Multimessenger studies of blazars

Felicia Krauß, Matthias Kadler, Karl Mannheim, Joern Wilms
GRAPPA & API, UvA • Felicia.Krauss@uva.nl
1) Cosmic rays & IceCube neutrinos

2) Multimessenger astronomy & blazars

3) Results & current work
Blazar: FSRQ/BL Lac

$10^{-3} \text{ pc}$
The figure illustrates the spectral energy distribution (SED) of the source 1714-336, showing data points across different wavelengths, with annotations for various observatories and instruments. The peak of the Big Blue Bump and the synchrotron emission are highlighted, with questions on the leptonic (SSC, EC) and hadronic nature of the source. The frequency range spans from $10^9$ Hz to $10^{24}$ Hz, with corresponding values of $\nu F_\nu$ in $10^{-12}$ erg s$^{-1}$ cm$^{-2}$. The plot is attributed to Krauss F., Kadler M., et al., A&A, 2014, 556, L7.
The cosmic ray spectrum

after Hillas 2006
Which sources can accelerate particles to Ultra-High Energies and how?

How do we identify the sources of UHECR?
\[
p \gamma \pi^+ + n \rightarrow \mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_{\mu} + \nu_e + \nu_{\mu} + \nu_e
\]
Deposited EM-Equivalent Energy in Detector (TeV)

Events per 1347 Days

- Background Atmospheric Muon Flux
- Bkg. Atmospheric Neutrinos (π/K)
- Background Uncertainties
- Atmospheric Neutrinos (90% CL Charm Limit)
- Bkg.+Signal Best-Fit Astrophysical (best-fit slope $E^{-2.58}$)
- Bkg.+Signal Best-Fit Astrophysical (fixed slope $E^{-2}$)
- Data

IceCube Preliminary

Detection of high-energy photons is not proof for hadronic processes!

→ Upscattering of Synchrotron photons by relativistic electrons via Inverse Compton
Pion photoproduction and neutrinos

\[ p + \gamma \rightarrow \pi^+ + \pi^- + p + \mu^+ + \nu_\mu + \nu_e + e^- + \nu_\mu + e^- + \nu_e + \gamma + \pi_0 \]

\[
\begin{align*}
F_\nu &= \frac{2}{3} \cdot \frac{3}{4} F_\pi = \frac{1}{2} F_\pi \\
F_\gamma &= \frac{1}{3} F_\pi + \frac{1}{4} \cdot \frac{2}{3} F_\pi = \frac{1}{2} F_\pi \\
\text{BUT: } F_\gamma - \gamma \neq F_\nu
\end{align*}
\]

Mannheim 1993, 1995
Mücke 2000
HIGH ENERGY PHOTONS AS TRACERS OF NEUTRINO EMITTERS
HAS A NEUTRINO BEEN ASSOCIATED WITH A HIGH-ENERGY PHOTON EMITTER?
MAYBE!
RESULTS
Cumulative search: no significant counterparts (Glüsenkamp et al. 2016)

Contribution from Blazars & Pulsar Wind Nebulae (PWNe; Padovani et al. 2014)?

Blazars as a class capable of producing observed neutrino flux (Krauss et al. 2014);
Krauss et al. 2014
<table>
<thead>
<tr>
<th>Source</th>
<th>$F_\gamma$ (erg cm$^{-2}$ s$^{-1}$)</th>
<th>events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0235–618</td>
<td>$(1.0^{+0.5}_{-0.5}) \times 10^{-10}$</td>
<td>$0.19^{+0.04}_{-0.04}$</td>
</tr>
<tr>
<td>0302–623</td>
<td>$(3.4^{+0.7}_{-0.7}) \times 10^{-11}$</td>
<td>$0.06^{+0.01}_{-0.01}$</td>
</tr>
<tr>
<td>0308–611</td>
<td>$(7.5^{+2.9}_{-2.9}) \times 10^{-11}$</td>
<td>$0.14^{+0.05}_{-0.05}$</td>
</tr>
<tr>
<td>1653–329</td>
<td>$(4.5^{+0.5}_{-0.5}) \times 10^{-10}$</td>
<td>$0.86^{+0.10}_{-0.10}$</td>
</tr>
<tr>
<td>1714–336</td>
<td>$(2.4^{+0.5}_{-0.6}) \times 10^{-10}$</td>
<td>$0.46^{+0.10}_{-0.12}$</td>
</tr>
<tr>
<td>1759–396</td>
<td>$(1.2^{+0.3}_{-0.2}) \times 10^{-10}$</td>
<td>$0.23^{+0.50}_{-0.40}$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>1.9 ± 0.4</strong></td>
</tr>
</tbody>
</table>

Krauss et al. 2014
Blazars & AGN

Cumulative search: no significant counterparts (Glüsenkamp et al. 2016)

Contribution from Blazars & Pulsar Wind Nebulae (PWNe; Padovani et al. 2014)?

Blazars as a class capable of producing observed neutrino flux (Krauss et al. 2014; Krauss et al. 2015)
Blazars & AGN

Cumulative search: no significant counterparts (Glüsenkamp et al. 2016)

Contribution from Blazars & Pulsar Wind Nebulae (PWNe; Padovani et al. 2014)?

Blazars as a class capable of producing observed neutrino flux (Krauss et al. 2014; Krauss et al. 2015)

Constraints on neutrino spectrum (ANTARES&TANAMI collaborations 2015)
Blazars & AGN

Cumulative search: no significant counterparts (Glüsenkamp et al. 2016)

Contribution from Blazars & Pulsar Wind Nebulae (PWNe; Padovani et al. 2014)?

Blazars as a class capable of producing observed neutrino flux (Krauss et al. 2014; Krauss et al. 2015)

Constraints on neutrino spectrum (ANTARES&TANAMI collaborations 2015)

Coincidence of blazar outburst and high-energy neutrino event (Kadler, Krauss et al. 2016)
$F_{100 - 300000 \text{ MeV}} \left[ 10^{-6} \text{ cm}^{-2} \text{s}^{-1} \right]$ vs. MJD
Variability as indicator for association!
Conclusions

★ Association not expected for each HE neutrino

★ Connection between high-energy (not LAT!) flux and neutrino flux

★ Blazars & AGN are the most promising candidates

★ Currently extending study to 100 TeV

★ Track events are promising for direct association

★ Further blazar flares promising for ruling out/confirming blazar hypothesis
BACKUP
37 LAT photons

(after IceCube Collaboration 2014)

→ Only 1 photon associated with a resolved source, a blazar
Extragalactic origin consistent with isotropic distribution
 Galactic sources are not capable of producing PeV neutrinos


**Fermi Bubbles:** Crocker 2012, Lunardini & Razzaque 2012, Razzaque 2013, Lunardini et al. 2015
Extragalactic
- Gamma-ray Bursts
- Blazars
- Radio Galaxies
- Starburst Galaxies
- Fermi Bubbles
- Globular Cluster
- Novae
- LMC & SMC
- SNR & PWN
- $\gamma$-ray binaries
- Pulsars: Binaries & MSP

Galactic
- Solar Flares
- Terrestrial $\gamma$-ray flashes

Local
Gamma-ray Bursts (GRBs)

Gamma-ray Bursts (GRBs)
Starforming Galaxy

\[ \times \sim 300 \text{ TeV} \] (Loeb & Waxman 2006, Thompson et al. 2006, Tamborra et al. 2014)
Starforming Galaxies

* LAT evidence against star-forming galaxies as dominant source of IC neutrinos (Bechtol et al. 2016)
$\phi_\nu (100 \text{ TeV}) [10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}]$

Fermi upper bounds on direct & cascade $\gamma$-ray flux

- $\nu_\mu + \bar{\nu}_\mu$ 2yr
- MESE 2yr
- HESS 3yr
- combined fit

Bechtol et al. 2016
GRBs

- If large number of hypernovae vs. supernovae (Senno et al. 2016)
- Low flux of $\nu$ from GRBs (Becker 2010)
GRBs

- If large number of hypernovae vs. supernovae (Senno et al. 2016)
- Low flux of $\nu$ from GRBs (Becker 2010)
- No prompt neutrino event consistent with a known GRB (IceCube Collaboration 2015)
GRBs

- If large number of hypernovae vs. supernovae (Senno et al. 2016)
- Low flux of $\nu$ from GRBs (Becker 2010)
- No prompt neutrino event consistent with a known GRB (IceCube Collaboration 2015)
- Afterglow neutrinos possible at PeV-EeV but no detection (Razzaque 2013)
GRBs

- If large amount of hypernovae vs. supernovae (Senno et al. 2016)
- Low flux of $\nu$ from GRBs (Becker 2010)
- No prompt neutrino event consistent with a known GRB (IceCube Collaboration 2015)
- Afterglow neutrinos possible at PeV-EeV but no detection (Razzaque 2013)
GRBs

- Low flux of $\nu$ from GRBs (Becker 2010)
- No prompt neutrino event consistent with a known GRB (IceCube Collaboration 2015)
- Afterglow neutrinos possible at PeV-EeV but no detection (Razzaque 2013)
- But: choked jets and low luminosity GRBs (Senno et al. 2016)