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Neutrino Cadence of TXS 0506+056 Consistent with Supermassive Binary Origin

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Abstract

On 2022 September 18, an alert by the IceCube Collaboration indicated that a ∼170 TeV neutrino arrived in directional coincidence with the blazar TXS 0506+056. This event adds to two previous pieces of evidence that TXS 0506+056 is a neutrino emitter, i.e., a neutrino alert from its direction on 2017 September 22, and a 3σ signature of a dozen neutrinos in 2014/2015. De Bruijn el al. showed that two previous neutrino emission episodes from this blazar could be due to a supermassive binary black hole (SMBBH) central engine where jet precession close to the final coalescence of the binary results in periodic emission. This model predicted a new emission episode consistent with the 2022 September 18 neutrino observation by IceCube. Here, we show that the neutrino cadence of TXS 0506+056 is consistent with an SMBBH origin. We find that the emission episodes are consistent with an SMBBH with mass ratios $q \lesssim 0.3$ for a total black hole mass of $M_{\rm tot} \gtrsim 3 \cdot 10^8\, M_\odot$. For the first time, we calculate the characteristic strain of the gravitational wave emission of the binary, and show that the merger could be detectable by LISA for black hole masses $< 5 \cdot 10^8\, M_\odot$ if the mass ratios are in the range $0.1 \lesssim q \lesssim 0.3$. We predict that there can be a neutrino flare existing in the still-to-be-analyzed IceCube data peaking some time between 2019 August and 2021 January if a precessing jet is responsible for all three detected emission episodes. The next flare is expected to peak in the period 2023 January to 2026 August. Further observation will make it possible to constrain the mass ratio as a function of the total mass of the black hole more precisely and would open the window toward the preparation of the detection of SMBBH mergers.

Unified Astronomy Thesaurus concepts: Neutrino astronomy (1100); Gravitational waves (678); Active galaxies (17); Blazars (164); Supermassive black holes (1663); Gamma-ray sources (633); High-energy cosmic radiation (731); Secondary cosmic rays (1438)

1. Introduction

The blazar TXS 0506+056 is of central interest in multimessenger astronomy, since several tantalizing hints of neutrino emission from this source have been published. First evidence at the 3σ level was seen when a neutrino of ∼300 TeV energy was detected in coincidence with the direction of TXS 0506+056, while an intense flare at GeV gamma-ray energies shown by the same blazar was ongoing, as detected by Fermi Large Area Telescope (IceCube Collaboration et al. 2018b). The past 10 yr of IceCube data from the direction of TXS 0506+056 were analyzed in a blind fashion subsequently, and another significant piece of evidence (3.5σ) was detected at the turn of the year 2014/2015. This potential flare was only found in an offline analysis, as it is very different in its nature as compared to the flare from 2017 September: the background deviation comes from an excess of ∼10 events at ∼10 TeV (IceCube Collaboration et al. 2018a). This is also the reason that it was not revealed by the real-time analysis, as it is only triggered for the highest-energy events, as it is only triggered for the highest-energy events with individual high signalness. For this episode in 2014/2015, the signalness comes from the large number of neutrinos in a short time interval. At the same time of the neutrino flare, the gamma-ray light curve is in a low state. The picture of a low gamma state together with a high neutrino state is puzzling to begin with, as neutrinos and gamma rays are coproduced. It can be best explained by gamma absorption as outlined later. First evidence that neutrino sources must be connected to gamma absorption was already seen in the first signal of the diffuse neutrino flux (Kimura et al. 2015; Murase et al. 2016). Even here, theoretical models are in need of gamma-ray absorption in order not to overshoot the diffuse gamma-ray flux as measured by Fermi (Murase et al. 2013; Ahlers & Halzen 2015). Further coincidences of high-energy neutrinos with blazars also point to the fact that these arrive at times of low gamma-ray activity (Kun et al. 2020). Even the IceCube event IC170922A, detected from the direction of TXS 0506+056 during a gamma-ray flare arrived at a time in which the gamma-ray emission was in a local minimum. All of these pieces of evidence point toward a scenario in which the production of high-energy neutrinos happens in very dense regions in which gamma rays are absorbed and cascade down to MeV energies (Halzen & Kheirandish 2020).

The detection of a high-energy neutrino on 2022 September 18 represents the newest piece of evidence that TXS 0506+056 is in fact a neutrino emitter. The event is detected with an estimated energy of ∼170 TeV and classified as a "bronze alert," with a signalness of 42% (Blaufuss et al. 2022). The event is centered at the direction (R.A., decl.) = ($+05^h00^m36^s$, $+03^d$ 34′48″) (J2000 coordinates), with an uncertainty of ∼3°.58 (90% containment). While typical track-like events have a much smaller uncertainty (Aartsen & IceCube 2020), this event was skimming the edge of the detector and the track is therefore not fully contained, as described in Blaufuss et al. (2022). Follow-up observations by the optical MASTER-Amur robotic telescope resulted in upper limits up to a magnitude of 18.9 (Lipunov et al. 2022). In a search of IceCube data of 1000 s and 2 days centered around the arrival time of IC220918A, no further track was found (Thwaites & IceCube Collaboration, 2022). An analysis of Fermi data reveals seven Fermi-detected sources in the 90% uncertainty interval of the event, among which the source Fermi J0502.5+0037 was newly detected in this dedicated search in 14 yr of Fermi data (Garrappa et al. 2022).

With this new event, multimessenger modeling is confronted with a third potential neutrino flare from TXS 0506+056, again somewhat different from the one in 2017, as the gamma-ray light curve is in a low state. As pointed out by Murase et al. (2018) and Reimer et al. (2019), modeling the two first flares in 2014/2015 and 2017 with the same emission model is difficult to impossible, while fitting the multimessenger data for the event IC170922A works quite well in the standard approach of high-energy cosmic rays in a blob propagating along a jet axis, interacting with ambient photons and gas targets (Gao et al. 2019; Rodrigues et al. 2019; Petropoulou et al. 2020). As the two flares are separated in time by about ∼2.5 yr, assuming that the plasmoid propagates relativistically along a jet axis, it is clear that the local environment in which cosmic rays interact with ambient targets may have changed significantly, so that even the flare properties can change with time.

In de Bruijn et al. (2020), the hypothesis of TXS 0506+056 harboring a precessing active galactic nucleus jet was made and future high-energy neutrino flares were predicted. The next flare was expected around 2019–2020, the next-to-next flare around 2022–2023. It was already argued in de Bruijn et al. (2020) that the 2019–2020 flare could still hide in the offline data of the IceCube Neutrino Observatory. The new event IC220918A falls right into the period of a potential fourth flare and therefore strengthens the hypothesis presented in de Bruijn et al. (2020).

In this paper, we substantiate the predictions of de Bruijn et al. (2020) based on the new observational evidence, and compute expectations to flaring periods and gravitational wave emission by incorporating all observed data. We perform calculations at 2.5 post-Newtonian order of the flaring behavior of a jet that is precessing due to a supermassive binary black hole (SMBBH) in the center of the active core of the galaxy. In Section 2, we present the general scheme of the model. The results, including the prediction of the timing of a third neutrino flare and the prediction of the emission of the merger of the SMBBH, as well as the expected signatures of gravitational waves of the merger, are presented in Section 3. We close with a short summary of our findings and predictions.

2. Spin–Orbit Precession Model

Massive galaxies typically host supermassive black holes, which can be formed through several mergers of smaller black holes over time (Press & Schechter 1974; Conselice et al. 2003; Caramete & Biermann 2010). It is therefore expected that a large fraction of galaxies hosts supermassive binary black holes (SMBBHs; e.g., Volonteri et al. 2003). Evidence for such SMBBH systems can be found by looking for quasiperiodic emission from jets of active galaxies, as the binary nature of the central black holes leads to the prediction of jet precession (Gergely & Biermann 2009). We apply this model of a precessing jet to the case of TXS 0506+056 and shortly summarize the model here. We base our calculations in the model presented in Kun et al. (2022), which is an extension of the model presented in de Bruijn et al. (2020). Here, it is assumed that there is a jet that is oriented along the dominant spin of the SMBBH, which is given by an angle ϕ as a function of the remaining time until the binary coalescence, $\Delta T_{\rm GW}$. The angle ϕ covers the range 0°–360° in one spin–orbit precession period and is defined to be in the plane perpendicular to the total angular momentum. We slightly modified the model of de Bruijn et al. (2020; which in turn was based on earlier work by Gergely & Biermann 2009) as described in Kun et al. (2022). The resulting description of the angle ϕ as a function of $\Delta T_{\rm GW}$ and the mass ratio of the two black holes with the heavier mass m_1 and the lighter mass m_2, $q = m_2/m_1$, is given as

$$\phi(\Delta T_{\rm GW}, q) = -\frac{2\,(4+3q)}{(1+q)^2} \times \left(\frac{5\,c}{32\,G^{1/3}M^{1/3}} \cdot \frac{(1+q)^2}{q}\right)^{3/4} (\Delta T_{\rm GW})^{1/4} + \psi. \quad (1)$$

Here, G is the gravitational constant, c is the speed of light, and $M = m_1 + m_2$ is the total mass of the SMBBH. Further, ψ is an integration constant, which gives the initial direction of the jet in the inspiral phase of the merger before it changes significantly due to spin–orbit interactions.

We apply the above model to the neutrino data by assuming that the flares from 2014/2015, 2017 September, and 2022 September come from a jet precession motion. We assume that the jet made a full rotation from the detection of the first to the second flare (2014/2015 to 2017 September). The connection between the two flares is therefore given as

$$\phi(\Delta T_{\rm GW}, q) = \phi(\Delta T_{\rm GW} - P_{\rm jet}, q) \pm \zeta. \quad (2)$$

Here, $P_{\rm jet}$ is the precession period. The parameter ζ is introduced to model the half-opening angle of the jet in the equations, which translates into the duration of the flare in terms of observables. The constant ψ in Equation (2) can be eliminated by inserting Equation (1), once as a function of $\Delta T_{\rm GW}$ and once as a function of $\Delta T_{\rm GW} - P_{\rm jet}$.

The above equations can now be used to determine the further evolution of the systems, thus also predicting future flares. In our case, we actually do know the occurrence of the fourth flare, consistent with the prediction. This helps us to further pinpoint the possible location of the third flare as described in the next section.

The results are being determined as a function of the mass ratio q, which can be constrained better the more flares have been detected.

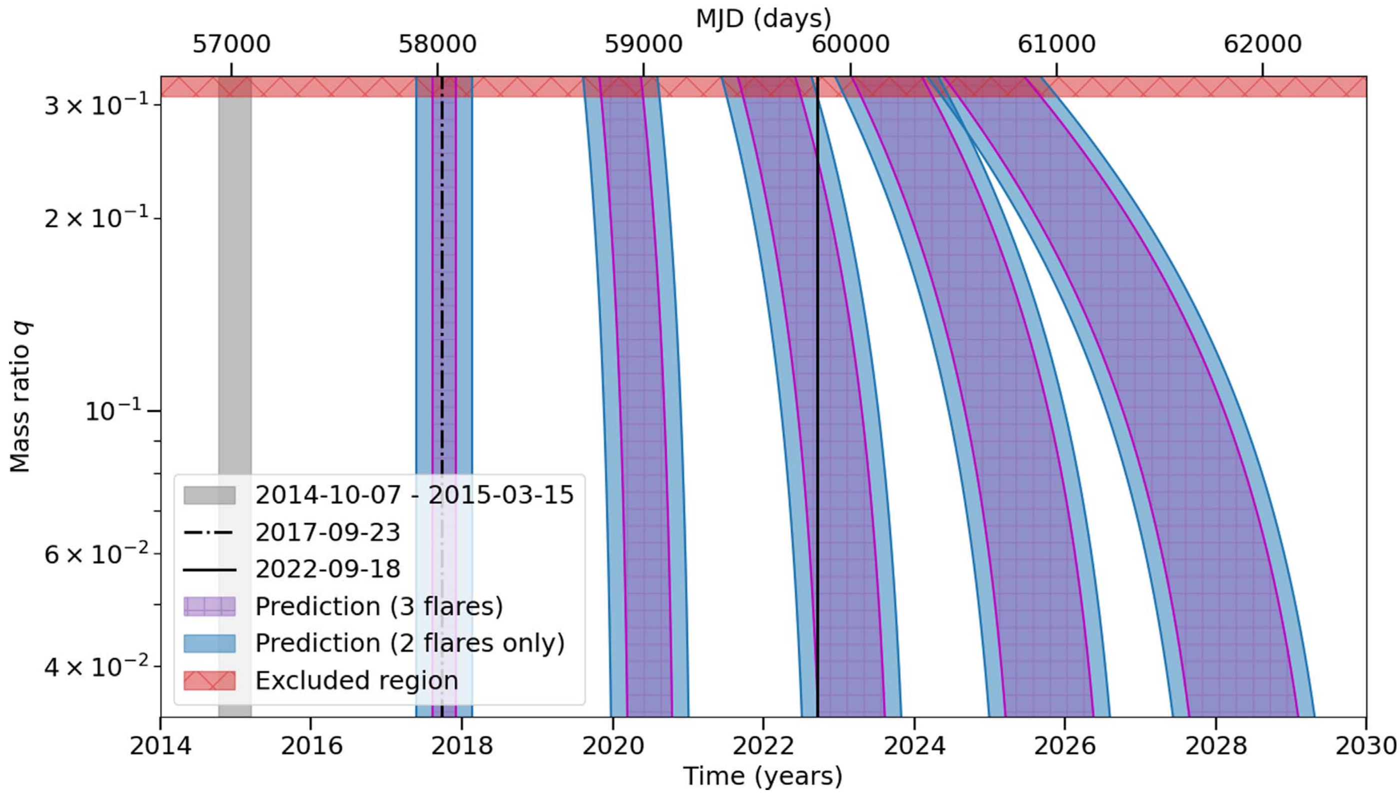

Figure 1. Prediction of the time of the neutrino flares from TXS 0506+056 in 2.5 post-Newtonian order. Mass ratios of $q > 0.3$ can be excluded by the detection of the three flares assuming a black hole mass of $M_{\rm tot} = 3 \cdot 10^8\, M_\odot$. The blue shaded regions show the predictions using the two first flares (gray shaded band and dotted–dashed line) as a starting condition; the purple, hashed regions show the prediction when including the event from 2022 September 18 (black, solid line). The exclusion region of mass ratios $q > 0.3$ is derived from the occurrence of the 2022 September 18 event. The blue and purple shaded regions around the second flare (2017 September 23) show its possible time windows assumed in this model of two respectively three flares.

3. Signal Prediction from TXS 0506+056

Figure 1 shows the flare predictions in dependence of the mass ratio q. The blue shaded areas are predictions that are using the first two flares (2014/2015, gray area and 2017 September, dotted–dashed line) only. The event on 2022 September 18 (black, solid line) falls right into the prediction of the fourth flare. Including this as a known parameter, the predictions can be specified (purple, hashed regions). In particular, the detection of the flare constrains the mass ratio of the system to $q < 0.3$, consistent with the range of typical mass ratios in the merger of 0.03–0.3 (see, e.g., Gergely & Biermann 2009). The total black hole mass of TXS 0506+056 was assumed to be $M_{\rm tot} = 3 \cdot 10^8\, M_\odot$ and was estimated by Padovani et al. (2019) using the black hole mass and bulge luminosity relationship by McLure & Dunlop (2002). In this estimation, it was assumed that the host galaxy is a typical giant elliptical with absolute R-band magnitude $M(R) \approx -22.9$ (Paiano et al. 2017). Changing the total black hole mass changes the limit on the mass ratio somewhat, i.e., to $q < 0.2$ for $M_{\rm tot} = 10^9\, M_\odot$. Thus, we cannot constrain the total mass with the model very well, but rather the combination of mass ratio and total mass. Within our model, we predict that any time between 2019 August and 2021 January a neutrino flare could exist in the still-to-be-analyzed IceCube data. We also predict the occurrence of the next flare, which should peak any time between 2023 January and 2026 August. The exact time of the flare will further constrain the mass ratio of the system as a function of the total mass.

After the submission of the manuscript, the Baikal Collaboration published the detection of a 224 ± 75 TeV neutrino with TXS 0506+056 being in the uncertainty range of the event direction (Baikal-GVD Collaboration et al. 2022). The event arrived in 2021 April, so close to the time window of our prediction, yet outside of it. There are different explanations, which make this detection compatible to our model. One option is that the event is not associated with TXS0506+056. The 90° uncertainty range of the event is given as 6°. It is a cascade event; such events are difficult in directional reconstruction, so the probability that TXS 0506+056 falls into this window by coincidence is very large. Another option would be to assume that the event indeed comes from TXS 0506+056. In that case, we can find a solution in which the 2021 April event would represent the fourth flare, and IC220918A event represents the fifth flare. With the total black hole mass $M_{\rm tot} = 3 \cdot 10^8\, M_\odot$, such a solution can be found for extremely high mass ratios of $0.38 < q < 0.66$, which are higher than the typical mass ratios of SMBBHs as discussed above, so this is why we did not consider such a solution before. If TXS 0506+056 is indeed such a rare case with a high mass ratio close to 1, then we would expect the merger to happen in the next 6 yr. Again, a neutrino flare should be hidden in the IceCube data, for this scenario in the time interval 2019 April and 2020 July.

We can further model the expected characteristic strain h_c, following Sesana (2016):

$$h_c = \sqrt{\frac{2}{3}}\, \frac{1}{r(z)}\, \frac{1}{\pi^{2/3} c^{3/2}}\, \frac{(G\mathcal{M})^{5/6}}{(1+z)^{1/2}}\, f^{-1/6}. \tag{3}$$

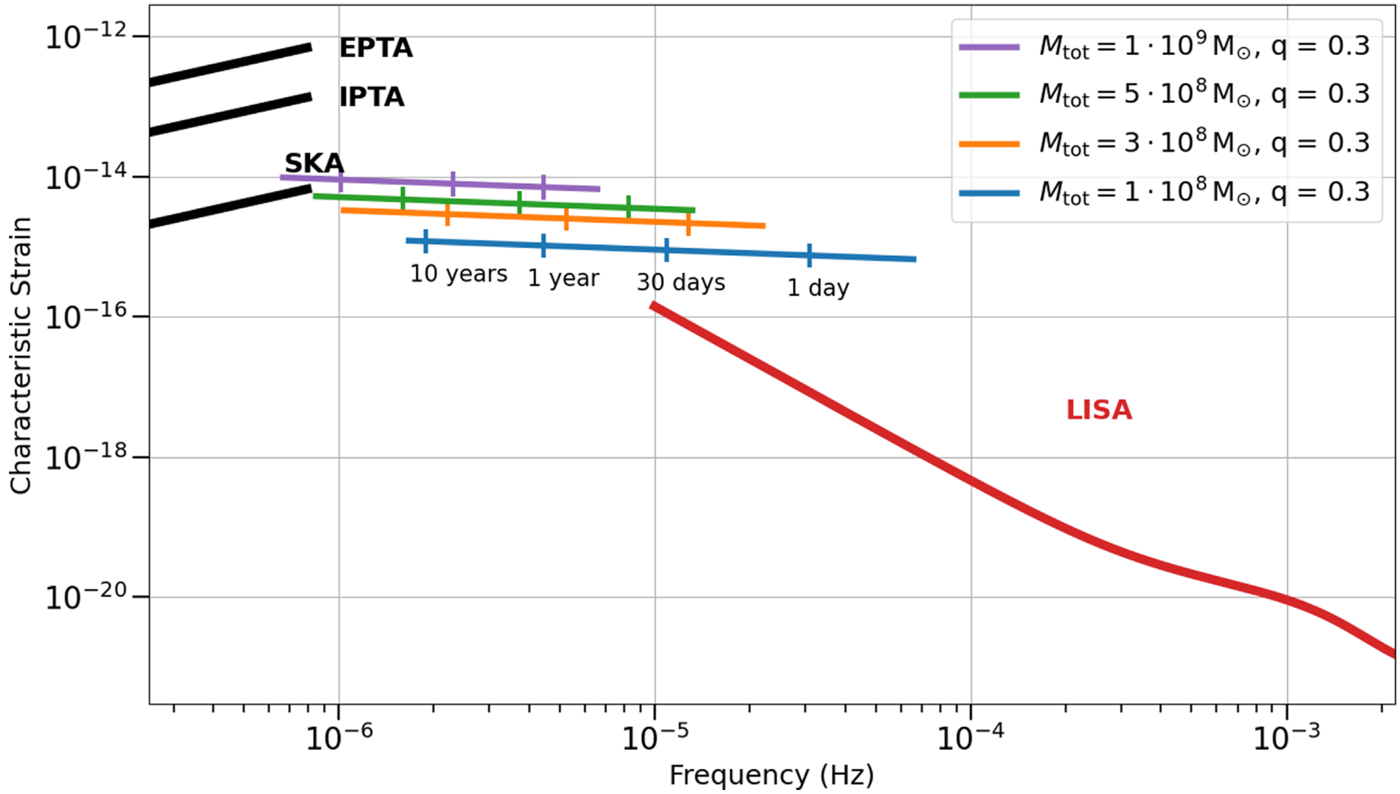

Figure 2. Characteristic strain expected for the merger of the SMBBH in TXS 0506+056 for a mass ratio of $q = 0.3$ and for different total masses. The lowest curve (blue) is for $M_{\rm tot} = 10^8\,M_\odot$, followed by orange ($M_{\rm tot} = 3 \cdot 10^8\,M_\odot$) and green ($M_{\rm tot} = 5 \cdot 10^8\,M_\odot$). The upper line (purple) shows $M_{\rm tot} = 10^9\,M_\odot$. The dashes show the time to merger (10 yr, 1 yr, 30 days, and 1 day, from the left). Except the lowest curve with $M_{\rm tot} = 10^8\,M_\odot$, the 10 yr dash is missing from the other curves as the time to merger as of today for the corresponding total masses and mass ratios is lower.

Here, $r(z)$ is the comoving source distance, $\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$ is the chirp mass, and f the observed gravitational wave (GW) frequency.

Figure 2 shows the expected characteristic strain for TXS 0506+056 for different total black hole masses and mass ratios. We show the figure for the maximum allowed mass ratio $q = 0.3$. For lower mass ratios $q < 0.3$, the intensity decreases and the strain at a fixed time to merger is shifted to lower frequencies. Four cases are shown in the figure from the top one, in order to test the detectivity of several masses: $M_{\rm tot} = 10^9$, $5 \cdot 10^8$, $3 \cdot 10^8$, $10^8\,M_\odot$ (colors: purple, green, orange, and blue, respectively). Each line shows the characteristic strain expected as a function of the time to merger for the time span from the time to merger as of today (smallest frequencies) to the moment of the merger, or rather the transition time from the inspiral to the merger according to Vecchio (2004; largest frequencies). The current and future expected sensitivity curves from three pulsar timing arrays, the European Pulsar Timing Array (five pulsars with 10 yr of observation time), International Pulsar Timing Array (20 pulsars with 15 yr of observation time), and Square Kilometer Array (SKA; 100 pulsars with 20 yr of observation time), are shown in black (Moore et al. 2015). The LISA sensitivity curve is shown in red (Robson et al. 2019). The goal for the frequency band, in which LISA is sensitive, lies between 2 and $3 \cdot 10^{-5}$ and 1 Hz, with 10^{-4} Hz until 1 Hz required (Amaro-Seoane et al. 2012, 2013, 2017). The newest LISA pathfinder results (Armano et al. 2018) show that noise down to $2 \cdot 10^{-5}$ Hz is measurable with good statistics, allowing the sensitivity band to possibly reach this low frequency. Here, we show an even more extended frequency band down to 10^{-5} Hz. Such frequencies come along with a lower signal to noise ratio (see, e.g., Amaro-Seoane et al. 2013). It remains to be seen, if LISA will be sensitive in this frequency region. Most interesting for SKA is the scenario of a heavy mass system, while LISA has easier access to the lighter black holes, simply due to the different frequency ranges. It can be seen that it will be difficult for SKA to observe this specific source, since it is too close to the final coalescence. For a successful detection with LISA, on the other hand, several cycles of GWs have to be observable. At a frequency of 10^{-5} Hz, one GW cycle takes about 1.2 days, so that the binary, entering the LISA sensitivity band, must have several days left until the merger at 10^{-5} Hz, in order to be detectable. This is the case for masses below $5 \cdot 10^8\,M_\odot$ and is helped by smaller mass ratios. Especially for lower masses of $10^8\,M_\odot$, the characteristic strains very close to the merger may happen during the uptime of LISA. So, in general what needs to happen is that the characteristic strain is at frequencies and intensities accessible to LISA, but also that the merger happens at the right time. Analyzing this parameter space, we can derive this for masses $M_{\rm tot} < 5 \cdot 10^8\,M_\odot$ and for mass ratios $0.1 \lesssim q \lesssim 0.3$. So, if the neutrino emission is confirmed to be periodic by future data, TXS 0506+056 is a clear candidate for a detection of the merger in gravitational waves.

4. Summary, Conclusions, and Outlook

In this paper, we have shown that the high-energy neutrino detected by IceCube Neutrino Observatory in spatial coincidence with TXS 0506+056 on 2022 September 18, was predicted by de Bruijn et al. (2020). With this new event, we can now sharpen the prediction of the timing of subsequent neutrino flares. We conclude that the mass ratio of the two black holes must fulfill $q < 0.3$ for masses $M_{\rm tot} > 3 \cdot 10^8\, M_\odot$. Within our model, we predict the following:

1. Neutrino flare in the unanalyzed IceCube data: a flare should be existing in the still-to-be-analyzed IceCube data with the peak emission happening any time during the period 2019 August and 2021 January.[10]
2. Upcoming neutrino flare during the lifetime of IceCube: the next flare should peak in the time period 2023 January and 2026 August. The exact time of the flare will further constrain the mass ratio of the system as a function of the total mass.
3. Possible detection of gravitational waves: in the uptime of LISA, assumed between 2034 and 2044, the parameter space allows gravitational wave detection for masses $M_{\rm tot} < 5 \cdot 10^8\, M_\odot$ and mass ratios of $0.1 \lesssim q \lesssim 0.3$.

The first flare that happened at the turn of the year 2014/2015 was also not captured by an alert, but remained hidden in the offline data until unblinding. The reason was that the signal consisted of a larger number of ∼10 events above the expected atmospheric background, which all had a relatively moderate energy (∼10 TeV) so that individual events did not trigger alerts. The difference in the signatures, together with a multiwavelength behavior that is not periodic is the largest challenge for this model. If we assume that the difference in the flaring behavior is of an intrinsic nature, what might be considered is the existence of two jets instead of one. A binary system should have two jet systems in general, but typically with one of them dominating the system (Gergely & Biermann 2009). Britzen et al. (2019) argue that there is evidence for a binary jet in the data. From a typical merger history, it is expected that the two jets can have similar precessing periods. If the jets are somewhat different in their intrinsic nature concerning parameters that determine the observables like the opening angle of the jet and the acceleration power, gas, and photon field distribution can be very different, which would explain why the nature of the 2014/2015 flare and the hidden flare in 2020 are not detectable in the IceCube alerts, while the 2017 and 2022 events are caught by the alerts. The prediction would be that one jet produces a high-intensity signal, but with an energy cutoff at ∼100 TeV proton energy (2014/2015 and 2020 flares), while the other one produces a flatter spectrum with a higher energy cutoff at ∼PeV energies. But depending on the reason for the different behavior of the different flares, it is not clear yet what the 2019/2020 and 2023–2026 flares would look like exactly.

We also note that there could be other reasons for a quasiperiodic behavior of TXS 0506+056, like the precession of a single jet, the lighthouse effect, pulsational accretion flow instabilities or the Lense–Thirring precession. In the following, we comment on these scenarios:

1. It cannot entirely be excluded that the periodic neutrino emission comes from the jet precession of a single SMBH. Such a jet precession is apparent as a periodic shift in its Doppler factor alone, with a fixed period between the flares. We find our analysis with the spin–orbit precessing binary scenario more compatible because the time between the neutrino flares seems to be decreasing, if the flare on 2022 September 18 is indeed the fourth one. Taking into account that the period is 2.78 ± 0.15 yr between the first and second neutrino flare, this would mean that $(2.78 \pm 0.15) \cdot 3 = 8.34 \pm 0.45$ yr lie between the first and forth neutrino flare, meaning that the forth neutrino flare would be expected at the earliest 2 months later, on 2022 November 2. We note that determining the duration of the 2014/2015 neutrino flare not with a Gaussian function but with another suitable function could lead to somewhat different periods, making the flare expectation not that well defined and possibly explainable with a single SMBH precession.
2. Other potential explanations for periodic neutrino flares include the lighthouse effect (Camenzind & Krockenberger 1992). However, it also does not explain a decrease in the periodic signal and is more suited in explaining periodicity on scales of several days to months. On top of that, the lighthouse effect disfavors a one zone neutrino emission model.
3. Pulsational accretion flow instabilities also only explain periodicities on scales of hours to days, but not on the scales of years (Honma et al. 1992).
4. For the Lense–Thirring precession (Lense & Thirring 1918), the accretion disk has to be massive in order for it to cause a periodicity on scales of years, but fails to explain a decrease in periodic signals.

As for the gamma-ray emission, we argue that it is not correlated to the neutrino emission, as the neutrinos are produced in a gamma-absorbed environment. There is evidence that even other potential neutrino sources represent a dense environment in which gamma rays are highly absorbed (see, e.g., Kun et al. 2020; Murase et al. 2020; Eichmann et al. 2022). These findings are in accordance with the fact that even the diffuse neutrino flux is too bright to come from transparent gamma-ray sources, because all models will overshoot the diffuse gamma-ray background for the observed spectral index.

Finally, the possible detection of the merger by LISA opens the exciting possibility of following up on a periodic neutrino source until the merger is detectable in gravitational waves years to decades later. This way, we are starting to finally identify binary black hole (BBH) mergers early on and to understand their physics by connecting multimessenger data of gamma rays, neutrinos, and gravitational waves.

In order to establish this model of a precessing jet, more data especially from IceCube are needed. Once a periodicity can be confirmed in neutrinos, a theoretical model including all wavelengths can be developed. We can also learn from the measurements of the diffuse flux as discussed in Jaroschewski et al. (2022). Here, we evaluate the possibility that the detected diffuse flux is composed of the emission from a combination of SMBBHs and BBHs, as suggested by the ultrahigh-energy cosmic-ray data. We find that the fraction of energy that has to go into the production of neutrinos with respect to the gravitational wave energy is on the order of $\sim 10^{-6}$–$3 \cdot 10^{-4}$, and the data require an SMBBH merger rate of $\sim 10^{-7}$ and 10^{-5} Gpc^{-3} yr^{-1} on average. For stellar mass BBH mergers, the energy fraction going to neutrinos is on the order of $\sim 2 \cdot 10^{-5}$–10^{-3}, and the merger rate needs to be ∼10–100

[10] This is possible if the flare can be detected by a larger number of neutrinos in the TeV range, rather than one neutrino at 100–1000 TeV. While the latter case would become visible in the real-time analysis, the former can only be found in a dedicated offline analysis, which has not been performed in a time-dependent way yet.

Gpc^{-3} yr^{-1}. These values are in concordance with our current knowledge of such mergers, so the idea of SMBBHs (and BBHs) contributing significantly to the flux of high-energy neutrinos in the universe is very promising.

For now, this paper makes very precise predictions of what to expect from TXS 0506+056 in the near future, which makes this a model that can be tested on short timescales and adds to the fact that this is an exciting time for multimessenger astronomy.

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