Review of recent neutrino astronomy results

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Contents

- The multi-messenger strategy and the TXS 0506+056 observations
- Other results for point sources and diffuse searches
- Results on neutrino nature
- Future experiments
Cosmic ray sources

- accelerators (steady or variable) accelerating protons, nuclei, electrons and positrons to extreme energies
- The presence of neutrino is the smoking gun to trace matter in sources
Black holes are hungry devourers of matter that in part can be emitted under the form of jets of hot relativistic plasma departing from the region outside the horizon along the rotation axis.
The multi-messenger network

IceCube sends ~8 public alert/year of tracks with energy $> 10^{14}$ eV since 04/2016 with median latency of 30 s. Around 3 have probability of being of cosmic origin $> 50\%$ (depends on assumed cosmic spectrum).
**IC-170922A**

23.7$\pm$2.8 TeV muon energy loss in the detector, 15 arcmin error (50% containment)

Signalness: 56.5%

Most probable neutrino energy $\sim$290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV) for a spectral index of -2.13 (-2).

https://gcn.gsfc.nasa.gov/NOTICES_AMON/50579430_130033.AMON
The gamma-ray partner observations

Shortly after, Fermi-LAT (20 MeV-300 GeV) detected a blazar in a high state at 0.06° from IceCube event (ATel#10791). MAGIC followed up and the blazar was observed at > 100 GeV energies with >6.2σ (ATel#10817, Ahnen, M. L., et al., ApJL 2018), later confirmed by VERITAS (Abeysekara et al, ApJL, 2018). The probability that this coincidence happens by chance is excluded at 3σ level.
How Likely is it a Chance Probability?

**Step I:** Draw a random neutrino from a representative Monte-Carlo sample of high-energy muon-track events (EHE, 10 public alerts and 41 archival events)

**Step II:** Are there any extra-galactic Fermi sources close in space to the neutrinos?

**Step III:** What is the gamma-ray energy flux in the time bin when the neutrino arrives?

Post-trial p-value $3\sigma$

Anna Franckowiack et al., TeVPA 2018
Spectral energy distribution of TXS 0506+056

How to reconcile the TXS 0506+056 observation with general consensus that BL Lac objects are inefficient neutrino emitters (Murase et al. 2014), due to the relatively low density of UV to soft X-ray synchrotron photons expected inside the jet?

Use observed neutrino luminosity and limits on observed UV/X-ray flux of $F_x \sim 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1}$ for TXS 0506+056 to constrain the target photon luminosity and required proton power.
Source confusion

Analysis is based on the VOU-Blazar tool developed by the United Nations Open Universe initiative [http://www.openuniverse.asi.it/]

- **Input data combines 28 radio and X-ray catalogs, as well as additional data points from Swift observations following IceCube-170922A**

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**2WHSP J050833.3+05310**
- HBL source
- Only 2 sigma gamma-ray detection between MJD 55900 - 56300

**PKS 0502+049**
- LBL/FSRQ source
- $z = 0.3366$

**TXS 0506+056**
- IBL/HBL source
- $z = 0.3365 \pm 0.0010$
- Top 4% brightest X-ray objects in Fermi 3LAC
- Radio: 1Jy at 6cm, 537mJy at 20cm, Top 0.3% in NVSS

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**Theo Glauch**
TeVPA Berlin, August 2018

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Padovani et al
MNRAS 480 (2018) 192
Solving the confusion: electromagnetic - neutrino flares

Analysis of 9.5 yr in 6 independent periods. An excess of 13 muon neutrino events in a period of ~5 months (2014-2015) in sample of 3yr is inconsistent with atmospheric neutrino origin at 3.5σ CL correcting for lifetime of IC86b: 9.5/3.

6 independent analyses periods

Best fit parameters of two flares:

<table>
<thead>
<tr>
<th>2012-2015 period</th>
<th>Gaussian PDF</th>
<th>Box PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>ns</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>2.1</td>
<td>2.2</td>
</tr>
<tr>
<td>Width</td>
<td>110 days</td>
<td>158 days</td>
</tr>
<tr>
<td>Time</td>
<td>2014-12-26</td>
<td>2014-12-13</td>
</tr>
<tr>
<td>Significance</td>
<td>3 x 10^{-5}</td>
<td>7 x 10^{-5}</td>
</tr>
</tbody>
</table>

DOI:10.1126/science.aat1378

A. Christov TeVPA 2016
The bright 2017/18 gamma-ray flare shows fast variability on ~daily timescale, suggesting a compact emission region.

During 2014/15 neutrino flare no significant gamma-ray flaring activity or spectral change have been observed.
ν-γ time correlation analysis at higher energy

Selection of high energies maybe the key.

The light curve of TXS 0506+056 shows a large flux/soft spectrum state during the EHE event and an indication (at 2σ level) for a small flux/hard spectrum state during the ν - flare.

Padovani et al
MNRAS 480 (2018) 192
ν-γ time correlation analysis: MAGIC followup

41 hrs 24/9-2/11 Energy spectrum up to 400 GeV with spectral index between -3.5 ÷ -4
Two flares around Oct 3-4 and Oct 31, 2017.

E. Bernardini TeV PA 2018
AGN unified model

(a) The central engine is a supermassive black hole surrounded by an accretion disc with jets emerging perpendicular to the accretion disc.
(b) The engine is surrounded by an obscuring torus of gas and dust. The broad-line region (BLR) occupies the hole in the middle of the torus and the narrow-line region lies further out.
(c) The entire AGN appears as a bright nucleus in an otherwise normal galaxy. The jets extend to beyond the host galaxy and terminate in radio lobes.

- Plasma of leptons (e+/−) distributed in a one-zone homogeneous spherical emitting region.
- Accelerated electrons interact with the B-field, and emit synchrotron radiation.
- Self Compton model (SSC, Jones et al 1974): synchrotron photons produced by these relativistic electrons seed photons for the Inverse Compton (IC).
- External Radiation Compton (EC, Sikora et al. 1994): UV photons generated by the accretion disk are reflected toward the jet by the Broad Line Region (BLR) and seed IC.

Photopion production threshold: 
\[ E_{\text{thr}} = \frac{m_p m_\pi c^4}{2 E_{\text{ph}}} \left(1 + \frac{m_\pi}{2 m_p}\right) \sim 10^{17} \text{ eV} \ E_{t,\text{eV}^{-1}} \]

The photon field energy

\[ E_{V} \sim \frac{1}{3} \left( m_p - m_\mu - m_e \right) c^2 \sim 10^7 \text{ eV} \quad \text{(in p rest frame - at threshold in CM frame)} \]

\[ E_{V}' = E_{V}/\delta \sim 10^7 \gamma_p \text{ eV} \quad \text{(in emission-region rest frame)} \]

To produce IceCube neutrinos \( \sim 100 \text{ TeV} \) → \( \gamma' P \sim \gamma'_e \sim \gamma' \pi \sim 10^6 E_{14} \delta_{1}^{-1} \equiv \gamma_6 \)

need protons with \( E'_p \sim 10^{15} E_{14} \delta_{1}^{-1} \text{ eV} \) (emission region rest frame, not UHECRs!)

and target photons with \( E'_t \sim 170 E_{14}^{-1} \delta_{1} \text{ eV} \) (X-rays!)

Associated to this
- Proton synchrotron at \( f_{p,sy} \sim 2 \times 10^{18} g_{6}^2 B_{2} d_{1} \text{ Hz} \quad \sim 10 \text{ keV} \)
- Secondary electron synchrotron at \( f_{esy} \sim 4 \times 10^{21} g_{6}^2 B_{2} d_{1} \text{ Hz} \quad \sim 20 \text{ MeV} \)

Protons producing IceCube neutrinos do not produce \( > 300 \text{ MeV} \) gamma-rays from proton or secondary electron synchrotron!

Gamma-rays from:
- \( \pi^0 \) decay \( \sim 700 \text{ TeV} \)
- IC: \( \sim 5 \text{ TeV} \) with intense IR-optical target photon field with \( u'_{\text{ph}} >> u'_{B} \sim 400 B_{2}^2 \text{ erg/cm}^3 \)
Origin of target photon field

(At least) two possible scenarios:

a) Target photons co-moving with the emission region
=> $E_{t}^\text{obs} \sim 1.7 E_{14}^{-1} \delta_1^2/(1+z) \text{ keV}$
=> Observed as X-rays

b) Target photons stationary in the AGN frame
=> $E_{t}^\text{obs} \sim 17 E_{14}^{-1}/(1+z) \text{ eV}$
=> Observed as UV

Use observed neutrino luminosity and limits on observed UV/X-ray flux of $F_x \sim 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ for TXS 0506+056 to constrain the target photon luminosity and required proton power

=> Unrealistically large kinetic power;
Requires low B-field (< 1 G) to suppress p-synchrotron below X-ray flux limit of $F_x \sim 10^{-12} \text{ erg/(cm}^2 \text{ s)}$

=> p-sy suppressed below UV/X-ray limit for B ~10G. IceCube 170922A / TXS 0506+056
favours UV / soft X-ray target photon field external to the jet.

The source maybe opaque with few photons coming out and a flux mostly produced during propagation in EBL.

M. Boettcher, TeVPA2018
A dedicated time-integrated analysis for the region of TXS 0506+056 using 7 yr of data shows compatible results with the time dependent search. The a-posteriori significance of the 2015-2017 period is 2.1σ (4σ if the EHE event period is included) and the total fluence is $E^2 J_{100} = 2 \times 10^{-4}$ TeV cm$^{-2}$ at 100 TeV.

DOI:10.1126/science.aat1378
Diffuse flux observed by IceCube is composed of many individual sources. Their non-observation constrains source populations.

Implications of Point-Source limits

lower density ($\rho$) \implies higher luminosity ($L$) \implies brighter sources ($\phi$)

$20$ Murase & Waxman, 2016

TXS0506+056

excluded by non-observation of closest source in Northern Hemisphere

$E^2\phi_{PS} < 2 \times 10^{-12}$ TeV/cm$^2$/s

LL AGN

Starburst

Galaxy Clusters

FR-II

BL Lac

FSRQ

diffuse flux ($\zeta_\nu = 2.6$)

diffuse flux ($\zeta_\nu = 0.5$)

$\left[\text{MA & Halzen'18}\right]$

Murase & Waxman, 2016
Stacking neutrinos from Fermi blazars

3FHL catalog (3rd catalog of hard Fermi LAT sources) [Ajello et al 2017, Chang et al 2017]: 1301 blazars with $E > 10\text{GeV}$; 8 yr IceCube up-going muon neutrinos

Assumptions:
- all blazars are equally strong neutrino emitters
- all sources in a population follow a global spectral distribution

Previous result (ICRC2017): while blazars account for ~85% of the extragalactic gamma-ray background, IceCube neutrinos < 6% (but model dependent)

Post-trial 1.9$\sigma$
Energy in multi-messenger diffuse fluxes

L. Mohrmann, PhD thesis
Diffuse neutrino fluxes

- Knee
- Ankle
- Cosmogenic (GZK) neutrinos induced by the off-source (<50Mpc) interactions of cosmic-ray and CMB photons via GZK (Greisen-Zatsepin-Kuzmin) mechanism

\[ \text{Flux} \left[ \frac{(\text{GeV cm}^2 \text{ sec sr})^{-1}}{} \right] \]

\[ \text{Energy} \left[ \text{eV} \right] \]

Cosmogenic neutrinos

- Atmospheric
- Cosmic rays

\[ \Delta \]

Cosmic-ray photon

\[ \nu \]
Cosmogenic neutrinos

Limit for neutrino energy between $5 \times 10^6$ - $2 \times 10^{10}$ GeV

9 years of iceCube data
Strong constraints proton dominated UHECR sources
Mildly evolving models (e.g. star formation rate) disfavoured

https://doi.org/10.1103/PhysRevD.98.062003
The neutrino flavour of events

Track
Standard reconstruction; about x2 energy resolution
Angular resolution ~0.5° (0.3° for E > 100 TeV)

Cascade
10-15% energy resolution for E > 100 TeV
Angular resolution O(10°)

Tau neutrino double bang
Decay length ~ 50 m/PeV

amount of light \propto energy
The biggest events (HESE)

Science di Novembre 2013: discovery of first astrophysical neutrinos in 4 yrs of data.


A tau neutrino from oscillations in the cosmos?  

High probability to be a double bang event.  
Still to do: evaluation of p-value for not being of prompt origin

J. Stachurska, TeVPA2018
No significant clustering observed (82 events)

Arrival directions compatible with isotropy. => dominance of extragalactic sources?
Diffuse fluxes in IceCube

8 years of muon tracks

Preliminary: 102 High-Energy Starting Events (HESE) in 7.5 yr, 60 with $E_{\text{vis}}$$>$60 TeV

Background: 0.65±0.2 (atm.$\mu$), 14.5$^{+10.1}_{-8.1}$ (atm.$\nu$, incl. prompt)

Best Fit: -2.91 spectral index A, Schneider, TeVPA2018
μ → νμ disappearance probes high energy (TeV scale) neutrino cross-section
Current projects and experiments

ANTARES
Deep water
0.01 km$^3$
2008 – 2019

KM3NeT
Deep water
1 + 0.006 km$^3$
Construction

Baikal/GVD
Deep water
~1 km$^3$
Construction

IceCube
Deep ice
1 km$^3$
2011 –

IceCube-Gen2
Deep ice
~10 km$^3$
Projected, 1st phase imminent
The Future

update: arXiv:1607.02671

KM3NeT: The concept
- Deep-sea array of photodetectors
- 31 3''-PMTs in one digital optical module (DOM)
- 18 DOMs per string (Detection Unit, DU)
- 115 DUs per building block
- All data to shore

NSF initial funds just approved!

The Baikal GVD:
Final goal: 27 clusters, 1.5 km³
Neutrino oscillations

After 3 yr from upgrade with 7 compact strings, constraints on nutau normalisation are at 10% level.
CONCLUDING REMARK
Most of presented results are from IceCube Collaboration

http://icecube.wisc.edu

12 countries — 48 institutes — 300 scientists