The Transient High-Energy Sky and Early Universe Surveyor (THESEUS)

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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 European consortium and currently under study by ESA as one of the three candidates for next M5 mission (launch in 2032). As detailed in Amati et al. 2017 [1] and Stratta et al. 2017 [2], THESEUS aims at exploiting high-redshift GRBs for getting unique clues to the early Universe and, being an unprecedentedly powerful machine for the detection, accurate location (from ~arcmin to ~arcsec) 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 time-domain astrophysics. 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.

Keywords: THESEUS, Gamma-Ray Bursts, Early Universe, Gravitational Waves, Multi-Messenger Astrophysics

1. Introduction

The main feature of the modern astrophysics is the rapid development of multi-messenger astronomy. At the same time, relevant open issues still affect our understanding of the cosmological epoch (a few millions years after the “big-bang”) at which first stars and galaxies start illuminating the Universe and re-ionizing the inter-galactic medium.

In this context, a substantial contribution is expected from the Transient High Energy Sky and Early Universe Surveyor (THESEUS), a space mission concept developed by a large European consortium including Italy, UK, France, Germany, Switzerland, Spain, Poland, Denmark, Czech Republic, Ireland, Hungary, Slovenia, ESA, with Lorenzo Amati (INAF, Italy) as a lead proposer. In May 2018 THESEUS was selected by ESA for a Phase 0/A study as one of the three candidates for theM5 mission within the Cosmic Vision program. End of Phase A and down-selection to one mission is expected for mid-2021, mission adoption for 2024 and launch in 2032. Details on the THESEUS science objectives, mission concept and expected performances are reported in Amati et al. 2018 [1], Stratta et al. 2018 [2] and on the THESEUS consortium website [3]. The Proceedings of the THESEUS Workshop 2017, held at INAF – Osservatorio di Capodimonte in Naples, Italy, are also available on the internet [4].

The program of the workshop covered such topics as THESEUS mission design and science objectives, probing the Early Universe with GRBs, multi-messenger and time domain astrophysics, the transient high energy sky, synergy with the next generation large facilities

(E-ELT, SKA, CTA, ATHENA, GW and neutrino detectors).

2. THESEUS scientific objectives

THESEUS is designed to vastly increase the discovery space of high energy transient phenomena over the entirety of cosmic history, whose modern concept is presented in Fig1.

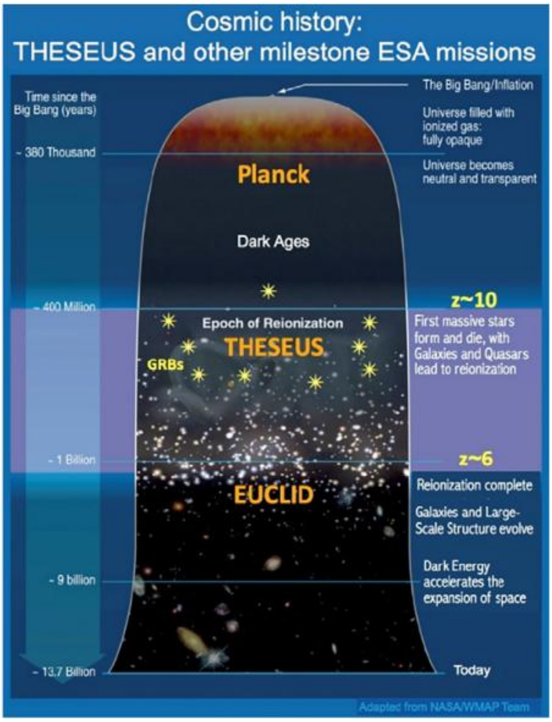

Fig1. *Gamma-Ray Bursts in the cosmological context and the role of THESEUS (adapted from a picture by the NASA /WMAP Science team).*

Because of their huge luminosities, mostly emitted in the X and gamma-rays, their redshift distribution extending at least to z ~9 and their association with explosive death of massive stars and star forming regions, GRBs are unique and powerful tools for investigating the early Universe: SFR evolution, physics of re-ionization, galaxies metallicity evolution and luminosity function, first generation (pop III) stars.

A statistical sample of high–z GRBs can provide fundamental information [1]:

- measure independently the cosmic star–formation rate, even beyond the limits of current and future galaxy surveys;
- directly (or indirectly) detect the first population of stars (pop III);
- the number density and properties of low-mass galaxies (Even JWST and ELTs surveys will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>8-10));
- the neutral hydrogen fraction;
- the escape fraction of UV photons from high-z galaxies;

- the early metallicity of the ISM and IGM and its evolution (Abundances, HI, dust, dynamics etc. even for very faint hosts. E.g. GRB 050730: faint host (R>28.5), but z=3.97, [Fe/H]=-2 and low dust, from afterglow spectrum (Chen et al. 2005; Starling et al. 2005).)

On the other side, a mission capable of substantially increase the rate of identification and characterization of high-z GRBs will also provide a survey of the high-energy sky for sof X-rays to gamma-rays with an unprecedented combination of wide Field Of View (FOV), source location accuracy and sensitivity below 10 keV. This features will give THESEUS the possibility of providing a substantial contribution also to time-domain astrophysics, in general, and in particular to the newly born and rapidly growing field of multi-messenger astrophysics. For instance, THESEUS will be able to provide detection, accurate location, characterization and possibly redshift measurement of electromagnetic emission (short GRBs, possible soft X-ray transient emission, kilonova emission in the near-infrared) from gravitational-wave sources like NS-NS or NS-BH mergers [2].

Indeed, THESEUS will be an unprecedentedly powerful machine for the detection, accurate location (from ~arcmin to ~arcsec) 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 time-domain astrophysics.

THESEUS's capabilities in exploring the multi-messenger transient sky can be summarized as follow:

- 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 like aLIGO/aVirgo, eLISA, ET, or Km3NET;
- Provide real-time triggers and accurate (~1 arcmin within a few seconds; ~1'' within a few minutes) high- energy transients for follow-up with next-generation optical-NIR (E-ELT, JWST if still operating), radio (SKA), X-rays (ATHENA), TeV (CTA) telescopes; synergy with LSST;
- Provide a fundamental step forward in the comprehension of the physics of various classes of transients and fill the present gap in the discovery space of new classes of transients events.

LIGO, Virgo and partners make first detection of gravitational waves and light from colliding neutron stars.

THESEUS capabilities in these directions are:

- short GRB detection over large FOV with arcmin localization;
- Kilonova detection, arcsec localization and characterization;
- Possible detection of weaker isotropic X-ray emission.

4. THESEUS mission concept

THESEUS will be capable to achieve the exceptional scientific objectives summarized above thanks to a smart combination of instrumentation and mission profile. The mission will carry on-board two large FOV monitors covering simultaneously a 1sr FOV in the soft X-rays (0.3 – 5 keV) with unprecedented sensitivity and arcmin location accuracy) and several sr FOV form 2 keV up to 20 MeV, with additional source location capabilities of a few arcmin from 2 to 30 keV. Once a GRB or a transient of intereste is detected by one or both the monitors, the

TEHSEUS spacecraft will quickly slew to pint, within a few minutes, an on-board near infra-red telescope (70 cm class operating from 0.7 to 1.8 micron) to the direction of the transient, so to catch the fading NIR afterglow or, e.g., kilonova emission, localizing it a 1 arcsec accuracy and measuring its redshift through photometry and moderate resoluton spectroscopy.

The detailed description of THESEUS can be found in [1], [2] and [3]. The total view is presented in Fig2.

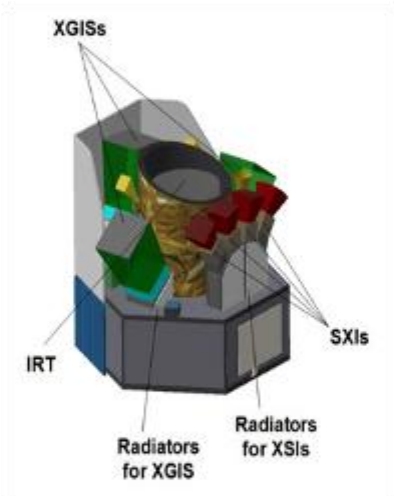

***Fig2**. THESEUS Satellite Baseline Configuration and Instrument suite accommodation*

The main components are described below.

4.1. The Soft X-ray Imager (SXI) is led by UK

Soft X-ray Imager (SXI): a set of four sensitive lobster-eye telescopes observing in 0.3 - 5 keV band, total FOV of ~1sr with source location accuracy 0.5-1’. The appearance of the device can be seen in Fig3.

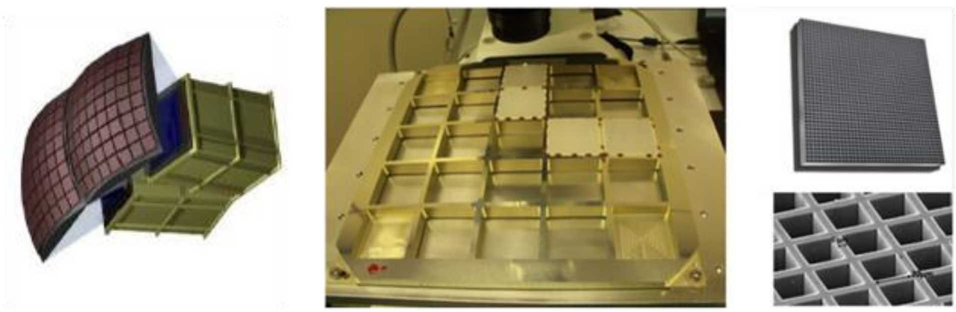

***Fig3.** Left: the SXI optical elements. Middle: The SVOM MXT lobster eye optic aperture frame. Top right: A schematic of a single square pore MCP. Bottom right: A micrograph of a square pore MCP showing the pore structure. This plate has a pore size d = 20 µm and a wall thickness w = 6 µm.*

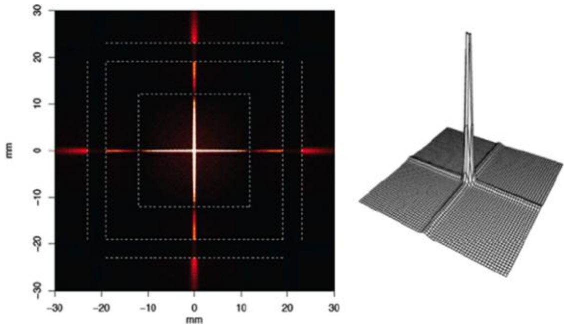

Fig4. *The point spread function of the SXI.*

4.2. The X-Gamma-rays imaging spectrometer (XGIS) – led by IT

X-Gamma rays Imaging Spectrometer (XGIS,): 3 coded-mask X-gamma ray cameras using bars of Silicon diodes coupled with CsI crystal scintillators observing in 2 keV – 10 MeV band, a FOV of ~2-4 sr, overlapping the SXI, with ~5' source location accuracy.

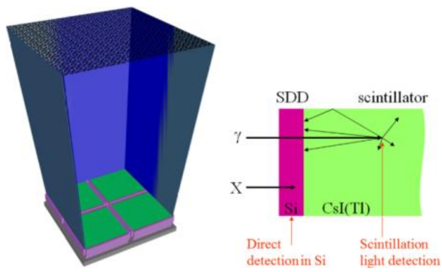

Fig5. *Left: Sketch of the XGIS Unit. Right: Principle of operation of the XGIS detection units: low-energy X-rays interact in Silicon, higher energy photons interact in the scintillator, providing an energy range covering three orders of magnitude. A pulse shape discriminator determines if the interaction has occurred in Si or in the crystal.*

3.3. The InfraRed Telescope (IRT) – led by FR

The InfraRed Telescope (IRT): a 0.7m class IR telescope observing in the 0.7 – 1.8 μm band, providing a 10′×10′ FOV, with both imaging and moderate resolution spectroscopy capabilities (→ redshift).

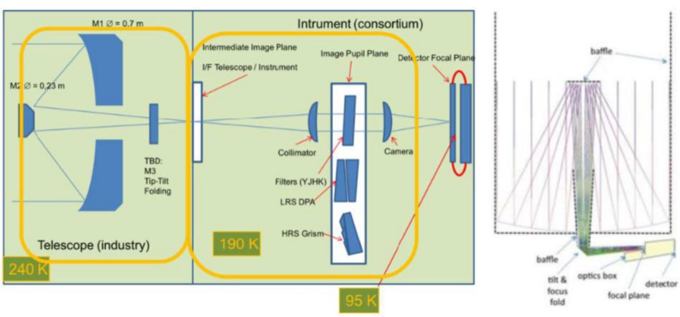

Fig6. *The IRT Telescope block diagram concept.*

The THESEUS total field of view is shown in Fig7.

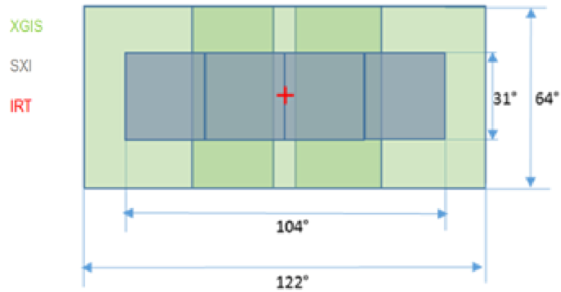

Fig7. *Field of view of all instruments*

4. The main capabilities of THESEUS

THESEUS will have the ideal combination of instrumentation and mission profile for detecting all types of GRBs (long, short/hard, weak/soft, high-redshift), localizing them from a few arcmin down to arsec and measure the redshift for a large fraction of them (Fig. 8).

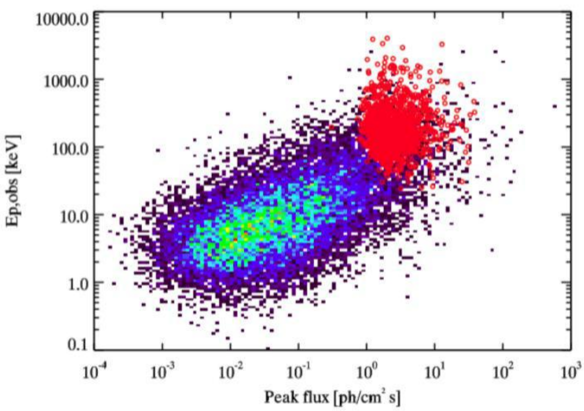

Fig8. *GRB distribution in the peak flux – spectral peak energy (Ep) plane according to most recent population synthesis models and measurements (see [1] and references therein). For all the shown GRBs TEHSEUS will be able to provide detection, accurate location, characterization and measurement of redshift. The low-Ep – low peak flux region is populated by high-redshift GRBs (shown in dark blue, blue, light blue, green, yellow), a population inaccessible by current facilities, while the high Ep region highlighted with red points shows the region where most short GRBs will lay.*

In addition the GRB prompt emission, THESEUS will also detect and localize down to 0.5-1 arcmin the soft X-ray short/long GRB afterglows, of NS-NS (BH) mergers and of many classes of galactic and extra-galactic transients. For several of these sources, THESEUS/IRT will provide detection and study of associated NIR emission, location within 1 arcsec and redshift.

The impact of these measurements for shedding light on the early Universe with GRBs is represented in Fig. 9, where we show the expected number per year of GRBs detected, localized and with redshift measurement from THESEUS compared to the present situation achieved with the main efforts of the Swift, Konus-WIND, Fermi/GBM satellites and several on-ground robotic and large telescopes.

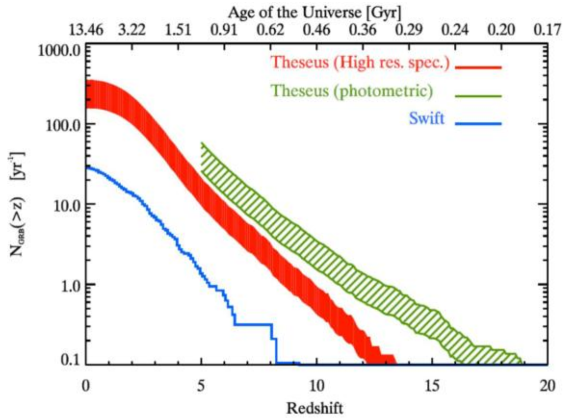

Fig9. *The yearly cumulative distribution of GRBs with redshift determination as a function of the redshift for Swift and THESEUS. We note that these predictions are conservative in so far as they reproduce the current GRB rate as a function of redshift. However, with our sensitivity, we can detect a GRB of E_{iso}~ 10^{53} erg (corresponding to the median of the GRB radiated energy distribution) up to z = 12. Indeed, our poor knowledge of the GRB rate-SFR connection does not preclude the existence of a sizable number of GRBs at such high redshifts, in keeping with recent models of Pop III stars.*

5. GW/multi-messenger and time-domain astrophysics.

As discussed in previous sections, GW transient sources that will be monitored in the e.m. domain by THESEUS include:

- NS-NS / NS-BH mergers:
    - collimated EM emission from short GRBs and their afterglows (rate of ≤ 1/yr for 2G GW detectors but up to 20/yr for 3G GW detectors as Einstein Telescope);
    - Optical/NIR and soft X-ray isotropic emissions from macronovae, off-axis afterglows and, for NS-NS, from newly born ms magnetar spindown (rate of GW detectable NS-NS or NS-BH systems, i.e. dozens-hundreds/yr).
- Core collapse of massive stars: Long GRBs, LLGRBs, ccSNe (much more uncertain predictions in GW energy output, possible rate of ~1/yr) ;
- Flares from isolated NSs: Soft Gamma Repeaters (although GW energy content is ~0.01%-1% of EM counterpart)

In particular, THESEUS will be able to detect, localize, characterize and measure the redshift for NS-NS / NS-BH mergers through the following channels:

- collimated on-axis and off-axis prompt gamma-ray emission from short GRBs;
- Optical/NIR and soft X-ray isotropic emissions from kilonovae, off-axis afterglows and, for NS-NS, from newly born ms magnetar spindown.

Thus, THESEUS will beautifully complement the capabilities of next generation GW detectors (e.g., Einstein Telescope, Cosmic Explorer, further advanced LIGO and Virgo, KAGRA, etc.) by promptly and accurately localizing e.m. counterparts to GW signals form NS-NS and NS-BH mergers and measuring their redshift. These combined measurements will provide unique clues on the nature of the progenitors, on the extreme physics of the emission and, by exploiting simultaneous redshift (from e.m. counterpart) and luminosity distance (form GW signal modeling) of tens of sources, fully exploit multimessenger astrophysics for cosmology.

6. Time-domain astronomy and GRB physics

The unique capabilities of THESEUS, will also allow to provide relevant contributions to the more general field of time-domain astronomy and, of course, to GRB science. As a few examples, THESEUS will provide the astrophysical community with:

- survey capabilities of transient phenomena similar to the Large Synoptic Survey Telescope (LSST) in the optical: a remarkable scientific synergy can be anticipated;
- substantially increased detection rate and characterization of sub-energetic GRBs and X-Ray Flashes;
- unprecedented insights in the physics and progenitors of GRBs and their connection with peculiar core-collapse SNe.

7. Conclusions

THESEUS, under study by ESA and a large European collaboration with strong interest by international partners (e.g., US) will fully exploit GRBs as powerful and unique tools to investigate the early Universe and will provide us with unprecedented clues to GRB physics and sub-classes. This mission will also play a fundamental role for GW/multi-messenger and time domain astrophysics at the end of next decade, also by providing a flexible follow-up observatory for fast transient events with multi-wavelength ToO capabilities and guest-observer programs. THESEUS observations will thus impact on several fields of astrophysics, cosmology and even fundamental physics and will enhance importantly the scientific return of next generation multi messenger (aLIGO/aVirgo, LISA, ET, or Km3NET;) and e.m. facilities (e.g., LSST, E-ELT, SKA, CTA, ATHENA)

In addition, THESEUS scientific return will include significant Observatory Science, e.g.: study of thousands of faint to bright X-ray sources by exploiting the unique simultaneous availability of broad band X-ray and NIR observations; providing a flexible follow-up observatory for fast transient events with multi-wavelength ToO capabilities and guest-observer programs.

We would like to remark that THESEUS is also a unique occasion for fully exploiting the European leadership in time-domain and multi-messenger astrophysics and in key-enabling technologies (lobster-eye telescopes, SDD by INAF, INFN, FBK, Un.).

In conclusion, THESEUS will be a really unique and superbly capable facility, one that will do amazing science on its own, but also will add huge value to the currently planned new photon and multi-messenger astrophysics infrastructures in the 2020s to > 2030s.

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