PROCEEDINGS OF SCIENCE

First constraints on binary black hole environments with LIGO-Virgo observations

Giada Caneva Santoro,[a,*] **Soumen Roy,**[b,c] **Rodrigo Vicente,**[a] **Maria Haney,**[b] **Ornella J. Piccinni,**[a] **Walter Del Pozzo**[d] **and Mario Martinez**[a,e]

[a] *Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, UAB Campus, E-08193 Barcelona, Spain*

[e] *Catalan Institution for Research and Advanced Studies (ICREA), E-08010 Barcelona, Spain*

[b] *Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*

[c] *Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University Princetonplein 1, 3584 CC Utrecht, The Netherlands*

[d] *Dipartimento di Fisica "Enrico Fermi", Università di Pisa and INFN Sezione di Pisa, Pisa I-56127, Italy*

E-mail: gcaneva@ifae.es

The LIGO-Virgo analyses of signals from compact binary mergers observed so far have assumed isolated binary systems in a vacuum, neglecting the potential presence of astrophysical environments. We present here the first investigation of environmental effects on each of the events of GWTC-1 and two low-mass events from GWTC-2. We find no evidence for the presence of environmental effects. Most of the events decisively exclude the scenario of dynamical fragmentation of massive stars as their formation channel. GW170817 results in the most stringent upper bound on the medium density ($\lesssim 21$ g/cm^3). We find that environmental effects can substantially bias the recovered parameters in the vacuum model, even when these effects are not detectable. We forecast that the Einstein Telescope and B-DECIGO will be able to probe the environmental effects of accretion disks and superradiant boson clouds on compact binaries.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023), 21-25 August 2023 Hamburg, Germany

*Speaker

1. Introduction

LIGO-Virgo-KAGRA (LVK) routinely conducts analyses looking for gravitational-wave (GW) events, including parameter estimation, population and cosmology studies, and tests of general relativity (GR) [2–15]. These analyses have traditionally assumed GW sources exist in a vacuum. However, there is a growing interest in understanding the impact of astrophysical environments on these observations, particularly in scenarios like binary black hole (BBH) formation in star clusters [16–21] and active galactic nuclei (AGN) accretion disks [23, 24]. While prior studies mainly focused on LISA-relevant sources [25–32], we explore LVK's current ability to detect environmental effects in events of the first LIGO-Virgo catalog (GWTC-1) provided by the Gravitational Wave Open Science Center (GWOSC) [1]. We perform a Bayesian analysis to identify environmental effects and constrain the environment density. This study introduces a parameterized post-Newtonian (PN) test tailored for lower-mass binary systems, addressing environmental effects during the inspiral stage. Geometrized units with $G = c = 1$ are used throughout.

2. Environmental effects

In astrophysical environments, the phase evolution of compact binaries is subject to modifications due to various effects: accretion affects the masses of binary components and the orbital phase. In some media, Bondi-Hoyle-Lyttleton accretion (BHLA)[35] is a good description of the binary accretion scenario. In other cases, such as environments with particle dark matter overdensities or plasmas around black holes, collisionless accretion (CA) provides a better description. For LVK binaries, accretion dynamical friction (DF) [33, 34] from the gravitational wake in the medium are expected to be the most prominent effects on the GW phase evolution for binaries in quasi-circular orbits. While the specifics of these effects depend on the particular environment and binary source, certain generic features can be well approximated through semi-analytic expressions. These effects generally result in small corrections, $\widehat{\delta\Phi}_k$, to the vacuum GW phase, $\phi^{\rm vac}$. These corrections introduce additive terms at different low negative PN orders ($k = -4.5$PN, -5.5PN) in the GW phase evolution [43] in the following way

$$\widehat{\delta\Phi}_k \propto -\beta_k \rho M^2 \tag{1}$$

where the expressions for β_k are shown in Tab.1.

Table 1: Dependence of environmental dephasing coefficients on physical parameters.

Effect	β_k	k
CA	$\frac{125\pi(1-3\eta)}{357\eta^2}$	-4.5
BHLA	$\frac{125\pi[1-5\eta(1-\eta)]}{1824\eta^4}$	-5.5
DF	$\frac{25\pi(1-3\eta)}{304\eta^3}$	-5.5

	GW150914	GW151012	GW151226	GW170104	GW170608	GW170729	GW170809	GW170814	GW170817	GW170818	GW170823
$\delta\Phi_{-4.5\text{PN}}$	−2.09	0.86	−4.20	−1.29	−4.95	–	−1.91	−3.17	−5.45	−2.55	–
$\delta\Phi_{-11\text{PN}}$	−3.30	0.77	−5.52	−3.33	−6.17	–	−2.59	−2.81	−6.47	−2.57	–

Table 2: Logarithmic Bayes factor ($\log_{10}\mathcal{B}^{\text{env}}_{\text{vac}}$) for GWTC-1 events. For the events GW170729 and GW170823, we could not find informative $\delta\Phi_k$ posteriors even with a broad prior range due to the low SNR of their inspiral.

3. Bayesian analysis

We introduce an agnostic dephasing parameter $\delta\Phi_k$ representing the environmental shift in the GW phase. In frequency domain, the phase of a binary in an environment is given by:

$$\phi^{\text{env}} = \phi^{\text{vac}} + \frac{3}{128\eta}\delta\Phi_k v^k, \tag{2}$$

with $v := (\pi M_z f)$, where $f/2$ denotes the orbital frequency and we define $M_z := (1+z)M$, with M the binary's total mass (in the source frame) and z the cosmological redshift to the source. The symmetric mass ratio is defined as $\eta := m_1 m_2/M^2$, ρ is the (local) average mass density of the environment and $k = -4.5$ for CA, and $k = -5.5$ for BHLA or DF. We adopt the model-agnostic framework of parameterized tests of GR [36] to incorporate this environmental correction. Our waveform models `IMRPhenomPv2` [37–39] and `IMRPhenomPv2_NRTidalv2` [40] for BBH and binary neutron star (BNS) systems, respectively, account for spin-induced precession effects. We perform Bayesian parameter estimation to measure $\delta\Phi_k$ and assess the evidence for the environment. The Bayes factor $\mathcal{B}^{\text{env}}_{\text{vac}}$ compares the hypotheses: (i) data d described by the environmental model $\mathcal{H}_{\text{env}}$ with nonzero $\delta\Phi_k$, and (ii) data described by the vacuum model $\mathcal{H}_{\text{vac}}$ with no additional parameters. We obtain the marginalized posterior probability distribution of $\delta\Phi_k$ within $\mathcal{H}_{\text{env}}$ using Bayes' rule with a zero-centred uniform prior for $\delta\Phi_k$. We choose the prior range of $\delta\Phi_k$ to ensure sampler convergence to the global maximum, considering the sensitivity to low-mass systems. To address specific environmental effects causing phase deformation, we vary a single phase parameter at a time.

4. Results

We analyzed the eleven events in GWTC-1: almost all events showed negative log Bayes factor values, Tab.2, except for GW151012, which remained inconclusive due to its low statistical significance. While the data do not support the evidence for an environment around the analysed events, the possibility of an environmental influence cannot be definitely ruled out. Environmental corrections appear most effective in the early inspiral phase, but their detection can be challenging due to noise.

We use the results to estimate upper limits on environmental density as shown in Fig.1. For events

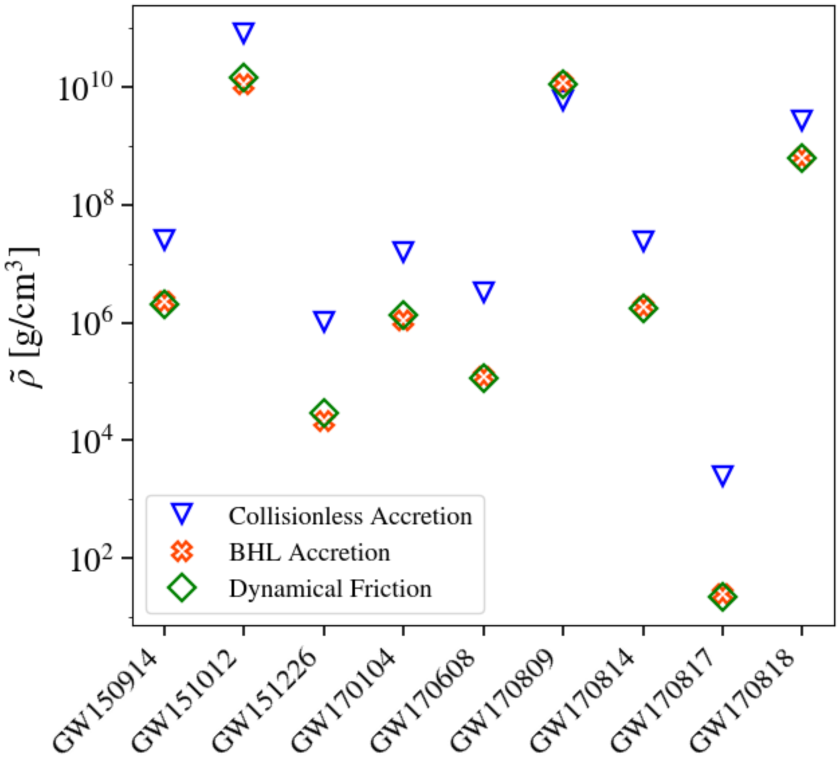

Figure 1: 90% upper bounds on the environmental density obtained considering the effect of CA (blue triangle), BHLA (red cross), and DF (green diamond).

GW150914, GW151226, GW170104, GW170608, GW170814, and GW170817, we find density constraints in the range of $\rho \lesssim \times 10^6 \mathrm{g/cm^3}$, decisively ruling out the binary formation scenario of dynamical fragmentation [41, 42]. However, for the remaining events, characterized by low inspiral SNR and fewer inspiral cycles, the density constraints are inconclusive. Of particular note is the constraint from GW170817, where we obtain $\rho \lesssim 21 \mathrm{g/cm^3}$. This constraint stands out as the tightest result in GWTC-1, and it roughly corresponds to the density of gold at room temperature on Earth.

5. Prospects

In Figure 2, we show the required SNR for detecting environmental effects versus the environmental density curves, needed to obtain a $\log_{10} \mathcal{B}^{\mathrm{env}}_{\mathrm{vac}} = 3$ for events mimicking GW170817 and GW170608 events. Our results indicate that ET can detect DF effects in a GW170817-like event when the surrounding environment has a density of approximately $10^{-3} \mathrm{g/cm^3}$. Additionally, it can identify CA effects in environments about 10^3 times denser. B-DECIGO [22], with its extended low-frequency coverage, will detect environmental effects at even lower densities. For B-DECIGO, DF effects in a GW170817-like event become observable when the environment density is approximately $10^{-12} \mathrm{g/cm^3}$, and CA effects are detectable for densities roughly 10^4 times larger.

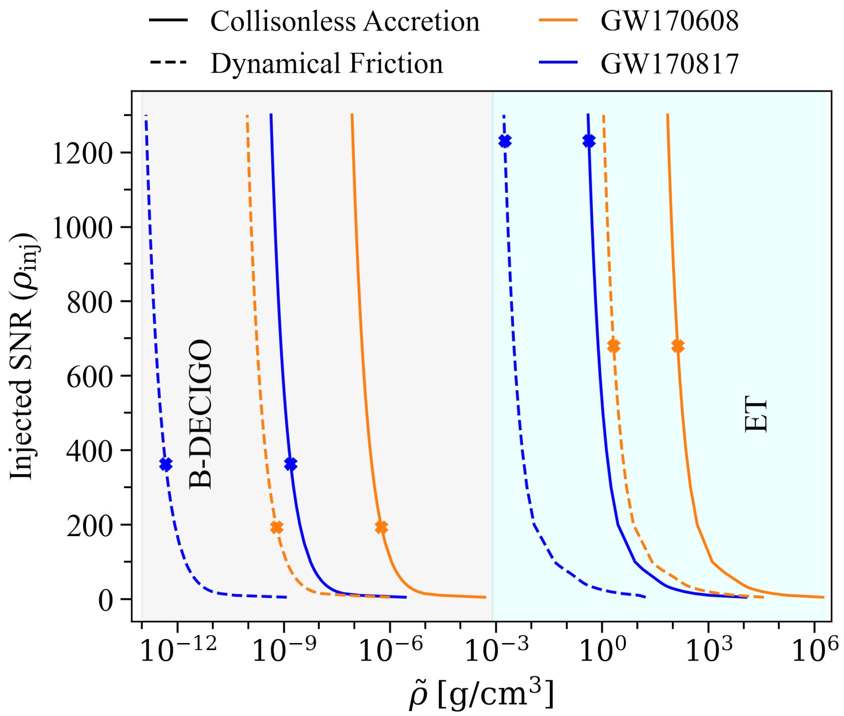

Figure 2: Curves of required SNR for a given density value to achieve $\log_{10} \mathcal{B}^{\rm env}_{\rm vac} = 3$ for a specific environmental effect, in the configuration of the third-generation detector ET (cyan shade) and the Japanese space-detector B-DECIGO (gray shade). The dots represent the expected SNR if we replace the LIGO-Hanford detector with those future detectors. We omit the BHLA curve since it follows very closely the DF one.

6. Conclusions

We developed a model-agnostic Bayesian analysis to detect environmental effects around compact binary systems, focusing on accretion and DF effects. Our analysis included individual events from the GWTC-1 catalog, and we found no evidence supporting the existence of environments around these binaries. We also derived upper bounds on environmental densities. we explored the prospects for future detectors like ET and B-DECIGO. ET showed promise in detecting DF and BHLA effects in environments as diluted as $\rho \sim 10^{-3}$g/cm^3, while B-DECIGO's low-frequency sensitivity extended the reach to even less dense environments. Our model-agnostic approach aimed to assess the detectors' overall capability and derive initial constraints. Future work will focus on specific environments and consider higher multipoles for asymmetric binaries.

7. Acknowledgements

This research has made use of data or software obtained from the Gravitational Wave Open Science Center (gwosc.org), a service of the LIGO Scientific Collaboration, the Virgo Collaboration, and KAGRA. This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation, as well as the Science and

Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. Virgo is funded, through the European Gravitational Observatory (EGO), by the French Centre National de Recherche Scientifique (CNRS), the Italian Istituto Nazionale di Fisica Nucleare (INFN) and the Dutch Nikhef, with contributions by institutions from Belgium, Germany, Greece, Hungary, Ireland, Japan, Monaco, Poland, Portugal, Spain. KAGRA is supported by Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan Society for the Promotion of Science (JSPS) in Japan; National Research Foundation (NRF) and Ministry of Science and ICT (MSIT) in Korea; Academia Sinica (AS) and National Science and Technology Council (NSTC) in Taiwan. The authors are grateful for computational resources provided by the LIGO Laboratory and supported by National Science Foundation Grants PHY-0757058 and PHY-0823459. This work is partially supported by the Spanish MCIN/AEI/ 10.13039/501100011033 under the Grants No. SEV-2016- 0588, No. PGC2018-101858-B-I00, and No. PID2020– 113701 GB-I00, some of which include ERDF funds from the European Union, and by the MICINN with funding from the European Union NextGenerationEU (PRTR- C17.I1) and by the Generalitat de Catalunya.

References

[1] Abbott, R. and others, LIGO Scientific, Virgo Collaboration, "Open data from the first and second observing runs of Advanced LIGO and Advanced Virgo", arXiv:1912.11716 [gr-qc], LIGO-P1900206, SoftwareX, 13, 100658 (2021), doi:10.1016/j.softx.2021.100658.

[2] B. P. Abbott et al., Collaboration: LIGO Scientific, Virgo, "GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs", arXiv:1811.12907, archivePrefix: "arXiv", primaryClass: "astro-ph.HE", reportNumber: "LIGO-P1800307", doi: 10.1103/PhysRevX.9.031040, journal: "Phys. Rev. X", volume: 9, number: 3, pages: 031040, year: 2019

[3] R. Abbott et al., Collaboration: LIGO Scientific, Virgo, "GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run", arXiv:2010.14527, archivePrefix: "arXiv", primaryClass: "gr-qc", reportNumber: "P2000061", doi: 10.1103/PhysRevX.11.021053, journal: "Phys. Rev. X", volume: 11, pages: 021053, year: 2021

[4] R. Abbott et al., Collaboration: LIGO Scientific, VIRGO, "GWTC-2.1: Deep Extended Catalog of Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run", arXiv e-prints, keywords: General Relativity and Quantum Cosmology, year: 2021, month: aug, eid: arXiv:2108.01045, pages: arXiv:2108.01045, doi: 10.48550/arXiv.2108.01045, archivePrefix: arXiv, eprint: 2108.01045, primaryClass: gr-qc, adsurl: https://ui.adsabs.harvard.edu/abs/2021arXiv210801045T, adsnote: Provided by the SAO/NASA Astrophysics Data System

[5] R. Abbott et al., Collaboration: LIGO Scientific, VIRGO, KAGRA, "GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run", arXiv e-prints, year: 2021, month: nov, eid: arXiv:2111.03606, pages: arXiv:2111.03606, doi: 10.48550/arXiv.2111.03606, archivePrefix: arXiv, eprint: 2111.03606, primaryClass: gr-qc, adsurl: https://ui.adsabs.harvard.edu/abs/2021arXiv211103606T, adsnote: Provided by the SAO/NASA Astrophysics Data System

[6] B. P. Abbott et al., Collaboration: LIGO Scientific, Virgo, "Binary Black Hole Population Properties Inferred from the First and Second Observing Runs of Advanced LIGO and Advanced Virgo", arXiv:1811.12940, archivePrefix: "arXiv", primaryClass: "astro-ph.HE", reportNumber: "LIGO-P1800324", doi: 10.3847/2041-8213/ab3800, journal: "Astrophys. J. Lett.", volume: 882, number: 2, pages: L24, year: 2019

[7] R. Abbott et al., Collaboration: LIGO Scientific, Virgo, "Population Properties of Compact Objects from the Second LIGO-Virgo Gravitational-Wave Transient Catalog", arXiv:2010.14533, archivePrefix: "arXiv", primaryClass: "astro-ph.HE", reportNumber: "LIGO-P2000077", doi: 10.3847/2041-8213/abe949, journal: "Astrophys. J. Lett.", volume: 913, number: 1, pages: L7, year: 2021

[8] R. Abbott et al., Collaboration: KAGRA, VIRGO, LIGO Scientific, "Population of Merging Compact Binaries Inferred Using Gravitational Waves through GWTC-3", arXiv:2111.03634, archivePrefix: "arXiv", primaryClass: "astro-ph.HE", reportNumber: "LIGO-P2100239 ; Data release: https://zenodo.org/record/5655785, LIGO-P2100239", doi: 10.1103/PhysRevX.13.011048, journal: "Phys. Rev. X", volume: 13, number: 1, pages: 011048, year: 2023

[9] B. P. Abbott et al., Collaboration: LIGO Scientific, Virgo, 1M2H, Dark Energy Camera GW-E, DES, DLT40, Las Cumbres Observatory, VINROUGE, MASTER, "A gravitational-wave standard siren measurement of the Hubble constant", arXiv:1710.05835, archivePrefix: "arXiv", primaryClass: "astro-ph.CO", reportNumber: "LIGO-P1700296, FERMILAB-PUB-17-472-A-AE", doi: 10.1038/nature24471, journal: "Nature", volume: 551, number: 7678, pages: 85–88, year: 2017

[10] B. P. Abbott et al., Collaboration: LIGO Scientific, Virgo, VIRGO, "A Gravitational-wave Measurement of the Hubble Constant Following the Second Observing Run of Advanced LIGO and Virgo", arXiv:1908.06060, archivePrefix: "arXiv", primaryClass: "astro-ph.CO", reportNumber: "LIGO-P1900015", doi: 10.3847/1538-4357/abdcb7, journal: "Astrophys. J.", volume: 909, number: 2, pages: 218, year: 2021

[11] R. Abbott et al., Collaboration: LIGO Scientific, Virgo,, KAGRA, VIRGO, "Constraints on the Cosmic Expansion History from GWTC–3", arXiv:2111.03604, archivePrefix: "arXiv", primaryClass: "astro-ph.CO", reportNumber: "LIGO-P2100185-v6, LIGO-P2100185-v5", doi: 10.3847/1538-4357/ac74bb, journal: "Astrophys. J.", volume: 949, number: 2, pages: 76, year: 2023

PoS(EPS-HEP2023)068

[12] B. P. Abbott et al., Collaboration: LIGO Scientific, Virgo, "Tests of General Relativity with the Binary Black Hole Signals from the LIGO-Virgo Catalog GWTC-1", arXiv:1903.04467, archivePrefix: "arXiv", primaryClass: "gr-qc", reportNumber: "LIGO-P1800316", doi: 10.1103/PhysRevD.100.104036, journal: "Phys. Rev. D", volume: 100, number: 10, pages: 104036, year: 2019

[13] R. Abbott et al., Collaboration: LIGO Scientific, Virgo, "Tests of general relativity with binary black holes from the second LIGO-Virgo gravitational-wave transient catalog", arXiv:2010.14529, archivePrefix: "arXiv", primaryClass: "gr-qc", reportNumber: "LIGO-P2000091", doi: 10.1103/PhysRevD.103.122002, journal: "Phys. Rev. D", volume: 103, number: 12, pages: 122002, year: 2021

[14] R. Abbott et al., Collaboration: LIGO Scientific, VIRGO, KAGRA, "Tests of General Relativity with GWTC-3", arXiv e-prints, keywords: General Relativity and Quantum Cosmology, Astrophysics - High Energy Astrophysical Phenomena, High Energy Physics - Theory, year: 2021, month: dec, eid: arXiv:2112.06861, pages: arXiv:2112.06861, doi: 10.48550/arXiv.2112.06861, archivePrefix: arXiv, eprint: 2112.06861, primaryClass: gr-qc, adsurl: https://ui.adsabs.harvard.edu/abs/2021arXiv211206861T, adsnote: Provided by the SAO/NASA Astrophysics Data System

[15] B. P. Abbott et al., Collaboration: KAGRA, LIGO Scientific, Virgo, VIRGO, "Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA", arXiv:1304.0670, archivePrefix: "arXiv", primaryClass: "gr-qc", reportNumber: "LIGO-P1200087, VIR-0288A-12, JGW-P1808427", doi: 10.1007/s41114-020-00026-9, journal: "Living Rev. Rel.", volume: 21, number: 1, pages: 3, year: 2018

[16] Sambaran Banerjee, Holger Baumgardt, Pavel Kroupa, "Stellar-mass black holes in star clusters: implications for gravitational wave radiation", Mon. Not. Roy. Astron. Soc., keywords: black hole physics, gravitational waves, scattering, stellar dynamics, methods: N-body simulations, galaxies: star clusters, Astrophysics - Solar and Stellar Astrophysics, Astrophysics - Astrophysics of Galaxies, Astrophysics - High Energy Astrophysical Phenomena, year: 2010, month: feb, volume: 402, number: 1, pages: 371-380, doi: 10.1111/j.1365-2966.2009.15880.x, archivePrefix: arXiv, eprint: 0910.3954, primaryClass: astro-ph.SR, adsurl: https://ui.adsabs.harvard.edu/abs/2010MNRAS.402..371B, adsnote: Provided by the SAO/NASA Astrophysics Data System

[17] Sourav Chatterjee, Carl L. Rodriguez, Frederic A. Rasio, "Binary Black Holes in Dense Star Clusters: Exploring the Theoretical Uncertainties", , keywords: black hole physics, globular clusters: general, methods: numerical, methods: statistical, stars: black holes, stars: kinematics and dynamics, Astrophysics - Astrophysics of Galaxies, year: 2017, month: jan, volume: 834, number: 1, eid: 68, pages: 68, doi: 10.3847/1538-4357/834/1/68, archivePrefix: arXiv, eprint: 1603.00884, primaryClass: astro-ph.GA, adsurl: https://ui.adsabs.harvard.edu/abs/2017ApJ...834...68C, adsnote: Provided by the SAO/NASA Astrophysics Data System

PoS(EPS-HEP2023)068

[18] Brunetto Marco Ziosi, Michela Mapelli, Marica Branchesi, Giuseppe Tormen, "Dynamics of stellar black holes in young star clusters with different metallicities – II. Black hole–black hole binaries", arXiv:1404.7147, archivePrefix: "arXiv", primaryClass: "astro-ph.GA", doi: 10.1093/mnras/stu824, journal: "Mon. Not. Roy. Astron. Soc.", volume: 441, number: 4, pages: 3703-3717, year: 2014

[19] Carl L. Rodriguez, Meagan Morscher, Bharath Pattabiraman, Sourav Chatterjee, Carl-Johan Haster, Frederic A. Rasio, "Binary Black Hole Mergers from Globular Clusters: Implications for Advanced LIGO", arXiv:1505.00792, archivePrefix: "arXiv", primaryClass: "astro-ph.HE", doi: 10.1103/PhysRevLett.115.051101, journal: "Phys. Rev. Lett.", volume: 115, number: 5, pages: 051101, year: 2015, note: "[Erratum: Phys.Rev.Lett. 116, 029901 (2016)]"

[20] Michela Mapelli, Yann Bouffanais, Filippo Santoliquido, Manuel Arca Sedda, M. Celeste Artale, "The cosmic evolution of binary black holes in young, globular, and nuclear star clusters: rates, masses, spins, and mixing fractions", arXiv:2109.06222, archivePrefix: "arXiv", primaryClass: "astro-ph.HE", doi: 10.1093/mnras/stac422, journal: "Mon. Not. Roy. Astron. Soc.", volume: 511, number: 4, pages: "5797–5816", year: 2022

[21] Michela Mapelli, "Formation Channels of Single and Binary Stellar-Mass Black Holes", arXiv:2106.00699, archivePrefix: "arXiv", primaryClass: "astro-ph.HE", doi: 10.1007/978-981-15-4702-$7_16-1, booktitle: ''Handbook of Gravitational Wave Astronomy'', year: 2021, eid: 16, pages: 16$

[22] Soichiro Isoyama, Hiroyuki Nakano and Takashi Nakamura, "Multiband Gravitational-Wave Astronomy: Observing binary inspirals with a decihertz detector, B-DECIGO", eprint: "1802.06977", archivePrefix: "arXiv", primaryClass: "gr-qc", doi: 10.1093/ptep/pty078, journal = "PTEP", volume: "2018", number: 7, pages: 073E01, year:2018

[23] Manuel Arca Sedda, Smadar Naoz, Bence Kocsis, "Quiescent and Active Galactic Nuclei as Factories of Merging Compact Objects in the Era of Gravitational Wave Astronomy", arXiv:2302.14071, archivePrefix: "arXiv", primaryClass: "astro-ph.GA", doi: 10.3390/universe9030138, journal: "Universe", volume: 9, number: 3, pages: 138, year: 2023

[24] Connar Rowan, Tjarda Boekholt, Bence Kocsis, Zoltán Haiman, "Black hole binary formation in AGN discs: from isolation to merger", Mon. Not. Roy. Astron. Soc., keywords: gravitational waves, hydrodynamics, binaries: general, galaxies: nuclei, (transients:) black hole mergers, Astrophysics - Astrophysics of Galaxies, year: 2023, month: sep, volume: 524, number: 2, pages: 2770-2796, doi: 10.1093/mnras/stad1926, archivePrefix: arXiv, eprint: 2212.06133, primaryClass: astro-ph.GA, adsurl: https://ui.adsabs.harvard.edu/abs/2023MNRAS.524.2770R, adsnote: Provided by the SAO/NASA Astrophysics Data System

[25] Laura Sberna and others, "Observing GW190521-like binary black holes and their environment with LISA", arXiv:2205.08550, archivePrefix: "arXiv", primaryClass: "gr-qc", doi: 10.1103/PhysRevD.106.064056, journal: "Phys. Rev. D", volume: 106, number: 6, pages: "064056", year: 2022

[26] Lorenzo Speri, Andrea Antonelli, Laura Sberna, Stanislav Babak, Enrico Barausse, Jonathan R. Gair, Michael L. Katz, "Probing Accretion Physics with Gravitational Waves", arXiv:2207.10086, archivePrefix: "arXiv", primaryClass: "gr-qc", doi: 10.1103/PhysRevX.13.021035, journal: "Phys. Rev. X", volume: 13, number: 2, pages: "021035", year: 2023

[27] Nicholas Speeney, Andrea Antonelli, Vishal Baibhav, Emanuele Berti, "Impact of relativistic corrections on the detectability of dark-matter spikes with gravitational waves", arXiv:2204.12508, archivePrefix: "arXiv", primaryClass: "gr-qc", doi: 10.1103/PhysRevD.106.044027, journal: "Phys. Rev. D", volume: 106, number: 4, pages: "044027", year: 2022

[28] Vitor Cardoso, Kyriakos Destounis, Francisco Duque, Rodrigo Panosso Macedo, Andrea Maselli, "Gravitational Waves from Extreme-Mass-Ratio Systems in Astrophysical Environments", arXiv:2210.01133, archivePrefix: "arXiv", primaryClass: "gr-qc", doi: 10.1103/PhysRevLett.129.241103, journal: "Phys. Rev. Lett.", volume: 129, number: 24, pages: "241103", year: 2022

[29] Philippa S. Cole, Gianfranco Bertone, Adam Coogan, Daniele Gaggero, Theophanes Karydas, Bradley J. Kavanagh, Thomas F. M. Spieksma, Giovanni Maria Tomaselli, "Disks, spikes, and clouds: distinguishing environmental effects on BBH gravitational waveforms", arXiv:2211.01362, archivePrefix: "arXiv", primaryClass: "gr-qc", doi: 10.48550/arXiv.2211.01362, journal: "arXiv e-prints", year: 2022, month: nov, eid: "arXiv:2211.01362", pages: "arXiv:2211.01362"

[30] Adrien Kuntz, Konstantin Leyde, "Transverse Doppler effect and parameter estimation of LISA three-body systems", arXiv:2212.09753, archivePrefix: "arXiv", primaryClass: "gr-qc", doi: 10.1103/PhysRevD.108.024002, journal: "Phys. Rev. D", volume: 108, number: 2, pages: "024002", year: 2023

[31] Alexis Boudon, Philippe Brax, Patrick Valageas, Leong Khim Wong, "Gravitational waves from binary black holes in a self-interacting scalar dark matter cloud", arXiv e-prints, year: 2023, month: may, eid: "arXiv:2305.18540", pages: "arXiv:2305.18540", doi: 10.48550/arXiv.2305.18540, archivePrefix: "arXiv", eprint: "2305.18540", primaryClass: "astro-ph.CO"

[32] Aditya Vijaykumar, Avinash Tiwari, Shasvath J. Kapadia, K. G. Arun, Parameswaran Ajith, "Waltzing Binaries: Probing the Line-of

[33] Subrahmanyan Chandrasekhar, "Dynamical Friction. I. General Considerations: the Coefficient of Dynamical Friction", doi: 10.1086/144517, journal: "Astrophys. J.", volume: 97, pages: 255, year: 1943

[34] Eve C. Ostriker, "Dynamical friction in a gaseous medium", journal: "Astrophys. J.", volume: 513, year: 1999, pages: 252, doi: 10.1086/306858, eprint: "astro-ph/9810324", archivePrefix: "arXiv", primaryClass: "astro-ph", SLACcitation: "

[35] H. Bondi and F. Hoyle, "On the mechanism of accretion by stars", journal: "Mon. Not. Roy. Astron. Soc.", volume: 104, pages: 273, year: 1944

[36] Michalis Agathos, Walter Del Pozzo, Tjonnie G. F. Li, Chris Van Den Broeck, John Veitch, Salvatore Vitale, "TIGER: A data analysis pipeline for testing the strong-field dynamics of general relativity with gravitational wave signals from coalescing compact binaries", eprint: 1311.0420, archivePrefix: "arXiv", primaryClass: "gr-qc", doi: 10.1103/PhysRevD.89.082001, journal: "Phys. Rev. D", volume: 89, number: 8, pages: 082001, year: 2014

[37] Sascha Husa, Sebastian Khan, Mark Hannam, Michael Pürrer, Frank Ohme, Xisco Jiménez Forteza, Alejandro Bohé, "Frequency-domain gravitational waves from nonprecessing black-hole binaries. I. New numerical waveforms and anatomy of the signal", eprint: 1508.07250, archivePrefix: "arXiv", primaryClass: "gr-qc", doi: 10.1103/PhysRevD.93.044006, journal: "Phys. Rev. D", volume: 93, number: 4, pages: 044006, year: 2016

[38] Sebastian Khan, Sascha Husa, Mark Hannam, Frank Ohme, Michael Pürrer, Xisco Jiménez Forteza, Alejandro Bohé, "Frequency-domain gravitational waves from nonprecessing black-hole binaries. II. A phenomenological model for the advanced detector era", eprint: 1508.07253, archivePrefix: "arXiv", primaryClass: "gr-qc", doi: 10.1103/PhysRevD.93.044007, journal: "Phys. Rev. D", volume: 93, number: 4, pages: 044007, year: 2016

[39] Mark Hannam, Patricia Schmidt, Alejandro Bohé, Leïla Haegel, Sascha Husa, Frank Ohme, Geraint Pratten, Michael Pürrer, "Simple Model of Complete Precessing Black-Hole-Binary Gravitational Waveforms", eprint: 1308.3271, archivePrefix: "arXiv", primaryClass: "gr-qc", doi: 10.1103/PhysRevLett.113.151101, journal: "Phys. Rev. Lett.", volume: 113, number: 15, pages: 151101, year: 2014

[40] Tim Dietrich, Anuradha Samajdar, Sebastian Khan, Nathan K. Johnson-McDaniel, Reetika Dudi, Wolfgang Tichy, "Improving the NRTidal model for binary neutron star systems", eprint: 1905.06011, archivePrefix: "arXiv", primaryClass: "gr-qc", doi: 10.1103/PhysRevD.100.044003, journal: "Phys. Rev. D", volume: 100, number: 4, pages: 044003, year: 2019

[41] Abraham Loeb, "Electromagnetic Counterparts to Black Hole Mergers Detected by LIGO", eprint: 1602.04735, archivePrefix: "arXiv", primaryClass: "astro-ph.HE", doi: 10.3847/2041-8205/819/2/L21, journal: "Astrophys. J. Lett.", volume: 819, number: 2, pages: L21, year: 2016

[42] Joseph M. Fedrow, Christian D. Ott, Ulrich Sperhake, Jonathan Blackman, Roland Haas, Christian Reisswig, Antonio De Felice, "Gravitational Waves from Binary Black Hole Mergers inside Stars", eprint: 1704.07383, archivePrefix: "arXiv", primaryClass: "astro-ph.HE", reportNumber: "YITP-17-40", doi: 10.1103/PhysRevLett.119.171103, journal: "Phys. Rev. Lett.", volume: 119, number: 17, pages: 171103, year: 2017

[43] Vitor Cardoso, Andrea Maselli, "Constraints on the astrophysical environment of binaries with gravitational-wave observations", eprint: 1909.05870, archivePrefix: "arXiv", primaryClass: "astro-ph.HE", doi: 10.1051/0004-6361/202037654, journal: "Astron. Astrophys.", volume: 644, pages: A147, year: 2020

PoS(EPS-HEP2023)068