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Abstract

This document reports on the development of the software package used to localize gravitational wave events. This is crucial in a multi-messenger approach, since a very low latency localization of a gravitational wave event is necessary to provide an electromagnetic follow-up.

Description

The birth of gravitational wave astrophysics

The first detection of gravitational waves, made in September 2015 by the LIGO and Virgo collaborations (Abbott et al. 2016a), has opened a new way to study the cosmos. In particular, thanks to gravitational waves we can probe astrophysical sources that do not emit electromagnetic radiation, such as black holes. In fact, the first signals detected by LIGO and Virgo were produced by the coalescence of two black holes, i.e. their inspiraling and subsequent merger into a single black hole. The activities of Work Package 2 (WP2) "Gravitational Wave Physics" are focused on extracting the maximum amount of physics results from the gravitational wave data alone and in combination with electromagnetic observations, in a fully multi-messenger perspective. In particular, it is involved in the development of data analysis code, with particular attention to the localization of gravitational wave events, which is a key ingredient in the electromagnetic follow-up of gravitational wave transients.

The first detections of gravitational waves (GW) have been possible because the LIGO and Virgo detectors are now in their *advanced* stage, i.e. they have been entirely upgraded in order to reach a sensitivity of ten times that of the previous detector generation (Abbott et al. 2016b). This implies the capability of probing a volume a thousand of times larger, thus improving by the same factor the number of accessible sources. LIGO started its first observation run (O1) in 2015, and Virgo started operations in August 2017, joining LIGO in a single international network of gravitational wave detectors.

During this second observing run (O2), LIGO and Virgo detected a new signal on August (GW170817), the first one produced by the coalescence of two neutron stars (Abbott et al. 2017b). This event also produced an electromagnetic (EM) emission that was observed first at the high energies by the Fermi and INTEGRAL missions, and later by the ground-based observatories in optical and infrared. A later emission was also detected at X rays and radio bands (Abbott et al. 2017c).

The role of localization strategies in multi-messenger observations

A key aspect of multi-messenger observations is to provide a quick alert every time LIGO and Virgo detect a GW signal. These alerts are distributed to the astronomical communities and contain the parameters of the GW sources, including a best estimate of the localization. During O1 and O2 the alerts were sent to a community of teams of astronomers that signed a Memorandum Of Understanding, while from O3 the alerts will be sent out publicly in the form of Open Public Alerts. Developing the code for localization of gravitational wave events is one of the main tasks within the LIGO and Virgo collaboration, and various pipelines have been developed. In particular, a rapid Bayesian localization code (Bayestar, Singer & Price, 2016) has been used for sending out alerts from the first detection and also for GW170817. Later on, a more detailed parameter estimation code, LALInference (Veitch et al 2015) has also been employed in order to obtain a refined estimation of the binary system parameters, such as chirp mass, final mass of the black hole, and of course distance and localization. For GW170817, these localization codes have been also used with the localization provided by the gamma-ray instruments Fermi and INTEGRAL, as seen in Figure 1.

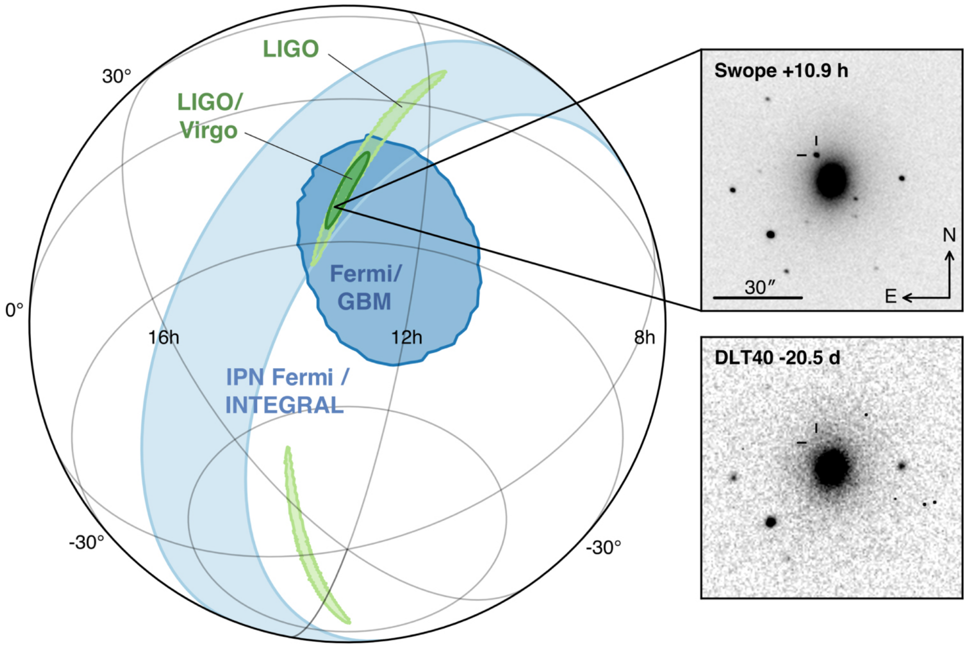

Figure 1: Localization of Gravitational Waves, gamma rays and optical calculated for the event GW170817.

LIGO and Virgo scientists are investing lots of effort to develop localization code that can be used to provide precise and fast localization region in a low-latency regime. This effort is becoming more and more important, since with the improvement in sensitivity also the number of events has significantly increased. Recently, the collaboration LIGO and Virgo has published the GWTC-1, the first catalogue of gravitational wave events detected during O1 and O2 (REF), that contains ten binary black hole events and one binary neutron star merger, GW170817.

Furthermore, the LIGO and Virgo teams are moving toward the release of gravitational wave data through the Gravitational Wave Open Science Centre (GWOSC) [REF] (Url is https://www.gw-openscience.org).

In order to improve the localization, a detailed knowledge of the detectors and of their background noise is fundamental. One of the main contributions of NEWS scientists has been improving the contribution on the detector characterization, with the study of transient noise.

Due to the commissioning of Virgo for O3, part of this work has been necessarily developed at the Virgo site, in collaboration with scientists of the LIGO collaboration. One approach that we have investigated is using machine learning to identify transient noise events, called glitches, that could sometimes mimic the signal or mask it. We have developed a deep learning pipeline to analyze images representing the time-frequency evolution of the output of gravitational wave detectors, and recognize different classes of glitches. We have tested this pipeline on simulated data showing that this approach is very promising (Cuoco & Razzano, 2018), and later applied these methods to the real data. Figure 2 shows an example of accuracy detection of glitches

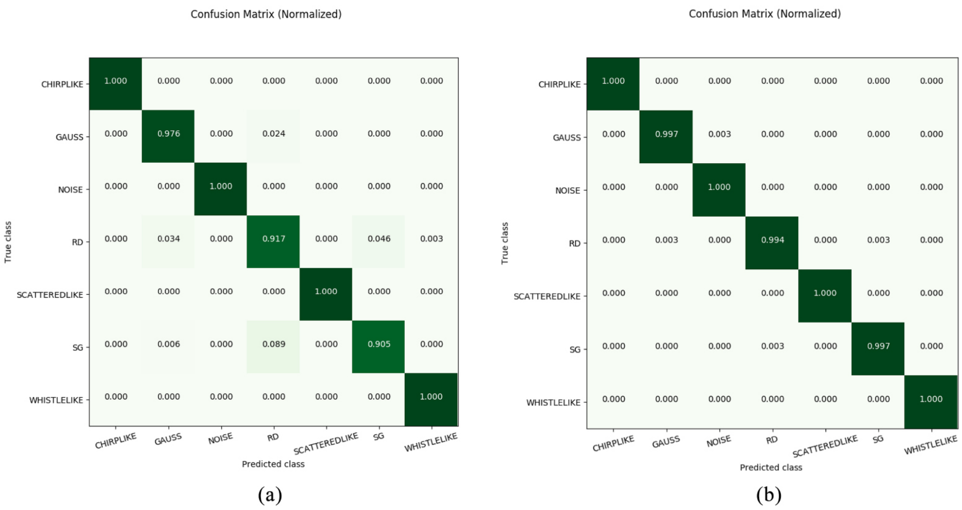

Figure 2: Confusion matrices showing the accuracy of deep-learning pipeline in distinguishing glitch from signal.

A more recent approach is focused on the full analysis of the auxiliary channels with the aim of detecting the origin of glitches and possibly reducing it. This work has been carried on in collaboration with the University of Missouri, that recently has joined NEWS.

Improving the gravitational detectors for O3

The new born gravitational wave astronomy using the LIGO-Virgo network strongly relies on three elements:

- **Coincidence duty cycle**, namely the operation time of the two LIGO detectors in US and Virgo working together, independently vetoed using local instrumentation and environmental channels, and exchanging, as a whole, alerts with electromagnetic observatories.
- **Good overall quality** of the data, i.e. calibration (and inter-calibration) of the strain signals (usually called h(t)), both in amplitude and time, reasonably comparable sensitivities and low

glitchness (absence of instrumentally generated fast disturbance on the data streams, blanketing possible actual signals).

Towards Observation Run O3

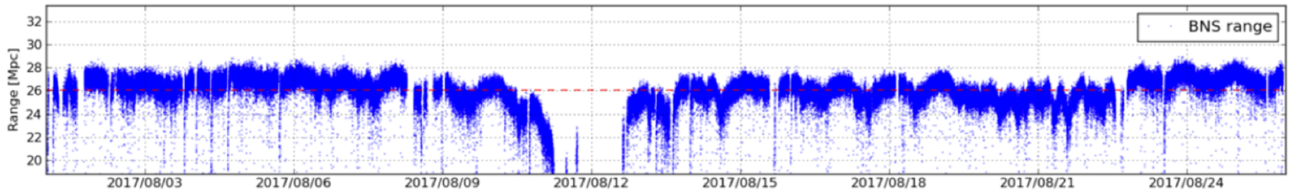

Figure 3: Advanced Virgo Interferometer joined LIGO operation at the end of observation run O2, to constitute a single, three-detector plant.

Figure 3 shows how the data produced during run O2 by Virgo were rich of glitches. The run lasted from August 1st to August 25th, providing just 16 days of coincidence duty cycle. Just after the technical accident occurred almost in parallel to a storm that prevented the operation two events, in series, on the 14th and on the 17th of August were detected (Abbott et al. 2017a, Abbott et al. 2017b). A third event with triple Coalescing Binary Black Hole detection on Aug 23rd was identified and accounted as just after the run through a deeper analysis of the data. The time schedule to join the run was very tight and forced the commissioning plan to join O2 (Figure 4).

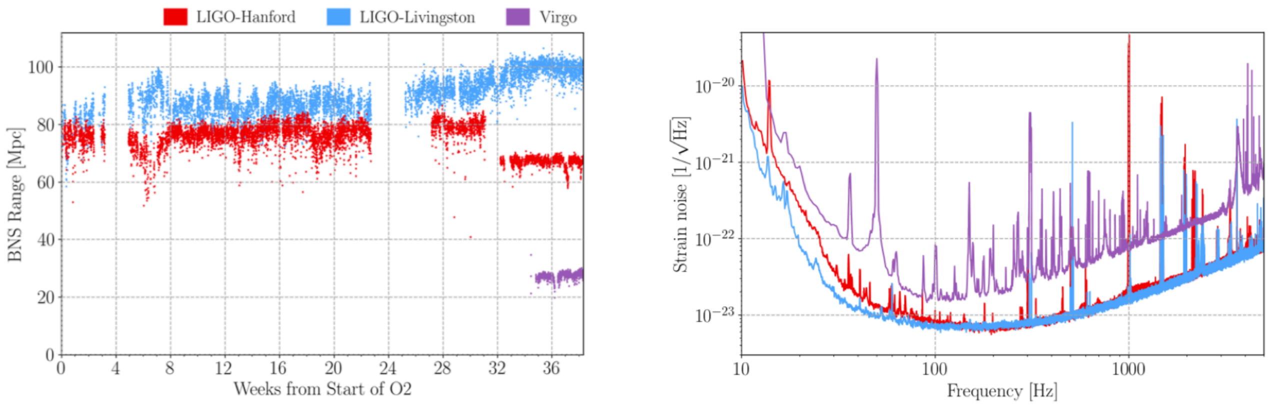

Figure 4: During O2, after almost eight months of coincidence run of the two detectors in US, with some interruptions, Advanced Virgo joined the network. The comparison of the individual ranges of the individual detectors was unfavourable for Virgo, as shown on the right by the strain sensitivities.

Nevertheless, a total of 11 detections were very successfully published in the reference paper (Abbott et al. 2019), among them the three ones involving three detectors, are qualitatively different, as they allow a much more accurate localization reconstruction in the sky (Figure 5).

Moreover, while ten events were associated just to gravitational waves, pure space-time geometry ripples, and in particular to coalescing Black Holes, just one was related to radiation in observational counterparts, as due to coalescing matter in a neutron star binary system. An incredible coverage of crucial issues from fundamental physics and astrophysics was reported to the community.

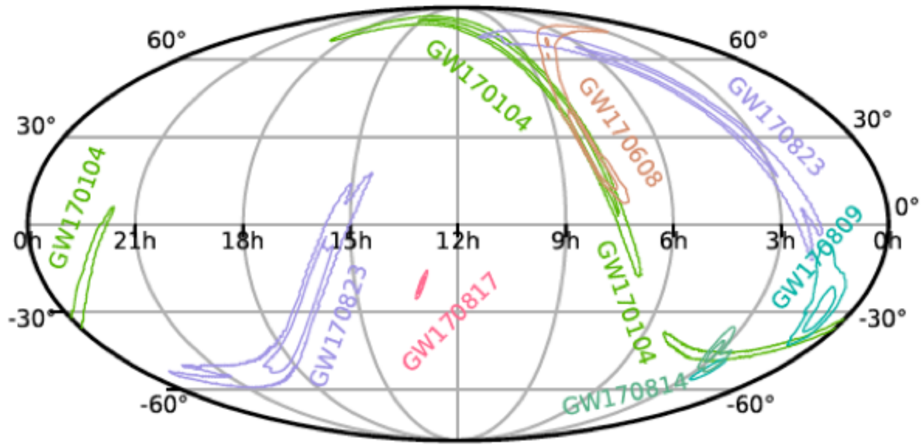

Figure 5: Sky areas of 50% and 90% credible regions of posterior probability for the GW events detected during O2 (GW170817, GW170104, GW170823, GW170608, GW170809, GW170814); for all of them alerts to Electromagnetic observers were sent.

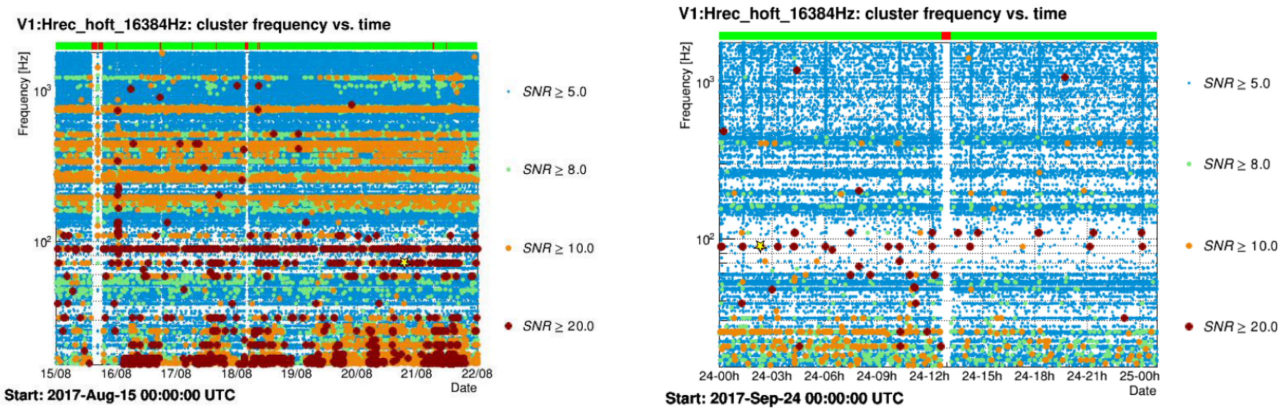

Figure 6: Example of glitchness reduction in the GW strain signal channel h(t). After O2, the number of glitches associated to large SNR (Signal to Nose Ratio) decreased as the angular control of the interferometer was improved.

Before O3 the Global Inverted Pendulum control was implemented in Advanced Virgo. Such a control strategy is crucial for Virgo seismic suspension system to prevent ground tilt and micro-seismic contamination in control sensors, as the mechanical passive attenuation of test masses requires inertial damping of its internal modes. A significant effort was done before O3 in order to optimize local and global test-mass suspension control system (Figure 6).

In Figure 7, at a glance, the effect on auto-alignment control accuracy, crucial to reduce the number of glitches is reported. Similarly, to what shown in Figure 7, in O3, from April 2019, also mode cleaner angular control benefits from major improvements related to the global control of seismic isolation chains, and a much smaller jitter of the beam is injected into the machine.

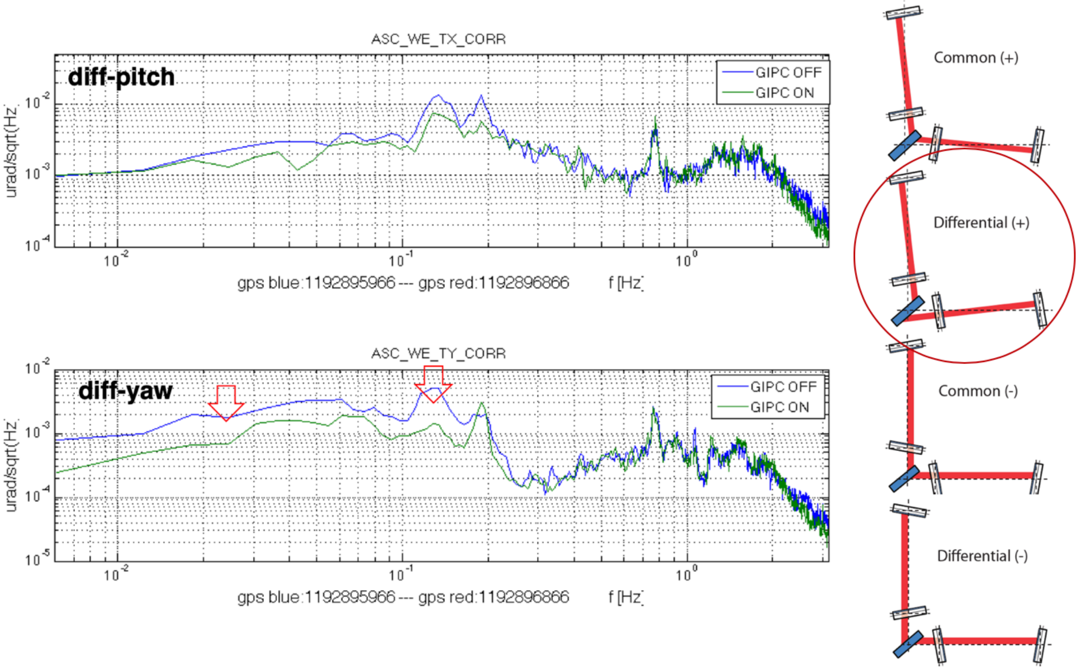

Figure 7: Power spectrum of Fabry-Perot cavity differential angle controlled by the auto-alignment of the interferometer. The accuracy of in loop signals is a key feature in glitchness reduction.

At present nine suspension control chains run under global control, meaning that each optical element (mirrors or benches) suspended through a complex passive attenuation system is controlled in real time using a combination of signals, deduced from both local and global signals (derived by the main beam).

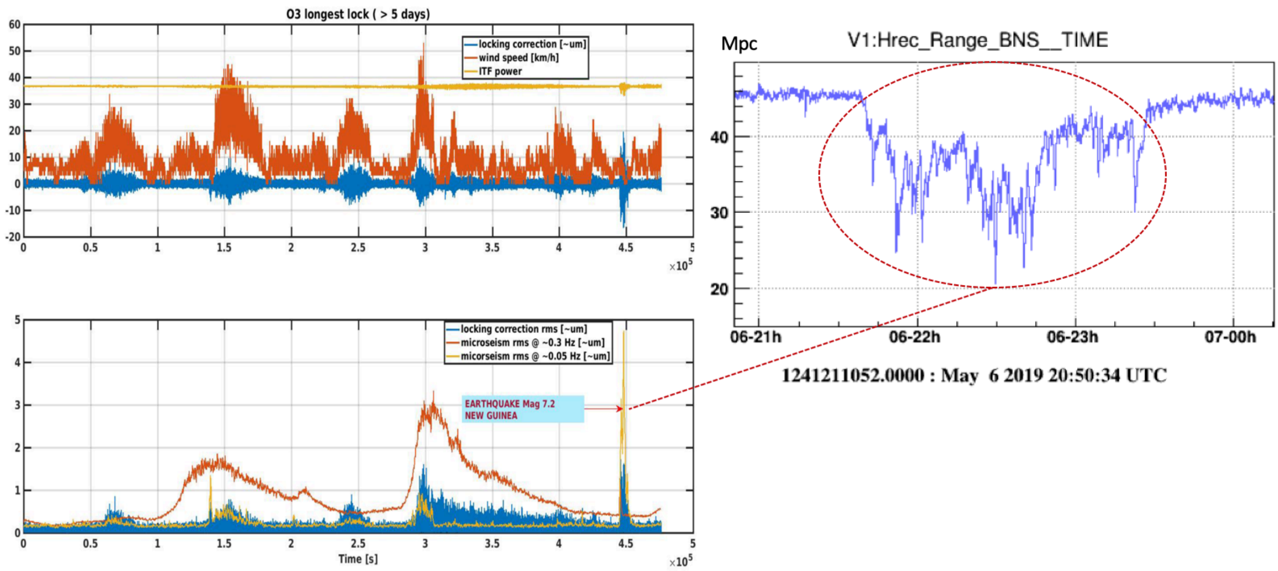

Figure 8: The robustness of the lock strongly relies on overall suspension control system, which in turns impacts on the number of events selected by the pipelines. Wind and micro-seismic conditions, as well as earthquakes typically dramatically affect the duty-cycle of detectors and the increase the number glitches, to be vetoed.

The robustness reached for O3, for all the interferometers of the network is significantly improved. In Figure 9 we see the case of Virgo, as that is quite advanced with respect to O2. The interferometer's locked state is preserved during sustained micro-seismic sea activity as well as in windy conditions or under the influence of far earthquakes. In Figure 9 we notice remarkable stability of Virgo, while the worse sensitivity is, as known, explained by the different optical configuration (no signal recycling mirror and ¾ shorter Fabry-Perot arms).

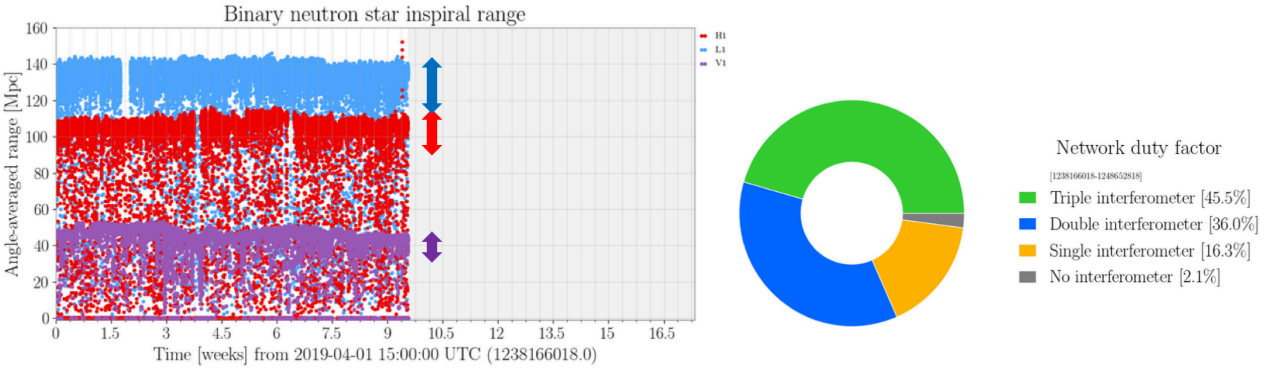

Figure 9: Range covered by the three detectors of the network at the beginning of O3. We notice a small glitcheness and better duty cycle in favour of Virgo (purple), in spite of a smaller range for Virgo, this aspect is mostly explained by the optical configuration. Right: the overall duty-cycle where the localization through GW is achieved is roughly 50%.

In Figure 10, the range for NSNS (neutron star – neutron star) events (SNR=8, direction averaged) of the present network at the beginning is shown. It must be clarified that, expectedly, the observation of a significant rate of NSNS coalescence events is a key target of O3 and subsequent runs, whose plan is shown in Figure 10.

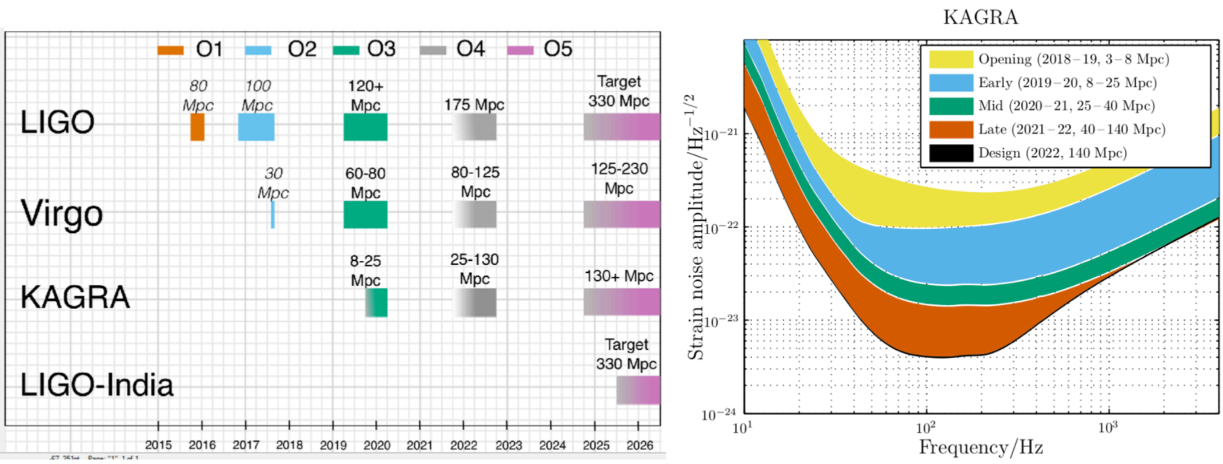

Figure 10: Living Relativity (https://link.springer.com/article/10.1007%2Fs41114-018-0012-9); On the right the nominal sensitivity for the next detector will join the network: KAGRA

Remarkably, the KAGRA collaboration has decided to join the network before the end of O3, i.e. on April 1st 2020. While the network of three detectors allows, for NSNS and NSBH (neutron star – black hole) events, to determine with the accuracy of few tents of squared degrees the localization in the sky, and to promptly exchange alerts with E.M. observatories, for the physics of gravitational waves more detectors are needed and KAGRA will play a great role in the future. In order to focus on the scientific target of NEWS WP2 “Gravitational Wave Physics”, we can focus some of the overall benefits of using more detectors. They are briefly the following:

1) General Relativity studies: polarization and nature of Gravitational Waves, tensor, vector, scalar;
2) Compact object matter studies: Soft of hard NS Equation of State, strongly connected with multi-messenger;
3) Population studies (both binary NS and BH);
4) Cosmology studies, measurements of Hubble constant, dark energy, dark matter.

Prospects after O3

Remarkably, with the conclusion of O2, (Aug 25th 2017), the first bunch of gravitational event observations was assessed. First, preliminary, predictions on event rates were done and the importance of multi-detector GW observations versus specific performance of each one of them started to be considered as a key method for designing next upgrades. Hence, in parallel with O3, which is leading to improve the rate statistics and to detect new relevant sources, as pulsars and SNe, the study for the best investment for the future commenced in US, in Europe, and in Japan. This aspect is remarkable. Indeed, Japan is forcing on the commissioning effort to join the network during O3 (Figure 10), and KAGRA has to approach at the same time its first detection and future upgrades, representing and extraordinary playground towards localization/observational studies for both Advanced detectors+ and 3G detectors like Einstein Telescope and Cosmic Explorer.

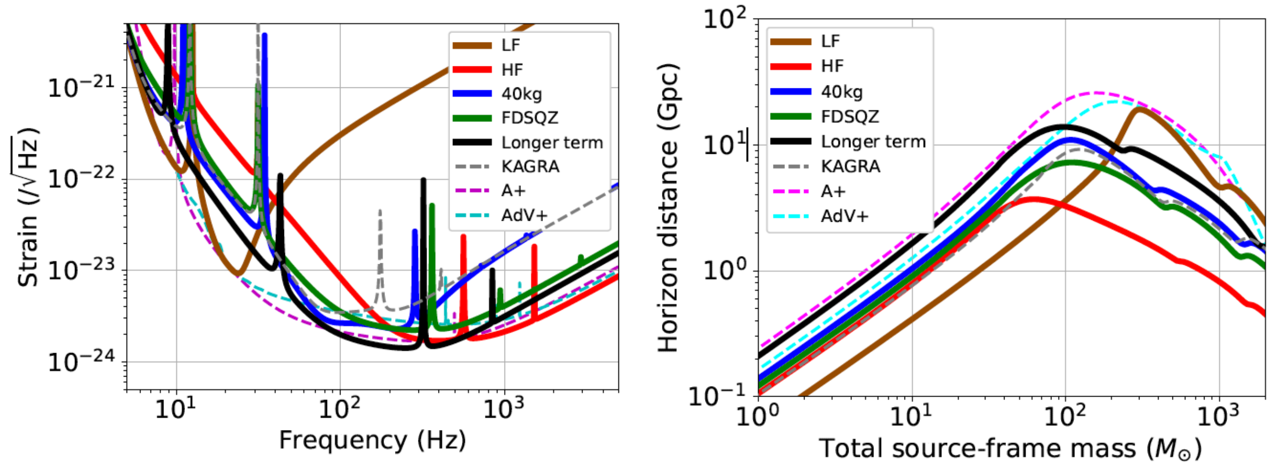

Figure 11: An example of ruling the roadmap of a single detector by working out the aspects to be improved as a function of the network performance. LF (Low Frequency) in KAGRA is strongly connected to the usage of lower power (otherwise the thermal noise increases due to limited cooling power) and is accomplished by using large test masses (as in AdV). Squeezing is accomplished (green) using a short auxiliary cavity (30 m).

Latest approach to detector improvements can be designed upon the base of network reasoning (Michimura et al, 2018, 2019). For instance, assigning priority to low frequency would make possible the detection and localization of IMBH (Intermediate Mass Black Hole) (KAGRA, A+, AdV), but the sensitivity at high frequency would be so low that there would be a low impact of KAGRA for multi-messenger studies as, for instance Equation of State of well localized BNS (Binary Neutron Star). Hence an intermediate strategy, first developing quantum noise reduction to improve the sensitivity at high (Squeezing and Higher power) and adopting a moderate increase of the test mass (blue, 40 kg), constitutes a valuable advantage for the network. Considering as an example the BNS GW170817, the localization would be 0.156 deg^2 and 10.119 deg^2 respectively.

NEWS WP2 “Gravitational Wave Physics” foresees a tight collaboration with WP3 “Gravitational Wave Detectors” in the next years, as detector improvements being designed in Europe, in US and in Japan to be implemented after O3 (middle 2020) will be done upon observational reasoning about the network.

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