Constraints on Neutrino Natal Kicks from Black-Hole Binary VFTS 243

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The recently reported observation of VFTS 243 is the first example of a massive black-hole binary system with negligible binary interaction following black-hole formation. The black-hole mass ($\approx 10 M_\odot$) and near-circular orbit ($e \approx 0.02$) of VFTS 243 suggest that the progenitor star experienced complete collapse, with energy-momentum being lost predominantly through neutrinos. VFTS 243 enables us to constrain the natal kick and neutrino-emission asymmetry during black-hole formation. At 68% confidence level, the natal kick velocity (mass decrement) is $\lesssim 10$ km/s ($\lesssim 1.0 M_\odot$), with a full probability distribution that peaks when $\approx 0.3 M_\odot$ were ejected, presumably in neutrinos, and the black hole experienced a natal kick of 4 km/s. The neutrino-emission asymmetry is $\lesssim 4\%$, with best fit values of ~0–0.2%. Such a small neutrino natal kick accompanying black-hole formation is in agreement with theoretical predictions.

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Introduction.—Stars several times more massive than the Sun end their lives with the collapse of their iron cores. The explosion mechanism and the physics driving the formation of the compact object are still a matter of intense research [1–8]. In the delayed neutrino-driven mechanism, neutrinos revive the stalled shock wave, eventually leading to a successful explosion. In this case, the stellar mantle is successfully ejected and the compact-object remnant is a neutron star (NS) in most cases. However, if the explosion mechanism fails, continuous accretion of matter onto the transiently stable proto-NS pushes the latter over its mass limit and a black hole (BH) forms.

The extreme speeds of pulsars [9–11] indicate that NSs experience a natal kick during formation [12]. This natal kick is attributed mainly to asymmetric mass ejection, but asymmetric neutrino emission may contribute [13–21]. Simulations of the collapse of massive stars show that hydrodynamical instabilities leading to large-scale asymmetries in the mass distribution—such as neutrino-driven convection [22–24], the standing accretion shock instability [25,26], or the lepton emission self-sustained asymmetry instability [27,28]—could also have important consequences on the natal kick of the compact remnant [16–18,27]. In addition, fast rotation and the presence of magnetic fields at the moment of collapse are likely to affect the natal kick [16].

In the extreme scenario of *complete collapse* into a BH, the ejecta mass and natal kicks are thought to be very low (~1–10 km/s) [29–31]. In this case, mass-energy is lost via neutrinos and, to a lesser extent, gravitational waves [1,21]. This differs from the archetypical scenario in which anisotropic baryonic ejecta are the main carriers of momentum [32].

Observations of stellar-mass BHs in high-mass x-ray binaries (HMXBs) have been employed to constrain the impact of natal kicks of collapsing stars on the orbital configuration of massive binary systems [33–35]. HMXBs are binary systems comprising OB-type stars that transfer matter via stellar winds [36] to their compact-object companion [37]. To date about 150 HMXBs have been discovered in the Milky Way, but only a handful of these are associated with BH companions [38,39].

Recently, spectroscopy [40–43] and astrometry [44,45] have allowed the first detection of *inert* (i.e., x-ray quiescent or dormant) stellar-mass BH binaries [46] in the field [47]. This population of BH binaries is especially intriguing. These objects have wider orbital periods than HMXBs and the stellar companions are well within their Roche lobes. This configuration, which implies little interaction following BH formation [49], makes inert BH binaries better probes of natal kicks than HMXBs. In this Letter, we present direct inference on neutrino natal kicks for the most massive inert BH detected to date: VFTS 243 [41]. Our findings are summarized in Fig. 1.

For BH binaries, the plausibility of the complete collapse scenario can be assessed because the impact on the orbital evolution of mass ejection (dM) and a natal kick ($v_{\rm kick}$) during compact-object formation on binary star systems are well understood [67–69]. For example, near-instantaneous (quasi)spherically symmetric mass ejection during the stellar collapse results in a recoil (the Blaauw effect [70]) that leads to a systemic velocity of the binary as a whole, widens the orbit, makes it more eccentric, and can even disrupt the binary [71]. On the other hand, asymmetries in the ejected mass lead to a wider variety of configurations, potentially modifying the separation (increase or decrease), eccentricity, and inclination of the orbit. Such asymmetries could play an important role in the formation of BH-BH mergers [72], BH HMXBs [73], and inert BH binaries [74,75].

Properties of VFTS 243.—VFTS 243 belongs to the family of inert BH binaries recently discovered in the Milky Way [43] and the Large Magellanic Cloud [41] via spectroscopy (Fig. 2). It comprises a main-sequence O star with inferred mass of $M_* = 25.0 \pm 2.3 M_\odot$ and a BH companion with $M_{\rm BH} = 10.1 \pm 2.0 M_\odot$, orbital period of $P = 10.4031 \pm 0.0004$ d, and eccentricity $e = 0.017 \pm 0.012$, where the errors are the 1σ uncertainty intervals [41]. The relatively high mass of the BH and the nearly circular orbit suggest that the system experienced complete collapse. With a stellar radius (R) well within the binary Roche lobe ($f_{\rm RL} = R/R_{\rm RL} \approx 0.33$) [41], VFTS 243 is a relatively wide BH binary (for example, in contrast, Cygnus-X1 is close to filling its Roche lobe with $f_{\rm RL} \gtrsim 0.99$ [76,77]). Moreover, the supersynchronously rotating massive star of VFTS 243 suggests that the effects of tides in synchronizing and circularizing the orbit are negligible [41].

Constraints on natal kicks.—In order to analyze the formation of VFTS 243, we use a semianalytic approach [34] to calculate the probability that a circular

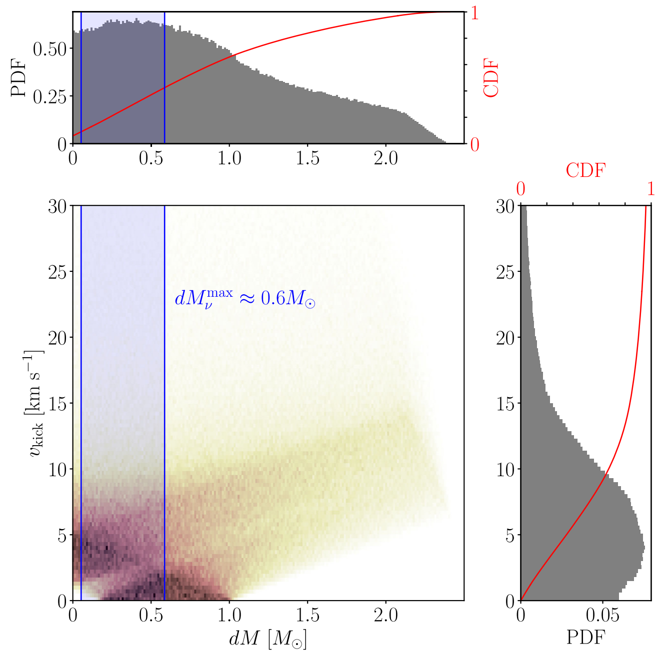

FIG. 1. Constraints on the natal kick from VFTS 243. This figure shows the probability distribution of matching the current orbital period, eccentricity, and systemic velocity of VFTS 243, given a certain mass loss (dM) and natal-kick magnitude ($v_{\rm kick}$) following BH formation. In the heat map, darker (lighter) regions indicate a higher (lower) probability for a certain dM-$v_{\rm kick}$ pair to reproduce the orbital configuration of VFTS 243. The blue shaded region, delimited by the solid blue vertical lines, shows the estimates for neutrino mass-loss decrements from stellar models of BH progenitors [66]. The side panels display the marginalized probability distribution functions (PDF, gray histograms) and cumulative distribution functions (CDF, red curves). With CDF($dM = 1.0 M_\odot$) = CDF($v_{\rm kick} = 10$ km/s) = 0.68, we conclude that solutions with low mass loss and small natal kicks are preferred. The marginalized distributions peak at around $dM = 0.3 M_\odot$ and $v_{\rm kick} = 4$ km/s, which is consistent with a solution where the mass decrement comes exclusively from neutrino emission.

precollapse binary that received a natal kick during BH formation could reproduce the orbital configuration of the system as observed today. Models of the precollapse binary suggest it initially had a short (~1 d) orbital period and experienced mass transfer [41]. For such configurations, the tidal circularization timescale (~10^4 yr [78]) is significantly shorter than the time the stars spend on the main sequence (~10^6 yr [79]) prior to BH formation. Therefore, we assume the binary was circularized prior to collapse. Given that the current configuration is barely eccentric, it is reasonable to assume that the orbit was circular and the marginal eccentricity was induced during BH formation. Alternatively, the current eccentricity could be a small residual from incomplete circularization via tides prior to collapse. For the precollapse orbital configurations we assume independent, uniform wide

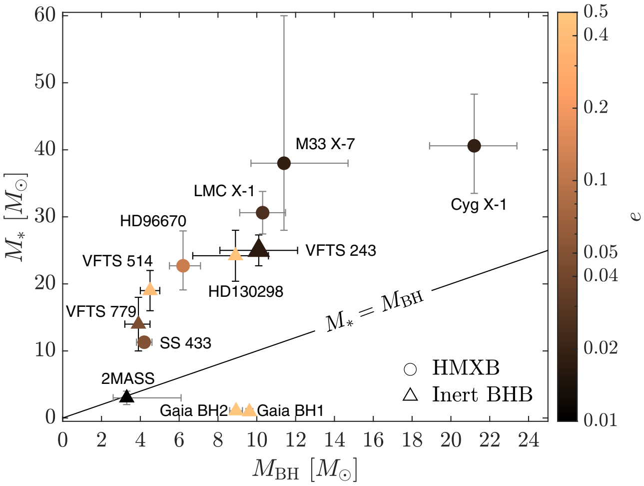

FIG. 2. Observed sample of field black-hole (BH) binaries with massive companions. For each binary, we show the BH mass ($M_{\rm BH}$) on the abscissa, the stellar companion mass (M_*) on the ordinate, and the eccentricity (e) through the color bar. We use circles to indicate high-mass x-ray binaries (HMXBs) and triangles for inert BH binaries (Inert BHB). The symbol of VFTS 243 is slightly larger for clarity.

prior distributions on the orbital period between $5 \leq P_i/\mathrm{d} \leq 15$, on the natal-kick magnitudes between $0 \leq v_{\rm kick}/(\mathrm{km/s}) \leq 200$ and on the amount of mass ejected between $0 \leq dM/M_\odot \leq 5$. We also assume that the direction of the imparted natal kick is isotropic. We use the postcollapse orbital period, eccentricity, and systemic radial velocity as independent constraints [49], which we justify by the lack of correlation in the observationally inferred orbital parameters [41].

Figure 1 shows the results of our analysis. The heat map presents two distinct hot spots. In the limit where $v_{\rm kick} \to 0$, we have the solution for pure mass loss (Blaauw effect [70]), where the amount of ejected mass is linearly proportional to the newly acquired eccentricity of the binary. The other spot has $dM \to 0$, i.e., a very small amount of mass is ejected asymmetrically in the frame of reference of the exploding star, and a natal kick makes the orbit eccentric. The marginalized one-dimensional probability distributions have modes at $dM \approx 0.3 M_\odot$ and $v_{\rm kick} \approx 4$ km/s. Explosions with moderate mass loss ($\gtrsim 1 M_\odot$) and natal kicks ($\gtrsim 10$ km/s) can occur (see yellow in the heat map from Fig. 1), but require natal kick directions and magnitudes fine-tuned to balance the mass loss in order to form a low-eccentricity BH binary [74], as demonstrated by the diagonal structure of Fig. 1. Under the assumption that the binary was circular prior to BH formation and has a small but nonzero eccentricity at present, there is no support for a solution with $dM = v_{\rm kick} = 0$.

In Fig. 1, the vertical blue band shows the estimated mass decrements associated with the total radiated neutrino energies of collapsing stripped stars [66]. Numerical simulations of the collapse of massive stars without concomitant supernova explosion in 2D [31] and 3D [80] by the Garching group yield final neutrino-induced BH kick velocities of magnitudes similar to those favored by our analysis of VFTS 243 (0–4 km/s), in particular also for a precollapse stellar model with similar mass. Contesting 3D simulations by the Princeton group found that the final neutrino-induced natal kick velocities of BHs formed via failed supernovae could be larger (7–8 km/s [81]), but still within our 1-σ credible intervals. These quantitative differences may be connected to different life times of the NS prior to BH formation or to intrinsic differences of the neutrino asymmetries due to transport.

Under the hypothesis of complete collapse, we perform a back-of-the-envelope estimate on long-term ($\gg 1$ s) neutrino asymmetries during BH formation. We follow Refs. [14,29] and parametrize the linear momentum transferred to the BH as a result of anisotropic neutrino emission as

$$M_{\rm BH} v_{\nu,\rm kick} = \alpha_\nu E_\nu^{\rm tot}/c = \alpha_\nu dM_\nu c, \tag{1}$$

where α_ν is the neutrino emission asymmetry factor, $v_{\nu,\rm kick}$ is the neutrino natal kick, dM_ν is the mass decrement from neutrino emission, and c is the speed of light in vacuum. To estimate α_ν and $v_{\nu,\rm kick}$ we assume the following (see [49] for more details). We choose $M_{\rm BH} = 10 M_\odot$, similar to VFTS 243. We obtain the interval $E_\nu^{\rm tot} \approx 1\text{–}11 \times 10^{53}$ erg from the stripped-star BH progenitors from Ref. [66]. Finally, the value of $v_{\nu,\rm kick}$ is determined by obtaining the subset of the complete natal kick probability distribution that is consistent with complete collapse. These assumptions result in an upper limit on the neutrino asymmetry of ≈4%, where 0% implies spherically symmetric neutrino emission (in the rest frame of the NS), and 33% implies that the dipole component of the neutrino luminosity equals the monopole amplitude [80]. However, the asymmetries are between ~0–0.2% for the most likely solution of $v_{\nu,\rm kick} \approx 3$ km/s [49], though a solution with no natal kick is allowed. These values are in overall agreement with the estimates of the anisotropy parameter of the total neutrino emission in recent 3D core-collapse simulations with detailed neutrino transport, namely 0.45%–0.76% for successful supernova explosions [80] and 0.05%–0.15% in simulations of nonexploding models [80] (see, however, Ref. [21], which reports considerably higher values, probably because of differences in the analysis).

Discussion.—Our results provide evidence of neutrino-induced natal kicks and add strong support to the complete collapse formation scenario [41]. In general, the total natal kick of a compact object has a baryonic, neutrino, and gravitational-wave component. If matter ejection in a successful explosion takes place, it generally dominates the total kick for higher-mass progenitors [32,80,82,83], and gravitational waves contribute to the natal kick negligibly, since they carry orders of magnitude less energy with respect to baryons and neutrinos (e.g., [31,83]). Our calculations provide constraints on the total natal kick and mass loss, which we find to be largely in agreement with mass loss exclusively through neutrino emission and an associated natal kick, rather than baryonic mass ejecta. Depending on the magnitude and direction, a natal kick from baryonic ejecta [75] could further reduce our limit on neutrino natal kicks. Alternatively, there could be a yet-to-be-determined physical mechanism that results in baryonic and neutrino kicks of a similar magnitude that are antialigned and almost completely cancel.

Astrometric microlensing has been suggested as a method to constrain BH natal kicks [84,85]; as long as the observed velocity dispersion is much larger than the presumed neutrino kicks, the latter are unconstrained. The entire BH kick distribution cannot be completely explored with bound binaries [71], but systems similar to or more massive than VFTS 243 are ideal to explore and constrain low natal kicks. The broad implications of the natal kick that VFTS 243 received during BH formation has been recently investigated in the literature [41], showing support for small [75] and moderate natal kicks [74]. The solution of very low natal kicks for VFTS 243 is in agreement with neutrino kick estimations from hydrodynamical simulations [31,86,87]. In particular, recent hydrodynamical simulations of core-collapse events yield a range of model-dependent neutrino kicks between ≈0–4 km/s in 2D [31] and between ≈0–3 km/s in 3D [80,87]. However, other simulations of BH-forming collapses produce neutrino natal kicks between 30 km/s $\lesssim v_{\nu,\mathrm{kick}} \lesssim$ 100 km/s [21], which would be partially compatible with the tail of our distribution in Fig. 1 but may be difficult to reconcile with other existing theoretical constraints, if confirmed.

For BH progenitors that have been stripped during a mass transfer episode, the complete collapse scenario suggests almost no baryonic ejecta and a mass decrement exclusively from neutrinos. A very massive proto-NS can lead to a total neutrino energy emission of $E_\nu^{\mathrm{tot}} \approx 10^{54}$ erg [66], which roughly corresponds to a neutrino mass decrement of $dM_\nu^{\max} \approx 0.6 M_\odot$. Therefore, $dM < 0.6 M_\odot$, and more realistically $0.1 \lesssim dM/M_\odot \lesssim 0.4$ [49], is consistent with natal kicks induced from neutrino emission exclusively [66]. Alternatively, $dM \gtrsim 0.6 M_\odot$ implies at least some baryonic-mass ejecta.

In addition to VFTS 243, several other inert BH binaries have been recently reported: HD 130298 [43], Gaia BH1 [44,88], and Gaia BH2 [45], as well as inert BH binary candidates 2 MASS J05215658 + 4359220 [89,90], HD 96670 [40], VFTS 514 [42], and VFTS 779 [42], all of them presented in Fig. 2. Arguably, the most atypical systems in the sample are the astrometric BH binaries Gaia BH1 and Gaia BH2. With massive BHs ($M_{\mathrm{BH}} \approx 10 M_\odot$), they are at wide orbital periods (≳100–1000 d), have low-mass ($M_* \approx 1 M_\odot$) companions and possibly formed dynamically [91,92], which could explain their large eccentricity ($e \approx 0.5$), putting them in a different class with respect to the other BH binaries, whose assembly is more in line with that of stellar binaries [46].

The sample of single line spectroscopic (SB1) inert BH binaries is diverse (Fig. 2). VFTS 243 is the most massive and least eccentric of SB1 BH binaries. HD 130298 is slightly less massive than VFTS 243 (with $M_{\mathrm{BH}} \approx 9 M_\odot$ and $M_* \approx 24 M_\odot$), has a similarly small Roche-lobe filling factor ($f_{\mathrm{RL}} = 0.26$) and a similar orbital period ($P_{\mathrm{orb}} \approx 15$ d), but it is quite eccentric ($e \approx 0.5$). VFTS 514 is even less massive (with $M_{\mathrm{BH}} \approx 5 M_\odot$ and $M_* \approx 19 M_\odot$) and is also quite eccentric ($e \approx 0.4$); with a long orbital period ($P_{\mathrm{orb}} \approx 185$ d), it is likely far from Roche-lobe overflow. VFTS 779 is the least massive of the SB1 BH binaries (with $M_{\mathrm{BH}} \approx 4 M_\odot$ and $M_* \approx 14 M_\odot$), has a near circular orbit ($e \approx 0.02$) and a long orbital period (≈60 d). The spectral type of the star of VFTS 779 indicates it has evolved past the main sequence [42]; at this stage, it is developing a convective envelope that makes tidal circularization orders of magnitude more efficient than for main-sequence stars with radiative envelopes [49].

The sample of BH HMXBs [39,93] is broader in the mass parameter space, but otherwise is more homogeneous (Fig. 2). Most BH HMXBs have short orbital periods ($P_{\mathrm{orb}} < 6$ d), small eccentricities ($e \lesssim 0.1$), and large Roche-filling factors ($f_{\mathrm{RL}} \gtrsim 0.9$). Large Roche-filling factors in HMXBs are in agreement with the theory of wind-accreting x-ray binaries, which predicts a threshold of $f_{\mathrm{RL}} \gtrsim 0.8$–0.9 as a condition for observability [94]. Cygnus X-1 is the archetype of BH HMXBs, with $M_{\mathrm{BH}} \approx 21 M_\odot$ and $M_* \approx 41 M_\odot$, a short-day orbital period ($P_{\mathrm{orb}} \approx 6$ d), a large Roche-lobe filling factor ($f_{\mathrm{RL}} > 0.99$), and a near-circular orbit ($e \approx 0.02$). While the eccentricities of Cygnus X-1, LMC X-1, and M33 X-1 are similar to that of VFTS 243, both wind accretion onto the compact object [35,78] and tides could have played a role in circularizing these BH HMXBs. For massive, main-sequence stars with radiative envelopes, the dynamical tide is the dominant tidal dissipation mechanism [95]. Dynamical tides are not an efficient dissipation mechanism for VFTS 243 [42], the most compact inert BH binary detected to date. The circularization timescale via dynamical tides is a strong function of the separation [$\tau_{\mathrm{circ}} \propto (a/R)^{21/2}$ [96], where a is the semimajor axis of the binary], which implies that tides are significantly less efficient for the SB1 sample than for the observed BH HMXBs. For example, doubling the orbital period of Cygnus X-1 would result in a similar period to VFTS 243 and would reduce the impact of tides by ∼2 orders of magnitude. Moreover, HD 130298 has rather similar properties (masses, periods, and Roche-filling factors) to VFTS 243, but is rather eccentric; this demonstrates that dynamical tides are not efficient at circularizing the orbit at such large separations.

Finally, we highlight that for BH binaries with $M_* > M_{\mathrm{BH}}$ there seems to be a sharp drop in eccentricity for systems with $M_{\rm BH} \gtrsim 10 M_\odot$. We speculate that this drop could denote the transition between luminous, mass-shedding explosions and complete collapse [97–100]. The early theory of stellar collapse suggested that less massive cores eject some mass during BH formation, while complete collapse could only occur for cores of mass $\gtrsim 11 M_\odot$ [101]. However, a growing body of theoretical work shows evidence that the compact-object remnant mass function is a nonmonotonic function of mass [1,6,102–111] that could even be stochastic [112], dependent on initial rotation and composition [113], and that might be affected by binary interactions [114–116]. This means that more massive stars do not always result in more massive compact objects; some stellar cores above a certain threshold can result in mass-shedding explosions and form NSs [117]. Based on the sharp eccentricity transition between HD 130298 and VFTS 243 (both SB1 BH binaries with similar masses and orbital periods) and the results presented in this Letter, we consider that helium cores with a mass of $\approx 10 M_\odot$ could undergo complete collapse. However, this does not rule out the possibility that complete collapse occurs for less massive stars, or that incomplete collapse returns at higher masses. Future observations should provide more precise values on the actual mass threshold for complete collapse.

Conclusions.—We explore the effect of mass loss and natal kicks during BH formation in VFTS 243, the heaviest inert stellar-mass BH binary detected to date. Our results show that the marginalized distributions peak around $dM = 0.3 M_\odot$ and $v_{\rm kick} = 4$ km/s, respectively; these values are consistent with recent simulations of the stellar collapse predicting mass loss via neutrino emission exclusively [66], fully in agreement with the complete collapse scenario [102]. Under the hypothesis of complete collapse, we estimate the asymmetry in the neutrino emission to be ~0%–0.2% and provide an upper limit of ≈4%. We find that mass loss $\lesssim 1.0 M_\odot$ and $v_{\rm kick} \lesssim 10$ km/s are preferred at a 68% confidence level, in agreement with other studies in the literature [41,75]. Moreover, our results also accommodate solutions with no natal kick and no asymmetries in neutrino emission. The progenitor of the BH component of VFTS 243 is likely a massive stripped star [42] that experiences negligible mass loss during BH formation. Following recent observations of inert BH binaries in the Local Group (Fig. 2), we suggest that complete collapse can occur for stars that end their lives with cores of $\gtrsim 10 M_\odot$.

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