IMPLICATIONS OF RECOIL KICKS FOR BLACK HOLE MERGERS FROM LIGO/VIRGO CATALOGS

GIACOMO FRAGIONE$^{1, 2}$, ABRAHAM LOEB$^3$

$^1$Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA), Evanston, IL 60202, USA
$^2$Department of Physics & Astronomy, Northwestern University, Evanston, IL 60202, USA
$^3$Astronomy Department, Harvard University, 60 Garden St., Cambridge, MA 02138, USA

Draft version November 19, 2020

ABSTRACT

The first and second Gravitational Wave Transient Catalogs by the LIGO/Virgo Collaboration include 50 confirmed merger events from the first, second, and first half of the third observational runs. We compute the distribution of recoil kicks imparted to the merger remnants and estimate their retention probability within various astrophysical environments as a function of the maximum progenitor spin ($\chi_{\text{max}}$), assuming that the LIGO/Virgo binary black hole (BBH) mergers were catalyzed by dynamical assembly in a dense star cluster. We find that the distributions of average recoil kicks are peaked at about 150 km s$^{-1}$, 250 km s$^{-1}$, 350 km s$^{-1}$, 600 km s$^{-1}$, for maximum progenitor spins of 0.1, 0.3, 0.5, 0.8, respectively. Only environments with escape speed $\gtrsim 100$ km s$^{-1}$, as found in galactic nuclear star clusters as well as in the most massive globular clusters and super star clusters, could efficiently retain the merger remnants of the LIGO/Virgo BBH population even for low progenitor spins ($\chi_{\text{max}} = 0.1$). In the case of high progenitor spins ($\chi_{\text{max}} \gtrsim 0.5$), only the most massive nuclear star clusters can retain the merger products. We also show that the estimated values of the effective spin and of the remnant spin of GW170729, GW190412, GW190519, and GW190620 can be reproduced if their progenitors were moderately spinning ($\chi_{\text{max}} \gtrsim 0.3$), while for GW190517 if the progenitors were rapidly spinning ($\chi_{\text{max}} \gtrsim 0.8$). Alternatively, some of these events could be explained if at least one of the progenitors is already a second-generation BH, originated from a previous merger.

1. INTRODUCTION

The LIGO/Virgo Collaboration has recently released the second Gravitational Wave Transient Catalog (GWTC-2), which includes events from the first half of the third observational run (Abbott et al. 2020b). In addition to the events in the first catalog GWTC-1 from the first two observational runs (Abbott et al. 2019), 50 confirmed events have been reported, revolutionizing our understanding of black holes (BHs) and neutron stars (NSs). Thanks to the growing number of detected events, the distributions of masses, spins, and merger rates can be constrained with unprecedented statistical precision and GW events provide a unique opportunity to probe fundamental physics (Abbott et al. 2020c,d).

The origin of binary mergers is still highly uncertain, with several possible scenarios that could potentially account for most of the observed events (e.g., Antonini & Perets 2012; Belczynski et al. 2016; Ascar et al. 2017; Bartos et al. 2017; Giacobbo & Mapelli 2018; Liu & Lai 2018; Banerjee 2018; Fragione & Kocsis 2018; Rodriguez et al. 2018; Fragione et al. 2019; Fragione & Kocsis 2019; Hamers & Samsing 2019; Kremer et al. 2019; Rasskazov & Kocsis 2019; Fragione & Silk 2020; Mapelli et al. 2020). Other processes include stellar mergers, formation of BHs from Population III stars, or growth via accretion in an AGN disk (e.g., Kinugawa et al. 2020; Kremer et al. 2020; Tagawa et al. 2020; van Son et al. 2020). The main barrier to the formation of second- (or higher-) generation BHs via hierarchical mergers stems from the recoil kick imparted to the merger remnant as a result of anisotropic GW emission (Lousto et al. 2010, 2012), which could eject it from the parent stellar cluster (e.g., Fragione et al. 2018a,b). Therefore, the relative magnitude of the cluster escape speed, set by its mass and density, compared to the magnitude of the recoil kick determines the maximum mass achievable through repeated mergers.

Assuming that LIGO/Virgo BBH mergers were catalyzed by dynamical assembly and interactions in a dense star cluster (e.g., Wong et al. 2020), we compute the distribution of recoil kicks imparted to their merger remnants and estimate their retention probability within various astrophysical environments. If the retention probability is high enough, the remnants of LIGO/Virgo BBH mergers could eventually form a new binary and merge again (e.g., Antonini et al. 2019; Fragione & Silk 2020; Mapelli et al. 2020).

The Letter is organized as follows. In Section 2, we describe the method we use to compute the recoil kicks imparted to merger remnants from anisotropic gravitational wave emission. In Section 3, we present the results of our calculations. Finally, in Section 4, we draw our conclusions.

2. METHOD

We model the recoil kick following Lousto et al. (2010, 2012)

$$v_{\text{kick}} = v_{m} \hat{e}_{\perp,1} + v_{\perp} (\cos \xi \hat{e}_{\perp,1} + \sin \xi \hat{e}_{\perp,2}) + v_{||} \hat{e}_{||},$$

(1)
\[ v_m = A \eta^2 \sqrt{1 - 4\eta(1 + B\eta)} \]  
\[ v_{\perp} = \frac{H\eta^2}{1 + \eta^2}(\chi_{2,\perp} - q\chi_{1,\perp}) \]  
\[ v_{\parallel} = \frac{16\eta^2}{1 + \eta^2}[V_{1,1} + V_A\delta\perp + V_B\delta_{1,\perp} + V_C\delta_{1,\parallel}] \times \]  
\[ \times |\chi_{2,\perp} - q\chi_{1,\perp}| \cos(\phi_{\Delta} - \phi_1). \]  

where \[ q = m_2/m_1 \] is the mass ratio, \( q = m_2/m_1 < 1 \) is the binary mass ratio, \( m_1 \) and \( m_2 \) are the masses of the merging BHs, and \( |\chi_1| \) and \( |\chi_2| \) the magnitudes of their dimensionless spins. The \( \perp \) and \( \parallel \) refer to the directions perpendicular and parallel to the orbital angular momentum, respectively. Finally, \( \hat{e}_{\perp,1} \) and \( \hat{e}_{\perp,2} \) are orthogonal unit vectors in the orbital plane. We also define

\[ \bar{S} = 2\frac{\chi_{2,\perp} + q\chi_{1,\perp}}{(1 + q)^2}, \]  
with \( \phi_1 \) as the phase angle of the binary, and \( \phi_{\Delta} \) as the angle between the in-plane component of the vector

\[ \Delta = M^2\frac{\chi_2 - q\chi_1}{1 + q}. \]  

and the infall direction at merger. We adopt \( A = 1.2 \times 10^4 \) km s\(^{-1}\), \( H = 6.9 \times 10^3 \) km s\(^{-1}\), \( B = -0.93 \), \( \xi = 15^\circ \) (González et al. 2007; Lousto & Zlochower 2008), and \( V_{1,1} = 3678 \) km s\(^{-1}\), \( V_A = 2481 \) km s\(^{-1}\), \( V_B = 1793 \) km s\(^{-1}\), \( V_C = 1507 \) km s\(^{-1}\) (Lousto et al. 2012). We compute the final total spin of the merger product and its mass following Rezzolla et al. (2008).

To compute the recoil kick imparted to the remnants of LIGO/Virgo BBH mergers, we consider the estimated masses \( m_1 \) and \( m_2 \) reported in GWTC-1 and GWTC-2. We sample the spins of the merging BHs uniformly in the range \([0, \chi_{\text{max}}]\). We run \( 10^5 \) Monte Carlo simulations and compute the recoil kicks, using Eq. 1. We discard all the simulations whose computed effective spin \( \chi_{\text{eff}} \) and spin of the merger remnant \( \chi_{\text{fin}} \) are not in the range allowed by LIGO/Virgo.

3. RESULTS

We use our framework to compute the recoil kick imparted to the merger remnants in the catalogs. In Figure 1, we show the probability distribution function (PDF) of the recoil kick \( (v_{\text{kick}}) \) imparted to the merger remnant of GW190512 (top) and GW190521 (bottom), for different values of \( \chi_{\text{max}} \). GW190512 and GW190521 have mass ratio of about 0.54 and 0.73, respectively. The higher the spin, the larger the recoil kick imparted to the remnant and the broader its distribution. We find that the PDF for both events is peaked at \( \sim 100 \) km s\(^{-1}\) for \( \chi_{\text{max}} = 0.1 \), whereas it extends up to \( \sim 1000 \) km s\(^{-1}\) for \( \chi_{\text{max}} = 0.8 \). The merger remnant of GW190521 receives a larger kick as the progenitors’ spins increase.

Using the results of our simulations, we estimate the average recoil kick imparted to the merger remnants in GWTC-1 and GWTC-2. We illustrate this in Figure 2, where we plot the

---

**Figure 1.** Probability distribution function of the recoil kick \( (v_{\text{kick}}) \) imparted to the merger remnant of GW190512 (top) and GW190521 (bottom). Different colors represent different values of \( \chi_{\text{max}} \): 0.1 (blue), 0.3 (orange), 0.5 (green), 0.8 (red).

**Figure 2.** Distribution of average kick velocity for the LIGO/Virgo population in GWTC-1 (Abbott et al. 2019) and GWTC-2 (Abbott et al. 2020b) as a function of different values of \( \chi_{\text{max}} \).
Figure 3. Total mass as a function of the mass ratio for the BBH mergers in the LIGO/Virgo catalogs GWTC-1 (Abbott et al. 2019) and GWTC-2 (Abbott et al. 2020b). Color code: average kick velocity imparted to the merger remnant of BBH mergers from anisotropic gravitational wave emission. Different panels show different assumptions of $\chi_{\text{max}}$: 0.1 (top-left), 0.3 (top-right), 0.5 (bottom-left), 0.8 (bottom-right). Red circles represent events whose $\chi_{\text{eff}}$ and $\chi_{\text{fin}}$ cannot reproduce the LIGO/Virgo estimated range for a given $\chi_{\text{max}}$.

We find that the distributions are peaked at about $150\,\text{km}\,s^{-1}$, $250\,\text{km}\,s^{-1}$, $350\,\text{km}\,s^{-1}$, $600\,\text{km}\,s^{-1}$, for $\chi_{\text{max}} = 0.1$, $0.3$, $0.5$, $0.8$, respectively.

Figure 3 shows the average kick velocity imparted to the merger remnant of LIGO/Virgo BBH mergers as a function of their total mass and mass ratio. Different panels show different assumptions concerning $\chi_{\text{max}}$. As expected, the larger the spin of the progenitors, the larger the recoil kick. GW190412 (The LIGO Scientific Collaboration & the Virgo Collaboration 2020a), a BBH merger with a mass ratio of nearly four-to-one, and GW190814 (The LIGO Scientific Collaboration & the Virgo Collaboration 2020b), a merger between a BH and a compact object of about $2.5M_\odot$, have the lowest average recoil kicks owing to their small mass ratio. We represent in red circles the events whose $\chi_{\text{eff}}$ and $\chi_{\text{fin}}$ cannot reproduce the LIGO/Virgo estimated range for a given $\chi_{\text{max}}$. We find that the estimated values of $\chi_{\text{eff}}$ and $\chi_{\text{fin}}$ of GW170729, GW190412, GW190519, and GW190620 can be reproduced if the spin of their progenitors was $\gtrsim 0.3$, and of GW190517 if the spin of their progenitors was $\gtrsim 0.8$. This would imply that BHs could have not been born with low spins (Fuller & Ma 2019). Alternatively, some of these events could be explained if at least one of the progenitors is already a second-generation BH, in agreement with the recent findings of Kimball et al. (2020a,b, see also Veske et al. (2020)).

We also estimate the probability that a given merger remnant would be retained within a star cluster of escape speed $v_{\text{esc}}$, calculating the number of realizations for which $v_{\text{kick}} < v_{\text{esc}}$. The escape speed from the core of a star cluster is essentially determined by its mass and density profile: the more...
massive and denser the cluster is, the higher is the escape speed (e.g., Antonini & Rasio 2016). Open clusters, globular clusters, and nuclear star clusters have typical escape speeds of $\sim 1 \, \text{km s}^{-1}$, $\sim 10 \, \text{km s}^{-1}$, and $\sim 100 \, \text{km s}^{-1}$ respectively.\footnote{The escape speed may change over time depending on the details of its formation history and dynamical evolution (Rodriguez et al. 2020).}

We show in figure 4 the probability to retain the merger remnant of LIGO/Virgo BBH mergers in environments with escape speed $v_{\text{esc}}$. We plot results in different panels for different assumptions on $\chi_{\text{max}}$. As in the previous figure, red circles represent events whose $\chi_{\text{eff}}$ and $\chi_{\text{fin}}$ cannot reproduce the LIGO/Virgo estimated range for a given $\chi_{\text{max}}$. We find that only environments with escape speed $\geq 100 \, \text{km s}^{-1}$, as found in galactic nuclear star clusters as well as the most massive globular clusters and super star clusters, could efficiently retain the merger remnants of the LIGO/Virgo BBH population even for low progenitor spins ($\chi_{\text{max}} = 0.1$). In the case of high progenitor spins ($\chi_{\text{max}} \gtrsim 0.5$), we conclude that only the most massive nuclear star clusters can retain the merger products.

4. CONCLUSIONS

The first and second Gravitational Wave Transient Catalogs have reported a total of 50 confirmed events, providing a unique insight into their origin.

Assuming that LIGO/Virgo BBHs mergers were catalyzed by dynamical assembly and interactions in a dense star cluster, we compute the distribution of recoil kicks imparted to their merger remnants and estimate their retention probability within various astrophysical environments. We have found that the distributions of average recoil kicks are peaked at about $150 \, \text{km s}^{-1}$, $250 \, \text{km s}^{-1}$, $350 \, \text{km s}^{-1}$, $600 \, \text{km s}^{-1}$, for maximum progenitor spins of 0.1, 0.3, 0.5, 0.8, respectively. Only environments with escape speed $\geq 100 \, \text{km s}^{-1}$, as found in

---

Figure 4. Total mass as a function of the mass ratio for the BBH mergers in the LIGO/Virgo catalogs GWTC-1 (Abbott et al. 2019) and GWTC-2 (Abbott et al. 2020). Color code: probability to retain the merger remnant of BBH mergers in environments with escape speed $v_{\text{esc}}$. Different panels show different assumptions of $\chi_{\text{max}}$: 0.1 (top-left), 0.3 (top-right), 0.5 (bottom-left), 0.8 (bottom-right). Red circles represent events whose $\chi_{\text{eff}}$ and $\chi_{\text{fin}}$ cannot reproduce the LIGO/Virgo estimated range for a given $\chi_{\text{max}}$. 

---
galactic nuclear star clusters as well as the most massive globular clusters and super star clusters, could efficiently retain the merger remnants of the LIGO/Virgo BBH population even for low progenitor spins ($\chi_{\text{max}} = 0.1$). In the case of high progenitor spins ($\chi_{\text{max}} \gtrsim 0.5$), only the most massive nuclear star clusters can retain the merger products.

Finally, we have found that some of the LIGO/Virgo events can be reproduced only if the BH progenitors were rapidly spinning. Alternatively, some of these events could be explained if at least one of the progenitors is already a second-generation BH.

ACKNOWLEDGEMENTS

GF acknowledges support from a CIERA Fellowship at Northwestern University. This work was supported in part by Harvard’s Black Hole Initiative, which is funded by grants from JFT and GBMF.

REFERENCES

Abbott, B. P., et al. 2019, Physical Review X, 9, 031040
Abbott, R., et al. 2020a, arXiv e-prints, arXiv:2009.01075
—. 2020b, arXiv e-prints, arXiv:2010.14527
—. 2020c, arXiv e-prints, arXiv:2010.14533
—. 2020d, arXiv e-prints, arXiv:2010.14529
Antonini, F., Gieles, M., & Gualandris, A. 2019, MNRAS, 486, 5008
Antonini, F., & Perets, H. B. 2012, ApJ, 757, 27
Antonini, F., & Rasio, F. A. 2016, ApJ, 831, 187
Askar, A., Szkudlarek, M., Gondek-Rosińska, D., Giersz, M., & Bulik, T. 2017, MNRAS, 464, L36
Banerjee, S. 2018, MNRAS, 473, 909
Bartos, I., Kocsis, B., Haiman, Z., & Mára, S. 2017, ApJ, 835, 165
Belczynski, K., Repetto, S., Holz, D. E., et al. 2016, ApJ, 819, 108
Fishbach, M., Holz, D. E., & Farr, B. 2017, ApJL, 840, L24
Fragione, G., Ginsburg, I., & Kocsis, B. 2018a, ApJ, 856, 92
Fragione, G., Grishin, E., Leigh, N. W. C., Perets, H. B., & Perna, R. 2019, MNRAS, 488, 47
Fragione, G., & Kocsis, B. 2018, Phys. Rev. Lett., 121, 161103
—. 2019, MNRAS, 486, 4781
Fragione, G., Leigh, N. W. C., Ginsburg, I., & Kocsis, B. 2018b, ApJ, 867, 119
Fragione, G., Loeb, A., & Rasio, F. A. 2020, ApJL, 895, L15
Fragione, G., & Silk, J. 2020, arXiv e-prints, arXiv:2006.01867
Fuller, J., & Ma, L. 2019, ApJL, 881, L1
Giacobbo, N., & Mapelli, M. 2018, MNRAS, 480, 2011
Gondán, L., Kocsis, B., Raffai, P., & Frei, Z. 2018, ApJ, 860, 5
González, J. A., Sperhake, U., Brügmann, B., Hannam, M., & Husa, S. 2007, Physical Review Letters, 98, 091101
Hamers, A. S., & Samsing, J. 2019, MNRAS, 487, 5630
Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, ApJ, 591, 288
Kimball, C., Talbot, C., Berry, C. P. L., et al. 2020a, ApJ, 900, 177
—. 2020b, arXiv e-prints, arXiv:2011.05332
Kimura, T., Nakamura, T., & Nakano, H. 2020, arXiv e-prints, arXiv:2009.00922
Kremer, K., Rodriguez, C. L., Amarpo-Seaone, P., et al. 2019, Phys. Rev. D, 99, 063003
Kremer, K., Spera, M., Becker, D., et al. 2020, ApJ, 903, 45
Liu, B., & Lai, D. 2018, ApJ, 863, 68
Lousto, C. O., Campanelli, M., Zlochower, Y., & Nakano, H. 2010, Classical and Quantum Gravity, 27, 114006
Lousto, C. O., & Zlochower, Y. 2008, Phys. Rev. D, 77, 044028
Lousto, C. O., Zlochower, Y., Dotti, M., & Volonteri, M. 2012, Phys. Rev. D, 85, 084015
Mapelli, M., Santoliquido, F., Bouffanais, Y., et al. 2020, arXiv e-prints, arXiv:2007.15022
O’Leary, R. M., Kocsis, B., & Loeb, A. 2009, MNRAS, 395, 2127
Perna, R., Wang, Y.-H., Farr, W. M., Leigh, N., & Cantiello, M. 2019, ApJ, 878, L1
Rasskazov, A., & Kocsis, B. 2019, ApJ, 881, 20
Rezzolla, L., Barausse, E., Dorband, E. N., et al. 2008, Phys. Rev. D, 78, 044002
Rodriguez, C. L., Amarpo-Seaone, P., Chatterjee, S., & Rasio, F. A. 2018, PRL, 120, 151101
Rodriguez, C. L., Kremer, K., Grudic, M. Y., et al. 2020, ApJL, 896, L10
Tagawa, H., Haiman, Z., & Kocsis, B. 2020, ApJ, 898, 25
The LIGO Scientific Collaboration, & the Virgo Collaboration. 2020a, arXiv e-prints, arXiv:2004.08342
—. 2020b, ApJL, 896, L44
van Son, L. A. C., De Mink, S. E., Broekgaarden, F. S., et al. 2020, ApJ, 897, 100
Veske, D., Sullivan, A. G., Mára, Z., et al. 2020, arXiv e-prints, arXiv:2011.06591
Wong, K. W. K., Breivik, K., Kremer, K., & Callister, T. 2020, arXiv e-prints, arXiv:2011.03564
Woosley, S. E. 2017, ApJ, 836, 244