Methods to identify high-energy tau neutrino interactions in IceCube, a cubic-kilometer neutrino detector deployed in the glacial ice at the geographical South Pole will be described. An algorithm will be presented for detecting double pulse signature, which can be an indication of the tau neutrino interaction and subsequent decay of the tau lepton inside the detector. The recent results for astrophysical tau neutrinos with three years of IceCube data will be shown. Future prospects for tau neutrino detection in IceCube will be discussed.
Outline

- IceCube detector
- Detection principle
- $\nu_T$ signatures in IceCube
- Lollipop analysis (22 string configuration)
- Double bang analysis
- Double pulse signature analysis (in 3y of IceCube data)
- Conclusions
86 strings with 60 Digital Optical Modules (DOMs) (IceCube + DeepCore)

Optical sensor
10" photomultiplier (PMT) + in situ signal digitization in pressure glass sphere

Deployed between 1450 and 2450 m depth

81 IceTop surface stations

Construction complete December 2010 (data taking since 2005)
Detection Principle

Neutrino → Charged lepton

IceCube
Detection of the Cherenkov light
Emitted by secondary particles

Run 114305 Event 10091078 [0ns, 14000ns]
The characteristic pattern (topology) of the Cherenkov light provides information about the energy, direction, and flavor of the parent neutrino.

**Track-like events**
- good angular resolution, limited energy resolution when not fully contained in the detector volume
- source - $\nu_\mu$ CC interactions

**Cascade-like events**
- good energy resolution, limited angular resolution
- source - $\nu_e$, $\nu_\mu$, $\nu_\tau$ NC + $\nu_e$, $\nu_\tau$ CC interactions

**Composite events**
- mixture of track-like and cascade-like events or multiple cascade events
- high-energy $\nu_\tau$ CC as a possible source
**ν_τ** signatures in IceCube

- BR = 82%, 2π, <σ_{E_μν} > ~ 1^o
- BR = 100%, 2π, <σ_{E_μν} > ~ 1^o, Bkgd = ↓μ
- BR = 18%, 2π, ~σ_{E_μν} ~ 1^o
- BR = 82%, 4π, ~σ_{E_μν} ~ 1^o, Bkgd = ν_e

- **Lollipop**: Partially contained double bangs
- **Inverted Lollipop**: Sugar-daddy
- **Double Bang**: Double Pulse
- **Tautsie Pop**

**Log(E_τ) eV**

5cm 50cm 5m 50m 500m 5km 50km

**Taue Decay Length**
The first dedicated search for PeV-scale tau neutrinos of astrophysical origin

22-string configuration with an instrumented volume of roughly 0.25 km$^3$

- Predicted background: $0.6 \pm 0.19$ (stat.) +0.56 (syst) – 0.58 (syst) events
- 3 events observed (after inspection emerge as being compatible with background)
E: all flavor limit from this analysis
E*: all flavor sensitivity from this analysis

[A]: AMANDA-II cascade all-flavor limit (1001 live-days)
[B]: IC22 cascade all-flavor limit (257 live-days)
[C]: Baikal all-flavor limit (1038 live-days)
[D]: AMANDA-II UHE all-flavor limit (457 live-days)

[F]: ANTARES ’07-’09 νμ x 3 334 d
[G]: IC40 muon neutrino sensitivity x3

[aa]: Waxman-Bahcall (νμ and ντ) model 1998 x 3/2
[bb]: Stecker AGN (Seyfert) 2005
[cc]: Waxman-Bahcall Prompt GRB model
[dd]: Atmospheric neutrino flux (Bartol + Sarcevic standard model)
Double bang analysis
Predicted event rates

A search for well separated double bangs

Data Sample | Events in 1 y
--- | ---
Astrophysical $\nu_\tau$ CC | $(4.93 \pm 0.01) \times 10^{-1}$
Atmospheric muons | $(9.5 \pm 1.8)$
Astrophysical $\nu_e$ | $(8.2 \pm 1.3) \times 10^{-1}$
Astrophysical $\nu_\mu$ | $(8.9 \pm 0.2) \times 10^{-1}$
Atmospheric $\nu_e$ | $(4.4 \pm 0.2) \times 10^{-2}$
Atmospheric $\nu_\mu$ | $(9.3 \pm 0.2) \times 10^{-2}$

Still background dominated by atmospheric muons. Further studies underway to reduce background.

Astrophysical per flavor flux is $E^2 \Phi_\nu = 1.0 \times 10^{-8} \text{ GeV s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$
Double Pulse analysis

Double bang → Double pulse

For close cascades, a double pulse signature can appear in the digitized waveform.

Simulated double pulse waveform from a ντ CC interaction.
Double Pulse analysis Signature

Resolved double pulses will only be produced in high energy $\nu_\tau$ interactions

→ Event selection: IceCube Extremely High Energy (EHE) filter + at least 2000 PE + more cascade-like event cut + containment cut.

Individual DOM waveforms are then examined for double pulse characteristics

$\nu_\tau$ double bang event topology

Simulated double pulse waveform from a $\nu_\tau$ CC interaction
**Double Pulse analysis**

**Predicted event rates**

First IceCube search to be more sensitive to tau neutrinos than to any other flavor

<table>
<thead>
<tr>
<th>Data Sample</th>
<th>Events in 914 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astrophysical $\nu_\tau$ CC</td>
<td>$(5.4 \pm 0.1) \times 10^{-1}$</td>
</tr>
<tr>
<td>Astrophysical $\nu_\mu$ CC</td>
<td>$(1.8 \pm 0.1) \times 10^{-1}$</td>
</tr>
<tr>
<td>Astrophysical $\nu_e$</td>
<td>$(6.0 \pm 1.7) \times 10^{-2}$</td>
</tr>
<tr>
<td>Atmospheric $\nu$</td>
<td>$(3.2 \pm 1.4) \times 10^{-2}$</td>
</tr>
<tr>
<td>Atmospheric muons</td>
<td>$(7.2 \pm 5.8) \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Astrophysical per flavor flux is

\[ E^2 \Phi_V = 1.0 \times 10^{-8} \text{ GeV s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \]

*IceCube Preliminary*
No candidate events found in 914 days of data
\( \nu_\tau \) flux limit is \( 5.1 \times 10^{-8} \text{ GeV s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \) between 0.21 and 72 PeV
Conclusions

- No astrophysical $\nu_\tau$ candidate events observed yet
- Different types of IceCube analyses are undergoing
  > **Double bang** (ongoing studies to reduce background)
  > **Double pulse search**, which is more sensitive to PeV tau neutrinos than to any other flavor, can be enriched with more data (4th year)
  > ... new ideas are under investigation
- Proposed high-energy array will have significantly higher (5 – 10 times) sensitivity to astrophysical tau neutrinos
BACKUP SLIDES
High Energy Array:

- The sensitivity studies are underway using full detector simulations of several benchmark geometries.

- String spacing: ~240m
  ~ 200 PeV
  cascade events/10 years
  ~ 500 – 1000 $\nu_\mu$
  above 100 TeV ($\mu$ energy)

- Comparable number of strings -> neutrino energies above 50 TeV with high efficiency
High Energy Array and PINGU

Precision IceCube Next Generation Upgrade (PINGU):
• low-energy in-fill array

• **Neutrino mass ordering**
  • Atmospheric muon neutrino disappearance
  • Tau neutrino appearance
  • $\theta_{23}$ mixing angle
  • probe the lower WIMP dark matter mass range
  • open the possibility of future neutrino-based
tomography of the Earth

New PINGU baseline geometry:
40 strings with 20m horizontal separation;
96 DOMs per string with 3m vertical separation

Tomasz Palczewski - EPS HEP 2015  7/24/15
High Energy Array and PINGU

Precision IceCube Next Generation Upgrade (PINGU):
- low-energy in-fill array

**Neutrino mass ordering**
- Atmospheric muon neutrino disappearance
- Tau neutrino appearance
- $\theta_{23}$ mixing angle
- probe the lower WIMP dark matter mass range
- open the possibility of future neutrino-based tomography of the Earth

New PINGU baseline geometry:
40 strings with 20m horizontal separation;
96 DOMs per string with 3m vertical separation

Still reach 3$\sigma$ in ~3.5 – 4 yrs

PRELIMINARY
• Neutrino mass ordering

Livetime to 3\(\sigma\) (yrs)

- Best Case
- Worst Case

\(\delta_{cp} = -90^\circ, 10kT\)
\(\delta_{cp} = 90^\circ, 34kT\)
\(\sigma_E = 3\%\)
\(\theta_{23} = 39^\circ, IH\)
\(\theta_{23} = 51^\circ, NH\)
\(\theta_{23} = 49^\circ, NH\)

\(\delta_{cp} = 90^\circ, \theta_{23} = 40^\circ, NH\)

NOvA, T2K

Water Cherenkov
Atmospheric Calorimeter
Atmospheric Reactor
Future Long-baseline
The analysis was recently enriched with the fourth year of data (1347 days of total effective detector live-time).

54 neutrino candidate events

39 cascade-like,
15 track-like events

dominant component:
cascade-like events from the southern sky (down-going)
Evidence for Extraterrestrial Neutrinos in four years of data