Can Thorne-Żytkow objects source GW190814-type events?

Ilias Cholis[1,*] Konstantinos Kritos,[2,†] and David Garfinkle[1,‡]

[1]*Department of Physics, Oakland University, Rochester, Michigan 48309, USA*

[2]*Physics Division, National Technical University of Athens, Zografou, Athens 15780, Greece*

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The LIGO-Virgo collaboration reported in their third run the coalescence event GW190814 involving a 2.6 $M_\odot$ object with a 23 $M_\odot$ black hole. In this article we study the conditions under which Thorne-Żytkow objects (TŻOs) can be connected to that type of event. We evaluate first the rate of appearance of TŻOs in the local Universe. Under the assumption that TŻOs eventually become low mass gap black holes we evaluate how those black holes end up in binaries with other stellar mass black holes and compare to the reported rate for GW190814-type of events (1–23 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$). We find that TŻOs in dense stellar clusters can not explain the LIGO-Virgo rate without a TŻO population in the field providing a dominant contribution. We also find that TŻOs formed within hierarchical triple systems in the field with the third more distant star being the progenitor of a stellar mass black hole may be able to give a rate comparable to that of GW190814-type events. In that case, future observations should discover mergers between stellar mass and low mass gap black holes, with the lower mass spanning the entire low mass gap range.

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I. INTRODUCTION

The detection of the LIGO-Virgo coalescence event GW190814, between a 2.6 $M_\odot$ object and a 23 $M_\odot$ black hole represents a new class of gravitational wave (GW) events, involving compact objects in the low mass gap range of 2.5–5 $M_\odot$. For the remainder of this article we will refer to merger events involving a regular stellar mass black hole with a low mass gap object as "GW190814-type events". The 2.6 $M_\odot$ object may be the lightest black hole (BH) or the most massive neutron star (NS) observed [1–9]. The detection suggests both that objects with such masses are more common than previously anticipated and that these objects exist in environments where they can merge with stellar mass black holes. It is a puzzling question as to what scenario could plausibly satisfy both these criteria. Potential pathways to objects in the low mass gap range may involve objects that are formed from NSs by accretion of matter [10]. One of these pathways can be Thorne-Żytkow objects (TŻOs) that contain a NS inside a red giant [11,12]. Different mechanisms have been proposed for the creation of TŻOs. One possibility is that the NS's natal kick moves it in a bound orbit with a pericenter distance that is smaller than the companion star's radius, thus disrupting the companion and embedding the NS in it [13]. Another mechanism to create TŻOs is in massive X-ray binaries where as a result of the mass transfer from the companion star to the NS the two objects coalesce [14]. A third mechanism is in dense stellar environments, where direct collisions between NSs and main-sequence stars may happen [15].

However, no TŻOs have been identified so far. In this work we focus on the case where the NS accretes enough mass from the giant's core to grow to more than 2 $M_\odot$. Then it could be distinguishable from regular NSs. Taking the Kroupa initial stellar mass function, that for stellar mass $m_{\mathrm{star}} > 0.5\ M_\odot$ scales as $dN_{\mathrm{star}}/dm_{\mathrm{star}} \propto m_{\mathrm{star}}^{-2.3}$ [16], and assuming that the neutron star of the TŻO will accrete $1/5$th of the red giant's mass, we estimate that about half of TŻOs with a red giant more massive than 4 $M_\odot$ will form low mass gap range objects, while only $O(10\%)$ of those TŻOs will grow to masses larger than 5 $M_\odot$. This makes low mass gap objects a probe to search for the remnants of the exotic TŻOs, hypothesized for a long time, but up to now only searched for through their brief lifetimes. We note that given that TŻOs require tight binary systems as their starting point we expect that such objects are mostly found in regions rich in stars.

In this article we examine the conditions under which low mass gap BHs sourced from TŻOs can form binaries with regular stellar mass range BHs (i.e., $\geq 5\ M_\odot$) that are tight enough to merge within a Hubble time and at a rate similar to the GW190814 class, evaluated to be 1–23 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ [17]. We find that while dense stellar environments can not contribute significantly to the observed rate, hierarchical triple systems in the field may be able to explain such events as the GW190814.

*cholis@oakland.edu
†ge16004@central.ntua.gr
‡garfinkl@oakland.edu

II. AN UPPER BOUND ESTIMATION OF TŻOs BECOMING LOW MASS GAP BHs

Using massive X-ray binaries Ref. [18] estimated that in a Milky Way-size galaxy, the emergence rate of TŻOs is $1–2 \times 10^{-4}$ yr^{-1}. More recent estimates give rates of 0.9×10^{-4} yr^{-1} [19] and $\simeq 1.5 \times 10^{-4}$ yr^{-1} [20]. We take that TŻOs composed of a massive red giant emerge with a rate of 1.5×10^{-4} yr^{-1} per Milky Way-like galaxy.[1] We focus on TŻOs where the red giant's initial mass was at least 5 $M_\odot$ and refer to them as simply TŻOs. The number of TŻOs in a galaxy is directly proportional to the number of its massive binaries, thus also proportional to the number of its stars and to a galaxy's total stellar mass $M^\star$. Normalizing to the rate of the Milky Way that has $M^\star_{\rm MW} = 10^{10.79}\ M_\odot$, a galaxy of stellar mass $M^\star$ will have a TŻO emergence rate of

$$\Re^{\rm T\dot{Z}O}_{\rm gal}(M^\star) = 1.5 \times 10^{-4} \left(\frac{M^\star}{10^{10.79}\ M_\odot}\right)\ {\rm yr}^{-1}. \quad (1)$$

The Sloan Digital Sky Survey has measured the number density of galaxies in the redshift range of 0.02–0.06 [22]. The number density of galaxies in a mass bin $dM^\star$ follows a Schechter mass function Φ:

$$\begin{aligned} n_{\rm gal} &= \Phi(M^\star) dM^\star \\ &= \Phi^\star e^{-M^\star/M^\star_0} \left(\frac{M^\star}{M^\star_0}\right)^\alpha dM^\star. \end{aligned} \quad (2)$$

$\Phi^\star$ is the normalization, α is the mass function power-law and $M^\star_0$ sets an exponential suppression at high masses. Late- and early-type galaxies mass functions are described by similar values of $M^\star_0$. The combined mass function for the entire sample is (in $\log M^\star$) [22]

$$\begin{aligned} \Phi d\log_{10} M^\star = \ln(10) e^{-M^\star/M^\star_0} \bigg\{ \Phi^\star_1 \left(\frac{M^\star}{M^\star_0}\right)^{\alpha_1+1} \\ + \Phi^\star_2 \left(\frac{M^\star}{M^\star_0}\right)^{\alpha_2+1} \bigg\} d\log_{10} M^\star. \end{aligned} \quad (3)$$

The appropriate normalizations are $\Phi^\star_1 = h^3 10^{-3.31}$ Mpc^{-3}, $\Phi^\star_2 = h^3 10^{-2.01}$ Mpc^{-3} with $\alpha_1 = -1.69$ and $\alpha_2 = -0.79$ for $M^\star_0 = 10^{10.79}\ M_\odot$ and $h = 0.7$ [22].

Taking that TŻOs emerge at the same rate per stellar mass in early and late galaxies, Eqs. (1)–(3) give a local ($z \geq 0.06$) TŻO emergence rate density of

$$R^{\rm T\dot{Z}O}(z < 0.1) = \int_{M^\star_{\rm min}}^{M^\star_{\rm max}} dM^\star \Re^{\rm T\dot{Z}O}_{\rm gal}(M^\star) \frac{\Phi(M^\star)}{M^\star}. \quad (4)$$

Taking $M^\star_{\rm min} = 10^9\ M_\odot$ ($M^\star_{\rm min} = 10^{10}\ M_\odot$) and $M^\star_{\rm max} = 10^{11.5}\ M_\odot$ we get a local TŻO emergence rate density of 1.2×10^3 (1.0×10^3) Gpc^{-3} yr^{-1}. Values for $M^\star_{\rm max}$ larger than $10^{11.5}\ M_\odot$ change our results by 1%. Moreover, if in Eq. (3) we use instead the separate parametrizations of [22] for the early-, intermediate- and late-type galaxies our rate results change only by 2%.

As all TŻOs composed by a NS and a massive red giant end up in a BH, we can evaluate the rate by which BHs are created just from these objects.[2] To distinguish these BHs from those originated directly from regular core-collapse we will denote these as BH$^{\rm T\dot{Z}O}$. Their rate is

$$\mathcal{R}_{\rm BH^{T\dot{Z}O}}(z) = \int_0^z dz' R^{\rm T\dot{Z}O}(z') \frac{dV_c}{dz'} (1+z')^{-1}, \quad (5)$$

where dV_c/dz is the comoving volume element. Integrating to redshift of 0.1 we get $\mathcal{R}_{\rm BH^{T\dot{Z}O}}(0.1) = 3.8 \times 10^2$ yr^{-1} from galaxies with stellar mass of $M^\star \geq 10^9\ M_\odot$ and $\mathcal{R}_{\rm BH^{T\dot{Z}O}}(0.1) = 3.3 \times 10^2$ yr^{-1} from galaxies with stellar mass of $M^\star \geq 10^{10}\ M_\odot$, making our estimates insensitive to the low-mass end of the galaxies mass-function.

Only the BH$^{\rm T\dot{Z}O}$s in the low mass gap are important here. These are created if the initial NS accretes at least 1 $M_\odot$ [23,24]. Assuming that the neutron star of the TŻO accreted 1/5th of the mass of the red giant, only stars with initial mass between 6 and 18 $M_\odot$ will give BH$^{\rm T\dot{Z}O}$ inside the low mass gap. Relying on the Kroupa initial mass function [16], and focusing only on TŻOs that will grow into BH$^{\rm T\dot{Z}O}$ (i.e., have companion stars with a mass $\geq 6\ M_\odot$), we find that 60–90% of the TŻOs will lead to such a low mass BH$^{\rm T\dot{Z}O}$. Using the central values of [16][3] we get a local formation rate density of BH$^{\rm T\dot{Z}O}$ in the low mass gap of 9×10^2 Gpc^{-3} yr^{-1}. That rate is based on observations of massive X-ray binaries (Ref. [20]), most common in active star formation regions and may have been larger in past epochs that also contribute to the creation of BH$^{\rm T\dot{Z}O}$. Our rate is insensitive to the exact fraction of the mass of the red giant that is being absorbed. As an example, we note that if the NS accretes 1/3rd of the total mass of the giant instead, the birth rate density varies by only $\simeq$5%.

Of the Milky Way's stellar mass about 1/3rd is in the bulge [25–27]. For small elliptical galaxies formed in a single epoch of gas collapse, the fraction of the stellar mass in dense regions may be higher than the Milky Way. Also

[1] A NS forming a binary with a red giant with a semimajor axis of ∼1 AU can merge with its He core while it is in the common envelope phase [21]. That is similar to TŻOs and would only enhance the production rate of low mass gap BHs.

[2] TŻOs where the original companion of the NS was a low mass star may still give a NS as a final product. All our rates here rely on the observational constraints where the companion will become a massive red giant.

[3] Assuming a Kroupa initial mass function that scales with the mass of the star $m_{\rm star}$ as $\propto m_{\rm star}^{-2.3}$.

for the massive elliptical galaxies that are the result of mergers of smaller galaxies the relevant fraction will be as large as their progenitor galaxies. Thus of the local $\mathrm{BH}^{\mathrm{T\dot{Z}O}}$ birth rate density of $9\times10^2\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, $3\times10^2\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ will be in dense stellar environments where the $\mathrm{BH}^{\mathrm{T\dot{Z}O}}$ can interact and merge with other BHs.

III. FORMING BINARIES OF A LOW MASS GAP AND A REGULAR STELLAR MASS BH

We consider two distinct paths for the formation of binaries composed of a $\mathrm{BH}^{\mathrm{T\dot{Z}O}}$ within the low mass gap and a BH of $5\ M_\odot$ or larger. In the first one, the $\mathrm{BH}^{\mathrm{T\dot{Z}O}}$ only after dynamical interactions forms a binary with another BH. In the second, originally there is a hierarchical triple containing a tight binary forming the TŻO and a third object that will evolve to a stellar mass BH. After the formation of the $\mathrm{BH}^{\mathrm{T\dot{Z}O}}$ since its natal kick is weak it will remain in a binary with the stellar mass BH.

A. Forming binaries inside globular clusters

In globular clusters all stars enter the main sequence at approximately the same moment. Thus the massive red giants of 6 to 18 $M_\odot$ which will give intermediate mass $\mathrm{BH}^{\mathrm{T\dot{Z}O}}$, are present only for a short amount of time early in the history of these systems. Relying on Eq. (1), the formation rate of $\mathrm{BH}^{\mathrm{T\dot{Z}O}}$s with mass of 2.5 to 5 $M_\odot$ is

$$\Gamma_{\mathrm{sc}}^{\mathrm{BH}^{\mathrm{T\dot{Z}O}}}(M^\star_{\mathrm{sc}},t) = (0.6-0.9)\times1.5\times10^{-4}\left(\frac{M^\star_{\mathrm{sc}}}{10^{10.79}\,M_\odot}\right) \times H(t-T_1)H(T_2-t)\,\mathrm{yr}^{-1}. \quad (6)$$

$M^\star_{\mathrm{sc}}$ is the mass in stars within a given stellar cluster, i.e., $M^\star_{\mathrm{sc}}\sim10^5\ M_\odot$ for a massive globular cluster. The source is taken for simplicity to be constant in time t between T_1 and T_2, though the product of two Heaviside functions $H(t-T_1)H(T_2-t)$. $T_1 = 10$ Myr and $T_2 = 130$ Myr are the timescales of collapse of a 18 $M_\odot$ and a 6 $M_\odot$ star respectively.[4] Beyond that top hat in time distribution it is quite difficult to set a distribution; it can be tilted either toward the T_1 point as the 18 $M_\odot$ stars may more easily form TŻOs or toward the T_1 point as there are more 6 $M_\odot$ stars. We remind that our estimate relies on current star forming regions and may be different for the early stages of globular clusters. However, as we will show the final rate of GW190814-type events from $\mathrm{BH}^{\mathrm{T\dot{Z}O}}$ in globular clusters is going to be very suppressed compared to the reported rate and thus the details of the early cluster history are unimportant.

The rate $\Gamma_{\mathrm{sc}}^{\mathrm{BH}^{\mathrm{T\dot{Z}O}}}(M^\star_{\mathrm{sc}})$ of Eq. (6), can be used as a source term of low mass gap BHs inside clusters. In Ref. [28], a numerical scheme was developed to model the dynamical interactions of low mass gap objects (as $\mathrm{BH}^{\mathrm{T\dot{Z}O}}$s) with regular mass stellar BHs, massive second generation BHs and stars. Once formed, the $\mathrm{BH}^{\mathrm{T\dot{Z}O}}$s will first bind in binaries with stars. Those first binaries will then have exchange interactions with other $\mathrm{BH}^{\mathrm{T\dot{Z}O}}$s and more massive BHs, creating binaries composed solely by compact objects. At the same time since these new binaries are surrounded by stars, binary-single star interactions will take place resulting in the loose binaries breaking up and the hard ones becoming even tighter. In [28], all those interactions are included for a sequence of the observed globular cluster systems, taking into account their environmental parameters (density and velocity distribution profiles). We implement the same code in this work taking all the observed Milky Way clusters as reference to evaluate a merger rate between low mass gap $\mathrm{BH}^{\mathrm{T\dot{Z}O}}$ and BHs. In Fig. 1, we show the total rate of mergers from all Milky Way globular clusters $\mathfrak{R}^{\mathrm{GW190814}}_{\mathrm{gcs\,in\,gal}}$. That rate can be taken to be roughly constant up to redshift of 1:

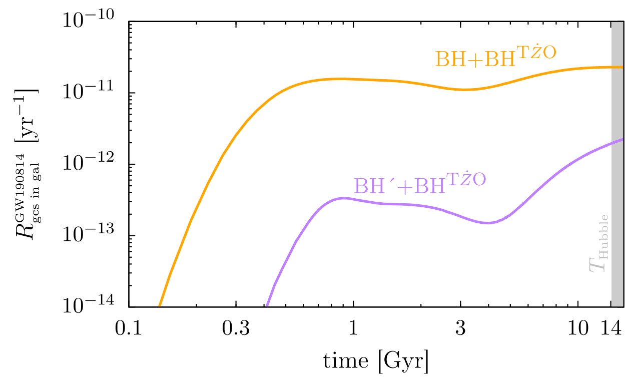

FIG. 1. The merger rate of $\mathrm{BH}^{\mathrm{T\dot{Z}O}}$ with 1st generation black hole "BH" (orange) and 2nd generation black holes "BH′" (purple) as it evolves in the Milky Way globular clusters. We are assuming that all clusters were formed at the same time.

$$\mathfrak{R}^{\mathrm{GW190814}}_{\mathrm{gcs\,in\,gal}}(M^\star) = 2\times10^{-11}\left(\frac{M^\star}{10^{10.79}\ M_\odot}\right)\ \mathrm{yr}^{-1}. \quad (7)$$

Combining Eq. (7) with Eq. (4), where in the place of $\mathfrak{R}^{\mathrm{T\dot{Z}O}}_{\mathrm{gal}}$ we substitute with $\mathfrak{R}^{\mathrm{GW190814}}_{\mathrm{gcs\,in\,gal}}$, we get that the local GW190814-like event rate density of

$$R^{\mathrm{GW190814}}_{\mathrm{in\,gcs}}(z<0.1) = \int_{M^\star_{\mathrm{min}}}^{M^\star_{\mathrm{max}}} dM^\star \mathfrak{R}^{\mathrm{GW190814}}_{\mathrm{gcs\,in\,gal}}(M^\star)\frac{\Phi(M^\star)}{M^\star}. \quad (8)$$

This gives $R^{\mathrm{GW190814}}_{\mathrm{in\,gcs}}(z<0.1) = 1.6\times10^{-4}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. This is about four orders of magnitude smaller than the reported GW190814 rate density. Globular clusters are excluded as the only environment where TŻOs can create a

[4] Time of collapse or full loss of envelope is taken to be $\sim1.2\times$ the main sequence lifetime.

low mass gap object that subsequently, via dynamical interactions, will form a binary with a BH and merge giving GW190814-type events. If instead of the Milky Way sample, we use more massive clusters observed in elliptical galaxies as Ref. [29], our result does not change substantively. We note that in our simulations we calculate first the expected rates of R^{GW190814} from all individual globular clusters within the Milky Way and then evaluate the integrated rate up to redshift of 1. The source of uncertainty in our calculations is not of a statistical nature, but instead comes from the modeling of complex star clusters (our semianalytic prescriptions of Ref. [28]) which we simplify by focusing only on those processes relevant for us.

B. Binaries in nuclear star clusters

Nuclear star clusters come with a variety of masses; however, their stellar mass is related to the mass of the host galaxy [30]:

$$\log_{10}(M_{\mathrm{NSC}}) = 1.094 \cdot \log_{10}\left(\frac{M^\star}{10^6\ M_\odot}\right) + 2.881. \quad (9)$$

Following [30], we evaluate the tidal radius r_t of nuclear star clusters hosted by galaxies of given stellar mass. Taking all clusters to have the same concentration parameter $c = 0.7$, where $c = \log_{10}(r_t/r_c)$ and r_c is the core radius where all BHs reside, and using the numerical code of [28] we evaluate the rate of BH–BH$^{\mathrm{T\dot{Z}O}}$ mergers in a nuclear star cluster hosted by a galaxy of a given stellar mass. We get the rate of mergers from all nuclear star clusters in galaxies $\mathfrak{R}^{\mathrm{GW190814}}_{\mathrm{nsc\,in\,gal}}$ as

$$\mathfrak{R}^{\mathrm{GW190814}}_{\mathrm{nsc\,in\,gal}}(M^\star) = \begin{cases} 10^{-15}\ \mathrm{yr}^{-1}\ \mathrm{for}\ M^\star < 10^7\ M_\odot, \\ 10^{-15}\left(\frac{M^\star}{10^7\ M_\odot}\right)\ \mathrm{yr}^{-1}\ \mathrm{for}\ M^\star > 10^7\ M_\odot. \end{cases} \quad (10)$$

That gives us a rate density from nuclear star clusters that is $R^{\mathrm{GW190814}}_{\mathrm{in\,nsc}}(z < 0.1) = 1 \times 10^{-8}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. Nuclear star clusters are very dense environments at their cores where all BHs segregate to. Thus all BH–BH$^{\mathrm{T\dot{Z}O}}$ binaries even when formed will not remain binaries for long enough to merge via GW emission. Instead, in such dense environments the merging BH binaries will contain approximately equal mass members. In a nuclear star cluster with size of $10^8\ M_\odot$ over a course of 10 Gyr there will be $\simeq 2 \times 10^3$ BH$^{\mathrm{T\dot{Z}O}}$ objects formed. Yet, the probability of even one of them merging with a stellar mass BH is only 10^{-4}.

Nuclear star clusters do not have a clearly observed concentration-mass relation. Thus we have treated the concentration parameter c as a free parameter. The value of $c = 0.7$ represents a low estimate of the allowed concentration in these environments. Higher values of c will only further suppress significantly the estimated rate of Eq. (10).

Inside nuclear star clusters direct capture events between stellar mass BHs and BH$^{\mathrm{T\dot{Z}O}}$ may also happen. Such events will create very hard binaries with high eccentricities that will rapidly merge via GW emission [31]. For the direct captures higher concentrations enhance the creation of tight BH–BH$^{\mathrm{T\dot{Z}O}}$ binaries. However, even for a very high value of $c = 2$, we get a rate density of $3 \times 10^{-6}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ from direct capture events, that still is orders of magnitude smaller than the rate for GW190814-type events.

C. Hierarchical triples in the field

As we described most TŻOs and in turn BH$^{\mathrm{T\dot{Z}O}}$s are created in the field with a rate density of $6 \times 10^2\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. However, we need to include the probability that the BH$^{\mathrm{T\dot{Z}O}}$ will merge in a Hubble time with a stellar mass BH. Given the very low density of BHs in the field, the only possibility for BH–BH$^{\mathrm{T\dot{Z}O}}$ mergers in the field is that the final BH–BH$^{\mathrm{T\dot{Z}O}}$ binary originated from a hierarchical triple of a specific configuration. We denote m_1, m_2 and m_3 the Zero Age Main Sequence (ZAMS) star masses of the three initial stars, with $m_1 > m_2 > m_3$. The relevant configuration leading to a GW190814-like event has to be such that in the triple, at its creation, the inner binary contained the stars of masses m_2 and m_3 in an orbit with semimajor axis a_{in} and eccentricity e_{in}. The star with ZAMS mass m_2 has to be between 8 and up to 25 $M_\odot$, so that when it had its supernova (SN) explosion it created a NS. Instead, the least massive star with mass m_3 has to be between 6 and 18 $M_\odot$ giving us the red giant that with the NS will create the TŻO. Finally, m_1 has to be massive enough that it will give a BH of mass 10–30 $M_\odot$, i.e., m_1 has to be at least $m_1 > 30\ M_\odot$. That star was on an initial outer orbit with respect to the $m_2 - m_3$ binary with semimajor axis a_{out} and eccentricity e_{out}.

The rate density of $6 \times 10^2\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ for BH$^{\mathrm{T\dot{Z}O}}$s already accounts for the fact that the inner binary will survive the SN explosion of m_2 and that a_{in} is small enough for the TŻO to form. To connect that rate density to a BH–BH$^{\mathrm{T\dot{Z}O}}$ merger rate density we need to include first the fact that the TŻO will be in a triple, second that the third object is the most massive member with a ZAMS mass of at least 30 $M_\odot$, third that the outer binary will survive both the SN kicks of m_1 and m_2, and fourth that once the BH–BH$^{\mathrm{T\dot{Z}O}}$ binary is created it will merge within a Hubble time. In the following we address the first three points.

In [32] it is noted that about 10% of low mass stars are in triples, with that fraction rising to about 50% for spectral type B stars. Given the high value of the m_2 mass we take that about 30% of systems that give rise to TŻOs start out as triple systems. Using the Kroupa initial stellar mass function we estimate that if the m_1 mass is independent of the masses of the other stars in the hierarchical triple system then only in 0.1–2% of the triple systems, the m_1 mass will be $> 30\ M_\odot$.[5] That is a very dominant suppression and at face value would bring the BH–BH$^{\mathrm{T\dot{Z}O}}$ merger rate density down to 0.2–4 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ without including the third and fourth conditions. However, that suppression may be significantly mitigated by the fact that star systems likely form due to fragmentation processes. It is unlikely that the masses of the three stars are independent of each other, and since by having a TŻO the mass m_2 is already massive enough, there may be an enhanced probability that the outer star is massive as well enhancing the BH–BH$^{\mathrm{T\dot{Z}O}}$ merger rates.

For these triples the mass ratio is $m_1/(m_2 + m_3) \simeq 1$. Since we have already included the suppression factor of hierarchical triples, stability arguments give that the semi-major axes ratio of the outer orbit to the inner orbit $a_{\mathrm{out}}/a_{\mathrm{in}}$ is between 5 and 20 [33], a result that we also confirmed by semianalytical calculations and is in agreement with numerical simulations and observations of triple systems [34]. The initial (pre-SN explosions) eccentricity of the outer orbit of these triple systems follows a thermal distribution. Systems where the inner orbit will give a TŻO are already very tight. Relying on observed orbital properties of binary systems [35], we find that the equivalent triple system will not break up by the SN kicks of either the m_1 or m_2 stars as the typical SN kicks are only $\sim$100 km/s [36].[6] In fact, the first natal kick of the m_1 SN explosion will marginally affect the system's binding energy increasing the semimajor axis of the outer binary by a factor of $\simeq$3, which equals the fraction of the m_1 mass to that of its resulting BH remnant. We also find that the eccentricity distribution even after the SN explosion of m_1 is still going to be a thermal one. Thus, we find that effectively all triples where the inner binary will give a TŻO survive the SN kicks of m_1 and m_2.

Finally, we want to know the probability that the BH–BH$^{\mathrm{T\dot{Z}O}}$ will merge within a Hubble time. That binary has to be sufficiently tight. We propose that a common envelope phase between the TŻO and the more massive BH allows for the eventual BH–BH$^{\mathrm{T\dot{Z}O}}$ binary to become tight enough for it to coalesce. As noted in [37] in binary BH mergers from binary star systems, the objects get close to each other through a common envelope phase preceding the formation of the second black hole. This would require a reliable estimate of the probability that the common envelope scenario takes place for our case, which in turn requires specialized codes that take into account both stellar evolution and orbital dynamics [32,37]. Additional modifications to take into account the formation of TŻO and BH$^{\mathrm{T\dot{Z}O}}$ would be necessary to such codes. That is beyond the scope of the present work. We note that during the common envelope phase tidal effects can be important for binaries with separation of $\alpha_{\max} \sim 5R_g$, where R_g is the radius of the red giant [38,39]. For stars in the mass-range of 10–30 $M_\odot$, that suggests a separation distance of $\sim$30 AU up to which such a phase can significantly reduce the separation of what will eventually become the BH–BH$^{\mathrm{T\dot{Z}O}}$ binary. If all BH–BH$^{\mathrm{T\dot{Z}O}}$ merge within a Hubble time the merger rate density in the field from hierarchical triples can be 0.2–4 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ which is within the claimed LIGO-Virgo rate for GW190814-like events. Thus we find that it is important that such modifications to include TŻOs are performed in the future. Until then we are not yet able to rule this scenario out. We also clarify that, if the fraction of galactic stellar mass in dense stellar environments is less than the assumed 1/3, our basic result that such environments can not account for the GW190814-like event rate and that hierarchical triplets in the field may be able to explain this becomes stronger.

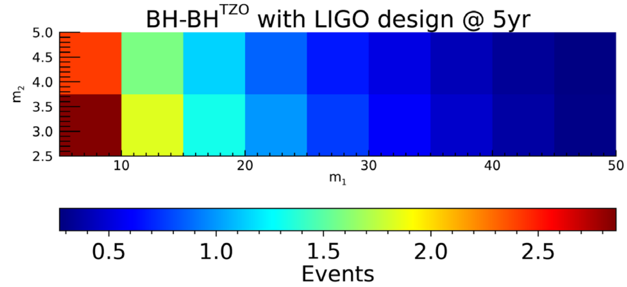

FIG. 2. Number of BH–BH$^{\mathrm{T\dot{Z}O}}$ events at $\mathrm{S/N} > 8$ at design sensitivity after 5 years. We take the rate density of these mergers to be 2 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$.

IV. OBSERVATIONAL PERSPECTIVES

As a final note, if the observed rate of GW190814-like events is $\sim$2 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ then with the enhanced LIGO-Virgo-KAGRA sensitivity we expect a gradual filling up of the low mass gap range. The BH$^{\mathrm{T\dot{Z}O}}$s will cover the entire low mass gap range, as we show in Fig. 2. However, the most likely BH$^{\mathrm{T\dot{Z}O}}$s are the lower $\simeq 2.5\ M_\odot$ as their mass comes from the NS accreting a fraction of the red giant's mass. That makes the observed 2.6 $M_\odot$ mass of GW190814 a quite likely outcome.

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[5]The 2% fraction comes from taking into account the Kroupa mass function parametrization uncertainties such that more stars are predicted at its massive end.

[6]We take the semimajor axis to be log-flat in the range 0.01 AU to 1000 AU, while eccentricities are thermalized.

[1] F. Özel and P. Freire, Annu. Rev. Astron. Astrophys. **54**, 401 (2016).
[2] M. Fishbach and D. E. Holz, Astrophys. J. Lett. **851**, L25 (2017).
[3] D. Wysocki, J. Lange, and R. O'Shaughnessy, Phys. Rev. D **100**, 043012 (2019).
[4] T. A. Thompson *et al.*, arXiv:1806.02751.
[5] V. Takhistov, G. M. Fuller, and A. Kusenko, Phys. Rev. Lett. **126**, 071101 (2021).
[6] I. Tews, P. T. Pang, T. Dietrich, M. W. Coughlin, S. Antier, M. Bulla, J. Heinzel, and L. Issa, Astrophys. J. Lett. **908**, L1 (2021).
[7] H. Tan, J. Noronha-Hostler, and N. Yunes, Phys. Rev. Lett. **125**, 261104 (2020).
[8] N.-B. Zhang and B.-A. Li, Astrophys. J. **902**, 38 (2020).
[9] E. R. Most, L. J. Papenfort, L. R. Weih, and L. Rezzolla, Mon. Not. R. Astron. Soc. **499**, L82 (2020).
[10] M. Safarzadeh and A. Loeb, Astrophys. J. Lett. **899**, L15 (2020).
[11] K. S. Thorne and A. N. Zytkow, Astrophys. J. Lett. **199**, L19 (1975).
[12] K. S. Thorne and A. N. Zytkow, Astrophys. J. **212**, 832 (1977).
[13] P. J. T. Leonard, J. G. Hills, and R. J. Dewey, Astrophys. J. Lett. **423**, L19 (1994).
[14] R. E. Taam, P. Bodenheimer, and J. P. Ostriker, Astrophys. J. **222**, 269 (1978).
[15] A. Ray, A. K. Kembhavi, and H. M. Antia, Astron. Astrophys. **184**, 164 (1987), https://adsabs.harvard.edu/full/1987A%26A...184..164R.
[16] P. Kroupa, Science **295**, 82 (2002).
[17] R. Abbott *et al.* (LIGO Scientific, Virgo Collaborations), Astrophys. J. **896**, L44 (2020).
[18] P. Podsiadlowski, R. C. Cannon, and M. J. Rees, Mon. Not. R. Astron. Soc. **274**, 485 (1995).
[19] E. Michaely, D. Ginzburg, and H. B. Perets, arXiv: 1610.00593.
[20] B. Hutilukejiang, C. Zhu, Z. Wang, and G. Lü, J. Astrophys. Astron. **39**, 21 (2018).
[21] C. Fryer, S. Woosley, and D. Hartmann, Astrophys. J. **526**, 152 (1999).
[22] A. K. Weigel, K. Schawinski, and C. Bruderer, Mon. Not. R. Astron. Soc. **459**, 2150 (2016).
[23] R. A. Chevalier, Astrophys. J. Lett. **411**, L33 (1993).
[24] G. E. Brown, Astrophys. J. **440**, 270 (1995).
[25] E. Valenti, M. Zoccali, O. A. Gonzalez, D. Minniti, J. Alonso-García, E. Marchetti, M. Hempel, A. Renzini, and M. Rejkuba, Astron. Astrophys. **587**, L6 (2016).
[26] J. Bland-Hawthorn and O. Gerhard, Annu. Rev. Astron. Astrophys. **54**, 529 (2016).
[27] M. Zoccali, E. Valenti, and O. A. Gonzalez, Astron. Astrophys. **618**, A147 (2018).
[28] K. Kritos and I. Cholis, Phys. Rev. D **104**, 043004 (2021).
[29] J. Lim, E. Wong, Y. Ohyama, T. Broadhurst, and E. Medezinski, Nat. Astron. **4**, 153 (2020).
[30] R. Pechetti, A. Seth, N. Neumayer, I. Georgiev, N. Kacharov, and M. den Brok, Astrophys. J. **900**, 32 (2020).
[31] R. M. O'Leary, B. Kocsis, and A. Loeb, Mon. Not. R. Astron. Soc. **395**, 2127 (2009).
[32] S. Toonen, A. Hamers, and S. Portegies Zwart, Comput. Astrophys. Cosmol. **3**, 6 (2016).
[33] R. A. Mardling and S. J. Aarseth, Mon. Not. R. Astron. Soc. **321**, 398 (2001).
[34] M. F. Sterzik and A. A. Tokovinin, Astron. Astrophys. **384**, 1030 (2002).
[35] A. Duquennoy and M. Mayor, Astron. Astrophys. **500**, 337 (1991), https://ui.adsabs.harvard.edu/abs/1991A%26A...248..485D/abstract.
[36] I. Mandel, Mon. Not. R. Astron. Soc. **456**, 578 (2016).
[37] M. Zevin, S. S. Bavera, C. P. L. Berry, V. Kalogera, T. Fragos, P. Marchant, C. L. Rodriguez, F. Antonini, D. E. Holz, and C. Pankow, Astrophys. J. **910**, 152 (2021).
[38] N. Soker, Astrophys. J. Lett. **460**, L53 (1996).
[39] N. Ivanova, S. Justham, X. Chen, O. De Marco, C. L. Fryer, E. Gaburov, H. Ge, E. Glebbeek, Z. Han, X. D. Li *et al.*, Astron. Astrophys. Rev. **21**, 59 (2013).