Particle Identification in Astroparticle Physics and for Space Applications

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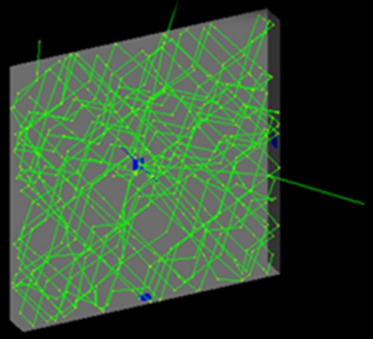
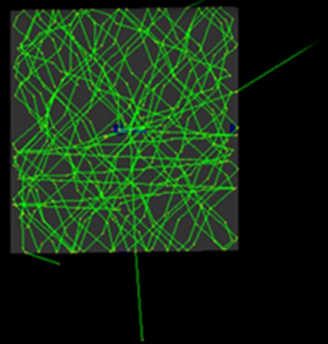
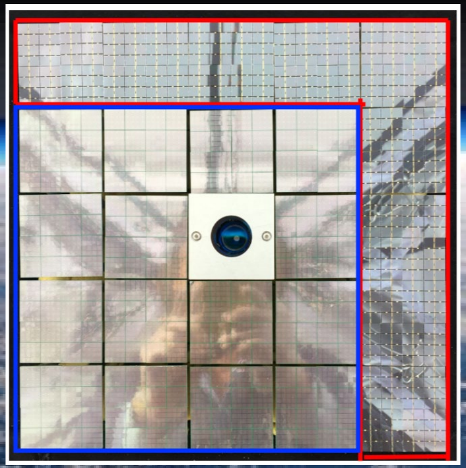






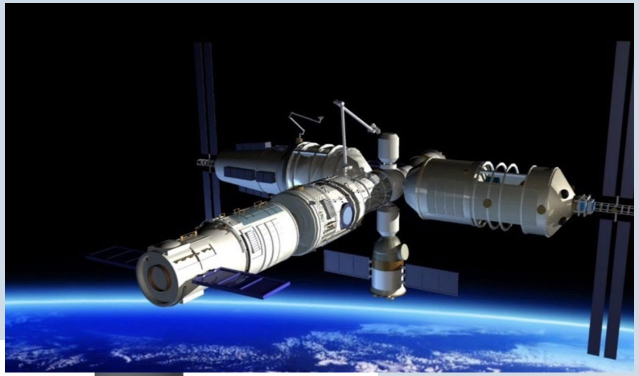
Outline

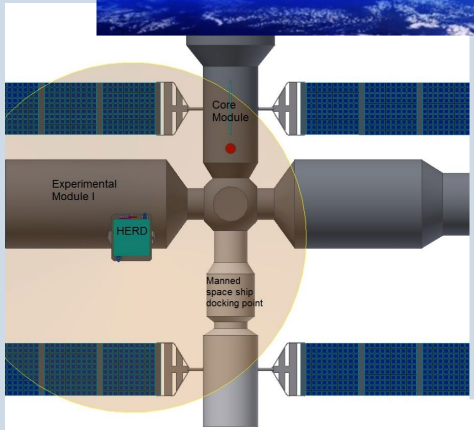
- Particle identification in satellite experiments
- Particle identification for telescope experiments
- Particle identification for environmental monitoring

Particle identification for satellite experiments

High Energy cosmic-Radiation Detection (HERD)

- International space mission to be installed onboard the Chinese Space Station (CSS) (to be completed in 2025)
- It will start operation around 2026
- Collaboration of several scientific institutions





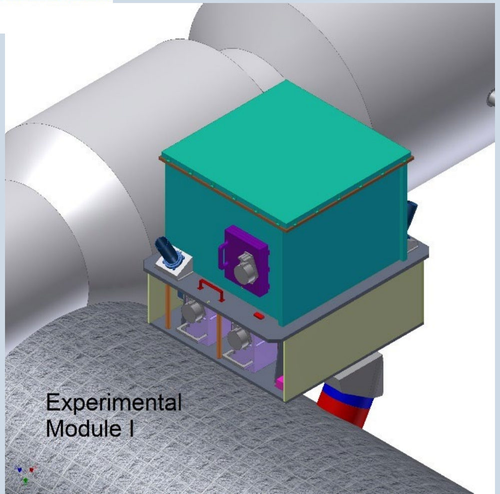
CHINA:
Institute of High Energy Physics CAS (IHEP)
Xi'an Institute of Optical and Precision Mechanics CAS (XIOPM)
Guangxi University (GXU)
Shandong University (SDU)
Southwest Jiaotong University (SWJTU)
Purple Mountain Observatory, CAS (PMO)
University of Science and Technology of China (USTC)
Yunnan Observatories (YNAO)
North Night Vision Technology (NVT)
University of Hong Kong (HKU)
Academia Sinica

SPAIN:
CIEMAT – Madrid
ICCUB – Barcellona
IFAE – Barcellona

ITALY:
INFN Bari and Bari University
INFN Firenze and Firenze University
INFN Pavia and Pavia University
INFN Perugia and Perugia University
INFN Pisa and Pisa University
INFN Laboratori Nazionali del Gran Sasso and GSSI Gran Sasso Science Institute
INFN Napoli and Napoli University
INFN Lecce and Salento University
INFN Roma2 and Tor Vergata University
INFN Trieste and Trieste University

SWITZERLAND:
University of Geneva

Contact:
Gargano F.

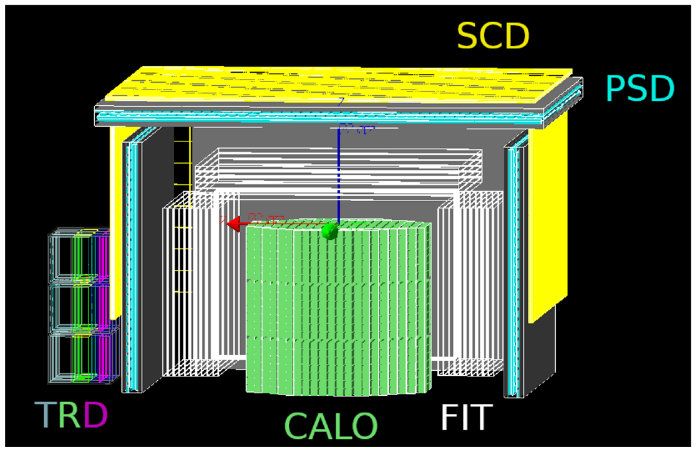


High Energy cosmic-Radiation Detection (HERD)

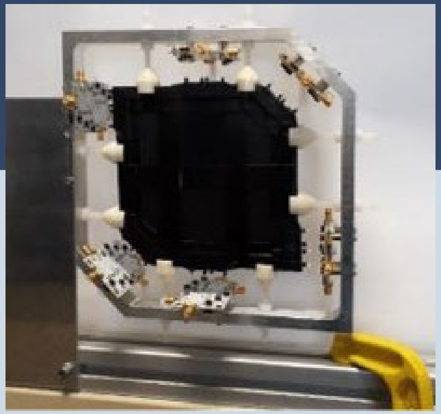
- **3D homogeneous, isotropic and finely-segmented calorimeter with following requirements**

	γ	Electrons	P, nuclei
Energy range	0.5 GeV – 10 TeV	10 GeV – 100 TeV	30 GeV – 3 PeV
Energy resolution	1% @ 200 GeV	1% @ 200 GeV	20% @ 100 GeV – 1 PeV
Effective geometric factor	> 1 m^2sr @ 200 GeV	> 3 m^2sr @ 200 GeV	> 2 m^2sr @ 100 TeV

- **Subdectors:**
  - **FIT**: *The CALO is surrounded by Fiber trackers (FiTs) (except the bottom)*
    - Trajectory Reconstruction, Charge Identification
  - **CALO**: *The HERD core is a 3D, homogeneous, isotropic and finely-segmented calorimeter*
    - Energy Reconstruction, e/p Discrimination
  - **PSD**: *The CALO and the FIT are covered by the plastic scintillator detector (PSD)*
    - CRs charge measurement, γ identification
  - **SCD**: *The silicon charge detector (SCD) is the outermost detector*
    - charge measurement
  - **TRD**: *A Transition Radiation Detector (TRD) will be located on the lateral side*
    - Calibration of CALO

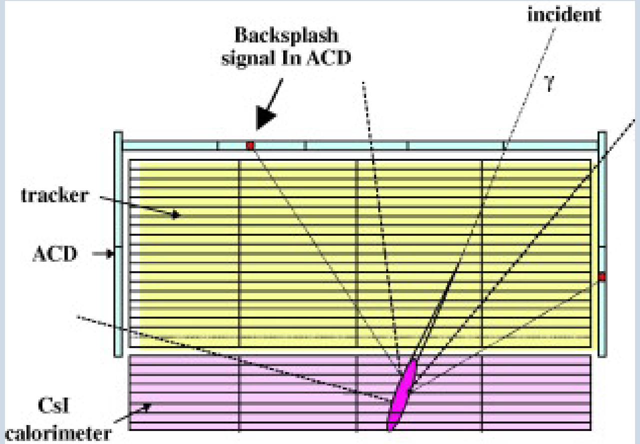


Plastic Scintillator Detector (PSD)



- Two main purposes:
  - gamma-ray identification (VETO of charged particles)
  - Charge measurement
- Must be highly segmented to avoid backsplash effect
- Requirements:
  - High efficiency for charged particle identification
  - Good energy resolution and a frontend readout with high dynamic range for charge measurement
  - Low power consumption for space application
- Layout configuration – being studied:
  - Segmented scintillator (tile geometry)
  - Silicon Photomultiplier (SiPM) directly coupled to the scintillator

Backsplash effect



https://doi.org/10.1016/j.astropartphys.2004.07.008

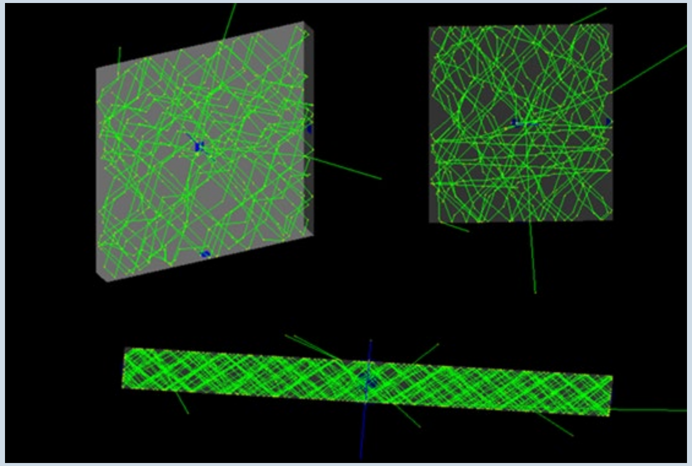
PSD activities

- Several prototypes have been assembled and tested
- Optimization of
  - Geometry
  - Wrapping material
  - SiPM type, number and position
- Tests in our labs:
  - CR sources
  - Radioactive sources
- Tests at accelerators
  - PS/SPS @CERN
  - CNAO
- GEANT4 simulations

Thanks to mechanical design and workshop staff!

GEANT4 Simulation overview

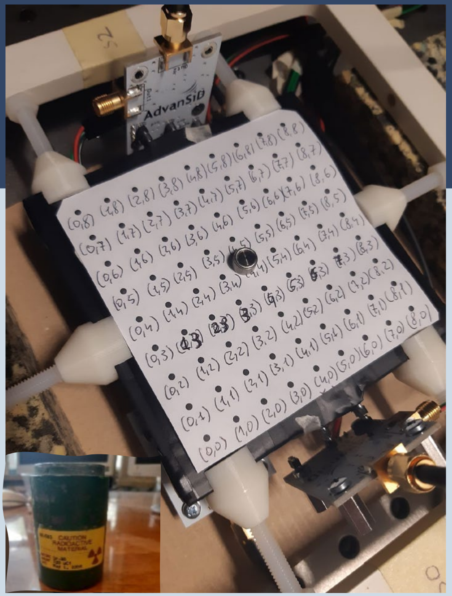
- GEANT4 framework developed to study the PSD performance
- Option to track the scintillation optical photons
- Geometrical settings:
  - Scintillator shape, size, width and material (BC-404, EJ200 ..)
  - Wrapping thickness and material
  - SiPMs size and position
- Set the bulk and the surface optical properties:
  - Light Yield and attenuation length of the scintillator material, refractive index, surface optical properties of the wrapping: e.g. a polished or rought-cut wrapping



Credits to Serini D.

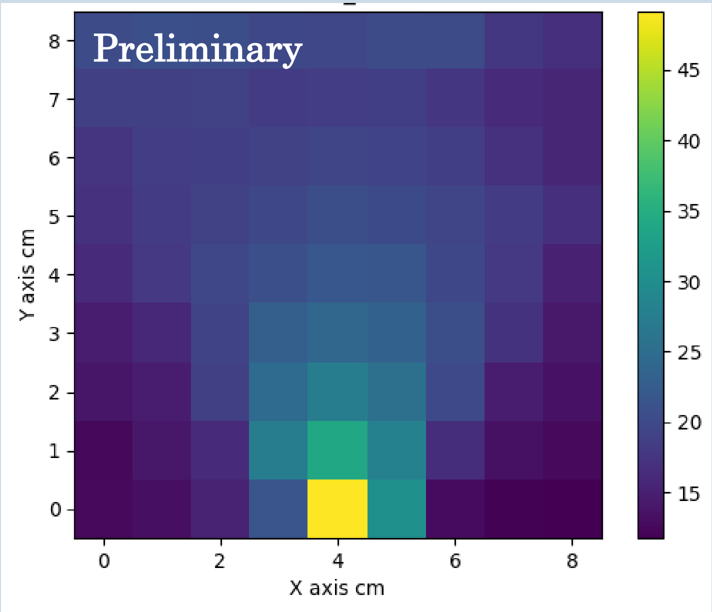
PSD uniformity tests

- Uniform response within the tile allows for a more precise trigger threshold adjustment and energy measurement
- BUT a non-uniform response gives info on the position of the particle
- SiPM position and wrapping are key parameters

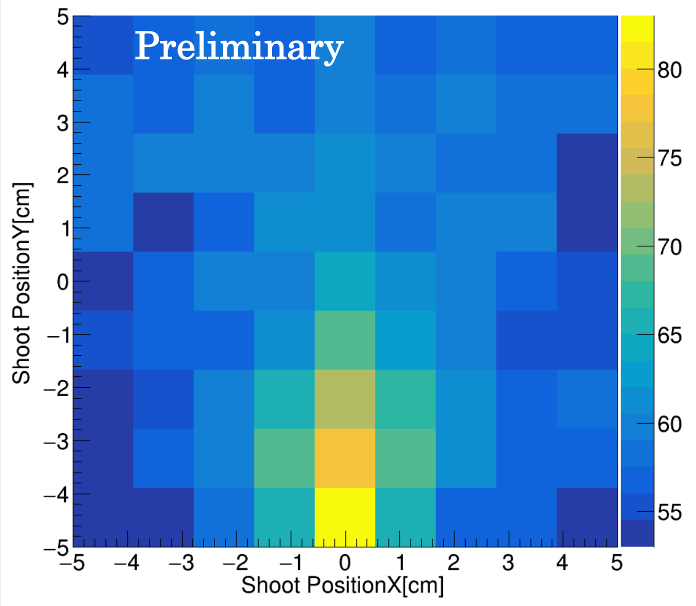


^{90}Sr radioactive source placed in different positions with a 1-cm step to study the uniformity in light collection on a SiPM placed at the bottom of the tile

Data



Simulation

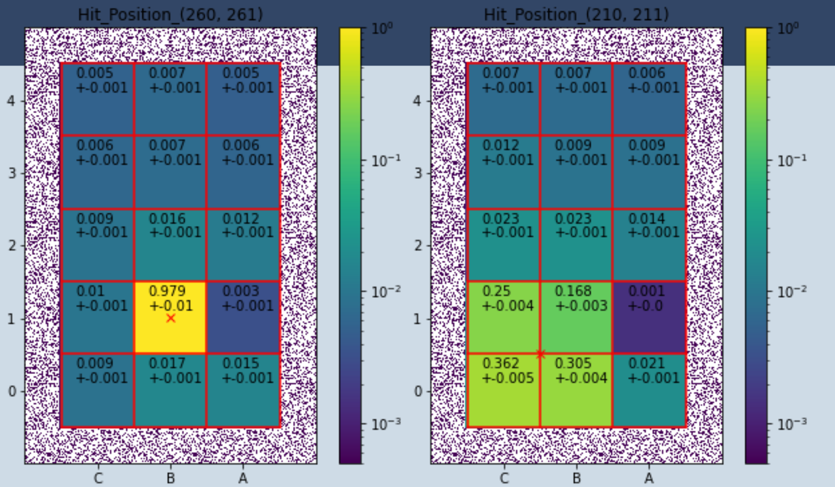


Credits to Altomare C.

PSD prototype tests

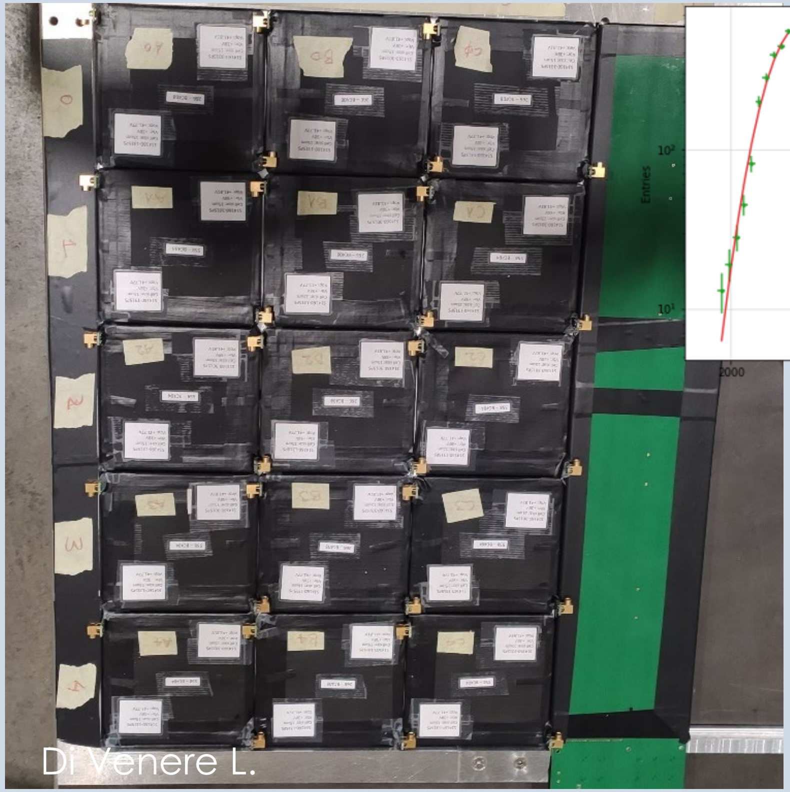
- Tile array prototype (15 tiles) assembled and tested @CERN PS/SPS
- Each tile with 1x1mm² and 3x3mm² SiPMs

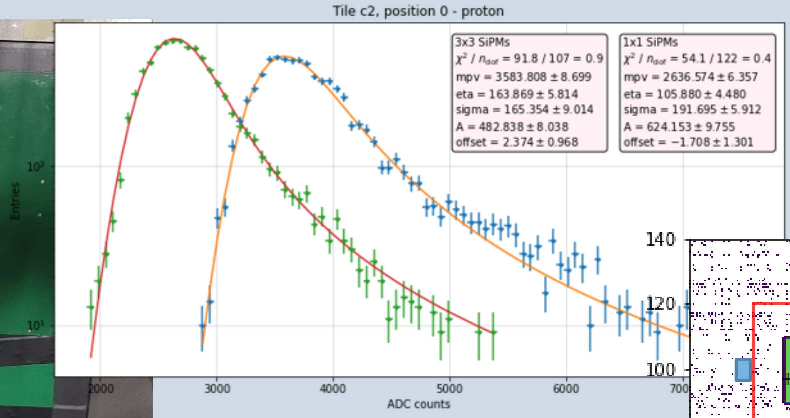
Hit maps



Preliminary

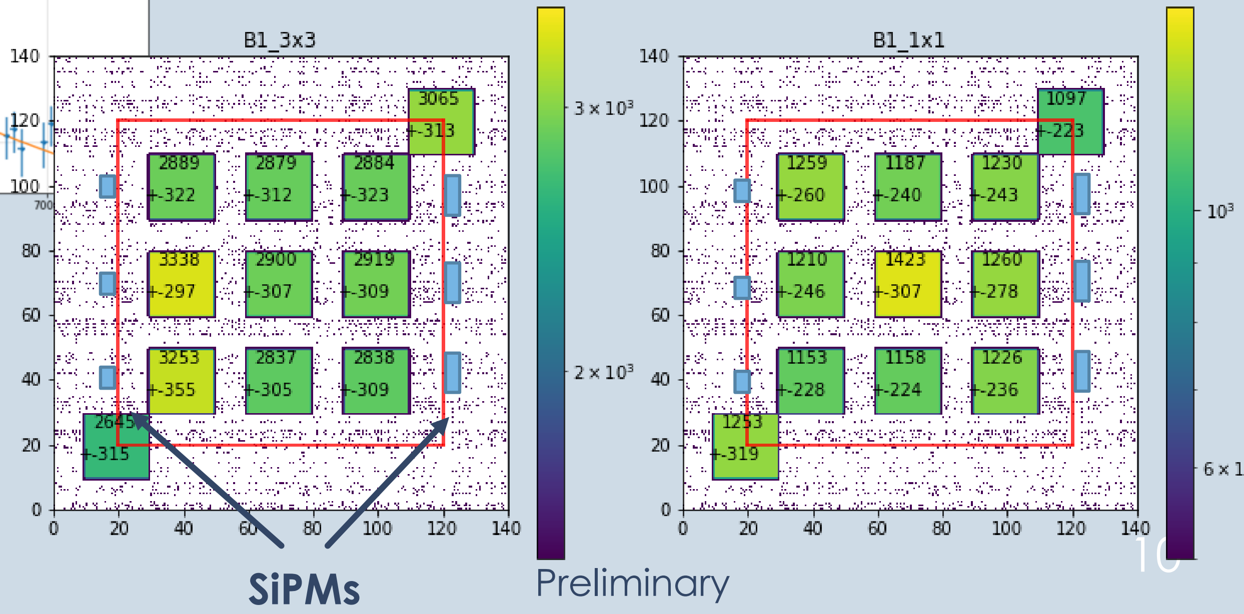
Credits to Altomare C.





Credits to Pillera R.

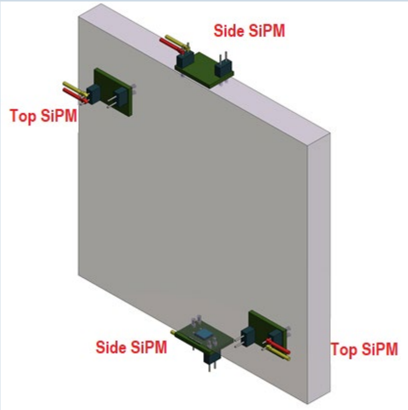
Uniformity tests

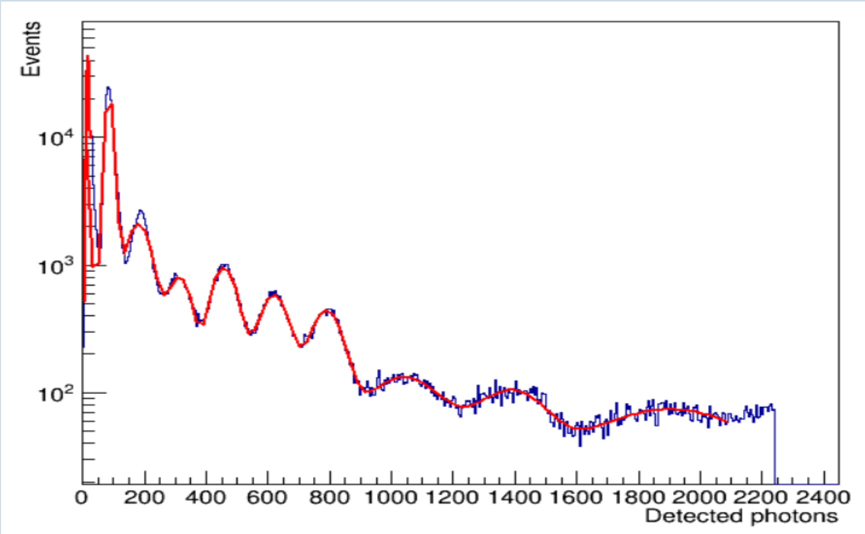


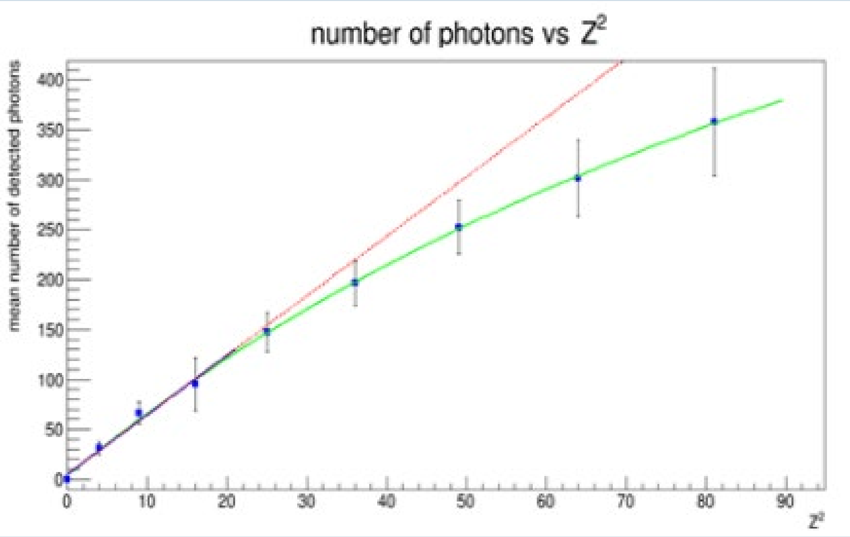
Preliminary

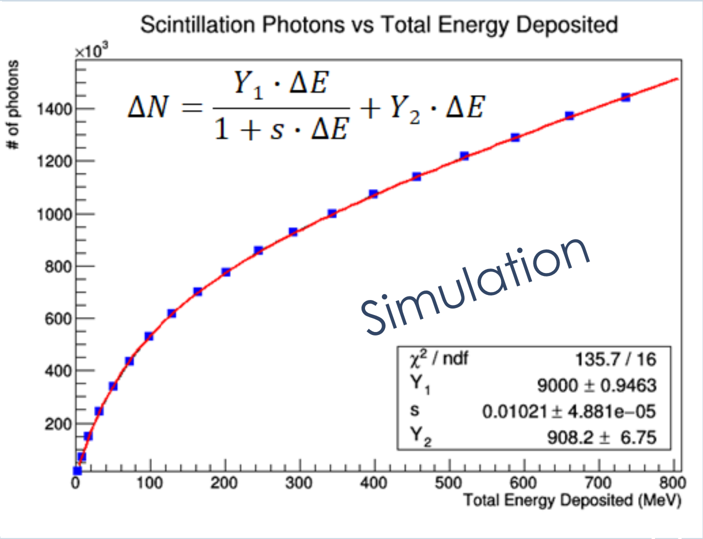
Ion identification

- Charge of Cosmic rays can be reconstructed by measuring the energy released in the scintillator: $\Delta E \propto Z^2$
- Scintillation light:
  - proportional to energy released for low ΔE
  - Birks' effect at high ΔE
- Beam tests @CERN SPS H4



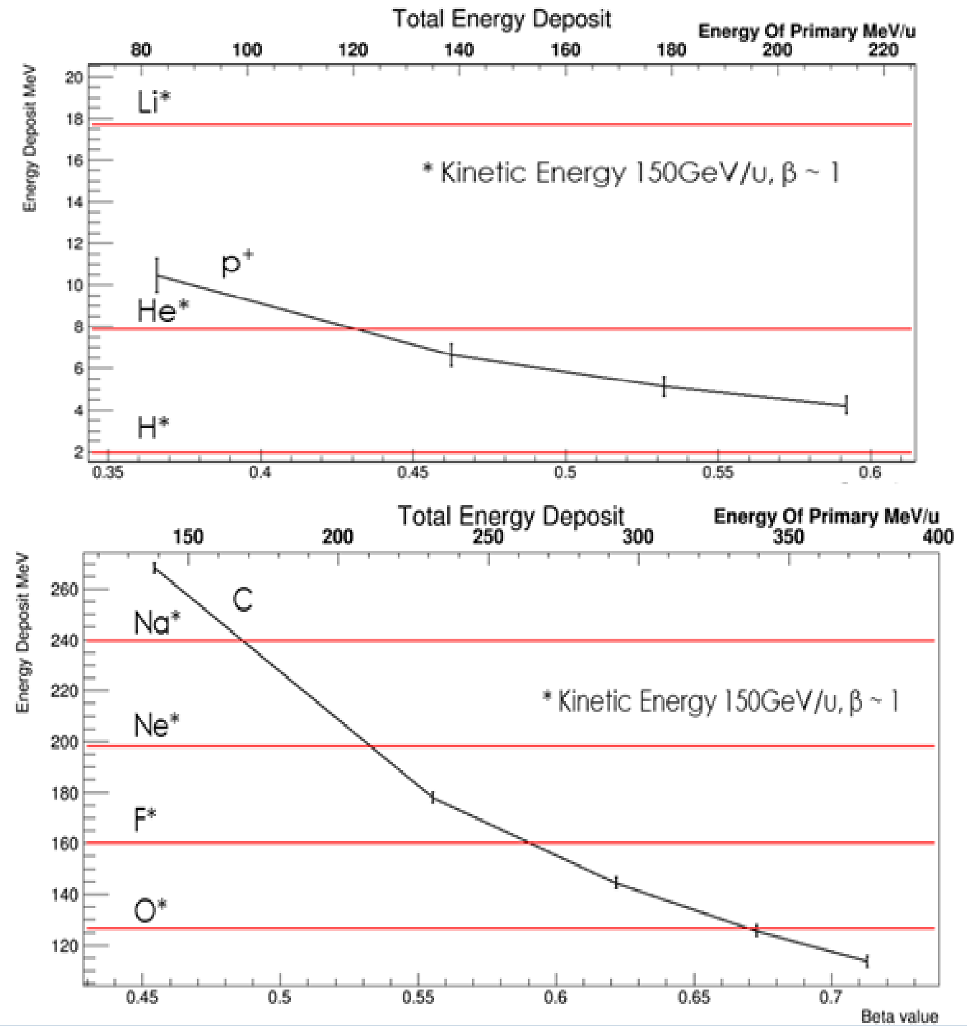






Birks' effect with low energy ion beams

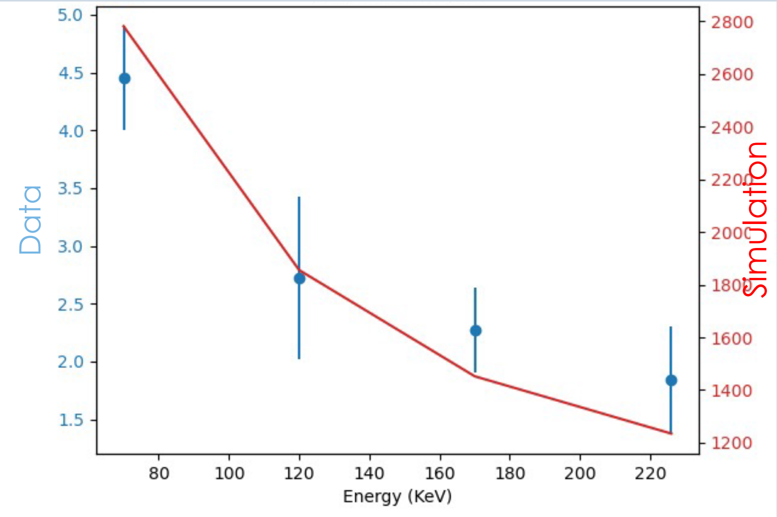
- The high energy ion (m.i.p.) interaction with scintillator can be mimicked by low β ions.
  - Scanning β allows to study Birks' law: saturation of light yield in presence of large local energy release.
- Beam test @CNAO: Centro Nazionale di Adroterapia Oncologica



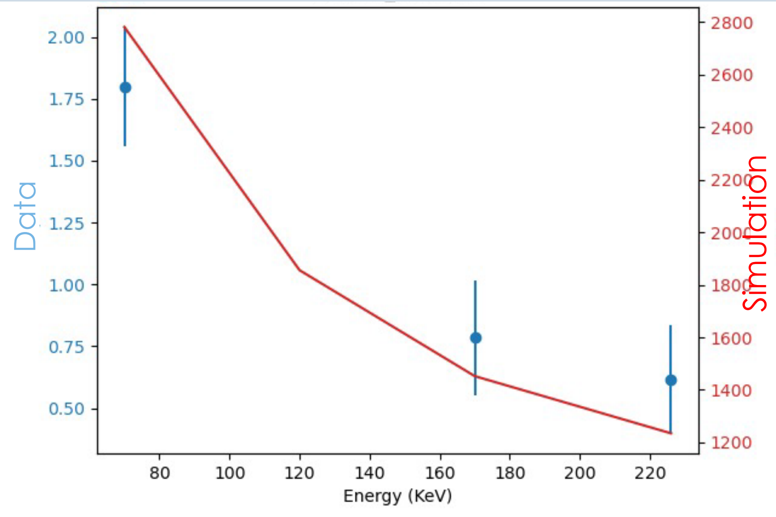
Credits to Altomare C.

BC-404 tile coupled with Hamamatsu SiPMs (15 and 50 μm cell size)

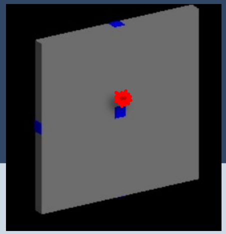
3x HAM-50μm cell



HAM-15μm cell



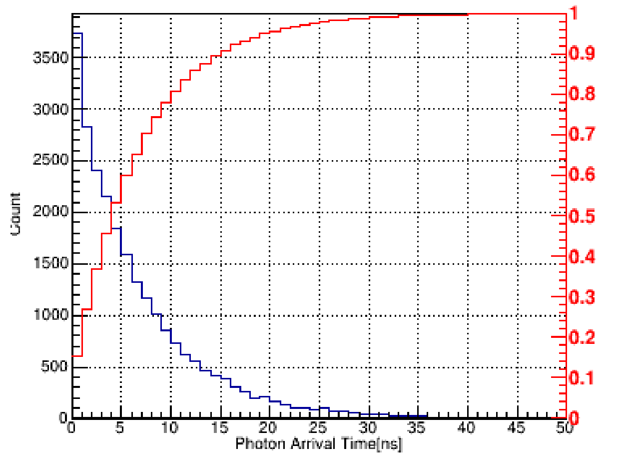
Ion identification studies - simulation



10x10cm^2

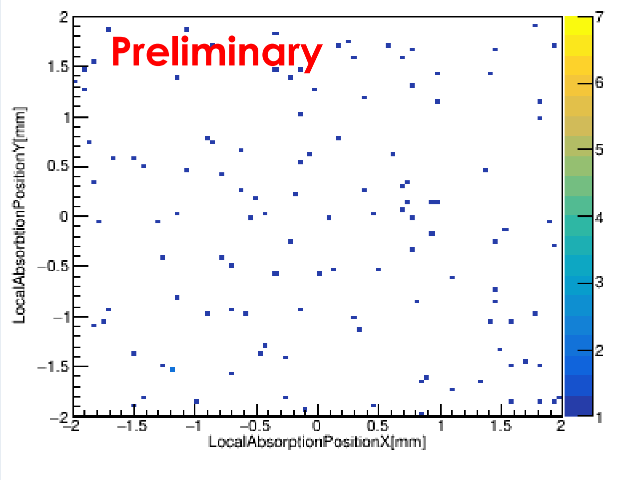
Tracking of all scintillation photons allows a detailed study of:

- Photon collection time → SiPM's timing response to optimize the electronic read-out
- Photon spatial density → SiPM's cell occupancy to optimize the SiPM design in terms of cell size in order to avoid the saturation



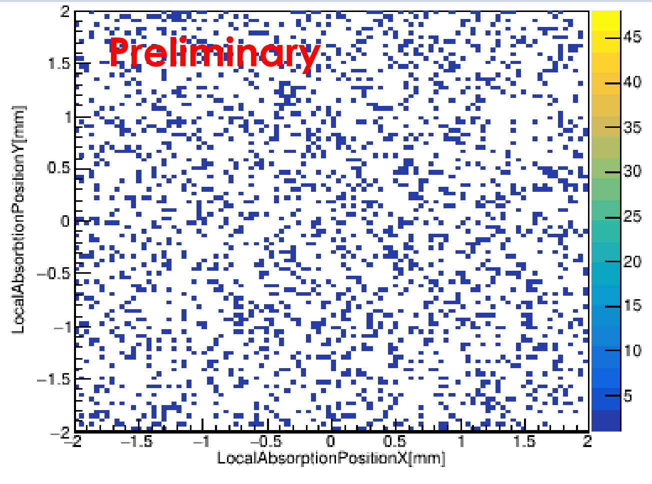
50% ph. in 5ns
80% ph. in 10ns

Protons



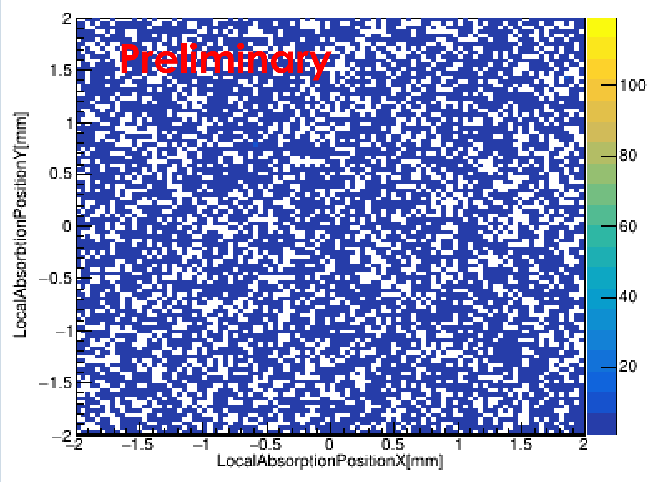
Fired cells/collected ph. = 1

Carbon



Fired cells/collected ph. = 0.87

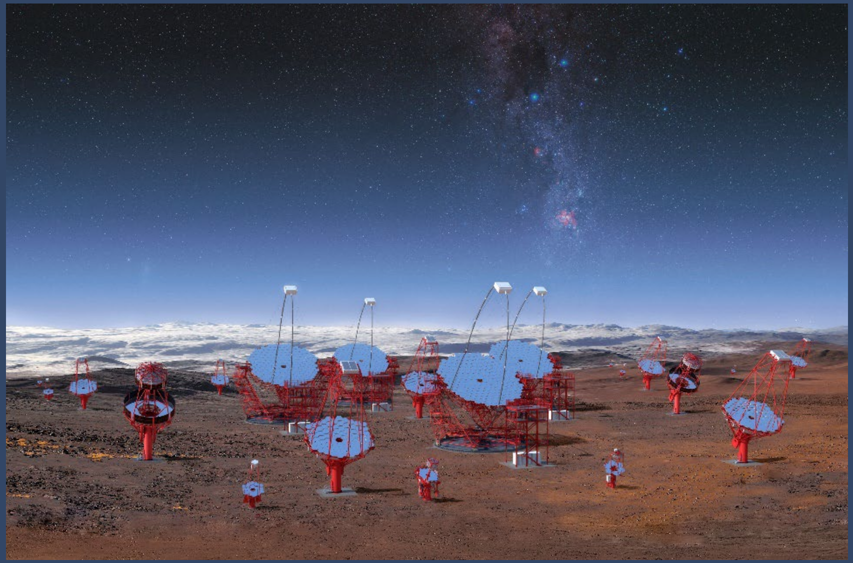
Iron



Fired cells/collected ph. = 0.59

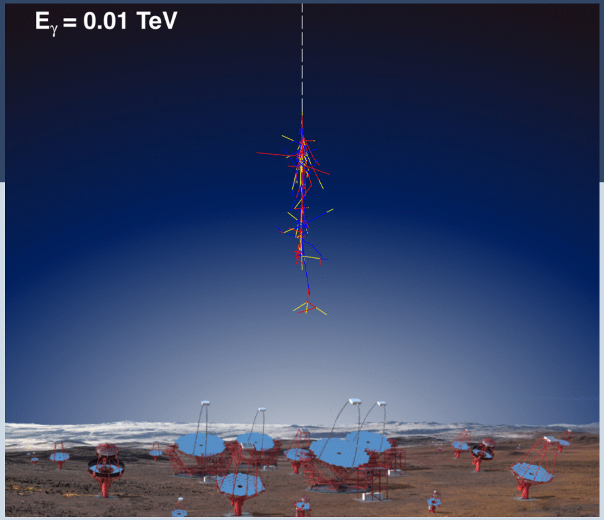
4x4mm^2 SiPM with 40μm cells

Credits to Serini D. & Altomare C.



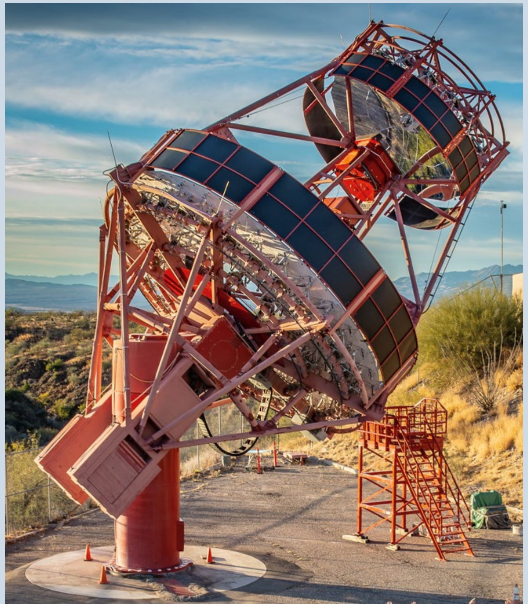
Particle identification for telescope experiments

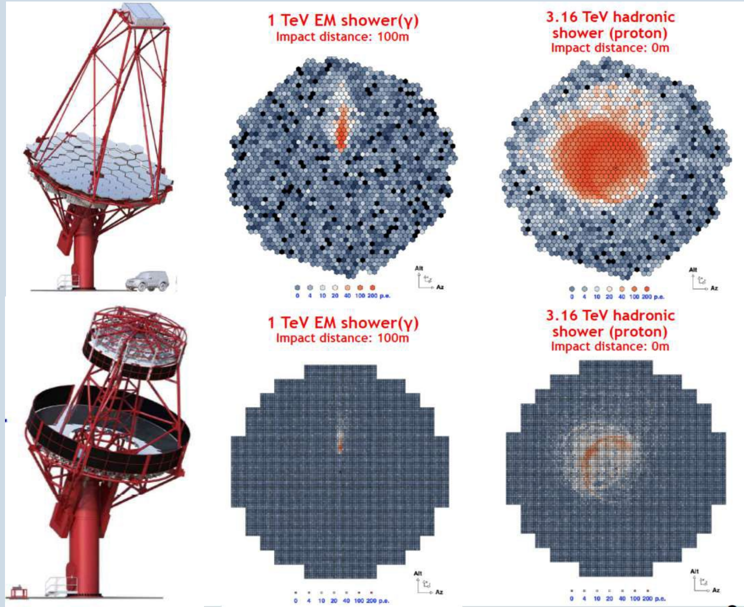
The Cherenkov Telescope Array



Credits to Pillera R.

- Gamma-rays and cosmic rays produce particle showers in atmosphere
- Cherenkov telescopes reconstruct shower images to identify and measure the primary particle
- INFN Bari involved in the Schwarzschild-Couder dual mirror optics Medium Size Telescope
  - Joint effort of US and Italian institutes
  - Dual mirror optics designed to cancel aberration and de-magnify images
  - compatible with compact high-resolution SiPM camera
  - Improved angular resolution
  - 3M$ MRI&INFN funded project ongoing



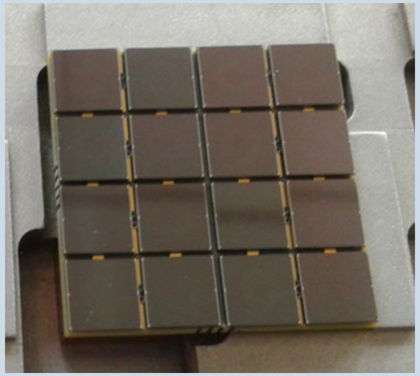


Di Venere L.

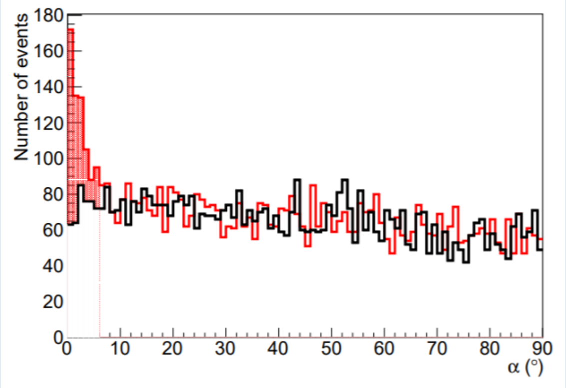
Contact: Giordano F.

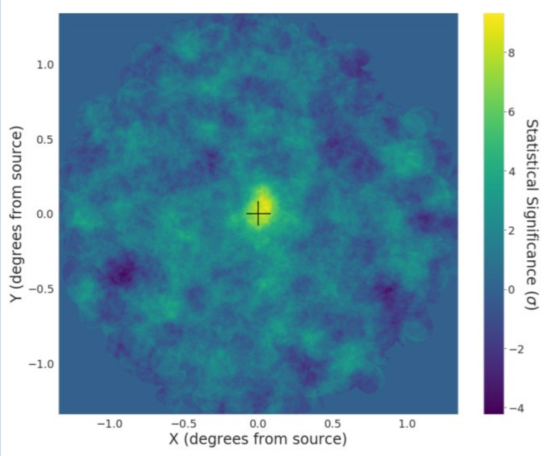
The prototype Schwarzschild-Couder Telescope

- SiPM development carried out in FBK with INFN collaboration
- NUV-HD technology established and adopted for CTA
- First 9 modules already installed using FBK SiPMs in 2019
- **pSCT installed @FLWO, Arizona**



Crab Nebula detected in 2020!





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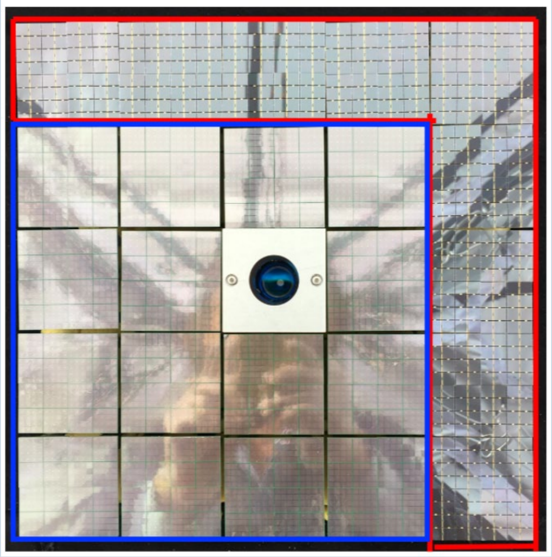
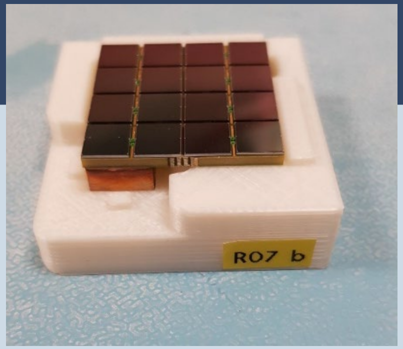
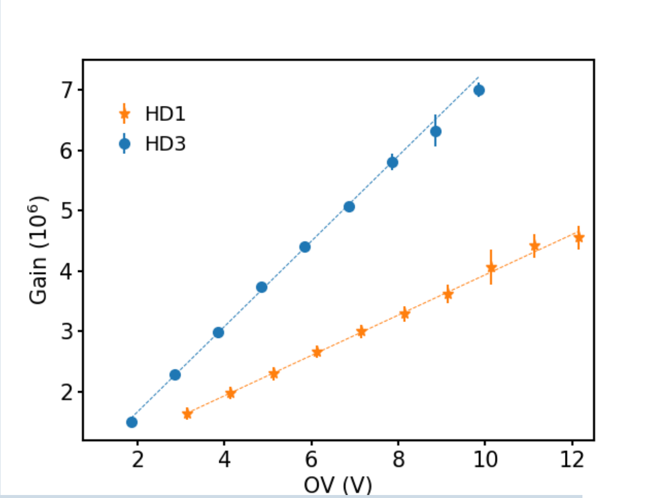


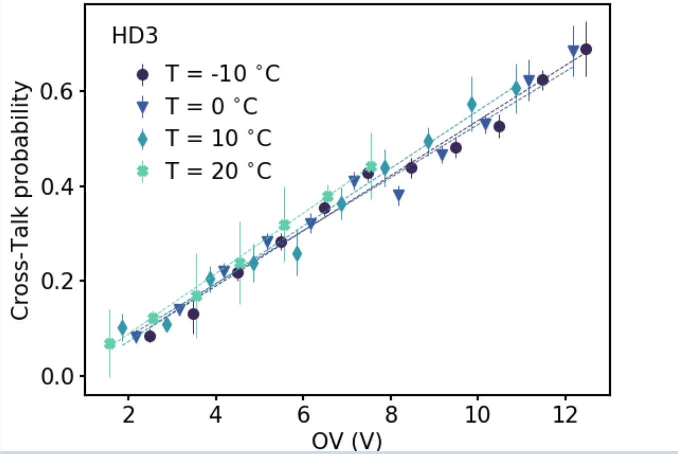
Credits to Loporchio S.

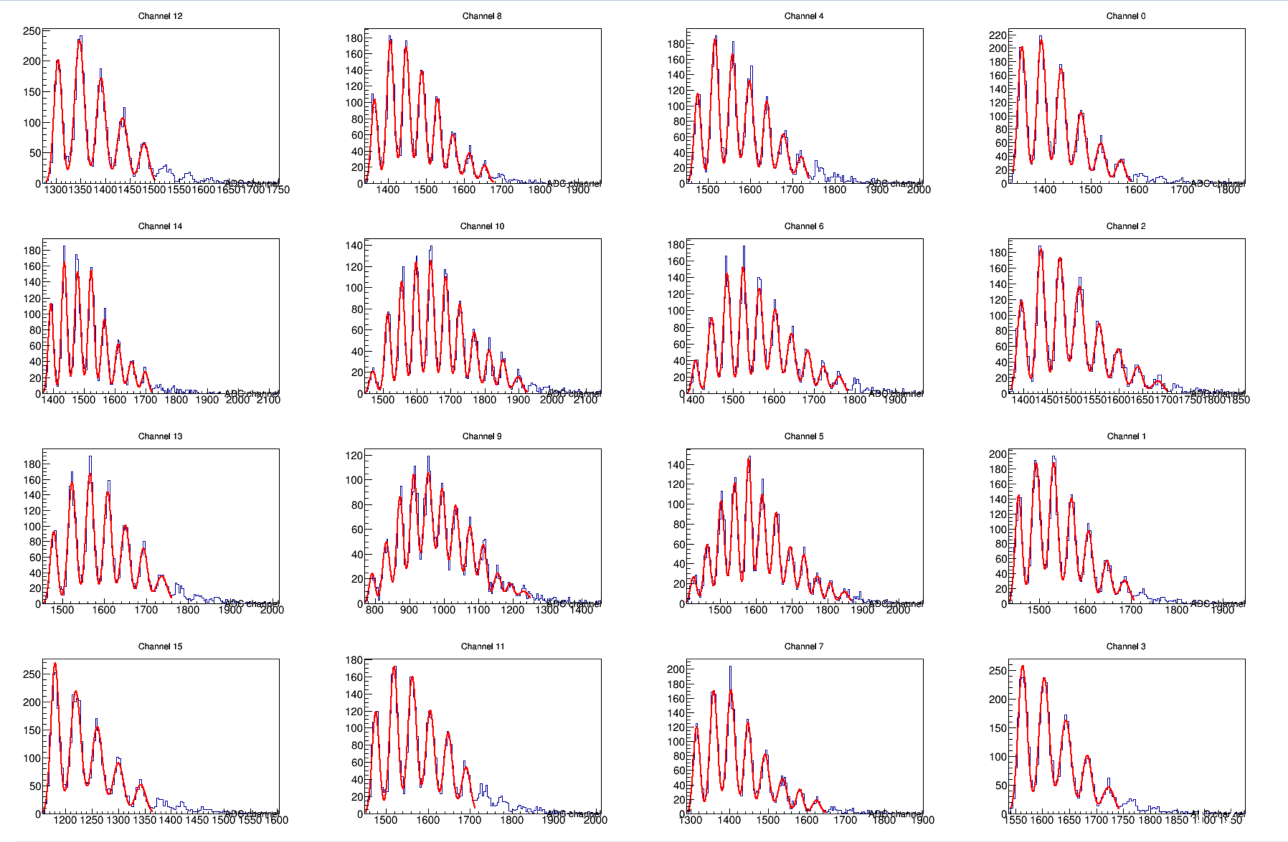
SiPM & electronics characterization

- SiPM deeply characterized in our labs
- ~200 SiPM matrices tested so far







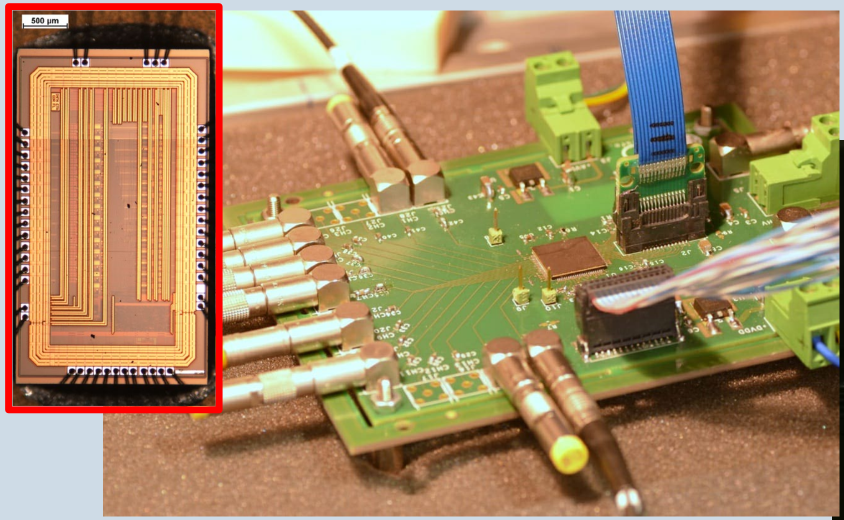


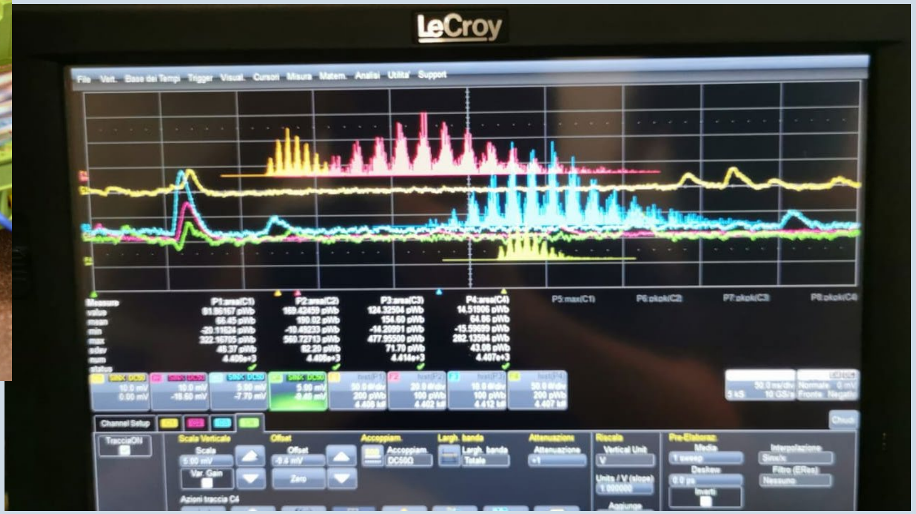
Di Venere L.

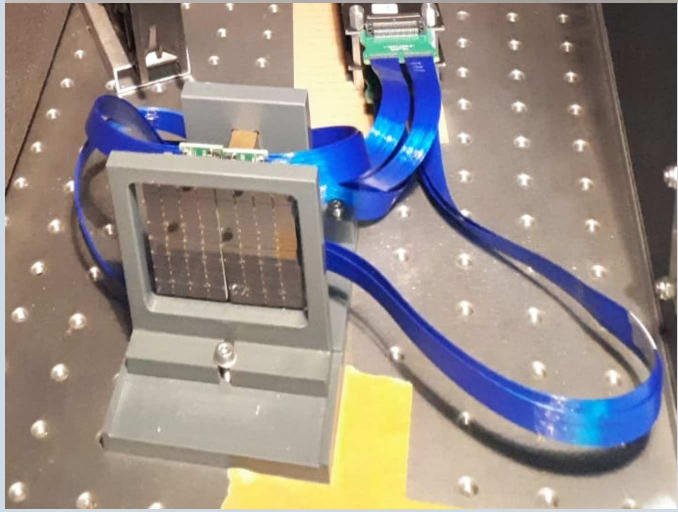
The pSCT frontend electronics

- Camera upgrade project ongoing
- New readout electronics
- Preamplification stage with a dedicated ASIC: **SMART**
  - designed @INFN Bari
  - ~800 ASICs tested @INFN Bari

See talk later by F.Licciulli







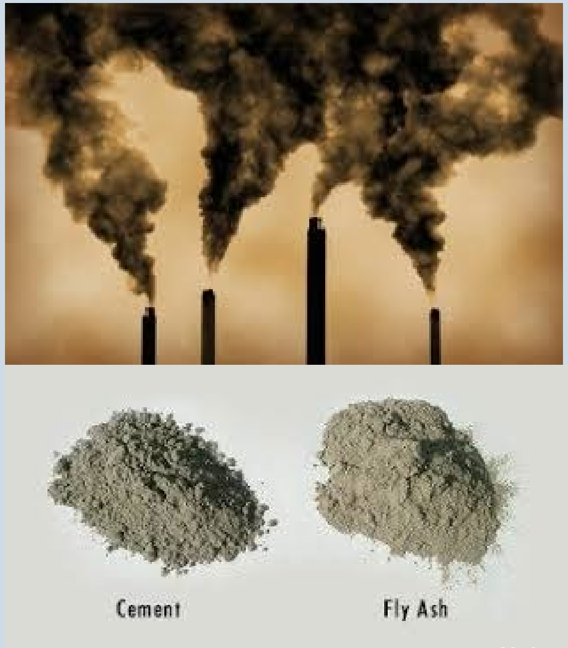
Particle identification for environmental monitoring

Radioactive gamma-ray sources identification

- Gamma-ray detection is hot topic in several fields
  - Homeland security
  - Safety control in industrial environment
  - NORM and TENORM environmental monitoring
  - Survey of areas from UAVs
- Gamma-ray detection requirements:
  - High sensitivity
  - Gamma spectroscopy over a wide energy range (100 keV – 3 MeV)
  - Source localization
  - Fast response

Gate monitoring for homeland security

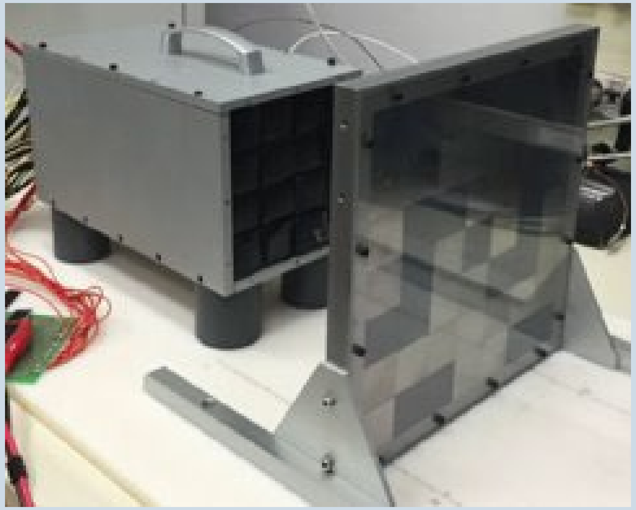
Nuclear waste drums

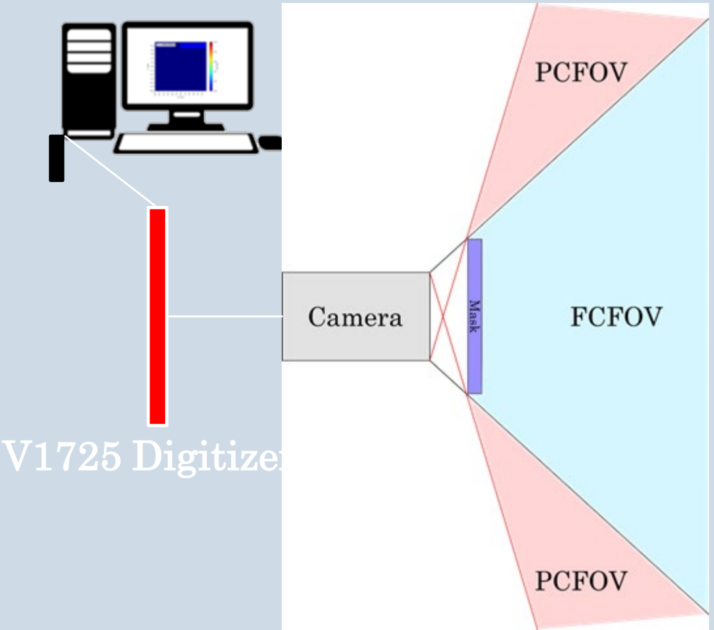


Fly coal ash (example of TENORM)

The High Efficiency fast-Response GAmma detector (HERGA) prototype

- 4x4 CsI(Tl) scintillator array (3x3x10 cm^3 crystals)
- Photomultiplier Tubes PMTs
- Signal digitized by CAEN V1725
  - 14-bit, 250 MS/s digitizer
- Source localization performed with a coded mask technique
  - Mask is made of 7x7 PVC and tungsten tiles, transparent and opaque to gamma-rays respectively

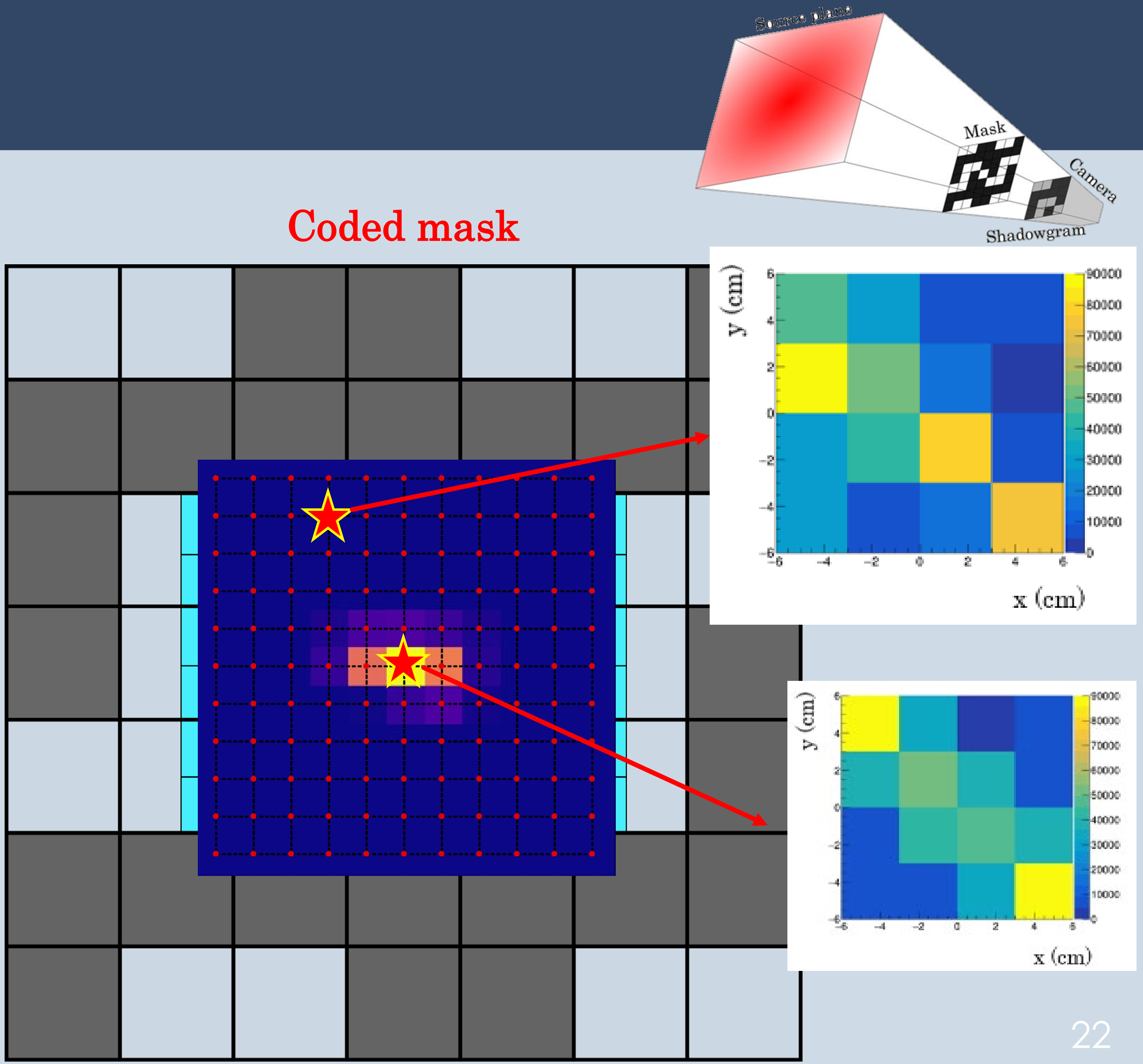




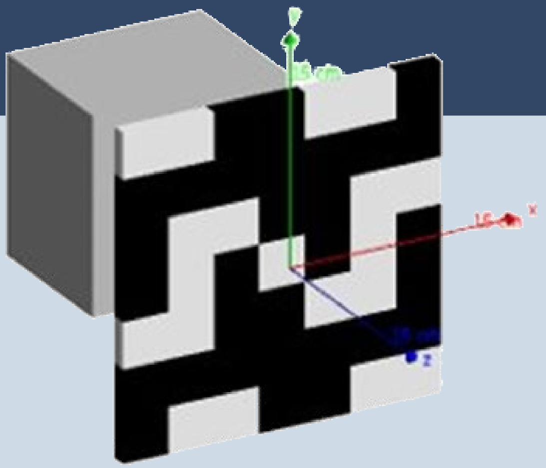
Contact: Giordano F.

Image recostruction

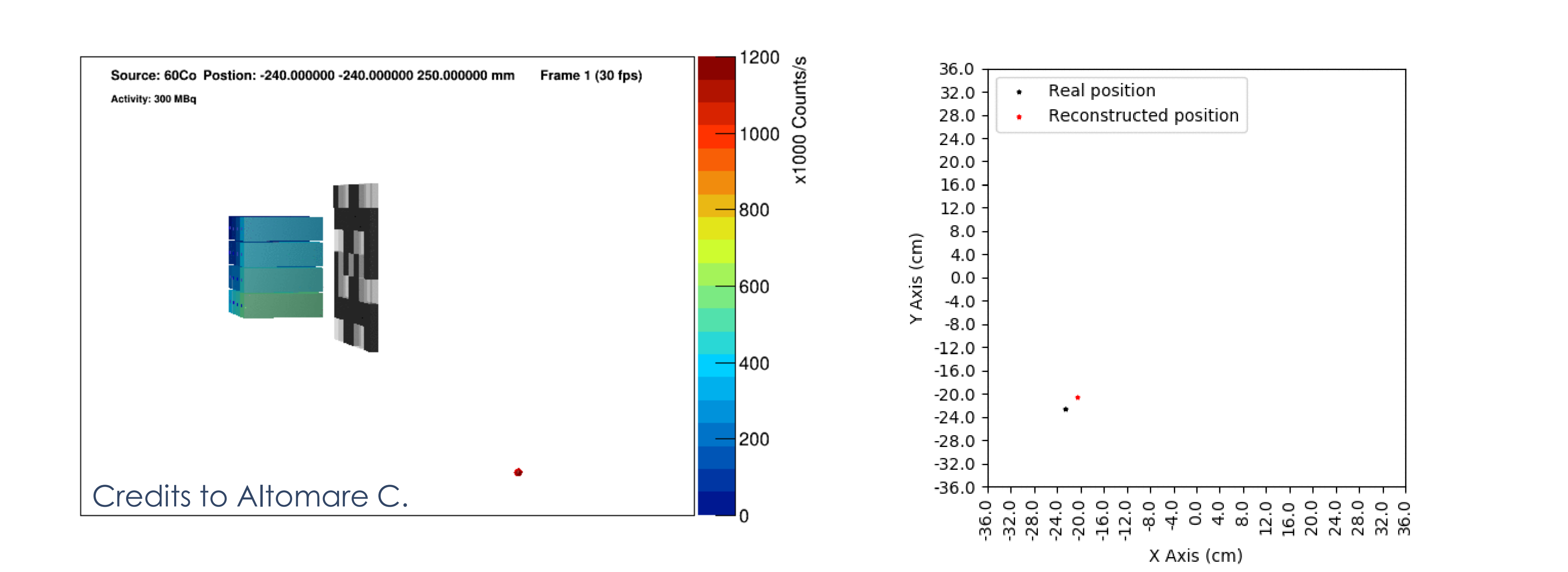
- The mask produces a shadow on the camera, depending on the gamma-ray source position
- The shadowgrams for several positions are recorded and stored into a database
- The source position reconstruction is based on the comparison of the shadowgram with the recorded database using a Kolmogorov-Smirnov test (KS2D)



Monte Carlo detector simulation



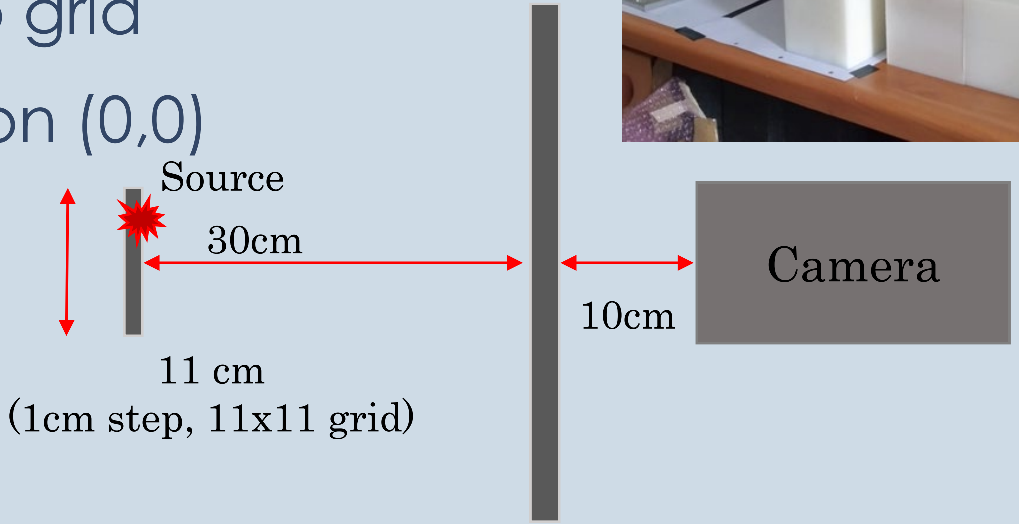
- Monte Carlo simulation based on GEANT4
- Simulation of a source in several positions to define the image reconstruction database



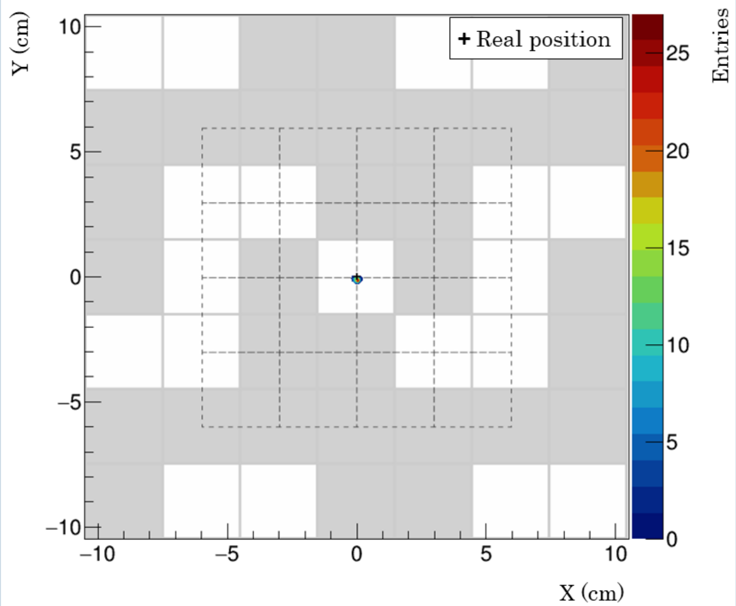
Simulation of a ^{60}Co source with an activity of 300MBq at 20 cm from the camera

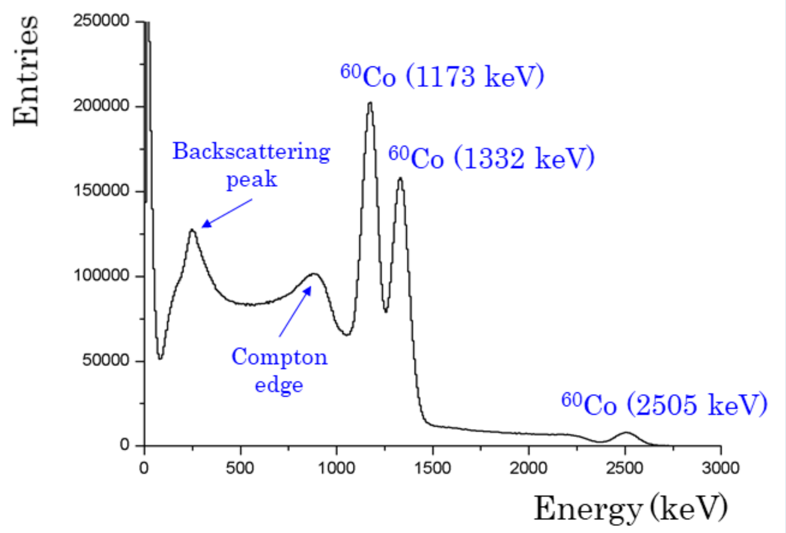
Experimental measurements

- Shadowgrams for sources in 1 cm-step grid
- Reconstruction tested in central position (0,0) and a shifted position (-3cm, 3cm)



^{60}Co in central position





^{60}Co energy spectrum

Energy resolution is ~7-8% for ^{60}Co

For ^{60}Co in the central position PSF ~ (4±2.5) mrad

Results in agreement with MC simulations

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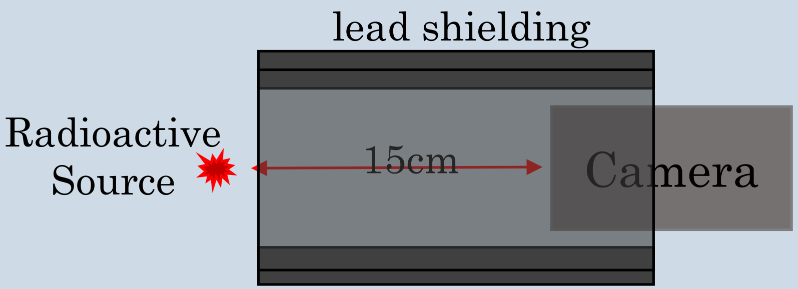
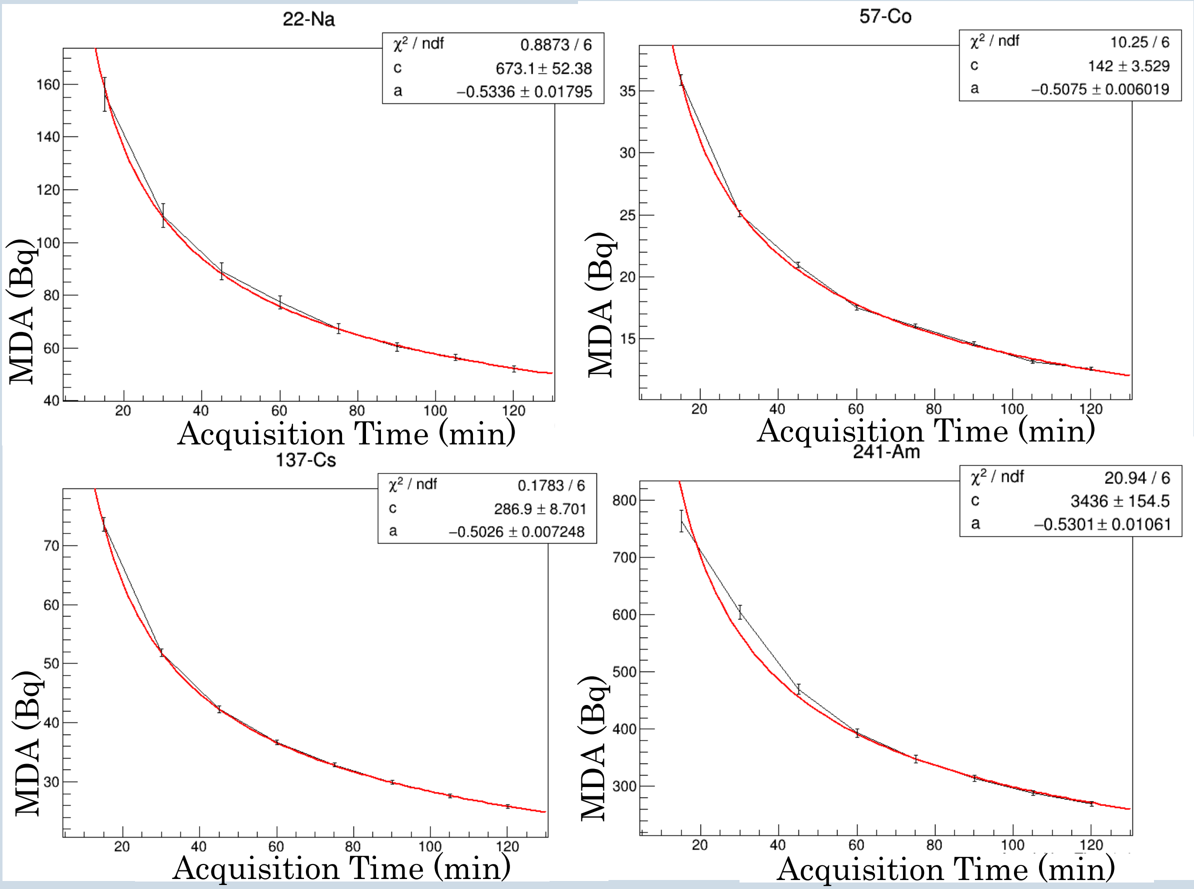
Minimum detectable activity (MDA)

- MDA is the minimum activity which can be detected in specific conditions (acquisition time, shielding, source position)
- Camera was shielded on all sides except for the front side
- MDA measured as a function of the acquisition time for four radionuclides: ^{241}Am, ^{57}Co, ^{137}Cs, ^{22}Na





Future upgrades

- More compact detector with:
  - Optimized crystal geometry
  - SiPMs instead of PMTs
- Installation on drones for large area surveys

Credits: FRANCOIS NASCIMBENI/AFP/Getty Images

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