The High-Energy Particle Detector (HEPD-01): observations and results after 4 years in orbit

RICAP-2022
September 7th 2022
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The CSES-Limadou Collaboration

- Collaboration between China National Space Administration (CNSA) and the Agenzia Spaziale Italiana (ASI)

- *Limadou* refers to the Italian contribution to the mission that includes the realization of High-Energy Particle Detector (**HEPD-01**) and the participation in the realization of the Electric Field Detector (**EFD**)

- Several Italian institutes and universities involved together with **many sections of the INFN** (Roma "Tor Vergata", Bologna, Perugia, LNF, Napoli, TIFPA)

LIMADOU 利瑪竇

Mission Objectives & Scientific Goals

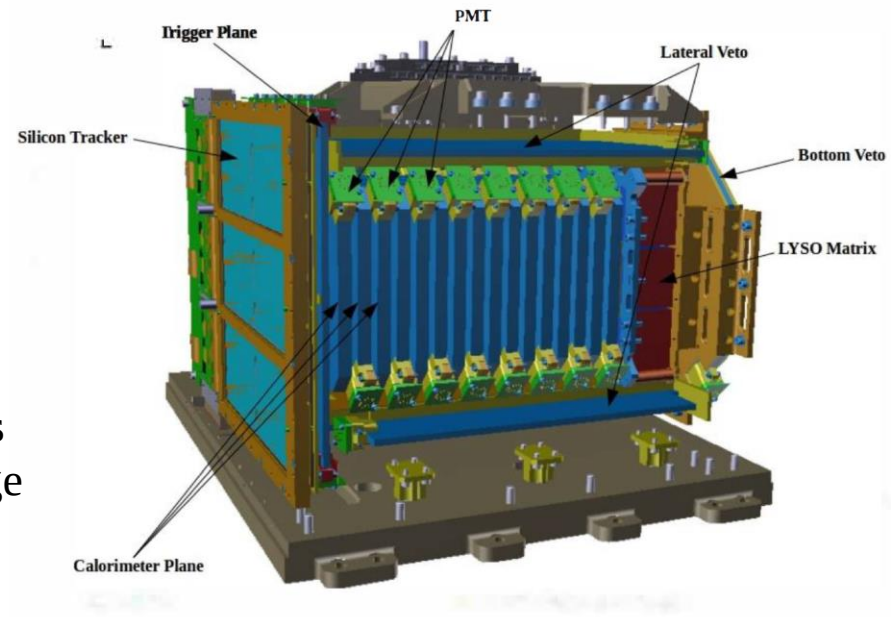
- Monitoring of the electromagnetic near-Earth space environment
- Analysis of the ionospheric and plasmaspheric fluctuations
- Measurements of iono-magnetospheric perturbations possibly due to seismo-electromagnetic phenomena
- Measurements of **magnetospheric and solar activity** (both on short and lomg 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** in quiet conditions and under the effects of geomagnetic storms
- Monitoring of the e.m. anthropic effects at LEO altitude
- Observations of e.m. transient phenomena caused by tropospheric activity

The High-Energy Particle Detector (HEPD-01)

- HEPD-01 was launched on **Feb 2, 2018** on a circular LEO orbit onboard the CSES satellite

- Of the 4 instruments detecting particles, **the High Energy Particle Detector has been entirely designed and integrated in Italy**

- It covers the highest energy threshold of sensitivity of CSES, providing unique opportunities for sub-GeV cosmic-ray physics (below AMS-02 observations) and MeV–range studies of electron/positrons populations



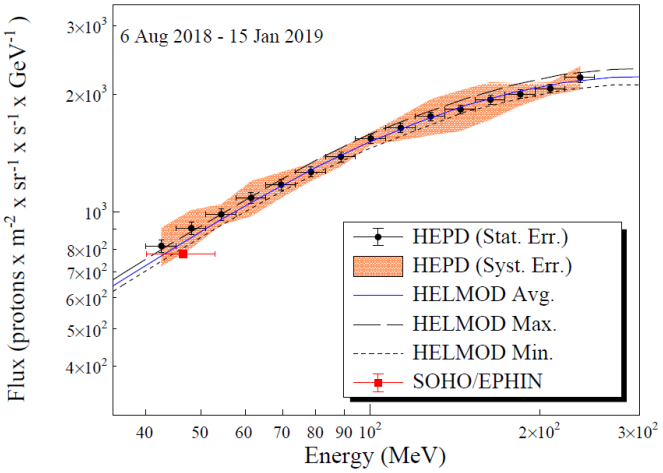
- **HEPD-01 structure:**
  - **Tracker** : particle trajectory
  - **Trigger** : starts acquisition
  - **Calorimeter**
    - **TOWER** : energy deposit, range
    - **LYSO** : enlarge energy threshold
  - **Veto** : rejects secondaries , out of acceptance particles

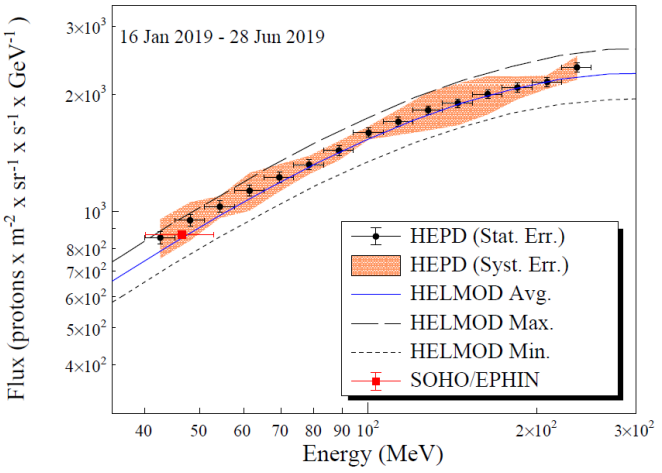
30 - 250 MeV (protons)
3 – 100 MeV (e^-/e^+)
30 – 250 MeV/n (nuclei)

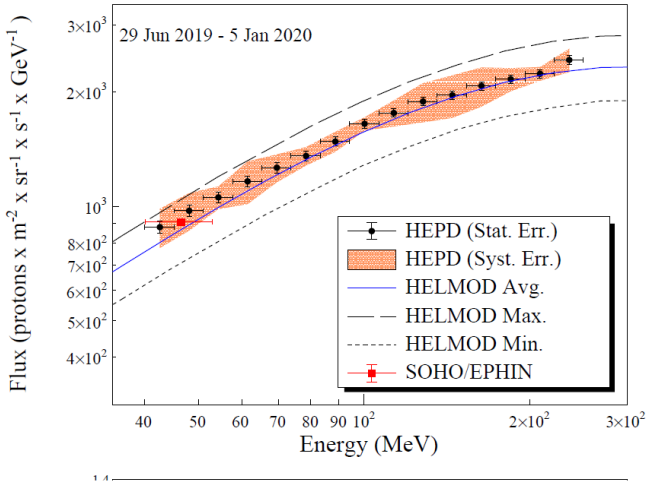
Galactic Cosmic Rays (GCRs)

GCR Protons

Bartocci, S. *et al*. *ApJ* **901** 8 (2020)

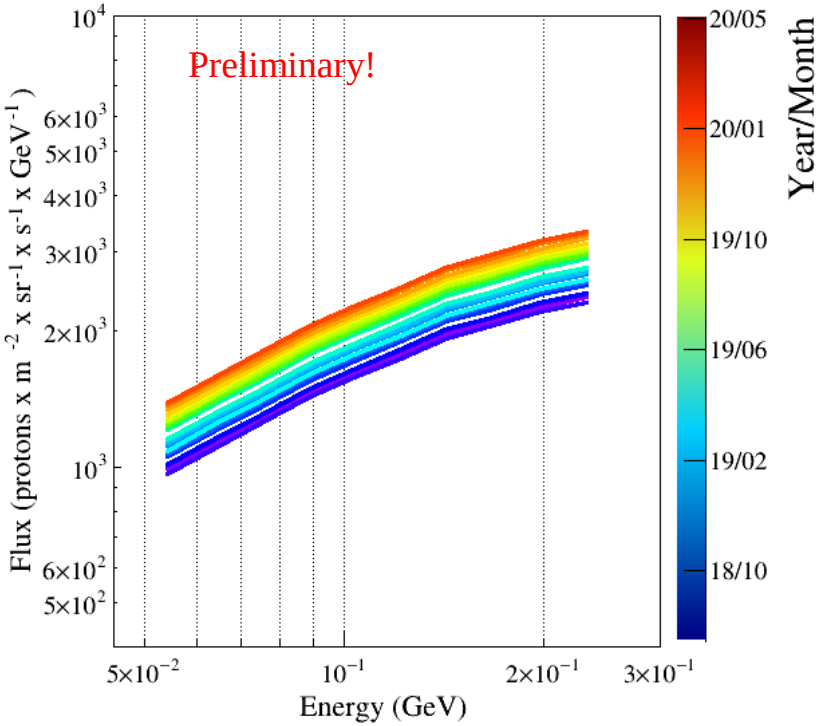


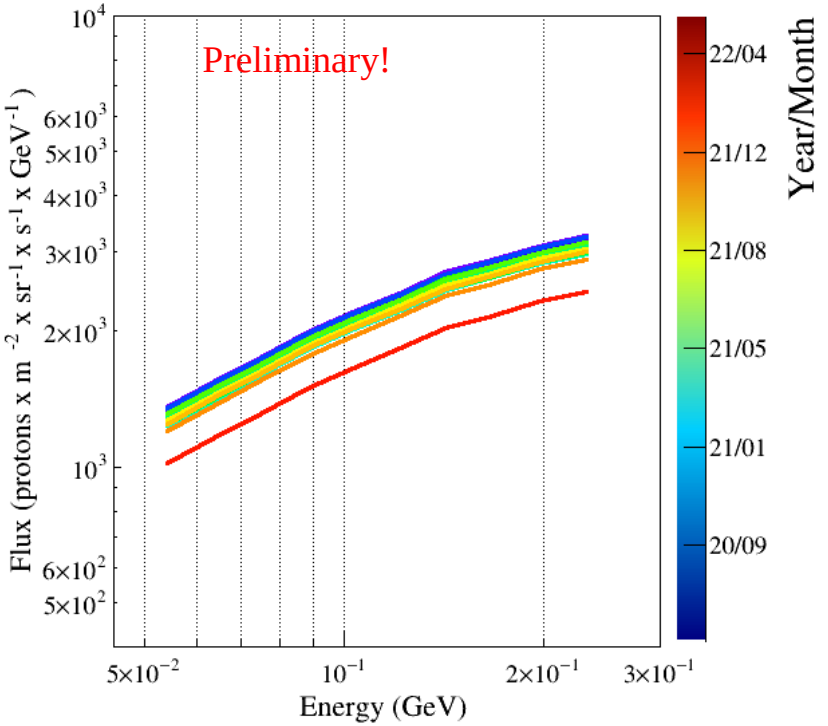




- New results on GCR spectra between 40 and 250 MeV from **2018 August 6** to **2020 January 5** (6-months bunches)
- Comparison with SOHO/EPHIN proton data shows **a good agreement**
- The predicted HelMod model for GCR protons propagation is also in **good agreement** with HEPD-01 data

GCR Protons





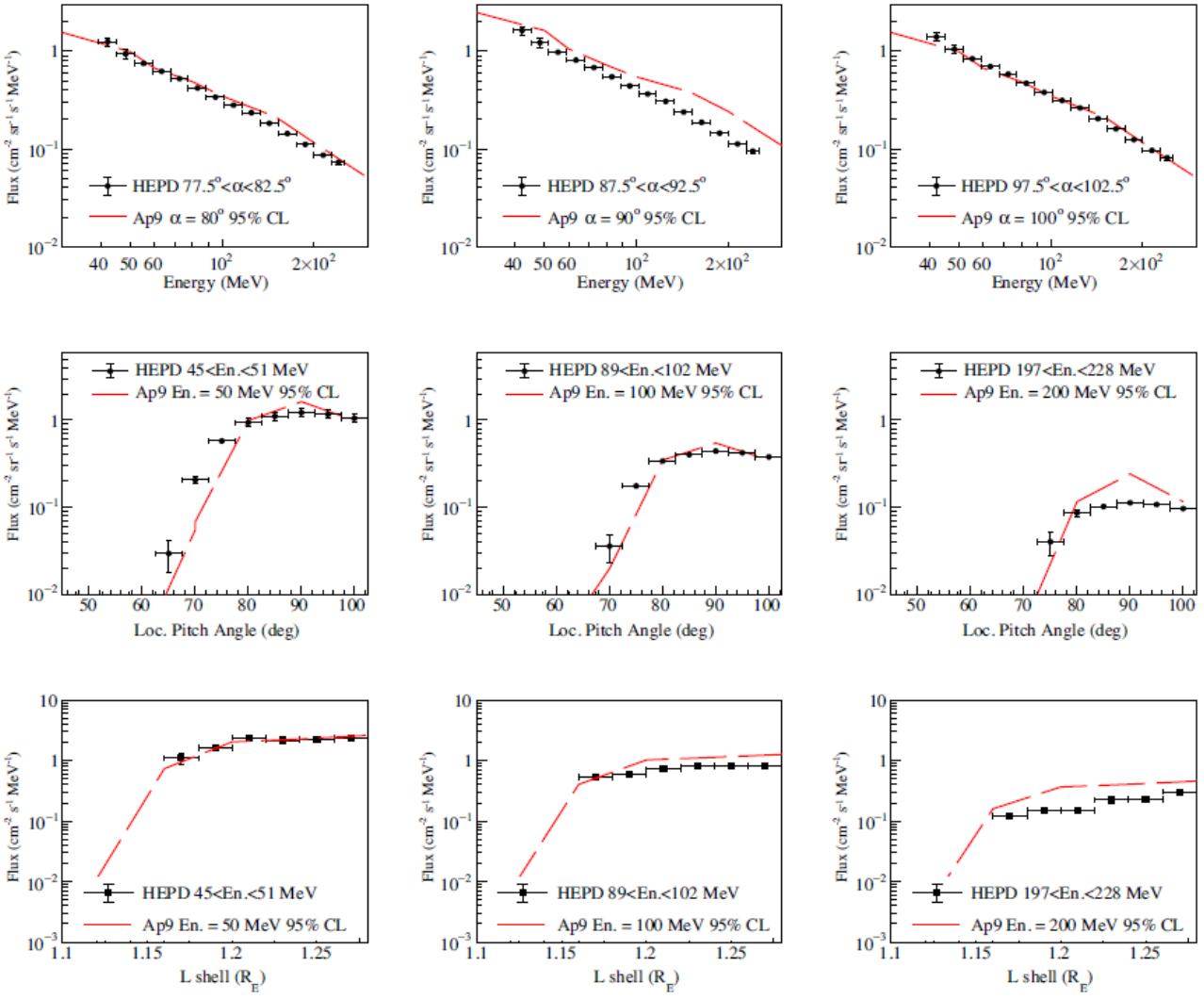
- Preliminary results on GCR proton modulation during the end of the **minimum** (left) and the start of the **maximum** (right) among solar cycles 24 and 25, measured by HEPD-01 between 50 MeV and 250 MeV (1-month bunch)

- White spaces in the right panel refer to the periods of high solar activity (SEPs) and data were removed because of contamination

Particles Inside SAA

Protons in SAA

Martucci, M. *et al. Phys. Rev. D* **105**, 062001 (2022)

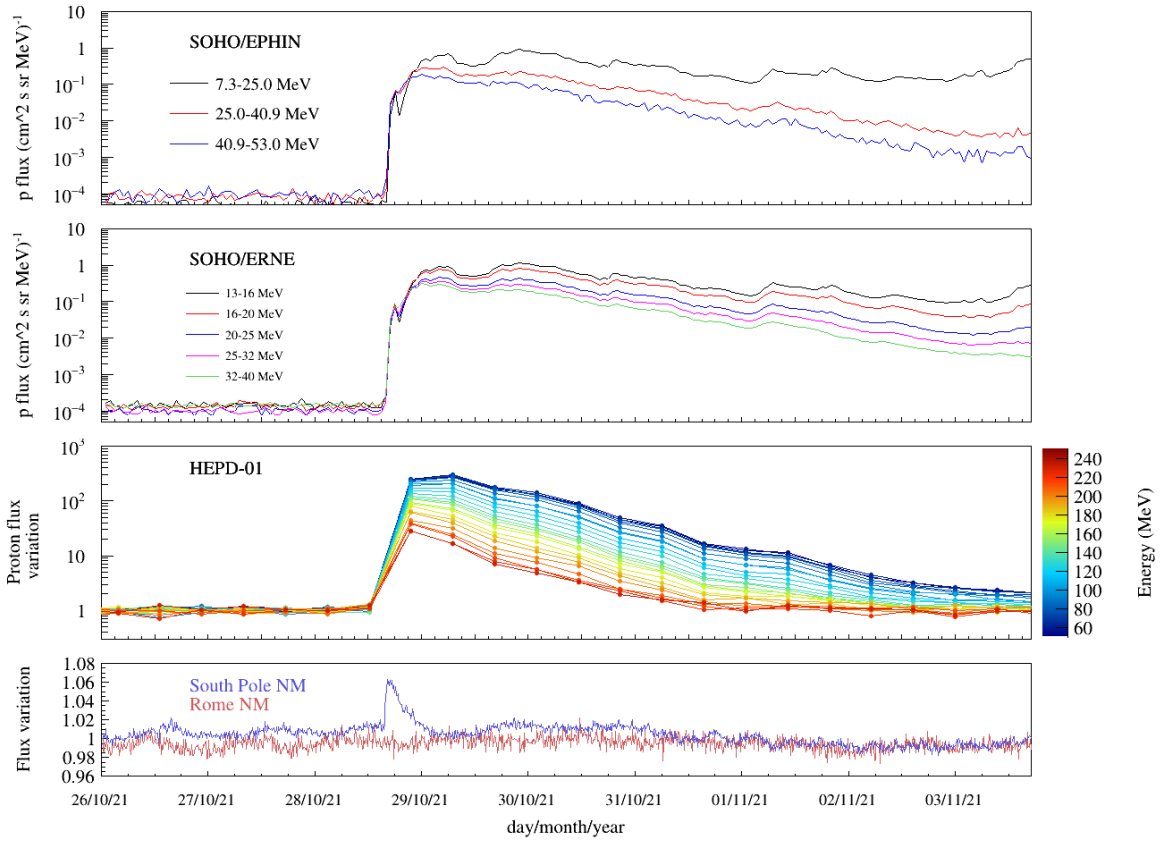


- South Atlantic Anomaly (SAA) proton fluxes as a function of energy (top panels), local pitch angle (middle panels) and L-shell (Earth radii, bottom panels) obtained by HEPD-01 (black squares) between August 2018 and December 2020
- Comparison with predictions from the AP9 model at 95% C.L. (red dashed line)

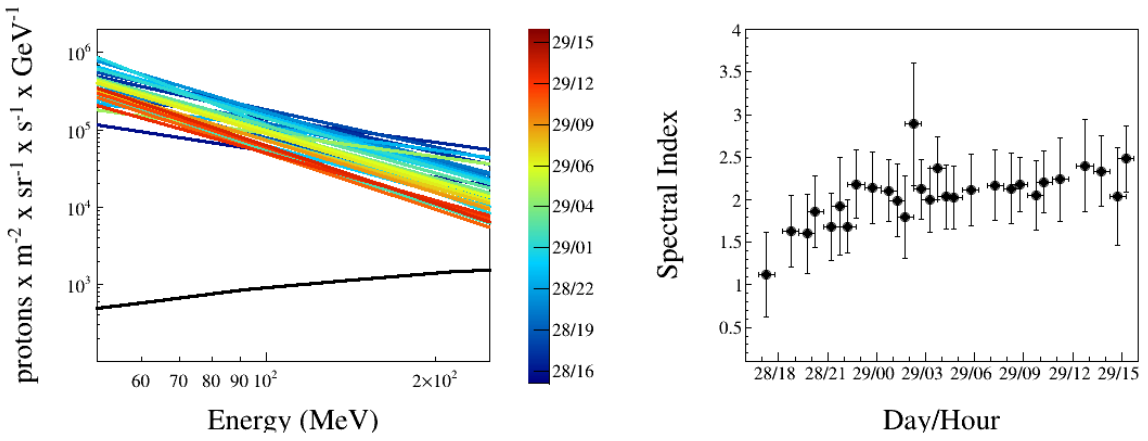
Solar Activity

SEP and Forbush Decrease

- After a series of C- and M-class flares a long duration **X1 Solar Flare** was emitted at 1535 UTC on October 28th, 2021, either triggered by or triggering the filament eruption
- A Coronal Mass Ejection (**CME**) associated with the filament eruption
- **First SEP** of the current solar cycle **within the range of the HEPD** detector (p+ with E > 40 MeV)
- The event also triggered a Ground Level Enhancement (GLE) detected minutes later by the Neutron Monitor network → **GLE#73** is the first GLE of solar cycle 25

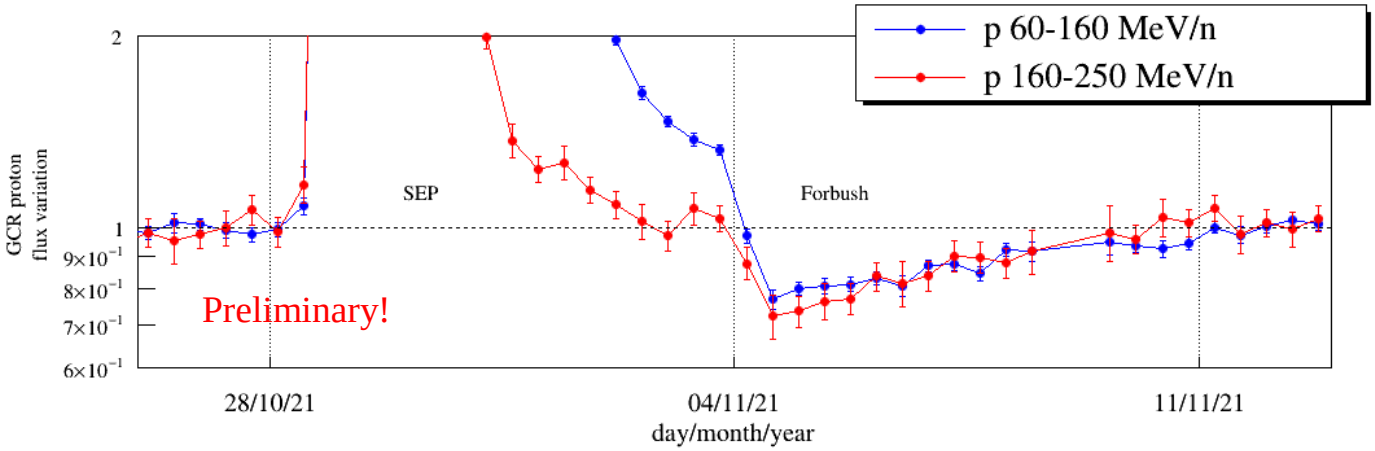


SEP and Forbush Decrease

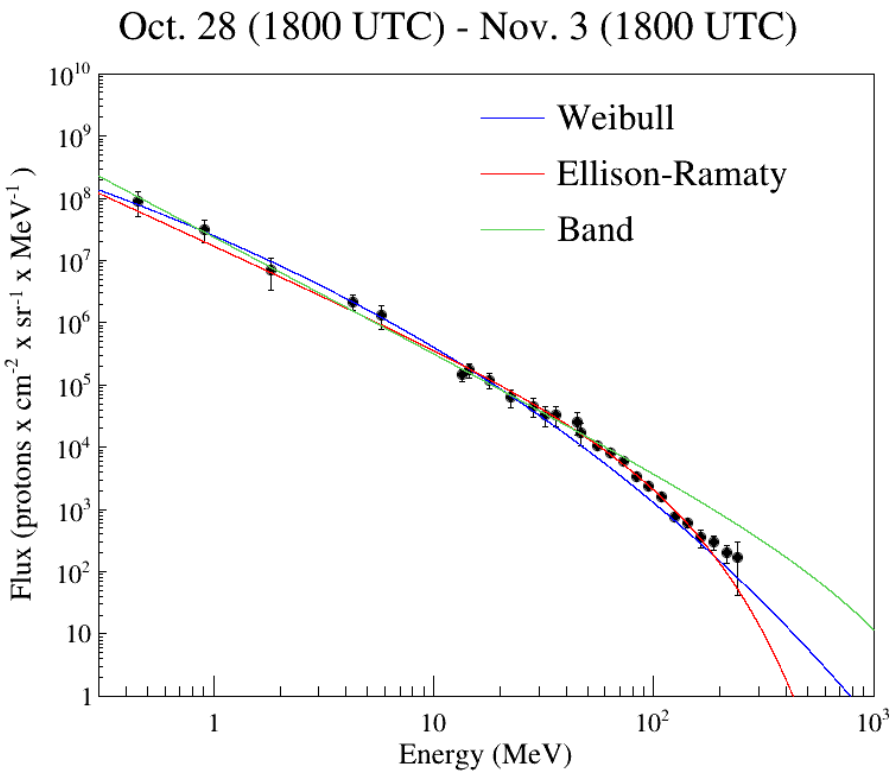


- Differential solar proton evolution during the SEP of Oct. 28 2021 w.r.t. a quiet GCR background
- The spectral shapes seem to vary during the first hours of the SEP itself
- Investigation of > 1 GeV energies is not possible, still HEPD-01 data **could bridge a very interesting gap between low-energy and high-energy measurements**

- After a few days from the Oct. 28, 2021 SEP,
  - around Nov.4 – a CME reached the Earth causing a FD
- Study on charge sign dependence are ongoing



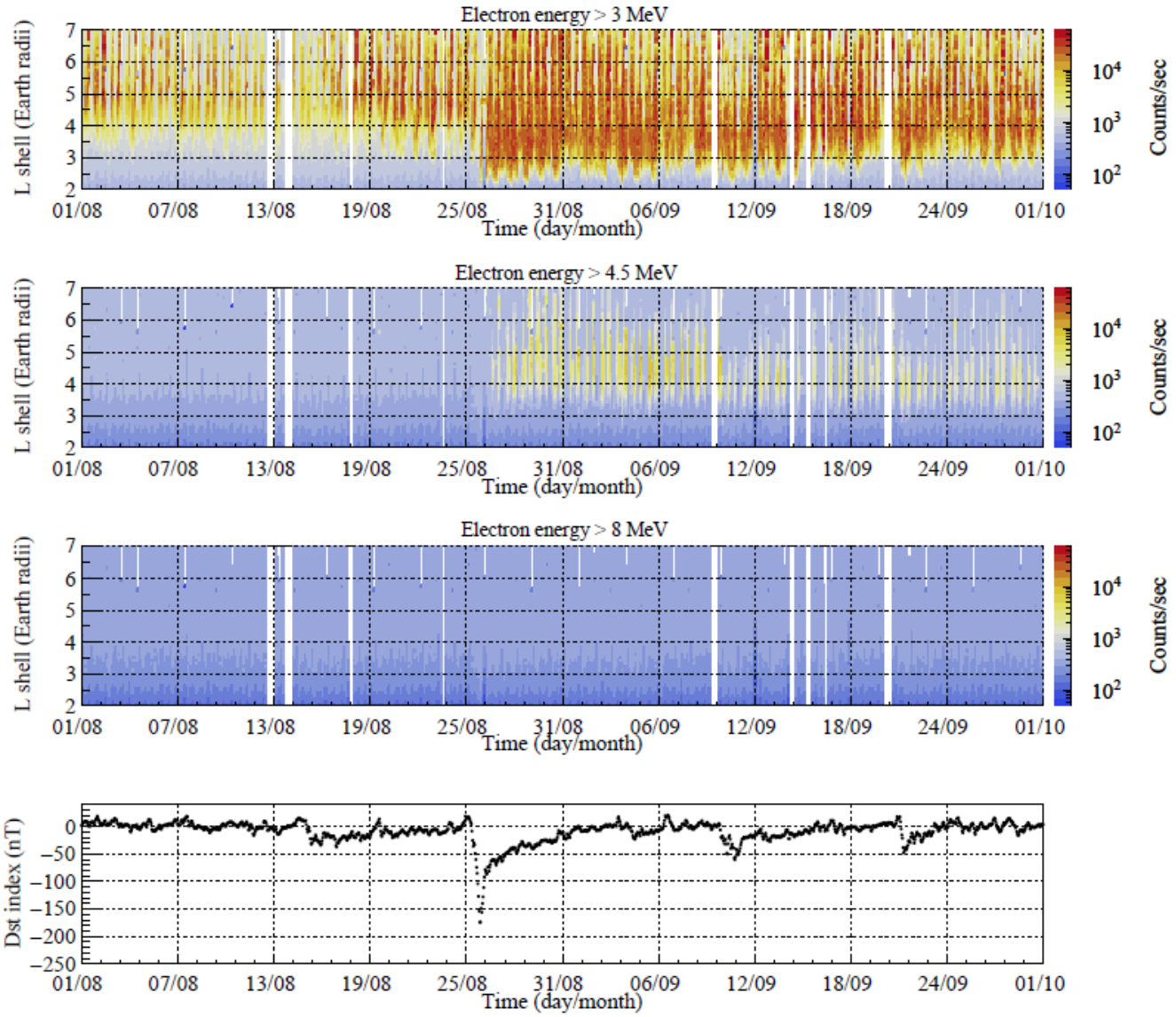
SEP and Forbush Decrease



- Using also data from other experiments like **ACE, EPHIN and ERNE** we were able to construct an extended pure-solar, time-integrated energy proton spectrum of the GLE event
- A fit with various model functions (see legend in the Figure) has shown that the **Weibull** is the best choice to reproduce some characteristics of this event
- **This favours the mechanism of acceleration from CME**, even if transport inside the heliosphere could still play an important role and modify the spectral shape
- Other SEPS are being currently studied

The Geomagnetic Storm of August 27, 2018

- HEPD-01 is also sensitive enough to measure the effects of geomagnetic storms NOT associated with SEPs
- A slow CME (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 ICME gave rise to a compression of the magnetopause from ~10 R_E before the storm down to ~7.7 R_E and a backward motion of the plasmapause from ~5 R_E down to ~3.8 R_E

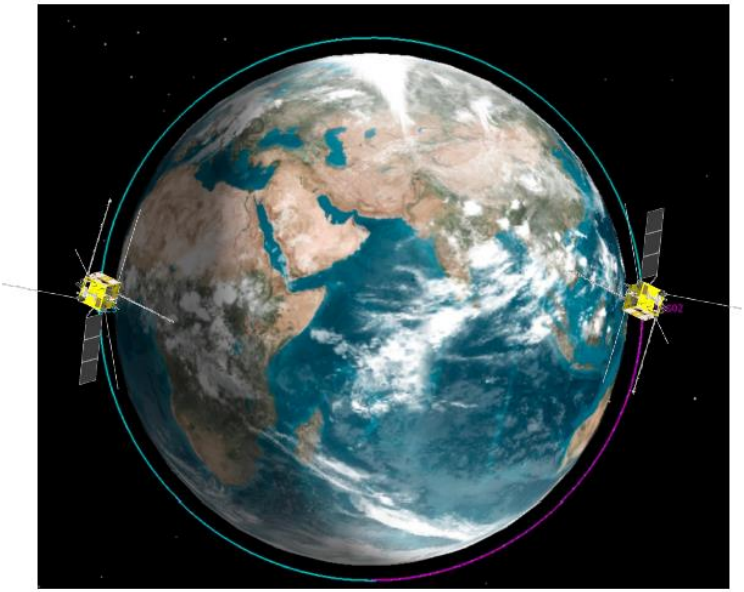


Palma, F. *et al. Appl. Sci.* **11,** 12 (2021)

The future: CSES-02 & HEPD-02

CSES-02

- Same model platform of CSES-01 with **some upgrades**
  - Earth oriented 3-axis stabilization system with orbit maneuver capability
  - X-Band Data Transmission 150 Mbps
  - Storage 512Gb
  - Peak Power Consumption: ~900W
  - Identical Orbit Plane
  - 180° Phase Difference
  - Track interval: 5°→2.5°
  - Operation mode: Full time operational



Launch scheduled by 2023

HEPD-02

- **first silicon-pixel tracker** ever designed for space
- ~biggest LYSO scintillators ever produced for space
- increased energy resolution
- **concurrent trigger system** allowing for lower energy measurements over the poles and on the SAA
- **sensitivity to gamma-rays**

Conclusions

- The CSES initiative is a successful cooperation between China National Space Administration (CNSA), China Earthquake Administration (CEA) and Italian Space Agency (ASI)
- Limadou is the Italian collaboration **led by INFN** which designed and constructed HEPD for CSES-01
- HEPD-01 obtained important results in cosmic ray physics: measurements of cosmic rays down to 40 MeV, where solar modulation can be studied in detail
- Measurements of protons inside the SAA, strongly constraining available models
- Measurements of SEPs at the beginning of the 25th solar cycle
- The **Limadou Collaboration is currently committed to construct the HEPD-02** payload for the CSES-02 satellite, expected to be launched in 2023
- **CSES-01 and CSES-02 will provide the first opportunity for multi-site observations of the upper ionosphere**