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Multi-Messenger Astrophysics with THESEUS: synergies with next generation gravitational wave detectors

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Abstract. Among several breakthrough discoveries in multi-messenger astrophysics achieved in the last decade, there is the first short gamma-ray burst (GRB) associated to the gravitational wave (GW) source GW170817, which confirmed binary neutron star (NS-NS) mergers as short GRB progenitors. More identifications are expected over the next years, but it will only be during the second half of the 2030s that statistically large samples of NS-NS mergers, as well as other GW sources as neutron star-black hole mergers and core collapse supernovae, will become available thanks to the anticipated one order of magnitude increase in sensitivity of next-generation GW detectors. Here we discuss how a gamma/X-ray surveyor like THESEUS will play a crucial role in independently detecting and accurately localizing the electromagnetic counterparts of such GW events, enabling multi-band follow-up campaigns and detailed source characterization of an unprecedented number of multi-messenger sources.

1 Introduction

Multi-messenger astrophysics is becoming a major avenue to explore the Universe and address fundamental questions of physics and astrophysics. Thanks to the recent breakthrough discoveries of Advanced LIGO [1] and Advanced Virgo [2], compact binary coalescences (CBCs) have been confirmed as the main sources of detectable gravitational wave (GW) signals in the frequency range covered by ground-based detectors [3]. Electromagnetic (EM) radiation across the whole spectrum, from radio to gamma-rays, is expected from binary neutron star (NS-NS) and neutron star-black hole (NS-BH) mergers, as confirmed by the first multi-messenger observation of August 2017 from a NS-NS system at about 40 Mpc distance [4], which was associated with the short gamma-ray burst (GRB) named GRB 170817

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[5, 6]. A radical advance in multi-messenger astrophysics is expected from the mid 2030s, when the third generation (3G) of GW detectors will be operational. Ground-based interferometers such as the Einstein Telescope (ET; [7]) and Cosmic Explorer (CE; [8]) with an anticipated ten times larger sensitivity, will allow us to observe GW sources up to one order of magnitude larger distances with respect to the current generation instruments, corresponding to a detection rate for NS-NS of order 10^5 per year [9]. A crucial aspect for the EM counterpart identification, is the limited source sky localization capabilities of GW interferometers (e.g. $> 10 - 100$ deg^2 for the vast majority of NS-NS mergers, [10]). In order to identify the EM counterpart in such large sky areas and to fully exploit the scientific potential of multi-messenger astrophysics, it is essential to have a facility operating in the second half of the 2030s that (i) can detect, accurately localize, and disseminate the most promising EM counterparts independently from GW triggers, (ii) can guarantee a wide spectral coverage to characterize the transients, also accounting for the large uncertainties in their expected properties, and (iii) has the ability to cover with good sensitivity the relatively large sky areas indicated by the GW detections. These combined requirements are uniquely fulfilled by the mission concept *Transient High-Energy Sky and Early Universe Surveyor* (THESEUS, [11]), whose launch in 2037, as envisaged by the ESA M7 mission call schedule, will be simply ideal for a full overlap with the third generation of GW detectors.

2 THESEUS mission concept

THESEUS aims to fully exploit the unique GRB potential for investigating the early Universe [12] and to provide substantial advancement in multi-messenger astrophysics [13]. THESEUS will detect and characterise GRBs and other X/gamma-ray transients over a very broad energy band (0.3 keV to 10 MeV) and wide field of view (FoV), including on-board near-infrared imaging and spectroscopy. Specifically, THESEUS will enable the identification, accurate localisation and study of the EM counterparts to sources of GW through the following set of on-board instruments: 1) the X-ray/gamma-ray imager spectrometer (XGIS, 2 keV-10 MeV), with FoV $\sim 2\pi$ sr and source position accuracy below 150 keV of $< 7'$ ($< 15'$) for 50% (90%); 2) the Soft X-ray Imagers (SXI, 0.3-4 keV) with FoV ~0.5 sr and source position accuracy of $< 3'$; 3) the autonomous optical/NIR telescope (IRT), with FoV = $15' \times 15'$, photometric (I, Z, Y, J, H) and slit-less spectroscopic (R~400, 0.8-1.6 μm) capabilities, that will allow for fast follow-up, arcsec location and redshift measurement of detected GRB/transients with optical/NIR counterpart.

3 Short GRB detections

During its nominal mission lifetime, THESEUS/XGIS and SXI are expected to detect and accurately localize about 40 short GRBs (~12/yr assuming 3.45 years of observations) inside their imaging field of view. This number is computed by taking into account all payload observational constraints and by considering the prompt emission (see below) of a population synthesis model of short GRBs normalized to past Fermi and Swift observations [14]. In addition, 25-30/yr short GRBs at higher energies (>150 keV) will be detected outside the XGIS imaging field of view, with coarse sky localization (~500 deg^2) yet enough to establish, together with the temporal coincidence, an association with a GW event.

4 Joint GRB and NS-NS detections

Based on state-of-the-art GRB jet structure modeling, the number of NS-NS mergers detected with the 3G GW network and, at the same time, by THESEUS/XGIS+SXI in survey mode

Table 1. Expected number of joint EM+GW detections of NS-NS mergers for 3.45 years of THESEUS observations in synergy with two different 3G GW detector network configurations. Numbers are taken from [15] (revised version) and corrected for instrument duty cycle (~65% and ~75% for XGIS and SXI, respectively). Ranges in square parentheses give the 1σ intervals. The total number of joint GW+EM detections with XGIS and SXI are quoted in the second column (where any multiple counting of the same event detected in more than one emission component is properly avoided). The third column quotes the number of joint detections considering only the GRB prompt emission observed with XGIS. The fourth and fifth columns include the high-latitude emission (HLE) and afterglow (AG) components as detected with SXI only and with SXI and XGIS, respectively.

GW detectors	Total	prompt (XGIS)	HLE+AG (SXI)	HLE+AG (SXI+XGIS)
ET	70[56-87]	22[13-34]	28[21-36]	55[43-70]
ET+2CE	87[72-107]	34[25-47]	34[26-44]	65[53-82]

has been estimated [15]. Beside the high-energy prompt emission (which generate the main GRB episode), two other components have been considered: the jet high-latitude emission (HLE, see [15] for more details), and the afterglow generated in the forward shock of the relativistic jet propagating across the interstellar medium. The GW signals have been computed by assuming two scenarios for the 3G interferometers: 1) ET alone, 2) ET plus 2 CE, one located in the LIGO-Livingston site (US) and the other one in Australia. Table 1 summarizes the results. We note that the numbers quoted in Table 1 do not include the short GRBs detected outside the XGIS imaging field of view (25-30/yr). Furthermore, the above computations do not consider the so-called “extended emission” (EE) [16], which is observed in the X-ray/soft-gamma-ray band for a significant fraction of short GRBs, and last for tens to hundreds of seconds following the prompt GRB emission. Simulations of EE detection using currently available detector response matrices show that THESEUS/XGIS and SXI are perfectly suited to observe such a component, which could be detected up to z~2 [13]. The actual fraction of bursts accompanied by this extra component and the degree of collimation with respect to the prompt emission are still a matter of debate, but a further increase of the number of joint THESEUS+GW detections remains a very likely possibility. For the above reasons, the estimates reported in Table 1 are conservative. The large number of joint detections shows how THESEUS will allow for the first time statistical studies on multi-messenger NS-NS (and possibly NS-BH) merger events, enabling us to answer fundamental open questions on these mergers and their EM counterparts. In particular, THESEUS will shed light on the efficiency to form a relativistic jet and the jet launching mechanisms, the nature of the short GRB central engines, the jet angular structures and GRB energetics, the role of compact binary mergers in the chemical enrichment of r-process elements in the Universe. Moreover, exploiting NS-NS/NS-BH mergers as “standard sirens” for luminosity distance measurements, accurate independent Hubble constant estimates will be obtained [10].

5 Other GW sources

GWs from core-collapse supernovae (CCSNe) encode crucial information on the explosion inner dynamics, inaccessible to electromagnetic observations (e.g., [17]). Predictions on the explosion GW signal and its detectability are much more uncertain than for CBCs since they strongly depend on the rather unknown SN explosion mechanism. If the core-collapse results in the formation of a millisecond spin-period NS, strong GW emission may be expected from the remnant, although the rate of such an occurrence is uncertain. Realistic estimates predict a few GW detections within a several tens of Mpc with 3G interferometers during the nominal THESEUS lifetime (considering extreme emission core-collapse models or the GW signal from new-born magnetars). For those events, THESEUS will offer the opportunity to catch the accompanying high-energy signals as nearby low-luminosity GRBs, supernova breakouts, or Soft Gamma Repeaters.

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