Modeling neutrino emission from blazar TXS 0506+056

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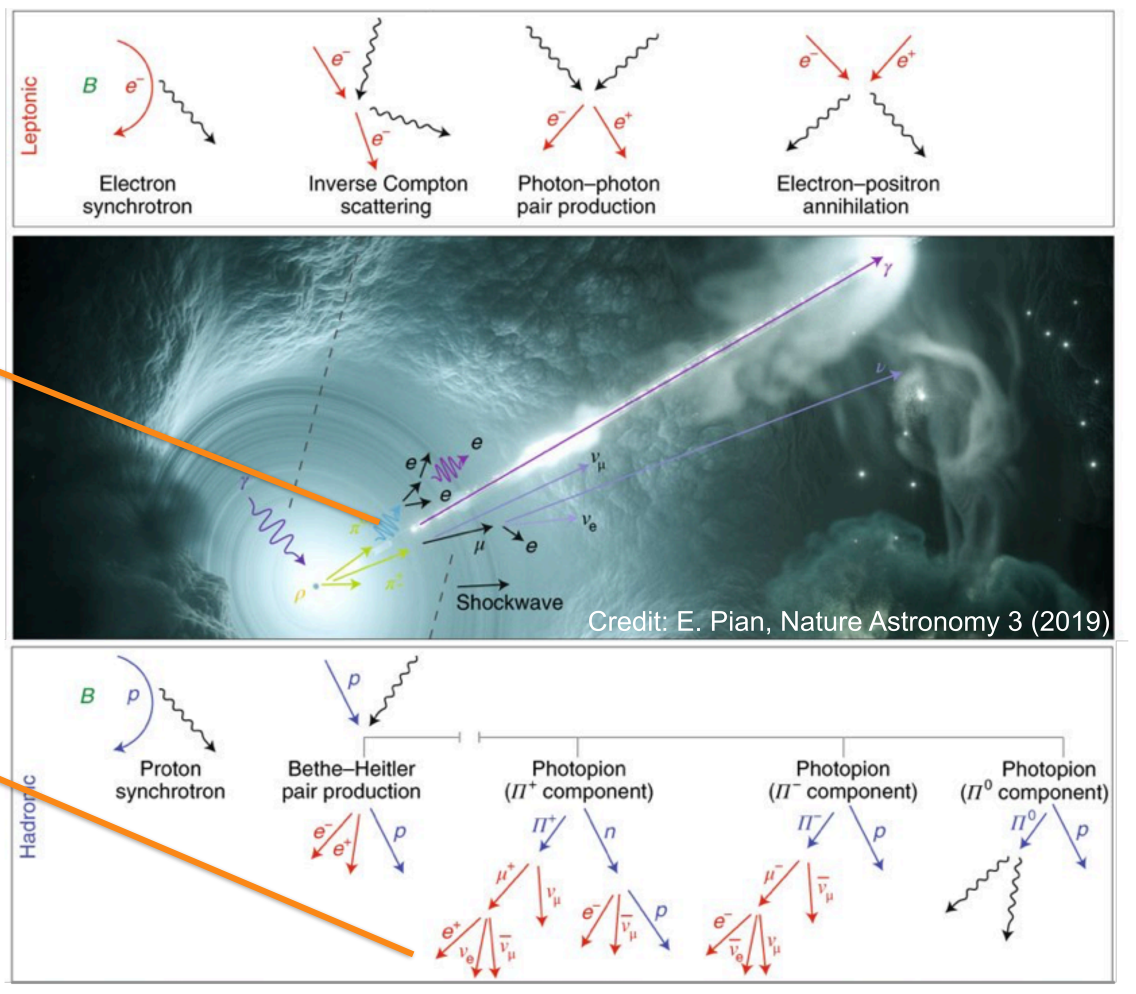
Abstract

We discuss interpretations of the neutrino signal observed from the AGN blazar TXS 0506+056 in the multi-messenger and multi-wavelength context, including both the 2014-15 and 2017 neutrino flares. While the neutrino observed in September 2017 has to describe contemporary data in e.g. the X-ray and VHE gamma-ray ranges, data at the 2014-15 excess are much sparser. We demonstrate that in both cases the simplest possible one-zone AGN blazar models face challenges. While the 2017 flare can be well interpreted by considering more sophisticated source geometries, the 2014-15 flare is much harder to reconcile with conventional models. One challenge is the energy injected into the electromagnetic cascade coming together with the neutrino production, which cannot be reconciled with the 13 observed neutrino events. We also speculate if a common interpretation of both flares is feasible.

Blazar simulations with AM3

Blazars as cosmic accelerators

- ***Blazars:*** subclass of active galactic nuclei (AGN) where a central supermassive black hole launches a **relativistic jet** in the direction of us observers
- **Brightest** persistent sources in the **gamma-ray** sky
- The dissipation of the jet kinetic energy may lead to acceleration of **cosmic rays** to high energies
- **Neutrinos** and high-energy **gamma rays** can then be produced by proton interactions
- Neutrinos travel cosmic distances unimpeded, making them **smoking-gun signatures** of proton interactions



Time-dependent hadro-leptonic code (AM3*)

*Astrophysical Modeling with Multiple Messengers

- We developed the numerical code AM3 to simulate the physics taking place in the blazar jet.
- AM3 numerically solves a coupled integral-differential equation system for all relevant particles.
- Written in C++ (high efficiency)
- One complete blazar simulation takes 2 to 5 minutes.
- Millions of simulations can be performed in one day using the DESY computing cluster.

Each equation describes evolution of the spectrum of a particle species

First and second order differential terms for continuous energy loss/gain

Sink terms for particle escape and disappearance

Source terms for particle injection

$$\partial_t n(\gamma,t) = -\partial_\gamma\{\dot{\gamma}(\gamma,t)n(\gamma,t) - \partial_\gamma[D(\gamma,t)n(\gamma,t)]/2\} - \alpha(\gamma,t)n(\gamma,t) + Q(\gamma,t)$$

2017 event

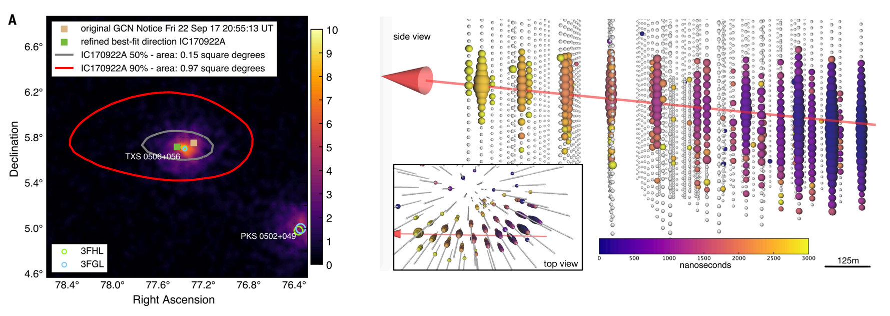


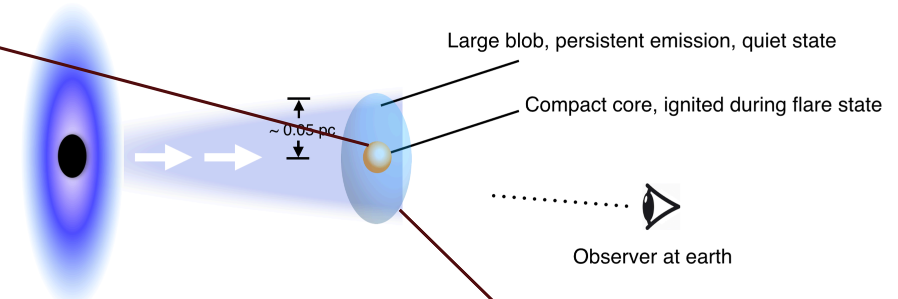
Figure credit: [1]

- On Sep. 22, 2017, a **muon neutrino** around 300 TeV was observed by IceCube **from the direction of blazar TXS 0506+056**
- A flares of the same blazar was observed simultaneously across in several wavelengths
- **Significance** of the correlation **exceeds 3σ**.

Compact-core (two-zone) model

Small region within the jet blob *(the core)* that is only activated during the flare, producing **neutrinos** and **gamma rays** with high efficiencies.

We can also explain the SED and neutrinos without a compact core, but that would require a large proton luminosity that far exceeds the Eddington limit.



Larger blob responsible for part of the **SED**, while **neutrino** emission is **not efficient**

Flare explained by rise and decline of proton injection

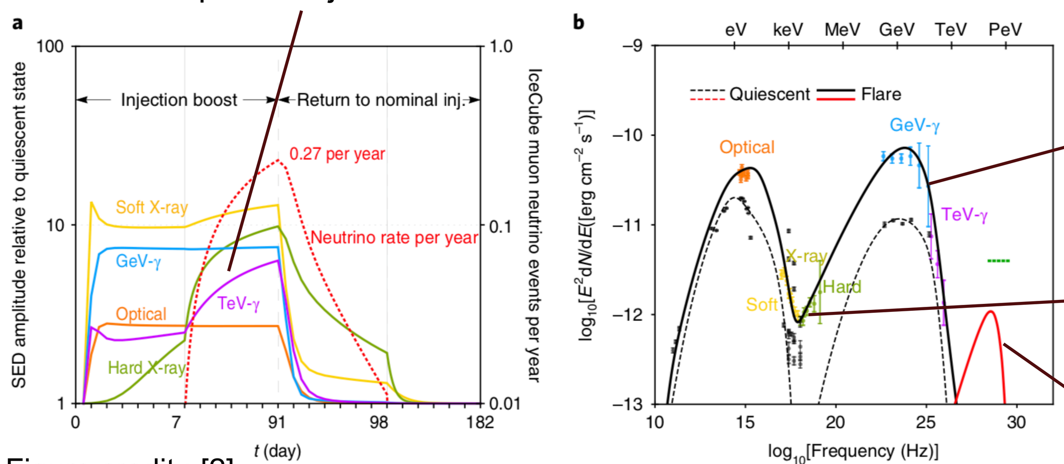


Figure credit : [2]

Neutrinos correlated with hard X-rays and TeV gamma rays

The SED is dominated by the **leptonic components**

The **hadronic** ingredient is severely **constrained** by the **X-rays** around the saddle point in the SED.

Predicted neutrino event rate well below 1.0

2014-2015 flare

- In 2014-15 an excess of 13+-5 muon neutrinos were observed
- However, no simultaneous activity was observed in radio, optical or gamma-ray bands (but possible spectral hardening in gamma rays [4])

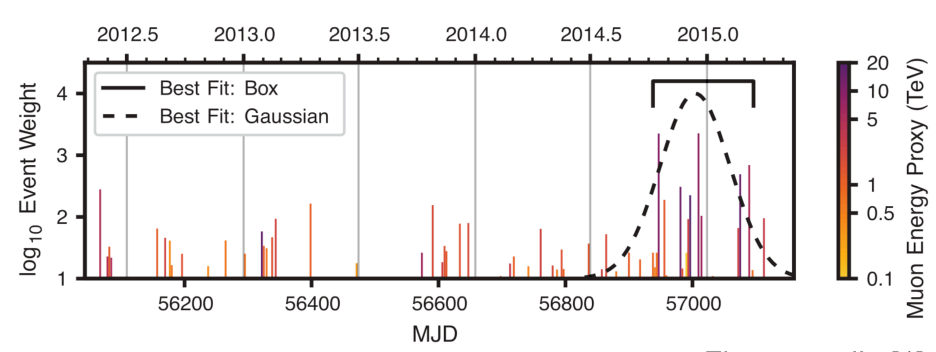
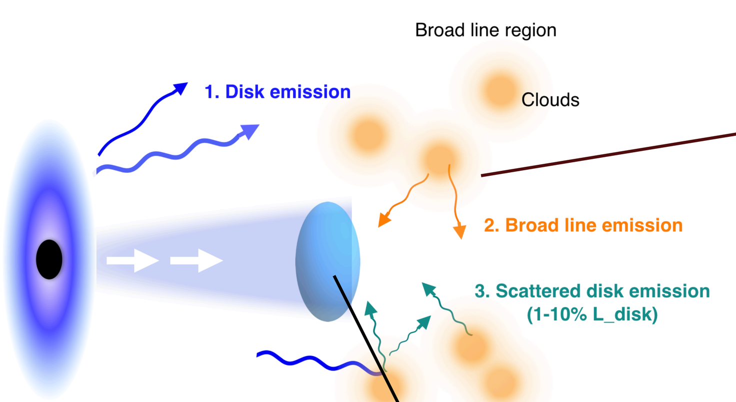


Figure credit: [1]

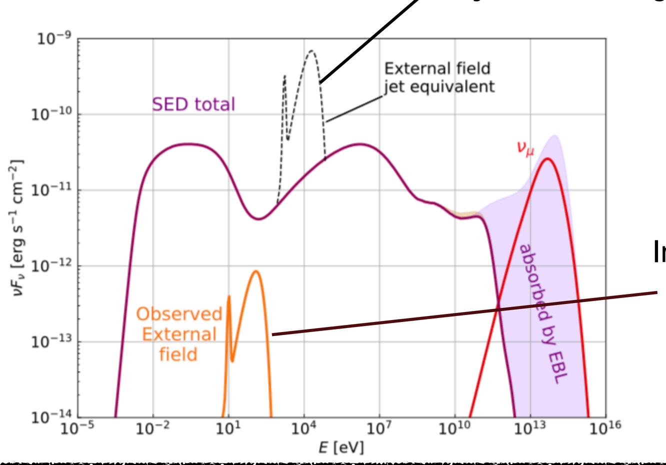
External field model



There is evidence that TXS 0506+056 may be a **Flat-Spectrum Radio Quasar (FSRQ)** with **external structures** to the jet, which re-process radiation from the disk.

Hadronic gamma rays **cascade** in the source down to **MeV energies**

The external radiation appears **boosted** in the rest frame of the **jet**, enhancing neutrino production



In the **observer's** frame, the external fields are **out-shined by the jet**

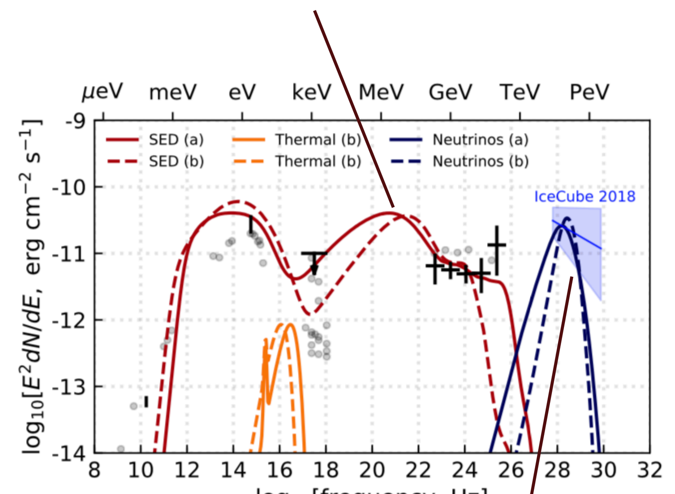


Figure credit: [3]

Up to **5 neutrino events** are explained in this model

Conclusions

From the theory perspective

Three major challenges (current models can only address any two):

1. Fully explaining the observed neutrinos
2. Not exceeding the Eddington Luminosity (realistic energy budget)
3. We would hope to explain observations with a simple source geometry

- Address (1) + (2) : compact core model (only for 2017 event); external radiation field model; spine-shealth model; jet-cloud interaction (proton-proton) model
- Address (1) + (3) : one-zone lepto-hadronic model (only for 2017 event)
- Address (2) + (3) : one-zone pure leptonic model; one-zone proton-synchrotron model.

From the observational perspective

- For 2017 event, time-response of SED and X-ray data point to **leptonically dominated** model
- For 2014-15 flare, description of 13 events seems **contradictory** to *Fermi* observations (up to 5 events explained in the external radiation field model).
- The predicted neutrino shape (peaked curve) is very different from IceCube analysis (13 signal events under a broad power-law shape). We need new analysis with **realistic neutrino assumptions**.
- So far **no model** can **explain both** the 2017 (accompanied by SED boost) and 2014-15 flare (no significant SED activities)
- No solid conclusion can be made due to sparseness of data; **need multi-wavelength monitoring** to confirm/exclude signals elsewhere.

References

- [1] M. Aartsen, M. Ackermann, J. Aguilar et al., Science 361 (2018).
- [2] S. Gao, A. Fedynitch, W. Winter, and M. Pohl, Nature Astronomy 3 (2019) 88.
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- [4] P. Padovani, P. Giommi, E. Resconi et al, Mon. Not. Roy. Astron. Soc. 480 (2018) 192.
- [5] P. Padovani, F. Oikonomou, M. Petropoulou et al, Mon. Not. Roy. Astron. Soc. 484 (2019) L104.
- [6] Other models of TXS 0506+056 (2017 event): Keivani et al. 2018 ApJ; Cerruti et al. 2018 MNRAS; Gokus et al 2018 IBWS Proc.; Sahakyan 2018 ApJ; Murase et al. 2018 ApJ; 2014-15 flare: Liu et al, PRD 2018, Wang et al. 2018, Reimer 2019 ApJ.
- [7] Blazar population studies: see Palladino et al. 2019 ApJ, Oikonomou et al. 2019 MNRAS.