上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

李政道研究所 TSUNG-DAO LEE INSTITUTE

TRIDENT 海 | 铃 | 计 | 划

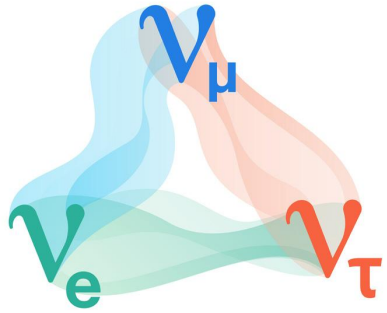
TRIDENT : A Multi-cubic-kilometer Neutrino Telescope in the Western Pacific Ocean

Donglian Xu (TDLI)

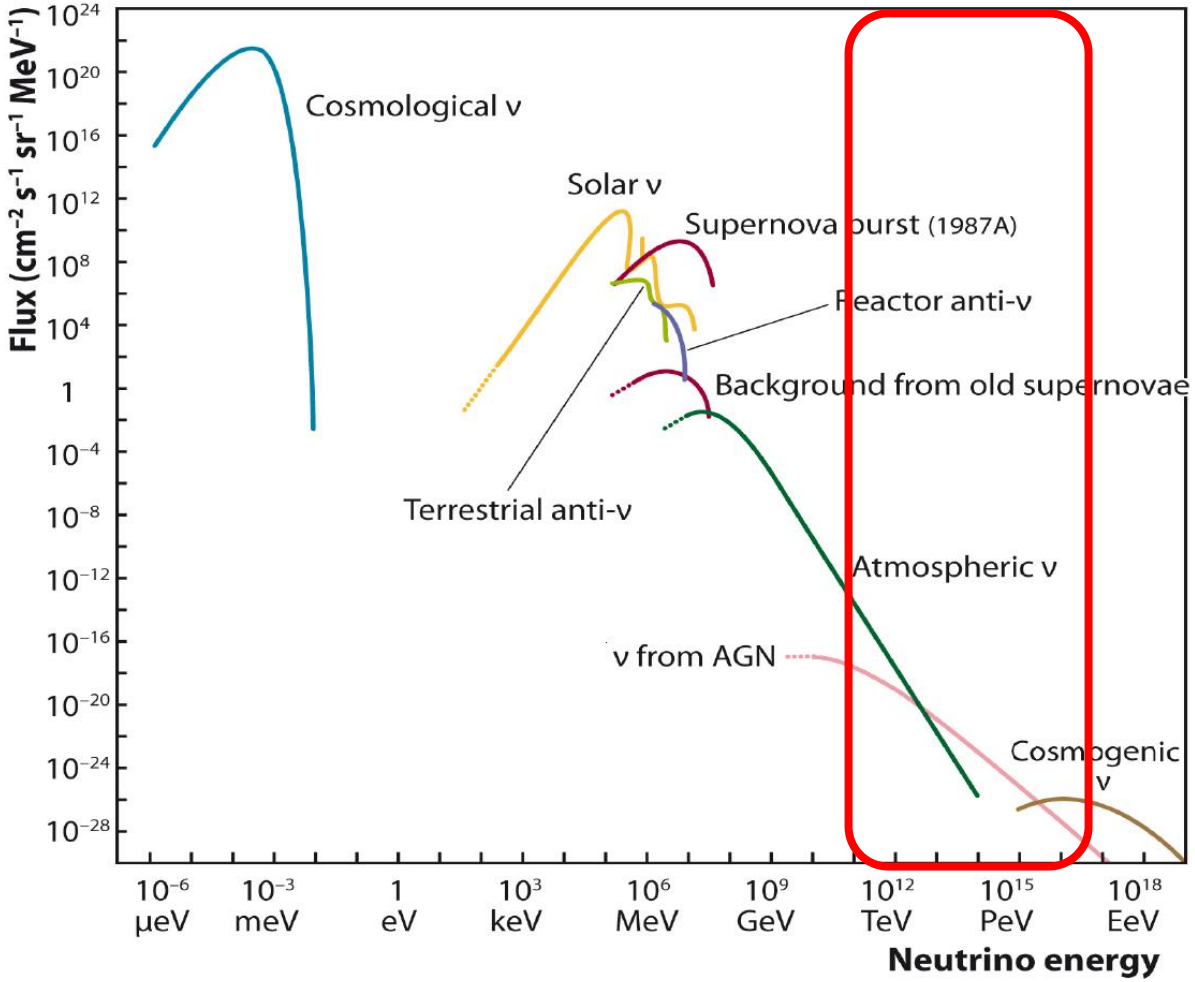
32nd Texas Symposium on Relativistic Astrophysics

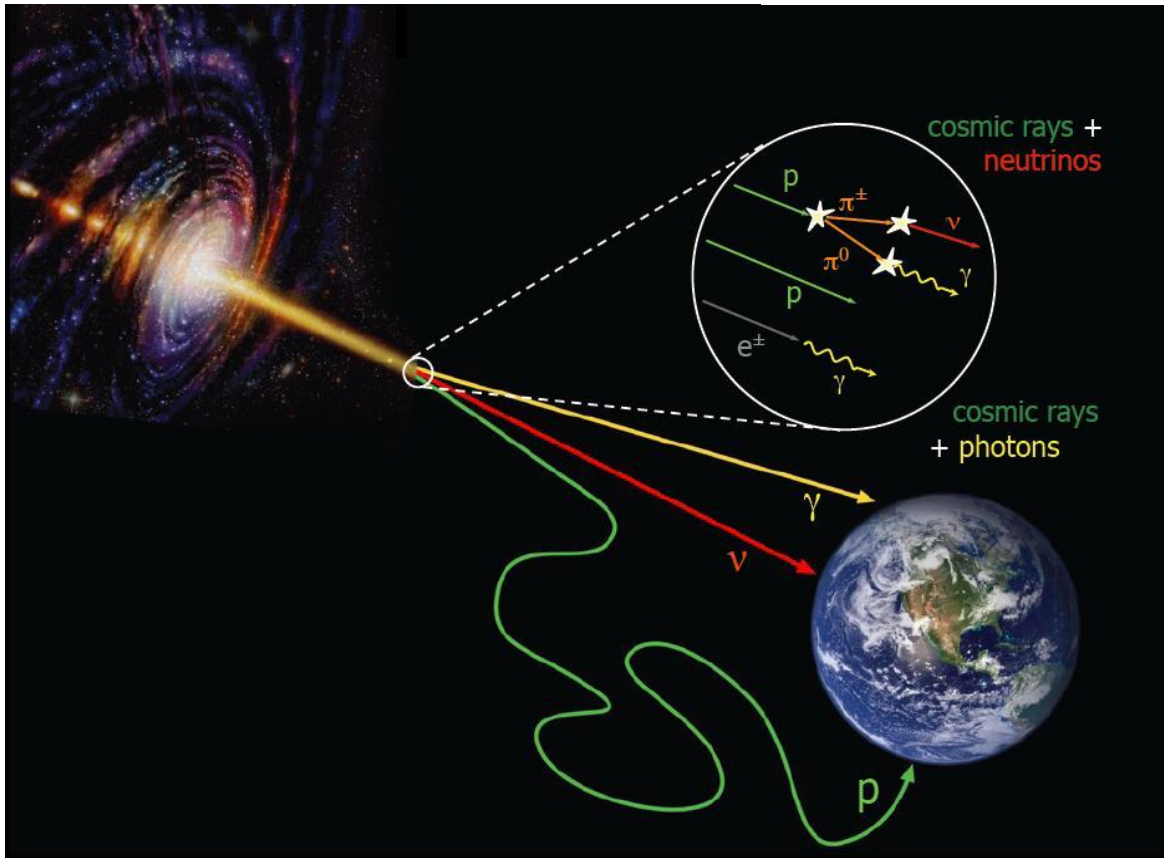
Dec. 14, 2023 | Shanghai

Neutrino: a unique cosmic messenger



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

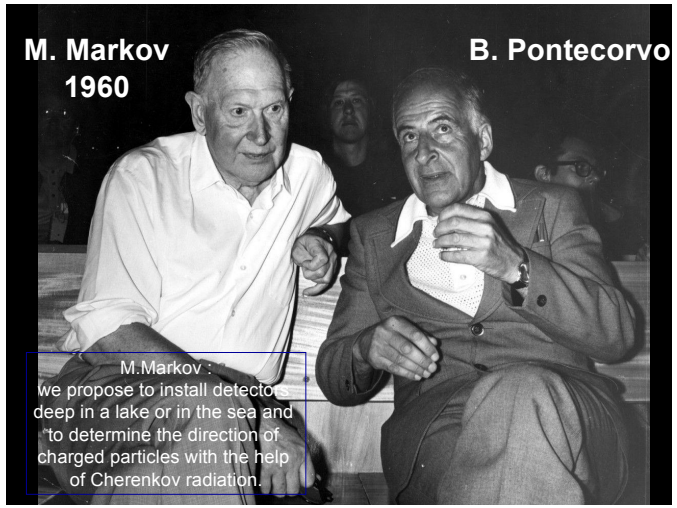


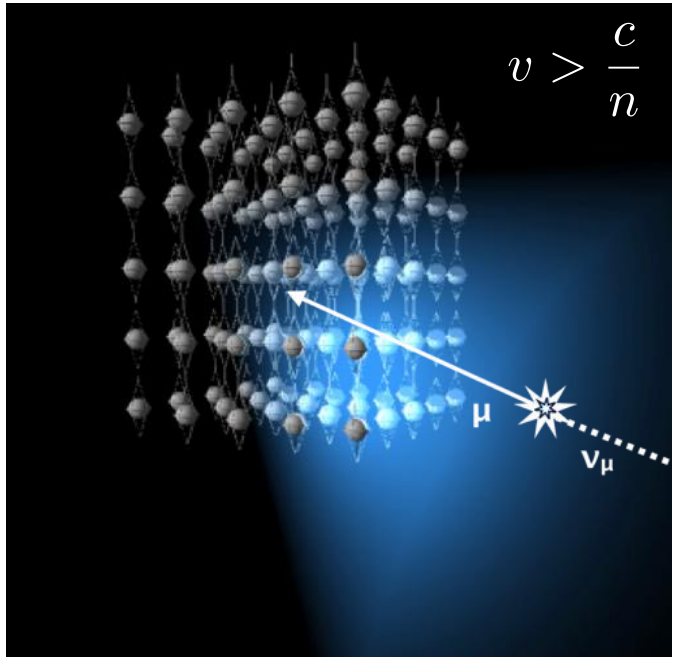


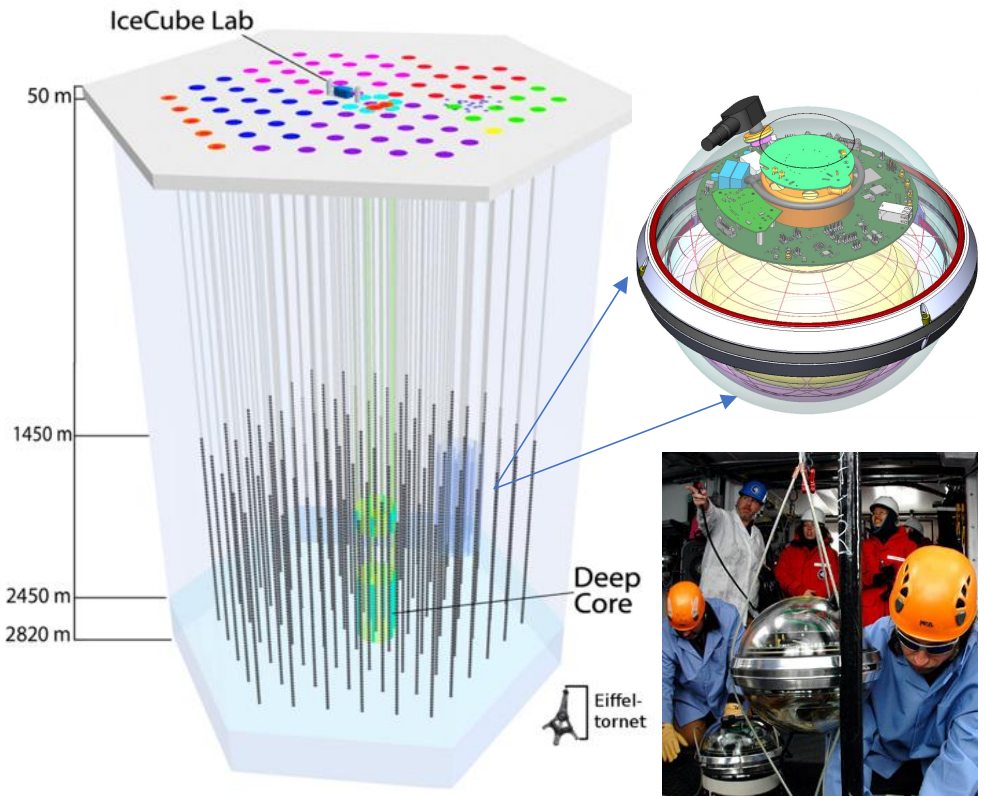
Detection of high-E astrophysical neutrinos would be smoking evidence for the origins of cosmic rays!

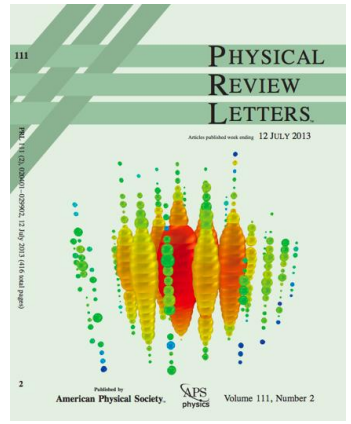
Neutrino telescopes

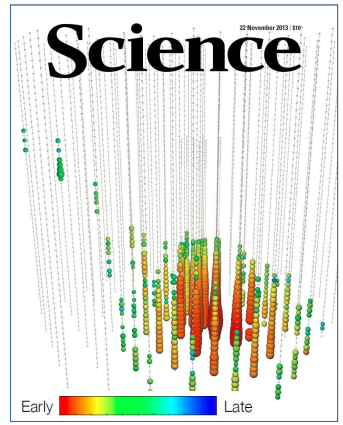
IceCube: world's largest neutrino telescope

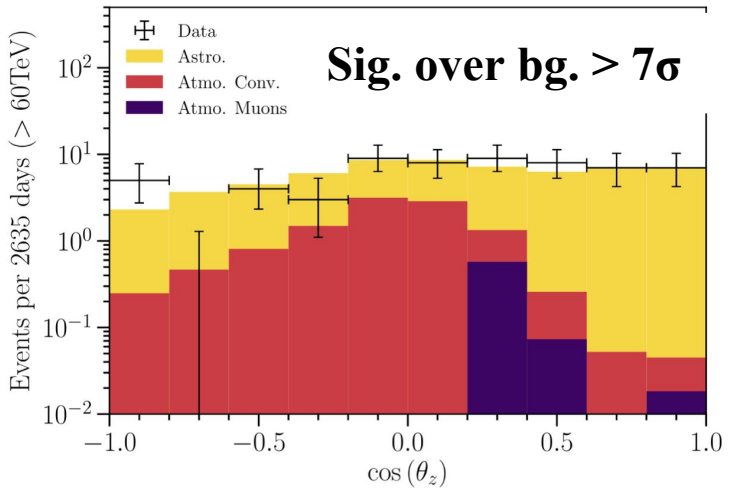










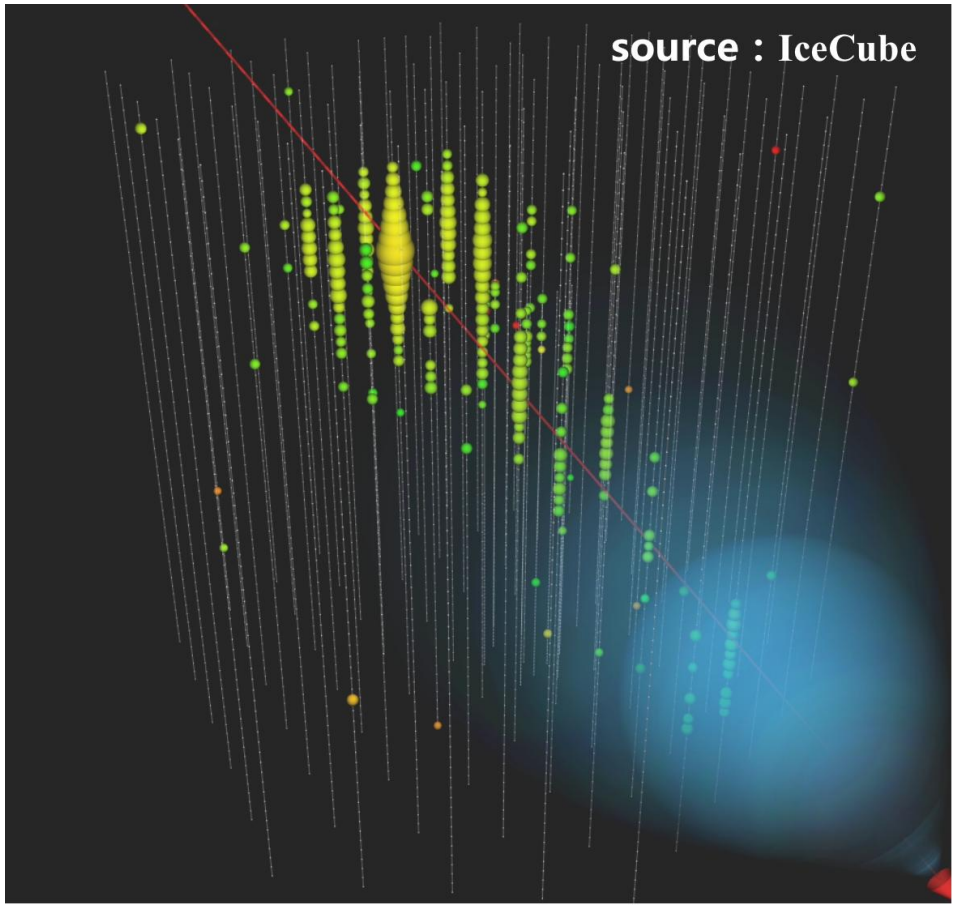


- **86** strings, **5160** DOMs
  → a cubic-kilometer array
- Fully operating since 2010

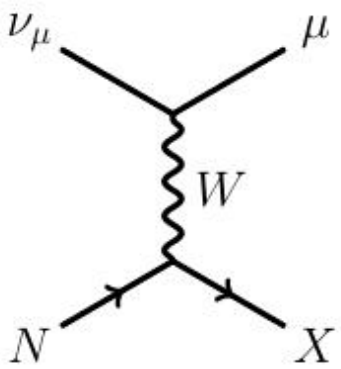
Phys. Rev. D 104, 022002 (2021) (7.5-yr)
Phys. Rev. Lett. 113, 101101 (2014) (3-yr)
Science 342, 6161 (2013) (2-yr)

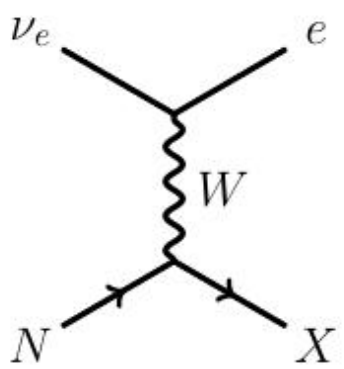
Neutrino telescope events

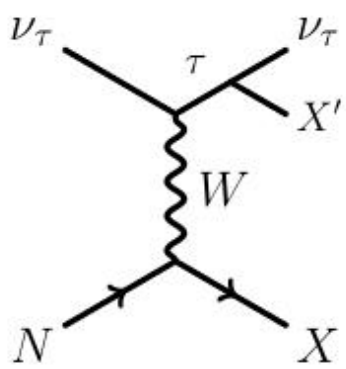
Tracks: relied primarily on for pointing

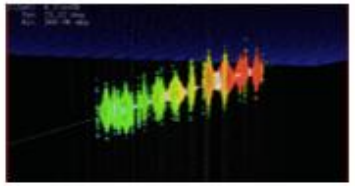


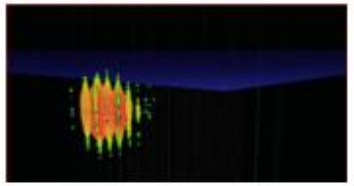
IceCube event topologies

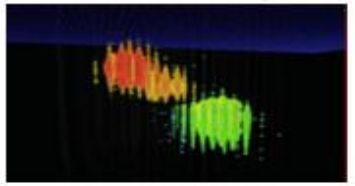










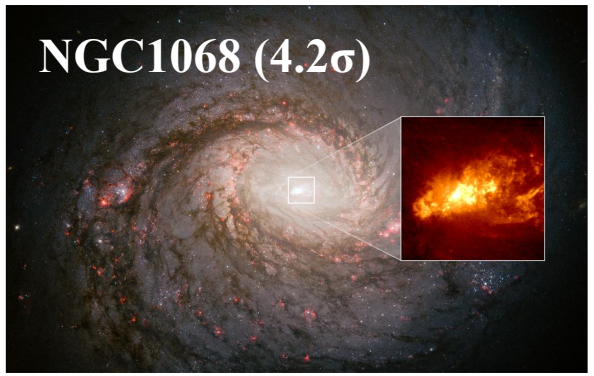


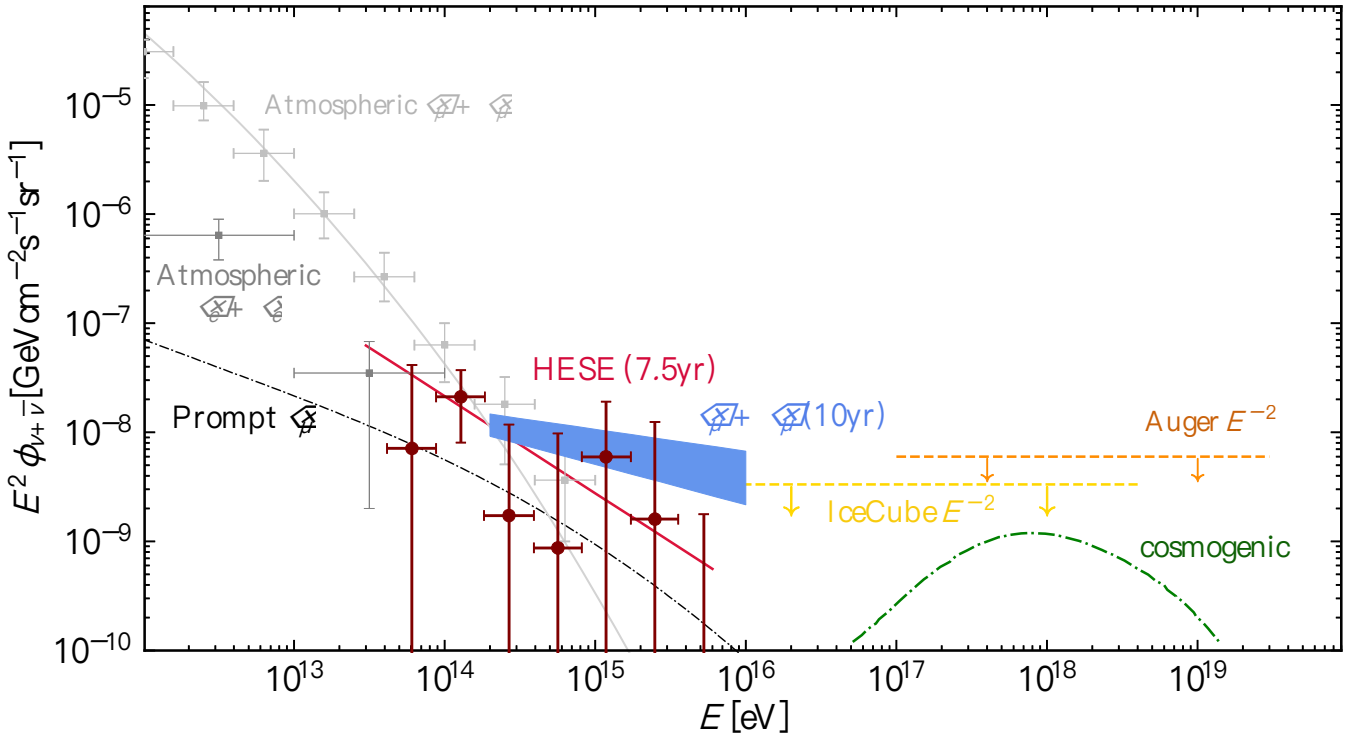
Track
~ 1°

Cascade
~ 10°

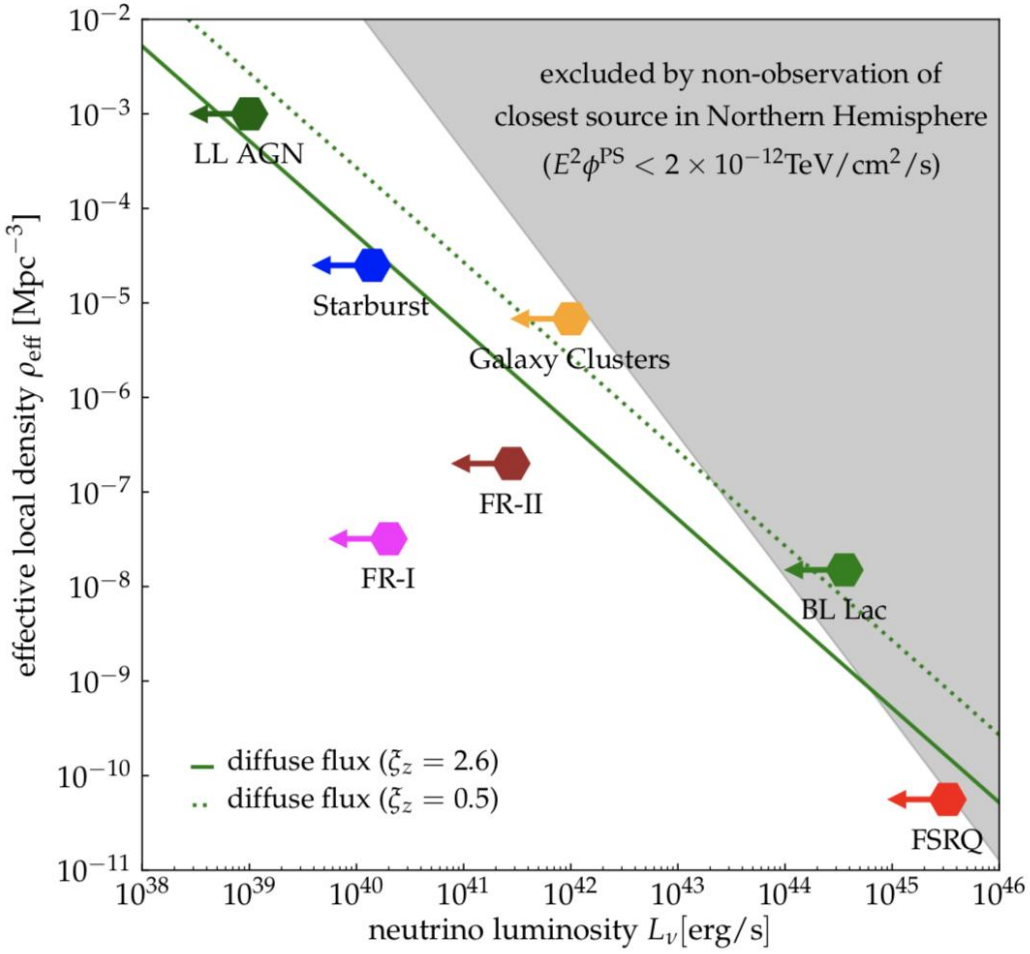
Double Cascade

A new era of neutrino astronomy



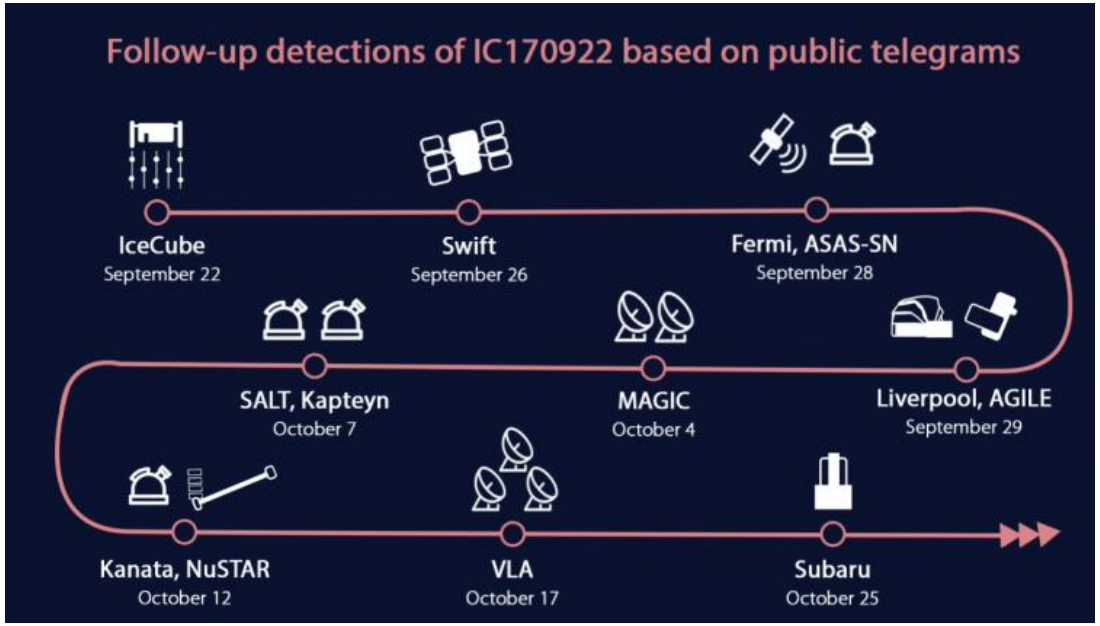


Halzen & Khierandish, arXiv:2202.00694



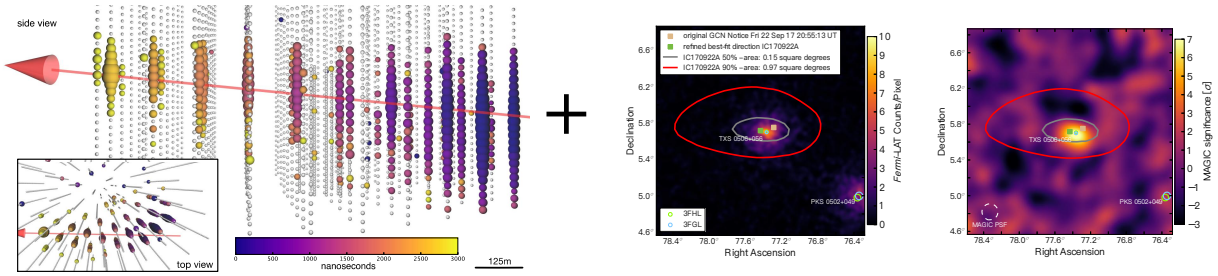
See Murase's talk at this conference

A new era of neutrino astronomy

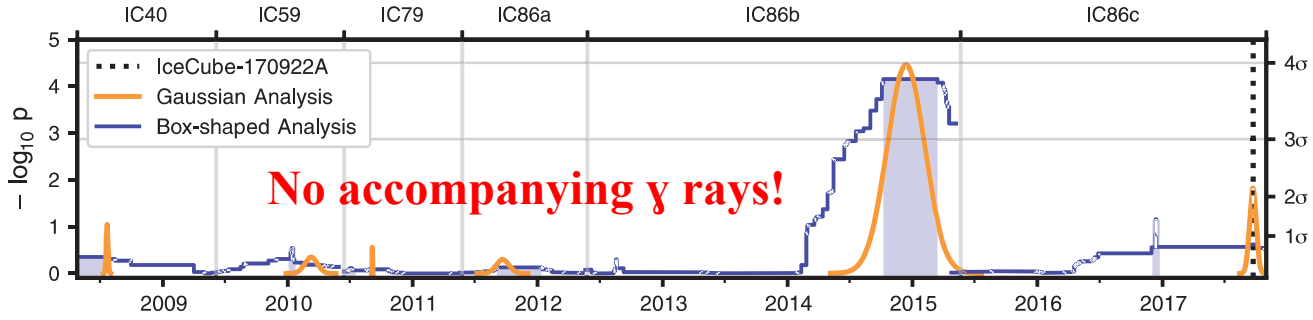


~~IC170922 (290 TeV) coincided with TXS0506+056~~

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



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



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

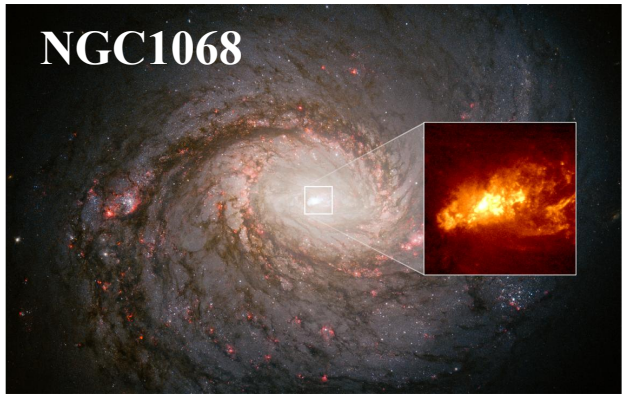
A new era of neutrino astronomy

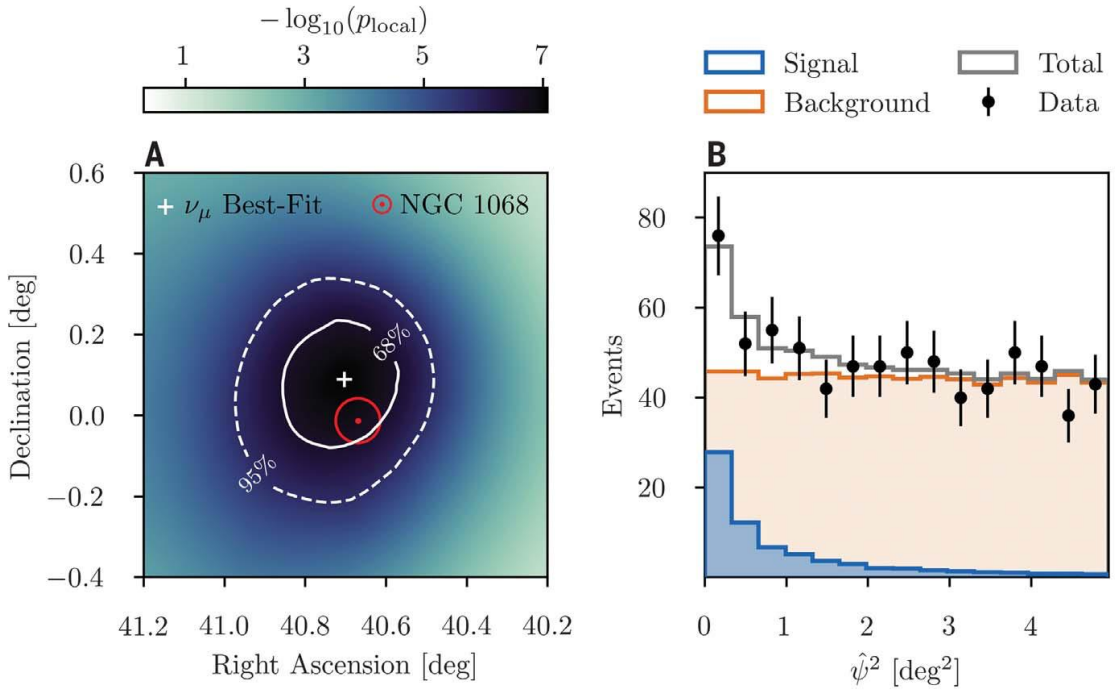
IceCube Collaboration, **Science 378, 538 (2022)**

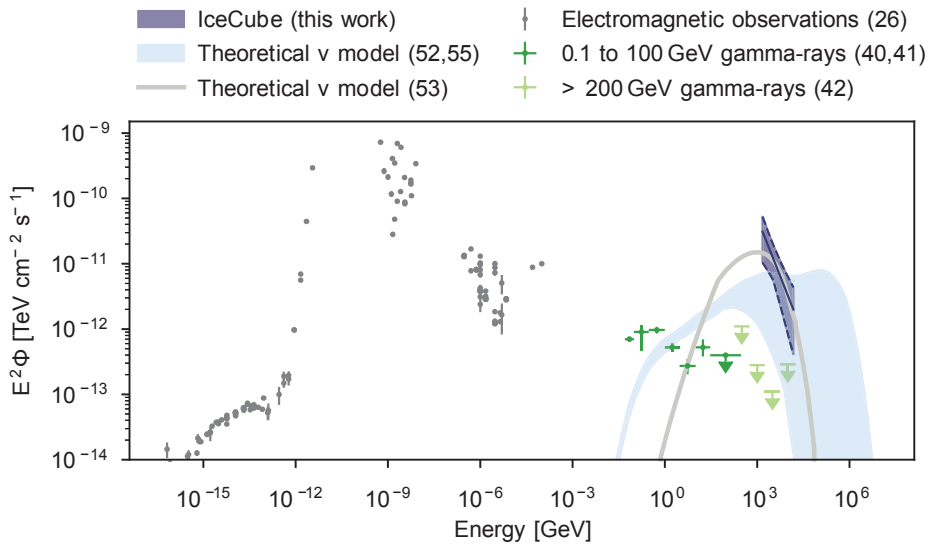
Event excess: **79** $^{+22}_{-20}$

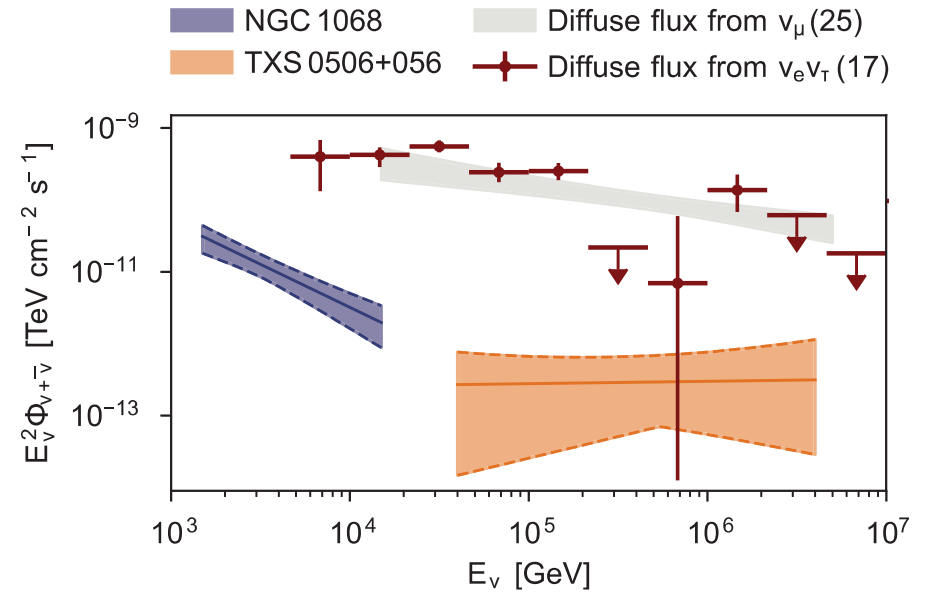
Global significance: **4.2σ**

Data collected: 2011.05 – 2020.05









Most significant astrophysical neutrino source to date !

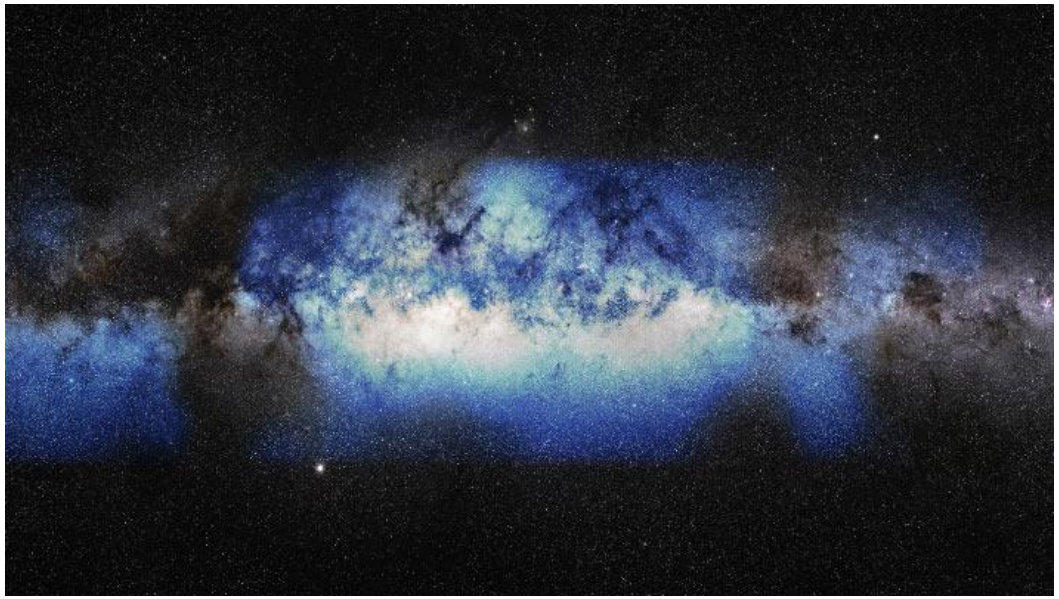
A new era of neutrino astronomy

See Ke Fang's talk at this conference

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 !

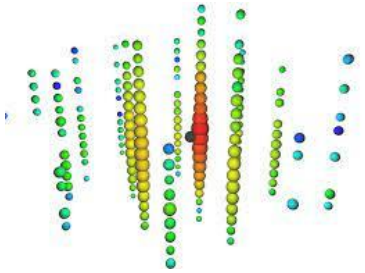


RESEARCH ARTICLE

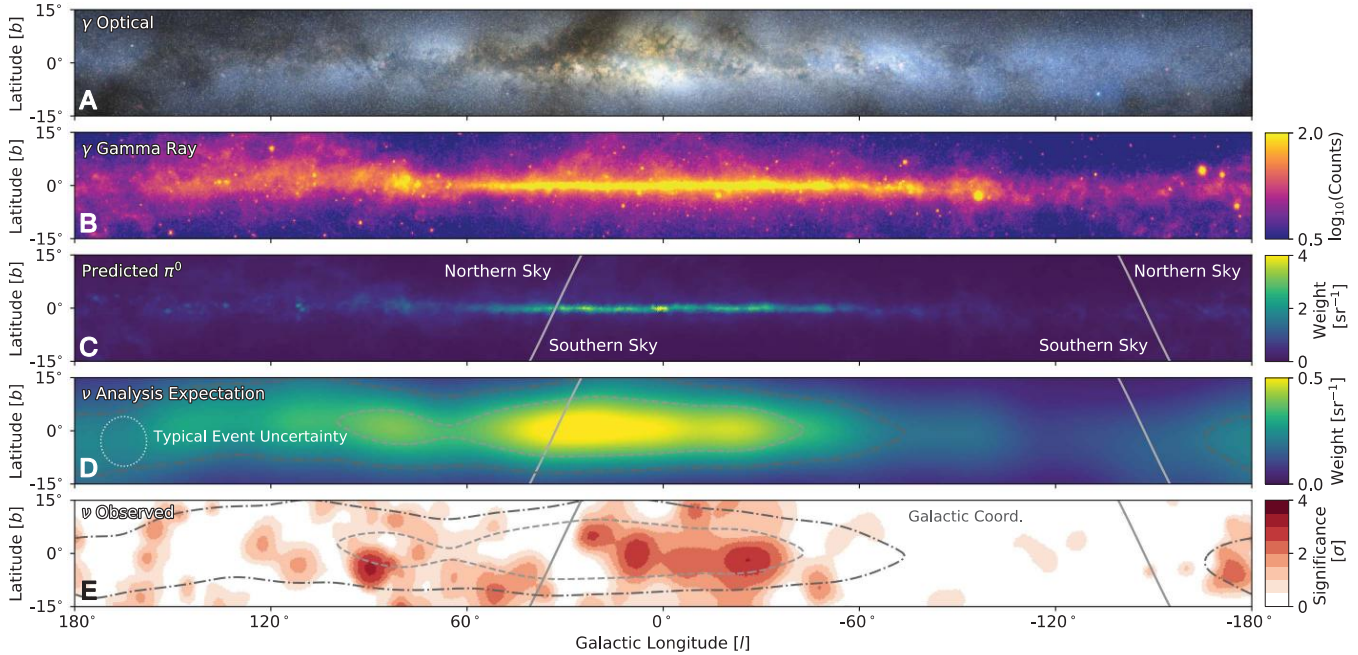
NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane

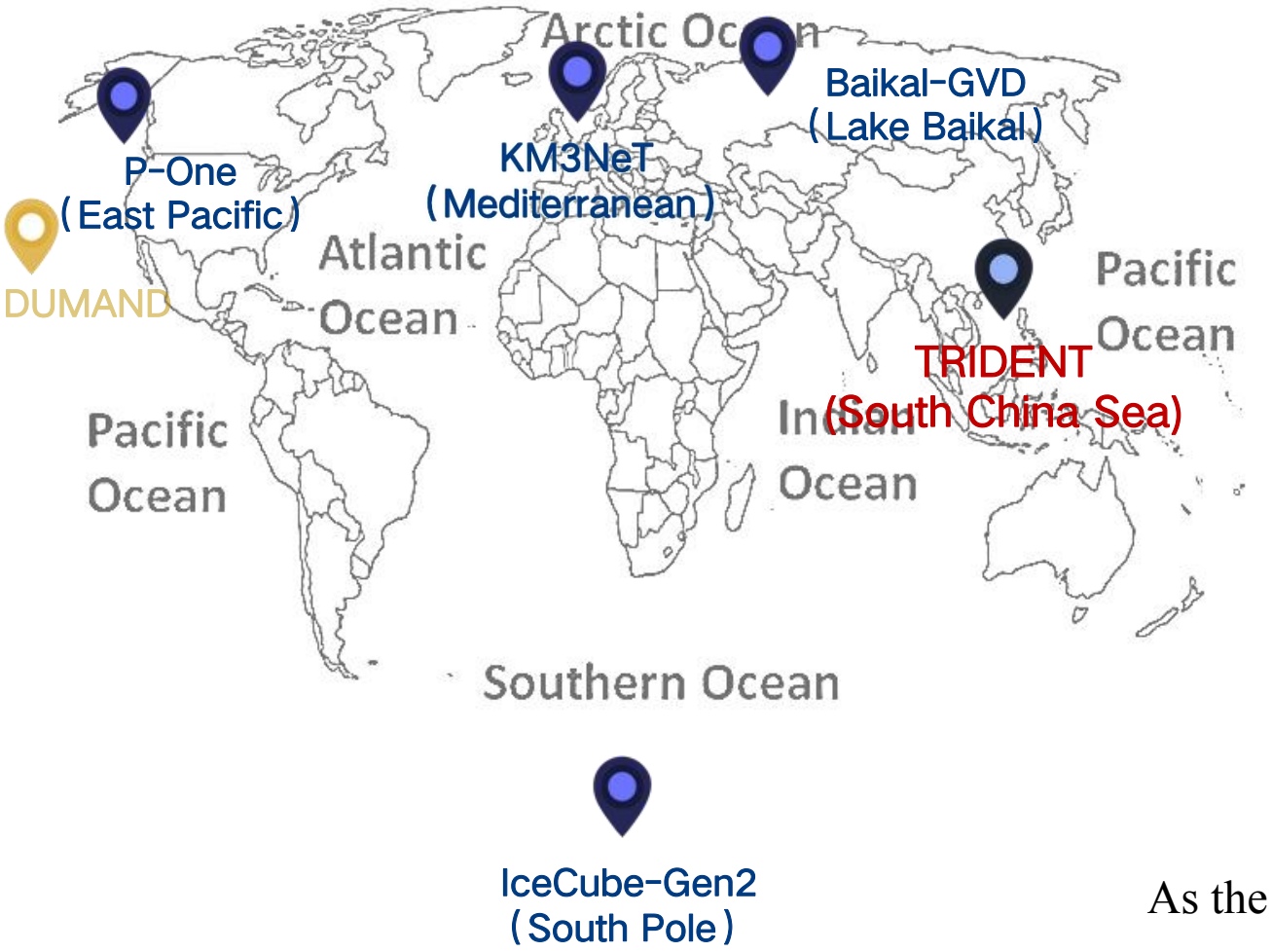
IceCube Collaboration*†



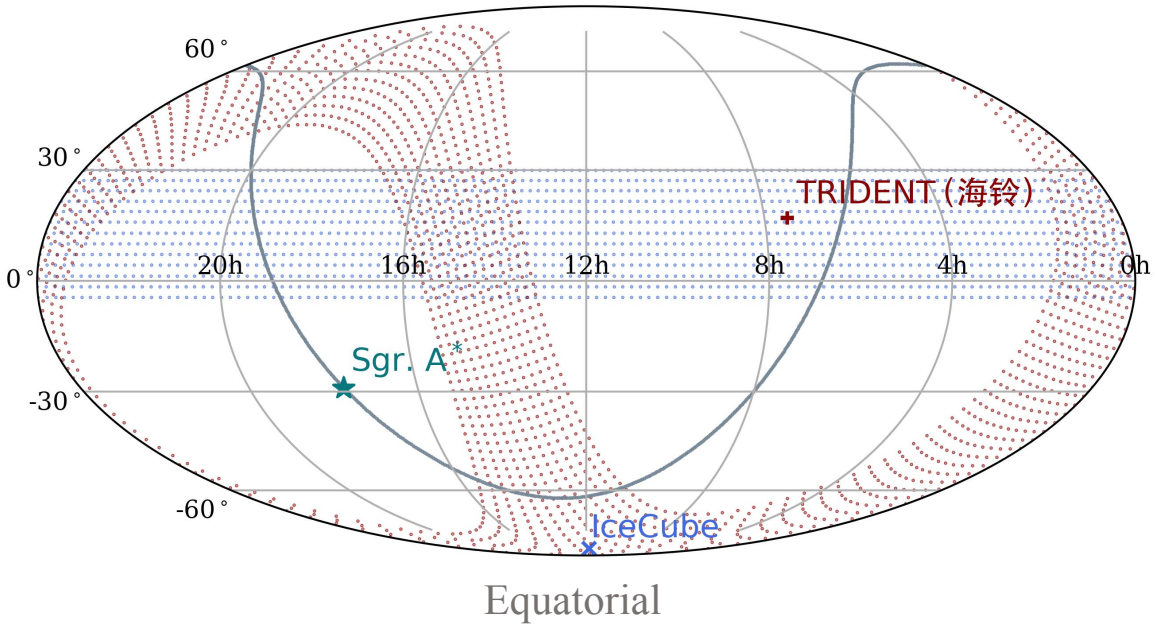
IceCube Collaboration, Science 380, 1338–1343 (2023)



Next-gen neutrino telescopes under planning



TRopIcal DEep-sea Neutrino Telescope

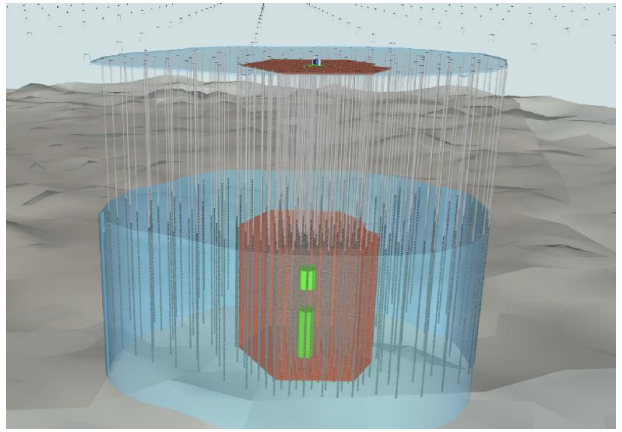


Equatorial

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

Next-gen neutrino telescopes under planning

IceCube-Gen2

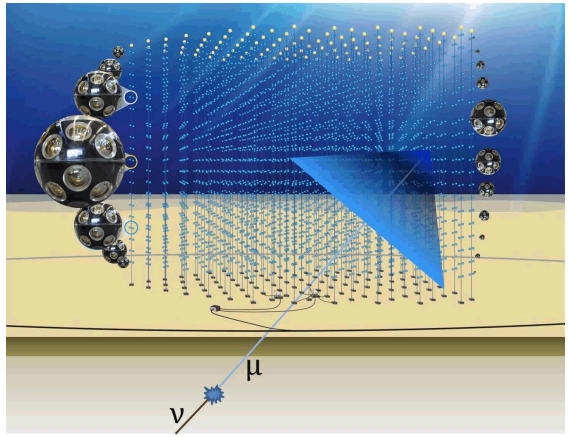


10 km³ + **500 km²** surface array for radio UHE neutrinos

5-10 times improvement in **sensitivity**

Timeline: **~2035 / 2038**

KM3NeT-ARCA

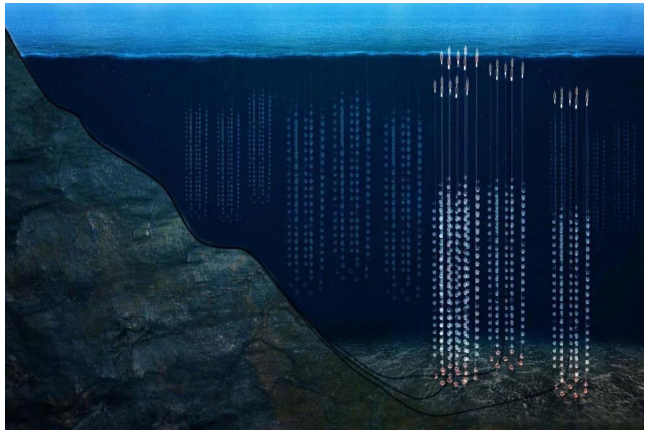


230 strings

Reaching **~1km³**

Timeline: **2028**

Baikal-GVD

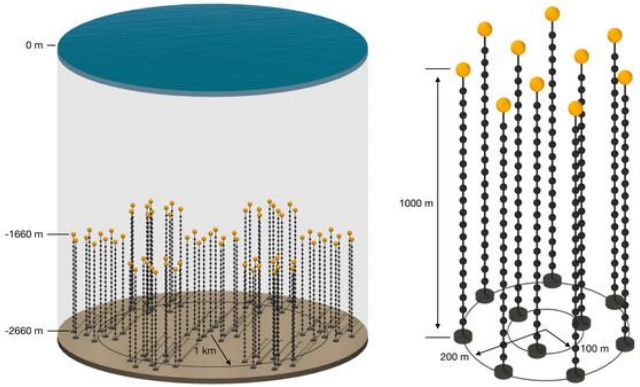


total **16-18 clusters**

Reaching **~1km³**

Timeline: **~2025/2026**

P-One



70 strings

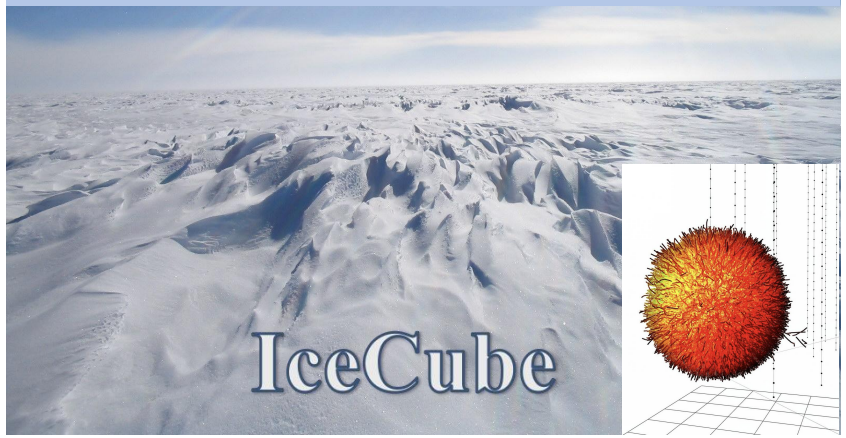
Reaching **km³** volume

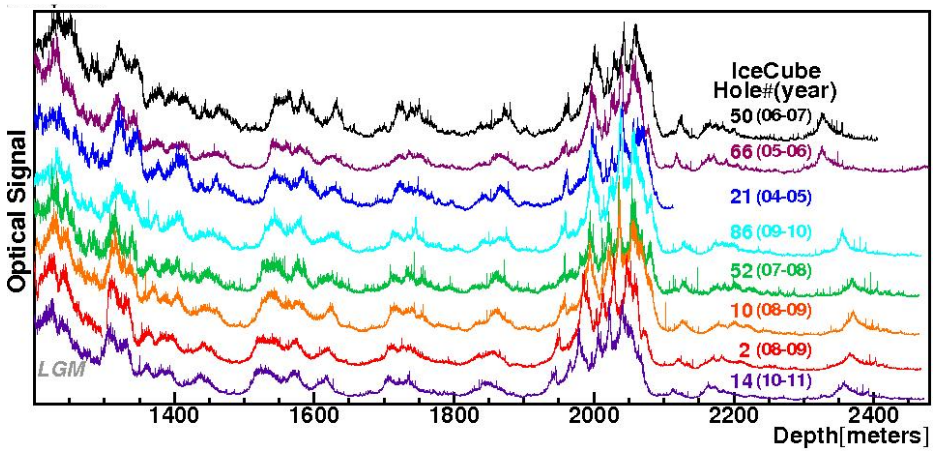
Timeline: **~2028**

Interaction medium: Ice vs Water

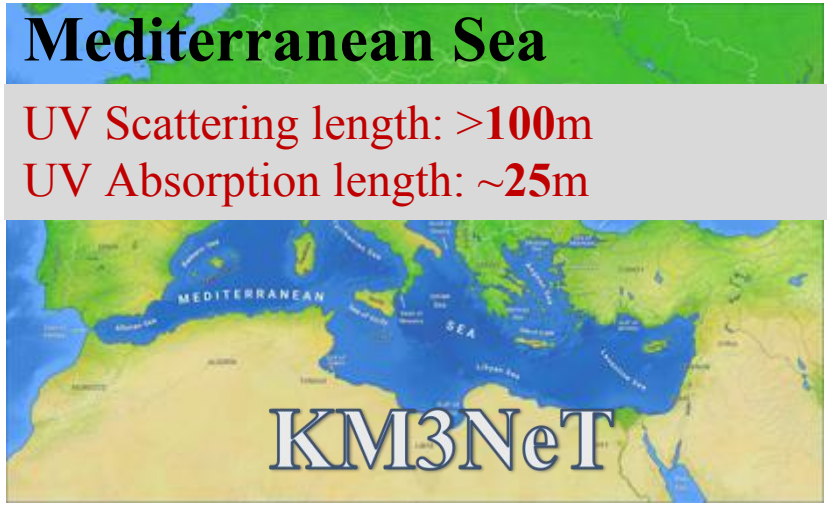
Glacial ice

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





Lake/sea water

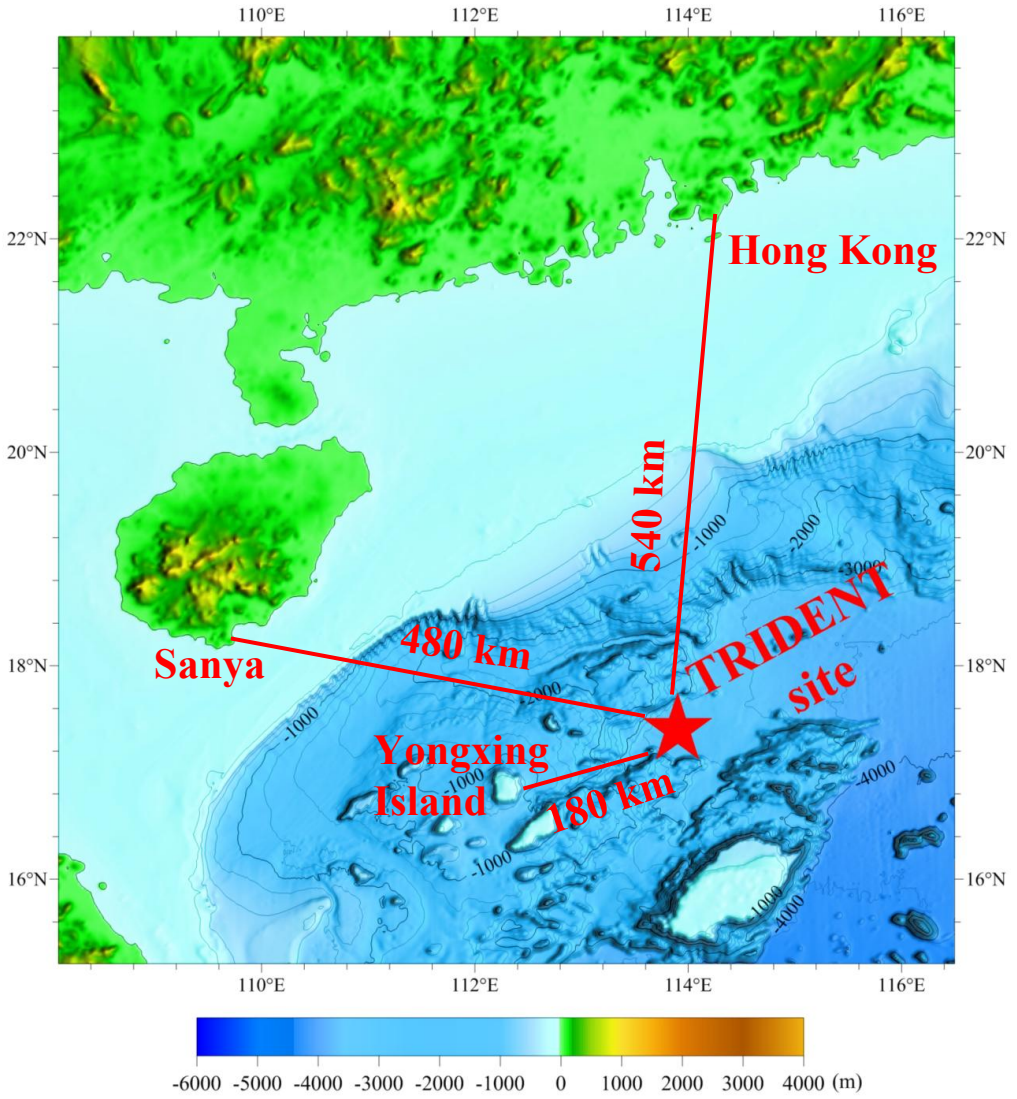


On average, ice is more transparent / less absorbing, while water is less scattering

⇩

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

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

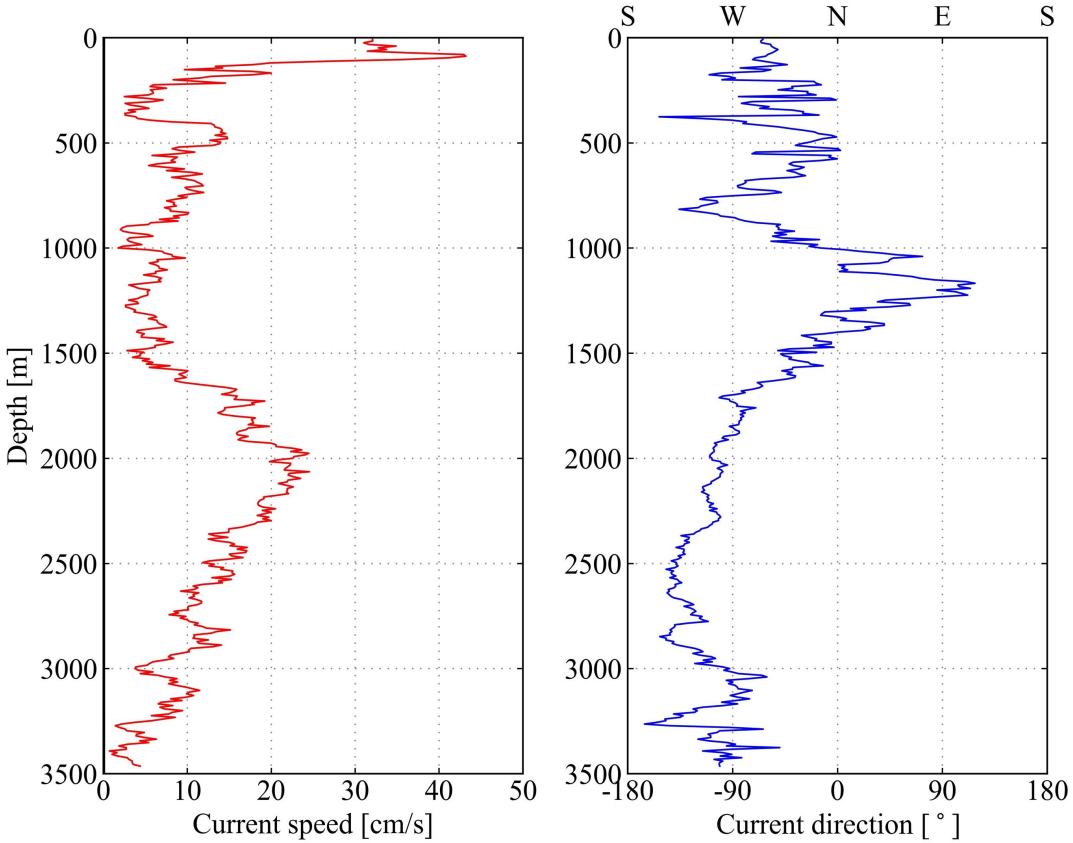
- Current field
- Radioactivity
- Optical properties

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

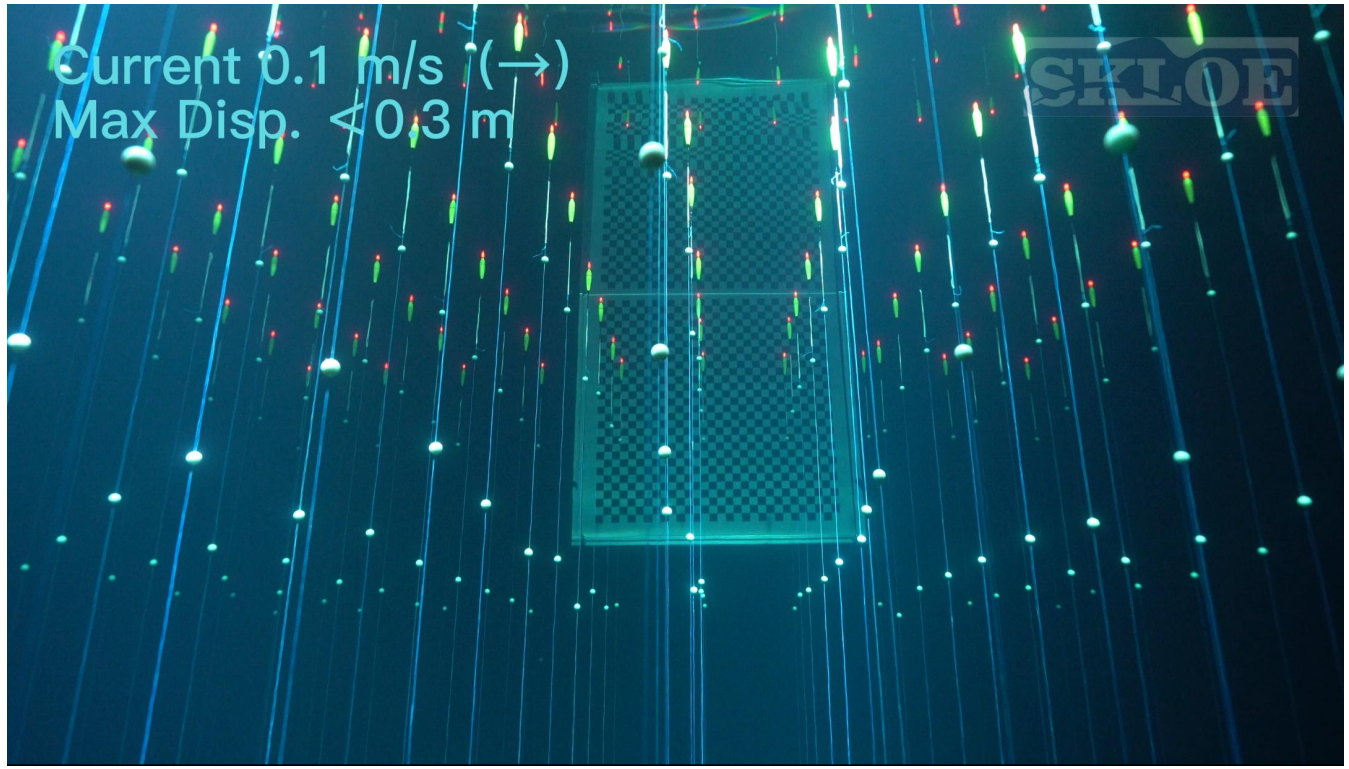
TRIDENT Explorer : Current Field

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

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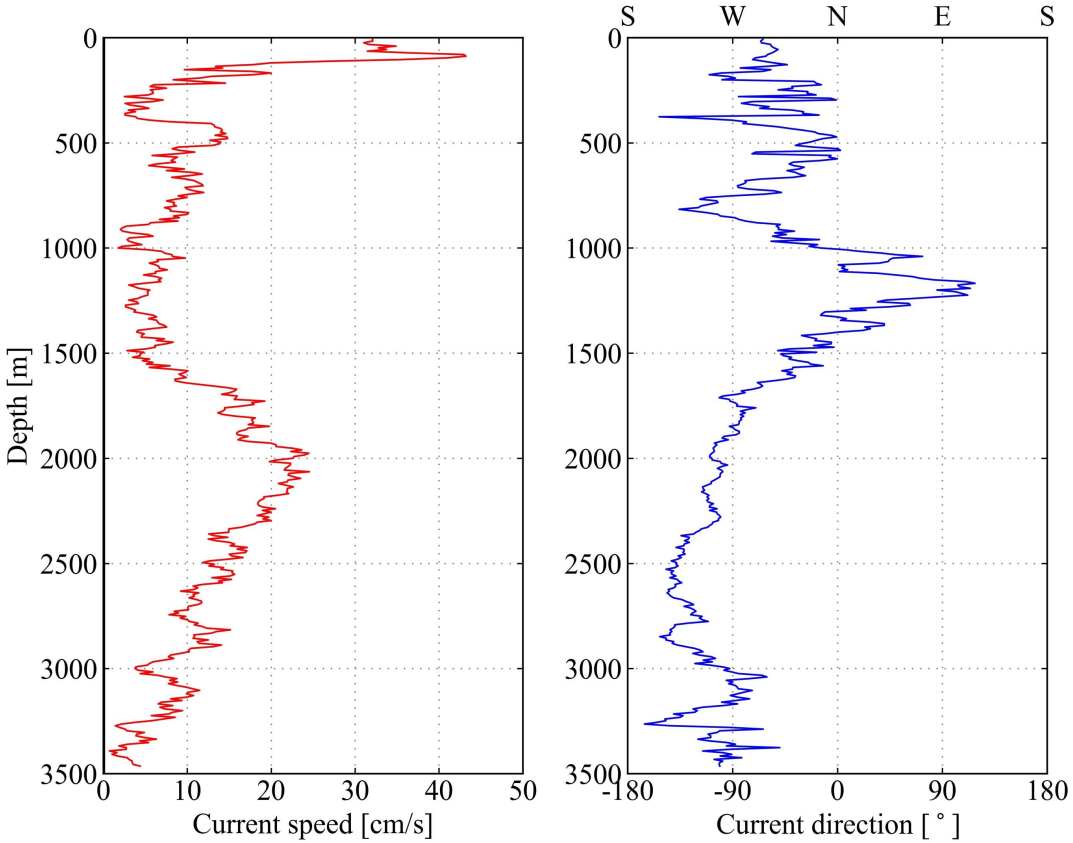

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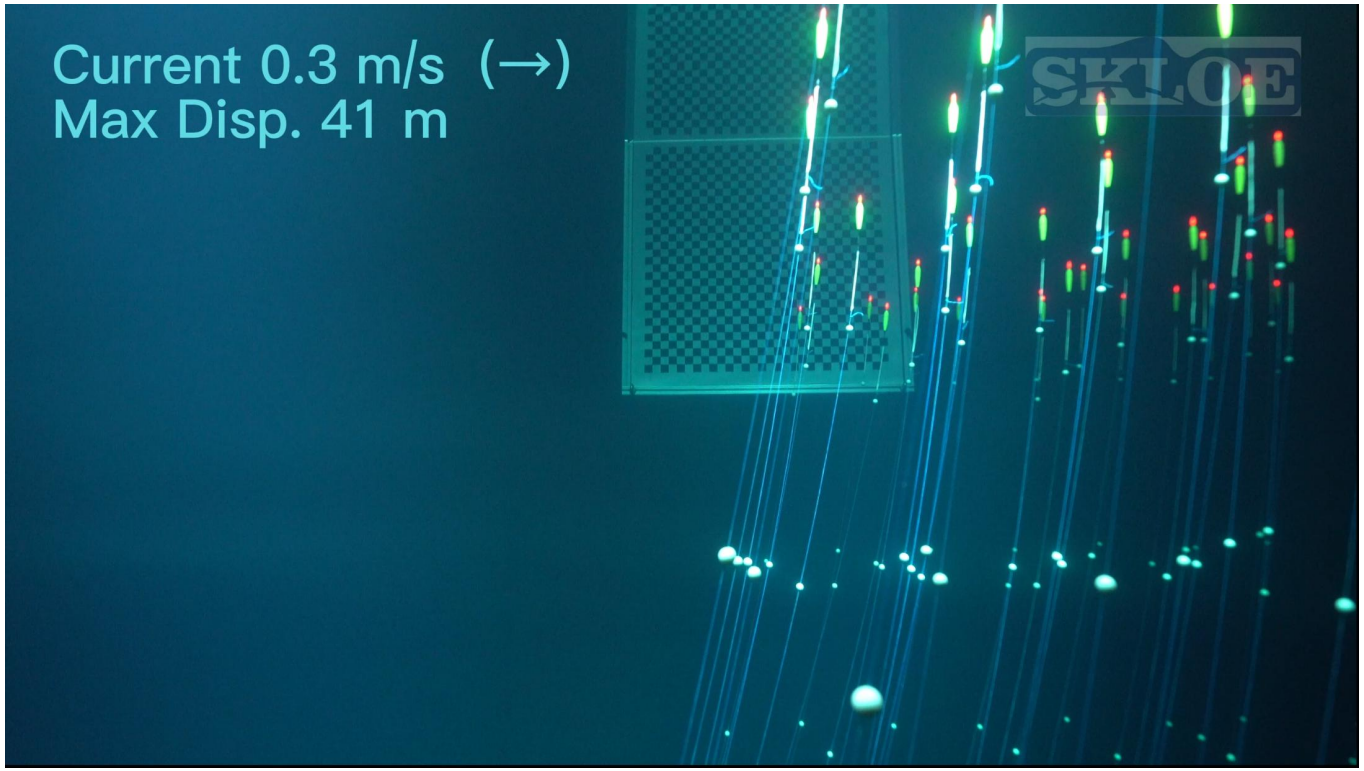

Animation link

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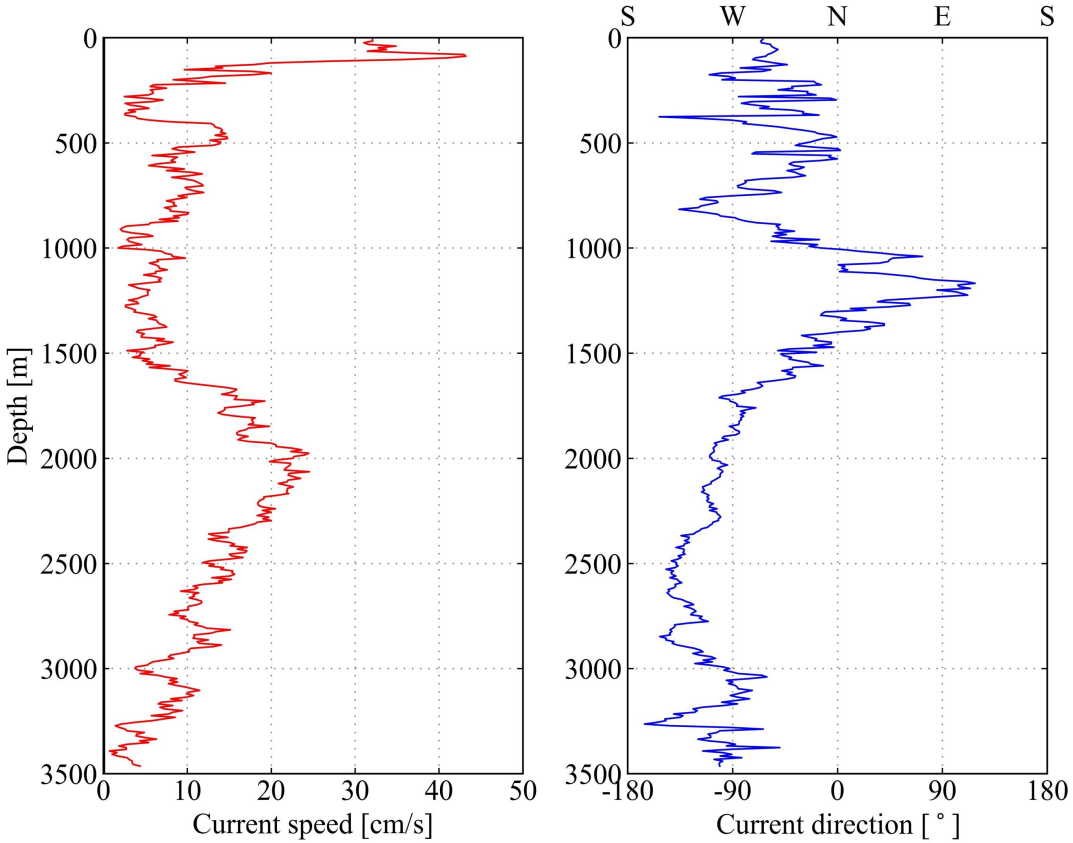

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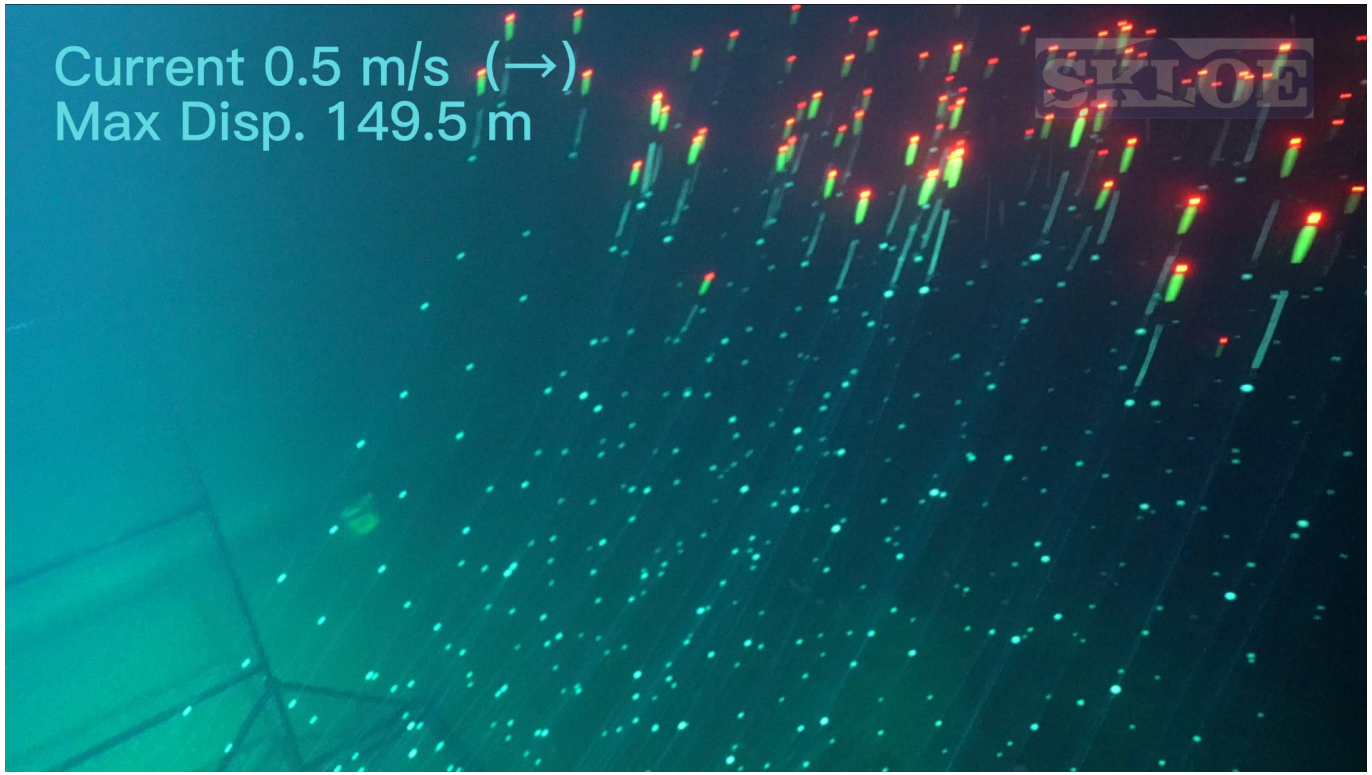
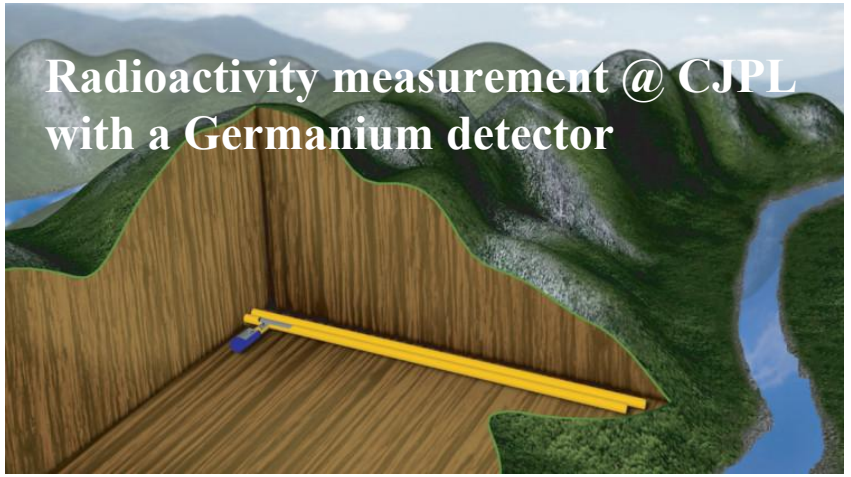


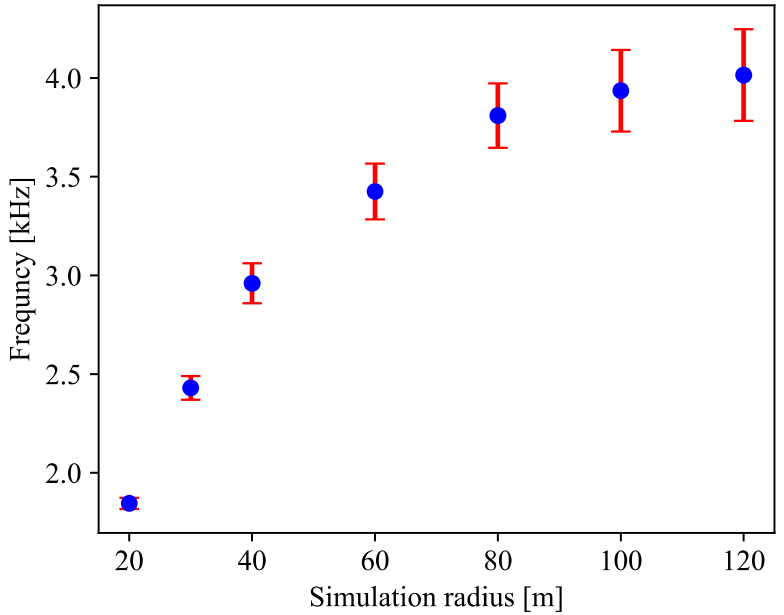
Animation link

TRIDENT Explorer : Radioactivity



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

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



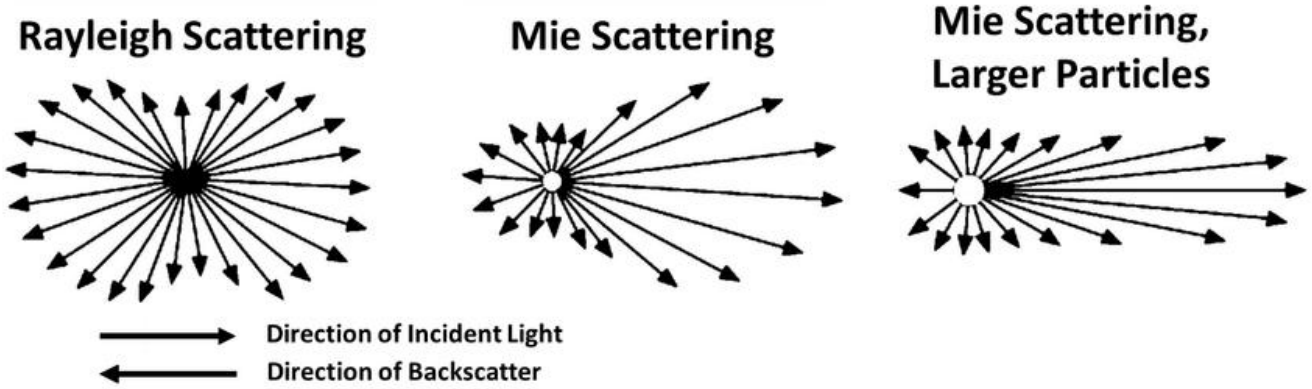
Optical properties of deep-sea water

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

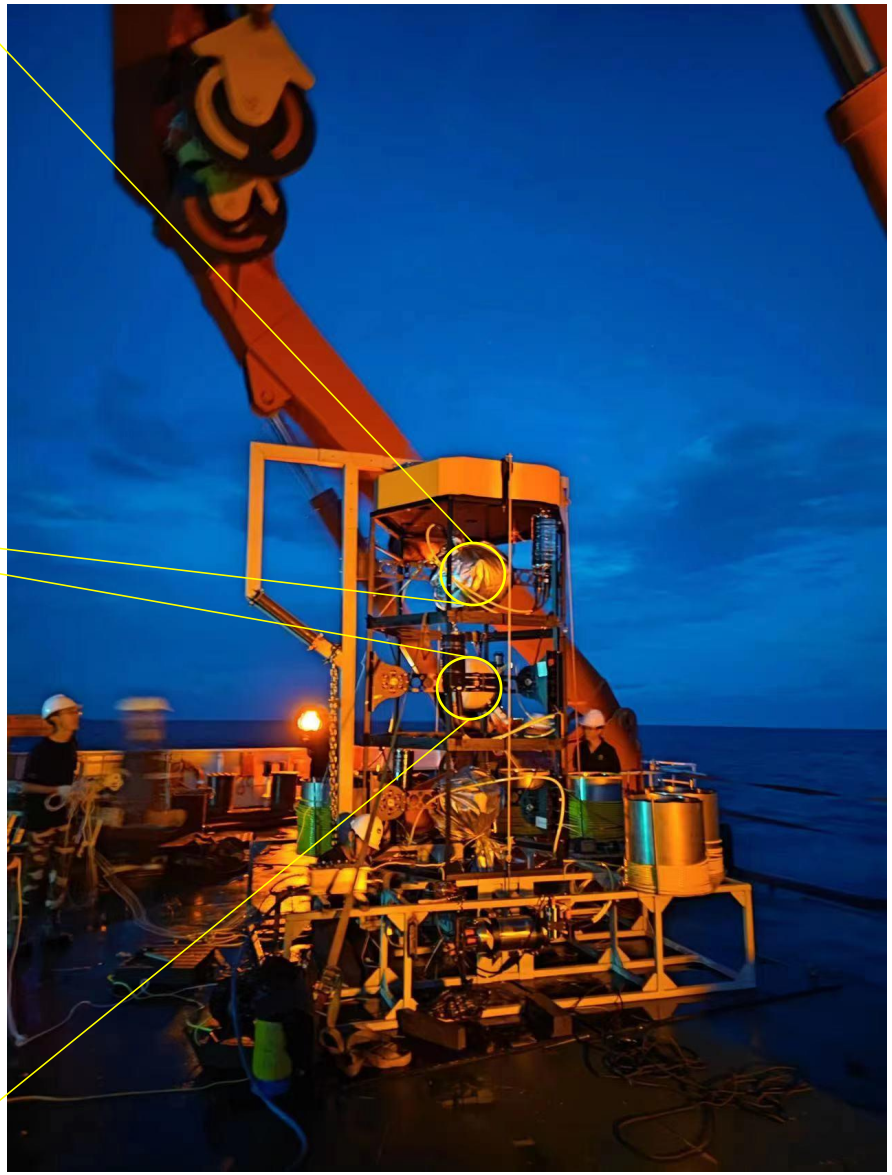
$$\widetilde{\beta^{HG}}(g,\cos\theta) = \frac{1}{4\pi}\frac{1-g^2}{(1+g^2-2g\cos\theta)^{3/2}}$$

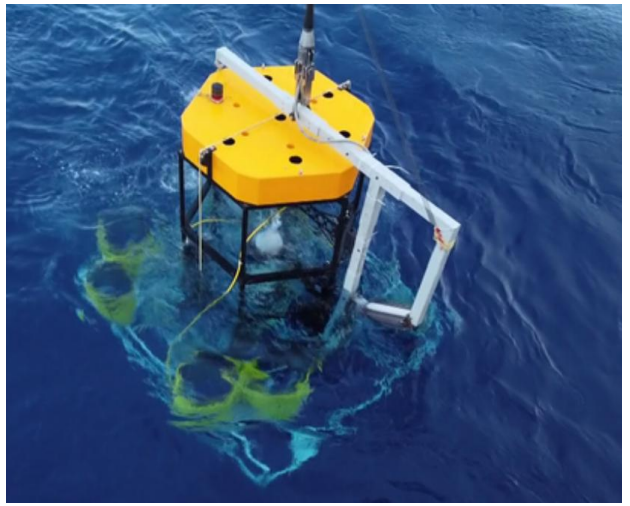
Attenuation length:

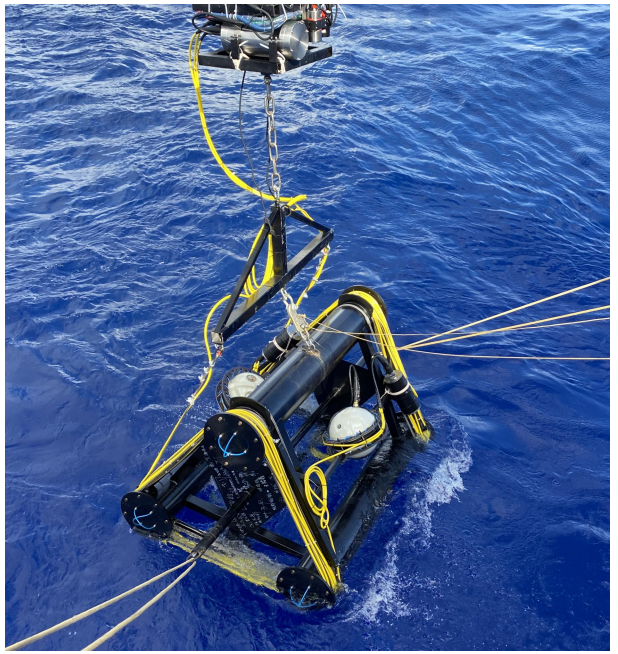
$$I(L) = I_0 \cdot e^{-(\frac{L}{\lambda_{abs}}+\frac{L}{\lambda_{sca}})} = I_0 \cdot e^{-\frac{L}{\lambda_{att}}}$$

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

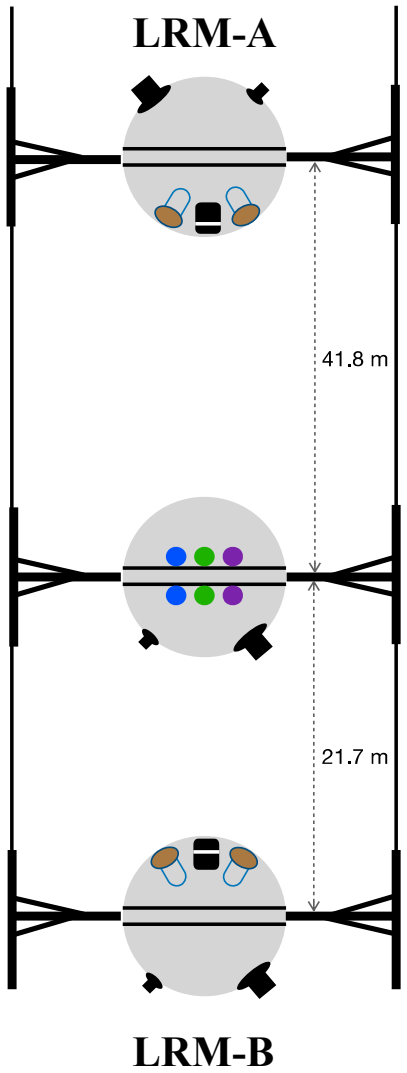
TRIDENT Explorer : T-REX Apparatus

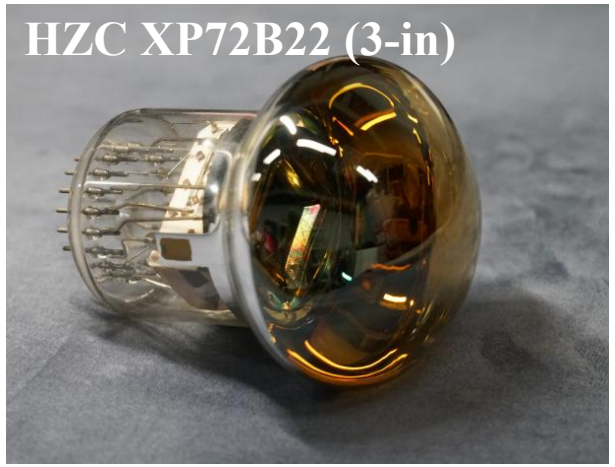


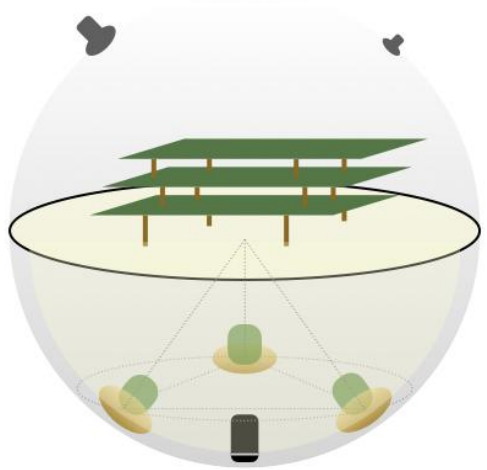




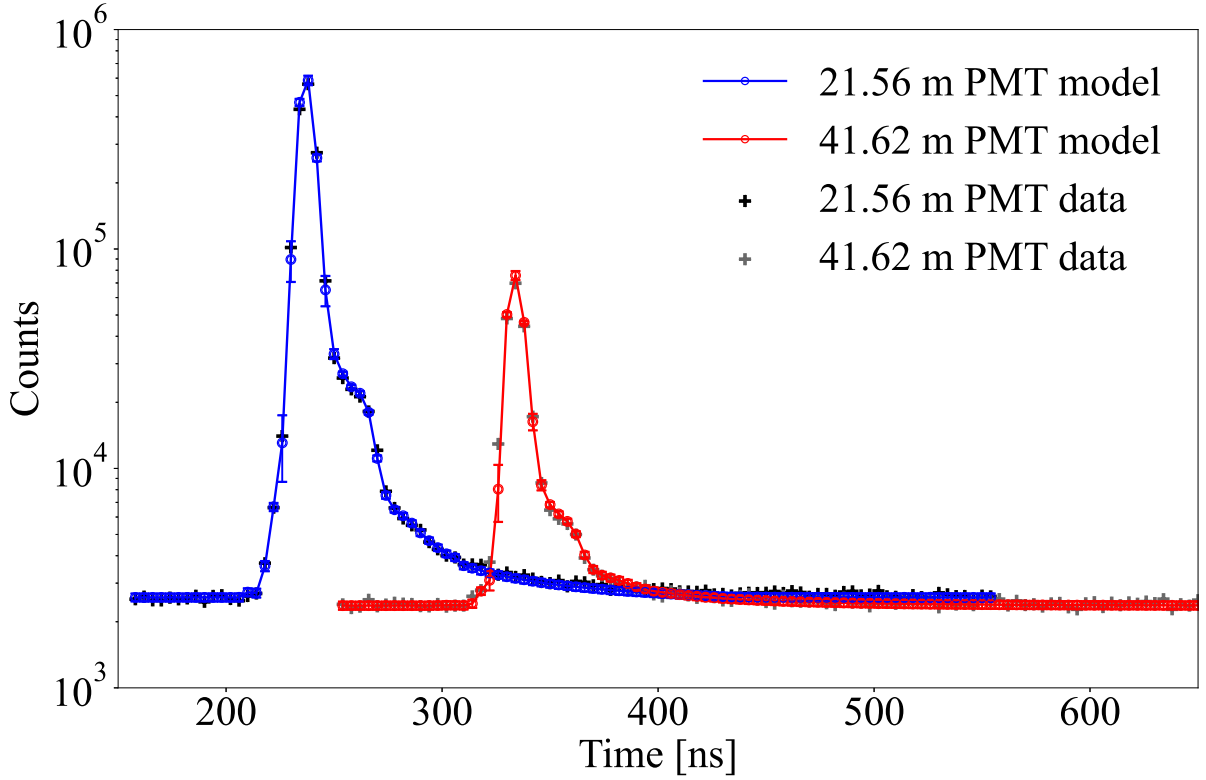
T-REX PMT system







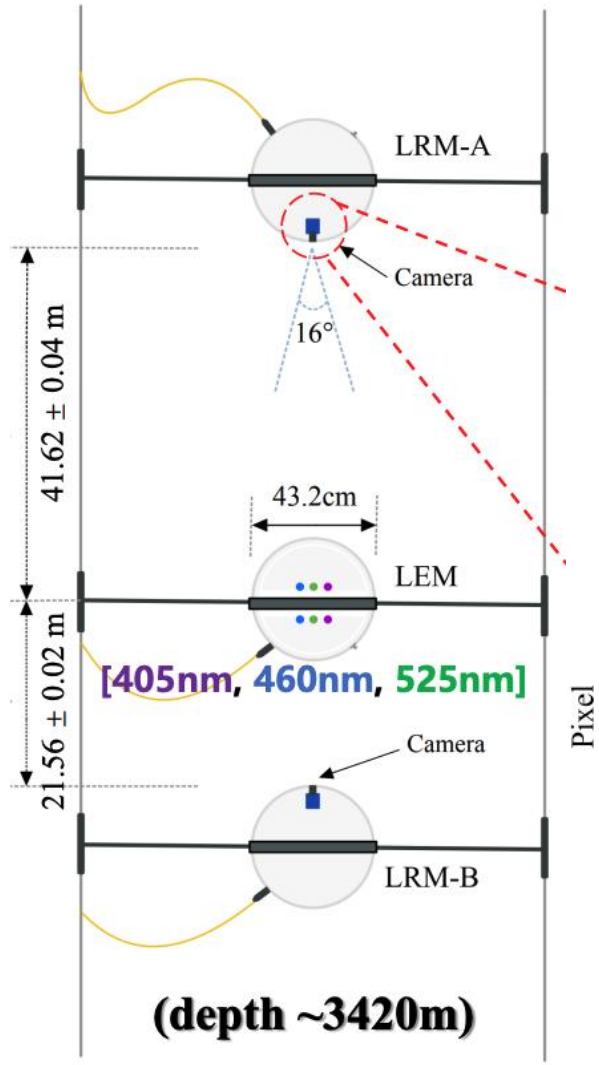
Use relative measurement method to mitigate hidden systematics



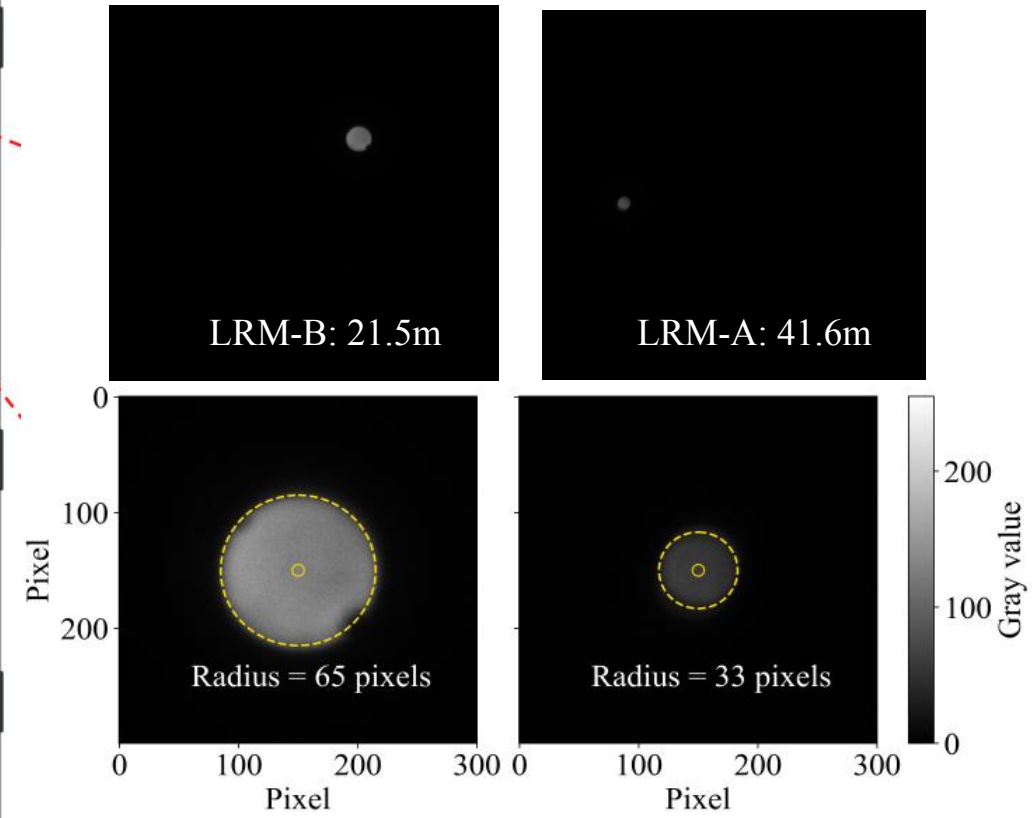
Electronics: J. N. Tang *et. al.*, **Journal of Instrumentation**, vol.18 T08001 (2023);
M. X. Wang *et. al.*, **IEEE Transactions on Nuclear Science**, vol. 70, 2240–2247 (2023)

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

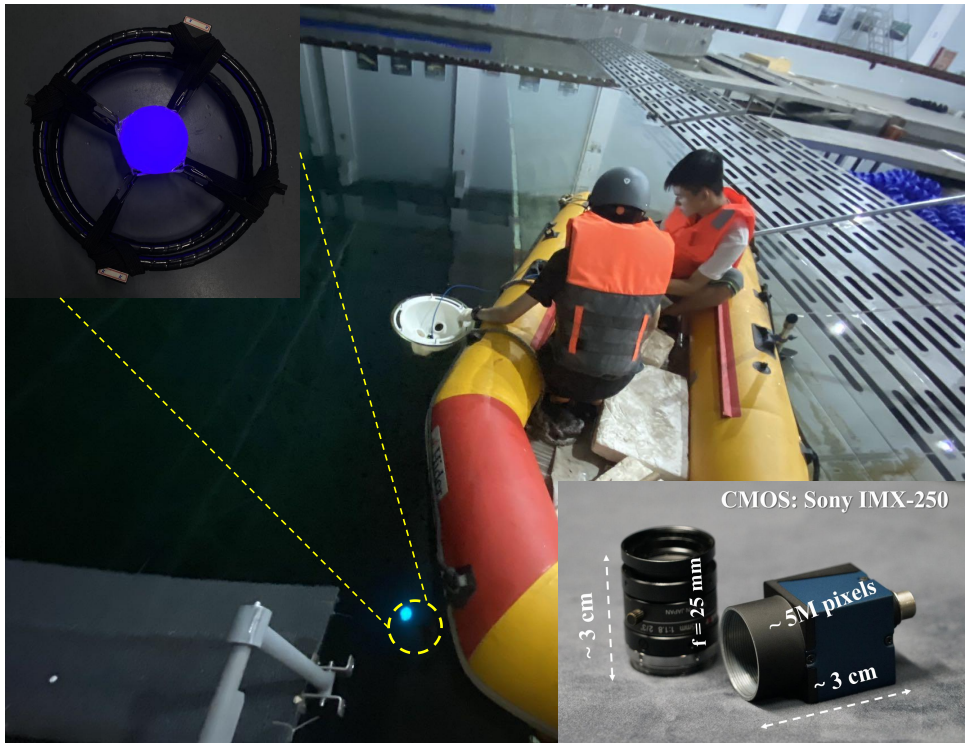
T-REX Camera system



Images captured at depth of 3420m



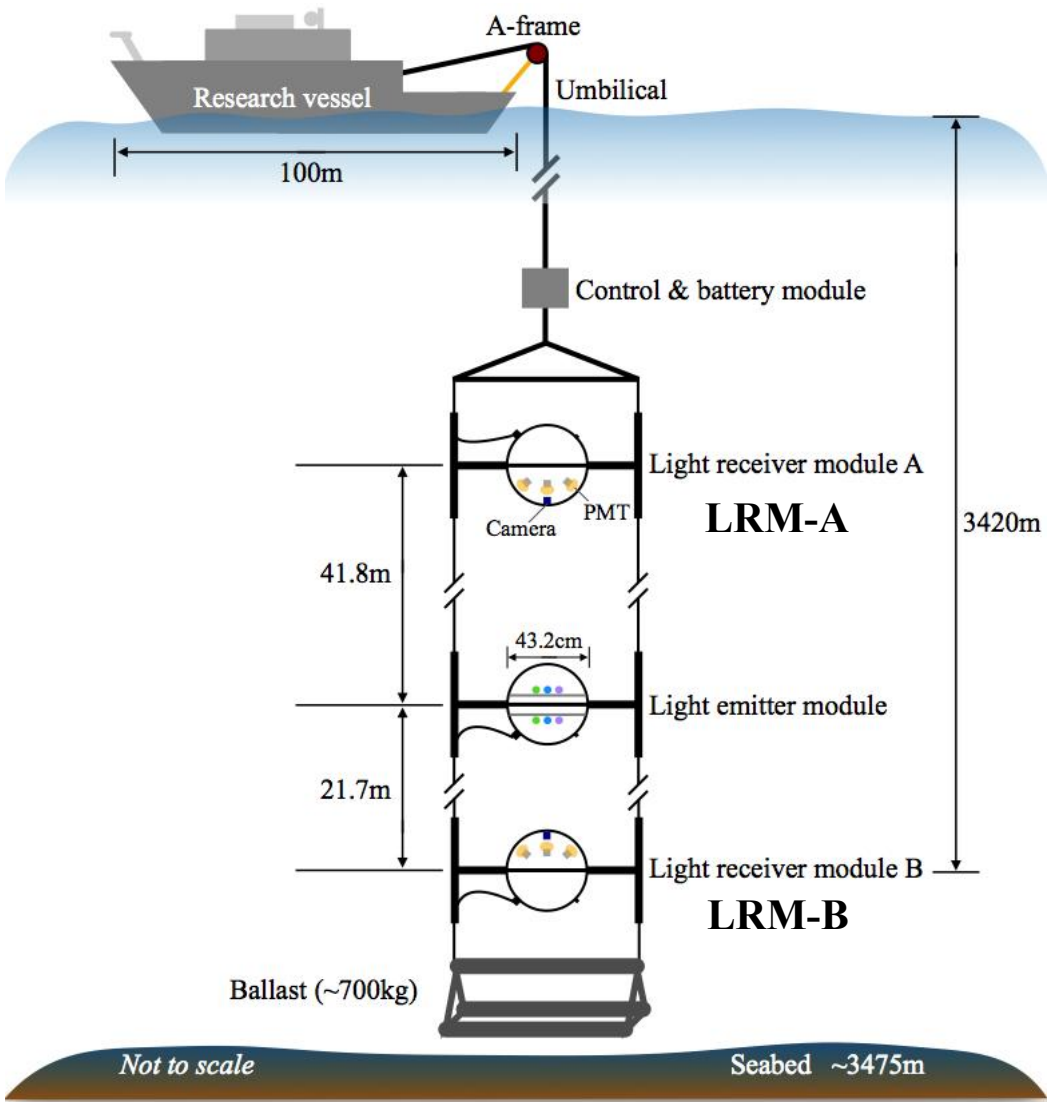
Camera-calibrating in a ship towing tank



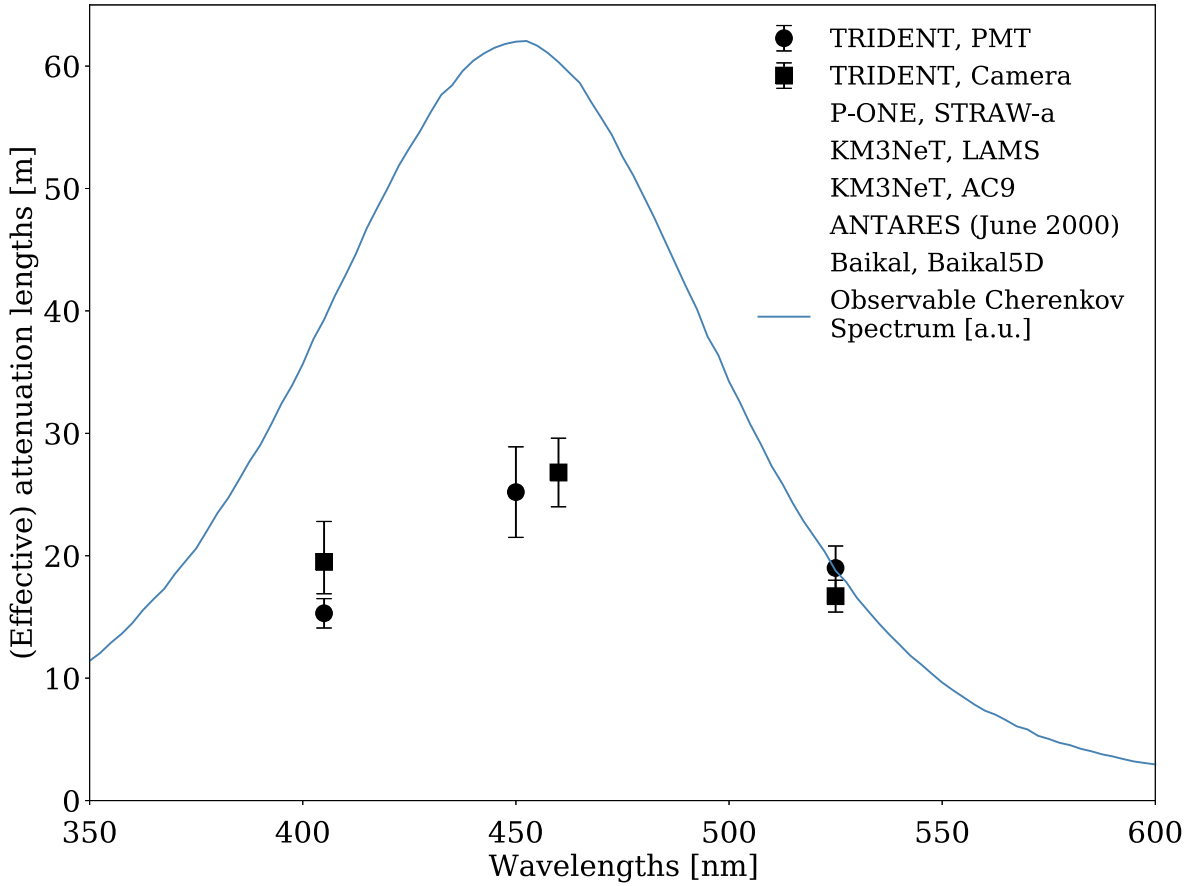
PoS (ICRC2023) 1094

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

TRIDENT Explorer : Optical Properties

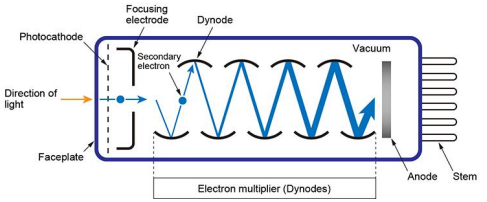


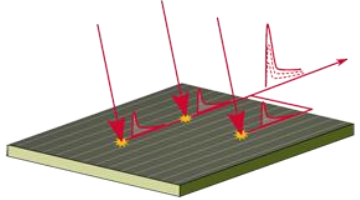
- Dedicated analytical and numerical modeling
- Exp. data: ~ **1**TB ⇔ Simulated data: ~ **100** TB, **10M** files

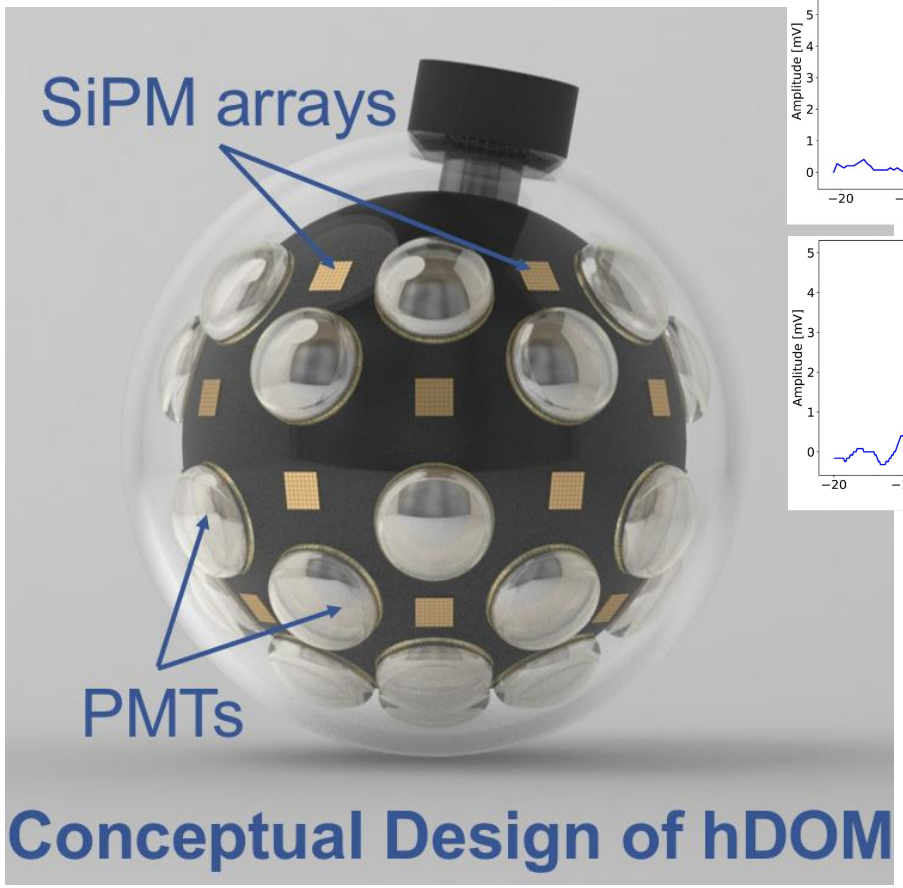


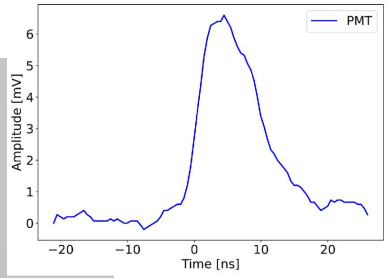
Nature Astronomy (2023). 10.1038/s41550-023-02087-6

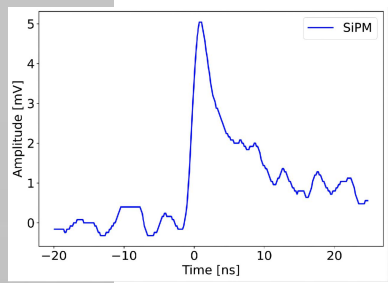
TRIDENT hybrid DOM – hDOM

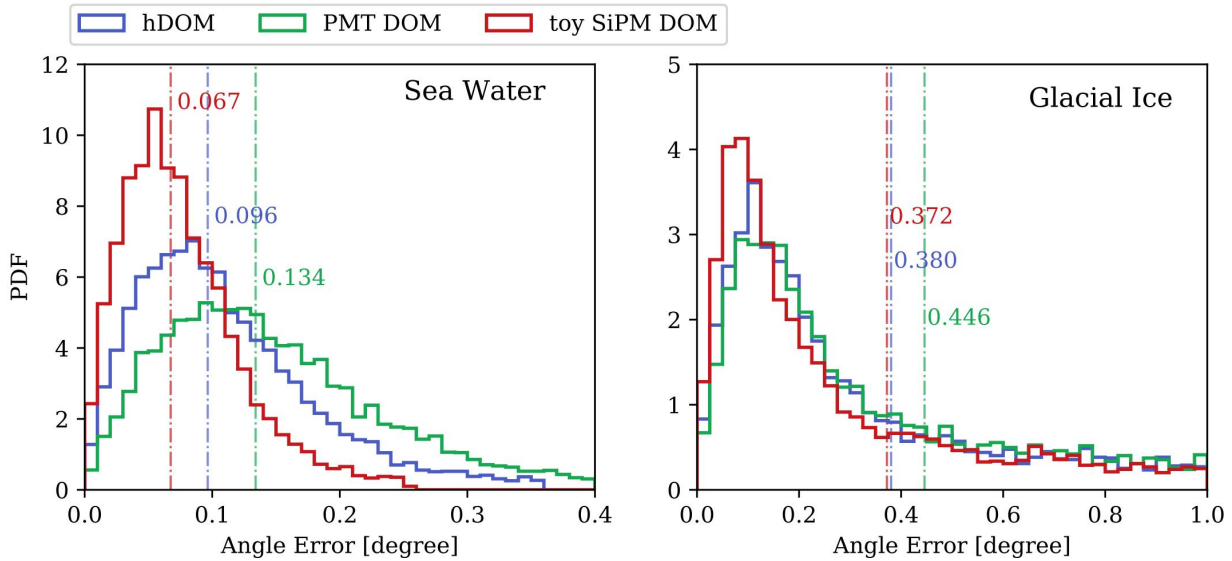












- Better than 0.1° @ E_ν> 100 TeV
- **>40% improvement** (cf mDOM) in angular resolution, assuming PMT TTS ~5ns

Updated:

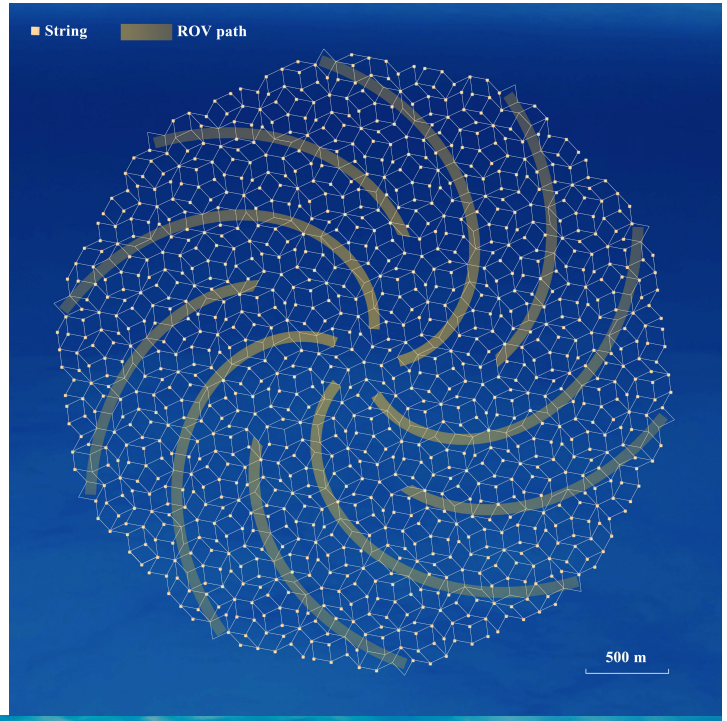
PMT TTS ~3ns + 10cm hDOM position smearing: 40% → 30%

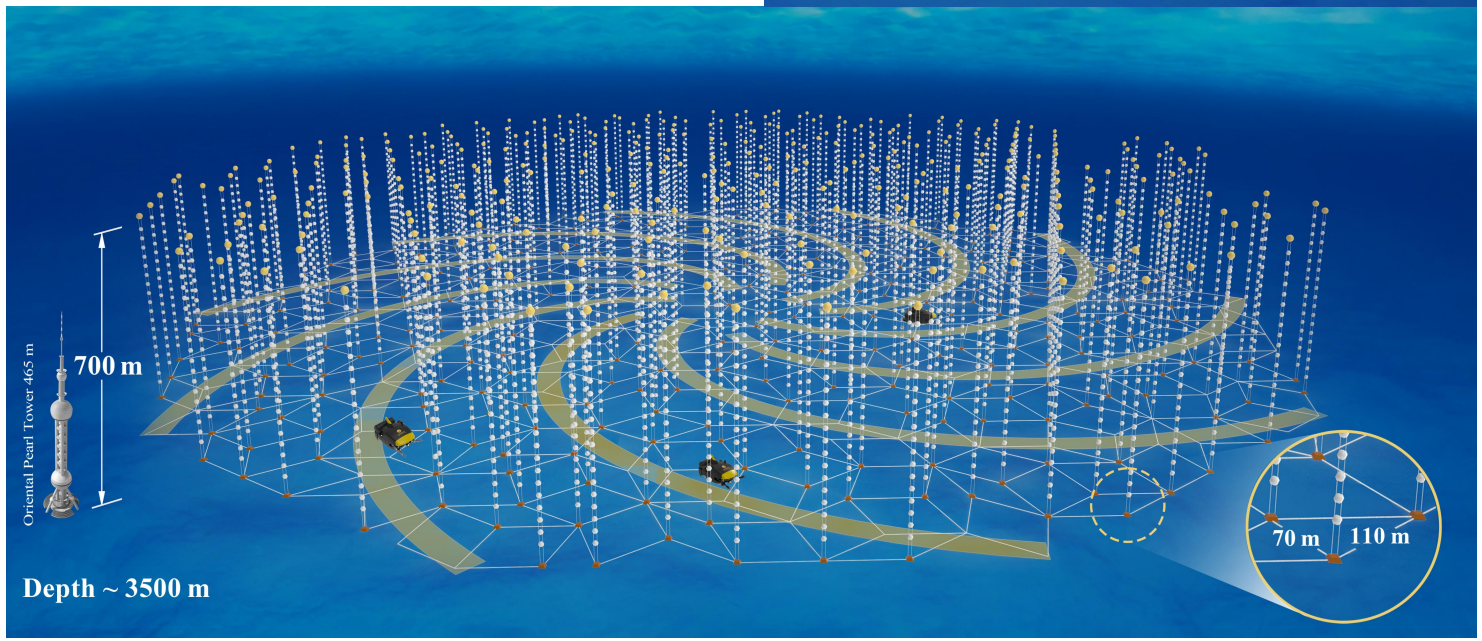
Conceptual design: PoS (ICRC2021) 1043 **Development progress**: PoS (ICRC2023) 1213

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**

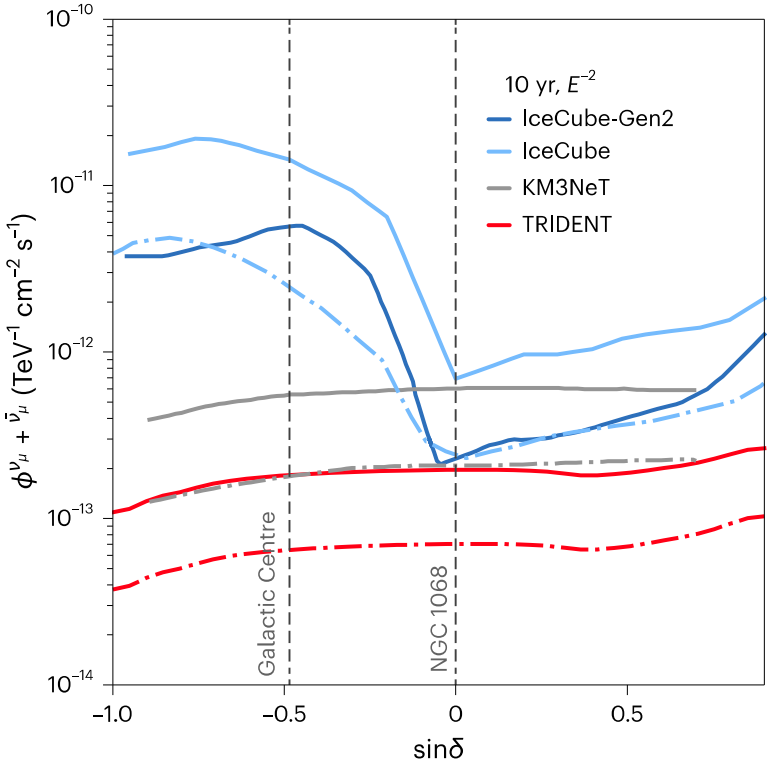
- **1200** strings
- **20** hDOMs / string
- Volume: ~ **8** km^3
- Underwater ROV for deployment & maintenance

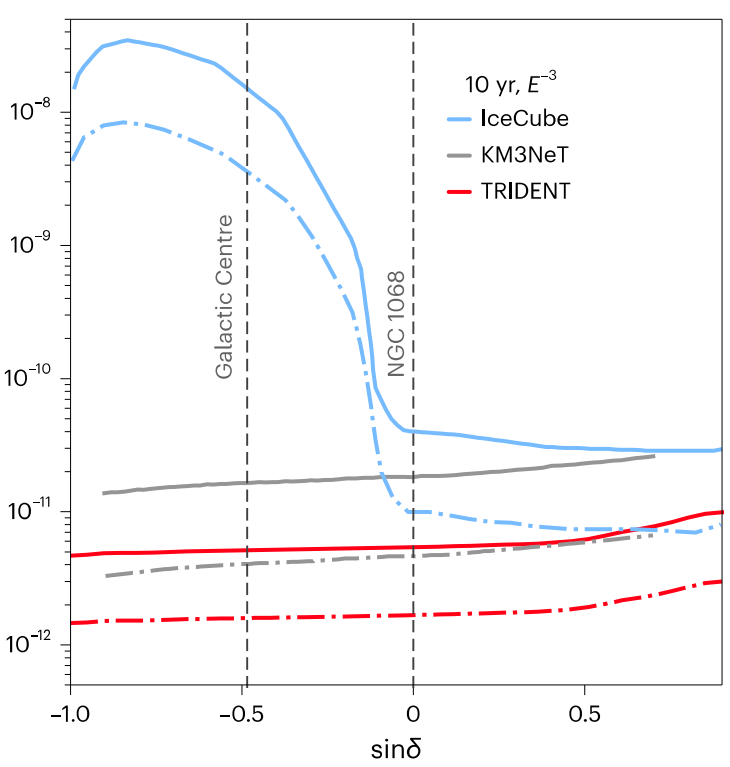
Nature Astronomy (2023). 10.1038/s41550-023-02087-6

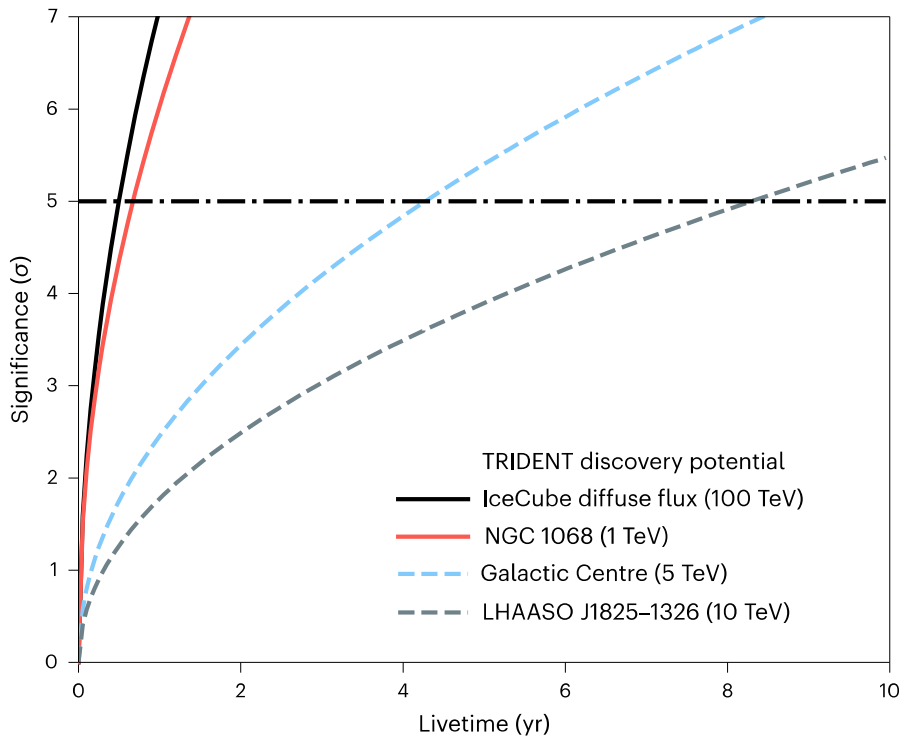
Geometry comparison: PoS (ICRC2023) 1203

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 (2023). 10.1038/s41550-023-02087-6

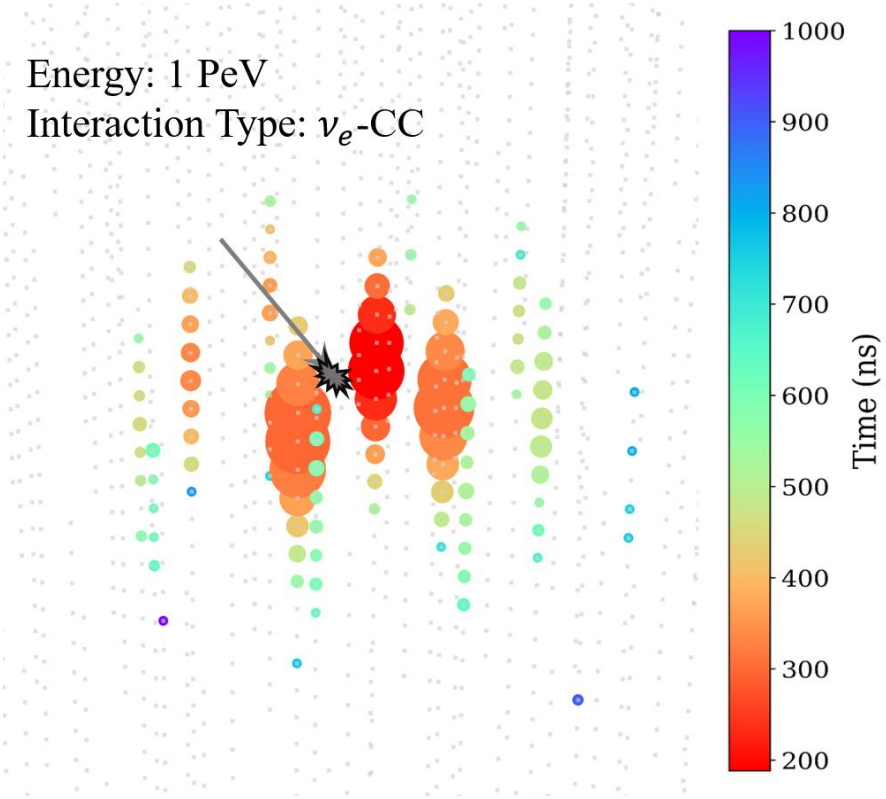
Sensitivity to all neutrino flavors

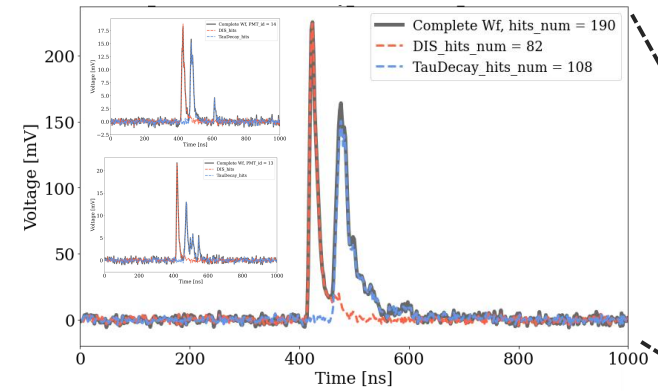
See Arguelles's talk at this conference

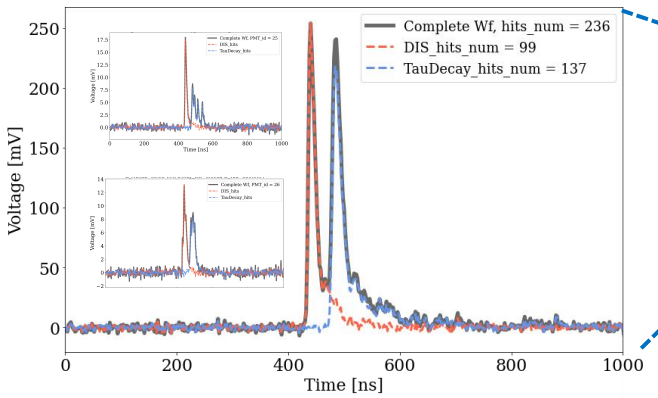
Angular resolution for cascades:

- **~1.8° @ 1PeV** (likelihood)
- **~ 1.5° @ 100 TeV & 1 PeV** (GNN)

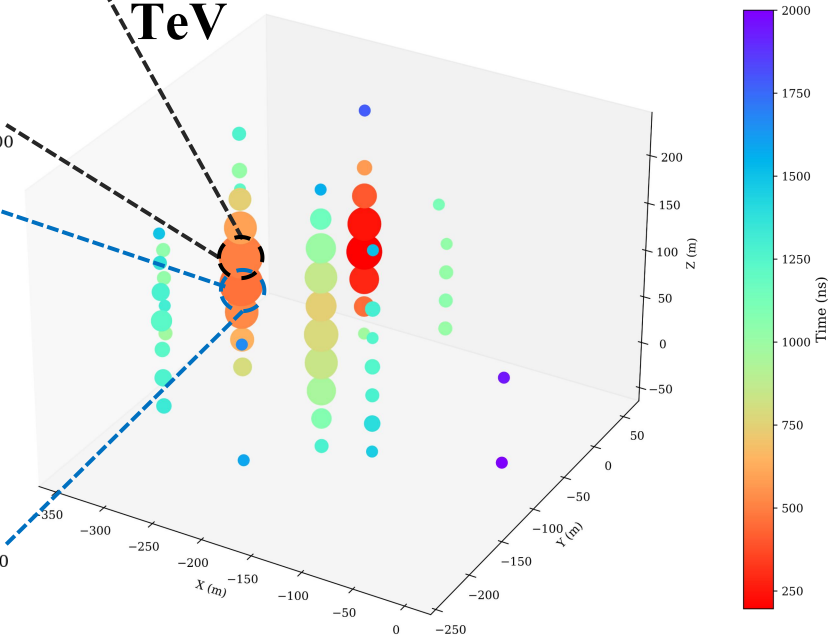
Where are the ν_e and ν_τ from NGC 1068 and TXS 0506+056 ?







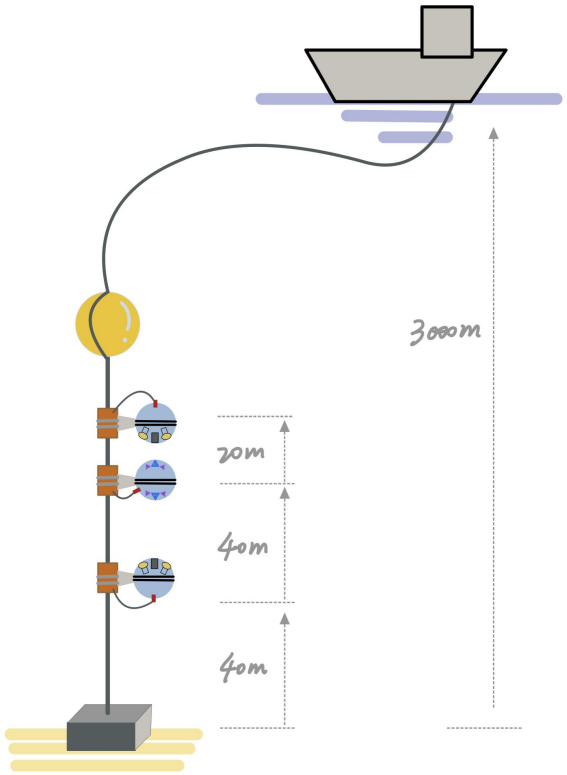
$E\nu_\tau = 334.3$ TeV

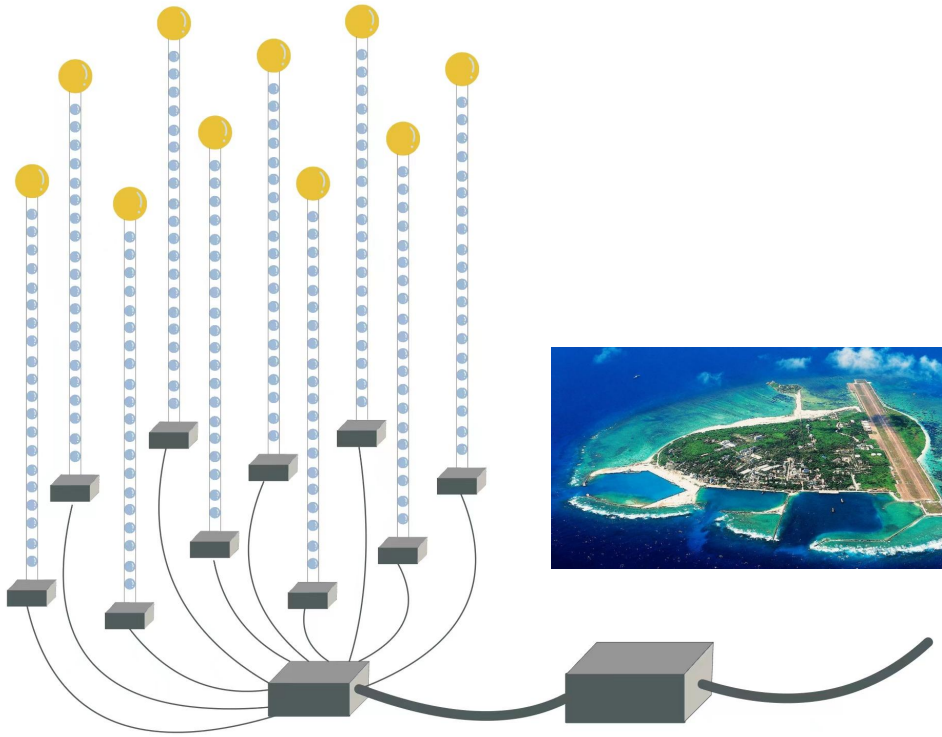


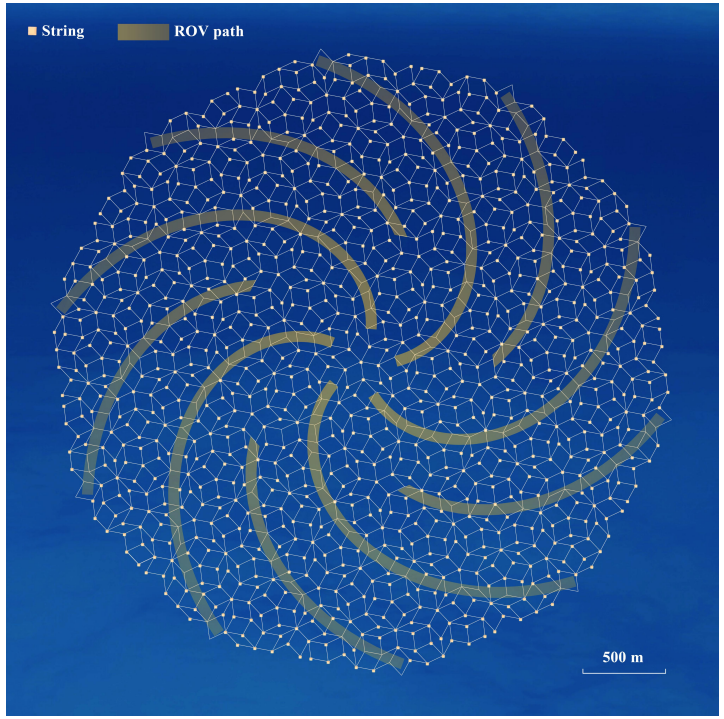
Cascade reco : PoS (ICRC2023) 1207

Tau double pulse : PoS (ICRC2023) 1092

Brief timeline





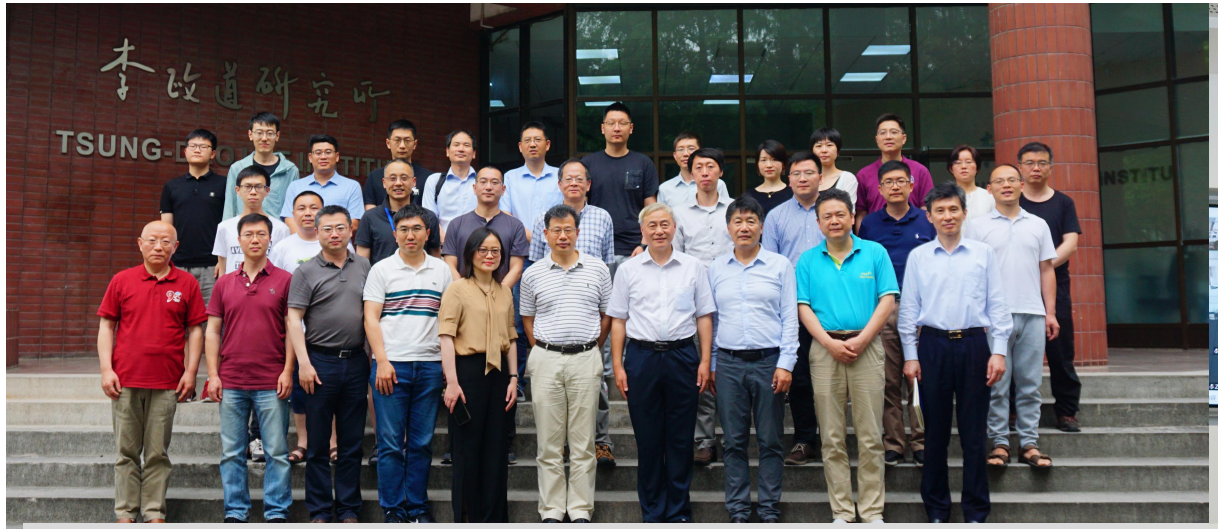


Pathfinder: 2019–2022
completed

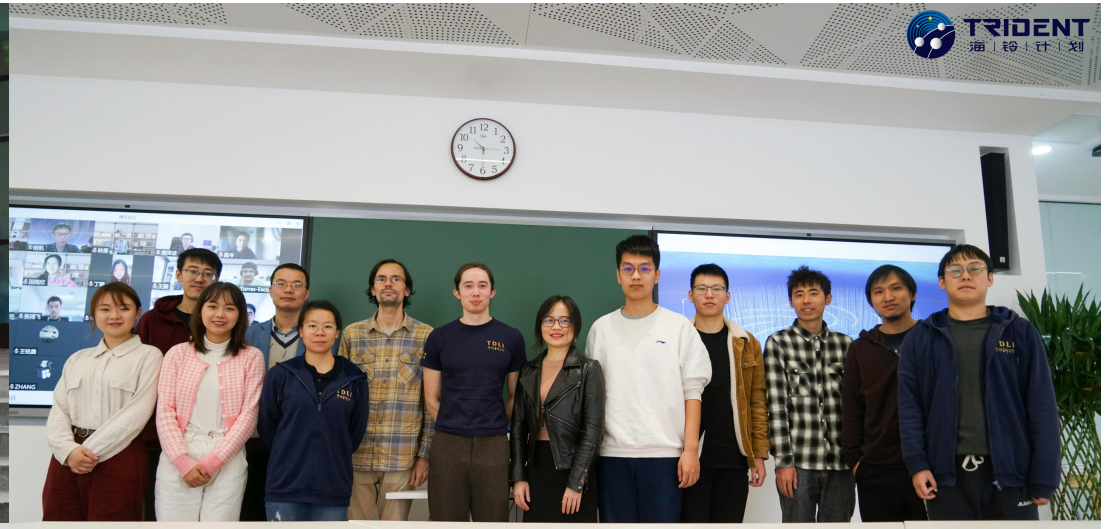
Phase-I project: 2022–2026
in progress

Big array construction: 2026–
under planning

Interdisciplinary collaborations: ~ 100 members



Establishment of the TRIDENT collaboration, June 8, 2021, TDLI, Shanghai



First TRIDENT collaboration meeting, Nov.18, 2022, Tsung-Dao Lee Institute, Shanghai

1st TRIDENT interdisciplinary forum, Nov. 16, 2022

2nd TRIDENT interdisciplinary forum, Nov. 27-28, 2023

Summary

- IceCube has opened a new era for high-energy neutrino astronomy
- Neutrino astronomy is still in its infancy, the future is bright and could be well beyond our imagination
- **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
- We propose to build a next-gen neutrino telescope (TRIDENT) for rapid source discoveries and further neutrino astrophysics exploration.