# F-class mission

# Wide-field Explorer for Discovering Gravitational wave Electromagnetic counterparts

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## Scientific goals of the mission

The advent of the second-generation interferometers, LIGO, Virgo and KAGRA, marked the beginning of the Gravitational Wave (GW) astronomy era and opened a new observation window into the population of stellar-mass compact-object binaries. The combination of GWs and traditional electromagnetic (EM) observations has a huge and broad impact on our understanding of stellar evolution, nucleosynthesis, fundamental physics, and cosmology. The best example is represented by the first and, up to now, only GW trigger (GW170817) from a binary neutron star (NS) merger. The EM counterpart has been discovered as a dim, short gamma-ray burst (GRB170817A), and a bright kilonova (AT2017gfo), a thermal transient powered by the decay of heavy radioactive species produced by rapid neutron capture (*r*-process), which are the most important sites for heavy element production in the Universe.

These multi-messenger events are associated with mergers involving at least one NS (either binary NSs - BNS, or black hole NS systems). With the current instrumentation, these events are rare and come with very large error regions. The GW170817 counterpart was detected thanks to a very peculiar combination of its extremely good localisation for a GW event (28 deg$^2$ error region, 90% confidence) and its close distance (40 Mpc). The associated GRB170817A was identified by *Fermi*-GBM and *INTEGRAL* with a very poor angular localisation, comparable to the GW error region.

Optical searches with wide-field telescopes started immediately, together with a galaxy-targeted search with narrow-field instruments, such as the X-ray telescope (XRT, 0.12 deg$^2$ field of view) and the Ultra-Violet Optical Telescope (UVOT, 0.08 deg$^2$ field of view) onboard *Swift*. The electromagnetic counterpart was discovered 11 hr after the GW trigger by the 1m Swope optical telescope. At 15.3 hr, the *Swift* satellite detected a bright, ultraviolet emission with an *m2* (~2250 Å) magnitude *m2*=21.1, rapidly fading within a few days and no X-ray emission (0.3-10 keV), with an upper limit of ~$2 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. The X-ray counterpart was detected later (~15 d) by *Chandra* with ~50 lower X-ray flux.

In the late '20s, we expect upgrades in the performance of the current interferometers, followed by (late '30s) a third generation of instruments such as the Einstein Telescope or the Cosmic Explorer, all of them being sensitive in the frequency range of emission of the mergers of compact objects of stellar mass. From space, in the late '30s, we will have the Laser Interferometer Space Antenna (*LISA*), sensitive to GWs at lower frequencies that will enable the detection of other binary populations, such as massive black hole binary (MBHB) mergers or binary white dwarfs. Unfortunately, the large error regions remain a drawback of future GW experiments, too. Over the 100-300 events yr$^{-1}$ expected with a 3rd-generation telescope like the Einstein Telescope, we expect ~1% of the events with a localisation better than 10 deg$^2$ and ~10% with a localisation better than 100 deg$^2$. With *LISA*, the predictions for MBHB are for error regions of the order of 10-100 deg$^2$.

Clearly, this represents the major challenge to face in designing future facilities to fully exploit the potential of multi-messenger astronomy. At optical wavelengths, the Schmidt design was invented long ago to cover aberration-corrected fields up to 50 deg$^2$. Several facilities are in place using 1-4 m diameter telescopes with innovative optical designs, allowing the astronomers to perform wide-field corrected observations. In this context, the field will be revolutionised with the upcoming advent of the Vera Rubin 8 m-equivalent telescope, covering a 10 deg$^2$ area. In the near-infrared, there are 1-2m class telescopes, covering only ~1 deg$^2$, hampered by the costs of the detectors. From space, *Euclid* and soon *Roman,* will provide access to a larger field of view, even if with a limited capacity of fast repointing. In the UV, the few facilities available have a very small field of view. In the near future, the launch of small missions is foreseen, like *QUVIK*, as well as the *ULTRASAT* and *UVEX* missions with 30 cm and 75 cm telescopes covering a field of view of ~210 deg$^2$ and ~12.5 deg$^2$, respectively.

In the X-ray band, there is a long tradition of all-sky monitors, especially at high energies, with coded-mask instruments. These instruments, however, are not particularly sensitive. A relatively small improvement in sensitivity has been obtained thanks to the Lobster-eye X-ray focusing telescopes onboard the *Einstein Probe* (WXT) and *SVOM* (MXT) missions. In particular, the first telescope has a very large field of view (~3600 deg$^2$), but only a few cm$^2$ of effective area, reaching shallow sensitivities

($\sim10^{-10}$ ergs $s^{-1}$ $cm^{-2}$ for 100s, 0.5-4 keV). On the other hand, there are clear advantages in performing rapid and sensitive searches of the EM counterpart of GW events in X-rays. At variance with the optical and UV bands, the X-ray sky is poor in new transients and allows for a prompt identification of the GW counterparts. Besides, the kilonova emission is very dim, and the horizon for its detection with Rubin is limited to ~300 Mpc in the most optimistic case.

We aim to overcome the present (and future) limitations on X-ray telescopes by studying a new concept mission for a wide-field, focusing X-ray telescope. We call this mission concept the Wide-field Explorer for Discovering Gravitational wave Electromagnetic counterparts (WEDGE).

When searching for the EM counterpart of a GW trigger, in the optical/NIR, one can look for the dim kilonova emission; in the UV, one can look for the cocoon shock cooling (a.k.a. blue kilonova) emission, which, however, might be hampered by absorption. One may wonder what to look for in the X-ray band. The cooling cocoon emission might be observable in the X-ray band, too, but it lasts for too short (~200 s), making the detection challenging. The most promising emission is instead the cocoon afterglow emission (see Fig. 1).

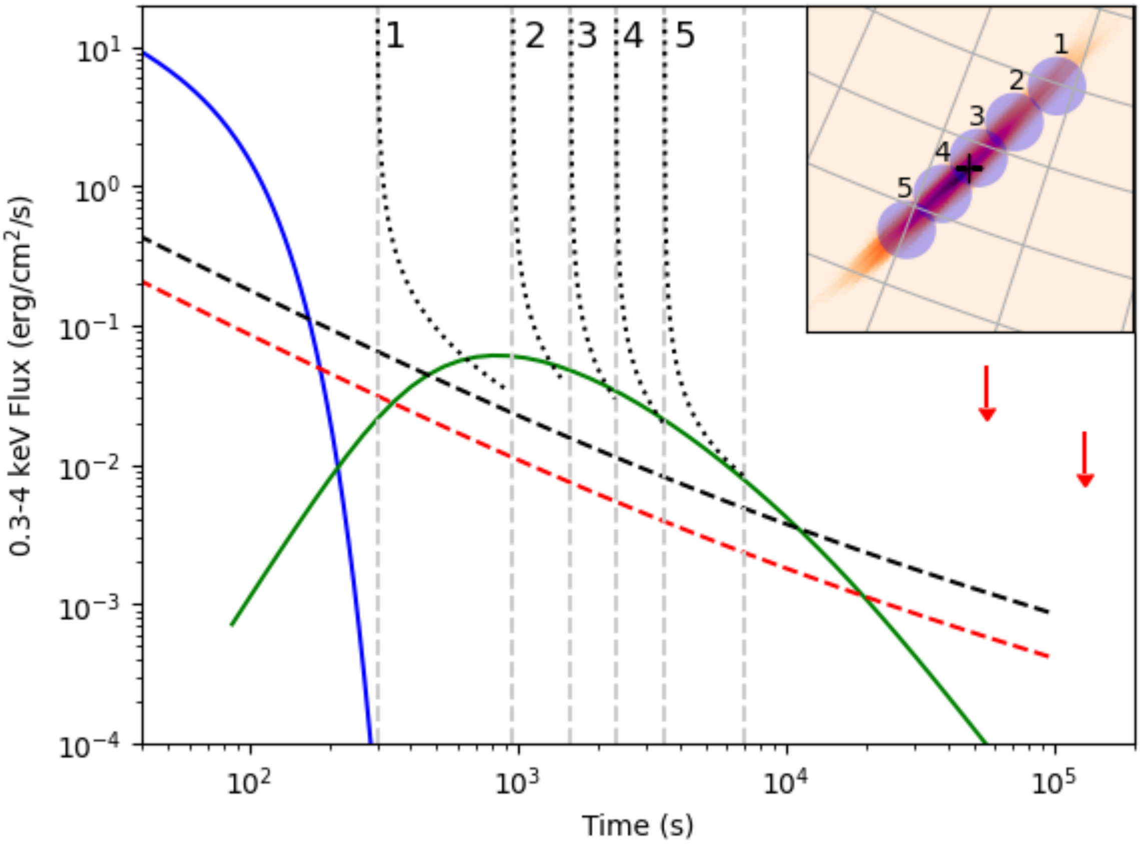


*Fig.1 Early time evolution of GW170817 X-ray flux (0.3-4 keV). The dashed lines are the WEDGE sensitivity for its nominal (black) and goal (red) effective area over 10 deg². The blue line is the predicted cocoon emission and the green line is the afterglow cocoon emission (for efficiencies $\varepsilon_e\sim0.1$ and $\varepsilon_B\sim0.01$) for GW170817 as simulated with the jetsimpy package. The downward arrows are the early Swift/XRT upper limits for GW170817. The dotted lines represent the sensitivity during the time window for 5 different and consecutive exposures (the first starting at 300 s) and covering a ~50 deg² error region. The dashed grey lines mark the start and the end of each exposure, including the satellite repointing. In all the time windows, the cocoon afterglow emission is detected. The inset shows the 5 pointings (numbered as 1 to 5) covering the GW170817 error region, with the counterpart position marked with a cross. Note that the Einstein Probe/SVOM sensitivities (a factor ~100 worse than WEDGE) are neither good enough to detect the cocoon emission nor its afterglow.*

The cocoon afterglow of GW170817 is detectable by WEDGE up to a distance of ~200 Mpc for the nominal configuration of WEDGE (see below) and up to ~1000 Mpc for the goal one. Further contribution to the early X-ray emission might come from an active magnetar produced during the BNS merger, or from the fallback disc accretion. Still, the cocoon afterglow emission is not long-lasting, calling for a fast-repointing capability (~5 min timescale).

Besides discovering the GW counterparts, WEDGE will also contribute to shedding light on the early emission mechanics. The expected rate of binary neutron star mergers is 10-1000 Gpc$^{-3}$ yr$^{-1}$ and 150 Gpc$^{-3}$ yr$^{-1}$ for neutron star black hole mergers, and a horizon for GW experiments of at least 300 Mpc results in a suitable number of objects observable during the mission lifetime. We also note that the discovery of even a limited number of GW counterparts will have an enormous impact on cosmology (e.g. Hubble constant), rather than relying on dark sirens.

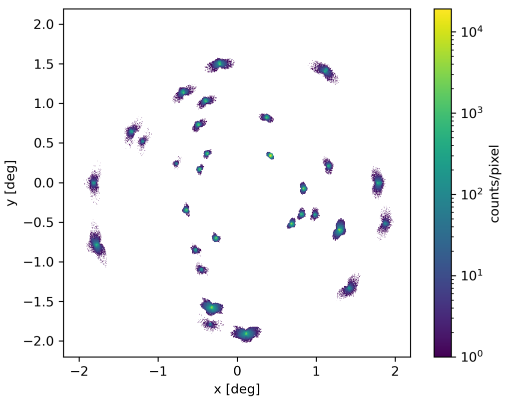


*Figure 2: Left: Example of a short exposure of a field crowded by bright X-ray sources observed by WEDGE.*

Characteristic X-ray counterparts are also expected both during the final phases of the *LISA* MBHB inspiral and after the binary merger. Unlike higher-frequency GW triggers, the low-latency data analysis of the *LISA* data stream promises to identify sources up to weeks before coalescence, when the MBHB light curve is expected to be periodically modulated by multiple physical processes.

Doppler boosting, in particular, is expected to imprint large (on the order of 0.1) relative fluctuations on the observed flux when the binary is in the *LISA* frequency band. Assuming a million solar mass binary accreting at the Eddington limit and a bolometric-to-X-ray conversion of 0.1, WEDGE will be capable of detecting pre-merger *LISA* sources out to a $z$~0.2, and of detecting their variability up to a $z$~0.1. WEDGE's large field of view will be instrumental in detecting pre-merger *LISA* MBHBs, as the *LISA* sky localisation uncertainties at this stage will remain large (~100 deg$^2$) despite the low redshift of the source. Accretion activity is expected to cease shortly before coalescence (~1 d), and to resume at a fraction of the Eddington rate months to years later under the most optimistic scenarios. The wide field of view of WEDGE will enable the identification of this drastic drop in the X-ray flux, helping to pinpoint the host galaxy of the merging MBHB and guide future, longer-timescale follow-up observations.

Besides its main goal (i.e. detect the electromagnetic counterparts of gravitational wave triggers in the X-ray band), WEDGE can perform a plethora of secondary science goals. Thanks to its repointing capabilities, WEDGE can follow up fast-evolving transients to improve their positional accuracy (as *Fermi* GRBs) or to search for their X-ray emission (as shock breakout discovered by the *ULTRASAT* UV satellite in orbit, or the Rubin telescope on ground), magnetar tails, superoutbursts from X-ray binaries, fast radio bursts. Thanks to the short time needed to repoint the satellite (~5 min), WEDGE is also suited to monitor a number of transient sources, from X-ray binary outbursts in our Galaxy to Tidal Disruption Events. Thanks to the large field of view, WEDGE can also monitor large regions of the sky to look for transients, like *Swift*/XRT is doing for the Galactic centre, 1 ks a day (see Fig. 2). These regions can be, e.g., the Galactic centre and its bulge, the Andromeda galaxy (~7 deg$^2$), the Magellanic clouds (~200 deg$^2$ the Large and ~75 deg$^2$ the Small) or the Virgo cluster (~200 deg$^2$). In addition, the EM counterpart of neutrino sources can be searched for to take advantage of the new generation of neutrino detectors (P-ONE, KM3NeT, etc.).

WEDGE has basically the same grasp (i.e., effective area × field of view) as eROSITA, with a slightly worse angular resolution. Thanks to its low Earth orbit, the WEDGE background will be low, comparable with the *Swift*/XRT one, thus allowing for the extensive study of diffuse emission. This can be used to map the external regions of clusters and groups of galaxies, as well as supernova remnants and *Fermi* or eROSITA bubbles.

## Mission configuration, mission profile, payload/instrument configuration

To achieve the sensitivities required for the faint X-ray emission of GW merger events (see above), one should rely on focusing X-ray telescopes rather than on coded-mask instruments. Up to now, classical Wolter-I grazing-incidence telescopes were able to reach ~3 deg$^2$ field of view (FOV) and ~150 arcsec Half Energy Width (HEW) at 1 deg off-axis radius with *ROSAT*, whereas Lobster-eye telescopes, such as the one flying nowadays on *Einstein Probe*, which covers ~3600 deg$^2$, but with a very small effective area and a much worse angular resolution (a few arcmin FWHM).

We developed a modified Wolter I design able to cover a 10.2 deg$^2$ FOV (1.8 deg radius) with an HEW (at 1 keV), always better than ~130 arcsec (Fig. 3). The effective area is larger than ~100 cm$^2$ at 1 keV (Fig. 3). The FOV is limited by the grazing incidence angles, the area by the allocated payload mass.

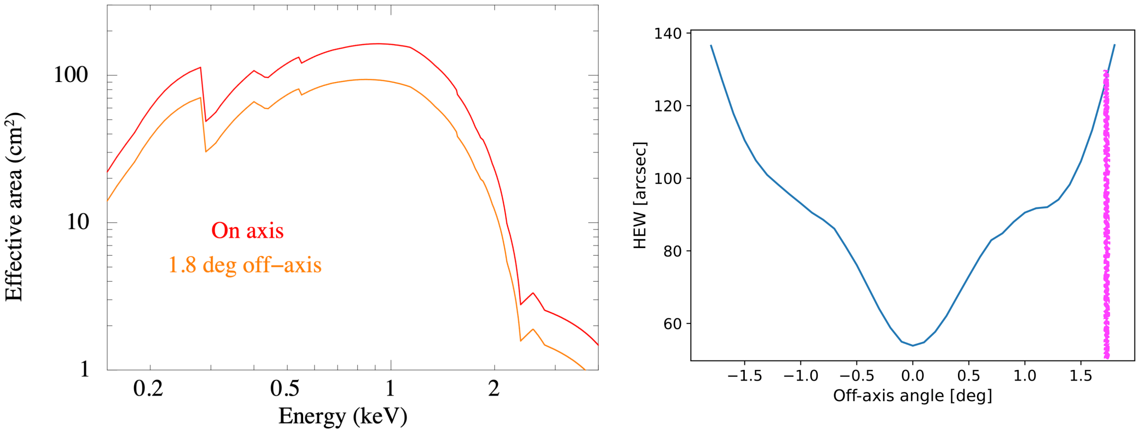


*Figure 3: Left: Effective area as a function of energy on-axis (red) or at the edge of the field of view (1.8 deg radius, orange) as a function of energy. Right: Half energy width (HEW) of the modified Wolter-I design.*

The design of the WEDGE X-ray telescope modifies the standard Wolter-I system to achieve a significantly larger field of view. Wolter-I optics typically consist of many confocal paraboloid and hyperboloid shells nested together, which increases the effective area compared to a single grazing incidence shell. By tilting the shells in various directions, we can expand the field of view. In such a way, we obtain a much larger field of view and grasp, at the cost of slightly reducing the effective area and worsening the angular resolution on-axis.

The WEDGE X-ray telescope baseline design comprises 25 nested parabolic + hyperbolic monolithic mirror shells, with radii ranging from 120 mm to 341 mm and a total height of 150 mm; the focal length is 1600 mm. In the innovative WEDGE system, the shells are tilted by 0.9 degrees each, with tilt position angles distributed uniformly in all directions.

The grazing-incidence shells will be manufactured using nickel electroforming replication, a ready-off-the-shelf technology (TRL=9) developed in Italy that has been successfully employed in making the mirrors of several telescopes, including *BeppoSAX*, *XMM-Newton*, *Swift*, eROSITA, and *Einstein Probe*/FXT. Moreover, the replication mandrels have already been developed, as we intend to use the ones fabricated for the eROSITA and *Einstein Probe*/FXT X-ray telescopes. This will significantly reduce development and manufacturing time, as well as minimise the risks associated with implementing the WEDGE X-ray telescope. For WEDGE, the mirror weight can be further reduced compared to previous missions by thinning the mirror shells. The adopted thickness depends on the length of the mirrors and the desired on-axis half-energy width. Thus, the shells can be made significantly thinner than usual instead, given our relaxed requirements regarding the on-axis HEW. Compared to eROSITA (thickness/radius of 0.005), we can assume a ratio of 0.00175, with a very relevant gain in terms of mass saving. The total weight of the mirror module is ~25 kg, including its supporting structure and spiders. If more mass is allocated to the mirror module, we can increase the total effective area by increasing the number of mirror shells. Since the large field of view is produced by the tilting of shells in different directions, the incidence angles are higher than usual for on-axis Wolter-I systems, causing the overall effective area to decrease rapidly with energy, and resulting in an effective energy range of 0.3-2 keV (see Fig. 3). The efficiency up to 4 keV can be extended by studying an appropriate multilayer coating – effective at these higher angles.

Charge-Coupled Devices (CCDs) have long been the standard for soft X-ray observations due to their excellent image quality and high sensitivity. Today, scientific Complementary Metal-Oxide-Semiconductor (CMOS) sensors approach the image quality and readout noise levels of CCDs. For soft X-ray applications, the introduction of backside-illuminated (BSI) CMOS sensors has been particularly impactful, addressing the shallow penetration depth of X-rays in silicon. Optimised BSI CMOS sensors, with minimised dead layers, have now demonstrated excellent quantum efficiency in the soft X-ray regime.

The core element of a CMOS sensor is the pixel. The signal is buffered by an in-pixel amplifier and read out via column-parallel architectures. Each column (or group of columns) is typically equipped with its own amplifier and analogue-to-digital converter. This parallel readout scheme enables high frame rates, up to several frames per second, greatly enhancing the pile-up handling capability for single-photon detection. Furthermore, the high-speed readout reduces the need for extreme cooling, relaxing thermal requirements and simplifying instrument design. Another critical advantage of CMOS sensors in the context of space applications is their inherent resistance to radiation-induced Charge Transfer Inefficiency. The technology readiness level of CMOS is high (TRL=9). Monolithic CMOS image sensors are already in use (*Einstein Probe*) or planned for several upcoming space missions targeting the soft X-ray band. We plan to adopt 4 CMOS detectors mounted in an inverted pyramidal shape (as *Einstein Probe*/FXT) to cover the 10 deg$^2$ WEDGE focal plane.

The following major points drive the preliminary exercise of the spacecraft design for the WEDGE mission:

- The payload module (PLM, composed of a Mirror unit and Detector unit) is assembled in a single module to be accommodated on the spacecraft.
- The service module (SVM) is preliminarily sized for the mission. Anyhow, the policy is for the utilisation of a recurrent, well-proven service module. The service module class is widely available in the European Space sector (e.g. PROTEUS from CNES).
- The ground station characteristics (S-band, one contact per orbit) are assumed to be Equatorial (e.g. ASI's S-band ground station in Malindi, Kenya).
- For procurement selection, as far as possible, off-the-shelf or recurrent equipment and proven technology (TRL>5, for critical components of the payload cases, we are almost at TRL = 8 or 9).
- No procurement risk for components (ITAR free).
- Full redundancy has to be provided for service subsystems.
- Simple system architecture concept.
- A detailed resource budget to verify the consistency of the choice.
- Standard ESA margin philosophy is applied to the budgeting of resources.

The main sub-systems which have been considered in the preliminary design are:

- Structure and accommodation of the payload
- Thermal Control System
- Attitude and Orbit Control System
- On-board data handling
- Telecommunication and ground link
- Electrical Power System

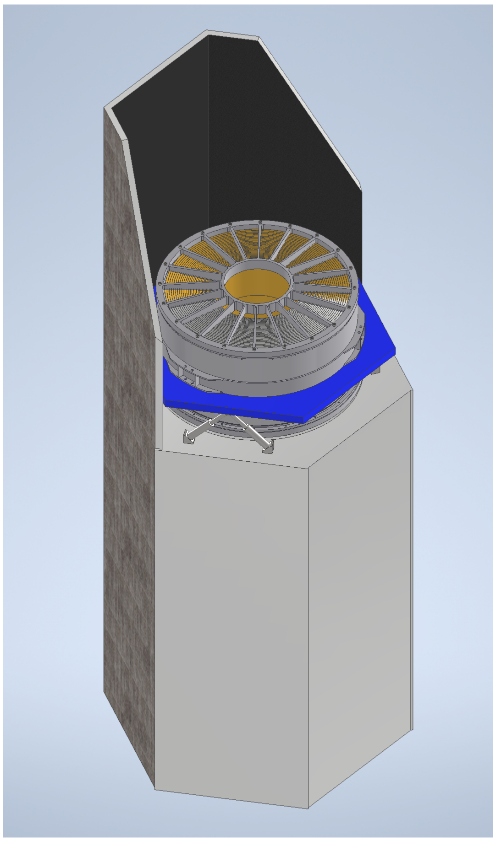


*Figure 4: Top view of the WEDGE satellite.*

A preliminary concept of WEDGE was carried out in collaboration with Apogeo Space (https://www.apogeo.space).

WEDGE will have an equatorial Low Earth Orbit to allow for prompt communications and reduce the background. An agile slew manoeuvre is guaranteed by the use of Control Momentum Gyro (CMG). At present being the identified CMG is the model CMG 15-45 S from Airbus.

The Thermal Control System (TCS) can be implemented following a standard approach. This is clearly an area which can be significantly optimised by means of detailed thermal and orbital analysis. The TCS will be developed into two levels: the PLM dedicated thermal control and the SVM thermal control.

The telecommunication (TT&C) sub-system includes a standard S-band TM/TC link between S/C and Earth for standard S/C operations. This standard link operates in S-band for a TC rate of about 2-4 kbps. For the TM rates, we envisage the use of the high transmission rate, expected to be available (2 Mbps). Uploading/ downloading foreseen in the framework of flight operations will be done through equatorial ground stations (e.g., @ Malindi and/or @ Korou).

The satellite includes a functionality named WEDGE GW Broadcasting (WGB), which shall allow GW alerts to be uplinked to the satellite to perform a series of pointing, as well as to download data to the ground. This functionality has two options:

- A low-frequency bidirectional link (VHF or UHF) to a network of compact ground stations (this is the strategy adopted by CNES for the *SVOM* mission).
- A bidirectional intersatellite link (already proven for the ASI-AGILE).

A preliminary breakdown of the payload was made, which formed the basis of the accommodation study for the satellite and was also used to estimate mass, volume and power. The top-level hardware tree, including all satellite systems, has been produced. In Table 1, we summarise the total satellite budgets.

We have identified no critical items, but during the next phase, detailed modelling of the thermal design and the fast-repointing system will have the highest priority.

*Table 1: Total (preliminary) satellite budget.*

| Parameter | Mass (kg) | Power (W) | Max Power |
|---|---|---|---|
| Payload Module | 58 | 50 | 50 |
| Service module | 341 | 259 | 323 |
| Propellant | 10 | | |
| System margin* | 81 | 31 | 37 |
| Total | 490 | 340 | 411 |

** 20% on mass, 10% on max power.*

## Planned management structure, payload consortia composition and expected main funding agencies

The management structure is led by an agile Project Office, headed by INAF, and comprises the Principal Investigator (Campana), his deputy (Bernardini), and the responsible for the WEDGE focal plane (Uslenghi), along with the support of other key project members with proven experience in the implementation of X-ray missions. Scientific and pragmatic matters are addressed by the Science Board, which includes one representative from each of the participating institutes.

The WEGDE project has a profound heritage. All the Science Board members are involved in successful missions: Campana and Evans are the European PIs for the *Swift* mission; Rea is one of the ESA representatives for the *Einstein Probe* mission; Vergani is a member of the French team for the *SVOM* mission and oversees the GRB follow-up; Merloni is the project scientist for the eROSITA experiment. Italy (INAF and ASI) will lead the project. INAF, with the support of MPE, will be responsible for the optomechanical design of the X-ray telescope. INAF and MPE will support ESA in following the industrial contract for the implementation of the X-ray telescope. In an earlier stage of the project, we will investigate the impact of stray light and the need for a mirror buffle. The mirror will be replicated on mandrels, reusing (part of) the eROSITA mandrels, reducing costs and speeding up the project timeline. As the baseline design, WEDGE will consist of 25 mirror shells (in case, the production time for one new mandrel is ~1 month). The estimated overall cost for the realisation of the optics system (including the possible need for rapid repolishing of mandrels, as they have already been used for numerous replications after eROSITA and *Einstein Probe*/FXT; this point will be evaluated by careful measurement of the microroughness of the eROSITA mandrels) is 10 M€, with just the replica costing around 5 M€. The likely industry capable of producing the mirror replica is Media Lario (I) (https://www.medialario.com), with a successful history of projects carried out in collaboration with ESA, ASI, INAF, and MPE. We plan to establish a preliminary integration facility at the INAF-Brera Observatory (1 M€) to test the integration of the new thin shell system with off-axis distribution of the mirror shells. The developed know-how will then be transferred to Medialario to integrate the mirror module fully. In our vision, as already happened for the *XMM-Newton* mirrors, ESA will fund these activities. The X-ray testing and calibrations will be carried out using the ESA-supported Beatrix+ and Panter facilities installed at the INAF-Brera (Merate, Italy) and MPE (Munich, Germany) facilities.

Italy will provide the focal plane. We estimate the need for 6 engineering and 6 science CMOS detectors. We will develop the real-time, photon event processing unit, based on a Field Programmable Gate Array (FPGA) for on-board processing. The industry of CMOS sensors is fast-evolving, and a mature assessment is not available at present. We expect an overall cost of ~25-30 M€ (which can be reduced if progress in CMOS sensors is fast). The focal plane and related electronics will be worked out under the responsibility of INAF-IASF Milano and paid for by Italy.

The Instrument Control Unit (ICU), which is aimed at operating all the subsystems, as well as at implementing the main functional interfaces of the instrument with the S/C control unit, will be built by ICE-CSIC, building on the experience of *NewAthena*'s ICU.

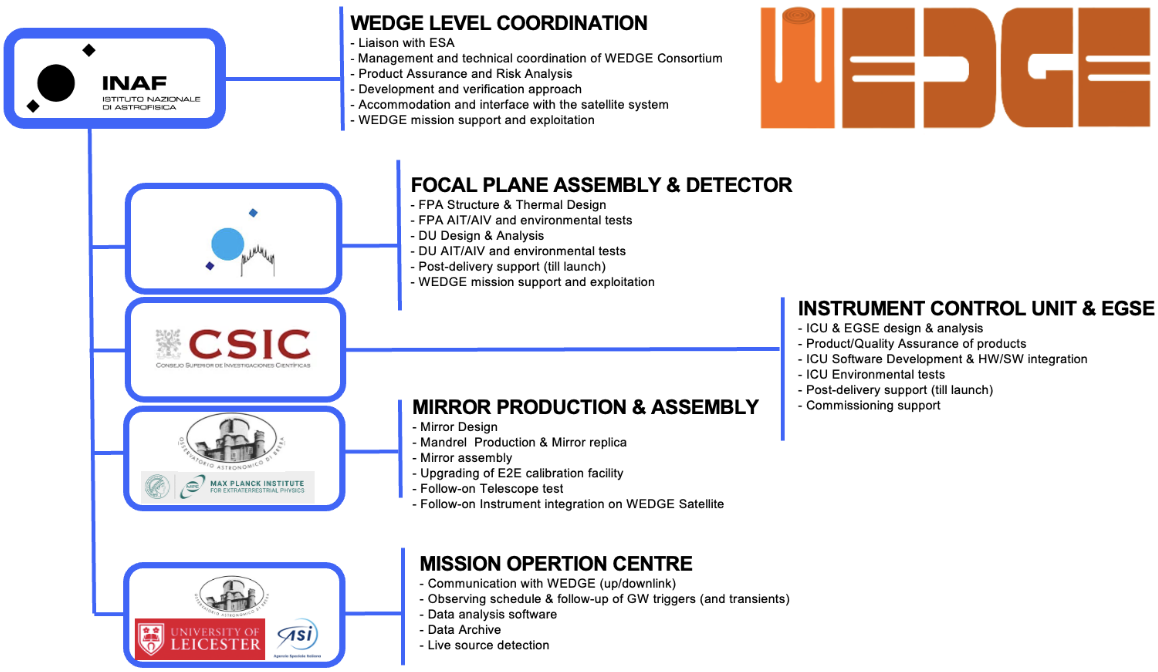
WEDGE will be in low Earth orbit with the Malindi (ASI) ground station able to download the data with one passage per orbit.

The continuous connection with the WEGDE satellite can be guaranteed by the (to be upgraded) VHF/UHF network of CNES currently used by the SVOM mission, or by a commercial infrastructure, as has been selected for *HERMES* or is foreseen for the cubesat *CHIPS*, such as IRIDIUM. This will assure us the possibility to upload the new observational sequence and to download a limited amount of scientific data.

WEDGE requires a dedicated Mission Operation Centre (MOC). This is needed to allow for 24/7 commanding of the WEDGE satellite, in response to the unpredictable GW events and other fast-reaction transients. This represents a crucial aspect of the WEDGE mission. The heritage with the *Swift*

MOC here is heavy. We plan to work out pre-defined procedures to react to GW alerts (and other fast transients) and produce, in real time, a new observing schedule (several pointings) to be uploaded to the satellite to cover the GW error region. The incoming GW alert and the production of the new observing schedule will take less than half a minute, and then WEDGE will start the follow-up observations within ~5 minutes. If this cannot be provided by ESA, we estimate a cost of 5-10 M€ for the initial 3 years of the mission, based on the current *Swift* MOC operations.
The WEDGE Science Data Centre will be shared by ASI and the University of Leicester, where a pipeline for the detection in real-time of new transients in the WEDGE images will be carried out, as is currently ongoing with the Living Swift XRT Point Source Catalogue.

## WEDGE Consortium organisation chart



**WEDGE LEVEL COORDINATION**

- Liaison with ESA
- Management and technical coordination of WEDGE Consortium
- Product Assurance and Risk Analysis
- Development and verification approach
- Accommodation and interface with the satellite system
- WEDGE mission support and exploitation

**FOCAL PLANE ASSEMBLY & DETECTOR**

- FPA Structure & Thermal Design
- FPA AIT/AIV and environmental tests
- DU Design & Analysis
- DU AIT/AIV and environmental tests
- Post-delivery support (till launch)
- WEDGE mission support and exploitation

**INSTRUMENT CONTROL UNIT & EGSE**

- ICU & EGSE design & analysis
- Product/Quality Assurance of products
- ICU Software Development & HW/SW integration
- ICU Environmental tests
- Post-delivery support (till launch)
- Commissioning support

**MIRROR PRODUCTION & ASSEMBLY**

- Mirror Design
- Mandrel Production & Mirror replica
- Mirror assembly
- Upgrading of E2E calibration facility
- Follow-on Telescope test
- Follow-on Instrument integration on WEDGE Satellite

**MISSION OPERTION CENTRE**

- Communication with WEDGE (up/downlink)
- Observing schedule & follow-up of GW triggers (and transients)
- Data analysis software
- Data Archive
- Live source detection