

# Future Astrophysical Neutrino Experiments

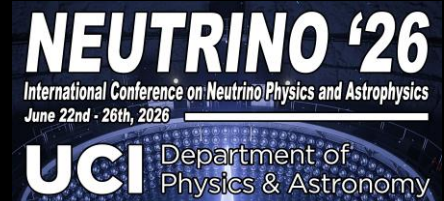


Illustration by  
Eloi Cartraud  
@eloi.ctrrd



李政道研究所  
TSUNG-DAO LEE INSTITUTE

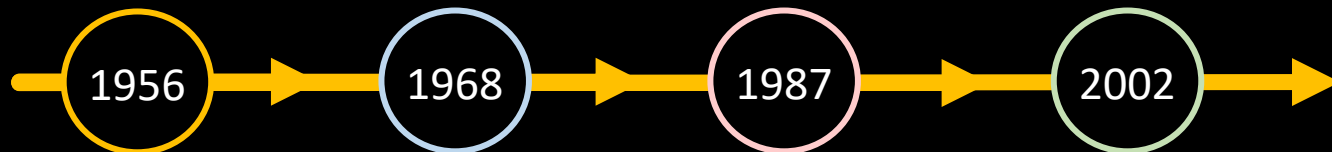
Iwan Morton-Blake, on behalf of Donglian Xu  
Tsung-Dao Lee Institute / Shanghai Jiao Tong University  
26<sup>th</sup> June 2026



# Neutrino Sources

~70 years experience in neutrino measurement!

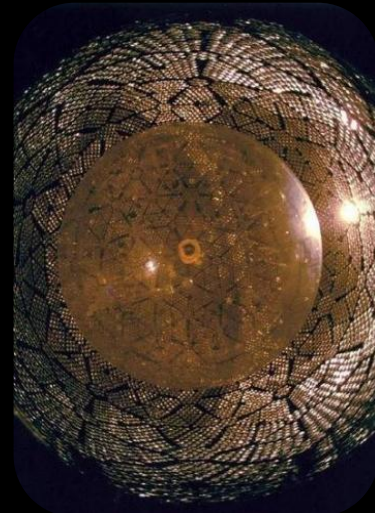




Solar neutrinos measured deficit in the expected rate



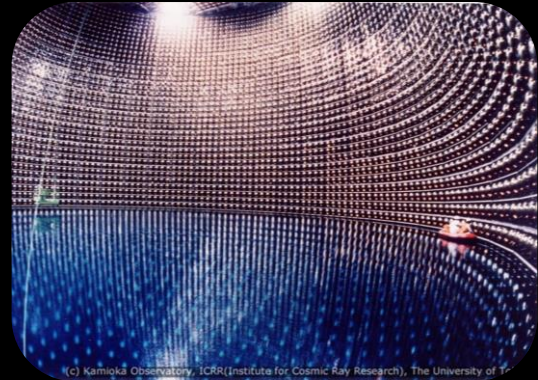
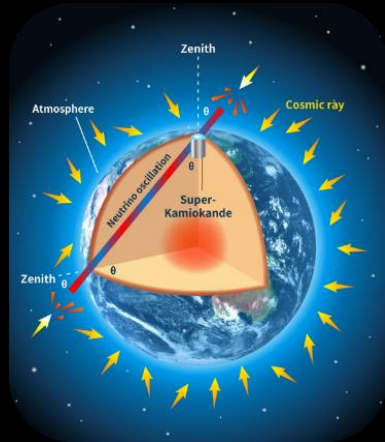
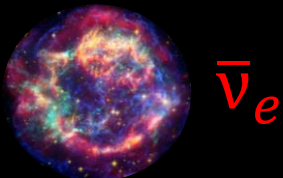
Measurement of neutrino oscillations  
Neutrinos have (very small) mass!



Neutrino experimental discovery



First and only CCSN neutrino measurement



F. Reines and C. L. Cowan Jr. et al., *Detection of the free neutrino: A confirmation*, Science 124 (1956) 103.

R. Davis Jr., D. S. Harmer, and K. C. Hoffman, *Search for neutrinos from the sun*, Phys. Rev. Lett. 20, 1205 (1968).

Kamiokande-II Collaboration, *Observation of a neutrino burst from the supernova SN1987A*, Phys. Rev. Lett. 58, 1490

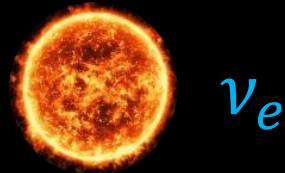
Super-Kamiokande Collaboration, *Evidence for oscillation of atmospheric neutrinos*, Phys. Rev. Lett. 81 (1998) 1562.

SNO Collaboration, *Measurement of the rate of ν<sub>e</sub> + d → p + p + e<sup>-</sup> interactions*, Phys. Rev. Lett. 87 (2001) 071301.

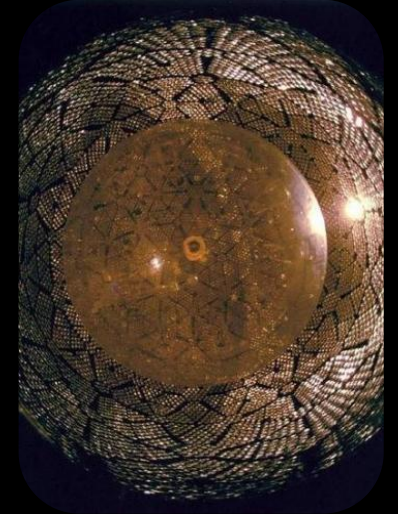
# Astro sources heavily feature!



Solar neutrinos measured deficit in the expected rate

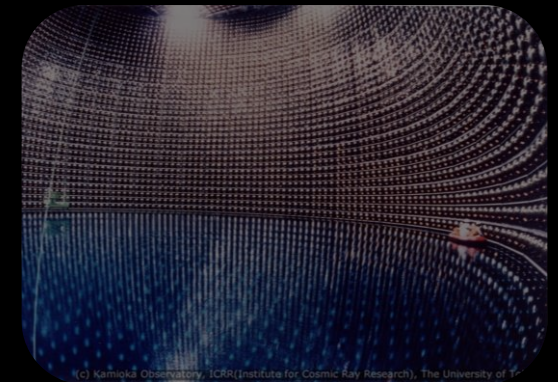
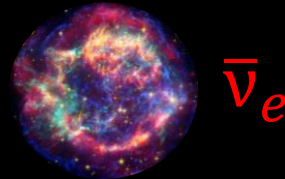


Measurement of neutrino oscillations  
Neutrinos have (very small) mass!



Neutrino experimental discovery

First and only CCSN neutrino measurement



F. Reines and C. L. Cowan Jr. et al., *Detection of the free neutrino: A confirmation*, Science 124 (1956) 103.

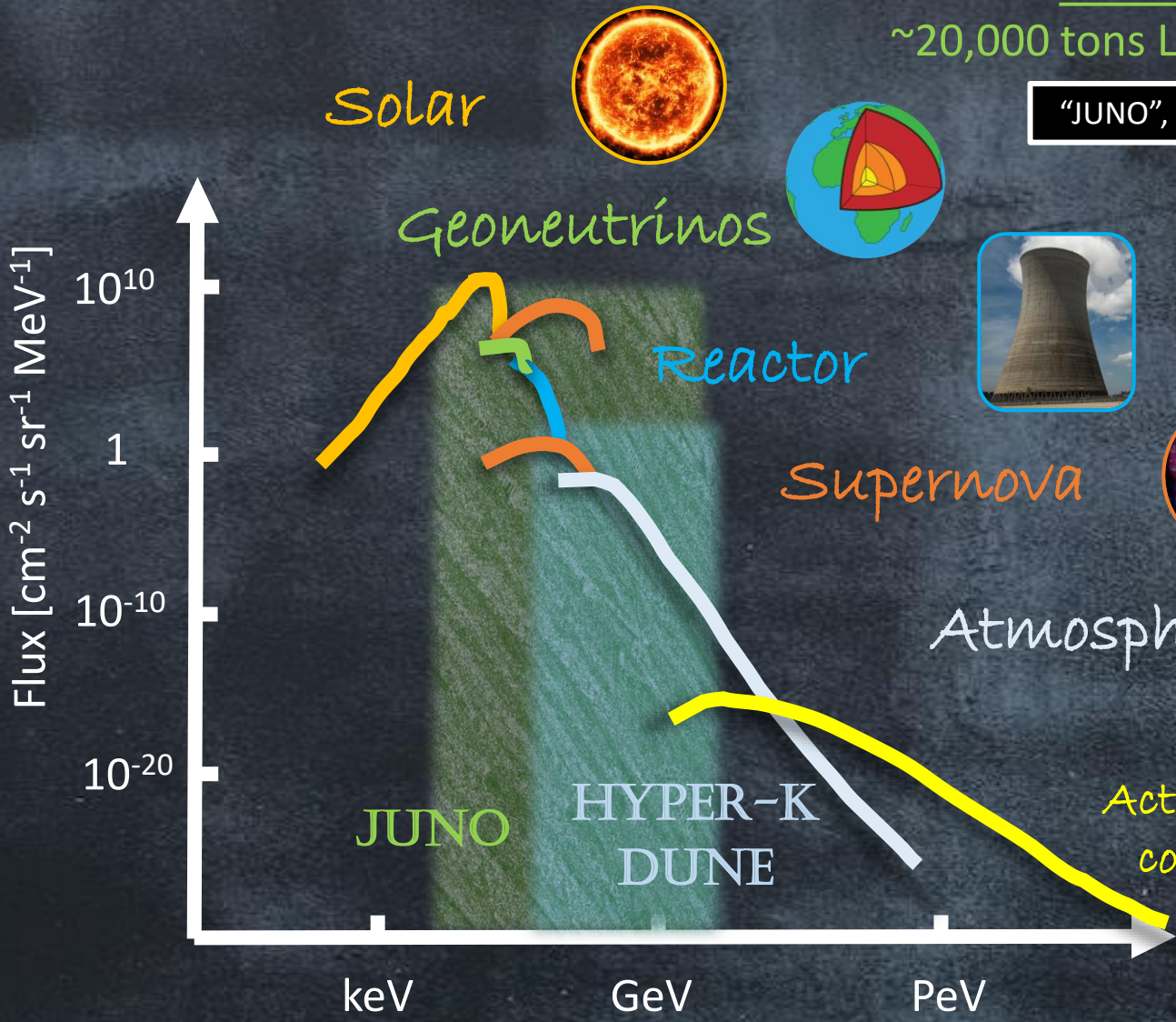
R. Davis Jr., D. S. Harmer, and K. C. Hoffman, *Search for neutrinos from the sun*, Phys. Rev. Lett. 20, 1205 (1968).

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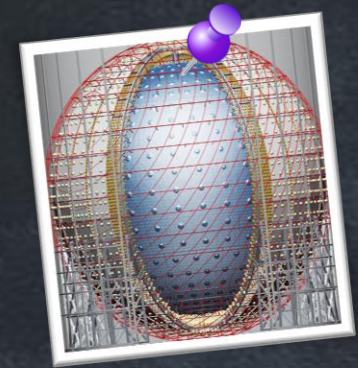
# The Precision Era



JUNO (2025-)

~20,000 tons Liquid scintillator

“JUNO”, Yifang Wang



Hyper-Kamiokande (2028-)

~260,000 t Water fiducial vol.

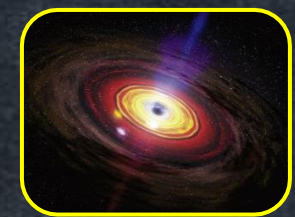
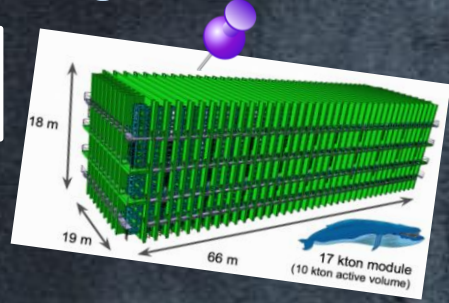
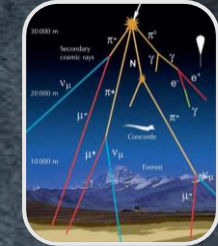
“Hyper-Kamiokande”, Ryosuke Akutsu



DUNE (2030-)

~4x17 kt Liquid Argon

“DUNE”, Sowjanya Gollapinni





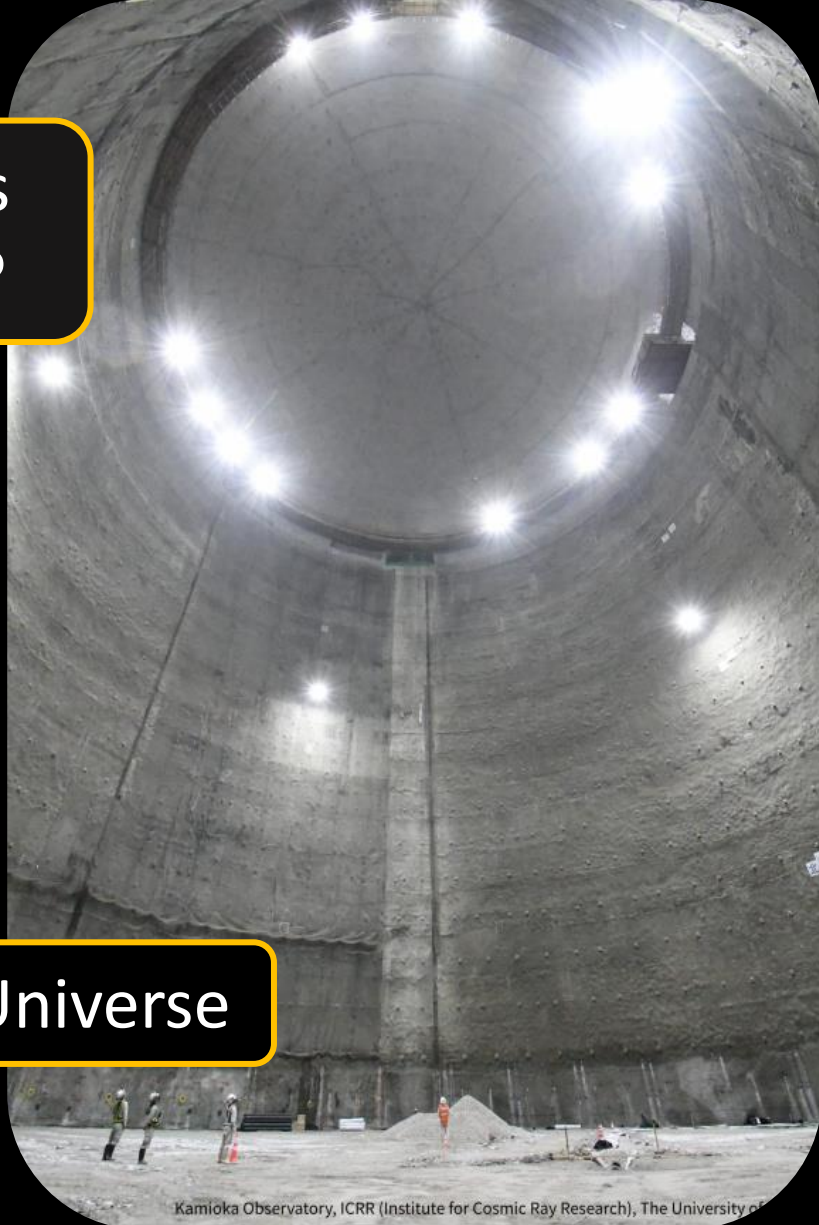
What astrophysical questions  
can these detectors address?



Complementary views of the same Universe

JUNO Collaboration

Fermilab / SURF



Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of

Hyper-Kamiokande Collaboration

# All-rounder precision detectors

## Solar neutrinos

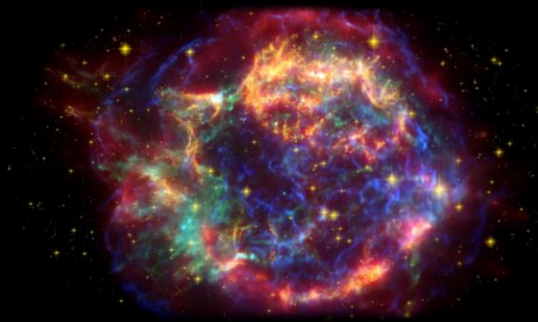
Precision tests of stellar fusion  
and neutrino flavour evolution



(Ranging from  
0 – O(10 MeV))

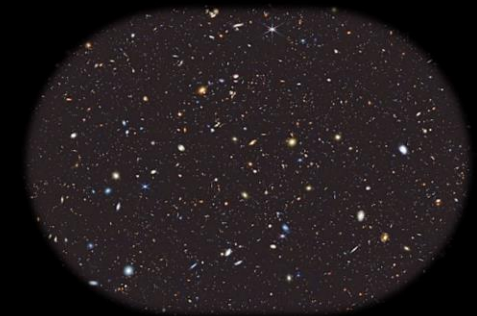
## Core-collapse supernovae

Time- and flavour-resolved  
tracking of stellar explosions



## Diffuse Supernova Neutrino Background

First detection, a census of all stellar  
collapses across cosmic history



# Solar Neutrinos



## JUNO

- 20 kT liquid scintillator detector
- Low energy threshold  $O(10 \text{ keV})$
- Excellent energy resolution

- Low energy spectroscopy
- Solar metallicity via CNO neutrinos (backgrounds permitting)
- Probe the vacuum-to-matter oscillations

“Model Independent Approach of the JUNO  $^8\text{B}$  Solar Neutrino Program,” APJ (2024)

“JUNO sensitivity to  $^7\text{Be}$ , pep, and CNO solar neutrinos” JCAP (2023)

Great complementarity shown at this conference!

“SNO+”, Tanner Kaptanoglu

“PandaX”, Ke Han

“LZ”, Dongqing Huang

“Super-K”, Zhoujun Hu

## DUNE

- 4x17 kT Liquid Argon Trackers
- Large  $\nu_e$  cross section, clean sample

- Direct  $\nu_e$  measurement
- Precise  $^8\text{B}$  flux and hep flux sensitivity
- Precision solar oscillation parameter measurement, day-night asymmetry

DUNE as the Next-Generation Solar Neutrino Experiment, PRL (2019)

## HyperK

- 260 kT, water Cherenkov
- Largest target mass
- Directional reconstruction

- Largest  $^8\text{B}$  sample, directional measurements
- Precision measurements of matter-enhanced oscillations

Hyper-Kamiokande Design Report, arXiv:1805.04163 (2018)

# Core-collapse Supernova



## JUNO

- 20 kT liquid scintillator detector
- Low energy threshold  $O(10 \text{ keV})$
- Excellent energy resolution

- Ideal  $\bar{\nu}_e$  detector
- Low energy threshold: Efficient all-flavour  $\bar{\nu}_{e\mu\tau}$  uniquely w/ proton recoil
- Precision energy spectroscopy
- Approx. pointing w/  $\bar{\nu}_e \sim 25^\circ$  (summed IBDs)

Real-time monitoring for the next core-collapse supernova in JUNO JCAP (2024)

## DUNE

- 4x17 kT Liquid Argon Trackers
- Large  $\nu_e$  cross section, clean sample

- Direct  $\nu_e$  sensitivity, strong CCSN neutronization burst sensitivity
- Supernova pointing  $\sim 5^\circ$

Supernova pointing capabilities of DUNE, PRD (2025)

## HyperK

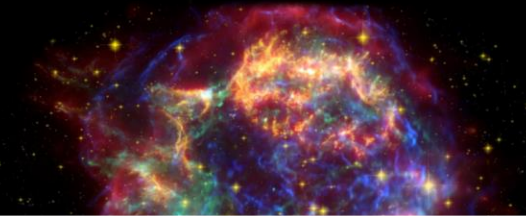
- 260 kT, water Cherenkov
- Largest target mass
- Directional reconstruction

- Largest CCSN sample through  $\bar{\nu}_e, \nu_e$
- Supernova pointing with  $\nu_e \sim 1^\circ$

Supernova Model Discrimination with Hyper-Kamiokande, APJ (2021)

“Supernova Neutrinos (Theory)”, John Beacom

# Core-collapse Supernova



## JUNO

20 kT liquid scintillator detector

→ Low energy threshold  $O(10 \text{ keV})$

→ Excellent energy resolution

- Ideal  $\bar{\nu}_e$  detector
- Low energy threshold: Efficient all-flavour  $\bar{\nu}_{e\mu\tau}$  uniquely w/ proton recoil
- Precision energy spectroscopy
- Approx. pointing w/  $\bar{\nu}_e \sim 25^\circ$  (summed IBDs)

Real-time monitoring for the next core-collapse supernova in JUNO JCAP (2024)

## JUNO, now running!

Multiple CCSN alert systems running

Distinct  $E_{\min}$  ( $\sim 100\text{keV} - 5\text{MeV}$ ), backgrounds, alert times

Now joined SNEWS 2.0: global neutrino-detector

early warning network for CCSNe

CCSNe detectable out to  $\sim 300 \text{ kpc}$

Alerts received also from gravitational wave, X-ray experiments through a Multi-Messenger trigger system

of DU

SNEWS 2.0: A Next-Generation SuperNova Early Warning System for Multi-messenger Astronomy, New J. Phys. (2021)

APJ (2021)

“Supernova Neutrinos (theory)”, John Beacom

# Diffuse Supernova Neutrino Background



## JUNO

- 20 kT liquid scintillator detector
- Low energy threshold  $O(10 \text{ keV})$
- Excellent energy resolution

- 100% efficient  $\bar{\nu}_e$  detection
- Precision spectral measurement
- Low atmospheric backgrounds, potentially lower w/ PSD

“Prospects for Detecting the Diffuse Supernova Neutrino Background with JUNO,” JCAP (2022)

## DUNE

- 4x17 kT Liquid Argon Trackers
- Large  $\nu_e$  cross section, clean sample

- Complementary sensitivity to neutrinos (instead of antineutrinos)

## HyperK

- 260 kT, water Cherenkov
- Largest target mass
- Directional reconstruction

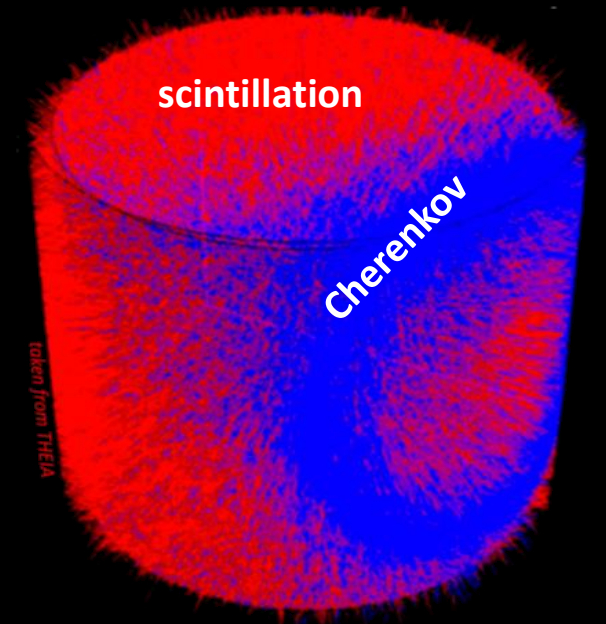
- Largest DSNB signal sample
- Spectral measurement
- Efficiency can be boosted through Gd-loading

“Supernova Neutrinos in Super-Kamiokande”, Hiroyuki Sekiya

# Hybrid Detectors – Theia

- Implement a hybrid Cherenkov/Scintillation medium
- PMTs, LAPPDs, Dichroicons
- Eos technology demonstrator
  - Completed first performance tests, direction, energy and PID

Performance of the Eos detector with water,  
[arXiv:2606.10234 \(2026\)](https://arxiv.org/abs/2606.10234)

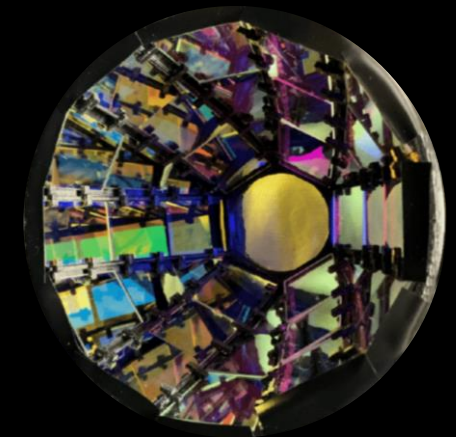


Solar neutrinos: Precision measurement of CNO  $\nu$ 's at 5% level

CCSN: Flavour resolving (Scint) with strong pointing (Cherenkov)

DSNB: Discrimination of atmospheric NC background with Cherenkov/Scint ratio with spectroscopy

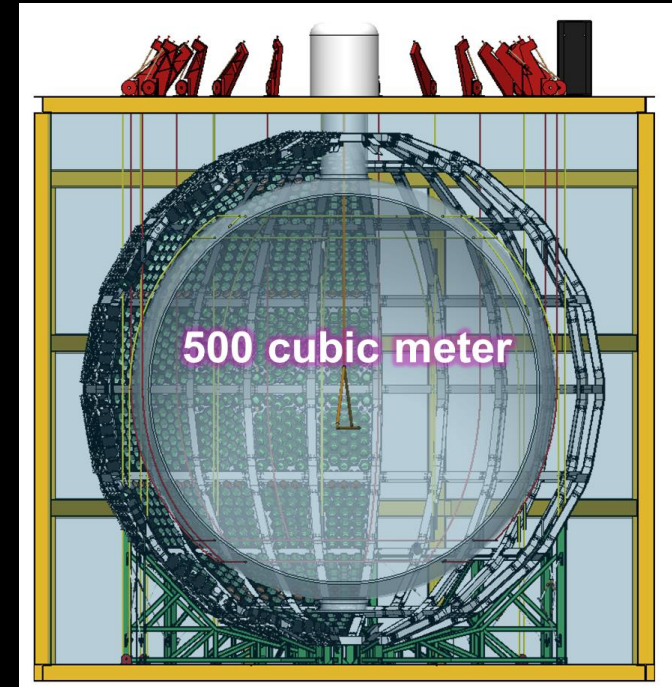
“Theia”, Josh Klein  
“The Future of Neutrinoless Double Beta Decay”, Gabriel Orebi Gann



Spectral photon sorting for large-scale Cherenkov and scintillation detectors, PRD (2020)

# Hybrid Detectors – JNE

- Proposed solar neutrino experiment *Jinping Neutrino Experiment*
- 2.4km rock overburden in CJPL
- Water/Slow-scintillator or LiCl solution (high  $\nu_e$  cross-section)
- JNE-1t prototype demonstrated reconstruction with slow scintillator and fast PMTs
- Multi-hundred ton detector expected first data in 2027
- Solar: Charged current on Li-7 has an advantage than  $\nu_e$  ES in measuring solar neutrino upturn effect
- DSNB: Capability for PID to suppress atmospheric neutrino neutral current background



Optical property measurements of lithium chloride aqueous solution for a novel solar neutrino experiment, arXiv2211.05023 (2023)

Study of neutron production for 360 GeV cosmic muons, arXiv:2409.04169 (2024)



JNE-1t

# A Complementary Worldwide Network

SNEWS: The Global Supernova  
Early Warning System  
(→ SNEWS 2.0 this year)

The next Galactic supernova  
will be observed by a  
worldwide network of  
complementary detectors

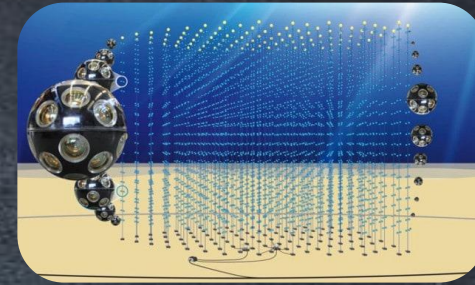
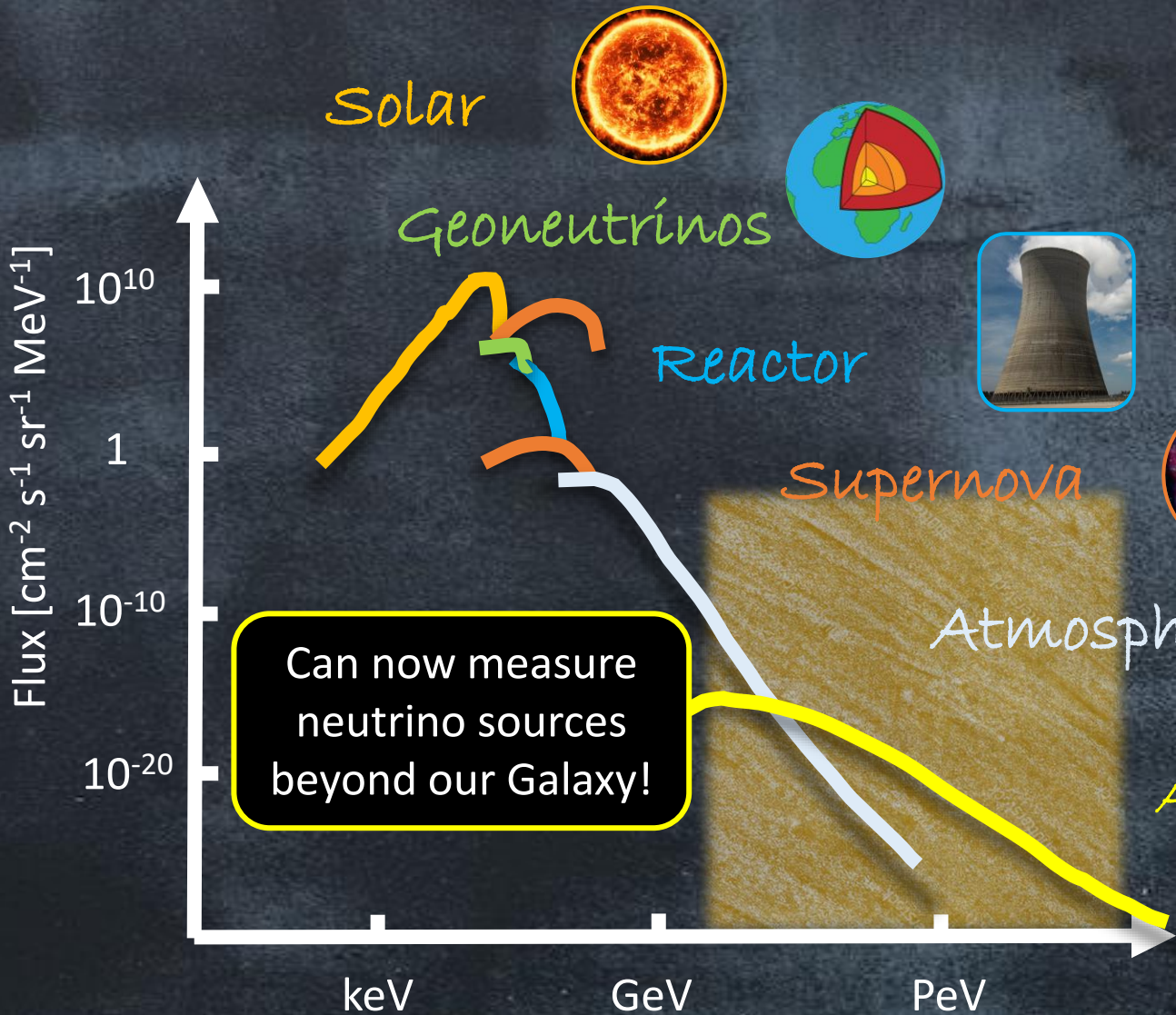


# Ramping up in energy

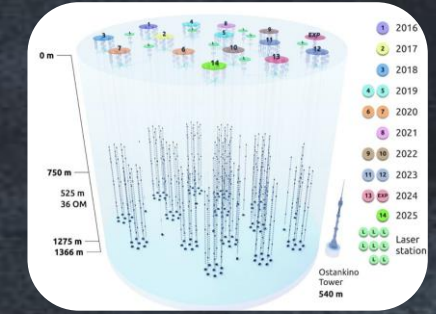
# Higher Energies

"Atmospheric Neutrinos at IceCube", Spencer Axani  
 "Astrophysical Neutrinos at IceCube", Ali Kheirandish

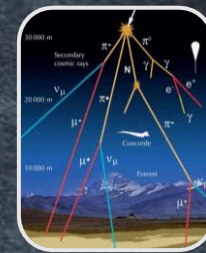
"Astrophysical Neutrinos at KM3Net", Silvia Celli  
 "Atmospheric Neutrinos at KM3Net", Paul De Jong



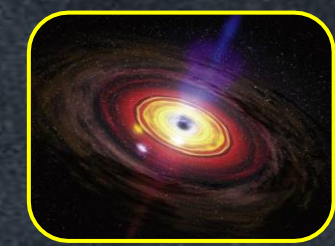
**KM3NeT**  
 ARCA/ORCA  
 (running, expanding)  
 1km<sup>3</sup> seawater

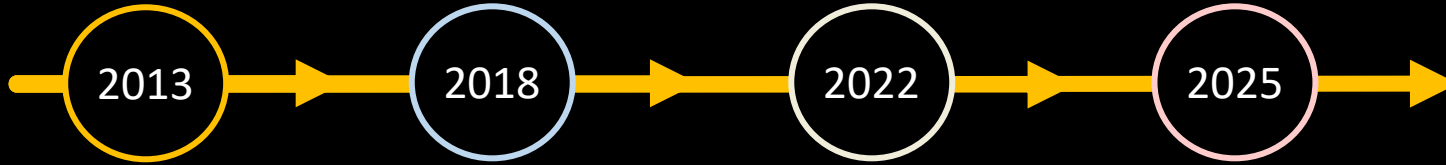


**Baikal GVD**  
 (running, expanding)  
 → 1km<sup>3</sup> lake water



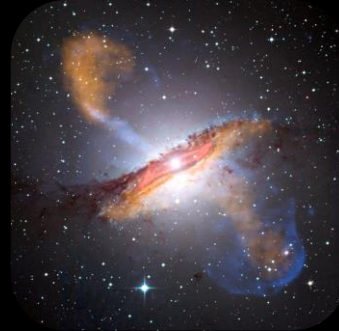
**IceCube**  
 ~1km<sup>3</sup> Ice





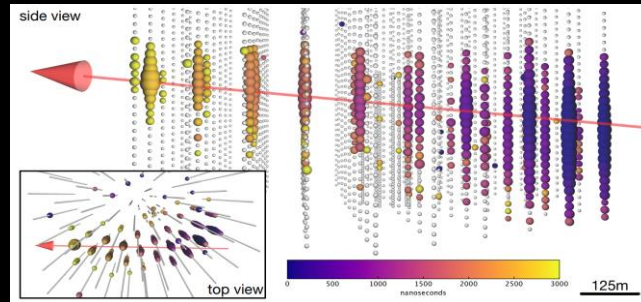
Detection of high-energy diffuse astrophysical neutrino flux

*Science. 342 6161*



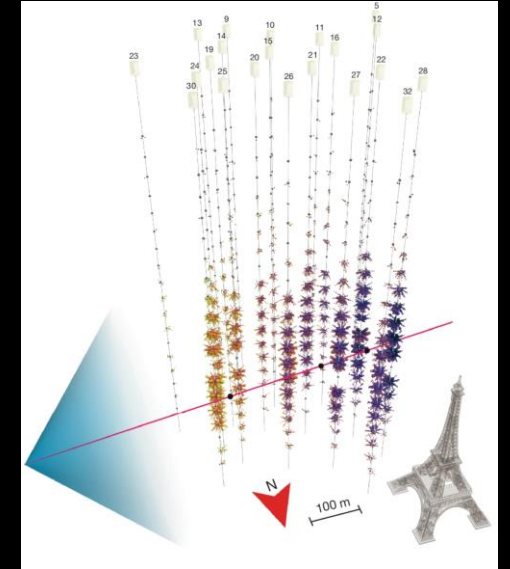
Neutrino emission from active galaxy NGC 1068 reaches  $4\sigma$

*Science 378 538-543 (2022)*



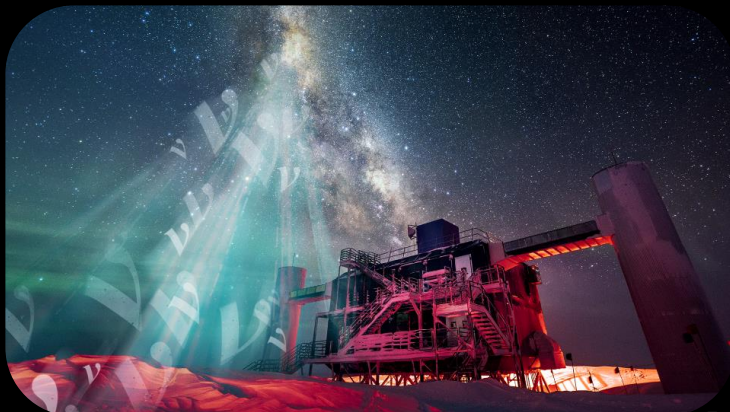
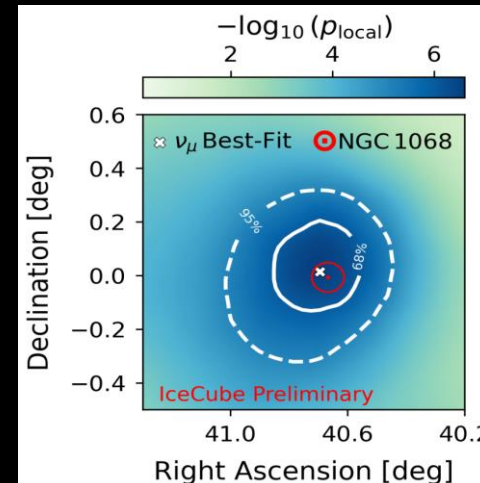
Evidence for neutrino emission from a flaring blazar

*Science. 361 6398 (2018)*

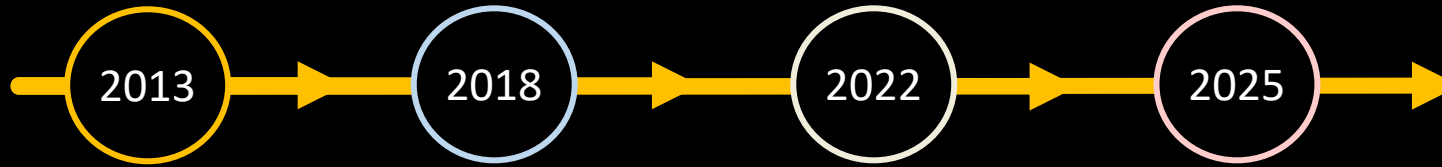


Ultra-high-energy cosmic neutrino measured by KM3NeT

*Nature 638 376–382 (2025)*



20/07/2020



A transition point for Neutrino Astronomy?

High-energy astro. neutrinos are now established

The next-generation aims to move:

**Discovery → Precision**

Resolve the neutrino sky

Measure flavour compositions ( $\nu_\mu, \nu_e, \nu_\tau$ )

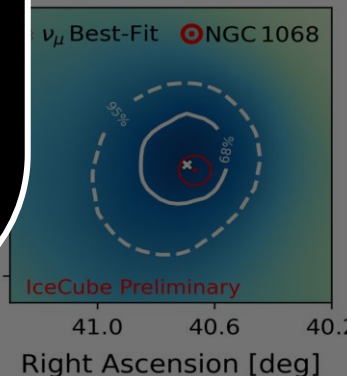
Understand source physics/mechanisms

“High-Energy Cosmic Neutrinos”,  
Kohta Murase

More and better neutrino  
telescopes are on the way!

Ultra-high-energy  
cosmic neutrino  
measured by KM3NeT

*Nature 638 376–382 (2025)*



What do we need?

They grow up so fast [?][?]

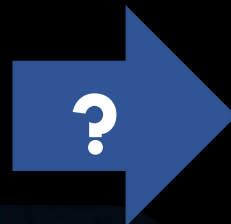
3 kilotons



23 kilotons



190 kilotons



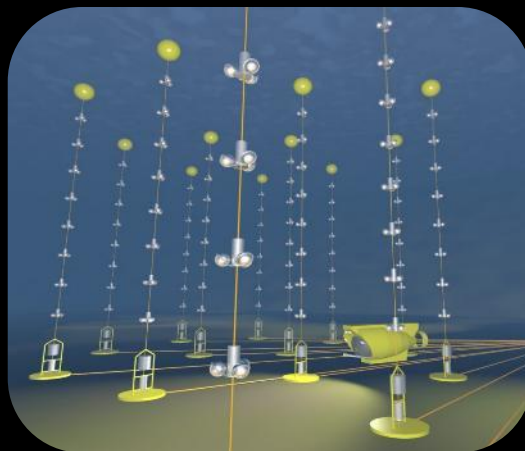
200 kgs



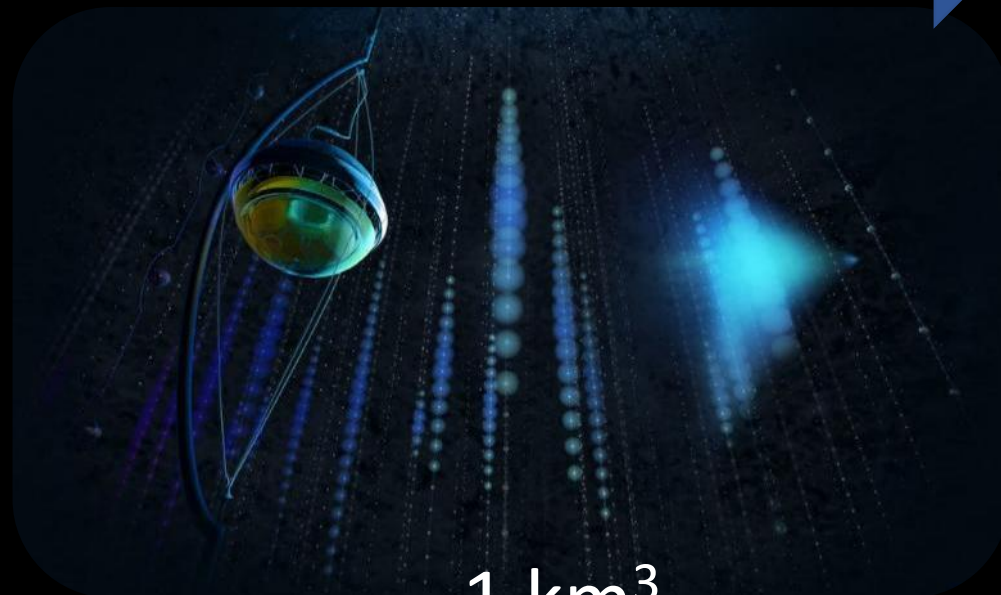
1 kiloton



1 kiloton



0.1 km<sup>3</sup>



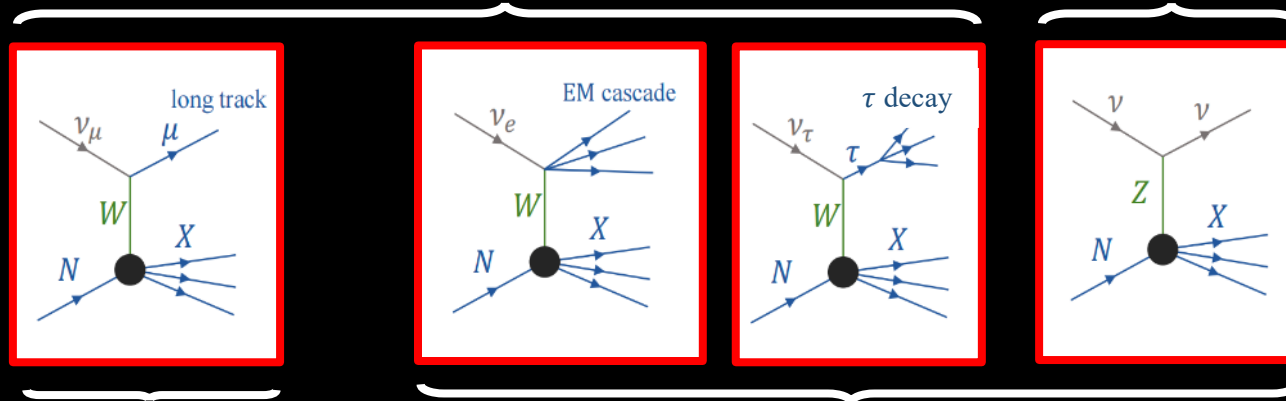
1 km<sup>3</sup>

# Event interaction types

Charged-Current

Neutral-Current

➤ Golden channel for pointing

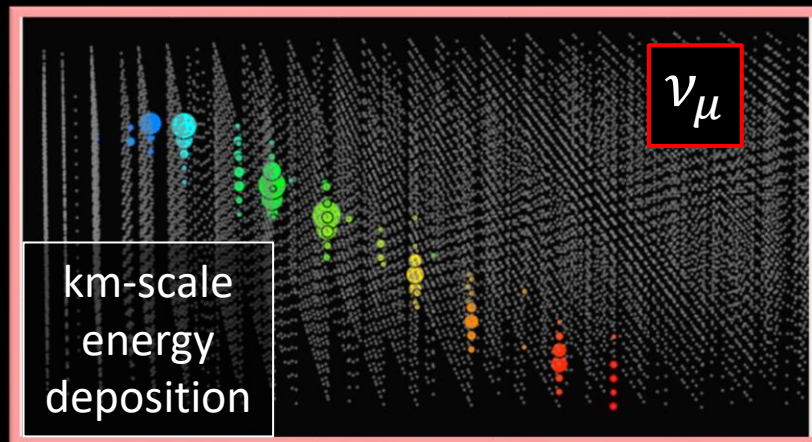


- Moderate pointing
- Better energy resolution
- Lower backgrounds
- Neutrino flavour separation

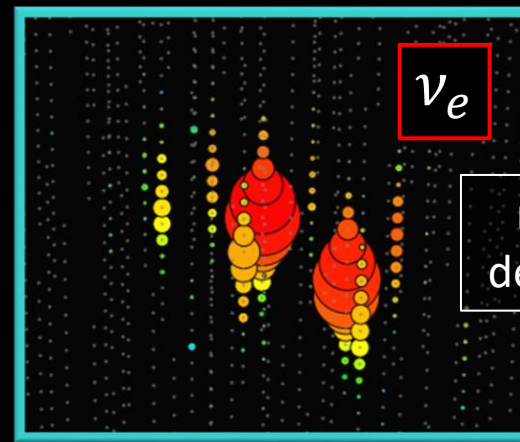
Muon tracks

Cascades

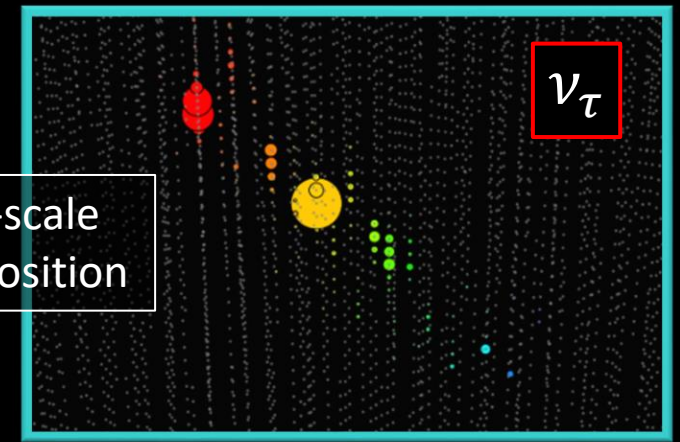
(τ decay can also produce muons)



km-scale energy deposition



m-scale deposition



TRIDENT simulation

# Upcoming Detector Needs

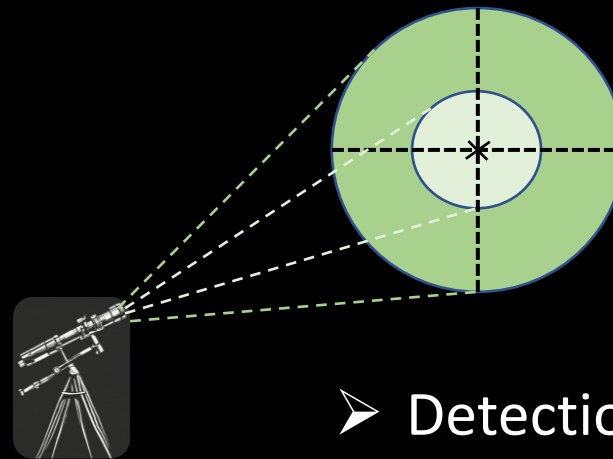
## 1) More Events

*E.g. NGC1068 source candidate  
~4 $\sigma$  after a decade by IceCube*

$\text{Sig.} \propto \sqrt{N}$   
(but  $N \propto \text{Volume?}$ )

## 2) Better Pointing

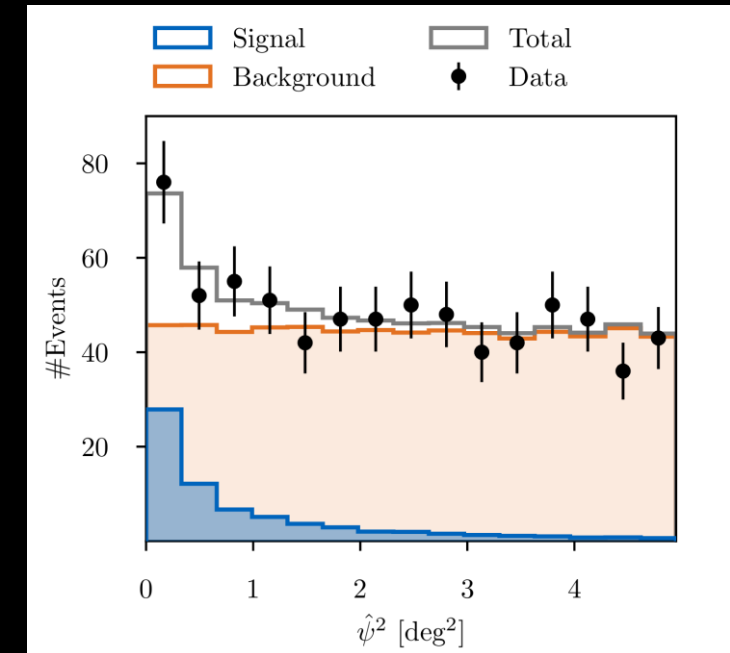
➤ More and larger detectors



*Backgrounds scale  
roughly with  
(angular resolution)<sup>2</sup>*

➤ Detection medium water vs ice

➤ Photodetection technology

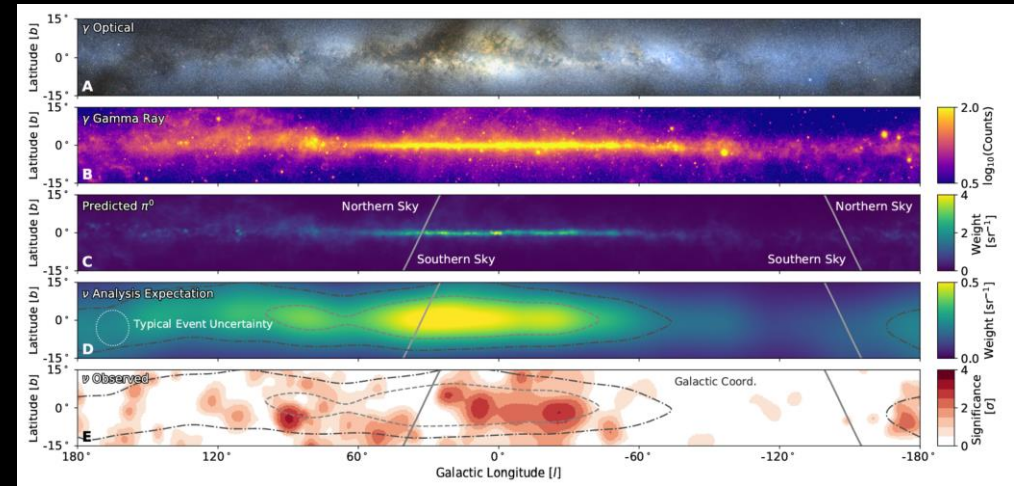


# Upcoming Detector Needs

## 1) More Events

*Galactic plane neutrinos at  $5\sigma$  cascade events prove essential!*

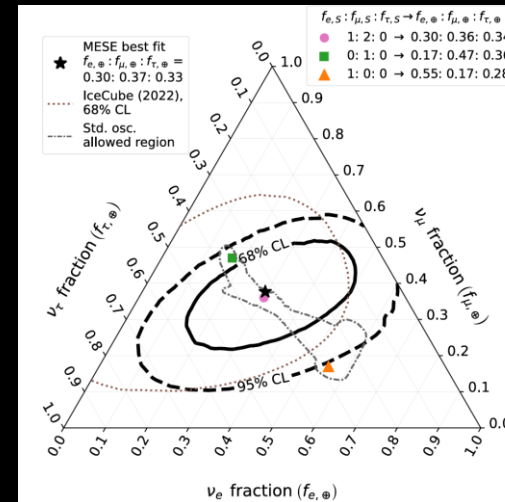
“Astrophysical Neutrinos at IceCube”, Ali Kheirandish



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

## 2) Better Pointing

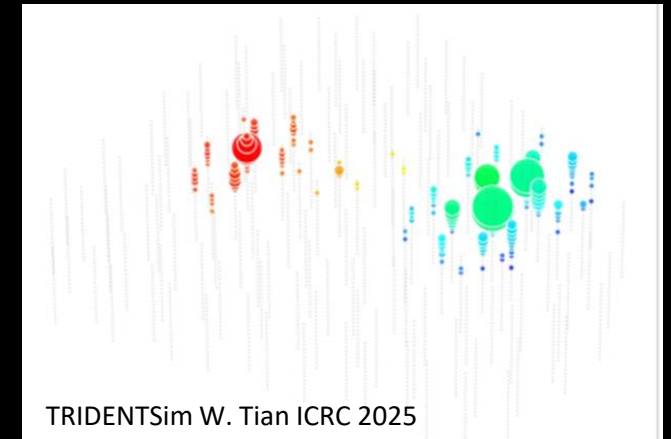
Characterization of the Three-Flavor Composition of Cosmic Neutrinos with IceCube, arXiv:2510.24957 (2025)



*Flavour ratio  $1\sigma$  contours now fully contained*

## 3) $\nu_\mu, \nu_e, \nu_\tau$ detection/separation

➤ Detector hardware and size



TRIDENTS W. Tian ICRC 2025

*>1000s of  $\nu_\mu, \nu_e$ ,  
~10  $\nu_\tau$  candidates*

Observation of Seven Astrophysical Tau Neutrino Candidates with IceCube PRL (2024)

# Upcoming Detector Needs

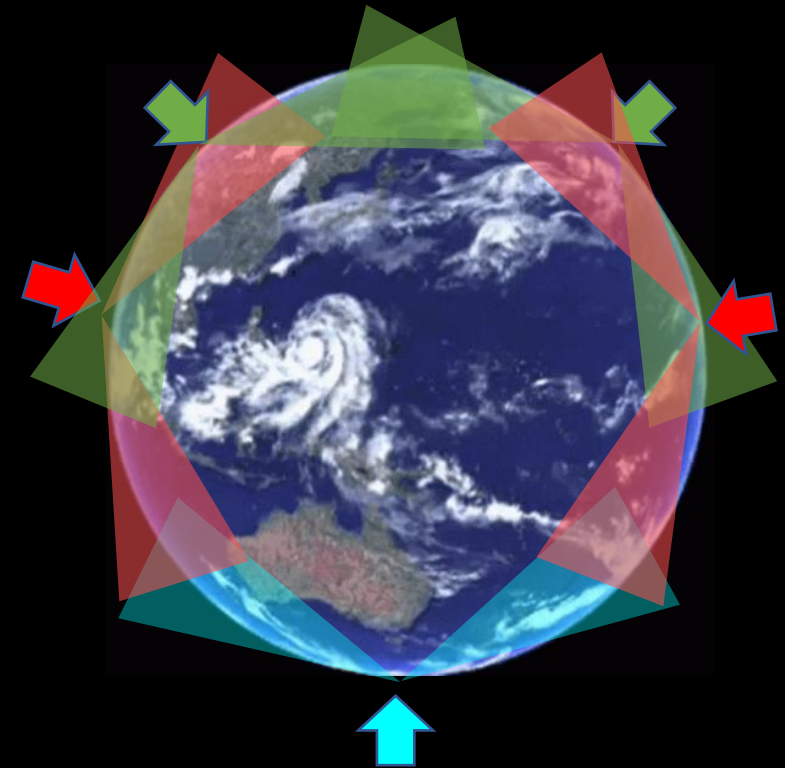
## 1) More Events

Global follow ups e.g.  
Transient sources, Rare  
UHE events  
e.g. KM3NeT

## 2) Better Pointing

## 3) $\nu_\mu, \nu_e, \nu_\tau$ detection/separation

## 4) Combined full-sky coverage



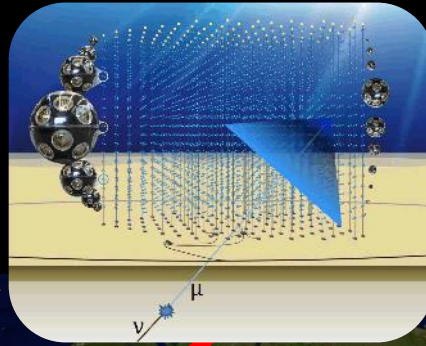
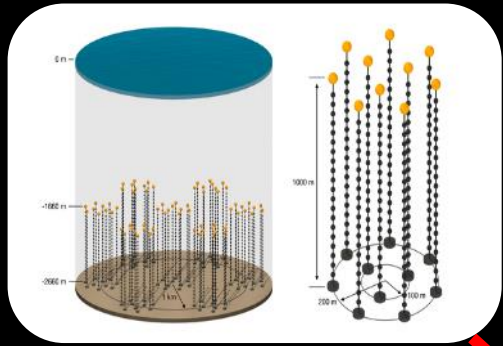
*Optimal viewing angle of telescopes  
world wide covers the whole sky*

- Detectors world-wide
- Track and Cascade events

What's on the way?

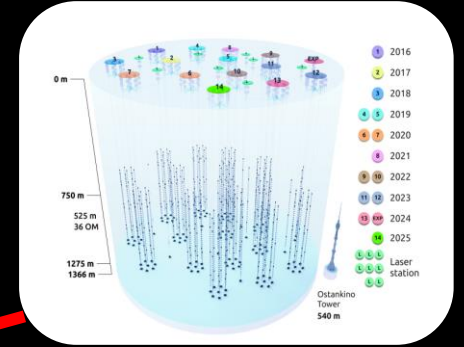
# KM3NeT (ARCA + ORCA)

Operating and  
Expanding  
(dedicated talks  
by Silvia, Paul!)

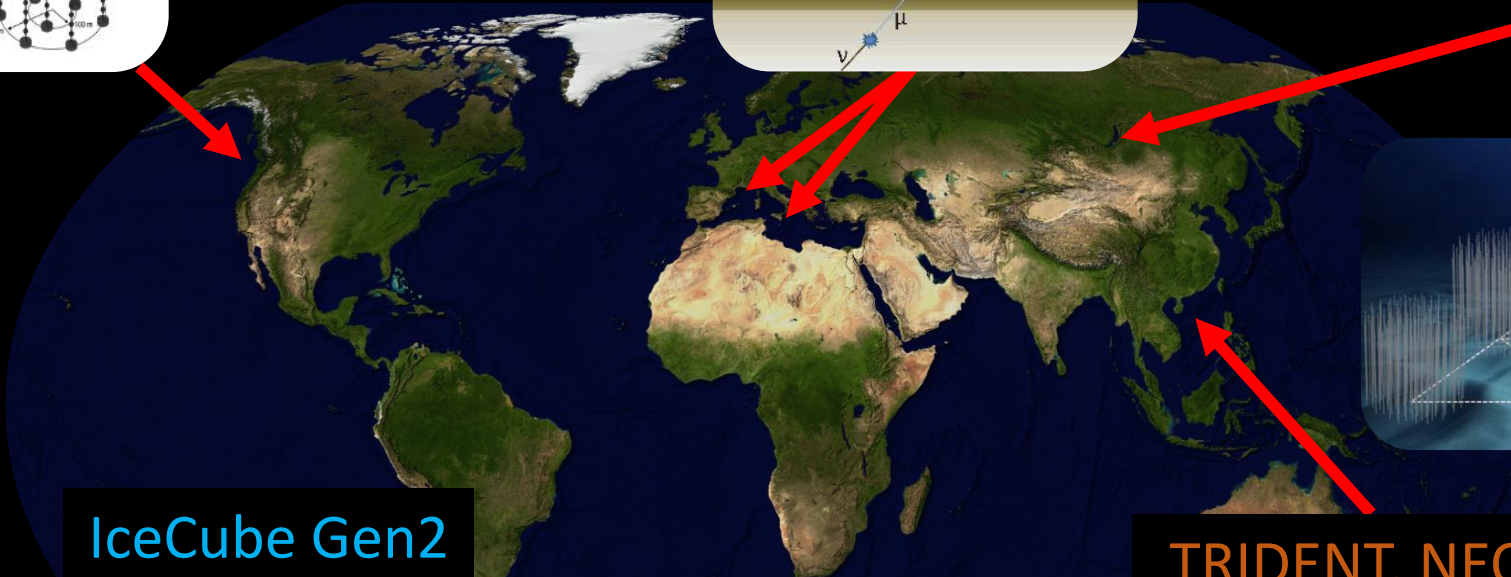


# Baikal-GVD

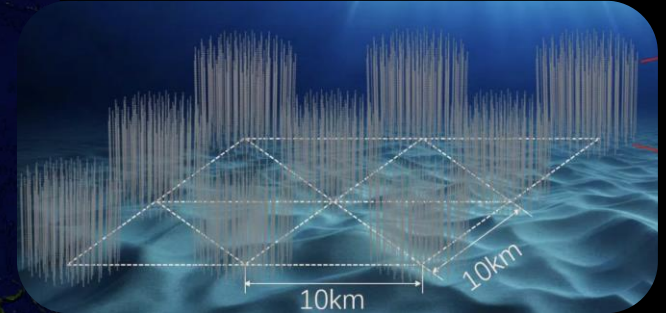
Operating and  
Expanding



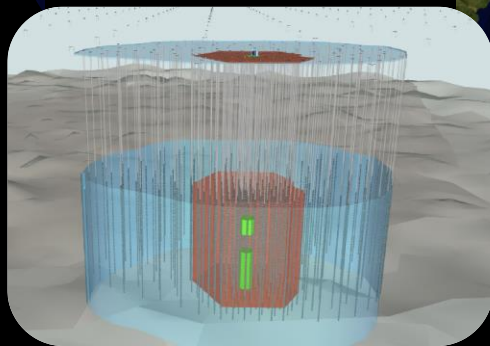
# P-ONE



# HUNT

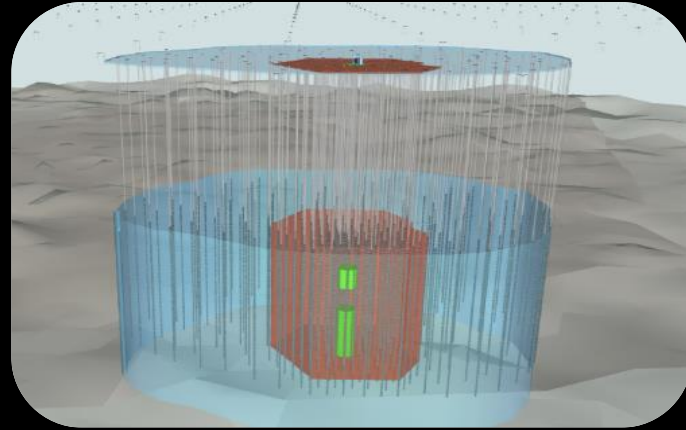


# IceCube Gen2



# TRIDENT, NEON



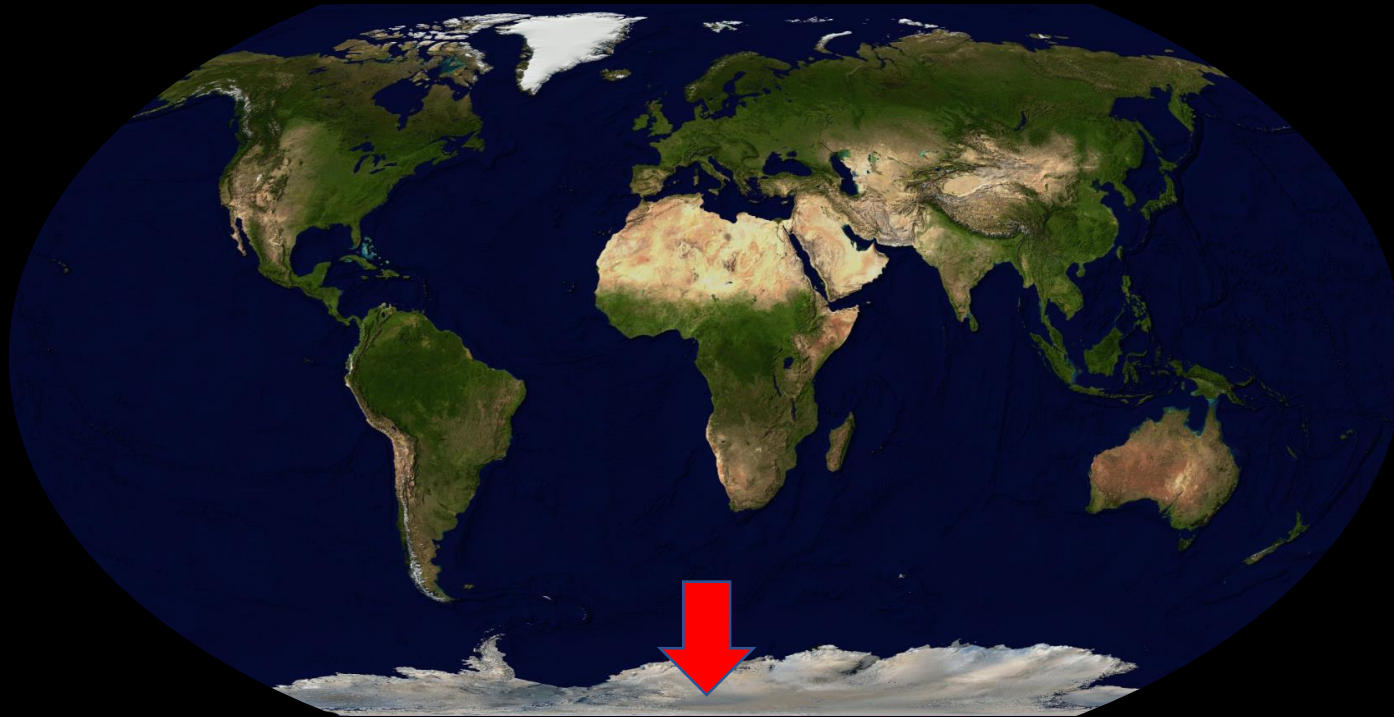


## IceCube Gen2

Depth: 2.5km

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

# strings: 86 + 120



# IceCube Gen2

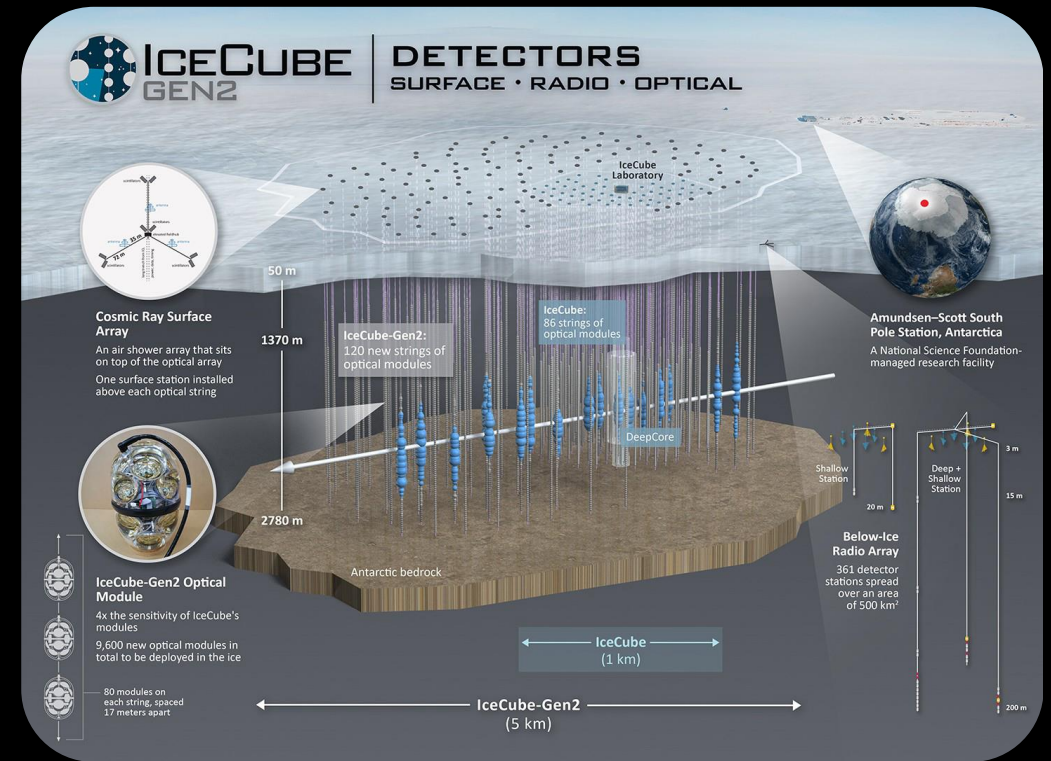
The successor to IceCube

- Expanding optical modules to 8km<sup>3</sup> (+ expanded surface and radio arrays!)

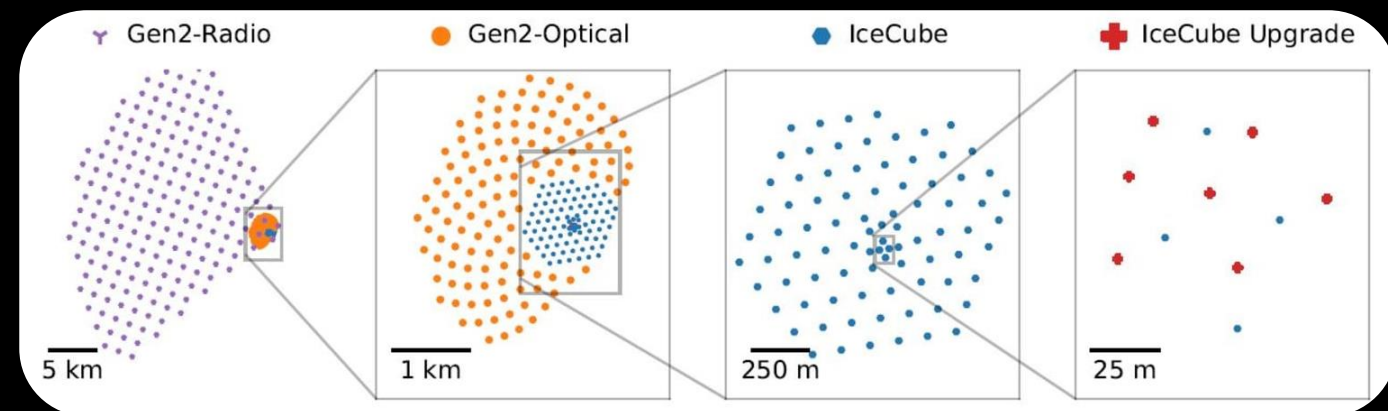
Detector design: +120 strings

- Sparse sunflower geometry: Optimised for uniform coverage and maximal point-source sensitivity with tracks

Optimization of the optical array geometry for IceCube-Gen2, PoS (ICRC2021)



IceCube-Gen2 Technical Design Report, 2024



# IceCube Gen2

## Optical modules:

- Single 10" PMT → Multiple small PMTs
  - Gen2 tested designs feature x16/18 4" PMTs
  - KM3NeT established benefits of increased photocoverage, directional info, background rejection and large dynamic range

The KM3NeT multi-PMT optical module, JINST (2022)

## Calibration:

- Lasers, isotropic light sources, cameras expect important improvements in ice modelling and reconstruction

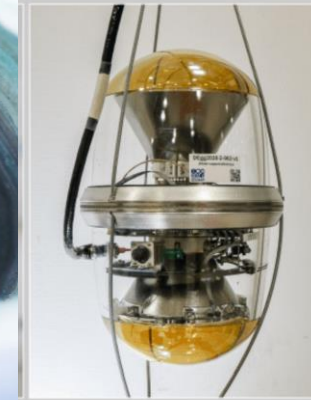
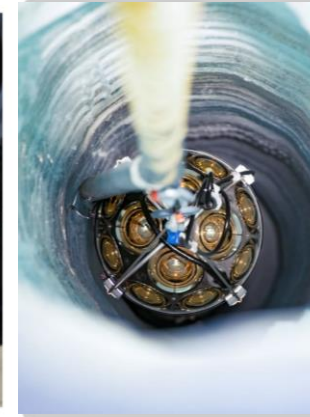
The LED calibration systems for the mDOM and D-Egg sensor modules of the IceCube Upgrade JINST (2025)

Camera Calibration for the IceCube Upgrade and Gen2, Eng. Proc. (2023).

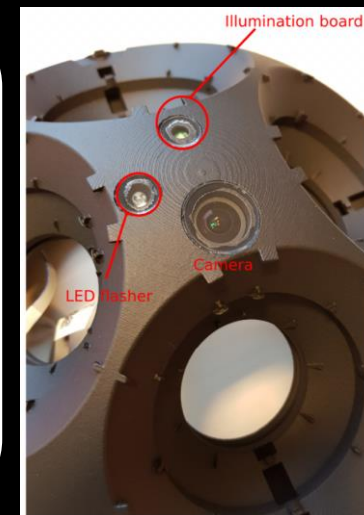
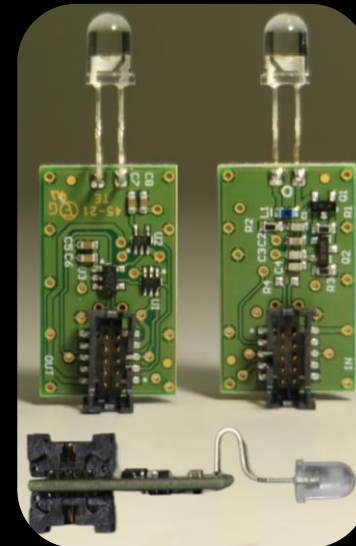
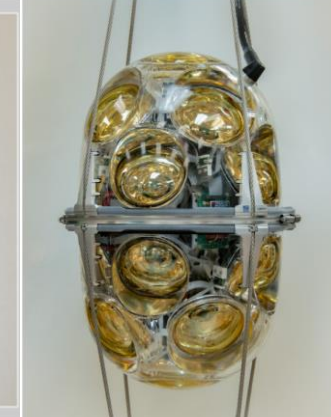
Gen1



Upgrade



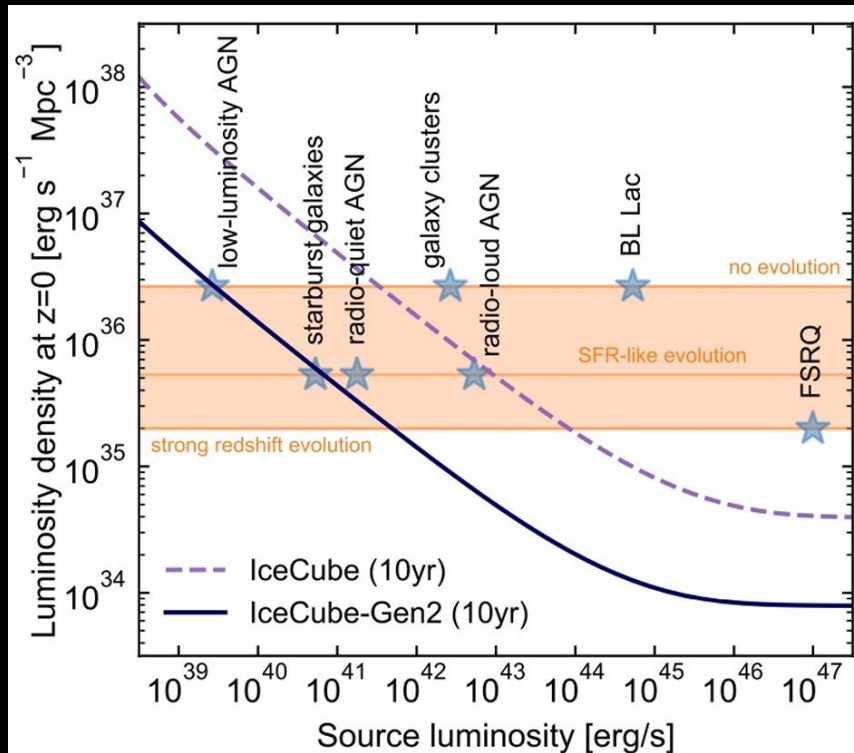
Gen2



# IceCube Gen2

More Events  Better Pointing  Flavour separation

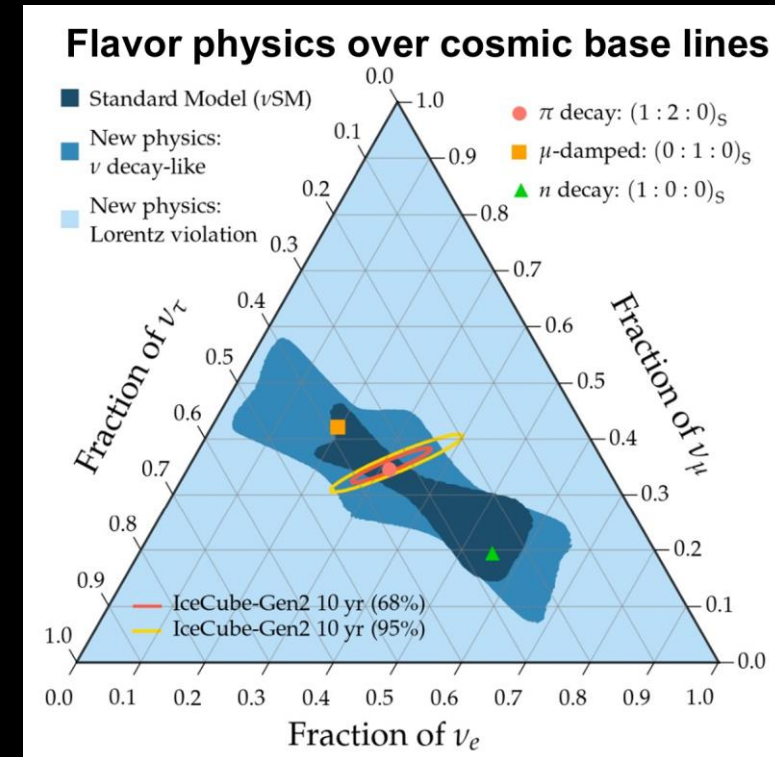
## Resolving the TeV-EeV neutrino sky



IceCube-Gen2 Technical Design Report (2024)

Expects  $\sim 5x$  improvement in point source discovery compared to IceCube

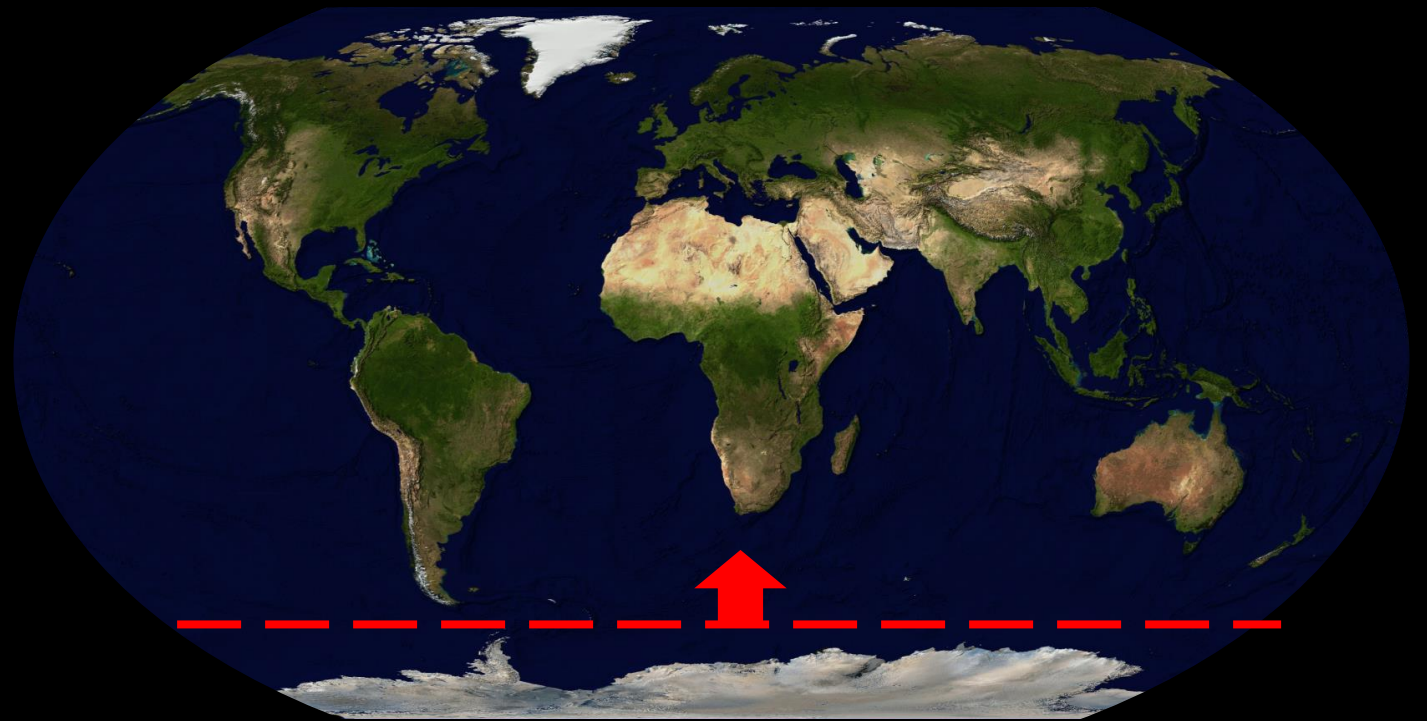
## Flavour physics over cosmological L, E



Plot from "IceCube-Gen2", Marek Kowalski ICRC25

Strong constraints on the flavour ratio expected in 10 years

Ice → Water-based  
telescopes



# Ice and Water

Optical photon scattering and absorption

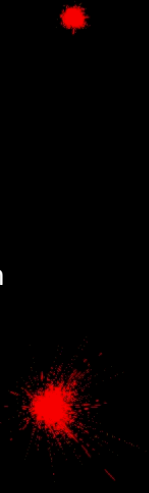
$$\text{Ice: } \lambda_{abs} > \lambda_{scat}$$

$$\text{Water: } \lambda_{abs} < \lambda_{scat}$$

With efficient and precise photon collection in water:

→ Expect strong resolution of direction and topology of interactions!

TRIDENT  
Simulation



$\nu_{\mu}$  track in ice

$\nu_{\mu}$  track in water

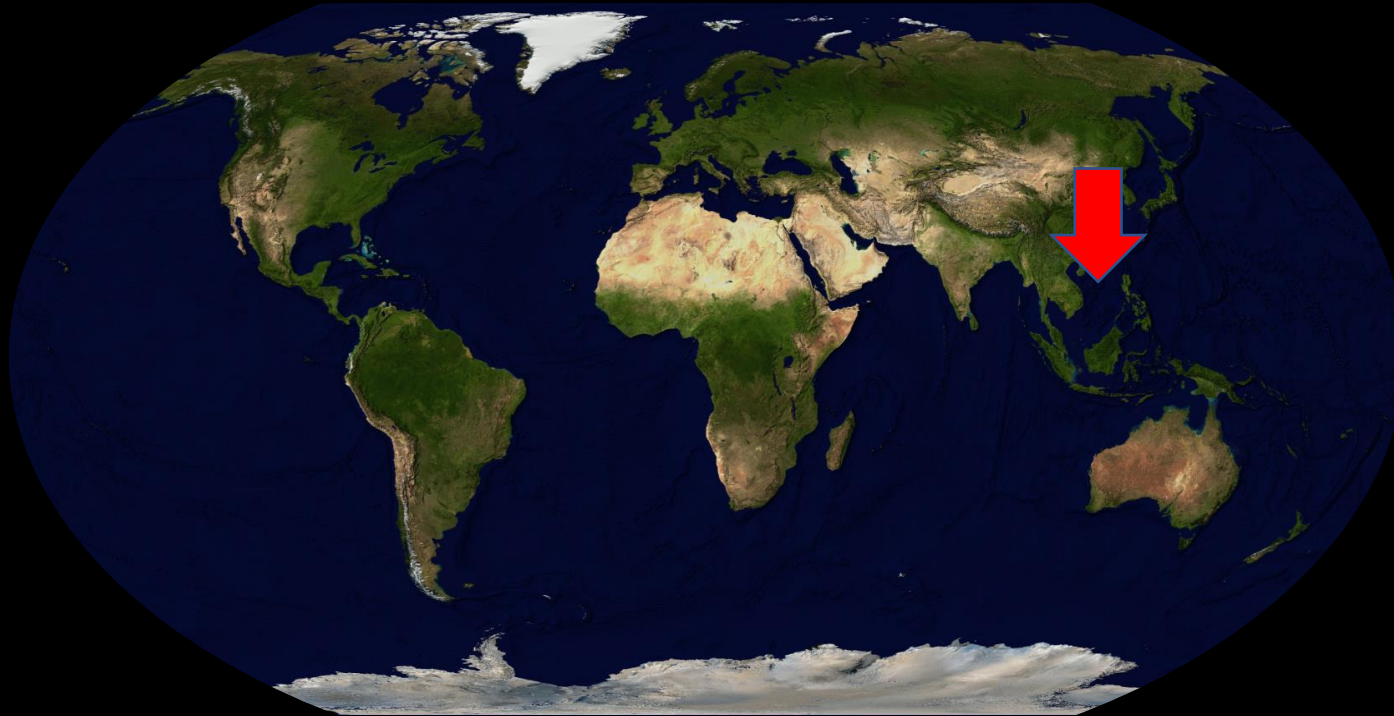
$\nu_e$  cascade in ice

$\nu_e$  cascade in water

(x4 videos of simulated events)

# TRIDENT

3.5km deep  
~8 km<sup>3</sup>  
~1000 strings



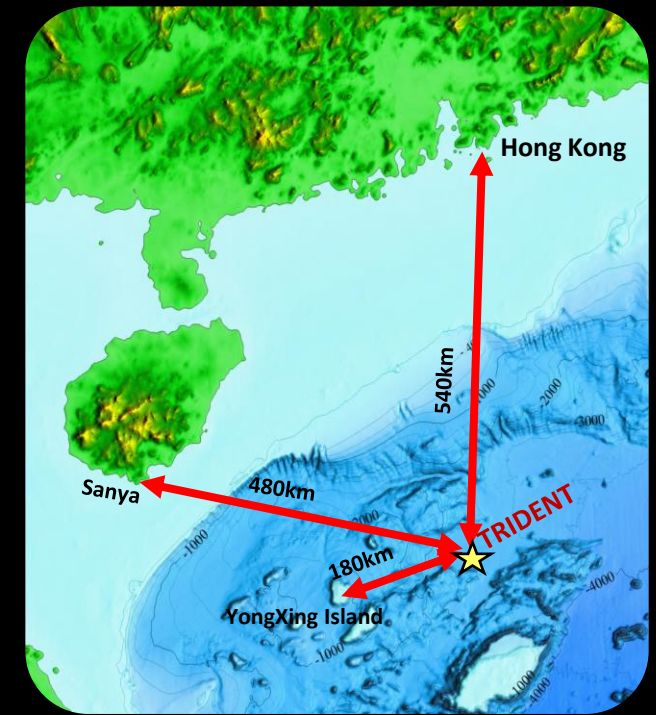
# TRIDENT

## What is it?

- $\sim 8\text{km}^3$ ,  $\sim 1000$  string telescope in the South China Sea

Primary experimental goals:  
**1) Rapidly discover neutrino sources**  
**2) Sensitivity to all flavors**

*3.5km deep, flat  
plane site chosen  
Data/power cable  
to nearest island*

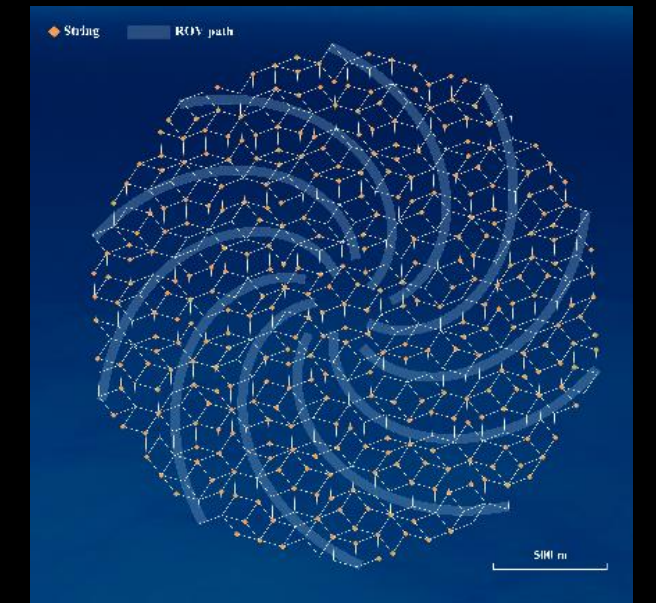


## Detector design:

- Penrose tiling – Irregular 70-110m spacing.
- Optimised for source discovery, with both tracks and cascades
- Curved wider pathways for inner string access, to reduce muon corridor events

Optimizing underwater neutrino telescopes for all-flavor point source sensitivity, PRD (2026)

“A multi-cubic-kilometre neutrino telescope in the western Pacific Ocean”, Nature Astronomy, (2023)



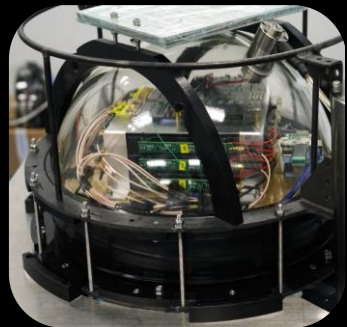
# TRIDENT

## Optical modules:

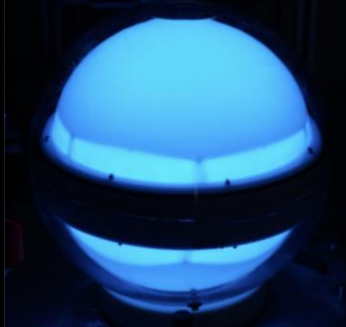
- Hybrid DOMS combining PMTs and SiPMs
- Record PMT waveforms: aim to boost precision in event topology and energy reconstruction

## Calibration:

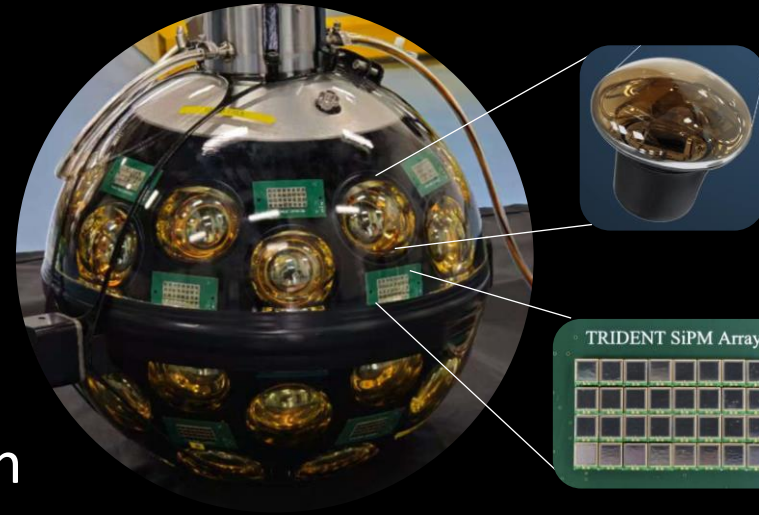
- LEDs, cameras, spectrometer, plastic scintillator slabs, acoustic sensors



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)

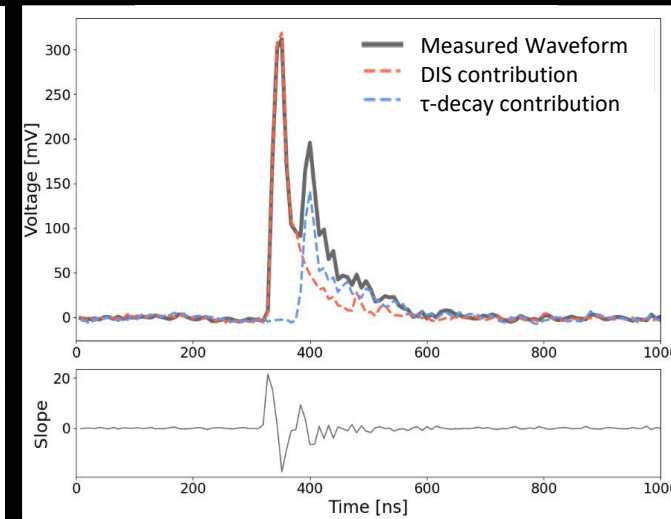
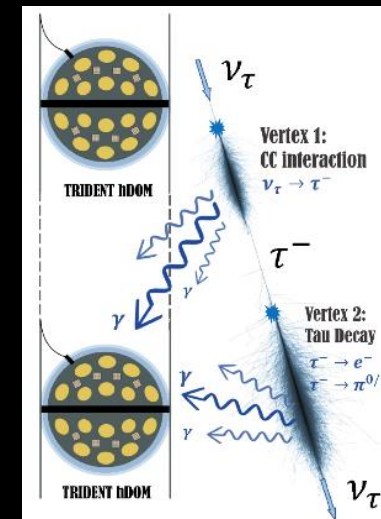


Preliminary Mechanical Design of the hDOM, PoS (ICRC2023)

PMTs:  
 $< 2\text{ ns TTS}$   
 $\sim 30\% \text{ QE}$

SiPMs:  
 $< 0.3 \text{ ns jitter}$

## Waveform-based search for $\nu_\tau$ double-pulse events



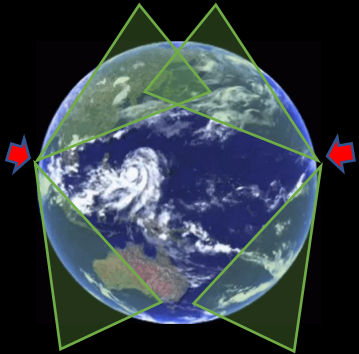
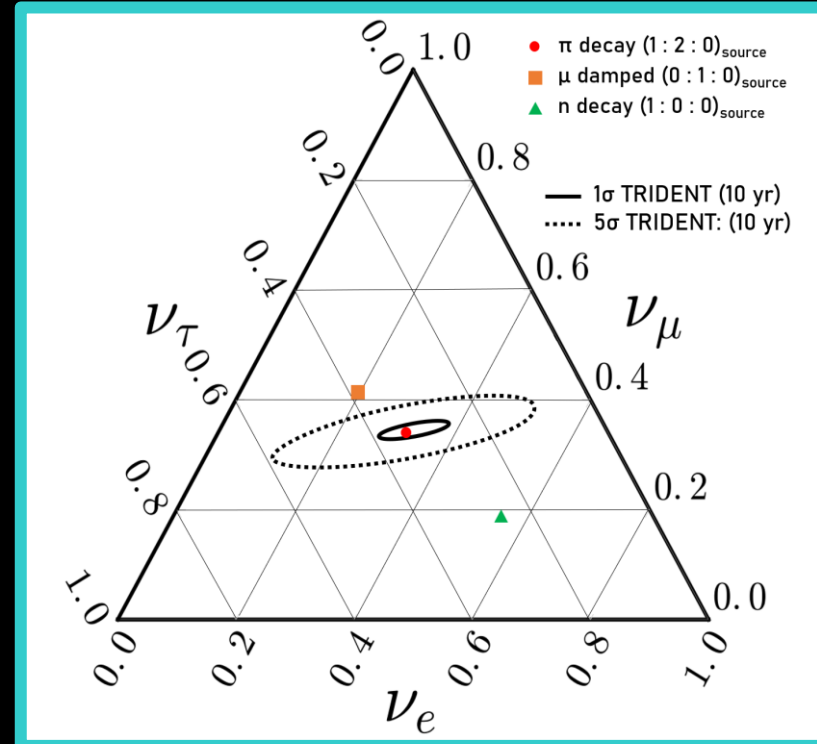
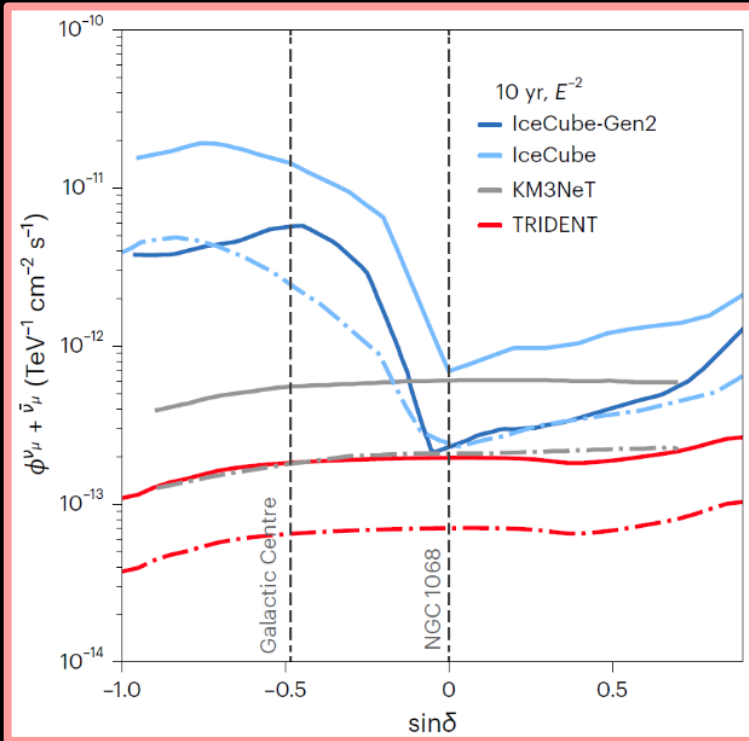
Searching for astrophysical  $\tau$  neutrinos with hDOM waveforms in TRIDENT, PoS (ICRC2023)

# TRIDENT

More Events  Better Pointing  Flavour separation

## Sensitivity/Discovery Potential vs declination

## Diffuse astrophysical neutrino flavour ratio sensitivity



A multi-cubic-kilometre neutrino telescope in the western Pacific Ocean, Nature Astronomy, (2023)

Rapid discovery expected:  
IceCube NGC1068 candidate  $5\sigma$  expected in  $<1$  yr

Strong flavor ratio sensitivity  
expected in 10 years

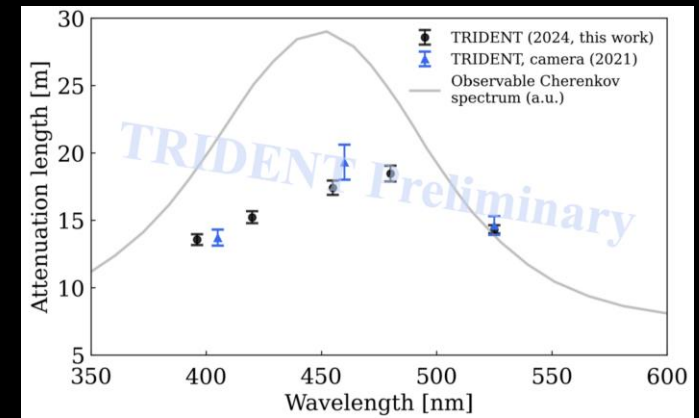
Detection Sensitivity of  
Astrophysical Tau  
Neutrino and Flavour  
Ratio in TRIDENT  
Publication in prep.

# TRIDENT

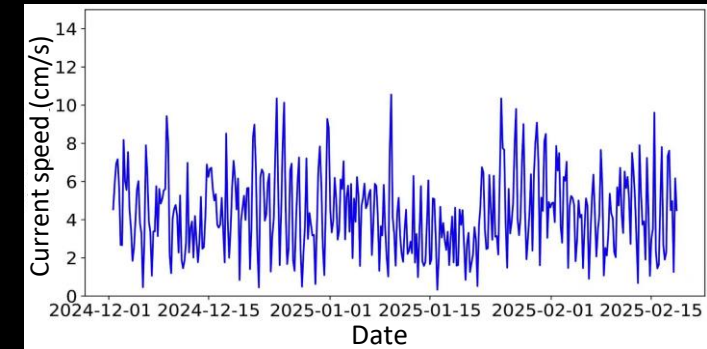
## Status

- 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 →

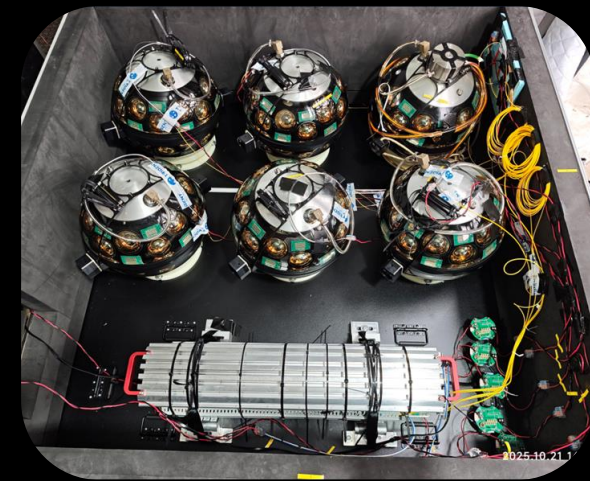
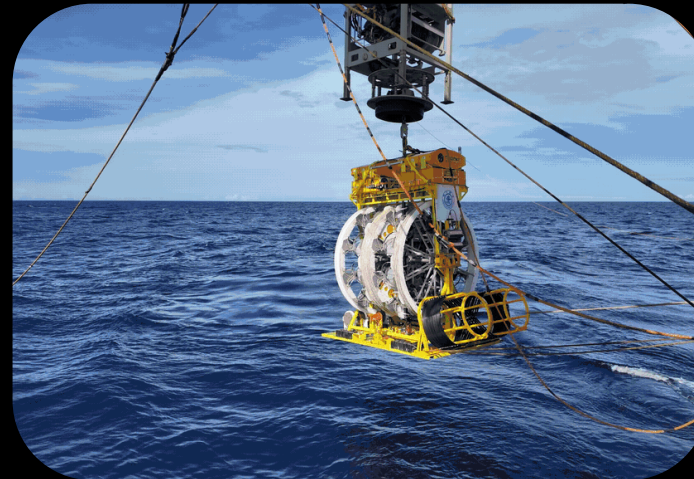
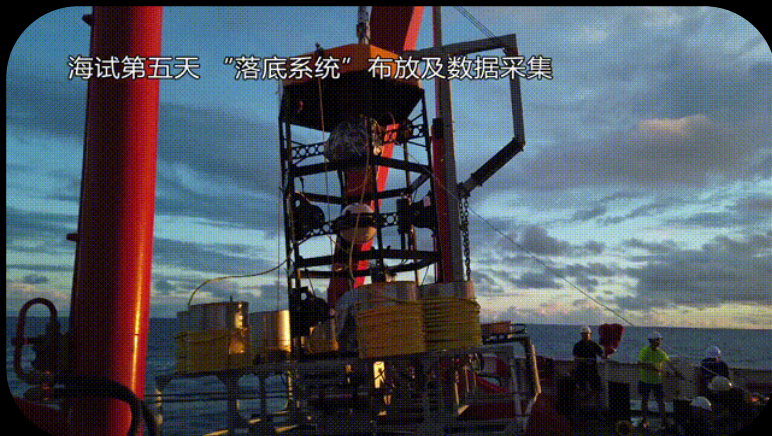


Sea current speeds over 3.5 months



First pathfinder mission

Testing string deployment system



Prototype  
string  
testing

(video)

26/6/2026

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

(video)

# TRIDENT

## Next:

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

**Deployment  
planned for 2027**

## Primary physics:

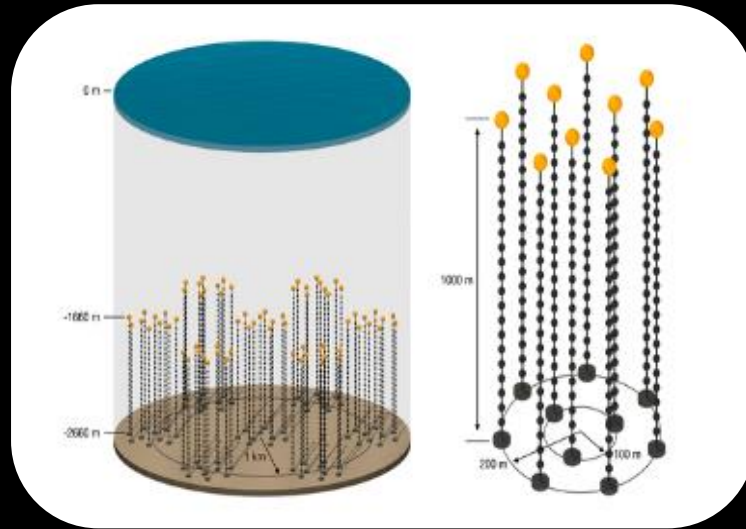
- TeV all-flavour atmos.  $\nu$  in the Hai-ling Basin
- Join Astro. neutrino source search campaign (CCSN monitoring , southern sky sources)

## Key technology demonstration:

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

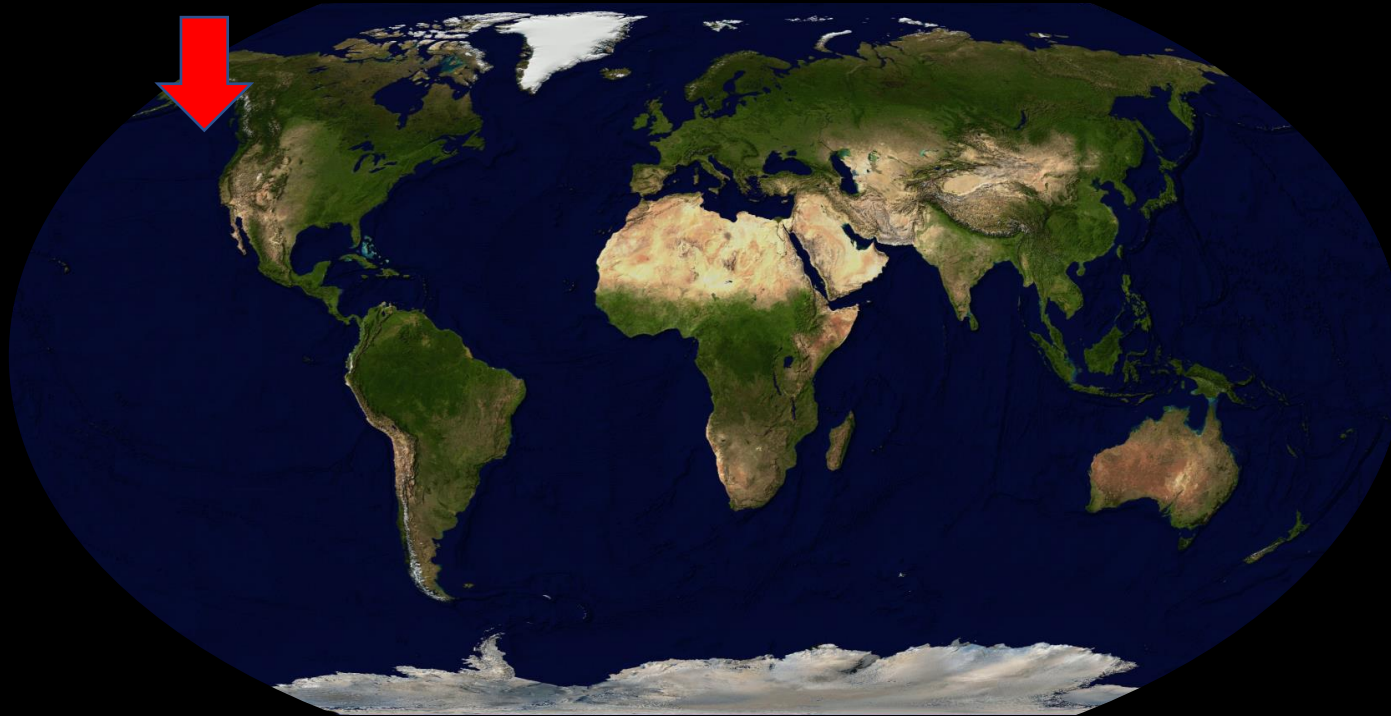


*Dedicated assembly lab in Sanya, starting mass production of detection modules*



## P-ONE

2.6km deep  
 $\sim 1 \text{ km}^3$   
70 strings



# P-ONE

## Detector: The Pacific Ocean Neutrino Experiment

- $\sim 1\text{km}^3$  instrumented volume, 70 strings
- 2.6km deep site at existing undersea infrastructure Ocean Networks Canada

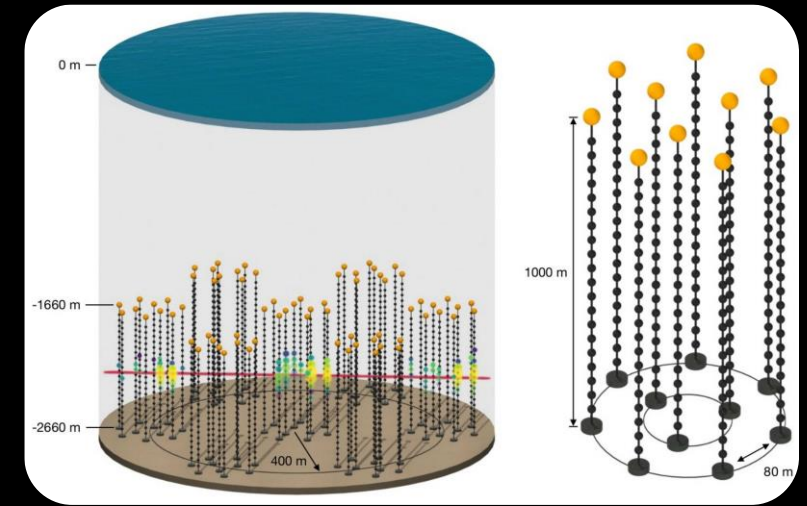
## Optical Modules:

- Multi-3" PMT optical module + dedicated calibration modules

## Performance:

- Expect precise reconstruction
- $<0.1^\circ$  @ 100TeV,  $<2^\circ$  for cascades

The Pacific Ocean Neutrino Experiment, Nature Astronomy (2020)



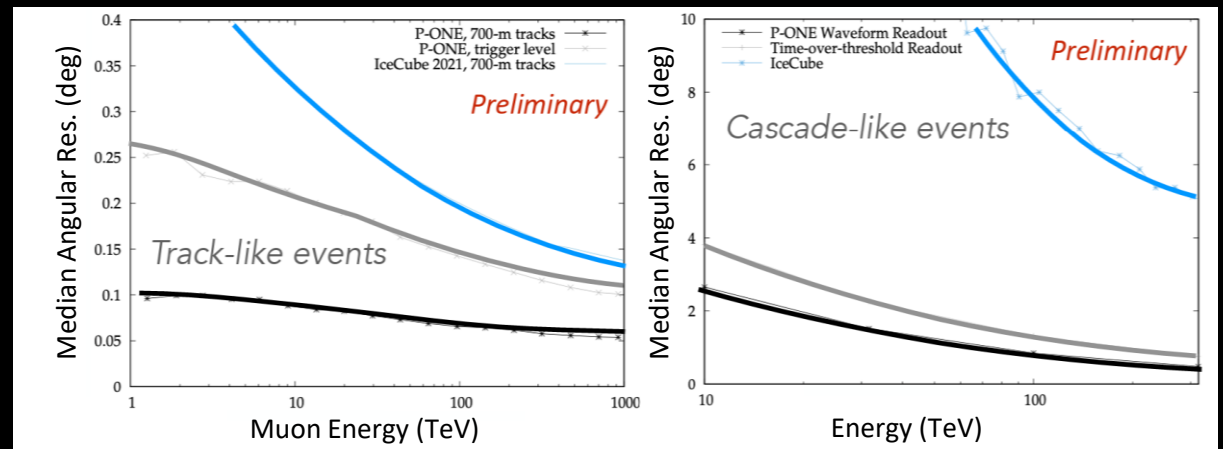
Optical Module



Calibration Module



First instrumented line of the Pacific Ocean Neutrino Experiment: status, development and outlook, PoS (ICRC2025)



# P-ONE

4-year monitoring of photodetection efficiency

## Status:

### Measurements at site:

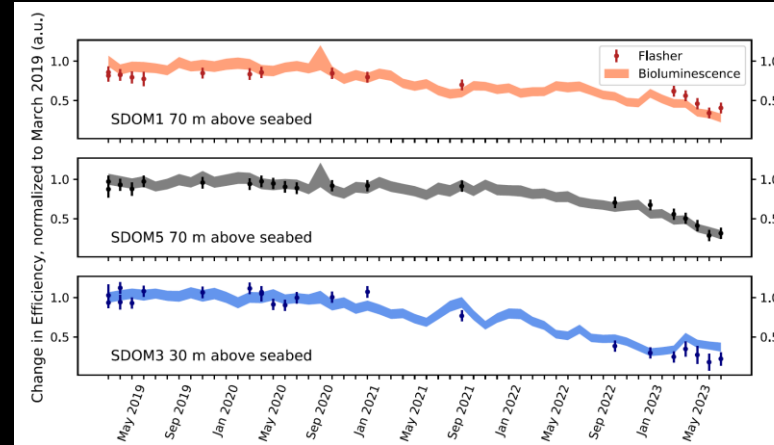
- 2 pathfinders deployed in 2018 and 2020 Straw a/b
- ~27m max. effective attenuation length measured
- Highlighted challenges faced by underwater detectors
  - Bioluminescence
  - Sedimentation/biofouling

Long term study of sedimentation and biofouling at cascadia basin, the site of the pacific ocean neutrino experiment, EPJC(2026)

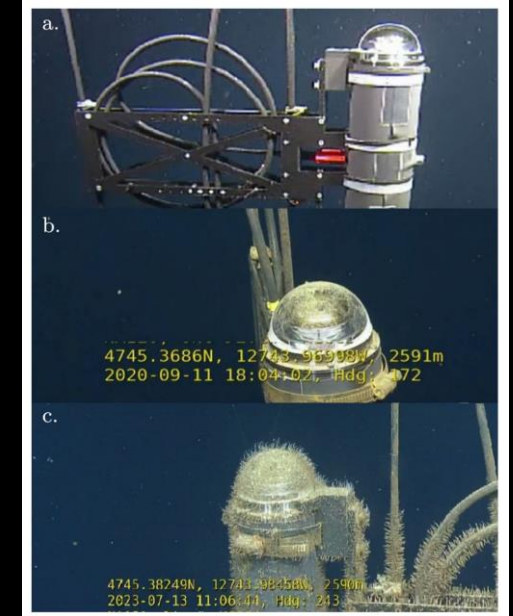
## Entering deployment phase:

- P-ONE-1 string deployment planned for August this year
- Now in demonstrator phase, deployment of first 4(+) strings underway

Recent successful submersion tests

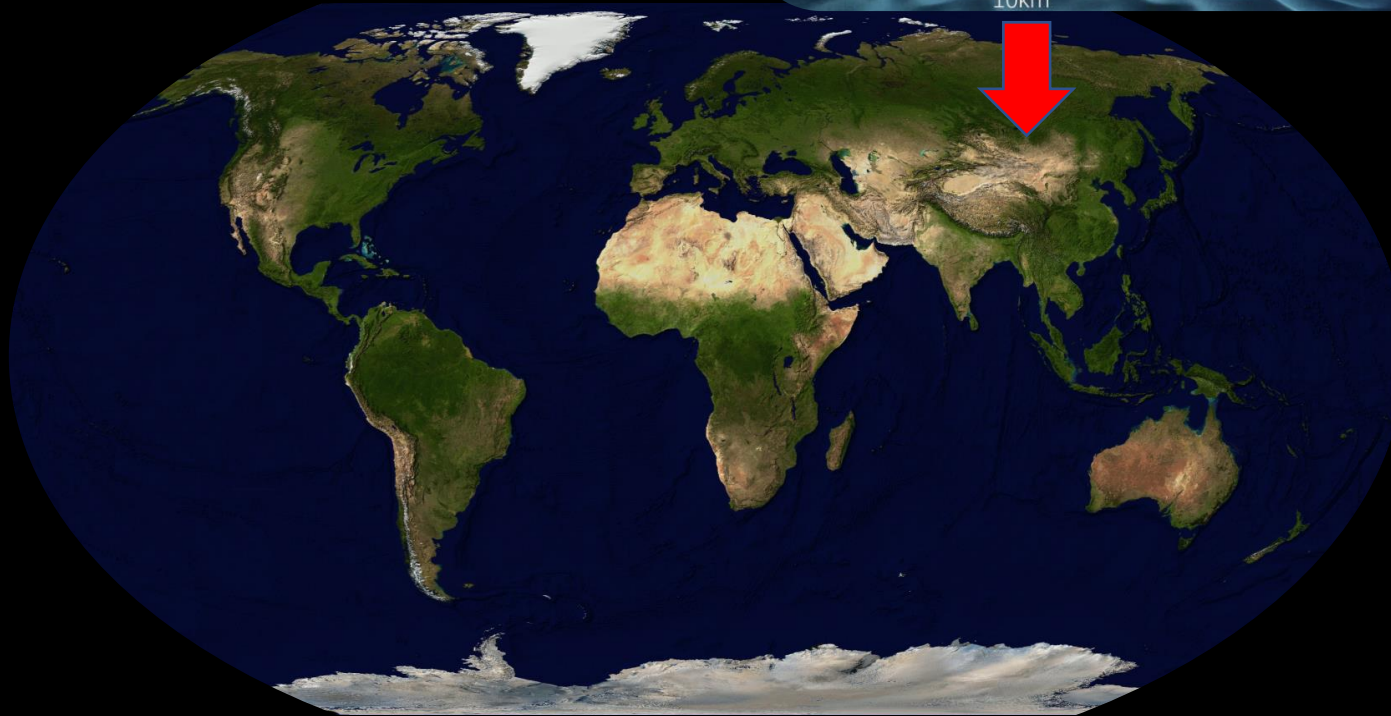
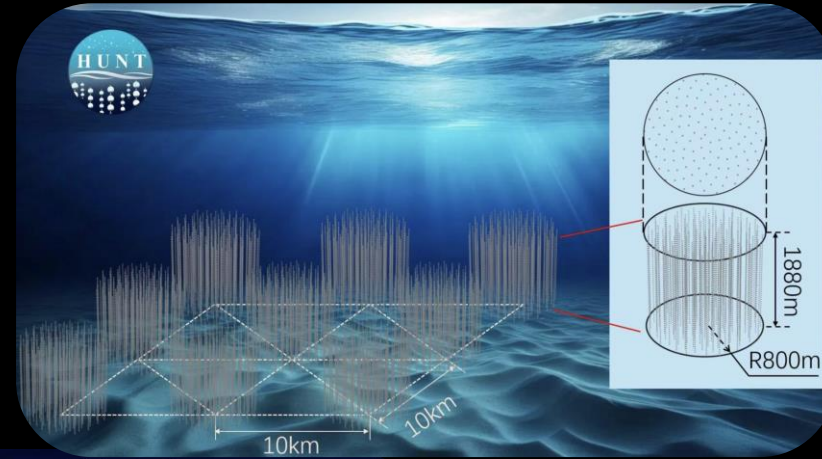


Visual biofouling of up-facing PMT over 4 years



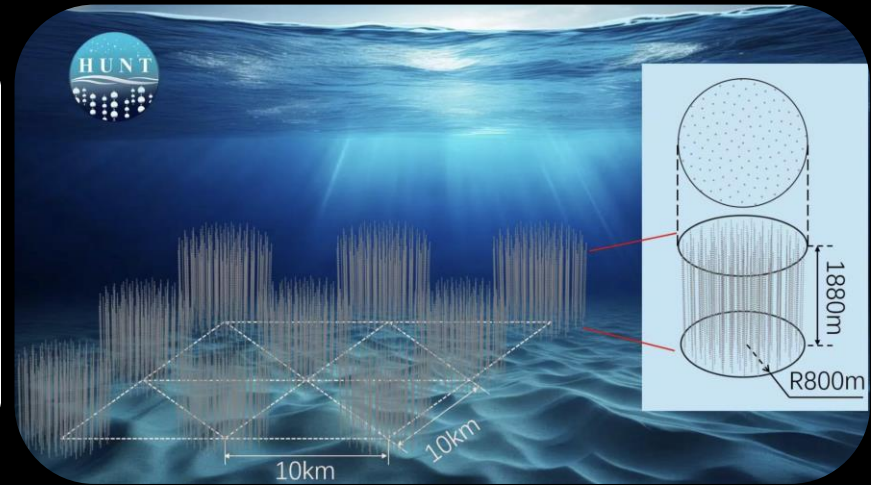
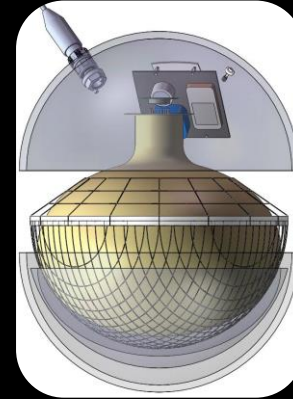
## Baikal-HUNT

1.4/3 km deep  
~30 km<sup>3</sup>  
~1200 strings



# Baikal-HUNT

HUNT: An ultra-large-scale neutrino astronomy telescope, NIM-A (2026)

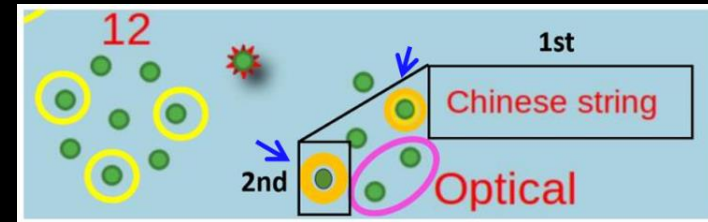


Detector: High Energy Underwater Neutrino Telescope

- $\sim 30\text{km}^3$ ,  $\sim 1200/2200$  strings in 9 clusters
- **Higher** energy focus: 100 TeV – 100 PeV

Optical Modules:

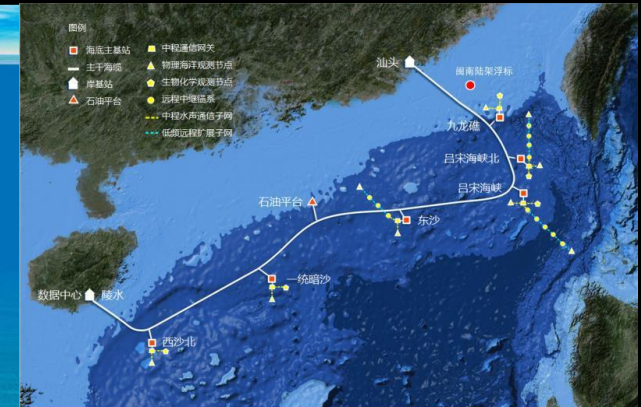
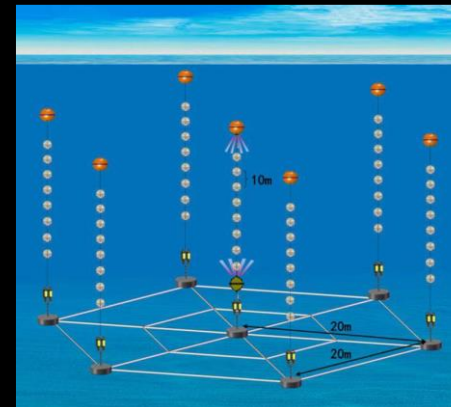
- Single downward 20" PMT



Status:

- Two deployments with Baikal-GVD in 2024/25
- 2025 string deployment in South China Sea
- 7 densely arrange strings for oscillation measurements, planned this year

"The Recent Status of HUNT Prototypes: 2025", T.Q. Huang, ICRC 2025



# Baikal-GVD

## Detector:

- $\sim 1\text{km}^3$  Cherenkov detector in Lake Baikal
  - Absorption length: 21 - 23 m, Scattering length: 30 - 50 m
- Independent clusters of strings, 60m in radius

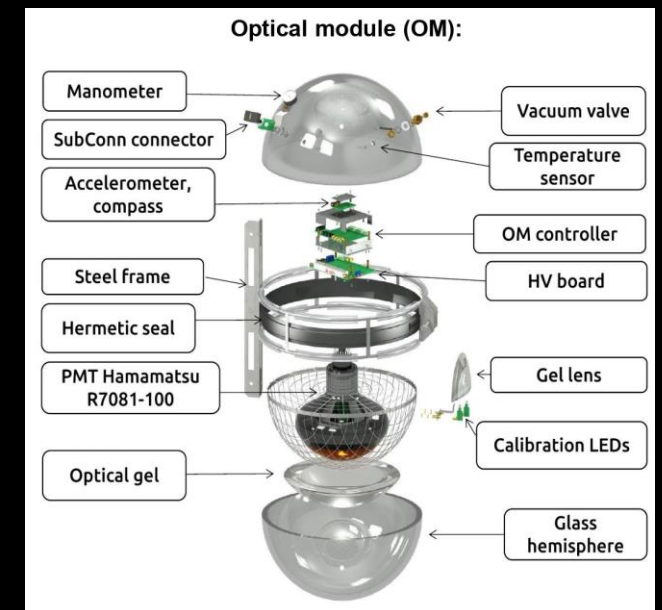
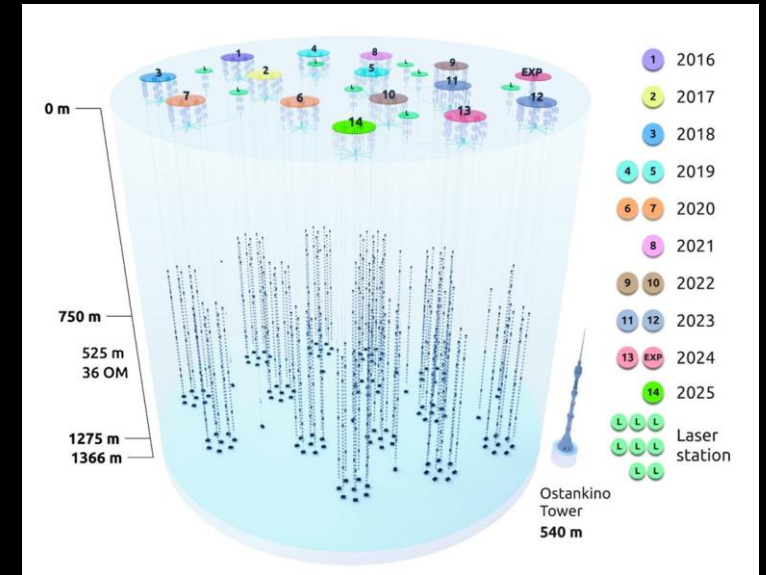
## Optical Modules:

- Single downward 10" PMTs

## Status:

- Currently expanding detector  $\sim 0.7\text{km}^3$  in volume
- $\sim 4200/6000$  optical modules, expected to reach  $1\text{km}^3$  in 2028
- High energy cascade event analysis confirms the diffuse flux observation at the level above  $5\sigma$

“Baikal-GVD neutrino telescope status and results”, Rastislav Dvornický, Moriond 2026



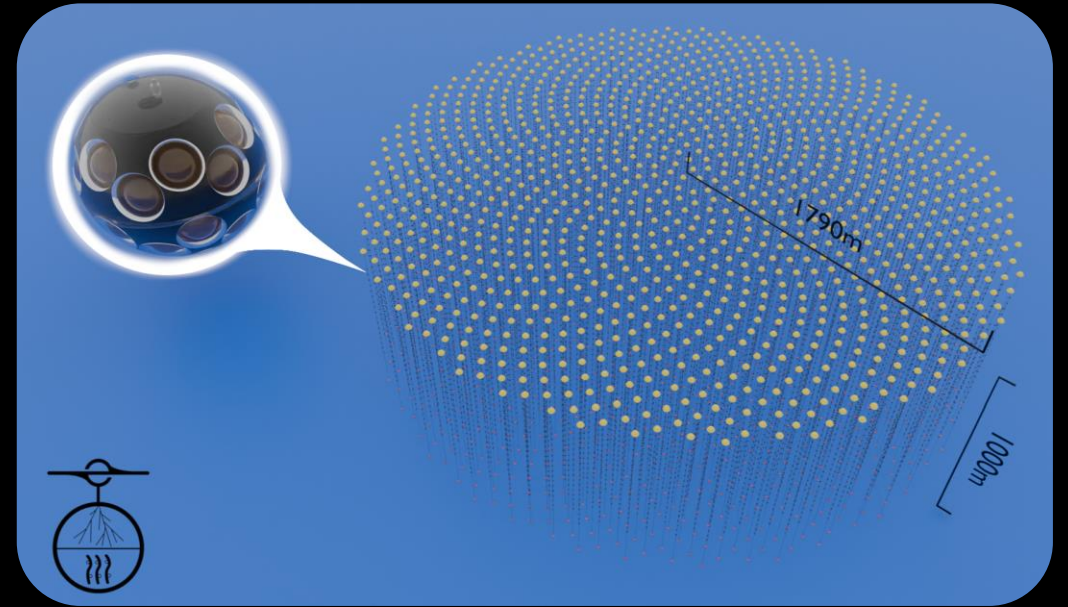
# NEON

Detector: Neutrino Observatory in the Nanhai

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

Status:

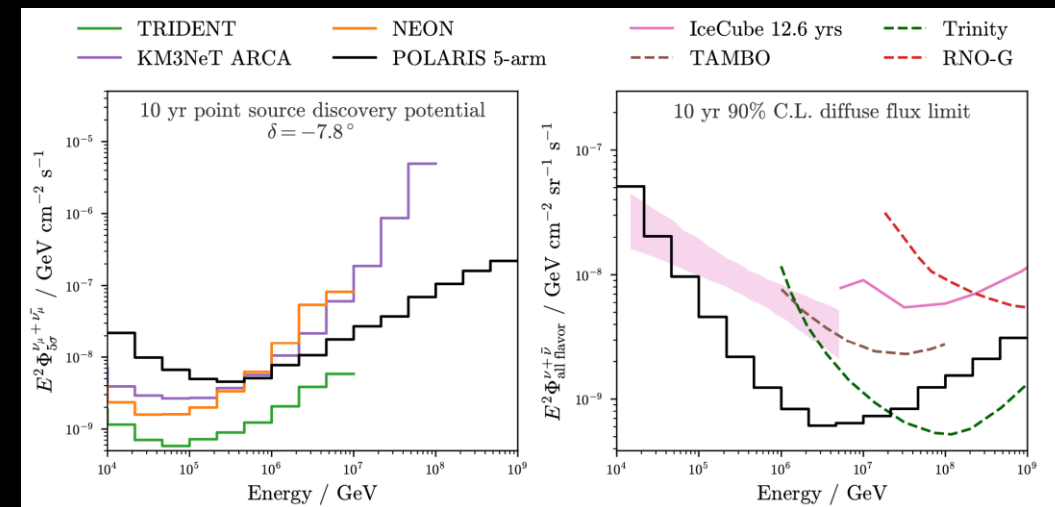
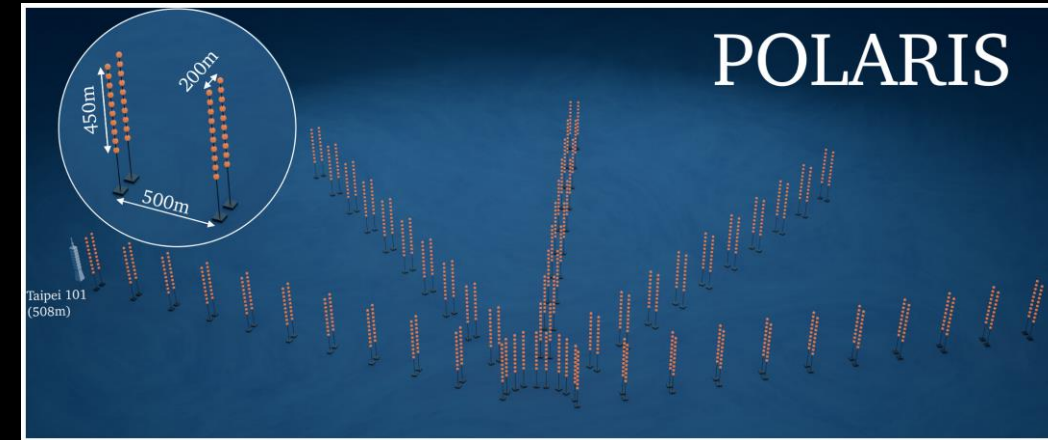
- Lake trials of optical modules, long-term hardware stability verified



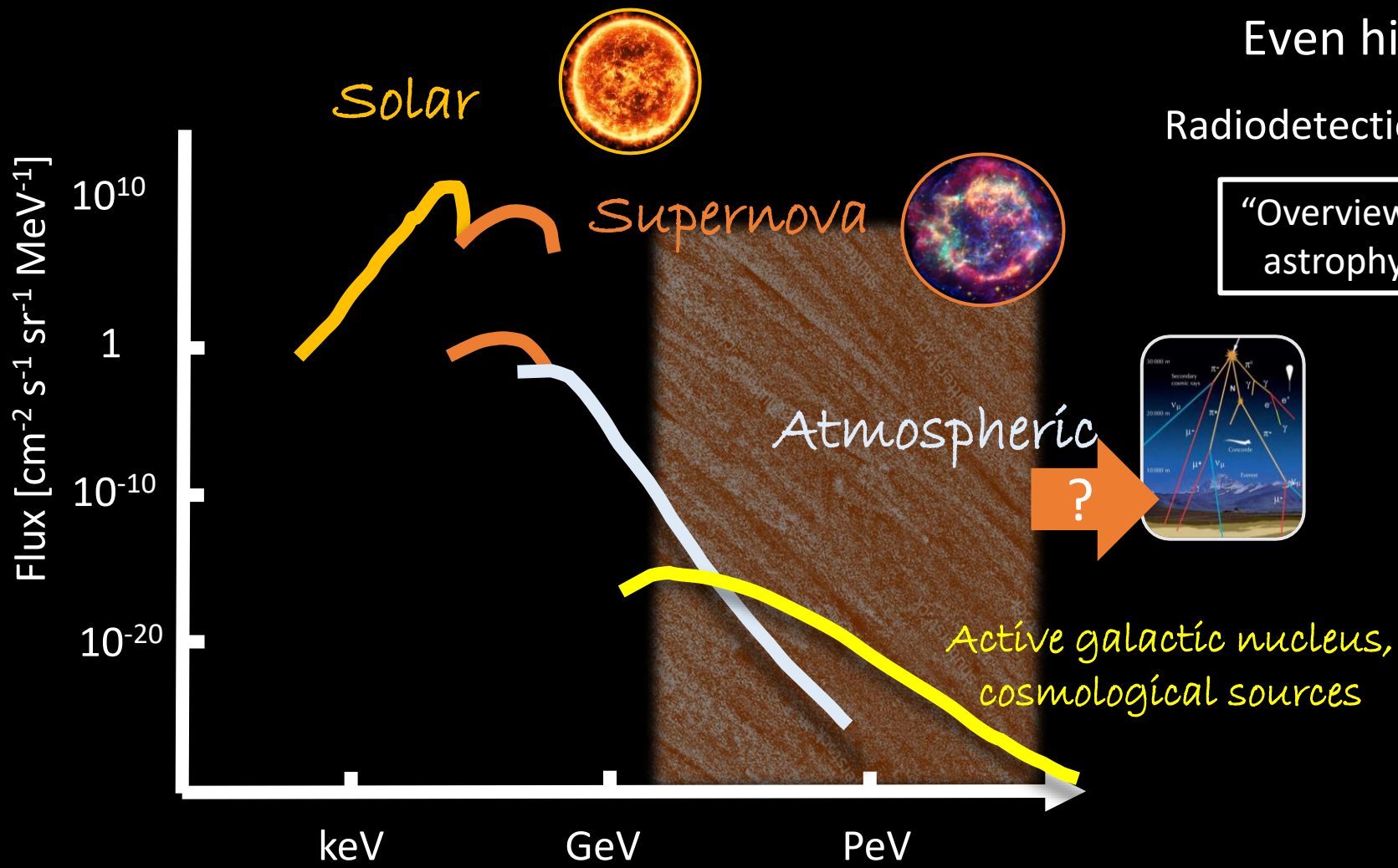
# Other Interesting Ideas - POLARIS

Detector: Pacific Ocean Large Area Radial Instrumented Sparse array

- Focuses on horizontal track events in the multi-TeV to PeV regime
- 5 “arms” made up of gates: pairs of strings
- Detector runs with fewer DOMS, 1100 in total
- POLARIS expects to surpass KM3NeT-ARCA in point source sensitivity at PeV energies



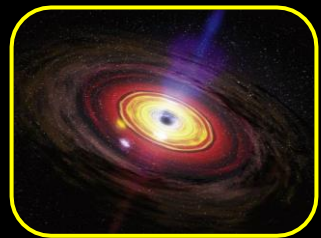
# Beyond the TeV to EeV sky?



Even higher energies?

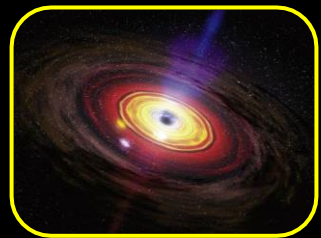
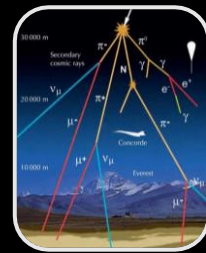
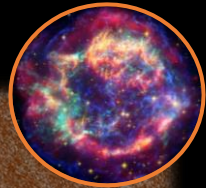
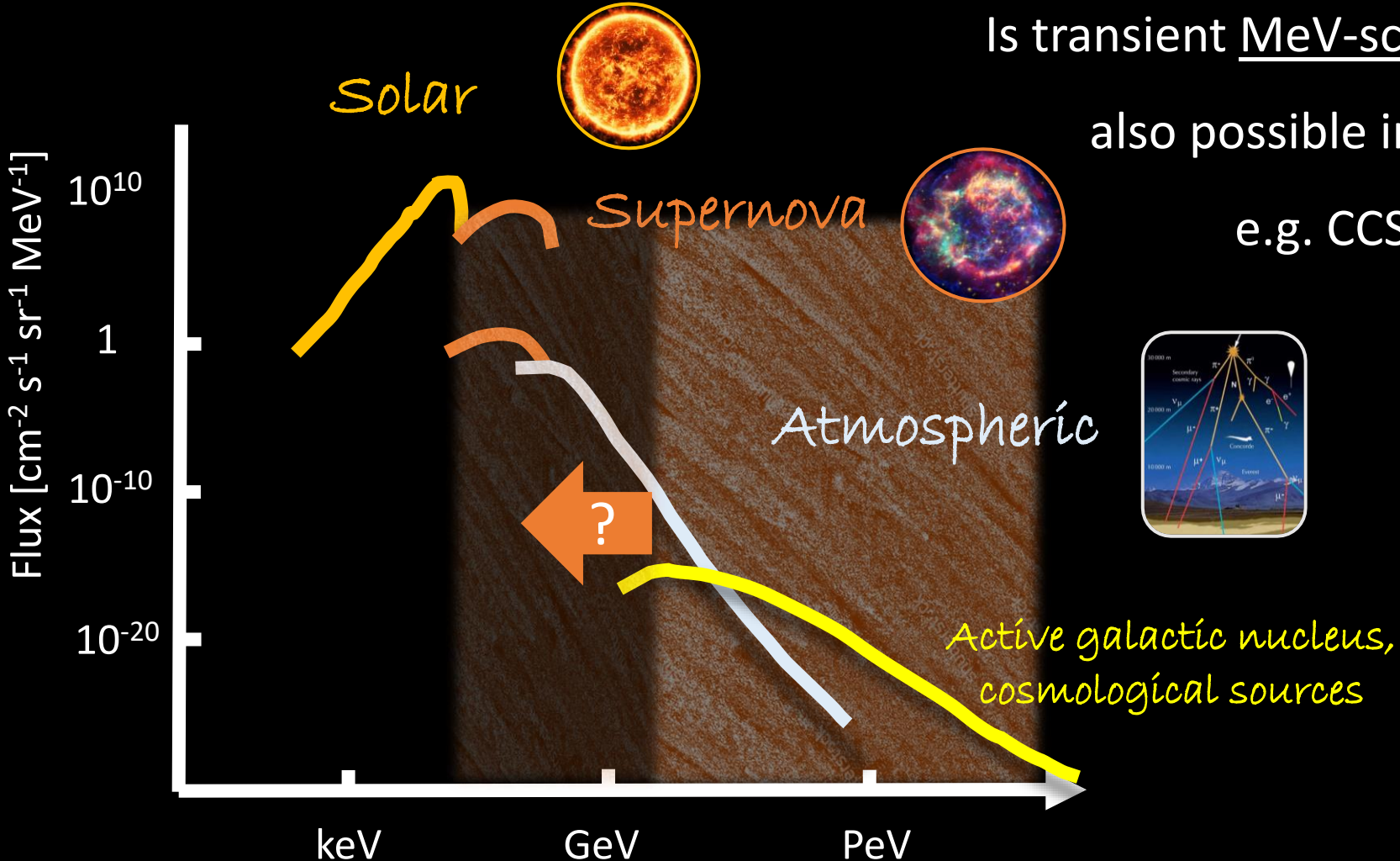
Radiodetection covered by Abigail!

“Overview Radio-wave neutrino astrophysics”, Abigail Viereg



# Beyond the TeV to EeV sky?

Is transient MeV-scale neutrino astronomy also possible in giant telescopes?  
e.g. CCSN detection



# Low-Energy supernova detection

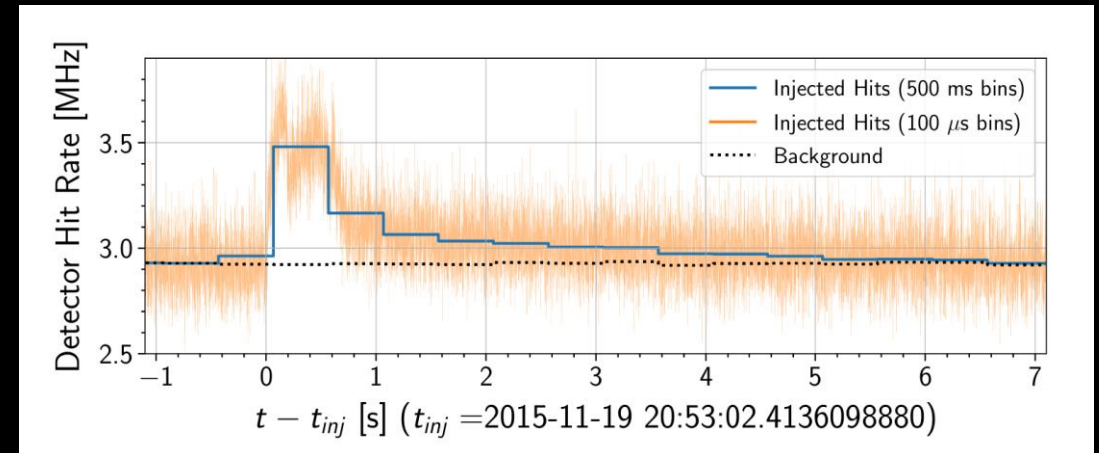
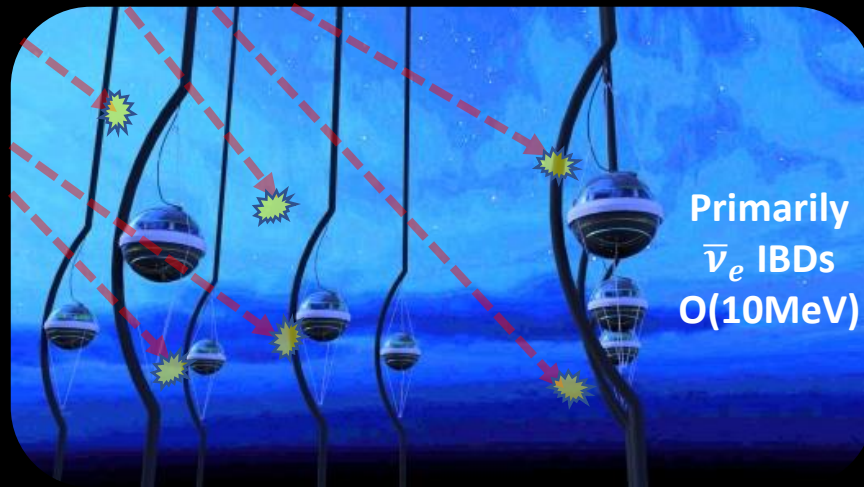
Ultrasensitive Antarctic ice as a supernova detector F. Halzen and J. E. Jacobsen, PRD 53(12) (1996)

Example: IceCube, individual MeV events are not reconstructed.

CCSN  $\rightarrow$  correlated increase in hit rates across thousands of optical modules.

Gigaton-scale statistics: strong sensitivity of fast time evolution of nearby CCSNe

R. Abbasi et al., "IceCube Supernova Fire Drills and Follow-up", ICRC 2023, PoS(ICRC2023)1111.



IceCube Gen2:

Noise rejection with multi-PMT DOM design + more DOMs + improved photon collection

$\rightarrow$  Strong CCSN distance improvement expected

*Increase in noise globally across all DOMs*

Prospects for detecting generic fast-time features in the neutrino lightcurve of nearby supernovae in neutrino telescopes, PRD (2025)

# Low-Energy supernova detection

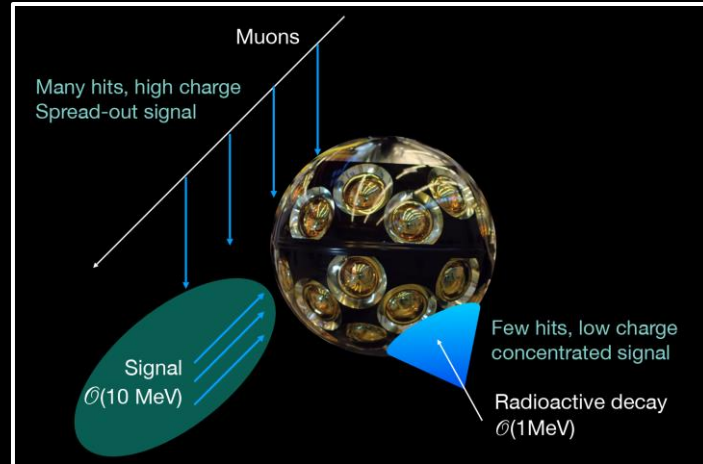
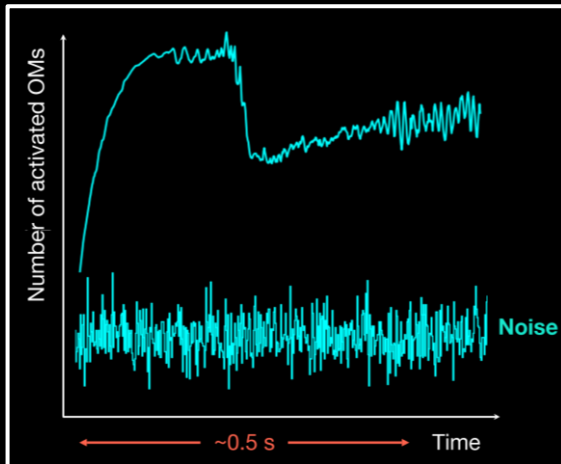


Similarly underwater detectors, e.g. KM3NeT also have strong capabilities to detect global event bursts

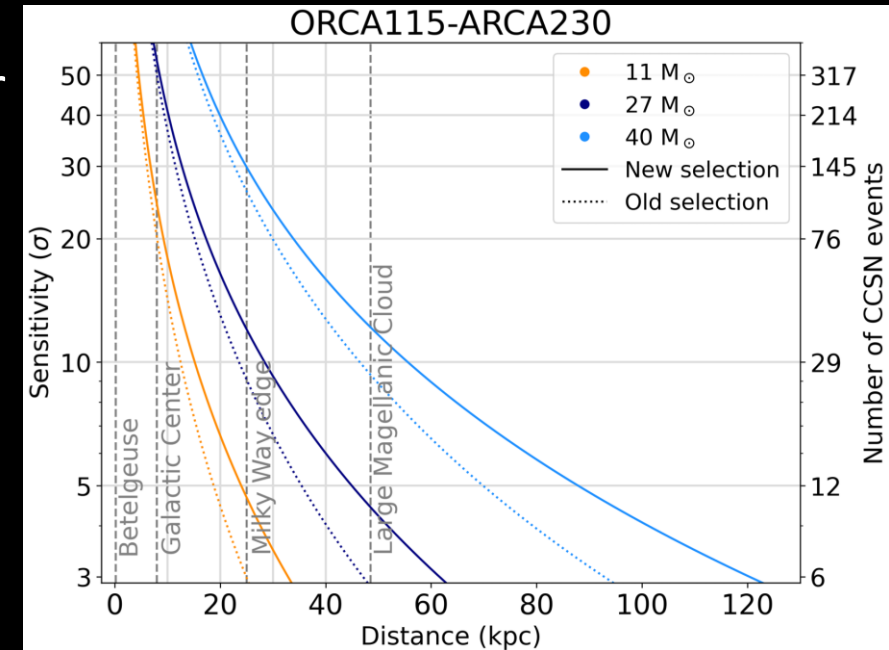
However, for seawater detectors, extra background

→  $^{40}\text{K}$  radioactive decays

Multi-PMT DOM: individual  $\nu$  detectors xN. Design allows for extra handles using hit multiplicity, hit spatial/time patterns



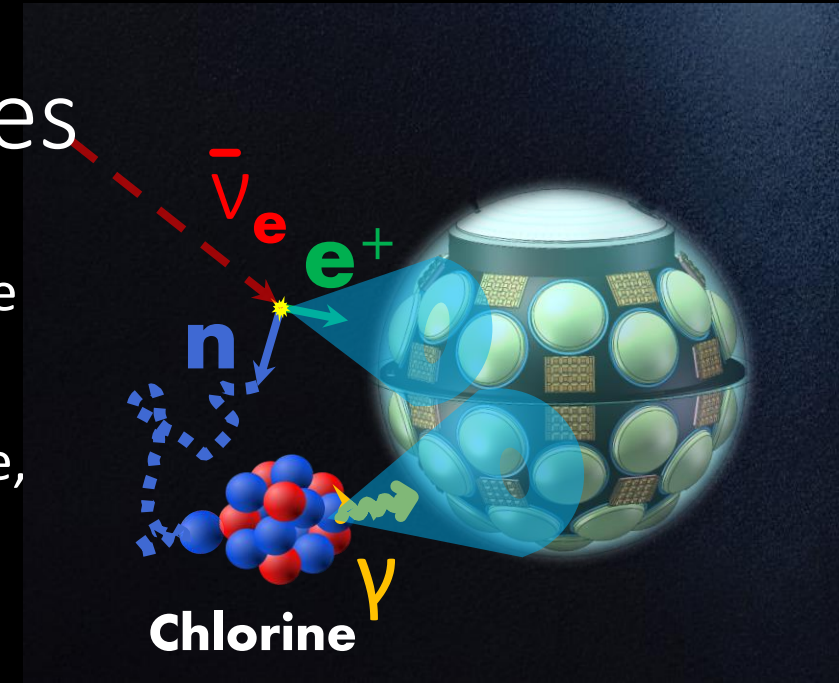
Detection significance vs CCSN distance



Optimizing the potential of KM3NeT in detecting core-collapse supernovae, JCAP (2026)

# Further improving seawater telescopes

- While saltwater  $^{40}\text{K}$  generally a negative, presence of Chlorine (2% in mass) could help
- Search for IBD coincidence  $e^+$  ( $\sim 10\text{MeV}$ ) and neutron capture, emission of  $\sim 8\text{MeV}$   $\gamma$  from  $^{35}\text{Cl}$

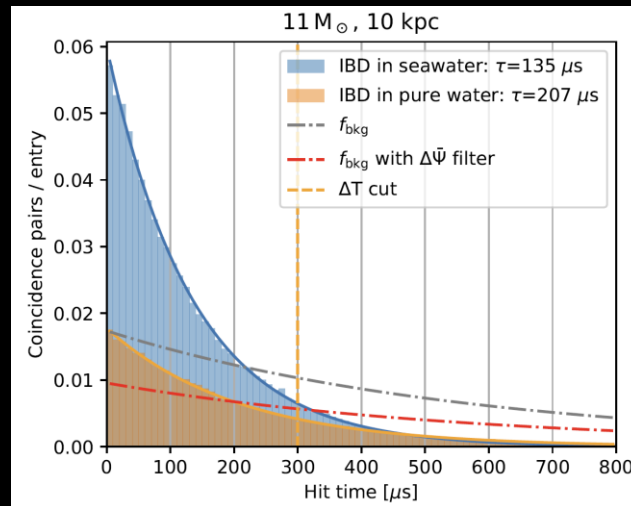


“New” IBD pair selection in telescopes

→ Cowan-Reines → SNO NaCl in  $\text{D}_2\text{O}$  → Neutron tagging in Super-K

Time difference  
between  $e^+$   
and  $n$ -capture

Primarily  $n$ -H  
and  $n$ -Cl



Detecting the Next Galactic  
Core-Collapse Supernova with  
TRIDENT, PoS (ICRC2025) 1004

Large  $^{35}\text{Cl}$  capture cross section

Nuclei	n (number fraction)	$\overline{E}_\gamma$ [MeV]	$\sigma$ [bar]
$^1\text{H}$	66.1%	2.22	0.333
$^{16}\text{O}$	33.2%	4.14	0.0002
$^{23}\text{Na}$	0.28%	6.96	0.52
$^{35}\text{Cl}$	0.25%	8.58	43.6
$^{37}\text{Cl}$	0.08%	6.11	0.43
$^{24}\text{Mg}$	0.03%	7.33	0.054

# Further improving seawater telescopes

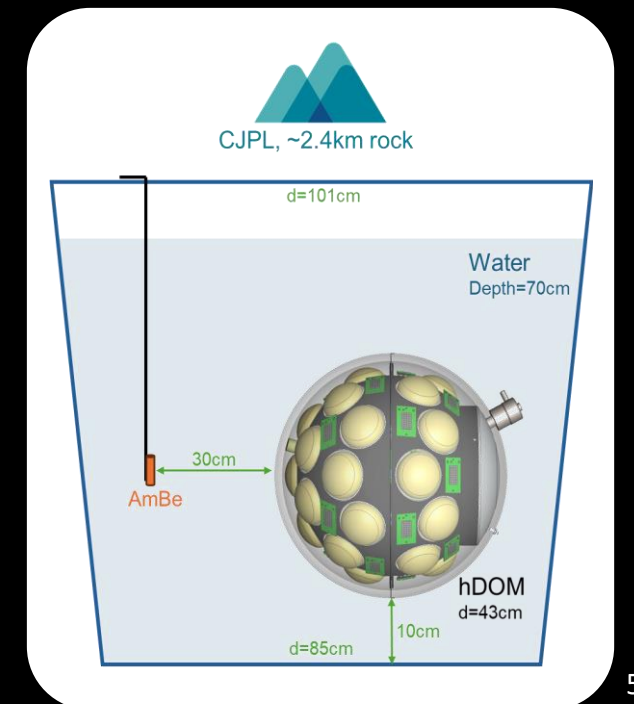
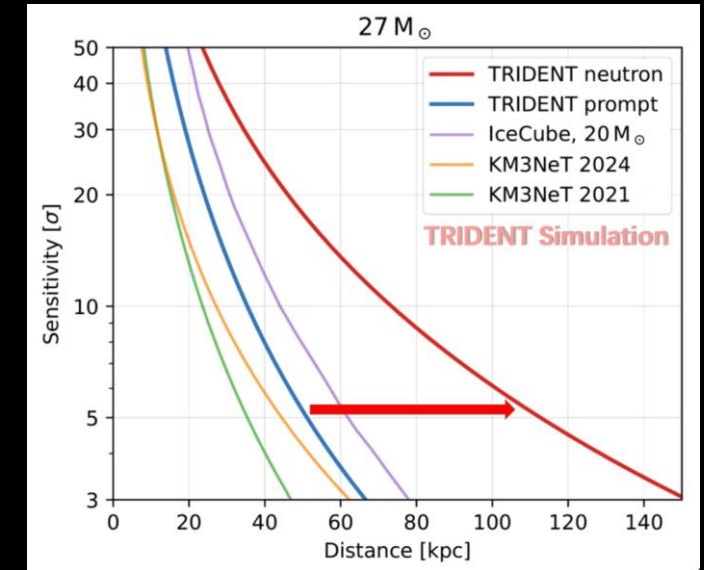
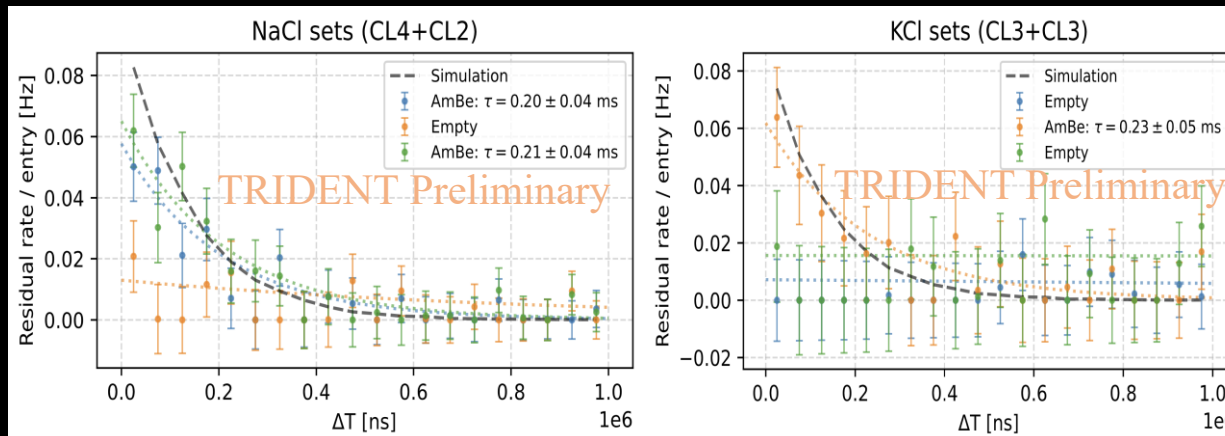
- TRIDENT as a case study – singles vs coincidence event bursts:  
Simulations indicate doubling in supernova detection distance

## Experimental demonstration:

- Placed hDOM 2.4km deep in Jinping lab (thanks to PandaX!)
- Placed neutron source in pure water, NaCl and KCl solutions, excess of pairs for solutions with Cl present
- Other undersea detectors with multi-PMTs should test for CCSN!

## Prompt-delayed time difference:

“Enhancing electron antineutrino detection with Chlorine in deep-sea detectors”  
→ Publication in prep.



# Climbing out of the Water

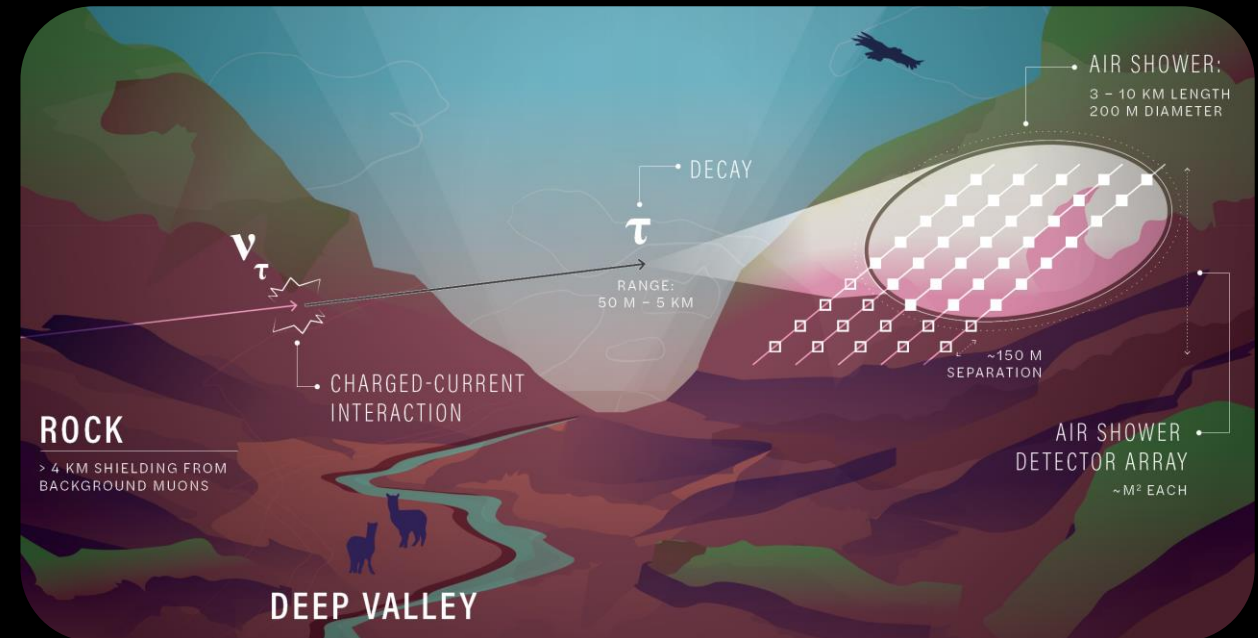
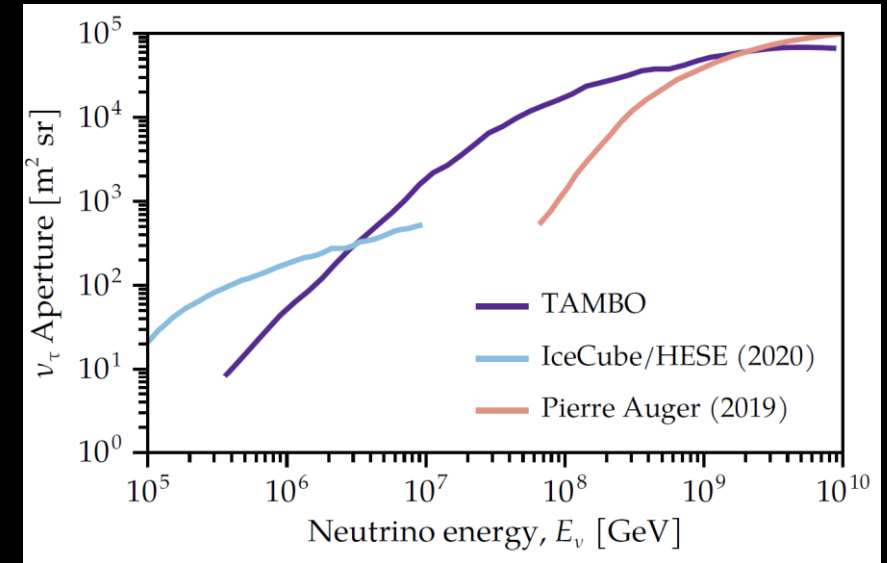
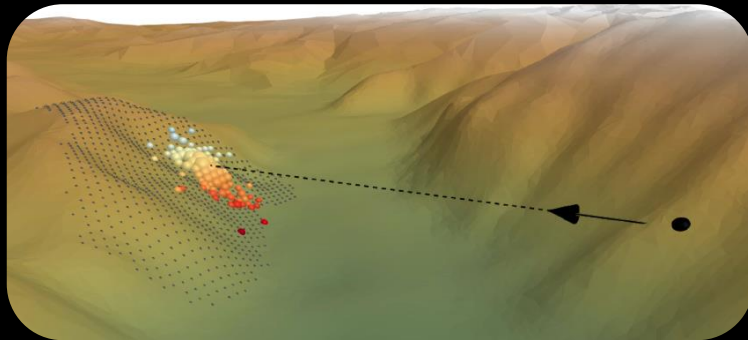
# TAMBO

Tau-focused neutrino detector for  $\sim 1$  PeV to 100 PeV

- Searching for skimming earth neutrinos
- Array of  $\sim 5000$  particle detectors on the side of a valley
- Expect  $O(1)$   $\nu_\tau$  neutrinos per year

## Status:

- TAMBO-100 “TAMBITO” pilot array is planned for 2025-2028
- TAMBO-5k expected from 2028

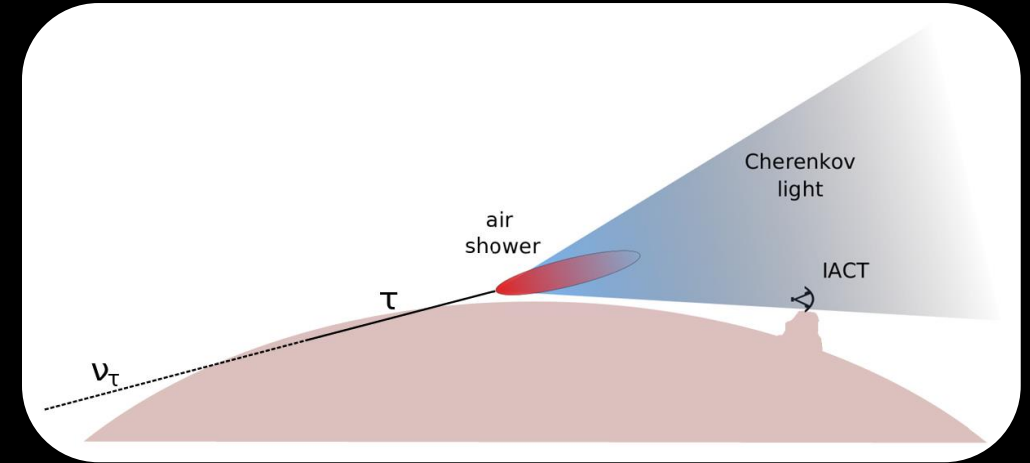


TAMBO: A Deep-Valley Neutrino Observatory, arXiv:2507.08070 (2025)

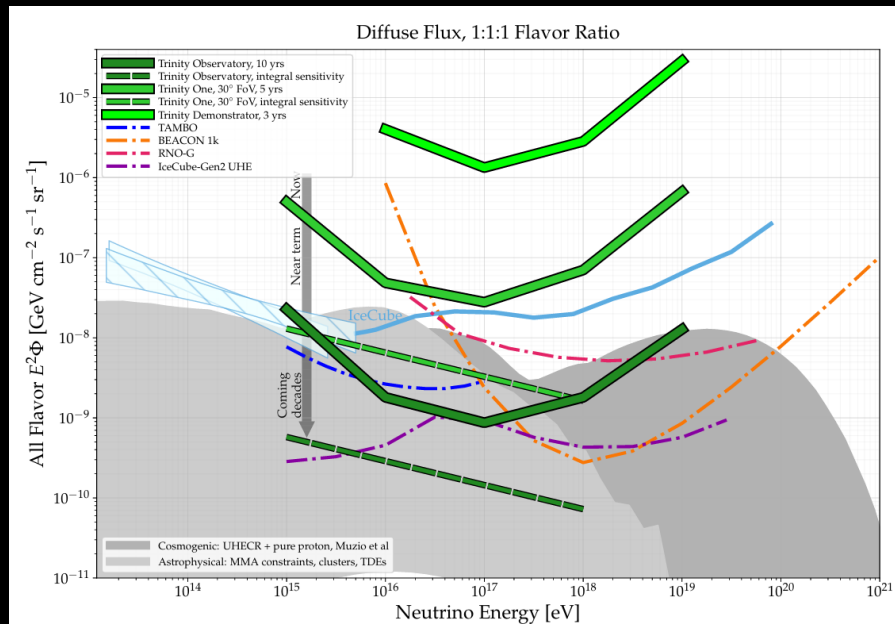
# Trinity

Tau neutrino detector in the  $\sim$ PeV to EeV

- Air-shower imaging of Earth-skimming tau neutrinos
- Using atmospheric Cherenkov telescope, mirrors reflect light into SiPMs
- Demonstrator successfully took data over 2024-25



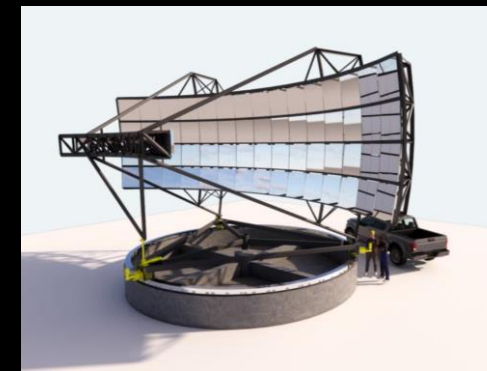
“Status of the Trinity PeV Neutrino Observatory”, ICRC 2025, Sofia Stepanoff, arXiv:2509.18236v1



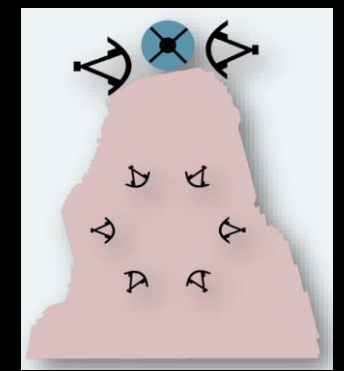
Trinity demonstrator



Trinity One



Trinity Observatory



# Conclusion

## **The future is bright** (in neutrinos)

- **Energy:** MeV to  $>EeV$  energies
- **Medium:** Liquid scintillator to argon, water, ice and air
- **Location:** Underground laboratories, oceans, lakes, polar ice, mountains and valleys

A global network of complementary detectors is emerging.

High-E telescopes in water show promise. KM3NeT, Baikal-GVD continue to expand,  
**First lights of a number of telescopes are 1-2 years away.** E.g. Hyper-K, TRIDENT, P-ONE

## **Small steps towards filling the oceans with neutrino detectors**

Expect neutrino astronomy to move from **discovery to precision** over the next decade — enabling detailed studies of source populations, flavour composition, and particle physics under the most extreme conditions in the Universe

*Apologies for any experiments/studies  
that weren't included!*

# Backup

# Detector Design – hDOMs

[“A Cost Effective Optimization of the hybrid-DOM Design for TRIDENT”](#)

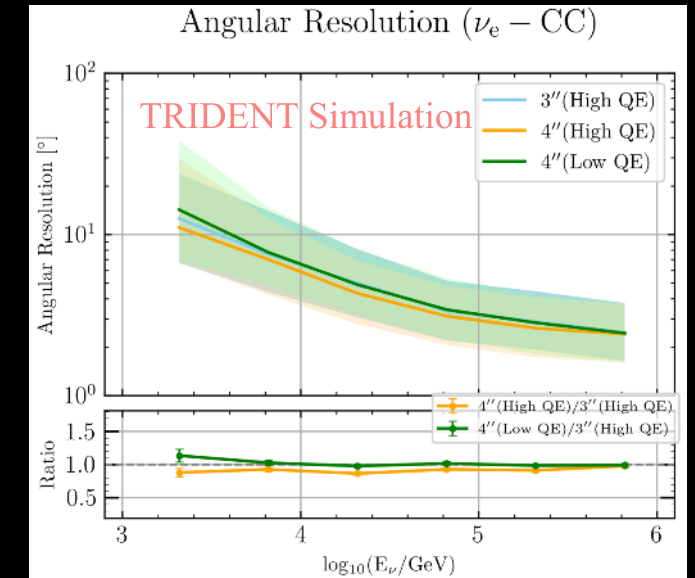
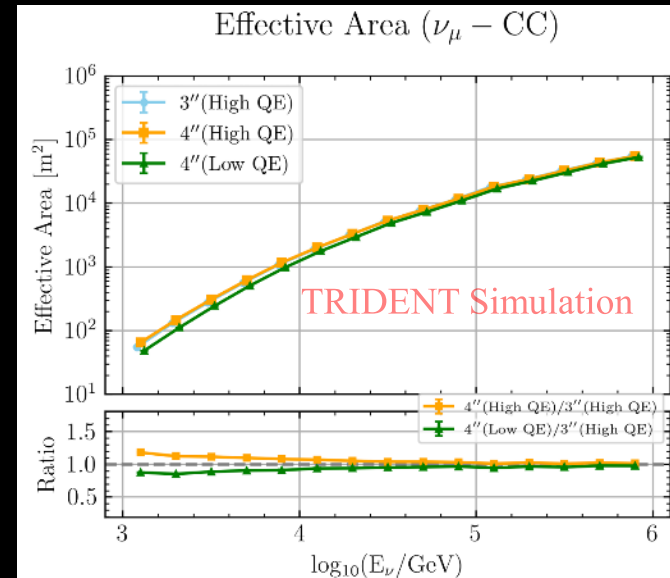
- 3-inch PMT hDOM design
- 31 3" PMTs
  - 24 SiPMs (4x8 array)



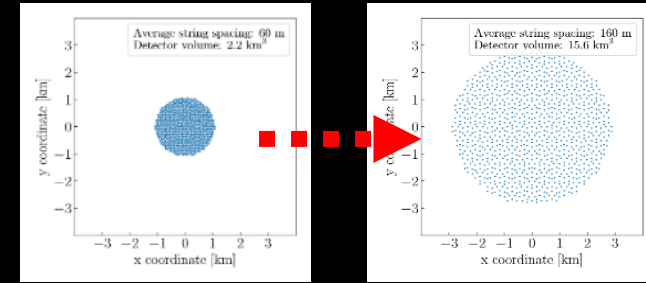
- 4-inch PMT hDOM design
- 19 4" PMTs
  - 5 SiPMs (8x8 array)



Check / compare performances for various designs:  
e.g. neutrino detection efficiency + angular resolution



# Source Discovery Potential



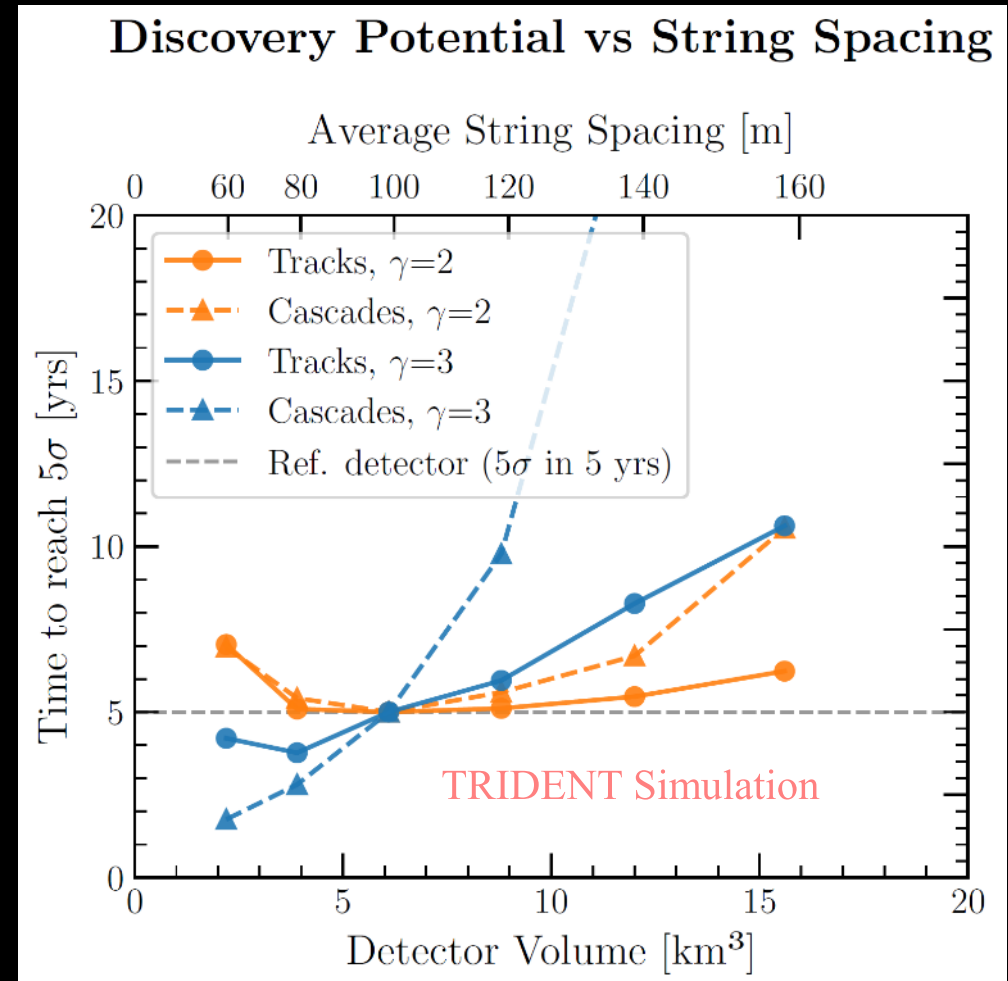
Assuming the “standard” geometry takes 5 years to discover a given source

$$\phi(E_\nu) \propto \begin{matrix} E^{-2} & \text{“hard” source} \\ E^{-3} & \text{“soft” source} \end{matrix}$$

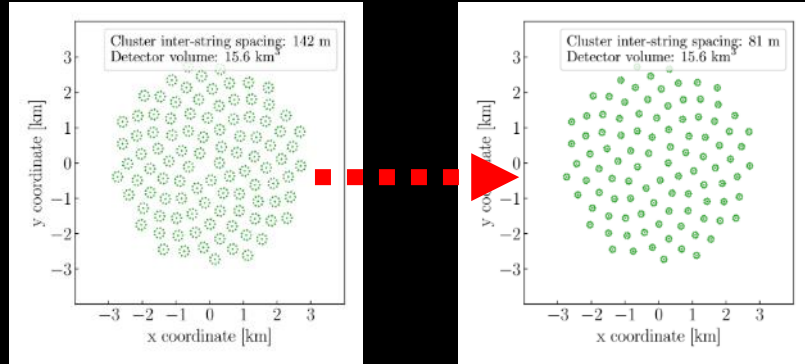
How much slower/faster can each geometry discover same source?

Bigger detector is **not necessarily better**

- Worse at **low energies** tracks and cascades:
  - Worse at **high energies** tracks and cascades:
- Dense detector favours low energy events

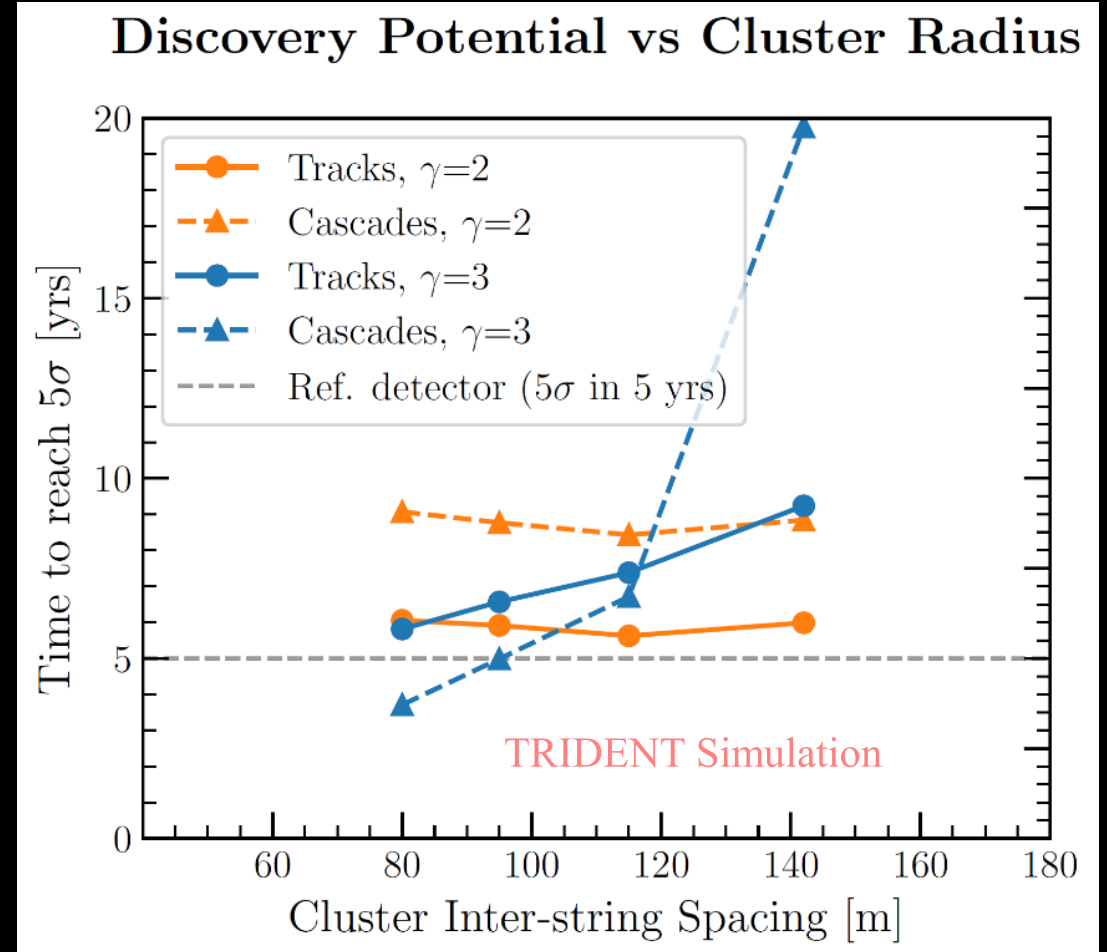


# Source Discovery Potential – String Clustering



String clusters show poorer performance for all channels, except for low energy cascades.

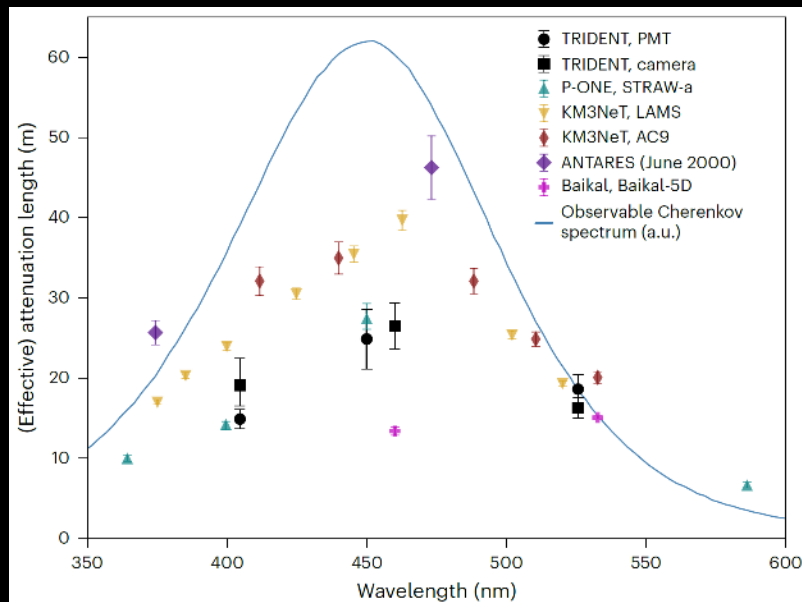
However, physics must be weighed against deployment & maintenance cost, safety



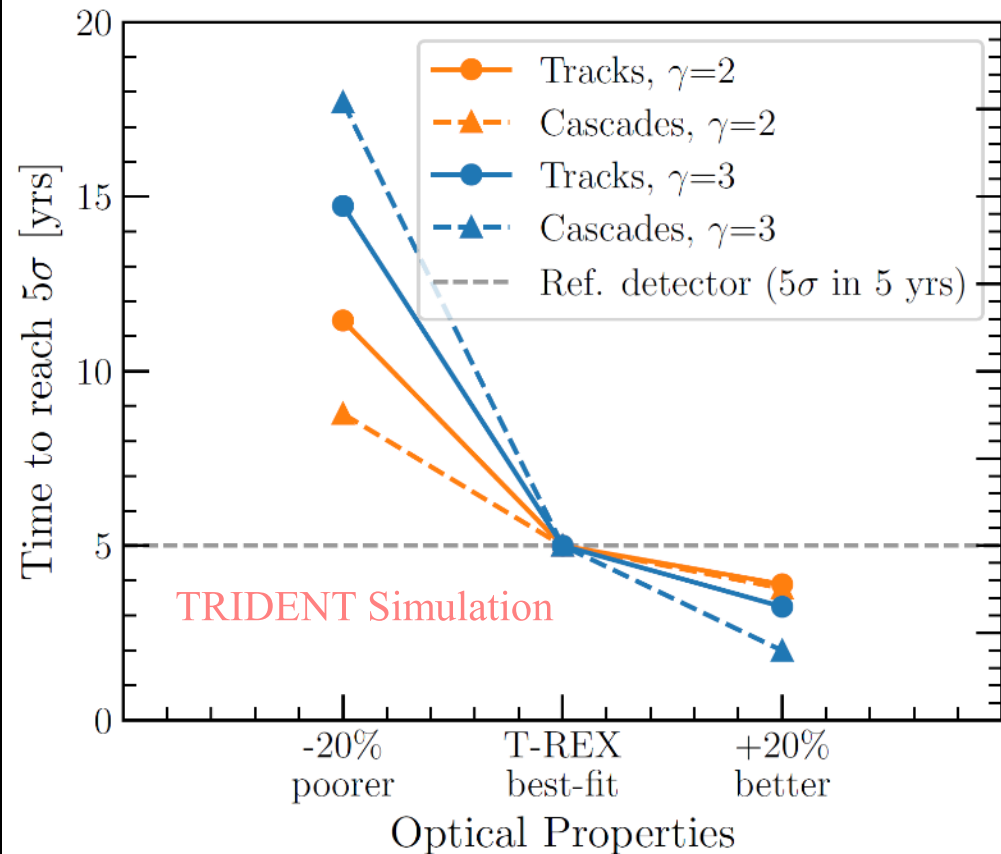
# Source Discovery Potential – Optical properties

While geometry choice is significant, water optical properties are essential!

→ Attenuation length can have larger impact than geometry choices



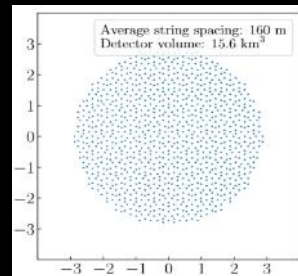
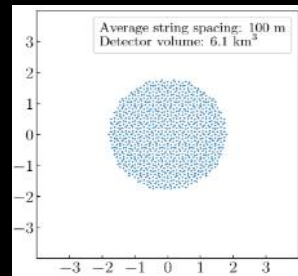
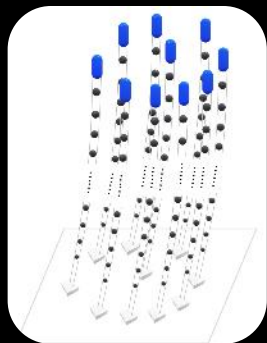
## Discovery Potential vs Optical Properties



# Source Discovery Potential – Optical properties

Photon detection efficiency should therefore lead the design of a detector.

Ongoing/future measurements at site and in TRIDENT Phase-1 will influence the final design choice



## Discovery Potential vs Optical Properties

