Tau neutrinos in the Pacific Ocean Neutrino Experiment (P-ONE)

Andreas Gaertner for the P-ONE Collaboration
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Neutrino Astronomy

• Classical astronomy: photons only
• Multi-messenger astronomy:
  – Cosmic rays
  – Gravitational waves
  – Neutrinos

• Neutrinos are the only particles that travel unperturbed by matter or magnetic fields
Neutrino Astronomy

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  − Gravitational waves
  − Neutrinos
• Neutrinos are the only particles that travel unperturbed by matter or magnetic fields

Neutrino spectra from different sources
Vitagliano et al. Rev. Mod. Phys. 92, 45006 (2020)
Neutrino Telescopes

- Neutrinos (>100 GeV) interact with matter to produce high-energy charged lepton
- Charged lepton produces Cherenkov light
  - Photomultipliers (PMTs) for light detection
  - Large volume (\(\approx 1 \text{ km}^3\)) of transparent medium (water or ice)

Visualization of a tau event (blue). Each dot represents an optical module.
Goals

General

• find the sources of high energy (TeV-PeV) astrophysical neutrinos

IceCube measurements of neutrino point sources and the galactic plane
Goals

General

- find the sources of high energy (TeV-PeV) astrophysical neutrinos

Tau-specific

- Test if flavour ratio agrees with neutrino production models and SM oscillation parameters

(IceCube talk on Friday)

IceCube measurements, astrophysical neutrino flavour composition
Neutrino Telescopes

**IceCube (South Pole)**
*Operational*

**GVD (Lake Baikal)**
*Partially operational*

**KM3NeT (Mediterranean)**
*Partially operational*

**P-ONE (Pacific)**
*In preparation*

Image: IceCube Collaboration

Image: F. Henningsen

Image: KM3NeT
Neutrino Telescopes

**Looking up:**
- Background from atmospheric muons

**Looking down:**
- Works for low energies
- At high energies (PeV) earth becomes opaque
  - Small band around horizon
  - Multiple telescopes are needed across the planet

Plot: L. Schumacher
NEPTUNE Observatory

- 800 km cable loop in the Pacific Ocean by Ocean Networks Canada
- Cascadia Basin
  - Abyssal plain
  - Low currents (0.1 m/s)
  - Low temperature (2°C)
  - Flat sea floor
  - 2.6 km depth
- ideal environment for neutrino telescope
Pathfinder missions

- Two successful pathfinder missions
- Relevant environmental parameters are determined
  - Attenuation length (30m)
  - Optical background
    - K40
    - Bioluminescence

Boehmer et al. JINST 14 P02013 (2019)

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Current work: First P-ONE string

- 20 modules on 1km string
- Multi-PMT modules based on KM3NeT OM and IceCube mDOM
- First of 6-7 financed strings (P-ONE Demonstrator)

Planned deployment: 2025
Next steps

First string
- Proof of concept
- Atmospheric muons

Cluster
- Atmospheric neutrinos
- Moon shadow

Full detector (possible geometry)
- Astrophysical neutrinos
- >1km³ instrumented volume

[Diagram of detector geometry]
• What do astrophysical neutrino events look like?

• How can taus be distinguished from muons and electrons?
Event signatures

Neutral current
hadronic cascade
neutrino

Charged current
electron neutrino
hadronic cascade
neutrino
EM cascade

➔ Cascade

Charged current
muon neutrino
hadronic cascade
neutrino

➔ Track

Charged current
tau neutrino
hadronic cascade
neutrino

➔ Double bang
Event signatures

→ Cascade

→ Track

→ Double bang

> 1 TeV: 5 cm, \(\approx 1000 \, \nu_\tau / \text{yr} / \text{km}^3\)

> 1 PeV: 50 m, \(\approx 1 \, \nu_\tau / \text{yr} / \text{km}^3\)
Tau detection

- Angular (single module)
  - Not too promising
    (low angular resolution)

- Temporal (single module)

- Spatial (multi-module)
Tau detection

- Angular (single module)

- Temporal (single module)
  - Search for double-peaked waveforms
  - Limited by digitizer resolution
    → 5 m tau track length
    → >100 TeV

- Spatial (multi-module)

(preliminary)
Tau detection

- Angular (single module)

- Temporal (single module)

- Spatial (multi-module)
  - Relies on event reconstruction
  - Tau track length > cascade extension
    $\rightarrow >100$ TeV
Fitting two exponentially modified Gaussian distributions to single module photon distribution
Use peak to valley (with some modifications) as test statistic
Compare to single cascades

NuTau, peak to valley significance = 5.8

(preliminary)
**Tau identification – Multi-module**

- Compare single cascade reconstruction to double cascade reconstruction
- Crosscheck by looking for single-module double-peaked waveform

**Baikal (arXiv:2108.00333)**
- Reconstruct for each combination of 5 modules
- Look at distribution of reconstructed vertices
Tau identification – Multi-module

Possible P-ONE method

• Decouple tau identification from event reconstruction
• Reconstruct event as single cascade
  ➔ Use good resolution of cascades and low scattering in water
• Based on timing, calculate emission point of detected light

Relativistic track: all particles are almost collinear, moving at c
Tau identification – Multi-module

Possible P-ONE method

- Decouple tau identification from event reconstruction
- Reconstruct event as single cascade
  - Use good angular resolution of cascades in water
- Based on timing, calculate emission point of detected light

Electron (single cascade)  
Muon (cascade and low intensity track)  
Tau (two cascades)
False positive? (double peak structure created by detector geometry)

False positive? (catastrophic loss along track)

Electron (single cascade)

Muon (cascade and low intensity track)

Tau (two cascades)

➔ Work in progress

(preliminary)
Rate estimates

MC simulation of tentative 70-string geometry

Regardless of detection method, need
• $\tau > 5$ m
• $O(10)$ photons from each cascade
• 5 modules hit for event reconstruction

→ $O(1)$ event per year possible

Rate estimates (preliminary)
Conclusion

• New neutrino telescope in the Pacific Ocean under construction

• Capable of detecting astrophysical tau neutrinos

• Early studies indicate detection rates O(1) event per year
Further reading


M. Boehmer et al., JINST 14 (2019) 02, P02013, arxiv:1810.13265


www.pacific-neutrino.org
Backup - P-ONE Optical Module (P-OM)

- Multi-PMT module based on KM3NeT OM and IceCube mDOM
- 16 PMTs per module (3” Hamamatsu R14374)
  - measure direction of incident light
- Spring-loaded mounting structure
- Gel pads with reflectors to increase light yield
- Individually adjustable HV
Backup - Calibration and timing

- Calibration modules 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
Backup - P-OM Electronics

- PMTs read out by 200 MHz 12-bit ADC + FPGA
  - Full waveform digitization
- Microprocessor, 4GB shared memory with FPGA
  - Local data buffering, coincidence triggering, communication
Backup - Deployment
Backup - P-ONE Demonstrator

- 6-7 strings of first 10-string cluster
- Funding secured from European agencies, positive messages from Canadian agencies
- First physics measurements
  - Atmospheric neutrinos
  - Moon shadow
  - Bioluminescence study
  - Trigger algorithm development
Backup - Ocean Networks Canada (ONC)

- Initiative of the University of Victoria
- Provides power and network connections on the sea floor for scientific instruments
- Over 15 years of experience in deploying and maintaining sea floor infrastructure
- Multiple observatories all over Canada
Backup – Angular resolution

- Less scattering in water compared to ice
  - Better angular resolution (0.1 degrees)
Backup - Resolution

Detection only possible if cascades are sufficiently separated

→ Require tau track length \( \geq O(\text{cascade length}) \)

→ Neutrino energy \( \geq O(100 \text{ TeV}) \)
Backup - Resolution

- 200 MHz digitizer in each module (5ns per sample)
- minimum 3 samples for double pulse identification
  - $15\text{ ns} \approx 5\text{ m}$ minimum tau track length
  (Rule of thumb: tau track length = $50\text{ m} / \text{PeV}$)

Simulated single-module digitizer waveforms
Backup – Photon emission reconstruction
Backup - Expected tau rates

1.7±0.2 (0.9±0.1) events per year with 5 (50) photons from each Cascade

→ Spatial separation

1.4±0.2 (0.6±0.1) events with individual modules seeing 5 (50) photons from each Cascade

→ Temporal/waveform separation

(preliminary)
Backup – Neutrino flux

• Astrophysical flux (all flavours)
  “Characteristics of the diffuse astrophysical electron and tau neutrino flux with six years of IceCube high energy cascade data”, arxiv:2001.09520

• Atmospheric flux (electron and muon neutrinos)
  – Can oscillate to tau neutrinos
  – Conventional (pion decays)
    SIBYLL 2.3
  – Prompt (higher meson decays)
    BERSS
nuSQUIDS for propagating neutrinos through Earth

PREM model for Earth’s density
Backup – Oscillations and Absorption

- $E < 1$ TeV: Oscillations
- $E > 1$ TeV: Absorption
  (for upgoing events)
Backup – Attenuation length

Attenuation length

- Determines P-ONE module spacing and energy resolution
- Measured at 28m for 450nm

Site is suitable for neutrino telescope

Backup - K40

**Potassium-40 decays**

- Source of coincident photons
- K-40 measurements agree with predictions

Backup – Bioluminescence

Backup – Bioluminescence

Extrapolating from STRAW to 16-PMT module
→ 1-10 MHz single photons per module
Looking at time distribution of photons

Relative to first photon

*O*(100ns), expect noise *O*(1 photon) per module