李政道研究所 TSUNG-DAO LEE INSTITUTE

TRIDENT 海铃计划

The TRIDENT Deep-sea Neutrino Telescope

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TeVPA 2024

2024.08.26-30

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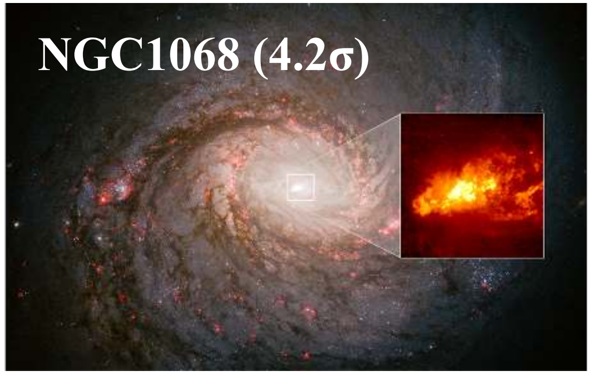
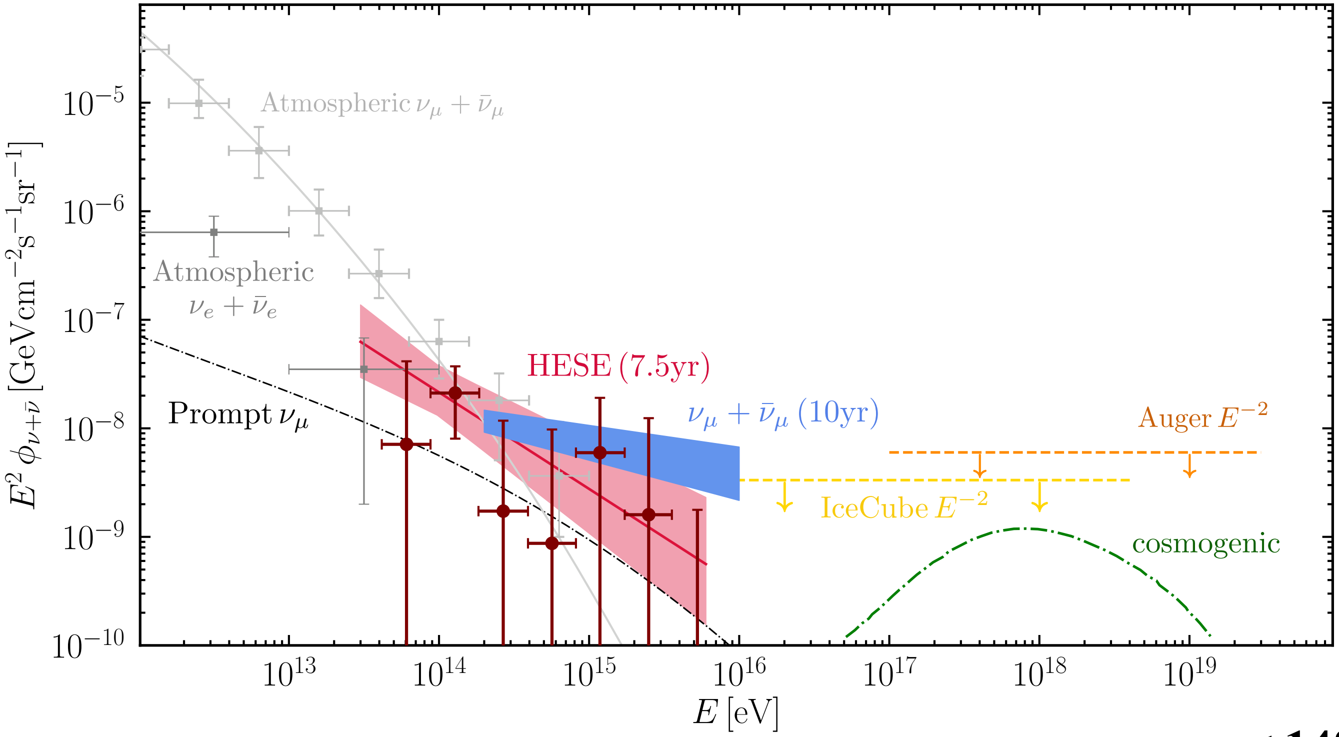
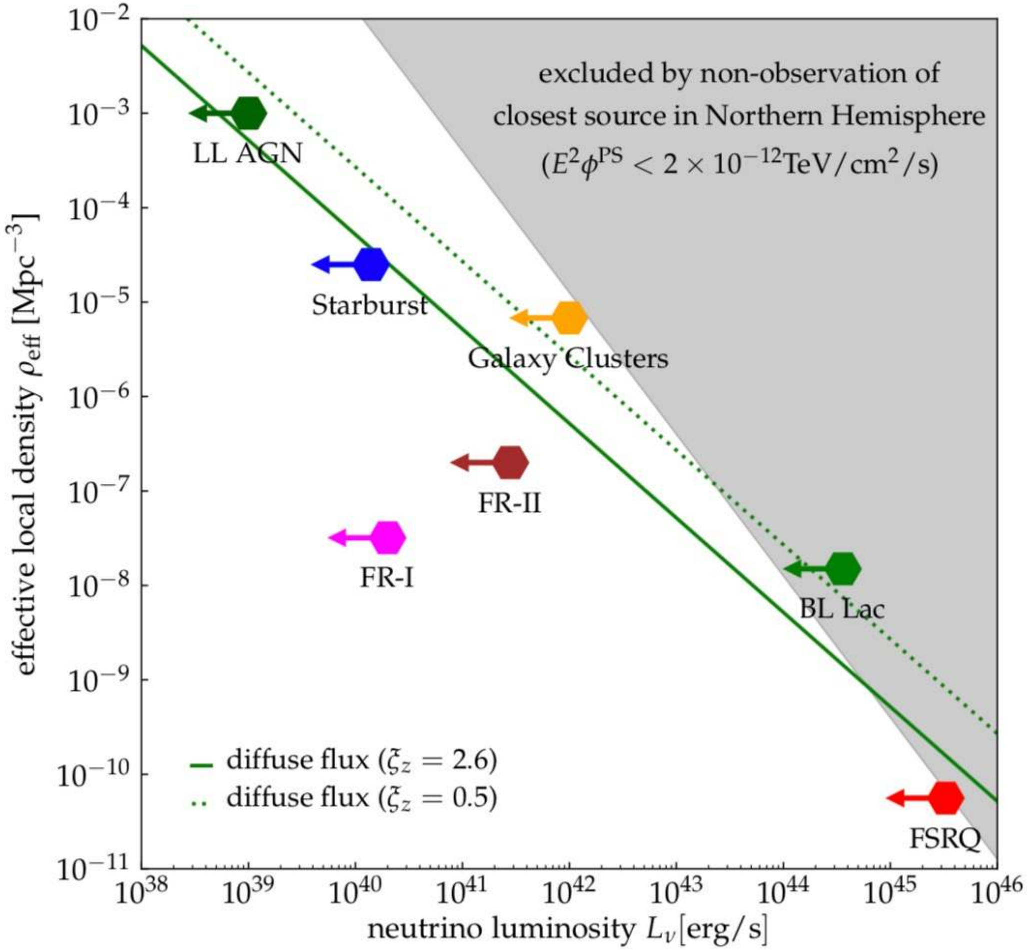
A new era of neutrino astronomy



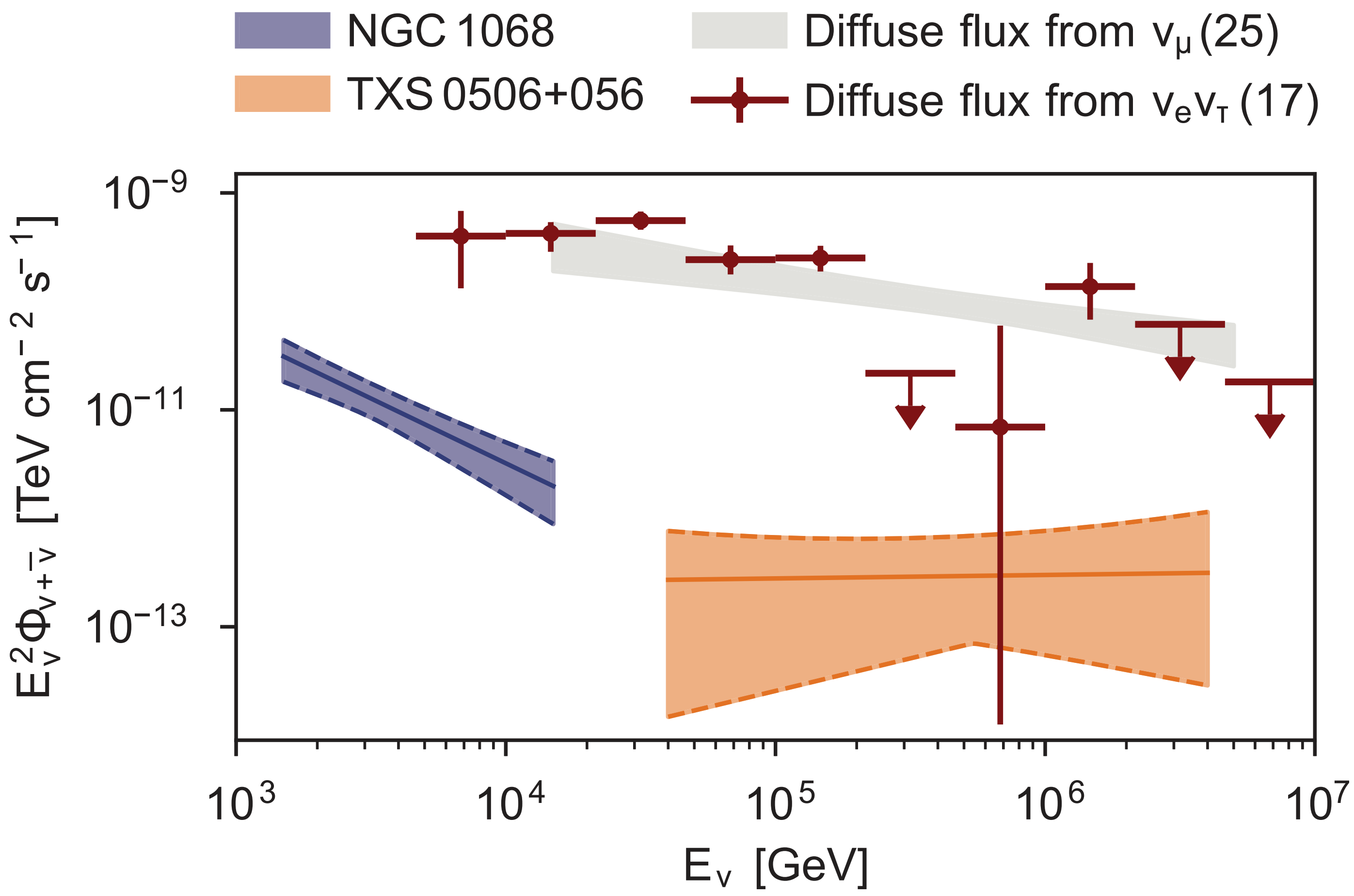


Halzen & Khierandish, arXiv:2202.00694



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

Astrophysical ν sources



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

- **At least two distinctive categories of sources**
- **Diffuse flux largely unresolved**

↓

1) How to **optimize** next-gen neutrino telescopes for **low** and **high energies?**

2) Room to **improve** on **angular resolution?** Need better than 0.1° @ 100TeV to resolve the diffuse flux

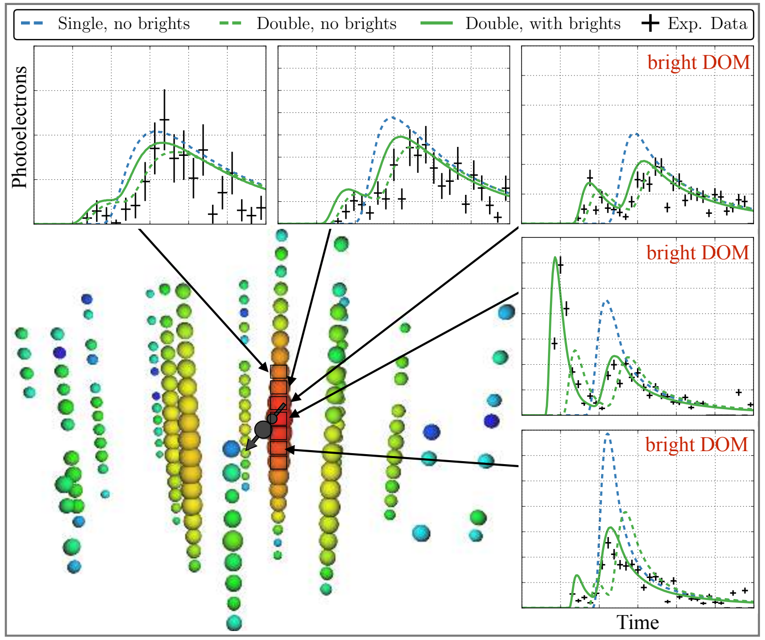
3) How to **boost flavor identification** for discovered sources?

Astrophysical ν flavor identification

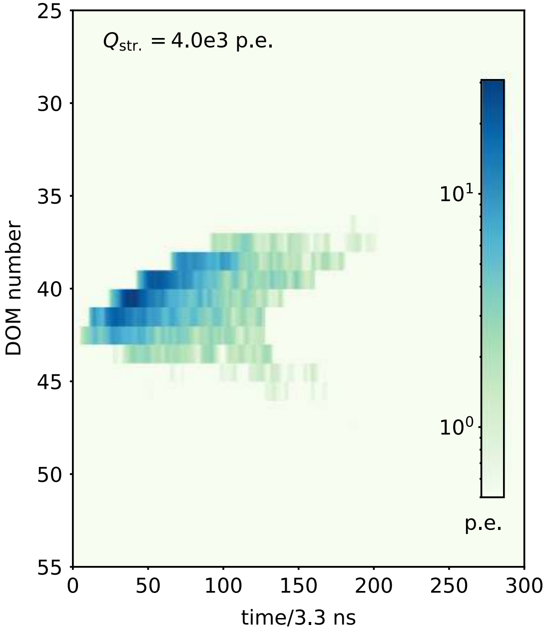
How can we improve? →

1) **Larger detectors** for more high-energy events

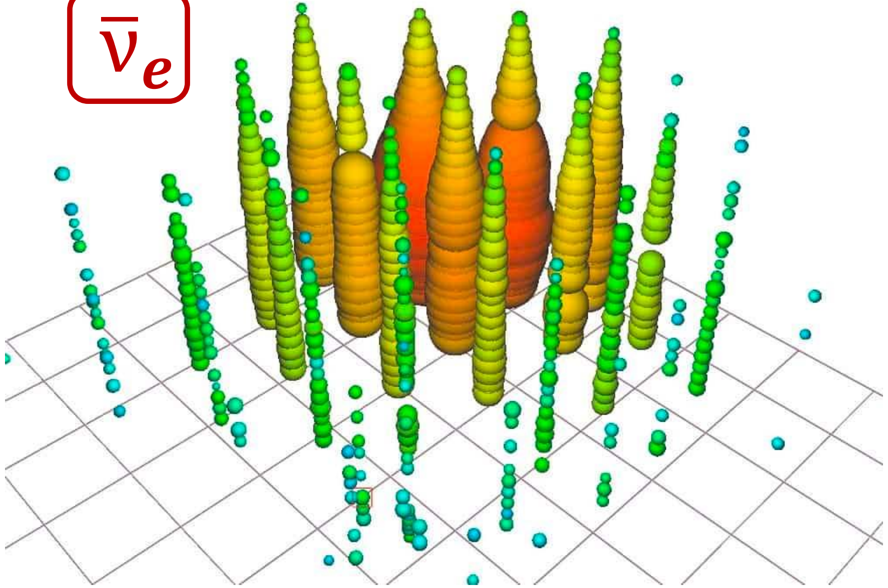
2) **Pixelized DOMs with waveforms** for recording kinetic info



ν_τ



$\bar{\nu}_e$



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

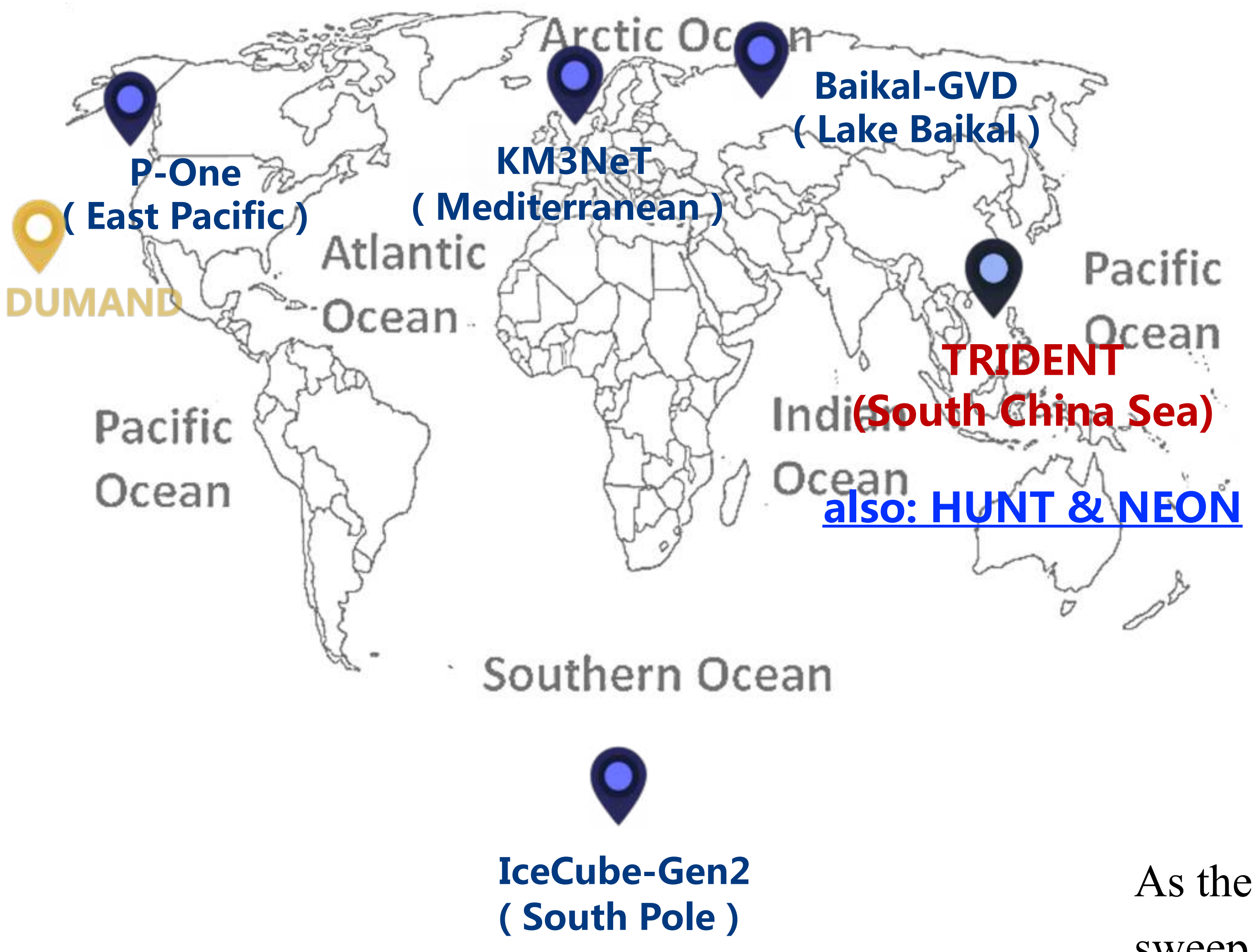
M. Meier, J. Soedingrekso, PoS (ICRC2019) 960

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

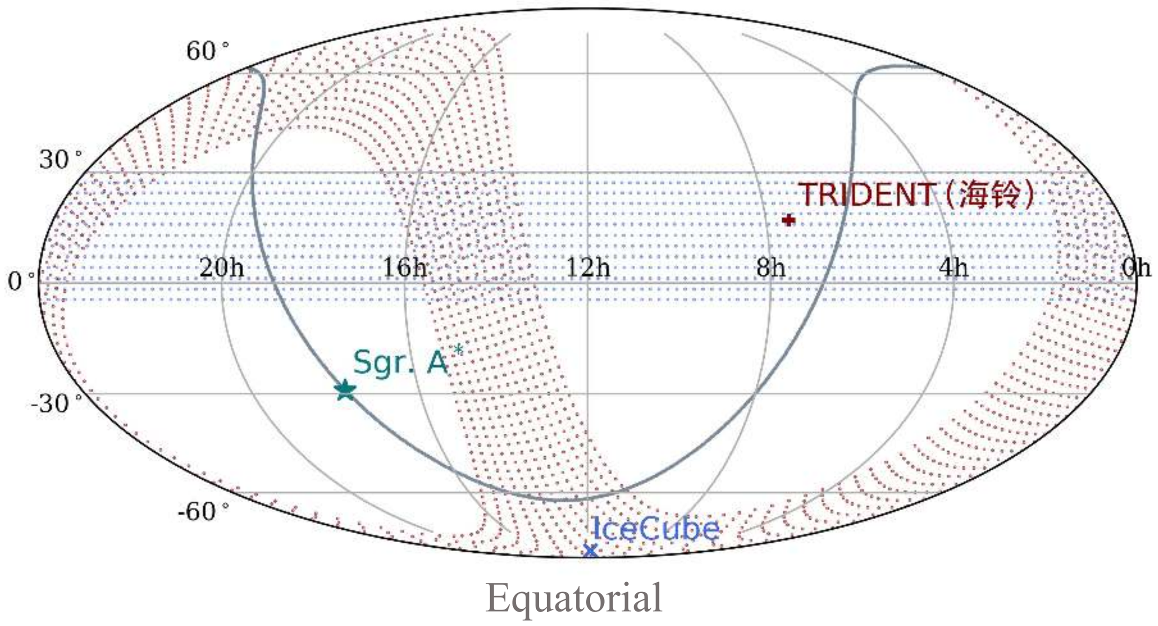
IceCube Collaboration, Phys. Rev. Lett. 132, 151001 (2024)

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

(Next-gen) neutrino telescopes under planning



TRopIcal DEep-sea Neutrino Telescope

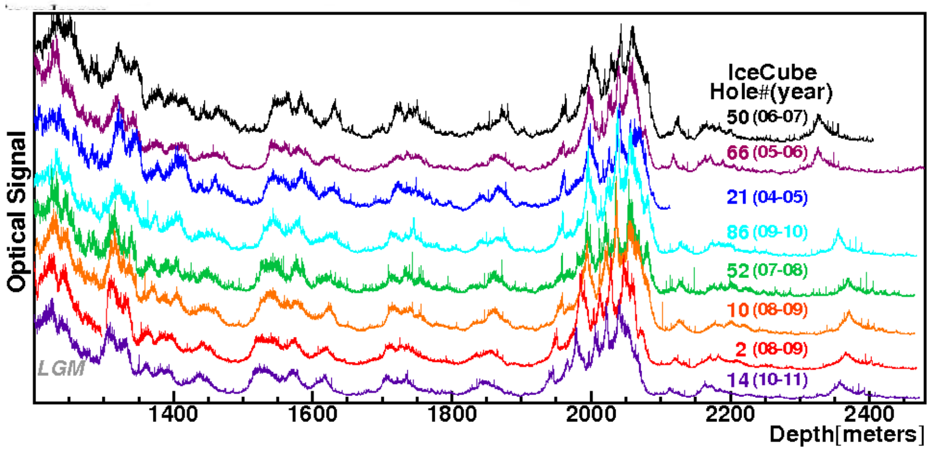


As the Earth rotates, TRIDENT's best sensitivity band will sweep through the entire sky, complementing IceCube-Gen2 well

Interaction medium: Ice vs Water

Glacial ice

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



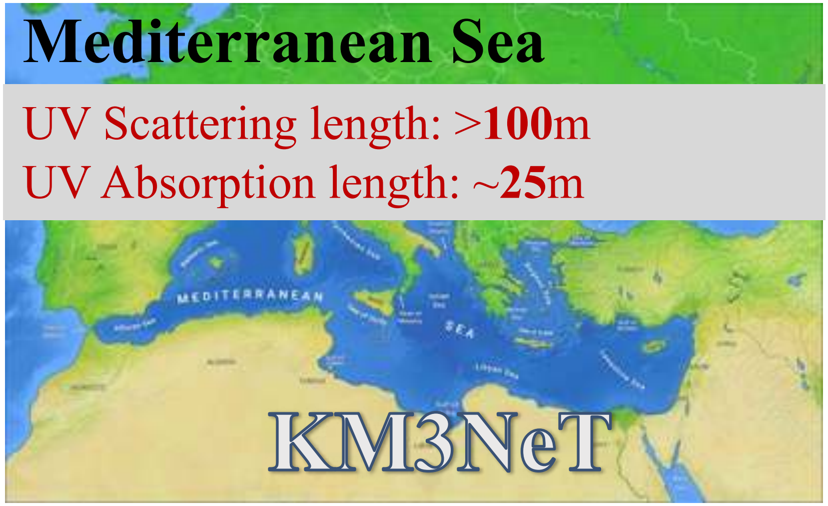
Lake/sea water

Lake Baikal

Water properties:
Abs. length: 22 ± 2 m
Scatt. length: L_s ~ 30-50 m
L_s /(1- <cosθ>) ~ 300-500 m

Mediterranean Sea

UV Scattering length: >**100**m
UV Absorption length: ~**25**m

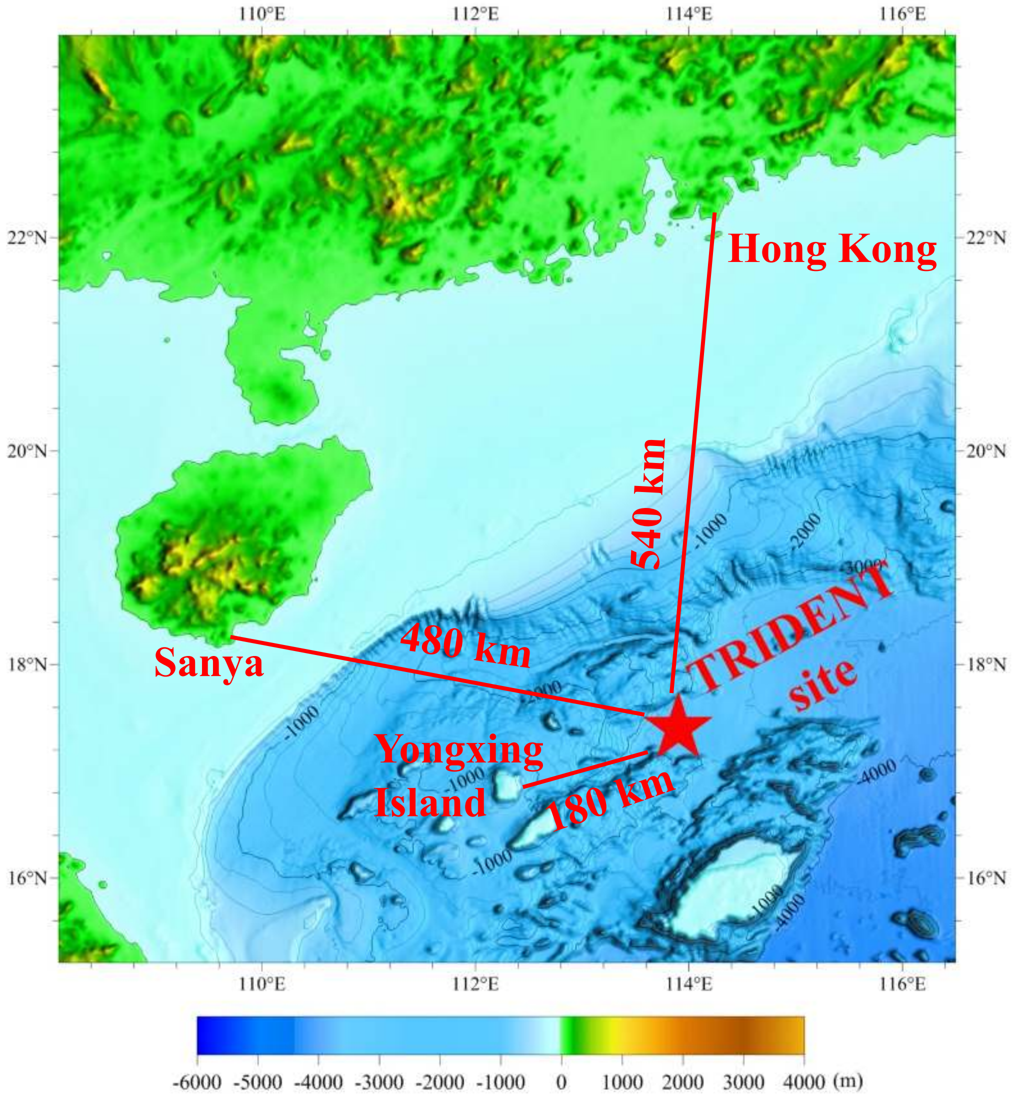


On average, ice is more transparent / less absorbing, while water is less scattering

⇩

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

TRIDENT Explorer : T-REX



Pre-selected site conditions

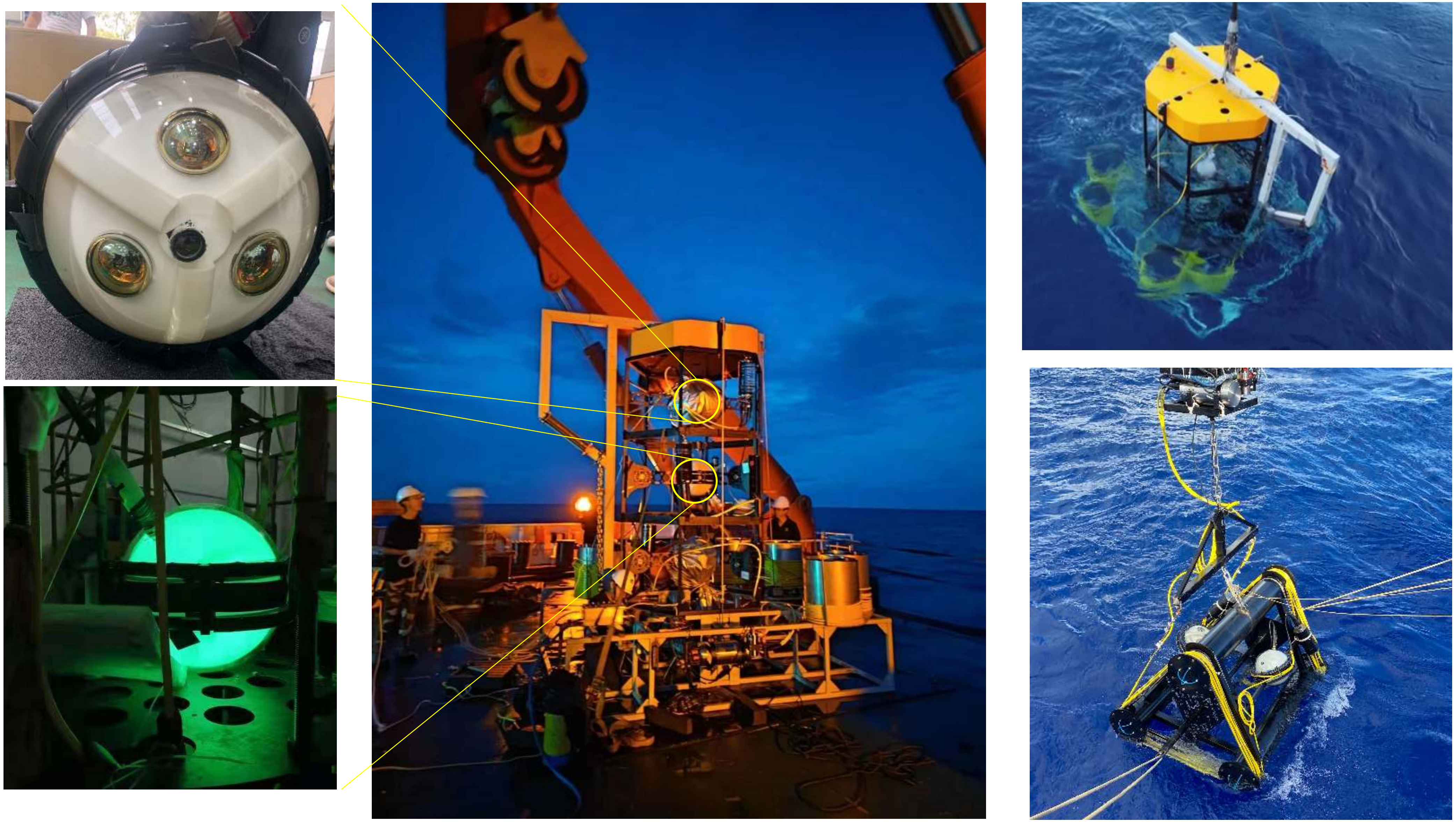
- Flat seabed
- No nearby high rises or deep trenches
- Depth >3km
- Close proximity to a shore

Measured params

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

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

TRIDENT Explorer : T-REX Apparatus



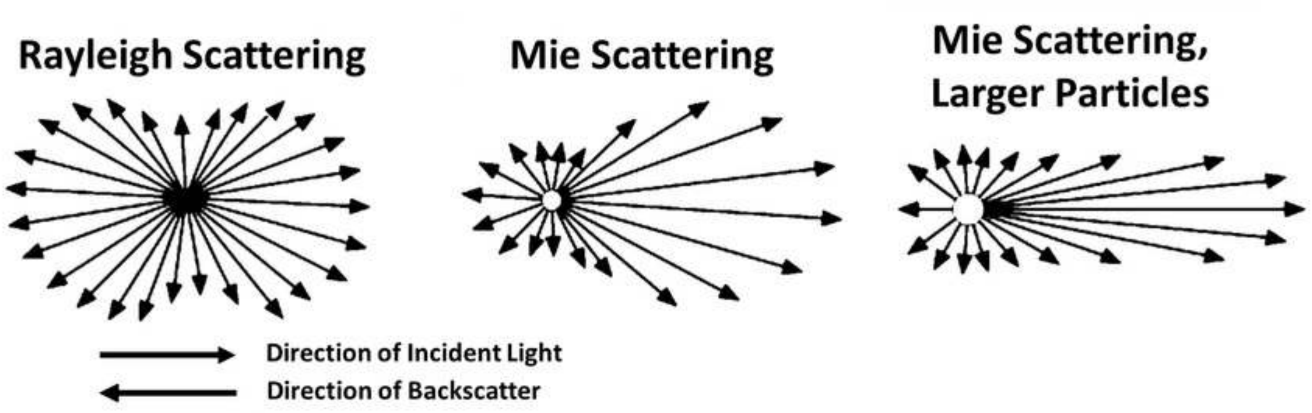
Modeling the optical properties of deep-sea water

Absorption process (λ_{abs})

kill the photons, spacing design

Scattering process (λ_{sca})

photon direction, angular resolution



Rayleigh scattering (λ_{Ray}):

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

Attenuation length:

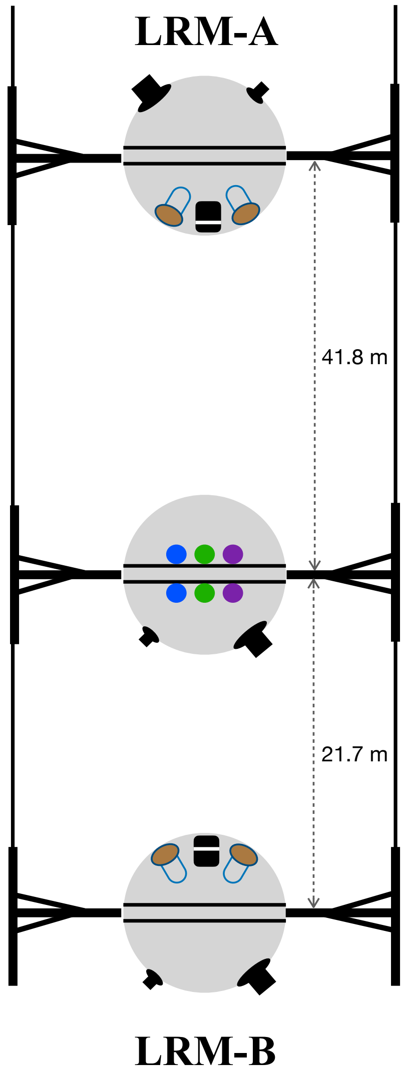
$$I(L) = I_0 \cdot e^{-\left(\frac{L}{\lambda_{abs}}+\frac{L}{\lambda_{sca}}\right)} = I_0 \cdot e^{-\frac{L}{\lambda_{att}}}$$

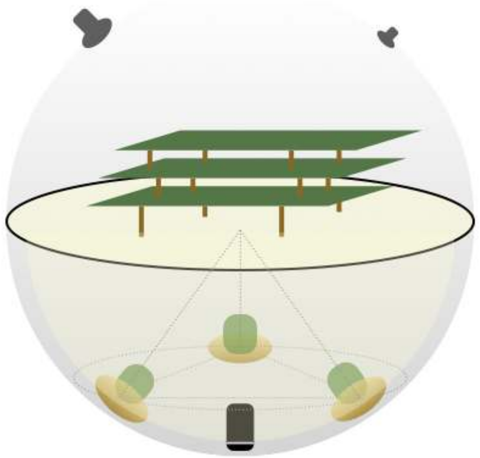
Mie scattering (λ_{Mie}, $\langle cos\theta_{Mie}\rangle$):

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

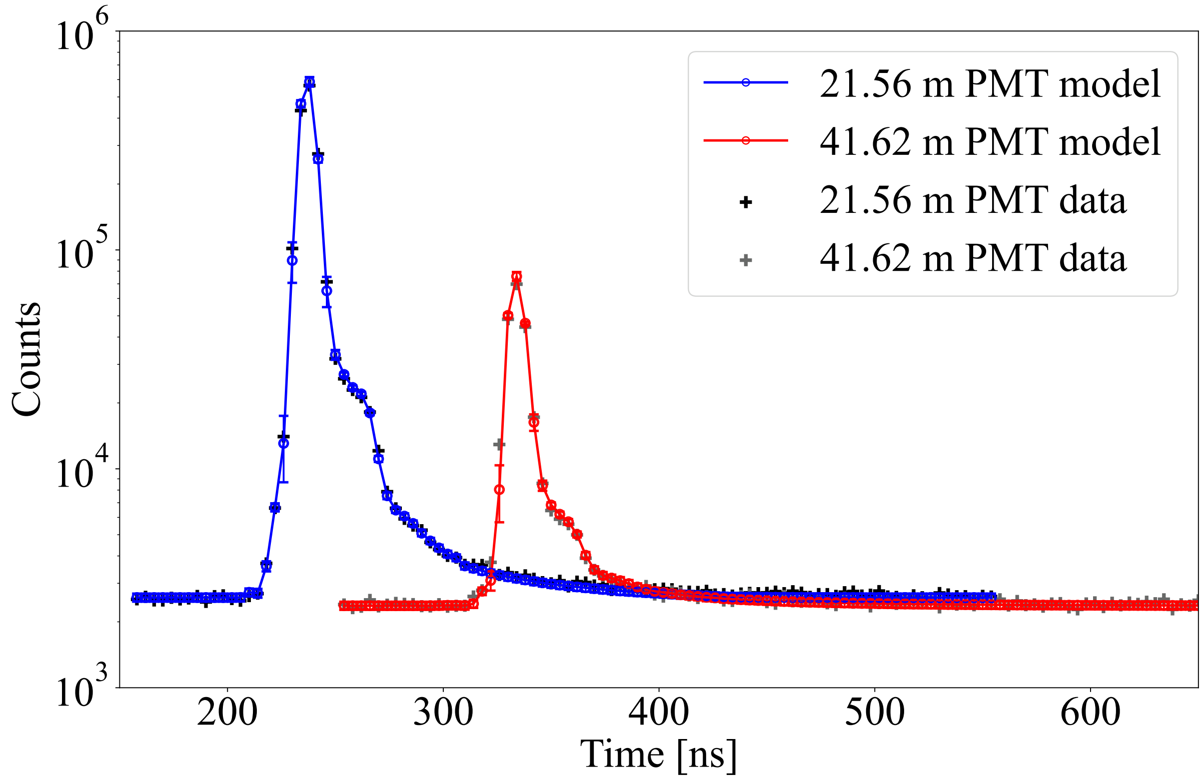
F. Hu *et. al., Simulation study on the optical processes at deep-sea neutrino telescope sites,* NIMA 1054 (2023) 168367

T-REX PMT system





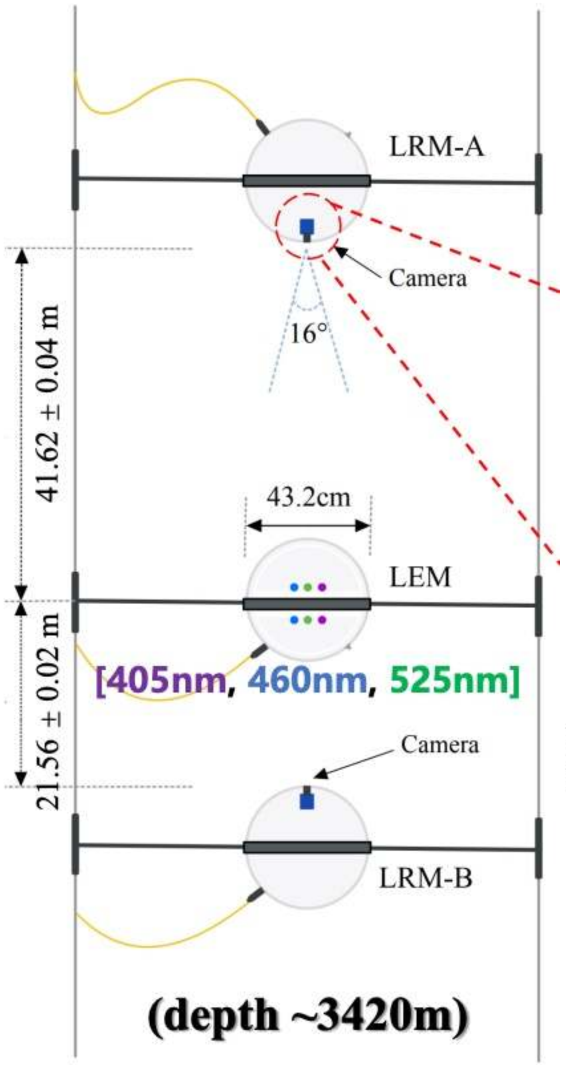
Use relative measurement method to mitigate hidden systematics



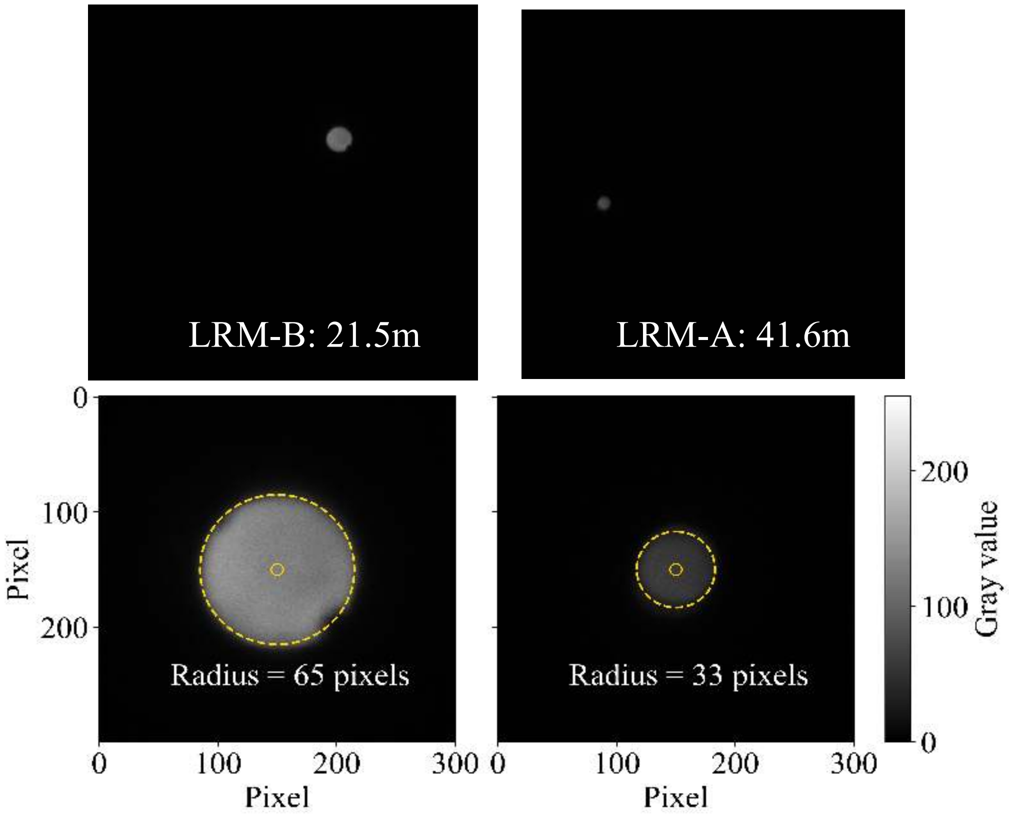
Electronics: J. N. Tang *et. al.*, Journal of Instrumentation, vol.18 T08001 (2023)
M. X. Wang *et. al.*, IEEE Transactions on Nuclear Science, vol. 70, 2240–2247 (2023)

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

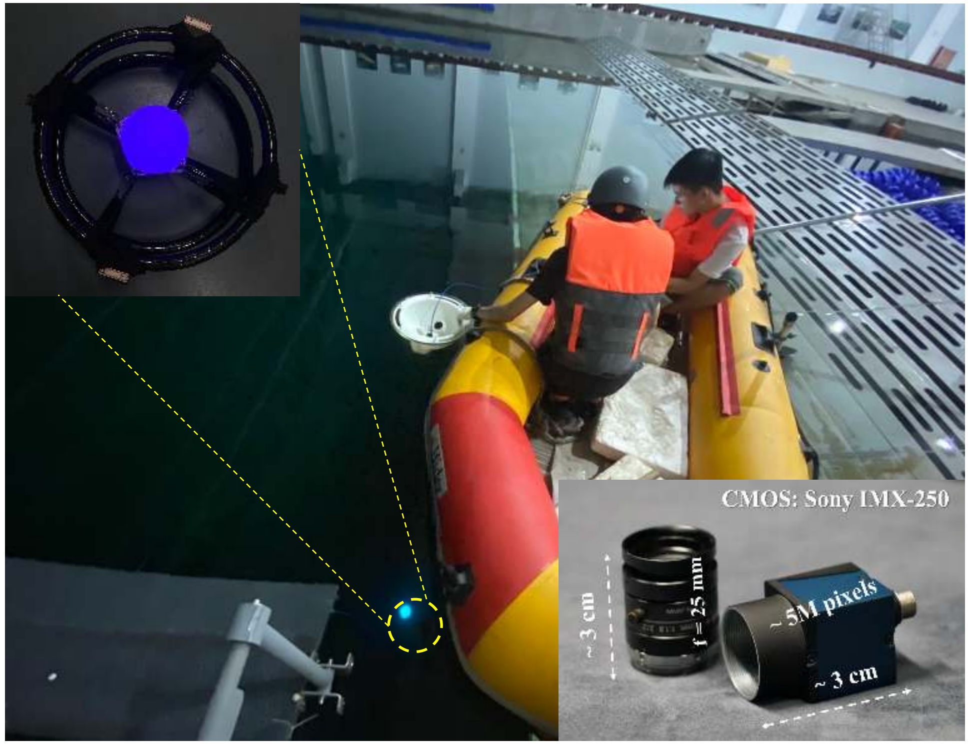
T-REX Camera system



Images captured at depth of 3420m

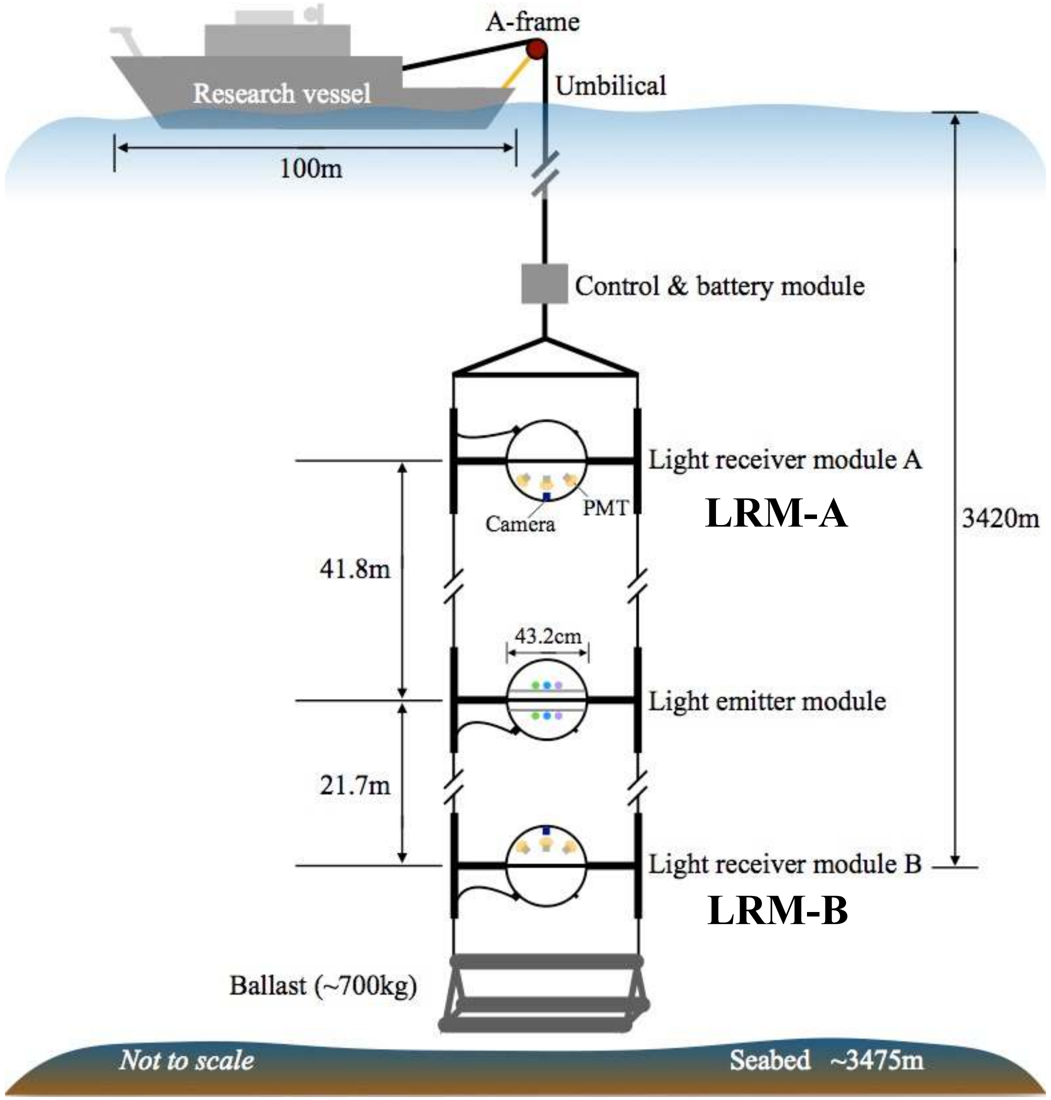


Camera-calibrating in a ship towing tank

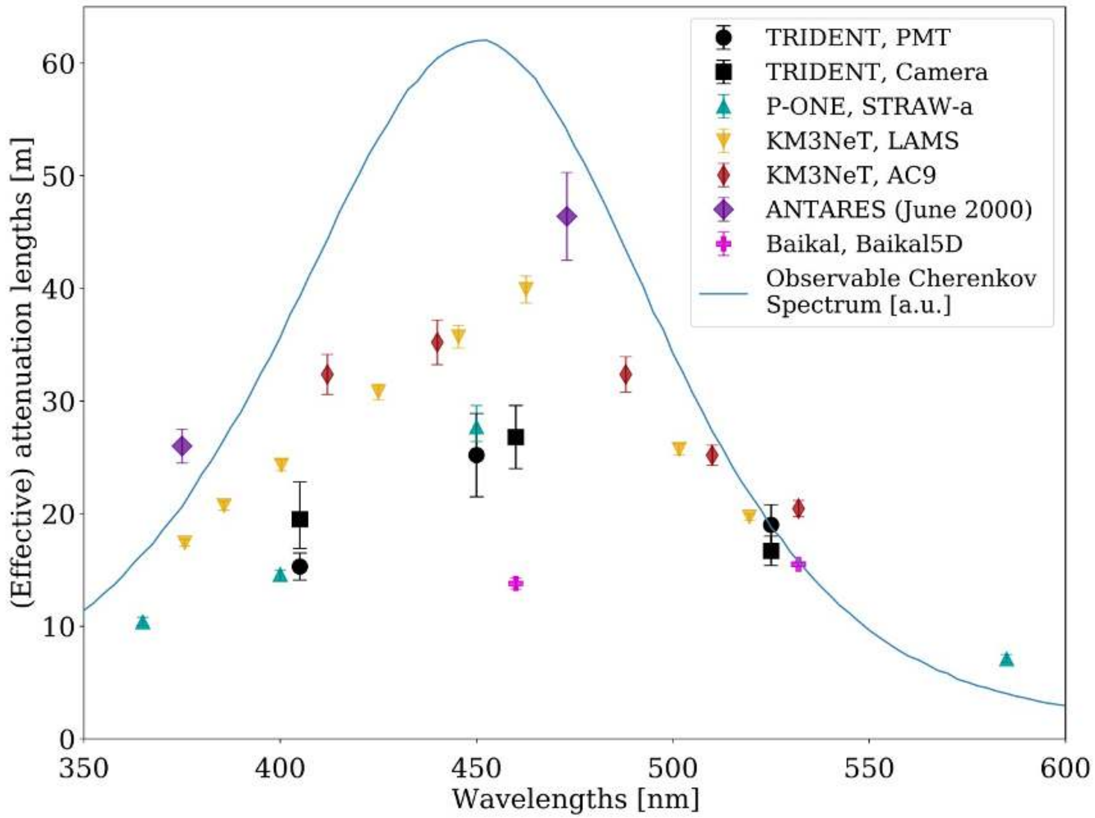


W. Tian *et. al., A camera system for real-time optical calibration of water-based neutrino telescopes arXiv 2407.19111 (submitted to NIMA)*

TRIDENT Explorer : Optical Properties



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

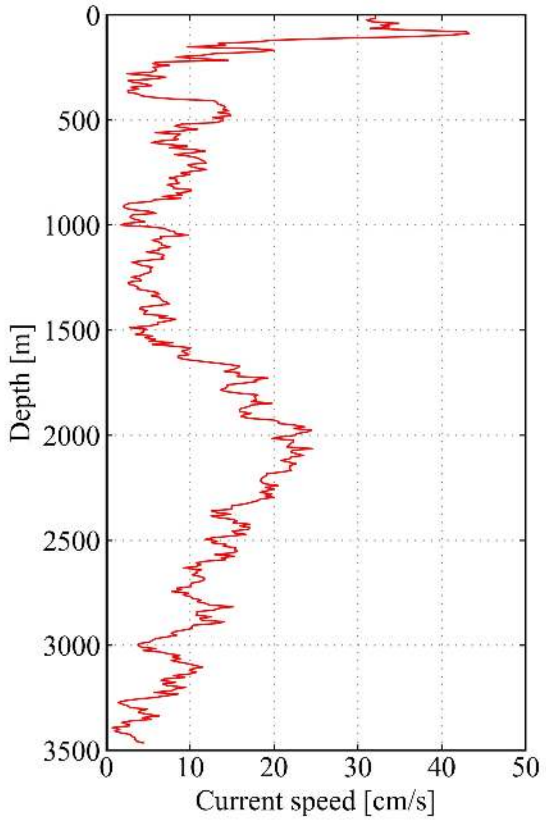


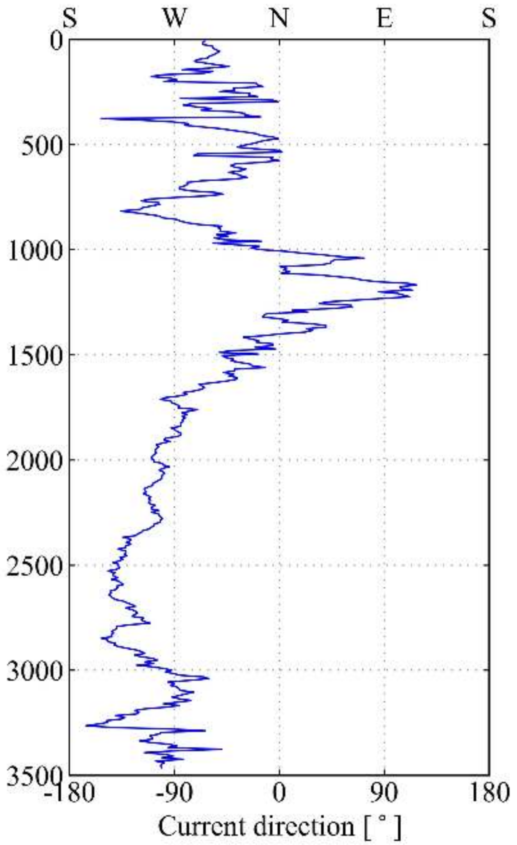
Nature Astronomy 7, 1497-1505 (2023)

TRIDENT Explorer : Current Field

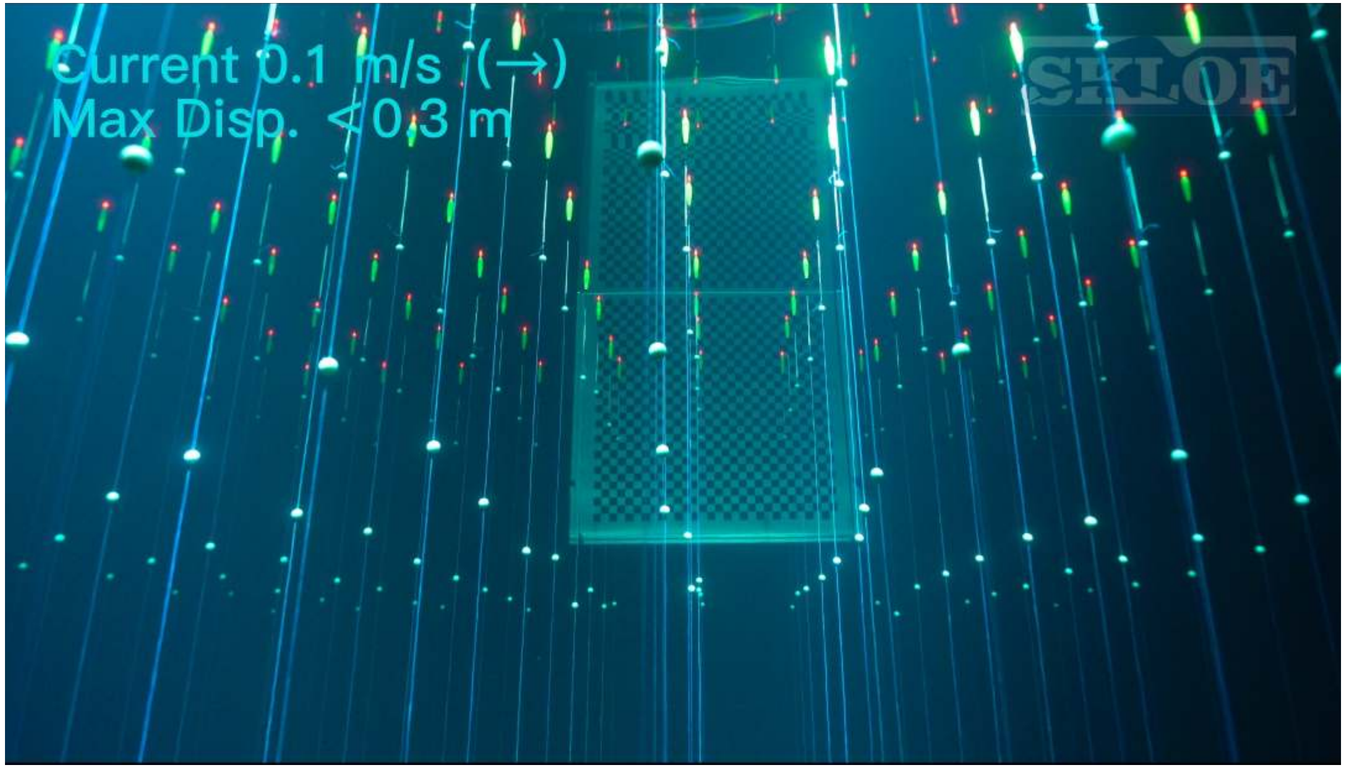
Site current field measured on Sep. 6, 2021

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



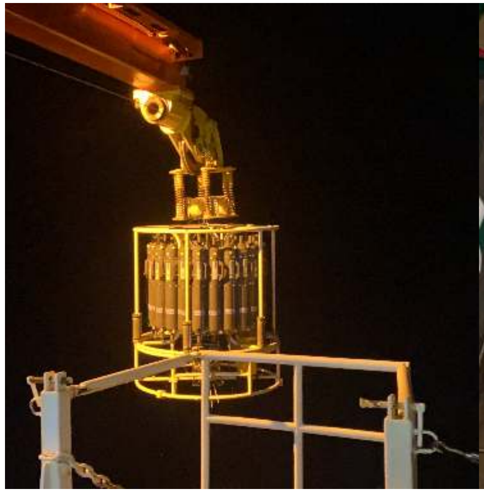


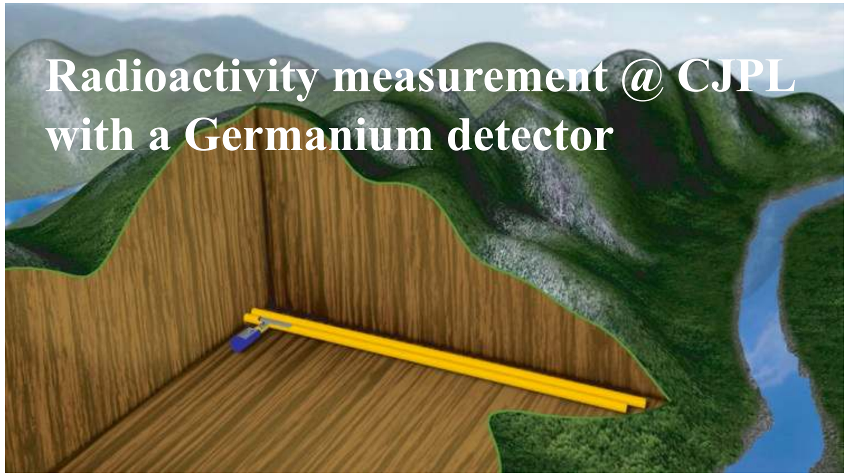
Scaled-down (1:25) experiments in a ship towing tank on SJTU campus



[Animation link]

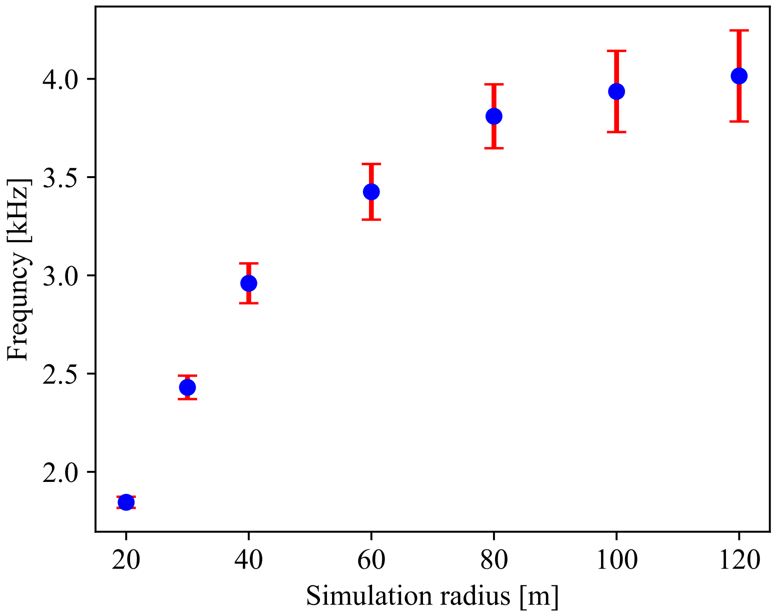
TRIDENT Explorer : Radioactivity



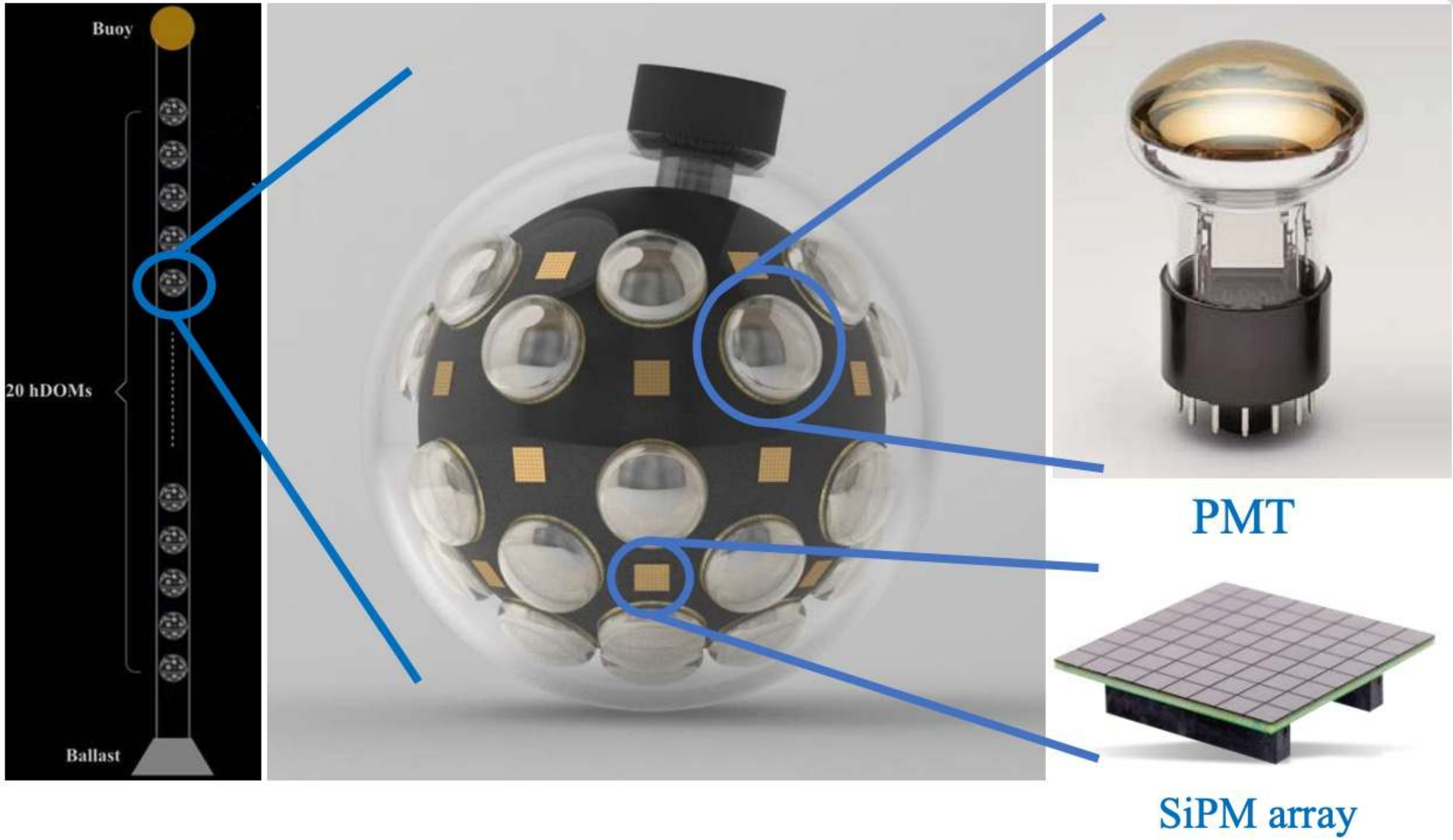


	West Pacific	Mediterranean	East Pacific
^{40}K Radioactivity [$\mathbf{Bq/m^3}$]	**11101 ± 119**	13700 ± 200	12526 ± 752
Experiments	**TRIDENT**	**ANTARES**	**P-ONE**

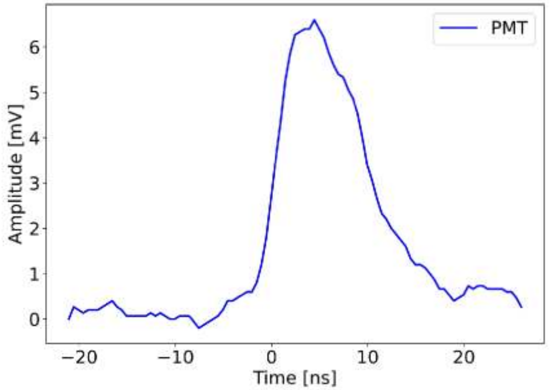
Simulated hit on each PMT caused by ^{40}K



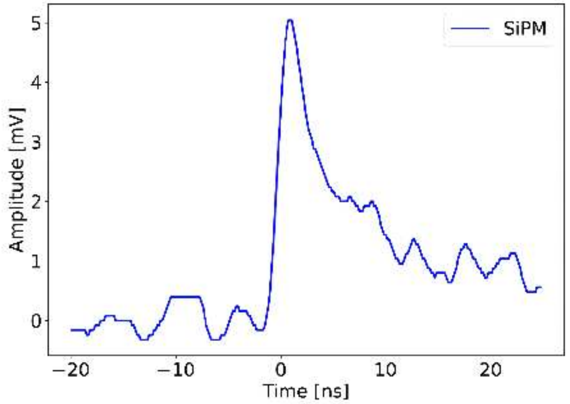
TRIDENT hybrid DOM – hDOM



TTS: < 2ns



Array time jitter: < 300ps

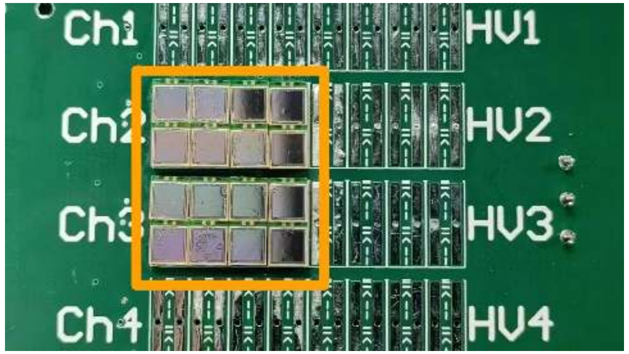


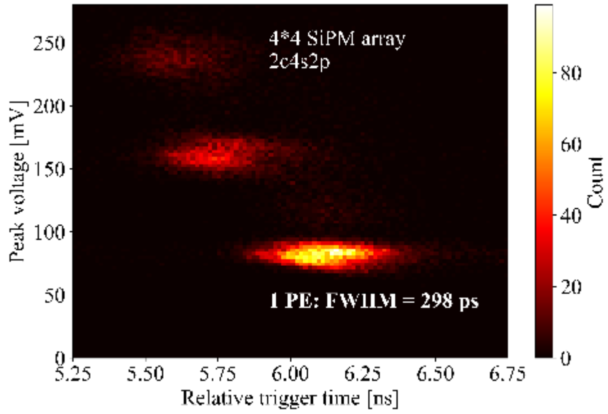
- Maximize photo-sensitive area & improve timing with SiPMs
- Event-by-event tau neutrino identification with PMT waveform readouts

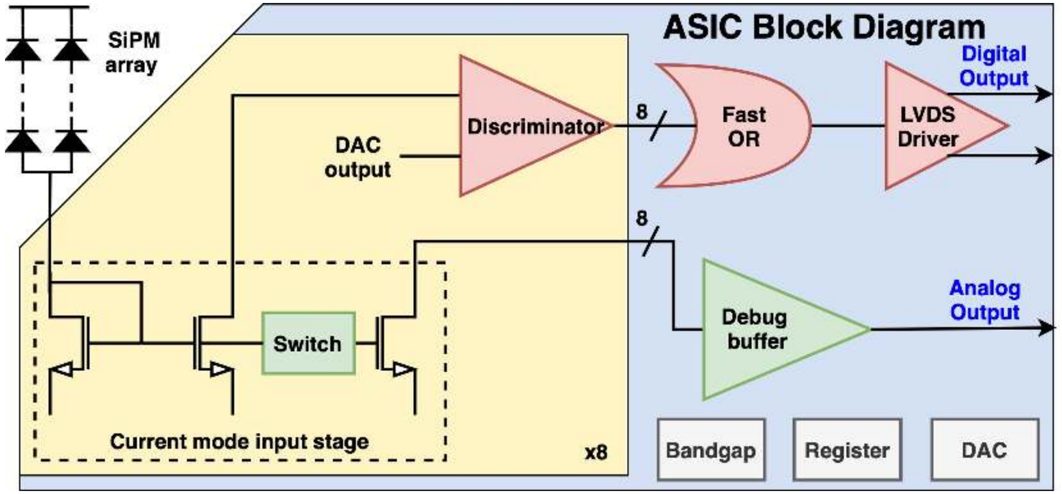
→ **Track better than 0.1°** @ E_ν > 100 TeV

hDOM development status

SiPM array forming & readout electronics







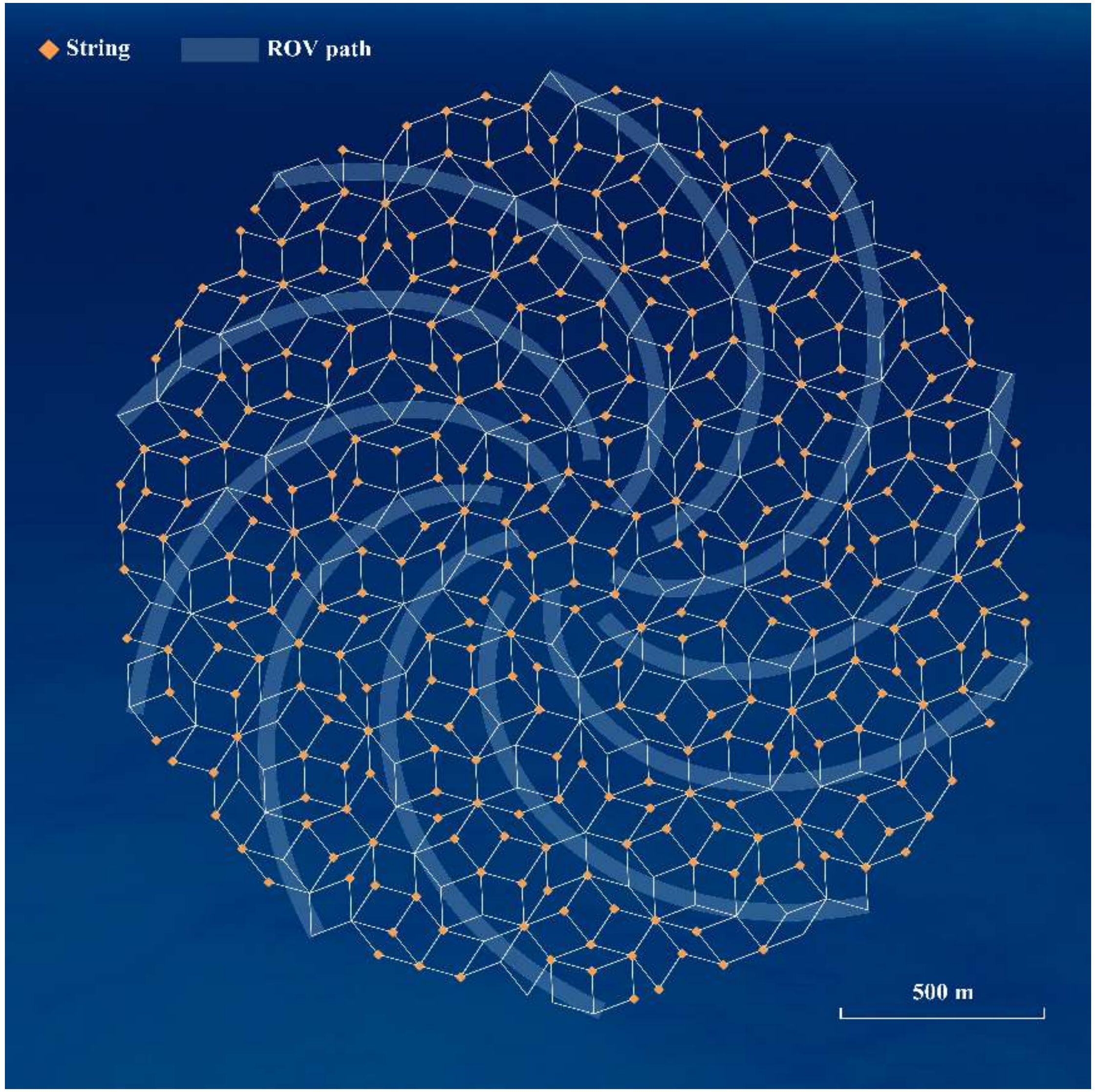
W. Zhi *et al* 2024 *JINST* **19** P06011

Mechanical structure of hDOM

Development progress: PoS (ICRC2023) 1213

Conceptual design: PoS (ICRC2021) 1043

TRIDENT detector geometry



Penrose tiling layout

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

→ expanded energy window of **sub TeV – EeV**

No translational or rotational **symmetry**

→ better rejection of "corridor" atmo. muons

1200 strings; **20** hDOMs / string

Volume: ~ **8** km^3

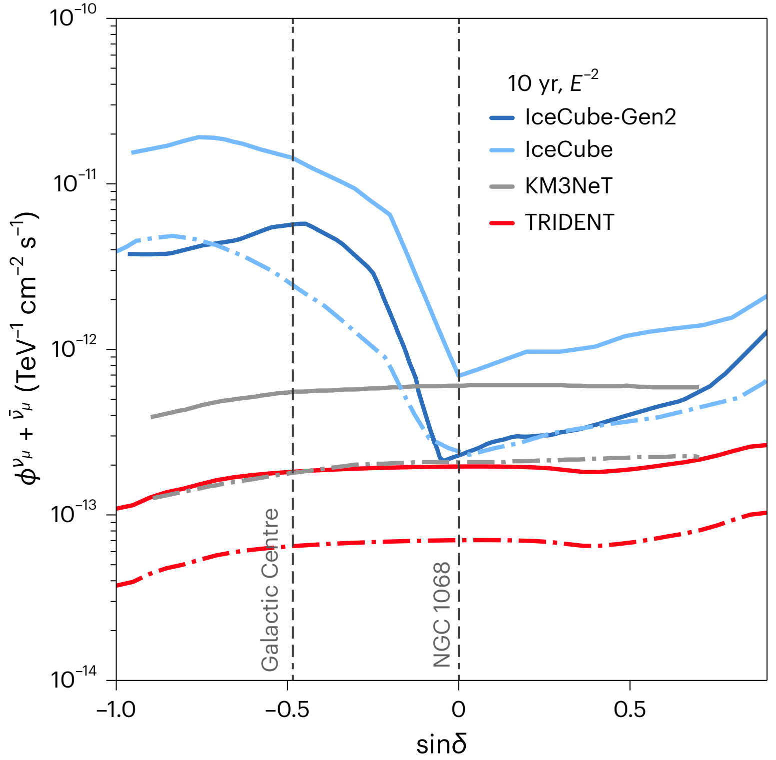
Underwater ROV for deployment & maintenance

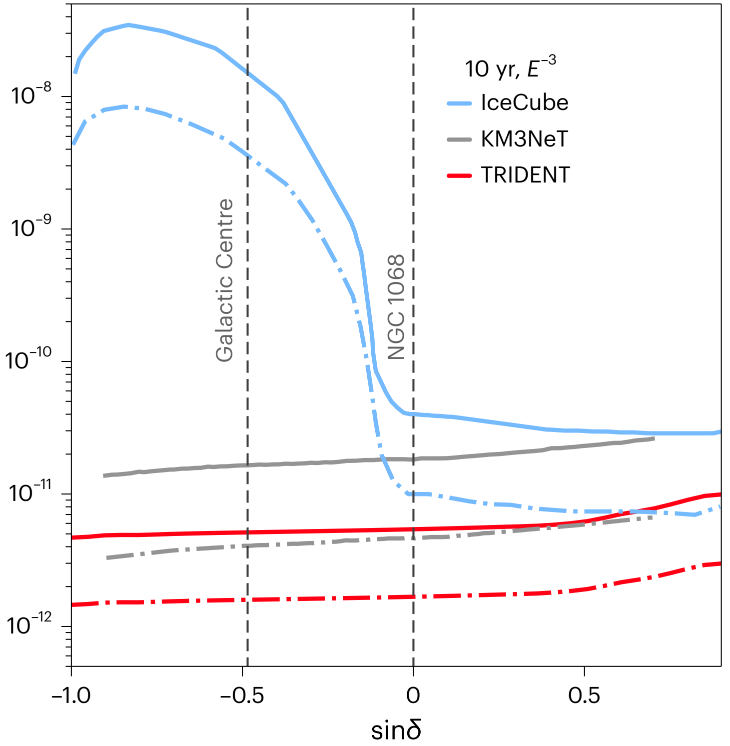
Nature Astronomy 7, 1497-1505 (2023)

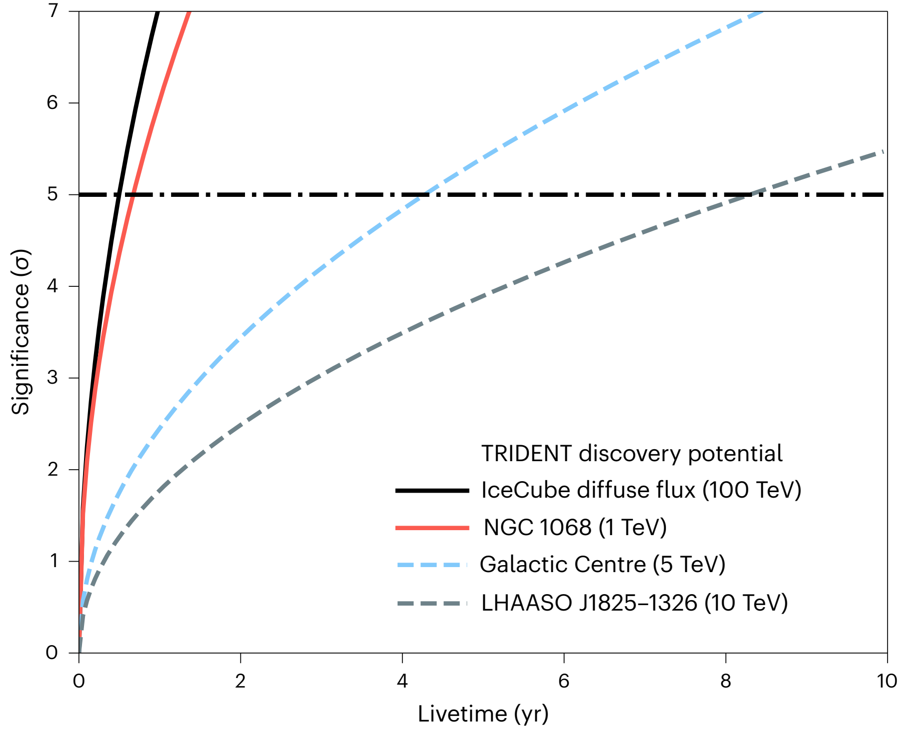
Geometry comparison: PoS (ICRC2023) 1203

TRIDENT Source sensitivity & discovery potentials

Track events only







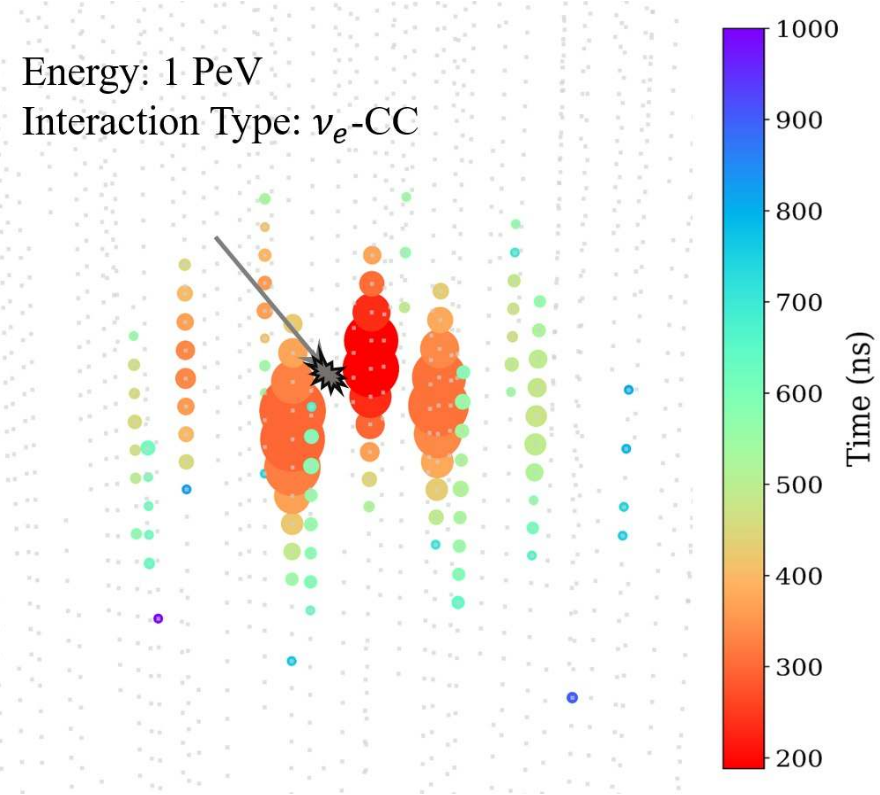
TRIDENT is expected to detect the IceCube steady source candidate **NGC1068 at 5σ level within one year** of operation

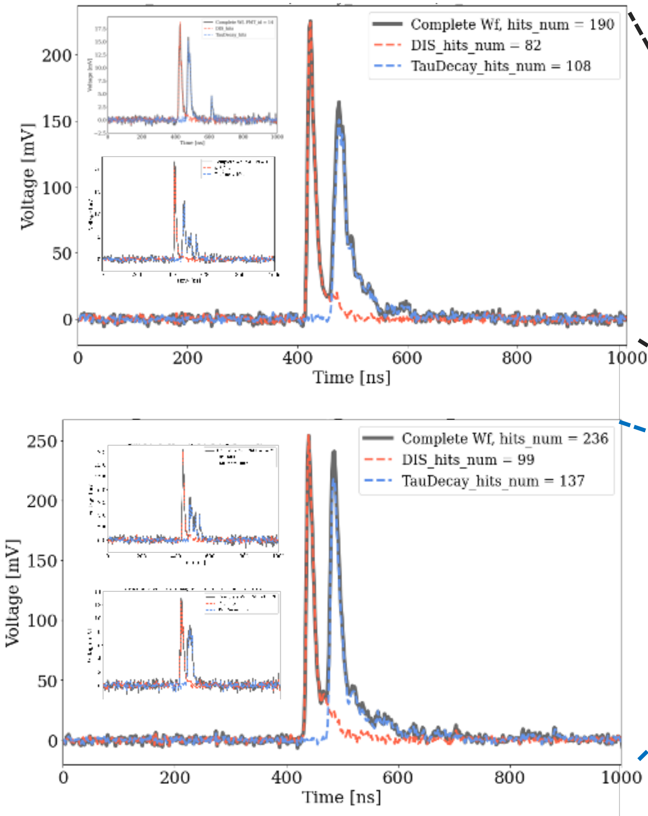
Nature Astronomy 7, 1497-1505 (2023)

TRIDENT Sensitivity to all neutrino flavors

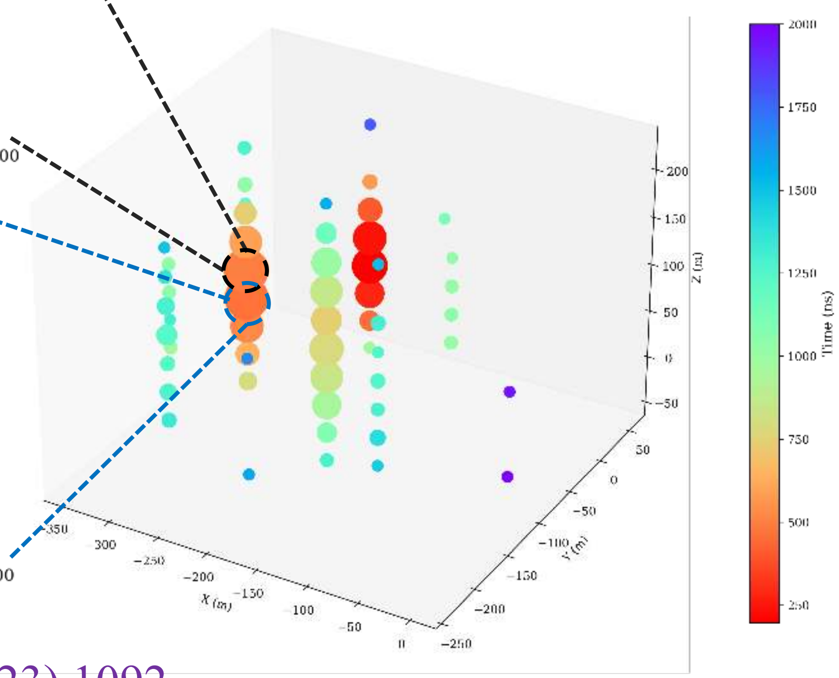
Angular resolution for cascades:
- **~1.8° @ 1PeV** (likelihood)
- **~ 1.5° @ 100 TeV & 1 PeV** (GNN)

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





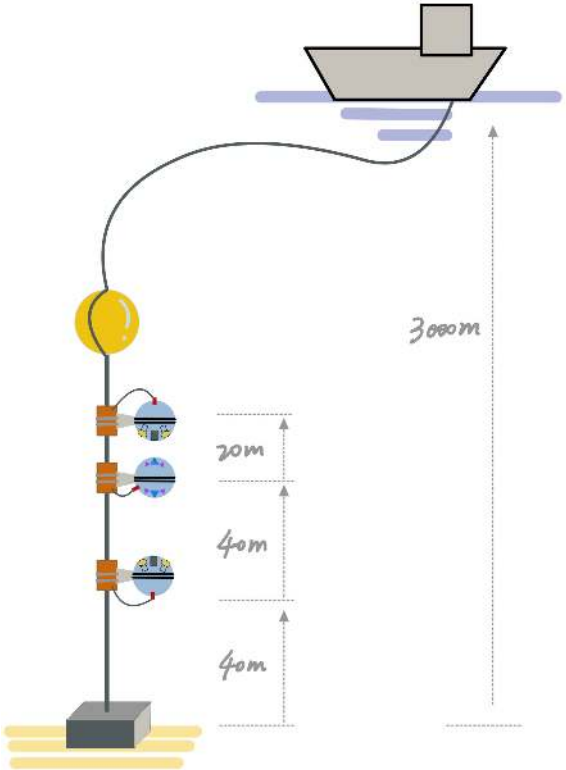
$E\nu_\tau$ = 334.3 TeV

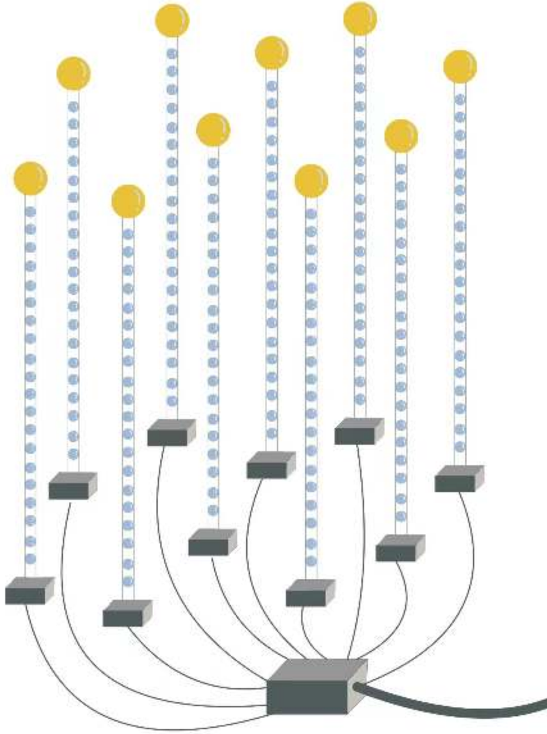


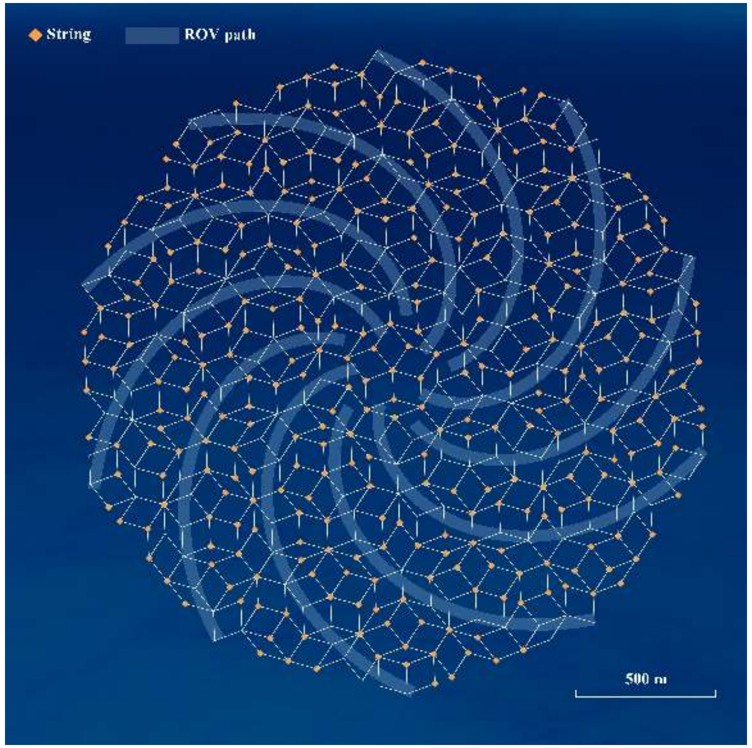
Cascade reco : PoS (ICRC2023) 1207

Tau neutrinos : PoS (ICRC2023) 1092

Brief timeline of TRIDENT







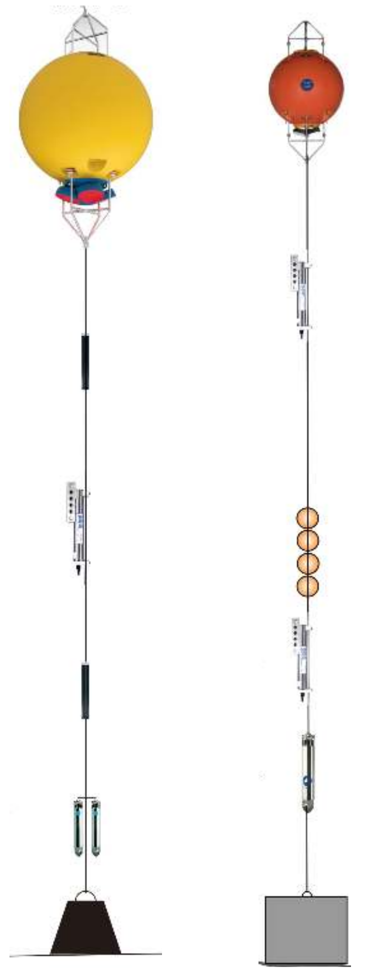
Pathfinder: 2019-2022
completed

Phase-I project: 2022-2026
in progress

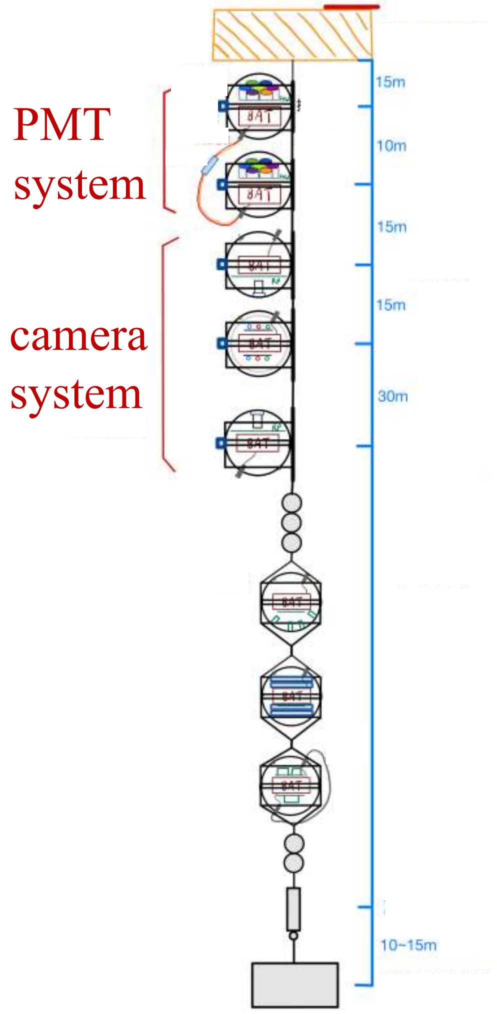
Big array construction: 2026-
under planning

Sea trial experiments scheduled

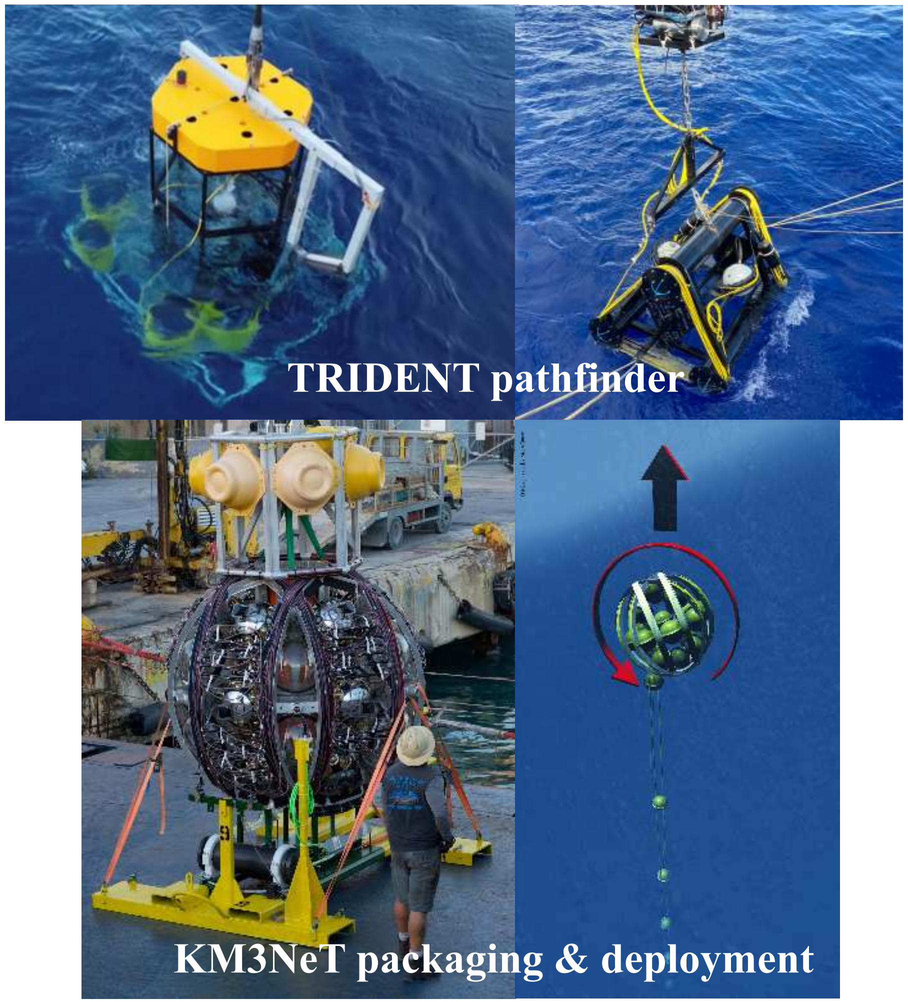
1) Environmental monitoring moorings



2) Prototype telescope strings



3) Deployment device & strategies



Summary

- IceCube has opened a new era for high-energy neutrino astronomy
- **More telescopes with improved detection ability are needed** to catch PLENTY of neutrinos for further scrutiny
- **New**: a viable site was found at a depth of 3.5km in South China Sea for constructing large-scale deep-sea neutrino telescopes
- A multi-cubic-kilometer next-gen deep-sea neutrino telescope (TRIDENT) has been proposed to rapidly push beyond IceCube’s horizons, to exploit the discovery opportunities in the nascent field of **ν** astronomy

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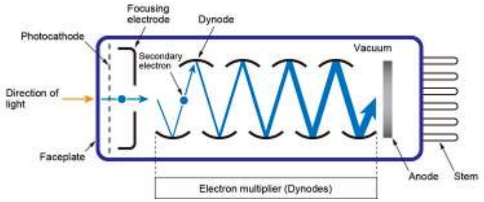
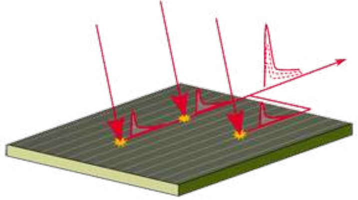
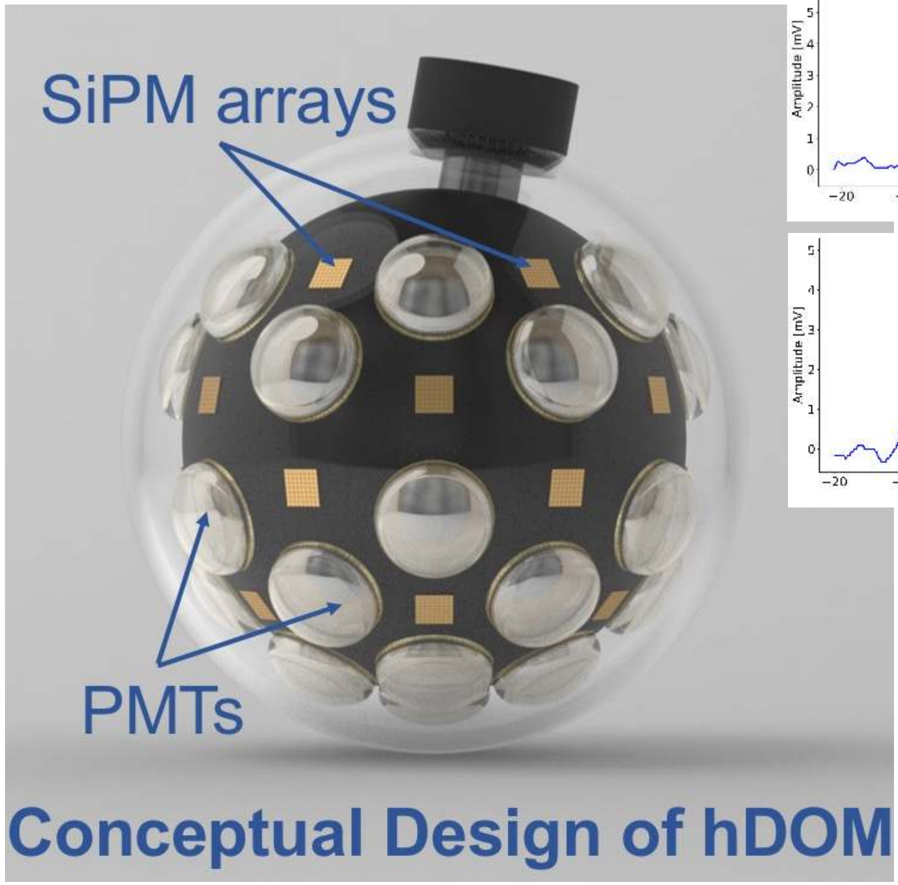
TRIDENT 海 | 铃 | 计 | 划

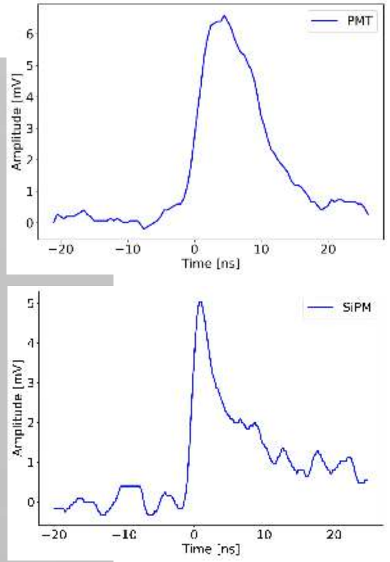
Thank you & welcome to join us !

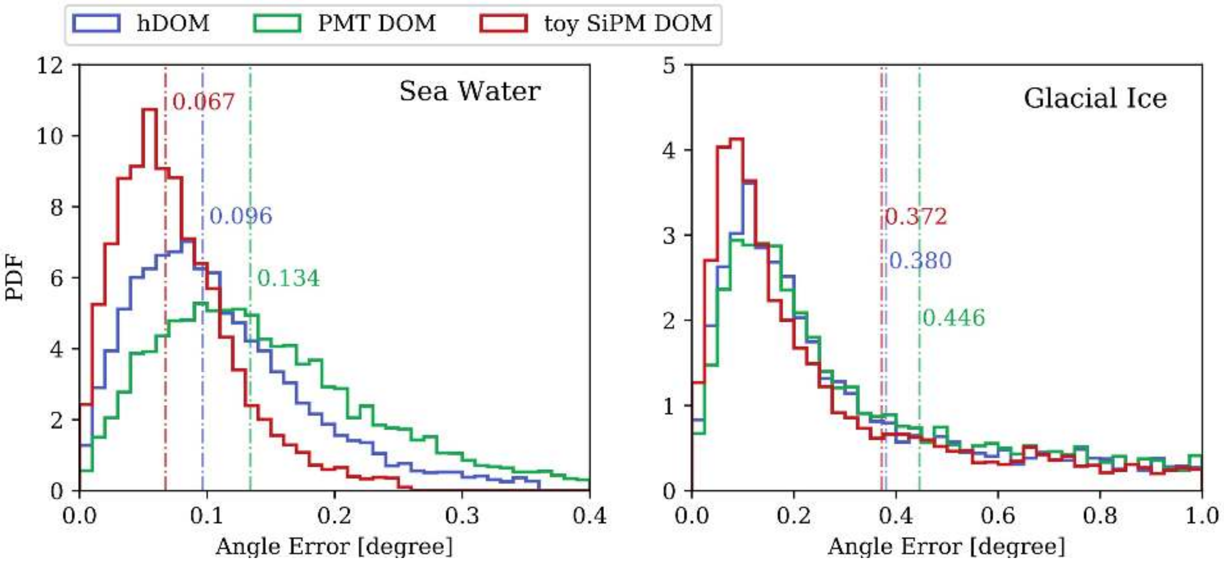
TRIDENT hybrid DOM – hDOM











- 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