PHD PROJECTS IN THE ANALYSIS OF GRAVITATIONAL WAVE DATA

VIRGO COLLABORATION (LIGO-VIRGO-KAGRA COLLABORATION)

The analysis of the gravitational wave data gathered in the third observing run of the LIGO-Virgo-KAGRA Collaboration (O3) is nearly complete, and a new run (O4) is scheduled to start at the end of 2022 after the upgrade and commissioning of the detectors. The Trieste group takes part to the data-analysis effort and we look forward to the new data that shall be collected with an unprecedented sensitivity and which will provide an even deeper look into the populations of compact binary objects (black holes and neutron stars).

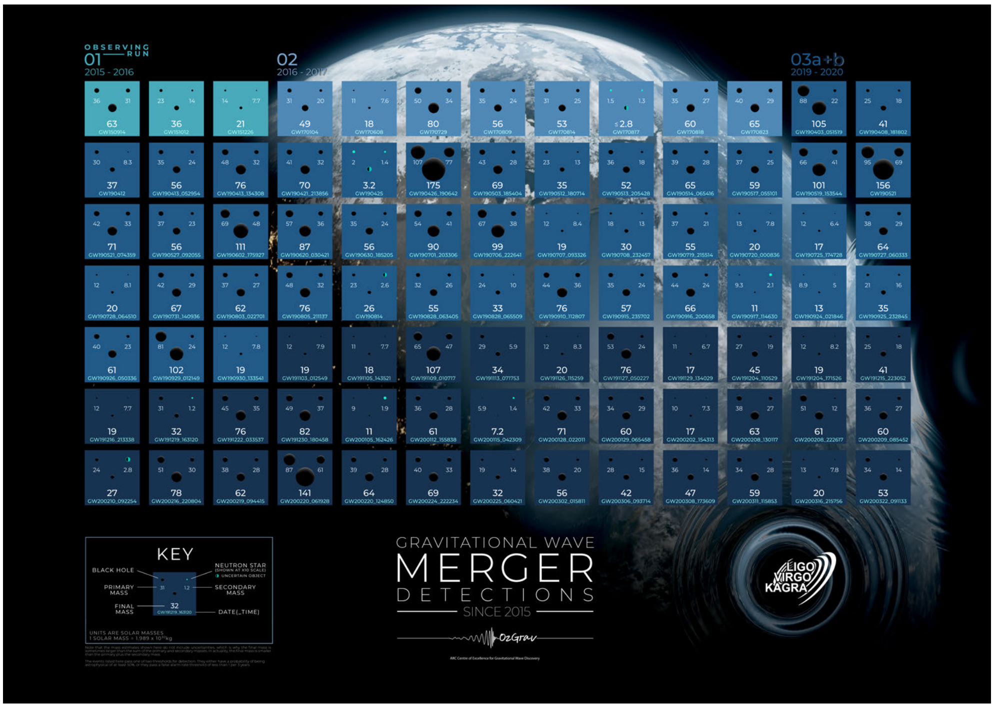

FIGURE 1. Table showing the main features of all the gravitational wave mergers detected during the O1/O2/O3a/O3b observing runs. The large majority of them (80) has been detected during the O3 run, which was the one with the highest sensitivity to date. During the O2 run we detected the first BNS (binary neutron star) coalescence, which marked the beginning of a new era of multi-messenger astronomy. During O3, we detected the first NSBH (neutron star – black hole) coalescences, but we were not as lucky as in the O2 run, and we could not observe any electromagnetic or neutrino counterpart. Hopefully, O4 shall bring a larger crop of BNS and NSBH observations, including EM counterparts.

The quality of the reconstructed gravitational waveforms is essential: as the interferometers of the LIGO-Virgo-KAGRA (LVK) Collaboration gradually increase their sensitivity, they also probe into a more varied population of coalescing binary systems, and in O4 the signals shall display a larger and larger variety of features such as higher order modes, precession, orbital eccentricity, which are difficult to model and extract. The challenge of an accurate waveform reconstruction is quite important for the merger and the ringdown phases, which contain detailed information about important source-specific physical processes.

The detection and reconstruction of the gravitational waves produced by the coalescence of compact objects is carried out by several analysis pipelines in the framework of the LVK Collaboration. Some of these pipelines are based on the accurate knowledge of the theoretical models, while others – like the *coherent WaveBurst* (cWB) pipeline – are unmodeled and aim at detecting all short-duration signals, including the long-sought bursts from supernova explosions and more. In cWB, the event reconstruction is based on the patterns that populate the time-frequency map. This approach is both a liability and a strength of cWB. It is a liability, because it gives up some prior knowledge that other pipelines use to detect the gravitational wave signals with optimal matched filters. However, it is also an important strength in the search of poorly-modeled signals, where matched filters fail or simply do not exist, like in the case of gravitational waves from supernova explosions.

All of this means that cWB has an excellent discovery potential and that it could play again the important role it played at the time of the very first detection, when it was the first online pipeline to report the gravitational wave GW150914. The next great discovery could be a gravitational wave from a core-collapse supernova explosion, where the LVK Collaboration could join a host of other observatories in a historic multi-messenger observation that would finally shed new light on the mysterious mechanisms at the heart of core-collapse supernovae.

Novel methods based on neural networks and machine learning (ML) algorithms provide alternative routes to gravitational data analysis, and are also explored inside the Collaboration. The fast response of ML methods makes them excellent candidates for fast online detection of GW signals and a quick estimate of the source parameters. This is essential to enable multimessenger astronomy and will become even more crucial in the next observing runs when the expected increase in sensitivity of the detectors will have as consequence a higher rate of expected events (of the order of one per day in O4).

The PhD projects currently offered in Trieste are carried out in the framework of the Virgo Collaboration and are related both to cWB – and specifically to the many problems of feature extraction from the time-frequency maps and more generally of the data analysis of short gravitational wave transients – and to machine learning – which presents many new possibilities, both to enhance current pipelines like cWB and to go alone with completely new detection methods.

In preparation for the forthcoming fourth observing run (O4) of the LVK Collaboration, the projects are based on the analysis of public data of the O1, O2 and O3 observing runs, and include – although they are not limited to – the following topics:

- studies finalized to under-the-hood improvements in the internal cWB algorithms
- explorations into a Bayesian extension of the statistical approach used by cWB
- explorations of novel machine learning methods, applied to signal detection and/or to source parameter estimation
- multimessenger searches matching gravitational transients signals with signals from electromagnetic or neutrino observatories

We welcome students willing to explore the new and exciting field of gravitational wave astrophysics.

The current members of the local Virgo unit are:

- Prof. Edoardo Milotti
- Dr. Agata Trovato
- Dr. Stefano Ansoldi
- Dr. Giuseppe Cabras
- Dr. Enrico Fragiacomo
- Andrea Virtuoso (PhD student)

If you are interested in these activities, please contact

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Figure 2. To get a glimpse of Collaboration life, you can take a look at the free LIGO Magazine.

List of basic references.

- The complete description of the cWB pipeline is publicly available at the address `https://gwburst.gitlab.io/post/2019-04-12-first_cwb_public_release/`

- In Trieste, we contribute to the distribution of public collaboration data, see `https://www.gw-openscience.org`

- The latest catalog of gravitational wave transients has been submitted to PRX and is available as a preprint `https://arxiv.org/abs/2111.03606`.

- A series of papers that describe the algorithms used in the cWB pipeline:
  - S. Klimenko and G. Mitselmakher, A wavelet method for detection of gravitational wave bursts, Class. Quantum Grav. 21 S1819-S1830 (2004)
  - S. Klimenko et al., Constraint Likelihood analysis for a network of gravitational wave detectors, Phys. Rev. D 72, 122002 (2005)
  - V. Necula et al., Transient analysis with fast Wilson-Daubechies time-frequency transform, J. Phys.: Conf. Ser. 363, 01203 (2012)
  - S. Klimenko, G. Vedovato, M. Drago, F. Salemi, V. Tiwari, G.A. Prodi, C. Lazzaro, K. Ackley, S. Tiwari, C.F. Da Silva, and G. Mitselmakher, Method for detection and reconstruction of gravitational wave transients with networks of advanced detectors, Phys. Rev. D 93, 042004 (2016)
  - M. Drago, S. Klimenko, C. Lazzaro, E. Milotti, G. Mitselmakher, V. Necula, B. O'Brian, G. A. Prodi, F. Salemi, M. Szczepanczyk, S. Tiwari, V. Tiwari, Gayathri V, G. Vedovato, I. Yakushin: "coherent WaveBurst, a pipeline for unmodeled gravitational-wave data analysis", SoftwareX, 14 (2021) 100678