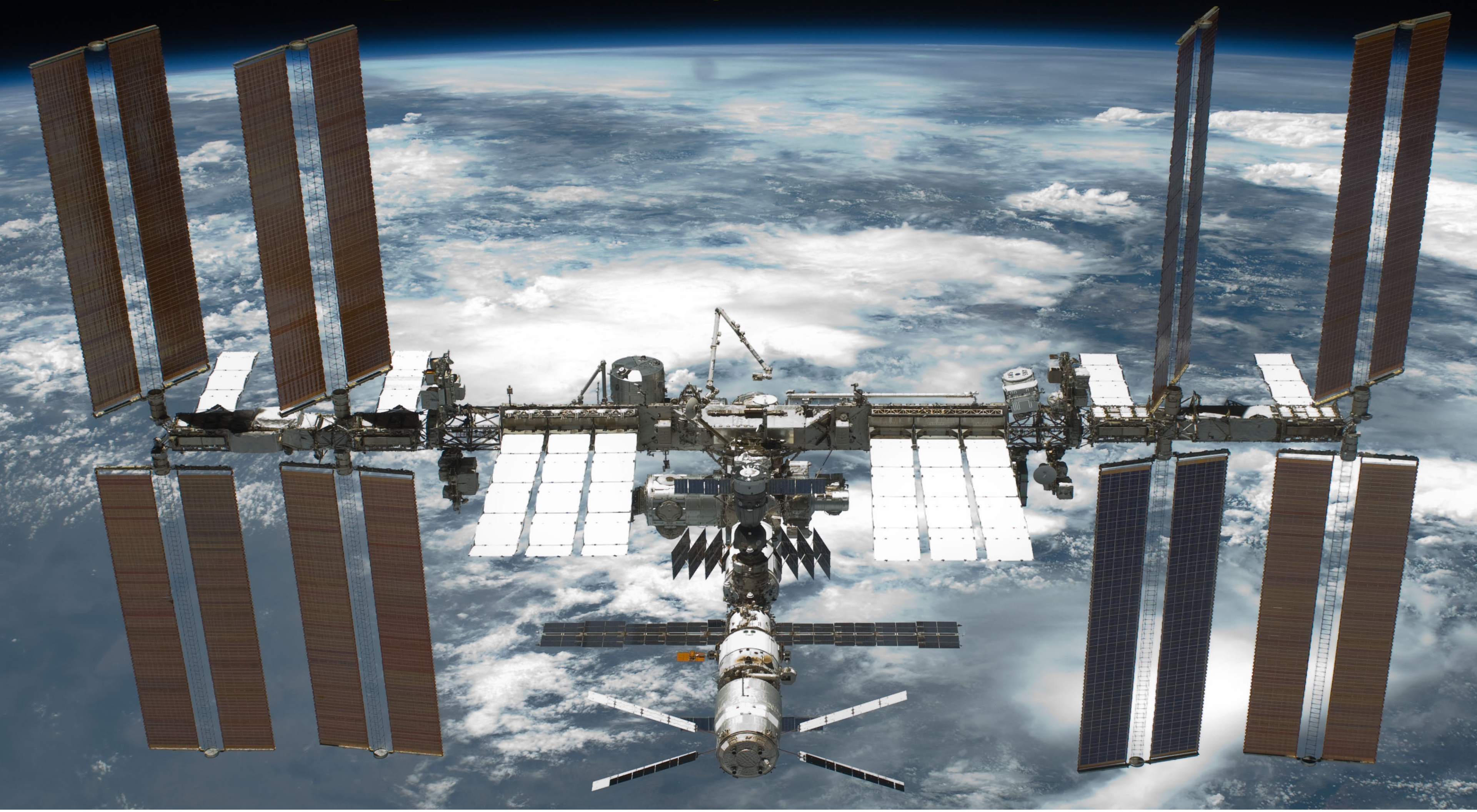
Requirements for Si-microstrip (LGAD) for next-generation space detectors



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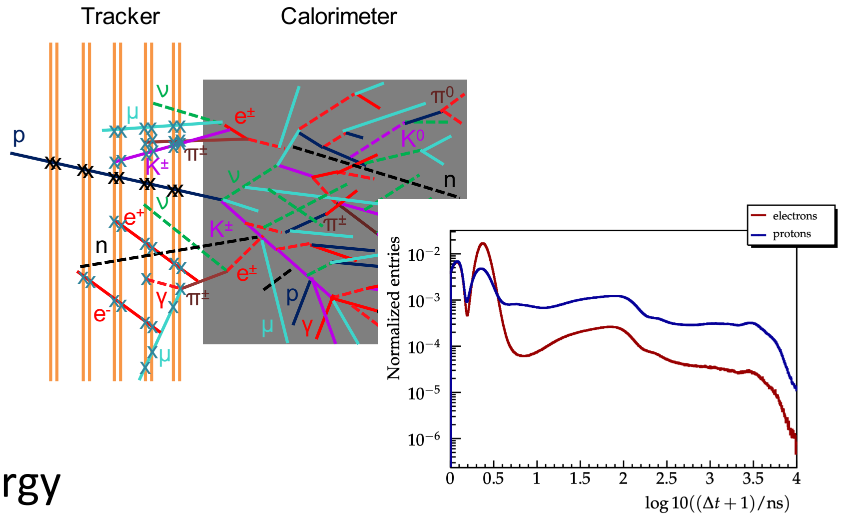
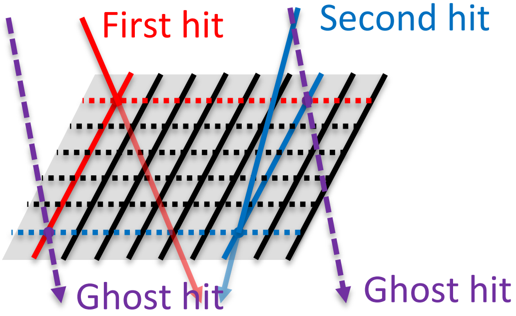
Timing in an astro-particle tracker

(see M. Duranti, V. Vagelli *et al.*, *Advantages and requirements in time resolving tracking for Astroparticle experiments in space*, Instruments 2021, 5(2), 20; https://doi.org/10.3390/instruments5020020)

Including the timing into the Tracker of an astro-particle detector permits to:

- substitute (or provide full redundancy to) any other **ToF detector** (i.e. planes of scintillators) in measuring β → arrival direction (downward vs upward), isotopic composition for nuclear species (combined with *E* or *p* measurement), …;
- help to mitigate/solve different limitations in current operating experiments such as:
  - identification of the hits coming from **back-scattering** from the calorimeter. Example: identify photons without vetoing when large back-scattering (DAMPE: photons lost due to back-scattering 30%@100GeV, 50%@1TeV);
  - **e/p identification**. The presence of a low energy (i.e. *β<1*) back-scattered particles (i.e. hadrons) from a shower identifies the CR as hadron;
  - solve the **"ghost"** problem, typical of a microstrip silicon sensor, from back-scattering, pile-up particles, etc…;

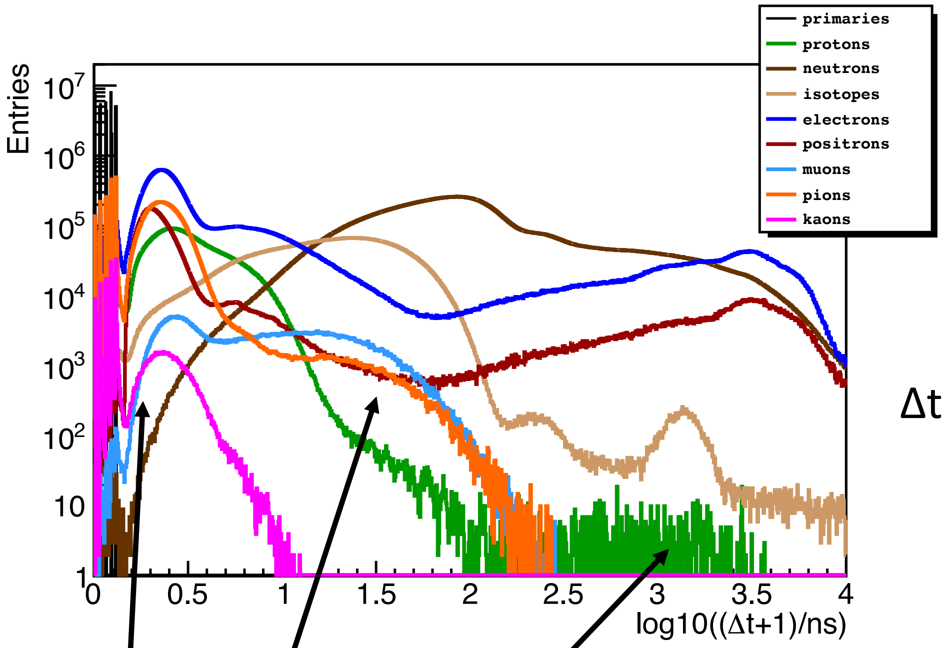




Back-scattering

1 TeV protons

Hits in the tracker (E_{dep} >10 keV vs Δt between the i^{th} hit and the 1^{st} hit (i.e. the CR passing in the first layer of the tracker)



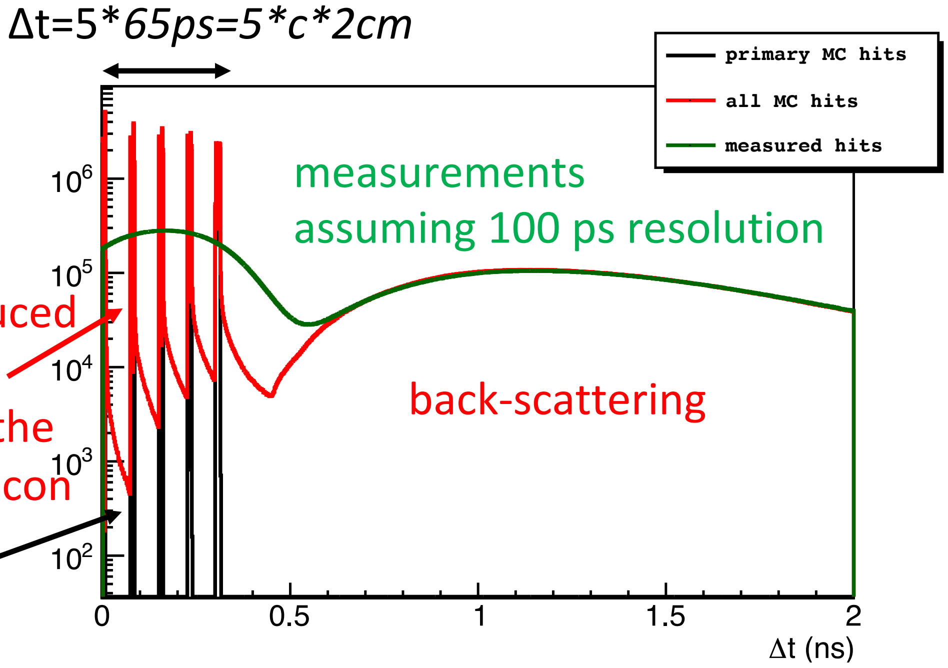
Δt=O(100ps)

Δt=O(10ns)

Δt=O(10μs)

Hits from back-scattering

Δt=5*65ps=5*c*2cm



measurements assuming 100 ps resolution

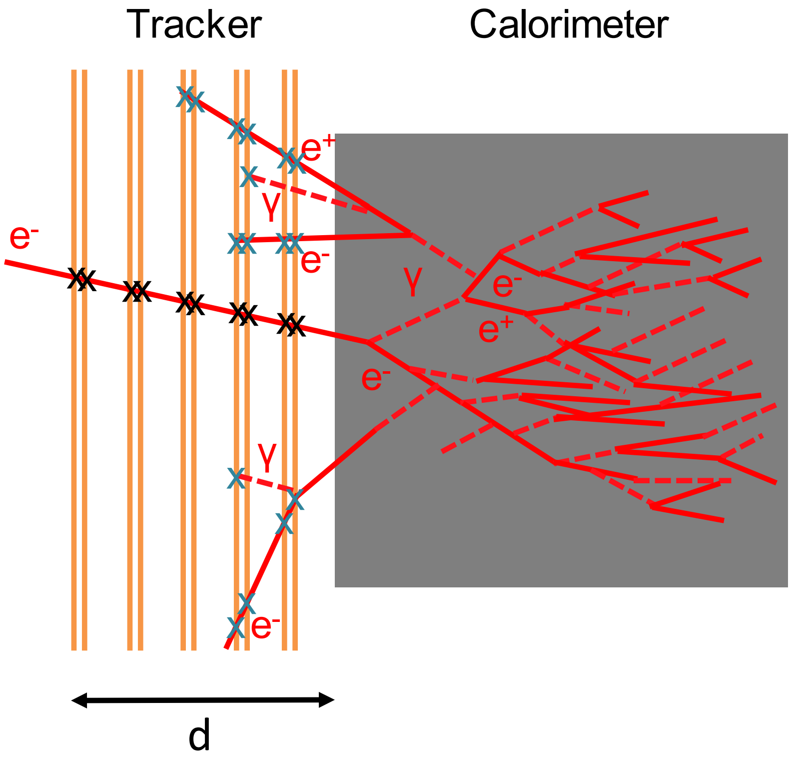
particles produced from the interaction of the CR with the silicon detectors

back-scattering

tracker layers

O(100ps) timing resolution enables to separate back-scattering from primary hits in the tracker → improved efficiency in track reconstruction

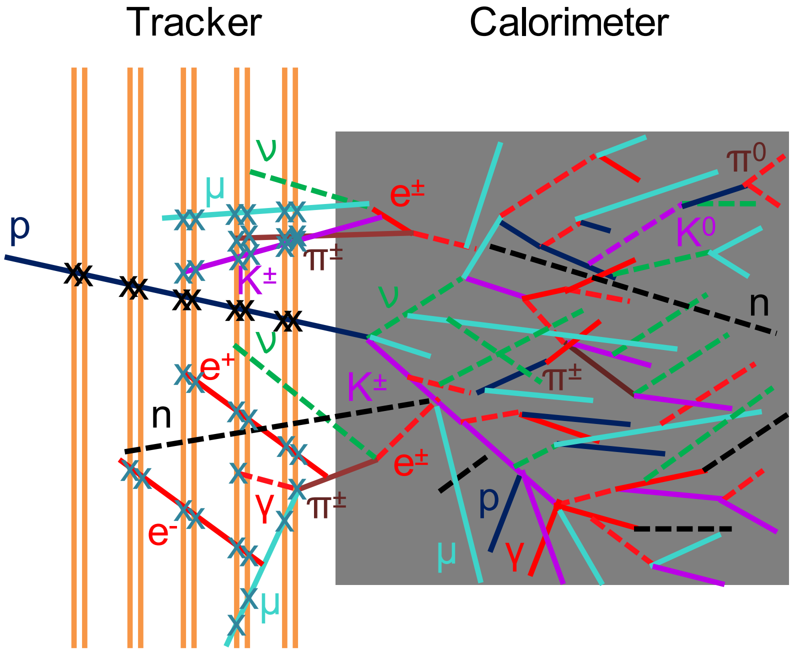
e/p identification



the electromagnetic shower is composed only by "ultra-relativistic" particles
→ the time arrival in the tracker is (at most):

$$\sim 2d / c$$

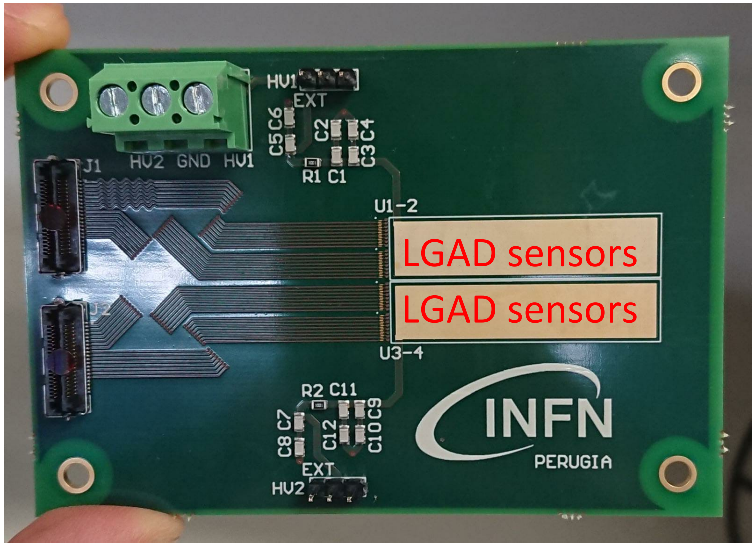
the hadronic shower could be composed by "slow" particles
→ the time arrival in the tracker could be delayed



LGAD detectors

Requirements:

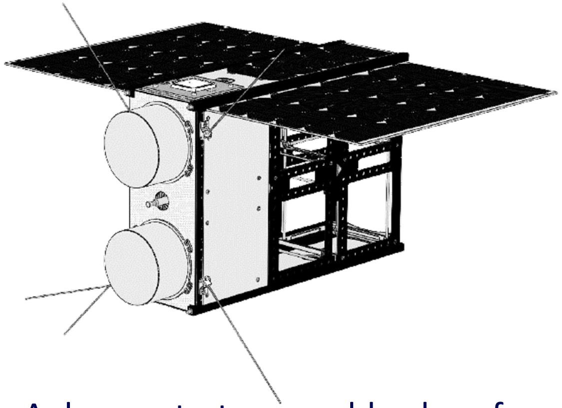
- measure the coordinate with < 10 µm accuracy
- measure the time with < 100 ps accuracy
- keep the linearity with the *Z* (i.e. energy deposit), up to *Z*~=30 and more
- possibly measure the *Z* with < 0.3 c.u. accuracy
- consume < 20 W/m^2 for the coordinate measurement
- consume < 20 W/m^2 for the time measurement
- very moderate radiation hardness (~ krads) required

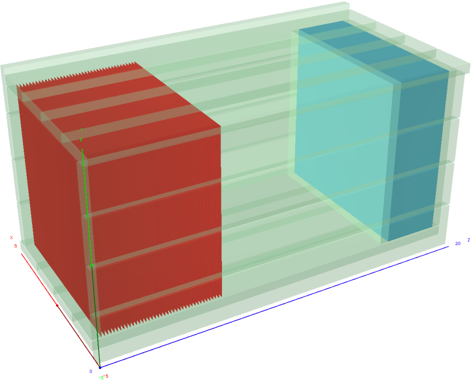


How to read-out these sensors with a very low power budget available?

- produce a custom ASIC (optimal solution)
- use a COTS ASIC (i.e. PETIROC-2A) developed per other sensors (SiPM) and "see what happens"

Space LGAD for Astroparticle - SLA





A demonstrator, capable also of some physics measurements, can be done in a 3U or 6U CubeSat:

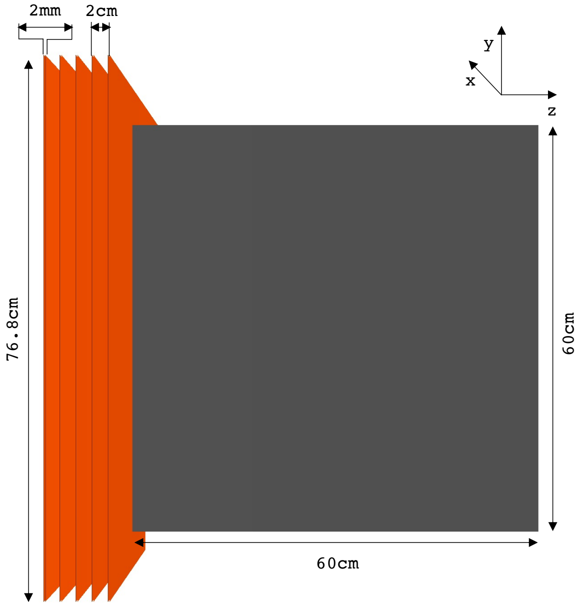
- the idea has been proposed in an Italian Space Agency (ASI) "topical board"
- the idea was included in a Italian Research Ministry call for fundings (PRIN, "SLA")
- the detector (launch included!) is doable with a ~ 1M€ budget envelope

Backup

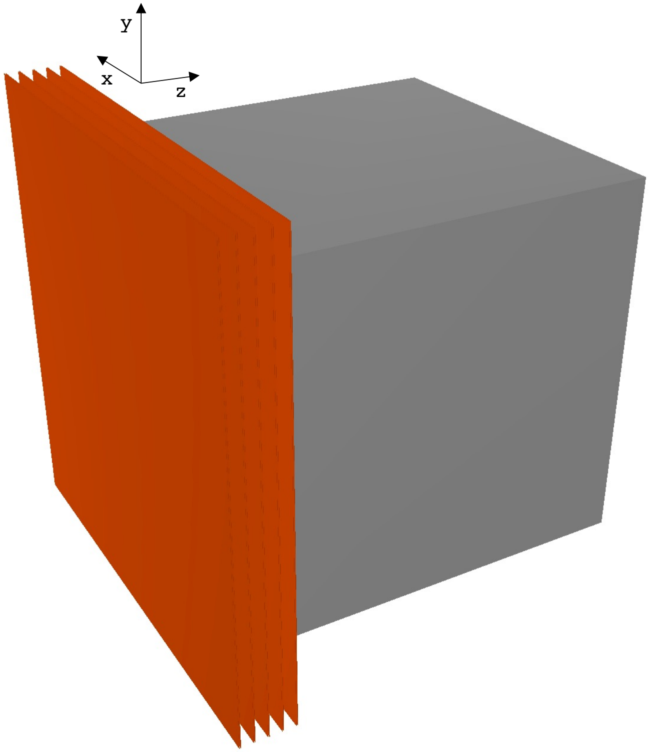
MC simulation

MC Simulation:

- based on Geant4 (via Generic Geant Simulation, GGS, *Mori, N Nuc. Instr. Meth. Section A, Volume 1002, 21 Jun 2021*)
- simple geometry "a la DAMPE": only tracker + calorimeter



Silicon Tracker BGO calorimeter

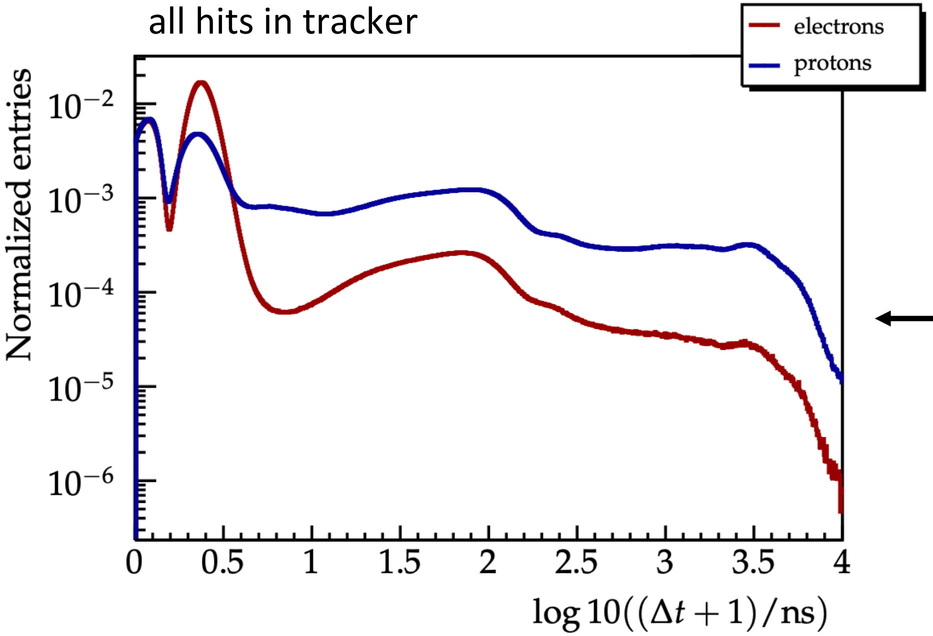


Informations saved:

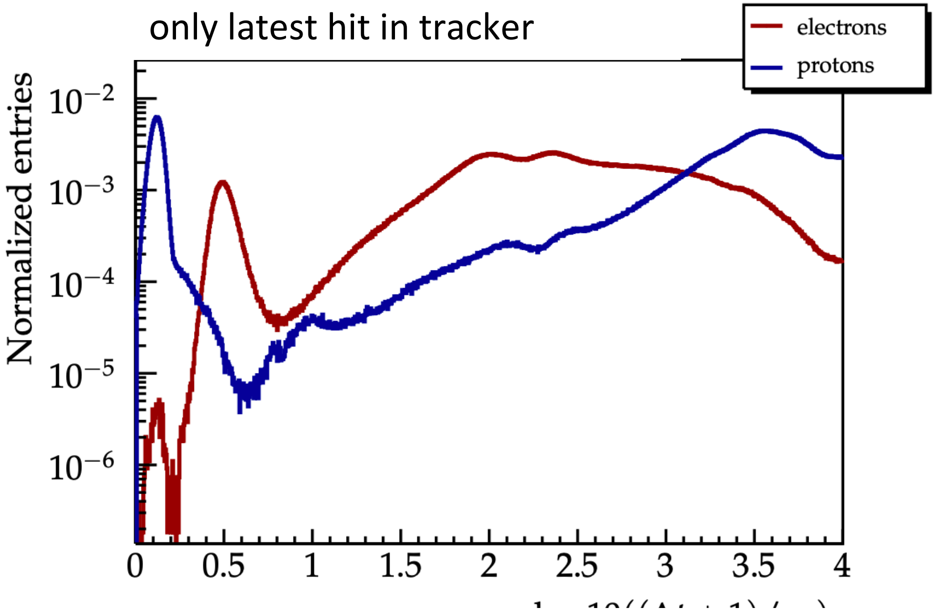
- energy lost and deposited
- spatial coordinates
- timing
- ...

e/p identification

5M primaries generated:
- 700 GeV electrons
- 1 TeV protons (depositing ~ 700 GeV in the ECAL)


all hits in tracker

looking at all the hits in tracker offers an "high statistic" tool to, for example, train a Multi-Variate algorithm


only latest hit in tracker

even the naive idea to look only at the "slower" hit in tracker shows two populations crearly distinct

the two populations (electrons and protons) are clearly distinct –> the e/p identification capability seems confirmed and seems also improving with energy

Silicon Microstrip detectors in space

Most of space detectors for charged cosmic ray and γ-ray measurements require **solid state tracking systems based on Si-µstrip sensors.**

Si-µstrip detectors are the only solution to instrument **large area detectors** with larger number of electronics channels coping with the **limitations on power consumption in space**

Operating Missions

	Mission Start	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
Fermi-LAT	2008	$\sim 74\,\mathrm{m}^2$	38 cm	$\sim 880 \cdot 10^3$	$228\,\mu\mathrm{m}$	$\sim 66\,\mu\mathrm{m}$
AMS-02	2011	$\sim 7\,\mathrm{m}^2$	29–62 cm	$\sim 200 \cdot 10^3$	$110\,\mu\mathrm{m}$	$\sim 7\,\mu\mathrm{m}$
DAMPE	2015	$\sim 7\,\mathrm{m}^2$	38 cm	$\sim 70 \cdot 10^3$	$242\,\mu\mathrm{m}$	$\sim 40\,\mu\mathrm{m}$

Future Missions

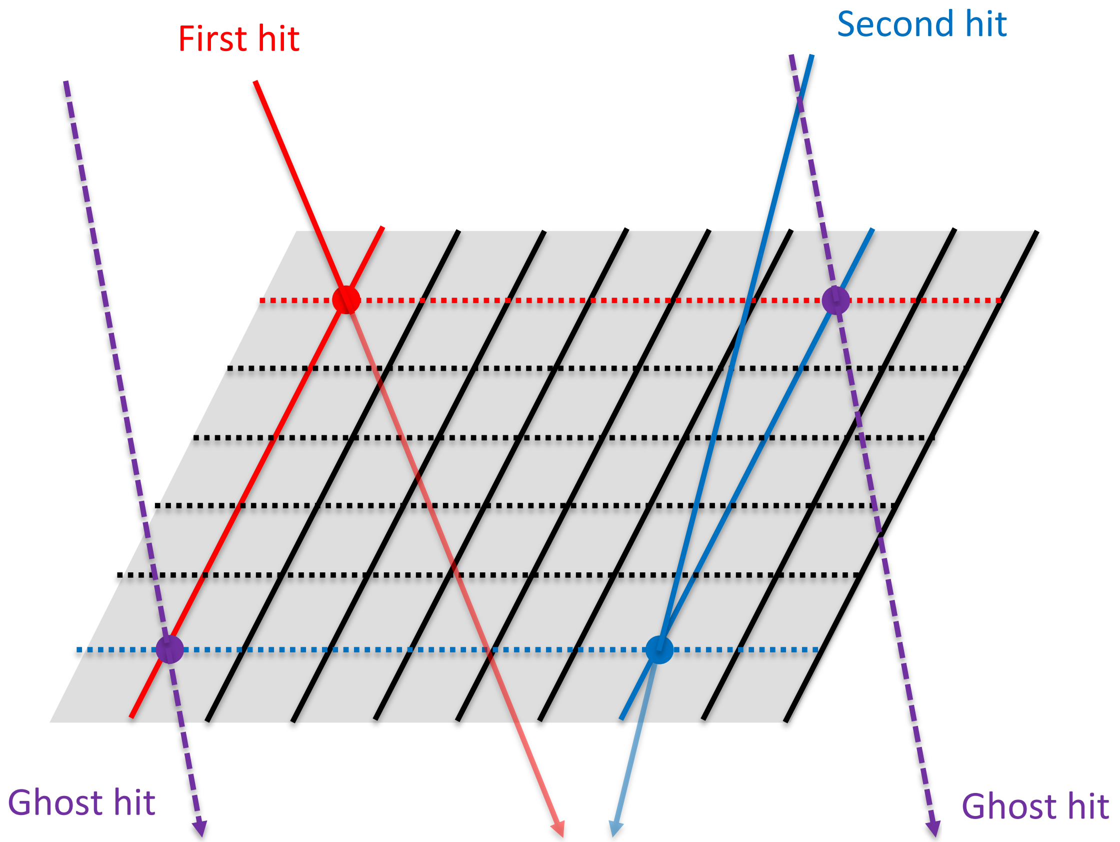
	Planned operations	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
HERD	2030	$\sim 35\,\mathrm{m}^2$	48–67 cm	$\sim 350 \cdot 10^3$	$\sim 242\,\mu\mathrm{m}$	$\sim 40\,\mu\mathrm{m}$
ALADInO	2050	$\sim 80\text{-}100\,\mathrm{m}^2$	19–67 cm	$\sim 2.5 \cdot 10^6$	$\sim 100\,\mu\mathrm{m}$	$\sim 5\,\mu\mathrm{m}$
AMS-100	2050	$\sim 180\text{-}200\,\mathrm{m}^2$	$\sim$ 100 cm	$\sim 8 \cdot 10^6$	$\sim 100\,\mu\mathrm{m}$	$\sim 5\,\mu\mathrm{m}$

[1] HERD Collaboration. *HERD Proposal, 2018* https://indico.ihep.ac.cn/event/8164/material/1/0.pdf

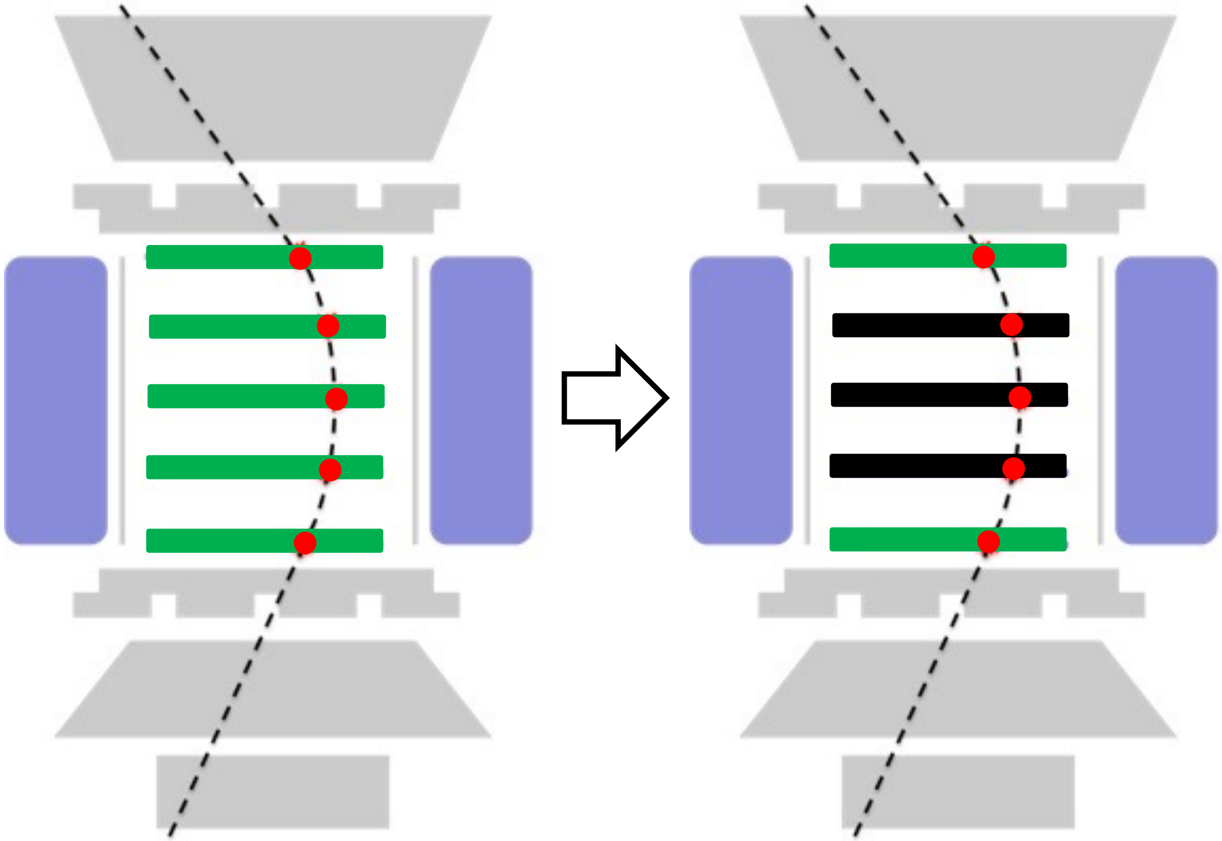
[2] Battiston, R.; Bertucci, B.; *et al. High precision particle astrophysics as a new window on the universe with an Antimatter Large Acceptance Detector In Orbit (ALADInO)*. Experimental Astronomy 2021. https://doi.org/10.1007/s10686-021-09708-w

[3] Schael, S.; *et al. AMS-100: The next generation magnetic spectrometer in space – An international science platform for physics and astrophysics at Lagrange point 2*. NIM-A 2019, 944, 162561. https://doi.org/10.1016/j.nima.2019.162561

"Ghost"



How to stay into the power limitations?



- "timing" layer
- "normal" layer

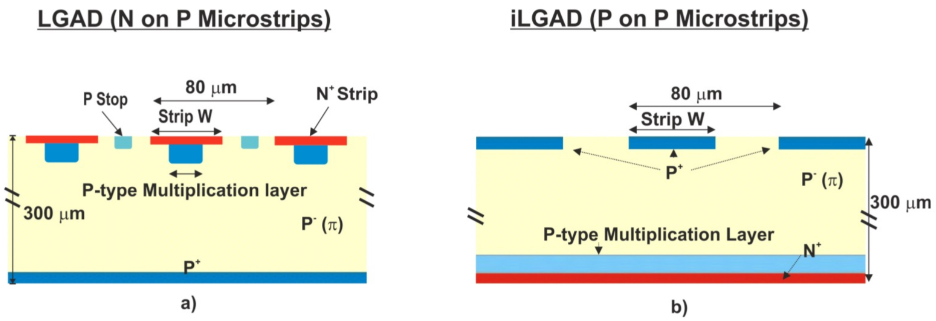
- basic capabilities kept
- isotopic separation / β resolution degraded
- timing redundancy and efficiency reduced

How and how to cope with power limitations?

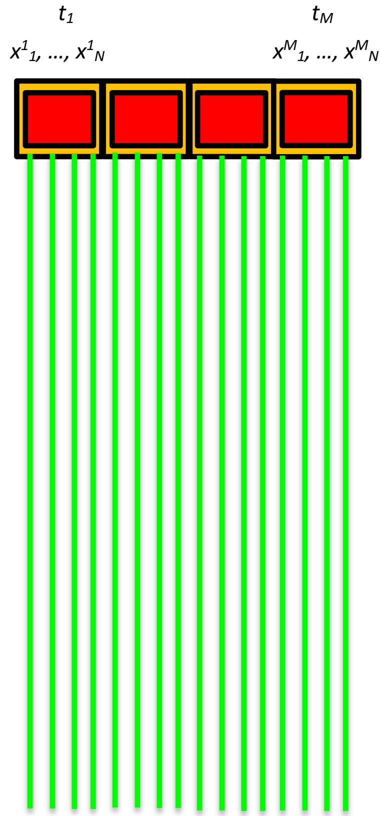
→ Si LDAG <u>microstrip</u>

→ "group" N *position* channels into one *timing* channel, or create large timing channels

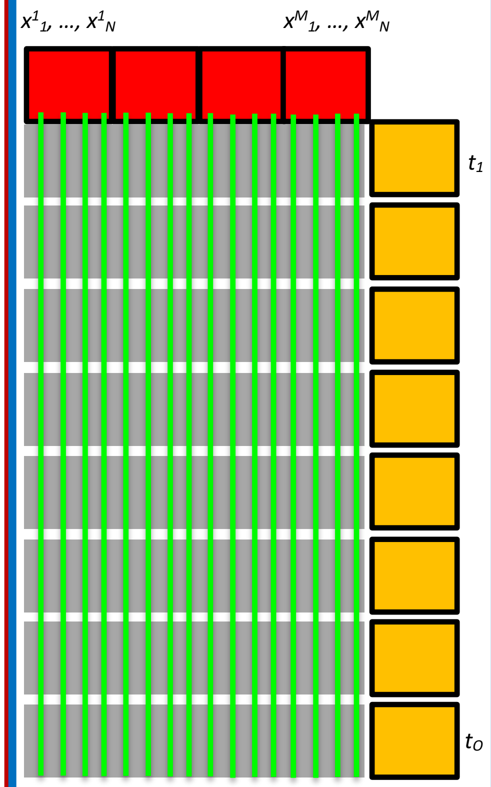
cfr.
M. Duranti, V. Vagelli *et al., Advantages and requirements in time resolving tracking for Astroparticle experiments in space*, accepted for publications in Instruments



taken from
E. Currás, et al. *Inverse Low Gain Avalanche Detectors (iLGADs) for precise tracking and timing applications*, NIM-A Volume 958, 2020, 162545,
https://doi.org/10.1016/j.nima.2019.162545



- standard LGAD with a dedicated Front-End ASIC
- iLGAD with separate Front-End ASICs for position and timing (on the back)



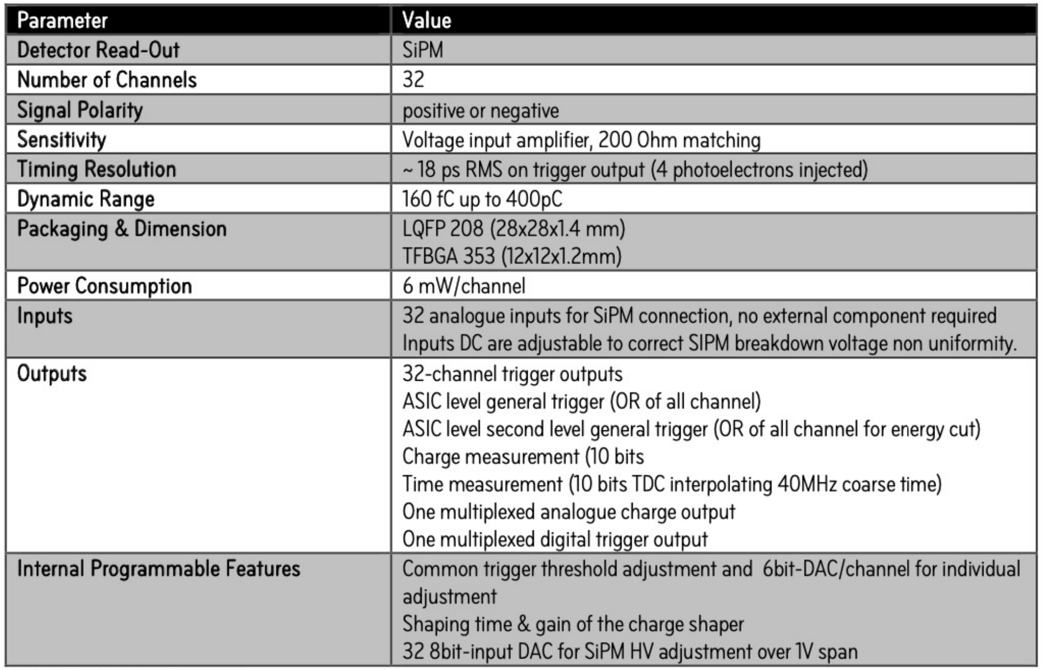
- positon and timing strip orthogonal
- iLGAD (or AC-LGAD?) fop the timing

Weeroc Petiroc 2A

weeroc

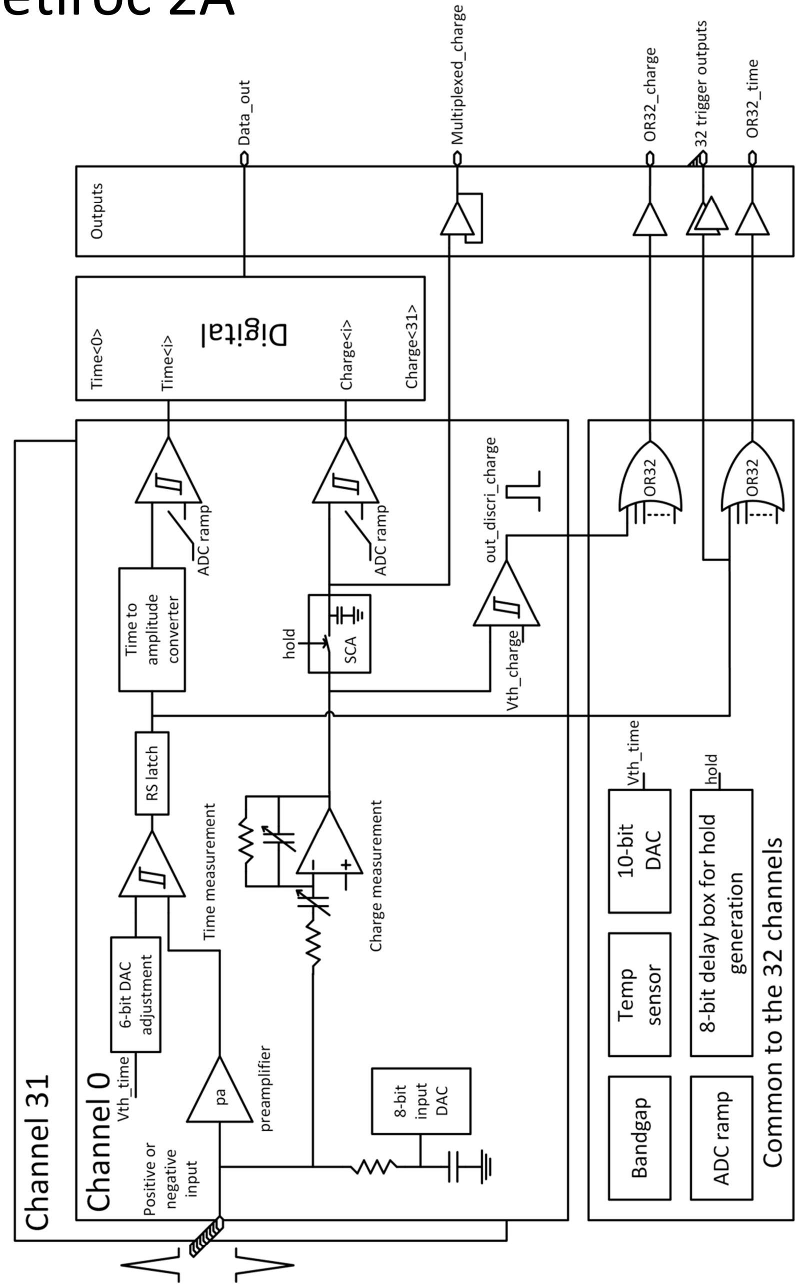
Petiroc 2A

SiPM read-out for time-of-flight PET



Parameter	Value
Detector Read-Out	SiPM
Number of Channels	32
Signal Polarity	positive or negative
Sensitivity	Voltage input amplifier, 200 Ohm matching
Timing Resolution	~ 18 ps RMS on trigger output (4 photoelectrons injected)
Dynamic Range	160 fC up to 400pC
Packaging & Dimension	LQFP 208 (28x28x1.4 mm) TFBGA 353 (12x12x1.2mm)
Power Consumption	6 mW/channel
Inputs	32 analogue inputs for SiPM connection, no external component required Inputs DC are adjustable to correct SIPM breakdown voltage non uniformity.
Outputs	32-channel trigger outputs ASIC level general trigger (OR of all channel) ASIC level second level general trigger (OR of all channel for energy cut) Charge measurement (10 bits Time measurement (10 bits TDC interpolating 40MHz coarse time) One multiplexed analogue charge output One multiplexed digital trigger output
Internal Programmable Features	Common trigger threshold adjustment and 6bit-DAC/channel for individual adjustment Shaping time & gain of the charge shaper 32 8bit-input DAC for SiPM HV adjustment over 1V span

Table 1 – ASIC main parameters



Space LGAD for Astroparticle - SLA

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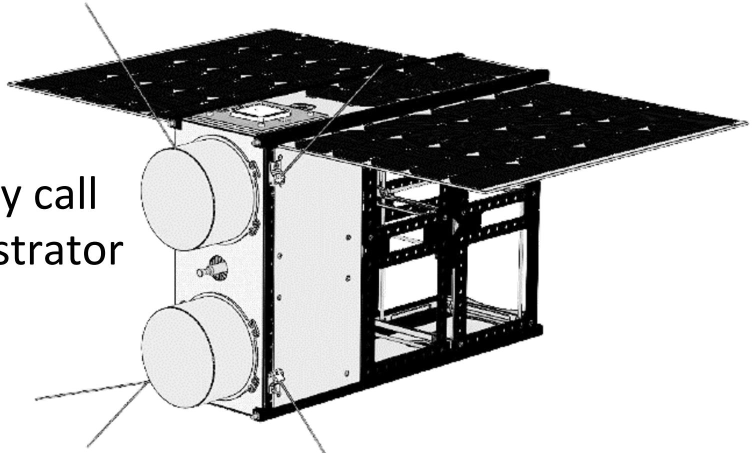
Space LGAD for Astroparticle - SLA

The two developments could have something in common: LGAD sensors!

→ timing and 4D tracking

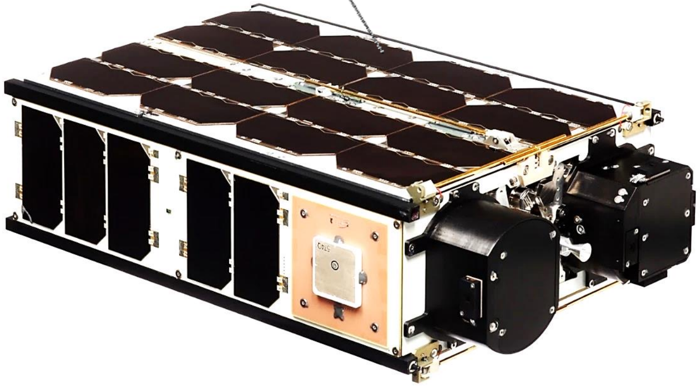
→ hits with very high S/N even with very thin detectors



- the idea has been proposed in an Italian Space Agency (ASI) "topical board"

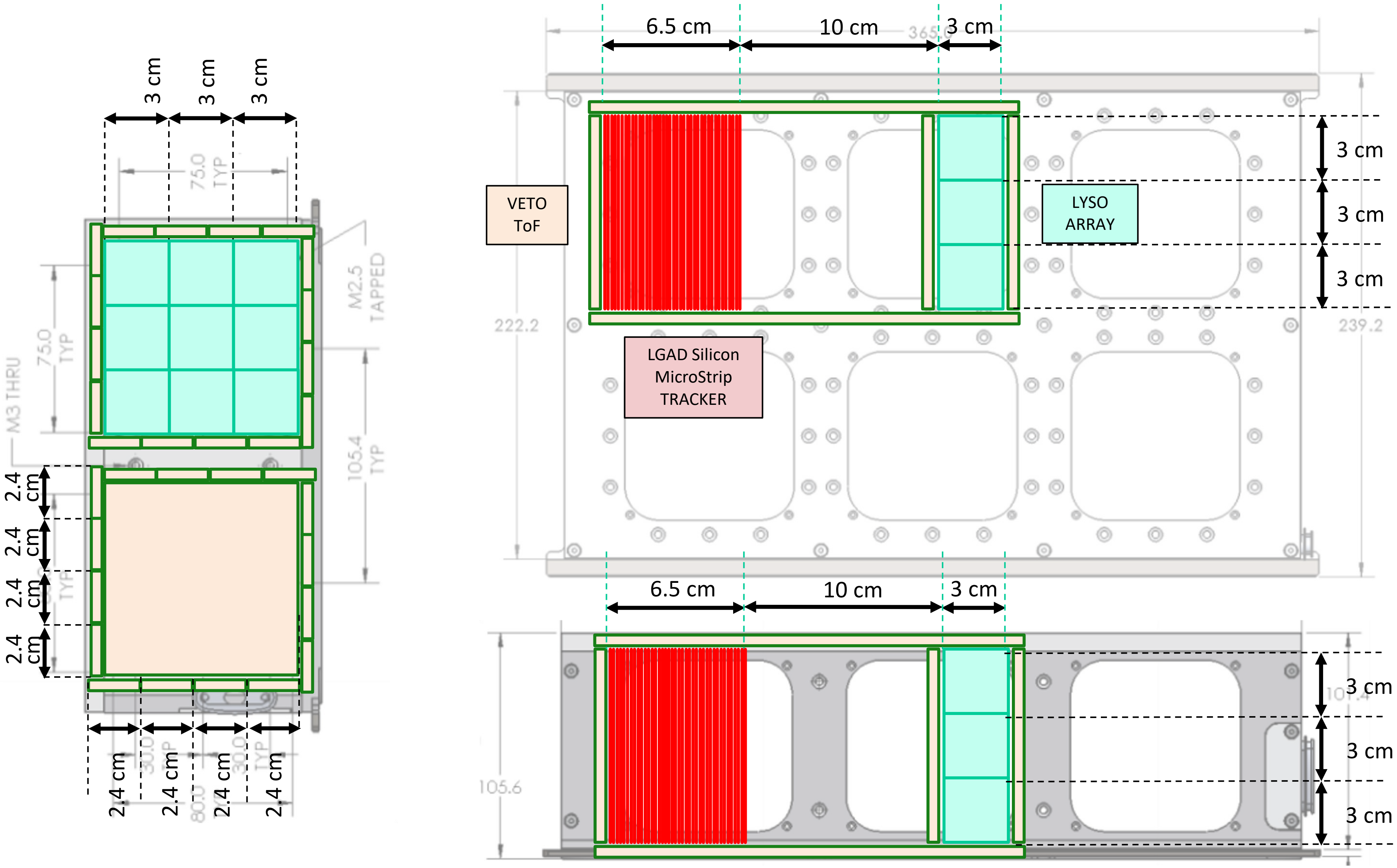
- the idea has been included in a Italian Research Ministry call for fundings (PRIN, "SLA"): the project includes a demonstrator in a 3U or 6U CubeSat

- the detector (launch included!) is doable with a ~ 1M€ budget envelope



*images from public websites(D-orbit, NanoAvionics, ISIS, …)

SLA layout


3 cm
3 cm
3 cm
75.0 TYP
M3 THRU
M2.5 TAPPED
105.4 TYP
2.4 cm
2.4 cm
2.4 cm
2.4 cm
2.4 cm
2.4 cm
2.4 cm
2.4 cm
6.5 cm
10 cm
3 cm
365.0
VETO ToF
LYSO ARRAY
222.2
239.2
3 cm
3 cm
3 cm
LGAD Silicon MicroStrip TRACKER
6.5 cm
10 cm
3 cm
105.6
3 cm
3 cm
3 cm

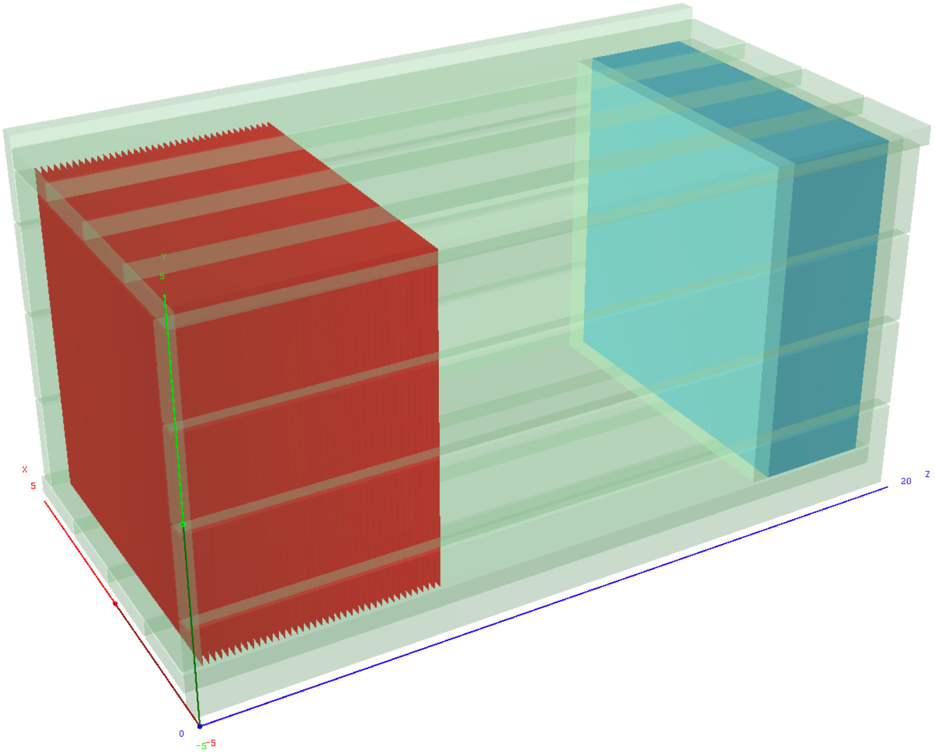
Space LGAD for Astroparticle - SLA

A conceptual design of the demonstrator compatible with the constraints in weight, volume and power budget of a CubeSat platform.
hosted in 2 units of a 3U CubeSat, with one additional units dedicated to the FEE and DAQ of the demonstrator.

LGAD SiMS Tracker
40 layers of 150 μm thick SiMS LGAD sensors
readout pitch: 150 μm → expected $\Delta x \sim 15\mu$m
Target timing resolution ~ 100 ps

Veto / Time of Flight system
0.5 cm thick Sci-paddles
SiPM readout using commercial FEE.
$\Delta t \sim 30$ ps

Electromagnetic Calorimeter
3x3x3 cm^3 array of LYSO crystals
SiPM readout using commercial FEE
Feasibility to add another stack of LYSO array under study



Weigth < 3 kg   Power < 20 W

Simulation of the detector performances is ongoing
FEE power mitigation techniques under investigation

*Geant4 geometry by G. Aristei

Space LGAD for Astroparticle - SLA

GOAL 1. (Technological)
Demonstrate the feasibility of constructing and operating thin LGAD SiMS sensors in harsh space environment

GOAL 2. (Scientific)
Show that LGAD performances are adequate for next generation astroparticle experiments in space

Measurement of converting photons with E > 20 MeV in the LGAD SiMS tracker with reconstruction of the e^+/e^- pair angle in the tracker
with improved vertex reconstruction by identification of backsplash hits

Observation of photons with E > 20 MeV from the Crab Nebula
Verification of detector PSF and confirmation of conversion technique
Observation of photons from Crab in the 20 MeV – 50 MeV range
Comparison with previous experiments (CGRO/EGRET) above 50 MeV

Study of charged CRs using the 5D tracking (position, energy deposit and timing) enabled by the LGAD SiMS tracker
Data-driven characterization of Tof capabilities for LGAD SiMS detectors
Data-driven characterization of e/p separation capabilities for LGAD SiMS detectors
Monitor the time variation of charged CRs and SEP events