Pentadimensional Tracking Space Detector on a CubeSat demonstrator for 5D tracking in space

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on behalf of the PTSD team

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Pentadimensional Tracking Space Detector (PTSD)

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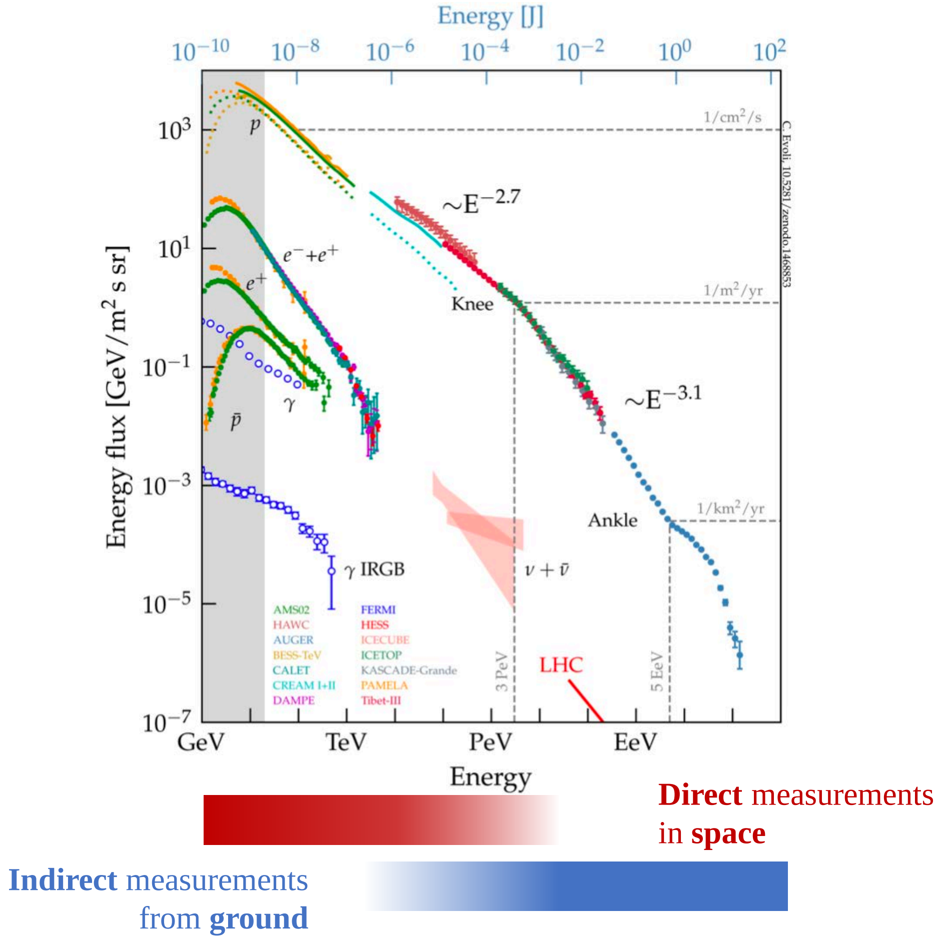
Scientific motivation



- CR study at PeV energy -> direct measure from space
- Flux decreases with energy -> high statistics -> high area
- Large acceptance missions remain the most promising approach to new discoveries and high-accuracy space measurements
- Future missions require 30 m^2 (HERD) to 200 m^2 (AMS-100) tracking areas
- Limits in space experiments: power consumption
- Si-µstrip detectors are the preferred solution to instrument **large area detectors** with larger number of electronics channels coping with the **limitations on power consumption in space**

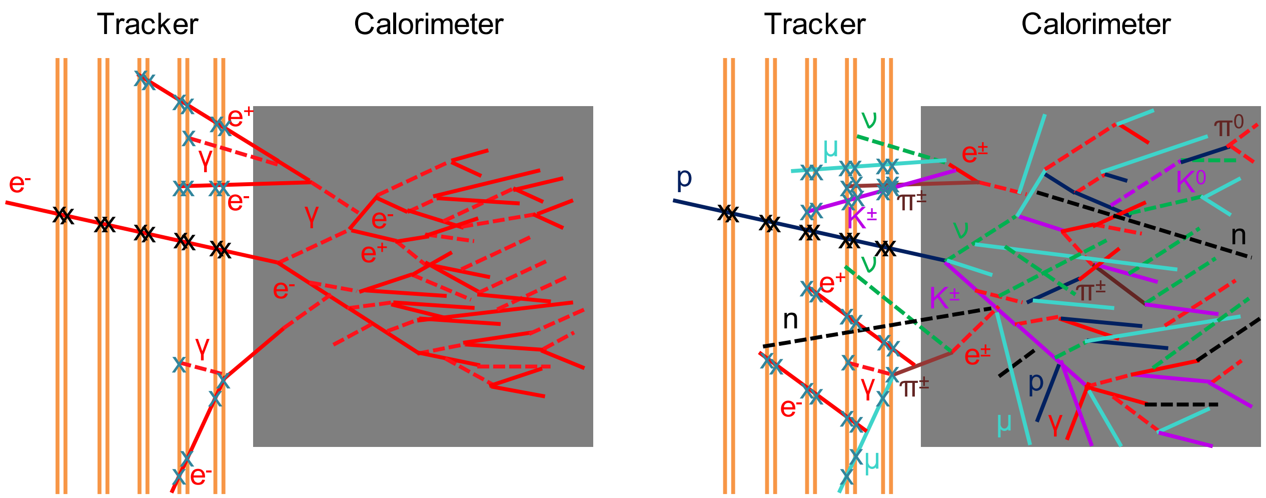
The Pentadimensional Tracking Space Detector (PTSD) project aims for developing a demonstrator to increase the Technological Readiness Level of LGAD Si-µstrip tracking detectors

Large area 5D-Tracking in space

M. Duranti et al., *Instruments* 2021, 5(2), 20

Backsplash particles from downstream calorimeter affect tracking efficiency by tens % at 1 TeV

Different backsplash timing signatures in upstream tracker from primary $e^{+/-}$ or h



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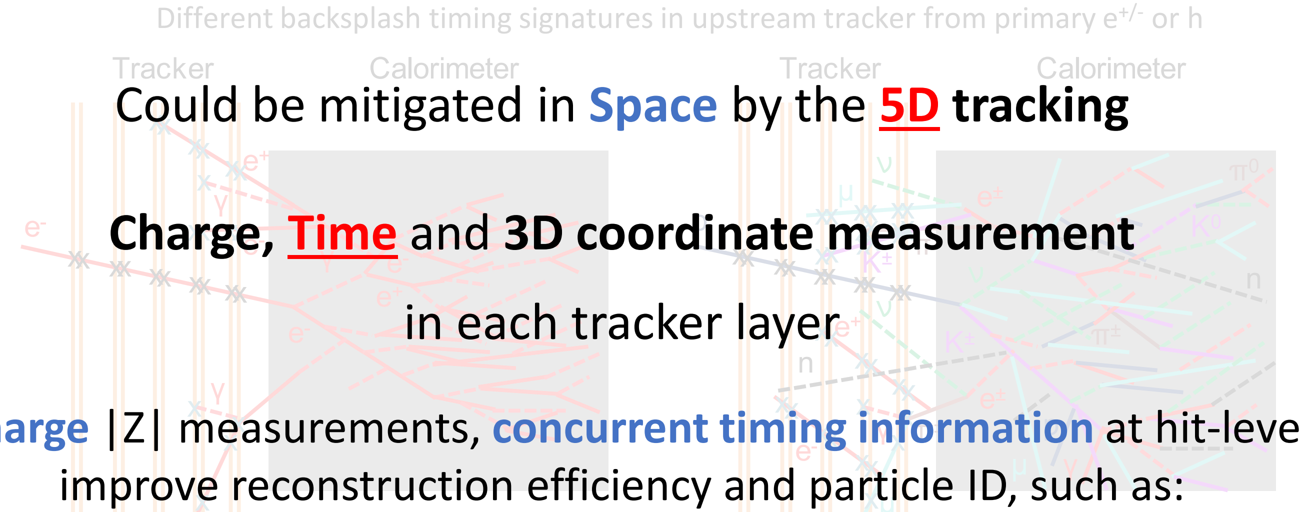


Could be mitigated in **Space** by the **5D tracking**

Charge, Time and **3D coordinate measurement**

in each tracker layer

In addition to **coordinate** and **charge** |Z| measurements, **concurrent timing information** at hit-level in tracker **(5D-tracking)** may improve reconstruction efficiency and particle ID, such as:

IMPROVED TRACK FINDING
Hit timing information improves track reconstruction on high rate environments and identifies back-scattering hits from downstream calorimeters

REMOVE "GHOST" HITS
Separating tracks in time can mitigate the ambiguity of "ghost" hits in SiMS with strips running in perpendicular directions

TIME OF FLIGHT
Hit timing resolutions of ~ 100 ps enable ToF measurements with SiMS complementary to scintillators with fast light readout

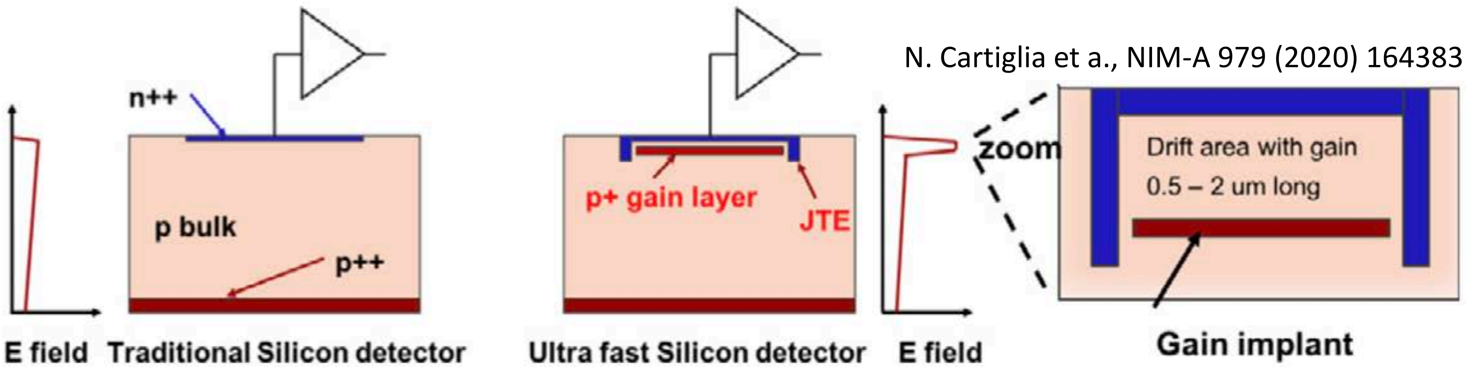
PARTICLE ID
Track timing identifies slow low-energy particles backscattering from downstream calorimeters for primary hadronic particle crossings

Timing resolution benchmark: < 100 ps (enabled with Si-µstrip LGAD [+ mitigation of FE consumption])

Break-through objectives (e.g.: performant isotope separation**): < 50 ps** (requires readout noise mitigation approaches)

LGAD Si-Microstrip Detectors

N. Cartiglia et a., NIM-A 979 (2020) 164383



- Low Gain Avalanche Diode: semiconductor devices with intrinsic moderate gain (10-50x)
- Key advantages for space: **thin active layer**, **excellent timing (<100 ps)**, better S/N
- Enables simultaneous measurement of 3D coordinates, charge, and precise timing --> **optimal candidate to enable 5D tracking in space**
- Proven technology from particle physics colliders, now to be adapted for space astrophysics

Tracking with Low Gain Avalanche Diodes

Gains from material budget reduction in low-energy CR and g-ray measurements

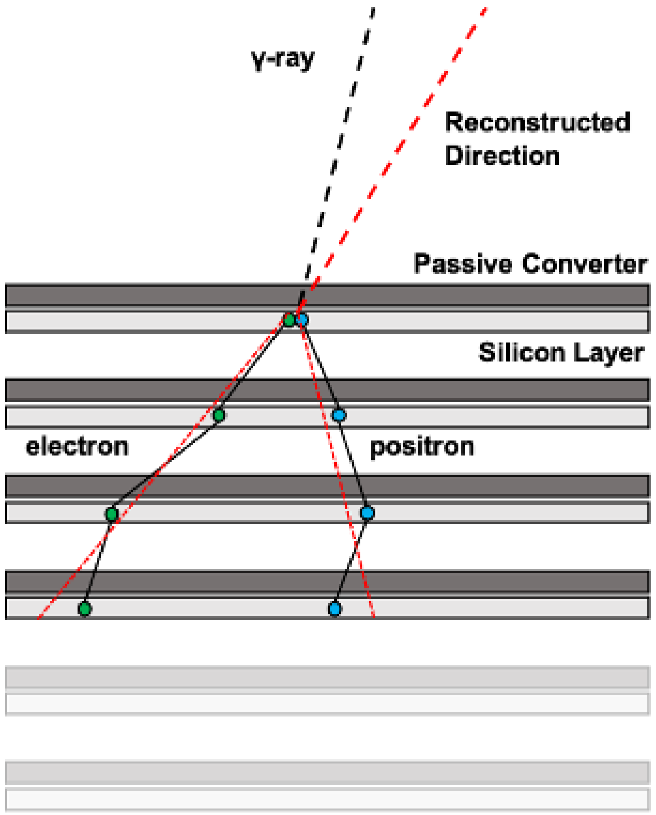
Thin high signal Si sensors: the LGAD intrinsic gain improves the SNR for thin sensors and allows for reduced active material budget tracking planes

The PSF of γ-ray experiments (Fermi-LAT, DAMPE, ...) is degraded at low energies by Coulomb MS in materials (passive converter and Si-sensors)

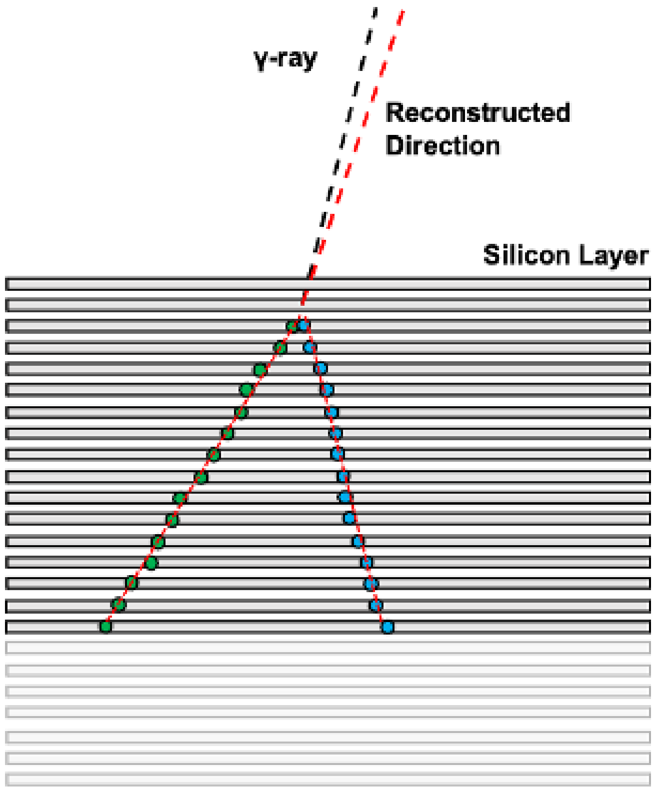
- **Remove passive materials**
- **Use thin active detectors**
- **Increase number of active layers to boost the GR conversion probability** (approach first proposed in X. Wu et al., "PANGU: A high resolution gamma-ray space telescope", Proc. SPIE 9144 (2014))

Sub-GeV γ-ray detectors
Opportunity for improved PSF below 1 GeV

PANGU ref.: 1 deg PSF @ 100 MeV (1/5 Fermi-LAT)
0.2 deg PSF @ 1 GeV (1/5 Fermi-LAT)



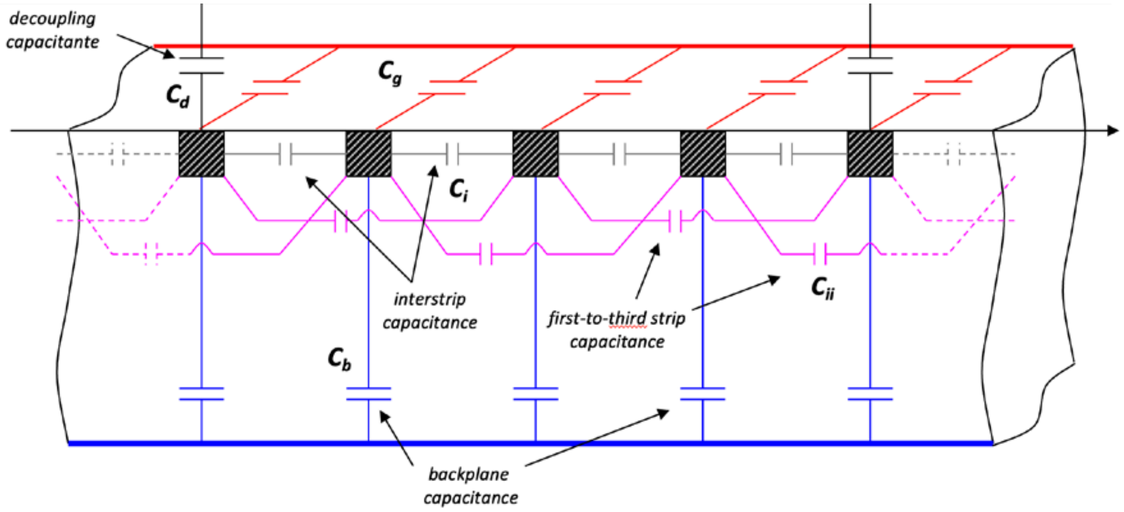
Standard approach
converter tracker



Novel approach
fully active multi-layer tracker

PTSD Project

Develop a breadboard laboratory model for verification of requirements, functionalities and space qualification of LGAD µstrips



p = pitch
l = strip lenght
d = thickness

C_i = interstrip capacitance ~ 1 pF/cm * *l* = 10 – 100 pF
C_d = decoupling capacitance ~ 1000 pF (DC sensors) or 120 pF/mm^2 (AC sensors) > C_i C_b C_g C_{ii}
C_b = **backplane capacitance ~ 1 pF/cm * *l* * *p/d*** = 0.5 – 2 * 10 – 100 pF
C_g = guardring capacitance << C_i
C_{ii} = first-to-third strip capacitance << C_i

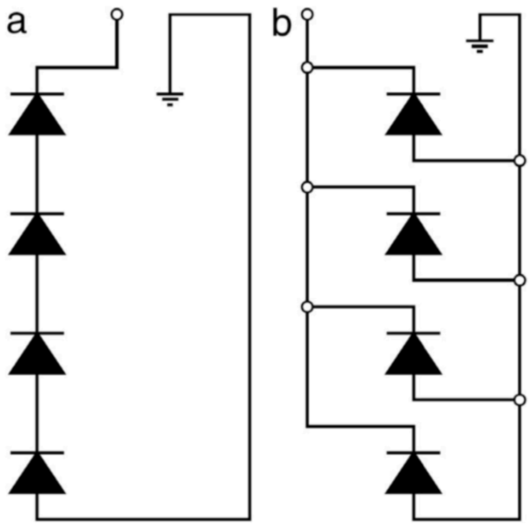
For thin and long strips capacitance must be kept under limit

Length of Si-µstrip sensors limited at production level
- typically, max ~ 10 cm long

50-100 cm long strips are obtained through daisy-chain

Long strips
↓
Parallel connection

Long daisy-chained LGAD timing performances will be limited by capacitance noise



N. Kratochwil et al., PANDA experiment

b) standard "parallel" readout
√ bias voltage independent on number of sensors
X total capacitance seen by readout FEE scales with number of sensors

a) "serial" readout
X bias voltage scales with number of sensors
√ total capacitance seen by readout FEE scales **down** with number of sensors

--> can we "port" this approach to LGADs?

PTSD project – HW developments

Is it feasible to cover tens of m² of tracking areas with LGADs and

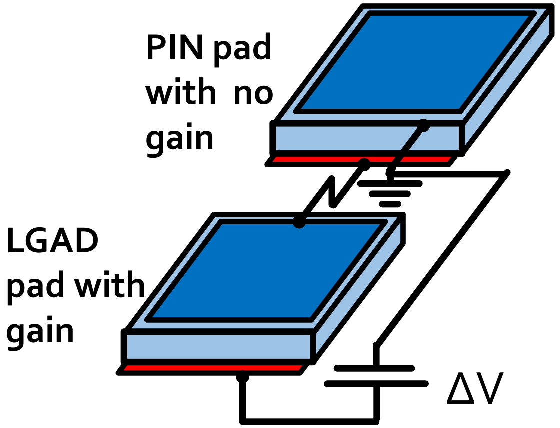
- < 100 (ideally 20-30) ps timing resolution
- < 10 µm spatial resolution
- < 100 W/m²
- < 100 kch/m²

How large is the maximum length of a Si LGAD µstrip?

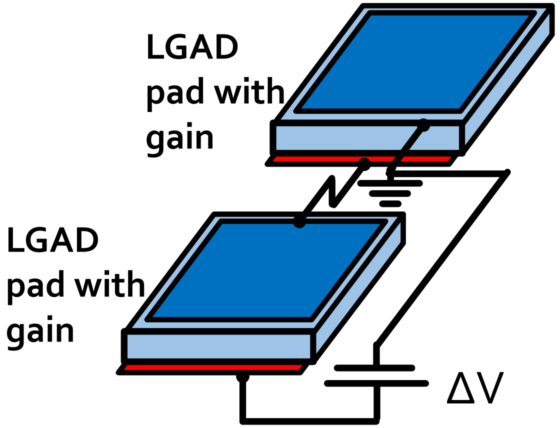
Is it possible to "daisy chain" LGADs?

Is there a way to mitigate the related problems and, for example, reduce the capacitance even with very thin LGAD sensors?

Breadboard characterization ongoing at INFN - Perugia



Preliminary results: capacitance for LGAD series is lower than single LGAD



Space LGAD for Astrophysics (SLA) Demonstrator

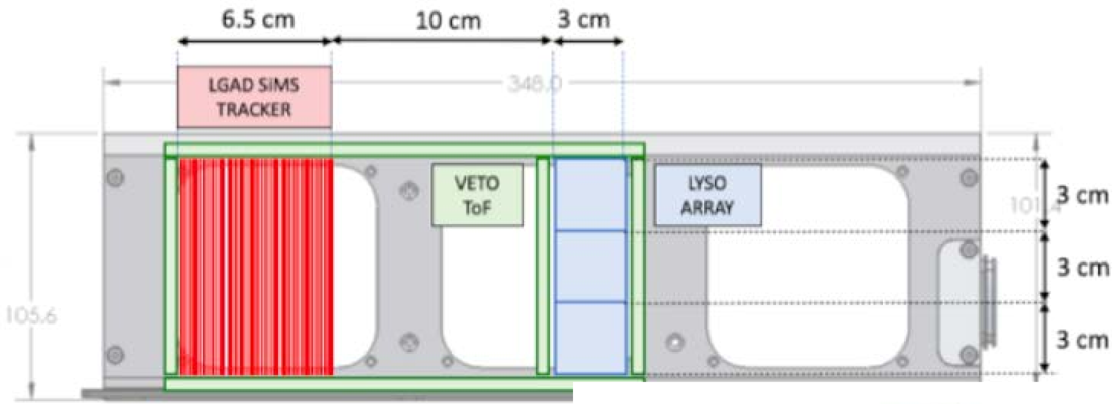
Design of a In-Orbit Demonstrator of the 5D tracking approach and LGAD technology

Goal 1 (Technology): Demonstrate feasibility of operating thin LGAD Si-microstrip sensors in space → TRL 9 (space proof)

Goal 2 (Science): Measure CRs with 5D tracking (< 100ps), backsplash identification, and advanced particle ID capabilities

Goal 3 (Science): Measure γ-rays >20 MeV from Crab Nebula with improved angular resolution in fully-converting tracker

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 + 3 service units -> 6U-XL cubesat.

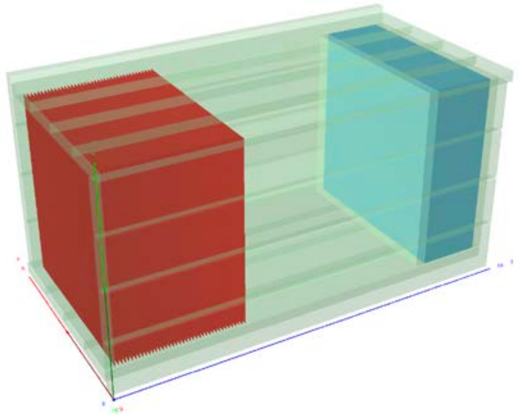


LGAD SiMS Tracker
40 layers of 150 µm thick SiMS LGADs
readout pitch: 150 µm
- expected Δx ~ 15µm

Target timing resolution ~ 100 ps

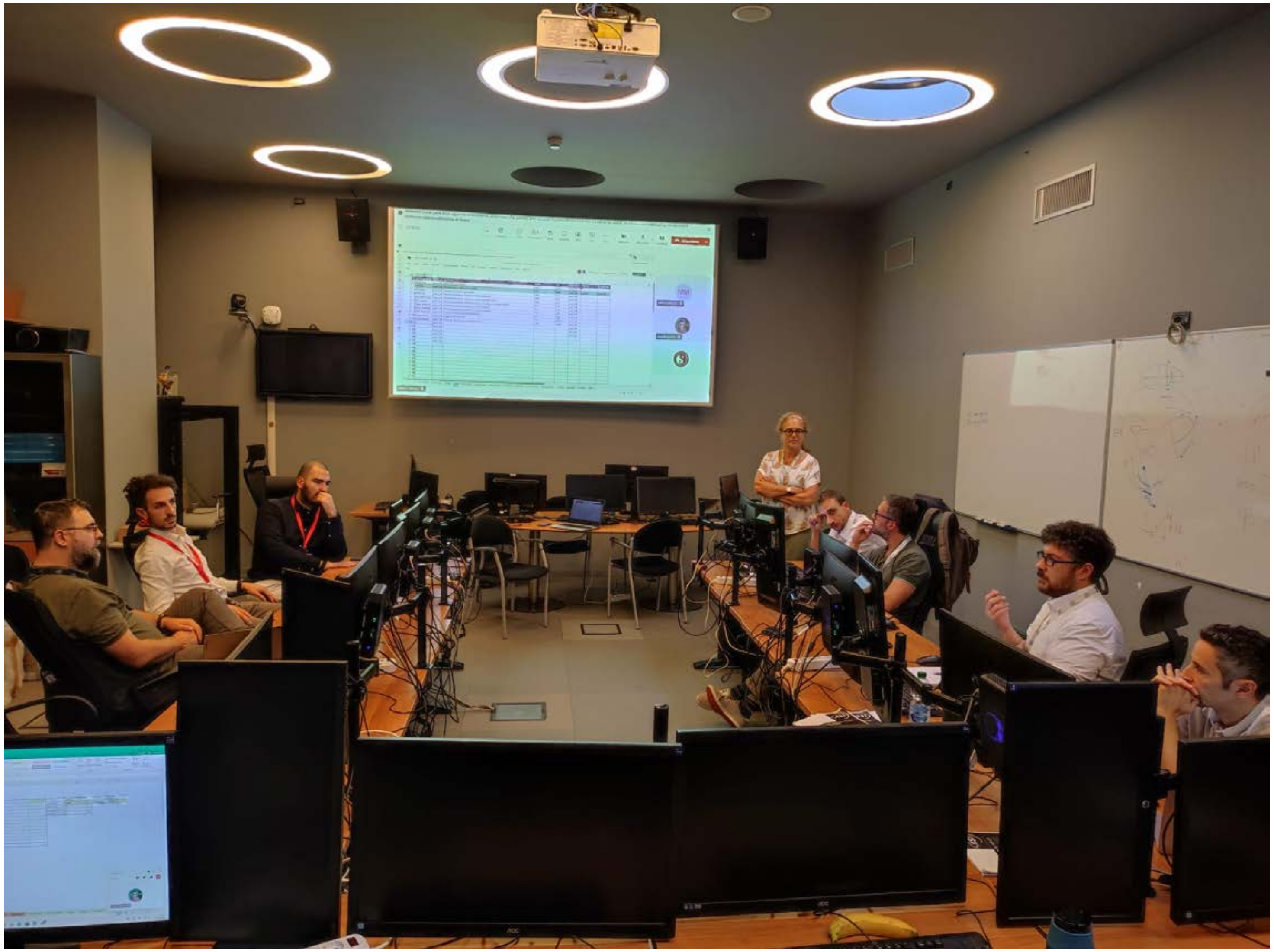
Veto / Time of Flight system
0.5 cm thick Sci-paddles
SiPM readout using commercial FEE
Δt ~ 30 ps

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

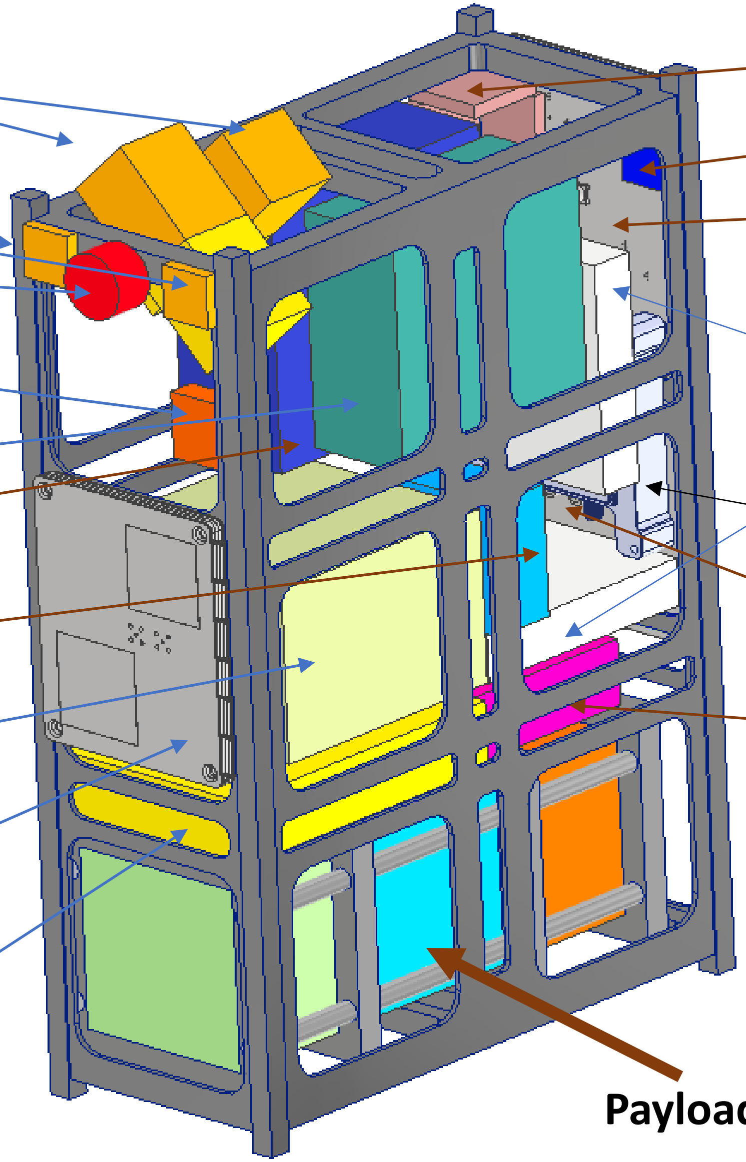


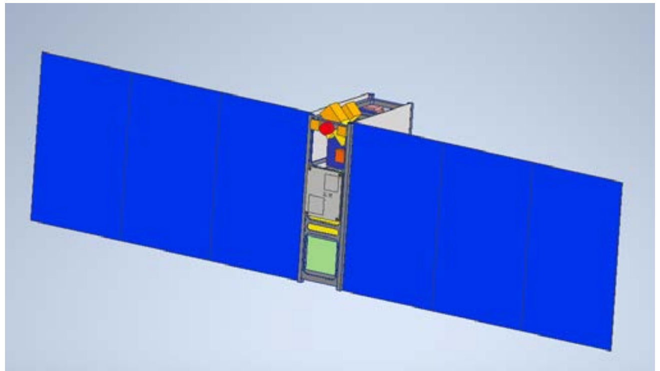
Perspectives to fly a cubesat demonstrator to reach TRL=9 in a follow-up activity

What is a Concurrent Engineering Facility

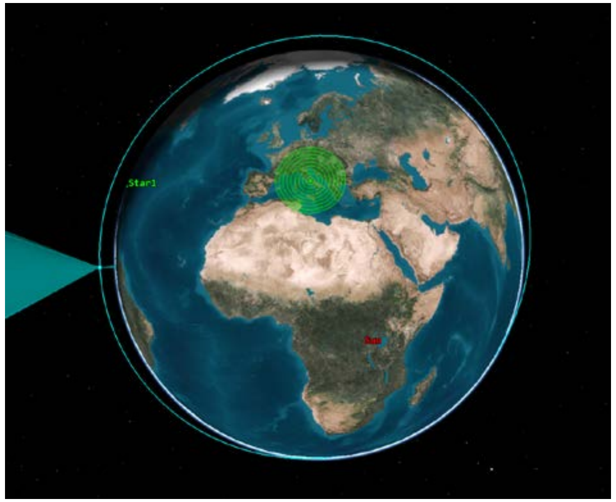


SLA Cubesat configuration

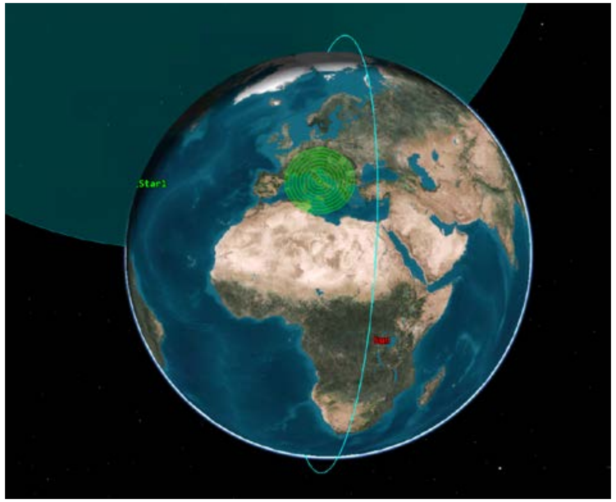




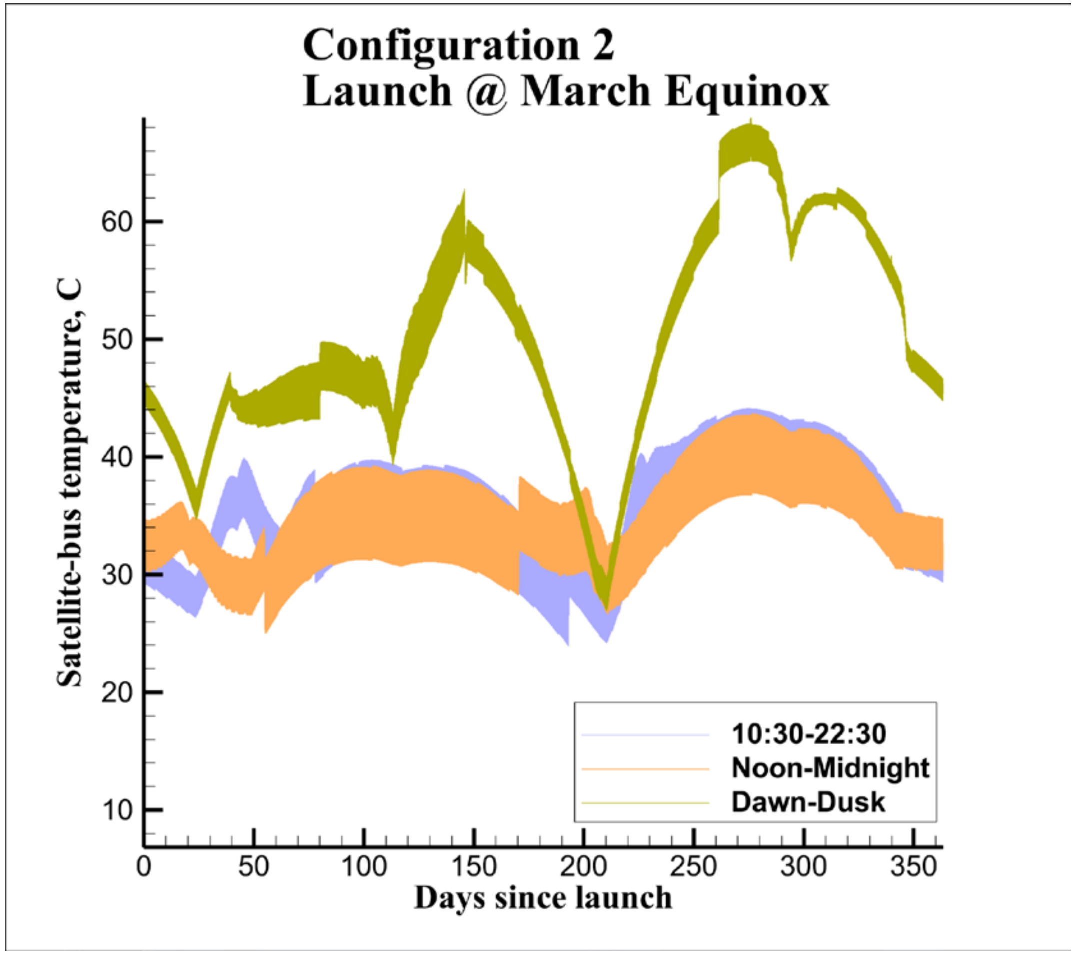
SLA Cubesat orbit and thermal-control study



SSO 6-18



SSO 12-24



Passive thermal-control: trade off taking into account the SSO orbit and 30% full exposure to the Sun during sunpointing.

Noon-Midnight is best for thermal balance

The Concurrent Engineering Facility trades-off

- **ORBIT**:
  - **SSO polar orbit** (Altitude: 490 km; Inclination: 97.38°C) offers the *wider launch opportunities*, even though the passage to the poles causes downtime in data acquisition (worst case scenario approximately 30% of the entire orbit) -> this does not compromise the success of the mission in terms of the time required for data acquisition.

- **POWER**:
  - **PWR consumption**: average 40 Wh, peak 68 Wh - It considers *the devices in use during the modes that intervene in the orbit* (data acquisition, download, etc.), calculates the correlation between panel power, time required for recharging, acquisition time, and orbit duration.
  - **Solar panels**: 120 W - This implies a *recharging time* of approximately 30% of the orbit, so the “sunpointing” mode will last 0.5 hours. Considering the expected average consumption, the recharging time of the solar panels is approximately 30% of the absorbed power.

- **Flight Dynamic System: Crab visibilty in SSO orbit**
  - the total interval during which the Crab is visible from the Cubesat, i.e., it is not “obscured” by the Sun or Earth.

Outcome of the Concurrent Engineering Facility Study

- The instrumentation used (excluding payload, to be developed) is fully based on COTS and fits in a 6U configuration (mass, volume)
- The SSO orbit allows for several launch opportunities and the cubesat is compatible with the VegaC launcher
- The subsystems temperatures remain within operating limits.

- Breadboard development with proof-of-concept stacked LGAD tests
- FEE Board: Custom 32-channel readout in production (2-stage amplifier design)
- Spatial & timing resolution measurements on test structures underway

Conclusions

5D Tracking: Breakthrough Technology for Space Astrophysics

LGAD Si-microstrip detectors enable unprecedented cosmic-ray and gamma-ray measurements in space

CubeSat demonstrator validates technology and opens new opportunities for future missions

The dinosaurs became extinct because they didn't have a space program. Larry Niven

Thanks for your attention

Backup slides

Cubesat payload: mission objectives

GOAL 1. (Technological)
Demonstrate the feasibility of constructing and operating thin LGAD Si-μstrip sensors in harsh space environment – TRL 9

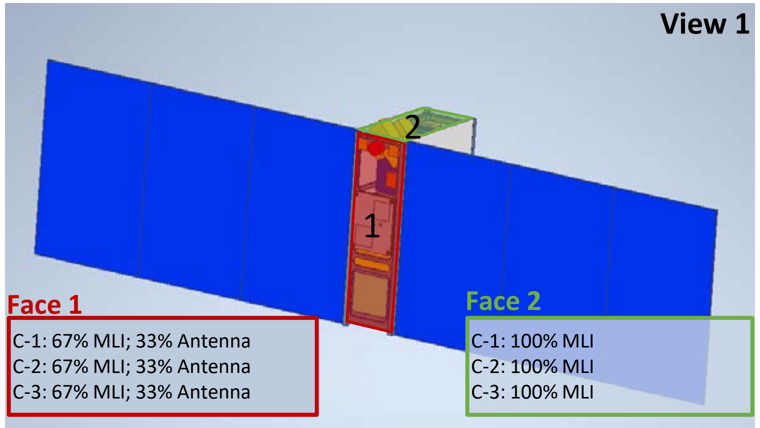
GOAL 2. (Scientific)
Show that LGAD performances are adequate for next generation astroparticle experiments in space

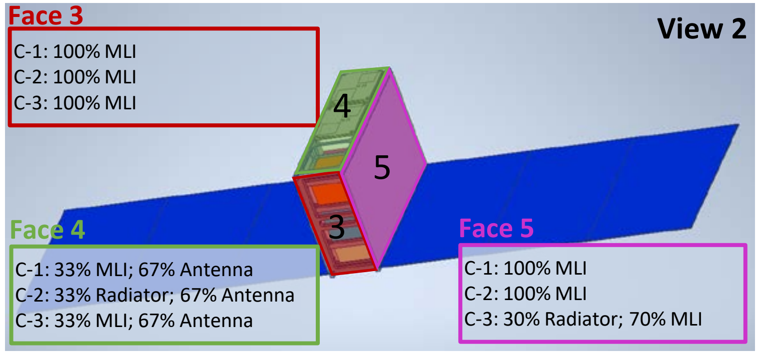
Measurement of converting photons with E > 20 MeV in the LGAD Si-μstrip tracker with reconstruction of the e^+/e^- pair angle in the tracker
with improved vertex reconstruction by identification of backsplash hits

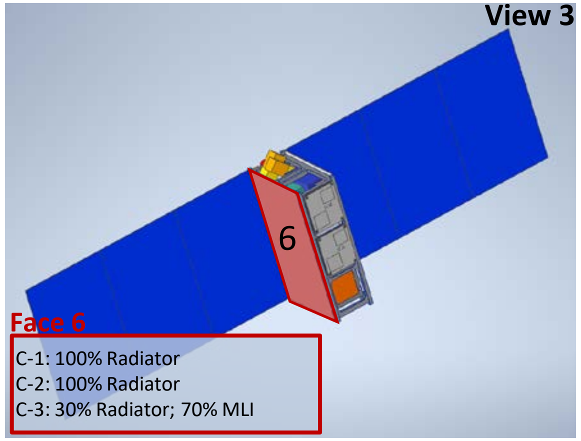
Observation of photons with E > 20 MeV from the Crab Nebula
Verification of detector PSF and confirmation of conversion technique
Observation of photons from Crab in the 20 MeV – 50 MeV range
Comparison with previous experiments (e.g., CGRO/EGRET) above 50 MeV

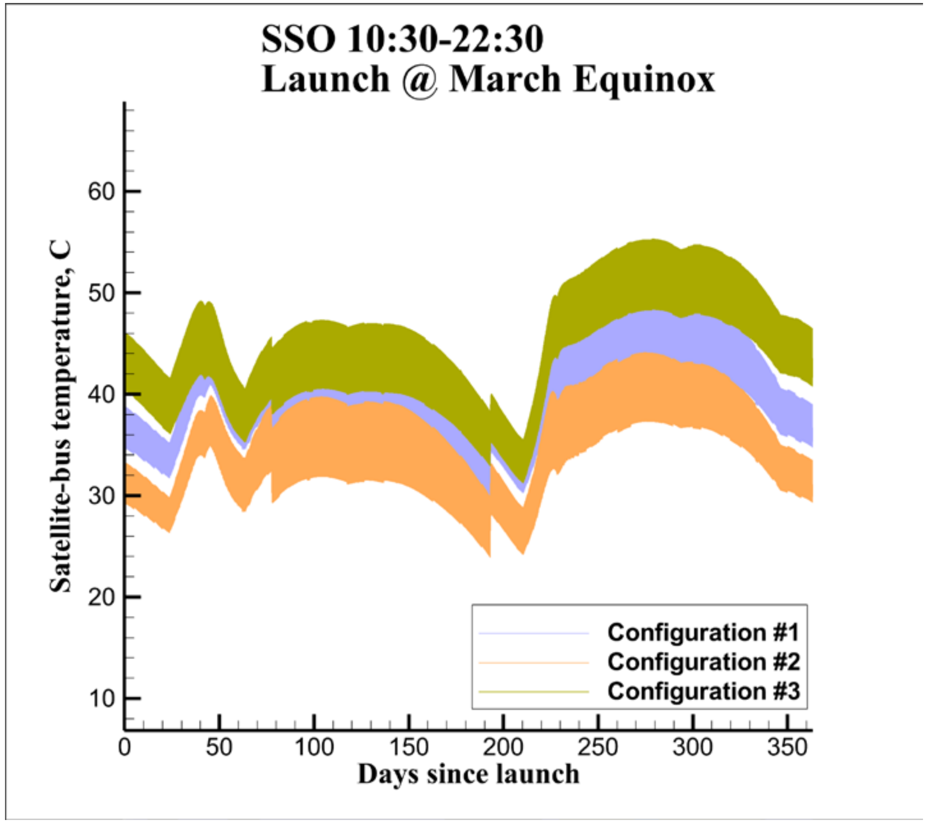
Study of charged CRs using the 5D tracking (position, energy deposit and timing) enabled by the LGAD SiMS tracker
Data-driven characterization of Tof capabilities for LGAD SiMS detectors
Data-driven characterization of e/p separation capabilities for LGAD SiMS detectors
Monitor the time variation of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

Passive thermal-control: configuration trade off









Limit temperature: 50 °C ⟶ Configuration #2 preferred