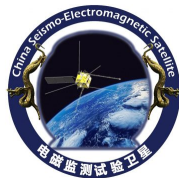


The HEPD-01 instrument as a Gamma-Ray Burst detector on board the CSES-01 satellite and future perspectives

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July 18, 2024

China Seismo-Electromagnetic Satellite (CSES-01)

CSES scientific goals:

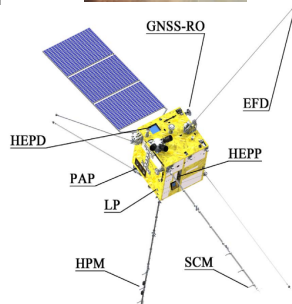
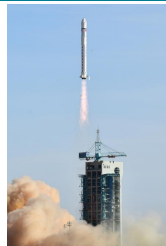
- ▶ Monitoring the near-Earth electromagnetic environment
- ▶ Measuring iono-magnetospheric perturbations possibly due to seismo-electromagnetic phenomena
- ▶ Monitoring electromagnetic anthropic effects at low-Earth orbit altitude
- ▶ Studying spectra of charged particles precipitating from the Van Allen radiation belts
- ▶ Observing changes in solar activity

CSES satellites:

- ▶ **The first satellite (CSES-01) was launched** from the Jiuquan Satellite Launch Center in the Gobi Desert (Inner Mongolia) **on February 2, 2018**, hosting **eight payloads**, among which the **Italian High-Energy Particle Detector (HEPD-01)**

Platform	Mass	$\simeq 700$ kg
Orbit	Type	Sun-Synchronous
	Altitude	507 km
	Inclination	97°
	Period	94 minutes
	Revisit period	5 days
Mission	Life Span	≥ 5 years

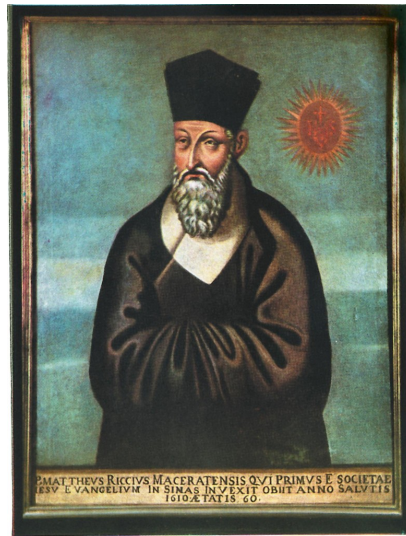
- ▶ **The second satellite (CSES-02) will be launched** from the Jiuquan Satellite Launch Center **in December 2024**



CSES-01 satellite

The CSES-Limadou Collaboration

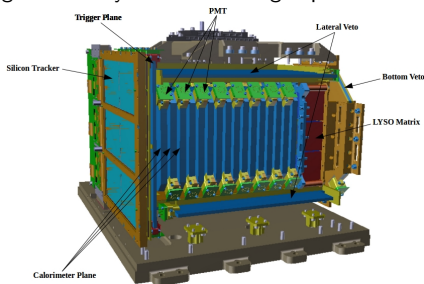
- ▶ The **Italian Collaboration** is named after the Italian missionary in China, Matteo Ricci (1552-1610), whose Mandarin name was **Li-madou**
- ▶ The Italian contribution to the CSES mission:
 - CSES-01: design and realization of the High-Energy Particle Detector (HEPD-01) on board the China Seismo-Electromagnetic Satellite (CSES-01) and the participation in the realization of the Electric Field Detector (EFD-01)
 - CSES-02: design and realization of two instruments on board the CSES-02 satellite, the second High-Energy Particle Detector (HEPD-02) and the Electric Field Detector (EFD-02)
- ▶ Several Italian institutes and universities involved:
 - Italian National Institute for Nuclear Physics (INFN)
 - Universities of Trento, Bologna, Rome "Tor Vergata", UNINETTUNO and Naples
 - Italian National Institute of Astrophysics and Planetology (INAF-IAPS)
 - Italian National Institute of Geophysics and Volcanology (INGV)



The High-Energy Particle Detector (HEPD-01)

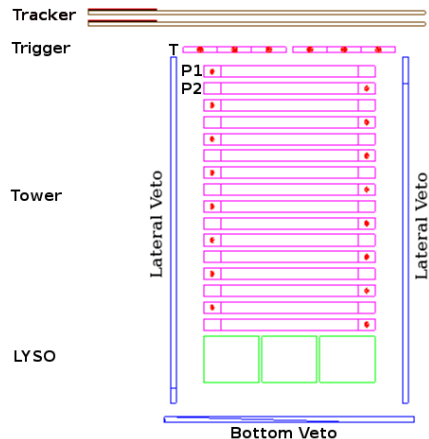
- ▶ 2 planes ($213.2 \times 214.8 \times 0.3 \text{ mm}^3$) of double-sided silicon microstrip sensors (**Tracker**) → track-related information
- ▶ 1 layer ($20 \times 18 \times 0.5 \text{ cm}^3$) of plastic scintillator (**Trigger**) → start acquisition
- ▶ range calorimeter comprising:
 - 16 layers of $15 \times 15 \times 1 \text{ cm}^3$ plastic scintillators (**Tower**), read out by 2 PMTs each → energy deposit
 - 3×3 matrix ($15 \times 15 \times 4 \text{ cm}^3$) of inorganic crystals (**LYSO**), read out by 1 PMT each → increase range
- ▶ 5 5 mm-thick plastic scintillator planes (**Veto**) → reject up-going or not fully-contained charged particles

Energy range (e^-)	3-100 MeV
Energy range (p)	30-250 MeV
Energy range (nuclei)	30-250 MeV/n
Angular resolution	$< 8^\circ$ @ 5 MeV
Energy resolution	$< 10\%$ @ 5 MeV
Acceptance	$\sim 400 \text{ cm}^2\text{sr}$
Mass	$\sim 45 \text{ kg}$



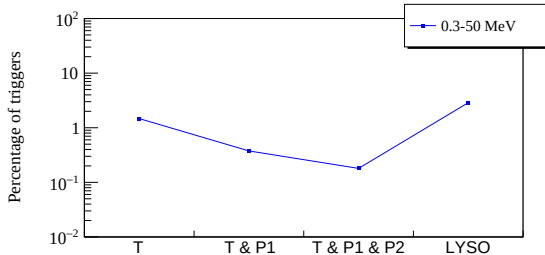
HEPD-01 trigger masks and GRB indirect detection

- ▶ For HEPD-01 online trigger condition, a single trigger mask can be chosen from a set of 8 predefined trigger mask configurations, which are given by different logic combinations of the various subdetectors
- ▶ The upmost trigger condition T corresponds to an above-threshold signal only in the trigger plane, and it is associated with the lowest energy threshold (e.g., > 3 MeV electrons). Other trigger masks require a deeper penetration of the charged particle inside the detector (i.e., T&P1, T&P1&P2, and so on)
- ▶ For each of the 8 predefined masks, even when not selected for the online acquisition, a rate meter independently provides the corresponding trigger counting rate with a 1 s resolution
- ▶ As for previous space weather studies, the rate meter of the most superficial trigger configuration T was the only one out of the 8 to exhibit a significant response to GRBs, due to the very low-energy particles involved in such phenomena
- ▶ Monte Carlo simulations showed that the GRB photon interaction in the upmost sections of HEPD-01 leads to the generation of secondary electrons which, in turn, are detected by the T trigger mask



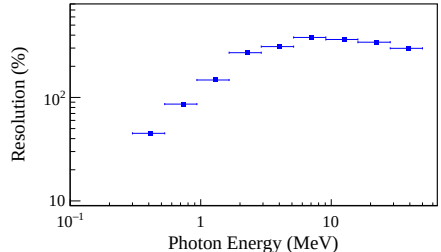
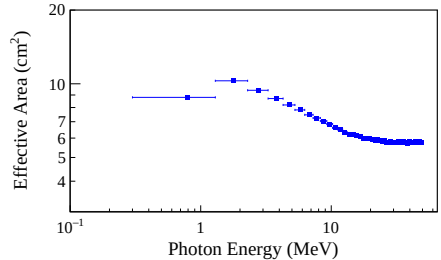
HEPD-01 as a Gamma-Ray Detector (1/2)

- ▶ Geant4 simulation of **100 million photons isotropically generated** according to a **logarithmic energy distribution (300 keV - 50 MeV)** from a $40 \times 40 \text{ cm}^2$ surface immediately above HEPD-01 particle entrance window
- ▶ As observed from in-flight rate meters, **the trigger configurations, requiring the coincidence among above-threshold signals from the T trigger plane and an increasing number of tower planes (such as T&P1, T&P1&P2, and so on), are less and less efficient in detecting the low-energy secondary electrons, which are produced by the simulated primary photons interacting with the active and passive materials of the upmost sections of the apparatus**
- ▶ Conversely, even after passing through all the 16 tower planes, **a significant fraction of photons interacts in the dense high-Z LYSO cubes**. However, **a dedicated trigger mask including only the LYSO subdetector is not implemented in HEPD-01**



HEPD-01 as a Gamma-Ray Detector (2/2)

- ▶ Geant4 simulation of **100 million vertical photons** generated according to a **flat energy distribution (300 keV - 50 MeV)**
- ▶ **HEPD-01 effective area and resolution are related to secondary electrons, which are generated by the interactions of the simulated primary photons in the upper sections of the instrument** and which deposit above-threshold signals in the T trigger plane (the same trigger configuration as used for the GRB data analysis)
- ▶ Monte Carlo simulations show **HEPD-01 is sensitive to gamma-ray photons in the 300 keV - 50 MeV energy range, even if with a moderate effective area above ~ 5 MeV (peak sensitivity at ~ 2 MeV)**
- ▶ A dedicated time correlation analysis between GRBs reported in literature and signals from the most superficial HEPD-01 trigger configuration T has confirmed the anticipated detector sensitivity to high-energy photons



GRB observations by HEPD-01

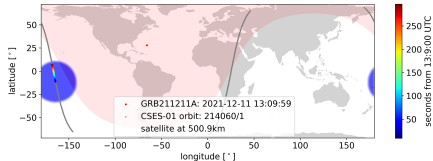
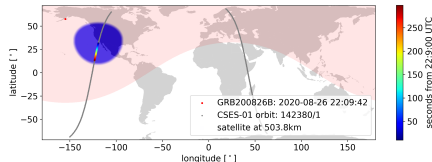
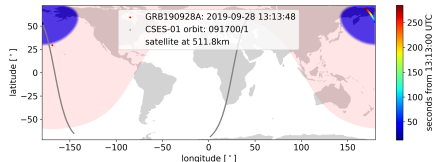
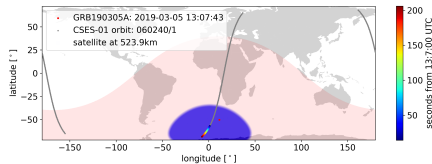
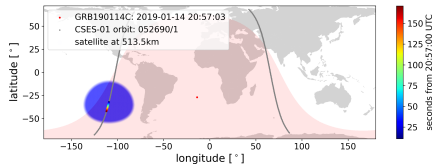
- ▶ The entire HEPD-01 data set since the end of commissioning (August 2018) was analyzed in search for signals time-correlated with GRBs detected by dedicated gamma-ray instruments
- ▶ We only considered GRB Coordinates Networks reporting GRBs during periods when HEPD-01 was in operation and data were not affected by strong solar activity, the South Atlantic Anomaly passage, etc.
- ▶ We found a **good agreement between HEPD-01 time profiles of the low-energy (> 3 MeV) electrons** (produced by the GRB-impinging photons and detected by the most superficial trigger configuration T) **and the time profiles of the signals from INTEGRAL/PICsIT and INTEGRAL/SPI-ACS for the following 5 GRBs: GRB190114C, GRB190305A, GRB190928A, GRB200826B and GRB211211A**

GRB identifier	Right ascension (deg.)	Declination (deg.)	Trigger time (UTC)
GRB190114C	56.2	-31.8	20:57:03
GRB190305A	11.3	-50.1	13:05:19
GRB190928A	36.6	+29.5	13:13.48
GRB200826B	296.3	+71.8	22:09:42
GRB211211A	211.3	+27.1	13:59:09

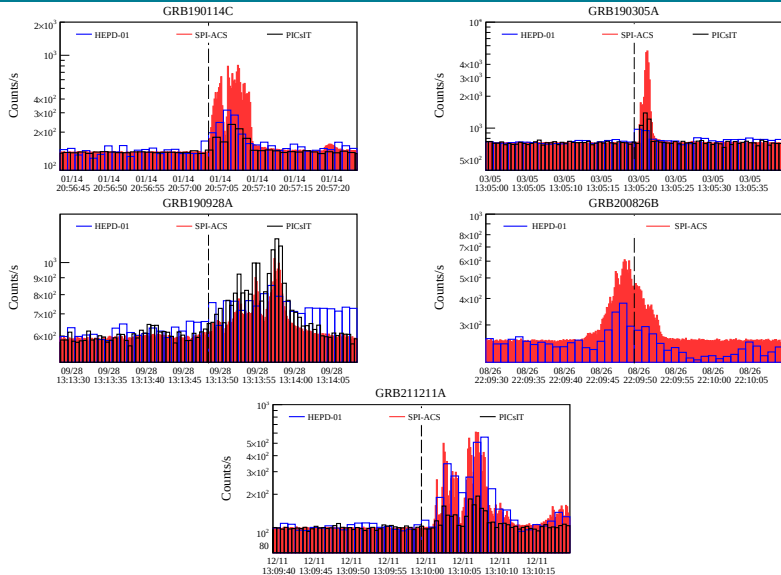
- ▶ We published our observations of these 5 GRBs in the following paper:
Gamma-Ray Burst Observations by the High-Energy Particle Detector on board the China Seismo-Electromagnetic Satellite between 2019 and 2021
F. Palma et al. 2024 ApJ 960 21

CSES-01 orbits during the 5 observed GRBs

Overlap between **the GRB illumination area (red area)** and **the satellite's horizon (blue area)**



GRB time profiles from HEPD-01



GRB fluences from HEPD-01

- ▶ We used the spectral parameters and spectral model (a phenomenological model called a Band function) reported by Konus-Wind to extrapolate the HEPD-01 flux to the 300 keV to 50 MeV energy range, which is well outside the Konus-Wind energy range (from 20 keV to 10 MeV)
- ▶ Errors on HEPD-01 fluences take into account a 20% contribution due to systematic uncertainties

GRB identifier	HEPD-01 duration (s)	Konus-Wind fluence (300 keV - 50 MeV) (erg cm^{-2})	HEPD-01 fluence (300 keV - 50 MeV) (erg cm^{-2})
GRB190114C	6	$(1.6 \pm 0.1) \times 10^{-4}$	$(2.2 \pm 0.3) \times 10^{-4}$
GRB190305A	3	$(1.2 \pm 0.3) \times 10^{-4}$	$(1.0 \pm 0.3) \times 10^{-4}$
GRB190928A	11	$(3.3 \pm 0.2) \times 10^{-4}$	$(2.6 \pm 0.5) \times 10^{-3}$
GRB200826B	6	$(1.1 \pm 0.1) \times 10^{-4}$	$(3.0 \pm 0.5) \times 10^{-4}$
GRB211211A	9	$(3.4 \pm 0.1) \times 10^{-4}$	$(7.9 \pm 0.9) \times 10^{-4}$

- ▶ For GRB190114C and GRB190305A, the fluences are statistically compatible within 2σ .
For GRB190928A, GRB200826B and GRB211211A, the HEPD-01 fluences are incompatible with the extrapolations of the Konus-Wind spectra values
- ▶ GRB190928A, GRB200826B and GRB211211A show an additional high-energy spectral component above 10 MeV, as also observed in GRB190114C up to ~ 100 MeV.
We hypothesized the HEPD-01 fluences are higher because the instrument observes a spectral component Konus-Wind doesn't

Near future: HEPD-02 on board CSES-02

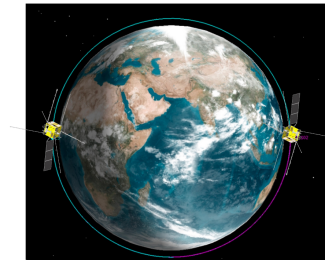
CSES-02 (launch scheduled in December 2024):

- ▶ **11 instruments on board:** e.m. field, plasma and particles
- ▶ Same CAST-2000 platform as CSES-01 with **some upgrades**:
 - Earth oriented 3-axis stabilization system with orbit maneuver capability
 - X-Band data transmission: 120 Mbps → **150 Mbps**
 - Storage: 160 Gb → **512 Gb**
 - Total mass: 730 kg → **900 kg**
 - Peak power consumption: ~ **900 W**
 - Design life-span: 5 years → **6 years**
- ▶ **Complementary ground track with respect to CSES-01:** identical orbit plane with 180° phase difference
(track interval: 5° → 2.5°, return cycle: 5 days → 2.5 days)
- ▶ **Full-time operational mode:** $[-70^\circ; +70^\circ]$ latitude → **full coverage**

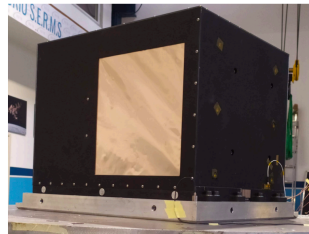
HEPD-02 (installed on CSES-02 since December 2023):

- ▶ **First silicon-pixel tracker ever designed for space**
- ▶ **Two trigger planes**
- ▶ **Improved LYSO calorimeter** with 6 bars (3 in each layer and orthogonal)
- ▶ **Concurrent and pre-scaled triggers**
- ▶ **Sensitivity to Gamma-Ray Bursts**

CSES-01 & CSES-02

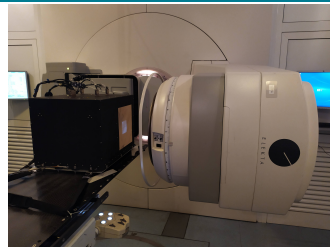


HEPD-02

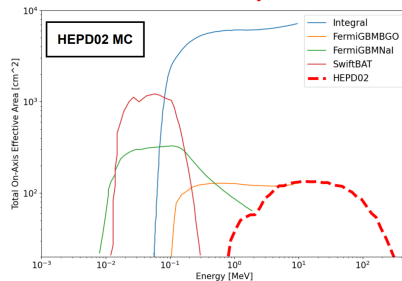


GRB detection by HEPD-02

- ▶ The HEPD-02 detector is a major upgrade of HEPD-01. Among novelties, **an improved trigger logic with a dedicated mode for GRB detection** has been implemented:
 - **Two trigger masks for GRB detection** have been implemented: one exploits the high density of the **two LYSO layers to detect high-energy photons**, while the other relies on **the plastic scintillator tower to detect lower energy photons**
 - Trigger configuration dedicated to gamma-rays tracked **on a time basis of 5 ms**
- ▶ The GRB detection algorithm has been tested using 10 MV photons of varying durations from an **Elekta medical LINAC at the Trento Santa Chiara Hospital**
- ▶ For GRB detection, HEPD-02 will cover the energy range between **0.5 and 100 MeV** with a peak effective area of 150 cm^2 at $\sim 10 \text{ MeV}$ and a 20%-30% energy resolution



Preliminary!



Follega, F. M. 2023, ICRC (Nagoya), 444, 116

Conclusions and perspectives

- ▶ Although not specifically designed for gamma-ray detection, **the HEPD-01 instrument observed 5 strong Gamma-Ray Bursts between 2019 and 2021 (GRB190114C, GRB190305A, GRB190928A, GRB200826B and GRB211211A) with a typical fluence above $\sim 3 \times 10^{-5}$ erg cm $^{-2}$** , which corresponds to the 2σ detection limit of HEPD-01 in the trigger configuration running during the reported GRB observation (*F. Palma et al. 2024 ApJ 960 21*)
- ▶ For a complete catalogue of GRB observations by HEPD-01 in the period 2018-2022 and in the 300 keV-50 MeV energy range, please see the presentation by Francesco Maria Follega in E1.6 session
- ▶ For the reported five GRBs, **a comparison between HEPD-01 time profiles of electron counts and the time profiles of the light curves from INTEGRAL/PICsIT and INTEGRAL/SPI-ACS showed a remarkable similarity, in spite of the different energy ranges**
- ▶ Moreover, **the high-energy extension of HEPD-01 measured fluences up to 50 MeV provided a valuable contribution to the single GRB characterization**. HEPD-01 results are valuable both as an independent source of data and as a valid test for the second-generation detector (HEPD-02), whose launch on board the CSES-02 satellite is scheduled in December 2024
- ▶ **Given the instrumental improvements with respect to HEPD-01 and thanks to a dedicated trigger system for gamma-ray detection, HEPD-02 will aim to contribute to a wider, real-time alert program (InterPlanetary Network, etc.) during the second mission**

Backup slide: details about each observed GRB

5.2. GRB190114C

This GRB was the first detected at sub-TeV energy by MAGIC during prompt and afterglow phases (MAGIC Collaboration et al. 2019), after the first report at $T_0 = 20:57:03$ UTC by Swift-BAT (Gropp et al. 2019) in the 15–350 keV band ($T_{90} = 362$ s), and by Fermi Gamma-Ray Burst Monitor (GBM; Hamburg et al. 2019) in the 50–300 keV range ($T_{90} = 116$ s). The 10–1000 keV fluence reported by Fermi was 4.433×10^{-4} erg cm $^{-2}$ (Ajello et al. 2020). The

redshift of the GRB is $z = 0.42$ (Selsing et al. 2019), which was used to estimate $E_{\text{iso}} = 2.5 \times 10^{53}$ erg, where E_{iso} is the energy emitted in gamma rays, assuming that the emission is isotropic. Konus-Wind reported a 20 keV–10 MeV fluence of $(4.83 \pm 0.10) \times 10^{-4}$ erg cm $^{-2}$ (Frederiks et al. 2019a). Further information on the burst characteristics at optical wavelength is given in Melandri et al. (2022) via the monitoring between 1.3 and 370 days after the trigger, which revealed a supernova component (SN 2019jrr), underlying the GRB emission. The afterglow emission from this GRB was detected at various wave bands from 0.65 GHz to 23 GeV.

5.3. GRB190305A

This bright and long-duration GRB was first reported by Astro Rivellatore Gamma a Immagini Leggero (AGILE; Ursi et al. 2019a) at $T_0 = 13:05:19.34$ UTC, followed by Swift (Evans et al. 2019), Monitor of All-sky X-ray Image (Nakahira et al. 2019), Insight Hard X-ray Modulation Telescope (Insight-HXMT; Xiao et al. 2019), InterPlanetary Network (IPN) triangulation (Svinkin et al. 2021), and Konus-Wind (Kozlova et al. 2019). The fluence, as reported by Konus-Wind, was 1.47×10^{-4} erg cm $^{-2}$.

5.4. GRB190928A

This bright and long GRB was first reported by AGILE (Ursi et al. 2019b) followed by the IPN triangulation (Hurley et al. 2019) and the Calorimetric Electron Telescope (Pal'Shin et al. 2019). The light curve showed multi-peaked pulses with periods of low emission. It was also detected by Konus-Wind (Frederiks et al. 2019b) for a total of about 195 s up to ~ 15 MeV at fluence of 4.9×10^{-4} erg cm $^{-2}$, including a 256 ms peak detected at $T_0 + 103$ s with a fluence of 9×10^{-5} erg cm $^{-2}$ and peak energy of 591 keV. The burst was also reported by Insight-HXMT (Luo et al. 2019) and AstroSat (Gaikwad et al. 2019).

5.5. GRB200826B

First reported by the Fermi/GBM team (Malacaria et al. 2020) as an exceptionally bright and long GRB with $T_{90} = 7.4$ s in the 50–300 keV band, peak energy of 410 keV and fluence of 1.4×10^{-4} erg cm $^{-2}$. The reported 20 keV–10 MeV fluence from Konus-Wind was $(2.0 \pm 0.1) \times 10^{-4}$ erg cm $^{-2}$ (Ridnaia et al. 2020). An IPN triangulation by Konus-Wind, INTEGRAL, and Mars-Odyssey was reported in Hurley et al. (2020). Konus-Wind (Ridnaia et al. 2020) showed a light curve with bright multipulse peaks of a total duration of 23 s and weak emission detected up to

$T_0 + 250$ s and 10 MeV, with a fluence of 2×10^{-4} erg cm $^{-2}$ and peak energy of 337 keV.

5.6. GRB211211A

This enigmatic, hybrid GRB was reported by Swift as the second brightest and most complex up to that time (D'Ai et al. 2021) with emission extending up to $T_0 + 100$ s. Optical afterglow was promptly detected by Zheng & Filippenko (2021). A Swift fluence of 1.5×10^{-4} erg cm $^{-2}$ (15–150 keV) was then reported in Stamatikos et al. (2021). Fermi/GBM showed a low-energy curve in the 10–300 keV range characterized by three separate pulses and a peak energy of 646.8 keV. The event fluence is 5.4×10^{-4} erg cm $^{-2}$ (10–1000 keV) from $T_0 - 1.264$ s to $T_0 + 54.033$ s (Mangan et al. 2021). The optical, ultraviolet, and X-ray counterparts were immediately searched and finally a nearby host galaxy at a distance of 346 Mpc was identified by different authors. Further observations confirmed the initial GRB location and reported a peculiar slow decay associated with such a long GRB type (Malesani et al. 2021a). In Malesani et al. (2021b), Malesani corrected the E_{iso} value to 6.9×10^{51} erg. The collected result from observational campaigns made clear the unusual nature of GRB211211A compared to the classical long GRBs at such a distance and suggested a generation mechanism from a compact binary merger (such as two neutron stars) in order to match location, rapid decay, and color (see Levan et al. 2021). The features of this event impacted the standard GRB scenario; characteristics, light curves, and new models are reported in Mei et al. (2022), Rastinejad et al. (2022), Troja et al. (2022), and Yang et al. (2022).