Blazar flares as the origin of High-Energy Cosmic Neutrinos?

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[1] full exposition in reference [1]

Introduction

The IceCube Collaboration has recently reported the observation of a >290 TeV muon neutrino, IceCube-170922A, coincident with a ~6 month-long γ-ray flare of the blazar TXS 0506+056 [2], at redshift z = 0.3365 [3]. The neutrino detection prompted electromagnetic follow-up of the event, and the blazar flare was seen with several instruments, including MAGIC at energies exceeding > 100 GeV [2]. The correlation of the neutrino with the flare of TXS 0506+056 is inconsistent with arising by chance at the 3σ level.

An archival search revealed 13±5 further, lower-energy neutrinos in the direction of TXS 0506+056 during a 6-month period in 2014-2015 [4]. These events were not accompanied by a γ-ray flare. Such an accumulation of events is inconsistent with arising from a background fluctuation at the 3.5σ level.

Motivated by these observations we here consider the implications of the possible neutrino-blazar flare association.

Blazar contribution to the diffuse IceCube flux: Clustering constraints

The absence of high-energy multiplets in the IceCube data constrains the number density of sources contributing to the diffuse neutrino background. The upper limit to the contribution of a source population with number density $n_0^{\rm eff}$ is,

$$E_\nu^2 \Phi_\nu = \frac{\xi_z c t_H}{4\pi} 3\varepsilon_\nu L_{\varepsilon_\nu}^{\rm ave} n_0^{\rm eff} \lesssim 6.9\times10^{-9}\ {\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}} \left(\frac{\xi_z}{0.7}\right)\left(\frac{6.6}{b_m q_L}\right)^{2/3} \times \left(\frac{n_0^{\rm eff}}{10^{-7}\ {\rm Mpc^{-3}}}\right)^{1/3} F_{{\rm lim},-9.2}\left(\frac{2\pi}{\Delta\Omega}\right)^{2/3} \quad (1)$$

Neutrinos can be produced during flares, as typically in models with leptonic γ-ray origin, $L_\nu \propto L_\gamma^{\gamma}$, with $\gamma \sim 1.5 - 2$. For a source with gamma-ray luminosity distribution $dN/dL_\gamma \propto L_\gamma^{-\alpha}$,

$$L_\nu^2\ dN/dL_\nu \propto L_\nu^{\,1 - [(\alpha - 1)/\gamma]} \quad (2)$$

Thus, neutrinos produced during flaring states can dominate the output of a source if $\alpha \lesssim 3$. We analysed data from the FAVA [7] catalogue, and found that the data of a sample of intermediate redshift BL Lacs, are well described by a power-law with $\alpha \sim 2$-4. For TXS 0506+056, $\alpha \sim 3$. We conclude that the contribution of flaring blazars to the diffuse background can be,

$$E_\nu^2 \Phi_\nu \lesssim 3.8\times10^{-10}\ {\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}} \left(\frac{2\pi}{\Delta\Omega}\right)\left(\frac{\xi_z}{0.7}\right)\left(\frac{6.6}{b_m q_L}\right)\left(\frac{0.05}{f_{\rm fl}}\right)^{1/2} \times \left(\frac{10^{46}\ {\rm erg\ s^{-1}}}{\varepsilon_\nu L_{\varepsilon_\nu}}\right)^{1/2} F_{{\rm lim},-9.2}^{3/2}$$

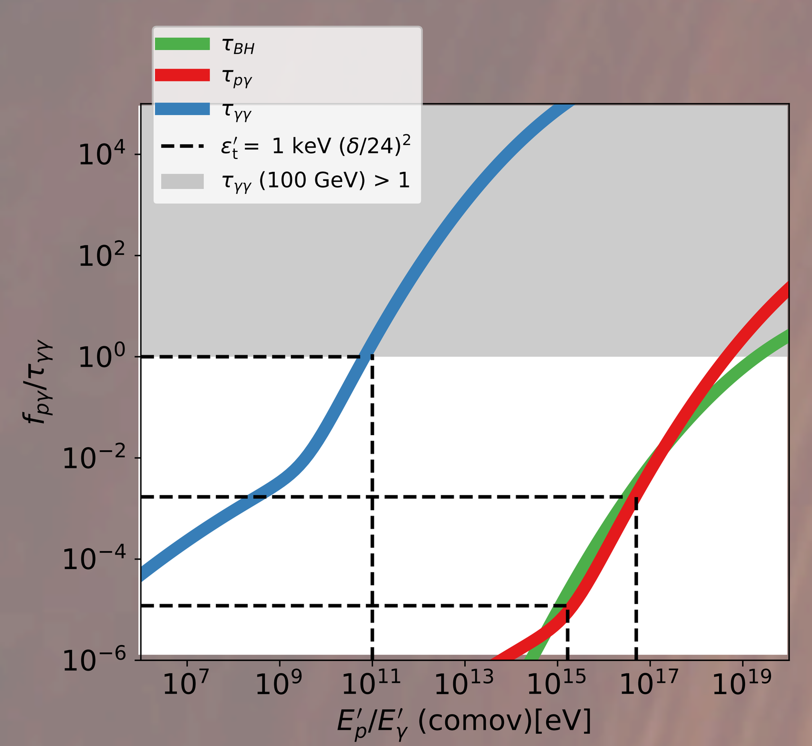
with, $f_{\rm fl}$, the time spent in a flaring state, but cannot exceed the limit of eq (1).

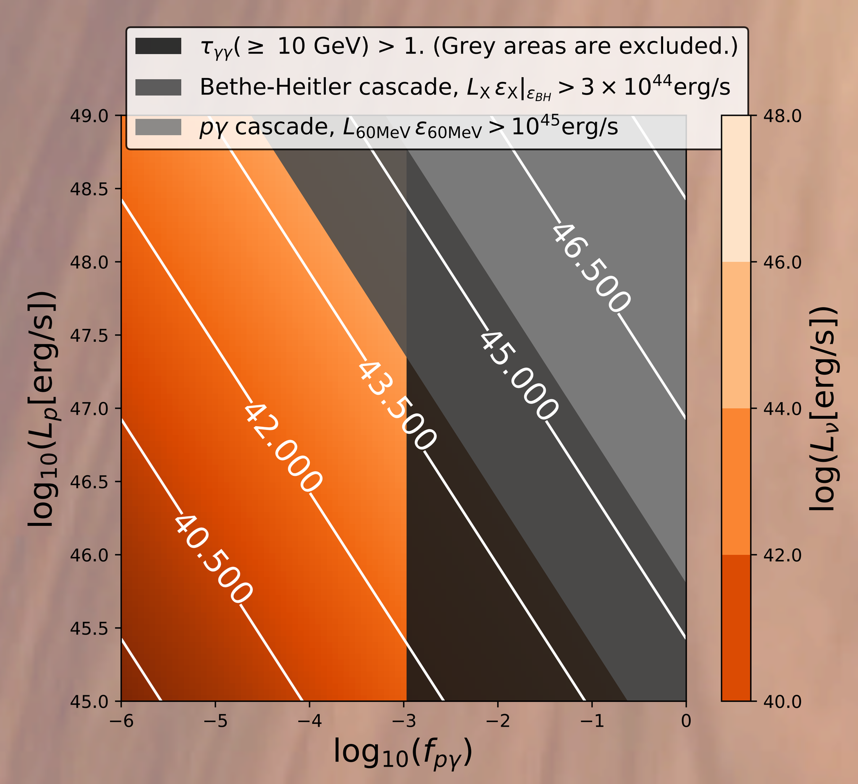
X-ray and γ-ray constraints on the maximum neutrino flux

The observation of >10-100 GeV photons from TXS 0506+056 during the 2017 flare, implies that the optical depth for photons to $\gamma\gamma$ interactions on low-energy photons, $\tau_{\gamma\gamma}(10\text{-}100\ {\rm GeV}) < 1$. The same photons are the target photons for $p\gamma$ interactions. The optical depth to $p\gamma$ interactions is related to the photo-meson production efficiency, $f_{p\gamma}$, via

$$\tau_{\gamma\gamma}[\varepsilon_{\gamma\gamma\text{-}p\gamma}] = 10^3 f_{p\gamma}[20\ \varepsilon_\nu],$$

where $\varepsilon_{\gamma\gamma\text{-}p\gamma} \sim 10\ {\rm GeV}\ (\varepsilon_\nu / 300\ {\rm TeV})$. This poses a limit to $f_{p\gamma}$, and thus to the maximum neutrino luminosity, L_ν, in a one-zone scenario, illustrated below. A further limit is imposed to L_ν, from the requirement that the cascade photon flux produced in Bethe-Heitler and $p\gamma$ interactions don't exceed the observed X-ray and gamma-ray flux of TXS 0506+056.

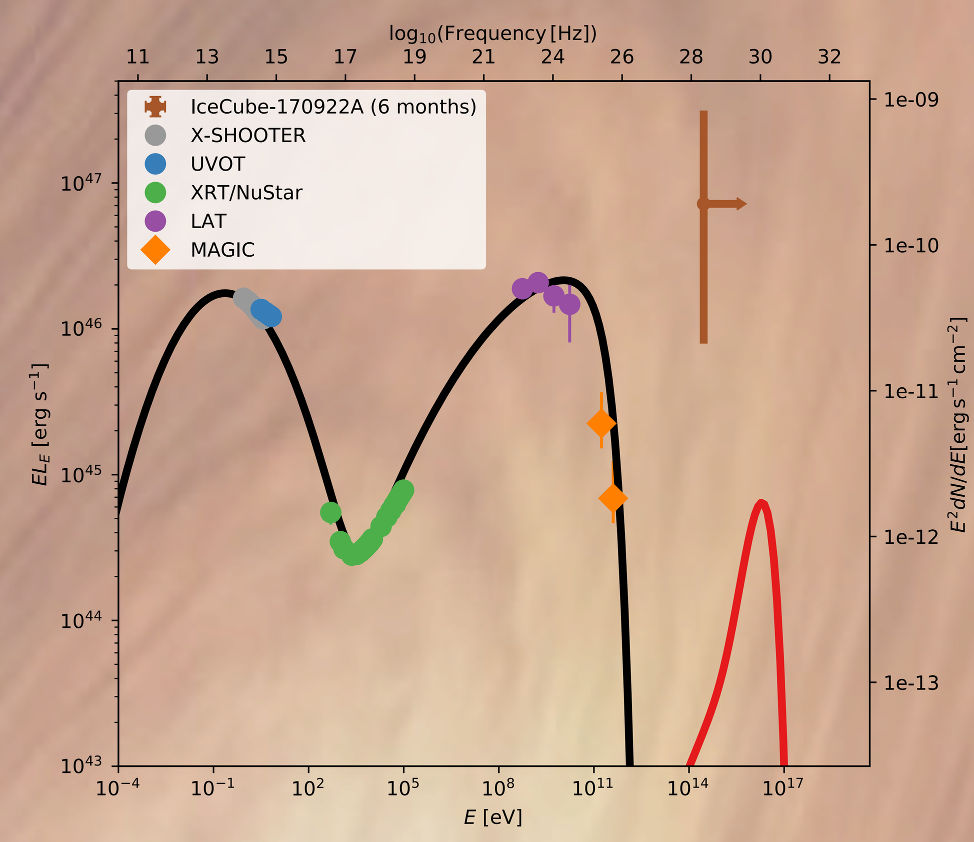




Maximum neutrino flux in single-zone model

The maximum neutrino flux during the flare of TXS 0506 +056 consistent with the X-ray and gamma-ray observations is illustrated here.

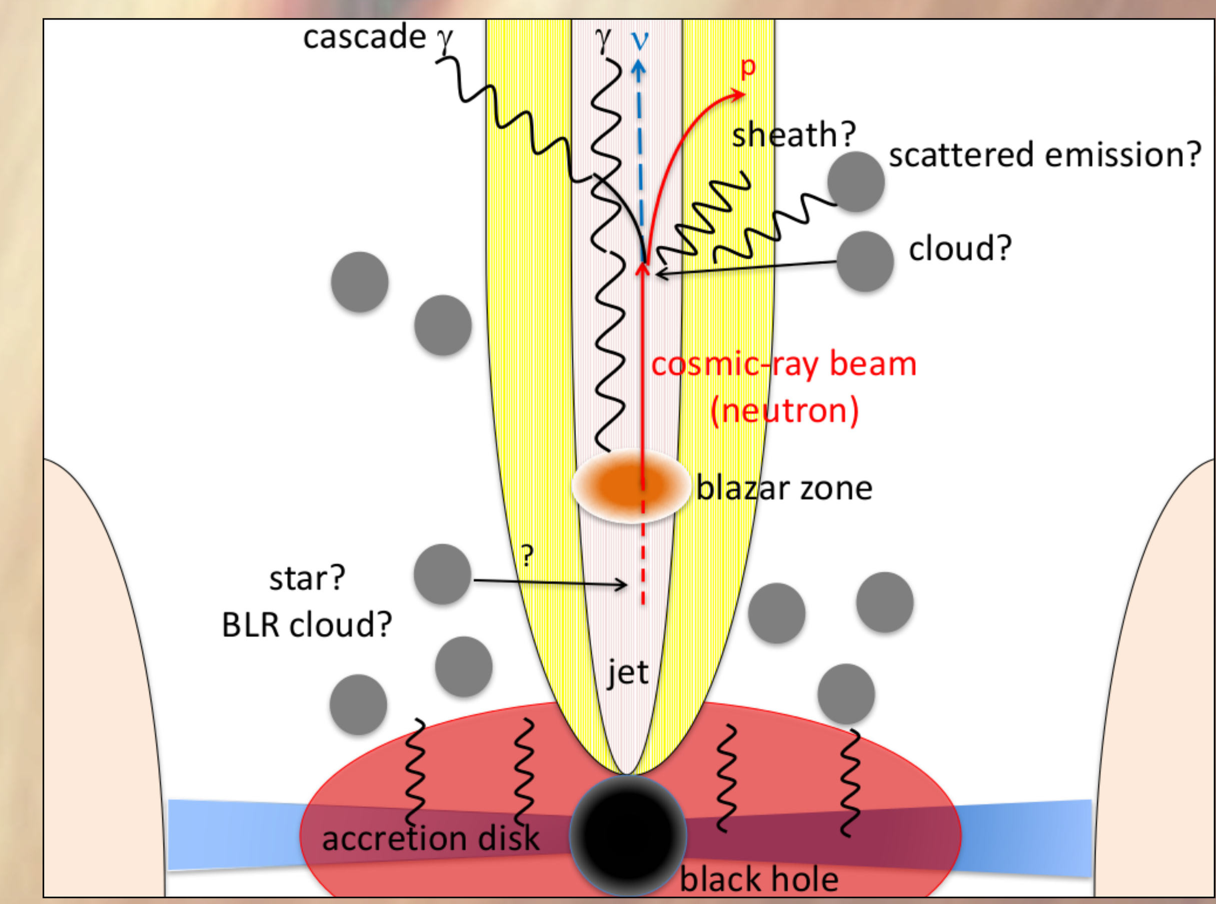
The parameters that maximise the neutrino luminosity in a single-zone model were derived in [5].



Multi-zone model and cosmic-ray induced neutral beams

The CR induced neutral beam can avoid the cascade constraints if isotropisation of high energy electrons and positrons takes place.

a. Neutrons are produced via the photo-disintegration of nuclei in the CR acceleration region.
b. Nuclei and protons remain confined and eventually cool via adiabatic losses while neutrons escape the CR acceleration zone.
c. The neutrons interact with external radiation fields (e.g. sheath) or dense cloud that could exist at larger radii producing neutrinos.
d. The relativistic pairs produced in $\gamma\gamma$ interactions get isotropised by ambient magnetic fields in the jet or surrounding medium, suppressing the electromagnetic cascade that is otherwise expected.



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