THESEUS Conference 2021
Welcome!

23-26 March 2021

Welcome address by L. Amati and S. Paltani
Organized by THESEUS Consortium and the THESEUS Science Study Team (TSST) nominated by ESA

Celebrating the ESA/M5 Phase A study of the mission together with the worldwide scientific community

Formerly to be held in Malaga (Spain), turned to virtual conference due to COVID-19 related limitations

Great participation: more than 460 registrants!

A beautiful scientific programme including almost 80 presentations by THESEUS key persons (ESA, consortium and community) and worldwide top-level scientists in related fields
The THESEUS Conference 2021

- **Follows** successful THESEUS Workshop 2017 (Naples) and THESEUS scientific meetings in 2019 (Bologna) and 2020 (virtual)

- **Hosted by University of Geneva** (Switzerland, one of the main partners of THESEUS Consortium)

- **SOC:** L. Amati (INAF-OAS Bologna, IT; CHAIR); D. Gotz (CEA Saclay, FR; co-chair); P. O'Brien (Univ. Leicester, UK; co-chair); S. Basa (LAM Marseille, FR); M. D. Caballero-Garcia (IAA-CSIC, Spain); A. J. Castro-Tirado (IAA Granada, ES); L. Christensen (Univ. Copenhagen, Denmark); M. Guainazzi (ESA/ESTEC); L. Hanlon (UCD, IE); S. Paltani (Univ. Geneva, CH); V. Reglero (Univ. Valencia, ES); A. Santangelo (Univ. Tubingen, DE); G. Stratta (INAF-OAS Bologna, IT); N. Tanvir (Univ. Leicester, UK).

- **Special thanks to E. Bozzo and C. Ferrigno** for great efforts
ESA/M5 Phase A Study and selection process: mission selection review (MSR) and Science Assessment Review (SAR) currently on-going; selection of final M5 candidate (THESEUS or EnVision) expected in early June 2021.

Thank you so much to the many excellent scientists and technologists of the Consortium for their great efforts put in THESEUS Phase A study, as well as to the THESEUS ESA Study Team and the Coordination Office for continuous nice and efficient interactions and support.

Wish you a nice conference, look forward meeting you at next THESEUS Conference (hopefully in Malaga!). And... let’s keep fingers crossed!!!
The THESEUS Mission Concept

L. Amati (INAF) on behalf of the THESEUS Consortium

THESEUS CONFERENCE 2021, VIRTUAL - 23-26 March 2021
THESEUS
Transient High Energy Sky and
Early Universe Surveyor

Lead Proposer (ESA/M5): Lorenzo Amati (INAF – OAS Bologna, Italy)

Coordinators (ESA/M5): Lorenzo Amati, Paul O’Brien (Univ. Leicester, UK), Diego Gotz (CEA-Paris, France), A. Santangelo (Univ. Tuebingen, D), E. Bozzo (Univ. Genève, CH)

Payload consortium: Italy, UK, France, Germany, Switzerland, Spain, Poland, Denmark, Belgium, Czech Republic, Slovenia, Ireland, NL, ESA
Probing the Early Universe with GRBs
Multi-messenger and time domain Astrophysics
The transient high energy sky
Synergy with next generation large facilities (E-ELT, SKA, CTA, ATHENA, GW and neutrino detectors)

First Stars and Reionization Era

- 360 Thousand
- 400 Million
- 1 Billion
- 9 billion
- 13.7 Billion

The Big Bang/Inflation
Universe filled with ionized gas: fully opaque
Universe becomes neutral and transparent

Epoch of Reionization
Galaxies and Quasars begin to form - starting reionization.

GRBs

Reionization complete - 10% opacity
Galaxies evolve
Dark Energy begins to accelerate the expansion of space
Our Solar System forms

Today: Astronomers look back and understand

Gravitational-wave time-frequency map

Curve from Fermi/GBM (50 – 300 keV)
May 2018: THESEUS selected by ESA for Phase 0/A study (with SPICA and ENVISION)

<table>
<thead>
<tr>
<th>Activity</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 0 kick-off</td>
<td>June 2018</td>
</tr>
<tr>
<td>Phase 0 completed (EnVision, SPICA and THESEUS)</td>
<td>End 2018</td>
</tr>
<tr>
<td>ITT for Phase A industrial studies</td>
<td>February 2019</td>
</tr>
<tr>
<td>Phase A industrial kick-off</td>
<td>June 2019</td>
</tr>
<tr>
<td>Mission Selection Review (technical and programmatic review for the three mission candidates)</td>
<td>Completed by June 2021</td>
</tr>
<tr>
<td>SPC selection of M5 mission</td>
<td>June 2021</td>
</tr>
<tr>
<td>Phase B1 kick-off for the selected M5 mission</td>
<td>December 2021</td>
</tr>
<tr>
<td>Mission Adoption Review (for the selected M5 mission)</td>
<td>March 2024</td>
</tr>
<tr>
<td>SPC adoption of M5 mission</td>
<td>June 2024</td>
</tr>
<tr>
<td>Phase B2/C/D kick-off</td>
<td>Q1 2025</td>
</tr>
<tr>
<td>Launch</td>
<td>2032</td>
</tr>
</tbody>
</table>
Shedding light on the early Universe with GRB

- **Long GRBs**: huge luminosities, mostly emitted in the X and gamma-rays

- **Redshift distribution** extending at least to $z \sim 9$ and association with exploding massive stars

- **Powerful tools for cosmology**: SFR evolution, physics of re-ionization, high-z low luminosity galaxies, pop III stars
A statistical sample of high–z GRBs can provide fundamental information:

• 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)
• Detecting and studying primordial invisible galaxies

Even JWST and ELTs surveys will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>6-8)
Even JWST and ELTs surveys will not be able to probe the faint end of the galaxy Luminosity Function at high redshifts (z > 6 - 8).

- Detecting and studying primordial invisible galaxies
- Neutral hydrogen fraction
- Escape fraction of UV photons from high-z galaxies
- Early metallicity of the ISM and IGM and its evolution
• Detecting and studying primordial invisible galaxies

- Even JWST and ELTs surveys will be unable to probe the faint end of the galaxy Luminosity Function at high redshifts (z > 6–8)
  - z = 6.29; $M_{AB} > 28.86$
  - z = 5.11; $M_{AB} > 28.13$
  - z = 5.47; $M_{AB} > 28.57$
  - z = 6.73; $M_{AB} > 27.92$
  - z = 8.23; $M_{AB} > 30.29$
  - z = 9.4; $M_{AB} > 28.49$

- Tanvir+12

- Robertson & Ellis 12

- Detecting and studying primordial invisible galaxies
Exploring the multi-messenger transient sky

THESEUS ensures:

- Immediate coverage of gravitational wave and neutrino source error boxes
- Real time sky localizations
- Temporal & spectral characterization from NIR to gamma-rays
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

Lightcurve from Fermi/GBM (50 – 300 keV)

Gravitational-wave time-frequency map
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

Lightcurve from Fermi/GBM (50 – 300 keV)

THESEUS:

- Short GRB detection over large FOV with arcmin localization

- Kilonova detection, arcsec localization and characterization

- Possible detection of weaker isotropic X-ray emission
THESEUS mission concept

- **Soft X-ray Imager (SXI):** a set of two sensitive lobster-eye telescopes observing in 0.3 - 5 keV band, total FOV of ~0.5sr with source location accuracy <2’;
- **X-Gamma rays Imaging Spectrometer (XGIS,):** 2 coded-mask X-gamma ray cameras using Silicon drift detectors coupled with CsI crystal scintillator bars observing in 2 keV – 10 MeV band, a FOV of >2 sr, overlapping the SXI, with <15’ GRB location accuracy in 2-150 keV
- **InfraRed Telescope (IRT):** a 0.7m class IR telescope observing in the 0.7 – 1.8 μm band, providing a 15’x15’ FOV, with both imaging and moderate resolution spectroscopy capabilities (-> redshift)

- Low Earth Orbit (< 5°, ~600 km)
- Autonomously rapid slewing bus
- 4-years nominal
The Soft X-ray Imager (SXI)

<table>
<thead>
<tr>
<th>Energy band (keV)</th>
<th>0.3-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optics configuration</td>
<td>8x8 square pore MPOs</td>
</tr>
<tr>
<td>MPO size (mm²)</td>
<td>40x40</td>
</tr>
<tr>
<td>Focal length (mm)</td>
<td>300</td>
</tr>
<tr>
<td>Focal plane detectors</td>
<td>CMOS array</td>
</tr>
<tr>
<td>CMOS size (mm²)</td>
<td>80x40</td>
</tr>
<tr>
<td>CMOS pixel size (µm)</td>
<td>40</td>
</tr>
<tr>
<td>CMOS pixel number</td>
<td>2000x1000</td>
</tr>
<tr>
<td>Number of CMOS</td>
<td>8</td>
</tr>
<tr>
<td>Module field of view (sr)</td>
<td>0.25</td>
</tr>
<tr>
<td>Centroiding accuracy (best, worst) (arcsec)</td>
<td>(&lt;30, 180)</td>
</tr>
</tbody>
</table>
The X-Gamma-ray imaging spectrometer

Targets: long (hi-z) and short (black-hole mergers/GW counterparts) GRBs

<table>
<thead>
<tr>
<th>Energy band</th>
<th>2 keV – 20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td># detection plane modules</td>
<td>100</td>
</tr>
<tr>
<td># of detector pixel /module</td>
<td>8x8</td>
</tr>
<tr>
<td>Pixel size (= mask element size)</td>
<td>4.5x4.5 mm²</td>
</tr>
<tr>
<td>Low-energy detector (2-30 keV)</td>
<td>Silicon Drift Detector 450 μm thick</td>
</tr>
<tr>
<td>High energy detector (&gt; 30 keV)</td>
<td>CsI(Tl) (3 cm thick)</td>
</tr>
<tr>
<td>Discrimination Si/CsI(Tl) detection</td>
<td>Pulse shape analysis</td>
</tr>
<tr>
<td>Dimension [cm]</td>
<td>49x49x74</td>
</tr>
<tr>
<td>Power [W]</td>
<td>123.0</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>72.0</td>
</tr>
</tbody>
</table>

**XGIS**

<table>
<thead>
<tr>
<th>XGIS</th>
<th>Lead: INAF Bologna, IT</th>
<th>2x units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Budgets (total)</td>
<td>158 kg</td>
<td>211 W</td>
</tr>
<tr>
<td>Dimensions/ unit (mm)</td>
<td>740 (h) x 600x600 (@ mask) 490x490 (@ detector)</td>
<td></td>
</tr>
<tr>
<td>Energy ranges</td>
<td>2-30 keV</td>
<td>30 – 150 keV</td>
</tr>
<tr>
<td>Detector technologies</td>
<td>Silicon drift detectors (SDD)</td>
<td>CsI(Tl) scintillating crystal + SDD</td>
</tr>
<tr>
<td>Imaging capability</td>
<td>&lt;15’ loc. accuracy FoV 2 sr</td>
<td>None, 4 sr</td>
</tr>
<tr>
<td>Energy resolutions</td>
<td>20% @ 6keV</td>
<td>6% @ 600 KeV</td>
</tr>
</tbody>
</table>
**The InfraRed Telescope (IRT)**

<table>
<thead>
<tr>
<th>IRT characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photometric wavelength range</td>
<td>0.7-1.8 μm</td>
</tr>
<tr>
<td>Spectroscopic wavelength range</td>
<td>0.8-1.6 μm</td>
</tr>
<tr>
<td>Photometric field of view</td>
<td>15 x 15 arcmin (goal: 17’ x 20’)</td>
</tr>
<tr>
<td>Pixel size/scale</td>
<td>18 μm / 0.6 arcsec</td>
</tr>
</tbody>
</table>
| Required Photometric sensitivity (AB, in150 s, SNR=5) for each implemented filter | I: 20.9 (goal: 21.3)  
Z: 20.7 (goal 21.2)  
Y: 20.4 (goal: 20.8)  
J: 20.7 (goal: 21.1)  
H: 20.8 (goal: 21.1) |
| Expected photo-z accuracy                                    | < 10%                                      |
| Astrometric accuracy                                         | < 5 arcsec in near-real time               |
|                                                               | < 1 arcsec after ground processing         |
| Spectroscopic field of view                                  | 2 x 2 arcmin                               |
| Resolving Power at 1.1 μm                                    | > 400                                      |
| Required Spectroscopic sensitivity (AB, II filter, 1800 s, SNR=3 for each spectral bin) | 17.5 (goal: 19)                           |
Possible spacecraft design (ESA/M5 Phase A)

Figure 5-4 - Schematic view of the spacecraft design for the Phase A ADS (left) and TAS (right) Studies.

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>THESEUS (dry mass)</td>
<td>1583</td>
<td>100%</td>
</tr>
<tr>
<td>System margin (20%)</td>
<td>316.7</td>
<td></td>
</tr>
<tr>
<td>Satellite (dry mass incl. system margin)</td>
<td>1900</td>
<td></td>
</tr>
<tr>
<td>Propellant (incl. 2% residuals)</td>
<td>290.0</td>
<td></td>
</tr>
<tr>
<td>Satellite (wet mass)</td>
<td>2190</td>
<td></td>
</tr>
</tbody>
</table>
THESEUS mission operation concept

Survey Mode
XGIS+SXI (IRT GO)

Burst Mode
XGIS+SXI (IRT not operating)

IRT Follow-up Mode (12.5 minutes)
(IRT imaging; XGIS+SXI Survey Mode)

Candidate GRB

Characterization Mode (1h)
(IRT imaging + spectroscopy; XGIS+SXI Survey Mode)

Candidate GRB

Deep Imaging Mode (1h)
(IRT deep imaging; XGIS+SXI Survey Mode)

Combined THESEUS instruments FoVs

Equatorial declination of GRBs achieved at z>6 (deg)

Right ascension
THESEUS will have the ideal combination of instrumentation and mission profile for detecting all types of GRBs (long, short/hard, weak/soft, high-redshift), providing accurate location and redshift for a large fraction of them.

![Graph showing the distribution of GRBs with Fermi/GBM and GRB170817A/GW170817 markers.](image-url)
Shedding light on the early Universe with GRBs
Exploring the multi-messenger transient sky

- **THESEUS** will detect and localize down to 0.5-1 arcmin the soft X-ray short/long GRB afterglows, of NS-NS mergers and of many classes of galactic and extra-galactic transients.

- For several of these sources, **THESEUS/IRT** may provide detection and study of associated NIR emission, location within 1 arcsec and redshift.
Promptly and accurately localizing e.m. counterparts to GW events with THESEUS

110° × 30°

1 arcsec!
THESEUS measurements + sinergy with large e.m. facilities -> substantial improvement of redshift estimate for e.m. counterparts of GW sources -> cosmology

Estimating $H_0$ with GW170817A (LVC 2017)

Investigating dark energy with a statistical sample of GW + e.m. (Sathyaprakash et al. 2019)
GRB prompt emission physics through unprecedented SXI+XGIS energy band (0.3 keV – 20 meV)

GRB spectrum measured simultaneously over 5 orders of magnitudes in energy!!!
THESEUS Synergies

- Spectro-imaging of GRB afterglows and hosts
- ISM metallicity and physics
- IGM along the line of sight

**ELTs**
- Archival ID of transients’ hosts
- Real-time detection of HE transients

**Rubin Obs/LSST**

**Athena**
- Warm-Hot Intergalactic Medium
- Circum-burst medium physics

**GW 3G detectors**
- Electro-magnetic counterparts of GW events

**THESEUS**
- Cosmic $\nu$’s from flaring AGN, GRBs, transient galactic sources

**SKA**
- Reionization epoch via 21 cm forest
- IGM around primordial minihosts

**CTA**
- VHE emission from GRBs
- HE transient trigger and detection

**$\nu$-detectors**
Cosmic chemical evolution, Pop III
Neutral fraction of IGM, ionizing radiation escape fraction
GRB accurate localization and NIR, X-ray, Gamma-ray characterization, redshift
Star formation history, primordial galaxies

THESEUS SYNERGIES
• **THESEUS Core Science** is based on two pillars:
  o probe the **physical properties of the early Universe**, by discovering and exploiting the population of high redshift GRBs.
  o provide an **unprecedented deep monitoring** of the soft X-ray transient Universe, providing a fundamental contribution to multi-messenger and time domain astrophysics in the early 2030s (synergy with aLIGO/aVirgo, eLISA, ET, Km3NET and EM facilities e.g., LSST, E-ELT, SKA, CTA, ATHENA).

• **THESEUS Observatory Science** includes:
  o study of thousands of faint to bright X-ray sources by exploiting the **unique simultaneous availability of broad band X-ray and NIR observations**
  o provide a **flexible follow-up observatory** for fast transient events with multi-wavelength ToO capabilities and **guest-observer programmes**.
In summary

- THESEUS, submitted to ESA/M5 by a large European collaboration 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.

- THESEUS 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 programmes.

- THESEUS is a unique occasion for fully exploiting the European leadership in time-domain and multi-messenger astrophysics and in related key-enabling technologies.

- THESEUS observations will impact on several fields of astrophysics, cosmology and 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).

- Phase A will be concluded in Spring 2021; final selection on June.


http://www.isdc.unige.ch/theseus/
Back-up slides
Theseus in multi-messenger astrophysics context
Theseus data policy

- All other data taken during the nominal mission will be public as soon as they are processed. The consortium will release regular XGIS and SXI survey products, and near real-time on-line data products will be available for monitoring many known transients and for alerting the community to new transients found in survey data processing.

- All mission data are reserved to the instrument teams until and including the Early Orbit Phase (LEOP); data rights are extended to scientists in the whole THESEUS Consortium during the Performance Verification Phase.

- GRB data at \( z > 6 \) will be reserved for the THESEUS Consortium for a period of 6 months during any mission phase; alerts will in any case be diffused to the community, for most efficient follow-up observations.

- GO program data will be subjected to a proprietary period of 6 months for the proposer and will become public afterwards.
Figure 6-2: Overview of the THESEUS ground segment organization and data flow.
THESEUS product tree and responsibilities
THESEUS product tree and responsibilities
<table>
<thead>
<tr>
<th>Country</th>
<th>Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Italy</td>
<td>THESEUS consortium lead, XGIS instrument PI, TBU PI, Consortium Project Office, XGIS instrument design, detection plane procurements and assembly, electronics, integration, testing, simulations, and calibrations, Malindi ground station provision (ASI in-kind), XGIS instrument operation centre lead, Contribution to the SDC</td>
</tr>
<tr>
<td>France</td>
<td>THESEUS consortium co-lead, IRT instrument PI &amp; IRT science lead, IRT instrument design, detection plane assembly, electronics, integration, testing, simulations, calibrations, filter wheel grism, IRT Telescope optical requirements, IRT instrument operation centre lead, Contribution to the SDC, Theseus Burst Alert Ground Segment (CNES VHF Network of ground receivers and the Burst Alert Centre)</td>
</tr>
<tr>
<td>Germany</td>
<td>THESEUS consortium co-lead, SXI and IRT DHU design, electronics, integration, testing, and software development, Overviewing of the XGIS DHU development, Contribution to the consortium project office, SDC contribution</td>
</tr>
<tr>
<td>Denmark</td>
<td>XGIS DHU design, electronics, integration, testing, and software development</td>
</tr>
<tr>
<td>Belgium</td>
<td>Contribution to the SXI instrument integration, characterization, and tests</td>
</tr>
<tr>
<td>Slovenia</td>
<td>Investigation of possible mobile round station additional antennas (for telemetry downlink), Contribution to the SDC</td>
</tr>
<tr>
<td>Netherlands</td>
<td>Contribution to the SDC</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>THESEUS consortium co-lead, SXI instrument PI, SXI instrument design, detection plane characterization, optics assembly, electronics, integration, testing, simulations, and calibrations, SXI instrument operation centre lead, Contribution to the SDC</td>
</tr>
<tr>
<td>Switzerland</td>
<td>THESEUS consortium co-lead, SDC PI, Contribution to the consortium project office, SDC engineering, software development, data processing, quick-look, data scientific validation, sky monitoring, community alert broadcasting, IRT filter wheel mechanism and optical elements (filters)</td>
</tr>
<tr>
<td>Spain</td>
<td>XGIS coded mask and collimator, Contribution to SXI focal plane assembly and mechanical structure</td>
</tr>
<tr>
<td>Poland</td>
<td>XGIS power supply units</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>Contribution to the SXI instrument mechanical structures and thermal mechanical control</td>
</tr>
<tr>
<td>Ireland</td>
<td>Contribution to the SDC</td>
</tr>
</tbody>
</table>