The technology roadmap of the XGIS instrument for the THESEUS mission and other mission opportunities

E. Virgilli, L. Amati, C. Labanti, R. Campana, E. Marchesini, S. Srivastava, P. Sarra, P. Lorenzi, S. Mereghetti, F. Frontera

on behalf of the **XGIS** collaboration

Summary

– GRBs as probes for Cosmology and MultiMessenger Astrophysics;

– THESEUS mission and the on board instruments;

– X and Gamma-ray Imager and Spectrometer (XGIS);

– Technological activities within the XGIS collaboration (Demonstration Module);

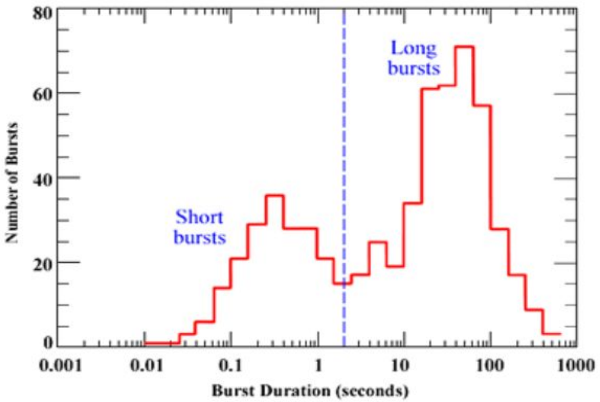
– R&D foreseen in the next future (hopefully in THESEUS M7 / Phase A);

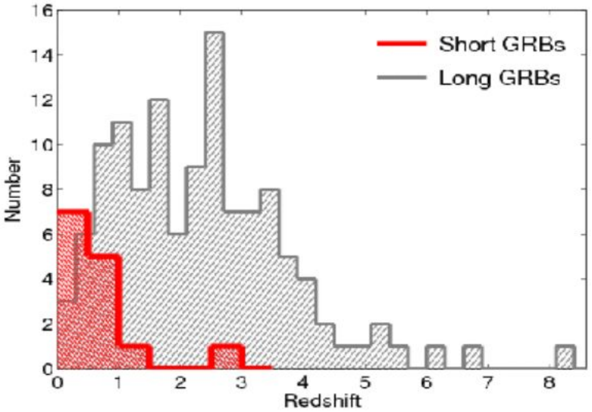
Gamma-Ray Bursts

Long
> 2 s, huge luminosities, mostly emitted in the X and gamma-rays, extending to high redshift z ~ 9, collapse of massive stars

Short
< 2 s, NS-NS or NS-BH mergers, associated with GW sources

GRBs are unique tools for Cosmology and Multimessenger Astrophysics



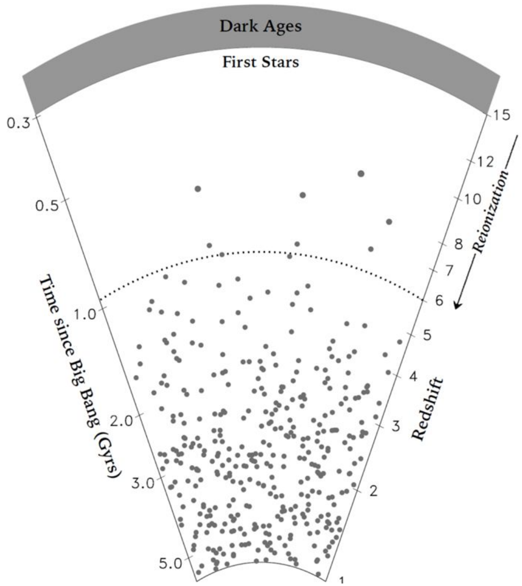


THESEUS Core Science pillars (I)

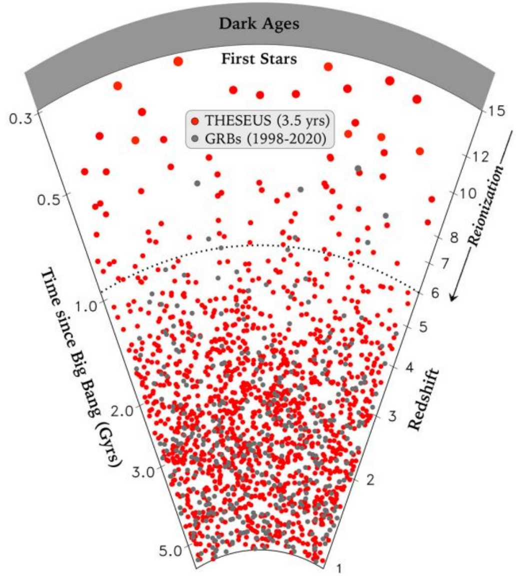
Exploit **long GRBs** for cosmology

- – direct detection of Pop-III stars;
- – star formation rate evolution;
- – metallicity

GRBs 1998 - 2020



GRBs THESEUS 3.5 years

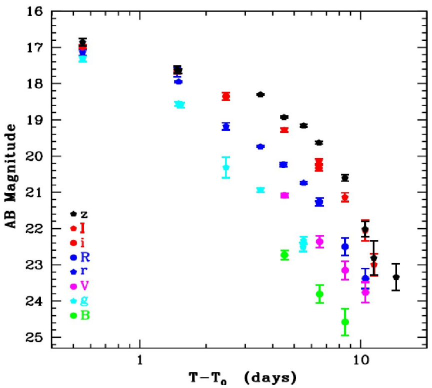


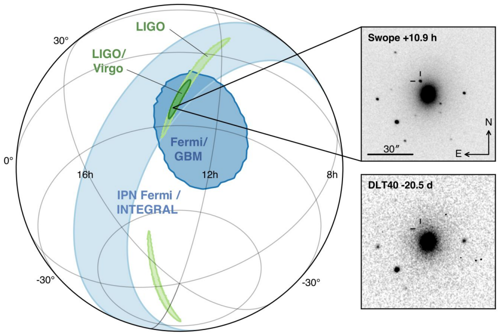
THESEUS Core Science pillars (II)

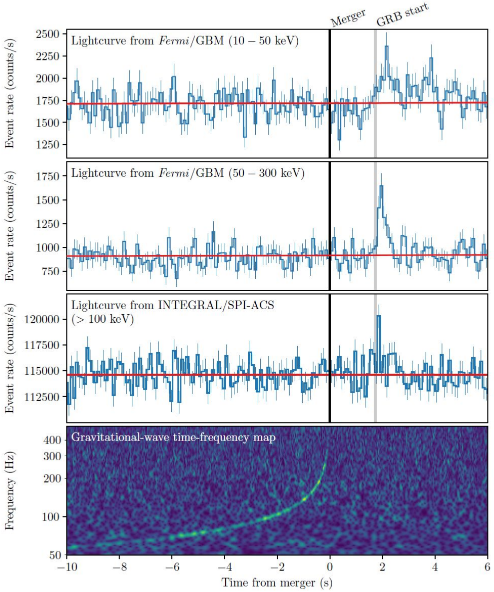
Provide fundamental contribution to **Multimessenger Astrophysics**

– detect short GRB associated with GW which will be routinely observed in ‘30s with eLISA, ET, advanced LIGO-Virgo;

– detect kilonova with arcsec localization and characterization;





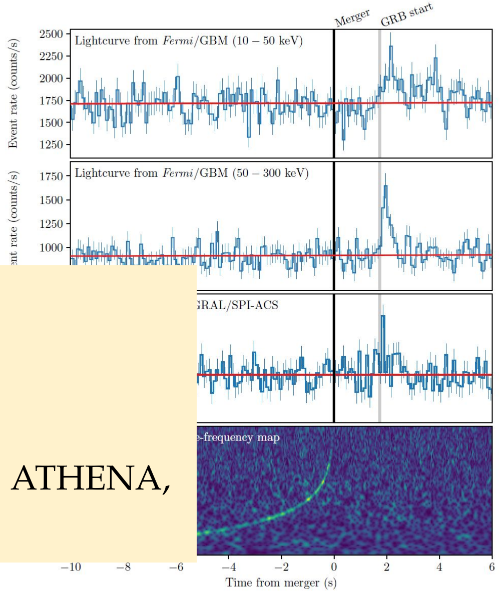


THESEUS Core Science pillars (II)

Provide fundamental contribution to **Multimessenger Astrophysics**

– det
eLISA

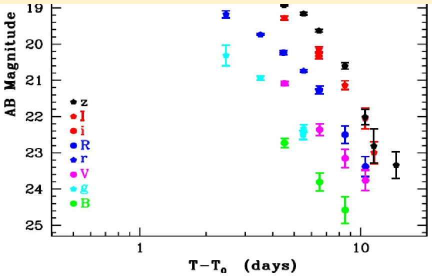
– dete

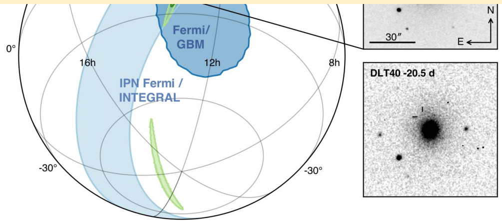


THESEUS Observatory Science

– Contribute to the detection of new classes of high-energy transient events

– Strong synergy with the large observatories in the '30s like SKA, CTA, ATHENA, 3-generation GW detectors





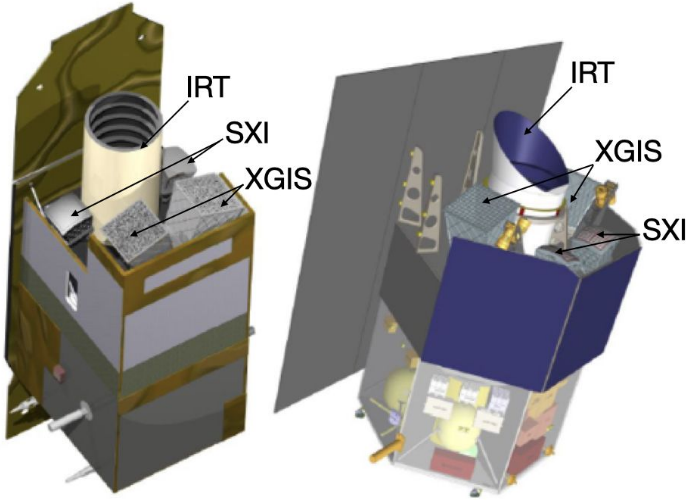
The THESEUS instrument configuration (ESA M5 → M7)

Soft X-ray Imager (SXI)
Two sensitive lobster-eye telescopes observing in 0.3 - 5 keV band, total FOV ~0.5 sr
source location accuracy < 2’

X-Gamma rays Imaging Spectrometer (XGIS)
Two 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
<15’ GRB location accuracy

InfraRed Telescope (IRT)
A 0.7 m 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
arcsecond localization

M5 industrial Phase A from **Airbus** and **Thales**



Unique combination for detecting every class of GRBs

Timeline

2018 - 2021: ESA Phase A study as M5 candidate

2022: selected for ESA Phase 0 study in M7 selection process

M7 timeline Phase A 2024 - 2025 – Launch 2037

Reference papers:

Amati et al. 2018 (Adv.Sp.Res., arXiv:1710.04638)
Stratta et al. 2018 (Adv.Sp.Res., arXiv:1712.08153)

https://www.isdc.unige.ch/theseus/

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

Coordinators: 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

The X-Gamma Ray Imaging Spectrometer (XGIS)

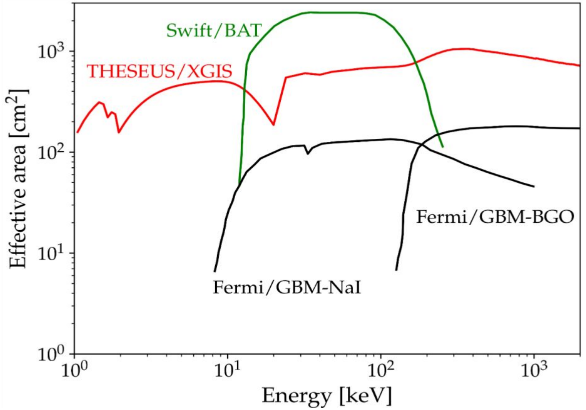
Unprecedented combination of:

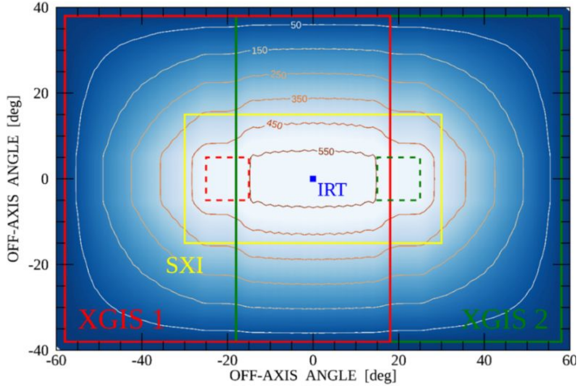
– Effective area (min. >500 cm^2, max. >1000 cm^2)

– Energy pass-band (2 keV – 10 MeV)

– FoV:
  - – 2 sr with imaging capabilities < 150 keV
  - – half sky < 10 MeV

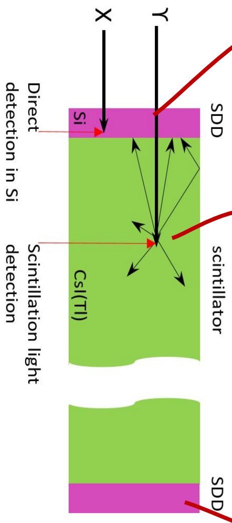
– Timing (< 5 µs)



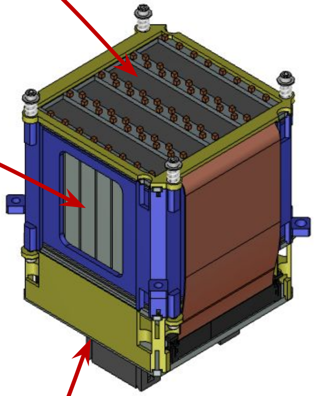


Full modularity of the architecture proposed in M5 and M7

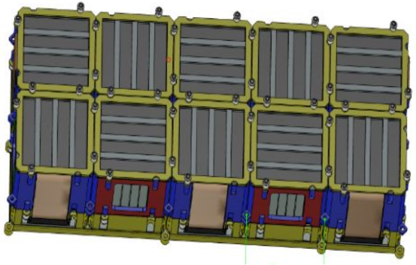
Working principle

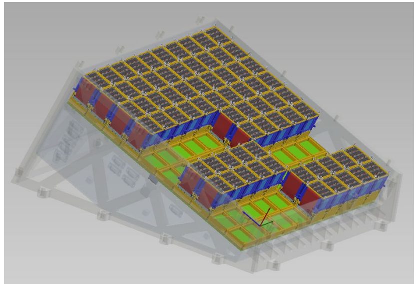


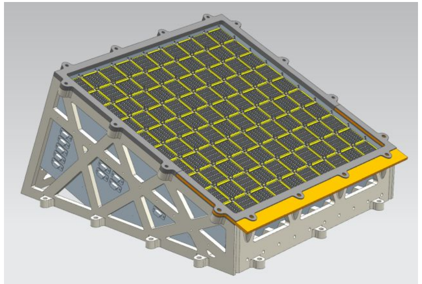
Module (DM)

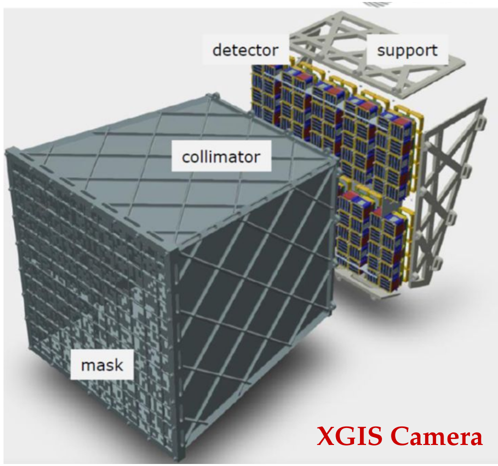


Super module





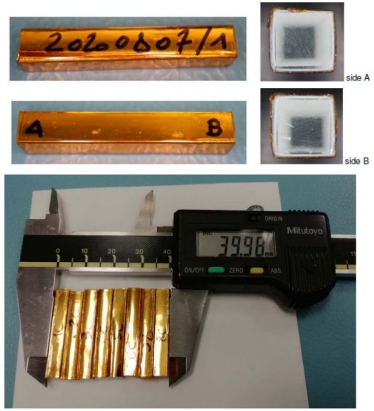


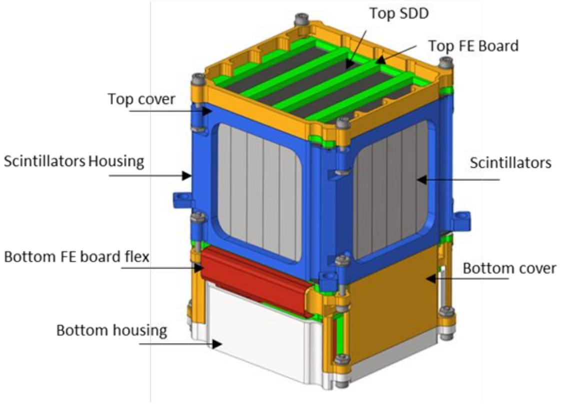


XGIS Camera

XGIS Demonstration Module (DM) overview

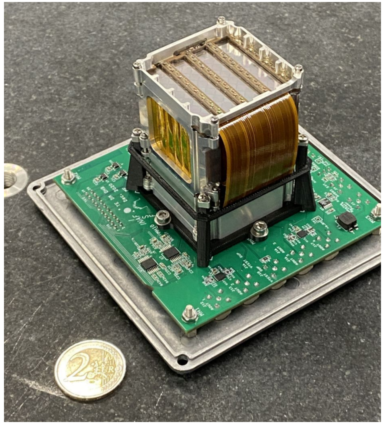
- Single wrapped scintillators enclosed in mechanical housing
- CsI(Tl) crystals mass 176 grams
- Readout Electronics in a single PCB with flex connections
- Clamped FE boards to preload SDD/optical couplers/scintillators
- **Total mass 250 grams**



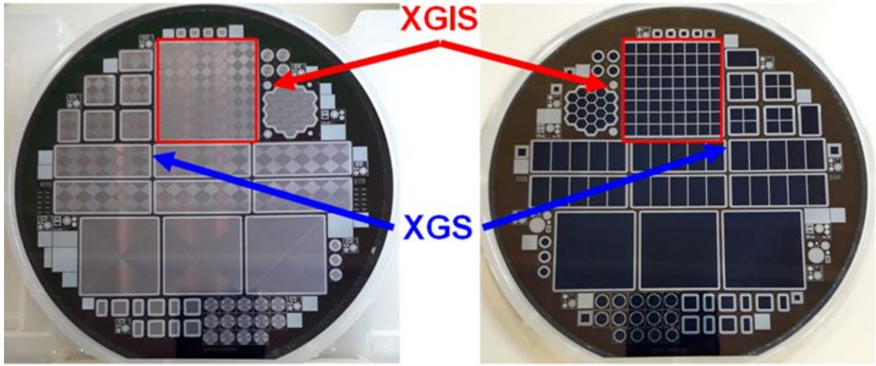


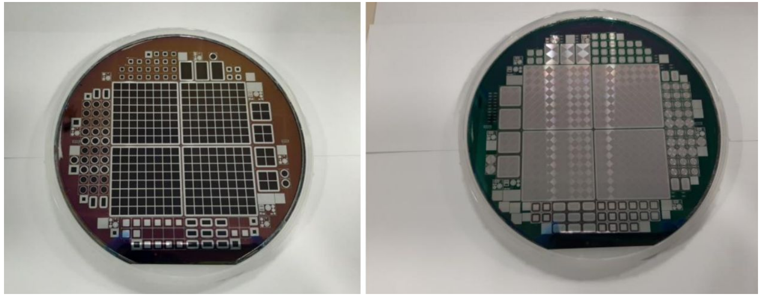
Goals of doing a DM

- implement SDDs and ASICs new technologies with CsI(Tl) scintillators
- compact design (40 mm + 5 mm pitch) to minimize XGIS Detector dead area
- SDD/scintillator optical coupling compatible with temperature range
- Robust design compatible with vibration loads



Main technologies implemented in the XGIS



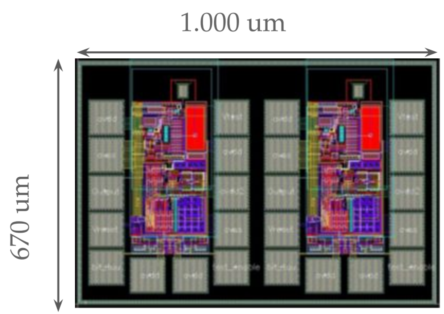


ReDSoX 2019 batch with highlighted the monolithic SDD matrix (FBK Trento) designed for the XGIS instruments for THESEUS.

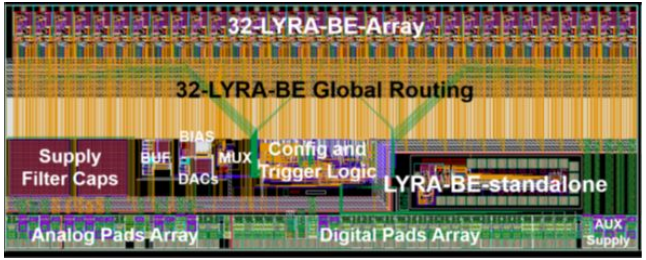
2020 batch implemented on XGIS DM.

Built around LYRA ASICs developed for HERMES Scientific Pathfinder:

– Politecnico di Milano (LYRA-FE)
– Università di Pavia (LYRA-BE)

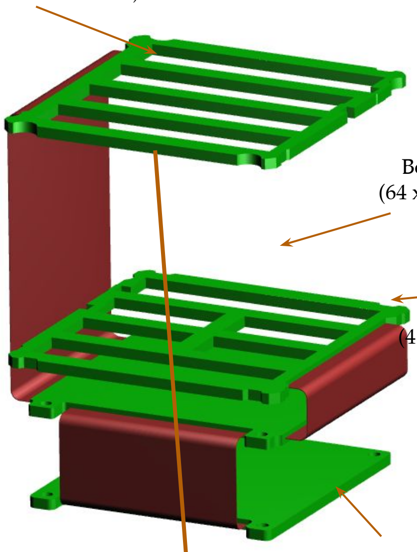


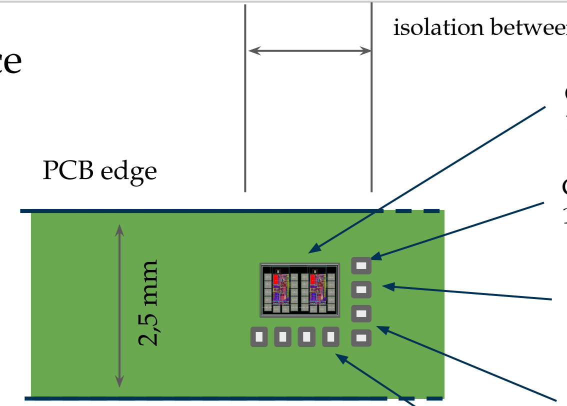
LYRA-FE



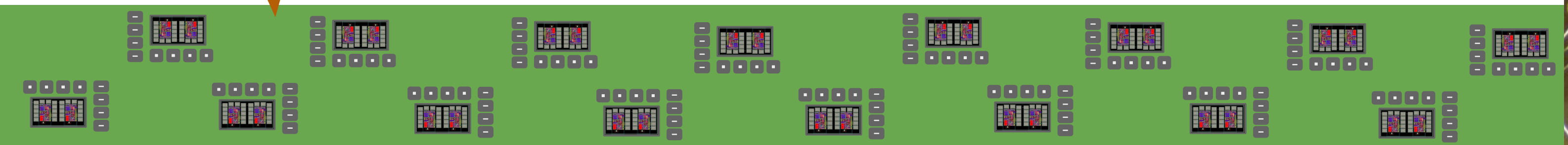
LYRA-BE

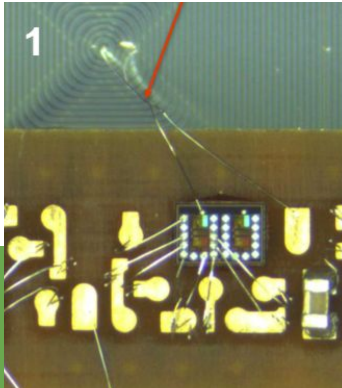
LYRA-FE ASIC: footprint and ECSS compliance





Very compact structure, but **inspection limitations,** especially for the **lower SDD**, which may be required after vibration or environmental tests.

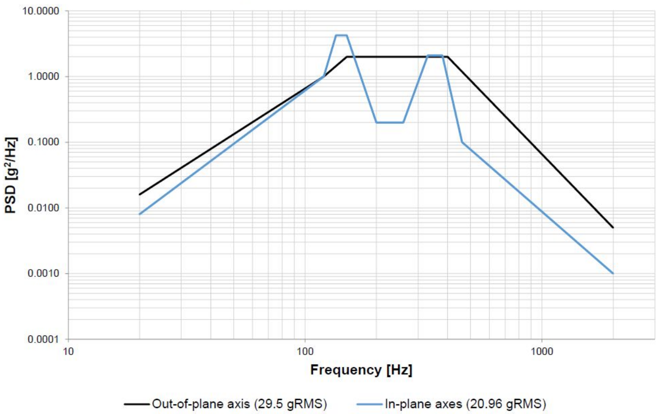




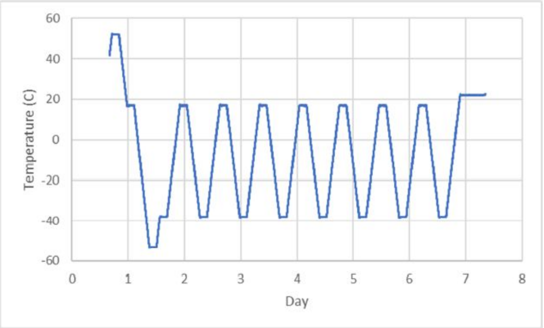
XGIS DM environmental tests

– Thermal cycling
– Random Vibrations

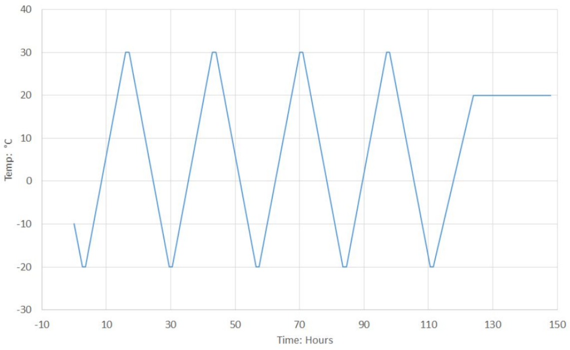
Dummy and DM test:
Random qualification loads: 29.5 grms out-of-plane Z; 21.0 grms in-plane X and Y



Dummy DM test:
1 cycle non-operational +50/-50 °C
7 cycles operational +15/-35 °C



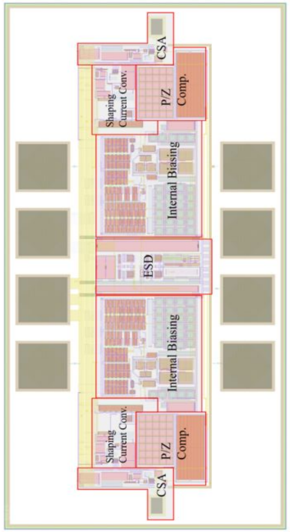
DM test:
4 cycles operational +30/-20C
No light output degradation observed during and after DM test



ORION ASIC - a dedicated ASIC for XGIS

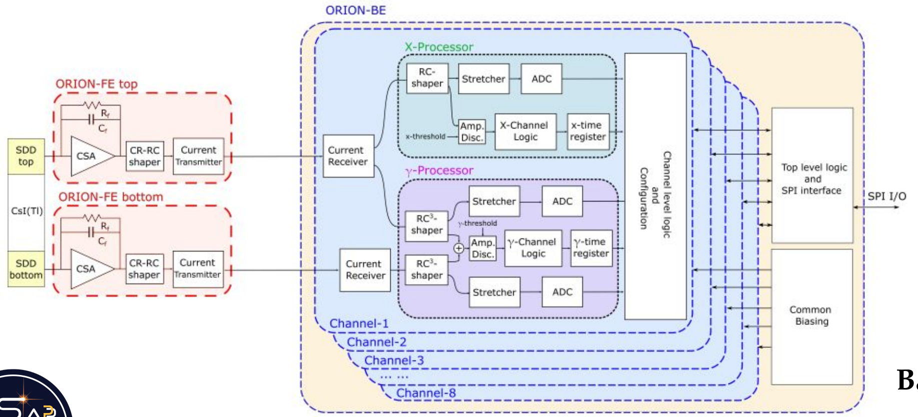
Mele et al. 2020

dual channel ORION-FE



- ORION-FE current geometry is similar to LYRA-FE therefore **not compliant with ECSS rules**

- Preliminary geometry (**two preamplifier on the same die**, back-to-back faced) **which allows to design the PCB compliant to ECSS rules**



Baseline is 1 BE serving 16 FE (8 channels / 8 pixels)

Lesson learnt – optical coupling

Transparent grid (3D printing tolerances) and separate square silicon pads.

Optical coupling between crystal and SDD needs to be improved to reduce the light output loss.

Possible improvements:

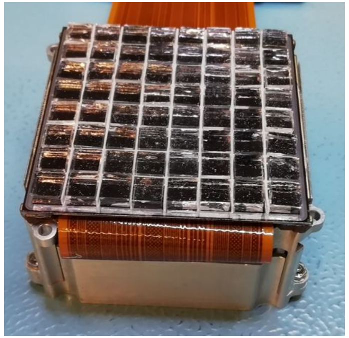
– Reflecting grid (reflecting material or reflective coating)

– Glue the grid on the SDD (on both sides like experienced on Hermes nanosat)

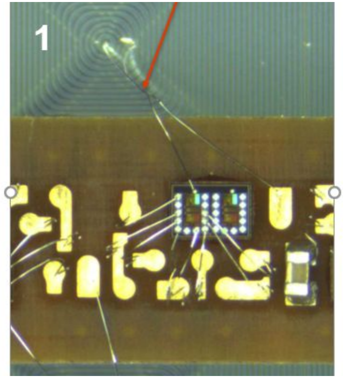
– Cast in place optical pads on the SDD/glued grid

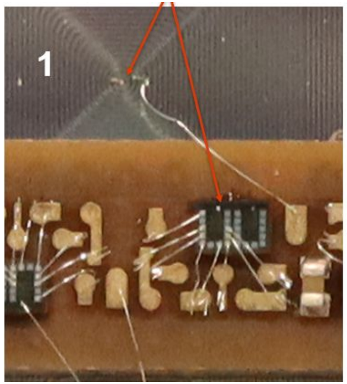
top side Silicone pads on CsI crystals

bottom side Silicone pads on SDD



Lesson learnt – wire bonding





Weakness of wire bondings and risk to short-circuit to be mitigated

– Segmentation of the DM circuitry (Orion ASIC will serve just 8 SDDs instead of the 32 of the Lyra ASIC)

– Review handling procedure to de-risk bonding contact during integration

– Passivation of the bonded PCB with a (thin) conformal coating

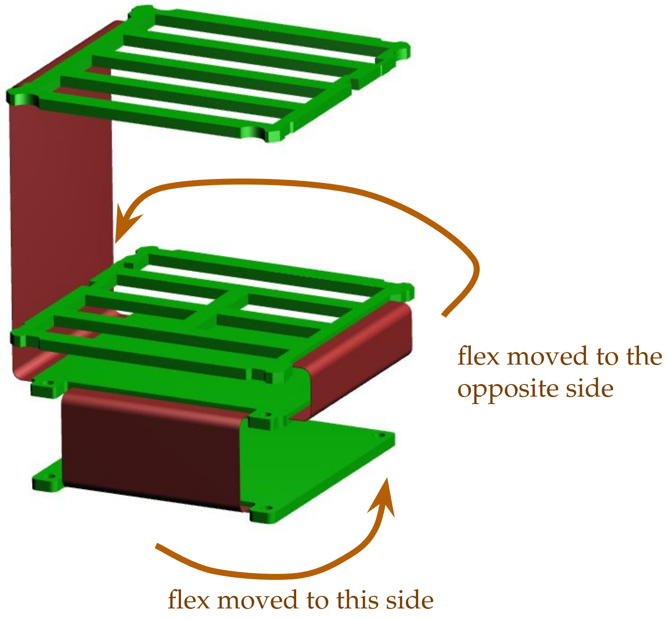
Lesson learnt – mechanical housing

Mechanical Housing design and integration procedure to be consolidated

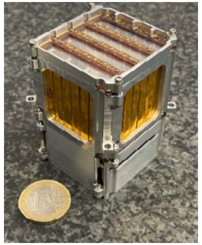
– Review mechanical design to allow more smart inspection of both top and bottom SDDs

– Crystals/SDDs/FEs assembly housed separately by BE/HV boards to ease and to better control clamping preloads

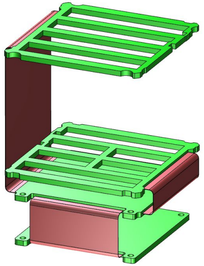
– More robust mechanical housing and fixation points with respect to in-plane loads



Future/potential R&D activities

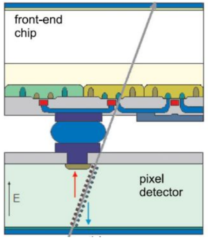


– New DM with the ORION ASIC (the ASIC specifically dedicated to XGIS);



– Optimization of the mechanical mounting: different assembly of the PCBs but **with the same mechanical concept**;

– Investigate a faster and more reliable SDD/ASIC assembly based on the **flip-chip ball-bonding method**



– Study of a mass production process for scintillator crystals bar cutting and wrapping

Conclusions I: THESEUS mission concept

– THESEUS is a powerful and innovative mission to fully exploit GRBs for studying the **Early Universe;**

– THESEUS will provide a fundamental contribution to **Multi-messenger astrophysics;**

– THESEUS was evaluated excellent for scientific, programmatic and technological aspects in Phase A of ESA M5, although it was not adopted;

– THESEUS has been assessed in Phase A of ESA M5: excellent evaluation under scientific, programmatic, technological aspects even if not adopted;

– THESEUS is now competing in M7. Downselection 6 → 3 mission proposals is expected in November 2023;

Conclusions II: the XGIS instrument status

A compact XGIS 8 x 8 pixels, 5 mm pitch DM **has been successfully realized**. Thermal-mechanical design needs to be consolidated

Light yield is preserved during temperature cycling. Light yield can be optimized to achieve the same light output of the single scintillator bar.

Mechanical housing needs to be consolidated to get a robust design able to survive the severe launch loads. The design concept needs to be refined considering the constraints in DM dimensions and pitch size using possibly a larger number of fasteners acting with a more uniform preload.

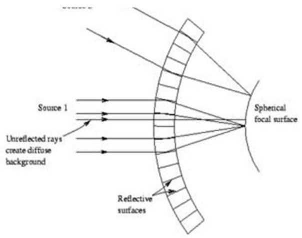
The DM design with ORION ASIC will offer advantages in some areas of the design that can be consolidated: more reliable SDD to PCB electrical bonding connections and the possibility to perform inspection on both detector sides.

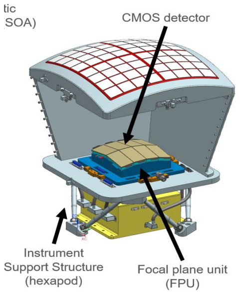
The THESEUS instrument configuration

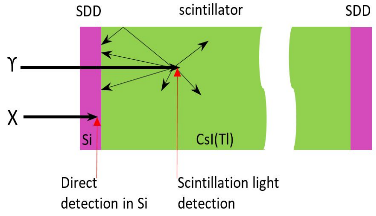
Soft X-ray Imager (SXI)
Two sensitive lobster-eye telescopes observing in 0.3 - 5 keV band, total FOV of ~0.5 sr with source location accuracy <2′

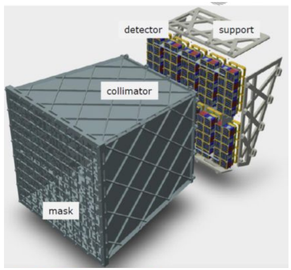
X-Gamma rays Imaging Spectrometer (XGIS)
Two coded-mask X-gamma ray cameras using Silicon drift detectors coupled with CsI crystal scintillator bars observing in 2 keV – 10 MeV band, a FOV of >2 sr, overlapping the SXI, with <15′ GRB location accuracy

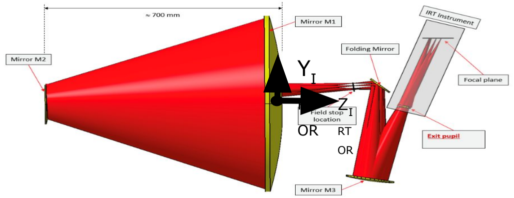
InfraRed Telescope (IRT)
A 0.7 m class IR telescope observing in the 0.7 – 1.8 μm band, providing a 15′x15′ FOV, with both imaging and moderate resolution spectroscopy capabilities



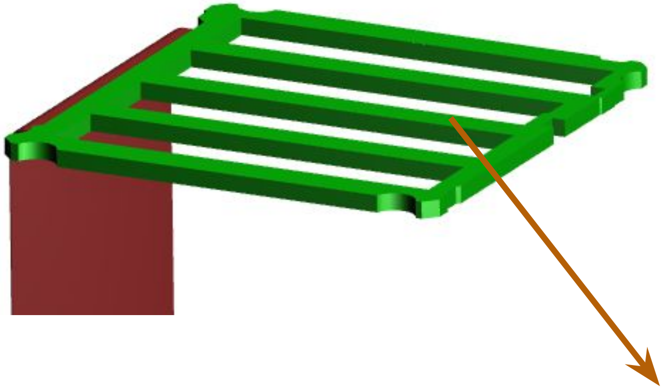


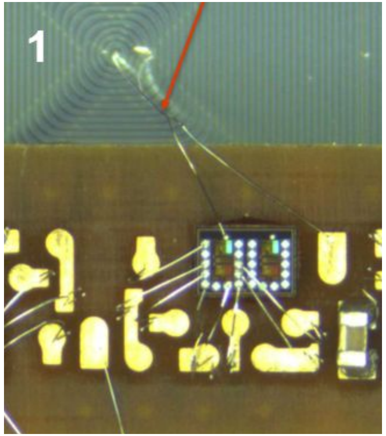


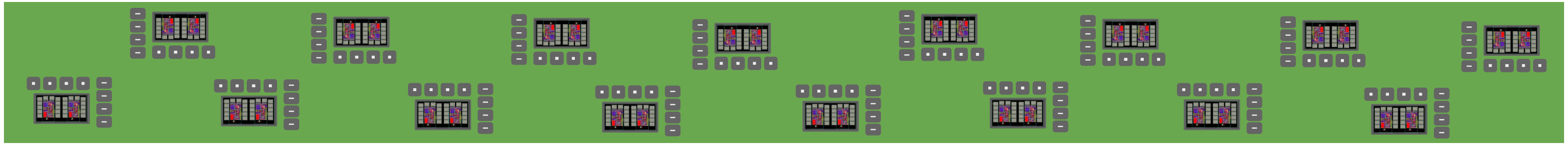




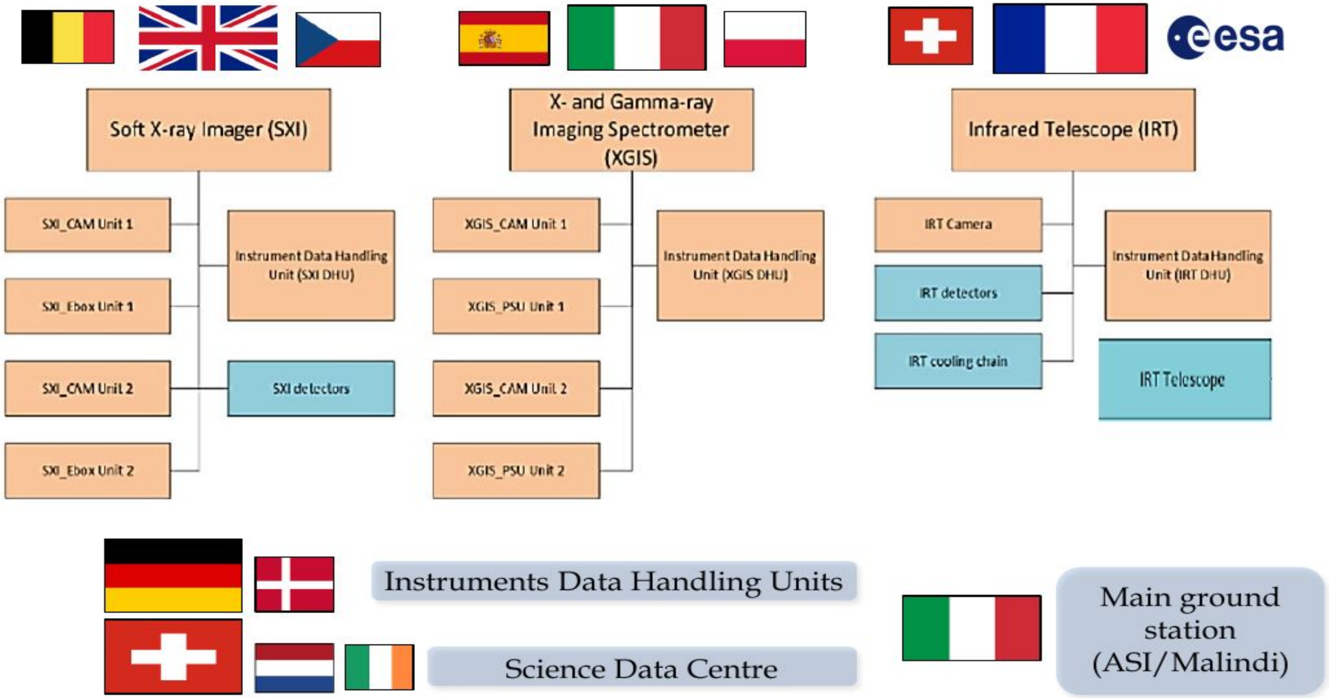
LYRA-FE ASIC: footprint and ECSS compliance







THESEUS consortium in **M5**



THESEUS consortium in **M7**