Tau Neutrinos in IceCube, KM3NeT and Pierre Auger

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Outline

• Ice and water Cherenkov neutrino detectors and their detection principles

• IceCube:
  • Discovery of an astrophysical neutrino flux
  • Evidence for a possible astrophysical neutrino source
  • Tau neutrinos in IceCube
    • High-energy: neutrino oscillations at cosmic baselines and direct detection
    • Low-energy: indirect detection through neutrino oscillations

• KM3NeT: prospects for tau physics

• Pierre Auger: tau neutrino detection using a UHE cosmic ray detector
Motivation for Neutrino Astroparticle Physics
Ice/Water Cherenkov Neutrino Detectors Around the Globe

**ANTARES**
- Deep water
- 0.01 km$^3$
- 2008 -

**KM3NeT**
- Deep water
- 1 km$^3$
- Under construction

**Baikal-GVD**
- Deep water
- 1 km$^3$
- Under construction

**IceCube**
- Deep ice
- 1 km$^3$
- 2011 -
Ice/Water Cherenkov Neutrino Detectors Around the Globe
The IceCube Detector

IceTop
- 81 Stations
- 324 optical sensors

IceCube Array
- 86 strings including 8 DeepCore strings
- 5160 optical sensors
- String spacing 125 m, DOM spacing 17 m
- Neutrino energy: TeV - PeV

DeepCore
- 8 strings-spacing optimized for lower energies
- 480 optical sensors
- String spacing 70 m, DOM spacing 7 m
- Neutrino energy: 5 GeV - 100 GeV
Neutrino Detection

- Neutrino-induced charged particles emit Cherenkov radiation
- Backgrounds from atmospheric muons reduced via timing, direction, energy and vetoing techniques

Angular resolution: < 1°
Energy resolution: factor of ~2

Angular resolution: 10° above 100 TeV
Energy resolution: ±15%

NB: Θ(100 TeV) events shown for clarity...
IceCube’s Discovery of an Astrophysical Neutrino Flux

**HESE**

- All-sky, all-flavor, starting events, containment required, effective volume smaller than detector

**Through-going muons**

- Through-going muon track events, northern sky only, no containment required, effective volume larger than detector
IceCube’s Discovery of an Astrophysical Neutrino Flux

Through-going muons

HESE

Atmospheric-only hypothesis excluded by more than $6\sigma$

PoS(ICRC2017)1005

$E_{\nu}^2 \cdot \Phi_{\nu+\bar{\nu}}$ (GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$)

$E_{\nu}$/GeV
IceCube Point Source Searches

HESE

Through-going muons

No significant clustering found yet
IC-170922A and TXS 0506+056

* Most probable neutrino energy: 290 TeV
* Very ‘cosmic neutrino-like’
Follow-up Observations of IceCube Alert IC170922

Gamma rays (20 MeV - 300 GeV)

VHE gamma rays (>100 GeV) observed at >6σ
Energy Spectrum of TXS 0506+056: Multi-Messenger Astronomy
IceCube ‘Precovery’ of a Neutrino Flare from IC-170922A’s Location

Science 361 (2018), 147
TXS 0506+056 Summary and Open Questions

- First high energy cosmic neutrino with compelling EM counterpart from a flaring blazar, active across many wavelengths
- No neutrino candidates observed in ANTARES, neither coincident with IC-170922A, nor in the 2014-2015 neutrino flare

- Which models can explain the multi-messenger data?
- Why is there no EM activity coincident with the IceCube 2014-2015 neutrino flare from the same location?
- Why this blazar? It’s neither the closest, nor the brightest in the sky. So where are the neutrinos from other blazars?
- The TXS IceCube averaged flux over 9.5 years is <1% of the all-sky astrophysical neutrino flux
- In addition, (model-dependent) calculations show that blazars contribute to the astrophysical neutrino flux for at most ~25%.
- So what and where are the other astrophysical neutrino sources?
High-Energy Tau Neutrinos in IceCube

- $\nu_\tau$ CC interaction (71%)
- Resulting tau decays to hadrons/electrons, creating another cascade (83%)
- If high enough in energy: double cascade topology
  - Tau decay length scales as $\sim 1\text{PeV}/50\text{m}$
- Two double cascade candidates have been identified and are under investigation

Simulated 10 PeV event
An IceCube Tau Neutrino Candidate
Neutrino Oscillations at Cosmic Baselines

• High-energy tau neutrino production in Earth’s atmosphere is negligible

• Therefore, an observed high-energy tau neutrino would have to be astrophysical in origin

• And it would serve as a probe to test the standard neutrino oscillation paradigm at cosmic baselines

• Neutrino oscillations cause the neutrino flavour ratio to change from source to Earth

• For neutrinos created in pion decay:
  • Assumed flavour ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ at source
  • Expected flavour ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ on Earth

\[\begin{align*}
\text{Assumed flavour ratio} & : \nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0 \\
\text{Expected flavour ratio} & : \nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1
\end{align*}\]

• Consistent with $1 : 1 : 1$

• But zero $\nu_\tau$ can’t be excluded, either
Neutrino Oscillations at Earth-Crossing Baselines

- Atmospheric neutrino oscillations observable in IceCube from a wide range of baselines and energies (few GeV up to 100 TeV)
- $\cos(\text{zenith angle})$ is a proxy for the baseline $L$
- Neutrino oscillations produce distinct patterns in narrow regions of 3D energy/angle/PID oscillograms
Tau Neutrino Normalisation

- In standard 3 flavour PMNS paradigm, $\nu_\mu$ disappearance is predominantly $\nu_\mu \rightarrow \nu_\tau$, i.e. $\nu_\tau$ appearance in the energy relevant in IceCube

- $\nu_\tau$ appearance has previously been confirmed by OPERA, but with relatively large uncertainties

- Need high-precision measurements on PMNS matrix elements to determine its unitarity

- Use so-called $\nu_\tau$ normalisation factor (1 = SM expectation, 0 = no $\nu_\tau$ appearance) in the neutrino oscillation parameter fits as a proxy
IceCube Tau Neutrino Normalisation Results

[Graphs showing data and analysis results for IceCube tau neutrino normalisation.]
KM3NeT is Under Construction

**KM3NeT ORCA**
(Oscillation Research with Cosmics in the Abyss)

- GeV (low-energy) atmospheric neutrinos
- 30 km off French coast, 2.5 km depth
- Horizontal string spacing ~20 m
- Vertical OM spacing 9 m
- 5.7 Mton detector
- Deployment: 2019-2021

- Exclude $\nu_\tau$ normalisation factor = 0 (i.e. no $\nu_\tau$ appearance) at $5\sigma$ within 2 months of full ORCA detector operation
- 20% constraint on $\nu_\tau$ normalisation at $3\sigma$ after one year of detector operation

**KM3NeT ARCA**
(Astrophysics with Cosmics in the Abyss)

- TeV-PeV (high-energy) astrophysical neutrinos
- 100 km off Sicilian coast, 3.5 km depth
- Horizontal string spacing ~100 m
- Vertical OM spacing 36 m
- 1 km$^3$ detector
- Deployment: 2019-2021

- Cascade angular resolution < 2°
- Cascade energy resolution 5-10%
IceCube Upgrade is Underway

- Upgrade includes new calibration devices to characterise the ice optical properties
  - Improved (cascade) reconstruction:
    - Retro-actively increase statistics of and sensitivity to astrophysical neutrino flux
    - 3-4σ observation of cosmic tau neutrinos
  - Science goals also include:
    - <10% uncertainty on $\nu_\tau$ normalisation
  - Deployment in 2022-2023
High-Energy Neutrinos in Pierre Auger

• The Pierre Auger Observatory studies ultra-high energy (UHE) cosmic rays using Cherenkov telescopes and surface water tanks covering ~3000 km²

• The existence of cosmic rays at energies >10^{18} eV implies an astrophysical neutrino flux at similar energies

• A subcategory of these neutrinos could be detected by Pierre Auger:
  • Neutrino energy > 10^{17} eV
  • Down-going neutrino-induced shower deep in the atmosphere
  • Earth-skimming $\nu_\tau$ events
Pierre Auger High-Energy Neutrino Flux Limit

- No candidates found from 2004-2017
- Best limits for EeV neutrino flux
- Complementary in energy to IceCube and ANTARES

See Marta Trini’s poster: “Search for Ultra-High Energy Neutrinos with the Pierre Auger Observatory"
Conclusion

• IceCube has discovered an astrophysical neutrino flux and found evidence that a flaring blazar, TXS 0506+056, is a possible astrophysical neutrino source.

• IceCube can measure neutrino oscillations at cosmic baselines: no conclusive result on an astrophysical $\nu_\tau$ flux yet.

• Two possible $\nu_\tau$ candidates with double cascade signature have been observed.

• At lower neutrino energies, IceCube can measure the $\nu_\tau$ normalisation.

• KM3NeT is currently under construction: unprecedented angular and energy resolution will allow direct $\nu_\tau$ detection, to pinpoint astrophysical neutrino sources, to determine the neutrino mass ordering and measure $\nu_\tau$ normalisation to high precision.

• The IceCube Upgrade is underway: recalibration of ice optical properties will improve (cascade) angular resolution and astrophysical neutrino results. In addition, the dense detector geometry will improve neutrino oscillation results.

• Pierre Auger Observatory can detect EeV neutrinos, complementary in energy to IceCube and ANTARES. No events found in 13 years -> world-best limits.