Large Area SiPM Pixels for SPECT:
from high energy astrophysics to medical imaging

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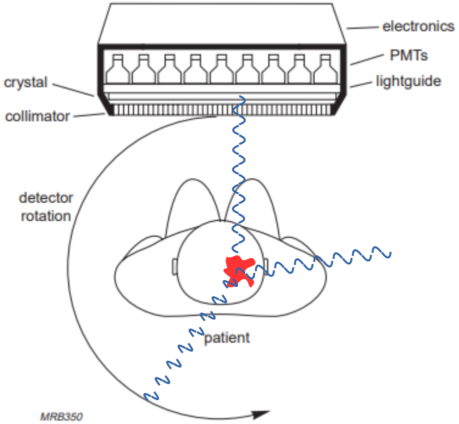
SPECT in 30”

Single Photon Emission Computed Tomography (SPECT):

- A single-gamma-ray tracer is injected to the patient
- One or more gamma-ray sensitive cameras equipped with a collimator rotate around him
- Several planar images are taken to build a 3D functional image



Flyckt & Marmonier (2002)

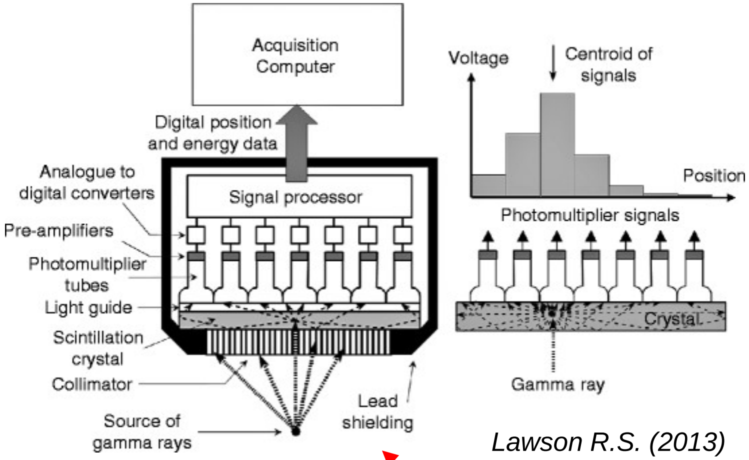
GE Healthcare

VisualSnow (2014)

The bulky gamma camera

Typical camera for full-body SPECT:

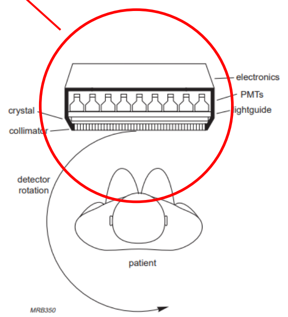
- **50 x 40 cm²** area **NaI(Tl) scintillator**
- **~50-100** Photomultiplier tubes (**PMTs**) of **~2-3" diameter**
- A **lead collimator**
- **~1-3 cm thick** layer of **lead** shielding the whole volume



Lawson R.S. (2013)

→ A SPECT camera is a heavy (a few hundred kg) and bulky system

→ A large fraction of the volume is occupied by the PMTs



SiPMs in full-body SPECT?

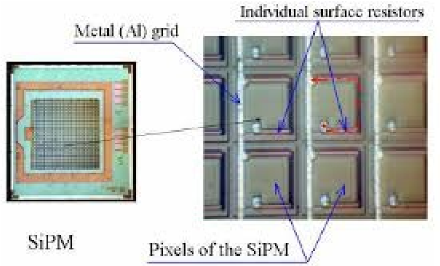
Silicon Photomultipliers (SiPMs) are natural candidates to replace PMTs

- **SiPMs** are **compact photodetectors**:
  → Reduce camera volume
  → Reduce amount of lead needed for the shielding
  → **Reduce weight** and **size** of a camera

Ben.Glauss

Main obstacle: No large-area SiPMs

- SiPM typical size < 6 x 6 mm^2 (capacitance increases with SiPM area)
  → ~ 4000 channels needed to equip a full-body SPECT camera



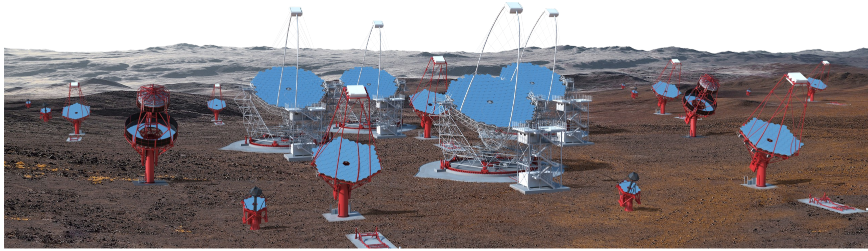
C. Jendrysik

Solutions in gamma-ray astrophysics

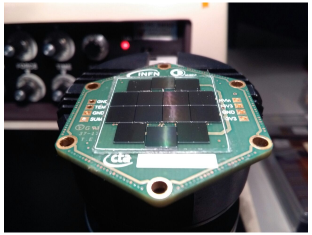
Same problem in Very-High-Energy Astrophysics:

- Typical **pixel diameter** in large telescopes **~ 25 mm**
- **~1000 channels** per telescope
- Moving towards **more telescopes** and **larger cameras**
- Several developments aiming to build Large-Area SiPM pixels

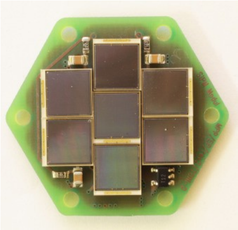
→ **Can we apply one of this solutions in SPECT?**



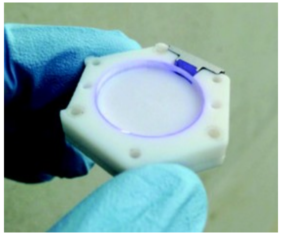
CTA-observatory



Mallamaci, M. et al. (2019)



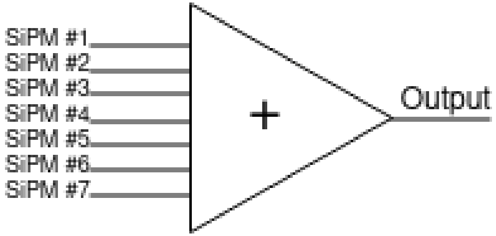
Hahn, A. et al. (2018)

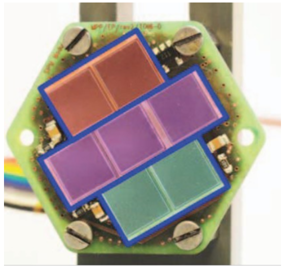


Guberman, D. et al. (2019)

Large-Area SiPM Pixels (LASiPs)

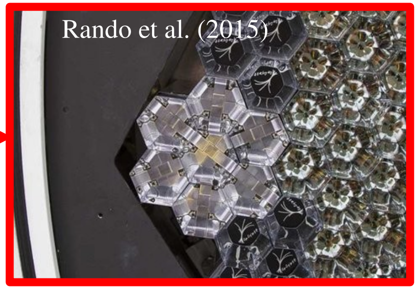
A **LASiP** is built by **summing** the individual currents of **several SiPMs** into a **single output:**





Fink et al. (2016)

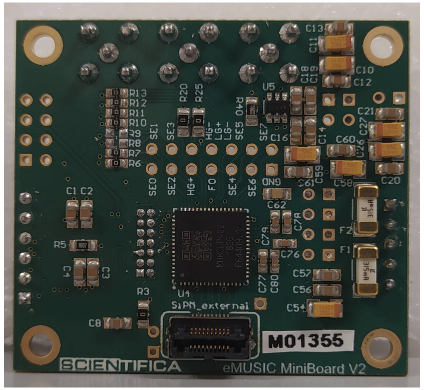
- **Less readout channels** without a dramatic increase in capacitance
- Solution already tested in high-energy astrophysics
- **Sum** can be performed with passive components or using a **dedicated ASIC...**

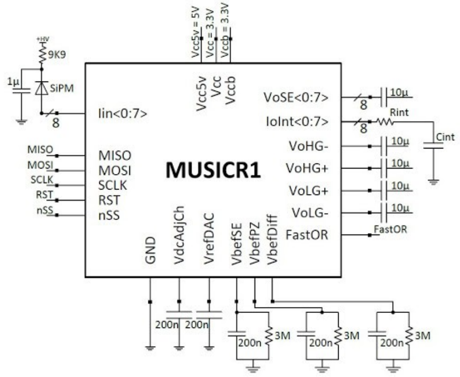


The MUSIC ASIC[1]

Multiporpose ASIC for **SiPM readout** developed at ICCUB (Barcelona)

- **Preamplifier**, **shaper** and **summation** in a single chip
- Has many other functionalities (e.g. SiPM bias adjustment)
- Can sum **up to 8 SiPMs**

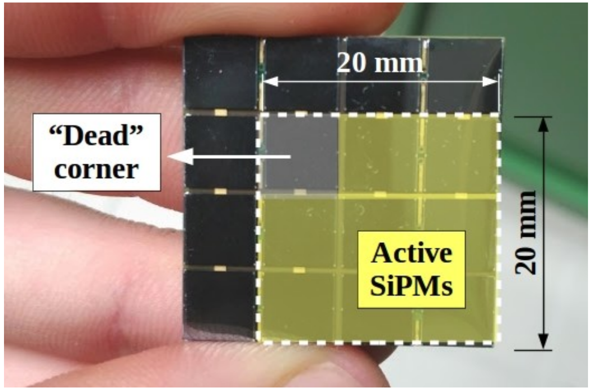




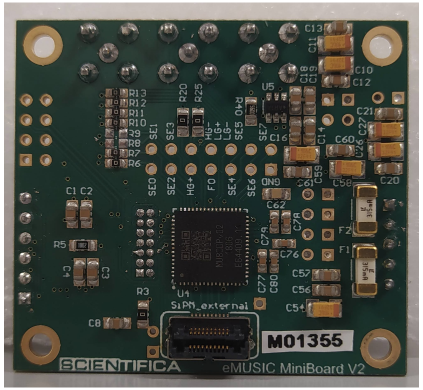
[1] Gómez S, et al. *Multiple Use SiPM Integrated Circuit (MUSIC) for Large Area and High Performance Sensors*. Electronics. 2021; 10(8):961.

LASiP Prototype

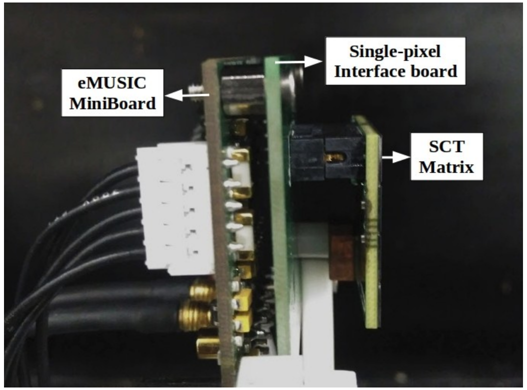
- It uses a **matrix** of 16 **SiPMs** of **6 x 6 mm^2** (FBK NUV-HD) and an **eMUSIC MiniBoard** (plug-and-play board from SCIENTIFICA SRL)
- **8 SiPMs** are **summed** by the **MUSIC** (the remaining 8 are not used)
- Pixel is a 2 x 2 cm^2 square with a *dead corner* (**~2.2 cm^2 active area**)



16-SiPM matrix from FBK (SCT Matrix). Active SiPMs that are part of the LASiP prototype are shown in yellow.



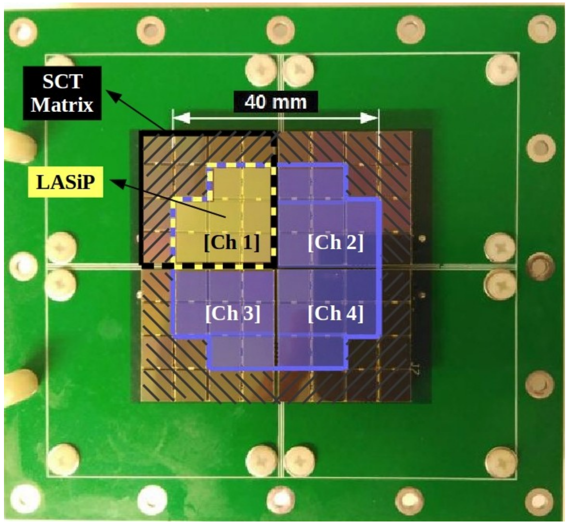
eMUSIC MiniBoard

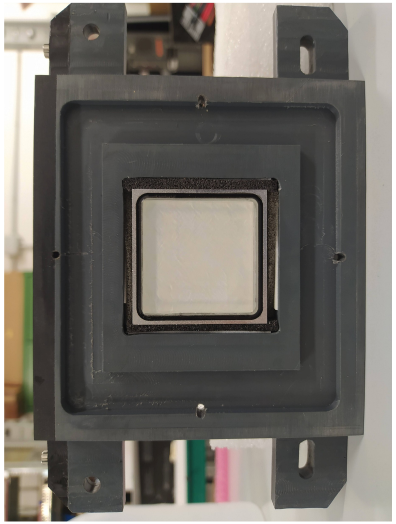


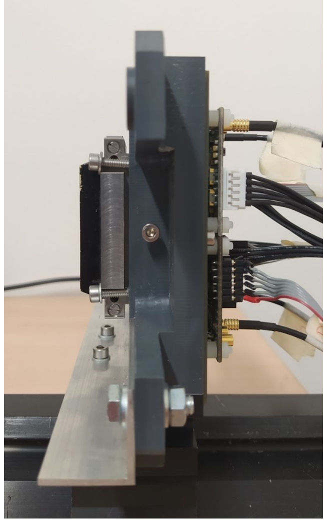
Side view of the LASiP prototype: The SiPMs (SCT Matrix) are connected to the eMUSIC MiniBoard

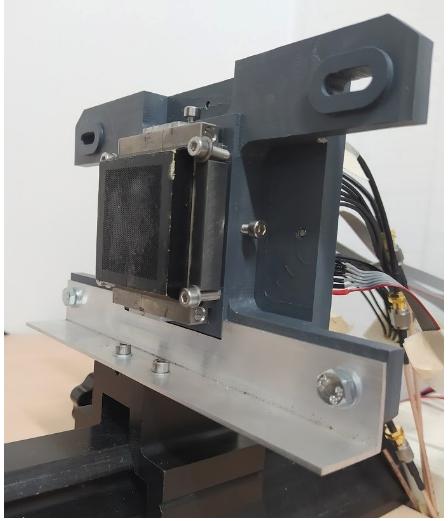
Proof-of-concept micro camera

- **4 LASiP** prototypes coupled to a **40 x 40 x 8 mm^3 NaI(Tl)** crystal (OST Photonics)
- Custom-made holder compatible with 2 different collimators
- Took images using ^{99m}Tc (140 keV) and ^{241}Am (60 keV) gamma-ray sources





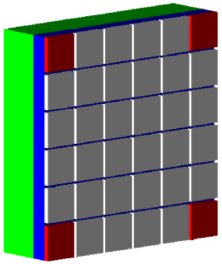


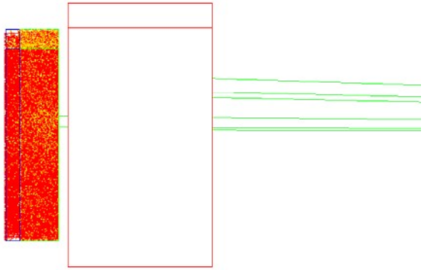


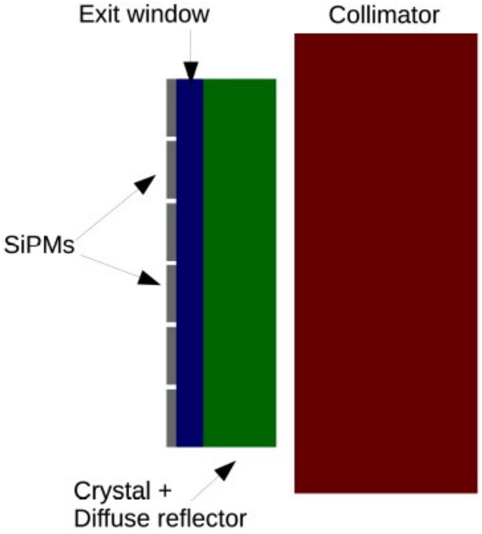
Monte Carlo simulations

We simulated the **micro-camera** response to gamma-rays with **Geant4:**

- **Scintillation photons** are **tracked** until they reach the LASiPs, they escape or are absorbed
- **Electronic** and **SiPM noise** was **injected in the simulations...**

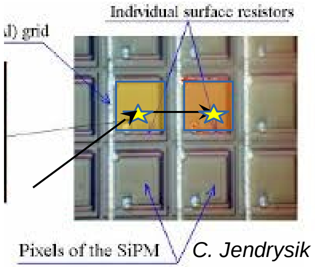






SiPM noise

- **Optical crosstalk probability.** Probability that a triggered cell generates a trigger in a neighboring cell.
- **Dark counts.** A cell that undergoes an spontaneous trigger. Randomly distributed in time, their rate increases linearly with the area.
- **Single photoelectron resolution.** Variations in the charge generated by a single photon. Depends on the number of SiPMs that are being summed...



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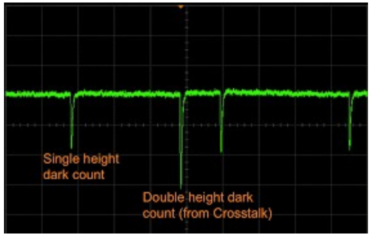
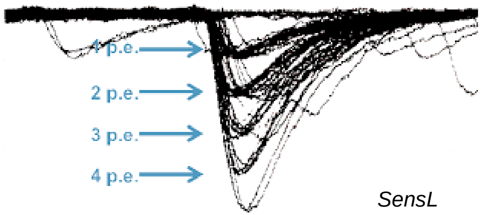


SensL



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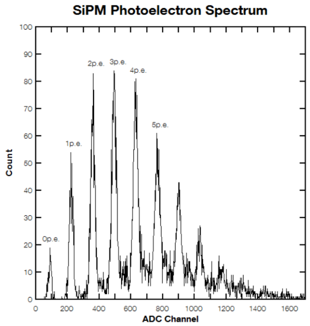


Single-phe resolution vs summed SiPMs

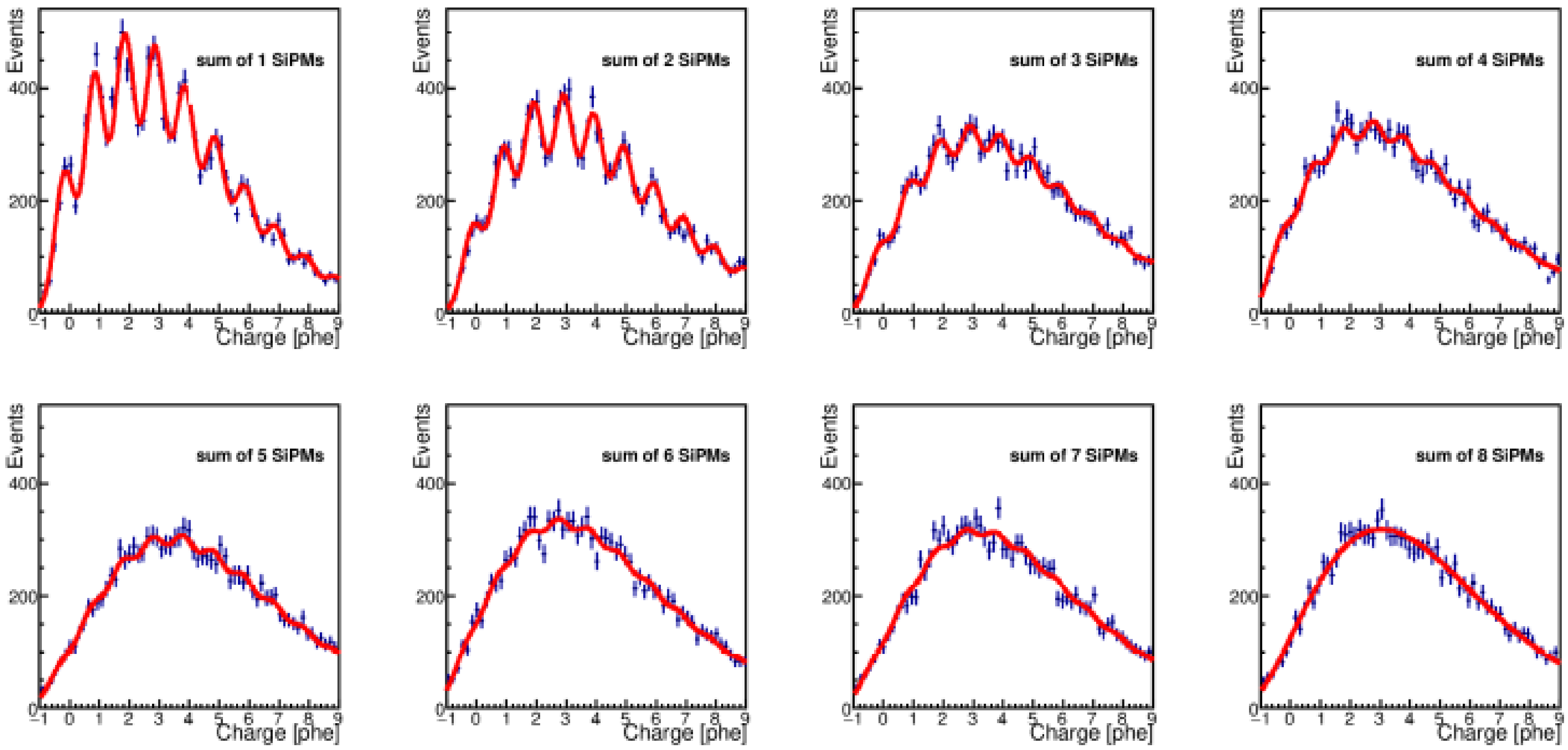
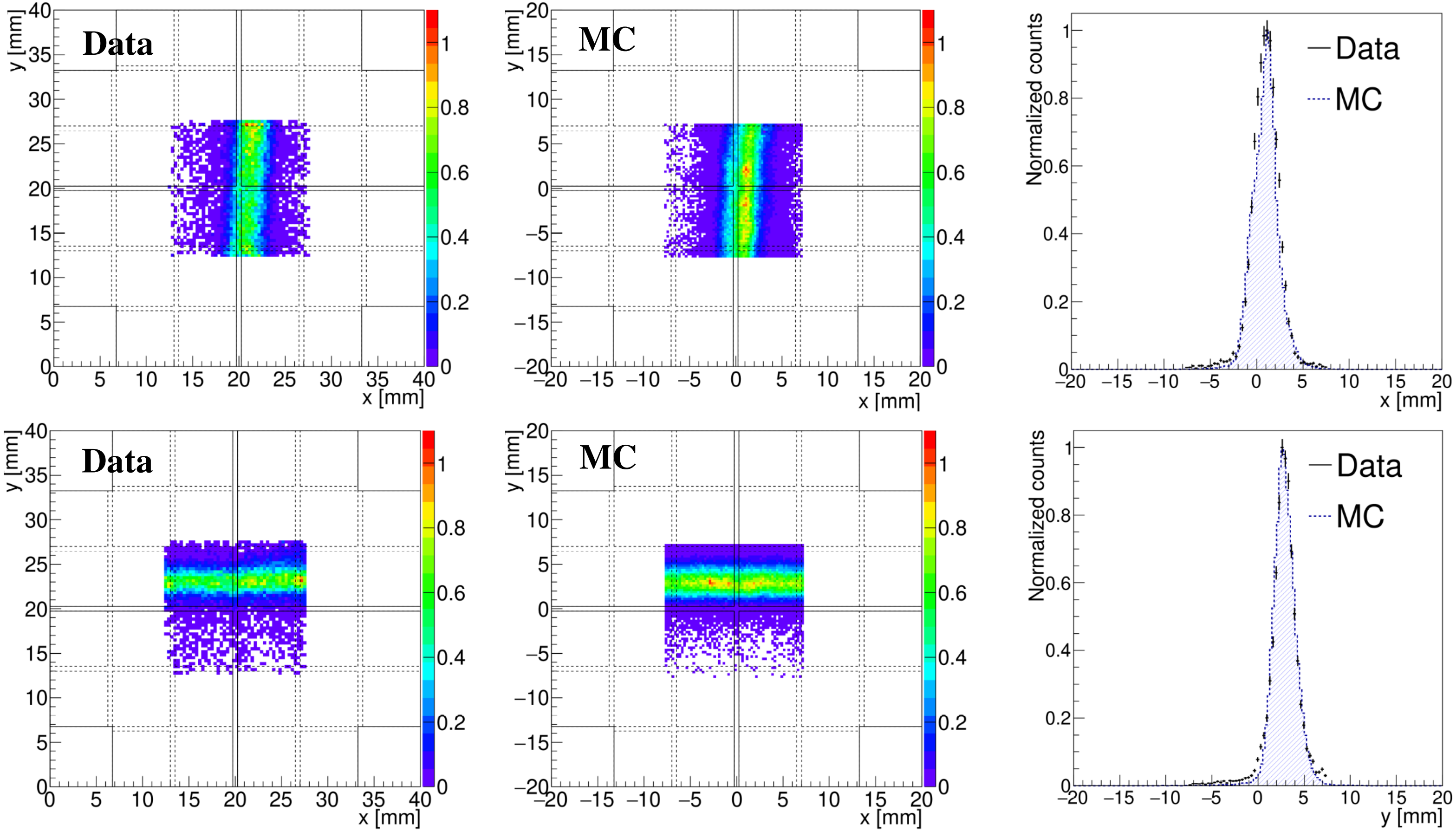


Image Reconstruction

- ^{99m}Tc capillary
  (0.5 mm diameter, 140 keV)
- LEUHR Collimator
- 2cm src-collimator distance
- Reconstruction algorithm: centroid (Anger logic) + linearity and uniformity corrections



Micro-camera performance

- We were able to reconstruct simple images (capillary and point-like sources)
- We **measured** an **energy resolution** of **~11%** and an **intrinsic spatial resolution** of **~2 mm**
- Good agreement between data and Monte Carlo simulations (MC)
- Simulations:
  - ***Dead corners*** significantly **degrade the performance**
  - **Low impact** of SiPM **optical crosstalk** on Energy resolution (<5%)
  - **Moderate impac**t of **Dark Count Rate** at room temperature, gets worse at higher rates

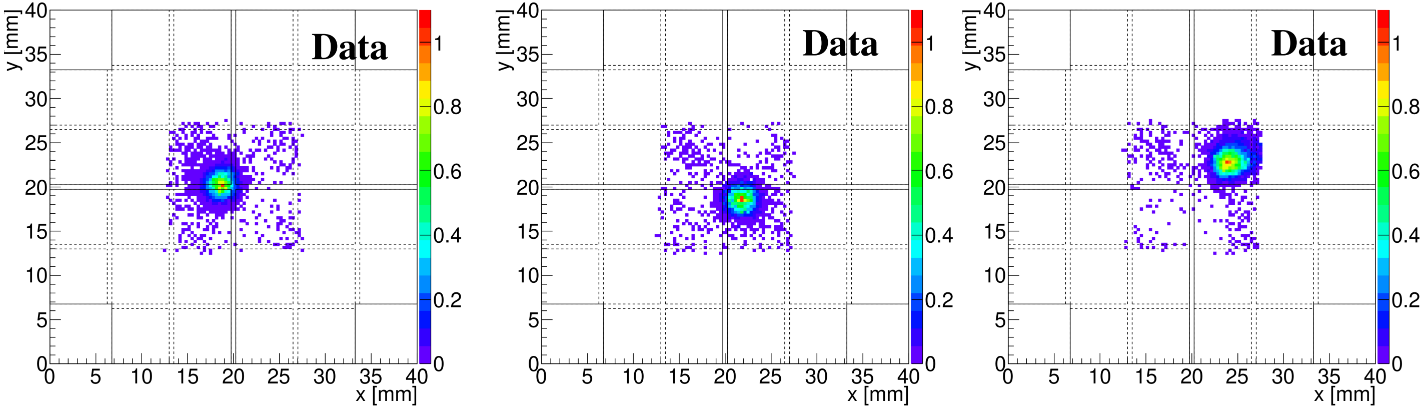
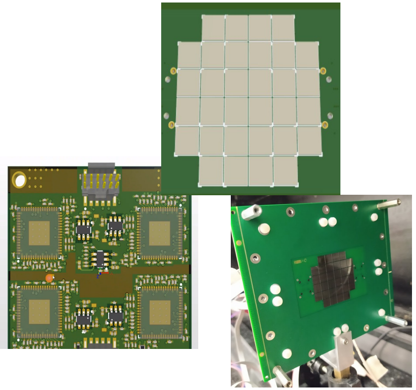


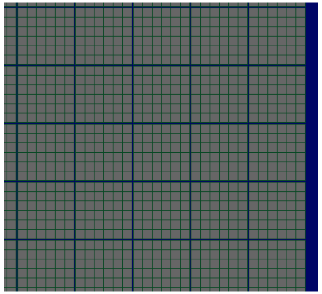
Image reconstruction of a ^{241}Am point-like source using an 0.5 mm x 2 cm collimator.

Towards a large LASiP-SPECT camera (I)

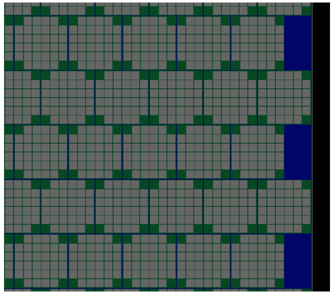
- **~ 500 channels** needed to equip a **full-body SPECT camera** if using **LASiPs** of **~2 x 2 cm²**
  - → **Larger LASiPs** (e.g. ~ 4 x 4 cm²) desirable to reduce the number of **readout channels to ~100**
  - → A **32-SiPM LASiP** is **under development** (sums the output of 4 MUSICs)



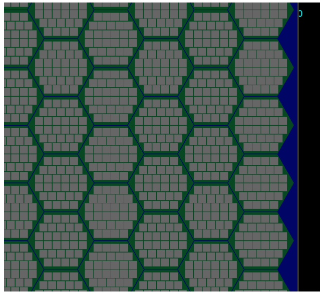
- In larger LASiPs we can also play with **pixel geometry**



36 SiPM-Pixel



32 SiPM-Pixel



30 SiPM-Pixel

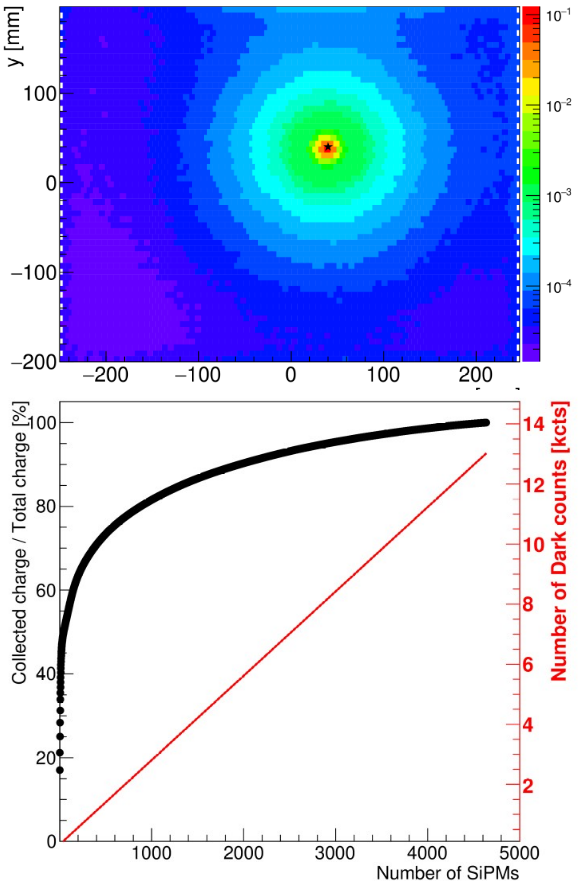
Towards a large LASiP-SPECT camera (II)

Scintillation light produced in a single event will be **distributed over many more SiPMs**…

… and with more SiPMs the **impact of dark counts** will be **higher**

→ **Trigger settings** (Nr of LASiPs used to collect the charge, integration time) **should be optimized**. This optimization will depend on:

- LASiP size, geometry and distribution inside the camera
- SiPM PDE vs DCR



Top: Distribution of the mean charge collected by 4636 SiPMs of 6×6 mm^2 filling a camera of 500x400x9 mm^3 for a collimated gamma-ray beam of 140 keV. **Bottom**: Percentage of the total charge collected as a function of the number of SiPMs employed for the trigger. In red the expected number of integrated dark counts (DCR =0.13 MHz/mm^2) for an integration time of 0.6 μs.

Conclusions

LASiPs could be an alternative to build low-cost, compact, large gamma cameras, providing that:

- Pixel size and geometry are optimized
- Trigger settings are optimized
- Impact of DCR is mitigated

We provided two key ingredients for such optimization:

- We proved that LASiPs can be used to reconstruct simple images with a comparable performance to standard SPECT systems.
- We validated MC simulations that can be extended to simulate a larger camera with larger LASiPs

Extended version of the results and methods in:

Guberman D, et al (2021). *Large-Area SiPM Pixels (LASiPs): A cost-effective solution towards compact large SPECT cameras.* Phys Med 82:171-184
doi:10.1016/j.ejmp.2021.01.066

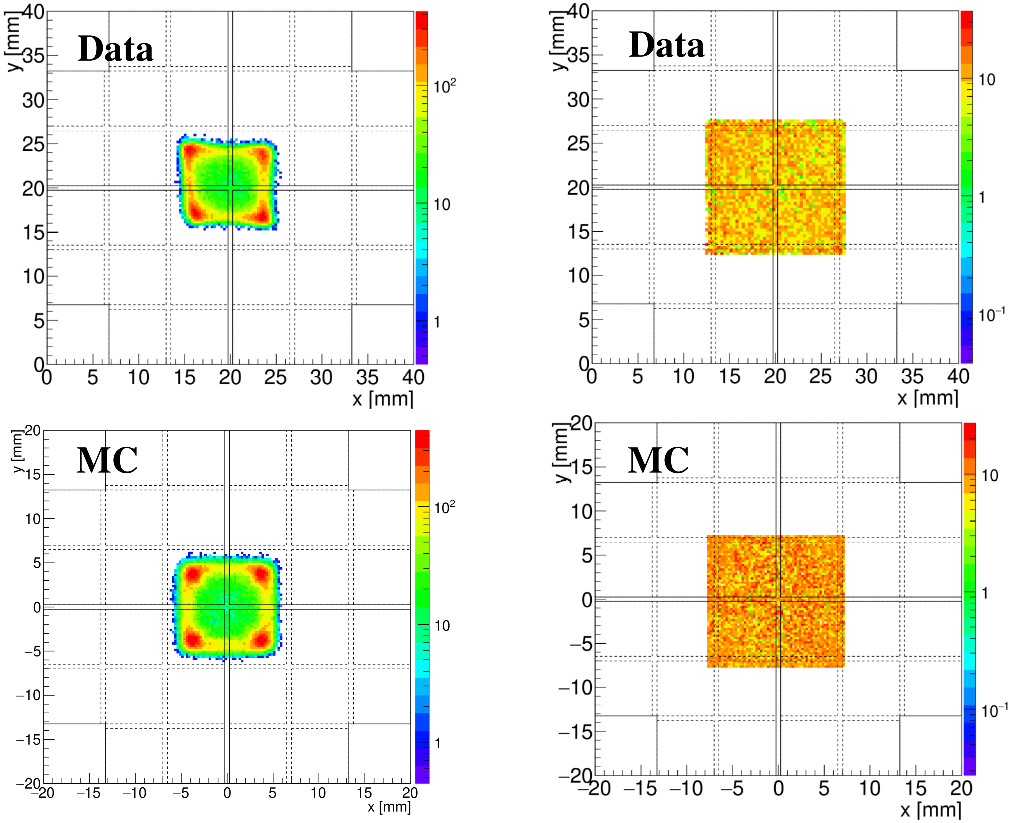
Backup

Image Reconstruction

Simple centroid method + corrections
(uniformity, linearity)

- Simple and fast: useful for the proof-of-concept and comparing experiment and simulations
- Worse spatial resolution compared to more elaborated techniques

Raw image | After corrections



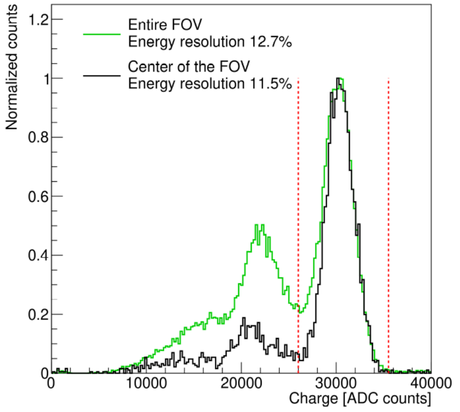
Simulation results

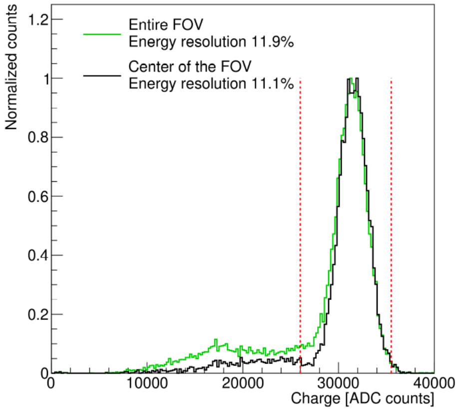
Nr	XT [%]	σ_0 [m.c.u]	σ_1 [m.c.u]	U.N. [m.c.u.]	ϵ (LASiP) [%]	ϵ (36 SiPMs) [%]
1	-	-	-	-	9.7	9.1
2	**10**	-	-	-	10.1	9.4
3	**25**	-	-	-	10.2	9.5
4	**40**	-	-	-	10.5	9.9
5	25	**1**	**1**	-	10.3	9.6
6	25	**10**	**1**	-	10.7	9.9
7	25	**1**	**5**	-	10.7	9.9
8	25	**1**	**10**	-	11.3	10.8
9	25	1	1	**1**	10.7	10.0
10	25	1	1	**2**	11.5	10.8
11	25	1	1	**5**	16.7	15.8

Table 1: Simulations performed with Geant4. d_1 and d_2 are the distance between disk and side and bottom mirrors, respectively, R is the reflectivity of the mirrors and Δ is the thickness of the coupling. The trapping efficiency ϵ is computed por quantum yields Y of 100 and 84%.

Micro-camera performance

- We were able to reconstruct simple images (capillary and point-like sources)
- We **measured** an **energy resolution** of **~11.5%** and an **intrinsic spatial resolution** of **~2 mm**
- Good agreement between data and Monte Carlo simulations (MC)

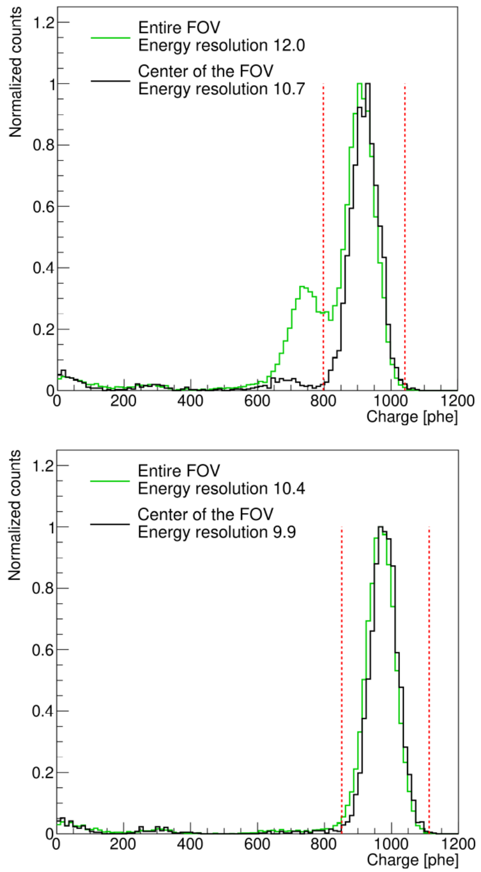




Charge spectrum of ^{99m}Tc sources obtained with a micro-camera for a flood-field irradiation (**left**) and a 0.5 mm capillary at a distance of 2 cm from a LEUHR resolution collimator (**right**)

Simulations: LASiP impact in the performance

- LASiP ***dead corners*** significantly **degrade the performance**
- **Low impact** of SiPM **optical crosstalk** on Energy resolution (< 5 %)
- **Moderate impac**t of **Dark Count Rate** at room temperature, degrades faster at higher rates (x 2 increase in DCR can worsen Energy resolution by 10-15%)



Simulated charge spectrum of a flood-field irradiation with ^{99m}Tc for LASiPs with (**top**) and without (**bottom**) dead corners.