High-Energy Neutrino Astronomy: Current Status and Prospects

Gwenhaël de Wasseige
Neutrino telescopes

Non-exhaustive list
Neutrino telescopes

Non-exhaustive list
Non-exhaustive list

- Neutrino telescopes
  - T. Chiarusi’s talk on Saturday
  - O. Suvorova’s talk in this session
  - K. Holzapfel’s talk in this session
  - C. di Stefano’s talk in Neutrino
How to detect high-energy neutrinos?

Dielectric medium

Cherenkov radiation

e, μ, τ

ν

1 km³

~ 5000 sensors or Digital Optical Modules (DOMs)
How to detect high-energy neutrinos?
Which information can we get?

- Amount of light -> Energy
- Timing -> Direction
- Topology -> Flavour
Figures not to scale
What do we learn from HE neutrinos?

\[ \pi^+ \rightarrow \mu^+ + \nu \mu \]

Assumption:

\[ p + p/\gamma \rightarrow \pi^0 \rightarrow 2 \ \gamma \]

\[ \mu^+ \rightarrow e^+ + \nu e + \bar{\nu} \mu \]
Outline

1. What did we discover?
2. What's new? / What else?
3. What's next?
1. What did we discover?

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

22 Nov. 2013
Updated calibration and ice model

Changes to RA, Dec, energy

103 events, with 60 events > 60 TeV

Diffuse neutrino flux 7.5 year

IceCube Work In Progress

Events per 2635 days

10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}

Deposited Energy [GeV]

Data
Astro.
Atmo. Conv.
Atmo. Muons
Atmo. Prompt 90% U.L.
No evidence for point sources
No correlation with the galactic plane
**Best fit:** Single power law with spectral index $\gamma = 2.89^{+0.20}_{-0.19}$
all-flavor flux normalization $\Phi = 6.45^{+1.46}_{-0.46}$
Data does not prefer a broken power law model
1. What did we discover?

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

13 Jul. 2018

F. Oikonomou’s talk
Neutrino Energy: 290 TeV (>180 TeV, 90% CL)
RA: 77.43° (-0.65°/+0.95° 90% CL)
Dec: 5.72° (-0.30°/+0.50° 90% CL)
Fermi observations of a known blazar TXS 0506+056, in a state of enhanced gamma-ray emission

MAGIC detection of > 400 GeV gamma rays from the blazar

Neutrino Energy: 290 TeV (>180 TeV, 90% CL)
RA: 77.43° (-0.65°/+0.95° 90% CL)
Dec: 5.72° (-0.30°/+0.50° 90% CL)

Significance for the overlap: 3σ
Archival data search

- Time-dependent point source search at location of TXS blazar
- 13 ± 5 neutrino excess in 2014-2015 over 110 days
- Significance defined using identical searches using randomized event directions: 3.5σ
2. What’s new? What else?

- Astrophysical neutrino search using through-going $\nu_\mu$ events
- First Glashow resonance candidate observed by IceCube
  (C. Haack’s talk in the session)
- Neutrino point source searches with 10 years of IceCube data
- Search for correlations of high-energy neutrinos and ultra-high-energy cosmic rays
- Study of the high-energy neutrino diffuse flux with the ANTARES neutrino telescope
- ANTARES search for point sources of neutrinos with 9 yr of data
- ANTARES-IceCube Combined Search for Neutrino Point Sources
- Combined ANTARES and IceCube search for neutrinos from dark matter annihilation in the GC
2. What’s new? What else?

- Astrophysical neutrino search using through-going $\nu_\mu$ events
- First Glashow resonance candidate observed by IceCube (C. Haack’s talk in the session)
- Neutrino point source searches with 10 years of IceCube data
- Search for correlations of high-energy neutrinos and ultra-high-energy cosmic rays
- Study of the high-energy neutrino diffuse flux with the ANTARES neutrino telescope
- ANTARES search for point sources of neutrinos with 9 yr of data
- ANTARES-IceCube Combined Search for Neutrino Point Sources
- Combined ANTARES and IceCube search for neutrinos from dark matter annihilation in the GC
2. What’s new? What else?

T. Carver and T. Montaruli, NuTel 2019

10 year All-Sky Scan Results

- Scan the entire sky and evaluate the likelihood of signal over background.
- The position with the smallest p-value in each hemisphere is taken as the hottest spot.
- The post-trial p-value is calculated by comparing this p-value with many background hotspots.

**Hottest Point in Northern Hemisphere**: $\delta \geq -5^\circ$

$RA = 40.87^\circ, Dec = -0.30^\circ$

\[ n_{signal} = 61.45, \gamma = 3.411 \]

$P_{val} = 6.45, TS = 25.34 \Rightarrow 9.9 \%$ post-trial

**Hottest Point in Southern Hemisphere**: $\delta < -5^\circ$

$Ra = 350.18^\circ, dec = -56.45^\circ$

\[ n_{signal} = 17.75, \gamma = 3.34 \]

$P_{val} = 5.37, TS = 19.95 \Rightarrow 75 \%$ post-trial
2. What’s new? / What else?

• Neutrinos in the multi-messenger era

• Flavor ratio and tau neutrinos
2. What’s new? / What else?

- Neutrinos in the multi-messenger era
- Flavor ratio and tau neutrinos
Neutrino search from known sources

Potential high-energy $\nu$ emitter

Goal: Identifying hadronic accelerators in the Universe
Neutrino search from known sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Contribution to the HE $\nu$ flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blazars (Fermi 2LAC catalog)</td>
<td>$&lt; 27%$</td>
</tr>
<tr>
<td>Gamma-ray burst</td>
<td>$&lt; 1%$</td>
</tr>
<tr>
<td>Galactic plane</td>
<td>$&lt; 14%$</td>
</tr>
</tbody>
</table>

What can we do to find sources?
Real-time multi-messenger astronomy

Multi-messenger partners

IACTs
Gamma-ray satellites
Ground based observatories
Satellites
Neutrino telescopes
Interferometers

-> See also ANTARES program
   in T. Chiarusi’s talk
Real-time multi-messenger astronomy

Multi-messenger partners

IceCube 170922A!

• New alert categories since June 17th 2019
  - Gold = 50% signal probability 1/month
  - Bronze = 30% signal probability 1.3/month

• Alert contains:
  - data and time
  - right ascension + declination
  - angular radii of the 50% and 90% containment circles
  - the signal probability
Real-time multi-messenger astronomy

Multi-messenger partners

- Fast-response analysis for interesting events, such as flares from the Crab Nebula or unknown bright transients
- Systematic follow-up of GW events
Real-time multi-messenger astronomy

IceCube Multi-messenger partner

• Fast-response analysis for interesting events
• Systematic followup of GW events

GW170817 [-500s, +500s]

• So far in O3:
  • > 10 BBH candidates
  • 2 (1) BNS candidates
  • 1 NS-BH candidate
• No coincident neutrino detection reported
• Followup in the GeV energy range @ ICRC

GW170817 Neutrino limits (fluence per flavor: $\nu_e + \bar{\nu}_e$)

IceCube

ANTARES

Auger

$\pm 500$ sec time-window

Kimura et al. EE moderate

Kimura et al. EE optimistic

Kimura et al. prompt
2. What’s new? / What else?

- Neutrinos in the multi-messenger era
- Flavor ratio and tau neutrinos
- Good E resolution
- Bad angular resolution

- Bad energy resolution
- Good angular resolution

+ Starting track!

- Good E resolution
- Better angular resolution than single cascade
Double cascade

- Both cascades with $E > 1$ TeV
- Separation distance $> 10$ m
- Ternary-PID of cascades, tracks and double-cascades
- 2 double-cascade candidates
- $\nu_\tau$ or mis-identified background
Event 1: Big Bird

- Energy of the cascades = 1.2 PeV and 0.6 PeV
- Separation = 16m
- Observed in 2012
- No clear preference between a single cascade and double-cascade
Event 2: Double Double

- Energy of the cascades = 9 TeV and 80 TeV
- Separation = 17m
- Observed in 2014
- Observed light arrival pattern clearly favors double cascade
**Flavor composition**

<table>
<thead>
<tr>
<th>Cosmic particle accelerator</th>
<th>$\nu_e:\nu_\mu:\nu_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pion decay</td>
<td>1:2:0</td>
</tr>
<tr>
<td>Muon-damped Neutron decay</td>
<td>0:1:0</td>
</tr>
<tr>
<td>Neutron decay</td>
<td>1:0:0</td>
</tr>
<tr>
<td>+ others</td>
<td></td>
</tr>
</tbody>
</table>

- Study of the composition at Earth
- Oscillation back to the source
- Information on the emission mechanism
- Non-zero best-fit for $\nu_\tau$  
- Zero $\nu_\tau$ flux not excluded
3. What's next?
KM3NeT

- 3 x 115 Detector Units
  - InterDU spacing: 20m or 90m
- 18 DOMs
  - Interdom spacing: 9m or 36m

Currently 1 ARCA + 4 ORCA DUs taking data

Oscillation Research with Cosmics in the Abyss

Astroparticle Research with Cosmics in the Abyss

Expected 2025
ORCA - 4 Dus

Downgoing muon event

Real data!
ARCA:

- $\nu_\mu$ angular resolution < 0.1° for $E_\nu$ > 100 TeV
- $\nu_e$ angular resolution < 2° and energy resolution ~ 5%

- Diffuse flux combining tracks and cascades

-> IceCube flux equivalent at 5σ in 6 months

ORCA:

- Multi-messenger astronomy down to 1 GeV @ ICRC
- Neutrino physics with ORCA

See C. Distefano's talk!
ORCA:

- Multi-messenger astronomy down to 1 GeV @ ICRC
- Opportunity of e.g., GW follow-up with reduced configuration
The Upgrade

- 7 new strings of modules
  - Interstring spacing 20m (DC 70m)
  - InterDOM spacing 2.4m (DC 7m)

- Neutrino physics:
  - oscillations
  - atmospheric tau neutrino
  - appearance, test of unitarity of PMNS mixing matrix

- Astrophysics:
  precise calibration of ice optical properties and DOM response
  -> apply to 10-years of existing data
The Upgrade

Deployment planned for 2022-2023

- Neutrino physics:
  - oscillations
  - atmospheric tau neutrino
  - appearance, test of unitarity of PMNS mixing matrix

- Astrophysics:
  precise calibration of ice optical properties and DOM response
  -> apply to 10-years of existing data
Take-home message

• High-energy neutrino astronomy is a young field of research but already...

• Several breakthroughs

• Many new results coming

• Promising future with the next generation being deployed

Thanks!
Neutrino telescopes

Instrumentation density

Particle detectors (e.g., pixel detector in CMS) ~ 1k modules/m²

HE neutrino detectors (e.g., IceCube) ~ 5k sensors/km³

Non-exhaustive list