© The P-ONE Collaboration

Pacific Ocean Neutrino Experiment (P-ONE)

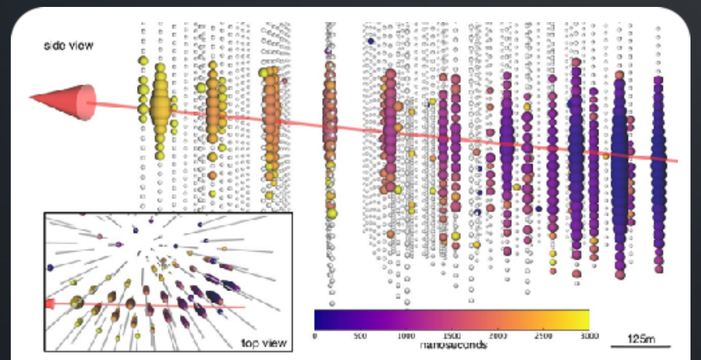
Woosik Kang

On behalf of the P-ONE Collaboration

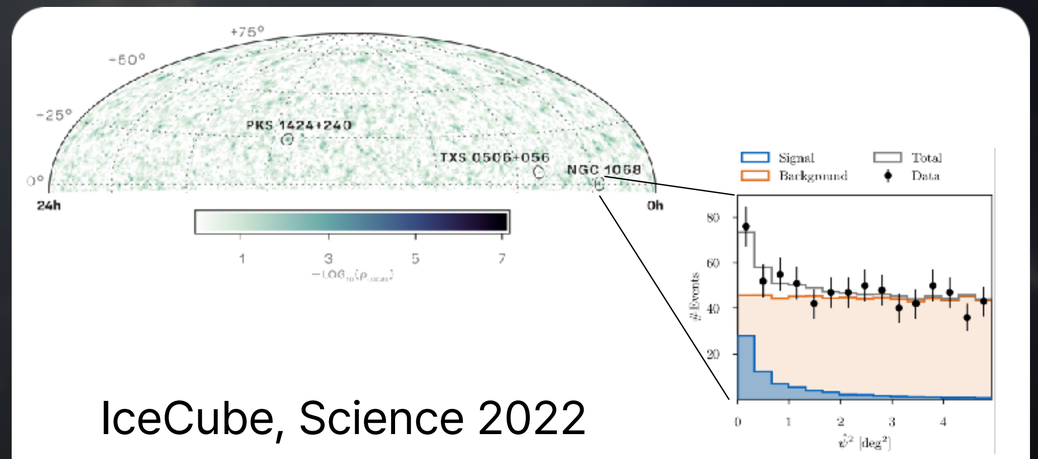
NSF P-ONE

Drexel UNIVERSITY

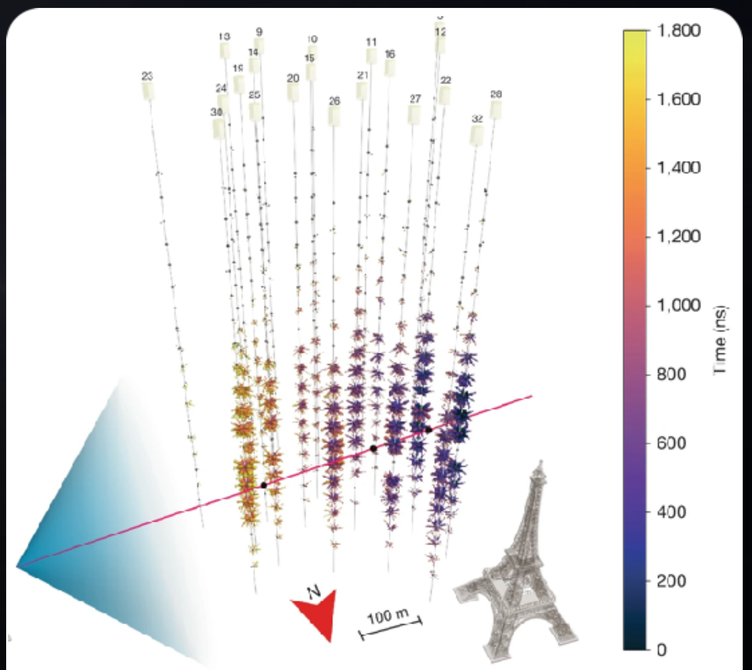
Era of Neutrino Astronomy / Astrophysics



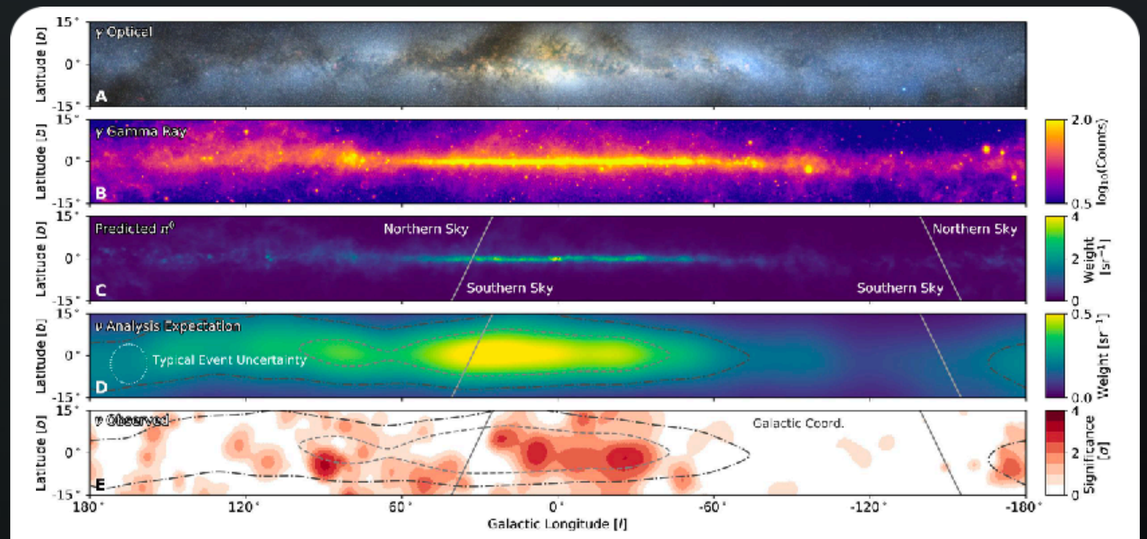
IceCube, Science 2018



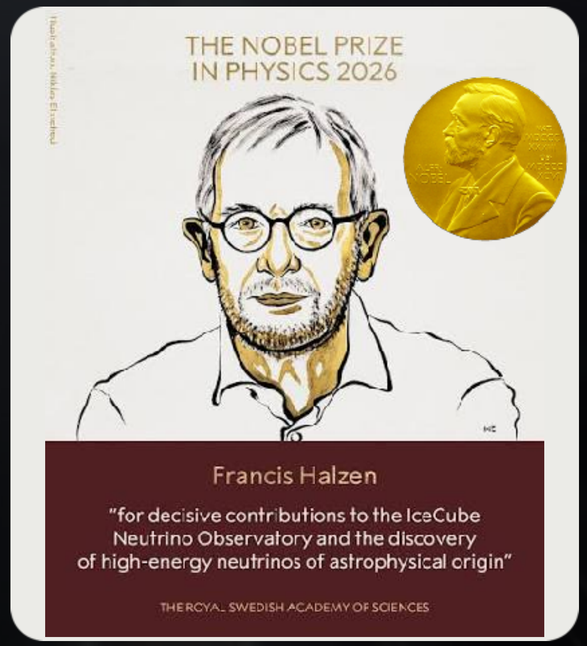
IceCube, Science 2022



KM3NeT, Nature 2025



IceCube, Science 2023



Ph.D. Dissertation

Search for Interactions of Dark Matter with High-Energy Neutrinos from Extragalactic Astrophysical Sources with the IceCube Neutrino Observatory

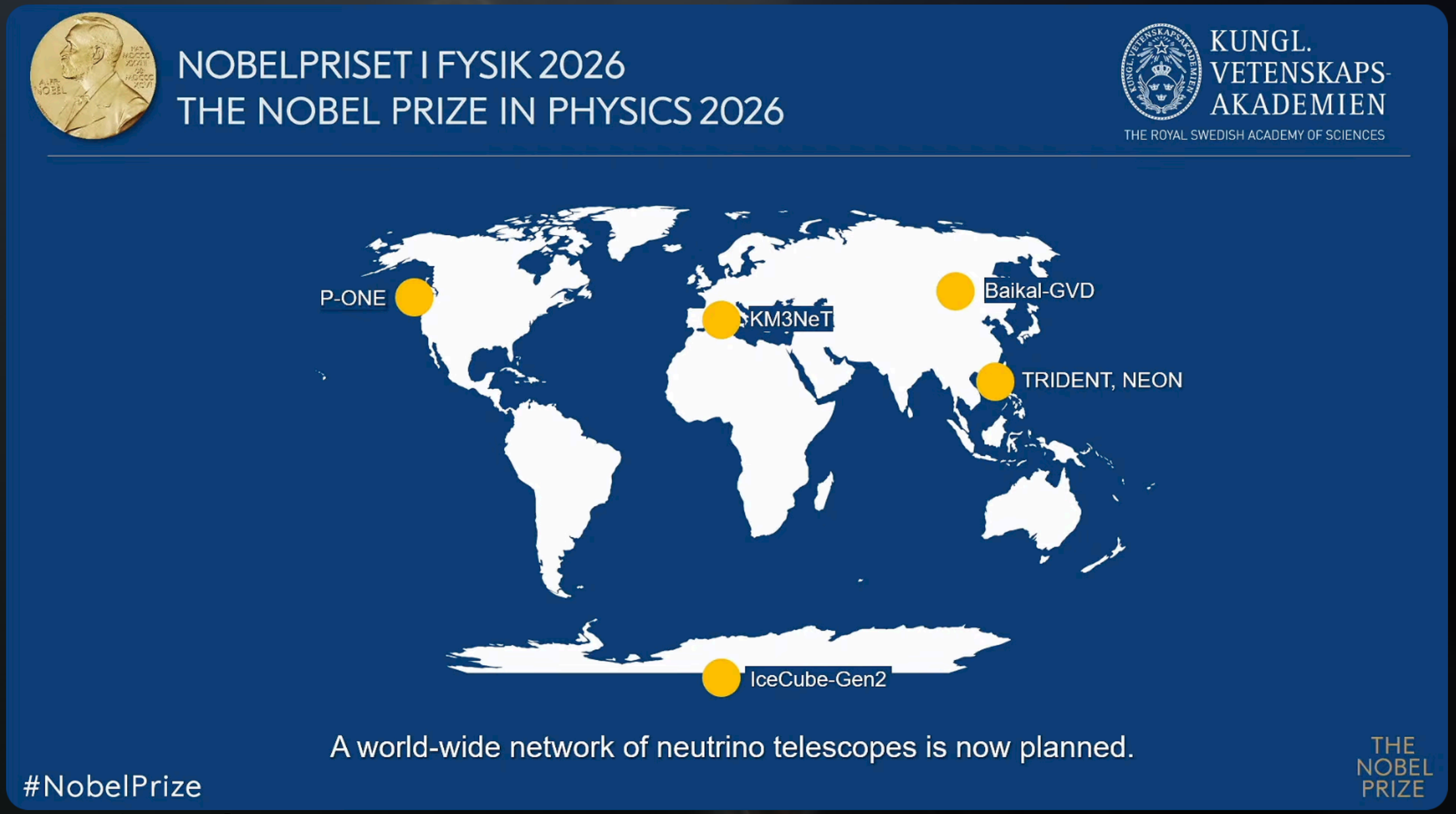
- The whispering of Shadow and Petite -

Woosik Kang

The Graduate School
Sungkyunkwan University
Department of Physics

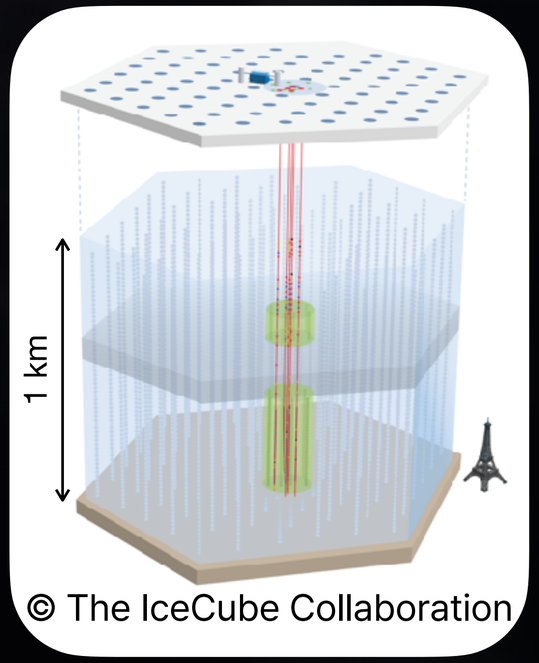
I've been working in the IceCube collaboration since 2015, and also joined the P-ONE collaboration in 2025!

Global Neutrino Telescope Network



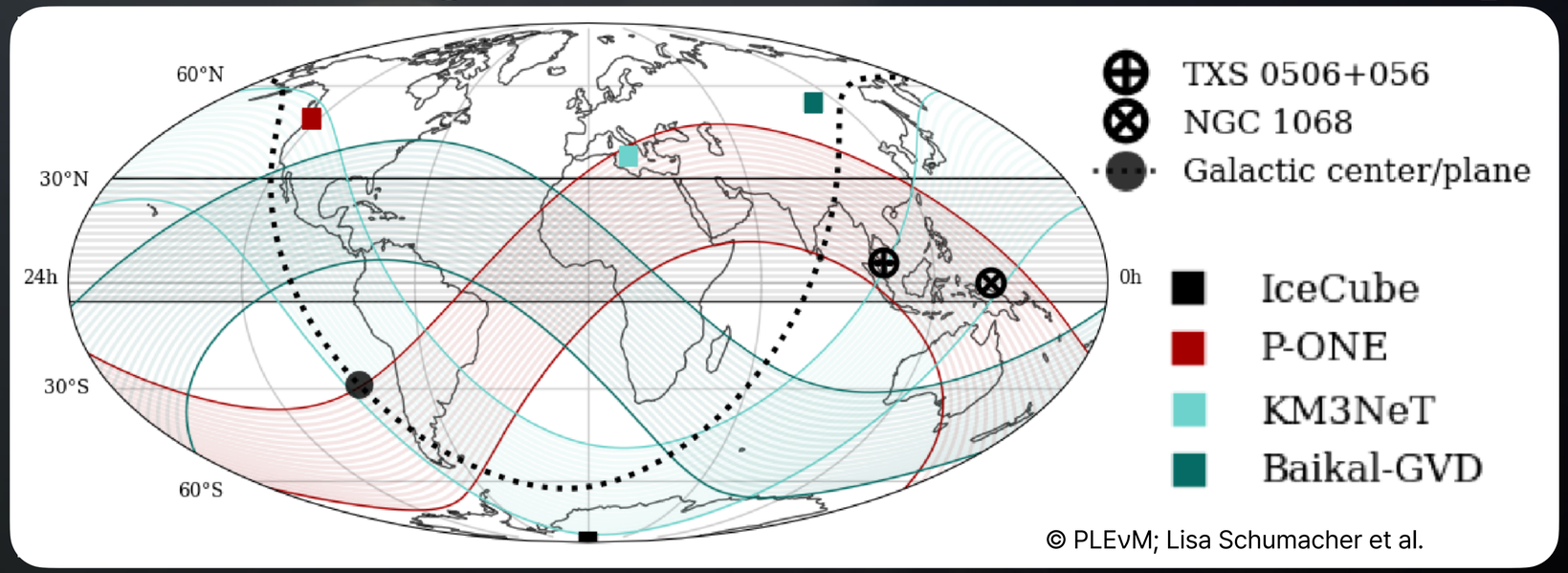
Reminder: What is Neutrino Telescope

- Large-scale water/ice-Cherenkov arrays with detector instruments volume $\gtrsim 1\ \mathrm{km}^3$
  - Target energy is **TeV and above** for astrophysical neutrinos
  - Larger volume for **more events** and better reconstruction (direction or energy)
- Events from all directions at every moment, but most of them are atmospheric background resulting from cosmic-ray interactions in the atmosphere
    - Approximate event rates at IceCube (~ 2.7 kHz at trigger level)
      - Atmospheric Background:
        - Muons: ~ 10^{11} events/yr
        - Neutrinos: ~ 10^{5} events/yr
      - Astrophysical Signal Neutrinos: ~ 10^{2} events/yr



Building giant detectors is challenging, yet detecting astrophysical signals remains difficult

All-sky Sensitivity of Neutrino Telescopes

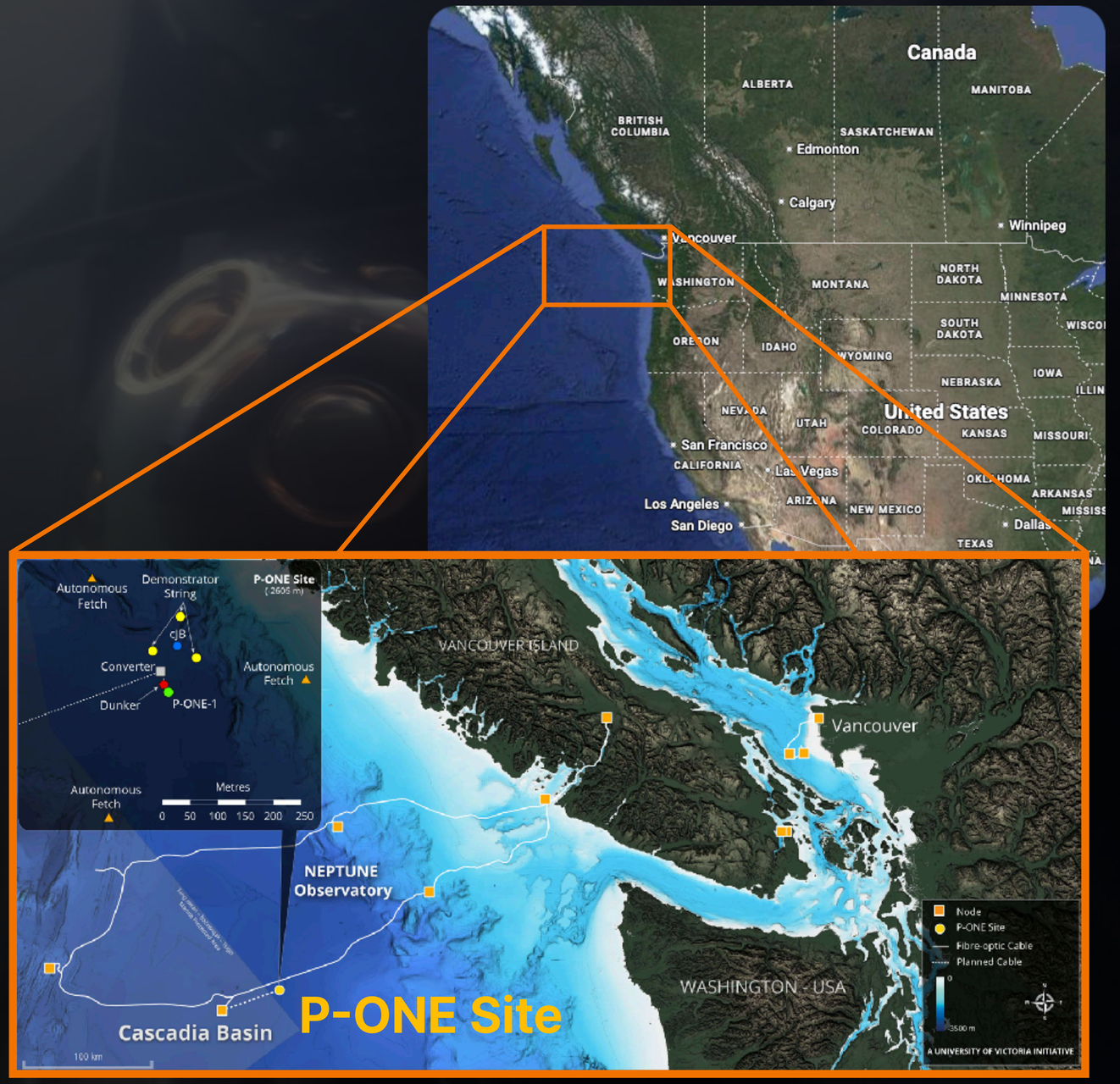


- Coloured regions cover a region for -5 ° < zenith < 30 ° of each detector, where the highest detection efficiency of each detector is with E^{-2} energy spectrum
  - The efficiency drops by a factor of 2 at boundaries
  - It is an instantaneous snapshot; the bands move as Earth rotates
- One telescope becomes a complement of the others
  - Global neutrino network, using data from all neutrino telescopes
    ➔ improved sensitivity and better coverage

Pacific Ocean Neutrino Experiment (P-ONE)

P-ONE site

- **Cascadia Basin**
  - Abyssal plain in depth ~ 2660 m
  - Low currents (< 10 cm/s)
  - Stable temperature (~ 2 °C)
- **Ocean Networks Canada (ONC)**
  - World’s largest undersea network
  - 850 km loop
  - 8 kW x 6 nodes
  - 2 Gbit/s via fibre-optic cable

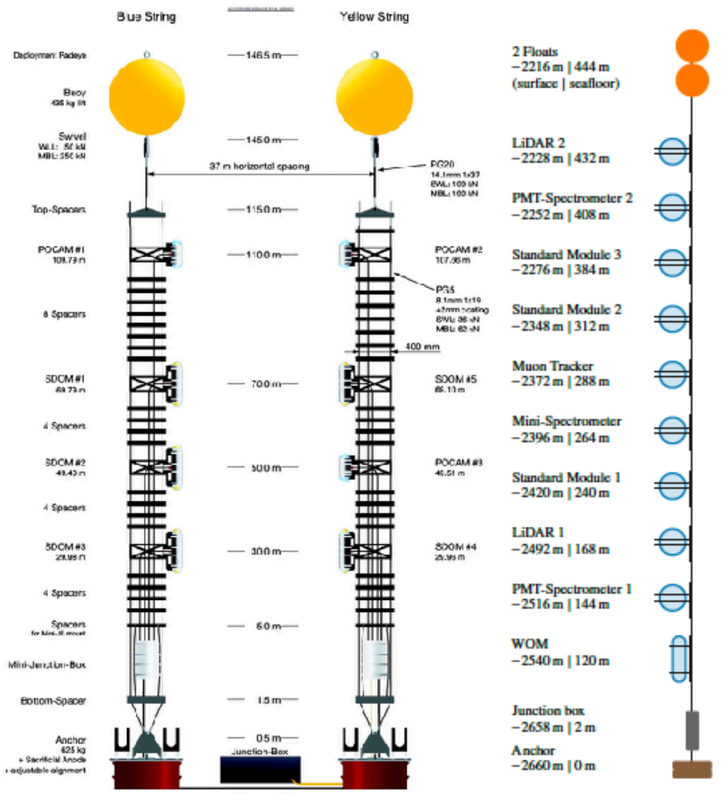


P-ONE Detector

❖ NOT TO SCALE

STRAW

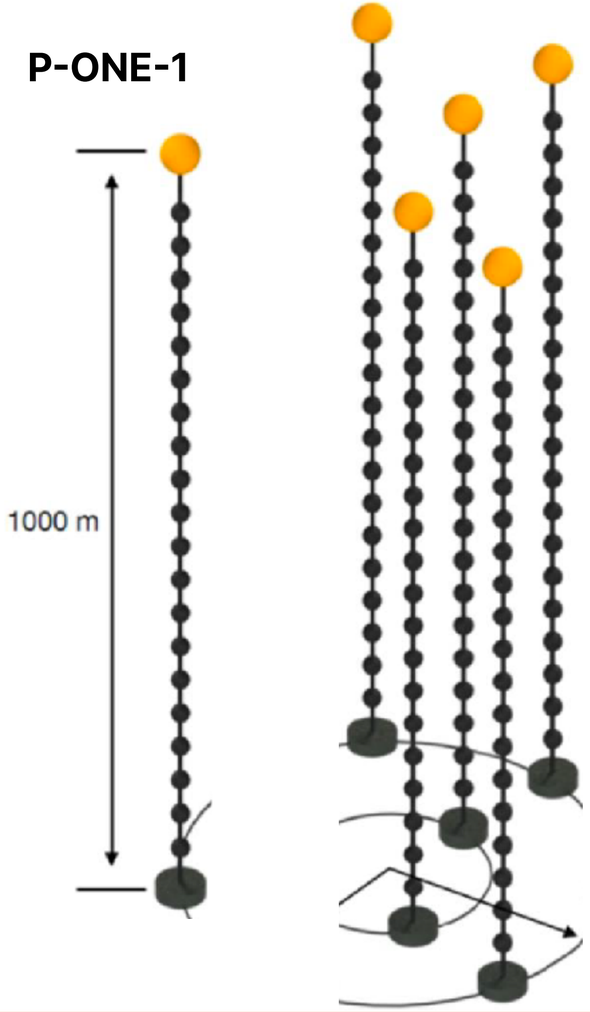
STRAW-b



Operation 2018-2023
Recovered

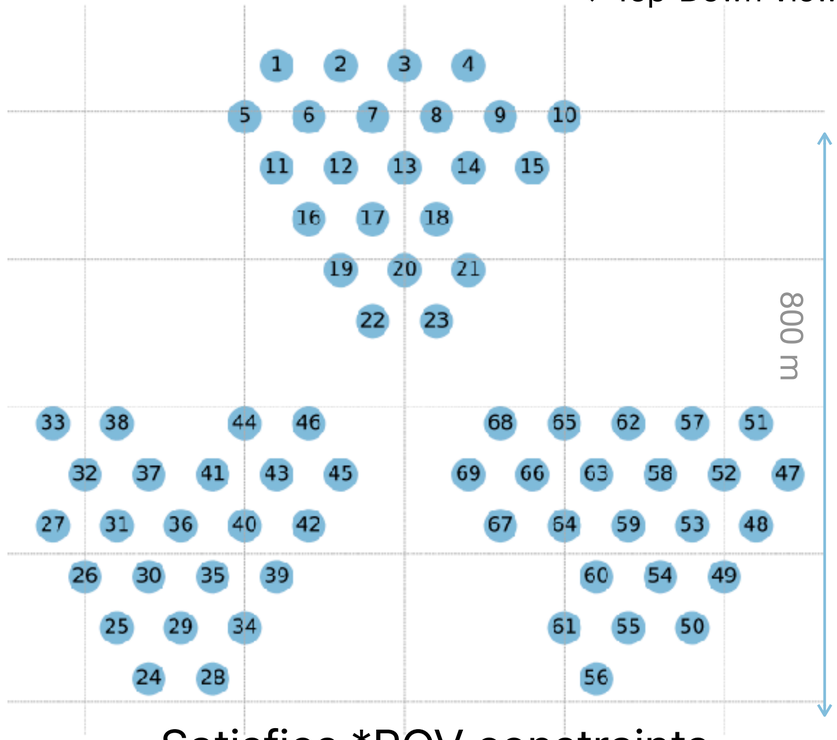
P-ONE-Demonstrator (P-ONE-D)

P-ONE-1



P-ONE
(Baseline Geometry as of 2026)

❖ Top-Down View

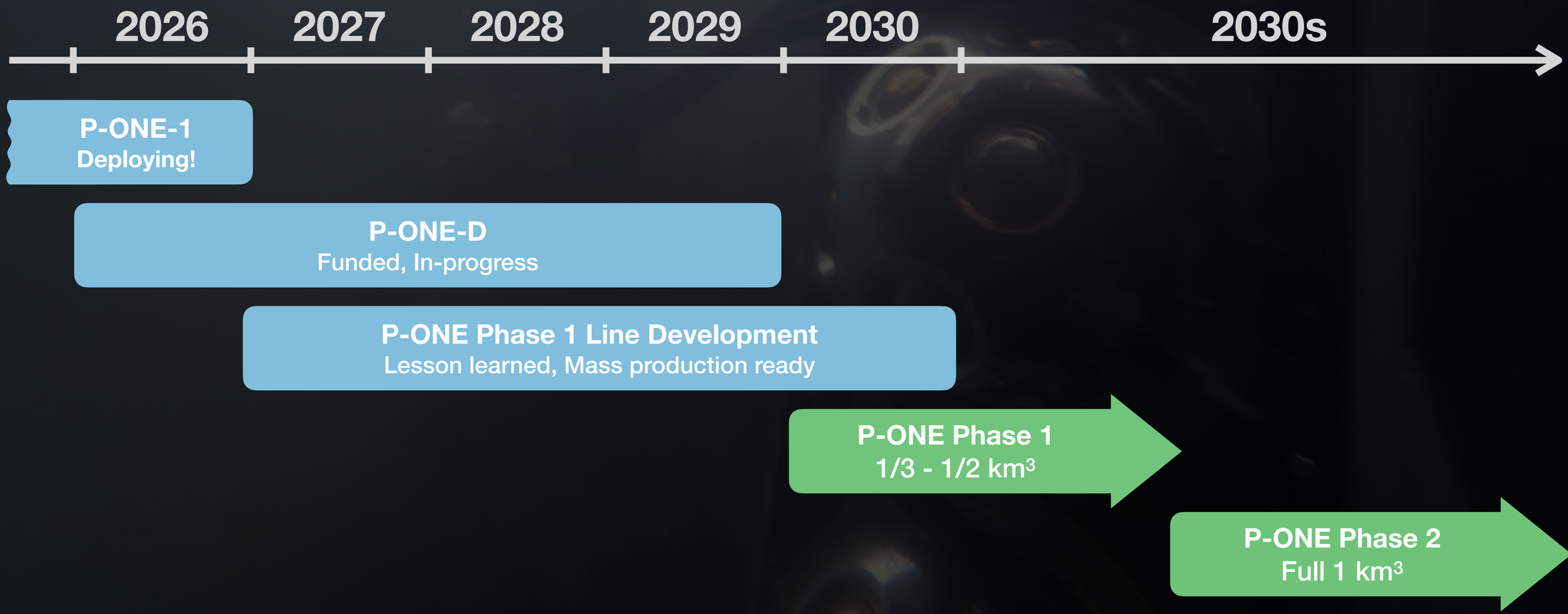


Satisfies *ROV constraints

*Remotely Operated Vehicle



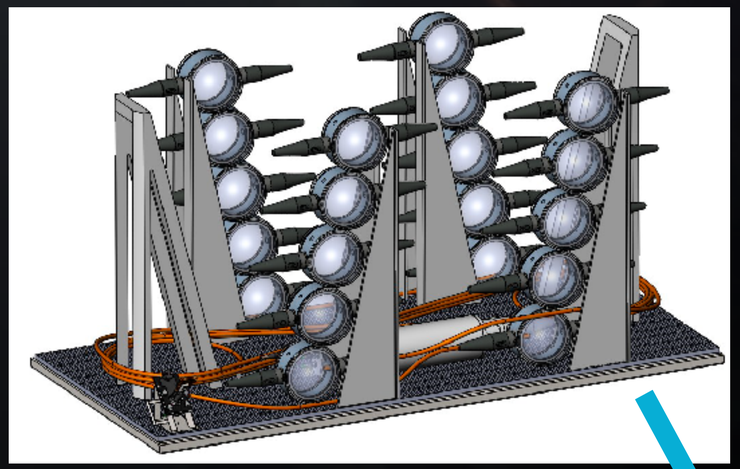
P-ONE Timeline



P-ONE Lines

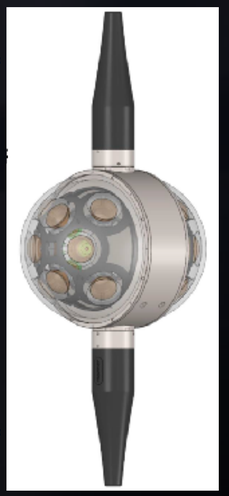
❖ NOT TO SCALE

- 1 km line with 20 modules = 50 m segments
  - 18 Optical and 2 calibration modules
  - Module serves as breakout box
    ➔ No connectors
  - Cable serves as mechanical backbone
    ➔ Reduced cable shadow
    ➔ Designed for easy deployment (bottom-up)
- Many calibration systems
  ➔ acoustic & optical
- Sub-ns time synchronisation
- Deployment frame serves as anchor and contains mooring network infrastructure



Deployment Frame



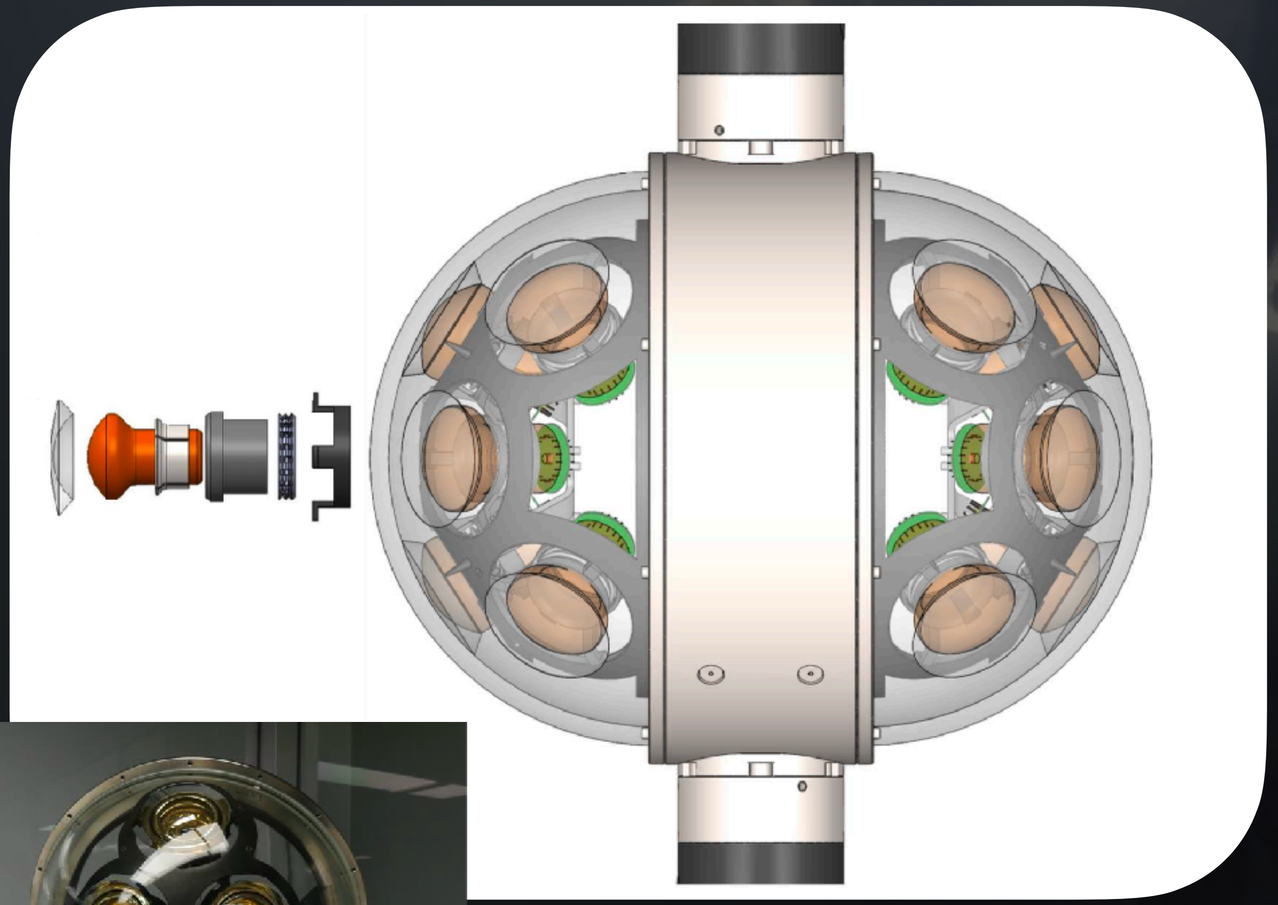


Optical Module (P-OM)



Calibration Module (P-CAL)

P-ONE Optical Modules (P-OM)







KM3NeT OM



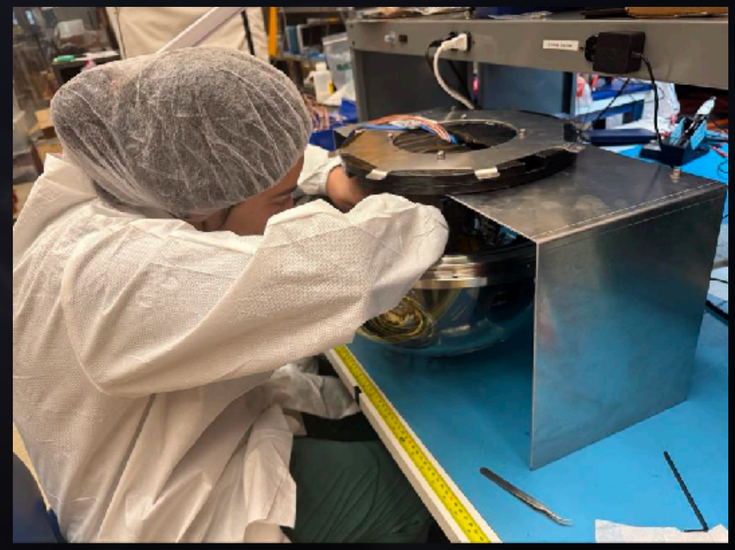
IceCube mDOM

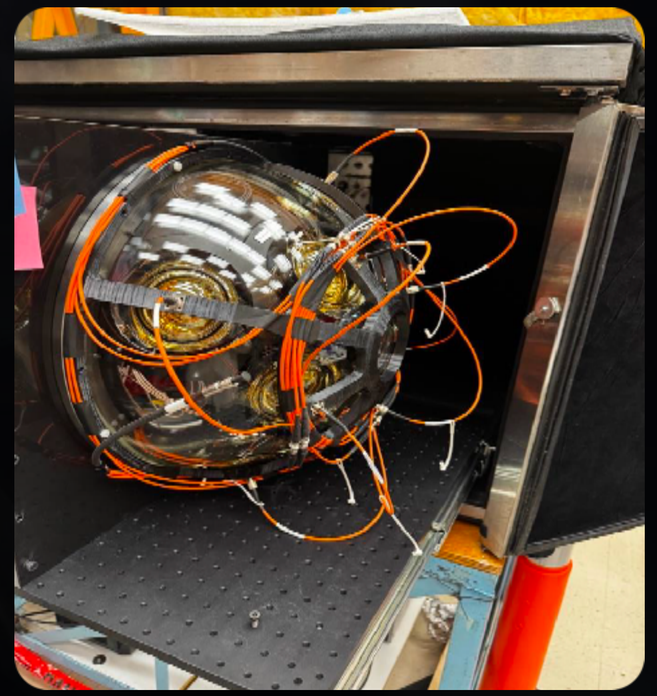
- Multi-PMT module based on KM3NeT OM and IceCube mDOM
- 17″ glass pressure housing
- 16 PMTs
  - 3″ Hamamatsu R14374-10
  - TTS ~ 1.3 ns
  - QE ~ 27 %
- 10 inserts for calibration devices
- Modular, spring-loaded mounting structure
- Optical gel pads to match index of refraction

P-ONE-1: Integration and Testing @ TRIUMF









Integration and Dry test completed successfully!

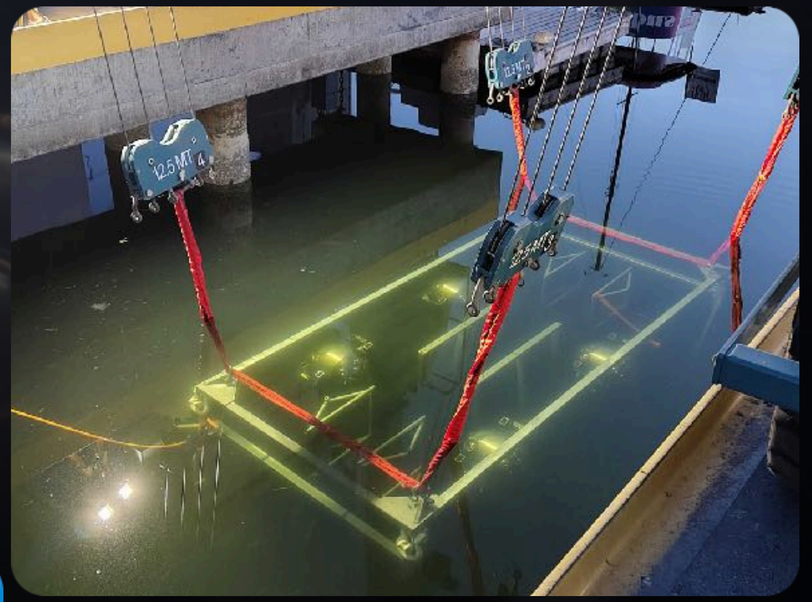
P-ONE-1: Wet Test in Vancouver Bay

Granville Island Boatyard,
Vancouver, BC, Canada
June 23rd, 2026



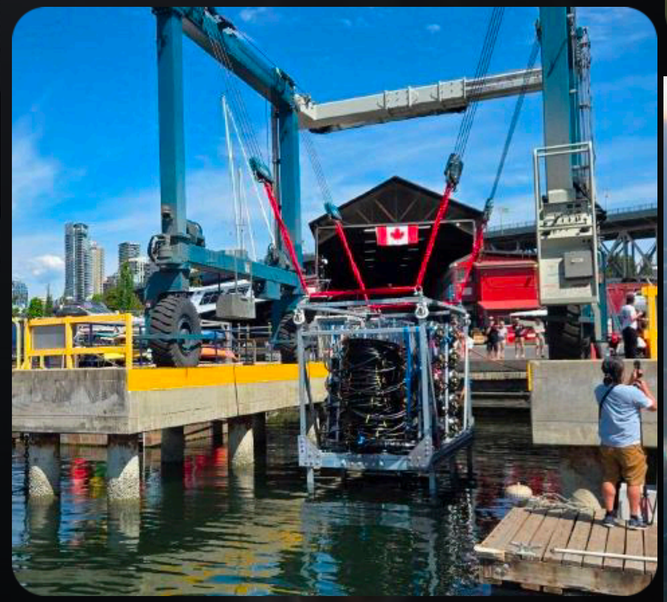


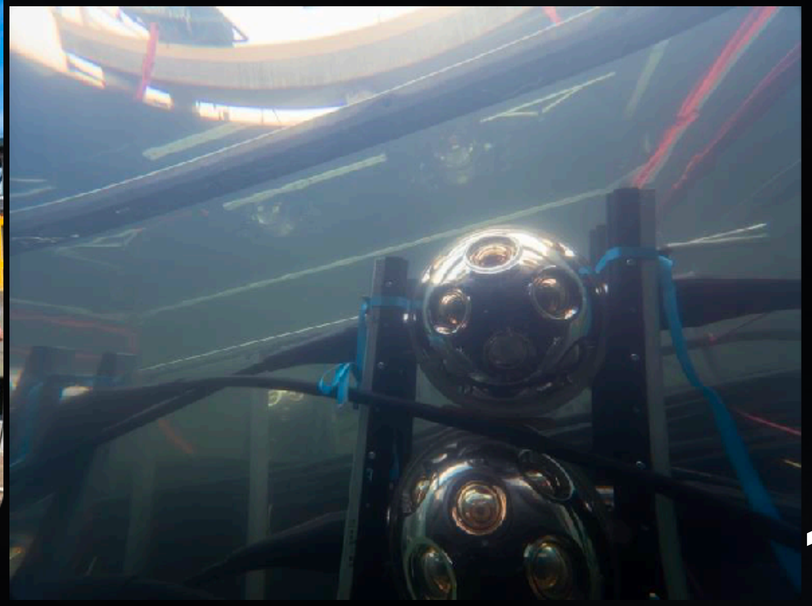












Wet test went well,
all green and go for deploy!

P-ONE-1: Deployment

Live

❖ NOT IN TIME SCALE

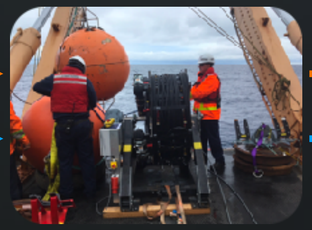
ROV



ROV Ship

Deployment Frame / P-ONE-1 Line

Node Extension Cable



Cable Ship

Frame/Line Deployment

Cable Deployment

Node-Cable-Line Connection

Visual Inspection

Digital Inspection

Line Unfurling

Line Monitoring

Post-unfurling Inspection

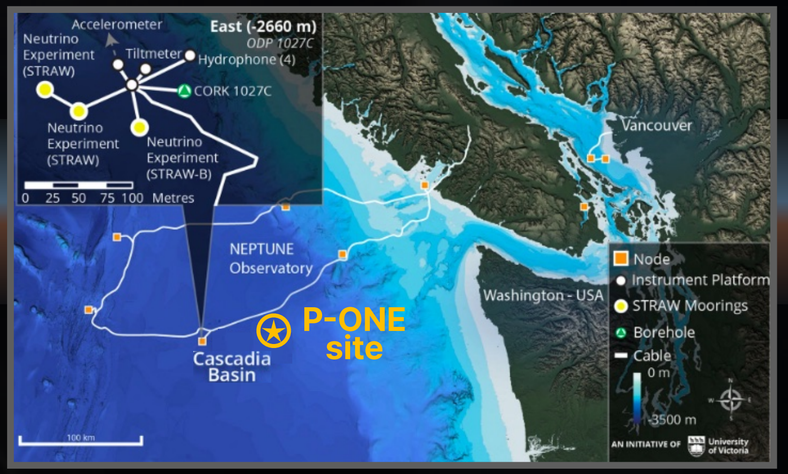
Completion of Deployment

Sea Operation

Shore Operation

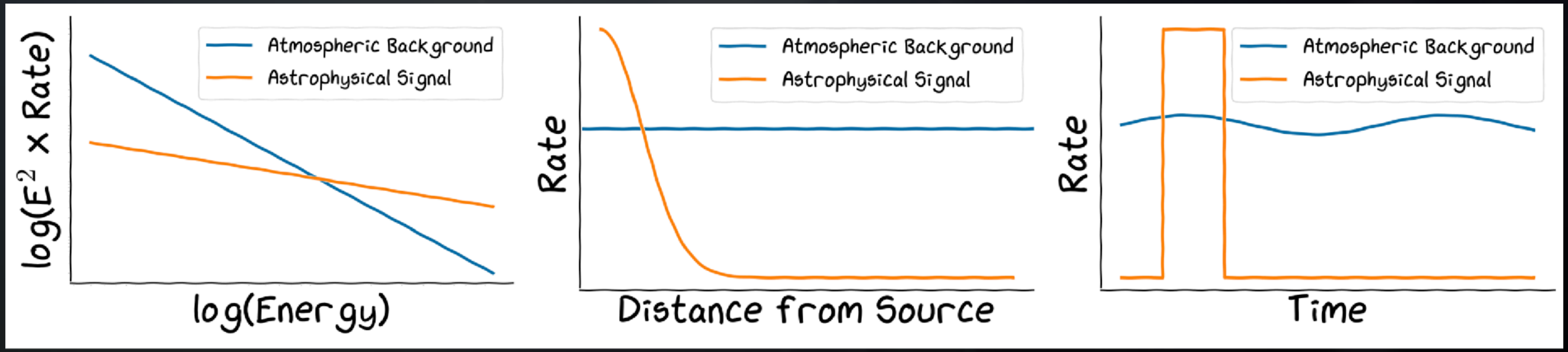
Detector Operations (Power/Comm)

P-ONE



Neutrino Source Search with P-ONE

Searching for Astrophysical Neutrino Signals

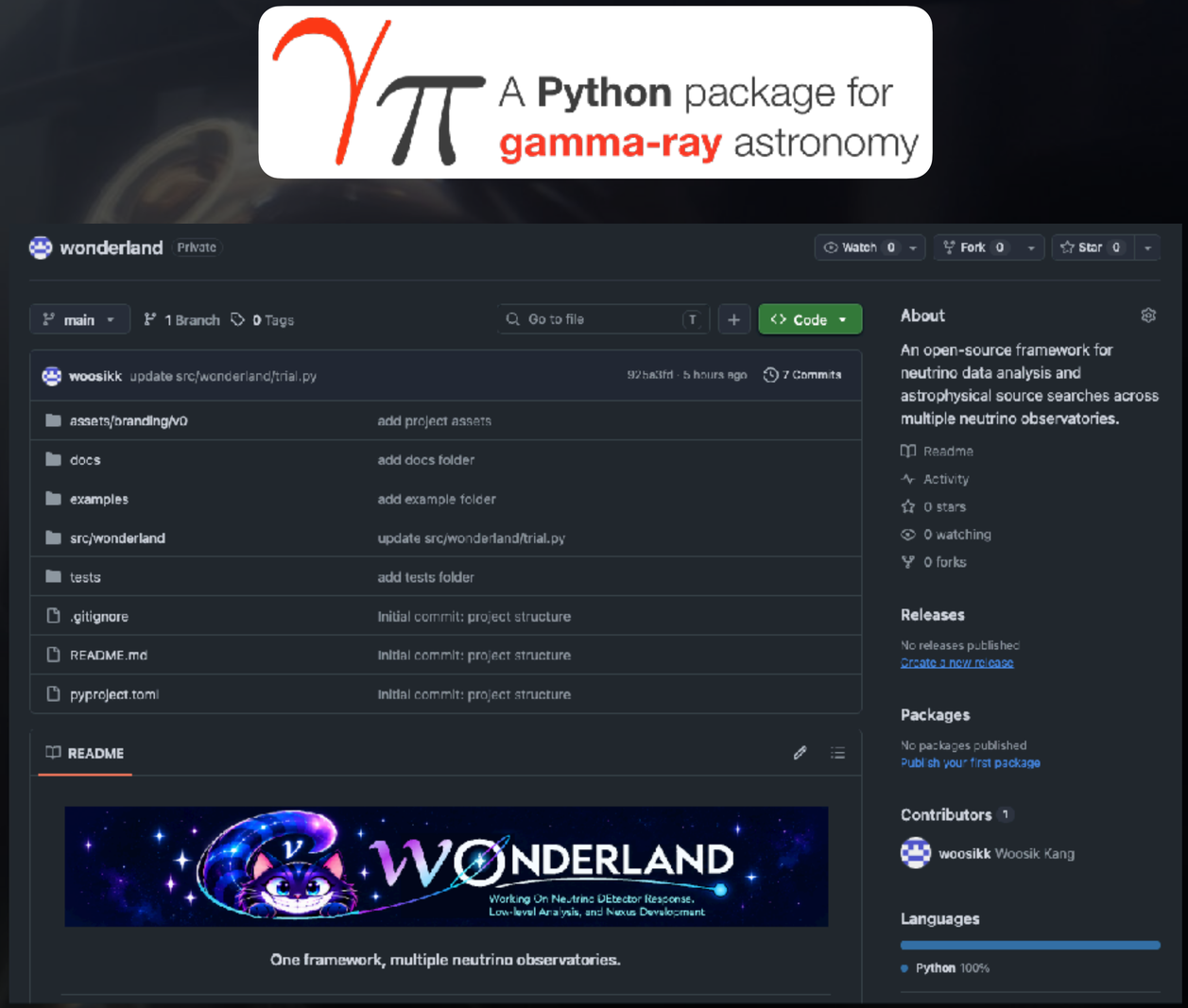


Statistical analyses generally use energy, direction, and time information to determine the significance of astrophysical signals against the backgrounds

Excesses over the backgrounds!

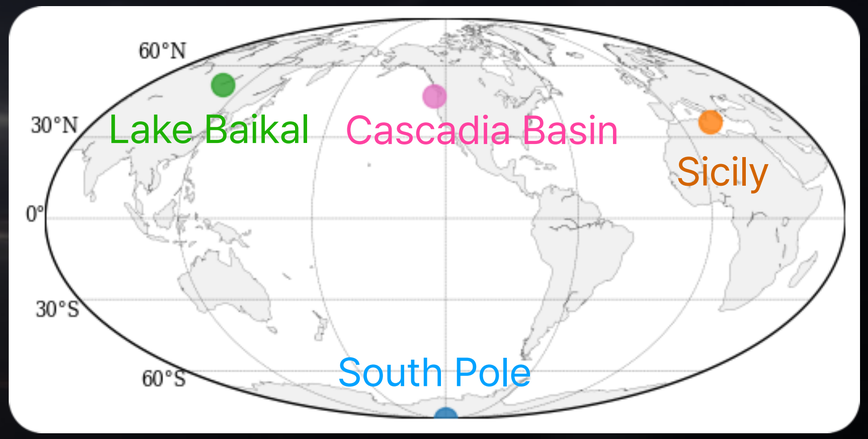
New Analysis Framework: WONDERLAND

- Working On Neutrino DEtector Response, Low-level Analysis, and Nexus Development
- New neutrino source analysis framework, open source and Python-based, pipeline to GammaPy for likelihood analysis
  - Adoptable to any locations and any neutrino detectors
  - Easy to carry out multi-detector analysis with multiple neutrino telescopes or even multi-messenger analysis with Gamma-ray experiments
  - Applicable to other types of analysis, such as indirect Dark Matter searches
- Publication in progress, along with public release of the software



(Pre-pre-) Preliminary Sensitivity to Galactic Centre

- Sensitivity tests to Galactic Centre as a point-like source
  - Assumed that IceCube is relocated from South Pole to elsewhere
    - Not an actual sensitivity of a known detector at a location, except for South Pole
    - Apple-to-apple comparison of locations
  - 12 years of through-going track events
  - Injected signal flux (E^2dNdE) = 1.5×10^{-12} TeV cm^{-2} s^{-1} at 100 TeV ($\gamma = 2.1$)



	South Pole	Cascadia Basin	Sicily	Lake Baikal
p-value	~ 2.5 x 10^{-2}	~ 9.2 x 10^{-10}	~ 1.6 x 10^{-6}	~ 1.3 x 10^{-13}
Median Significance	~ 1.95 σ	Preliminary ~ 5.04 σ	~ 4.65 σ	Preliminary ~ 7.21 σ

Summary

- P-ONE is a new neutrino telescope under construction in the Pacific Ocean
  - Two successful pathfinder experiments
  - P-ONE-1 is now in deployment stage!
  - P-ONE Demonstrator in 2029
- A new software for neutrino source search is soon to be ready to use
  - Preliminary studies are in progress

More to come, stay tuned!



P-ONE Collaboration Meeting in Edmonton, June 2026

P-ONE

Ocean Networks Canada · Technische Universität München · SFU Simon Fraser University · NSERC CRSNG · erc European Research Council · NSF U.S. National Science Foundation · UCL University College London · Elmhurst University · Michigan State University · FAU Friedrich-Alexander Universität Erlangen-Nürnberg · Drexel University · The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences · University of Alberta · UVic · Duke University · Queen's University · The University of Chicago · Georgia Institute of Technology

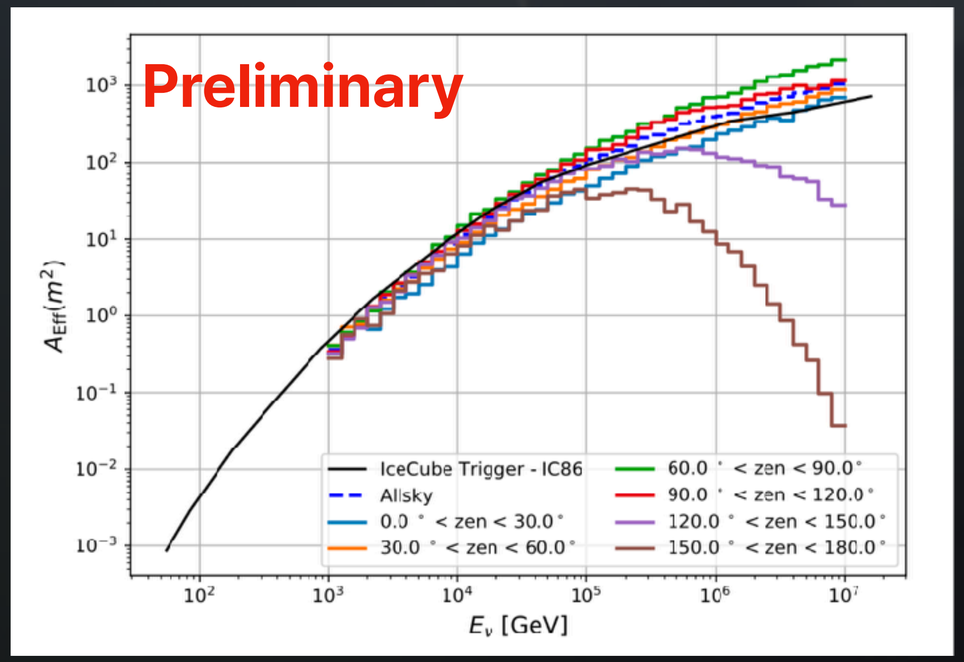
More to read

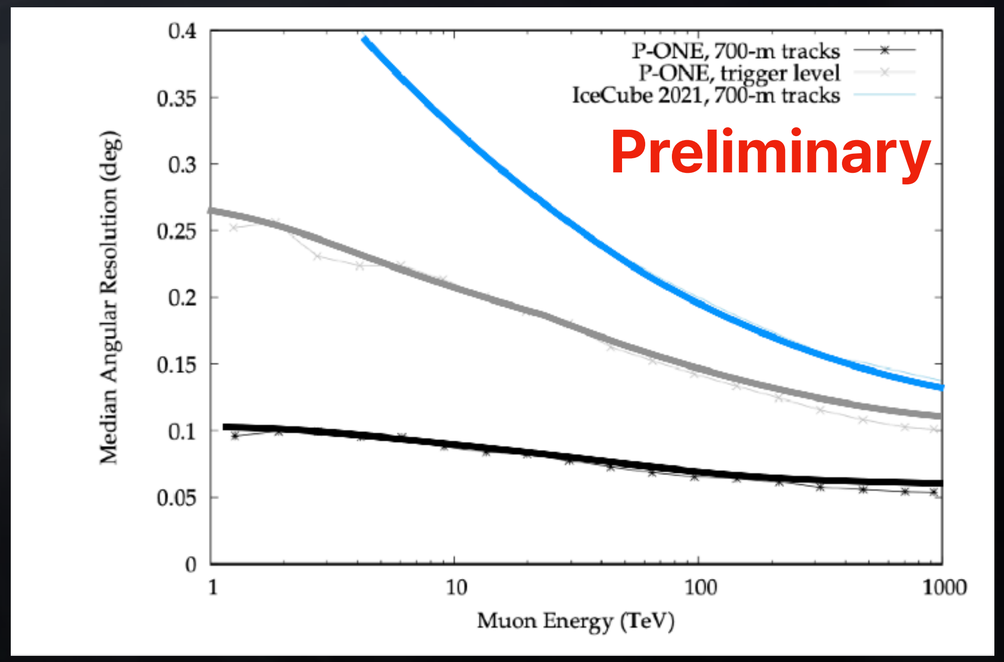
- Acoustic system: JINST 20 (2025) P07003; https://arxiv.org/abs/2504.13323
- Long-term study of sedimentation and biofouling: Eur. Phys. J. C. 86 (2026) 2 172; https://arxiv.org/abs/2507.09086
- Optical calibration system: JINST 21 (2026) P07029; https://arxiv.org/abs/2603.09495
- PMTs characterization: https://arxiv.org/abs/2610.26299 (submitted - under journal review)
- P-ONE-1 detector and integration: https://arxiv.org/abs/2610.27415 (submitted - under journal review)

- Many papers in preparation
  - DAQ
  - Optical module
  - Commissioning
  - ...

Back Up

Angular Resolution in P-ONE





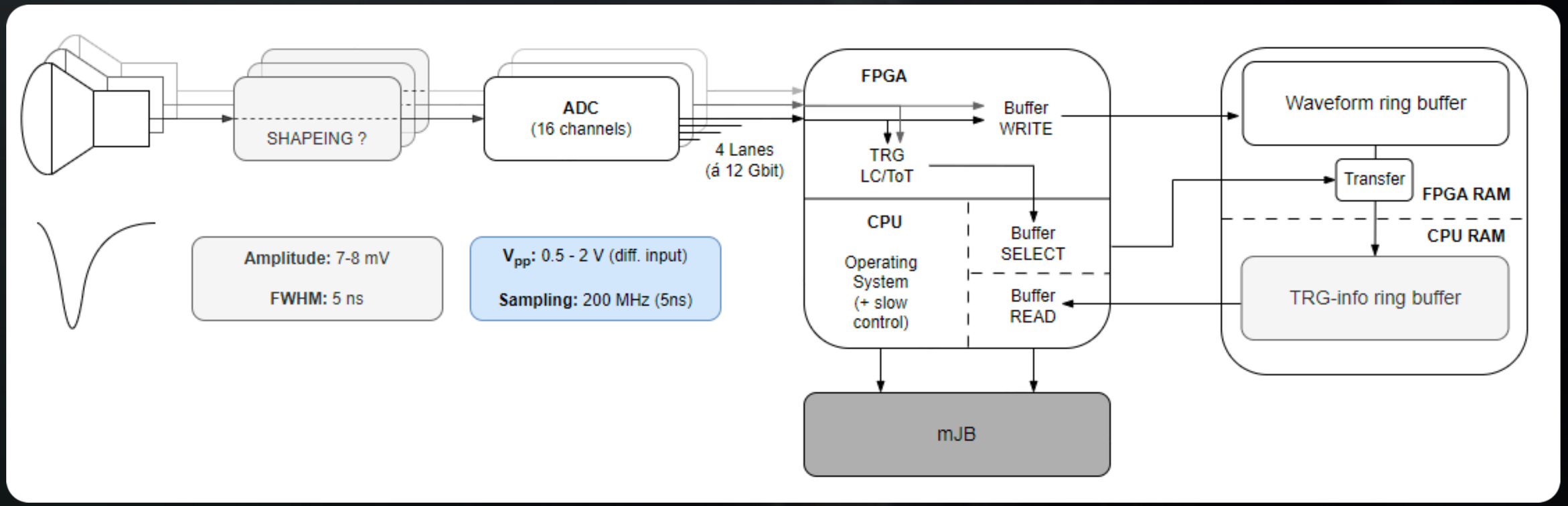
Twagirayezu et al. (P-ONE) PoS (ICRC2023) 1175

- 5x better angular resolution → 10x more extragalactic sources

P-OM Electronics

- PMTs read out by 210 MHz 12-bit ADC + FPGA
  ➔ Full waveform digitization

- Microprocessor, 4GB shared memory with FPGA
  ➔ Local data buffering, coincidence triggering, communication



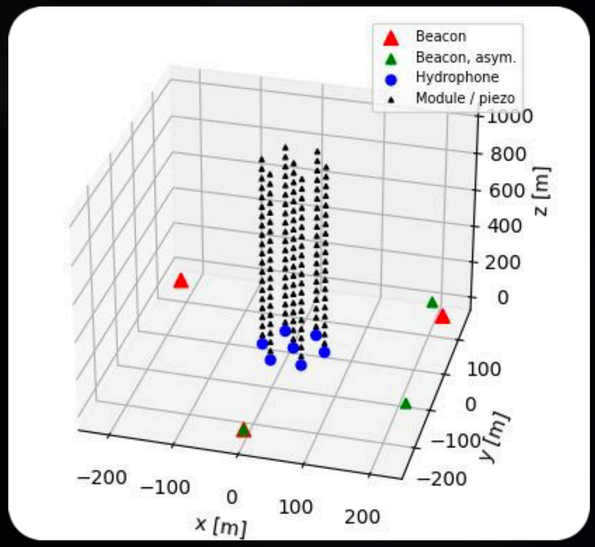
Calibration and Timing

- P-ONE Calibration Module (P-CAL)
  - replacing 4 PMTs with hollow PTFE diffuser and flasher matrix producing nanosecond pulses
    ➔ Monitor water properties
    ➔ Triangulate module positions
  - Cameras in calibration modules
    ➔ Bioluminescence/biofouling





- Piezo receivers in all modules, acoustic beacons on sea floor
  ➔ Triangulate module positions (backup to optical triangulation)
- Network: GbE inside TRBnet
  ➔ Sub-ns timing accuracy

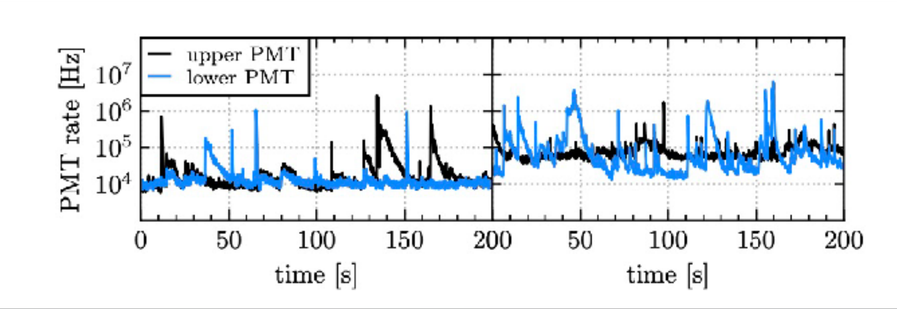


P-ONE-1 Goal

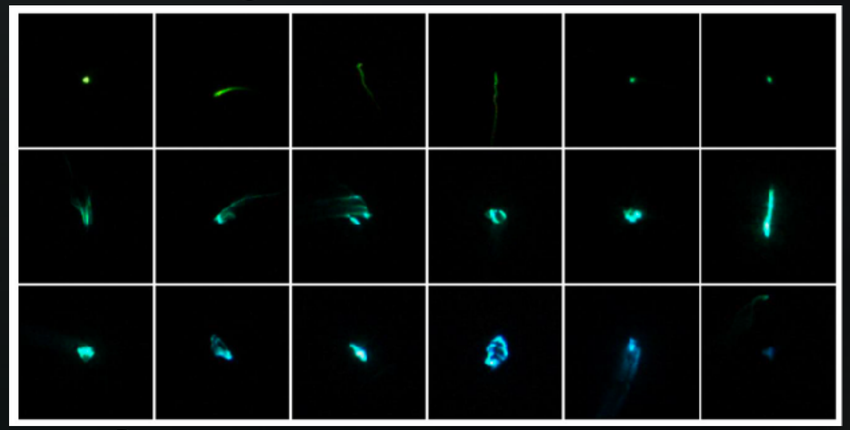
1. Detector: prove the modular and scalable design, prove the deployment concept
2. Physics : collect as much data as possible, and resolve muon energies and directions
3. Bioluminescent : catalogue new ocean depths
4. Background : understand ^{40}K background and detector noise
5. Calibration and resolution:
   - Select biofouling solutions for P-ONE-Demonstrator
   - Develop calibration protocol
   - Understand module movement

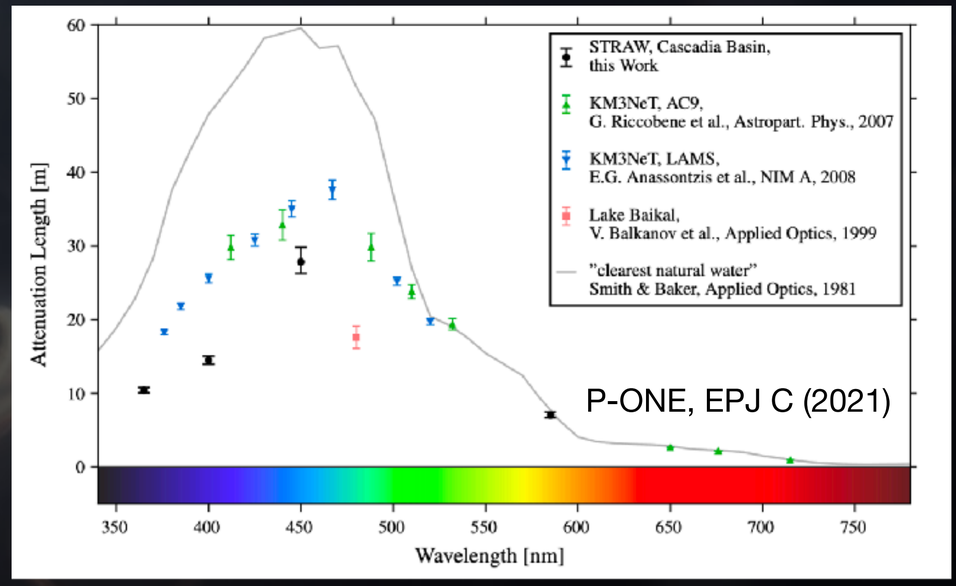
STRAW and STRAW-b

- 5-year operation of STRAW (98% uptime)
- Attenuation Length ~30m @ 450nm
- ^{40}K background quantified

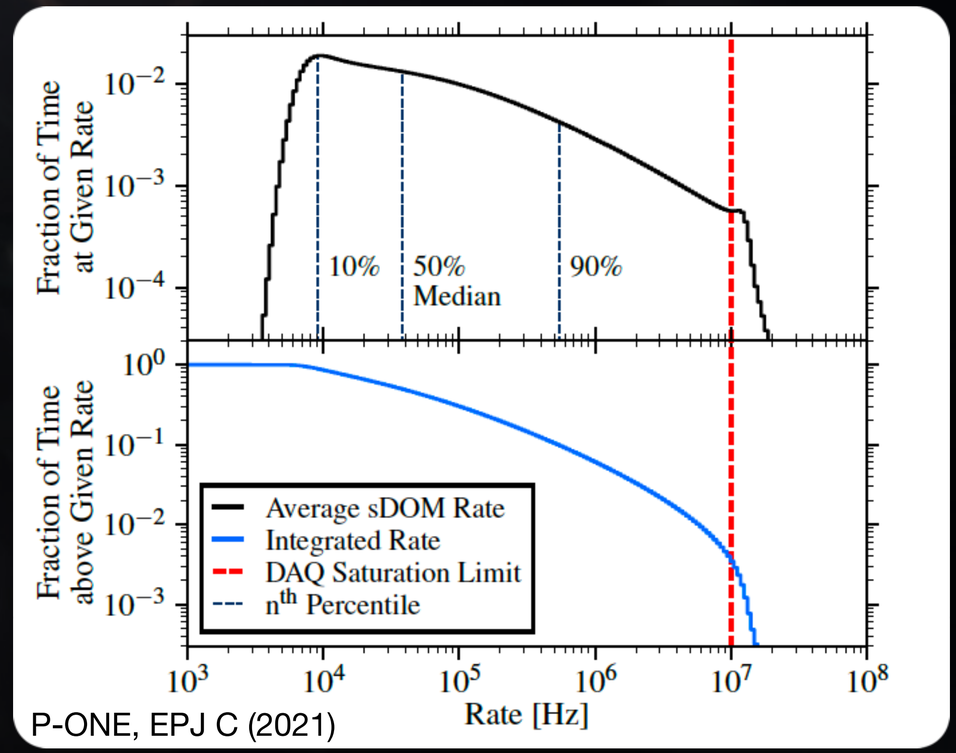


- Bioluminescence and biofouling identified as main challenges



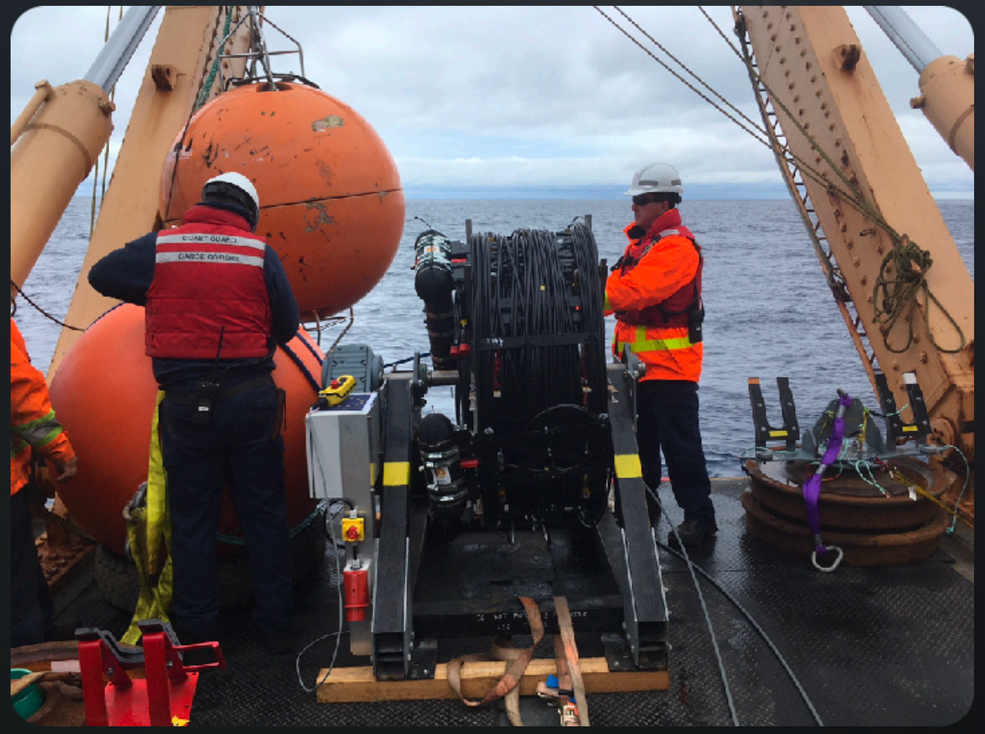


P-ONE, EPJ C (2021)

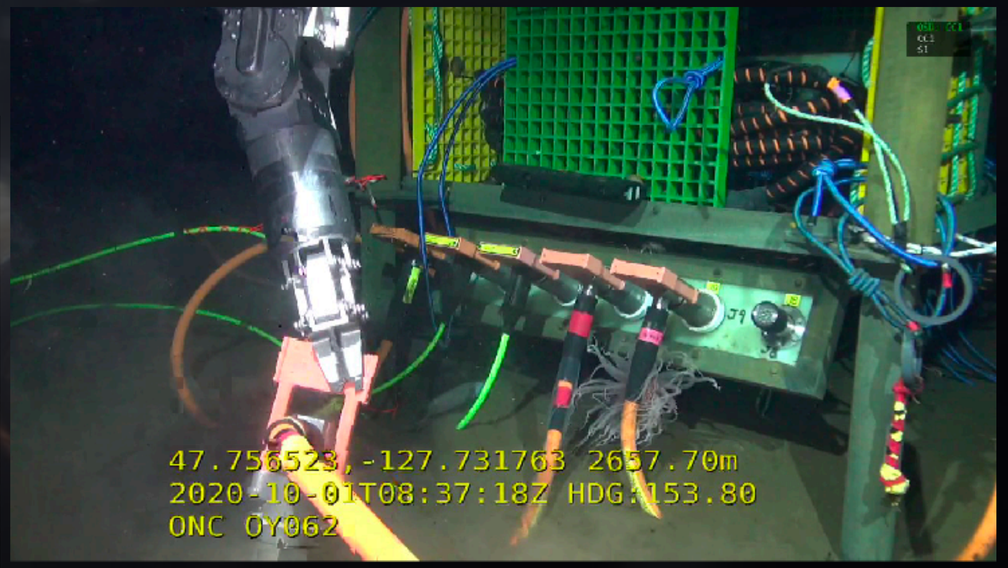


P-ONE, EPJ C (2021)

STRAW and STRAW-b: Deployment



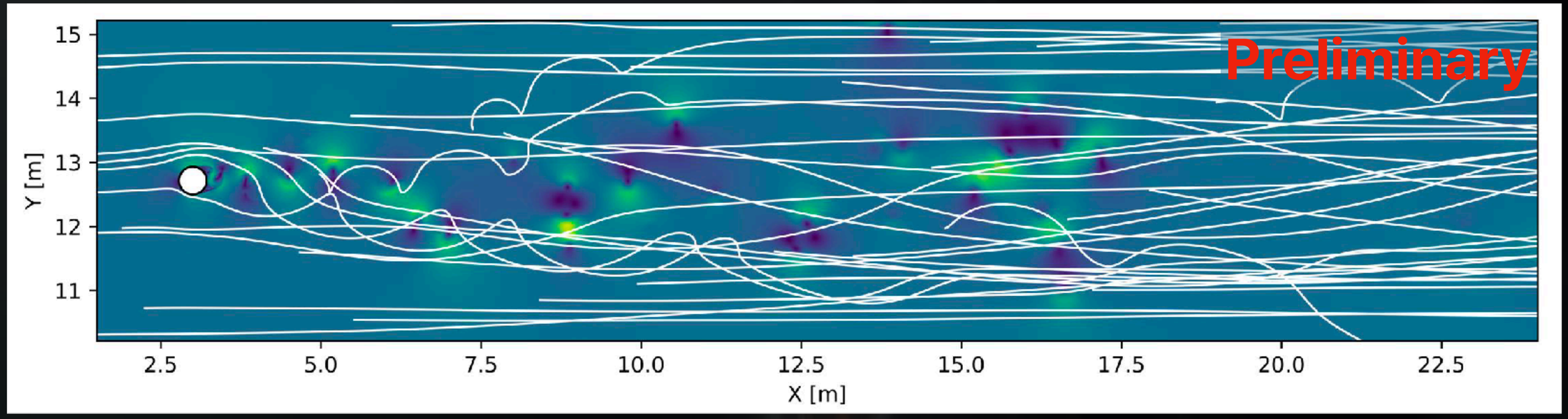






Bioluminescence Simulations

- Navier-Stokes in 2-D, stitched into a 3-D simulation
  - v = 1, 2, 10 cm/s
- Organism density to match STRAW observations
- Use Firedrake / Fourth Day code (Meighen-Berger et al. arXiv:2103.03816)
- Validate trigger algorithm





* What WONDERLAND manages

Detector response,
Filtering & Reconstruction,
…

IRFs



Interface

Target Source

Signal events

Background Source

Background events

Detector

Data

MC

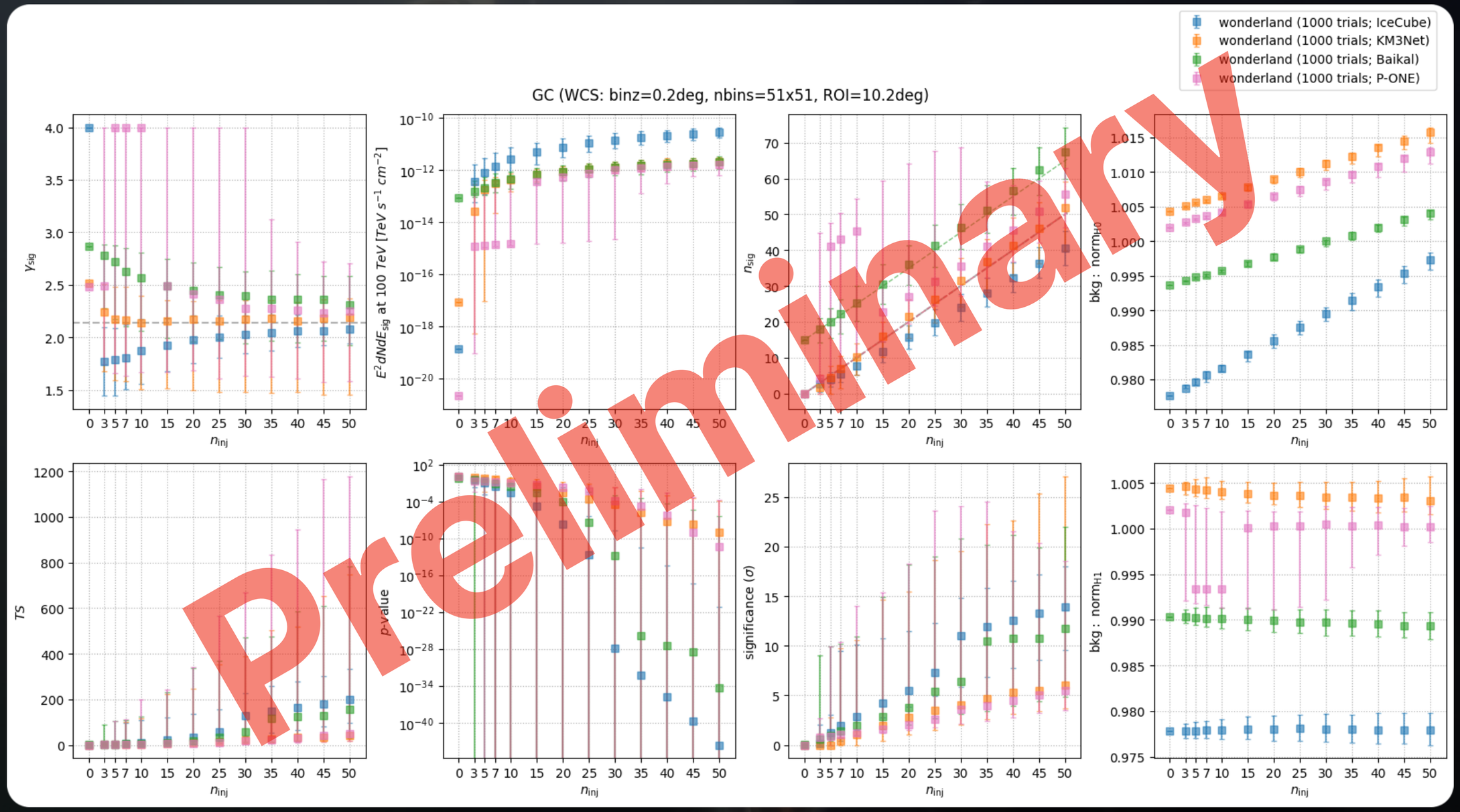
Analysis

Signal Excesses over Backgrounds
with the coincidences:
spatial, spectral, temporal, …

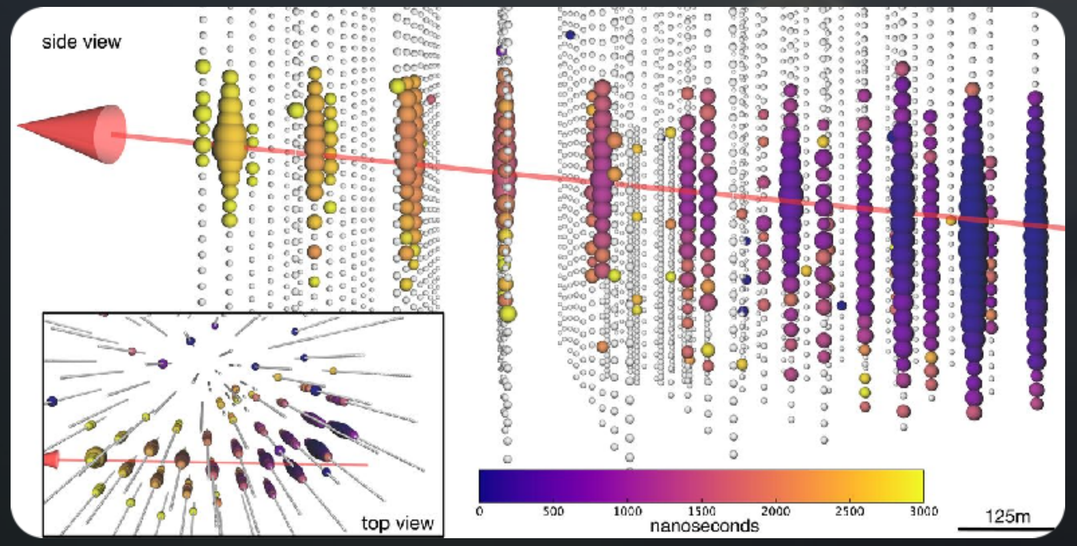
Sensitivity

Significance, signal (and background) properties (best-fit parameters)

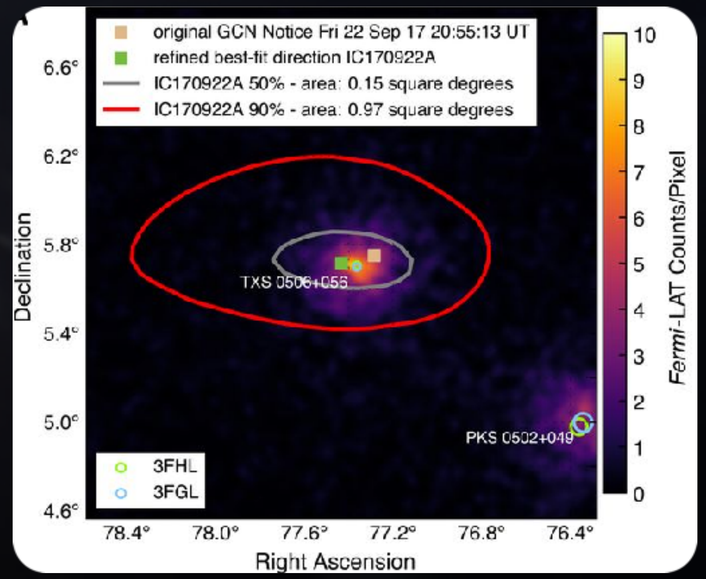
WONDERLAND Fitting Results Example

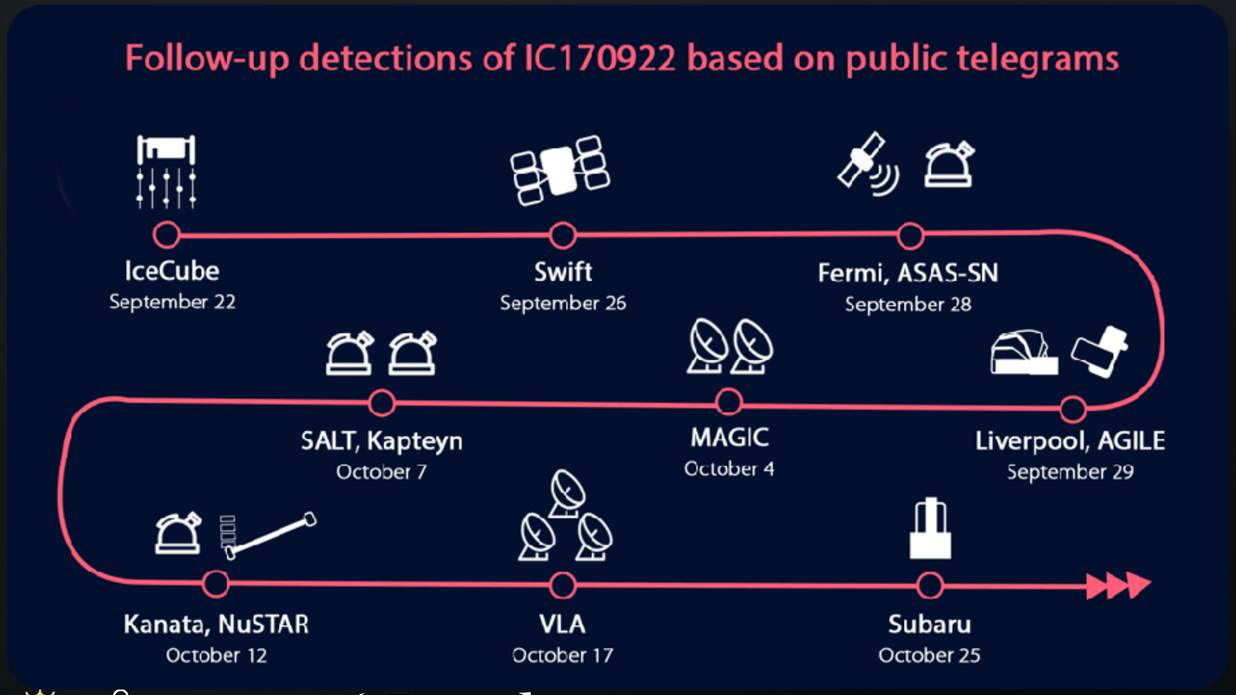


First Neutrino Initiated Multi-Messenger Observation

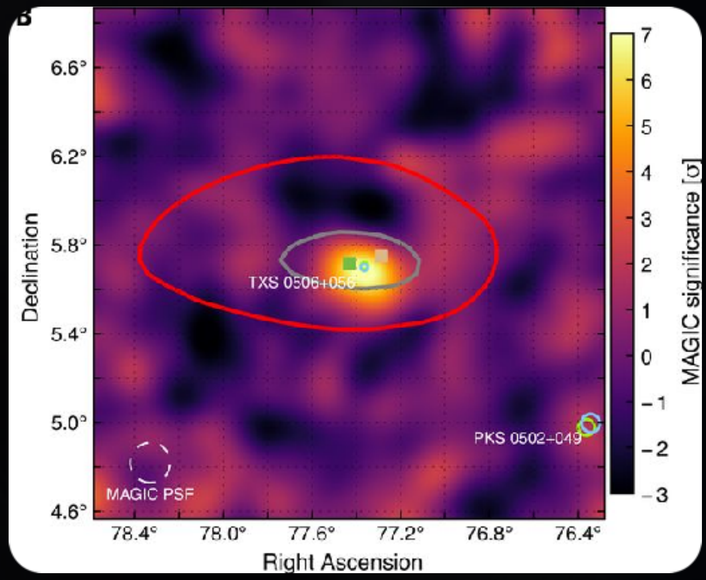


IceCube-170922A
(September 22, 2017)



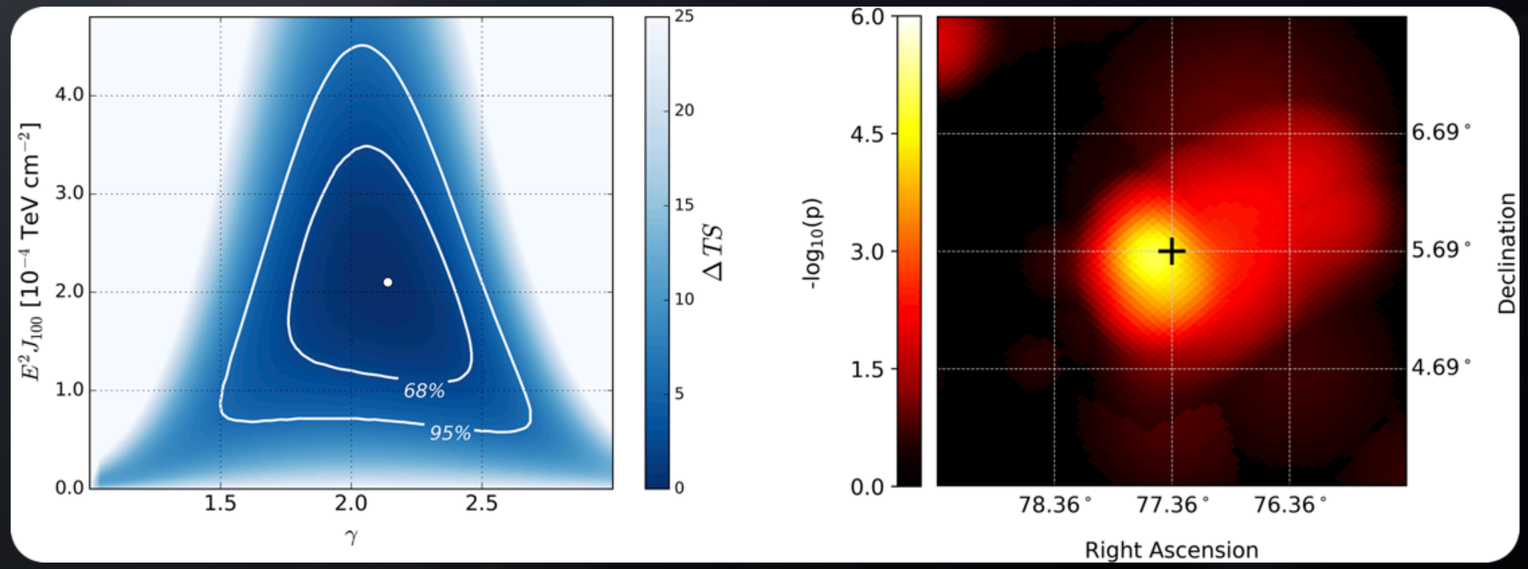


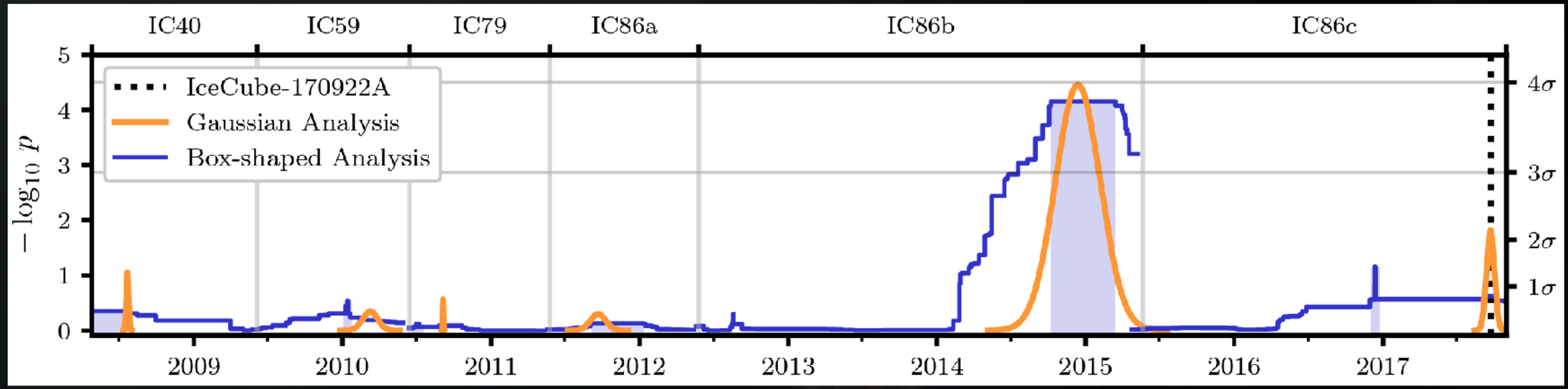
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift NuSTAR, VERITAS, and VLA//17B-403 Collaborations; *Science* **361**, no.6398, eaat1378 (2018).



TXS 0506+056

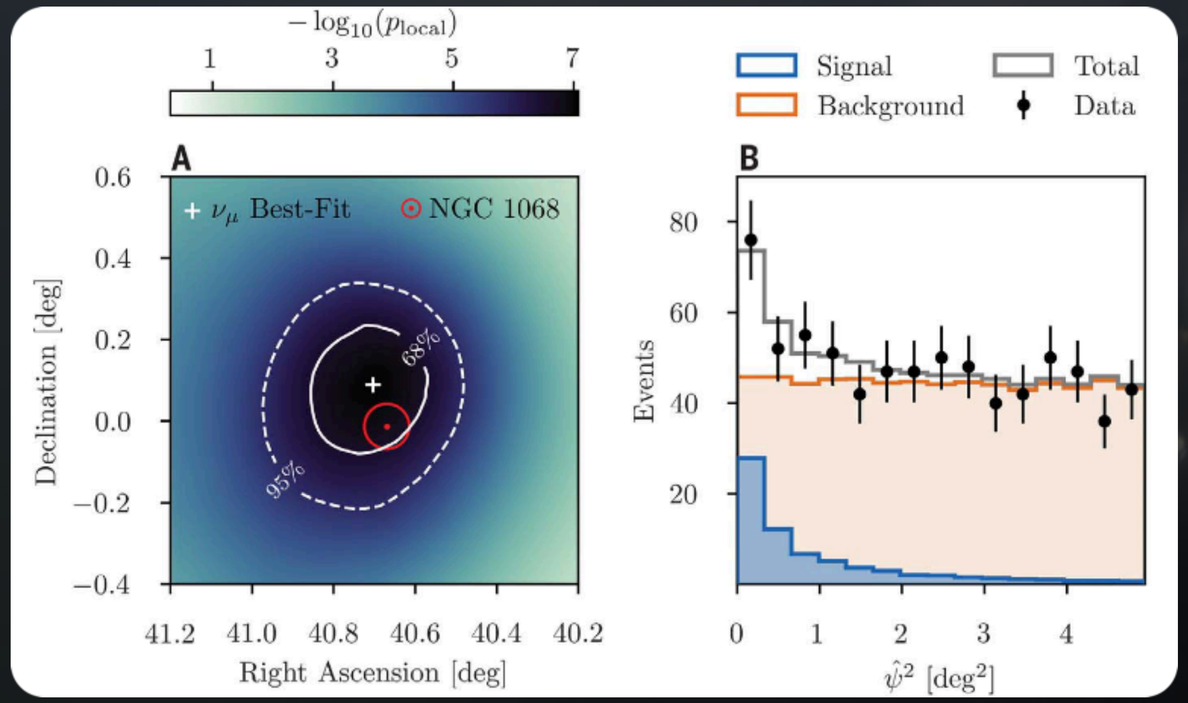
- Not just a transient event
- From the archived IceCube data, it was identified that the blazar made several more events prior to IC170922A
- Highest significance over the span of observation is 3.5σ

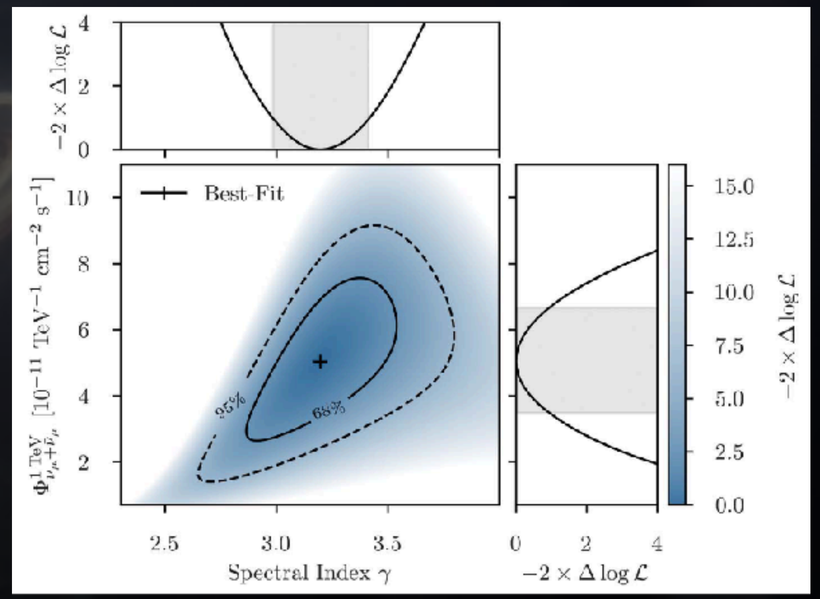




NGC 1068

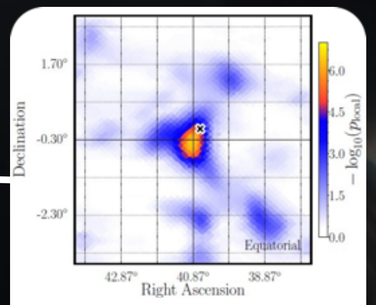
- Seyfert II galaxy with AGN: highest significance among the candidate sources



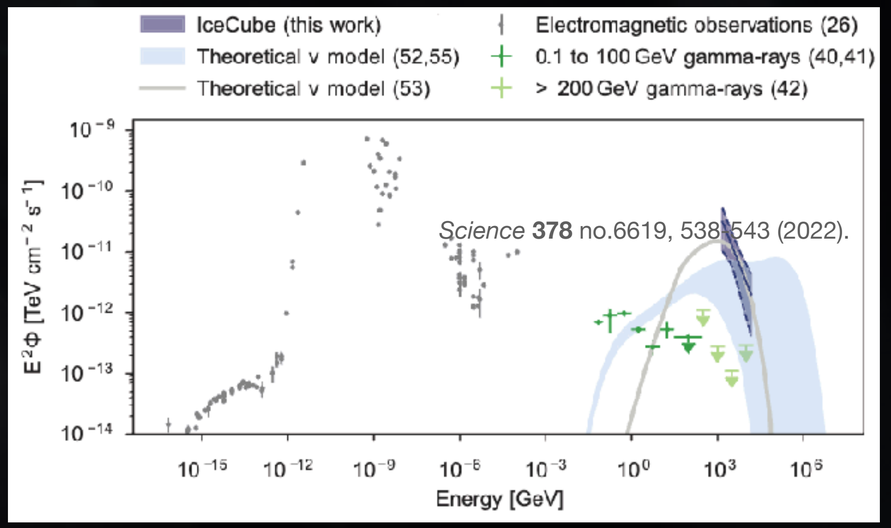


- At the location of NGC 1068: 79^{+22}_{-20} neutrinos observed
- Spectral index: -3.2 ± 0.2
- **Post-trial significance 4.2σ**

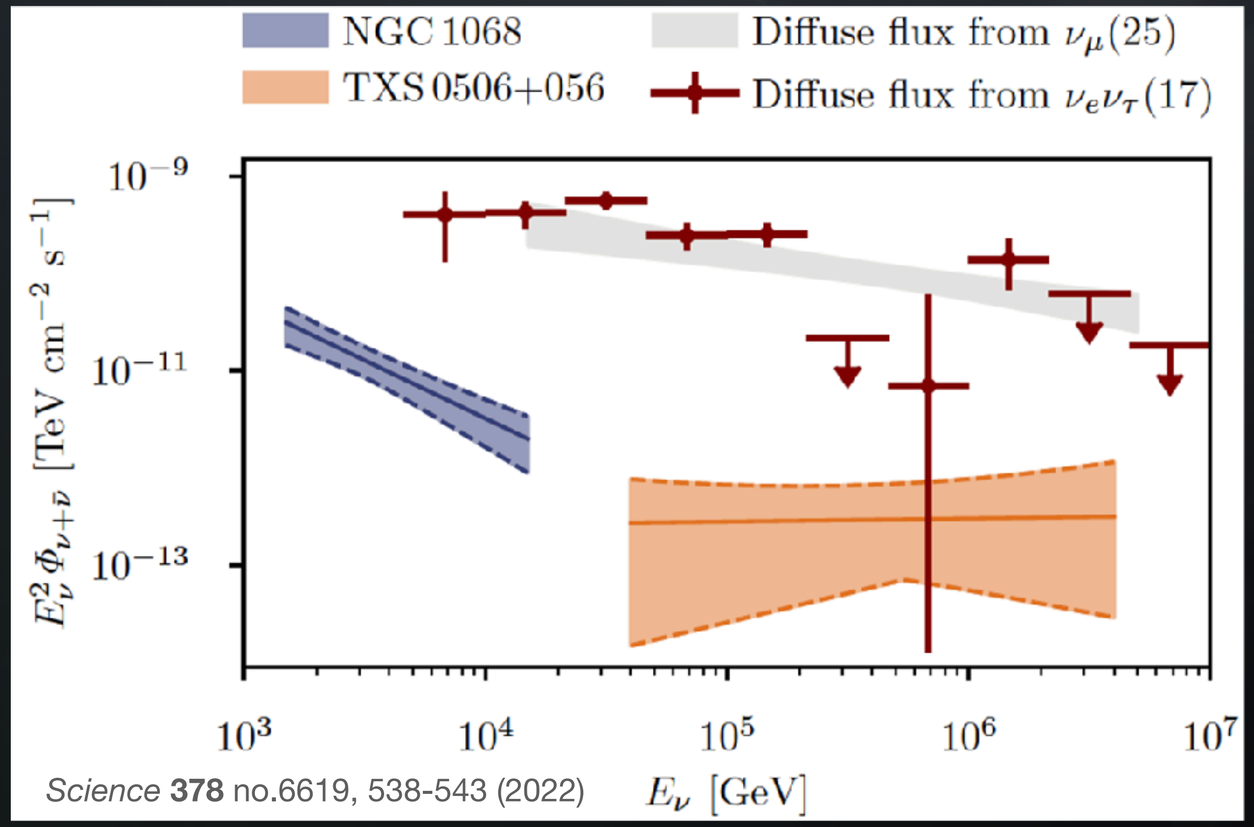
Previously 2.9σ



PRL **124** 051103 (2020)



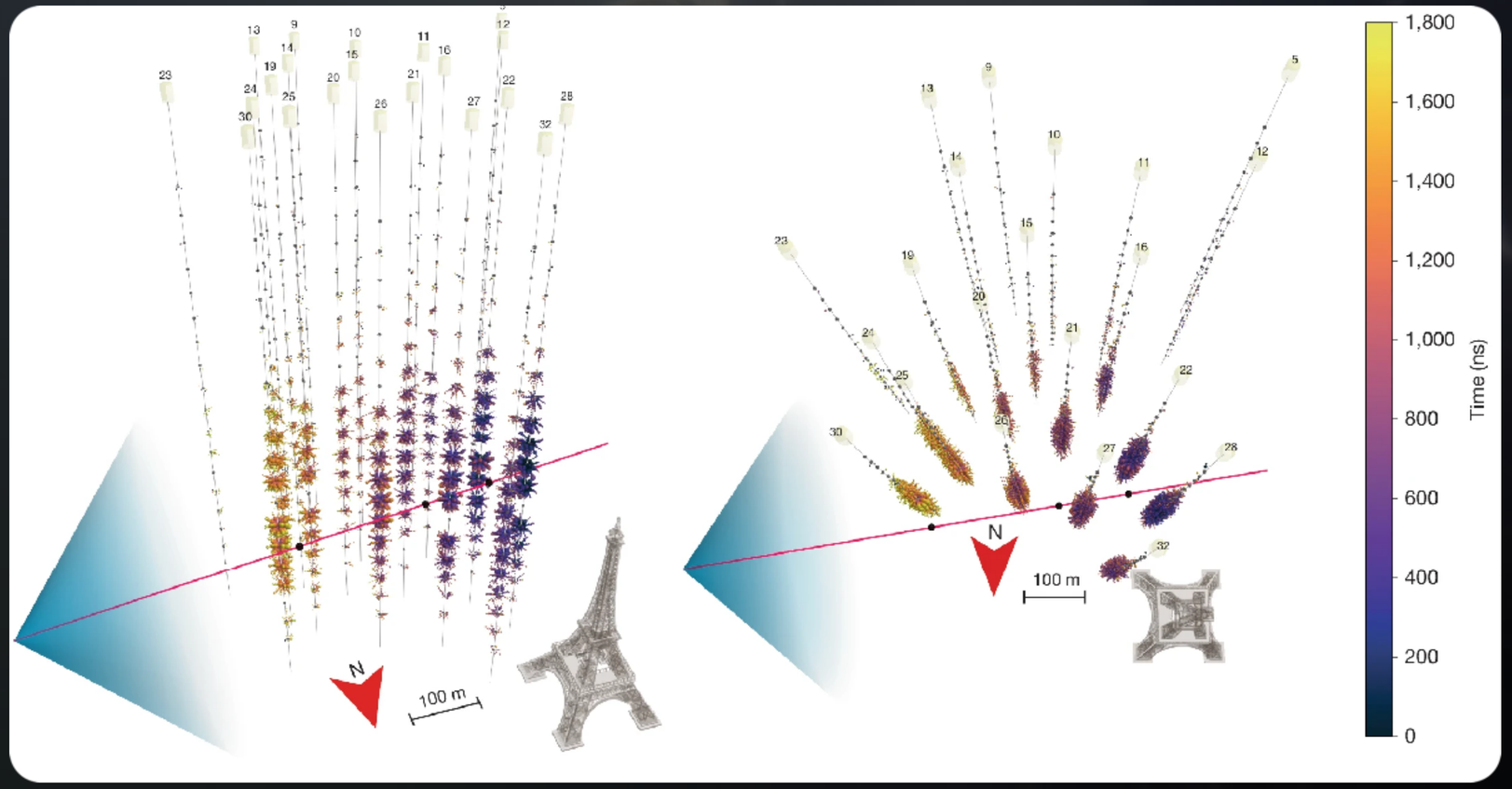
More Extragalactic Neutrino Sources?



Science **378** no.6619, 538-543 (2022)

- NGC 1068, TXS 0506+056 are ~1% of extragalactic flux observed at IceCube
  - NGC 1068 is steady source – a benchmark source
- We need more neutrinos to identify the sources!

KM3-230213A

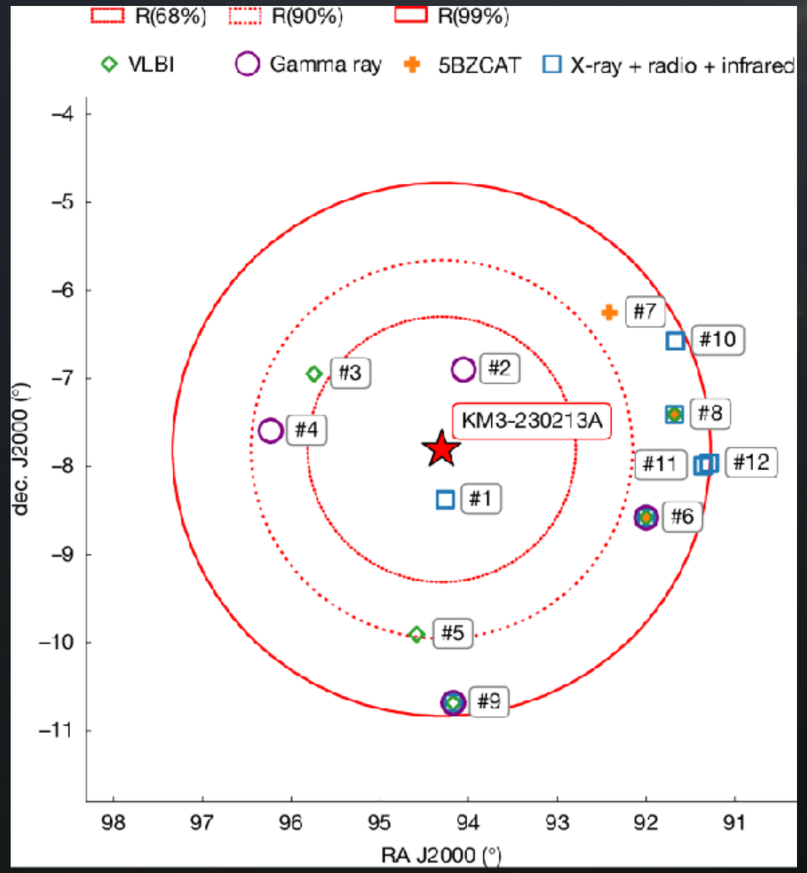


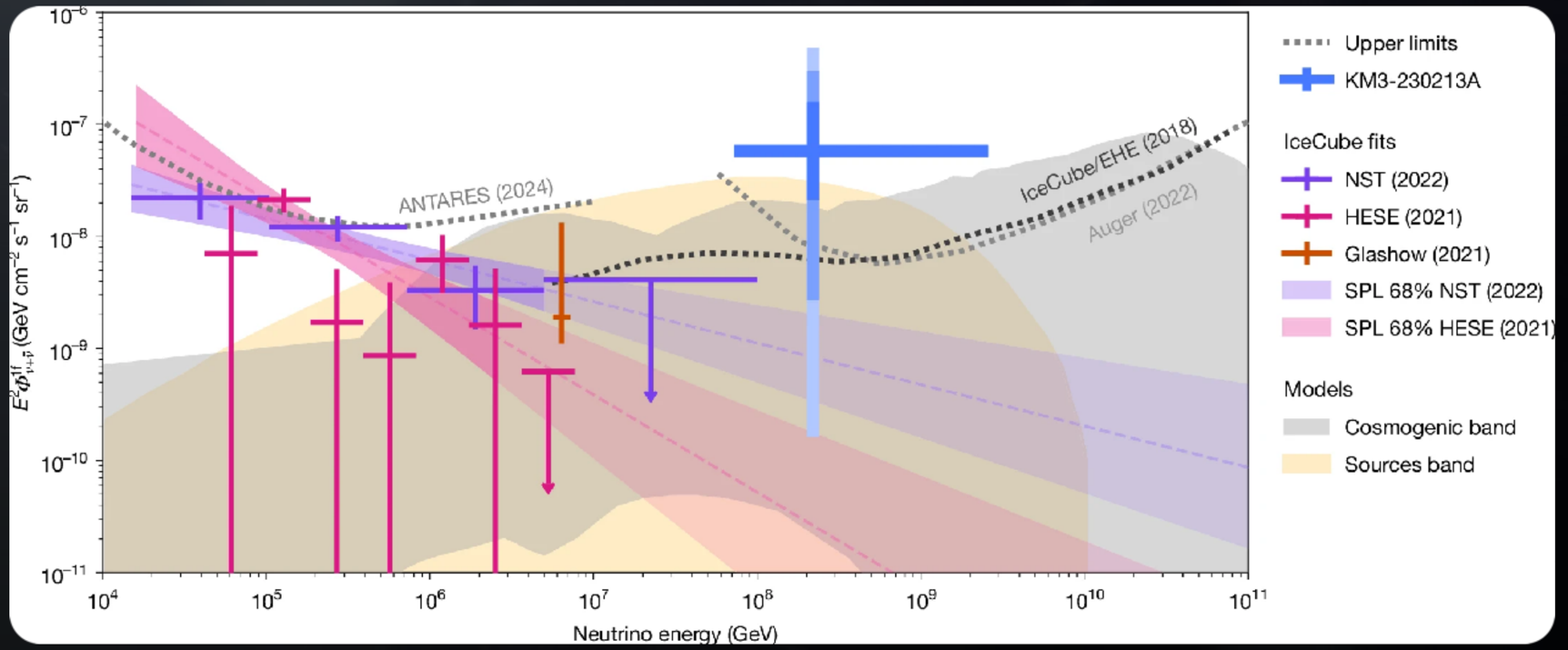


- Very bright horizontal track event on Feb. 12, 2025 at KM3Net
- A muon with energy of 120^{+110}_{-60} PeV → an initial neutrino with energy of 220^{+570}_{-110} PeV

Highest energy ever detected by neutrino telescope

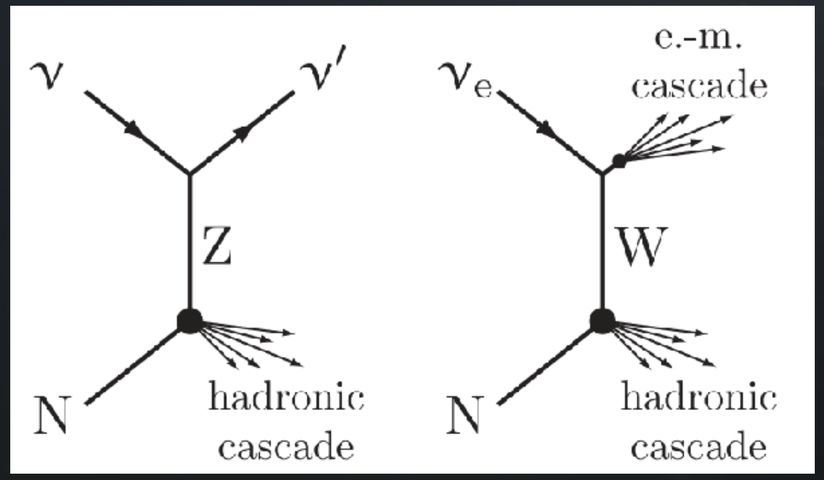
KM3Net-20250312A

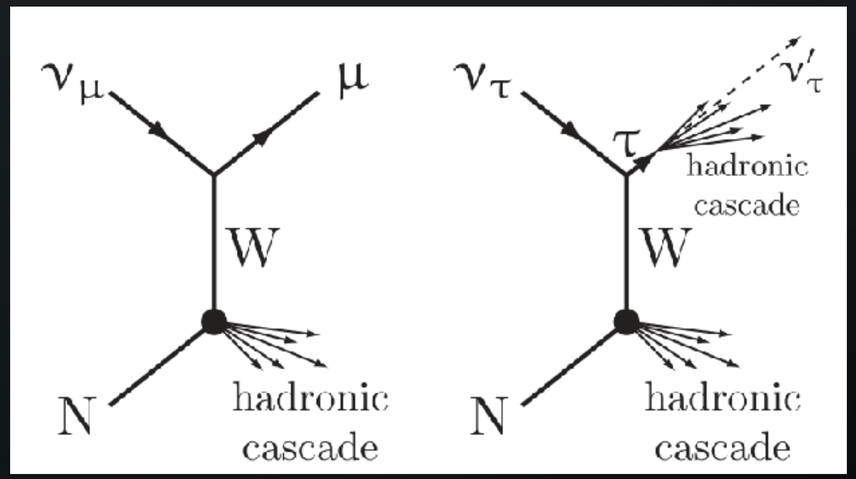




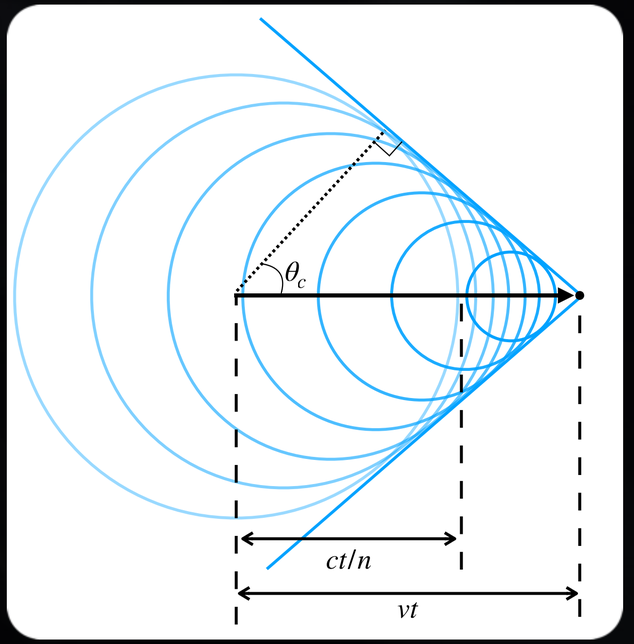
- No identified source of the event yet → cosmogenic neutrino?
- A lucky fluctuation, confirming the opportunity for very-high-energy neutrino observations
  - Telescopes for air-showers and radios!

Neutrino Interactions for Neutrino Telescopes



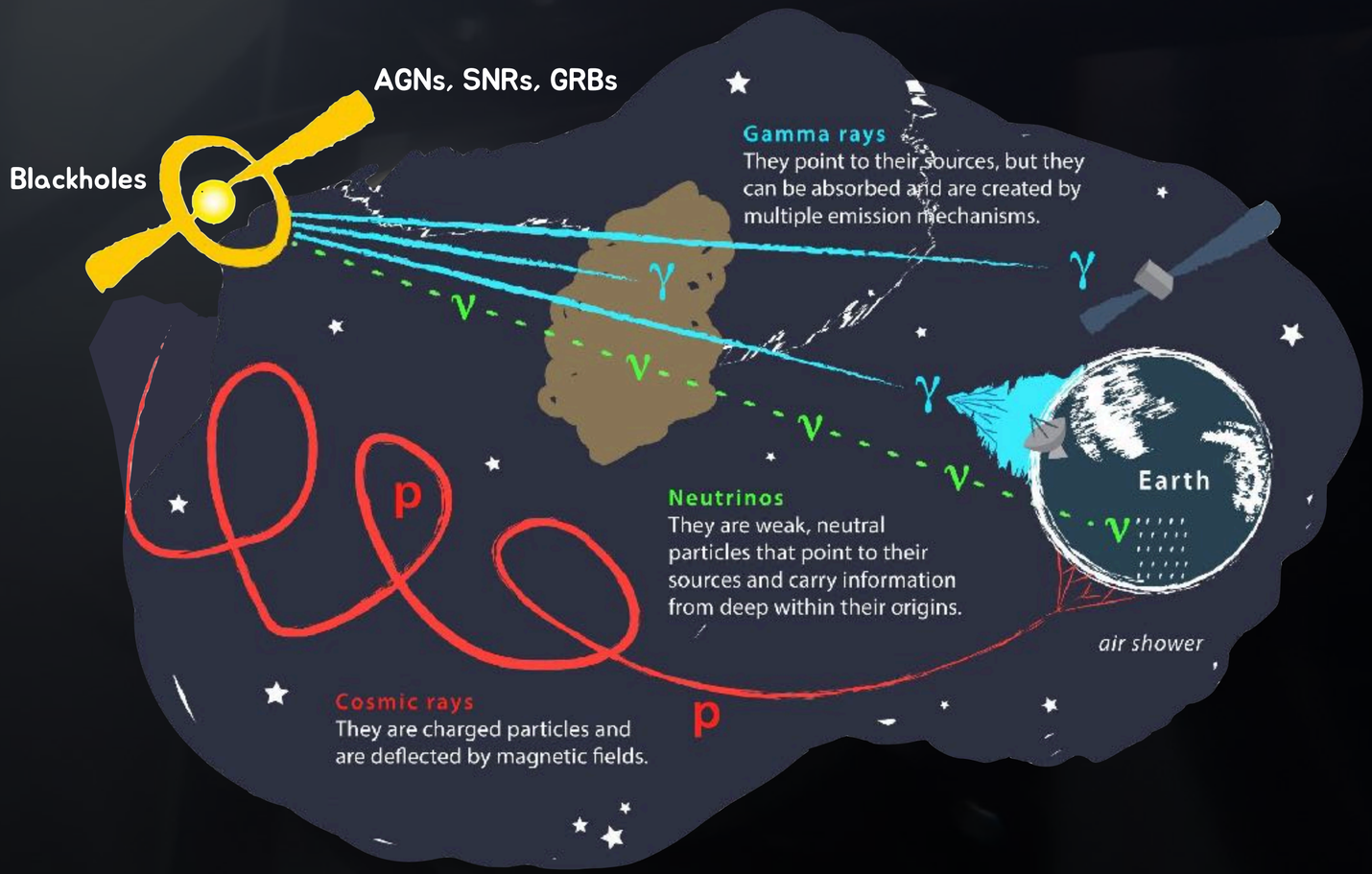


- Neutrino interacts with molecule of dielectric medium (e.g. water or ice)
- Outgoing charged particle(s) travel faster than light in the medium
- Charged particle excites surrounding molecules which emit photons when they return to ground state
- Cherenkov radiation!



Why is It Difficult to Identify CR Sources?

- Charged particles are deflected by magnetic fields
  - Stellar/interstellar/intergalactic
- Photons interact with other photons and matter
- Neutrinos are not deflected and don't often interact with matter



Neutrinos form an important component of multi-messenger astrophysics!