Multimessenger observations of the flaring gamma-ray blazar TXS 0506+056 coincident with the high-energy neutrino IceCube-170922A

Anna Franckowiak
for the IceCube and Fermi-LAT Collaborations

HELMHOLTZ Young Investigators
Fermi Symposium 2018, Baltimore, October 15, 2018
The Multi-Messenger Picture

- Electro-magnetic emission
- Gravitational waves
- Cosmic rays
  - Direction
  - Time
  - Spectrum
Diffuse Neutrino Flux detected, but where do the Neutrinos come from?

IceCube high-energy events > 30 TeV (2010 - 2016)

Compatible with an isotropic distribution

→ extragalactic origin of cosmic neutrinos
IceCube Target of Opportunity Program
Public alerts since April 2016

- Single high-energy muon track events (> ~100 TeV)
- 8 / yr, ~3 / yr of cosmic origin
- Median latency: 30 sec
IC-170922A – a 290 TeV Neutrino

Signalness: 56.5%

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018
Fermi-LAT finds Flaring Blazar

Fermi-LAT finds Flaring Blazar: TXS 0506+056
MAGIC observes >100 GeV gamma rays

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018
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

**Step II:** Are there any extragalactic 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?
How Likely is it a Chance Probability?

\[ TS = 2 \log \frac{\mathcal{L}(n_s = 1)}{\mathcal{L}(n_s = 0)} = 2 \log \frac{S}{\beta} \]

Pre-trials p-value: 4.1σ

10 public alerts and 41 archival events \( \rightarrow \)
Post-trials p-value: 3.0σ

Three tested models yield similar p-values

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018
The Multi-Messenger Light Curve

VHE gamma-rays

GeV gamma-rays

X-rays

X-rays spectral index

optical

radio

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018
The Multi-Messenger SED

![Graph showing energy vs. log(frequency)]

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018
TXS 0506+056 in 3LAC

Among 50 brightest blazars (3%) in 3LAC

ISP

Redshift 0.3365±0.0010

(S. Paiano et al. 2018)
Are there more Neutrinos from this Source?
Are there more Neutrinos from this Source?

13±5 above the background of atmospheric neutrinos, 3.5σ
Are there more Neutrinos from this Source?

13±5 above the background of atmospheric neutrinos, 3.5σ

Neutrino luminosity (averaged over 158 days):

\[
(1.2^{+0.6}_{-0.4}) \times 10^{47} \text{ erg s}^{-1}
\]

4 times larger than average gamma-ray luminosity!
Is there also a Gamma-ray Flare?

Neutrinos 2014/15 neutrino flare IC-170922A

13±5 above the background of atmospheric neutrinos, 3.5σ

Fermi gamma-rays

preliminary
Gamma-ray Spectral Variations during neutrino flare?

No gamma-ray activity during 2014/15 neutrino flare

Spectral change significance ≤2σ

Garrappa et al. in preparation

See also Padovani et al. MNRAS, 2018
Modeling Papers on the arXiv on July 12

• “Interpretation of the coincident observation of a high energy neutrino and a bright flare”, Gao, Fedynitch, Winter, Pohl, arXiv:1807.04275

• “A multiwavelength view of BL Lacs neutrino candidates”, Righi, Tavecchio, Pacciani, arXiv::1807.04299

• “The blazar TXS 0506+056 associated with a high-energy neutrino: insights into extragalactic jets and cosmic ray acceleration”, MAGIC Collaboration, arXiv:1807.04300


• “Blazar Flares as an Origin of High-Energy Cosmic Neutrinos?” Murase, Oikonomou, Petropoulou, arXiv:1807.04748

See talk by Azadeh Keivani
Modeling – leptonic

Gao et al., Keivani et al., Murase et al.
Modeling – leptonic, hadronic

Simple one-zone hadronic models violate X-ray constraints
→ More complex models needed

Gao et al., Keivani et al., Murase et al.
Modeling – leptonic, hadronic, Gin & Tonic

2017 neutrino + gamma flare:

2014/15 neutrino flare:

neutrino luminosity is ~4 times higher than gamma-ray luminosity

→ challenge for models

Two zone-model with dense blob (Gao+ 2018) or structured jet (MAGIC Coll. 2018)

Gao et al. 2018

Reimer et al. in preparation, M. Boettcher at TeVPA 2018
Other interesting candidates

PKS B1424–418 + cascade event
5% chance coincidence

PKS 0723-008 + track event,
Barely outside 90% error circle,
dim gamma-ray source

Kadler et al. 2016

Kun et al. 2017
Another interesting case?

Arrival of IC-141209A

Fermi gamma-rays

optical

See talk by Simone Garrappa

Garrappa et al. in preparation
Do gamma-ray blazars produce all diffuse neutrinos?

- 40 high-energy neutrinos, 20 signal neutrinos, 1-2 neutrino blazar coincidences $\rightarrow$ 10% blazar contribution
- Averaged over 9.5 years, the neutrino flux of TXS 0506+056 by itself corresponds to 1% of the astrophysical diffuse flux

- **2LAC Blazar Stacking:**
  - Upper limit of 27% of the diffuse flux fit between 10 TeV and 100 TeV with a soft $E^{-2.5}$ spectrum
  - Upper limit of 40% and 80% for an $E^{-2}$ spectrum (compatible with the diffuse flux fit $> 200$ TeV)

[Graph showing neutrino flux and blazar stacking results]

Fully compatible with blazar catalog stacking results

What can we improve in the Future?

• **Archival Data**: Carefully check for more candidates in archival IceCube and Fermi data

• **Blazar Stacking**: Preselection of Fermi blazars / flares

• **Realtime Program**: Upgrade of IceCube realtime stream will deliver higher rate with higher purity

• **Detector Upgrade**: IceCube upgrade will improve angular uncertainty due to ice systematics

Fermi data is crucial input!
Summary

Other messengers:
- Electro-magnetic emission
- Gravitational waves
- Cosmic rays

These can provide:
- Direction
- Time
- Spectrum

- gamma-rays
- visible light
- neutrinos
- cosmic rays
- theory
Summary

Other messengers

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- Direction
- Time
- Spectrum

Gamma-rays

Visible light

Neutrinos

Cosmic rays

Unique messengers from the high-energy Universe

Theory
Summary

• Electro-magnetic emission
• Gravitational waves
• Cosmic-rays can provide:
  • Direction
  • Time
  • Spectrum

Neutrinos can reveal the sources of high-energy cosmic rays

Neutrinos

gamma-rays

visible light

cosmic rays

theory
Summary

- Electro-magnetic emission
- Gravitational waves
- Cosmic rays

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Gamma-rays and visible light are crucial to identify the sources. First compelling candidate found!

IC170922A + TXS flare: 3σ
2014/15 neutrino flare (13 events): 3.5σ
Summary

Other messengers

- Electro-magnetic emission
- Gravitational waves
- Cosmic-rays

Can provide:
- Direction
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- Spectrum

How does this all fit together?
Stay tuned!
Back-up
All have distinct electro-magnetic counterparts
MAGIC finds variability on 1-day scale

Compact emission region
How Likely is it a Chance Probability?

\[ TS = 2 \log \frac{\mathcal{L}(n_s = 1)}{\mathcal{L}(n_s = 0)} = 2 \log \frac{S}{B} \]

\[ \mathcal{B}(\vec{x}) = \frac{\mathcal{P}_{BG}(\sin \theta)}{2\pi} \]

\[ S(\vec{x}, t) = \sum_s \frac{1}{2\pi \sigma^2} e^{-|\vec{x}_s - \vec{x}|^2/(2\sigma^2)} w_s(t) w_{acc}(\theta_s) \]

Spatial term

acceptance

gamma-ray energy flux at time t
Three models tested

Neutrino emission correlates with:

1. gamma-ray energy flux in the range 1-100 GeV

\[ w_s(t) = \phi_E(t) = \int_{1 \text{ GeV}}^{100 \text{ GeV}} E_{\gamma} \frac{d\phi_{\gamma}(t)}{dE_{\gamma}} dE_{\gamma} \]

2. relative gamma-ray flux variations in the range 1-100 GeV

\[ w_s(t) = \frac{\phi_{\gamma}(t)}{\langle \phi_{\gamma} \rangle} \]

3. very high-energy gamma-ray energy flux in the range 100GeV-1TeV (extrapolated from Fermi energy range)

\[ w_s(t) = \phi_E(t) = \int_{100 \text{ GeV}}^{1 \text{ TeV}} E_{\gamma} \frac{d\phi_{\gamma}(t)}{dE_{\gamma}} dE_{\gamma} \]

All tested models yield similar p-values
Modeling – leptonic, hadronic, Gin & Tonic

Solution: two-zone models
Modeling – leptonic, hadronic, Gin & Tonic

Alternative two-zone model: spine sheath

Taveccio, TeVPA 2018
Blazar Spine Sheath Model
(by Ghisellini & Tavecchio 2005)

Table 3. Parameters for the jet-sheath model for $E_{p,\text{max}}=10^{16}$.

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<thead>
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<th>State</th>
<th>MJD 58029-30</th>
<th>Lower VHE</th>
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<td>$B$ [G]</td>
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<td>2.6</td>
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<tr>
<td>$E_{\text{min}}$ [eV]</td>
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<td>$2.0 \times 10^8$</td>
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<td>$E_{\text{br}}$ [eV]</td>
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<td>$E_{\text{max}}$ [eV]</td>
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<tr>
<td>$U_B$ [erg cm$^{-3}$]</td>
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<td>0.27</td>
</tr>
<tr>
<td>$U_p$ [erg cm$^{-3}$]</td>
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<td>0.7</td>
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<td>$P_e$ [erg s$^{-1}$]</td>
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</tr>
<tr>
<td>$P_p$ [erg s$^{-1}$]</td>
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<td>$3 \times 10^{45}$</td>
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<tr>
<td>$P_B$ [erg s$^{-1}$]</td>
<td>$1.2 \times 10^{45}$</td>
<td>$1.2 \times 10^{45}$</td>
</tr>
</tbody>
</table>
Blazar Spine Sheath Model – applied to TXS (by Ghisellini & Tavecchio 2005)
Event Signatures

a) through-going muon track $E \sim 140$ TeV
b) Starting muon track $E \sim 70$ TeV
c) Shower event $E \sim 1$ PeV
d) “double bang” event $E \sim 200$ PeV (simulated)

Resolvable for deposited energy $>100$ TeV
The Redshift

From the 10.4m Gran Telescopio Canarias

Redshift $z=0.337$

Light travel distance:
~ 4 billion light years