The High-Energy Particle Detector (HEPD-01) in orbit since 2018: achieved results and ongoing studies

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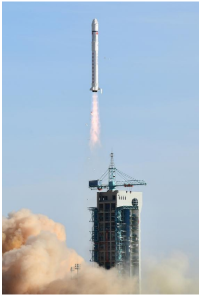
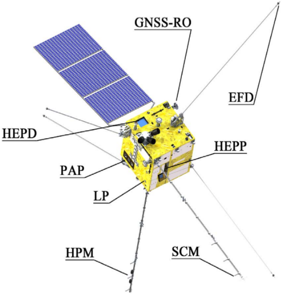
China Seismo-Electromagnetic Satellite (CSES-01)

- 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-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 HEPD-01**

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



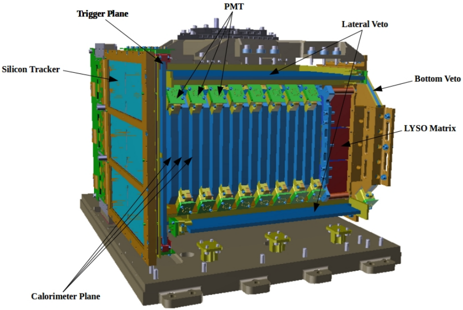
The CSES-Limadou Collaboration

- 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 (launch scheduled in late 2024): 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 ($213.2 \times 214.8 \times 0.3$ mm^3) of double-sided silicon microstrip sensors (**Tracker**) → track-related information
- 1 layer ($20 \times 18 \times 0.5$ cm^3) of plastic scintillator (**Trigger**) → start acquisition
- range calorimeter comprising:
  - 16 layers of $15 \times 15 \times 1$ cm^3 plastic scintillators (**Tower**), read out by 2 PMTs each → energy deposit
  - 3×3 matrix ($15 \times 15 \times 4$ 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

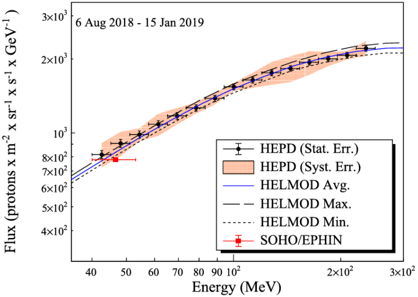
En. range (e^-)	**3-100 MeV**
En. range (p)	**30-250 MeV**
En. range (nuclei)	**30-250 MeV/n**
Angular resol.	$< 8^\circ$ @ 5 MeV
Energy resol.	$< 10\%$ @ 5 MeV
Acceptance	~ 400 cm^{2}sr
Mass (+ el.)	~ 44 kg

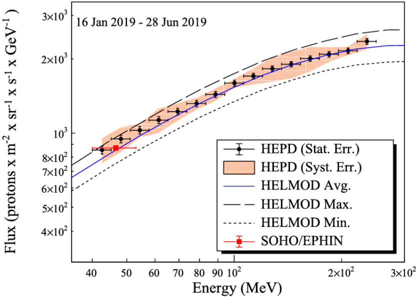


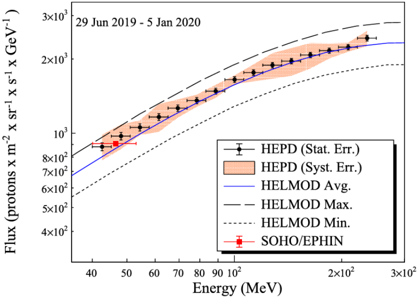
HEPD-01 published (black) & ongoing (blue) studies

- **Galactic Cosmic Ray (GCR) physics:**
  - **GCR proton spectra in the 40–250 MeV range between 2018 and 2020**
    (*S. Bartocci et al. 2020 ApJ 901 8*)
  - **Time Dependence of 50–250 MeV GCR protons between solar cycles 24 and 25**
    (*M. Martucci et al. 2023 ApJL 945 L39*)
  - **Recurrent variations in the daily GCR proton fluxes between 2018 and 2022**
  - **Solar modulation of GCR Helium nuclei in the 70-200 MeV/n range between 2018 and 2022**
- **Solar physics and space weather:**
  - **The first Ground-Level Enhancement (GLE) of solar cycle 25 (on October 28, 2021)**
    (*M. Martucci et al. 2023 Space Weather 21 e2022SW003191*)
  - **Multi-spacecraft observations of electrons, protons and Helium nuclei in some Solar Energetic Particle Events (SEPs) towards the maximum of solar cycle 25**
  - **Study of the November 4, 2021 Forbush decrease**
  - **Study of the August 2018 geomagnetic storm**
    (*F. Palma et al. 2021 Appl. Sci. 11 5680*)
  - **Study of the May 2021 geomagnetic storm**
    (*M. Piersanti et al. 2022 Space Weather 20 e2021SW003016*)
- **Magnetosphere physics:**
  - **Re-entrant albedo protons in the 40–250 MeV range**
    (*M. Martucci et al. 2024 Astroparticle Physics 162(3):102993*)
  - **Re-entrant leptons outside the South Atlantic Anomaly (SAA) in the 20-100 MeV range**
  - **Trapped protons inside the SAA in the 40–250 MeV range between 2018 and 2020**
    (*M. Martucci et al. 2022 Phys. Rev. D 105 062001*)
- **Gamma-Ray Bursts:** please see the talk by Roberto Iuppa in this conference

Galactic Cosmic-Ray (GCR) protons







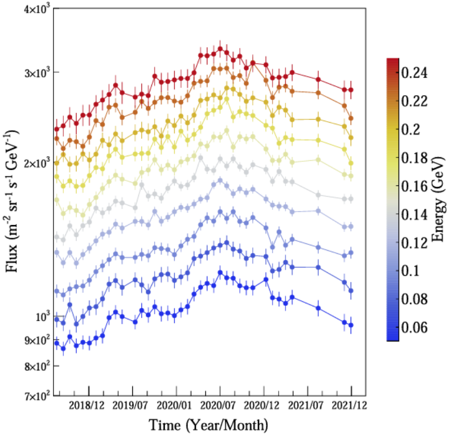
- New results on the **GCR proton energy spectra between 40 and 250 MeV from August 6, 2018 to January 5, 2020** (three semiannual spectra) in *S. Bartocci et al. 2020 ApJ 901 8*
- Comparison with **SOHO/EPHIN** proton data shows a **good agreement**
- The predicted **HelMod model** for GCR proton propagation is also in **good agreement** with HEPD-01 data

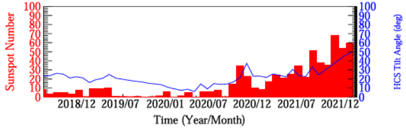
Solar modulation of GCR protons

- A total of **49 proton energy spectra were obtained on a Carrington rotation basis from August 2018 up to March 2022**, during an initial phase of minimum activity, before July 2020, and a subsequent rise towards the maximum phase from the second half of 2020 onward

- The upper panel shows the time profiles of GCR protons measured by HEPD-01 in 10 energy intervals from ∼50 to ∼250 MeV between August 2018 and March 2022.
  During the period between May and July 2020, the proton flux reaches its maximum value

- The bottom panel shows **the sunspot number (red) and the Heliospheric Current Sheet or HCS (blue) tilt angle**.
  The HCS tilt angle represents the misalignment of the magnetic dipole axis of the Sun with respect to the solar rotational axis and is one of the best proxies for modulation of charged particles in cosmic rays because its time variations are globally related to the solar magnetic field

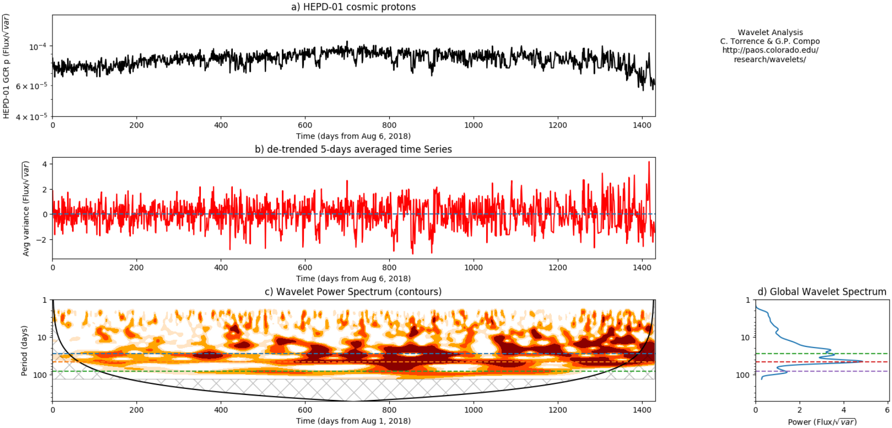




M. Martucci et al. 2023 ApJL 945 L39

Recurrent variations in HEPD-01 GCR proton fluxes

- In order to investigate possible periodicities in GCR proton fluxes, **we have selected the daily GCR proton fluxes measured by HEPD-01 in the energy range 50-250 MeV and in the period between August 2018 and July 2022**
- We have employed **the wavelet analysis by Torrence & Compo** (the Morlet wavelet mother function, see *Torrence et al. 1998*)
- **27, ∼50 and ∼80 day periodicities can be observed**

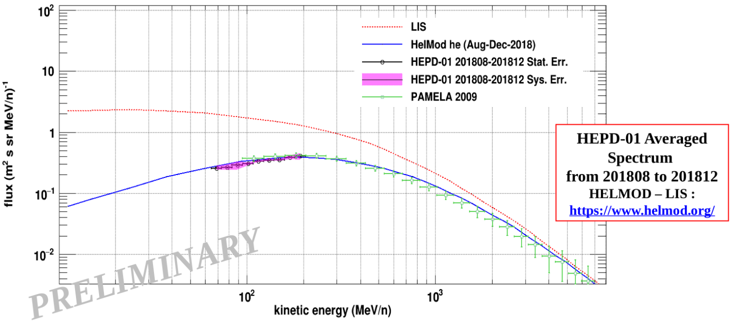


Galactic Cosmic-Ray Helium

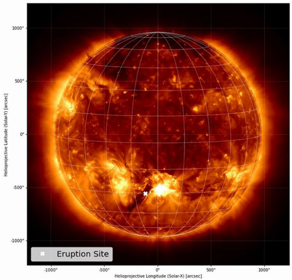
- We have obtained a **preliminary galactic Helium spectrum in the period between August 2018 and January 2019, which shows a good agreement with both HelMod model and PAMELA data**. Once finalized this analysis, we will perform a p/He ratio as a function of energy, to be compared with PAMELA data

- In *N. Marcelli et al. 2020 ApJ 893 145*, PAMELA p/He ratio shows an overall decrease from 2006 to 2009 of about 20% at lower rigidities (∼200 MV). If there is no fundamental difference between proton and helium modulation in the heliosphere, a nonconstant p/He flux ratio over time, for a given rigidity, could possibly be the result of their different velocities, related to the different particle masses

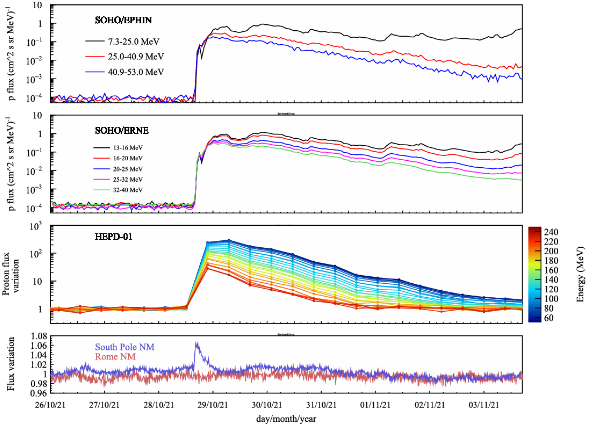
- **HEPD-01 could explore regions with lower energies than PAMELA**, investigating on the nature of this behavior and if such decrease is also present during the solar maximum



The October 28, 2021 Ground-Level Enhancement



- After a series of C- and M-class flares, a long-duration **X1.0-class solar flare** was emitted at 15:35 UTC on October 28, 2021, either triggered by or triggering the filament eruption
- A Coronal Mass Ejection (CME) was associated with a filament eruption in the southern solar hemisphere (white cross in the above figure)
- **First Solar Energetic Particle (SEP) event of solar cycle 25 within HEPD-01 energy range** ($>$ 40 MeV protons)

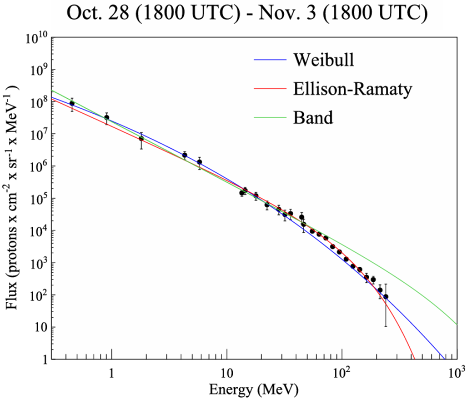


M. Martucci et al. 2023 Space Weather 21 e2022SW003191

- The event also triggered a **Ground-Level Enhancement (GLE#73)**, detected minutes later by the Neutron Monitor (NM) network (South Pole and Rome NMs in the bottom panel)
- The first two panels show EPHIN and ERNE temporal profiles of the SEP event up to about 50 MeV. An overall $\sim$**300x variation of** $\sim$**50 MeV proton fluxes**, due to the injection of solar protons, **was registered by HEPD-01** (third panel)

The October 28, 2021 Ground-Level Enhancement

- The figure shows the **pure, energy-extended event-integrated solar proton spectrum of the SEP/GLE event in the wide energy range 300 keV–250 MeV** obtained by combining the observations of HEPD-01 with the ones from ACE, SOHO/EPHIN, and SOHO/ERNE
- We found that the **Weibull** functional form reproduces the SEP/GLE event spectrum better than the alternative proposed functions like Band and Ellison-Ramaty
- **This favours the mechanism of acceleration from CME**, even if the transport inside the heliosphere could still play an important role and modify the spectral shape
- Other SEPS are currently being studied



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Study of some SEP events in 2021-2022

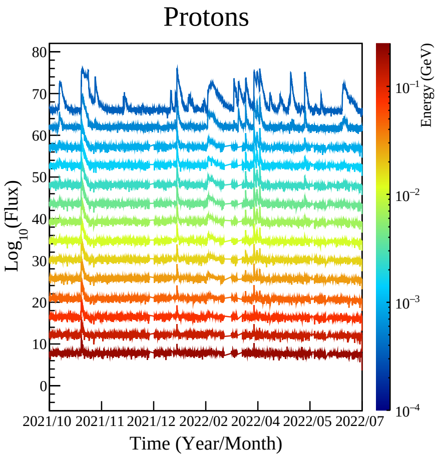
- We are finalizing a **paper on multi-spacecraft observations of electrons, protons and Helium nuclei in some Solar Energetic Particle Events between the end of 2021 and the middle of 2022**

- The figure shows the time profiles of energetic protons during the period from October 1, 2021 to June 30, 2022.

  Hourly proton data are a composition of:

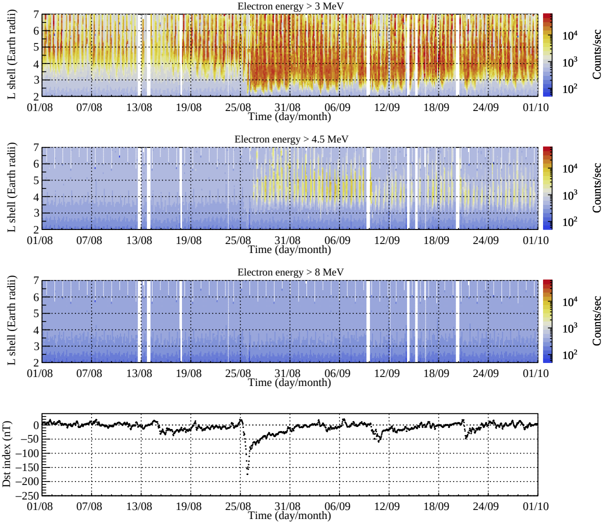
  - ACE/ULEIS (0.320-7.24 MeV/n)
  - SOHO/EPHIN (∼4-53 MeV)
  - SOHO/ERNE (20-100 MeV)
  - HEPD-01 (∼55-250 MeV)

- The occurrence of SEPs can be inferred as spikes appearing over the flat galactic proton background



The August 26, 2018 geomagnetic storm

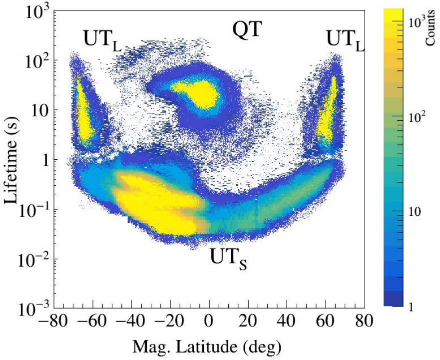
- HEPD-01 is also sensitive enough to measure the effects of geomagnetic storms which are not associated with SEPs
- A slow Coronal Mass Ejection – caused by a filament eruption observed on August 20, 2018 – affected the Earth's environment starting on late August 25, 2018 and gave rise to the **G3-class and third largest geomagnetic storm of solar cycle 24**. The hit of the CME gave rise to a compression of the magnetopause from $\sim 10\ R_E$ before the storm down to $\sim 7.7\ R_E$ and a backward motion of the plasmapause from $\sim 5\ R_E$ down to $\sim 3.8\ R_E$
- A **clear enhancement of HEPD-01 trigger rate during the storm recovery phase** was observed at **L-shells $\gtrsim$ 3**, thus suggesting a phenomenon of **acceleration of energetic electrons**, which lasted for several days, in coincidence with prolonged and intense substorm activity



F. Palma et al. 2021 Appl. Sci. 11 5680

Measurements of re-entrant albedo protons

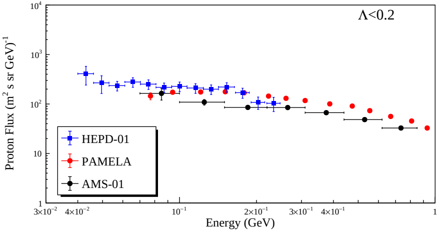
- Moving to lower L-shells, particle populations become more stable, as in the case of the re-entrant albedo protons
- Albedo particles come from the interaction between galactic cosmic rays and the atmosphere. A fraction of this population is not absorbed in the atmosphere and becomes **trapped by the geomagnetic field in closed-loop orbits, which causes them to return towards the Earth, hence the name re-entrant albedo particles**
- A **trajectory-tracing software** has been extensively used to simulate the motion of particles inside the Earth's magnetosphere, allowing to classify the albedo component into three populations: **quasi-trapped, precipitating, and pseudo-trapped**
- Different proton populations occupy different sectors of the plot:
  - **Quasi-trapped (QT) protons**: localized at low latitudes – near the South Atlantic Anomaly region – with lifetimes of a few tens of seconds
  - **Untrapped Short (UT_S) protons**: spread all over latitudes, with much shorter lifetimes. A double-band can be spotted in UT_S distribution, corresponding to albedo protons crossing the magnetic equator once and twice, respectively
  - **Untrapped Long (UT_L) protons:** restricted to the higher latitudes, with a lifetime extending up to ∼100 seconds

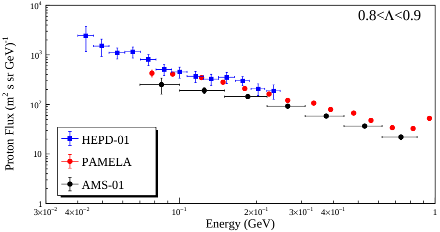


M. Martucci et al. 2024 Astropart. Phys. 162(3):102993

Measurements of re-entrant albedo protons

- The figure reports the comparison between the **total albedo proton spectra outside the SAA** measured by HEPD-01 (blue), PAMELA (red) and AMS-01 (black) for two different magnetic latitude ranges
- The agreement between HEPD-01, PAMELA and AMS-01 measurements is not perfect, probably due to different epochs of data-taking and orbits:
  - HEPD-01: intermediate phase between the 24th and 25th solar cycles (∼507 km of altitude, ∼ 97° of inclination)
  - PAMELA: period 2006-2009 at the minimum of the 23rd solar cycle (∼350/∼600 km of altitude, ∼ 70° of inclination)
  - AMS-01: in 1998 during the early 23rd solar cycle (∼350 km, ∼ 52° of inclination)





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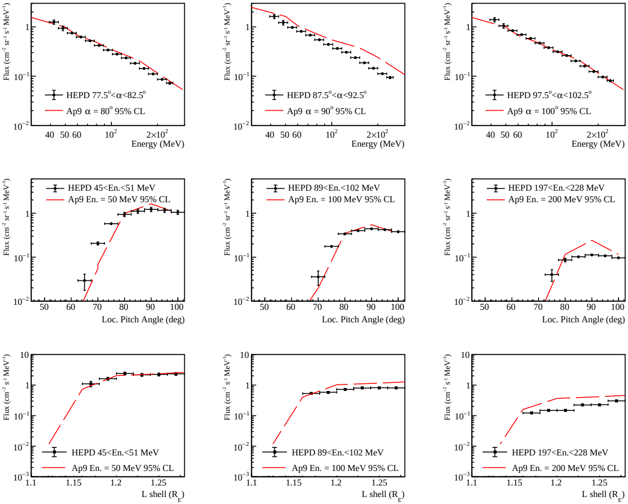
Trapped protons in the South Atlantic Anomaly

- Finally, the most stable particles are those trapped in the South Atlantic Anomaly
- The figure shows the **SAA proton fluxes as a function of energy between 40 and 250 MeV (top panels), local pitch angle (middle panels) and L-shell (Earth radii, bottom panels)** obtained by HEPD-01 (black squares) between August 2018 and December 2020
- SAA proton fluxes are compared with predictions from the AP9 model at 95% C.L. (red dashed line)



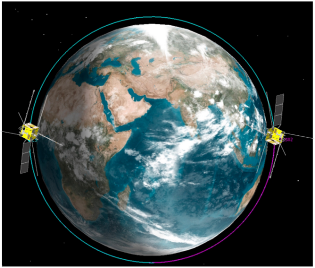
M. Martucci et al. 2022 Phys. Rev. D 105 062001

Near future: HEPD-02 on board CSES-02

CSES-02 (launch scheduled in late 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 w.r.t. CSES-01:** identical orbit plane with 180° phase difference and track interval 5° → 2.5°
- **Full-time operational mode:** [−70°; +70°] latitude → **full coverage**

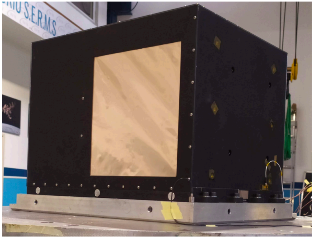
CSES-01 & CSES-02



HEPD-02 (currently installed on CSES-02):

- **First silicon-pixel tracker ever designed for space** → increased tracking capability (see the talk by Umberto Savino)
- **Two trigger planes** → decrease energy threshold (MeV level for electrons) and increase position sensitivity and redundancy
- **Improved LYSO calorimeter** with 6 bars (3 in each layer and orthogonal) → increased particle containment and energy resolution
- **Concurrent and pre-scaled triggers**
- **Sensitivity to Gamma-Ray Bursts**

HEPD-02



Conclusions and perspectives

- The scientific goals of the **CSES mission** are achieved by monitoring of the electromagnetic near-Earth space environment
- CSES satellites are designed to host a suite of different scientific payloads to **comprehensively observe phenomena in the upper ionosphere and magnetosphere**
- Since August 2018, **the Italian HEPD-01** instrument on board the first satellite (CSES-01) has been returning **valuable information on:**
  - **Galactic Cosmic-Ray physics:** in a low-energy interval, where solar modulation can be studied in detail
  - **Solar physics:** both for space weather purposes and for gaining insights into particle acceleration mechanisms
  - **Magnetosphere physics:** strongly constraining available models
- The new phase of the CSES mission will start with the **launch of the second satellite (CSES-02) in late 2024**. CSES-01 and CSES-02 will provide the first opportunity for multi-site observations of the upper ionosphere
- **HEPD-02 (a major upgrade of HEPD-01) and the Chinese particle detectors on board CSES-02 will provide a further insight into cosmic-ray and solar physics in an extended energy range from tens of keV to hundreds of MeV**