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Multi-messenger astronomy of gravitational-wave transients: Current status and future prospects

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Summary. — The search for electromagnetic counterparts or neutrino emissions from gravitational-wave sources engages a wide scientific community with a growing trend of collaborations. Here, we outline the pathway that led to the birth of multi-messenger astronomy with the first direct observations of the three gravitational-wave signals measured to date, focusing on the new challenges to face in the near future.

1. – The birth of gravitational-wave astronomy

On 14 September 2015 and on 26 December 2015 —during the first observing run, *O1*— the two detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) simultaneously observed two transient gravitational-wave signals([1]). The aforementioned events match the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole [1, 2].

Advanced LIGO (aLIGO) began its second observing run, *O2*, on 30 November 2016, and on 4 January 2017 the LIGO-Hanford and LIGO-Livingston detectors registered a highly significant gravitational-wave signal GW170104 from the coalescence of two stellar-mass black holes [3].

The inferred source-frame initial black hole masses, the final black hole masses, the radiated energy and the luminosity distance are reported in table I.

([1]) A marginal candidate from Advanced LIGO's first observing run is reported with the acronym LVT151012.

TABLE I. – *Source properties for GW150914, GW151226 and GW170104. Data from* [3, 4]

	GW150914	GW151226	GW170104
Primary black hole mass m_1	$36.2^{+5.2}_{-3.8}M_\odot$	$14.2^{+8.3}_{-3.7}M_\odot$	$31.2^{+8.4}_{-6.0}M_\odot$
Secondary black hole mass m_2	$29.1^{+3.7}_{-4.4}M_\odot$	$7.5^{+2.3}_{-2.3}M_\odot$	$19.4^{+5.3}_{-5.9}M_\odot$
Final black hole mass M_f	$65.3^{+4.1}_{-3.4}M_\odot$	$21.8^{+5.9}_{-1.7}M_\odot$	$48.7^{+5.7}_{-4.6}M_\odot$
Radiated energy E_{rad}	$3.0^{+0.5}_{-0.4}M_\odot c^2$	$1.0^{+0.1}_{-0.2}M_\odot c^2$	$2.0^{+0.6}_{-0.7}M_\odot c^2$
Luminosity distance D_L	420^{+150}_{-180} Mpc	440^{+180}_{-190} Mpc	880^{+450}_{-390} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.18^{+0.08}_{-0.07}$

Such measurements represent the first direct detection of GWs and the first observation of the black-hole binaries, ushering in a new era of observational astronomy. Multi-messenger analysis could reveal never before observed relationships and interactions and the Einstein's theory of gravity can be tested in a dynamical strong field regime that was previously inaccessible [4-7].

2. – Multi-messenger research

LIGO and Virgo Collaborations communicate low-latency GW event candidates via private channels in the Gamma-ray Bursts Coordinates Network (GCN) [8]. More than 90 Memoranda of Understanding (MoU) have been signed with LIGO and Virgo Collaboration (LVC), with approximately 200 instruments covering all accessible wavelengths from radio to very high energies(2). Technical documentation, tutorials, and tools to support efforts by astronomers and instructions for registering for LV-EM services are collected in a public wiki page(3).

A preliminary sky localization of the gravitational-wave source candidate is readily disseminated to maximize the chances of making a joint detection. Further location estimates with increasing accuracy will be provided using a dedicated sequence of algorithms. Figure 1 shows the *final* probability skymaps of the gravitational-wave events confirmed to date. The sky location of the sources is primarily determined through time of arrival differences at the two aLIGO sites. The observed amplitudes and relative phase of the signals were also used to further improve the sky location.

Although the areas enclosing 90% probability span several hundred square degrees, extensive electromagnetic (EM) and neutrino follow-up campaigns have been carried out demonstrating remarkable capabilities to survey large sky regions and to characterize the nature of several transients within a few days of an event. Deep photometry, multi-frequency observations, and spectroscopy investigations —employing medium- and large-class telescopes— identified the majority of the candidates to be normal population type Ia and type II SNe, dwarf novae and active galactic nuclei (AGNs) [9-11].

The recently use in *O2* of the so-called 3D-skymap with the evaluation of the conditional distance distribution along a line of sight, dramatically reduces contamination sources in the field [12]. In addition, a potential *EM-bright* flag is quoted, quantifying

(2) After four GW events have been published, further event candidates with high confidence will be shared immediately with the entire community, while lower-significance candidates will continue to be shared promptly only with partners who have signed a MoU.
(3) `https://gw-astronomy.org/wiki/LV_EM/TechInfo`

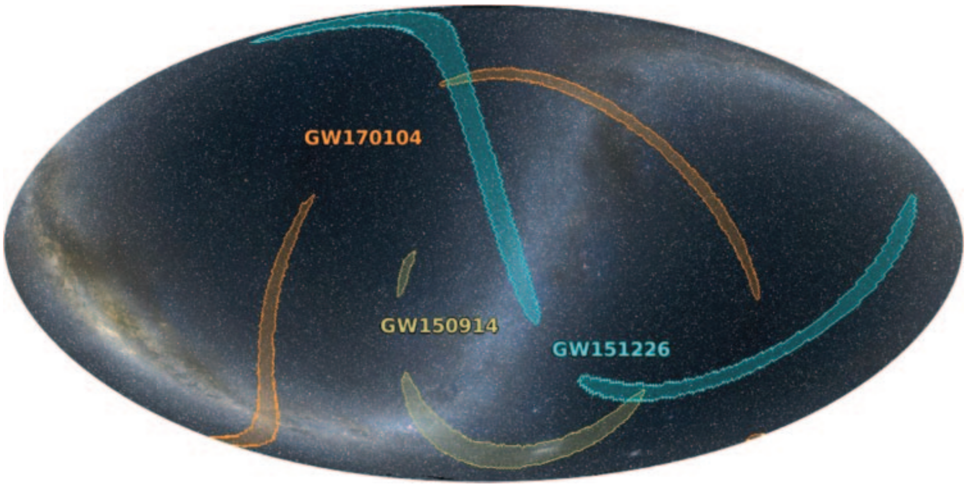

Fig. 1. – *Final* sky localizations of the three gravitational-wave events detected so far. The shaded regions represent the 90% enclosed probabilities. Sky localization files in fits format are available at the LIGO Open Science Center [13] and the plot has been produced using *GWsky* as in [14].

the probability that the system contains a neutron star (ProbHasNS) and the probability that there is material from the neutron star tidal disruption to power an electromagnetic transient (ProbHasRemnant) [15, 16].

No reasonable candidates appear to be related to the GW events, except two very weak transients detected by Fermi and AGILE satellites in the cases of GW150914 and GW170104, respectively [17, 18].

3. – Astrophysical implication and future prospective

With the Advanced Virgo (AdV) coming into operation, in the later part of the observing run *O2*, parameter estimation and sky localization will be improved with a significant impact on the efficiency of searches for EM counterparts. In particular, binary neutron star (BNS) sky localization has been investigated in [19]. The authors of [19] found that the median 90% credible region (the smallest area enclosing 90% of the total posterior probability) for BNS signals is $\sim$200 square degrees, assuming a signal-to-noise ratio (SNR) threshold of 12.

With four or more detectors (+ KAGRA + LIGO-India) timing information alone is sufficient to localize to a single sky region, and the additional baselines help to limit the region to below 10 square degrees for some signals. Full-scale operation of these five detector network is expected to commence later in the next decade [20].

The masses of black holes measured directly confirm the existence of a *heavy* stellar-mass black hole family (see, *e.g.*, [21]). Such heavy stellar-mass black holes are consistent with formation through several different evolutionary pathways, *dynamical and isolated binary evolution* [22]. The first scenario, the dynamical assembly of binaries, is expected in dense stellar clusters while the isolated binary evolution in galactic fields.

EM-counterparts are not predicted for the coalescing binary black holes —assuming a lack of material to fuel the emission— although the weak transients detected by Fermi satellite has motivated the scientific community to investigate probable emissions under particular physical conditions [23-25]. Additional observations of binary black holes will provide further insight into their formation and evolution, and allow for tighter constraints on potential modifications to General Relativity.

Furthermore, the detection of compact binary coalescing (CBC) systems containing at least one neutron star can shed new light on the progenitors of short gamma ray bursts (GRBs) and their multi-wavelength afterglows [26] as well as the synthesis of r-process heavy elements that powered optical and near-infrared emissions in macronova phenomena [27-30].

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