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AGENCIA
ESTATAL DE
INVESTIGACIÓN



INSTITUTO DE
ASTROFÍSICA DE
ANDALUCÍA

The ESA's M7 THESEUS mission and its Spanish contribution



*M. D. Caballero-Garcia (IAA-CSIC; Spanish coordinator),
on behalf of a larger collaboration*

LISA Spain Meeting 2024 - Barcelona, 15-16 October 2024

THESEUS satellite: Summary



1. *Current status.*
2. *Science.*
3. *Technology.*
4. *Programatic.*
5. *Spanish contribution (Phase A+B1).*
 - 5.1. *Organization.*
 - 5.2. *Payload.*
 - 5.3. *Objectives/Tasks.*

THESEUS satellite: Overview



Current status

Space Missions



8 NOV 2023

**BREAKING NEWS: SELECTED AMONG 3
MISSIONS FOR PHASE A STUDY FOR THE M7
MISSION OPPORTUNITY**

IP: Lorenzo Amati, University of Bologna

Spanish contribution: UV, INTA, IAA

Contact person in Spain: M. Caballero-Garcia (IAA-CSIC)



SWG1: Exploring the early Universe with GRBs

SWG2: Multi-Messenger Astrophysics

SWG3: Time-domain Astronomy

THESEUS Science Working Groups Coordinators



0. Science coordination group		
Surname and Name	Country	Institute
Amati Lorenzo	Italy	INAF-OAS Bologna
O'Brien Paul	United Kingdom	University of Leicester
Gotz Diego	France	CEA
Santangelo Andrea	Germany	IAAT Tuebingen
Bozzo Enrico	Switzerland	University of Geneva

1. Exploring the Early Universe with GRBs		
Surname and Name	Country	Institute
Tanvir Nial	United Kingdom	University of Leicester
Christensen Lise	Denmark	University of Copenhagen
Emeric Le Floch	France	CEA
Ferrara Andrea	Italy	Scuola Normale Superiore di Pisa

2. Multi-messenger Astrophysics		
Surname and Name	Country	Institute
Stratta Giulia	Italy	INAF-OAS Bologna
Ciolfi Riccardo	Italy	INAF-OA Padova
Paltani Stephane	Switzerland	University of Geneva
Rezzolla Luciano	Germany	ITP Frankfurt

3. Time-domain Astronomy		
Surname and Name	Country	Institute
Hanlon Lorraine	Ireland	University College Dublin
Caballero-Garcia Maria	Spain	CSIC-IAA
Mereghetti Sandro	Italy	INAF-IASF Milano
Osborne Julian	United Kingdom	University of Leicester

4. Populations & GRB science		
Surname and Name	Country	Institute
Ghirlanda Giancarlo	Italy	INAF-OA Brera

M5 + M7



theseus

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

News

[THESEUS 2021 conference](#)
[2020 Nobel prize in Physics](#)

THESEUS Mission

[Mission Overview](#)
[Mission Payload and Profile](#)
[Science with THESEUS](#)
[Scientific Requirements](#)
[THESEUS White Paper 2017](#)
[Multi-Messenger Astrophysics with THESEUS](#)
[2017 Workshop Proceedings](#)

name

Amati Lorenzo	+
O'Brien Paul	+
Götz Diego	+
Stratta Giulia	+
Hanlon Lorraine	+
Santangelo Andrea	+
Basa Stephane	+
Paltani Stephane	+
Tanvir Nial	+
Guainazzi Matteo	+
Caballero-Garcia Maria Dolores	+
Christensen Lise	+

M5 call
(obsolete)

Representing
Spain

Caballero-Garcia Maria Dolores

THESEUS ESA mission

List of publications & projects

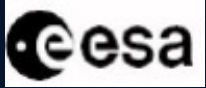


- “*The THESEUS space mission: science goals, requirements and mission concept*”, Amati, L, et al., 2021, ExA, 52, 183
- “*Time domain astronomy with the THESEUS satellite*”, Mereghetti, S., et al., 2021, ExA, 52, 309
- “*The XGIS imaging system onboard the THESEUS mission*”, Mereghetti, S., et al., 2020, SPIE, 11444E, 8
- “*The X/Gamma-ray Imaging Spectrometer (XGIS) for THESEUS and other mission opportunities*”, Amati, L, et al., 2022, SPIE, 12181E, 26
- *THESEUS ASSESSMENT STUDY REPORT (YELLOW BOOK)*. Publication date: 18 February 2021; Pages: 1-105; Year: 2021; Copyright: ESA; Reference: ESA/SCI(2021)2
- Name of the project: Principal Investigator (PI) of the 2yr (INTRAMURAL-CSIC) project entitled “*Misión THESEUS de ESA: desarrollo del proyecto*”. Total amount: 100 kEUR.
- Name of the project: Principal Investigator (PI) of the 3yr PID2023 Coordinated project “*CONTRIBUCION ESPAÑOLA A LA MISION THESEUS DE ESA (M7)*”. Total amount: 274 kEUR.

THESEUS satellite: Overview



Science



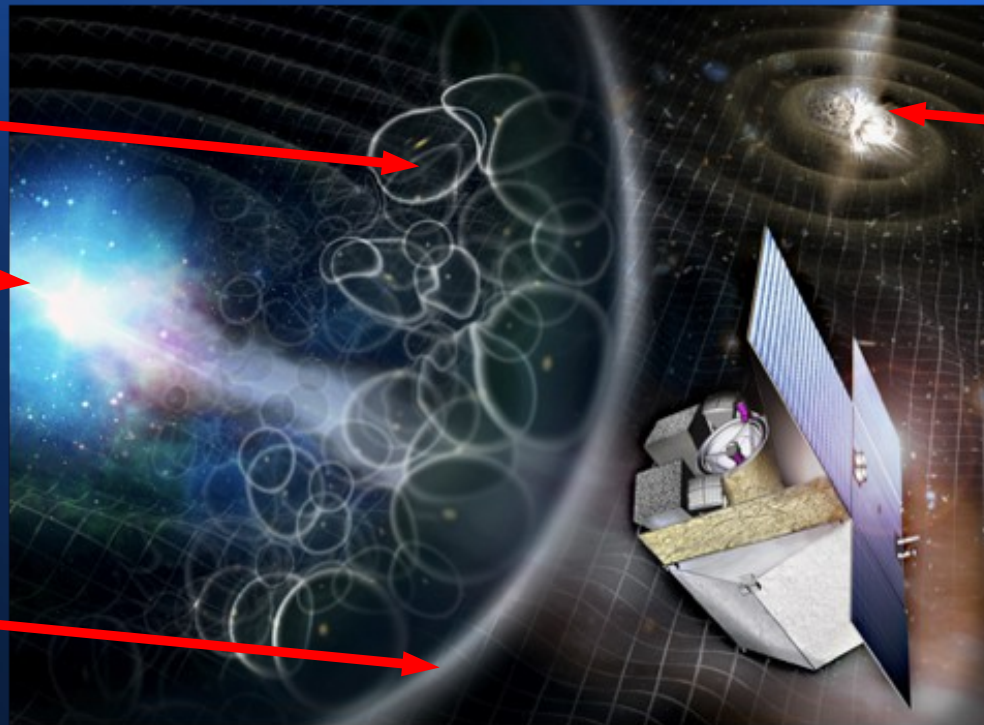
THESEUS

Transient High-Energy Sky and Early Universe Surveyor

First structures of the Universe

Pop III stars

Epoch of Reionization ($z > 6$)



Gravitational Wave (GW) Counterparts

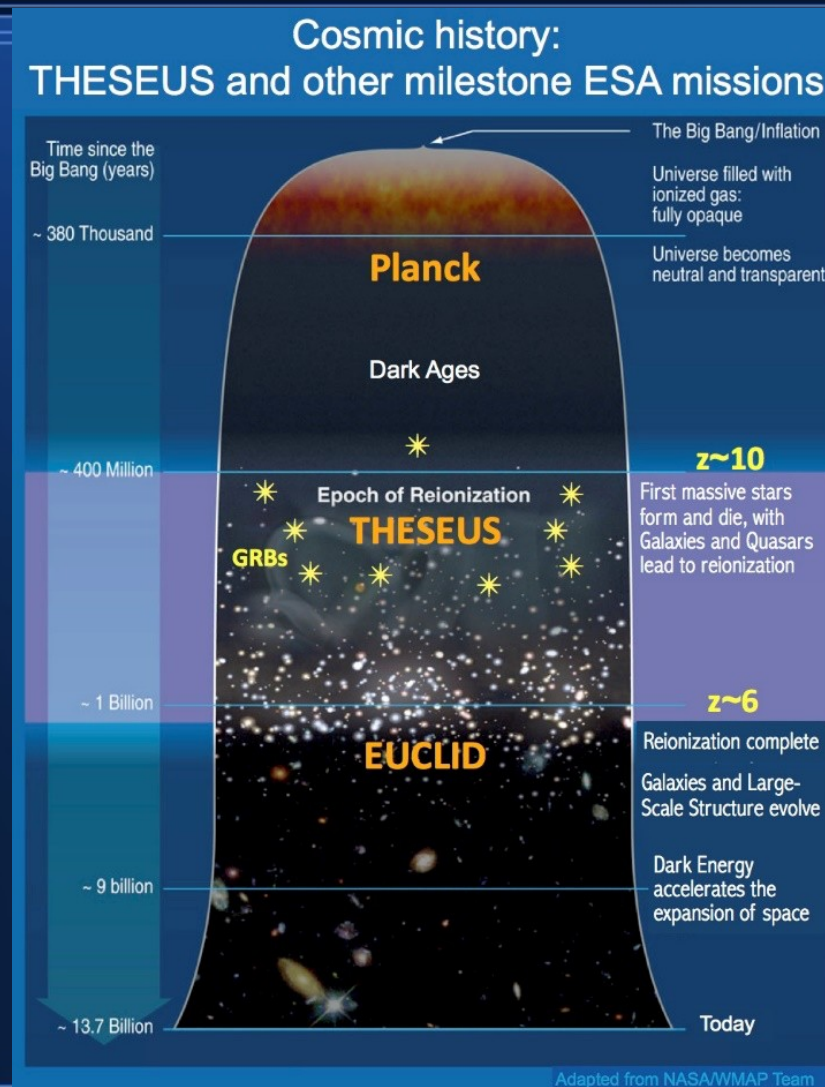
Main scientific themes of the THESEUS mission (previous ESA M5 candidate)

THESEUS satellite: Scientific goals



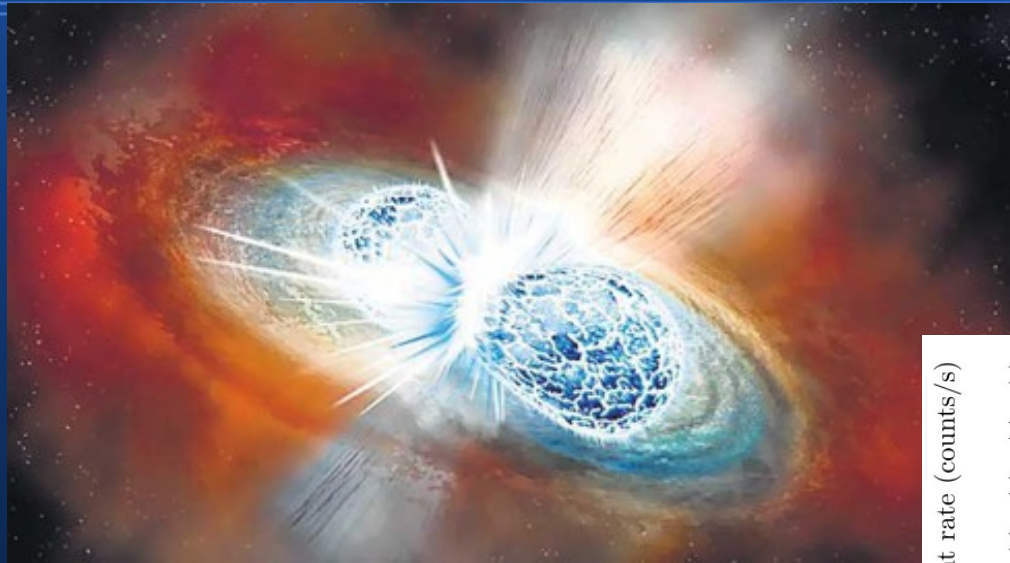
- *THESEUS* is designed to vastly increase the discovery space of **high-energy transient phenomena over the entirety of cosmic history**.
- Its driving science goals aim at finding answers to multiple fundamental questions of modern cosmology and astrophysics, exploiting the mission's unique capability to:
 - a) explore the physical conditions of the Early Universe (the cosmic dawn and reionization era) by unveiling the GRB population in the first billion years;
 - b) perform unprecedented deep monitoring of the soft X-ray transient Universe, thus providing a fundamental synergy with the next-generation of gravitational wave and neutrino detectors (multi-messenger astrophysics), as well as the large electromagnetic (EM) facilities of the next 2030-2040 decade.

THESEUS satellite: core programme (1/2)

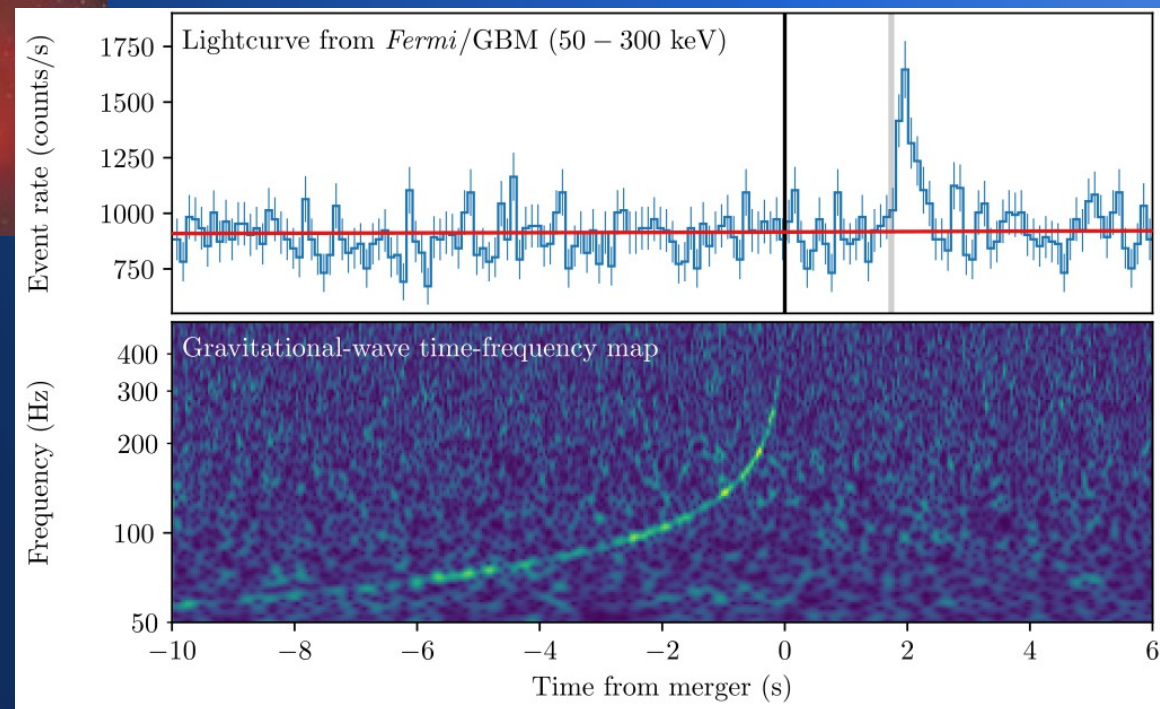


Long gamma-ray bursts in the cosmological context (adapted from the NASA/WMAP team).

THESEUS satellite: core programme (2/2)

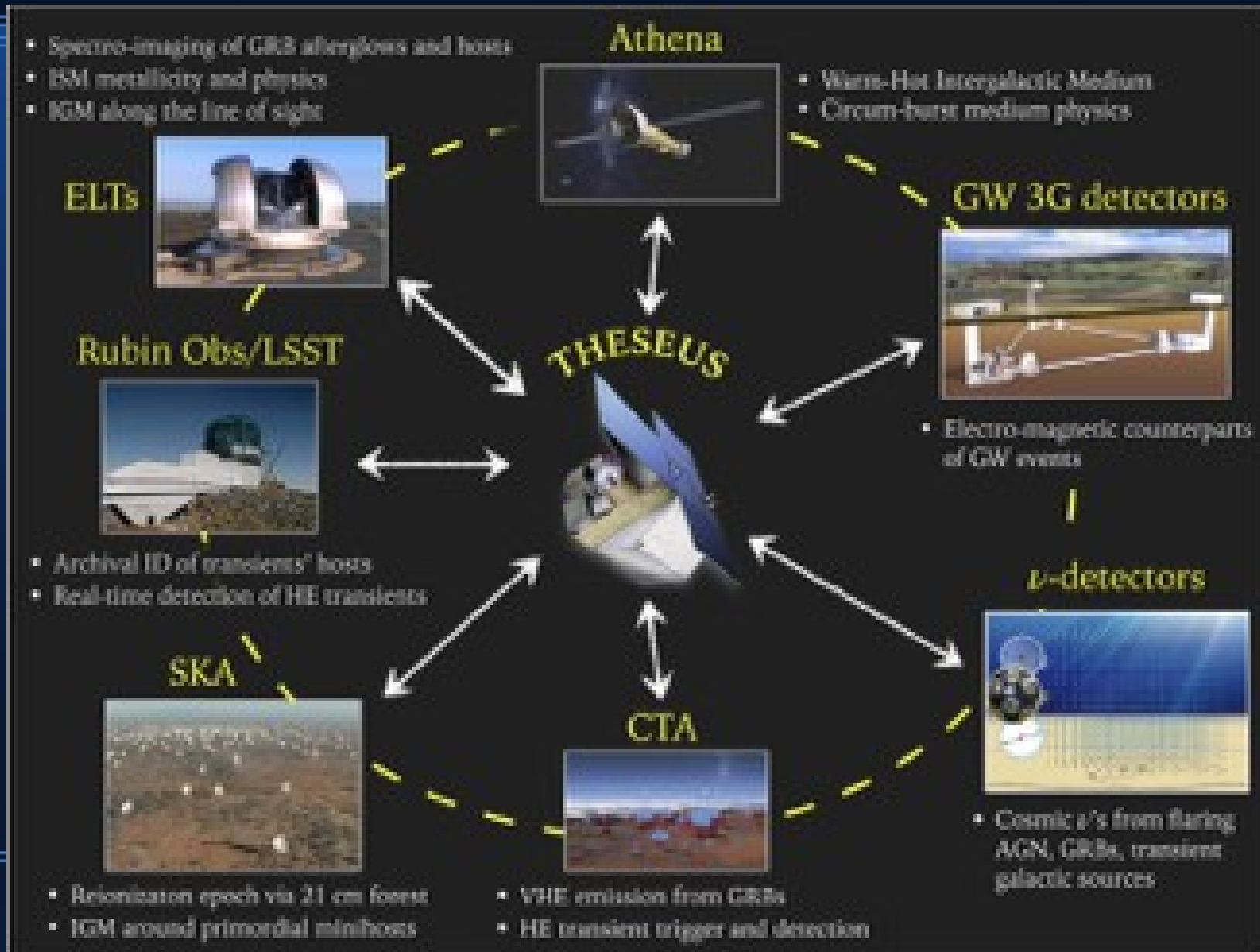


IN REAL TIME !!!



Short gamma-ray bursts as electromagnetic counter-parts of the gravitational wave signal emitted by merging neutron stars (credits: LIGO/VIRGO collaboration).

THESEUS: Synergies with next generation large observatories

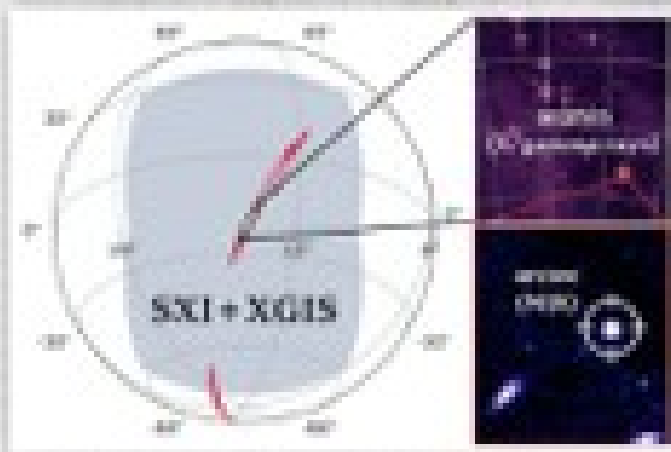


But also any kind of compact object (ancilliary programme)



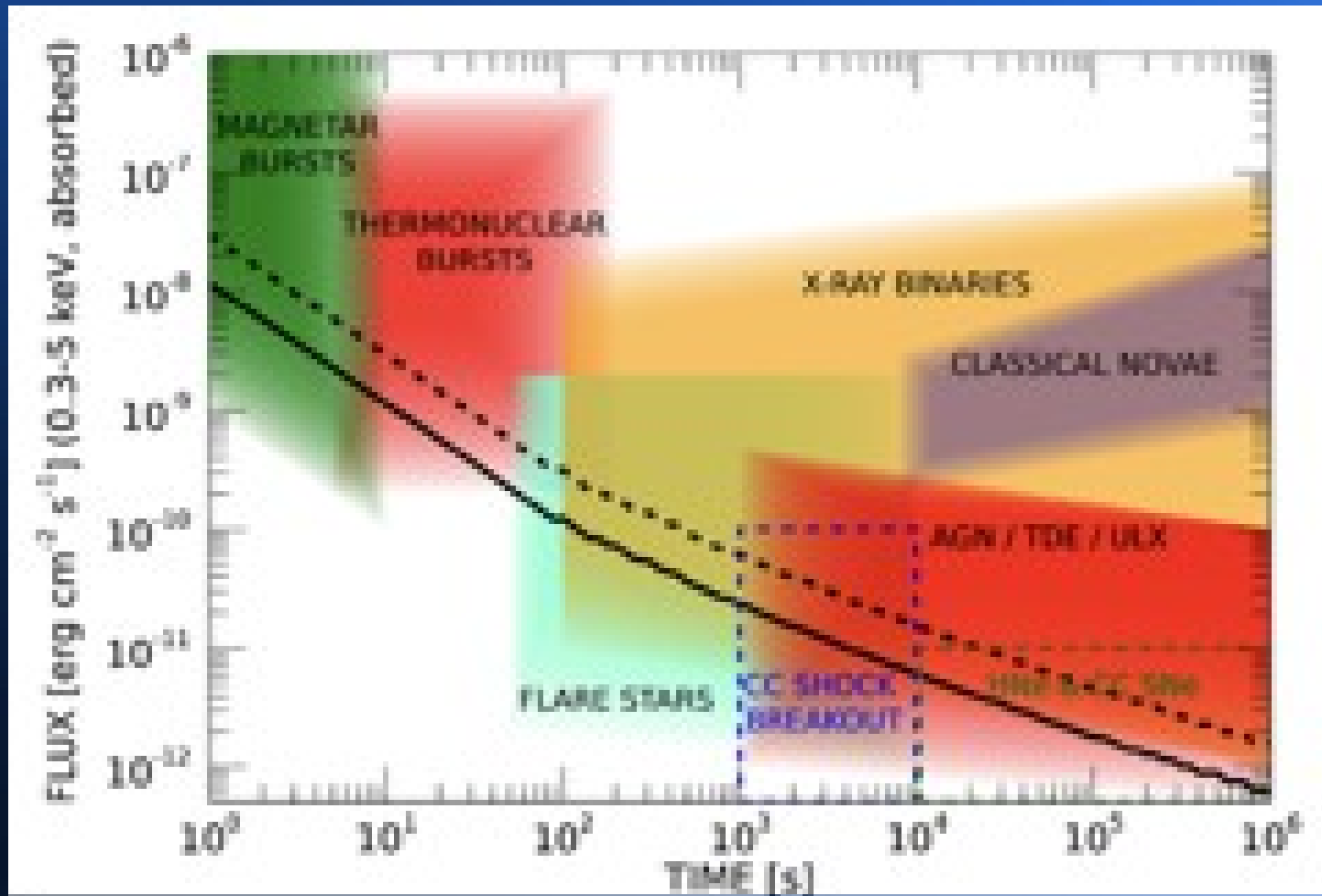
THESEUS ensures:

- Immediate coverage of gravitational wave and neutrino source error boxes
- Real time sky localizations
- Temporal & spectral characterization from NIR to gamma-rays





But also any kind of compact object (Time domain astronomy)



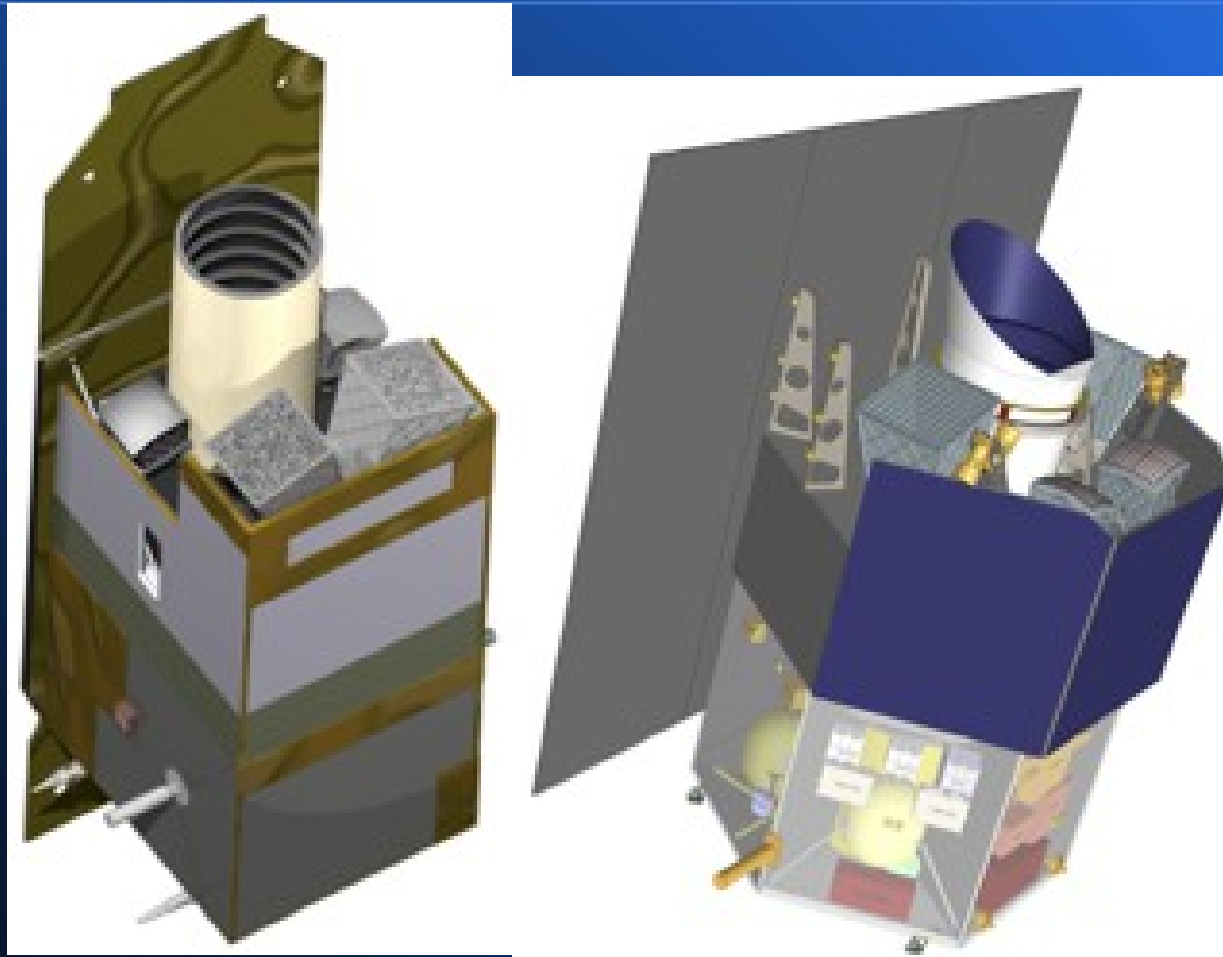
Typical variability time scales and soft X-ray fluxes of different classes of sources compared to the SXI sensitivity for a power-law prototype source (Mereghetti et al. 2021).

THESEUS satellite: Overview



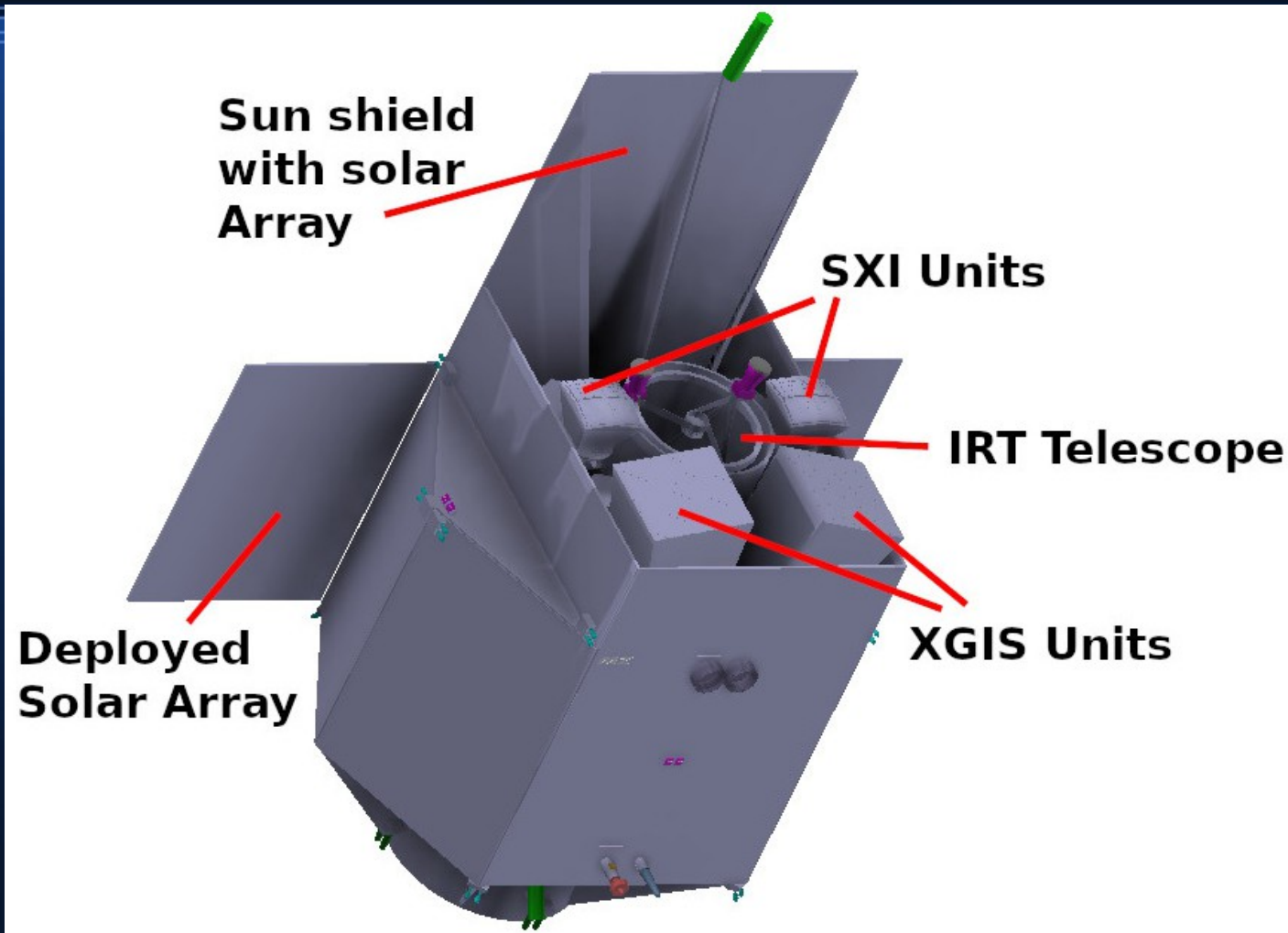
Technology

THESEUS satellite ***(re-proposed as ESA M7 mission – for launch in 2037)***



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

THESEUS satellite



Sketch of the *THESEUS* satellite showing the instruments accommodation is shown on the left panel (credits: ESA).

THESEUS satellite: instrumentation



- **Soft X-ray Imager (SXI, 0.3 – 5 keV)**: a set of 2 lobster-eye telescopes units, covering a total field of view (FOV) of ~ 0.5 sr with source location accuracy < 1 - $2'$;
- **InfraRed Telescope (IRT, 0.7 – 1.8 μm)**: a 0.7m class IR telescope with $15' \times 15'$ FOV, for fast response, with both imaging and spectroscopy capabilities;
- **X-Gamma rays Imaging Spectrometer (XGIS, 2 keV – 20 MeV)**: a set of 2 coded-mask cameras using monolithic X-gamma rays detectors based on bars of Silicon diodes coupled with CsI crystal scintillator, granting a ~ 2 sr FOV and a source location accuracy of ~ 10 arcmin in the 2-150 keV, as well as a > 4 sr FoV at energies > 150 keV.

THESEUS satellite: The Soft X-ray Imager (SXI)

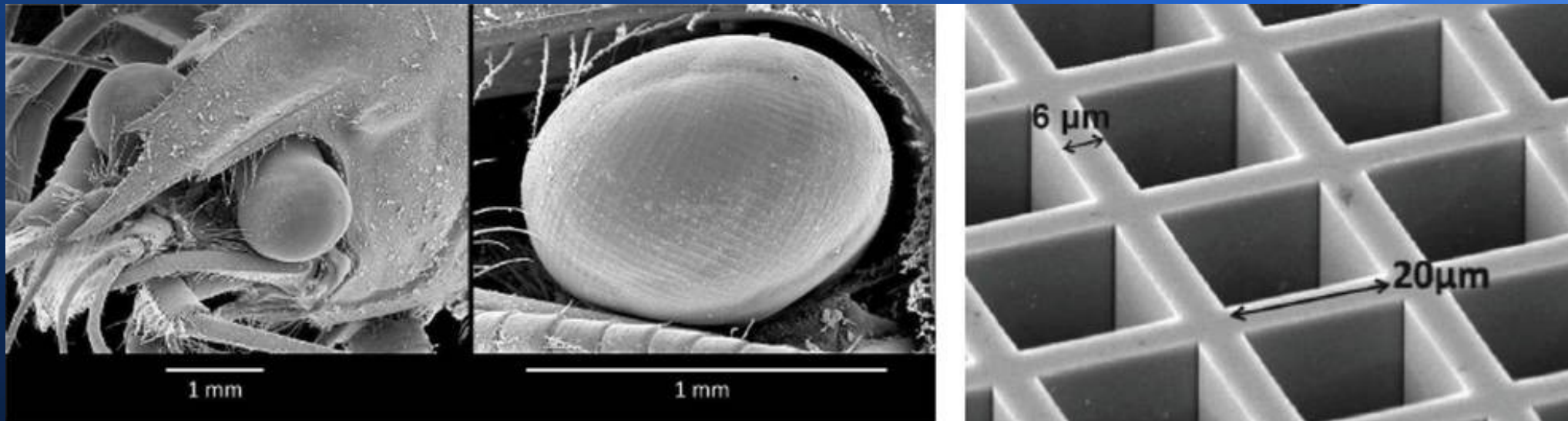


Optical elements of a SXI module.

Energy band (keV)	0.3-5
Telescope type:	Lobster eye
Optics configuration	8x8 square pore MCPs
MCP size (mm ²)	40x40
Focal length (mm)	300
Focal plane shape	spherical
Focal plane detectors	CMOS
Pixel Number per device	1000x2000
Number of devices per module	8
Field of View (square deg)	~0.5 sr
Angular accuracy	<2 arcmin
Power per module [W]	~35
Mass per module [kg]	~40

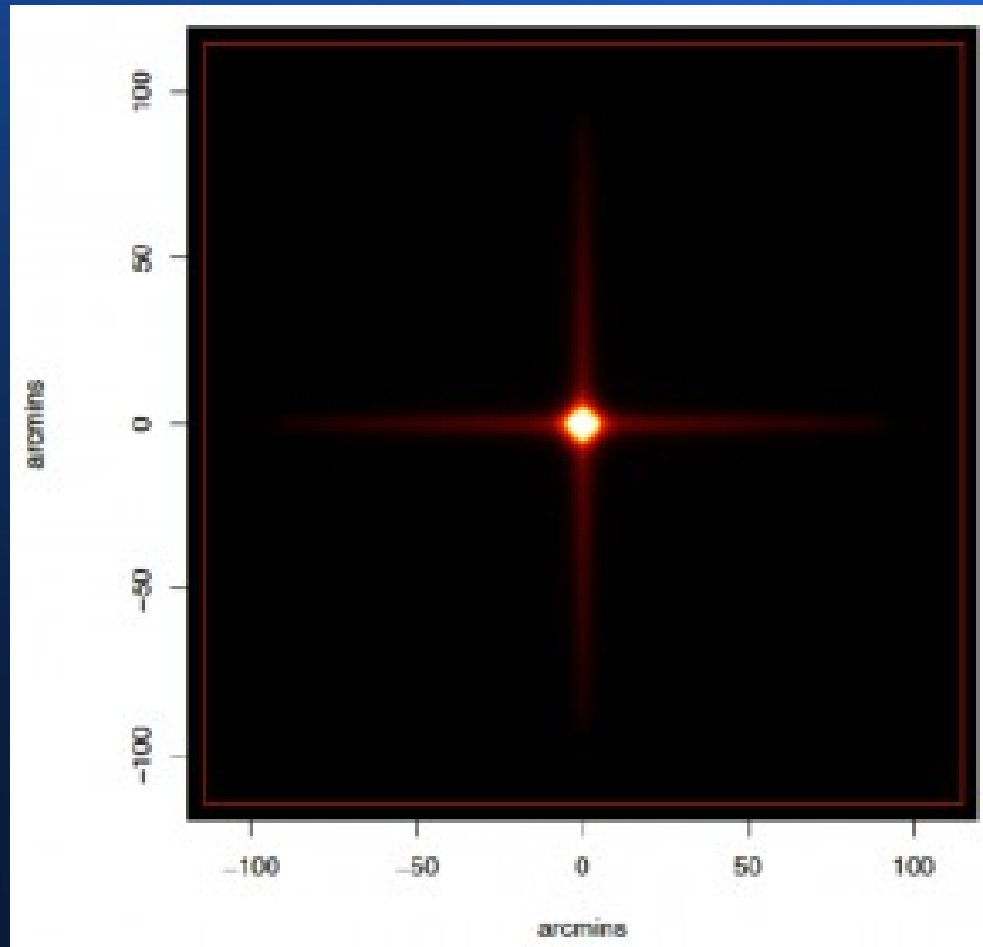
Table 1. The SXI characteristics.

THESEUS satellite: The Soft X-ray Imager (SXI)



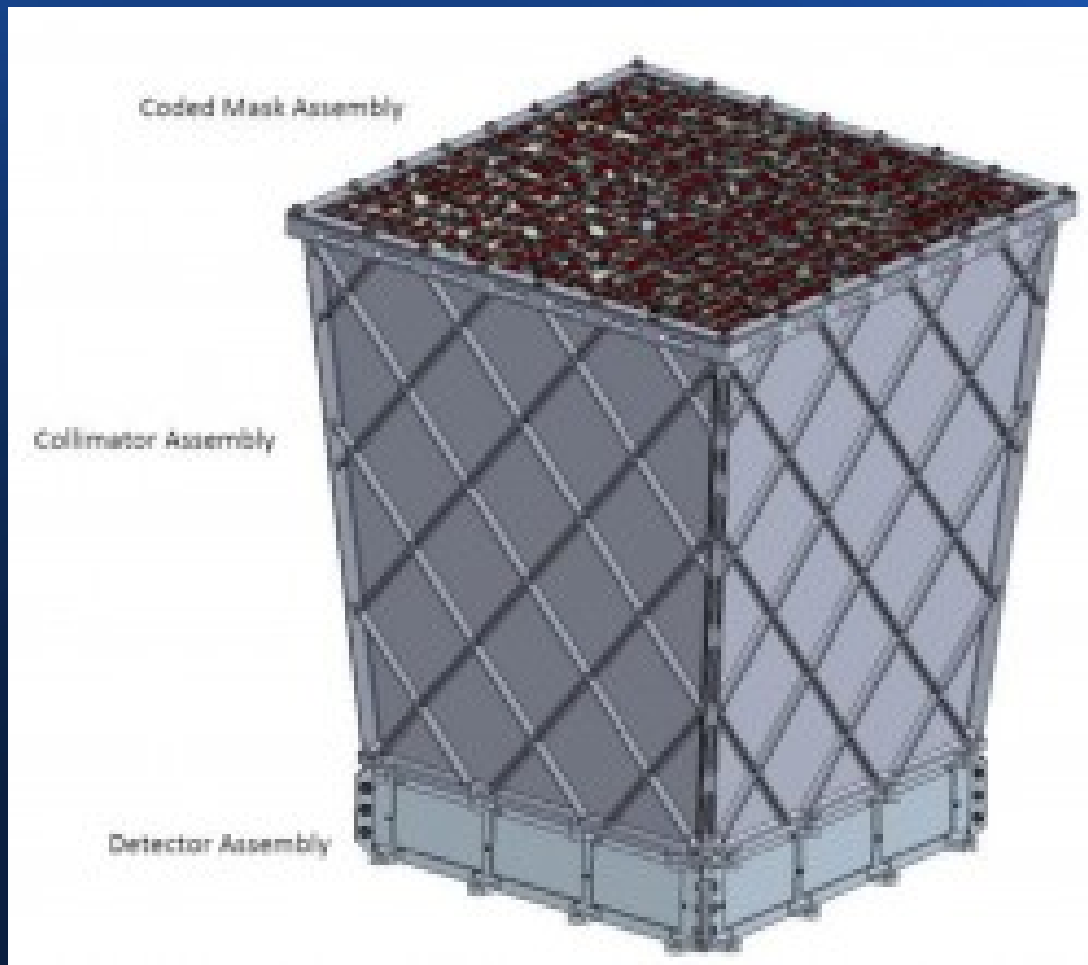
The images on the left and center show close-up views of a crustacean's eyes; the image on the right shows a manmade microchannel plate. Both operate the same way. Both gather light from multiple angles, focusing it into a single image to provide a wide field of view. Credits: NASA-Goddard

THESEUS satellite: The Soft X-ray Imager (SXI)



The point spread function of the SXI obtained from a ray-tracing simulation at 1 keV.

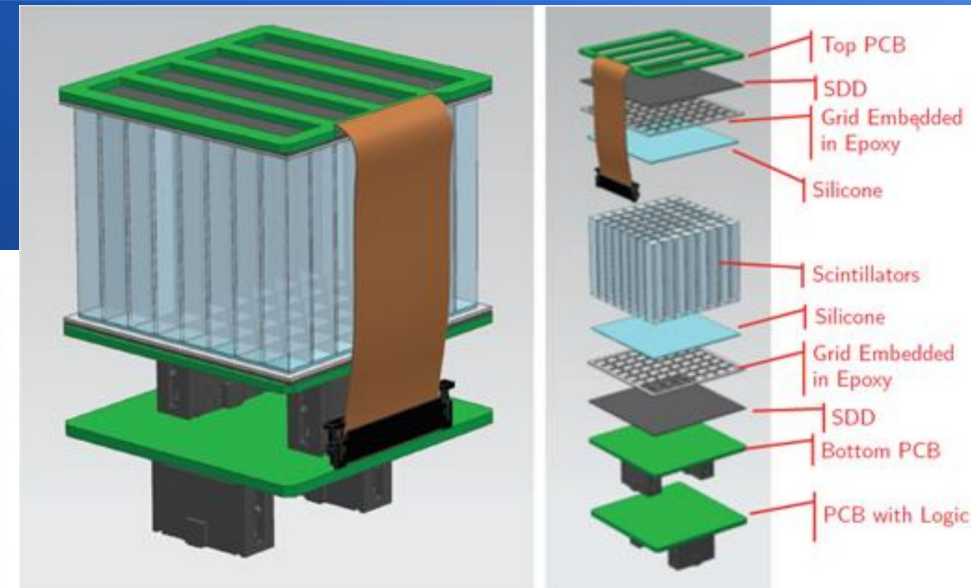
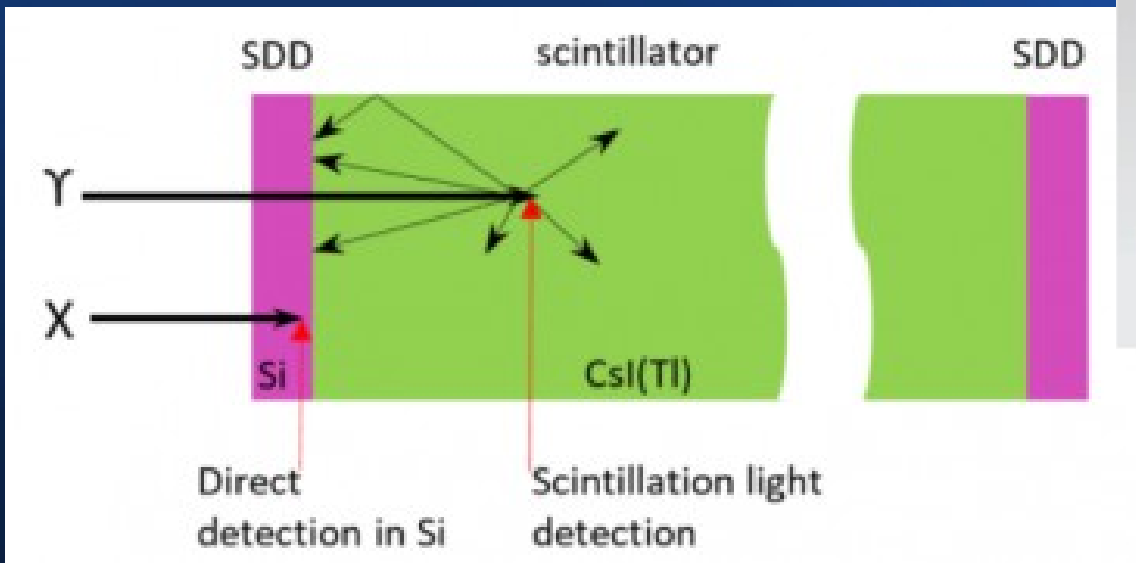
THESEUS satellite: The X-Gamma ray Imaging Spectrometer (XGIS)



Mechanical design of one XGIS camera.

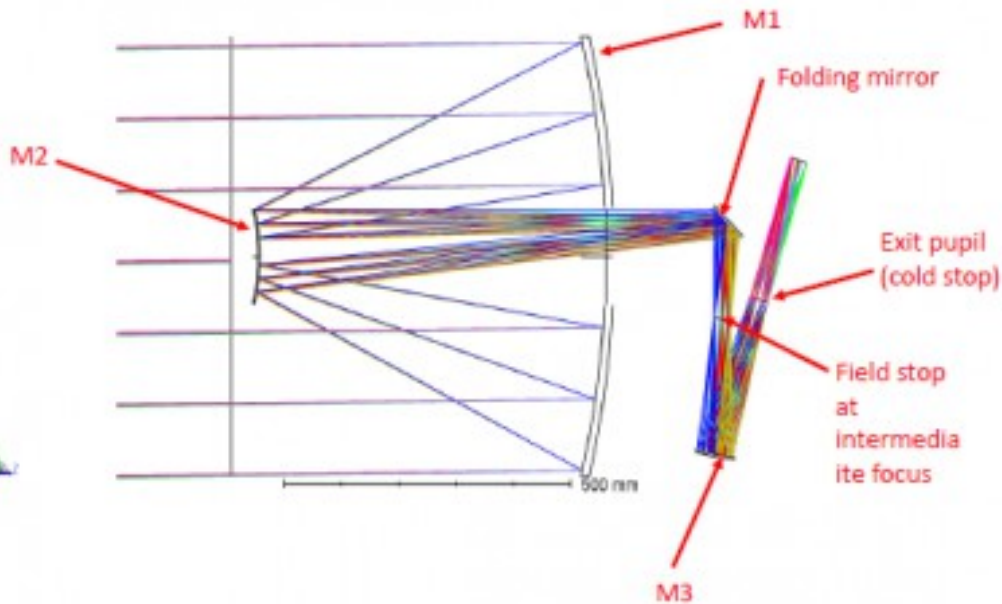
Energy band	2 keV – 20 MeV
# detection plane modules	100
# of detector pixel /module	8x8
pixel size (= mask element size)	4.5x4.5 mm ²
Low-energy detector (2-30 keV)	Silicon Drift Detector 450 μm thick
High energy detector (> 30 keV)	CsI(Tl) (3 cm thick)
Discrimination Si/CsI(Tl) detection	Pulse shape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

THESEUS satellite: The X-Gamma ray Imaging Spectrometer (XGIS)



Left: Principle of operation of the XGS detection units: low-energy X-rays interact in Silicon, higher energy photons interact in the scintillator, providing an energy range extended to three orders of magnitude. Right: sketch of one XGIS module. A module is made of an array of 8x8 scintillator bars with SDDs at both ends. Both the SDDs and scintillators are used as active detectors. The PDs readout electronics consist of an ASIC pre-amp mounted near each PD's anode while the rest of the processing chain is placed at the module sides and bottom.

THESEUS satellite: The InfraRed Telescope (IRT)



Optical design of the IRT instrument and telescope.

Telescope type	Off-axis Korsch
Primary & Secondary Size	>600 mm (goal 700 mm) & 214-250 mm
Detector type	Baseline: European ALFA detector (2048x2048 15 mpixels) Back-up: Teledyne Hawaii 2-RG 2048x2048 18 mpixels
Imaging plate scale	0.6 arcsec/pixel with 18 mm pixel size
Field of view	15x15 arc min in imaging and LRS modes, 5x5 arc min in HRS mode
Resolution (DI/I)	20 in LRS mode; 500 in HRS mode
Sensitivity (H band)	20.6 (AB; 300 s) in imaging mode; 18.5 (AB; 300 s) in LRS mode; 17.5 (AB, 1800 s) in HRS mode
Wavelength range	0.7-1.8 μ m imaging mode; 0.8-1.6 μ m LRS and HRS modes

Table 3. IRT specifications

THESEUS satellite: Overview



Programmatic

COSMIC OBSERVERS



CONCEPTS

IN DEVELOPMENT

ACTIVE

microwaves

sub-millimetre

infrared

optical

ultraviolet

x-rays

gamma rays

gravitational waves

LEGACY

planck
(2009–2013)

herschel
(2009–2013)

iso
(1995–1998)

akari
(2006–2011)

hipparcos
(1989–1993)

corot
(2006–2014)

iae
(1978–1996)

exosat
(1983–1986)

hitomi
(2016)

suzaku
(2005–2015)

cos-b
(1975–1982)

lisa pathfinder
(2015–2017)

microscope
(2016–2018)

webb
(2021)

ariel
(2028)

roman
(2020s)

euclid
(2022)

plato
(2026)

xrism
(2021)

einstein probe
(2022)

athena
(2031)

theseus

lisa
(2034)

hubble
(1990–)

gaia
(2013–)

cheops
(2019–)

xmm-newton
(1999–)

integral
(2002–)



M7 Phase-A timeline

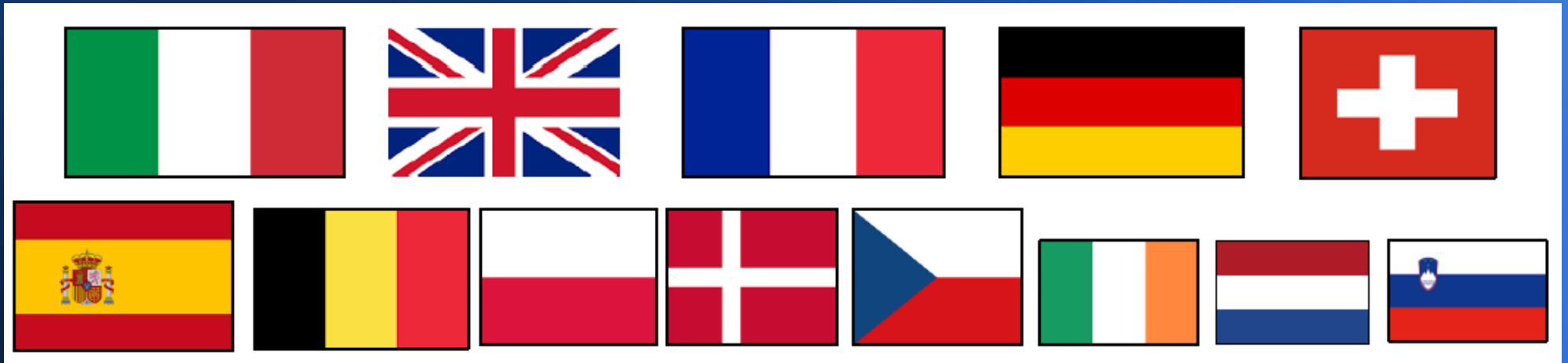
- **Nov. 8th, 2023:** SPC approval and ESA announcement of the three selected candidates (THESEUS, M-Matisse, Plasma Observ.)
- **Dec. 2023:** ESA: preparation of ITT for Industrial Phase-A; Consortium: start of discussions on organization and funding
- **Jan. 2024:** ESA internal Phase-A KO (17th); **ESA KO with Consortium (29th)**, set-up of ESA Study Team and Science Study Team (TSST) soon after; **first ESA/NPMC meeting (mid-Jan)**
- **Apr. 2024:** KO of industrial Phase-A
- **Jun. 2025:** Mission Consolidation Review (MCR)
- **Early (Feb/Mar) 2026:** Mission Selection Review (MSR)
- **June 2026:** Selection of one M7 candidate for Phase-B1

THESEUS satellite: Overview



Spanish contribution

THESEUS satellite's Consortium countries



As in the previous ESA M5 call.

THESEUS satellite: Consortium



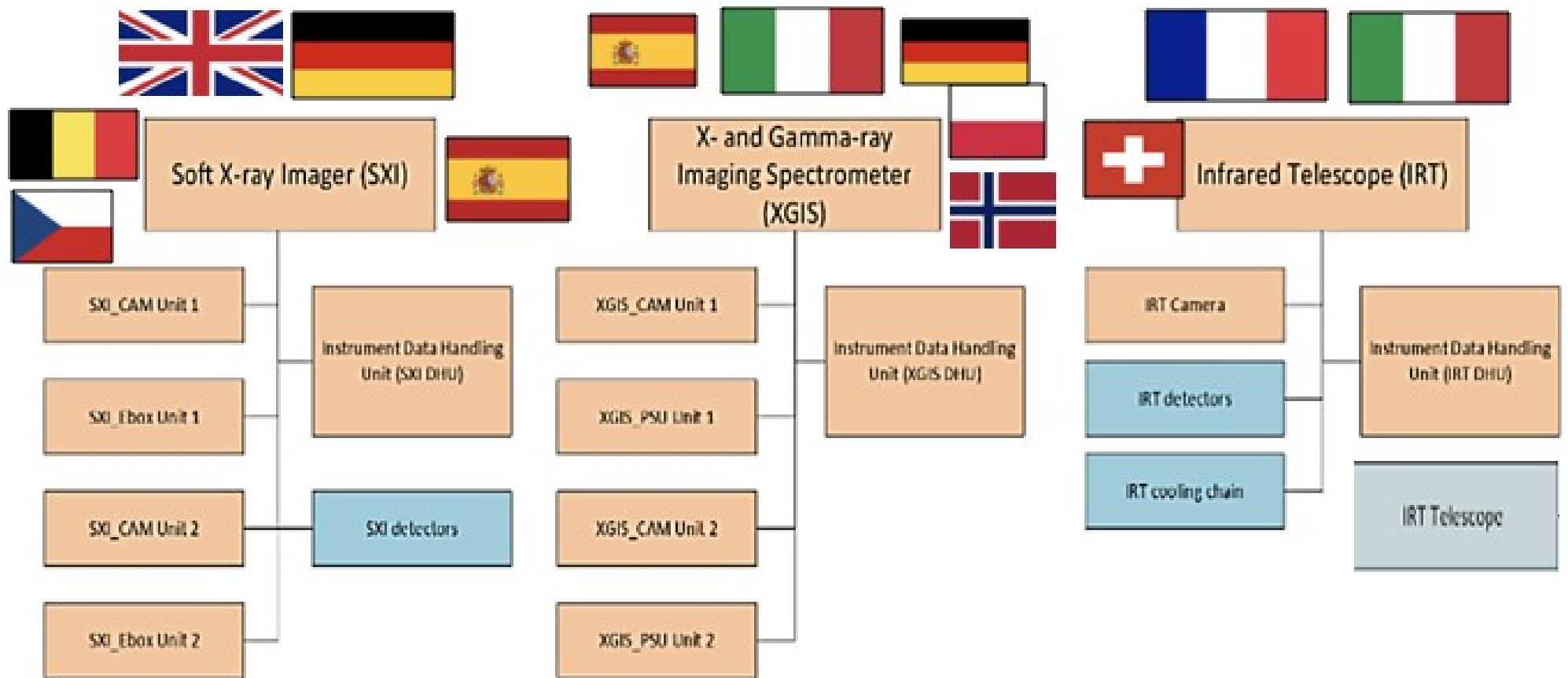
- THESEUS was selected by ESA for a new 2.5-year Phase-A study as one of the three candidates for M7 missions (together with M-Matisse and Plasma Observatory).
- Currently, the mission THESEUS (proposed again for M7) maintains the same structure (as in M5) in terms of the Spanish contribution (IAA-CSIC+INTA+UV).
- Spain is part of the mission consortium (occupying the fifth position of the contributing countries – with Italy being the main contributor) and participates in the construction of SXI (INTA) and XGIS (University of Valencia).
- Spain also participated successfully in all stages of phase A during the previous M5 phase A (prior to the current selection of the mission).

THESEUS satellite: Overview



Spanish contribution: Payload

THESEUS payload procurement scheme M7



Instruments Data Handling Units



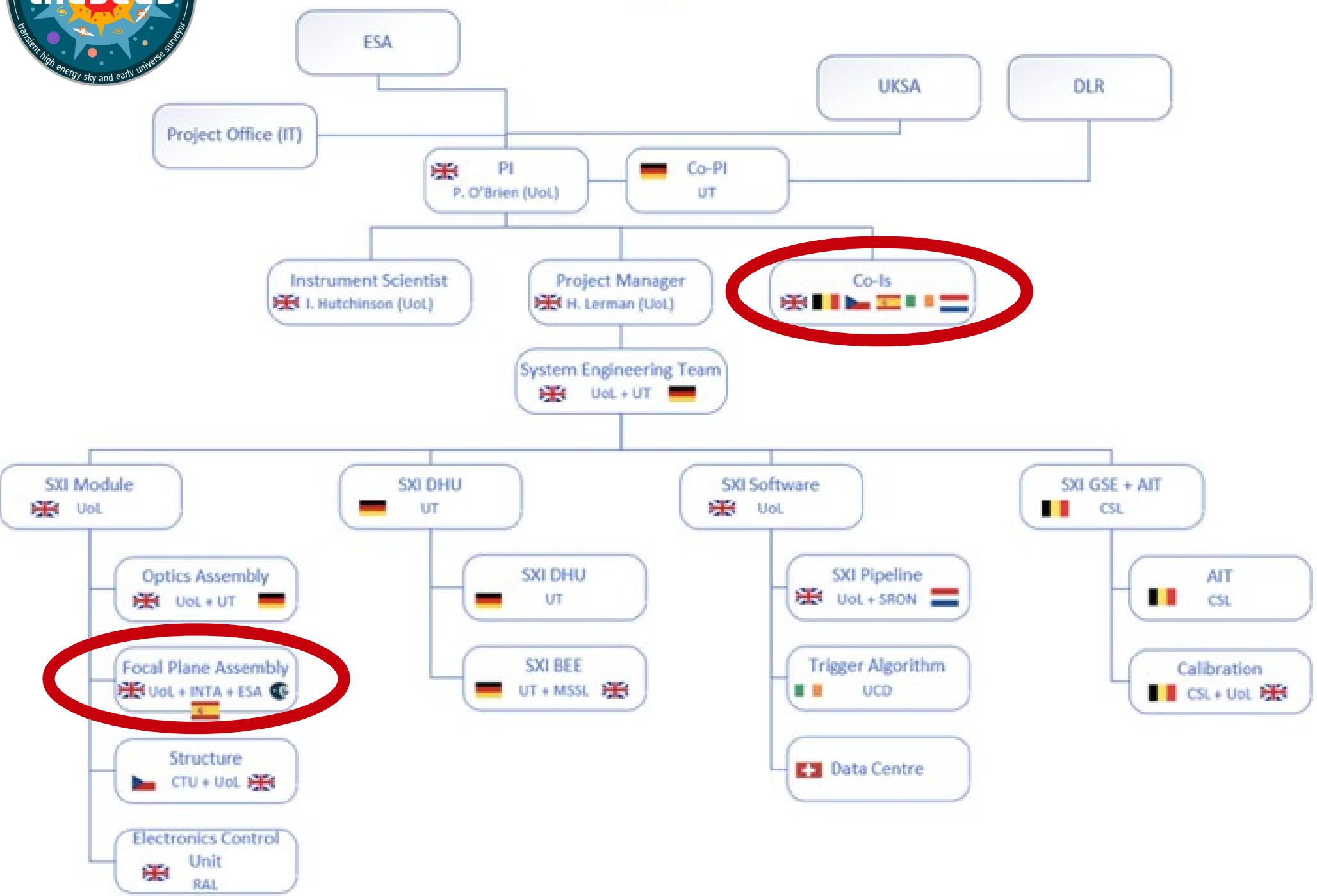
Science Data Centre



Main ground station (ASI/Malindi)



The SXI Organization

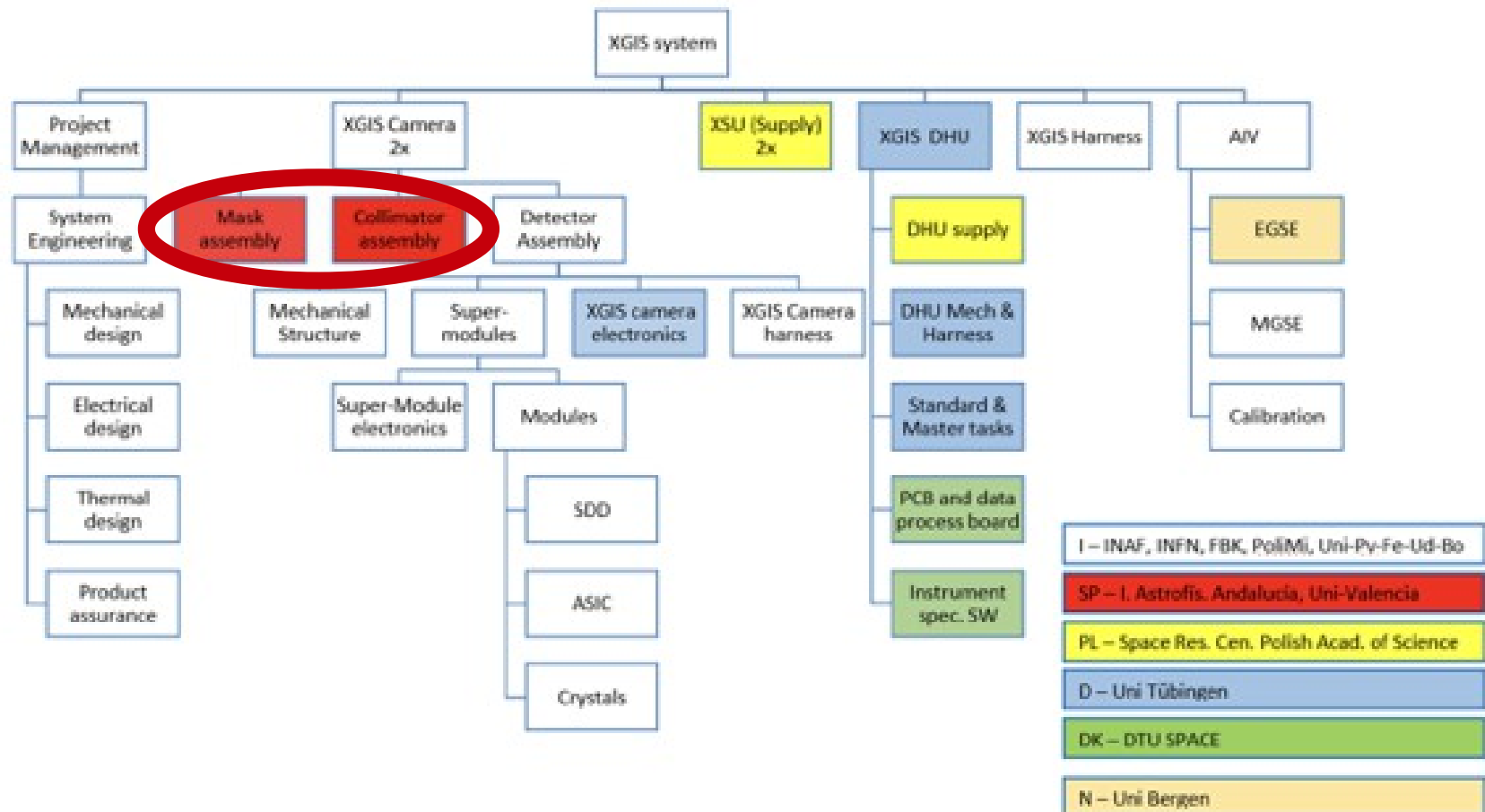


XGIS M7 Consortium



Relevant contribution given by:

Italy (overall coordination, science, mechanical design, SDD, electronics), **Spain** (imaging system), **Poland** (power Supply Units), **Germany** (XGIS camera electronics and responsibility of DHU system), **Denmark** (contribution to DHU hardware and software), **Norway** (EGSE), possible contribution from **Ireland** (R&D on scintillator crystals)



Italy	<ul style="list-style-type: none"> • THESEUS consortium lead • XGIS instrument 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 	United Kingdom	<ul style="list-style-type: none"> • THESEUS consortium co-lead • SXI instrument PI • SXI instrument design, detection plane characterization, optics assembly, electronics, integration, testing, simulations, and calibrations, front-end electronics • SXI instrument operation centre lead • Contribution to the SDC
France	<ul style="list-style-type: none"> • THESEUS consortium co-lead • IRT instrument PI & 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 • IRT DHU scientific software 	Switzerland	<ul style="list-style-type: none"> • <i>THESEUS</i> 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)
Germany	<ul style="list-style-type: none"> • THESEUS consortium co-lead • SXI and IRT DHU design, electronics, integration, testing, and software development • Overviewing of the XGIS DHU development • SXI MPO procurement • SXI back-end electronics • End-to-end simulations • Contribution to the consortium project office • SDC contribution 	United States	<ul style="list-style-type: none"> • IRT telescope optical assembly • IRT detectors and read-out electronics • Contribution to the SDC
Belgium	<ul style="list-style-type: none"> • Contribution to the SXI instrument integration, characterization, and tests 	Spain	<ul style="list-style-type: none"> • XGIS coded mask and collimator • Contribution to SXI focal plane assembly and mechanical structure
Slovenia	<ul style="list-style-type: none"> • Investigation of possible transportable ground station additional antennas for enhanced scientific data downlink • Contribution to the SDC 	Poland	<ul style="list-style-type: none"> • XGIS power supply system
Netherlands	<ul style="list-style-type: none"> • Contribution to the SDC 	Denmark	<ul style="list-style-type: none"> • XGIS DHU design, electronics, integration, testing, and software development
		Czech Republic	<ul style="list-style-type: none"> • Contribution to the SXI instrument mechanical structures and thermal control
		Ireland	<ul style="list-style-type: none"> • Contribution to the SDC
		Norway	<ul style="list-style-type: none"> • Contribution to XGIS FoV delimiter and anti-coincidence system

THESEUS satellite: Overview



Spanish contribution: Objectives/Tasks (Phase A+B1)

THESEUS satellite: Overview



IAA-CSIC (coordinator)

INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA (IAA-CSIC)

El IAA es un instituto del Consejo Superior de Investigaciones Científicas (CSIC) ubicado en Granada

Desarrolla investigación en astrofísica, así como tecnología para el estudio del Cosmos



Sede de Granada



Observatorio de Calar Alto (Almería)



Observatorio de Sierra Nevada (Granada)

THESEUS consortium: IAA-CSIC (1/2)



- The tasks to be developed at IAA will be regarding the coordination of the Consortium structure of the SXI and XGIS instruments' teams in addition to the ones of scientific kind (organization of meetings, Workshops; production of simulated data, participation in scientific collaborations, and publication of scientific results related to the project) .
- **[GO1-IAA] To coordinate the Spanish participation in the THESEUS ESA/M7 mission.** THESEUS was selected for study A this year and in middle 2026 it will be known which of the three M7 missions will be adopted for launch. The IAA is leading the Spanish participation, involving different institutions (IAA-UV-INTA), so coordination is a must, paving the way to a coordinated project to be submitted in 2027 (if the mission is selected for phase B study by ESA).

THESEUS consortium: IAA-CSIC (2/2)



- [GO2-IAA] To assist on the scientific side to the THESEUS Consortium during the phase A Study. The methodology during the THESEUS phase A involves the *participation at scientific level and programmatic/technological*. Further work in several major Working Groups is envisaged.
- **Organization of Workshops:**
 - “Spanish participation in X-ray observatories: past, present and future”, SEA symposium on 15-19th July (2024);
 - “THESEUS international Conference” in late 2025/early 2026 in Spain.

THESEUS satellite: Overview



INTA (SXI instrument)



THESEUS consortium: INTA



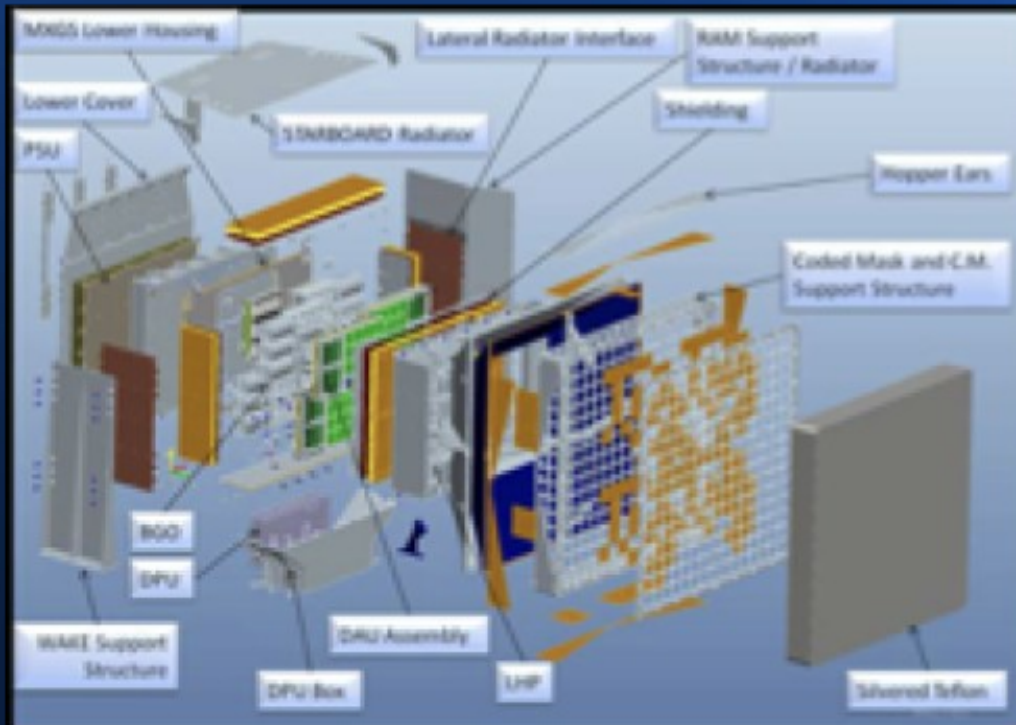
- [GO1-INTA] The objective is to complete the Phase A activities related to the SXI (Soft X-ray Imager) instrument of the THESEUS mission and to address, if selected, phase B1.

Two objectives of different nature are contemplated: a first one (ObjEesp1-INTA) related to the thermo-mechanical design of the structure that will support the detectors (focal plane), the thermal interface, and the support structure (hexapod) that will serve as interface and junction with the platform, and a second one (ObjEesp2-INTA) that will consist in the elaboration of a preliminary plan of alignment and integration of the CMOS detectors in its support structure and another one of metrological verification that will allow to assure the strict positioning requirements.

THESEUS satellite: Overview



IPL (U. of Valencia; XGIS instrument)



THESEUS consortium: UV



- [GO2-UV] Technical contribution to XGIS instrument and to THESEUS mission. The XGIS instrument consists of two units (two telescopes) FOVs partially overlap. *The group is responsible of the whole XGIS Imaging System of each unit.* This includes on the one hand the optimization of the Coded Mask Assembly together with the Collimator Assembly for each unit, and on the other hand the mechanical and structural requirements and their interface definition with the rest of XGIS and with the platform, the system budgets, mechanical design, and structural analysis. In addition, members of the team are part of the THESEUS System Engineering Working Group and of the THESEUS National Project Management Committee.

THESEUS consortium: UV



- [GO2-UV] Technical contribution to XGIS instrument and to THESEUS mission. The XGIS instrument consists of two units (two telescopes) FOVs partially overlap. *The group is responsible of the whole XGIS Imaging System of each unit.* This includes on the one hand the optimization of the Coded Mask Assembly together with the Collimator Assembly for each unit, and on the other hand the mechanical and structural requirements and their interface definition with the rest of XGIS and with the platform, the system budgets, mechanical design, and structural analysis. In addition, members of the team are part of the THESEUS System Engineering Working Group and of the THESEUS National Project Management Committee.

***THESEUS satellite:
Spanish contribution
(Phase A+B1)***



**WORK IN
PROGRESS**