



Future Underwater (Optical) Neutrino Experiments

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10/09/26

The Multimessenger Sky at Extreme Energies: From Sources to Fundamental Physics
indico.gssi.it/e/multimessenger2026

**~10 years of cosmic neutrinos:
what have we actually learned?**

A new astronomy is opening

We need more, better, larger telescopes
But what makes one "better"?

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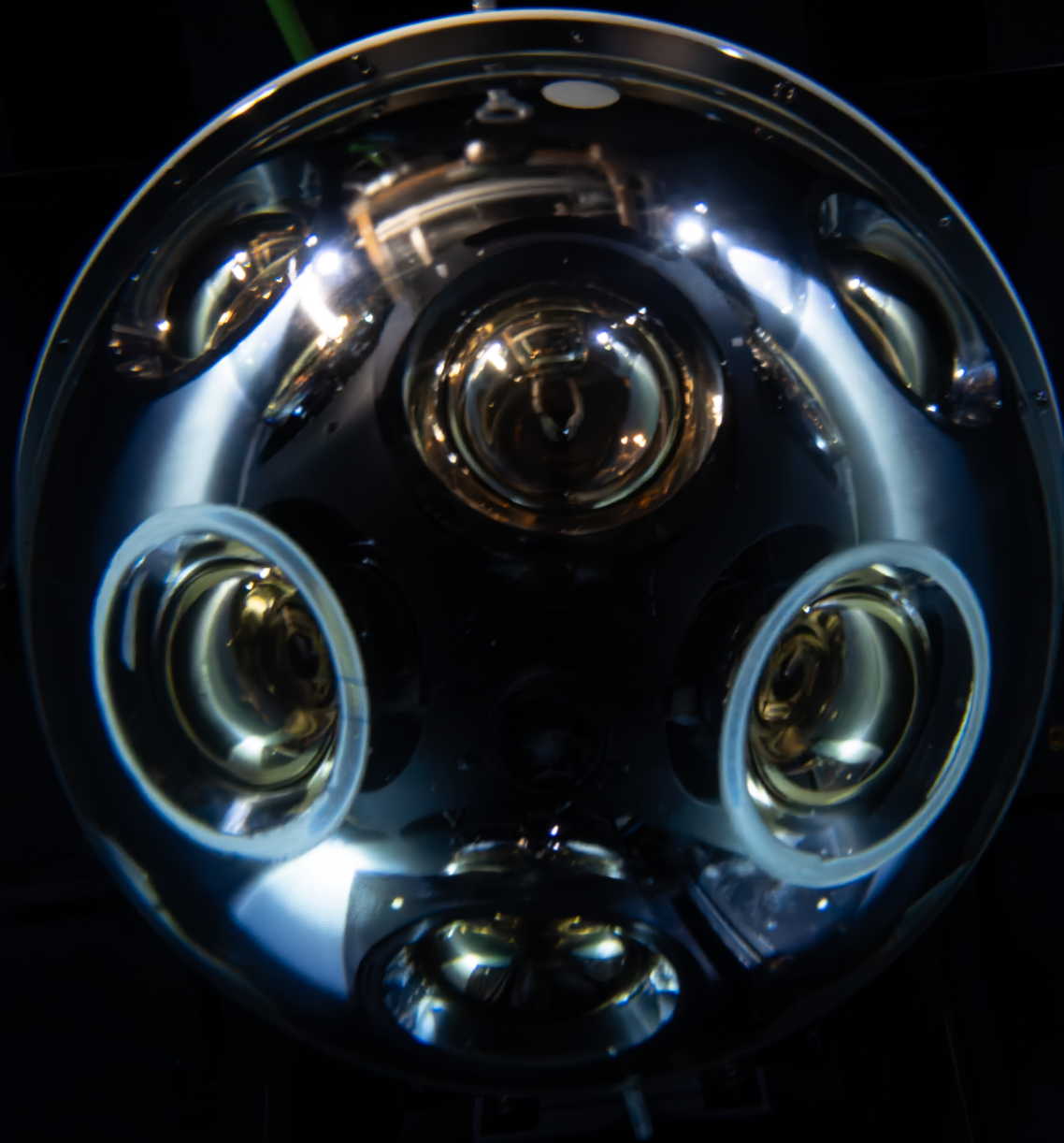
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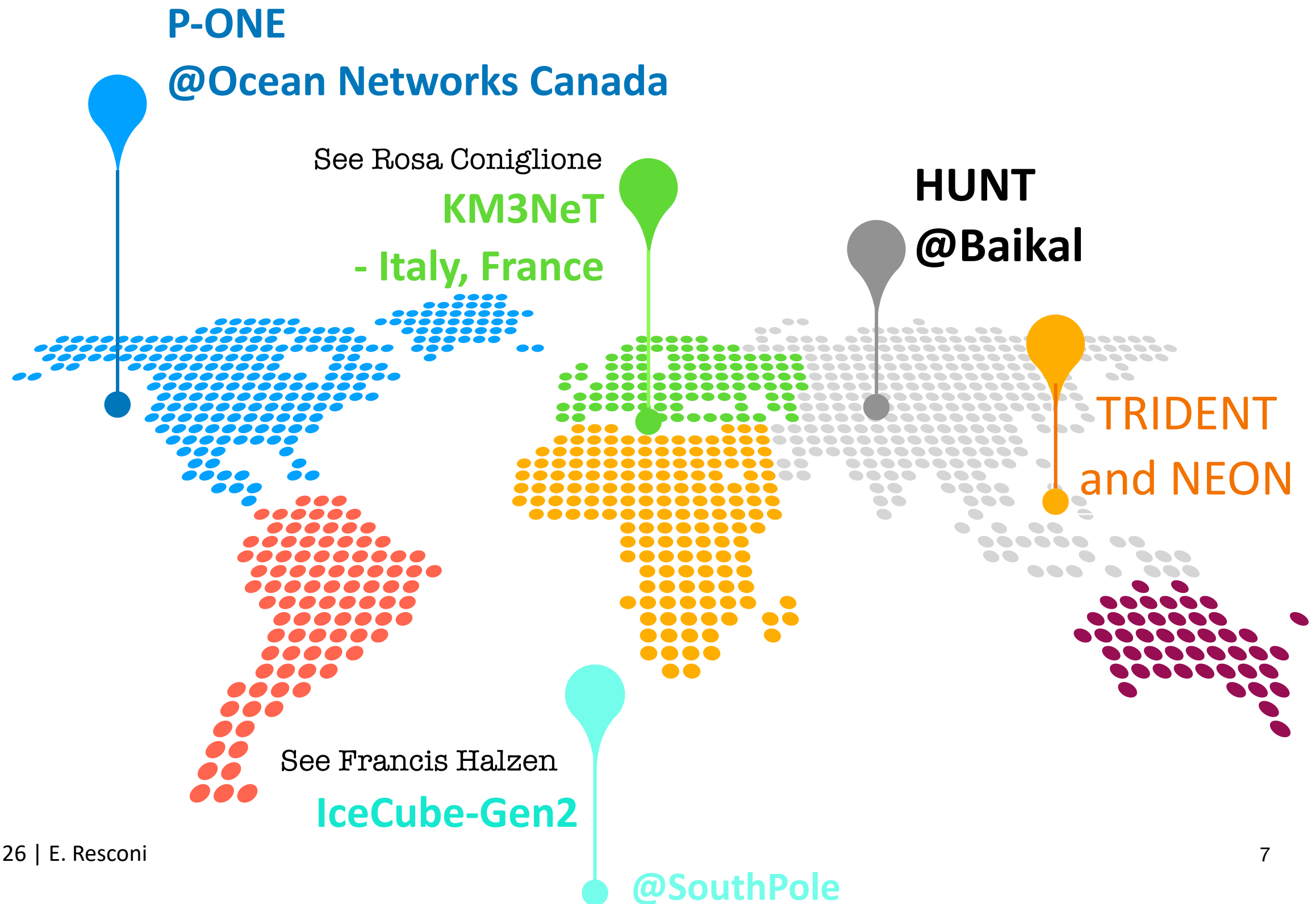
We need more, better, larger telescopes
But what makes one "better"?

The present and future observatories



Credits: Ben Nührenbörger/P-ONE

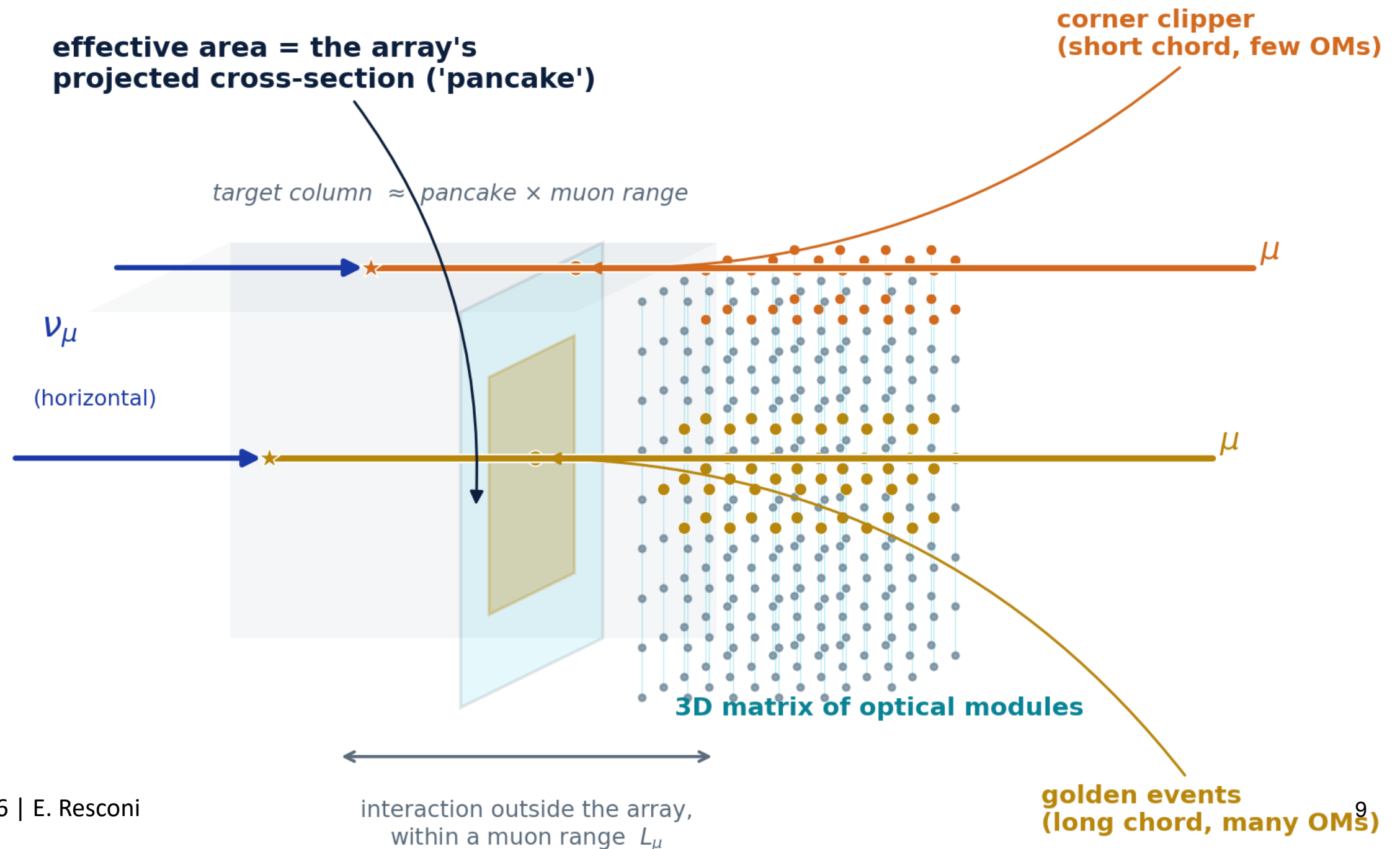
Future Observatories for HE neutrinos



What's important for a Neutrino Telescope

The idea of a neutrino telescope

The information is sparse, making sense of it is the trick.



The four pillars of a neutrino telescope

Performance · Backgrounds · Engineering & Operations · Readiness

1 Performance (what it can measure)

- Channel/topology
- Effective area/volume vs Energy
- Sky coverage (declination, energy×zenith window)
- Angular resolution (+ absolute pointing)
- Energy resolution.

2 Backgrounds & discrimination (can it isolate the signal)

- Environmental (lake vs sea: K-40, bioluminescence, sediment, noise)
- Atmospheric muons (bundles, depth, veto, mis-reconstruction leakage)
- Atmospheric neutrinos (containment).

3 Engineering & operations (can it be built and run)

- Deployment (top-down/bottom-up → geometry limits)
- Connectivity → resilience, longevity
- Infrastructure (power, data, timing, calibration hardware)
- Maintenance, reliability, duty cycle

4 Readiness / maturity (is the performance demonstrated)

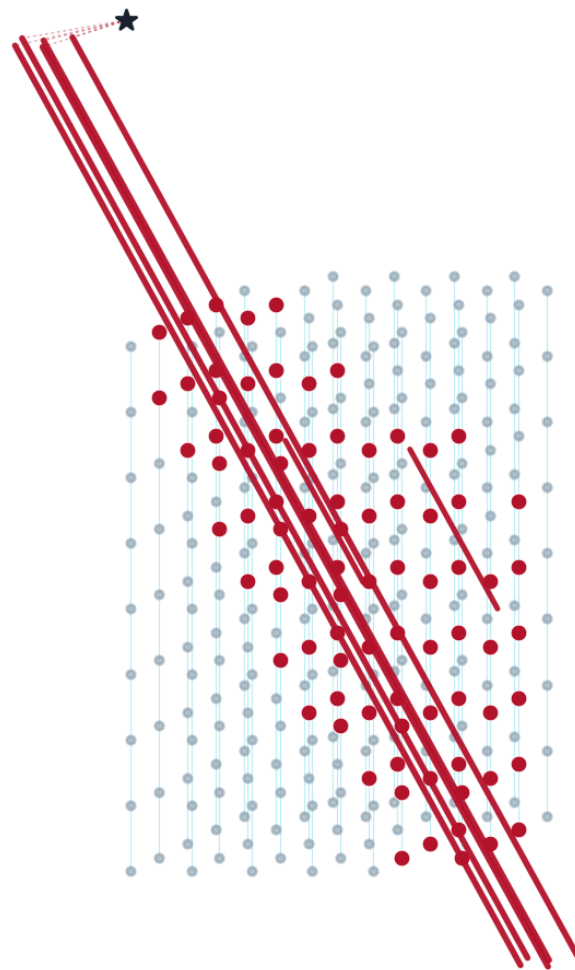
The four pillars of a neutrino telescope

• Backgrounds •

Spacing:

Density and spacing of optical modules relative to optical properties of the medium

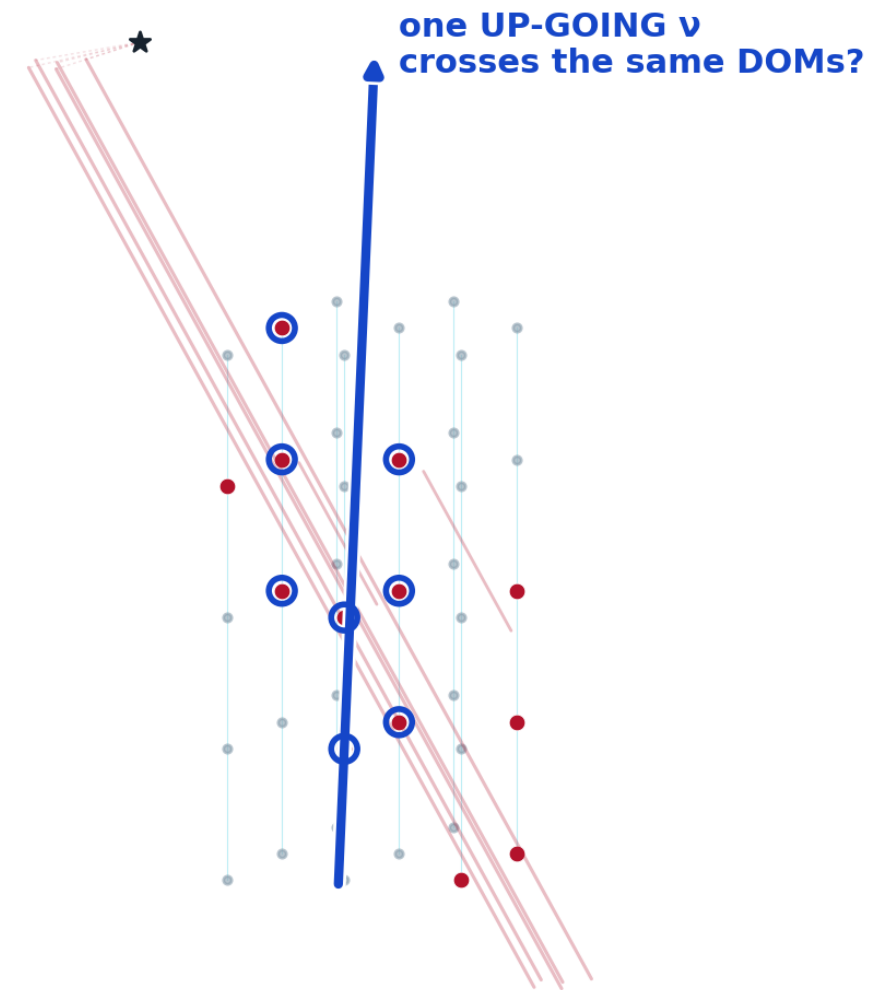
air shower



$$\Phi(x) = \Phi_0 e^{-x/\lambda_{\text{att}}}$$

$$\frac{1}{\lambda_{\text{att}}} = \frac{1}{\lambda_{\text{abs}}} + \frac{1}{\lambda_{\text{sca}}}$$

air shower



The four pillars of a neutrino telescope

Performance ·

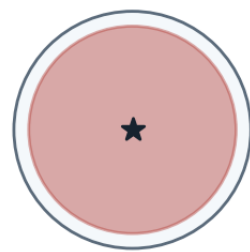
Timing:

The time resolution of the photosensors and the (relative) time synchronisation of the array directly set the angular resolution of the telescope

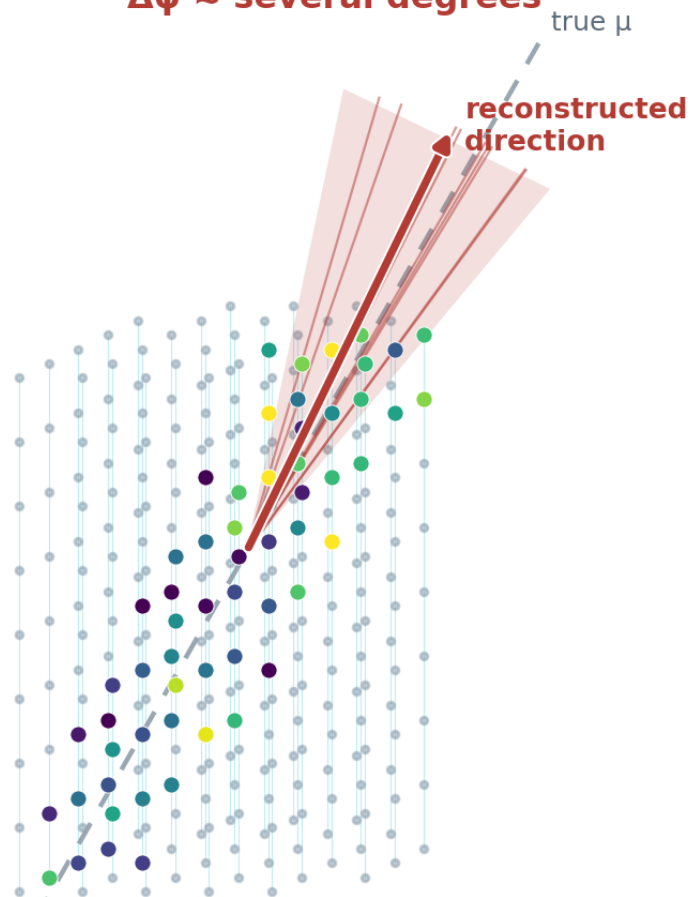
Poor timing

$\sigma_t \sim \text{few ns}$ · slow PMT, loose sync

$\Delta\psi \approx \text{several degrees}$



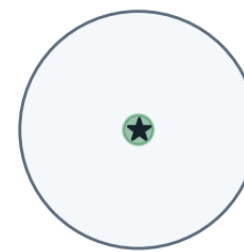
source localisation



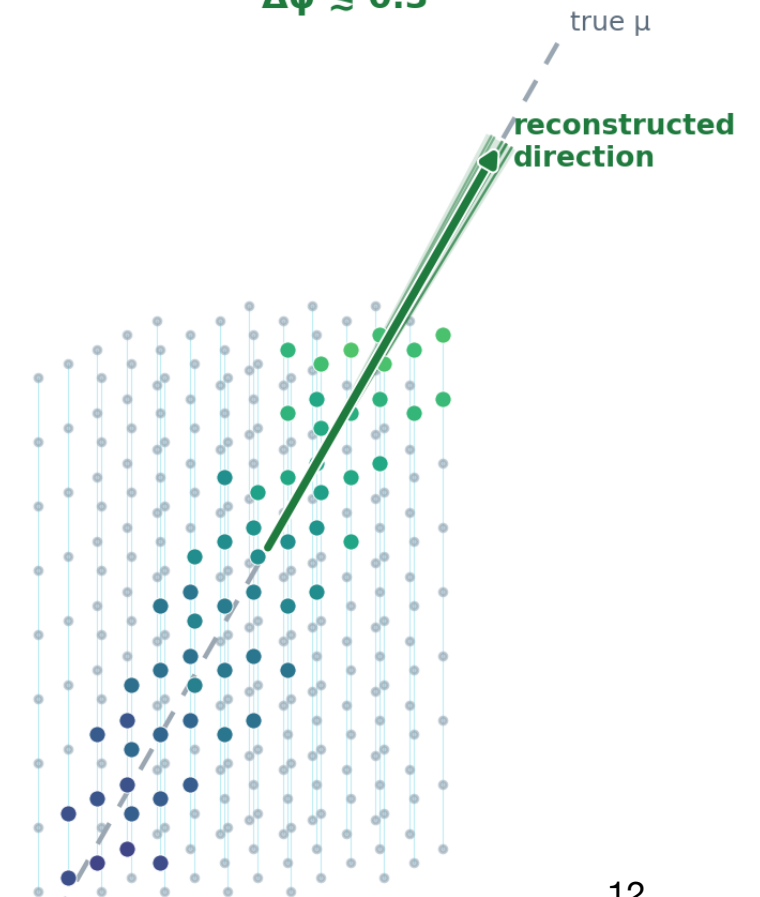
Good timing

$\sigma_t \sim 1 \text{ ns}$ · fast PMT + ns time-sync

$\Delta\psi \lesssim 0.3^\circ$



source localisation



The four pillars of a neutrino telescope

• Engineering & Operations

Neutrino astronomy is '**slow**' — a telescope integrates its signal over **many years**. The build window, by contrast, is **short**.

**INSTALLATION
FAST**

short, seasonal deployment window

-  **Deployment type** → capabilities
-  **Seasonal window** → capabilities
-  **ROV operation** → geometry



**OPERATION
STABLE**

24/7 × N years — continuous, multi-year data taking

-  **Hardware longevity**
sensors, electronics & optical modules survive years underwater
-  **On-/off-shore infrastructure longevity**
power, data link & shore station keep running

short build window

long, continuous observation

The four pillars of a neutrino telescope

- Different approaches to 'Readiness'

Different approaches:

- target directly a very ambitious / huge array
- anticipate the R&D need; decide later what to build
- anticipate extending an *existing* collaboration

These are all large-scale infrastructures and they raise many questions:

- How to finance it all?
 - What does the community want?
 - Where does geopolitics stand?
- ... not covered here

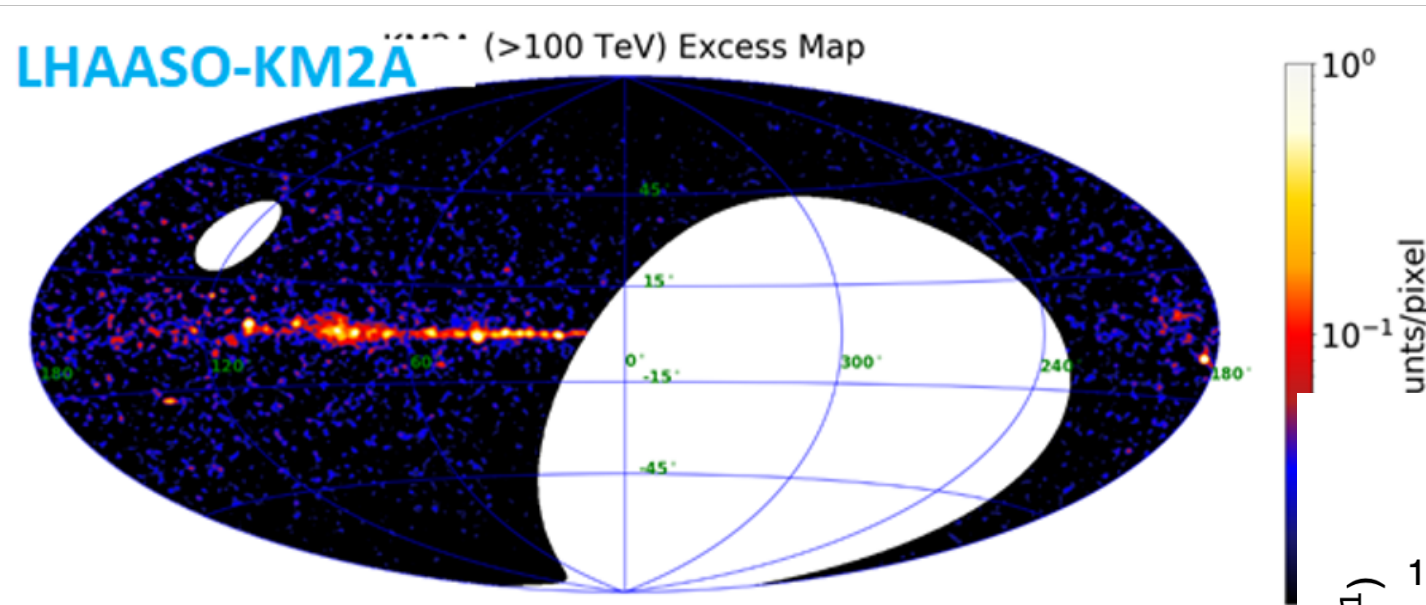
High-energy Underwater Neutrino Telescope (HUNT) @ Baikal

Input from Zhen Cao and
Nuclear Instruments and Methods in Physics Research A 1086 (2026) 171374



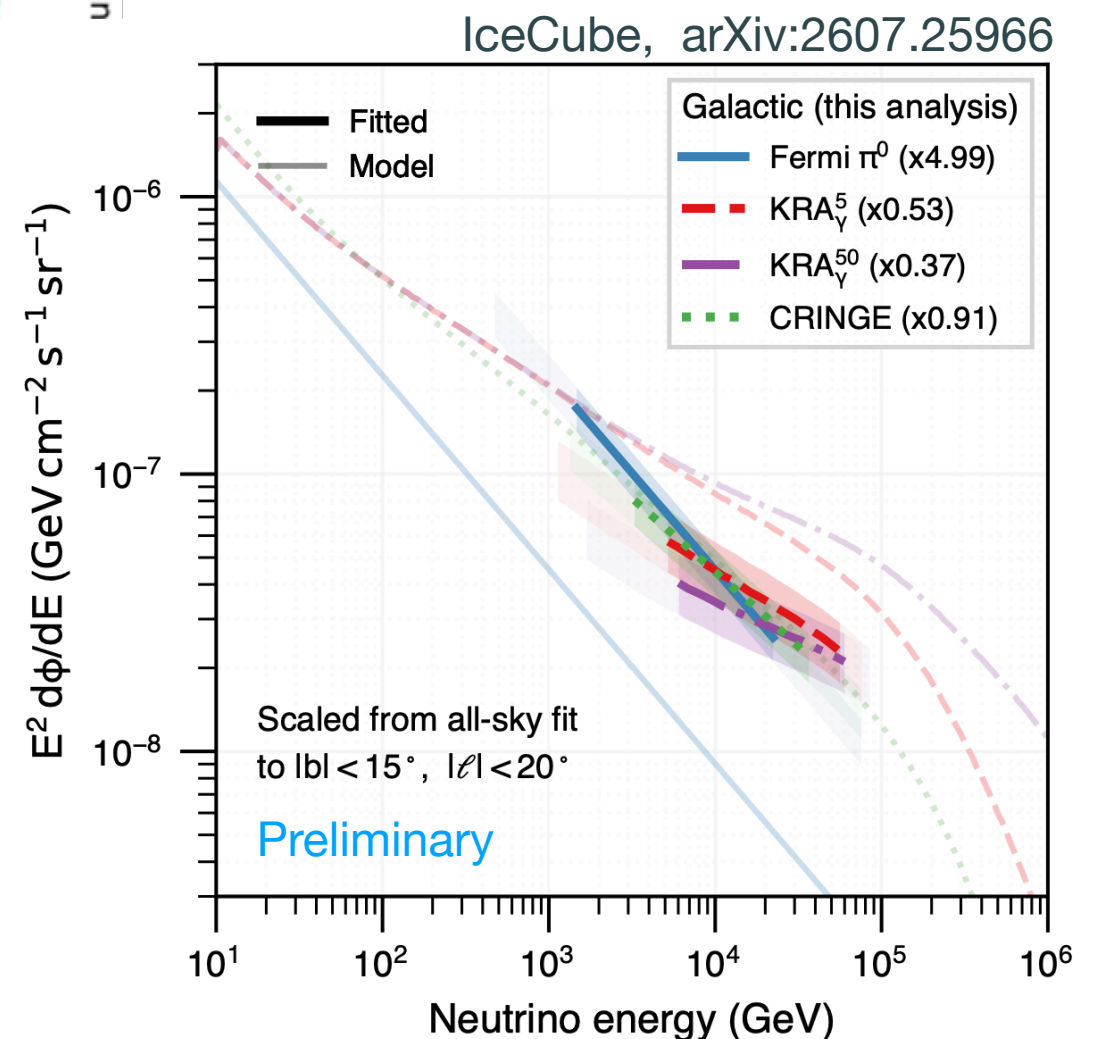
Baikal-HUNT*: Scientific Goals

Identifying the hadronic PeVatrons in our Galaxy(>100TeV)
for the first time!



LHAASO Collaboration, 2021, Nature, 594, 33.
LHAASO Collaboration, 2024, ApJS, 271, 25

- IceCube, arXiv:2607.25966 -
TS mostly from the inner Galaxy
- Significance driven by Cascades,:
 - Cascades: 5.29σ
 - Tracks: 2.22σ
 - Starting events: 1.61σ



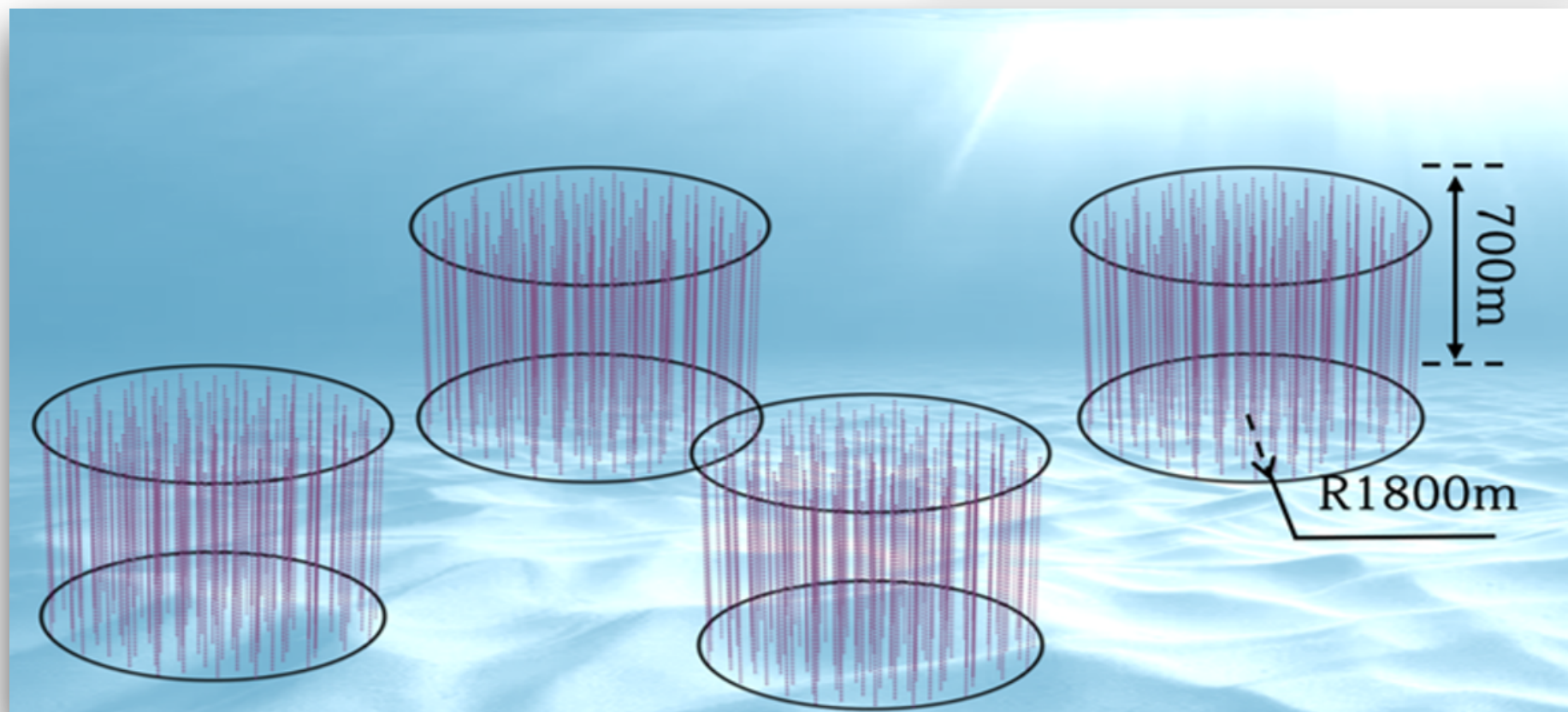
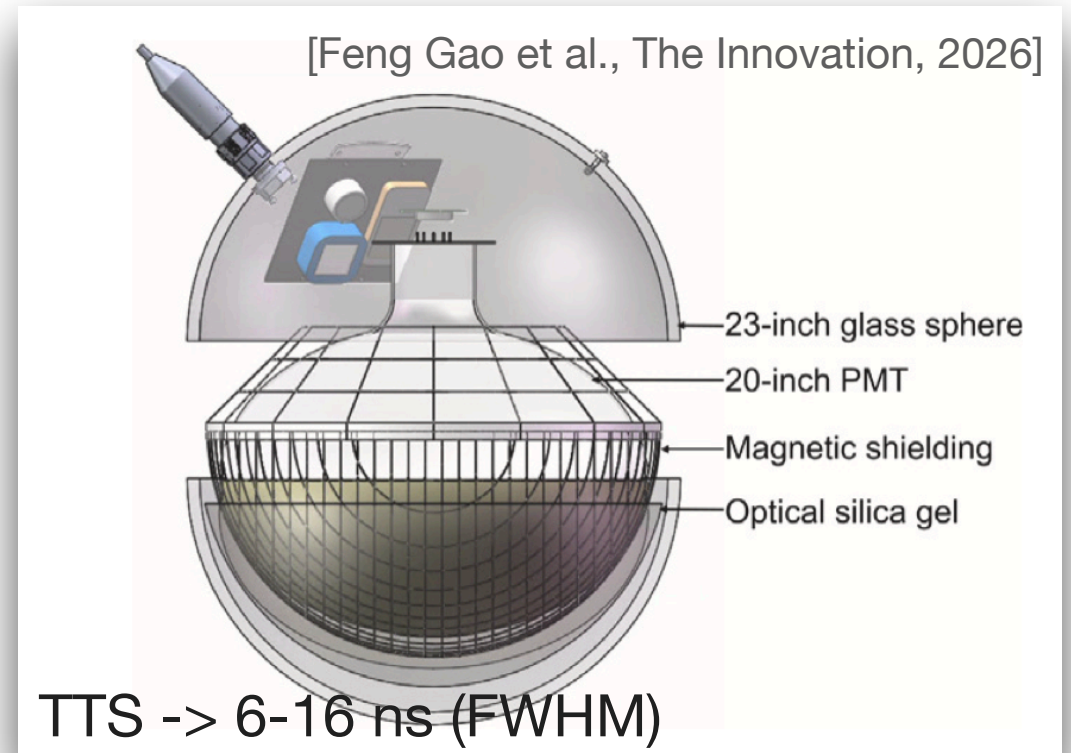
*Since December 2025, the official name of the project was changed from HUNT to Baikal-HUNT.



Baikal-HUNT: Site and Geometry

Proposed baseline

- 4 x cluster of
 - Radius: ~ 1.8 km,
 - Distance between clusters: > 10 km
 - Horizontal distance: ~ 130 m,
 - Height of string: ~ 700 m
 - 24 PMTs/string
 - Clock synch ~ 1 ns
 - Readout electronics 500 MHz waveform sampling.

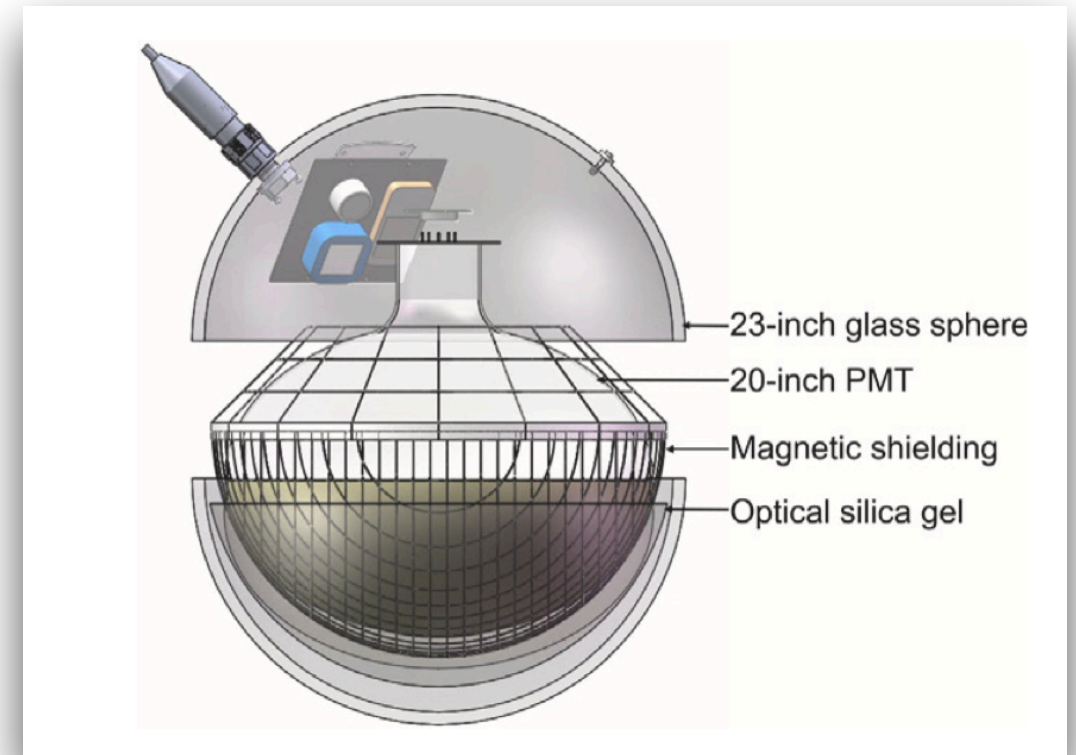




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TTS $\rightarrow$ 6-16 ns (FWHM)

[Feng Gao et al., The Innovation, 2026]

Baikal-HUNT: Optical Properties

Proposed baseline

Flat lakebed at a depth of ~1366 m

Optical properties monitored in previous GVD seasons

<https://arxiv.org/pdf/2309.16300>

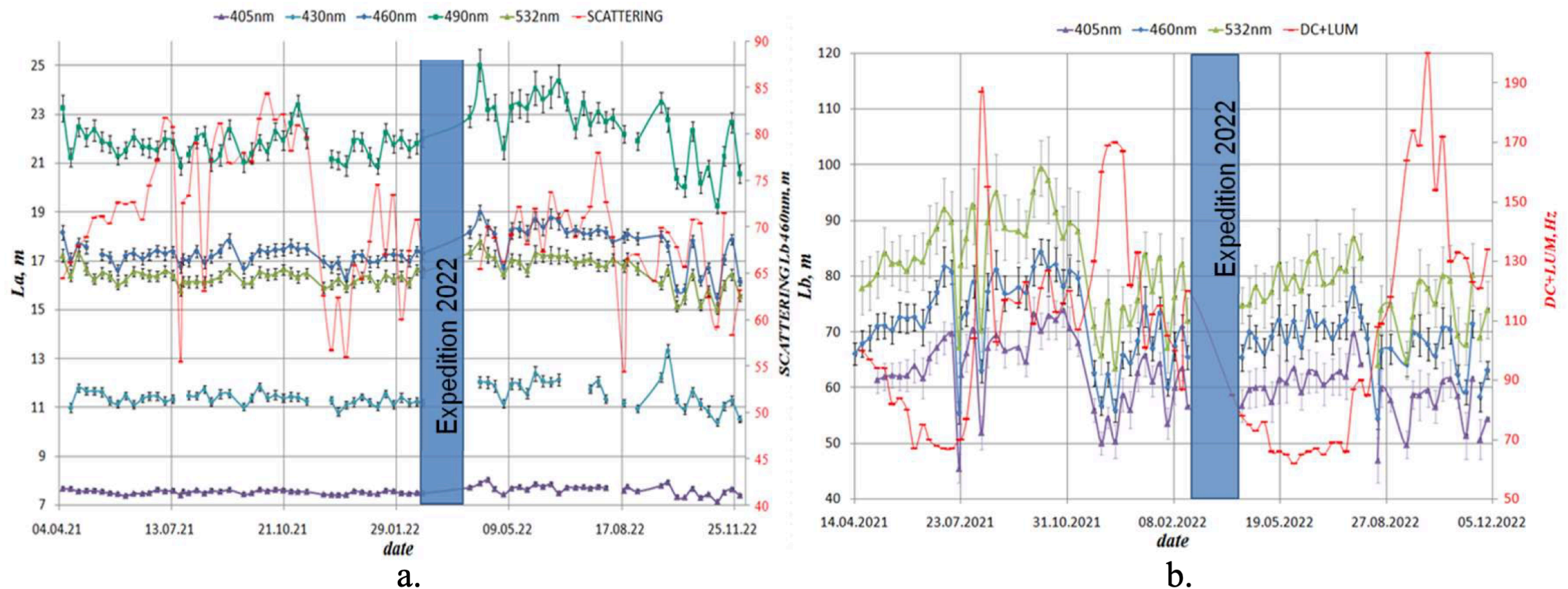
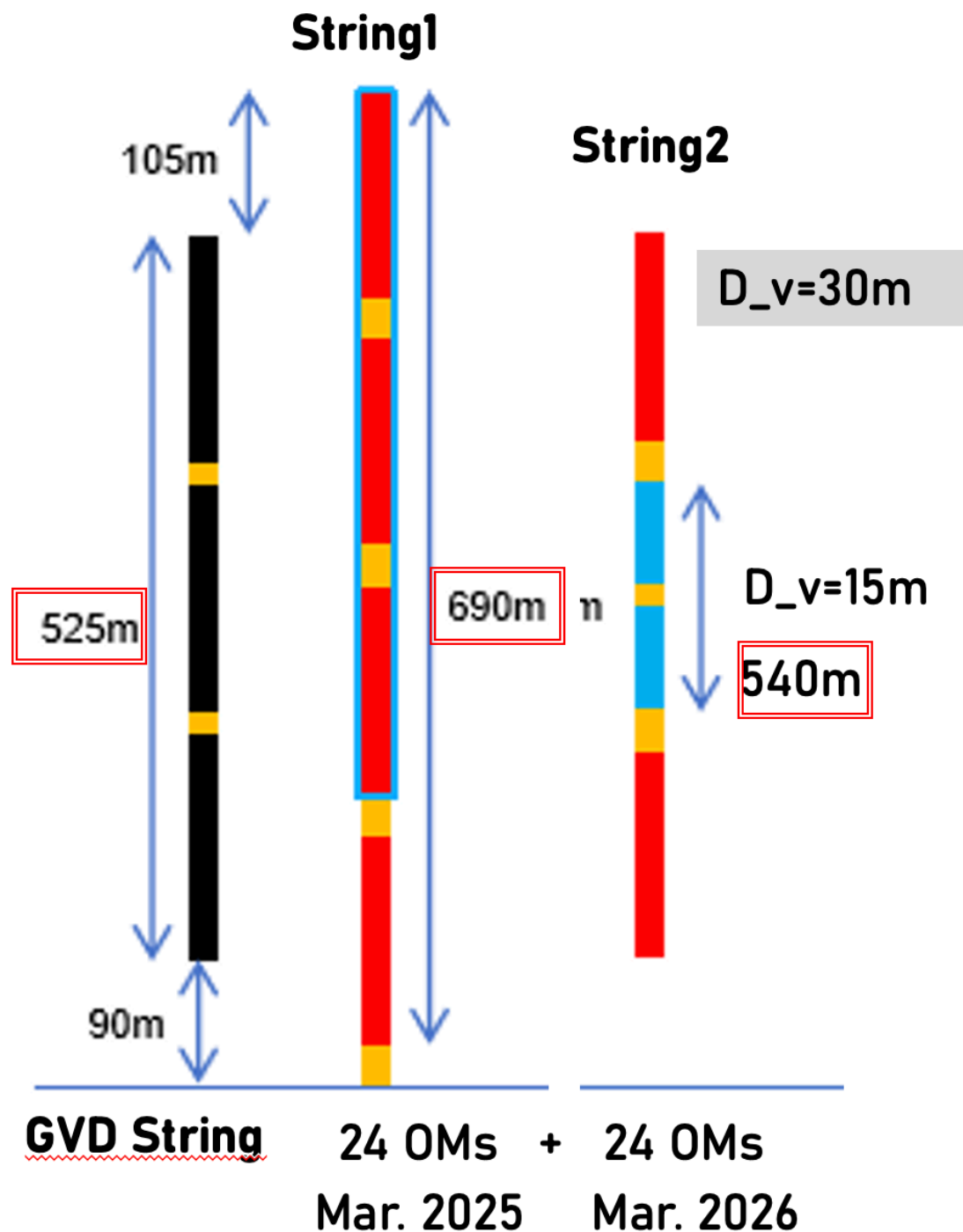


Figure 2. The time dependence of absorption (a) and scattering (b) lengths in 2021-2022. On the right axes of the graphs are plotted to compare the time dependence of scattering length for $\lambda=460\text{nm}$ (Fig. 2,a) and the time dependence of total signal of the dark current and the glow of water (Fig. 2, b).

On-going Activities: Two prototype strings in Lake Baikal

2025-2026



Baikal GVD

GNN News (C. Spiering), Feb/March'26

Two new clusters have been deployed this season, so that GVD now comprises 16 clusters in total. Both clusters contain the nominal 8 strings plus one "external" string to fill the room between the clusters. Also, a new shore cable for the new clusters has been laid. Last but not least, two Chinese test strings with a total of 42 OMs have been deployed.

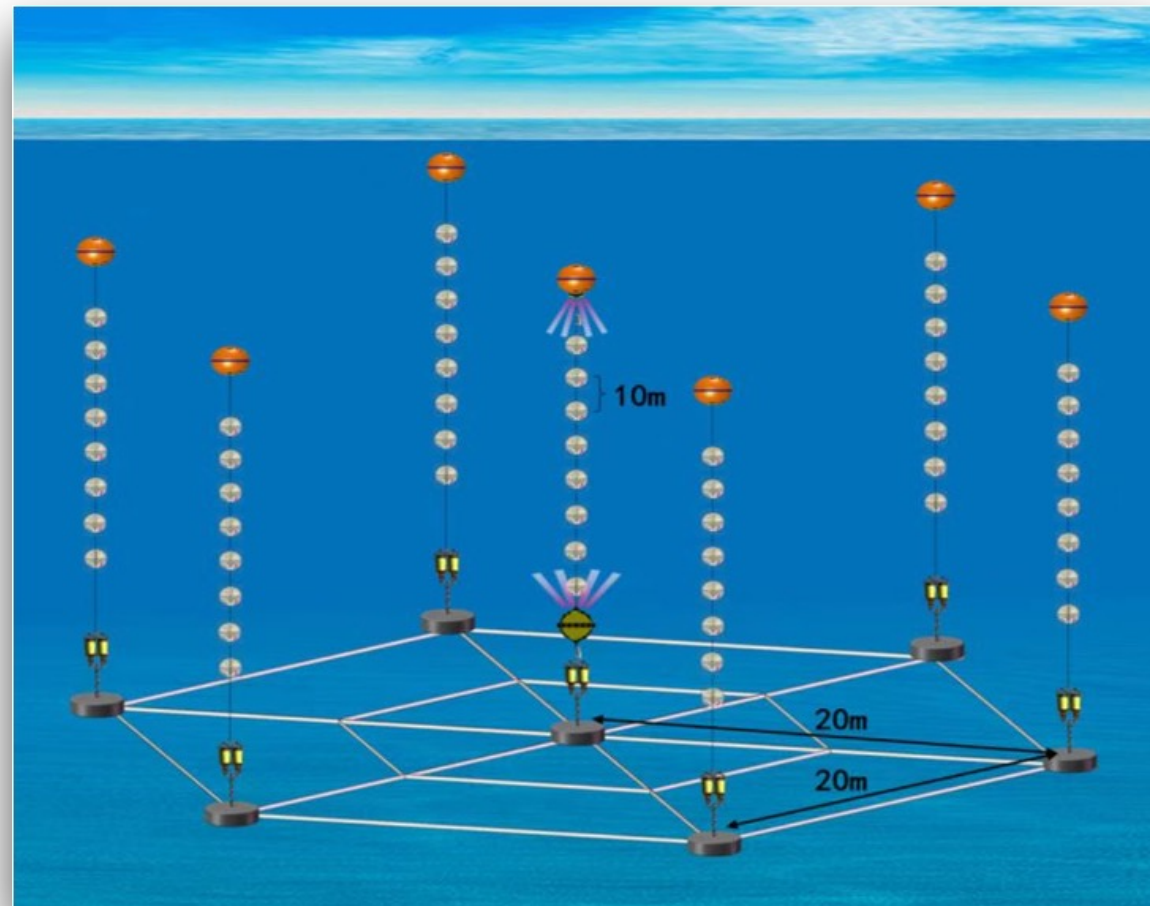


Nikolaj (Kolja) Budnev, Baikal neutrino pioneer from the first hours on, at a winch.

On-going Activities: Prototype strings @ South China Sea

Phase I: Long-term monitor string (Jan 2025)
4 OMs, vertical spacing: ~10 m

Phase II: small 7-string array (2026)



TRIDENT NEON

(input from Lili Yang
Sun Yat-sen University)

TRIDENT: scientific goal

[Nature Astronomy \(2023\)](#) , [PRD \(2026\)](#)

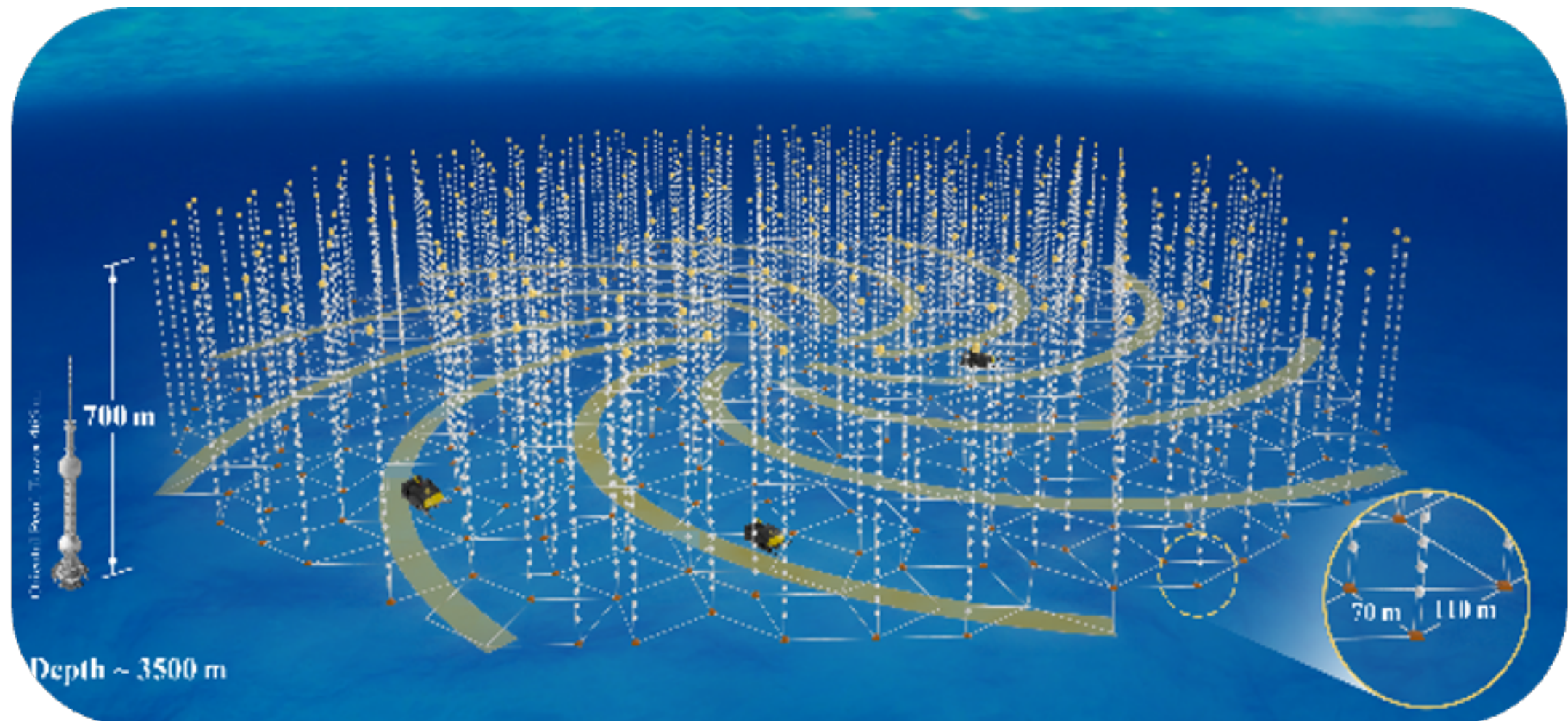
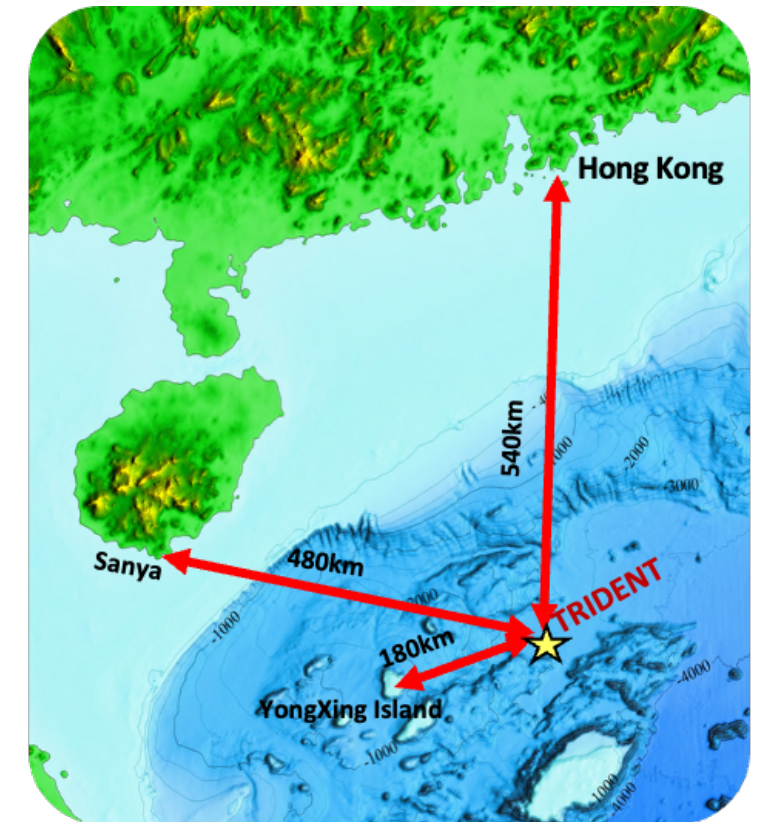
Primary experimental goals:

- 1) *Rapidly* discover neutrino sources
- 2) Sensitivity to all flavors

3.5 km deep

$\sim 8 \text{ km}^3$

~ 1000 strings



TRIDENT: on-going activities

Iwan Morton-Blake, on behalf of Donglian Xu (Neutrino 2026)

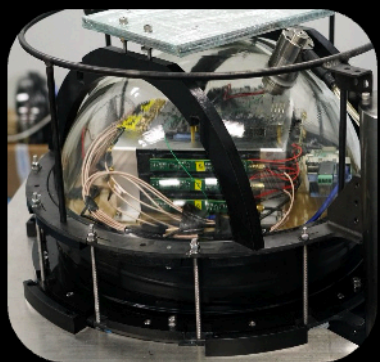
TRIDENT

Optical modules:

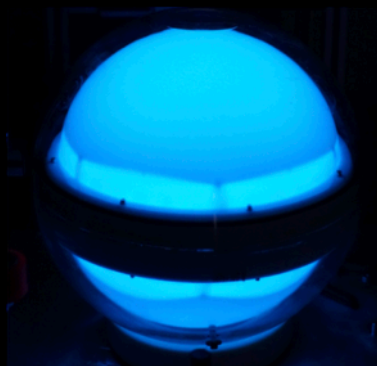
- Hybrid DOMS combining PMTs and SiPMs
- Record PMT waveforms: aim to boost precision in event topology and energy reconstruction

Calibration:

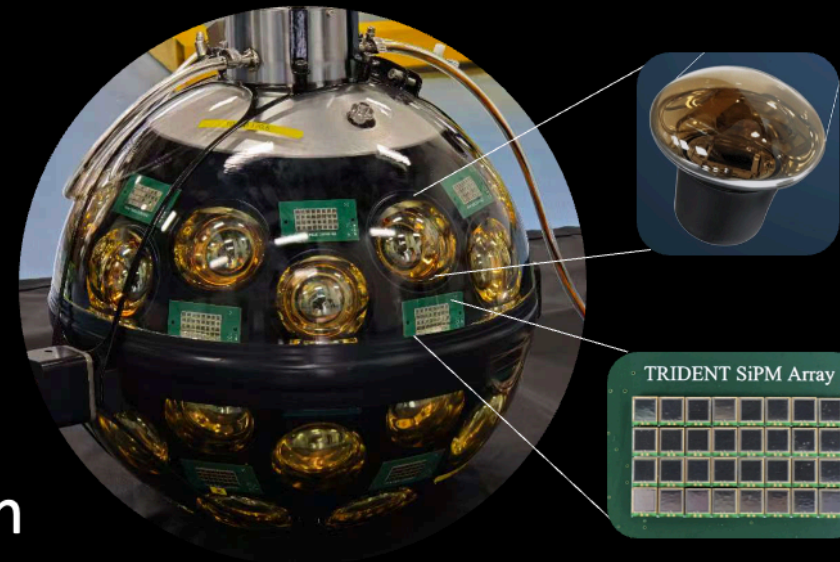
- LEDs, cameras, spectrometer, plastic scintillator slabs, acoustic sensors



MuonSlab: A plastic scintillator based detector for muon measurement in the deep ocean, JINST (2025)



An Updated Camera System for Real-Time Optical Calibration in TRIDENT, PoS (ICRC2025)

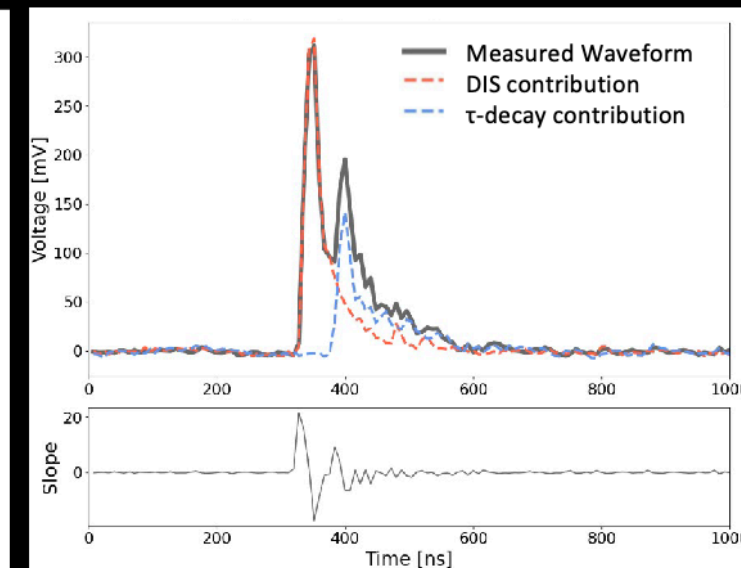
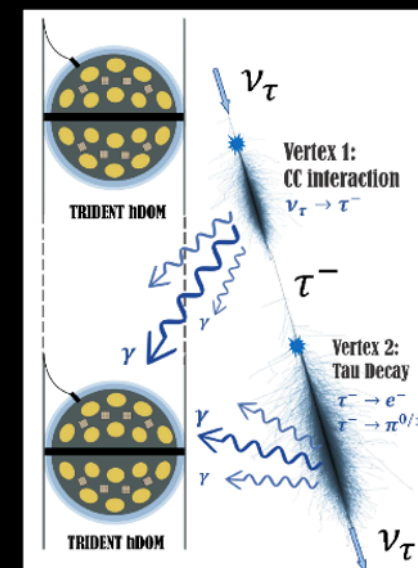


PMTs:
< 2ns TTS
~30% QE

SiPMs:
< 0.3 ns jitter

Preliminary Mechanical Design of the hDOM, PoS (ICRC2023)

Waveform-based search for ν_τ double-pulse events



Searching for astrophysical τ neutrinos with hDOM waveforms in TRIDENT, PoS (ICRC2023)

TRIDENT: on-going activities

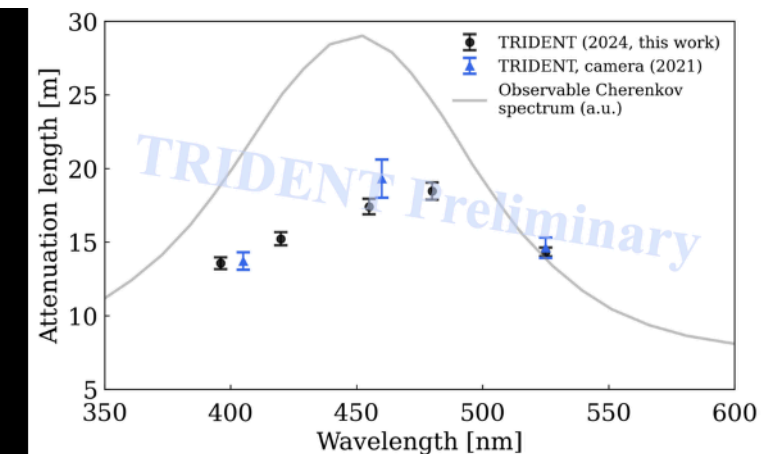
Iwan Morton-Blake, on behalf of Donglian Xu (Neutrino 2026)

TRIDENT

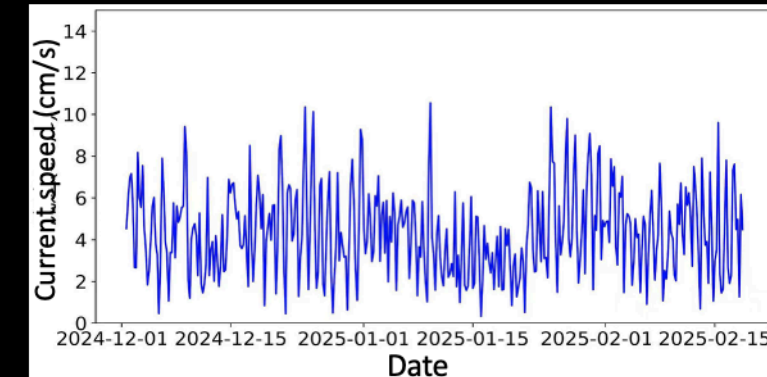
Status

- Pathfinder missions to site in 2021, 2024 and 2025
- Measured good water quality, low sea current speeds
- Developed and tested new string deployment methods/devices
- Prototype optical + calibration strings to be deployed this year

Camera-measured
effective attenuation
length →



Sea current speeds over 3.5 months



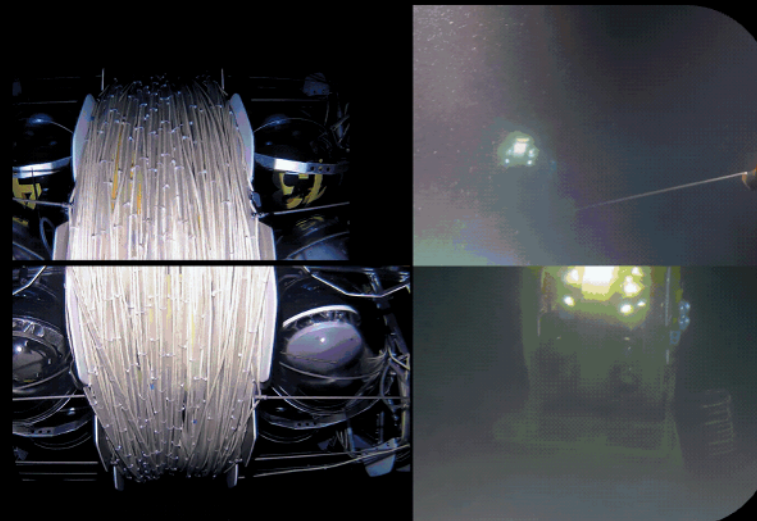
First pathfinder mission



(video)

26/6/2026

Testing string deployment system



(video)



*Prototype
string
testing*

Design and lake trial of a deep-sea neutrino detection mooring deployment system, Ocean Engineering, 2025

TRIDENT: on-going activities

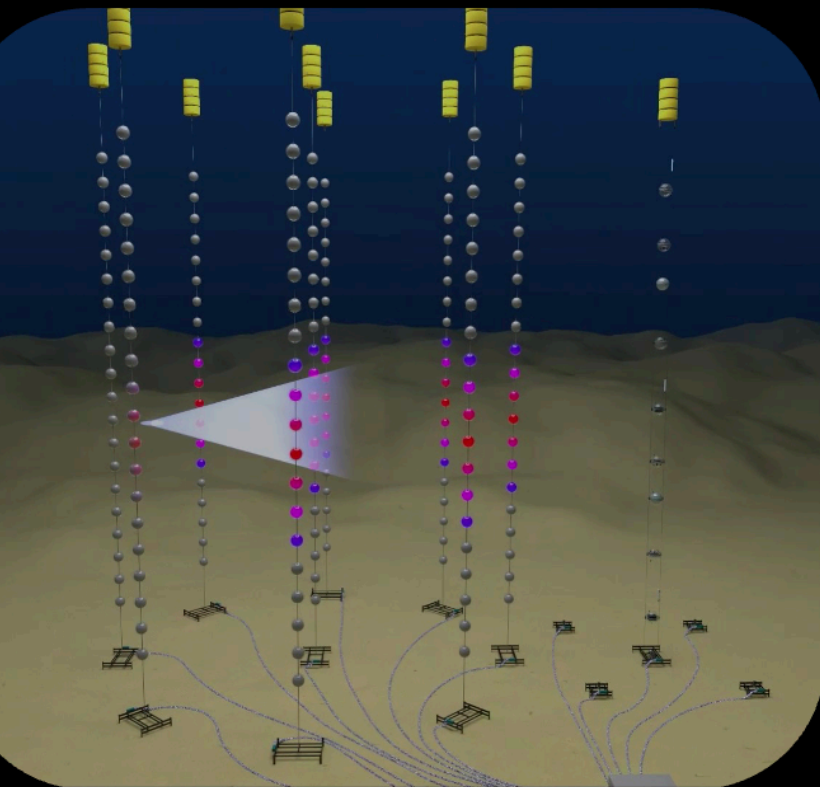
Iwan Morton-Blake, on behalf of Donglian Xu (Neutrino 2026)

TRIDENT

Next:

- Phase-1 : deployment of first 10 optical strings + 1 calibration string

**Deployment
planned for 2027**



Primary physics:

- TeV all-flavour atmos. ν in the Hai-ling Basin
- Join Astro. neutrino source search campaign (CCSN monitoring , southern sky sources)

Key technology demonstration:

- Precise Cherenkov light detection w/ hDOMs
- Long-distance power and data transmission
- Dynamic calibration strategies
- Data acquisition
- Deployment and maintenance strategies



*Dedicated assembly lab in
Sanya, starting mass production
of detection modules*

NEON

Iwan Morton-Blake, on behalf of Donglian Xu (Neutrino 2026)

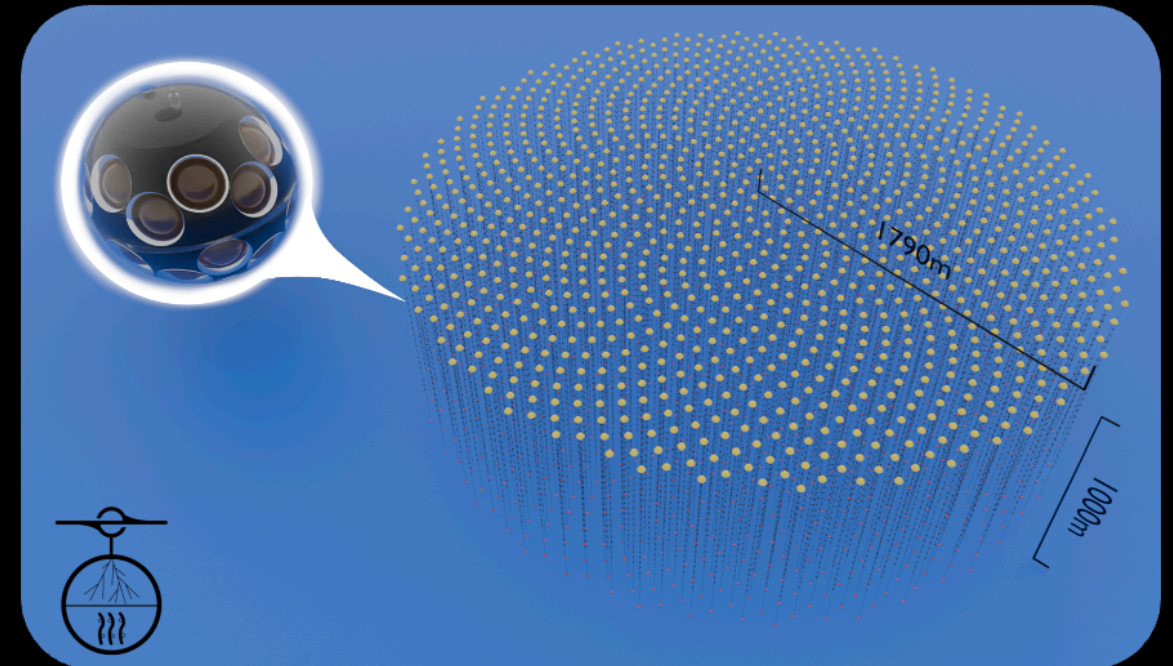
NEON

Detector: Neutrino Observatory in the Nanhai

- $\sim 10\text{km}^3$ volume, ~ 1200 strings
- 1.7 km or 3.5 km deep
- Multi x31 3" PMT DOM
- Fibonacci layout pattern, $\sim \text{TeV-EeV}$ range

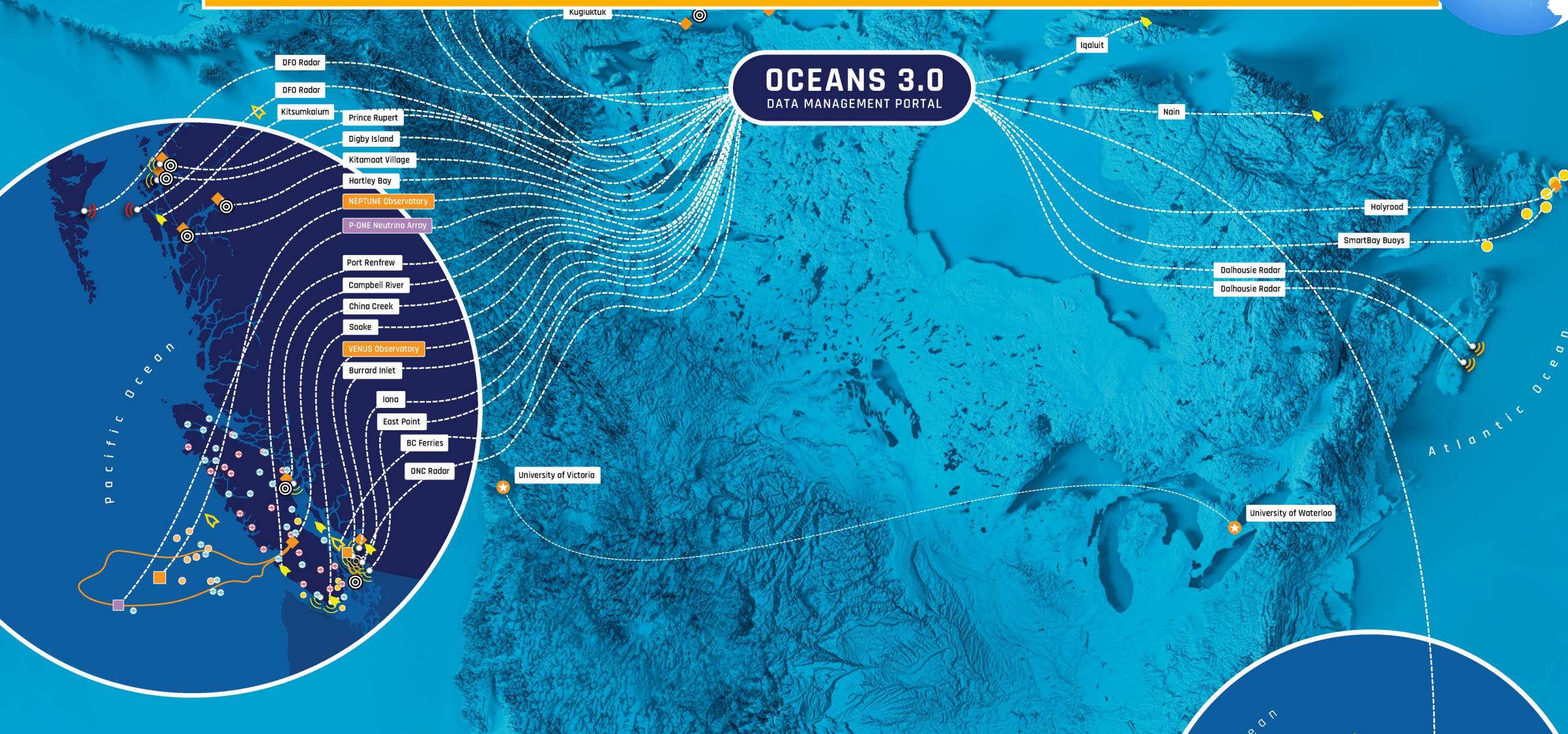
Status:

- Lake trials of optical modules, long-term hardware stability verified



The Pacific Ocean Neutrino Experiment (P-ONE)

The Pacific Ocean Neutrino Experiment @ Ocean Networks Canada



AN INITIATIVE OF

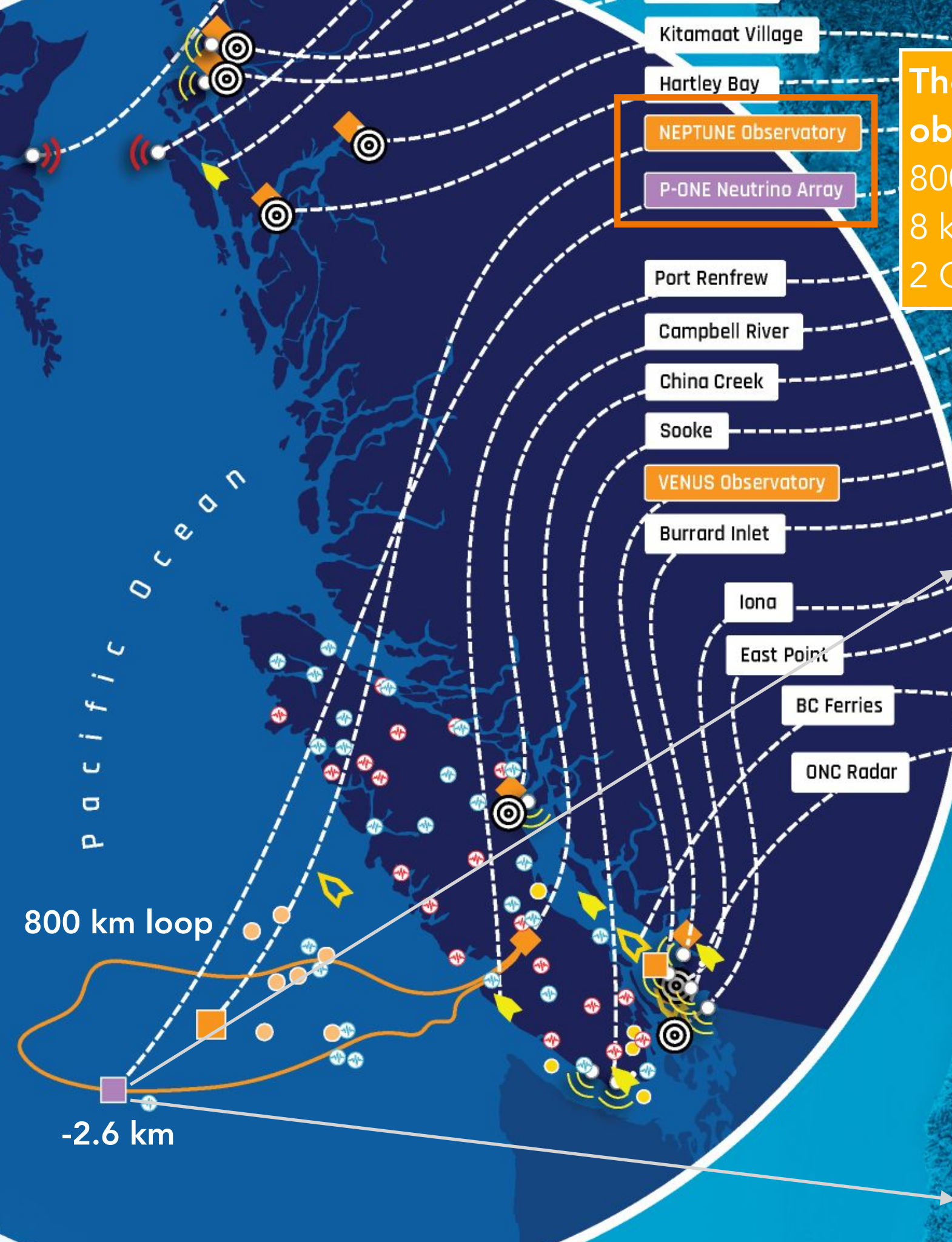


University of Victoria

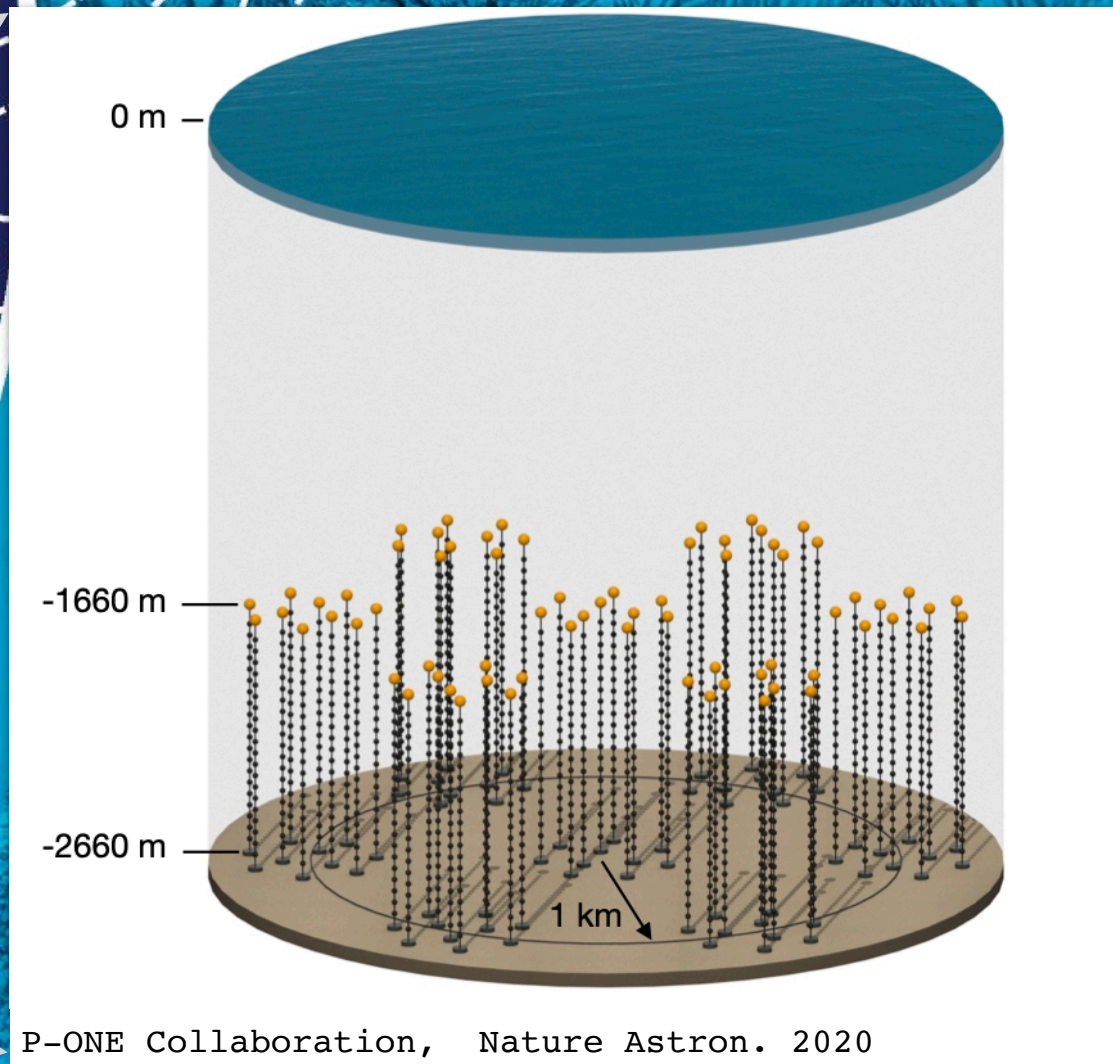


- Mobile Asset
- AIS Receiver
- RADAR
- RADAR (Department of Fisheries and Oceans)
- RADAR (Dalhousie University)

<https://www.oceannetworks.ca/>



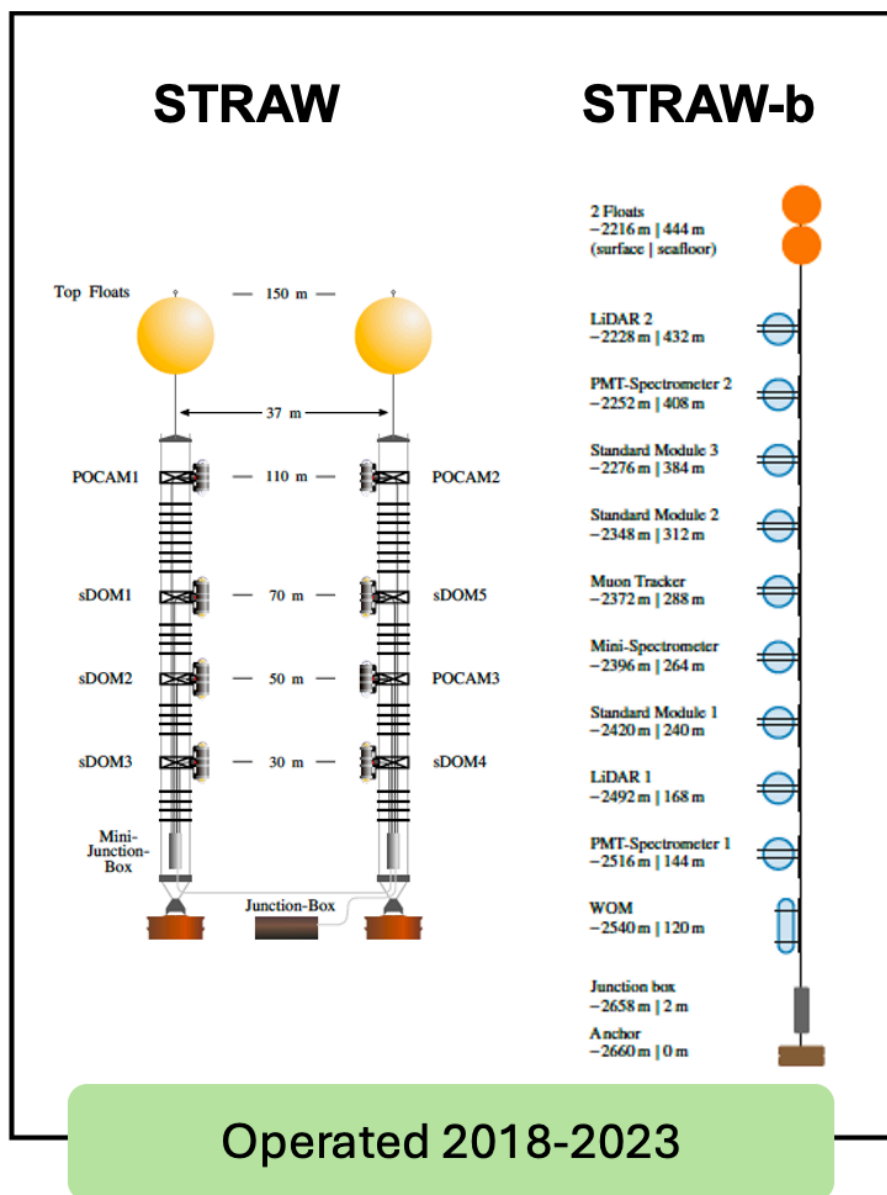
The world's largest undersea, real-time observatory network -
800 km loop of fibre-optic cables,
8 kW x 6 nodes,
2 Gbit



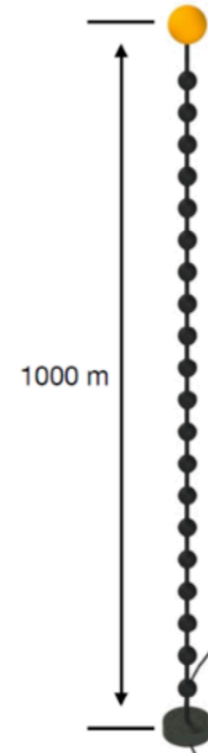
P-ONE Collaboration, Nature Astron. 2020

P-ONE: phased approach

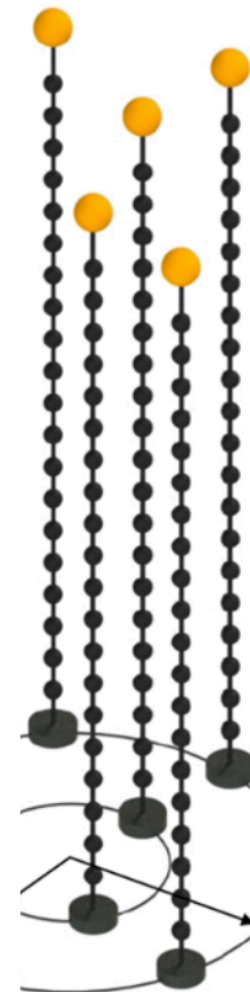
Not to scale



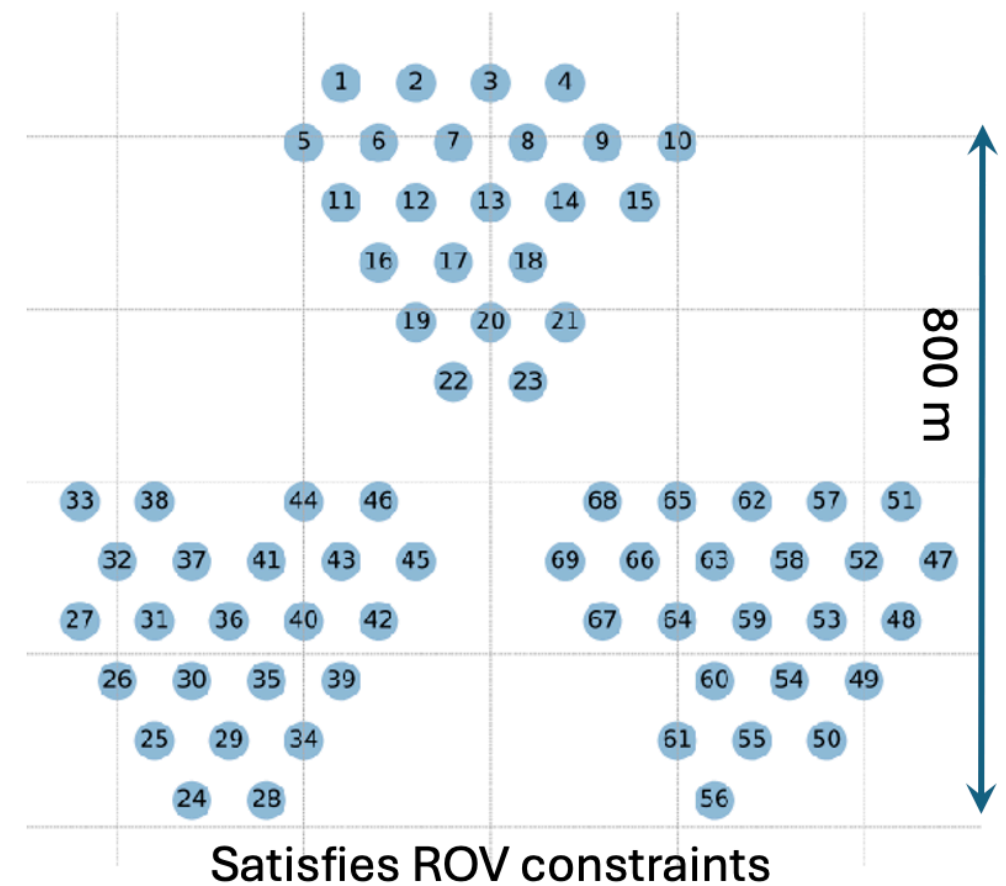
P-ONE-1



P-ONE
Demonstrator



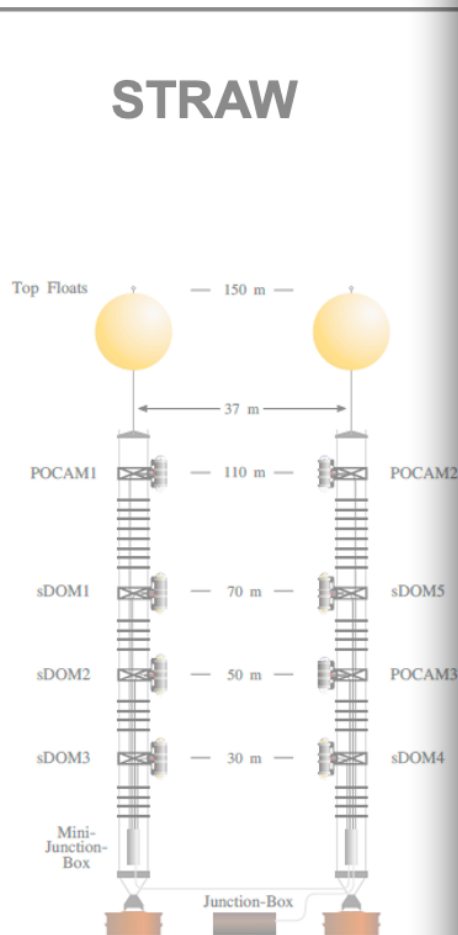
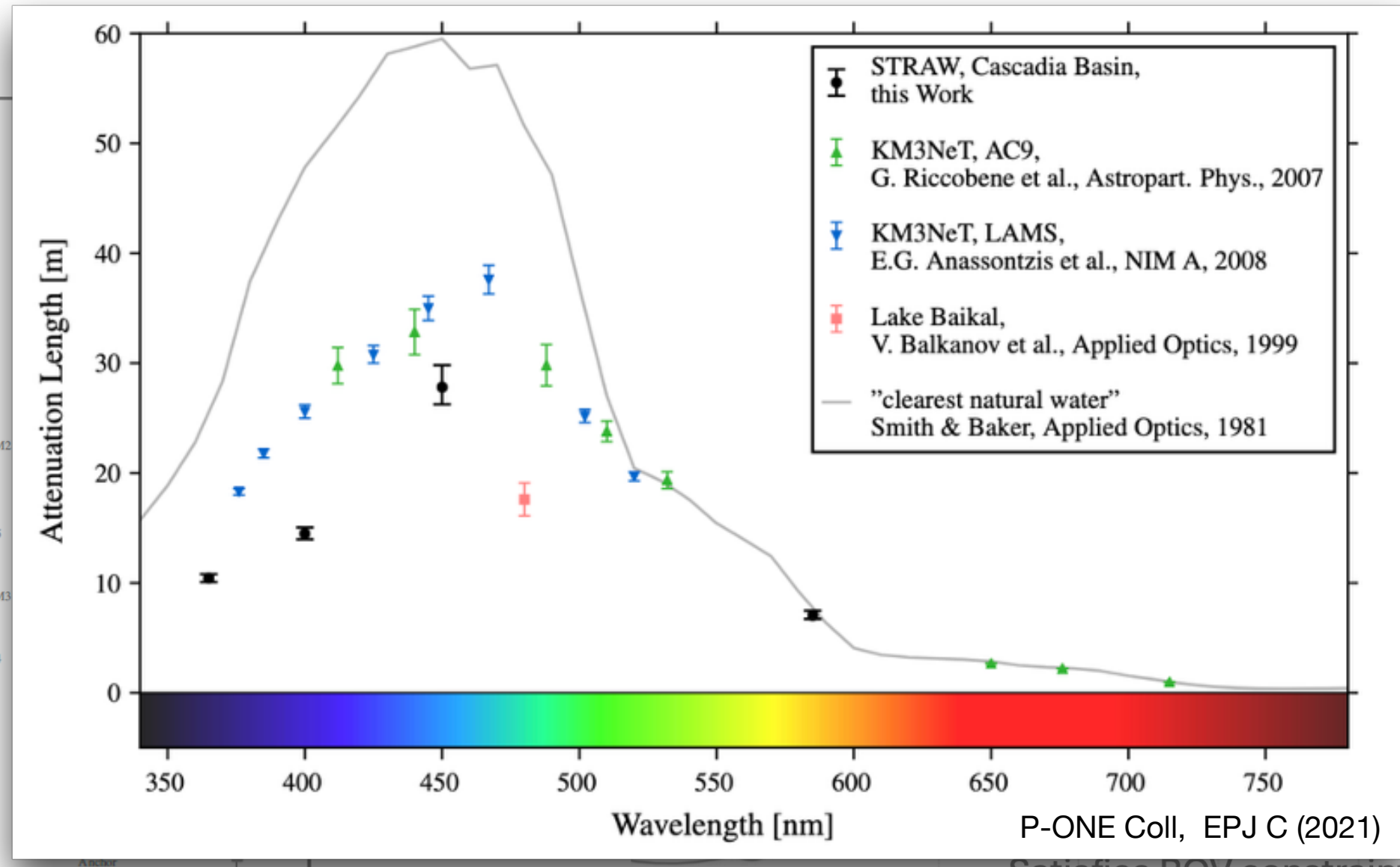
P-ONE
Baseline geometry 2026



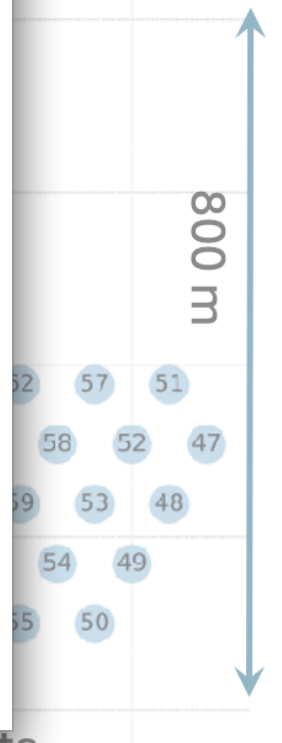
P-ONE: phased approach

In-situ Attenuation Length

Not to scale



- How far light travels in water fixes the optical-module spacing and hence the array geometry;
- To first order, when targeting energies above $\sim 1\text{--}10$ TeV, a spacing of 2–3 attenuation lengths is a good intuitive starting point.



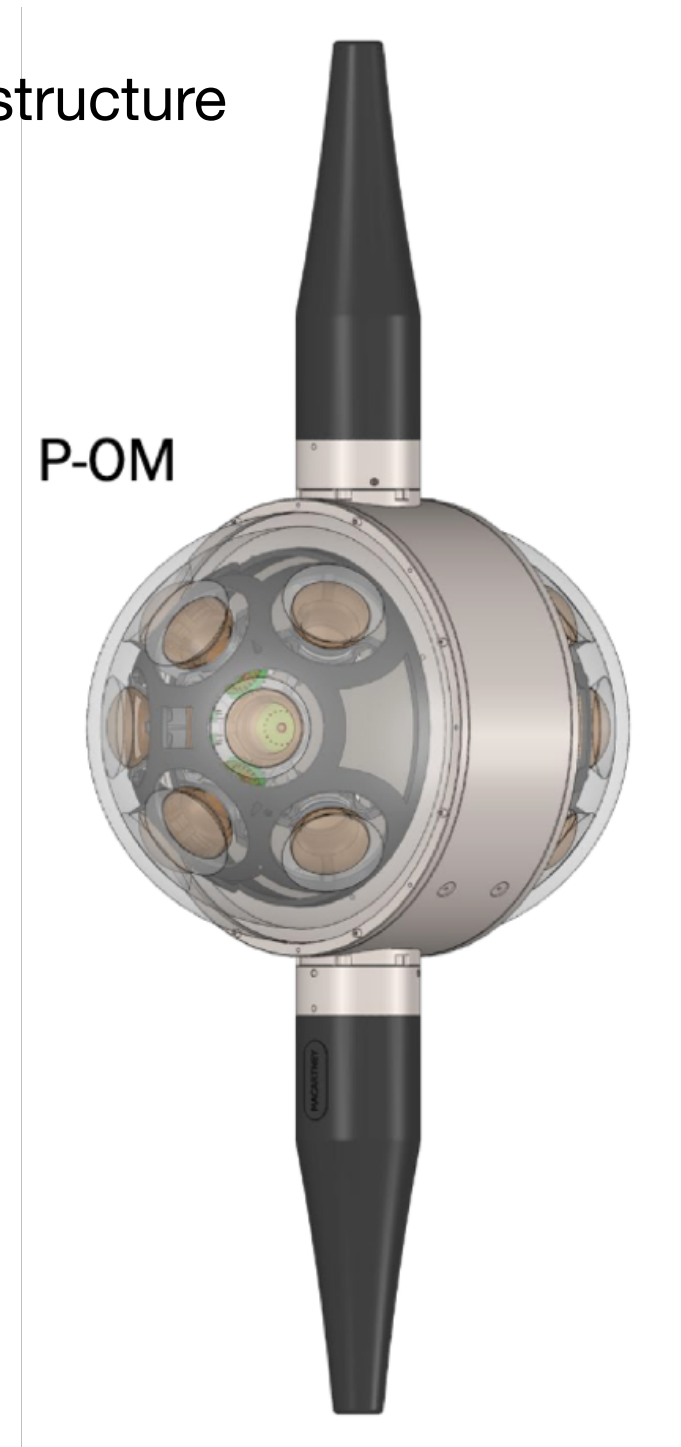
P-ONE: Engineering Principles

Lessons learned from the community:

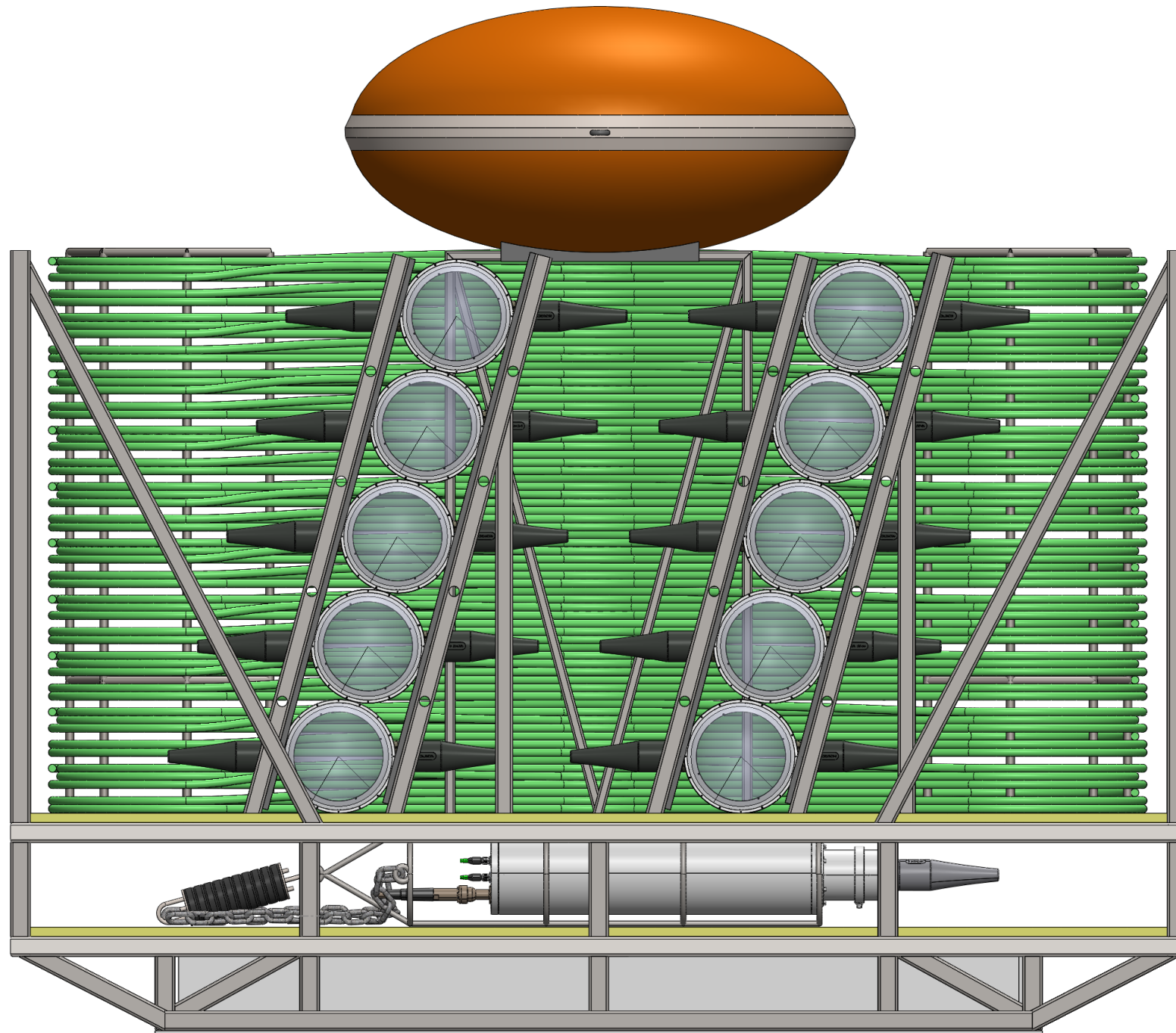
1. Connectors are a dominant failure mode for cabled subsea infrastructure
-> minimize them
2. Volume scales in 3D
—> so how tall can a single line realistically be?
3. Design for longevity from the start!

Design Choices:

- 1 km line · 20 modules (18 optical + 2 calibration)
- Connector-less design
- Acoustic + optical calibration throughout
- Sub-ns time synchronization
- Deployment frame = anchor + mooring network hub



P-ONE: Engineering Principles



P-ONE: Construction of the first line

Esbjerg (Denmark) '25

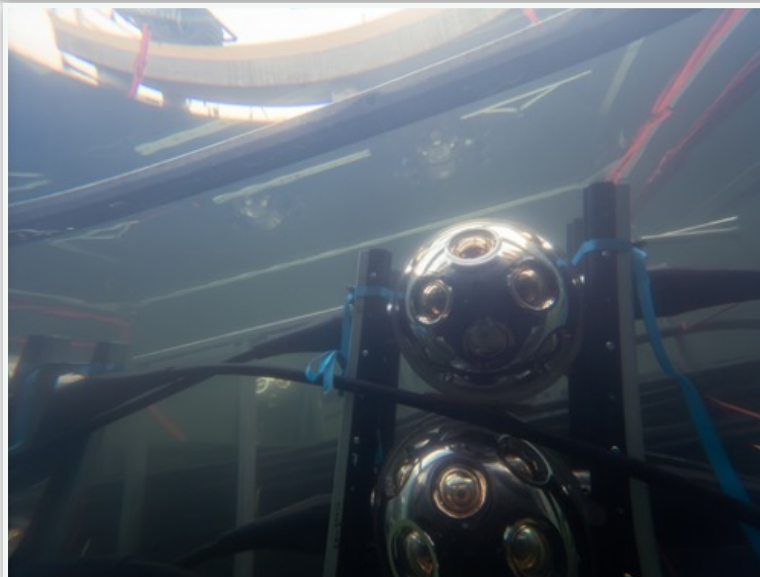
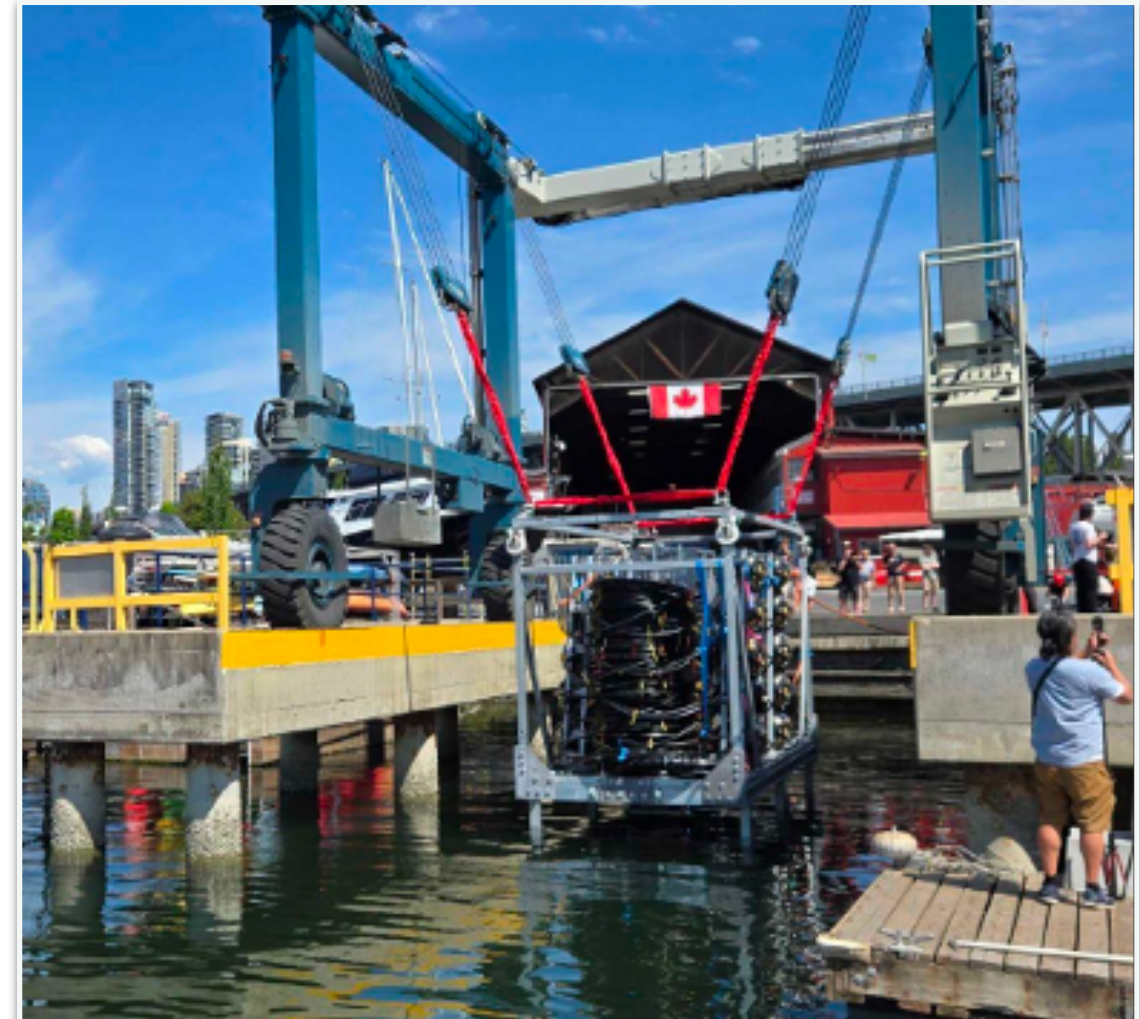
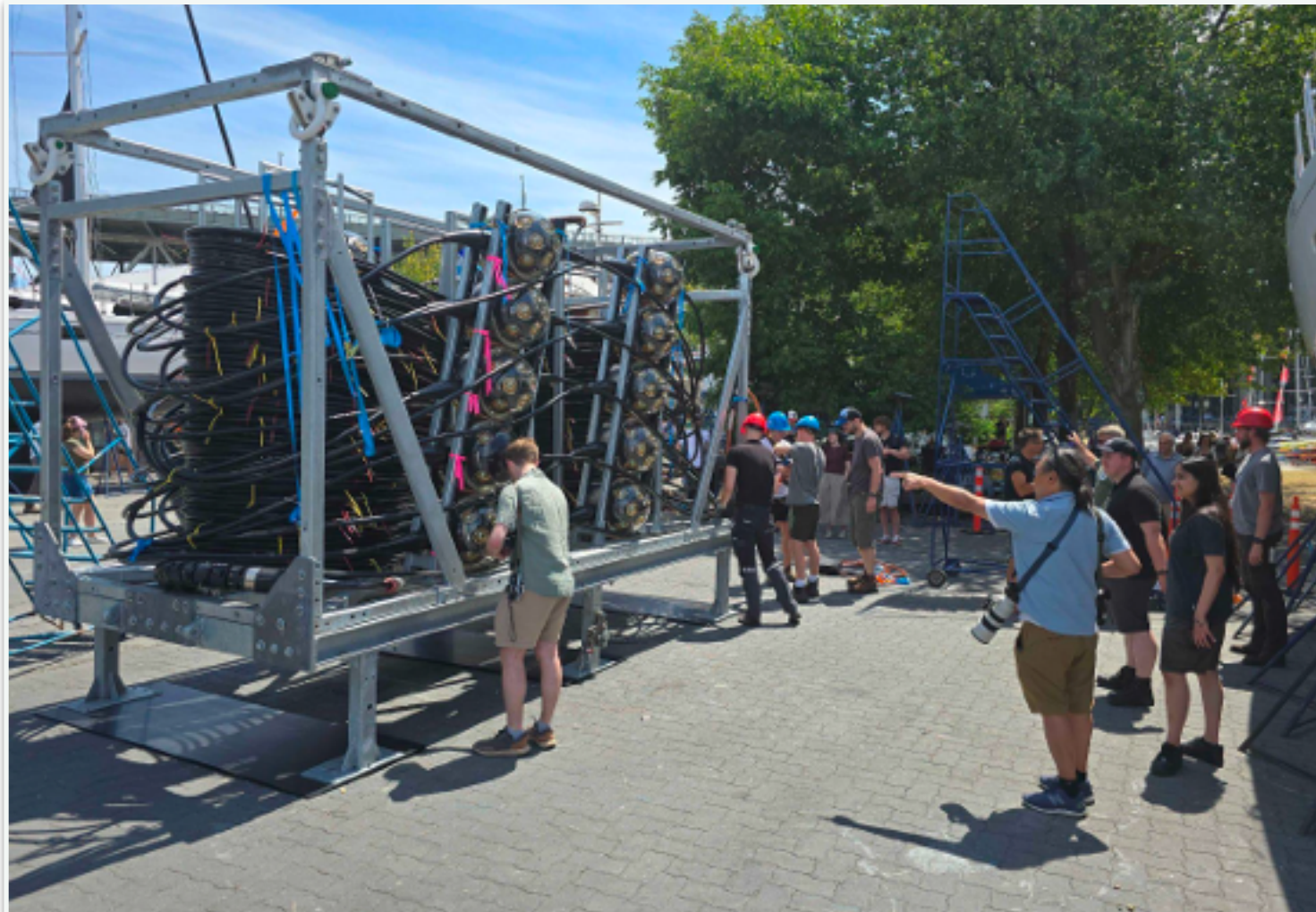


TRIUMF (Canada) '26



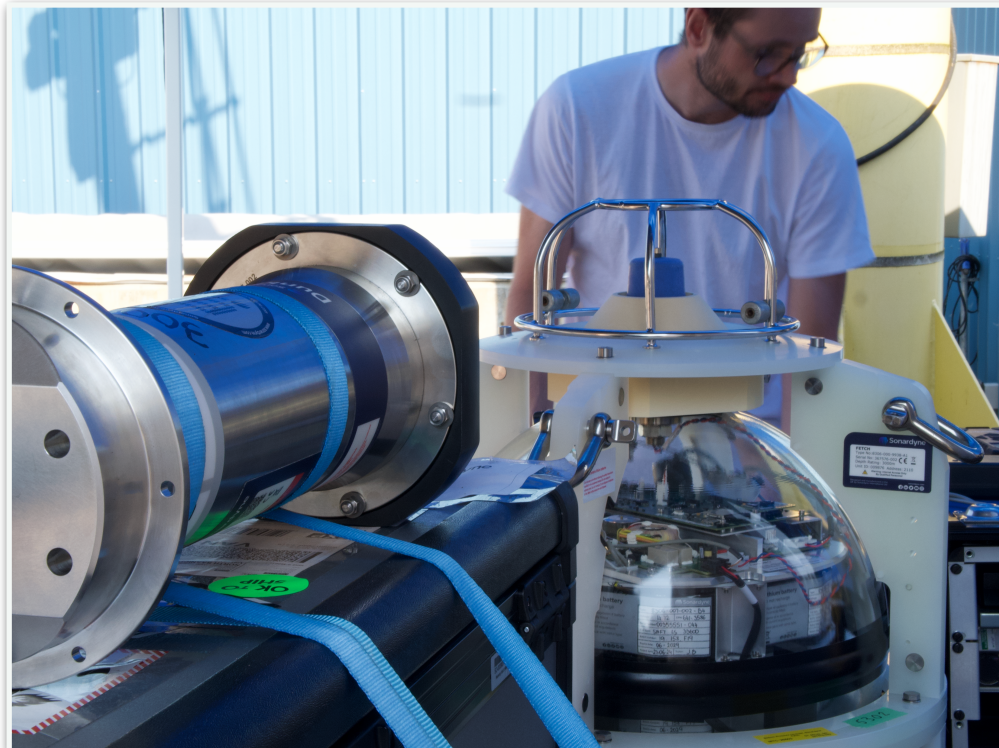
P-ONE: Integration and water test

Vancouver bay. June 2026 (Pictures from Ben Nührenbörger)



P-ONE: Precommissioning, done

Victoria, August/September '26 (Pictures from Armin Linke)



Summary & Outlook

A new astronomy has opened: the task now is to build better and larger telescopes.

Four yardsticks for "better":

Performance, Backgrounds, Engineering & Ops, Readiness

A global fleet is coming online:

- KM3NeT, P-ONE, Baikal-HUNT, TRIDENT, NEON (+ IceCube-Gen2): water & ice, both hemispheres.

Engineering is destiny: minimize connectors, design for longevity, build fast.

In P-ONE we are developing and testing connector-less line embodying these lessons.

The future is a network: several telescopes multiply sky coverage and discovery reach.

P-ONE is ready to deploy: first line integrated, tested and precommissioned in 2026