Actively operated from 2006 to 2022



- First neutrino detection in 2007
- **1.8σ** mild excess of astrophysical diffuse flux with 9 yr of collected data
- First hint of Galactic neutrino flux
- …

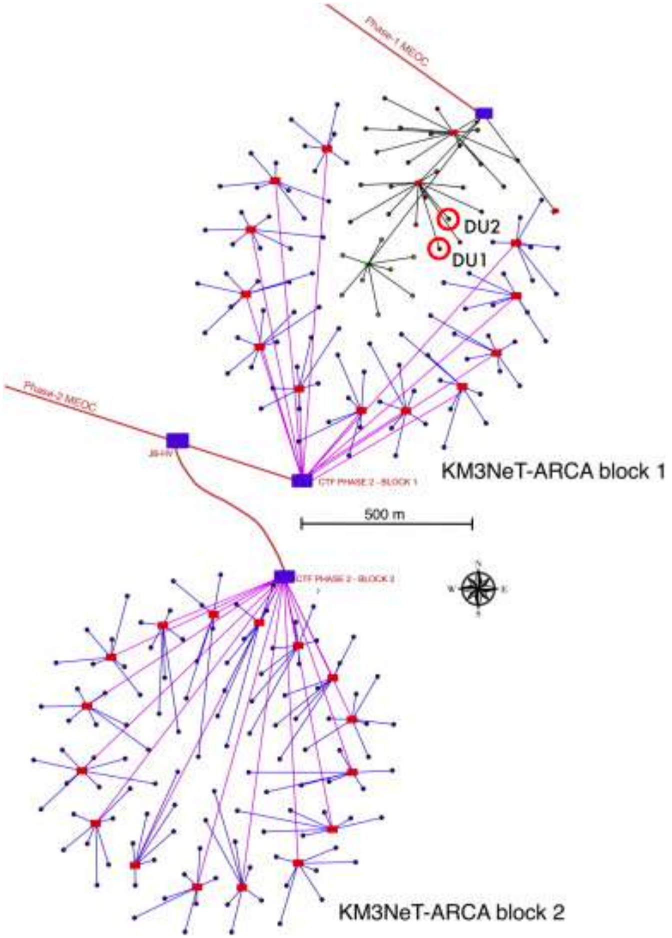
Lesson learned:

"…despite the challenges faced, it is possible to reliably operate a neutrino telescope in the hostile environment of the deep sea. "

POS(TAUP2023)127

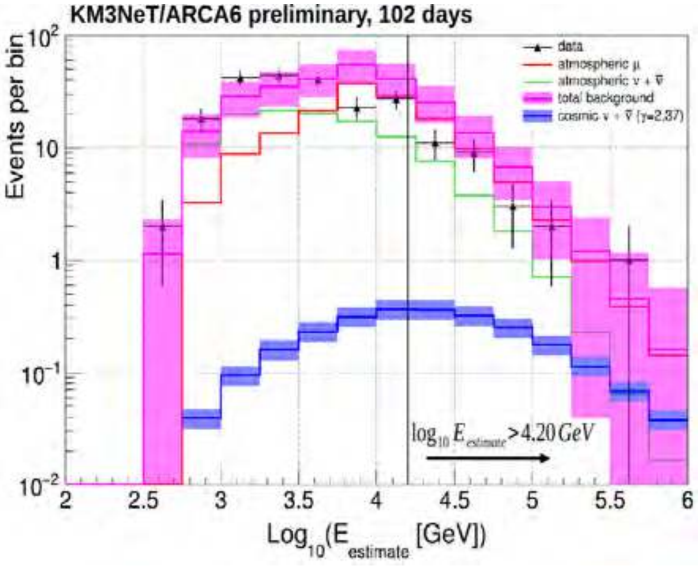
Results from KM3NeT

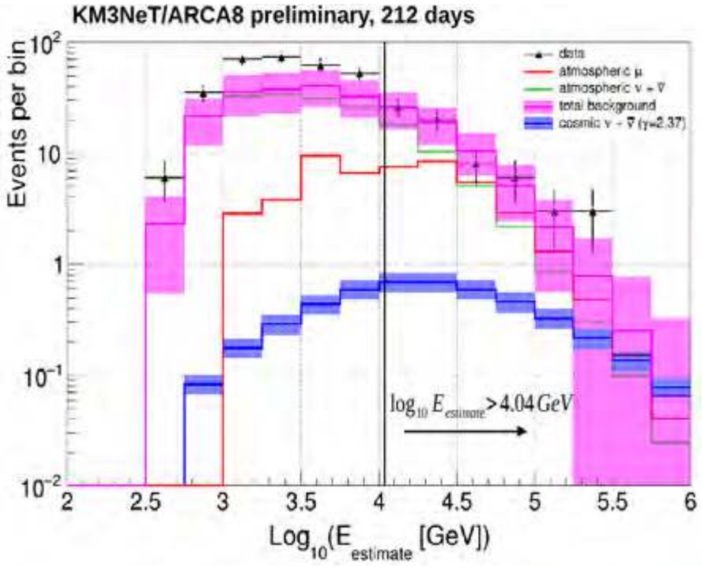
21 strings (DUs), **378** mDOMs since 2021 (as of ICRC2023)



- ***Up-going*** events with partial detector collected between 2021 and 2022
- Setting upper limits in unit of $\mathbf{10^{-18}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$

	ARCA6+8	ARCA19+21	ARCA6+8+19+21	ANTARES	5% quantile	95% quantile
$\gamma = 2.0$	5.11	3.13	2.09	4.0	15.07 TeV	11.71 PeV
$\gamma = 2.37$	6.92	4.68	3.06		5.88 TeV	1.73 PeV
$\gamma = 2.5$	6.76	4.94	3.12	6.8	4.43 TeV	1.03 PeV





POS(ICRC2023)1195

Results from Baikal-GVD

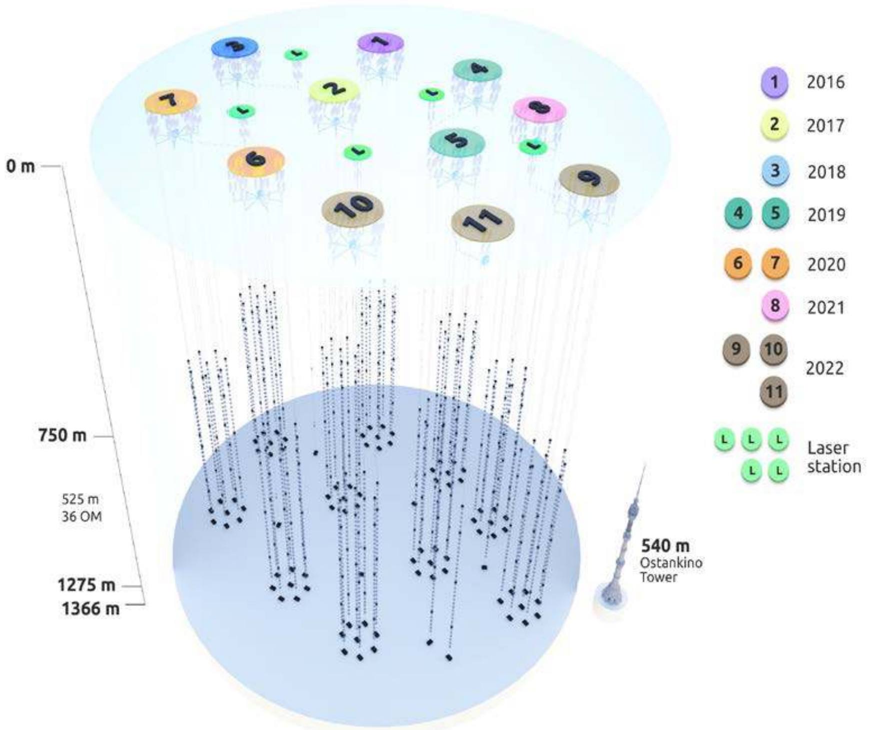
Now largest neutrino telescope in the North!

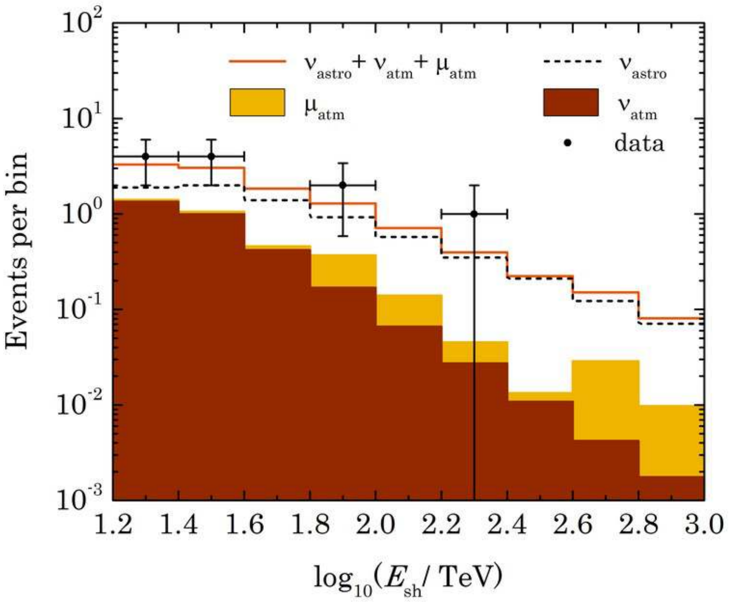
Construction started in 2016

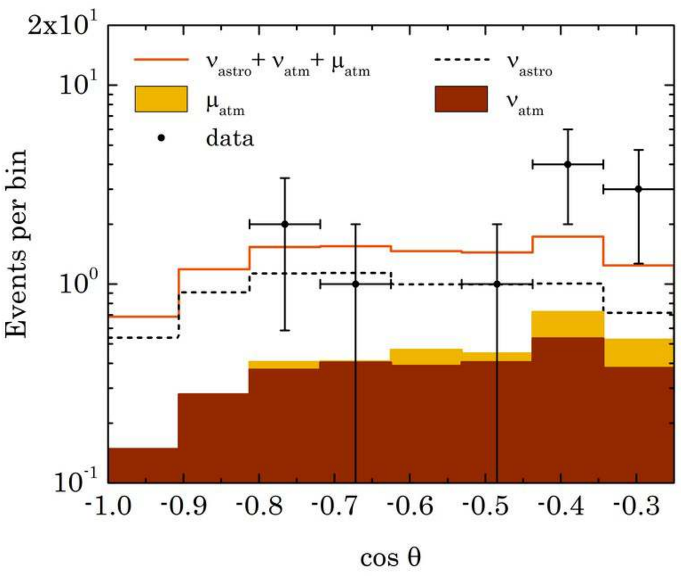
12 clusters, **96** strings, **3456** DOMs

→~**50%** IceCube volume (2023)

- **Cascade** events with partial detector collected between 2018 and 2022
- **17** events over 4.4 expected atmospheric bg
- Confirm the IceCube diffuse flux at **3σ level**

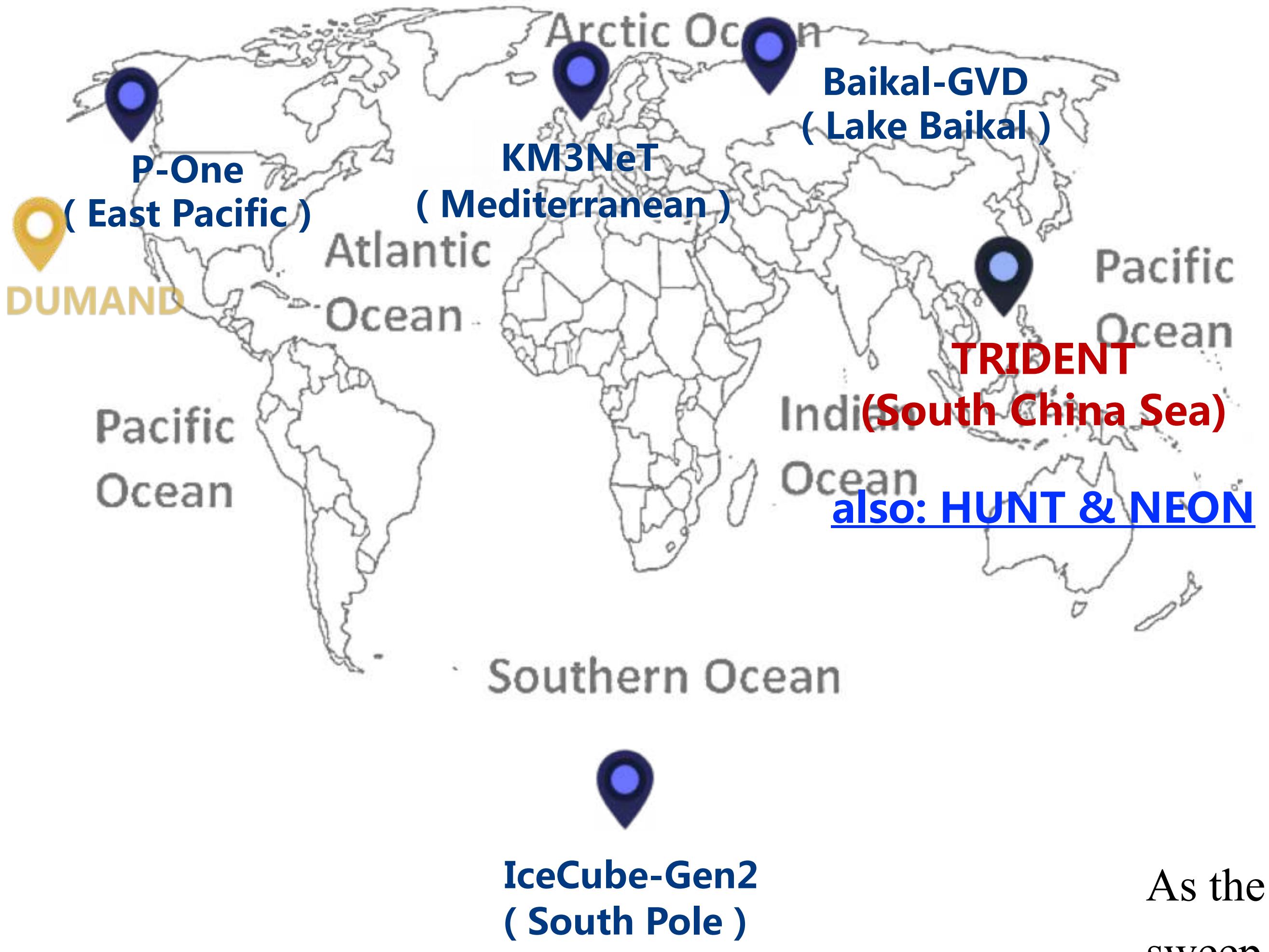




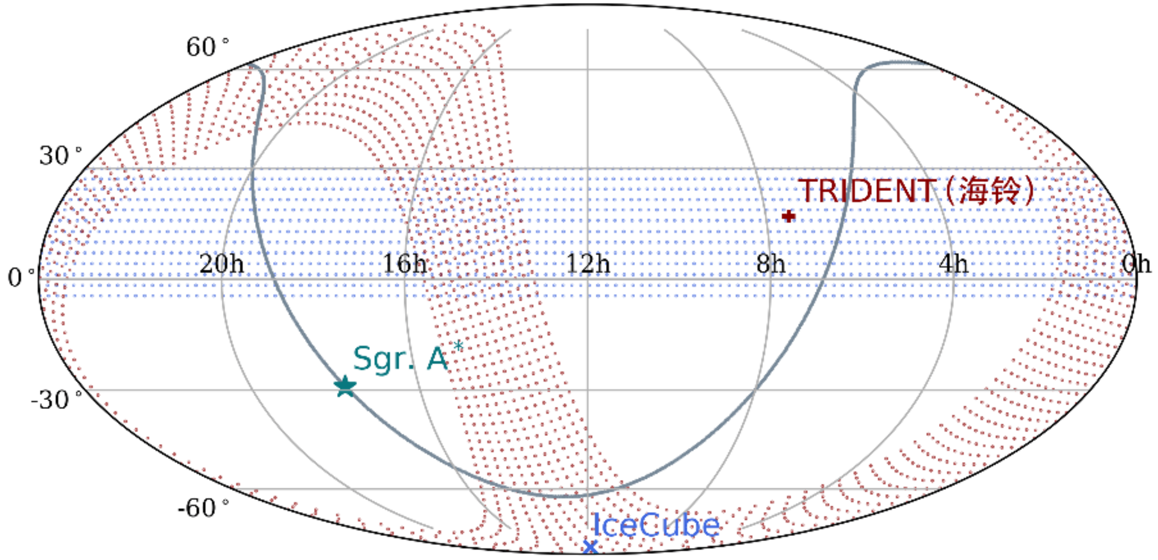


POS(ICRC2023)1015

(Next-gen) neutrino telescopes under planning



TRopIcal DEep-sea Neutrino Telescope



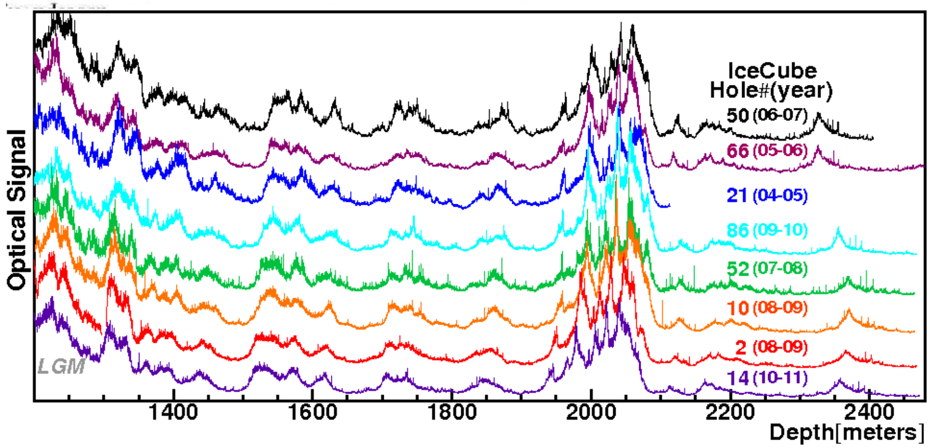
Equatorial

As the Earth rotates, TRIDENT's best sensitivity band will sweep through the entire sky, complementing IceCube-Gen2 well

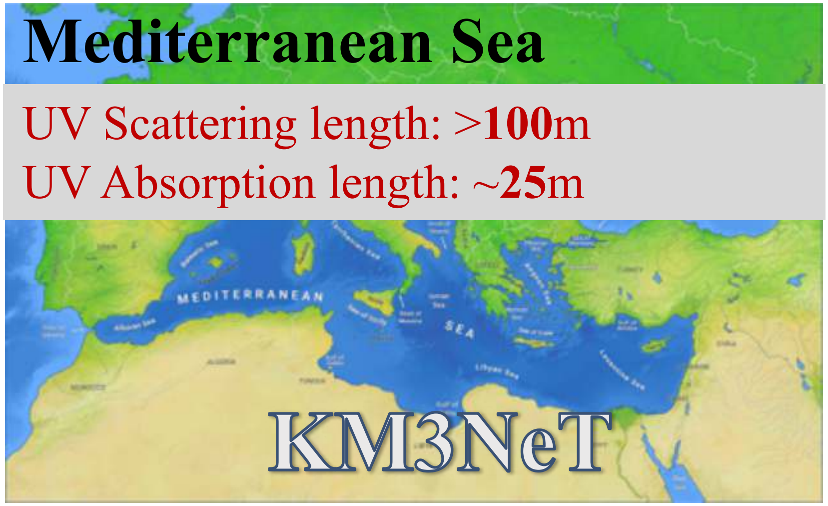
Interaction medium: Ice vs Water

Glacial ice

Most transparent medium on Earth!
Scattering length: ~**25**m
Absorption length: >**100**m



Lake/sea water



On average, ice is more transparent / less absorbing, while water is less scattering

More "direct" photons in water-based telescopes → intrinsically better pointing can be achieved

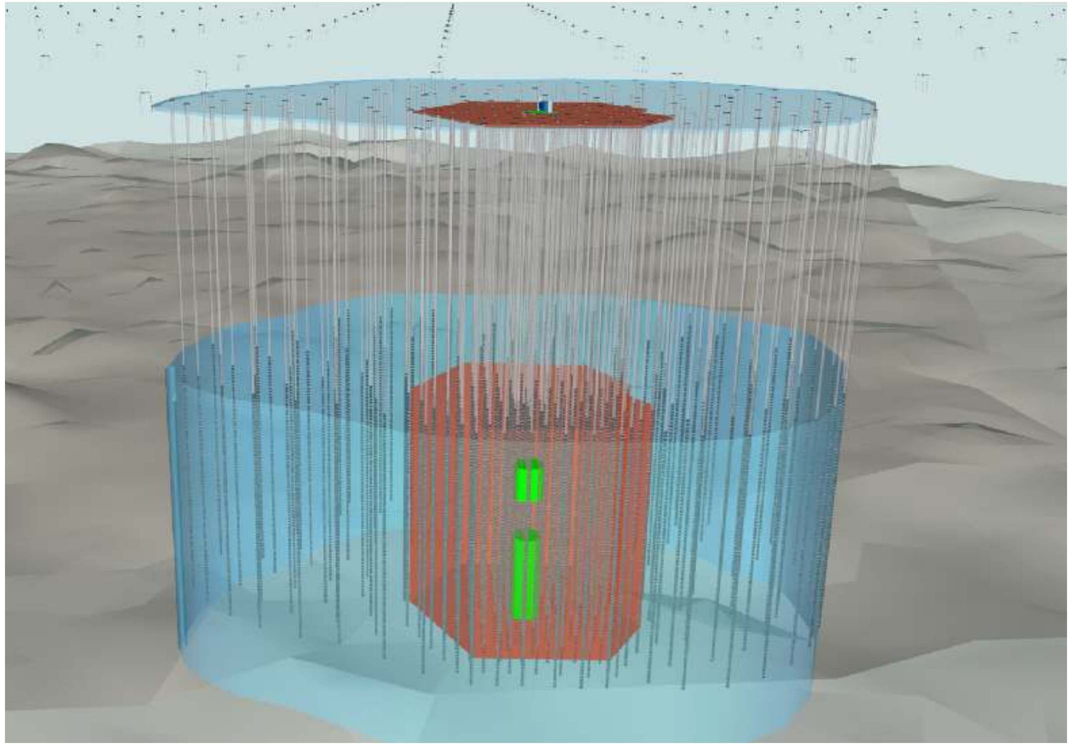
(Next-gen) neutrino telescopes under planning

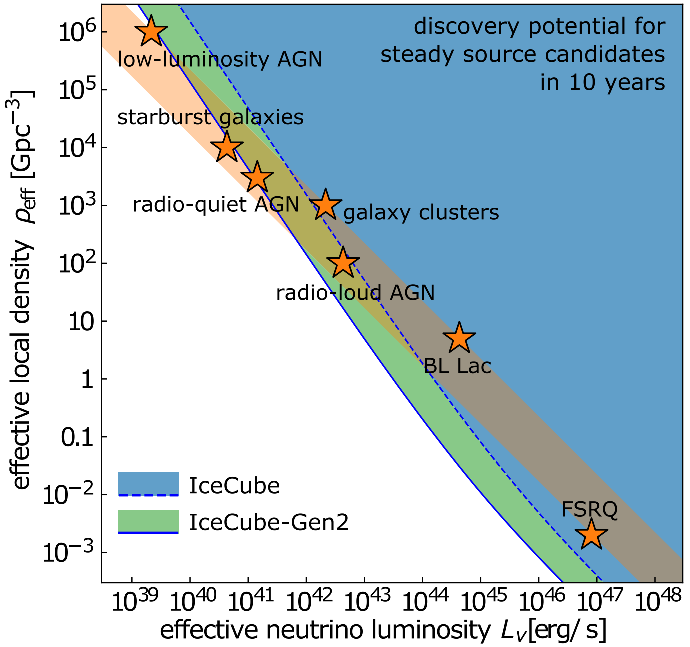
IceCube-Gen2

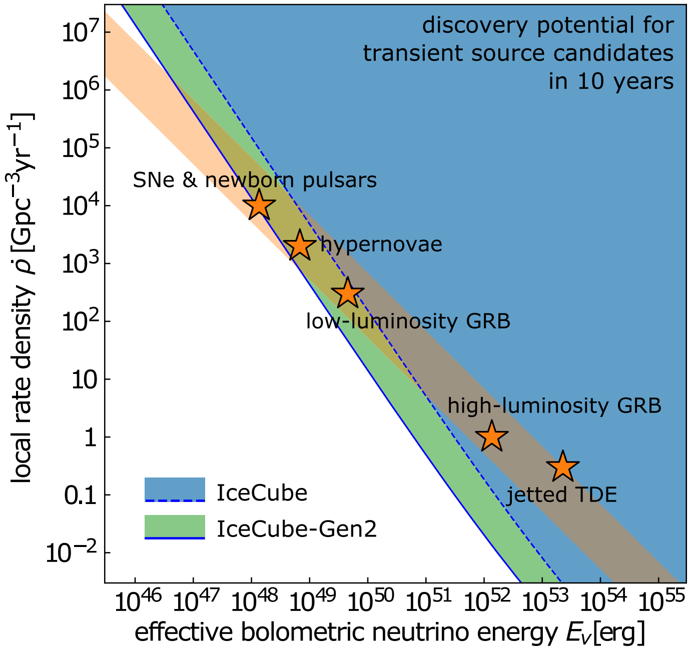
10 km^3 + **500 km^2** surface array for radio UHE neutrinos

~5 times improvement in **point source sensitivity**

Timeline: **~2035 / 2038**



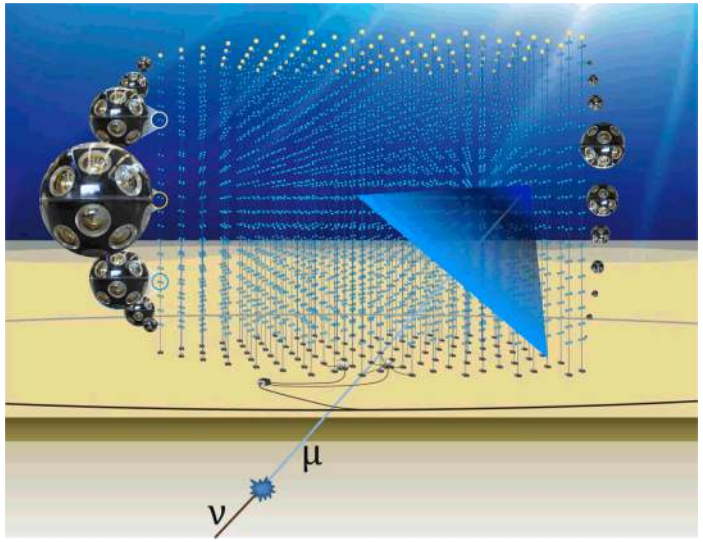




J. Phys. G: Nucl. Part. Phys. 48 (2021) 060501

(Next-gen) neutrino telescopes under planning

KM3NeT-ARCA

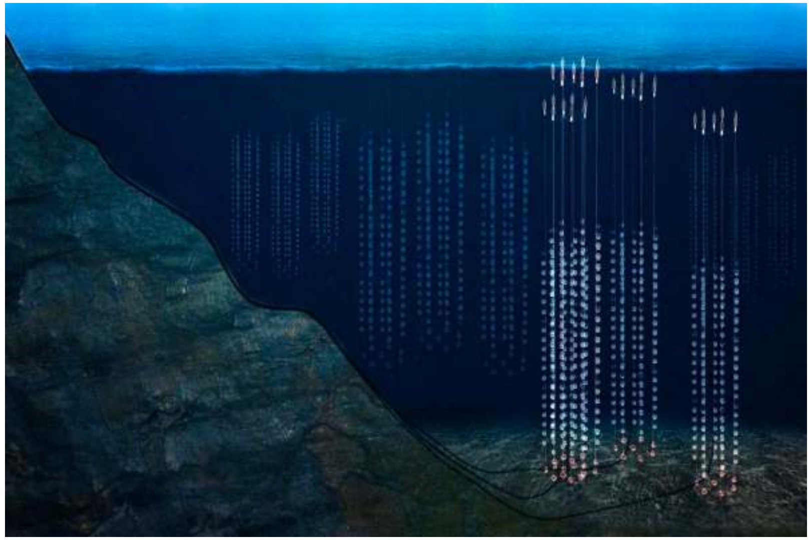


230 strings

Reaching **~1km³**

Timeline: **2028**

Baikal-GVD

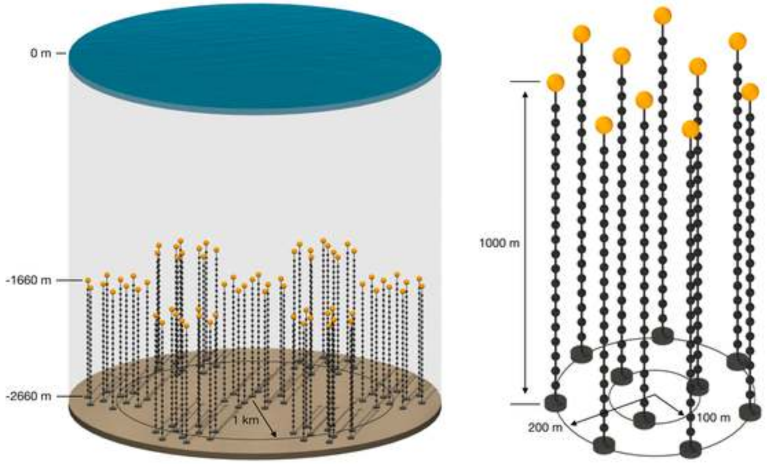


total **16-18 clusters**

Reaching **~1km³**

Timeline: **~2025/2026**

P-One



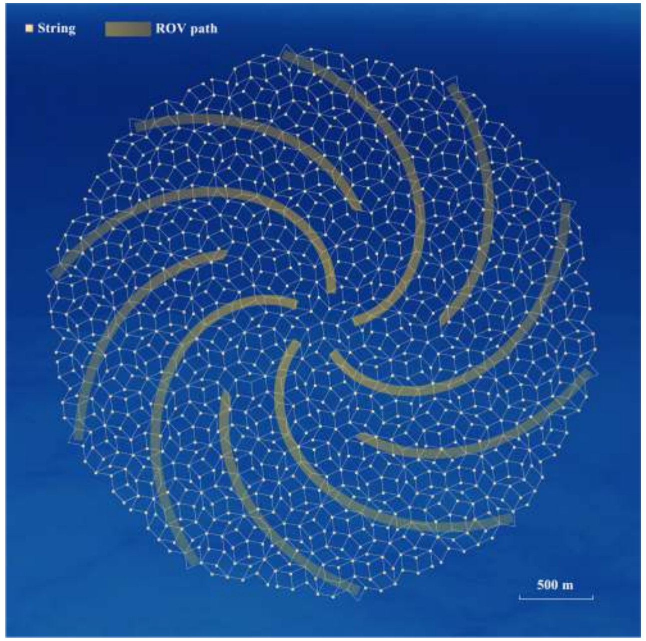
70 strings

Reaching **km³** volume

Timeline: **~2035**

Neutrino telescopes under planning in China

TRIDENT



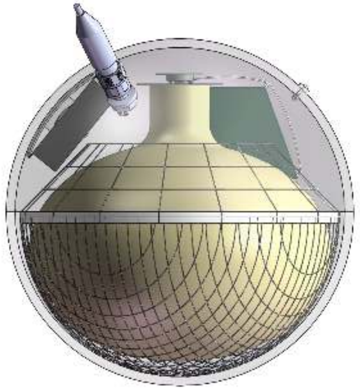
1200 strings

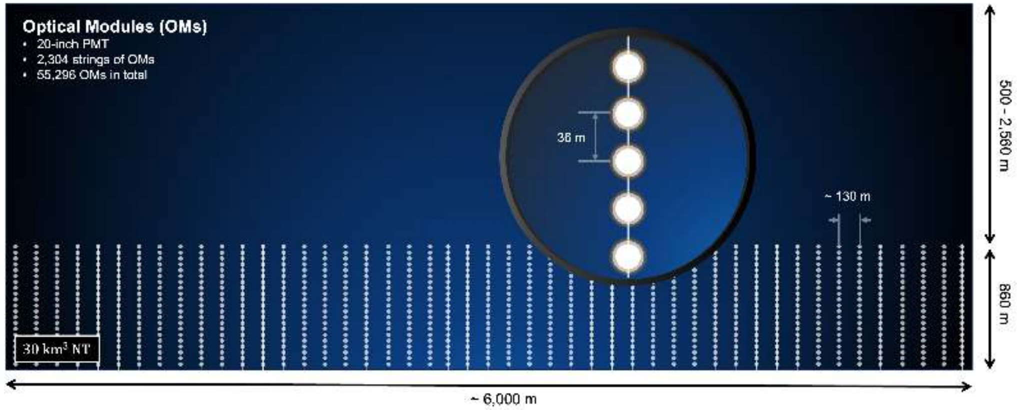
Reaching **~8 km³**

Timeline: ~**2030-2035**

Nature Astronomy (2023)

HUNT





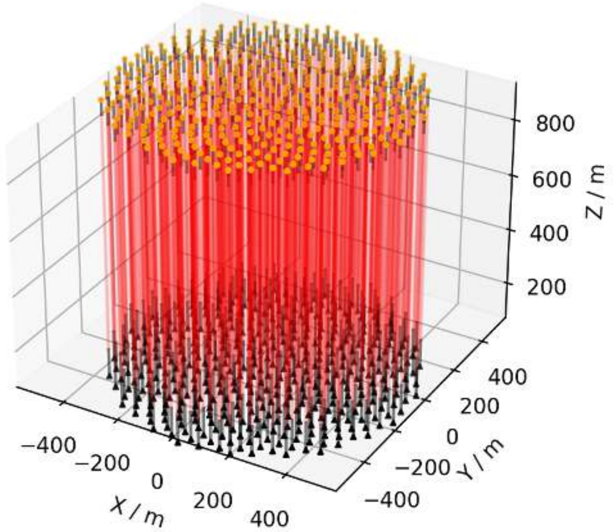
2304 strings

Reaching **~30 km³**

Timeline: **???**

POS(ICRC2023)108

NEON



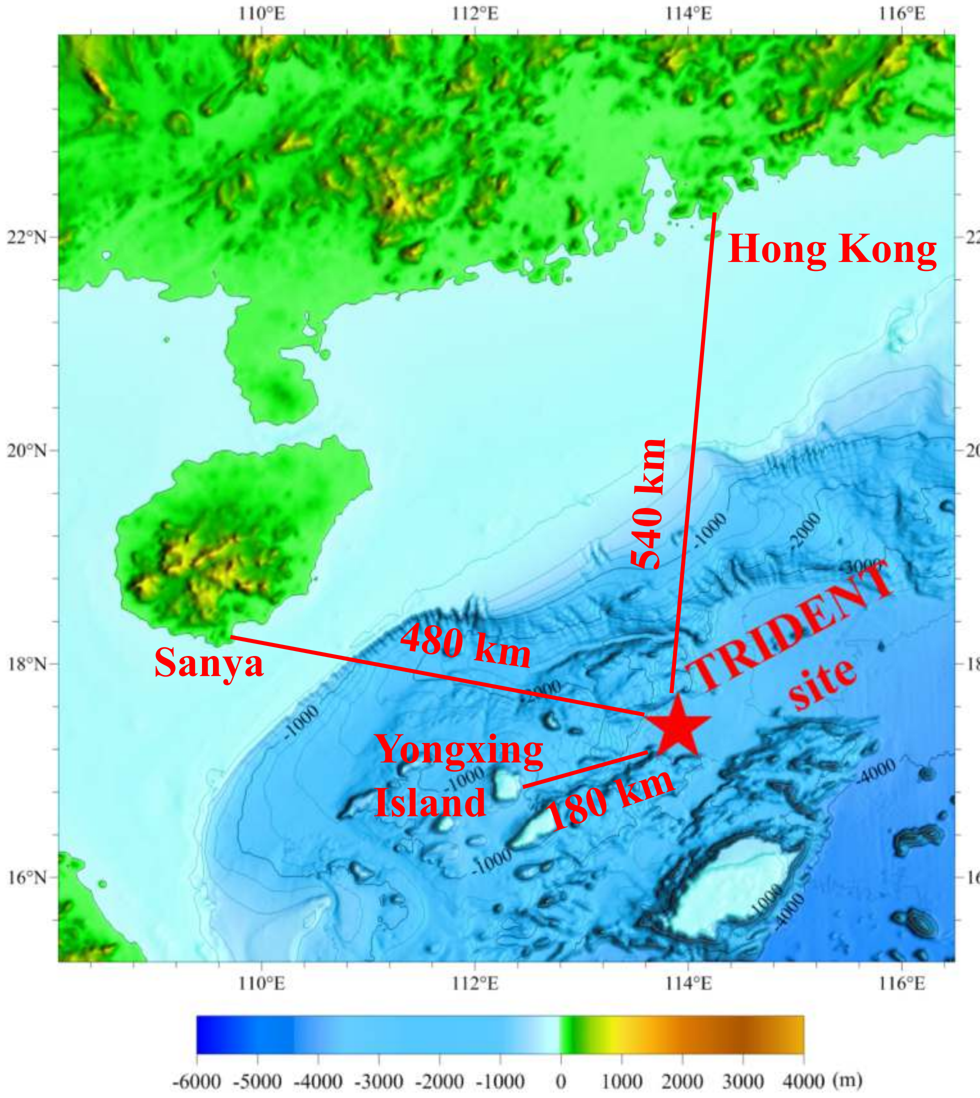
400 strings

Reaching **0.8 km³**

Timeline: **???**

POS(ICRC2023)1017

TRIDENT Explorer : T-REX



Pre-selected site conditions

- Flat seabed
- No nearby high rises or deep trenches
- Depth >3km
- Close proximity to a shore

Measured params

- **Optical properties**
- Current field
- Radioactivity

https://trident.sjtu.edu.cn/en

Optical properties of deep-sea water

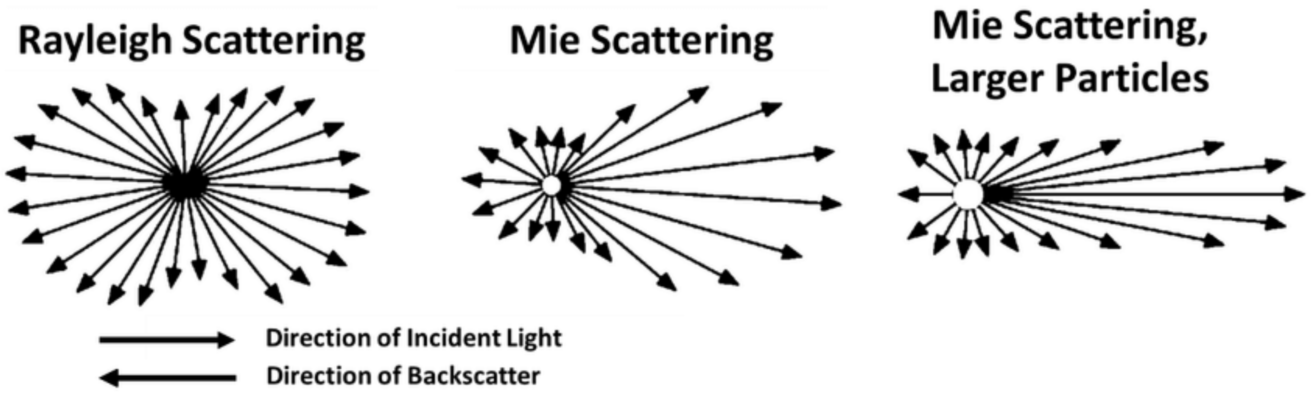
TRIDENT 海 | 铃 | 计 | 划

Absorption process (λ_{abs})

kill the photons, spacing design

Scattering process (λ_{sca})

photon direction, angular resolution



Rayleigh scattering (λ_{Ray}):

$$I = I_0 \frac{8\pi^4\alpha^2}{\lambda^4 R^2}(1+\cos^2\theta)$$

Mie scattering ($\lambda_{Mie}, \langle cos\theta_{Mie}\rangle$):

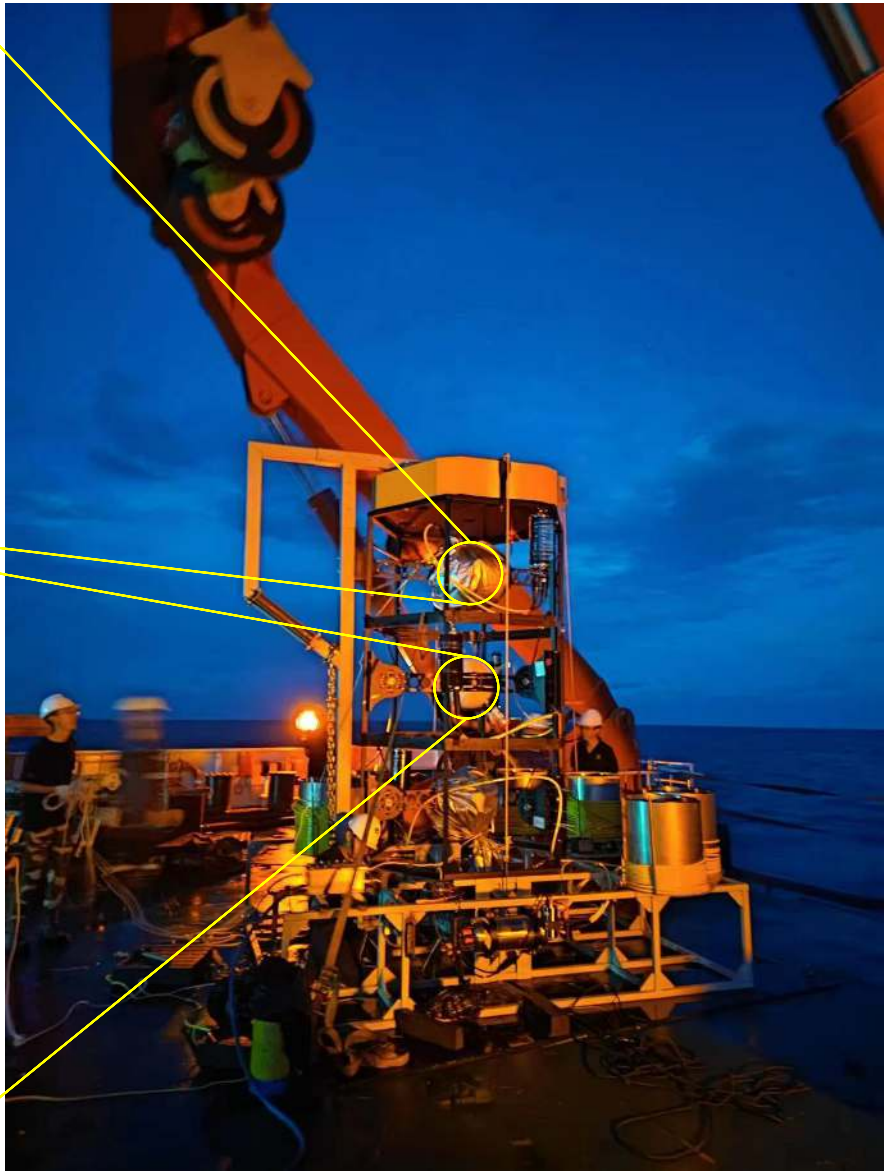
$$\widetilde{\beta^{HG}}(g,\cos\theta) = \frac{1}{4\pi}\frac{1-g^2}{(1+g^2-2g\cos\theta)^{3/2}}$$

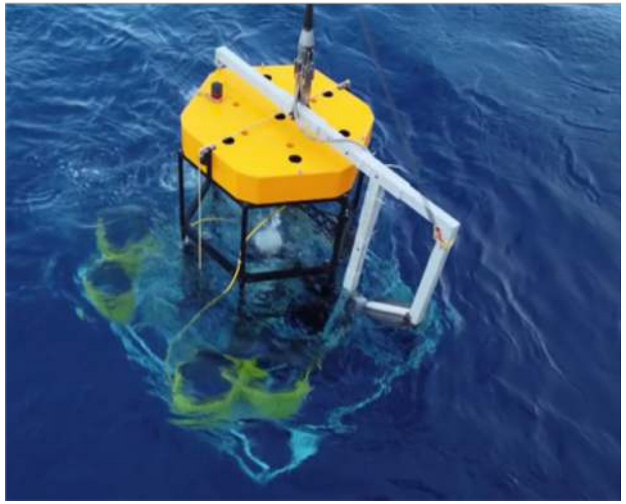
Attenuation length:

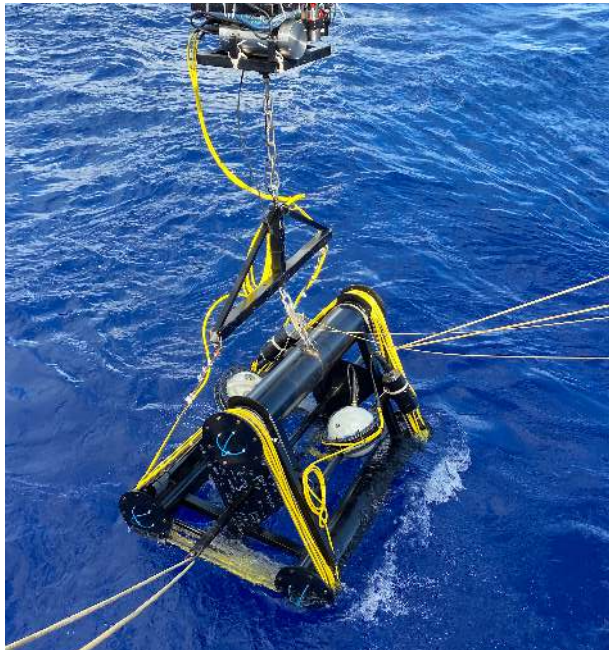
$$I(L) = I_0 \cdot e^{-(\frac{L}{\lambda_{abs}}+\frac{L}{\lambda_{sca}})} = I_0 \cdot e^{-\frac{L}{\lambda_{att}}}$$

F. Hu *et. al.*, *Simulation study on the optical processes at deep-sea neutrino telescope sites,* **NIMA** 1054 (2023) 168367

TRIDENT Explorer : T-REX Apparatus

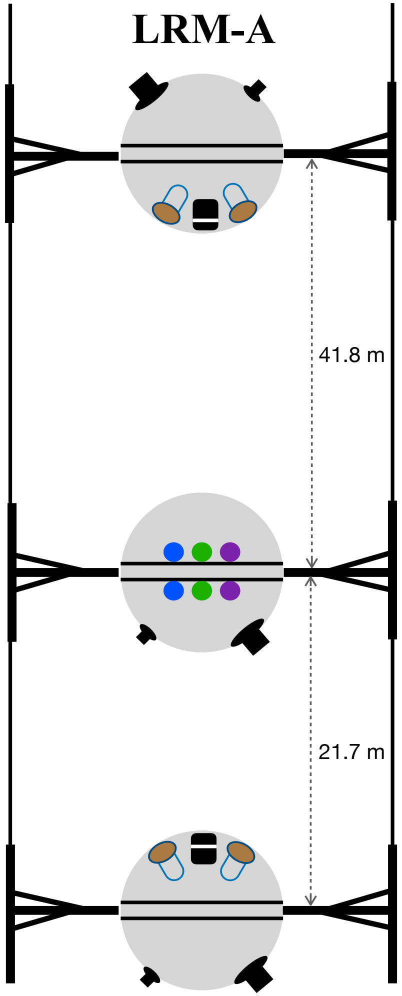




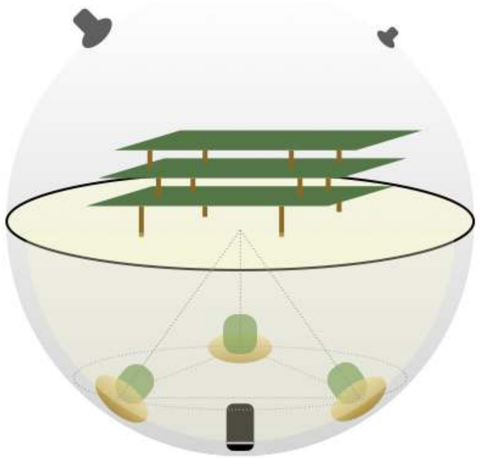


T-REX PMT system

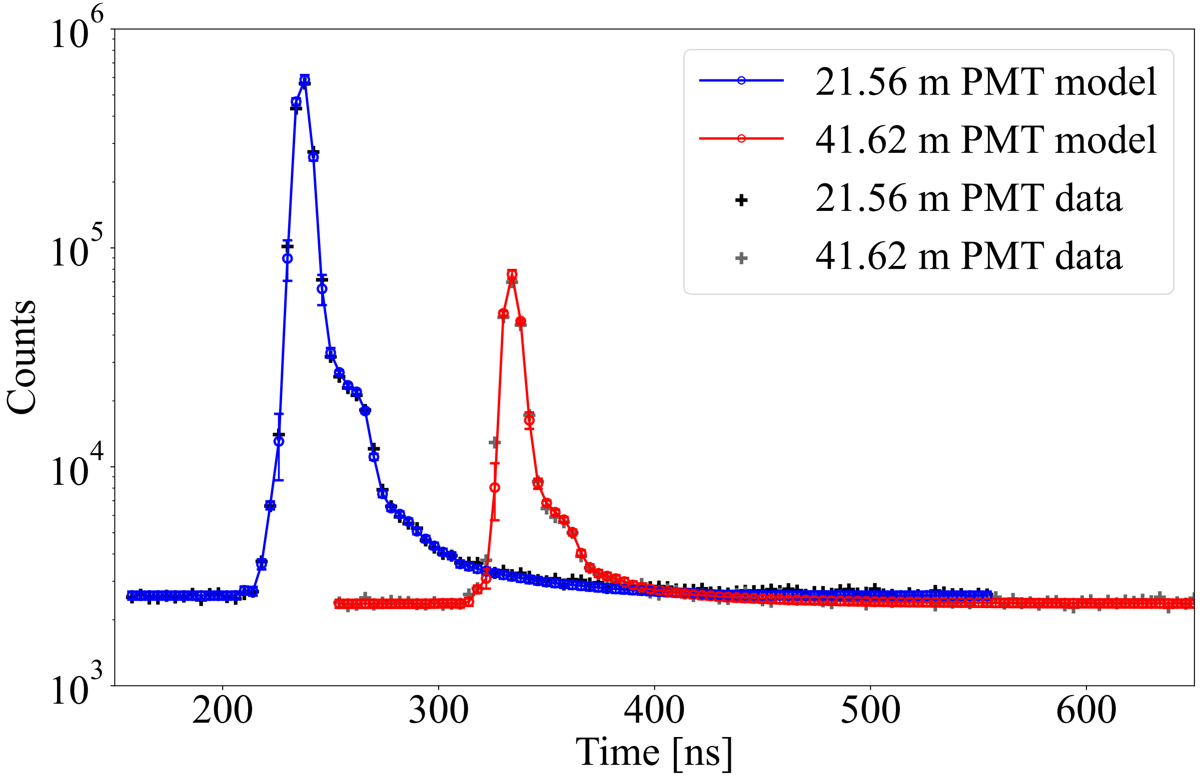
LRM-A



LRM-B



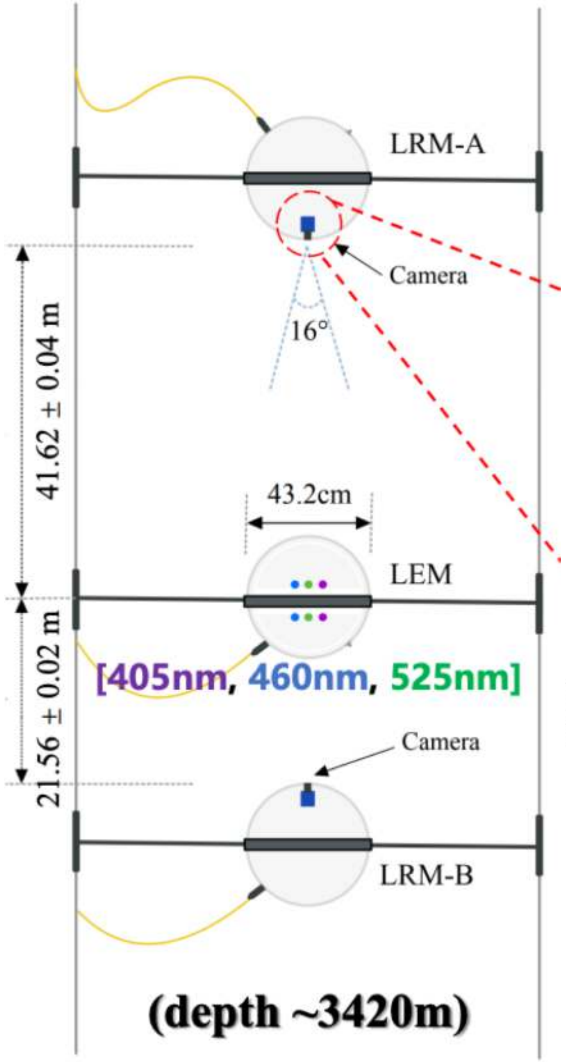
Use relative measurement method to mitigate hidden systematics



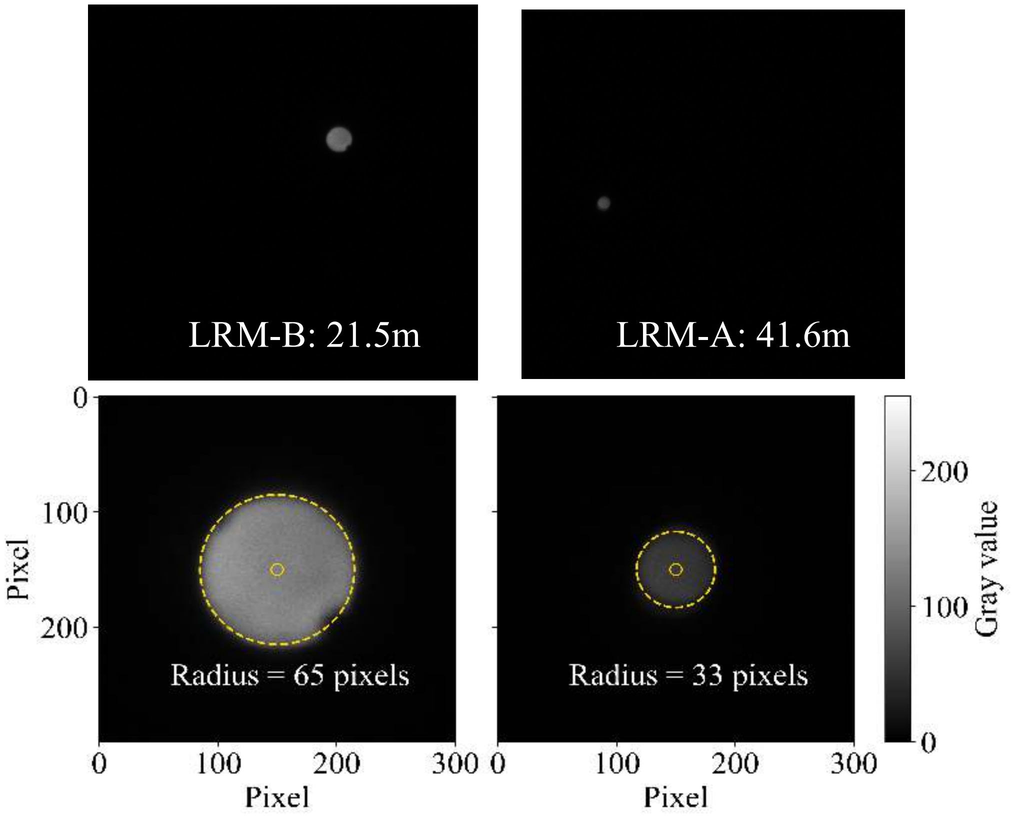
Electronics: J. N. Tang *et. al.*, **Journal of Instrumentation**, vol.18 T08001 (2023);
M. X. Wang *et. al.*, **IEEE Transactions on Nuclear Science**, vol. 70, 2240–2247 (2023)

Light source: W. L. Li *et. al., The Light Source of the TRIDENT Pathfinder Experiment*, **NIMA** 1056 (2023) 168588

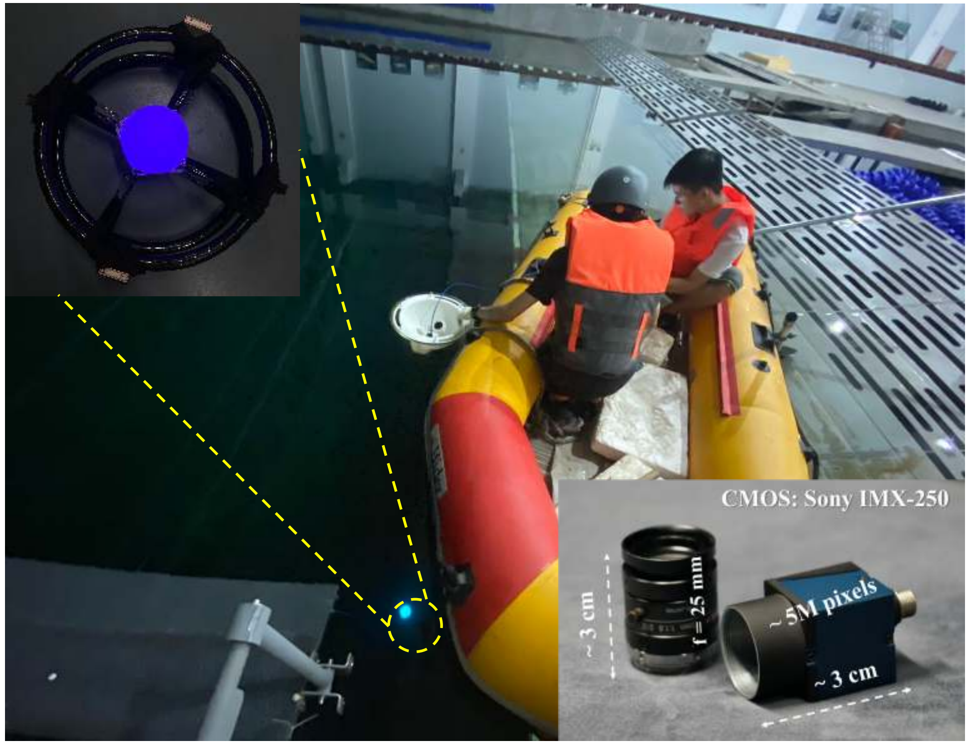
T-REX Camera system



Images captured at depth of 3420m



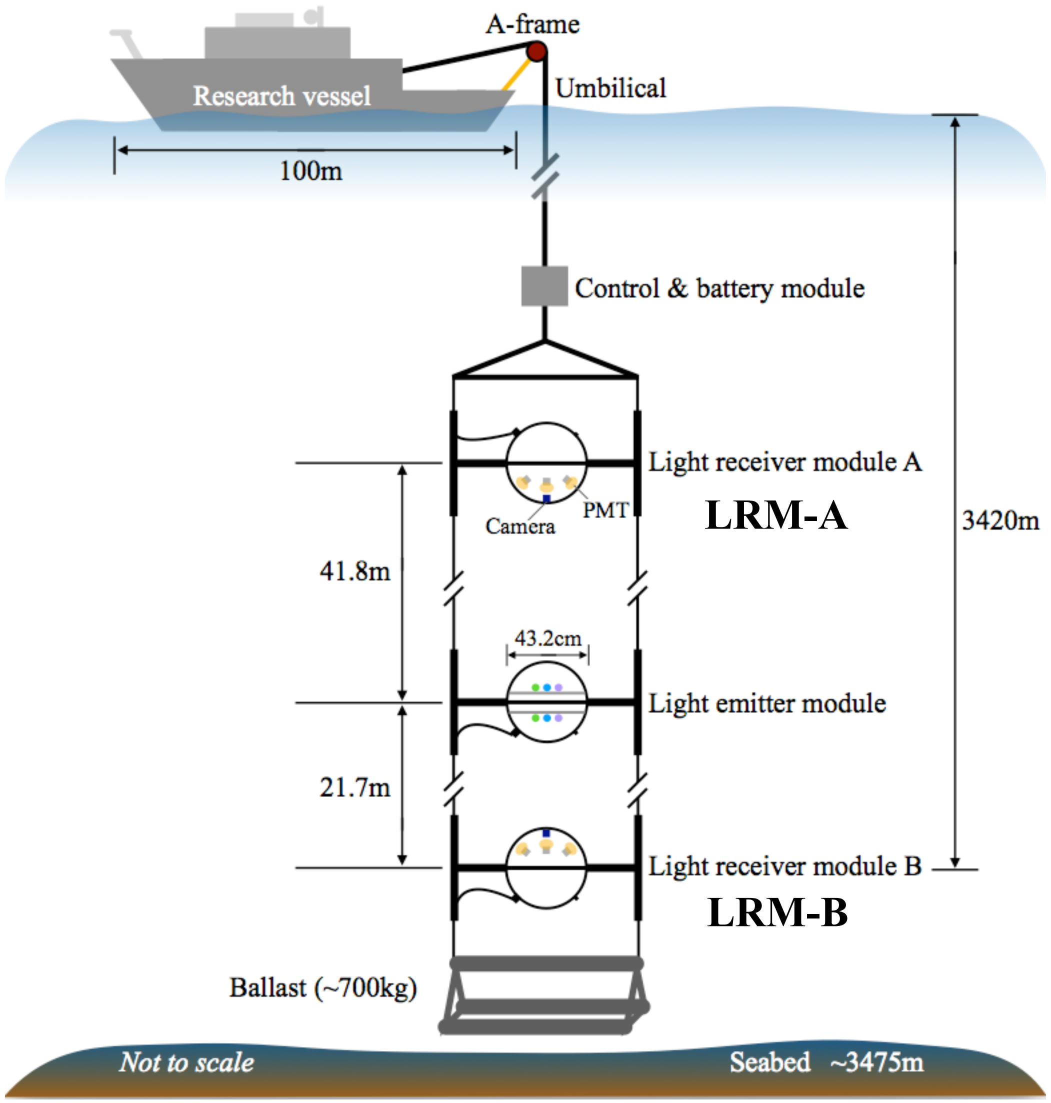
Camera-calibrating in a ship towing tank



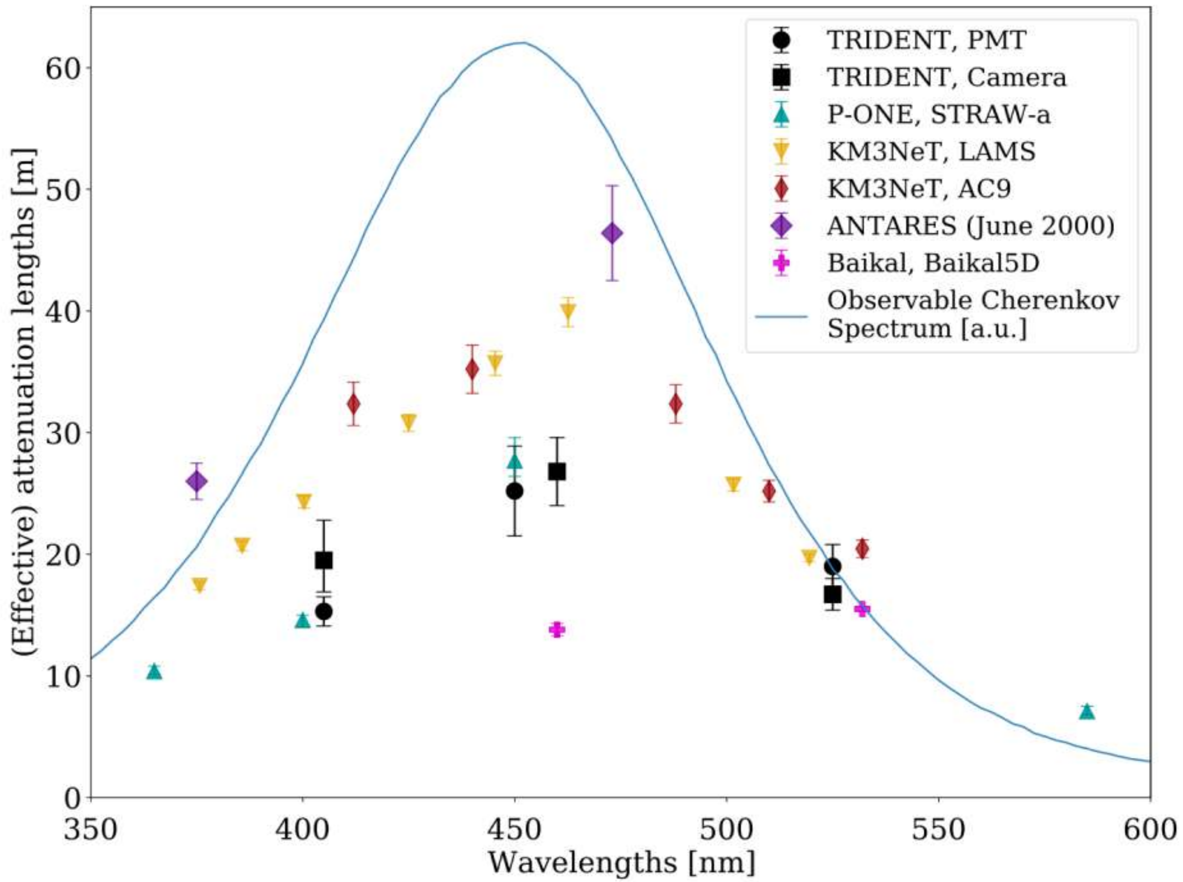
PoS (ICRC2023) 1094

W. Tian *et. al.*, *A camera system for optical calibration of water-based neutrino telescopes* (in prep)

TRIDENT Explorer : Optical Properties

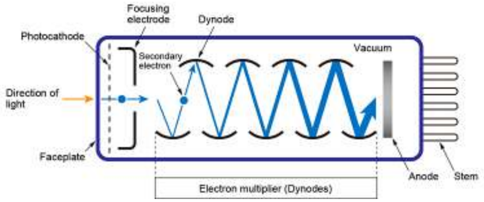


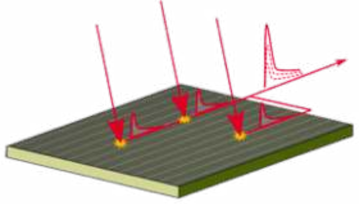
- Dedicated analytical and numerical modeling
- Exp. data: ~ **1**TB ⇔ Simulated data: ~ **100** TB, **10M** files

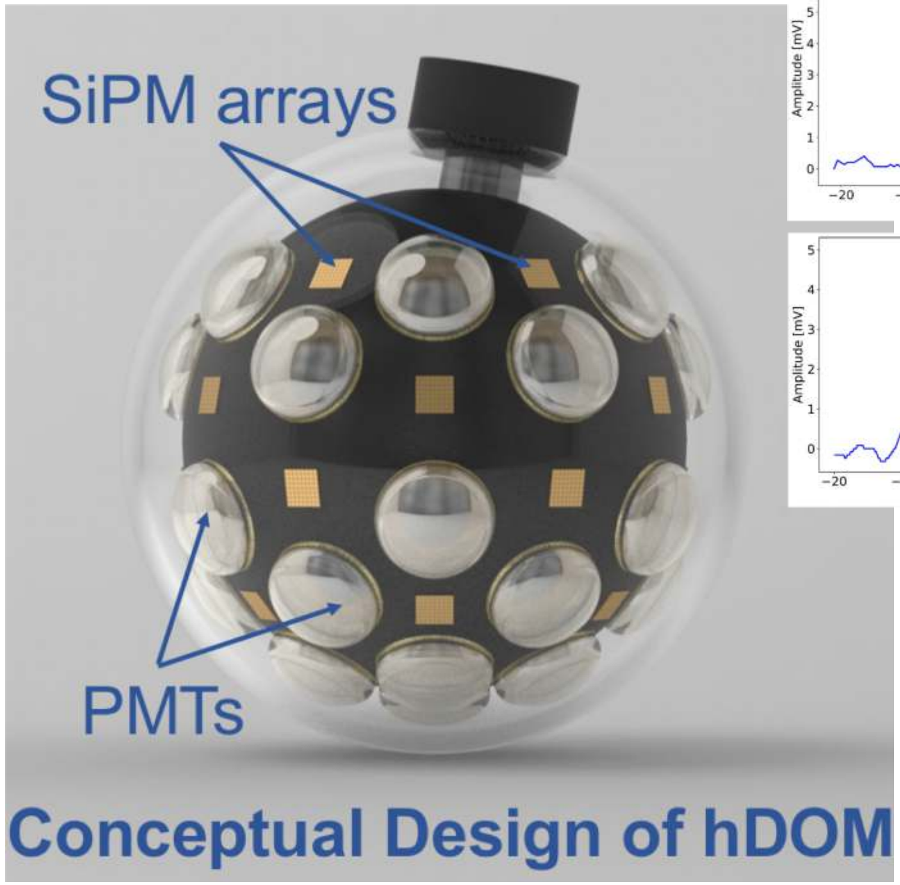


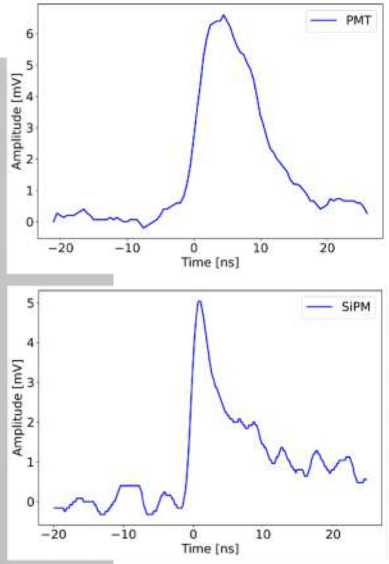
Nature Astronomy **7, 1497-1505 (2023)**

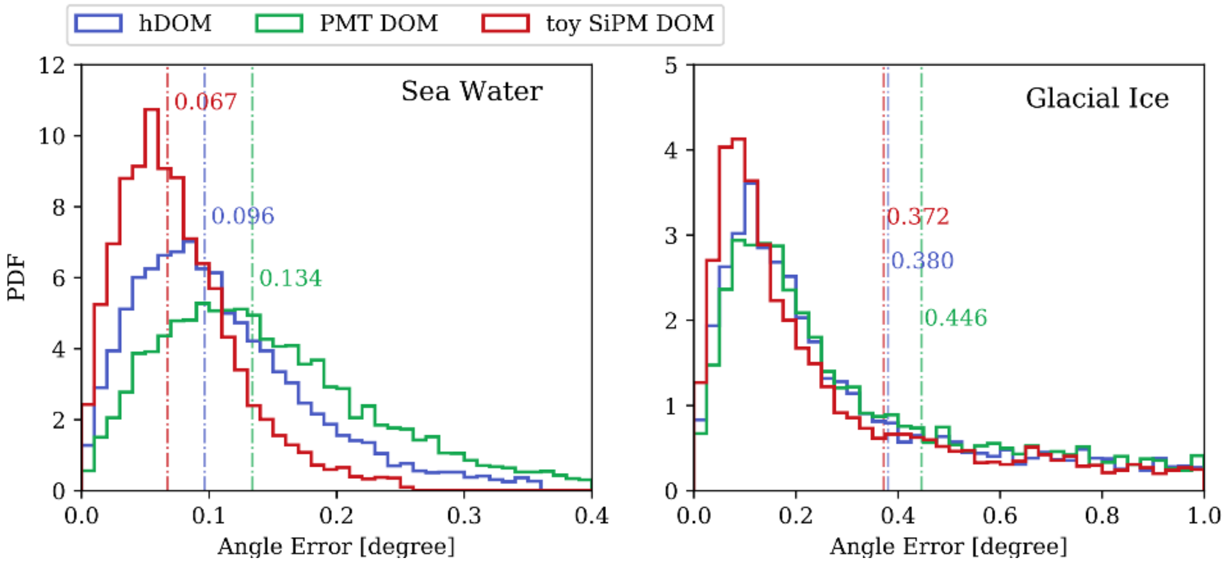
TRIDENT hybrid DOM – hDOM











- Better than 0.1^{o} @ E_{ν} > 100 TeV
- **>40% improvement** (cf mDOM) in angular resolution, assuming PMT TTS ~5ns

Updated:

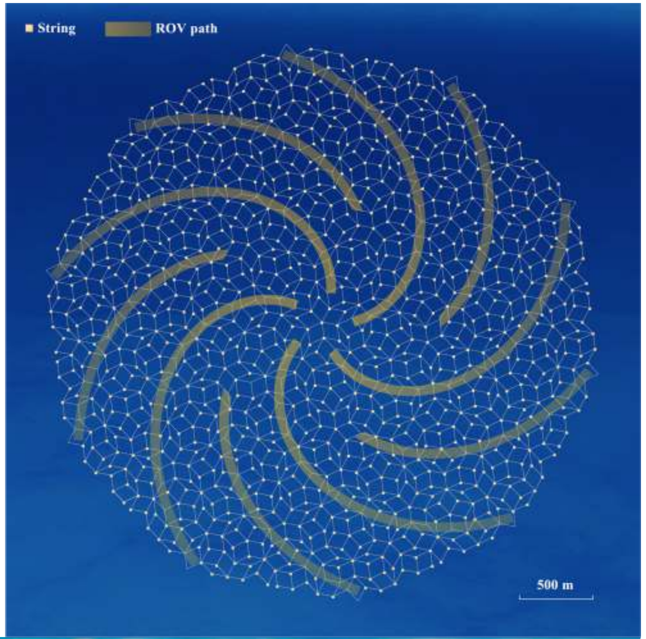
PMT TTS ~3ns + 10cm hDOM position smearing: 40% → 30%

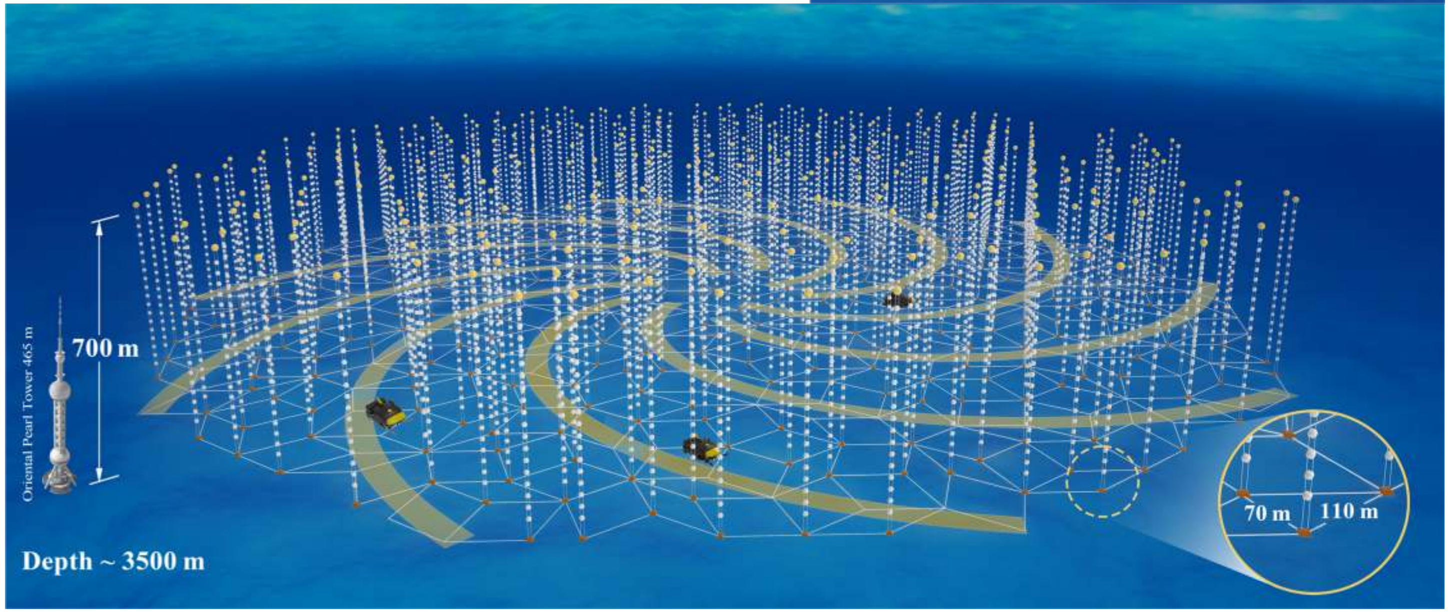
Conceptual design: PoS (ICRC2021) 1043 **Development progress**: PoS (ICRC2023) 1213

TRIDENT detector geometry

Primary aim of design:

To rapidly resolve point sources out of the diffuse flux





Penrose tiling

Uneven inter-string spacing **70m** and **110m**

Expanded energy window of **sub TeV – EeV**

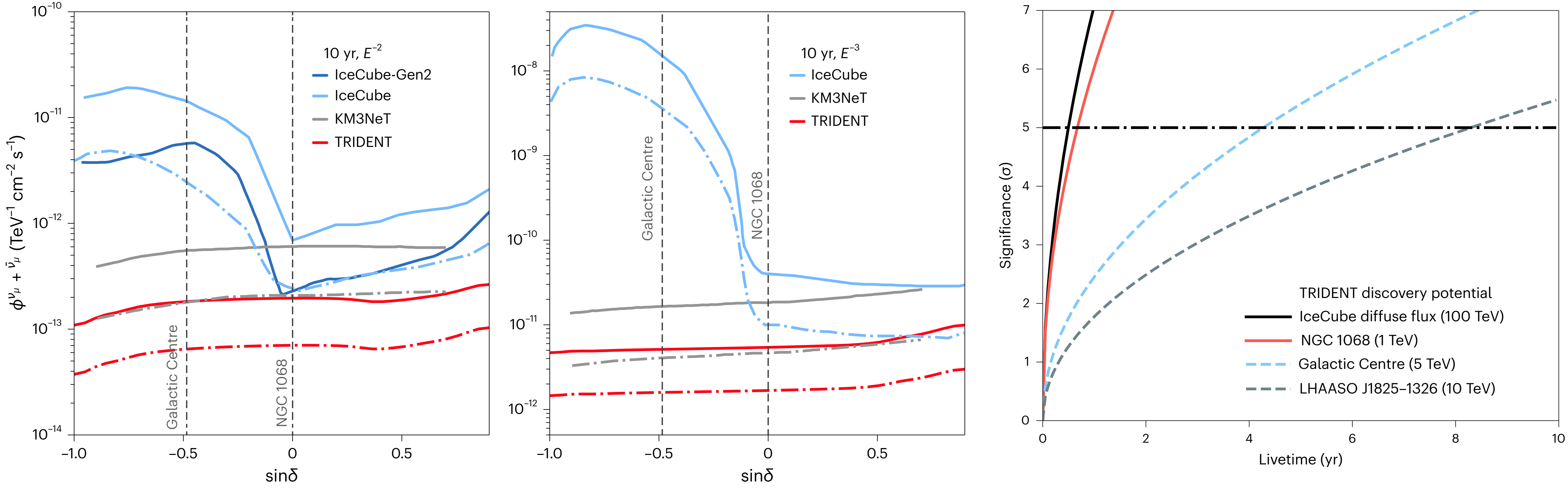
- **1200** strings
- **20** hDOMs / string
- Volume: ~ **8** km^3
- Underwater ROV for deployment & maintenance

Nature Astronomy **7, 1497-1505 (2023)**

Geometry comparison: PoS (ICRC2023) 1203

TRIDENT Source sensitivity & discovery potentials

Track events only



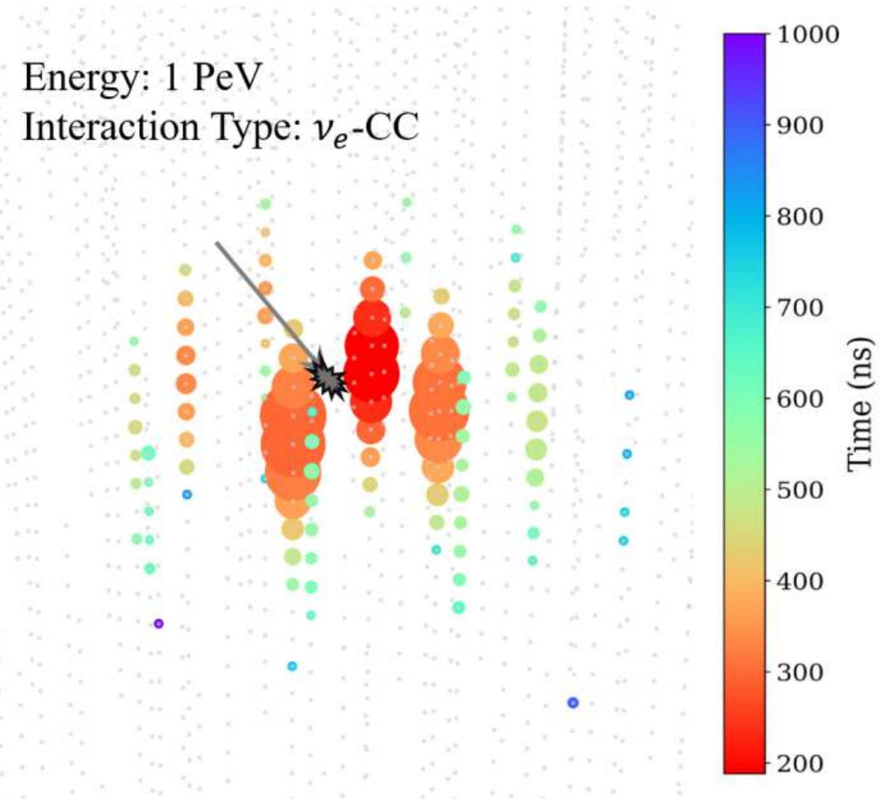
- TRIDENT is expected to detect the IceCube steady source candidate NGC1068 at 5σ level within one year of operation

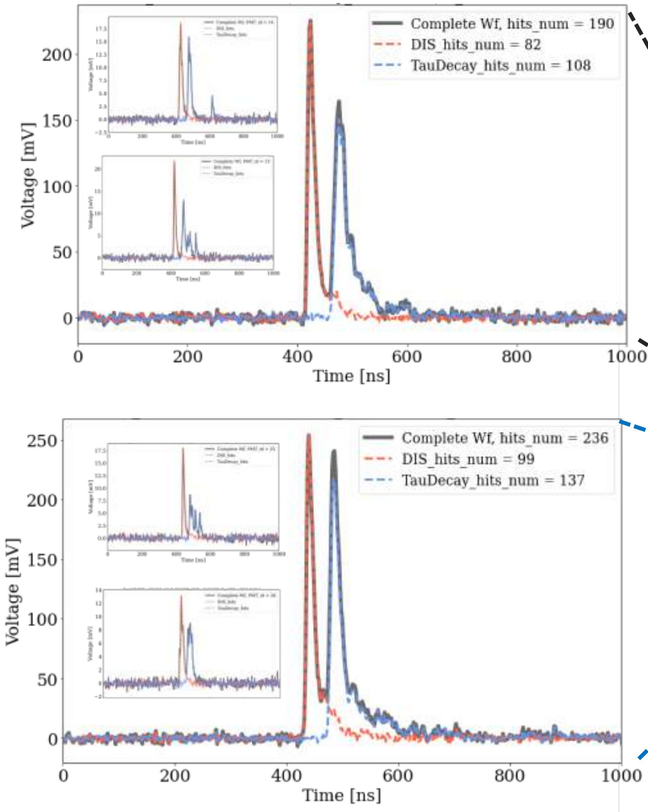
Nature Astronomy **7, 1497-1505 (2023)**

TRIDENT Sensitivity to all neutrino flavors

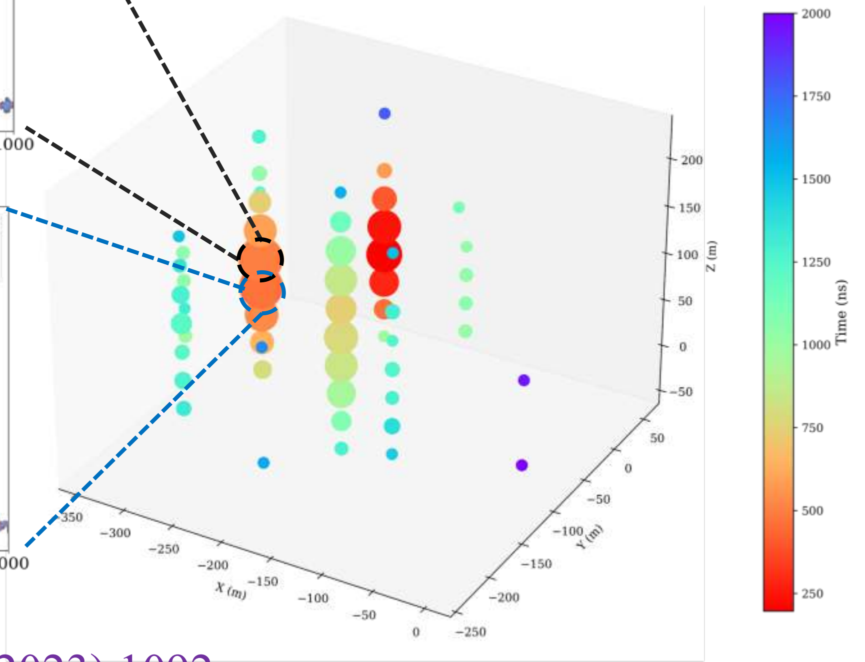
Angular resolution for cascades:
- ~1.8° @ 1PeV (likelihood)
- ~ 1.5° @ 100 TeV & 1 PeV (GNN)

Where are the ν_e and ν_τ from NGC 1068 and TXS 0506+056 ?





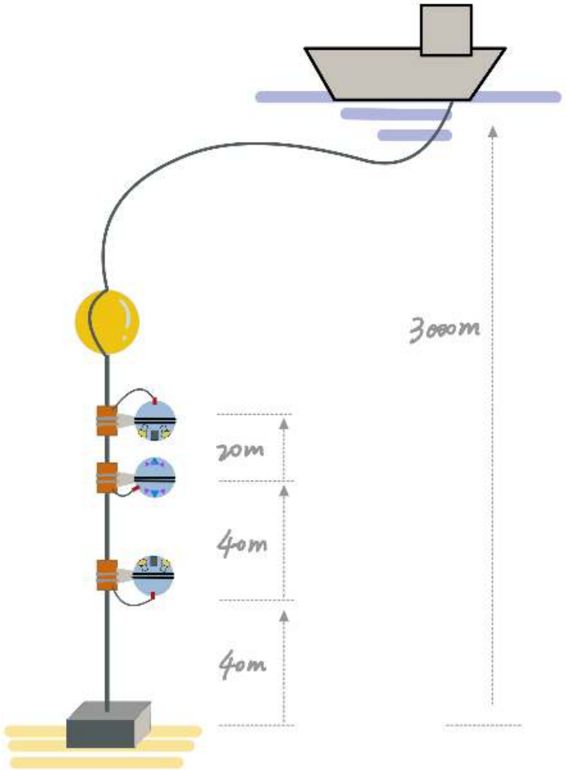
$E\nu_\tau$ = 334.3 TeV

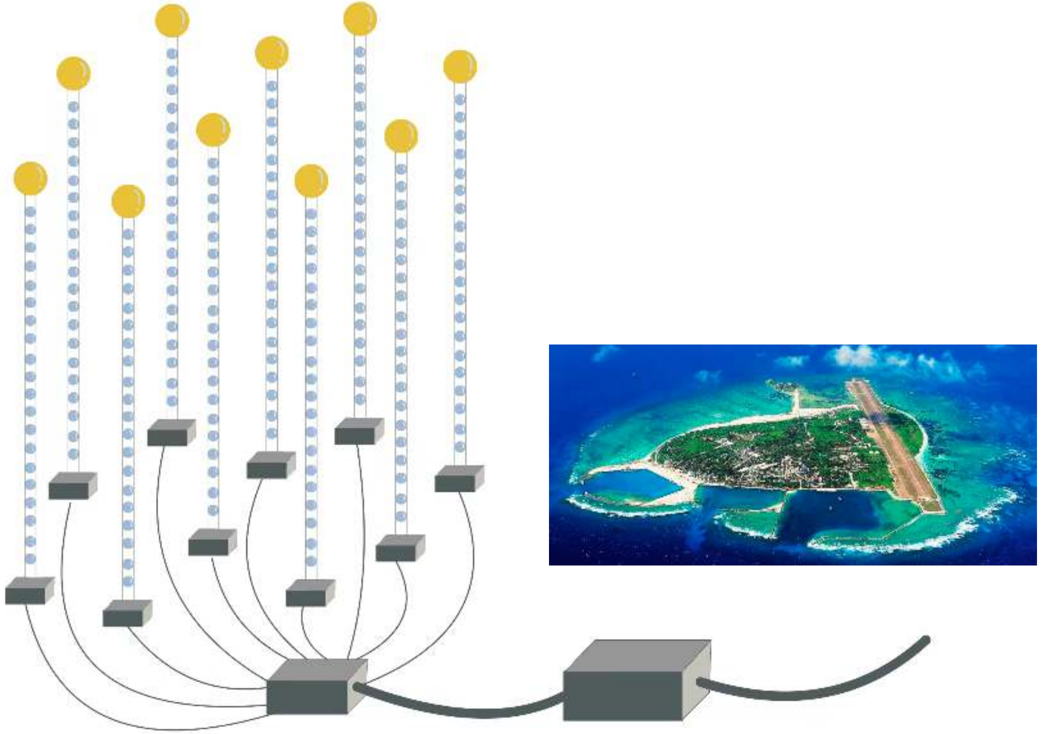


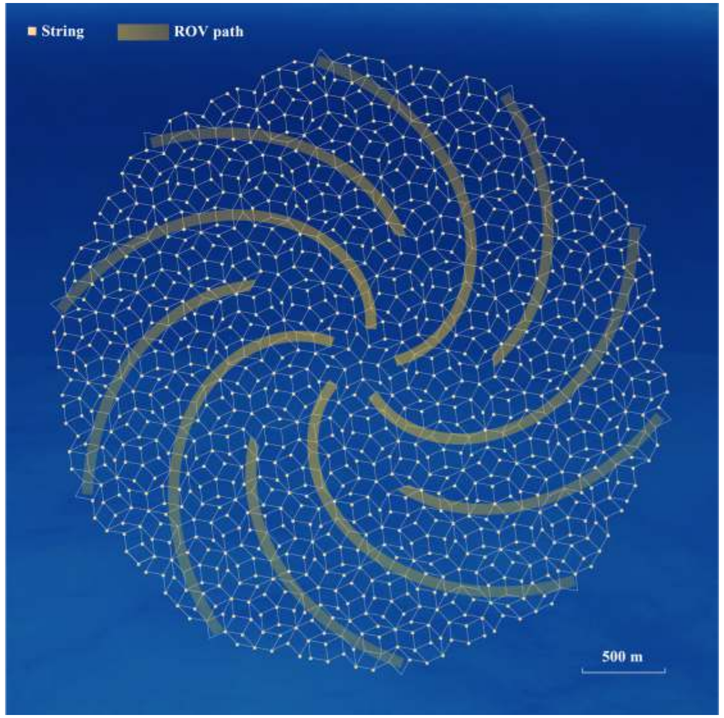
Cascade reco : PoS (ICRC2023) 1207

Tau double pulse : PoS (ICRC2023) 1092

Brief timeline of TRIDENT







Pathfinder: 2019-2022	Phase-I project: 2022-2026	Big array construction: 2026-
completed	in progress	under planning

Summary

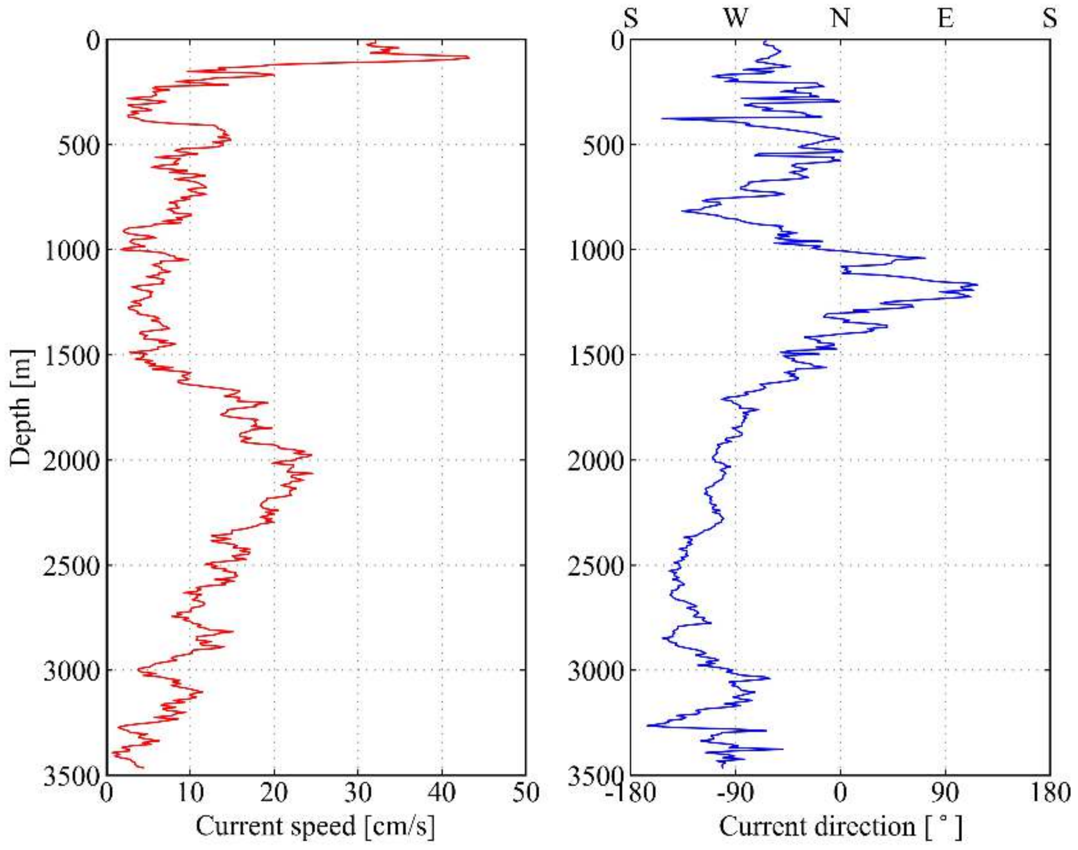
- IceCube has opened a new era for high-energy neutrino astronomy
- **More detectors with improved detection ability** to catch PLENTY of neutrinos for further scrutiny
- A viable site was found at a depth of 3.5km in South China Sea for constructing large-scale deep-sea neutrino telescopes
- Several new proposals in place to build large-scale neutrino telescopes for further neutrino astrophysics exploration

Backup

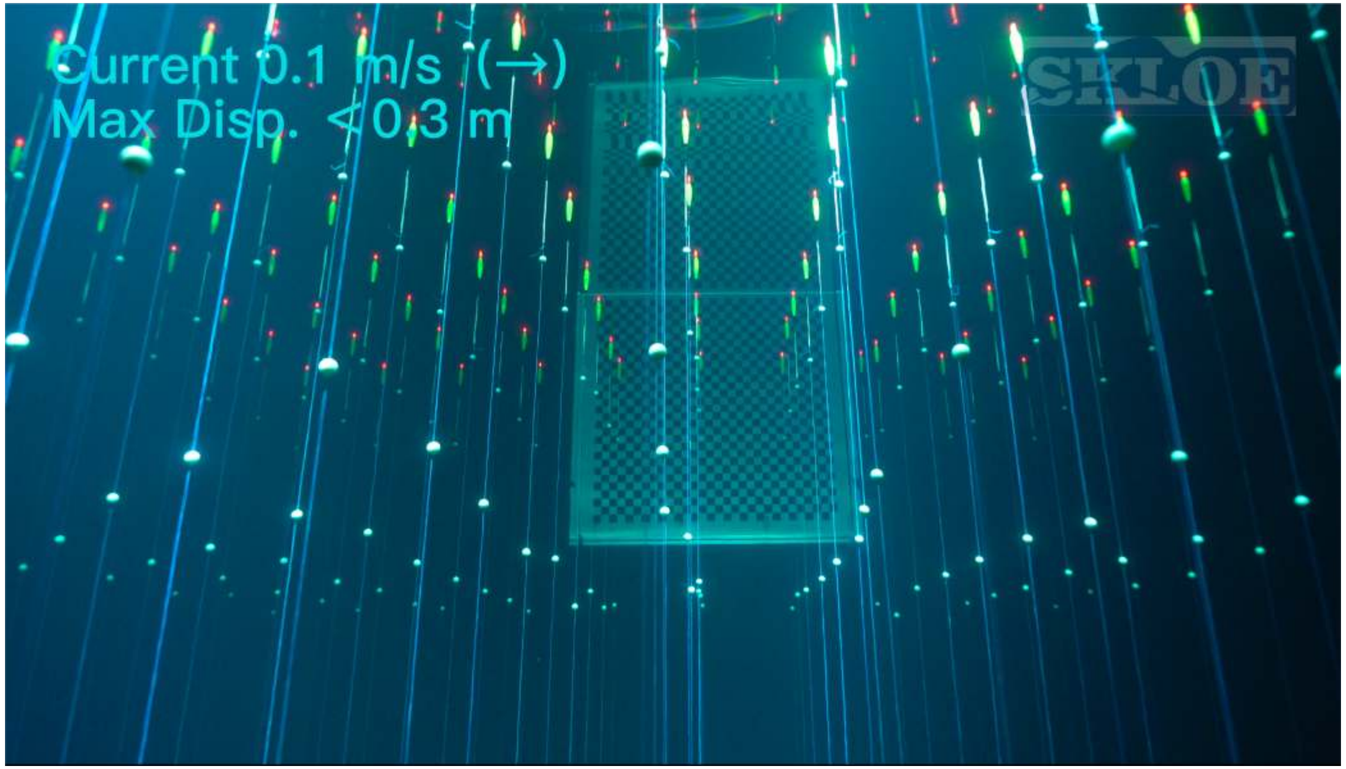
TRIDENT Explorer : Current Field

Site current field measured on Sep. 6, 2021

Simulation (30-yr): ave. 6 cm/s, max < 26 cm /s

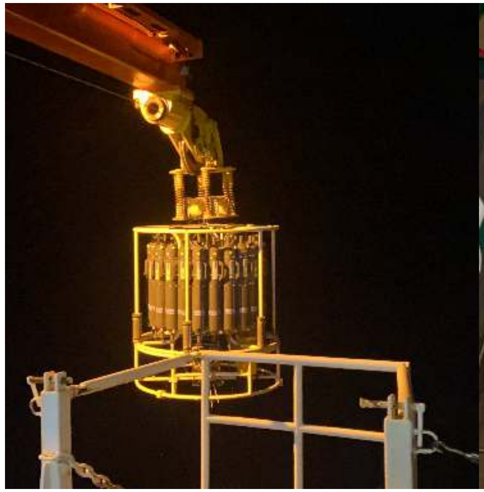


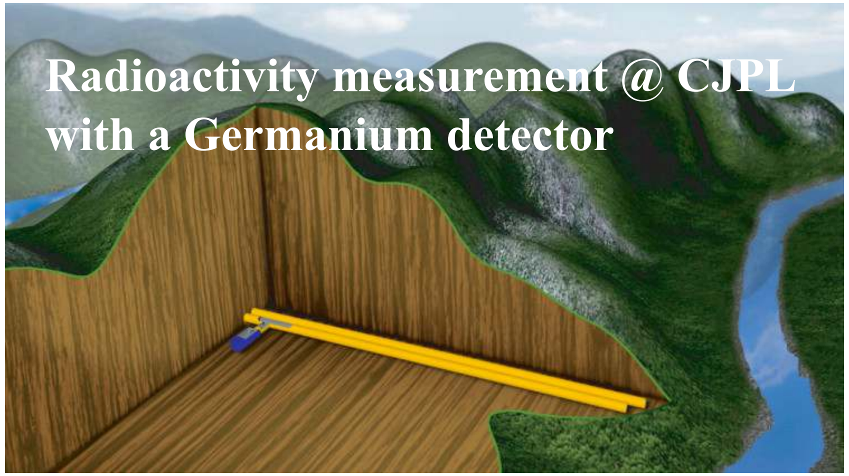
Scaled-down (1:25) experiments in a ship towing tank on SJTU campus



Animation link

TRIDENT Explorer : Radioactivity





	West Pacific	Mediterranean	East Pacific
^{40}K Radioactivity [$\mathbf{Bq/m^3}$]	**11101 ± 119**	13700 ± 200	12526 ± 752
Experiments	**TRIDENT**	**ANTARES**	**P-ONE**

Simulated hit on each PMT caused by ^{40}K