ISOTDAQ 2023
International School of Trigger and Data AcQuisition

TDAQ for space experiments

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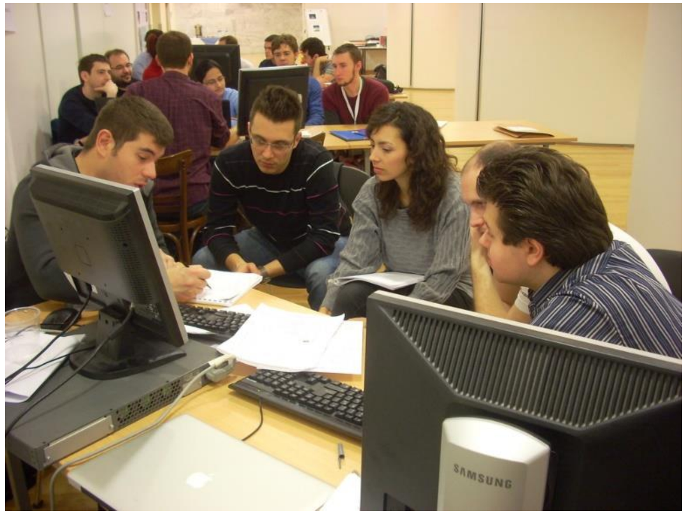
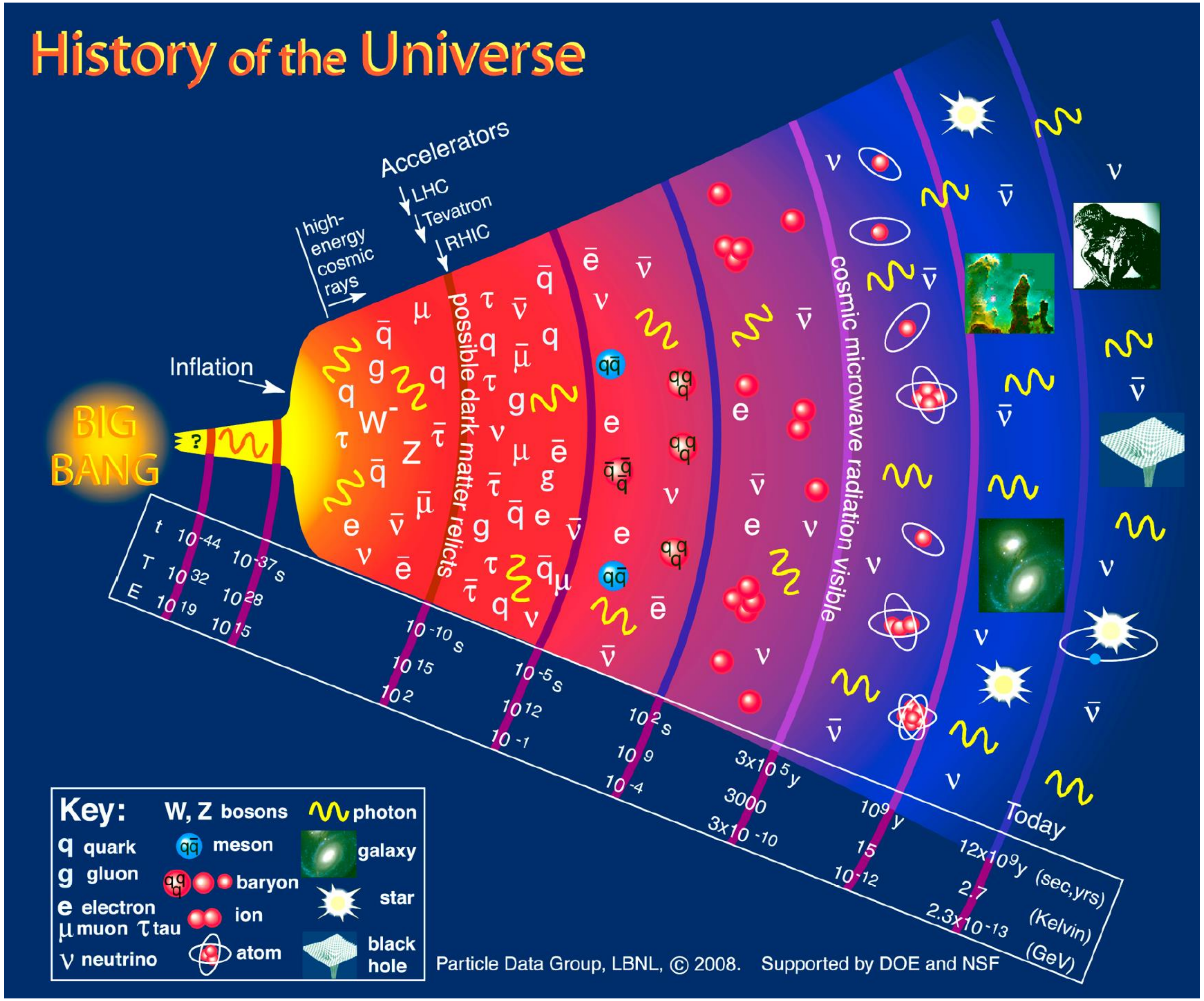
Thanks to… ISOTDAQ 2013



Outline

- ❑ Why space?
- ❑ Cosmic rays
- ❑ Challenges for electronics in space
- ❑ Space qualification
- ❑ Examples of TDAQ in space

Space: why bother?



Deep connection between very small and very high distances!

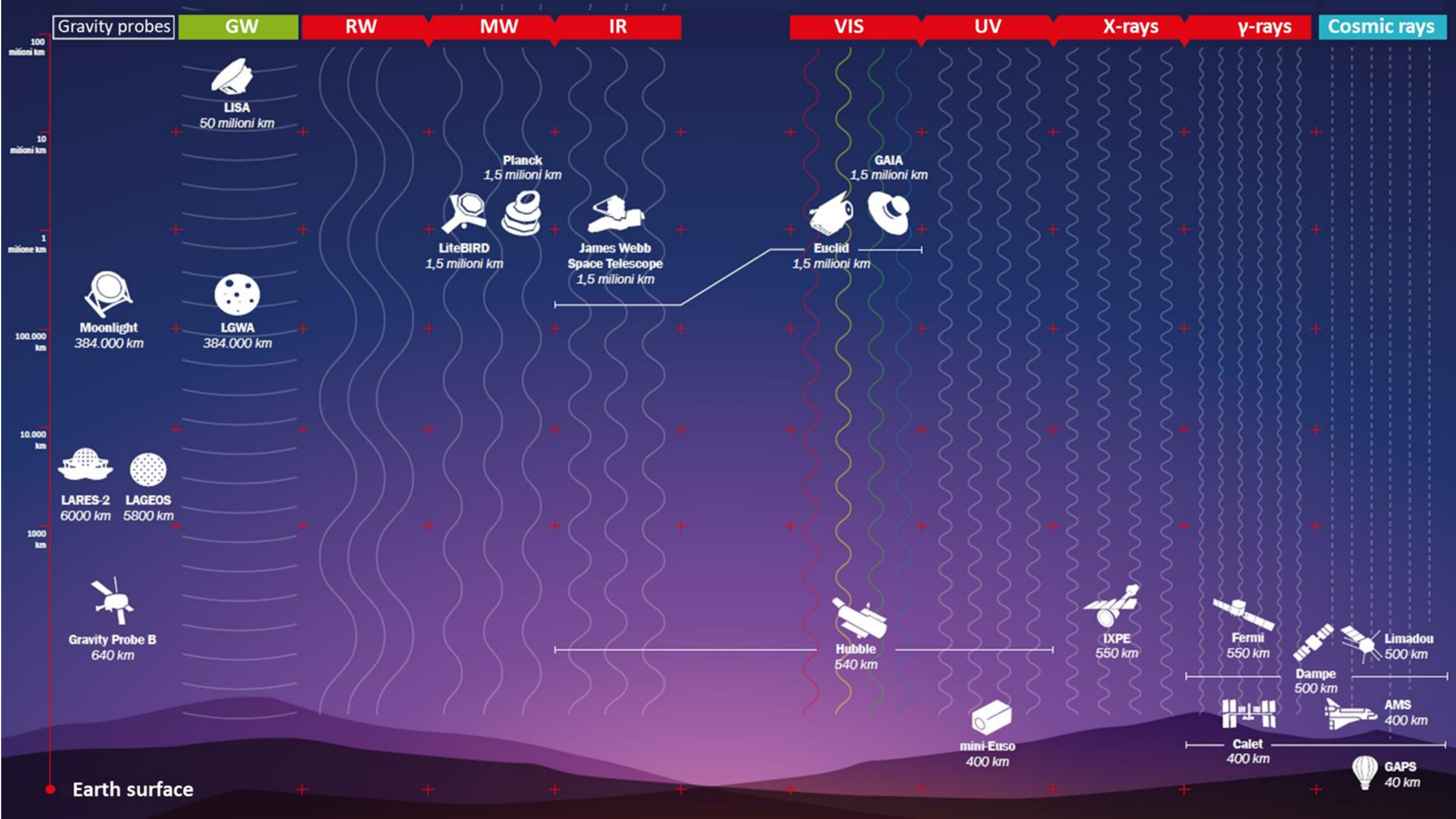
Accelerator Vs Space

- Particle physics developed by studying CR in the Earth's atmosphere: positrons, muons, pions and strange particles were revealed detecting CR or their interaction products
- 40 years of technological efforts to reproduce CR energies with accelerators and to compete in intensity

Accelerators based experiments
- Rapid evolution
- Huge technological effort
- Huge number of channels
- Power limitation mainly to reduce thermal problems and heating
- Radiation hardness is a real challenge
- Reliability in the harshest and not accessible parts
- Cost/large scale applications

Space-based experiments
- Traditionally used to 'old and safe technologies': significant 'philosophical changes' in the last decades
- Reduced power consumption
- Limited radiation hardness: Single Event Effects
- Reliability
- Harsh environment
  - Launch phase
  - Thermal environment

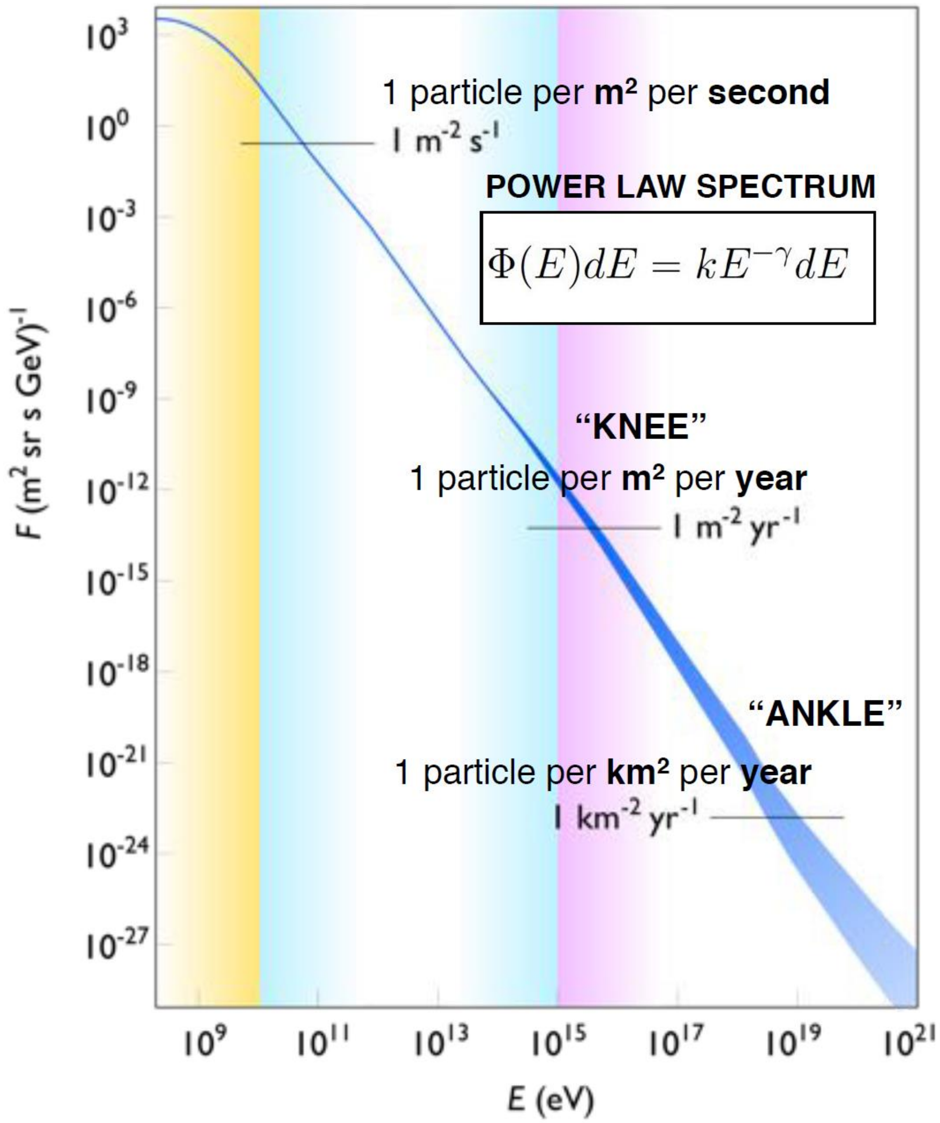
Shared software and hardware **solutions** and **common challenges**:
- Ever-increasing volume of data
- Need for fast and close-to-real-time analysis of the data



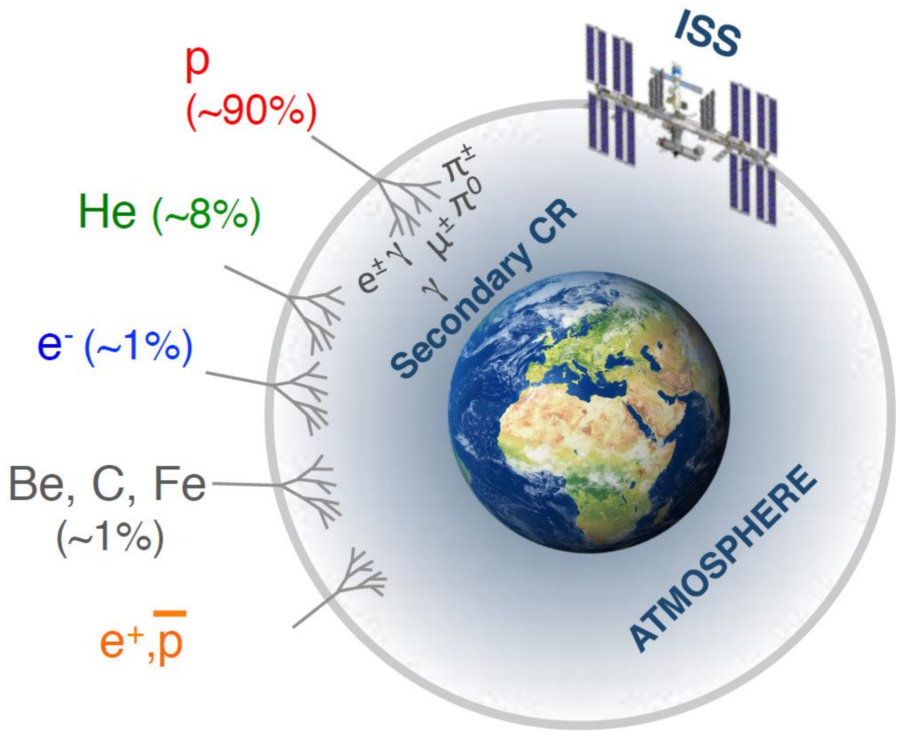
Gravity probes
GW
RW
MW
IR
VIS
UV
X-rays
γ-rays
Cosmic rays
100 milioni km
10 milioni km
1 milione km
100.000 km
10.000 km
1000 km
LISA
50 milioni km
Planck
1,5 milioni km
GAIA
1,5 milioni km
LiteBIRD
1,5 milioni km
James Webb Space Telescope
1,5 milioni km
Euclid
1,5 milioni km
Moonlight
384.000 km
LGWA
384.000 km
LARES-2
6000 km
LAGEOS
5800 km
Gravity Probe B
640 km
Hubble
540 km
IXPE
550 km
Fermi
550 km
Limadou
500 km
Dampe
500 km
AMS
400 km
mini-Euso
400 km
Calet
400 km
GAPS
40 km
Earth surface

- ❑ Why space?
- ❑ **Cosmic rays**
- ❑ Challenges for electronics in space
- ❑ Space qualification
- ❑ Examples of TDAQ in space

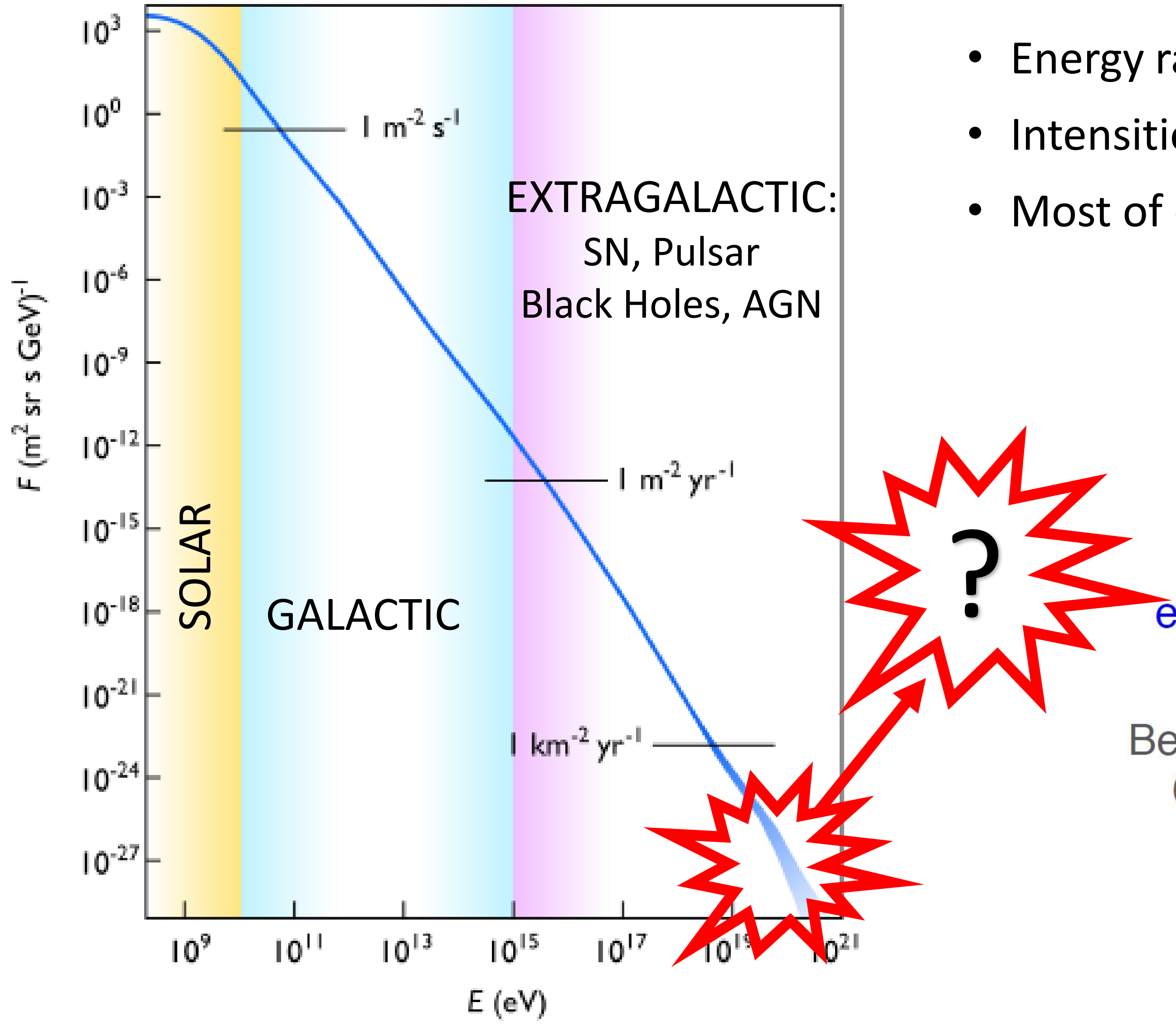
Cosmic rays



- Energy range up to 10^{20} eV
- Intensities spanning 30 orders of magnitude
- Most of cosmic rays are protons and nuclei



Cosmic rays



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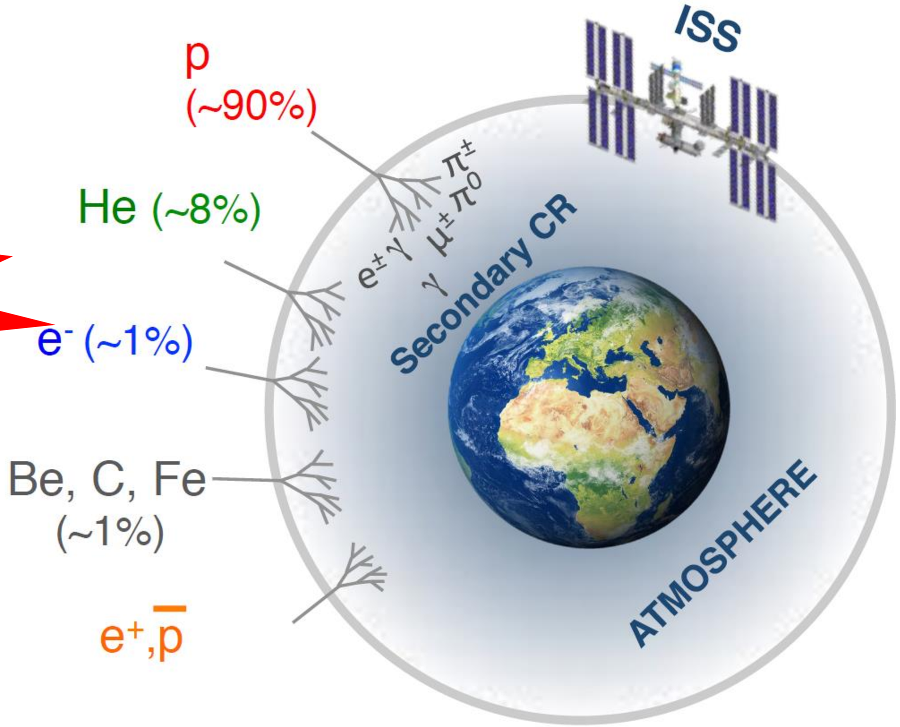


What have we learnt from CR?

Astrophysics

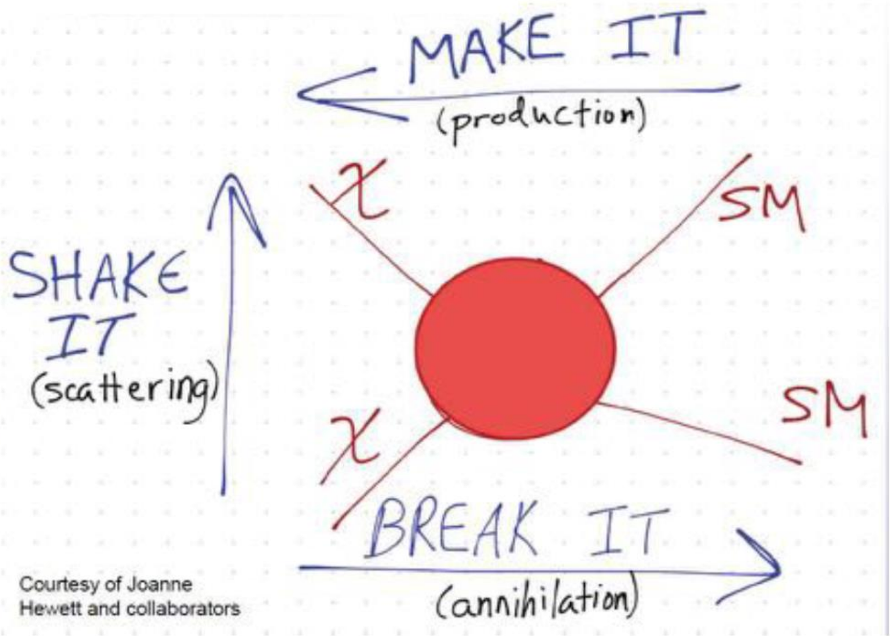
- Origin of CR
- Acceleration of charged particles up to PeV energies
- Peculiar sources (pulsars, quasars, black holes, ….)
- Star and solar system evolution
- Solar physics

Particle physics & cosmology

- Hadronic interactions and X-sections (above LHC energies)
- Matter/Antimatter asimmetry
- Dark Matter searches

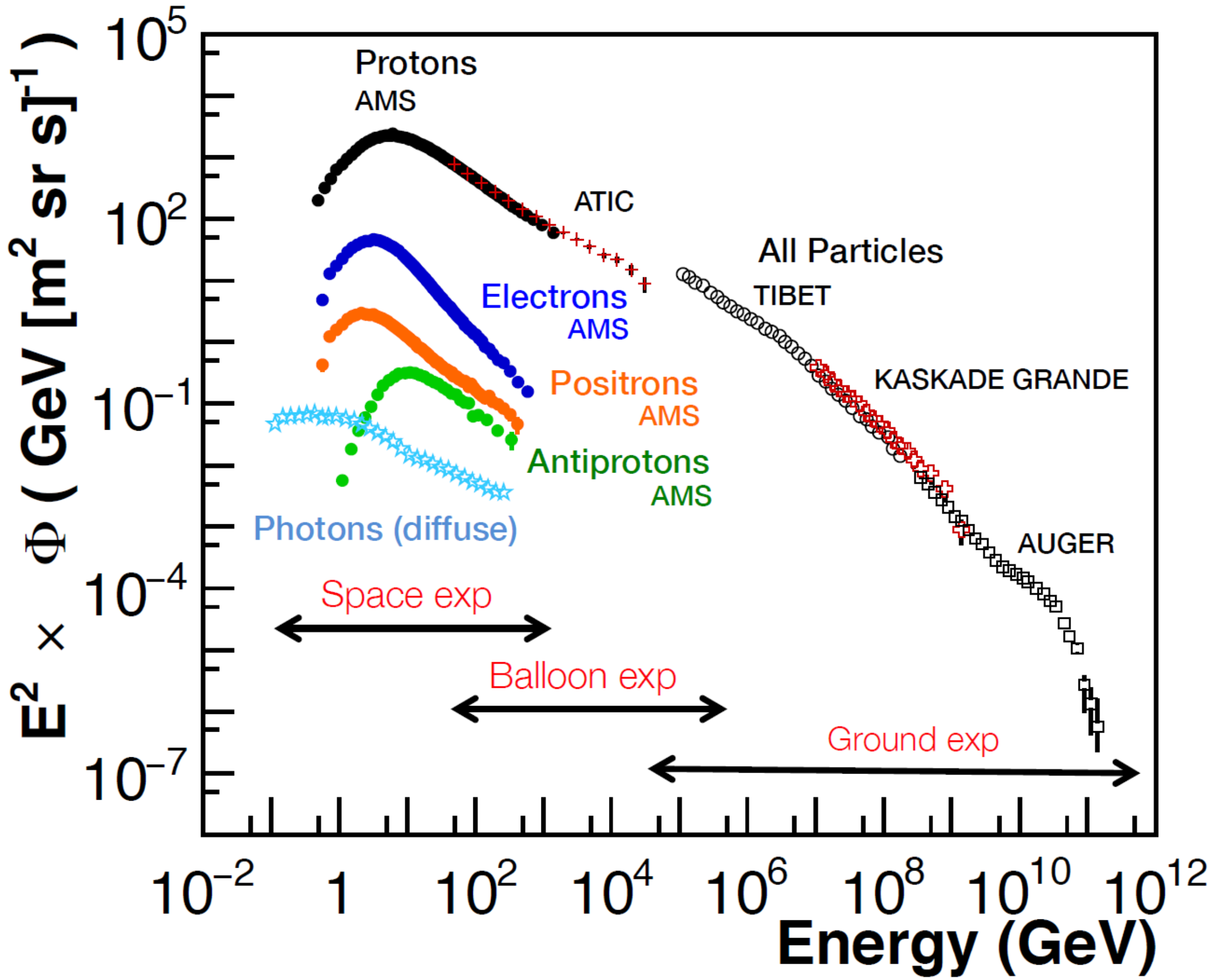
LHC + future colliders

Underground nuclear recoil experiments (DAMA, CRESST, Edelweiss, LUX, …)

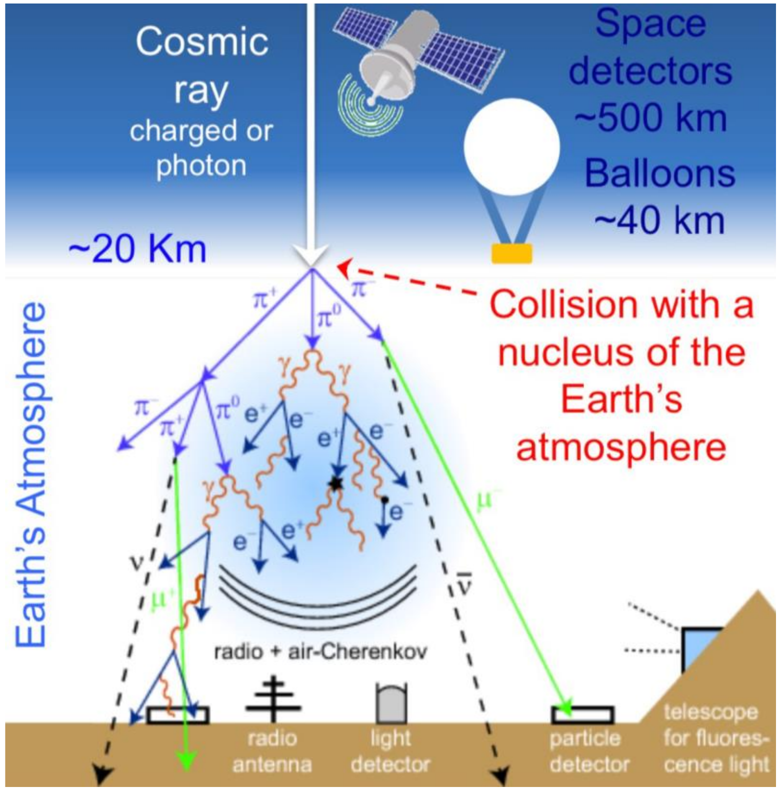


Cosmic Ray Experiments (Fermi, Pamela, AMS-02, DAMPE, Gaps,….)

Experimental detection

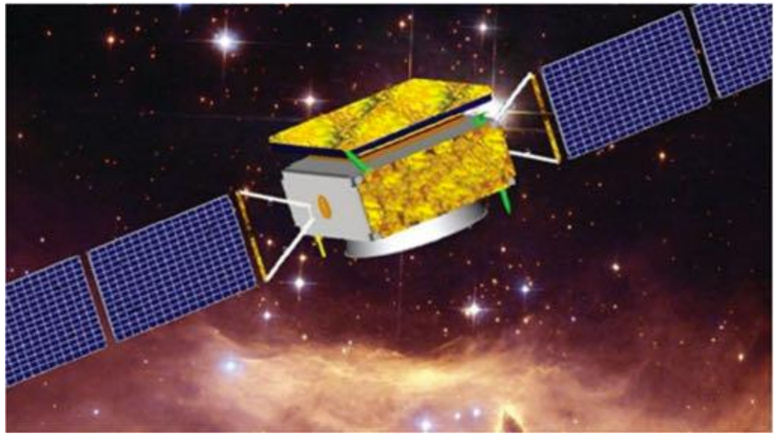


- Primary CRs interact with atmosphere: only secondary CRs reach the ground
- Flux steeply falling as function of energy: need large collection areas



Ground based experiments:
- ✓ large collection areas, needed for TeV –Eev CR
- χ only indirect measurements (highly rely on MC simulations)

Space Borne experiments



✓ Direct measurements outside atmosphere

✓ Continuous duty cycles, typically many years of lifetime

✓ Field of view covering the whole sky

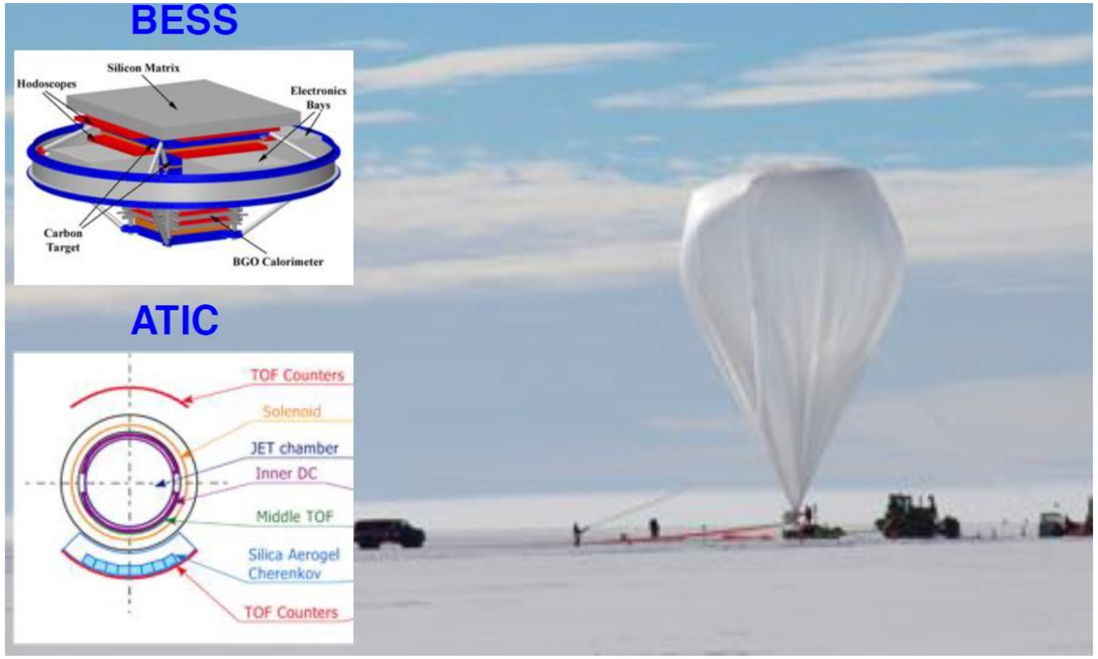
χ Smaller acceptances

χ Operation in space and communications not trivial

χ Expensive

χ “Use once and destroy”

Balloon experiments



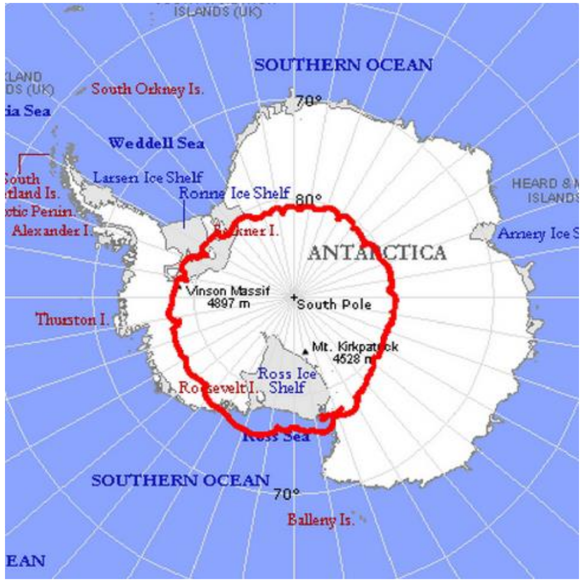
✓ Larger acceptances than space borne experiments

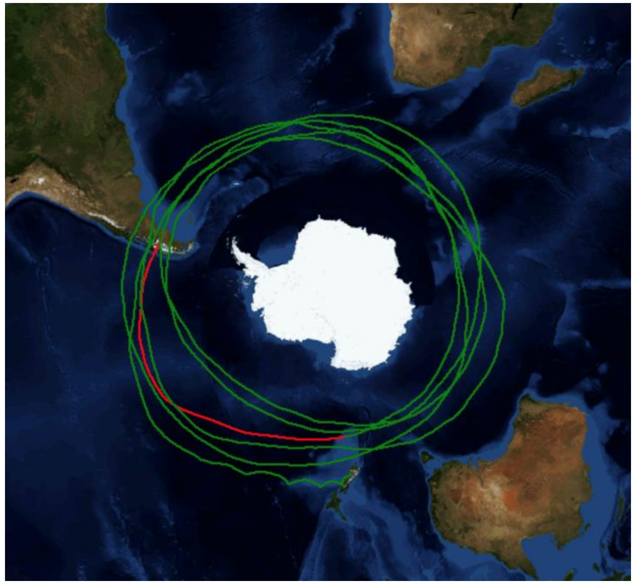
✓ Direct measurements

✓ The payload can be recovered

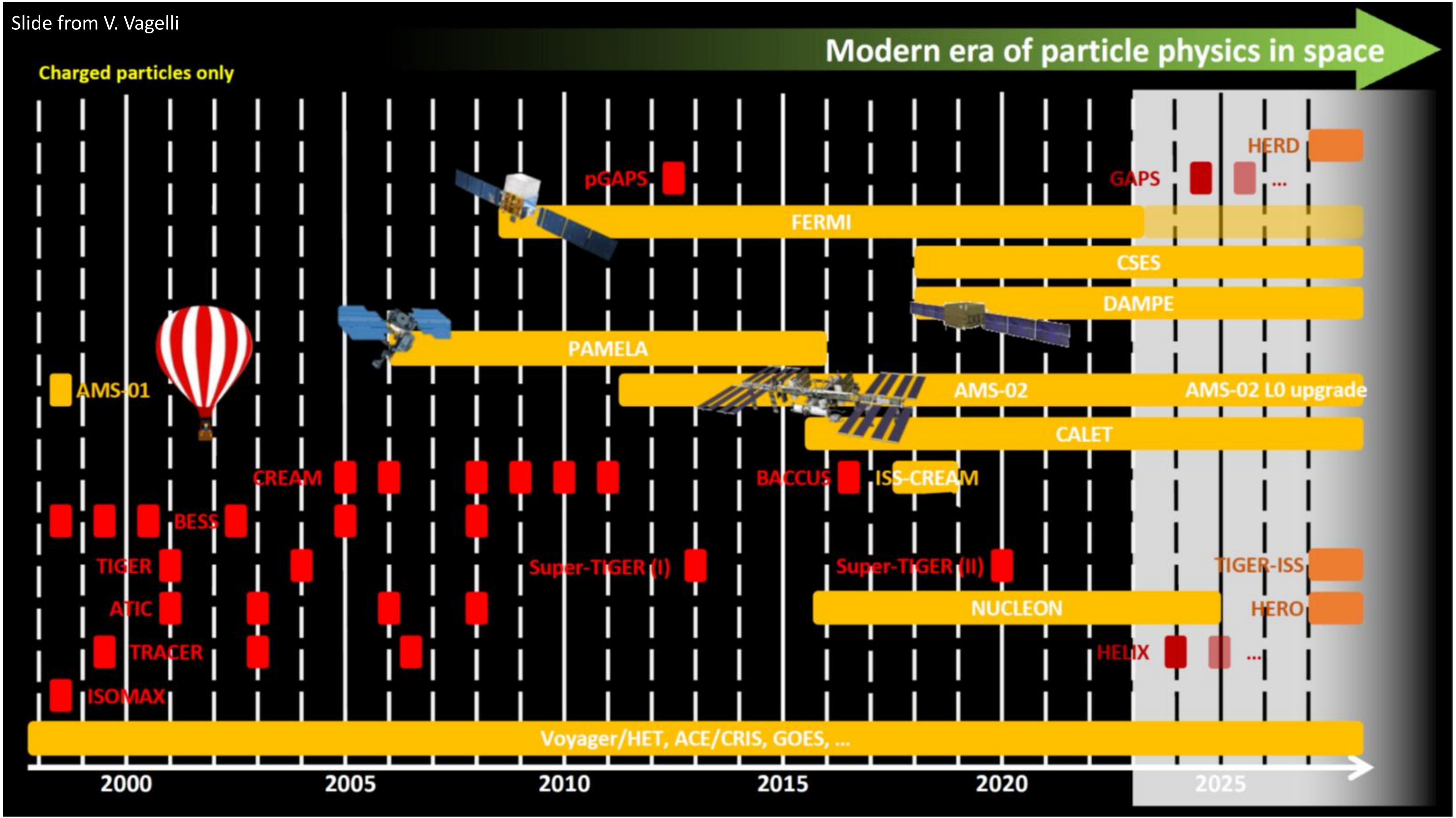
χ Orbit limited at poles for maximum 1 month

χ Residual atmosphere above the payload





Cosmic rays from space since 2000



- ❑ Why space?
- ❑ Cosmic rays

❑ Challenges for electronics in space

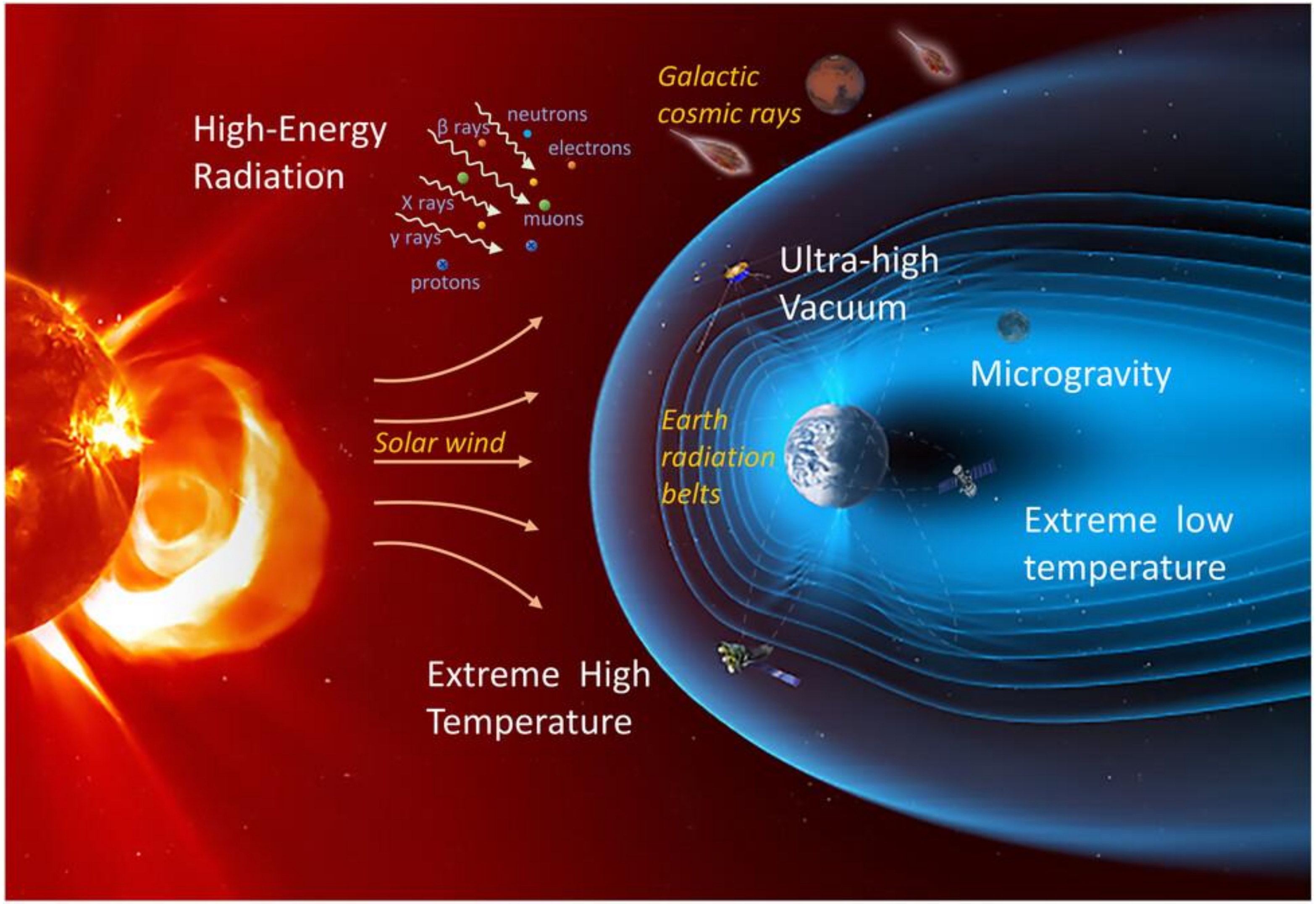
- ❑ Space qualification
- ❑ Examples of TDAQ in space

Getting to space

Mechanical stress at launch: huge mechanical vibrations can cause problems, such as resonance, in the electronic components

- Static acceleration
- Random vibration
- Sinusoidal vibration
- Pyroshock

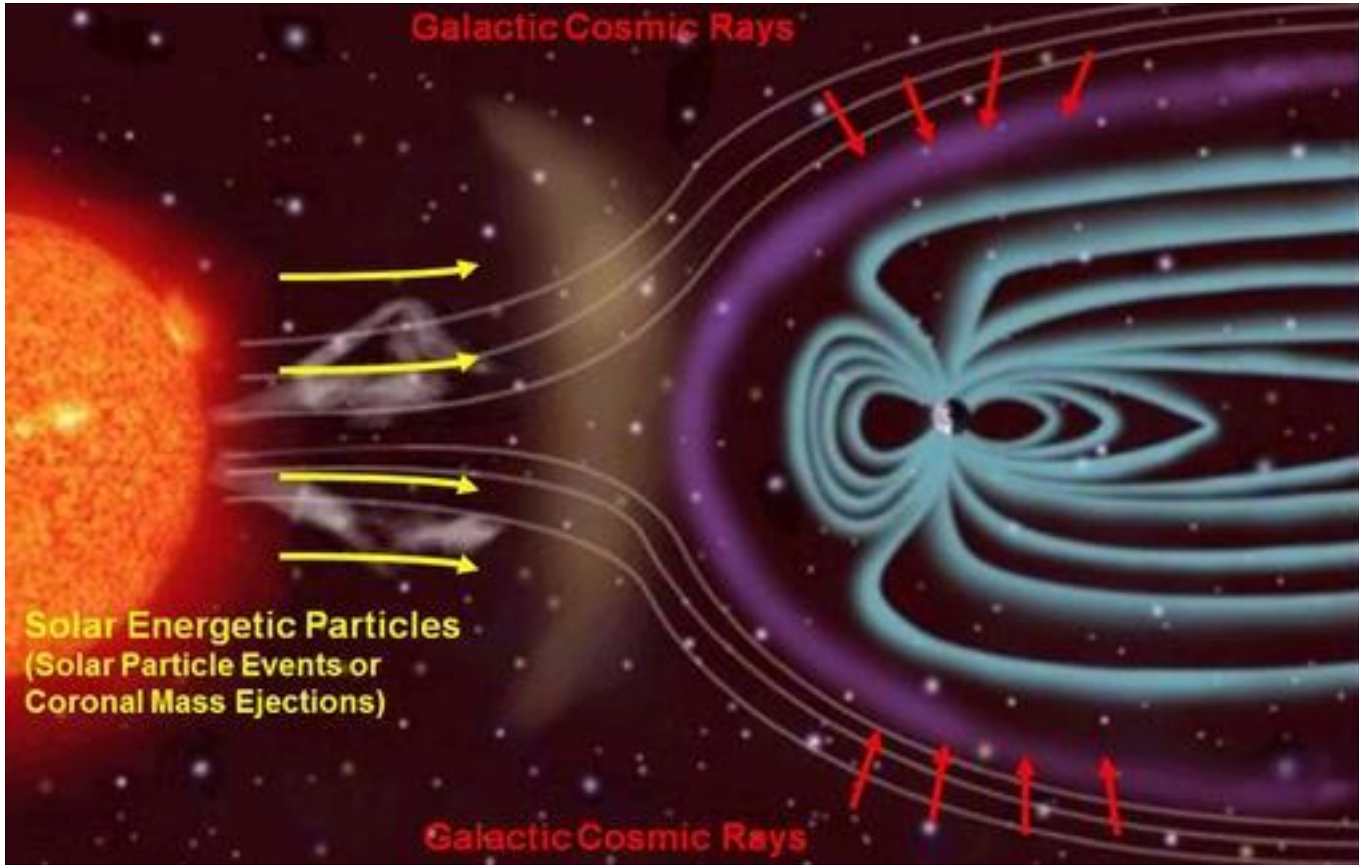
The hard life of electronics in space



Space is a harsh environment from many points of view:

- **Thermal**: extreme temperature variations due to Sun-light (seasonal, day-night effects): no atmosphere, hence no heat dissipation
- **Vacuum**: prevents heat dissipation, can cause outgassing and it's a favorable environment for tin whiskers
- **Electromagnetic**: high levels of contamination on surfaces can contribute to electrostatic discharge

Cosmic rays, aren't they dangerous?



Radiation: large variations in the levels of and types of radiation a spacecraft may encounter (Low Earth Orbit, Geostationary Orbits or Interplanetary Missions). The radiation levels also vary with the solar cycle.

The radiation environment close to Earth is divided into two categories:

- particles **trapped** in the Van Allen belts: energetic protons, electrons, and heavy ions
- **transient** radiation: galactic cosmic ray particles and particles from solar events (coronal mass ejections and solar flares)

There are two primary ways that radiation can affect satellite electronics:

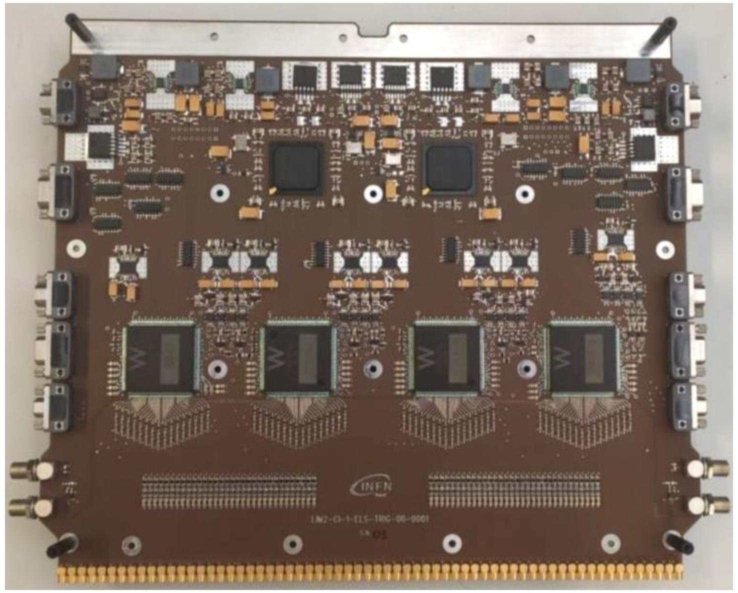
- Total Ionizing Dose (TID): long-term failure mechanism
- Single Event Effects (SEEs): instantaneous failure mechanism (soft/hard)

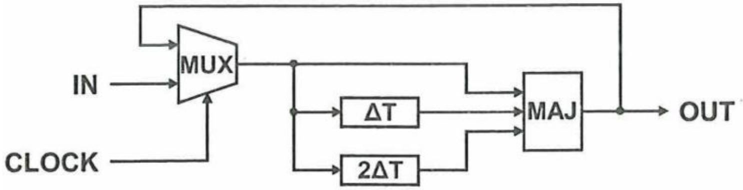
Electronics in space, how to survive

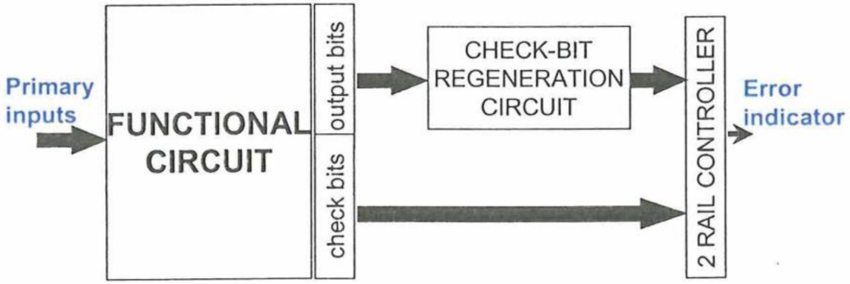
Careful design, model validation and qualification are needed to ensure highest possible reliability

- **Conductive**/radiative heat transfer
- **Ceramic** rather than plastic components to avoid outgassing
- **Lead-based** solder to eliminate the risk of electrical shorts
- Coating/**potting** to prevent discharge and improve mechanical resistance
- Use of **polyimide** material for the manufacturing of PCBs to improve resistance to mechanical stresses
- **Hot/cold redundancy** (i.e. two identical copies of the circuit completely independent of each other that cannot be powered at the same time) to increase overall reliability during flight against hard errors
- High reliability: devices with heritage or beam tested

Programmable electronics in space





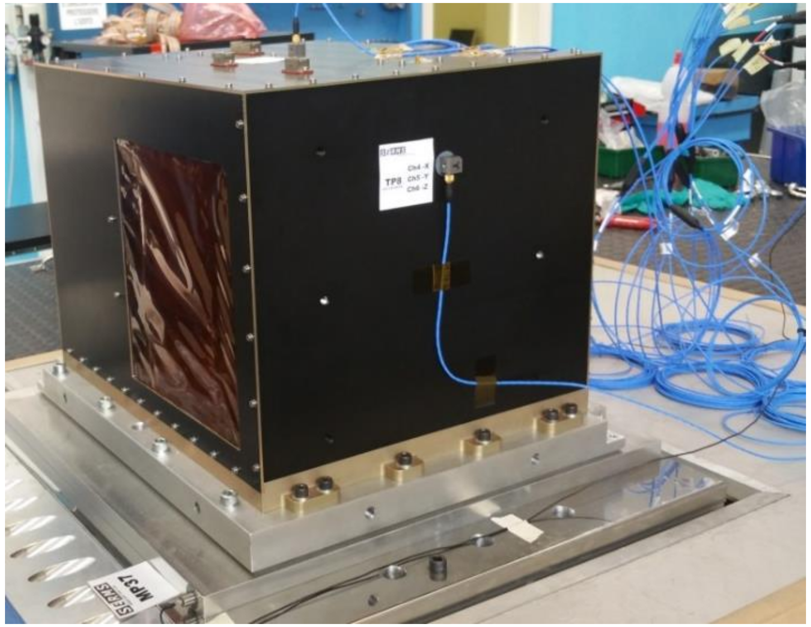


More complex electronics, greater risk from radiation effects

- Thinner IC are less sensitive to TID radiation
- Reduced IC scaling increases SEEs: less energy is required to produce Single Event Transient (SET) and Single Event Upset (SEU)
- With higher frequency devices, SETs can turn into more SEUs, increasing the number of functional interruptions. Mitigation techniques for higher speed transient signals are more challenging
- Design choices the increase the tolerance to radiation at primitive, macrocell and functional level [area, power and speed penalties]
  - triple-modular design (time/space): comparison logic to provide the output before performing a recovery operation on the failed system
  - EDAC
- Protection and recovery mechanisms of memories
  - Error checking and correction for ensuring that memory arrays affected by SEEs do not cause SEUs

- Why space?
- Cosmic rays
- Challenges for electronics in space
- **Space qualification**
- Examples of TDAQ in space

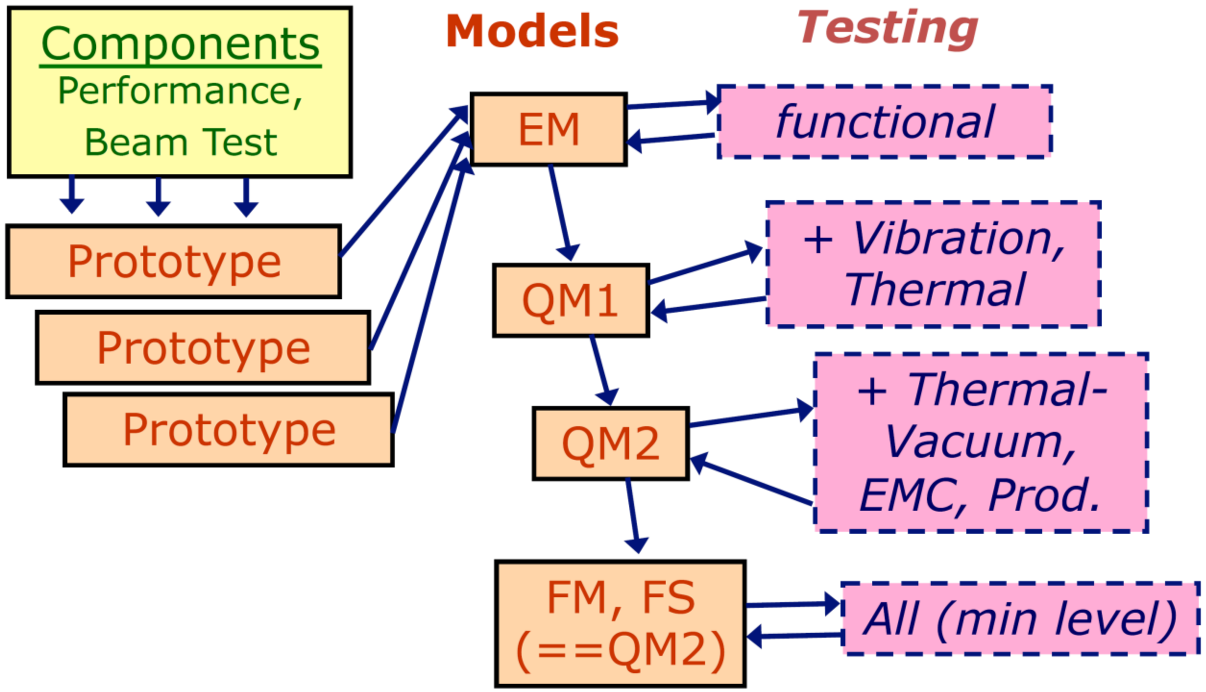
Space qualification



- **Functional**/electrical tests of prototypes to assure that the behavior of the component satisfies all the expected functional performances and specifications after each stress test
- **Mechanical** tests:
  - shock (only for QM)
  - sinusoidal vibration
  - random vibration
- **Thermal** tests:
  - ambient-pressure thermal-cycles
  - in-vacuum thermal-cycles
  - burn-in
- **ElectroMagnetic Compatibility** test
- Calibration/beam test (hopefully)
- Satellite **communication** system compatibility test

Thermal and vacuum test necessary for ballons too

Payload models



Electrical Model (EM): mock-up of the payload with all electric and electronic interfaces (power bus, TM/TC, CAN-bus and RS422) with satellite

- demonstrate HW and SW design
- verify electric and electronic compatibility w/ satellite
- test the compatibility w/ Electrical Ground Support Equipment

Structural and Thermal Model (STM): complete mechanical mock-up with dummy sensors and electronics to emulate the real heat dissipation

- validate the structural and mechanical design
- test the payload thermal control design

Qualification Model (QM): identical to the Flight Model (FM), developed and submitted to a complete qualification test campaign to assess the design and the technological solutions, and to demonstrate its performance

Additional requirements on TDAQ for space

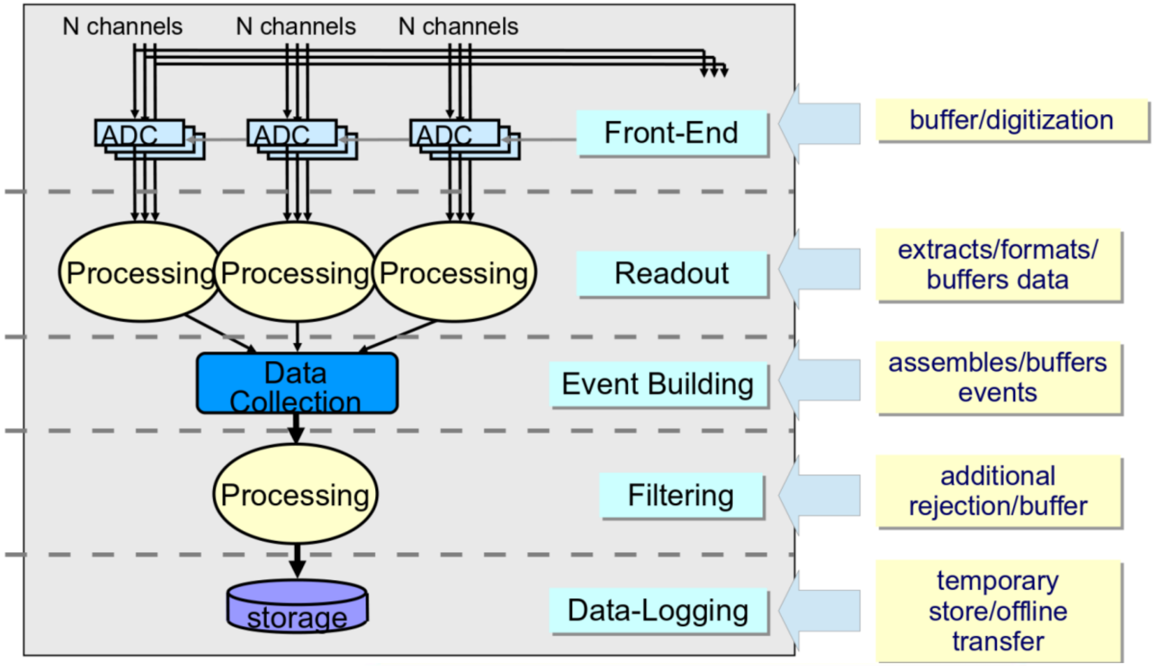
- **Low power**
- **Lightweight**
- **Limited bandwidth** for data transfer (and command broadcasting too!)
- Guarantee reliability and performance over a very long time
- Reliable communication protocols (not the fastest) and connectors
- ITAR constraints
- Rad-hard parts generally lag the state of the art by about 10 years
- Can't shield from cosmic rays

DAQ operations depend on orbit position: increase of trigger rate in polar region (low magnetic field and trapped particles) and in the South Atlantic Anomaly

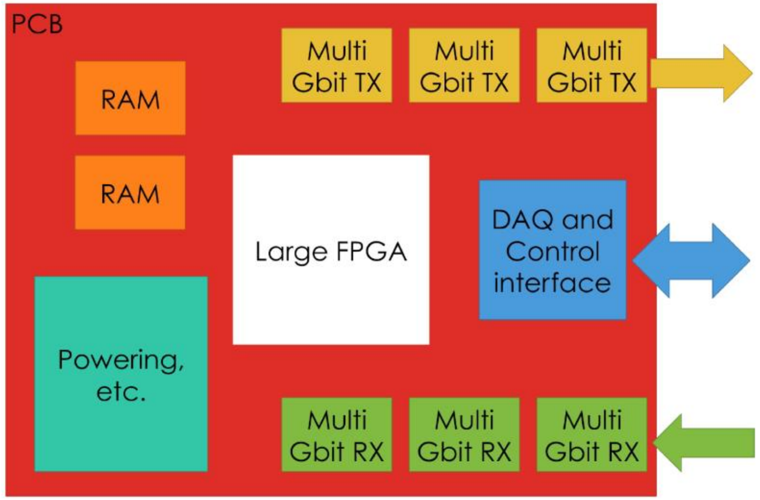
Additionally… everything has to work automatically: no shifters, no possibility to fix anything

- Safety and recovery procedures in case of system failures/issues
- Watchdog for reset and power procedure
- Short data-acquisition runs

Generic DAQ hardware (for space)



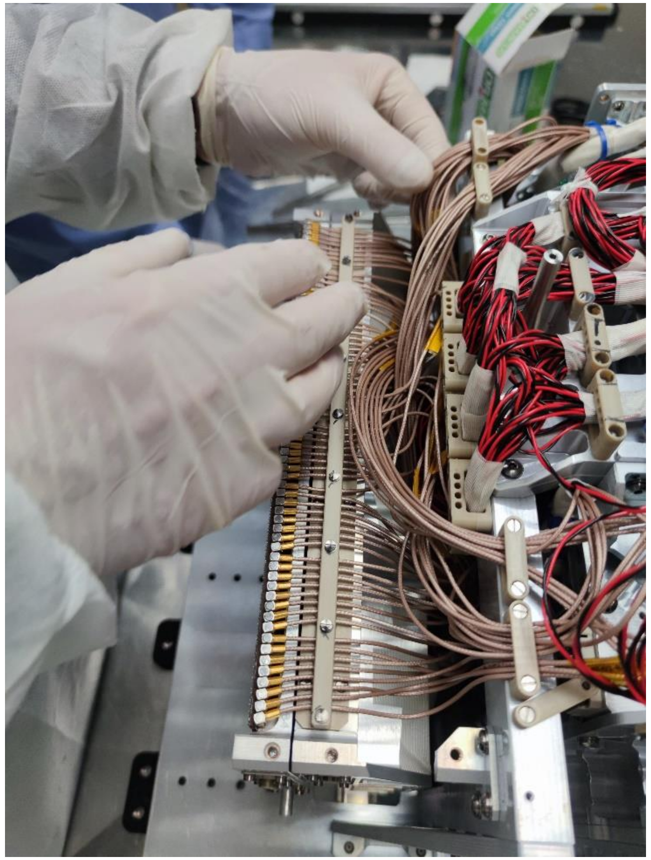
R. Ferrari's talk on Thu.

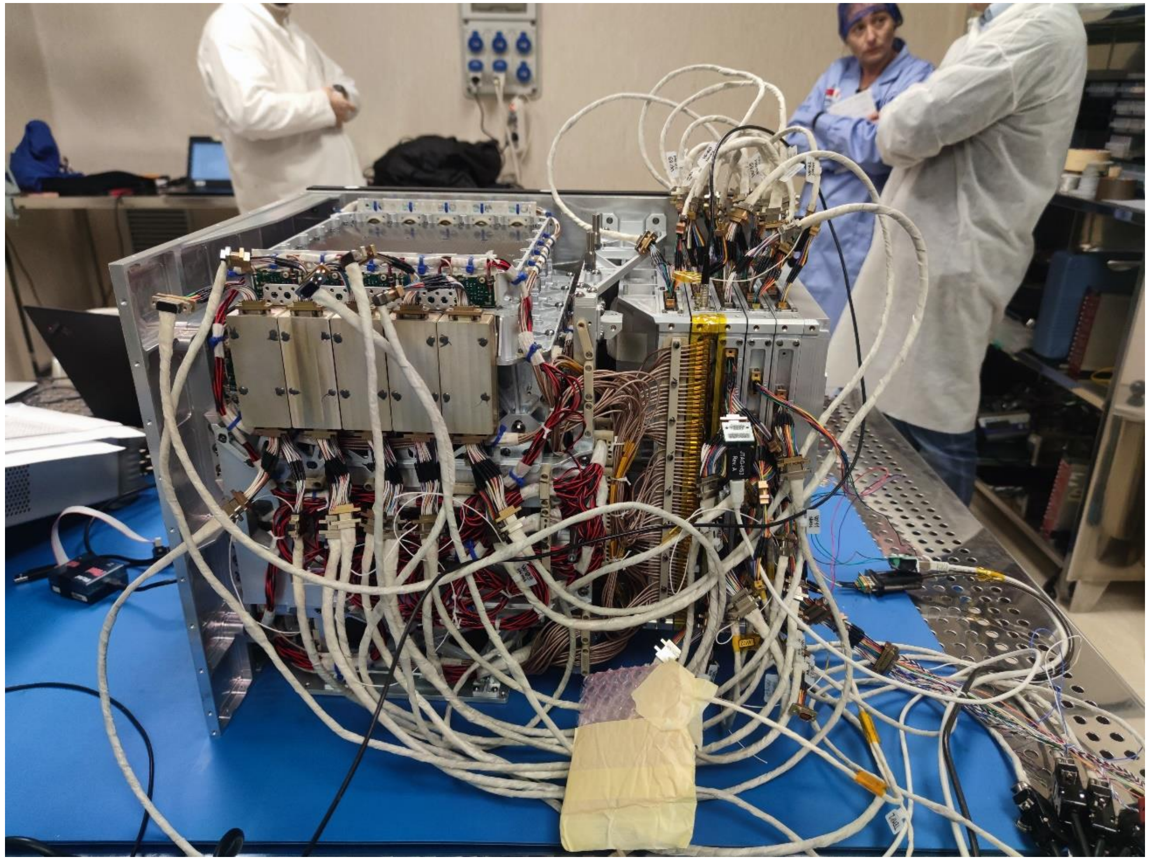


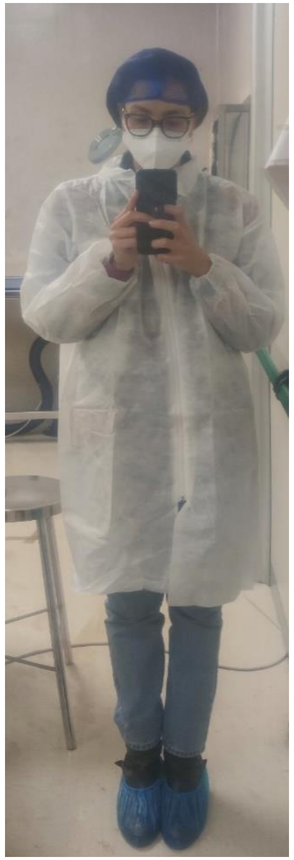
D. Rabady's talk on Fri.

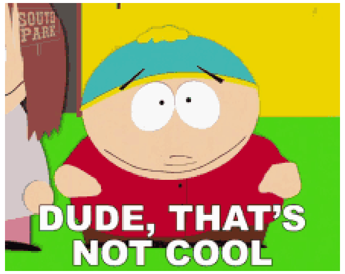
- Space-validated protocols for data transfer
- Front-end ASICs
- On-chip nonvolatile flash EEPROM to store the configuration of the FPGA logic structure
    - no susceptibility to TID
    - cross-section for SEE of the order of 10^{-4} cm^2/kbit, w/ negligible SEL/device
- Storage of non-volatile data (firmware and run-time data) on FRAMs and flash type memories:
    - Lower voltage to perform a write operation, which implies lower power consumption (1:21)
    - write operations are faster (16:1)
    - SEU response is good
    - Elevated device endurance: larger number of write cycles. Endurance is crucial issue because FRAMs are used to store the program codes of the DSPs, and detector calibration data calculated at every satellite orbit

TDAQ for space: life in a clean room









- ❑ Why space?
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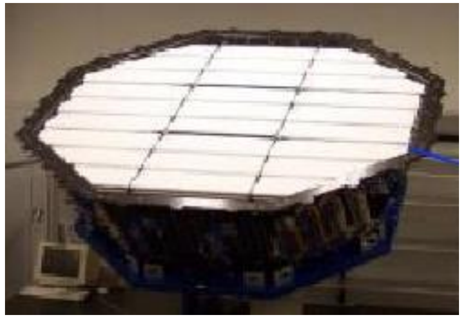
❑ Examples of TDAQ in space

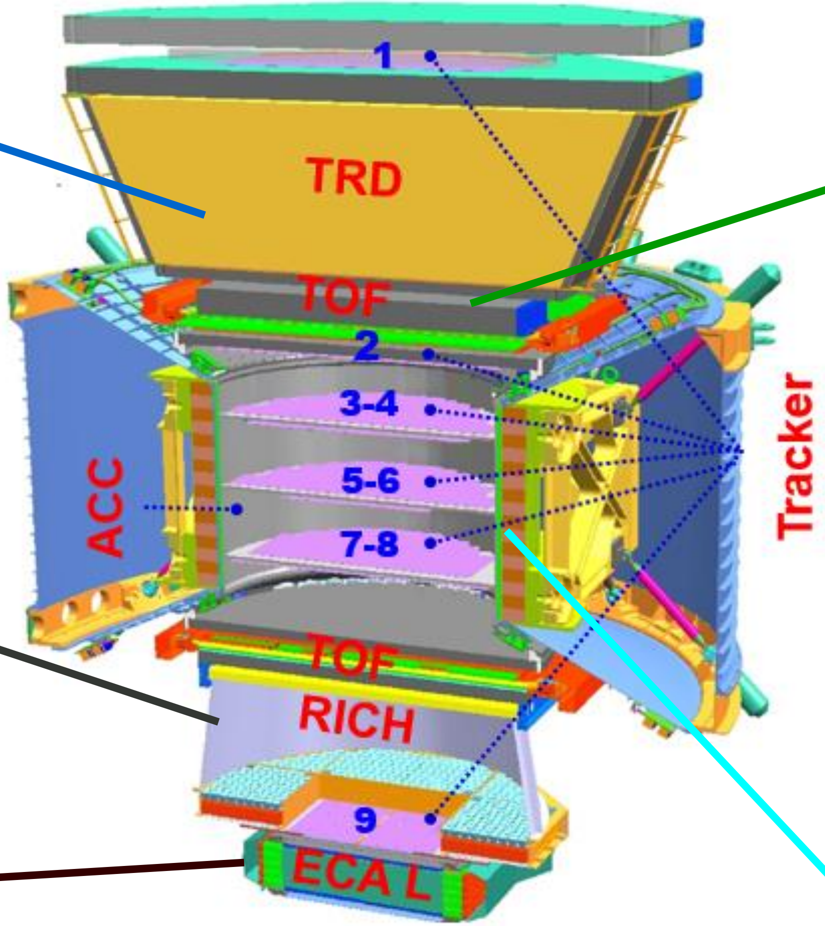
AMS: TeV precision spectrometer

TRD:
identifies e+/e-



RICH:
Z, E

Ecal:
E of e+/e-



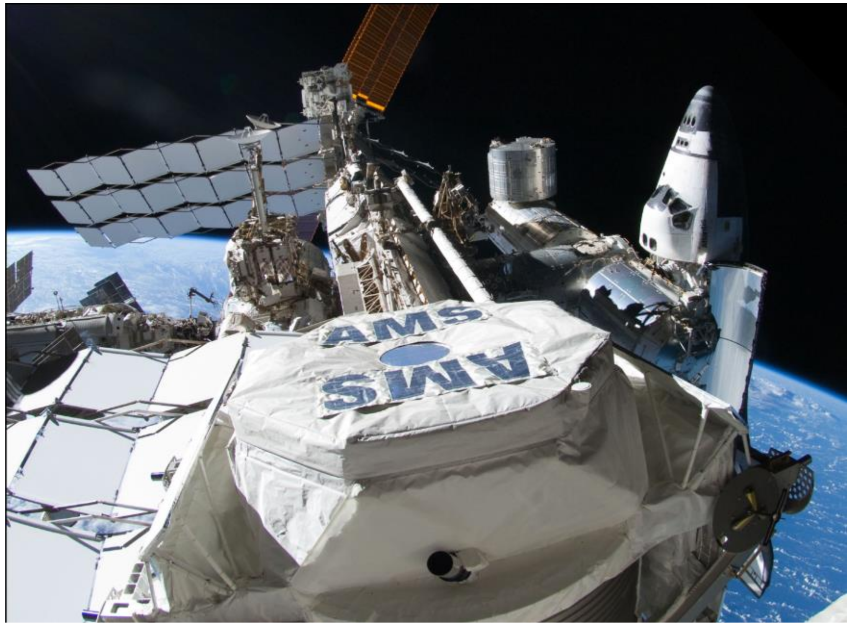
ToF:
Z, E

Silicon tracker:
Z, P

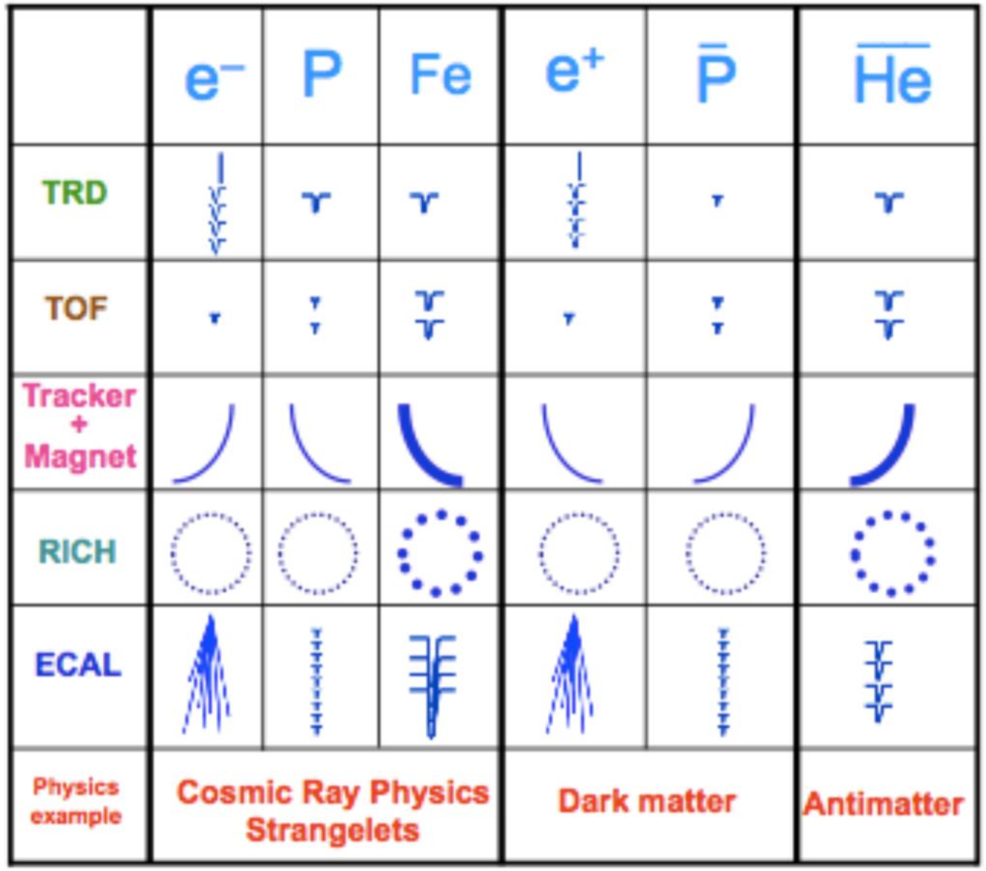
Magnet:
±Z

Particles and nuclei are defined by their charge (Z), energy (E) and momentum (P) which are measured independently

AMS characteristics



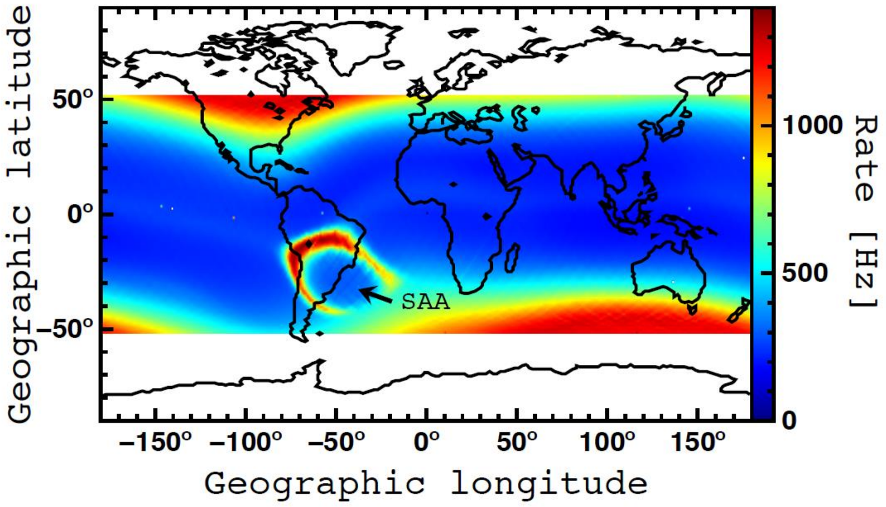
- ISS orbit period ~ 90min
- +/- 50 deg latitude covered
- Mission duration from 2011 until the end of the ISS life (it needed some refurbishment from the ISS crew)

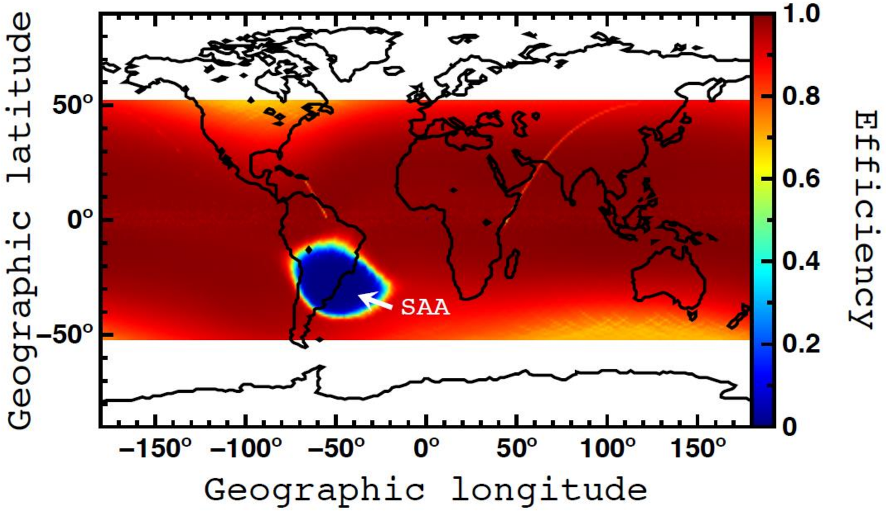


- Size 5 x 4 x 4 m^3
- 7500 kg
- Power 2500 W

- Data Readout 300’000 channels
- <Data Downlink> ~ 12 Mbps
- Magnetic Field 0.14 T

AMS DAQ





DAQ operations depend on orbit position: increase of trigger rate in polar region and in the SAA

For each trigger, the DAQ:

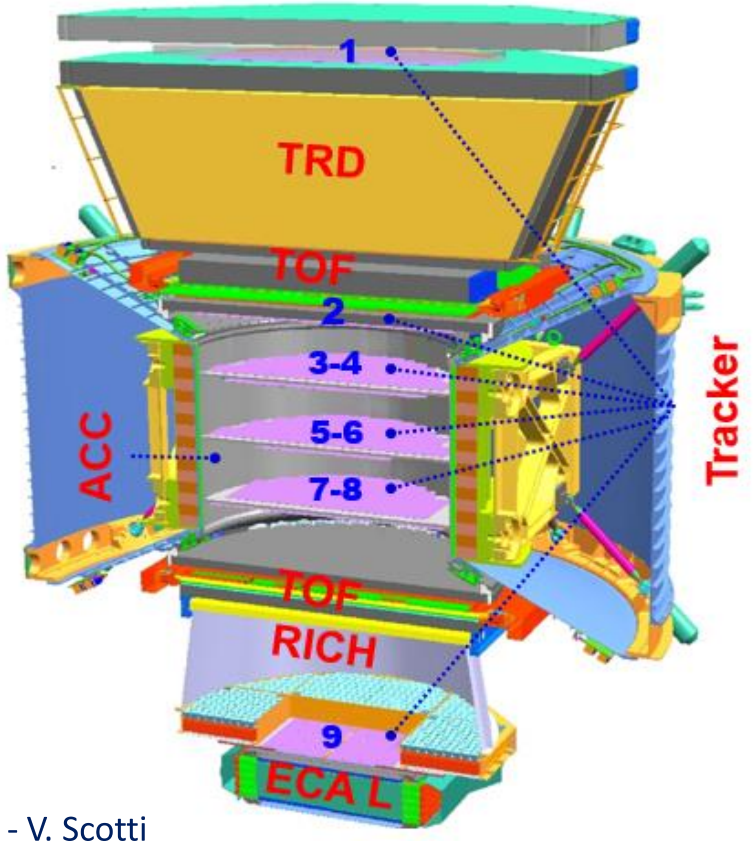
1. freezes the analog information on all the sensors (~300’000)
2. digitizes analog signals
3. package data to send to ground

The flux of CR through the detector is higher than the digitization capabilities: only a fraction of the CR crossing the detector has to be recorded

- Average rate ~700 Hz
- DAQ efficiency: 85%
- DAQ processing: O(100 µs – 1 ms)
- 60 millions particles/day
- 39 TB raw data/yr

AMS trigger

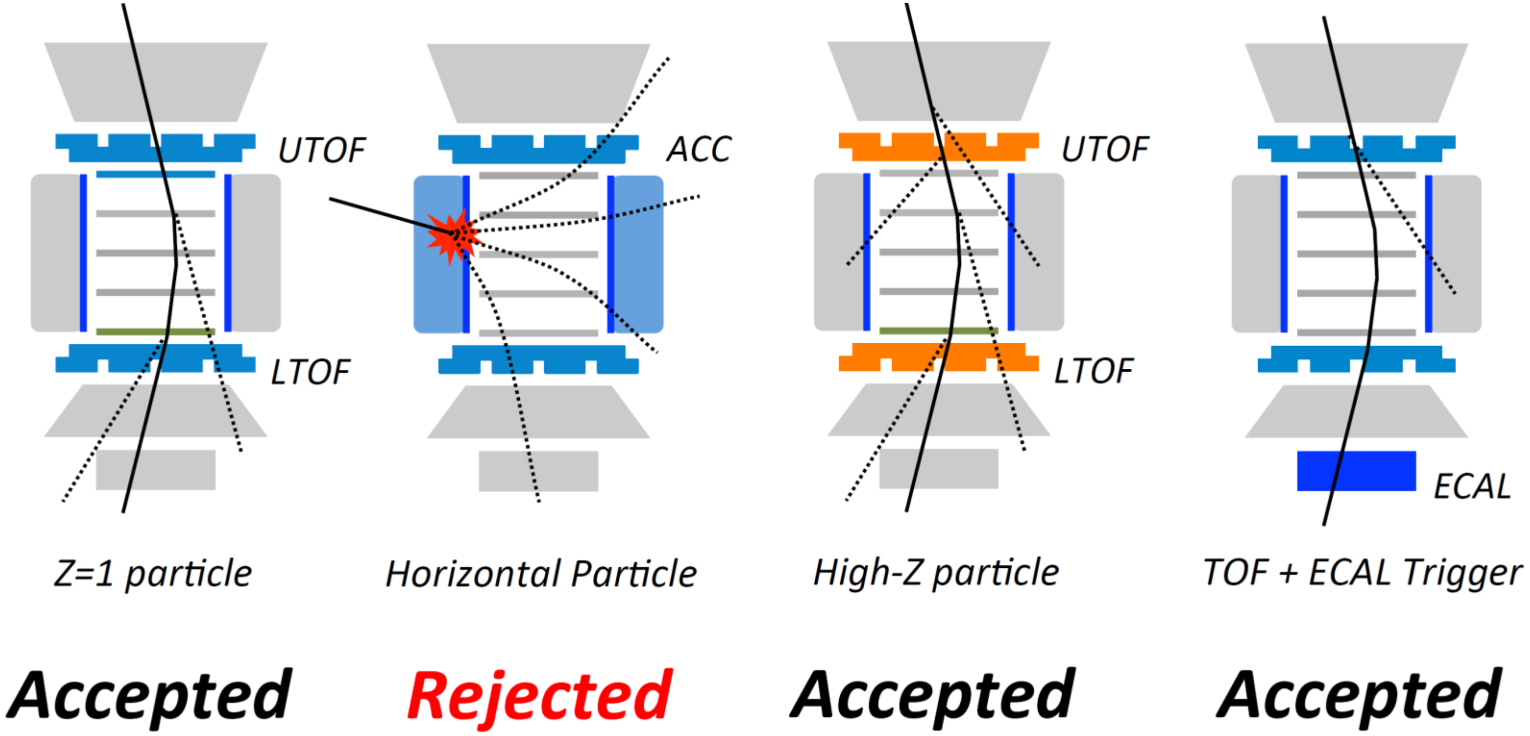
- the trigger needs to be fast enough to trigger readout system of the other sub-detectors
- a compromise between the maximum number of events stored with respect to the capabilities of data storage and transfer and event pileup
- largest efficiency while keeping the detector rate < 2kHz (bandwidth limitation)



AMS uses information from fast detectors combining it in a simple AND-OR logic:

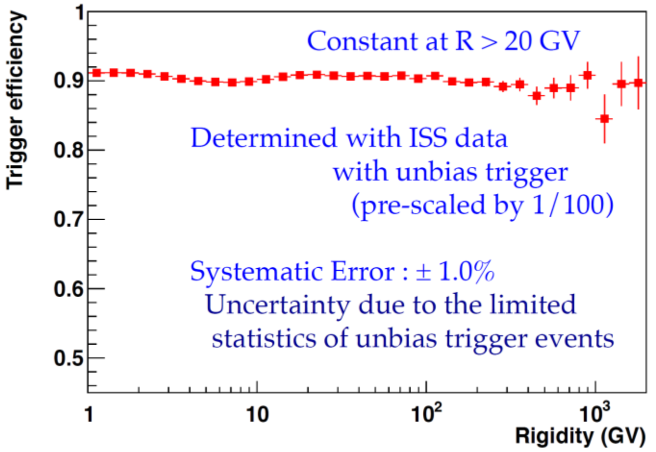
- the fast information of the TOF for charged CR
- the external anticoincidence to veto CR outside the acceptance
- the fast ECAL information for photons (that don't leave energy in the TOF)

AMS trigger topology



Global Trigger = OR between 4 triggers:

1. **unbias**: TOF 3/4, scaled by 100: efficiency close to 100%, no energy dependence, use to estimate the efficiency of other triggers
2. **proton**: TOF 4/4, Nacc = 0
3. **ion**: TOF 4/4 Signal>(Z=1), Nacc < 3
4. **electron**: TOF 3/4 HT, ECAL shower



AMS is able to identify 1 positron from 10^6 protons, unambiguously separate positrons from electrons up to a TeV

HEPD: multipurpose, precise compact detector

CSES-02: China Seismo-Electromagnetic Satellite

- Total Mass: 900 kg
- Orbit: 500 km, sun-synchronous, 97° inclination
- Design life cycle > 6 years
- Launch expected in 2023

Several payloads for electromagnetic and plasma measurements in the Van Allen belts

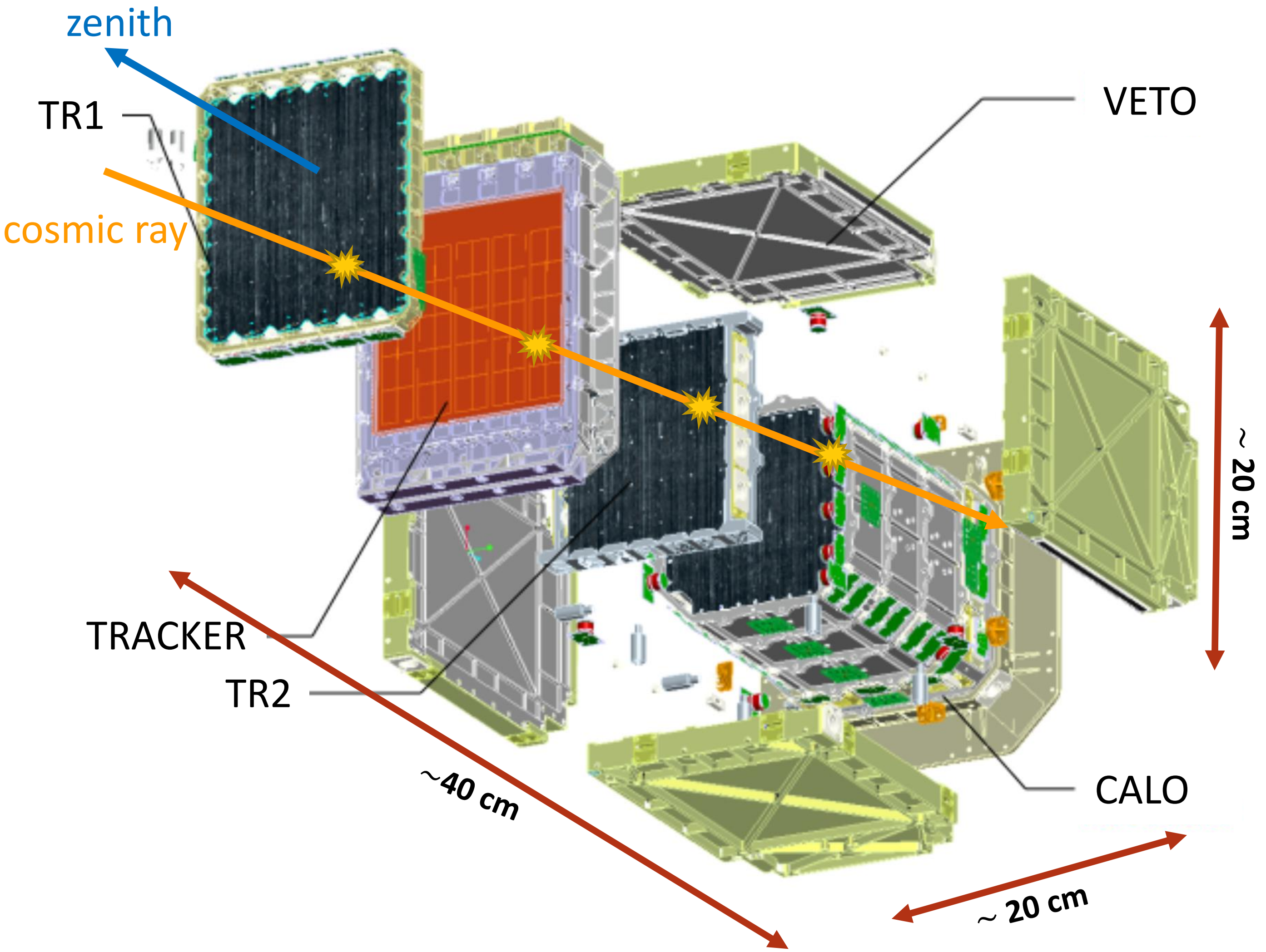
Low energy Cosmic Rays with energy 3 ÷ 300 MeV

For each particle:

- identification (proton, electron, nucleus)
- energy
- pitch angle

Goal: **maximize the geometrical acceptance** according to weight and power budgets constraints

Operative temperature	-10°+35°
Mass	< 45 kg
Power Consumption	< 45 W
Data budget	< 100 Gb/day

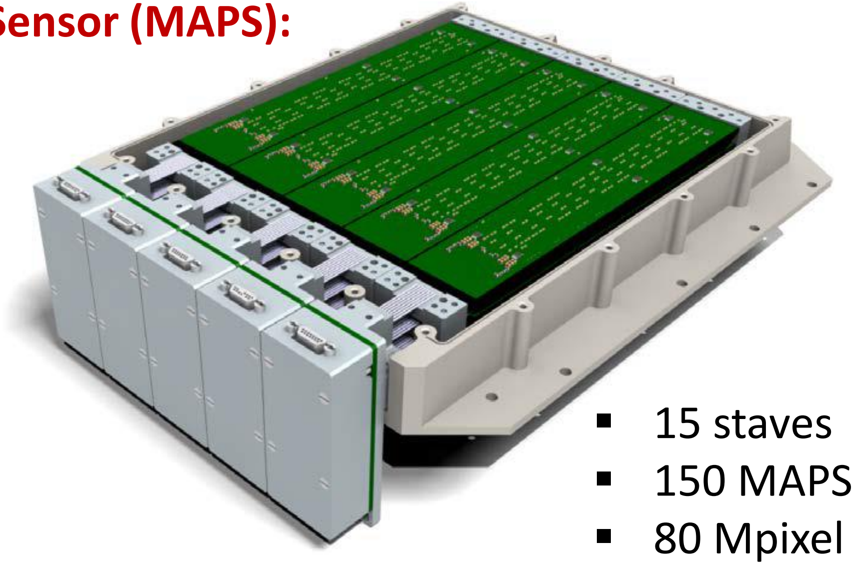


HEPD tracker

3 sensitive planes of 5 independent tracking modules Monolithic Active Pixel Sensor (MAPS):

- based on the MAPS developed for ALICE experiment at LHC
- ✓ reduces systematic uncertainties on tracking: up to 6x single-hit resolution
- ✓ no multi-hit degeneracy

- Each plane has 10 sensors of 512x1024 pixels in 15x30 mm^2
- Control and read-out based on ultra-thin (180 mm) flexible printed circuits

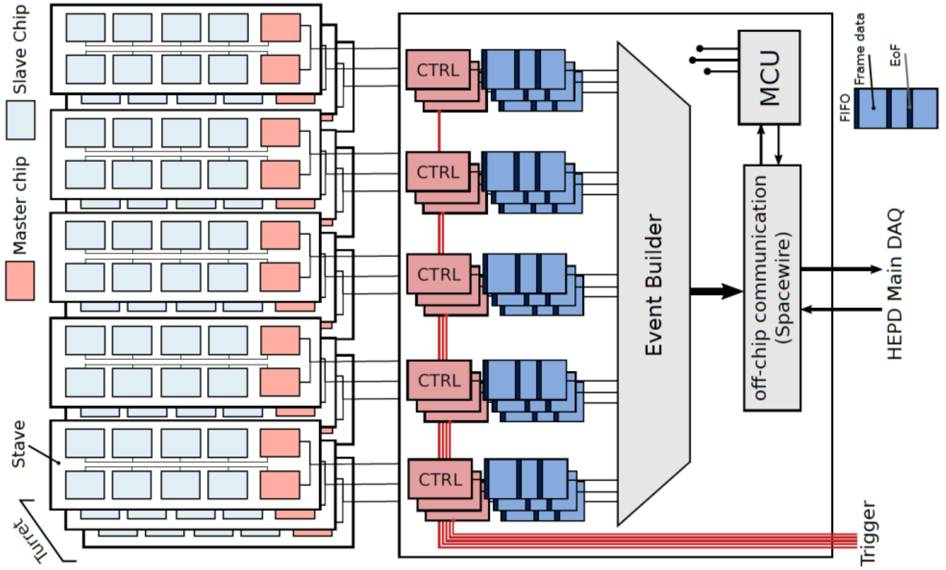


- 15 staves
- 150 MAPS
- 80 Mpixel

Challenges for use in Space:

- Tradeoff for mechanical supports: avoid multiple scattering but withstand launch acceleration and vibrations
- Heat dissipation and material outgassing in vacuum
- Limited power budget

Huge technological effort to spatialize the technology



HEPD DAQ

Data acquisition:

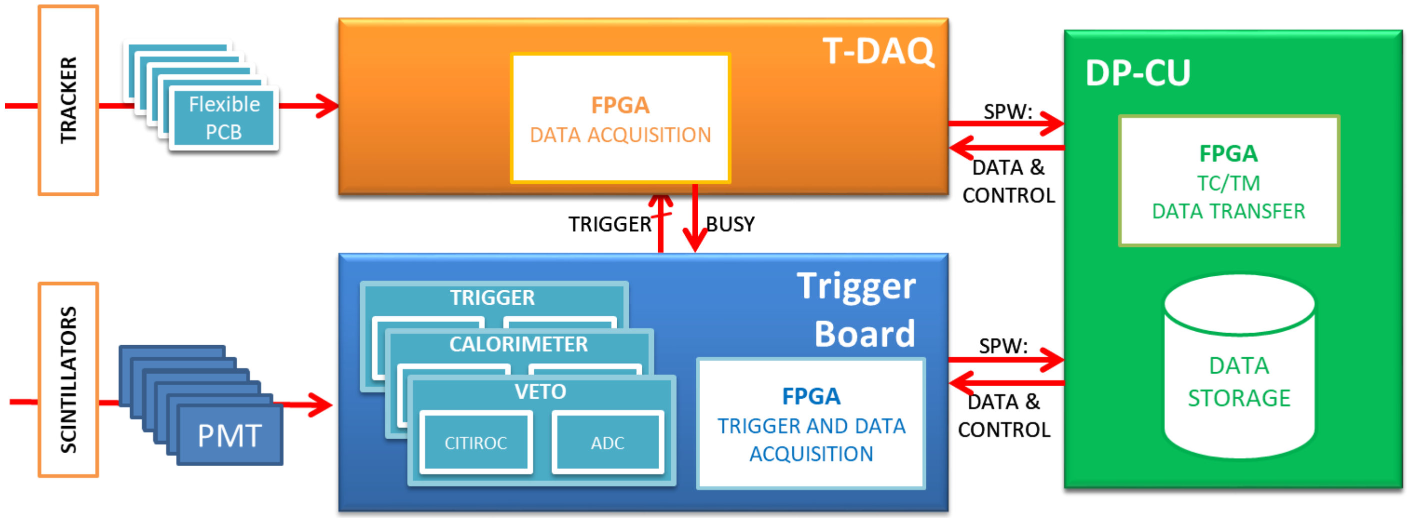
1. Tracker detector (T-DAQ)
2. Scintillator detectors: trigger, calorimeter and veto (Trigger Board)

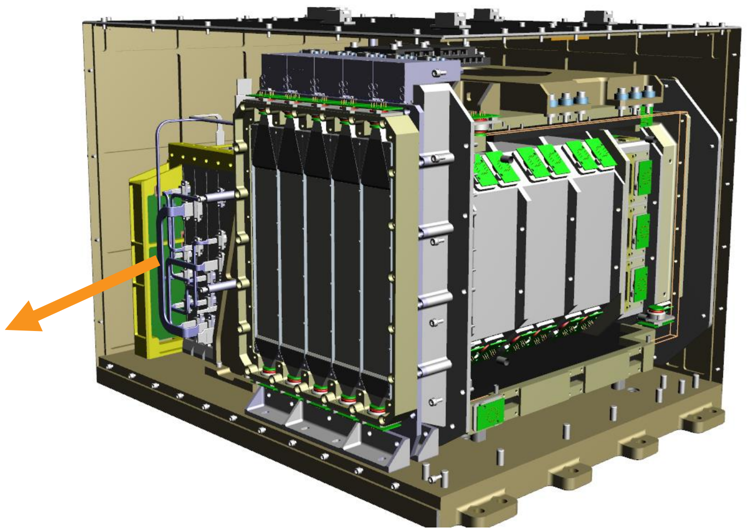
Design driven by power consumption limits

Managing and control

1. Control and data managing (DP-CU)
2. LV-PS and HV-PS

- Dedicated mechanics that allow anchoring to the HEPD-02 base plate and heat dissipation
- Communication via SpaceWire Light protocol
- Embedded “HOT/COLD” redundancy
- -30°C to +50°C qualification temperature range
- Max data transfer rate from satellite = 100 Gb per day

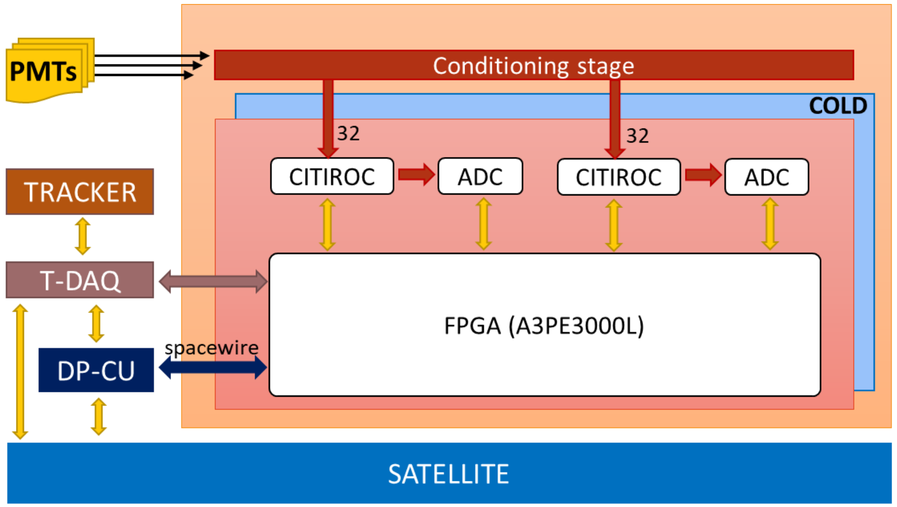


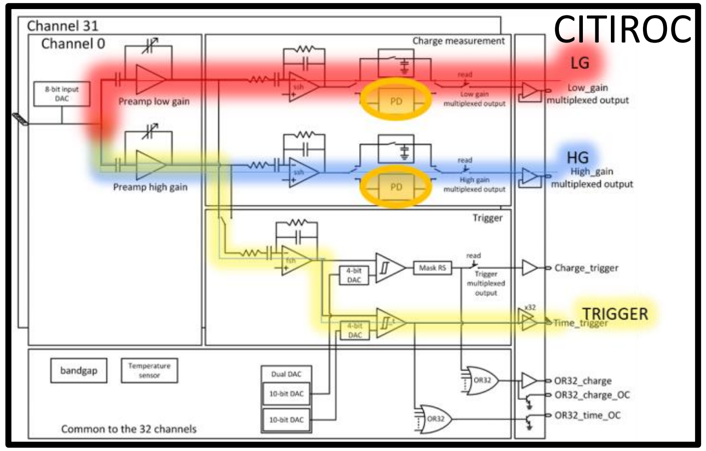


HEPD trigger board

Functionalities:

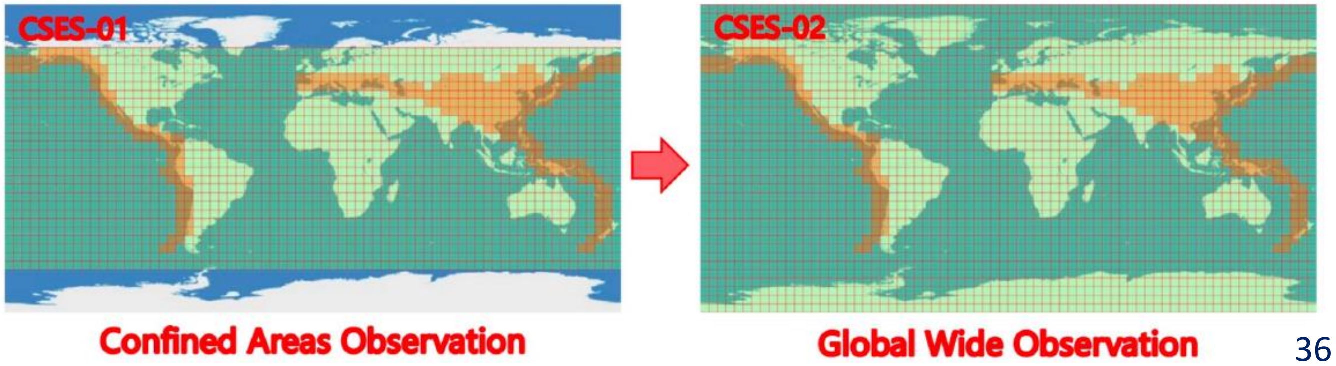
- Readout of 64 PMT: 2×32-channel ASICs CITIROC (Weeroc)
- Digitalization of PMT signals
- Configurable gain/trigger threshold to optimize the acceptance
- Two configurable gain chain
- Different trigger configurations to match different orbital zones and particles
- Rate meters for each PMT and trigger configuration



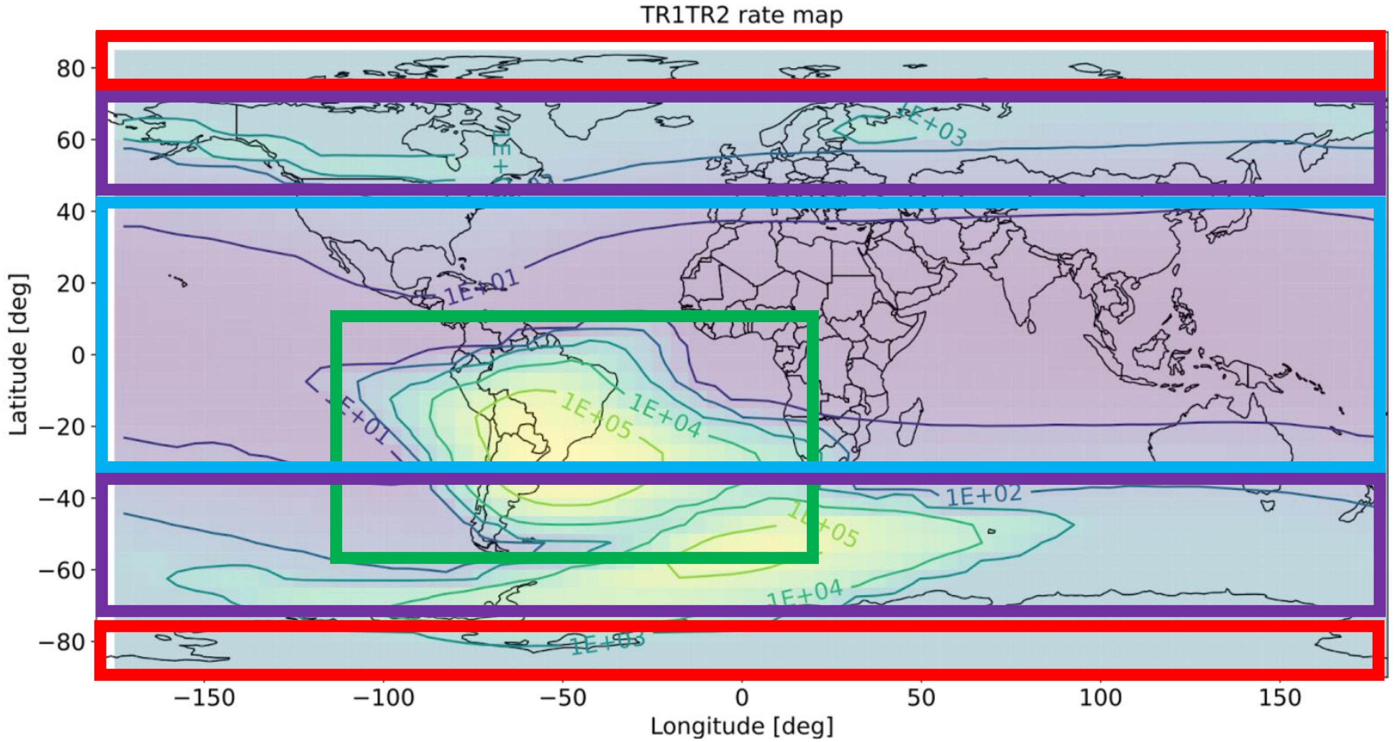


From HEPD-01 to HEPD-02:

- High trigger rate at polar regions: improved trigger logic and pre-scaling
- Larger amount of acquired data: mass memory on board for buffering



HEPD trigger requirements



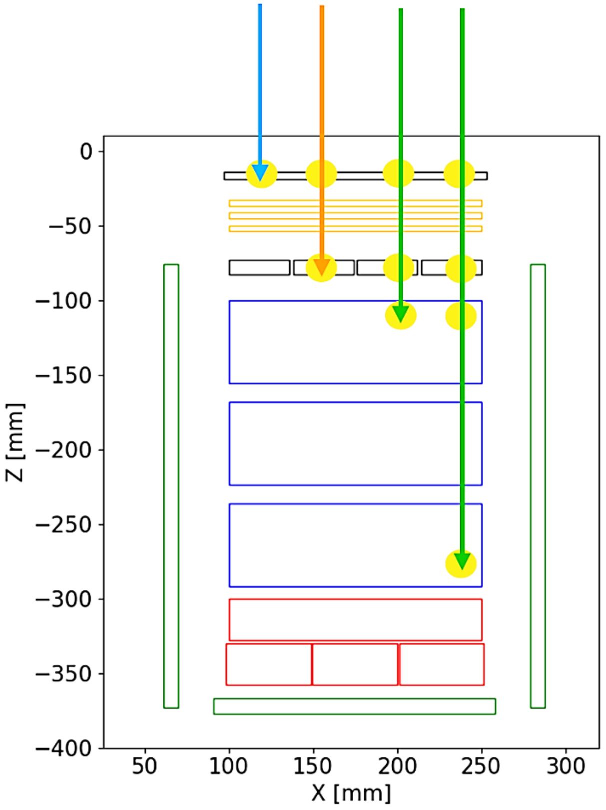
Along the orbit of CSES-02 particle fluxes span several orders of magnitude and different population of particle dominates each zone:

1. **SAA:** trapped electrons (dominant at 1 MeV) and protons (dominant above 8 MeV)
2. **Equatorial**: re entrant and cosmic protons
3. **Outer belt**: low energy trapped electrons (below 10MeV)
4. **Polar**: primary electrons and protons and havier nuclei

- 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
- Data acquisition must guarantee the measurement of energy spectra with a high duty cycle

HEPD: concurrent trigger and prescaling

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

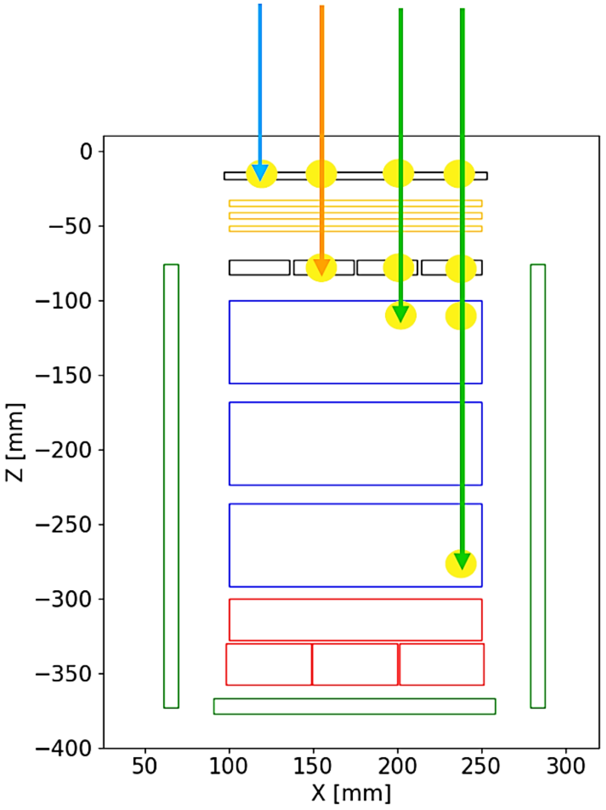


Flexible: combinations of signals from TR and CALO form trigger masks selectable in flight
Strong: to cope with increased fluxes of particles at polar orbits

Usual approach: global prescale factor to prevent saturation keeping a "calibration" data-stream

HEPD: concurrent trigger and prescaling

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



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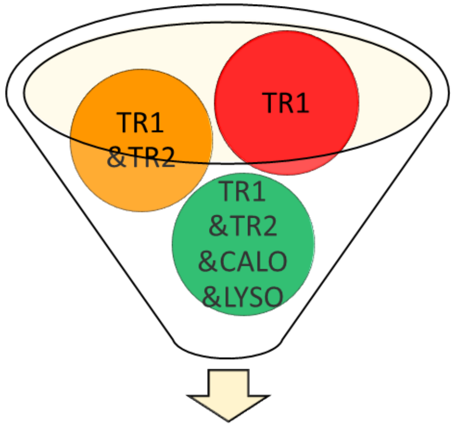


HEPD-02 trigger

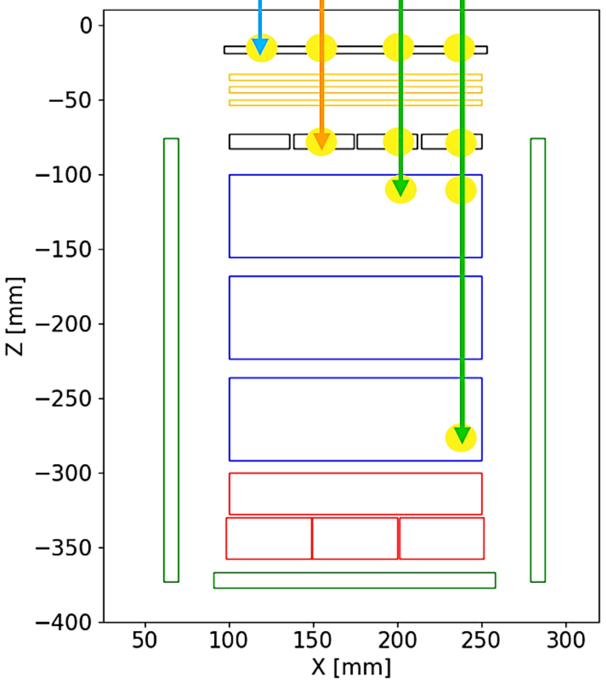
HEPD-02 approach:

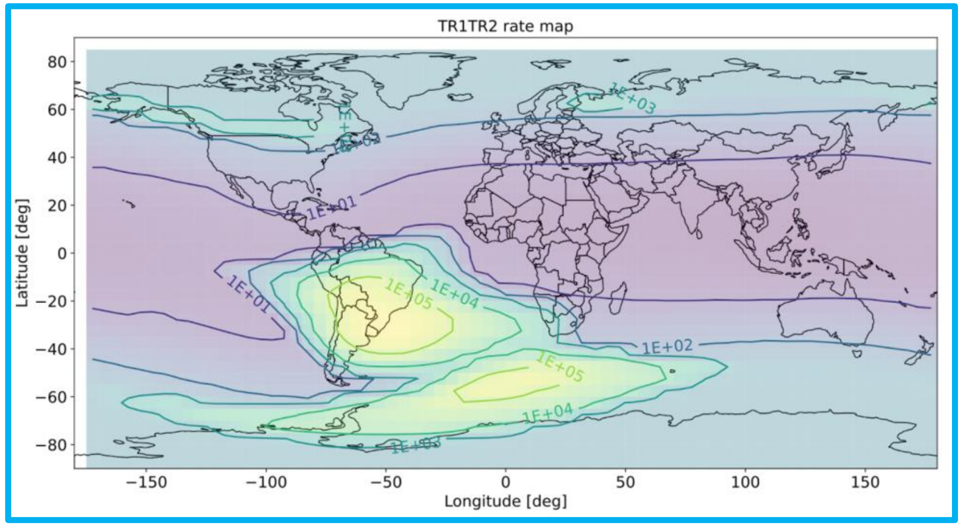
- **concurrent trigger** system allowing for measurements over the poles and on the SAA
- **Scale factors** adjusted for each trigger pattern to share resources among different physics cases, optimized after scientific requirements about FoV and kind of particle

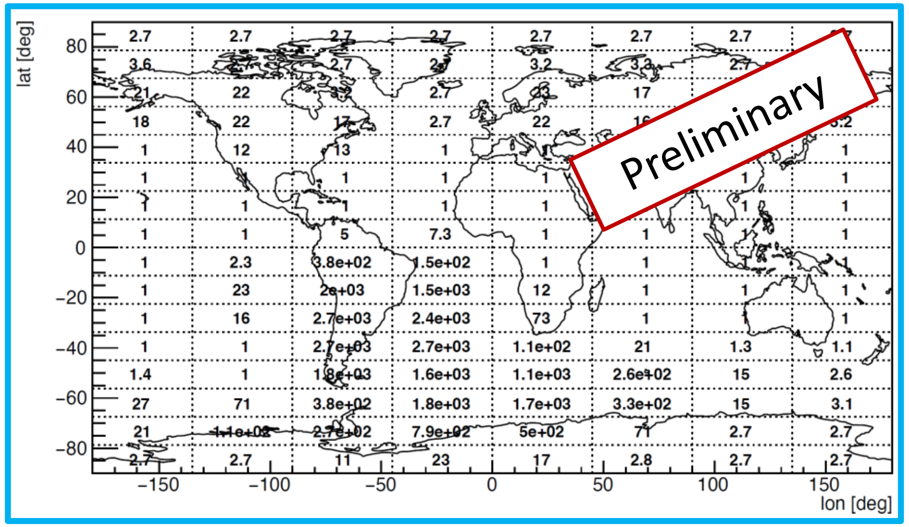
The sharing of data troughput among different physics channels is controlled via online selection: the largest rate trigger are prescaled to not saturate the available bandwidth.

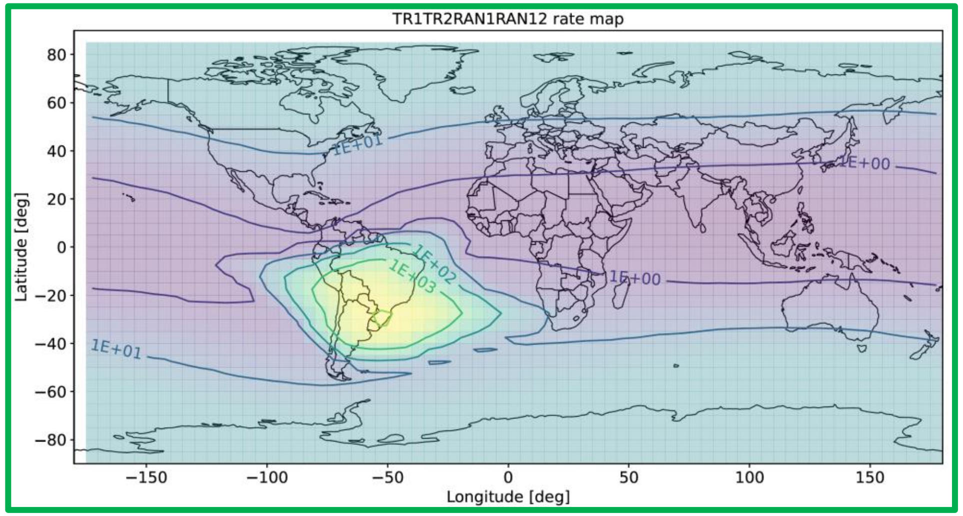
HEPD trigger: orbital zones

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



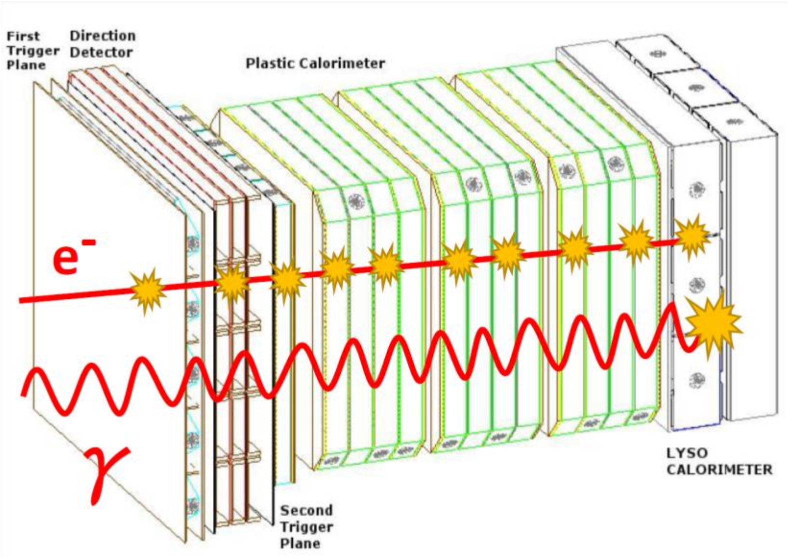






Capability to acquire data on the SAA by selecting appropriate trigger configurations

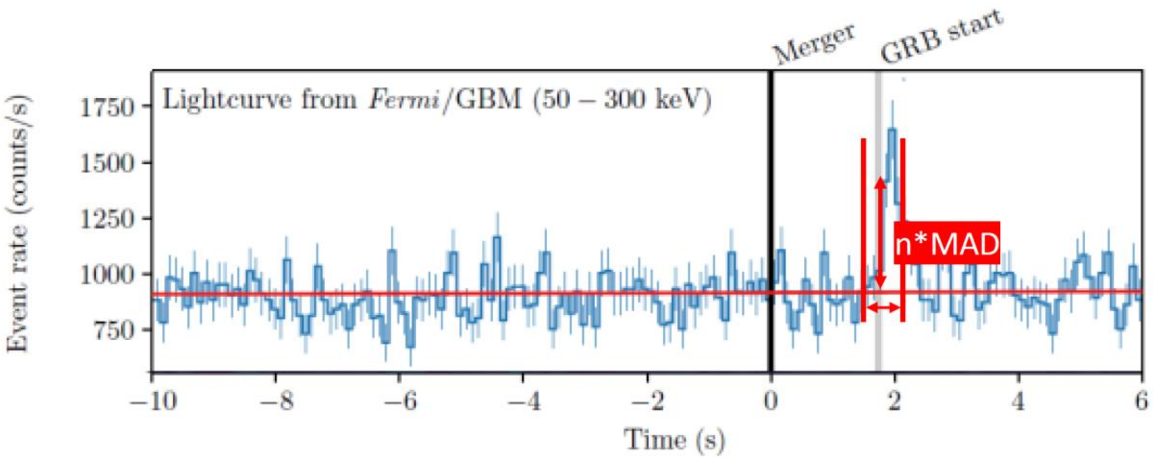
HEPD: gamma-ray observation

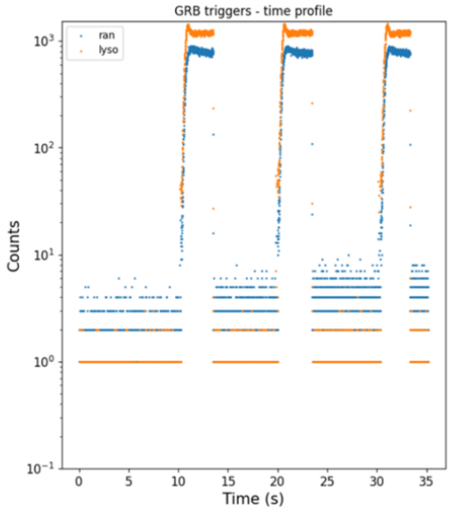


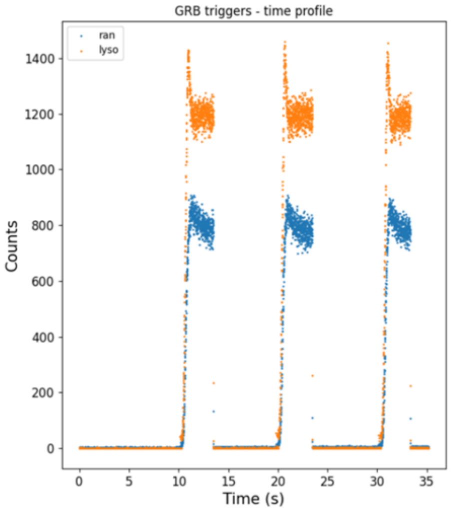
3 classes of trigger masks:

1. **Event acquisition**: validate the acquisition of the event and use the TR1 and TR2 planes and the plastic scintillators of the CALO
2. **Event monitor:** provide information about the efficiency of the detector
3. **Gamma Ray Burst:** 6 LYSO bars as large as 150x25x50 mm^3 → excellent opportunity to detect MeV photons

- ➢ Trigger configuration dedicated to γ-rays tracked on a time basis of 5 ms
- ➢ 2^{nd} level trigger introduced to consider veto
- ➢ Moving average and Mean Absolute Difference calculated in the DP/CU







EUSO-SPB2: a pathfinder for UHECR and ν from space

using the Earth as a particle detector

Fluorescence: UHECR, EeV

- First observation of UHECRs from space with the fluorescence technique
- Search for upward event candidates

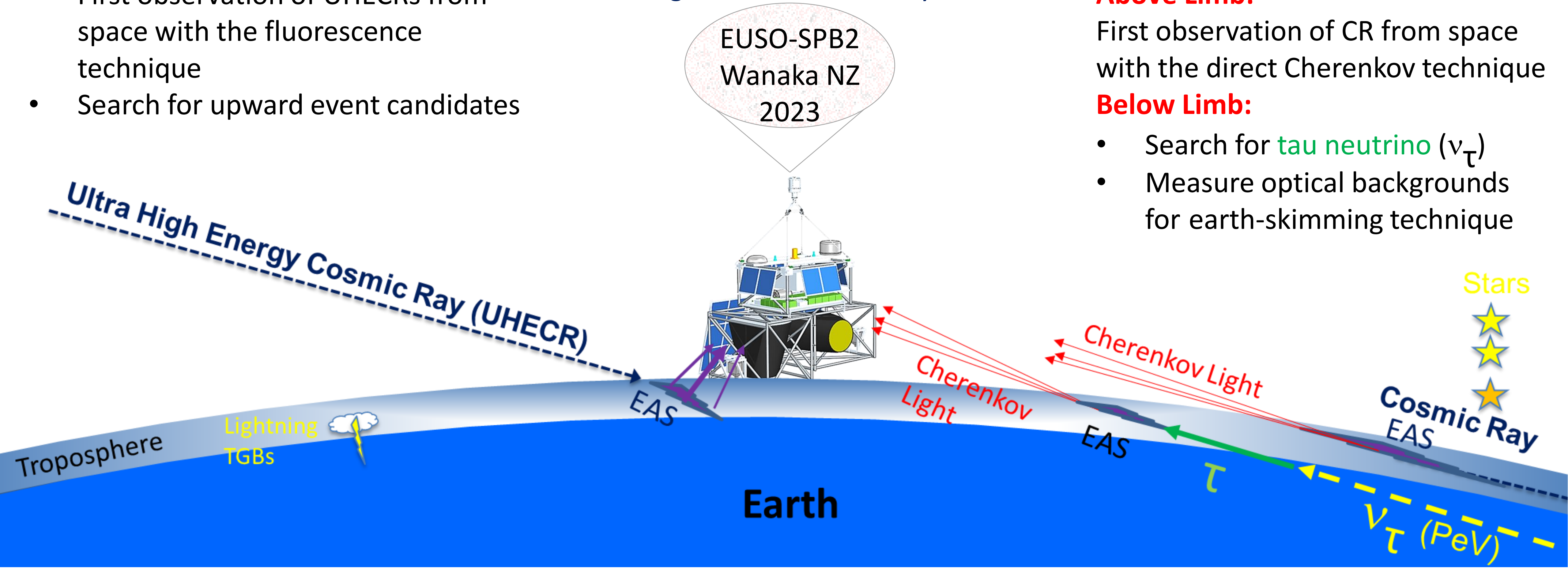
Floating altitude: 33 km, 7 mbar
Target duration: 100 days

Cherenkov: UHECR, PeV

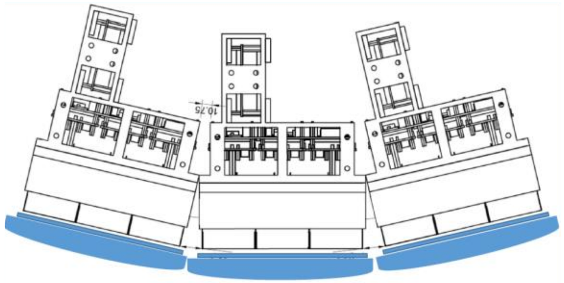
Above Limb:
First observation of CR from space with the direct Cherenkov technique

Below Limb:

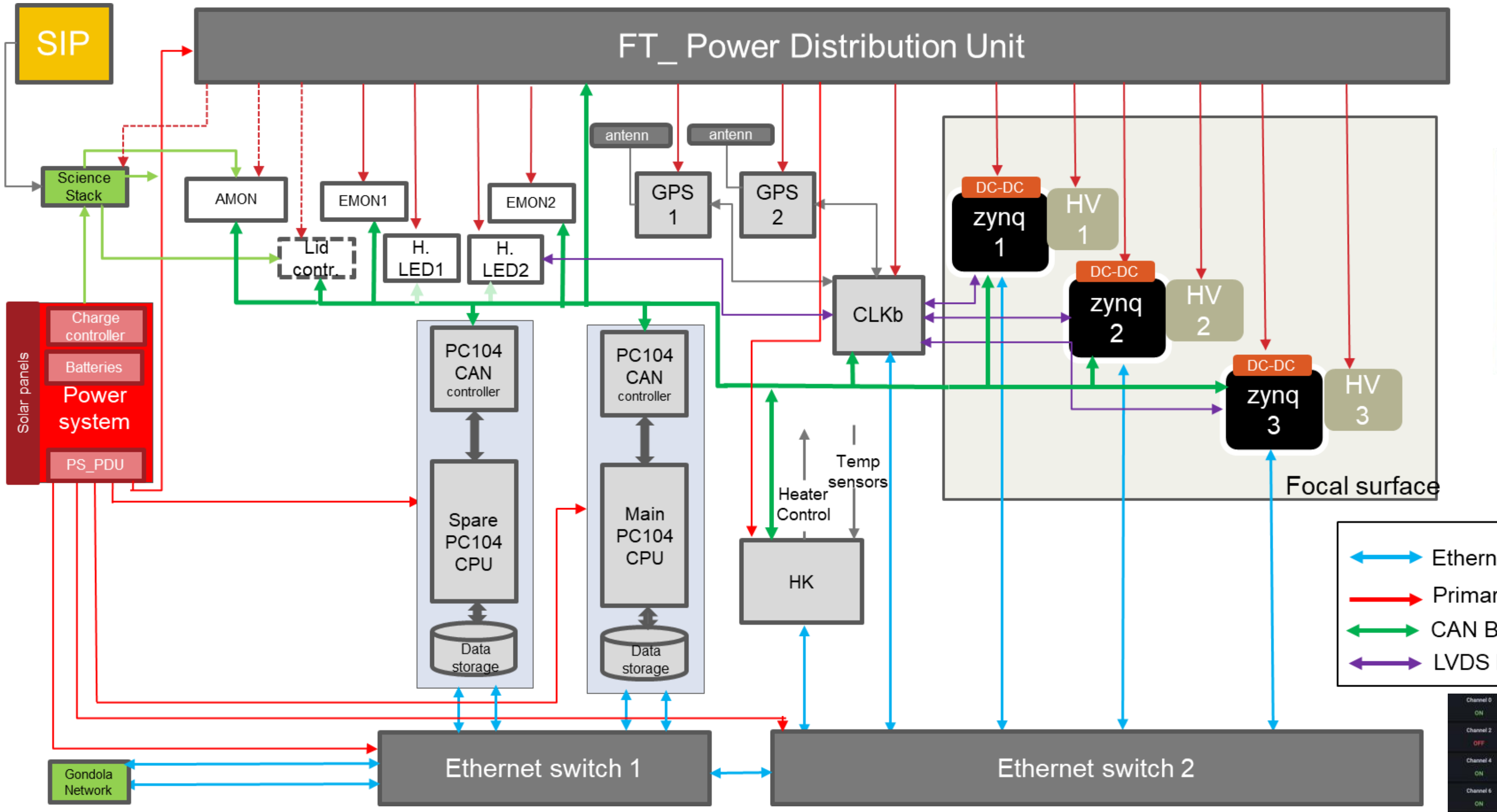
- Search for tau neutrino (ν_τ)
- Measure optical backgrounds for earth-skimming technique

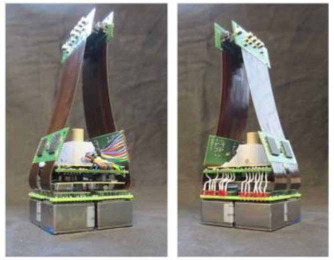


EUSO-SPB2 DAQ



MAPMT w/ single photoelectron counting
1 µs time bins, 1 “video clip” = 128 time bins
~15 watts



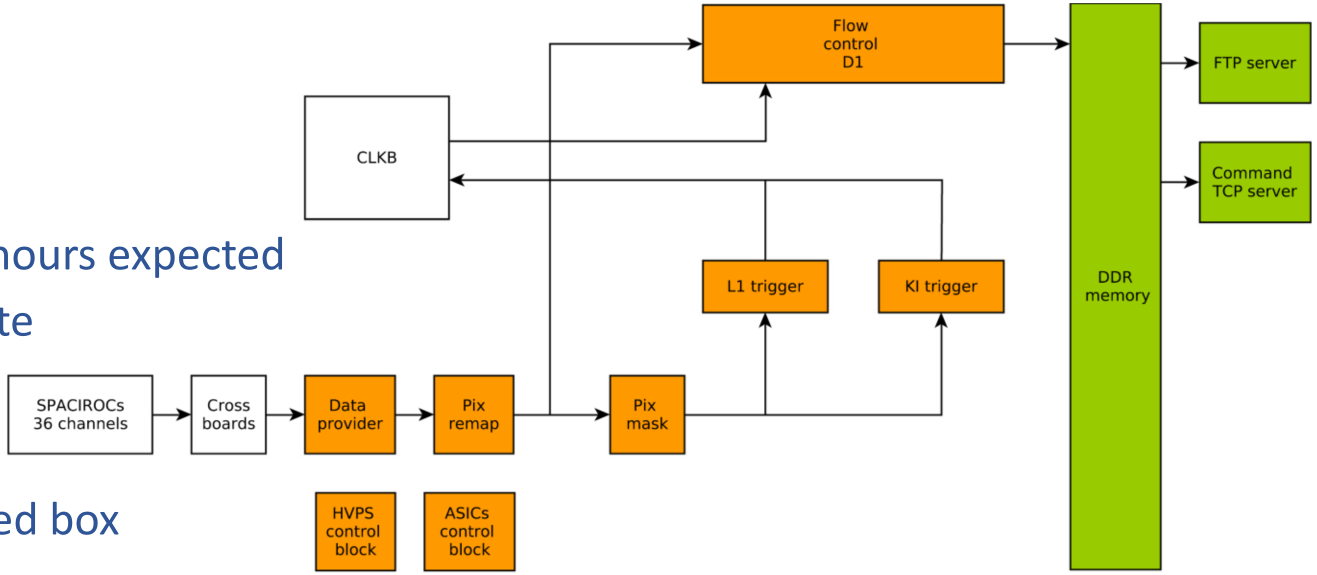


New integrated digitization

BGA packaged Spaciroc3 ASIC

- Mass < 25 kg
- Peak Power consumption < 135 W
- 7000 channels

EUSO-SPB2 trigger



Physics:

- UHECR induced signals are rare: 1 event every 13 hours expected
- Low signal relative to background: 10 Hz trigger rate

Technological:

- Difficult environment: high altitude in unpressurised box
- Power and mass budget restrictions
- Balloon and data stored on board may be lost, but the data bandwidth is limited: telemetry budget/Day: 1GB
  - Need to prioritize data for downloading
  - Want to only record and transfer high quality events
  - ➢ To be done on board with minimal intervention from ground
  - 10 MB max compressed science file size for downlink

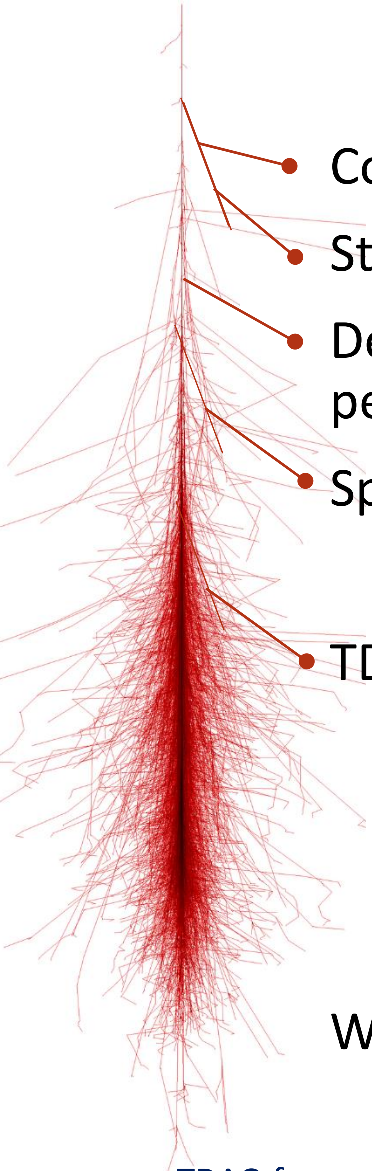
eventually Starlink saved us!

- Synchronus trigger evaluated every μs
- Asynchronous data transfer
- SOC: Xilinx Zynq 7, FPGA for trigger/DAQ, microprocessor for communication/data storage

Trends in space experiments

- **Nano Satellites and Mega Constellations**
  - “1U” CubeSat is 10 cm^3 and weighs around 1 to 1-1/3 kg
  - 1.5U, 2U, 3U, and 6U, and more
  - CubeSats contain ARM, Atmel, Texas Instruments’ MSP430, and Microchip Technology PIC microcontrollers
  - ✓ Cost reduction
  - ✓ Low risk/high benefit missions
  - ✓ Useful to measure quantities which scale with area (X, gamma, low energy charged), to sample in different points, to reduce the statistical error, to ensure full solid angle coverage
- **Advanced «FPGA»**
- **Machine-learning for trigger algorithms**

Summary



- Cosmic Rays are an important piece of the puzzle for our understanding of the Universe
- Studying direct CR calls for detectors in space
- Designing a detector and its electronics for space is a *tradeoff* between cost, reliability and performance
- Space qualification process is *cumbersome, but necessary*

  time-consuming, expensive, dangerous

- TDAQ for space is
  - ✓ **fun**: can touch almost every part of the stack and learn to understand the whole system
  - χ **challenging**: "easy" tasks on ground become nontrivial due to reliability issues and limitations on weight, power, data-bandwidth

We're always on a hunt for new ideas are for the next generation of space detectors!

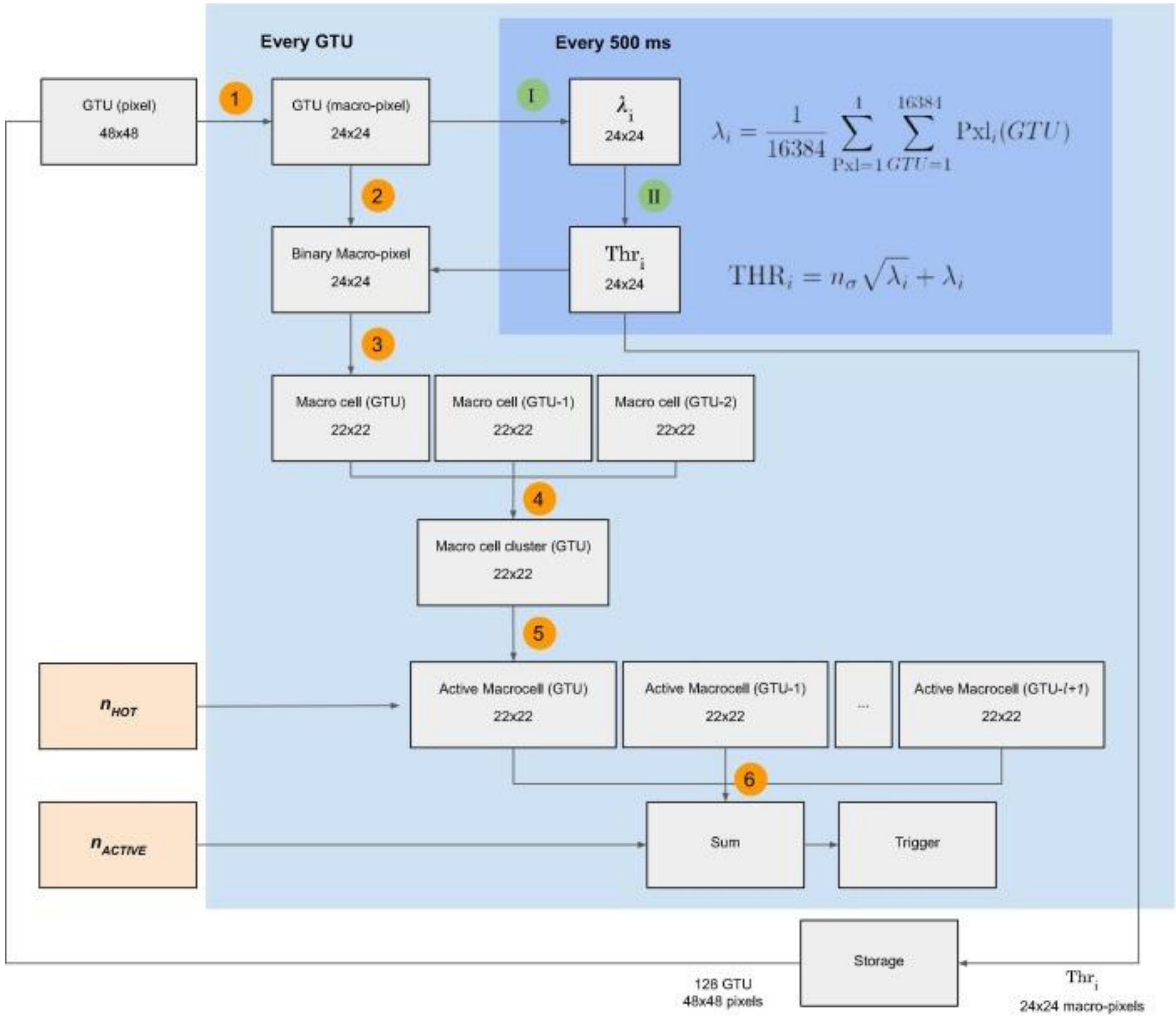
Thank you!

Any question?

Some (non-exaustive) references

- **Why space?**
  - O. Adriani, ASAPP2023
- **Cosmic rays**
  - 10.1016/j.ppnp.2020.103765
- **Challenges for electronics in space**
  - 10.1109/IPFA.2018.8452608
  - https://l.infn.it/w1
  - https://l.infn.it/w2
- **Space qualification**
  - 10.1109/NSSMIC.2004.1462214
  - https://l.infn.it/w3
- **Examples of TDAQ in space**
  - AMS: https://ams02.space/detector/electronics
  - HEPD: 10.1016/j.nima.2021.165639
  - EUSO-SPB2: 10.48550/arXiv.2208.07466

EUSO-SPB2 trigger algorithm

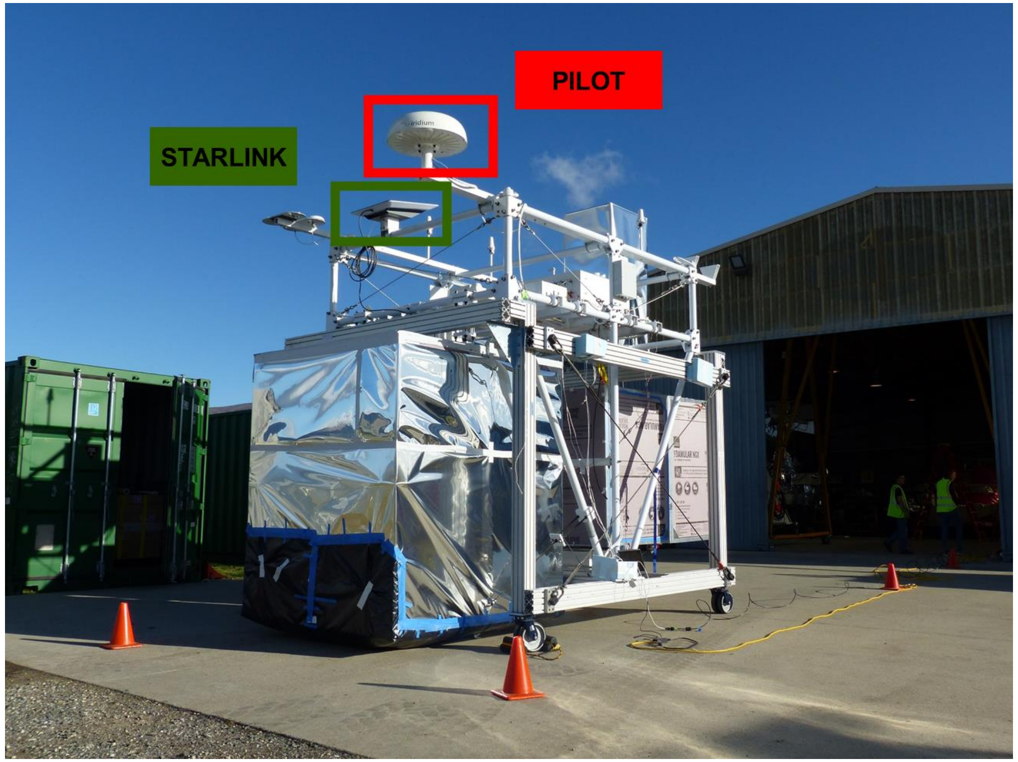


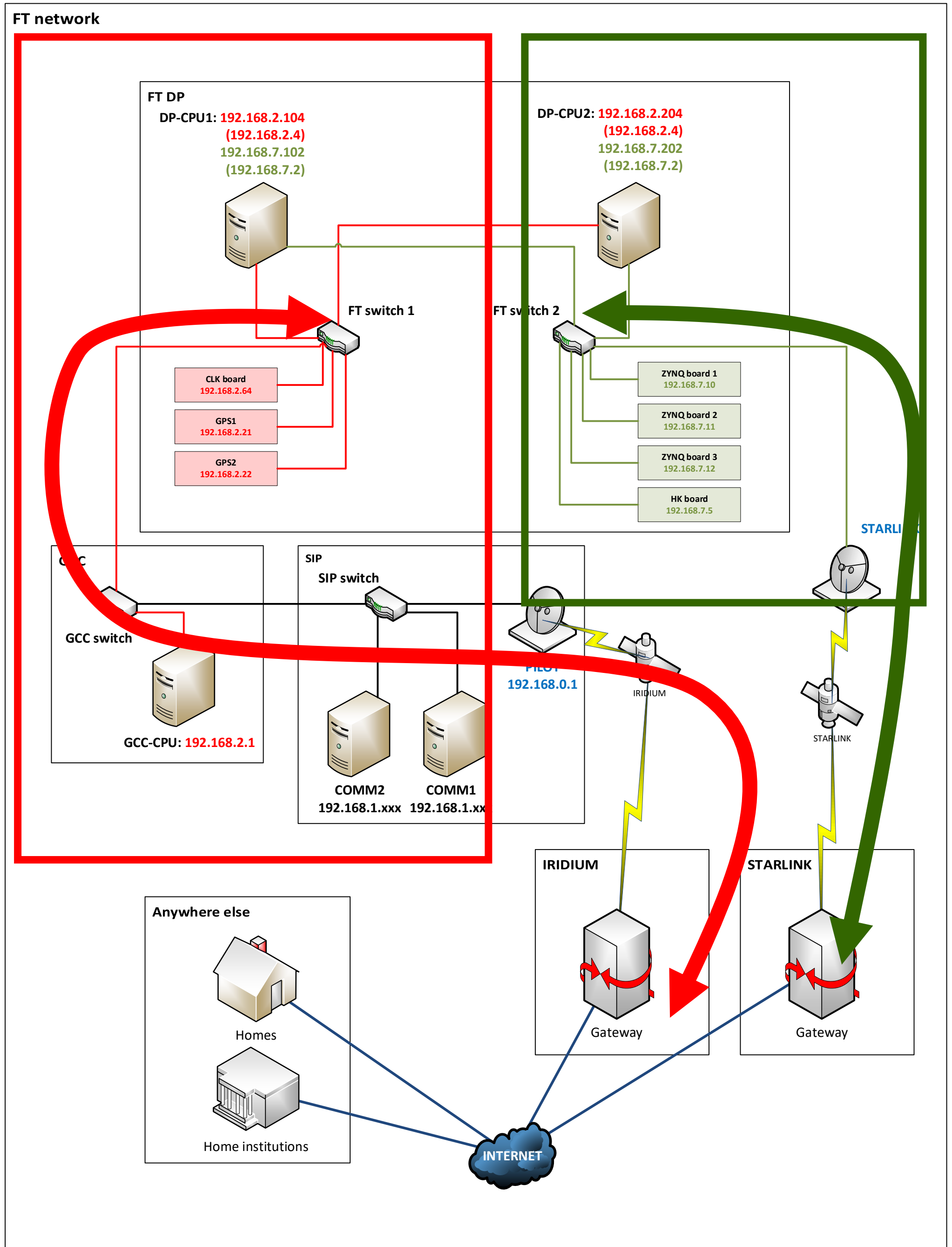
https://doi.org/10.1016/j.asr.2021.12.028

1) The values of the macro-pixels are computed, obtaining a view of the PDM.
2) The Binary Matrix is created through a comparison between each macro-pixel and its threshold.
3) The PDM is divided into overlapping macro-cells, excluding macro-pixels on the border of the PDM, the value of each cell is the number of macro-pixels over threshold. This matrix is stored in a 3 slots FIFO circular buffer, containing the values for the current and the two previous GTUs.
4) The sum over the 3 GTUs is performed. Each element of the Cluster matrix contains the number of macro-pixels over threshold in the last 3 GTUs in each macro-cell.
5) The number of clusters with more than macro-pixels over threshold n_hot is stored in a *l* length FIFO circular buffer.
6) The total number of active macro-cells over the last *l* GTUs is computed and compared to the value of n_active . If SUM> N_act a trigger is issued.
7) In parallel, every 500 ms the average of each macro-pixel over the previous 16384 GTUs is computed. This value is used to compute the threshold for each macro-pixel.

Starlink

- Starlink is a low Earth orbit satellite constellation that delivers high-speed, low-latency internet.
- Thousands of satellites orbit at about 550km, and cover the entire globe. Because Starlink satellites are in a low orbit, latency is significantly lower, respect to the geostationary satellites, orbiting at about 36000km: ~25 ms vs 600+ ms





Courtesy F. Cafagna