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TRIDENT 海 | 铃 | 计 | 划

The Camera System & Tau Neutrino Search in the TRIDENT Experiment

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@ Harvard University, Boston

08.23.2024

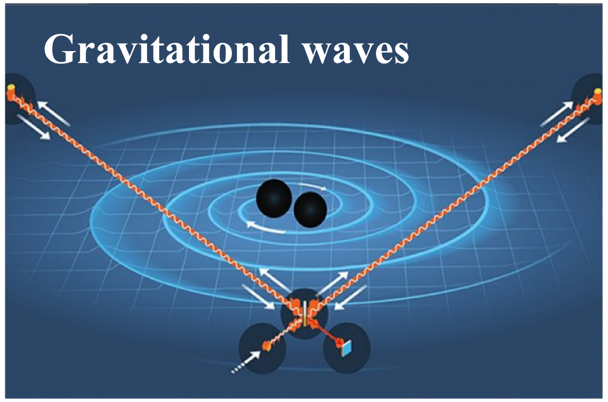
Outline

1. **Neutrino astronomy & Neutrino telescopes**
2. **TRIDENT (海铃计划)：A proposed next-generation neutrino telescope**
   (1) Location (2) Detector layout (3) hDOM design (4) Pathfinder (5) Physics potential
3. **The camera system: an eye for real-time optical calibration**
   (1) Hardware design (2) Image processing methods (3) Calibration process
4. **Identifying astrophysical tau neutrinos based on hDOM waveforms**
   (1) Simulation pipeline (2) Double Pulse algorithm (3) Exploration of using GNN

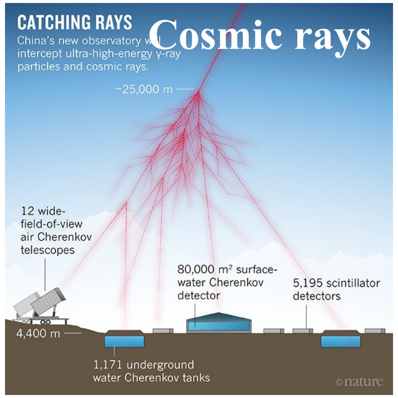
5. **Summary**

High-energy astrophysical neutrinos

❖ Multi-messenger Astronomy Era

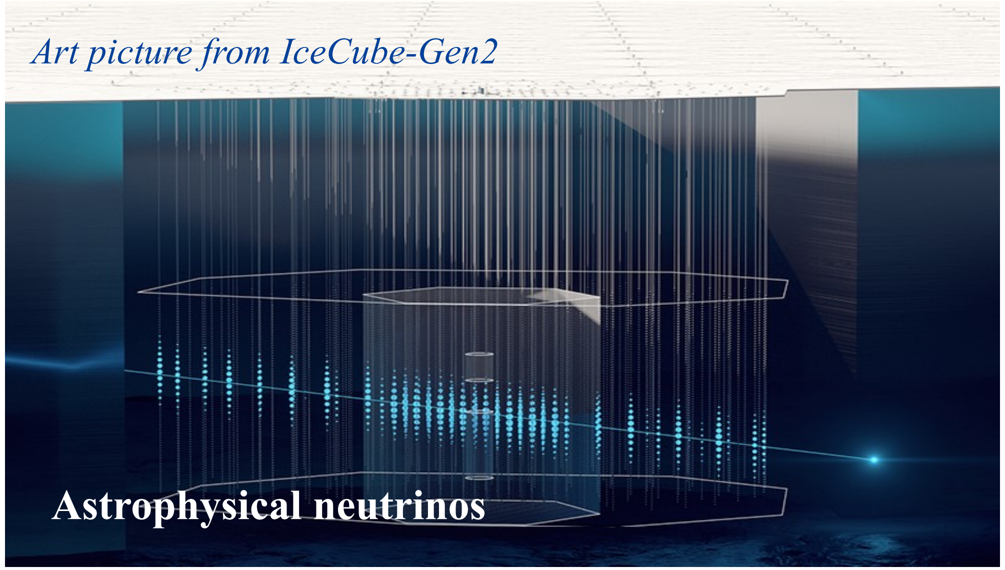


Art picture from LIGO



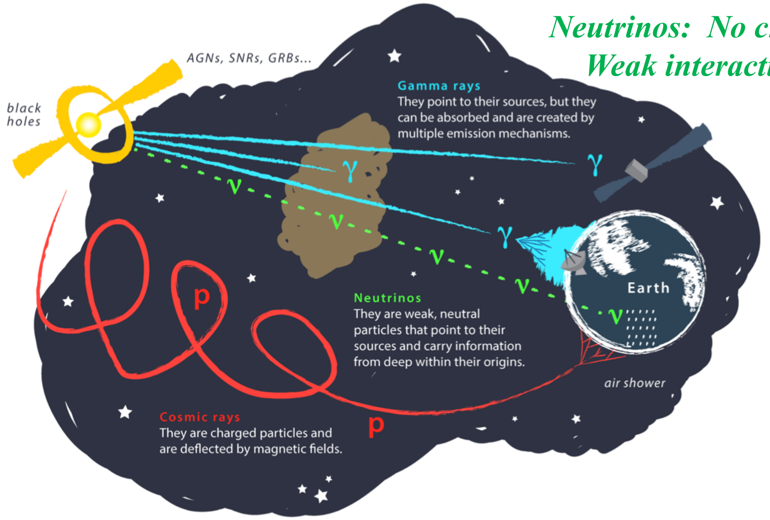
Art picture from LHAASO

Art picture from IceCube-Gen2



❖ Neutrino as an astrophysical messenger:

Neutrinos: No charge
Weak interaction

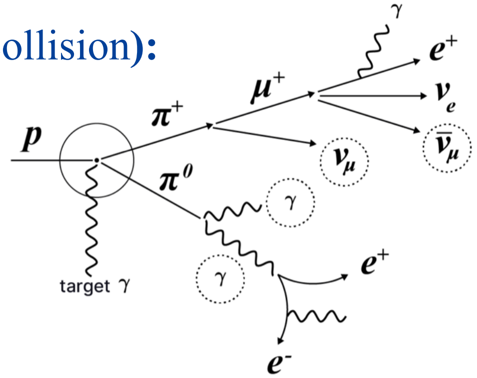


Art picture by Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

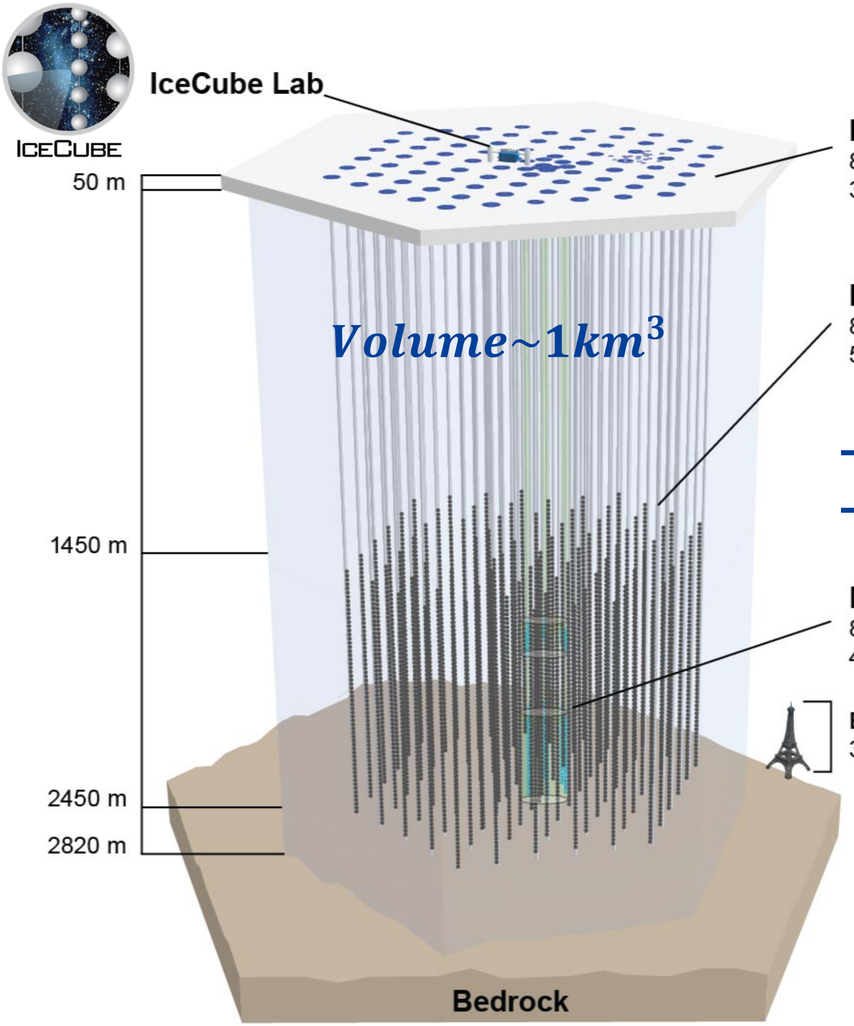
❖ Exploring the origin of cosmic rays

Hadronic processes (*pγ or pp* **collision):**

$$\pi^+ \to \mu^+ + \boxed{\nu_\mu}$$
$$\mu^+ \to e^+ + \boxed{\nu_e + \overline{\nu_\mu}}$$



Neutrino telescopes: IceCube & ANTARES



IceTop
81 stations
324 optical sensors

Volume~1km^3

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

-- 86 strings
-- 5160 DOMs

DeepCore
8 strings—spacing optimized for lower en

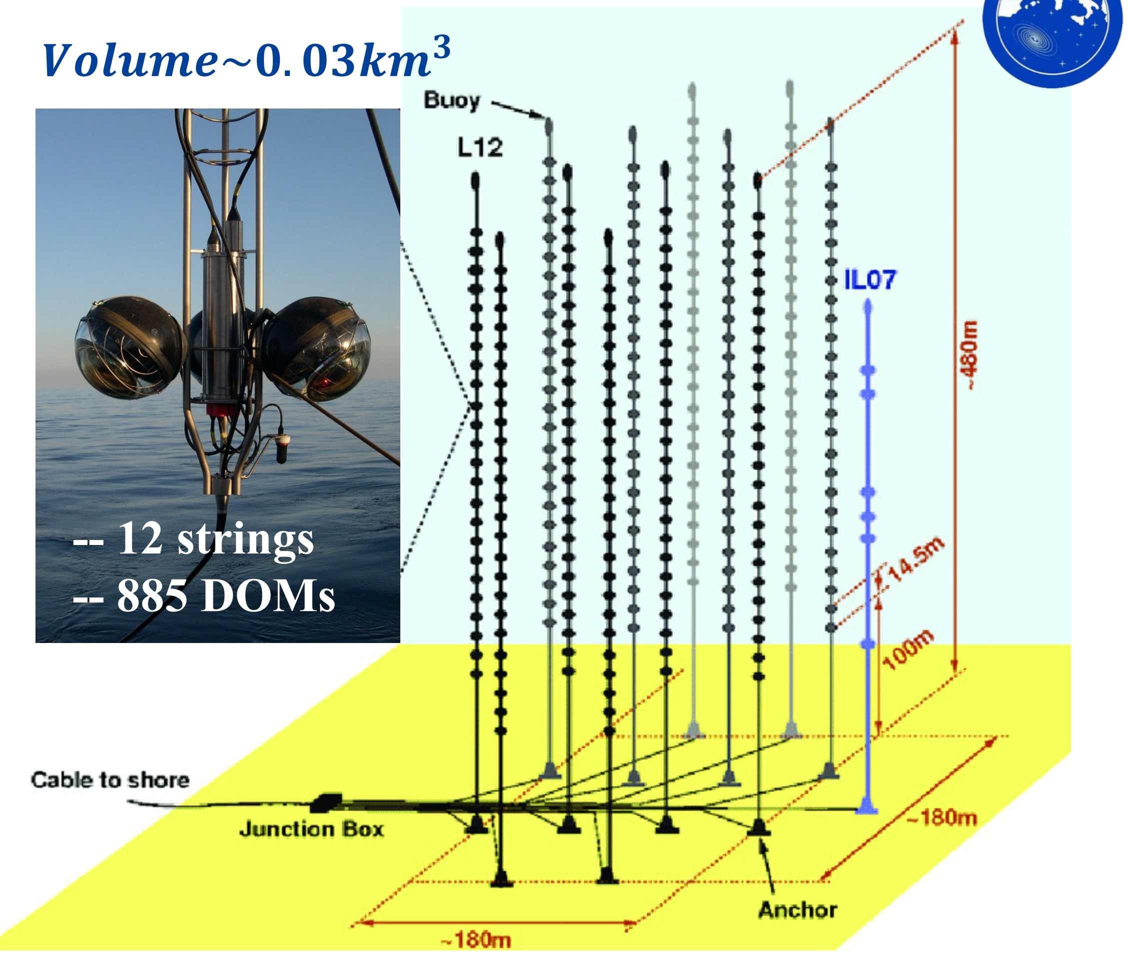
480 optical sensors

Eiffel Tower
324 m

*Art picture by **IceCube***

10-inch PMT

Volume~0.03km^3

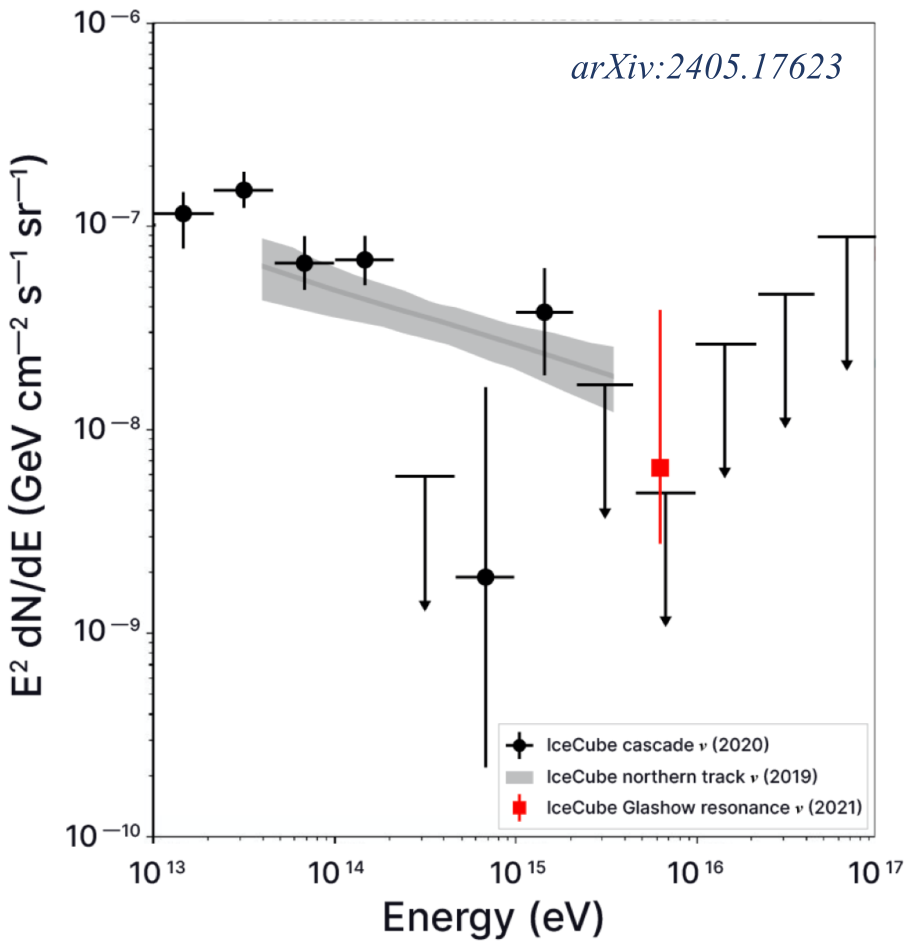


-- 12 strings
-- 885 DOMs

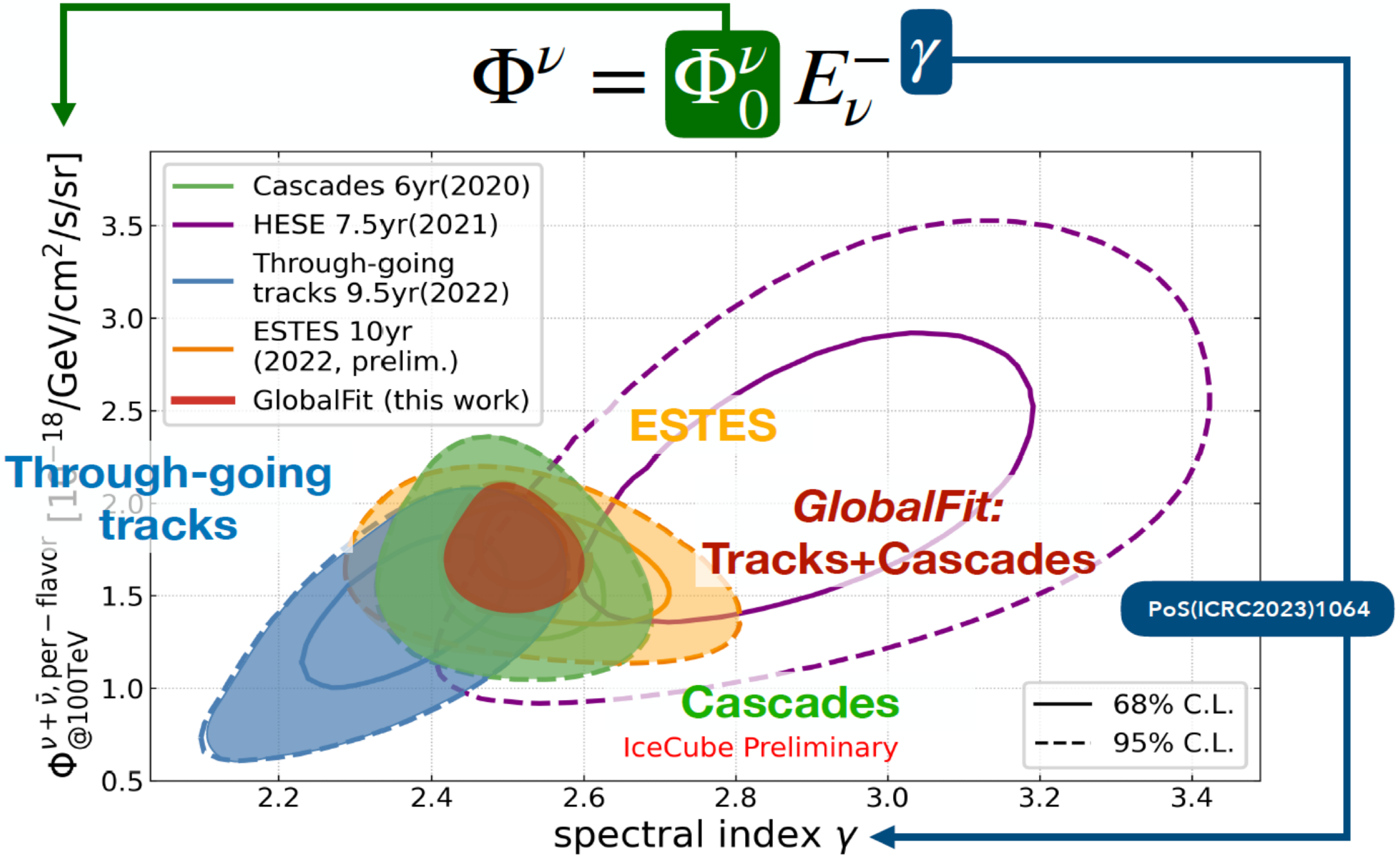
*Art picture by **ANTARES***

Observation of astrophysical neutrino flux

- ❖ **All-sky observation of neutrino flux**
- ❖ **A global fit of the flux by both Track and Cascade events**



$$\Phi^{\nu} = \Phi_0^{\nu} E_{\nu}^{-\gamma}$$



from J. A. Aguilar, on behalf of IceCube, Neutrino2024, Milan

Origins of astrophysical neutrinos

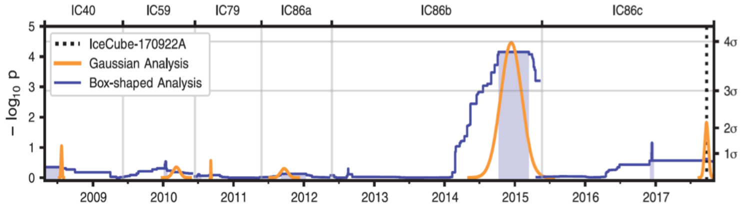
NEUTRINO ASTROPHYSICS

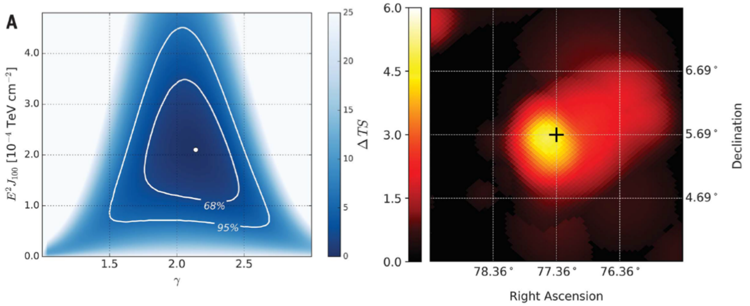
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

(2017)

IceCube Collaboration*†

Science 361 (2018) 6398, 147-151





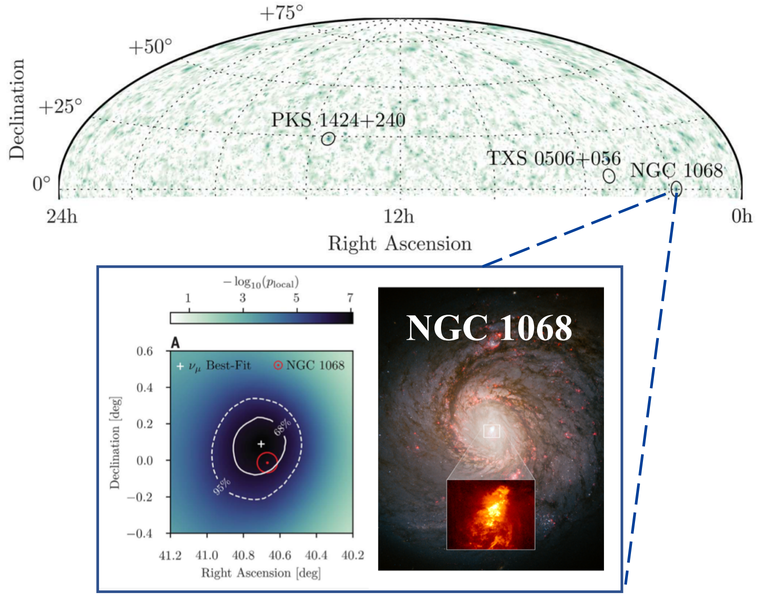
Neutrino energy: **~290 TeV**

Significance: $\mathbf{3.5\sigma}$

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

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



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

Significance: $\mathbf{4.2\sigma}$

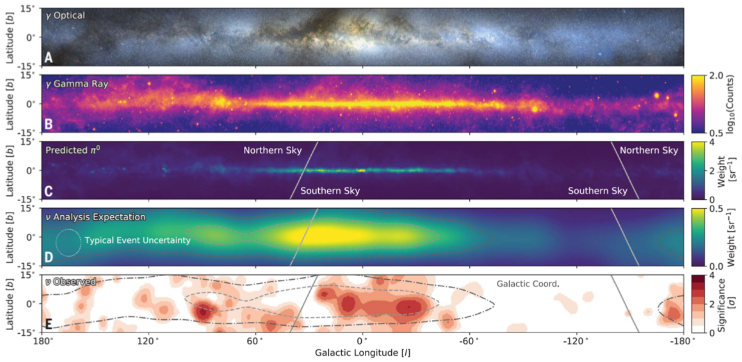
NEUTRINO ASTROPHYSICS

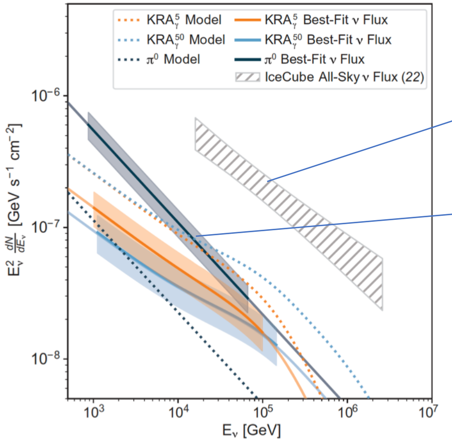
Observation of high-energy neutrinos from the Galactic plane

IceCube Collaboration*†

Science 380, 1338–1343 (2023)

(2023)





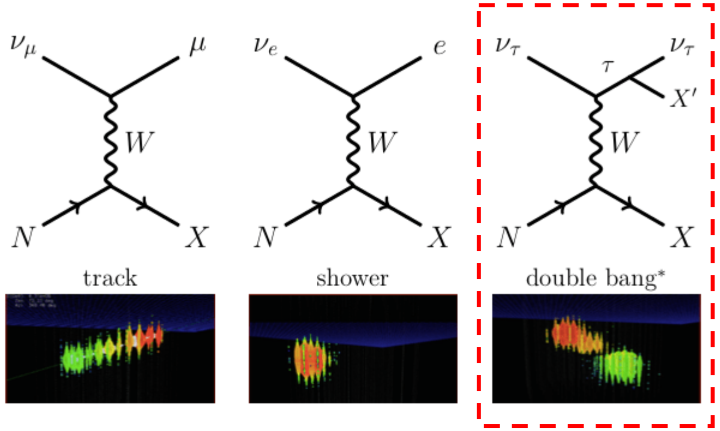
Diffuse flux

Galactic flux

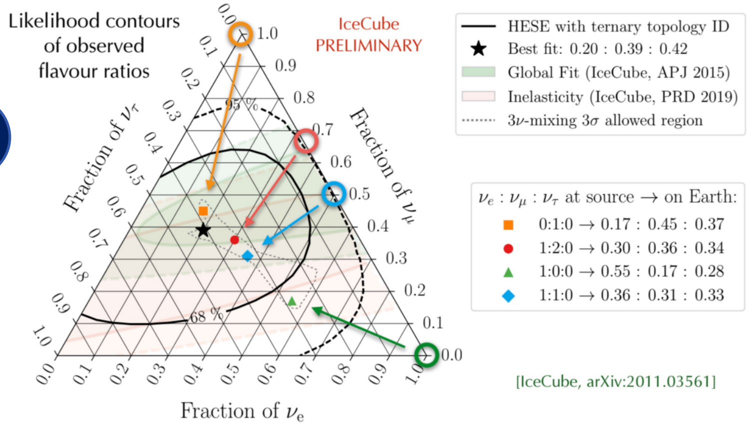
$(> \mathbf{TeV}, \mathbf{4.5\sigma})$

Neutrino flavor detection

❖ **Flavor ratio: a powerful probe for exploring new physics:**

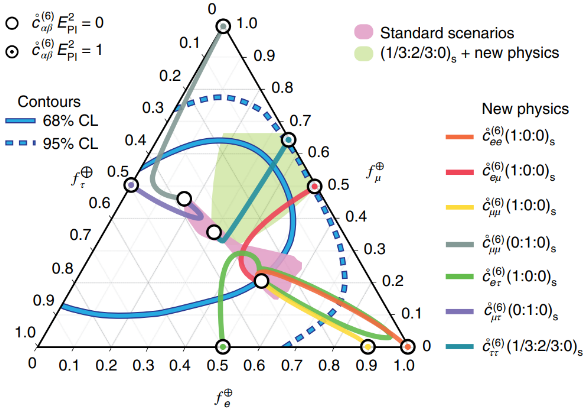


ν_τ



[IceCube, arXiv:2011.03561]

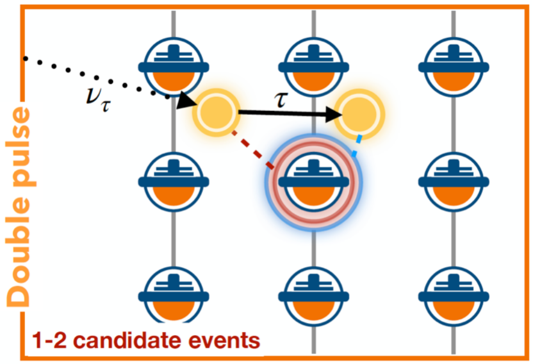
Probe quantum gravity:



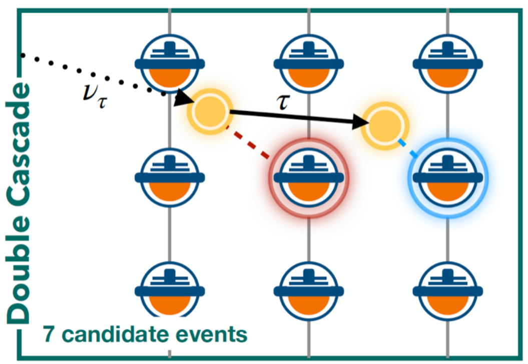
Nature Phys. 18 (2022) 11, 1287-1292

❖ **Observation of astrophysical tau neutrinos with IceCube:**

DOM level

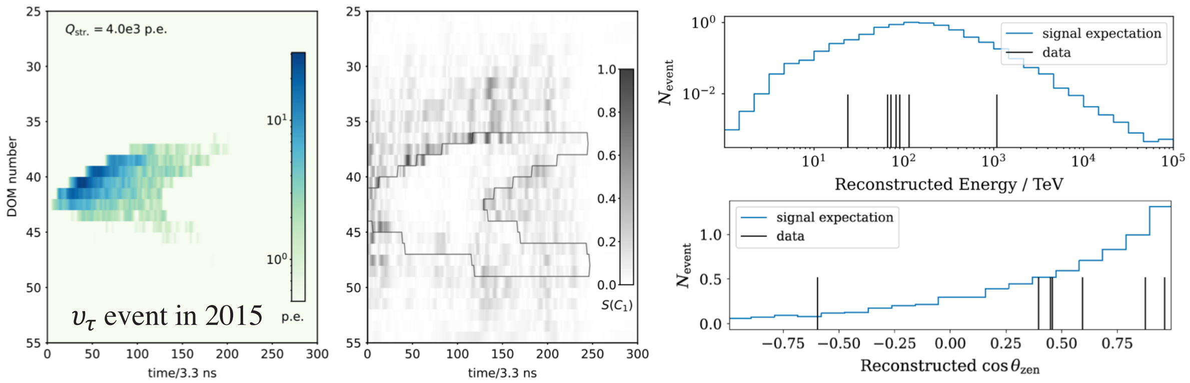


Detector level



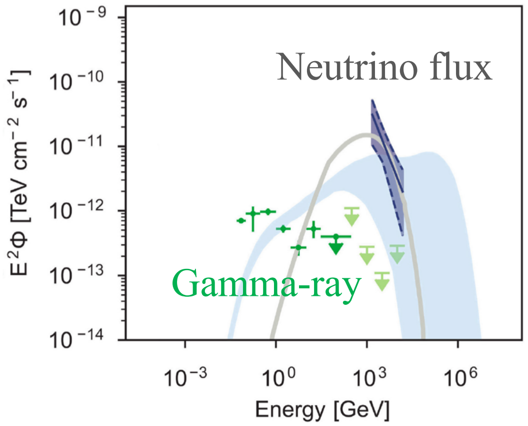
from J. A. Aguilar, on behalf of IceCube, Neutrino 2024, Milan

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

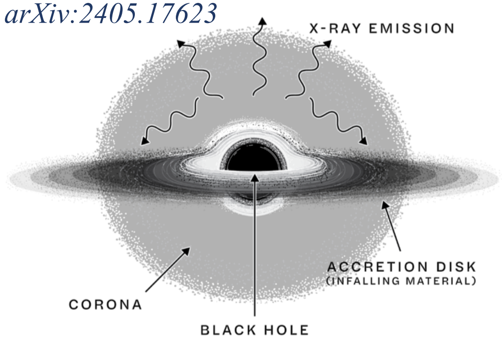


The dawn of neutrino astronomy

❖ Neutrino production region & mechanism



arXiv:2405.17623

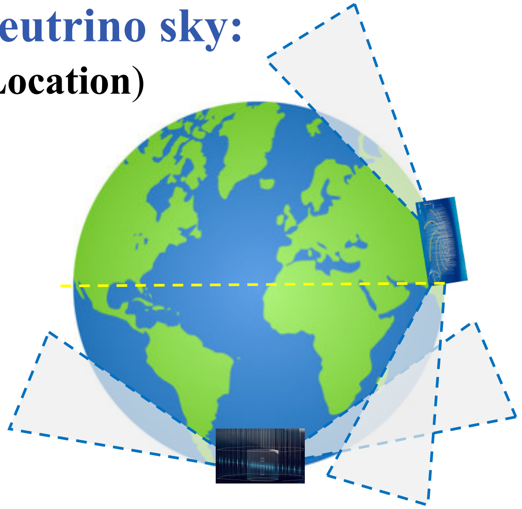


❖ Questions remained for cosmic neutrinos

1. More astrophysical neutrino sources
2. Cosmic-ray production & propagation
3. Neutrino mass/oscillation
4. Physics environment of black hole
5. Fundamental physics: Lorentz invariance, etc.

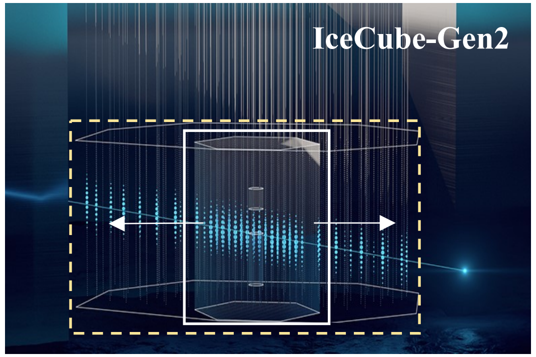
Neutrino sky:

(Location)



Event statistics:

(**Volume**, Detector layout, Depth)

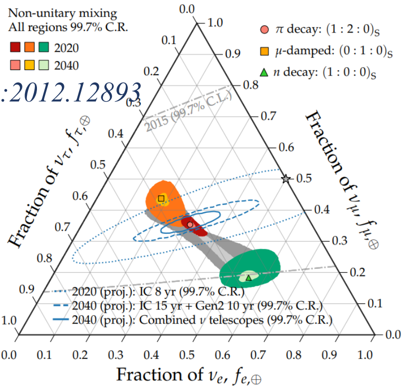


Angular/Energy resolution:

(**Optical medium**, Detector layout)

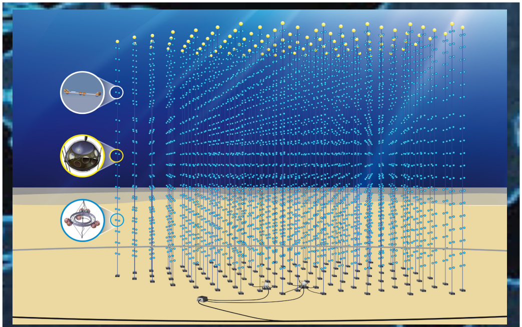
Flavor separation: υ_τ

arXiv:2012.12893



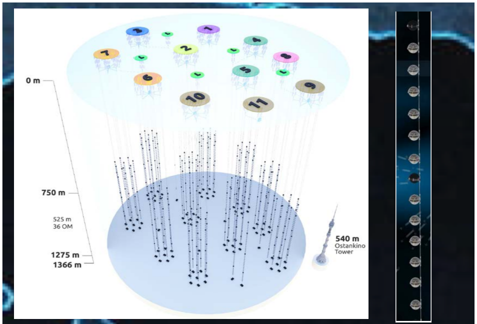
Precise flavor detection at 2040

Next-generation of neutrino telescopes



KM3NeT (Mediterranean Sea)

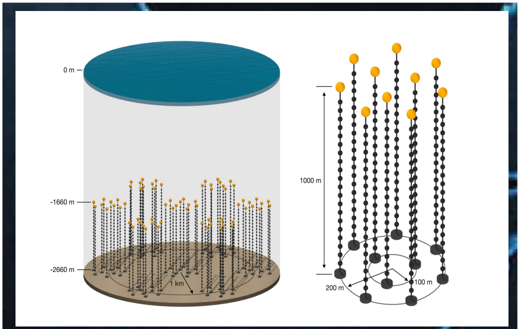
Medium: Deep-sea water
Depth: ~ 3.5 km
Volume: ~ 1 km^3
String number: 115*2 blocks



Baikal-GVD (Lake Baikal)

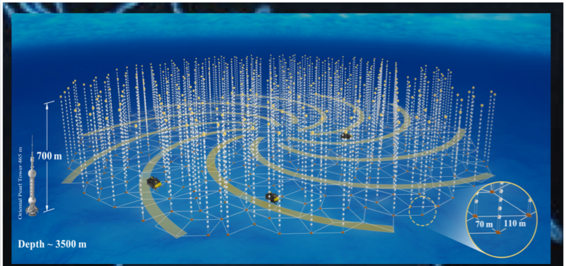
Medium: Deep-lake water
Depth: ~ 1.4 km
Volume: ~ 1 km^3
String number: ~140

(HUNT, NEON)



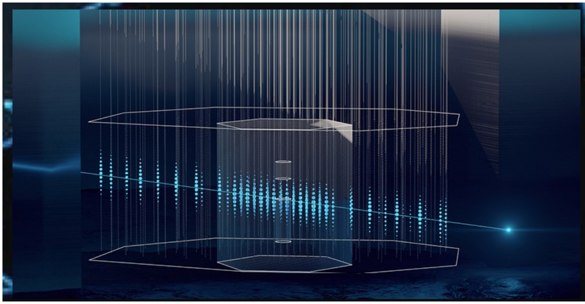
P-ONE (East Pacific Ocean)

Medium: Deep-sea water
Depth: ~ 2.6 km
Volume: ~ 1 km^3
String number: ~70



TRIDENT (West Pacific Ocean)

Medium: Deep-sea water
Depth: ~ 3.5 km
Volume: ~ 8 km^3
String number: ~1000

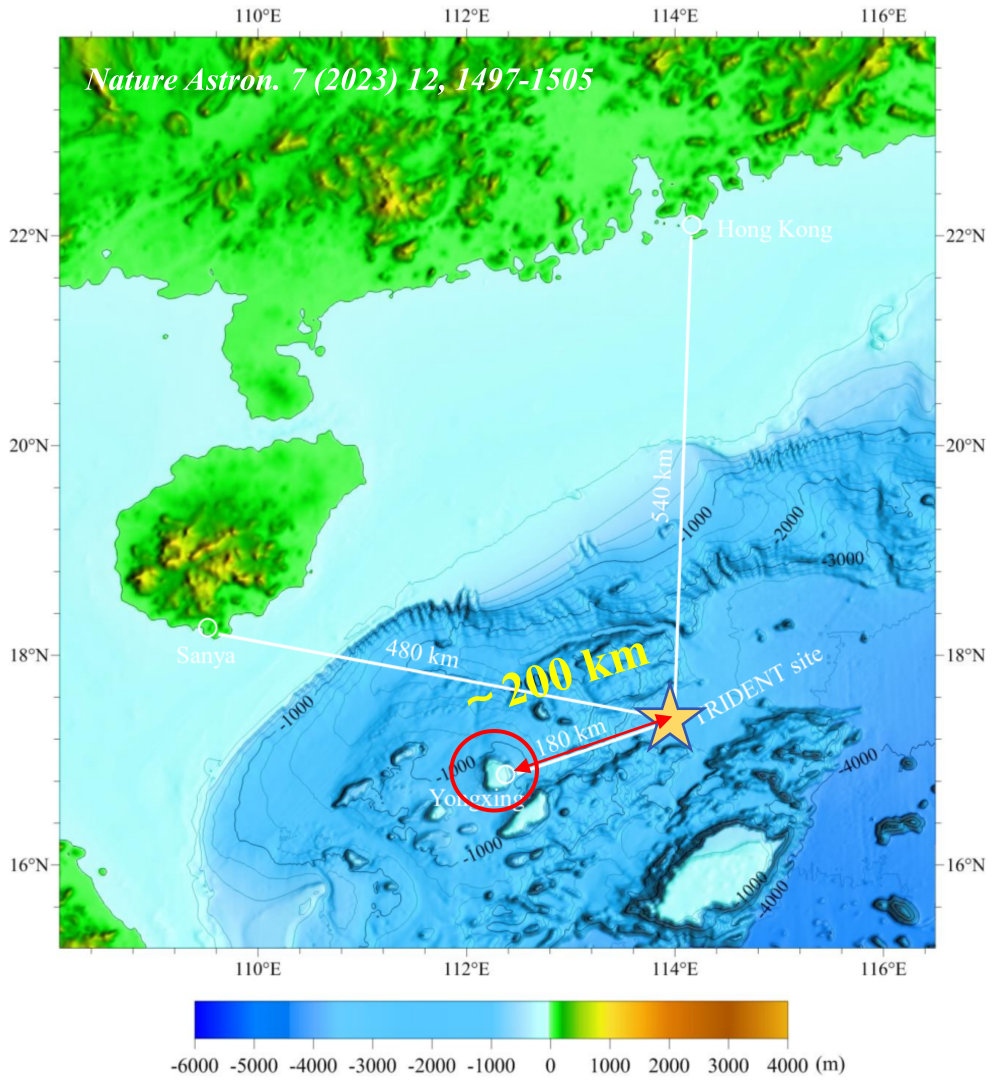


IceCube Gen-2 (South Pole)

Medium: Glacial ice
Depth: ~ 2.5 km
Volume: ~ 8 km^3
String number: ~210

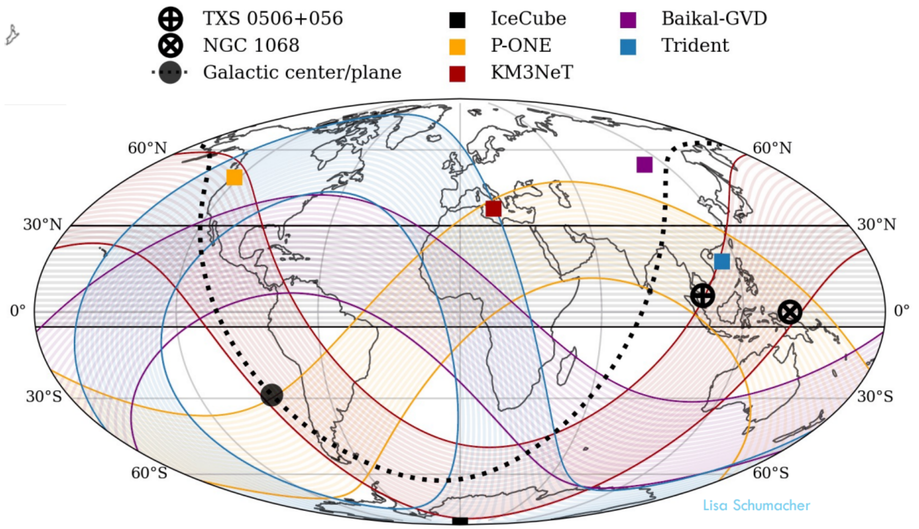
TRopIcal DEep-sea Neutrino Telescope (TRIDENT)

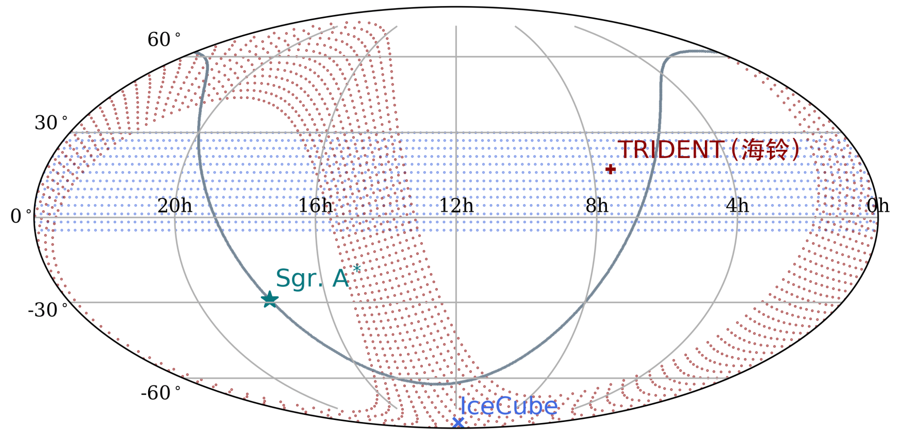
- ❖ **TRIDENT location (~ $114.0^{\circ}E, 17.4^{\circ}N$) :**



Nature Astron. 7 (2023) 12, 1497-1505

- ❖ **All-sky scanning of astrophysical neutrinos:**





Detector layout of TRIDENT

Water depth: ~3500m

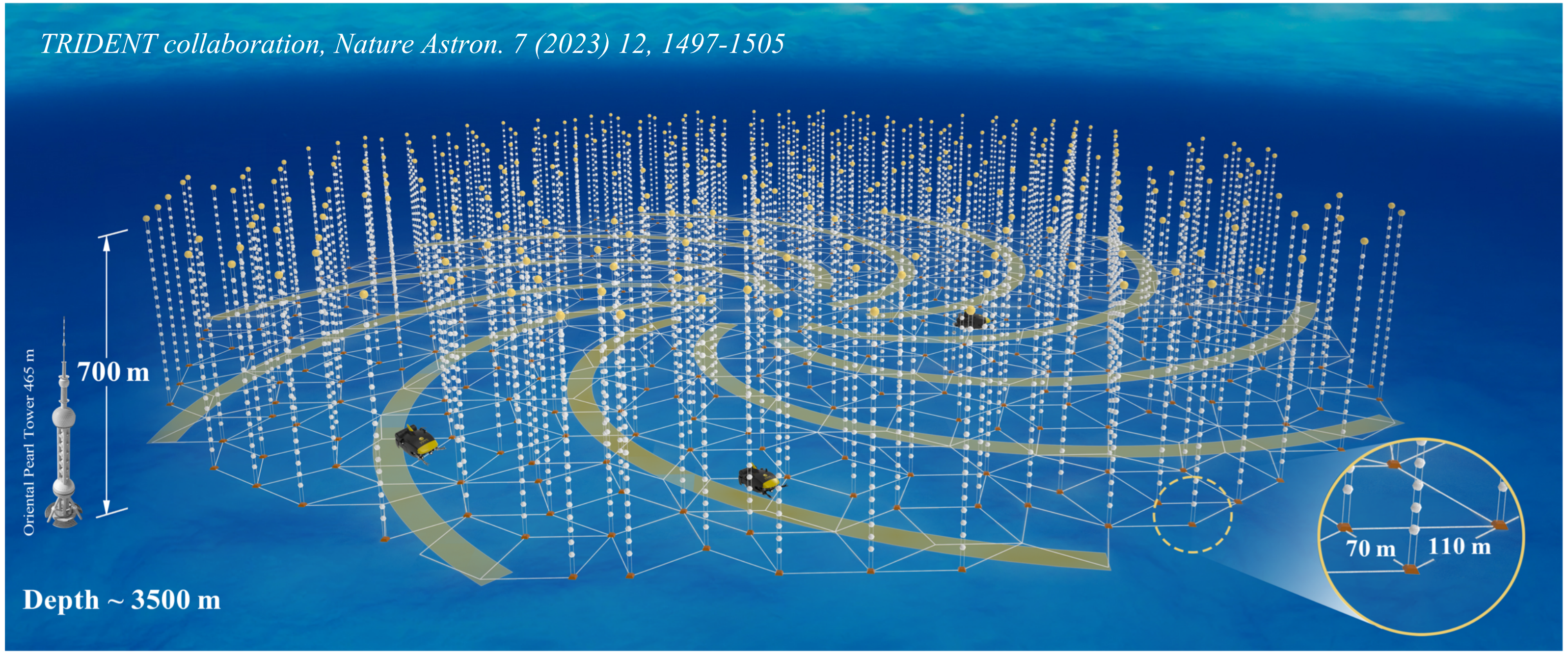
Number of strings: ~1000 (20 hDOMs per string)

Inter-string distance: 70m/110m, **Inter-DOM distance:** 35m

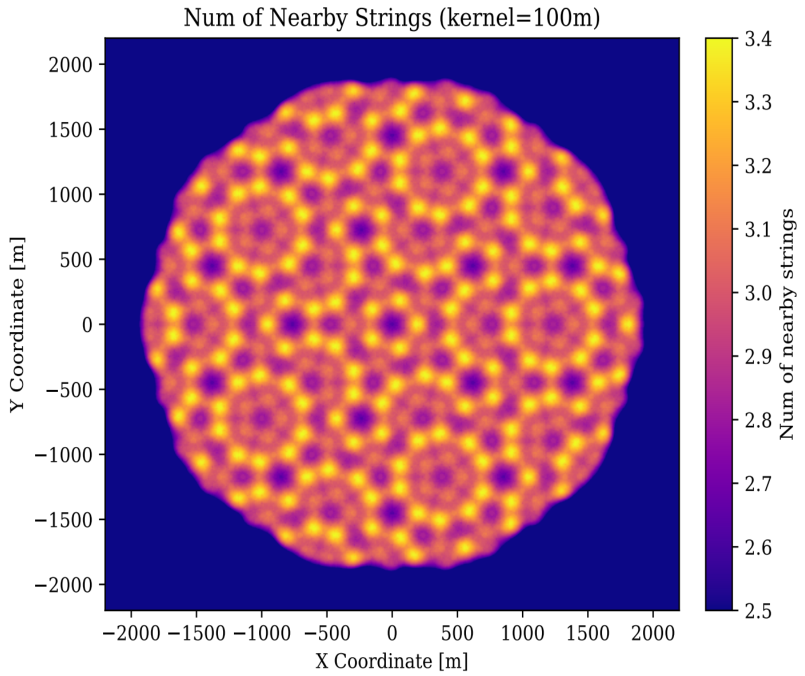
Detection Volume: ~8 km^3

Penrose-tiling geometry:

1. Avoid corridor events
2. Balance track/cascade events
3. Paths for underwater-maintenance

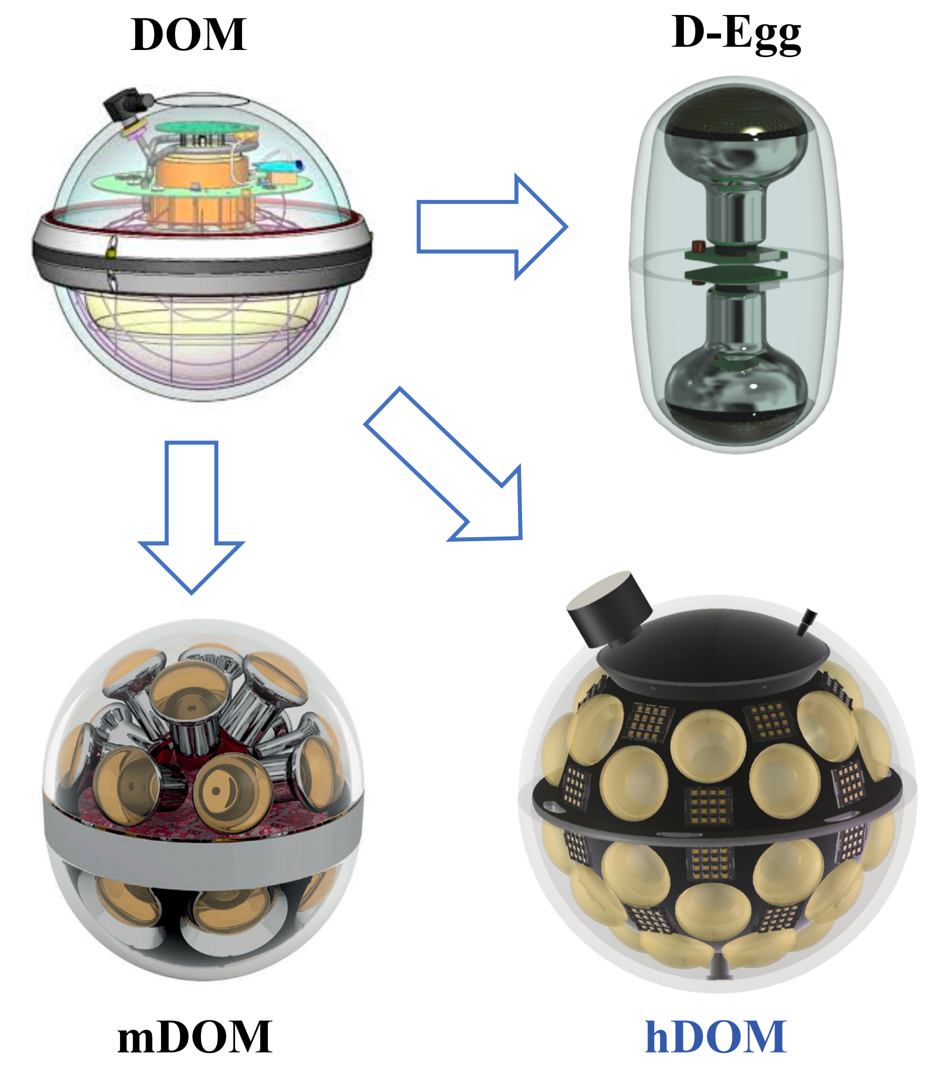


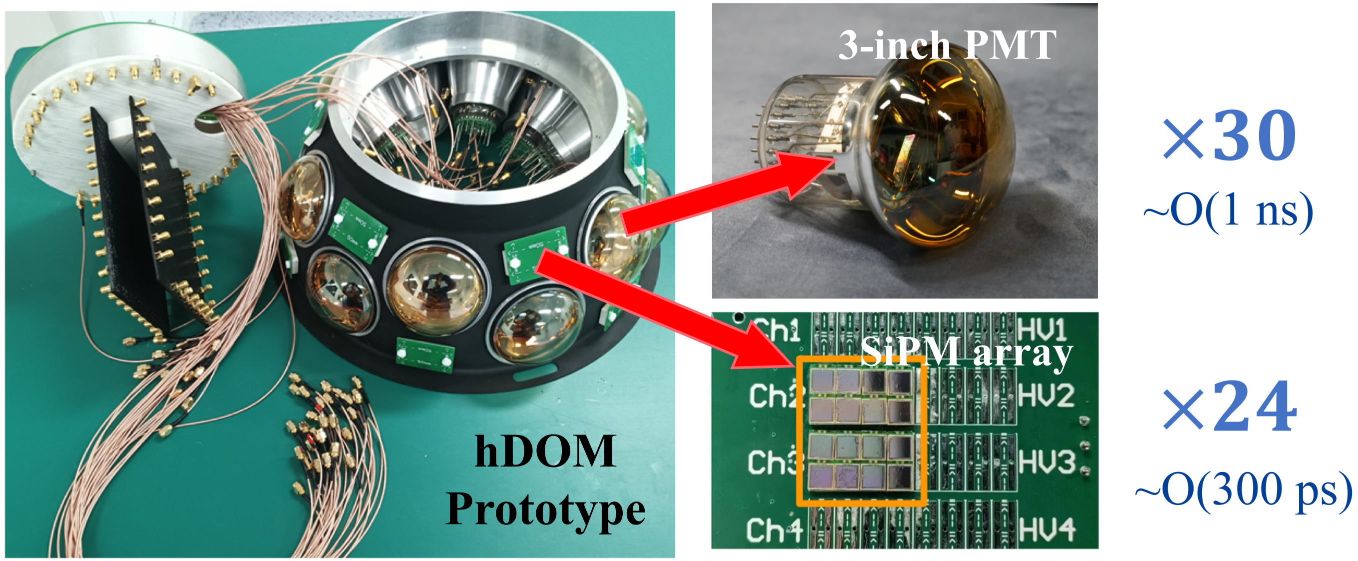
TRIDENT collaboration, Nature Astron. 7 (2023) 12, 1497-1505



Num of Nearby Strings (kernel=100m)

hybrid Digital Optical Module (hDOM)





TRIDENT hDOM: PoS ICRC2023 (2023) 1213

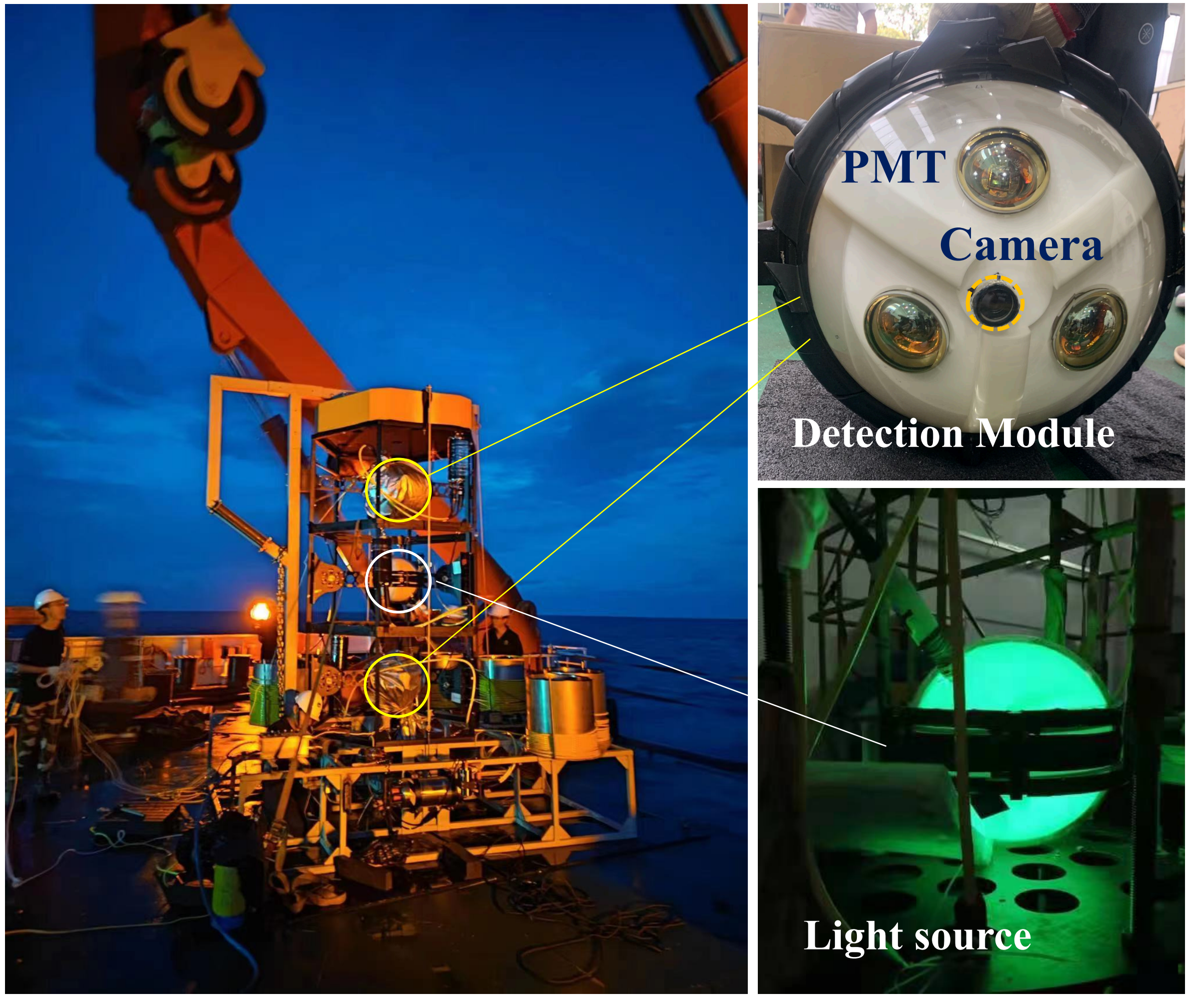
TRIDENT SiPM: JINST 19 (2024) 06, P06011

Pixelized PMT + SiPM layout:

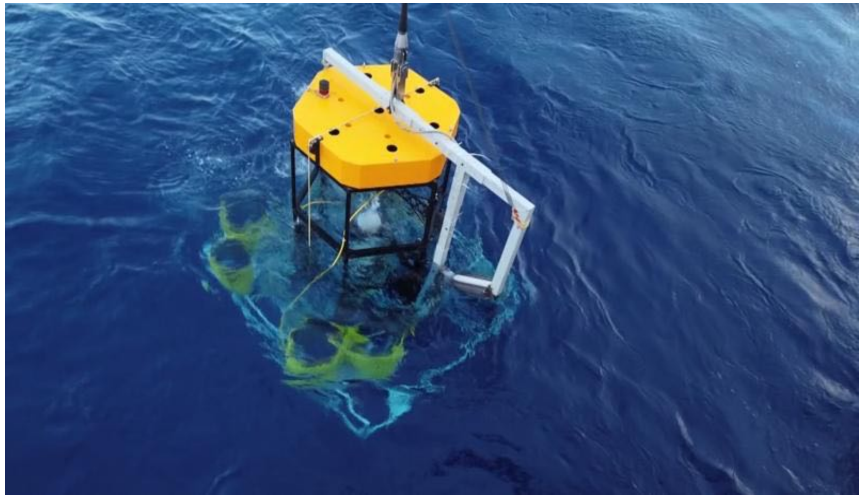
1. 4π photon coverage (+10% by SiPM)
2. Better SPE time resolution (without magnetic shielding)
3. PMT coincidence trigger for K40/dark noise
4. Photon distribution on hDOM surface

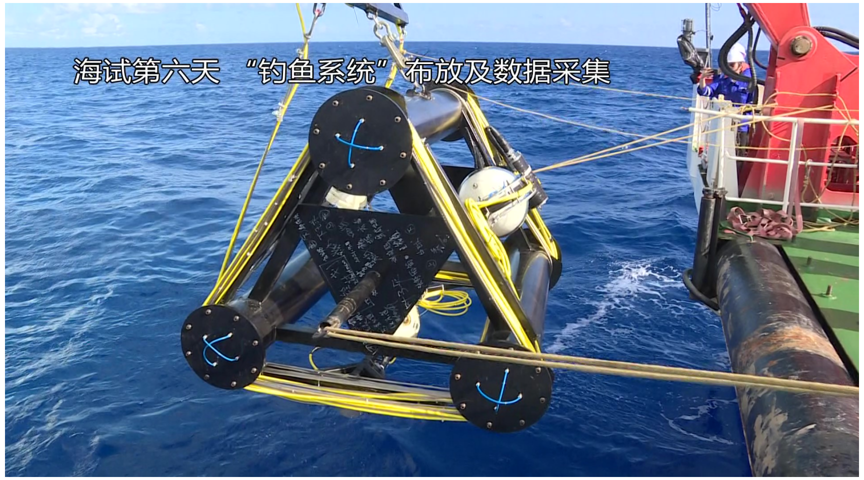
TRIDENT Pathfinder experiment (2021)

- ❖ TRIDENT Explorer (T-REX)

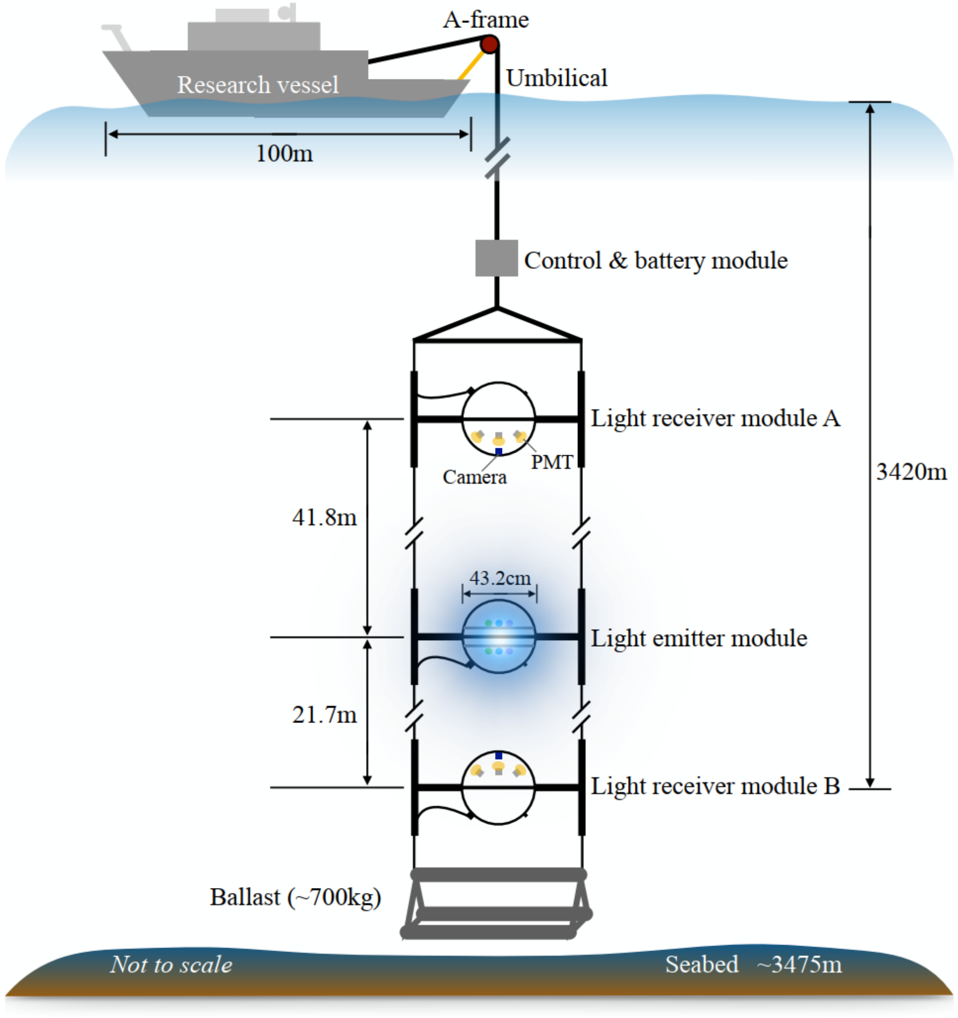


- ❖ T-REX deployment (depth of 3420m)





T-REX apparatus



Experiment goals:

1. **Optical properties**
2. Oceanographic conditions
3. Radioactivity (K40 decay)
4. Prototype test at 35MPa

Light Receiver Module A&B :

Two systems: **PMT** and **Camera** systems

Synchronization :White Rabbit (< 1ns)

(PMT: JINST 19 (2024) 05, P05040, Camera: arXiv:2407.19111)

Light Emitter Module :

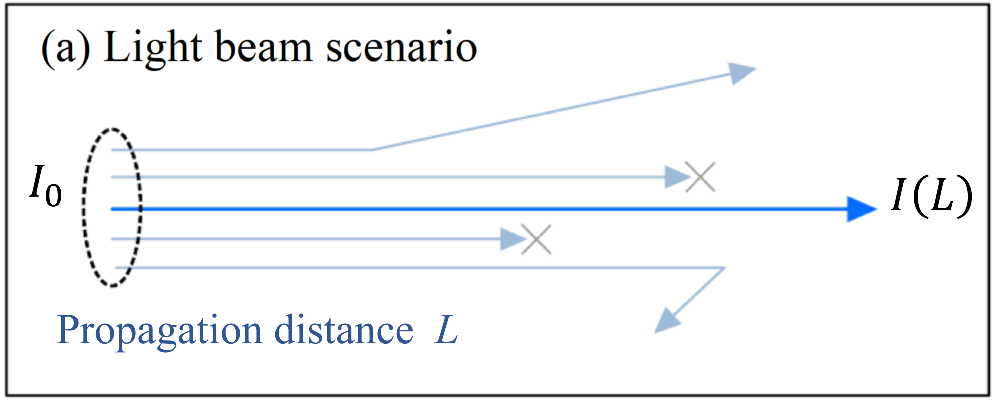
Three wavelengths: **405nm, 460nm, 525nm**

Pulsing mode (PMT) & Steady mode (Camera)

(Light source: NIM-A 1056 (2023) 168588)

Optical calibration in water-based neutrino telescopes

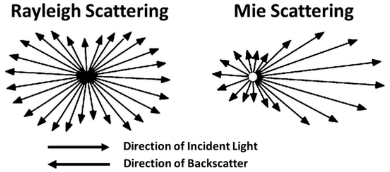
❖ The canonical optical parameters:



Absorption length (λ_{abs}) ~ photon loss

Scattering length (λ_{sca}) ~ photon deflection

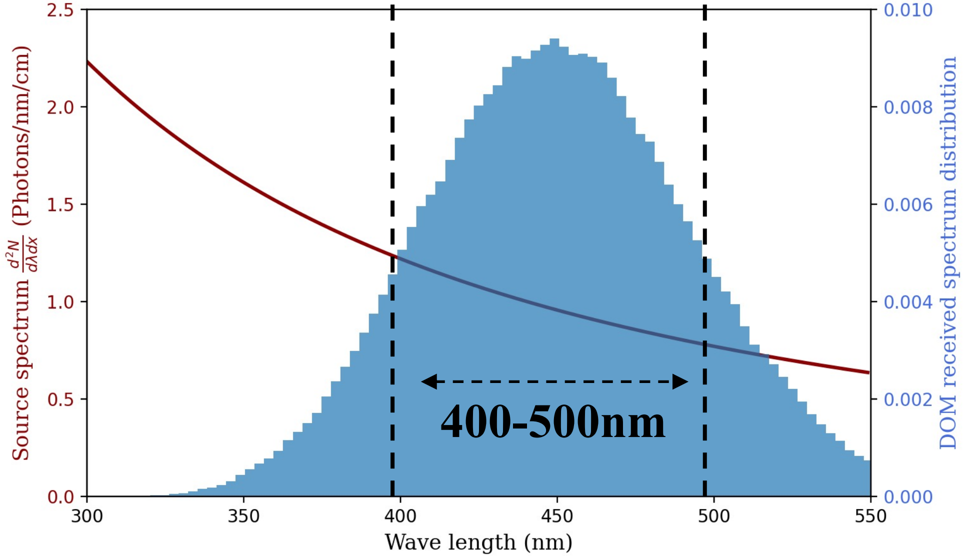
- Rayleigh scattering (λ_{Ray}):
- Mie scattering ($\lambda_{Mie}, \langle cos\theta_{Mie} \rangle$):



Attenuation length (λ_{att}):

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

❖ Cherenkov waveband in water medium



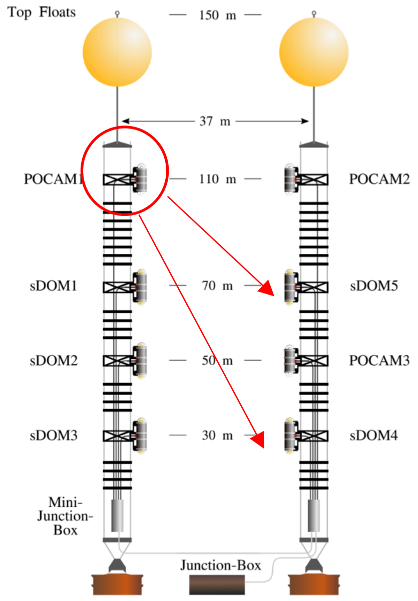
❖ Extra challenge in optical calibration:

1. Dynamic water medium
2. Time-varying optical properties
3. Non-uniformity in large volume/different depths
4. Bio-activity / Sedimentation

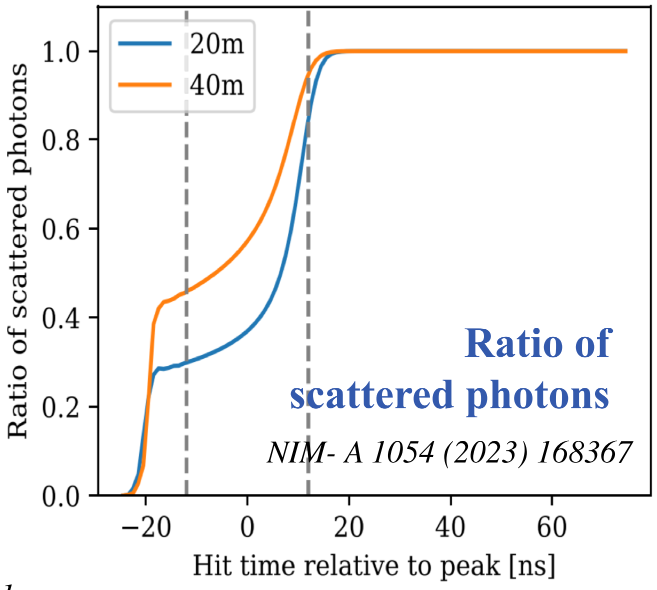
The commonly-used optical calibration methods

PMT + Pulsing light source:

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



Eur.Phys.J.C 81 (2021) 12, 1071



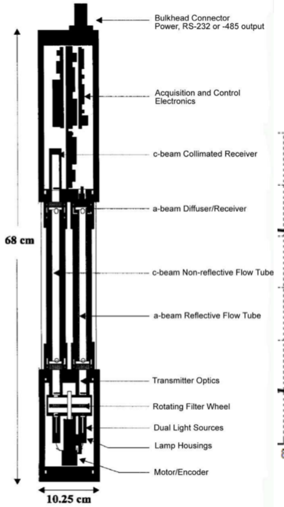
Ratio of scattered photons

NIM- A 1054 (2023) 168367

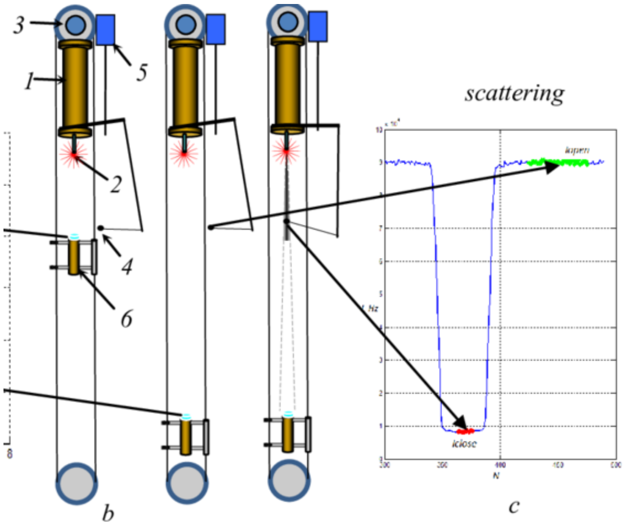
1. **Must work under single-photon mode**
2. **Hours-long data accumulation**
3. **Hard to separate the direct photons, “$\lambda_{\mathrm{eff,att}}$”**

Specialized laser facility:

(KM3NeT-AC9, Baikal-5D)



WET lab, AC9



Baikal-5D, PoS ICRC2023 (2023) 977

1. **Nice precision of canonical optical parameters**
2. **Need extra calibration/deployment**
3. **Localized measurement**

The camera system and its control module

Camera + Isotopic steady light source:

1. **O(~0.05s) exposure time**: **Real-time calibration**
2. **~8cm size**: Integrated in DOMs, across the detector
3. **Other applications:** Environment & Self-monitoring
4. **Robustness:** no need for precise synchronization

Lens: Computar-M2518

f =25mm

Camera: MER-502-79U3M

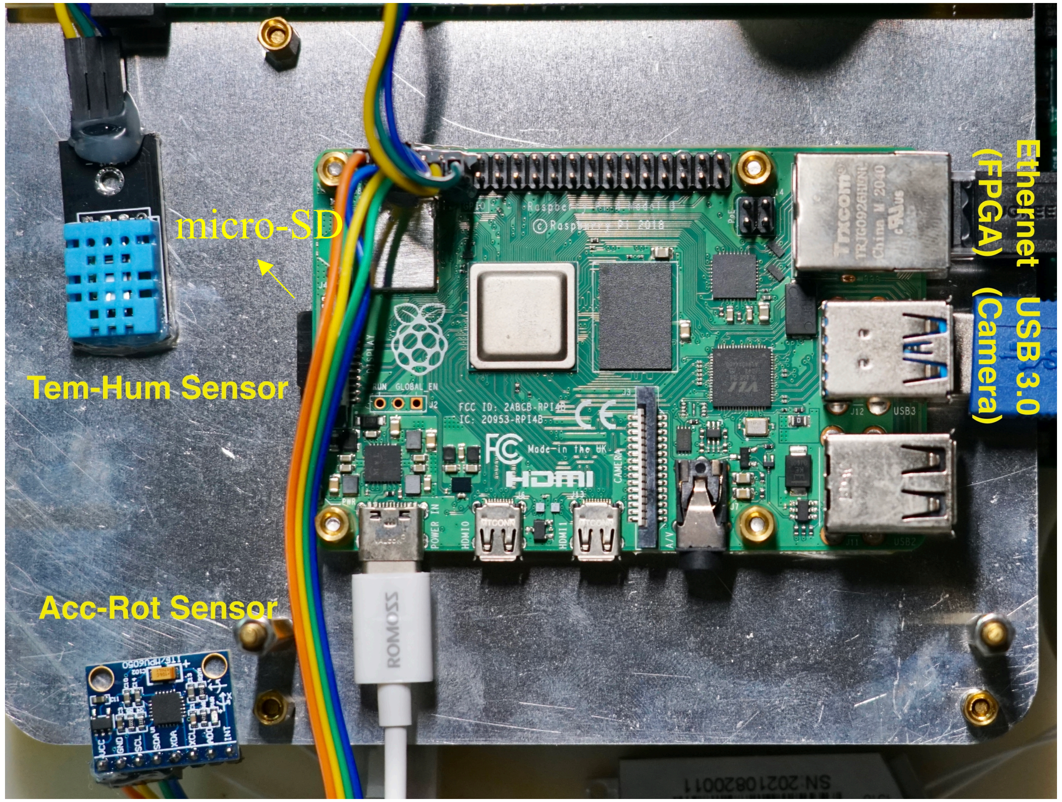
CMOS: Sony IMX-250,~5M Pixels

Power~2.7 W

Viewing angle ~16° in water

Control & DAQ module : Raspberry 4Pi & FPGA

1. Two additional sensors for DOM monitoring
2. **Real-time data transmission/ Remote operation**



Camera settings during the data taking process

1. Exposure time scanning:

Fast mode: 0.02s

For 460nm: 0.05s

For 525nm: 0.07s

For 405nm: 0.11s

LED brightness calibration in lab

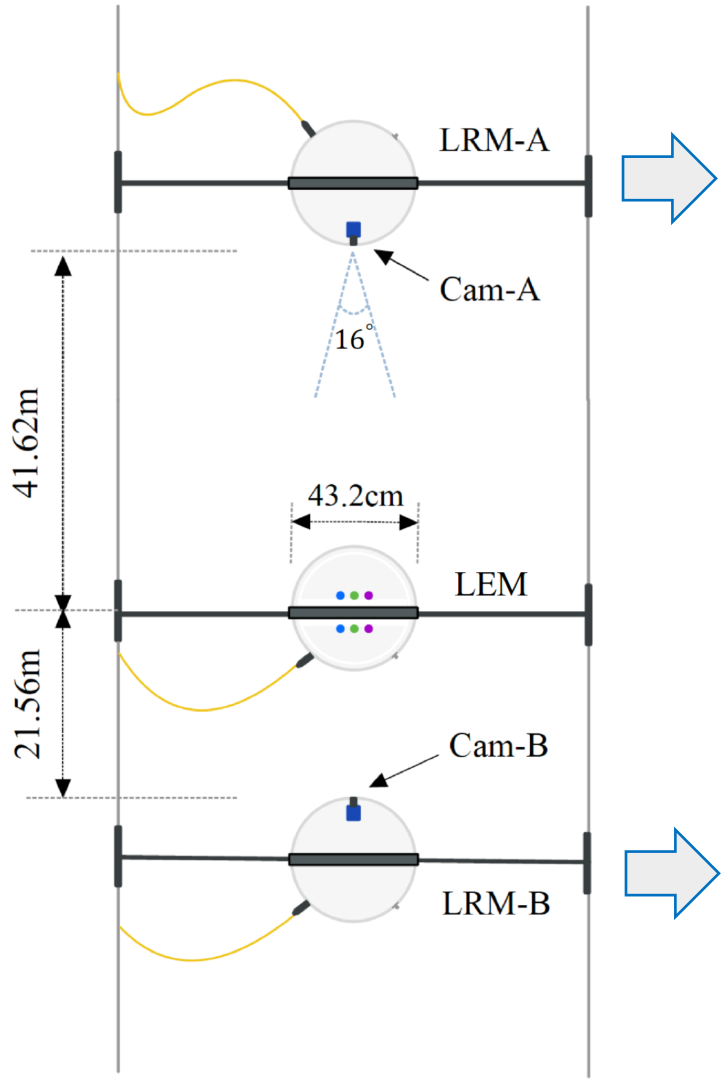
Environment mode: 0.5s, 1.0s

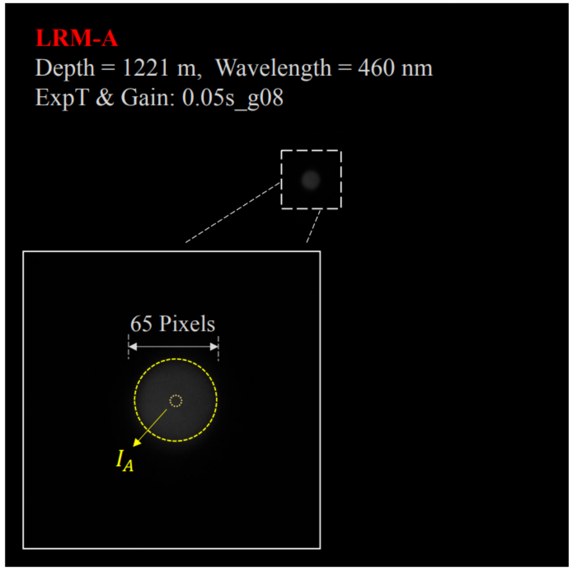
2. Gain scanning:

Gain = 0~20, step2

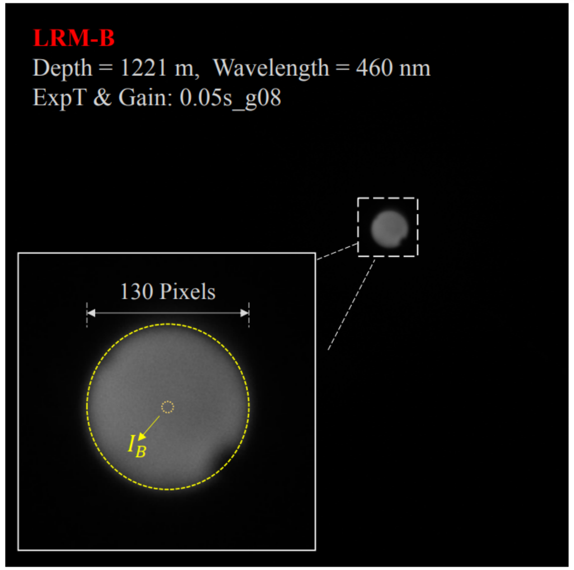
For each wavelength (< 8 min):

ExpT * Gain * 20 pics = 1200 pics





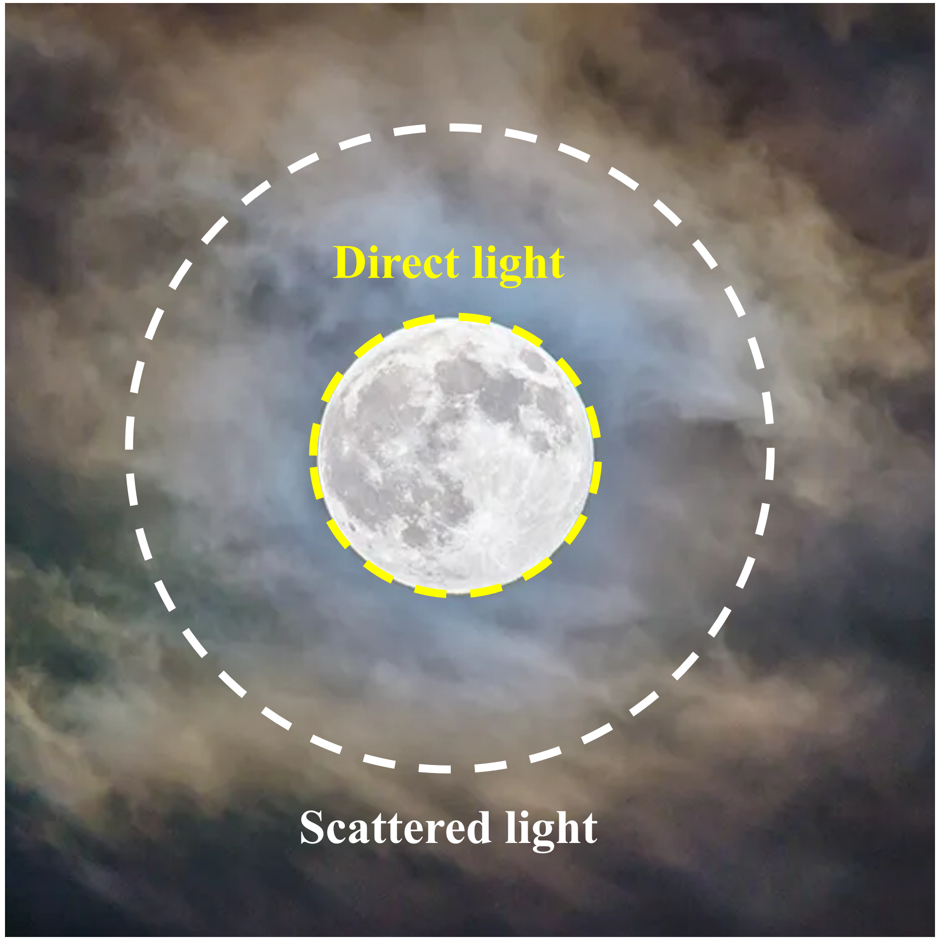
LRM-A
Depth = 1221 m, Wavelength = 460 nm
ExpT & Gain: 0.05s_g08



LRM-B
Depth = 1221 m, Wavelength = 460 nm
ExpT & Gain: 0.05s_g08

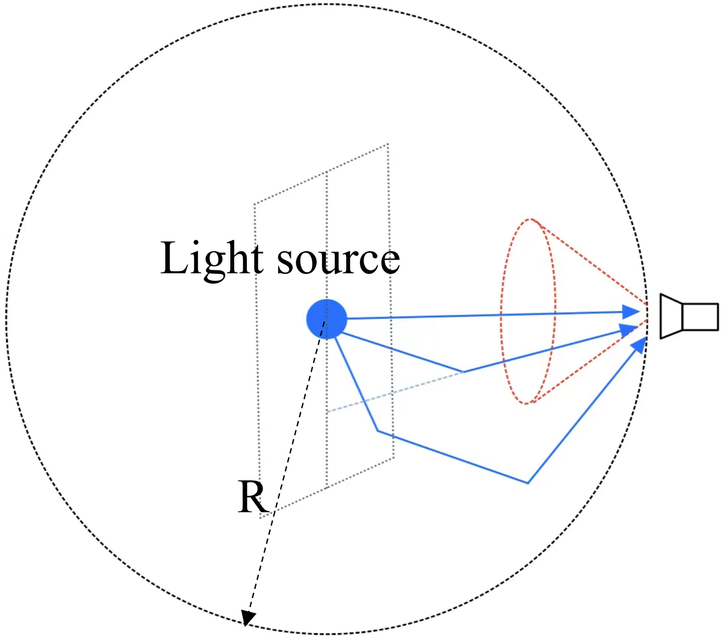
Optical measurement strategies of the camera system

- **Exclude scattered light by viewing angle:**



Direct light: $I_{dir}(R) = I_0 \cdot e^{-\left(\frac{R}{\lambda_{abs}}+\frac{R}{\lambda_{sca}}\right)} = I_0 \cdot e^{-\frac{R}{\lambda_{att}}}$

Separate the direct light:



Camera (direction, pixel)

PMT(time ~ ns)

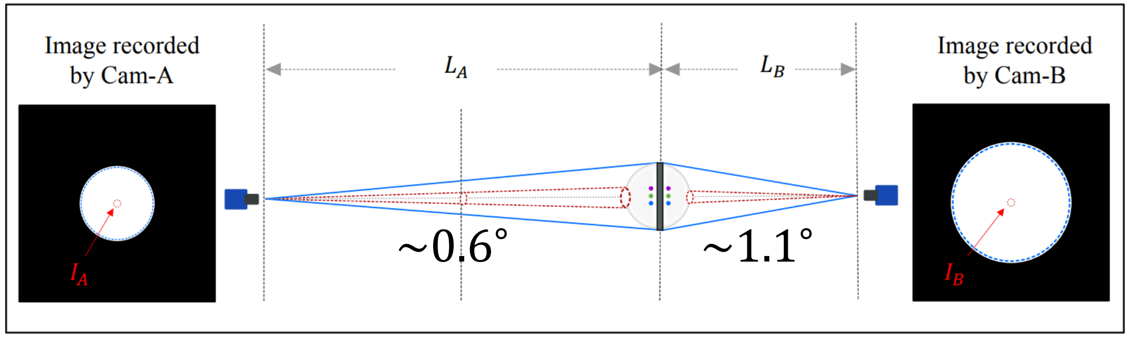
The I_{center} method for λ_{att} measurement

❖ **Using the mean gray value of the Centroid Pixel:**

Pixel (Exclude scattered light by a small angle)

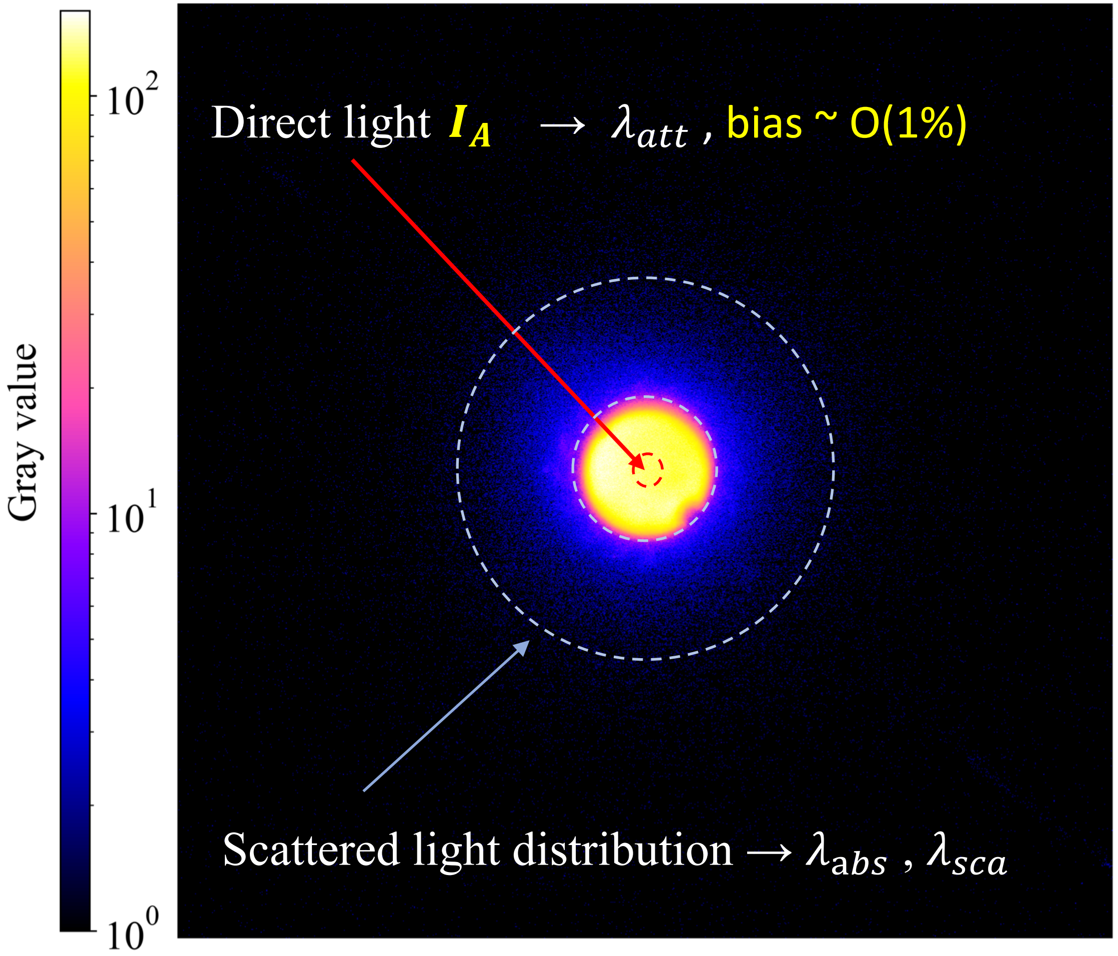
⇕

Within a unit solid angle: $I_{dir}(R) = I_0 \cdot e^{-\frac{R}{\lambda_{att}}}$



I_{center} method: $\lambda_{att} = -(L_A - L_B)/\ln(-\frac{I_A}{I_B} \cdot \frac{I_0'}{I_0})$

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

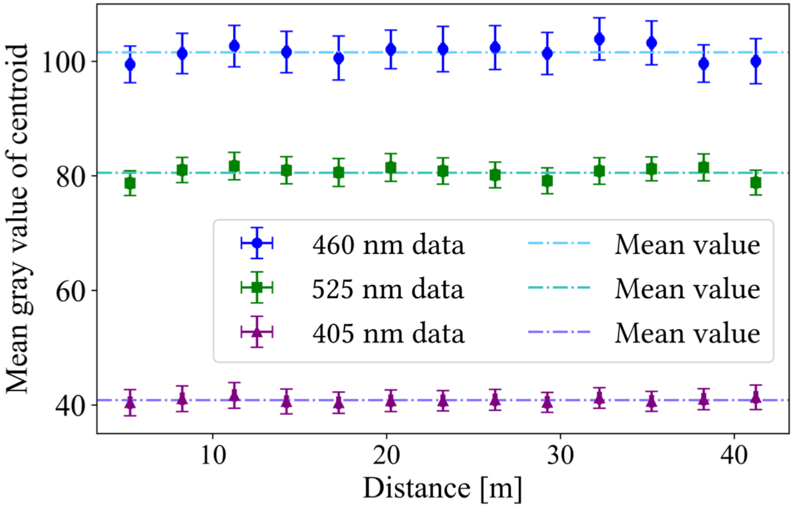


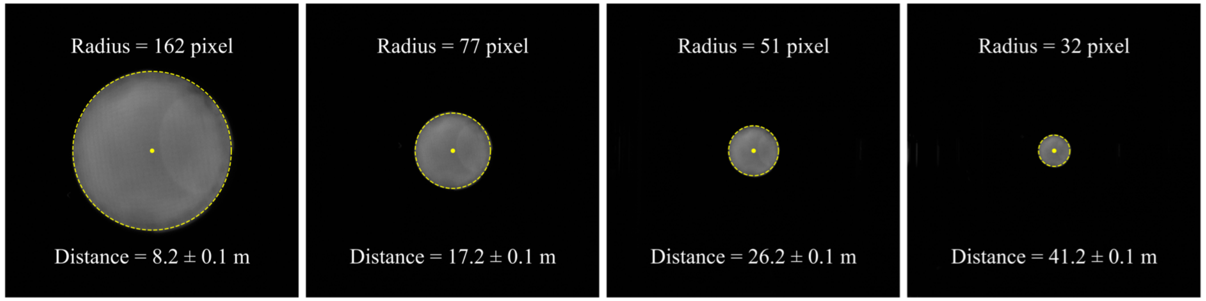
Direct light I_A → λ_{att} , bias ~ O(1%)

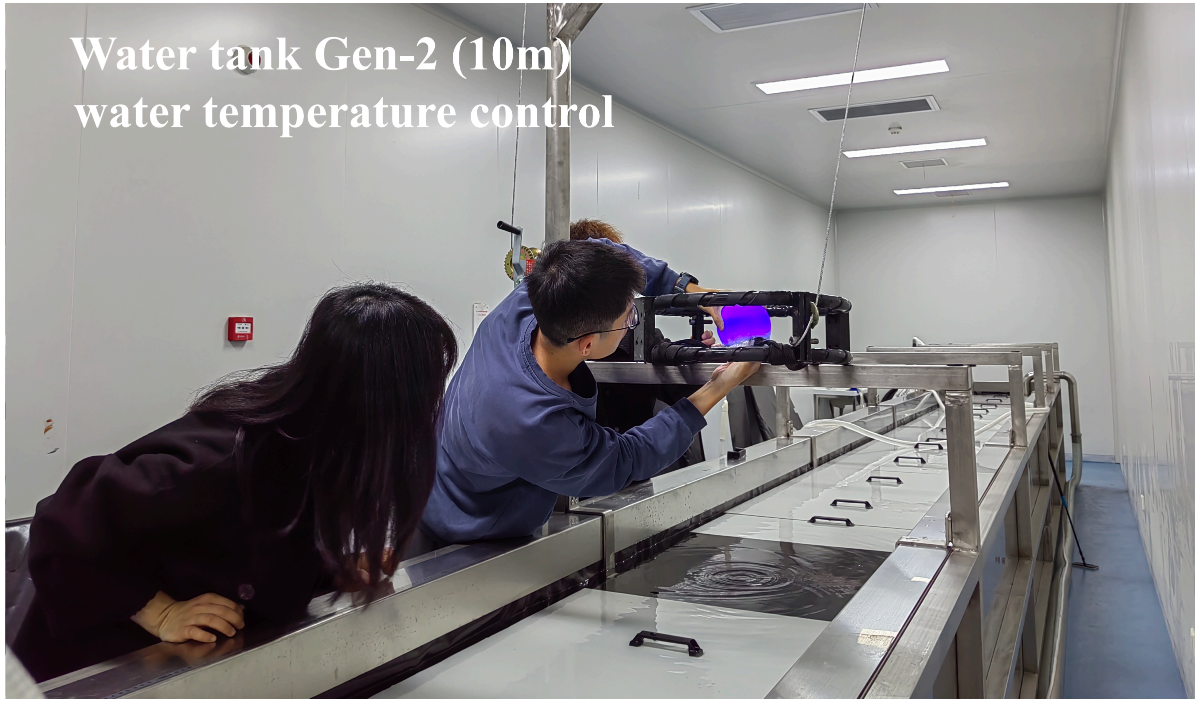
Scattered light distribution → λ_{abs} , λ_{sca}

Verification of the I_{center} method

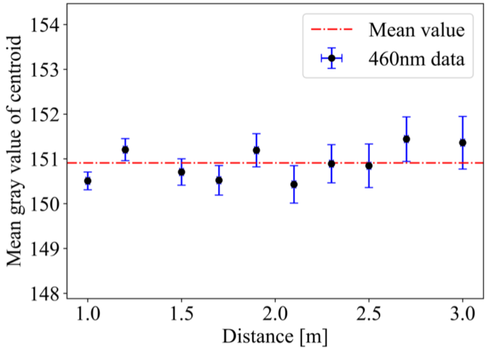
❖ **Long-distance test in air [5m, 42m]**



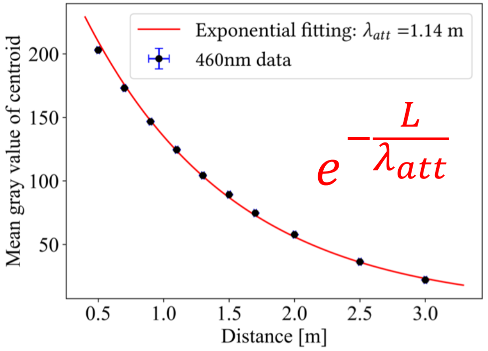




❖ **Water tank experiment to test I_{center}**



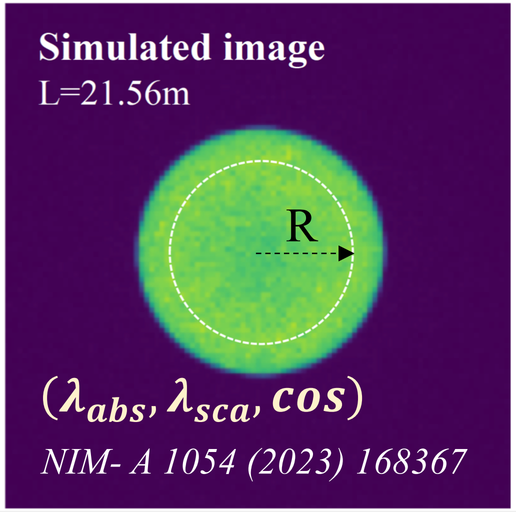
No water

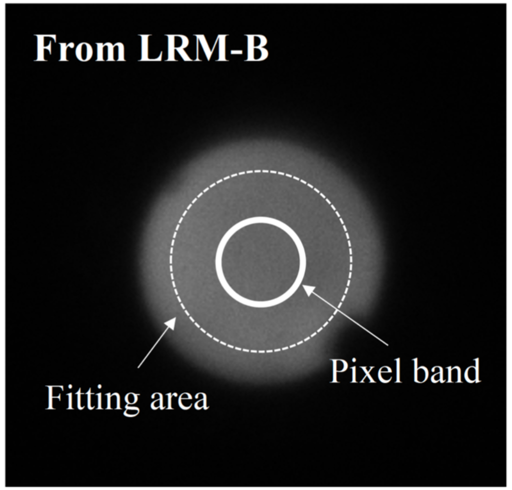


After filling water

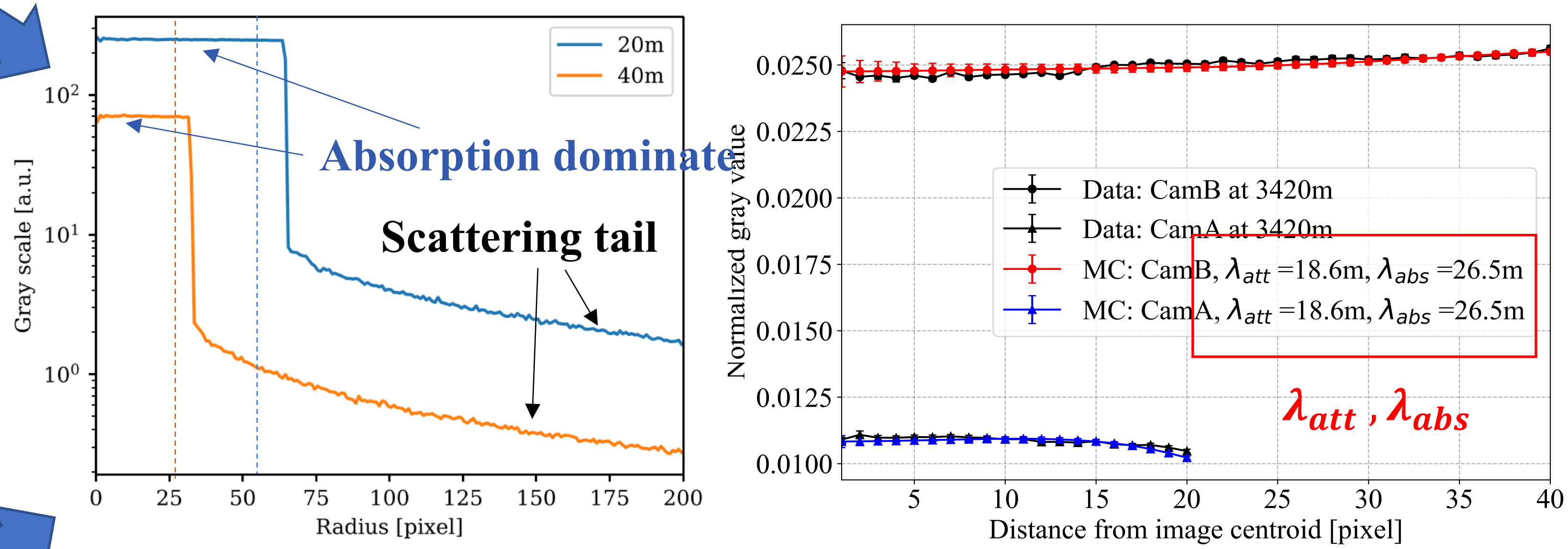
χ^2 fitting method for λ_{att}, λ_{abs}, λ_{sca} measurement

- **Comparing the gray value distribution of Real & Geant4 Simulated images:**





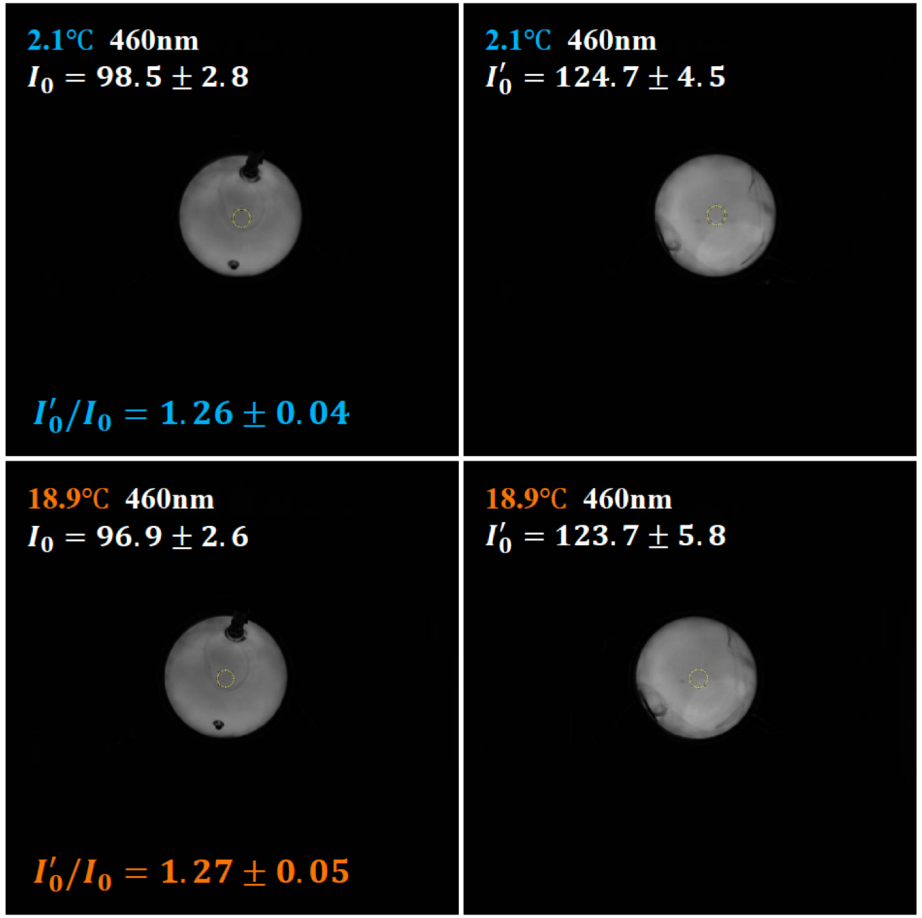
2D image → Normalized 1D gray value profile



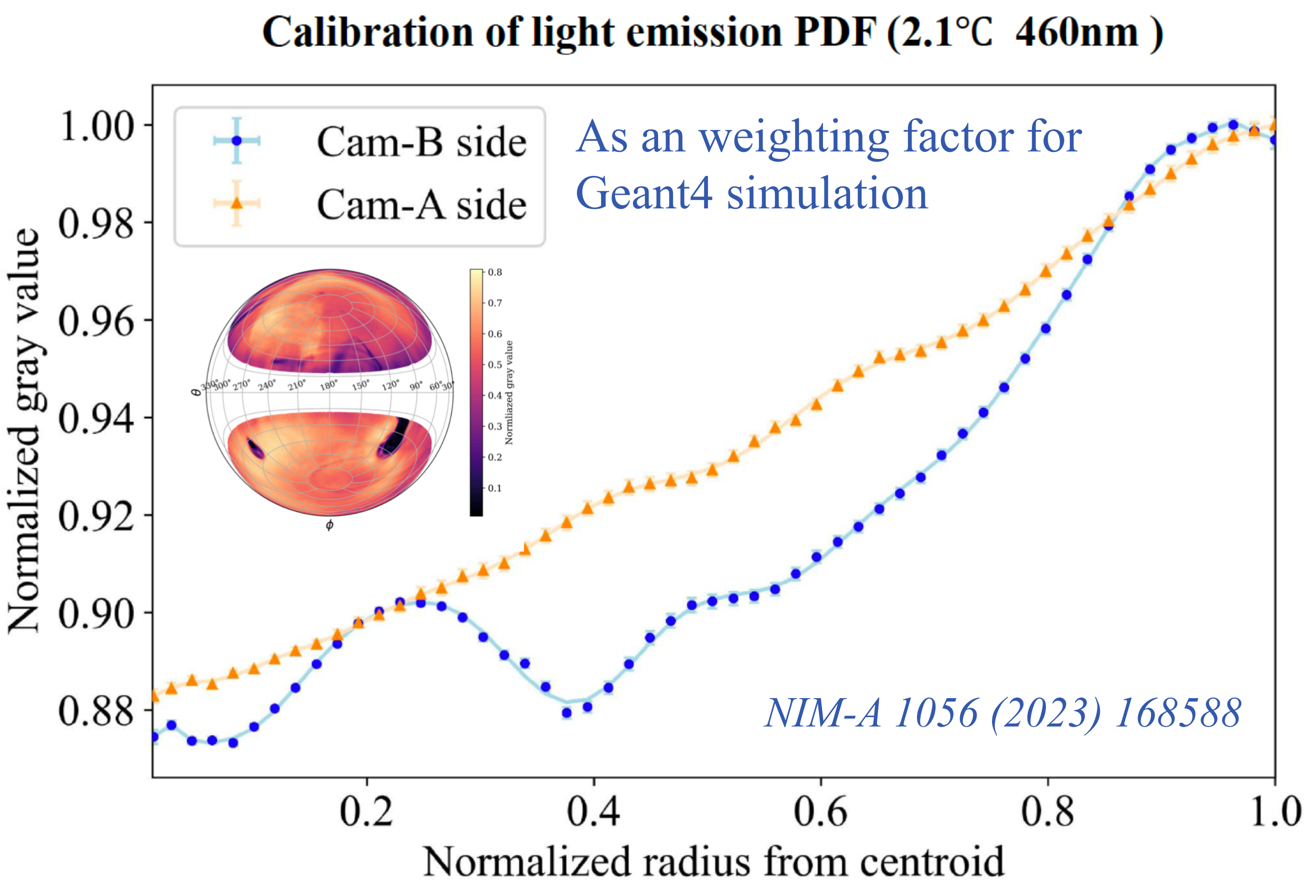
By minimizing: $$\chi^2 = \sum_{i=1}^{N} \frac{[M_i - T_i(1+\sum_{k=1}^{K}\epsilon_k)]^2}{\sigma_{Mi}^2 + \sigma_{Ti}^2} + \sum_{k=1}^{K} \frac{\epsilon_k^2}{\sigma_k^2}$$

Low-temperature calibration

Calibrate the cameras in deep-sea temperature



Calibrate the emission PDF of the T-REX light source

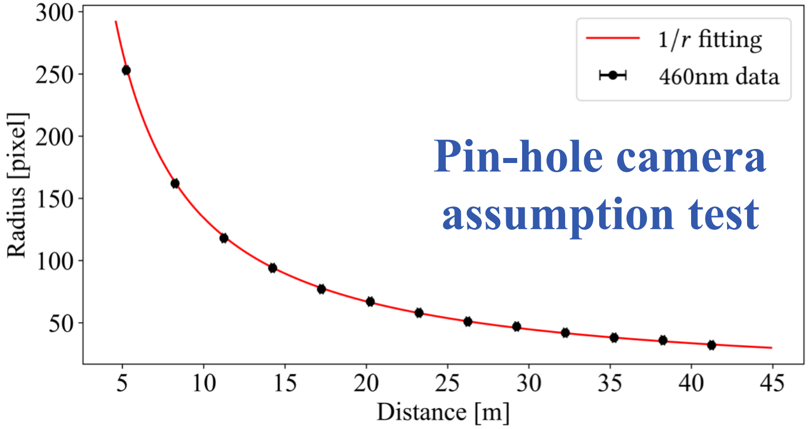

Calibration of light emission PDF (2.1℃ 460nm)

As an weighting factor for Geant4 simulation

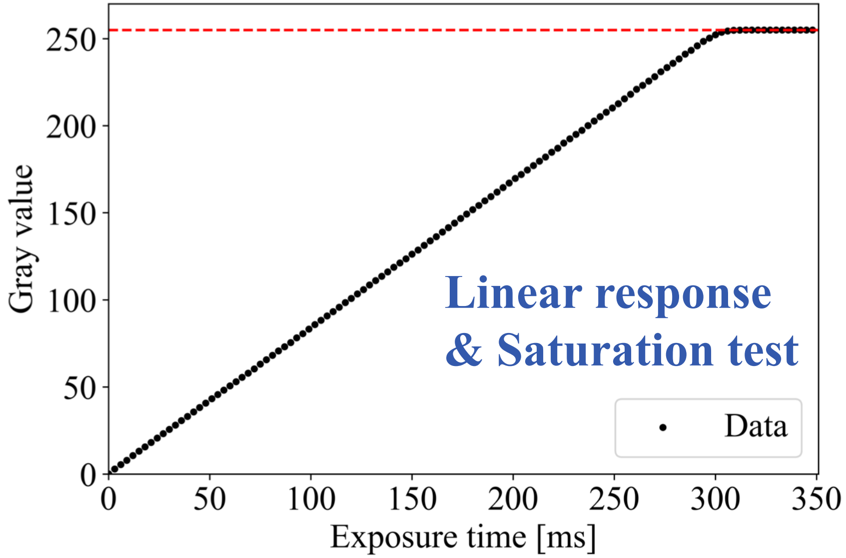
NIM-A 1056 (2023) 168588

Camera response calibration

- **Distortion test in long distance**



Pin-hole camera assumption test



Linear response & Saturation test

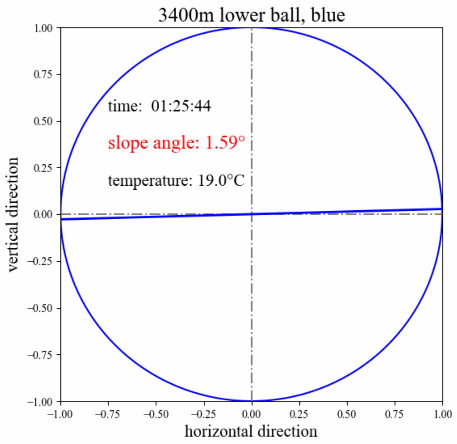
- **Focal length recalibration in water**

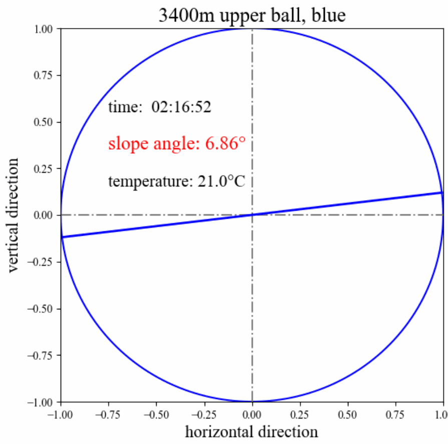
An extra 'lens' caused by curvature of glass vessel

Ship Towing Tank in SJTU

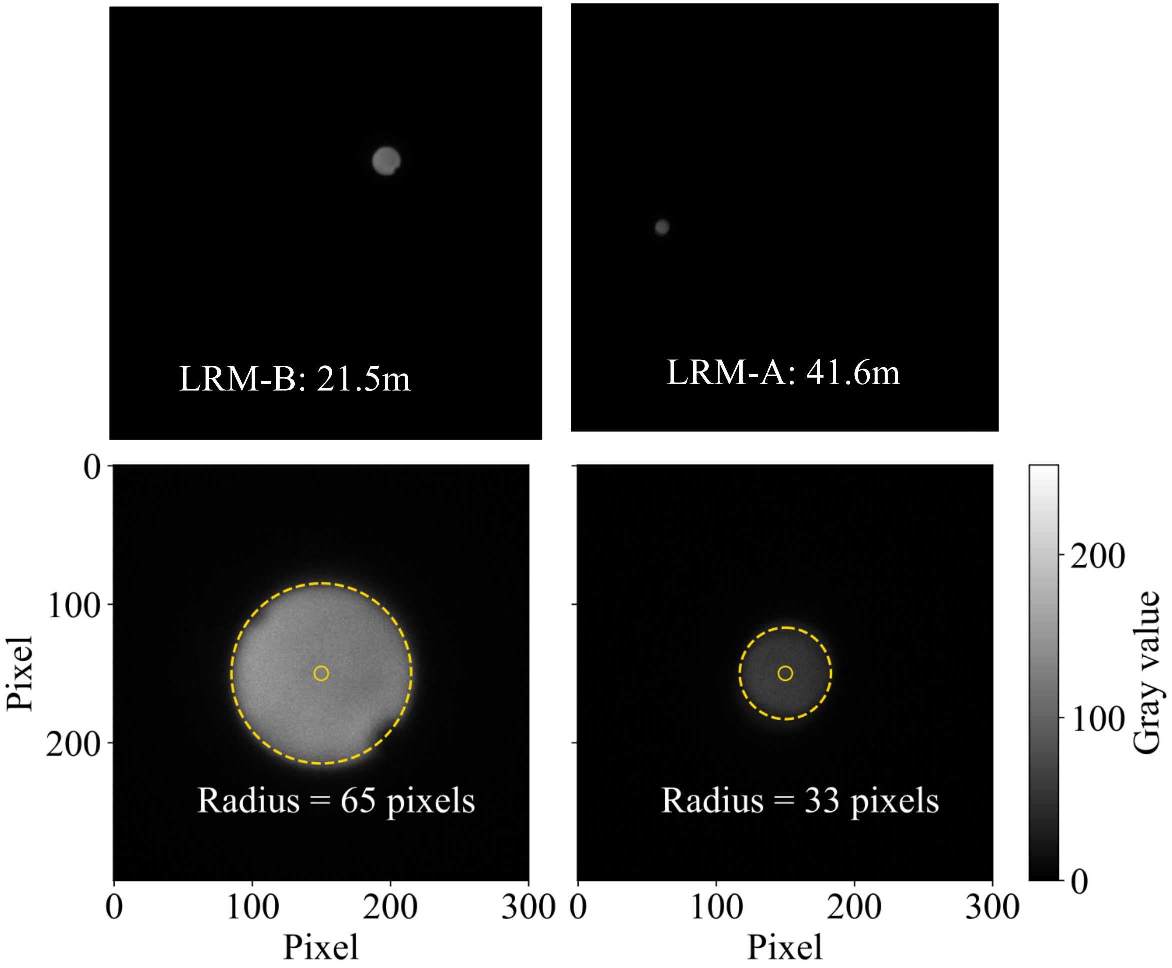
Remote operation of the camera system

- **Deep sea operation:**



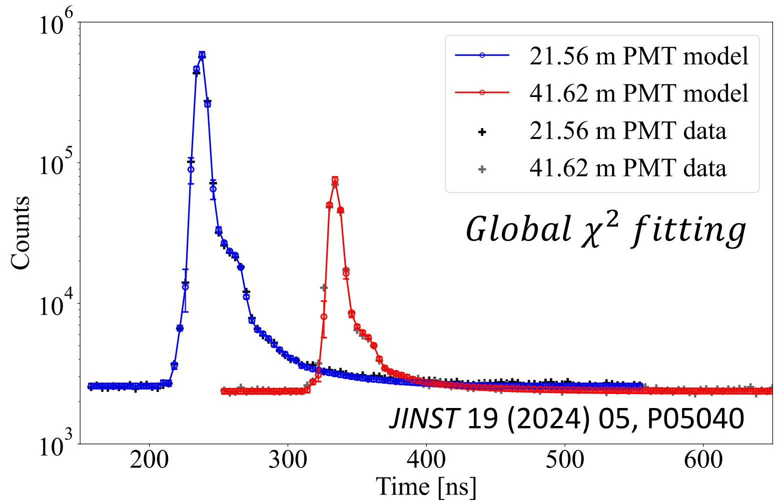


Depth 3420m, wavelength 460nm, 0.05s gain08

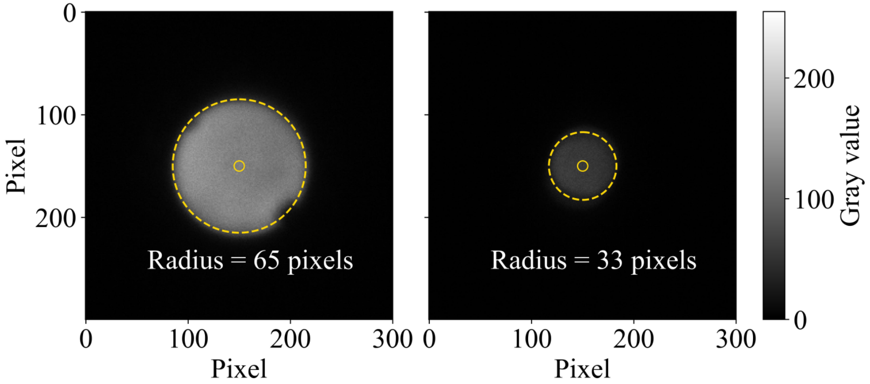


Optical measurement results from T-REX

T-REX PMT system



T-REX Camera system



PMT (at ~ 450 nm, ~ 50 minutes)						
Method	λ_{abs} [m]	λ_{ray} [m]	λ_{mie}[m]	$\cos\theta_{\text{mie}}$	λ_{att} [m]	$\lambda_{\text{att,eff}}$ [m]
χ^2 fitting	$27.4^{+1.1}_{-0.9}$	200^{+13}_{-10}	84^{+12}_{-8}	$0.97^{+0.02}_{-0.02}$	$18.7^{+3.0}_{-2.1}$	25.2 ± 3.7
MCMC	$26.4^{+1.2}_{-1.0}$	203^{+15}_{-11}	64^{+12}_{-14}	$0.97^{+0.01}_{-0.01}$	$17.2^{+0.8}_{-1.3}$	
Camera (at ~ 460 nm, ~ 8 minutes)						
Method	λ_{abs} [m]	λ_{sca} [m]			λ_{att} [m]	$\lambda_{\text{att,eff}}$ [m]
χ^2 fitting	26.5 ± 0.5	62.9 ± 3.7			18.7 ± 0.2	26.8 ± 2.8
I_{center}	$\lambda_{\text{att}} = 19.3 \pm 1.3$					

Wavelengths [nm]	Depth [m]	λ_{att} [m]
460	1221	17.8 ± 1.1
460	2042	18.7 ± 1.2
460	3420	19.3 ± 1.3
525	3420	14.6 ± 0.7
405	3420	13.7 ± 0.6

Effective model: $I(L) \approx I_0 \cdot \frac{A}{4\pi L^2} \cdot e^{-L/\lambda_{\text{eff,att}}}$

Refined model: $I(L) = I_0 \cdot e^{-\frac{\bar{L}}{\lambda_{abs}}}, \ \bar{L}\,(L, \lambda_{Mie}, \lambda_{Ray}, \langle\theta_{Mie}\rangle)$

(TRIDENT camera: arXiv:2407.19111)

A preliminary timeline for TRIDENT

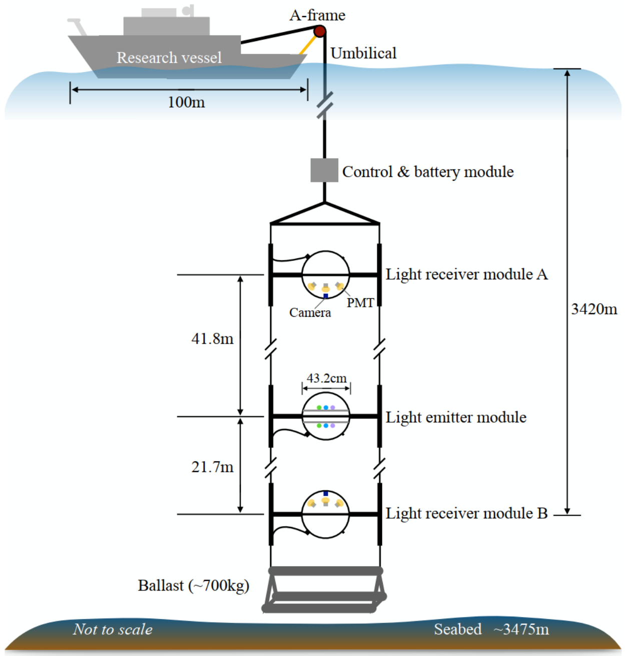
Pathfinder experiment (2021)

Done

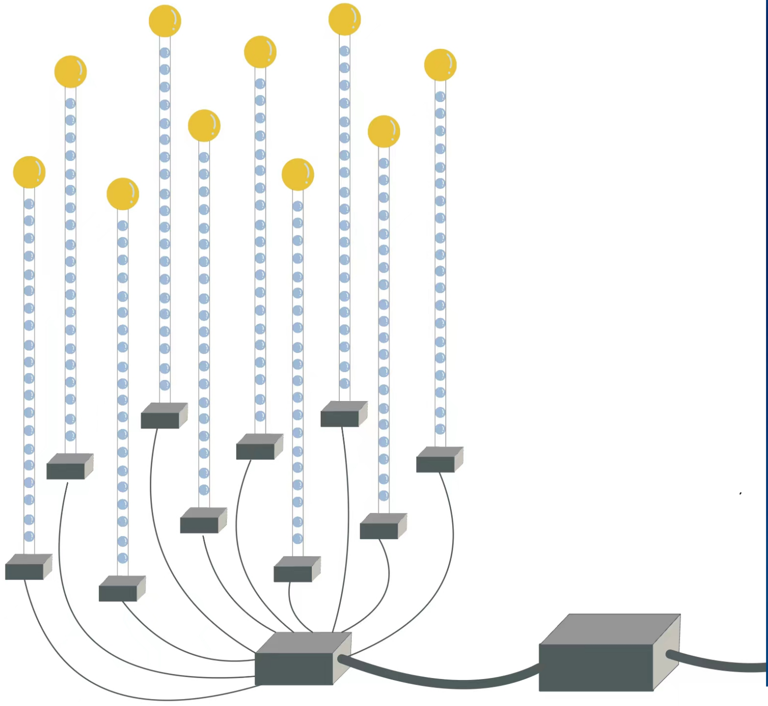
TRIDENT Phase-1 (~2026)

Funded

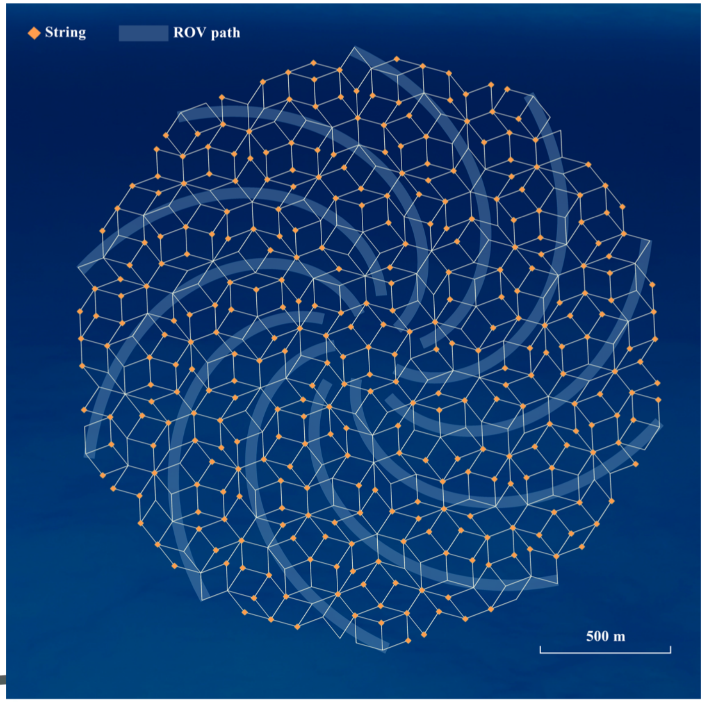
TRIDENT Phase-2 (~2030)



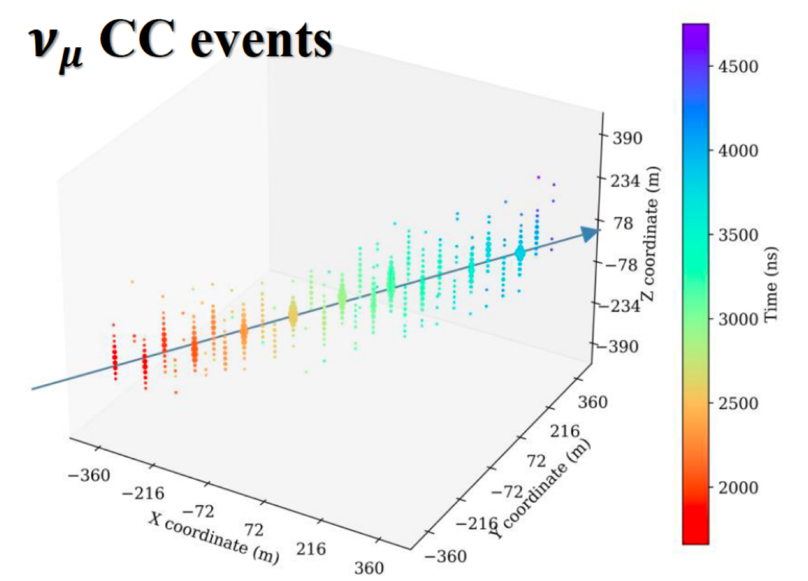
T-REX



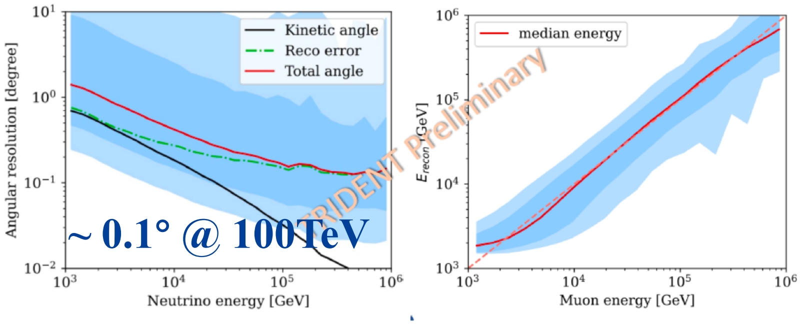
10 strings, 200 hDOMs
200km electric-optical cable



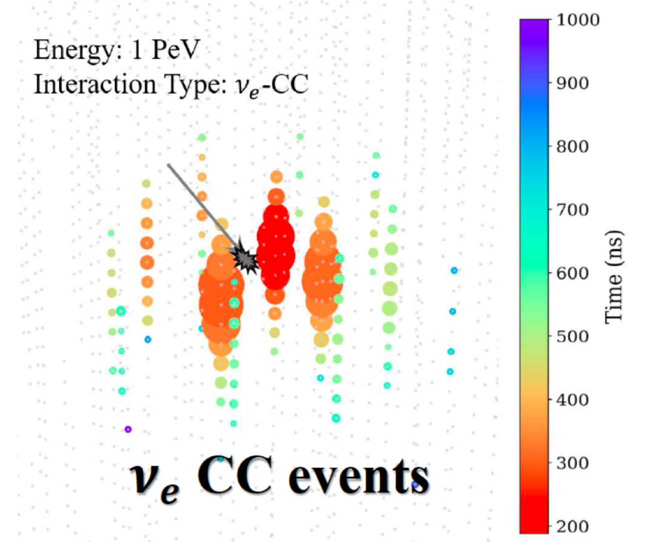
All-flavor neutrino detection in TRIDENT


ν_μ CC events

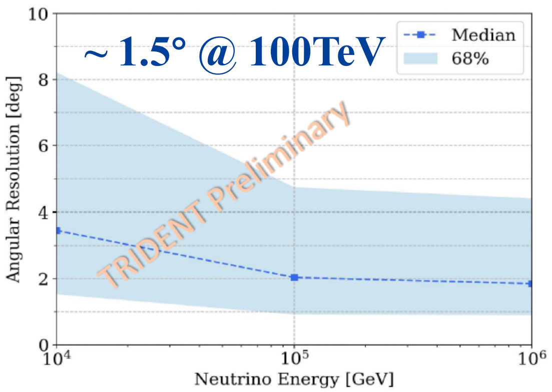
Angular Resolution & Energy Reconstruction

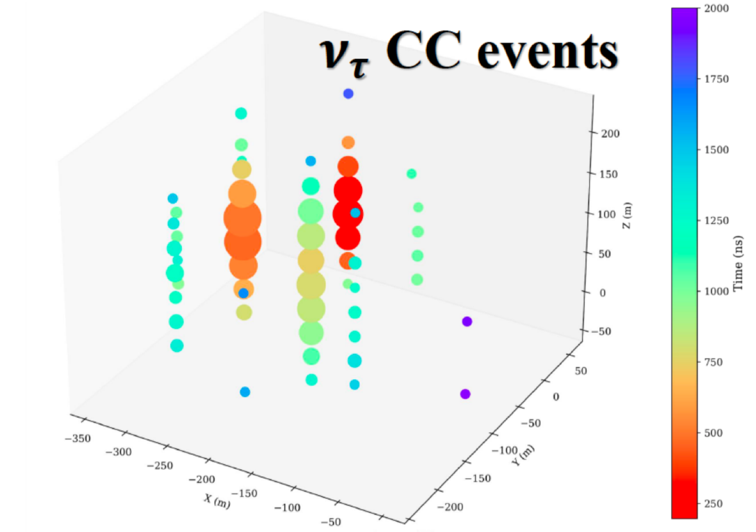


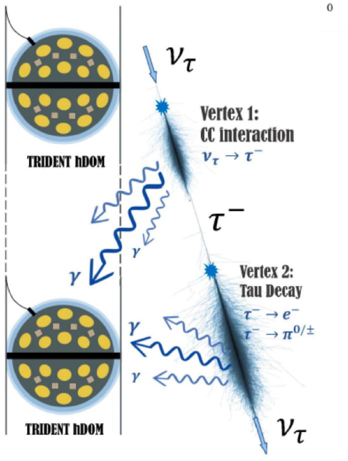
~ 0.1° @ 100TeV

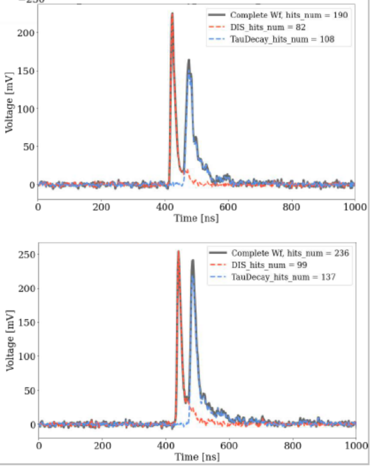

Energy: 1 PeV
Interaction Type: ν_e-CC
ν_e CC events

Median: ~1.5° @ 100 TeV & 1PeV


~ 1.5° @ 100TeV

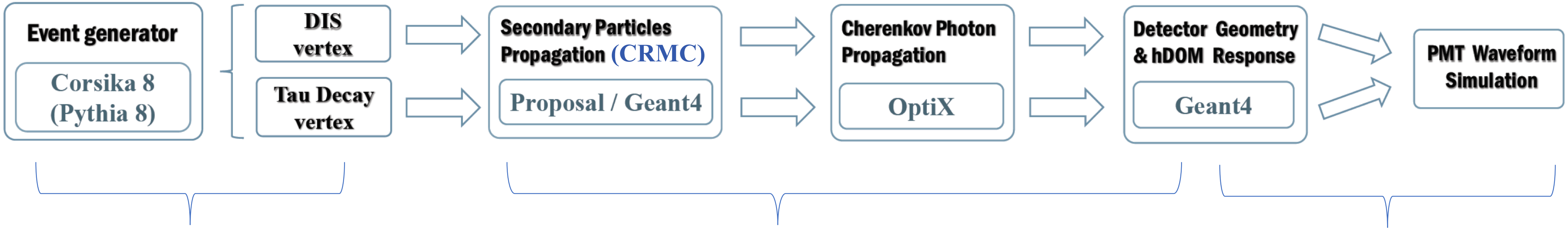

ν_τ CC events





TRIDNET simulation pipeline

Tau neutrino simulation:



Event generator

Corsika 8 (Pythia 8)

DIS vertex

Tau Decay vertex

Secondary Particles Propagation (CRMC)

Proposal / Geant4

Cherenkov Photon Propagation

OptiX

Detector Geometry & hDOM Response

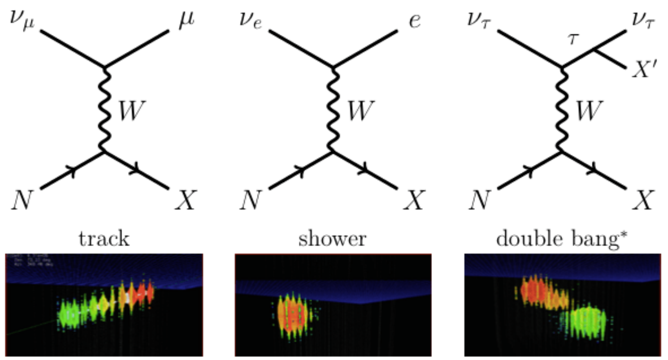
Geant4

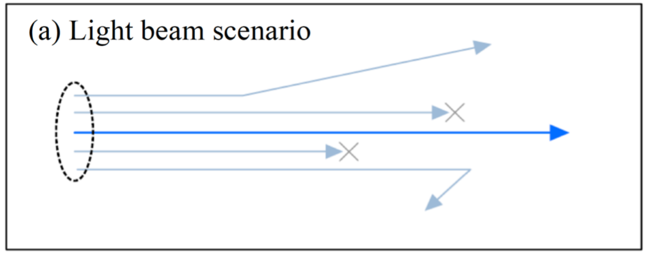
PMT Waveform Simulation

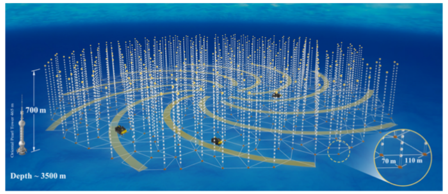
Neutrino Physics

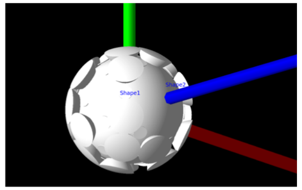
Detector/Optical Simulation

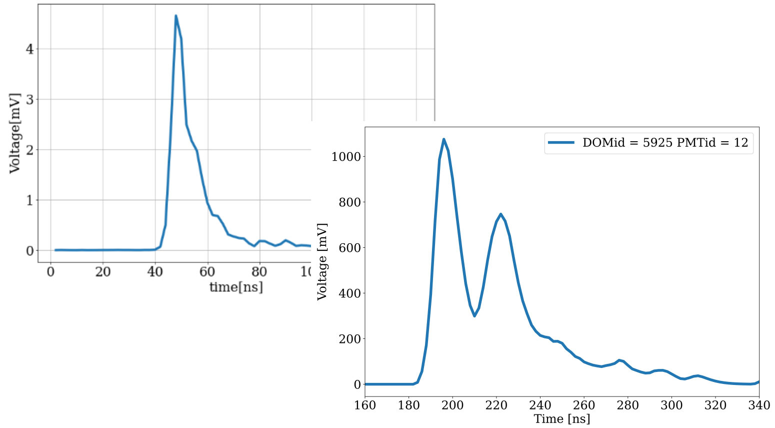
PMT Waveform Simulation





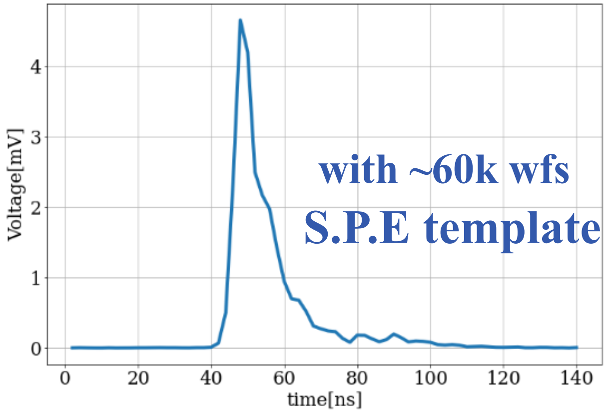




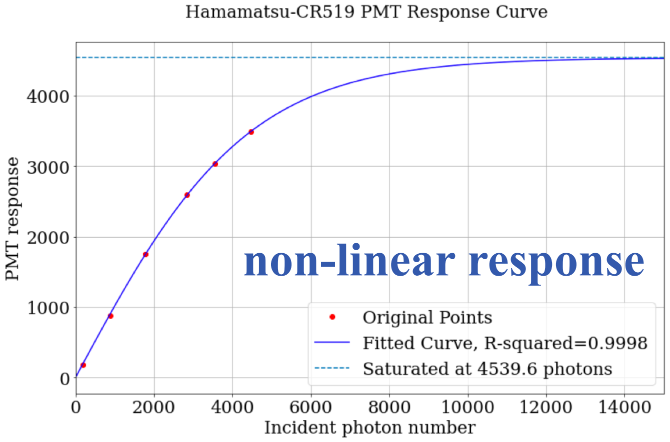


PMT & ADC characterization in waveform simulation

PMT characterization


with ~60k wfs

S.P.E template


Hamamatsu-CR519 PMT Response Curve

non-linear response

SPE waveform template

Transit Time Spread (1.8 ns)

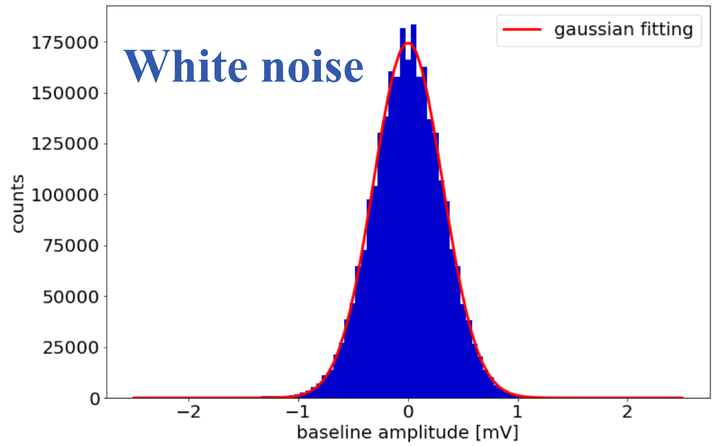
Quantum Efficiency (~28%)

PMT non-linear response

After-pulsing rate (~1% in 1μs)

Dark Count Rate (~300Hz)

ADC characterization


White noise

ADC saturation (2.16V)

ADC sampling rate (125 MHz)

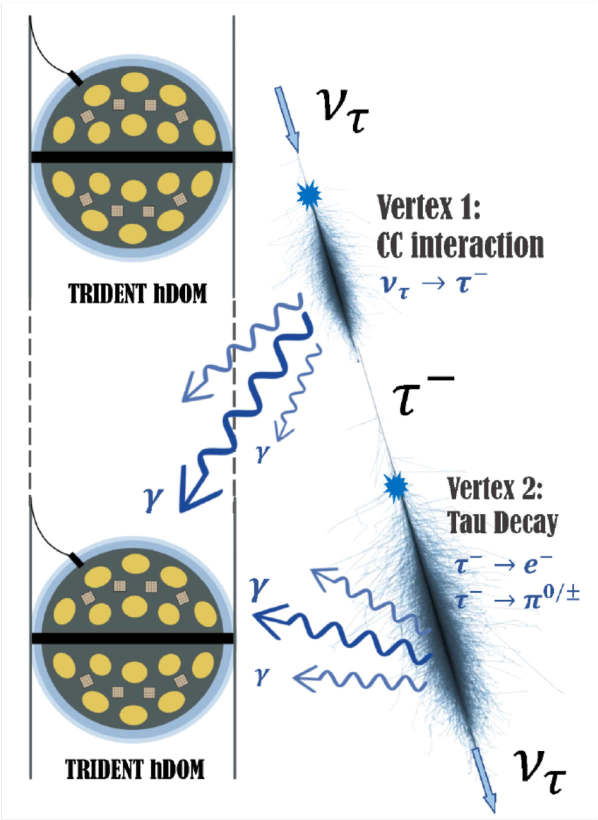
White noise (sigma=0.31mV)

Time window (1000 ns)

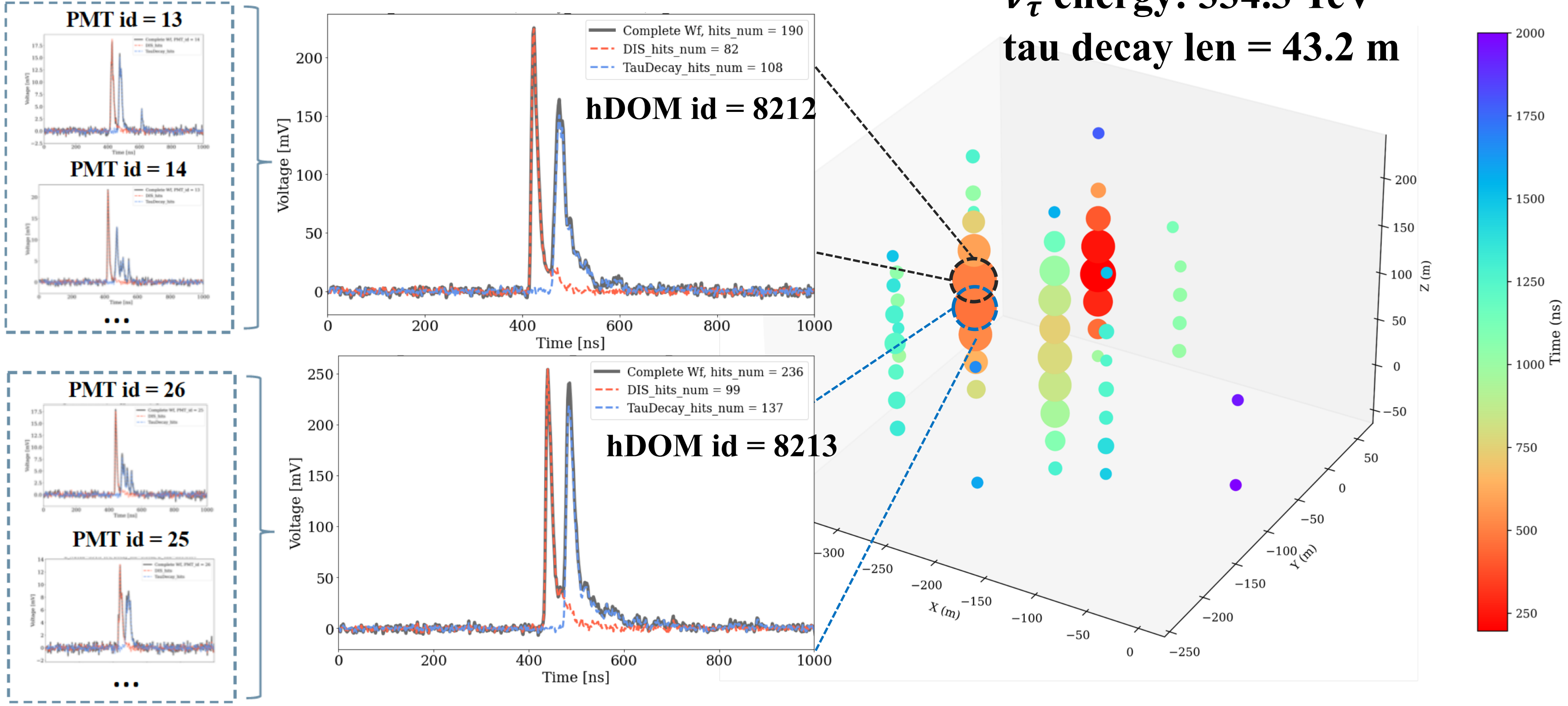
Three levels for υ_τ identification

TRIDENT 海铃计划

- **A typical tau neutrino event (CC interaction) in TRIDENT:**



Tau decay length ~ 50m / PeV



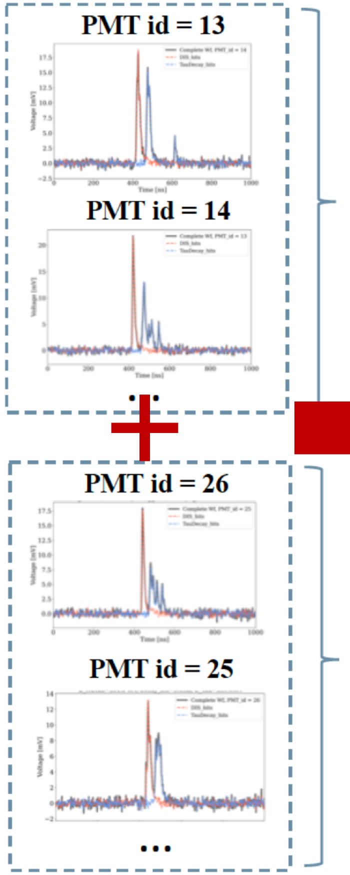
ν_τ energy: 334.3 TeV

tau decay len = 43.2 m

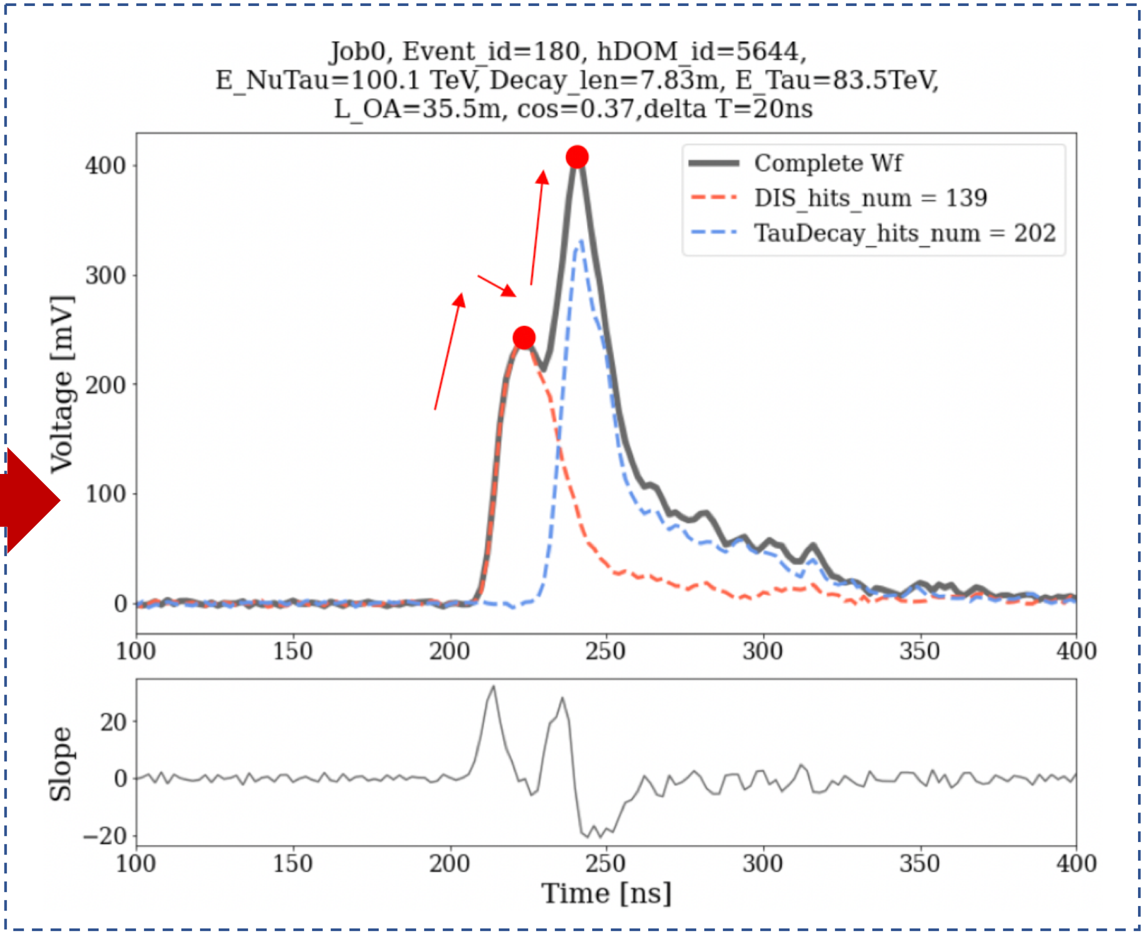
PMT level (waveform) **DOM level (Hits)** **Detector level (event topology)**

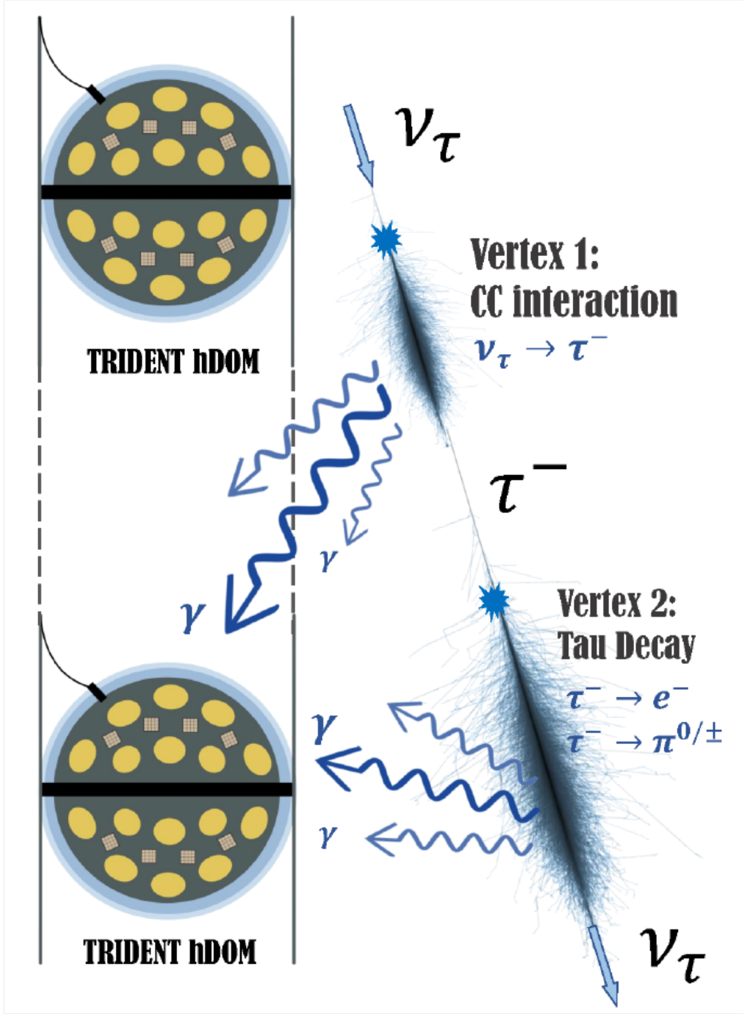
DOM-level waveforms & Double Pulse waveform

PMT stacking



DOM-level double pulse waveform from NuTau CC

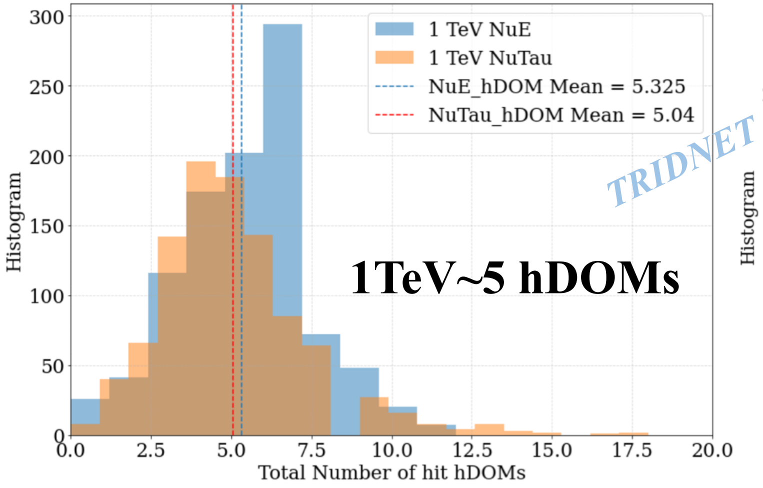


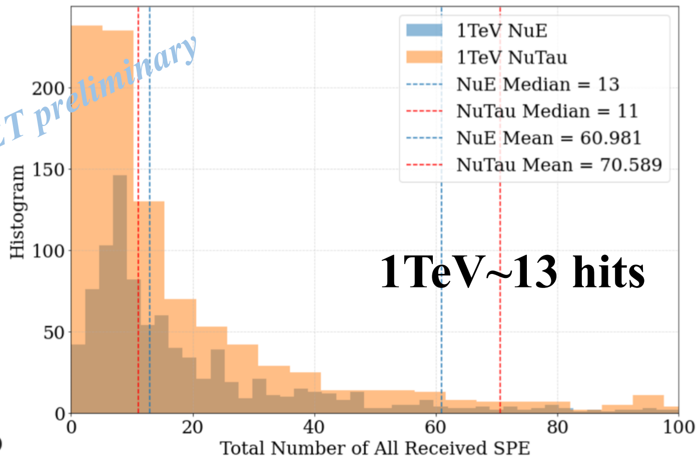


Parameters in Double Pulse Algorithm (DPA)

Level 1: Pre-cuts

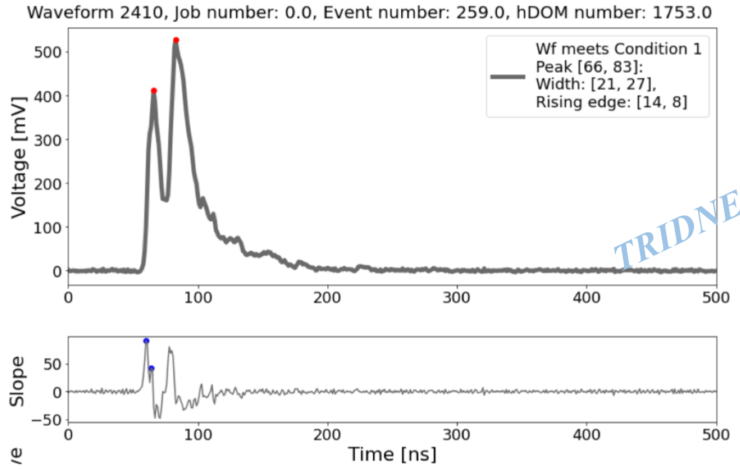
1. **Total hits number** >= 50
2. **Triggered DOM number** >= 5

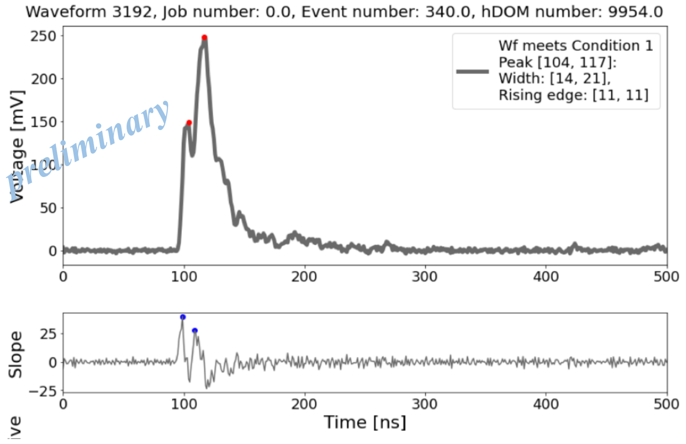




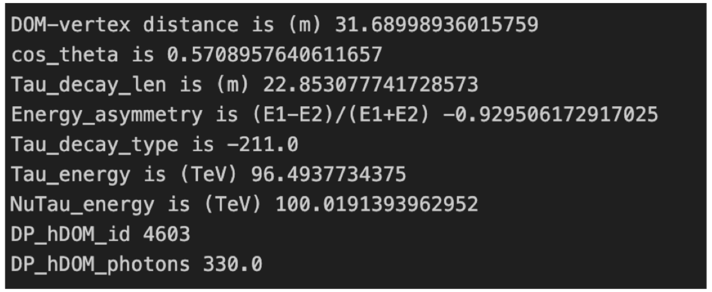
Level 2: Double Pulse Algorithm

1. **Peak Voltage threshold** >= 50 mV (~10 P.E)
2. **Peak Width threshold** >= 28ns
3. **Peak Rising-Edges** >= 16 ns
4. **Peak Falling-Edges** >= 12 ns
5. **Peak number** >= 2
6. **Time distance of two main peaks** >= 16ns
7. **Voltage ratio of two main peaks** < 3

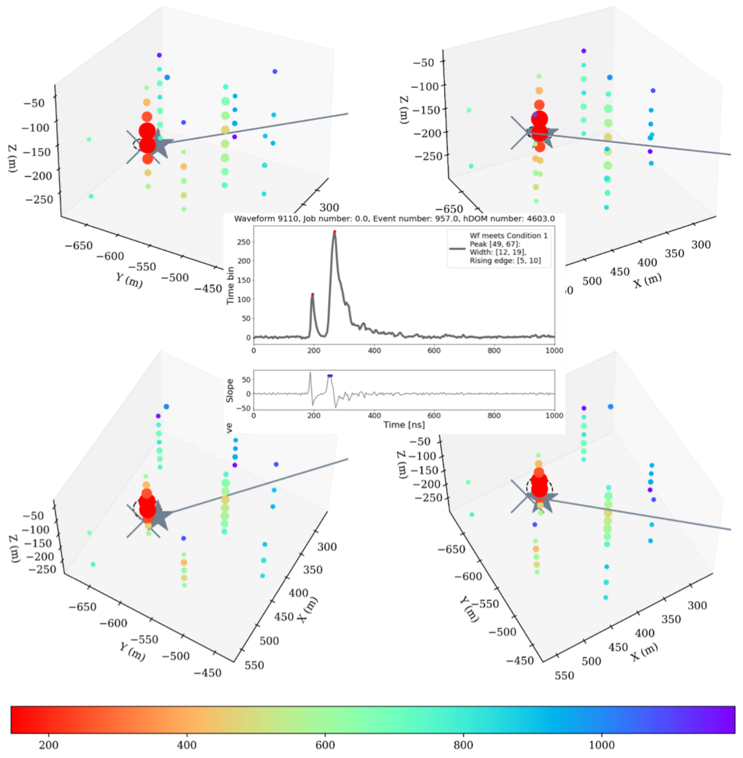


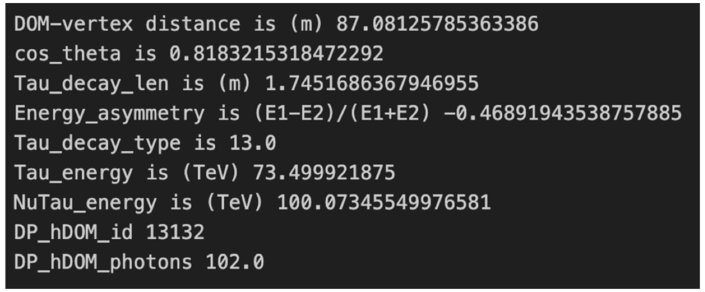


Double Pulse NuTau examples @ 100TeV

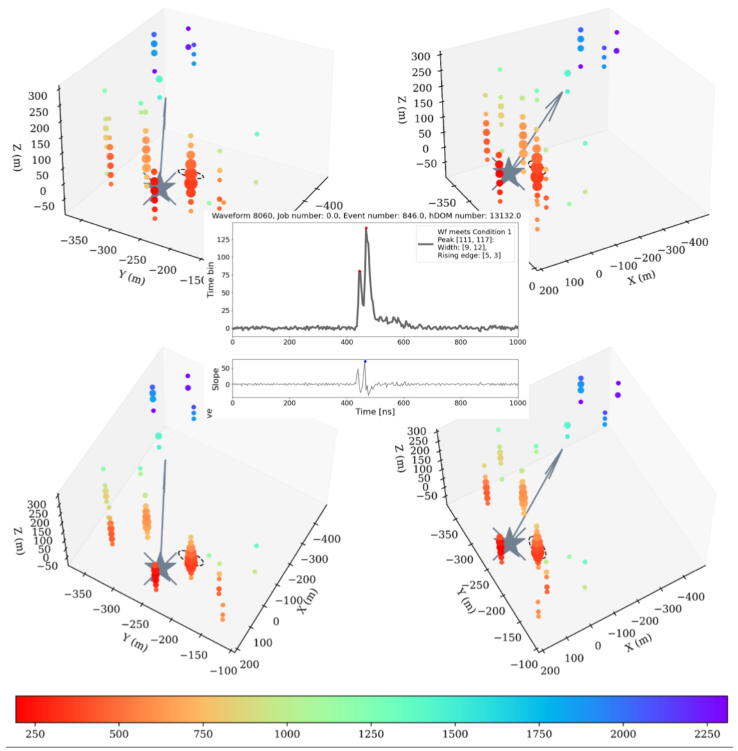


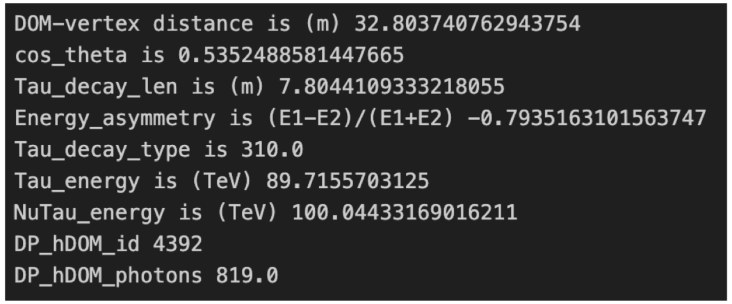
```
DOM-vertex distance is (m) 31.68998936015759
cos_theta is 0.5708957640611657
Tau_decay_len is (m) 22.853077741728573
Energy_asymmetry is (E1-E2)/(E1+E2) -0.929506172917025
Tau_decay_type is -211.0
Tau_energy is (TeV) 96.4937734375
NuTau_energy is (TeV) 100.0191393962952
DP_hDOM_id 4603
DP_hDOM_photons 330.0
```



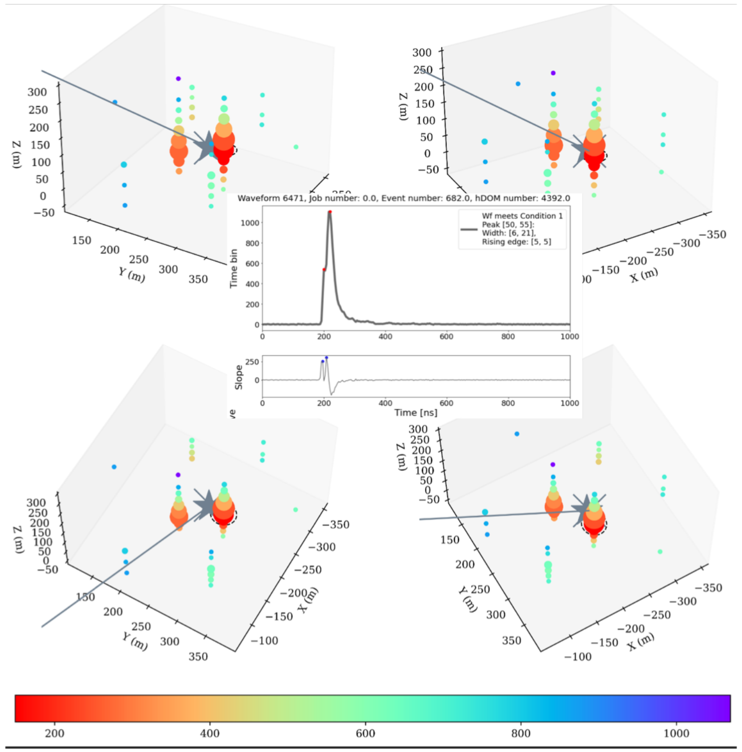


```
DOM-vertex distance is (m) 87.08125785363386
cos_theta is 0.8183215318472292
Tau_decay_len is (m) 1.7451686367946955
Energy_asymmetry is (E1-E2)/(E1+E2) -0.46891943538757885
Tau_decay_type is 13.0
Tau_energy is (TeV) 73.499921875
NuTau_energy is (TeV) 100.07345549976581
DP_hDOM_id 13132
DP_hDOM_photons 102.0
```

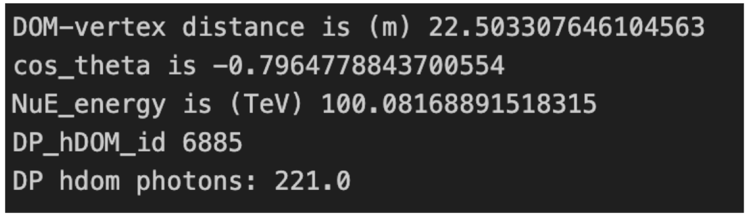




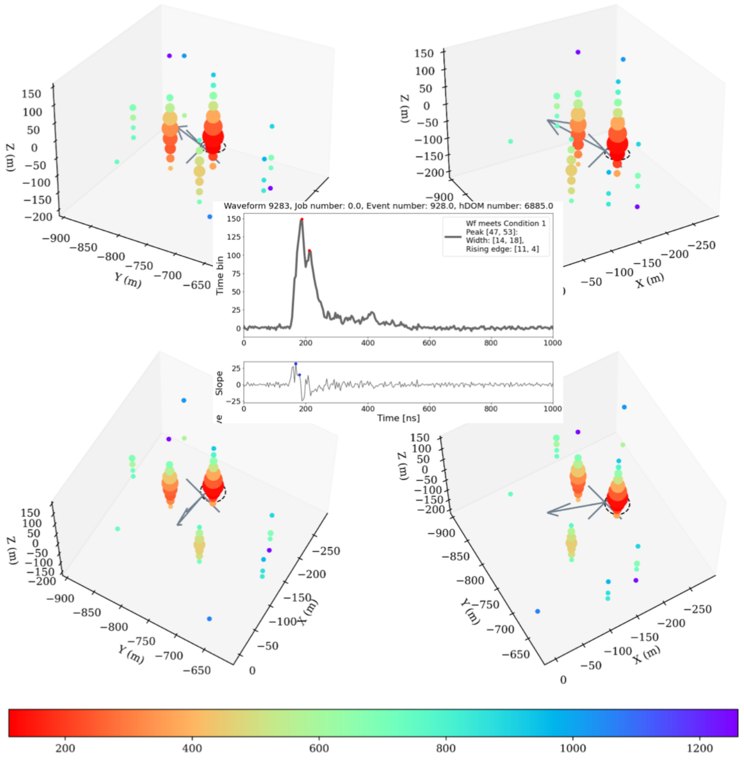
```
DOM-vertex distance is (m) 32.803740762943754
cos_theta is 0.5352488581447665
Tau_decay_len is (m) 7.8044109333218055
Energy_asymmetry is (E1-E2)/(E1+E2) -0.7935163101563747
Tau_decay_type is 310.0
Tau_energy is (TeV) 89.7155703125
NuTau_energy is (TeV) 100.04433169016211
DP_hDOM_id 4392
DP_hDOM_photons 819.0
```

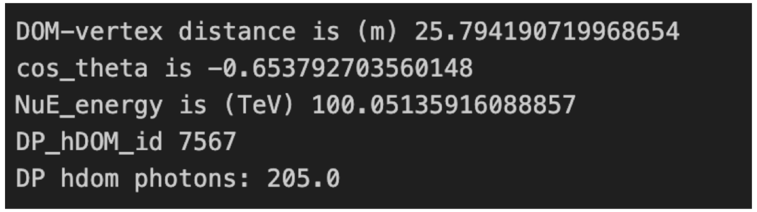


“Double Pulse” NuE examples @ 100TeV

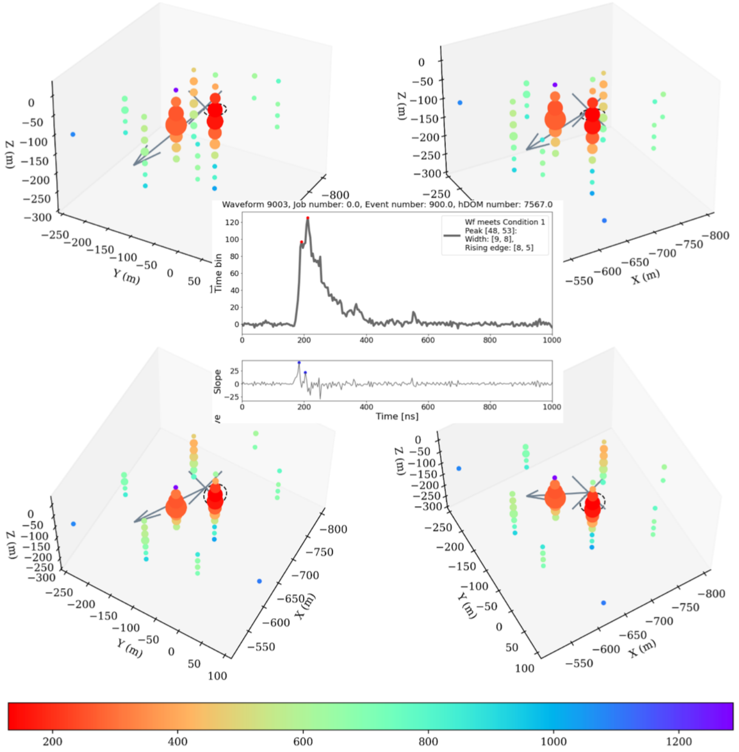


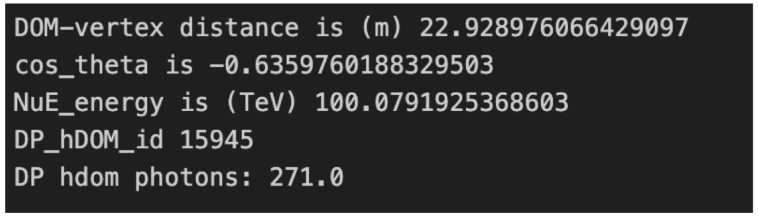
```
DOM-vertex distance is (m) 22.503307646104563
cos_theta is -0.7964778843700554
NuE_energy is (TeV) 100.08168891518315
DP_hDOM_id 6885
DP hdom photons: 221.0
```



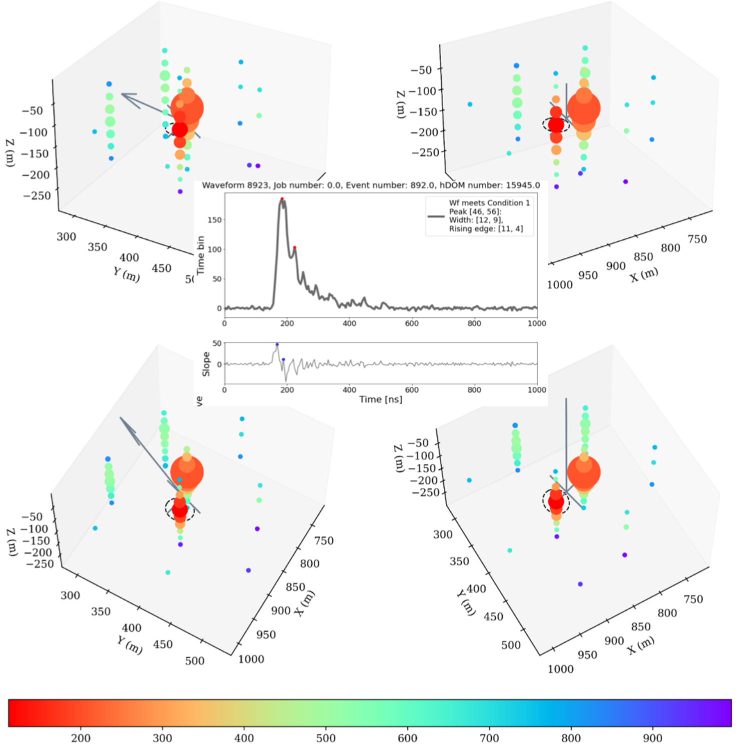


```
DOM-vertex distance is (m) 25.794190719968654
cos_theta is -0.653792703560148
NuE_energy is (TeV) 100.05135916088857
DP_hDOM_id 7567
DP hdom photons: 205.0
```



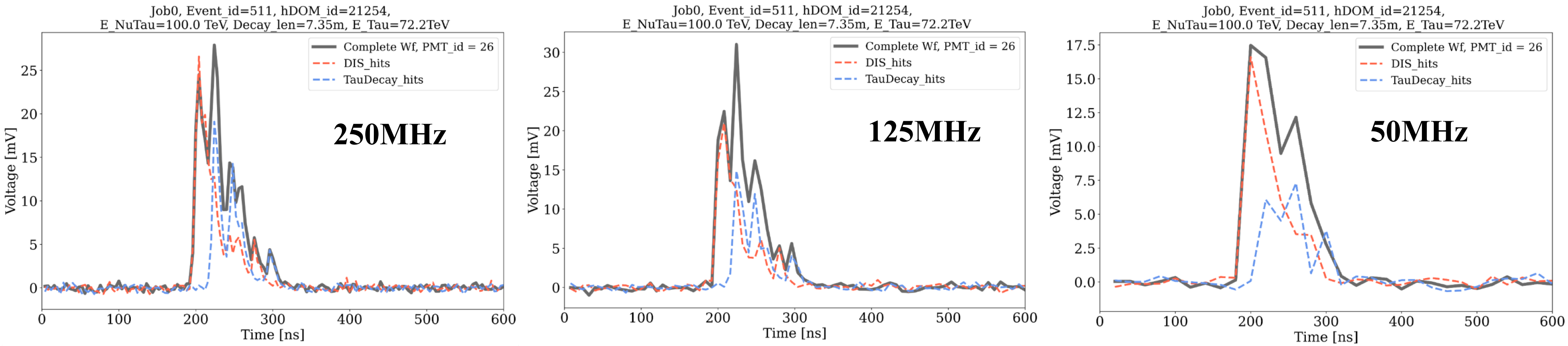


```
DOM-vertex distance is (m) 22.928976066429097
cos_theta is -0.6359760188329503
NuE_energy is (TeV) 100.0791925368603
DP_hDOM_id 15945
DP hdom photons: 271.0
```



DPA under various waveform sampling rates

Waveform examples under different ADC sampling rates:



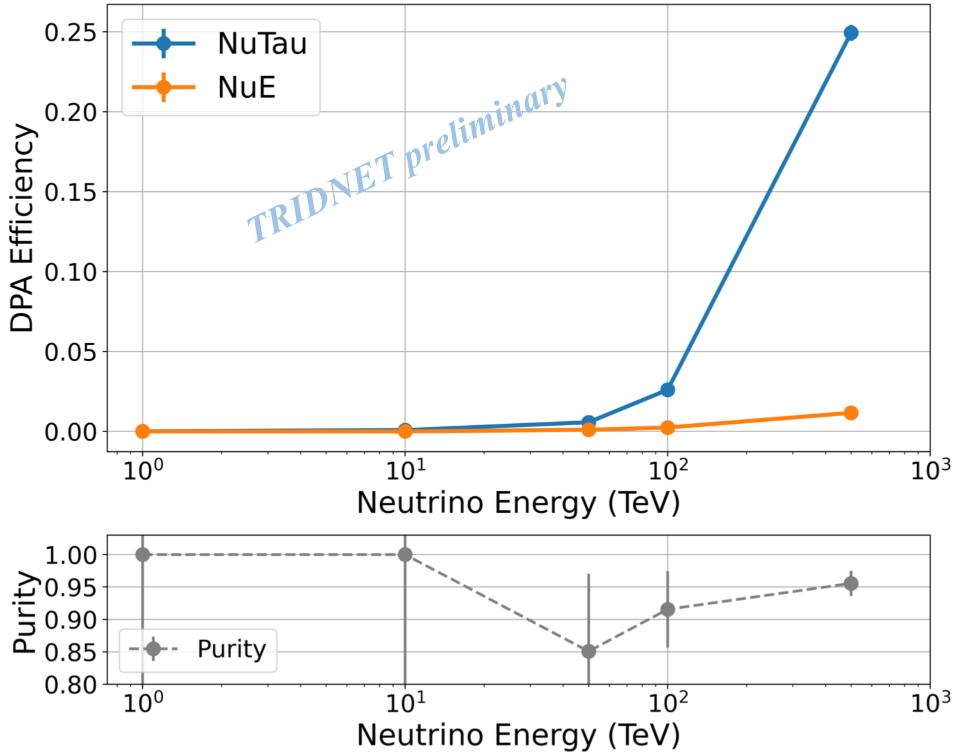
For fixed 100TeV NuTau & NuE (10k events, fixed random seed)

	500MHz	250MHz	125MHz	100MHz	50MHz
NuTau CC	140/10k	253/10k	260/10k	261/10k	134/10k
NuE CC	5/10k	22/10k	24/10k	25/10k	30/10k

DPA efficiency and expected event rate in TRIDENT

@125MHz	1TeV	10TeV	50TeV	100TeV	500TeV
NuTau CC	0/10k	8/10k	57/10k	260/10k	1247/5k
NuE CC	0/10k	0/10k	10/10k	24/10k	58/5k

1-100TeV	100TeV-1PeV
10/10k	1193/9k
4/10k	53/10k



Assumed an isotropic diffused flux : *[IceCube: Arxiv 2402.18026]*

$$\Phi_{Astro}^{per-flavor} = 1.68\times\left(\frac{E_\nu}{100TeV}\right)^{-2.58}\times 3\times 10^{-18} GeV^{-1}s^{-1}cm^{-2}sr^{-1}$$

Expected double pulse events per year in TRIDENT :

	1-100TeV	100TeV-1PeV	>1PeV (not yet)
NuTau CC	0.60 ± 0.51	3.98 ± 0.15	(~0.75)
NuE CC	0.27 ± 0.21	0.12 ± 0.03	(~0)

Tau neutrino identification by Graph Neural Networks

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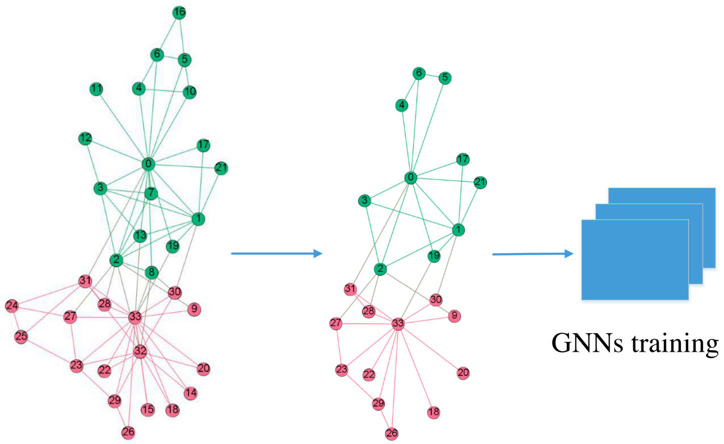
❖ TRIDENT-Net: a GNN-based point cloud for event identification *(PoS ICRC2023 (2023), 1092)*



complete graph G partial observed graph G_O

GNN node: each hDOM

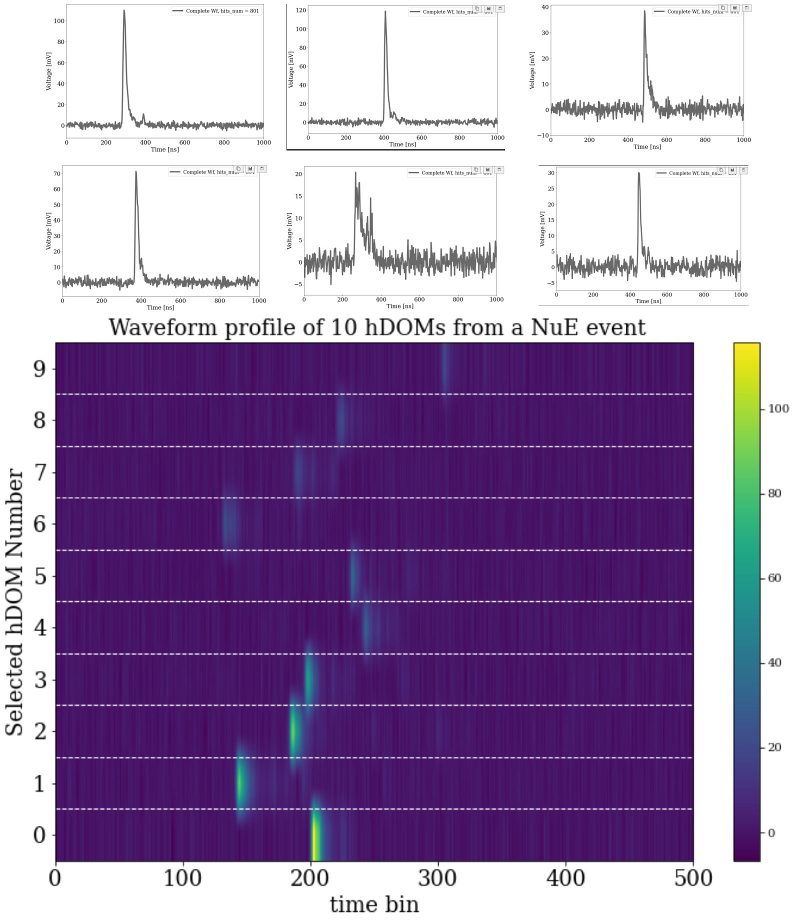
Connection: 10 brightest hDOMs

Feature: hDOM[x, y, z] + [waveform]

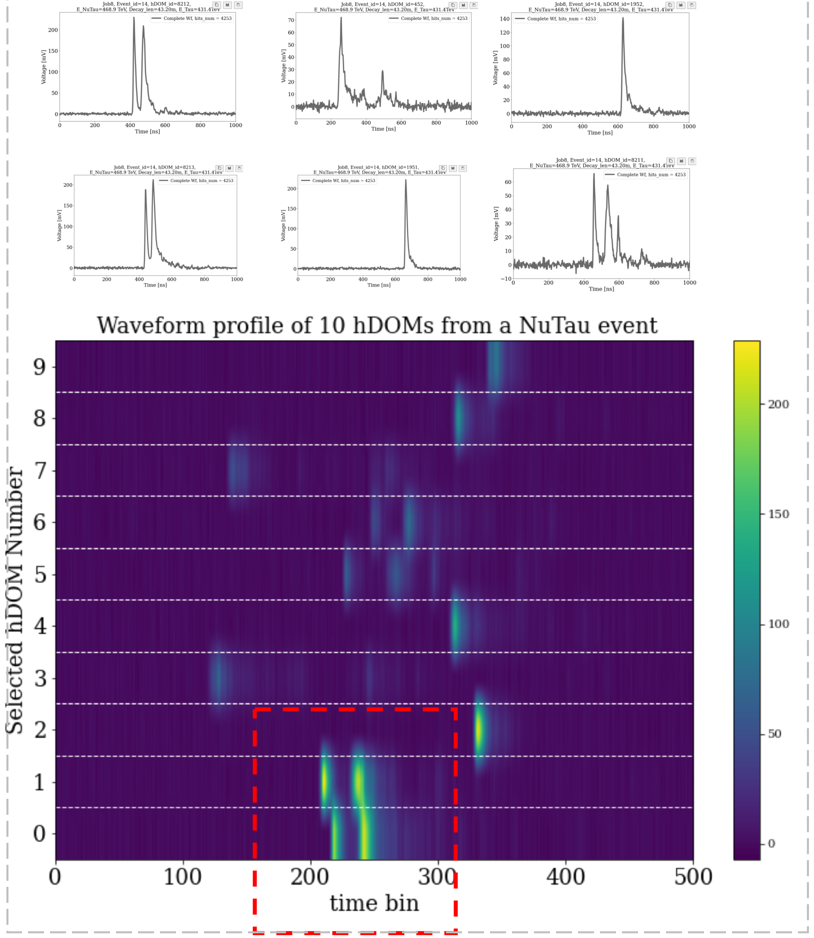
Label: ν_τ as 1, ν_μ/ν_e as 0

$$H(P^*|P) = -\sum_i \underbrace{P^*(i)}_{\text{TRUE CLASS DISTRIBUTION}} \log \underbrace{P(i)}_{\text{PREDICTED CLASS DISTRIBUTION}}$$

A typical NuE CC event:


Waveform profile of 10 hDOMs from a NuE event

A typical double pulse NuTau event


Waveform profile of 10 hDOMs from a NuTau event

Two GNN models for different energy ranges

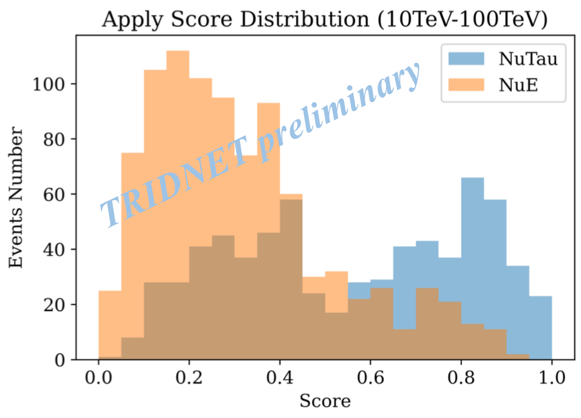
MC dataset: Training set (70%) + Test set (20%) + Apply set (10%)

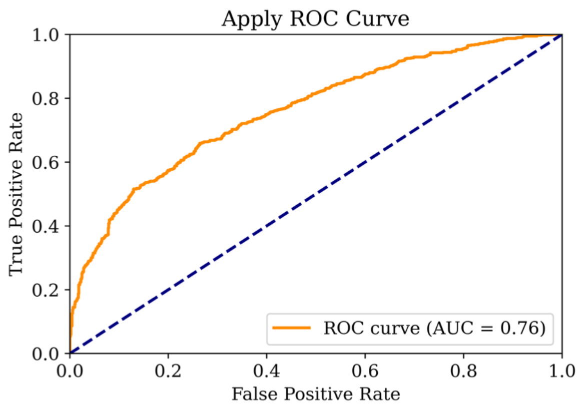
[10TeV, 100TeV] GNN model

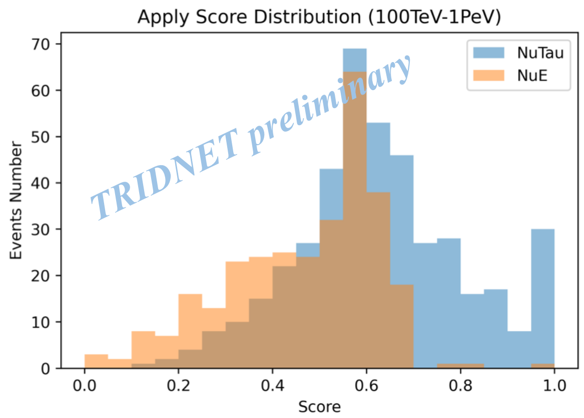
Flavor	Injection Volume	Event Number
ν_τ CC	hh=200m, R=1000m	100k
ν_e CC	hh=200m, R=1000m	100k

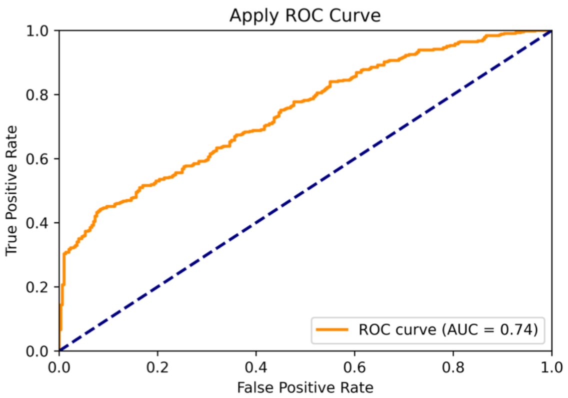
[100TeV, 1PeV] GNN model

Flavor	Injection Volume	Event Number
ν_τ CC	hh=100m, R=500m	~20k
ν_e CC	hh=100m, R=500m	~20k









(Need further optimization & more MC data …)

Summary

- **IceCube**’s observation leads the dawn of neutrino astronomy.
- **TRIDENT** is a 8km3 neutrino telescope with 1000 strings, 20,000 hDOMs.
- **TRIDENT Pathfinder experiment** was successfully conducted in 2021 for site selection
- The T-REX **Camera System** demonstrated a **Real-time Optical Calibration** tool in deep sea
- By using **Double Pulse Algorithms** for NuTau identification in TRIDENT, **~5 NuTau CC/year**
- We are also exploring using **GNN** for NuTau identification, need further optimization

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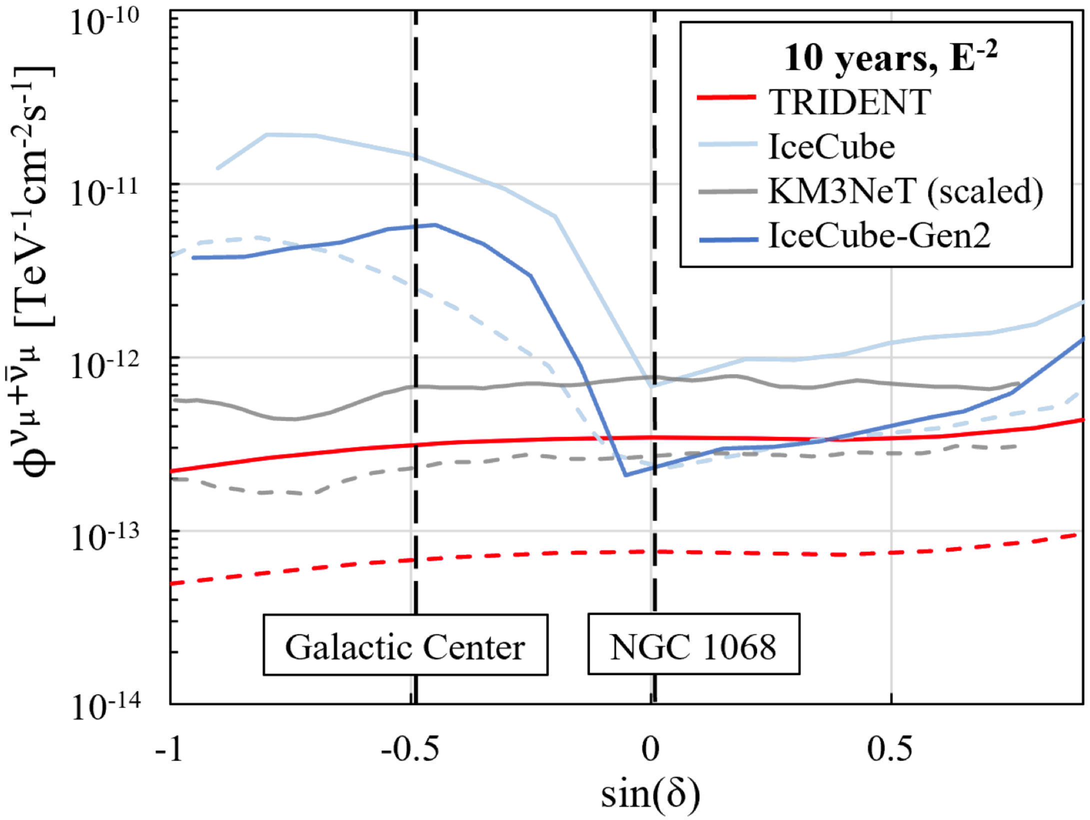
Thanks for listening!

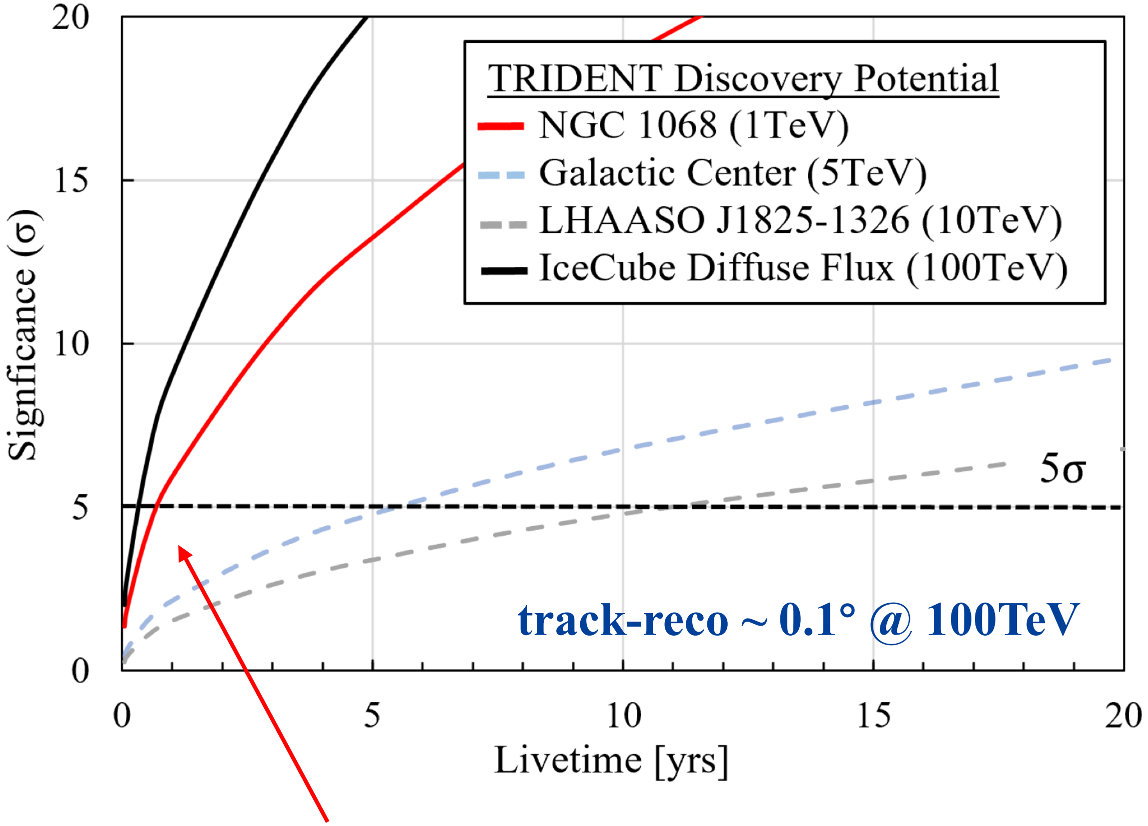
Physics potential of TRIDENT by υ_μ events

- **Detection sensitivity of neutrino flux:**



TRIDENT, Nature Astron. 7 (2023) 12, 1497-1505

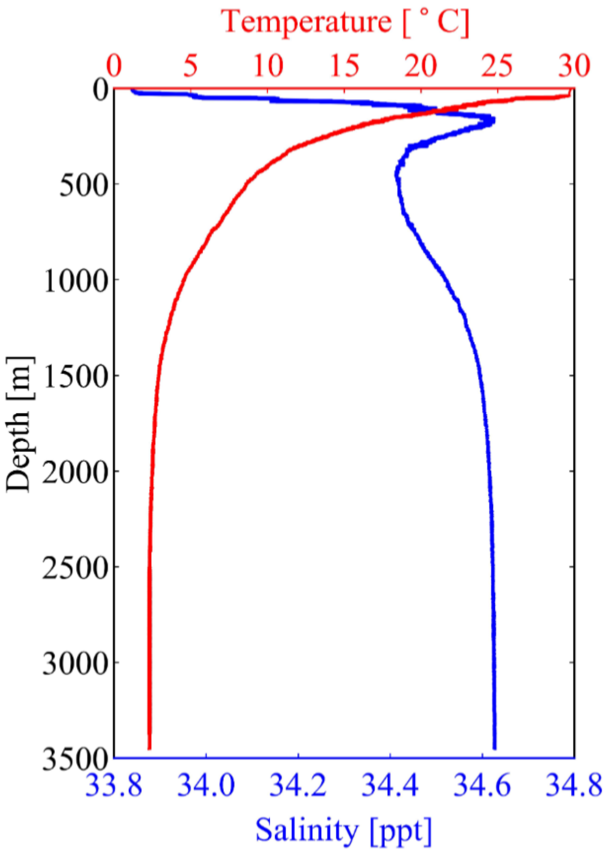
- **Discovery potential for different sources:**

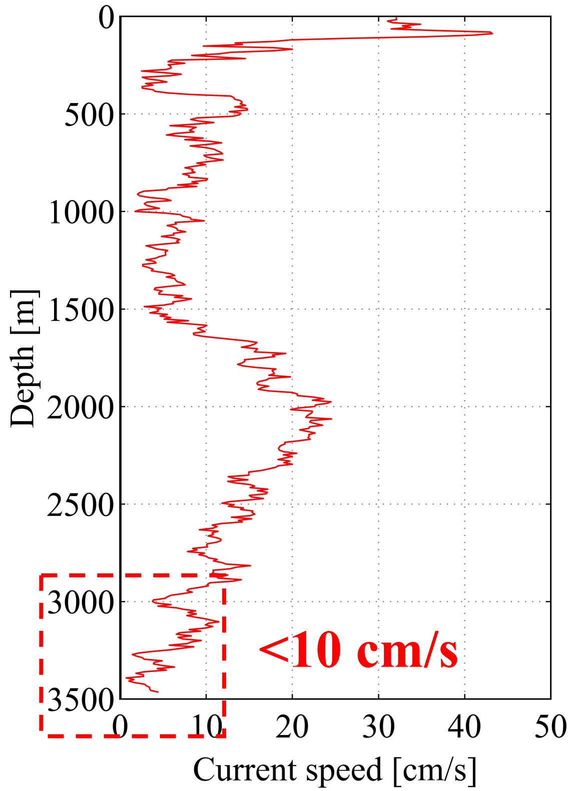


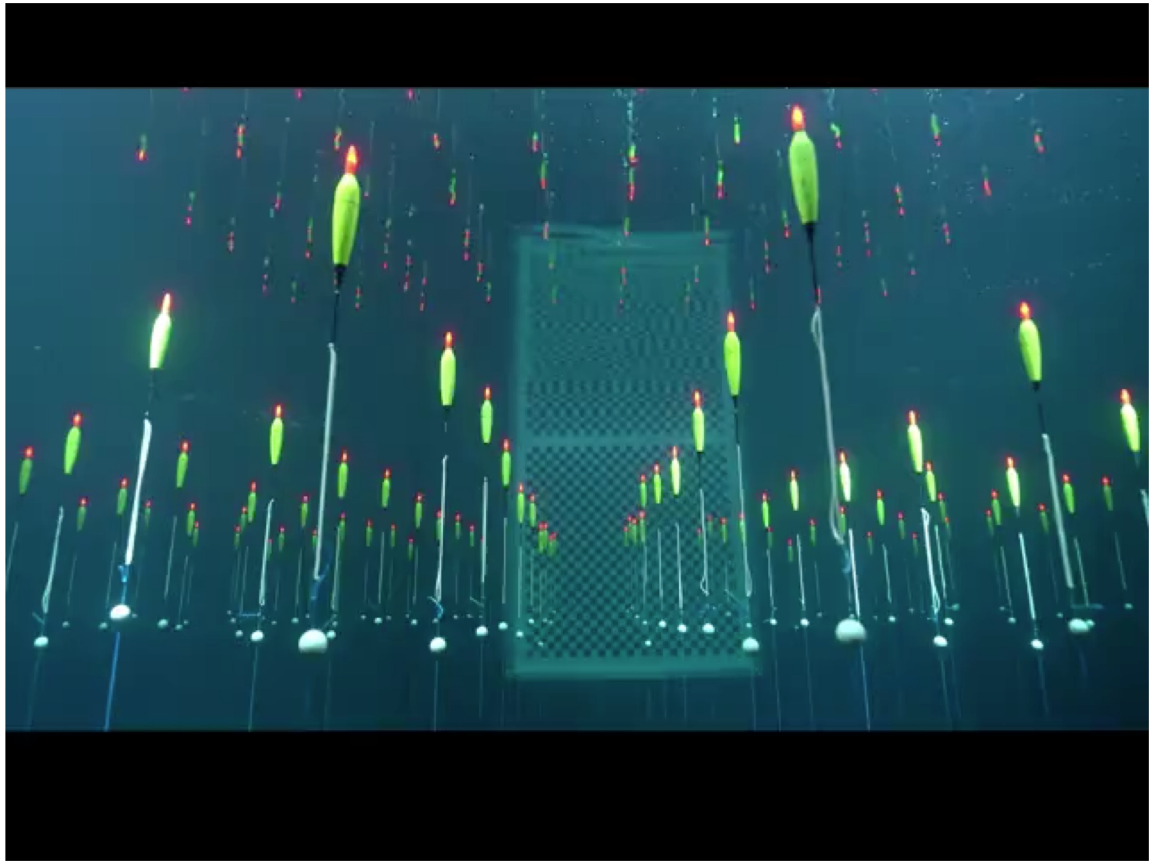
track-reco ~ 0.1° @ 100TeV

-NGC1068: 5σ within 1 year!

Oceanographic conditions







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

Ship towing tank experiment in SJTU

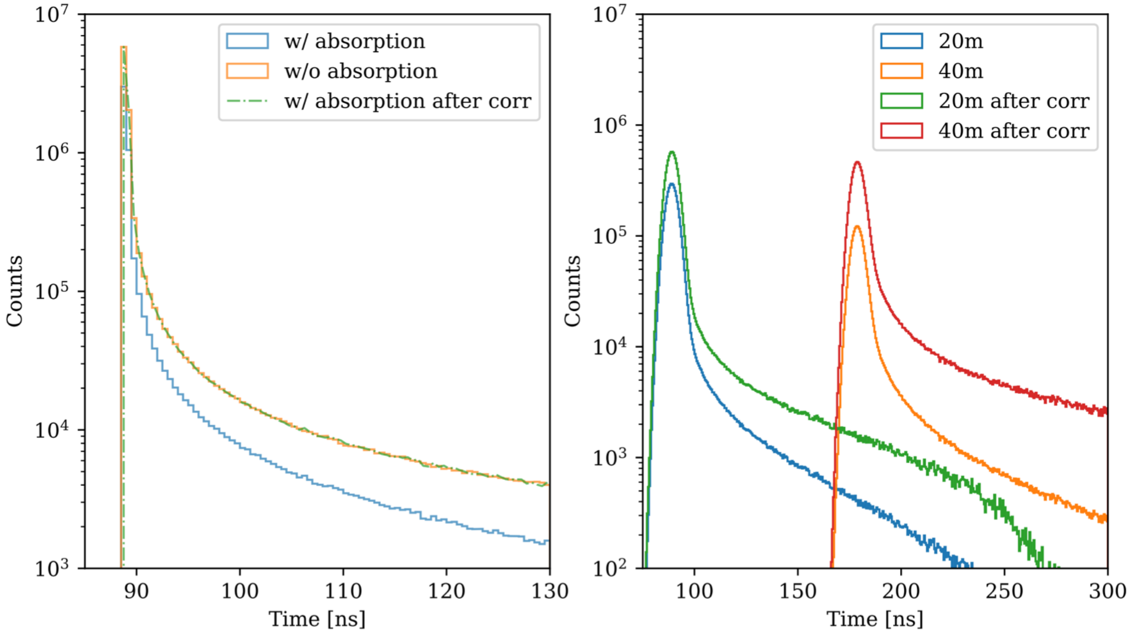
Radioactivity measurement

	West Pacific	Mediterinian	East Pacific
^{40}K radio acticity $(\mathbf{Bq}/\boldsymbol{m}^{3})$	**11101 ± 119**	13700 ± 200	12526 ± 752
Experiment	**TRIDENT**	**ANTARES**	**P-ONE**

3. TRIDENT Pathfinder experiment

- **PMT : quick measurement of λ_{abs} :**

Data re-weight: $1/L^2 \cdot e^{-ct_i/\lambda_{abs}}$



- **PMT: Global χ^2 fitting for all parameters:**

with Geant4: $\chi^2 = \sum_{i=1}^{N} \frac{[M_i - T_i(1 + \sum_{k=1}^{K} \epsilon_k)]^2}{\sigma_{Mi}^2 + \sigma_{Ti}^2} + \sum_{k=1}^{K} \frac{\epsilon_k^2}{\sigma_k^2}$