PROCEEDINGS OF SCIENCE

PoS(Regio2021)029

LIGO signals from mirror world

Revaz Beradze[a,b,*] **and Merab Gogberashvili**[a,b]

[a] *Javakhishvili Tbilisi State University,*
3 Chavchavadze Avenue, Tbilisi 0179, Georgia
[b] *Andronikashvili Institute of Physics,*
6 Tamarashvili Street, Tbilisi 0177, Georgia

E-mail: `revazberadze@gmail.com`

We consider the possibility that some events from the gravitational wave transient catalog can be linked with mirror world theory. Some theories of star evolution predict the existence of upper and lower mass gaps for remnant compact objects. GWTC-3 includes some odd events that fall in these forbidden mass intervals. In order to explain these challenging signals, very specific assumptions are required. We argue that mirror world binaries could be good candidates for these gravitational waves. Mirror world seems to be dominated by helium, encouraging formation of heavy stars at early times and as mirror matter abundance can exceed ordinary matter density, merger rates can be amplified, promoting a hierarchical merger scenario. Absence of follow-up optical radiation supports this suggestion.

RDP online PhD school and workshop "Aspects of Symmetry"(Regio2021),
8-12 November 2021
Online

---

[*] Speaker

1. Introduction

The first direct detection of Gravitational Waves (GW) in 2015 began a new era in multi-messenger astronomy. Analysis of three observing runs that have been conducted so far, in overall revealed 90 events with probability $P_{\text{astro}} > 0.5$ being of an astrophysical origin [1–3]. Amount of the data recorded up to now, already includes the events that are challenging to be explained within existing models. Among these 90 events, the majority are black hole - black hole mergers, with few of them containing black holes (BH) from the upper mass gap. Two events are from the merger of BH with an object of lower mass gap. Two more events are from BH - neutron star (NS) coalescence, and other two from NS-NS merger. The event GW170817 of binary NS coalescence [4] still remains the only GW detection accompanied by a gamma-ray counterpart [5, 6]. No other electromagnetic radiation associated with GW has been found yet [7, 8].

This paper intends to spot a possible link between the odd events from GW data and a particular dark matter model - a mirror matter theory. We start with a brief review of the LIGO/VIRGO events that were unexpected within the framework of currently existing models of stars' evolution. After that, we discuss the possibility that these events may have emerged from the mirror world.

1.1 The sources from the upper mass gap

Several events of LIGO/VIRGO data contain unusually heavy BHs that fall in the so-called upper mass gap, produced by pair-instability supernova processes. Current models for evolution of heavy stars predict that temperature in a He core reaches the point when production of electron-positron pairs is allowed. So, part of the energy of photons that was providing pressure against gravity, is consumed by pair production and the star becomes unstable. Stars with He core mass $\sim 32-64 M_\odot$ are subject to pulsational pair instability, decreasing mass by ejection of some amount of matter, and leaving remnants with mass less than $\sim 65 M_\odot$. Stars with He mass $\sim 65-135 M_\odot$ are affected by pair instability, disrupting the entire star and leaving no remnant compact object. Stars with He core $\gtrsim 135 M_\odot$ are considered to directly collapse to intermediate mass BHs [9]. So, the collapse of a heavy star is unable to produce BHs in the mass range $\sim 65-150 M_\odot$.

Despite this fact, LIGO/VIRGO were able to detect GWs coming from the systems in which one or both components are BH with masses in the range $50-107 M_\odot$. The most massive binary GW190426_190642 contained components with masses $107 M_\odot$ and $77 M_\odot$, producing a BH with mass $175 M_\odot$ after merger and radiating $11 M_\odot$ energy through gravitational waves [1]. The second most massive system GW190521 consisted of BHs with masses $95 M_\odot$ and $69 M_\odot$, radiating $8 M_\odot$ energy and producing a final BH with mass $156 M_\odot$ [10].

BHs with such high masses are currently discussed to be formed by a hierarchical mergers of smaller BHs [11–13]. In order to coalesce again, initial first generation BHs should be formed in triple or higher multipole systems, or such systems must be assembled in the dense stellar clusters. However, merger product receives a recoil kick from the anisotropic GW emission [14, 15], and it may eject them from clusters and leave unavailable to form new generations of binary BHs [16]. Also, even if effective spin parameter of binary BH system was almost zero, BH formed after their merger is characterized by high spin; so spin value may be a good indication for genealogy of BHs [17, 18]. In [11], the analyses of the ten BHs coalescence events from the first two observing runs of LIGO/VIRGO detectors was made and no definite evidence of hierarchical mergers was found.

Merger rate of the events in which mass of one of the components lies in $50 - 100 M_\odot$ was estimated to be $f = 0.099 - 0.4$ Gpc^{-3}yr^{-1} (Table IV in [19]). Simulations done for nuclear stellar clusters (where the hierarchical mergers are orders of magnitude more common than in globular and young star clusters) with low spin and broad distribution of escape velocities, yield $10^{-2} - 0.2$ Gpc^{-3}yr^{-1} [12]. In order to obtain such high merger rates, some optimistic assumptions are required. More specifically, in [13], merger rate of GW190521-like events was estimated as,

$$f = f_{1\mathrm{G}} \times f_{\mathrm{triple}} \times f_{\mathrm{survival}} \times f_{\mathrm{merger}} \,, \tag{1}$$

where $f_{1\mathrm{G}} \sim 10 - 100$ Gpc^{-3}yr^{-1} is merger rate of first generation BHs and the value obtained from the first two observing runs [3]. Assuming a high survival, $f_{\mathrm{survival}} \simeq 60\%$, and the large merger fraction, $f_{\mathrm{merger}} \simeq 20\%$, together with the admission that formation fraction of stellar triple systems is $f_{\mathrm{triple}} \simeq 50\%$, the coalescence rate of GW190521-like events was calculated to be $0.6 - 6$ Gpc^{-3}yr^{-1} [13]. We update this merger rate using the value from GWTC-3, $f_{1\mathrm{G}} \sim 2.5 - 6.3$ Gpc^{-3}yr^{-1} (Table IV in [19]), obtained for the systems in which the mass of the first component is $20 - 50 M_\odot$ and $5 - 50 M_\odot$ for the second component, i.e. systems that can potentially give 'heavy' systems through hierarchical mergers. Inserting this larger merger rate in (1) one gets

$$f = 0.15 - 0.38 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1} \,, \tag{2}$$

being in agreement with LIGO/VIRGO estimations, but in the price of some extreme postulations.

Possibility of primordial origin of BHs of the event GW190521 was also considered [20]. But, there are tight constraints on mass distribution of primordial BHs [21] and some theories of primordial BH formation predict small component spins [22], that is inconsistent with GW190521. It was also shown that GW190521 cannot be explained within the primordial BH scenario if primordial BHs do not accrete efficiently during their cosmological evolution [23]. Opportunity of strong gravitational lensing by galaxies or galaxy clusters for the signal GW190521 was also discussed. However, low expected lensing rate and optical depth, and the absence of a multi-image counterpart, disfavor strong lensing hypothesis [20].

1.2 The sources near the lower mass gap

The latest version of GW catalog includes some other notable events:

- GW190425 is probably the coalescence of NS-NS system with masses $2.0^{+0.6}_{-0.3} M_\odot$ and $1.4^{+0.3}_{-0.3} M_\odot$ [24];
- GW200105 with component masses $8.9^{+1.2}_{-1.5} M_\odot$ and $1.9^{+0.3}_{-0.2} M_\odot$ and GW200115 with component masses $5.9^{+2.0}_{-2.5} M_\odot$ and $1.44^{+0.85}_{-0.29} M_\odot$ are the very first detection of merger of BH-NS systems [25];
- GW190814 is a merger of a $23.2^{+1.1}_{-1.0} M_\odot$ BH with a $2.59^{+0.08}_{-0.09} M_\odot$ compact object [26].

Uncertainties are given at the 90% credible level. It is important to notice, that none of these events had accompanying electromagnetic radiation, while it is expected that such cataclysmic events should emit GRBs.

Moreover, what matters is that the distribution of masses of X-ray binaries reveal apparent so-called lower mass gap $2.5-5M_{\odot}$ between NSs and BHs [27, 28]. The aforementioned components of LIGO events lie on the edge of that mass gap. Some theoretical models of supernova explosions predict existence of the observed mass gap [29, 30]. Nonetheless, some models suggest a smooth transition from NS to BH masses [31, 32].

In principle, both components of GW190425 are consistent with being NSs. While the mass of the one component, $1.4^{+0.3}_{-0.3}M_{\odot}$, falls in a typical range of observed pulsars, the heavier component with the mass $2.0^{+0.6}_{-0.3}M_{\odot}$ also can be a NS, as far as existence of pulsars with mass of $\sim 2M_{\odot}$ were confirmed by observations [33, 34]. But there was no optical counterpart to GW190425, unlike the famous NS-NS merging event GW170817. With the source-frame chirp mass $1.44M_{\odot}$ and the total mass $3.4M_{\odot}$, the GW190425 system is significantly more massive than any binary NS system observed through electromagnetic radiation.

The most common mechanism for formation of binary NS systems is an isolated binary evolution channel (for a review see [35]). Following this path, GW190425 may suggest a population of binary NSs formed in ultra-tight orbits with sub-hour orbital period [24]. In order to achieve the system like this, it is required to have a phase of mass transfer from post-helium main sequence star onto NS. If the mass ratio between He-star and NS is high enough, a common-envelope phase is formed that would shrink the binary orbit to sub-hour periods [36]. If binary survives this common envelope phase, the subsequent supernova kick may be suppressed, as the secondary would likely be ultra-stripped [37]. The small supernova kick, together with very tight orbital separation, increases the chance for binary to remain bound after supernova. Hierarchical mergers of NSs or mass accretion in active galactic nuclei disks, may also be responsible for the creation of compact objects in the lower mass gap [38]. Other possible scenarios, like dynamical formation channels in globular clusters or gravitational lensing of the source of GW190425, is also discussed [24]. However, lack of objects discovered with given properties, does not allow to have a definite theory for their formation mechanism for now.

In the case of GW190814, the first component is definitely a BH. But the second object certainly lies in the lower mass gap, if such really exists. It is heavier than the most massive known pulsar and lighter than any BH discovered so far. The mass of the secondary component $2.59^{+0.08}_{-0.09}$ exceeds the possible maximum mass allowed for a stable NS in most of the models [39, 40]. However, due to theoretical uncertainties the NS-BH scenario cannot be ruled out, e.g. the second component can be a NS in view of some stiffer equation of state of dense nuclear matter [41]. It is also possible that it is a quark star in which the original NS was transformed due the fallback of the material after the gravitational collapse of a progenitor star [42]. Thus, GW190814 can be viewed as a BH-NS (or QS) merger which in principle could have an associated GRB and optical counterpart. The probability for the secondary component of GW190814 being exotic compact object, like boson star [43], gravastar [44], strange-quark star [45] or up-down quark star [46] was also considered.

For the completeness note that the secondary of the event GW190814 is presumably a BH, which may have formed by coalescence of NSs, e.g. the remnant of the event GW170817 has the similar mass [3]. But to merge again, hierarchical triple system in the field [47, 48] or in the galactic center [49, 50] must be considered.

By the end of the analyses of the trird run, merger rates were estimated to be $10-1700\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ for BNS systems, $7.8-140\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ for BH-NS and $9.4\times10^{-5}-25\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ for BH-mass gap objects [19]. Still having relatively high uncertainties in the measured merger rates, many models of compact binary formation and evolution can fit with the observations.

2. Sources from mirror world

With so much confusion arisen during the third observing run, we want to discuss a new scenario relating the masses of component compact objects. In [51–54] it was suggested that some GWs detected by LIGO may have emerged from the Mirror World (M-World). M-World is a candidate of Dark Matter (DM) and mirror particles interact with our ordinary world only through gravity. That is why we very rarely see the electromagnetic counterpart of GWs (the only one event so far), and as DM density exceeds baryonic matter density 5 times, estimated merger rates are higher than expected in standard scenarios and they agree better with measurements. We make a brief review of the M-World theory, before considering its possible link with LIGO's odd events.

2.1 Mirror world scenario

Mirror World (M-World) was introduced to restore left-right symmetry of nature, suggesting that each Standard Model particle has its mirror partner, which has opposite chirality. Mirror particles are invisible for ordinary observers and vice versa. Only way for the interaction between these two worlds is gravity. So, GW radiated by mirror matter can be sensed by an ordinary observer. For a review of theoretical foundations and cosmological applications of M-World see [55–57].

If M-World really exists, it was created by the Big Bang, along with ordinary matter. But the temperature of the M-world, T', must be lower than the temperature of our world, T. This requirement emerges from the fact that, mirror particles, having similar cosmological abundance, also contribute into the Hubble expansion rate and they should not violate the Big Bang Nucleosynthesis (BBN) bounds [58, 59]. This could be achieved if mirror and ordinary worlds are reheated asymmetrically after an inflationary epoch. Then the contribution of mirror neutrinos could be suppressed by a factor x^4, where $x = T'/T$ is the temperature ratio parameter [58, 59]. If these two worlds receive different initial temperatures and after that evolve adiabatically, interacting only weakly through gravity, they maintain the initial temperature ratio x until today [57, 59]. BBN bounds require $x < 0.5$ [59], but stronger limit $x < 0.3$ comes from constraints imposed by the cosmological large scale structure formation and cosmic microwave background data [60, 61].

In the context of grand unified theories, or electroweak baryogenesis scenario, due to lower temperature, baryon asymmetry in M-World is greater than in our world [59]. Certain leptogenesis mechanism via common $B - L$ violating interactions between ordinary and mirror particles [62], with $x \lesssim 0.2$, can imply $\Omega'/\Omega \approx 5$ (Ω and Ω' are ordinary and mirror matter densities), which can naturally solve the so-called coincidence problem between amounts of visible and dark matter [63].

2.2 Mirror stars

Due to some factors, the evolution of mirror stars can be somehow different from ordinary stars. As M-World is several times colder, at ordinary BBN epoch the universe expansion rate is completely determined by the ordinary world itself. So, M-World contribution into ordinary light element production is negligible [57, 59]. Contrary, in the M-World nucleosynthesis epoch, the contribution of ordinary matter scales as x^{-4} and plays a crucial role. It was shown that, for $x \lesssim 0.3$, the mirror helium mass fraction can reach 75 – 80% [59]. Thus, M-World is dominated by mirror helium [57] and mirror stars are mostly He-stars [64].

During the process of gravitational collapse of protogalaxy, it fragments into hydrogen clouds, which then cools and collapses until the opacity of the system becomes so high that the gas prefers to fragment into protostars. This is a way how first stars (Pop. III stars) in the Universe are formed. The lack of metals for that time makes the cooling process less efficient within clouds. So, their fragmentation could produce only high mass stars.

In M-World with lower temperature, H and He recombination is more efficient, which leaves a lower density for free electrons at late times [65]. Also, residual density of H_2 is suppressed by low H abundance. Free electrons and H_2 are two main cooling channels and their low abundances imply that cooling and fragmentation of mirror gas clouds are less efficient. That, in turn, entails that mirror helium stars are born more massive [64, 65].

Evolution of He-stars should be similar to ordinary stars, when they have converted most of hydrogen into He and formed a helium core. We know that higher is the mass of the star, the shorter is its life, as it burns out fuel faster. Increasing the initial helium abundance of a star, corresponds to the increase of the mean molecular weight, and correspondingly in both luminosity and effective temperature, that leads to the shorter lifetime. For instance, $10M_\odot$ star with 70% initial He content has the evolution timescale $\sim$ 10 times faster than the star with ordinary He abundance (24%) [64].

2.3 Possible sources of some LIGO events

Firstly, let us consider the possible M-World origin of the upper-mass-gap BHs of the LIGO catalog. In principle, BH-BH mergers, which account for the most amount of LIGO events, should not have optical counterparts, so they can be originated from both normal stars and mirror ones. However, BH binaries of mirror origin merely amplifies the chance of these BH-BH mergers [52, 53]. As the microphysics of mirror stars is similar to that of ordinary stars, they probably also are subject to pair instability and produce the mass gap for intermediate mass BHs. However, stars in M-World are born with higher initial mass, compared to ordinary stars, they evolve faster and higher quantities of massive BHs are formed in a short period of time. Also, adding the fact that the mirror matter density can be $\sim$ 5 times the ordinary matter density, BHs formed in the mirror matter environment, can increase in mass by accretion of mirror matter. Altogether, collisions of BHs formed by mirror stars are more frequent, increasing merger rate naturally [52, 53].

As a consequence, formation of intermediate mass BHs is easier in M-World, which could be a good interpretation for LIGO's upper-mass-gap BHs. In the framework of the M-World scenario, the extreme assumptions made by [13] in equation (1) may seem more reasonable, and the obtained merger rate for the first generation BHs, that formed the heavy components of GW190426_190642 and GW190521, can look more natural.

Another outcome of the M-World scenario can be explanation of issues relating the compact objects residing in or next to the lower-mass-gap in LIGO catalog. NS-NS or BH-NS mergers, in case they contain normal NSs, should be typically accompanied by GRB and optical afterglows. However, neither NS-NS event GW190425, or BH-NS mergers GW200105 and GW200115, nor BH-mass gap event GW190814 had such associations. In our paper [54] we suggested that binary NS merger with no optical counterpart can be a manifestation of its mirror origin.

So, the fact that "heavy" NSs are not detected through the electromagnetic spectrum but are observed through gravitational radiation, may be an indication that they exist in the mirror world. As discussed above, in order to form a binary NS system like GW190425, an ultra-tight binary with NS and massive He-star is required, that is more easily achieved in mirror world, as M-World is inhabited mostly by He-stars. The formation of GW190814-like systems is also challenging for current theories and their abundance is expected to be extremely low. However, in M-World the abundance of matter exceeds ~ 5 times the abundance of ordinary matter and stars in M-World evolve a way faster. This increases the probability of hierarchical mergers by an order of magnitude, and the formation of GW190814-like systems is more common.

3. Conclusions

In our previous papers [52–54] we had proposed that most of LIGO events may have emerged from Mirror World. This gives a good explanation for the absence of electromagnetic counterpart radiation and the high merger rates. In this article, we extended that idea to the odd events, recently detected LIGO/VIRGO. To form the binaries, components of which inhabit the upper or the lower mass gap, hierarchical mergers of very rare systems are required. We argue that such scenario is orders of magnitude more probable in M-World, since it can fully explain DM and so its matter abundance may exceed ordinary matter abundance ~ 5 times. Moreover, M-World is dominated by helium and He-stars evolve faster and create compact objects earlier, so hierarchical mergers are more probable and second-generation compact objects (remnants of first-generation compact object mergers) are formed with higher rate.

Acknowledgements

The work of R.B. was supported by Shota Rustaveli National Science Foundation of Georgia (SRNSFG), grant #48/04 and Volkswagenstiftung grant 93 562.

References

[1] R. Abbott *et al.* [LIGO Scientific, VIRGO and KAGRA], arXiv: 2111.03606 [gr-qc].

[2] R. Abbott *et al.* [LIGO Scientific and VIRGO], arXiv: 2108.01045 [gr-qc].

[3] B. P. Abbott *et al.* [LIGO Scientific and Virgo], Phys. Rev. X **9** (2019) 031040 [arXiv: 1811.12907 [astro-ph.HE]].

[4] B. P. Abbott *et al.* [LIGO Scientific and Virgo], Phys. Rev. Lett. **119** (2017) 161101 [arXiv: 1710.05832 [gr-qc]].

[5] A. Goldstein *et al.*, Astrophys. J. Lett. **848** (2017) L14 [arXiv: 1710.05446 [astro-ph.HE]].

[6] V. Savchenko *et al.*, Astrophys. J. Lett. **848** (2017) L15 [arXiv: 1710.05449 [astro-ph.HE]].

[7] R. Abbott *et al.* [LIGO Scientific and Virgo], Astrophys. J. **915** (2021) 86, [arXiv: 2010.14550 [astro-ph.HE]].

[8] R. Abbott *et al.* [LIGO Scientific, VIRGO and KAGRA], arXiv: 2111.03608 [astro-ph.HE].

[9] S. E. Woosley, S. Blinnikov and A. Heger, Nature **450** (2007) 390 [arXiv: 0710.3314 [astro-ph]].

[10] R. Abbott *et al.* [LIGO Scientific and Virgo], Phys. Rev. Lett. **125** (2020) 101102 [arXiv: 2009.01075 [gr-qc]].

[11] C. Kimball *et al.*, Astrophys. J. **900** (2020) 177 [arXiv: 2005.00023 [astro-ph.HE]].

[12] M. Mapelli *et al.*, Symmetry **13** (2021) 1678 [arXiv: 2007.15022 [astro-ph.HE]].

[13] B. Liu and D. Lai, Mon. Not. Roy. Astron. Soc. **502** (2021) 2049 [arXiv: 2009.10068 [astro-ph.HE]].

[14] C. O. Lousto and Y. Zlochower, Phys. Rev. Lett. **107** (2011) 231102 [arXiv: 1108.2009 [gr-qc]].

[15] B. Bruegmann, J. A. Gonzalez, M. Hannam, S. Husa and U. Sperhake, Phys. Rev. D **77** (2008) 124047 [arXiv: 0707.0135 [gr-qc]].

[16] V. Varma, M. Isi and S. Biscoveanu, Phys. Rev. Lett. **124** (2020) 101104 [arXiv: 2002.00296 [gr-qc]].

[17] M. A. Sedda, M. Mapelli, M. Spera, M. Benacquista and N. Giacobbo, Astrophys. J. **894** (2020) 133 [arXiv: 2003.07409 [astro-ph.GA]].

[18] V. Baibhav *et al.*, Phys. Rev. D **102** (2020) 043002 [arXiv: 2004.00650 [astro-ph.HE]].

[19] R. Abbott *et al.* [LIGO Scientific, VIRGO and KAGRA], arXiv: 2111.03634 [astro-ph.HE].

[20] R. Abbott *et al.* [LIGO Scientific and Virgo], Astrophys. J. Lett. **900** (2020) L13 [arXiv: 2009.01190 [astro-ph.HE]].

[21] M. Sasaki, T. Suyama, T. Tanaka and S. Yokoyama, Class. Quant. Grav. **35** (2018) 063001 [arXiv: 1801.05235 [astro-ph.CO]].

[22] T. Chiba and S. Yokoyama, PTEP **2017** (2017) 083E01 [arXiv: 1704.06573 [gr-qc]].

[23] V. De Luca, V. Desjacques, G. Franciolini, P. Pani and A. Riotto, Phys. Rev. Lett. **126** (2021) 051101 [arXiv: 2009.01728 [astro-ph.CO]].

[24] B. P. Abbott *et al.* [LIGO Scientific and Virgo], Astrophys. J. Lett. **892** (2020) L3 [arXiv: 2001.01761 [astro-ph.HE]].

[25] R. Abbott *et al.* [LIGO Scientific, KAGRA and VIRGO], Astrophys. J. Lett. **915** (2021) L5 [arXiv: 2106.15163 [astro-ph.HE]].

[26] R. Abbott *et al.* [LIGO Scientific and Virgo], Astrophys. J. Lett. **896** (2020) L44 [arXiv: 2006.12611 [astro-ph.HE]].

[27] F. Ozel, D. Psaltis, R. Narayan and A. S. Villarreal, Astrophys. J. **757** (2012) 55 [arXiv: 1201.1006 [astro-ph.HE]].

[28] W. M. Farr *et al.*, Astrophys. J. **741** (2011) 103 [arXiv: 1011.1459 [astro-ph.GA]].

[29] C. S. Kochanek, Astrophys. J. **785** (2014) 28 [arXiv: 1308.0013 [astro-ph.HE]].

[30] O. Pejcha and T. A. Thompson, Astrophys. J. **801** (2015) 90 [arXiv: 1409.0540 [astro-ph.HE]].

[31] S. E. Woosley, A. Heger and T. A. Weaver, Rev. Mod. Phys. **74** (2002) 1015.

[32] T. Ertl, S. E. Woosley, T. Sukhbold and H. T. Janka, Astrophys. J. **890** (2020) 51 [arXiv: 1910.01641 [astro-ph.HE]].

[33] P. Demorest, T. Pennucci, S. Ransom, M. Roberts and J. Hessels, Nature **467** (2010) 1081 [arXiv: 1010.5788 [astro-ph.HE]].

[34] J. Antoniadis *et al.*, Science **340** (2013) 6131 [arXiv: 1304.6875 [astro-ph.HE]].

[35] V. Kalogera, K. Belczynski, C. Kim, R. W. O'Shaughnessy and B. Willems, Phys. Rept. **442** (2007) 75 [arXiv: astro-ph/0612144 [astro-ph]].

[36] T. M. Tauris *et al.*, Astrophys. J. **846** (2017) 170 [arXiv: 1706.09438 [astro-ph.HE]].

[37] T. M. Tauris, N. Langer and P. Podsiadlowski, Mon. Not. Roy. Astron. Soc. **451** (2015) 2123 [arXiv: 1505.00270 [astro-ph.SR]].

[38] Y. Yang *et al.*, Astrophys. J. **901** (2020) L34 [arXiv: 2007.04781 [astro-ph.HE]].

[39] Y. Lim and J. W. Holt, Eur. Phys. J. A **55** (2019) 209 [arXiv: 1902.05502 [nucl-th]].

[40] R. Essick, P. Landry and D. E. Holz, Phys. Rev. D **101** (2020) 063007 [arXiv: 1910.09740 [astro-ph.HE]].

[41] H. Mueller and B. D. Serot, Nucl. Phys. A **606** (1996) 508 [arXiv: nucl-th/9603037].

[42] Z. Berezhiani, I. Bombaci, A. Drago, F. Frontera and A. Lavagno, Astrophys. J. **586** (2003) 1250 [arXiv: astro-ph/0209257].

[43] D. J. Kaup, Phys. Rev. **172** (1968) 1331.

[44] P. O. Mazur and E. Mottola, Proc. Nat. Acad. Sci. **101** (2004) 9545 [arXiv: gr-qc/0407075 [gr-qc]].

[45] I. Bombaci, A. Drago, D. Logoteta, G. Pagliara and I. Vidaña, Phys. Rev. Lett. **126** (2021) 162702, [arXiv: 2010.01509 [nucl-th]].

[46] Z. Cao, L. W. Chen, P. C. Chu and Y. Zhou, arXiv: 2009.00942 [astro-ph.HE].

[47] F. Antonini, S. Toonen and A. S. Hamers, Astrophys. J. **841** (2017) 77 [arXiv: 1703.06614 [astro-ph.GA]].

[48] G. Fragione and A. Loeb, Mon. Not. Roy. Astron. Soc. **486** (2019) 4443 [arXiv: 1903.10511 [astro-ph.GA]].

[49] F. Antonini and H. B. Perets, Astrophys. J. **757** (2012) 27 [arXiv: 1203.2938 [astro-ph.GA]].

[50] G. Fragione, E. Grishin, N. W. C. Leigh, H. B. Perets and R. Perna, Mon. Not. Roy. Astron. Soc. **488** (2019) 47 [arXiv: 1811.10627 [astro-ph.GA]].

[51] A. Addazi and A. Marciano, Int. J. Mod. Phys. A **33** (2018) 1850167 [arXiv: 1710.08822 [hep-ph]].

[52] R. Beradze and M. Gogberashvili, Mon. Not. Roy. Astron. Soc. **487** (2019) 650 [arXiv: 1902.05425 [gr-qc]].

[53] R. Beradze and M. Gogberashvili, MDPI Physics **1** (2019) 67 [arXiv: 1905.02787 [gr-qc]].

[54] R. Beradze, M. Gogberashvili and A. S. Sakharov, Phys. Lett. B **804** (2020) 135402 [arXiv: 1910.04567 [astro-ph.HE]].

[55] L. B. Okun, Phys. Usp. **50** (2007) 380 [arXiv: hep-ph/0606202].

[56] M. Y. Khlopov, *Fundamentals of Cosmic Particle Physics* (CISP-Springer, Cambridge 2012).

[57] Z. Berezhiani, In *From Fields to Strings*, vol. 3 (eds. M. Shifman, et al.) p. 2147 [arXiv: hep-ph/0508233].

[58] Z. G. Berezhiani, A. D. Dolgov and R. N. Mohapatra, Phys. Lett. B **375** (1996) 26 [arXiv: hep-ph/9511221].

[59] Z. Berezhiani, D. Comelli and F. L. Villante, Phys. Lett. B **503** (2001) 362 [arXiv: hep-ph/0008105].

[60] A. Y. Ignatiev and R. R. Volkas, Phys. Rev. D **68** (2003) 023518 [arXiv: hep-ph/0304260].

[61] Z. Berezhiani, P. Ciarcelluti, D. Comelli and F. L. Villante, Int. J. Mod. Phys. D **14** (2005) 107 [arXiv: astro-ph/0312605].

[62] L. Bento and Z. Berezhiani, Phys. Rev. Lett. **87** (2001) 231304 [arXiv: hep-ph/0107281].

[63] Z. Berezhiani, Int. J. Mod. Phys. A **19** (2004) 3775 [arXiv: hep-ph/0312335].

[64] Z. Berezhiani, S. Cassisi, P. Ciarcelluti and A. Pietrinferni, Astropart. Phys. **24** (2006) 495 [arXiv: astro-ph/0507153].

[65] J. S. Roux and J. M. Cline, Phys. Rev. D **102** (2020) 063518 [arXiv: 2001.11504 [astro-ph.CO]].