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Mission Concept Documentation (MCD) of CAPIBARA's Gamma-/X-ray Mission CAPIGX

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ABSTRACT

Outline: *Here's the problem, here's the opportunity, here's our solution, and here's how we get there.*

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1. INTRODUCTION AND MOTIVATION

We are heading to an era of multi-messenger astronomy, where electromagnetic (EM) observations, gravitational wave (GW) signals, and neutrino detections provide different channels or 'messengers' to explore the Universe. The high-energy domain of astrophysics is central to this new revolution in astrophysics, since the majority events detectable with multi-messenger methods are cataclysmic events like binary neutron star (BNS) or black hole (BH) mergers, BH accretion and relativistic jets.

In the 2030s, many GW observatories as well as X-ray and γ-ray telescope will be going online. Both Einstein Telescope (ET) and ESA's Laser Interferometer Space Antenna (LISA) are expected to commission around 2035 M. Maggiore et al. (2020) P. Amaro-Seoane et al. (2017), while Cosmic Explorer will probably come a few years later M. Evans et al. (2021). On the EM side, ESAs' flagship missions NewAthena (X-ray) and THESEUS (γ-ray) are planned to launch in 2037 M. Cruise et al. (2024) and 2032 L. Amati et al. (2021) respectively.

Despite this wide coverage of the high energy sky, there are still observational and strategic gaps that would affect the progress of scientific discovery, if not completely eliminate the possibility for some discoveries. This gap lies in the observations and follow-ups of high-energy transients like gamma-ray bursts (GRBs) or magnetar flares. New GW observatories will provide massive amounts of GW signals with possible EM counterparts, simulations project more than 10^4 signals per year detectable by ET A. Colombo et al. (2025). and the until now presented X-ray and γ-ray telescope will not be able to follow-up such a great amount of observations. Additionally, flagship missions like THESEUS and NewAthena will have other parallel priorities alongside transient monitoring/follow-up, leading to not-detections of these high energy transients.

We propose a new mission called CAPIGX which will monitor the sky for these transients and be available for follow-up of many phenomena providing EM data for GW events. CAPIGX is a mission planned and developed by the CAPIBARA[2] Collaboration, a fully student-led work group with the aim to explore the high energy cosmos J. Alcaide-Núñez (2025). The mission we propose consists of a constellation of 3 3U CubeSats which will enable great localization accuracy using intensity interferometry, the main feature of CAPIGX. In the following paper, we will go through the details, planning, and feasibility of this mission.

2. STATE OF THE FIELD

From the early 2000s, there still remain two flagship missions: FERMI (γ-ray) and Swift (X-ray), however these missions are planned to decommission in some years. Additional satellites have been launched since then, including Chandra (X-ray), NICER (X-ray), IXPE (X-ray), EP (X-ray), SVOM ($\gamma - ray$), and HERMES (γ-ray). Some of these do monitor for transient phenomena (e.g, Einstein Probe (EP) and SVOM), but other do observe other types of objects. For the 2030s, we can predict that only EP and SVOM will still be online in the X-ray and γ-ray range respectively. Both ~ 10

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year old observatories will support the new 2030s fleet (THESEUS and NewAthena). HERMES is a CubeSat mission, with expected lifetime of 5 years, i.e. ending its mission in 2030. While other telescope may be also online during the early 2030s, they will probably provide lower quality scientific data and won't be as productive as they are now.

As seen in figure 1, while there is some existing coverage in the X-ray and γ-ray ranges, two key gaps remain in current and upcoming mission plans that need addressing:

1. **Availability of transient detection across the keV to MeV range**: Currently, there are several missions observing in the X-ray and γ-ray domains, such as Fermi, Swift, and EP for X-rays, and Fermi, INTEGRAL, SVOM, and HERMES for γ-rays. While these provide some coverage, none offer the flexibility and precision needed for rapid follow-up and detailed localization of transient phenomena across this broad energy range. With the explosion in the number of gravitational wave (GW) signals expected from the next generation of GW detectors like Cosmic Explorer and Einstein Telescope, there is a critical need for a dedicated, agile system to detect and localize multi-messenger transients within the keV to MeV range.

2. **Coverage gaps during the transition between 2020 and 2030**: There is a significant gap in terms of operational X-ray and γ-ray missions between the current wave of observatories (e.g., Fermi, Swift) and the next generation of high-energy telescopes expected in the 2030s, such as NewAthena and THESEUS. This period (from the early 2020s to the late 2030s) will see a lull in mission upgrades and new launches, leaving a critical period during which transient events may go undetected or poorly localized. This timing gap can be filled by an innovative and cost-effective solution, providing both continuity and new capabilities during this transitional phase.

Add more specifications about the capabilities of the next generation telescopes. What will THESEUS and NewAthena focus on and their energy range/properties/capabilities? What's new about the next gen GW observatories?

3. SCIENTIFIC OBJECTIVES AND MOTIVATION

The scientific objectives of a high energy transient observing mission are many. With the help of intensity interferometry, we will be able to detect transients with arcminute-scale precision. The branches of modern astrophysical research that CAPIBARA will foster the most are the following:

1. Multi-Messenger Astronomy: host galaxy identification
2. Early Universe, Early Star and GRB/AGN Population
3. Nature of high energy phenomena
4. Cosmology

While some research initiatives are developed within the Collaboration[3], we will publish the entirety of our data for international researchers to join in and be able to use our data.

3.1. *Multi-Messenger Astronomy: host galaxy identification*

Multi-messenger astronomy is not only a new research line but a new way of literally 'seeing' the Universe. For centuries, we have performed observations exclusively with telescopes, observing the light of distant worlds. However, in the last 30 years humankind has achieved to feel the Universe through different channels. In addition to traditional electromagnetic (EM) telescopes, neutrinos from outside the solar system were first detected in from SuperNova 1987 M. Koshiba (1987) and the first gravitational wave detection was in 2015 B. P. Abbott et al. (2016). Both events opening new paths for astronomy to explore, since these other 'messengers' provide different types of information about the sources we observe.

The 2020 decadal survey set as a priority to invest in mission around MM astronomy.

This research line comprises the Multi-Messenger Cosmology research initiative within the CAPIBARA Collaboration, in which we intend to combine GW signals and GRB counterpart observations to further constraint the cosmological parameters and trying to find an accurate cosmological model for the Universe.

3.2. *Early Universe, Early Star and GRB/AGN Population*

As CAPIGX's energy range extends through the X-ray (see section 4 it will be able to detect high-z transients, since this are considerably redshifted they are visible in the X-ray regime. Moreover, their high energy makes them visible at great distances, posing a great

[3] See https://capibara3.github.io/capigx/index.html

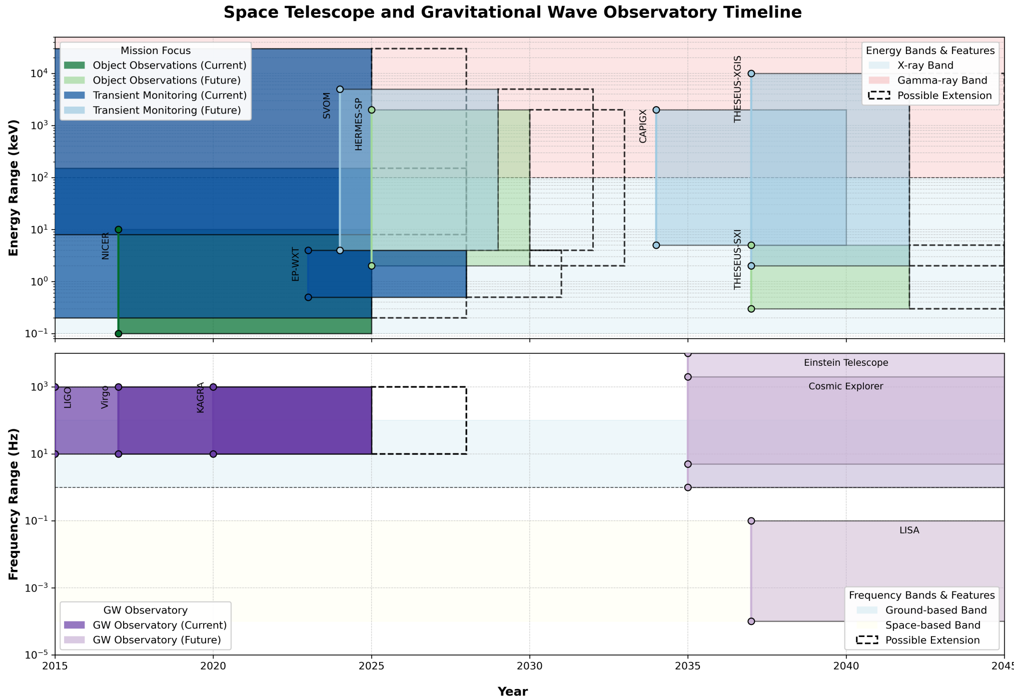

Figure 1. Gantt diagram of the available high energy and GW observatories from the 2010s until 2040. Includes actual launch and mission end life as well as expectations for current and future missions. Dark colors indicate current or launched missions, while pastel colors stand for planned missions. Missions focusing on transient monitoring and follow-up are highlighted in blue, while green-shaded missions prioritize discrete object observations. We are not showing the COSI mission (MeV γ-ray range), since without being a high priority flagship mission of NASA and with the vast cuts in funding to the agency's budget will not see light in the foreseeable future.

opportunity to studying the early Universe and its environment. The population, number, and properties of detected transients are directly related to the characteristics of stellar formation, population and death at the time. **?**

3.3. *Nature of high energy phenomena*

The nature of high energy phenomena like the acceleration of particles to relativistic speeds **?**, the equation of state (EoS) of neutron stars (NS) or the engine of GRBs **?** are still being unknown or disputed. High energy transients are the most violent and powerful phenomena in the Universe, showing us the limits of physics and nature, like the BOAT event M. E. Ravasio et al. (2024). Thus, by detecting these extreme events promptly and performing follow-up observations in coordination with other observatories (space- and ground-based).

This research line related to the AGN cosmic ray interactions and SNR environments research initiatives within the CAPIBARA Collaboration.

3.4. *Cosmology*

The Hubble Tension or Crisis in Cosmology is the fact that different methods to compute the Hubble constant (the expansion rate of the Universe) deliver different results. While they where in agreement 20 year ago, the tension between both methods (distance ladder vs CMB) has done nothing but increase with advanced analysis techniques and more precise telescopes.

Another way of exploring the properties of the Universe (H_0, Ω_m, $\Omega_{\rm de}$, ...) is to use the energy relations of GRBs, see G. Ghirlanda et al. (2006) for a thoughtful review. Thus, building a vast catalog of high energy transient data will help to further constraint and learn both energy properties and relations of GRBs as well as cosmological parameters.

This research line comprises the Multi-Messenger Cosmology research initiative within the CAPIBARA Collaboration, in which we intend to combine GW signals and GRB counterpart observations to further constraint the cosmological parameters and trying to find an accurate cosmological model for the Universe.

mention TDEs and magnetar flares at some point

CAPIGX complements larger missions by being responsive, distributed, and cost-effective.

4. MISSION CONCEPT

To address the observational gap identified in section 2, we propose a constellation of three CubeSats to enhance localization capabilities for high-energy transients. By deploying three small spacecraft in coordinated Low Earth Orbits (LEOs), the mission achieves redundancy, improved source localization, and host galaxy identification for multi-messenger events via triangulation.

For two satellites separated by a baseline B, the difference in time of arrival (ToA) of a signal is

$$\Delta t = \frac{B \cdot \hat{s}}{c}, \tag{1}$$

resulting in an angular localization error

$$\delta \approx \frac{c\,\sigma_t}{B_\perp}, \tag{2}$$

where $B_\perp$ is the baseline component perpendicular to the source direction, and σ_t is the timing uncertainty, $\sigma_t = \delta\theta B_\perp/c$. With a timing accuracy of $\lesssim 10$ μs (triangulation) and a separation of 1000 km, localization of ~ 10 arcmin is achievable. Increasing timing precision to $\lesssim 1$ μs (intensity interferometry) improves accuracy to ~ 1 arcmin.

This concept leverages a modular, cost-effective CubeSat platform, using commercial bus components while enabling student-developed scientific payloads. The constellation is scalable: additional units can be integrated to enhance coverage or redundancy.

4.1. *Spacecraft Platform*

We plan a constellation of three 3U CubeSats (10×10×30 cm) to host the detectors, timing hardware, and supporting subsystems.

4.1.1. *Payload (student-developed)*

- X-ray detector (1–150 keV)
- Gamma-ray detector (150–2000 keV)
- Precision time-tagging electronics (< 1 μs)
- GPS-disciplined oscillator and inter-satellite timing links

4.1.2. *Attitude Determination and Control System (ADCS)*

- Reaction wheels
- Gyroscopes
- Star tracker
- Magnetorquers (momentum dumping)

4.1.3. *Power Subsystem (EPS)*

- Deployable solar panels compatible with detector field of view
- Batteries
- Power distribution and management electronics

4.1.4. *Onboard Data Handling (OBDH)*

- Radiation-tolerant, redundant onboard computer
- Data storage sufficient for high-rate transient logging
- Event processing and filtering
- Precision time synchronization module

4.1.5. *Communications*

- UHF/VHF for telemetry and telecommand
- S-band or X-band downlink for science data
- Optional low-latency relay (e.g., Iridium, TDRSS) for rapid alerts

4.1.6. *Thermal Control*

- Passive thermal coatings and radiators
- Heaters for detector temperature stability

4.1.7. *Structure and Protection*

- 3U CubeSat standard bus
- Radiation shielding for detectors and electronics
- Mechanical stability for detector alignment

The scientific payload is developed in-house, while the CubeSat bus is obtained from commercial providers. Engagement with vendors will begin in the upcoming months.

4.2. *Constellation Architecture*

- Three CubeSats in coordinated LEOs
- Triangulation and intensity interferometry improve localization
- Redundant design ensures mission continuity if a unit fails
- Modular and scalable: new satellites can be added
- Rapid alerts to the astronomical community for multi-wavelength and multi-messenger follow-up
- Spacecraft: 3U CubeSat per unit
- Payload: dual detectors covering 1–150 keV (X-ray) and 150–2000 keV (gamma-ray)
- Supporting subsystems: shielding, deployable solar panels, ADCS, communications
- Strategy: off-the-shelf CubeSat bus; student-developed scientific payload

5. TECHNICAL FEASIBILITY AND HERITAGE

- Feasibility within CubeSat constraints (power, telemetry, sensitivity, background suppression).
- Heritage missions: BurstCube, HaloSat, CUTE, HERMES, CuSPED.
- Detector technology: CZT or scintillator-based designs demonstrated in small satellites.
- Alignment with the trend toward distributed astrophysics missions.

6. PARTNERSHIPS AND RESOURCES

6.1. *Potential Industry Partners*

- **EnduroSat** (Bulgaria): modular CubeSat buses, science-friendly.
- **ISISpace** (Netherlands): strong ESA/university collaboration heritage.
- **NanoAvionics** (Lithuania): reliable 3U–6U platforms.
- **GomSpace** (Denmark): high-end, ESA-tested platforms.

6.2. *Academic and Institutional Partners*

- ESA Education Office (Fly Your Satellite!).
- National space agencies (CNES, DLR, UKSA, ASI, etc.).
- University laboratories for detector development and mission operations.

7. IMPLEMENTATION ROADMAP

- **2025**: Feasibility study and MCD (this document).
- **2026**: Payload design; industry partnership agreements.
- **2027**: Application to ESA FlyYourSatellite! and/or other programs.
- **2028–2032**: Development, integration, testing.
- **2032–2035+**: Launch window; mission operations.
- **2040**: End of mission; potential upgrade/expansion of constellation.

Emphasis on student-led character: training, education, and legacy.

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8. FUNDING CONSIDERATIONS

- Estimated cost per 3U CubeSat: €0.8–1.2M (bus + launch + ops).
- Primary sources: ESA Education, national agencies, university contributions.
- Secondary sources: crowdfunding for outreach and small components.
- Strategy: phased funding, linked to technical readiness and partnership milestones.

9. BROADER IMPACT AND LEGACY

- **Educational**: training a new generation of astrophysicists and engineers.
- **Scientific**: filling the observational gap in high-energy transient detection.
- **Strategic**: pathfinder for distributed astrophysics missions.
- **Long-term vision**: expandable student-led CubeSat network for multi-messenger astronomy.
- Train the next generation of astrophysicists and engineers through a fully student-led mission.

10. CONCLUSION

- Restate the necessity of CAPIGX in the 2030s.
- Emphasize the unique dual role: **scientific innovation + educational empowerment**.
- A feasible, visionary step toward democratizing access to space-based astrophysics.

From mission concept: This concept is based on a modular, cost-effective platform that holds commercial and accessible CubeSat technology while boosting the mission's scientific goals.

11. SOFTWARE AND THIRD PARTY DATA REPOSITORY CITATIONS

The code used to produce figure 1 can be found here https://github.com/CAPIBARA3/capigx-obs-stats.

The AAS Journals would like to encourage authors to change software and third party data repository references from the current standard of a footnote to a first class citation in the bibliography. As a bibliographic citation these important references will be more easily captured and credit will be given to the appropriate people.

The first step to making this happen is to have the data or software in a long term repository that has made these items available via a persistent identifier like a Digital Object Identifier (DOI). A list of repositories that satisfy this criteria plus each one's pros and cons are given at https://github.com/AASJournals/Tutorials/tree/master/Repositories.

In the bibliography the format for data or code follows this format:

author year, title, version, publisher, prefix:identifier

L. Corrales (2015) provides a example of how the citation in the article references the external code at https://doi.org/10.5281/zenodo.15991. Unfortunately, bibtex does not have specific bibtex entries for these types of references so the "@misc" type should be used. The Repository tutorial explains how to code the "@misc" type correctly. The most recent .bst file, aasjournalv7.bst, will output bibtex "@misc" type properly.

Authors can also use the website https://www.doi2bib.org/ to create a BIBTeX entry for any DOI. Please check the output from this site carefully as its output is only as good as the DOI metadata. Some DOI creators do not provide enough metadata to construct an adequate citation.

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AUTHOR CONTRIBUTIONS

JAN came up with the mission concept and was responsible for the development of the feasibility study and the writing of this manuscript.

Software: dataclasses, typing, matplotlib, numpy (from capigx_obs_stats)

APPENDIX

A. APPENDIX INFORMATION

Appendices can be broken into separate sections just like in the main text. The only difference is that each appendix section is indexed by a letter (A, B, C, etc.) instead of a number. Likewise numbered equations have the section letter appended.

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