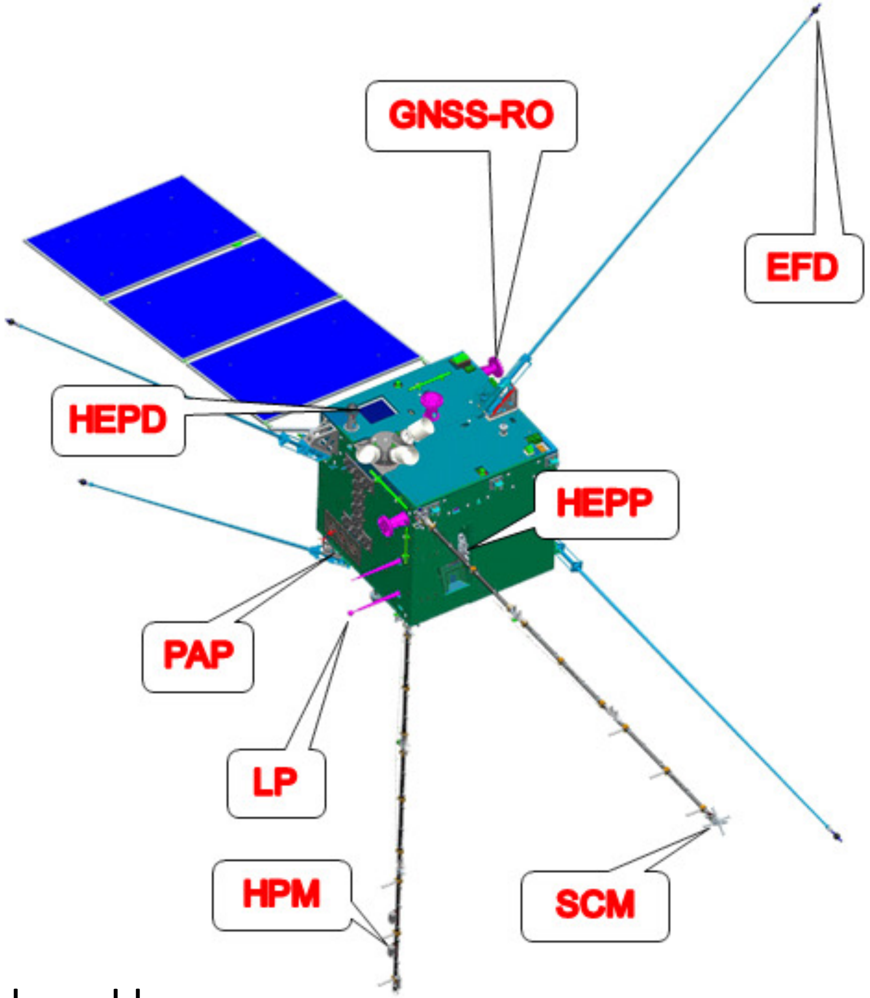
Advancements in GRB science with HEPD on CSES Satellites: current status and prospects

Roberto Iuppa
for the CSES-Limadou collaboration

University of Trento and INFN-TIFPA

CRIS-MAC, Trapani, June 20 2024

The CSES-01 satellite

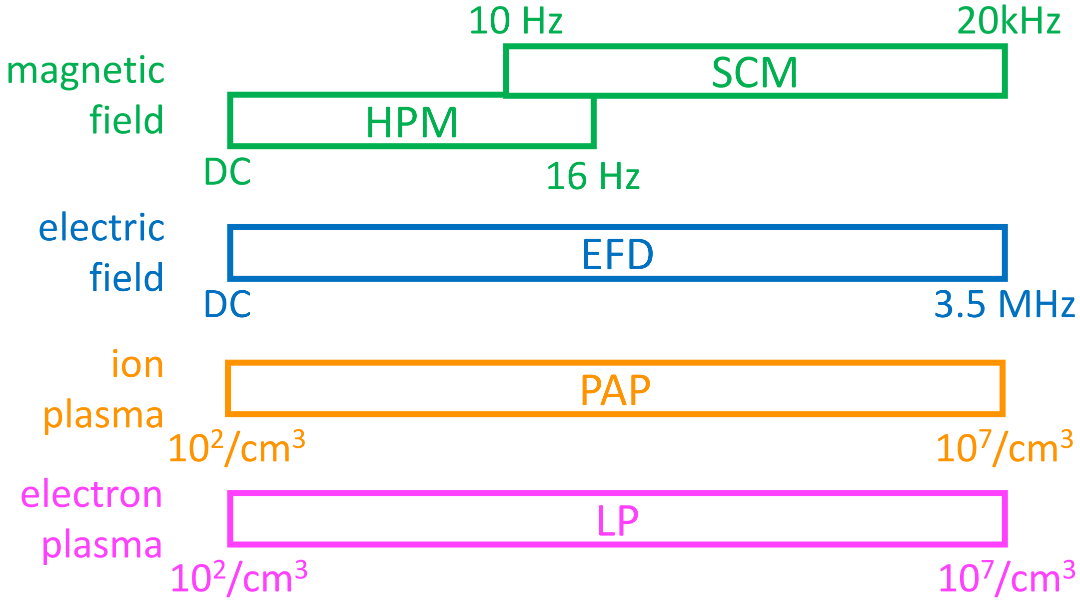


CSES: China Seismo-Elecromagnetic Satellite

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

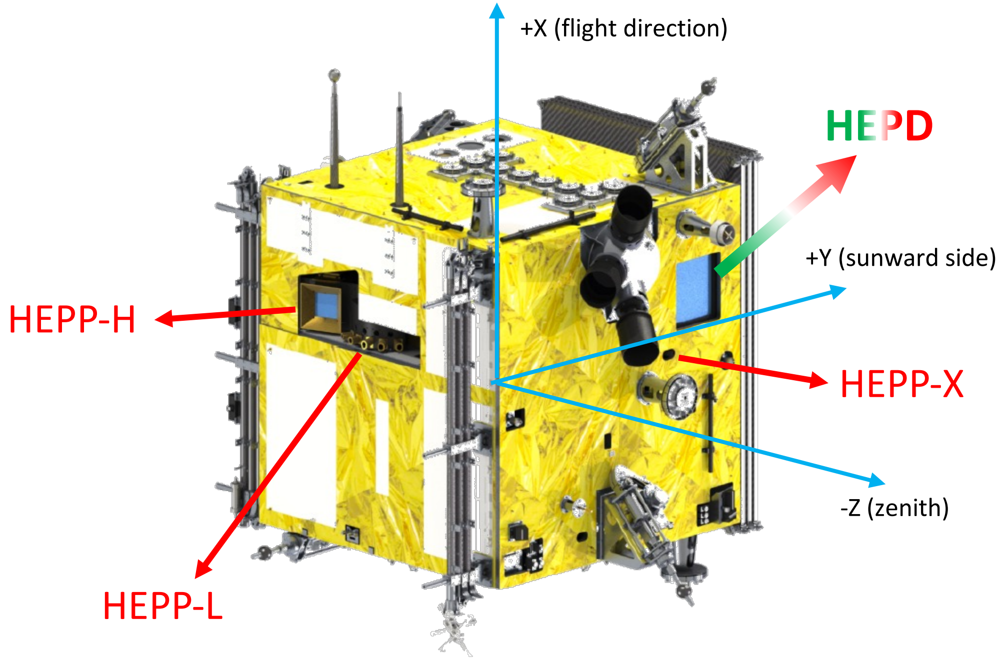
Payload working zone: −65° / +65° latitude

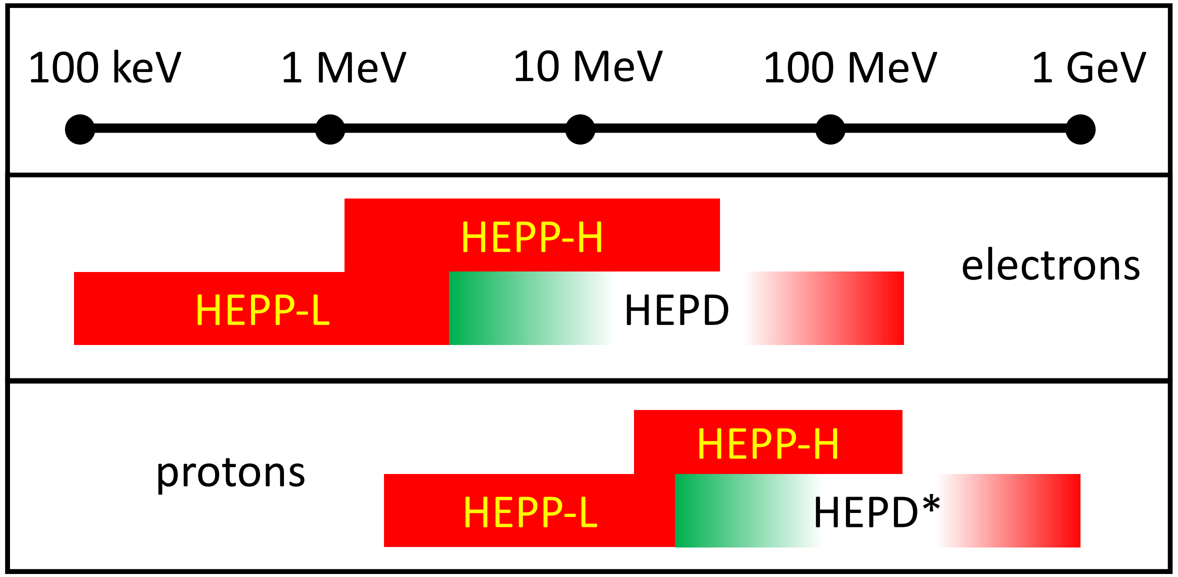


Developed by:

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

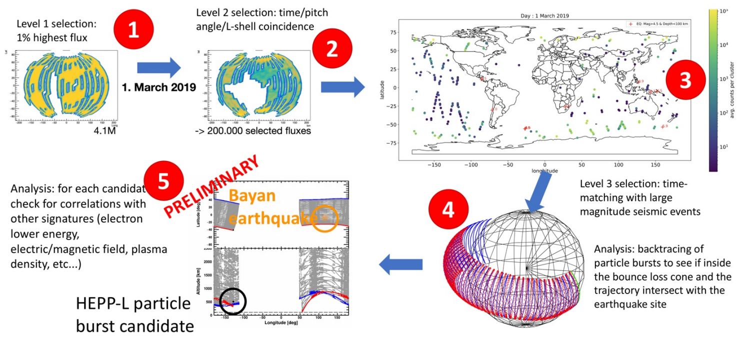
Particle/Photon detection onboard CSES-01





*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.
- As for all CSES payloads, calibrated data from particle detectors are publicly available at **https://leos.ac.cn**



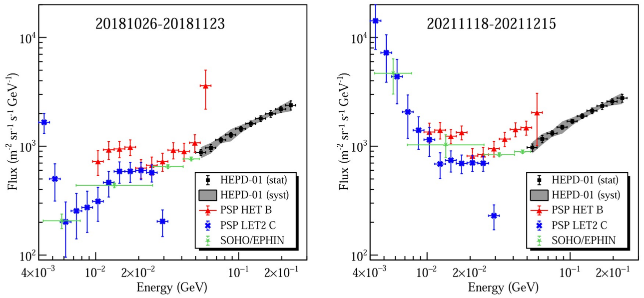
Example of search for HEPP-L particle burst candidates in correspondence of large-magnitude seismic events

Roberto Iuppa

Many results important results from HEPD-01

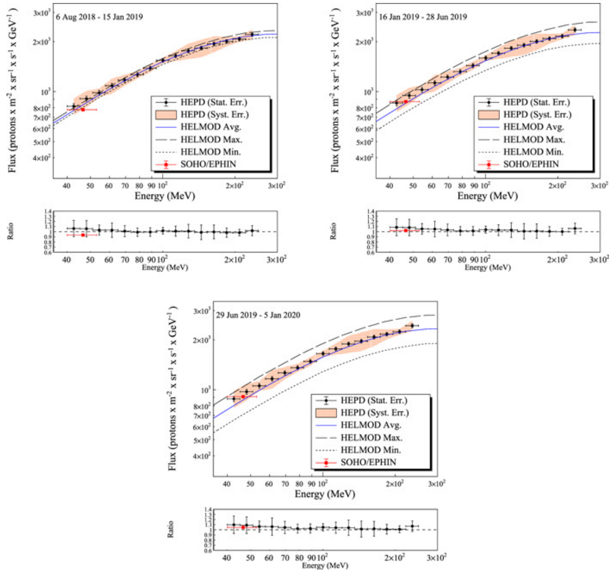
sub-GeV galactic CRs

The Astrophysical Journal Letters, 945:L39 (8pp), 2023



Time Dependence of 50–250 MeV gal. CR protons.

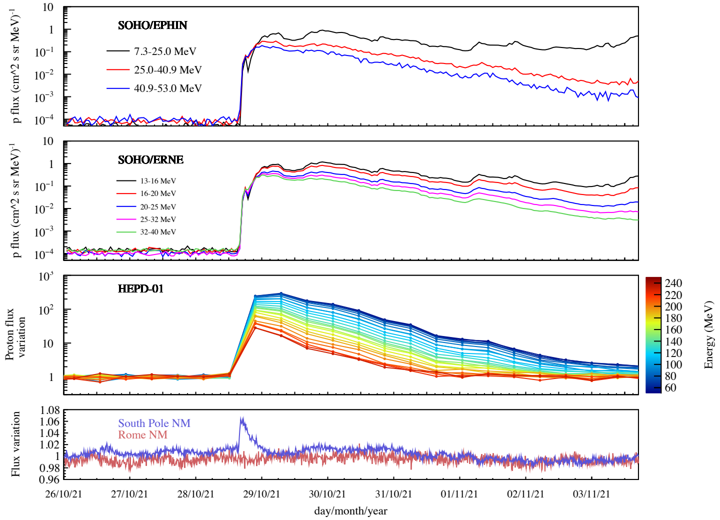
Bartocci *et al* 2020 *ApJ* **901** 8



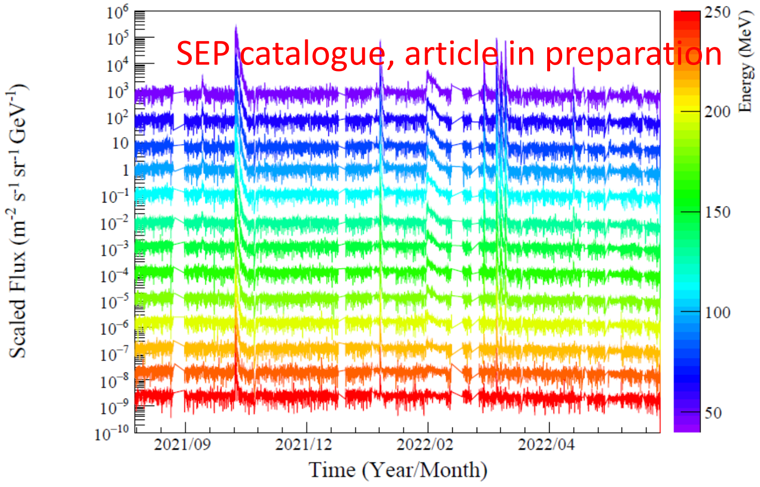
50-250 MeV proton spectra measurable vs time

solar physics

Space Weather 21, 1 (2023),

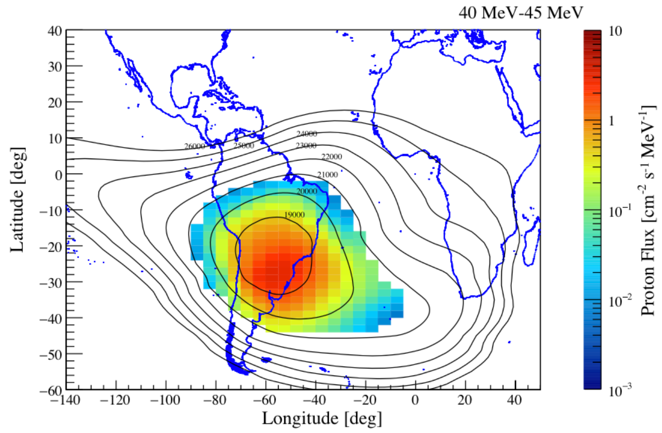


SEP event of cycle 25



trapped/reentrant particles

PHYS. REV. D 105, 062001 (2022)



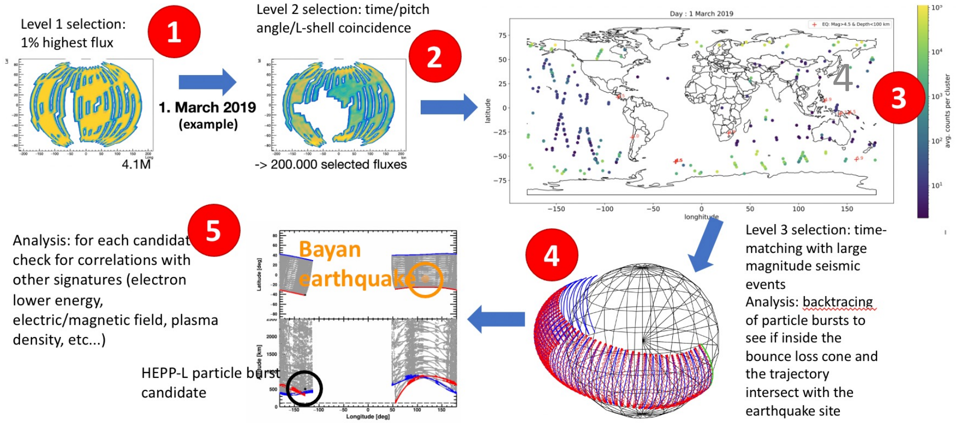
Roberto Iuppa

CRIS-MAC 2024

June 20, 2024

particle bursts around earthquakes

Search for correlations with large magnitude seismic events (particle data from 3 experiments, data from 8 payloads)



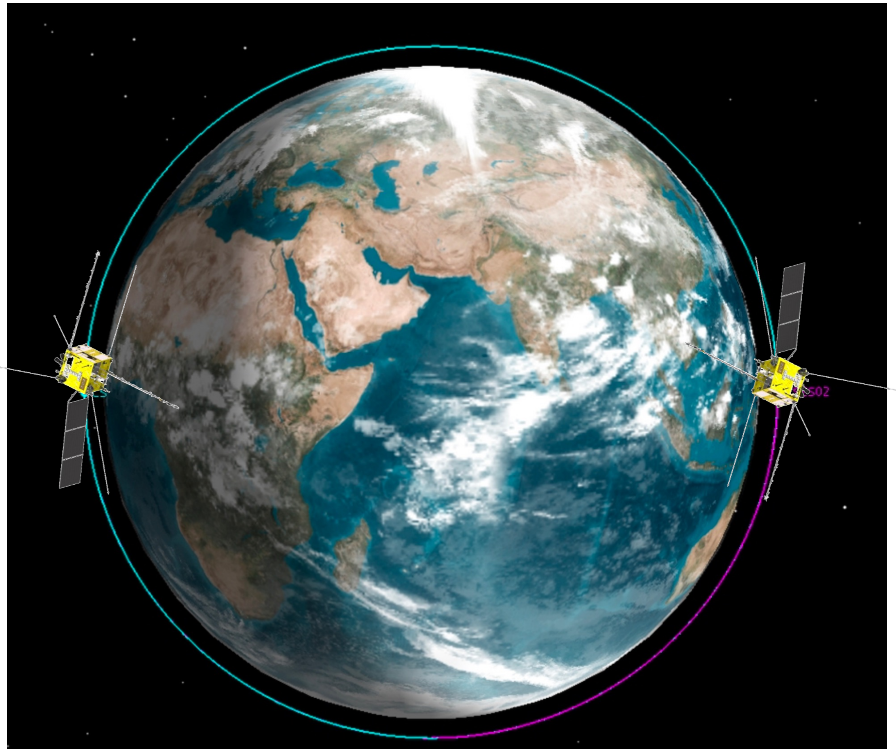
Status of the analysis: no single-event correlation evidence. Loooking at the fulll-stack EQ catalogue

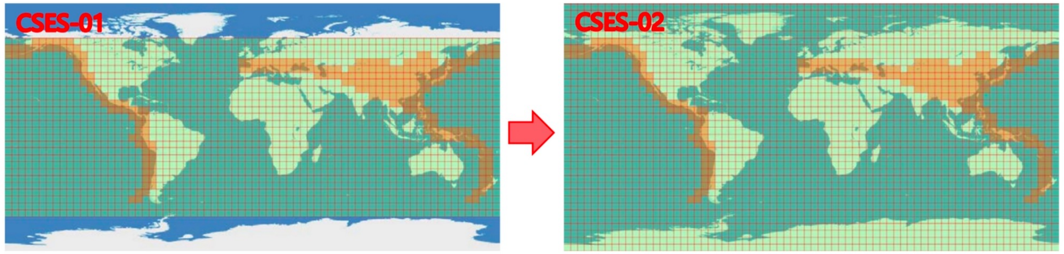
CSES-02

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

- Launch scheduled by december 2024
- Same DFH CAST-2000 platform of CSES-01 with some upgrades
    - Earth oriented 3-axis stabilization system with orbit manoeuvre 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.



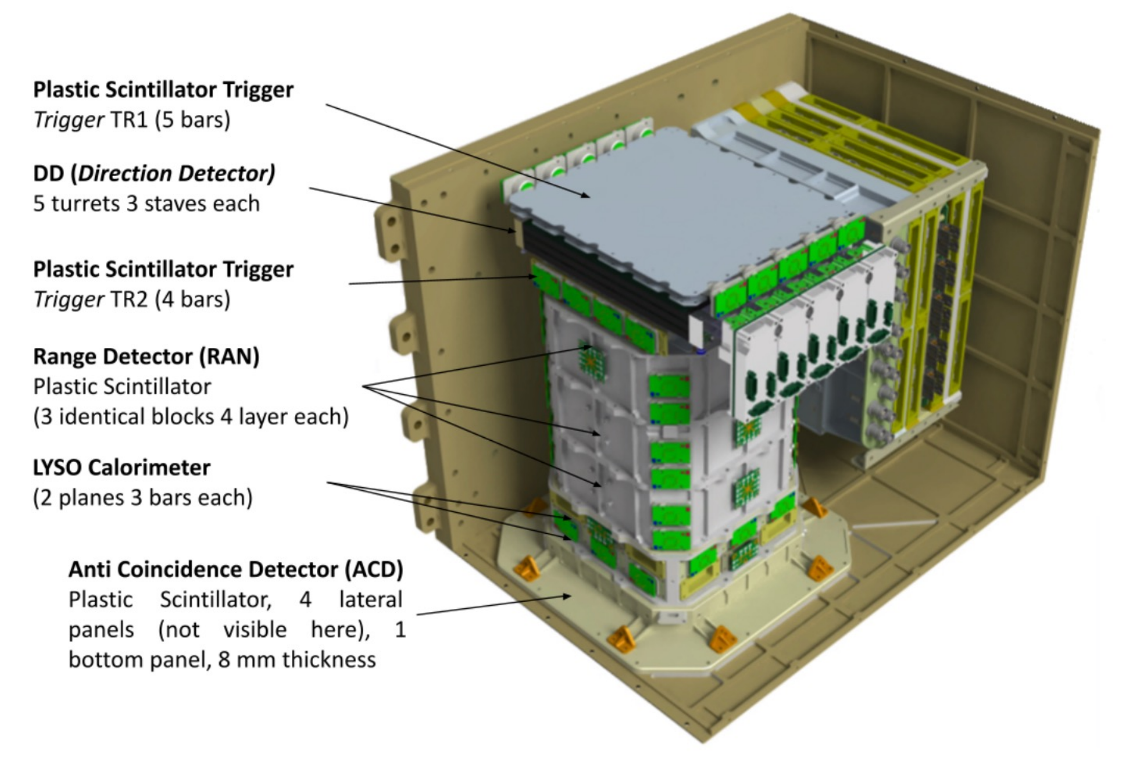


Confined Areas Observation

Global Wide Observation

Roberto Iuppa

The HEPD-02 payload



Requirements similar to HEPD-01

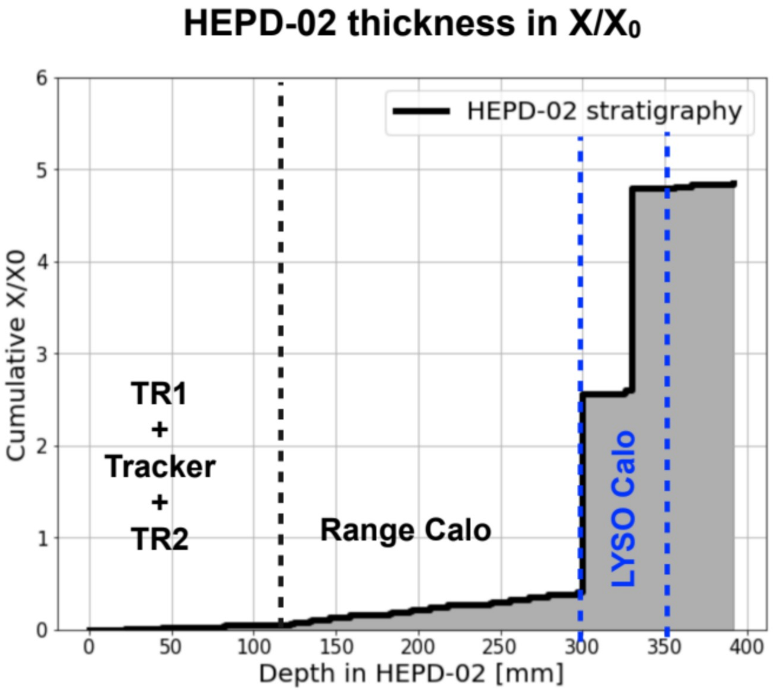
- Energy range
  - Electron: 3-100 MeV (contained)
  - Proton: 30-200 MeV (contained)
- Angular resolution<8º@ 5 MeV
- Energy resolution<10% @ 5 MeV
- Particle Identification efficiency > 90%
- Maximum Omni-directional Flux: 10^3 $cm^{-2}s^{-1}sr^{-1}$ (accepted by trigger before prescaling)
- Operating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

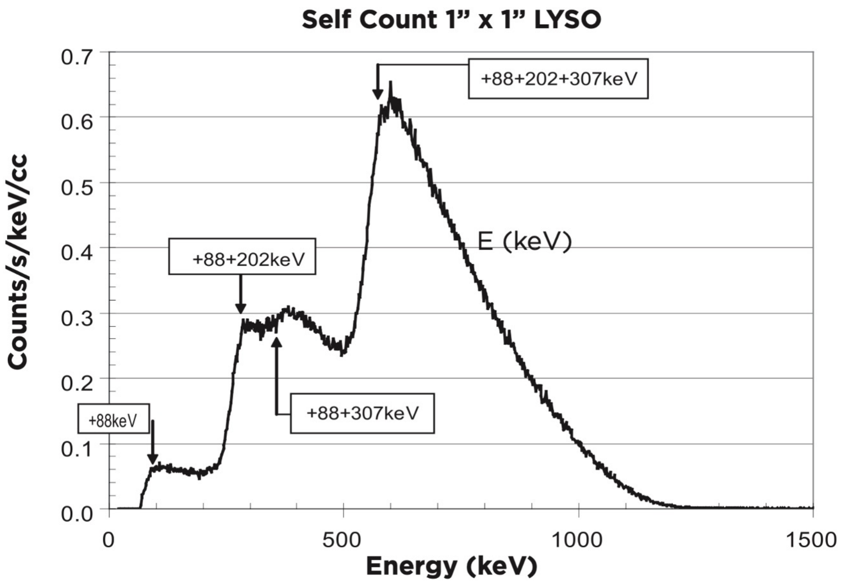
Major improvements wrt HEPD-01

- **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**

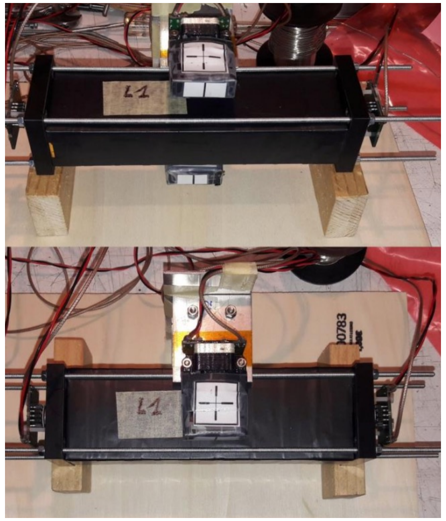
LYSO chosen for timing purposes, but radioactive

Table comparing principal properties	LYSO	BGO	LSO
Density [g/cm³]	7.1	7.1	7.4
Attenuation length for 511 keV (cm)	1.2	1.0	1.15
Decay time [ns]	36	300	40
Energy resolution @ 662 keV	8.0	12.0	10.0
Light output, photons per keV	33	9	26
Average temperature coefficient 25 to 50°C (%/°C)	-0.28	-1.2	-1.3



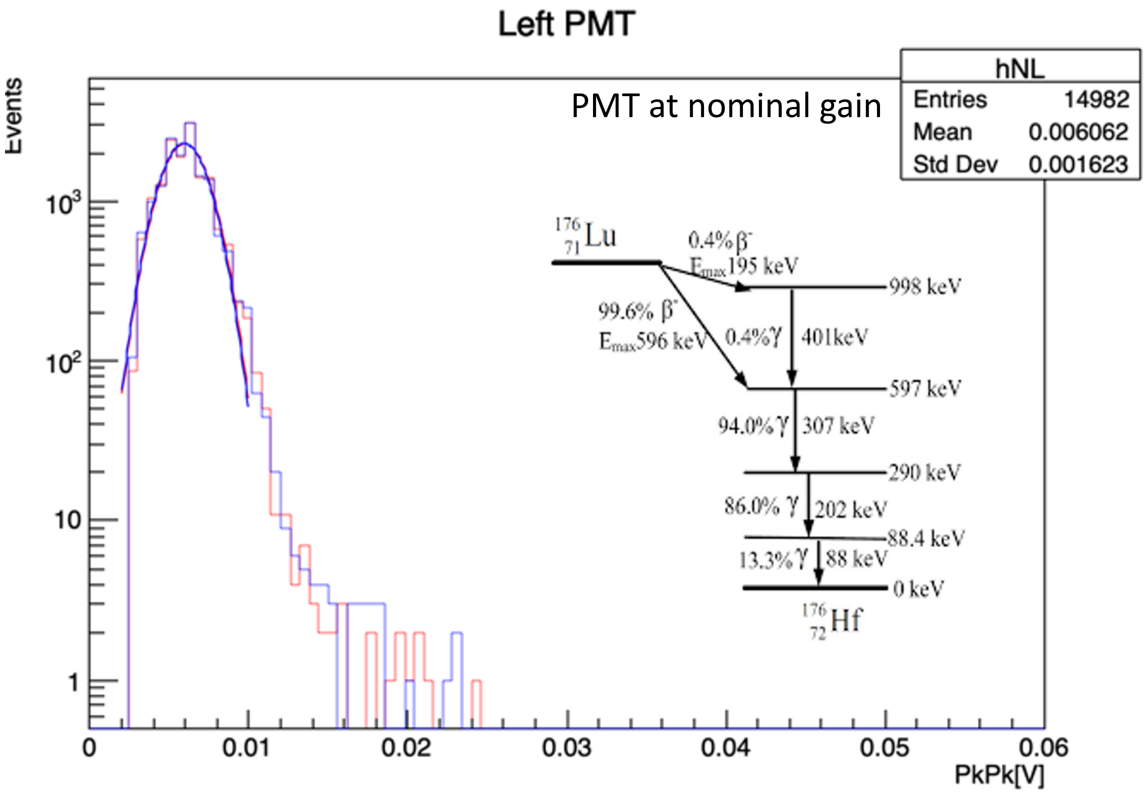


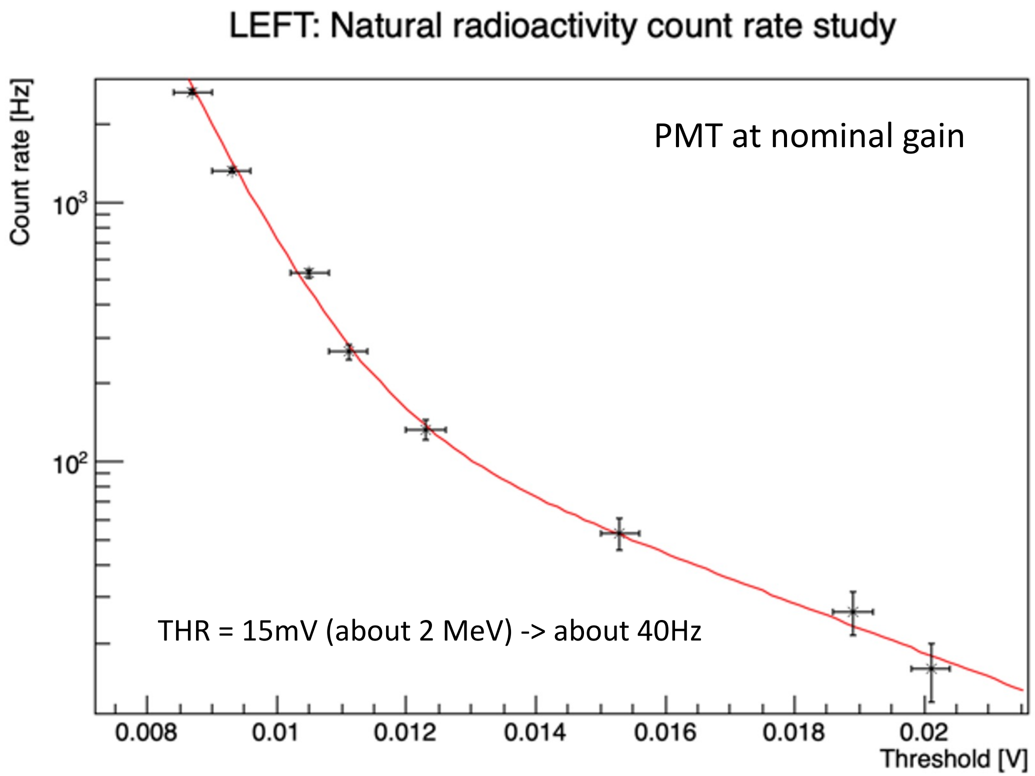
Among the largest LYSO crystals ever grown.
150X50X25 mm3 readout by two 8-mm PMTs on the farthest sides of the bar



Roberto Iuppa

LYSO intrinsic background





39kBq/kg → a set of crystals of 8kg would produce 320kBq

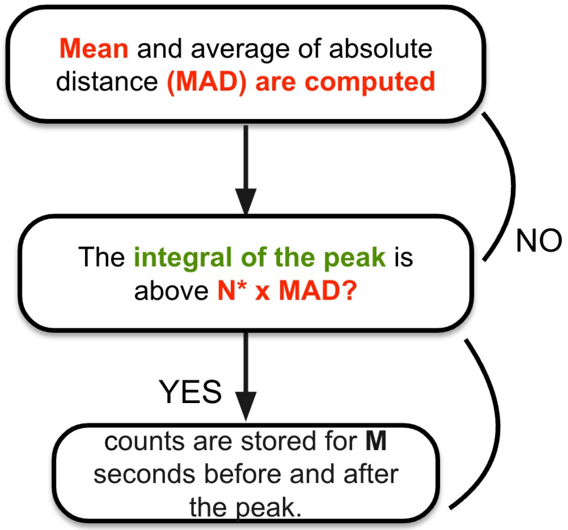
A. Lega, F. Nozzoli, R. Iuppa (2021)

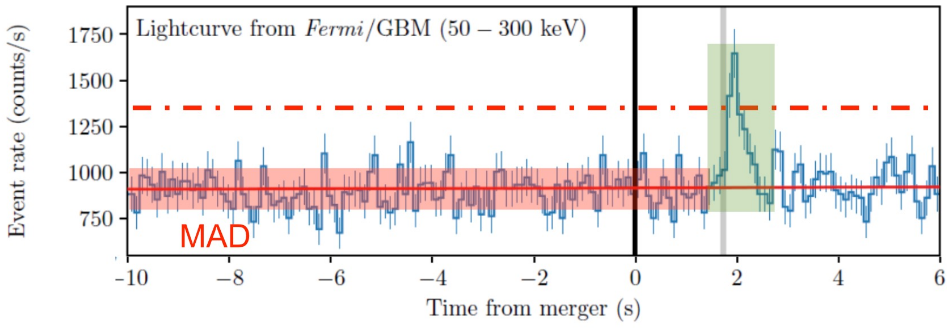
Result: with a threshold of 2-3 MeV on LYSO (necessary for energy resolution requirement on electrons and protons), the background due to LYSO activity on HEPD-02 is expected (and measured) as large as 300 Hz

Trigger algorithm

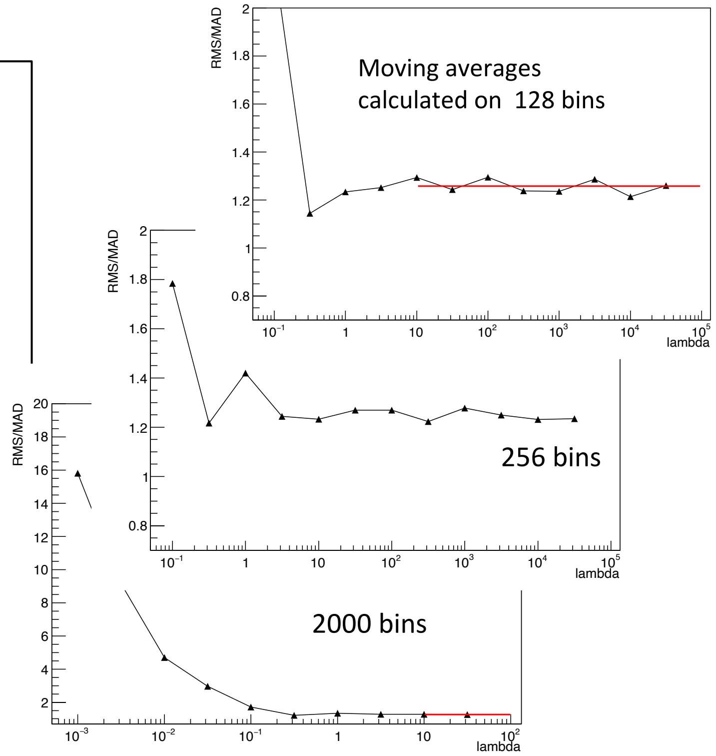
rto luppa

Simplified HEPD-02 GRB algorithm scheme





Low energy and high energy GRB mask combined + excellent time resolutior

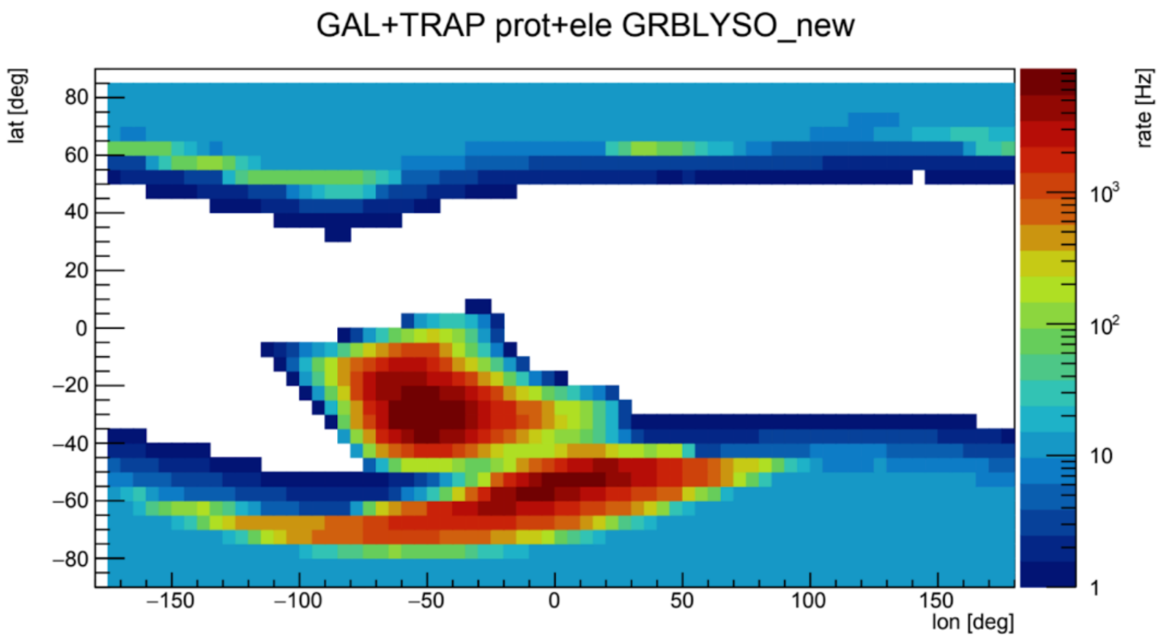


CRIS-MAC 2024

June 20, 2024

GRB sensitivity with HEPD-02

PROBLEM: Sun-synchronous quasi-polar orbit

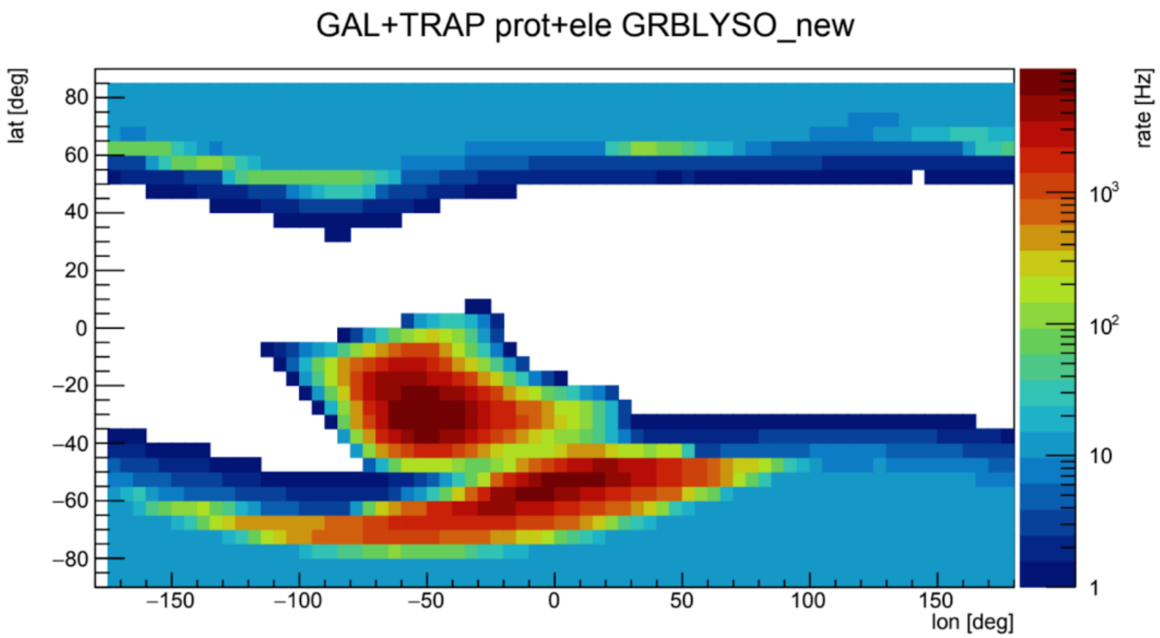


estimated false triggers at (*the boundaries of*) SAA and polar regions

Team:
F. Nozzoli
A. Lega

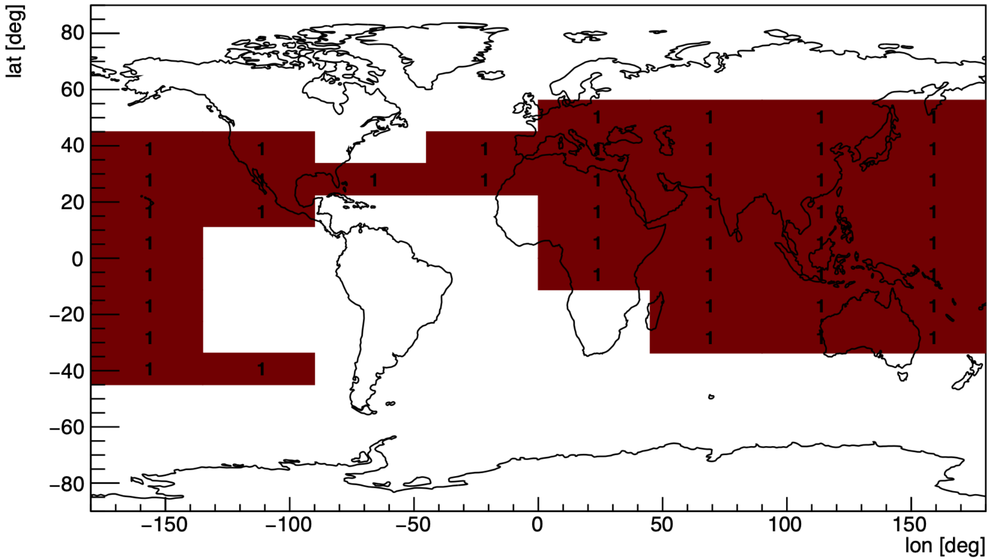
GRB sensitivity with HEPD-02

PROBLEM: Sun-synchronous quasi-polar orbit



estimated false triggers at (*the boundaries of*) SAA and polar regions

- A GRB trigger mask (coincidence of plastic scint. or LYSO crystals) in many orbital zones

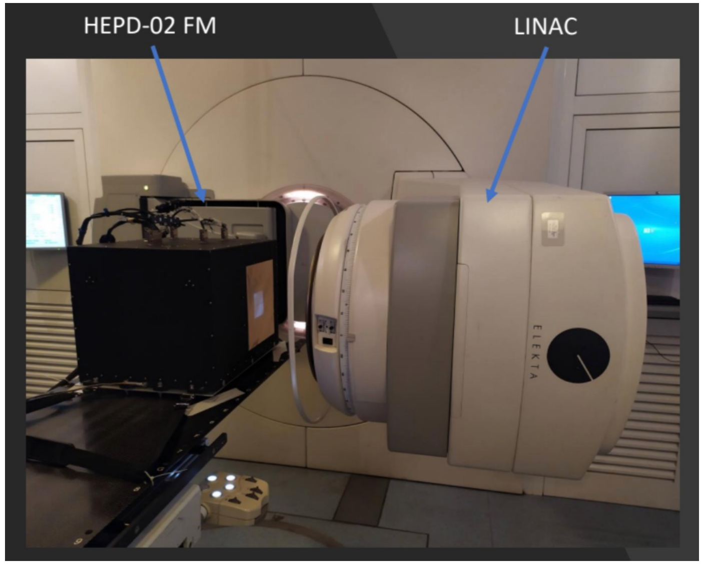


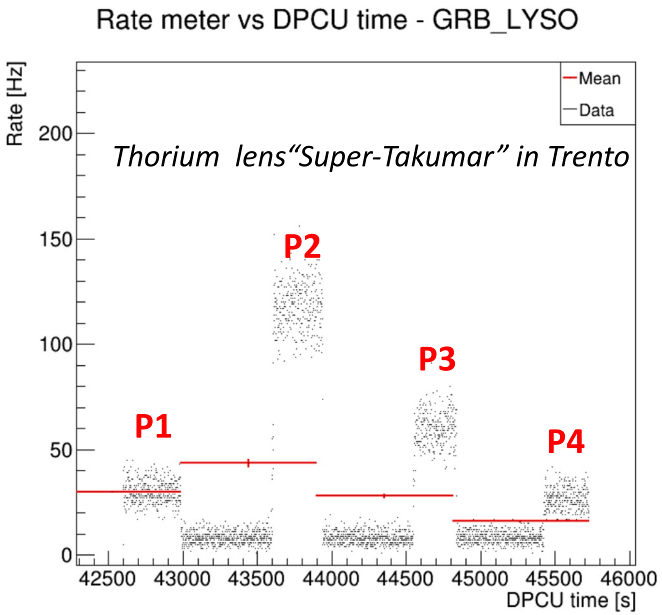
- Trigger configuration dedicated to γ-rays tracked on a time basis of 5 ms
- 2nd level trigger introduced to consider veto
- Moving average and MAD calculated in the DP/CU for GRB trigger rates on different time intervals (10, 40, 160, 360 ms)

Roberto Iuppa

Team:
F. Nozzoli
A. Lega

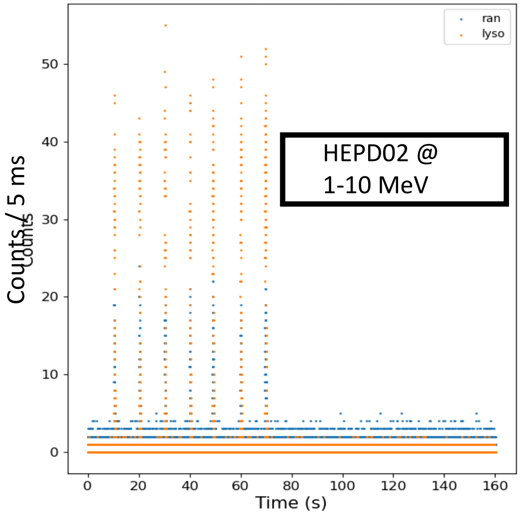
GRB mode tests



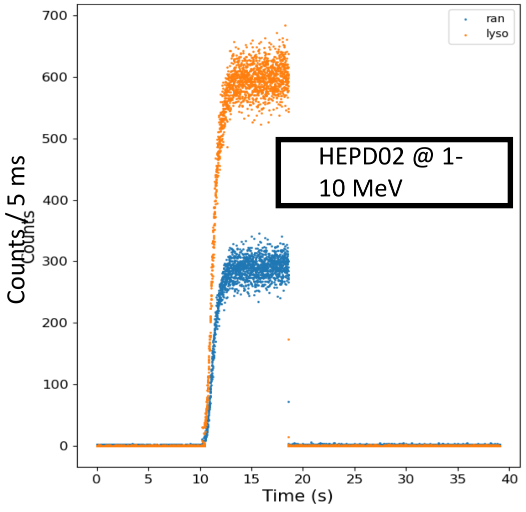


Tests of the GRB triggers carried out @ LINAC - Trento

7 consecutive ~ 1 sec gamma pulses



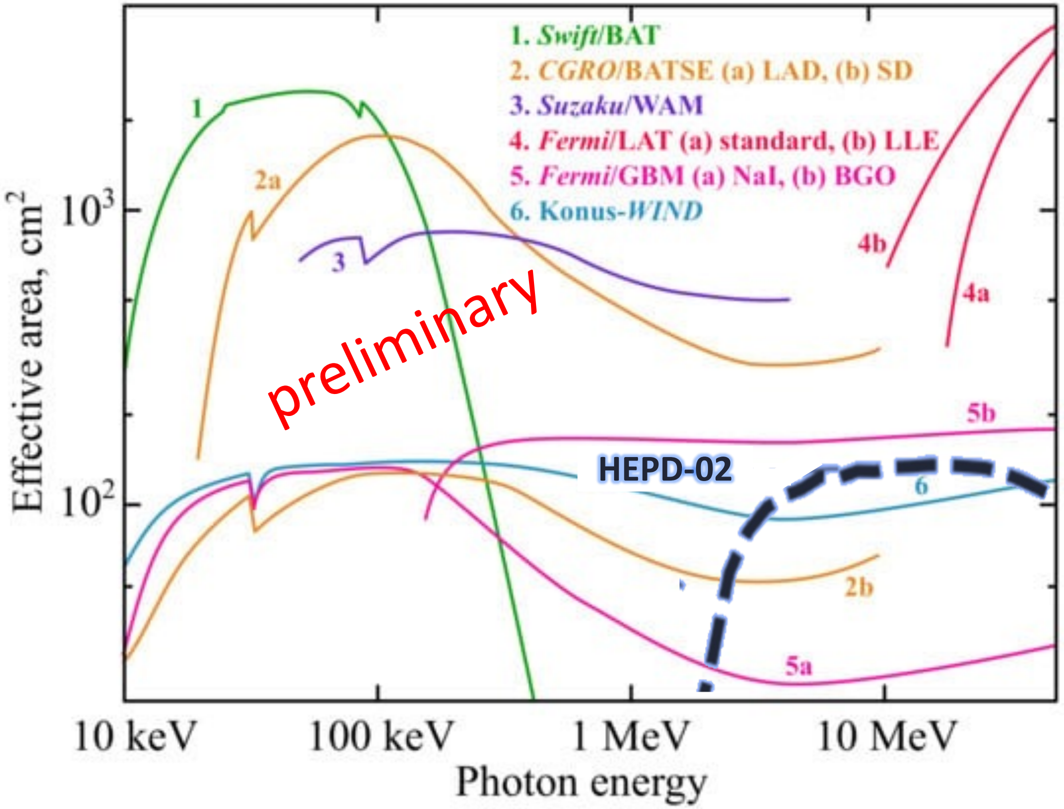
single ~10 sec pulse

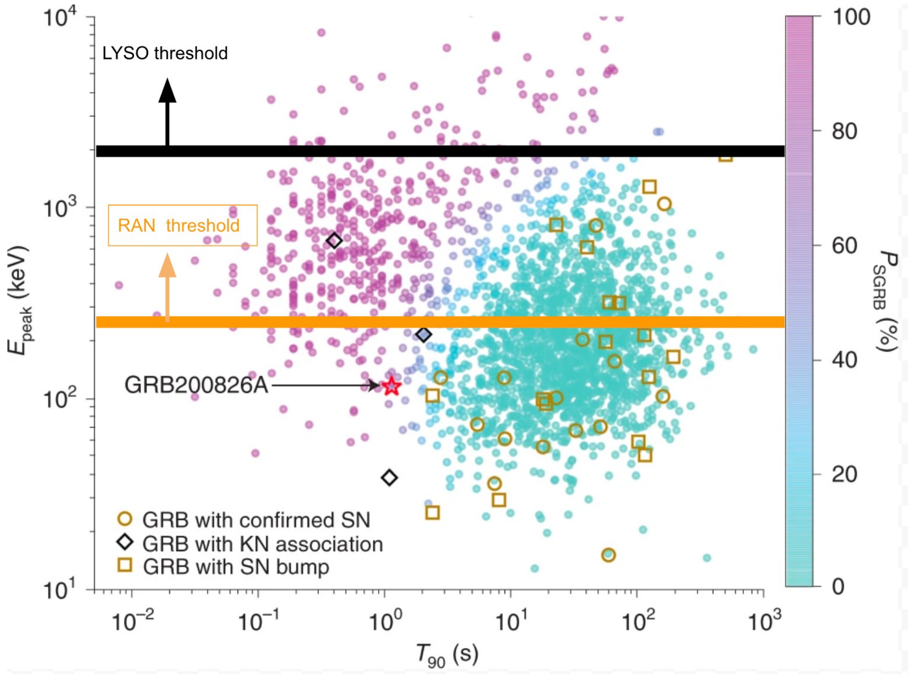


Roberto Iuppa

HEPD-02 GRB sensitivity

very good grasp at 3-30 MeV





Roberto Iuppa

CRIS-MAC 2024

June 20, 2024

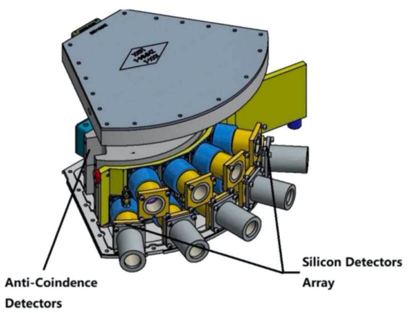
LIMADOU

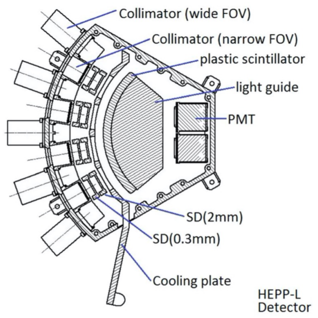
Roberto Iuppa

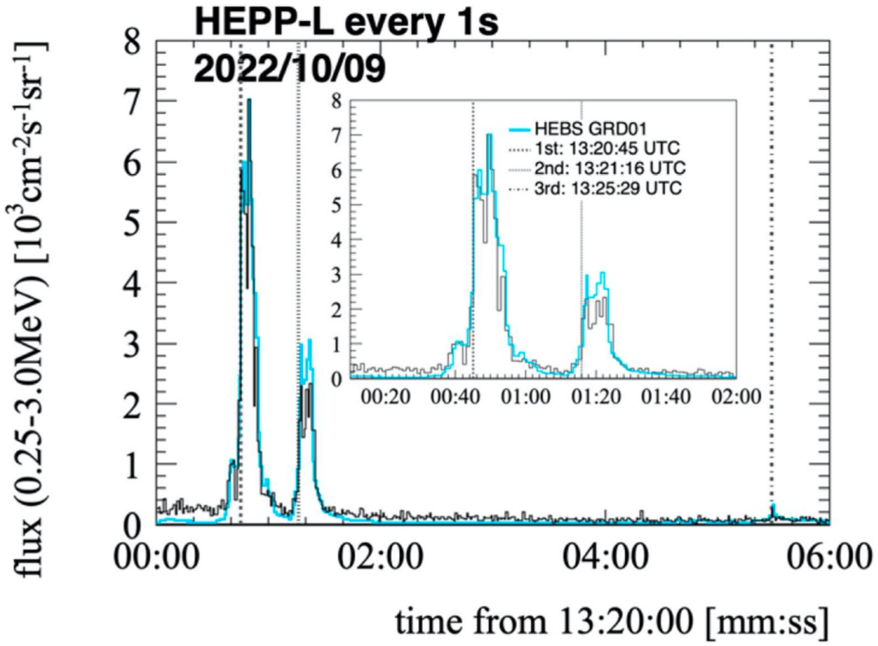
Setting up the machinery: GRBs with HEPD-01

GRB221009 and the others...

The Astrophysical Journal Letters, 946:L29 (6pp), 2023 March 20

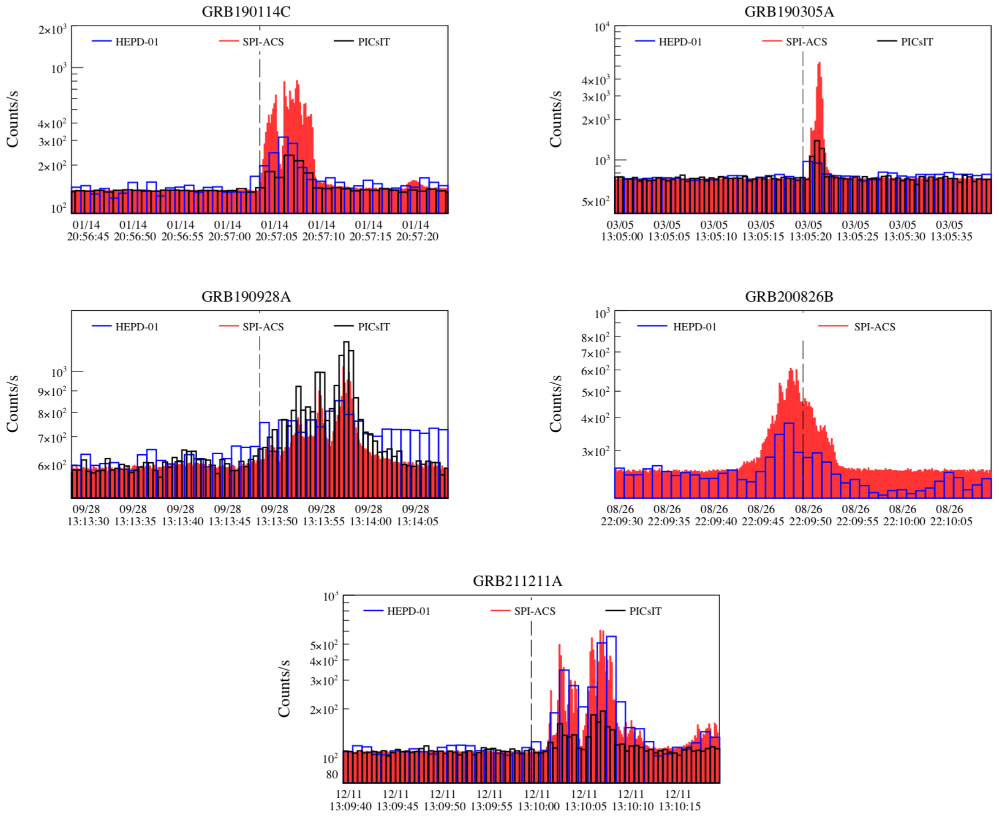




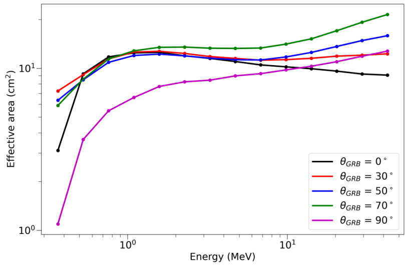


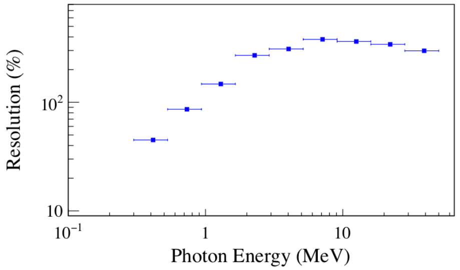
The time structure of the observed electron flux closely matches the very distinctive time dependence of the photon flux associated with the main part of the emission at around 13:20 UTC on 2022 October 9

[F. Palma *et al* 2024 *ApJ* **960** 21]



eff. area as large as few cm^2





see figures for HEPD-02 in a while...

CRIS-MAC 2024

Roberto Iuppa

June 20, 2024

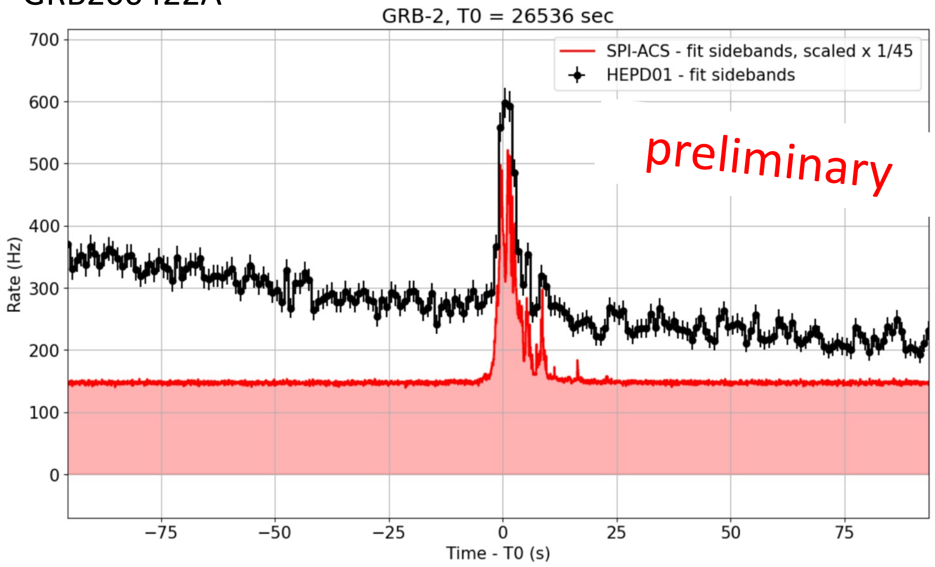
Build-up of of the pipeline for automatic GRB detection

Machinery set up for HEPD-01 data analysis. Automatic anomaly detection and alarm system set up.
Further work needed to join the international networks of multimessenger astrophysics.

System fully validated with HEPD-01 offline data analysis. Cross-check with other GRB detectors, like Integral and Fermi.

System ready for HEPD-02 online (*) GRB detection!

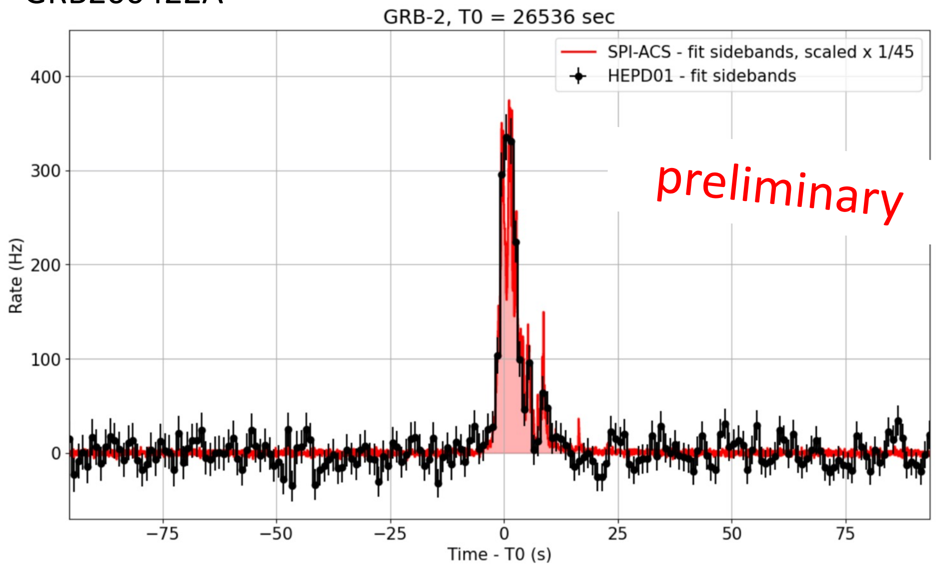
GRB200422A



HEPD-01 and SPI-ACS data (scaled)

detrending

GRB200422A



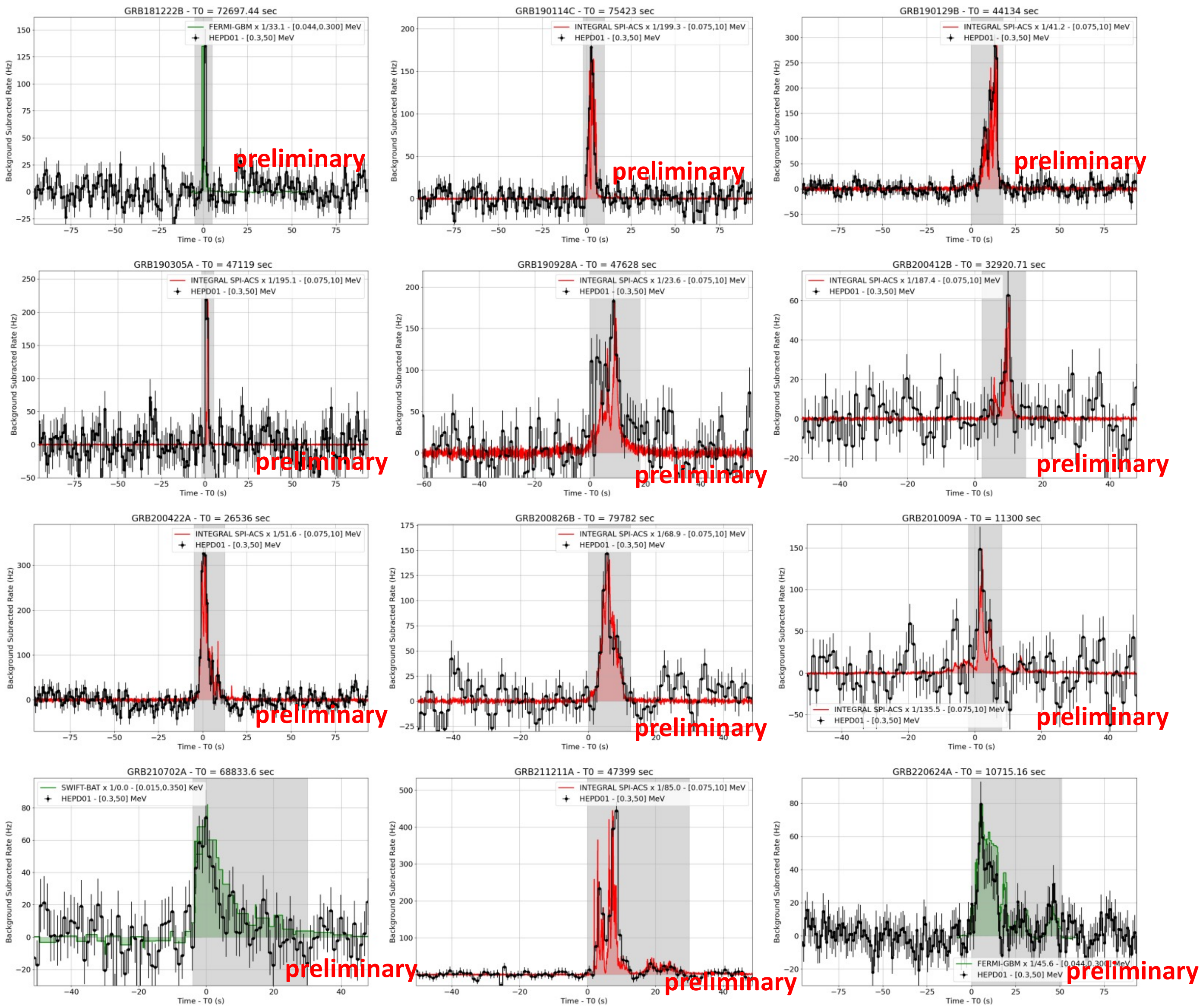
(*) few hours expected latency

SPI-ACS data: http://isdc.unige.ch/~savchenk/spiacs-online/spiacs.pl

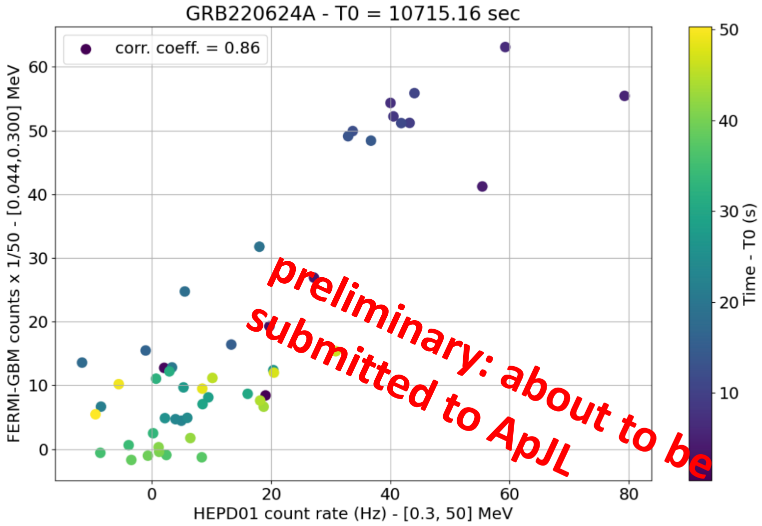
Roberto Iuppa

MeV GRB observation with the HEPD

Roberto Iuppa



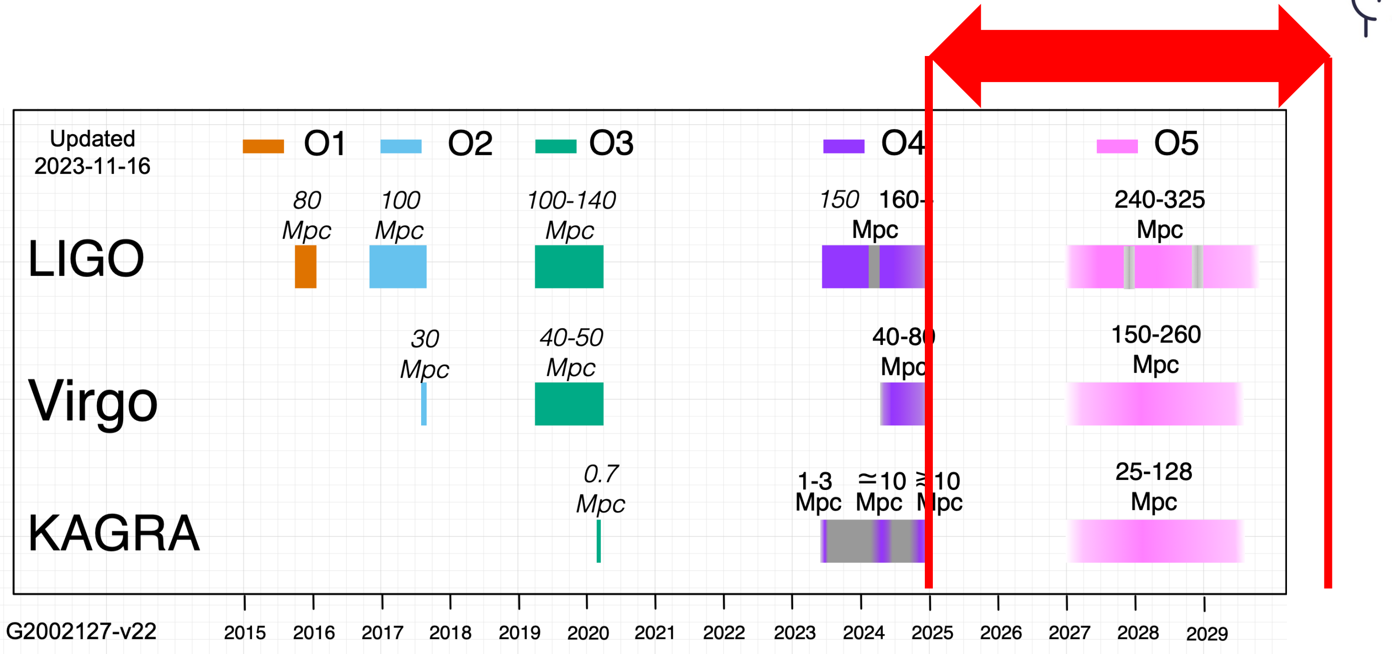
0.3-50 MeV measurement of duration, fluence and time-profile for 12 GRBs observed by INTEGRAL-SPI, Fermi-Lat and Konus Wind.



Important information retrieved from time-profile: comparison of tens of keV / tens of MeV emissions available for modelling

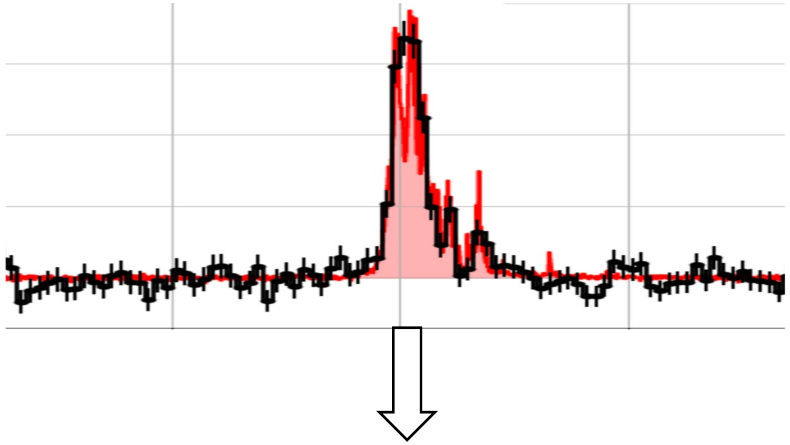
HEPD-02:
x200 improvement in time resolution
x10 improvement in energy resolution
x40 improvement in effective area

HEPD-02 GRB opportunity

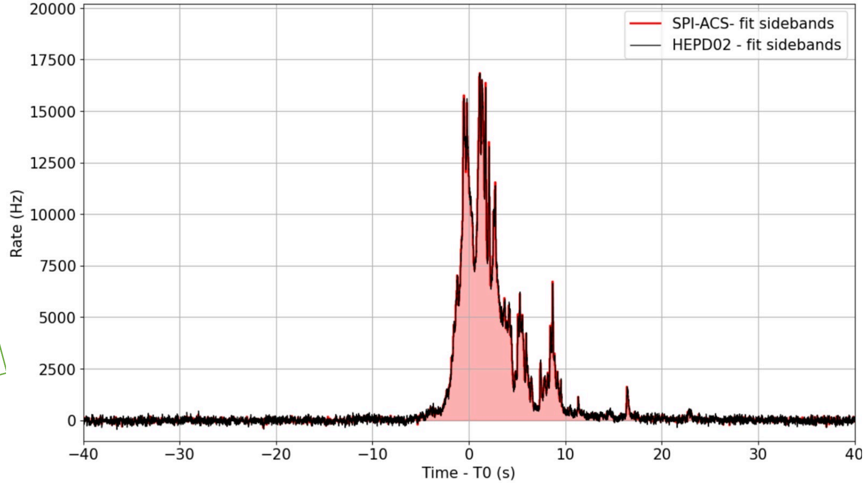


HEPD-02 observation campaign

HEPD-01 1000 ms resolution



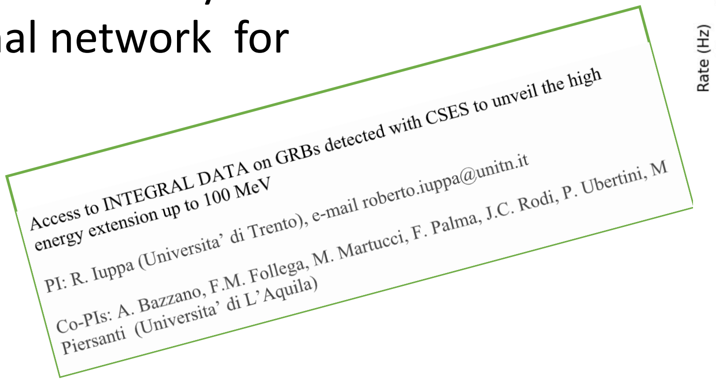
HEPD-02 10 ms resolution



Pointing accuracy ~15°

HEPD-02 will detect GRBs with good sensitivity in the 1-100 MeV range. Ready to join the international network for multimessenger observations.

Onging activity for agreements of joint observation campaigns for calibration purposes.



Access to INTEGRAL DATA on GRBs detected with CSES to unveil the high energy extension up to 100 MeV

PI: R. Iuppa (Universita' di Trento), e-mail roberto.iuppa@unitn.it

Co-PIs: A. Bazzano, F.M. Follega, M. Martucci, F. Palma, J.C. Rodi, P. Ubertini, M Piersanti (Universita' di L'Aquila)

Roberto Iuppa

CRIS-MAC 2024

June 20, 2024

Conclusions

- CSES is a constellation of satellites designed as a multi-site fleet of multi-messenger observatories of ionosphere and magnetosphere.
- Successful operation of CSES-01 since 2018, showcasing consistent performance and data acquisition reliability.
- Among the payloads, the High-Energy Particle Detectors are designed, assembled, integrated and tested by the Italian team Limadou-HEPD.
- The HEPD-02 detector is a major upgrade of HEPD-01. Among novelties, a GRB mode has been introduced, targeting the efficient measurement of 3-30 MeV photons from GRBs
  - Dedicated trigger algorithm, 5 ms time resolution, 20%-30% energy resolution
  - intense campaign of test and characterization: LYSO intrinsic radioactivity, sources, LINAC beams
- Data from trigger-rate counters of HEPD-01 have been used to validate the GRB search algorithm and offline tools for data analysis: successful test which also provided useful scientific information: in spite of poor trigger acceptance and low time resolution, important information about 12 GRBs in 2018-2022 were obtained and are going to be published.
- CSES-02 is going to be launched in December 2024, allowing the Limadou-HEPD team to contribute to multi-messenger observations in the period 2025-2030+

thank you

flight-cases just before shipment

iaps

INFN
Istituto Nazionale di Fisica Nucleare

ASI
Agenzia Spaziale Italiana

IFAC

ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

UNIVERSITÀ
DEGLI STUDI
DI TORINO

TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

UTIU
UNIVERSITÀ TELEMATICA
INTERNAZIONALE UNINETTUNO

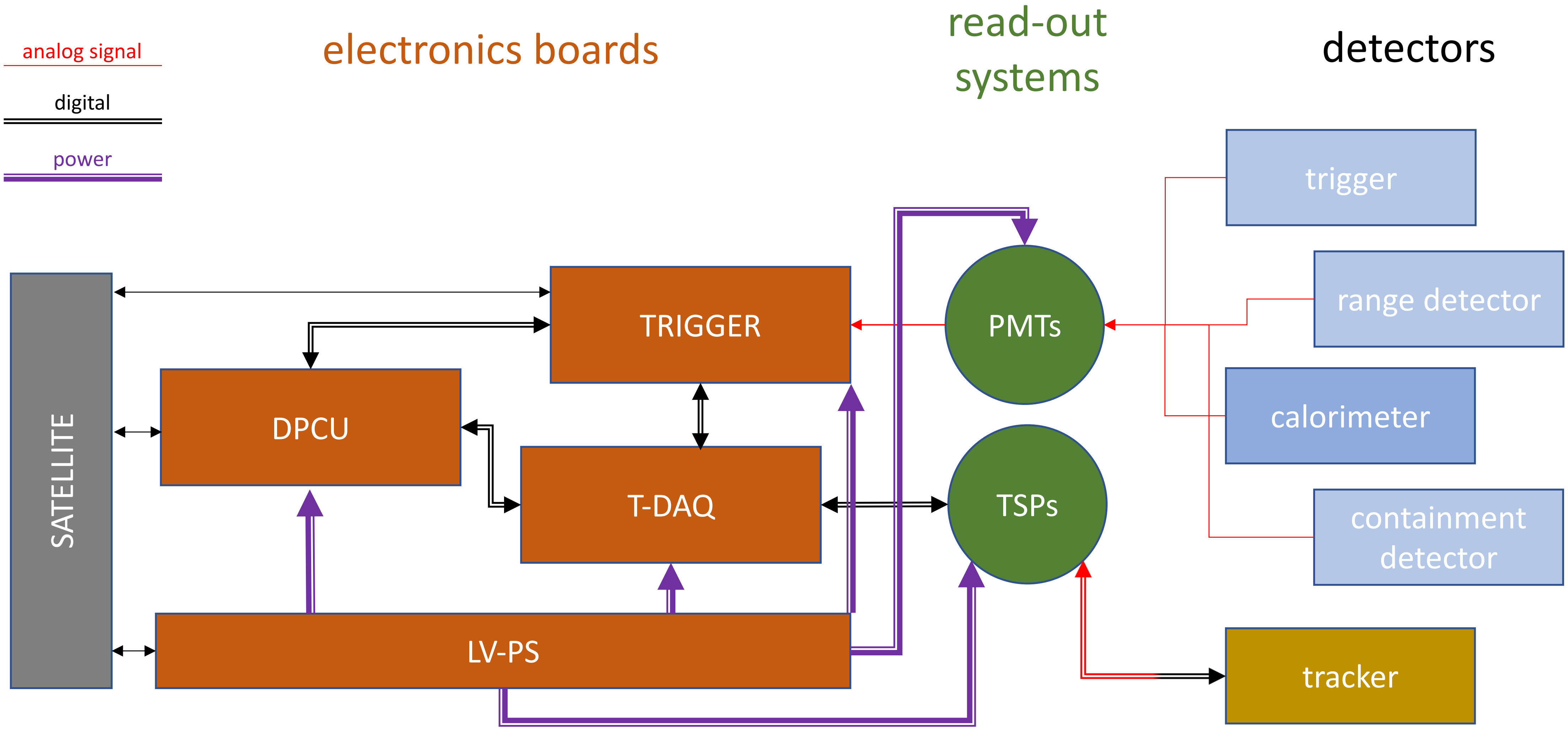
UNIVERSITÀ
DI TRENTO

UNIVERSITÀ DEGLI STUDI
DI NAPOLI FEDERICO II

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

backup slides

HEPD-02 subsystems



Roberto Iuppa

LYSO characterization in Trento

First tests in Trento with LYSO chip from HEPD-01

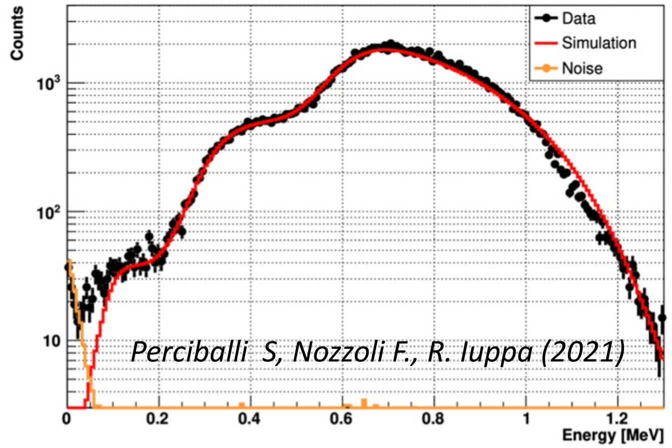
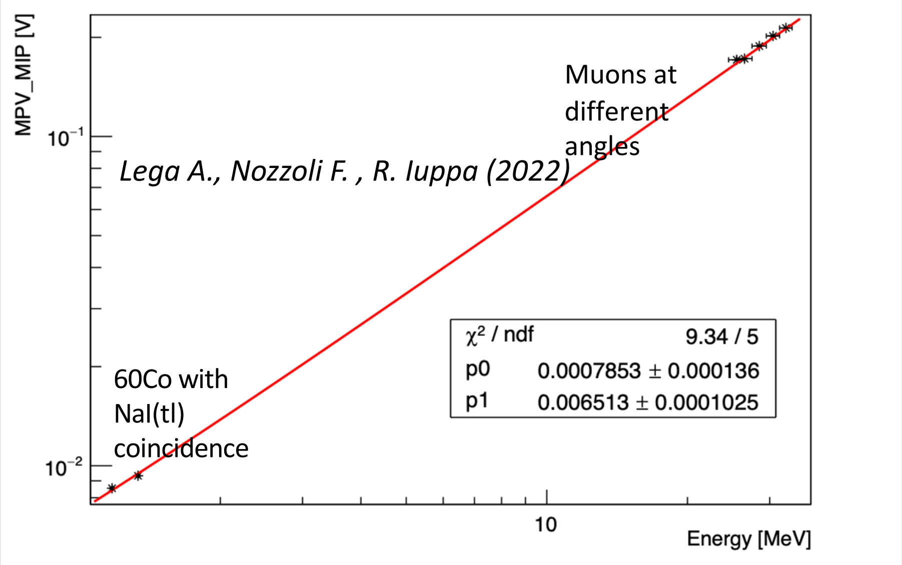
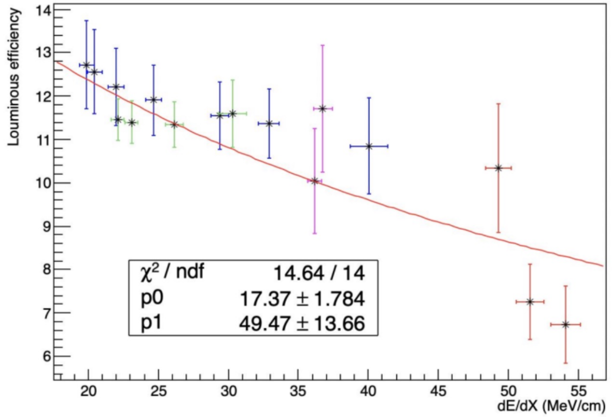


Figure 25: LYSO bakground spectrum as compared with Geant4 simulation. A residual noise component was identified below 50 keV and fitted with the noise template obtained by rejected data.

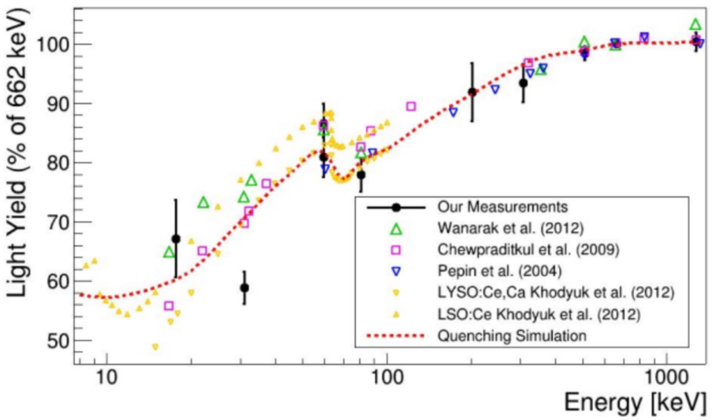
First tests in Trento with LYSO crystals for HEPD-02





Lega A., Nozzoli F., Iuppa R., Ricci E., Follega F.M., Gebbia G., Zuccon P., Rossi F., SIF2023

Full characterization of HEPD-02 crystals in Trento: measurement of Birks quenching

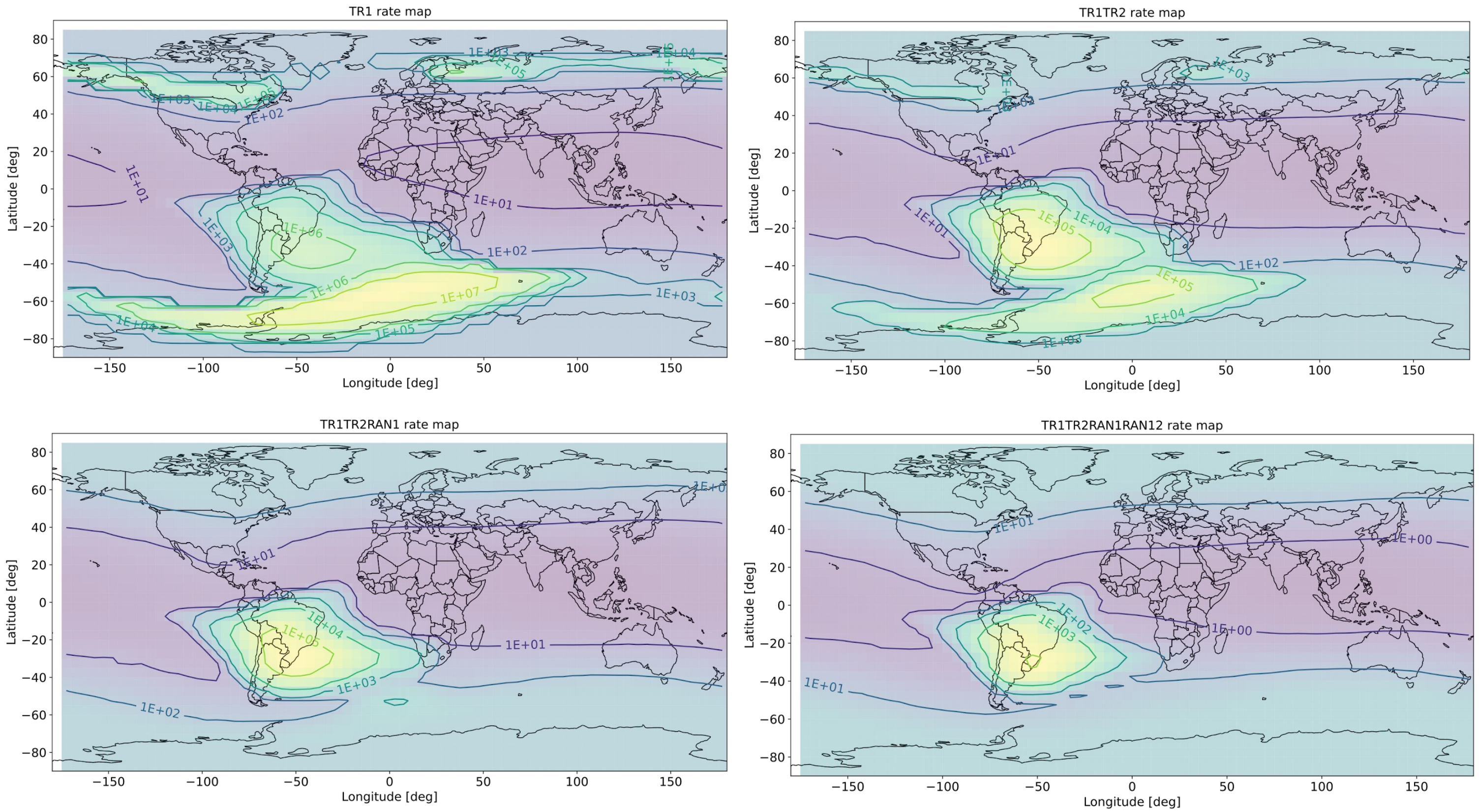


Nicolaidis R., Nozzoli F. , Ghezzer L.E., SIF2023

Roberto Iuppa

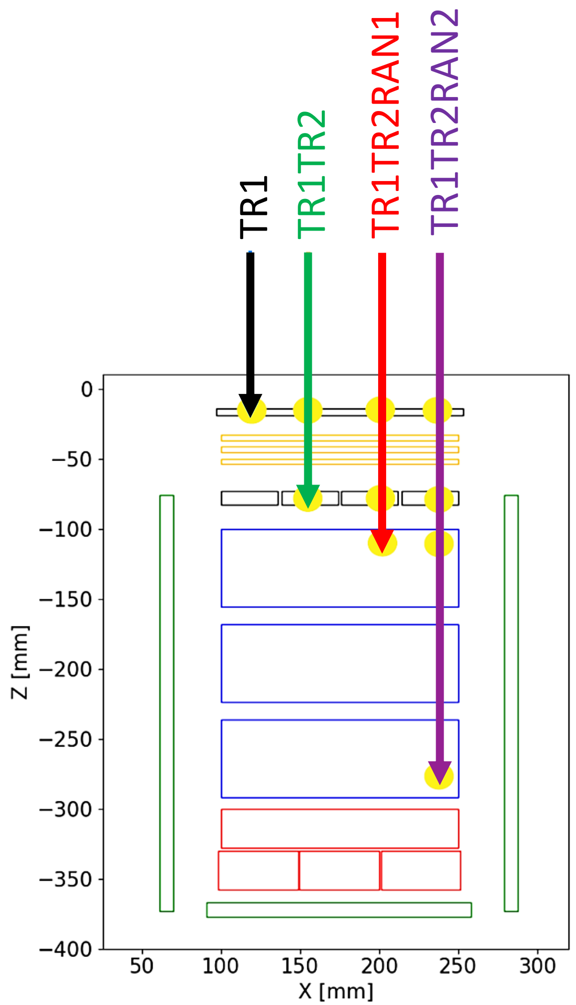
prescaled concurrent triggers

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)

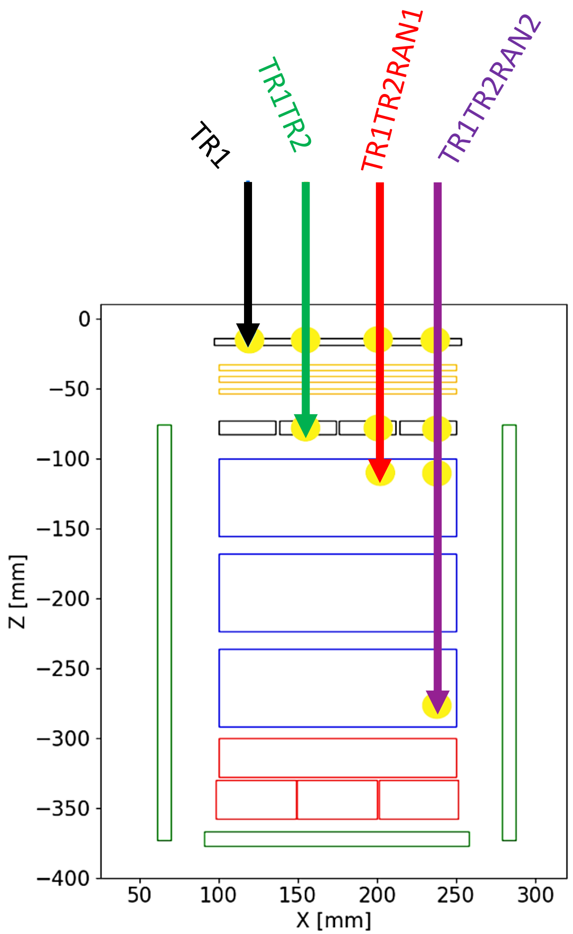


Roberto Iuppa

prescaled concurrent triggers

maximum HEPD-02 acquisition rate (e.g. 600 Hz)

scaled to 100 Hz	scaled to 100 Hz	scaled to 100 Hz	scaled to 100 Hz	150 Hz unscaled	150 Hz unscaled
TR1	**TR1TR2**	**TR1TR2RAN1**	**TR1TR2RAN2**	**MASK5**	**MASK6**

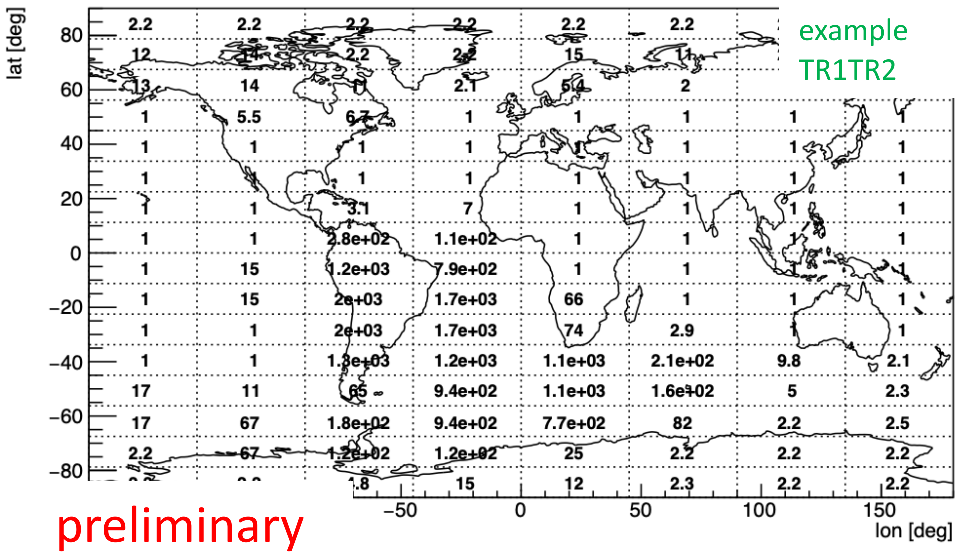


trigger patterns for different particle penetration (i.e. different energy thresholds) and for different purposes (e.g. calibration)

Scale factors are adjusted for each trigger pattern to share data-throughput 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

Lon/lat map segmented into 128 orbit zones (8x16 lon/lat zones); ascending and descending orbits are treated differently; 10 predefined trigger masks.



preliminary

Roberto Iuppa

Summary of TB runs used for calibration

Facility name	Particle type(s)	Energy ranges
LINAC of Santa Chiara Hospital, Trento	low-energy electrons	6, 9, 12 MeV
APSS Protontherapy center, Trento	Protons	30-200 MeV
Beam Test Facility, Frascati	electrons	30-120 MeV
CNAO, Pavia	Carbon nuclei	115 - 398 MeV/amu

Electrons/GAMMA
Linac
6 MeV, 9 MeV,
12 MeV

BTF
30 MeV, 60 MeV,
90 MeV, 120 MeV,
450 MeV

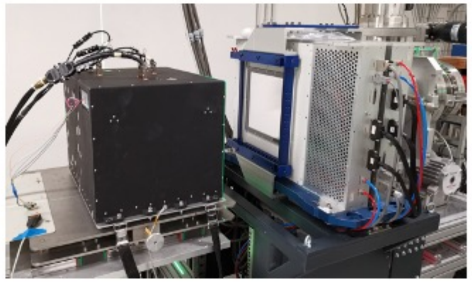
Protons
Degrader
37 MeV, 46 MeV,
51 MeV, 58 MeV,
64 MeV

Protons
70-228 MeV
(~ 15 MeV step)

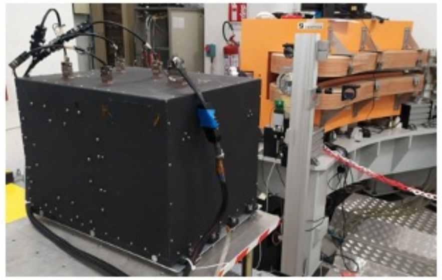
CNAO
115 - 398 MeV/amu
(~ 30 MeV/amu step)

Test beam runs after final tuning of the HEPD-02 HV/thr

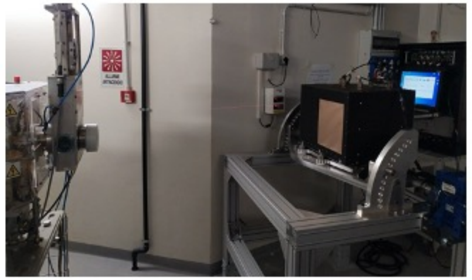
Carbon/proton @ CNAO July 2023



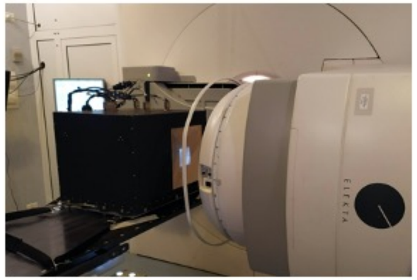
e^- (>30 MeV) @ BTF June 2023



Proton @ APSS (Trento) June 2023



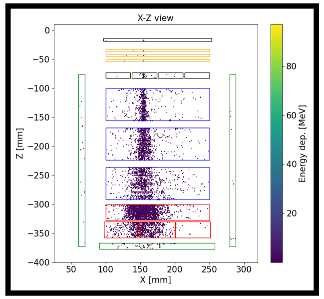
e^- (6-12 MeV) @ (Trento) June 2023



Roberto Iuppa

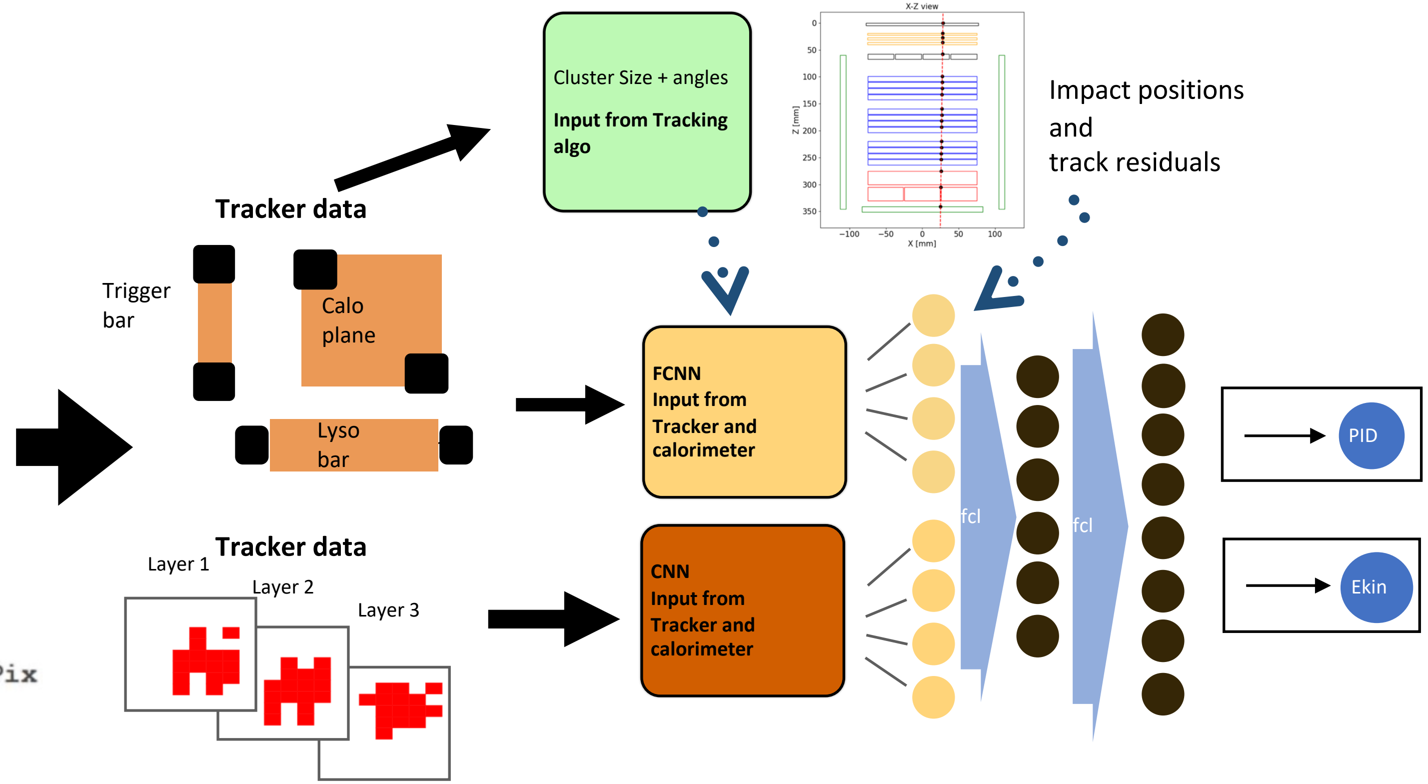
DL event reconstruction for energy reconstruction and PID

Simulation @CNAF

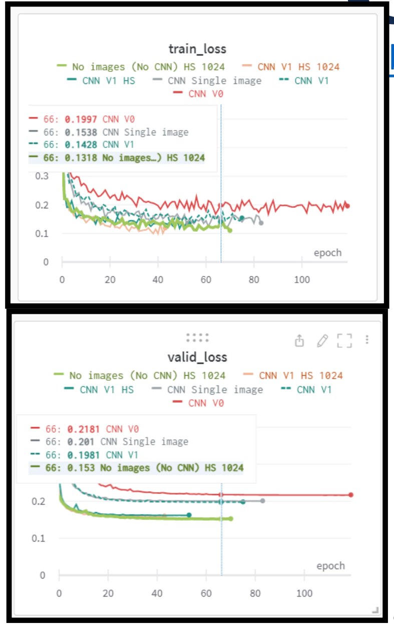


G4 + TROPix

ADC digitization

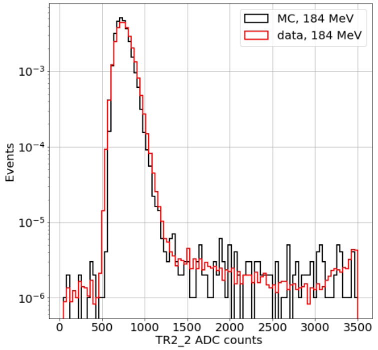


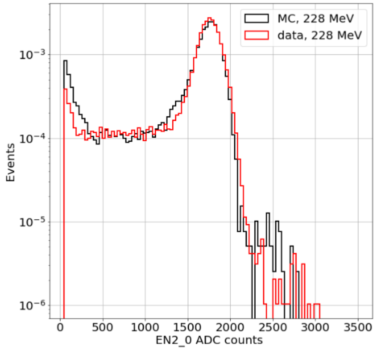
DNN training



berto Iuppa

Trained on HEPD-02
Digitized/Tuned Simulation





LIMADOU