



The Limadou project: status and results

Roberto Iuppa on behalf of the CSES-Limadou collaboration

University and INFN of Trento

RICAP 2022

Rome, 06-09 September 2022



The CSES initiative

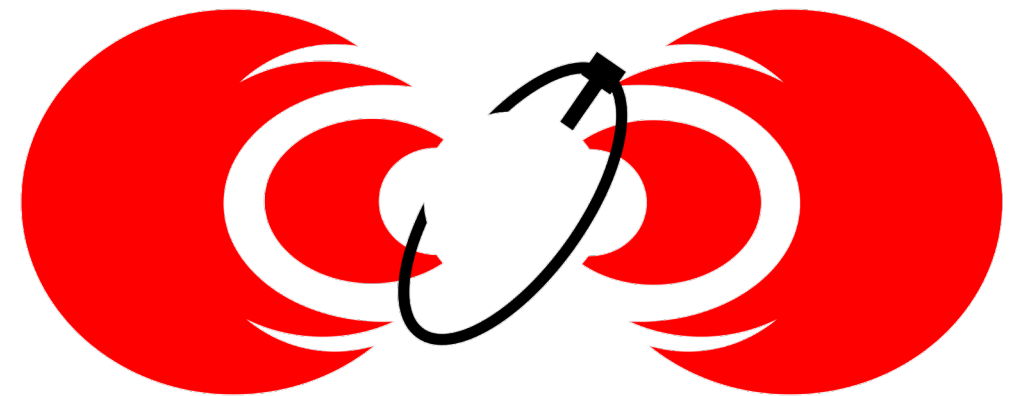
Collaboration between China National Space Administration (CNSA) and Italian Space Agency (ASI)

CSES 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
- *Study of fluxes of high- & low-energy charged particles precipitating from the Inner Van Allen radiation belt*
- *Measurements of magnetospheric and solar activity*
- Monitoring of the e.m. anthropic effects at LEO altitude
- Observations of e.m. transient phenomena caused by tropospheric activity

How to?

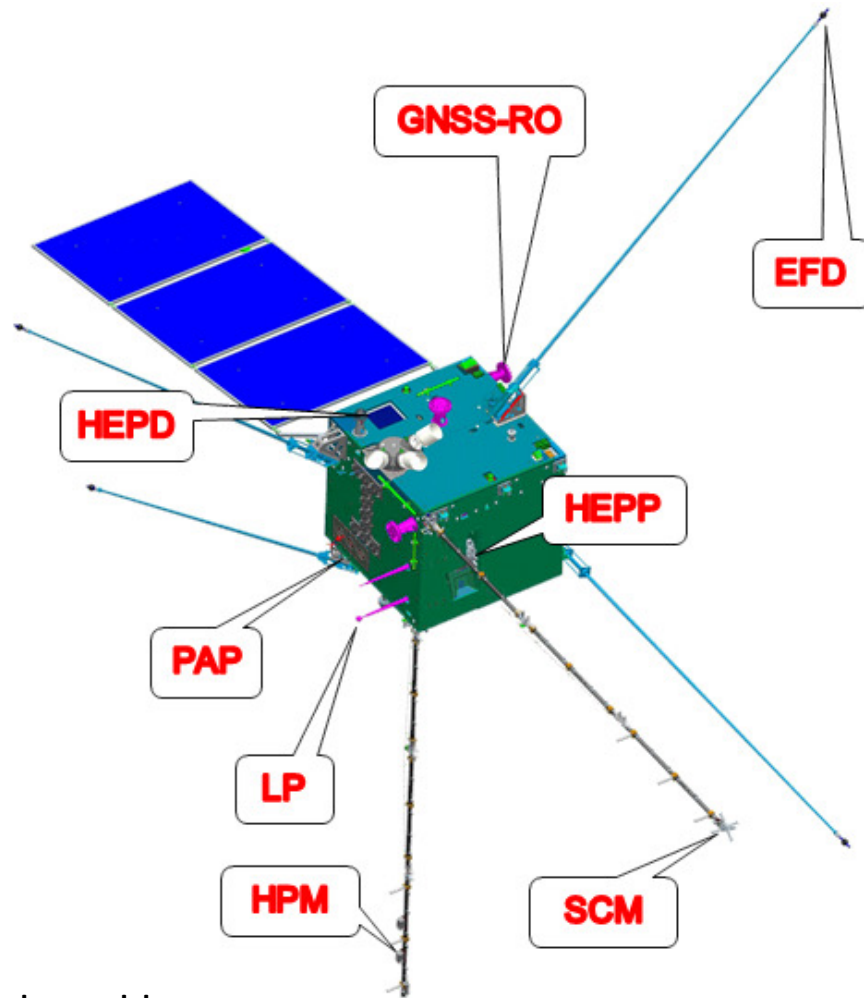
The CSES satellites are designed to host a suite of different scientific payloads to comprehensively observe phenomena in the upper ionosphere and in the magnetosphere. The series of CSES satellites allow for multisite observations as long as instruments are in operation.



LIMADOU 利瑪竇

(Li-Madou after Matteo Ricci)

The CSES-01 satellite



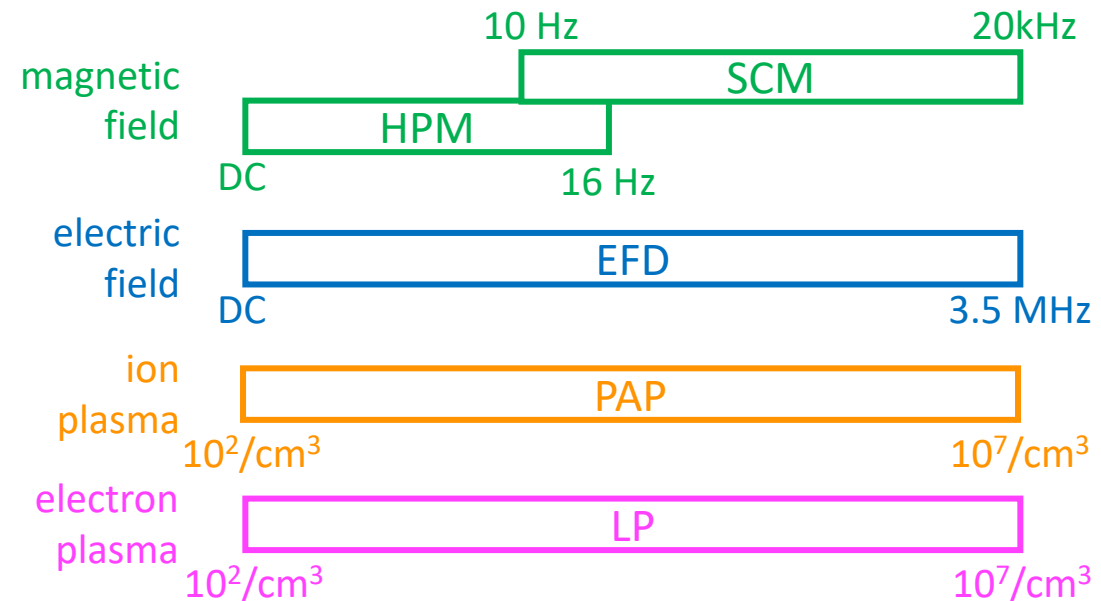
Developed by:

- China Earthquake Administration (CEA)
- Italian National Institute for Nuclear Physics (INFN)
- Chinese and Italian Universities

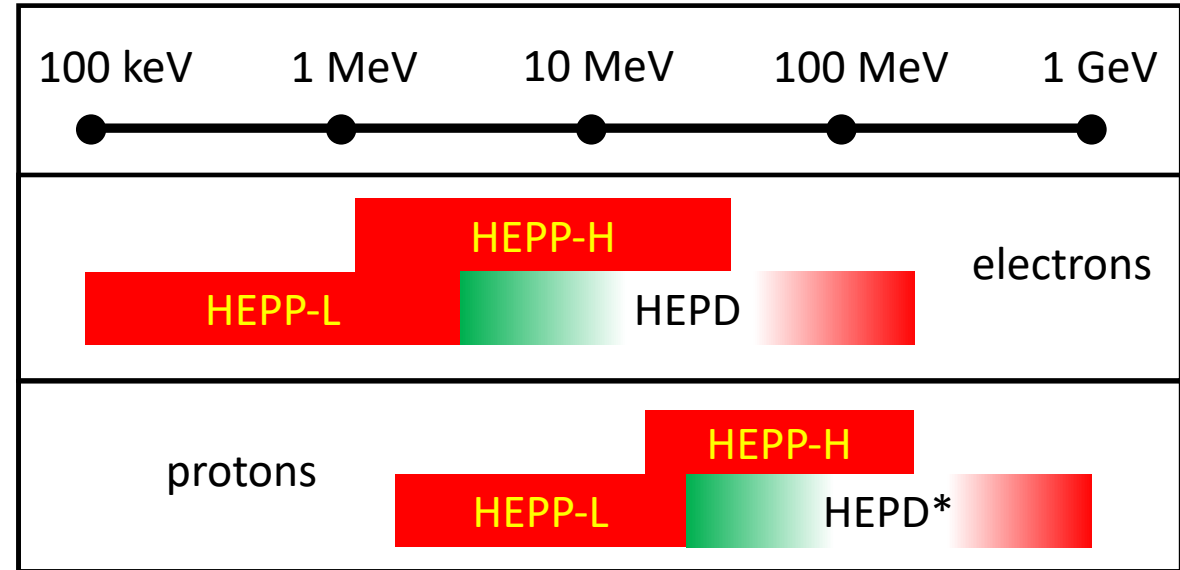
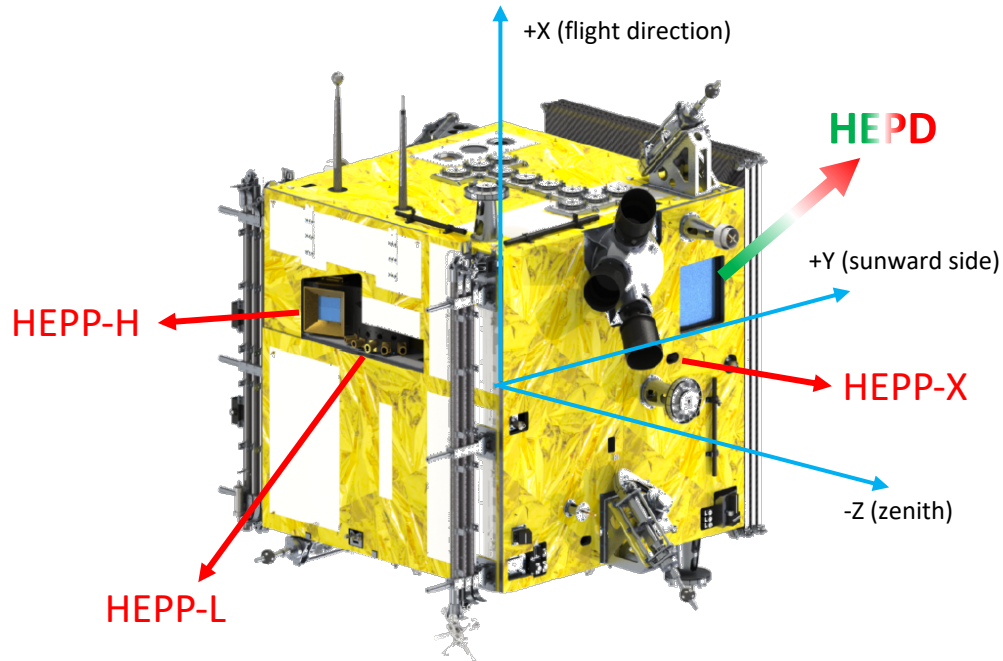
Launched into a sun-synchronous circular orbit (97.4°) on February 2nd, 2018 at an altitude of 507 km in the upper ionosphere

Details about the satellite and the orbital parameters will be provided in the section about CSES-02

Payload working zone: $-65^\circ / +65^\circ$ latitude



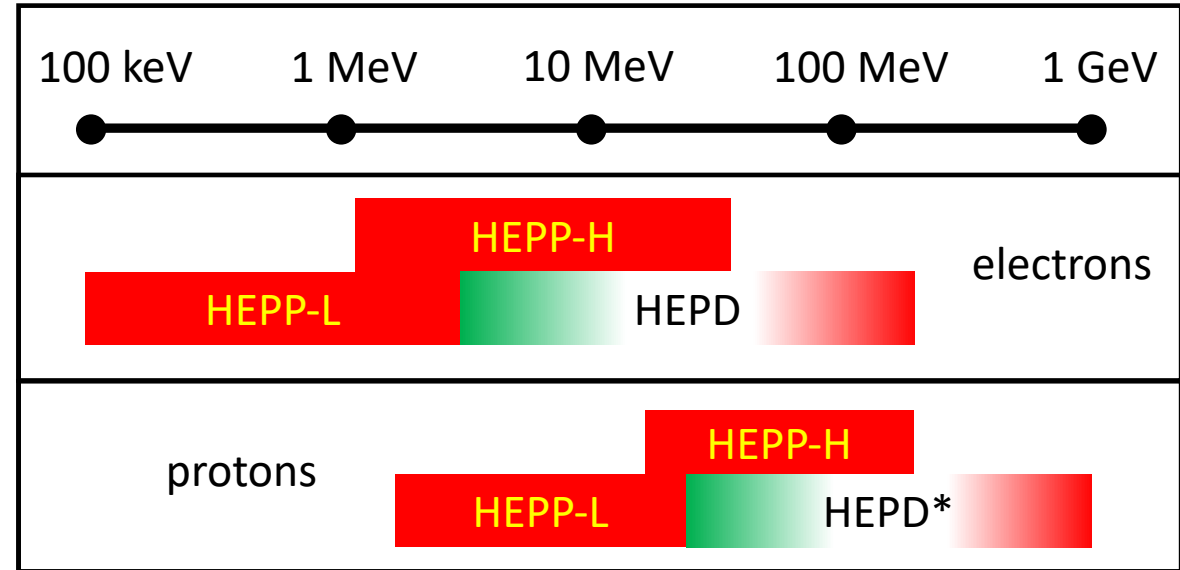
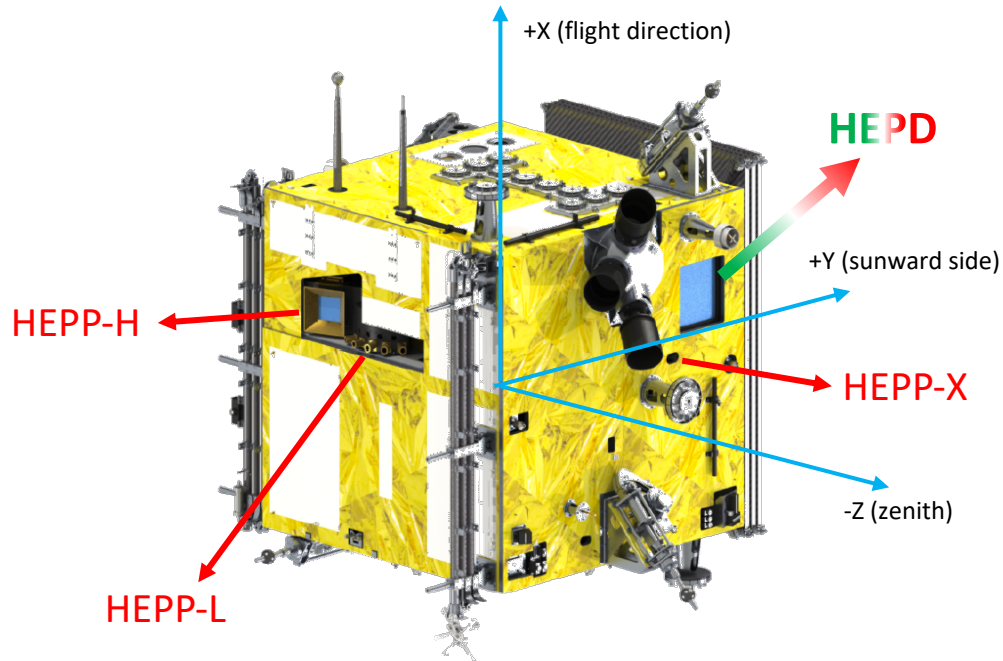
Particle detection onboard CSES-01



*HEPD is also sensitive to light-nuclei, calibration with flight-data ongoing

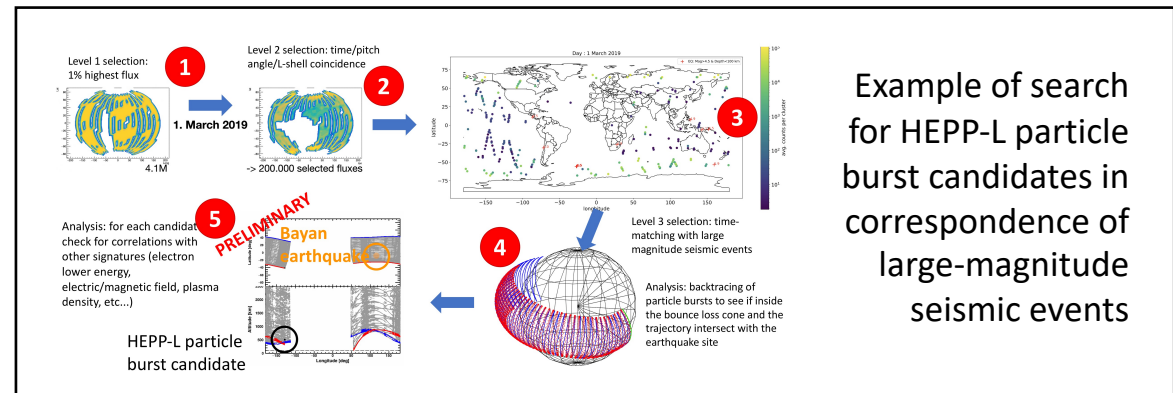
- Four instruments detect particles onboard CSES-01, allowing accurate measurements over four orders of magnitude in energy for each particle species.

Particle detection onboard CSES-01



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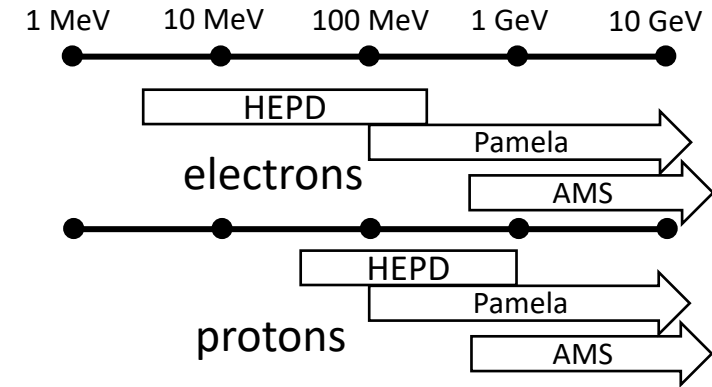
- Four instruments detect particles onboard CSES-01, allowing accurate measurements over four orders of magnitude in energy for each particle species.
- As for all CSES payloads, calibrated data from particle detectors are publicly available at <https://leos.ac.cn>



Example of search for HEPP-L particle burst candidates in correspondence of large-magnitude seismic events

HEPD: the High Energy Particle Detector

- The High Energy Particle Detector has been developed in Italy by the Limadou collaboration, led by the Italian Space Agency and INFN. It covers the highest energy region of sensitivity of CSES.
- Concerning cosmic rays, HEPD lowers the energy threshold of Pamela and AMS-02 and provides unique opportunities for sub-GeV cosmic-ray physics.
- This talk will not report about searches for Earthquake-ParticleBurst correlations or about studies off particle variations due to ionospheric perturbations: it will be focused on “cosmic rays”

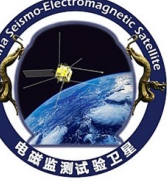


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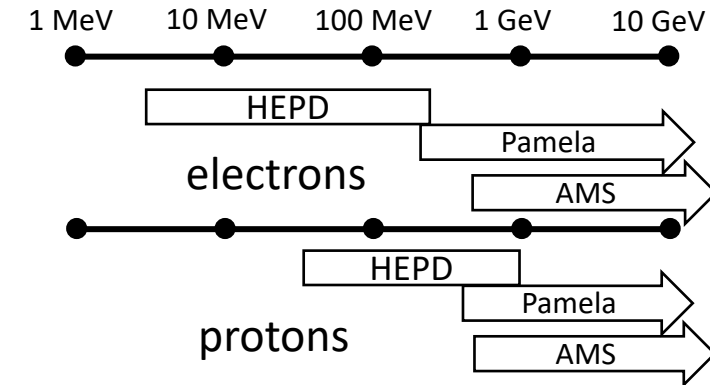
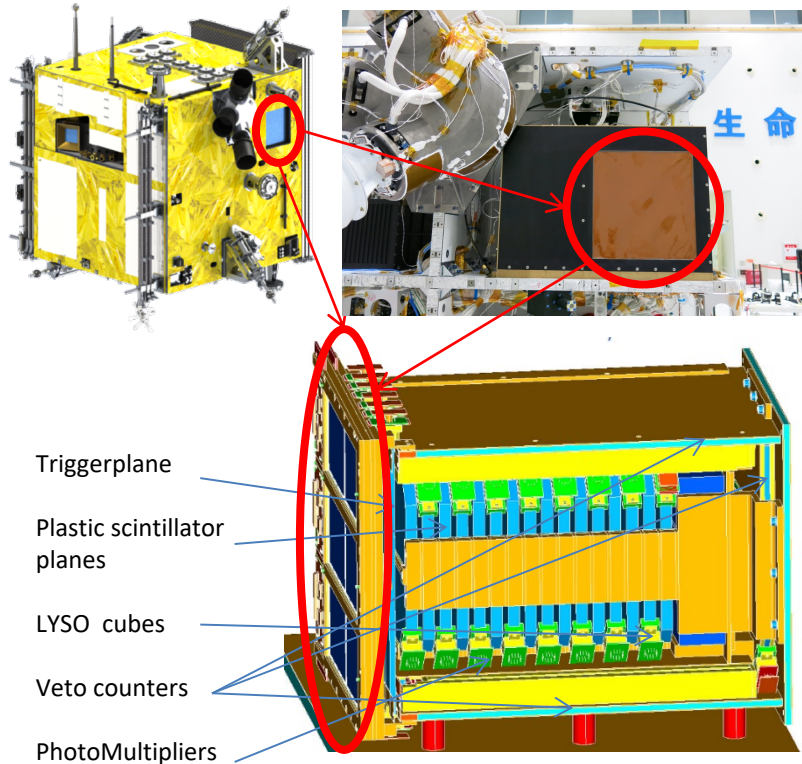
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6



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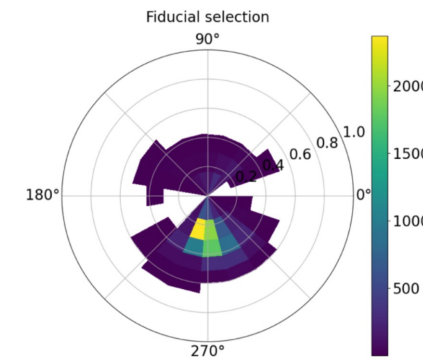
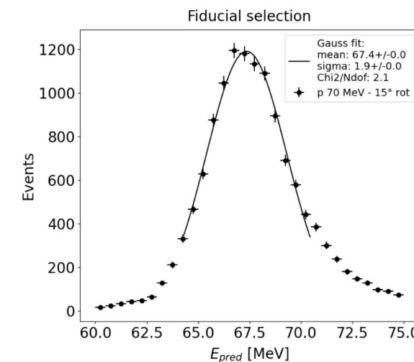
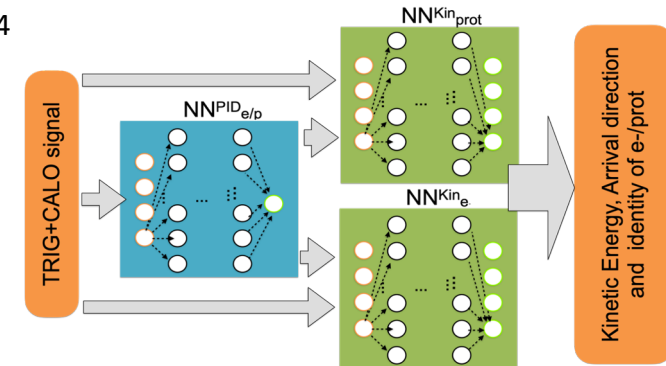


Phys. Rev. D 105, 022004

Full DL event reconstruction

powered by

deepPP.eu

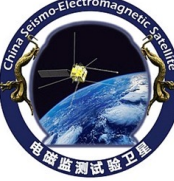


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7





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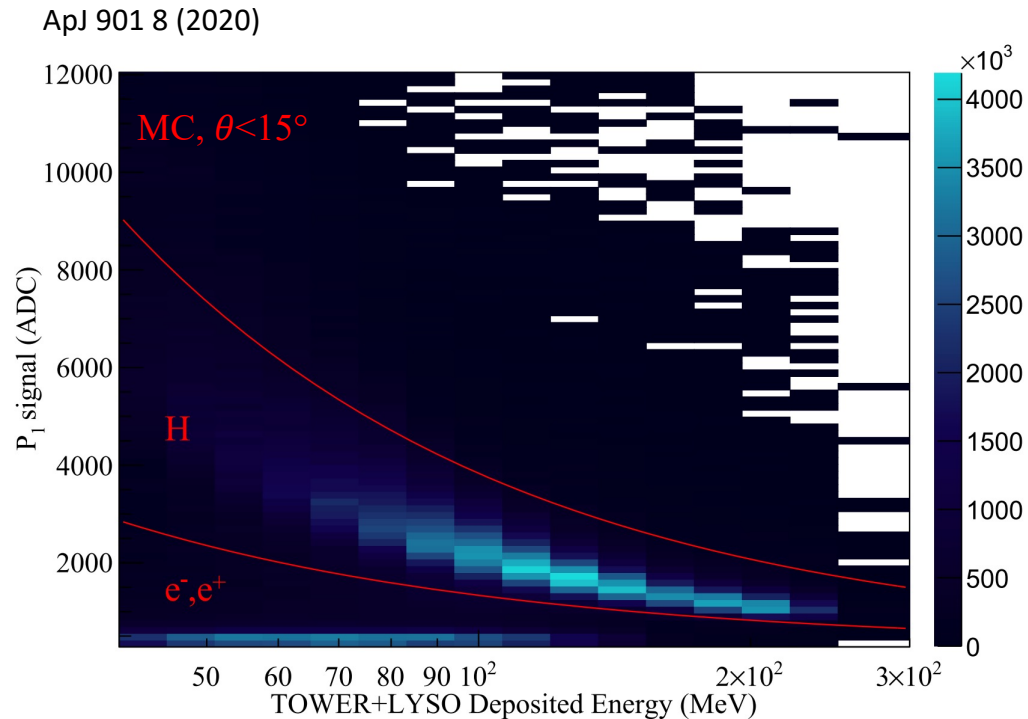
8

galactic cosmic rays

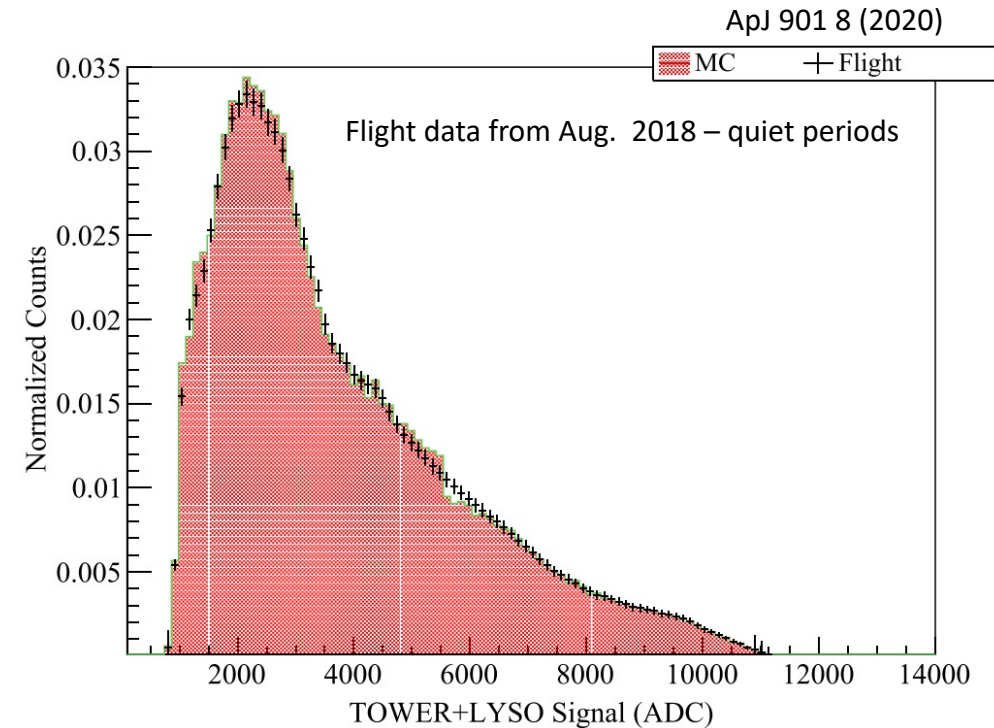


particle identification: protons vs electrons

Besides DL-based tagging, simple (yet powerful) PID criteria based on dE/dx and E_{dep} are implemented for calibration and selection in the analysis.



Efficiency and contamination of selection cuts have been evaluated with MC simulations tuned on data acquired at beam tests.



Very good agreement between data from flight and Monte simulations

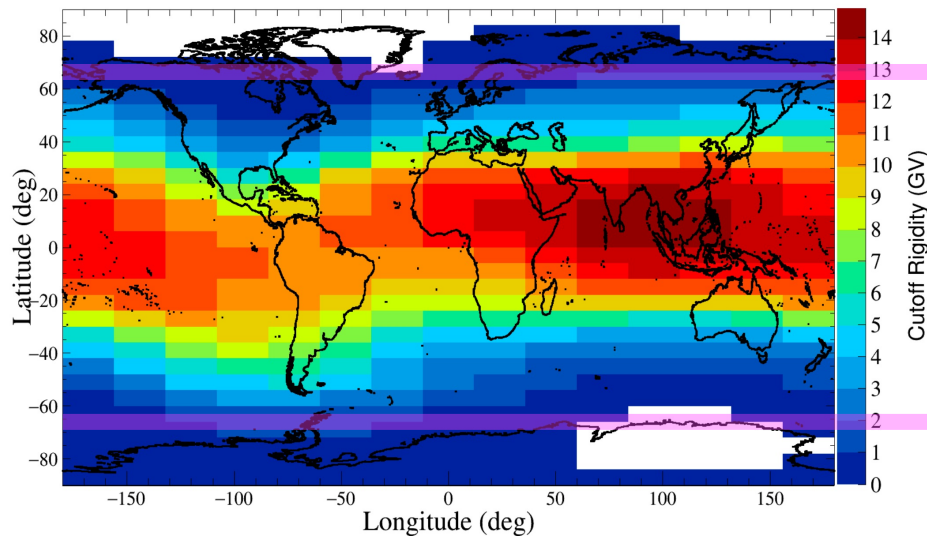
selecting cosmic protons

Sub-GV protons measured along the quasi-polar orbit of CSES have different origins: (i) produced via Cosmic Ray Albedo Neutron Decay and trapped, (ii) injected during SEPs, (iii) being primary cosmic rays.

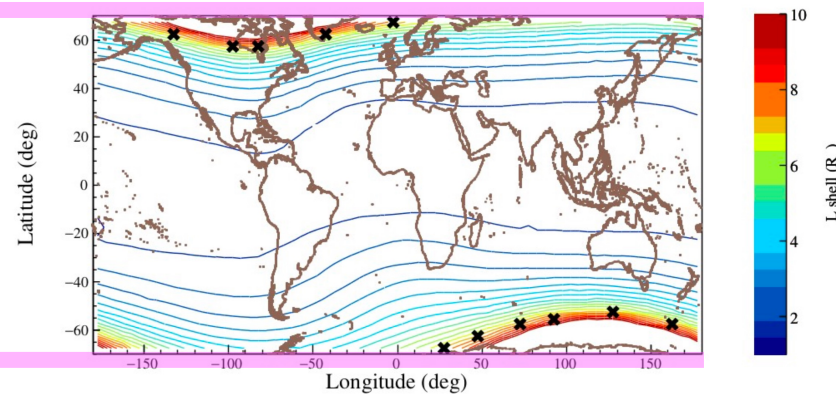
Besides selections due to detector-specific features*, selections to exclude unwanted contaminations are applied.

The fiducial selection for (iii) includes:

- excluding (ii) by selecting Sun-quiet periods (no major solar particle events or super-strong storms)
- excluding (i). Different approaches have been adopted (all equivalent to each other, even backtracing):



Use data only from regions where CSES is above the rigidity cutoff for the energy threshold of the analysis (e.g. 0.26 GV for 35 MeV protons).



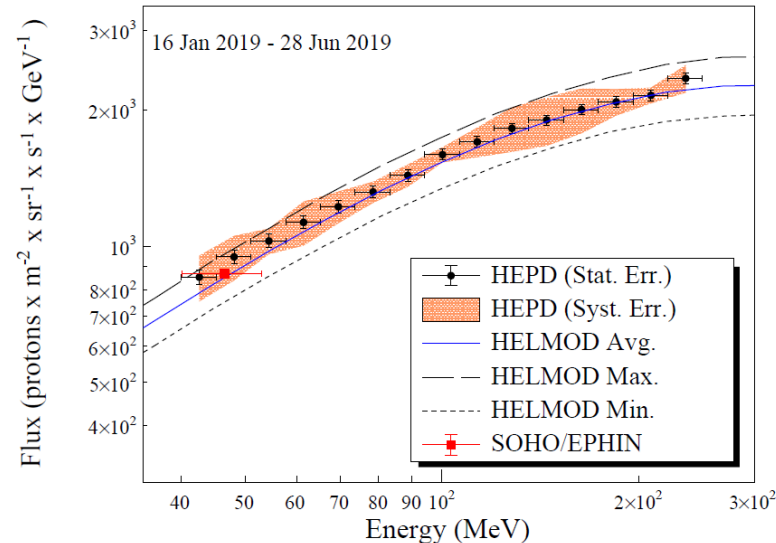
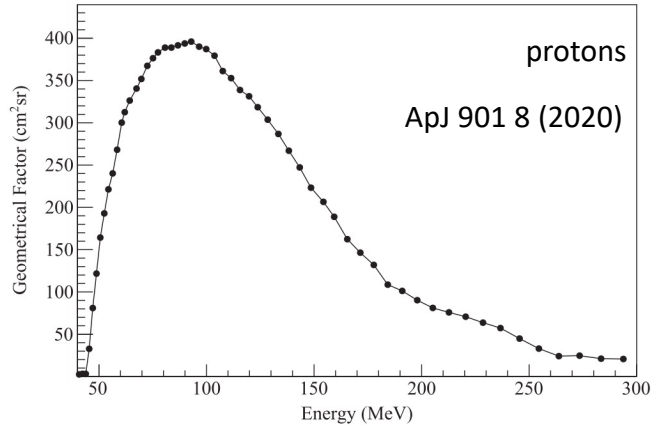
Use data only from regions $L > L_{\text{thresh}}$, where L_{thresh} guarantees no trapped protons below the energy threshold for the analysis (e.g. $L_{\text{thresh}} = 7$ for 50 MeV protons)

CSES-01 data taking limited to latitudes -65/+65: small fraction of data acquisition available for CRs

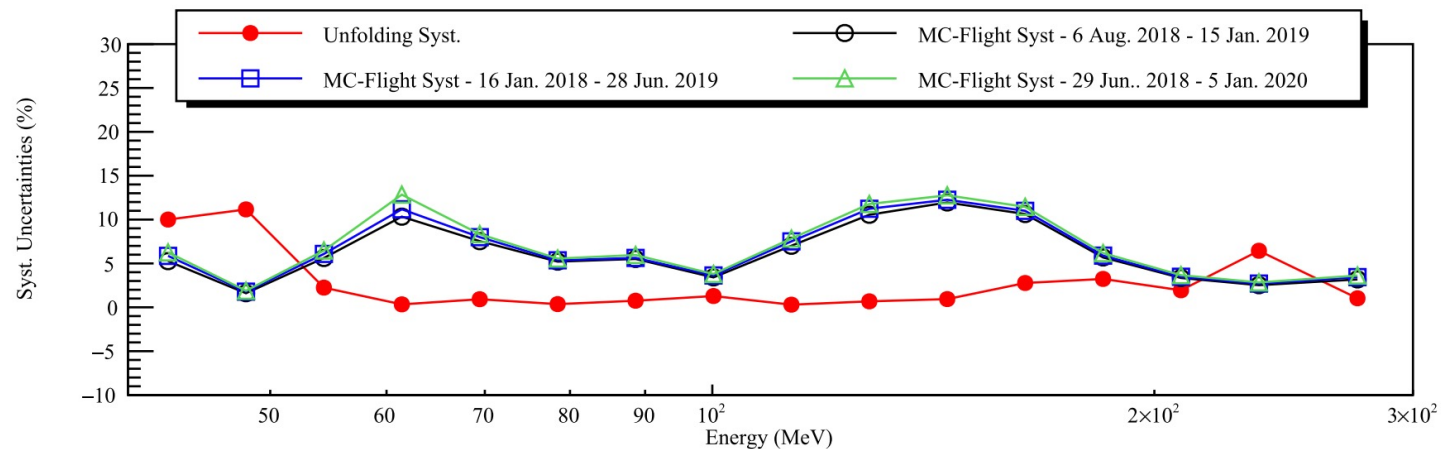
* E.g., data from SAA ($B < 26,000$ nT) is excluded to avoid saturation or pile-up issues that may occur under extremely high particle rates, unless stated otherwise.

cosmic proton time evolution

- Dead-time less than 0.5% in selected orbital regions
- Very large geometric factor

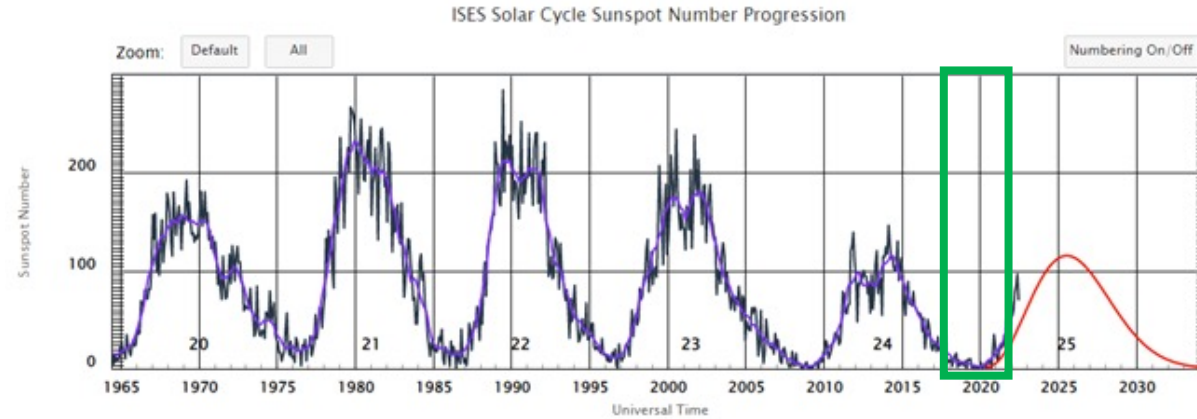


- The paper ApJ 901 8 (2020) already demonstrated high sensitivity to cosmic protons, with statistical and systematic uncertainties allowing to precisely measure the **solar modulation**
- Solar modulation impacts on all CR measurements up to tens of GV. When small S/N ratios are considered, the uncertainty on the solar modulation could be an **important systematic, limiting the sensitivity**
- **models during solar maxima are always more complicated** due to the turbulence in the heliosphere. HEPD data could help constraining some of these models, such as HelMod



solar modulation

- Low-energy galactic particles (< 1 GeV) inside the Heliosphere are known to be continuously changing in time, mostly due to the activity of the Sun (solar modulation)
- Their transport is well described by the Parker equation during minima of solar activity, but the same cannot be said during periods of high activity when the Heliosphere is turbulent and the Sun-Earth environment is disturbed by transients like Solar Energetic Particle Events (SEPs), Coronal Mass Ejections (CMEs) etc.

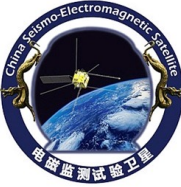


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status and results

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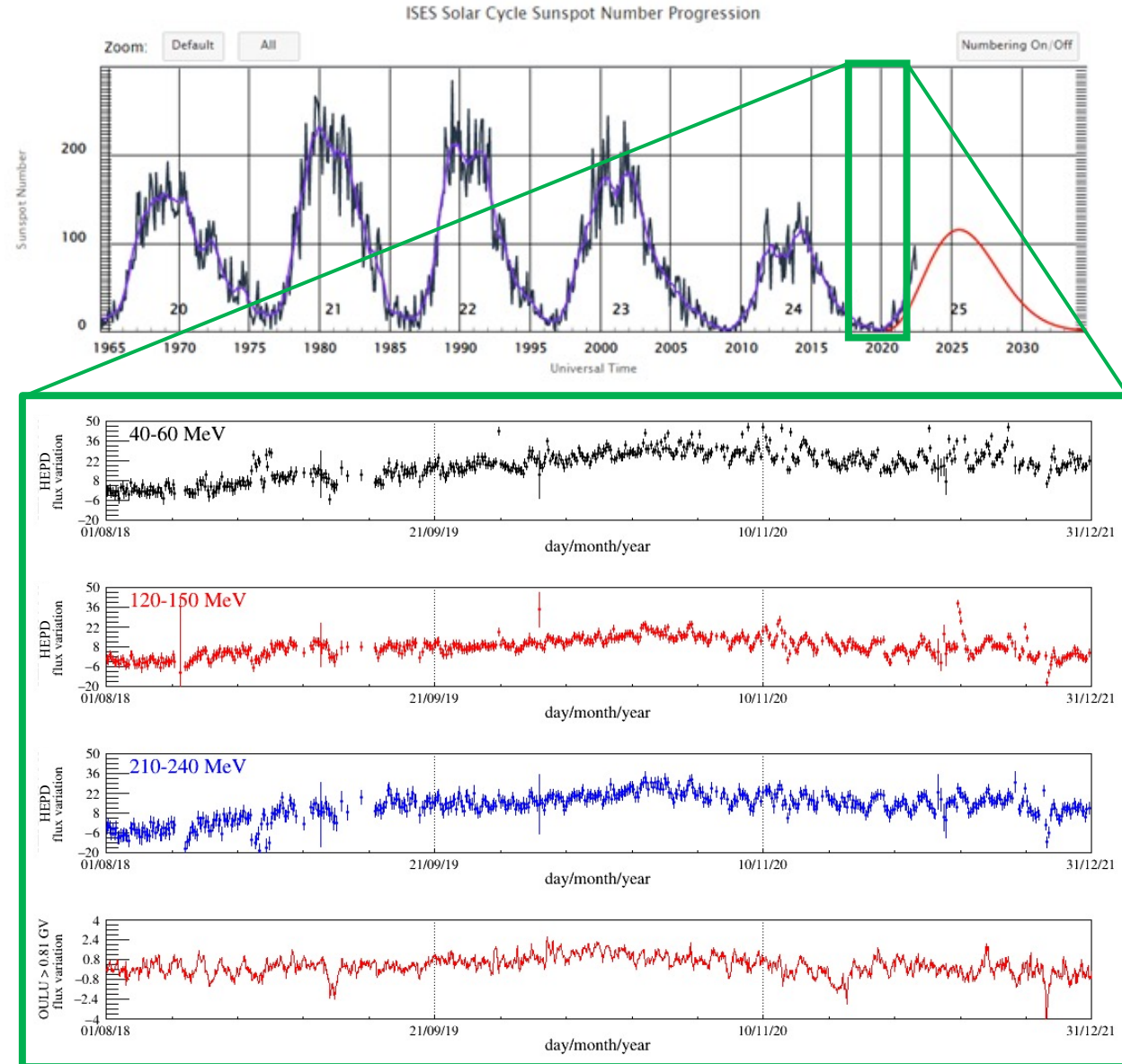
12



solar modulation

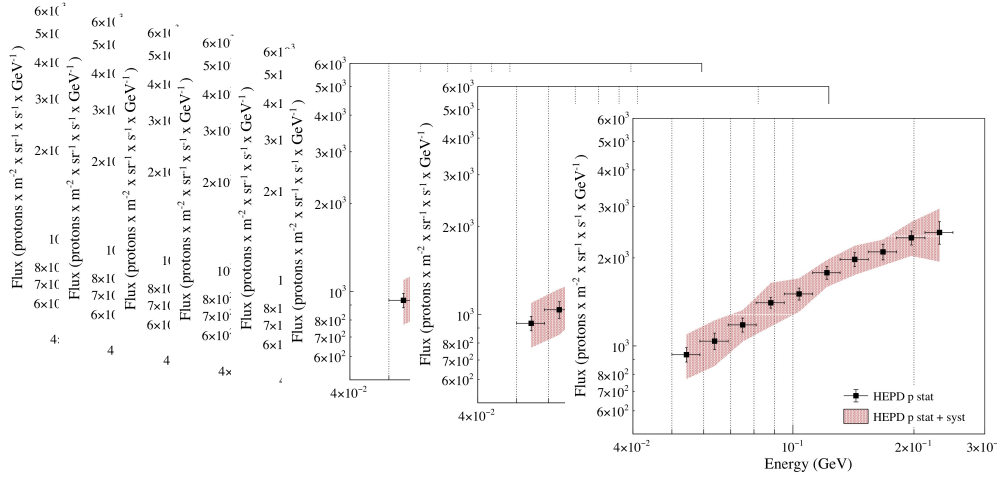
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HEPD-01 demonstrates remarkable sensitivity to daily monitor the variation of particle populations inside the Heliosphere

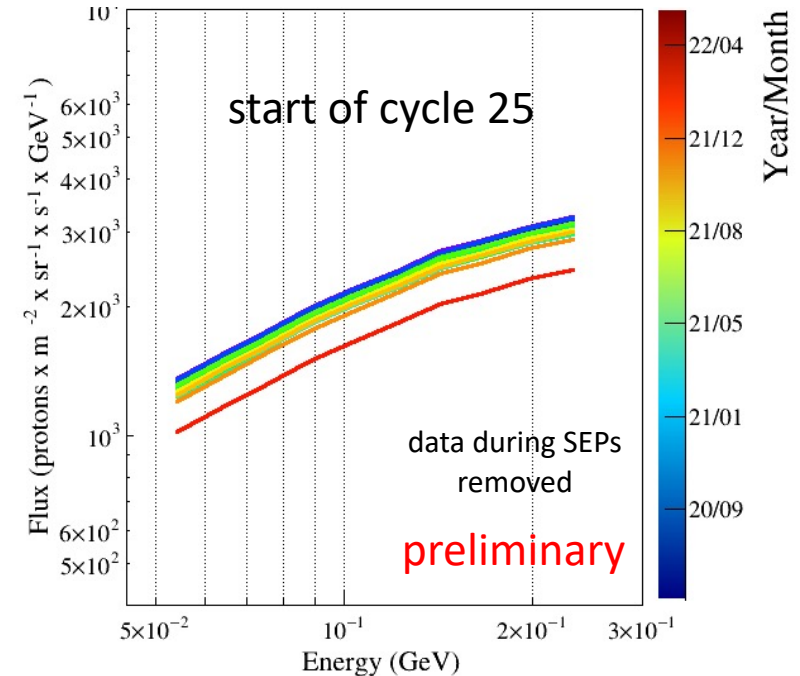
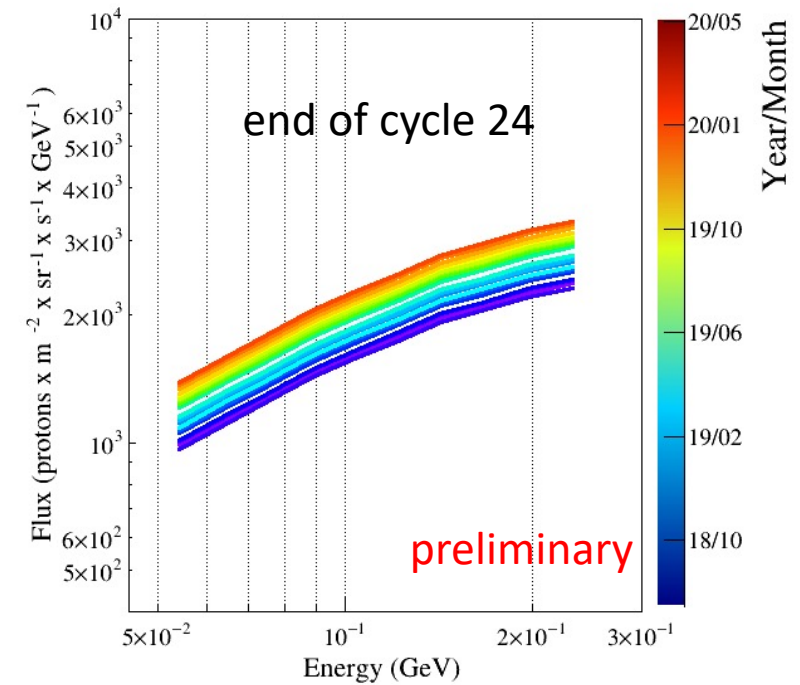
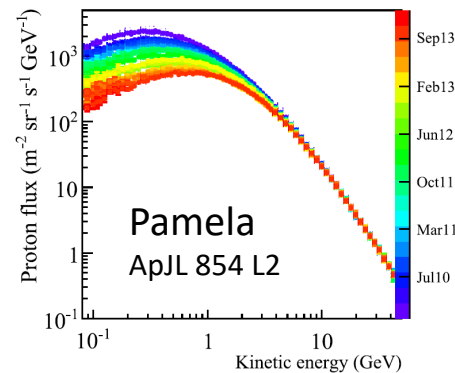


solar modulation

flux estimation for each Carrington rotation



- Preliminary results on GCR proton modulation during the end of the minimum (top) and the start of the maximum (bottom) measured by HEPD-01 between 50 MeV and 250 MeV
- Energy region very important to constrain 3D numerical models of proton spectra at Earth (e.g. based on SDE stochastic differential equation approach to solve the Parker equation)





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status and results

Sept. 9th,
2022

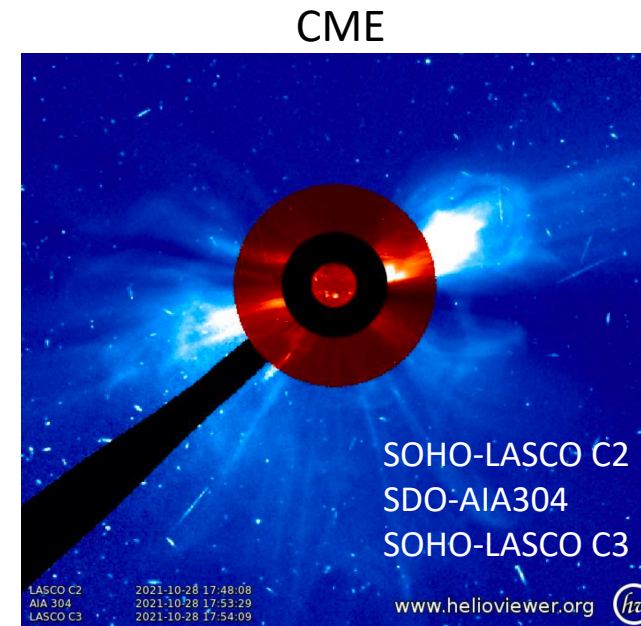
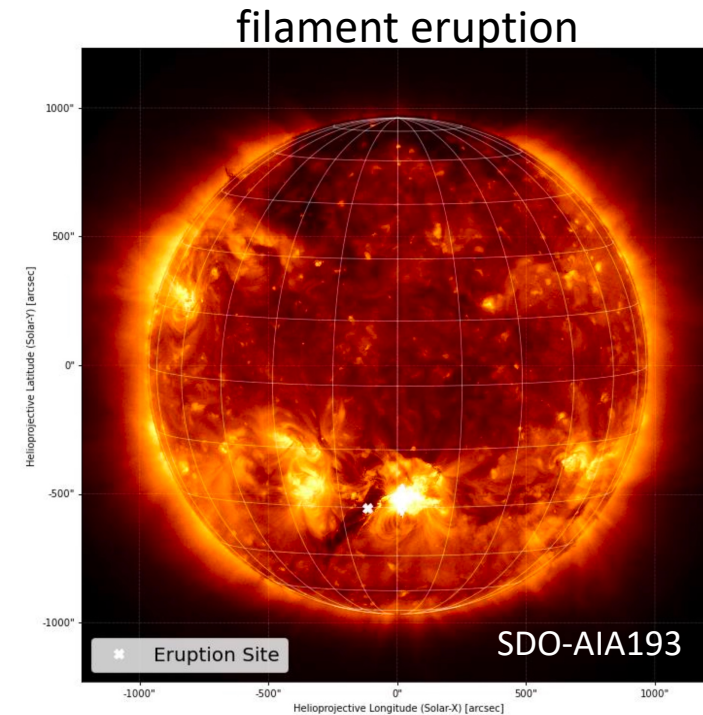
15

solar activity



first SEP event of cycle 25

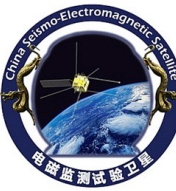
- After a series of C- and M-class flares a long- duration **X1 Solar Flare** was emitted at 15:35 UTC on October 28th, 2021, either triggered by or triggering the filament eruption
- A Coronal Mass Ejection (**CME**) associated with the filament eruption
- **First SEP** of the current solar cycle **within 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



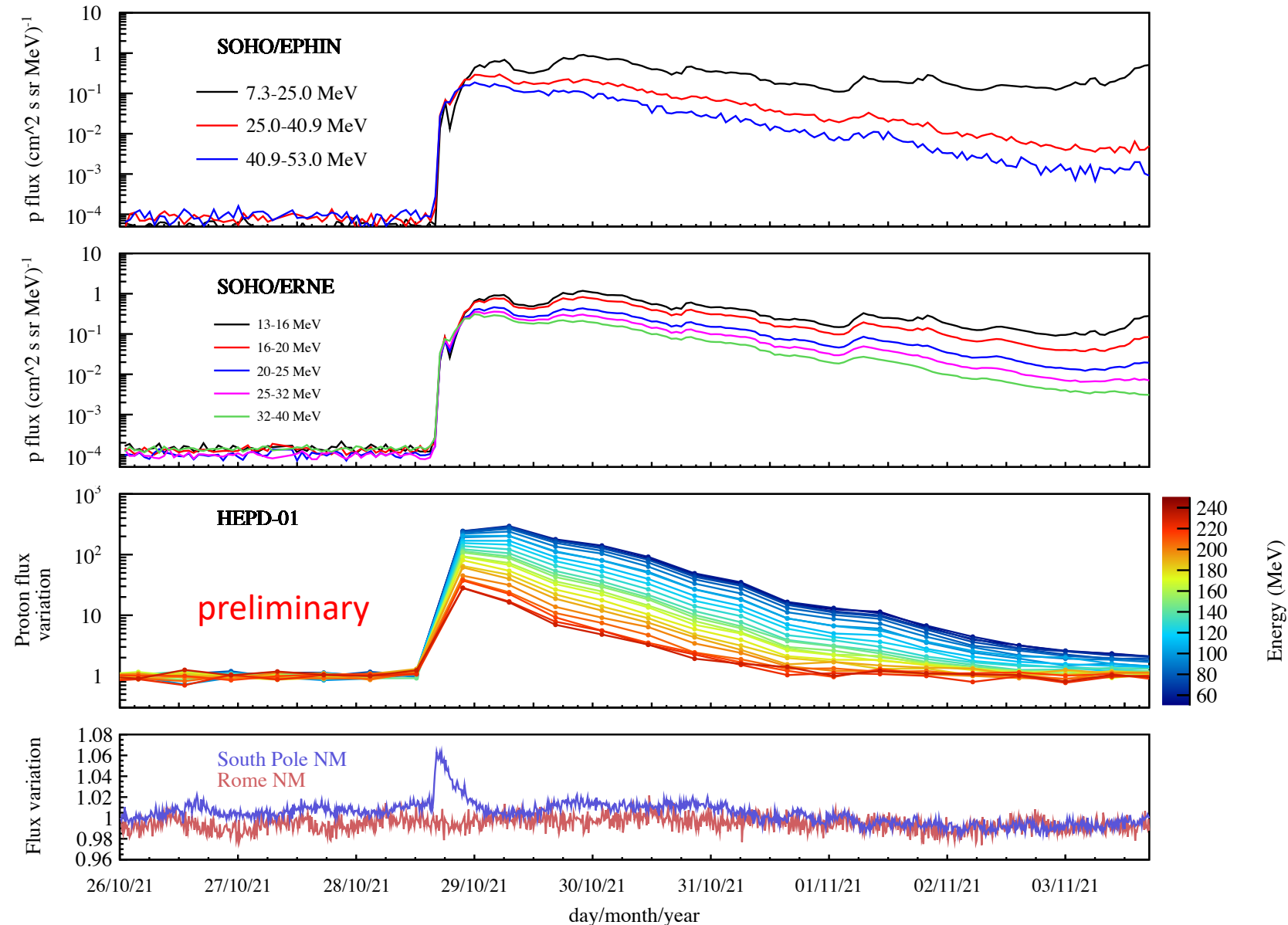
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status and results

Sept. 9th,
2022

16



first SEP event of cycle 25



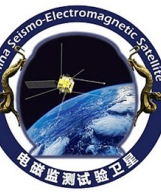
- Overall $\sim 300\times$ variation of ~ 50 MeV proton fluxes was registered by HEPD-01 (at Low-Earth orbit). The increase also protons with energies >200 MeV.
- The onset of the SEP was rapid, with a gradual fall to undisturbed levels in ~ 6 days for the low-energy protons.



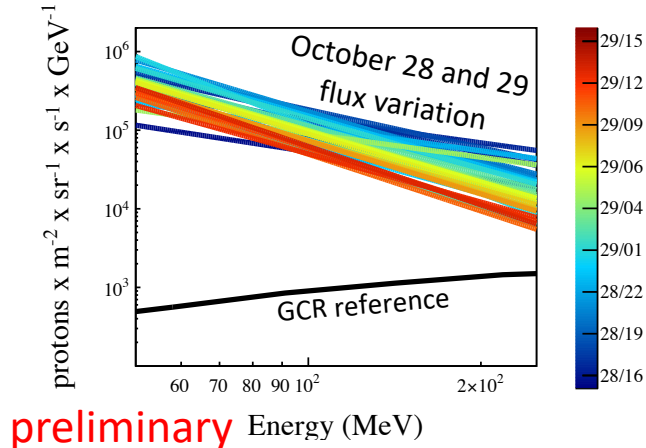
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status and results

Sept. 9th,
2022

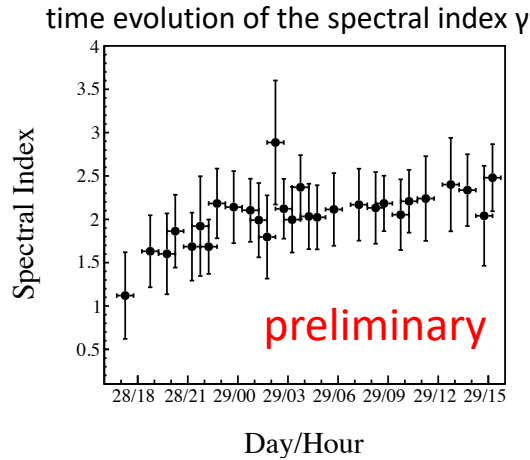
17



first SEP event of cycle 25

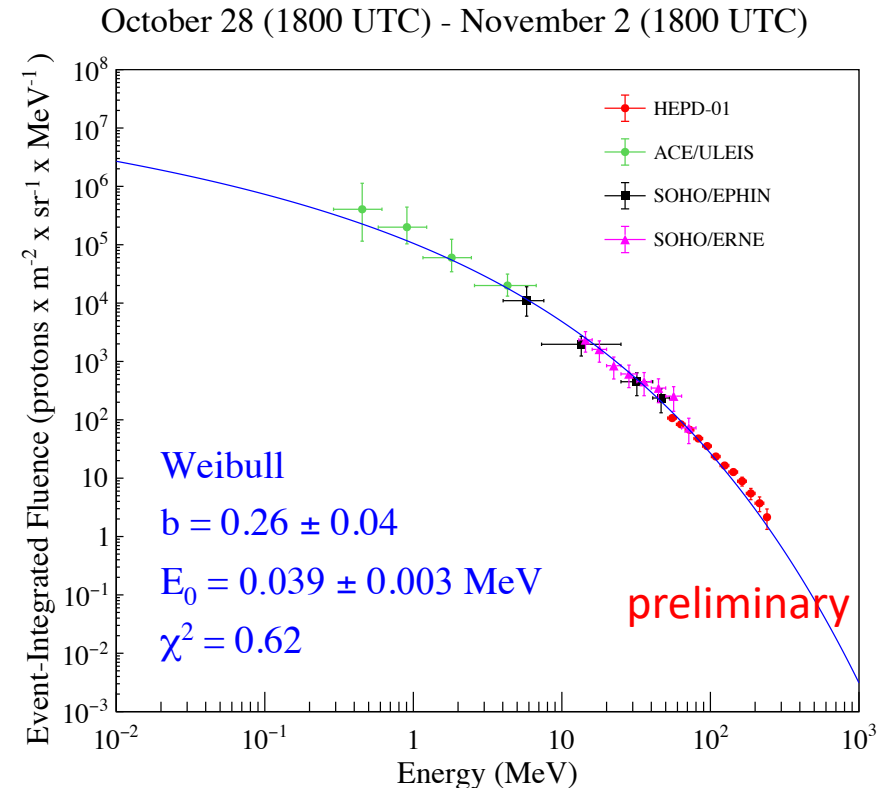


preliminary



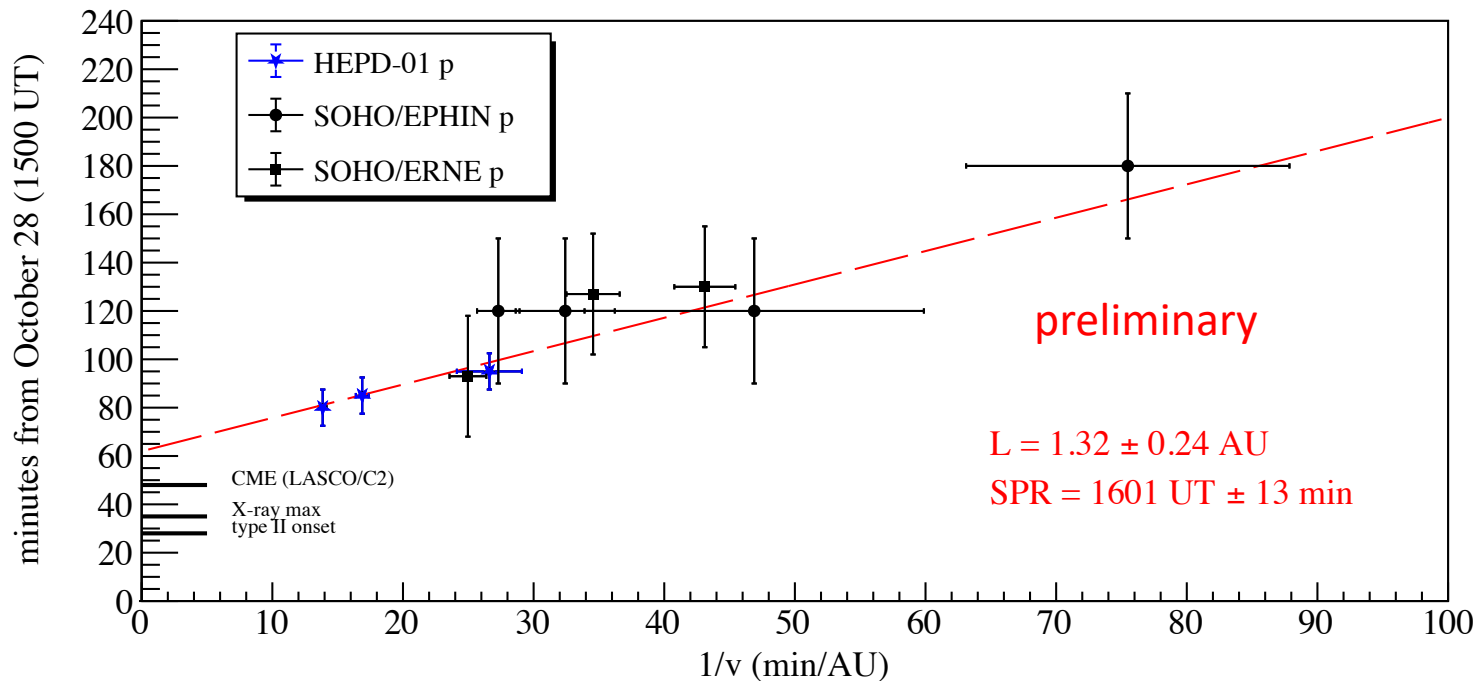
- Spectral index varying from 1.12 to 2.47

- Time-integrated proton energy spectrum of the SEP event was obtained by combining the observation of HEPD-01 with ACE/ULEIS, SOHO/EPHIN and SONO/ERNE data to extend the energy range from 300 keV up to 250 MeV .
- The fit provides essential information about the SEP acceleration sources.



first SEP event of cycle 25

If particles are all accelerated at the same time and from the same region of the Sun, and traverse the same magnetic path-length before being observed. Velocity dispersion due to interactions with magnetic fields implies that the increase of higher energy particles should be observed before that of lower energy ones



Particle energy \rightarrow velocity
Minutes from observation

linear fit

Solar Particle Release time (intercept)
Magnetic path-length traversed by the particles (slope).



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status and results

Sept. 9th,
2022

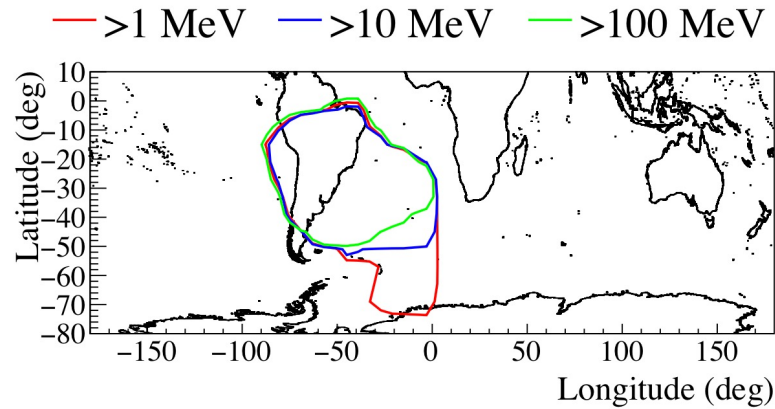
20

trapped protons

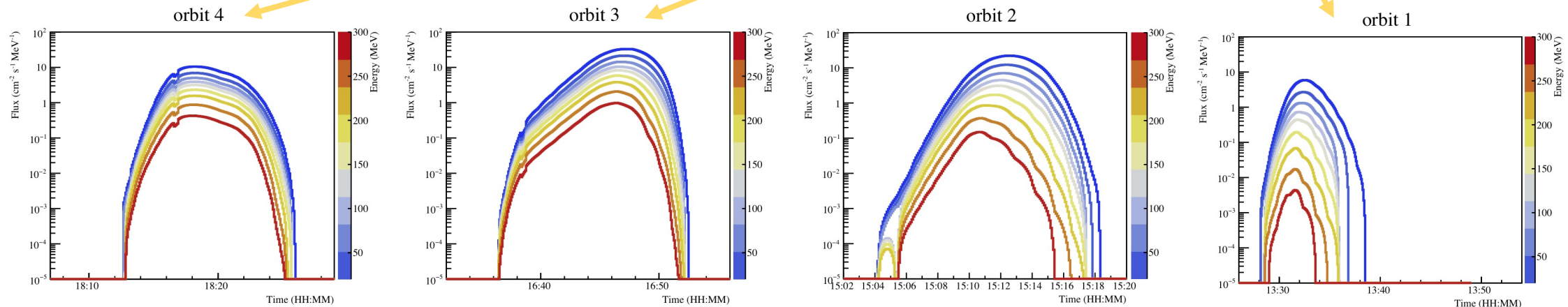
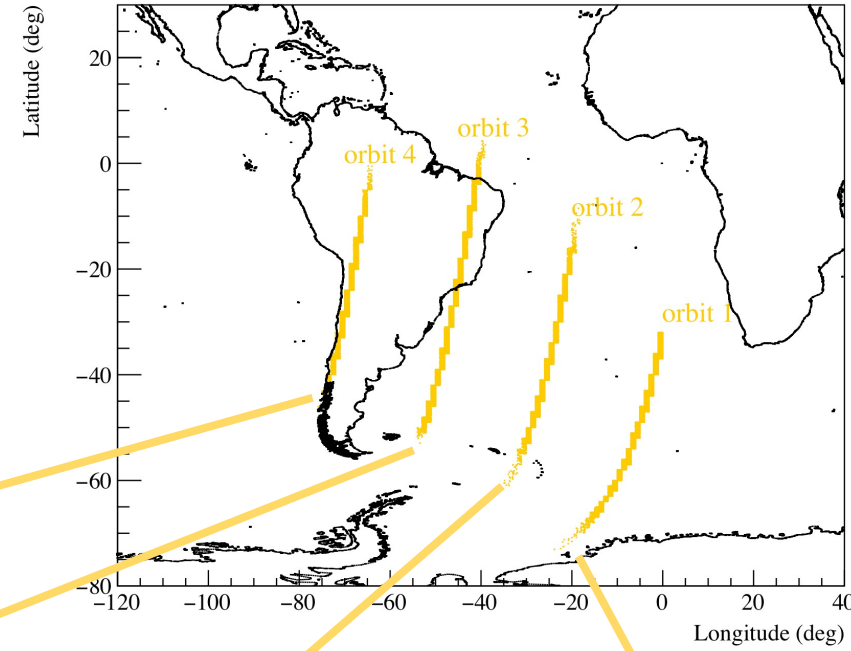


protons in the SAA : integral flux estimation (2018)

20 min orbit portions



Geographical extension of the SAA for >1, >10, and >100 MeV protons (respectively, blue, red, and green curves in the panel), obtained from the AP9 model

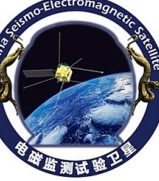


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status and results

Appl. Sci. 11, 3465 (2021)

Sept. 9th,
2022

21



protons in the SAA: integral flux estimation (2018)

Appl. Sci. 11, 3465 (2021)

- The characterization of the SAA using proton fluxes is very important because - after the Van Allen Probes stopped sending data - HEPD is one of the few instruments that can precisely measure particles inside this high-radiation environment
- The most reliable NASA models – AE9/AP9 – are flawed in some aspects and data on past LEO missions are scarce → HEPD could be a reliable source of such information

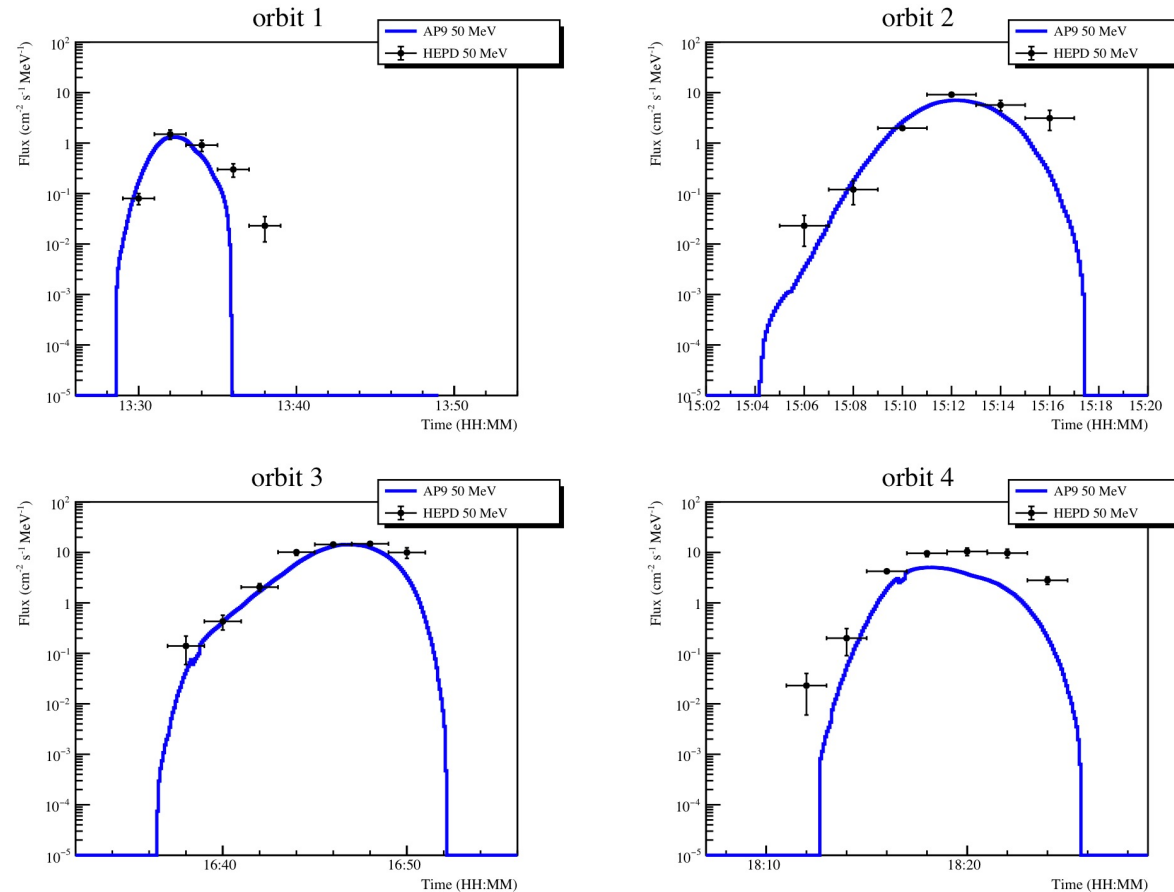


Figure 6. Time profiles (5-s resolution) of 50 MeV trapped protons estimated from the Ap9 model and compared with preliminary data of ~50 MeV proton data (black circles) from the HEPD instrument on board the CSES-01 satellite. The analysis has been carried out using the procedure described in [40]. The agreement between the data and the model appears generally good, despite showing small discrepancies, especially in the peripheral regions of the SAA. Only statistical errors are reported.

protons in the SAA: full characterization (2018-2020)

PHYS. REV. D 105, 062001 (2022)

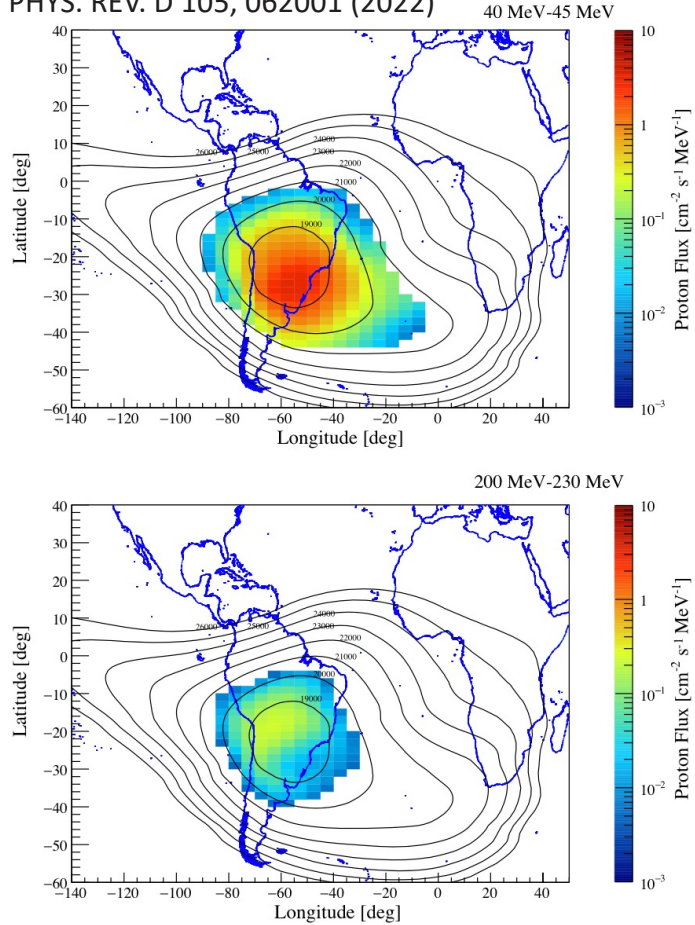


FIG. 4. Geographical maps of omnidirectional proton fluxes (August 2018–December 2020) as a function of latitude and longitude for a low-energy bin (40 MeV–45 MeV, upper panel) and for a higher one (200 MeV–230 MeV, bottom panel). In both panels, the isolines of the reconstructed magnetic field are also shown for clarity.

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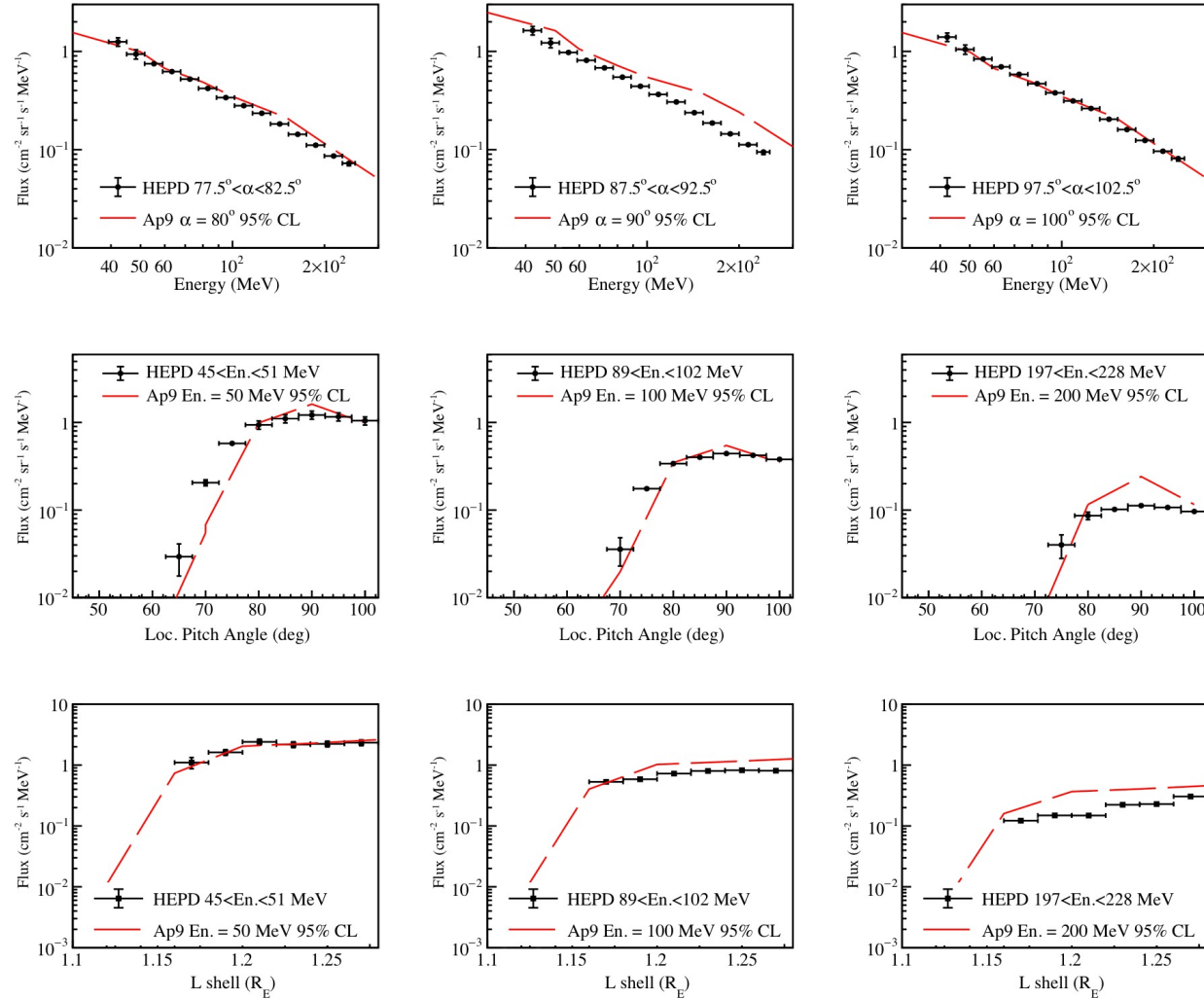


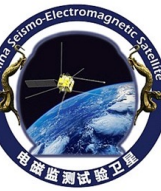
FIG. 2. South Atlantic Anomaly proton fluxes as a function of energy (top panels), local pitch angle (middle panels) and L-shell (Earth radii, bottom panels) obtained by HEPD (black squares) between August 2018 and December 2020, and compared with predictions from the AP9 model at 95% C.L. (red dashed line).



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R. Iuppa - The
Limadou project:
status and results

Sept. 9th,
2022
23





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status and results

Sept. 9th,
2022

24

CSES-02

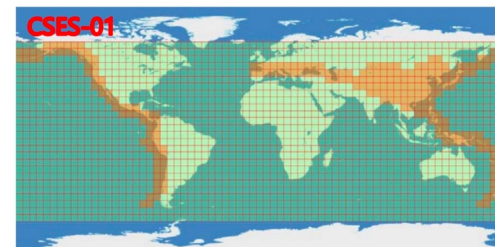
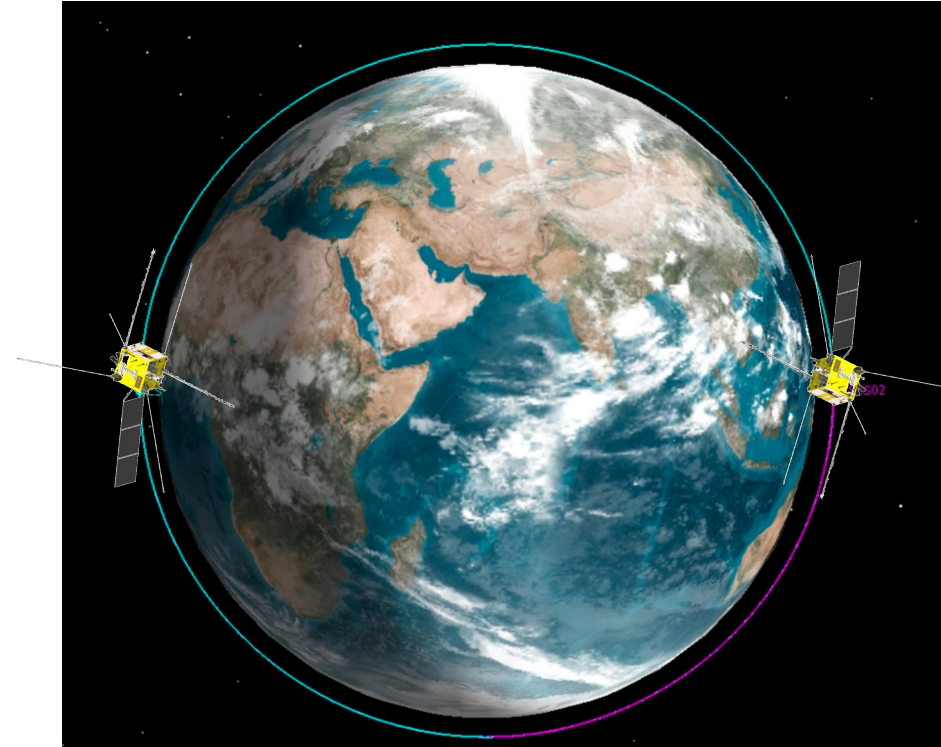


CSES-02

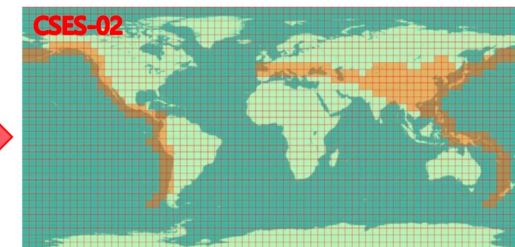
- Launch scheduled by 2023
- Same DFH CAST-2000 platform of CSES-01 with some upgrades
 - Earth oriented 3-axis stabilization system with orbit maneuver capability
 - X-Band Data Transmission 120Mbps → 150Mbps
 - Storage 160Gb → 512Gb
 - Total Mass: 730kg → 900kg
 - Peak Power Consumption: ~900W
 - Design Life-span: 5 years → 6 years
- Complementary Ground Track wrt CSES-01
 - Identical Orbit Plane
 - 180° Phase Difference
 - Track interval: 5° → 2.5°
 - Return cycle: 5 days → 2.5 days
- Operation mode: Full time operational

Limadou collaboration committed to design and construct the EFD-02 and HEPD-02 payloads.

a multi-satellite approach to the study and monitoring of ionosphere and magnetosphere



Confined Areas Observation



Global Wide Observation



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Sept. 9th,
2022

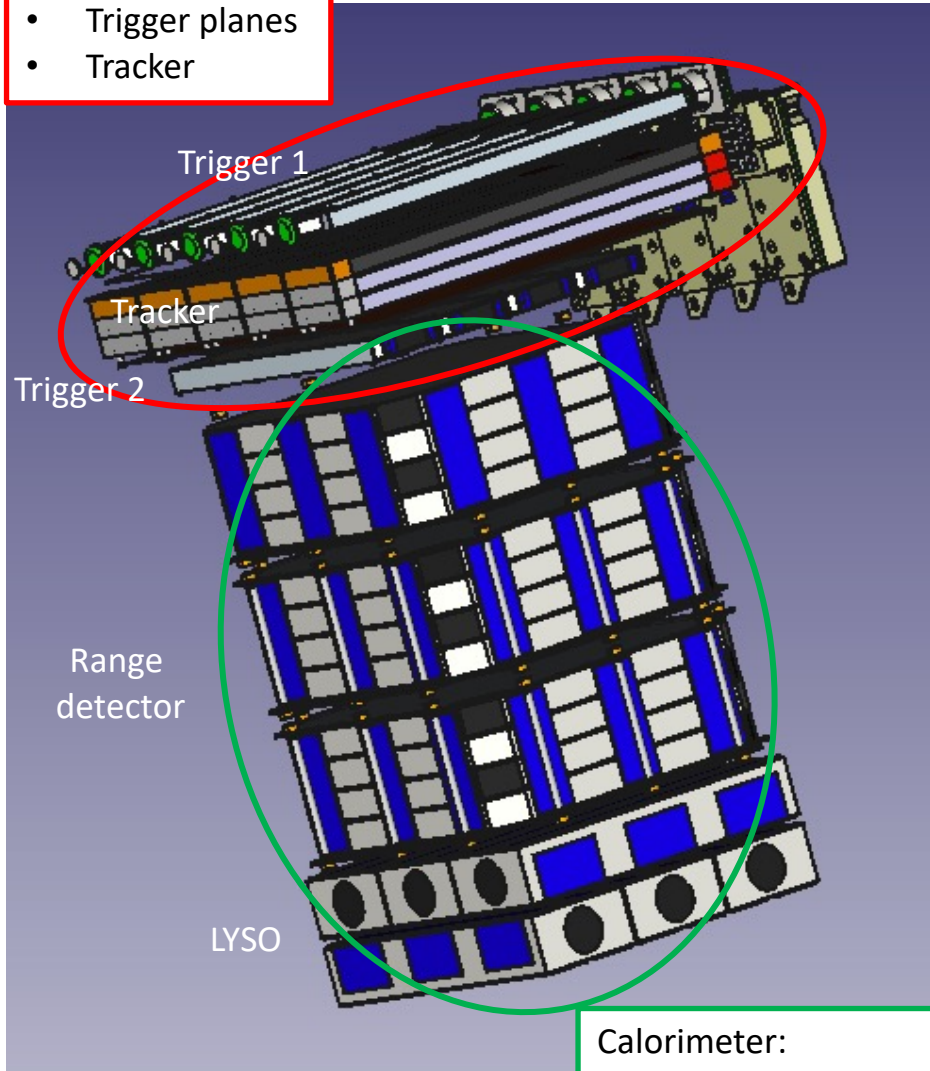
25



The HEPD-02 detector

Front Detector:

- Trigger planes
- Tracker



Calorimeter:

- Range detector
- Energy detector

Requirements similar to HEPD-01

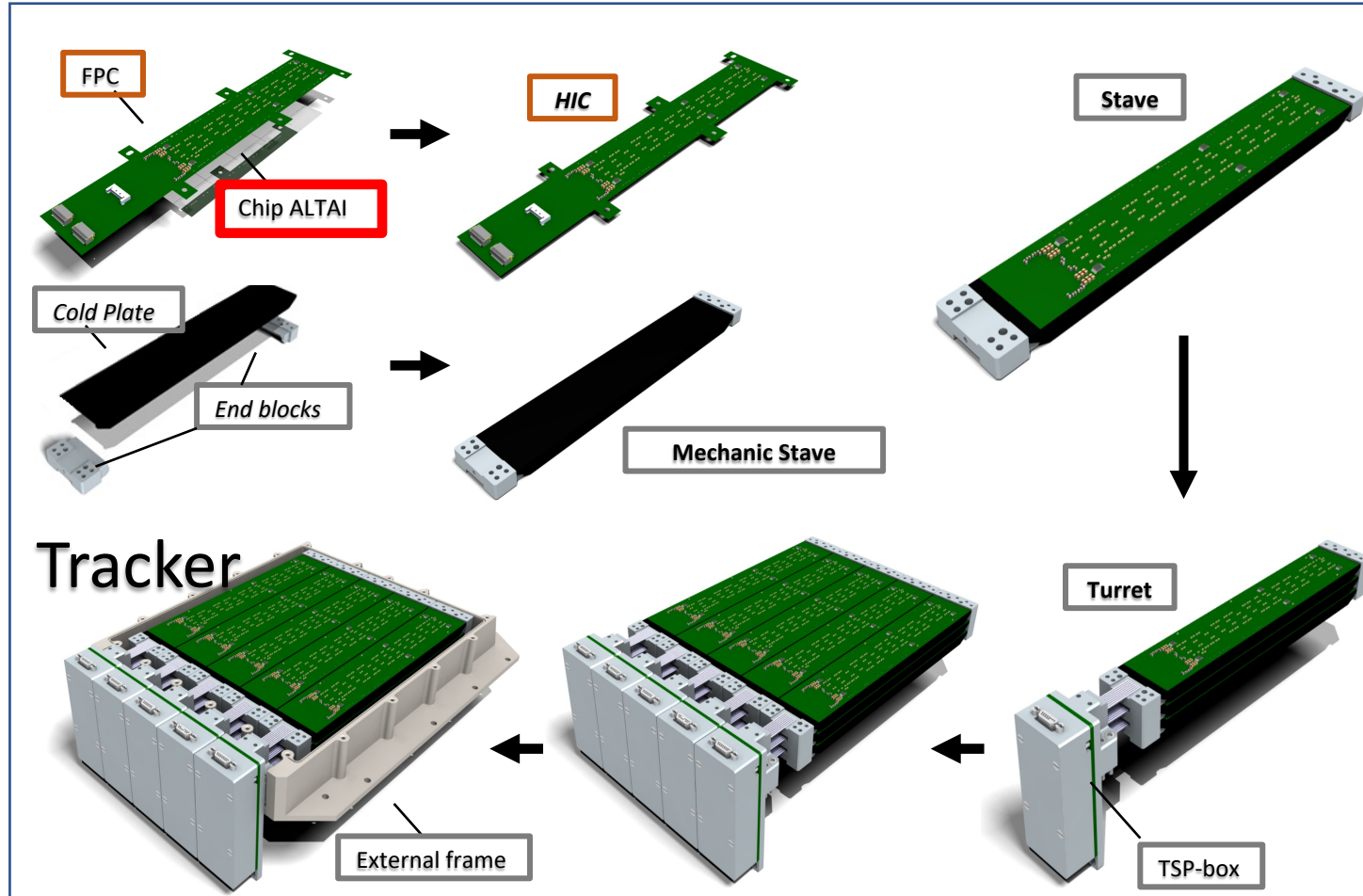
- Energy range
 - Electron: 3-100 MeV (contained)
 - Proton: 30-200 MeV (contained)
- Angular resolution $< 8^\circ$ @ 5 MeV
- Energy resolution $< 10\%$ @ 5 MeV
- Particle Identification efficiency $> 90\%$
- Maximum Omni-directional Flux: $10^3 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ (accepted by trigger before prescaling)
- Operating temperature: $-10^\circ\text{C} \sim +35^\circ\text{C}$
- Mass (including electronics) $\leq 50 \text{ kg}$
- Power Consumption $\leq 45\text{W}$
- Data budget $\leq 100 \text{ Gbit/day}$
- Life span: $\geq 6 \text{ Years}$

Major improvements wrt HEPD-01

- **first silicon-pixel tracker** ever designed for space
 - increased tracking capability
- double trigger system guaranteeing hermeticity
- ~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**

Monolithic Active Pixel Sensors: first use in space

Based on the MAPS developed for ALICE experiment at LHC



An 80 megapixel CMOS camera for charged radiation

Advantages:

- reduces systematic uncertainties on tracking: down to 4um single-hit resolution
- no multi-hit degeneracy
- Extremely low material budget: 50um thin, control and read-out based on ultra-thin (180 um) flexible printed circuits
- Cheaper than standard microstrips
- Monolithic: in-pixel FE electronics: unmatched S/N ratio (10^{-8} fake hits per trigger)

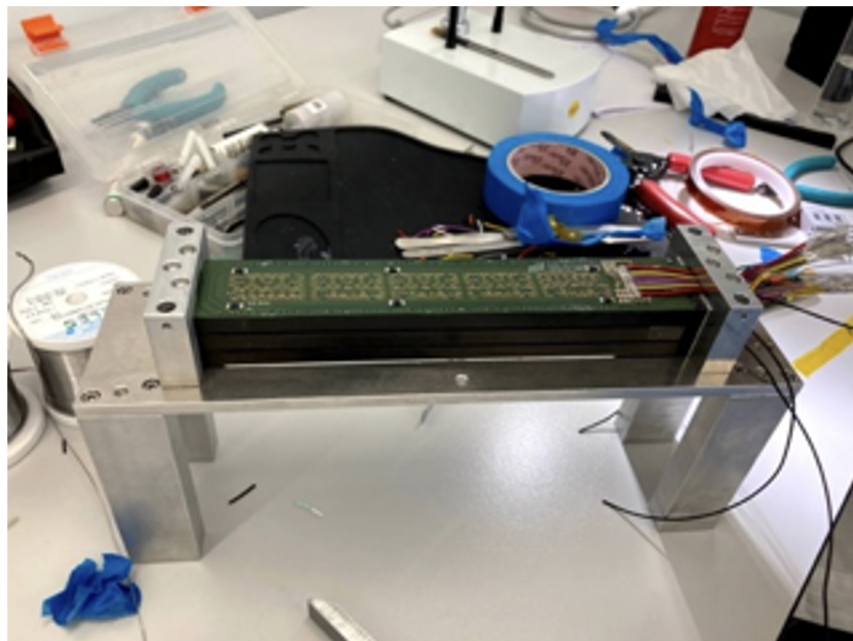
Challenges for use in space

- Tradeoff for mechanical supports: avoid multiple scattering but withstand launch acceleration and vibrations
- Limited power budget
- Heat dissipation
- Digital readout: limited information about charge

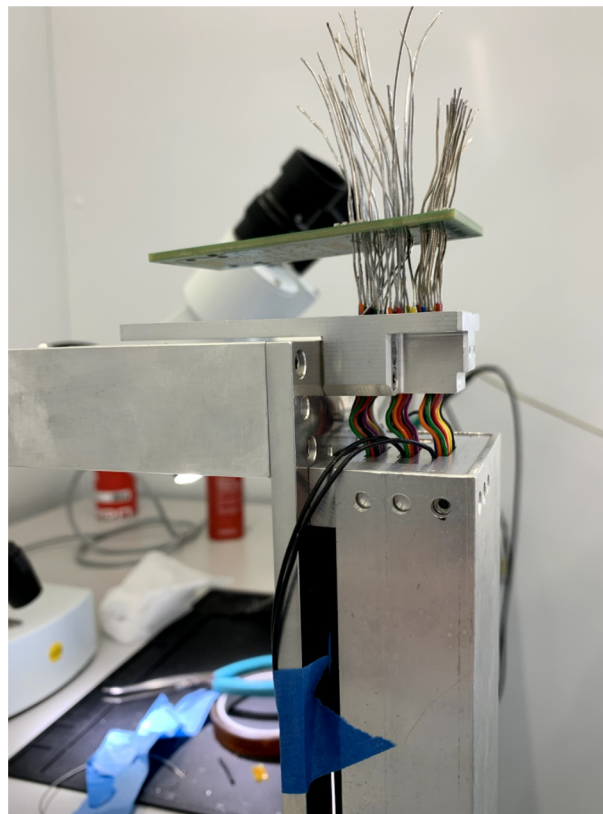
HEPD-02 tracker

First ever use of monolithic active pixel sensors in space.

Huge technological effort to spatialize the technology. TRL 7-8 gained. Ready for the construction of the Flight Model

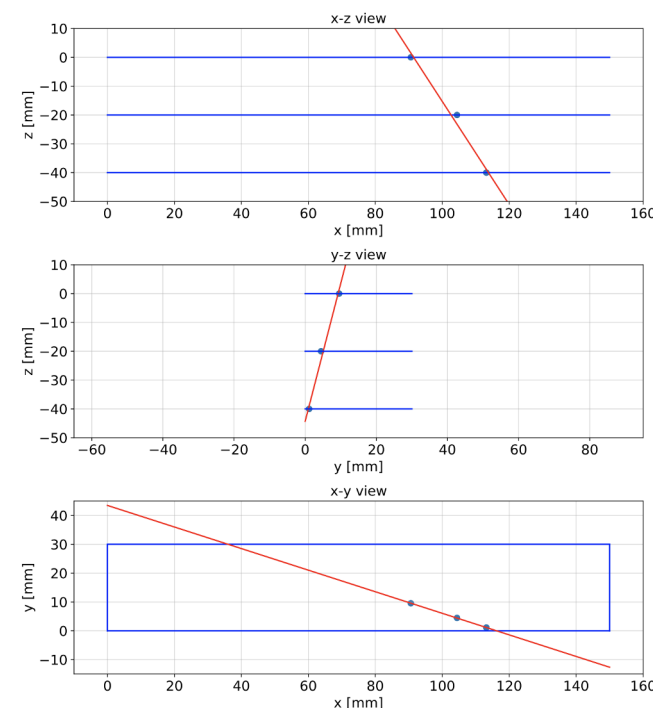


turret assembly

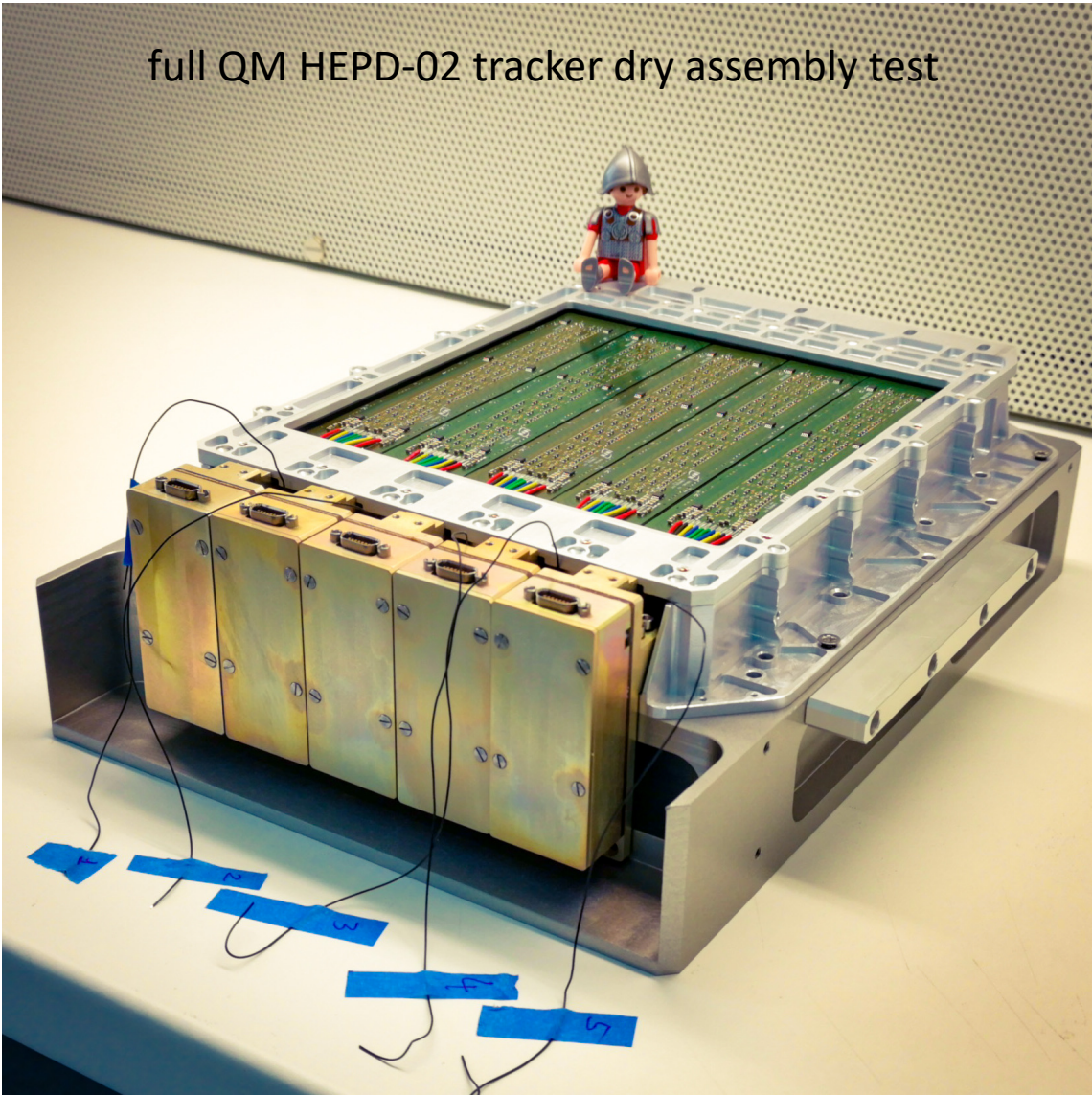


electronic connection

ON-LINE tracking capability demonstrated. Change of paradigm for future high-energy CR and gamma experiments

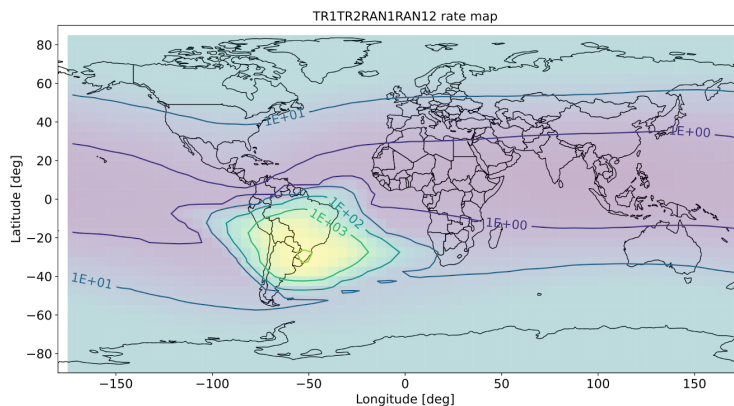
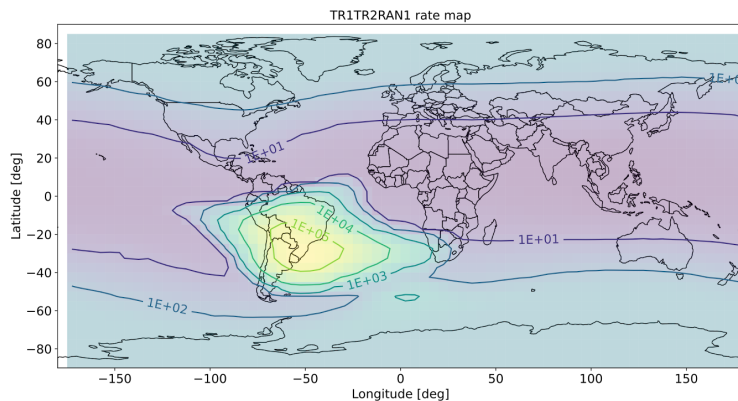
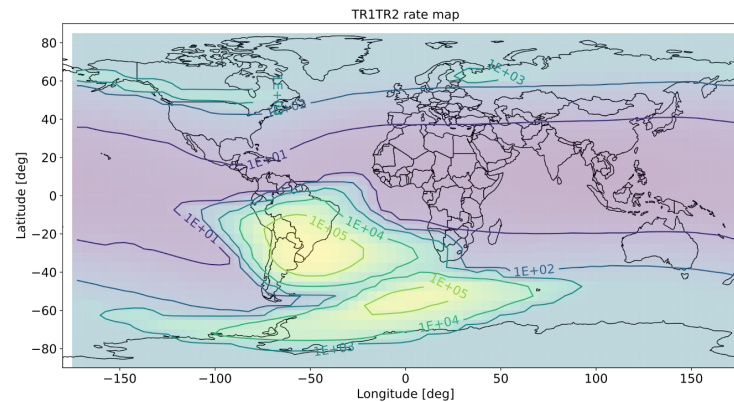
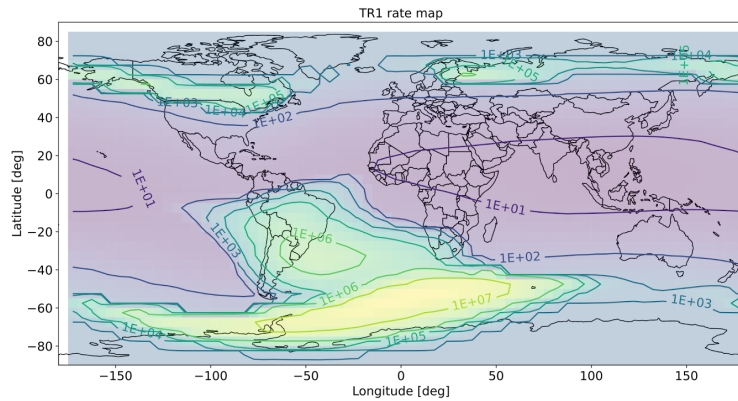


HEPD-02 tracker: connection and integration



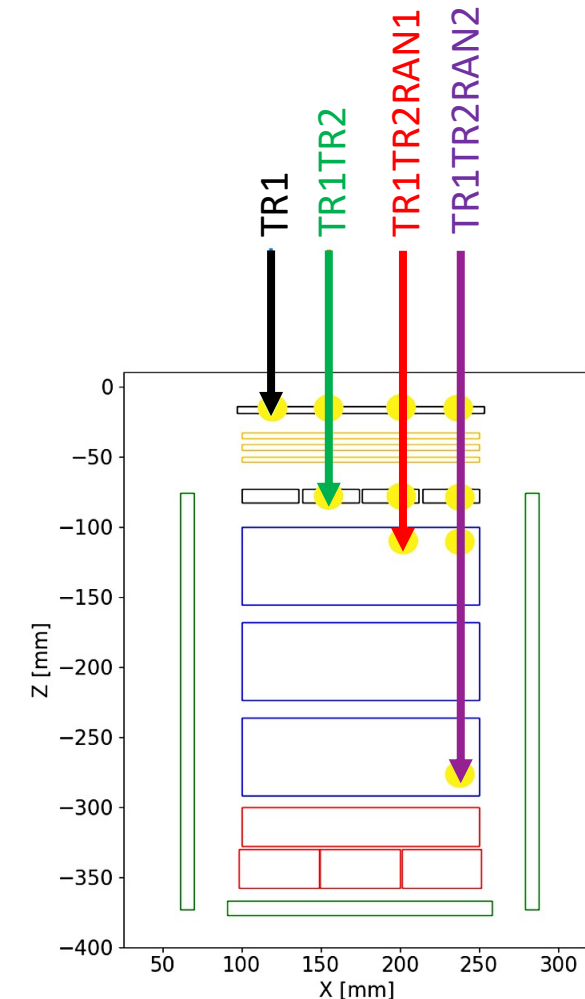
prescaled concurrent triggers

expected trigger rates obtained summing up contributions from all particle species
(cross-checked with measurements from HEPD-01)



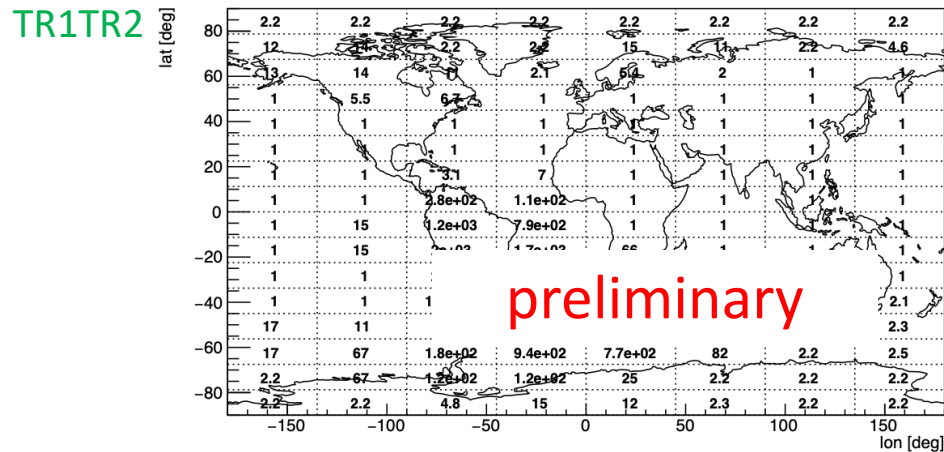
expected rates up to 10 MHz (SAA), not compatible with data budget nor with event acquisition dead time. Low-energy triggers would determine the saturation of HEPD-02

trigger patterns for different particle penetration
(i.e. different energy thresholds)

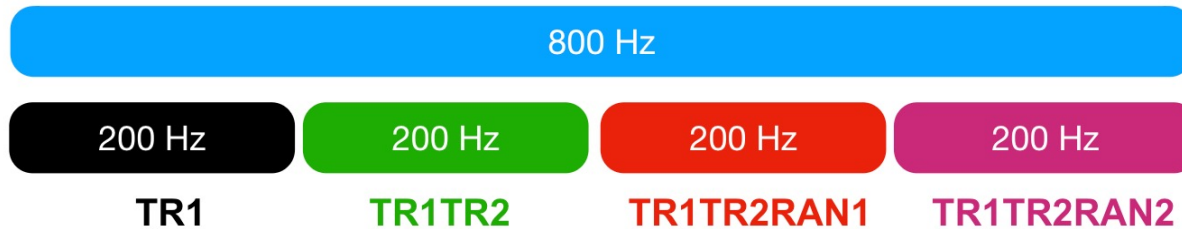


prescaled concurrent triggers

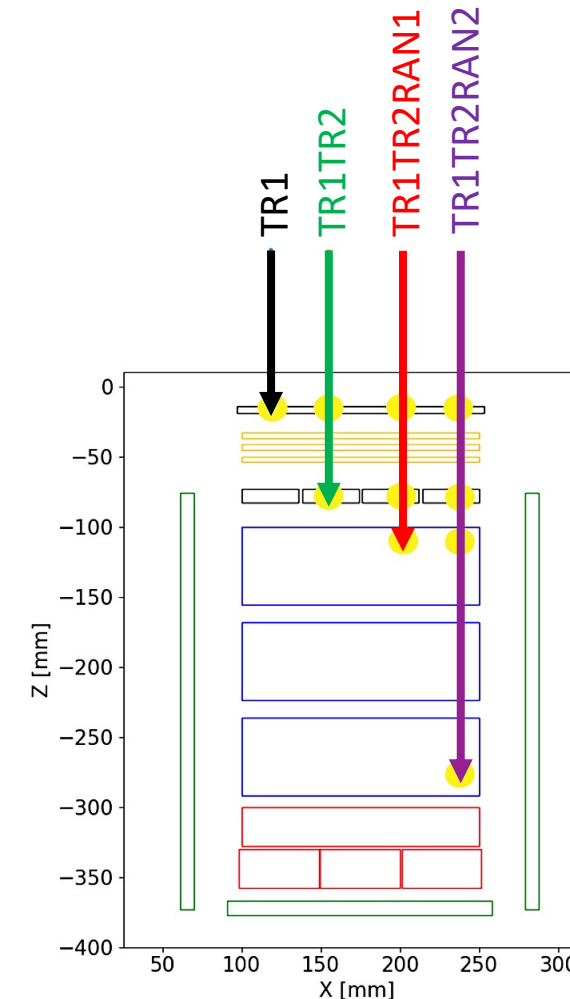
- Scale factors are adjusted for each trigger pattern to share resources among different physics cases, optimized after scientific requirements about FoV and kind of particle.



- Concurrent trigger configurations are prescaled to match the amount of data the instrument can process and send to the ground



trigger patterns for different
particle penetration
(i.e. different energy thresholds)



MC simulation and event reconstruction software

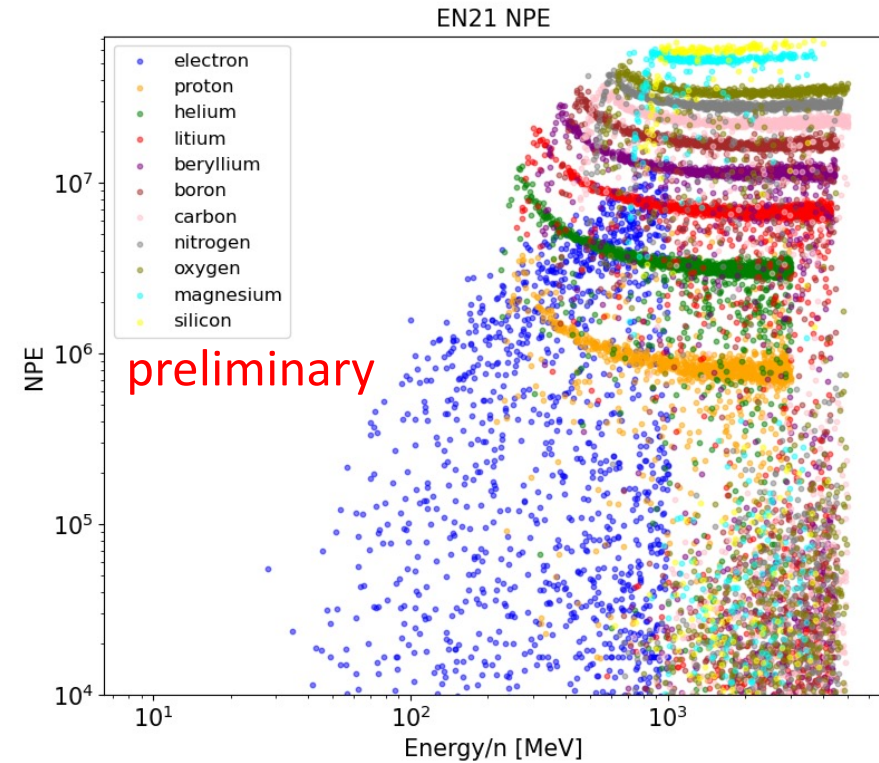
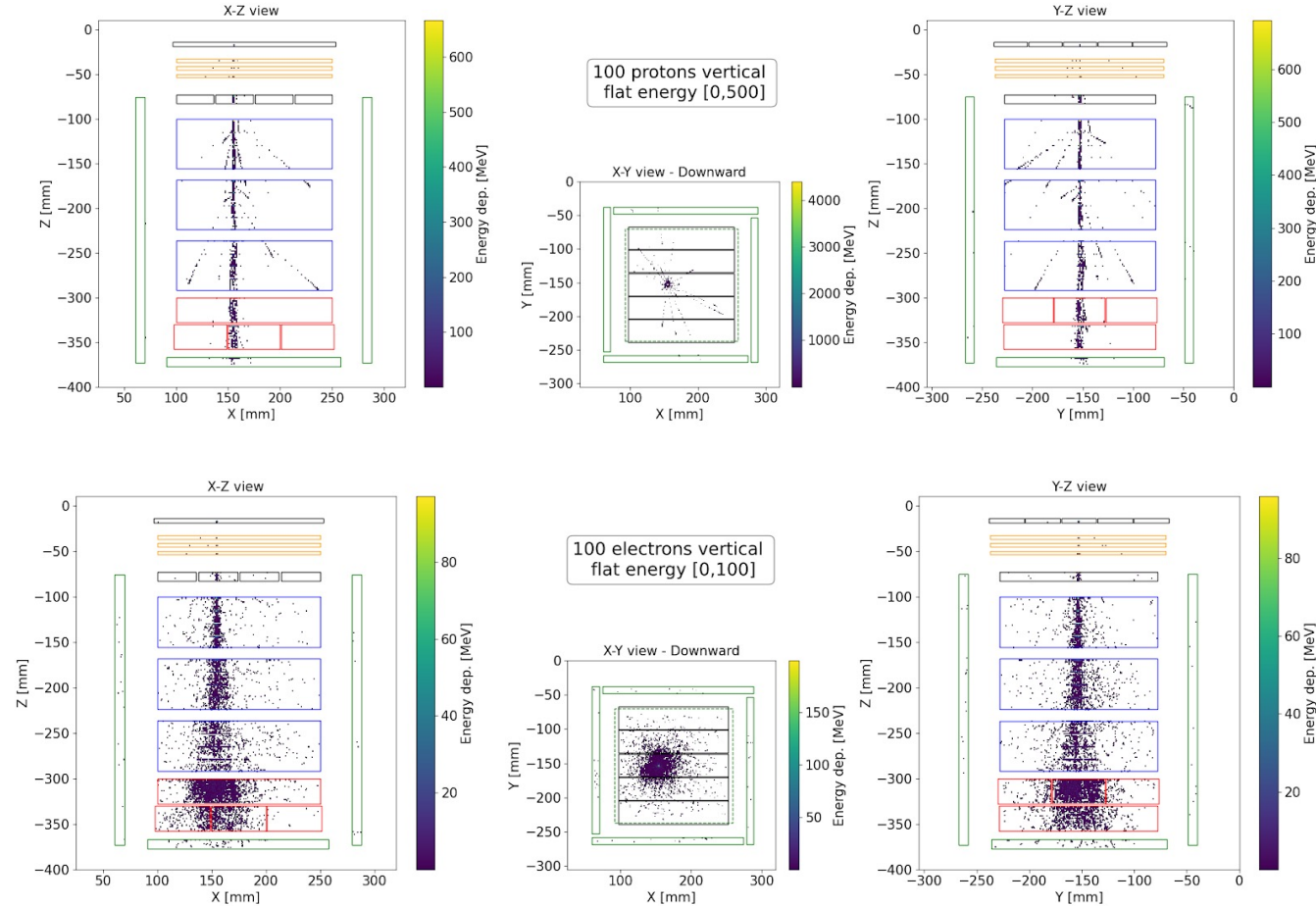
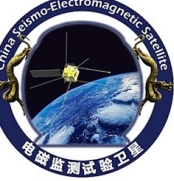


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status and results

Sept. 9th,
2022

32



HEPD-02 designed to be sensitive to light nuclei in the energy range 300-3000 MeV/n

fully digitized Monte Carlo simulation developed from CAD drawings
full DL-based event reconstruction chain validated with beam tests

Conclusions

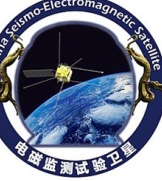
- The CSES initiative is a successful cooperation between China National Space Administration (CNSA), China Earthquake Administration (CEA) and Italian Space Agency (ASI)
- Its scientific goals are achieved by monitoring of the electromagnetic near-Earth space environment
- CSES satellites are designed to host a suite of different scientific payloads to comprehensively observe phenomena in the upper ionosphere and in the magnetosphere
- Limadou is the Italian collaboration led by INFN which designed and constructed HEPD for CSES-01
- The 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 trapped particles in the SAA, strongly constraining available models
 - Measurements of SEPs at the beginning of the 25h solar cycle
- The Limadou collaboration is currently committed to construct the HEPD and the EFD payloads 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
- HEPD-02 is a major upgrade of HEPD-01. Among the new features:
 - first MAPS tracker ever used in space
 - prescaled concurrent triggers
 - possible sensitivity to MeV photons



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Sept. 9th,
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33



thank you



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34



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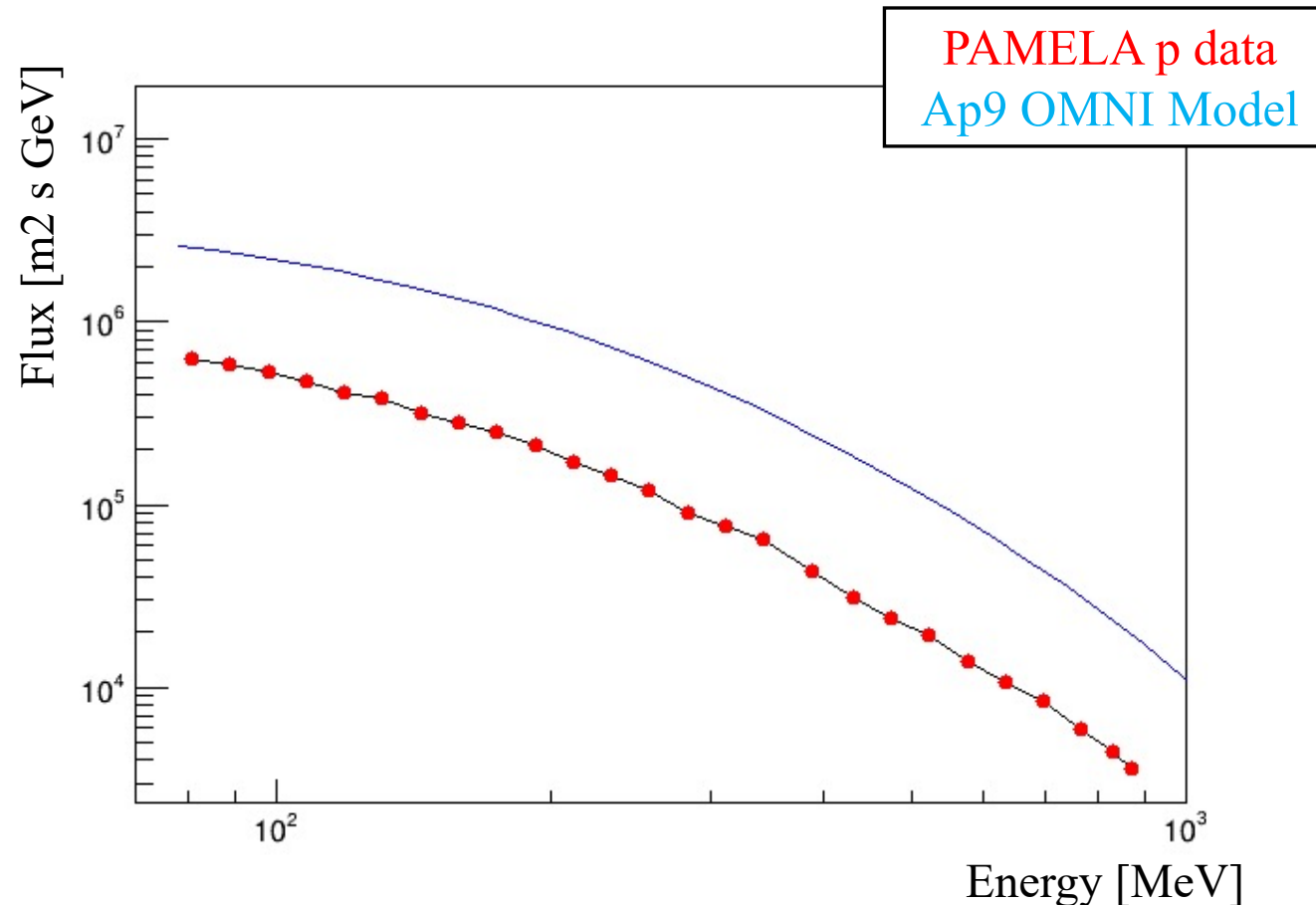
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backup

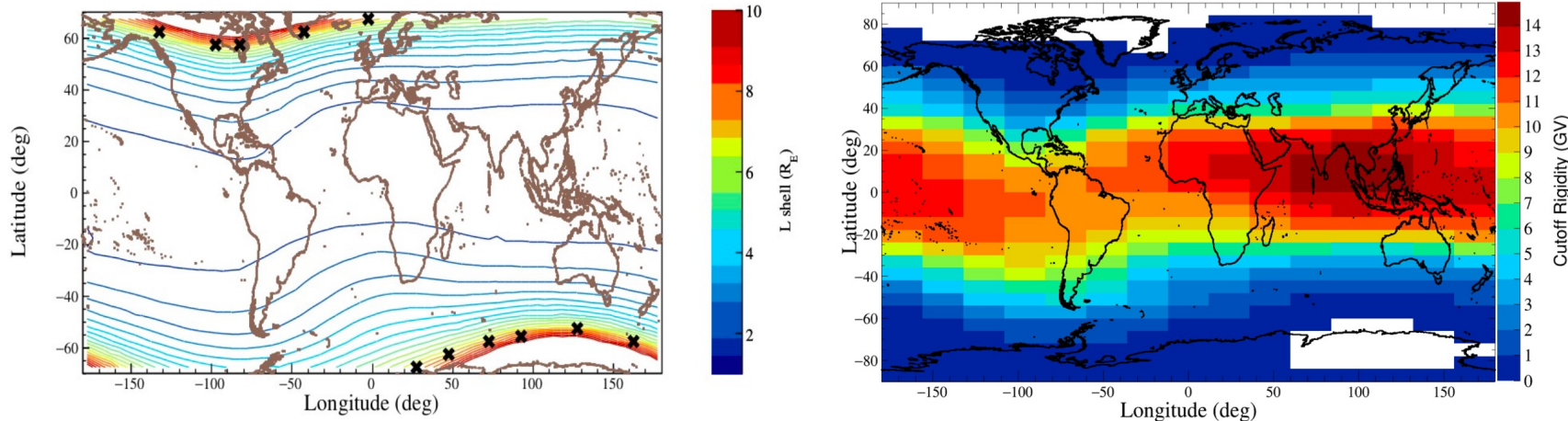


PAMELA/AP9 comparison

- ❑ A useful comparison can be performed using PAMELA data (the same used for the ESA project) together with the Resurs-DK TLEs (7 July 2006 – 8 July 2006)
- ❑ Even using PAMELA proton data in SAA, the agreement with model is not good, as expected : a overestimation is always present



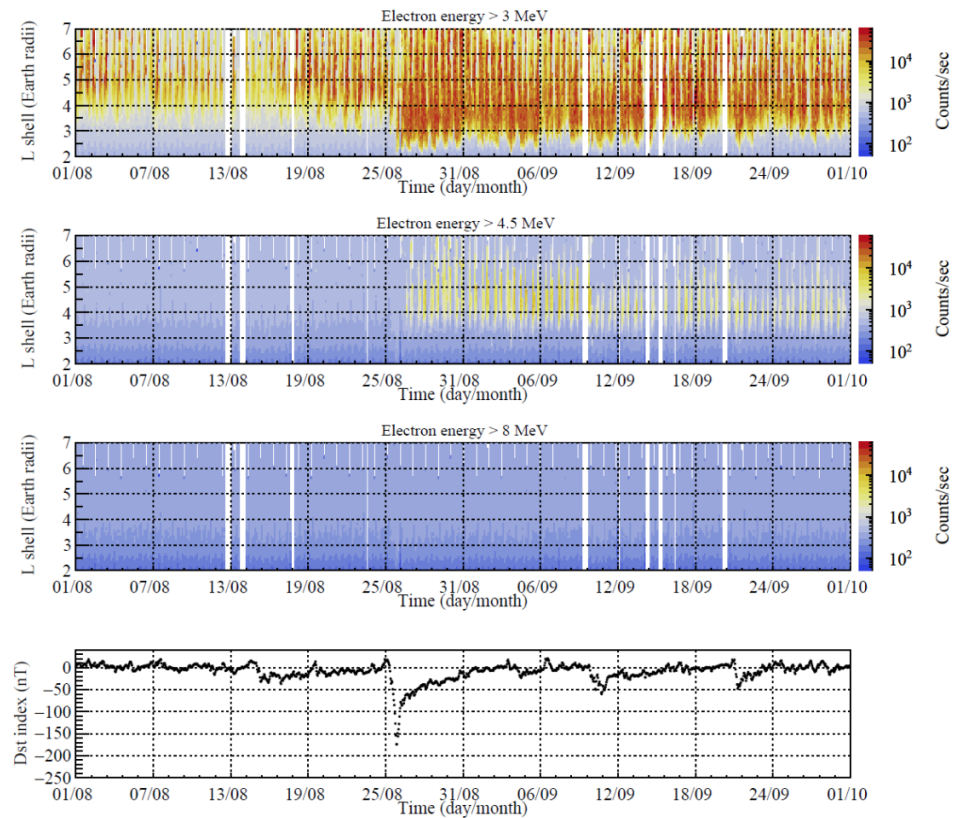
selection of galactic protons



- ✓ To discriminate protons coming from outside the magnetosphere and the under-cutoff re-entrant albedo populations we made use of the **AACGM** (Altitude-Adjusted Corrected GeoMagnetic) coordinates to calculate the McIlwain parameter L
- ✓ For the entire analysis, we selected only portions of CSES-01 orbits that were above a value of the **L-shell parameter greater than 7**
- ✓ This selection assures that all the protons with energy greater than 50 MeV were of cosmic origin
- ✓ A parallel approach using a rigidity cutoff map results in a very good agreement with the L-shell selection

Due to the large acceptance of HEPD, the Störmer approximation of vertical approaching particles (Shea et al. [1987](#)) is no longer valid. A simulation on all possible arrival directions of protons has been carried out, considering the instrument field of view (FoV). A combination of the International Geomagnetic Field Reference (IGRF) model (Thébault et al. [2015](#)), AACGM (Altitude-Adjusted Geomagnetic Coordinates; Shepherd [2014](#)) and the Tsyganenko89 model (Tsyganenko [1989](#)) is adopted to take into consideration both internal and external magnetic field sources.

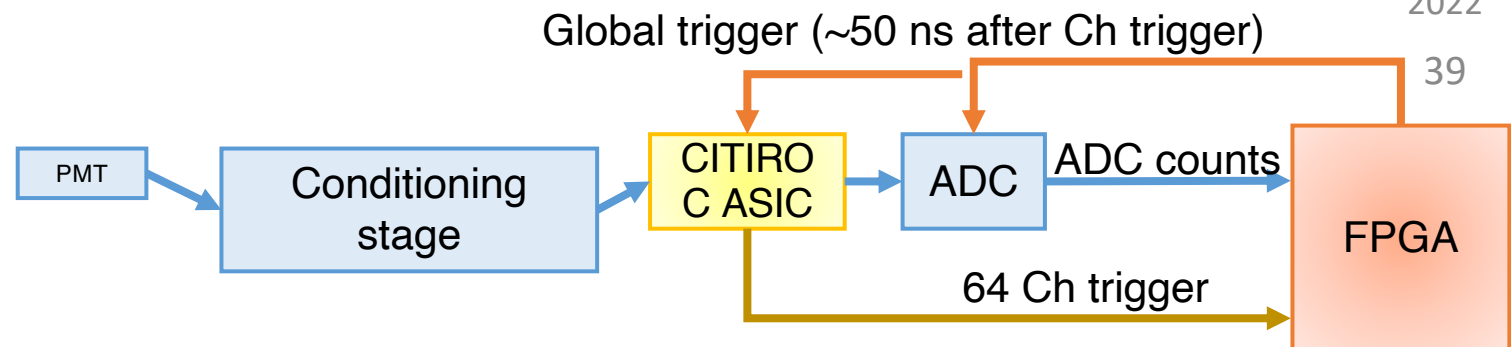
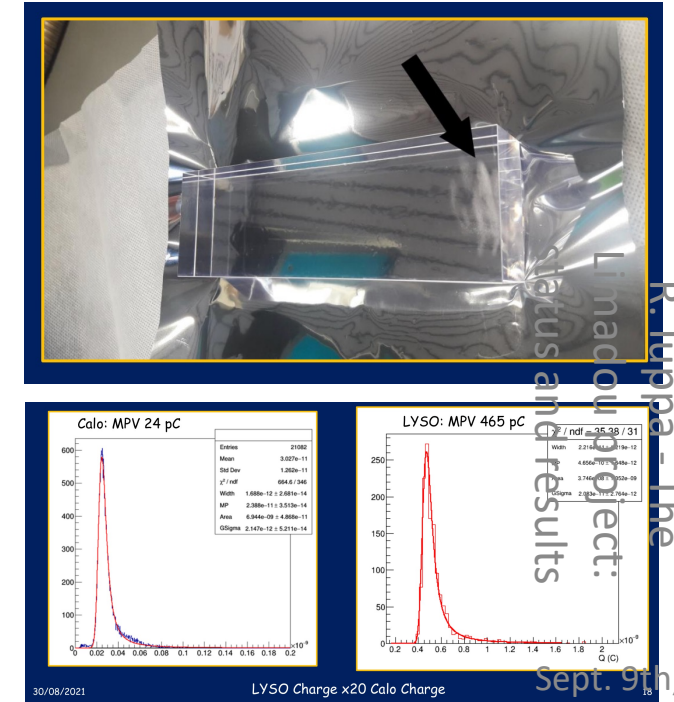
outer belts and geomagnetic storms



Appl. Sci. 11, 5680 (2021)

- Even without SEP events, we were able to assess the capability of HEPD during transient phenomena like the geomagnetic storms of August 25, 2018
- We found also another very interesting event (September 2020) which is being carefully studied right now
- More (and more powerful) geomagnetic storms will be studied in the next future

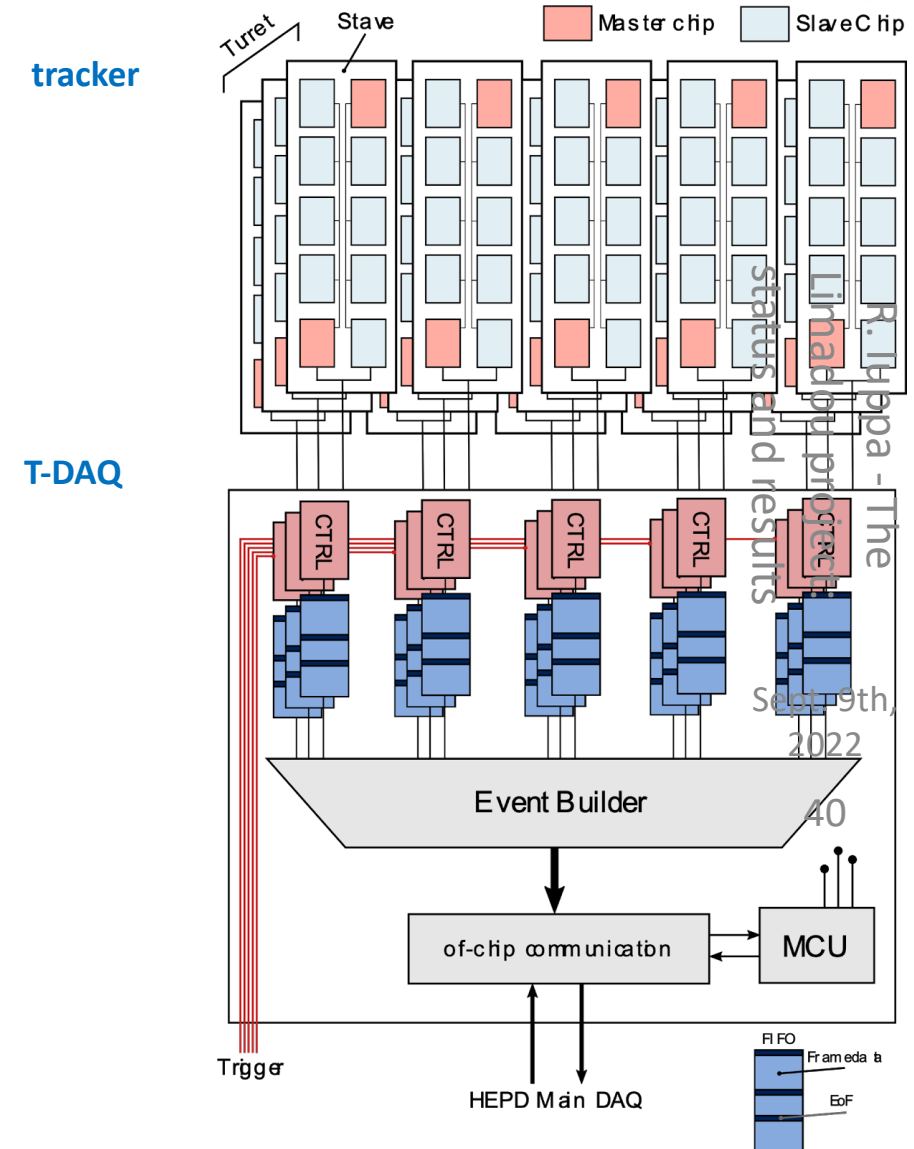
-
- The diagram illustrates the Trigger board architecture, which is part of a larger system labeled "SATELLITE". The Trigger board is divided into two main sections: "COLD" and "HOT".
- COLD Section:** Contains the "PMTs" (Photomultiplier Tubes) and the "ALPIDE sensors Front End".
 - HOT Section:** Contains the "Conditioning stage", "CITIROC" (Comparator in Time Interpolated Readout Circuit) blocks, "ADC (AD7274)" (Analog-to-Digital Converter) blocks, and the "FPGA (A3PE3000L)" (Field-Programmable Gate Array).
- Data Flow:**
- The "PMTs" send data to the "Conditioning stage".
 - The "ALPIDE sensors Front End" sends data to the "DAQ board".
 - The "DAQ board" (Data Acquisition board) is connected to the "CPU board" via "RS422" and "CANBUS" interfaces.
 - The "CPU board" is connected to the "FPGA" via "SpaceWire".
 - The "Conditioning stage" sends data to the "CITIROC" blocks, which then send data to the "ADC (AD7274)" blocks.
 - The "CITIROC" and "ADC (AD7274)" blocks are connected to the "FPGA" via bidirectional data paths.



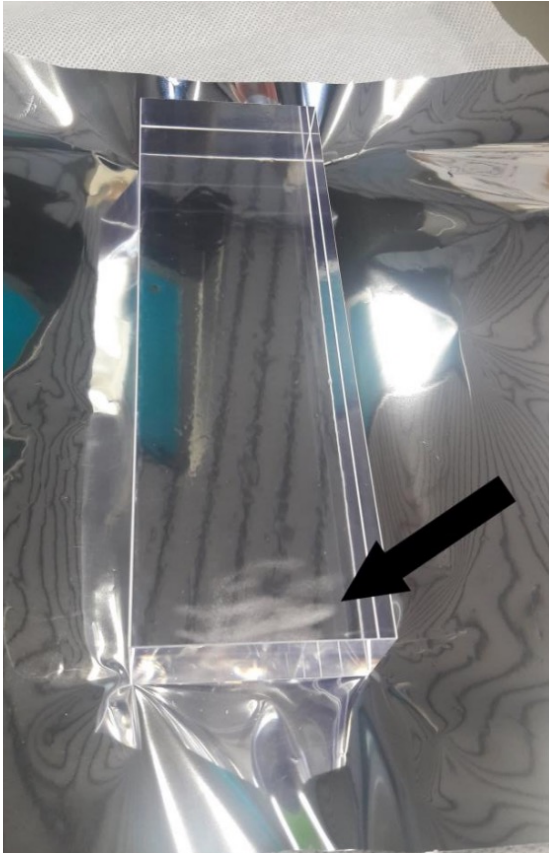
Control and read-out electronics



- **Fully customized for HEPD-02 space application.**
 - Compactness: whole tracker control and read-out in a single board (T-DAQ).
 - Design driven by power consumption limits (3 W budget for T-DAQ).
 - Hot/cold redundancy (i.e. two identical copies of the circuit in the same board) to increase overall reliability during flight.
- Control logics and Microblaze soft processor implemented on Xilinx Artix 7 FPGA.
- 15 CTRL logic modules (one per stave) handle the full ALTAI housekeeping and data acquisition through serial bidirectional line.
 - Tracker segmentation (and superposition of an independent trigger bar to each turret in HEPD-02 layout) allow to read-out a subset of the 5 turrets (or 2 planes only), if required to reduce power or dead time.
- The soft processor implements calibration and service procedures (switched-off most of time to save power).
 - Threshold calibration procedure identifies and excludes dead/noisy pixels.

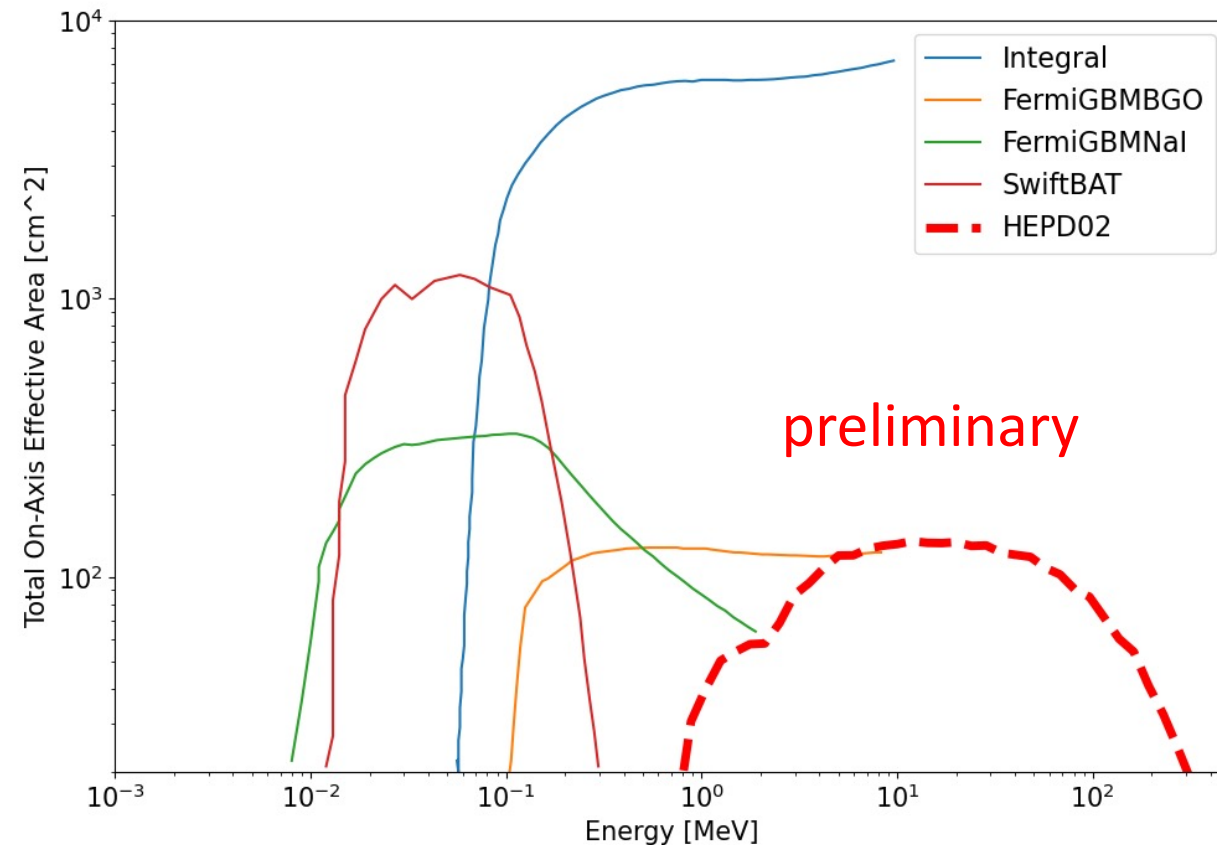


opportunity to detect gammas



- 6x LYSO bars as large as $150 \times 25 \times 50 \text{ mm}^3$
- Excellent opportunity to detect MeV photons

In HEPD-02 all PMTs can be used to define trigger patterns (also LYSO). Using active elements in NOT logic allows to define trigger patterns suitable for gamma-ray acquisition



assessing feasibility