condensed matter

Article

X-ray Technologies for Astrophysics Missions Supported by the Italian Space Agency

Marco Miliucci [1], Angela Volpe [1,*], Sergio Fabiani [2], Marco Feroci [2], Luca Latronico [3], Claudio Macculi [2], Luigi Piro [2], Matteo D'Andrea [2], Flavio Gatti [4], Simonetta Puccetti [1], Paolo Soffitta [2] and Elisabetta Cavazzuti [1]

1 Agenzia Spaziale Italiana, Via del Politecnico snc, 00133 Roma, Italy; marco.miliucci@asi.it (M.M.)
2 Istituto di Astrofisica e Planetologia Spaziali, Via del Fosso del Cavaliere 100, 00133 Rome, Italy
3 Sezione di Torino, Istituto Nazionale di Fisica Nucleare, Via Pietro Giuria 1, 10125 Torino, Italy
4 Physics Department, Genova University, Via Dodecaneso 33, 16146 Genova, Italy
* Correspondence: angela.volpe@asi.it

Abstract: The Italian Space Agency plays a key role in the fulfillment of space missions, contributing to the scientific, technological and economic progress in Italy. The agency accomplishes space experiments by collaborating with scientific and industrial entities, supporting them in the realization of new projects able to achieve, over the last two decades, unprecedented results and obtention of fundamental information on the birth and evolution of the universe. The paper describes a selection of X-ray technologies developed by the synergy between the Italian Space Agency and its principal collaborators which contributed to the main scientific results achieved over the years, together with the latest advances addressed to the next astrophysics missions.

Keywords: space; astrophysics; X/gamma ray technologies

PACS: 07.87.+v; 95.55.Ka; 95.55.Aq

check for updates

Citation: Miliucci, M.; Volpe, A.; Fabiani, S.; Feroci, M.; Latronico, L.; Macculi, C.; Piro, L.; D'Andrea, M.; Gatti, F.; Puccetti, S.; et al. X-ray Technologies for Astrophysics Missions Supported by the Italian Space Agency. *Condens. Matter* **2024**, *9*, 11. https://doi.org/10.3390/condmat9010011

Academic Editor: Bernardo Barbiellini

Received: 17 November 2023
Revised: 21 December 2023
Accepted: 4 January 2024
Published: 19 January 2024

1. Introduction

The Italian Space Agency (Agenzia Spaziale Italiana, ASI) is oriented towards developing a coherent and synergic action with the various components of the space community (private and public research centers, universities, start-up, small–medium–large enterprises) to achieve the advancement in knowledge, technology and competitiveness, strengthening the international dimension of the entire sector. The Agency supports the creation of the right conditions to seize the numerous opportunities offered by European development programs and those at an international level.

ASI funds and coordinates scientific space programs, from the design phase to final delivery, supporting the excellent Italian industrial and scientific skills for the construction of scientific instruments (payloads) for medium–large space missions (typically in collaboration with ESA and NASA) and the development of satellites and their ground management.

Among the wide range of science topics supported by the ASI, the sector presently defined as "Study of the Universe" involves several scientific missions addressing the following principal themes: Astrophysics, Solar System, Exoplanets, Cosmology and Fundamental Physics. The main objective concerns the implementation of the internationally agreed Scientific Program of ESA, in which the Italian scientific and industrial community are involved through the management and coordination of activities for the realization of scientific instrumentation, satellites and data analysis. In the international panorama of Space Science, Italy also participates in scientific missions of **NASA (National Aeronautics and Space Administration), JAXA (Japan Aerospace Exploration Agency), ROSCOSMOS and CNSA (China National Space Administration)**.

Moreover, in synergy with Study of the Universe, the Space Science Data Center, SSDC (http://www.ssdc.asi.it/ accessed on 1 January 2024), is an internationally recognized top level center for data **archiving**, distribution and analysis from all scientific missions funded by ASI [1].

The Italian scientific community and industry sector gained an internationally recognized leadership for the construction of scientific instruments employed in medium–large space missions for the development of satellites and the mission ground segment (SSDC and Luigi Broglio Space Center at Malindi). Thus, Italy is among the leading countries in the space sector under the coordination of the Italian Space Agency.

This paper focuses on the X-ray technologies within this context for astrophysics missions in view of both the scientific goals reached over the last 20 years and the future missions.

2. X-ray Technologies for Astrophysics Missions

High-energy astrophysics in the X and Gamma **ray** bands sees an internationally recognized leadership of the Italian scientific community. The excellence of the activities related to this topic is demonstrated by the scientific results obtained first with BeppoSAX [2] and currently with AGILE [3], as well as by the participation, with a primary role, in the NASA IXPE mission [4] and in close future missions, like eXTP [5] and ATHENA [6].

2.1. BeppoSAX

Astronomer Giuseppe (Beppo) Occhialini was one of the pioneers for the study of cosmic rays. The BeppoSax mission [7] was born from the collaboration between ASI and Netherlands Agency for Aerospace Programs (NIVR). It was launched in 1996 from the Kennedy Space Center in Cape Canaveral over a low-altitude equatorial orbit, taking advantage of its low noise (due to particles and modulation). The satellite was operated bidirectionally from the Rome Control Center (command transmission and telemetry acquisition) with the Malindi base in Kenya as an exchange node every 96 min, for 10 min. Due to the relevant scientific outcomes provided, the mission was awarded over the years with Bruno Rossi Prize (1998), Descartes Prize (2002), Fermi Prize (2010) and Shaw Prize (2011).

The goal of the mission was to study cosmic emissions in the X-ray energy band, not observable from Earth due to absorption by the atmosphere. In particular, it contributed to the study of cosmic phenomena that simultaneously emit X-rays from 0.1 keV to 300 keV to understand the related astrophysical mechanisms. During the 6-year mission, it was possible to observe all X-**ray** band emission classes (GRB, galactic sources, Supernovae, AGN) and release more than 1500 scientific publications. The greatest success was the observation of Gamma Ray Bursts, discovering for the first time the accompanying X-ray emission (X-rays afterglows). The GRB970228 [8] event was the first discovery of X-rays recognized as afterglows of a GRB and from which, being able to determine distances, it was possible to associate it with explosions of massive stars in distant galaxies. Subsequently, the GRB980425 [9] event demonstrated the association of a GRB event with the supernova.

The BeppoSax technological breakthrough [10] was the wide energy spectrum (0.1–300.0 keV) detectable by its instrument (see Figure 1), never obtained in previous missions. In addition to the extraordinary energy amplitude, the satellite allowed the observation of transient phenomena due to Wide Field Cameras [11] (WFCs) and Gamma Ray Burst Monitors [12] (GRBMs) coupled with the narrow field-high energy resolution instruments. Moreover, its flexible operational capabilities allowed relatively fast implementation for its epoch and targets of opportunities. The payload consists of Narrow Field Instruments (NFIs, aligned and with a spectral range of 0.1–300.0 keV); Wide Field Instruments (WFIs, orthogonal to the NFI and oppositely oriented, offering coverage between 2.0 and 30.0 keV) and the GRBMs, partial NFIs shield, to trigger for gamma rays due to the temporal resolution of 1 ms and spectral coverage within 60–600 keV.

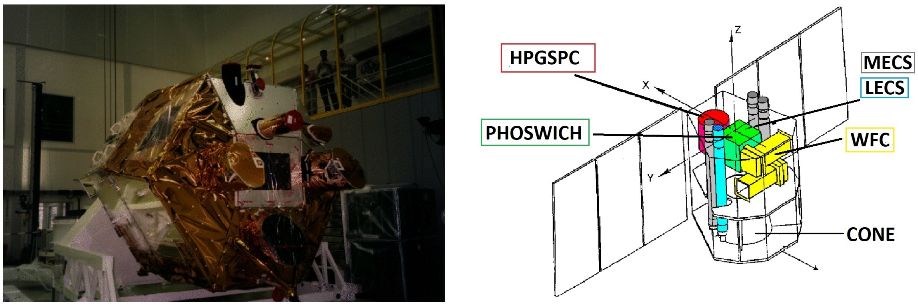

Figure 1. The BeppoSax satellite (**left**) and schematic view (**right**).

The Italian contribution was mainly aimed at the realization of the Medium Energy Concentrator Spectrometer (MECS), the High Pressure Gas Scintillation Proportional Counter (HPGSPC [13]) and the Phoswich Detection System [14] (PSD, including the Gamma Ray Burst Monitor, GRBM) detectors together with the optics for both the X-ray telescopes equipped with proportional scintillation counters at their focal plane: Low Energy and Medium Energy Concentrator Spectrometer (LECS [15] and MECS [16]). More details are presented below.

- MECS: three telescopes, each one consisting of a Conical Wolter I type grazing incidence X-ray optics coupled to a Gas Scintillation Proportional Counter for the X-ray detection in the 1.3–10 keV range;
- LECS: telescope with a thin window position sensitive Gas Scintillation Proportional Counter to extend, with respect to MECS, the detection range down to 0.1 keV;
- HPGSPC: Gas Scintillation Proportional Counter for the X-ray detection in the 4.0–120.0 keV range;
- PSD: Na(Tl)/CsI(Na) scintillator crystals in phoswich configuration to detect X-ray events, filtered by the gamma rays taking advantage of the "sandwich configuration".

The experience earned during the pioneering BeppoSax was helpful for successive missions, for example:

- *AGILE*: Italian mission. For the first time, AGILE [17] combined, in a single satellite (see Figure 2), a gamma detector (Si-W tracker [18,19], a 30 MeV–50 GeV), an X-ray detector (Si, 18–60 keV), a CsI Calorimeter [20] for the reconstruction of the ray energy gamma and an anti-coincidence system. Launched in 2007, in 2012 it was awarded with the Bruno Rossi prize for having revealed a variability in the emission of the Crab nebula, recording flares likely linked to the neutron star rapidly rotating on its axis [21].
- *Fermi*: Since 2008, it has been scanning the sky providing a map of the Universe in the gamma ray wavelength. It is the largest operating silicon strip detector in space, with its 70 m^2 of active surface. The mission [22] is the result of a collaboration between NASA and ASI, which supports the construction of the LAT detector [23]. Over the almost two decades of operations, FERMI has been awarded with four Bruno Rossi prizes.

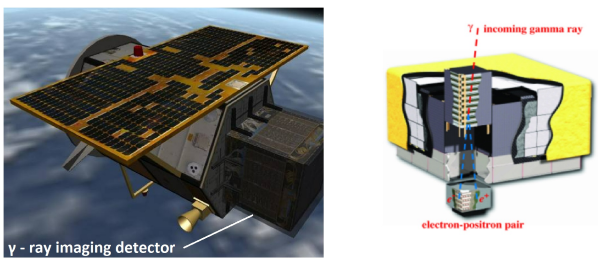

Figure 2. Artistic view of the AGILE satellite (**left**). Working principle of AGILE and Fermi Gamma ray monitor (**right**) [https://www-glast.stanford.edu/instrument.html, accessed 1 October 2023].

2.2. IXPE

IXPE is a NASA–ASI Small Explorers (SMEX) collaborative mission [4] (see Figure 3), selected in 2017 and launched on December 2021 aboard a SpaceX Falcon-9 rocket. The goal of the mission is measuring the X-ray polarization from neutron stars, black holes, active galactic nuclei (AGNs) and angular resolved polarimetry for the brightest extended sources like supernova remnants (SNRs), pulsar wind nebulae (PWNe) and large-scale jets in AGNs.

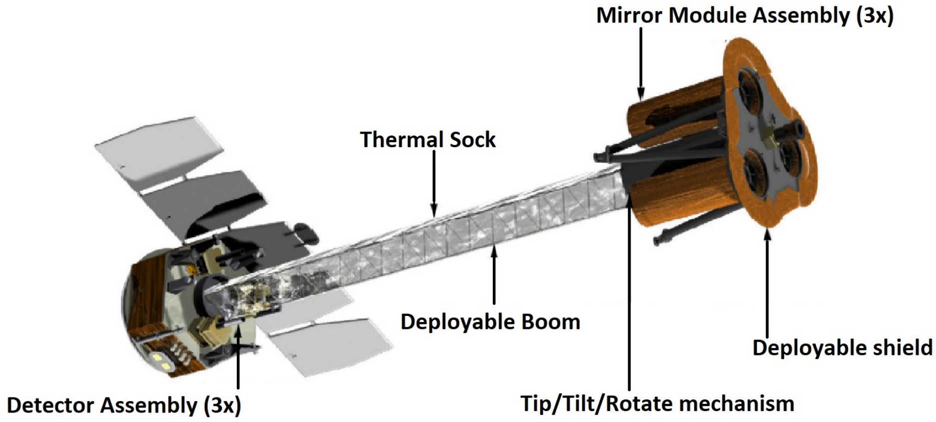

Figure 3. The IXPE telescope.

The observation of light originating from distant sources and their environments can solve fundamental questions about source geometry and emission mechanisms or even exotic effects in extreme environments, thus providing useful constraints to overcome the current proposed model of cosmic data explanation.

The two years of nominal operations brought many exciting results. Polarization allows assessment of the break of symmetries in the geometry of astrophysical sources including scattering of X-rays in accreting systems, magnetic field ordering or turbulence, and polarizing QED effects in a strong magnetic field. IXPE measured the polarization of the Vela Pulsar Wind Nebula (PWN) very close to the synchrotorn limit (exceeding 60% at the leading edge) and unveiling also the magnetic field structure responsible for the synchrotron emission in the X-rays [24]. The imaging capability of IXPE also allows measurement of the polarized X-rays from supernova remnants [25] and from the reflection of molecular clouds nearby the supermassive black hole in the center of our galaxy [26]. The unprecedented sensitivity of IXPE also allows exploration of the physics of point sources like X-ray binaries [27], isolated neutron star [28] and active galactic nuclei [29]. The IXPE scientific requirements [30], in terms of spectral, spatial and temporal characteristics, allow exploration of the observed celestial source properties of the X-rays in the range between 2 and 8 keV. The fundamental feature of the satellite, never exploited before by previous missions, relies on its sensitivity and its imaging capabilities, with the accompanying low background, for X-ray polarization from a celestial source. As an example, compared to the Bragg polarimeter onboard OSO-8, IXPE X-ray sensitivity is 30 times better for a 10 mCrab source and it also allows the performance of imaging in addition to spectral and temporal information. Furthermore, the presence of onboard polarized and unpolarized calibration sources and filter (INAF-IAPS) together with satellite dithering during observations allows for control of calibration and systematic effects of the three identical photoelectric polarimeters. Each detector is mounted with respect to the next one on the top deck of the spacecraft with an angle around the Z axis of 120°, improving the reduction and checks of spurious effects.

IXPE satellite instrumentation consists of three detector units, a detector service unit and three mirror modules provided by Marshall Space Flight Center which focus X-rays onto the detectors. The instrument is entirely designed, built, and tested in Italy. The responsibilities for the various items are shared between INAF-IAPS, INFN, and the industrial partner, OHB-Italy.

Each of the four DUs (Detector Units) (one spare) is composed of the following:

- Gas pixel detector (GPD): X-ray gas detector and dedicated integrated readout circuit (ASIC), specifically developed by INFN in collaboration with INAF-IAPS for X-ray polarimetry [31,32];
- Filter and calibration wheel (FCW): calibration set including sources and filters for specific observations. They are designed to monitor the performance of the detector during the life of the mission, keeping the gain calibrated during the observations, checking the low/high-energy modulation factor and spurious modulation;
- Back-end electronics (BEE): electronic boards (DAQ, data acquisition board to manage the ASIC) and power lines;
- Stray-light collimator (STC): coupled with the X-ray shield, prevent contamination induced by photons impinging from outside the FoV;
- DU housing (DUH): mechanical and thermal interface of the DU;
- DU wiring (DUW): electrical interfaces (internal to the DU) between the BEE and the GPD;
- Testing/calibration stations: X-ray sources, collimators, crystals and automated stages;

The IXPE detector breakthrough relies on the GPD [33] (see Figure 4), specifically in the innovative ASIC technology [34]. It is a gas detector where the primary charge is amplified by a Gas Electron Multiplier (GEM) specifically designed for X-ray polarimetry and the IXPE mission, and the signal is readout by a matrix of 105 k pixels (300 × 352 pixels arranged in a 50 μm pitch hexagonal pattern) made by a custom metal oxide semiconductor (CMOS) ASIC. The custom ASIC has self-triggering capabilities due to local triggers defining each group of four pixels called mini-clusters. Each event consists of a region of interest (ROI) made by all the triggering mini-clusters plus a selectable additional fiducial region of 10/20 pixels. The charge content of each pixel in the ROI is readout serially from a single buffer as differential current output by means of a 5 MHz clock. The charge content of only the signal pixels in the ROI is readout serially from a single buffer as differential current output by means of a 5 MHz clock, thus avoiding the long time necessary to readout the entire matrix, as typically needed for CCDs.

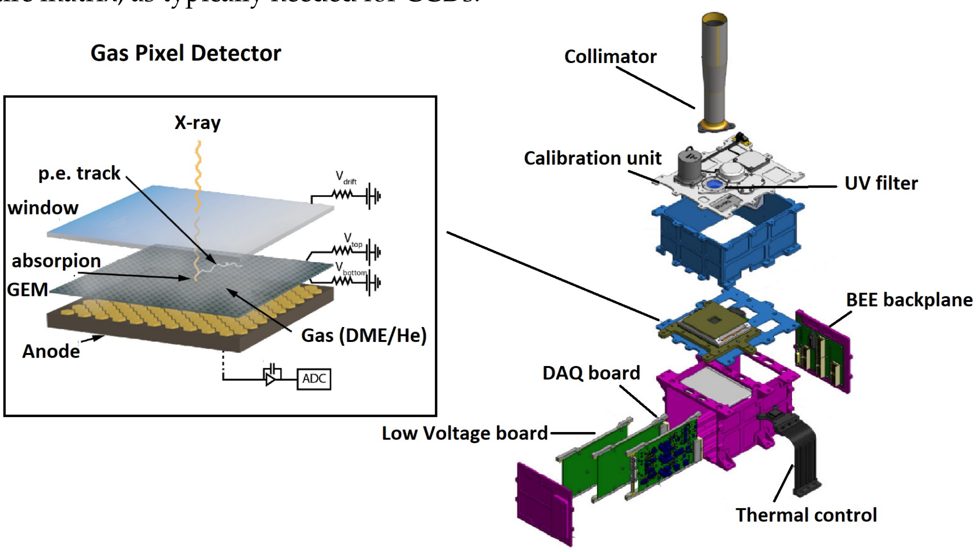

Figure 4. GPD working principle (**left**) and assembled view of the IXPE single telescope (**right**).

The GPD, filled with a dimethyl ether (DME) mixture at 800 mbar at room temperature, is sealed and does not require any gas-cycling systems. The GPD temperature is controlled in the operative range (15–30 °C) during the operation by means of a Peltier cooler and heaters to keep stable the performance of the GPD within 1–2 °C.

The filter and the calibration wheel (FCW) [35]are designed to monitor the performance of the detector during the life of the mission [36]. In particular, it is possible to check the low- and high-energy modulation factor and the spurious modulation during the observational life of the mission, as well as to monitor the gain that depends both on temperature and on charging.

2.3. eXTP

The enhanced X-ray Timing and Polarimetry mission (eXTP, led by Chinese Science Academy (CAS)) [37] (see Figure 5) performs polarimetry, spectroscopy and X-ray timing measurements, in the range of 0.5–30 keV, to study the equation of state (EoS) of matter in supra-nuclear density conditions, the accretion processes in the strong gravitational field regime and to measure the quantum electrodynamics (QED) effects in strongly magnetized neutron stars. The high precision X-ray measurements aimed to be performed by the eXTP mission provide crucial information on fundamental research areas still unknown, mainly related to the the space–time close to black holes (BHs), the matter inside neutron stars (NSs) and the extremely magnetized vacuum close to magnetars. Futhermore, due to its wide field monitoring capabilities, it is able to observe several galactic/extra galactic objects allowing the exploration of the electro-magnetic effects of transients related to gravitational waves and cosmic neutrinos. Overall, the eXTP observatory combines, for the first time ever, spectral-timing-polarimetry measurements to provide unprecedented results on fundamental physics research and multi-messenger astrophysics.

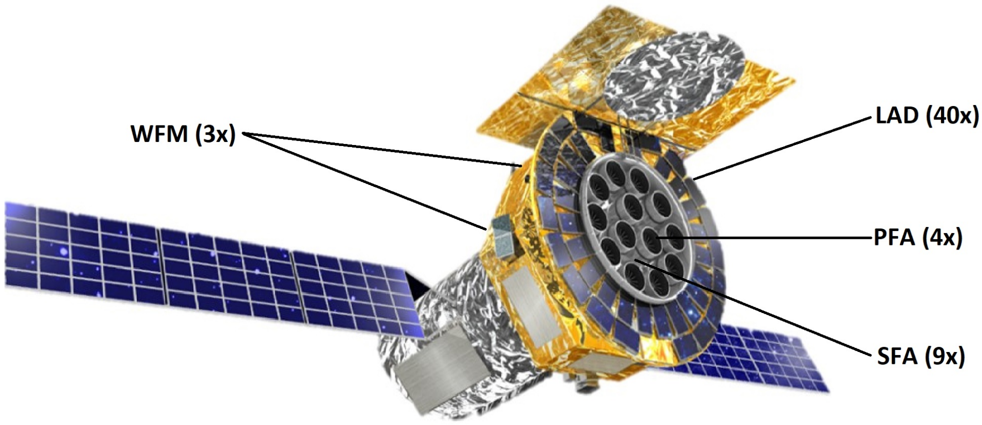

Figure 5. The eXTP telescope.

The eXTP mission is led by the Institute of High Energy Physics (IHEP) of Chinese Academy of Sciences (CAS) and includes several Chinese Universities and Institutions. European institutions and international partners are allowed to contribute. Italy, under the coordination of the ASI, holds the PI-ship of the Large Area Detectors (LAD) and contributes to the three Wide Field Monitors (WFM) (see Figure 6). In the framework of a European contribution, currently not confirmed, the scientific payload of the mission consists of the following:

- Spectroscopic focusing array (SFA): nine Wolter-I grazing incidence X-ray telescopes dedicated to the cosmic spectral and timing observations in the range between 0.5 and 10 keV. Focal plane camera is made by a 19-hexagonal cell **SDD (Silicon Drift Detector)** array (450 µm thick and 3.2 mm sides), with the energy resolution below 180 eV at 6 keV, the time resolution of 10 µs, the dead time (expected) of less than 5% at 1 Crab and angular resolution below 1 arcmin.
- Polarimetry focusing array (PFA): four X-ray imaging telescopes optimized for polarimetry, operating in the energy range of 2–8 keV. It is equipped with GPDs (possibly equipped with ASICs developed by Italy/INFN) at the focal plane to provide spatial, energy, and/or temporal resolved X-ray polarimetry at high sensitivity. GPDs

determine the 2D ionization track of the photoelectron in the gas chamber and infer the polarization of the incident X-ray beam via the modulation of the emission angle reconstructed from the track image.

- Wide Field Monitor (WFM): three pairs, orthogonal to each other, for accurate 2D position, of coded mask cameras equipped with position-sensitive SDDs (2–50 keV, FWHM 300 eV at 6 keV, time accuracy 1 µs and FoV 70° × 70°–90° × 90° at zero response). Each camera is composed of one detector tray with four SDDs, four FEEs (Front-End Electronics), four Be windows, one BEE (Back-End Electronic) assembly, one collimator, and one 150 µm Tungsten foil-coded mask (260 mm × 260 mm area, 1040 × 16 open/closed elements) to project images from a certain direction in the sky on the position-sensitive SDD.
- Large area detector (LAD): photon-by-photon spectral and timing measurements on a large collecting area in the energy range of 2–30 keV (80 keV for out-of-field-of-view burst events) with FoV of about 1° due to the collimator needed for an X-ray background. Each module consists of a set of a 4 × 4 large area SDDs and 4 × 4 capillary plate collimators, supported by two grid-like frame reduction. Overall, each module consists of a collimator (16 co-aligned collimator plate tiles), the detector tray (16 SDDs and the FEEs), the MBEE (Module Back-End Electronic) (two sectors, eight detectors each for SDDs, FEEs, PSUs, management and readout), the PSU, a 300 µm Lead back-shield to reduce the background events in the SDDs, and a 2 mm aluminum radiator for heat dissipation.

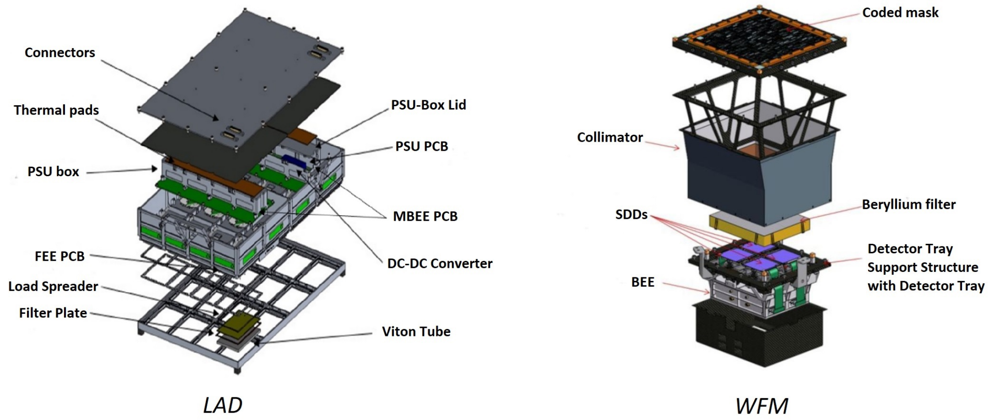

Figure 6. Schematic view of the LAD detector and WFM.

The technological breakthrough of eXTP detection instrument relies on LAD [38] and WFM [39] large-area SDDs (derived form those of the ALICE experiment at CERN and optimized for space) and capillary plate collimators, able to guarantee high efficiency in few mm thickness and reduced weight with respect to proportional counters and mechanical collimators used in the past generation of large-area instruments.

The WFM detector plane is based on the same large area SDD technology developed for the LAD, while its geometry is optimized for 2D imaging. In order to maximize the signal-to-noise ratio of the anode and drift position information, the design of the WFM SDD is optimized by means of Monte Carlo simulations [40].

2.4. NewAthena

NewAthena (New Advanced Telescope for High Energy Astrophysics) [6] is the next ESA Large X-ray observatory to be launched in the second half of 2030s at the L1 orbit. It will aim to answer key questions in astrophysics related to the origin/evolution of galaxies, galaxy groups/clusters, how black holes grow and shape their environment. NewAthena will reveal the formation and evolution of the most energetic and hottest sources that exist, such as the plasma contained in the filamentary structure of dark matter that gives shape to the universe, black holes, gamma ray bursts and sources of gravitational waves, going as far as at the time the first generation of stars formed. It will be a truly innovative observatory, operating in conjunction with other large observatories across the electromagnetic spectrum available in the 2030s (ALMA [41], ELT [42], JWST [43], SKA [44], CTA [45], etc.), and in multi-messenger synergies with facilities like LIGO A+ [46], Advanced Virgo+ [47], LISA [48], IceCube [49] and KM3NeT [50].

The observatory (see Figure 7) will perform both large area survey and spatially resolved high-resolution spectroscopy of faint and bright X-ray source observation, with fast re-pointing capability. To achieve this, it will house cutting-edge instrumentation on board, combining a large-area telescope with two focal plane instruments:

- the X-IFU [51], a TES-based (Transition Edge Sensor) cryogenic array spectrometer for simultaneous high-energy spectroscopy (about 3 eV @ 7 keV) and imaging over $4'$ FoV;
- the WFI [52], with good energy spectral resolution (about 170 eV @ 7keV) and imaging over a wide $40' \times 40'$ FoV.

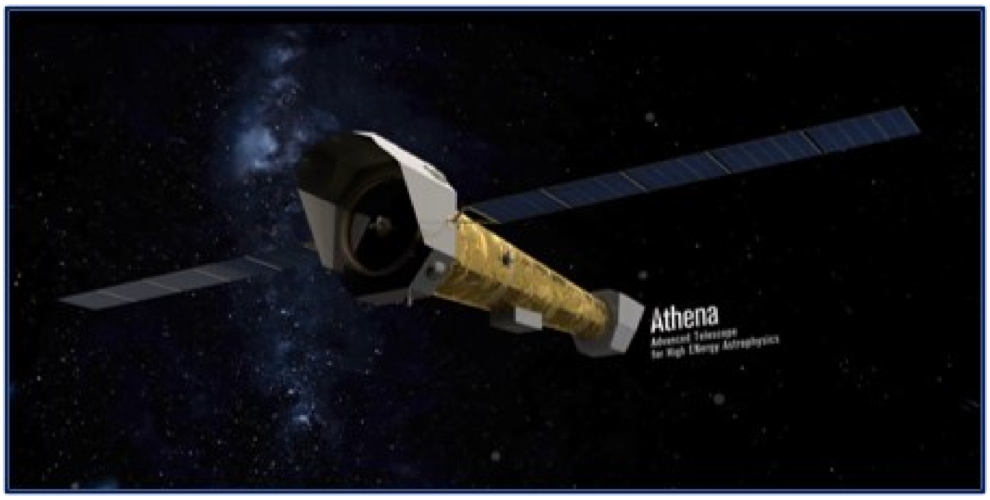

Figure 7. The Athena observatory.

The X-IFU TES array main sensor is not able to distinguish among photon and particle energy deposition (see Figure 8); thus, it is necessary to adopt a Cryogenic AntiCoincidence detector (CryoAC) [53,54] to veto particle background (primary solar and Galactic Cosmic Ray origin and secondary, mostly electrons, produced by primaries interacting with the materials surrounding the detector) to prevent X-IFU sensitivity degradation: it is worth noting that the required Non-X-ray Background level is <0.005 cts/cm^2/s/keV in a 2–10 keV energy bandwidth.

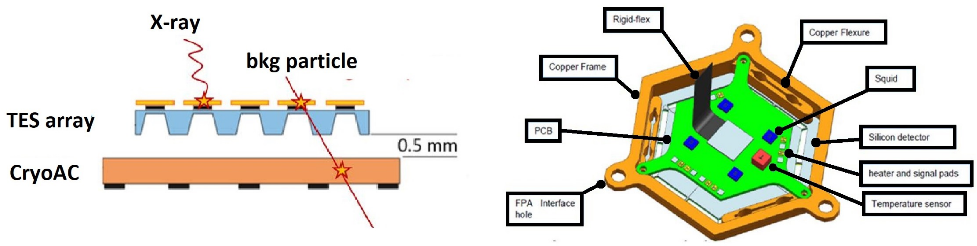

Figure 8. CryoAC: working principle (**left**) and Cold Stage assembly schematic view (**right**).

X-IFU will be provided by an international consortium led by France, Netherlands and Italy, with ESA member state contributions from Belgium, Czech Republic, Finland, Germany, Poland, Spain, Switzerland, with additional contributions from the United States and Japan. The Italian community has a fundamental role in the mission both on the scientific side and on the instrumentation. Italy is involved in the provision of both instruments, being the co-PI of the cryogenic instrument and responsible for supplying its cryogenic anti-coincidence detector (CryoAC) and thermal filters [51].

CryoAC is a four-pixel detector, each one associated with its own readout electronics chain, made of 500 µm thick silicon suspended absorbers, sensed by Ir/Au TESes operating at 50 mK, placed at a distance <1 mm below the TES array. The main sections are: Cold Stage Assembly (see Figure 8) made of Cold Front End Electronics, the supporting bracket and the chip, Warm Front End Electronics which is divided into four quadrants providing the bias for both TES and SQUID for each of the four pixels, routing the scientific signal to the Warm Back End Electronics which performs digital processing and detection, time stamps cosmic ray events by applying a proper trigger logic algorithm [55], and generating, at the end of the process, the associated telemetry.

An excerpt of CryoAC detector specifications can be found in Table 1. CryoAC is fully designed and developed in Italy. More details can be found in [56].

Table 1. Excerpt of CryoAC detector specifications. Some parameters are still TBC due to both the newAthena design and the CryoAC ongoing study.

Parameter	Value
Number of Pixels	4
Pixel size	1.23 cm^2 (TBC due to newAthena)
TES material	Ir/Au
Transition temperature	100 mK (TBC)
Absorber material	Silicon
Absorber thickness	500 µm
Distance from TES array	<1 mm
Detector dynamic energy range	6 keV–950 keV (TBC)
Low energy threshold	<6 keV
Power dissipation @ 50 mK	10 nW/pixel
Rise time	<15 µs (TBC)
ETF decay time	<250 µs (TBC)
Thermal decay time	<2.5 ms (TBC)

The NewAthena mission is currently undergoing a successful 'design-to-cost' redesign in which the payload will be revised to a more compact configuration that guarantees the scientific flagship quality of the mission. ASI fully supports the Italian participation in the NewAthena mission.

3. Conclusions

This paper reviews the fundamental past, present and future astrophysics X-ray missions supported by the Italian Space Agency. The synergistic research activity carried by the Italian Space Agency and its principal collaborators (Universities, Public Research Centers, Private companies) contributed to the main scientific results achieved over the years and will overcome the current technological limit opening new observational windows to explore the unknown.

Author Contributions: Methodology, M.M. and E.C.; validation, E.C. and A.V.; writing—original draft preparation, M.M., A.V., S.F., M.F., L.L., C.M., L.P., M.D., F.G., S.P., P.S. and E.C.; writing—review and editing, M.M., A.V., S.F., M.F., L.L., C.M., L.P., M.D., F.G., S.P., P.S. and E.C.; visualization, A.V.; supervision, E.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: Authors acknowledge all the agencies and researchers who supported and contributed to the realization of the instrumentation and results.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Pittori, C.; on behalf of SSDC Team. The AGILE data center and its legacy. *Rend. Lincei. Sci. Fis. Nat.* **2019**, *30*, 217–223. [CrossRef]
2. Frontera, F. The key role of BeppoSAX in the GRB history. *Rend. Lincei. Sci. Fis. Nat.* **2019**, *30*, 171–184. [CrossRef]
3. D'Amico, F.; Tavani, M.; Annoni, G.; Contini, C.; Tempesta, P.; Masci, E.; Pittori, C.; Argan, A.; Negri, B. In-orbit operations of AGILE mission: 11 years successfully in space. *Rend. Lincei. Sci. Fis. Nat.* **2019**, 30, 231–240. [CrossRef]
4. Deininger, W.D.; Peterson, C.; Kalinowski, W.; Bladt, J.; Ly, T.; Mithcell, S.; Maddox, T.; Osborne, D.; Ruswick S.; Davis, K.; et al. Imaging X-Ray Polarimetry Explorer (IXPE)-One Year On-Orbit. In Proceedings of the 2023 IEEE Aerospace Conference, Big Sky, MT, USA, 4–11 March 2023; pp. 1–18.
5. Zhang, S.-N.F.; Santangelo, A.; Feroci, M.; Xu, Y.P.; Lu, F.J.; Chen, Y.; Feng, H.; Zhang, S.; Brandt, S.; Hernanz, M.; et al. The enhanced X-ray Timing and Polarimetry mission-eXTP. *Sci. China Phys. Mech. Astron.* **2018**, *62*, 1869–1927. [CrossRef]
6. Barcons, X.; Barret, D.; Decourchelle, A.; den Herder, J.W.; Fabian, A.C.; Matsumoto, H.; Lumb, D.; Nandra, K.; Piro, L.; Smith, R.K.; et al. Athena: ESA's X-ray observatory for the late 2020s. *Astron. Notes* **2017**, *338*, 153–158. [CrossRef]
7. Piro, L. BeppoSAX overview. *AIP Conf. Proc.* **1997**, *410*, 1485–1492.
8. Frontera, F.; Costa, E.; Piro, L.; Muller, J.M.; Amati, L.; Feroci, M.; Fiore, F.; Pizzichini, G.; Tavani, M.; Castro-Tirado, A.; et al. Spectral Properties of the Prompt X-ray Emission and Afterglow from the Gamma-Ray Burst of 1997 February 28. *Astrophys. J.* **1998**, *493*, 67–70. [CrossRef]
9. Pian, E.; Amati, L.; Antonelli, L.A.; Butler, R.C.; Costa, E.; Cusumano, G.; Danziger, J.; Feroci, M.; Fiore, F.; Frontera, F.; et al. BeppoSAX detection and follow-up of GRB 980425. *Astron. Astrophys. Suppl. Ser.* **1999**, *138*, 463–464. [CrossRef]
10. Boella, G.; Butler, R.C.; Perola, G.C.; Piro, L.; Scarsi, L.; Bleeker, A.M. BeppoSAX, the wide band mission for X-ray astronomy. *Astron. Astrophys. Suppl. Ser.* **1997**, *122*, 299–307. [CrossRef]
11. Jager, R.; Mels, W.A.; Brinkman, A.C.; Galama, M.Y.; Goulooze, H.; Heise, J.; Lowes, P.; Muller, J.M.; Naber, A.; Rook, A.; et al. The Wide Field Cameras onboard the BeppoSAX X-ray Astronomy Satellite. *Astron. Astrophys. Suppl. Ser.* **1997**, *122*, 557–572. [CrossRef]
12. Costa, E.; Frontera, F.; Dal Fiume, D.; Amati, L.; Cinti, M.N.; Collina, P.; Feroci, M.; Nicastro, L.; Orlandini, M.; Palazzi, E.; et al. The Gamma-Ray Bursts Monitor onboard SAX. *Adv. Space Res.* **1998**, *22*, 1129–1132. [CrossRef]
13. Manzo, G.; Giarrusso, S.; Santangelo, A.; Ciralli, F.; Fazio, G.; Piraino, S.; Segreto, A. The high pressure gas scintillation proportional counter on-board the BeppoSAX X-ray astronomy satellite. *Astron. Astrophys. Suppl. Ser.* **1997**, *122*, 341–356. [CrossRef]
14. Frontera, F.; Costa, E.; Dal Fiume, D.; Feroci, M.; Nicastro, L.; Orlandini, M.; Palazzi, E.; Zavattini, G. The high energy instrument PDS on-board the BeppoSAX X-ray astronomy satellite. *Astron. Astrophys. Suppl. Ser.* **1997**, *122*, 357–389. [CrossRef]
15. Parmar, A.N.; Martin, D.D.E.; Bavdaz, M.; Favata, F.; Kuulkers, E.; Vacanti, G.; Lammers, U.; Peacock, A.; Taylor, B.G. The low-energy concentrator spectrometer on-board the BeppoSAX X-ray astronomy satellite. *Astron. Astrophys. Suppl. Ser.* **1997**, *122*, 309–326. [CrossRef]
16. Boella, G.; Chiappetti, L.; Conti, G.; Cusumano, G.; Del Sordo, S.; La Rosa, G.; Maccarone, M.C.; Mineo, T.; Molendi, S.; Re, S.; et al. The medium-energy concentrator spectrometer on board the BeppoSAX X-ray astronomy satellite. *Astron. Astrophys. Suppl. Ser.* **1997**, *122*, 327–340. [CrossRef]
17. Tavani, M.; Barbiellini, G.; Argan, A.; Boffelli, F.; Bulgarelli, A.; Caraveo, P.; Cattaneo, P.W.; Chen, A.W.; Cocco, V.; Costa, E.; et al. The AGILE mission. *Astron. Astrophys.* **2009**, *502*, 995–1013. [CrossRef]
18. Barbiellini, G. AGILE development and silicon detector. *Rend. Lincei. Sci. Fis. Nat.* **2019**, *30*, 51–56. [CrossRef]
19. Prest, M.; Barbiellini, G.; Bordignon, G.; Fedel, G.; Liello, F.; Longo F.; Pontoni, C.; Vallazza, E. The AGILE silicon tracker: an innovative gamma-ray instrument for space. *Nucl. Instrum. Methods Phys. Res.-A* **2003**, *501*, 280–287. [CrossRef]
20. Labanti, C.; Marisaldi, M.; Fuschino, F.; Galli, M.; Argan, A.; Bulgarelli, A.; Di Cocco, G.; Gianotti, F.; Tavani, M.; Trifoglio, M. Design and construction of the Mini-Calorimeter of the AGILE satellite. *Nucl. Instrum. Methods Phys. Res.-A* **2009**, *598*, 470–479. [CrossRef]
21. Striani, E.; Tavani, M.; Vittorini, V.; Donnarumma, I.; Giuliani, A.; Pucella, G.; Argan, A.; Bulgarelli, A.; Colafrancesco, S.; Cardillo, M.; et al. Variable gamma-ray emission from the crab nebula: Short Flares and long "waves". *Astrophys. J.* **2013**, *765*, 52. [CrossRef]
22. Michelson, P.F.; Atwood, W.B.; Ritz, S. Fermi Gamma-ray Space Telescope: High-Energy Results from the First Year. *Rep. Prog. Phys.* **2010**, *73*, 074901. [CrossRef]
23. Atwood, W.B.; Abdo, A.A.; Ackermann, M.; Althouse, W.; Anderson, B.; Axelsson, M.; Baldini, L.; Ballet, J.; Band, D.L.; Barbiellini, G.; et al. The large area telescope on the fermi gamma-ray space telescope mission. *Astrophys. J.* **2009**, *697*, 1061. [CrossRef]
24. Xie, F.; Di Marco, A.; La Monaca, F.; Liu, K.; Muleri, F.; Bucciantini, N.; Romani, R.W.; Costa, E.; Rankin, J.; Soffitta, P.; et al. Vela pulsar wind nebula X-rays are polarized to near the synchrotron limit. *Nature* **2022**, *612*, 658–660. [CrossRef] [PubMed]

25. Ferrazzoli, R.; Slane, P.; Prokhorov, D.; Zhou, P.; Vink, J.; Bucciantini, N.; Costa, E.; Di Lalla, N.; Di Marco, A.; Soffitta, P.; et al. X-Ray Polarimetry Reveals the Magnetic-field Topology on Sub-parsec Scales in Tycho's Supernova Remnant. *Astrophys. J.* **2023**, *945*, 14. [CrossRef]
26. Marin, F.; Churazov, E.; Khabibullin, I.; Ferrazzoli, R.; Di Gesu, L.; Barnouin, T.; Di Marco, A.; Middei, R.; Vikhlinin, A.; Costa, E.; et al. X-ray polarization evidence for a 200-year-old flare of Sgr A*. *Nature* **2023**, *619*, 41–45. [CrossRef] [PubMed]
27. Krawczynski, H.; Muleri, F.; Dovčiak, M.; Veledina, A.; Rodriguez Cavero, N.; Svoboda, J.; Ingram, A.; Matt, G.; Garcia, J.A.; Loktev, V.; et al. Polarized x-rays constrain the disk-jet geometry in the black hole x-ray binary Cygnus X-1. *Science* **2022**, *378*, 650–654. [CrossRef] [PubMed]
28. Taverna, R.; Turolla, R.; Muleri, F.; Heyl, J.; Zane, S.; Baldini, L.; González-Caniulef, D.; Bachetti, M.; Rankin, J.; Caiazzo, I.; et al. Polarized x-rays from a magnetar. *Science* **2022**, *378*, 646–650. [CrossRef]
29. Di Gesu, L.; Donnarumma, I.; Tavecchio, F.; Agudo, I.; Barnounin, T.; Cibrario, N.; Di Lalla, N.; Di Marco, A.; Escudero, J.; Errando, M.; et al. The X-ray Polarization View of Mrk 421 in an Average Flux State as Observed by the Imaging X-ray Polarimetry Explorer. *Astrophys. J. Lett.* **2022**, *1*, L7. [CrossRef]
30. Soffitta, P.; Baldini, L.; Bellazzini, R.; Costa, E.; Latronico, L.; Muleri, F.; Del Monte, E.; Fabiani, S.; Minuti, M.; Pinchera, M.; et al. The Instrument of the Imaging X-ray Polarimetry Explorer. *Astron. J.* **2021**, *162*, 208. [CrossRef]
31. Baldini, L.; Barbanera, M.; Bellazzini, R.; Bonino, R.; Borotto, F.; Brez, A.; Caporale, C.; Cardelli, C.; Castellano, S.; Ceccanti, M.; et al. Design, construction, and test of the Gas Pixel Detectors for the IXPE mission. *Astropart. Phys.* **2021**, *133*, 102628. [CrossRef]
32. Manfreda, A. The Gas Pixel Detectors for the Imaging X-Ray Polarimetry Explorer mission. *Nucl. Instrum. Methods Phys. Res.-A* **2023**, *1049*, 168044. [CrossRef]
33. O'Dell, S.L.; Baldini, L.; Bellazzini, R.; Costa, E.; Elsner, F.R.; Kaspi, V.M.; Kolodziejczak, J.J.; Latronico, L.; Marshall, H.L.; Matt, G.; et al. The Imaging X-ray Polarimetry Explorer (IXPE): Technical overview. In Proceedings of the SPIE Astronomical Telescopes + Instrumentation, 2018, Austin, TX, USA, 10–15 June 2018; Volume 10699.
34. Minuti, M.; Baldini, L.; Bellazzini, R.; Brez, A.; Ceccanti, M.; Krummenacher, F.; Latronico, L.; Lucchesi, L.; Manfreda, A.; Orsini, L.; et al. XPOL-III: A new-generation VLSI CMOS ASIC for high-throughput X-ray polarimetry. *Nucl. Instrum. Methods Phys. Res.-A* **2023**, *1046*, 167674. [CrossRef]
35. Muleri, F.; Piazzolla, R.; Di Marco, A.; Fabiani, S.; La Monaca, F.; Lefevre, C.; Morbidini, A.; Rankin, J.; Soffitta, P.; Tobia, A.; et al. The IXPE instrument calibration equipment. *Astropart. Phys.* **2021**, *136*, 102658. [CrossRef]
36. Di Marco, A.; Fabiani, S.; La Monaca, F.; Muleri, F.; Rankin, J.; Soffitta, P.; Xie, F.; Amici, F.; Attinà, P.; Bachetti, M.; et al. Calibration of the IXPE Focal Plane X-ray Polarimeters to Polarized Radiation. *Astron. J.* **2022**, *164*, 103. [CrossRef]
37. in't Zand, J.J.M.; Bozzo, E.; Qu, J.; Li, X.-D.; Amati, L.; Chen, Y.; Donnarumma, I.; Doroshenko, V.; Drake, S.A.; Hernanz, M.; et al. Observatory science with eXTP. *Sci. China Phys. Mech. Astron.* **2019**, *62*, 29506. [CrossRef]
38. Rachevski, A.; Antonelli, M.; Bellutti, P.; Bonvicini, V.; Borghi, G.; Campana, R.; Ceraudo, F.; Cirrincione, D.; Del Monte, E.; Evangelista, Y.; et al. eXTP Large Area Detector: Qualification procedure of the mass production. *Nucl. Instrum. Methods Phys. Res.-A* **2023**, *1046*, 167750. [CrossRef]
39. Hernanz, M.; Brandt, S.; Feroci, M.; Orleansky, P.; Santangelo, A.; Schanne, S.; Xin, W.; in't Zand, J.; Zhang, S.N.; Xu, Y.P.; et al. The wide field monitor onboard the eXTP mission. In Proceedings of the Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, Austin, TX, USA, 10–15 June 2018; Volume 10699, p. 1069948.
40. Evangelista, Y.; Donnarumma, I.; Campana, R.; Schmid, C.; Feroci, M. Instrumental and scientific simulations of the LOFT wide field monitor. In Proceedings of the Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray, Montréal, QC, Canada, 22–27 June 2014; Volume 9144, p. 914468.
41. Carpenter, J.; Iono, D.; Kemper, F.; Wooten. A. The ALMA Development Program: Roadmap to 2030. *arXiv* **2020**, arXiv:2001.11076. [CrossRef]
42. Padovani, P.; Cirasuolo, M. The Extremely Large Telescope. *Contemp. Phys.* **2023**, *64*, 47–64. [CrossRef]
43. Milam, S.N.; Stansberry, J.A.; Sonneborn, G.; Thomas, C. The James Webb Space Telescope's Plan for Operations and Instrument Capabilities for Observations in the Solar System. *Publ. Astron. Soc. Pac.* **2016**, *128*, 018001. [CrossRef]
44. McMullin, J.P.; Diamond, P.; McPherson, A.M.; Laing, R.; Dewdney, P.; Casson, A.; Stringhetti, L.; Rees, N.; Stevenson, T.; Lilley, M.; et al. The Square Kilometre Array project. In Proceedings of the Ground-Based and Airborne Telescopes VIII, Online Only, CA, USA, 14–18 December 2020; Volume 11445, p. 1144512.
45. The CTA Consortium; Ong, R.A. The Cherenkov Telescope Array Science Goals and Current Status. In Proceedings of the EPJ Web of Conferences, RICAP18, 7th Roma International Conference on Astroparticle Physics, Roma, Italy, 4–7 September 2018; Volume 219, p. 01038.
46. Cahillan, C.; Mansell, G. Review of the Advanced LIGO Gravitational Wave Observatories Leading to Observing Run Four. *Galaxies* **2022**, *10*, 36. [CrossRef]
47. Nardecchia, I. Detecting Gravitational Waves with Advanced Virgo. *Galaxies* **2022**, *10*, 28. [CrossRef]
48. Amaro-Seoane, P.; Andrews, J.; Arca Sedda, M.; Askar, A.; Baghi, Q.; Balasov, R.; Bartos, I.; Bavera, S.; Bellovary, J.; Berry, C.P.L.; et al. Astrophysics with the Laser Interferometer Space Antenna. *Living Rev. Relativ.* **2023**, *26*, 2. [CrossRef]
49. The IceCube Collaboration. Highlights from the IceCube Neutrino Observatory. *arXiv* **2023**, arXiv:2310.12840. [CrossRef]
50. Margiotta, A.; on behalf KM3Net Collaboration. The KM3NeT deep-sea neutrino telescope. *Nucl. Instrum. Methods Phys. Res.-A* **2014**, *766*, 83–87. [CrossRef]

51. Barret, D.; Albouys, V.; den Herder, J.-W.; Piro, L.; Cappi, M.; Huovelin, J.; Kelley, R.; Mas-Hesse, J.M.; Paltani, S.; Rauw, G.; et al. The Athena X-ray Integral Field Unit: A consolidated design for the system requirement review of the preliminary definition phase. *Exp. Astron.* **2023**, *55*, 373–426. [CrossRef]
52. Meidinger, N.; Albrecht, S.; Beitler, C.; Bonholzer, M.; Emberger, V.; Frank, J.; Lederhuber, A.; Müller-Seidlitz, J.; Nandra, K.; Oser, J.; et al. Development status of the wide field imager instrument for Athena. In Proceedings of the Space Telescopes and Instrumentation 2020: Ultraviolet to Gamma Ray, Online Only, CA, USA, 14–18 December 2020; Volume 11444, p. 114440T.
53. Macculi, C.; Argan, A.; Brienza, D.; D'Andrea, M.; Lotti, S.; Minervini, G.; Piro, L.; Biasotti, M.; Ferrari Barusso, L.; Gatti, F.; et al. The Cryogenic AntiCoincidence Detector for ATHENA X-IFU: The Project Status. *J. Low Temp. Phys.* **2020**, *199*, 416–424. [CrossRef]
54. D'Andrea, M.; Macculi, C.; Torrioli, G.; Argan, A.; Brienza, D.; Lotti, S.; Minervini, G.; Piro, L.; Biasotti, M.; Ferrari Barusso, L.; et al. The Demonstration Model of the ATHENA X-IFU Cryogenic AntiCoincidence Detector. *J. Low Temp. Phys.* **2020**, *199* , 65–72. [CrossRef]
55. Chiarello, F.; Torrioli, G.; Argan, A.; D'Andrea, M.; Macculi, C.; Piro, L. Study on the trigger logic for the X-IFU Athena anticoincidence system. In Proceedings of the In Space Telescopes and Instrumentation 2022: Ultraviolet to Gamma Ray, Montréal, QC, Canada, 17–23 July 2022; Volume 12181; pp. 1218141-1–1218141-8.
56. Macculi, C.; Argan, A.; D'Andrea, M.; Lotti, S.; Minervini, G.; Piro, L.; Ferrari Barusso, L.; Boragno, C.; Celasco, E.; Gallucci, G.; et al. The Cryogenic Anticoincidence detector for the newAthena X-IFU instrument: A program overview. *Condens. Matter* **2023**, *8*, 108. [CrossRef]