Searching for astrophysical neutrino sources with high energy neutrino detectors

Jessie Thwaites

Postdoc, Queen's University

MI National Meeting, 29 July 2026

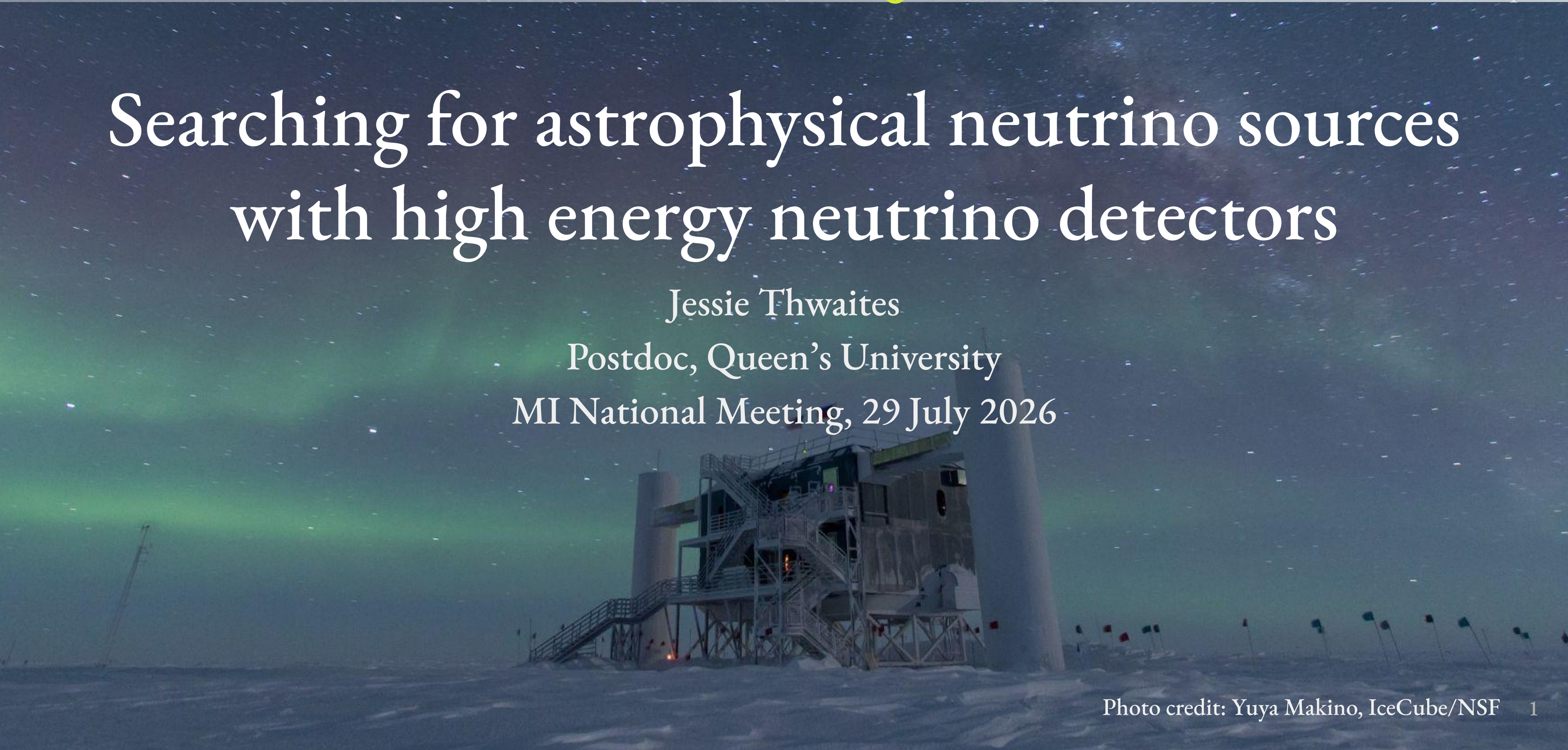
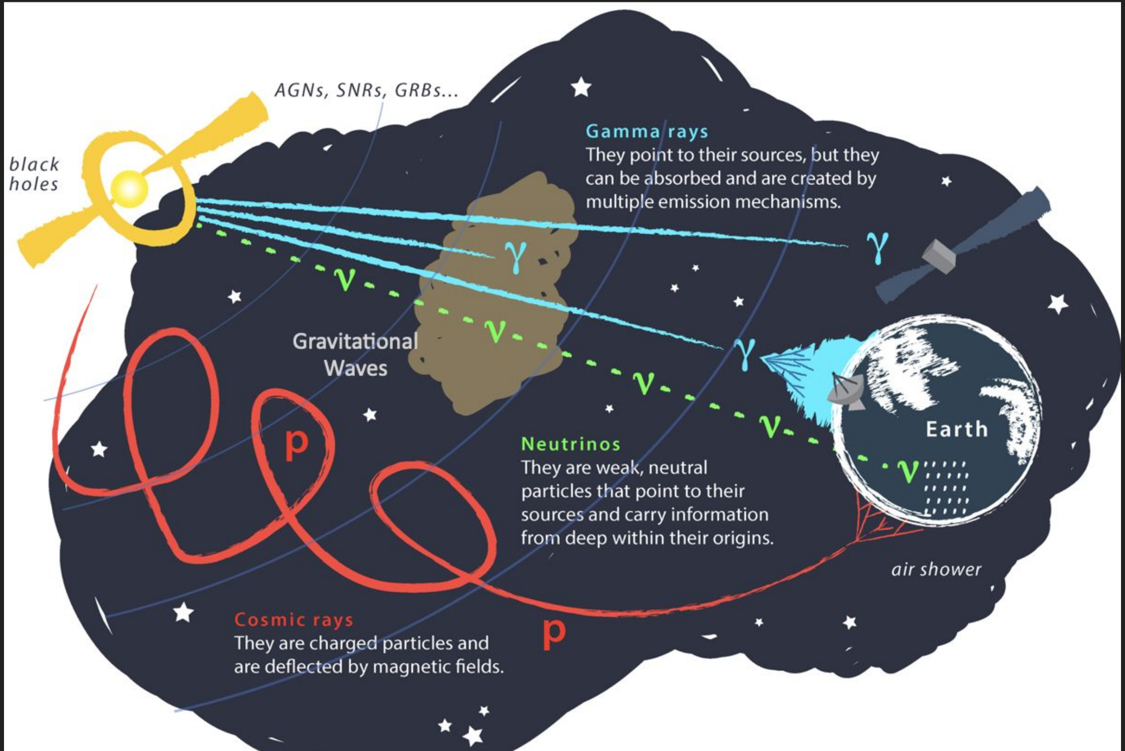


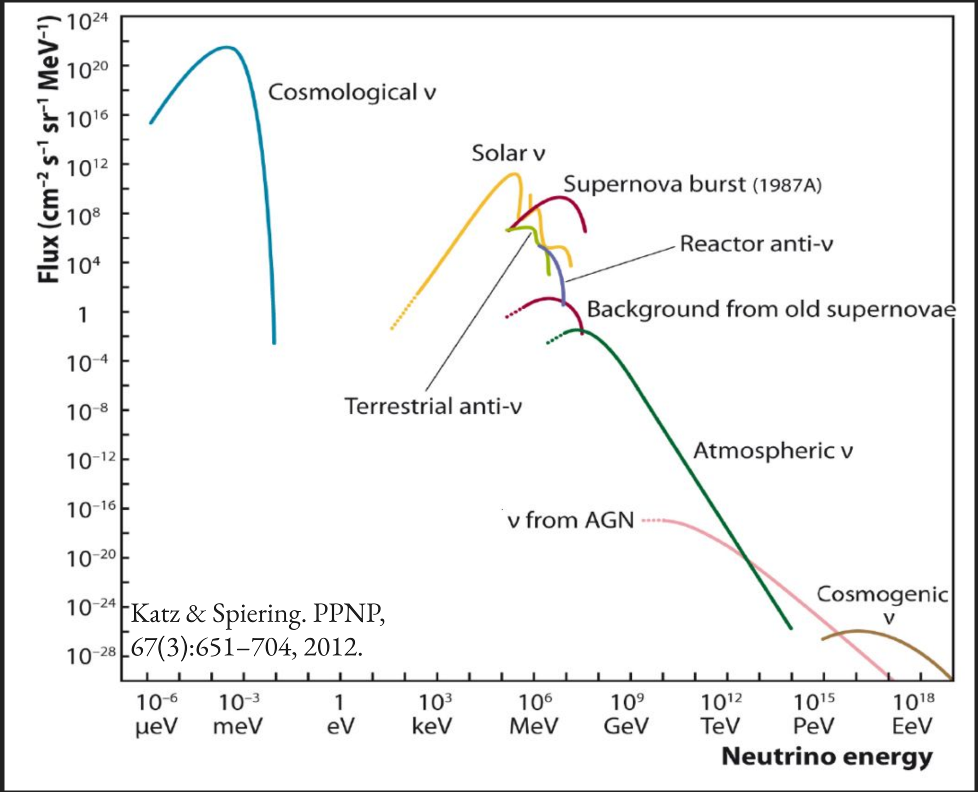
Photo credit: Yuya Makino, IceCube/NSF

Multimessenger astrophysics



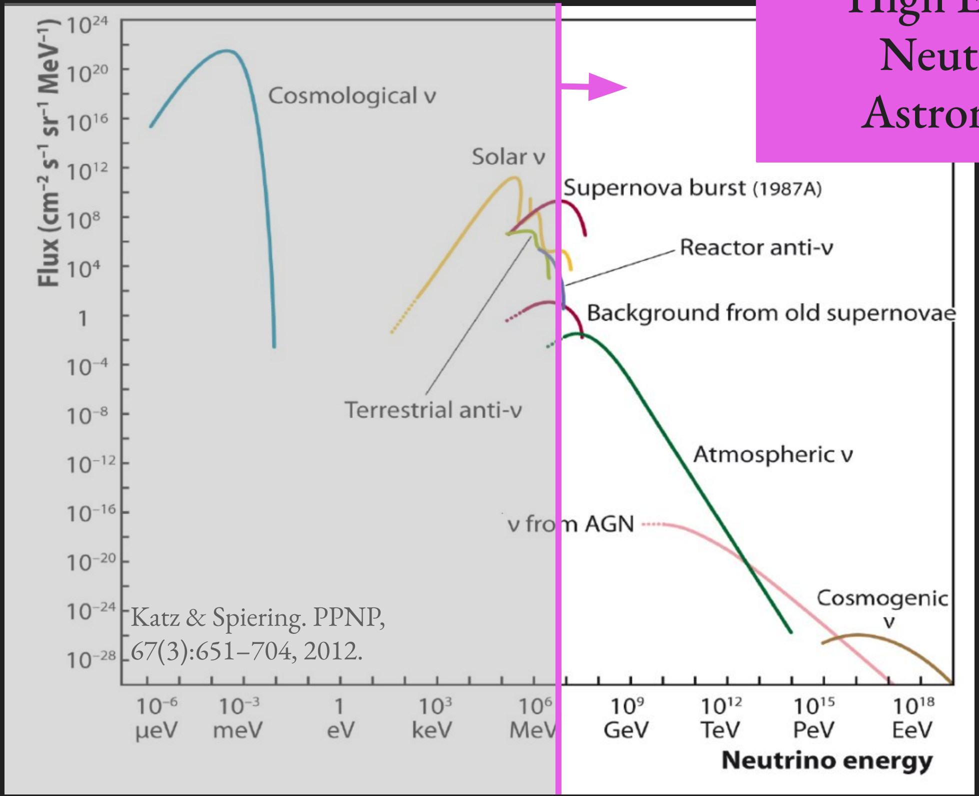
Credit: IceCube Collaboration

Neutrino fluxes across a wide energy range



Katz & Spiering. PPNP, 67(3):651–704, 2012.

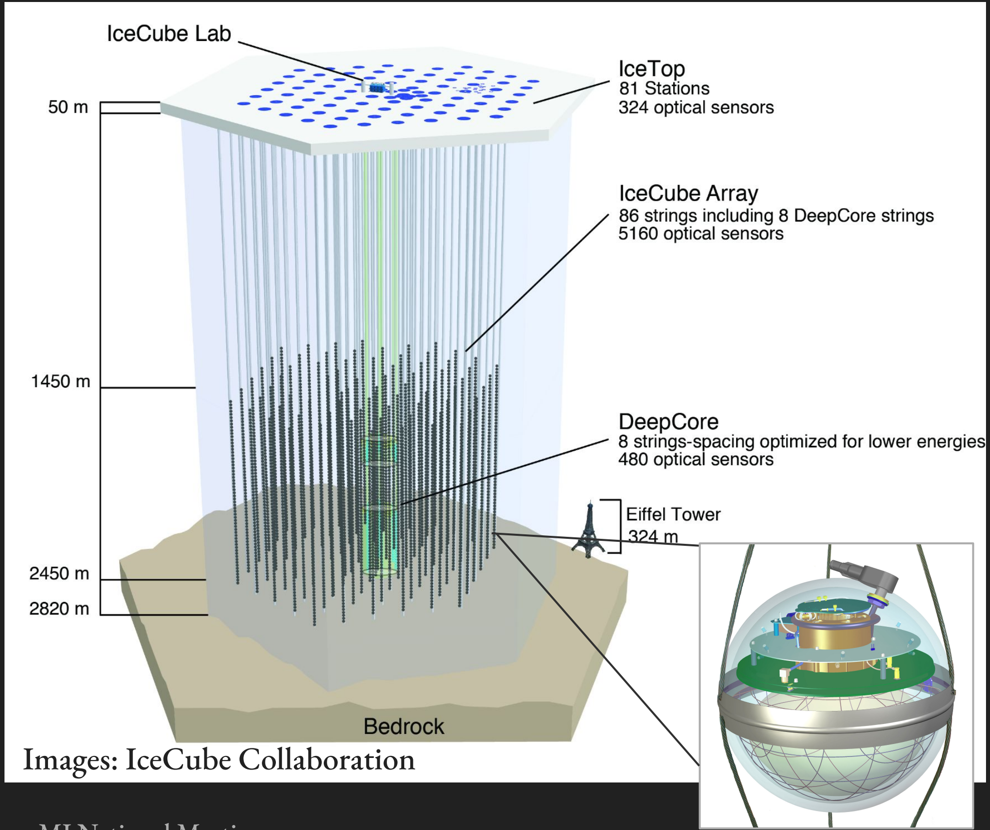
Neutrino fluxes across a wide energy range



High Energy Neutrino Astronomy

IceCube Neutrino Observatory

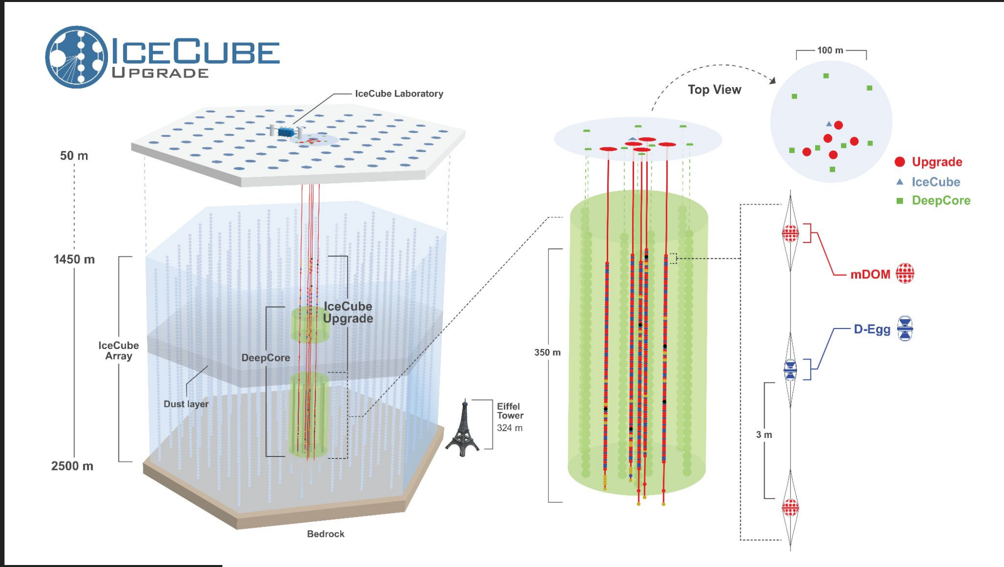
- Cubic kilometer detector instrumented in the ice at the South Pole
- 5160 Digital Optical Modules (DOMs) on 86 strings
- Detects Cherenkov light from interaction of neutrinos in the ice
- Main array: optimized for TeV-PeV neutrinos
- Infill array: IceCube-DeepCore (GeV neutrinos)



Images: IceCube Collaboration

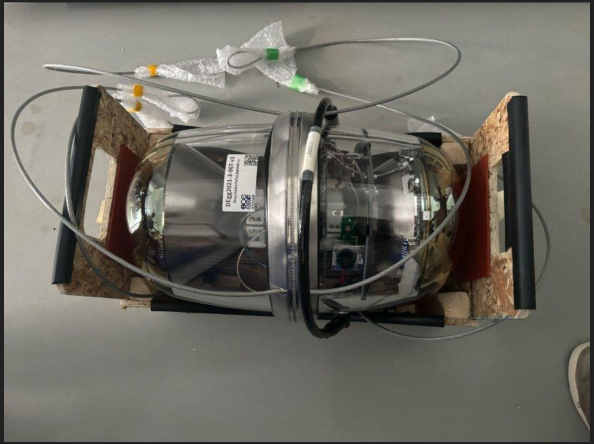
IceCube Neutrino Observatory - IceCube Upgrade

- Cubic kilometer detector instrumented in the ice at the South Pole
- 5665 ~~5160~~ Digital Optical Modules (DOMs) on ~~86~~ 91 strings
- Detects Cherenkov light from interaction of neutrinos in the ice
- Main array: optimized for TeV-PeV neutrinos
- Infill array: IceCube-DeepCore (GeV neutrinos)
- IceCube Upgrade: improved effective area for 1-10 GeV



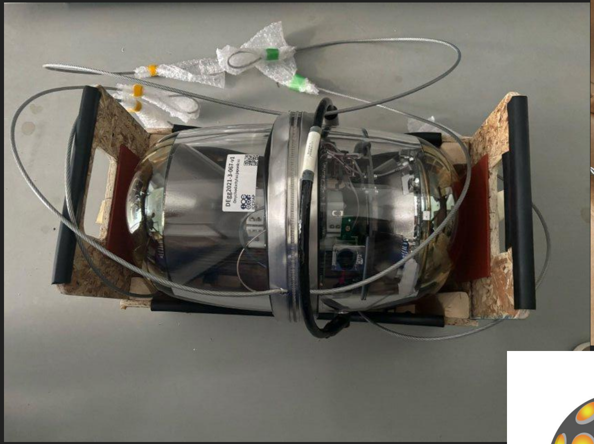
IceCube Upgrade modules at SNOLAB

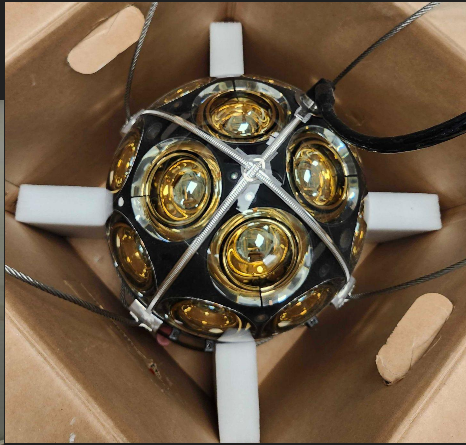
- Long-term study of module behaviour in a stable environment
- Compare to in-ice modules as the strings freeze

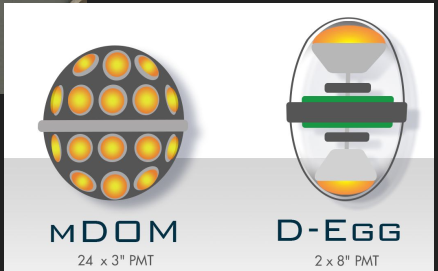


IceCube Upgrade modules at SNOLAB

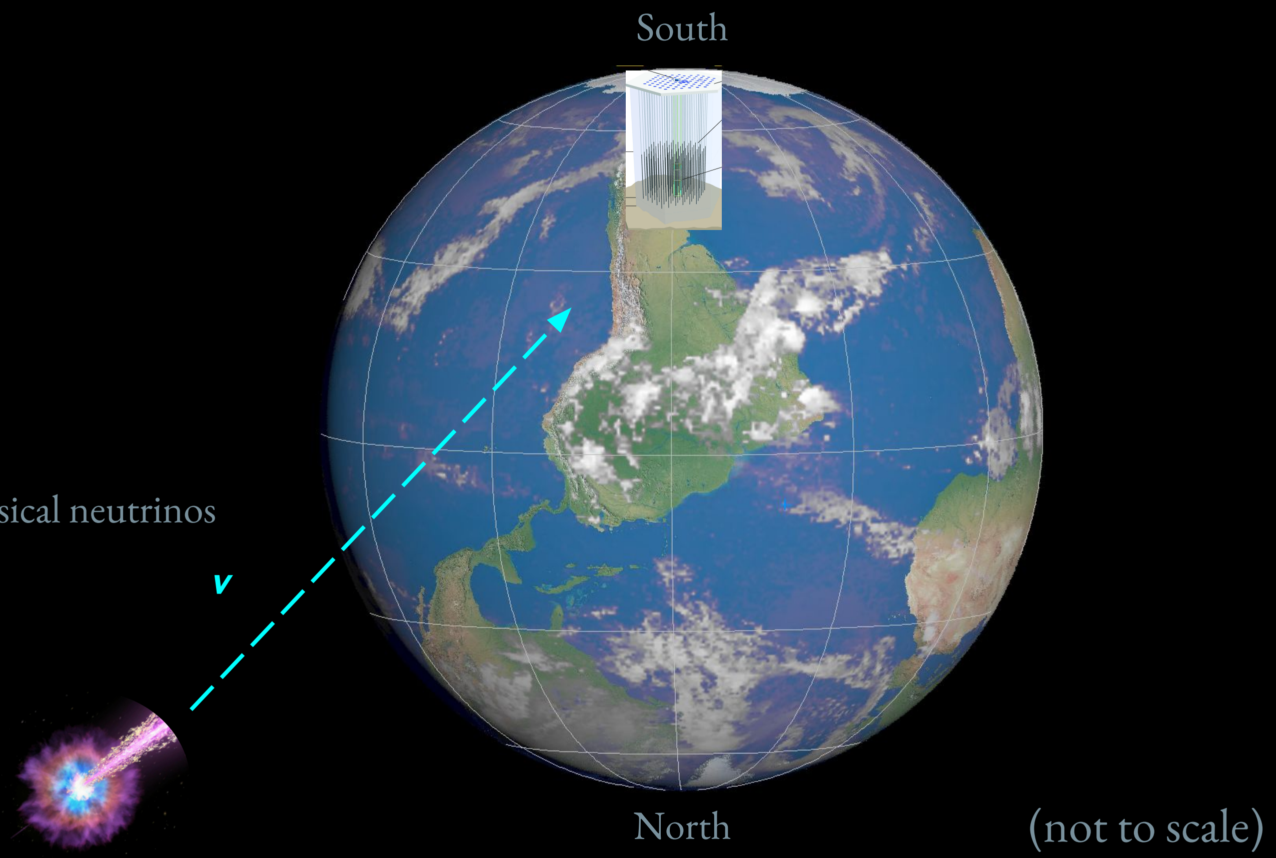
- Long-term study of module behaviour in a stable environment
- Compare to in-ice modules as the strings freeze







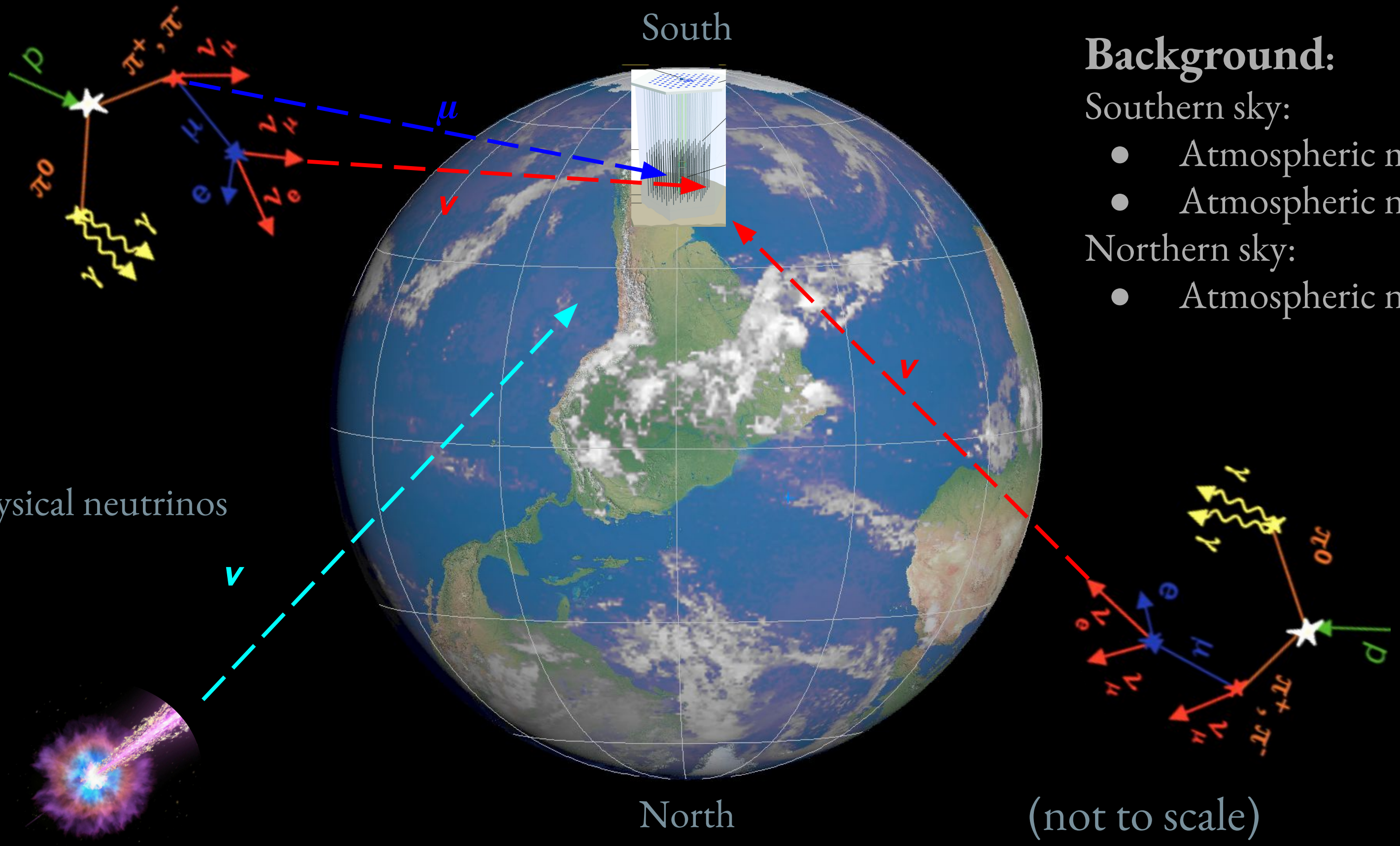
Distinguishing signal from backgrounds



Signal:

- Astrophysical neutrinos

Distinguishing signal from backgrounds



Background:

Southern sky:

- Atmospheric muons
- Atmospheric neutrinos

Northern sky:

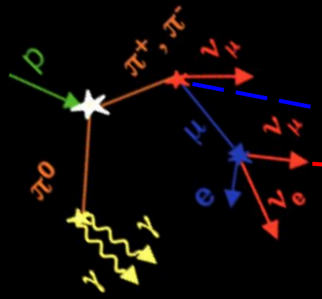
- Atmospheric neutrinos

Signal:

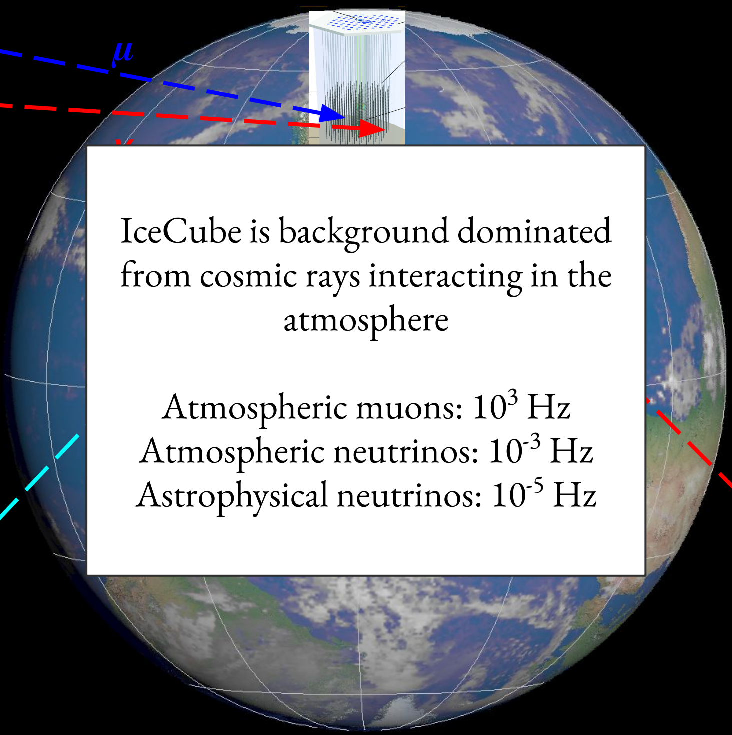
- Astrophysical neutrinos

(not to scale)

Distinguishing signal from backgrounds



South



IceCube is background dominated from cosmic rays interacting in the atmosphere

Atmospheric muons: 10^{3} Hz
Atmospheric neutrinos: 10^{-3} Hz
Astrophysical neutrinos: 10^{-5} Hz

North

Background:

Southern sky:

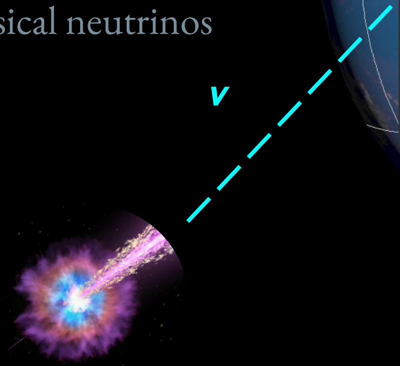
- Atmospheric muons
- Atmospheric neutrinos

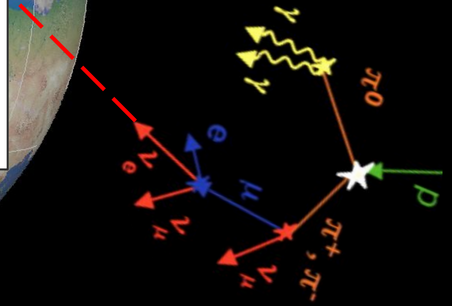
Northern sky:

- Atmospheric neutrinos

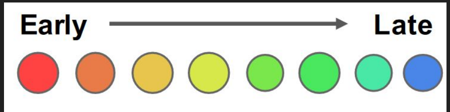
Signal:

- Astrophysical neutrinos





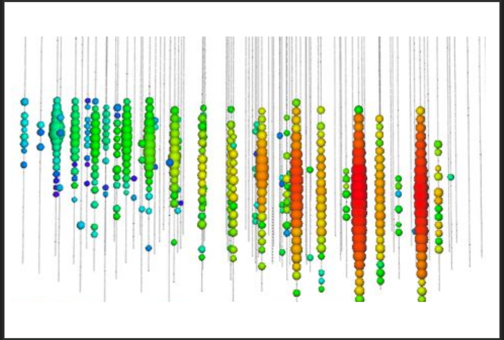
(not to scale)



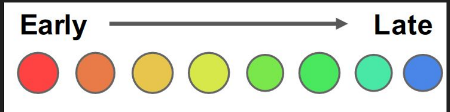
High energy neutrino detectors: event morphologies

Detect Cherenkov radiation emitted by charged particles from neutrino interactions in transparent medium (water or ice)

Tracks



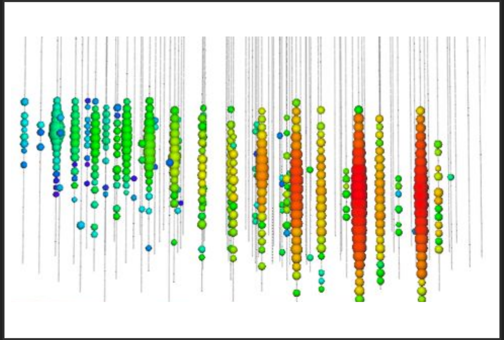
$\boldsymbol{\nu}_{\mu}$ charged current interactions
Outgoing muon leaves long track



High energy neutrino detectors: event morphologies

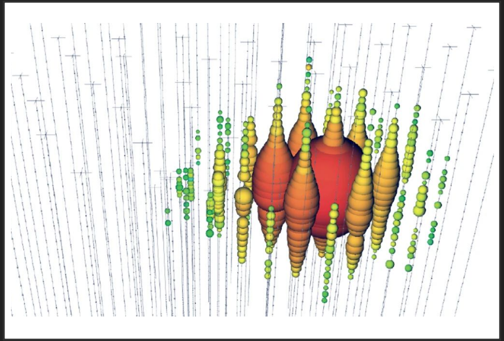
Detect Cherenkov radiation emitted by charged particles from neutrino interactions in transparent medium (water or ice)

Tracks

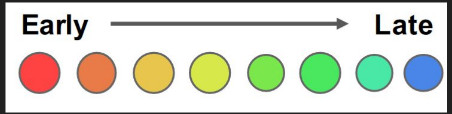


ν_μ charged current interactions
Outgoing muon leaves long track

Cascades



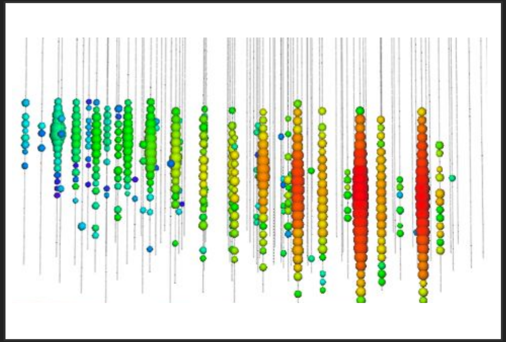
ν_e charged current, any flavor neutral current interactions
Calorimetric energy deposition



High energy neutrino detectors: event morphologies

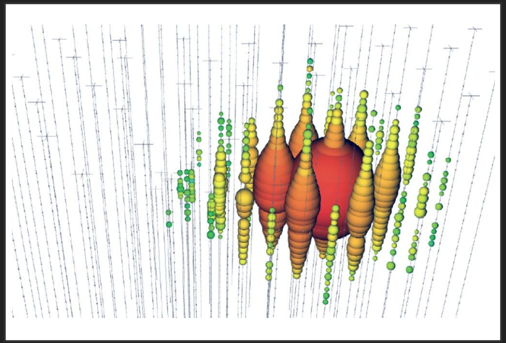
Detect Cherenkov radiation emitted by charged particles from neutrino interactions in transparent medium (water or ice)

Tracks



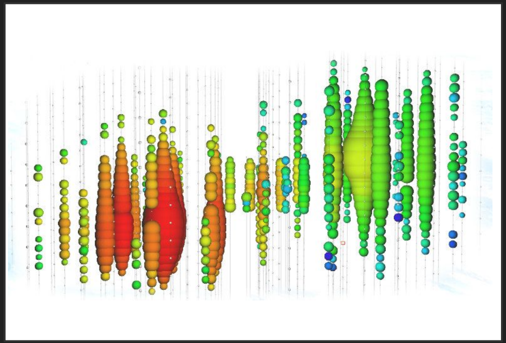
ν_μ charged current interactions
Outgoing muon leaves long track

Cascades



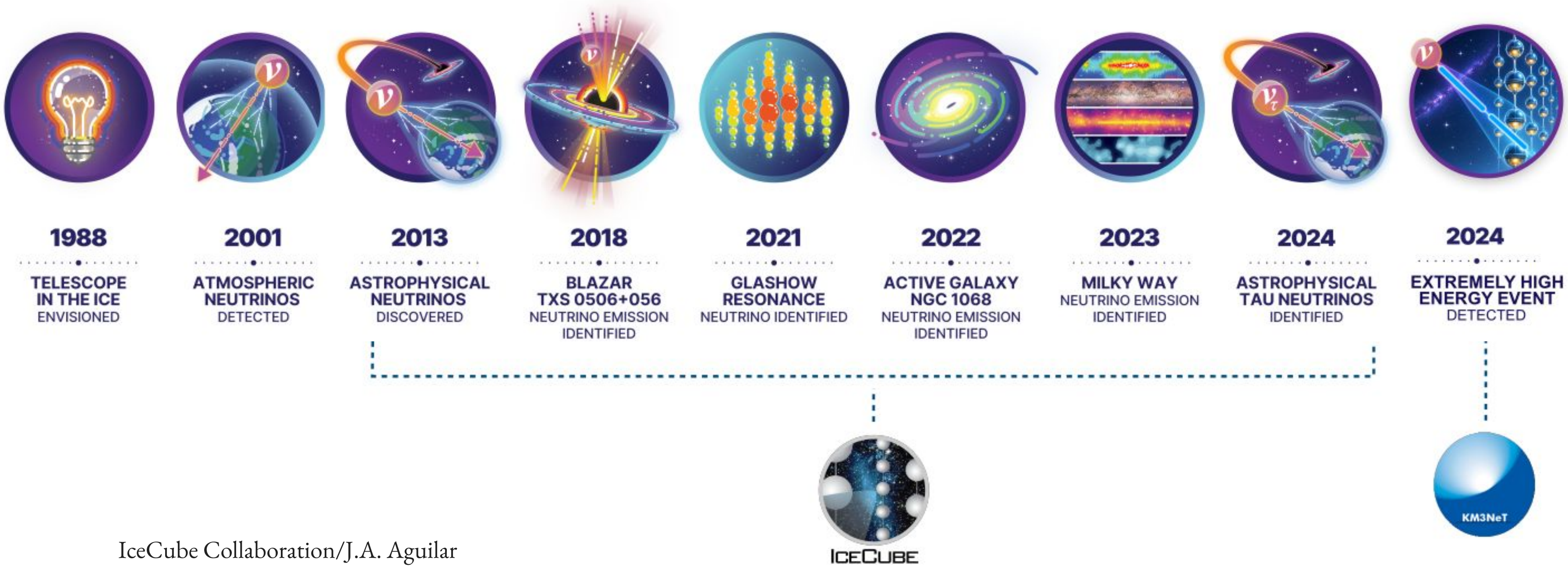
ν_e charged current, any flavor neutral current interactions
Calorimetric energy deposition

Double bang



High energy ν_τ charged current
$\lambda_\tau \approx 50\text{m}\ (E_\tau / \text{PeV})$

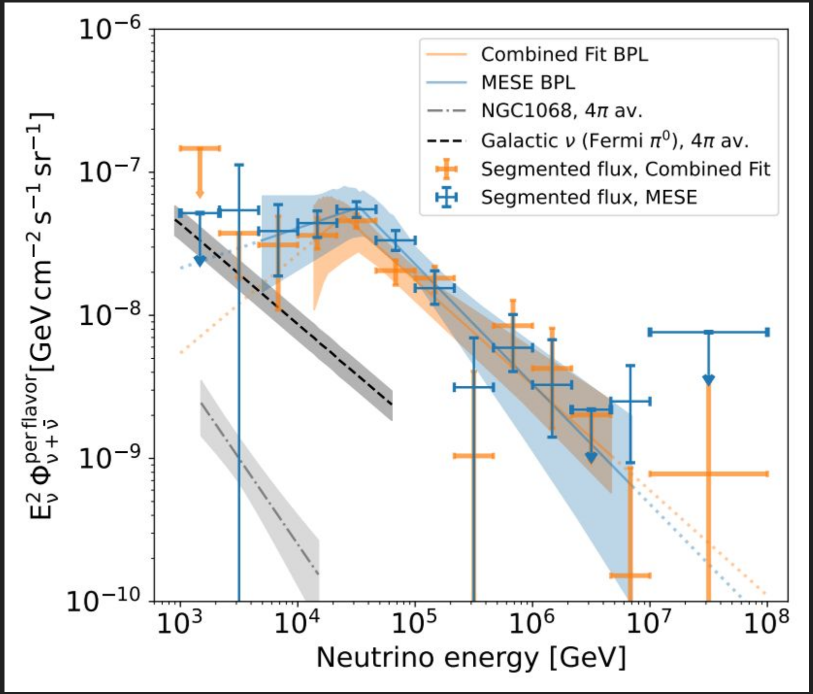
a brief History of Neutrino Astronomy



IceCube Collaboration/J.A. Aguilar

Status of high energy neutrino observations with IceCube

- Evidence of a spectral break or curvature in the diffuse astrophysical spectrum
- Neutrino emission from the Galactic plane
  - Identified using templates derived from other messengers (cosmic rays, EM)
  - Characterizing the neutrino emission
- Point sources:
  - Time integrated searches: NGC 1068, searches for X-ray bright AGN
  - Time-dependent emission: TXS 0506+056

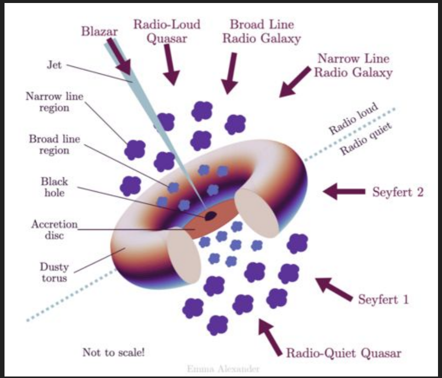


IceCube Collaboration, PRL 136, 121002 (2026)

Searching for neutrino emission from extreme blazars

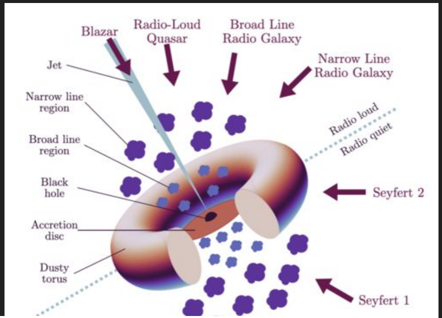
Photo credit: Yuya Makino, IceCube/NSF

Extreme blazars: possible hadronic sources?

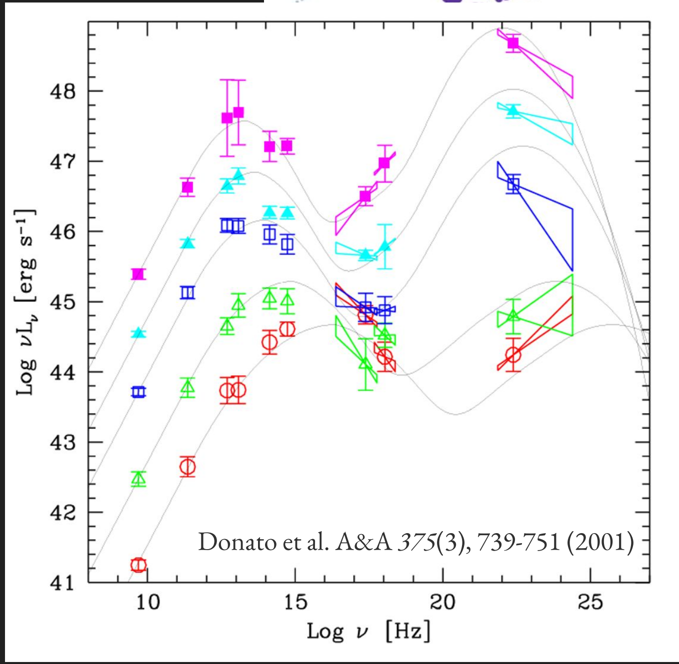


- AGN observed with a relativistic jet pointing towards Earth (FSRQs, BL Lacs)

Extreme blazars: possible hadronic sources?



- AGN observed with a relativistic jet pointing towards Earth (FSRQs, BL Lacs)
  - Two peaked spectrum: lower energy synchrotron peak and a higher energy peak which may be leptonic or hadronic in nature
  - Classified by location of low-energy peak: “Low”, “Intermediate”, “High”-frequency peaked

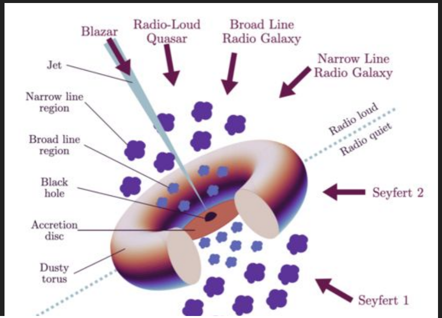


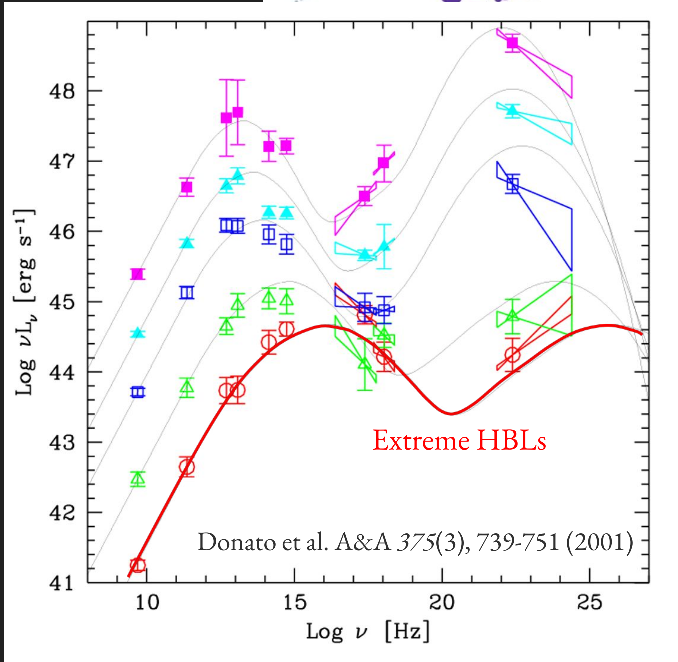
Donato et al. A&A *375*(3), 739-751 (2001)

Extreme blazars: possible hadronic sources?

- AGN observed with a relativistic jet pointing towards Earth (FSRQs, BL Lacs)
  - Two peaked spectrum: lower energy synchrotron peak and a higher energy peak which may be leptonic or hadronic in nature
  - Classified by location of low-energy peak: “Low”, “Intermediate”, “High”-frequency peaked

- Some HBL have “extreme” peaks – difficult to explain with leptonic models alone
  - Synchrotron peak: X-ray
  - High energy peak: >1 TeV gamma-rays





Neutrino emission in high energy blazars

- High energy neutrinos are a result of cosmic ray interactions with surrounding medium:

Hadronuclear (pp)

$$p + p \rightarrow N\pi + X$$

Spectral shape matches gamma-ray spectral index

Photohadronic (pγ)

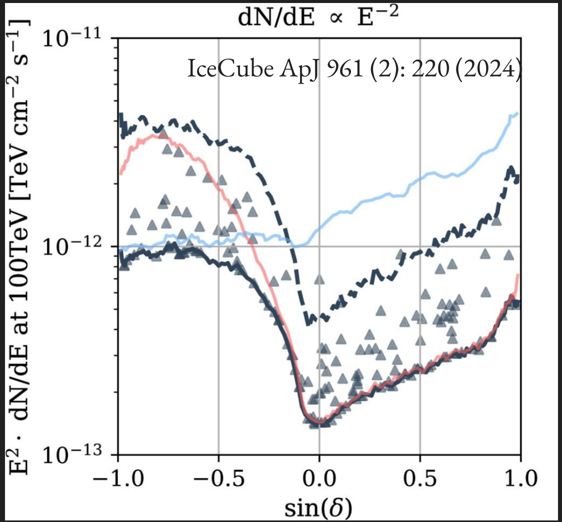
$$p + \gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} p + \pi^{0} \\ n + \pi^{+} \end{cases}$$

More complex spectral shape, peaks at very high energies

- pγ preferred for these sources (high photon density, low baryon density)

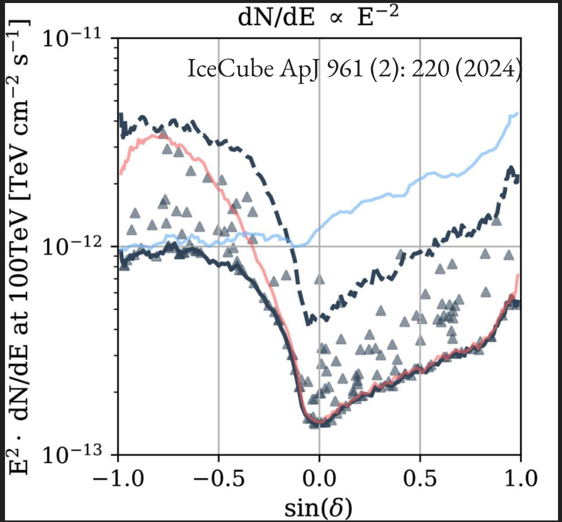
IceCube point source analyses of eHBLs

- All-sky analyses for neutrinos from extreme HBLs
  - Best sensitivity with track events at the horizon / Northern sky
  - Good sensitivity with cascade events in the Southern sky



IceCube point source analyses of eHBLs

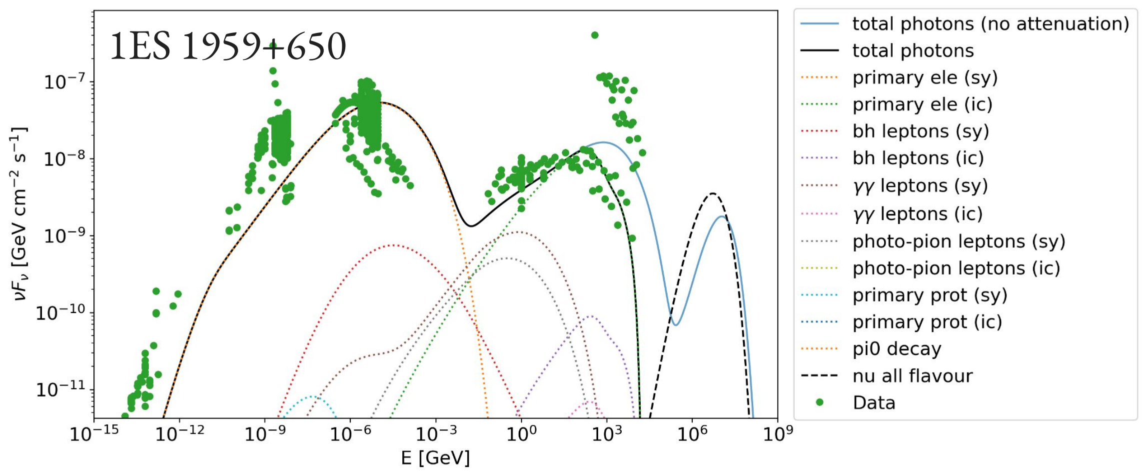
- All-sky analyses for neutrinos from extreme HBLs
  - Best sensitivity with track events at the horizon / Northern sky
  - Good sensitivity with cascade events in the Southern sky
- Constraints for eHBLs assuming:
  - pp emission: neutrino spectrum matches (deabsorbed) gamma-ray spectrum at TeV energies
  - pγ emission: modeling to predict the neutrino spectrum



Modeling pγ emission from eHBLs

Klinger et al., ApJS 275 4 (2024)

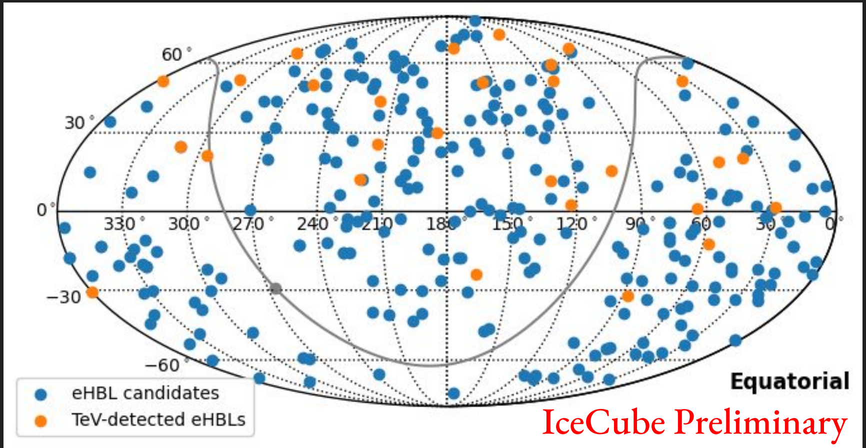
- AM^3: leptohadronic open source modeling code
- Source, electron and proton populations physical parameters
- Fit to multiwavelength data to get a neutrino expectation for each source



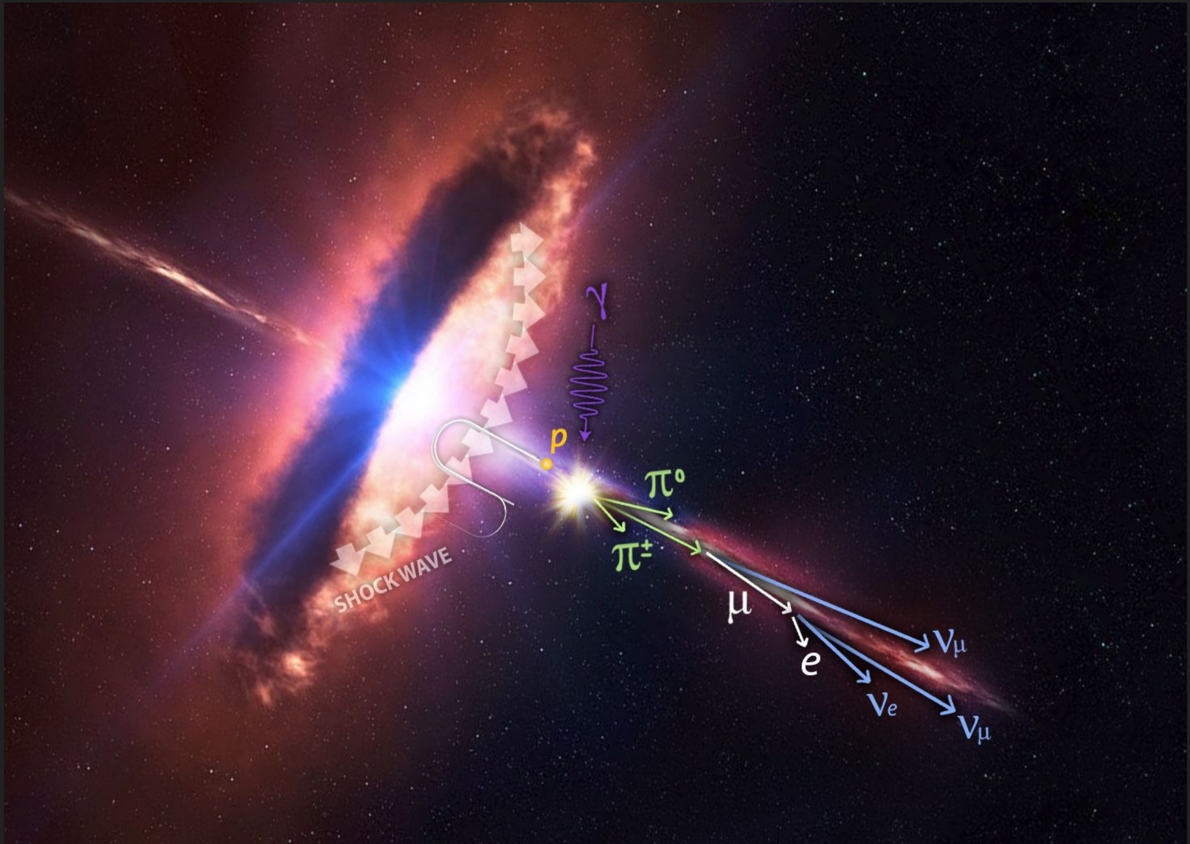
Observed and candidate extreme blazars

- 25 eHBLs observed with Imaging Atmospheric Cherenkov Telescopes (IACTs)
- Some high synchrotron peak candidates not observed at TeV energies, but good candidates to be eHBLs (260 candidates)

➔ Perform stacking analyses for these sources, assuming pp/pγ neutrino emission



A new neutrino detector: The Pacific Ocean Neutrino Experiment



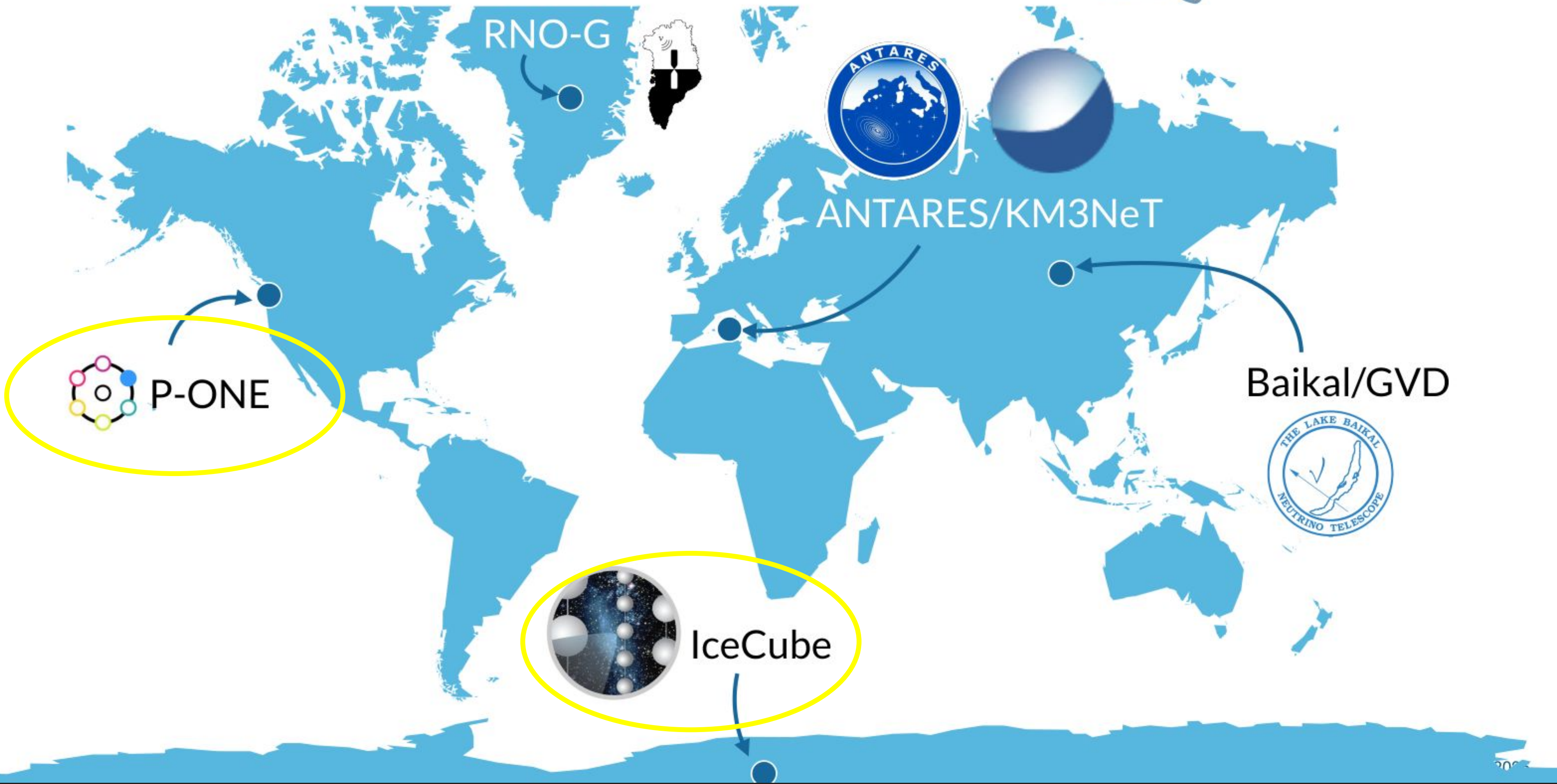
Credit: IceCube Collaboration

The Global Neutrino Network in 2026

GNN
The Global Neutrino Network

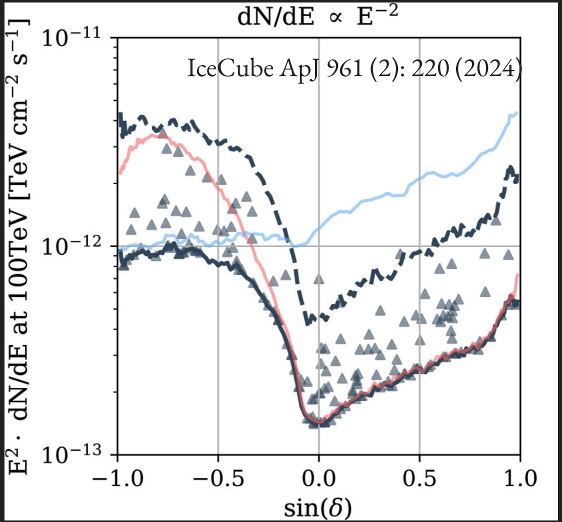
The Global Neutrino Network *in 2026*

GNN
The Global Neutrino Network



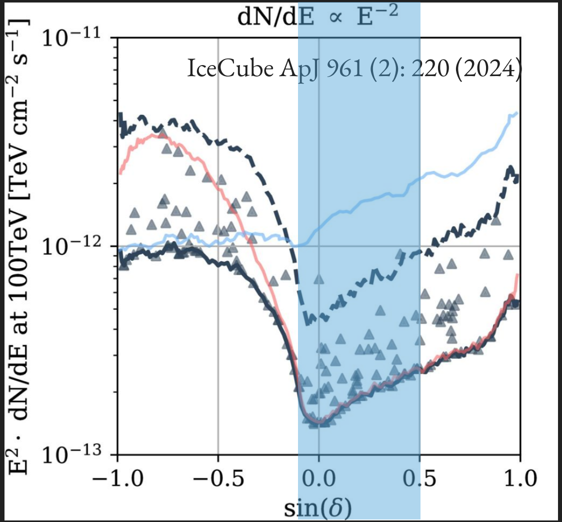
Optimising sensitivity over the whole sky

- Neutrino detectors necessarily have a region of “best sensitivity” where:
  - Atmospheric muons are attenuated by the Earth
  - High energy neutrinos still make it through the Earth to the detector



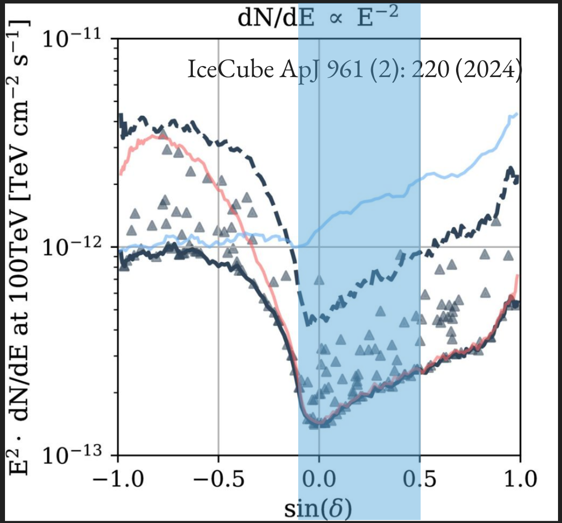
Optimising sensitivity over the whole sky

- Neutrino detectors necessarily have a region of "best sensitivity" where:
  - Atmospheric muons are attenuated by the Earth
  - High energy neutrinos still make it through the Earth to the detector

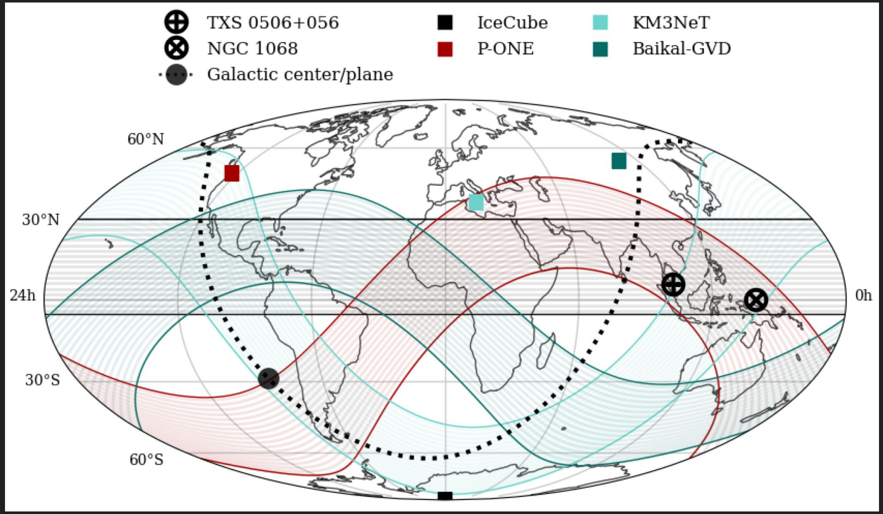


A global network of neutrino telescopes

- With a network of neutrino telescopes in many locations, we can increase the area of the sky in this "best sensitivity" region
- Telescopes in the North are optimised to view the Galactic center

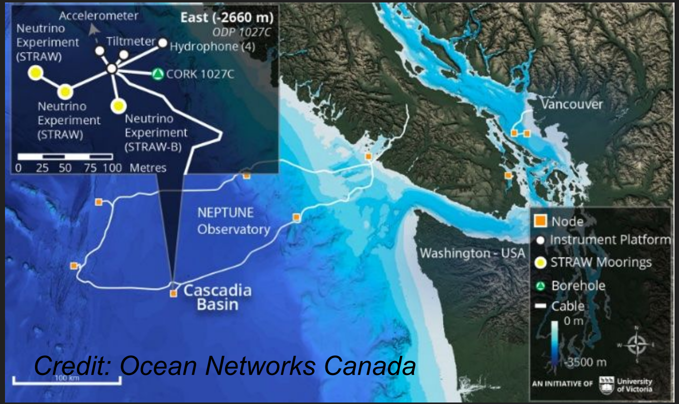


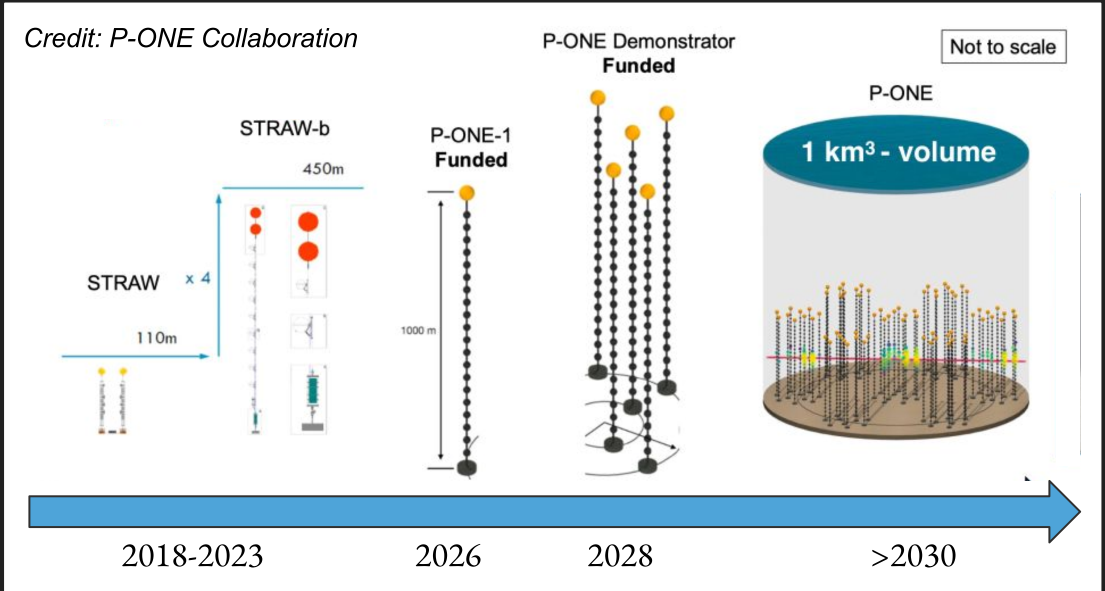
Instantaneous best sensitivity for 3 neutrino telescopes



The Pacific Ocean Neutrino Experiment

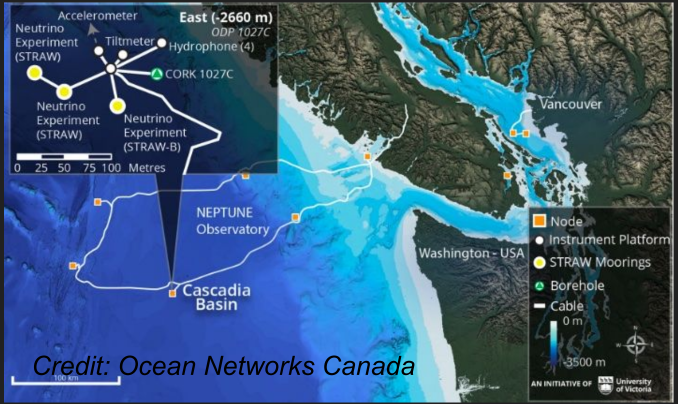
- Cubic kilometer neutrino experiment in the Pacific
- Stable ocean temperature (2° C)
- Infrastructure: Ocean Networks Canada (ONC)



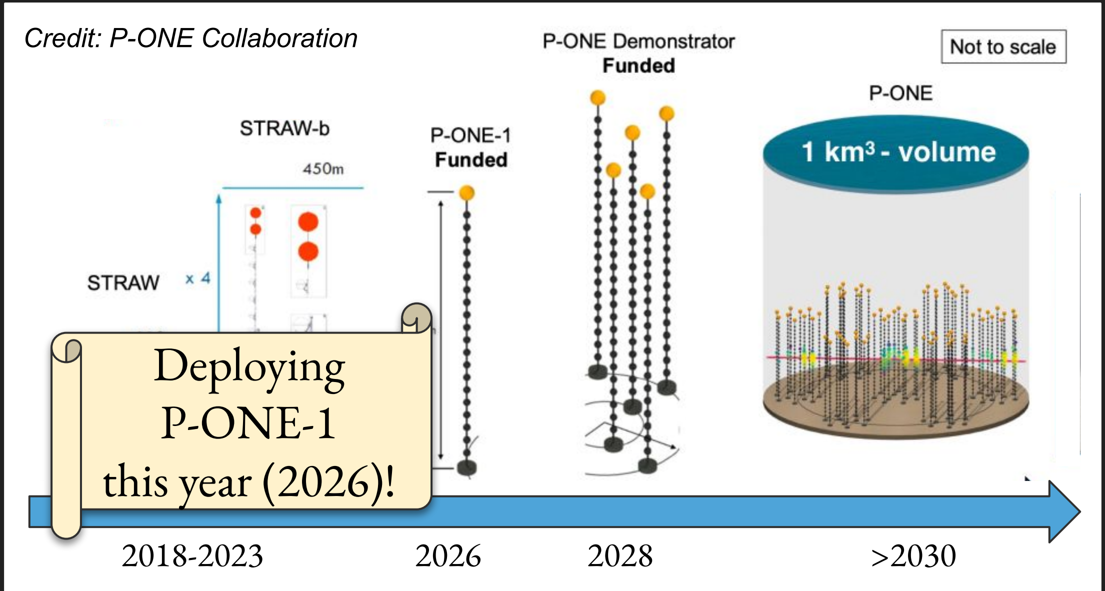


The Pacific Ocean Neutrino Experiment

- Cubic kilometer neutrino experiment in the Pacific
- Stable ocean temperature (2° C)
- Infrastructure: Ocean Networks Canada (ONC)



See talks by
Jakob Stacho &
Bryan Owens



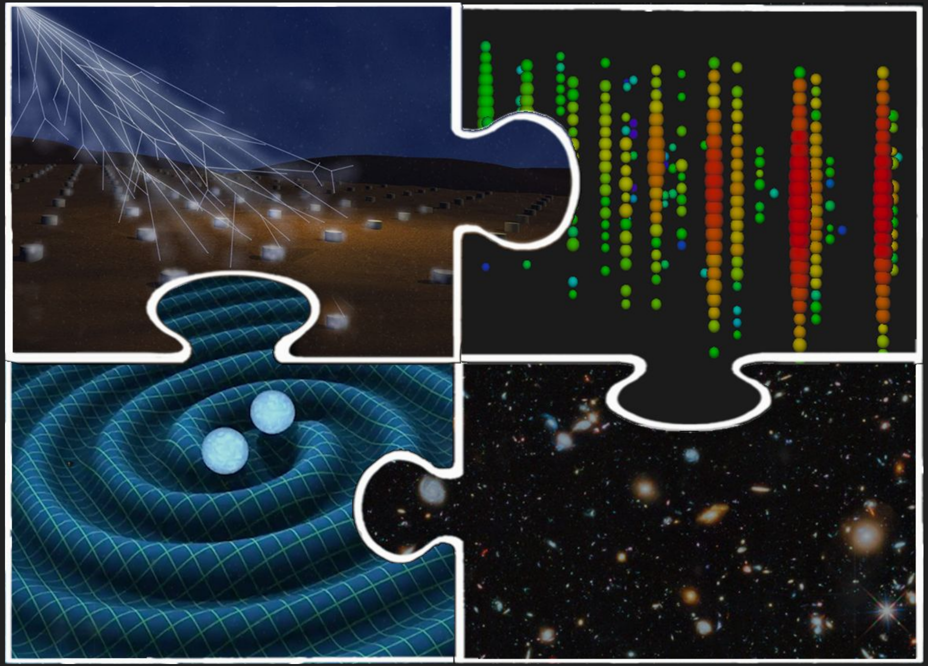
Deploying
P-ONE-1
this year (2026)!

Summary and Outlook

Neutrino astronomy is an exciting way of studying high energy astrophysical objects

Aim to differentiate hadronic vs leptonic processes in sources

Network of neutrino telescopes is important to have good continuous sensitivity to all-sky sources



Graphic: IceCube Collaboration