VERS UNE ASTRONOMIE NEUTRINO AVEC IceCube+ANTARES+KM3NeT

DAMIEN DORNIC (CPPM)

CFR Cos: Meeting de la communauté de recherche sur le rayonnement cosmique

APC - 26-28 mars 2018
Neutrinos: smoking gun for cosmic-ray interactions

- **3 GeV – 1 TeV**: atmospheric neutrinos, dark matter…  
  - ORCA
- **100 GeV - 30 TeV**: various galactic (TeV gamma) sources  
  - ANTARES
- **30 TeV – 3 PeV**: IceCube signal (astrophysical flux)  
  - ARCA
The sources of HE ν are not necessary the sources of UHECR
Cf O. Martineau’s talk
HE NEUTRINO DETECTORS

\[ \frac{\sigma(vp)}{\sigma(yp)} = 10^{-7} \text{ at 1 TeV} \]

Need very large detectors

KM3NET-ARCA
ICECUBE
1Gton

SuperK
50kton

KM3Net-ORCA
6Mton

ANTARES
20Mton

41 m

1000 m

400 m
GNN: Global Neutrino Network linked all HE neutrino telescopes + provide framework for regular combined meetings and combined analysis
• Direction:
  ➪ Gal. srcs: $0.2^\circ$ at 10TeV [0.4$^\circ$ for ANTARES]
  ➪ Extra-gal. srcs: $0.1^\circ$ at 100TeV [0.3$^\circ$ for ANTARES]
• Energy: 0.27 in Log10(E)

• Vertex: 6-8m (long), 0.5m (perp)
• Direction: $\sim1.5^\circ$ [3$^\circ$ for ANTARES]
• Energy: 5%
To have better discovery potential:
- Have the lowest angular precision (tracks)
- Have the lowest background contamination (cascades)
- Search for time+space-correlations
6 year HESE analysis (ICRC 2017)
80(+2) events
Bkg: 15.6+11.4-3.9 atm nu + 25.2+-7.3 atm mu
Hemisphere North and South
E_{th}: 60 TeV

8 year upgoing muon
E_{th}: 200 TeV
E_{event} >5 PeV

Significance: 6.5 sigma
Spectra: E^{-2.92(+0.33 -0.29)}

➡ Indication of a break in spectrum? (energy threshold different)
➡ Indication of galactic and extra-galactic components? (different hemispheres)
THE ICECUBE SIGNAL

Last update for the starting track analysis

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Index</th>
<th>Normalization @ 100 TeV</th>
<th>Significance (σ)</th>
<th>Energy range</th>
</tr>
</thead>
<tbody>
<tr>
<td>HESS 6 yr</td>
<td>2.92 ± 0.3</td>
<td>2.46 ± 0.8</td>
<td>8</td>
<td>60 TeV to 3 PeV</td>
</tr>
<tr>
<td>Northern tracks 6 yr</td>
<td>2.19 ± 0.10</td>
<td>1.01 +0.26 -0.23</td>
<td>6.7</td>
<td>119 TeV to 4.8 PeV</td>
</tr>
<tr>
<td>Cascades 4 yr</td>
<td>2.48 ± 0.08</td>
<td>1.57 +0.23 -0.22</td>
<td>4.7 (2 year)</td>
<td>10 TeV to 1 PeV</td>
</tr>
<tr>
<td>Global fit</td>
<td>2.50 ± 0.09</td>
<td>2.2 ± 0.4</td>
<td></td>
<td>25 TeV to 2.8 PeV</td>
</tr>
</tbody>
</table>
THE ICECUBE SIGNAL

Last update for the starting track analysis

- Indication of a break in spectrum? (energy threshold different)
- Indication of galactic and extra-galactic components? (different hemispheres)
**Track events**

- All-sky / All-flavor neutrino search
  - Look for excess above a given $E_{th}$
  - 9 (7) yrs of data for tracks (cascades)

<table>
<thead>
<tr>
<th></th>
<th>Bkg expectation</th>
<th>Signal expectation</th>
<th>Nb events measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track</td>
<td>13+/-3</td>
<td>3</td>
<td>19</td>
</tr>
<tr>
<td>Shower</td>
<td>5+/-2</td>
<td>1.5</td>
<td>7</td>
</tr>
</tbody>
</table>

=> Small excess (not significant)

**Cascade events**
KM3NeT/ARCA is expected to observe the IC signal in less than 1 yr.

- Precise characterization (spectral shape, flavor composition, anisotropy)
- Excellent sensitivity in the galactic plane: identify gal/extra-gal components?
⇒ Energy density of neutrinos in the non-thermal Universe is the same or higher as that in Fermi gamma-rays.

⇒ Common sources? Fermi/LAT γ-ray flux dominated by AGN/blazars (~ 85%)
Blazar space correlation

(862 ‘2LAC’ blazars)

Contribution max of the 2LAC blazars < 27% (10 TeV - 2 PeV), assuming equal weighting among blazars and single power-law with $\gamma = -2.5$.

7% of neutrino signal assuming $\nu$ flux $\leftrightarrow$ $\gamma$-ray flux

(correlation with 2FHL: < few % of the IC flux)

GRB time/space correlation

Contribute no more than 1% of the observed diffuse flux

$\Phi_{\nu}(E_{\nu}) = \Phi_0 \times \begin{cases} 
\varepsilon_b^{-1} E_{\nu}^{-1}, & E_{\nu} \leq \varepsilon_b \\
E_{\nu}^{-2}, & \varepsilon_b < E_{\nu} \leq 10\varepsilon_b \\
E_{\nu}^{-4} (10\varepsilon_b)^2, & 10\varepsilon_b < E_{\nu}.
\end{cases}$

(1172 GRBs - benchmark parameters)

arXiv:1702.06868

Astrophysical Journal 835 (2017) 1
Blazar space correlation

(862 ‘2LAC’ blazars)

Contribution max of the 2LAC blazars < 27% (10 TeV - 2 PeV), assuming equal weighting among blazars and single power law \([\gamma = -2.5]\).

**BUT, neutrinos originate from a larger volume**

50% of blazars not identified

Sources transparent to high energy gamma rays may not have the target density to produce neutrinos (GRB?)

Hidden sources? How to identify these sources ?

Neutrino only, neutrino+X-ray ?

7% of neutrino signal assuming \(\nu\) flux \(\leftrightarrow\) \(\gamma\)-ray flux

(correlation with 2FHL: < few % of the IC flux)

(1172 GRBs - benchmark parameters)

*Astrophysical Journal 835 (2017) 1*
Analysis of correlation with template map derived from interstellar gas distribution reproducing Fermi-LAT data Models in Gaggero et al, arXiv:1504.00227

Only small fraction of signal can originate from CR interactions in the Galaxy. UL for IC and ANTARES 1.2 x KRA-γ (50 PeV)

ANTARES arXiv:1602.03036 updated at this conference
Where are the PeV \(\gamma\)-rays together with PeV neutrinos?
IC NEUTRINO SKYMAP

Resolution for $\nu_e$

ANTARES

KM3NeT
LOOKING FOR POINT-SOURCES

IceCube (7 yrs - tracks)

ANTARES

All flavour

ANTARES+IceCube

Limits and sensitivities for $\gamma = 2.0$

- IC+ANTARES
- IC+ANTARES limits
- IC 40+59+79
- IC limits
- ANTARES
- ANTARES limits

Preliminary
KM3NeT/ARCA is expected to have more than one order of magnitude better sensitivity than IC in the Southern sky.

- Due to the quite good angular resolution for cascade events, the point-source search is also very efficient.

- Expected better performances for the transient neutrino sources (GRB, AGN...)

### KM3NeT: POINT-SOURCE

#### Generic source

![Graph showing sensitivity comparison](image)

<table>
<thead>
<tr>
<th>Source</th>
<th>Sensitivity, Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceCube</td>
<td>7 years</td>
</tr>
<tr>
<td>KM3NeT/ARCA</td>
<td>6 years</td>
</tr>
<tr>
<td>Antares</td>
<td>9 years</td>
</tr>
</tbody>
</table>

| KM3NeT preliminary                 |

<table>
<thead>
<tr>
<th>Source</th>
<th>Sensitivity, Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>KM3NeT/ARCA</td>
<td>6 years</td>
</tr>
<tr>
<td>IceCube</td>
<td>7 years</td>
</tr>
</tbody>
</table>

![Graph showing 5σ discovery flux](image)

<table>
<thead>
<tr>
<th>Source</th>
<th>Flux [GeV cm² s⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity flux (showers)</td>
<td></td>
</tr>
<tr>
<td>5σ discovery flux (showers)</td>
<td></td>
</tr>
<tr>
<td>Sensitivity flux (tracks)</td>
<td></td>
</tr>
<tr>
<td>5σ discovery flux (tracks)</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing sensitivity](image)
KM3NeT: POINT-SOURCE

Specific galactic sources

<table>
<thead>
<tr>
<th>Source</th>
<th>δ</th>
<th>extension</th>
<th>$\Phi_0$</th>
<th>$\Gamma$</th>
<th>$E_{\text{cut}}$</th>
<th>$\beta$</th>
<th>γ-ray data</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX J1713.7-3946 (1)</td>
<td>-39.77°</td>
<td>0.6°</td>
<td>1.68</td>
<td>1.72</td>
<td>2.1</td>
<td>0.5</td>
<td>13</td>
</tr>
<tr>
<td>RX J1713.7-3946 (2)</td>
<td>-39.77°</td>
<td>0.6°</td>
<td>0.89</td>
<td>2.06</td>
<td>8.04</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>Vela X</td>
<td>-45.6°</td>
<td>0.8°</td>
<td>0.72</td>
<td>1.36</td>
<td>7</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Vela Jr</td>
<td>-46.36°</td>
<td>1°</td>
<td>1.30</td>
<td>1.87</td>
<td>4.5</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td>HESSJ1614-518 (1)</td>
<td>-51.82°</td>
<td>0.42°</td>
<td>0.26</td>
<td>2.42</td>
<td>-</td>
<td>-</td>
<td>17</td>
</tr>
<tr>
<td>HESSJ1614-518 (2)</td>
<td>-51.82°</td>
<td>0.42°</td>
<td>0.51</td>
<td>2</td>
<td>3.71</td>
<td>0.5</td>
<td>17</td>
</tr>
<tr>
<td>Galactic Centre</td>
<td>-28.87°</td>
<td>0.45°</td>
<td>0.25</td>
<td>2.3</td>
<td>85.53</td>
<td>0.5</td>
<td>18</td>
</tr>
<tr>
<td>MGRO J1908+06 (1)</td>
<td>6.27°</td>
<td>0.34°</td>
<td>0.18</td>
<td>2</td>
<td>17.7</td>
<td>0.5</td>
<td>see text</td>
</tr>
<tr>
<td>MGRO J1908+06 (2)</td>
<td>6.27°</td>
<td>0.34°</td>
<td>0.16</td>
<td>2</td>
<td>177</td>
<td>0.5</td>
<td>see text</td>
</tr>
<tr>
<td>MGRO J1908+06 (3)</td>
<td>6.27°</td>
<td>0.34°</td>
<td>0.16</td>
<td>2</td>
<td>472</td>
<td>0.5</td>
<td>see text</td>
</tr>
</tbody>
</table>

$\gamma \to \nu$ flux conversion:


With reasonable 100% hadronic models, large probabilities to observe individual neutrino sources in the Galactic Plane
LOOKING FOR VARIABLE SOURCES

- No correlation with GRB, FRB
- Few hints with blazars (nothing significant)
- One hint with SN Ic (IC160427)

Connection $\nu$-$\gamma$-UHECR

Resconi et al 2017, 2.9 sigma correlation with sub-sample of HBLs, IC nu and Auger UHECR
KM3NeT MULTI-MESSENGER PROGRAMS

- Follow-up of neutrino alerts
- Joint sub-threshold analysis

Follow-up of EM/GW alerts
Offline time/space correlation search with catalogues (GRB, AGN, XRB, SN, FRB…)

CTA  LSST  HAWC  LIGO/VIRGO  SKA  SVOM  TAROT
IC170922 / TXS 0506+056?

- Event occurred at 22\textsuperscript{nd} Sept 2017 at 20:54:30 UTC
  - \textit{ATel 10791 - Fermi - increased gamma-ray activity of TXS 0506+056 (3FGL J0509.4+0541)}
  
- \textit{ATel 10817 – The First-time detection of VHE gamma rays by MAGIC}

  MAGIC observed this source under good weather conditions for 12 h of observations from September 28th till October 3rd. ...and a 5 sigma detection above 100 GeV was achieved!

  The first time measurement of VHE gamma-ray from a direction consistent with a detected neutrino event

- \textit{Distance to TXS 0506+056?}

Paiano et al. (2018): the 10.4m Gran Telescopio Canarias, an optical spectroscopy \( \Rightarrow z = 0.3365 +/- 0.0010 \)
For AGN, very few groups are developing lepto-hadronic models:
⇒ Produce very high energy neutrinos >1 PeV

**3C279**


*Richter, Spanier, arXiv:1802.08820*

**PKS 2155-304**


*+Winter et al, Böttcher et al., Petropoulou et al. , Zdziarski et al.,*

Is it possible to produce intermediate energy neutrinos [1-50 TeV] ?

In which condition ? Correlation with 100 MeV - 10 GeV or 100 GeV - 10 TeV γ-rays ?
For this special event, very different computations. Need to be ready for the next interesting events

Standard GRBs seem to not be efficient neutrino producers. Do we still have a chance to detect individual GRB? Which parameters?
To improve discovery potential, need to know where/when to look for neutrino association: correlation with TeV γ-ray?, GeV γ-ray?, X-ray? Radio flares?

For galactic sources, the sensitivities of future telescopes (ARCA/Gen-2) are closed to the model predictions, need also more sophisticated models (lepto-hadronic, better implementation of microphysics).

We have few hints that transient/variable sources could brighter HE neutrino sources (blazars, SN...), need to have time-dependent hadronic models (arXiv:1410.5380)

Most of the neutrino predictions are at very high or ultra high energies, need models for intermediate energy range [50 GeV - 50 TeV]

One strength of IceCube is that theoreticians are part of the collaboration. This interaction is quite weak in our collaboration.

[It is free to be observator in the KM3NeT Collaboration]
Summary

Multi-messenger astronomy era! (GW + neutrino)

- Diffuse flux of cosmic neutrinos observed by IceCube
- Higher level of hadronic activity in the non-thermal universe than previously thought
- Sources remain to be identified. Hints are pointing in MM analyses. We are quite closed!

Exciting times ahead!

⇒ KM3NeT: phased approach to next-generation neutrino telescope
   - ARCA (KM3NeT-It) for HE neutrino astronomy (tracks & showers)
   - ORCA (KM3NeT-Fr) for measurement of neutrino mass hierarchy
     → First strings performing well !!!

- Start to implement the multi-messenger programs in KM3NeT for both ORCA and ARCA based on the successful experience of ANTARES.
- The follow-up of gravitational waves have worked very well and the community is organizing itself to get an even better follow-up of GW events. Neutrinos are a bit left in this structurant process. Need to think more in a multi-messenger manner rather than separated the messenger.
In France, 4 groups:
APC, CPPM, IPHC, Subatech
(+LAM, MIO observator)
~ 15 permanent physicians 50/50 between low and high energy activities

KM3NeT is a multi-purpose experiment, we have access to all ORCA/ARCA data.
➡ KM3NeT neutrino data are proprietary but become public after a latency of 2 years after the data taking (except neutrino alerts).
➡ It is free to be observator in the Collaboration [only sign paper with contributions, no shift]

On KM3NeT, we have the responsibilities for:

- **Neutrino oscillation group**: PMNS oscillation parameters, neutrino mass hierarchy, CP phase
- **Multi-messenger group**: time-dependent searches for GRB, AGN, FRB…, real-time alerts, MM analysis (GW, IC, UHECR…), MeV neutrino SNe
The IceCube-Gen2 facility

A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science.

Multi-component observatory:
- IceCube-Gen2 High-Energy Array
- Surface air shower detector
- Sub-surface radio detector
- PINGU

see also Tienlu Yuan’s presentation