Blazars as the Astrophysical Counterparts of the IceCube Neutrinos

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Introduction
– High energy (HE) vs. Very high energy (VHE) neutrinos
– Overview of IceCube results
– How are the VHE neutrinos produced?

BL Lacs as probable astrophysical counterparts of IceCube neutrinos:
– Emission from individual sources
– Emission from the BL Lac population
– Model predictions

Summary
High energy vs. Very high energy $\nu$
High energy vs. Very high energy ν

Underground detectors

Underwater(ice) Cherenkov light detectors

Neutrino energy

Cosmological ν
Solar ν
Supernova burst (1987A)
Reactors anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
v from AGN
Cosmogenic ν

Energy (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)

10⁻²⁴
10⁻²²
10⁻²⁰
10⁻¹⁸
10⁻¹⁶
10⁻₁⁴
10⁻₁²
10⁻¹⁰
10⁻⁸
10⁻⁶
μeV
10⁻³ meV
1 eV
10⁻³ keV
10⁻⁶ MeV
10⁻⁹ GeV
10⁻¹² TeV
10⁻¹⁵ PeV
10⁻¹⁸ EeV

ν from AGN

IceCube Laboratory

IceCube

Digital Optical Module (DOM)

IceCube detector

50 m
1450 m
2450 m

IceCube

25 strings of DOMs, 1728 m² detector area

360 DOMs per string

60 DOMs per DOM

Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility
Overview of IceCube results

ICECUBE PRELIMINARY (ICRC 2015)

Left: Very high energy neutrino spectrum. In 4 years of data: 54 events in the range 30 TeV – 2 PeV. Spectral slope of astrophysical flux: $\gamma=2.58$

Right: Arrival directions of the 54 very high energy events found in IceCube using 4 years of data (2010–2014). Not significant clustering found. Consistent with isotropy.
How are VHE $\nu$ produced?

Jets as $\nu$ sources

CR reservoirs as $\nu$ sources

\[ p\gamma \rightarrow N\pi + X \]

\[ p \ p \rightarrow N\pi + X \]

AGN

GRBs

Star forming galaxies

Galaxy groups/clusters

target gas

CR confinement

magnetized region w. CR sources

\[ CR\ e \]

\[ CR\ p \]

\[ target\ \gamma \]

\[ \pi^+ \]

\[ \mu^+ \]

\[ e^+ \]

\[ \nu_\mu \]

\[ \nu_e \]

\[ n \]

\[ p \]

\[ \rightarrow \]

\[ \rightarrow \]

\[ \rightarrow \]
Neutrinos from blazars in a nutshell

Neutrino emission due to propagation of escaping cosmic rays from blazars

Hadronic (Abdo et al. 2011)

Leptonic

Multi-wavelength blazar emission

Neutrino emission in the jets of blazars
1. Cuts applied to the sample of 35 events:
   - $E > 60$ TeV
   - median angular error < 20 deg

2. “Energetic” criterion: create “hybrid” $\gamma$-v SEDs

3. All-sky $\gamma$-ray catalogs (GeV-TeV): TeVCat, WHSP, Fermi 1FHL.

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Table 4. List of most probable counterparts of selected IceCube high-energy neutrinos.

<table>
<thead>
<tr>
<th>IceCube ID</th>
<th>Counterpart(s)</th>
<th>Class</th>
<th>Catalogue(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>MKN 421</td>
<td>BL Lac (HSP)</td>
<td>TeVCat/WHSP</td>
</tr>
<tr>
<td>10</td>
<td>IES 1011+496</td>
<td>BL Lac (HSP)</td>
<td>TeVCat/WHSP</td>
</tr>
<tr>
<td>14</td>
<td>HESS J1809−193</td>
<td>PWN</td>
<td>TeVCat</td>
</tr>
<tr>
<td>17</td>
<td>PG 1553+113</td>
<td>BL Lac (HSP)</td>
<td>TeVCat/WHSP</td>
</tr>
<tr>
<td>19</td>
<td>IRXS J054357.3−553206</td>
<td>BL Lac (HSP)</td>
<td>WHSP</td>
</tr>
<tr>
<td>20</td>
<td>SUMSS J014347−584550</td>
<td>BL Lac (HSP)</td>
<td>WHSP</td>
</tr>
<tr>
<td>22</td>
<td>IH 1914−194</td>
<td>BL Lac (HSP)</td>
<td>WHSP</td>
</tr>
<tr>
<td>27</td>
<td>PMN J0816−1311</td>
<td>BL Lac (HSP)</td>
<td>WHSP</td>
</tr>
<tr>
<td>33</td>
<td>MGRO J1908+06</td>
<td>PWN</td>
<td>TeVCat</td>
</tr>
</tbody>
</table>
Mrk 421: possible positive detection of neutrinos might be achievable with some confidence (~3σ level) using preliminary discovery potentials based on 6 years IceCube life time

PG 1553+113: model prediction is much below the 3σ error bars. Gamma-ray emission mostly from SSC

Neutrino emission from all BL Lacs

Monte-Carlo simulation for blazar population (Giommi & Padovani 2012, 2013, 2015):

- Radio luminosity function & evolution
- Distribution of synchrotron peak $v$ (Hz)
- Redshift
- Distribution of Doppler factor
- $\gamma$-ray constraints

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$$E_{\nu} F_{\nu}(E_{\nu}) = \int_{x_{\text{min}}}^{\infty} dx \frac{x^{-s} e^{-x}}{E_{\nu, p}} \left( \frac{E_{\nu}}{E_{\nu, p}} \right)^{-s+1} \exp \left( -\frac{E_{\nu}}{E_{\nu, p}} \right)$$

$$E_{\nu, p}(\delta, z, \nu_{\text{peak}}^S) \approx \frac{17.5 \text{ PeV}}{(1+z)^2} \left( \frac{\delta}{10} \right)^2 \left( \frac{\nu_{\text{peak}}^S}{10^{16} \text{ Hz}} \right)^{-1}$$

Neutrino emission from *all* BL Lacs

Top left: Redshift distribution of ~0.5% of BL Lacs that make 95% of the NBG at 1 PeV.

Bottom right: Results from individual simulations showing the scatter in Monte Carlo simulations

An “outlier” in the Monte Carlo simulation (a single bright source) mimics the neutrino emission from a point source!
Extragalactic backgrounds

- Another source population? (e.g. starburst galaxies: Lacki et al. 2014; Stecker 2007; galaxy clusters: talk by F. Zandanel)
- Another physical process? (e.g. pp collisions; Mannheim 1995, Ahlers et al. 2012)
- Contribution from individual BL Lacs? (e.g. Mrk 421)
- Galactic contribution? (e.g. Padovani & Resconi 2014)
**Predicted # of events**

<table>
<thead>
<tr>
<th></th>
<th>With Glashow resonance</th>
<th>Without Glashow resonance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Y=0.8, Eγ=200GeV, ΔΓ=0.5</strong></td>
<td>7 (2-10 PeV)</td>
<td>4.6 (2-10 PeV)</td>
</tr>
<tr>
<td></td>
<td>9-10 (2-100PeV)</td>
<td>6.6-7.6 (2-100 PeV)</td>
</tr>
<tr>
<td><strong>Y=0.8, Eγ=100GeV, ΔΓ=1.0</strong></td>
<td>~6 (2-10 PeV)</td>
<td>4 (2-10 PeV)</td>
</tr>
<tr>
<td></td>
<td>~8-9 (2-100PeV)</td>
<td>6-7 (2-100PeV)</td>
</tr>
<tr>
<td><strong>Y=0.3, Eγ=200GeV, ΔΓ=0.5</strong></td>
<td>2.6 (2-10 PeV)</td>
<td>1.7 (2-10 PeV)</td>
</tr>
<tr>
<td></td>
<td>~4 (2-100PeV)</td>
<td>~3 (2-100PeV)</td>
</tr>
</tbody>
</table>

6.6 is the $3\sigma$ upper limit for 0 events (Gehrels 1985)

Using the effective areas from IceCube (2013) in the range 2-10 PeV and extrapolating for the energy range 10-100 PeV.
Neutrino emission from individual BL Lacs:
– successful leptohadronic fits to the Spectral Energy Distribution (SED) of 6 sources (with different $z$, SEDs etc)!
– Mrk 421 ($z=0.031$) and 1H 1914-194 ($z=0.137$) potential point sources of neutrinos
– the ratio $Y$ of the $\nu$ luminosity to the $\gamma$-ray (>10 GeV) luminosity is a measure of the hadronic “contamination” to the blazar SED

Neutrino emission from all BL Lacs:
– the NBG from BL Lacs explains the 1-2 PeV flux but requires another population for the sub-PeV neutrino flux
– only 0.5% of all BL Lacs is responsible for 95% of the NBG at 1 PeV
– only 11% of 0.5% of all BL Lacs would be detectable by the 3FGL Fermi catalog
– future non-detections above 2~PeV may be used to constrain the average $Y$ value of BL Lacs
Back-up slides
Model comparison

![Graph showing model comparison with data from IceCube.](image-url)
The case of Mrk 421: SED & ν


Dimitrakoudis et al., 2014, Aph, 54

The case of Mrk 421: Cosmic-rays

\[ n \rightarrow p + e^- + \bar{\nu}_e \quad \text{Neutron decay} \]

\[ p + CMB \rightarrow \ldots \text{cosmogenic } \nu \]

\[ p + B \rightarrow \ldots \text{deflection} \]

(Propagation was made using CRPropa 2.0)
Example of a SED

Secondary electrons

Photons

Dimitrakoudis et al. 2012

\[ R = 3 \times 10^{16} \text{cm} \]
\[ B = 1 \text{G} \]
\[ E'_p = 2 \times 10^{15} \text{eV} \]
Hadronic models: processes in a nutshell

**Leptonic emission models**
- Synchrotron radiation
- Inverse Compton scattering
- Photon-photon absorption
- Synchrotron self-absorption

**Hadronic emission models**
- Proton-proton (pp) pion production
- Bethe-Heitler pair production
- Proton-photon pion production
- Neutron-photon pion production
- Neutral pion decay into γ-rays
- Charged pion decay into muons
- Muon decay into pairs
- Neutrino production
- Proton (+pion, muon) synchrotron radiation

Courtesy of J.R. Protheroe
An introductory slide

How does IceCube work?
When a neutrino interacts with the Antarctic ice, it creates other particles. In this event graphic, a muon was created that traveled through the detector almost at the speed of light. The pattern and the amount of light recorded by the IceCube sensors indicate the particle’s direction and energy.

Each DOM is shown by a white dot
Color indicates arrival time:
red first, green last

Colored spheres show sensors have detected light
Size scales with the amount of recorded light

date: November 12, 2010 duration: 3,800 nanoseconds energy: 71.4 TeV
declination: -0.4° right ascension: 110° nickname: Dr. Strangepork

https://www.youtube.com/watch?v=3PZgfPHULHw
Overview of IceCube results

Left: Very high energy neutrino spectrum. In 3 years of data: 37 events in the range 30 TeV – 2 PeV. Spectral slope of astrophysical flux: $\gamma=2.3$

(PRELIMINARY: in 4-year data 54 events; Spectral slope of astrophysical flux: $\gamma=2.58$)

Right: Arrival directions of the 37 very high energy events found in IceCube using 3 years of data (2010–2013). Not significant clustering found. Consistent with isotropy.

(The IceCube collaboration, 2014, Phys.Rev.Lett)