Pacific Ocean Neutrino Experiment (P-ONE)

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P-ONE

Introduction

Introduction

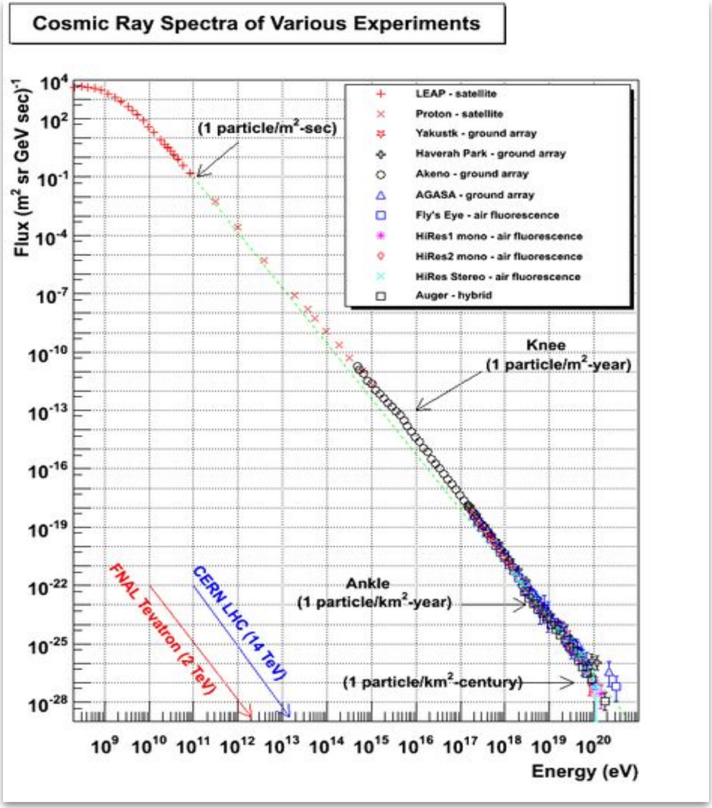
- Not long ago presented a talk about Baikal-GVD,
- Following the Russian aggression in the Ukraine the participation in Baikal-GVD is “suspended until further notice”.
- Need to continue the work not to lose the existing knowledge, experience, person-power, etc.
- Decision: join the P-ONE Collaboration:
  - Early stage - more possibilities for making significant impact,
  - Possibility of direct adaptation of the hardware solutions already designed,
  - Good perspectives for rapid development.

Neutrinos

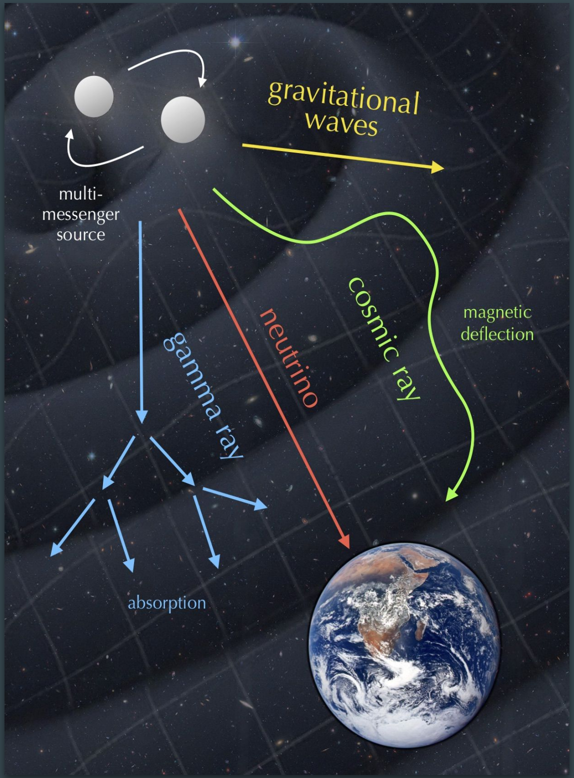
- Proposed by Pauli in 1930 to rescue energy conservation,
- Mysterious elements of the Standard Model,
- Electrically neutral - only weak interaction - very hard to detect.
- Should be massless, but...
  - They oscillate: $P(\nu_i \rightarrow \nu_j)$ is related to $(\Delta m)^2$ between all three flavours.
  - Non-zero $(\Delta m)^2$ -> neutrinos are massive. Neither the mass values nor their hierarchy are not known,
  - $m_\nu < 1.1$ eV.
- Majorana or Dirac particle?
- Why the mass is so small?

Cosmic rays

- Discovered by Hess in 1912,
- Energy range: 14 orders of magnitude, flux range: 32 orders of magnitude,
- The only imaginable source of particles with energies of EeV (10^{18} eV) and above:
    - A collider with such energies would be of the size of Mercury orbit...
- GZK limit: particles with $E > 5 \cdot 10^{19}$ eV should come from inside of our galaxy, yet no sources known so far...



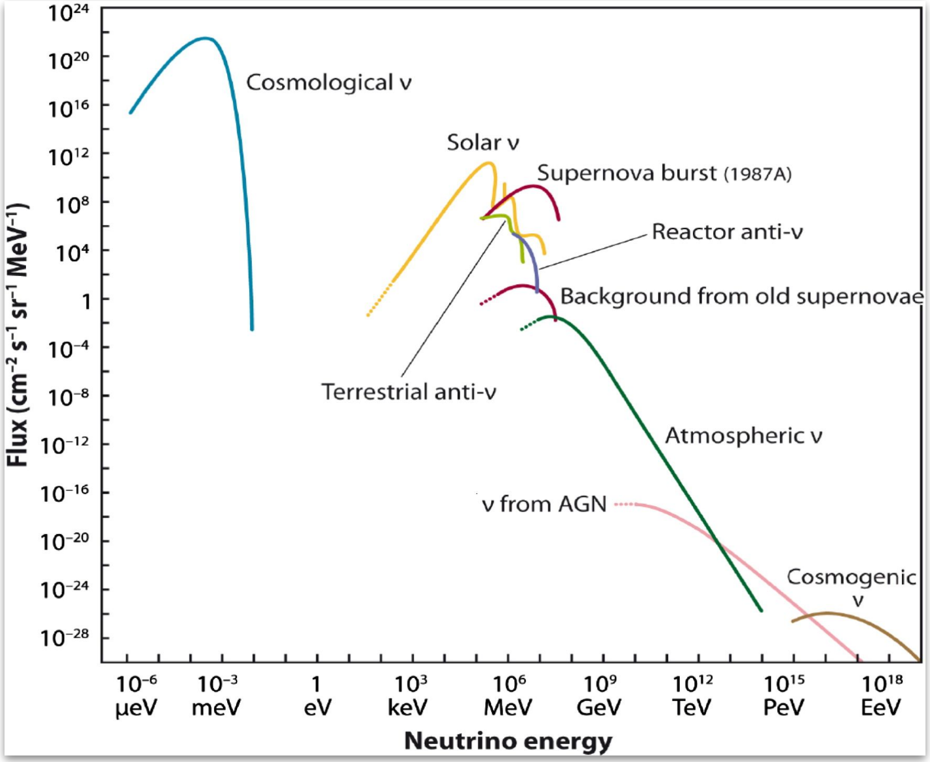
Neutrino astronomy



- While cosmic rays are mostly composed of nuclei, astrophysical neutrinos are also present.
- The universe is transparent to them, no deflection or bending of trajectories happens,
- They can escape very dense environments and provide undistorted picture of their sources.
- Therefore we may speak of *neutrino astronomy* - neutrinos point directly towards their sources!
- Yet the sources are still barely known in detail...

Neutrino flux

- Born in $p+X \rightarrow \pi^{+}+...$
  $\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow \mu^{+}+\nu_{\mu}$
  $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow e^{+}+\nu_{e}+\nu_{\mu}$
- Generic spectrum: $\sim E^{-2}$,
- Flavour content: 1:2:0 at the source, 1:1:1 at Earth.
- Direction:
  - From localized sources,
  - Diffuse flux (isotropic).

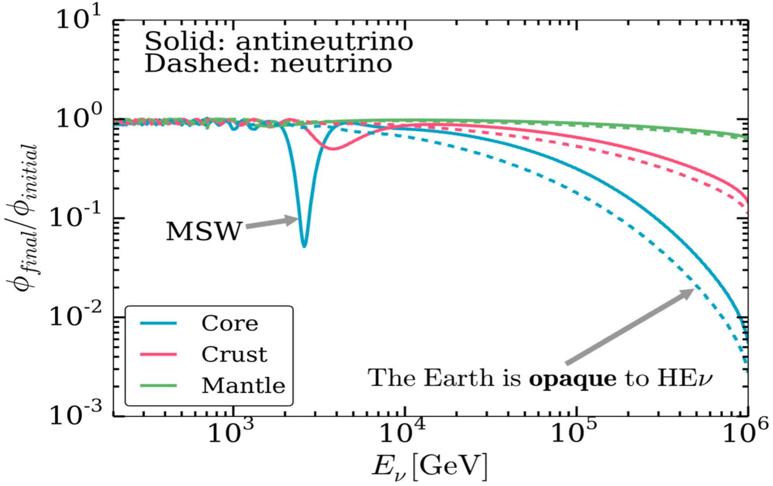


Progress in Particle and Nuclear Physics 67 (2012) 651–704

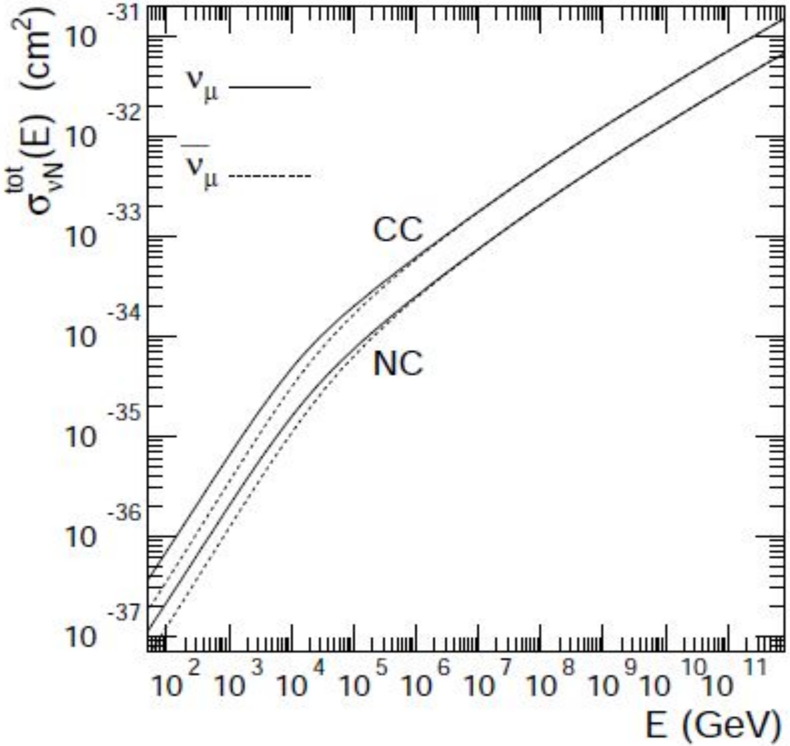
Neutrino cross-sections

Neutrino-nucleon cross-section increases with energy.

The Earth is opaque to the neutrinos above 100 PeV.



Delgado, Carlos Alberto Arguelles. "New physics with atmospheric neutrinos." (2015).



Naumov, V.A. et al., Neutrino propagation through dense matter, Astroparticle Physics 10(2-3):239-252

Neutrino telescopes: history

- 1960's - first ideas of using large reservoirs of water or ice as natural detectors (Markov, Greisen, Reines).
- 1970's - conceptual work on DUMAND[1],
- 1987 - deployment of DUMAND at Hawaii,
  - Only one string operational (out of 9) for only 10 hours. However - the work helped understanding the challenges facing neutrino detection in water.
- 1984 - first string of detectors deployed in the Baikal lake (to become NT-200 in 1998),
- 1997 - AMANDA[2] installed at South Pole.
- 2006 - beginning of the ANTARES[3], deployment in the Mediterranean Sea,
- 2004 - 2010 - construction of the IceCube detector in Antarctic ice.
- 2011: construction of Baikal - Gigaton Volume Detector (GVD) starts,
- 2014 - data taking in BGVD starts,
- 2015 - construction of KM3NeT[4] starts,
- 2018 - first P-ONE pathfinder line.

[1]DUMAND: Deep Underwater Muon And Neutrino Detector,
[2]AMANDA: Antarctic Muon And Neutrino Detector Array,
[3]ANTARES: Astronomy with a Neutrino Telescope and Abyss environmental RESearch,
[4]KM3Net - Cubic-KiloMeter Neutrino Telescope.

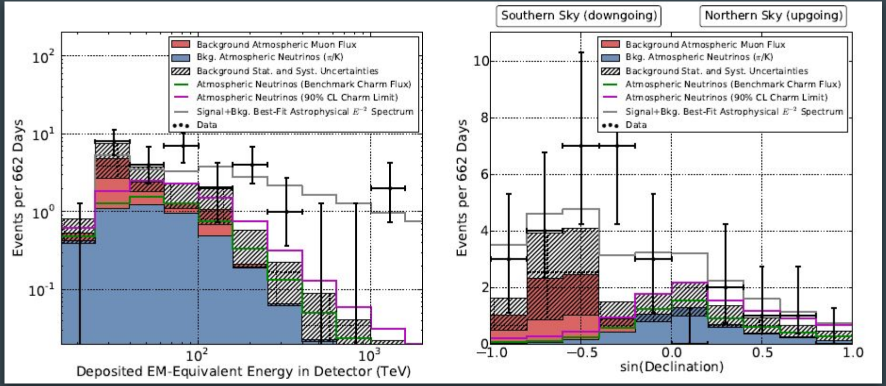
IceCube highlights

High-energy astrophysical neutrinos do exist!

In 2013 a pair of PeV neutrinos was observed (Phys.Rev.Lett. 111 (2013) 021103) - nicknamed “Bert and Ernie”, joined by “Big Bird” soon after (Phys.Rev.Lett. 113 (2014) 10110).

Further 28 events (30 - 1200 TeV) have their atmospheric origin rejected at 4σ level (Science 342 (2013) 1242856).

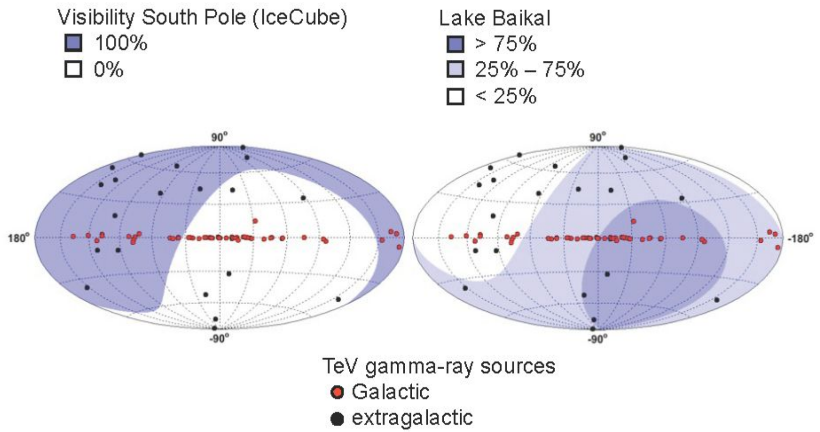
In 2018, a high-energy neutrino event was found to be in coincidence with a gamma-ray flare from the TXS 0506+056 blazar - first time a source has been identified (Science 361 (2018) 6398, 147-151).

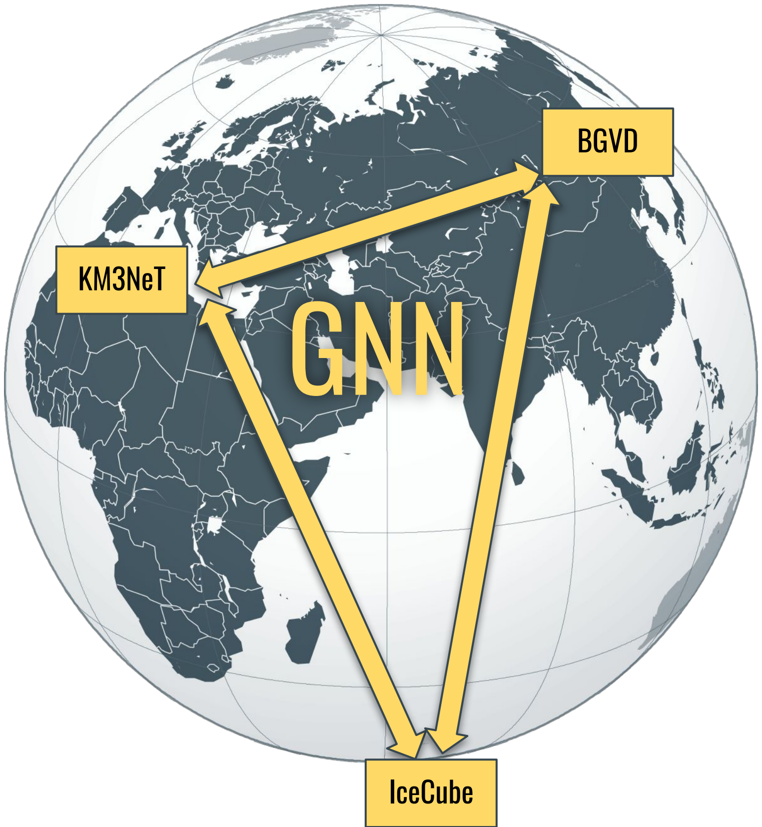


Neutrino telescopes: Global Neutrino Network

The leading telescope is IceCube in South Pole ($1\ km^3$ detector, fully operational and mature),

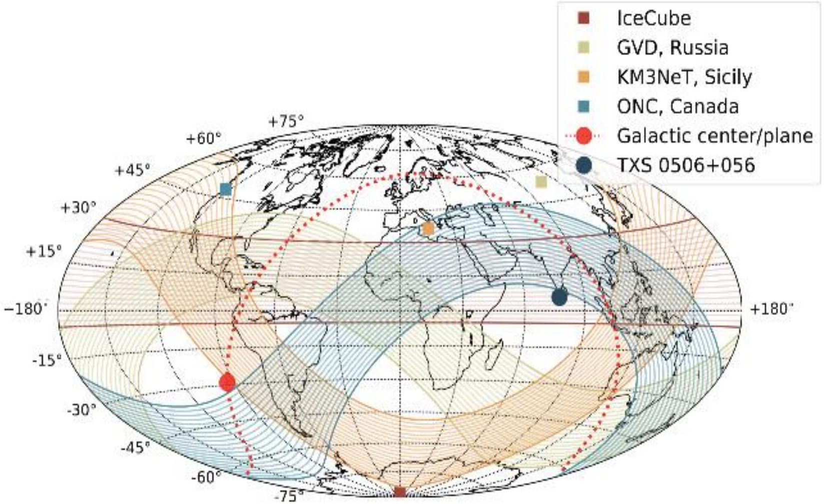
In the Northern Hemisphere there is Baikal-GVD providing, together with KM3NeT, data complementary to IceCube.



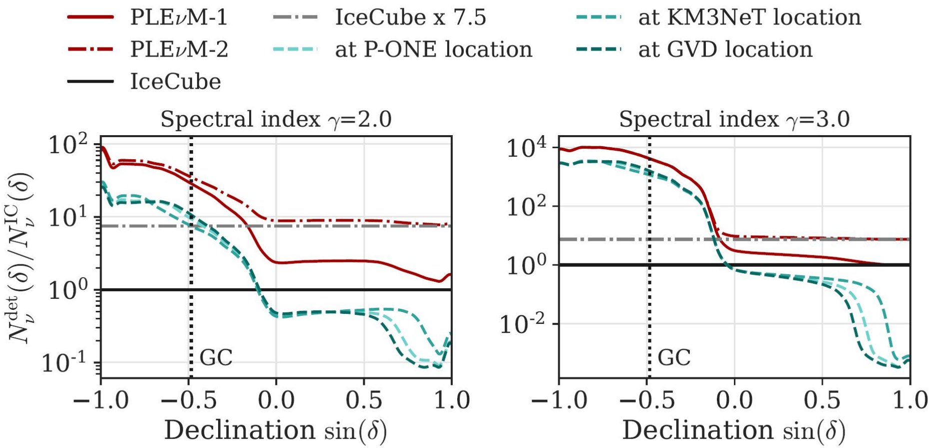


Towards increased sensitivity & coverage

A cubic-km scale detector at the P-ONE location would complement the coverage of the existing telescopes to nearly full-sky.



Courtesy M. Huber (TUM)



Schumacher, L.J. *et al.* “PLEνM: A global and distributed monitoring system of high-energy astrophysical neutrinos”, PoS ICRC2021 (2021), p. 1185.

Three km^3-scale detectors in the Northern Hemisphere will increase the sensitivity even by 2 orders of magnitude.

P-ONE

P-ONE: Collaboration

Member Institutions:

- Georgia Institute of Technology, USA,
- Simon Fraser University, Canada,
- Michigan State University, USA,
- University of Alberta–Edmonton, Canada,
- Queen’s University, Canada,
- University College London, UK,
- **Technische Universität München, Germany**,
- Drexel University, USA,
- TRIUMF, Canada,
- Ocean Networks Canada,
- **IFJ PAN**.

Most of the members have experience from IceCube,

Support from TUM (i.e. partial coverage of our trips to Munich, possible Polish-German grant applications),

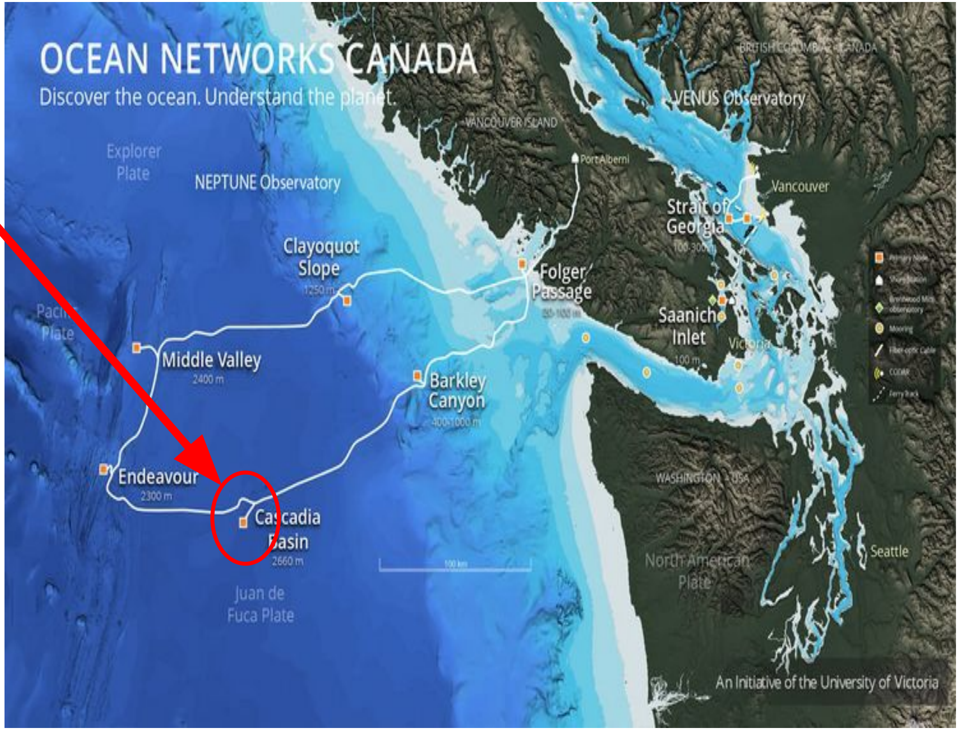
The Collaboration Governance document has been prepared with the participation of PM.

Physics program

- Search for sources of high-energy phenomena:
  - Extragalactic (50 TeV - 100 PeV): Active Galactic Nuclei (AGN), Gamma-ray bursts (GRB), starburst galaxies, etc.
  - Galactic (up to ~1 PeV): Supernovae, pulsars, the black hole Sgr A*, binary systems, etc…
- Diffuse neutrino flux:
  - Unidentified sources, check energy spectrum, anisotropies, flavor composition…
- Multi-messenger astronomy:
  - Simultaneous observations of the same part of the sky with cosmic rays, neutrinos, photons, gravitational waves…
- Search for dark-matter particles, magnetic monopoles, etc…

P-ONE: the site

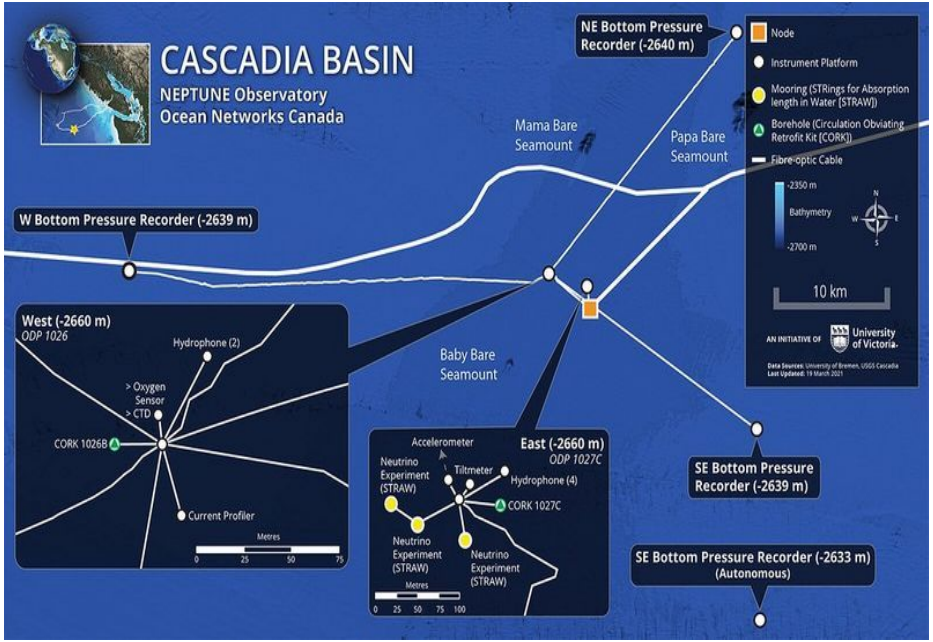
- P-ONE will be located in the Cascadia basin, North-East Pacific, 600-km West from Vancouver.
- Area of the NEPTUNE observatory of Ocean Networks Canada (ONC) - 800-km loop of power and data cables.
- The nodes provide plug & play installation, 8 kW power and 2 Gb/s data transfer.
- Designed for long life and reliability.



P-ONE: the site

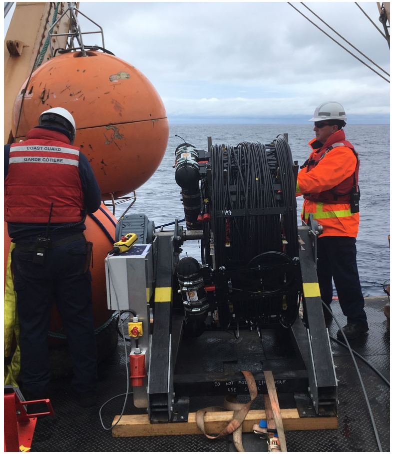
- Depth of ~2660 m,
- Good optical clarity of water (attenuation length ~28 m, similar as in Baikal),
- Low currents (0.1 m/s),
- Stable 2°C temperature,

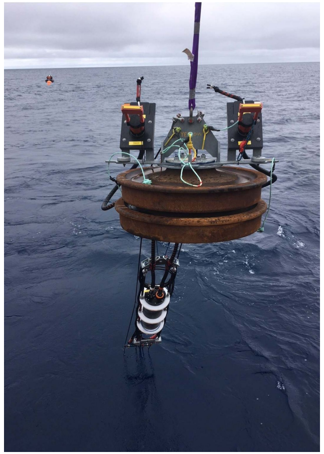
In addition, the ONC provides all the equipment & personpower for all maritime operations for deployment & maintenance.



Ocean Networks Canada

- Brings a large knowledge base for under-ocean operations,
- Expertise in deployment,
- Fully take over the job of deployment (no physicists allowed),
- Connected with many oceanographers and marine biologists that help diversify the scientific goals of P-ONE.





Detection principle: Cherenkov radiation

Particle detection in P-ONE bases on Cherenkov radiation detection.

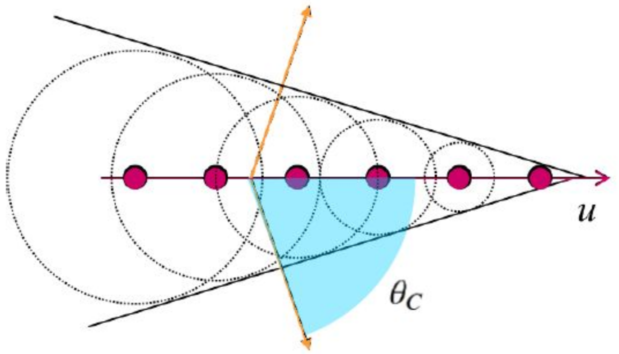
Cherenkov light is emitted when particle velocity exceeds the speed of light in the given medium (~0.75·c in water).

It is emitted by a charged particle: either prompt (like atm. muons) or resulting from neutrino interaction with water or bedrock.

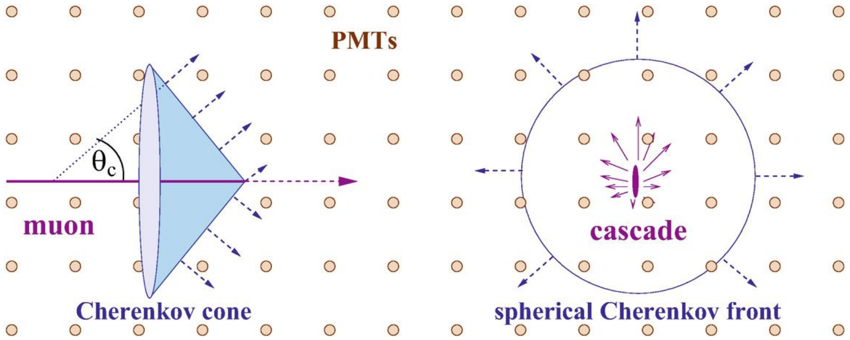
Intensity: $$\frac{dN_c}{d\lambda} = 2\pi\alpha\left(1 - \frac{1}{\beta^2 n^2}\right)\frac{1}{\lambda^2},$$

$N_c = 230\ \gamma/cm$ (350 – 600 nm, water)

Cherenkov angle: $\cos\theta_c = 1/(\beta n)$, $\theta_c = 42^\circ\ water$



Two detection modes



Spiering C. (2020) Neutrino Detectors Under Water and Ice. In: Fabjan C., Schopper H. (eds) Particle Physics Reference Library. Springer, Cham. https://doi.org/10.1007/978-3-030-35318-6_17

$$\nu_l + N \xrightarrow{CC} \begin{cases} e^- + X \rightarrow cascades \\ \tau^- + X \rightarrow cascades \\ \mu^- + X \rightarrow track + cascade \end{cases}$$

$$\nu_l + N \xrightarrow{NC} \nu_l + cascade$$

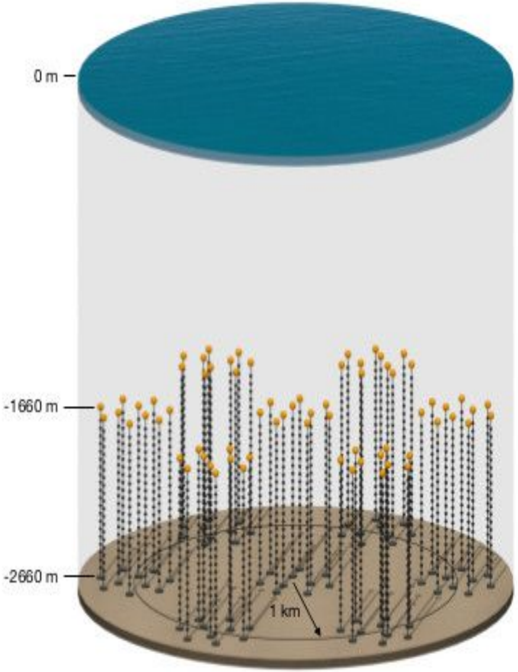
Two ways of detecting particles in neutrino telescopes:

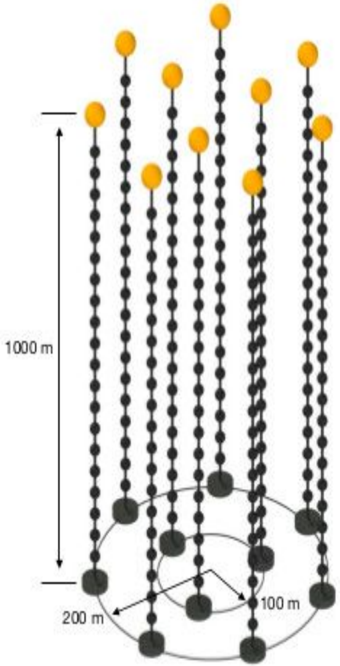
- Tracks (muon neutrinos),
- Cascades (electron, muon and tau neutrinos).

Muon tracks provide very good angular precision and enable for the study of point sources.

Cascades provide good energy-measurement precision, however their directional accuracy is much worse than of muon tracks.

P-ONE: planned structure





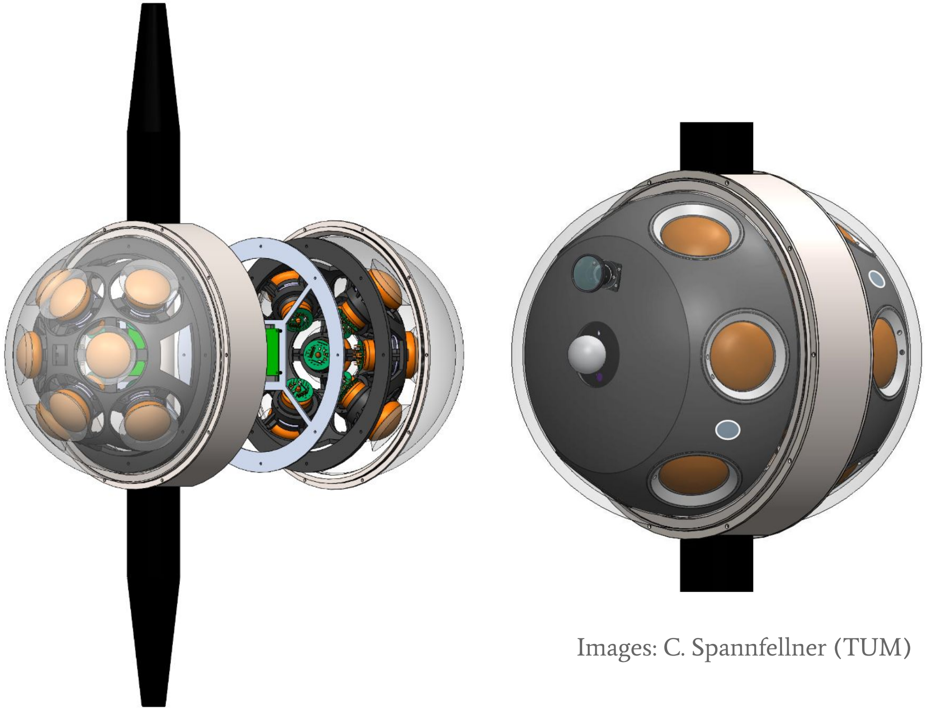
Uniform IceCube-style array would require thousands of measurement lines.

Instead, a segmented structure was chosen (as in BGVD) to cover 3 km^3 in the first stage.

7 clusters, 10 1-km strings in each are planned. Each string will host 20 optical modules.

Optimized for horizontal tracks but also good for up- and down-going.

P-ONE: planned structure



Images: C. Spannfellner (TUM)

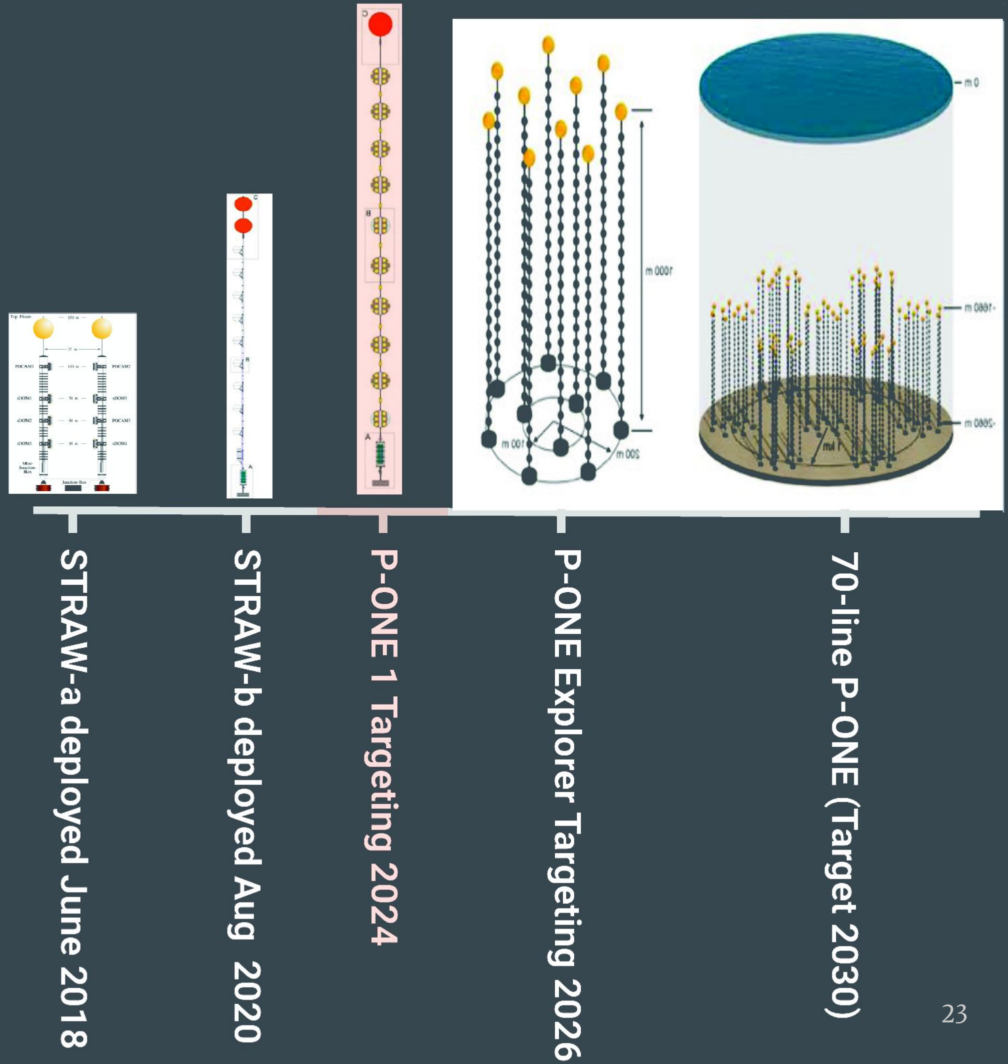
17-inch Multi-PMT Optical Modules (P-OM) containing 14-16 PMT* for better reduction of biological background and directional resolution.

Calibration modules: continuous monitoring of detector operation and geometry. Also containing PMT's (~10) plus additional light sources (LED flashers, laser).

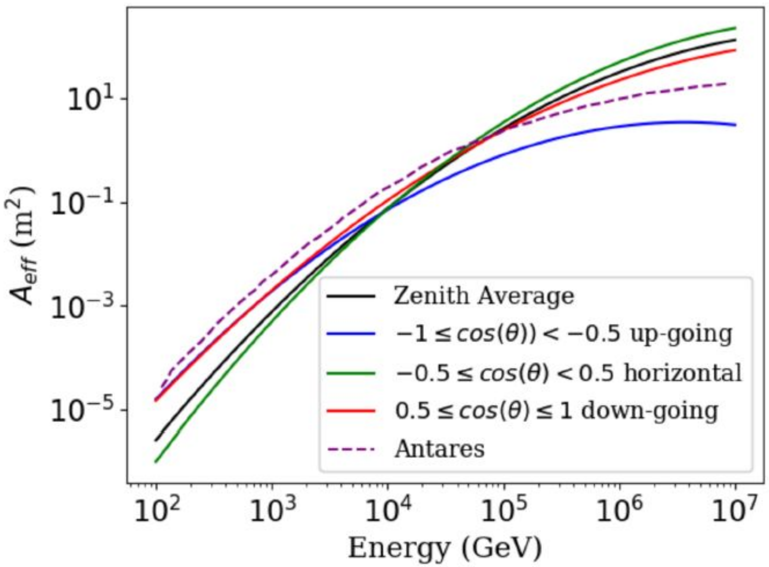
* 3-inch Hamamatsu R14374-10

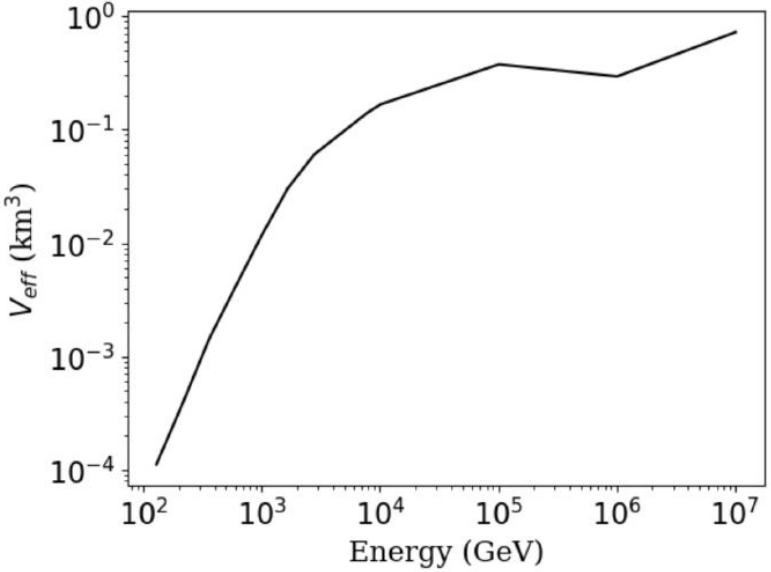
Timeline

- Pathfinder (STRAW-a)
  - Deployed June 2018,
  - Eur. Phys. J. C 81, 1071 (2021),
- Pathfinder (STRAW-b)
  - Deployed 2020,
  - Focused on bioluminescence,
  - Analysis ongoing.
- **P-ONE 1**
  - **Currently under development,**
  - **Anticipated deployment 2024.**
- P-ONE Explorer
  - Procuring Funding,
  - Target deployment (2025-2026).
- P-ONE
  - Targeting 2028-2030.



Effective area and volume

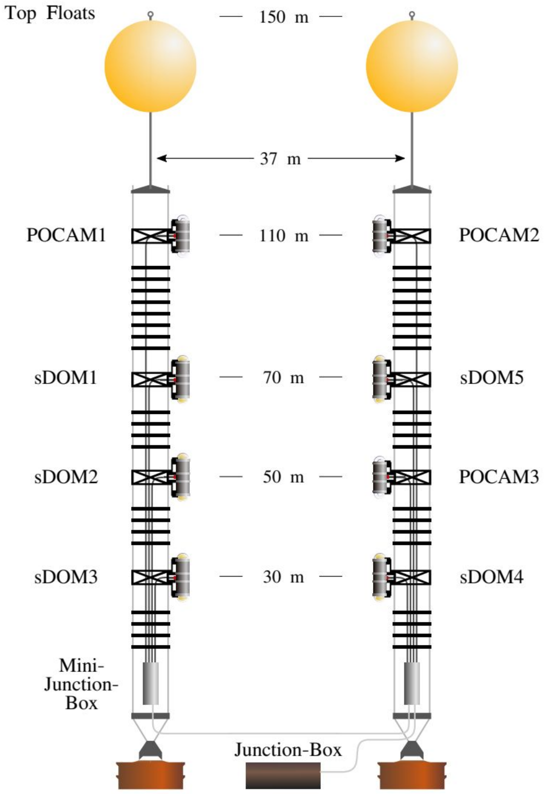


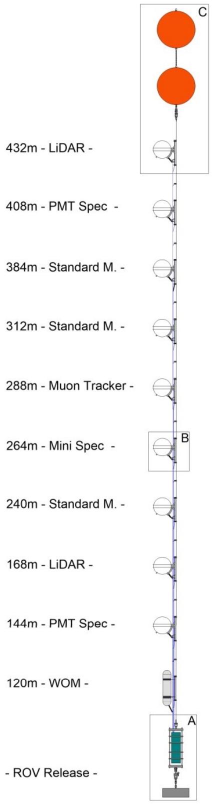


Effective area for muon neutrino tracks (left) and effective volume for cascades (right) of a single 6-string P-ONE cluster. This is already at the level of ANTARES, 6-string ARCA of KM3NeT and 7-cluster Baikal-GVD for 100-TeV neutrinos and beyond. Images from T. McElroy (UAlberta).

Current status: pathfinder missions

- Deployed 2 pathfinders, STRAW and STRAW-b,
- STRAW (2018, still working!):
    - Measure the water attenuation length.
    - Verify the amount of light from ^{40}K decays
    - Estimate rate for bioluminescence,
- STRAW-b (2020) deployed with a variety of modules to better study the site, analysis is ongoing.

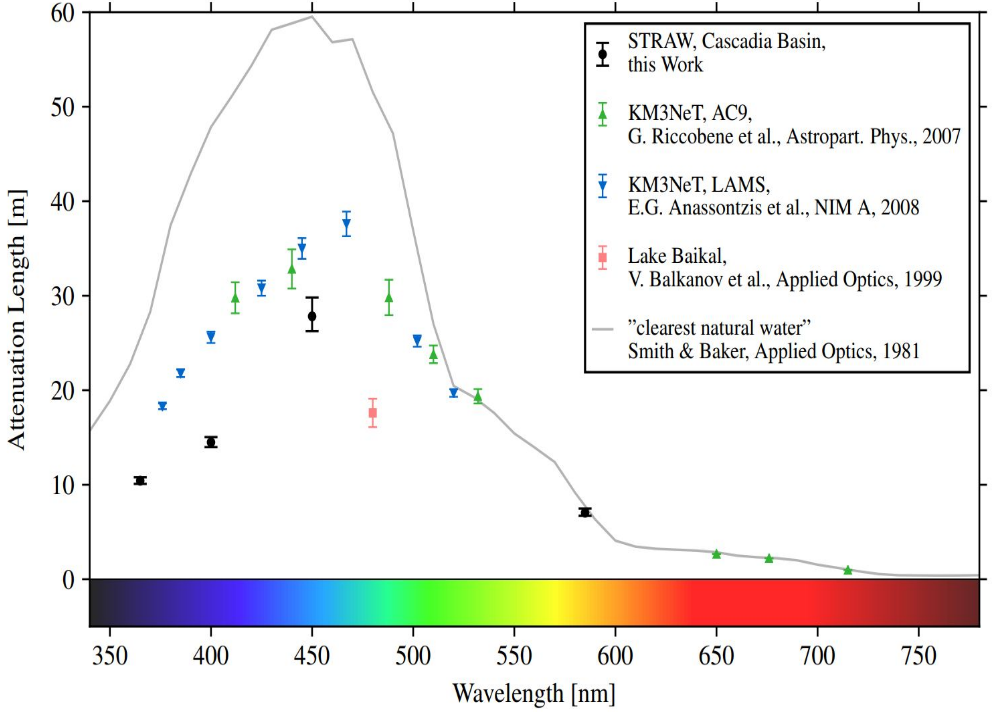




N. Bailly *et al.*, Eur.Phys.J.C 81 (2021) 12, 1071,
I.C. Rea *et al.*, PoS ICRC2021 (2021) 1092, July 2021

Water optical properties

- Using LED flashers at specific wavelengths, the attenuation length was measured at the P-ONE location the Cascadia Basin.
- Water is reasonably clear and suitable for a neutrino telescope.
- Attenuation length peaks at 27.7 ± 1.9 m at 450 nm.



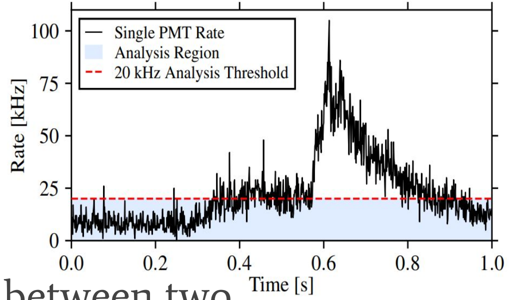
N. Bailly *et al.*, Eur.Phys.J.C 81 (2021) 12, 1071.

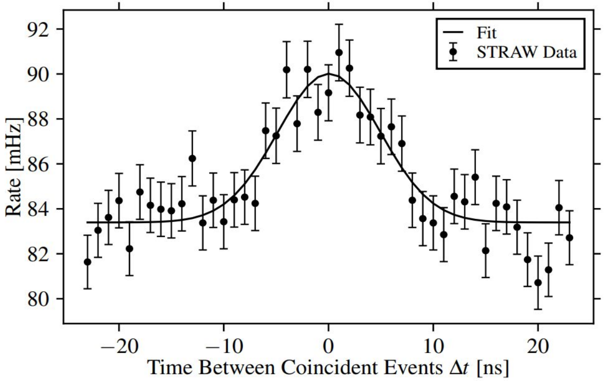
^{40}K decays and salinity

Background from:

$^{40}K \rightarrow {}^{40}Ca + e^- + \bar{\nu}_e$

$^{40}K + e^- \rightarrow {}^{40}Ar + \nu_e + \gamma.$



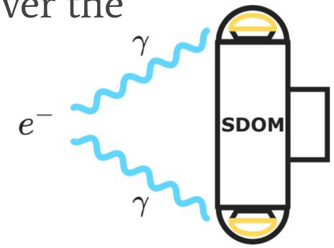


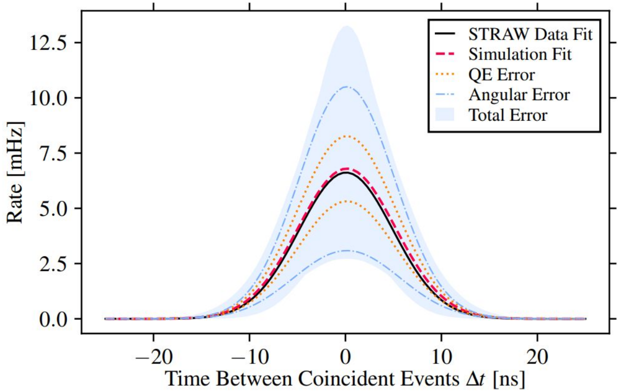
Idea: search for coincidences between two PMTs in the same module at rates < 20 kHz.

Compare with simulations to recover the salinity value:

This work: 2.5 ± 1.4 %,

ONC: 3.482 ± 0.001 %.





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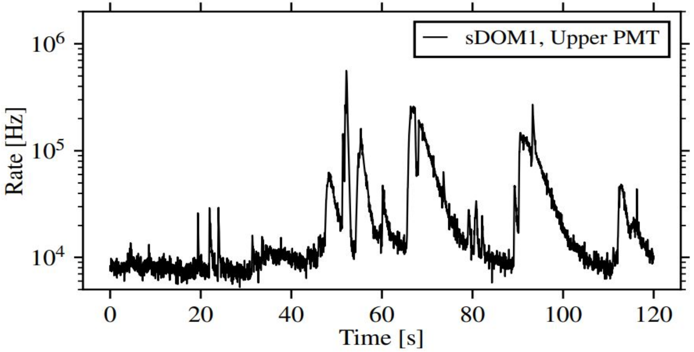
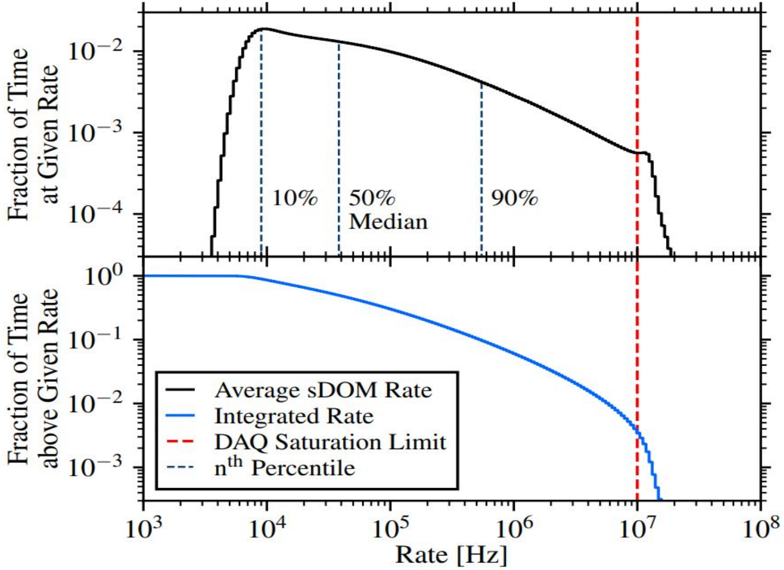
Bioluminescence

Emission of light by living organisms, from bacteria to large fish, for finding food, attracting mates, and evading predators.



Usually visible as large *spikes* over ~constant background.

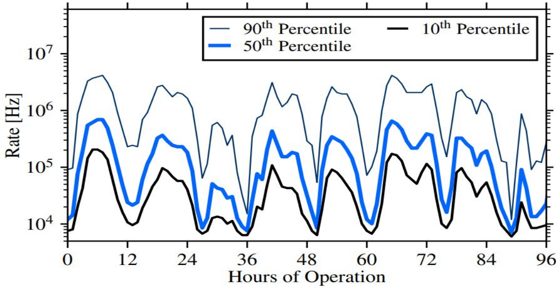


Distribution of single-PMT background rates. 10 kHz is from ^{40}K decays, the values above - from bioluminescence. The DAQ saturation is exceeded for small fraction of time.

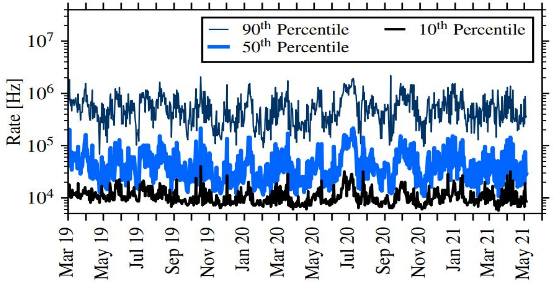
N. Bailly *et al.*, Eur.Phys.J.C 81 (2021) 12, 1071.

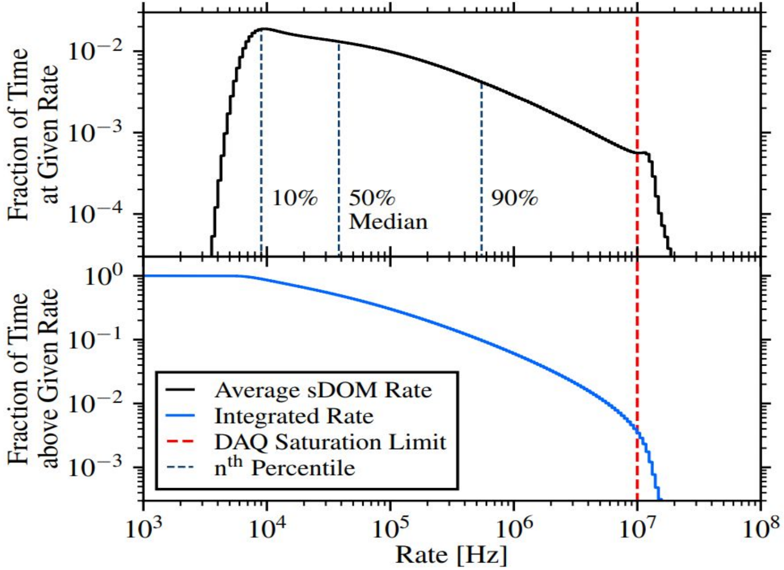
Bioluminescence

Percentile evolution over time reflects the tidal cycle (12.5 hours):



But no seasonal variation:





Distribution of single-PMT background rates. 10 kHz is from ^{40}K decays, the values above - from bioluminescence. The DAQ saturation is exceeded only for small fraction of time.

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Summary

IFJ PAN Contribution

Person-power:

- Paweł Malecki
- Konrad Kopański
- Wojciech Noga,
- Apoorva Bhatt.

Activities:

- Continuation of laser calibration system development - adaptation to P-ONE requirements,
- Development and validation of fast photon propagation simulation,
- Analysis of STRAW data,
- GEANT4 detector simulations.

Funding: submitted SONATA BIS proposal,
Exploring the Polish-German programs,
No common fund yet.

Outlook

P-ONE is approaching the deployment of first measurement line in 2024,

It provides an exciting potential for new discoveries and observations,

Funding is secured for first 3-5 measurement lines, applied for more,

Infrastructure & deployment support from ONC simplifies the development.