

Space-based cosmic-radiation detection with the Zirè instrument

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On behalf of the NUSES Collaboration

Supervisors: Adriano Di Giovanni, Dimitrios Kyratzis, Pierpaolo Savina

Outline

Introduction on NUSES space mission and Zirè instrument

SiPM characterization for the protoflight model (PFM)

ACS and PST detector optimization

Zirè Engineering Qualification Model (EQM): integration

Cosmic-muon tests at LNGS

Summary and future steps

The NUSES space mission

The mission

Italian led mission (Joint GSSI + TAS-I),
funded by the Italian government and ASI

Novel **scientific** and **technological**
pathfinder towards the detection of low and
high energy radiation

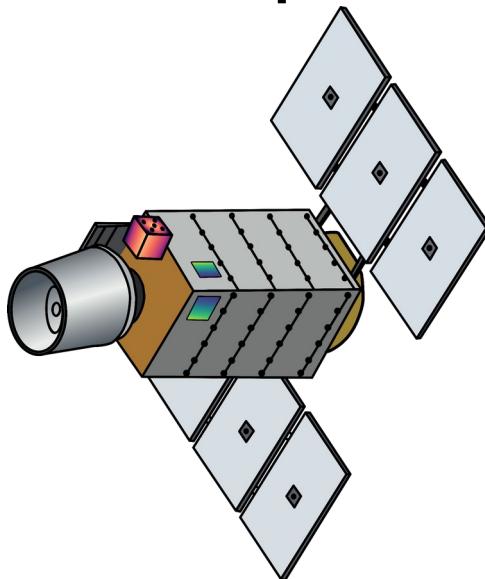
The orbit

Lifetime **3.5 years**

Mean altitude **550 km (LEO)**

Inclination **97.6 deg**

Pointing **<0.1 deg**



Scientific objectives

Measuring **UHECRs** + atmospheric **Cherenkov light detection from space** ($>10^{16.5}$ eV)

Low energy fluxes (<300 MeV) of **CRs** + **solar radiation** studying **Van Allen belts**, **space weather**, geomagnetic activity and **MILC couplings**

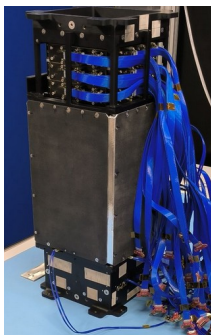
Low energy **photon** detection (0.1 - 50 MeV), of **transient gamma sources (GRBs)** + solar flares

New detector techniques and observational
methods with fully **optimized SiPM readout** for
space missions

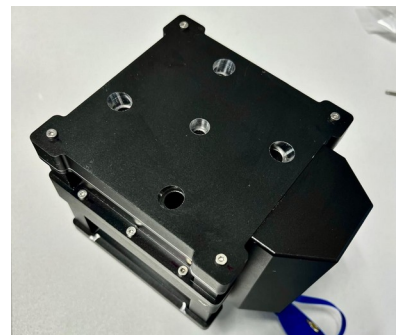
Terzina telescope



Zirè instrument



LEM



The NUSES collaboration



More than 60 scientists from Italian and international universities / institutions, assisted by industrial partners



Industrial Partners:



Research institutes

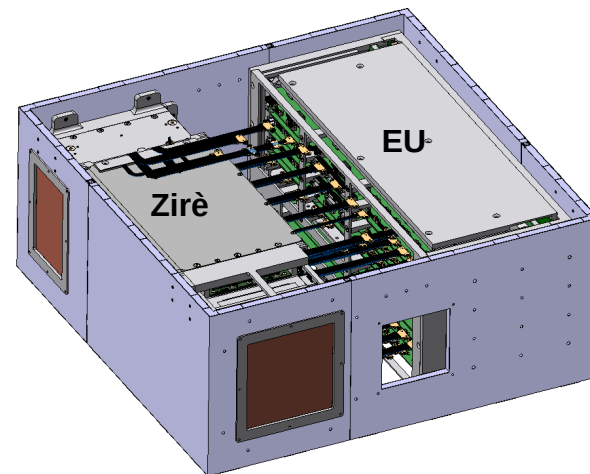
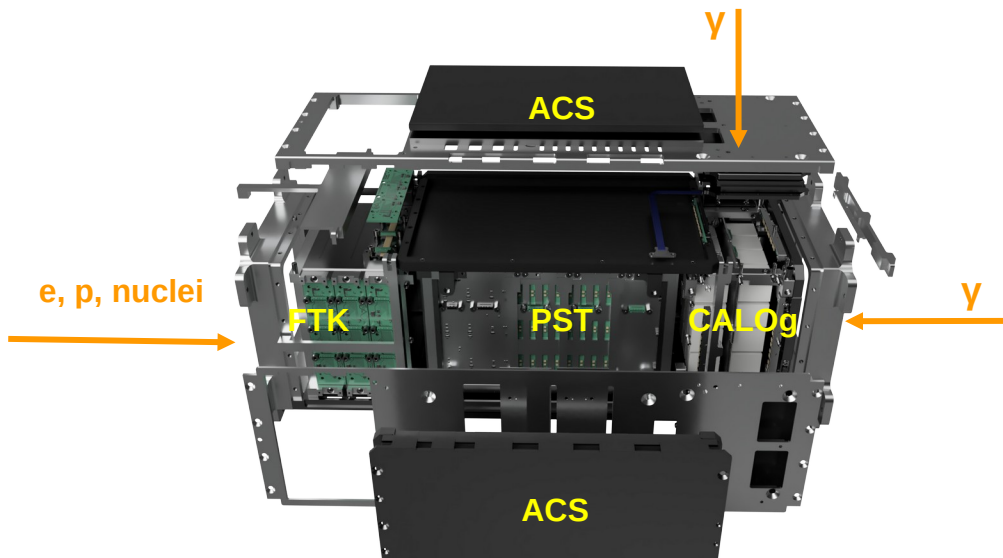
Gran Sasso Science Institute
Laboratori Nazionali del Gran Sasso
Università dell'Aquila
Università di Torino and INFN Torino
Università di Trento and INFN-TIFPA
Università di Bari, Politecnico di Bari and INFN Bari
Università di Padova and INFN Padova

Università "Federico II" and INFN Napoli
Università del Salento and INFN Lecce
University of Geneva
Columbia University
NASA Goddard Space Flight Center
Pennsylvania State University
New York University Abu Dhabi

Industrial partners

Thales Alenia Space Italia (TAS-I)
Sophia High Tech
Fondazione Bruno Kessler
Officina Stellare
Nuclear Instruments
AGE Scientific

Zirè: Detector Design



FTK

Fiber TrackKer

Track reco with scint. fibers
3 modules in X-Y
SiPM array linear readout
9.6 x 9.6 cm² (total area)

ACS

Anti-Coincidence System

Veto for charged particles
Plastic scintillator tiles
9 layers (0.5, 0.6 cm thick)
SiPM readout (3x3 mm²)

PST

Plastic Scintillator Tower

Particle Identification
32 PS layers (3 bars/layer) in X-Y
First 6 layers, dimensions: 12 x 4 x 1 cm³
Rest: 12 x 4 x 0.5 cm³
SiPM readout (1x1, 3x3 mm²)

CALog

Calorimeter

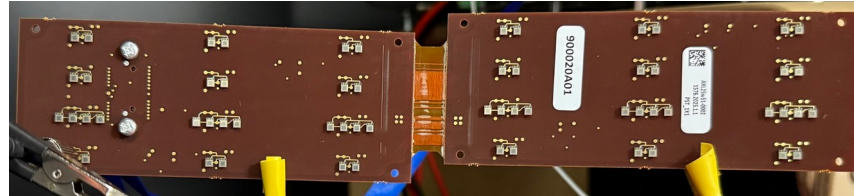
Energy measurement
4 x 4 x 2 matrix setup
GAGG crystal cubes
Module: 2.5 x 2.5 x 3.0 cm³
SiPM readout (1x1, 3x3, 6x6 mm²)

Zirè: Sub-detector highlights

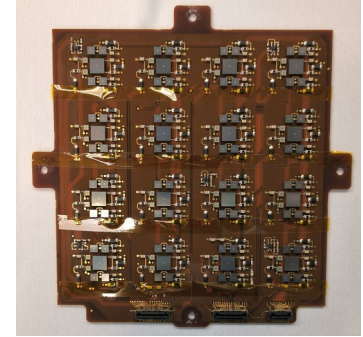
Hamamatsu SiPM readout
Series: S13552 and S14160



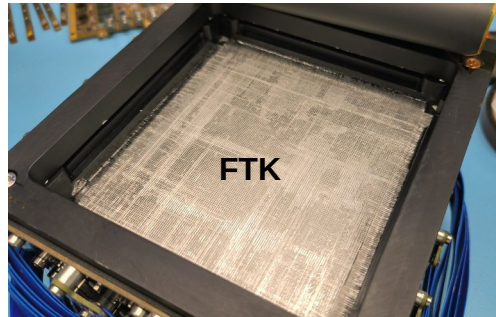
ACS board (SiPMs 3x3 mm²)



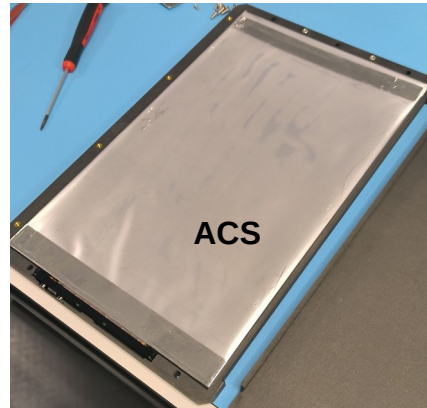
PST board (SiPMs 1x1 and 3x3 mm²)



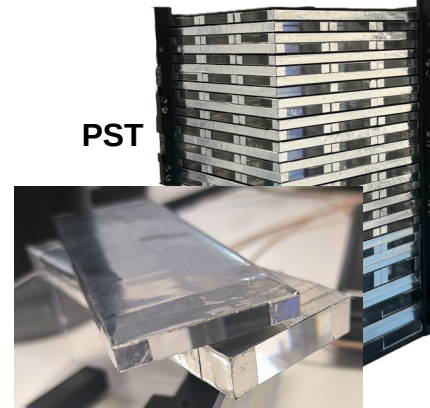
CALOg board (SiPMs 1x1, 3x3, 6x6 mm²)



FTK



ACS



PST



CALOg

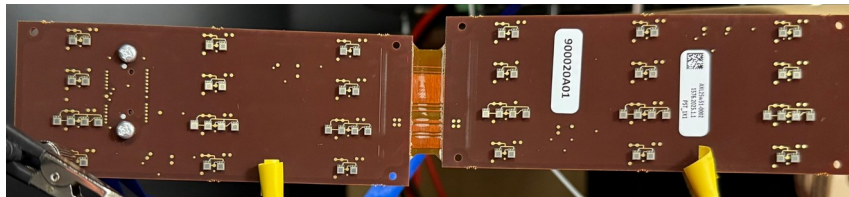
The SiPM characterization



Light pulser,
 $\lambda = 405 \text{ nm}$



Integrating sphere



PST SiPM board in the dark box



5 kHz

Photon incidence
rate

BIAS RANGE:

40.0 V to 43.0 V (0.5 V step) for $3 \times 3 \text{ mm}^2$

42.0 V to 44.4 V (0.4 V step) for $1 \times 1 \text{ mm}^2$

39.4 V to 40.4 V (0.2 V step) for $6 \times 6 \text{ mm}^2$

LIGHT

405 nm, 66 ps pulser →
sphere → fibre aimed at
one SiPM



READOUT

Samtec cable → DAQ
with $4 \times \text{CITIROC 1A}$



ACQUISITION

External (laser) trigger;
histograms saved as
data.csv + config.json

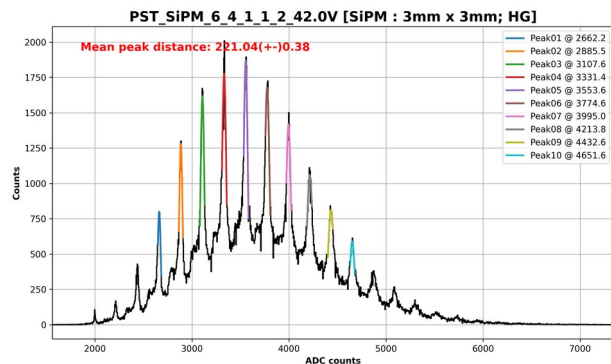
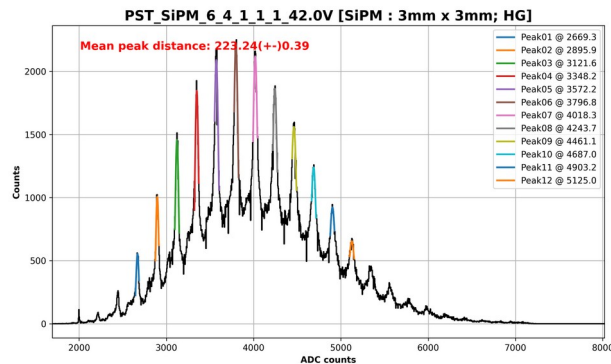


ANALYSIS

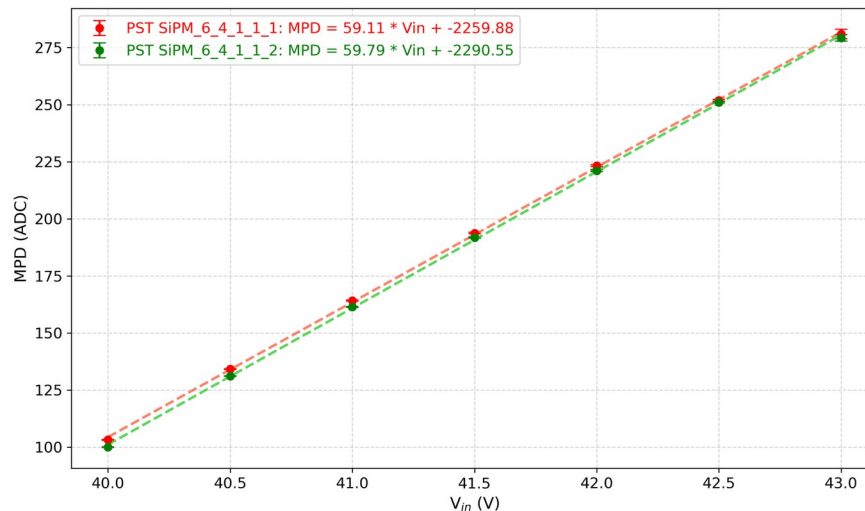
Peak finding + Gaussian
fits → MPD → V_{BD} and
gain vs V_{OV}

Analysing the data

PST SiPM spectra



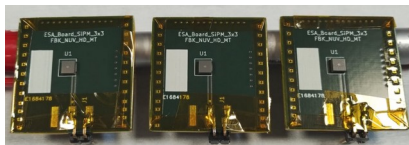
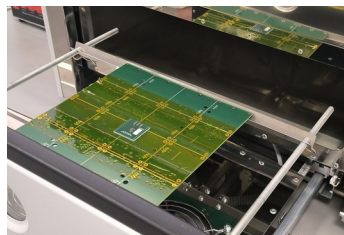
MPD (mean peak distance) = charge of 1 p.e. in ADC counts = gain



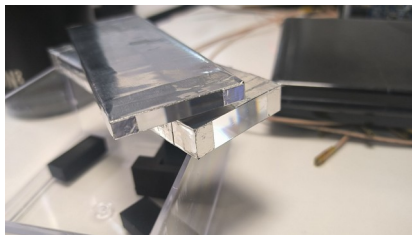
Two SiPMs of the same PST bar: MPD linear with bias $\rightarrow V_{BD}$

Finger plot at 42.0 V: k-th peak = k fired cells

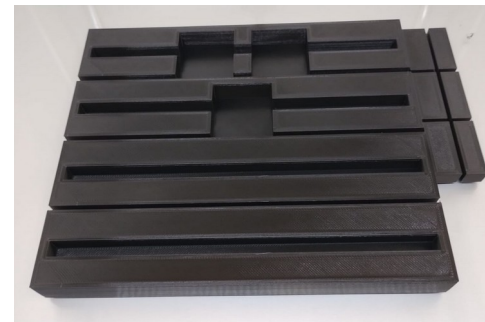
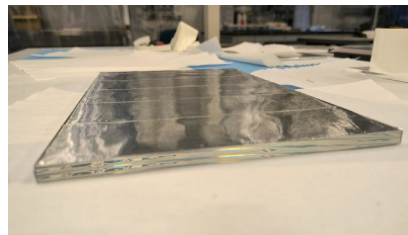
ACS and PST: prototype preparation



PST bar



ACS tile



Step 1:

ACS + PST SiPMs
Hamamatsu 3x3 mm² →
S14160-3050HS
mounted on PCBs +
soldered

Step 2:

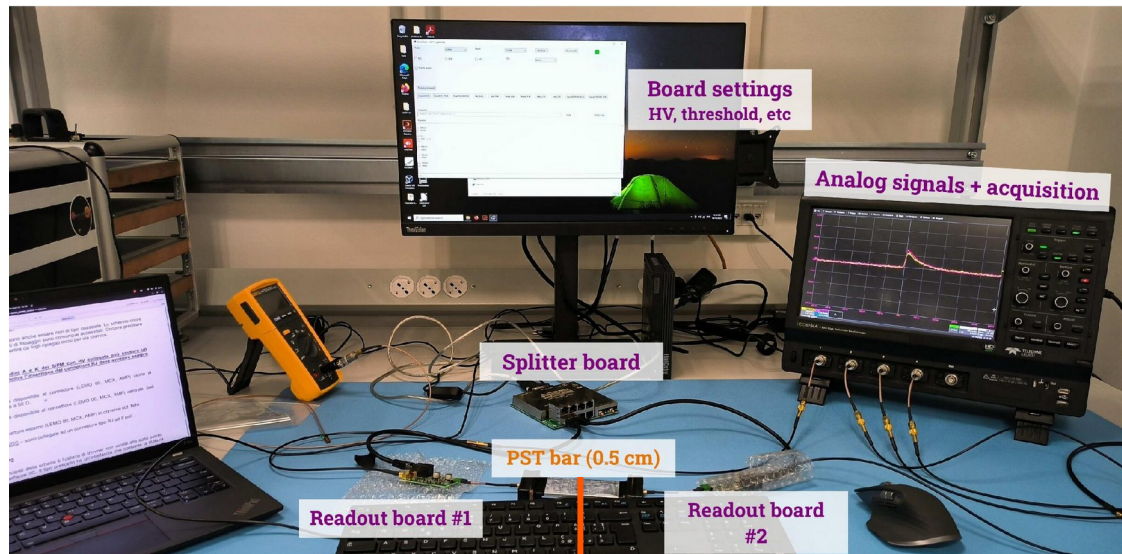
Cleaning → ESR reflector film → Chofoil wrapping (ACS
tile and PST bars)

ESR = 3M Enhanced Specular Reflector, a mirror film
(reflectivity ≈ 98 %) wrapped around the scintillator

Step 3:

Designed and 3D printed
endcaps
SiPM board + silicon coupling
fitted
Additional black tape used →
light-tightness

Performance optimization in PST and ACS



Measurement bench: PST bar
read by two SiPMs



PST bar with a SiPM
board at each end

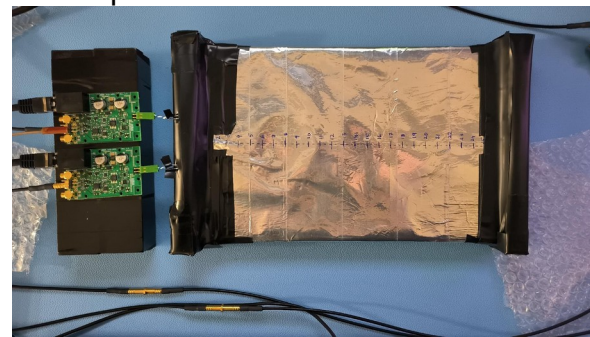
SiPMs: Hamamatsu S14160-3050HS

Full SiPM characterization + Gain
equalization

Radioactive ^{90}Sr source (handled by the
supervisors)

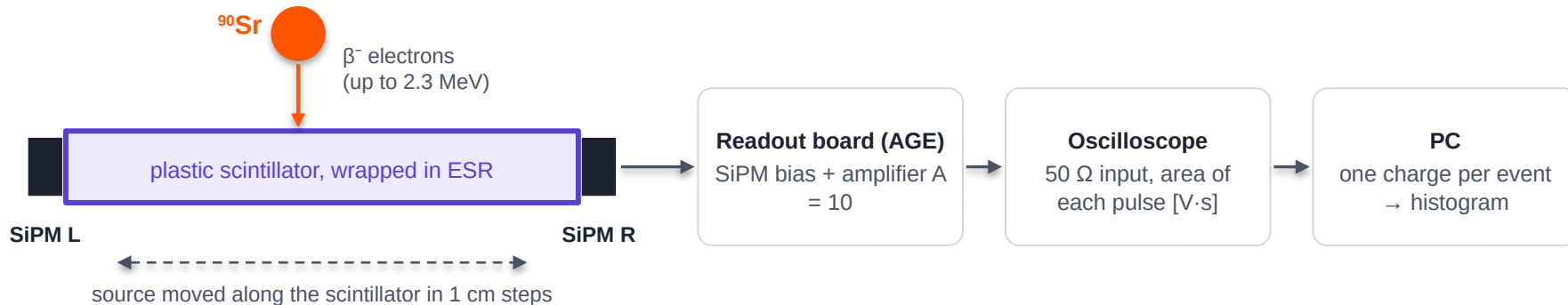
Photons detected at each source position

Measurement of light attenuation length in
both setups



ACS tile with its two readout boards (SiPM bias + amplifier
 $\times 10$)

Measurement procedure



1 • GAIN

DCR (dark counts, no light) at 9 bias voltages $\rightarrow$ SPE charge $Q_1 \rightarrow$ gain. Bias set for $G = 2.4 \times 10^6$ on both SiPMs

2 • SOURCE SCAN

^{90}Sr on top of the scintillator, $\sim 10^4$ events per SiPM at each position

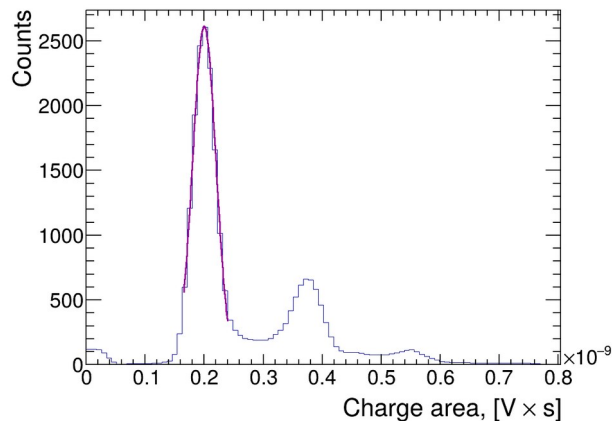
3 • PHOTO-ELECTRONS

Charge $\rightarrow$ photo-electrons: $N_{pe} = Q / Q_1$. LanGaus fit of each spectrum $\rightarrow$ MPV

4 • RESULTS

N_{pe} vs source position $\rightarrow$ light yield, uniformity, light attenuation

Gain equalization measurements



1. DCR (dark-count) runs, no light, 9 bias values; purple: fit of the 1 p.e. peak

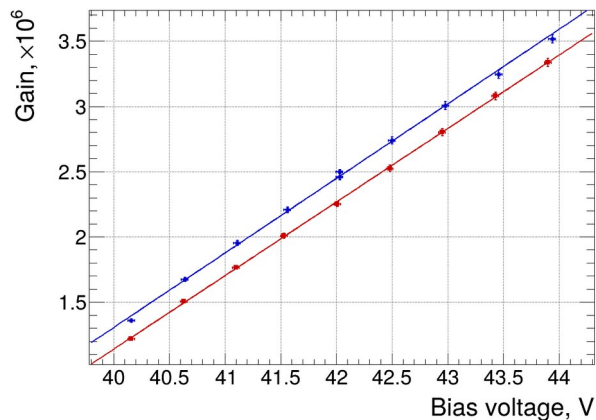
SPE (single photo-electron) peak $\rightarrow Q_1$

Gain $\rightarrow G = Q_1/e$

Q_1 = pulse area / (A·R)

A = 10: readout-board amplifier;

R = 50 Ω : oscilloscope input impedance

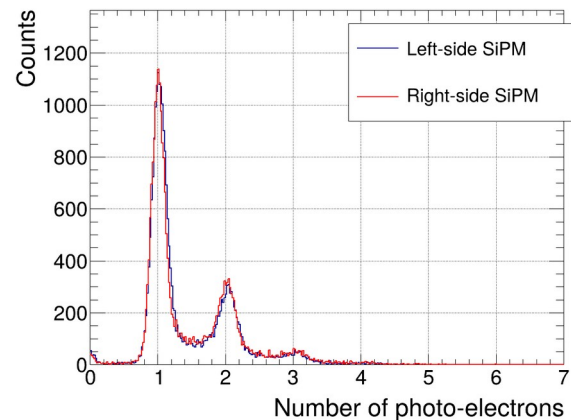


2. Gain vs bias: linear (blue: left-side, red: right-side SiPM)

Common gain $2.4 \times 10^6 \rightarrow$ bias 42.03 V (L), 42.25 V (R)

Left-side SiPM: $y = (5.7e+05 \pm 8e+03) x + (-2.15e+07 \pm 3e+05)$, $\chi^2/\text{ndf} = 0.6642$

Right-side SiPM: $y = (5.64e+05 \pm 8e+03) x + (-2.14e+07 \pm 3e+05)$, $\chi^2/\text{ndf} = 0.2179$

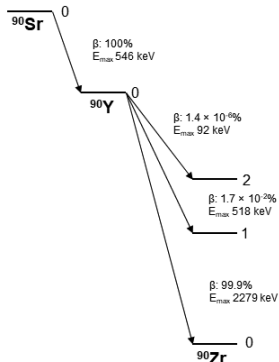


3. Check: DCR spectra in p.e. (blue: left-side, red: right-side SiPM) $\rightarrow$ peaks coincide
 Q_1 converts source charge $\rightarrow$ photo-electrons

The same operation steps done for both ACS and PST

PST: radioactive source measurements

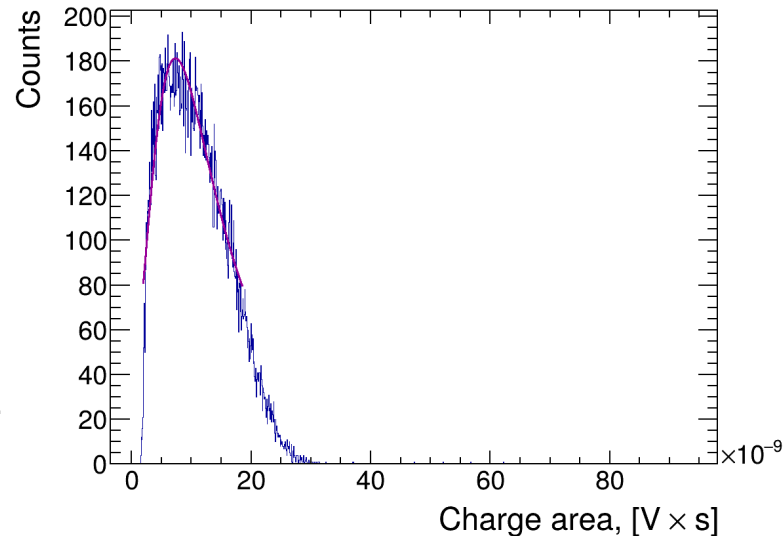
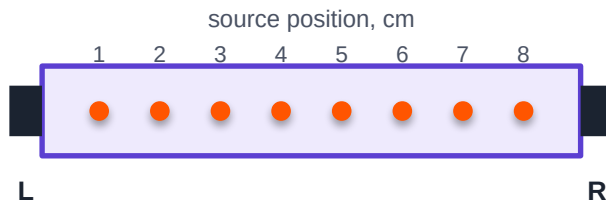
^{90}Sr decay scheme



Wiatr, Karol & Rubel, Barbara & Kardaś, Małgorzata. (2022). Rapid ^{90}Sr quantification method based on the Bateman equation for routine laboratory work. 67. 67-72. 10.2478/nuka-2022-0006.



PST bar 1.0 cm, Sr-90 on top, SiPM at each end.

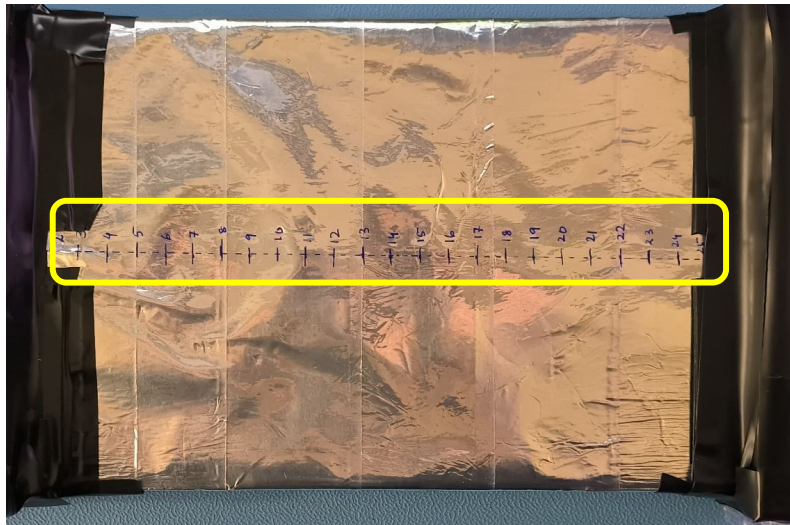


Spectrum: left-side SiPM, source at 5 cm;
purple: LanGaus fit

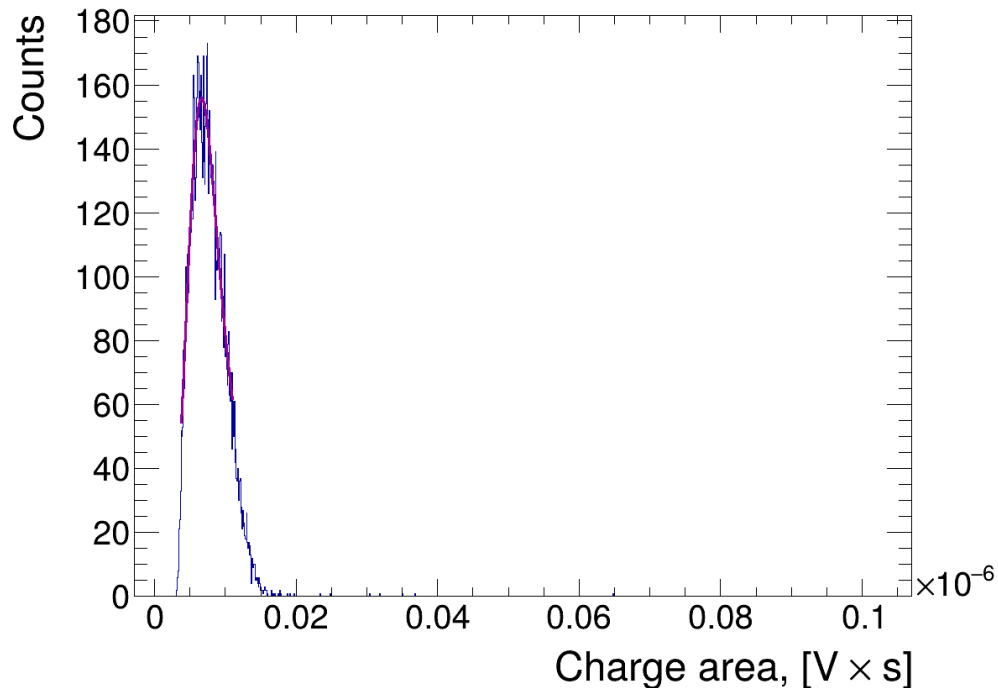
LanGaus = Landau (energy-loss fluctuations) $\otimes$ Gauss (photon statistics + noise) $\rightarrow$ MPV (most probable value)

Note: many Y-90 electrons stop in the bar $\rightarrow$ broad spectra; left edge = trigger threshold

ACS radioactive source measurements



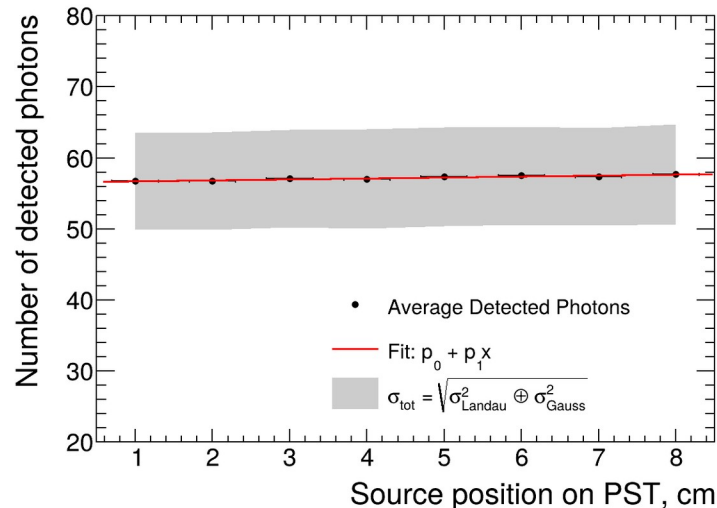
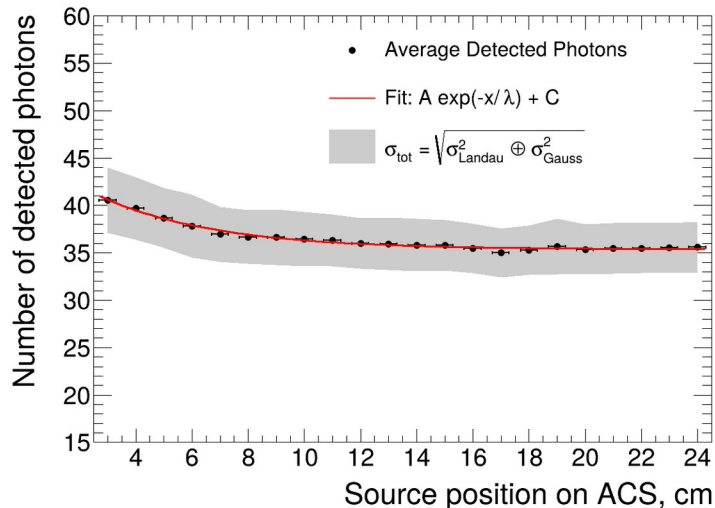
- Sr-90 along the yellow line, 1 cm steps;
- Both SiPMs at the left end
- Charge $\rightarrow$ photo-electrons: $N_{pe} = Q / Q_1$;



Charge spectrum of the left-side SiPM with the source at 13 cm

Uniform light collection with ESR wrapping

The number of photons detected **does not depend** on where the particle crosses the detector.



Left: ACS tile (both SiPMs on the same end) · right: PST bar 1.0 cm · points: mean of the left- and right-side SiPMs

35–40 p.e.

ACS tile light yield, per
SiPM

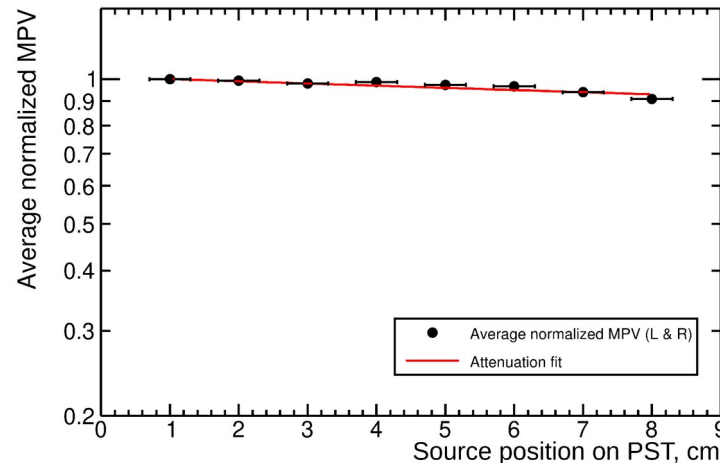
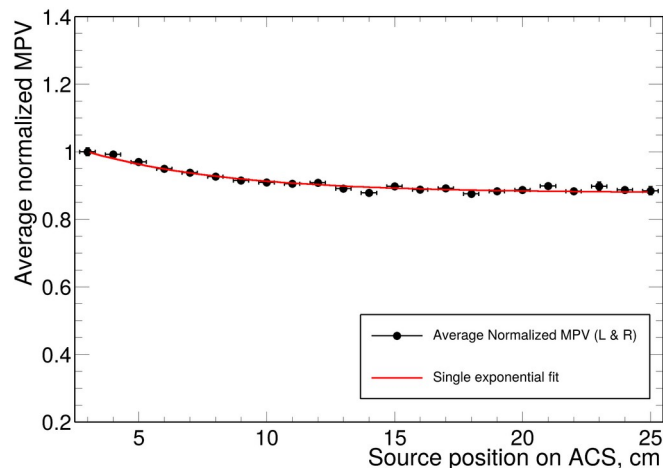
56–58 p.e.

PST light yield (0.5 cm bar:
same)

8–12 %

light loss along the
detector

Average light attenuation in the ACS and PST



ACS tile (SiPMs on one side only)

Single exponential fit: $f(x) = C + (1 - C) \cdot e^{-(x-3)/\lambda}$

→ **≈ 12 % less light from 3 cm to 25 cm**



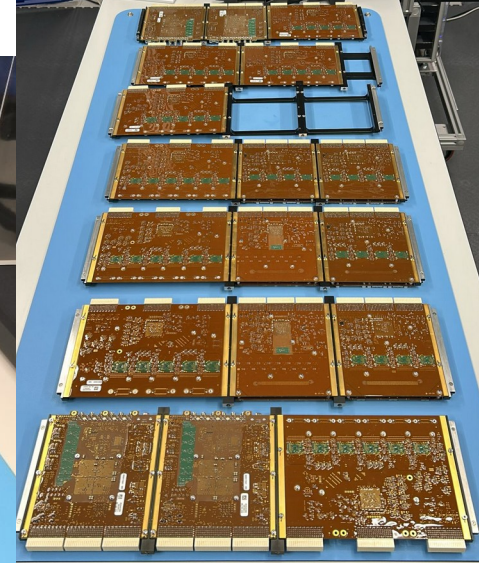
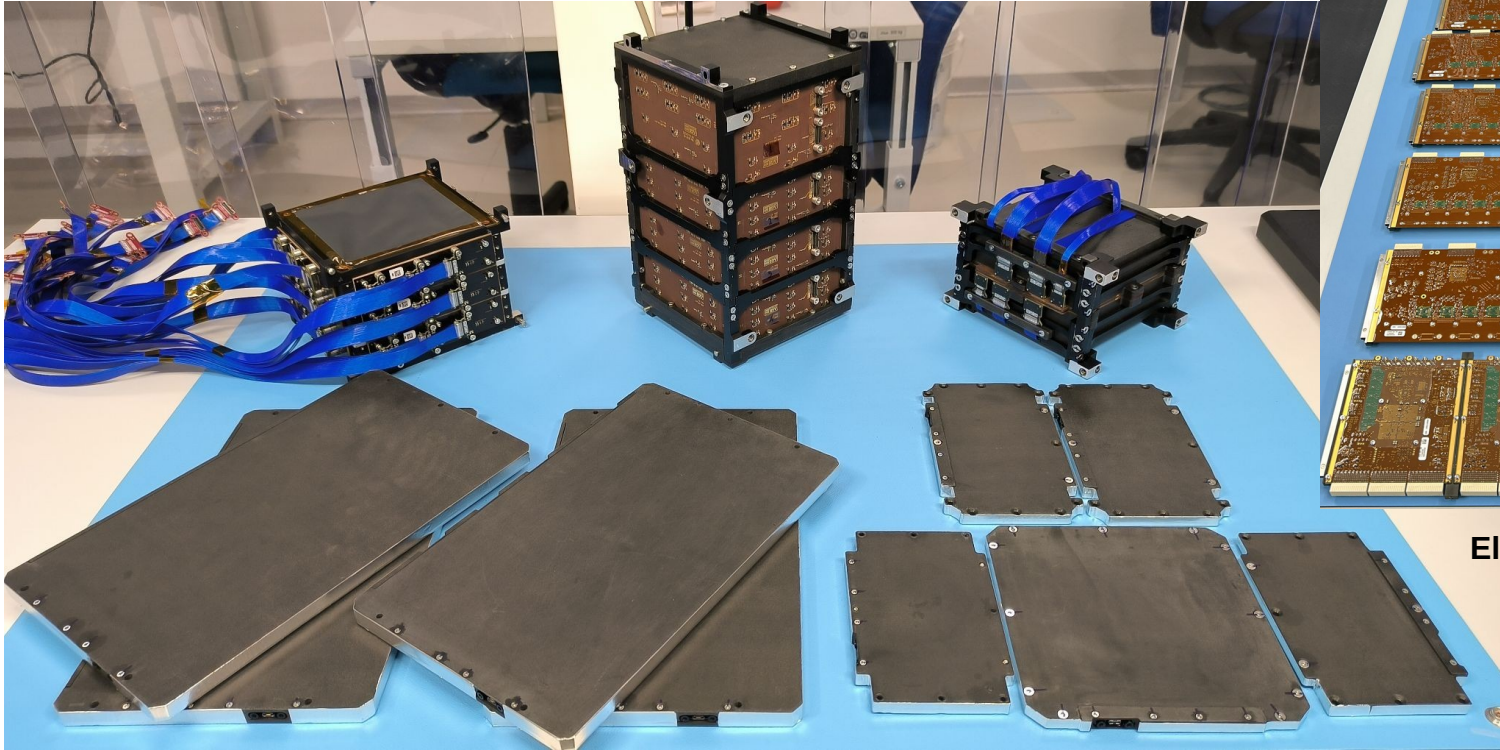
both SiPMs on the left end



one SiPM at each end

Points: LanGaus MPV, normalised to the first position, L & R averaged.
Without ESR: **≈ 40 % loss.**

Zirè EQM: Integration process

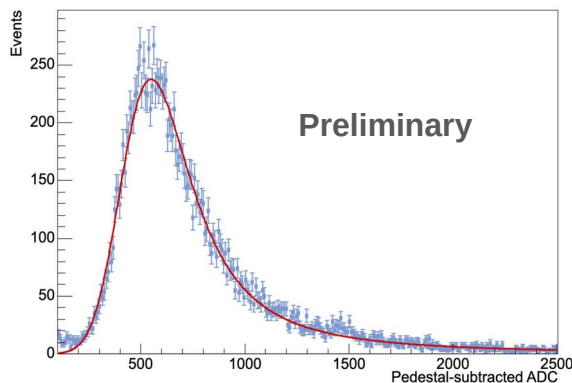
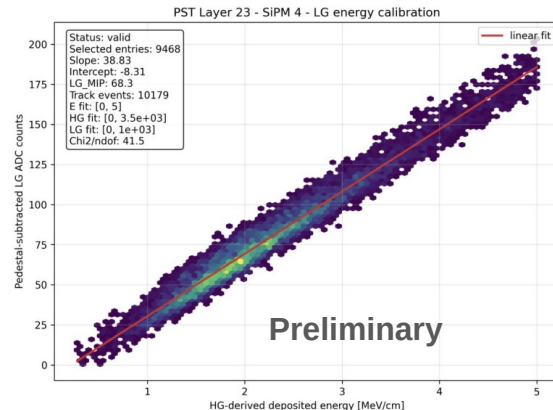


Electronic boards

EQM integration and first CR muons



Zirè EQM in its tray, LNGS clean room



Cosmic muons at LNGS

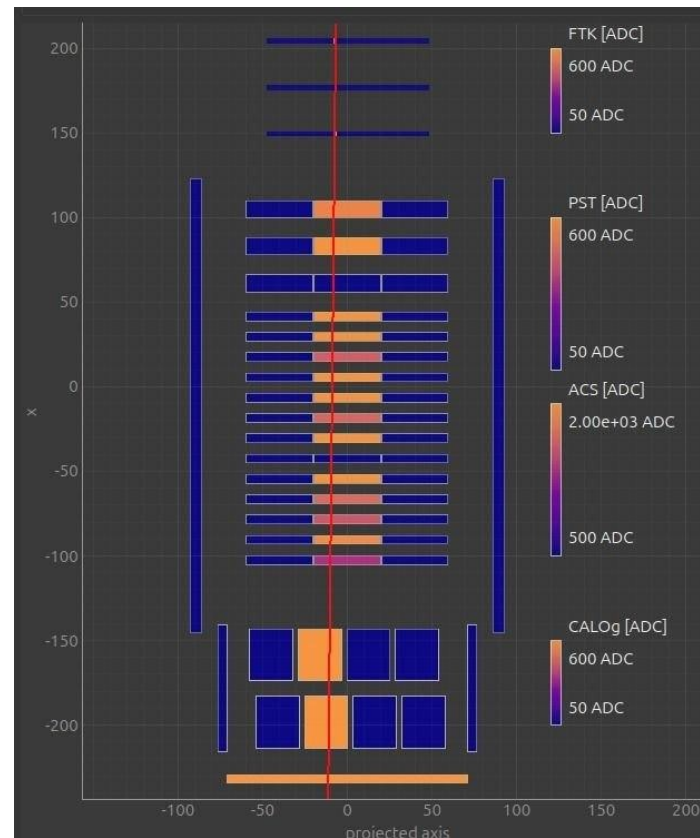
Zirè EQM in its tray in the LNGS clean room, operated with different trigger modes

Top: cross-calibration between low gain (LG) and high gain (HG)

Bottom: charge of one PST channel: MIP (minimum-ionising particle) peak, LanGaus fit

Channel efficiency with cosmic muons at LNGS

1. Calculate Pedestals (deriving μ and σ)
2. Reconstruct the FTK track
3. Select PST/CALog units (bar/crystal) according to the reconstructed track
4. Count number of times when a channel is above a pedestal-based threshold (12σ) when fired $\rightarrow N_{\text{active}}$
5. Count number of times when a channel is below the threshold when fired $\rightarrow N_{\text{blind}}$
6. Calculate efficiency as: $E = N_{\text{active}} / (N_{\text{active}} + N_{\text{blind}})$



PST channel efficiency (cosmic muons, LNGS)

Y view of the **PST 3x3** channels:

Efficiencies in %

Horizontal: layers of PST (32 total)

Vertical: bars in each layer

	98	100		99	99	99	99	99	99	99	99	99	99	100	
	100	100		100	100	99	99	99	96	99	99	99	99	100	
	100	99		99	99	99	99	99	99	99	99	99	100	100	
1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31

X view of the **PST 3x3** channels:

Efficiencies in %

	99	99		99	99	99	99	99	99	99	99	99	99	99	
	99	100		99	99	99	99	98	98	99	98	99	100	100	
	100	99		99	99	99	99	99	99	99	99	99	99	99	
2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32

Cell = one PST bar (3×3 mm² SiPM): fraction of muon tracks crossing it seen above threshold

Grey: trigger layers (1, 2, 7, 8, 31, 32), not evaluated

All evaluated channels: 96–100 %

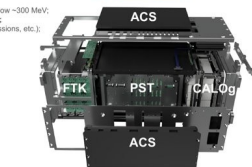
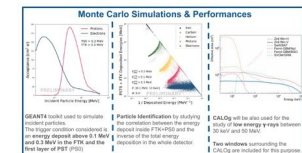
Activities since the start of my PhD



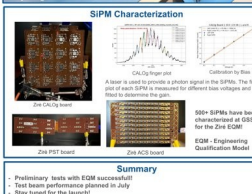
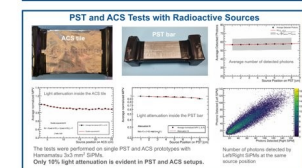
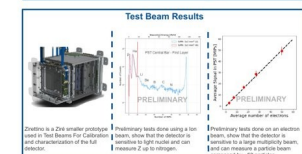
Science Goals

- Measuring the flux of cosmic electrons, protons (and nuclei), of solar/galactic origin, below ~ 300 MeV;
- Detection of 0.1 - 50 MeV photons for study of transient and stable gamma sources;
- Study of the cosmic radiation variability (Van Allen belt system, effects on space missions, etc.);
- Paving the way for future applications of new technology (SiPM only).

Zirè Detector Design



Fiber Transfer (FTK) 3 double type XY modules of Fibers is the used for track identification. The detector is composed by 3 main parts: Active Cosmic Shower (ACS), Passive Shower Trigger (PST) and CALog. The detector is designed to be lightweight and easy to transport, making it suitable for space missions.



IFAE 2026 • Bologna • 8–10 April 2026

The Zirè Detector on Board the NUSES Mission

Poster, and proceeding under review

Conferences and meetings

IFAE 2026, Bologna, 8–10 April 2026: poster (above)

14th Young Researcher Meeting, GSSI, L'Aquila, 29 Sep – 3 Oct 2025

Schools

SPACERAISE school, module “Artificial Intelligence for Space”, GSSI, L'Aquila, 11–15 May 2026

First steps with Geant4, CERN (online), 18–22 May 2026 (certificate)

Publications

S. Ashurov for the NUSES Coll., “The Zirè Detector on Board the NUSES Mission”, IFAE 2026 proceeding (under review)

Summary and Future Steps

My work this year:

- PFM SiPM characterization: measurements and analysis code (finger plots, gain, breakdown voltage) for the PST, CALOG and ACS boards
- ACS / PST optimization: ROOT analysis code for SiPM gain calibration and equalization, LanGaus fits of the ^{90}Sr spectra, light yield and attenuation
- Zirè Reconstruction Software: developed analysis modules, tested and validated the reconstruction
- EQM operation: cosmic-muon runs at LNGS, analysis of the CERN beam-test data; channel quality check
- IFAE 2026: poster and proceeding

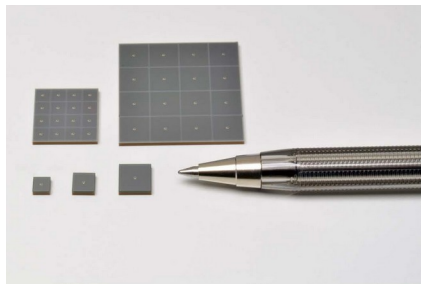
Future steps:

- Finish the PFM SiPM characterization and fill the database (PST, CALOG, ACS)
- Participate in the thermal-vacuum (TVac) tests and prepare the test plan and procedure to characterize the SiPMs as a function of temperature, in air and in vacuum
- Beam-test and muon analysis → absolute energy scale, particle identification, cross-calibrations
- Calibration procedures and preparation for the flight model (FM)



Backup

The SiPM and its gain



Hamamatsu S14160 MPPCs (SiPMs)

1 photon $\rightarrow$ 1 fired cell $\rightarrow$ charge Q_1

Gain $G = Q_1 / e \approx 10^6$

n photons $\rightarrow n \cdot Q_1$: discrete peaks (p.e. = photo-electron)

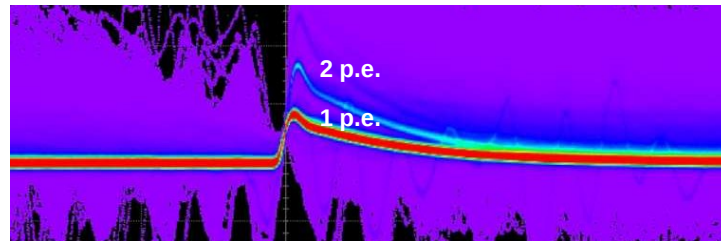
$G \propto V_{\text{bias}} - V_{\text{BD}}$ (V_{BD} = breakdown voltage)

SiPM = matrix of micro-cells;
avalanche photodiodes in Geiger mode

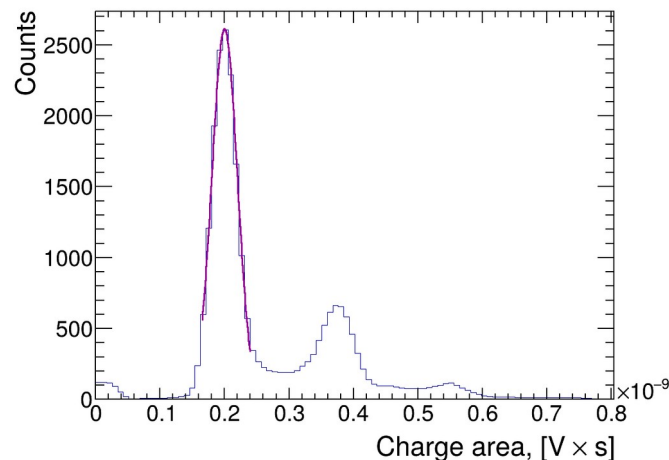
S14160-3050HS: $3 \times 3 \text{ mm}^2$, 3531 cells of $50 \mu\text{m}$

Gain converts charge $\rightarrow$ number of photons;
all channels set to the same gain

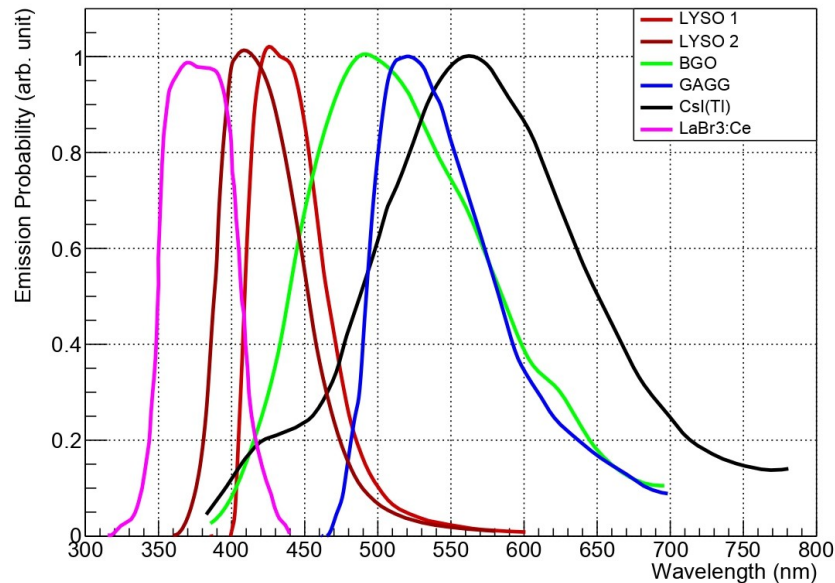
Photo: Hamamatsu Photonics, S14160/S14161 series datasheet (KAPD1064E)



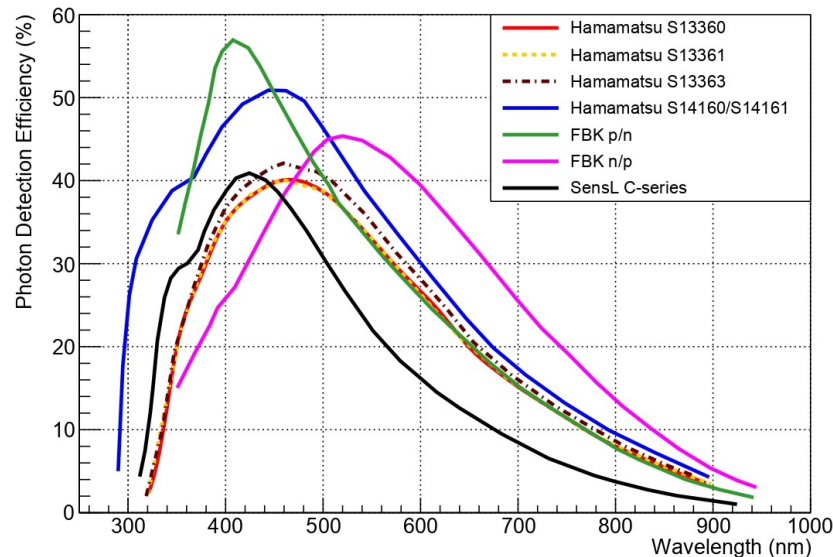
Dark-count pulses on the oscilloscope



Backup: scintillator emission vs SiPM photon detection efficiency



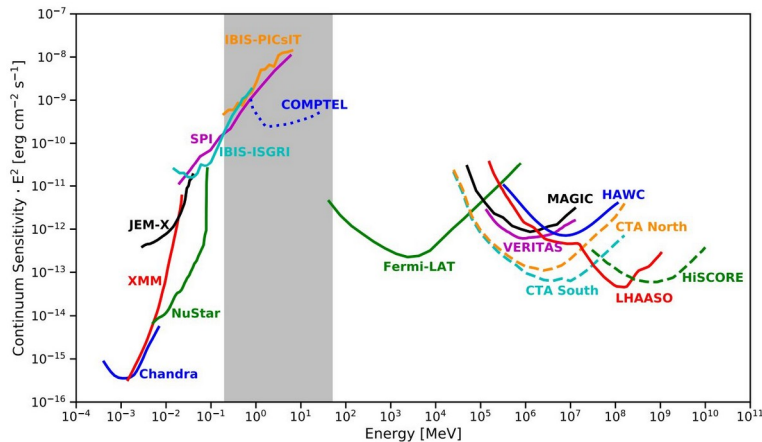
Emission spectra of common inorganic scintillators



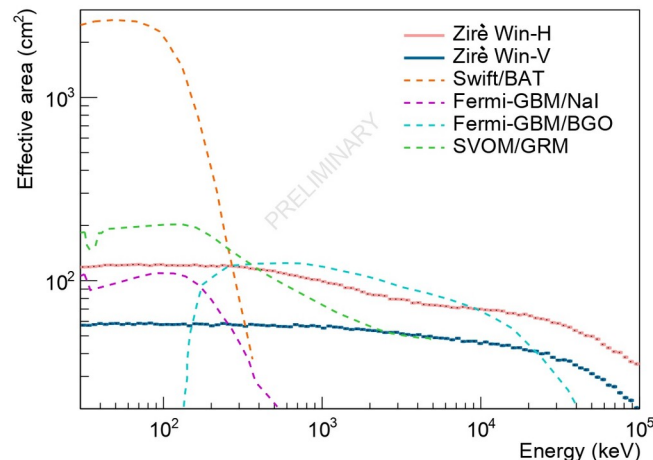
PDE vs wavelength of commercial SiPMs

Data from the manufacturers' websites (Hamamatsu, FBK, SensL/onsemi, scintillator suppliers), e.g. https://www.hamamatsu.com/eu/en/product/optical-sensors/mppc/mppc_array.html

Backup: gamma-ray bursts and the MeV gap



P. Savina, Zirè INFN report, June 2026



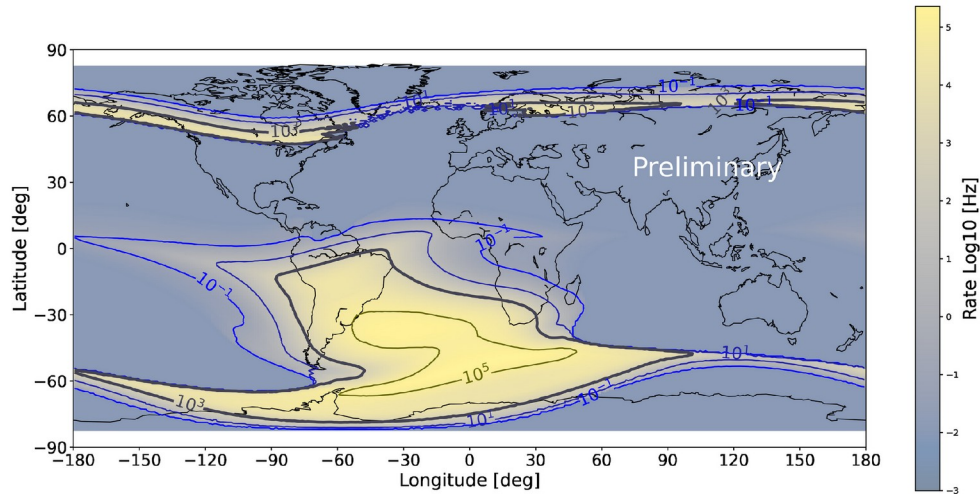
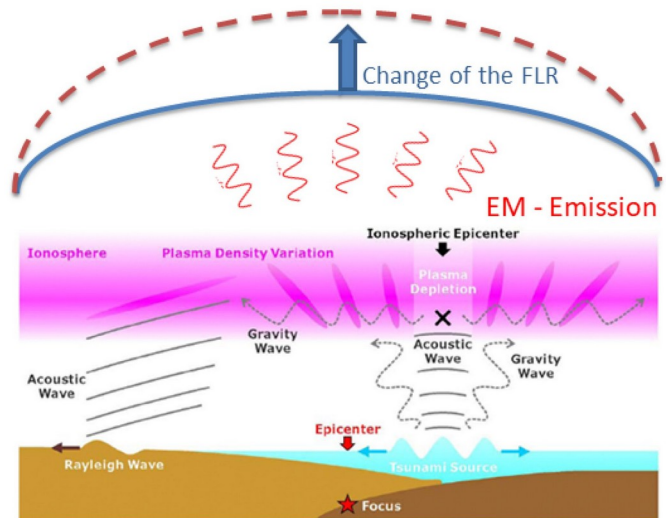
CALOG → for the study of **low energy γ -rays between 30 keV and 50 MeV**.
Two windows surrounding the CALOG: **Win-H** (horizontal) and **Win-V** (vertical)

GRBs: the brightest explosions in the Universe; short (< 2 s, neutron-star mergers) and long bursts

MeV gap (grey band): few instruments cover 0.1–50 MeV

Zirè (CALOG): minimum detectable flux (red) below the average GRB spectra (bands) → GRBs detectable

Backup: magnetosphere–ionosphere–lithosphere coupling (MILC)



Earthquakes and volcanic activity can disturb the ionosphere (acoustic / gravity waves, EM emission) → trapped electrons and protons may **precipitate from the Van Allen belts**.

Zirè + LEM measure electrons (0.1–7 MeV) and protons in LEO to look for such anomalies. Right: expected LEM rate along the orbit (South Atlantic Anomaly and radiation belts).

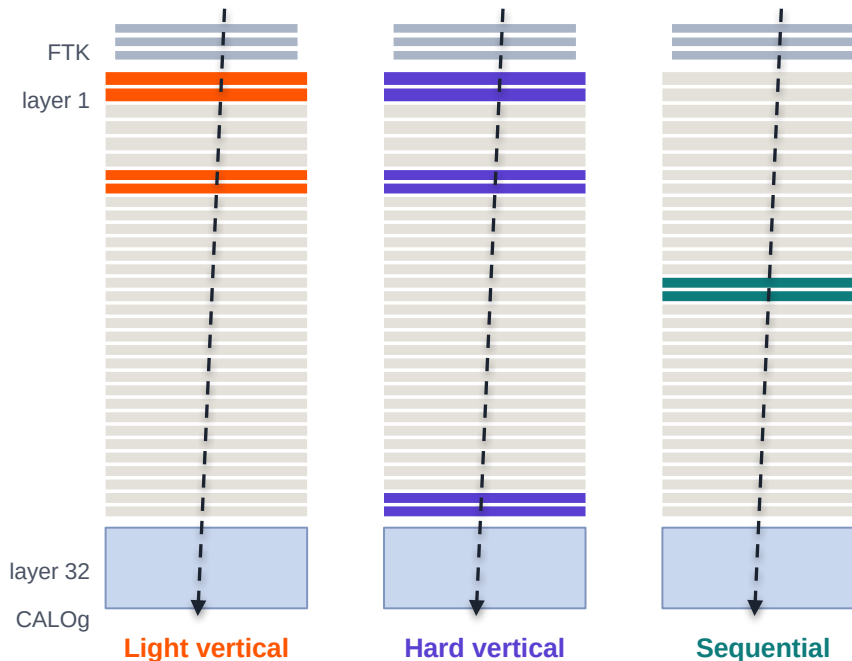
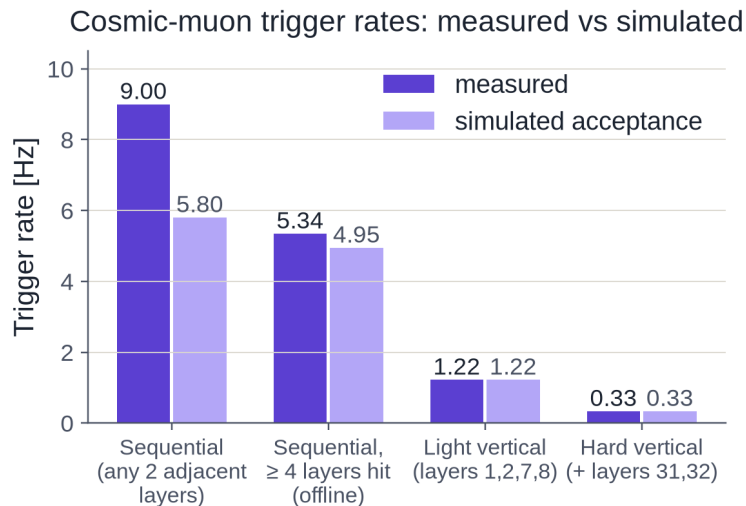
Left: P. Savina, Zirè INFN report, June 2026. Right: R. Nicolaidis et al. (NUSES Coll.), Instruments 7 (2023) 40.

Cosmic-muon triggers: configurations and rates

Light vertical trigger: PST Layers 1+2+7+8 in AND (while the 3 bars comprising a single layer in OR)

Hard vertical trigger: PST Layers 1+2+7+8+31+32 in AND (while the 3 bars comprising a single layer in OR)

Sequential trigger: Two consecutive PST layers in AND (while the 3 bars comprising a single layer in OR)

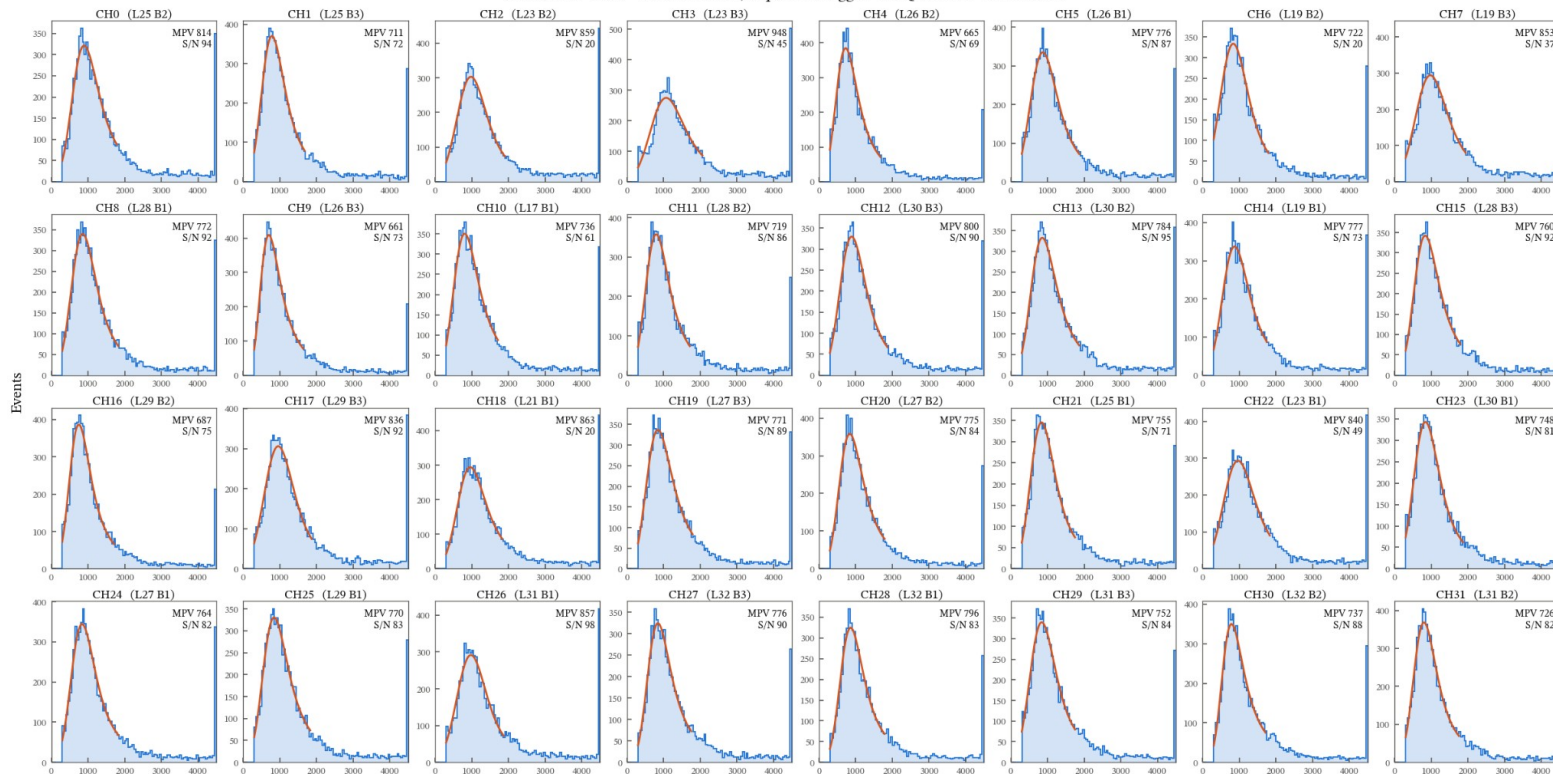


The measured rate is the number of triggered events divided by the run duration

$R = \text{muon flux} \times \text{effective area (geometric acceptance) of that trigger}$

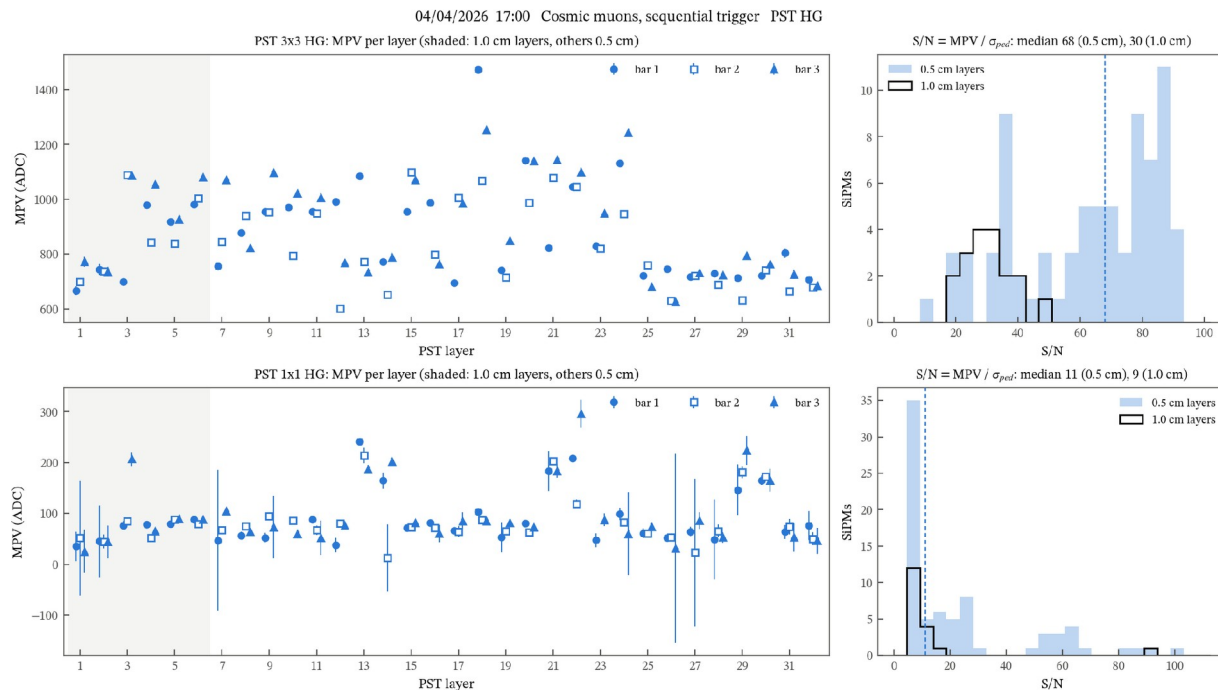
MIP fits by channel

04/04/2026 17:00 Cosmic muons, sequential trigger DAQ1 ASIC3 PST 3x3 HG



ADC

Cosmic muons: MIP signal per PST channel



68

median S/N, PST 3×3 SiPMs
(0.5 cm layers)

30

median S/N, PST 3×3 SiPMs
(1.0 cm layers 1–6)

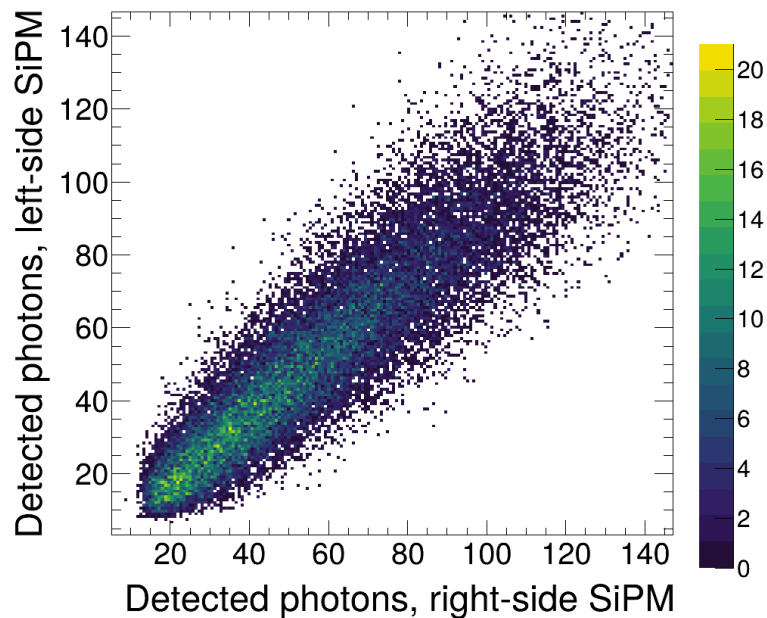
11 / 9

median S/N of the 1×1 end
(0.5 / 1.0 cm layers)

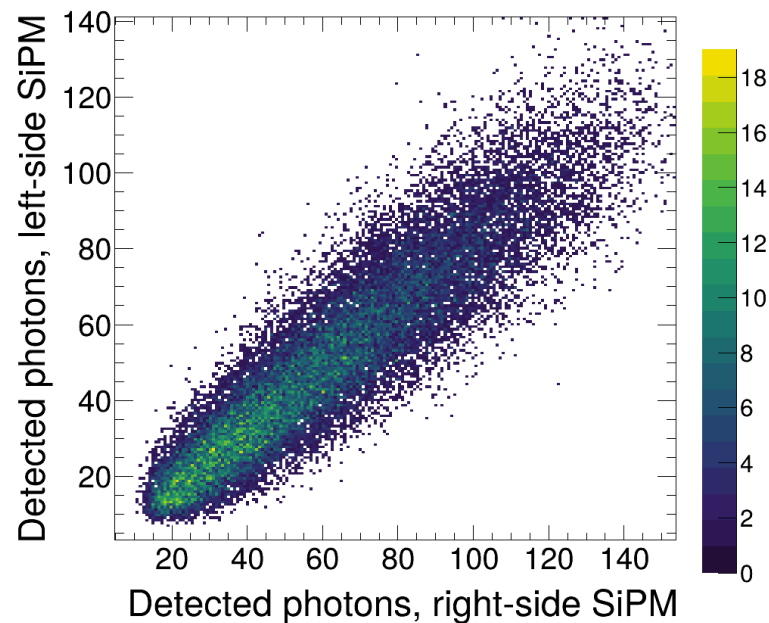
Run 04-04_17-00, sequential trigger, HG: LanGauss MPV per layer and S/N

The 3×3 end is the MIP detector;
the 1×1 end is meant for large
signals (heavy ions).

Backup: left-side vs right-side SiPM, PST bar (1.0 cm)



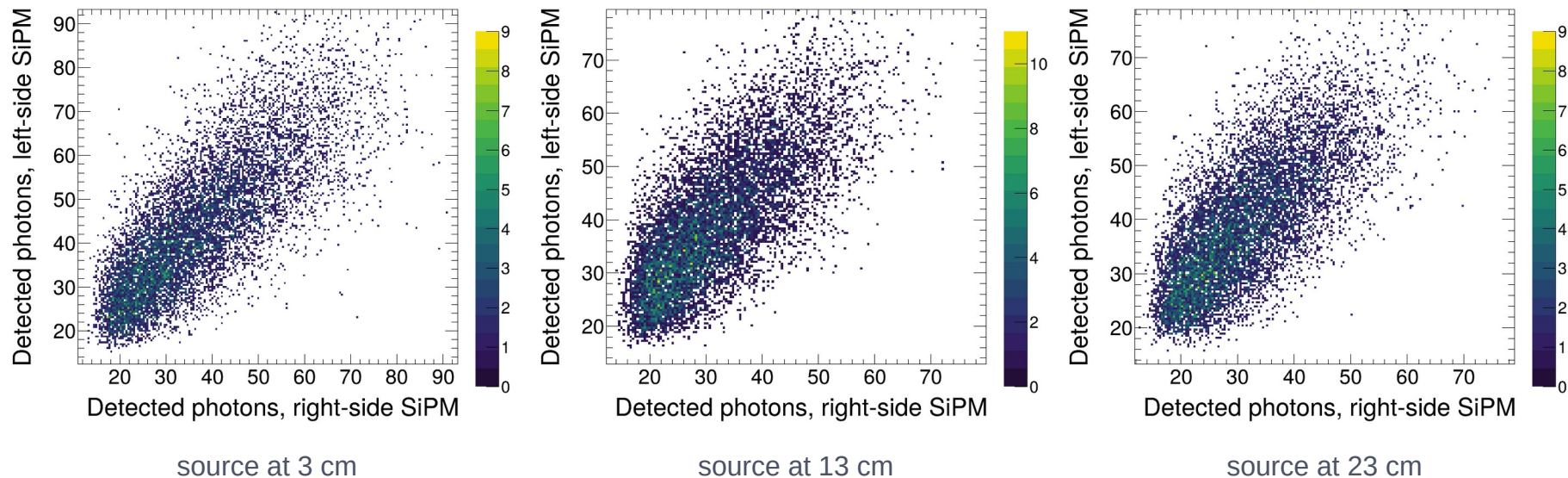
source at 1 cm



source at 3 cm

Each entry = one Sr-90 event: photons seen by the left-side vs the right-side SiPM → strongly correlated

Backup: left-side vs right-side SiPM, ACS tile



Each entry = one Sr-90 event: photons seen by the two SiPMs (both on the same end) → strongly correlated