galaxies

MDPI

Article

Breakthrough Multi-Messenger Astrophysics with the THESEUS Space Mission †

Giulia Stratta [1,2,*], Lorenzo Amati [2], Marica Branchesi [3], Riccardo Ciolfi [4], Nial Tanvir [5], Enrico Bozzo [6], Diego Götz [7], Paul O'Brien [5] and Andrea Santangelo [8]

1 Istituto Nazionale di Astrofisica-Istituto di Astrofisica e Planetologia Spaziali di Roma, Via Fosso del Cavaliere 100, 00133, Rome, Italy
2 Istituto Nazionale di Astrofisica-Osservatorio di Astrofisica e Scienza dello spazio Bologna, Via P. Gobetti 101, 40129, Bologna, Italy; lorenzo.amati@inaf.it
3 Gran Sasso Science Institute, Viale F. Crispi 7, I-67100 L'Aquila, Italy; marica.branchesi@gssi.it
4 INAF, Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy; riccardo.ciolfi@inaf.it
5 School of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK; nrt3@leicester.ac.uk (N.T.); pto2@leicester.ac.uk (P.O.)
6 Department of Astronomy, University of Geneva, 1205 Versoix, Switzerland; enrico.bozzo@unige.ch
7 Commissariat à l'Énergie Atomique et aux Énergies Alternatives, Centre National de la Recherche Scientifique, Astrophysics, Instrumentation-Modeling, Université Paris Saclay, F-91190 Gif-sur-Yvette, France; diego.gotz@cea.fr
8 Institut für Astronomie und Astrophysik, Abteilung Hochenergieastrophysik, Kepler Center for Astro and Particle Physics, Eberhard Karls Universitat, Sand 1, D 72076 Tuebingen, Germany; andrea.santangelo@uni-tuebingen.de
* Correspondence: giulia.stratta@inaf.it
† On behalf of the THESEUS Consortium: http://www.isdc.unige.ch/theseus/.

Citation: Stratta, G.; Amati, L.; Branchesi, M.; Ciolfi, R.; Tanvir, N.; Bozzo, E.; Götz, D.; O'Brien, P.; Santangelo, A. Breakthrough Multi-Messenger Astrophysics with the THESEUS Space Mission †. *Galaxies* **2022**, *10*, 60. https://doi.org/10.3390/galaxies10030060

Academic Editor: Elena Moretti, Francesco Longo and Yosuke Mizuno

Received: 28 February 2022
Accepted: 15 April 2022
Published: 21 April 2022

Abstract: The mission concept THESEUS (Transient High Energy Sky and Early Universe Surveyor) aims at exploiting Gamma-Ray Bursts (GRB) to explore the early Universe, as well as becoming a cornerstone of multi-messenger and time-domain astrophysics. To achieve these goals, a key feature is the capability to survey the soft X-ray transient sky and to detect the faint and soft GRB population so far poorly explored. Among the expected transients there will be high-redshift GRBs, nearby low-luminosity, X-ray Flashes and short GRBs. Our understanding of the physics governing the GRB prompt emission will benefit from the 0.3 keV–10 MeV simultaneous observations for an unprecedented large number of hundreds of events per year. In particular the mission will provide the identification, accurate sky localisation and characterization of electromagnetic counterparts to sources of gravitational wave and neutrino sources, which will be routinely detected during the 2030s by the upgraded second generation and third generation Gravitational Wave (GW) interferometers and next generation neutrino detectors.

Keywords: gamma–rays: bursts; cosmology: early universe; multi-messenger astrophysics: gravitational waves; neutrinos; instrumentation: X/gamma–ray astrophysics from space; fundamental physics

1. Introduction

Since their discovery in the late 1960s [1], the attention given by the scientific community to the gamma-ray burst (GRB) phenomenon has continuously increased. Nowadays, GRBs represent one of the most important sources in the Universe for observational cosmology, multi-messenger astronomy as well as extreme physics.

Their brightness in gamma-rays during the prompt phase allows us to detect the so-called "long-duration" GRBs, the GRBs generated by the gravitational collapse of rapidly rotating and massive stars, up to distances where the very first stars and galaxies form. The census of high-redshift GRBs allows us to shed light on the main processes responsible for Universe reionization after Dark Ages.

In the context of multi-messenger astronomy, "short-duration" GRBs are today playing a major role after the confirmation of their association with binary neutron star merger (BNS) systems, in particular for the case of GRB 170817A [2,3]. Electromagnetic counterparts of gravitational wave (GW) sources, are fundamental for accurate sky localization that allows us to improve GW parameter estimation accuracy and to measure the cosmological redshift of the GW sources. The latter has crucial implications for the measurement of cosmological parameters and, being an independent method, can potentially solve current tensions over the value of the Hubble constant [4].

Finally, GRBs provide a unique and extremely powerful benchmark for performing tests of fundamental physics. For instance, the vast photon flux emitted during the prompt emission phase of these phenomena over several orders of magnitude of energy, combined with their extreme cosmological distances, make these phenomena powerful probes for testing the Lorentz Invariance Violation (LIV), which is predicted by different families of Quantum Gravity theories [5].

In all these respects, future GRB missions (such as the proposed THESEUS and Gamow Explorer mission concepts) will provide an ideal synergy with the large electromagnetic facilities of the future like the VRO/LSST, ELT, TMT, SKA, CTA and ATHENA in the electromagnetic domain, and advanced second generation (2G) and third generation (3G) GW detectors and future large neutrino detectors (e.g., KM3NeT) in the non-photonic domain.

2. Multi-Messenger Astrophysics with Gamma-ray Bursts

In 2015 the advanced GW interferometers LIGO and Virgo [6,7] have detected gravitational waves for the first time [8,9]. Nowadays, the GW transient source catalogs published by the LIGO/Virgo collaboration counts several dozens of GW source candidates [10,11], all identified as compact binary coalescences. Among these sources, two are consistent with being BNSs and one has been associated with a short GRB (GRB170817A) [2,3]. In contrast, no neutrino counterpart has been found associated with any bright GRBs, putting stringent constraints on neutrino production in relativistic jets associated with these events [12]. The nearby class of long GRBs with low-luminosity (LL-GRBs) as well as ultra-long duration have been suggested as more promising candidates with respect to the bright GRBs (see e.g., [13] and references therein). The key feature of THESEUS is to independently detect these electromagnetic counterparts at the time of neutrino events and to provide refined sky localizations to allow multi-wavelength prolonged follow-up with other facilities.

2.1. GRB 170817

The first multi-messenger observations of a GRB happened on 17 August 2017 when a short GRB (GRB170817A) was detected with *Fermi* [14] and *INTEGRAL* [15].

The sky position and burst trigger time resulted to be consistent with an independent detection of GW event (GW 170817) achieved with the advanced LIGO and Virgo network [3,16]. The observed gravitational waveform of GW 170817 was consistent with the one expected from a BNS. The association with GRB 170817A has a gaussian-equivalent significance of 5.3σ [3] and marks the first direct evidence of short GRB progenitor. This breakthrough result confirmed a wealth of indirect evidence gathered in almost 20 years of short GRB observations, for instance the lack of any association with core-collapse supernova (contrary to long GRBs) yet plausible evidence for kilonova emission in some cases the mixed-type nature of the host galaxies (early and late) and the GRB sites within the host galaxy (see e.g., [17] and references therein).

Another milestone reached with GRB 170817A was the first direct evidence of a narrow, relativistic expanding jet. Indeed, from both the prompt and afterglow emission properties, it was realized that this burst was observed with a non-null viewing angle with respect to the jet axis. This allowed imaging and monitoring in time of the orthogonal component of the jet with the superb spatial accuracy of the VLBI and the results were consistent with a compact source moving at relativistic velocities [18]. This result in turn confirms that BNSs can produce ultra-relativistic jets.

A major advance was also achieved due to the fact that the gravitational waveform of compact binary coalescences encodes not only information on the masses, but also on the luminosity distance D_L. Indeed, by combining the measured D_L for GW170817 with the redshift measurement of the host galaxy NGC 4993, identified through the electromagnetic counterpart follow-up [2], it was possible to estimate the Universal expansion rate through the Hubble constant (H_0) measurement [4]. Despite the large uncertainties obtained with this single measure, this result showed the feasibility of a new, independent method to measure H_0, with strong implications for the current tension plaguing the outcomes from different probes used to measure this fundamental parameter (see [4] and references therein).

2.2. Next Achievements

In the next years, with the second generation GW interferometer network (i.e., LIGO, Virgo, KAGRA and by 2025 also LIGO-India, see [19]) we expect to detect other cases like GRB 170817A from BNS mergers and possibly short GRBs associated with NS-BH merger systems up to distances $z < 0.1 - 0.2$. The joint detection rate is still very uncertain but possibly limited to a few cases within the 2020s. This low rate is mainly due to the collimated nature of GRB emission that confines simultaneous detections to a tiny fraction of the total GW events associated with BNS or NS-BH, for which GWs are emitted isotropically.

Interesting predictions concern the possible formation of a NS remnant with large magnetic field (magnetar) after a BNS merger. In this case, the dipole radiation, expected mainly in the X-ray band and with low level of collimation, increases the chances of joint detection. The presence of a spinning-down, new-born magnetar is among the possible scenarios invoked to explain the "Extended Emission" detected after some short GRBs, a $\sim$100 s lasting component with softer spectrum than the main short burst, that may represents a potential X-ray counterpart of a BNS merger [20]. Another potential multi-messenger X-ray target expected to be less collimated than short GRBs is represented by the afterglow emission during the so called "plateau" phase, characterized by a nearly constant flux level lasting on a timescale that goes from a few hundreds of seconds up to $\sim$1 day. The origin of the plateaus is still debated: among the possible scenarios is the presence of a magnetar pumping energy into the forward shock. In this case, a long-transient continuous GW emission might be simultaneously detected [21]. An alternative scenario invokes the high-latitude prompt emission or afterglow emission from a structured jet for an observer line of sight slightly offset with respect to the jet axis (e.g., [22,23]). In this case, GW continuous emission is not necessarily expected. We note that X-ray plateaus are observed also for long GRBs: in this case, if a magnetar is the origin of this feature, long-transient continuous GWs may be detected also from this other class of GRBs.

During the 2030s, the third generation GW detectors are expected to be operational, with sensitivity nearly one order of magnitude higher. By that time, the distance up to which a BNS can be detected is $z \gtrsim 1$, thus implying a huge detection rate, of the order of O(10^5) per year [24].

With such large detection rate, the fraction of joint detection as short GRBs will be high and will allow statistical studies on large samples. Among the possible issues that can be tackled with a statistical approach there are: (i) jet launching mechanisms and efficiency, (ii) the universality of the jet structure, (iii) differences/commonalities among BNS and NS-BH systems; (iv) accurate cosmological parameter measurements. The high sensitivity of 3G detectors, in addition, will make the detection of the faint GW emission from cc-SN a realistic proposition, possibly up to Mpc scales, allowing us to gain crucial insights on the still uncertain explosion mechanisms.

3. The THESEUS Mission Concept

The Transient High Energy Sky and Early Universe Surveyor (THESEUS) mission concept (Figure 1), developed in recent years by a large European-led collaboration involving also scientists worldwide, aims to fully exploit the unique and breakthrough potential of GRBs for investigating the Early Universe and substantially advancing multi-messenger astrophysics, while simultaneously vastly increasing the discovery space of most high energy transient phenomena over the entirety of cosmic history and allowing tests of fundamental physics [25]. THESEUS will achieve these ambitious goals through a step change in capabilities for detection and characterisation of GRBs and other transients over a very broad energy band (0.3 keV to 10 MeV) and wide field of view, including on-board near-infrared imaging and spectroscopy, and is designed to be at the forefront of these science fields in the late 2030s.

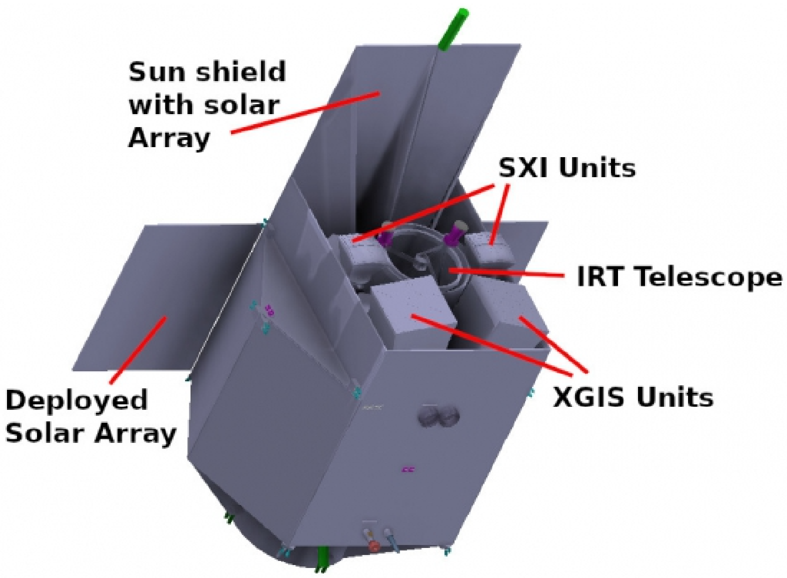

Figure 1. Possible spacecraft design and payload accomodation of THESEUS (Credit: ESA and THESEUS Consortium).

THESEUS will inherently be a mission enabling great synergies with the premier future observatories, providing simultaneous wide sky monitoring, rapid follow-up and real-time alerts (Figure 2). Figure 3 provides a tentative timeline of these observatories with respect to the THESEUS expected operational period. From *ELT* to *ATHENA*, *CTA* to Einstein Telescope, the Vera Rubin Observatory to the Roman Space Telescope, the science returns from combining observations with multiple facilities is a classic case of "the whole being much greater than the sum of the parts" [26]. A broad range of other science programmes will be enabled by THESEUS, including using observations of GRB emission as laboratories of ultra-relativistic matter and, e.g., for testing Lorentz invariance [5], as well as gathering statistics on large populations of other high-energy sources and transients [27]. Thus, THESEUS data will be of interest to a very wide user community, also through its open guest-observer programme.

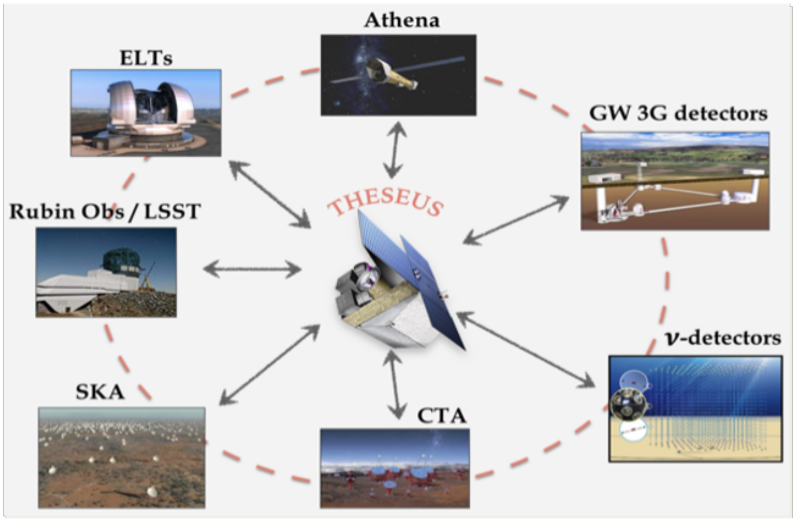

Figure 2. Synergy of THESEUS with next generation very large facilities in the multi-wavelength and multi-messenger domains [26].

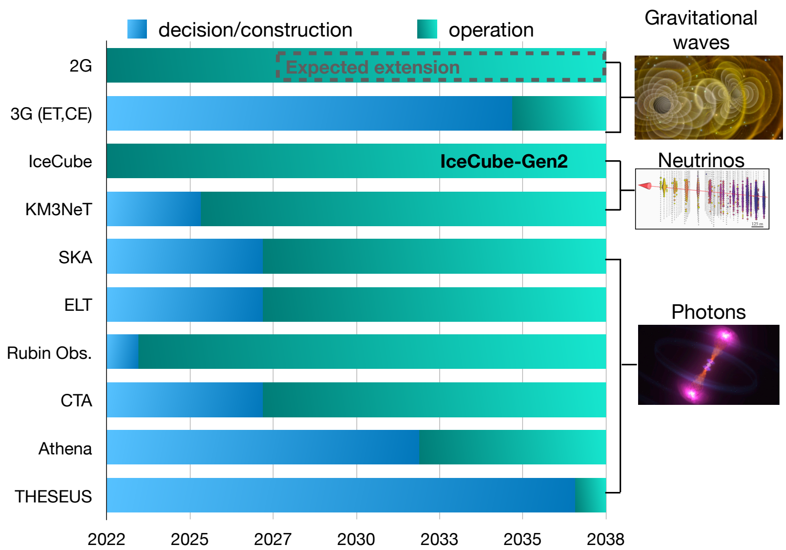

Figure 3. Planned timelines of the main failicities for Multi-Messenger Astronomy in the next decades with which THESEUS will operate in strong synergy (see Figure 2) [26].

3.1. Scientific Goals and Requirements

The scientific goals for the exploration of the early Universe require the detection, identification, and characterization of several tens of long GRBs occurring in the first billion years of the Universe ($z > 6$) within the 4 years of nominal mission lifetime of THESEUS [28]. This would be a giant leap with respect to what has been obtained in the last 20 years (8 GRBs at $z > 6$), using past and current GRB dedicated experiments like *Swift/BAT*, *Fermi/GBM*, *Konus-WIND* combined with intensive follow-up programs from the ground with small robotic and large telescopes (e.g., VLT). This breakthrough performance can be achieved by overcoming the current limitations through an extension of the GRB monitoring passband to the soft X-rays with an increase of at least one order of magnitude in minimum detectable flux with respect to previously-flown wide-field X-ray monitors. As well, a substantial improvement of the efficiency of counterpart detection, spectroscopy and redshift measurement will be enabled through prompt on-board near-infrared (NIR) follow-up observations (Table 1).

At the same time, the goals for multi-messenger astrophysics and time domain astronomy require:(i) a substantial advance in the detection and localization, over a large (>2 sr) FoV of short GRBs as electromagnetic counterparts of GW signals coming from BNS, and possibly NS-BH mergers; (ii) monitoring the high-energy sky with an unprecedented combination of sensitivity, location accuracy and field of view in the soft X-rays; iii) imaging up to the hard X-rays and spectroscopy/timing of the soft gamma-rays [27,29,30].

Table 1. Key science performance requirements of THESEUS[1]. The sensitivity requirements assume a power-law spectrum with a photon index of 1.8 and an absorbing column density of 5×10^{20} cm^{-2}.

SXI sensitivity (3σ)	1.8×10^{-11} erg cm^{-2} s^{-1} (0.3–5 keV, 1500 s) 10^{-10} erg cm^{-2} s^{-1} (0.3–5 keV, 100 s)
XGIS sensitivity (1 s, 3σ)	10^{-8} erg cm^{-2} s^{-1} (2–30 keV) 3×10^{-8} erg cm^{-2} s^{-1} (30–150 keV) 2.7×10^{-7} erg cm^{-2} s^{-1}(150 keV–1 MeV)
IRT sensitivity (imaging, SNR = 5, 150 s)	20.9 (I), 20.7 (Z), 20.4 (Y), 20.7 (J), 20.8 (H)
SXI FoV	0.5 sr – 31×61 deg^2
XGIS FoV ($\geq$20% efficiency)	2 sr (2–150 keV) – 117×77 deg^2 4 sr ($\geq$150 keV)
IRT FoV	$15' \times 15'$
Redshift accuracy ($6 \leq z \leq 10$)	$\leq$ 10%
IRT resolving power	$\geq$400
XGIS background stability	$\leq$10% over 10 min
Field-of-Regard	$\geq$50% of the sky
Trigger broadcasting delay to ground-based networks	$\leq$30 s (65% of the alerts) $\leq$20 min (65% of the alerts)
External alert (e.g., GW or ν events) reaction time	>4–12 h
SXI positional accuracy (0.3–5 keV, 99% c.l.)	$\leq$2 arcmin
XGIS positional accuracy (2–150 keV, 90% c.l.)	$\leq$7 arcmin (50% of triggered short GRBs) $\leq$15 arcmin (90% of triggered short GRBs)
IRT positional accuracy (5σ detections) real time post-processing	$\leq$5 arcsec $\leq$1 arcsec

3.2. On-Board Scientific Instruments

Based on the above mentioned mission scientific requirements and the unique heritage and worldwide leadership of the Consortium in the enabling technologies, the THESEUS payload (Figure 1) will include the following scientific instruments:

- Soft X-ray Imager (SXI, 0.3–5 keV): a set of two "Lobster-eye" telescope units, covering a total FoV of $\sim$0.5 sr with source location accuracy $< 2'$, focusing onto innovative large size X-ray CMOS detectors [31];
- X-Gamma ray Imaging Spectrometer (XGIS, 2 keV–10 MeV): a set of two coded-mask cameras using monolithic SDD+CsI X- and gamma-ray detectors, granting a $\sim$2 sr imaging FoV and a source location accuracy <15 arcmin in 2–150 keV, an energy band from 2 keV up to 10 MeV and few µs timing resolution [32];

- InfraRed Telescope (IRT, 0.7–1.8 μm): a 0.7-m class IR telescope with 15′ × 15′ FoV, with imaging (I, Z, Y, J and H) and moderate spectroscopic (resolving power, R 400, through 2′ × 2′ grism) capabilities [33].

The instruments' Data Handling Units (DHU) will operate in synergy, thus optimizing the capability of detecting, identifying and localizing likely transients in the SXI, XGIS and IRT FoVs, as well as providing the unprecedented capability of on-board autonomous redshift measurements.

3.3. Mission Profile

The baseline launcher / orbit configuration is a launch with a Vega-C to a low inclination (<6°) Low Earth Orbit (LEO, 550–640 km altitude), which has the unique advantages of granting a low and stable background level in the high-energy instruments, allowing the exploitation of the Earth's magnetic field for spacecraft fast slewing and facilitating the prompt transmission of transient triggers and positions to the ground. The mission profile will include: (a) a spacecraft autonomous slewing capability >7°/min; (b) the capability of promptly (within a few tens of seconds at most) transmitting to the ground the trigger time and positions of GRBs (and other transients of interest) through the Trigger Broadcasting Unit (TBU) transmitter (via inter-satellite systems like, e.g., ORBCOMM, Iridium and, in case of US contribution, the NASA/TDRSS) and the THESEUS Burst Alert Ground Segment (TBAGS). The main ground station will be 10 m antenna (X-band receiver) at ASI "Luigi Broglio Space Centre" in Malindi (Kenya). As assessed during ESA/M5 Phase A study through a sophisticated Mission Observation Simulator (MOS), the mission scientific goals could be achieved with a nominal duration of 4 years (about 3.5 years of scientific operations). The Mission Operation Control (MOC) and Science Operations Centre (SOC) will be managed by ESA, while the Science Data Centre (SDC) will be under the responsibility of the Consortium.

The thorough R&D activities carried on by the THESEUS Consortium and ESA during the M5 Phase A study, grant a Technology Readiness Level (TRL) already close to that required for mission adoption for the main payload elements. The technical feasibility of the spacecraft, including payload accommodation and thermal control, the required pointing accuracy and stability, the reliability of reaching TRL at mission adoption, the compatibility of a launch with Vega-C in LEO, as well of the overall mission profile, within the M-class mission boundaries and according to the THESEUS scientific requirements, has also already been successfully assessed by M5 Phase A study.

The baseline mission operation concept includes a Survey mode, during which the monitors are waiting for GRBs and other transients of interest. Following a GRB (or transient of interest) trigger validated by the Data Handling Unit (DHU) system, the spacecraft enters a Burst mode (improved data acquisition and spacecraft slewing), followed by a pre-determined (but flexible) IRT observing sequence (Follow-up and Characterization or Deep Imaging modes). The pointing strategy during the Survey mode will be such as to maximize the combined efficiency of the sky monitoring by SXI and XGIS and that of the follow-up with the IRT. Small deviations (of the order of a few degrees until core science goals are achieved) from the Survey mode pointing strategy will be possible so to point the IRT on sources of interest pre-selected through a Guest Observer (GO) programme. Scientific modes also include an external trigger (or Target of Opportunity) mode, in which the IRT and high-energy monitors will be pointed to the direction of a GRB, transient or, e.g., to the error region of a GW or neutrino signal, provided by an external facility.

4. Multi-Messenger Astrophysics with THESEUS

The large THESEUS/XGIS and SXI field of view and sky localization accuracy will secure independent triggers on the electromagnetic counterparts of several GW and neutrino sources and their localization down to arcmin/arcsec level. The synergies of THESEUS with next generation neutrino and GW observatories will significantly increase the number of multi-messenger detections, enabling unprecedented robust statistical studies of multi-messenger sources [30].

By the end of the 2030s, 3G GW interferometers as the Einstein Telescope [24,34] and the Cosmic Explorer [35], are expected to operate at full sensitivity and likely within a network configuration. In the left panel of Figure 4 we show the THESEUS/XGIS short GRB redshift distribution, where the expected detection rate is of the order of 12/year. These numbers are obtained from simulations of THESEUS pointing strategy, considering all observational constraints, and a random set of short GRB triggers based on the population model of Ghirlanda et al. (2016). This model is built on past short GRBs observed with *Swift* and *Fermi* (i.e., before GRB170817A), considered to be "aligned" (for which the line of sight falls inside the narrow core of the corresponding jet). By taking into account the BNS merger detection efficiency of the 3G interferometers, we also show in each redshift bin the expected fraction that will be jointly detected with ET only and by a network of ET located in Europe plus 2 CEs assumed to be located one in USA and the other in Australia. Expected joint detection rates are quoted in Table 1.

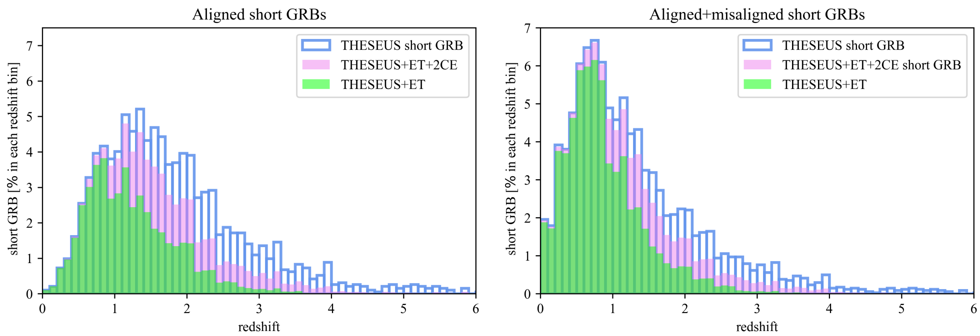

Figure 4. (**Left**): Short GRB redshift distribution detected with THESEUS/XGIS assuming an on-axis configuration (blue) and jointly with ET (green) and a network of 3G composed by 2CE and ET (pink). (**Right**): Same figure but now Short GRB with off-axis configurations are included.

THESEUS/XGIS is suitable to detect soft-faint bursts as those we expect to observe from large viewing angles ("misaligned") [30]: in the right panel of Figure 4 we included "misaligned" short GRBs by assuming a structured jet model from [18,36]. We find that the most nearby events can be detected up to large viewing angles [30]. As a consequence, the number of THESEUS short GRB detections at small redshifts is significantly increased with respect to the "aligned" only case. Since at low redshift the GW interferometers BNS merger detection efficiency is near 100%, this improvement is also reflected in the number of joint detections (see third column of Table 1).

With such joint detection rates, THESEUS will allow us to build statistical samples of multi-messenger sources with which a number of fundamental issues can be investigated [30]. To mention some examples:

- through the detection or non detection of a SGRB simultaneously with a BNS/NS-BH event for which the orbital inclination angle is accurately measured through the GW waveform, the jet formation efficiency in such systems can be estimated as well as a comparison between BNS and NS-BH systems.
- from the temporal gap between the GRB trigger and the GW events, jet launching mechanisms can be deeply investigated.
- from the detection or non detection of continuous GWs after the merger it will be possible to constrain the formation of a NS remnant versus a BH, a crucial issue that encodes information on the NS Equation of State and that will allow us to understand the origin of still unexplained features observed in short GRBs such as the Extended Emission and the plateau that THESEUS/XGIS and SXI will detect (Figure 5).

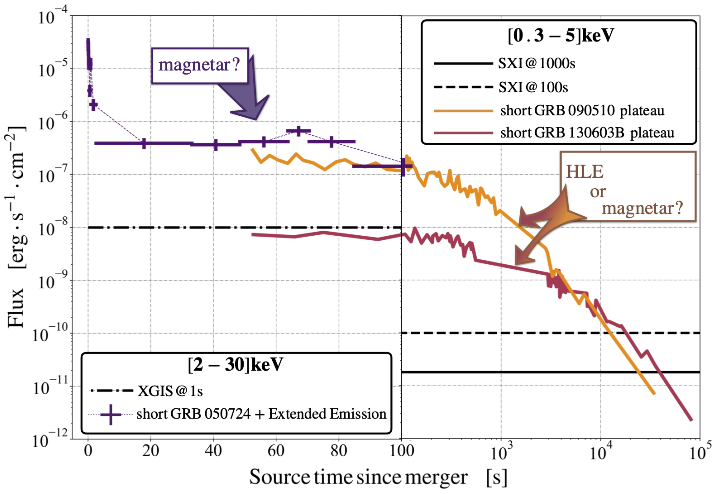

Figure 5. The X-raylong monitoring from prompt emission to the afterglow of relatively bright short GRB with THESEUS/XGIS and SXI. The linear temporal-scale plot on the left shows the short GRB prompt with the "Extended Emission" as it would be detected by THESEUS/XGIS possibly explained by invoking a magnetar remnant. The logarithmic temporal-scale plot on the right shows the X-ray plateau phase with the indication of two possible scenarios invoked for its origin, i.e., High-Latitude Emission of the prompt assuming a structured jet [22] and a spinning-down magnetar pumping energy into the external shock [37] [Credit: S. Vinciguerra].

Last but not least, from a large sample of sources with independent measurement of the cosmological redshift and luminosity distance, the Hubble constant can be measured with the sufficient accuracy to solve the current tensions among different measurements. In Figure 6 we plot the gaussian probability distributions of the current estimates of H_0 and the expected improvement of the GW170817 distribution by assuming a realistic number of 20 joint detected events (Table 2).

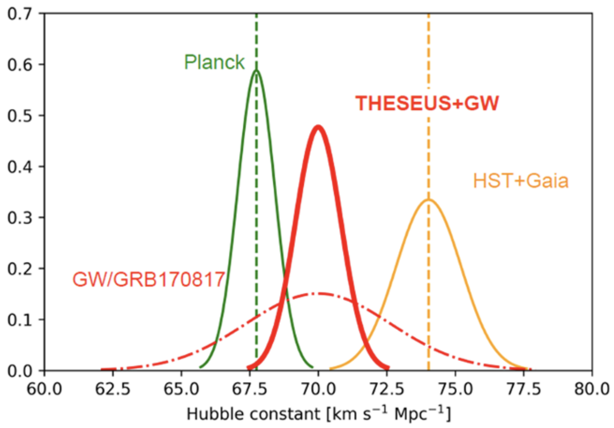

Figure 6. Gaussian probability distribution of the current H_0 measurements, including the one obtained from the BNS GW170817, and the expected one with ∼20 joint GW+GRB detections. During the end of the 2030s, 20 joint detection is a conservative estimate for three years of synergies between THESEUS and a network of ET and 2 CE by taking into account the expected fraction of short GRB for which a redshift can be measured.

Table 2. Expected joint detections of short GRBs with THESEUS and the 3G GW interferometers (ET = Einstein Telescope, CE = Cosmic Explorer) expected to be operational in the second half of the 2030s, by assuming 3.45 years of joint observations [30].

GW Detectors in the '30s	Joint Detections (Aligned Short GRBs)	Joint Detections (Aligned + Misaligned Short GRBs)
ET	20	45
ET + CE	25	55
ET + 2CE	30	60

THESEUS will disseminate accurate sky localization (arcmin/arcsecond uncertainties) within seconds/minutes to the astronomical community, thus enabling large ground and space-based telescopes available by the end of 2030s to observe and deeply characterise the nature of large sample of multi-messenger sources [26,38]. Figure 2 illustrates the main large multi-wavelength and multi-messenger facilities expected to operate in synergy with THESEUS and Figure 3 shows the planned timeline.

5. Conclusions and Perspectives

THESEUS mission concept aims to fully exploit the transformative potential of GRBs for investigating the Early Universe and multi-messenger astrophysics, while simultaneously vastly expanding the discovery space of most high energy transient phenomena over the entirety of cosmic history and allowing tests of fundamental physics. THESEUS will achieve these ambitious goals through a step change in capabilities for the detection and characterisation of GRBs and other transients over a very broad energy band (0.3 keV to 10 MeV) and wide field of view, including on-board near-infrared imaging and spectroscopy, and is designed to be at the forefront of these science fields in the late 2030s.

THESEUS will also enable huge synergies with the premier future observatories (e.g., ELT, ATHENA, CTA, the next generation GW and neutrino telescopes), providing simultaneous wide sky monitoring, rapid follow-up and real-time alerts. A broad range of other science programmes will be enabled by THESEUS, including using observations of GRB emission as laboratories of ultra-relativistic matter and, e.g., for testing Lorentz invariance, as well as gathering statistics on large populations of other high energy sources and transients. Thus, THESEUS data will be of interest to a very wide user community, also through its open guest-observer programme.

The European leadership in these scientific and technological area builds on past success and ongoing investment: in addition to the involvement in pioneering satellite missions (BeppoSAX, HETE-2, XMM-Newton, INTEGRAL, Swift, SVOM), Europe has been at the heart of developments in multi-messenger astrophysics (e.g., Virgo, Einstein Telescope, KM3Net) and in electromagnetic follow-up via European-led consortia (e.g., ENGRAVE, VINROUGE, STARGATE). THESEUS is one of the three mission concepts that were selected by ESA in 2018 for a Phase A study as candidates for the M5 mission. The ESA Phase A study as candidate M5 mission, conducted from Fall 2018 to Spring 2021 led to detailed, workable and well qualified solutions for the spacecraft, its payload and operations. It has also demonstrated the technical and programmatic feasibility of accomplishing the core science goals with this mission concept. Based on these great achievements and heritage, the THESEUS project is being further developed for responding to new opportunities for medium-class missions. The later launch schedule with respect to M5 of these new opportunities will further improve the scientific return of THESEUS for multi-messenger astrophysics and time-domain astronomy, allowing for a great synergy with third generation GW detectors (expected to begin operations only in the second half of the 2030s) and improving the synergy with, e.g., the ATHENA and LISA space observatories (expected to be launched in the mid '30s), while maintaining the relevance of the other key science goals.

Author Contributions: Conceptualization, L.A.; writing–original draft preparation, G.S.; formal analysis, G.S., M.B., R.C.; supervision, N.T., E.B., D.G., P.O. and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by ASI and INAF through agreement n 2018-29-HH.0., by the UE H2020 programme through the AHEAD2020 project and by the national space agencies and institutions supporting the THESEUS Consortium.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors, on behalf of the entire THESEUS consortium, are grateful to the ESA appointed THESEUS Science Study Team, as well as the entire ESA Study Team, for all their work and support across the mission assessment phase (2018–2021). The authors acknowledge the anonymous referees for their useful comments.

Conflicts of Interest: The authors declare no conflict of interest.

Note

[1] from the THESEUS Assessment Study Report https://sci.esa.int/s/8Zb0RB8 (18 February 2021).

References

1. Klebesadel, R.W.; Strong, I.B.; Olson, R.A. Observations of Gamma-Ray Bursts of Cosmic Origin. *Astrophys. J.* **1973**, *182*, L85. [CrossRef]
2. Abbott, B.P.; Bloemen, S.; Canizares, P.; Falcke, H.; Fender, R.P.; Ghosh, S.; Groot, P.; Hinderer, T.; el Hör, J.R.; Jonker, P.G.; et al. Multi-messenger Observations of a Binary Neutron Star Merger*. *Astrophys. J. Lett.* **2017**, *848*, L12. [CrossRef]
3. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B.; et al. Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A. *Astrophys. J. Lett.* **2017**, *848*, L13. [CrossRef]
4. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B.; et al. A gravitational-wave standard siren measurement of the Hubble constant. *Nature* **2017**, *551*, 85–88. [CrossRef]
5. Burderi, L.; Sanna, A.; Di Salvo, T.; Riggio, A.; Iaria, R.; Gambino, A.F.; Manca, A.; Anitra, A.; Mazzola, S.M.; Marino, A. Quantum gravity with THESEUS. *Exp. Astron.* **2021**, *52*, 439–452. [CrossRef]
6. Collaboration, T.L.S.; Aasi, J.E.A. Advanced LIGO. *Class. Quantum Gravity* **2015**, *32*, 074001. [CrossRef]
7. Acernese, F.A.; Agathos, M.; Agatsuma, K.; Aisa, D.; Allemandou, N.; Allocca, A.; Amarni, J.; Astone, P.; Balestri, G.; Ballardin, G.; et al. Advanced Virgo: A second-generation interferometric gravitational wave detector. *Class. Quantum Gravity* **2015**, *32*, 024001. [CrossRef]
8. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Abernathy, M.R.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; et al. Observation of Gravitational Waves from a Binary Black Hole Merger. *Phys. Rev. Lett.* **2016**, *116*, 061102. [CrossRef]
9. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Abernathy, M.R.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; et al. Localization and Broadband Follow-up of the Gravitational-Wave Transient GW150914. *Astrophys. J. Lett.* **2016**, *826*, L13. [CrossRef]
10. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Abraham, S.; Acernese, F.; Ackley, K.; Adams, C.; Adhikari, R.X.; Adya, V.B.; Affeldt, C.; et al. GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs. *Phys. Rev. X* **2019**, *9*, 031040. [CrossRef]
11. Abbott, R.; Abbott, T.D.; Abraham, S.; Acernese, F.; Ackley, K.; Adams, A.; Adams, C.; Adhikari, R.X.; Adya, V.B.; Affeldt, C.; et al. GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo during the First Half of the Third Observing Run. *Phys. Rev. X* **2021**, *11*, 021053. [CrossRef]
12. Aartsen, M.G.; Ackermann, M.; Adams, J.; Aguilar, J.A.; Ahlers, M.; Ahrens, M.; Al Samarai, I.; Altmann, D.; Andeen, K.; Anderson, T.; et al. Extending the Search for Muon Neutrinos Coincident with Gamma-Ray Bursts in IceCube Data. *Astrophys. J.* **2017**, *843*, 112. [CrossRef]
13. Kimura, S.S. Neutrinos from Gamma-ray Bursts. *arXiv* **2022**, arXiv:2202.06480.
14. Goldstein, A.; Veres, P.; Burns, E.; Briggs, M.S.; Hamburg, R.; Kocevski, D.; Wilson-Hodge, C.A.; Preece, R.D.; Poolakkil, S.; Roberts, O.J.; et al. An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: Fermi -GBM Detection of GRB 170817A. *Astrophys. J. Lett.* **2017**, *848*, L14. [CrossRef]
15. Savchenko, V.; Ferrigno, C.; Kuulkers, E.; Bazzano, A.; Bozzo, E.; Brandt, S.; Chenevez, J.; Courvoisier, T.J.L.; Diehl, R.; Domingo, A.; et al. INTEGRAL Detection of the First Prompt Gamma-Ray Signal Coincident with the Gravitational-wave Event GW170817. *Astrophys. J. Lett.* **2017**, *848*, L15. [CrossRef]

16. LIGO Scientific Collaboration and Virgo Collaboration; Abbott, B.P.; Abbott,R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R. X.; et al. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.* **2017**, *119*, 161101. [CrossRef] [PubMed]
17. Berger, E. Short-Duration Gamma-Ray Bursts. *Annu. Rev. Astron. Astrophys.* **2014**, *52*, 43–105. [CrossRef]
18. Ghirlanda, G.; Salafia, O.S.; Paragi, Z.; Giroletti, M.; Yang, J.; Marcote, B.; Blanchard, J.; Agudo, I.; An, T.; Bernardini, M.G.; et al. Compact Radio Emission Indicates a Structured Jet Was Produced by a Binary Neutron Star Merger. *Science* **2019**, *363*, 968. [CrossRef]
19. Abbott, B.P.; Abbott,R.; Abbott, T.D.; Abraham, S.; Acernese, F.; Ackley, K.; Adams, C.; Adya, V.B.; Affeldt, C.; Agathos, M.; et al. Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA. *Living Rev. Relativ.* **2020**, *23*, 3. [CrossRef]
20. Bucciantini, N.; Arons, J.; Amato, E. Modelling spectral evolution of pulsar wind nebulae inside supernova remnants. *Mon. Not. R. Astron. Soc.* **2011**, *410*, 381–398. [CrossRef]
21. Dall'Osso, S.; Stella, L. Millisecond Magnetars. *arXiv* **2021**, arXiv:2103.10878.
22. Oganesyan, G.; Ascenzi, S.; Branchesi, M.; Salafia, O.S.; Dall'Osso, S.; Ghirlanda, G. Structured Jets and X-Ray Plateaus in Gamma-Ray Burst Phenomena. *Astrophys. J.* **2020**, *893*, 88. [CrossRef]
23. Beniamini, P.; Granot, J.; Gill, R. Afterglow Lightcurves from Misaligned Structured Jets. *Mon. Not. R. Astron. Soc.* **2020**, *493*, 3521–3534. [CrossRef]
24. Maggiore, M.; Van Den Broeck, C.; Bartolo, N.; Belgacem, E.; Bertacca, D.; Bizouard, M.A.; Branchesi, M.; Clesse, S.; Foffa, S.; García-Bellido, J.; et al. Science case for the Einstein telescope. *J. Cosmol. Astropart. Phys.* **2020**, *3*, 050. [CrossRef]
25. Amati, L.; O'Brien, P.T.; Götz, D.; Bozzo, E.; Santangelo, A.; Tanvir, N.; Frontera, F.; Mereghetti, S.; Osborne, J.P.; Blain, A.; et al. The THESEUS space mission: Science goals, requirements and mission concept. *Exp. Astron.* **2021**, *52*, 183–218. [CrossRef]
26. Rosati, P.; Basa, S.; Blain, A.W.; Bozzo, E.; Branchesi, M.; Christensen, L.; Ferrara, A.; Gomboc, A.; O'Brien, P.T.; Osborne, J.P.; et al. Synergies of THESEUS with the large facilities of the '30s and GO opportunities. *arXiv* **2021**, arXiv:2104.09535.
27. Mereghetti, S.; Balman, S.; Caballero-Garcia, M.; Del Santo, M.; Doroshenko, V.; Erkut, M.H.; Hanlon, L.; Hoeflich, P.; Markowitz, A.; Osborne, J.P.; et al. Time domain astronomy with the THESEUS satellite. *Exp. Astron.* **2021**, *52*, 309–406. [CrossRef]
28. Tanvir, N.R.; Le Floc'h, E.; Christensen, L.; Caruana, J.; Salvaterra, R.; Ghirlanda, G.; Ciardi, B.; Maio, U.; D'Odorico, V.; Piedipalumbo, E.; et al. Exploration of the high-redshift universe enabled by THESEUS. *Exp. Astron.* **2021**, *52*, 219–244. [CrossRef]
29. Stratta, G.; Ciolfi, R.; Amati, L.; Bozzo, E.; Ghirlanda, G.; Maiorano, E.; Nicastro, L.; Rossi, A.; Vinciguerra, S.; Frontera, F.; et al. THESEUS: A key space mission concept for Multi-Messenger Astrophysics. *Adv. Space Res.* **2018**, *62*, 662–682. [CrossRef]
30. Ciolfi, R.; Stratta, G.; Branchesi, M.; Gendre, B.; Grimm, S.; Harms, J.; Lamb, G.P.; Martin-Carrillo, A.; McCann, A.; Oganesyan, G.; et al. Multi-messenger astrophysics with THESEUS in the 2030s. *Exp. Astron.* **2021**, *52*, 245–275. [CrossRef]
31. O'Brien, P.; Hutchinson, I.; Lerman, H.N.; Feldman, C.H.; McHugh, M.; Lodge, A.; Willingale, R.; Beardmore, A.; Speight, R.; Drumm, P. The soft X-ray imager on THESEUS: The transient high energy survey and early universe surveyor. *arXiv* **2021**, arXiv:2102.08700.
32. Labanti, C.; Amati, L.; Frontera, F.; Mereghetti, S.; Gasent-Blesa, J.L.; Tenzer, C.; Orleanski, P.; Kuvvetli, I.; Campana, R.; Fuschino, F.; et al. The X/Gamma-ray Imaging Spectrometer (XGIS) on-board THESEUS: Design, main characteristics, and concept of operation. *arXiv* **2021**, arXiv:2102.08701.
33. Götz, D.; Basa, S.; Pinsard, F.; Martin, L.; Arhancet, A.; Bozzo, E.; Cara, C.; Escudero Sanz, I.; Frugier, P.A.; Floriot, J.; et al. The Infra-Red Telescope (IRT) on board the THESEUS mission. *arXiv* **2021**, arXiv:2102.08696.
34. Punturo, M.; Abernathy, M.; Acernese, F.; Allen, B.; Andersson, N.; Arun, K.; Barone, F.; Barr, B.; Barsuglia, M.; Beker, M.; et al. The Einstein Telescope: A third-generation gravitational wave observatory. *Class. Quantum Gravity* **2010**, *27*, 194002. [CrossRef]
35. Reitze, D.; Adhikari, R.X.; Ballmer, S.; Barish, B.; Barsotti, L.; Billingsley, G.; Brown, D.A.; Chen, Y.; Coyne, D.; Eisenstein, R.; et al. Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO. *Bulletin Am. Astron. Soc.* **2019**, *51*, 35.
36. Salafia, O.S.; Ghirlanda, G.; Ascenzi, S.; Ghisellini, G. On-axis view of GRB 170817A. *Astron. Astrophys.* **2019**, *628*, A18. [CrossRef]
37. Dall'Osso, S.; Stratta, G.; Guetta, D.; Covino, S.; De Cesare, G.; Stella, L. Gamma-ray bursts afterglows with energy injection from a spinning down neutron star. *Astron. Astrophys.* **2011**, *526*, A121. [CrossRef]
38. Piro, L.; Ahlers, M.; Coleiro, A.; Colpi, M.; de Oña Wilhelmi, E.; Guainazzi, M.; Jonker, P.G.; Mc Namara, P.; Nichols, D.A.; O'Brien, P.; et al. Multi-messenger-Athena Synergy White Paper. *arXiv* **2021**, arXiv:2110.15677.