The HEPD detector on board CSES satellite: in-flight performance

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for the CSES-Limadou Collaboration

Outline of the talk:

The China Seismo Electromagnetic Satellite mission
The High Energy Particle Detector
Pre-launch activities
Launch and preliminary results

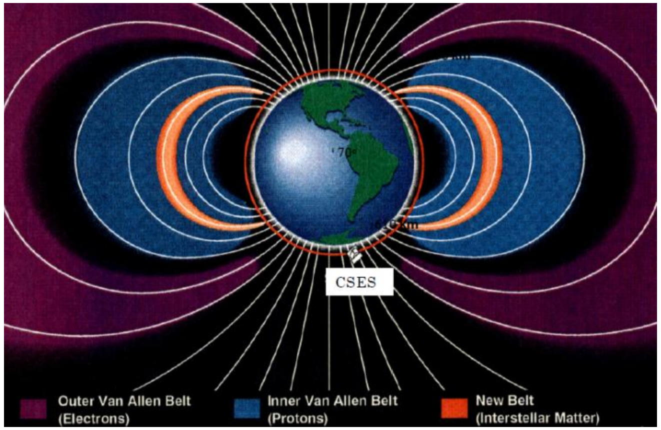
CRIS 2018 - 11th Cosmic Ray International Seminar - Portopalo di Capo Passero (SR) Italy

The CSES experiment

China Seismo-Electromagnetic Satellite

monitoring of earthquake-related electromagnetic field and particles in the ionosphere

This space mission will study seismo-ionospheric perturbations of electromagnetic field, plasma and particles and their correlation with geophysical activity.



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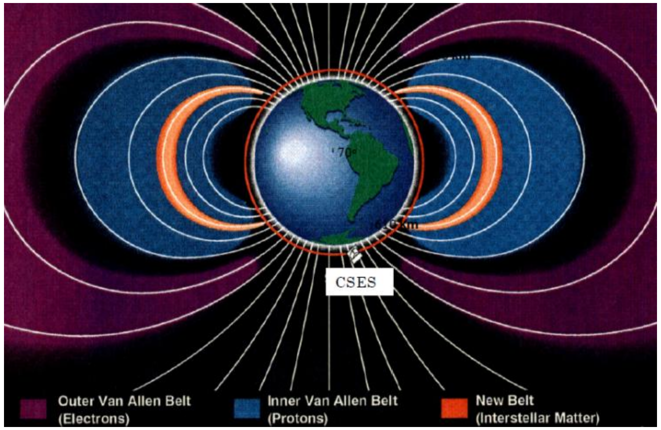
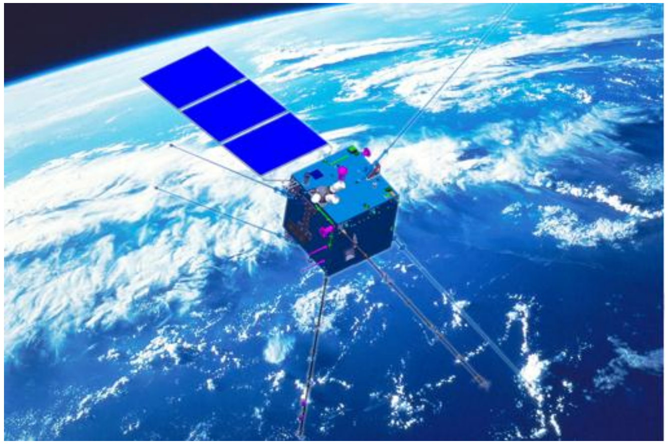
Space is a privileged place for the statistical study of pre-seismic effects: **covering large areas simultaneously**.

The satellite was launched on 2nd February 2018, with an expected lifetime of 5 years. It has a 98° Sun-synchronous circular orbit at 507 km of altitude

Two different orbital working zones:

- *payload operating zone*: instruments will collect measurements (latitude range of ± 65°)
- *platform adjustment zone*: all detectors switched off, satellite attitude and orbit control system activities will be performed





3-axis attitude stabilized satellite
based on CAST2000 platform
Mass = 730 kg
Peak power consumption = 900 W

Project objectives of CSES

SCIENTIFIC

- to study the **ionospheric perturbations** possibly associated with earthquakes
- to explore new approaches for short-term prediction and theoretic studies on the mechanism of earthquake preparation processes
- to measure **Cosmic Ray** in an energy range below the one which has been studied so far by current CR space missions (PAMELA, AMS-02)

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ENGINEERING

- to check the **reliability of the EM satellite earthquake monitoring system** by using new techniques and equipments
- to obtain world-wide data of the EM field, plasma and energetic particles in space environment
- to provide a good basis for a space-ground system in earthquake monitoring in the near future in China

APPLICATION

- to extract EM information associated possibly with the earthquakes of $M_s \geq 6$ in Chinese territory and that of $M_s \geq 7$ in the global scale
- to analyze seismo-ionospheric perturbations in order to test the possibility for **short-term earthquake forecasting** with satellite observation

CSES-Limadou Collaboration

- Collaboration:
  - China National Space Administration (CNSA)
  - Italian Space Agency (ASI)
- Developed by:
  - China Earthquake Administration (CEA)
  - Italian National Institute for Nuclear Physics (INFN)
  - Chinese and Italian Universities

LIMADOU Italian Collaboration for CSES

ASI Italian Space Agency

INFN - Italian National Institute for Nuclear Physics Sections of: Trento (TIPFA), Bologna, Perugia, LNF, Roma Tor Vergata and Naples

Physics Department of Roma Tor Vergata University

Physics Department of Trento University

Physics Department of Bologna University

Uninettuno University, Roma

INAF-IAPS Italian National Institute of Astrophysics and Planetology

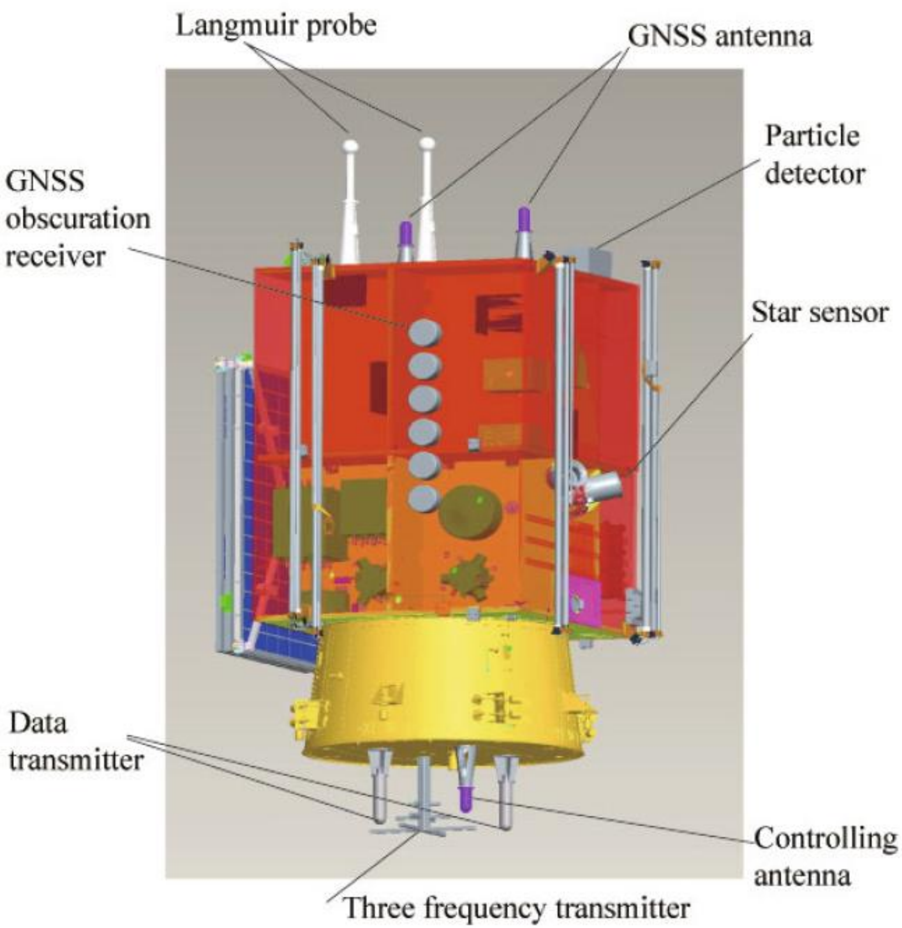
INGV Italian National Institute of Geophysics and Volcanology

IFAC – CNR, Firenze

The Italian Collaboration named the project LIMADOU after the Chinese name of the missionary Matteo Ricci who explored China in the 16th century

Instruments onboard CSES

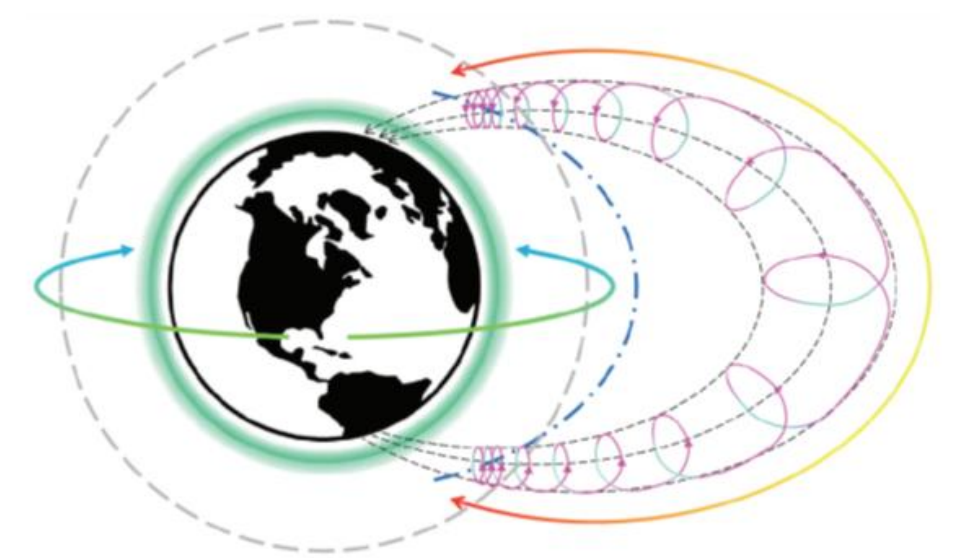
Measurements	Instruments
Electrical and magnetic fields and their perturbations in ionosphere	Search-Coil magnetometer (SCM) Fluxgate magnetometer Electrical field detector (EFD)
Disturbance of plasma in ionosphere	Plasma analizer (PAP) Langmuir probe (LAP)
Flux and energy spectrum of the particles in the radiation belts	High Energy Particle Package (HEPP) High Energy Particle Detector (HEPD)
Profile of electronic content	GPS occultation receiver (GNSS-RO) Tri-frequency transmitter (TBB)



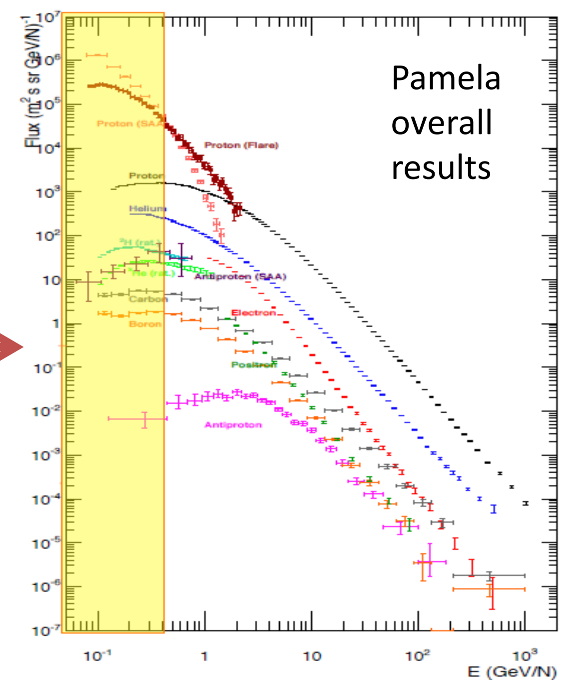
HEPD scientific objectives

The High Energy Particle Detector is aimed at studying:

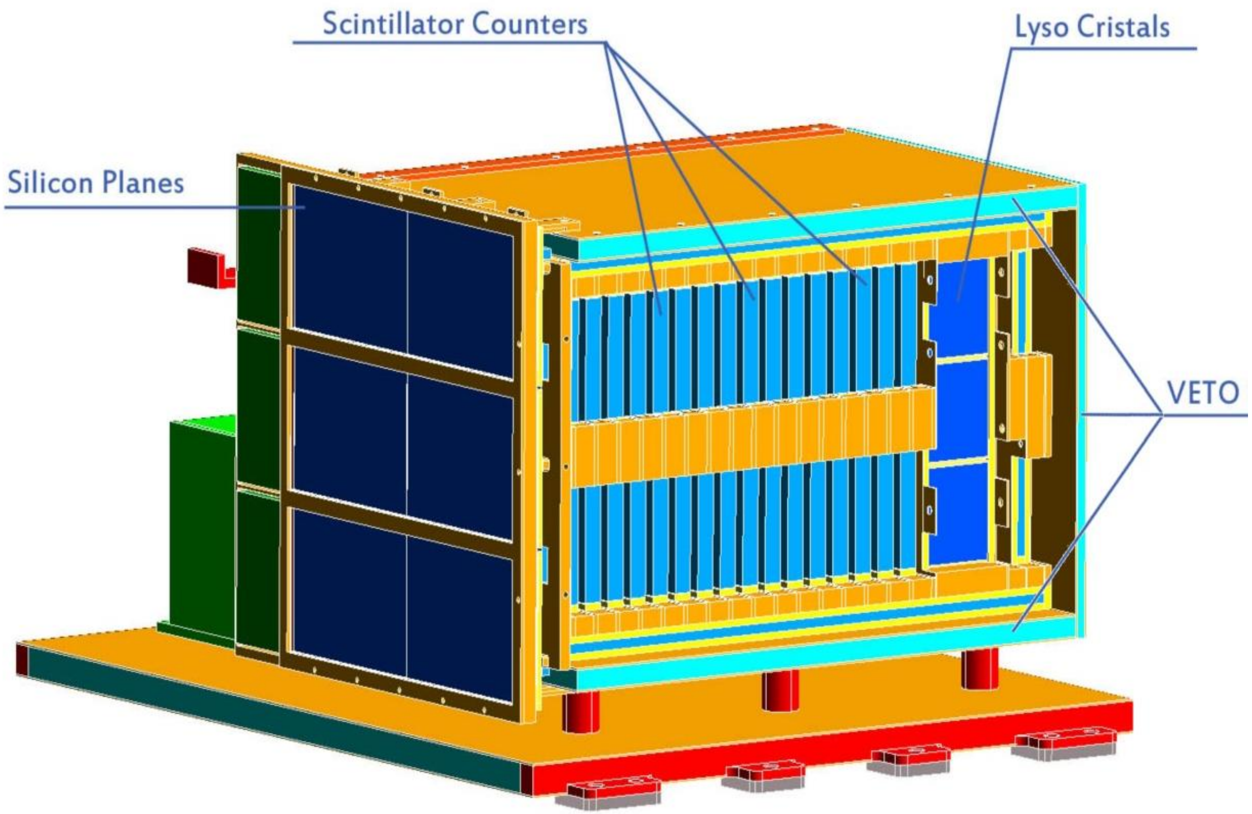
- **seismo-induced perturbations of the inner Van Allen belt** (particle precipitations)
- **composition and energy spectra of galactic and solar particles:** fluxes of p, e–, and light nuclei (He, Li, Be, B, C) up to hundreds MeV/n
- **solar-terrestrial environment** (heliosphere and magnetosphere), fundamental for space weather
  - **solar impulsive activity** (e.g., solar energetic particle (SEP) events)
  - **solar modulation of low-energy cosmic rays**



HEPD energy window

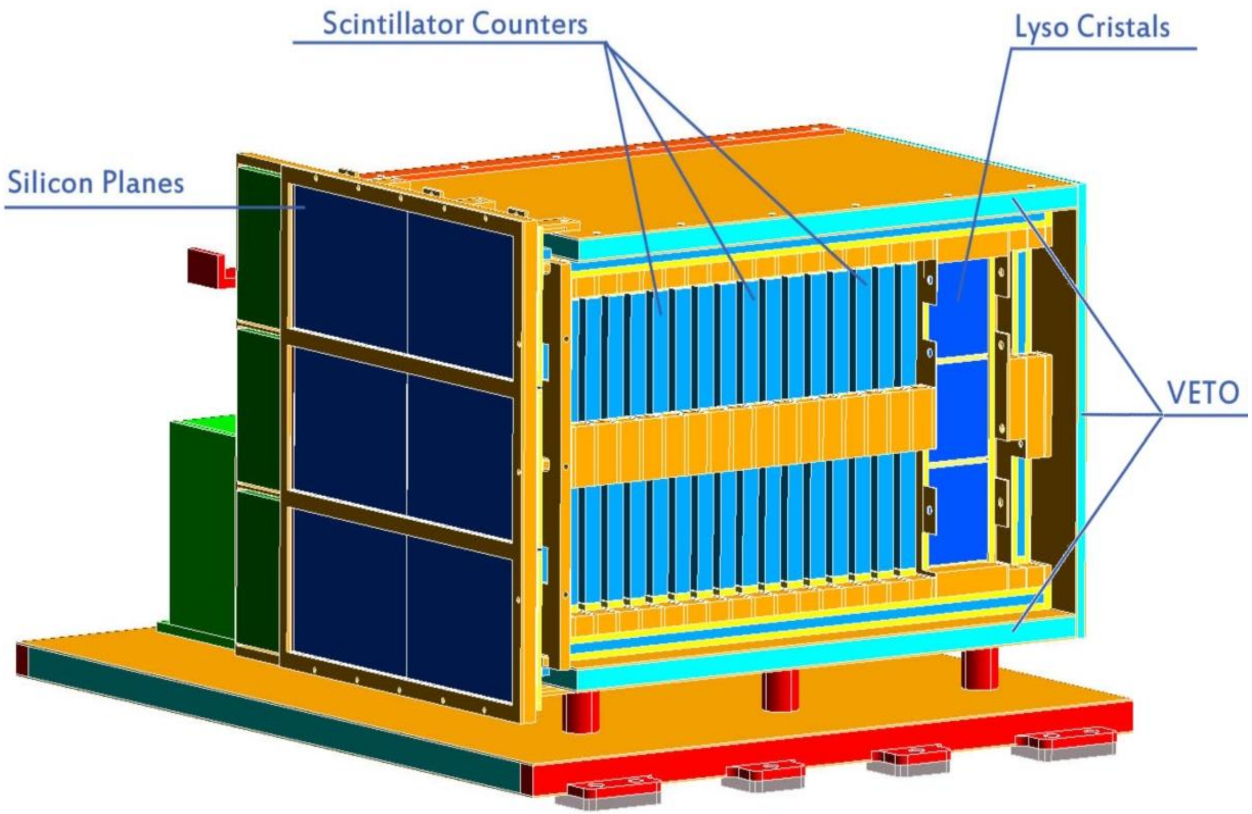


The HEPD detector



Silicon tracker: two planes of double-side **silicon micro-strip detectors** placed on the top of the HEPD in order to provide the direction of the incident particle
(213mm × 213mm x 0.3mm)

The HEPD detector



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(200mm × 30mm × 5mm each)

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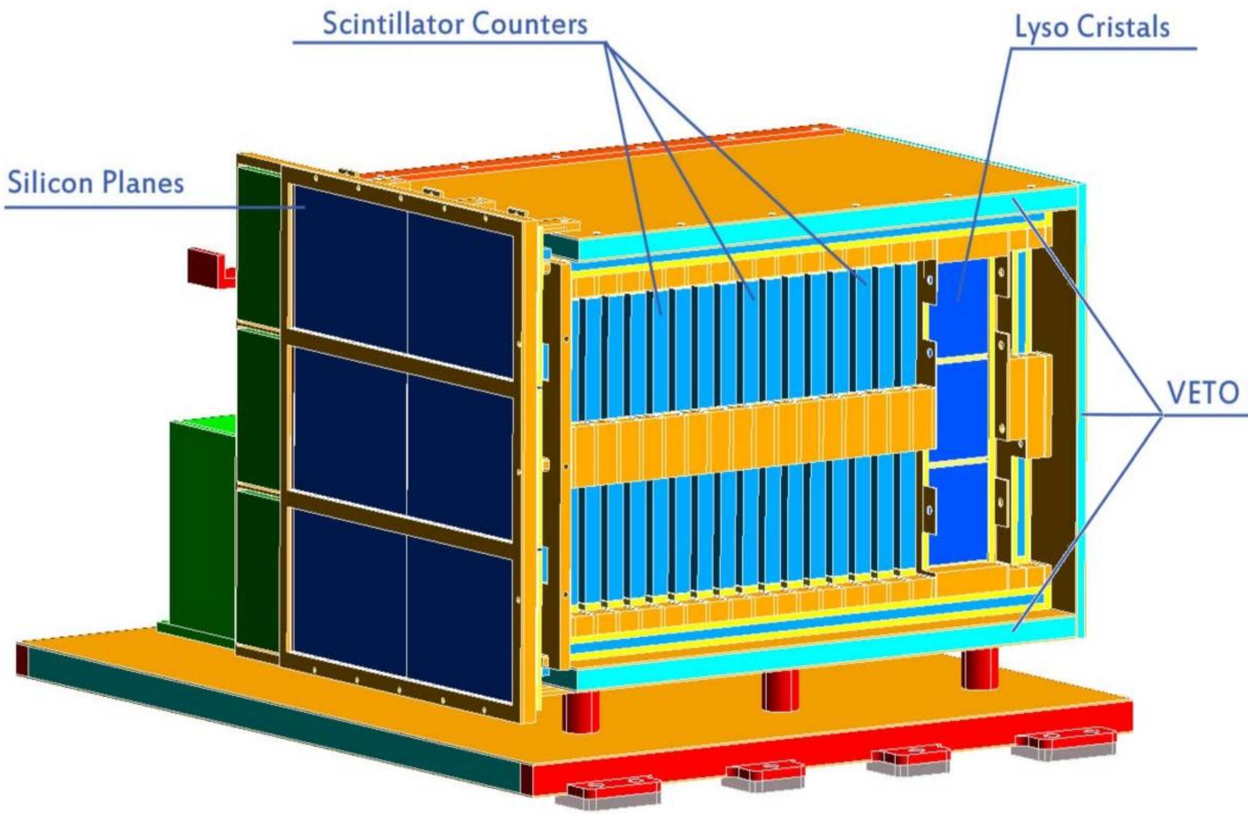

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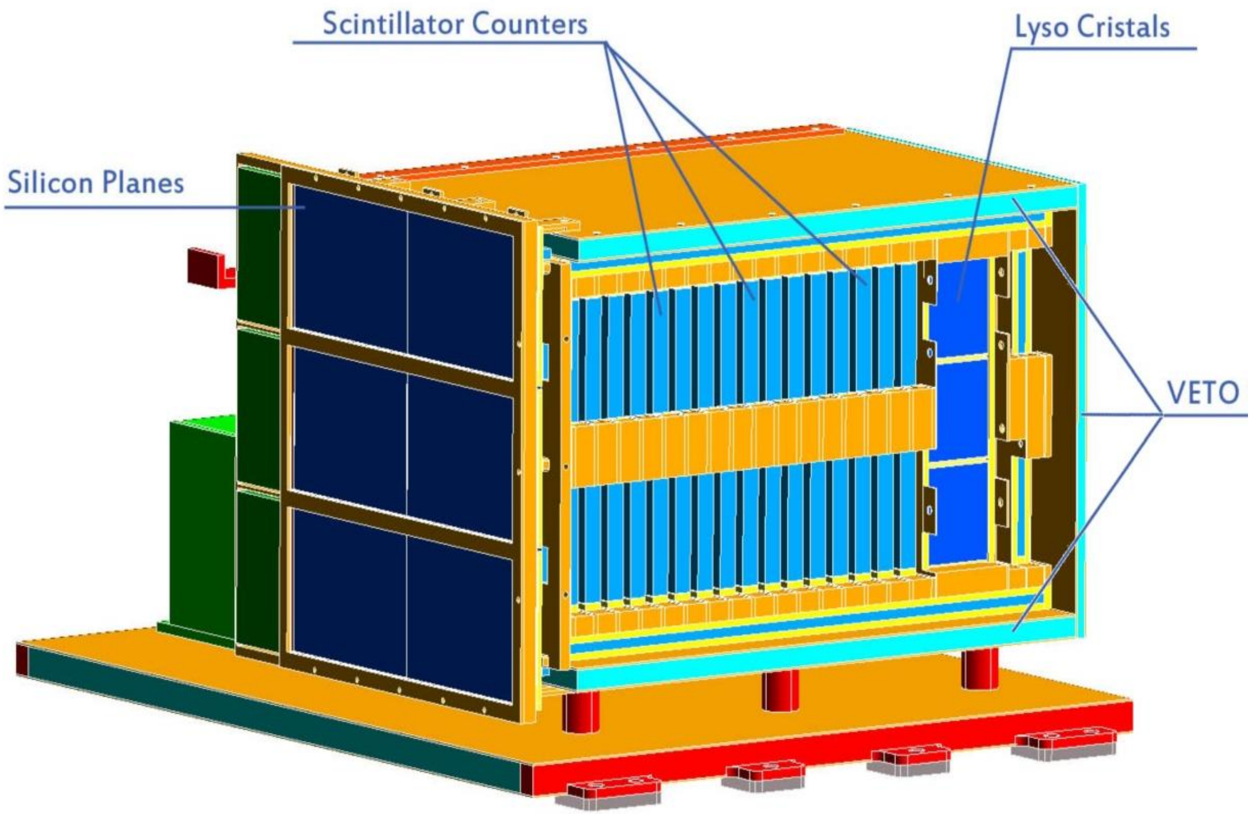
The HEPD detector



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The calorimeter volume is surrounded by 5mm thick plastic scintillator planes: **VETO**

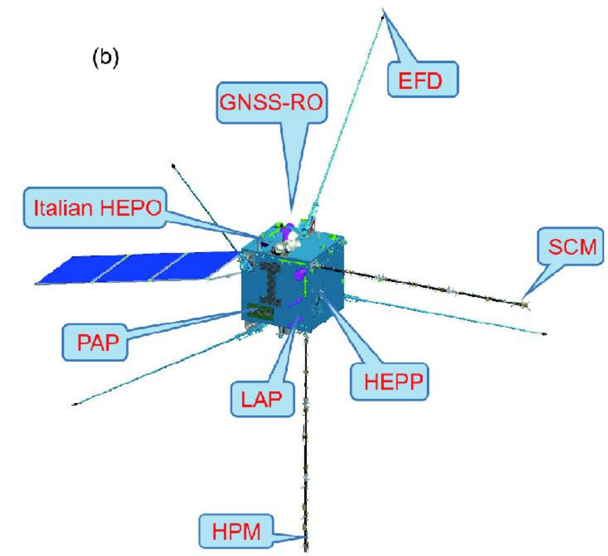
All the scintillator detectors (trigger, calorimeter and VETO) are read out by photomultiplier tubes (PMT R9880-210 from Hamamatsu)

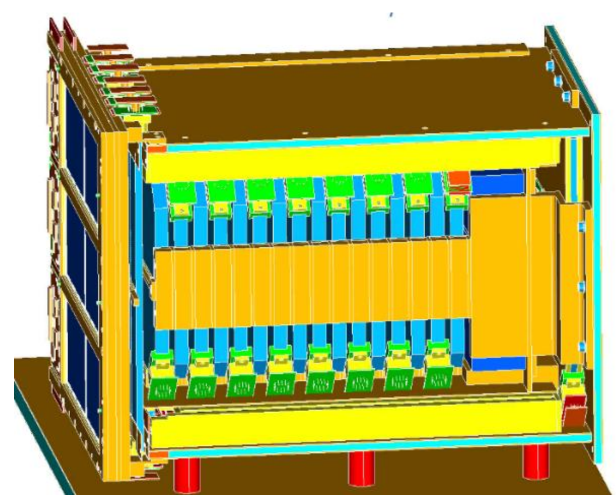
The HEPD main parameters

To reconstruct particle trajectories in Van Allen belts requires **good energy and angular resolution**

- **separate electrons and protons** identifying electrons within a proton background ($10^{-5} \div 10^{-3}$)
- **identify light nuclei**

Parameter	Value
Energy Range	**e: 3 ÷ 100 MeV** **p: 30 ÷ 200 MeV**
Angular resolution	**< 8° @ 5 MeV**
Energy resolution	**< 10% @ 5 MeV**
Particle identification	**> 90%**
Operation mode	Event by event
Scientific Data Bus	RS-422
Operative temperature	-10 ÷ +35°C
Mass	< 44 kg
Power Consumption	< 27 W
Mechanical dimensions	$53 \times 38 \times 40$ cm^3

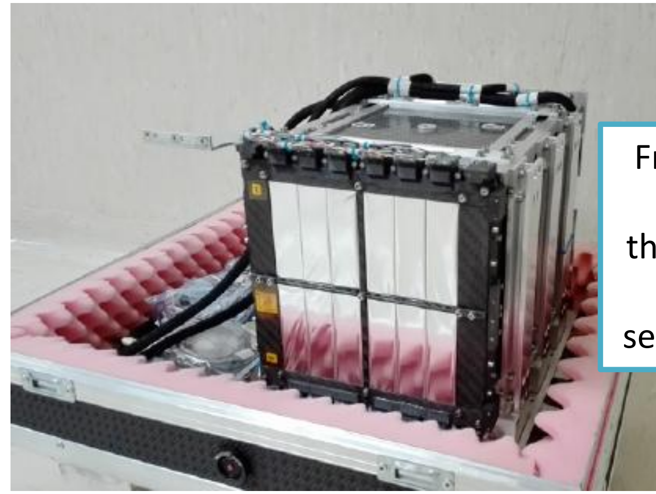




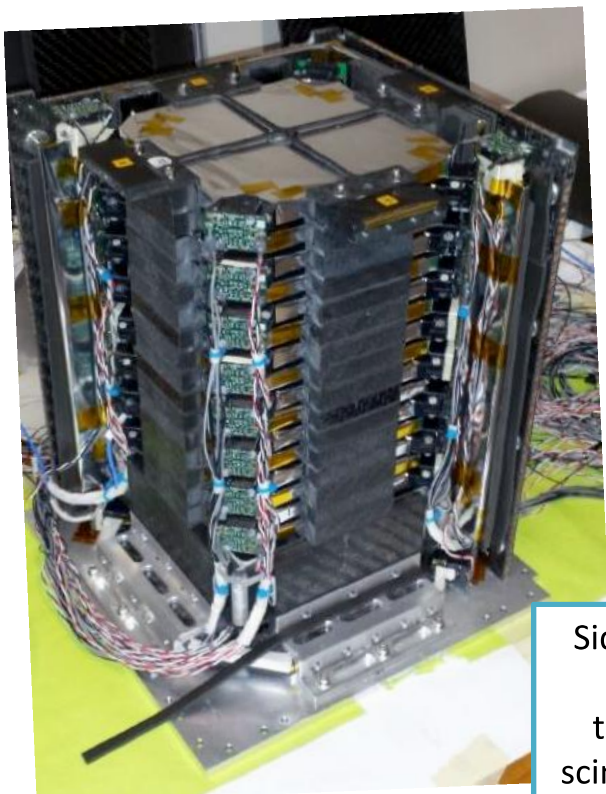
The HEPD models

4 HEPD versions produced:

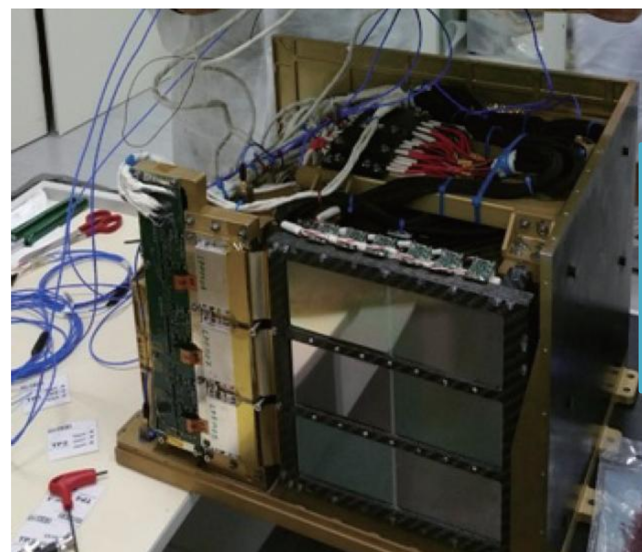
- Electrical Model, EM (2014)
- Structural and Thermal Model, STM (2015)
- Qualification Model, QM (2016)
- Flight Model, FM (2016)



Front view of the HEPD-QM: the trigger system with its six segments is visible



Side view of the HEPD-QM: the 16 plastic scintillator planes can be seen

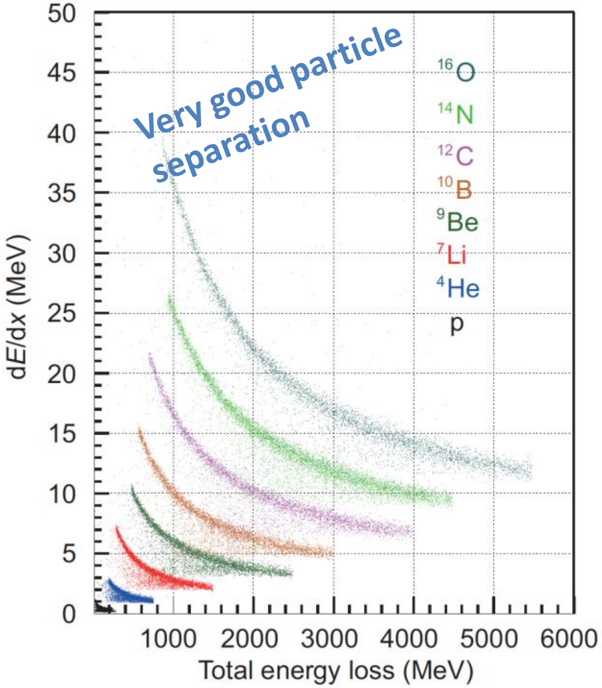


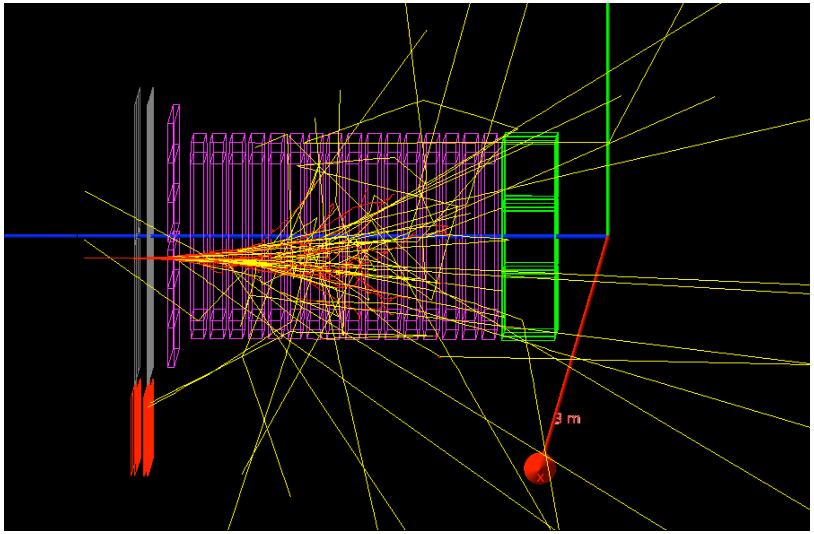
Front view of the HEPD-FM: the Silicon detector and its electronics


Pre-launch activities

MC simulation

A full GEANT4 simulation of the apparatus was performed, accounting for detector response to all particles and reproducing readout electronics and trigger conditions.

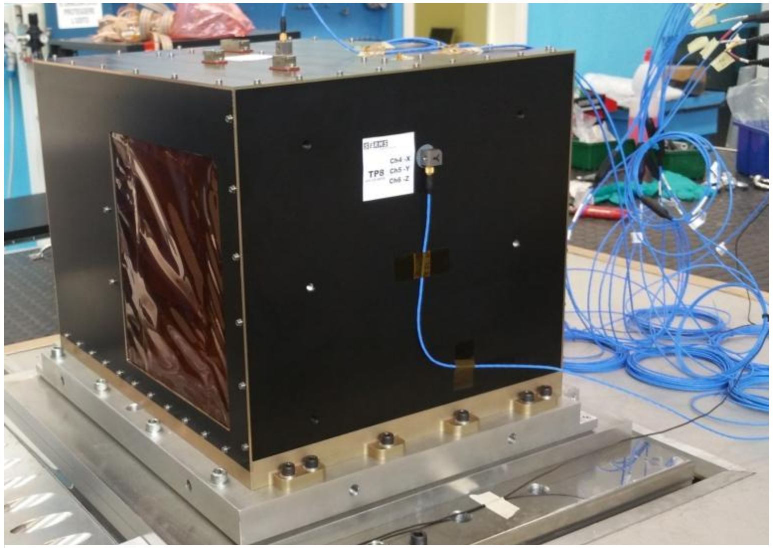




GEANT4 simulation of a 25 MeV electron entering the HEPD from the left.

Monte Carlo output and real data have the same format and the same software is used to reconstruct the event in both cases, allowing a fair comparison of reconstructed parameters and Monte Carlo truth.

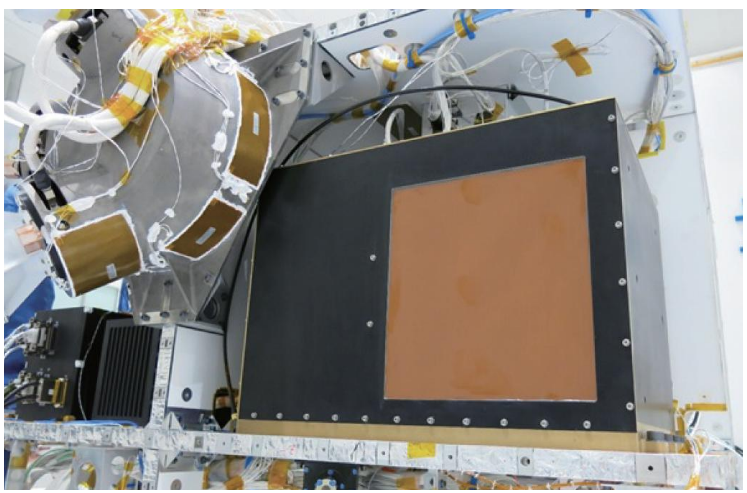
Qualification campaign



The QM during vibration test at SERMS.
The detector is housed within the black box.

Spring 2016: start of test and qualification campaign with the HEPD Qualification Model

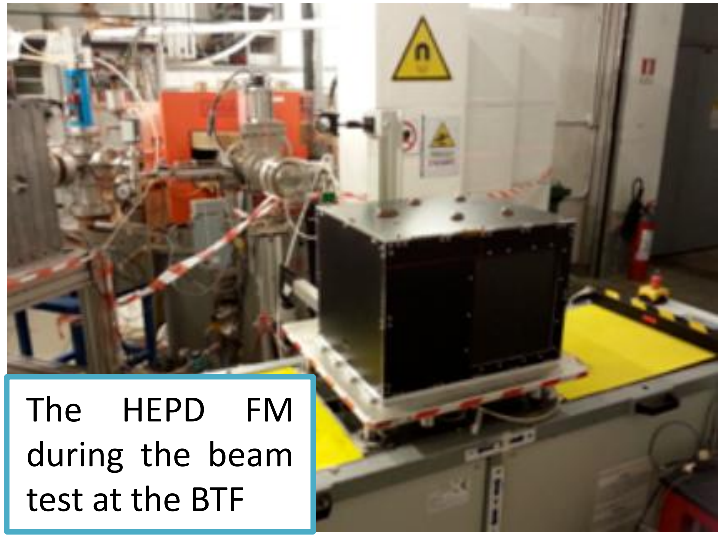
Vibration test at SERMS laboratory in Terni (PG) simulating launch and flight
Thermal and vacuum test at SERMS laboratory simulating space environment



The HEPD-FM installed on CSES satellite

January 2017: the HEPD Flight Model was installed on the CSES satellites.
Vibration, thermal-vacuum, magnetic cleanliness and aging tests were accomplished (Feb-May 2017)

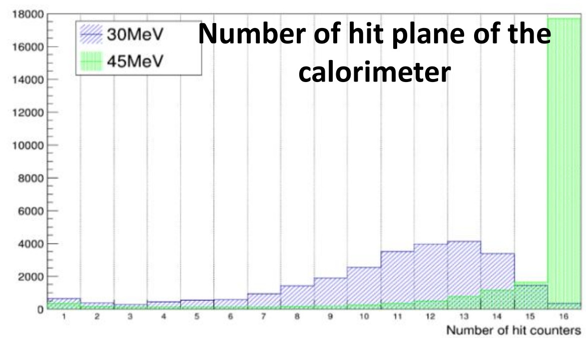
Calibration with electrons

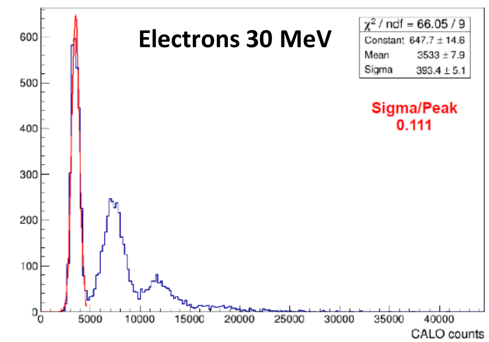


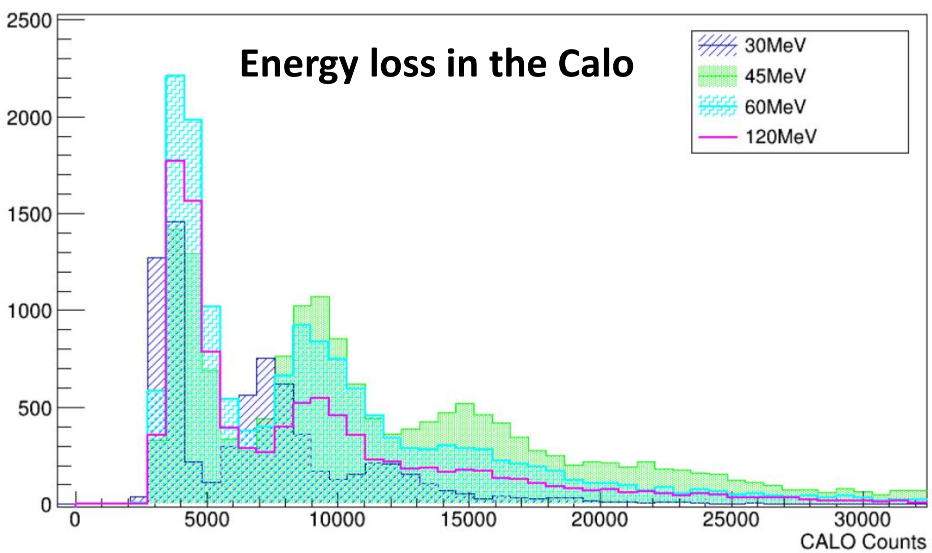
The HEPD FM during the beam test at the BTF

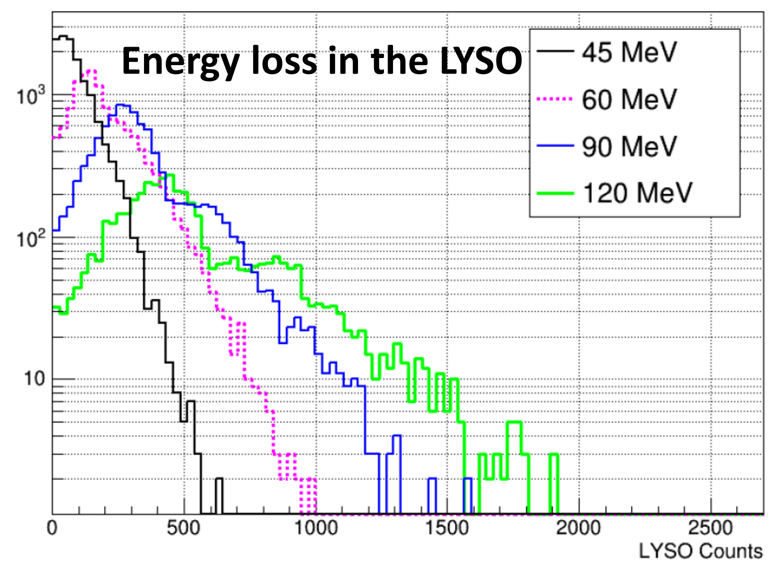
Beam Test @ Frascati BTF

Electrons and positrons from 30 to 150 MeV





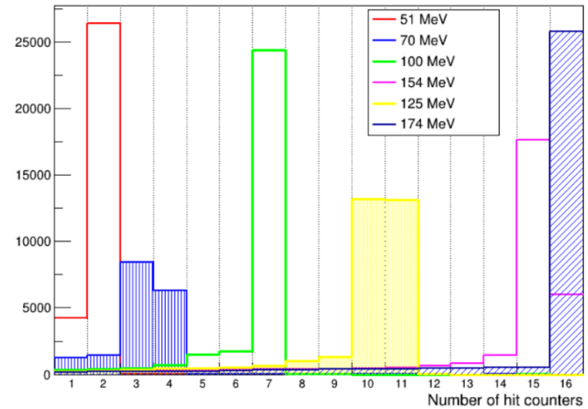




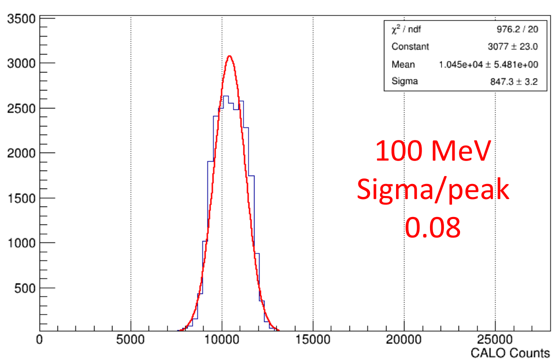
Calibration with protons

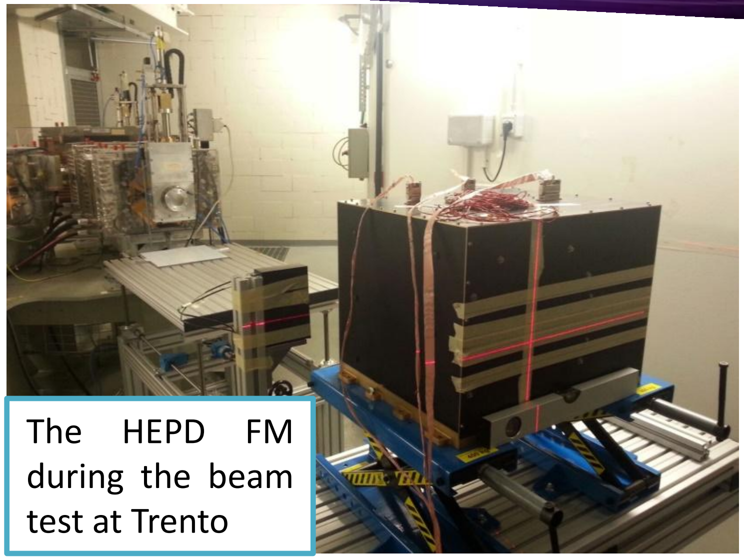
Beam test @ Proton Cyclotron of Trento
Protons from 51 to 300 MeV

Number of hit Calo planes

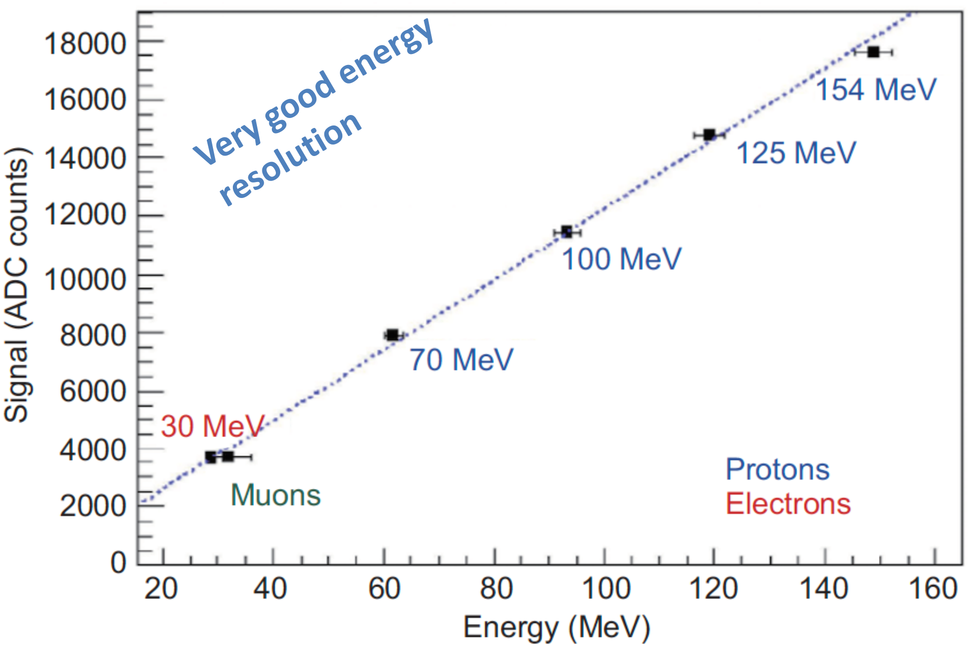


Energy loss in the Calo





The HEPD FM during the beam test at Trento



Launch and preliminary results

The launch

On February 2nd 2018 at 3:15 pm (Beijing time, GMT+8) the CSES Satellite was successfully launched from Chinese base "Jiuquan Satellite Launch Center", located in the Gobi desert in Inner Mongolia.

HEPD operation

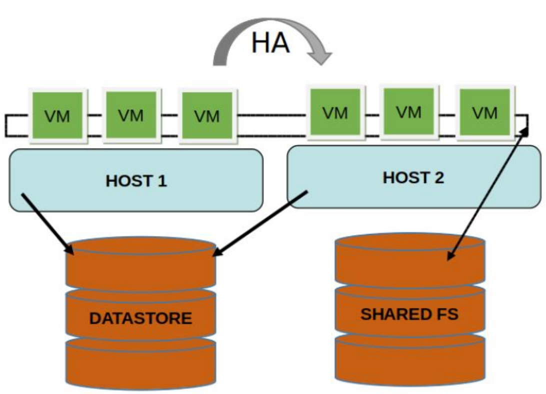
On February 6th, the HEPD **health check procedure** was successfully run.
Since February 12th, HEPD has been tested in **different configurations** in order to:

- study the **trigger rates** along the orbit in different trigger configurations;
- study to define the **optimal trigger thresholds** in flight;
- perform an **in-flight calibration** to be compared with beam test results;

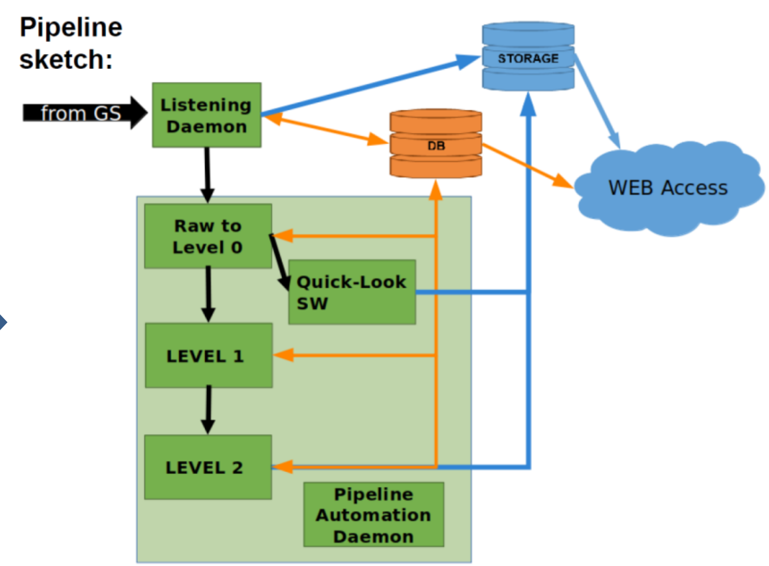
CSES **commissioning** activities will last until the end of July 2018

- Since the beginning of May an encrypted data transfer from CEA-ICS to ASI-SSDC has been working
- Till now HEPD has produced ~350 GB of data
- Construction of a dedicated pipeline for the HEPD data processing and storage is in progress (pipeline: satellite → raw file → L0 → L1 → L2)

Chinese Ground Segment



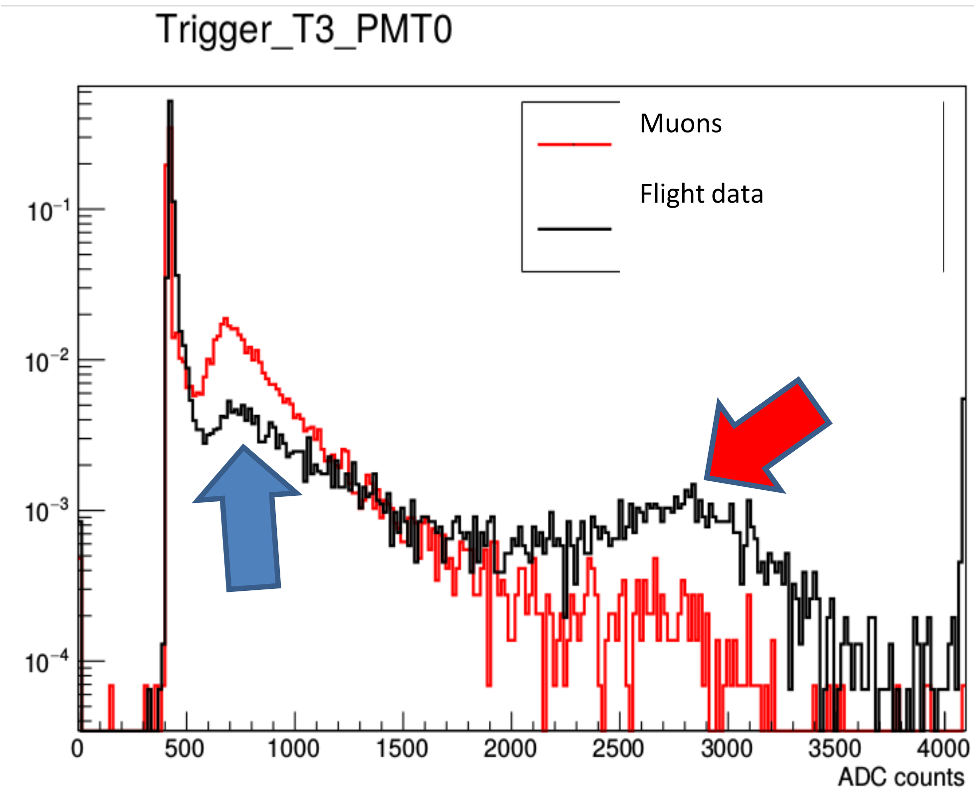
Italian Ground segment



HEPD preliminary results

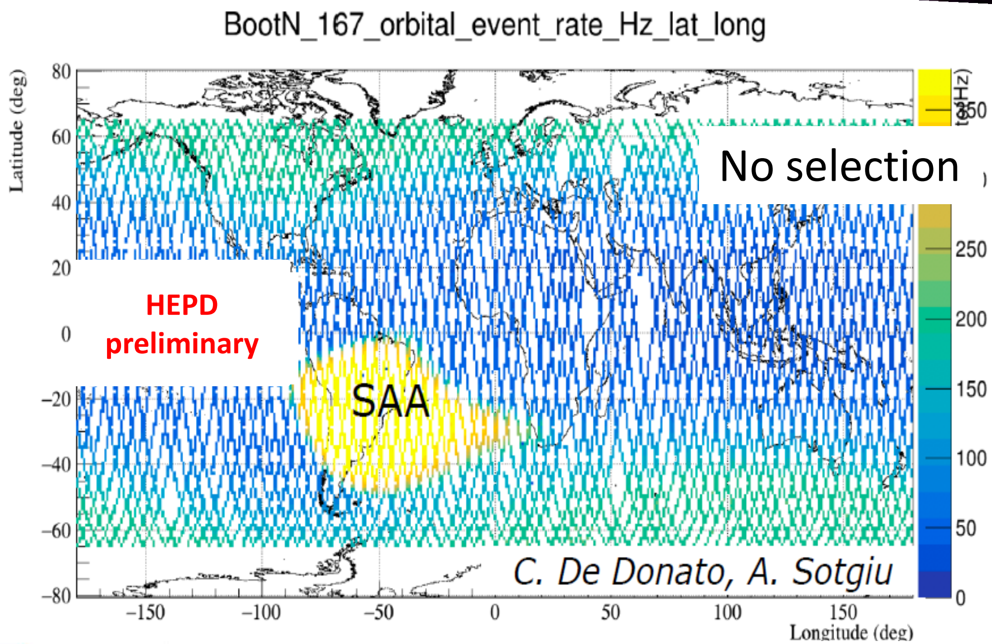
HEPD status monitoring in quasi-real time by quicklook software (executed from L0 format) to get immediate information about strips and PMTs ADC counts and trigger rate in different orbital zones.

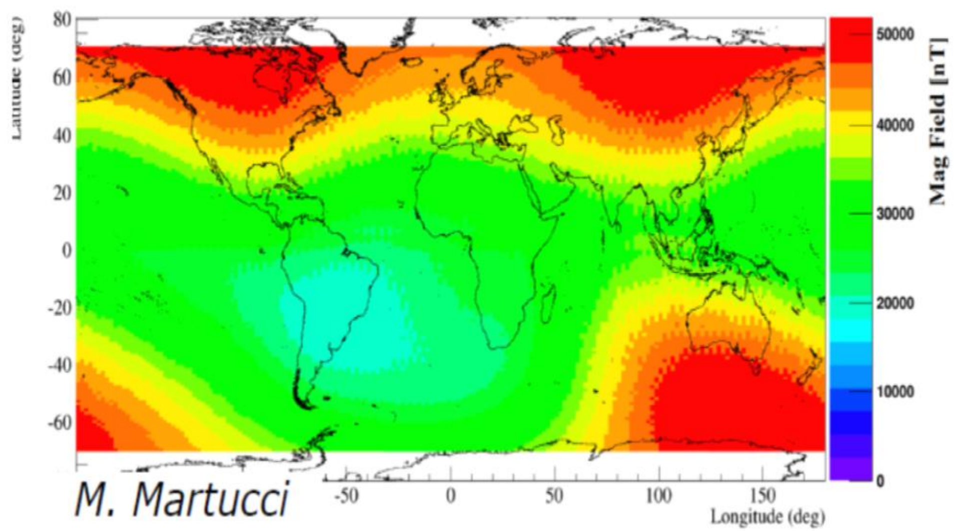
A comparison with atmospheric muon data confirms that pedestals, as well as the MIP peak, are in the same position, confirming the same behavior of the detector after the launch.
The highest **electron peak** at 600 counts and the **proton peak** at 2800 counts are visible.



Trigger rates

During the commissioning we performed a trigger threshold scan to optimize the detector acceptance

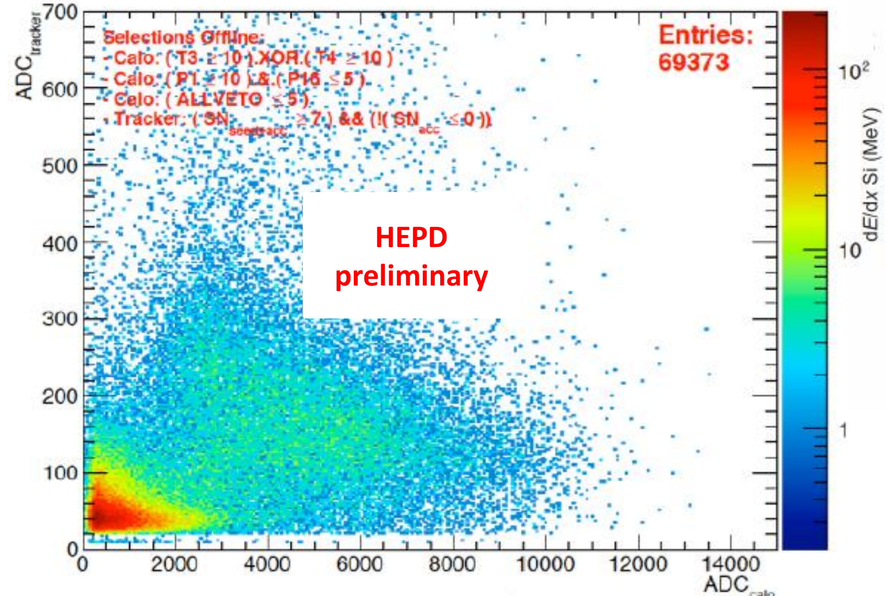




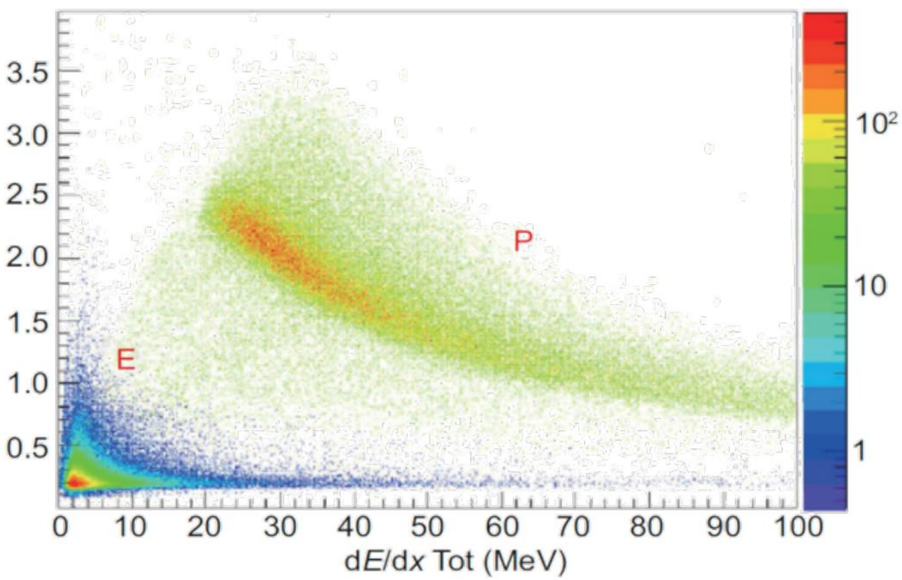
Raw trigger rate map compared with IGRF-computed field in CSES positions calculated from telemetry data

Particle identification

Particle identification analysis is still ongoing. Background contribution has to be accounted to obtain a proper separation between particle species

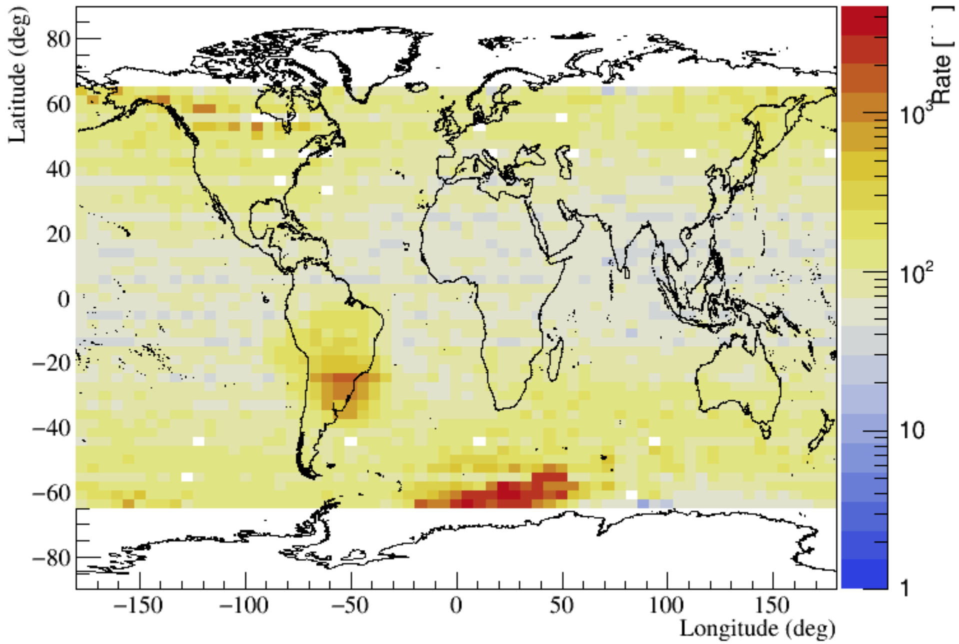


L. Carfora, F. M. Follega



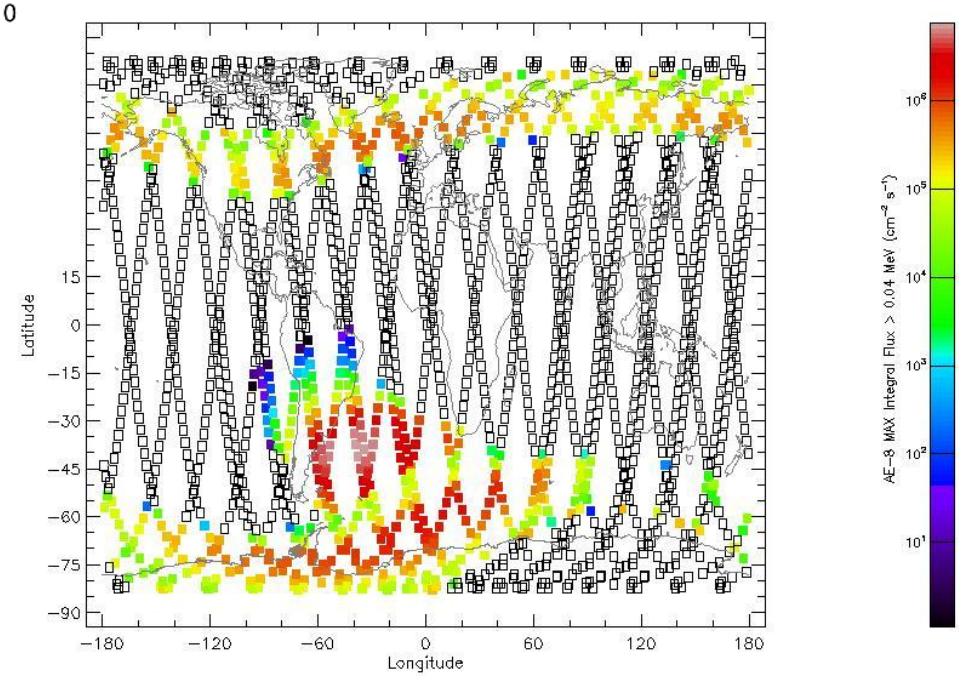
Preliminary results show that particle identification is compatible with expectations from simulation (where no satellite background is accounted for)

Particle rates



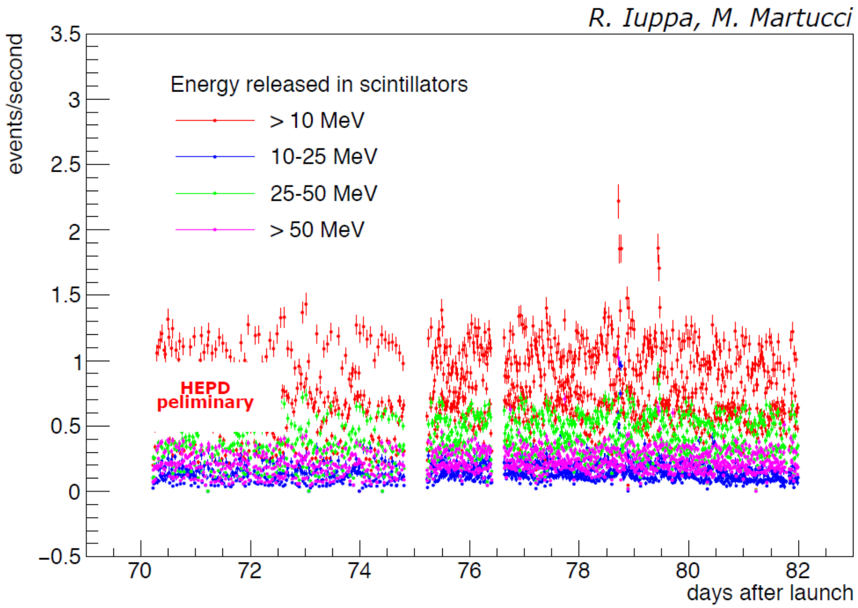
Preliminary reconstructed electron rate as a function of latitude and longitude (30th March – 30th April)

Preliminary work on electron rate reconstruction



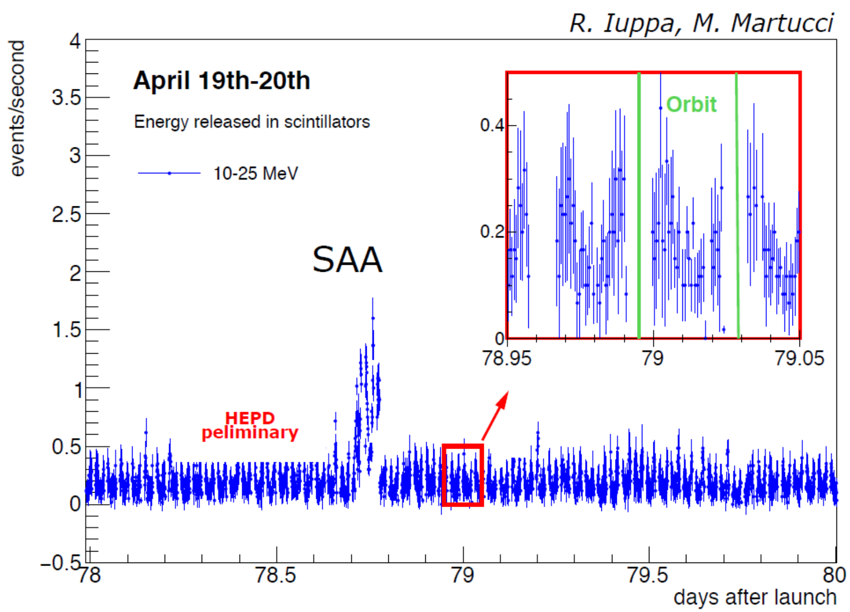
Electron flux (SPENVIS AE-8 MAX integral flux)

Electron rates



Electron acquisition rate (tight selection) as a function of time (10 minutes bin). Different periods of data taking appear, due to changes of configurations during commissioning. **Energy intervals well resolved.**

Sensitivity to variation of the electron flux



Electron acquisition rate (tight selection) on April 19th-20th (1 minute bin). **HEPD large area allows to be sensitive to percent level electron flux variation on time scales as short as few seconds.**

Summary

- The Limadou collaboration conceived, designed, constructed, qualified and is currently operating the High Energy Particle Detector.
- Huge testing work on HEPD preceded the launch, including beam tests and comparison with a Monte Carlo simulation developed on purpose.
- As the other CSES payloads, HEPD is still under commissioning but it is in good shape, providing good quality data and confirming expectations.

Outlook

- CSES satellite is the first of a constellation of “CSES-like” satellites expected to be launched in the coming years.
- The launch of CSES-2 is planned for the 2021
- The role of the Italian collaboration in CSES-2 could be bigger than in CSES-1
  - Improved version of HEPD (Lyso or BGO crystals used to measure gamma rays burst)
  - Electric Field Detector
- CSES follow up activity in Italy:

  Zirè experiment proposed as payload on NUSES mission

  “Zirè will perform characterization the coupling among Lithosphere-atmosphere-ionosphere-magnetosphere through the study of cosmic rays in the energy interval 1 MeV < E < 100 MeV”.

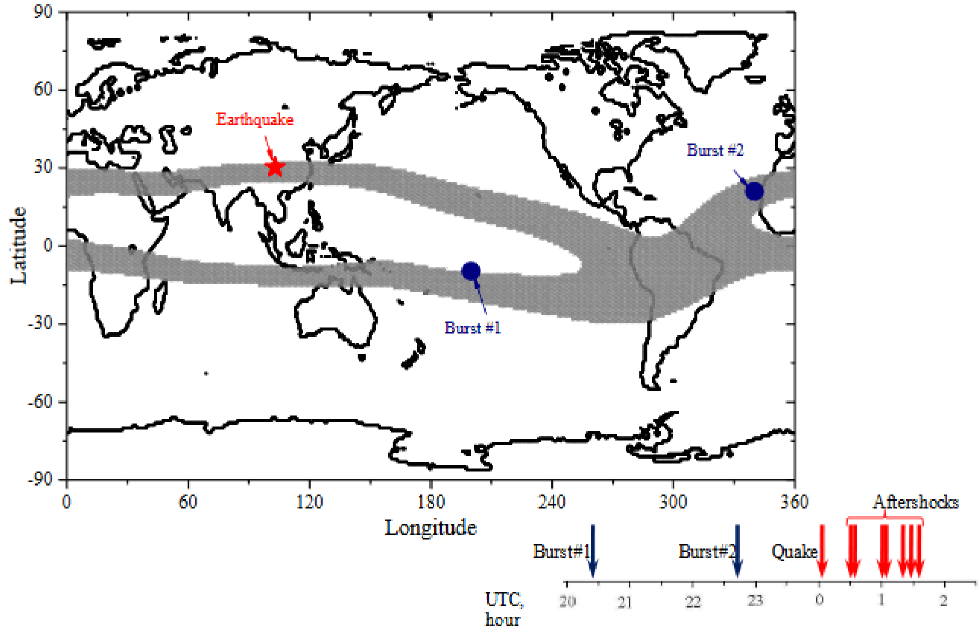
  NUSES is a mission proposed by (GSSI-INFN-FBK, industrial partner TAS-I) and approved by the Italian government as a flagship initiative to relaunch the economy of the L’Aquila area

  Time to fly 3-4 years since the final decision on funding will be taken (end of July)


Thank you!

Earthquake monitor

ARINA satellite experiment 2013



R. Battiston and V. Vitale 2013

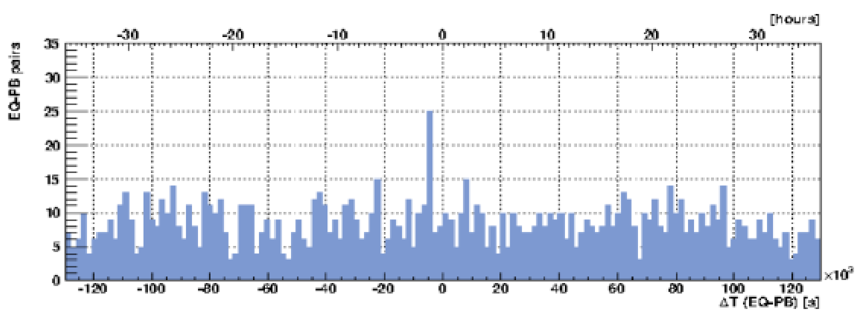
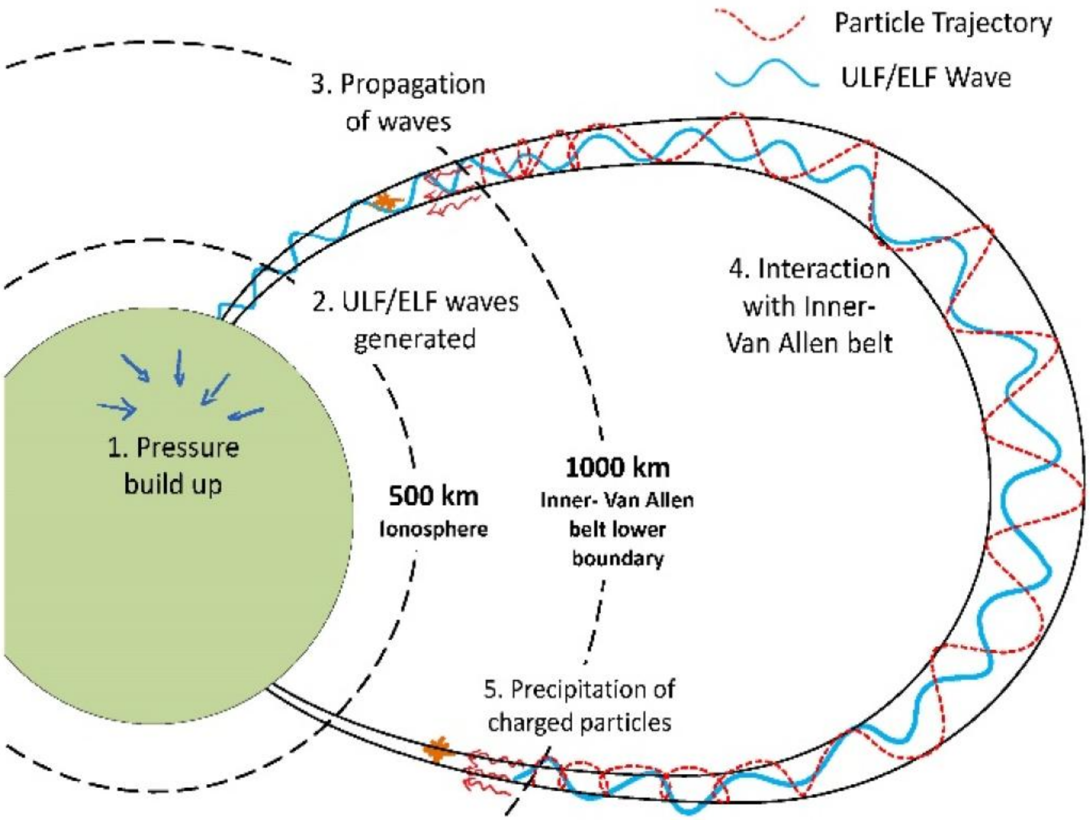


Figure 3: The Time Difference Distribution. Here the time delays between the seismic events and the selected particle bursts are ploted. EQ-PB pairs are taken within a time window of ±1.5 days. This distribution is uniform within the statistical errors but with an excess at -1.25±0.25 hours.

- ✓ The first statistically convincing evidence for the existence of a detectable coupling mechanism between the lithosphere and the magnetosphere having well defined time characteristics.

Physics of CSES



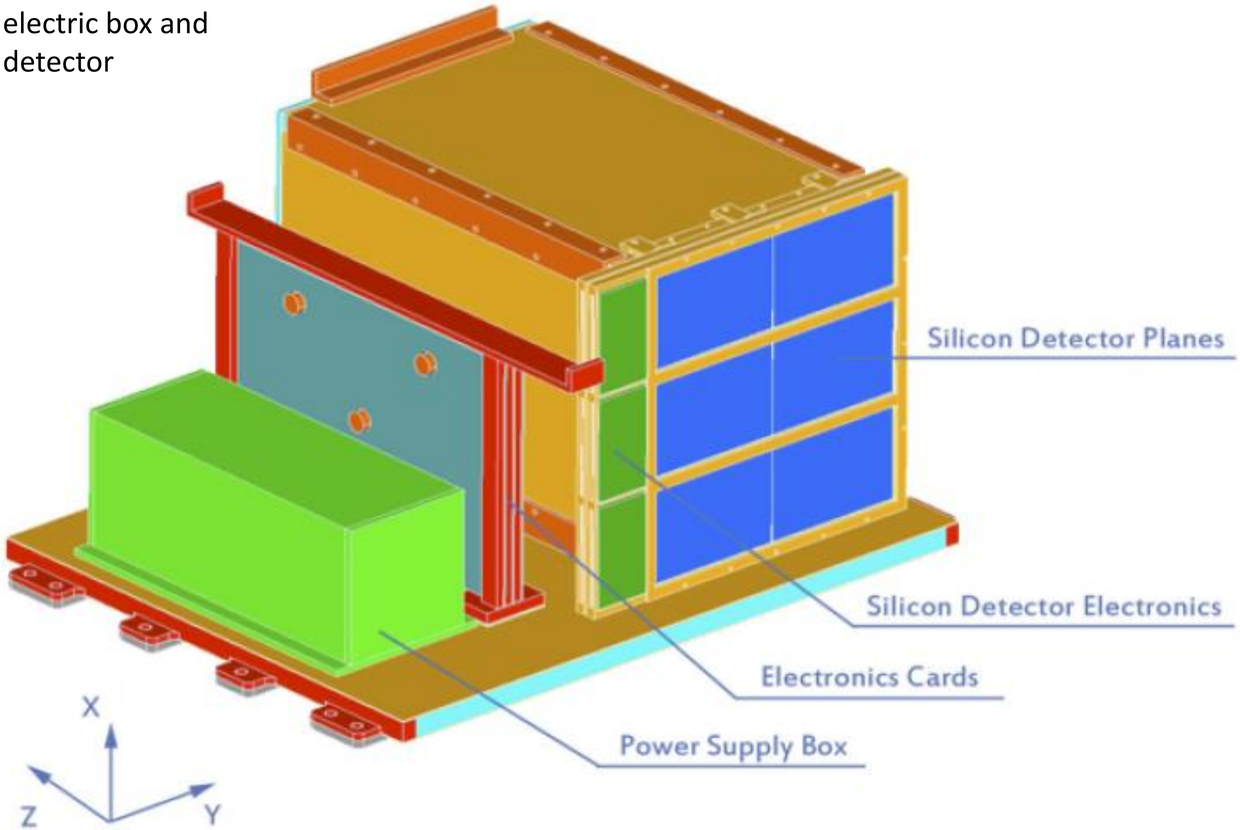
Among the possible anomalies generated by a seismic event, **bursts of Van Allen belt electron fluxes in the magnetosphere** have been repeatedly reported in literature by various experiments, though a statistical significance was always difficult to claim [1, 2, 3]. A recent study [4] presented a new search for correlation between the precipitation of low energy electrons (E > 0.3 MeV) trapped within the Van Allen Belts and earthquakes with magnitude above 5 Richter scale [13 years of electron data measured by the NOAA POES satellites corresponding to about 18 thousands M>5 earthquakes registered in the NEIC catalog of the U.S. Geological Survey]

A correlation peak with significance of 5.7 standard deviations has been found.

[1] X. Shen et al, Earthq Sci (2011) 24: 639A ¸S650.
[2] X. Zhang et al, Nat. Hazards Earth Syst. Sci., 13, 197 ¸S209, 2013
[3] V. Sgrigna, , et al 2005, Journal of Atmospheric and Solar-Terrestrial Physics, 67 1448S.
[4] S. Y. Alexandrin et al 2003, Annales Geophysicae 21, 597.

Physics of HEPD

View of the HEPD electric box and detector



The HEPD will study the temporal stability of the inner Van Allen radiation belts, investigating precipitation of trapped particles induced by magnetospheric, ionosferic and tropospheric EM emissions, as well as by seimo-electromagnetic disturbances. The HEPD scientific scope, besides monitoring the precipitation of trapped particles in the magnetospere, is studying the low energy component of cosmic rays.

CSES/Limadou will repeat the measurements of the two WIZARD/NINA missions (similar orbit, same energy window), which flew over the years 1998 – 2003, in a different period of the solar cycle, and will complement the cosmic ray measurements of PAMELA and AMS-02 at low energy. For its specific nature, CSES will be a powerful instrument for the Space Weather in the incoming solar cycle.

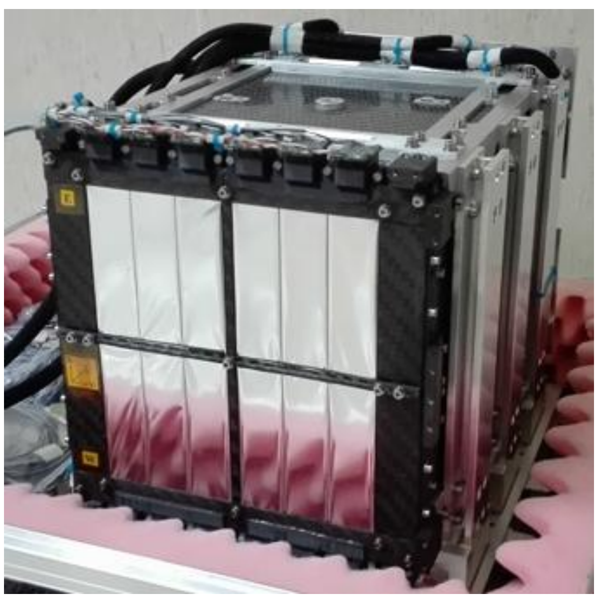
The HEPD electronics

The electronics can be divided in three blocks:

1. **Tracker**
2. **Scintillator detectors**
3. **Global control and data managing**

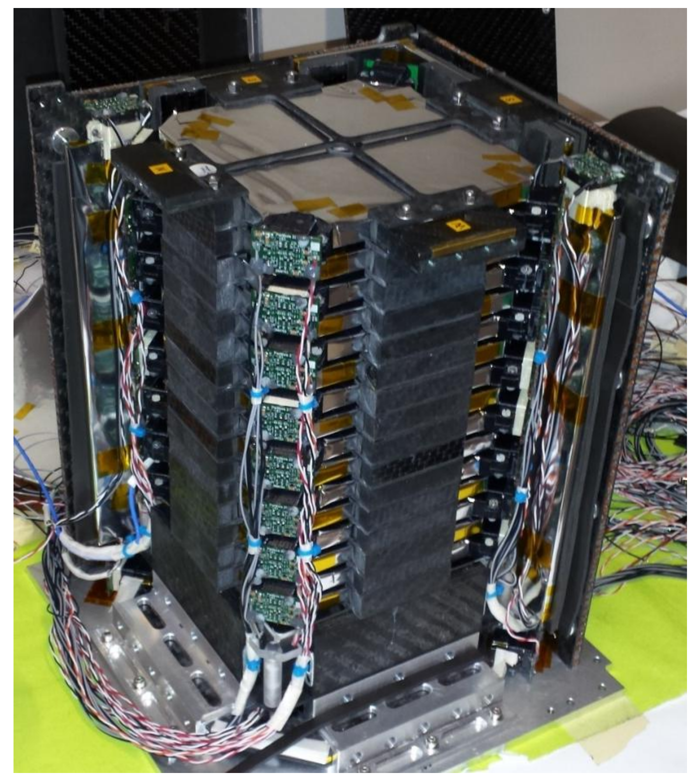
Each block includes power chain for bias distribution and a data acquisition and processing chain. The main power supply provides the low voltages to the detector electronics and the high voltages to PMTs and silicon modules.

- embedded "Hot/Cold" redundancy
- -40°C to +85°C operating range
- max data transfer rate from satellite = 50 GB per day

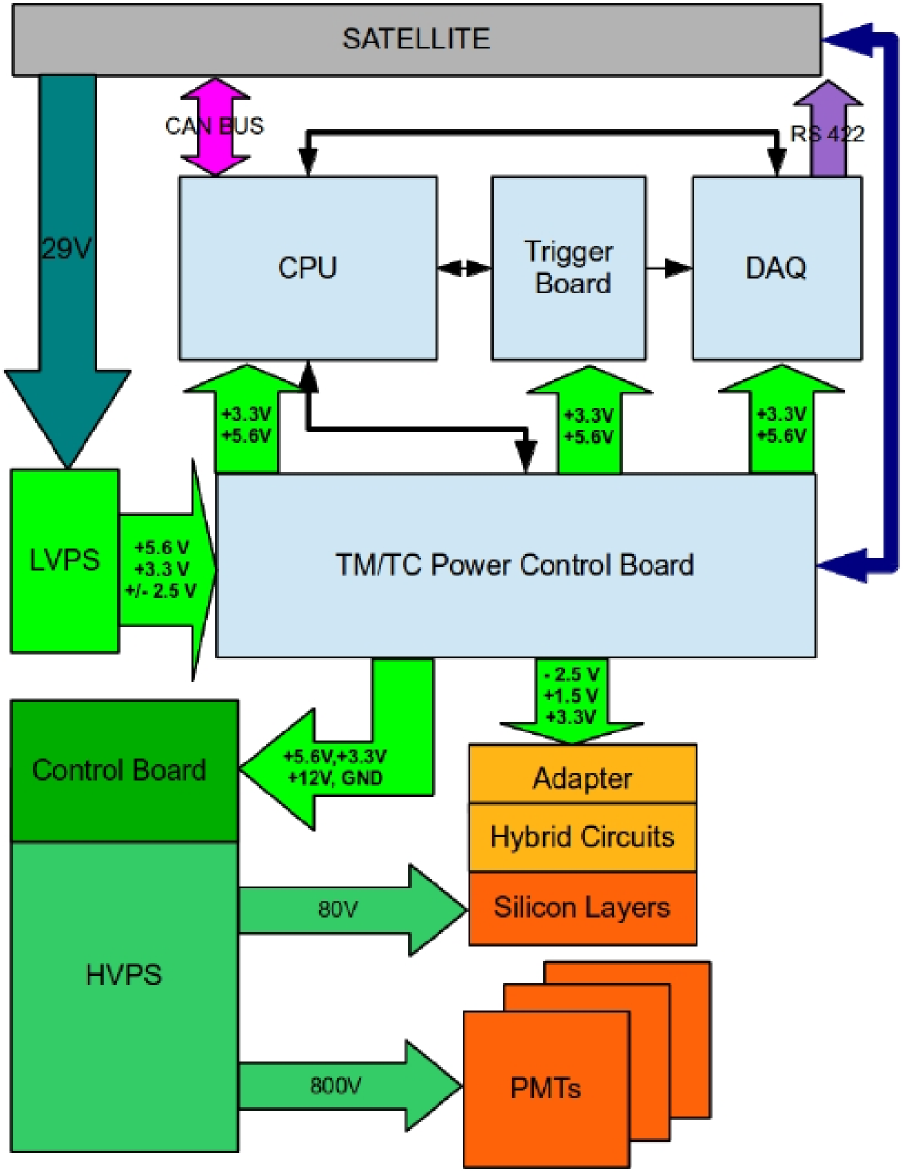


Front view of the QM: the trigger system with its six segments is visible.

Side view of the QM calorimeter which shows the plastic scintillator planes. The PMTs are at the corners of each calorimeter plane.

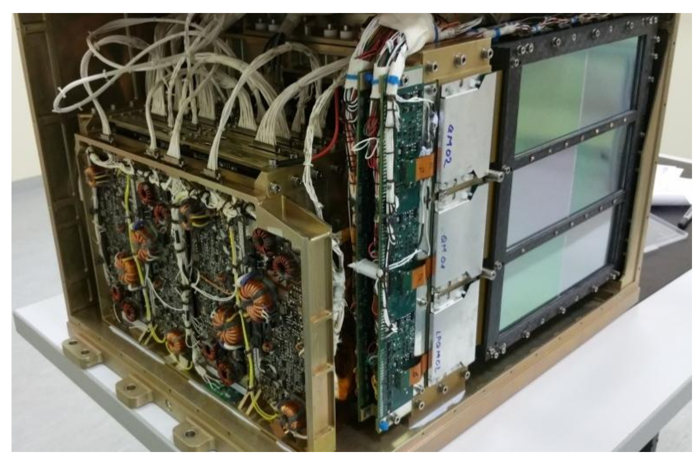


The electronics components



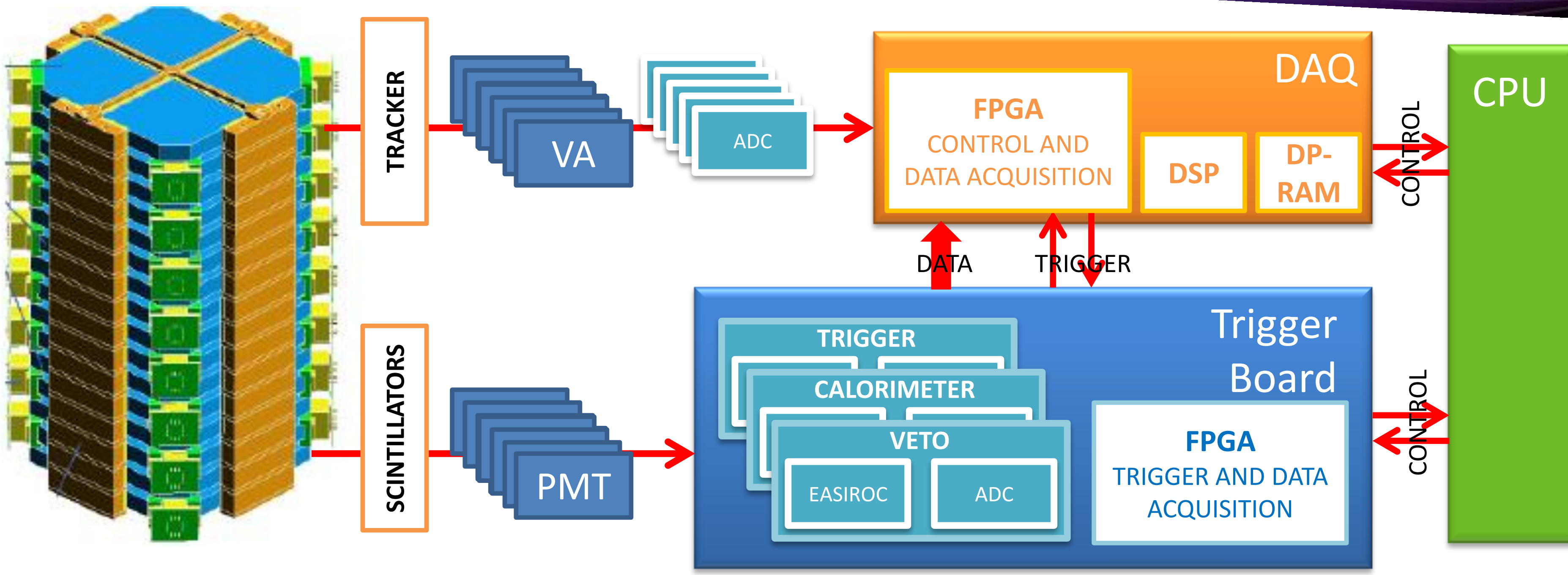
The system is composed by front-end electronics and **four main boards**:

- **Data Acquisition (DAQ)** : manages all the scientific data of the HEPD
- **Trigger Board**: manages the analog signals coming from the PMTs and generates trigger signals needed for data acquisition
- **CPU**: controls the detector and communicates with the platform of the satellite via CAN BUS interface
- **Telemetry/Telecommand (TM/TC) Board**



The electronics and the silicon detector

The electronics working principle



1. The analogical signal read out from the PMTs associated to scintillator detectors are transmitted directly to the Trigger Board.
2. Signals of each data processing block related to scintillators are managed by an FPGA which issues the FAST trigger signal needed to start the acquisition of the Tracker by DAQ.
3. After an handshake protocol, if the trigger is confirmed by DAQ, the Trigger Board sends Scintillators data to DAQ Board .
4. Scintillators and Tracker data are processed by a dedicated DSP and the results are written on a DP-RAM waiting to be transferred to satellite via RS-422 on a CPU command.