High-Energy Neutrino Astronomy:
Current Status and Prospects

Gwenhaël de Wasseige
Gamma rays

Cosmic rays

Neutrinos

Gamma rays

Earth

Air shower

$v_e$

$v_\mu$

$v_\tau$
Neutrino telescopes

Non-exhaustive list
Non-exhaustive list

Neutrino telescopes
Neutrino telescopes

(T. Chiarusi’s talk on Saturday)

(K. Holzapfel’s talk in this session)

(O. Suvorova’s talk in Neutrino)

(C. di Stefano’s talk in Neutrino)

Non-exhaustive list
How to detect high-energy neutrinos?

Dielectric medium

$\nu$

1 km$^3$

$\sim$ 5000 sensors or Digital Optical Modules (DOMs)

Cherenkov radiation

e,\mu,\tau
How to detect high-energy neutrinos?

Dielectric medium

Cherenkov radiation

$\nu, \mu, \tau$
Which information can we get?

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

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu + \nu_e \]

\[ \mu^+ \rightarrow e^+ + \nu_e + \nu_\mu \]

\[ \pi^0 \rightarrow 2\ \gamma \]
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
Diffuse neutrino flux
7.5 year

- Updated calibration and ice model
- Changes to RA, Dec, energy

103 events, with 60 events > 60 TeV
• 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)
22 September 2017
IceCube-170922A

- 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)
Archival data search

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

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°, Dec = -0.30°

$n_{\text{signal}} = 61.45$, $\gamma = 3.411$

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

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

Ra = 350.18°, dec -56.45°

$n_{\text{signal}} = 17.75$, $\gamma = 3.34$

$P_{\text{val}} = 5.37$, 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
Potential high-energy $\nu$ emitter

Goal: Identifying hadronic accelerators in the Universe

Neutrino search from known sources
Neutrino search from known sources

<table>
<thead>
<tr>
<th>Contribution to the HE $\nu$ flux</th>
<th></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>
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*

- New alert categories since June 17\textsuperscript{th} 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

• Fast-response analysis for interesting events, such as flares from the Crab Nebula or unknown bright transients

• Systematic follow-up of GW events
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
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
Double cascade

- Ternary-PID of cascades, tracks and double-cascades
- 2 double-cascade candidates
- $\nu_\tau$ or mis-identified background

@ICRC
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

Cosmic particle accelerator

<table>
<thead>
<tr>
<th>Process</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</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?

Non-exhaustive list
• 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
ORCA - 4 Dus

Downgoing muon event

Real data!
ARCA:
- $\nu_\mu$ angular resolution $< 0.1^\circ$ for $E_{\nu} > 100$ TeV
- $\nu_e$ angular resolution $< 2^\circ$ and energy resolution $\sim 5\%$
- Diffuse flux combining tracks and cascades
  -> IceCube flux equivalent at 5$\sigma$ 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!
Non-exhaustive list

Neutrino telescopes

Instrumentation density

- Particle detectors (e.g., pixel detector in CMS) ~ 1k modules/m²
- HE neutrino detectors (e.g., IceCube) ~ 5k sensors/km³