Fundamental physics in the era of gravitational-wave astronomy

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Gravitational-wave astronomy will reshape our understanding of the Universe.

The direct detection of gravitational waves (GWs) by the Laser Interferometer Gravitational-Wave Observatory (LIGO) and by the Virgo interferometer is one of the greatest achievements of modern science (Abbott *et al.*, 2019; Abbott *et al.*, 2020a). These observations opened a completely new window to the Universe and marked the birth of GW astronomy.

Five years after the first detection, GW observations have become almost routine (Abbott *et al.*, 2019; Abbott *et al.*, 2020a) and significant effort is now in place to further increase the sensitivity of current detectors and prepare for the construction of future ground and space-based GW detectors (Abbott *et al.*, 2020b; Amaro-Seoane *et al.*, 2017; GWIC, 2019). These developments promise to open an era of precision GW physics and have the potential to revolutionise our understanding of astrophysics, cosmology and fundamental physics (Barack *et al.*, 2019).

Interestingly, the same reason that makes GWs extremely challenging to detect is also what makes their observation such an extraordinary tool to study the Universe. Unlike electromagnetic waves, GWs interact very weakly with matter, thus travelling almost unimpeded throughout the Universe. In addition, GWs can be emitted by sources which are invisible to electromagnetic surveys, the prototypical example being the black-hole (BH) binary mergers detected by the LIGO and Virgo interferometers. The observation of GWs, therefore, gives us the unique opportunity to observe and study with great precision an otherwise invisible side of the Universe, with tremendous potential for new and unexpected discoveries. Indeed, GW observations can potentially help to answer some of the deepest unresolved puzzles in fundamental physics, such as the fundamental nature of gravity or the unknown nature of dark matter and dark energy (Barack *et al.*, 2019). Fulfilling such promises requires a significant theoretical effort to interpret the observations in view of our best theories. The research that was done within the FunGraW project aimed precisely at joining this effort. In particular, the information right will highlight some results that might help us address questions such as:

- Can GWs provide conclusive evidence for the existence of BHs and rule out alternative models?

- Can we use GW observations to probe the existence of new particles that could possibly explain the nature of dark matter?

This is a very limited selection of questions that one can hope to answer with GW observations. GW astronomy will have a tremendous impact in many branches of physics, too many to highlight here. For the interested reader, I refer to (Barack *et al.*, 2019) for a complete and up-to-date review on the subject.

Quantifying the evidence for the existence of black holes

Most of the GW signals observed by LIGO and Virgo so far are consistent with being emitted by the merger of two BHs (Abbott *et al.*, 2019; Abbott *et al.*, 2020a). According to Einstein's theory of general relativity, BHs are predicted to form under very generic conditions at the end of the life of the most massive stars, when no other forces inside the star can sustain it then it will collapse under its own weight. This prediction has huge implications: according to our current best theories, any dark and extremely compact object with mass above roughly three solar masses must be a BH. Any observations incompatible with this picture would imply new physics beyond our current knowledge (Cardoso and Pani, 2019). Given the fundamental role that BHs play in our understanding of gravity, quantifying the evidence for their existence is crucial.

The defining property of a BH is the existence of an event horizon—a one-way surface beyond which nothing can escape. This feature provides a very powerful tool to test that the dark compact objects that we observe in the Universe are indeed BHs. Any amount of radiation—either electromagnetic or gravitational—being reflected from such objects would be a smoking gun of departure from the classical BH picture. Therefore, constraining the reflectivity of a compact object provides a powerful and model-independent way to quantify its 'BH-ness'. GWs are an ideal tool to make such a measurement. For a binary BH, part of the gravitational radiation emitted by the system is absorbed at the event horizon, therefore affecting the rate at which the orbit shrinks over time. This, in turn, is encoded in the GW signal that the system emits. If at least one of the members in the binary does not have an event horizon, the absorption of radiation by the object is in general much smaller or even negligible compared to the BH case, leaving an imprint in the GW signal. In general, this effect is too small to be measurable by current detectors. However, it could be measurable with future detectors, especially with the detection of binaries where one small compact object with tens of solar masses orbits a much more massive compact object with millions of solar masses (Maselli *et al.*, 2018; Datta *et al.*, 2020), commonly known as extreme mass ratio inspirals (EMRI) (Figure 1).

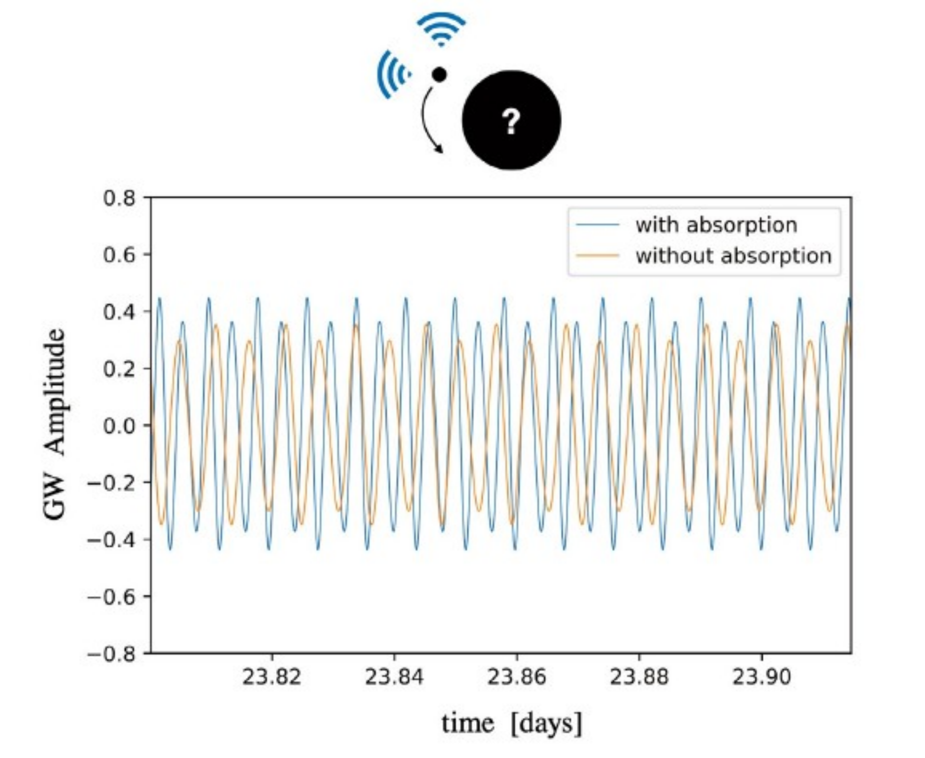

Figure 1: Comparison between the GW signal emitted by an EMRI if (i) the more massive central object is a BH ("with absorption") and (ii) if the central object is instead some exotic dark compact object that does not absorb radiation ("without absorption"). For both cases, the orbit starts at the same orbital radius with the same initial phase, such that the GW signal is initially indistinguishable. We show a number of cycles roughly 23 days after the beginning of the orbit where the difference between both signals is evident. The GW amplitude is given in an arbitrary scale for visualisation purposes. See (Datta et al., 2019) for details on the choice of the system's parameters.

EMRIs are among the most promising GW sources expected to be detected with the forthcoming space-based Laser Interferometer Space Antenna (LISA), a space-based GW observatory currently scheduled to be launched in 2034 (Amaro-Seoane *et al.*, 2017). The GW signal emitted by an EMRI will last years in the LISA frequency band, spanning tens of thousands of orbital cycles. This will allow us to measure the parameters of the system with exquisite precision. By comparing the signals emitted by these systems in the case where the more massive object is a BH, against the case where the object is instead some exotic object without an event horizon, in (Datta *et al.*, 2020), we projected that EMRIs detected by LISA could be used to provide some of the strongest constraints against alternatives to BHs or, in a more speculative but exciting scenario, obtain evidence for new physics appearing at the horizon scale.

Probing ultralight particles with gravitational waves

Besides testing the nature of compact objects, another example where GWs may have profound implications for fundamental physics is in the role that they may play in uncovering the nature of dark matter. Such a scenario has become increasingly popular in the last years, a particular example being the possibility that GWs could be used to directly detect the existence of new light particles, generically known as ultralight bosons (Arvanitaki *et al.*, 2010; Arvanitaki, Baryakhtar and Huan, 2015; Brito *et al.*, 2017). Ultralight bosons could have masses a trillion times smaller than that of a neutrino, the lightest massive particle known in nature. Such particles are predicted in several beyond-the-standard-model theories and have been proposed as strong candidates for dark matter (Arvanitaki *et al.*, 2010).

Experiments looking for signatures from ultralight bosons have so far proven unsuccessful, which should not come as a surprise given that they are expected to interact very weakly with matter. However, if ultralight bosons exist, they could turn spinning BHs unstable and form gigantic but invisible clouds around them. The formation of boson clouds around spinning BHs occurs due to a process known as the 'superradiant instability', in which an exponentially large number of boson particles is created around the BH at the expense of the hole's energy and angular momentum (Brito, Cardoso and Pani, 2020). The process leads to the formation of an oscillating cloud of bosons that subsequently dissipates through the emission of periodic GWs with a frequency directly related to the particle mass (Figure 2).

Signatures from such clouds have been studied in detail for the case of so-called 'scalar' particles (Arvanitaki, Baryakhtar and Huan, 2015; Brito *et al.*, 2017), 'vector' particles (Baryakhtar, Lasenby and Teo, 2017), and recently we also showed that the same phenomenon would occur for 'tensor' particles (Brito, Grillo and Pani, 2020). By searching for the GW signal emitted by boson clouds formed around spinning BHs, detectors such as LIGO, Virgo and the future space mission LISA could therefore be used to hunt for ultralight particles in an almost unexplored regime. Interestingly, even the absence of detections can be used to impose strong constraints on the possible masses and interactions of these particles (Palomba et al., 2019; Tsukada *et al.*, 2019; Sun, Brito and Isi, 2020; Zhu *et al.*, 2020; Tsukada *et al.*, 2020), and therefore help to narrow down the large spectrum of dark matter candidates.

Perspective

GW astronomy is still at its infancy, but the future promises to be bright. Current ground-based GW interferometers are scheduled to reach their design sensitivity in a couple of years (Abbott *et al.*, 2020b) and on the longer term, the science case for a third generation of ground-based interferometers is now actively being studied (GWIC, 2019). In addition, the space-based LISA mission, a GW interferometer that will be sensitive to GWs in the MHz band, is scheduled to be launched in 2034 by the European Space Agency with the support of NASA (Amaro-Seoane *et al.*, 2017). With this array of detectors, GW astronomy will become one the most active fields of research of the coming decades and promises to reshape our understanding of the Universe. The aim of this project was precisely to contribute to this greater worldwide scientific endeavour.

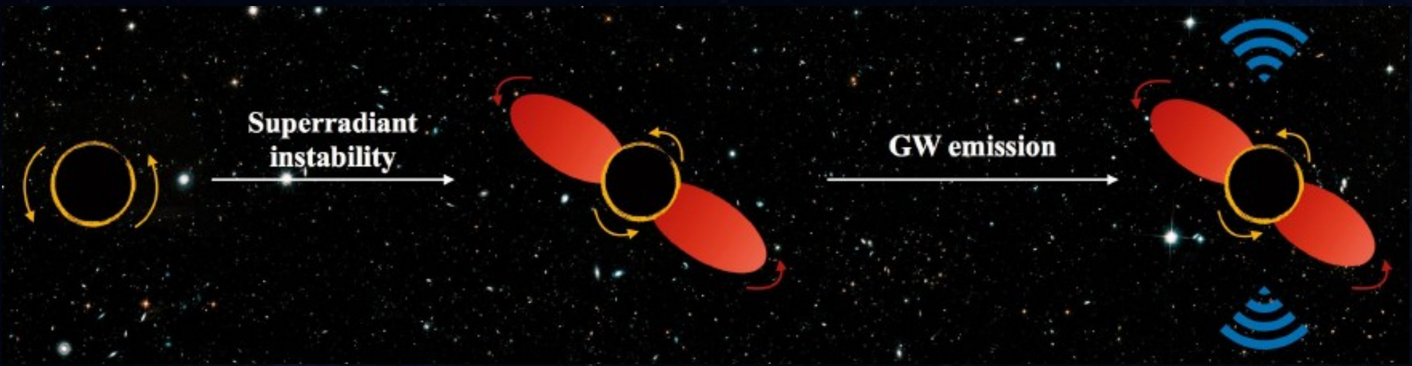

Figure 2: Schematic representation of the evolution of the superradiant instability and subsequent GW emission. Initial (e.g. quantum) fluctuations of the boson particles seed the instability, leading to an exponentially growing boson cloud (represented by red blobs in the picture) around a spinning BH. The boson cloud grows at the expense of the BH's energy and angular momentum. The instability stops when the cloud and BH rotate in complete synchronisation. After the instability saturates, the dynamics is dominated by the annihilation of boson particles into GWs, which leads to a slow decay of the cloud.

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PROJECT NAME

FunGraW

PROJECT SUMMARY

The main goal of the FunGraW project was to understand what gravitational-wave observations can tell us about fundamental questions such as the nature of black holes and dark matter, and ultimately to contribute to the recent theoretical efforts in developing the full scientific potential of the newborn field of gravitational wave astronomy.

PROJECT LEAD PROFILE

Dr Richard Brito is a researcher at the Sapienza University of Rome. He previously held a postdoc position at the Max Planck Institute for Gravitational Physics, Potsdam (Germany), and obtained his PhD at the Instituto Superior Técnico, Lisbon (Portugal). His research focuses on black-hole and gravitational-wave physics and in problems lying at the interface between gravitational and particle physics.

PROJECT PARTNERS

The project was carried out under the supervision of Prof. Paolo Pani at the Department of Physics of the Sapienza University of Rome and took place within Sapienza's gravity theory and gravitational wave phenomenology group.

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