The P-ONE Ocean-Based Neutrino Experiment

Status and Prospects

Steven Robertson
Institute of Particle Physics, Canada
&
University of Alberta

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INSTITUTE OF PARTICLE PHYSICS

UNIVERSITY OF ALBERTA

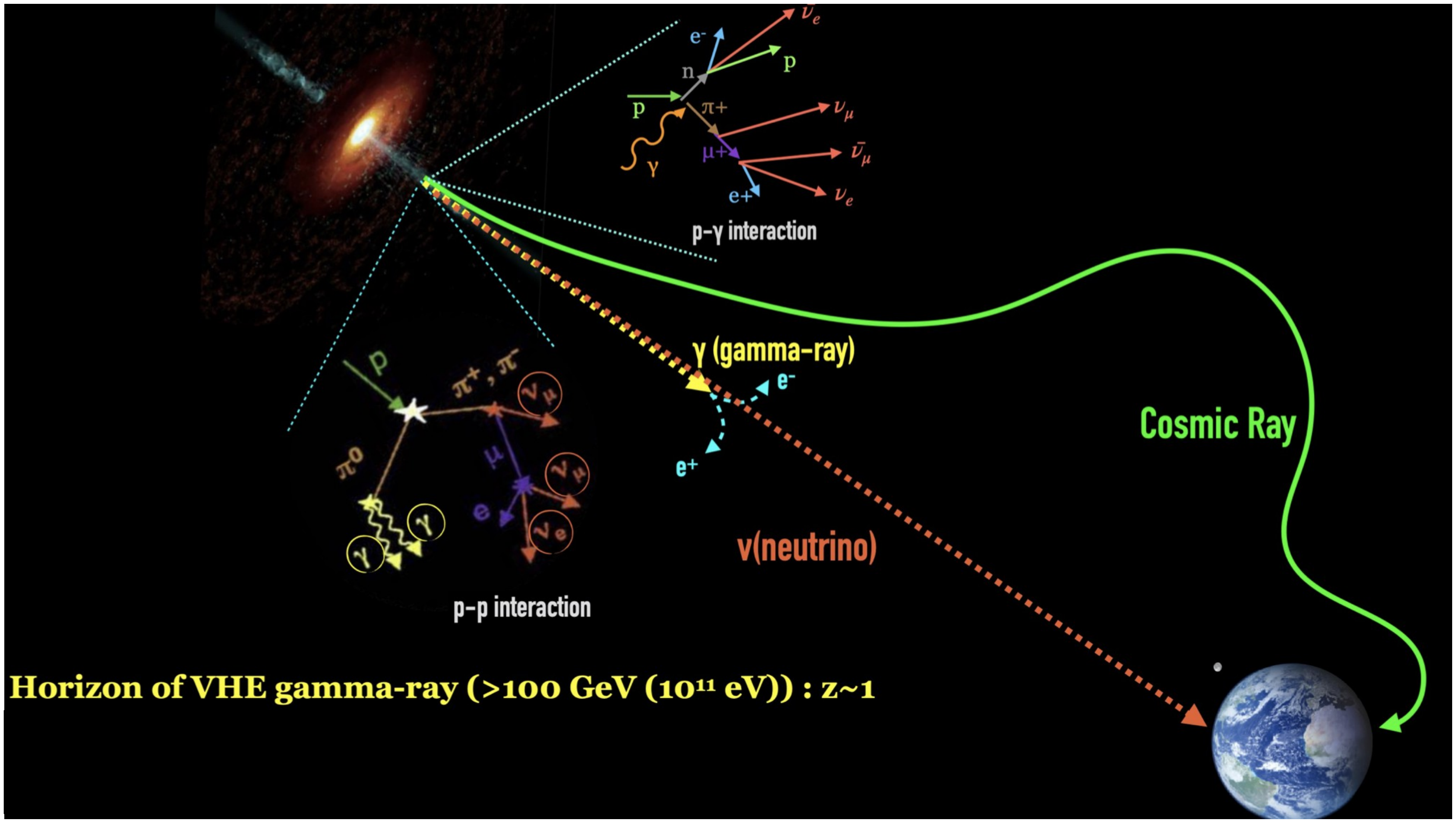
Outline

- Motivation: neutrino astronomy
- Neutrino telescopes
- P-ONE experiment and ONC
- Sensors, signals and DAQ

Disclaimer: I'm fairly new to P-ONE, so none of this work is mine. All credit goes to others, and any errors are due to my own lack of knowledge/experience with the project.

Neutrino astronomy

Neutrinos are useful probes of high energy astronomical phenomena due to their lack of interactions with interstellar media



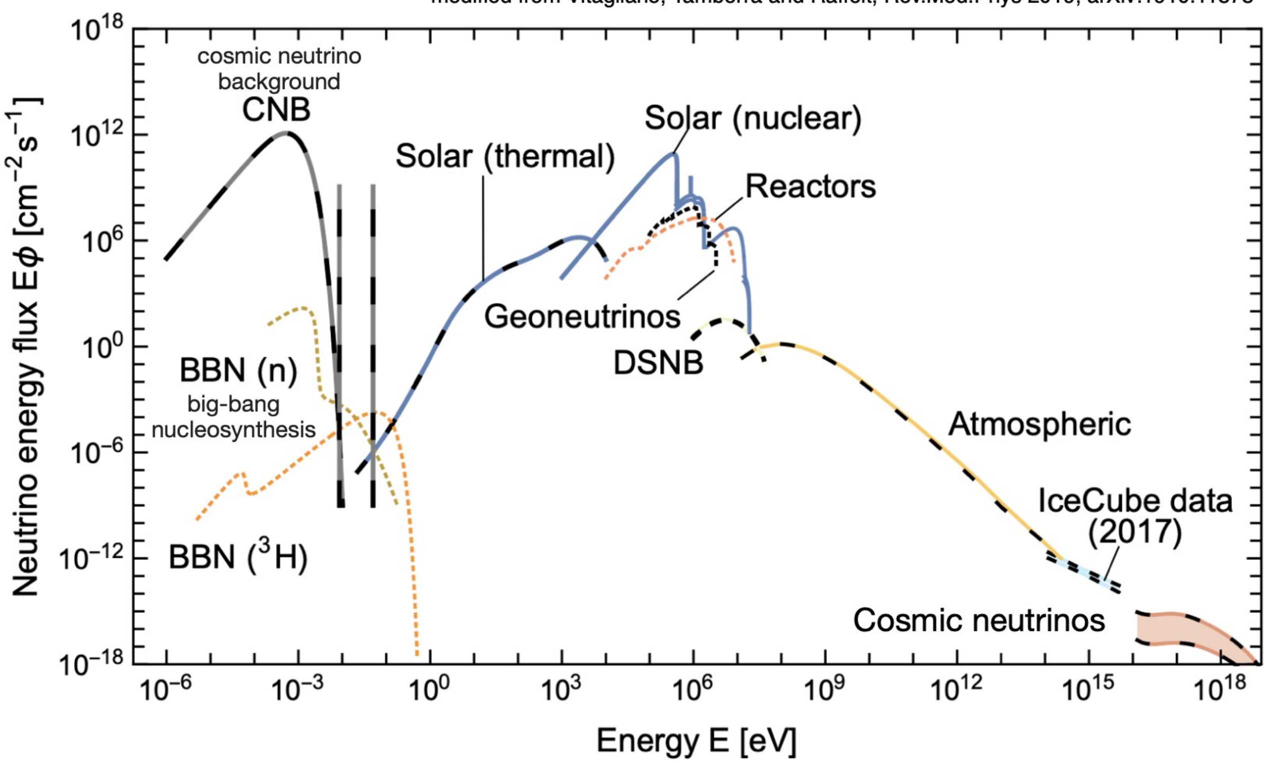
Probe physics of particle acceleration near black holes, particle interactions above PeV scale, and in general explore laws of nature under most extreme energy and gravitational conditions

- Not obscured by dust, or deflected by magnetic fields, but also difficult to detect

Neutrino astronomy

At the highest energies, the neutrino flux is extremely low, and the interaction cross section is also very low:

modified from Vitagliano, Tamborra and Raffelt, Rev.Mod.Phys 2019, arXiv:1910.11878



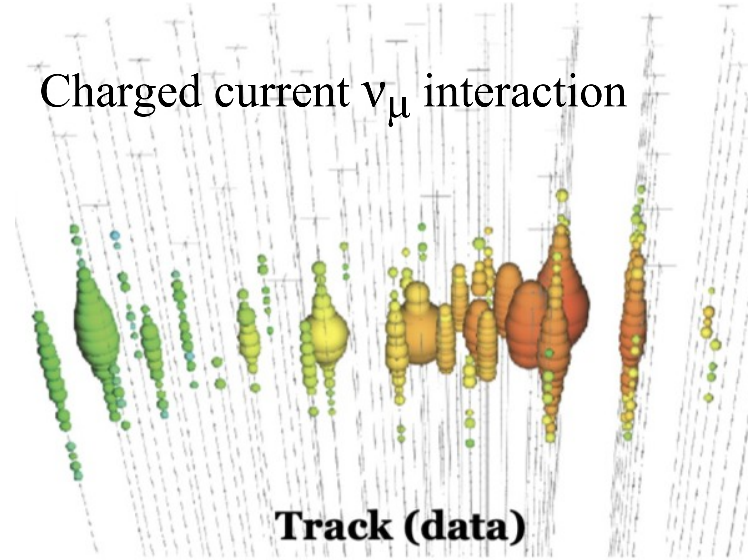
Grand Unified Neutrino Spectrum (GUNS) at Earth integrated over directions and flavors

- Neutrino telescopes require O(km^3) active detector volume, both to detect and to (partially) contain high energy events

Neutrino interactions

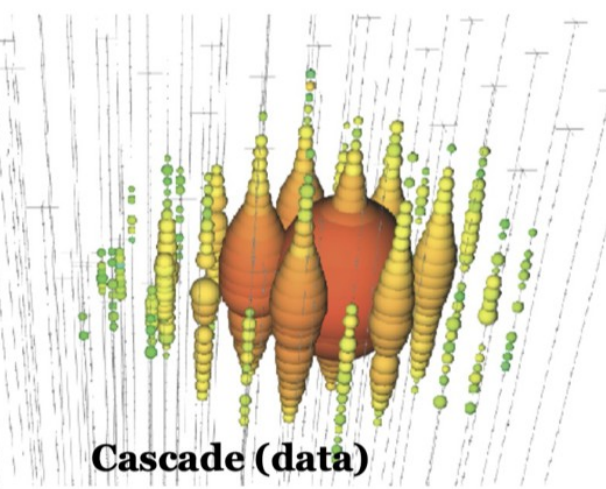
Neutrinos interact with matter via deep inelastic scattering with nucleons

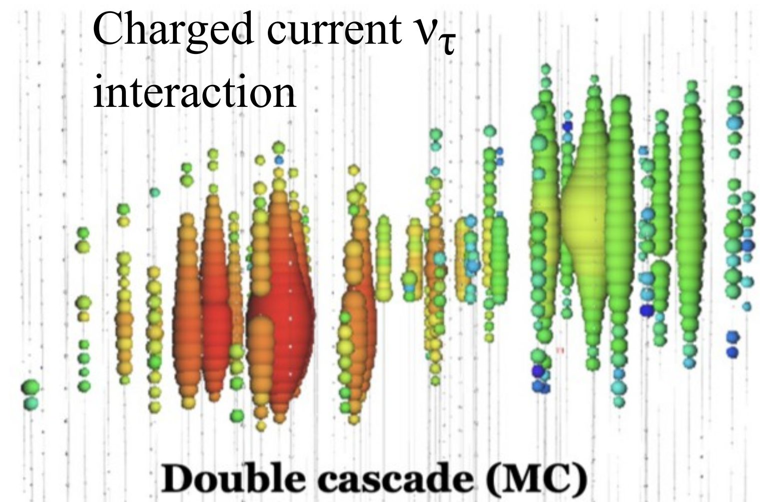
- via exchange of Z^0 bosons (neutral current NC), resulting in a scattered nucleon
- via a W boson (charged current CC), resulting in the production of a charged lepton e, μ, τ, depending on the flavour of the incident ν



Event morphology depends on interaction type and ν flavour:

Neutral current ν_μ interactions, charged current ν_e and (most) ν_τ interactions



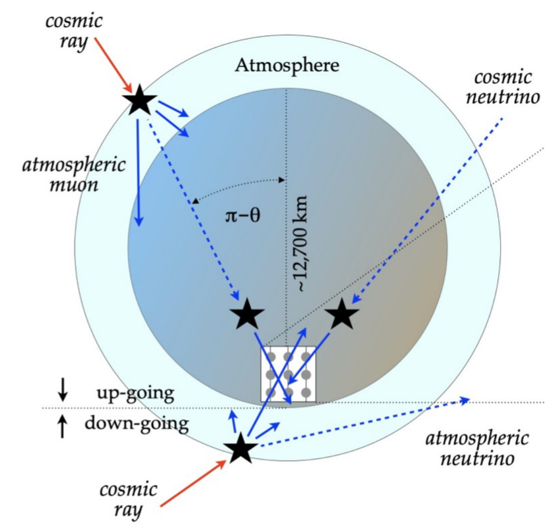


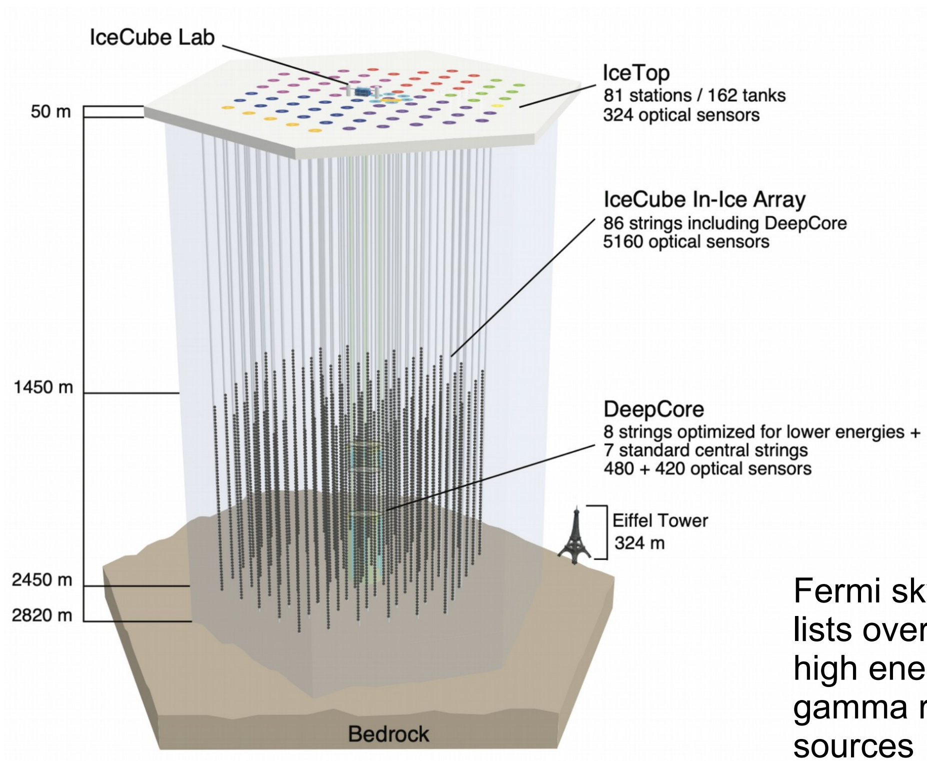
Want to determine neutrino **type**, **energy** and incident **direction**

IceCube

IceCube experiment has operated at the south pole since 2011

- Recent detection of first localized neutrino source, and evidence of neutrino emission from galactic plane
- Array of optical detectors imbedded in ice detect Cherenkov light from neutrino scattering events

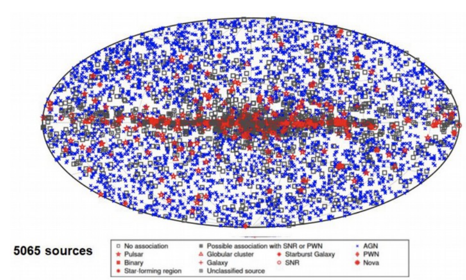


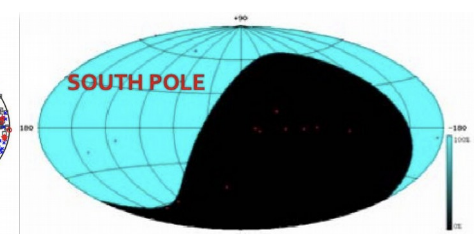


For cosmic neutrinos, IceCube views the northern sky

- Earth shields the detector from upwards-going cosmic rays

Fermi sky map lists over 5000 high energy gamma ray sources

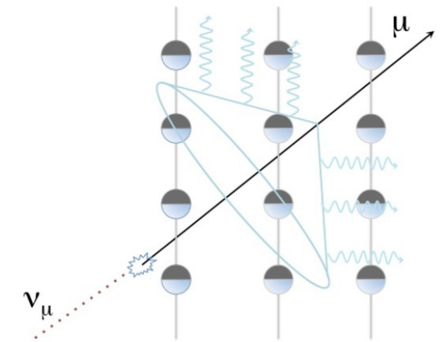


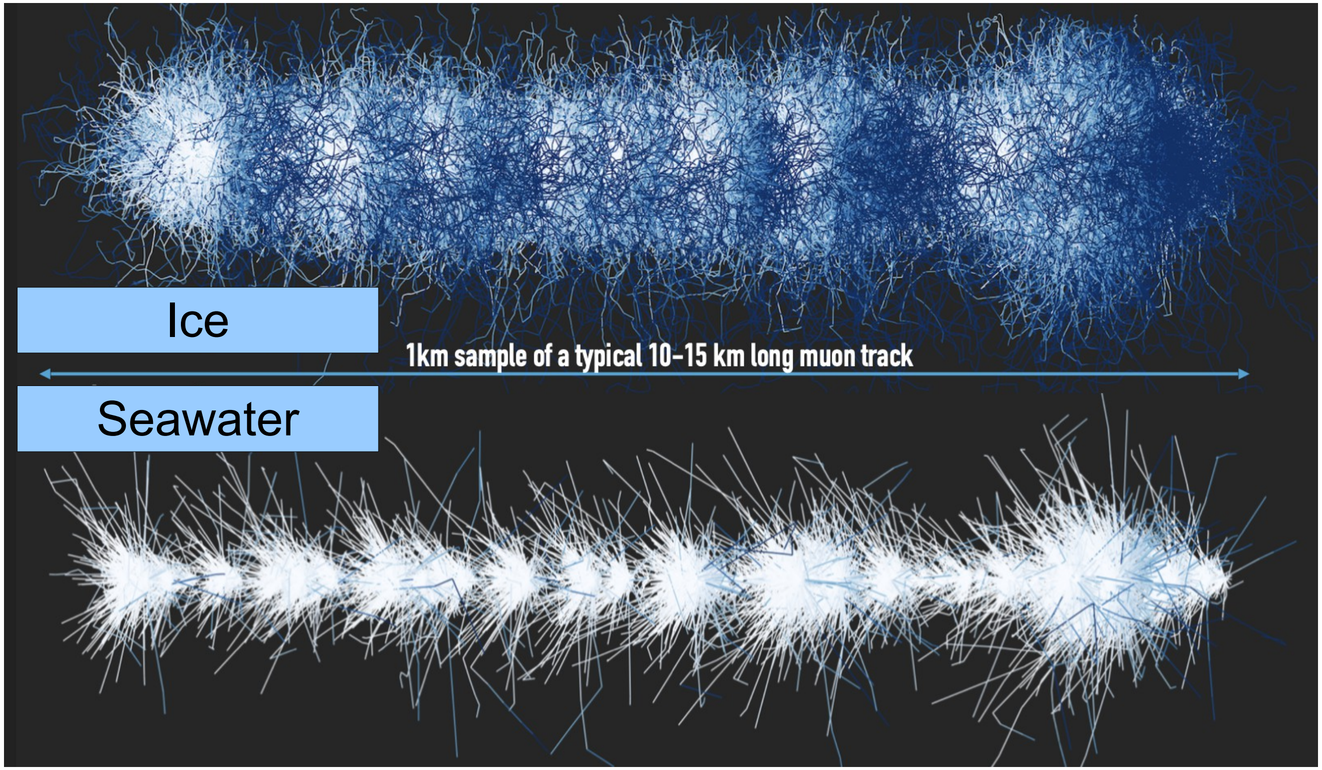


Detector medium

Water can also act as a detector medium

- Very different optical properties from ice with potentially better directional accuracy
- In principle, more easily accessible than the south pole





Challenges:

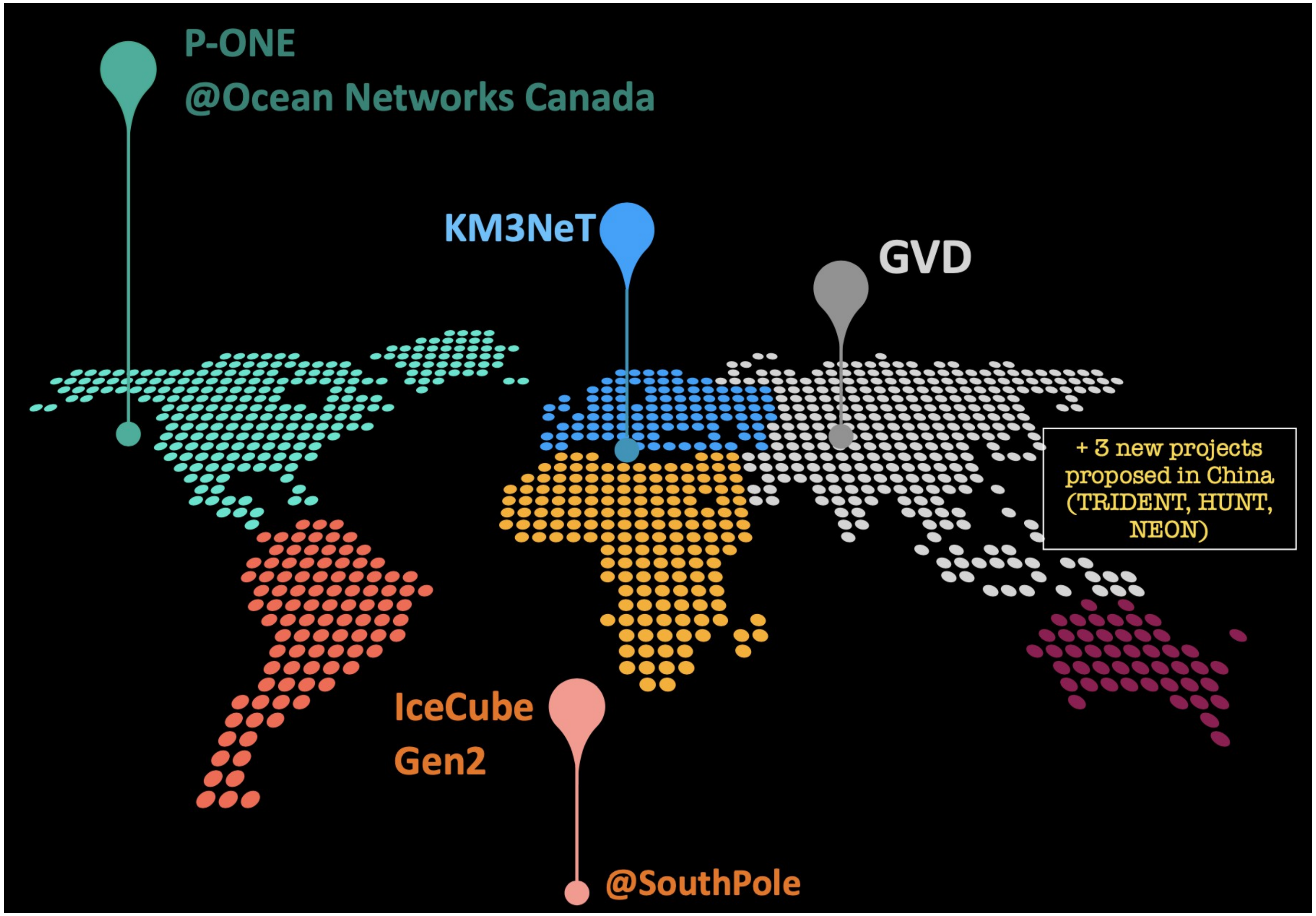
- Changing conditions (optical transparency, position of optical detectors, bioluminescence,...)
- Corrosive environment
- Biofouling
- Other environmental effects: temperature, pressure, remoteness, mechanical stresses (currents, etc)

Notably, first generation of water experiments were not very successful: DUMAND (Hawaii) and ANTARES (Mediterranean)

Neutrino observatories

Several km^3-scale projects in the northern hemisphere, including in the Mediterranean sea, and Lake Baikal (Russia)

- KM3Net based on previous ANTARES project
- GVD and KM3Net are (partially) deployed
- P-ONE is proposed and partially funded



P-ONE

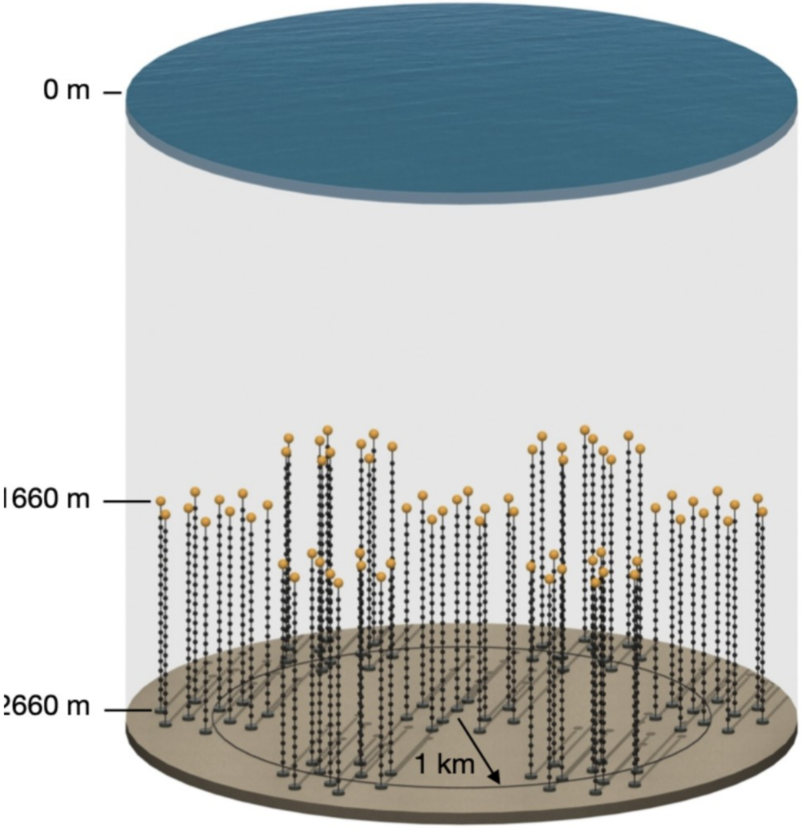
http://www.pacif c-neutrino.org

Pacific Ocean Neutrino Experiment (P-ONE) situated in the Cascadia basin off the west coast of Vancouver Island

- Primarily targets horizontal high energy muon tracks, but also sensitive to high energy induced showers

Water provides cosmic ray shielding, neutrino interaction medium and radiator

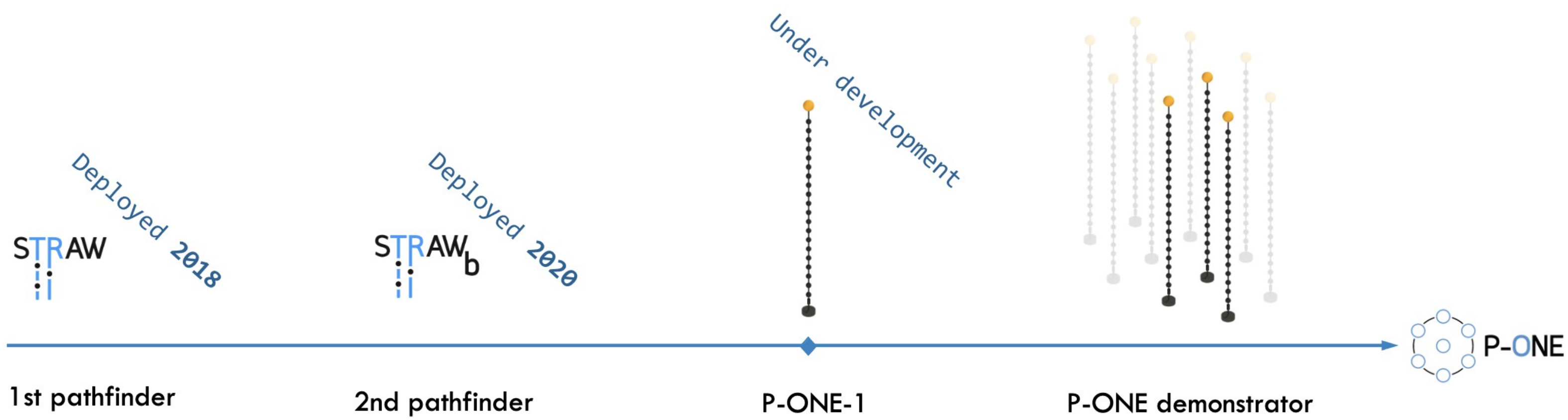
- Depth of 2660m
- Segmented array sampling approach, with 70 strings total, in 7 clusters of 10 strings
- 20 optical modules per string, 50m vertical spacing
- Fraction of a degree direction resolution for high muon tracks



P-ONE

Two "Pathfinder" strings (STRAWa and STRAWb) previously deployed to study underwater conditions
- optical attenuation length, bioluminescence, biofouling etc.

- Currently working towards deployment of first string(s) of P-ONE array
- Subsequently deployment of full "cluster", and ultimately full array of ~70 strings



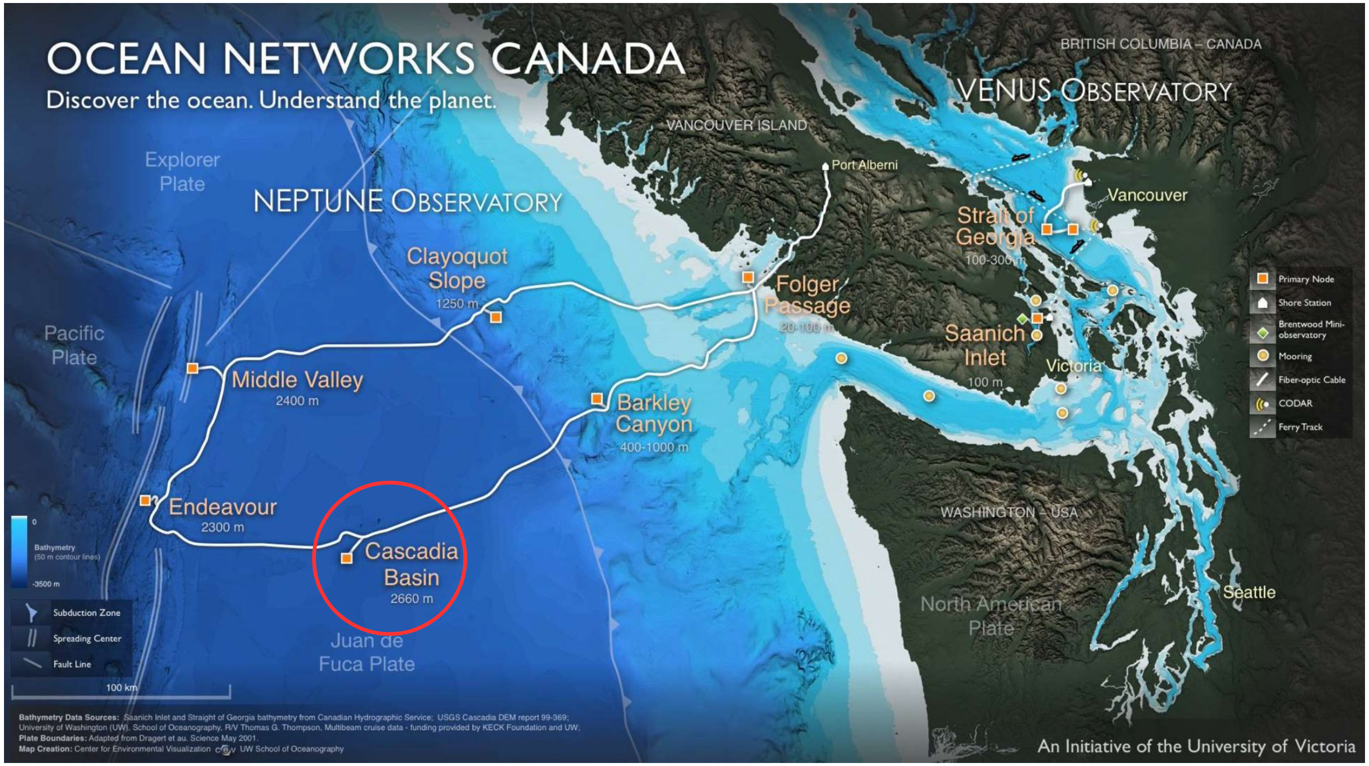
Neptune Observatory and ONC

Oceans Network Canada (ONC) operates the Neptune Observatory

- Underwater fibre optic cabled network providing power and GbE
- “Plug and play” network for scientific instrumentation

Shore station in Port Alberni

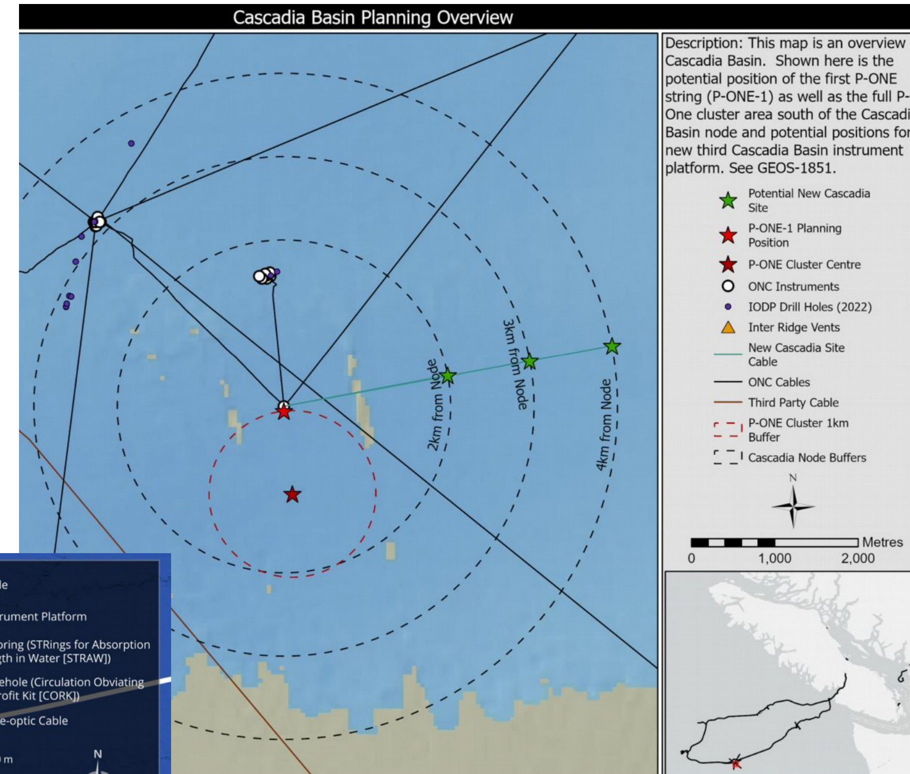
P-ONE will be located at the Cascadia node ~200km offshore

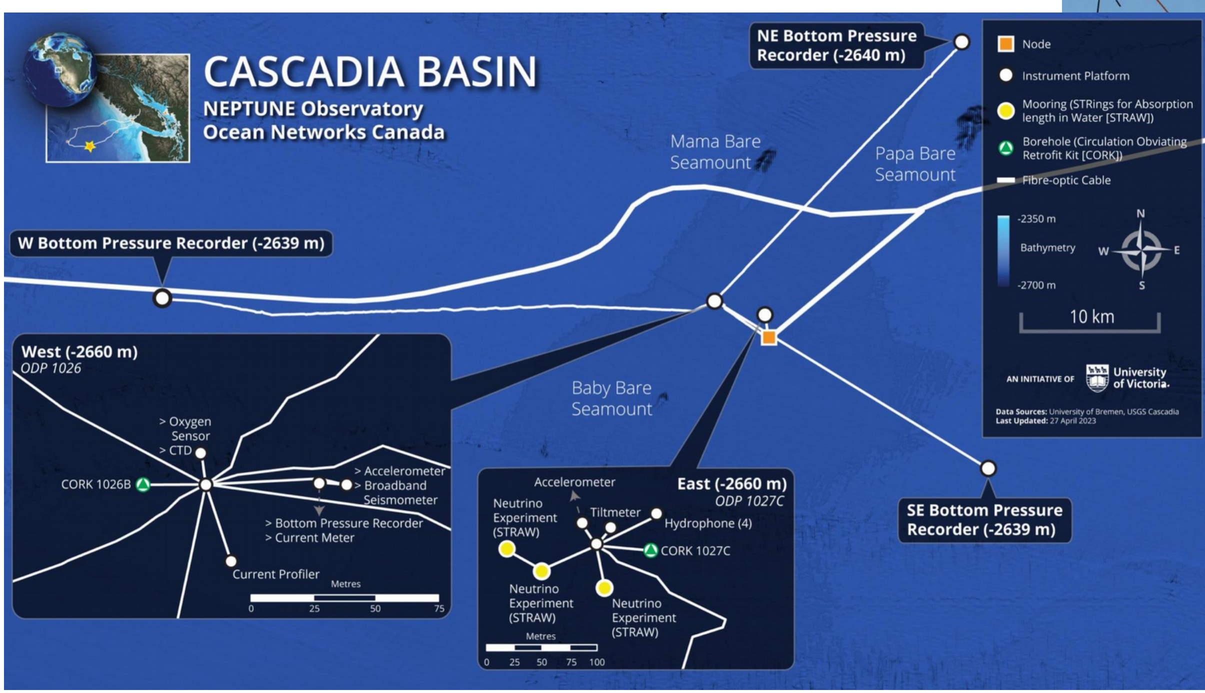


Importantly, ONC have very extensive experience in oceanography, engineering, and undersea operations

See presentation by Benoît Pirenne, Weds

Neptune Observatory and ONC

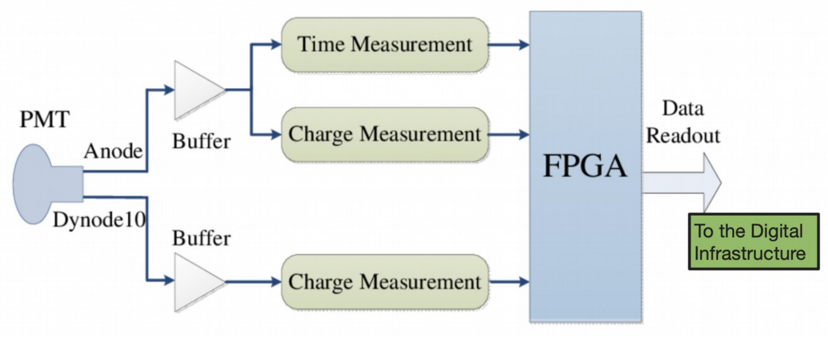


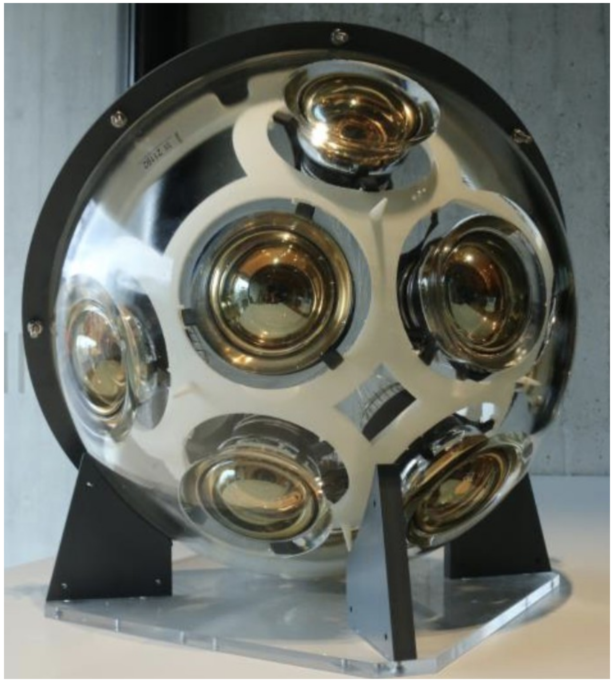


Detector

P-ONE detector made up of strings of Optical Modules (P-OMs) each instrumented with 16 PMTs with overlapping fields of view

- P-OMs contain onboard electronics for detection and digitization of optical signals, creation of trigger primitives, buffering of waveforms, and (in event of a trigger) readout





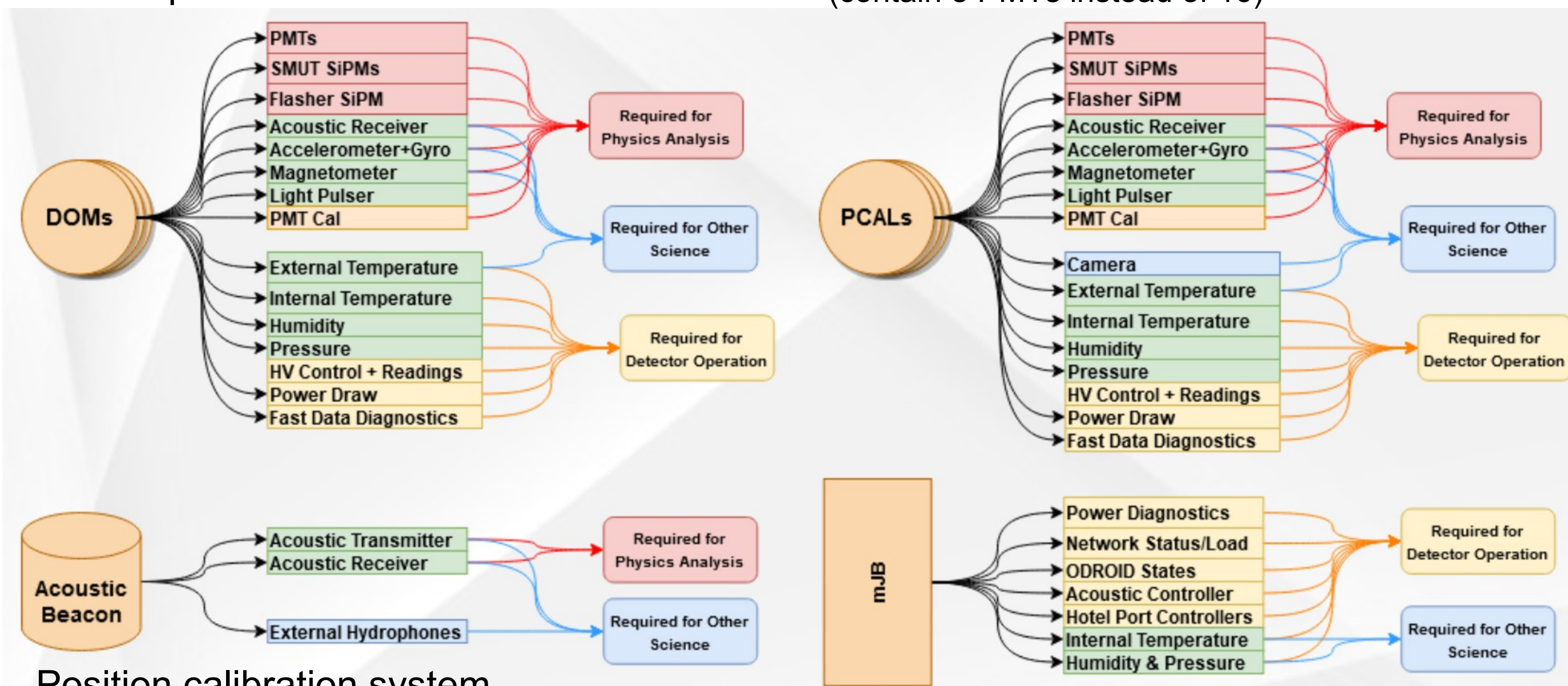
- Also special P-CAL optical modules with additional calibration optical sources and sensors
- Ancillary sensors for conditions and calibration data:
  - Acoustic and optical sensors for P-OM position and optical attenuation measurement, environmental sensors, and system monitoring sensors

Detector

In addition to PMTs, a large variety of sensors are utilized for detector calibration and monitoring:

P-OM optical modules

Calibration modules
(contain 8 PMTs instead of 16)



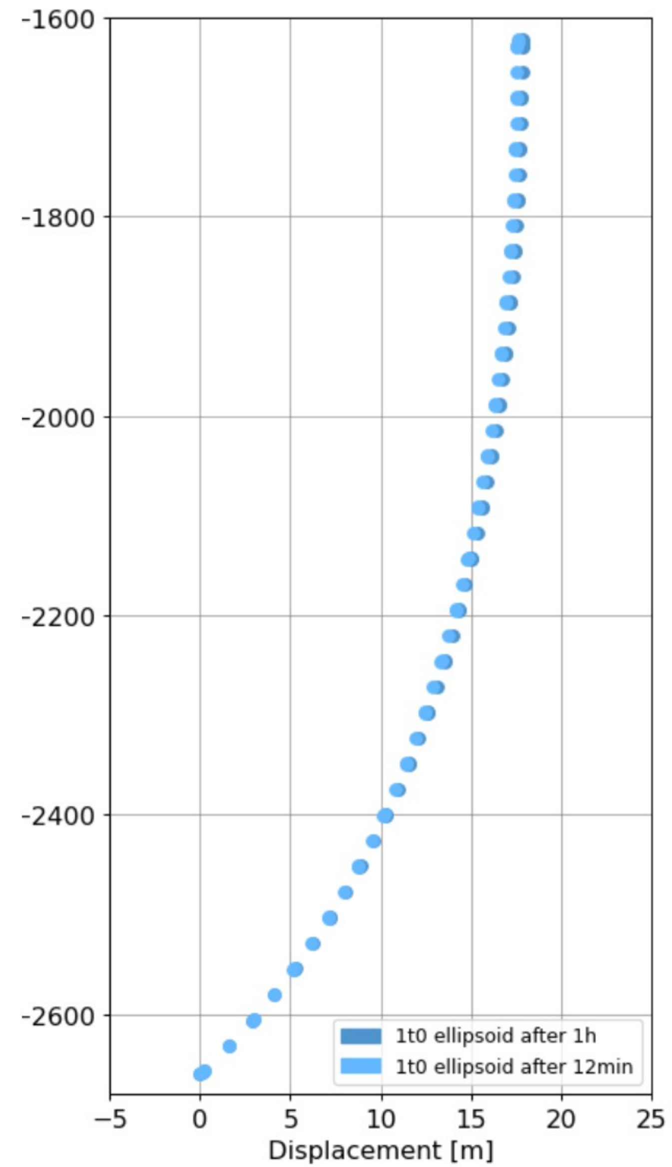
Position calibration system based on acoustic transponders

Network junction box

Position

Relative and absolute position of individual P-OM is needed for precise event reconstruction

- Ocean currents can change positions of strings by 10's of meters on timescales of ~10 min
- Optical systems based on flashers provides inter-P-OM relative positioning based on timing of detected photons
- Piezo sensors in P-OMs detect signals from seafloor acoustic transmitters for absolute positioning
- Vertical "knock-down" due to horizontal currents is small, but depends on size of float



Timing

M. Böhmer et al., ICRC
https://pos.sissa.it/444/1216/pdf

Detection of neutrino events relies on precise knowledge of the relative positions of the P-OMs, and the time at which PMT signals were detected

- P-ONE has developed a method to enable time synchronization of P-OMs across the P-ONE detector strings with sub-ns resolution

To measure the round trip delay on a link, a signal needs to be sent from a leader port and returned from the follower port, both in real time (see figure 3). This is not possible on IEEE 802.3 compliant endpoints, as an ongoing ethernet frame transmission must not be interrupted in any case.

We have developed a simple mechanism to overcome this limitation. In the leader port TX line, the INS (Inserter, see figure 2) unit can delay the data stream from the PHY by two clock cycles to provide space to insert a DLM (Link delay Measurement) code group without disturbing the data stream. As soon as IDLE code groups are sensed in the data stream (usually during the Inter Packet Gap (IPG)), the delay circuit is reset and one IDLE code group deleted to arm the inserter unit again.

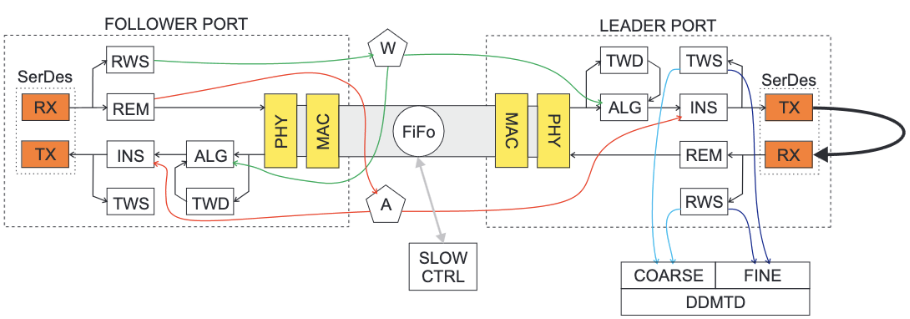


Figure 2: A BlackCat FiFo endpoint (only one leader port shown, loop back enabled) with SlowControl and delay measurement unit (DDMTD), as implemented in one FPGA. Standard IEEE components are marked in yellow, vendor specific ASIC circuits are marked in orange. All others are BlackCat addons. Acronyms are being described in detail in the text.

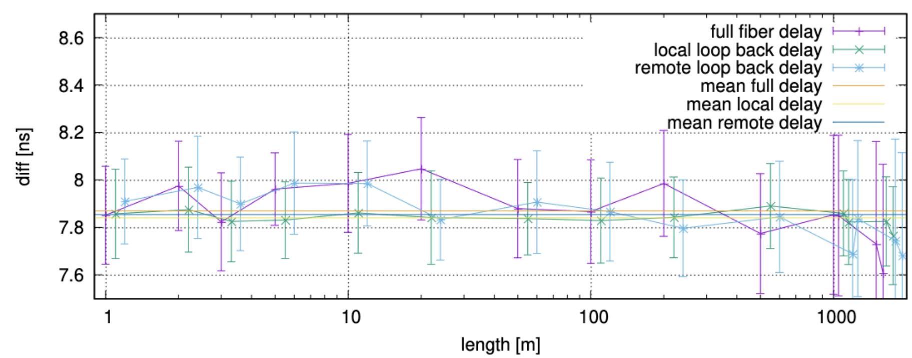


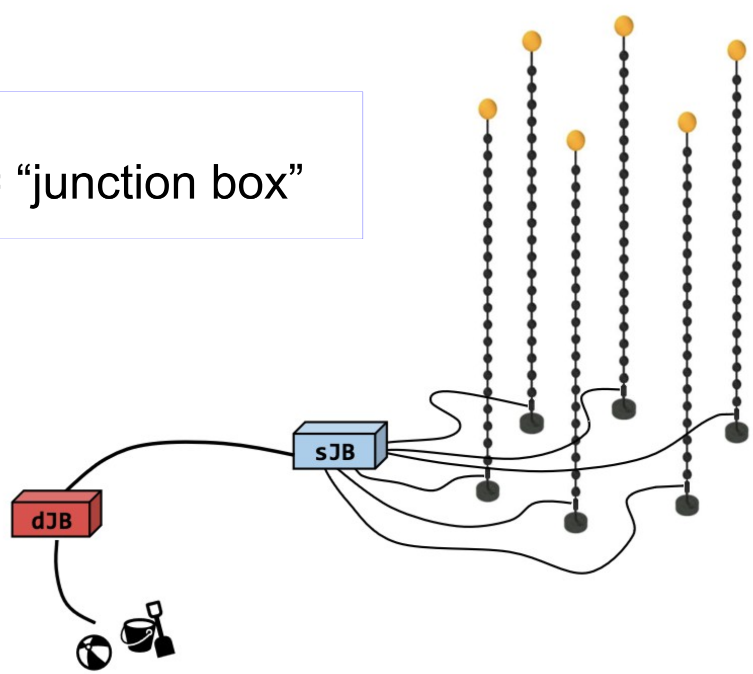
Figure 7: Difference of delay measurements taken by BlackCat and oscilloscope. Data points for loop back measurements are shifted for better view. The time difference originates from routing for scope probe pins inside FPGA fabric.

Trigger

"Interesting" particle interactions in the detector volume characterized by a pattern of Cherenkov photons detected across multiple P-OMs and strings

- Detector dimensions sets "natural" timescales for correlations ranging from a few ns (PMTs within a single P-OM) to O(1μs) for P-OMs in distant strings
- Backgrounds arise from PMT noise, atmospheric muons, ^{40}K decays and bioluminescence; different spatial distribution and time structure

JB = "junction box"



Global physics trigger based on P-OM-level trigger information

- Necessarily occurs at shore station (or node junction box)
- Limited bandwidth, hence full waveforms are not utilized
- Trigger primitives: DOM-id, timestamp,...

Trigger

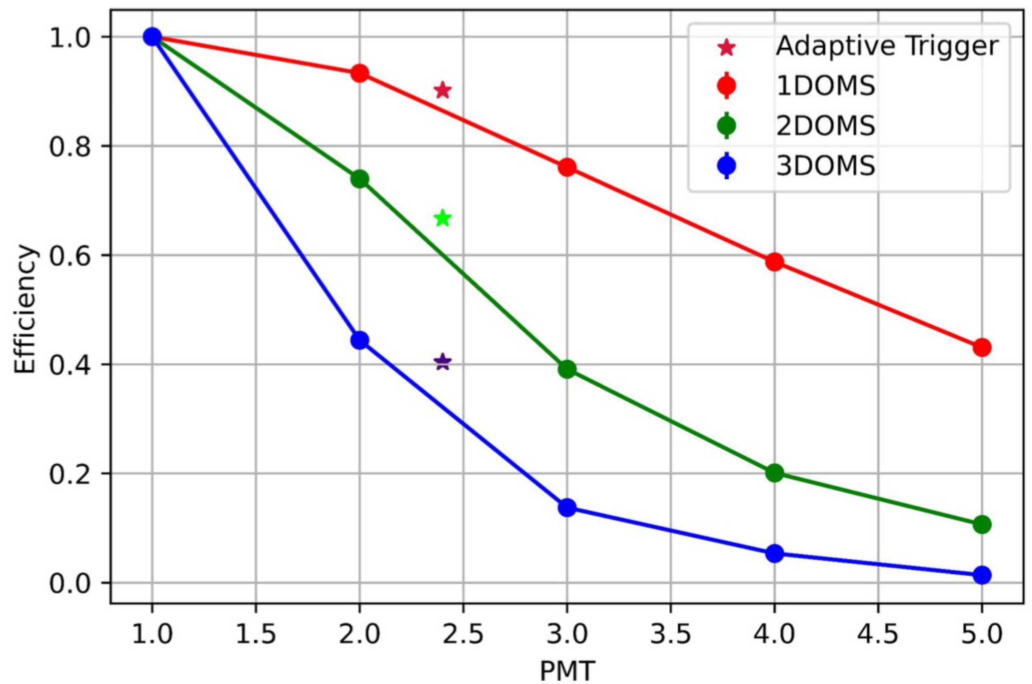
P-OM-level (L1) trigger must be able to cope with highly variable PMT rates from bioluminescence

- Adaptive trigger foreseen, based on N-PMT coincidence rates within each DOM (~10ns window)
- Waveforms buffered in each DOM for PMTs above threshold until global trigger decision

Additional intermediate trigger levels possible, based on local clusters within strings, or between strings etc.

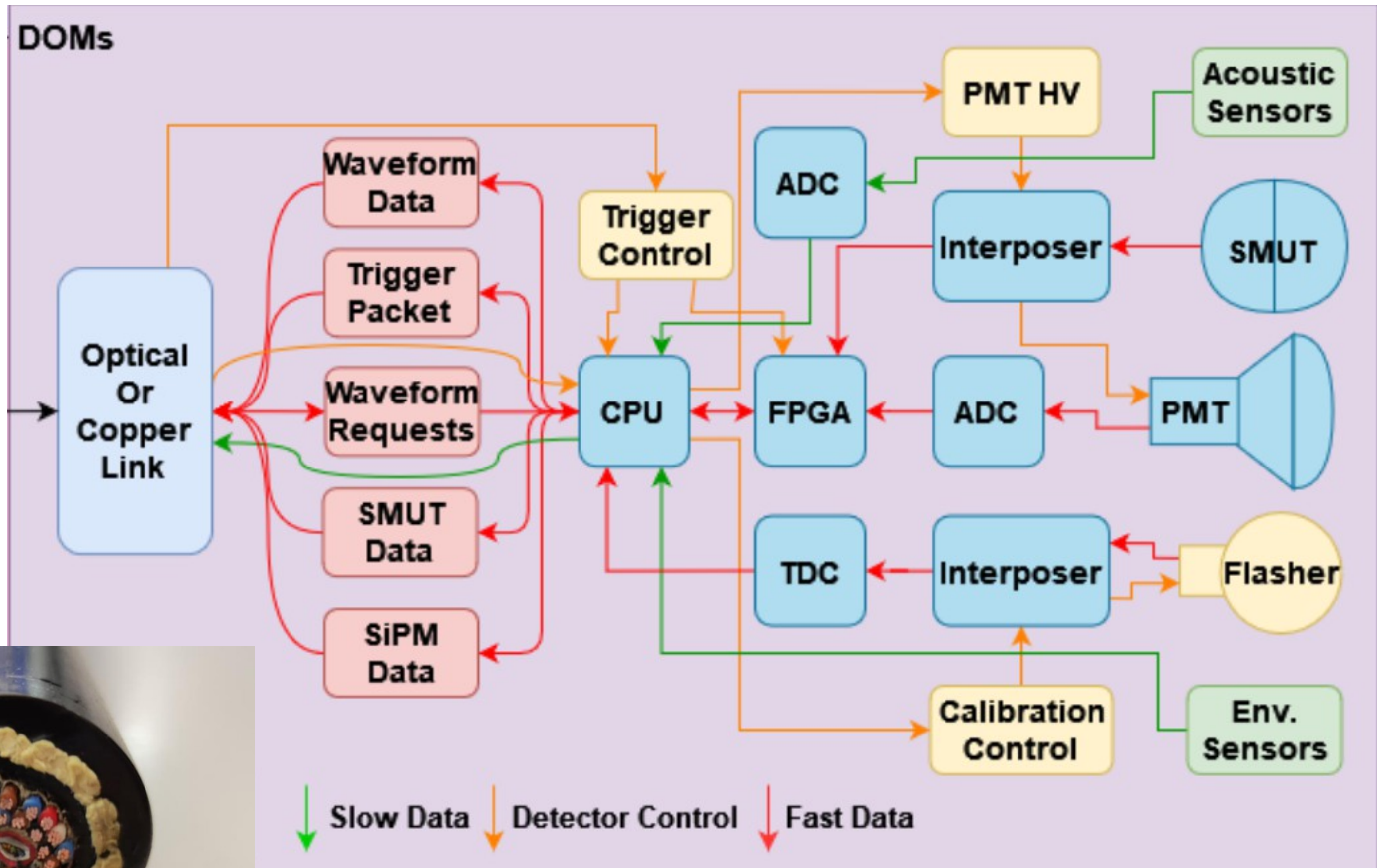
Rate	Fraction of time at n-pmt				
	1	**2**	**3**	**4**	**5**
2.5 kHz	0%	40%	44%	9%	7%

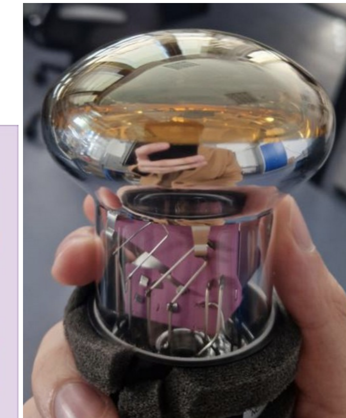
Santiago Miro, UofA

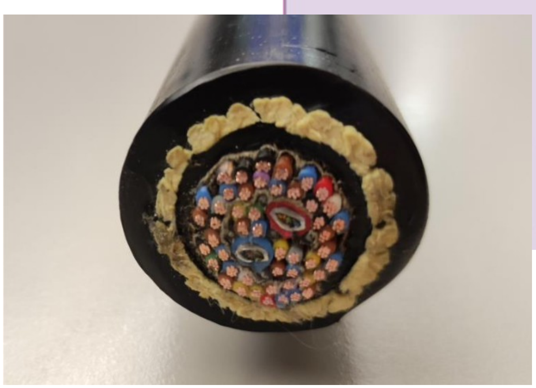


Dataflow: P-OMs

To string
junction box



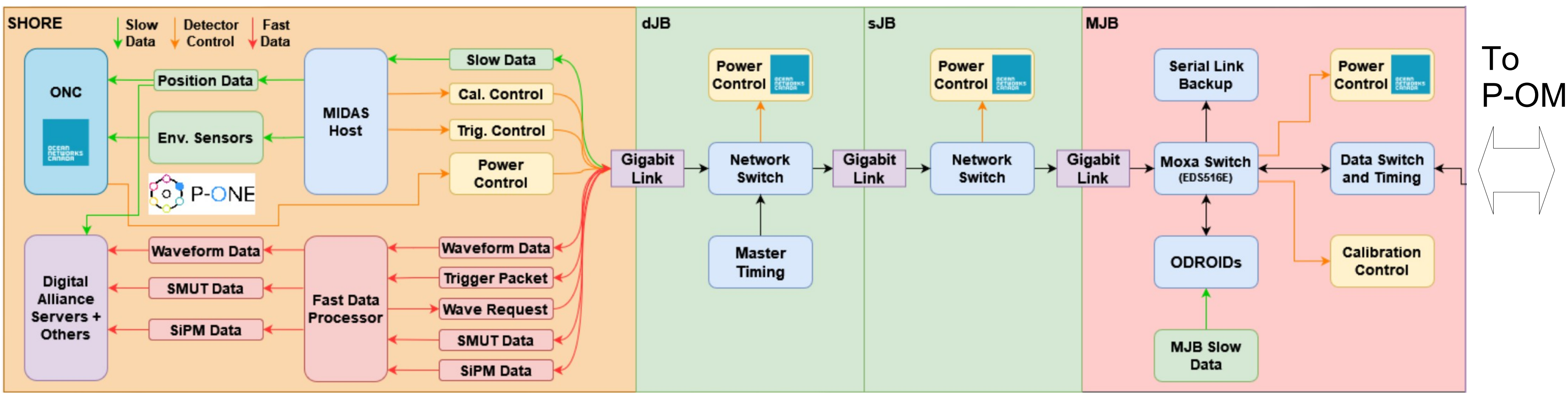




Nathan Molberg
UofA

Dataflow: the rest

- MIDAS provides detector state machine, slow controls and monitoring
- ONC necessarily maintains overall control of junction boxes, network, power, and shore station



- PMT waveform data from triggered events to permanent storage

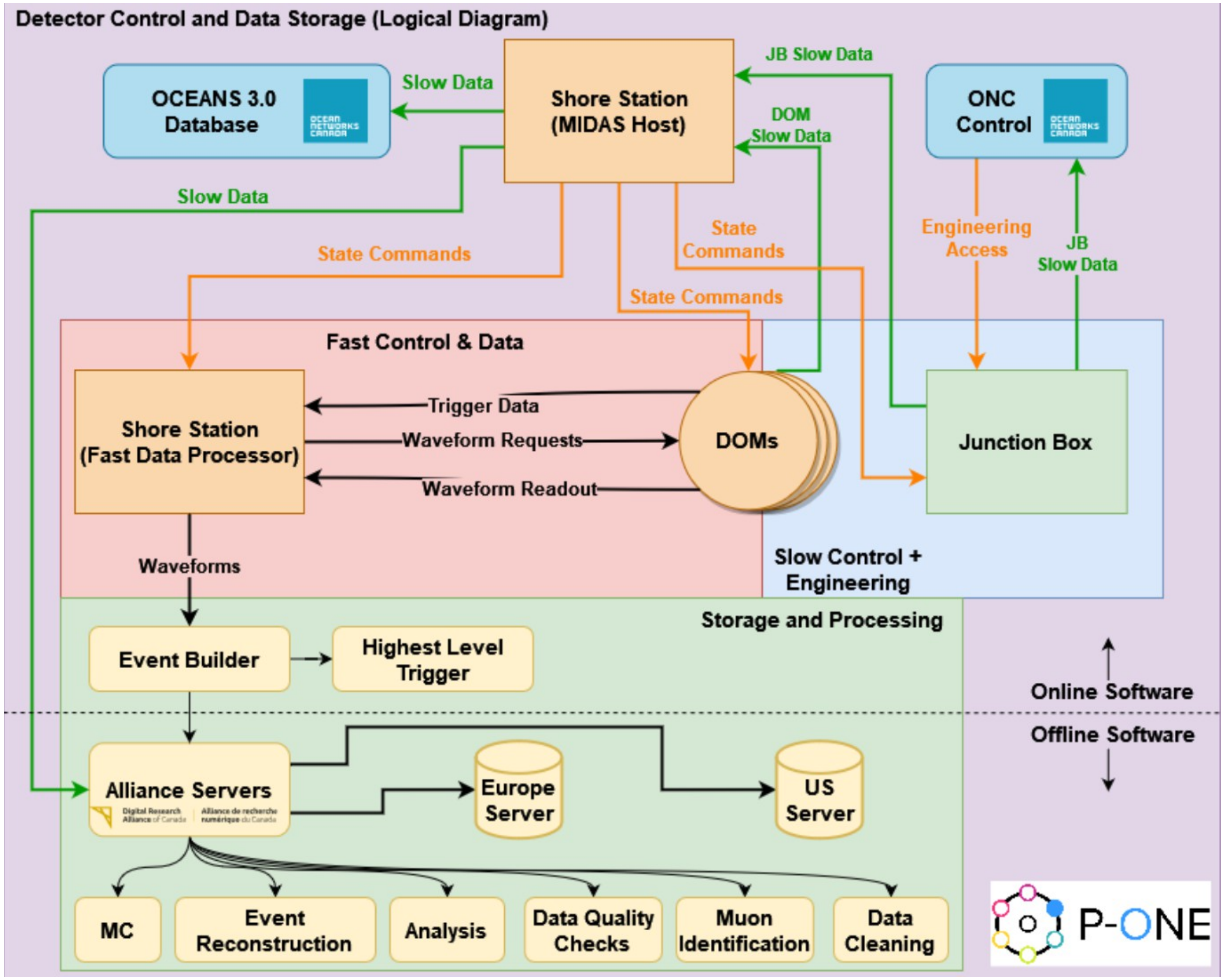
Array of P-ONE strings, and connection to Neptune

Base of each string

Dataflow logic

- ONC has direct control of all infrastructure
- P-ONE interacts with detector (primarily) via MIDAS*
- Alliance presumed to be primary data storage facility in Canada**

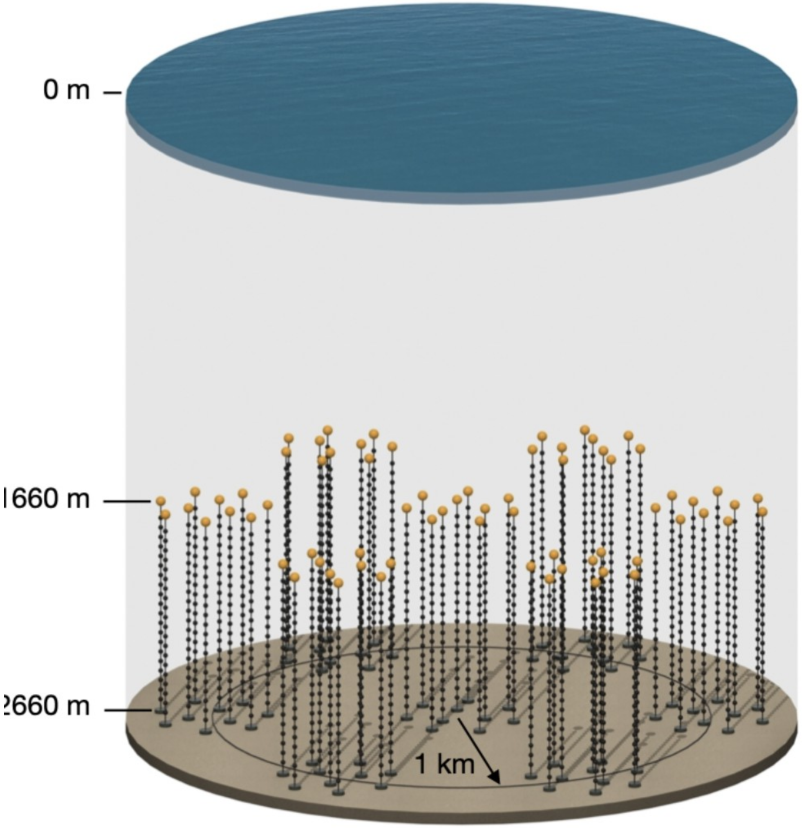
* details still very much under discussion
** details not even yet under discussion



- Sensor (non-PMT) data used for experiment monitoring, but also provides potential data products for ONC via OCEANS3.0

Conclusion

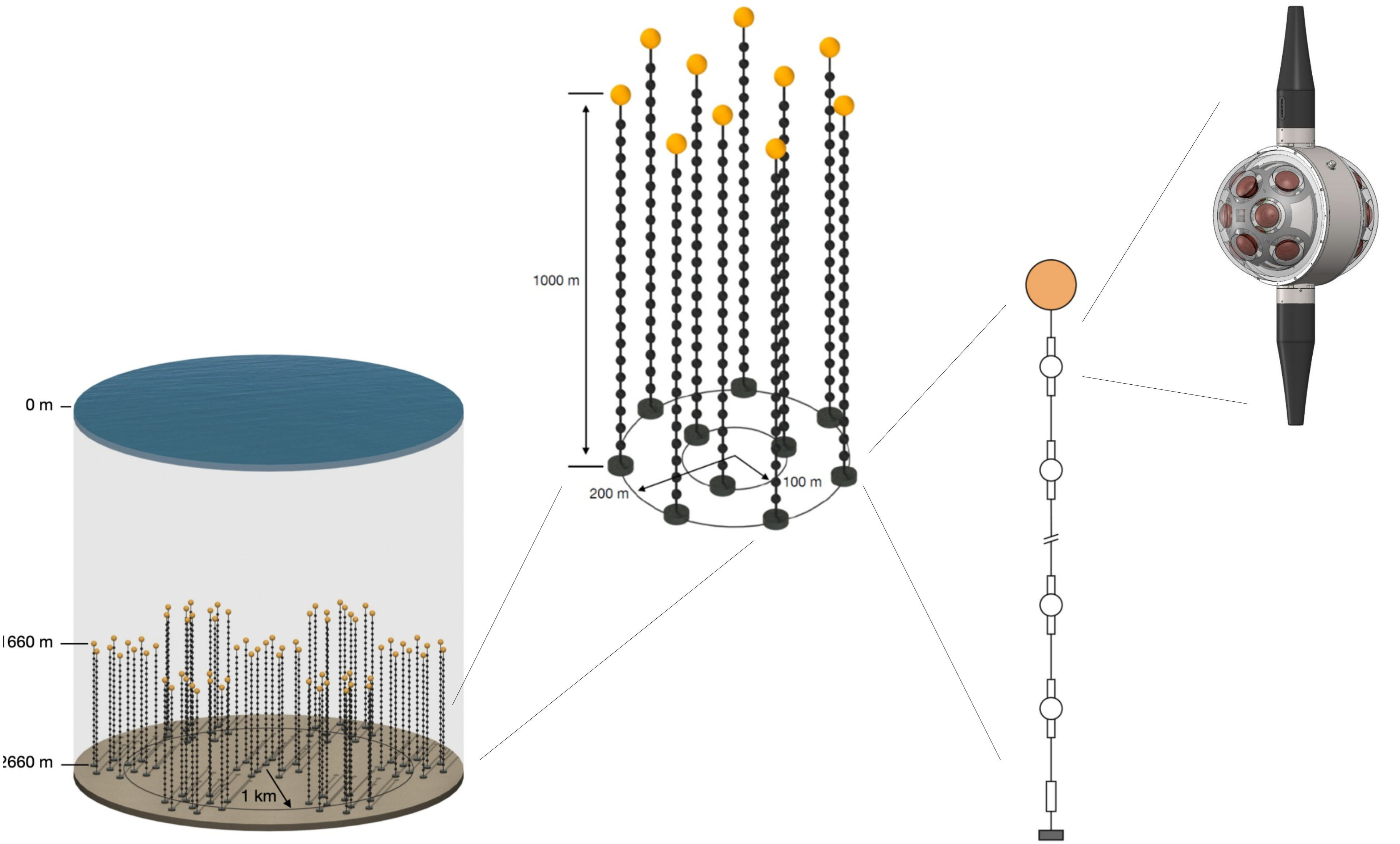
- P-ONE is a leading-edge km^3 scale neutrino astronomy experiment proposed to be based in the Cascadia Basin near Vancouver Island
- Takes advantage of the underwater network resources and vast oceanography experience of ONC and the NeptuneObservatory
- Development of the initial string is progressing, and CFI funding has been received in support of production and deployment



Thanks for your attention!

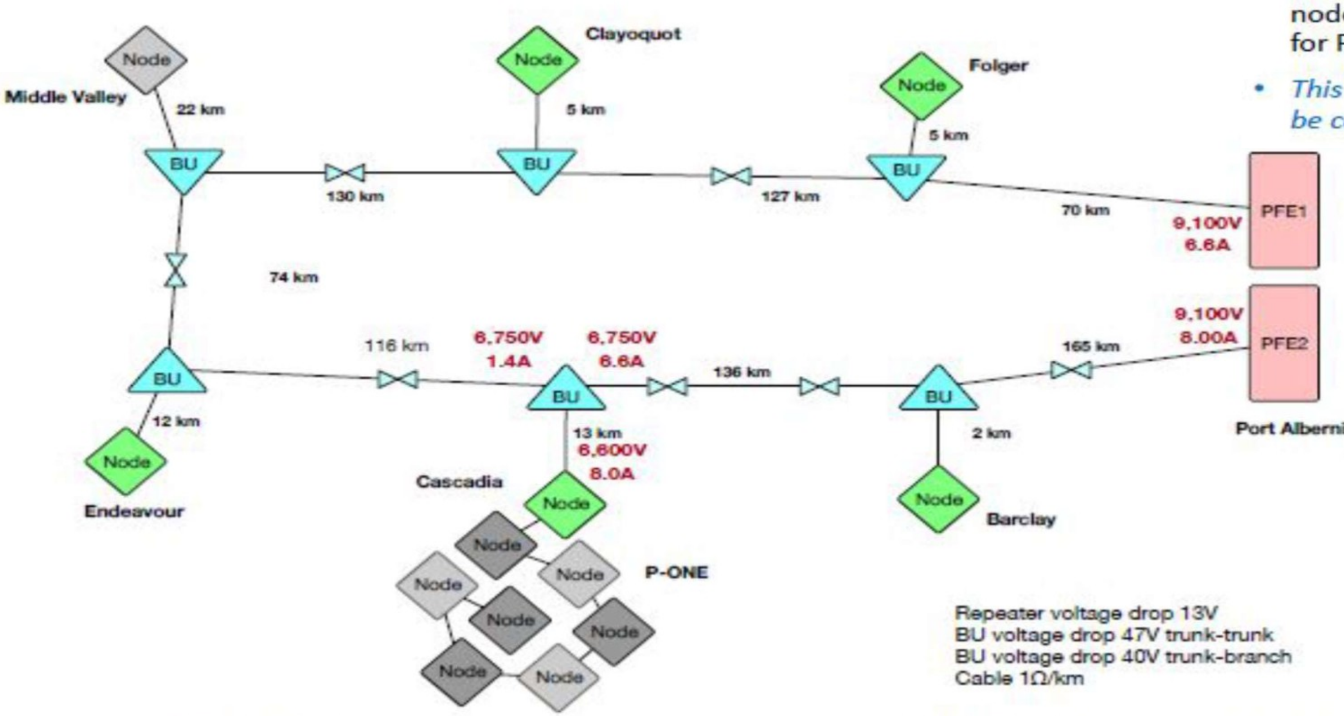
Additional material

Detector



Neptune

- NEPTUNE can deliver 100 kVA with 60 kVA for nodes and 40 kVA for P-ONE
- This is total power at the inputs to the MVC, before converter and extension cable losses
- The main limiting factor in powering P-ONE is the 8 Amp limit in branch cable
- Voltage in the backbone cable at the Cascadia BU is dynamic and depends on loads at other nodes
- In the solution shown, the voltage at the Cascadia node is 6,600V
- 6.6kV * 8 Amps – 10 kVA = 42.8 kVA available to P-ONE
- Additional power can be provided if power to other nodes is reduced; For example, if the six NEPTUNE nodes are limited to 2kVA, 62 kVA could be available for P-ONE
- *This is a spreadsheet estimate, a circuit model should be constructed and solved as part of the next steps.*

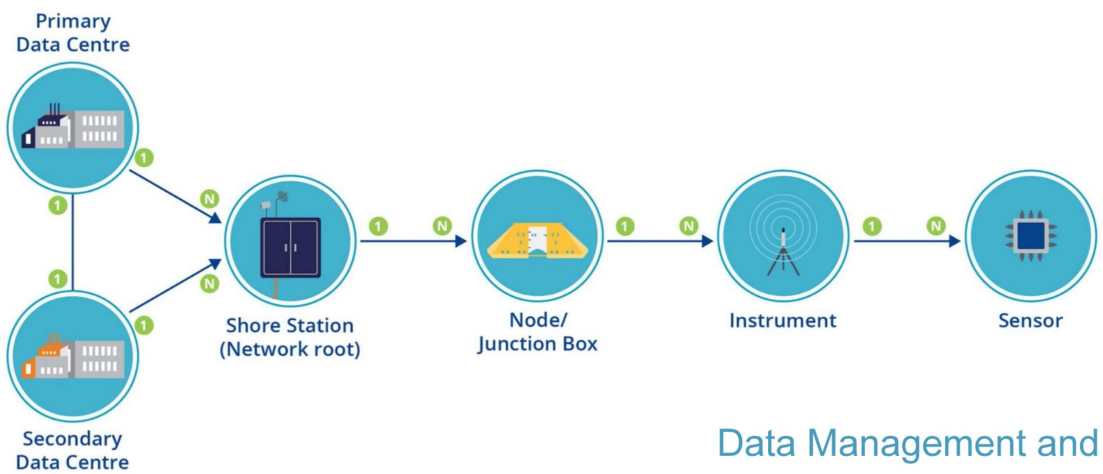


WORLD LEADING DISCOVERIES AT A CRITICAL TIME

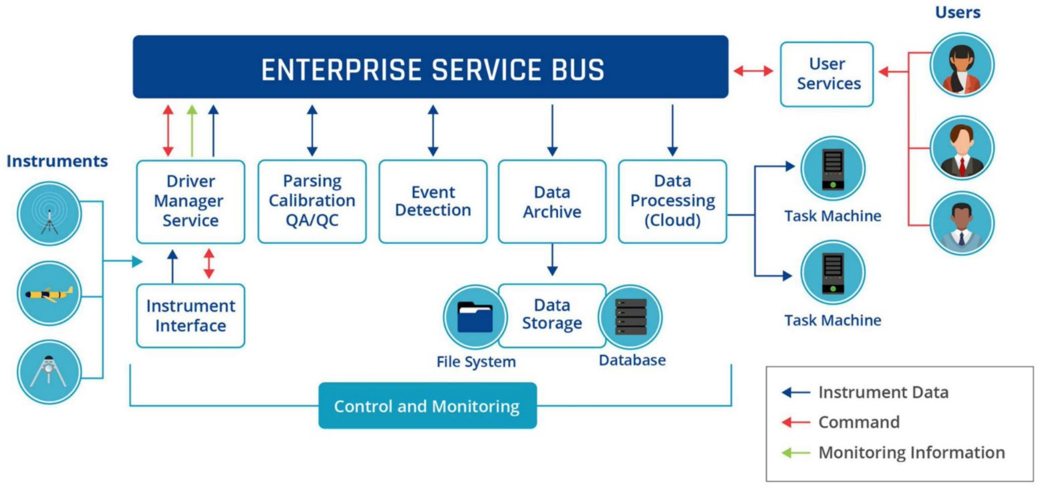
ONC Data Policy

- ONC-owned data follows the federal government of Canada's policies on open data: machine-readable, freely shared, used, and built-on without restrictions.
- ONC's data management follows best practices and does not discriminate users.
- Some ONC-hosted data is not necessarily readily available.
- ONC captures and delivers data owned by others. While encouraged to follow ONC's policy, other policies could be followed upon ONC's review and approval.
- Data Policy in full can be found here: https://www.oceannetworks.ca/data/data-policy/

Infrastructure Hierarchy from Data Center to Sensor

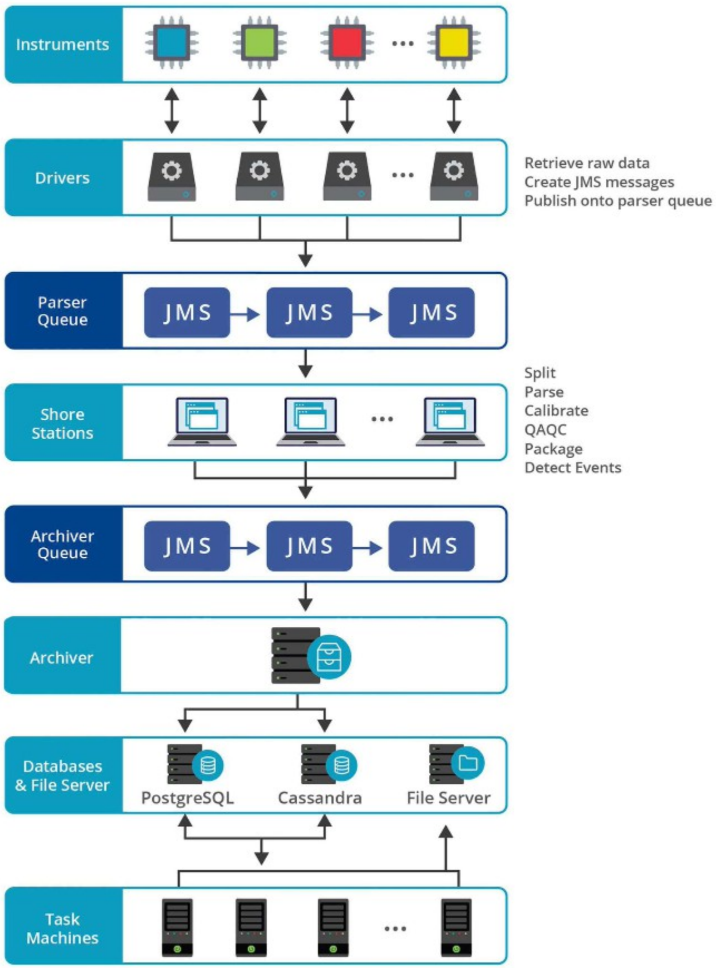


Data Management and Archival System (DMAS)



WORLD LEADING DISCOVERIES AT A CRITICAL TIME

Data Acquisition Process

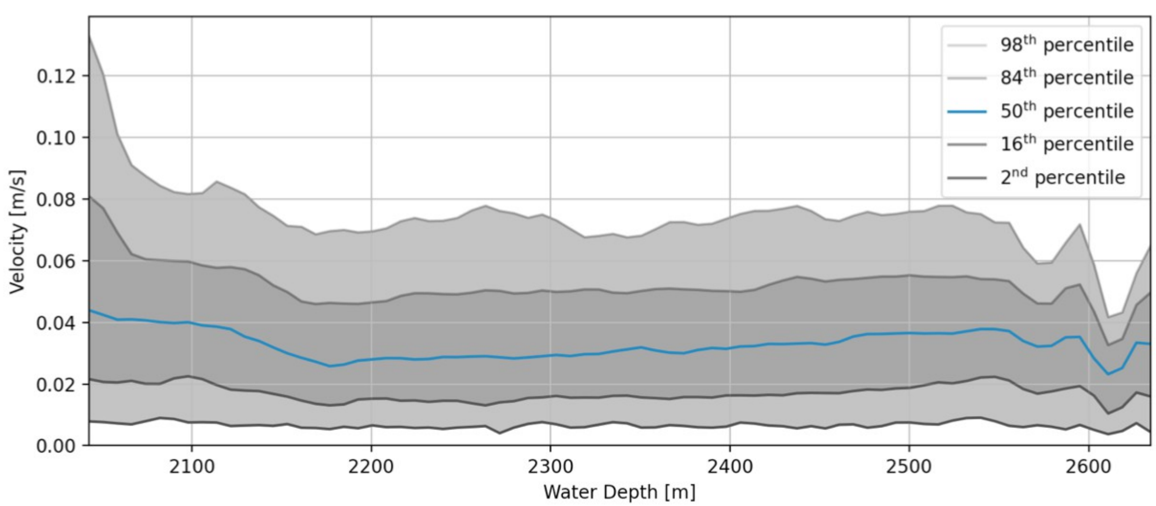


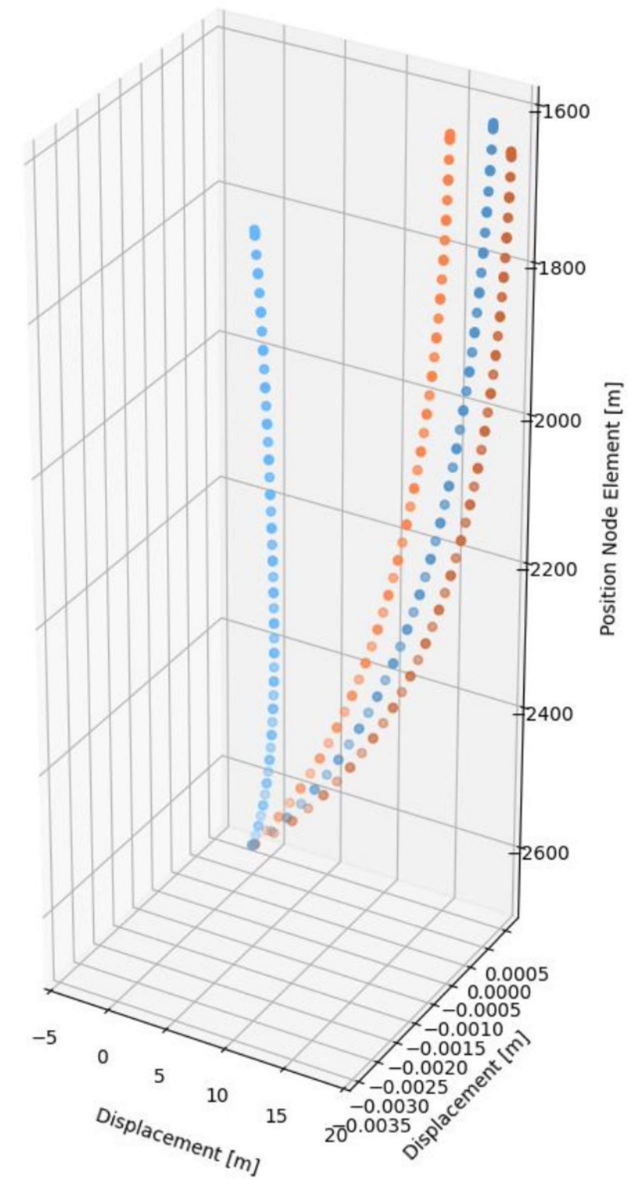
1. Acquiring data readings
2. Publishing onto parser queue
3. Processing by shore station
4. Publishing onto archiver queue
5. Archival
6. Task machines for scheduled jobs

WORLD LEADING DISCOVERIES AT A CRITICAL TIME

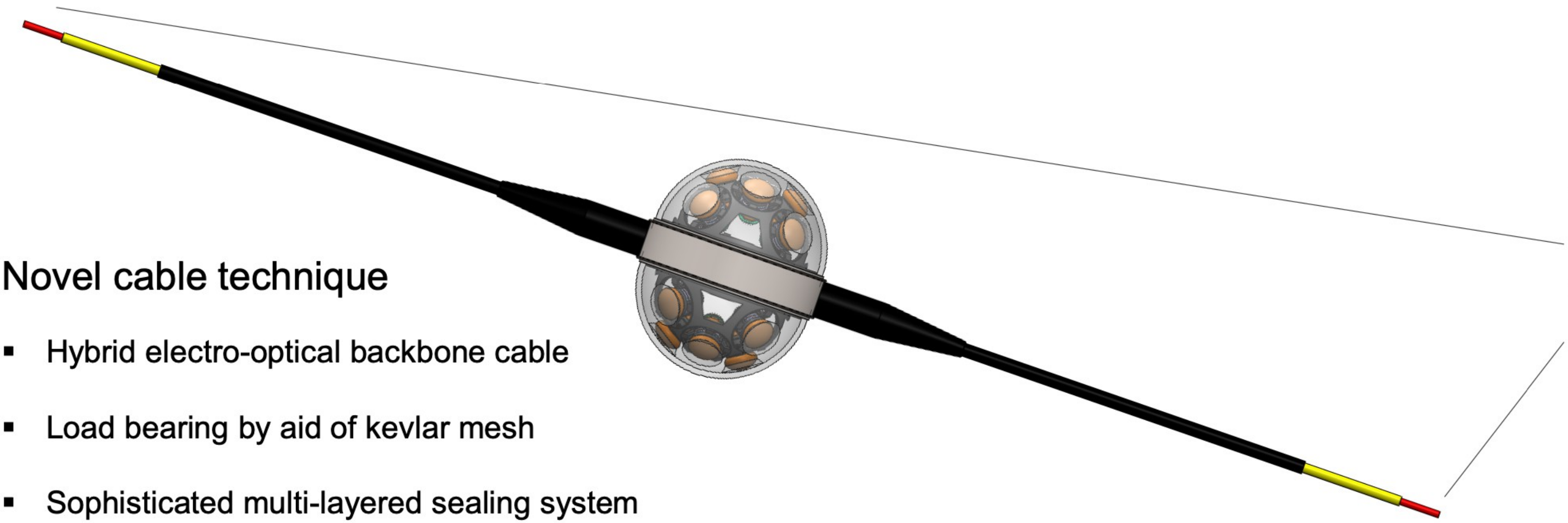
Current and knockdown

- Maximum current of about 10cm/s expected at P-ONE site
- Changes in current direction can result in position shifts of O(10m) on timescales of ~10min
- Horizontal displacements of strings results in very small vertical "knockdown"





Detector line design

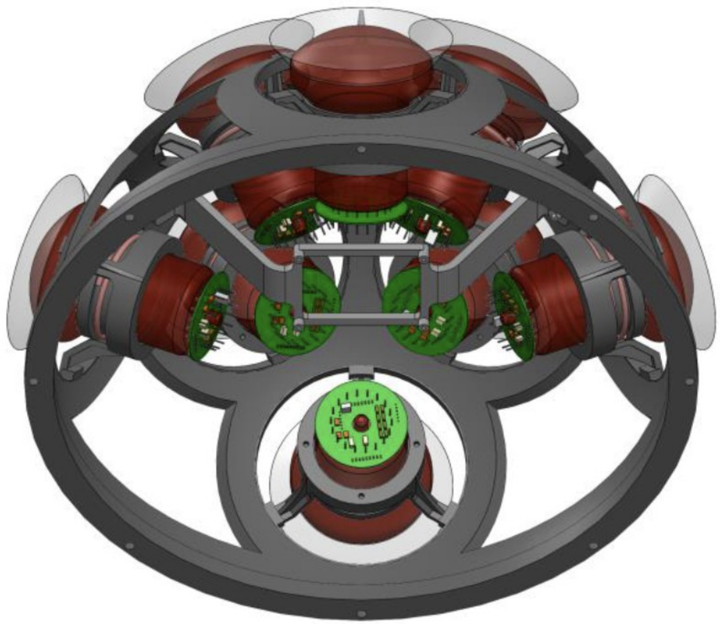


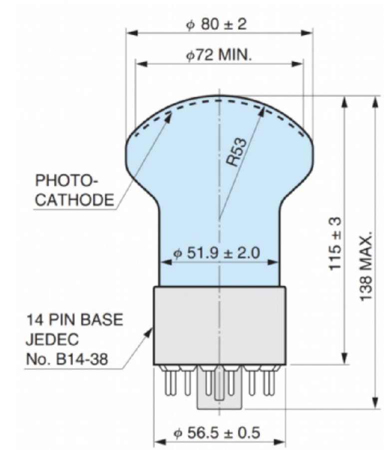
Novel cable technique

- Hybrid electro-optical backbone cable
- Load bearing by aid of kevlar mesh
- Sophisticated multi-layered sealing system
- No cable shadow for optical modules

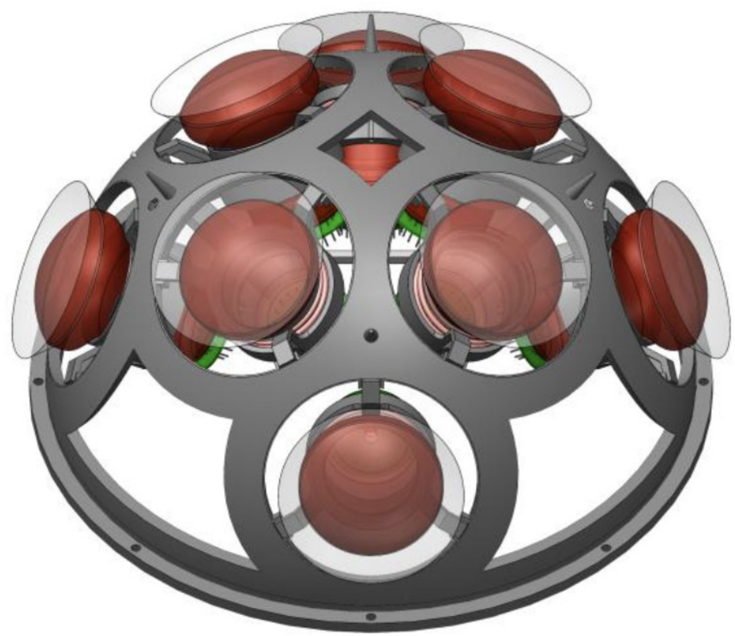
Instrument assembly

- Titanium cylinder as breakout can
- Cable terminates in Ti cylinder (feed-through of unused cable/fiber)

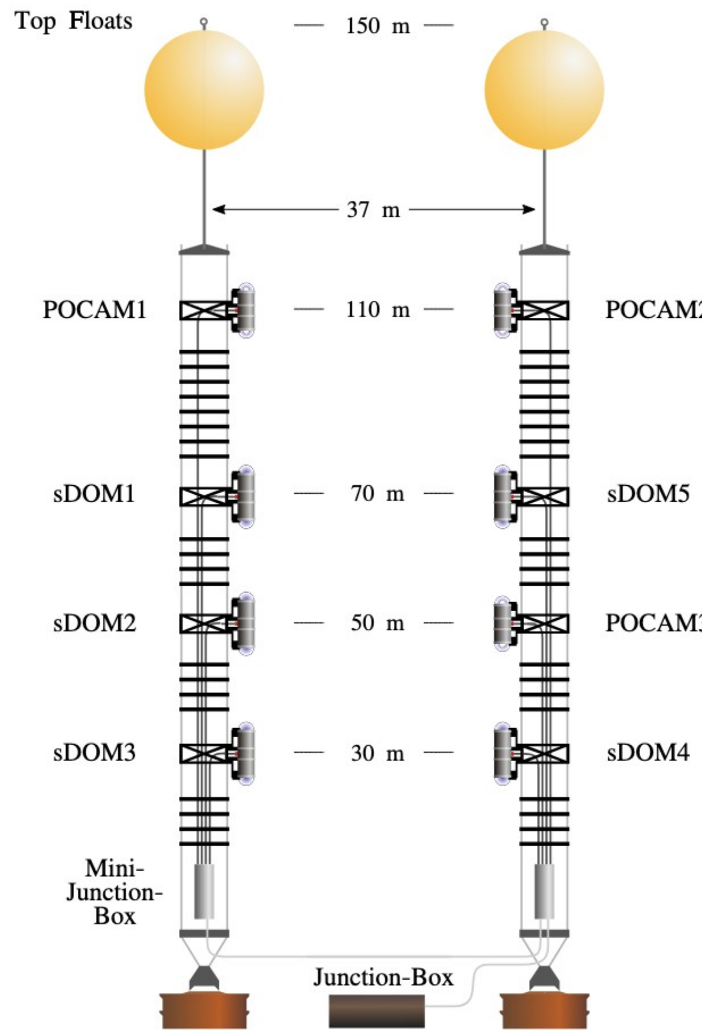




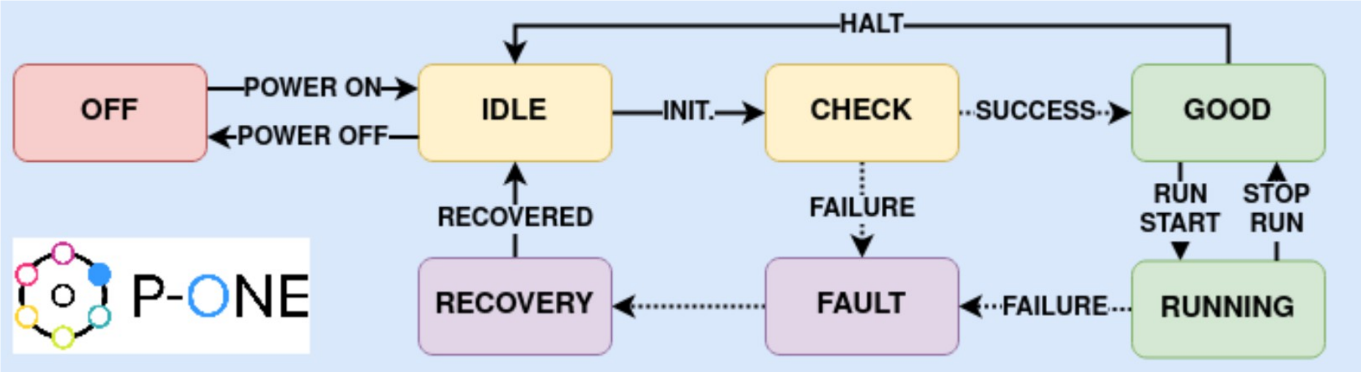
φ 80 ± 2
φ72 MIN.
R53
PHOTO-
CATHODE
φ 51.9 ± 2.0
115 ± 3
138 MAX.
14 PIN BASE
JEDEC
No. B14-38
φ 56.5 ± 0.5

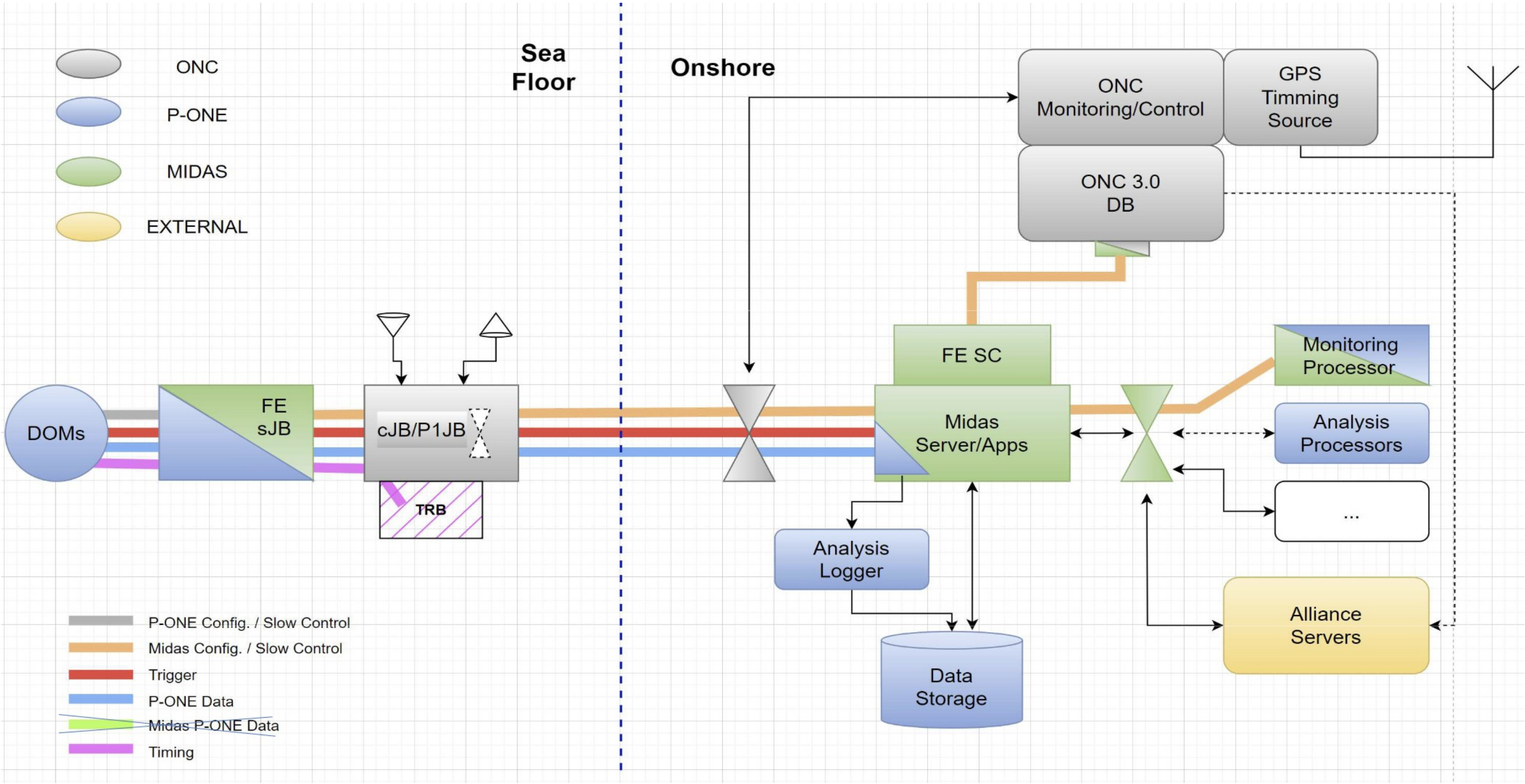


Pathfinders: STRAWa & STRAWb



Detector control



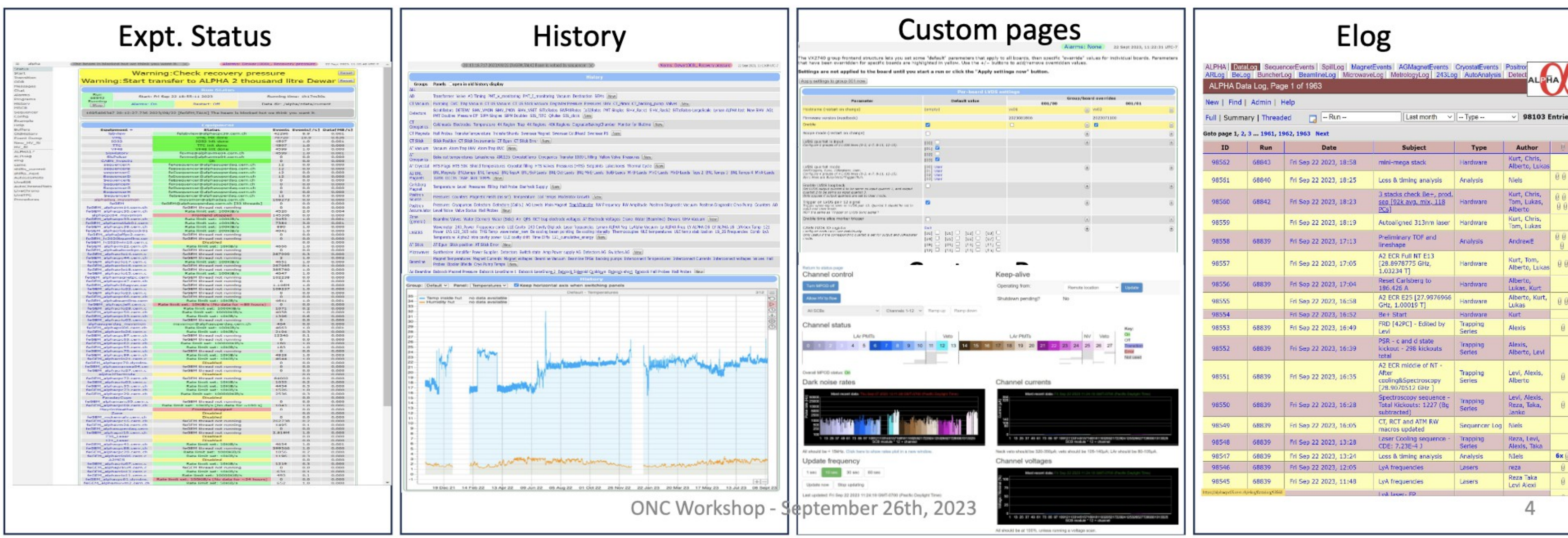


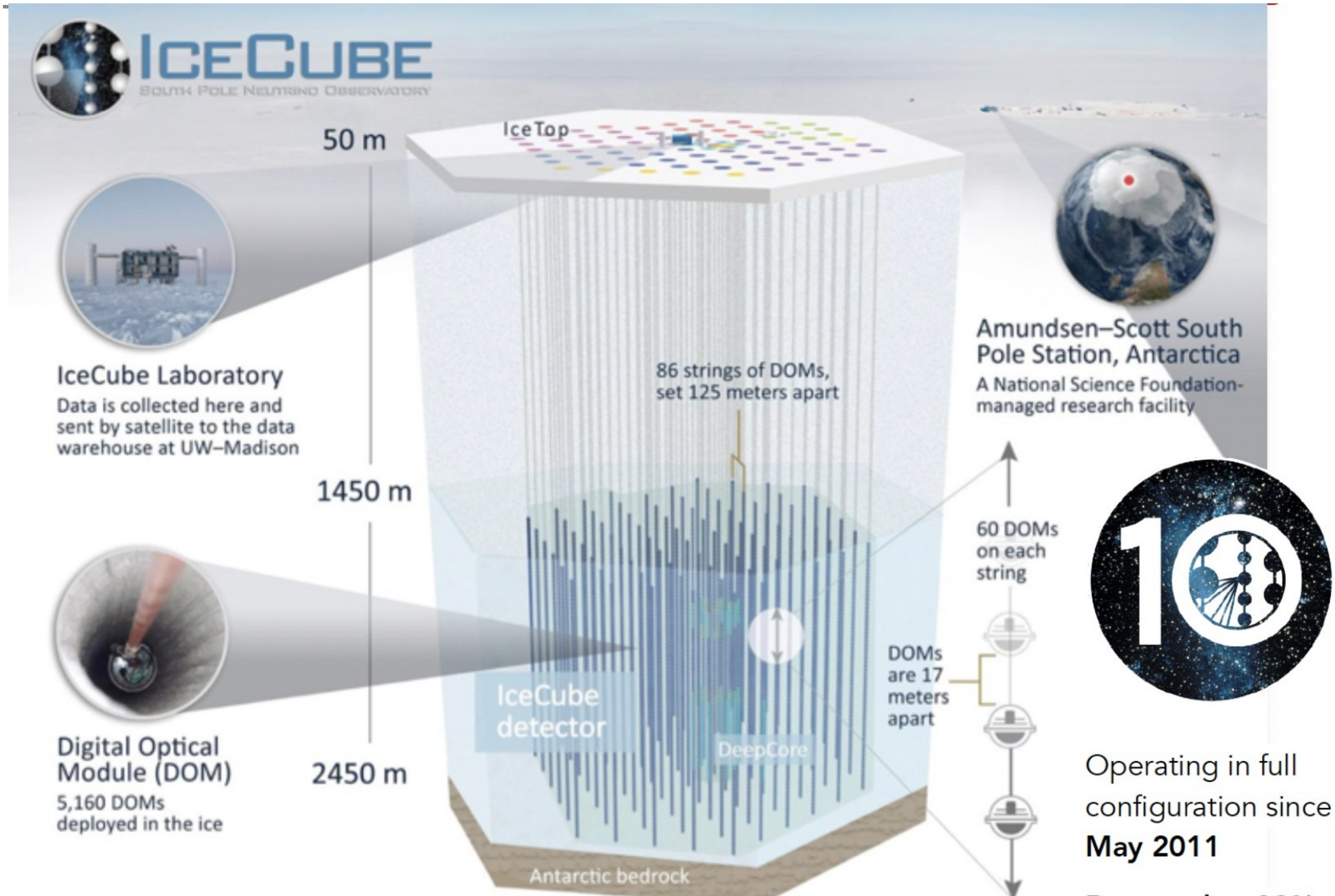
Midas

DAQ anticipated to utilize MIDAS

Pierre-A. Amaudruz
Triumf DAQ Group

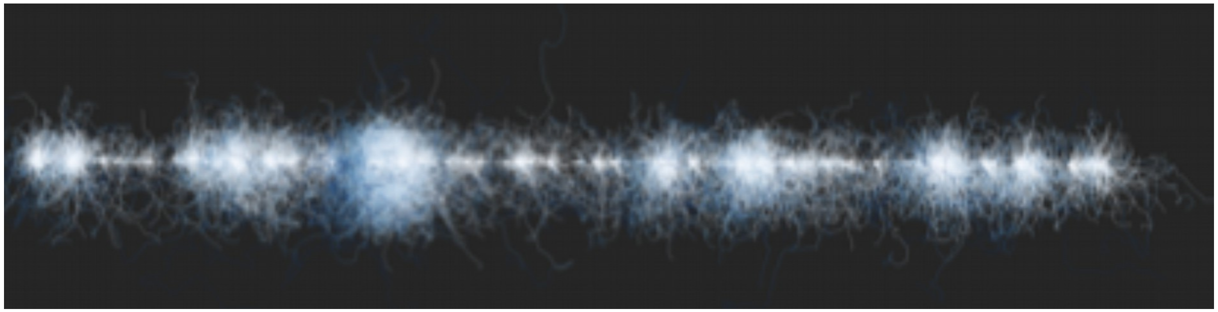
- Remote Run Operation, Experiment Monitoring
- Management of the Slow Control (ancillary devices)
- Common Physics DAQ aspects
- Readout & permanent storage of the Physics Data

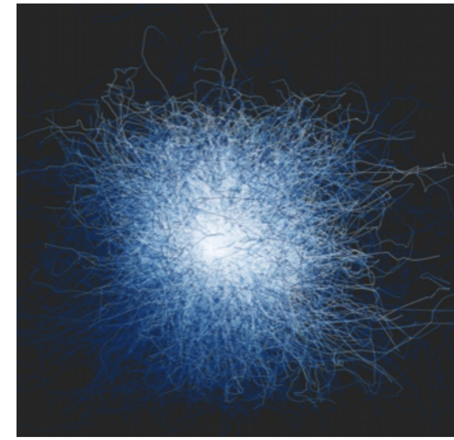


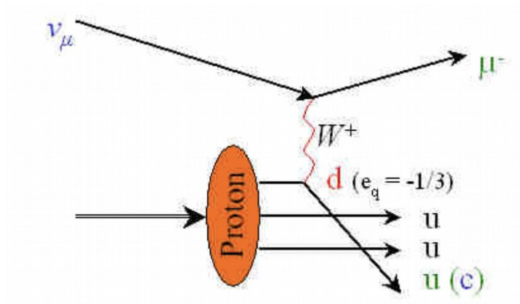


Operating in full configuration since **May 2011**

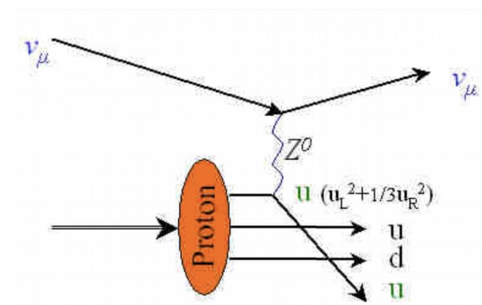
Duty cycle ~99%



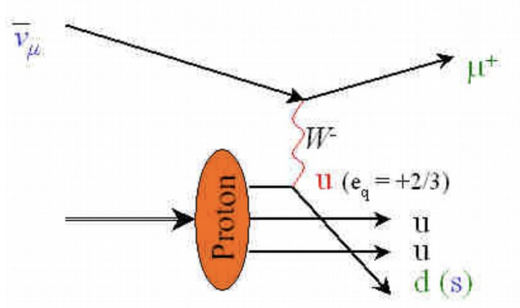




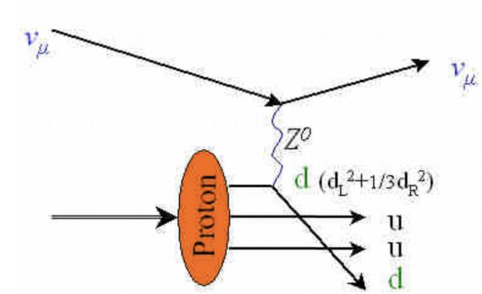
νμ
μ-
W+
d (eq = -1/3)
Proton
u
u
u (c)



νμ
Z0
u (uL2+1/3uR2)
Proton
u
d
u

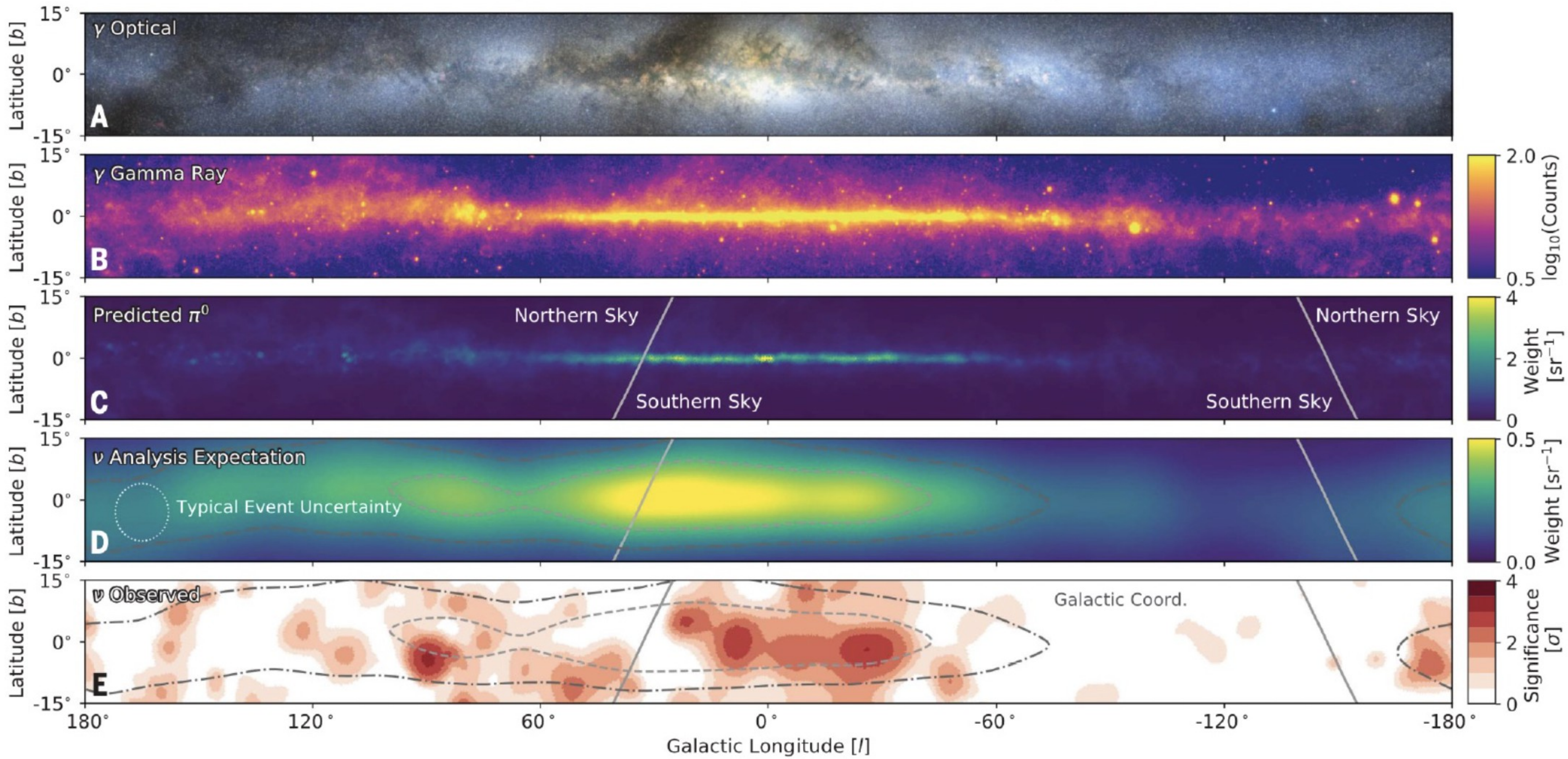


ν̄μ
μ+
W-
u (eq = +2/3)
Proton
u
u
d (s)



νμ
Z0
d (dL2+1/3dR2)
Proton
u
u
d

Galactic plane neutrinos



- 4.5 sigma evidence for galactic plane neutrinos

The IceCube Collaboration, Science 23
1. Ackermann et al. The Astrophysical Journal 750, no. 1 (April 2012): 3.
2. Gaggero et al The Astrophysical Journal 815, no. 2 (December 2015): L25.

Cosmic rays

atmospheric muons : ~ 10^{11} year^{-1} (3000 per second)

atmospheric neutrinos : ~ 10^5 year^{-1} (1 every 6 minutes)

astrophysical : ~ few -100 year^{-1}