The Camera System

in the TRIDENT Pathfinder

----An eye for real-time optical calibration

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The 8th Shanghai Symposium on Particle Physics and Cosmology

11.11. 2024

Outline

1. **Next-generation water-based neutrino telescopes**
2. **Optical calibration in weakly scattering water medium:**

   (1) Optical models in water medium (2) Extra challenges compared with ice

3. **The camera system of the TRIDENT Pathfinder:**

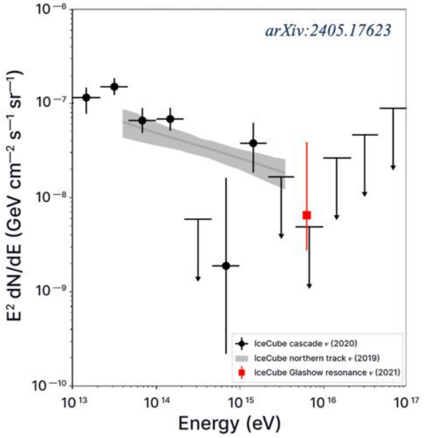
   (1) Hardware design (2) Image analysis methods (3) Simulation (4) real-time Calibration

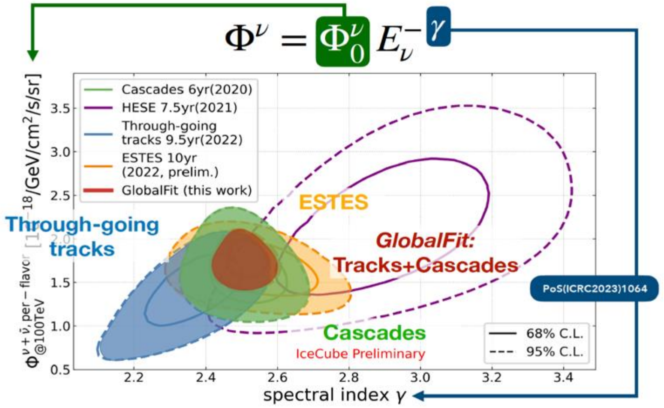
4. **Outlook & Summary**

The dawn of neutrino astronomy

TRIDENT 海铃计划

❖ **Observation of astrophysical neutrino fluxes:**





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

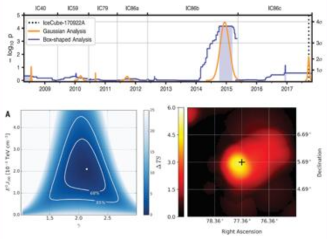
❖ **The origin of astrophysical neutrinos:**

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



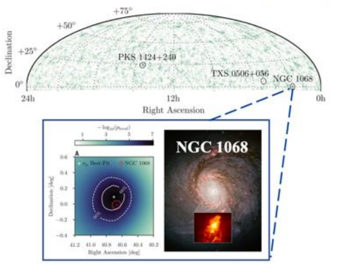
Neutrino energy: **~290 TeV**

Significance: **3.5σ**

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

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



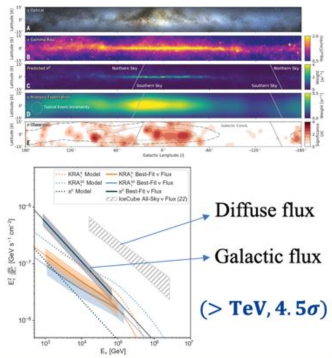
Event excess: **79^{+22}_{-20}** (1.5TeV~15TeV)

Significance: **4.2σ**

NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane

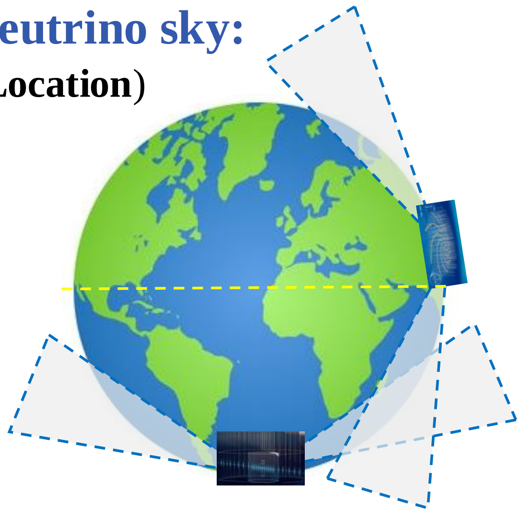
IceCube Collaboration *Science 380, 1338–1343 (2023)* **(2023)**



(> TeV, 4.5σ)

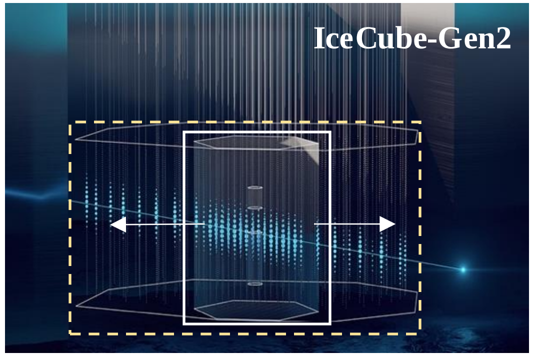
Neutrino sky:

(Location)



Event statistics:

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

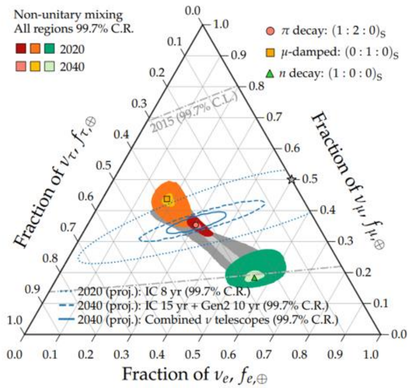


Angular/Energy resolution:

(**Optical medium**, Detector layout)

Flavor separation: υ_τ

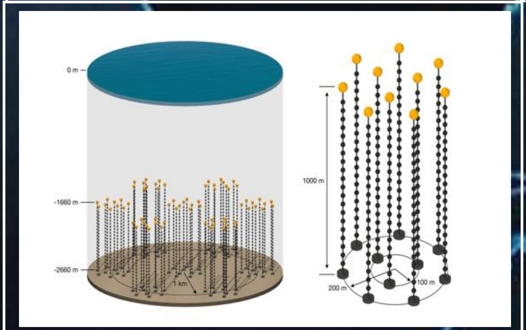
arXiv:2012.12893



Precise flavor detection at 2040

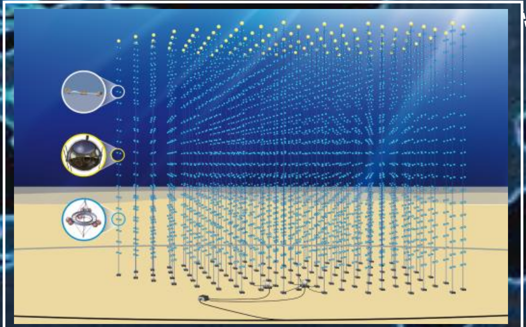
Global next-gen Cherenkov neutrino telescopes

TRIDENT 海 | 铃 | 计 | 划



P-ONE (East Pacific Ocean)

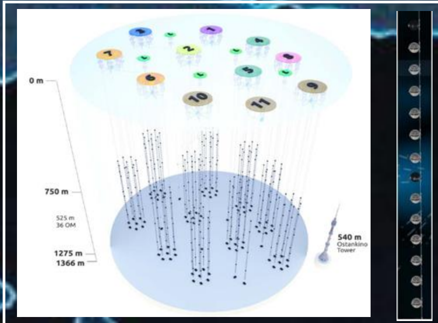
Medium: Deep-sea water
Depth: ~ 2.6 km
Volume: ~ 1 km^3
String number: ~70



KM3NeT (Mediterranean Sea)

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

#Talk 3. by Paschal Coyle



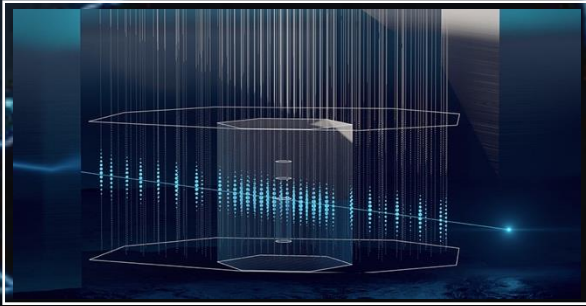
Baikal-GVD (Lake Baikal)

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

#Talk 8. by Lili Yang
#Talk 9. by Tianqi Huang

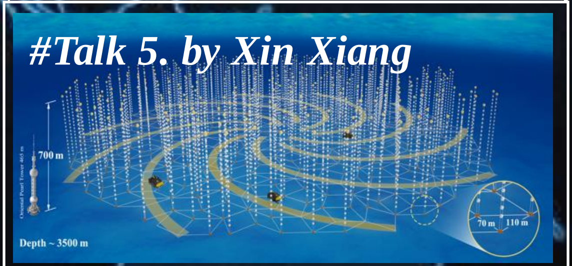
HUNT, NEON

#Talk 1. by Albrecht Karle



IceCube Gen-2 (South Pole)

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



TRIDENT (West Pacific Ocean)

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

Conceptual design of TRIDENT

Water depth: ~3500m

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

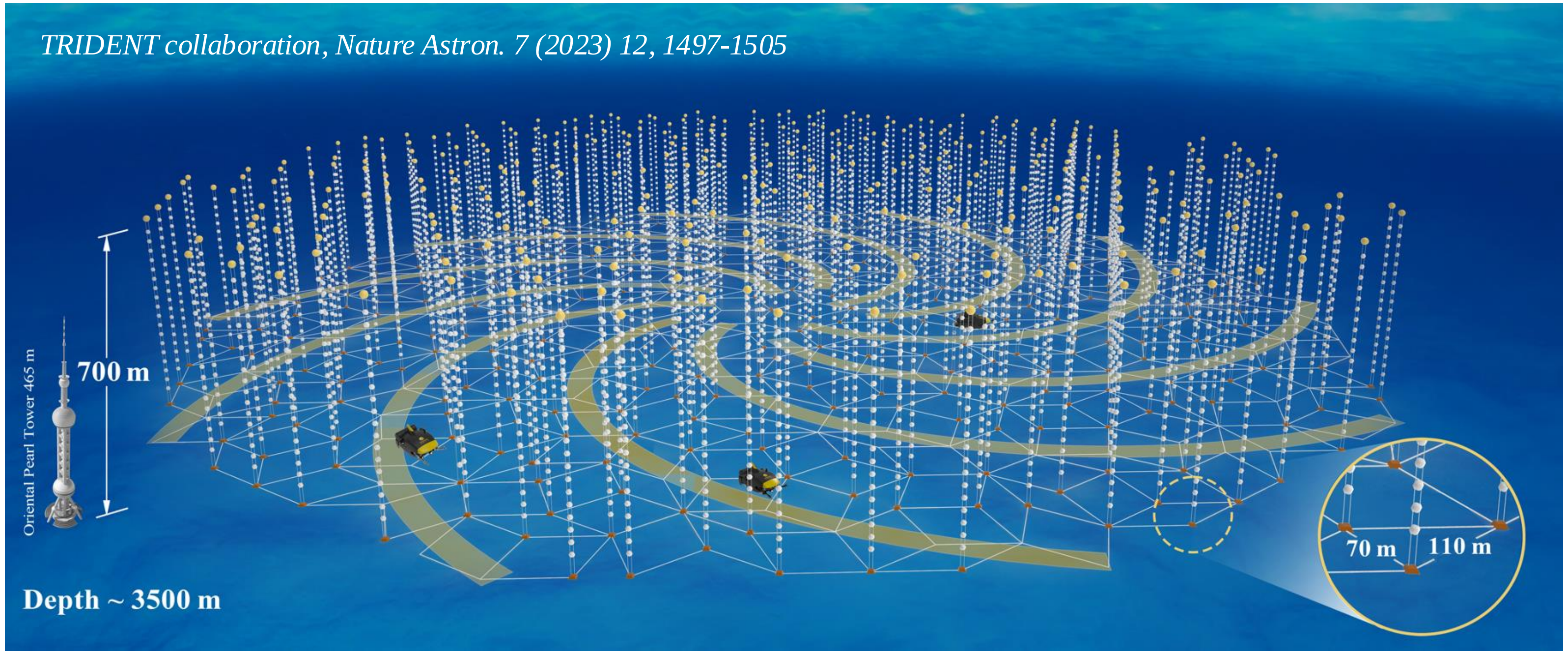
Inter-string distance: 70m/110m, **Inter-DOM distance:** 35m

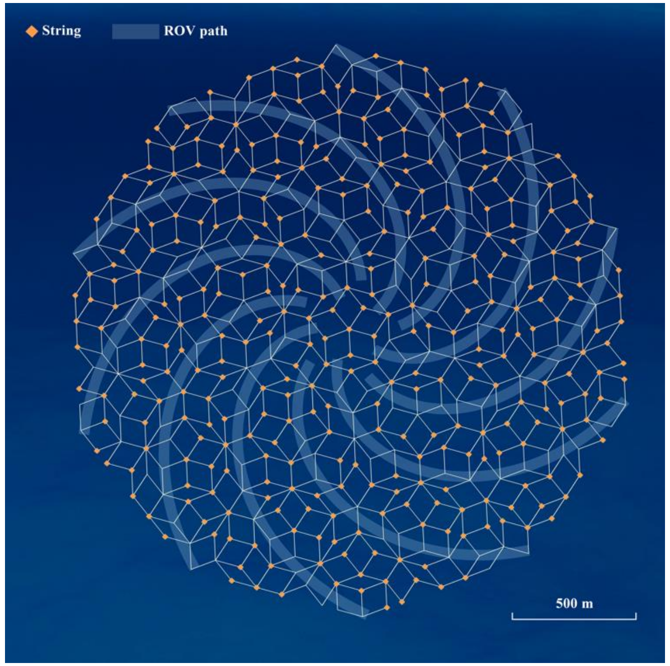
Detection Volume: ~8 km^3

hDOM = PMTs+SiPM

Penrose-tiling geometry:

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





Optical calibration in water-based neutrino telescopes

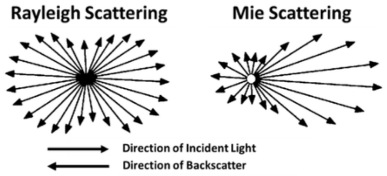
❖ The canonical optical parameters:

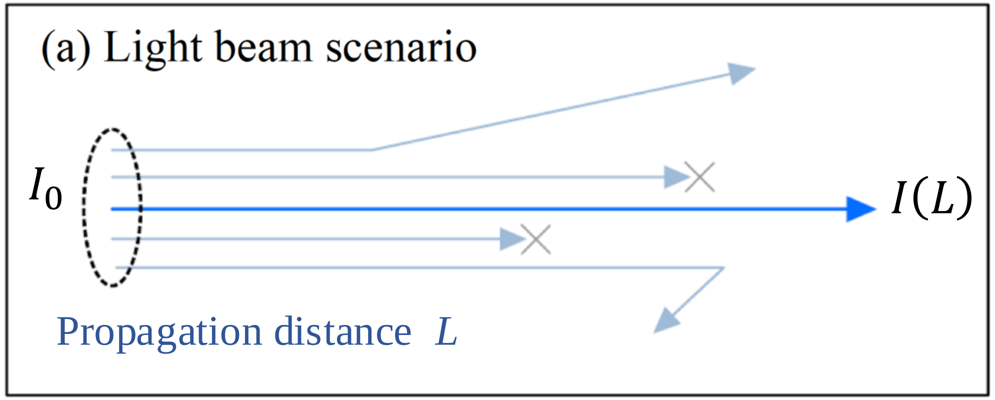
Absorption length (λ_{abs}) ~ photon loss

Scattering length (λ_{sca}) ~ photon deflection

Rayleigh scattering (λ_{Ray}):

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

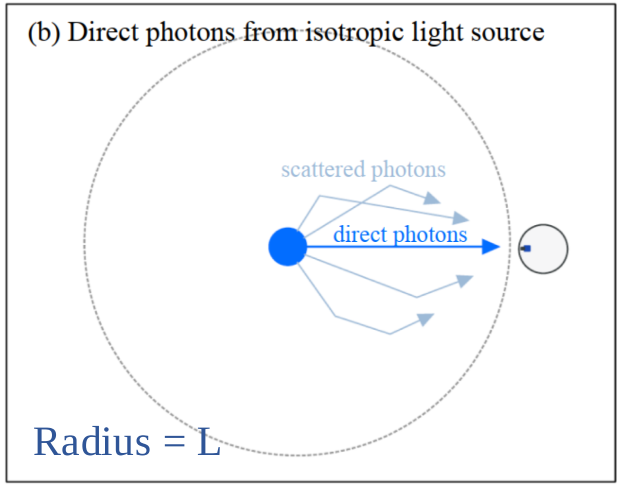




Attenuation length (λ_{att}):

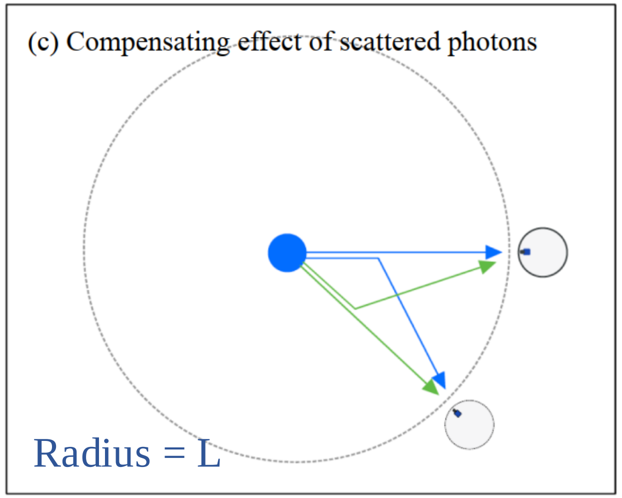
$$I(L) = I_0 \cdot e^{-\left(\frac{L}{\lambda_{abs}}+\frac{L}{\lambda_{sca}}\right)} = I_0 \cdot e^{-\frac{L}{\lambda_{att}}}$$

❖ For the isotropic light source scenario:



For the direct photons:

$$I(L) = I_0 \cdot \frac{dS}{4\pi L^2} \cdot e^{-\frac{L}{\lambda_{att}}}$$



Direct + Scattered photons:

$$I(L) = I_0 \cdot \frac{dS}{4\pi L^2} \cdot e^{-\frac{L}{\lambda_{eff,att}}}$$

(**$\lambda_{eff,att}$** is not a constant number!)

$$I(L) = I_0 \cdot \frac{dS}{4\pi L^2} \cdot e^{-\frac{\bar{L}}{\lambda_{abs}}}$$

$\bar{L}\ (L, \lambda_{Mie}, \lambda_{Ray}, \langle\theta_{Mie}\rangle)$ is a function

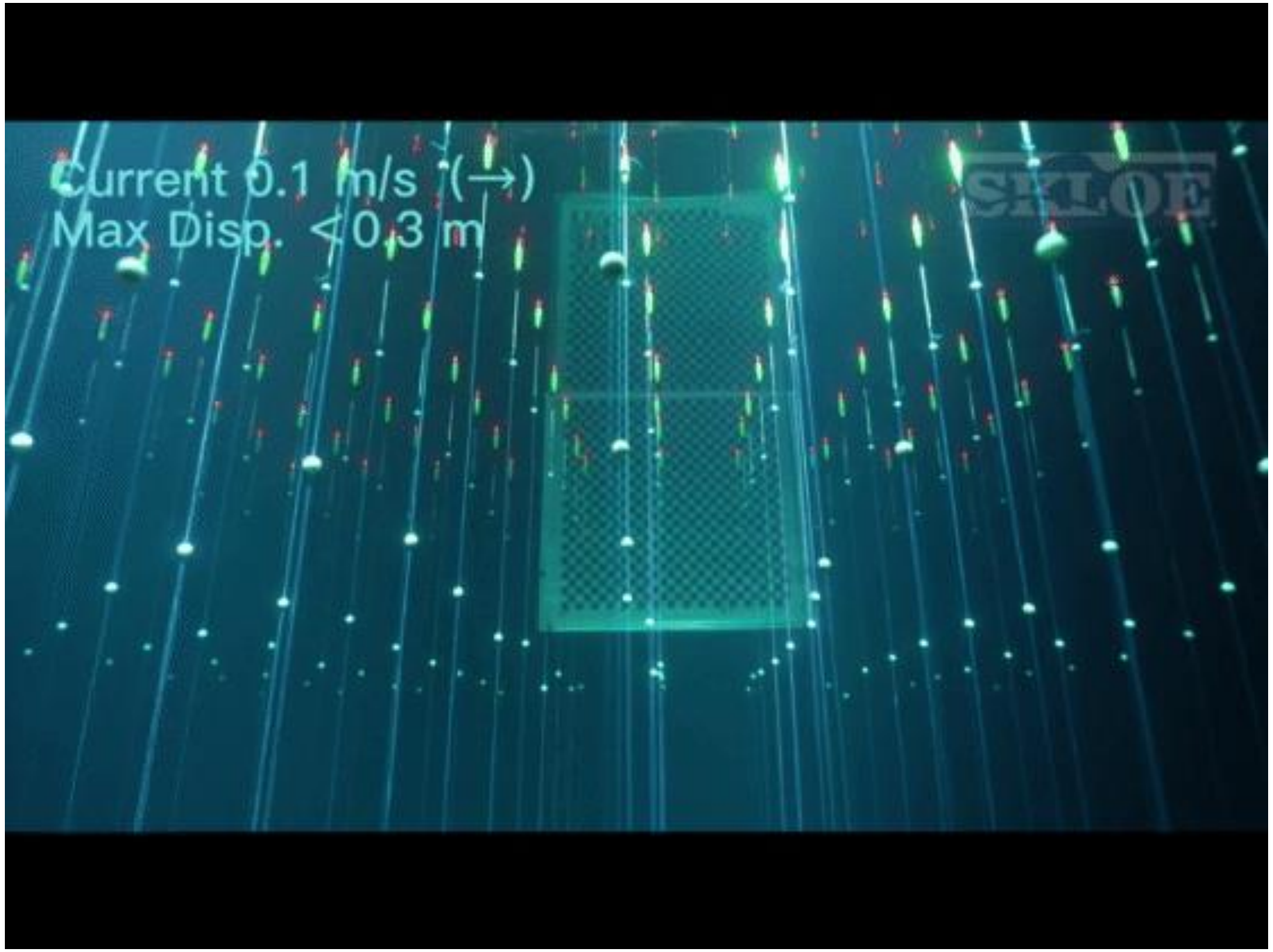
(TRIDENT Camera: arXiv:2407.19111)

Challenges of optical calibration in deep water

Extra challenges compared with ice:

1. Dynamic state of detector
2. Time-varying optical properties
3. Non-uniformity in different regions/depths
4. Bio-activity / Sedimentation

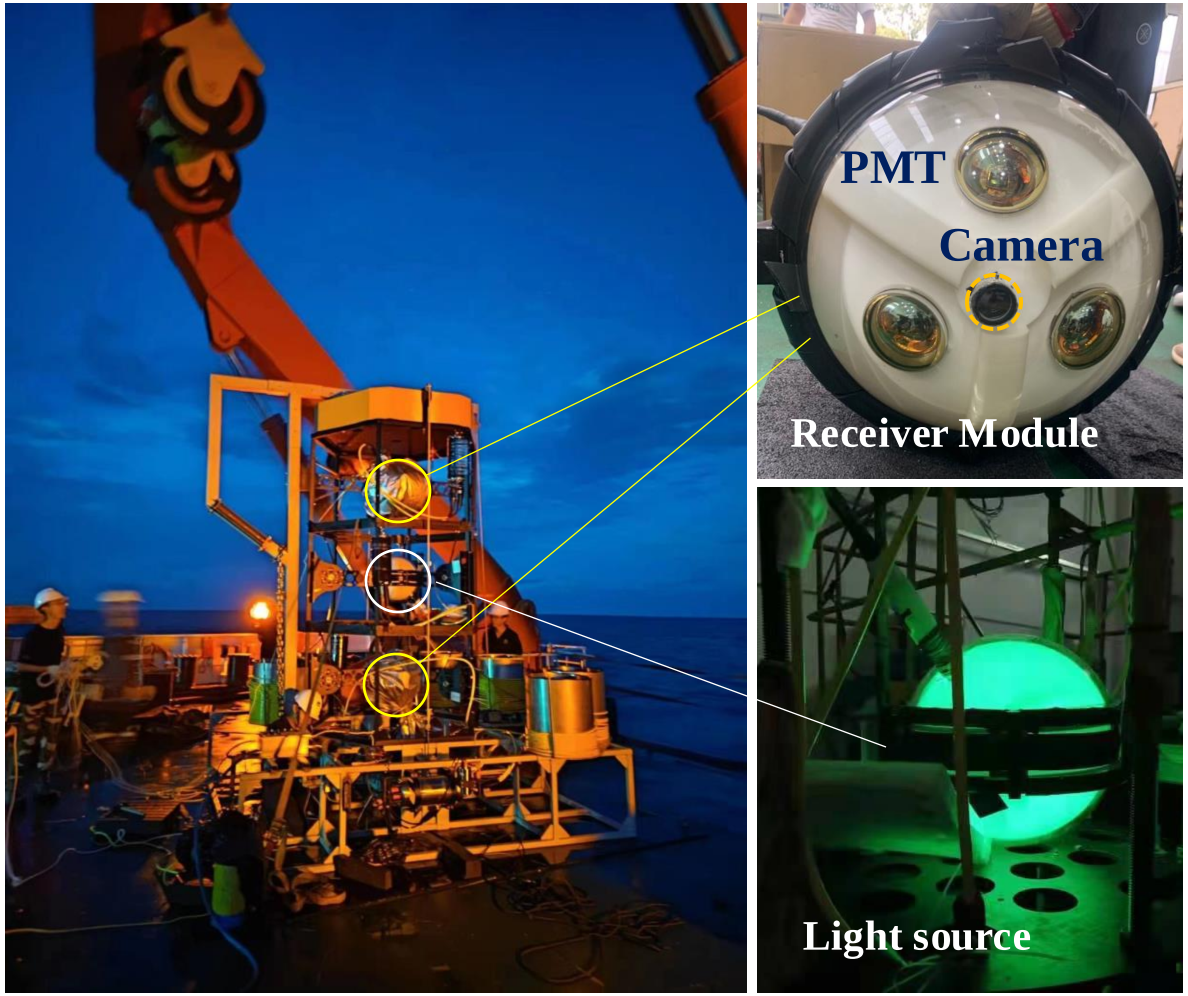
A real-time optical calibration system across detector arrays is necessary!



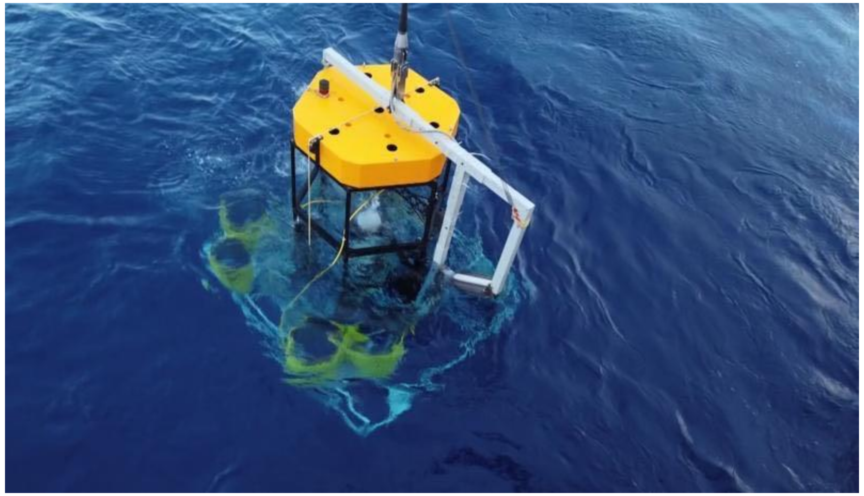
A detector demonstration in the SJTU ship towing tank

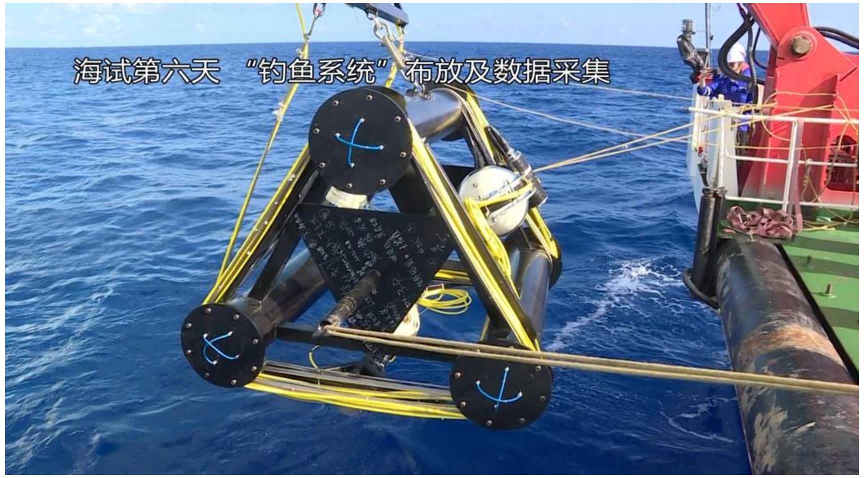
TRIDENT Pathfinder experiment (2021)

❖ **TRIDENT EXplorer (T-REX)**

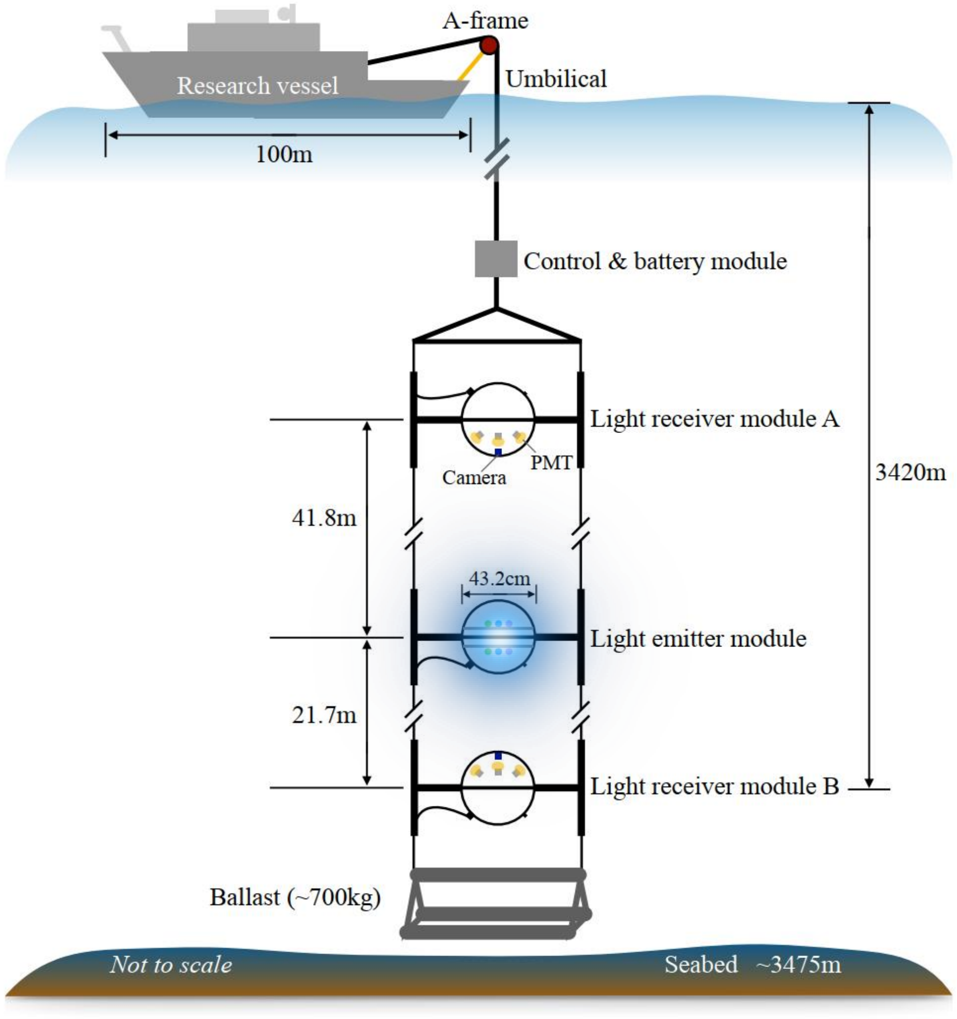


❖ **T-REX deployment (depth of 3420m)**





T-REX apparatus



Experiment goals:

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

Light Receiver Module (LRM) 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 (LEM) :

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

Pulsing mode (PMT) & Steady mode (Camera)

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

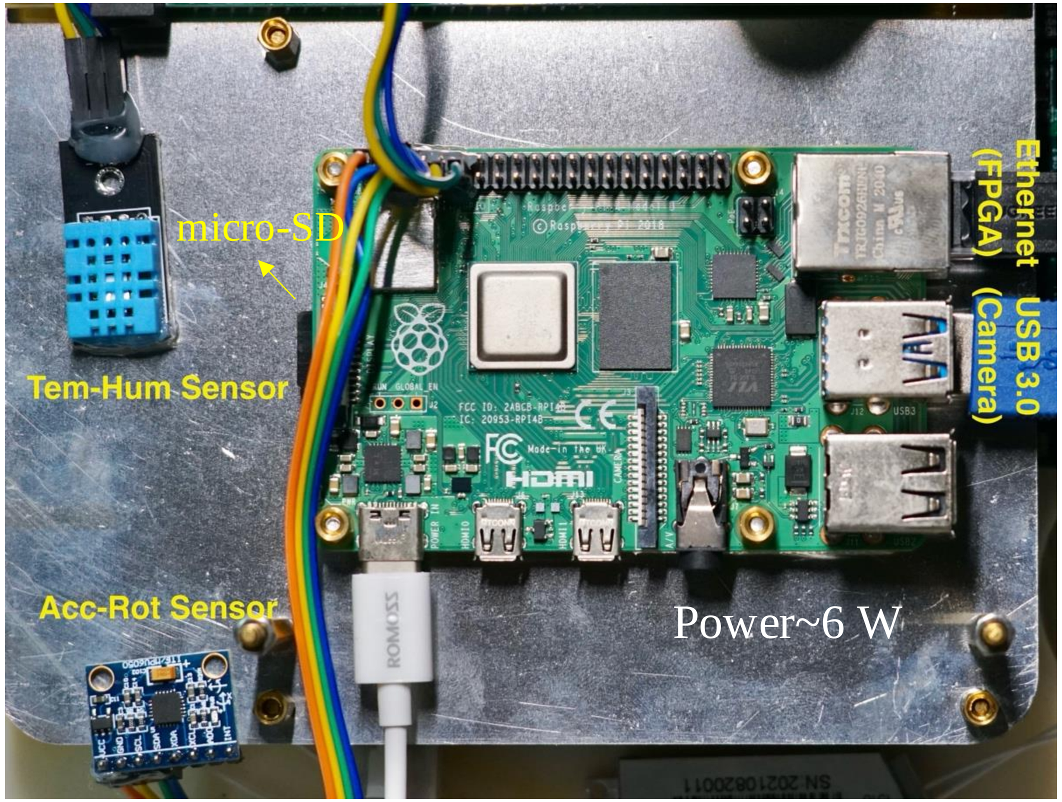
Hardware design of the camera system

Camera + Isotopic steady light source:

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

Control & DAQ module: **Raspberry 4Pi & FPGA**

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



Camera settings in the blind water condition

1. Exposure time scanning:

Fast mode: 0.02s

For 405nm: 0.11s
For 460nm: 0.05s
For 525nm: 0.07s

LED brightness calibration in lab

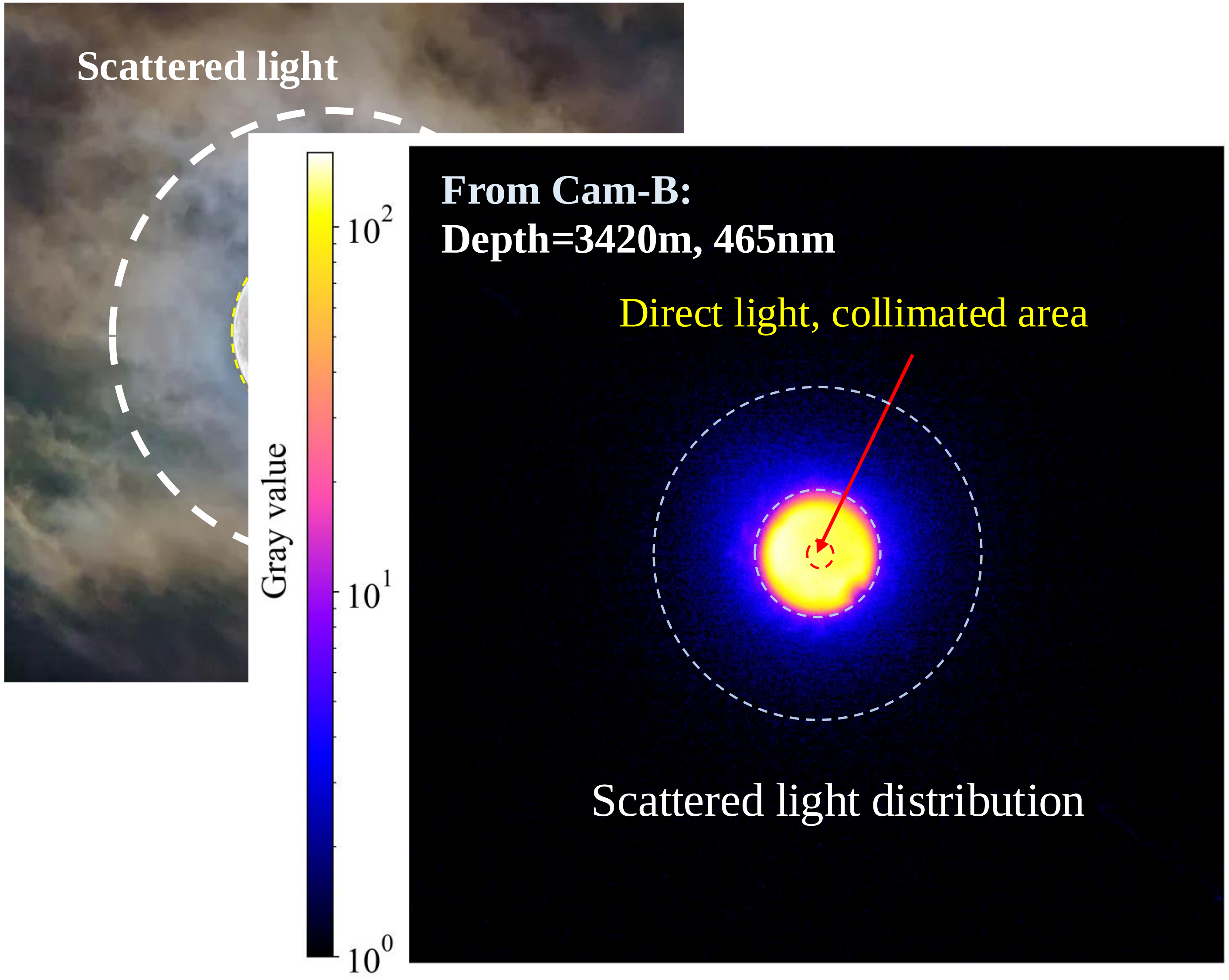
Environment mode: 0.5s, 1.0s

2. Gain scanning:

Gain = 0~20, step2

For each wavelength (~8 min):

ExpoTime * Gain * 20 pics = 1200 pics
(× three wavelengths)

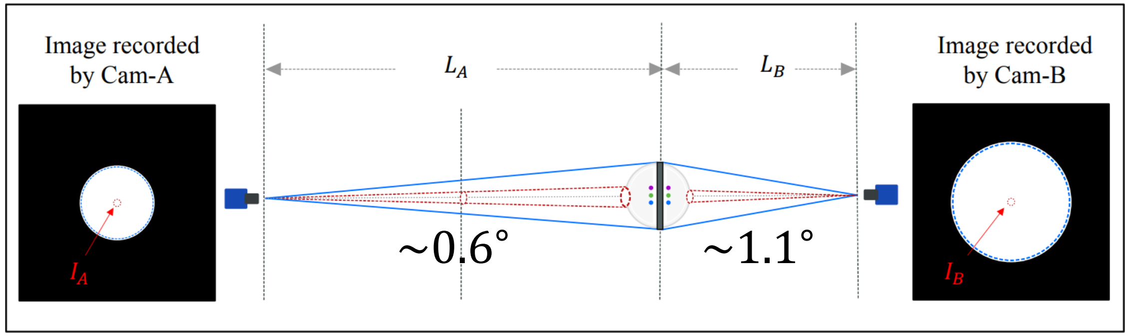


The I_{center} method for λ_{att} measurement

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

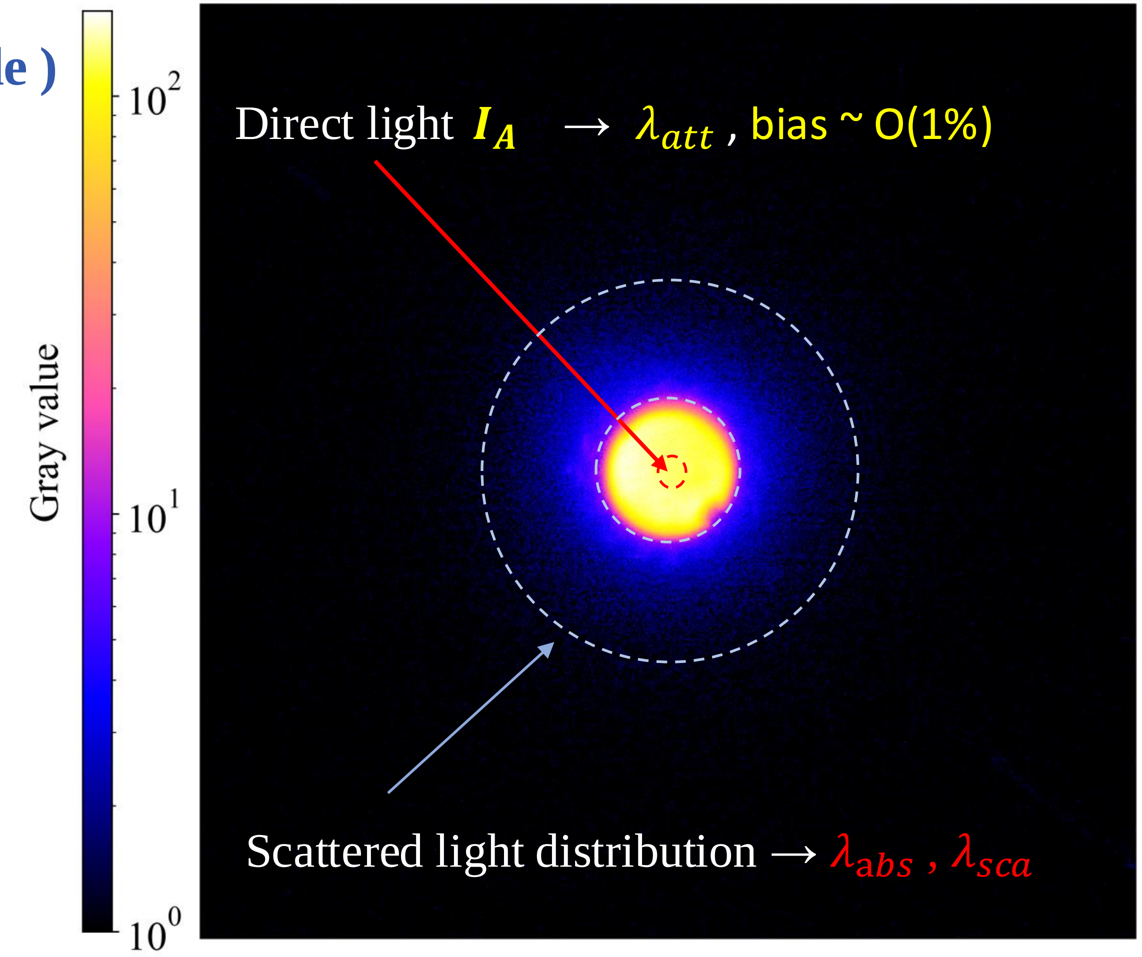
Pixel (Exclude scattered light by a small viewing angle)

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



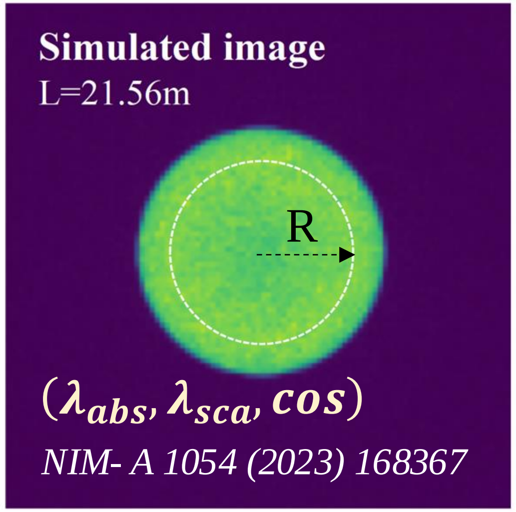
I_{center} method: $\lambda_{att} = -(L_A - L_B)/\ln(-\frac{I_A}{I_B} \cdot \frac{I_0'}{I_0})$

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

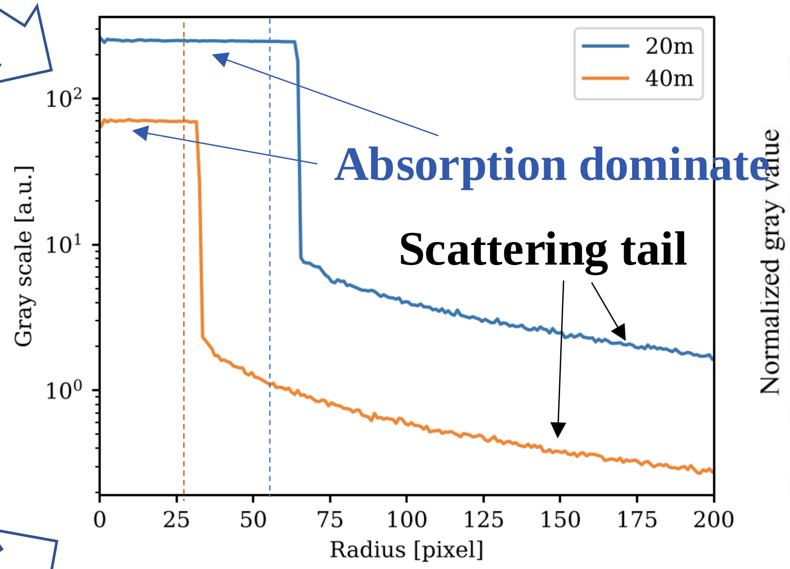


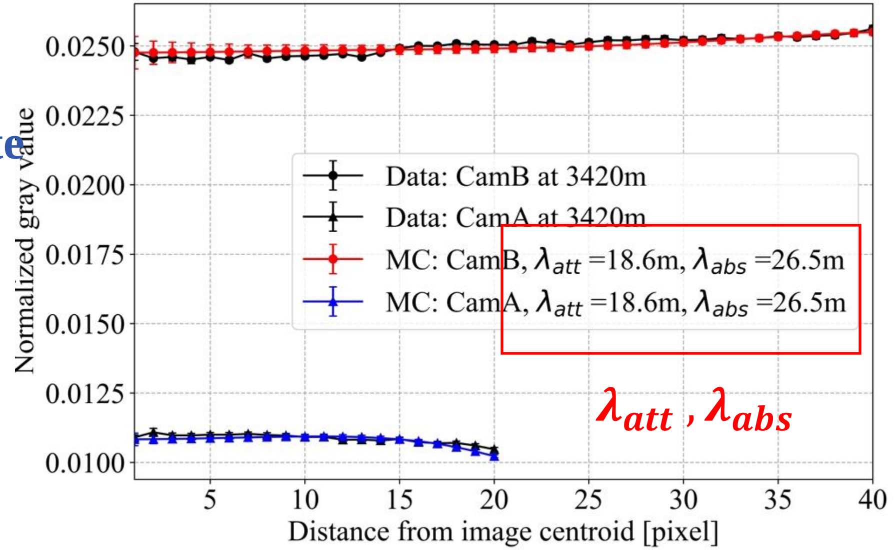
χ^2 fitting method for λ_{att} , λ_{abs}, λ_{sca} measurement

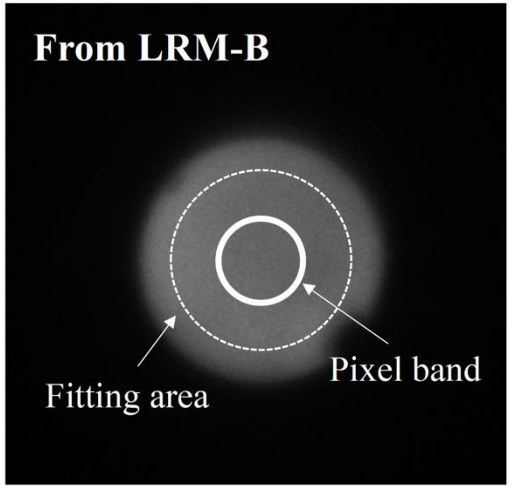
❖ **Comparing the gray value distribution of Real & Geant4 Simulated images:**



G4+ LEM emission profile: 2D image → Normalized 1D gray value profile



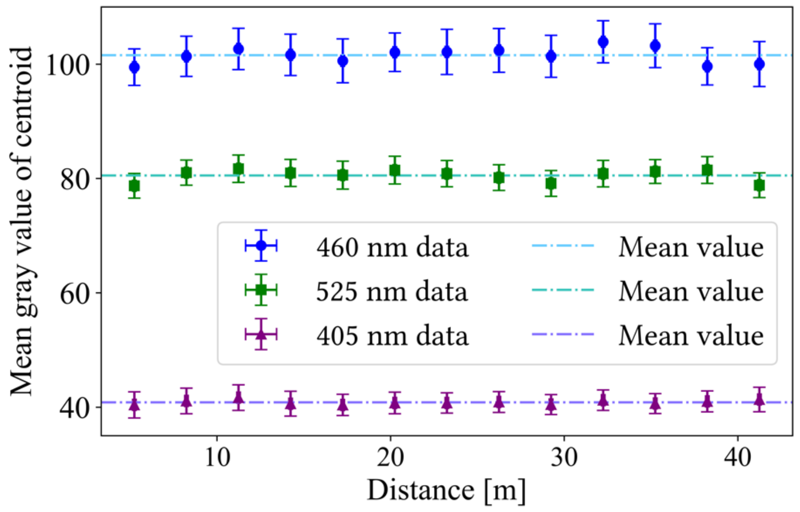


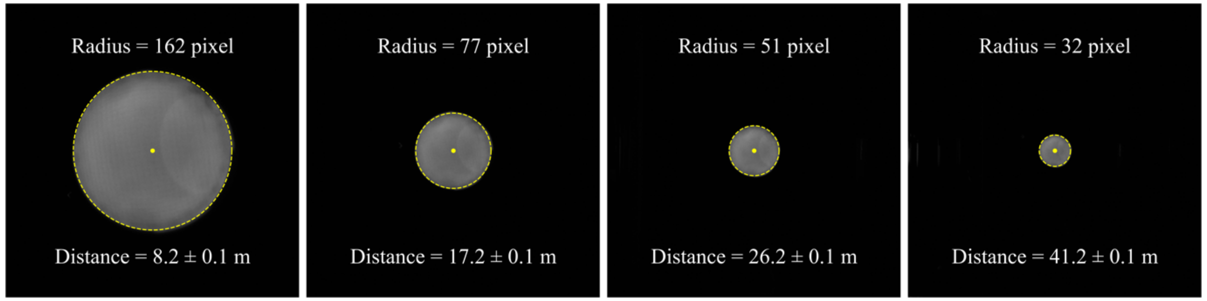


By minimizing:
$$\chi^2 = \sum_{i=1}^{N} \frac{[M_i - T_i(1+\sum_{k=1}^{K}\epsilon_k)]^2}{\sigma_{Mi}^2 + \sigma_{Ti}^2} + \sum_{k=1}^{K}\frac{\epsilon_k^2}{\sigma_k^2}$$

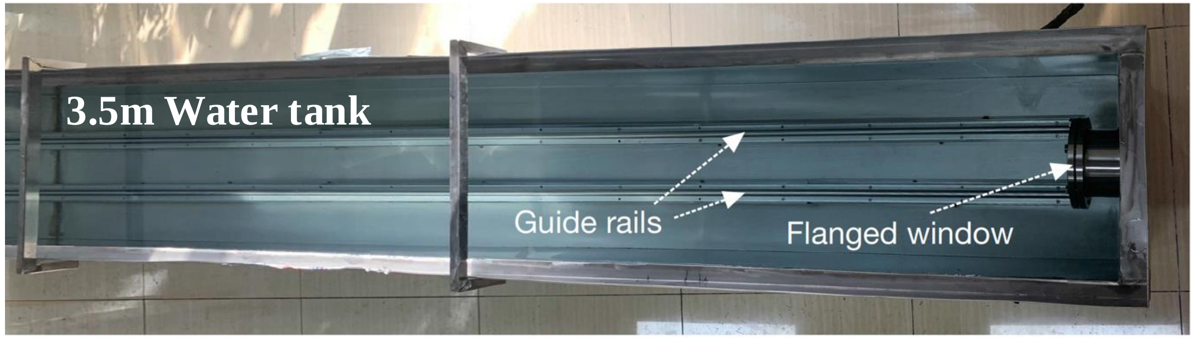
Verification of the I_{center} method

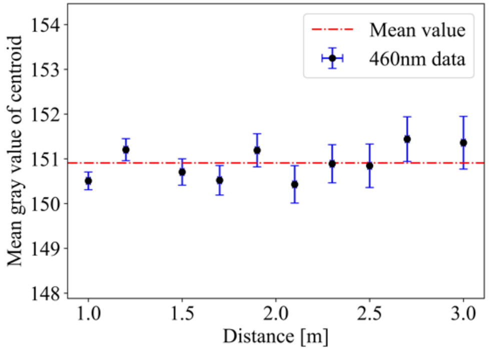
❖ **Long-distance test in air [5m, 42m]**



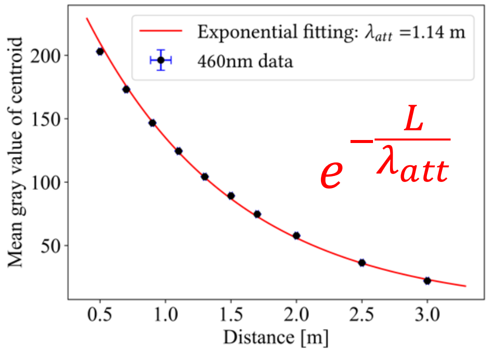


❖ **Water tank experiment to test I_{center}**



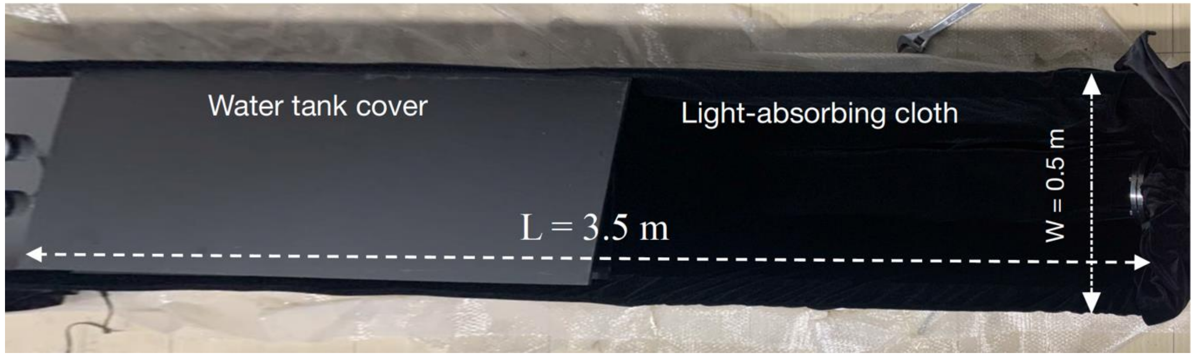


No water



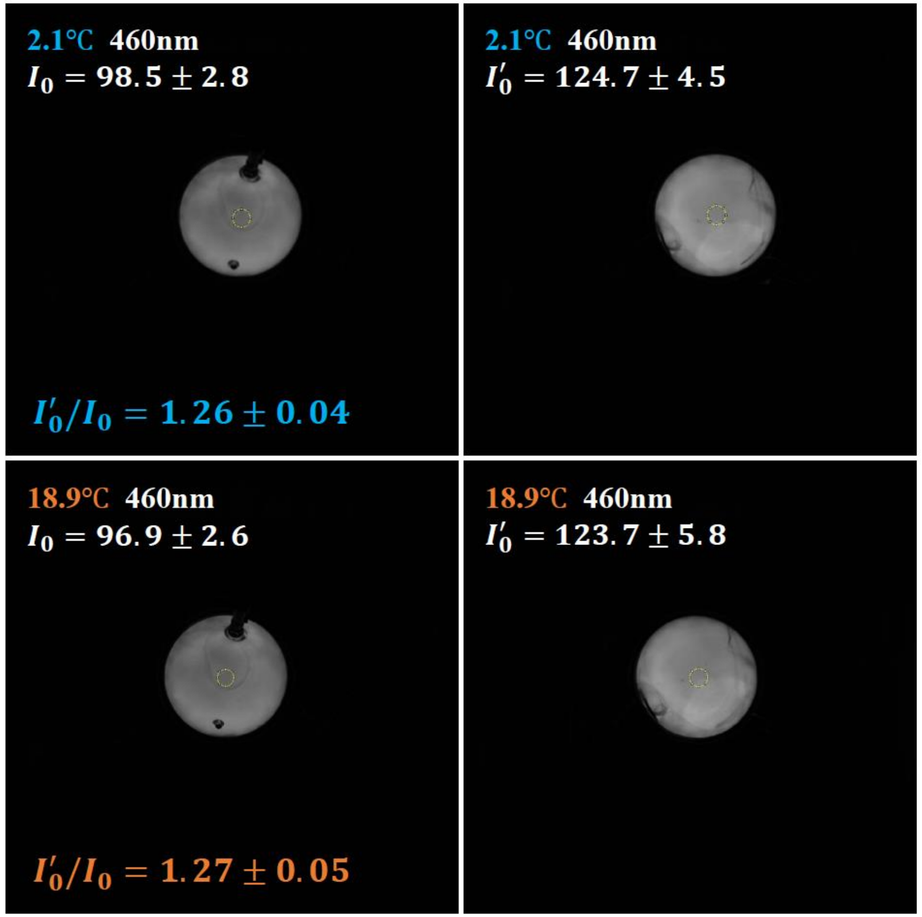
$$e^{-\frac{L}{\lambda_{att}}}$$

After filling water

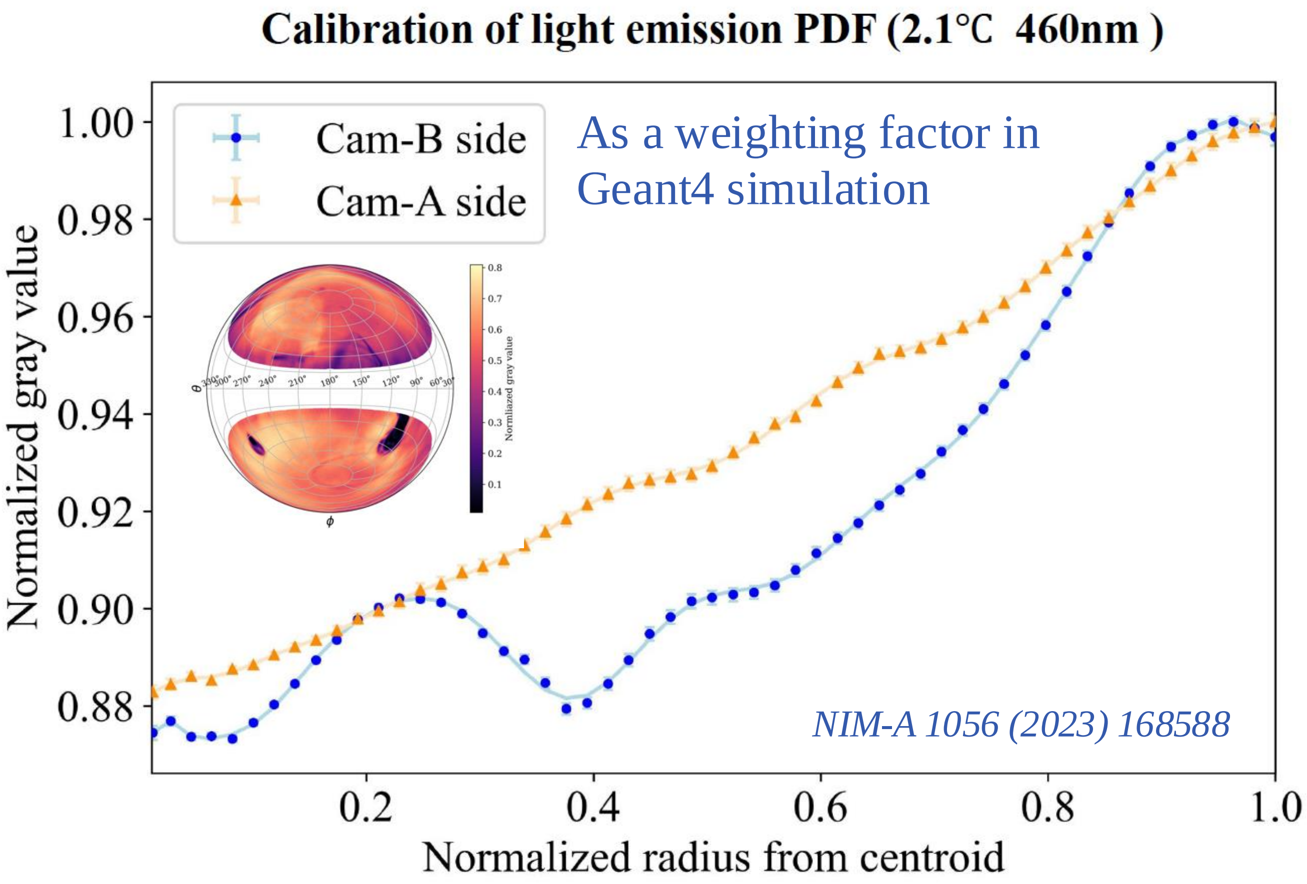


Low-temperature calibration

Calibrate the cameras in deep-sea temperature

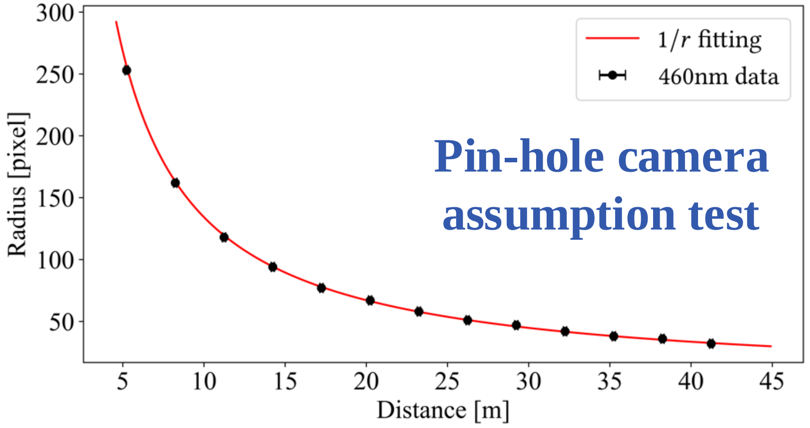


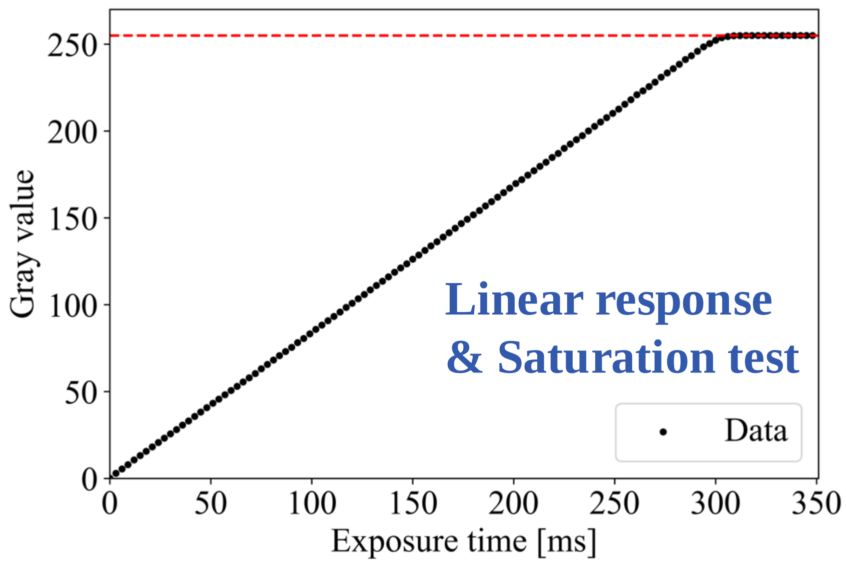
Calibrate the emission PDF of the T-REX light source



Camera response calibration

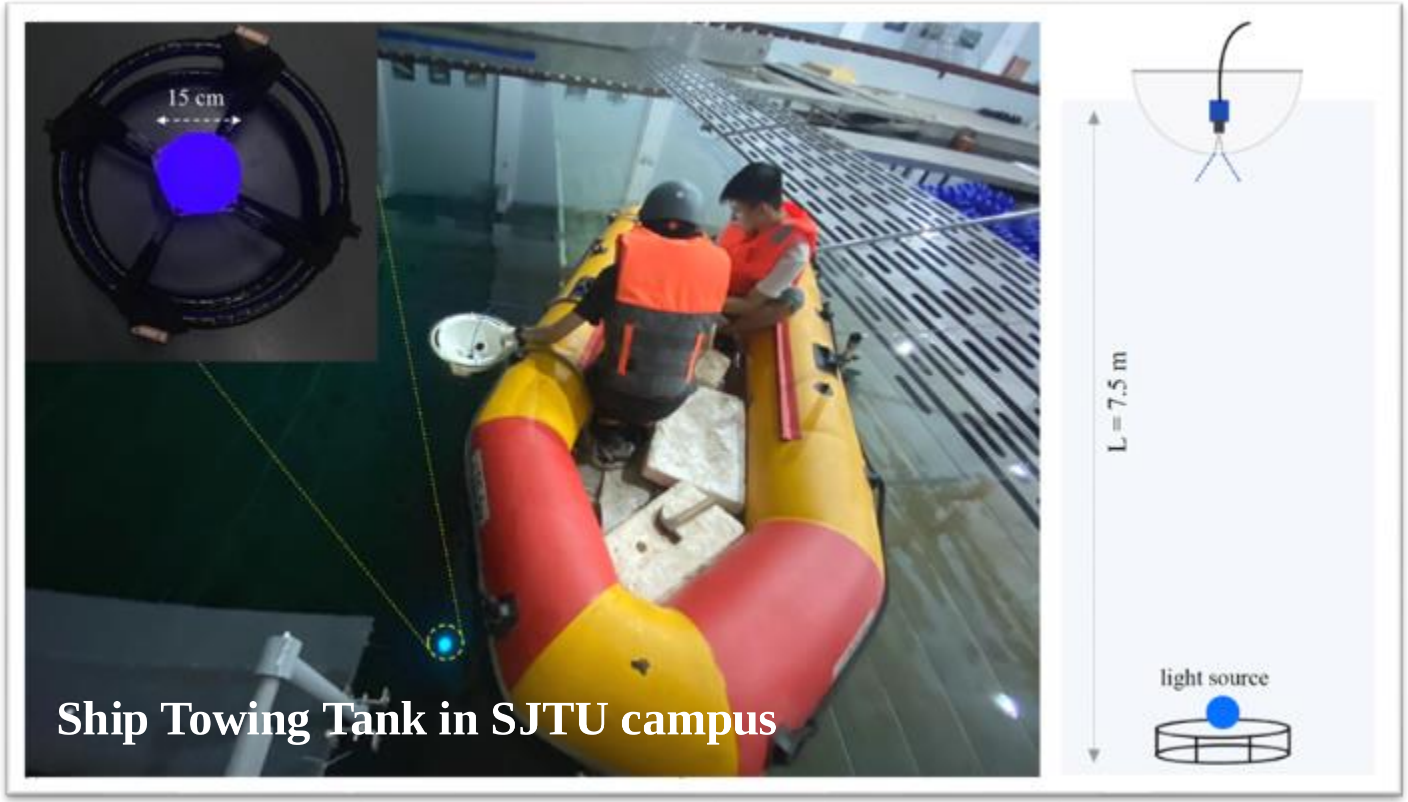
❖ Distortion & Linear response test





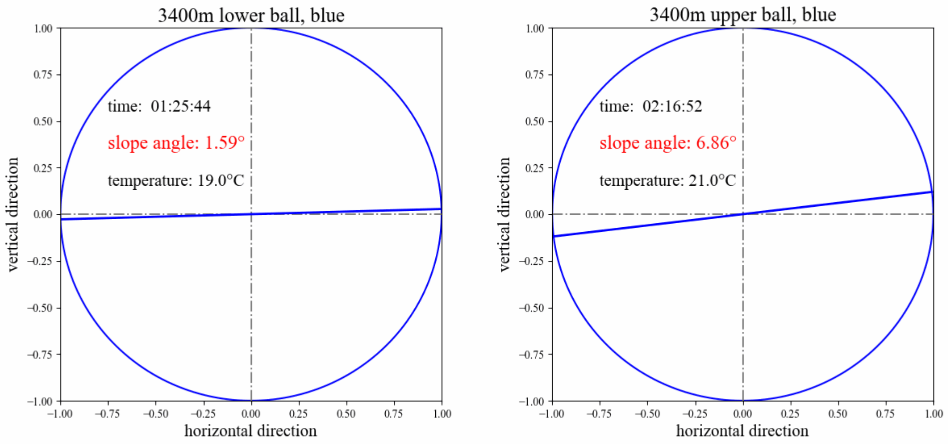
❖ Focal length recalibration in water

An extra 'lens' caused by curvature of glass vessel

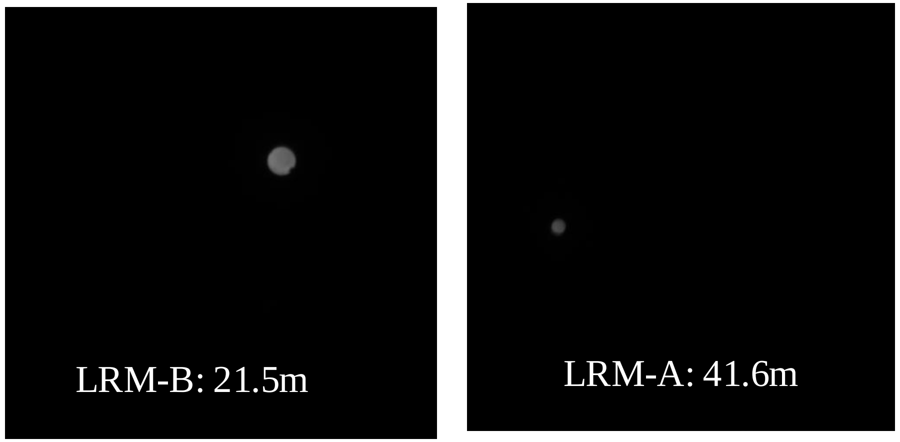


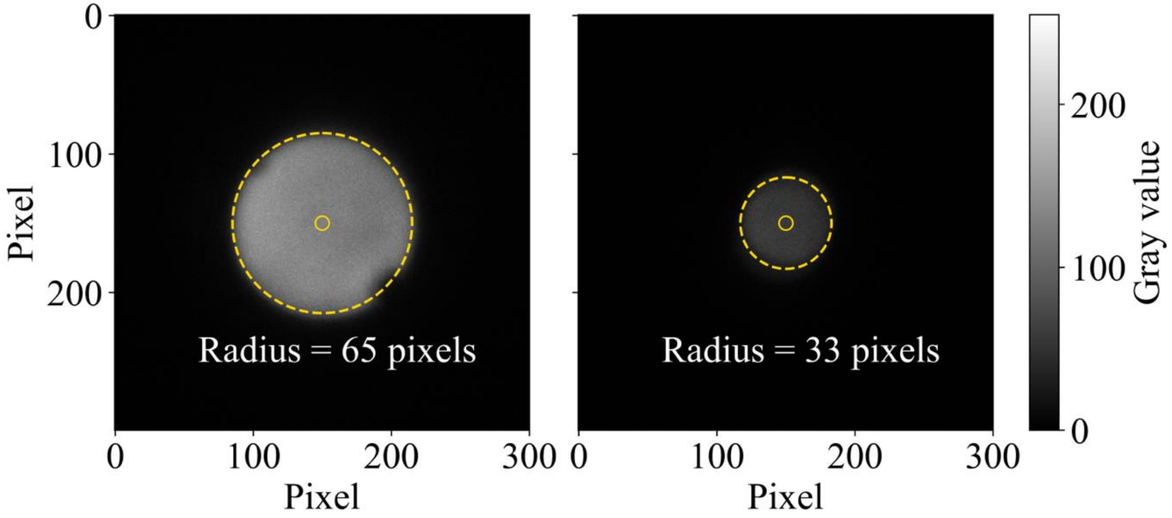
Remote operation of the camera system

❖ Monitoring on the research vessel:



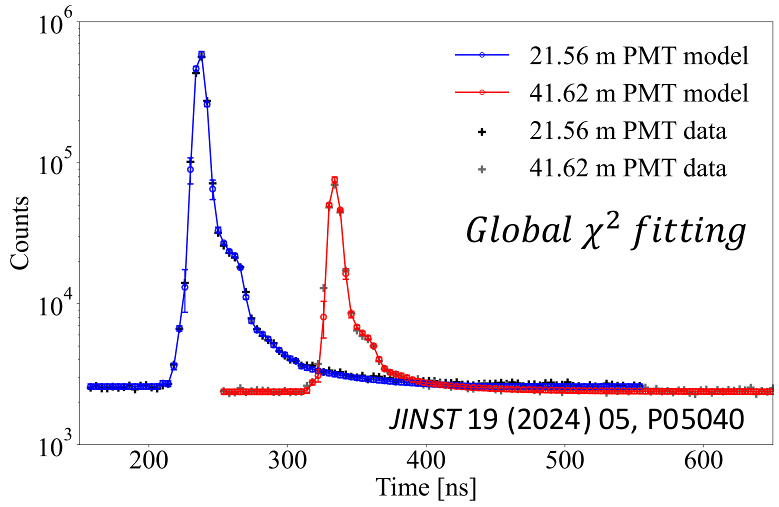
Depth 3420m, wavelength 460nm, 0.05s gain08



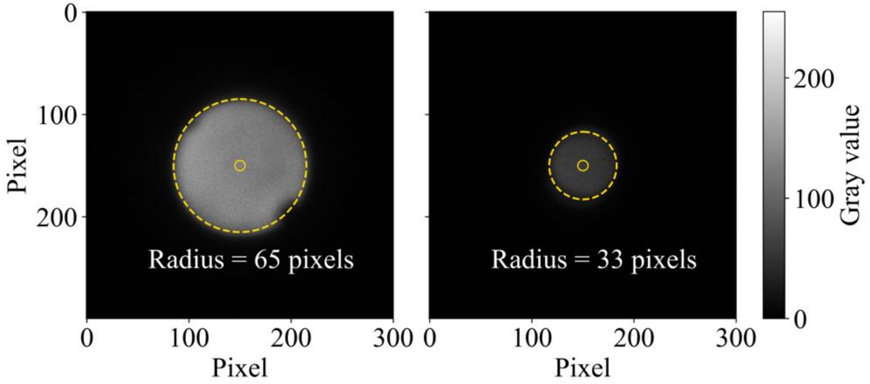


Optical measurement results from T-REX

T-REX PMT system



T-REX Camera system



PMT (at ~ 450 nm, ~ 50 minutes)						
Method	λ_{abs} [m]	λ_{ray} [m]	λ_{mie}[m]	$\cos\theta_{mie}$	λ_{att} [m]	$\lambda_{att,eff}$ [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]	$\lambda_{att,eff}$ [m]
χ^2 fitting	26.5 ± 0.5	62.9 ± 3.7	18.7 ± 0.2	26.8 ± 2.8
I_{center}	$\lambda_{att} = 19.3 \pm 1.3$			

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

Measurement Accuracy:

I_{center} method: λ_{att} ~ 6%

χ^2 fitting method: λ_{att}~ 1% λ_{abs} ~ 2% λ_{sca}~ 6%

Outlook & Summary

Upgrade of the camera system in TRIDENT Phase-1:

- Calibration string
- Well-controlled Light source flashing / Down time: ~ O(1-10s)
- Exploring the controlled light emission angle

@ Yingwei Wang's Flash talk on Friday!

Summary:

- TRIDENT is next-gen water-based neutrino telescope: 8 km3, 1000 strings, 20,000 hDOMs.
- The T-REX was deployed in 2021 for site selection, 3500m water depth
- The **Camera System of T-REX: real-time λ_{att} , λ_{abs}, λ_{sca} , with an accuracy of few percent level**
- Be careful to the canonical / effective parameters

TRIDENT
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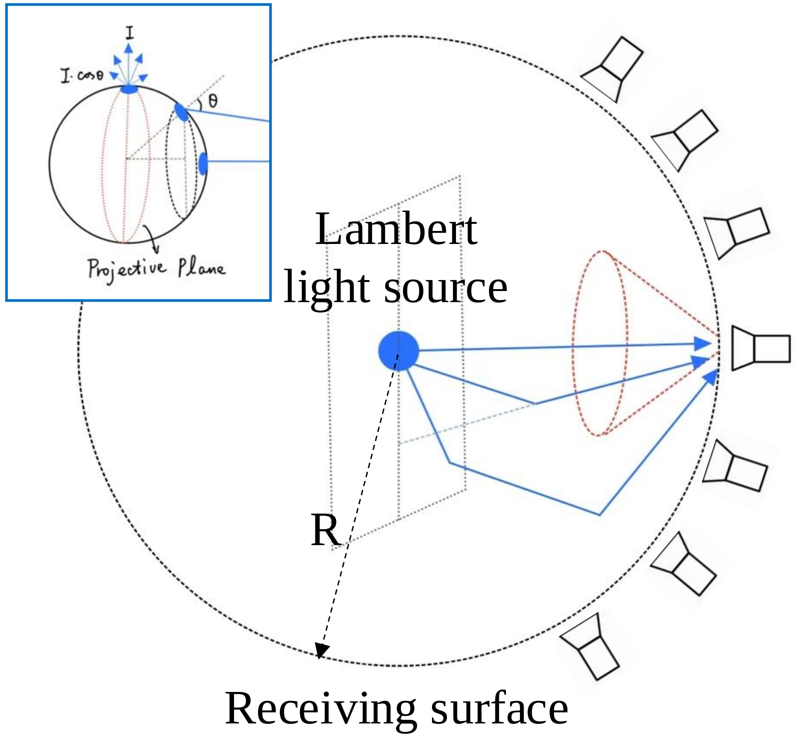
Thanks for listening!

Pin-hole camera simulation by Geant4

Simulation set-up in Geant4:

(T-REX Optical Sim: NIM-A 1054 (2023) 168367)

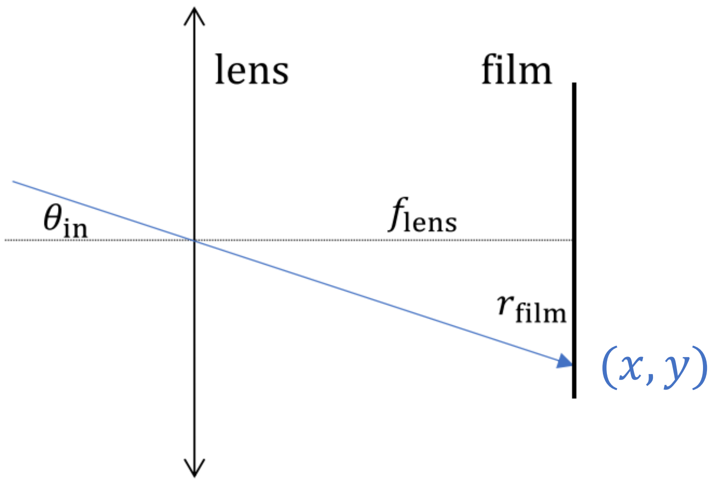


Optical parameters of the medium:

$$\lambda_{abs}, \lambda_{Ray}, \lambda_{Mie}, \langle cos\theta_{Mie} \rangle$$

Imaging process of the cameras

incident light $(\varphi, \theta) \rightarrow (X_{pixel}, Y_{pixel})$



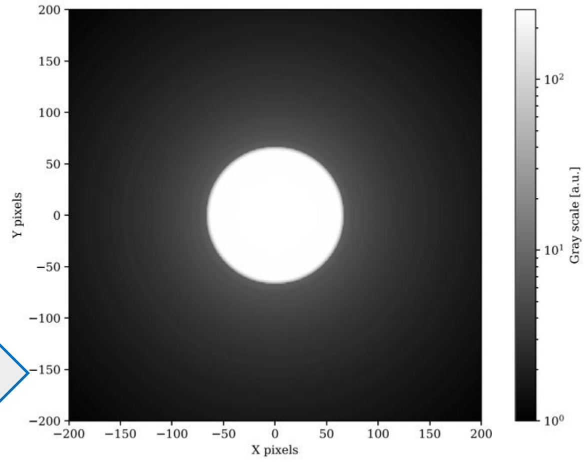
Camera settings:

Focal length,	Pixel size,	Pixels number
(25mm)	(3.45μm)	(2000*2000)

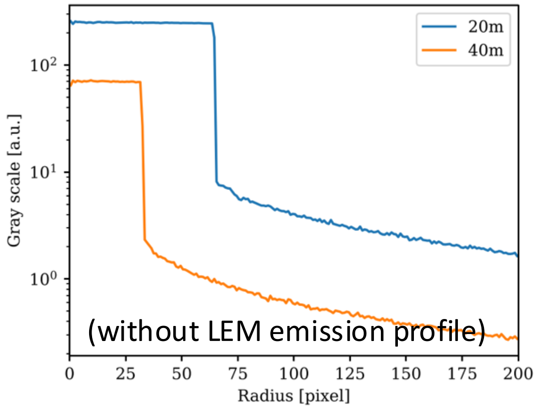
Output info for each pixel:

Photon/weight info N_{sca}, N_{total}, w_i

Simulated Images:

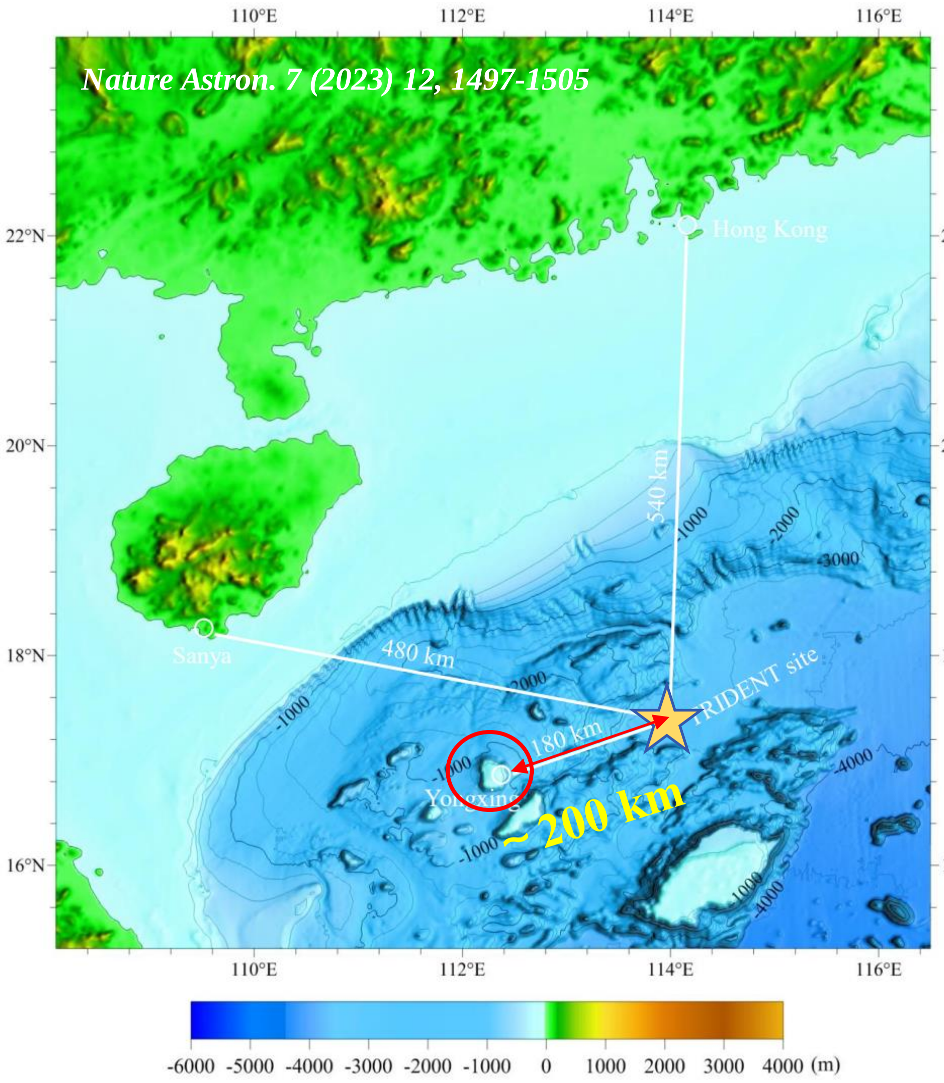


Gray value distribution:

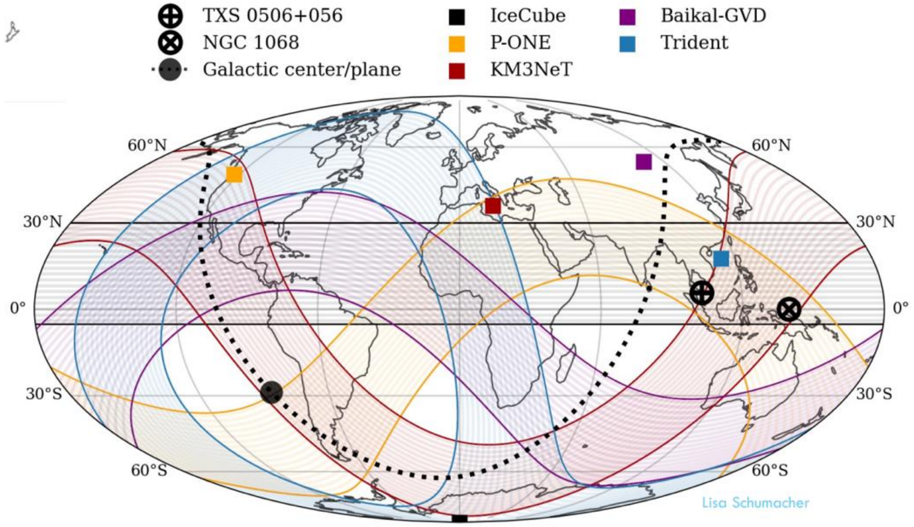


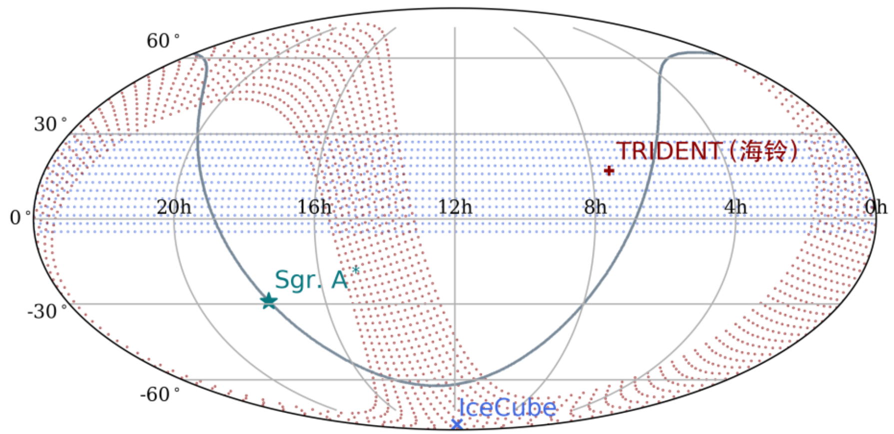
TRopIcal DEep-sea Neutrino Telescope (TRIDENT)

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



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



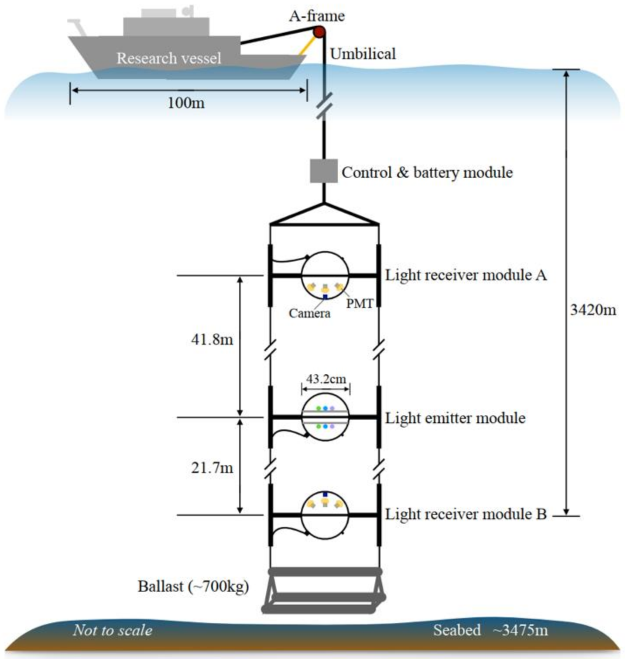


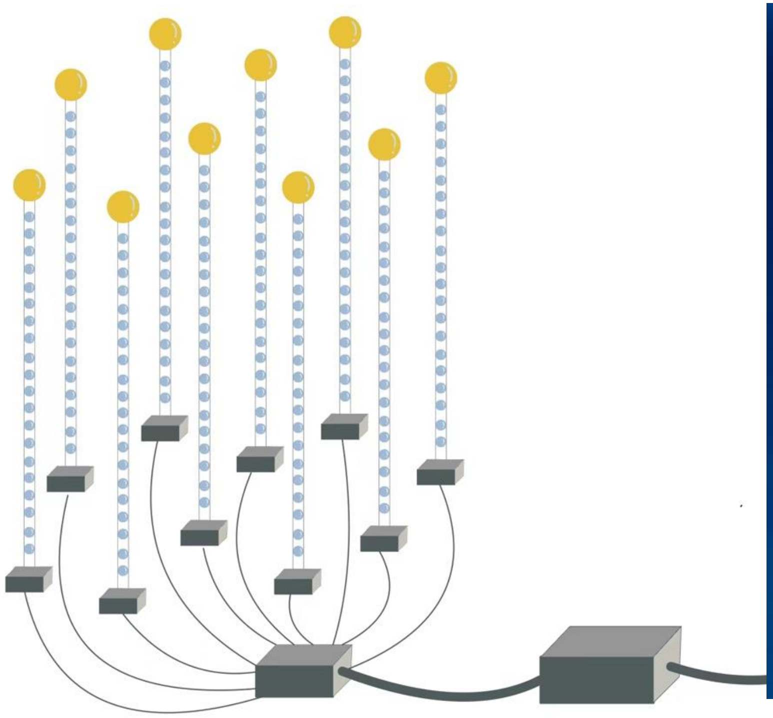
A preliminary timeline for TRIDENT

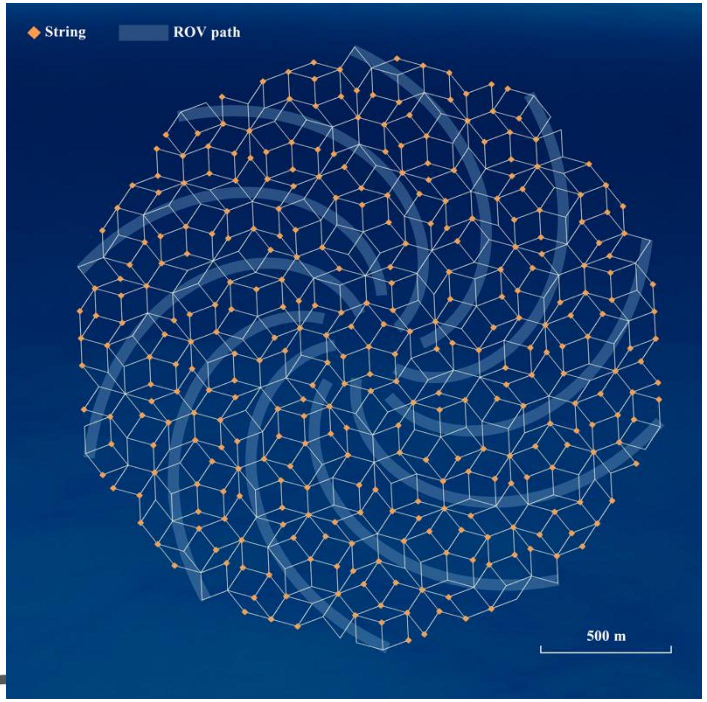
TRIDENT 海 | 铃 | 计 | 划

Pathfinder experiment (2021) | **TRIDENT Phase-1 (~2026)** | **TRIDENT Phase-2 (~2030)**

Done | **Funded**



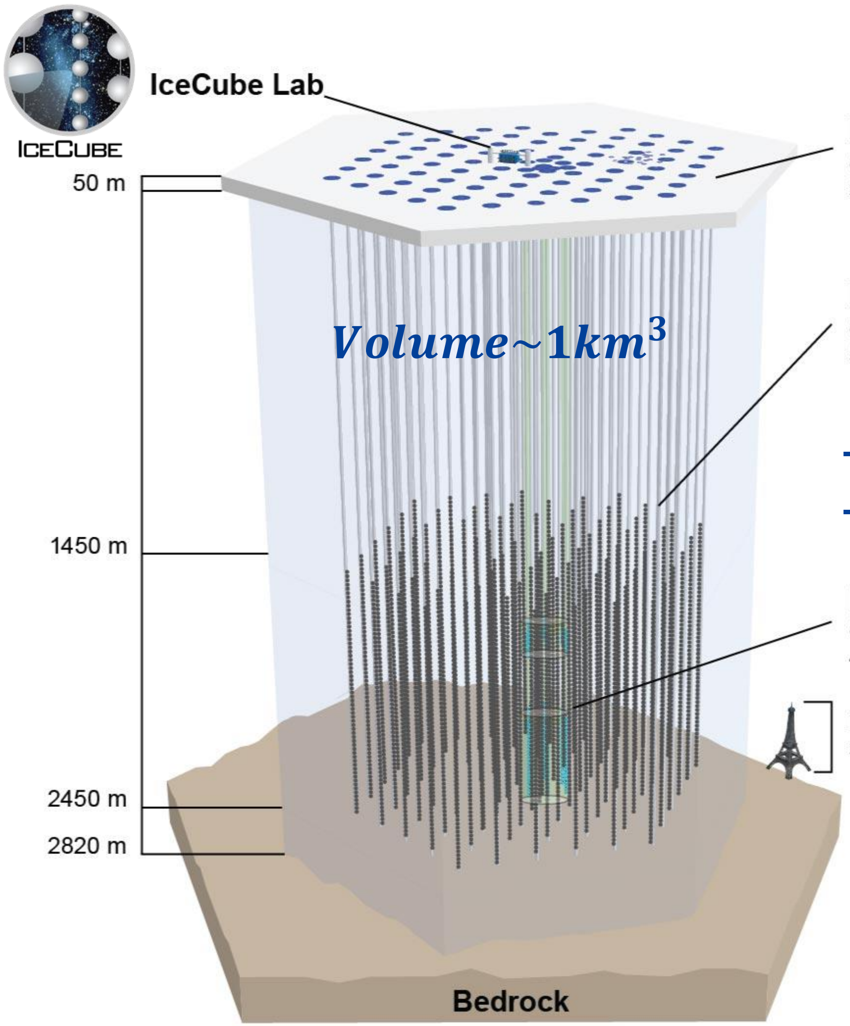




T-REX

10 strings, 200 hDOMs
200km electric-optical cable

Neutrino telescopes in glacial ice and deep water

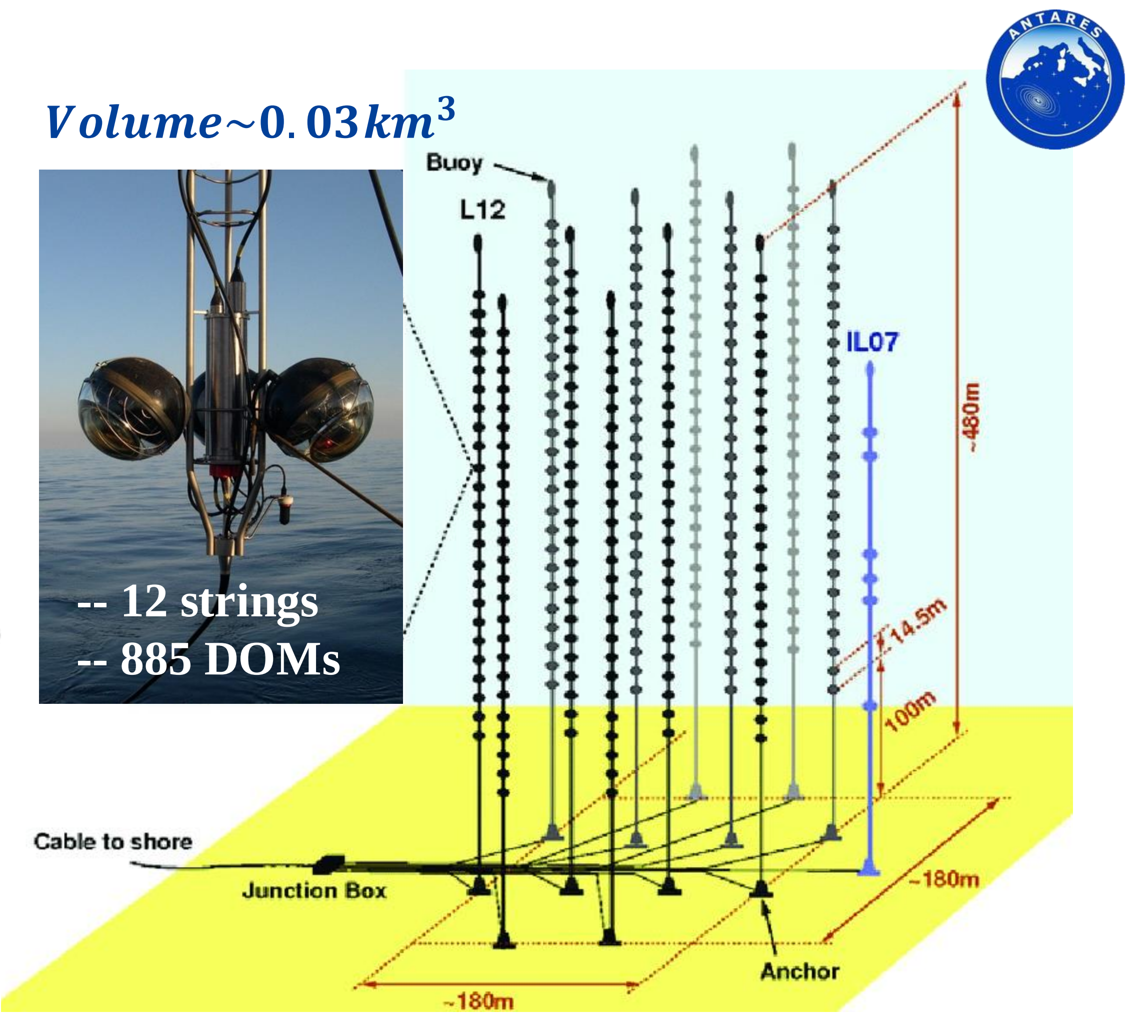


-- 86 strings
-- 5160 DOMs

Art picture by **IceCube**

10-inch PMT

$Volume\sim0.03km^3$

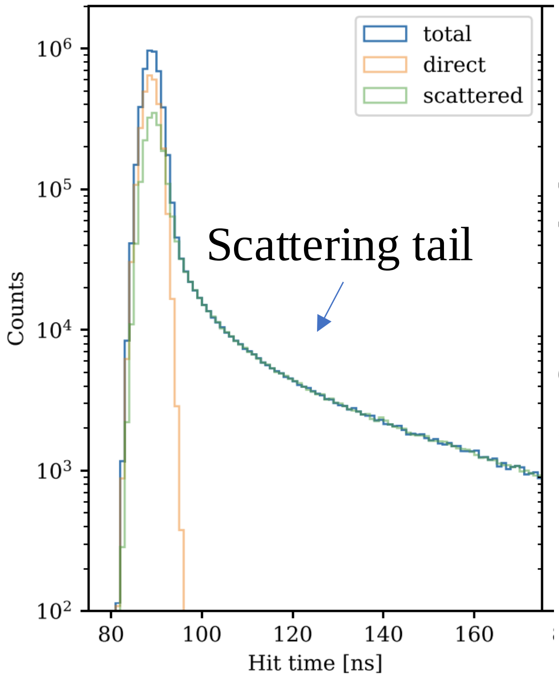


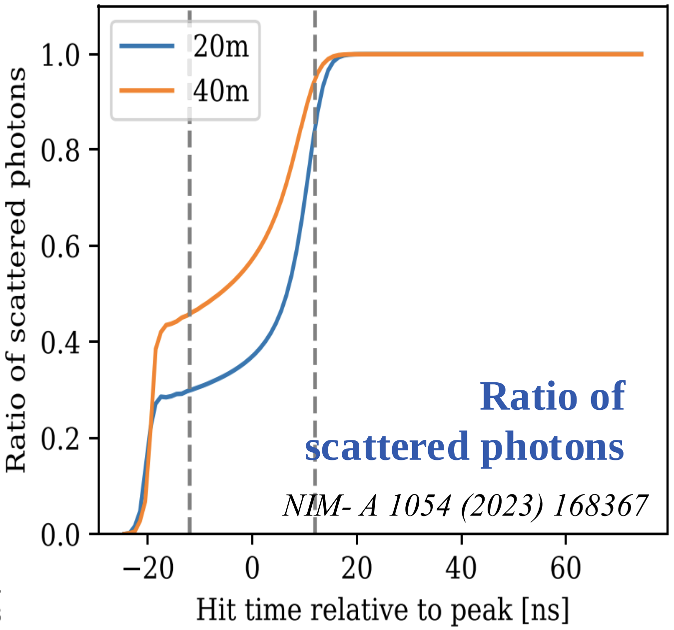
Art picture by **ANTARES**

The commonly-used optical calibration methods

PMT + Pulsing light source:

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

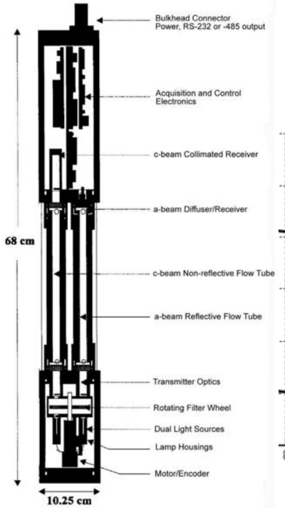




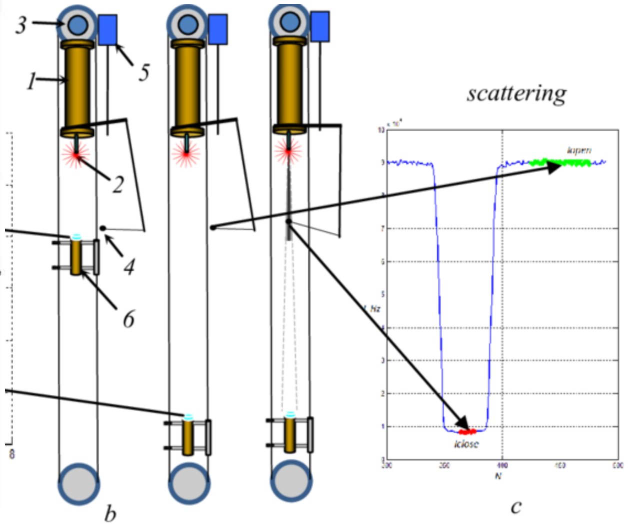
1. **Single-photon mode + Synchronization (~ns)**
2. **Hours-long data accumulation**
3. **Arrival time -> scattered/direct photons, "$\lambda_{eff,att}$"**

Specialized laser facility:

(KM3NeT-AC9, Baikal-5D)



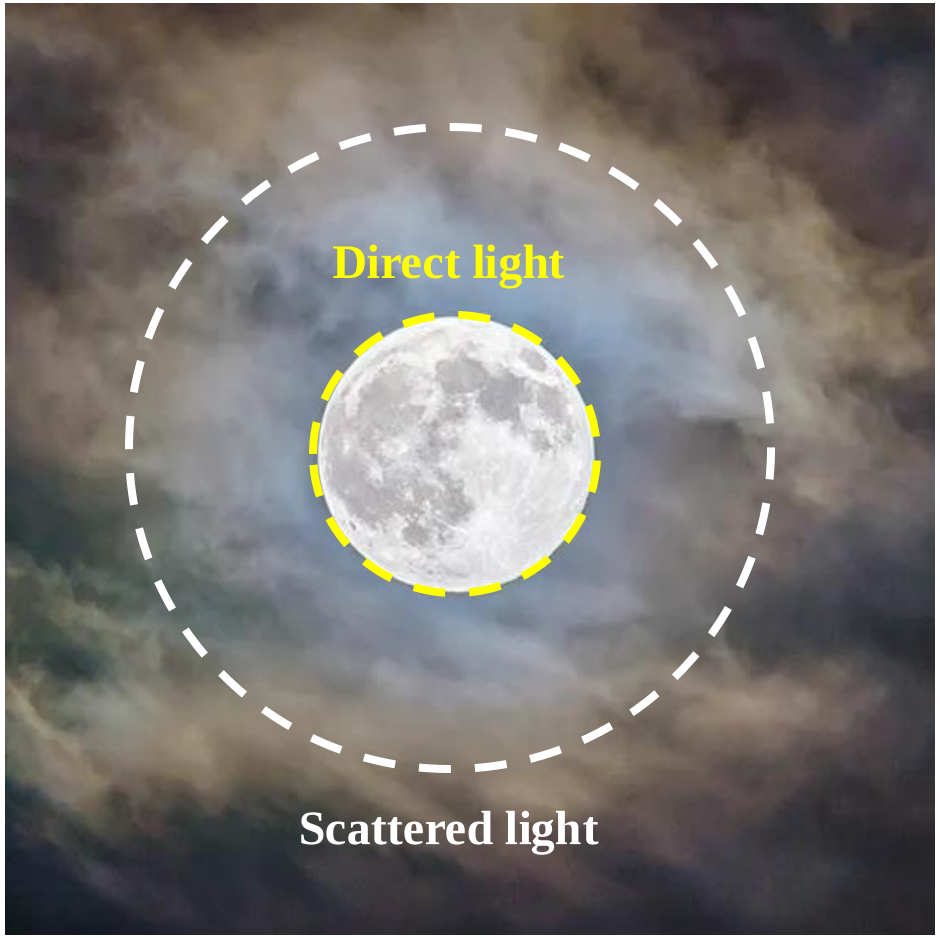
WET lab, AC9



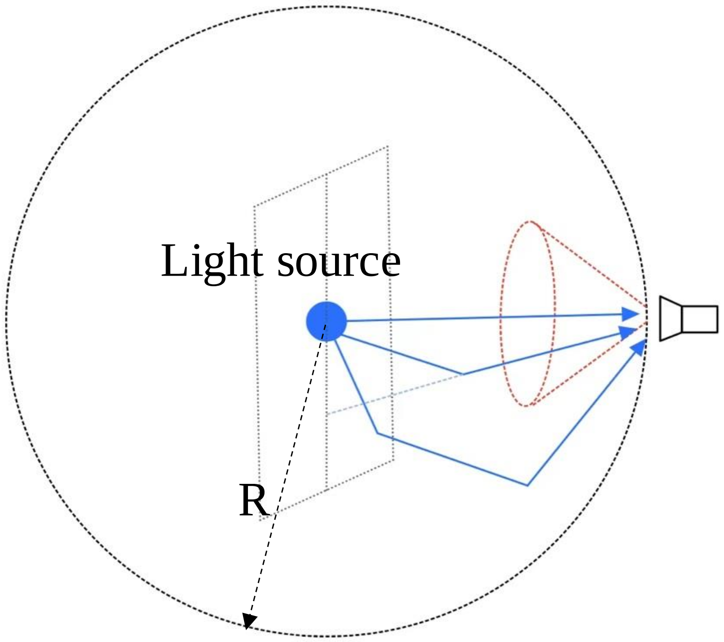
Baikal-5D, PoS ICRC2023 (2023) 977

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

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



Separation the direct light:



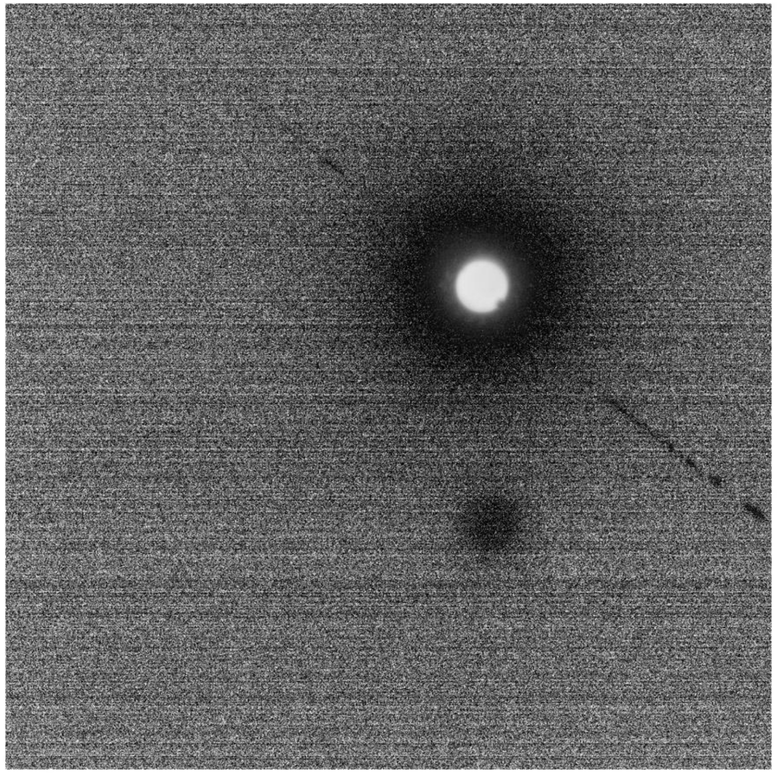
Camera (direction, pixel)

PMT(time ~ ns)

Double-imaging process

TRIDENT 海 | 铃 | 计 | 划

Shadow from the holding structure



The double-imaging effect caused by the small bump on the glass shell