Neutrino predictions for 3HSP J095507.9+355101, an extreme X-ray flaring blazar

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Blazars: AGN with jets viewed face-on

- ~10% of Active Galactic Nuclei (AGN) have relativistic jets.
- Blazars → jetted AGN viewed at small viewing angles.
- Blazar emission dominated by the jet due to Doppler beaming.

Credit: NASA, ESA, S. Baum and C. O’Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/ÅURA)

Credit: Chandra X-ray observatory

Urry & Padovani 1995
Multi-wavelength variable photon emitters

- Multi-wavelength emission.
- Double-humped photon spectra.
- Flux variability on multiple timescales (min to months).
- Flares across the EM spectrum (not always correlated)

Hayashida et al. 2012
Extreme blazars

Extreme synchrotron blazars:
- $h\nu_X > 1$ keV and $\Gamma_X < 2$

Extreme TeV blazars:
- $h\nu_\gamma > 1$ TeV and $\Gamma_\gamma < 2$

Extreme “appearance”: transient (flares) or long-lasting (quiescent)

Biteau et al. 2021
3HSP J095507.9+35510 / IceCube-200107

- 3HSP J095507.9+35510 is an extreme blazar at \( z \sim 0.56 \) (Paiano+2020, Paliya+2020)
- Spatially coincident with IceCube-200107A while undergoing its brightest X-ray flare.
- X-ray flux increased by a factor of \( \sim 3 \) and X-ray spectrum hardened.

(Giommi+2020, Paliya+2020)
• **Optical/UV**: *Swift/UVOT* (3 days starting ~1 day after ν alert)

• **X-rays**: *Swift/XRT, NuSTAR* (3 days starting ~1 day after ν alert)

• **γ-rays**: *Fermi-LAT* (time-average over 250 days prior to ν alert / full mission)
Leptohadronic blazar modeling

ATHEvA code (Dimitrakoudis+2012)

- Synchrotron radiation
- Inverse Compton scattering
- Photon-photon pair production
- Proton-photon pair production
- Proton-photon pion production
- Neutron-photon pion production

Mannheim+1991; Mannheim & Biermann 1992; Mannheim 1993; Petropoulou+2015; Cerruti+2015; Petropoulou+2016; Gao+2017 +++
Leptohadronic modeling of the X-ray flare

Petropoulou+2020

Photopion production efficiency:

\[ f_{p\gamma}(E'_p) \approx \frac{t_{\text{dyn}}}{t_{p\gamma}} \sim \frac{2\kappa \Delta \sigma_\Delta}{1 + \beta} \frac{\Delta \bar{\epsilon}_\Delta}{4\pi r_b \Gamma^2 c E'_s} \left( \frac{E'_p}{E'_b} \right)^\beta \]

Photopion production efficiency

Variability timescale

Jet photon number density

Spectral index

Jet photon number density

Spectral index
Leptohadronic modeling of the X-ray flare
Neutrino expectation in the leptohadronic model - 1

SED modeling of the X-ray flare

\[ \mathcal{N}_{\nu_\mu + \bar{\nu}_\mu} = \frac{1}{3} \int_{\varepsilon_{\nu, \text{min}}}^{\varepsilon_{\nu, \text{max}}} d\varepsilon_\nu A_{\text{eff}}(\varepsilon_\nu, \delta) \phi_{\varepsilon_\nu}. \]

<table>
<thead>
<tr>
<th>Model</th>
<th>( \mathcal{N}<em>{\nu</em>\mu + \bar{\nu}_\mu} (&gt; 100 \text{ TeV}) )</th>
<th>( \mathcal{P}<em>{1 \nu</em>\mu \text{ or } \bar{\nu}_\mu} (&gt; 100 \text{ TeV}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \times 10^{-4} \text{ yr}^{-1} )</td>
<td>Alert (Point Source)</td>
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<td></td>
<td>( \times 10^{-4} \text{ yr}^{-1} )</td>
<td>Alert (Point Source)</td>
</tr>
<tr>
<td>( A_{(B'=15G)} )</td>
<td>17 (190)</td>
<td>0.02 (0.2) %</td>
</tr>
<tr>
<td>( A_{(B'=30G)} )</td>
<td>50 (540)</td>
<td>0.06 (0.7) %</td>
</tr>
<tr>
<td>( A_{(B'=100G)} )</td>
<td>45 (490)</td>
<td>0.05 (0.6) %</td>
</tr>
<tr>
<td>B</td>
<td>18 (200)</td>
<td>0.02 (0.2) %</td>
</tr>
<tr>
<td>C</td>
<td>25 (100)</td>
<td>0.03 (0.1) %</td>
</tr>
<tr>
<td>D</td>
<td>40 (210)</td>
<td>0.05 (0.3) %</td>
</tr>
</tbody>
</table>

Probability to detect 1 \( \nu_\mu \) during X-ray flare (\( \sim 44 \text{ d} \) \( \ll 1 \))
Neutrino expectation in the leptohadronic model - 2

Full XRT light curve + ν /X-ray correlation

\[
\phi_{\nu}(t) = \left( \frac{CR(t)}{CR(t_0)} \right)^2 \phi_{\nu}(t_0)
\]

- ~ 0.02 - 0.1 \( \nu_\mu \) within 10 yrs (with Point Source effective area)
- Most optimistic neutrino prediction similar to TXS 0506+056 (Petropoulou, Murase+2020)
Alternative theoretical scenarios (BC)

Blazar Core (BC)

- X-ray coronal field
- Production from inner jet (close to black hole)
- Low jet Lorentz factor ($\Gamma \sim 5$)
- Very strong magnetic field ($B \sim 10^4$ G)
- Size ($R \sim 10^{14}$ cm)

Findings:

- Applies to transient & persistent emissions
- EM cascade peaks at sub-MeV energies
- Cannot explain optical/UV, X-rays and $\gamma$-ray emissions
Alternative theoretical scenarios (HEP)

Hidden External Photons (HEP)

- Weak BLR? \(L_{BLR} < 10^{43} \text{ erg/s}\)
- Production from sub-pc jet
- Typical jet Lorentz factor (\(\Gamma \sim 25\))
- Weak magnetic field (\(B \sim 1 \text{ G}\))
- Size (\(R \sim 2 \times 10^{15} \text{ cm}\))

Findings:

- Applies to transient & persistent emissions
- UV & soft X-rays from the same region or not
- Enhanced neutrino flux by a factor of \(~3\)
Alternative theoretical scenarios (PS)

**Proton Synchrotron (PS)**

- Ultra-high energy protons in jet ($E_{p,max} \sim 10$ EeV)
- Production from sub-pc jet
- Typical jet Lorentz factor ($\Gamma \sim 10$)
- Strong magnetic field ($B \sim 100$ G)
- Size ($R \sim 10^{15}$ cm)

**Findings:**

- Can explain the transient MW emission
- Neutrino flux peaks at EeV energies
- Neutrino flux similar to leptohadronic models
Intergalactic cascade (IGC)

- Ultra-high energy protons escaping the jet
  \(E_{p,\text{max}} \sim 0.2 \text{ EeV}, \ L_{CR} \sim L_{Edd}\)

Findings:

- Applies to persistent EM emissions
- IGC \(\gamma\)-ray emission does not overshoot LAT data
- Lower neutrino flux than leptohadronic models
Alternative theoretical scenarios

### Table

<table>
<thead>
<tr>
<th>Model</th>
<th>State</th>
<th>$\hat{N}<em>{\nu, \nu</em>{\mu} + \nu_{\mu}} (&gt; 100 \text{ TeV})$</th>
<th>$\mathcal{P}<em>{1 \nu</em>{\mu} \text{ or } \bar{\nu}_{\mu}}$</th>
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<tr>
<td></td>
<td></td>
<td>($\times 10^{-4} \text{ yr}^{-1}$)</td>
<td>($&gt; 100 \text{ TeV}$)</td>
</tr>
<tr>
<td>HEP</td>
<td>transient high</td>
<td>50 (190)</td>
<td>0.3 (1)%</td>
</tr>
<tr>
<td>PS</td>
<td>transient high</td>
<td>2.1 (7.3)</td>
<td>0.01 (0.05)%</td>
</tr>
<tr>
<td>BC</td>
<td>persistent average</td>
<td>33 (370)</td>
<td>3 (30)%</td>
</tr>
<tr>
<td>IGC</td>
<td>persistent average</td>
<td>3.6 (10)</td>
<td>0.4 (1)%</td>
</tr>
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</table>
Summary

- 3HSP J095507.9+355101 is an extreme synchrotron blazar possibly associated with IceCube-200107A.
- Hard X-ray flare (Jan 8-11 2020) followed by ~40 d high X-ray flux state.
- Association of IceCube-200107A with hard X-ray flare is likely coincidental.
- There is ~1% (3%) probability of the neutrino coming within 10 yrs in the Leptohadronic scenario (Blazar Core model) with the real-time IceCube alert analysis.

Conclusions

- IceCube-Gen 2 could detect ~1-3 muon neutrinos in 10 yrs. If not, most promising neutrino models could be constrained.
- If an IceCube archival search finds additional neutrinos, our models have to be revisited.
- If ~ 100 blazars similar to 3HSP J095507.9+355101 emit comparable neutrino flux, the summed expectation can be ~1.
- No TeV emission predicted in most promising neutrino emission model. Are extreme TeV blazars weak PeV neutrino emitters?