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Statement of Purpose: Pushing the frontiers of high-energy astrophysics with multi-messenger astronomy

Keywords: Multi-messenger Astronomy and Astrophysics - Cosmology and Fundamental physics -Stars: Neutron and Black Hole - Gravitational Waves - Gamma-Rays Bursts - nuclear reactions, nucleosynthesis abundances.

02 – Physics. ERC - PE2, PE9.

Besides binary black holes, the coalescences of binary systems composed by two neutron stars (BNS) or a neutron star and a stellar mass black hole (NS-BH), are powerful sources that emit gravitational waves (GWs) in the frequency range (10 Hz - 10 kHz) at which ground-based gravitational interferometer (such as Advanced LIGO and Advanced Virgo) are sensitive. These transient sources are expected to have also an associated electromagnetic (EM) emission: BNS and NS-BH are thought to be the progenitors of short gamma-ray bursts (sGRB), intense and highly variable flashes of γ-radiation whose duration is < 2 s (*prompt emission*), sometimes followed by a long lasting emissions at lower energies in X-rays, optical and radio (*afterglow*).

The first GW event (GW170817) originated by the merger of a BNS system was detected by LIGO and Virgo observatories during the second observing run (O2), at luminosity distance of ~40 Mpc. [REF1]. It was associated to the weak sGRB (GRB170817A) detected by the Fermi and INTEGRAL satellites with a time delay of 1.7 s and was followed by other observations spanning the electromagnetic pectrum. The EM counterpart, now called AT2017gfo [REF2], had thermal and non-thermal components. The non-thermal one consists of a prompt gamma-ray flash generated by a relativistic outflow and long-lasting synchrotron emission powered by the interaction of this outflow with the interstellar medium (ISM). The thermal one, the so-called kilonova (kN), is thought to have been powered by the radioactive decay of ∼0.03–0.06 MΘ of NS matter ejected during and shortly after the merger. These landmark observations had a far-reaching impact in nuclear and high-energy astrophysics. They provided the first direct evidence that BNS mergers power sGRB and confirmed they are one of the main sites of production of r-process nucleosynthesis elements. The simultaneous detection marked the dawn of multi–messenger astronomy, where GWs and photons combine to provide multi-messenger observations probing celestial bodies not seen before.

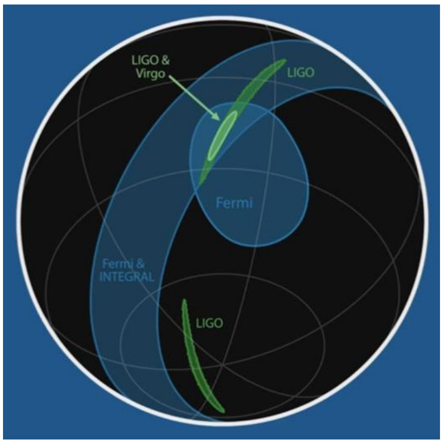

Figure 1- A combination of observations by LIGO, Virgo, Fermi, and INTEGRAL of the signal GW170817. *Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger).*

During the first part of the third observing run (O3a) of LIGO-Virgo, the Fermi and Swift satellites detected 141 GRBs. A sample of 32 short and ambiguous GRBs has been analyzed with a modelled search (PyGRB) that specifically targets BNS and NS-BH GWs inspiral signals. PyGRB [REF 3,4] is a tool within the general open-source software PyCBC, used to generate a data analysis workflow for a targeted, coherent gravitational wave search triggered by short duration gamma-ray bursts. When submitted, this workflow will run a pipeline to analyze data from multiple gravitational wave detectors coherently. It will then perform various signal-based veto cuts and data quality cuts to determine whether or not a compact binary coalescence signal is present in the given data coming from the same point in the sky and at the same time as an observed short duration gamma-ray burst. The output will be a webpage containing plots and other data files that can be used to understand the results of the analysis. The coherent method consists in considering the IFOs network as a single detector and adding the contributions of each detector weighted with its own sensitivity (BNS range) and orientation (antenna factors), that allows a larger observable gravitational horizon and a better localization of the source (~20%–25% in range). Through the association of sGRB with "face-on" oriented binary systems, the search focus on circularly polarized GWs, which may be emitted by binaries with inclinations in the ranges 0° and 180°. Thus, EM triggered observations enable GWs searches to dig deeper into the noise and to extend the detection horizon in comparison with an all-sky/all-time search.

For O3 (the entire science run) the predicted joint detection was 1-2 event at best, after six months the detection statistic count 1 BNS (GW190425a) and 1 NS-BH (GW190814a) candidate events.

The future prospect that this search can offers are remarkable. Observations of different messengers from the same source will provide more details on GRB physics and event rates and will investigate whether short GRBs are also powered by NS-BH mergers. A wider gravitational interferometers network, which in future will include the Japanese KAGRA and the Indian INDIGO (in the planning and construction stages with a 2024 operations date), will allow the increase of the coherent search sensitivity [REF5].

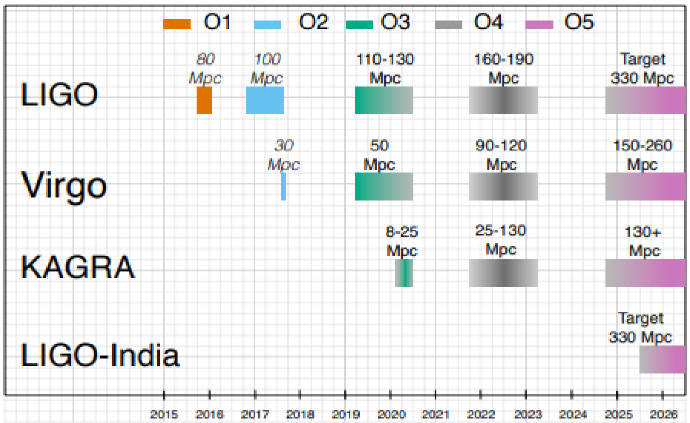

Figure 2- The planned sensitivity evolution and observing runs of the aLIGO, aVirgo and KAGRA detectors over the coming years. The colored bars show the observing runs, with achieved sensitivities in O1, O2 and O3, and the expected sensitivities in future runs by the data in [REF5]. Numbers in Mpc indicate average reach to BNS mergers

I am strongly motivated to focus my future and my research aspiration on the gravitational wave astronomy and multi-messenger observations. Co-working as an active member of LIGO-Virgo "Gamma-Ray Burst" data analysis group, during my master thesis I have build-up the necessary skills to become an expert in this field. Specifically, I become an expert in using cluster HPC (high performance computing) resources, I learnt to perform critical research and recognize GWs signals of the coalescing BNS and NS-BH systems, and I acquired the ability to perform rigorous understanding of the noise background and data quality. In addition, I sharpened my decision-making, teamwork and work-for-goals skills and developed the desire to face new challenges.

The PhD in "Research Methods in Science and Technology" at Urbino "Carlo Bo" University will give me the perfect chance to complete an outstanding education and consolidate my career in gravitational wave science. I will pursuit a research program that will be supported by both my advanced technical skills and my aspiration in contributing to improve the blossoming newly born field of multi-messenger astronomy. This include:

- Actively conducing off-line searches for gravitational waves associated with gamma-ray burst.
- Develop novel methods to improve the efficiency of the current search, implementing them in the pipeline officially used by LIGO-Virgo analysis group.

At the moment injection runs are too slow. Need to implement filtering conditions to make it go faster. Currently the workflow uses a mixture of PyCBC and lalapps_cohPTF executable. We are working to fully integrate PyGRB into PyCBC. This will allow us to use optimised PyCBC code to speed up our analysis and to drop the maintenance of lalapps_cohPTF. The postprocessing, which is very memory consuming, will be rewritten so that it uses hdf5 files, rather than xml ones.

The unique multi-messenger event GW170817/GRB170817A highlights the importance of the joint detection of both the gravitational and the EM signals to ensure a secure association of the two phenomena, furthermore revealed the existence of a population of low-luminosity short duration gamma-ray transients produced by BNS mergers in the nearby Universe. These new signals will enable the

possibility to prob the interior of the neutron stars shading a light on the nature of the unknow equation of state, and to dig the physics behind the central engine that power GRBs.
In the long term the joint GW-GRB detection may also provide to probe many areas of astrophysics, such as jet physics, speed of gravity, iron-heavy element production. We should also be prepared for serendipitous discoveries.

References

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