universe

Communication

Nucleosynthesis and Kilonovae from Strange Star Mergers

J. E. Horvath [1,*], O. G. Benvenuto [2,3], E. Bauer [3,4], L. Paulucci [5], A. Bernardo [1] and H. R. Viturro [3]

1 Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, R. do Matão 1226, 05508-090 São Paulo, SP, Brazil; alc.bernardo@gmail.com
2 Instituto de Astrofísica de La Plata, Universidad Nacional de La Plata, Paseo del Bosque S/N, 1900 La Plata, Argentina; omargbenvenuto@gmail.com
3 Facultad de CienciasAstronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque S/N, 1900 La Plata, Argentina; edubauer07@gmail.com (E.B.); hviturro@yahoo.com.ar (H.R.V.)
4 Instituto de Física de La Plata, CONICET, 1900 La Plata, Argentina
5 Universidade Federal do ABC, Av. dos Estados 5001, 09210-170 Santo André, SP, Brazil; lapaulucci@gmail.com
* Correspondence: foton@iag.usp.br

Received: 27 March 2019; Accepted: 7 June 2019; Published: 11 June 2019

Abstract: In this talk, we summarize the work in progress toward a full characterization of strange star–strange star (SS–SS) mergers related to the GW/GRB/kilonova events. In addition, we show that the a priori probability constructed from the observed neutron star mass distribution points toward an asymmetric binary system as the progenitor of the GW170817 event.

Keywords: kilonovae; compact star mergers; nucleosynthesis

1. Introduction

A series of exciting observations from a few different events have recently transformed the study of kilonovae [1], late afterglows of some transient events, into an exciting and true multimessenger field of high-energy astrophysics. Kilonovae were tentatively associated with compact star mergers (which we call "NS–NS"—neutron star-neutron star—hereafter, despite the fact that the "N" letter should be questioned by the very nature of our contribution, see below), but the announcement of the detection of a gravitational wave event [2] associated with this kind of merger, and the follow-up in several bands [3] has shown that there is indeed a deep connection between a catastrophic merger and the emergence of a "kilonova", which stems from the ejected material. As previously suspected, these events are expected to produce lanthanides, "third peak" r-process events (∼tens of Earth masses of *Au* and ∼ 100 of *Pt*), that are possibly the main contributor of heavy isotopes in the Periodic Table (see [4] for an overview). The quest is now manifold because it includes the systematics of the events, the identification of the ejected components and their physical features, and ultimately, the nature of the matter undergoing the merger itself. We shall present here a brief description of our work on some of the questions directly related to the NS–NS mergers, which remain under study.

2. Was GW170817 a Merger of Two "Strange Stars"?

The association of a class of gamma-ray bursts with compact star mergers has a long and interesting history. In the early 1990s, the theoretical models suggested that a "short" GRB should result along the direction perpendicular to the orbital plane, constituting most of the samples gathered by BATSE and related instruments that clustered around 0.1 s in time. Entering the 21st century, despite the direct evidence confirming this expectation, the NS–NS merger became "the" event associated with this short-duration class. The advent of the GW170817 event [2,5] was followed by the simultaneous detection of GRB170817A [6] and was received with great enthusiasm, precisely because it confirmed one model sustained for a long time. However, a few important concerns remain, mainly that the detected GRB was fainter than average by a factor of 1000 [6]. For some reason (physical or geometrical), the confirmation that NS–NS mergers do produce short GRBs is "abnormal" in this sense, which is a feature that is surely entangled with the production of the gamma-rays, but also with the matter ejection, as we shall see below. Was GRB "abnormal" indeed? Did it happened inside a "cocoon" [7]? Was it off-axis to a large degree? These questions are likely to be answered by collecting a substantial number of events that allow for the statistical determination and characterization of a full sample.

Another very important question is related to the nature (composition) of the merging objects themselves. The nucleosynthesis calculations overwhelmingly assume a "normal" (i.e., neutrons) composition, making the ejected matter and its fate calculable in a more or less standard form, albeit subject to a number of caveats. However, for almost 40 years, the idea that the true composition of "neutron" stars is actually a form of cold quark matter (the Strange Quark Matter [8–10]) has been seriously considered by many groups. It is clear that mergers and the associated emissions are a formidable tool to address the reality of the Bodmer–Terazawa–Witten hypothesis (see also [11,12] for an early discussion), a task that has not been undertaken yet and has some quite novel aspects to be considered in detail.

Within the SQM hypothesis for the composition of the merging stars (called "strange stars" or SS in the literature), and neglecting a tiny mass possibly attributed to a normal crust of the order of $\mathbf{10^{-5}} \boldsymbol{M_{@}}$ [13], the ejected mass initially composed of SQM evolves differently than normal nuclear matter. The expansion and cooling provokes that at a certain point, the fragmentation into quark fragments happens, in analogy with the fragmentation of nuclear matter into clusters and hadrons. Despite there being an absolute upper limit to the density at which this process should happen (the so-called "vacuum contribution" $\sim \mathbf{4}\boldsymbol{B}$ ensues a zero of the bulk SQM pressure) and at that stage, the temperature is expected to be $\sim \mathbf{10-20}\ \boldsymbol{MeV}$, so it is quite difficult to give an adequate assessment of these conditions. Fortunately, the result is not very dependent on the precise values and consistently yields a power-law in the $\mathbf{log}\boldsymbol{P_g}$- A plane when the machinery of the statistical multifragmentation framework is applied [14]. The probability of finding a fragment with mass A in the mass distribution is

$$P_g(\boldsymbol{A}) = \left(\frac{m_0 T}{2\pi}\right)^{3/2} A^{3/2} \exp\left[\frac{\left(\mu + W - bp_g\right)A - \sigma A^{2/3} - CA^{1/3}}{T}\right], \tag{1}$$

where $\boldsymbol{W}$ is the volume binding energy per baryon number of the bulk SQM; $\boldsymbol{bp_g}$ is a Van der Waals correction; and the two terms in the argument of the exponential are the surface and linear contributions, the latter known to be important for the quark matter description. The results can be appreciated in Figure 1 below. The vast majority of the matter was found to produce strangelets that later decay as they are not stable at high temperature, specifically those with $\boldsymbol{A} = \mathbf{2700}$ at $\boldsymbol{T} = \mathbf{30}\ \boldsymbol{MeV}$ and much lighter ones at lower temperatures, but it is important to remark that the peak of the fragmentation is always at the lowest possible A.

These results mean that we have to deal with ordinary hadrons after strangelet decay. Without a detailed calculation, and keeping in mind the high strangeness fraction, we expect that $\boldsymbol{\Lambda}$s are the main products, together with n,p, some clusters, and heavier hyperons. The whole ejecta ultimately will be n,p, after the decay of the $\boldsymbol{\Lambda}$s on a weak interaction timescale.

At this point, the study of the evolution of the ejecta, ultimately freezing out the n/p ratio and giving rise to nucleosynthesis shortly after, becomes much more difficult than that of its "big" famous cousin, the Big Bang nucleosynthesis. In the latter, the ambient is rather diluted and there is plenty of time for equilibration of the reactions driving the initial n/p toward its equilibrium value. If we propose this hypothesis for the mergers, and assume an adiabatic expression of the type $\boldsymbol{TV^{\gamma-1}} = \boldsymbol{constant}$ for the flow (considering the polar "blue" ejecta only for now), degeneracy is ignored, and the abundance *n/p* at freezeout can be calculated immediately [15], with the result that $\frac{n}{p} \geq \mathbf{0.7}$. The nucleosynthesis yield is essentially iron-peak elements at most, and no lanthanides or heavy r-process nuclei (actinides) can be produced. However, given that the initial state of the matter has a density of $\sim \mathbf{1.5}\boldsymbol{\rho_0}$ at least, degeneracy can be important. A full study of the filling of the Fermi seas by the reactions $\boldsymbol{\Lambda \rightarrow p\pi^-}$, $\boldsymbol{\Lambda \rightarrow n\pi^0}$, and $\boldsymbol{\Lambda N \rightarrow} \text{"}\mathbf{Nn}\text{"}$ in medium is being conducted, together with the later equilibration weak processes $\boldsymbol{n + e^+ \rightarrow \overline{\nu}_e + p}$ and $\boldsymbol{p + e^- \rightarrow \nu_e + n}$ to check whether or not blocking factors are important. This is crucial to assess the *n/p* at the time of nucleosynthesis, and confirm the kind of species produced. It is important to remark that the peak at $\sim \mathbf{1.4}\ \boldsymbol{\mu m}$ in the spectra of the kilonova associated with the GW170817 event has been widely interpreted as produced by lanthanides (despite the fact that individual line identification is practically impossible...), and therefore, the absence of these elements in all components can be used to argue against an exotic nature of the merging stars. However, the big "if" is related to the timescale for achieving the equilibrium *n/p* ratio, it is only for those high values of *n/p* that nucleosynthesis stops at the iron-peak elements, so partial equilibration may lead to a different outcome. If $\frac{n}{p} \geq \mathbf{0.7}$ or so finally results, one can argue that GW170817 was not produced by a SS–SS merger. We hope to soon offer concrete evidence for or against the SQM hypothesis along these grounds.

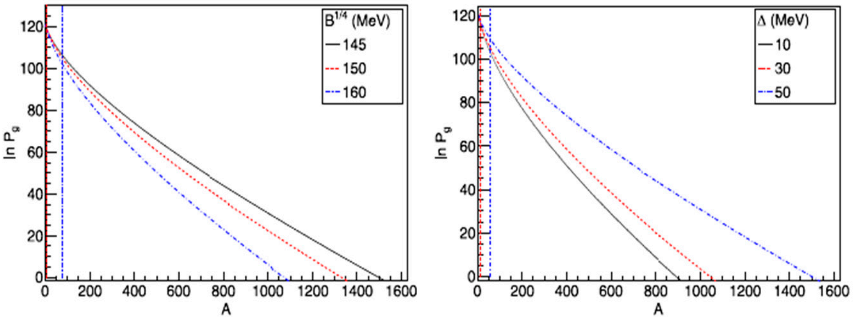

Figure 1. The outcome of multifragmentation calculations of SQM. (**Left**)The shape of the probability of a fragment as a function of the baryon number $\boldsymbol{A}$ for a fixed temperature $T = 30\ MeV$ for several values of the vacuum energy (inset). (**Right**)The same for $B^{1/4} = 145\ MeV$ and three representative values of the pairing energy Δ (inset). The vertical blue lines mark the value $\boldsymbol{A_{crit}}$ calculated self-consistently for the given set of parameters. The stability criterion indicates that all fragments (strangelets) to the left of this curve must decay into ordinary hadrons. We see that the overwhelming majority of the matter will not stay in the strangelet form.

3. Was GW170817 Caused by an Asymmetric Binary System?

Meanwhile, the only event at disposal, GW170817, has been analyzed by most works to be a *symmetric* system, where both stars feature two identical 1.37 $M_\odot$ neutron stars, an assumption which is quite consistent with the majority of known NS–NS systems. However, despite most measured binary NS systems being classified as "symmetric", there are some caveats in order. The first is related to the observed distribution of NS. A handful of analyses conducted on the "standard sample" [16] are now available [17–21], indicating that a one-size-fits-all mass distribution is no longer favored. The last results showed that three peaks were present with high significance, and a multimodal preference over the single-scale one was proven. Our own results reported in 2011 [22], recently updated with the inclusion of a few relevant additional systems, can be employed to address the issue of the mass symmetry of the merger. Employing a Gaussian parametrization (which is a reasonable, but not compelling choice), the latest results indicate that the peaks are located at the masses shown in Table 1, with their respective σ and amplitudes.

It is tempting to associate, at face value, progenitor masses that could have produced this distribution from an evolutionary point of view: the lowest-mass peak is what is expected from the collapse of $O - Mg - Ne$ [23]; some low-mass iron cores should be included in this bin since the lowest measured values of NS (~1.17 $M_\odot$) are actually *lower* than the minimum $O - Mg - Ne$ cores. The central, high-amplitude peak is just the "classical" value expected for the single-mass hypothesis, and its presence is not very surprising indeed. Finally, the highest-mass scale at 1.8 $M_\odot$ contains most of the systems that suffered a substantial amount of mass accretion (very massive iron cores would not require accretion, but seem not to contribute to produce high-mass NSs at birth [24,25]). The important point here is that binary systems containing a "first peak", light NS at birth should be produced, and the recent detection of PSR J0453+1559 by Martínez et al. [26] is likely to be an example of this expectation. This is why we favor the calculation of a joint probability extracting the masses from the whole distribution, and not just the double NS one. It is still unknown whether a sufficiently number of tight, asymmetric systems can be produced, but sticking to the small number of NSs with measured masses is not the best strategy at this point. As an example of how tricky things could be, we are reminded that 20 years ago, the entire community would have argued that the masses of NSs should be around ~1.4 $M_\odot$ based precisely on the (even smaller) number of double NSs measured at that time. Therefore, we advocate an open-minded attitude when binary NSs are considered today.

Table 1. The distribution of measured NS masses obtained from the analysis of the sample in [16] within a Gaussian parametrization normalized to the total number of measurements.

Location of the Peak ($M_\odot$)	$\sigma(M_\odot)$	Amplitude
1.25	0.07	0.14
1.4	0.08	0.50
1.8	0.28	0.36

If we accept that the whole NS distribution is given by the three-Gaussian expression, we can now address the problem of the symmetry of the GW170817 event. From the waveform analysis, a range of the primary M_1 and M_2 in the range $[1.17, 1.6] M_@$ has been derivedThe total mass of the system is a robust quantity measured with the help of the "chirp" mass determination, $M_1 + M_2 = 2.74 \pm \begin{array}{c} 0.04 \\ 0.01 \end{array} M_@$. Therefore, the probability of the pair as a function of the primary M_1 can be constructed by extracting the mass values from the reconstructed observed distribution from [16], where the result is displayed in Figure 2. The triple-peak distribution (where the "third" scale is too heavy to contribute) generates the desired $P(M_1, M_2)$ probability as shown in the figure. The "symmetry" can be now quantified in terms of the mass difference between the two components, which embodies some matter of choice. Taking into account that the mean measured mass in binaries is 1.33 $M_\odot$, we decided to consider a "symmetric" a system where M_1 lies between $[1.33–0.06, 1.33+0.06] M_@$, since $\sigma = 0.06\, M_@$ is the measured dispersion of this subgroup. Therefore, we can estimate that the probability of the system being *outside* the dotted lines (that is, being asymmetric) is just above 50%. This is a very large probability, not a marginal value, and indicates that an automatic assumption of symmetry in the analysis may be misleading. Moreover, this statement is further reinforced by the fact that the latest reanalysis [27] of the data favors a mass quotient $q = M_1/M_2 \approx 0.7 - 0.8$, although $q = 1$ is not excluded either.

We suggest that both the a priori probability of Figure 2, taken together with a reanalysis of the data, points toward an asymmetric system merger (see also [28] for a similar conclusion stemming from the joint analysis of the ejected mass and GW signal), probably of the type found by Martínez et al. [26] in the case of PSR J0453+1559. This system has component masses reported to be $M_1 = 1.559 \pm 0.005 M_@$ and $M_1 = 1.174 \pm 0.004 M_@$, yielding a value $q \approx 0.75$. However, the measured separation of the of PSR J0453+1559 system is too large to be identified as analogous to the progenitor of GW170817: its coalescence time is actually larger than the Hubble time H^{-1}. Therefore, an important question is whether *sufficiently tight* asymmetric systems can be formed at all. As is well-known, the simplest estimate for the coalescence time is

$$\tau_C = \frac{5}{256} \frac{c^5}{G^3} \frac{a_0^4}{\mu M^4}, \tag{2}$$

where a_0 is the value of the semi-axis at birth; μ is the reduced mass of the system; and M its total mass. The condition $\tau_C \leq H^{-1}$ is satisfied only for initial separations a_0 smaller than $2 - 3\ A.U.$ Large, massive progenitors with radii comparable to this required separation do not satisfy this condition. Therefore, independent quasi-simultaneous supernovae will not be able to produce tight enough systems that merge within a Hubble time. Recently, one viable scenario has been suggested [29] to provide an explanation of the explosive event iPTF14gqr, further identified with an *ultra-stripped* supernova. The main point is that the supernova happened inside a He-rich envelope, one in which a NS was already present. In this fashion, the final state would be a tight double NS system, and the authors further claimed that this may be the *only way* to produce very compact NS binaries to satisfy the time constraint. It is fair to say that these questions remain unsettled and need further work.

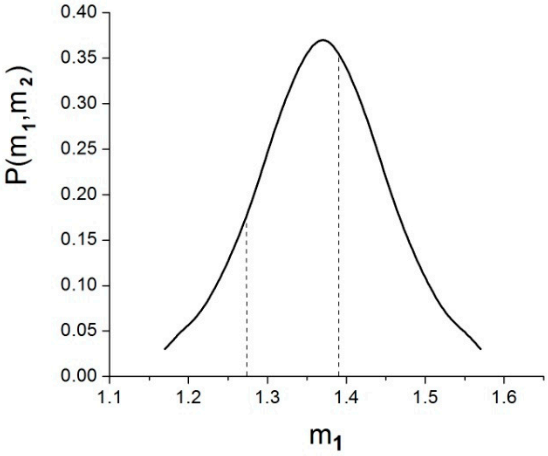

Figure 2. The construction of a joint probability $P(M_1, M_2)$ from the reconstructed NS distribution (**top**). The dotted lines correspond to ±1σ around the central average value obtained from binary systems 1.33 $M_{@}$. The area under the curve outside this range is in fact > 50% and suggests an asymmetry as emerging from the reanalysis. Note that the small errors stemming from the chirp mass determination have not been taken into account and would give the solid curve a narrow strip shape.

4. Discussion and Conclusions

The confirmation of a "NS–NS" merger associated with the production of a (faint) GRB and a kilonova has opened a new era in high-energy astrophysics. These events show the production of a variety of high-A elements, and this is precisely the feature that can be exploited to peep into the nature of the merging stars. Within the SQM hypothesis, the bulk matter will fragment into strangelets, and these will immediately decay into ordinary hadrons. In a previous publication [15], we showed that *if* equilibrium sets in, the *n/p* fraction at the time of freezeout would be so high that only iron-peak elements could be produced. However, since the matter fragments at densities above nuclear matter, the blocking factors of the reactions can be important and should be calculated. Our collaboration is working to provide a full assessment of this SQM scenario and establish the actual value of the *n/p* with confidence, since a large number would exclude GW170817 as a SS–SS event. On the other hand, we have analyzed the issue of the mass symmetry of the GW170817 pair and concluded from the whole NS distribution that an asymmetric system is likely, a result that is further supported by the latest reanalysis of the event [26]. We consider these as indicative, not as proof of asymmetry in the GW170817 event, although an analysis of the ejected mass together with the GW signal has been presented to argue for the asymmetry in stronger terms [28]. It is clear that a lot of physics and astrophysics will be learned by observing and modeling the NS–NS events in the future.

Author Contributions: J.E.H was involved from the beginning in the scientific conception and execution of the calculations, particularly in the asymmetry of the systems issue. O.G.B contributed with numerical calculations and physical insight on the dynamics and physics of the ejecta. E.B. added expertise in nuclear physics decays and related matters. L.P. performed the fragmentation calculations and contributed to the scientific shape of the work. A.B. was responsible for the development of present calculations and H.R.V. added work on the nucleosynthesis calculations to evaluate the yields.

Funding: This research was funded by FAPESP (São Paulo State, Brazil), grant number 2013/26258-4 and CNPq (Federal Agency, Brazil).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tanvir, N.R.; LeVan, A.J.; Fruchter, A.S.; Hjorth, J.; Hounsell, R.A.; Wiersema, K.; Tunnicliffe, R. A "kilonova" associated with short-duration gamma-ray burst 130603B. *Nature* **2013**, *500*, 547–549. [CrossRef]
2. Abbott, B.P. [LIGO Scientific Collaboration and Virgo Collaboration] GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.* **2017**, *119*, 161101. [CrossRef] [PubMed]
3. Science Site. Available online: http://www.sciencemag.org/news/2017/10/merging-neutron-stars-generate-gravitational-waves-and-celestial-light-show (accessed on 26 March 2019).
4. Cowan, J.J.; Sneden, C.; Lawler, J.E.; Aprahamian, A.; Wiescher, M.; Langanke, K.; Martínez-Pinedo, G.; Thielemann, F.-K. Making the Heaviest Elements in the Universe: A Review of the Rapid Neutron Capture Process. *arXiv* **2019**, arXiv:1901.01410.
5. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B.; et al. Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A. *Astrophys. J.* **2017**, *848*, L13. [CrossRef]
6. Goldstein, A.; Veres, P.; Burns, E.; Briggs, M.S.; Hamburg, R.; Kocevski, D.; Wilson-Hodge, C.A.; Preece, R.D.; Poolakkil, S.; Roberts, O.J.; et al. An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: Fermi -GBM Detection of GRB 170817A. *Astrophys. J.* **2017**, *848*, L14. [CrossRef]
7. Piran, T. Mergers and GRBs: Past, present and future. In Proceedings of the 8th International Workshop on Astronomy and Relativistic Astrophysics (IWARA 2018), Ollantaytambo, Peru, 8–15 September 2018.
8. Bodmer, A.R. Collapsed Nuclei. *Phys. Rev. D* **1971**, *4*, 1601. [CrossRef]
9. Terazawa, H. Super-hypernuclei in the quark shell model. *J. Phys. Soc. Jpn.* **1989**, *58*, 3555. [CrossRef]
10. Witten, E. Cosmic separation of phases. *Phys. Rev. D* **1984**, *30*, 272. [CrossRef]
11. Itoh, N. Hydrostatic Equilibrium of Hypothetical Quark Stars. *Prog. Theor. Phys.* **1970**, *44*, 291–292.
12. Ivanenko, D.; Kurdgelaidze, D.F. Remarks on quark stars. *Lett. Nuovo Cimento* **1969**, *2*, 13–14. [CrossRef]
13. Stenjer, M.; Madsen, J. Gaps below strange star crusts. *Phys. Rev. D* **2005**, *72*, 123005.
14. Paulucci, L.; Horvath, J. Strange quark matter fragmentation in astrophysical events. *Phys. Lett. B* **2014**, *733*, 164–168. [CrossRef]
15. Paulucci, L.; Horvath, J.E.; Benvenuto, O.G. Nucleosynthesis in strange star mergers. *Int. Jour. Mod. Phys. Conf. Series* **2017**, *45*, 1760042. [CrossRef]
16. Observed Neutron Star Masses. Available online: https://stellarcollapse.org/nsmasses (accessed on 26 March 2019).
17. Zhang, C.-M.; Wang, J.; Zhao, Y.H.; Yin, H.X.; Song, L.M.; Menezes, D.P.; Wickramasinghe, D.T.; Ferrario, L.; Chardonnet, P. Study of measured pulsar masses and their possible conclusions. *Astron. Astrophys.* **2011**, *527*, A83–A91. [CrossRef]
18. Kiziltan, B.; Kottas, A.; De Yoreo, M.; Thorsett, S.E. The Neutron Star Mass Distribution. *Astrophys. J.* **2013**, *778*, A66. [CrossRef]
19. Özel, F.; Psaltis, D.; Narayan, R.; Santos Villareal, A. On the Mass Distribution and Birth Masses of Neutron Stars. *Astrophys. J.* **2012**, *757*, 55. [CrossRef]
20. Özel, F.; Freire, P. Masses, Radii, and the Equation of State of Neutron Stars. *Annu. Rev. Astron. Astrophys.* **2016**, *54*, 401–440. [CrossRef]
21. Valentim, R.; (UFABC, Brazil). Personal communication, 2018.
22. Valentim, R.; Rangel, E.; Horvath, J.E. On the mass distribution of neutron stars. *Mon. Not. R. Astron. Soc.* **2011**, *414*, 1427–1431. [CrossRef]

23. Schwab, J.; Podsiadlowski, P.; Rappaport, S. Further Evidence for the Bimodal Distribution of Neutron-Star Masses. *Astrophys. J.* **2010**, *719*, 722–727. [CrossRef]
24. Ertl, T.; Janka, H.-T.; Woosley, S.E.; Sukhbold, T.; Ugliano, M. A Two-parameter Criterion for Classifying the Explodability of Massive Stars by the Neutrino-driven Mechanism. *Astrophys. J.* **2016**, *818*, 124. [CrossRef]
25. Raithel, C.A.; Sukhbold, T.; Özel, F. Confronting Models of Massive Star Evolution and Explosions with Remnant Mass Measurements. *Astrophys. J.* **2018**, *856*, 35. [CrossRef]
26. Martínez, J.G.; Stovall, K.; Freire, P.C.C.C.; Deneva, J.S.; Jenet, F.A.; McLaughlin, M.A.; Bagchi, M.; Bates, S.D.; Ridolfi, A. Pulsar J0453+1559: A Double Neutron Star System with a Large Mass Asymmetry. *Astrophys. J.* **2015**, *812*, 143. [CrossRef]
27. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B.; et al. Properties of the Binary Neutron Star Merger GW170817. *Phys. Rev. X* **2019**, *9*, 011001. [CrossRef]
28. Pankow, C. On GW170817 and the Galactic Binary Neutron Star Population. *Astrophys. J.* **2018**, *866*, 60–68. [CrossRef]
29. De, K.; Kasliwal, M.M.; Ofek, E.O.; Moriya, T.J.; Burke, J.; Cao, Y.; Cenko, S.B.; Doran, G.B.; Duggan, G.E.; Fender, R.P.; et al. A hot and fast ultra-stripped supernova that likely formed a compact neutron star binary. *Science* **2018**, *362*, 201–206. [CrossRef]