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The THESEUS Workshop 2017

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Abstract. The Transient High-Energy Sky and Early Universe Surveyor (THESEUS) is a mission concept developed in the last years by a large International consortium. THESEUS aims at exploiting high-redshift Gamma–Ray Bursts for getting unique clues on the early Universe and, being an unprecedentedly powerful machine for the detection, accurate location and redshift determination of all types of GRBs (long, short, high-z, under-luminous, ultra–long) and many other classes of transient sources and phenomena, at providing a substantial contribution to multi–messenger astrophysics and time–domain astronomy. Under these respects, THESEUS will show a beautiful synergy with the large observing facilities of the future, like E–ELT, TMT, SKA, CTA, ATHENA, in the electromagnetic domain, as well as with next–generation gravitational–waves and neutrino detectors, thus enhancing importantly their scientific return. Moreover, it will also operate as a flexible IR and X–ray observatory, thus providing an even larger involvement of the scientific community. In order to further explore the magnificent prospective science of the mission, the THESEUS consortium organized a Workshop in Naples on October 5-6 2017. The programme included about 50 reviews and talks from worldwide recognized experts of the fields, further showing the strong impact that THESEUS observations would have on several fields of astrophysics, cosmology and fundamental physics.

Key words. Astronomical instrumentation, methods and techniques – Cosmology: early Universe – Cosmology: dark ages, re-ionization, first stars – Multi–messenger astrophysics – Time–domain astronomy – X–rays: transients – Gamma–rays: bursts – Infrared: general

1. Introduction

Developed by a large European collaboration, with contributions by scientists from worldwide, the THESEUS (Transient High-Energy Sky and Early Universe Surveyor) project aims at developing a medium–size (e.g., M-class in the ESA Cosmic Vision programme) space astrophysics mission capable of providing a fundamental contribution to our understanding of the early Universe and to multi–messenger and

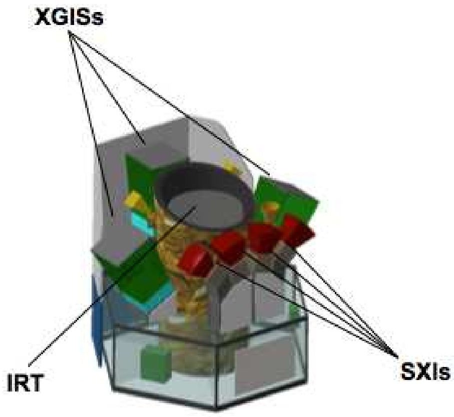

Fig. 1. THESEUS Satellite Baseline Configuration and Instrument suite accommodation (Amati et al. 2018)

time–domain astrophysics. THESEUS will operate in strong synergy with the next generation large electromagnetic-magnetic (e.g., E–ELT, TMT, ATHENA, CTA, SKA) and multi–messenger (i.e., advanced gravitational–waves and neutrino detectors) facilities, enhancing significantly their scientific return. It will also be an extremely flexible NIR and X–ray space observatory, granting the involvement of the broad astrophysical community and impacting many fields of research beyond the main scientific goals.

The THESEUS project exploits the unique European heritage and leadership in these research areas, as well as in key-enabling technologies like lobster–eye optics, broad band X and Gamma-ray monitors, space IR telescopes.

The science drivers, mission concept (instrumentation, spacecraft, mission profile) and expected performances of THESEUS are described in detail in the "white" papers Amati et al. (2018) and Stratta et al. (2018) and in several of the articles published as Proceedings of the THESEUS Workshop 2017. A non–exhaustive summary is provided in the text below, and in the corresponding Figures, as an introduction to these Proceedings volume.

1.1. Scientific objectives

The main goals of THESEUS can be summarized as follows:

a) Explore the Early Universe (cosmic dawn and re–ionization era) by unveiling a complete census of the Gamma-Ray Burst (GRB) population in the first billion years. Specifically to: perform unprecedented studies of the global star formation history of the Universe up to z$\sim$12 and possibly beyond; detect and study the primordial (pop III) star population (when did the first stars form and how did the earliest pop III and pop II stars influence their environments?); investigate the re-ionization epoch, the interstellar medium (ISM) and the intergalactic medium (IGM) up to z$\sim$10–12 (how did re-ionization proceed as a function of environment, and was radiation from massive stars its primary driver? How did cosmic chemical evolution proceed as a function of time and environment?); investigate the properties of the early galaxies and determine their star formation properties in the re-ionization era.
b) Perform an unprecedented deep monitoring of the X–ray transient Universe in order to: locate and identify the electromagnetic counterparts to sources of gravitational radiation and neutrinos, which may be routinely detected in the late '20s / early '30s by next generation facilities the further advanced LIGO and VIRGO, KAGRA, ILIGO, LISA, Einstein Telescope, LIGO-CE or Km3NET and IceCube-Gen2; provide real-time triggers, accurate ($\sim$1 arcmin within a few seconds; $\sim$1" within a few minutes) locations of (long/short) and possibly the redshift of GRBs and high-energy transients for follow-up with next-generation optical-NIR (E-ELT, TMT, JWST if still operating), radio (SKA), X-rays (ATHENA), TeV (CTA) telescopes; provide a fundamental step forward in the comprehension of the physics of various classes of Galactic and extra-Galactic transients (e.g.: tidal disruption events (TDE), magnetars /SGRs, SN shock break-outs, Soft X-ray Transients SFXTS, thermonu-

Table 1. Presentations given at the THESEUS Workshop 2017.

Presenter	Title
	Mission general description
L. Amati	THESEUS proposal for M5: overview
P. O' Brien	The Soft X-ray Imager (SXI)
R. Campana	The X/Gamma-Ray Imaging Spectrometer
D. Götz	The Infra-Red Telescope (IRT)
F. Frontera	Mission profile and observing strategy
C. Tenzer	The On-Board Data Handling system
T. Rodic	X-band satellite transmitter and mobile ground station solution
M. Briggs	Prospective USA contributions
E. Bozzo	Ground segment
	Exploring the Early Universe with GRBs
N. Tanvir	Overview
A. Ferrara	First galaxies, GRBs and cosmic re–ionization
S. Vergani	GRBs as tracers of SFR and metallicity evolution
S. Colafrancesco	Investigating cosmic re-ionization with GRBs: synergy with SKA
E- Maiorano	Synergy with ELT
L. Piro	ATHENA and the transient Universe
L. Izzo	THESEUS and the GRB-cosmology
E. Piedipalumbo	High redshift constraints on dark energy cosmology from the Ep,i - Eiso correlation
	Multi-messenger astrophysics
G. Stratta	Overview
P. D'Avanzo	The short GRBs - GW connection
R. Ciolfi	X-ray emission from GW sources
S. Piranomonte	IR emission from GW sources
A. Grado	VST optical follow-up of the first two gravitational waves events
S. Mereghetti	INTEGRAL results on GW signals
A. Drago	Short GRBs and quark deconfinement
	Observatory science
J. Osborne	Time-domain astronomy: overview
R. Willingale	Fast transients
P. Giommi	Active Galactic Nuclei
P. Casella	low mass X-ray binaries
L. Nava	GRB science: prompt X-gamma
A. Rossi	GRB science: multiwavelength emission and host galaxies
S. Capizziello	Investigating DE cosmologies by GRBs
M. G. Bernardini	Synergy with CTA
S. Covino	THESEUS as a flexible IR observatory
B. Cordier	The SVOM mission
E. Bozzo	The eXTP mission
A. Papitto	The HERMES project
M. van Putten	GPU-accelerated broadband analysis of high-frequency GRB light curves
R. Ruffini	Specific examples of separatrix between the collapsar and the BdHN models of GRBs
R. Basak	Spectral, timing and polarization study of GRB prompt emission
M. Hafizi	On the PDS of GRB light curves (Boci / Hafizi)
J. Rueda	Binary-driven hypernovae as multimesseger astrophysical systems (Rueda)
B. Zhang	A Tale from GRB 160625B and Beyond
Y. Wang	Early X-ray Flares in GRBs
H. Ito	Numerical Simulations of Photospheric Emission from Collapsar Jets
D. de Martino	Accretion and outflows in accreting white dwarf binaries
P. Chardonnet	Multidimensional simulations of pair-instability supernovae
M. G. Dainotti	X-ray plateaus and fundamental plane in GRBs: perspectives with THESEUS
	Poster contributions
L. M. Becerra	On the induced gravitational collapse scenario
G. Pizzichini	Search for properties of long Gamma Ray Bursts at high redshift
D. Fargion	Could GRBs be associated with nearby NS NS merging events?

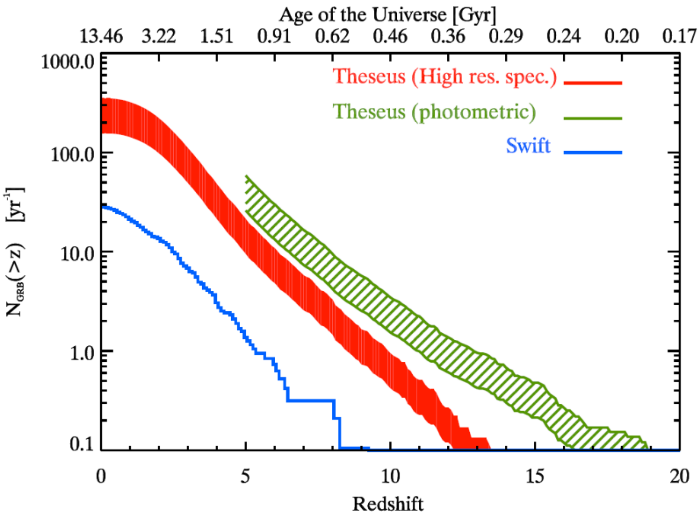

Fig. 2. The yearly cumulative distribution of GRBs with redshift determination as a function of the redshift for Swift and THESEUS (Amati et al. 2018). The THESEUS expected improvement in the detection and identification of GRBs at very high redshift w/r to present situation is impressive (more than 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 ealry Unverse science (star formation rate evolution, re–ionization, pop III stars, metallicity evolution of first galaxies, etc.).

clear bursts from accreting neutron stars, Novae, dwarf novae, stellar flares, AGNs and Blazars); provide unprecedented insights into the physics and progenitors of GRBs and their connection with peculiar core-collapse SNe and substantially increase the detection rate and characterization of sub-energetic GRBs and X-Ray Flashes; fill the present gap in the discovery space of new classes of high-energy transient events, thus providing unexpected phenomena and discoveries.

By satisfying the requirements coming from the above main science drivers, the THESEUS payload will also automatically enable excellent observatory science opportunities, including, e.g., performing IR observatory science, especially providing capability for response to external triggers, thus allowing strong community involvement. We remark that THESEUS has survey capabilities for high-energy transient phenomena complementary to the Large Synoptic Survey Telescope (LSST) in the optical. Their joint availability at the end of the next decade would enable a remarkable scientific synergy between them.

1.2. Instruments and mission profile

The exceptional scientific performances described above can be obtained through a smart and unique combination of instruments and mission profile. It is fundamental the inclusion in the payload of a monitor based on the lobster-eye telescope technology, capable of focusing soft X-rays in the 0.3–6 keV energy band over a large FOV. Such instrumentation can perform all-sky monitoring in the soft X-rays with an unprecedented combination of FOV (~1 sr), source location accuracy (0.5–1') and sensitivity, thus addressing both main science goals of the mission. An on-board infrared telescope of the 0.5–1m class is also needed, together with spacecraft fast slewing capability (e.g., 5-10°/min), in order to provide prompt identification of the optical/IR counterpart of GRBs and other transients, the refinement of their position down to ~arcsec precision (thus enabling follow-up with the largest

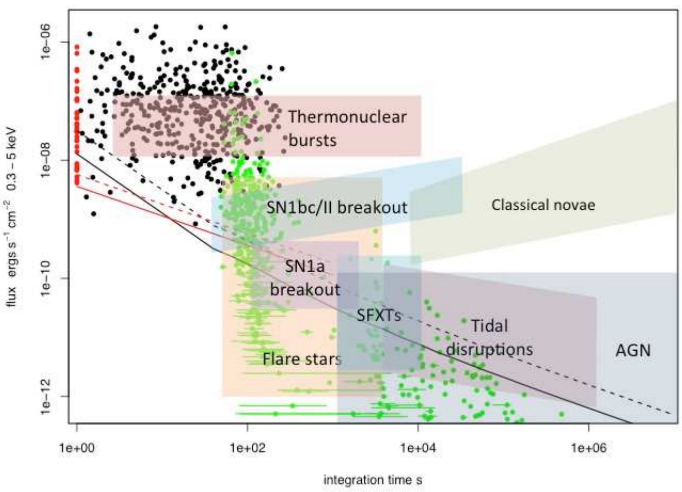

Fig. 3. Sensitivity of the SXI (black curves) and XGIS (red) vs. integration time (Amati et al. 2018). The solid curves assume a source column density of 5×10^{20} cm^{-2} (i.e., well out of the Galactic plane and very little intrinsic absorption). The dotted curves assume a source column density of 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). 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.

ground and space observatories), the on-board redshift determination and spectroscopy of the counterpart and of the host galaxy. The telescope, combined with the spacecraft Swift–like agility, can also be used for multiple observatory and survey science goals. Finally, the inclusion in the payload of a broad field of view hard X-ray imaging detection system covering twice the monitoring FOV of the lobster-eye telescopes at lower energies and up to $\sim 2\pi$ at higher energies, extending the energy band from few keV up to several MeV and with source location accuracy of a few arcmin will increase significantly the capabilities of the mission. As the lobster-eye telescopes can be triggered by several classes of transient phenomena (e.g., flare stars, X-ray bursts, etc), the hard X-ray detection system provides an efficient supplementary means to identify true high–z and soft GRBs and to detect and localize other transient sources (e.g., short GRBs, fundamental for multi–messenger astrophysics). The joint data from the three instruments will characterize transients in terms of luminosity, spectra and timing properties over a broad energy band, thus getting fundamental insights into their physics.

In summary, the foreseen payload of THESEUS includes the following instrumentation:

- *Soft X-ray Imager* (SXI, 0.3 –6 keV): a set of 4 lobster-eye telescopes units, covering a total FOV of ~1sr with source location accuracy 0.5–1' and sensitivity of $\sim 2\times 10^{-90}$ cgs in 10s and $\sim 7\times 10^{-11}$ cgs in 1000s (5σ);

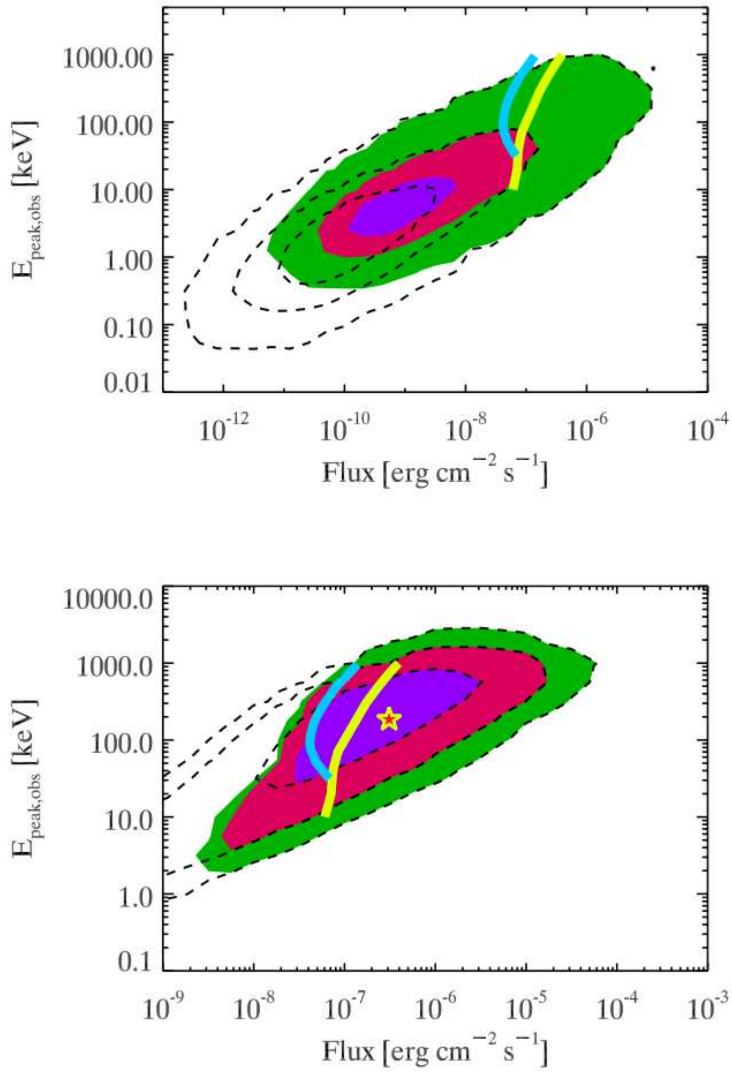

Fig. 4. Density contours (dashed lines) corresponding to 1, 2, 3 σ levels of the synthetic population of Long (top) and Short (bottom) GRBs (from Stratta et al. 2018 and references therein). Shaded coloured regions show the density contours of the population detectable by THESEUS. The yellow and cyan lines show the trigger threshold of Fermi/GBM and GCRO/Batse. The flux is integrated over the 10-1000 keV energy range. *As can be seen, THESEUS will carry on–board 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.* The star symbol in the right panel shows the short GRB170817A associated with the NS-NS gravitational–wave event GW170817. As can be seen, THESEUS will be capable of detecting and localizing substantially weaker and softer events with respect to, e.g., the Fermi/GBM, thus granting the detection of short GRBs associated to NS–NS or NS–BH mergin events up to a much larger horizon.

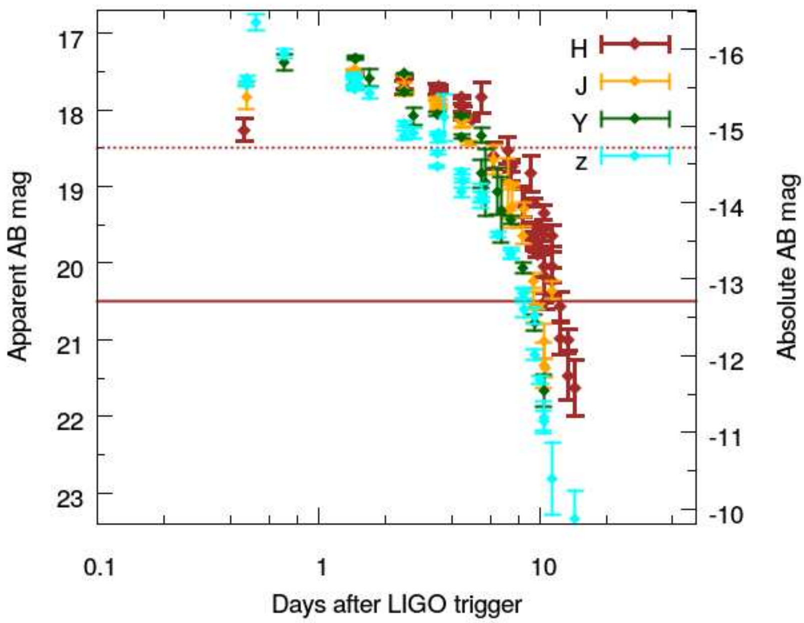

Fig. 5. Light curve of the kilonova associated to the gravitational wave/short GRB event GW170817/GRB170817A in the IRT filters (Stratta et al. 2018, and references therein). The continuous and dashed red lines indicate the THESEUS/IRT limiting H magnitudes for imaging and prism spectroscopy, respectively, with 300s of exposure (see Amati et al. 2018).

- *X-Gamma rays Imaging Spectrometer* (XGIS, 2 keV – 20 MeV): a set of coded-mask cameras using monolithic X-gamma rays detectors based on bars of Silicon diodes coupled with CsI crystal scintillator, granting a ~2sr FOV, a source location accuracy of ~5 arcmin and a sensitivity of ~250 mCrab (5σ, 1s) in 2-30 keV and a $\sim 2\pi$ FOV and ~1000 cm^2 effective area from ~100 keV up to several MeVs.
- *InfraRed Telescope* (IRT, 0.7–1.8 μ): a 0.7m class IR telescope with 10×10' FOV, for fast response, with both imaging (limiting magnitude H~20.6 in 300s) and spectroscopy (limiting magnitude H~18.5 in 300s and 17.5 in 1800s for R=30 and 500, respectively) capabilities.

The mission profile includes: an on-board data handling units (DHUs) system capable of detecting, identifying and localizing likely transients in the SXI and XGIS FOV; the capability of promptly (within a few tens of seconds at most) transmitting to ground the trigger time and position of GRBs (and other transients of interest); and a spacecraft slewing capability of ~10-20°/min). The baseline launcher / orbit configuration is a launch with Vega-C to a low inclination low Earth orbit (LEO, ~600 km, <5°), 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.

2. The Workshop

The THESEUS Workshop 2017 was held at the Osservatorio Astronomico di Capodimonte (INAF) in Naples on October 5–6, 2017. The overall organization was chaired by L. Amati (lead proposer of the THESEUS proposal for

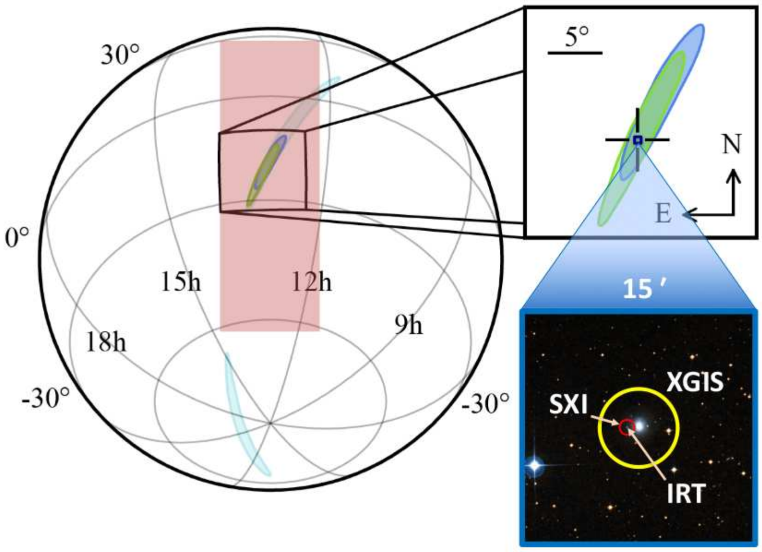

Fig. 6. The plot (Stratta et al. 2018 and references there in) shows the THESEUS/SXI field of view (~ 110×30 deg^2, pink rectangle) superimposed on the probability skymap of GW 170817 obtained with the two Advanced LIGO only (cyan) and with the addition of Advanced Virgo (green). THESEUS not only will cover a large fraction of the skymap (even those obtained with only two GW-detectors, e.g. cyan area), but will also localize 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 $z > 0.3$ and a GRB-localising satellite will be essential to discover EM counterparts.

ESA/M5), E. Bozzo, P. O'Brien, D. Götz and C. Tenzer (coordinators of the THESEUS project) and M. Della Valle (Director of the Osservatorio di Capodimonte). As can be seen in Fig.9, showing the nice poster of the conference, the Scientific Organizing Committee (SOC) included several experts of different fields of astrophysics and cosmology, many of them being part of the THESEUS collaboration. The aim of the Workshop was to collect the several astrophysical communities involved and interested in the scientific goals, and related technology, of THESEUS, in order to review the status of the project and further discuss and refine the expected scientific return for the several fields of cosmology and astrophysics on which this mission will have an important impact. Since the submission of the proposal in response to the ESA call for next M5 mission within the Cosmic Vision programme, the mission concept evolved significantly, thanks to the continuously growing interest in the project by astrophysicists, cosmologists and fundamental physics experts. The workshop was the occasion for consolidating the work done, to further expand the THESEUS community and to make the case for the mission even deeper and up to date.

The scientific programme (see Tab.1) included several review talks on the general mis-

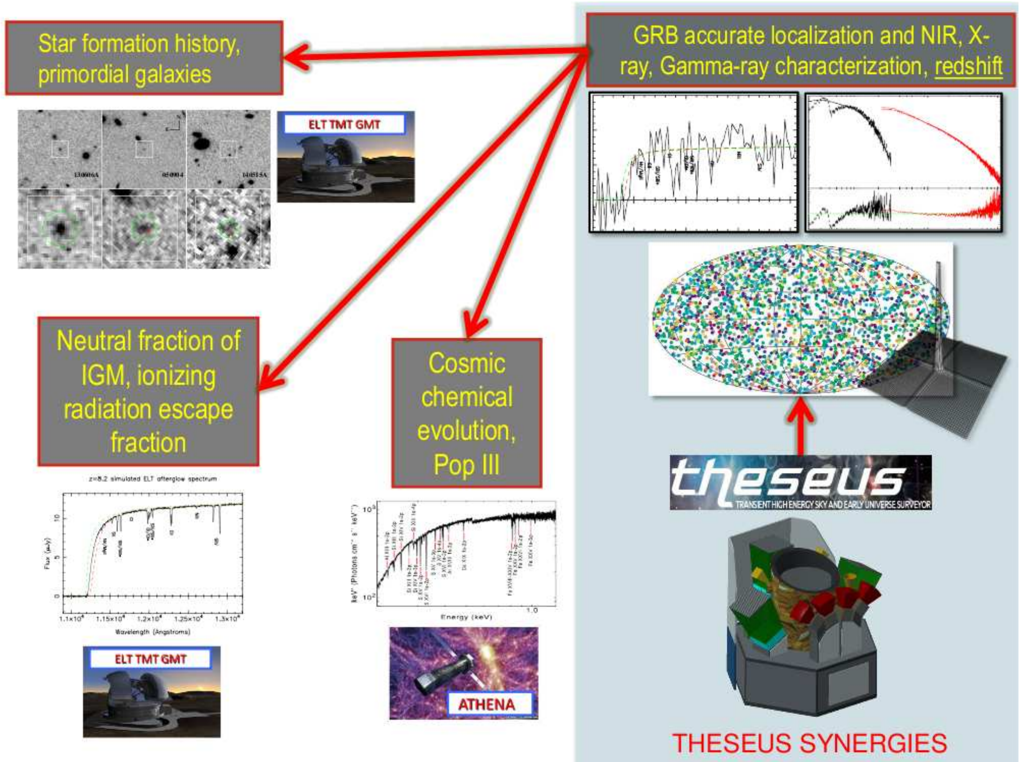

Fig. 7. Expected impact of THESEUS of early Universe science, also in synergy with large observing facilities of the near future like, e.g., E–ELT, TMT, ATHENA (see Amati et al. 2018 and Stratta et al. 2018 for credits and references of the figures composing this sketch). THESEUS (will provide a substantial step forward in the detection, accurate localization and redshift measurements of high–z GRBs (~20–40 at *z*¿8 and ~75–150 at *z*¿6 in 4 years of operations) and use its own measurements for getting unique clues to the first population of stars (pop III) and galaxies, the sources and evolution of the re–ionization process, SFR history and galaxy metallicity evolution up to the end of the dark ages and their interplay. However, for very high-¡ GRBs (e.g., $z > 8$), follow–up observations (deep spectroscopy of the afterglow, imaging and spectroscopy of the host galaxy) by very large and extremely large telescopes, will provide an important contribution in fully exploiting THESEUS measurements for early Universe science. Remarkable will be also the synergy with the future large X–ray observatory ATHENA. Indeed, THESEUS, by providing real time triggers, accurate location and redshift of GRBs over the whole cosmic history and up *z*¿10–12, will enable ATHENA to achieve some of its main goals: high-resolution X–ray spectroscopy of bright GRBs afterglow to probe the Warm Hot Intergalactic Medium (the WHIM) and hence get flues to the missing baryons problem; probe the first generation of stars through the study of the circum–burst environment. Many of the other transients found by THESEUS, such as tidal disruption events and flaring binaries will also be high-value targets for Athena

sion concept, the instruments and the mission profile by key–persons of the consortium, as well as many talks, presented by THESEUS contributing scientists and several experts from outside the collaboration, focusing and expanding on different aspects of the main science objectives, the prospective observatory science and related current or future space and ground projects. A significant fraction of these contributions have been converted into the nice, interesting and useful articles presented in this Proceedings volume.

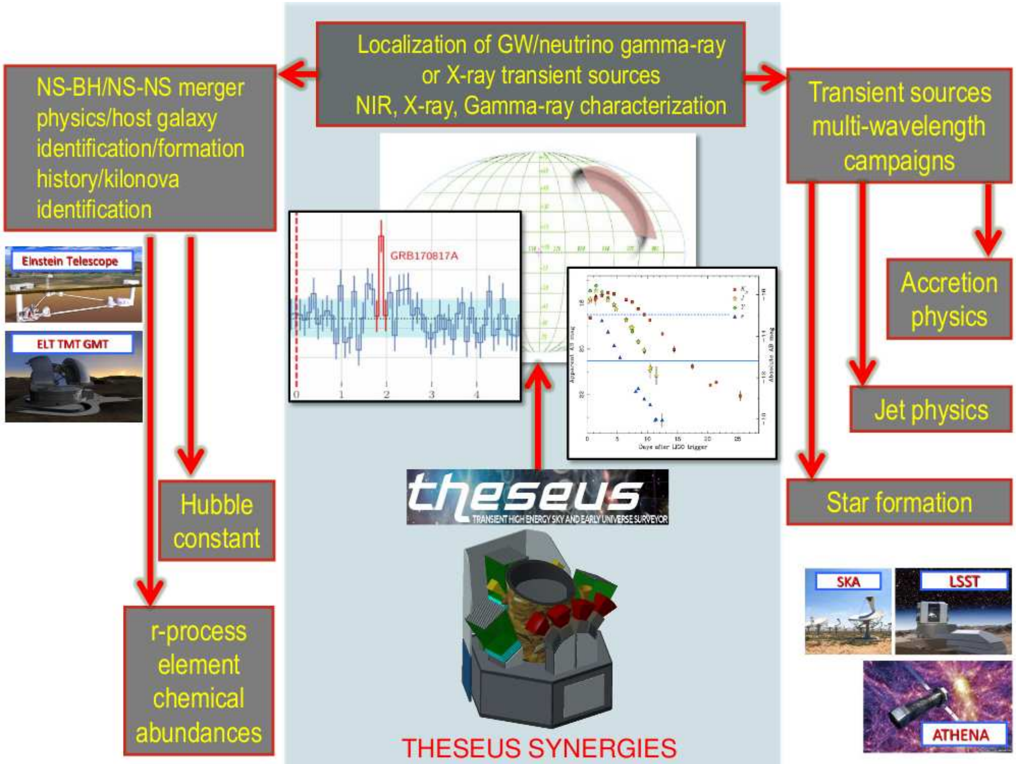

Fig. 8. Expected impact of THESEUS on multi–messenger and time domain astronomy (see Amati et al. 2018 and Stratta et al. 2018 for credits and references of the figures composing this sketch). THESEUS will have the unique capability of monitoring the X/soft gamma-ray sky with a FOV as large as the current "only-LIGO" error regions for GW events (such large regions may be expected also in the future for the farthest events that may be detected only by the most sensitive GW detector) with source location accuracy down to 0.5' and unprecedented sensitivity. Moreover, its payload will be perfectly suited to detect, accurately locate (down to 1") and measure the redshift of all classes of GRBs, including short GRBs, the most relevant for multi–messenger astrophysics. Thus, for NS-NS and NS-BH events like GW170817, THESEUS will have the possibility of detecting and localizing to a few arcmin the associated short GRB, of providing detection, 1 arcsec localization and redshift of the associated NIR kilonova emission and even of detecting the possible soft X–ray emission associated to the merger predicted by several models. More in general, THESEUS will be an unprecedentedly powerful transients machine, thus providing a unique synergy and complementarity with the large multi–wavelength observatories of the future (e.g., E-ELT, TMT, SKA, CTA, ATHENA) and a substantial contribution to time–domain astronomy.

Several of these works further expand and update the information of the mission concept and the expected scientific performances of the THESEUS mission, thus providing a complement to the main review of the THESEUS mission study reported in Amati et al. (2018) and Stratta et al. (2018).

The effort and enthusiasm of the contributors to this volume is an added value to the continuous work and support by the members of the collaboration in making the THESEUS project more and more mature, popular and recognized within the worldwide astrophysics and cosmology communities. We take this oc-

Fig. 9. Poster of the THESEUS Workshop 2017, showing the composition of the SOC and the LOC, as well as the main topics addressed during the Workshop.

casion to thank once more all the participants and contributors to this successful workshop and to acknowledge the kind financial and logistic support by INAF.

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