Blazars as sources of high-energy neutrinos

Maria Petropoulou
Lyman J. Spitzer Postdoctoral Fellow
Department of Astrophysical Sciences, Princeton University, USA

Torino, 14.06.2018
Neutrinos (ν) as astrophysical probes
The $\nu$ energy spectrum

- ~54 events with $E_\nu \sim 30$ TeV – 2 PeV
- Background-only hypothesis rejected at ~8σ
- Spectrum still compatible with single power-law
- No significant clustering of events on the sky
A zoo of astrophysical ν sources

AGN jets
blazars
GRBs
microquasars
Supernovae/Hypernovae
γ-ray novae
Star-forming galaxies
Magnetars
(AGN jets)
(Supernovae/Hypernovae)
(Magnetars)
(γ-ray novae)
(Star-forming galaxies)
(Microquasars)

(e.g. Guetta+2002, Torres+2005)
(e.g. Murase+2011, Zirakashvili & Ptuskin 2016, Petropoulou+2017)
(e.g. Fang & Metzger 2017)
(e.g. Metzger+2015)

(e.g. Loeb & Waxman 2006, Tamborra+2014, Bechtol+2017)
(e.g. Waxman & Bahcall 1999, Murase 2008, Hummer+2012, Petropoulou+2014)

(recent review by Ahlers & Halzen 2015)
Can the physical processes in jets support the observed neutrino fluxes?
Modeling of $\nu$ and photon emission

- Synchrotron radiation
- Inverse Compton scattering
  - Pair production
  - Pair annihilation
  ...

Leptonic models

- Synchrotron radiation
- Inverse Compton scattering
  - Pair production
  - Pair annihilation
- Photomeson production
- Photopair production
  ...

Leptohadronic models

Abdo et al. 2011


Boettcher+2013

3C273
Numerical approach

PROTONS
\[ \frac{\partial n_p}{\partial t} + \frac{n_p}{t_{p,\text{esc}}} = L_p^{\text{BH}} + L_p^{\text{photopion}} + L_p^{\text{syn}} = Q_p^{\text{inj}} + Q_p^{\text{photopion}} \]

NEUTRINOS
\[ \frac{\partial n_\nu}{\partial t} + \frac{n_\nu}{t_{\nu,\text{esc}}} = Q_\nu^{\text{photopion}} \]

ELECTRONS
\[ \frac{\partial n_e}{\partial t} + \frac{n_e}{t_{e,\text{esc}}} = L_e^{\text{IC}} + L_e^{\text{syn}} + L_e^{\text{ann}} + L_e^{\text{tpp}} = Q_e^{\text{inj}} + Q_e^{\text{BH}} + Q_e^{\text{IC}} + Q_e^{\text{YY}} + Q_e^{\text{photopion}} + Q_e^{\text{tpp}} \]

PHOTONS
\[ \frac{\partial n_\gamma}{\partial t} + \frac{n_\gamma}{t_{\gamma,\text{esc}}} = L_\gamma^{\text{IC}} + L_\gamma^{\text{ssa}} + L_\gamma^{\text{YY}} = Q_\gamma^{\text{syn}} + Q_\gamma^{\text{psyn}} + Q_\gamma^{\text{msyn}} + Q_\gamma^{\text{IC}} + Q_\gamma^{\text{ann}} + Q_\gamma^{\text{photopion}} + Q_\gamma^{\text{ext}} \]

NEUTRONS
\[ \frac{\partial n_n}{\partial t} + \frac{n_n}{t_{n,\text{esc}}} = L_n^{\text{photopion}} = Q_n^{\text{photopion}} \]

\(\mu, \pi, K\) synchrotron & decay

SHORT-LIVED MESONS

(Dimitrakoudis+2012)
Self-consistent $\nu$ fluxes

Photon flux matched to the data

Measured neutrino flux

Predicted neutrino flux

Log $(\nu F_\nu)$ [erg cm$^{-2}$ s$^{-1}$]

Log$(\nu)$ [Hz]

(Petropoulou+2015)
Ratio of $\nu$ to $\gamma$-ray luminosities

Data do not always allow for solutions with $L_\nu \sim L_\gamma$
Self-consistent $\nu$ fluxes

Mrk 421

H 1914-194

H 2356-309

1ES 1011+496

PG 1553+113

RXS J054357.3-553206

Neutrino fluxes

(Petropoulou + 2015)
Constraints on single sources

Constraints for Mrk 421:

- $Y_{\nu\gamma} < 0.5$
- Neutrino flux $< 2 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$
- Power in relativistic protons $< 5 \times 10^{47}$ erg s$^{-1}$

The $\nu$ flux is assumed to be constant over time.

$Y_{\nu\gamma} \leq 0.47$
Diffuse $\nu$ emission from BL Lacs

$$E_\nu F_\nu(E_\nu) = \int_{x_{\text{min}}}^{\infty} dx \frac{x^{-s} e^{-x}}{F_\gamma(> 10 \text{ GeV})} \left( \frac{E_\nu}{E_{\nu,p}} \right)^{-s+1} \exp\left( -\frac{E_\nu}{E_{\nu,p}} \right)$$

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

$$Y_{\nu\gamma} = 0.8$$

$$(\text{Padovani, PM+2015})$$
What did we learn so far?

- **Most blazar models** predict **hard spectra** with a cutoff that depends on the maximum energy of the accelerated protons.

- **Most blazar jet models** cannot explain the IceCube ν flux at <100 TeV.

- The normalization of the neutrino spectra depends **linearly** on the proton luminosity, which can be constrained by IceCube.

(Murase 2015, arXiv:1511.01590)
The role of blazar flares

Blazars are variable sources across the electromagnetic spectrum!

\( L_{\nu} \propto f_{p\gamma} L_p \propto L_{ph} L_p \epsilon_{ph} t_v \delta^4 \)

\( L_{\nu} \approx L_\gamma \)

Neutrino luminosity can increase during flares.

- If target photon luminosity increases, then:

- If \( \gamma \)-rays flare and have a pionic origin, then:

\( \sim \text{week} \)

Fossati et al. 2008

\( \gamma \text{-rays} \)

\( \text{X-rays} \)

\( \text{optical} \)

Date of 2001

March 19

March 20

March 21

March 22

March 23

March 24

11987

11988

11989

11990

11991

11992

[Graph showing data over time]
The “Big Bird” and PKS B1424-418 flare

Kadler+2016

- Big Bird is a HESE event with $E_\nu \sim 2$ PeV
- PKS B1424-418 is an FSRQ at $z=1.522$
- Association of the HESE event with the flare can be explained only if: $L_\nu \approx L_\gamma$
SED modeling of flares is crucial

Gao+2017

- Modeling of the PKS B1424-418 flare.
- The SED cannot be explained for parameters that lead to: $L_v \approx L_\gamma$

Cascades initiated by the absorption of high-energy photons, redistributes their power to lower energies (e.g., X-rays).

Cascades should not be neglected in the hadronic modeling of luminous flares.

Petropoulou+2017

PKS B1424-418

3C 279
IC170922A & TXS 0506+056

- Swift observations (Keivani+): GCN #21930, Atel #10942 (26/09/17)

- NuSTAR observations (Fox+): Atel #10861 (12/10/17)

- Swift detected initially several sources among them the blazar TXS 0506+056

- Fermi reported that TXS 0506+056 was in a flaring state: Atel #10781

- IC170922A is a track with $E_\gamma \sim 300$ TeV (ang.res. < 1deg)

- AMON circulated GCN ~43 s after its detection
Modeling of the TXS 0506+056 flare

Leptonic model with a sub-dominant hadronic component

Keivani, Murase, Petropoulou, Fox+, 2018, sub.

- Analysis of Swift/UVOT, X-SHOOTER, Swift/XRT, NuSTAR, Fermi-LAT data.

- UVOT + X-SHOOTER show that \( \nu_{pk} < 10^{14} \) Hz (ISP).

- External Compton explains \( \gamma \)-rays.

- SSC contribution to NuSTAR band.

- Hadronic cascade should not exceed X-ray data. \( \rightarrow \) Upper limits on \( \nu \) and baryon loading
Modeling of the TXS 0506+056 flare

Leptonic model with a sub-dominant hadronic component

Keivani, Murase, Petropoulou, Fox+, 2018, sub.

- Upper limits on $\nu$ fluxes for many model parameters.

- $\sim 0.01$ events for a flare $T=10^7$ s or $\sim 1\%$ probability to see 1 event.

<table>
<thead>
<tr>
<th>Model Variant</th>
<th>$F_{\nu}^{UL}$ [erg cm$^{-2}$ s$^{-1}$]</th>
<th>$N_{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMBB1a</td>
<td>$1.6 \times 10^{-14}$</td>
<td>$\leq 10$ PeV</td>
</tr>
<tr>
<td>LMBB1b</td>
<td>$5.2 \times 10^{-14}$</td>
<td>$1 \times 10^{-3}$</td>
</tr>
<tr>
<td>LMBB1c</td>
<td>$9.1 \times 10^{-14}$</td>
<td>$4 \times 10^{-3}$</td>
</tr>
<tr>
<td>LMBB2a</td>
<td>$4.5 \times 10^{-14}$</td>
<td>$6 \times 10^{-3}$</td>
</tr>
<tr>
<td>LMBB2b</td>
<td>$1.8 \times 10^{-13}$</td>
<td>$3 \times 10^{-3}$</td>
</tr>
<tr>
<td>LMBB2c</td>
<td>$2.5 \times 10^{-14}$</td>
<td>$8 \times 10^{-3}$</td>
</tr>
<tr>
<td>LMPL1a</td>
<td>$3.1 \times 10^{-14}$</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>LMPL1b</td>
<td>$9 \times 10^{-14}$</td>
<td>$1 \times 10^{-3}$</td>
</tr>
<tr>
<td>LMPL2a</td>
<td>$2.5 \times 10^{-13}$</td>
<td>$1 \times 10^{-3}$</td>
</tr>
<tr>
<td>LMPL2b</td>
<td>$1.2 \times 10^{-12}$</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td>HM3</td>
<td>$1.6 \times 10^{-16}$</td>
<td>$1 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Neutrino fluxes for different model variants
Modeling of the TXS 0506+056 flare

Leptohadronic model

Keivani, Murase, Petropoulou, Fox+, 2018, sub.

- Model with γ-rays coming from pion-induced cascade (L_γ – L_ν) is ruled out.
- Model with γ-rays from proton synchrotron leads to EeV neutrinos with very low luminosities.
- IC-170922A cannot be explained in this scenario.
The revival of the hadronic cascade model

Gamma-ray & neutrino flare from hadronic cascades

( Bednarek & Protheroe 1999)

( Khiali+2015)

Mastichiadis & Petropoulou, in prep.
Summary

- It is unlikely that blazars are the dominant contributors to the IceCube neutrino flux.

- IceCube places strong constraints on many blazar models for neutrinos. Still, these are derived assuming constant neutrino fluxes.

- Neutrino emission can be enhanced during blazar flares. A flaring blazar could be detected as a neutrino point source.

- Multi-wavelength data during flares is crucial to constrain emission models.

- 1-zone SED modeling of blazar flares shows that the naive expectation $L_\nu \sim L_\gamma$ is almost always ruled out.

- If the association of IC 170922A and TXS 0506+056 is physical, then we should start thinking beyond the 1-zone models.

THANK YOU!
Back-up slides
High-energy ν observations

- \(\sim 10^3\) astrophysical neutrinos
- Spectrum compatible with single power-law.
- No correlation of events \([E_\nu > 200\ \text{TeV}]\) with astrophysical sources

(I_CRC 2017) arXiv:1710.01191
Blazars as probable counterparts

* Catalogs used: PR 2014
  - TeVCat (VHE detected)
  - 1WHSP (~1000 VHE candidates)
  - 1FHL (>10 GeV)
  * Cuts applied to the sample of 35 events:
    - E >60 TeV
    - median angular error < 20 deg
  * “Energetic” criterion

* Catalogs used: Padovani+2016
  - 3LAC (>100 MeV)
  - 2WHSP (~1700 VHE candidates)
  - 2FHL (>50 GeV)
  * Cuts applied to the sample of 51 events:
    - E >60 TeV
    - median angular error < 20 deg
  * “Energetic” criterion

![Graphs showing data points and criteria for blazar counterparts](image)
Neutrino production in blazars

Photomeson production

Typical neutrino energies

\[ E_\nu \approx 0.05 \, E_p \geq 90 \, \text{PeV} \Gamma_1^2 \left( \varepsilon_s / 10 \, \text{eV} \right)^{-1} \]

\[ E_\nu \approx 0.05 \, E_p \geq 0.9 \, \text{PeV} \left( \varepsilon_{BLR} / 10 \, \text{eV} \right)^{-1} \]
Neutrino production in blazars

Neutrino spectrum depends on:

- Density of target photons & size of the source
- Spectrum of target photons

Photomeson production efficiency

Jet photons:

\[ f_{py} \propto \frac{L_{ph}}{\varepsilon_{ph} R \delta^3} \propto \frac{L_{ph}}{\varepsilon_{ph} t_v \delta^4} \]

- Strong dependence on the beaming.

BLR photons:

\[ f_{py} \propto \frac{L_{BLR}}{\varepsilon_{BLR} R_{BLR}} \]

- No dependence on the beaming.
X-ray/UVOT light curves of TXS 0506+056

Keivani, Murase, Petropoulou, Fox+, 2018, sub.
Unprecedented MW coverage & simultaneous observations for MJD 55265-55277 (data are adopted from *Aleksic et al. 2015*).

The 13-day flare of 2010

Petropoulou, Coenders & Dimitrakoudis, 2016, APh, 80, 115
The long term γ-ray activity

The 6.9 yr Fermi light curve (0.1-300 GeV) overlaps with the 5yr IceCube livetime

Latest published results
Major GeV flares

<table>
<thead>
<tr>
<th>No.</th>
<th>T (days)</th>
<th>$\nu_\mu + \bar{\nu}_\mu$</th>
<th>$P_{N_\nu \geq 1}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flares 1a+1b</td>
<td>105</td>
<td>0.61 ± 0.16</td>
<td>46 ± 8</td>
</tr>
<tr>
<td>Flare 2</td>
<td>70</td>
<td>0.32 ± 0.07</td>
<td>27 ± 5</td>
</tr>
<tr>
<td>Flare 3</td>
<td>98</td>
<td>0.26 ± 0.05</td>
<td>23 ± 4</td>
</tr>
<tr>
<td>Flares 4a+4b</td>
<td>112</td>
<td>0.26 ± 0.05</td>
<td>23 ± 4</td>
</tr>
<tr>
<td>$\Sigma$ Flares</td>
<td>385</td>
<td>1.46 ± 0.32</td>
<td>77 ± 7</td>
</tr>
</tbody>
</table>

Without GeV major flares

<table>
<thead>
<tr>
<th>Season</th>
<th>T (days)</th>
<th>$\nu_\mu + \bar{\nu}_\mu$</th>
<th>$P_{N_\nu \geq 1}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/2010-05/2011</td>
<td>364</td>
<td>0.43 ± 0.06</td>
<td>34 ± 4</td>
</tr>
<tr>
<td>06/2011-05/2012</td>
<td>364</td>
<td>0.38 ± 0.05</td>
<td>32 ± 3</td>
</tr>
<tr>
<td><strong>06/2012-05/2013</strong></td>
<td><strong>371</strong></td>
<td><strong>0.71 ± 0.11</strong></td>
<td><strong>51 ± 5</strong></td>
</tr>
<tr>
<td>06/2013-05/2014</td>
<td>364</td>
<td>0.70 ± 0.11</td>
<td>50 ± 5</td>
</tr>
<tr>
<td>06/2014-05/2015</td>
<td>350</td>
<td>0.47 ± 0.06</td>
<td>38 ± 4</td>
</tr>
<tr>
<td>$\Sigma$ w/o Flares</td>
<td><strong>1834</strong></td>
<td><strong>2.73 ± 0.38</strong></td>
<td><strong>94 ± 2</strong></td>
</tr>
<tr>
<td>$\Sigma$ w Flares</td>
<td><strong>1834</strong></td>
<td><strong>3.59 ± 0.60</strong></td>
<td><strong>97 ± 2</strong></td>
</tr>
</tbody>
</table>

* Similar probability for detecting at least 1 neutrino from the 2012 flare alone and the whole IC Season 3
* Still <50%