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THESEUS: A key space mission concept for Multi-Messenger Astrophysics

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Abstract

The recent discovery of the electromagnetic counterpart of the gravitational wave source GW170817, has demonstrated the huge informative power of multi-messenger observations. During the next decade the nascent field of multi-messenger astronomy will mature significantly. Around 2030 and beyond, third generation ground-based gravitational wave detectors will be roughly ten times more sensitive than the current ones. At the same time, neutrino detectors currently upgrading to multi km^3 telescopes, will include a 10 km^3 facility in the Southern hemisphere. In this review, we describe the most promising sources of high frequency gravitational waves and neutrinos that will be detected in the next two decades. In this context, we show the important role of the *Transient High Energy Sky and Early Universe Surveyor* (THESEUS), a mission concept accepted by ESA for phase A study and proposed by a large international collaboration in response to the call for the Cosmic Vision Programme M5 missions. THESEUS aims at providing a substantial advancement in early Universe science as well as in multi–messenger and time–domain astrophysics, operating in strong synergy with future gravitational wave and neutrino detectors as well as major ground- and space-based telescopes. This review is an extension of the THESEUS white paper (Amati et al., 2017), also in light of the discovery of GW170817/GRB170817A that was announced on October 16th, 2017.

Keywords: X-ray sources; X-ray bursts; Gamma-ray sources; Gamma-ray bursts; Astronomical and space-research instrumentation

1. Introduction

With the first detection in 2015 of gravitational waves (GWs) from black hole binary systems during their coalescing phase (Abbott et al., 2016a,b), a new observational window on the Universe has been opened. Stellar-mass black hole coalescences, together with binary neutron star (NS-NS), NS-black hole (BH) mergers, burst sources as core-collapsing massive stars and possibly NS instability episodes, are among the main targets of ground-based GW detectors.[1] Some of these sources are also expected to produce neutrinos and electromagnetic (EM) signals over the entire spectrum, from radio to gamma-rays.

These expectations were astonishingly satisfied for the first time on August 17th, 2017, when a GW signal consistent with a binary neutron star merger system (Abbott et al., 2017e) was found shortly preceding the short gamma-ray burst GRB170817A (Abbott et al., 2017d). The GW170817 90% confidence sky area obtained with the Advanced LIGO (Harry and LIGO Scientific Collaboration, 2010) and Advanced Virgo (Acernese et al., 2015) network was fully contained within the GRB error box. In addition, a “kilonova” (or “macronova”) emission (AT2017gfo), theoretically predicted from such systems (e.g. Li and Paczyński, 1998a), has been found

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[1] An ensemble of Michelson-type interferometers sensitive to the high frequency range, from few Hz to few thousand Hz.

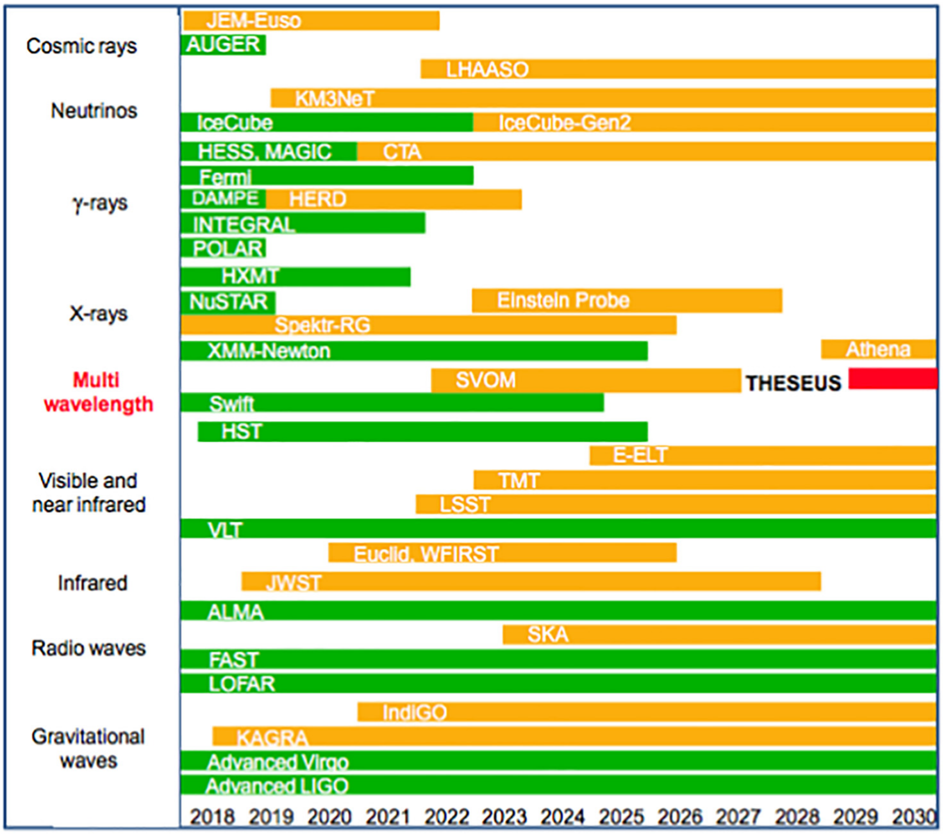

Fig. 1. THESEUS within the multi-messenger Astrophysics context of 2020–2030. Green and orange labels are for presently operating and future planned or under construction instruments (Figure credit: S. Schanne). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

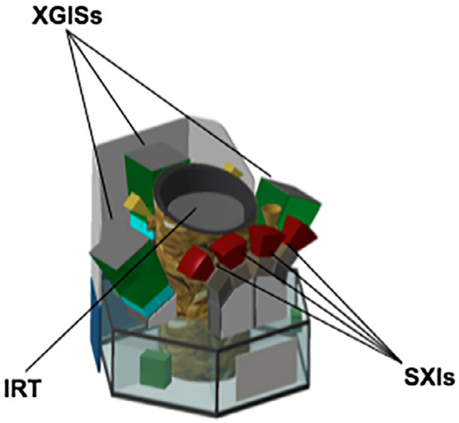

Fig. 2. THESEUS Satellite Baseline Configuration and Instrument suite accommodation.

within the GW-GRB error-box and positionally consistent with NGC4993, a lenticular galaxy at a distance compatible with the GW signal (Abbott et al., 2017f; Smartt et al., 2017; Tanvir et al., 2017; Pian et al., 2017; Coulter et al., 2017).

By the end of the twenties, the sky will be routinely monitored by the second-generation GW detector network, composed by the two Advanced LIGO (aLIGO) detectors in the US, Advanced Virgo in Italy, ILIGO in India (e.g. Abbott et al., 2016c) and KAGRA in Japan (Somiya, 2012). Then, around 2030, more sensitive third generation ground-based GW interferometers, such as the Einstein Telescope (ET, e.g. Punturo et al., 2010) and LIGO Cosmic Explorer (LIGO-CE, e.g. Abbott et al., 2017b), are planned to be operational and to provide an increase of roughly one order of magnitude in sensitivity. In parallel to these advancements, IceCube and KM3nNeT and the advent of 10 km^3 detectors (e.g. IceCube-Gen2, IceCube-Gen2 Collaboration et al., 2014, and references therein) will enable to gain high-statistics samples of astrophysical neutrinos. The 2030 will therefore coincide with a golden era of multi-messenger astrophysics (MMA, Fig. 1).

By that time, the ESA M5 approved missions for space-based astronomy will be launched. THESEUS (*Transient High Energy Sky and Early Universe Surveyor*[2] Amati et al., 2017) is a space mission concept developed by a large International collaboration currently accepted by ESA for phase A study within the selection process for next M5 mission of the Cosmic Vision Programme. If selected, the launch of THESEUS (2032) will provide a very strong contribution to MMA. In the following sections, after a short review of the main characteristics (Section 2; see Amati

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[2] http://www.isdc.unige.ch/theseus.

Table 1
THESEUS instruments.

	SXI		XGIS				IRT
Energy range	0.3–6 keV		2 −30 keV	30–150 keV	>150 keV		ZYJH (0.7–1.8 μm)
Field of view	1 sr	Half sens.:	50 × 50 deg^2	50 × 50 deg^2		Imaging	10′ × 10′
		Total:	64 × 64 deg^2	85 × 85 deg^2	2π sr	Low res	10′ × 10′
						High res	5′ × 5′
Source location accuracy	< 10″ (best) 105″ (worse)		5′ (for > 6σ source)	–	–		< 1″
Sensitivity	erg(ph) cm^{-2} s^{-1}		ph cm^{-2} s^{-1}				H (AB mag)
	2×10^{-8} (10) (1 s)		1 (1 s)	0.15 (1 s)	0.22 (1 s)	Imaging	20.6 (300 s)
	2×10^{-11} (0.01) (10 ks)		0.02 (1 ks)	0.004 (1 ks)	0.008 (1 ks)	Low res.	18.5 (300 s)
						High res.	17.5 (1800 s)

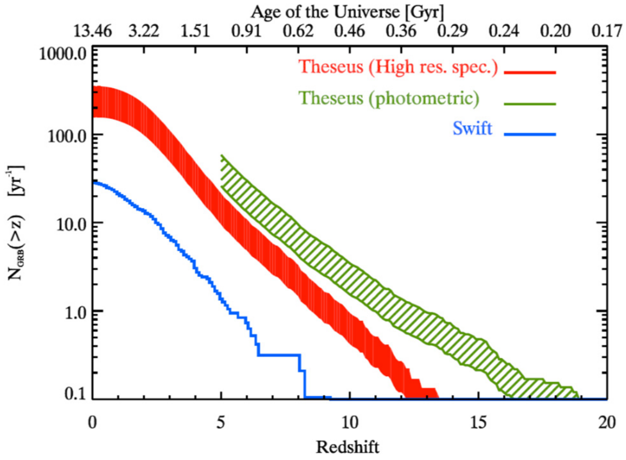

Fig. 3. The yearly cumulative distribution of GRBs with redshift determination as a function of the redshift for Swift and THESEUS (Amati et al., 2017). Low redshift GRBs are particularly relevant for simultaneous GW and/or neutrino detections. The THESEUS expected improvement in the detection and identification of GRBs at very high redshift w/r to present situation is impressive (more than 100–150 GRBs at z > 6 and several tens at z > 8 in a few years) and will allow the mission to shade light on main open issues early Universe science (star formation rate evolution, re-ionisation, pop III stars, metallicity evolution of first galaxies, etc.).

et al., 2017, for a more exhaustive description of the mission concept), we describe the role of THESEUS in the MMA and the most promising GW (Section 4) and neutrino (Section 5) sources that THESEUS will observe. We also provide the expected joint GW + EM detection rates for the most promising GW + EM sources (e.g. NS-NS) taking into account the facilities planned to be operational by the end of the twenties and beyond.

2. The THESEUS mission

The THESEUS mission aims at exploiting Gamma-Ray Bursts (GRBs) for investigating the early Universe and at providing a substantial advancement in multi-messenger and time-domain astrophysics (see Amati et al. (2017), for a detailed review).

The instrumentation foreseen on board, illustrated in Fig. 2, includes:

- Soft X-ray Imager (SXI, 0.3–6 keV): a set of 4 lobster-eye telescopes units, covering a total FoV of 1 sr with source location accuracy < 1 arcmin;
- X-Gamma ray Imaging Spectrometer (XGIS, 2 keV-20 MeV): a set of coded-mask cameras using monolithic X-gamma ray detectors based on bars of Silicon Drift Diodes coupled with CsI crystal scintillator, granting an unprecedentedly broad energy band, a FoV up to 2π sr, a source location accuracy of ~5 arcmin, and an energy resolution of ~200–300 eV in 2–30 keV;
- InfraRed Telescope (IRT, 0.7–1.8 μm): a 0.7 m class IR telescope with 10 × 10 arcmin FoV, for fast response, with both imaging and spectroscopy capabilities.

The main characteristics and sensitivities of these instruments are summarised in Table 1. The mission profile includes fast slewing capability, allowing to point the IRT to the position of GRBs and of other transient sources detected and localised by the SXI and/or the XGIS. Fast slewing observations will enable the possibility of promptly transmitting to ground trigger time, position, and redshift of these events (as evaluated on-board by means of IRT photometry and spectroscopy), thus enabling quick follow-up with large ground- and space-based multi-wavelength observatories. As shown in Fig. 3 and detailed in Amati et al. (2017), this unique combination of scientific instruments and mission profile will allow THESEUS to make a giant leap in the use of GRBs for shading light on the main open questions on the early Universe (star formation rate evolution up to the end of ”dark ages”, cosmic re–ionisation, metallicity evolution of the early galaxies, pop III stars, etc.). In the next section we describe how XGIS and SXI observations as well as fast slewing capabilities of IRT will be of great relevance also for multi-messenger observational campaigns.

THESEUS will be also used as a flexible infrared observatory complementary to other facilities, as it is the case for the Swift mission in X-rays and UV (see Amati et al.,

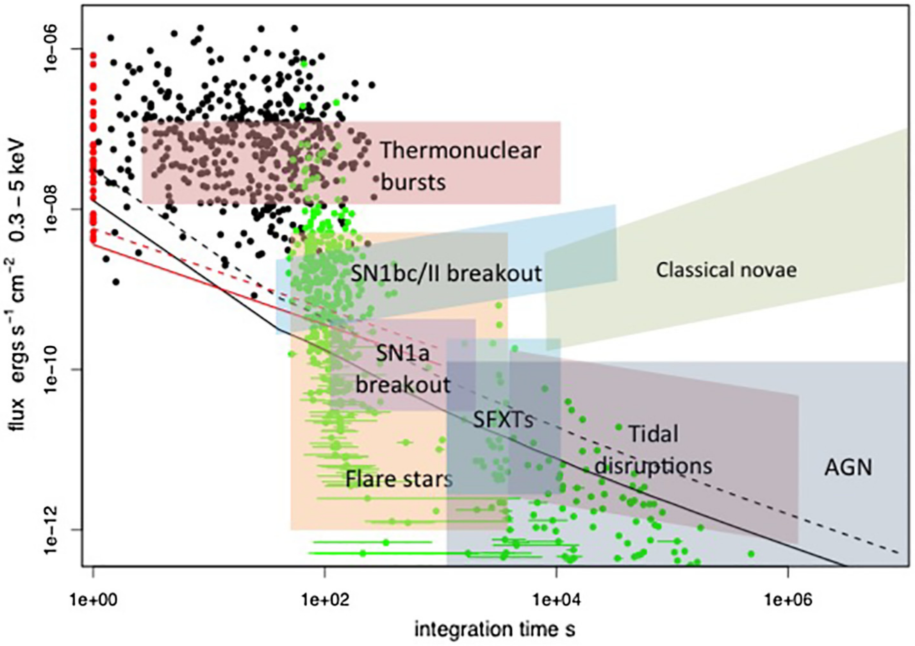

Fig. 4. Sensitivity of the SXI (black curves) and XGIS (red) vs. integration time (Amati et al., 2017). The solid curves assume a source column density of 5×10^{20} cm^{-2} (i.e., well out of the Galactic plane and very little intrinsic absorption). The dotted curves assume a source column density of 10^{22} cm^{-2} (significant intrinsic absorption). The black dots are the peak fluxes for Swift BAT GRBs plotted against T90/2 (where T90 is defined as the time interval over which 90% of the total background-subtracted counts are observed, with the interval starting when 5% of the total counts have been observed, Koshut et al., 1995). The flux in the soft band 0.3–10 keV was estimated using the T90 BAT spectral fit including the absorption from the XRT spectral fit. The red dots are those GRBs for which T90/2 is less than 1 s. The green dots are the initial fluxes and times since trigger at the start of the Swift XRT GRB light-curves. The horizontal lines indicate the duration of the first time bin in the XRT light-curve. The various shaded regions illustrate variability and flux regions for different types of transients and variable sources. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2017). The SXI can localise to better than an arcminute, and sometimes tens of arcsec depending on the source count rate, thus significantly better than the XGIS. The large grasp[3] (i.e. FoV × Effective Area) of the SXI, joined with the broad energy band, large effective area and few arcmin source location accuracy of the XGIS, will enable the discovery and study of a wealth of transient sources, both Galactic and extra-galactic (Fig. 4) many of which are expected to be also neutrino and/or GW sources (e.g. GRBs, Soft-Gamma Repeaters, core-collapse Supernovae, Active Galactic Nuclei).

THESEUS will observe in synergy with several telescopes operating at different wavelengths, as illustrated in Fig. 1, among which it is worth mentioning: (1) the space-based telescopes James Webb Space Telescope (JWST), ATHENA and WFIRST; (2) the ground-based telescopes with large FoV like zPTF and LSST; (3) the 30-m class telescopes GMT, TMT and ELT; (4) the Square Kilometer Array (SKA) in the radio; and (5) the very high-energy (GeV-TeV) Cherenkov Telescope Array (CTA). We note that the main differences between THESEUS and the other large X-ray telescope facility operational around 2030 as ATHENA, are the much larger field of views of the X-ray and gamma-ray detectors on board THESEUS that will make it a "surveyor" instrument, and the presence of an infrared telescope with both imaging and spectroscopic capabilities.

3. The role of THESEUS in the Multi-Messenger Astronomy

The detection of EM counterparts of GW and neutrino signals will enable a multitude of science programmes (see, e.g., Bloom et al., 2009; Phinney, 2009) by allowing for parameter constraints that the GW or neutrino observations alone cannot fully provide. GW detectors have relatively poor sky localisation capabilities, mainly based on triangulation methods, that on average will not be better than few dozens of square degrees (Abbott et al., 2016c). For GW sources at distances larger than the horizon of second-generation detectors (200 Mpc), therefore accessible only by the third-generation ones around 2030 (e.g. Einstein Telescope and Cosmic Explorer, Punturo et al., 2010; Abbott et al., 2017d), sky localisation may even worsen if the new generation network will be composed by only one or two detectors, with possible values of the order of few hundreds square degrees or more (e.g. Zhao and Wen, 2017). Neutrino detectors can localise to an accuracy

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[3] Grasp is an appropriate measure for large area, medium-deep surveys when monitoring on timescales of the order of seconds to days, over large sky areas.

of better than a few square degrees (see, e.g., Santander, 2016, and references therein). In order to maximise the science return of the multi-messenger investigation it is essential to have a facility that (i) can detect and disseminate an EM signal independently to the GW/neutrino event and (ii) can rapidly search with good sensitivity in the large error boxes provided by the GW and neutrino facilities.

These combined requirements are uniquely fulfilled by THESEUS. The hard XGIS and/or SXI will trigger and localise transient sources within the uncertain GW and/or neutrino error boxes. In particular, a very large fraction of the error boxes of poorly localised GW sources can be covered with SXI FoV within one orbit due to the large grasp of the instrument (see Amati et al., 2017 and Fig. 5). In response to an SXI/XGIS trigger, if an optical counterpart is present, arcsecond localisations can be obtained with IRT and disseminated within minutes to the astronomical community, thus enabling large ground-based telescopes to observe and deeply characterise the nature of the GW/neutrino source. Fig. 4 clearly show how the wide FoV of THESEUS will guarantee autonomous triggers of a large number of transient X-ray and gamma-ray sources. This will enable *independent* trigger of the EM counterpart of several GW/neutrino sources, as it was the case for GRB170817A triggered by Fermi/GBM. However, with respect to the Fermi/GBM, THESEUS will provide also accurate localisation, as sketched in Fig. 5. In response to THESEUS triggers, GW and neutrino archival data analysis will enable to search for simultaneous events at the time of the trigger (e.g., due to GRBs or supernovae), since these type of detectors record all their data almost continuously. This strategy has been already pursued by the LIGO-Virgo collaboration for a number of GRBs (e.g. Abbott et al., 2005, 2008, 2017a).

Several multi-wavelength and multi-messenger sources are among the main targets of THESEUS, as for example GRBs, flaring magnetars, core-collapse supernovae (CCSNe) and AGNs (Amati et al., 2017). The recent association of GW170817 with the short GRB 170817 makes the short GRB detection capabilities of crucial relevance for MMA in an epoch where almost all short GRBs will be accompanied by a GW signal detected by the third-generation interferometers (e.g. ET or LIGO-CE). Fig. 6 shows the density contours of the population of short GRBs (dashed contours) in the peak energy E_{peak}-peak flux plane (Ghirlanda et al., 2016). Due to their harder spectrum, short GRBs are more likely triggered by THESEUS/XGIS than SXI. Compared to the detection thresholds of BATSE and Fermi/GBM, THESEUS will slightly extend the detected population towards lower fluxes and softer peak energies. The plot shows how THESEUS will be able to fully access to events similar to GRB170817 and explore their nature. Although the XGIS sensitivity threshold improves over GBM, its smaller (by a factor of 2) FoV compensates this gain reaching a detection

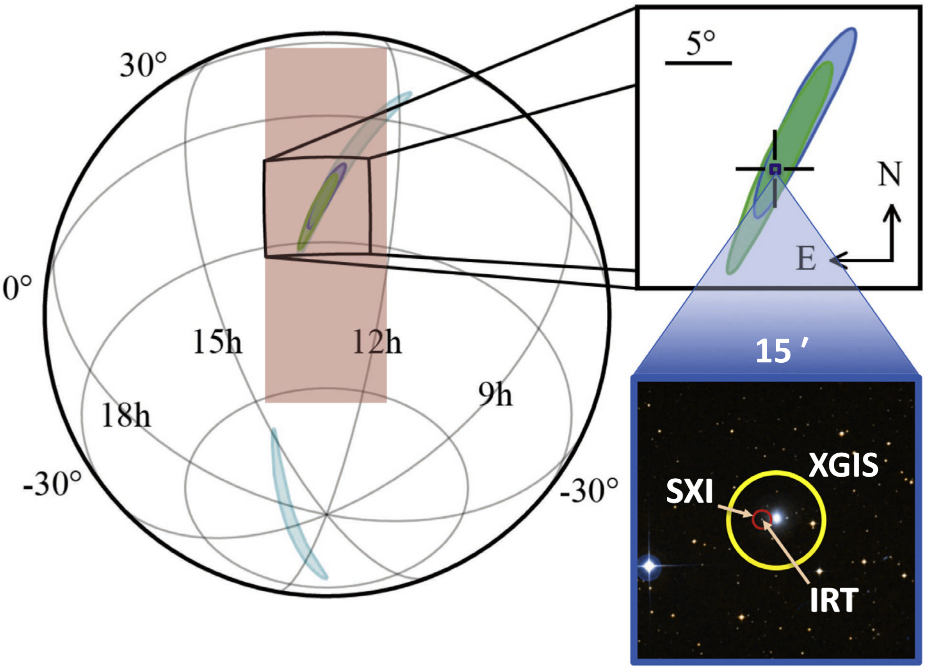

Fig. 5. The plot shows the THESEUS/SXI field of view (~ 110 × 30 deg^2, pink rectangle) superimposed on the probability skymap of GW 170817 obtained with the two Advanced LIGO only (cyan) and with the addition of Advanced Virgo (green) (Abbott et al., 2017e). THESEUS not only will cover a large fraction of the skymap (even those obtained with only two GW-detectors, e.g. cyan area), but will also localise the counterpart with uncertainty of the order of 5 arcmin with the XGIS and to less than 1 arcmin with SXI. *The THESEUS location accuracy of GW events produced by NS-NS mergers can be as good as 1 arcsec in case of detection of the kilonova emission by the IRT*. By the end of the 2020s, if ET will be a single detector, almost no directional information will be available for GW sources (>1000 deg^2 for BNS at $z > 0.3$, e.g. Zhao and Wen, 2017), and a GRB-localising satellite will be essential to discover EM counterparts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

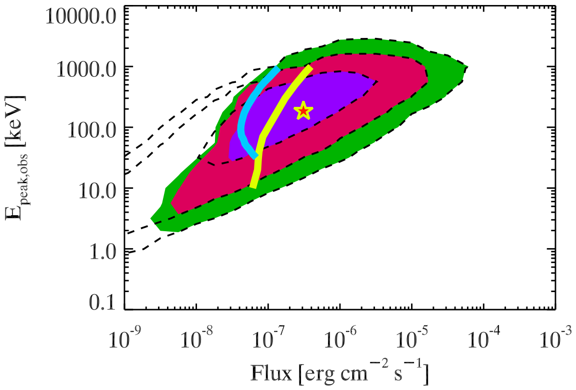

Fig. 6. Density contours (dashed lines) corresponding to 1, 2, 3 σ levels of the synthetic population of Short GRBs (from Ghirlanda et al., 2016). Shaded coloured regions show the density contours of the population detectable by THESEUS. The yellow and cyan lines show the trigger threshold of Fermi/GBM and GCRO/BATSE (from Nava et al., 2011). The flux is integrated over the 10–1000 keV energy range. The star symbol shows the short GRB170817A (Goldstein et al., 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

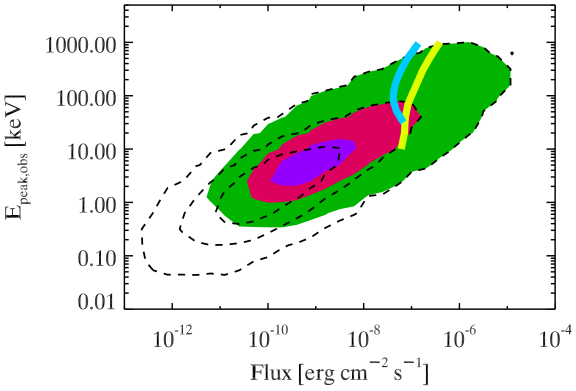

Fig. 7. Density contours (dashed lines) corresponding to 1, 2, 3 σ levels of the synthetic population of Long GRBs (from Ghirlanda et al., 2015c). Shaded coloured regions show the density contours of the population detectable by THESEUS. The yellow and cyan lines show the trigger threshold of Fermi/GBM and GCRO/BATSE (from Nava et al., 2011). The flux is integrated over the 10–1000 keV energy range. As can be seen, THESEUS will carry onboard the ideal instruments suite for detecting all classes of GRBs (classical long GRBs, short/hard GRBs, sub–energetic GRBs, and very high-redshift GRBs, which, in this plane, populate the region of weak/soft events), providing a redshift estimate for most of them (Amati et al., 2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

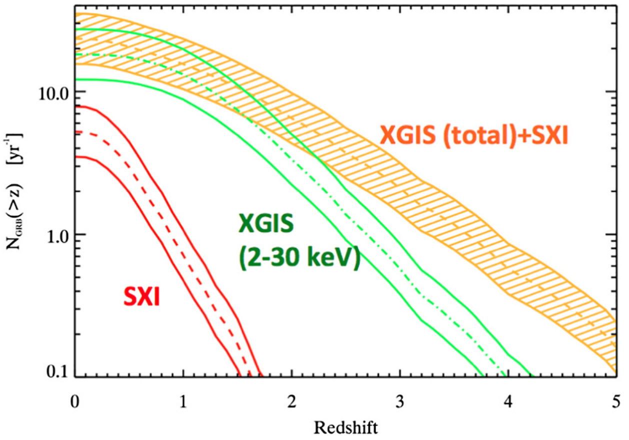

Fig. 8. Cumulative distribution of the rate of short GRBs as a function of redshift that Theseus will detect (yellow stripe filled region). The fraction of the population that will be detected by the soft coded mask instruments of XGIS (2–30 keV) is shown by the green stripe. The cumulative distribution of the fewer short GRBs also detected by SXI is shown by the red stripe. The vertical width of the stripes account for the uncertainties of the model parameters of the short GRB population adopted (Ghirlanda et al., 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rate of short GRBs which is comparable to that of GBM, that is about 15–35 per year (Fig. 8). What makes THESEUS XGIS unique, with respect to GBM, is the possibility to locate, thanks to the soft (2–30 keV) coded mask detectors, most of the detected short GRBs with an expected accuracy of 5 arcmin (to be compared with the average accuracy of > few degrees of GBM GRBs).

Fig. 7 shows the density contours (dashed lines) of synthetic population of long GRBs (Ghirlanda et al., 2015c) in the observer-frame plane representing the peak energy $E_{\rm peak}$ versus the (10–1000 keV) peak flux. Given the association of long GRB to CCSNe and the expected GW radiation as well as neutrino emission of these events (see Section 4.3), long GRBs detection capabilities are also relevant for multi-messenger joint observational campaigns. The plot shows how THESEUS will access a region of the $E_{\rm peak}$-peak flux plane totally unexplored by past and current instruments. A large fraction of its population will be constituted by soft low flux events. Among these there will be (i) low redshift/low luminosity events (with a $E_{\rm peak}$ due to the correlation between these two observables; Yonetoku et al., 2004) which are particularly relevant for simultaneous GW and/or neutrino detections and (ii) long GRBs at high redshifts which, used as beacons, will allow us to explore the high redshift Universe and its evolution and for which the redshift will be measured on board using by THESEUS/IRT (Fig. 9). A good fraction of optical/NIR afterglows detected by space- and ground-based observatories would be immediately visible by IRT. In particular long GRBs afterglows would be detectable both by imaging and low-resolution spectroscopy (LRS), making IRT capable to measure redshift for all $z > 5$ GRBs, after constraining the Lyman drop-out. Short GRBs will be harder to observe spectroscopically, however, thanks to the THESEUS/IRT arcsecond localisation of the afterglows, ground and space based telescope will be able to follow-up the IRT afterglows hours and days after the trigger (Fig. 9).

Besides the expected collimated GRB “prompt” emission, softer X-ray emission is also expected from the side and/or afterglow emission of the GRB jet, with a much lower degree of collimation (see Section 4.2). For short GRB sources and in particular NS-NS mergers, an

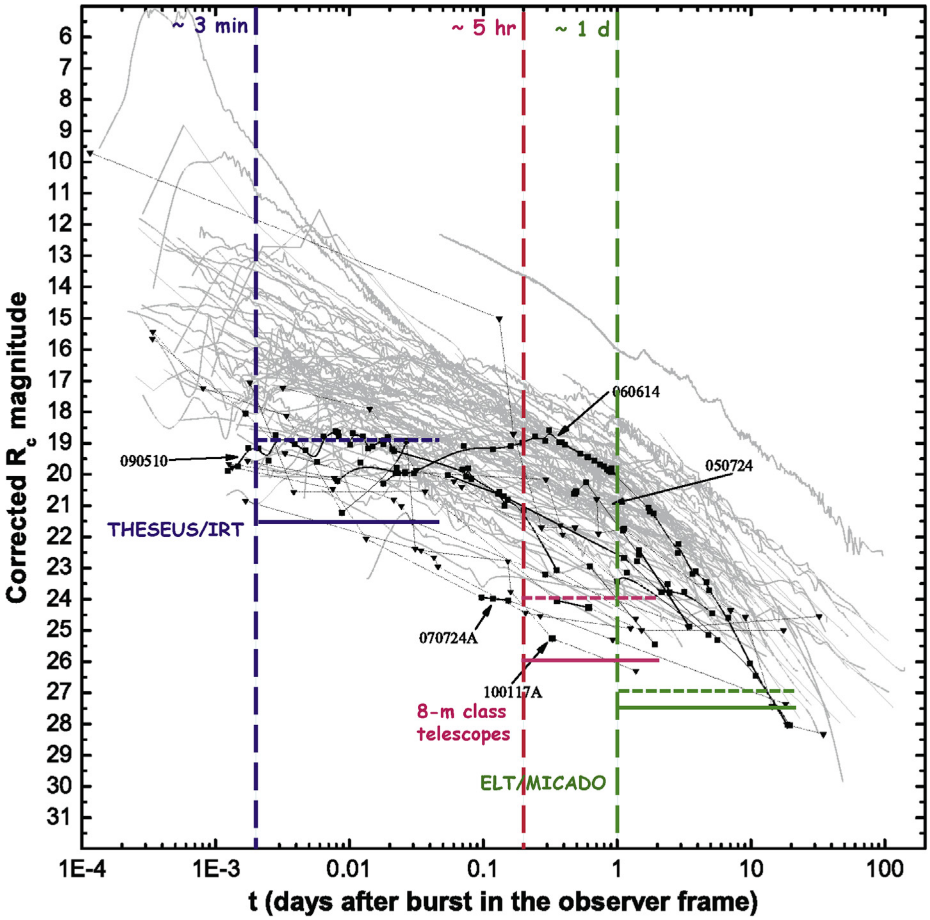

Fig. 9. R-band light curves of long (grey lines) and short (black dots) GRBs (adapted from Kann et al., 2011). The limiting magnitudes achievable with THESEUS/IRT with 300 s of exposure (blue lines), 8-m class telescopes (red lines) and ELT/MICADO (green lines) are also shown. Dashed horizontal line for the spectroscopy, solid line for the imaging. The magnitudes are rescaled from H-band to R-band assuming achromatic behaviour and a spectral index beta = 0.7. A tentative observation strategy could consist of the following steps: first starting the follow up with IRT, then activating the observations with 8-m class telescopes after few hours, finally, according to the brightness of the afterglow and thanks to the very high sensitivity of ELT, performing late observations for weeks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

additional nearly isotropic soft X-ray emission is possibly expected when the merger remnant is a long-lived NS or magnetar, where the corresponding transient is powered by the spindown of the latter (see Section 4.2).

3.1. Science return from joint GW + EM detections with THESEUS

Each individual joint observation of an EM source and its GW and/or neutrino counterpart, provides an enormous science return. To mention just few examples in the case of compact binary coalescences: (i) the determination of the GW polarisation ratio would constrain the binary orbit inclination and hence, when combined with an EM signal, the jet geometry and source energetics; (ii) a better understanding of the NS equation of state can follow from combined GW and X-ray emission signals (see Section 4.2) (see, e.g., Bauswein and Janka, 2012; Takami et al., 2014; Lasky et al., 2014; Ciolfi and Siegel, 2015b,a; Messenger et al., 2015; Rezzolla and Takami, 2016; Drago et al., 2016); (iii) an estimate of the amount of matter expelled during a NS-NS or a NS-BH merger (e.g. Fernández and Metzger, 2016, and references therein); (iv) tracing the history of heavy-metal enrichment of the Universe by promptly follow-up the kilonova/macronova IR emission, as shown in Fig. 10; (v) redshift measurements of a large sample of short GRBs combined with the absolute source luminosity distance provided by the CBC-GW signals can deliver precise measurements of the Hubble constant (Schutz, 1986), helping to break the degeneracies in determining other cosmological parameters via CMB, SNIa and BAO surveys (see, e.g., Dalal et al., 2006). The last point on the Hubble constant measure is of particular relevance for THESEUS especially during the third-generation GW detector era, when, as we will show in Section 4, almost all gamma-ray detected short GRBs will have a GW counterpart. The onboard IRT will enable to measure the redshift for all those events far away (mid to high redshifts) or hosted in faint galaxies for which there is no adequate galaxy catalog. When not taking spectra,

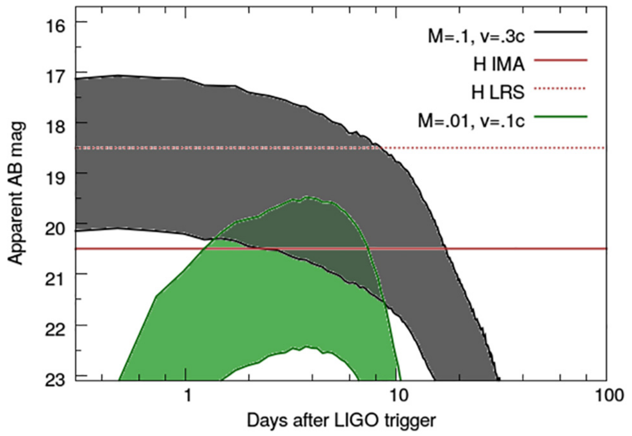

Fig. 10. Theoretical H-band lightcurves of kilonova based on models (from Barnes et al., 2016). The lightcurves are in observer frame for a source between 50 and 200 Mpc. Grey model is for the most optimistic case of a kilonova with $0.1 M_{\odot}$ ejected mass with speed of $0.3c$. Green model is for a weaker emission, corresponding to $0.01 M_{\odot}$ ejected mass with speed of $0.1c$. The continuous and dashed red lines indicate the THESEUS/IRT limiting H magnitudes for imaging and prism spectroscopy, respectively, with 300 s of exposure (see Amati et al., 2017).

it will transmit precise localisation to large size telescopes to get redshift measurements. A first attempt of Hubble constant measurement has been explored with GW170817 for which the recession velocity v_r of the optical transient AT2017gfo host galaxy NGC4993, was combined with the luminosity distance D_L measured directly from the gravitational waveform of GW170817. For small distances, as in this case (~ 40 Mpc), the Hubble constant depends only on these two variables as $H_0 = v_r/D_L$. Despite the large uncertainties on this first measurement, the results are very encouraging (Abbott et al., 2017c). The value obtained, $H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}, lies in between the measurements obtained from SNIa from SHoES (73.24 ± 1.74 km s^{-1} Mpc^{-1}, Riess et al., 2016) and CMB from Planck (67.74 ± 0.46 km s^{-1} Mpc^{-1}, Planck Collaboration et al., 2016). Furthermore, combining the observing angle vs. GW amplitude degeneracy measured by LIGO-Virgo interferometers with independent information on the observing angle derived from modelling the associated broadband afterglow, a further reduction by $\sim 5\%$ on the uncertainty interval of H_0 could be obtained (Guidorzi et al., 2017).

3.2. THESEUS and GRB170817A

In this section we explore THESEUS capabilities in the detection and characterisation of the short GRB170817A associated with GW170817 (Abbott et al., 2017e; Goldstein et al., 2017; Savchenko et al., 2017). The two events were found consistent with being originated from a common source with high confidence ($\sim 5 \times 10^{-8}$ probability of being independent, Abbott et al., 2017e). In addition, a bright optical transient was observed in NGC4993 (Smartt et al., 2017; Tanvir et al., 2017; Pian et al., 2017; Abbott et al., 2017d; Coulter et al., 2017) at ~ 40 Mpc. This was by far the closest short GRB yet observed. The gamma-ray peak photon flux (3.7 ± 0.9 ph cm^{-2} s^{-1} in the 10–1000 keV band, Goldstein et al. 2017) implies an extremely low isotropic luminosity short GRB if compared with typical values ($\sim 10^{51}$–10^{53} erg s^{-1}, see e.g. Ghirlanda et al., 2015b), with 1.7×10^{47} erg s^{-1} (e.g. Zhang et al., 2018). Since various indications point at a binary merger seen with viewing angle $\sim$ 20–40 deg away from the normal direction to the orbital plane, a possible explanation of the low luminosity is that the event was a short GRB with a structured jet observed off-axis (e.g. Troja et al., 2017; Alexander et al., 2017; Margutti et al., 2017; Haggard et al., 2017; Hallinan et al., 2017; Lazzati et al., 2017c). Within the latter scenario, GRB170817A suggests an extension of the observed short GRB population to include a larger fraction of dimmer events (e.g. Burgess et al., 2017), which can enhance the coincident short GRB/GW detection rate up to relatively small distances (i.e. <100 Mpc) with sensibile instruments such as THESEUS. The late-time X-ray, optical and radio counterparts detected weeks-months after merger (Troja et al., 2017; Margutti et al., 2017; Alexander et al., 2017; Hallinan et al., 2017; Haggard et al., 2017) are consistent with both the expectation of an afterglow emission from a structured jet (Rossi et al., 2002; Zhang and Mészáros, 2002; Kathirgamaraju et al., 2017; Lazzati et al., 2017a,b,c; Gottlieb et al., 2017, 2018; Salafia et al., 2017a) and from the deceleration of an isotropic mildly relativistic outflow (Mooley et al., 2017; Salafia et al., 2017b). Both scenarios can account reasonably well for the low luminosity of the prompt emission and the late-time rise up of the X-ray and radio emission, although the slow late-time radio increase might require

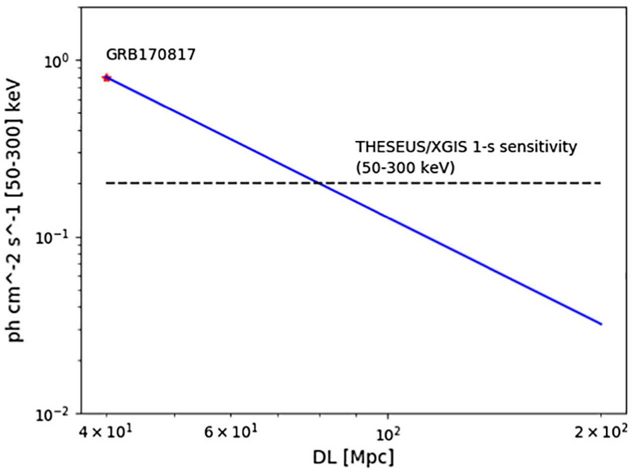

Fig. 11. The Fermi/GBM peak photon flux of the short GW/GRB 170817 (red star, Goldstein et al., 2017) rescaled with the distance (blue line) and compared with THESEUS/XGIS 1-s sensitivity in the 50–300 keV energy range. Off-axis short GRB similar to GRB 170817 could had been detected with THESEUS/XGIS up to $\sim$ 70–80 Mpc. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

some modifications of the simplest assumptions (Mooley et al., 2017; but see Lazzati et al., 2017c).

In Fig. 11 the measured Fermi/GBM flux in the 50–300 keV of 0.8 ± 0.3 ph cm^{-2} s^{-1} is extrapolated at distances larger than the distance of GRB170817A (∼40 Mpc) and compared with the THESEUS/XGIS sensitivity in the 30–150 keV band (Amati et al., 2017, see Fig. 36) rescaled to the 50–300 keV. From this plot, we can see that not only this source could had been clearly detected with XGIS but it could have been detected up to ∼ 70–80 Mpc, that is nearly twice the actual distance of the source. On the other hand, the faint X-ray emission detected weeks/months after the trigger with a flux of the order of a few times 10^{-15} erg cm^{-2} s^{-1} (Troja et al., 2017), could not had been detected with the SXI. Fig. 12 shows how IRT could had clearly detected the NIR counterpart of GW170817 recognised to be the expected "kilonova" (or "macronova", see next section). In particular, the observed emission was bright enough during the first 2 days to have allowed IRT low-resolution spectroscopy with unprecedented temporal coverage.

4. Gravitational wave sources

4.1. NS-NS/ NS-BH mergers: collimated emission from Short GRBs

Compact binary coalescences (CBCs) involving neutron stars (NS) and stellar mass black holes (BH) are among the sources of GWs that will be likely detected in spades in the next decade. These systems radiate GWs within the most sensitive frequency range of ground-based GW detectors (1–2000 Hz), with large GW energy output, of the order of $10^{-2} M_{\odot}c^2$, and gravitational waveforms well predicted by General Relativity (see, e.g., Baiotti and Rezzolla (2017) for a review). From the merger of two stellar-mass black holes the current consensus is that no significant EM counterpart emission is expected, with exceptions where a short GRB-like EM signal may be produced from those BH-BH systems merging in very high density environments (as for example in an AGN disk, Bartos, 2016), or in other exotic conditions (e.g. Perna et al., 2016; Seto and Muto, 2011; Loeb, 2016). On the other hand, EM emission is expected on robust theoretical ground for merging NS-NS or NS-BH. For more than a decade, mounting indirect evidence supported the long-standing hypothesis that short GRB progenitors are associated with CBC systems with at least one neutron star (e.g. Paczynski, 1986; Eichler et al., 1989; Narayan et al., 1992; Barthelmy et al., 2005; Fox et al., 2005; Gehrels et al., 2005). The most compelling pieces of evidence include (i) the observation of short GRBs in both elliptical and late-type star forming galaxies, with a preference for the most massive ones (ii) the relatively large projected offsets of these events with respect to the center of their host galaxies, and (iii) the lack of supernova associations, as opposed to the case of long GRBs (e.g., Berger (2014) and references therein). The most recent numerical simulations also provided supporting (though not conclusive) evidence that such merging systems might act as short GRB central engines (e.g. Rezzolla et al., 2011; Paschalidis et al., 2015; Ruiz et al., 2016; Kawamura et al., 2016; Rosswog et al., 2013). Short GRBs have been historically distinguished from long GRBs as those with gamma-ray burst (prompt emission) duration less than 2 s (Kouveliotou et al., 1993). However, there are similarities between the two classes of GRBs as far as their prompt emission (e.g. Ghirlanda et al., 2015a, 2009, 2011) and their afterglows (e.g. D'Avanzo, 2015). It is likely that the two populations overlaps and contaminate each other, especially when selection is based solely on the observed duration (Bromberg et al., 2013, but see Zhang et al., 2012). Therefore, GW signals from short GRBs might be an additional parameter to be considered to firmly distinguish core-collapse (long) from compact merger (short) progenitors.

Since GW events enable to individuate faint short GRBs as GRB170817A (Abbott et al., 2017e; Goldstein et al., 2017; Savchenko et al., 2017), future joint multi-messenger detections of such sources, ensured by the presence of space missions like THESEUS, will shed light on several still debated topics as: (1) the jet intrinsic structure and their properties, and ultimately the crucial issue of short GRB energetics; (2) the physics regulating the on- and off-axis emission; and (3) the late-time (e.g. after 1–2 weeks) component origin.

Table 2 shows the expected rate of THESEUS/XGIS short GRB detections with a GW counterpart from merging NS-NS systems (i.e. within the GW detector horizon). The quoted numbers in the first row are obtained by

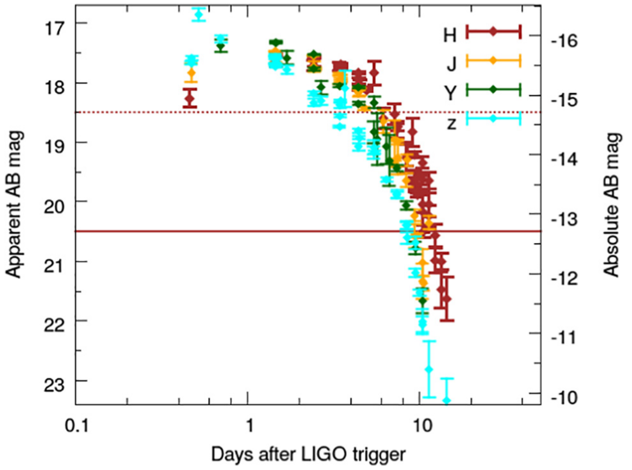

Fig. 12. Light curve of the kilonova associated to the gravitational wave/ short GRB event GW170817/GRB170817A in the IRT filters (from Tanvir et al., 2017; Pian et al., 2017; Arcavi et al., 2017; Cowperthwaite et al., 2017; Drout et al., 2017; Shappee et al., 2017; Kasliwal et al., 2017; Smartt et al., 2017; Troja et al., 2017). The continuous and dashed red lines indicate the THESEUS/IRT limiting H magnitudes for imaging and prism spectroscopy, respectively, with 300 s of exposure (see Amati et al., 2017). Credit: A. Melandri.

Table 2
Number of NS-NS (BNS) mergers expected to be detected in the next years by second- (2020+) and third- (2030+) generation GW detectors and the expected detection number of electromagnetic counterparts as short GRBs (collimated) and X-ray isotropic emitting counterparts (see Sections 3.1 and 3.2) with THESEUS SXI and XGIS (see text for more details). BNS rate is a realistic estimate from Abadie et al. (2010) and Sathyaprakash et al. (2012) and the BNS range indicates the sky- and orbital inclination-averaged distance up to which GW detectors can detect a BNS with $SNR = 8$.

GW observations			THESEUS XGIS/SXI joint GW + EM observations		
Epoch	GW detector	BNS range	BNS rate (yr^{-1})	XGIS/sGRB rate (yr^{-1})	SXI/X-ray isotropic counterpart rate (yr^{-1})
2020+	Second-generation (advanced LIGO, Advanced Virgo, India-LIGO, KAGRA)	~200 Mpc	~ 40*	~5–15	~1–3 (simultaneous) ~6–12 (+follow-up)
2030+	Second + Third-generation (e.g, ET, Cosmic Explorer)	~15–20 Gpc	>10,000	~15–35	≳ 100

* From Abadie et al. (2010).

assuming that all on-axis short GRBs will be detected with THESEUS/XGIS within the distance range of the 2G GW detectors (see Fig. 8). We correct the realistic estimate of NS-NS GW detection rate with the 2G GW detector network, $\sim 40\ \mathrm{yr}^{-1}$ (Abadie et al., 2010, see also Belczynski et al., 2017) for the fraction of the sky covered by the XGIS FoV, that is ~50%, and the short GRB jet collimation factor by assuming a jet half-opening angle range of 10–40 deg. We also considered the possibility to observe off-axis short GRBs up to 5 times a jet half-opening angle of 10 degrees and 2 times a jet of 40 degrees (Kathirgamaraju et al., 2017; Pescalli et al., 2016). The 5-times factor was obtained by considering the THESEUS/XGIS 1 s photon flux sensitivity $\sim 0.2\ \mathrm{ph\ cm^{-2}\ s^{-1}}$ (see also Amati et al., 2017). We are here assuming that every BNS merger produces a jetted short GRB, which is still an open issue. Results show that, during the 2020's, the GW + EM detection rate of short GRBs with THESEUS is found to be of the order of 5–15 per year. By the time of the launch of THESEUS, gravitational radiation from NS-NS and NS-BH mergers will be detectable by third-generation detectors such as the Einstein Telescope (ET) up to redshifts z~2 or larger (see, e.g., Sathyaprakash et al., 2012; Punturo et al., 2010), thus dramatically increasing the GW + EM on-axis short GRB detection rate. The important implication is that almost all THESEUS short GRBs will have a detectable GW emission by 2030 and beyond. Indeed, it is likely that at the typical distances at which ET detects GW events, the only EM counterparts that could feasibly be detected are short GRBs and their afterglows, making the role of THESEUS crucial for multi-messenger astronomy by that time.

4.2. NS-NS/NS-BH mergers: non-collimated soft X-ray and optical/NIR emission

In this section we introduce another possible electromagnetic counterpart of CBC events that is not collimated and is expected to peak in the soft X-ray band. GW emission from CBCs depends only weakly on the inclination angle of the inspiral orbit and therefore these events are in general observable at any viewing angle. As a consequence, most of the GW-detected mergers are expected to be observed off-axis (i.e. with a large angular distance of the observer from the orbital axis). This makes the non collimated, nearly isotropic EM components extremely relevant for the multi-messenger investigation of CBCs.

A potentially powerful nearly-isotropic emission is expected if a NS-NS merger produces a long-lived millisecond magnetar. In this case, soft X-ray to optical transients can be powered by the magnetar spin-down emission reprocessed by the baryon-polluted environment surrounding the merger site (mostly due to isotropic matter ejection in the early post-merger phase), with time scales of minutes to days and luminosities in the range 10^{43}–$10^{48}\ \mathrm{erg\ s^{-1}}$ (e.g. Yu et al., 2013; Metzger and Piro, 2014; Siegel and

Ciolfi, 2016a,b). In particular, in soft X-rays (at ~keV photon energies) these transients can last from minutes to hours and, for the most optimistic models, reach luminosities as high as 10^{48} erg s^{-1} (Siegel and Ciolfi, 2016a,b). According to alternative models, X-ray emission may also be generated via direct dissipation of magnetar winds (see, e.g., Zhang, 2013; Rezzolla and Kumar, 2015). Furthermore, the high pressure of the magnetar wind can in some cases accelerate the expansion of previously ejected matter into the interstellar medium up to relativistic velocities, causing a front shock which in turn produces synchrotron radiation in the X-ray band (with a high beaming factor of ~0.8; see, e.g., Gao et al., 2013).

Fig. 13 shows predictions for magnetar-powered X-ray emission following a NS-NS merger according to a number of different models. Overall, typical time scales for these transients are comparable to magnetar spin-down time scales of ~10^3–10^5 s and the predicted luminosities span a wide range that goes from 10^{41} to 10^{48} erg s^{-1}. Joint GW + EM detection rates with THESEUS/SXI are discussed below. These rates depend not only on the rate of NS-NS mergers, but also on the (essentially unknown) fraction of mergers forming a long-lived NS remnant, which is necessary to produce spindown-powered transients. The observation of this type of emission after a NS-NS merger would indeed indicate that the remnant is long-lived, allowing for significant constraints on the equation of state of the remnant itself (e.g. Piro et al., 2017; Drago and Pagliara, 2018).

In the case of GW170817/GRB170817A, no evidence for this type of emission was found in the soft X-ray band. However, the first deep pointed observations at ~keV photon energies only started ~15 h after merger with Swift/XRT (Evans et al., 2017). Possible constraints could be provided by the MAXI (2–10 keV) observations taken at 4.6 h after the trigger, with a flux limit of $\sim 8.6 \times 10^{-9}$ erg cm^{-2} s^{-1} (Sugita et al., 2018). We note that for GW170817 the nature of the remnant (BH vs. long-lived NS) was not established for this event, thus making it difficult to put constraints on theoretical expectations. For future observations, being able to catch the soft X-ray emission (or to firmly assess its absence) within the relevant time scale after a GW trigger will require a monitoring (wide-field) instrument sensitive to ~keV energies. THESEUS/SXI will perfectly respond to this need.

The expected detection rate of the isotropic X-ray emission from NS-NS mergers is quoted in Table 2. Taking into account the sensitivity vs exposure time provided in Amati et al. (2017) the SXI will detect almost all X-ray transients at < 200 Mpc, as shown in Fig. 13. Starting from the realistic rate of NS-NS mergers that will be detected with GW observatories in 2020–2030, we have accounted for: (1) the fraction of the sky covered by the SXI FoV, that is ~ 8%, for serendipitous discoveries and (2) the fraction of NS-NS systems that can produce X-ray emission (i.e. that do not form immediately a BH), that we assumed to be within 30–60% (Gao et al., 2013; Piro et al., 2017). Moreover, we consider the fraction of BNS sources that could be followed-up with SXI after a GW alert, estimated to be of the order of ~ 40%. From these computations, we find that during the 2020s the joint GW + EM detection rate with THESEUS of these X-ray counterparts of NS-NS mergers is ~6–12 per year. Starting from around 2030, with the third-generation GW detectors, isotropic X-ray emission from NS-NS mergers as predicted by some models (e.g. Siegel and Ciolfi, 2016b) could be detected up to ~ 10 times larger distances, with an improved joint GW + EM detection rate of few hundreds per year (depending on the largely uncertain intrinsic luminosity of such X-ray component, see Tables 2 and Fig. 13). With such statistics, THESEUS will provide a unique contribution to characterise this X-ray emission from NS-NS systems.

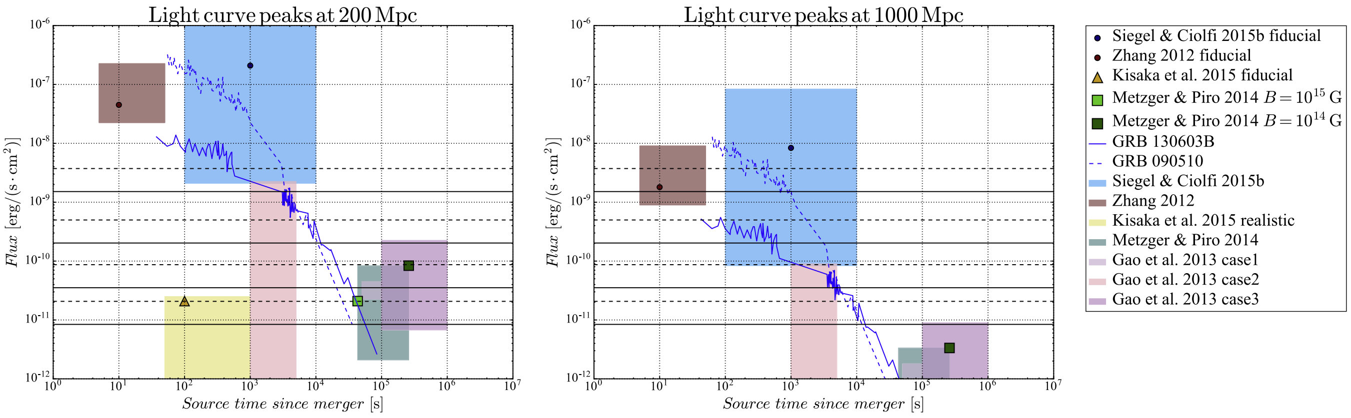

Fig. 13. Expected X-ray fluxes at peak luminosity from two different luminosity distances (z = 0.05 on the left panel, and z = 0.2 on the right panel) and from different models of magnetar-powered X-ray emission from long-lived NS-NS merger remnants. Predictions from each model are represented by a coloured region and/or by single dots that are indicative of fiducial cases (see the legend on the right). The blue lines show two short GRB X-ray afterglows observed with Swift/XRT. The black curves show the SXI sensitivity from higher to lower values at 10s, 100s, 1ks and 10ks, assuming a source column density of 5×10^{20} cm^{-2} (i.e., well out of the Galactic plane and very little intrinsic absorption, solid lines) and 10^{22} cm^{-2} (significant intrinsic absorption, dashed lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Another well known type of nearly-isotropic emission expected from CBCs involving NSs is the so-called "kilonova" or "macronova" (e.g., Li and Paczyński, 1998b; Metzger et al., 2010). NS-NS or NS-BH mergers can eject a substantial amount of matter (up $10^{-2}M_\odot$ or more) which becomes unbound and leaves the system. This material can be expelled both during merger (dynamical ejecta) and in the post-merger phase, in the form of baryon-loaded winds from the accretion disk surrounding the merger remnant (or from the remnant NS itself, for NS-NS mergers without prompt collapse to BH). Due to the unique conditions of high neutron density and temperature, r-process nucleosynthesis of very heavy elements takes place in the ejected matter and days after merger the radioactive decay of such elements heats up the material producing a thermal transient signal peaking in the optical/NIR bands and with typical luminosities of $\sim 10^{40} - 10^{41}$ erg s^{-1} (see, e.g., Fernández and Metzger, 2016; Metzger, 2017). The temporal and spectral properties of these signals encode crucial information on the nature of the merger progenitor (e.g., NS-NS or NS-BH), the equation of state of neutron stars, and the heavy element chemical enrichment of the Universe.

Before the GW170817 event, observational and photometric-only evidence of kilonova/macronova transients relied only on a few candidates observed during short GRB follow-up campaigns (e.g. Tanvir et al., 2013; Jin et al., 2015; Berger et al., 2013). The recent discovery of AT2017gfo has now provided the first compelling evidence, both photometric and spectroscopic, of the existence of kilonovae/macronovae (Pian et al., 2017, see also Abbott et al., 2017d; Tanvir et al., 2017; Nicholl et al., 2017; Smartt et al., 2017; Tanaka et al., 2017; Chornock et al., 2017). The observations of AT2017gfo consolidated the presence of a strong IR emission component reaching its maximum 1.5 days after merger, with 17.2 and 17.5 mag in the J and K bands, respectively (e.g. Tanvir et al., 2017). This provides a very strong science case for the IR instrument on-board THESEUS (IRT) as shown in Fig. 10.

Summarizing, both serendipitous discoveries within the large THESEUS/SXI FoV and re-pointing of THESEUS in response to a GW trigger will allow to study off-axis X-ray and NIR emission expected from NS-NS systems. With THESEUS/SXI in combination with the second-generation detector network, almost all predicted non-collimated X-ray counterparts of GW events from NS-NS merging systems will be easily detected simultaneously with the GW trigger and/or with rapid follow-up of the GW-individuated sky region. Among the open questions that THESEUS will help to address there are: (1) does the NS-NS merger create a NS or a BH, and how fast? (2) how much matter is expelled in the NS mergers? At which speeds? (3) what is the amount of asymmetry in the NS-NS merger ejecta and the corresponding optical emission?

4.3. Core-collapse of massive stars: supernovae and long GRBs

Core-collapse supernovae (CCSNe) represent another type of GW sources that are of great interest for the involved community. However, contrary to the CBC case, their expected GW emission is highly uncertain as it strongly depends on the rather unknown SN explosion mechanism (e.g. Logue et al., 2012; Powell et al., 2016). Not only the signal morphology (waveform), but also the expected energy output are still under debate. Thus, depending on the assumed model as well as dedicated data analysis techniques, during the second-generation GW detector network era the detection of GW from CCSNe is predicted up to few Mpc or less (e.g. Ott et al., 2010), or up to ~100 Mpc (e.g. van Putten et al., 2017). While this makes it difficult to predict the GW signal and its detectability, it also represents a unique opportunity to probe the CCSN inner dynamics that cannot be explored via the sole observation of EM signals.

The firm association of nearby long GRBs with temporally and spatially coincident CCSNe (e.g. Woosley and Bloom, 2006; Galama et al., 1998; Stanek et al., 2003)[4] implies that any long GRB, if close enough, could be associated with a detectable GW emission and thus offers a very interesting potential synergy between gamma-ray and GW detectors. The current uncertainties on the GW detection horizon of these events imply rates that can be as low as a few events per century, but third generation GW detectors such as the Einstein Telescope will offer much better prospects with possible horizons up to 1 Gpc. The first joined GW/GRB/SN observations, possibly combined also with neutrino detections (Section 5), will prove crucial to unravel the nature of these sources and their explosion mechanism. Observed long GRB rate density is ~ 1 Gpc^{-3} yr^{-1} (e.g. Le and Dermer, 2007) thus simultaneous GW + EM detection rate of possibly more than 1 event per year is realistically expected not before the third-generation GW interferometers. Off-axis X-ray afterglow detections ("orphan afterglows") (e.g. Granot et al., 2002; Ghirlanda et al., 2013, 2015b) can potentially increase the simultaneous GW + EM detection rate for nearby long GRBs by a factor that strongly depends on the jet opening angle and the observer viewing angle. THESEUS may also observe the appearance of a NIR orphan afterglow few days after the reception of a GW signal due to a collapsing massive star. In addition, the possible large number of low luminosity GRBs (LLGRBs, e.g. Toma et al., 2007; Virgili et al., 2009) in the nearby Universe, expected to be up to 1000 times more numerous than long GRBs, will provide clear signatures in the GW detectors because of their much smaller distances with respect to long GRBs.

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[4] For GRB 060614 (Della Valle et al., 2006; Fynbo et al., 2006), in spite of marginal evidence for an associated kilonova, which would make it a short GRB, this event, along with GRB 060505, leaves the possibility of long SN-less GRBs, see also Xu et al., 2009.

Beside the GRB-connected phenomenology, Wolf–Rayet stars as well as red and blue supergiants are expected to exhibit bright shock breakout soon after their core collapse, with X-ray bursts lasting 10–1000 s and with luminosities expected in the range 10^{43}–10^{46} erg s^{-1}. These progenitors are likely responsible for Type Ibc and most Type II SNe, which occur at rates of 2.6×10^{-5} and 4.5×10^{-5} Mpc^{-3} yr^{-1}, respectively (Li et al., 2011). THESEUS/SXI and XGIS can detect these events up to ~ 50 Mpc leading to a rate of a few per year (Amati et al., 2017). We expect up to few shock breakout events per year that can be detected with THESEUS/SXI simultaneously with their GW counterpart during the 3G GW detector era. Shock Breakout (SBO) components are temporally closer to the possibly associated GW events than the optical CCSNe counterpart, thus their detection can mark with more precision the start time of the gravitational radiation emission and can be used in the challenging signal search processes (Andreoni et al., 2016).

4.4. Magnetars

Fractures of the solid crust on the surface of highly magnetised neutrons stars and/or dramatic magnetic field readjustments represent the most widely accepted explanations to interpret the magnetar bursting activity and in particular the rare giant flares observed in X-rays from three different soft gamma repeaters (SGRs; see, e.g., Thompson and Duncan, 1995; Guidorzi et al., 2004; Mereghetti et al., 2015). The initial short (< 0.5 s) bright spikes of SGR can be detected with the XGIS to considerable distances. The XGIS low energy threshold is better suited for the detection of such events with respect to other coded-mask detectotrs. Flares and bursting episodes will be easily detectable with SXI (Amati et al., 2017).

The above events will inevitably excite non-radial oscillation modes that may produce detectable GWs (see, e.g., Corsi and Owen, 2011; Ciolfi et al., 2011). The most recent estimates for the energy reservoir available in a giant flare are between 10^{45} erg (about the same as the total EM emission) and 10^{47} erg. The efficiency of conversion of this energy into GWs was estimated in numerical relativity simulations and it was found to be likely too small to be within the sensitivity range of present GW detectors (Ciolfi and Rezzolla, 2012; Lasky et al., 2012). However, at the typical dominant (i.e. f-mode) oscillation frequencies in NSs ($\sim$kHz), ET will be sensitive to much lower GW energies (Punturo et al., 2010). Therefore, a relatively close giant flare event might lead to a detectable GW emission.

5. Neutrino sources

Several gamma-ray and X-ray sources that THESEUS will observe as GRBs, CCSNe and AGNs, are also expected to originate neutrinos. Due to their low interaction cross-section, neutrinos can probe the innermost regions similarly to gravitational waves but, in addition, neutrino detectors can provide a more refined sky localisation than GW interferometers, with an uncertainty that goes from few degrees down to a fraction of a degree. Current neutrino deep-water-based detectors include DUMAND, Lake Baikal, and ANTARES. These Northern hemisphere detectors complement the South Pole based IceCube, the first km-scale neutrino observatory, completed and in full operation since 2010. Two major upgrades for the near and far future are planned with the construction of Km3Net in the Northern hemisphere, started in 2015, and IceCubeGen2, an upgrade to a 10 km^3 detector of IceCube (e.g. IceCube-Gen2 Collaboration et al. (2014), and references therein). These are prevalently high-energy neutrino detectors but IceCube and Km3Net can detect also MeV neutrinos due to the capabilities to suppress background rate, together with other liquid scintillators and liquid Argon Time-Projection Chamber detectors (e.g. see reviews by Scholberg (2012), Gil-Botella (2016), and references therein).

Pulses of low energy neutrinos ($<$10 MeV) are expected to be released during CCSNe with an energy release up to 10^{53} erg. Indeed, MeV neutrinos have been detected so far only from one CCSN, namely SN1987A, in the Large Magellanic Cloud at 50 kpc distance (e.g. Gaisser et al., 1995). Comparison of the SN1987A neutrino signal with theoretical predictions showed that the general features of CCSNe are compatible with the observations (e.g. Giunti and Chung, 2007). However, significant uncertainties are still affecting CCSNe modelings and, more in general, the core-collapse processes of massive stars. Great advances are expected from GW and further neutrino detections that will be achieved with the next generation detectors. Both GW and neutrinos can provide important information as the degree of asymmetry in the matter distribution, as well as the rotation rate and the strength of the magnetic fields, that can be used as priors in numerical simulations (see, e.g., Chassande-Mottin et al. (2010), and reference therein).

Significant evidence of high-energy (TeV-PeV) cosmic neutrinos has recently been obtained from an extensive IceCube fourth-year data analysis (e.g. Aartsen et al., 2014). The lack of significant anisotropy in the data sky direction distribution is consistent with an (at least partially) extragalactic origin of the neutrino sources. High-energy neutrinos originate from hadrons acceleration, for example in jets, where after interacting with high energy photons produce charged pions decaying as high energy neutrinos ($>10^5$ GeV; see, e.g., Waxman and Bahcall, 1997). Among the candidates that have been proposed to be responsible for the observed high-energy neutrino flux there are GRBs, AGN and blazars that are part of the main THESEUS targets in the context of the Time-domain Universe (Amati et al., 2017). THESEUS/SXI will enable to monitor the X-ray flux of hundreds of AGN on daily timescales and provide an unprecedented look at long-term variability of large samples of AGN and Blazars. Deep monitoring will also performed with XGIS in the hard X-ray spectral regime. These observations will provide an ideal tool for neutrino simultaneous detection.

GRB are historically addressed among the best candidates of Ultra High Energy Cosmic Rays (UHCR) (e.g. Ghisellini et al., 2008), together with AGNs. Recent results from the Pierre Auger Observatory found evidence for dipolar anisotropy in CR at $E > 8 \times 10^{18}$ eV towards a given direction in the sky, which is compatible with an extra-galactic origin, with possible suggestion that they are due to Large Scale Structures, with relatively nearby sources within 300 Mpc (e.g. Globus and Piran, 2017). As UHECR sources, GRBs are therefore addressed as promising high-energy neutrinos source candidates together with AGN. However, searches for neutrino events in coincidence with GRBs have not provided any confirmed association so far, possibly because of the average large distances of GRBs and/or a low neutrino production efficiency in bright GRBs. Possible detection could be achieved with the next generation of neutrino detectors. For long GRB, neutrinos emitted along the jet direction give the highest chances of detection. The expected rate of on-axis GRB that can be detected with IceCube has been estimated to be of the order of $\sim$0.3 per year (e.g. Xiao et al., 2017). The lack of neutrinos from the very nearby short GRB associated with the GW170817 source has been interpreted to be due to the off-axis viewing angle of our line of sight with respect to the jet direction(Albert et al., 2017), but the feasibility of future joint EM and GW/neutrino observations are supported by theoretical background. In particular, for the case of short GRBs, according to the most recent studies (Kimura et al., 2017), high-energy neutrinos are thought to be most efficiently produced during the so called "Extended Emission" (EE), a softer, prolonged emission lasting few tens up to hundreds of seconds, that follows the initial count rate spike that characterises some short GRBs (Norris and Bonnell, 2006; Kaneko et al., 2015). It has been observed that about $\sim 25\%$ of short GRBs are accompanied by an EE (Sakamoto et al., 2011). This fraction is likely biased by the lack of X-ray survey instruments that could detect this component and likely more short GRBs are accompanied by EE (Nakamura et al., 2014), possibly up to 50% (Kimura et al., 2017). According to the neutrino detection probability estimates as a function of the short GRB with EE distance computed by Kimura et al. (2017), we expect that THESEUS/neutrino counterpart detection rate of on-axis short GRBs with EE within the horizon of IceCube and IceCubeGen2 is of the order of 0.02–0.25 and 0.1–0.5 per year, respectively. By considering the possibility to observe neutrinos also from short GRB with EE viewed off-axis, the THESEUS/neutrino counterpart detection rate may increase up to 0.2–4, and 0.5–7 per year, respectively. Future multi-messenger campaigns with deeper detector sensitivities will likely further constrain GRB progenitor models, clarifying the presence of a jet and its composition, and the relative neutrino/EM energy budgets and the role of GRBs as sources of UHCRs (Abbasi et al., 2012).

THESEUS/SXI and XGIS can detect SN shock breakouts events up to ~ 50 Mpc (see previous section), thus leading to a potential joint neutrino detections of a few events per year with new generation neutrino detectors as Km3Net or IceCubeGen2. Blazars have been considered among the possible source candidates for the recently detected IceCube cosmic high-energy neutrino flux. THESEUS/blazars detection rate is estimated to be of hundreds per year (see Table 2 in Amati et al., 2017).

6. Summary

The first detection of the electromagnetic counterparts of a GW source has confirmed a number of theoretical expectations and boosted the nascent multi-messenger astronomy. In this review we have discussed several classes of sources, including compact binary coalescences, core-collapsing massive stars, and instability episodes on NSs that are expected to originate simultaneously high-frequency GWs, neutrinos and EM emission across the entire EM spectrum, including in particular high energy emission (in X-rays and gamma-rays). We have shown that the mission concept THESEUS has the potential to play a crucial role in the multi-messenger investigation of these sources. THESEUS, if approved, will have the capability to detect a very large number of transient sources in the X-ray and gamma-ray sky due to its wide field of view, and to automatically follow-up any high energy detection in the near infrared. In addition, it will be able to localise the sources down to arcminute (in gamma and X-rays) or to arcsecond (in NIR). The instrumental characteristics of THESEUS are ideal to operate in synergy with the facilities that will be available by the time of the mission: several new generation ground- and space-based telescopes, second- and third-generation GW detector networks and 10 km^3 neutrino detectors. This makes THESEUS perfectly suited for the coming golden era of multi-messenger astronomy and astrophysics.

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