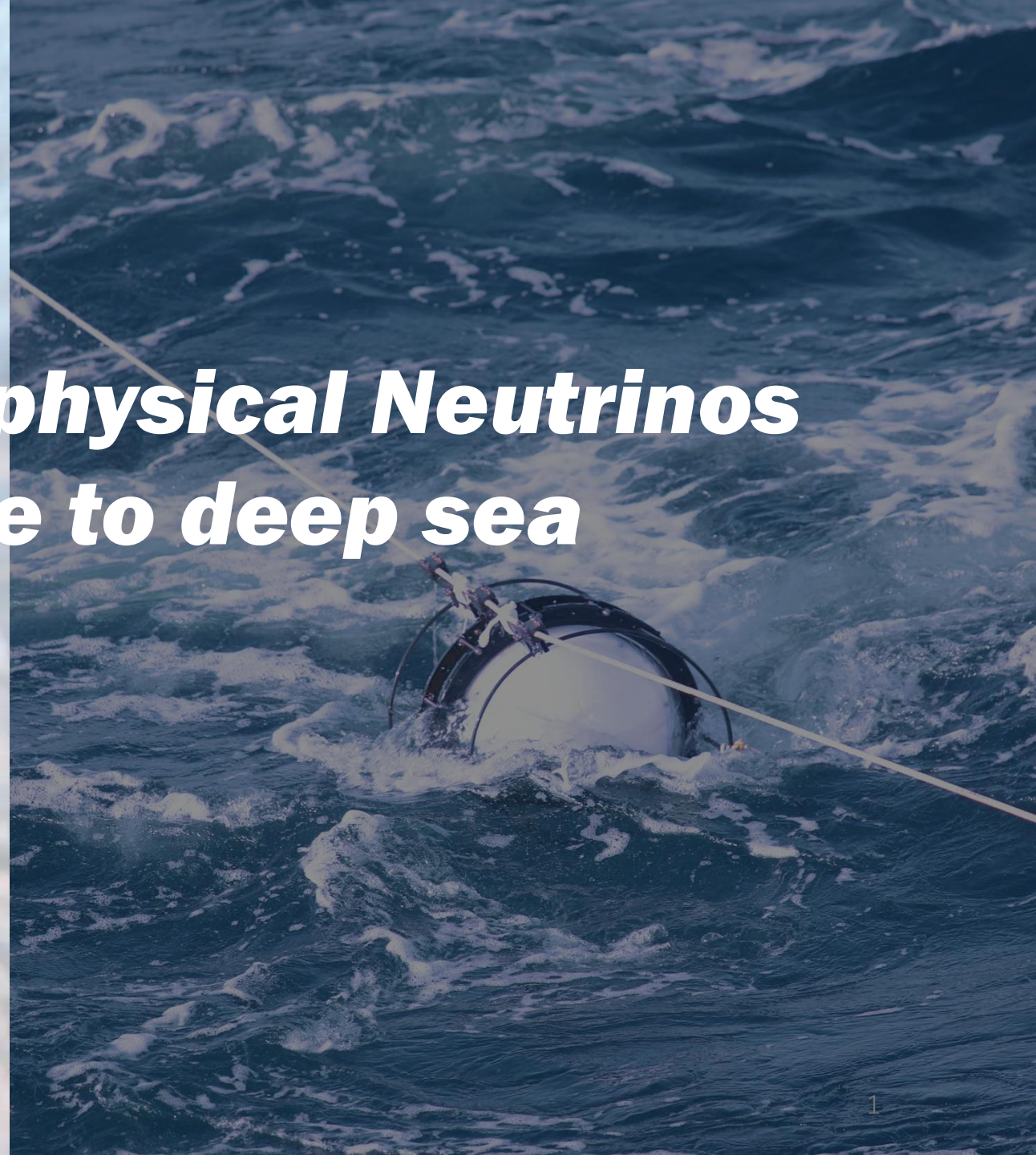


Chasing for Astrophysical Neutrinos from deep ice to deep sea

Wei Tian

IceCube Summer School

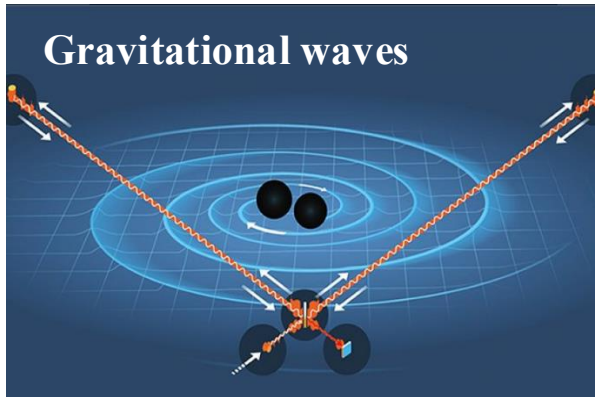
Jun 5th 2026 @WIPAC, UW-Madison



- 1. Multi-messenger astronomy and astrophysical neutrinos**
- 2. Global Cherenkov neutrino telescopes**
- 3. Development/Comparison of ice-based & water-based neutrino telescopes**
(1) Detector design (2) Calibration challenge
- 4. Summary**

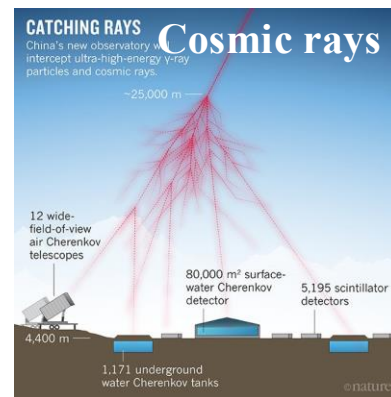
Astrophysical messengers in dark universe

❖ Multi-messenger Astronomy Era



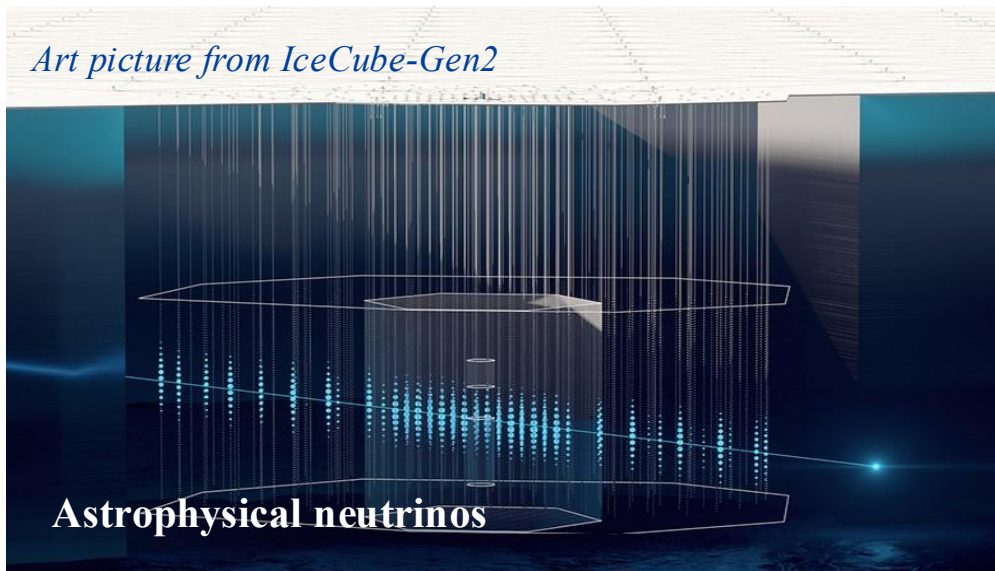
Gravitational waves

Art picture from LIGO



CATCHING RAYS Cosmic rays

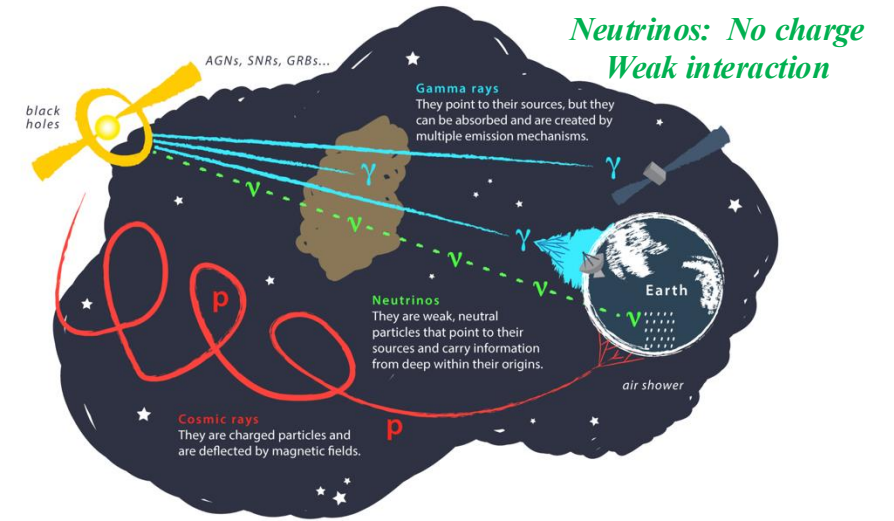
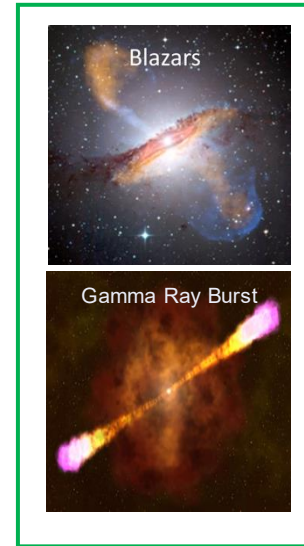
Art picture from LHAASO



Art picture from IceCube-Gen2

Astrophysical neutrinos

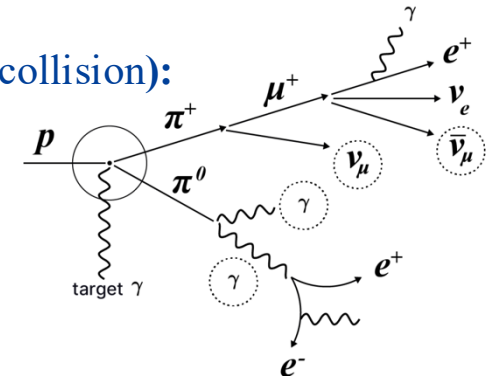
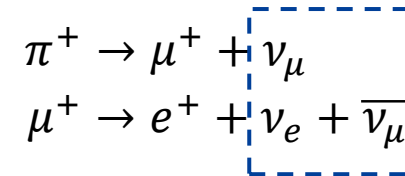
❖ Neutrino as an astrophysical messenger:



Art picture by Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

❖ Exploring the origin of cosmic rays

Hadronic processes ($p\gamma$ or pp collision):



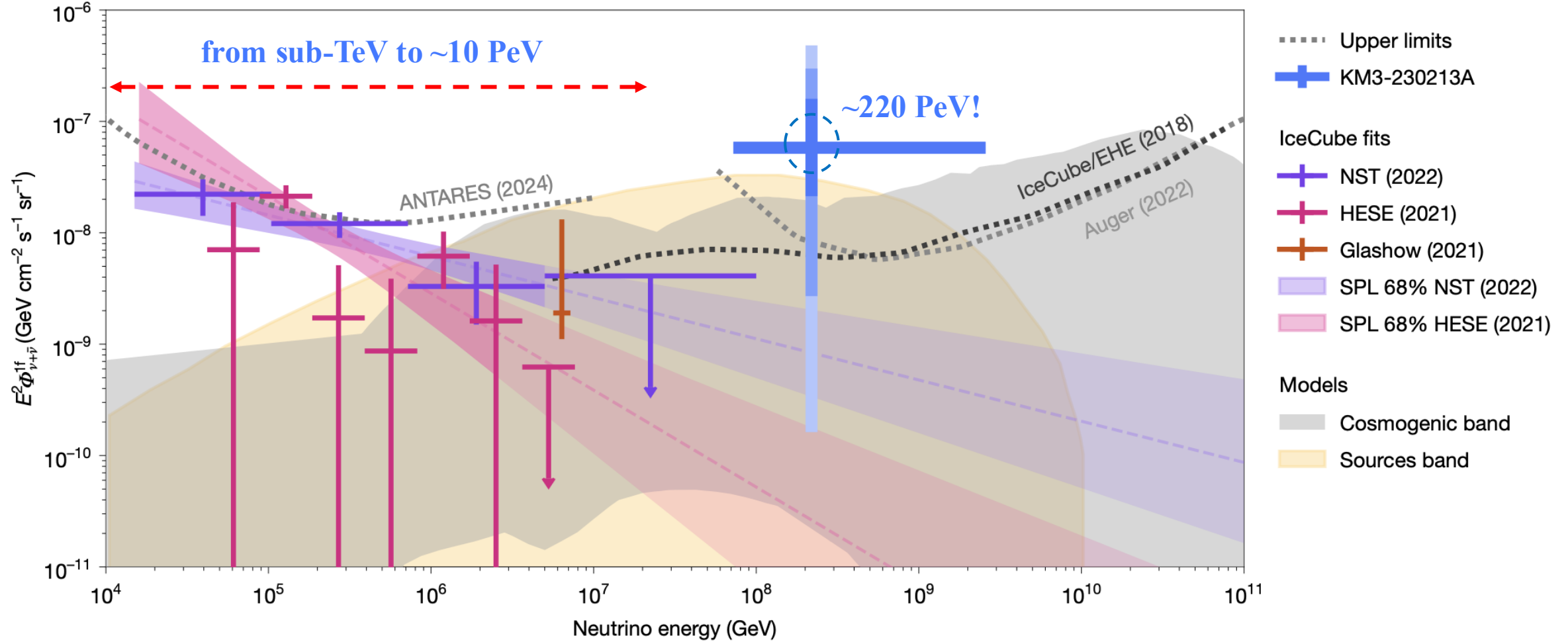
Observation of astrophysical neutrino flux

❖ Discovery of astrophysical neutrinos (2013)

IceCube: Phys.Rev.Lett. 113 (2014) 101101

❖ Most energetic neutrino ever observed (2023)

KM3NeT: Nature 638 (2025) 8050, 376-382

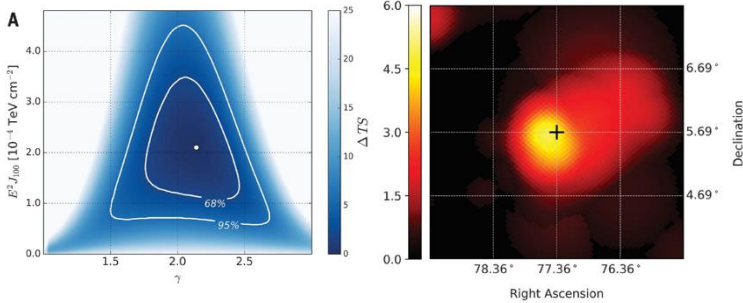
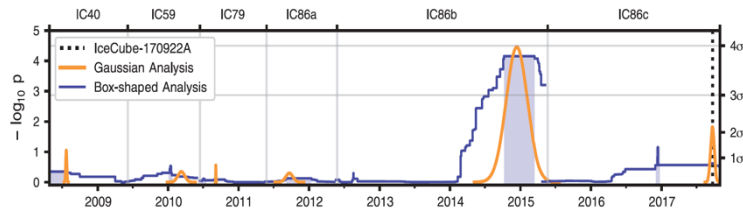


Origins of these astrophysical neutrinos ?

NEUTRINO ASTROPHYSICS

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert (2017)

IceCube Collaboration*†
Science 361 (2018) 6398, 147-151



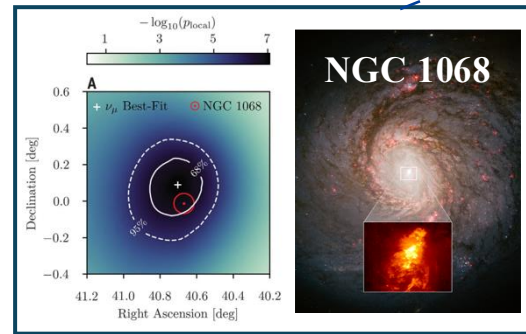
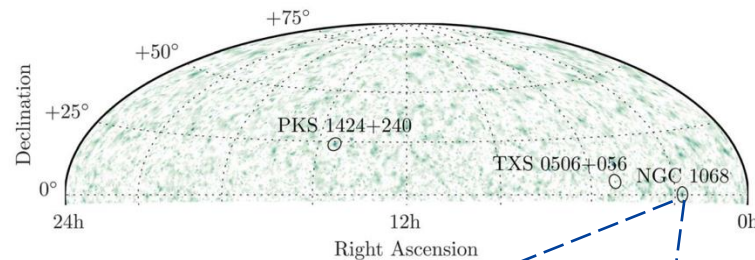
Neutrino energy: ~ 290 TeV

Significance: 3.5σ

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068 (2022)

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



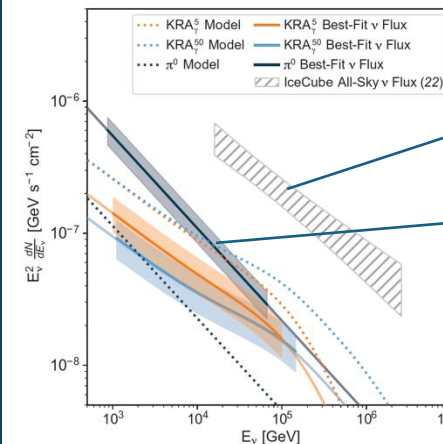
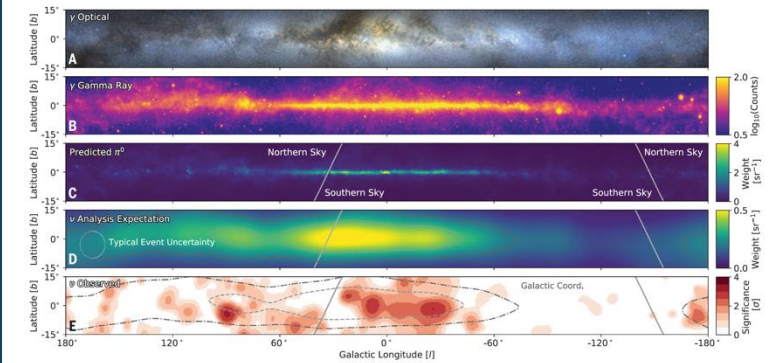
Event excess: 79^{+22}_{-20} (1.5TeV~15TeV)

Significance: 4.2σ

NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane (2023)

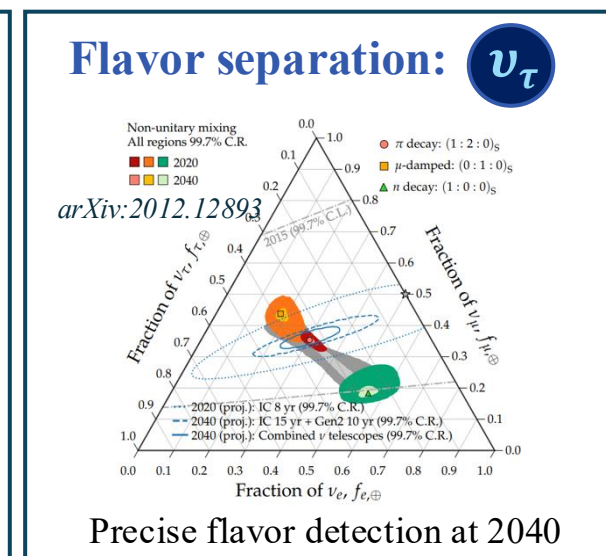
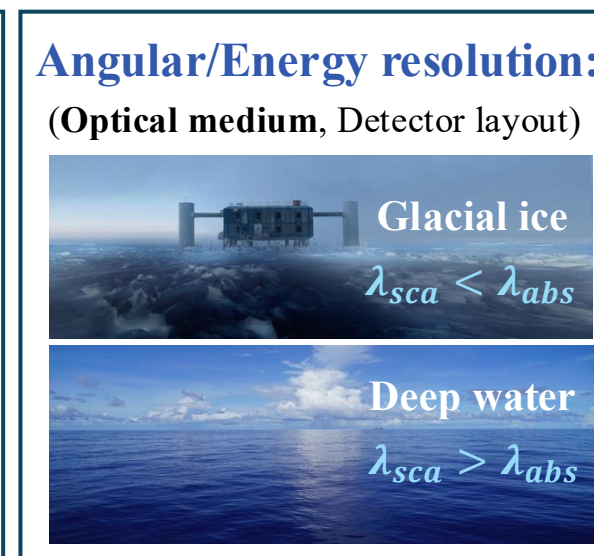
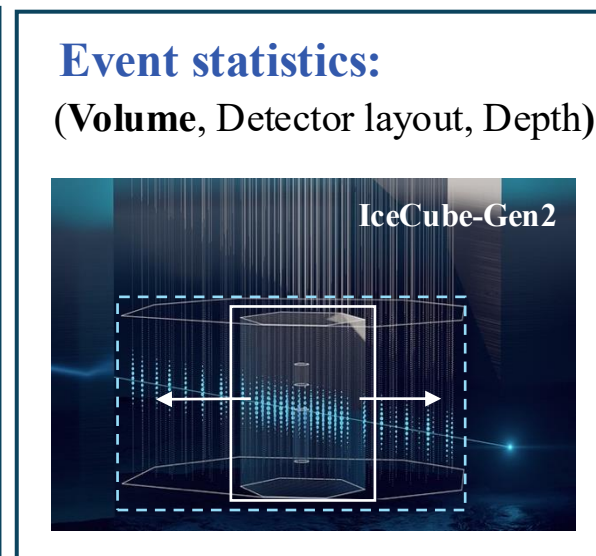
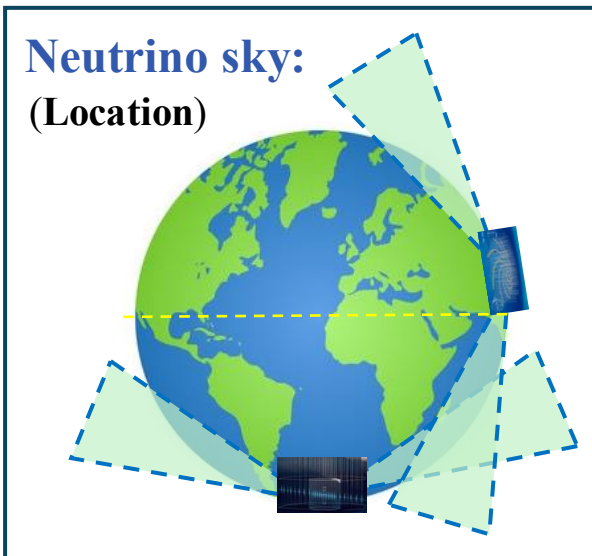
IceCube Collaboration*† *Science* 380, 1338–1343 (2023)



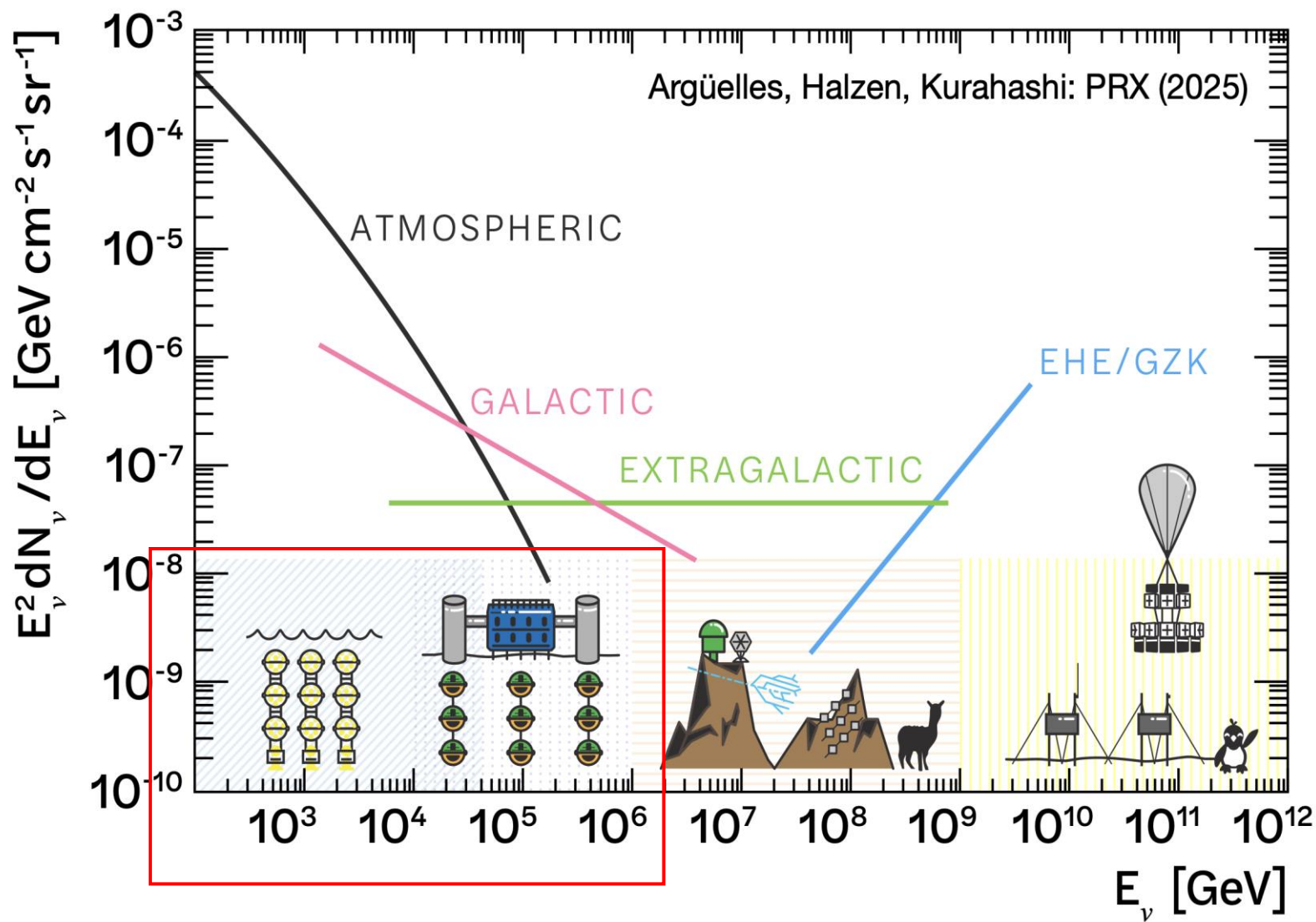
Diffuse flux
 Galactic flux
 ($> \text{TeV}, 4.5\sigma$)

Questions remained

- Other multi-messenger counterparts ?
- More discovered significant neutrino source?
- Neutrino production region and mechanism at the sources?
- Cosmic-ray acceleration?



Neutrino astronomy landscape



Cherenkov Neutrino Telescopes:

$O(\text{sub-TeV}) \sim O(10 \text{ PeV})$

IceCube, KM3NeT, Baikal-GVD, etc.

Tau Earth-skimming Detectors:

$O(\text{PeV}) \sim O(\text{EeV})$

TAMBO, Trinity, etc.

Radio-based Detector Arrays:

$O(100 \text{ PeV}) \sim O(100 \text{ EeV})$

ARA, RNO-G, Grand, etc.

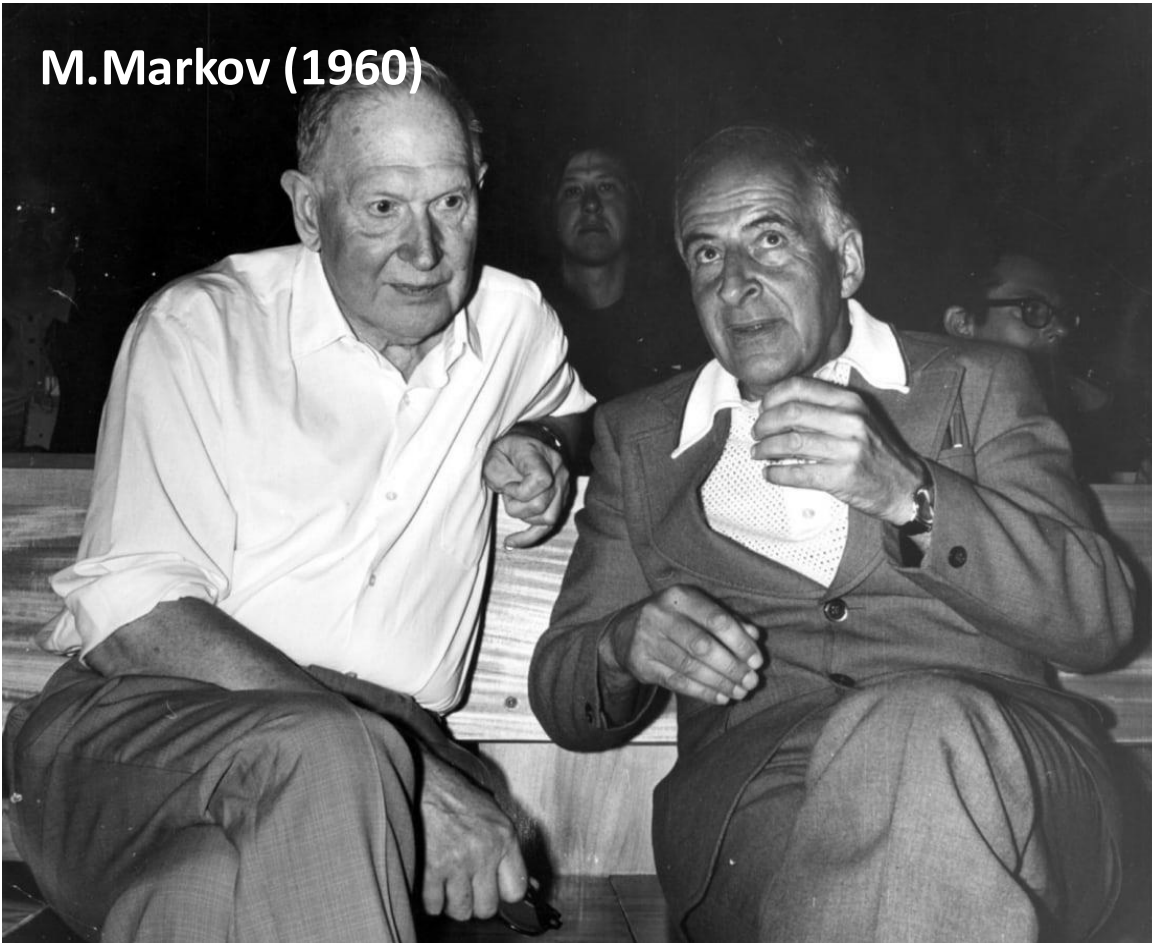
Radio-based Balloon Detectors:

$E > O(10 \text{ EeV})$

ANITA, PUEO, etc.

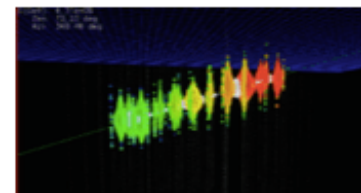
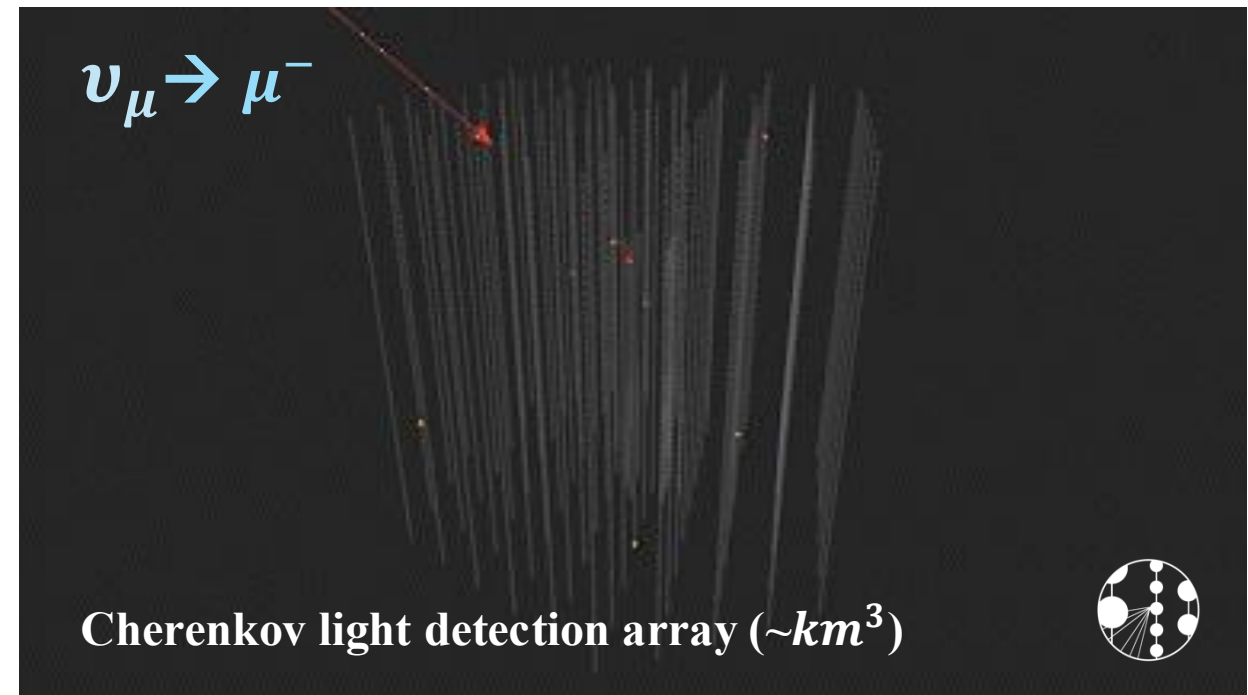
Hunting high-energy neutrinos by a detector array

M.Markov (1960)

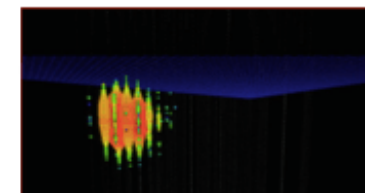


M.Markov: "We propose to install detectors deep in a lake or in the sea and determine the direction of charged particles with the help of Cherenkov radiation."

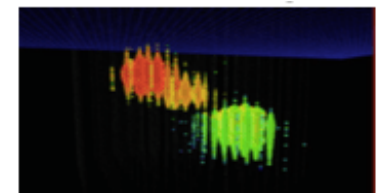
Wei Tian, IceCube Summer School, Jun 5th 2026



Track-like



Single / Double Cascade₈



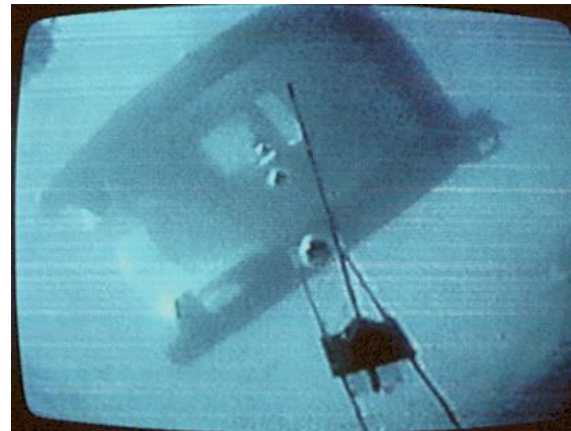
The first step to technical challenge: DUMAND

DUMAND (Deep Underwater Muon and Neutrino Detector)

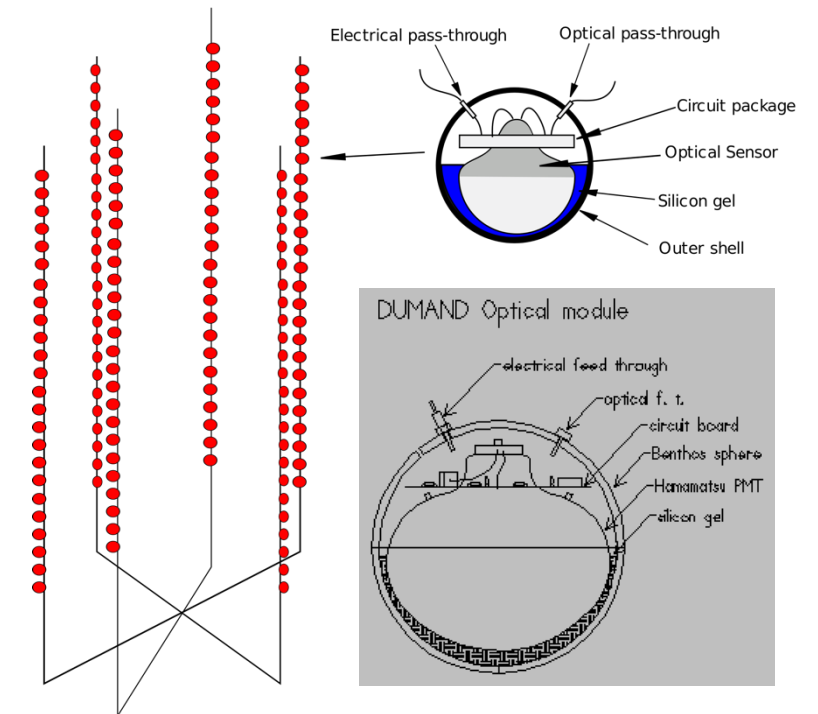
<https://www.phys.hawaii.edu/~dumand> @ Hawaii, 1970s-1990s

Experimental conditions:

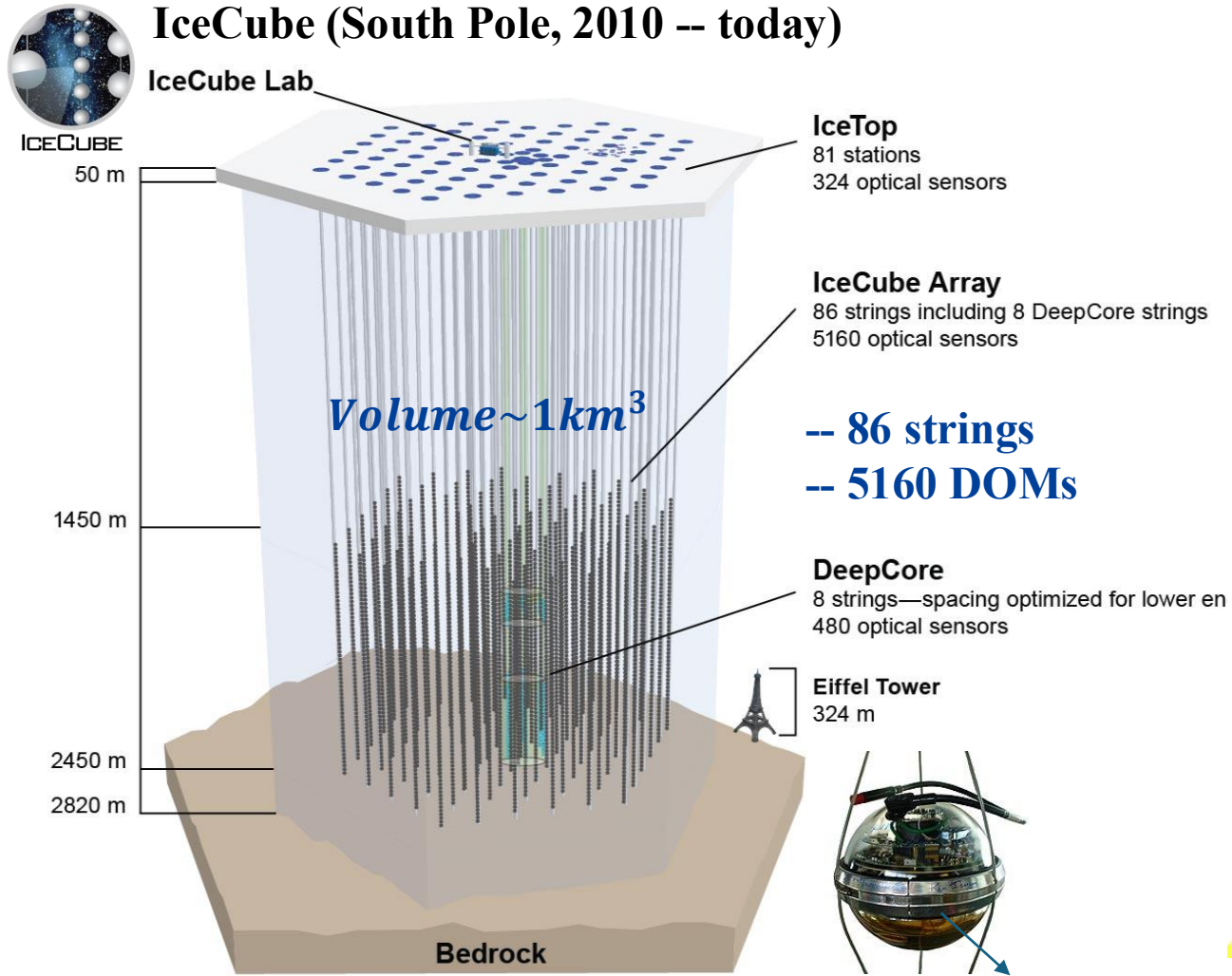
- (1) Transparent medium: target/optics
- (2) Deep: filtering cosmic/atmospheric noise
- (3) Large size: enough statistics
- (4) Long-term operation



Planned to build 9 strings, 216 Optical Modules at a water depth of 4.8 km



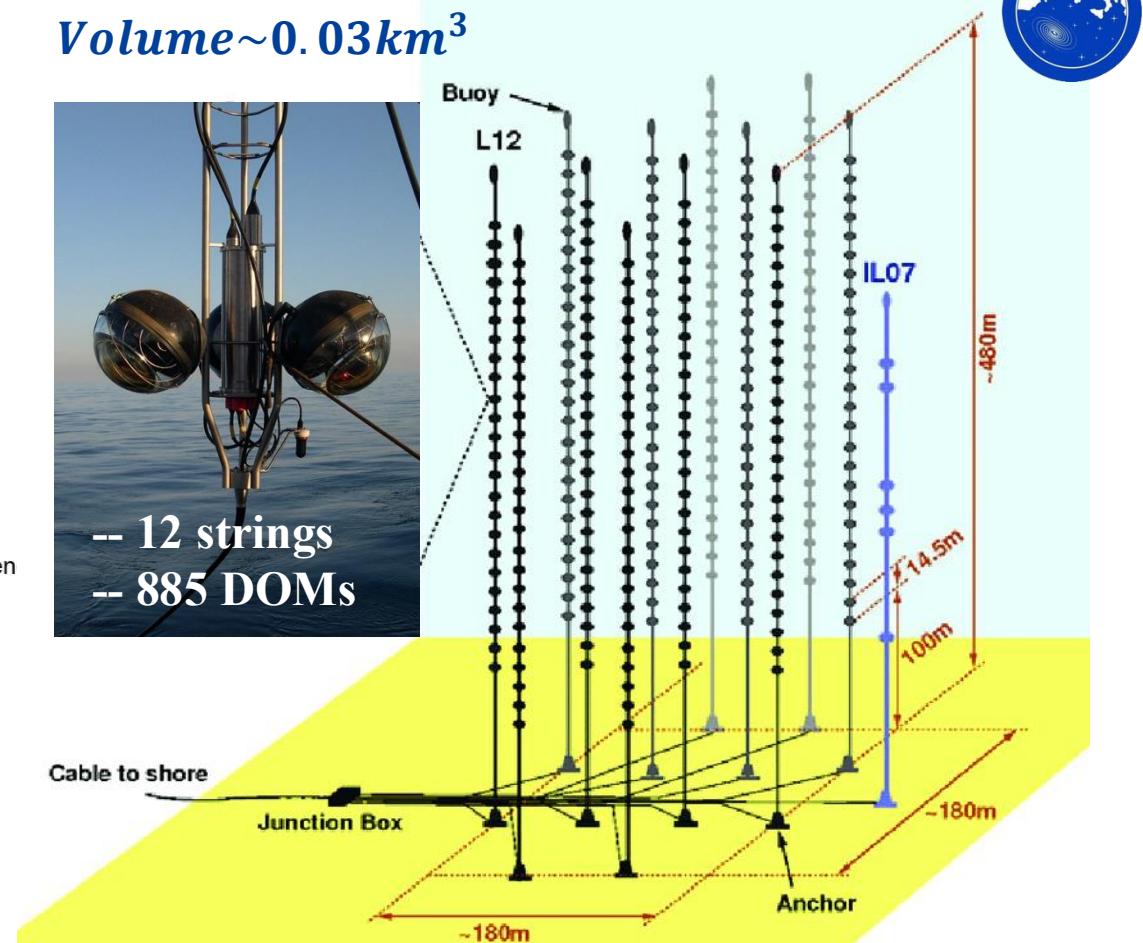
Existing fully constructed neutrino telescopes



Art picture by *IceCube*

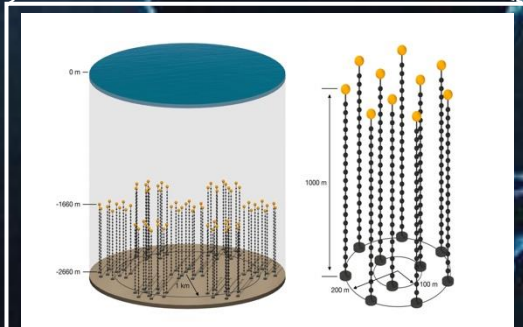
ANTARES (Mediterranean, 2008 -- 2022)

Volume ~0.03km³



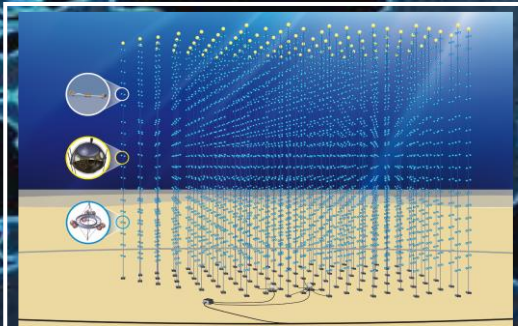
Art picture by *ANTARES*

Future Global Cherenkov Neutrino Telescopes



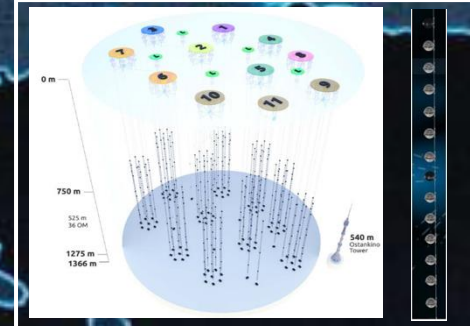
P-ONE (East Pacific Ocean)

Medium: Deep-sea water
Depth: ~ 2.6 km
Volume: ~ 1 km³
Number of strings: ~70



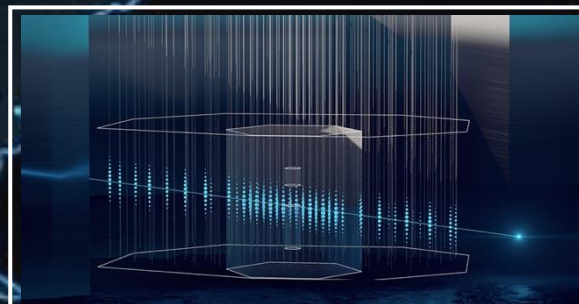
KM3NeT (Mediterranean Sea)

Medium: Deep-sea water
Depth: ~ 3.5 km
Volume: ~ 1 km³
Number of strings: ~230



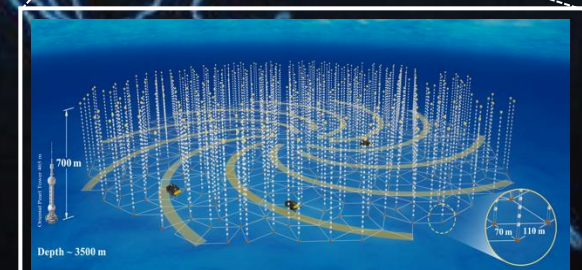
Baikal-GVD (Lake Baikal)

Medium: Deep-lake water
Depth: ~ 1.4 km
Volume: ~ 1 km³
Number of strings: ~140



IceCube Gen-2 (South Pole)

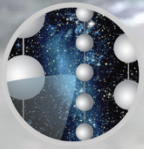
Medium: Glacial ice
Depth: ~ 2.5 km
Volume: ~ 8 km³
Number of strings: ~210



TRIDENT (West Pacific Ocean)

Medium: Deep-sea water
Depth: ~ 3.5 km
Volume: ~ 8 km³
Number of strings: ~1000

(HUNT, NEON)



ICECUBE
NEUTRINO OBSERVATORY

Detector Design in Ice/Water (DOMs/Detector Layout)



Development of Digital Optical Modules



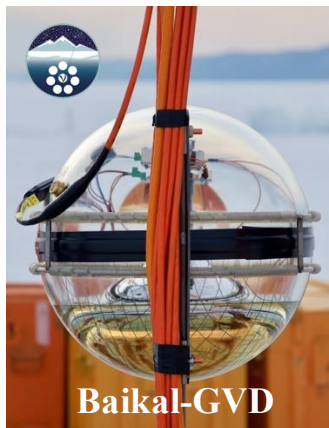
DOM



D-Egg



mDOM



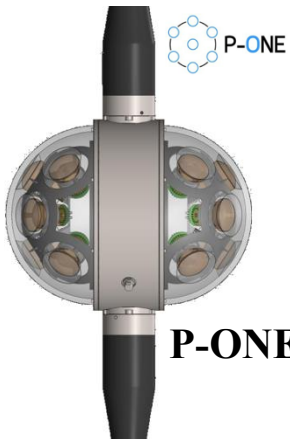
Baikal-GVD

DOM



KM3NeT

mDOM



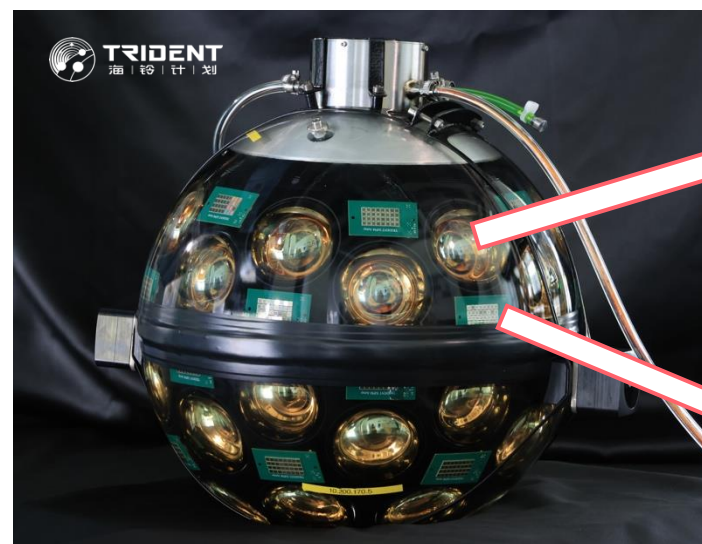
P-ONE

P-ONE

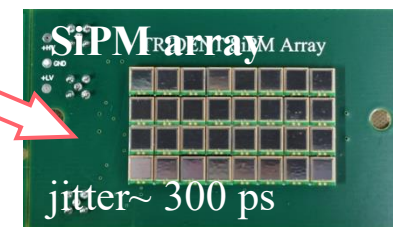
P-OM

Development by using pixelized PMTs:

1. 4π photon coverage (+10% by SiPM)
2. Better SPE time resolution (without magnetic shielding)
3. PMT coincidence trigger for removing K40/dark noise
4. Challenge from multi-channels/power/data readout



hybrid-DOM *TRIDENT hDOM: PoS ICRC2023 (2023) 1213*

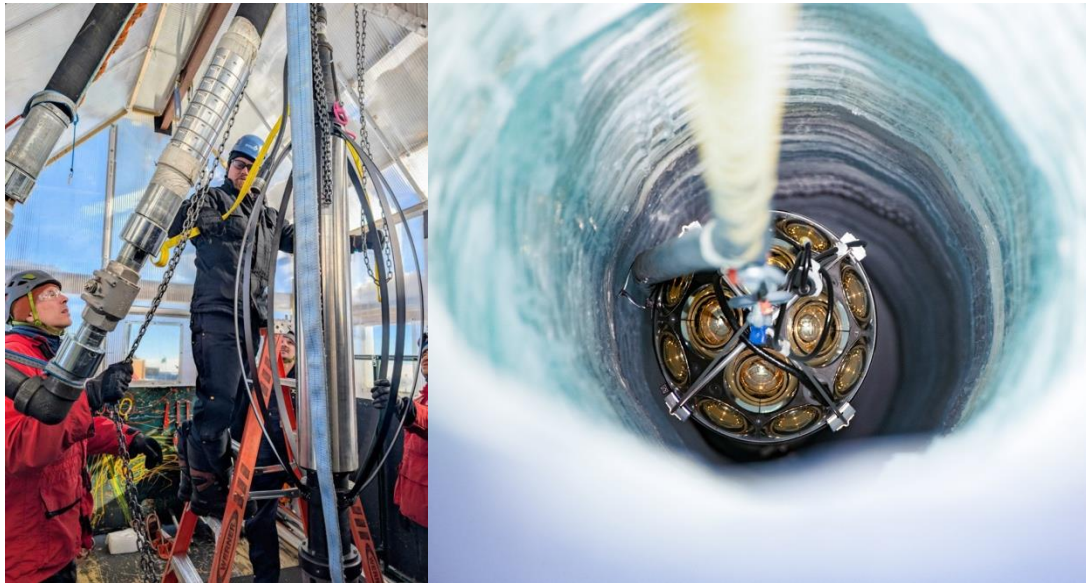


Detector array design and deployment

Key drivers of detector geometry design:

1. Physics goals (energy range, balance between track and cascade, self-veto..)
2. Optical properties of the medium
3. Deployment and engineering constrains (ice/water layers, power supply, maintenance, installation precision...)

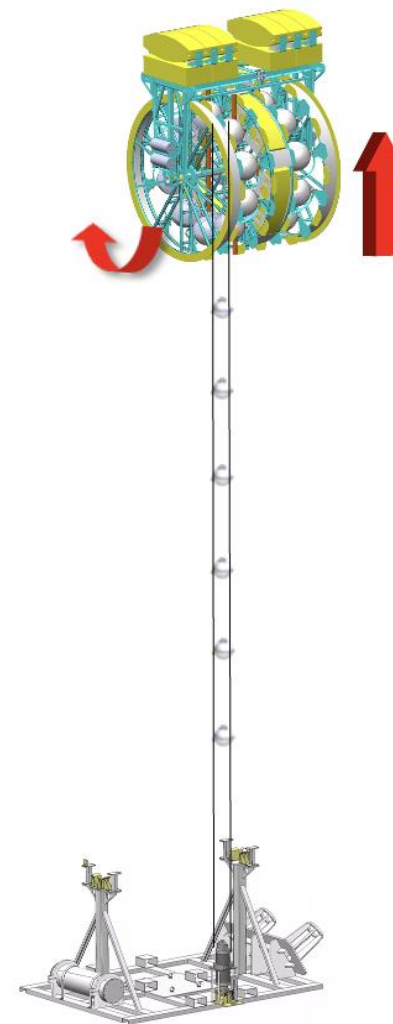
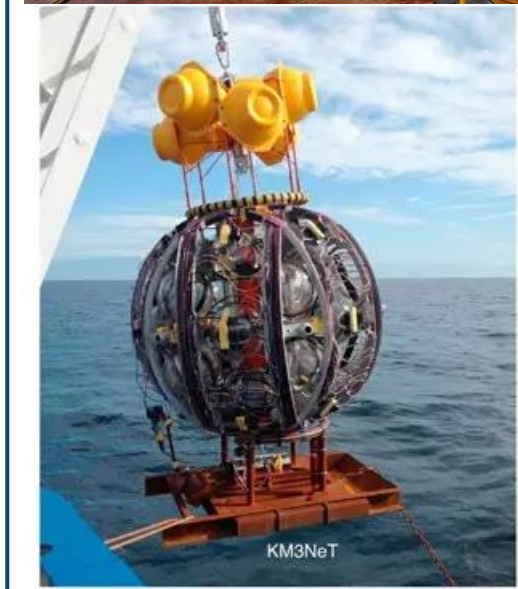
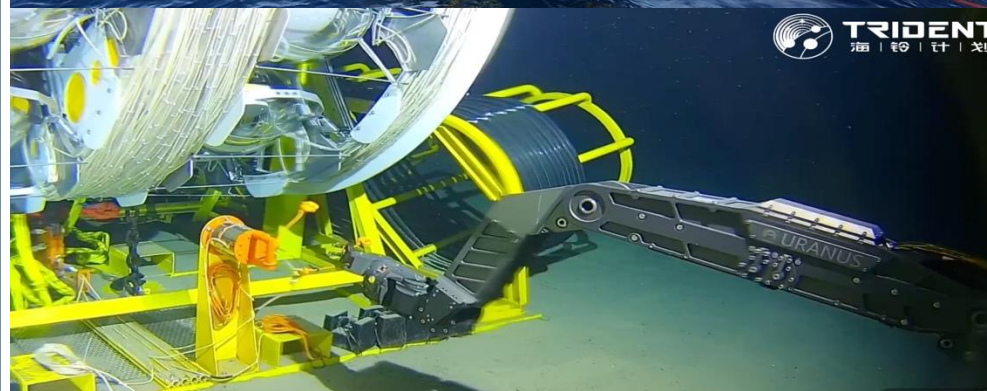
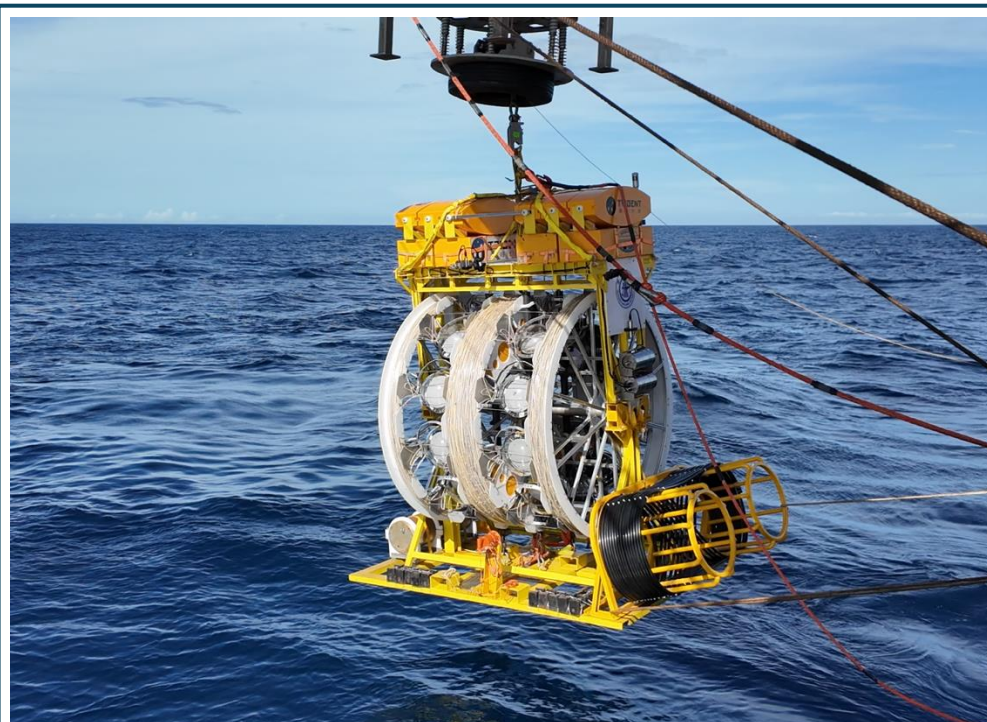
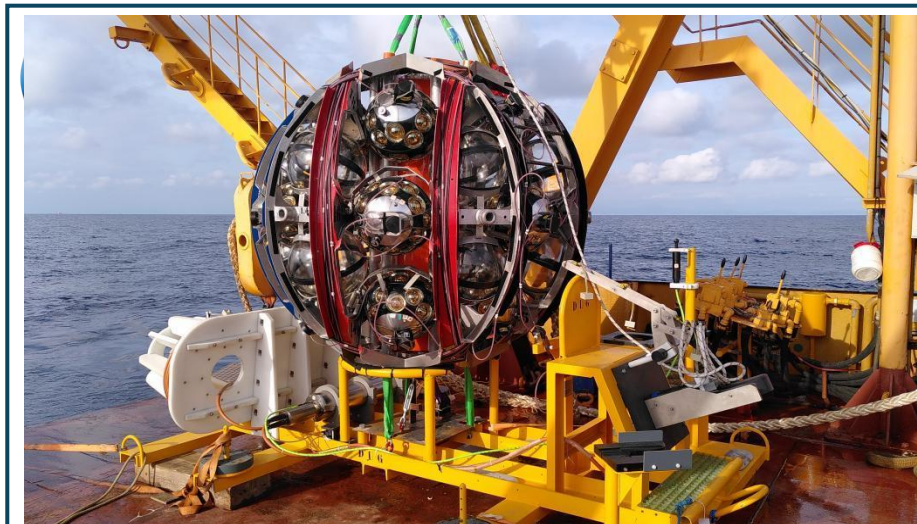
IceCube/Gen2 (hexagonal/sunflower):



Baikal-GVD (clustering):



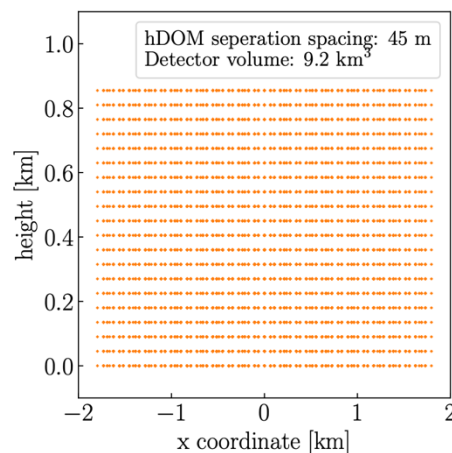
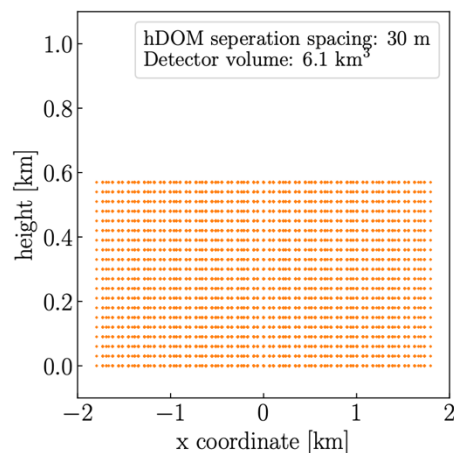
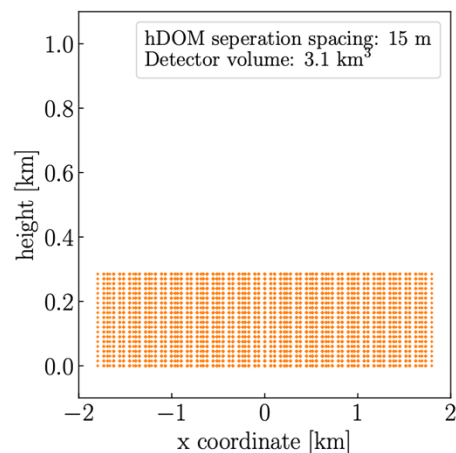
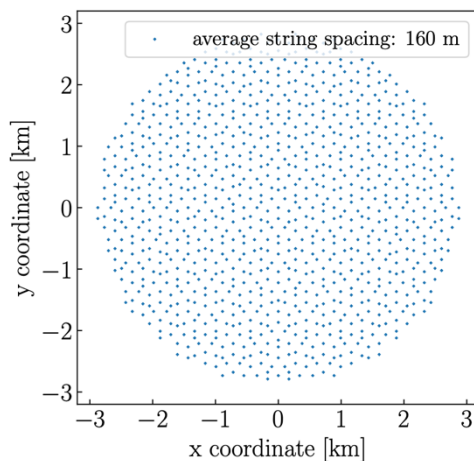
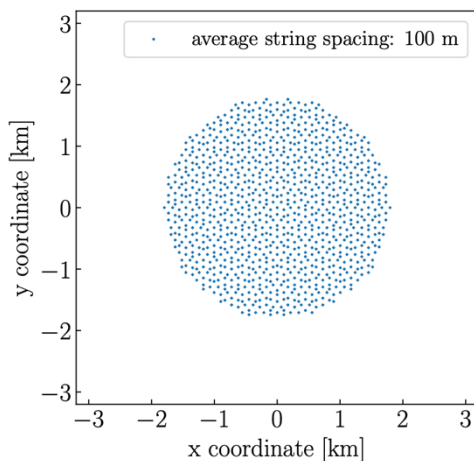
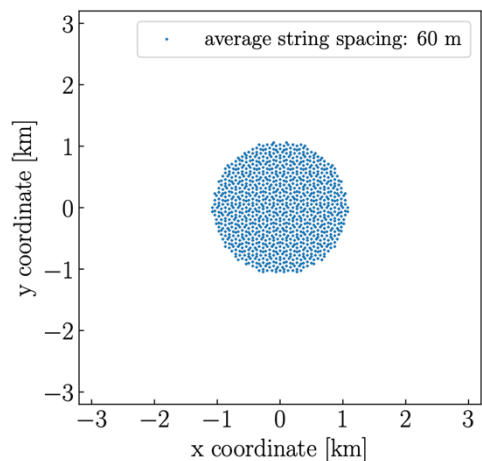
Detector array design and deployment



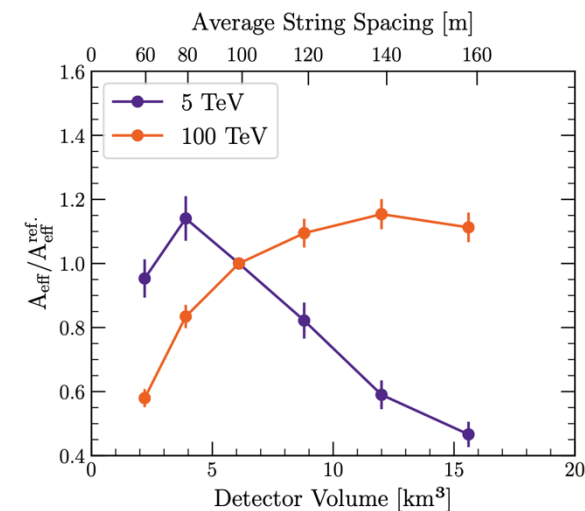
Detector geometry optimization

Scanning the vertical/horizontal spacing, Clustering/Uniform

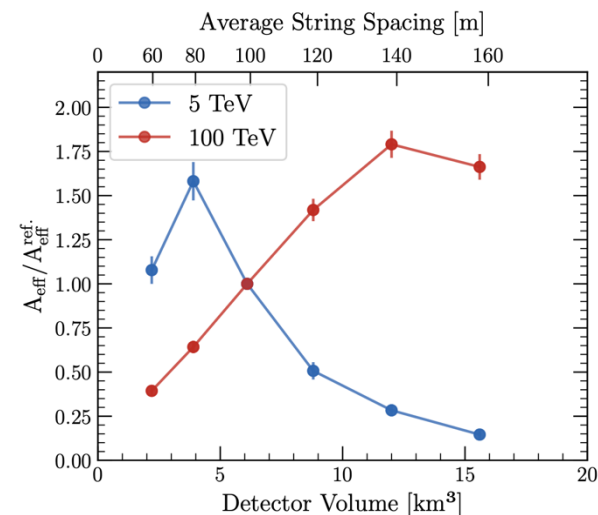
Phys.Rev.D 113 (2026) 4, 043030

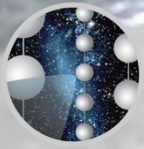


Effective Area vs String Spacing - Tracks



Effective Area vs String Spacing - Cascades



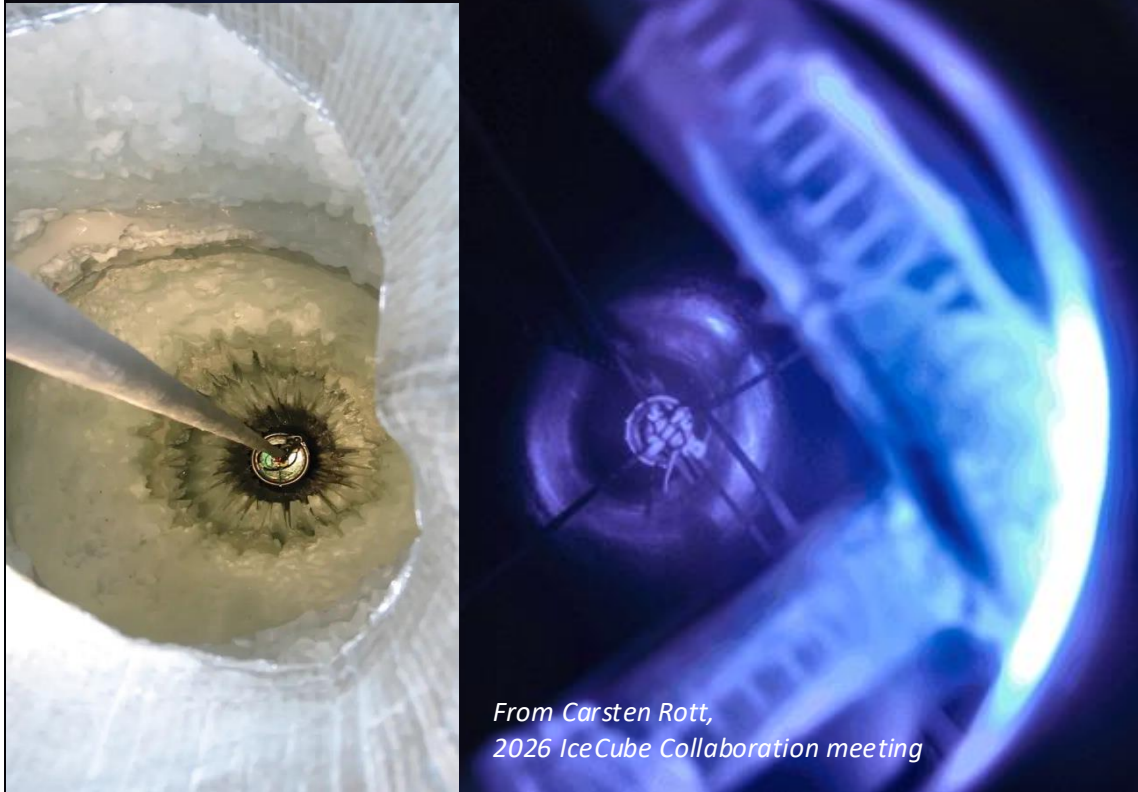


ICECUBE
NEUTRINO OBSERVATORY

Detector Calibration in Ice/Water (Optical properties/Positioning/Background)

Calibration challenges in deep ice / water

2026-01-08 19:40:26



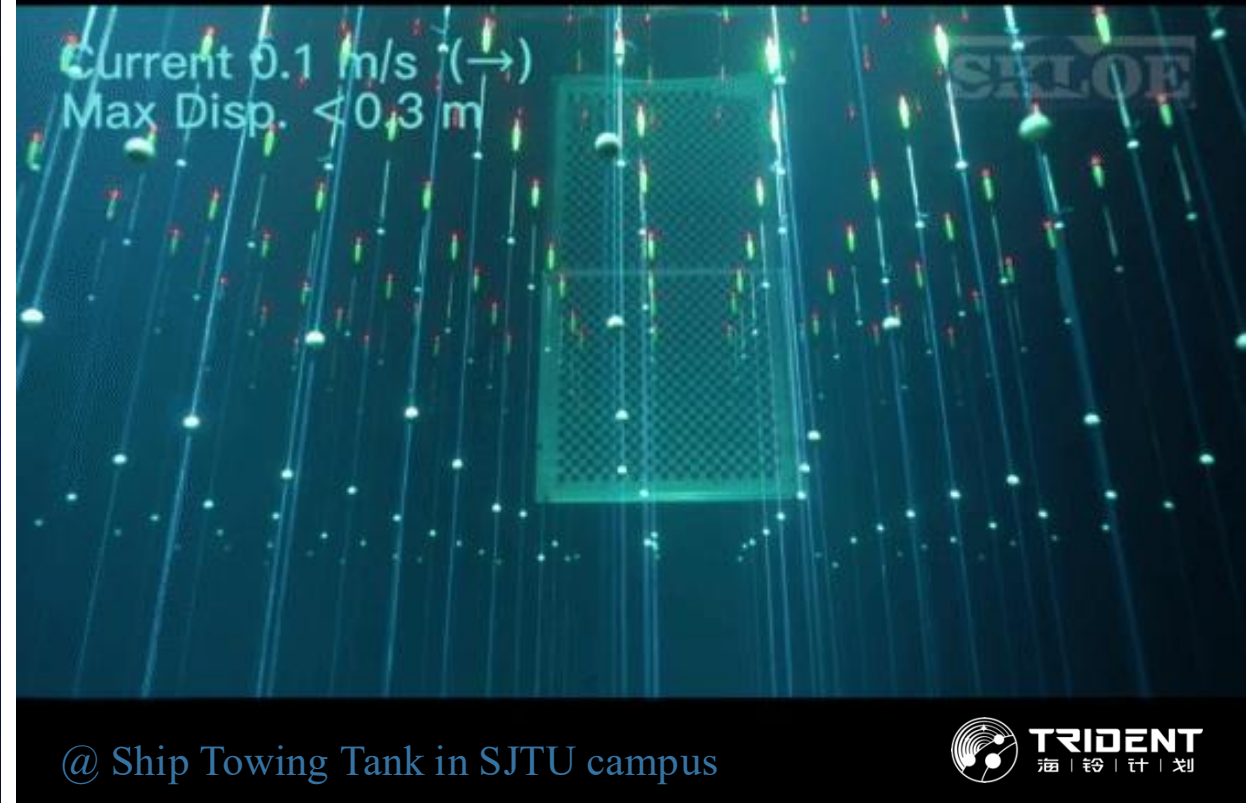
From Carsten Rott,
2026 IceCube Collaboration meeting

- Ice modeling: **hole/bulk ice, dust layer, anisotropy..**
- DOM positioning after refreezing/ glacial ice flow

(More details in Dmitry's talk)

Wei Tian, IceCube Summer School, Jun 5th 2026

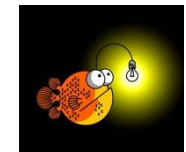
An underwater demonstration of the detector array



@ Ship Towing Tank in SJTU campus



- Time-varying optical properties of water
- DOM Positioning in sea current
- Extra natural radioactivity/Bio-activity



Optical properties in ice/water medium

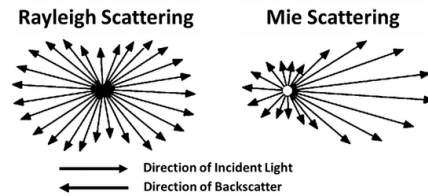
❖ The optical parameters:

Absorption length (λ_{abs}) \sim photon loss

Scattering length (λ_{sca}) \sim photon deflection

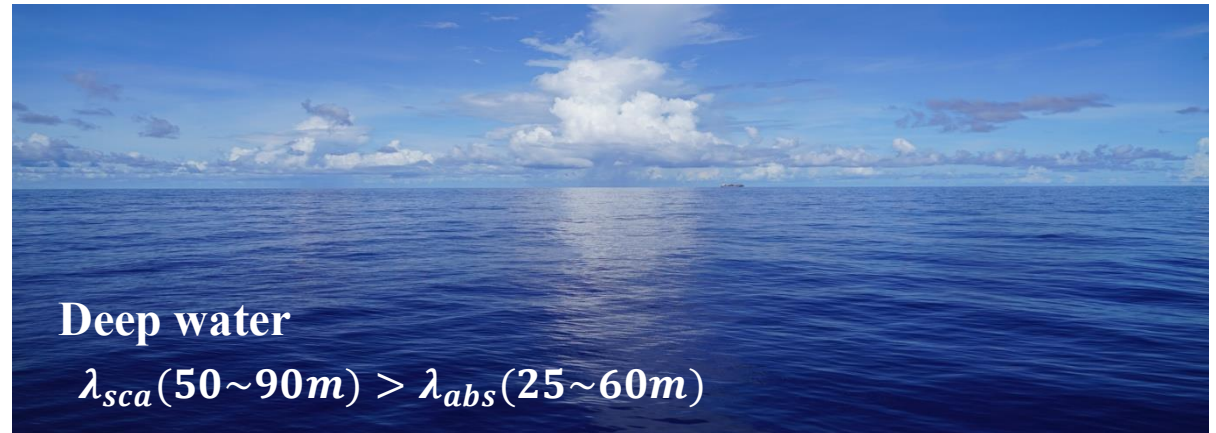
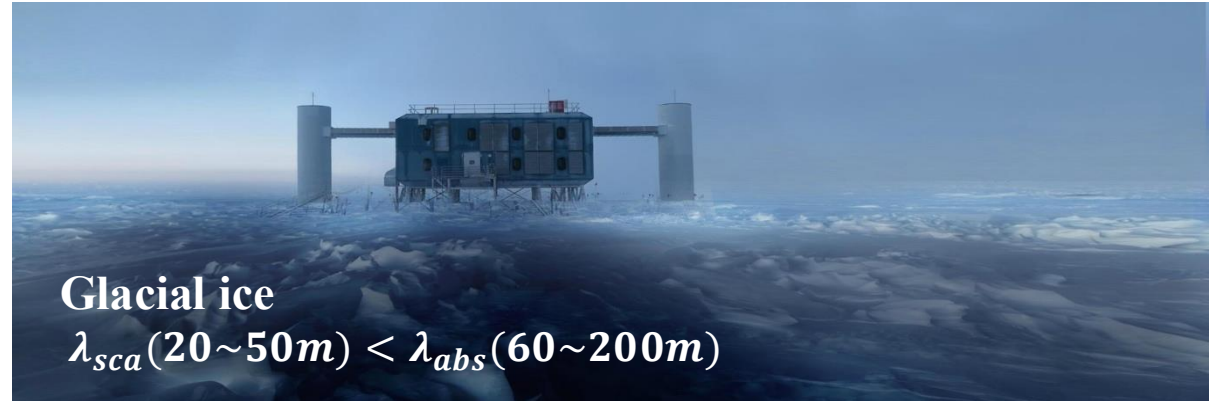
Rayleigh scattering (λ_{Ray}):

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



Attenuation length (λ_{att}):

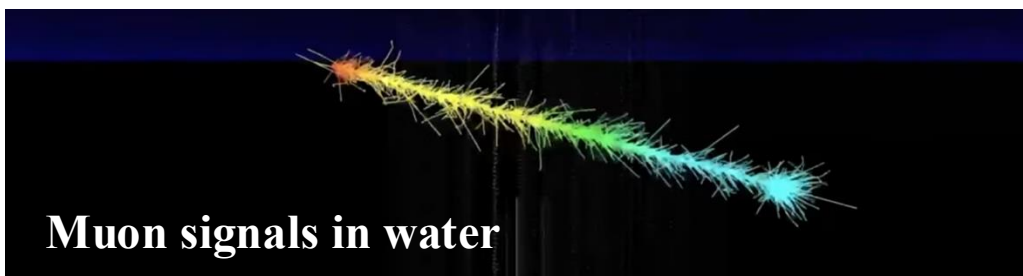
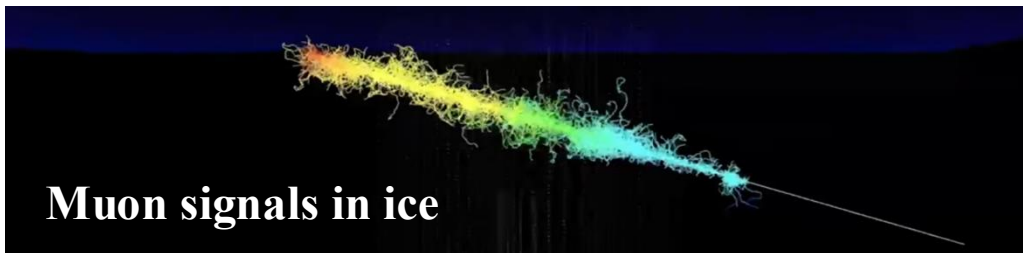
$$I(L) = I_0 \cdot e^{-\left(\frac{L}{\lambda_{abs}} + \frac{L}{\lambda_{sca}}\right)} = I_0 \cdot e^{-\frac{L}{\lambda_{att}}}$$



Time varying optical properties in deep water

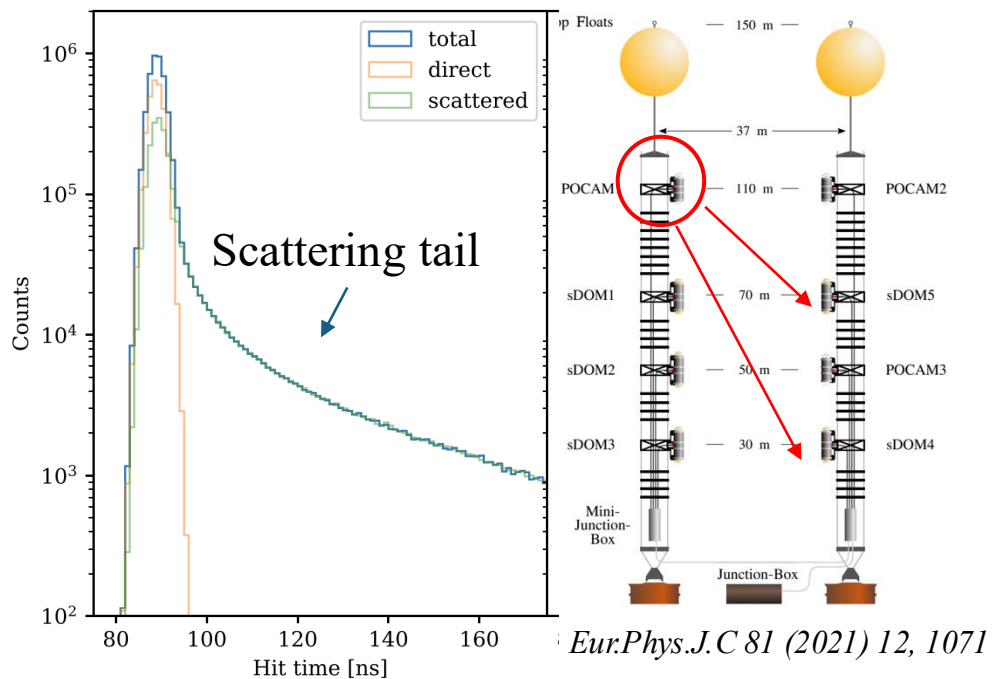


in-situ real-time optical calibration



PMT + Pulsing light source:

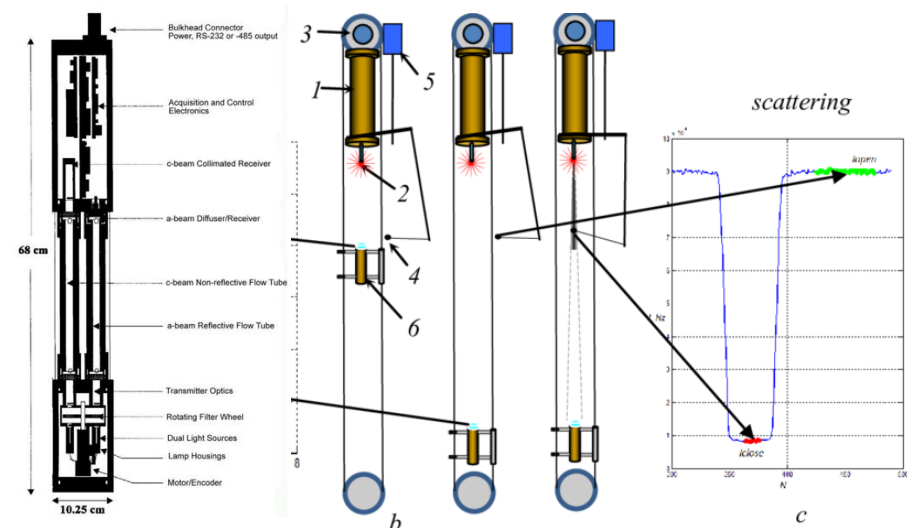
(Antares-2004, KM3NeT-LAMs, P-ONE Straw-a)



1. Single-photon mode + Synchronization (~ns)
2. Hours-long data accumulation
3. Arrival time -> scattered/direct photons, “ $\lambda_{eff,att}$ ”

Specialized laser facility:

(KM3NeT-AC9, Baikal-5D)



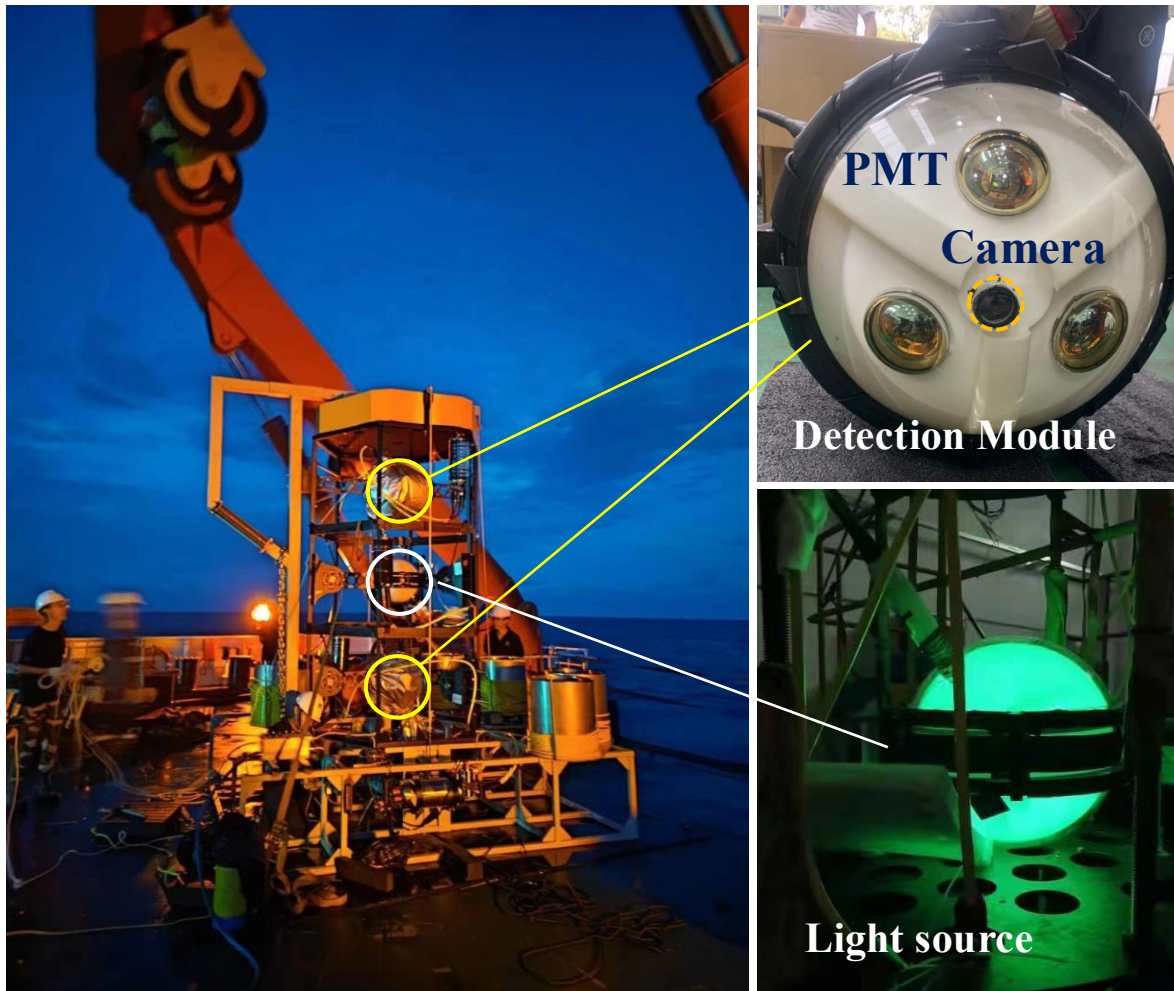
WET lab, AC9 Baikal-5D, PoS ICRC2023 (2023) 977

1. Good precision of canonical λ_{att} λ_{abs} λ_{sca}
2. Need extra calibration/deployment
3. Localized measurement

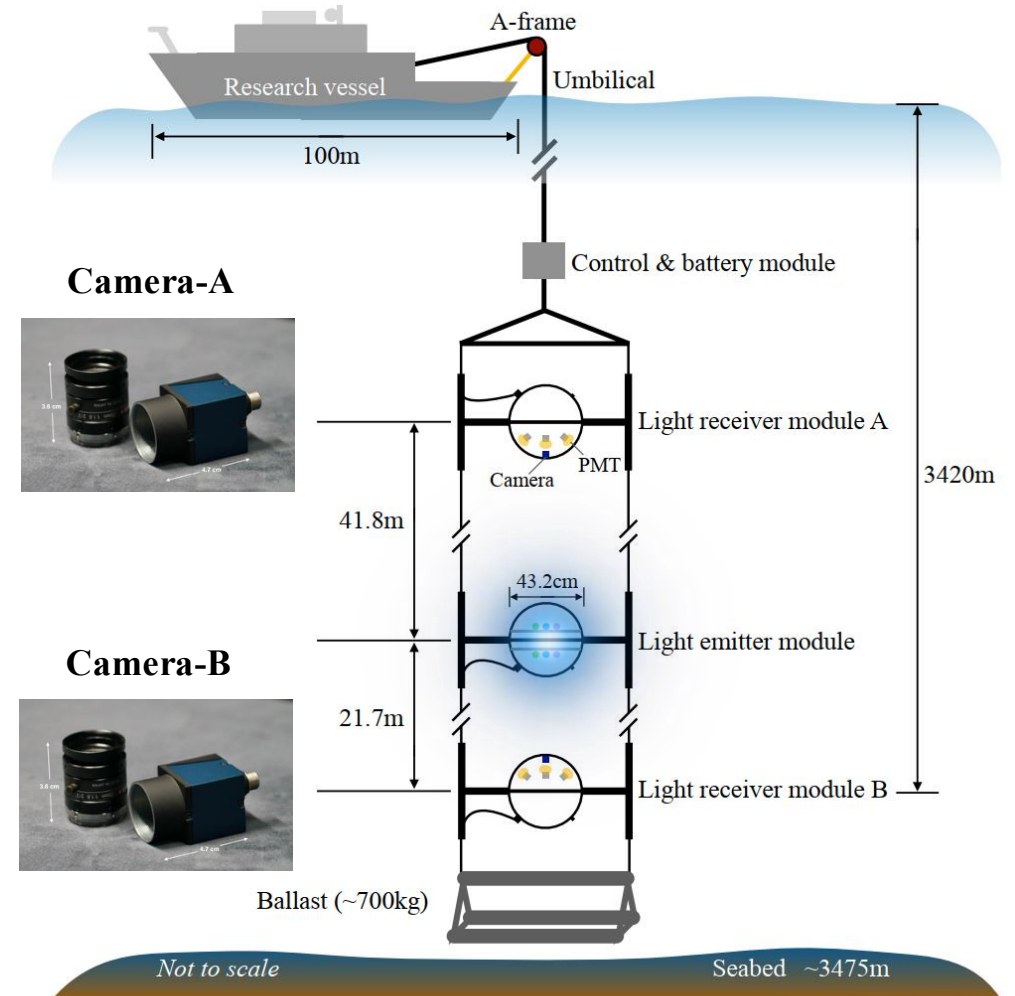
TRIDENT Pathfinder experiment (Sept. 2021)



❖ TRIDENT Explorer (T-REX)

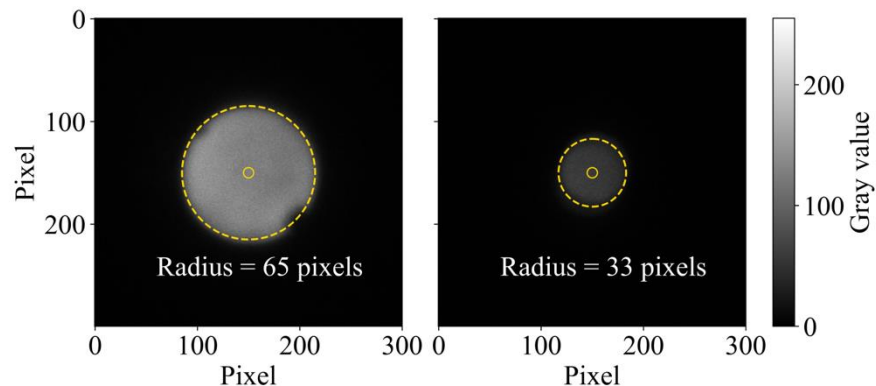


❖ T-REX deployment (depth~3420m)

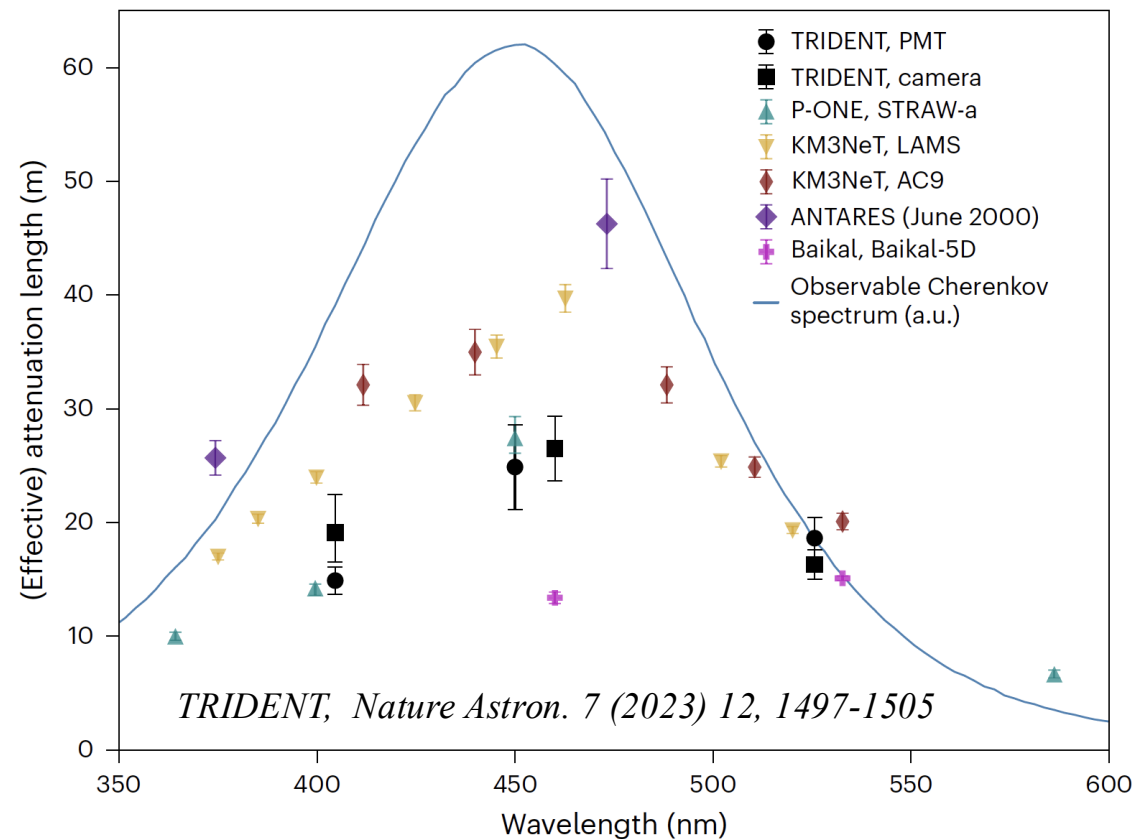
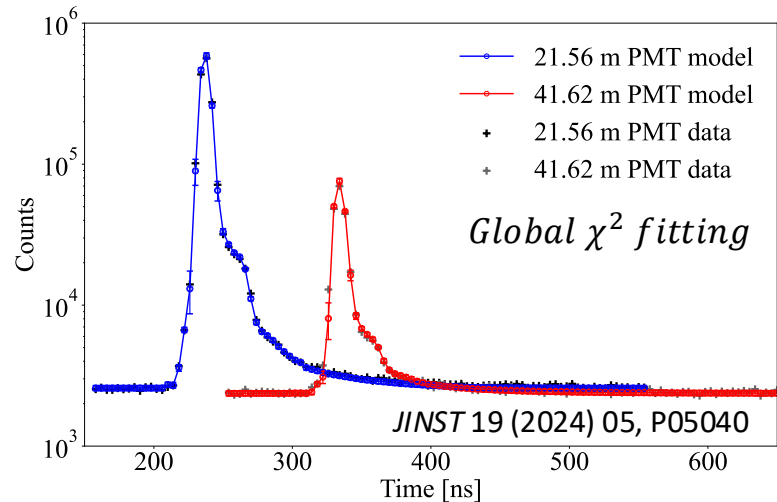


Optical measurement results from T-REX

T-REX Camera system



T-REX PMT system



Real-time Measurement by CMOS system within seconds:

I_{center} method: $\lambda_{att} \sim 6\%$

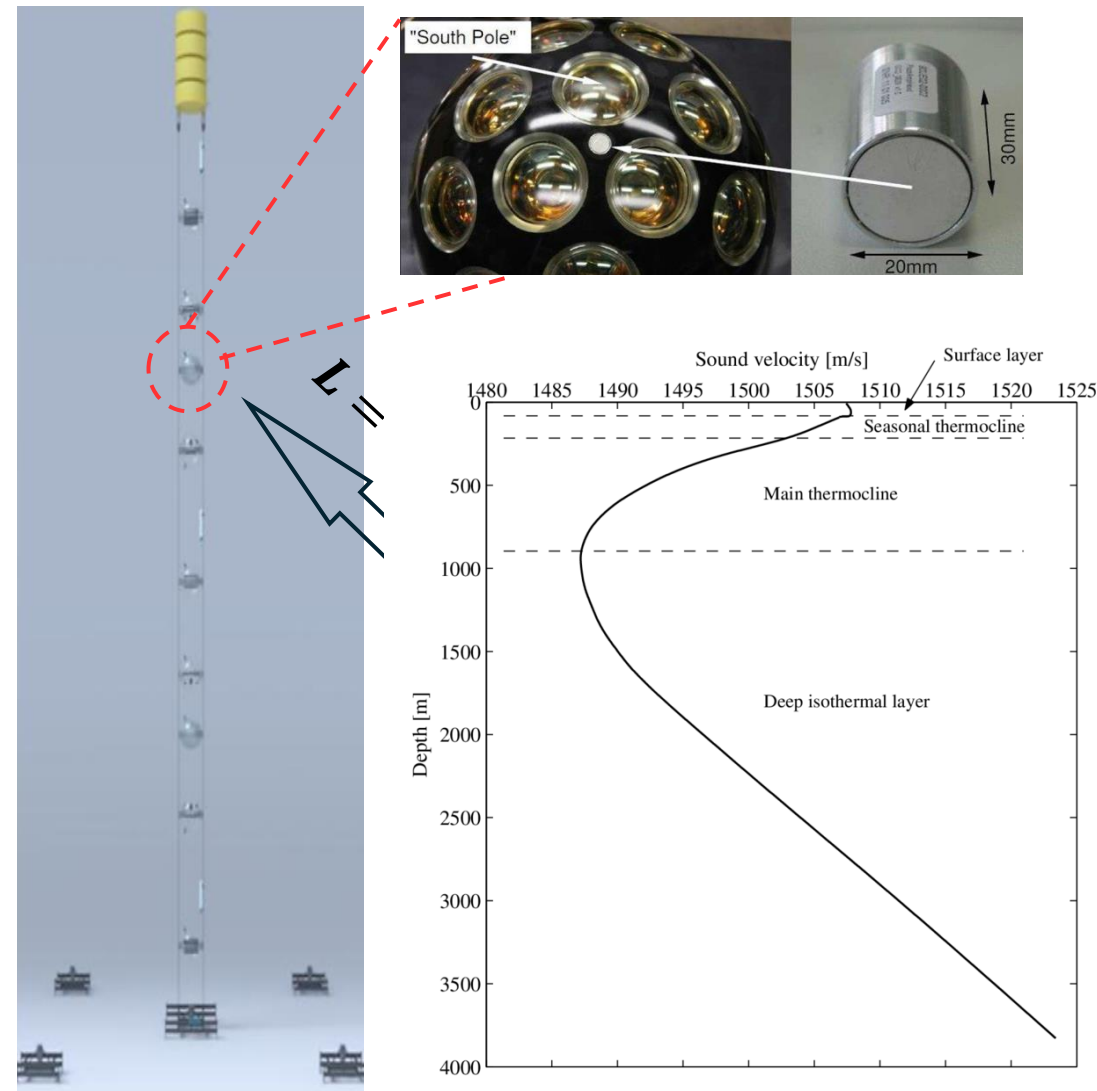
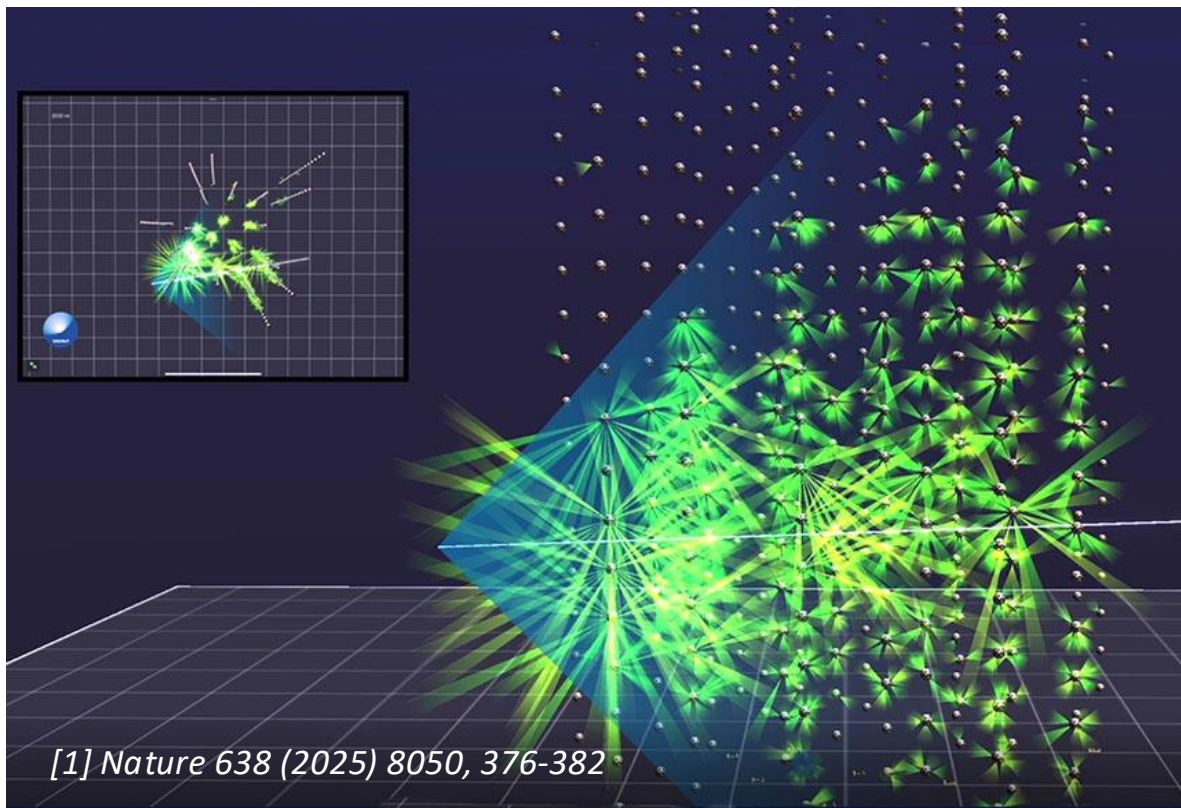
χ^2 fitting method: $\lambda_{att} \sim 1\%$ $\lambda_{abs} \sim 2\%$ $\lambda_{sca} \sim 6\%$

Acoustic positioning system in deep sea



from Luc Voorend, KM3NeT, GNN2026

- ❑ Current angular uncertainty of **KM3-230213A**^[1]:
 - **0.12°** intrinsic reconstruction resolution
 - **0.1°** relative positioning
 - **1.0°** absolute positioning (each axis)

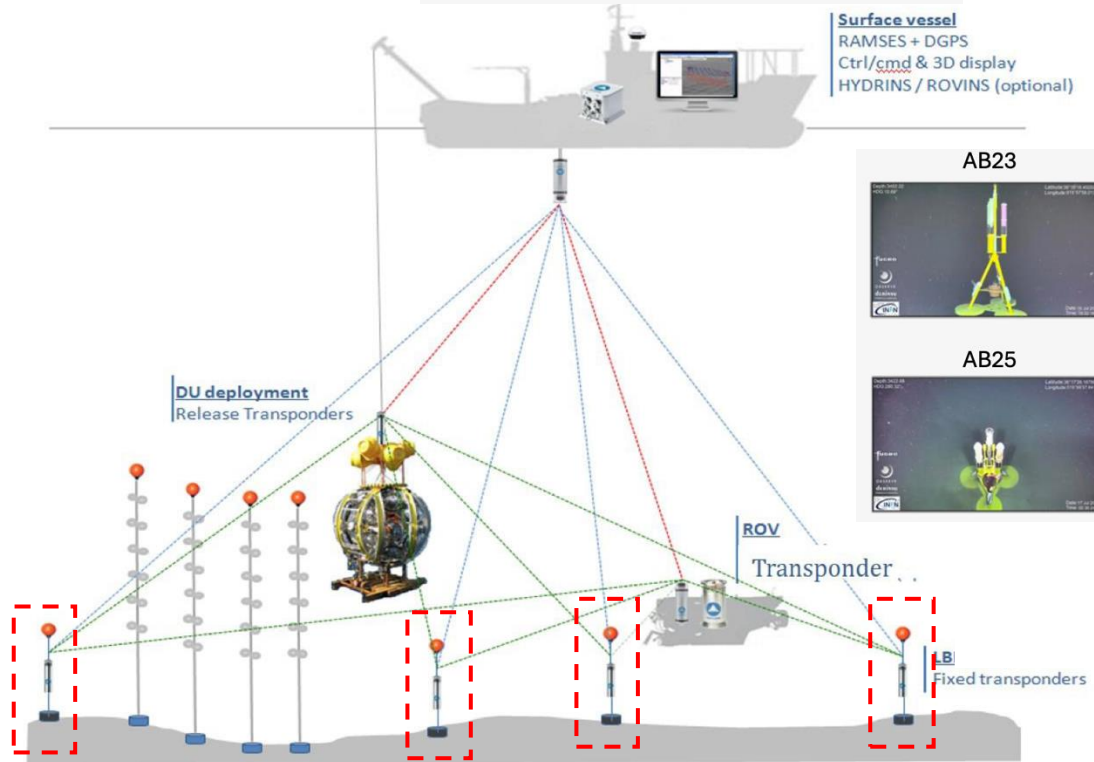


Acoustic positioning system in deep sea



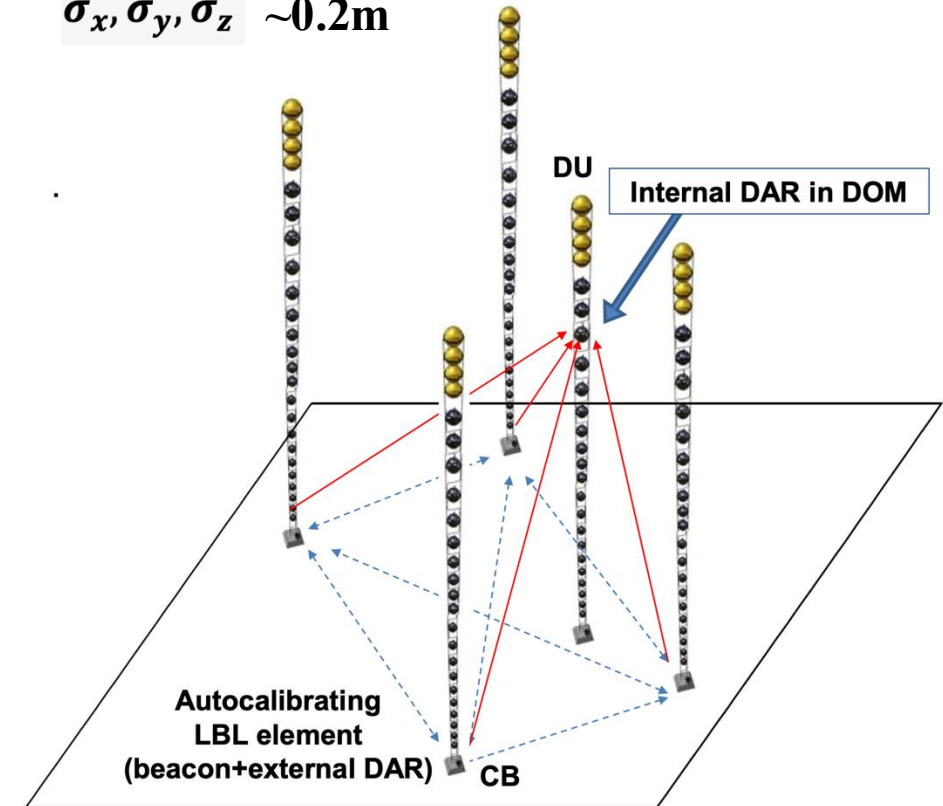
Absolute positioning during string deployment

Deployment $\sigma_x, \sigma_y, \sigma_z < 1m$



Relative positioning after deployment

$\sigma_x, \sigma_y, \sigma_z \sim 0.2m$



Background calibration in ice/water

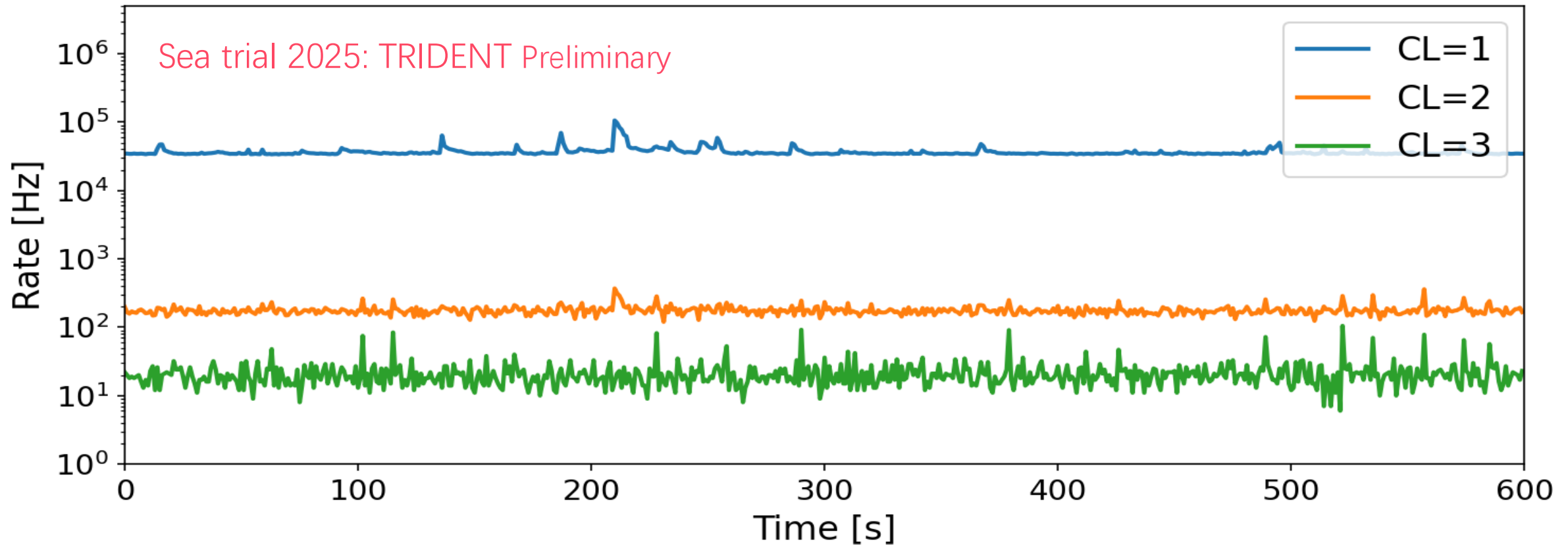
PMT noise components = PMT dark noise + Glass and Environment radio activity + Bioluminescence

(Atmospheric not included)

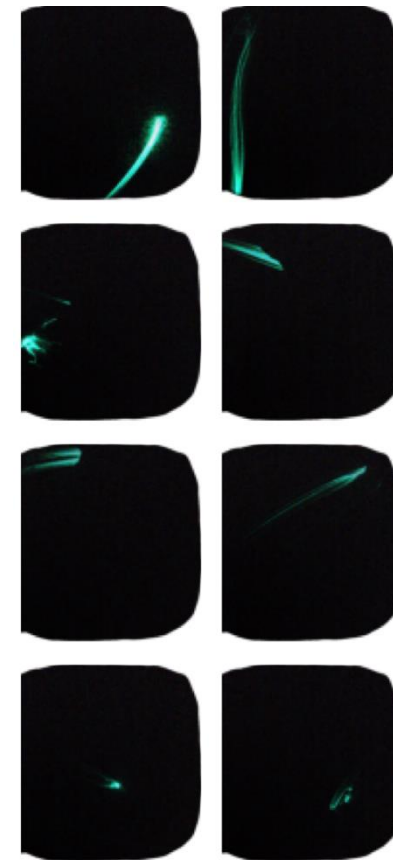
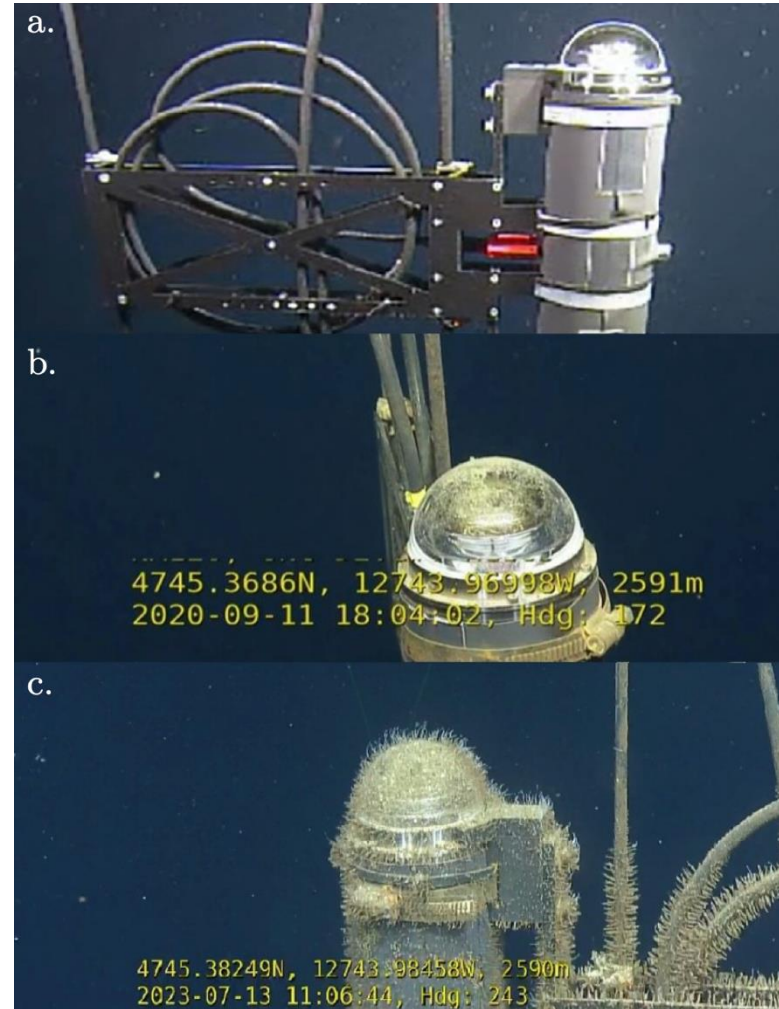
In ice $\sim O(100\text{Hz/PMT})$

In water $\sim O(\text{kHz/PMT})$

only in deep-sea



Bio-activity and Bio-fouling in deep sea



from Kilian Holzapfel, P-ONE

Chasing for the same dream!

- We are standing in the dawn of neutrino astronomy!
- More exciting neutrino telescopes are under development/construction.

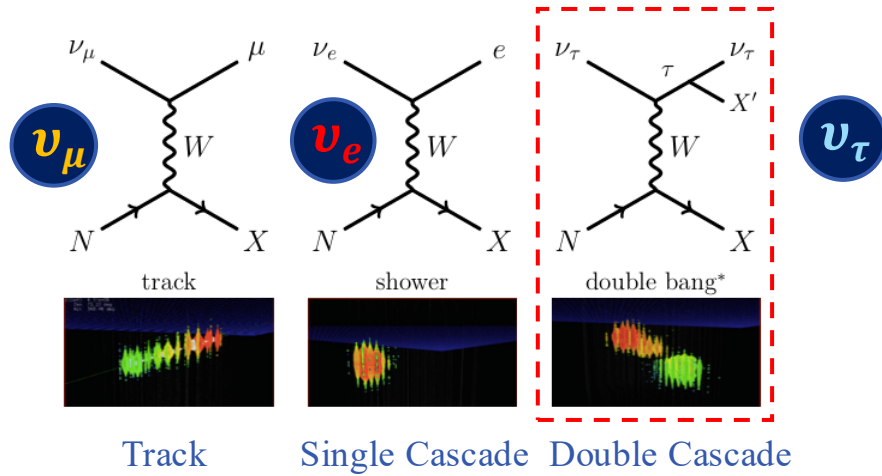
Wei Tian

IceCube Summer School

Jun 5th 2026 @WIPAC, UW-Madison

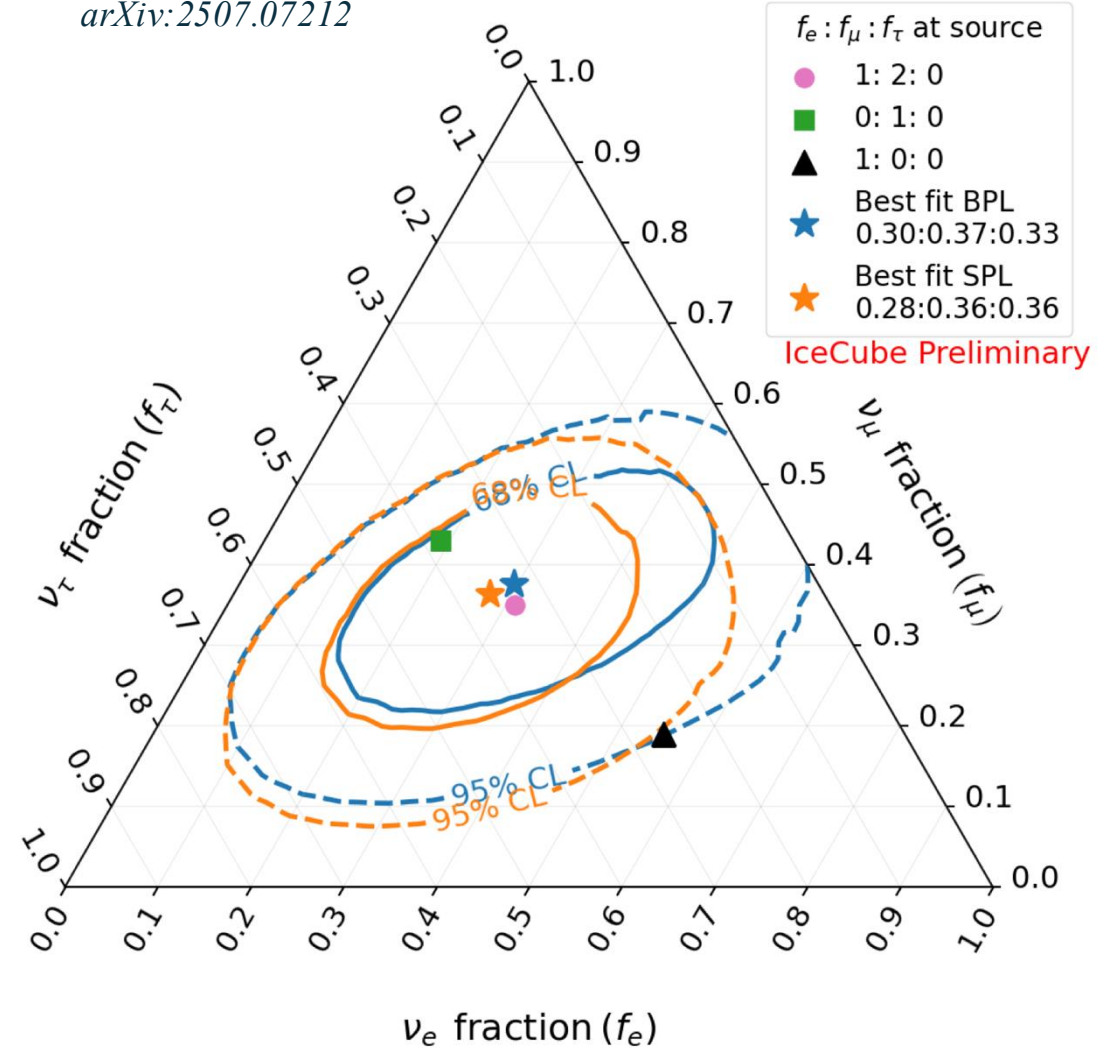
Neutrino flavor identification in IceCube

❖ Tau neutrino: the key component of flavor ratio:



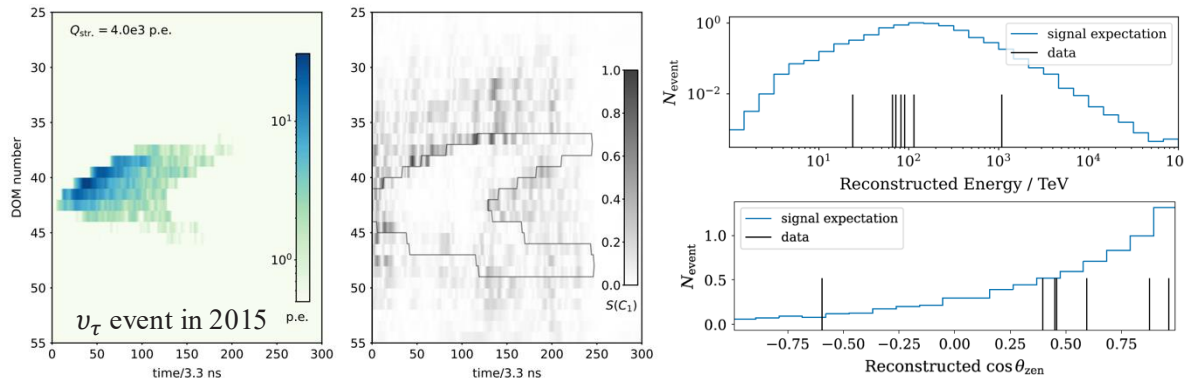
Probe source models or new physics by flavor :

arXiv:2507.07212

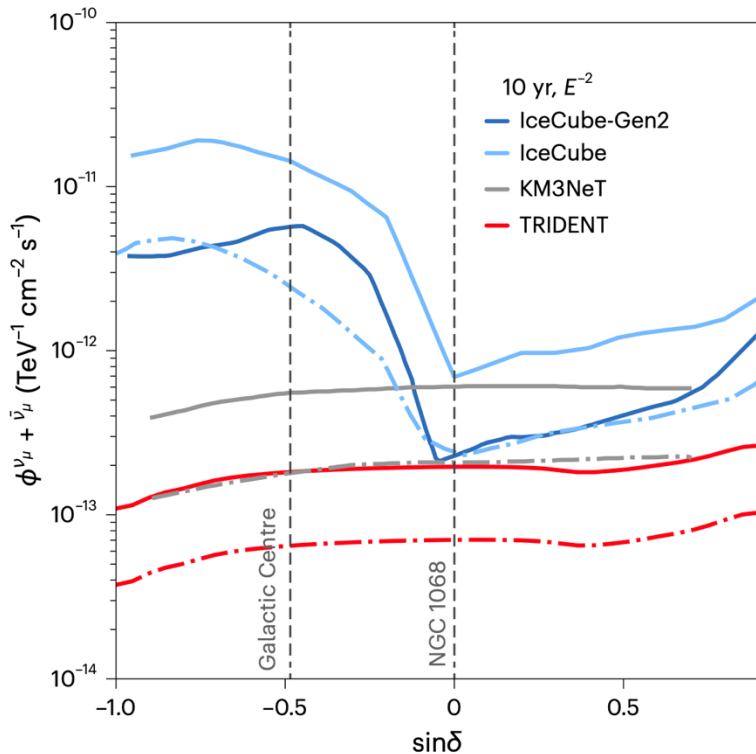


❖ Identification of tau neutrinos in IceCube:

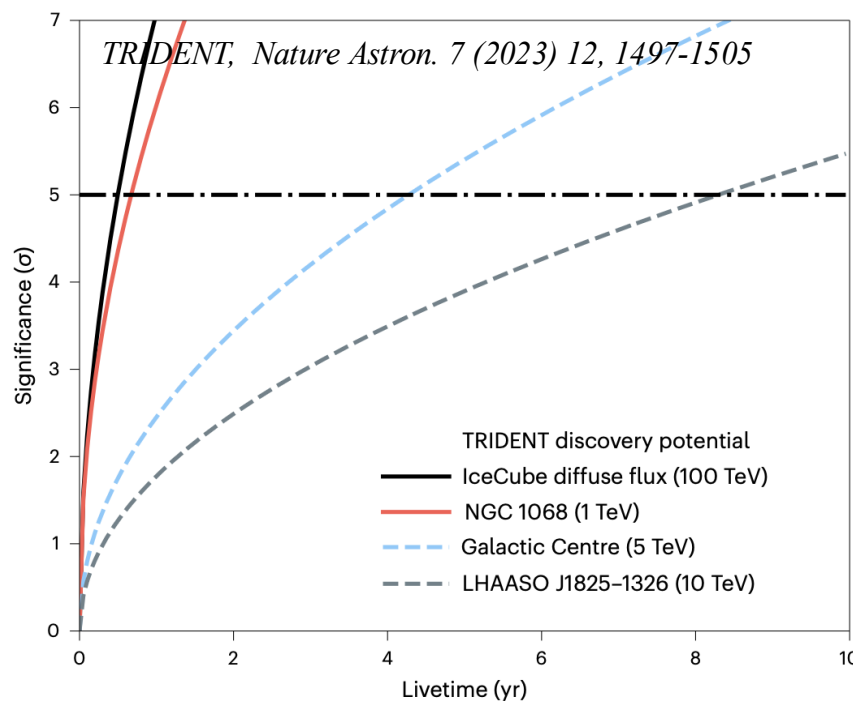
7 tau neutrinos candidates by CNN with 3 strings (2024) *PRL*, 132, 151001 (2024)



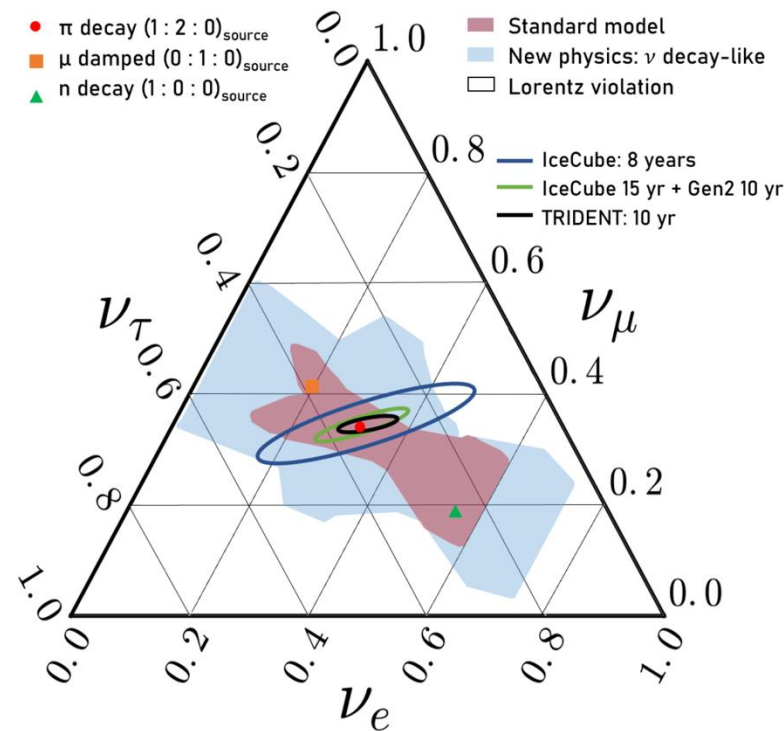
Neutrino Flux Sensitivity



Neutrino Sources Discovery Potential



Source Models & New Physics



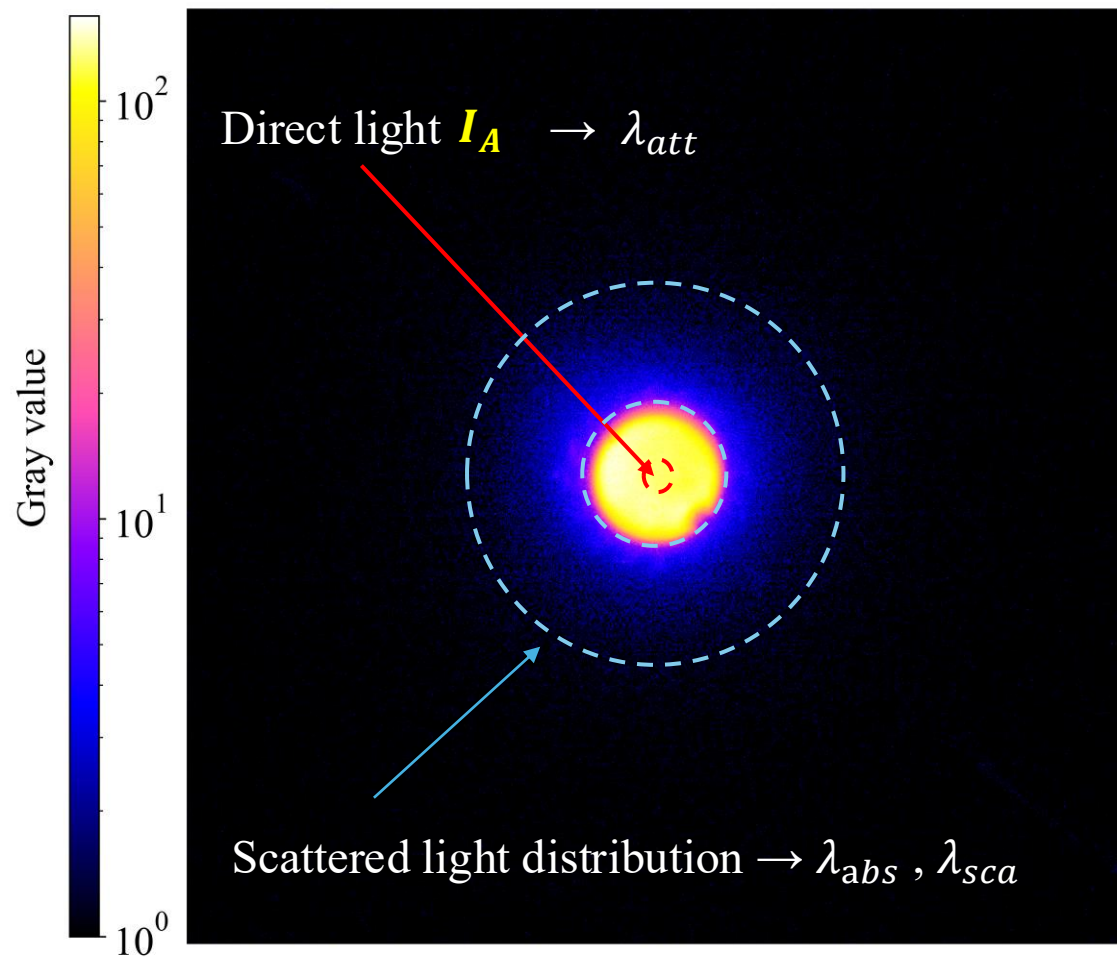
Angular Resolution $\sim 0.1^\circ$ @ 100TeV

For NGC1068: 5σ within 1 year!



Neutrino Flavor Ratio

Two algorithm for measuring optical parameters



Camera system : NIM-A 1076 (2025) 170489)

Optical attenuation in deep-sea water:

Absorption effect (λ_{abs}) \sim photon loss

Scattering effect (λ_{sca}) \sim photon deflection

(1) Center pixels for measuring total attenuation:

$$\lambda_{att} = -(L_A - L_B) / \ln\left(\frac{I_A}{I_B} \cdot \frac{I'_0}{I_0}\right)$$

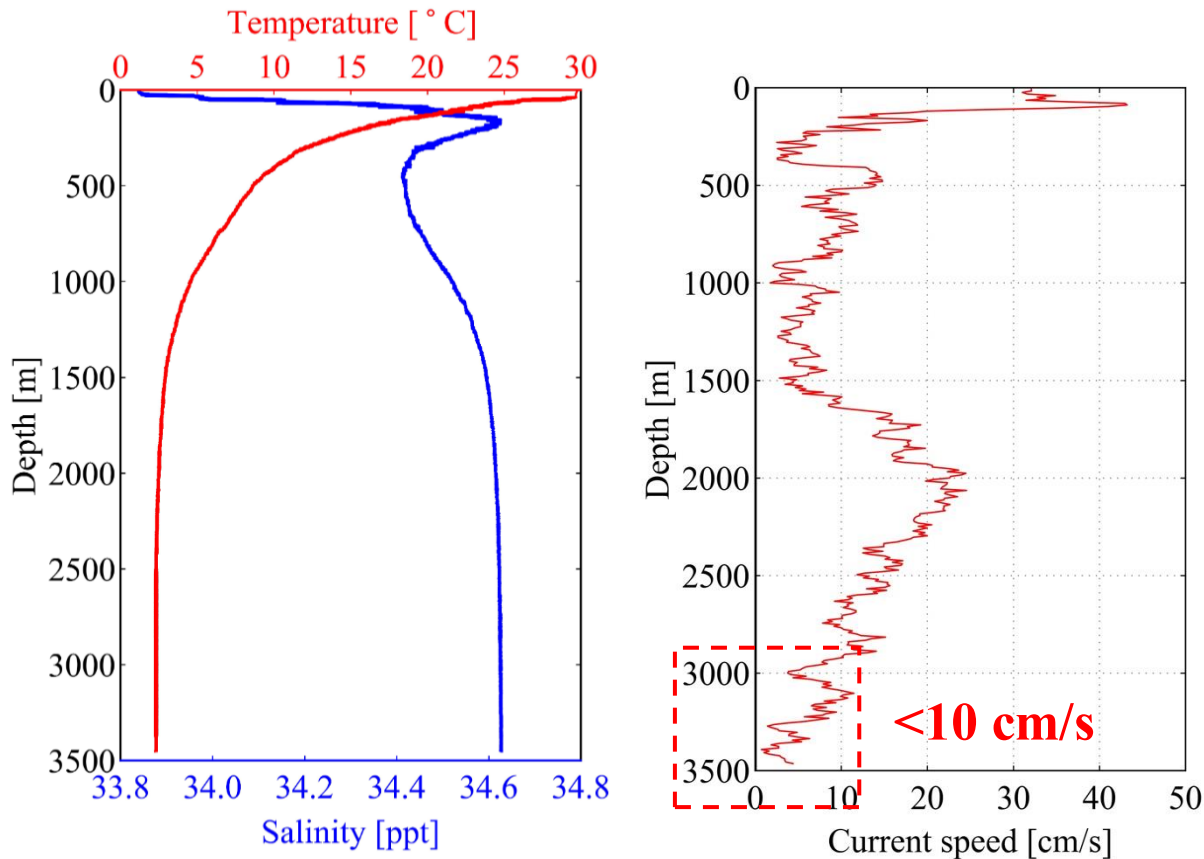
($\frac{I'_0}{I_0}$ indicates the non-uniformity of the light source)

(2) Gray value distribution for measuring λ_{abs} λ_{sca}

$$\chi^2 = \sum_{i=1}^N \frac{[M_i - T_i(1 + \sum_{k=1}^K \epsilon_k)]^2}{\sigma_{M_i}^2 + \sigma_{T_i}^2} + \sum_{k=1}^K \frac{\epsilon_k^2}{\sigma_k^2}$$

(χ^2 fitting with the Geant4 simulated images)

Oceanographic conditions



^{40}K decay activity : **$11101 \pm 119 \text{ Bq/m}^3$**

	West Pacific	Mediterranean	East Pacific
^{40}K radioactivity (Bq/m^3)	11101 ± 119	13700 ± 200	12526 ± 752
Experiment	TRIDENT	ANTARES	P-ONE