Blazar Constraints on Neutrino-Dark Matter Scattering

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Neutrino emission in coincidence with gamma rays has been observed from the blazar TXS 0506 + 056 by the IceCube telescope. Neutrinos from the blazar had to pass through a dense spike of dark matter (DM) surrounding the central black hole. The observation of such a neutrino implies new upper bounds on the neutrino-DM scattering cross section as a function of DM mass. The constraint is stronger than existing ones for a range of DM masses, if the cross section rises linearly with energy. For constant cross sections, competitive bounds are also possible, depending on details of the DM spike.

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Introduction.—The possible interactions of dark matter (DM) with ordinary matter have been constrained in many ways. The most challenging category is DM-neutrino interactions, due to the difficulty of observing neutrinos. A promising strategy is to consider astrophysical sources of high-energy neutrinos that could accelerate light DM particles to energies that would make them detectable in ground-based DM and neutrino search experiments [1–3]. This only works if, in addition to DM-ν interactions, there can also be scattering of DM from nuclei or electrons in the detector.

A more model independent strategy is to use the fact that a 290 TeV neutrino, known as event IC-170922A, has been observed by the IceCube experiment, and was identified as coming from the blazar TXS 0506 + 056 [4]. Reference [5] set limits on the DM-ν scattering cross section using the fact that the neutrino had to pass through cosmological and galactic DM between the blazar and Earth. In this Letter, we derive stronger limits, using the fact that the neutrino also had to traverse the dense DM spike surrounding the supermassive black hole powering TXS 0506 + 056.

IceCube additionally reported a statistical excess of lower energy neutrinos prior the 2017 flare of TXS 0506 + 056 [6], but the claimed excess is too large to be explained by state-of-the-art one-zone blazar models, likely requiring more complicated modeling [7–12]. Hence we do not include it in the present analysis. There have also been several candidate associations between neutrinos detected by IceCube and known γ-ray blazars subsequent to IC-170922A (e.g., [13–20]). Since none of them have been confirmed by the IceCube Collaboration, we do not include them in this study.

Expected neutrino events.—We start by describing the theoretical models of neutrino emission from blazars and the expected flux from TXS 0506 + 056. The observed spectra of electromagnetic emission from blazars is well described by lepto-hadronic models [11,12,21–23], in which protons and electrons are shock-accelerated to create a relativistic jet in a magnetized region that produces synchrotron radiation. The jet extends to distances $\sim 10^{11}$ km [12,22], around 1000 times smaller than the extent of the DM spike to be described next. Proton-photon interactions in the jet produce pions, whose decays are the source of high-energy neutrinos.

Purely hadronic models are also able to fit the combined electromagnetic spectra at optical, x-ray and gamma-ray frequencies, but they lead to either a detectable neutrino flux at much higher energies or a negligible low flux at energies compatible with IC-170922A [22,23]; hence we focus on lepto-hadronic models in the following. The impact of different choices is discussed later. Under the steady state approximation, the hadronic model of Ref. [22] predicts a neutrino flux between $E_\nu \sim 100$ TeV and 10 EeV, that peaks at a value $E_\nu \sim 10$ PeV, which is orders of magnitude higher than IC-170922A. We find that the probability of observing a neutrino with energy $\lesssim 300$ TeV is $\sim 3\%$ in this model. Hence we consider it to be disfavored for explaining IC-170922A.

On the other hand, the neutrino flux predicted by the lepto-hadronic model of Ref. [12], based on a fully time-dependent approach, peaks near $E_\nu = 100$ TeV and is compatible with the observation. Within the quasi-two neutrino oscillation approximation [12], the flux is well fit by the formula

$$\log_{10} \Phi_\nu(E_\nu) = -F_0 - \frac{F_1 x}{1 + F_2 |x|^{F_3}} \tag{1}$$

with $F_0 = 13.22, F_1 = 1.498, F_2 = -0.00167, F_3 = 4.119$, and $x = \log_{10}(E_\nu/\text{TeV}) \in [-1.2, 4.2]$. The expected number of muon neutrino events observed at IceCube is given by

$$N_{\text{pred}} = t_{\text{obs}} \int dE_\nu \Phi_\nu(E_\nu) A_{\text{eff}}(E_\nu), \tag{2}$$

where t_{obs} is the time interval of observation, Φ_ν is the predicted neutrino flux from the blazar, and A_{eff} is an effective area for detection, which depends on the geometry of the source direction and E_ν, and encodes the probability for a neutrino to convert to a muon through weak interactions. Data for A_{eff} from TXS $0506+056$ is provided by IceCube [24,25]. For the campaign IC86c during JD (Julian day) 57 161–58 057 that observed IC-170922A, $t_{\text{obs}} = 898$ d, and the reconstructed energy was $E_\nu = 290$ TeV. This yields $N_{\text{pred}} \approx 2.0$ from the flux (1), compatible with the observed event. We adopt this as the input model for constraining the DM-ν cross section in the following.

Dark matter spike.—The overdensity of DM surrounding the central black hole plays a crucial role for constraining ν-DM scattering from the blazar. The possibility of adiabatic accretion of DM around the black hole (BH) was first considered by Gondolo and Silk in Ref. [26]. They derived an inner radius for the spike of $r_i = 4R_S$, where $R_S = 2GM_{\text{BH}}$ is the BH Schwarzschild radius, and an outer profile $\rho'(r) \cong N(1-4R_S/r)^3 r^{-\alpha}$ with $\alpha = (9-2\gamma)/(4-\gamma) \in [2.25, 2.5]$, depending on the inner cusp of the initial DM halo density, $\rho \sim r^{-\gamma}$, with $0 \le \gamma \le 2$. The normalization N of ρ' can be determined using the finding that the mass of the spike is of the same order as M_{BH} [27], $4\pi \int_{r_i}^{r_o} dr r^2 \rho' \cong M_{\text{BH}}$, within a radius of typical size $r_o \cong 10^5 R_S$ [28]. The BH mass of the blazar TXS $0506+056$ is estimated to be $3.09 \times 10^8 M_\odot$ [29]. In Ref. [30], it was argued that gravitational scattering of DM with stars in the central region would lead to dynamical relaxation to a less cuspy profile with $\alpha = 3/2$; hence we also consider this possibility below.

The spike density is reduced relative to these initial profiles if there is subsequent DM annihilation, leading to a maximum density of $\rho_c = m_\chi/(\langle\sigma_a v\rangle t_{\text{BH}})$, where m_χ is the DM mass, $\langle\sigma_a v\rangle$ is an effective annihilation cross section, and t_{BH} is the age of the BH. The spike density then becomes $\rho_\chi = \rho_c \rho'/(\rho_c + \rho')$. The quantity $\langle\sigma_a v\rangle$ is "effective" in the sense that it could be negligible even if the actual annihilation cross section is large. This would be the case for asymmetric dark matter, in which the symmetric component has completely annihilated away in the early universe. Then annihilations would have no effect at later times, when the DM spike is formed. To illustrate the range of possible outcomes from varying $\langle\sigma_a v\rangle$, we follow Ref. [3] by considering three benchmark models BM1–BM3, in which $\langle\sigma_a v\rangle = (0, 0.01, 3) \times 10^{-26}\ \text{cm}^3/\text{s}$, respectively, and $t_{\text{BH}} = 10^9$ yr. These models assumed $\alpha = 7/3$ in $\rho' \sim r^{-\alpha}$. We also consider models BM1′–BM3′ using the less cuspy value $\alpha = 3/2$.

The probability for neutrinos to scatter from DM in the spike depends on the DM column density,

$$\Sigma_\chi = \int_{R_{\text{em}}}^{\infty} dr\, \rho_\chi \cong A_\Sigma \left(\frac{m_\chi}{1\ \text{MeV}}\right)^{1-B_\Sigma} \text{MeV}, \tag{3}$$

where $R_{\text{em}} \approx R'\delta \sim 2 \times 10^{17}$ cm is the distance from the central BH to the position in the jet where neutrinos and photons are likely to be produced [29]. $R' \sim 10^{16}$ cm is the comoving size of the spherical emission region and $\delta \sim 20$ is the Doppler factor for the lepto-hadronic model of Ref. [12]. One finds that Σ_χ/m_χ can be accurately fit by a power law, $\Sigma_\chi/m_\chi = A_\Sigma(\text{MeV}/m_\chi)^{B_\Sigma}$, with $B_\Sigma = 1$ for the case of $\langle\sigma_a v\rangle = 0$, and a fractional power when annihilation occurs. The parameters A_Σ, B_Σ for the benchmark models are given in Table I. Although the DM spike does not extend to arbitrary distances, the integral in (3) converges around $10R_S$ in the case of no DM annihilation, and at larger radii $\sim(10^6\text{–}10^8)R_S$ for the cases with annihilation.

Neutrino attenuation by DM.—One can make an initial estimate for the maximum DM-ν scattering cross section $\sigma_{\nu\chi}$ as being inverse to the column density Σ_χ/m_χ of the DM spike surrounding the central BH of TXS $0506+056$. To be more quantitative, we recompute the expected number of IceCube events from the 2017 flare that led to the observed event, taking into account the attenuation from scattering on DM. The analogous computation for scattering of neutrinos by galactic DM has been considered in Ref. [31]. The evolution of the flux due to scattering is described by the cascade equation,

$$\frac{d\Phi}{d\tau}(E_\nu) = -\sigma_{\nu\chi}\Phi + \int_{E_\nu}^{\infty} dE'_\nu \frac{d\sigma_{\nu\chi}}{dE_\nu}(E'_\nu \to E_\nu)\Phi(E'_\nu), \tag{4}$$

where $\tau = \Sigma(r)/m_\chi = \int^r dr \rho_\chi/m_\chi$ is the accumulated column density. The second term represents the effect of neutrino energies being redistributed, rather than simply being lost from the beam.

TABLE I. Normalization A_Σ and exponent B_Σ of power law fit to DM spike column density per mass Σ/m_χ; see Eq. (3). Models are distinguished by different values of the effective DM annihilation cross section (in units of $10^{-26}\ \text{cm}^3/\text{s}$) and the spike profile exponent α. A_Σ is in units of cm^{-2}.

$\langle\sigma_a v\rangle$	Model	α	$\log_{10} A_\Sigma$	B_Σ	Model	α	$\log_{10} A_\Sigma$	B_Σ
0	BM1	7/3	31.4	1	BM1′	3/2	31.9	1
0.01	BM2	7/3	30.0	0.48	BM2′	3/2	30.8	0.73
3	BM3	7/3	28.7	0.43	BM3′	3/2	29.5	0.66

To proceed, we must make an assumption about the energy dependence of the cross section. Below we will discuss particle physics models that predict $\sigma_{\nu\chi}(E_\nu)$. A particularly simple and well-motivated choice is linear energy dependence,

$$\sigma_{\nu\chi} = \sigma_0 E_\nu / E_0, \tag{5}$$

taking the reference energy $E_0 = 290$ TeV to be that of the observed event. Approximating the scattering as being isotropic in the center-of-mass frame, one can show that $d\sigma_{\nu\chi}/dE_\nu = \sigma_{\nu\chi}/E'_\nu = \sigma_0/E_0$. The cascade equation can be discretized, choosing equal logarithmic intervals Δx in $x = \log_{10}(E_\nu/\mathrm{TeV})$. Defining a dimensionless column density $y = (m_\chi/\Sigma_\chi)\tau$, it takes the form

$$\frac{d\Phi_i}{dy} = A\left(-\hat{E}_i\Phi_i + \Delta x \ln 10 \sum_{j=i}^{N} \hat{E}_j\Phi_j\right) \tag{6}$$

where $A = (\Sigma_\chi/m_\chi)(\sigma_0/\hat{E}_0)$, $\hat{E}_i = 10^{x_i}$ is the energy in TeV units, $\hat{E}_0 = 290$, and $y \in [0, 1]$.

To solve Eq. (6), one can either evolve the initial condition from $y = 0$ to $y = 1$ by incrementing in y, or use the algorithm presented in Ref. [32]. We have checked that both methods give the same results, resulting in the 90% Confidence Level (C.L.) limit

$$A \equiv \frac{\Sigma_\chi \sigma_0}{m_\chi \hat{E}_0} < 0.0047 \tag{7}$$

by demanding the number of events giving a neutrino of energy $E_\nu \geq 290$ TeV be greater than 0.1. The corresponding constraints in the plane of σ_0 versus m_χ are plotted in Fig. 1 for the six DM spike models. The constraint (7) can be expressed as $\sigma_0 < 1.4 m_\chi/\Sigma_\chi$, in agreement with the initial estimate. The effects of other kinds of energy dependence of $\sigma_{\nu\chi}$ are considered below [33].

We find that the constraint (7) is strengthened by a factor of ~4–10 for hadronic production models, like those of Refs. [12,22], relative to lepto-hadronic ones. In fact, a nonvanishing $\sigma_{\nu\chi}$ at such levels could reduce the too-high energies predicted by hadronic models, to better explain the IC-170922A event, but interpreted as an upper limit it is more stringent than Eq. (7), hence our adoption of lepto-hadronic models is a conservative choice.

Comparison to previous limits.—A model-independent signal of neutrino-DM interactions is the suppression in the primordial density fluctuations at temperatures ~1 eV, which would produce detectable effects in the cosmic microwave background (CMB) and matter power spectrum [34,35,38–41]. For a constant scattering cross section, Ref. [41] derived a limit of $\sigma_{\nu\chi} \lesssim 10^{-36}(m_\chi/\mathrm{MeV})$ cm^2 for massless neutrinos, which becomes weaker by about 5 orders of magnitude if a neutrino mass of ~0.06 eV is properly included [34]. A more recent analysis using

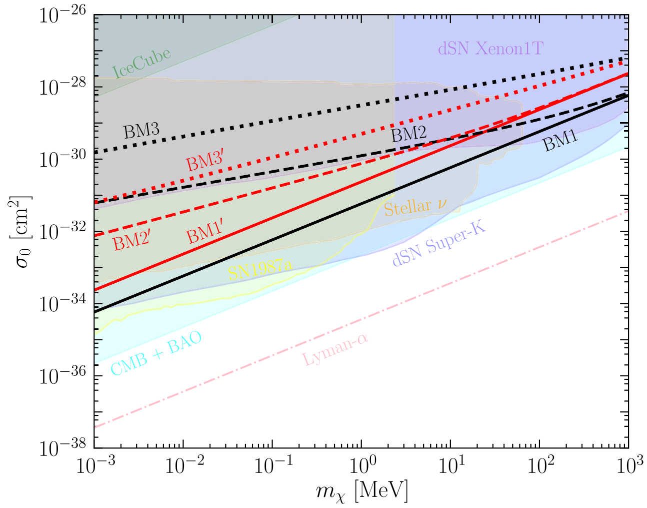

FIG. 1. 90% C.L. upper limits on the ν-DM scattering cross section at reference energy $E_0 = 290$ TeV, for the six benchmark DM spike models. Previous constraints are shown for comparison, assuming energy-independent cross section: (cyan) CMB and baryon acoustic oscillations [34], (pink) Lyman-α preferred model [35], (dark violet, blue) diffuse supernova neutrinos [2], (orange) stellar neutrinos [36], (yellow) supernova SN1987A [37], (green) IceCube bound from TXS 0506 + 056 [5].

Lyman-α forest data found a mild preference for DM interacting with massive neutrinos, which requires confirmation [35].

Besides its effect on cosmology, DM-ν scattering can also be probed in direct detection experiments and neutrino observatories, if further assumptions about the DM interaction with either leptons or nucleons are made. A prominent example involves boosting DM within our galaxy by astrophysical neutrinos such as those coming from stars [36,42], diffuse supernovae [2,43–45], or from supernova SN1987A [37], leading to larger energy deposition than could occur for light DM particles. Alternative ways to probe DM scattering with neutrinos is via attenuation of neutrino fluxes from supernovae [38,46] and the galactic center [47], delayed neutrino propagation [48–50], and through effects in the extragalactic distribution and spectra of PeV neutrinos [51,52].

Figure 2 shows a compilation of the most stringent bounds on $\sigma_{\nu\chi}$ after rescaling them to the common energy scale $E_0 = 290$ TeV, assuming Eq. (5). Here we include also constraints on DM-electron scattering, since it is natural for neutrinos and electrons to interact with DM with the same strength, as discussed next. DM-e scattering can be probed in a variety of ways. It would alter the CMB anisotropies, the shape of the matter power spectrum, and the abundance of Milky Way satellites [53–55], cause CMB spectral distortions [56,57], and heat or cool the gas in dwarf galaxies [58]. Similarly to the neutrino case, DM particles can be boosted by cosmic rays [59–79], particles in the solar interior [80] or in the relativistic jets of blazars

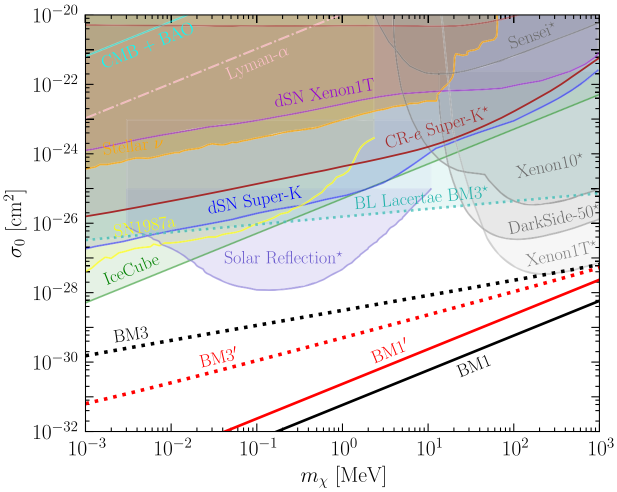

FIG. 2. Previous constraints on ν-DM and e-DM scattering, rescaled to $E_0 = 290$ TeV assuming $\sigma_{\nu\chi} \propto E_\nu$, compared to the least (BM3, BM3′) and most restrictive (BM1, BM1′) new limits of Fig. 1. The ν-DM scattering bounds are the same as in Fig. 1, while for e-DM scattering they are labeled with $\star$ and are as follows: (slate blue) solar reflection [80], (brown) Super-K for DM boosted by cosmic-ray electrons, (turquoise) blazar BL Lacertae for BM3 model [3], (gray) direct detection for light DM interacting with electrons [81–84].

[1,3] and be directly detected. Standard direct detection constraints on light DM particles can apply [81–94]. DM-electron scattering can alter the cosmic ray spectrum [95] and potentially heat neutron stars [96–98] and white dwarfs [99].

The new blazar limits on $\sigma_{\nu\chi}$ shown in Fig. 2, assuming $\sigma_{\nu\chi} \propto E_\nu$, are several orders of magnitude stronger than existing ones for sub-GeV DM, when the latter are rescaled to the blazar neutrino energy. In the case of light mediators that could lead to a constant-in-energy cross section, we lose this advantage, as shown in Fig. 1.

Particle physics models.—The simplest models for DM-ν scattering involve the exchange of a vector boson Z' between DM and neutrinos. We assume coupling g_ν to all flavors of neutrinos, and coupling g_χ to DM, taken to be a complex scalar; by dimensional analysis, the results are expected to be insensitive to the spin of the DM. [Exact expressions for $\sigma(E)$ in various models can be found in the appendix of Ref. [31].] At energies $E_\nu \gg m_\chi$, the cross section goes as

$$\sigma_{\nu\chi} \cong \frac{g_\nu^2 g_\chi^2}{4\pi m_{Z'}^2}\left[1 - \frac{m_{Z'}^2}{s}\ln\left(1 + \frac{s}{m_{Z'}^2}\right)\right], \qquad (8)$$

where $s \cong 2m_\chi E_\nu$. For $m_{Z'}^2 > m_\chi E_\nu \gtrsim 1$ GeV^2 (considering m_χ as low as 1 keV), $\sigma_{\nu\chi}$ rises linearly with E_ν by expanding the logarithm to second order in $s/m_{Z'}^2$, while for $E_\nu \gg m_{Z'}^2/m_\chi$, $\sigma_{\nu\chi}$ saturates to a constant value. The corresponding differential cross section that appears in the second term of the cascade equation (4) is

$$\frac{d\sigma_{\nu\chi}}{dE_\nu}(E'_\nu \to E_\nu) = \frac{(g_\nu^2 g_\chi^2/4\pi)(m_\chi E_\nu/E'_\nu)}{(m_{Z'}^2 + 2m_\chi(E'_\nu - E_\nu))^2}. \qquad (9)$$

This model is similar to that in Eq. (5) in having $\sigma_{\nu\chi} \propto E_\nu$ at low energy, but it is physically distinct because the differential scattering implied by (9) is not isotropic. One can show that its behavior in the cascade equation is determined by just two (dimensionless) parameters, that we take to be

$$A' = \frac{g_\nu^2 g_\chi^2 \Sigma_\chi \cdot (1\ \text{TeV})}{4\pi m_{Z'}^4}, \qquad B' \equiv \frac{m_\chi \cdot (1\ \text{TeV})}{m_{Z'}^2}. \qquad (10)$$

With this choice, A' plays the same role of A in Eq. (6) in the low-energy regime where $\sigma_{\nu\chi} \sim g_\nu^2 g_\chi^2 m_\chi E_\nu/(4\pi m_{Z'}^4)$. By solving the cascade equation on a grid of values in the A'-B'

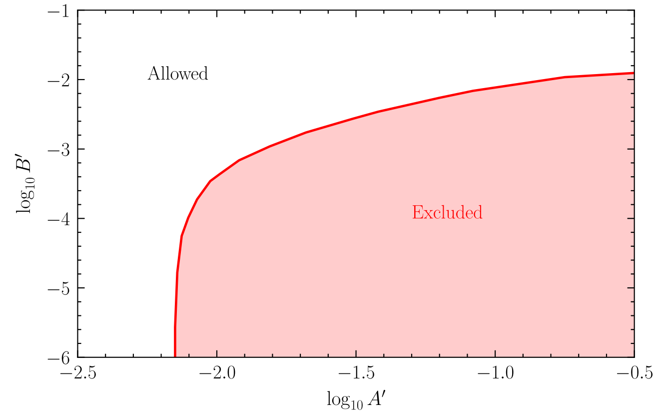

FIG. 3. Constraint on the dimensionless parameters defined in Eq. (10) in the model with a Z' mediator.

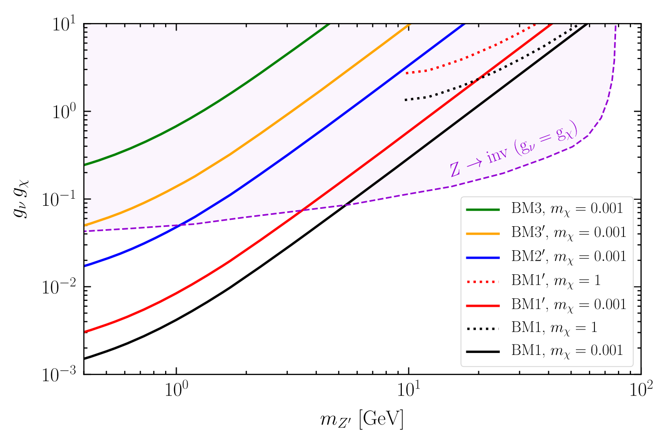

FIG. 4. Upper limit on the product of the couplings $g_\nu g_\chi$ versus $m_{Z'}$ in the vector boson mediator model, for several choices of DM spike model and mass m_χ, indicated in MeV units. Laboratory bound from $Z \to 4\nu$ [100,101] is shown for the case $g_\chi = g_\nu$.

plane, again demanding at least 0.1 predicted IceCube events above 290 TeV, we obtain the constraint shown in Fig. 3. We translate the A' versus B' bound into the microscopic model parameters, $g_\nu g_\chi$ versus $m_{Z'}$ in Fig. 4, for some choices of the DM spike models and DM masses. For comparison, the most stringent related constraint from $Z \to 4\nu$ is also shown [100,101], for the case that $g_\chi = g_\nu$. In a realistic model, Z' should couple not only to neutrinos, but to charged leptons in the $\mathrm{SU}(2)_L$ doublets, and to baryons so that the theory is anomaly-free. This leads to numerous further constraints in the parameter space of g_ν versus $m_{Z'}$, which are beyond the scope of the present work. This aspect will be considered in a follow-up paper [102].

Summary and conclusions.—It is not disputed that dark matter accumulates in the vicinity of supermassive black holes that power active galactic nuclei, but there are significant uncertainties from astrophysics, including the initial neutrino flux, the location along the jet where neutrinos are likely to be produced, the density profile of the DM spike, and the effective annihilation cross section of DM in the spike. Despite these uncertainties, we find strong and conservative constraints on the elastic scattering cross section $\sigma_{\nu\chi}$ for DM-neutrino scattering, so long as the IceCube event IC-170922A indeed came from the blazar TXS $0506 + 056$ during its 2017 flare, as is widely believed.

Since the single event has a unique neutrino energy E_0, our constraint applies to $\sigma_{\nu\chi}$ at that energy. A natural hypothesis is that such interactions arise from exchange of a massive mediator, which leads to the prediction of linear energy dependence $\sigma_{\nu\chi} = \sigma_0 E_\nu / E_0$ at sufficiently low energies. Under that assumption, we compared our limit to previous ones in the literature, which are set at much lower energies.

Even in the least optimistic case (models BM3–BM3′), our limits improve on the existing ones by several orders of magnitude, if rescaled to E_0, for sub-GeV DM masses (see Fig. 2). The stronger of our constraints (BM1–BM1′) are likely to be applicable in the case of asymmetric DM, where the effective annihilation cross section is essentially zero, due to the negligible proportion of a symmetric component that is necessary to have annihilation. Our constraints are weakened if the mediator mass is sufficiently small, which causes the cross section to stop rising with energy at a scale of order $m_{Z'}^2/m_\chi$, becoming constant at higher energies, and thereby reducing the leverage of our bound coming from the 290 TeV scale (see Fig. 1).

A further natural assumption, motivated by $\mathrm{SU}(2)_L$ gauge symmetry in the standard model, is that charged leptons should have an equal cross section with DM relative to neutrinos, allowing us to compare to existing electron-DM scattering constraints. Here too our constraints improve on previous limits, for linearly rising cross sections.

We look forward to future observations by neutrino telescopes that may confirm the multimessenger signals from blazars, and perhaps lead to refined constraints on lepton-DM scattering.

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