Gamma-Ray Burst observations by HEPD-01 space detector on board CSES-01 as an anticipation of future ones by HEPD-02 on CSES-02

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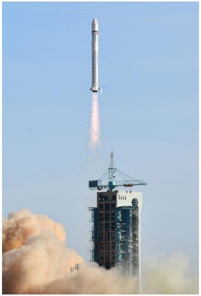
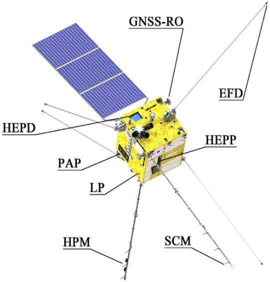
China Seismo-Electromagnetic Satellite (CSES-01)

- Monitoring of the near-Earth space environment
- Measurements of iono-magnetospheric perturbations possibly due to seismo-electromagnetic phenomena
- Measurements of magnetospheric and solar activity (both on short and long time-scales like solar events and solar modulation)
- Study of fluxes of high- & low-energy charged particles inside the Inner and Outer Van Allen radiation belts
- Monitoring of the e.m. anthropic effects at LEO altitude



CSES-01 was launched from the Jiuquan Satellite Launch Center in the Gobi Desert (Inner Mongolia) **on February 2, 2018**, hosting **8 payloads**, **among which the Italian High-Energy Particle Detector**

Platform	Mass	$\simeq$ 700 kg
Orbit	**Type**	**Sun-Synchronous**
	Altitude	**507 km**
	Inclination	**97°**
	Period	94 minutes
	Local time descending node	14:00
	Revisit period	5 days
Mission	Life Span	$\geq$ 5 years



The CSES-Limadou Collaboration

- CSES is part of a collaboration program between the China National Space Administration (CNSA) and the Italian Space Agency (ASI)
- 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 mission has included the 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)**
- 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).

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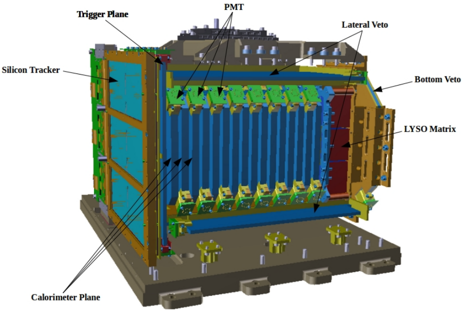
The High-Energy Particle Detector (HEPD-01)

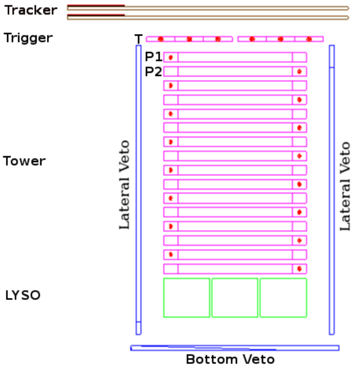
- 2 planes ($213.2\times214.8\times0.3$ mm^3) of double-sided silicon microstrip sensors (**Tracker**) $\rightarrow$ track-related information
- 1 layer ($20\times18\times0.5$ cm^3) of plastic scintillator (**Trigger**) $\rightarrow$ start acquisition
- range calorimeter comprising:
  - 16 layers of $15\times15\times1$ cm^3 plastic scintillators (**Tower**), read out by 2 PMTs each $\rightarrow$ energy deposit
  - 3×3 matrix ($15\times15\times4$ cm^3) of inorganic crystals (**LYSO**), read out by 1 PMT each $\rightarrow$ increase range
- 5 5 mm-thick plastic scintillator planes (**Veto**) $\rightarrow$ reject up-going or not fully-contained charged particles

En. range (e^-)	**3-100 MeV**
En. range (p)	**30-250 MeV**
En. range (nuclei)	**30-250 MeV/n**
Angular resol.	$< 8^\circ$ @ 5 MeV
Energy resol.	$< 10\%$ @ 5 MeV
Acceptance	$\sim$ 400 cm^{2}sr
Mass (+ el.)	$\sim$ 44 kg



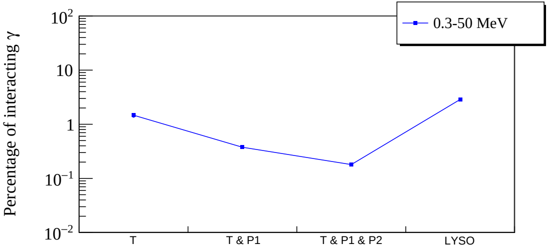
HEPD-01 trigger masks and GRB indirect detection

- **HEPD-01 can tap into 8 predefined trigger mask configurations**, which are given by different logic combinations of the various sub-detectors
- **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 1-second resolution**
- As for some previous space weather studies, **the most superficial HEPD-01 trigger configuration T has proven extremely helpful for Gamma-Ray Burst (GRB) indirect detection, since it was the only one out of the 8 to exhibit a significant response to some GRBs from 2019 to 2021**
- Monte Carlo simulation has shown 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 trigger mask T



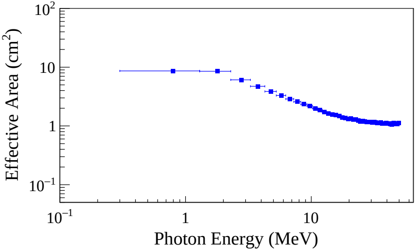
Monte Carlo simulations of γ-rays inside HEPD-01

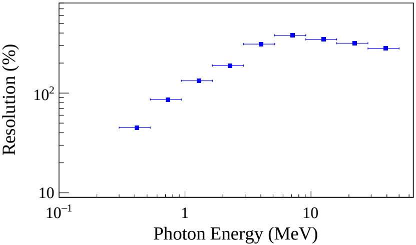
- Geant4 simulation of **100 million photons isotropically generated** according to a **logarithmic energy distribution (300 keV - 50 MeV)** from a 40×40 cm^2 surface immediately above HEPD-01 particle entrance window
- As observed from in-flight rate meters, **photons have lower and lower probability to convert into electrons and positrons as they penetrate deeper and deeper in the plastic scintillator tower**
- Conversely, even after passing through all the 16 tower planes, **a significant fraction of photons interacts in the dense high-Z LYSO crystals**. However, **a dedicated trigger mask requiring only an above-threshold signal from the LYSO matrix is not implemented in HEPD-01**



MC HEPD-01 performance in γ-ray indirect detection

- 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 only in the trigger plane T
- Monte Carlo simulations show **HEPD-01 is sensitive to gamma-ray photons in the energy range 300 keV - 50 MeV, even if with a moderate effective area (peak efficiency at $\sim$ 1 MeV)**





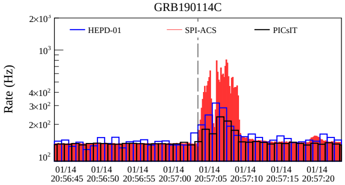
GRBs observed by HEPD-01 from 2019 to 2021

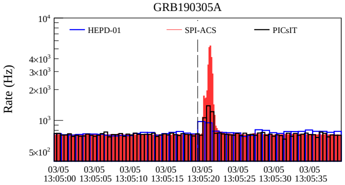
- We analyzed the entire HEPD-01 dataset since the end of commissioning (August 2018) in search for signals time-correlated with GRBs detected by dedicated gamma-ray instruments
- We only considered GRB Coordinates Networks reporting GRBs during periods when HEPD-01 was in operation and data were not affected by strong solar activity, South Atlantic Anomaly passage, etc.
- We found **a good agreement between HEPD-01 time-profiles of the low-energy ($>$ 3 MeV) electrons** (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 five GRBs: GRB190114C, GRB190305A, GRB190928A, GRB200826B and GRB211211A**

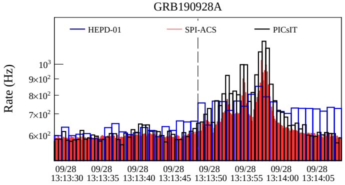
GRB identifier	**Right asc. (deg.)**	**Declination (deg.)**	**Trigger time**	**Duration (sec.)**	**Fluence* (erg cm^{-2})**	**Peak (keV)**	**E_{iso} (erg)**
GRB190114C	56.2	-31.8	20:57:03	$>$ 25	4.83×10^{-4}	815	2.5×10^{53}
GRB190305A	11.3	-50.1	13:05:19	11	1.47×10^{-4}	1313	
GRB190928A	36.6	$+29.5$	13:13.48	195	4.9×10^{-4}	591	
GRB200826B	296.3	$+71.8$	22:09:42	23	2.0×10^{-4}	337	
GRB211211A	211.3	$+27.1$	13:59:09	$>$ 50	1.4×10^{-3}	750	6.9×10^{51}

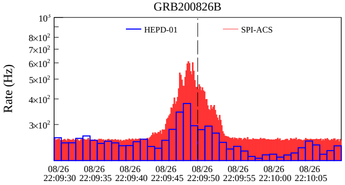
*** in 20 keV - 10 MeV energy range**

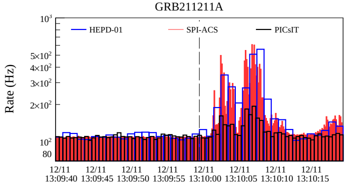
GRB observations by HEPD-01 from 2019 to 2021





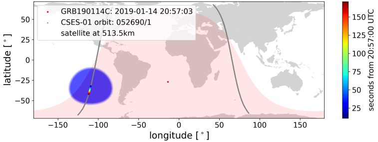


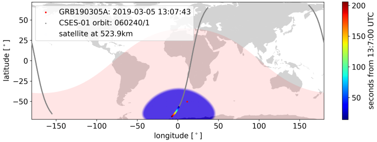


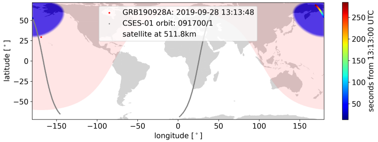


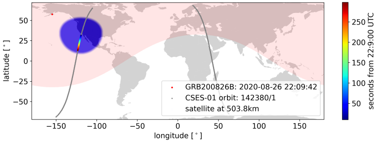
CSES-01 orbits during the five observed GRBs

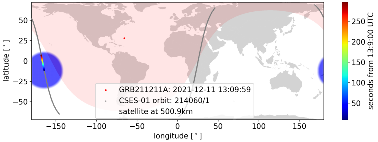
An overlap between the illuminated half-globe of the GRB (red area) and the horizon seen at the satellite altitude (blue area) confirms the visibility of all five GRBs by the HEPD-01 instrument on-board CSES-01.





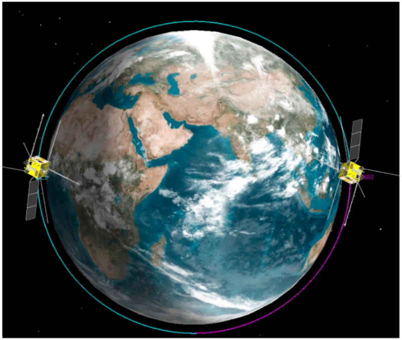






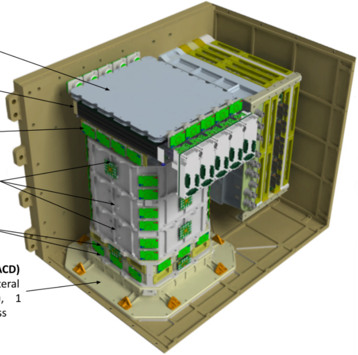
The future CSES-02 mission

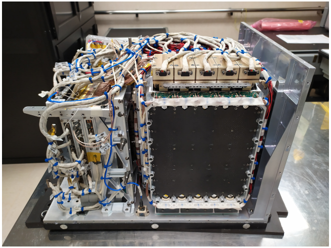
- **Launch scheduled by 2024**
- **Same CAST-2000 platform as CSES-01 with some upgrades**:
  - Earth oriented 3-axis stabilization system with orbit maneuver capability
  - X-Band data transmission: 120 Mbps $\rightarrow$ **150 Mbps**
  - Storage: 160 Gb $\rightarrow$ **512 Gb**
  - Total mass: 730 kg $\rightarrow$ **900 kg**
  - Peak power consumption: $\sim$ **900 W**
  - Design life-span: 5 years $\rightarrow$ **6 years**
- **Complementary ground track wrt CSES-01**:
  - Identical orbit plane, 180° phase difference
  - Track interval: 5° $\rightarrow$ **2.5°**
  - Return cycle: 5 days $\rightarrow$ **2.5 days**
- **Operation mode: full time operational**
- **Limadou collaboration committed to design and build HEPD-02 and EFD-02 detectors**



The HEPD-02 detector on board CSES-02

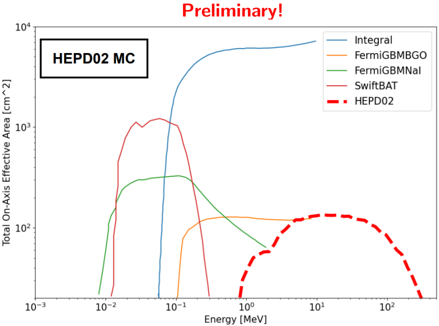
- **HEPD-02 requirements**
  En. range (e^-): 3-100 MeV
  En. range (p): 30-200 MeV
  Ang. resol. $\leq 10^\circ$ for > 3 MeV e^-
  En. resol. $\leq 10\%$ for > 5 MeV e^-
  Particle selection efficiency $> 90\%$
- **Improvements wrt HEPD-01**
  First silicon-pixel tracker ever designed for space ($\rightarrow$ increased tracking capability)
  Double trigger system guaranteeing hermeticity
  Largest LYSO scintillators ever produced for space ($\rightarrow$ increased energy resolution)
  Prescaled concurrent triggers allowing for lower energy measurements over the poles and the SAA
  Sensitivity to Gamma-Ray Bursts and dedicated trigger system for γ-ray detection
- **HEPD-02 Flight Model is fully integrated and has passed all the space-qualification tests**



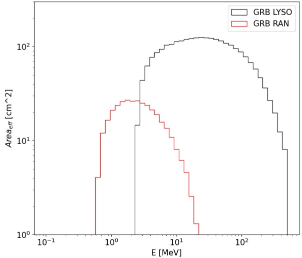


GRB detection by HEPD-02

- HEPD-02 will aim to observe **Gamma-Ray Bursts from a few MeV to hundreds MeV, thanks to the improved LYSO calorimeter and to a dedicated trigger logic**
- **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**
- **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**
- A Monte Carlo simulation is currently underway to further investigate the instrument response to photon events



Follega, F. M. 2023, PoS, ICRC2023, 116



Lega, A., Follega, F., Iuppa, R., et al. 2023, PoS, ICRC2023, 758

Conclusions

- Since 2018, HEPD-01 has been obtaining important results in cosmic-ray and solar physics (see talk by B. Panico - CCR - Sept. 11, 2023)
- Although not specifically designed for γ-ray detection, **the HEPD-01 instrument observed five strong Gamma-Ray Bursts with a typical fluence above $\sim 10^{-4}$ erg cm^{-2} between 2019 and 2021: GRB190114C, GRB190305A, GRB190928A, GRB200826B and GRB211211A**
- **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 has shown a remarkable similarity**
- **A fruitful collaboration started between people involved in Charged Particle Astrophysics (from CSES-Limadou team) and people involved in Gamma-Ray Astrophysics (from INTEGRAL team)**
- 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 by 2024**
- **Given the instrumental upgrades with respect to HEPD-01** (see talk by Z. Sahnoun - CCR - Sept. 11, 2023), **HEPD-02 aims to contribute to a real-time alert program, at least for the most intense GRBs**