P-ONE
The Pacific Ocean Neutrino Experiment

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UNIVERSITY OF ALBERTA

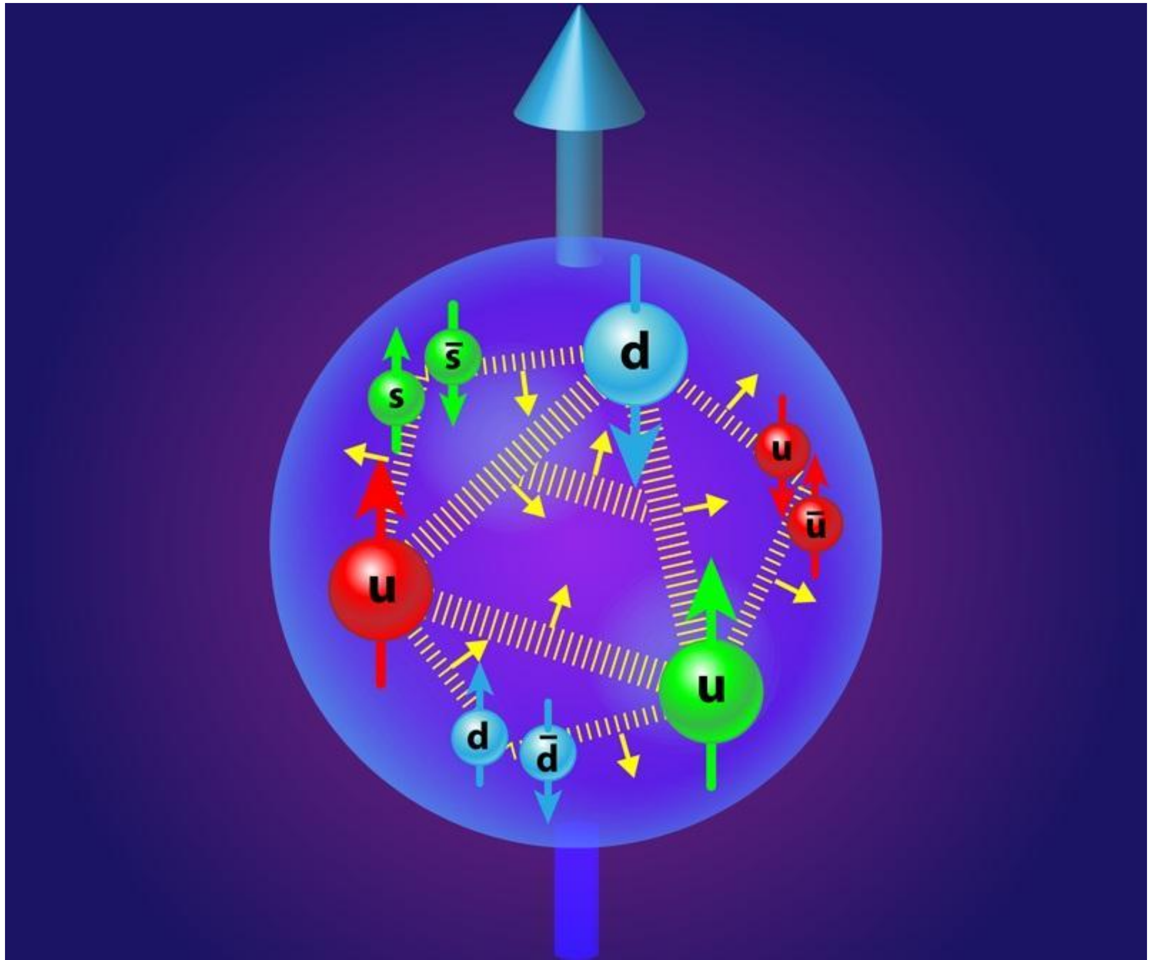
Outline

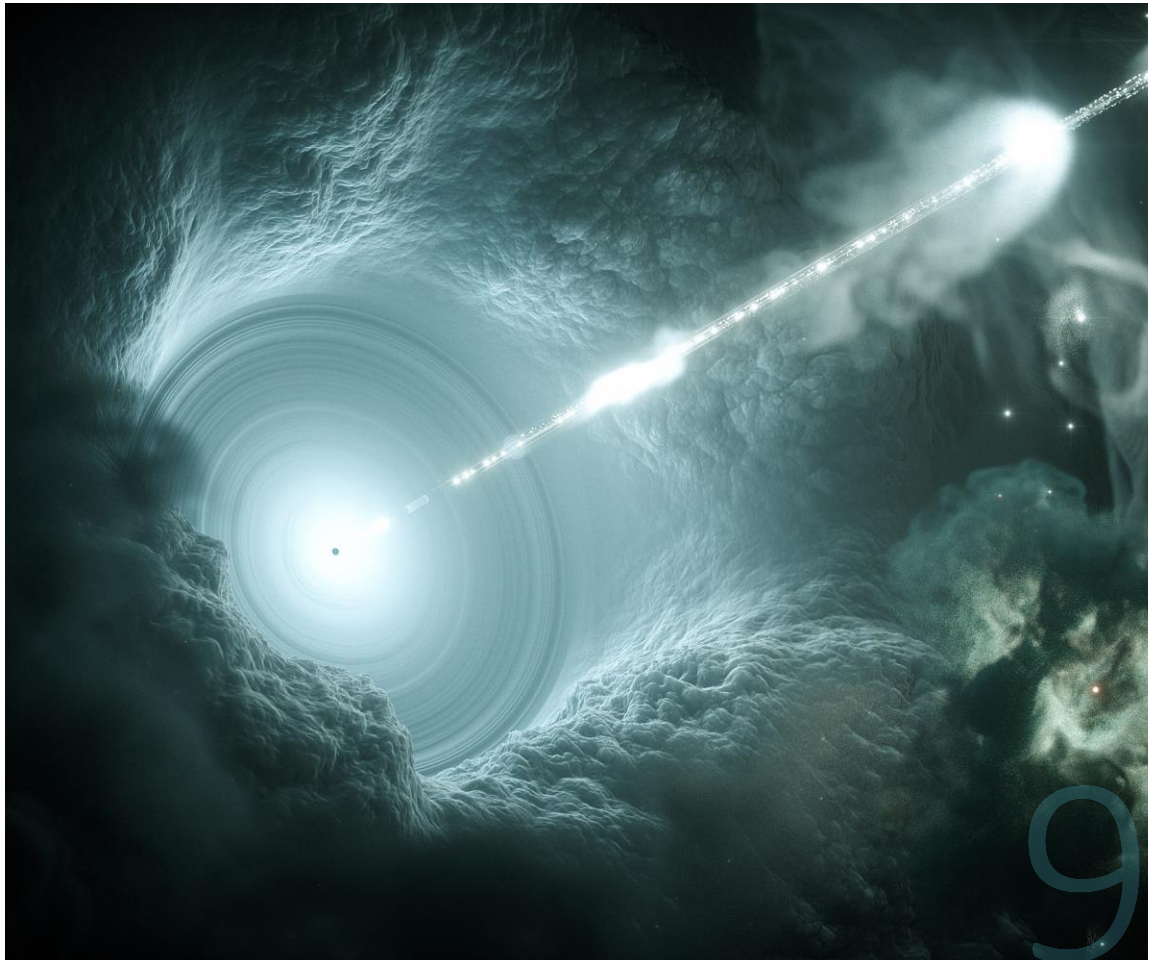
- Astroparticle physics: a new field
- Neutrino telescopes: astroparticle detectors
- What have we learned?
  - Physics
  - Technical challenges
- The Pacific Ocean Neutrino Explorer
  - General motivation
  - Novel ideas
  - Status of production
- What comes next for P-ONE?

A bit of motivation

High Energy Astroparticle Physics

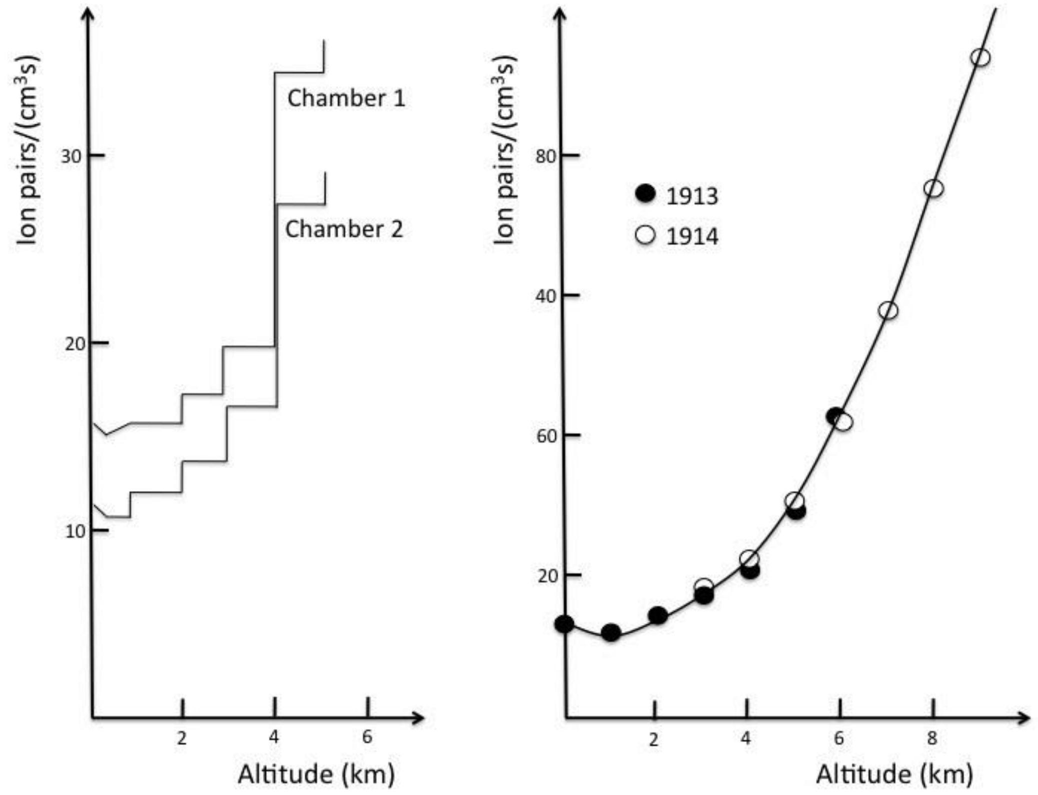
- Studying elementary particles of astrophysical origin – here focusing on neutrinos





The particle origin

- A hundred-year puzzle: cosmic ray origin

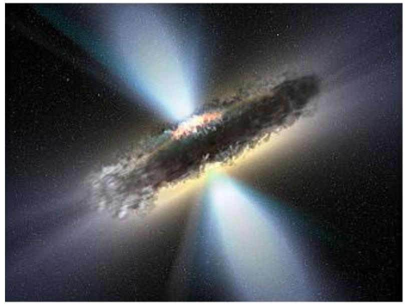


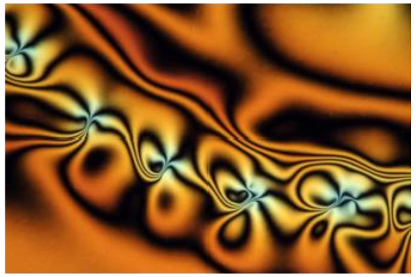
Victor Hess before his 1912 balloon flight in Austria, during which he discovered cosmic rays

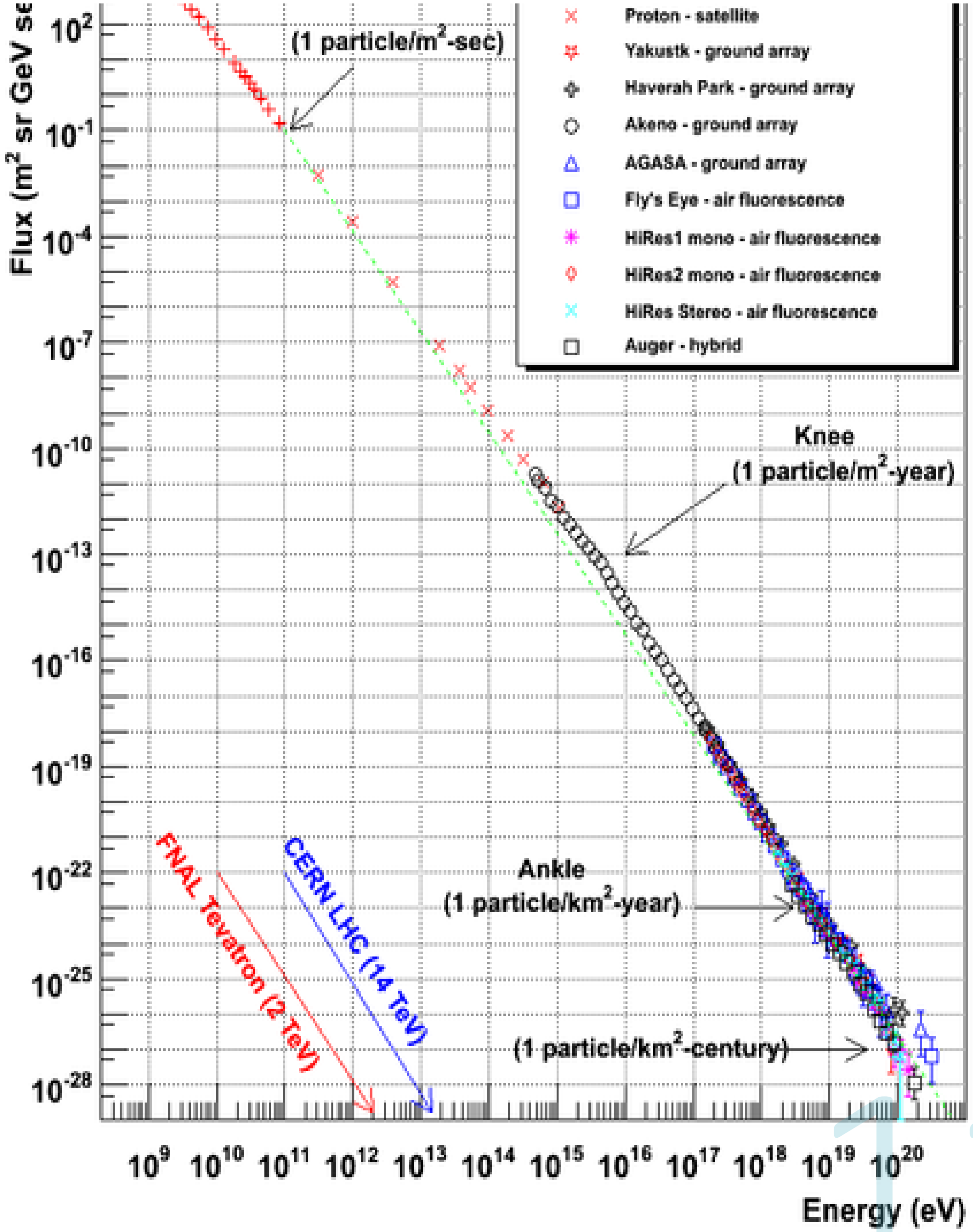
https://faculty.washington.edu/wilkes/salta/balloon/

The particle origin: ν's

- A hundred-year puzzle: cosmic ray origin
- Where do they come from?
  - Cosmic accelerators? Exotics?







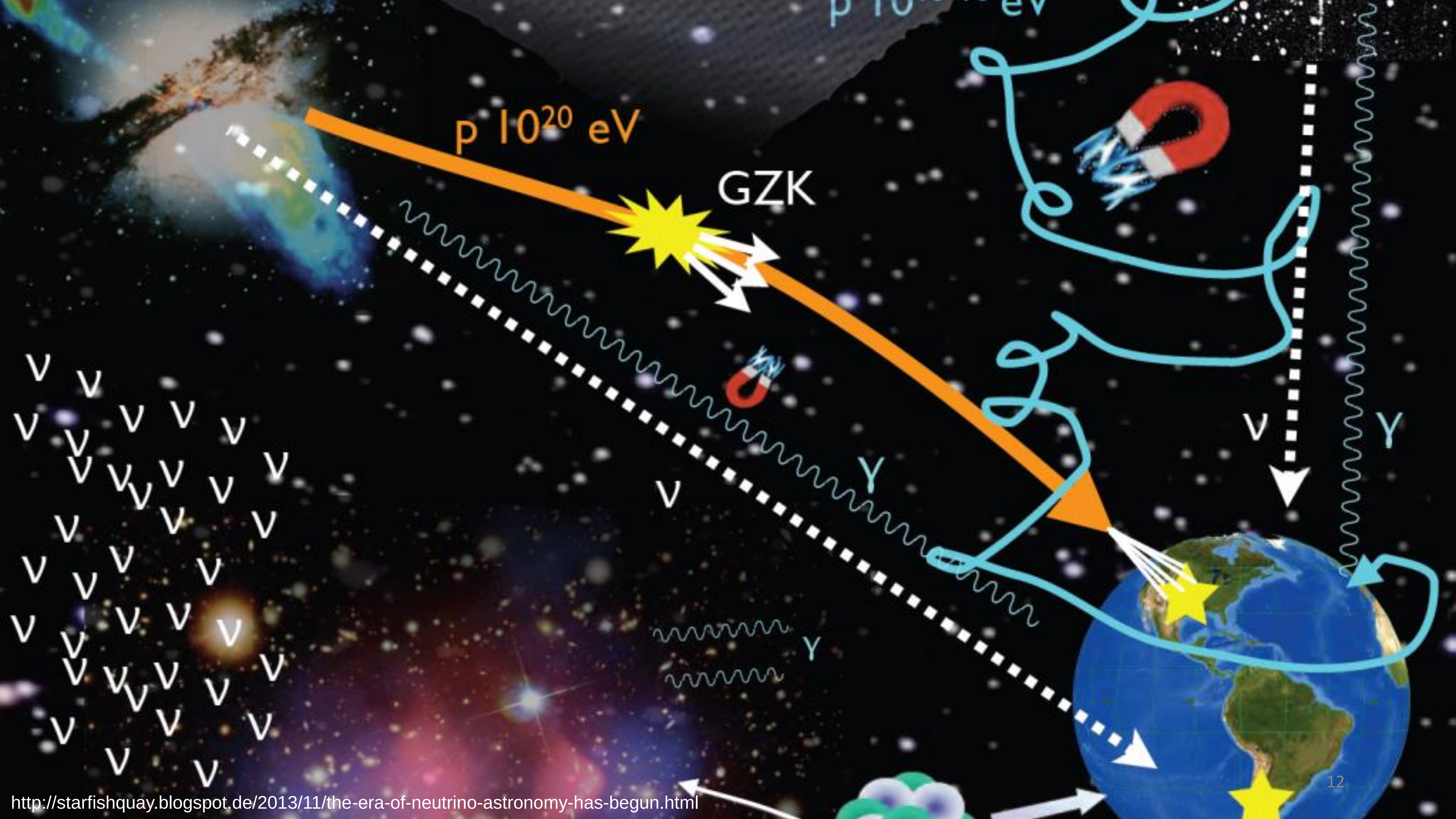
- ν's most likely involved

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$$\pi^+ \rightarrow \nu_\mu + \mu^+$$

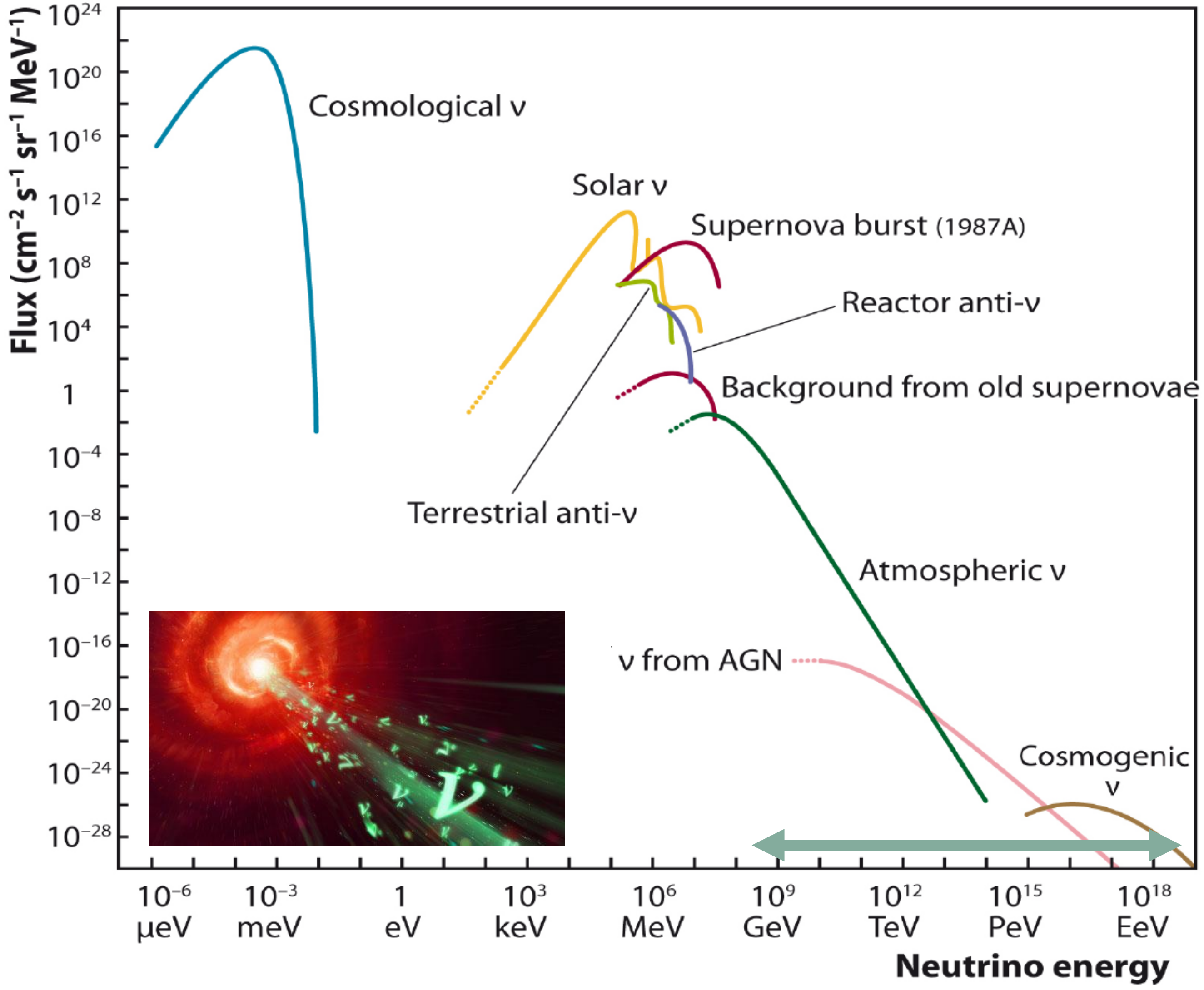
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Energies from TeV to PeV



http://starfishquay.blogspot.de/2013/11/the-era-of-neutrino-astronomy-has-begun.html

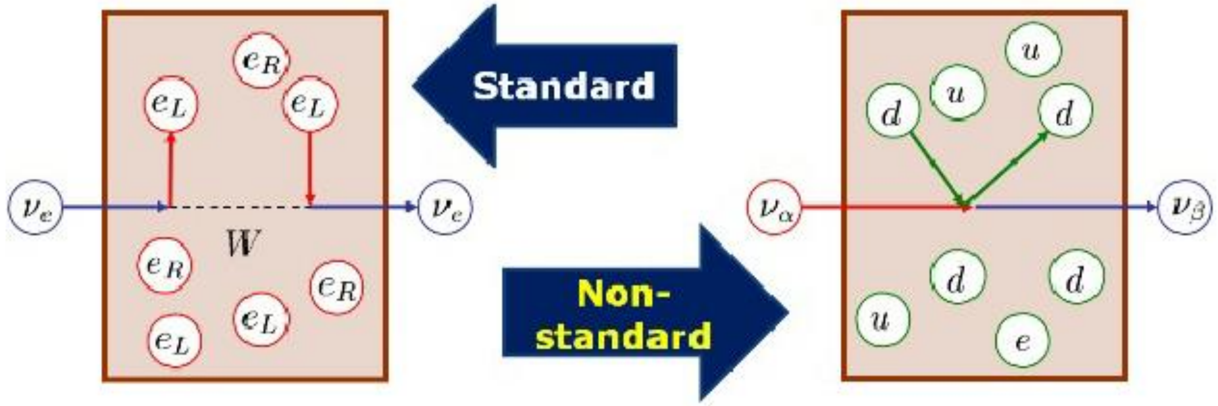
Particle physics with cosmic ν's

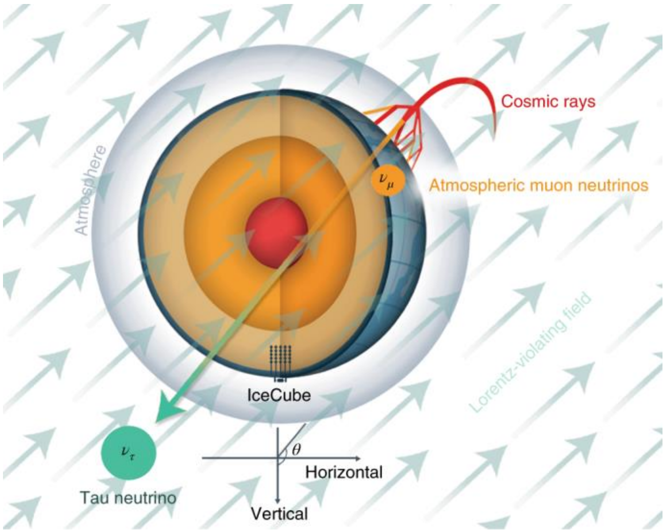


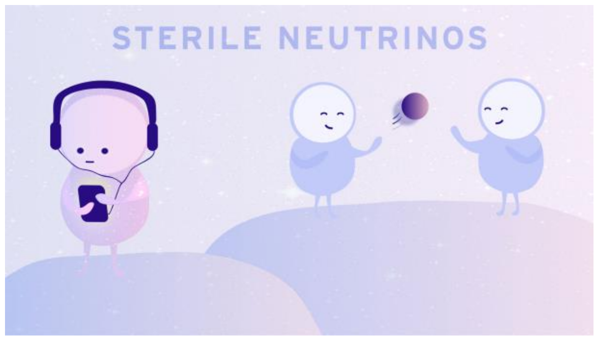
- Astrophysical
  - Neutrino production on sources
- Atmospheric
  - CR interactions on Earth's atmosphere

- Energies well above what can be easily done in a lab
  - Can study particle interactions at extreme energies
- Travel astronomical-scale distances
  - Probes for new in interactions
  - Test neutrino properties

Particle physics with cosmic ν's







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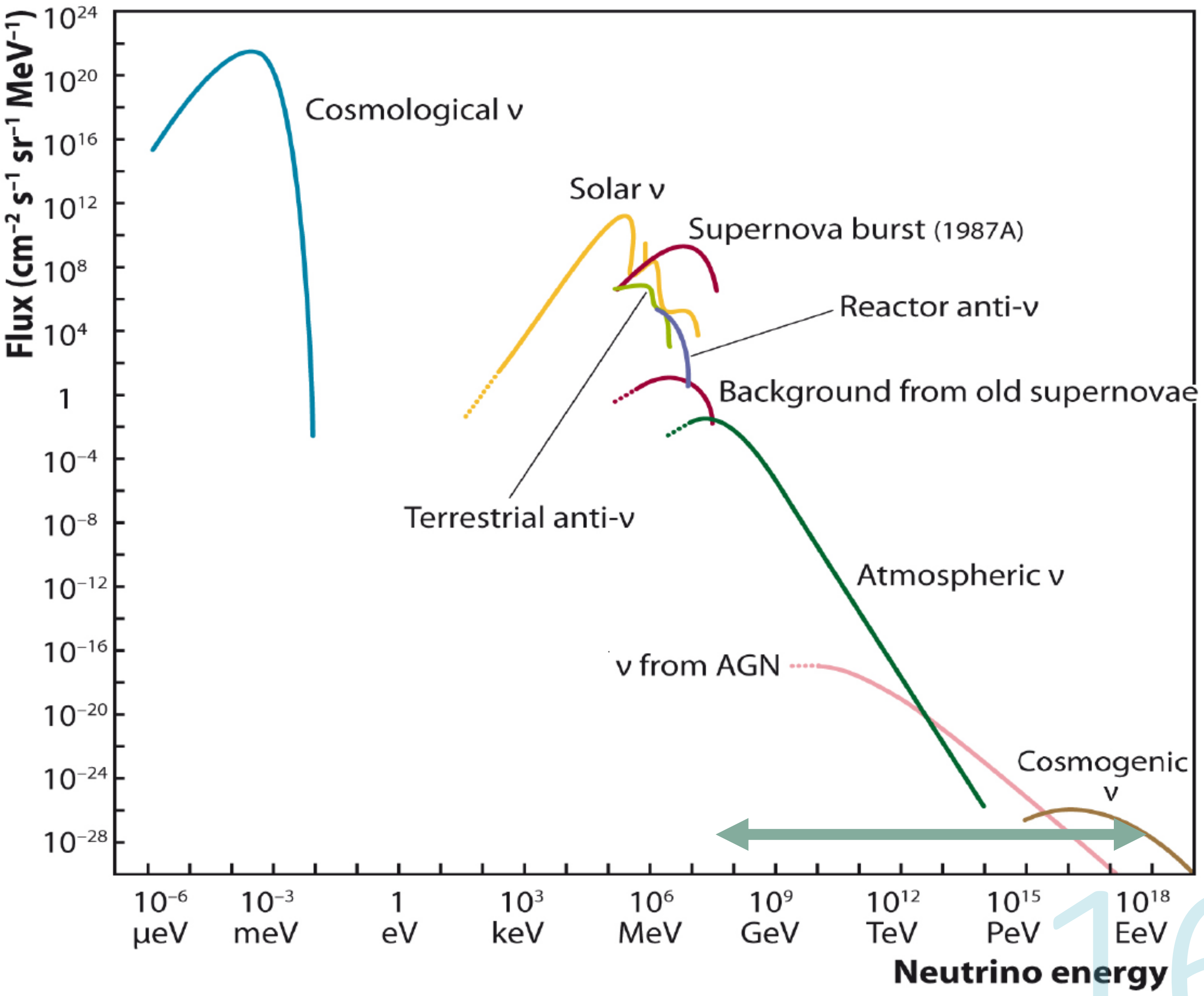
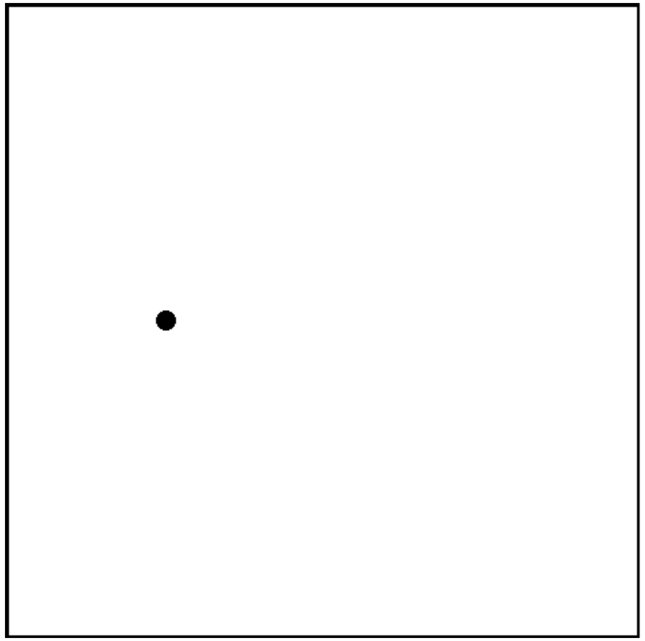
The role of Neutrino Telescopes

The challenge: low fluxes

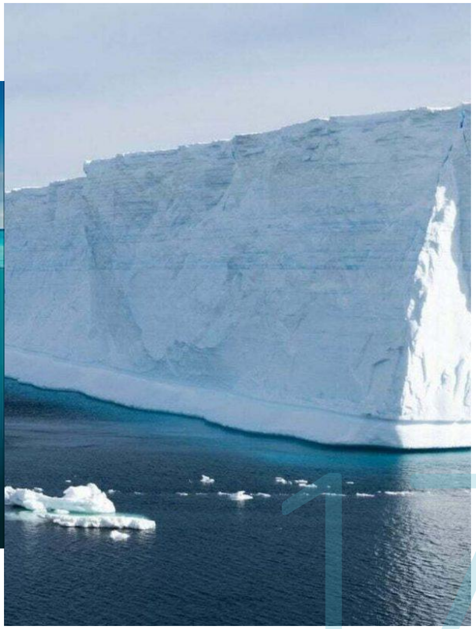
- The flux of neutrinos drops sharply as their energy increases
- To detect them, you need very large target volumes
  - Optimization between instrumentation density, cost and energy threshold
- A handful of technologies developed so far
  - -Optical
  - -Radio
  - -Acoustic



Optical ν telescope principles

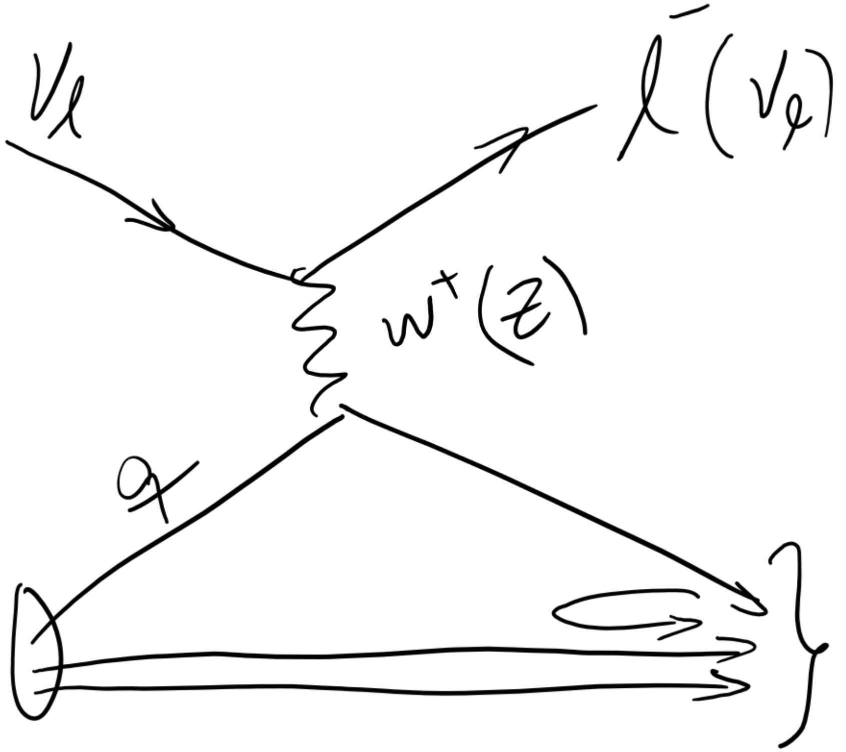


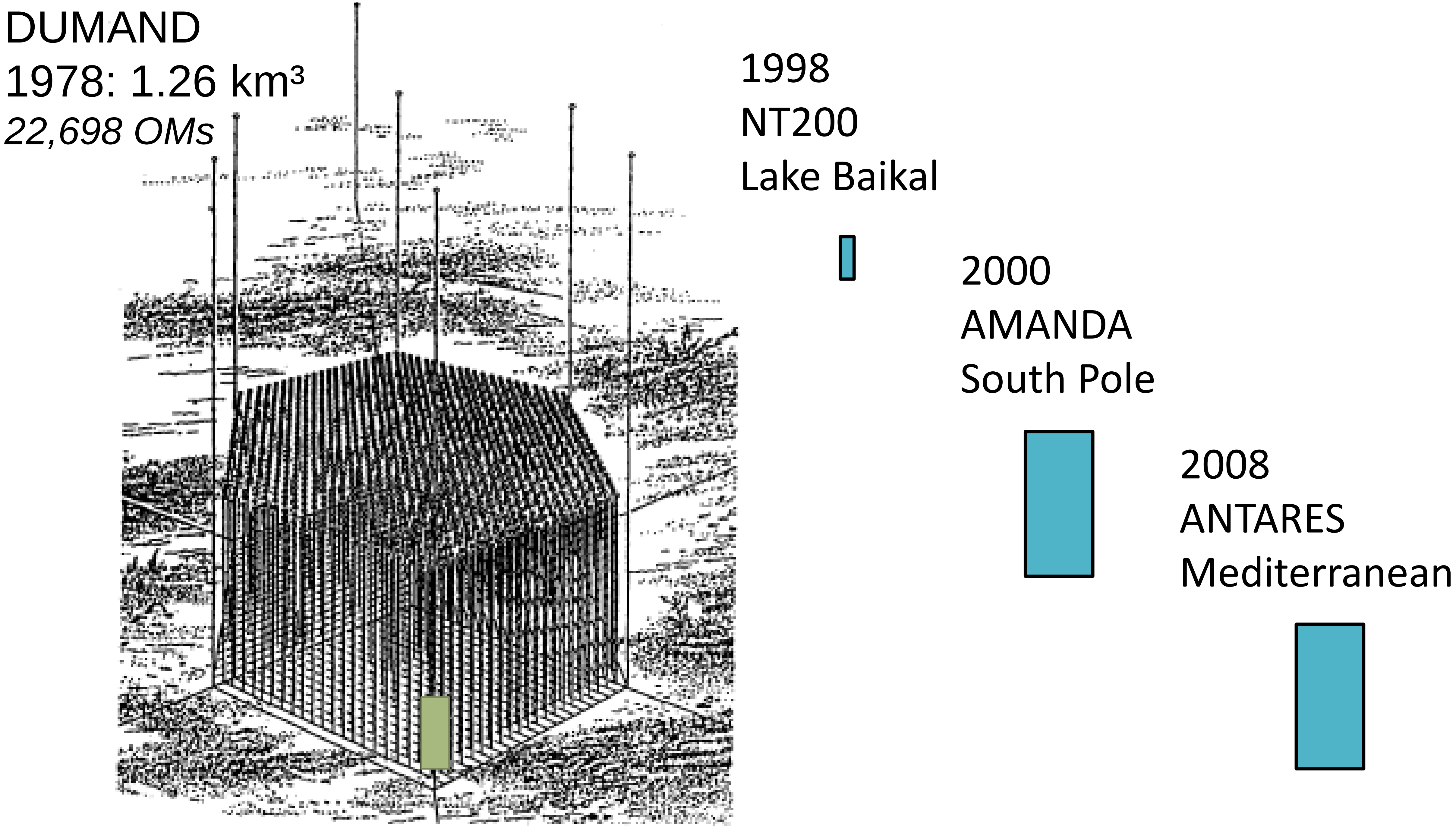
- Neutrino detection via Cherenkov light
- 3D array of light sensors
- Large, natural and transparent medium
- Deep underground



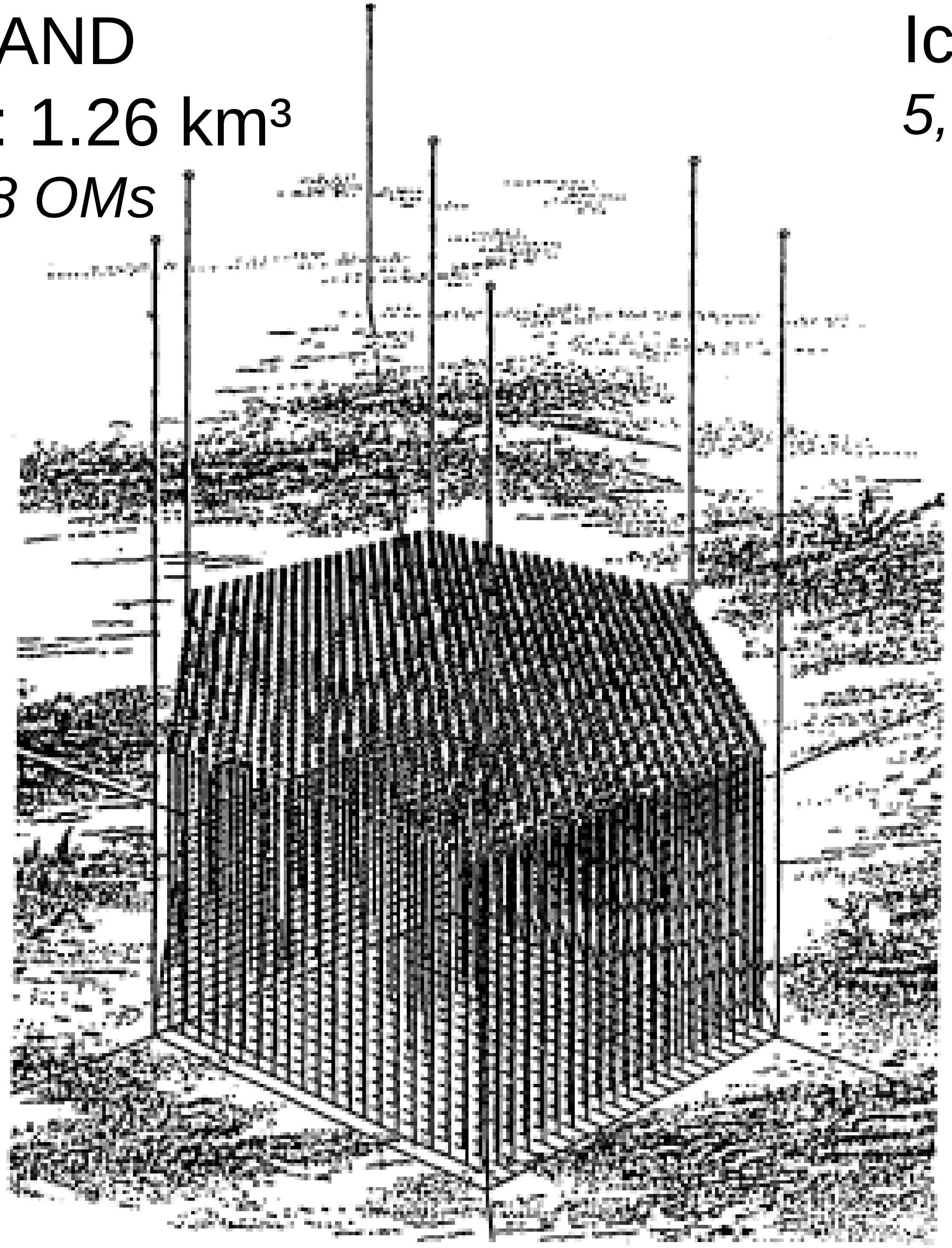
Detection by sampling

- The focus is on neutrino energies above GeV
- Two "types" of signatures
  - Muons can go from tens to thousands of kms – long tracks
  - Hadrons and electrons initiate showers over tens of meters
- About 300 Cherenkov photons/cm of track length
- Sparsely instrumented detectors sample a fraction of the light
  - Sufficient to reconstruct the neutrino interaction
- The idea is fairly old

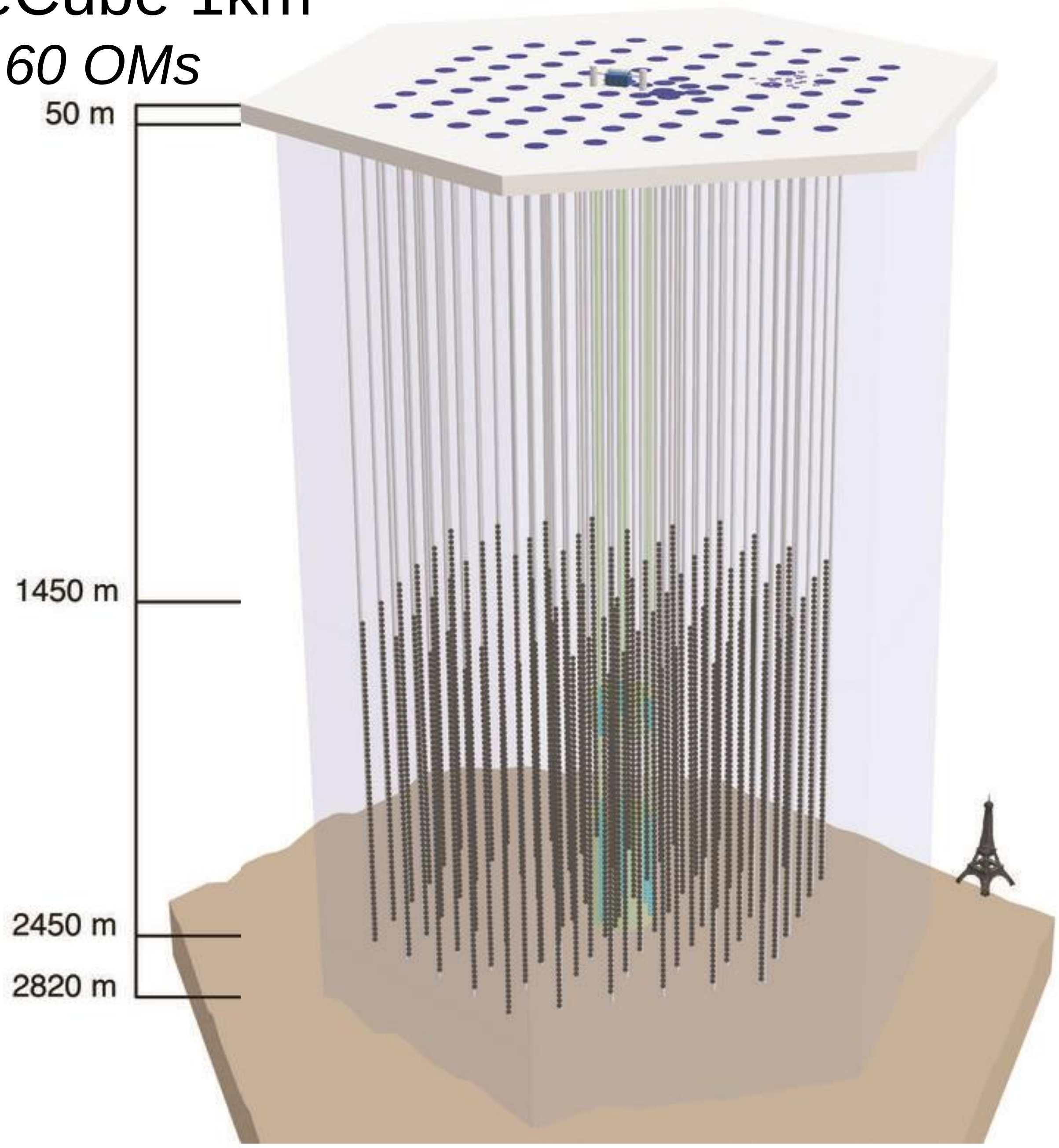



DUMAND
1978: 1.26 km³
22,698 OMs
1998
NT200
Lake Baikal
2000
AMANDA
South Pole
2008
ANTARES
Mediterranean

DUMAND
1978: 1.26 km³
22,698 OMs

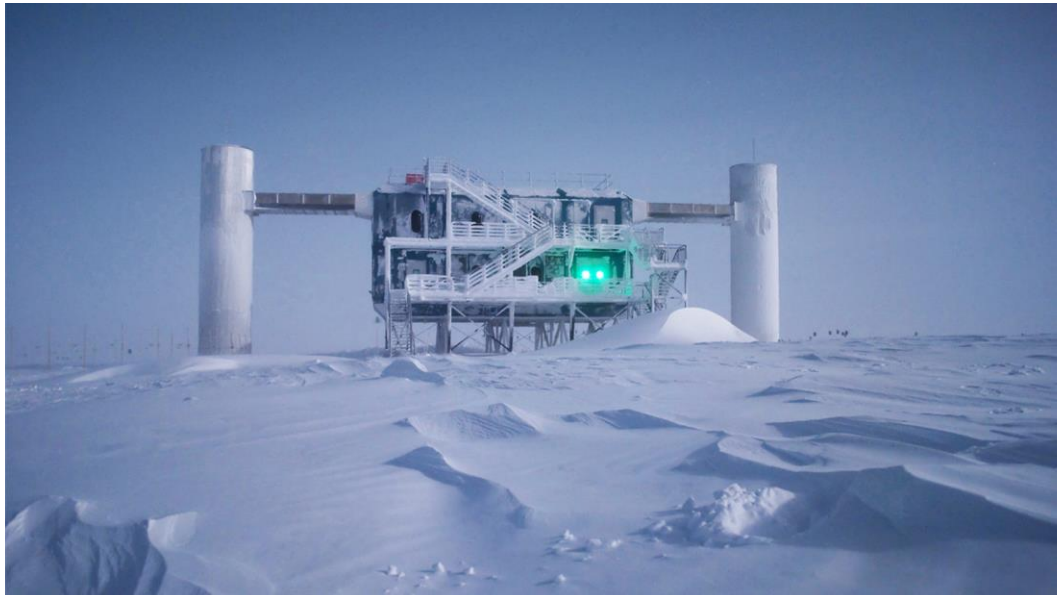


IceCube 1km³
5,160 OMs



IceCube

- The largest NT in operation
- 5,160 modules with a 10”-PMT
- At the geographic South Pole



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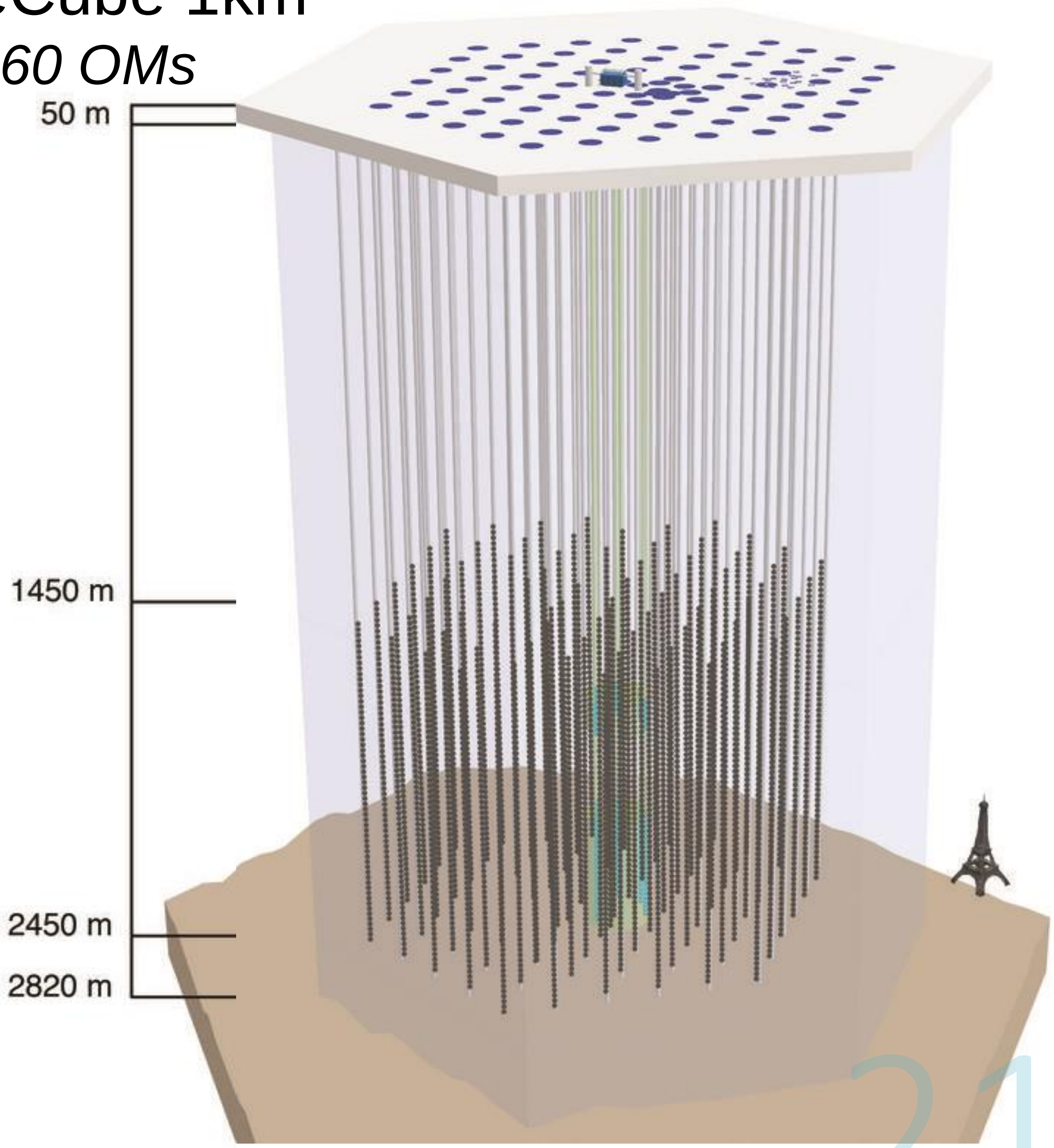
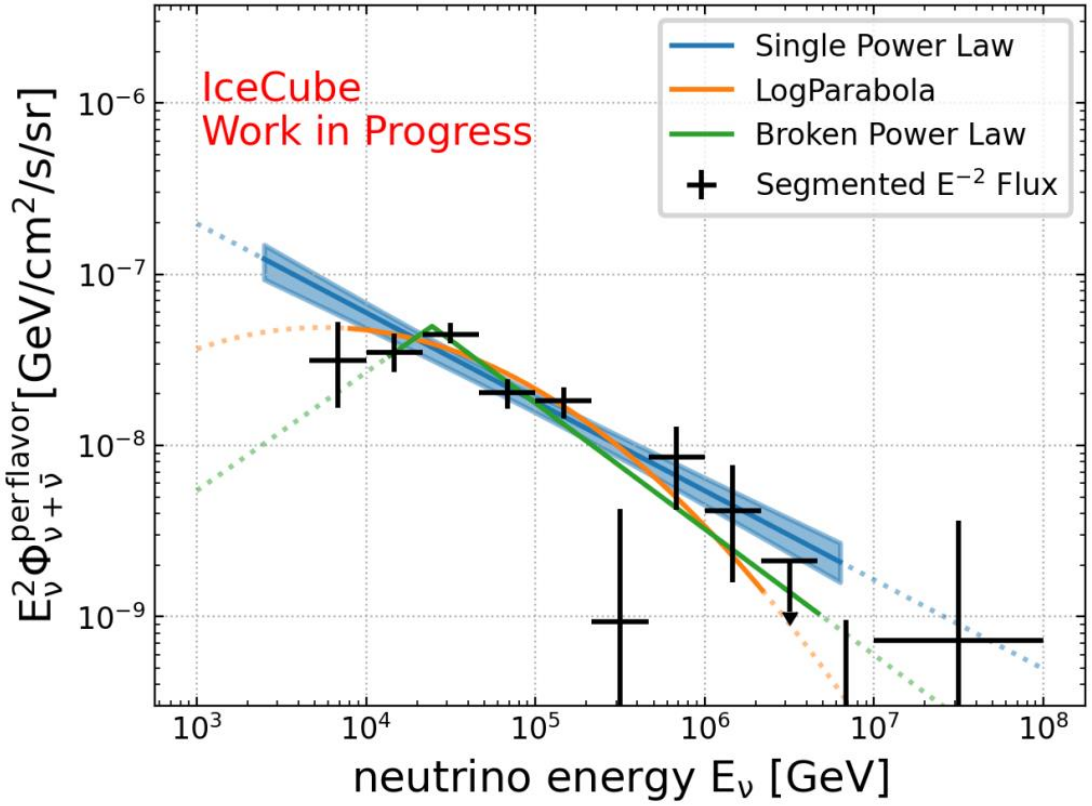


IceCube Highlights

- Observed O(1M) atmospheric neutrinos and O(100-1k) astrophysical neutrinos
  Astrophysical events number depends on how you count (e.g. above background or not)

PoS(ICRC2023)1064



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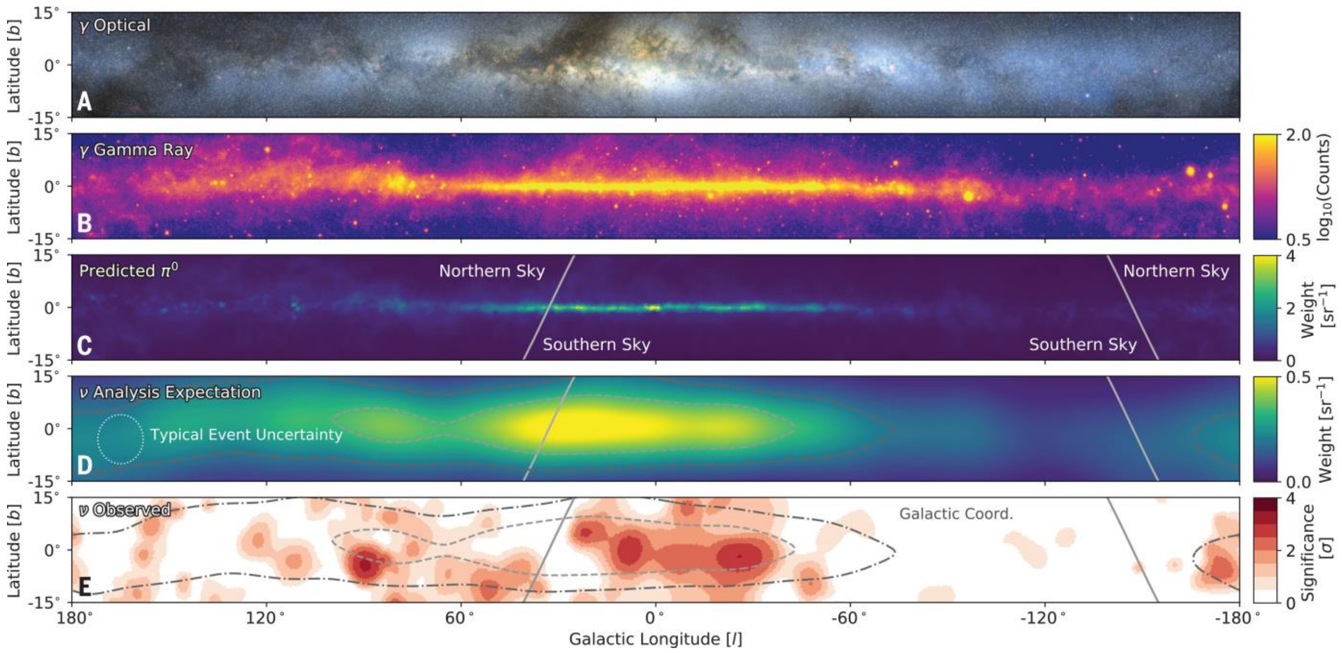
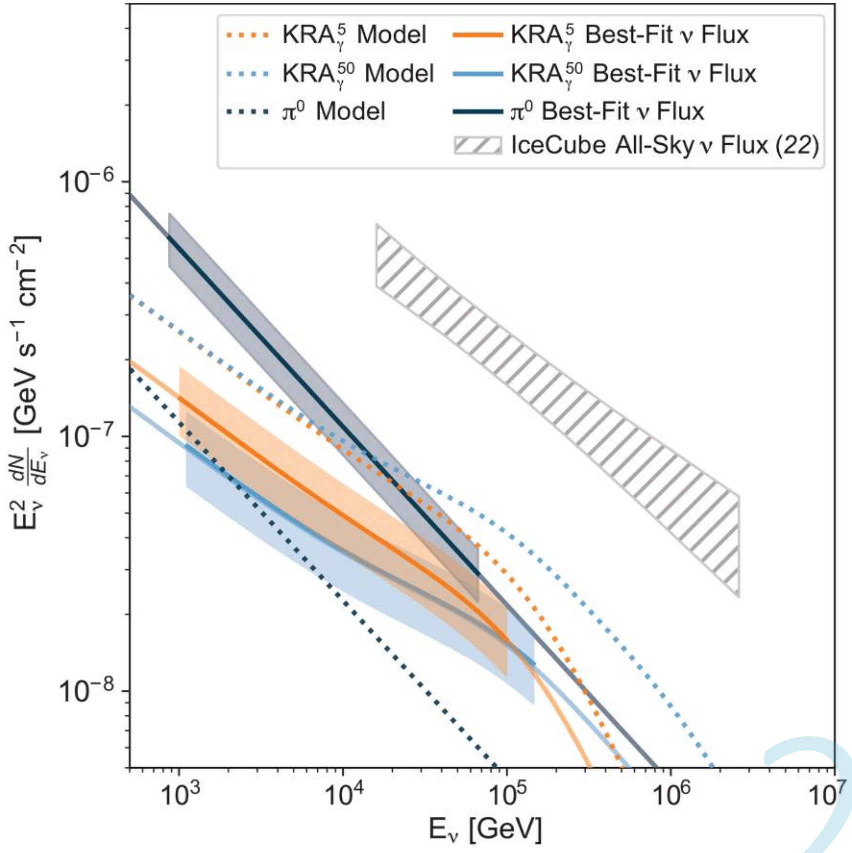
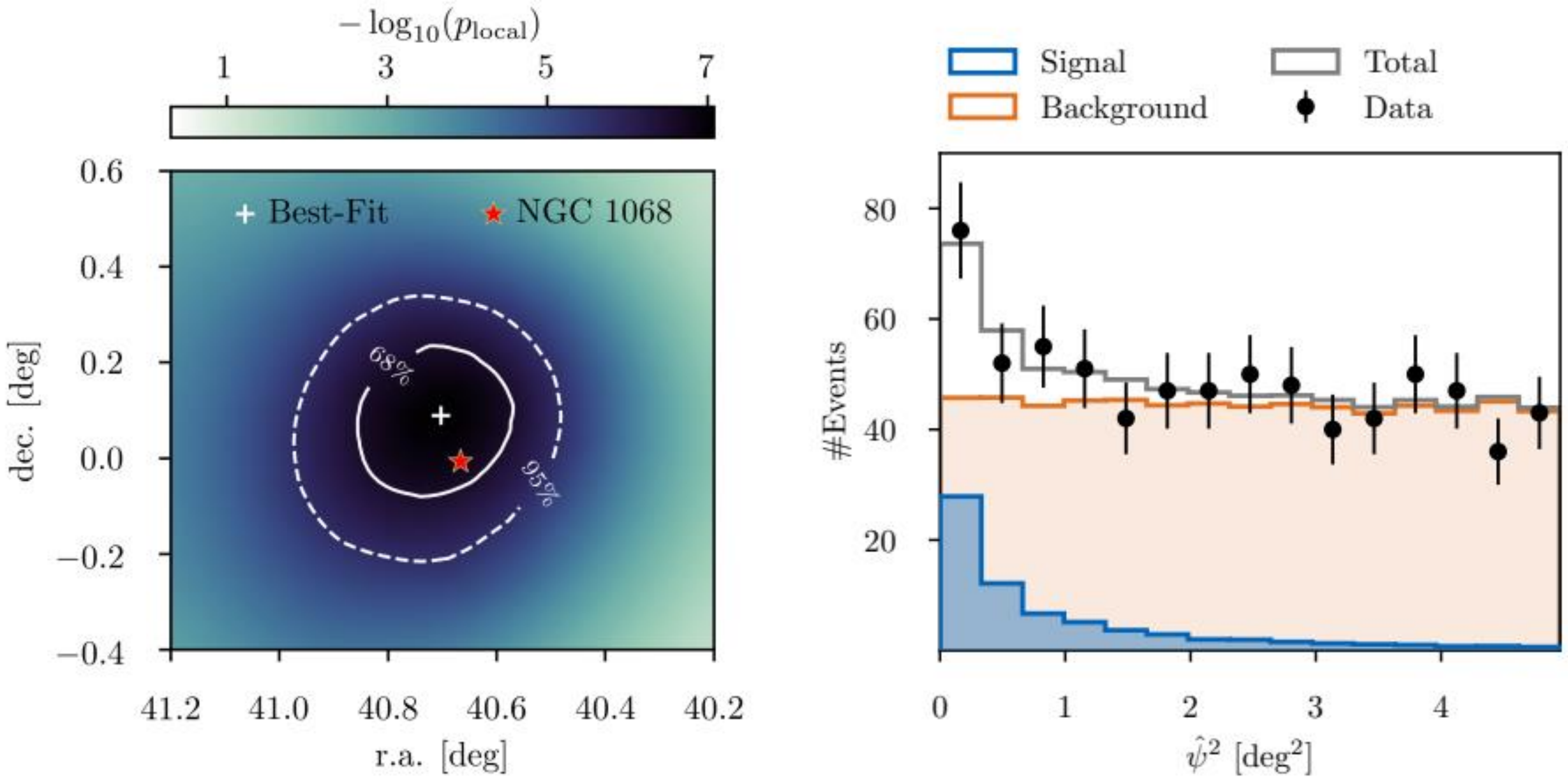
Science 380 (2023) 1338





IceCube Highlights

- First identifications of steady neutrino emitter

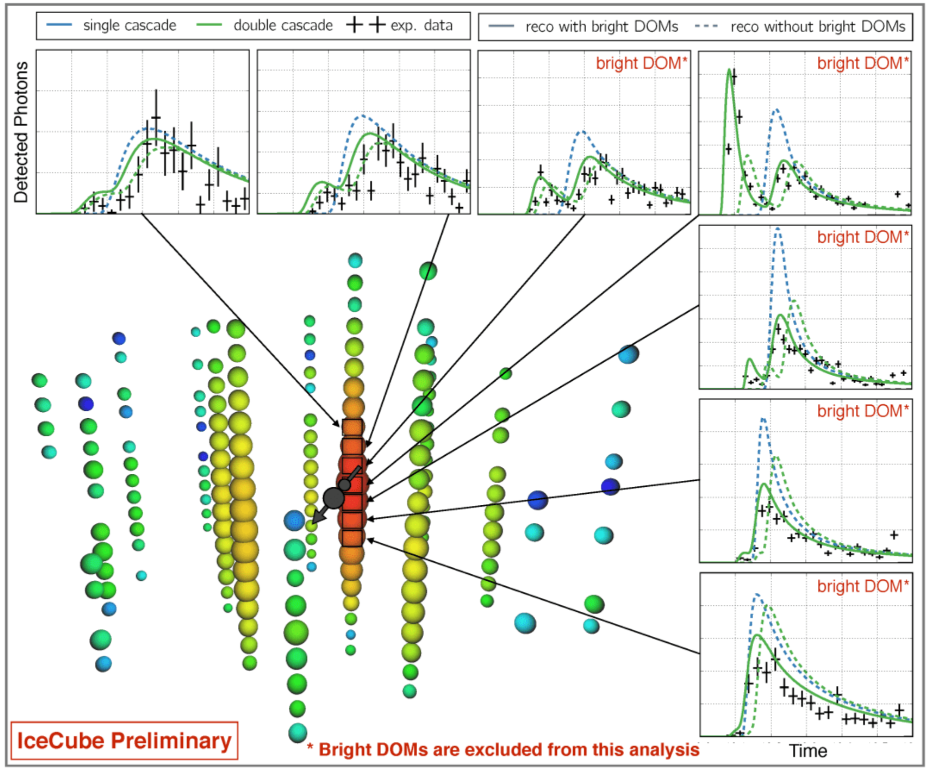


Science 378, 6619, 538-543 (2022)

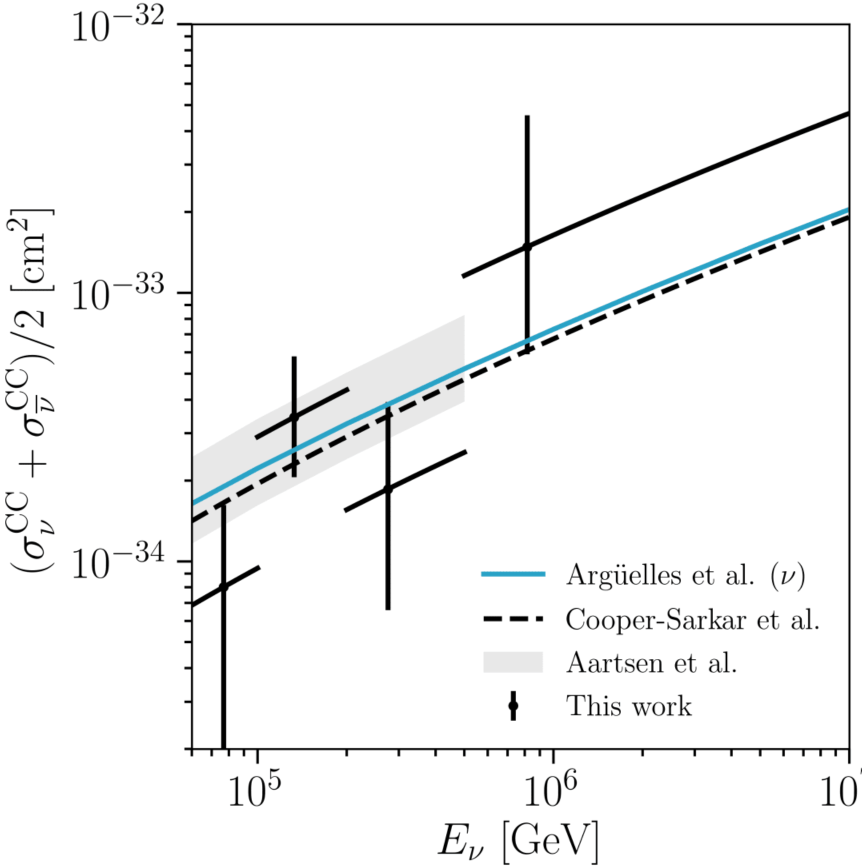
IceCube Highlights

- Studies of cross section and flavor composition of astro flux

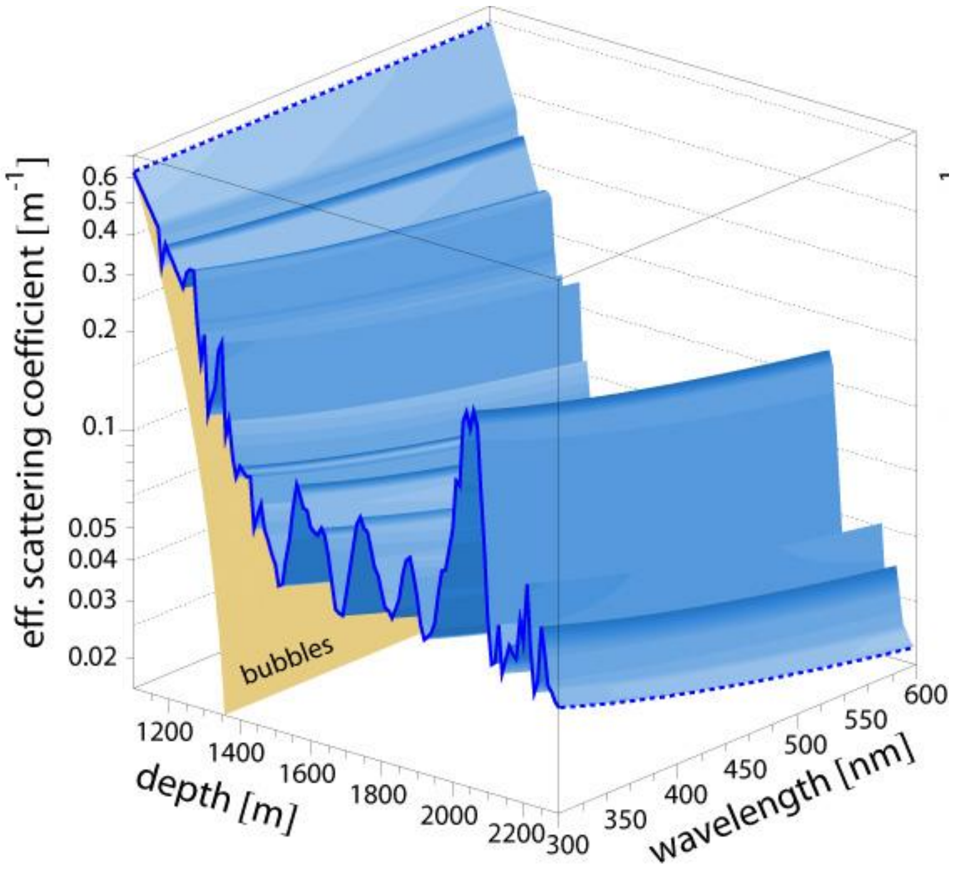
Eur. Phys. J. C 82, 1031 (2022)

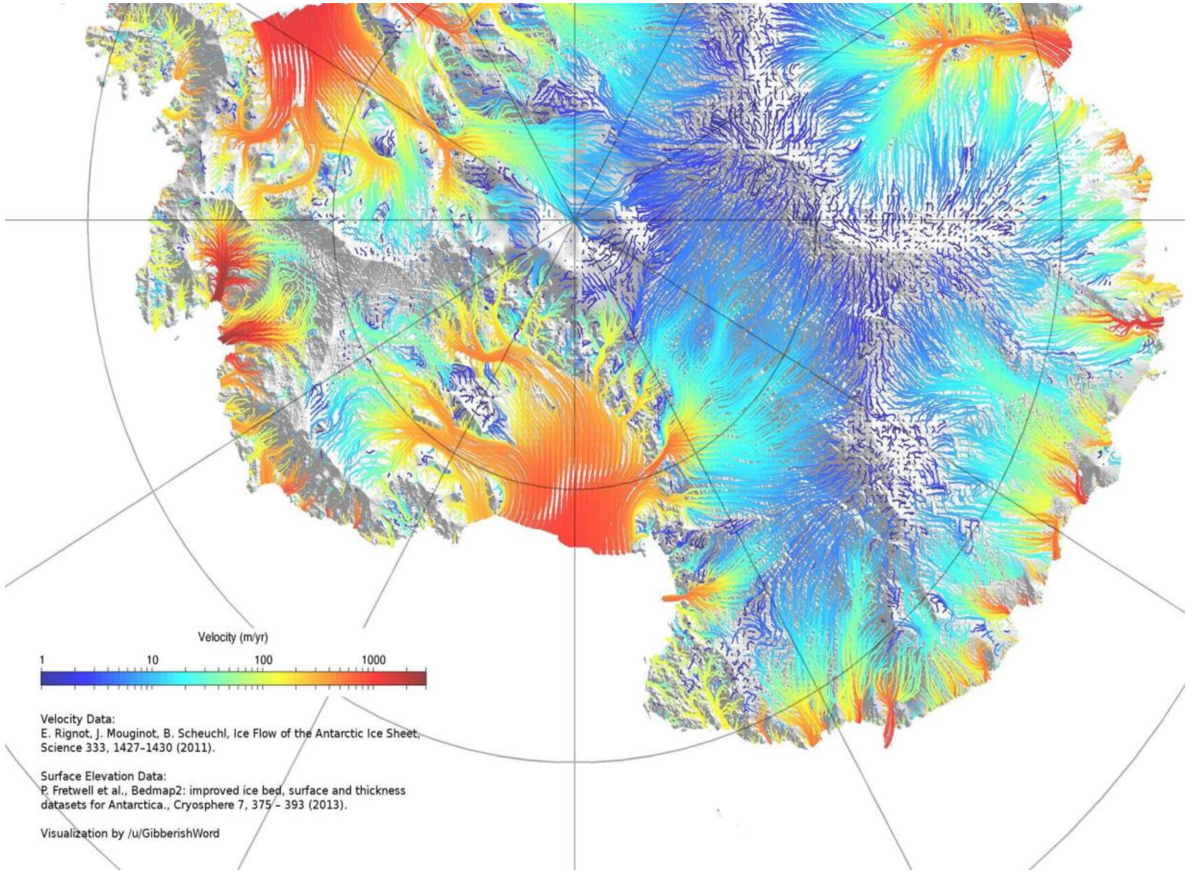


Phys. Rev. D 104, 022001 (2021)



IceCube challenges





IceCube challenges

Why not go back to the ocean?

In the deep ocean

- light is minimally scattered
- absorption lengths are tens of meters
- sensors can be deployed from a ship
- repairs and relocation are possible
- logistics should be relatively simple

Projects already under construction:

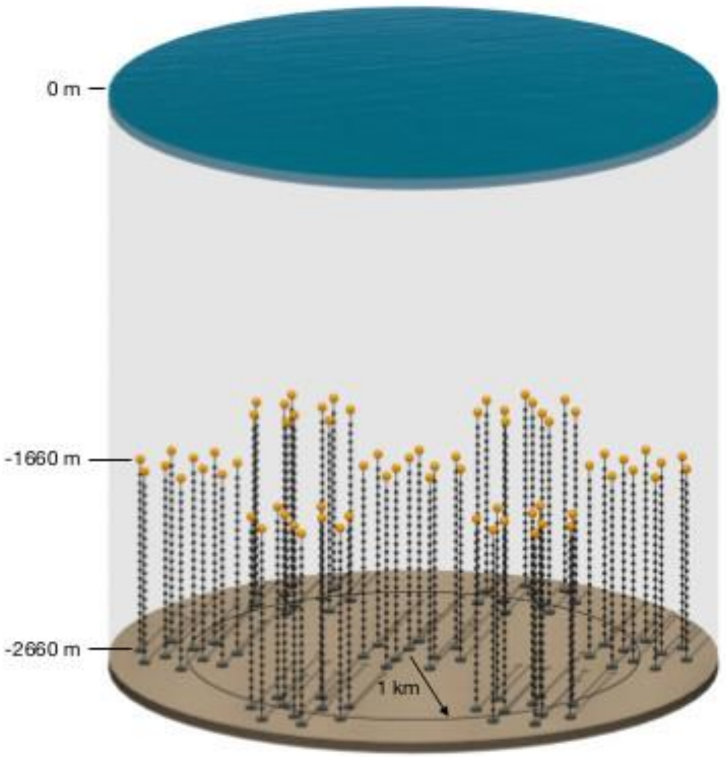
- Km3NeT – Mediterranean sea
- GVD-Baikal – Lake Baikal

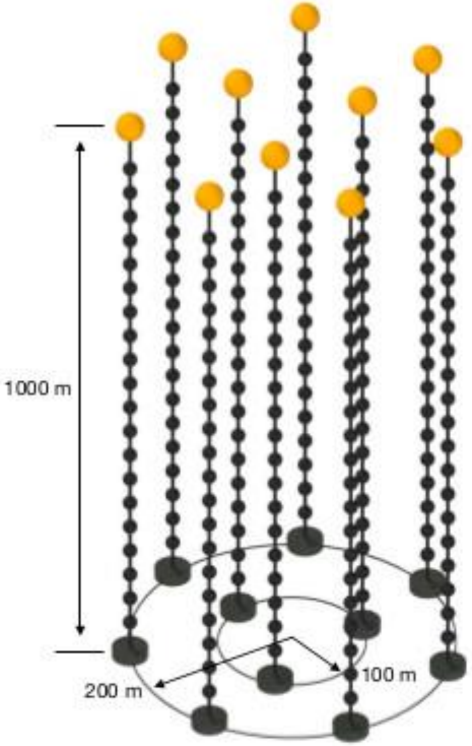
Not without challenges to reach km^3 scale

The Pacific Ocean Neutrino Experiment P-ONE

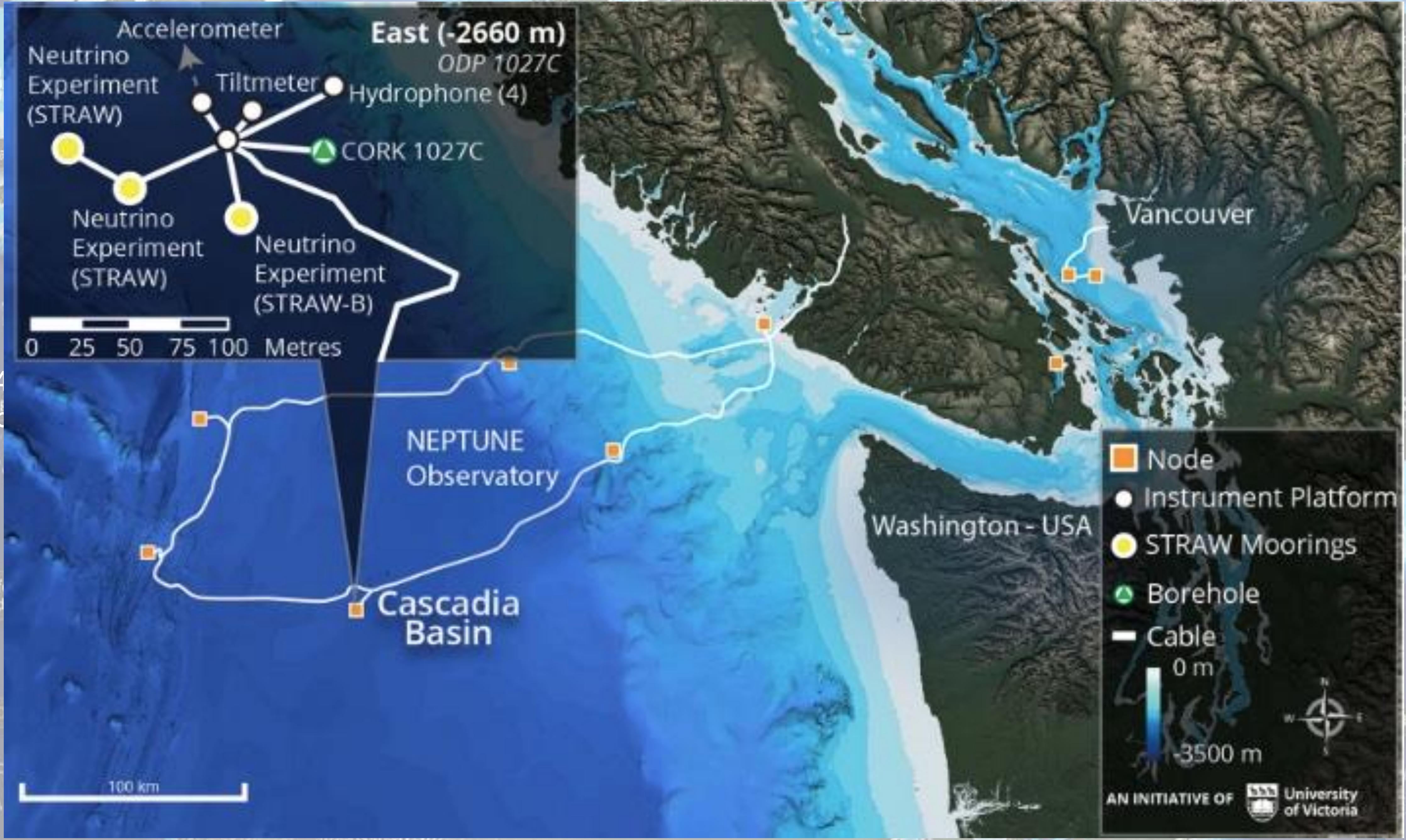
The Pacific Ocean Neutrino Experiment

- A neutrino telescope deep in the Pacific Ocean (Cascadia Basin, 2.6km depth)
- Aiming for **large volume** & **superb pointing resolution**
- Leveraging an existing investment: **Ocean Networks Canada (ONC)**
  - *Ocean observing facility*
  - *Goal is to support research*
  - *In operation since 2007*






OCEAN NETWORKS CANADA
CANADIAN INFRASTRUCTURE & PARTNERS
Resolute
Grise Fiord
To Cape Herschel, CFS Alert & Thule Research Station
Arctic Research Station
Gascoyne Inlet
Clyde River
Pond Inlet
Qikiqtarjuaq
Arctic Drifter Buoys
Coastal Community Ocean Observers Program
Gjoa Haven
Greenland Institute of Natural Resources
Kugluktuk
Canadian Ranger Ocean Watch Program
Cambridge Bay
Existing Installation
Funded Installation
Potential Installation
Existing Mobile Asset
Potential Mobile Asset
Industry Partner
Science Partner
Data Centre
Ship-based Observing
Data Transfer Line
Fibre-optic Cable
University of Victoria
Line Papa
Prince Rupert
Kitamaat Village
Hartley Bay
Campbell River
Defence Research Hydrophone Experiment
Salish Sea Marine Survival Program
Tofino
NEPTUNE
University of Victoria
VENUS
Neutrino Observatory
Mill Bay
Hudson Bay
Churchill
SmartBay
Defence Research & Development Canada CODARs
FORCE
OTN/DFO Halifax Line
Great Lakes
University of Waterloo
PACIFIC OCEAN
ATLANTIC OCEAN

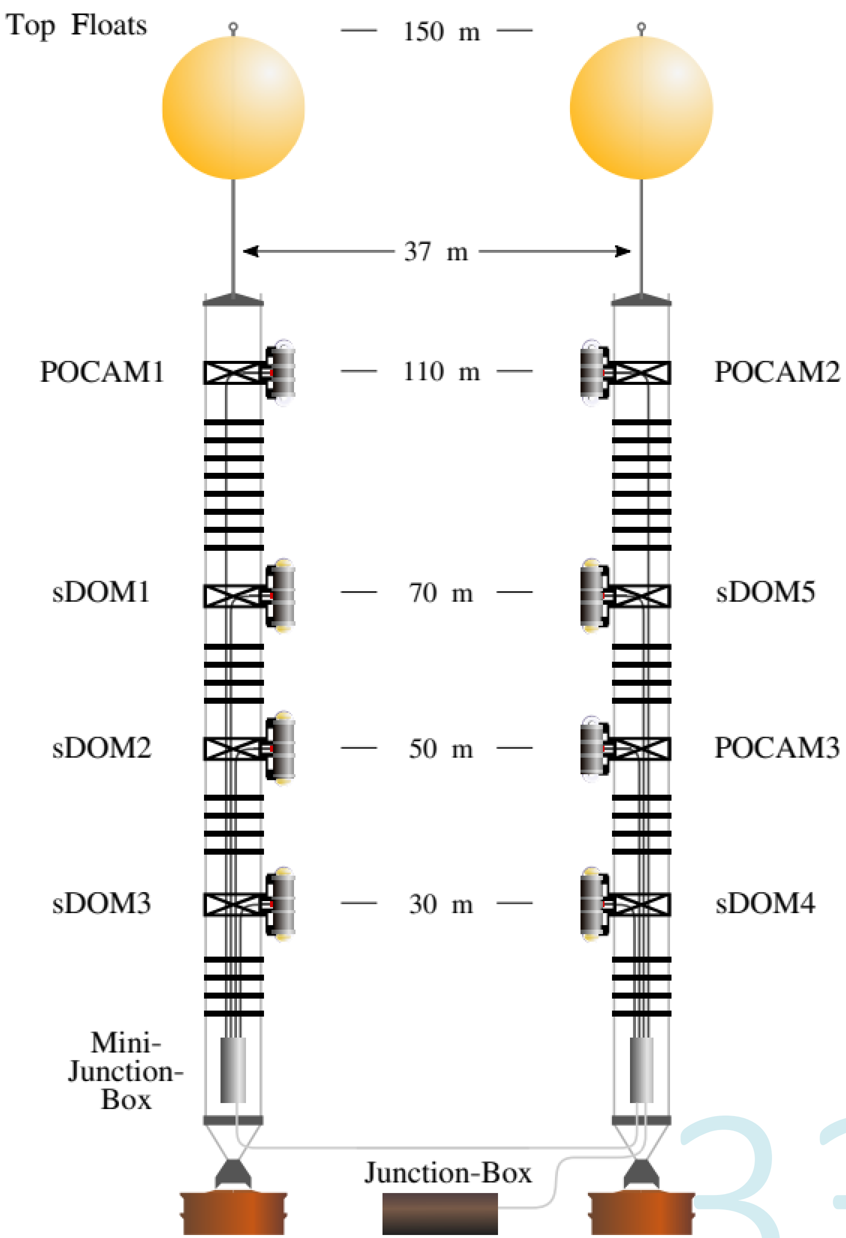


Accelerometer
East (-2660 m)
ODP 1027C
Neutrino Experiment (STRAW)
Tiltmeter
Hydrophone (4)
CORK 1027C
Neutrino Experiment (STRAW)
Neutrino Experiment (STRAW-B)
0 25 50 75 100 Metres
Vancouver
NEPTUNE Observatory
Washington - USA
Cascadia Basin
100 km
Node
Instrument Platform
STRAW Moorings
Borehole
Cable
0 m
-3500 m
AN INITIATIVE OF University of Victoria

The pathfinder missions

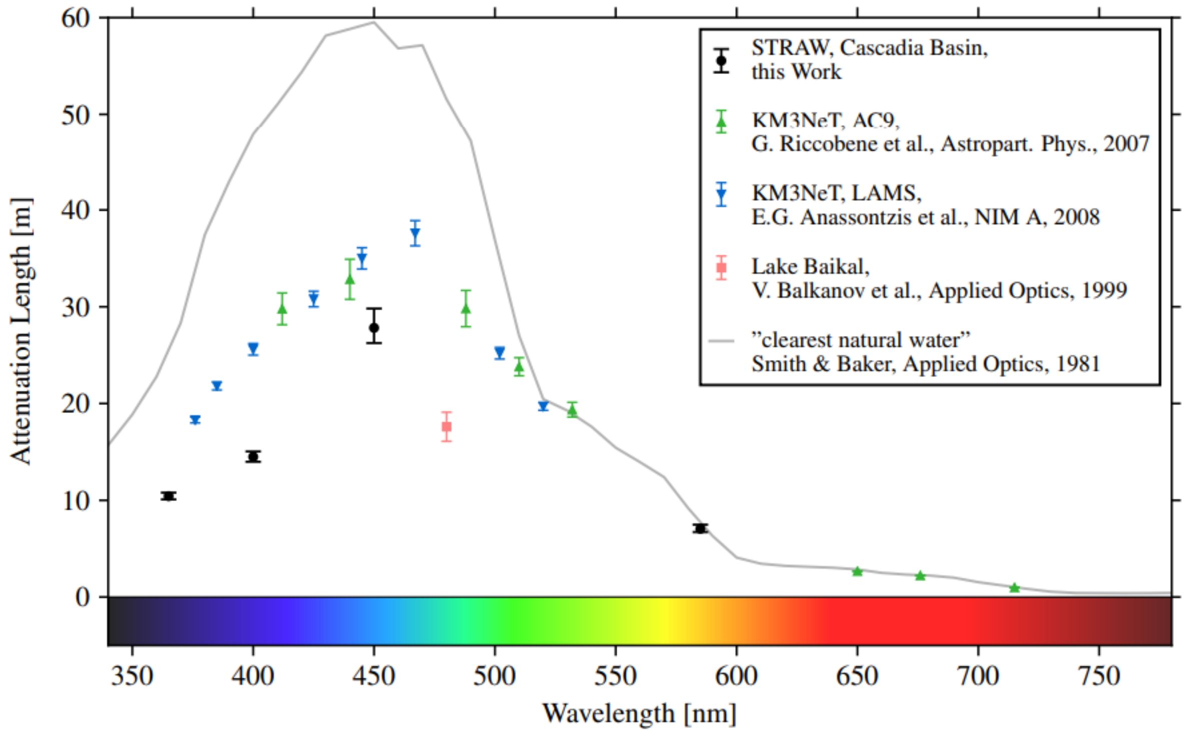
- STRings for Absorption length in Water - **STRAW**
  - Deployed in summer 2018, recovered in 2023 (98% uptime)
  - Array of PMTs and light emitters (POCAMs, originally developed for **IceCube**) to study the optical properties of the site
  - PMT rates continuously recorded over 5 years
  - High precision data collected in dedicated campaigns

2019 JINST 14 P02013

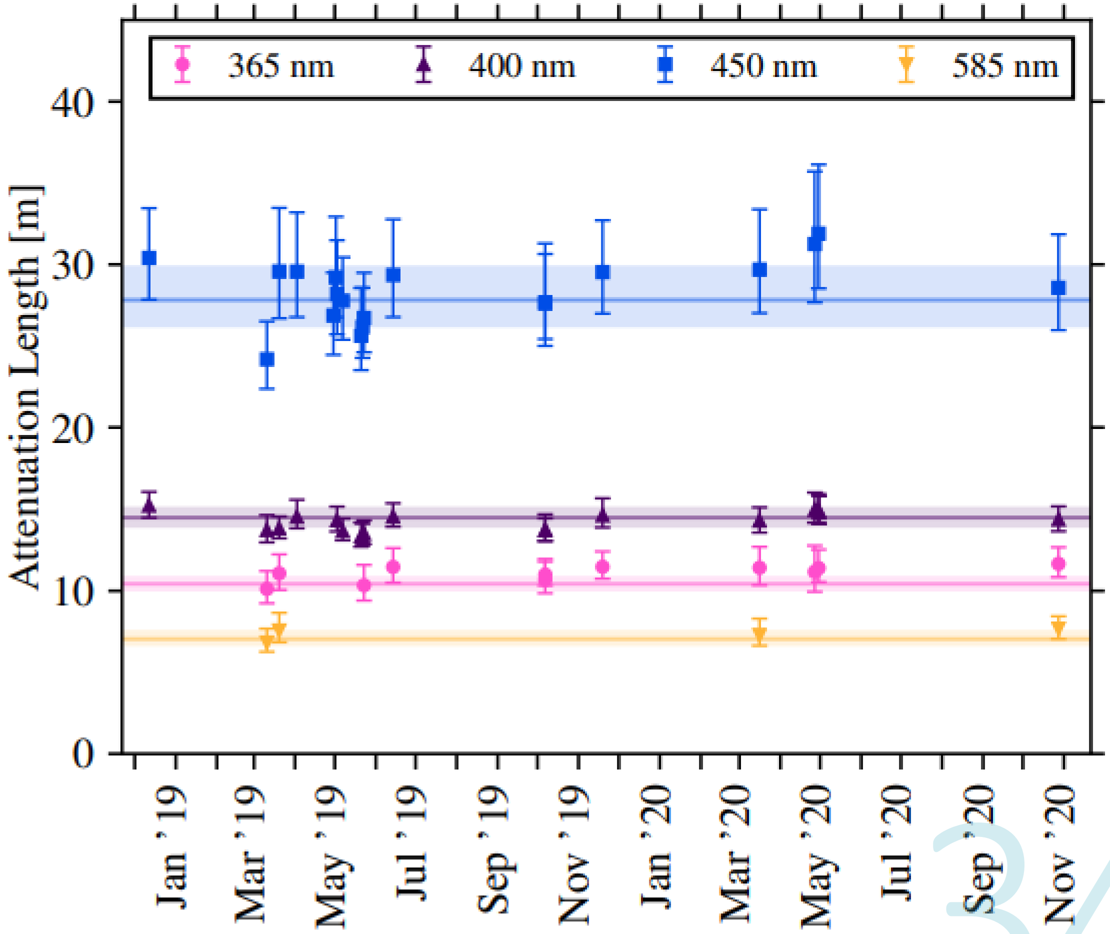


Optical transparency

- Attenuation length monitored over 2 years at 4 wavelengths
  - Measured $27.7^{+1.9}_{-1.3}$m at 450nm – **good transparency**
  - **Stable** over the period of data collection
  - Comparable with measurements at KM3NeT sites



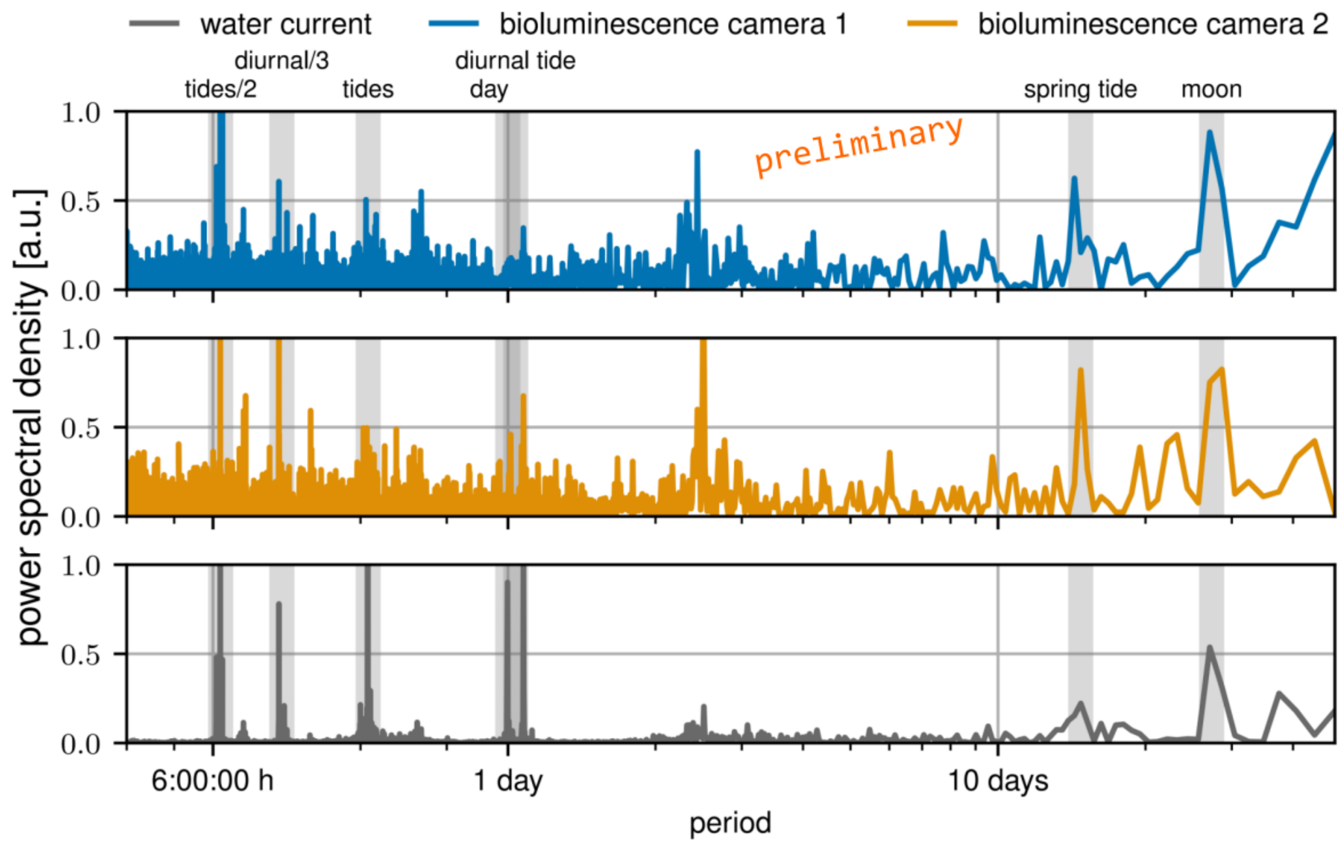
Eur. Phys. J. C 81, 1071 (2021)



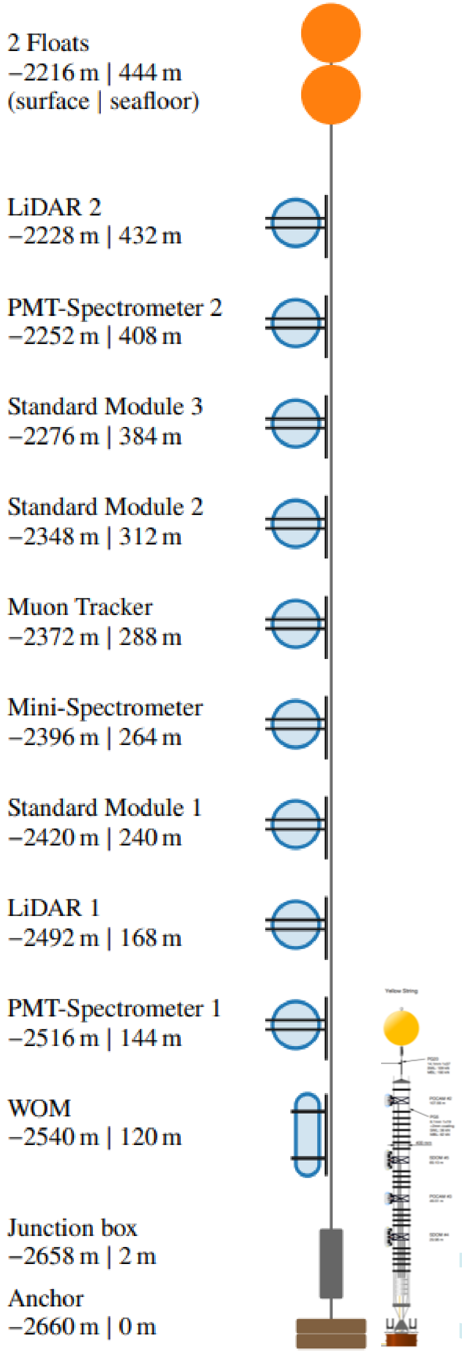
The pathfinder missions - b

- STRAW-b, a **400m+** long mooring line
  - PMT spectrometers, LiDARs, cameras and ambient sensors
  - Study site (bioluminescence) and deployment ideas

K. Holzapfel, et al., PoS (2023), ICRC



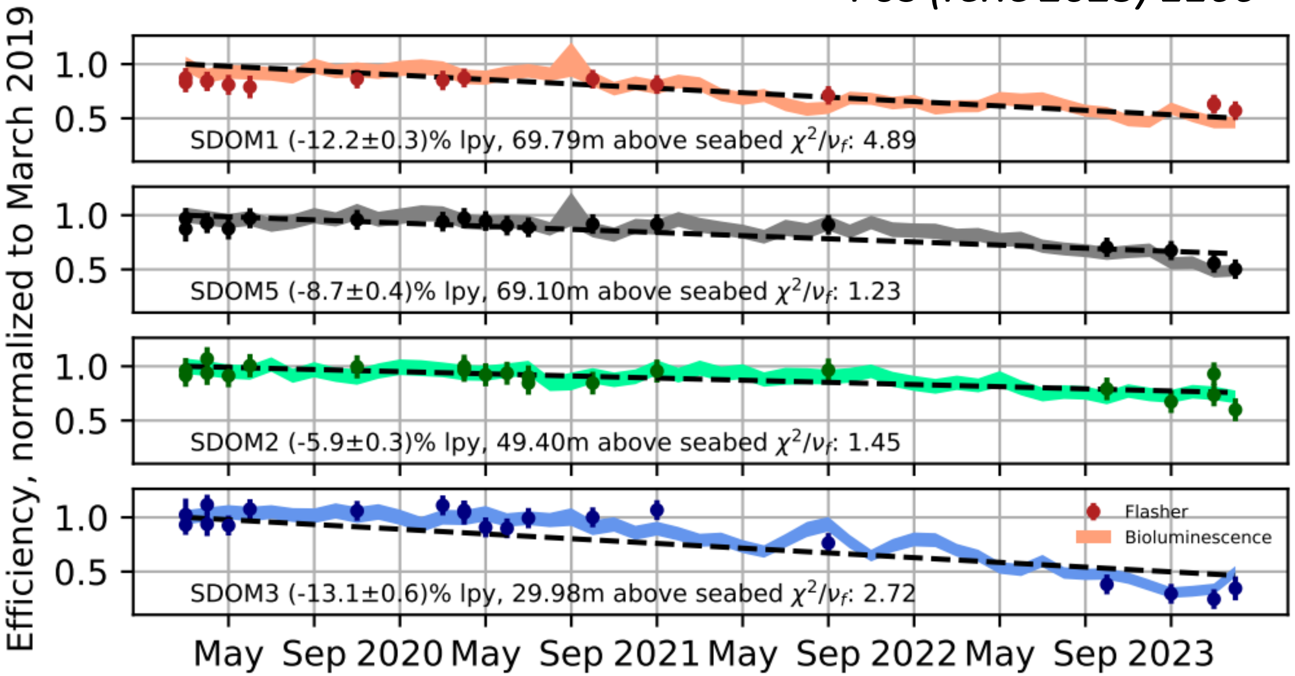
PoS (ICRC 2023) 1166
JINST 19 P05072

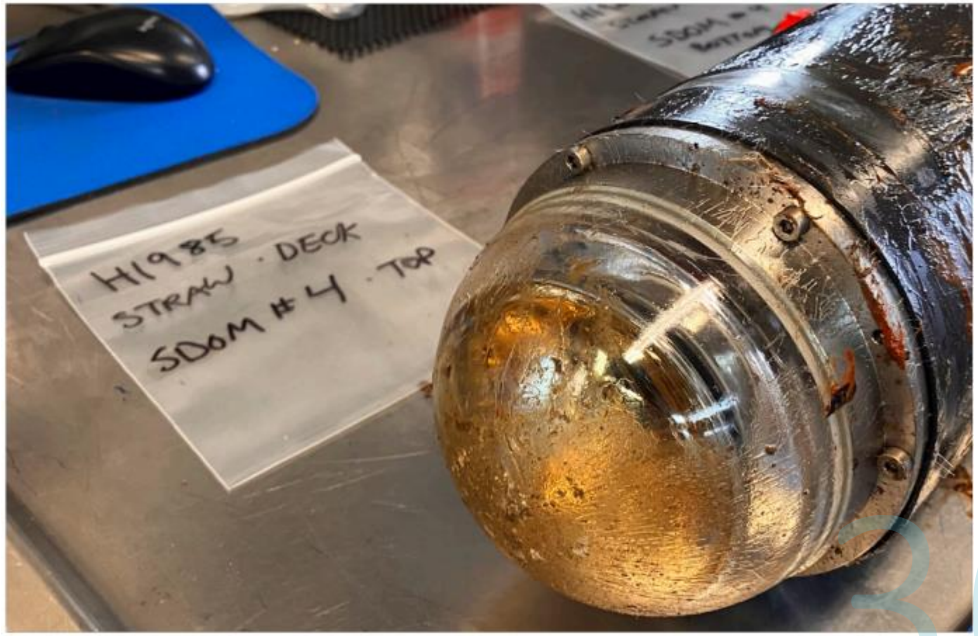


Sedimentation & biofouling

- Both systems were **recovered** in summer 2023
  - An inspection dive revealed sedimentation and biological growth
  - Loss of transparency confirmed in analysis
  - **Exploring** methods to mitigate this effect

PoS (ICRC 2023) 1166



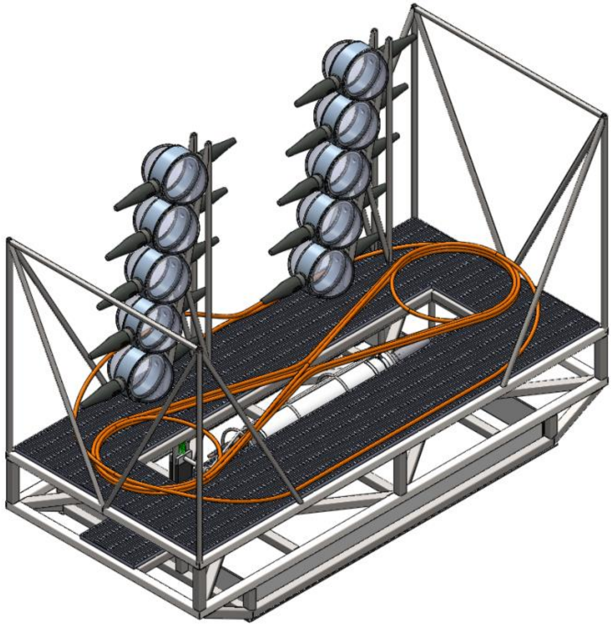


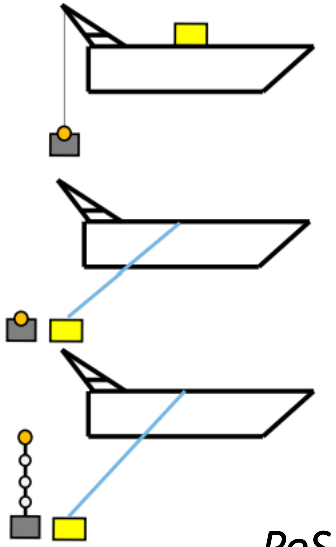
Towards a neutrino telescope in the Pacific

With lessons learned from KM3NeT and IceCube

P-ONE line design

- Mooring lines 1km long with 20 modules
- Designed for sub-ns synchronization
- The P-ONE line is an attempt to **minimize risk**
  - Single cable contains communications, power and structural support
  - No penetrators or breakouts – **connectorless** design





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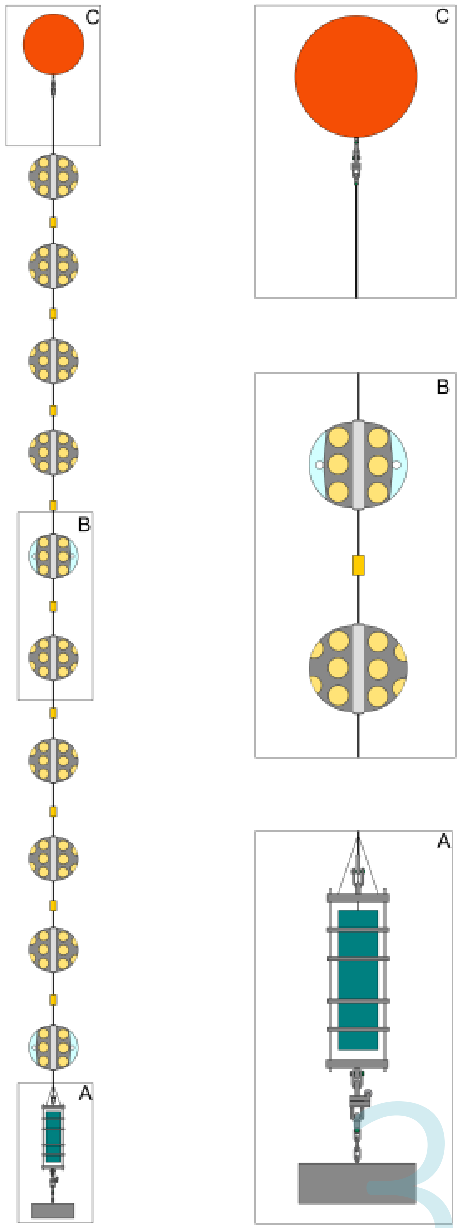


The P-ONE Optical Module (P-OM)

- The optical module follows the multi-PMT design from **KM3NeT**
  - 17” glass hemispheres coupled to a titanium cylinder
  - 16 x 3” PMTs point in all directions (Hamamatsu R14374-10)
  - Mounted on a 3D-printed structure
  - Modular, spring-loaded system
  - Individual gel pad couples PMTs to the glass hemisphere
  - PMT necks coated following **KM3NeT** advice

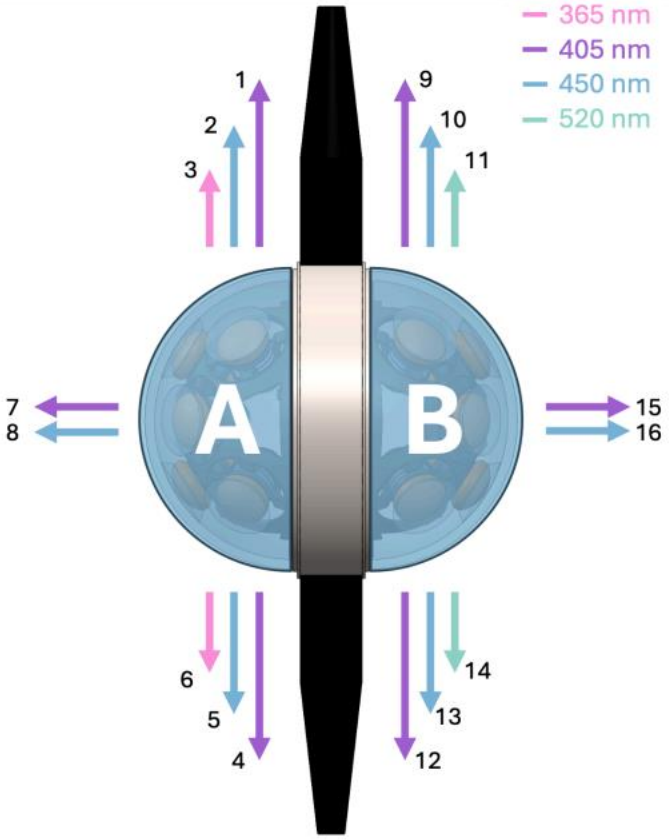
- Operation and DAQ highlights
  - Leveraging **IceCube’s** microBase for HV
  - Full waveform digitization (16 channel ADC)
  - Sampling rate 210 MSPS
  - Capabilities to buffer data (4GB in-module)

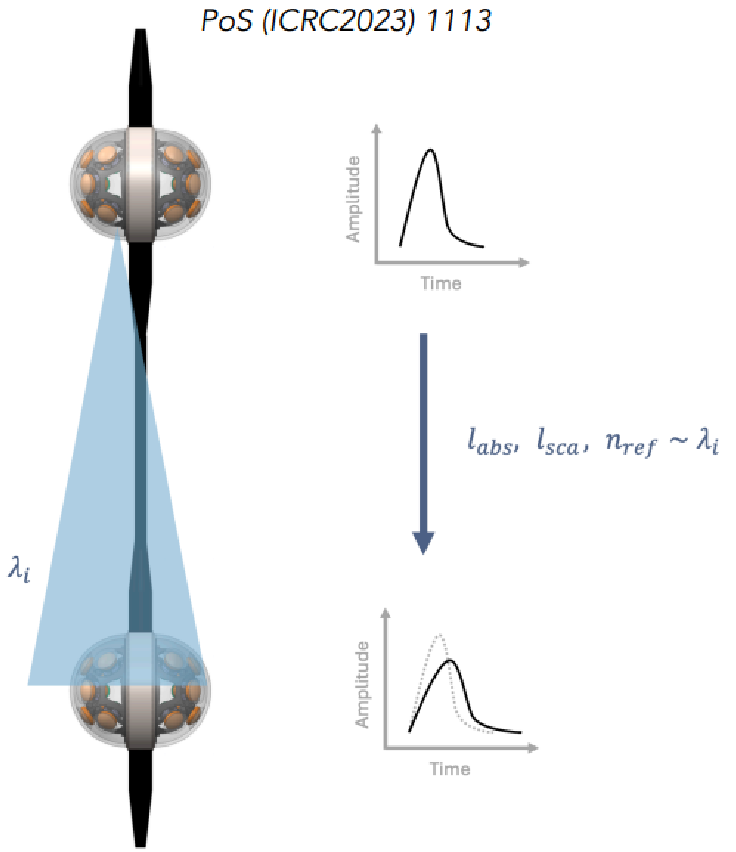
PoS (ICRC 2023) 1219

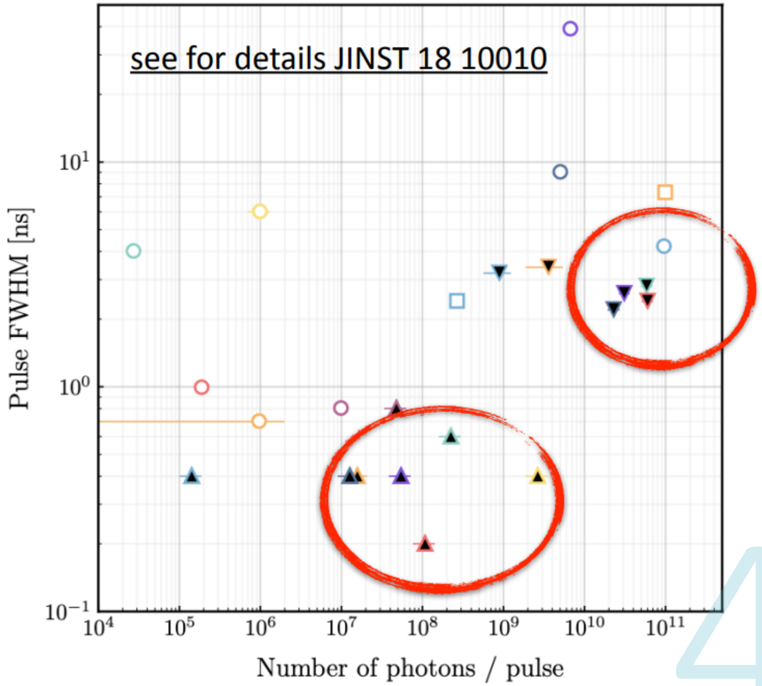
P-OM production in @TUM

The P-ONE Optical Module (P-OM)

- Loaded with calibration **LEDs**, lesson from **IceCube**
  - 16 emitters of multiple colors pointing in 4 directions
  - Enable studies of water column



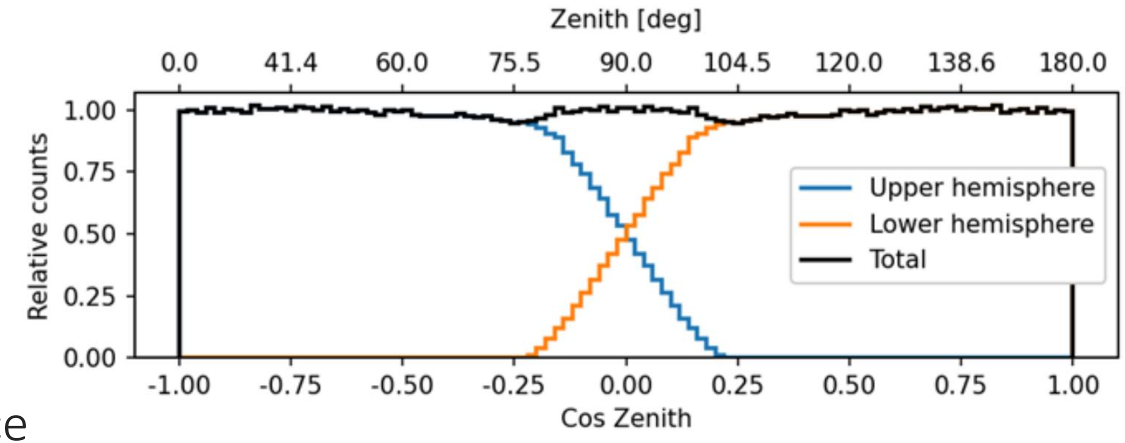


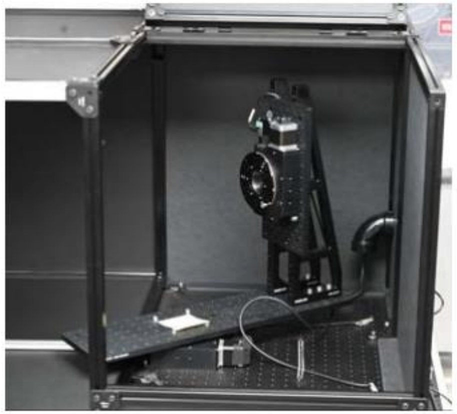


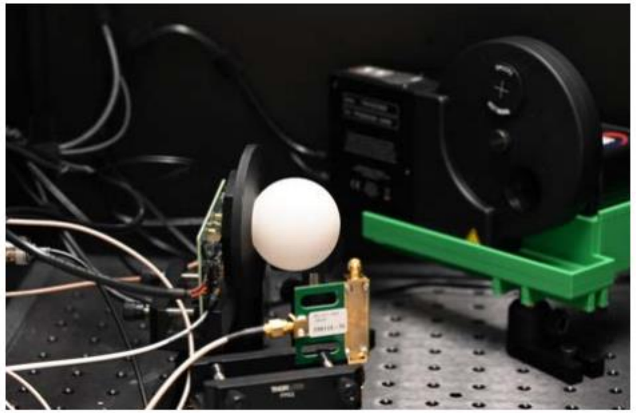
Calibration module (P-CAL) @SFU

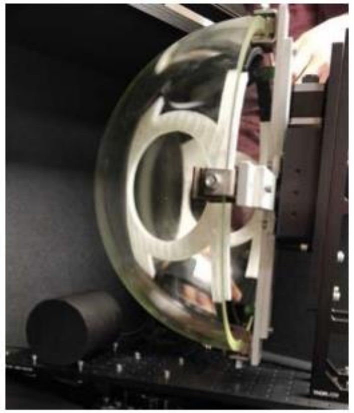
- P-ONE Calibration module inspired by **IceCube's POCAM**
  - Isotropic, bright and well understood light emission
  - Dual purpose: optical and position calibration
- Includes a **camera** with a fisheye les
  - To monitor bioluminescence and sediments
- It occupies the place of a regular module
  - Remove 4 PMTs per hemisphere to place a light source

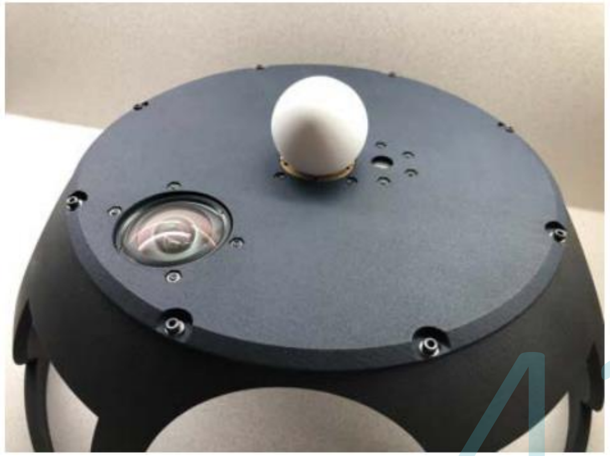
PoS (ICRC 2023) 1113





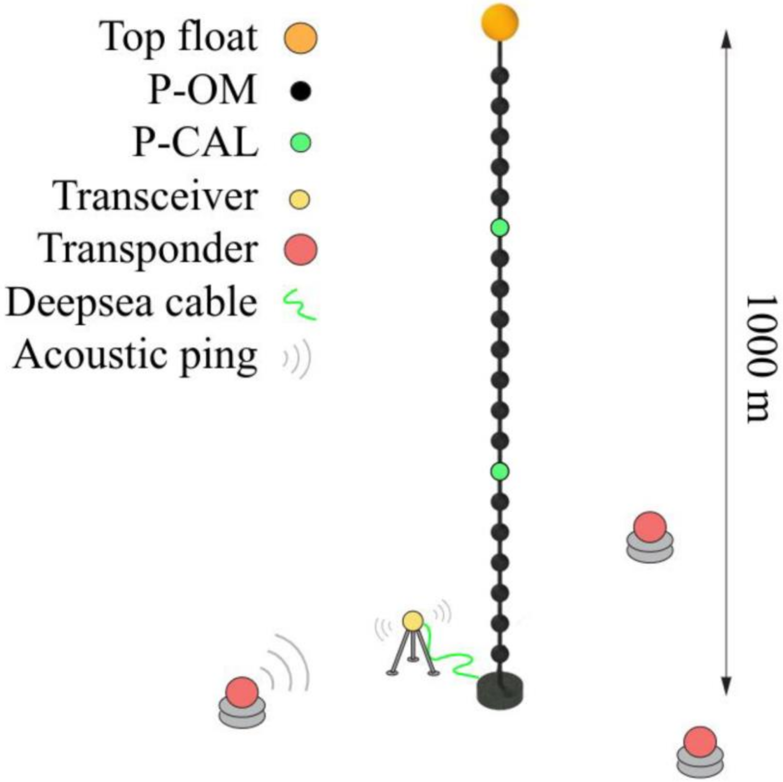


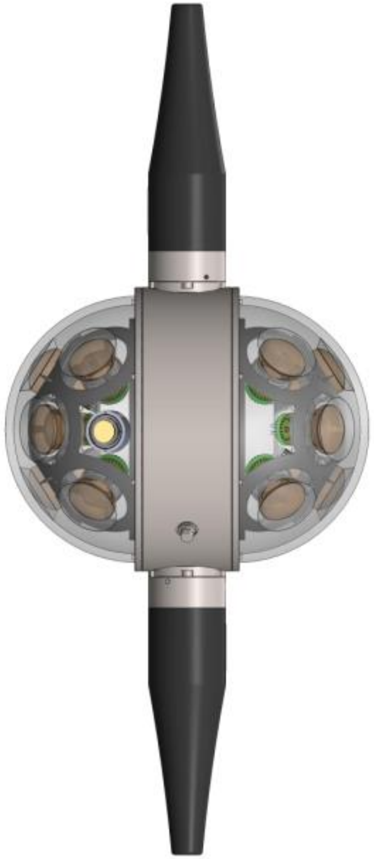


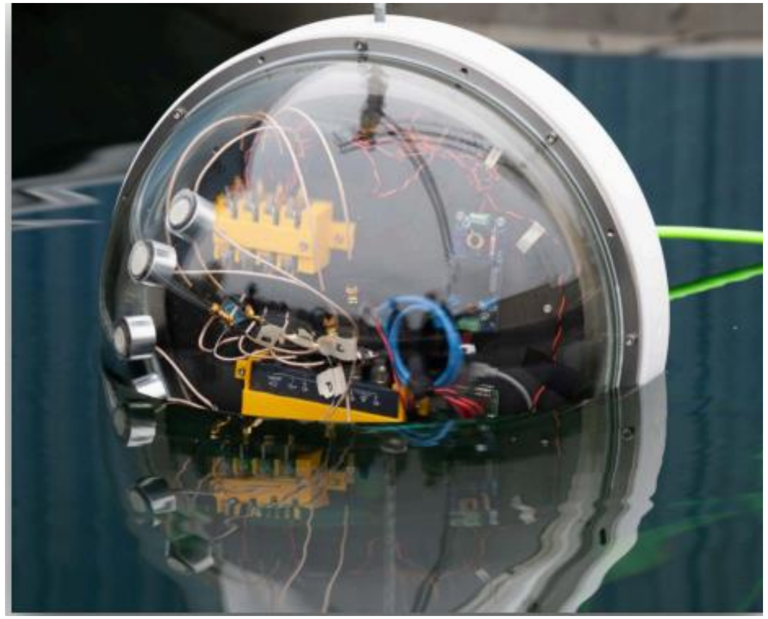


Positioning acoustic system @SFU

- Plan: P-CAL takes care of the position calibration of the detector
  - **Redundant** acoustic system for first deployments to prove it
  - 2x acoustic receivers (piezos) inside every module
  - Accuracy of @20cm expected





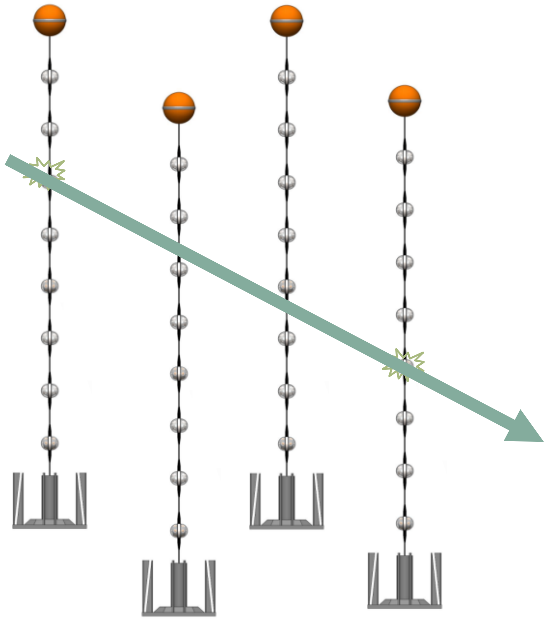


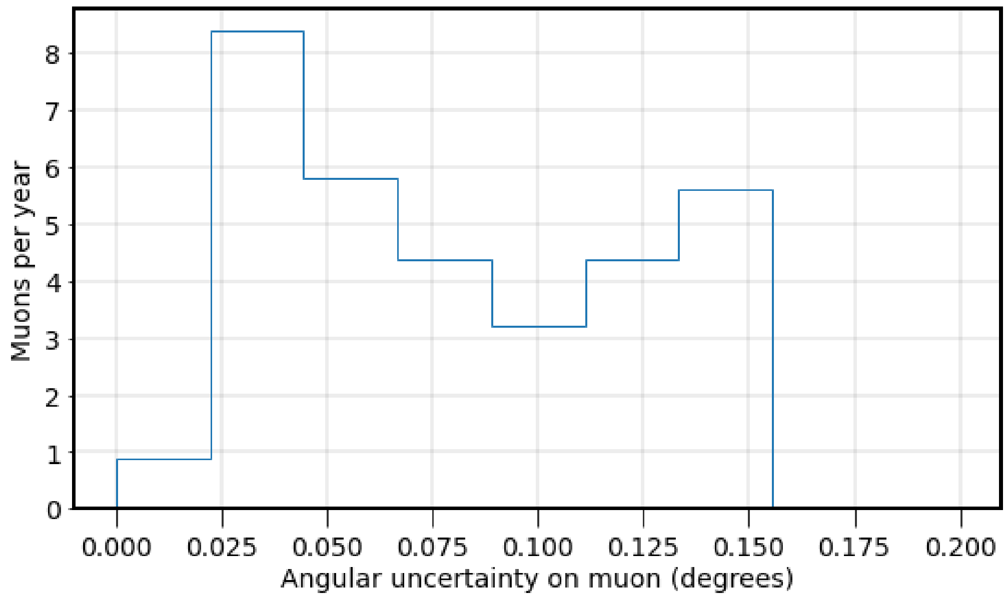
PoS (ICRC 2023) 1112

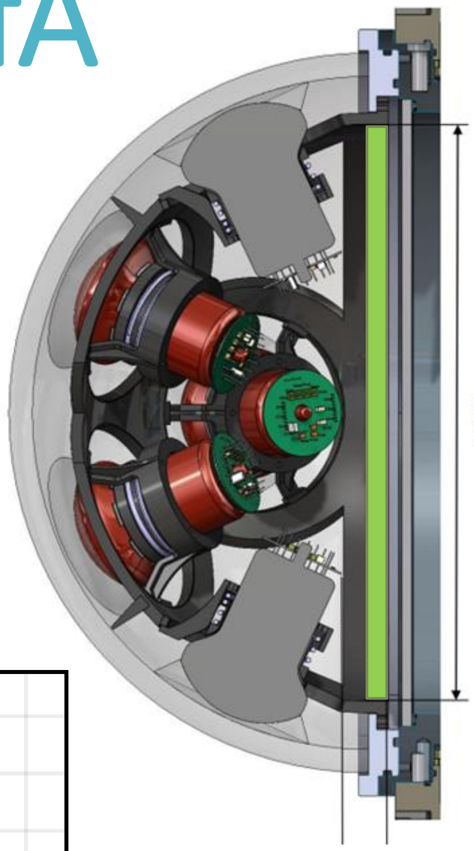
Muon In-Situ Tracker (MIST) @UofA

❖ Pointing calibration is ultimately based on MC
  - Moon/Sun shadows in CR help, but can we do more?

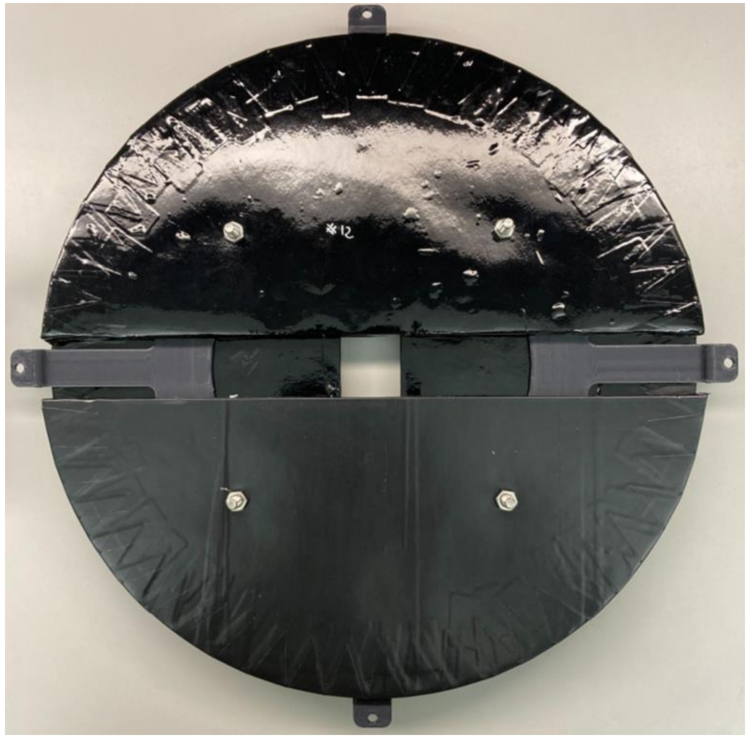
❖ Idea: tag **individual** cosmic muons going through modules
  - Use them to benchmark reconstruction resolution and bias using data
  - Simple system based on plastic scintillators that are inside every module

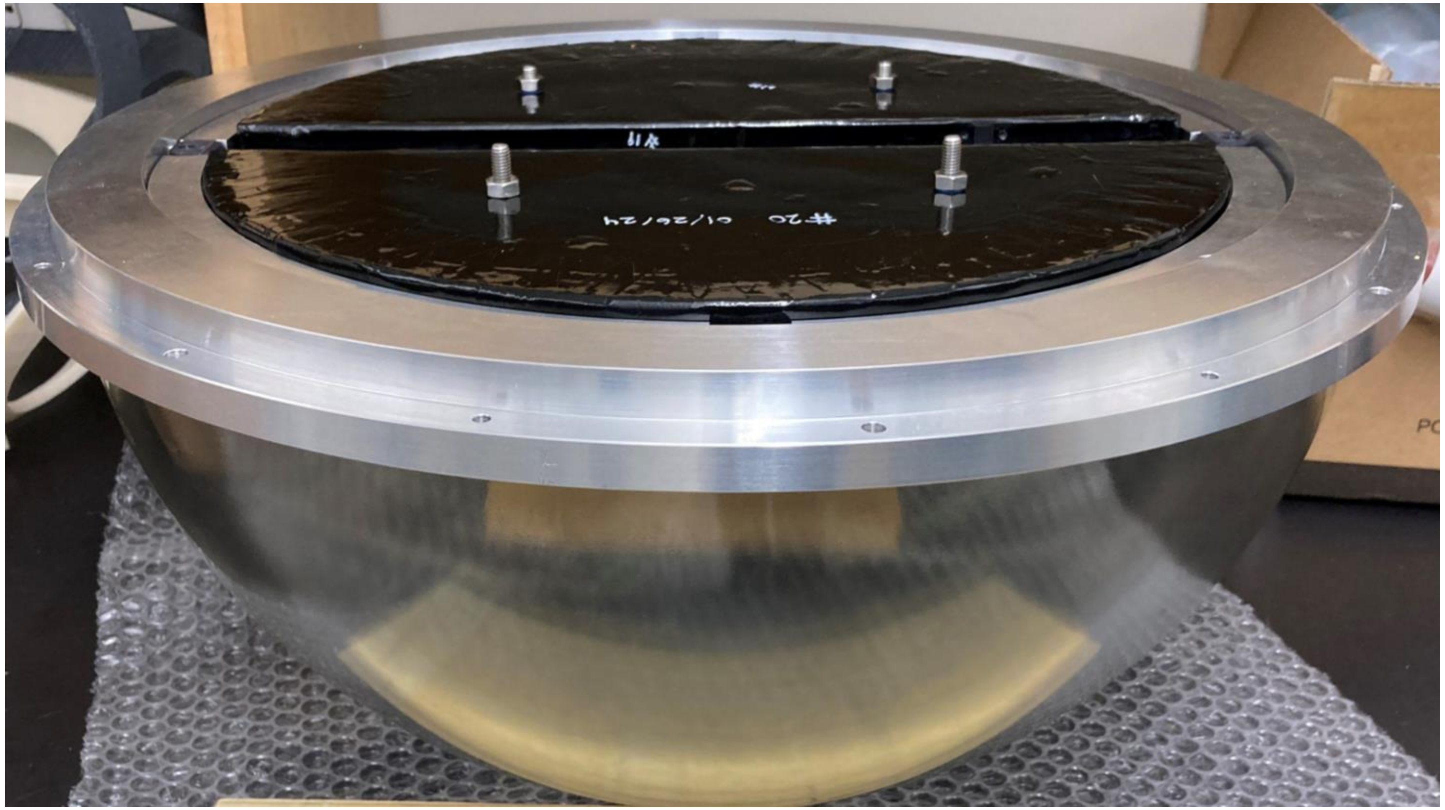






Muon In-Situ Tracker (MIST) @UofA

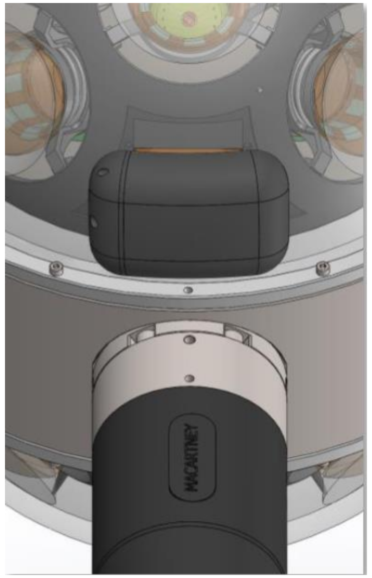


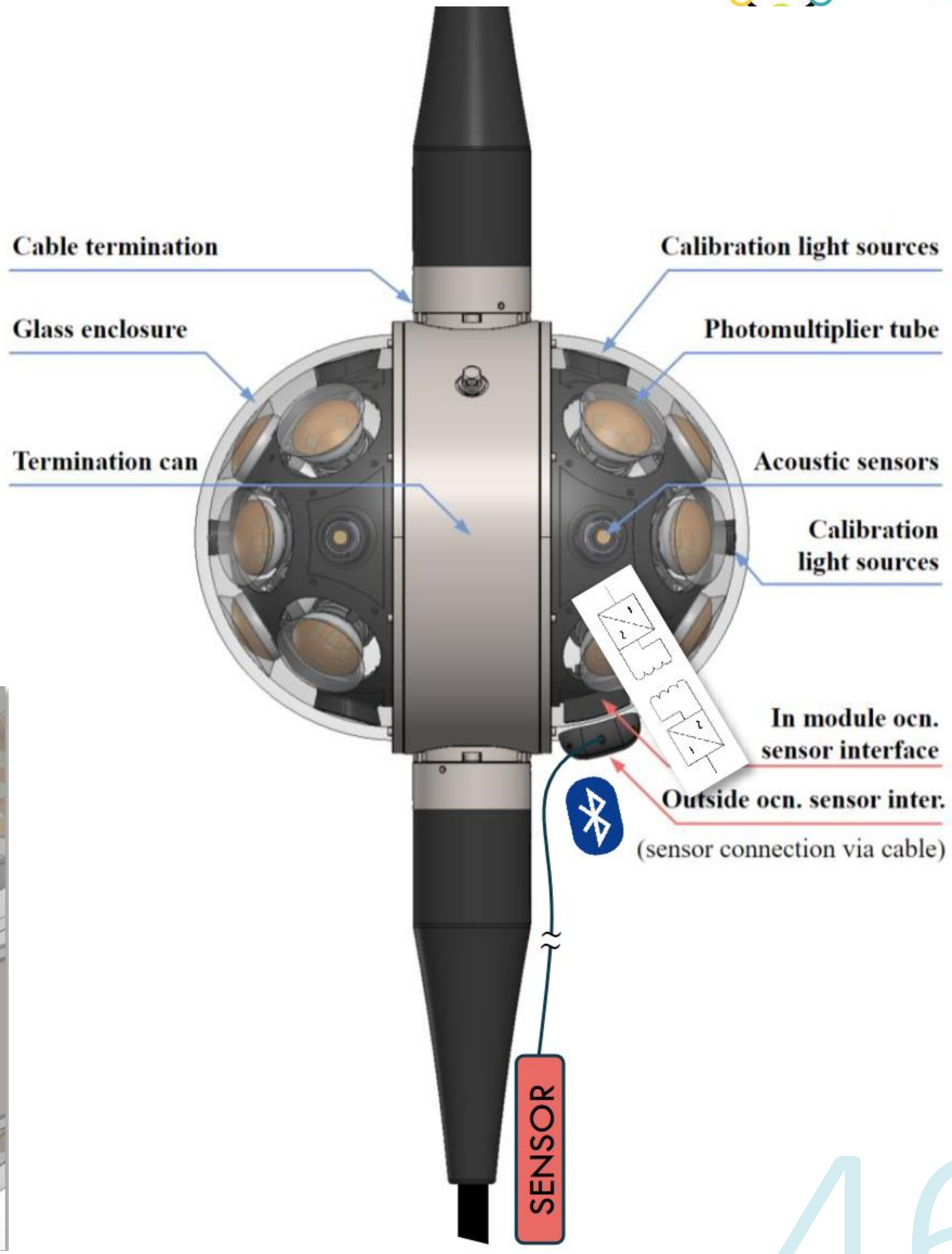


Ongoing projects

- Exploring coating options to prevent biofouling
  - Deploying a couple of spheres with coating in first line
  - Transmission degrades by 5%

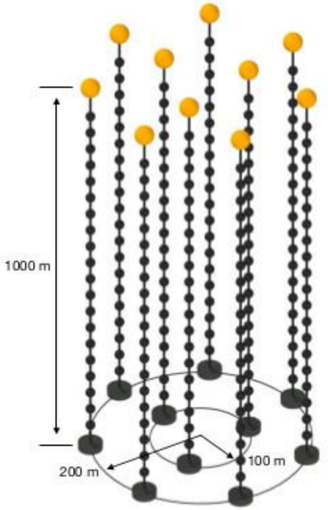
- Developing a device to communicate with outside
  - Low-power sensor in the water
  - Wireless power and communication
  - For multidisciplinary science

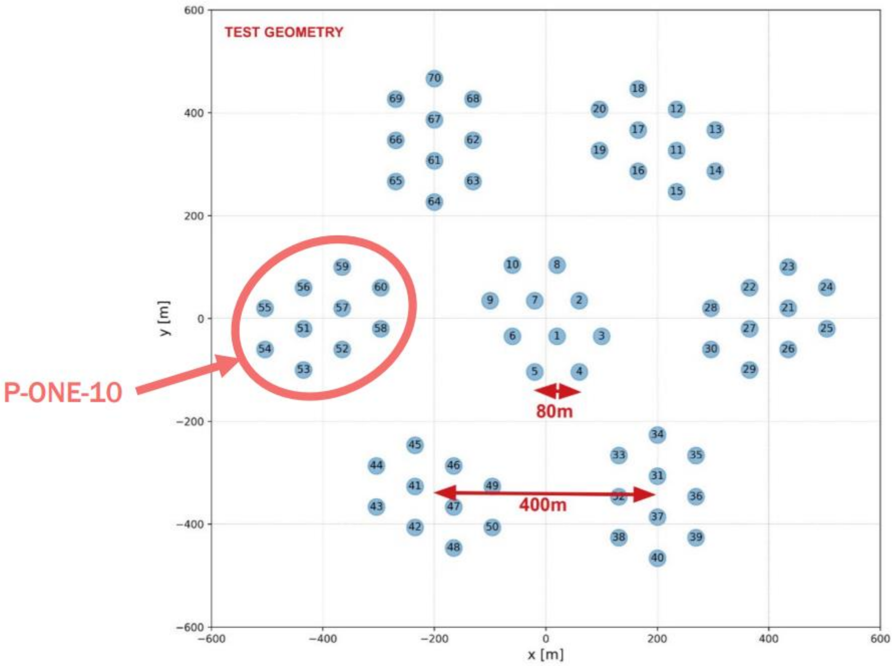


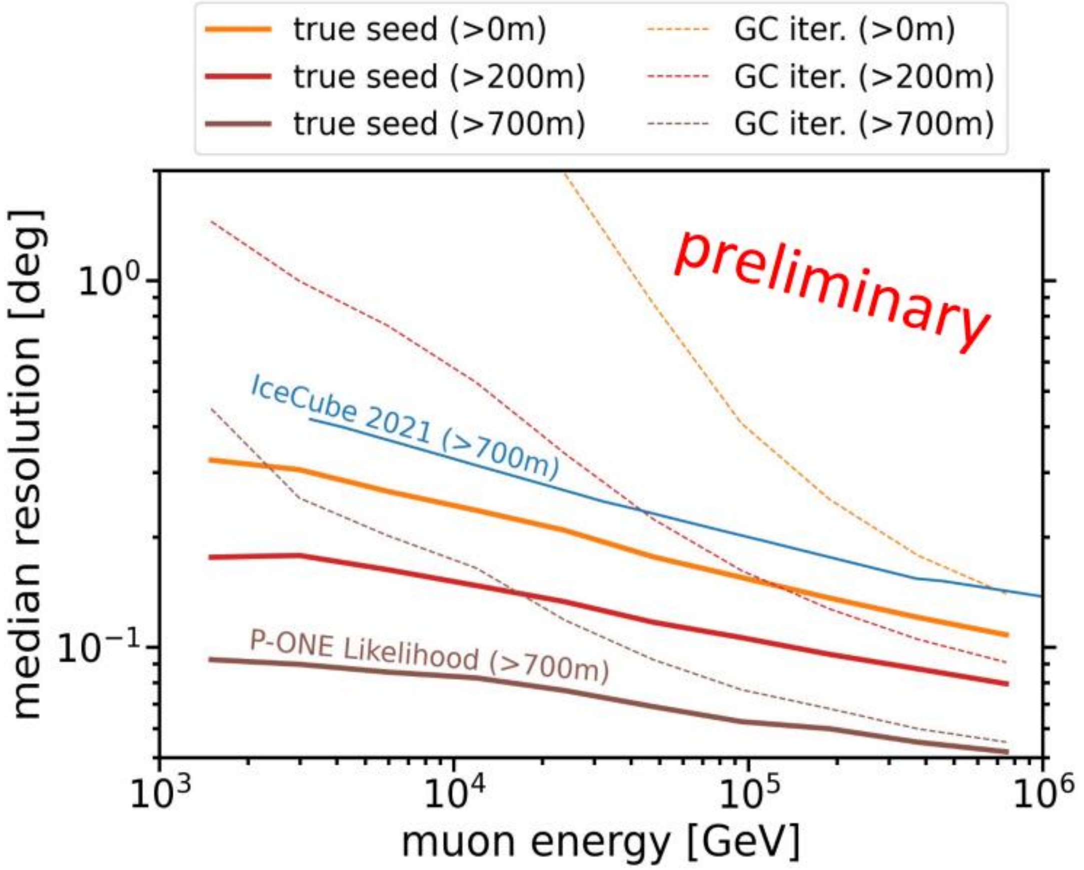


Geometry and performance studies

- Our **benchmark** geometry currently has
  - 70 strings, 80m separation
  - 20 modules per string, 50m apart
  - Infrastructure can support **up to 140 w/minimal upgrades**
- Studying **performance** and possible variations







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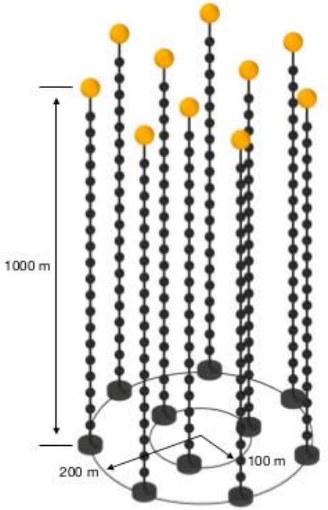
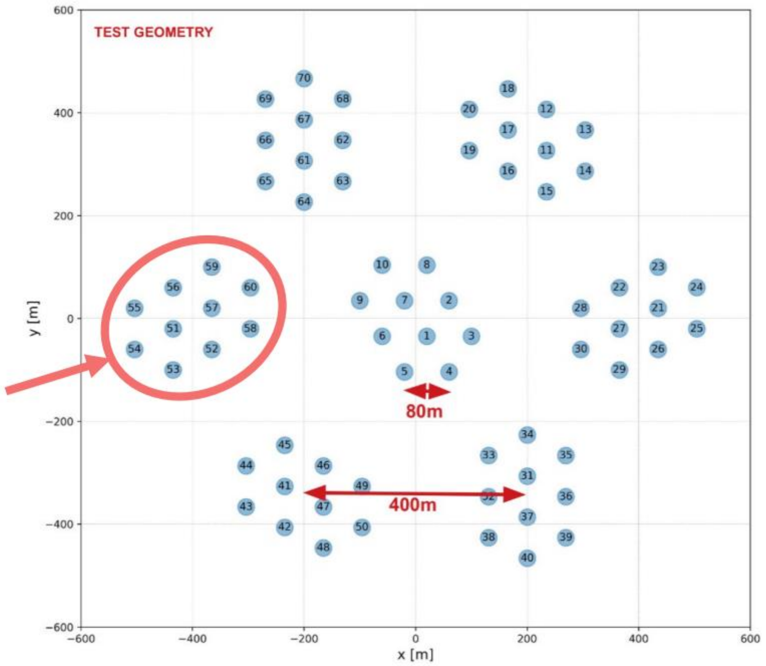
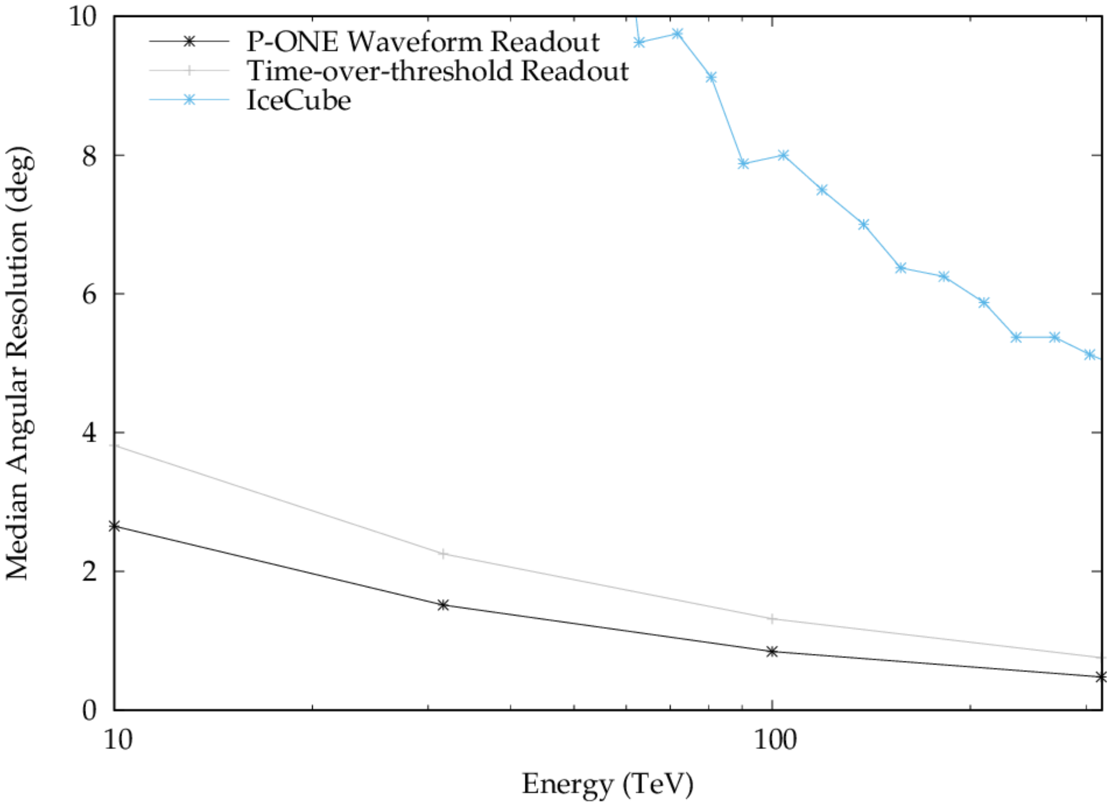
Geometry and performance studies

- Our **benchmark** geometry currently has
  - 70 strings, 80m separation
  - 20 modules per string, 50m apart
  - Infrastructure can support **up to 140 w/minimal upgrades**
- Studying **performance** and possible variations



P-ONE-10





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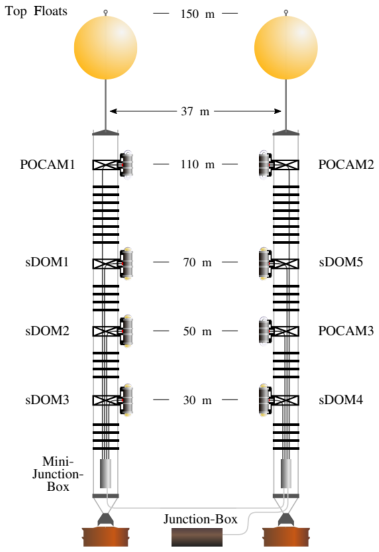
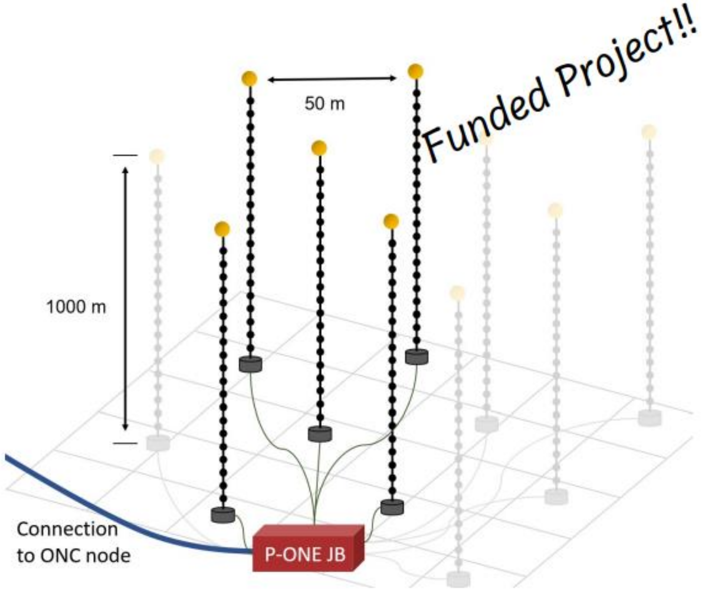
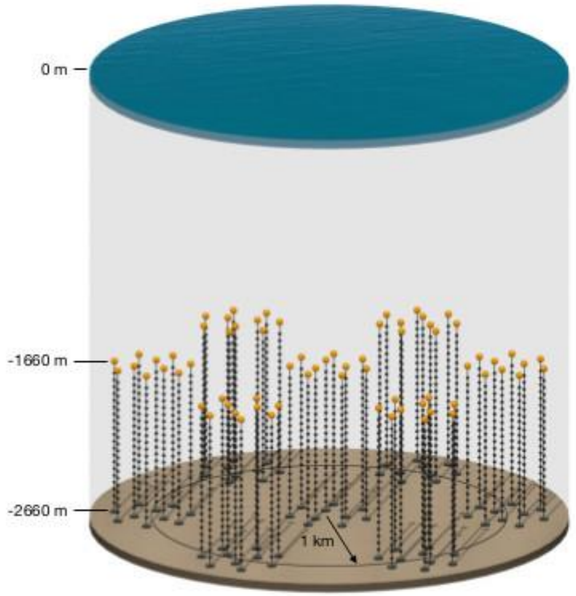
Where are we?

Timeline and milestones

- Funded by Canada (NSERC & CFI), Germany/Europe (TUM, ERC) and the US (NSF)
- Deployment of first cluster (*Demonstrator*), with up to 5 detector lines







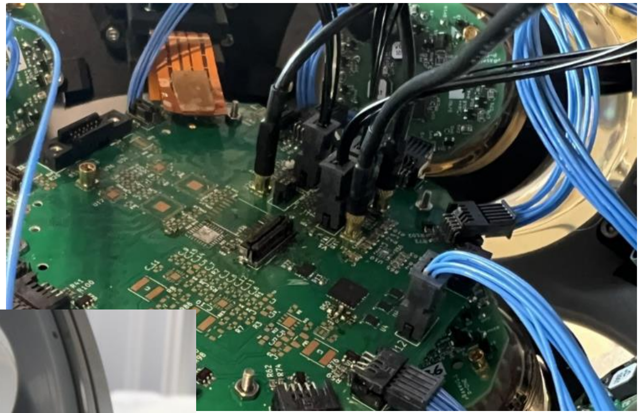
Pathfinders
Phase 1 (2018 – 2023)

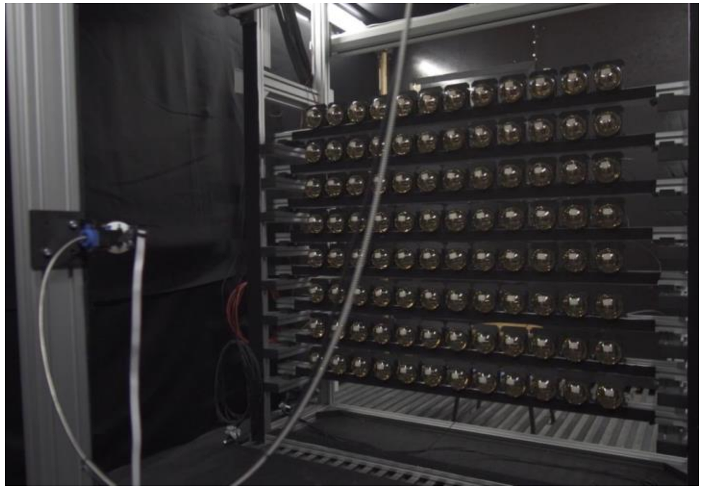
Demonstrator
Phase 2 (2023 – 2028)

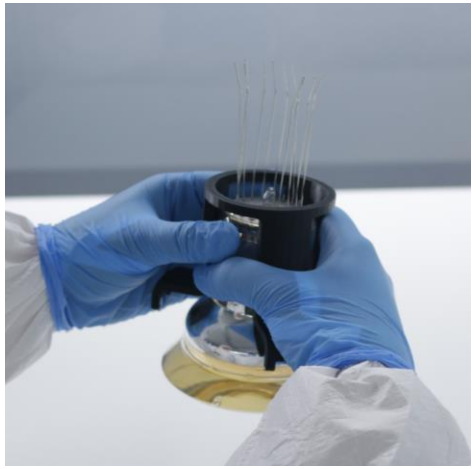
Full scale P-ONE
Phase 3 (2028 - ...)

Timeline and milestones

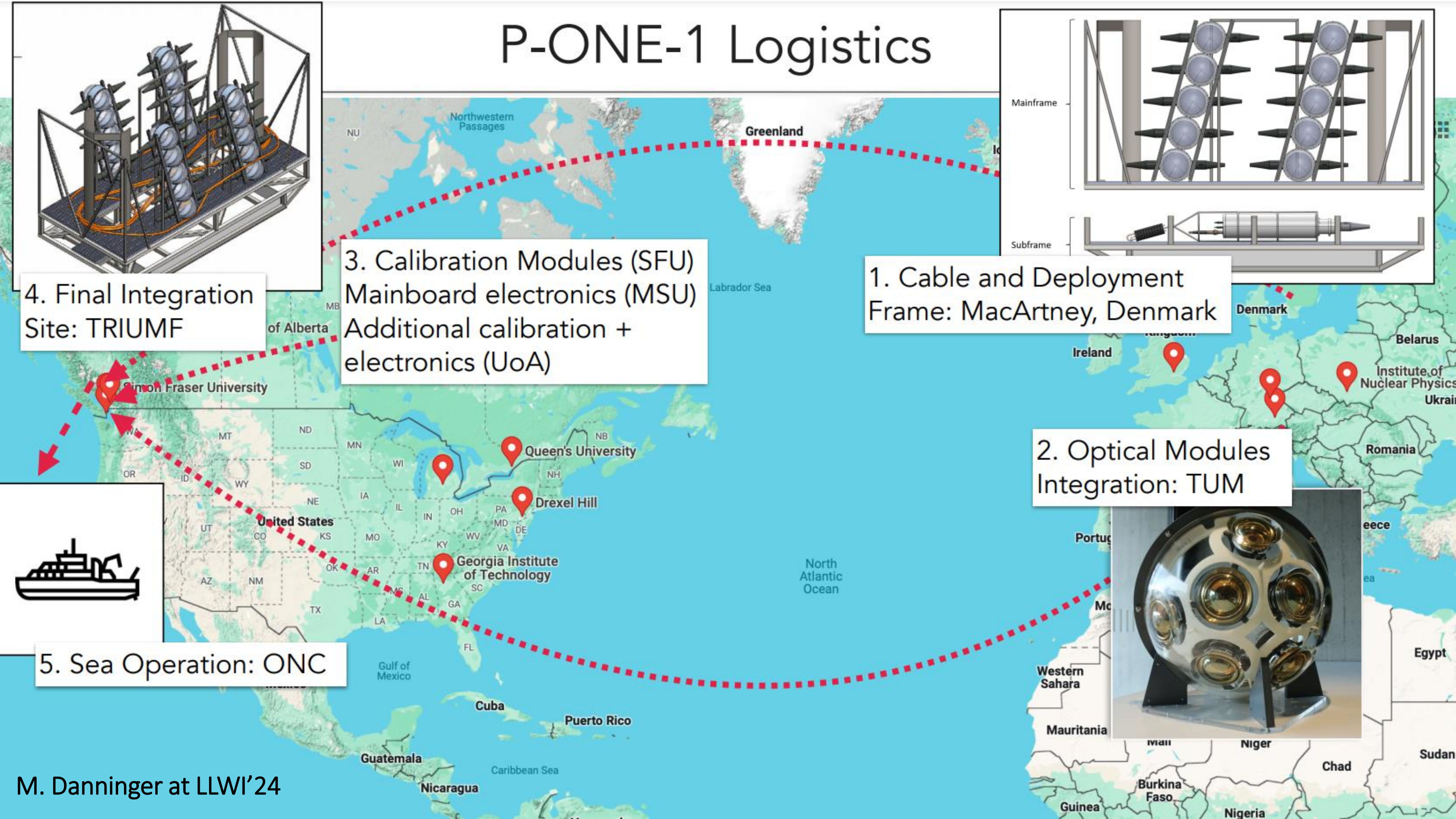
- **P-ONE-1 on track be deployed in 2025**
- PMTs have been characterized in Aachen's **IceCube** facility
- P-OM assembly/integration in TUM close to finished
- P-CAL assembly in SFU underway
- On-board electronics in production
- <u>Final testing and integration at TRIUMF this spring</u>







P-ONE-1 Logistics



1. Cable and Deployment Frame: MacArtney, Denmark

2. Optical Modules Integration: TUM

3. Calibration Modules (SFU) Mainboard electronics (MSU) Additional calibration + electronics (UoA)

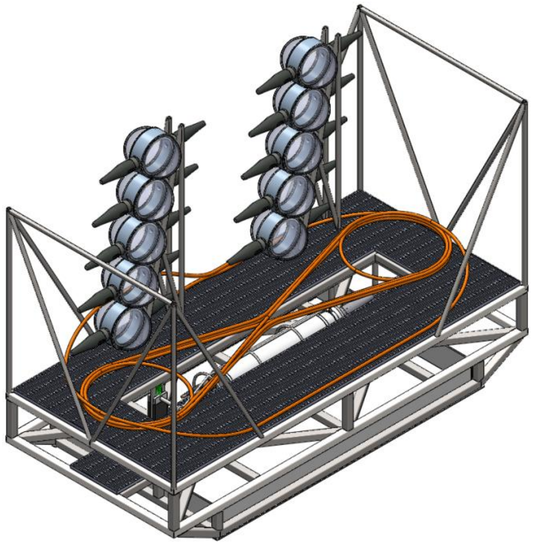
4. Final Integration Site: TRIUMF

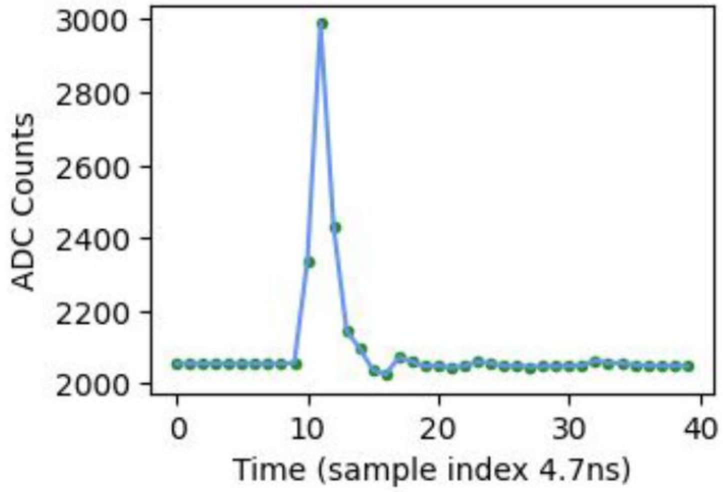
5. Sea Operation: ONC

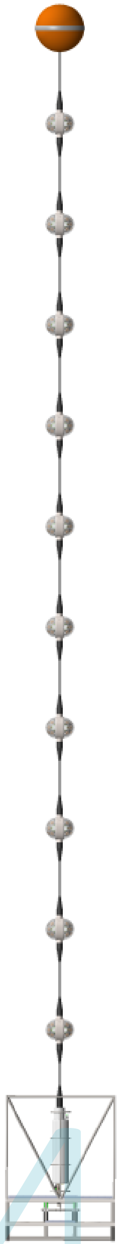
M. Danninger at LLWI'24

Next steps

- **Deploy** P-ONE-1
  - Show that the deployment mechanism works
  - Successfully connect the line to ONC
- Acquire and understand **P-ONE-1 data**
  - Operate calibration systems
  - Record PMT data and detect cosmic muons
  - Characterize the bioluminescence in detail
  - Exercise the acoustic positioning system
- Revisit the P-ONE-1 line **design**
  - Simplify, streamline components
- **Scale up** our construction, deploy the full Demonstrator







UCL

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Technical University of Munich TUM

UNIVERSITY OF ALBERTA

TRIUMF

Georgia Institute of Technology

SFU SIMON FRASER UNIVERSITY

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erc European Research Council Established by the European Commission

NSERC CRSNG

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

DFG Deutsche Forschungsgemeinschaft German Research Foundation

UKRI Science and Technology Facilities Council

INSTYTUT FIZYKI JĄDROWEJ IM. HENRYKA NIEWODNICZAŃSKIEGO POLSKIEJ AKADEMII NAUK

SFB 1258 Neutrinos Dark Matter Messengers

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