A compact gamma-ray imaging camera for radio-nuclides detection

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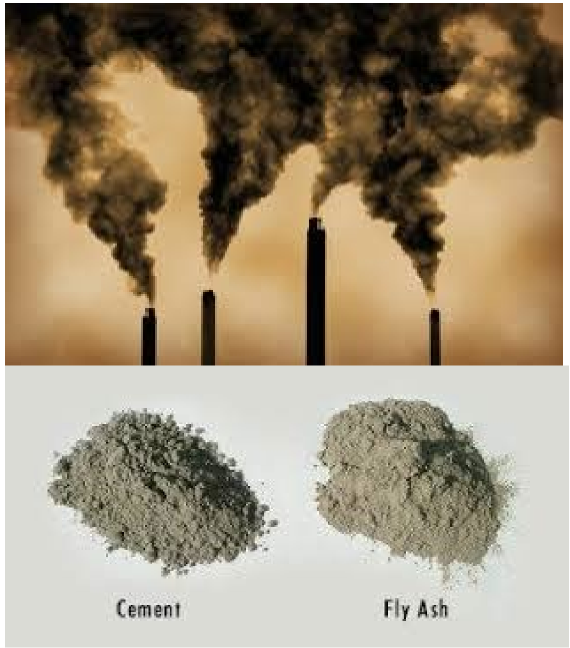
Context

- Gamma-ray detection is hot topic in several fields
  - Homeland security
  - Safety control in industrial environment
  - NORM and TENORM environmental monitoring
- 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

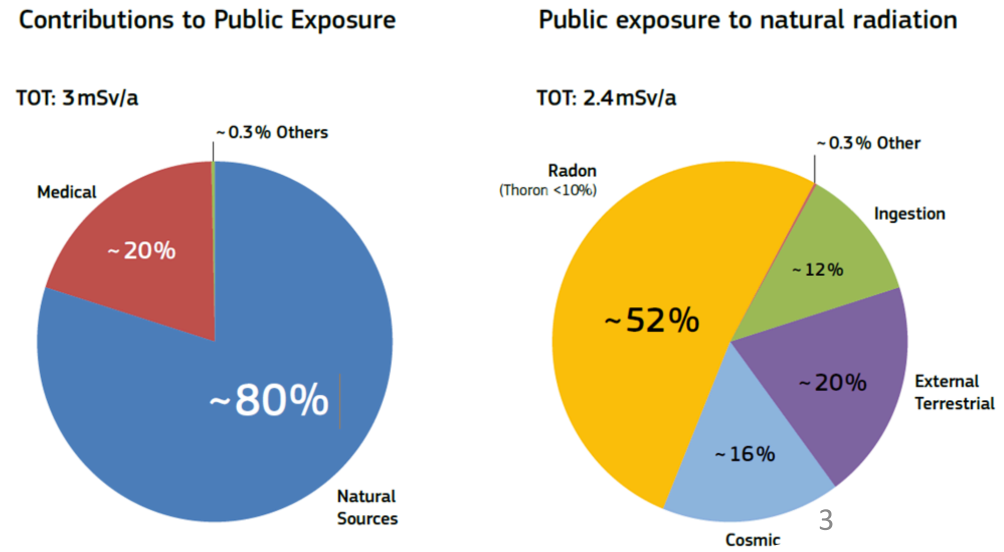


Fly coal ash (example of TENORM)

Nuclear waste drums

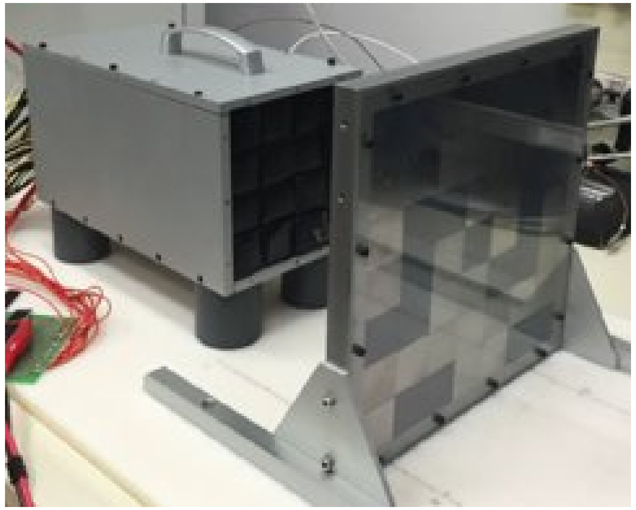
NORM and TENORM

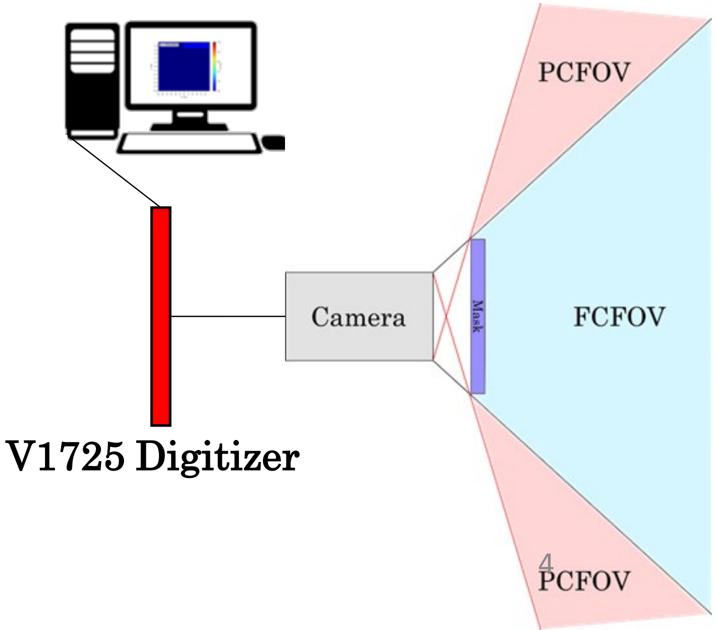
- **NORM:** Naturally Occurring Radioactive Materials
- **TENORM:** Technologically Enhanced Naturally Occurring Radioactive Materials
- Usually industrial wastes or by-products enriched with radioactive elements found in the environment
- Can cause dangerous increment of the natural radioactivity and increase the public exposure
- Generated from industrial processes that exploit natural resources such as coal combustion, fertilizers production, processing metal, oil mineral ores extraction, …



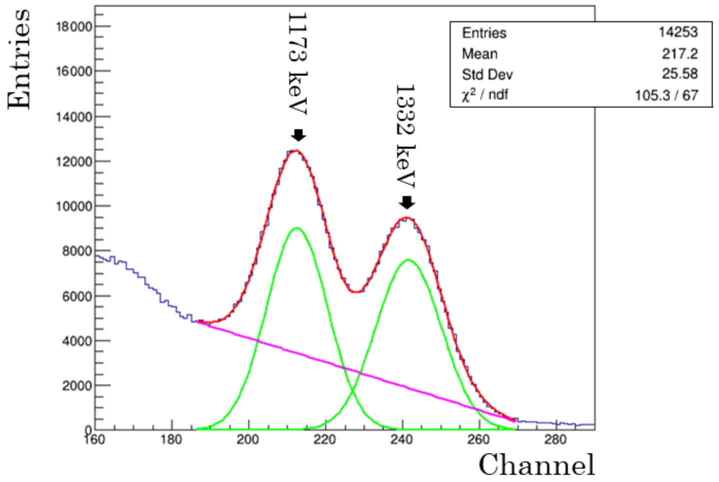
The High Efficiency fast-Response GAmma detector (**HERGA**) prototype

- 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



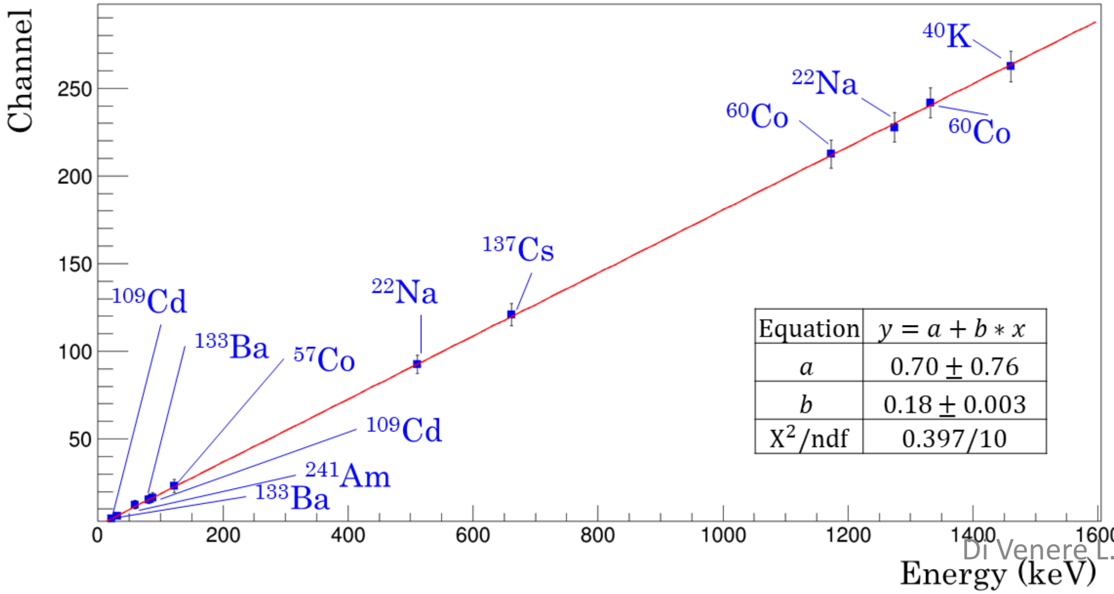


Energy calibration



- Spectra acquired for several radionuclides for each crystal
- Energy calibration curves derived for each crystal
- Energy resolution measured and fitted: $\frac{\sigma_E}{E} = \frac{4.1\%}{\sqrt{E(MeV)}}$

Energy calibration curve



Energy resolution

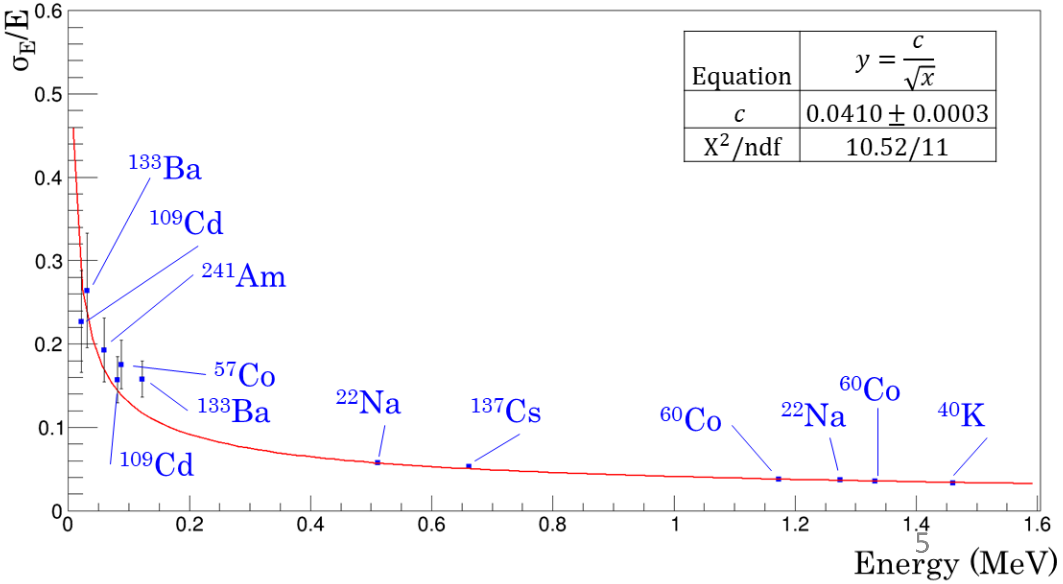
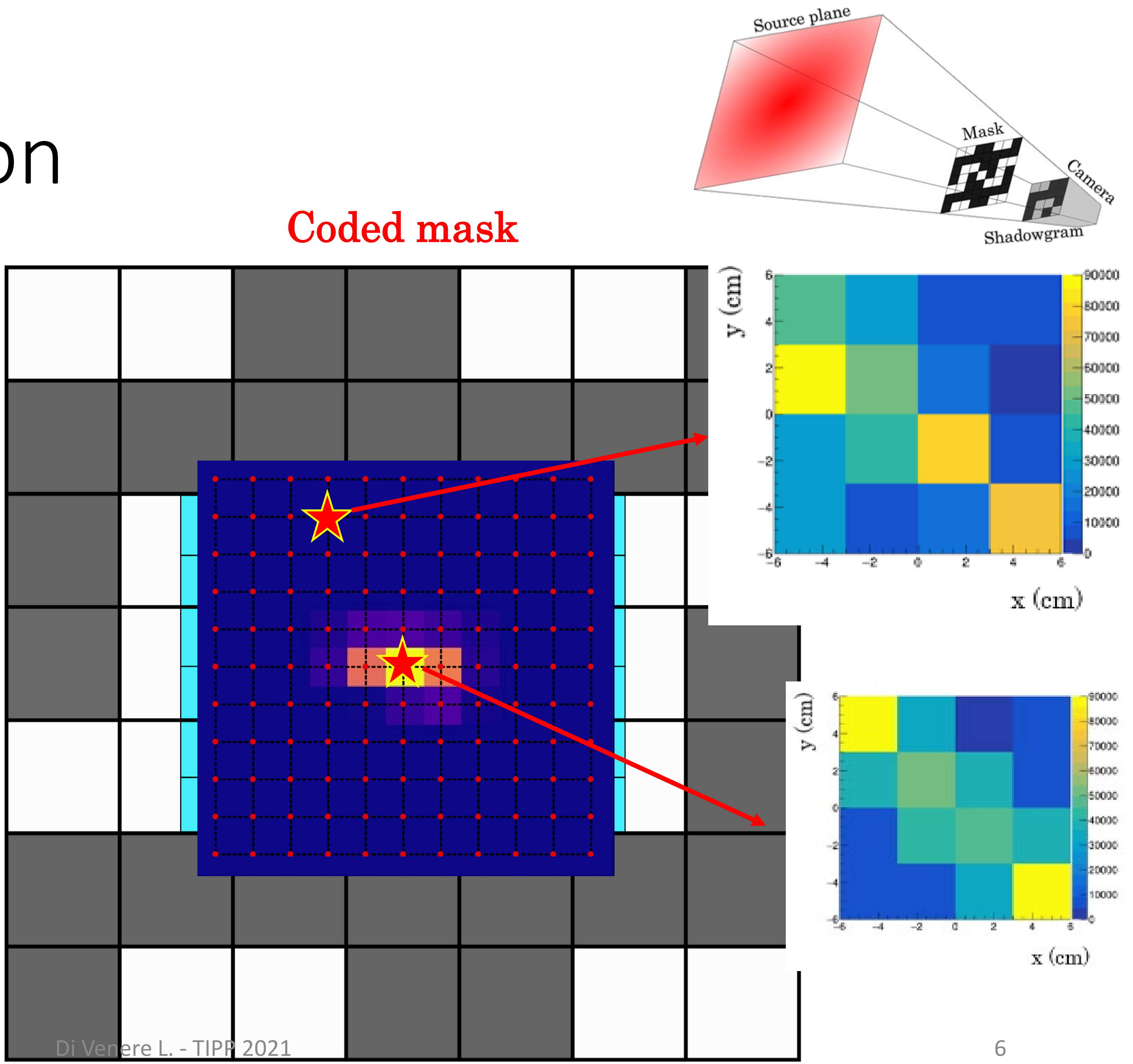
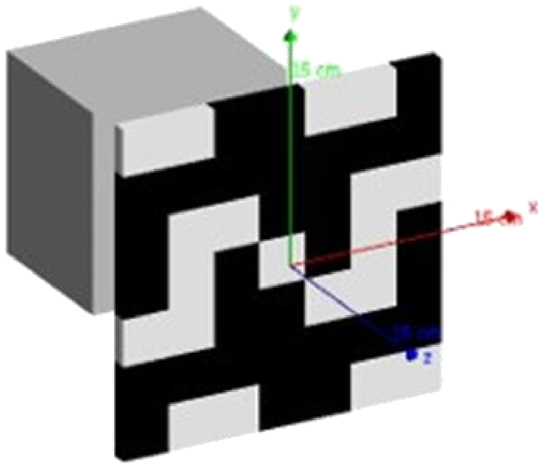


Image recostruction

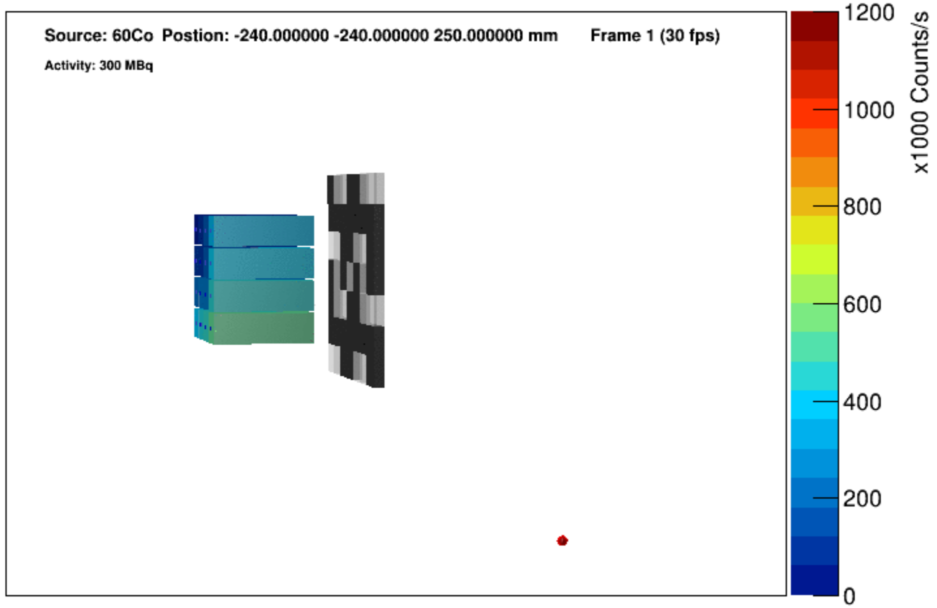
- The mask produces a shadow on the camera, depending on the gamma-ray source position
- The shadowgrams for several positions are recorded and stored into a database
- The source position reconstruction is based on the comparison of the shadowgram with the recorded database using a Kolmogorov-Smirnov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

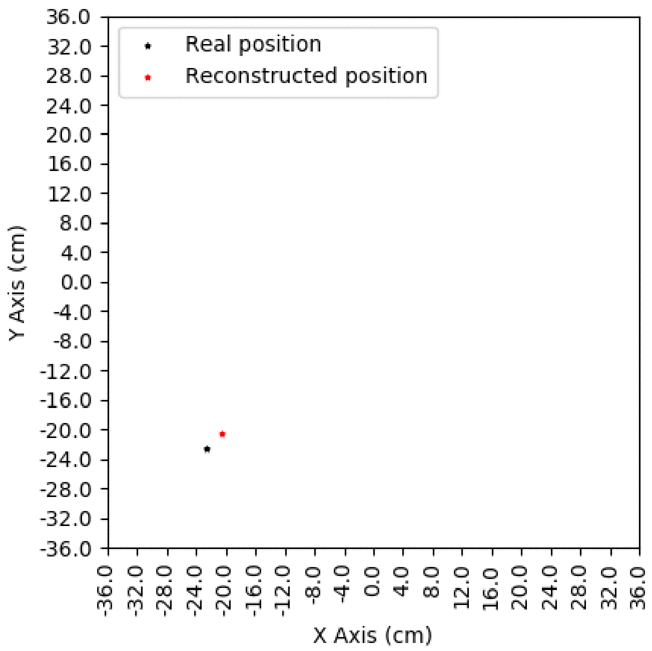


Monte Carlo detector simulation



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



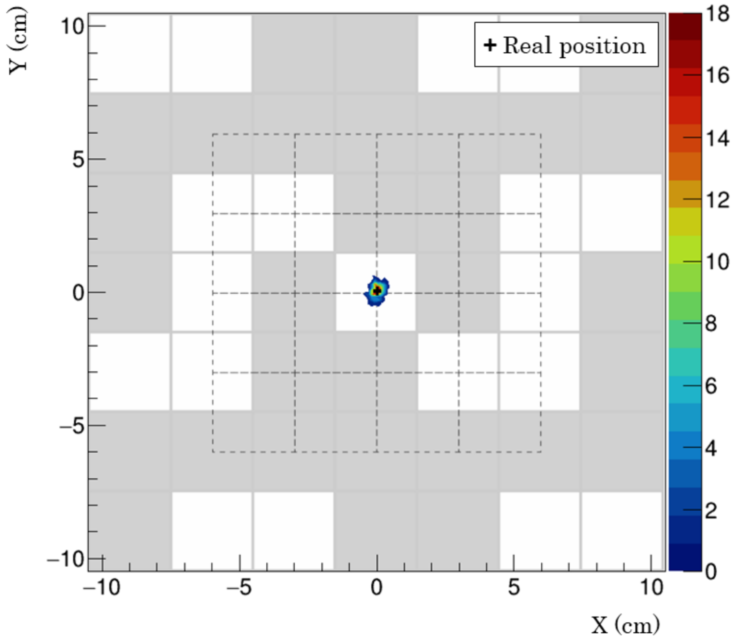


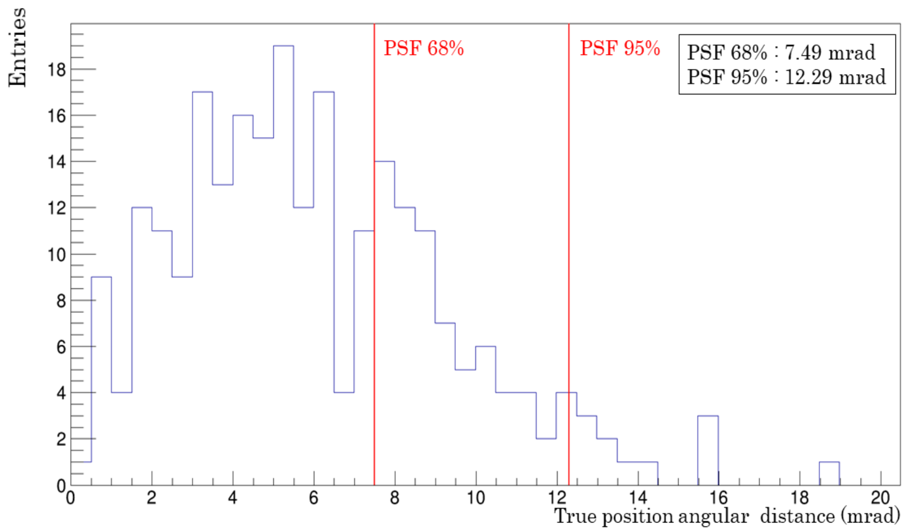
Simulation of a ^{60}Co source with an activity of 300MBq at 20 cm from the camera

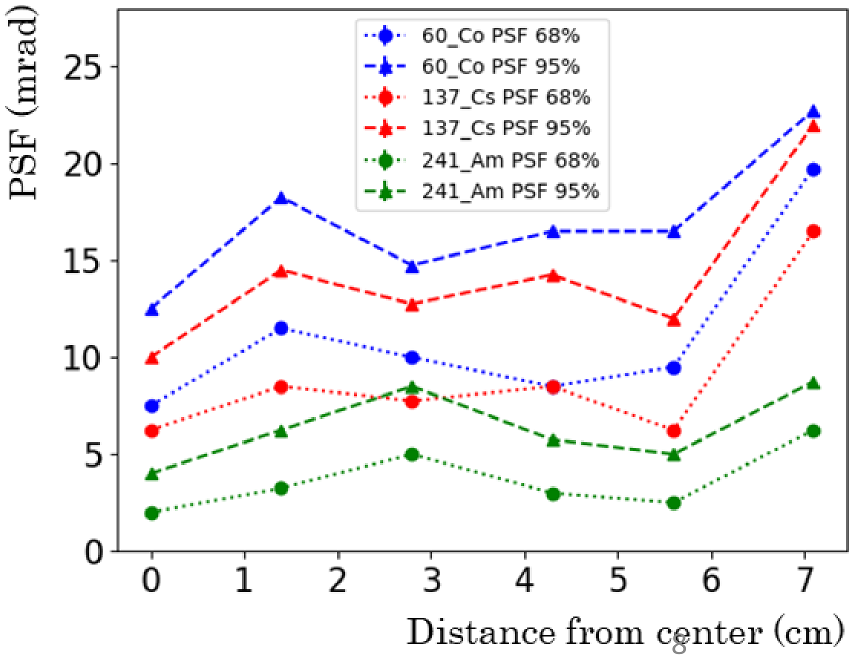
Point Spread Function (PSF)

- The PSF describes the goodness of the position reconstruction
- Several simulations of sources in the different positions and at different energies
- For each energy/position we calculate the offset between the true and reconstructed position

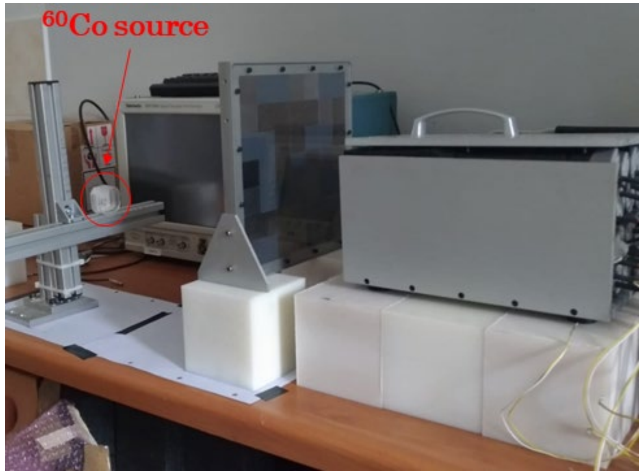
^{60}Co in central position





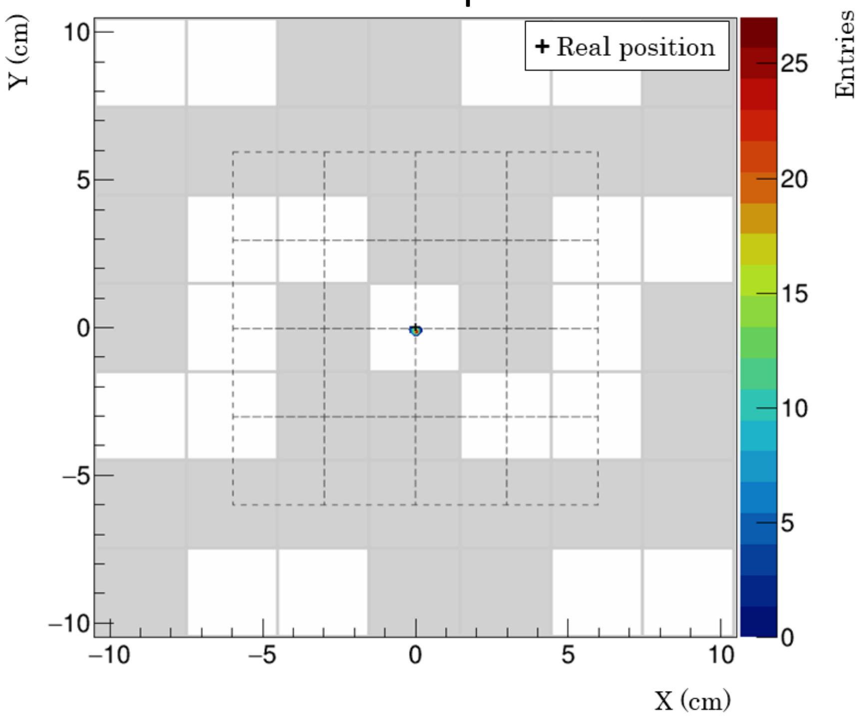


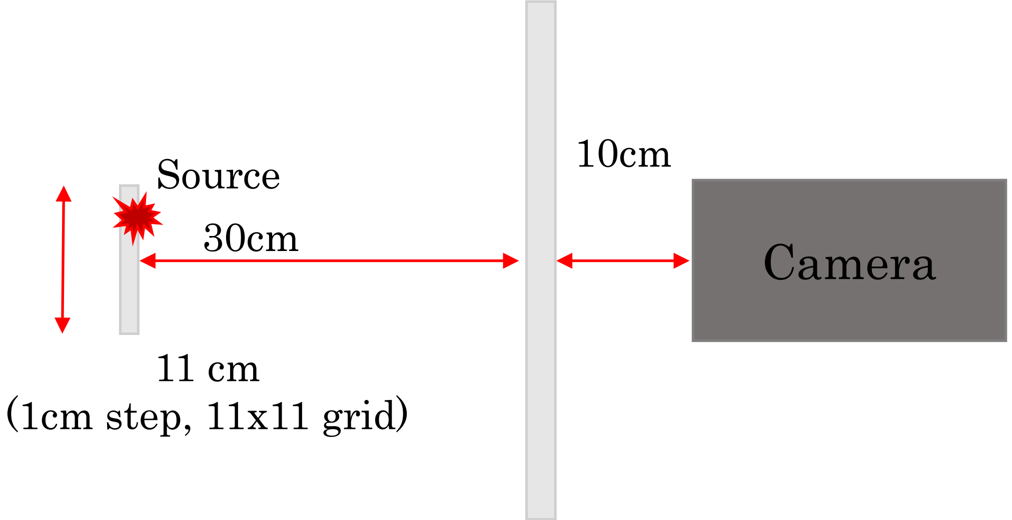
PSF – experimental measurements



- 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



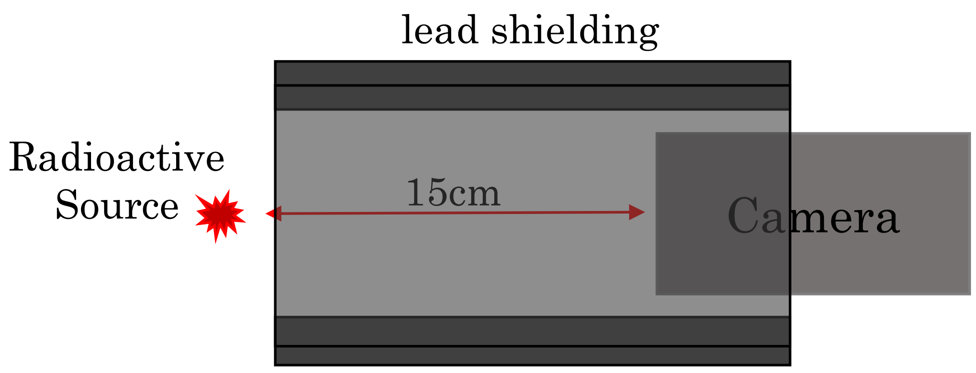


For ^{60}Co in the central position PSF ~ (4±2.5) mrad

Results in agreement with MC simulations

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
- No mask was used
- All 16 crystal signals summed together
- Radioactive sources with known activity placed at 15 cm distance for efficiency calibration
  - ^{241}Am, ^{57}Co, ^{137}Cs, ^{60}Co, ^{152}Eu and ^{22}Na

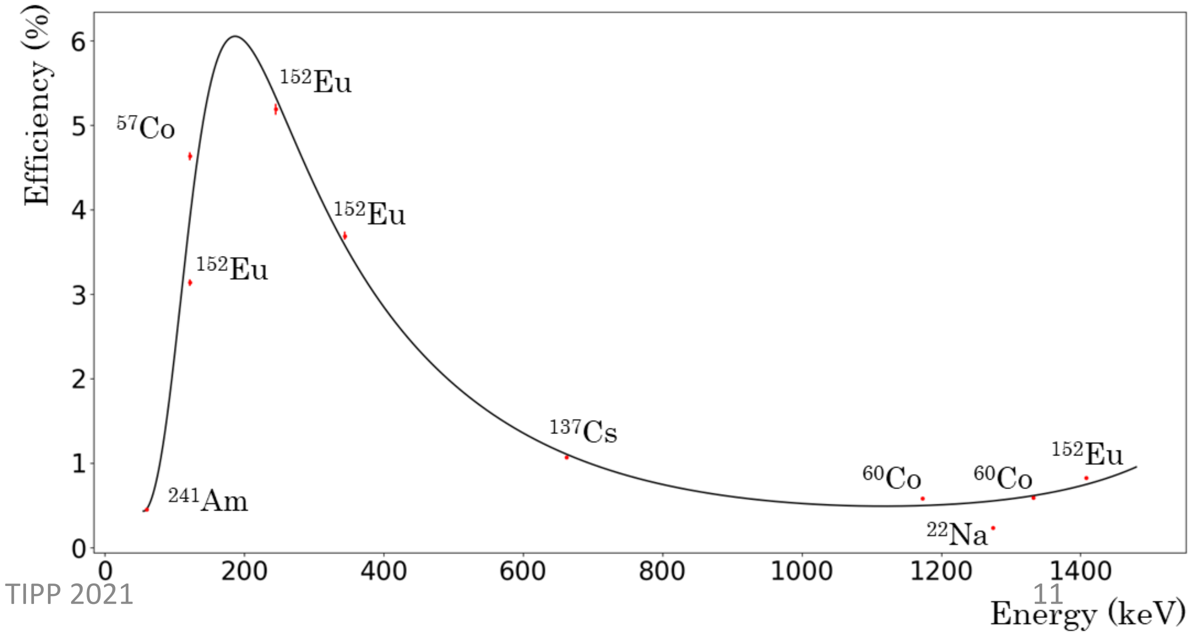


Minimum detectable activity (MDA)

- MDA is given by: $$MDA(Bq) = \frac{4.65 \times \sqrt{R_b(s^{-1}) \times t_m(s)} + 3}{t_m(s) \times \varepsilon \times b}$$

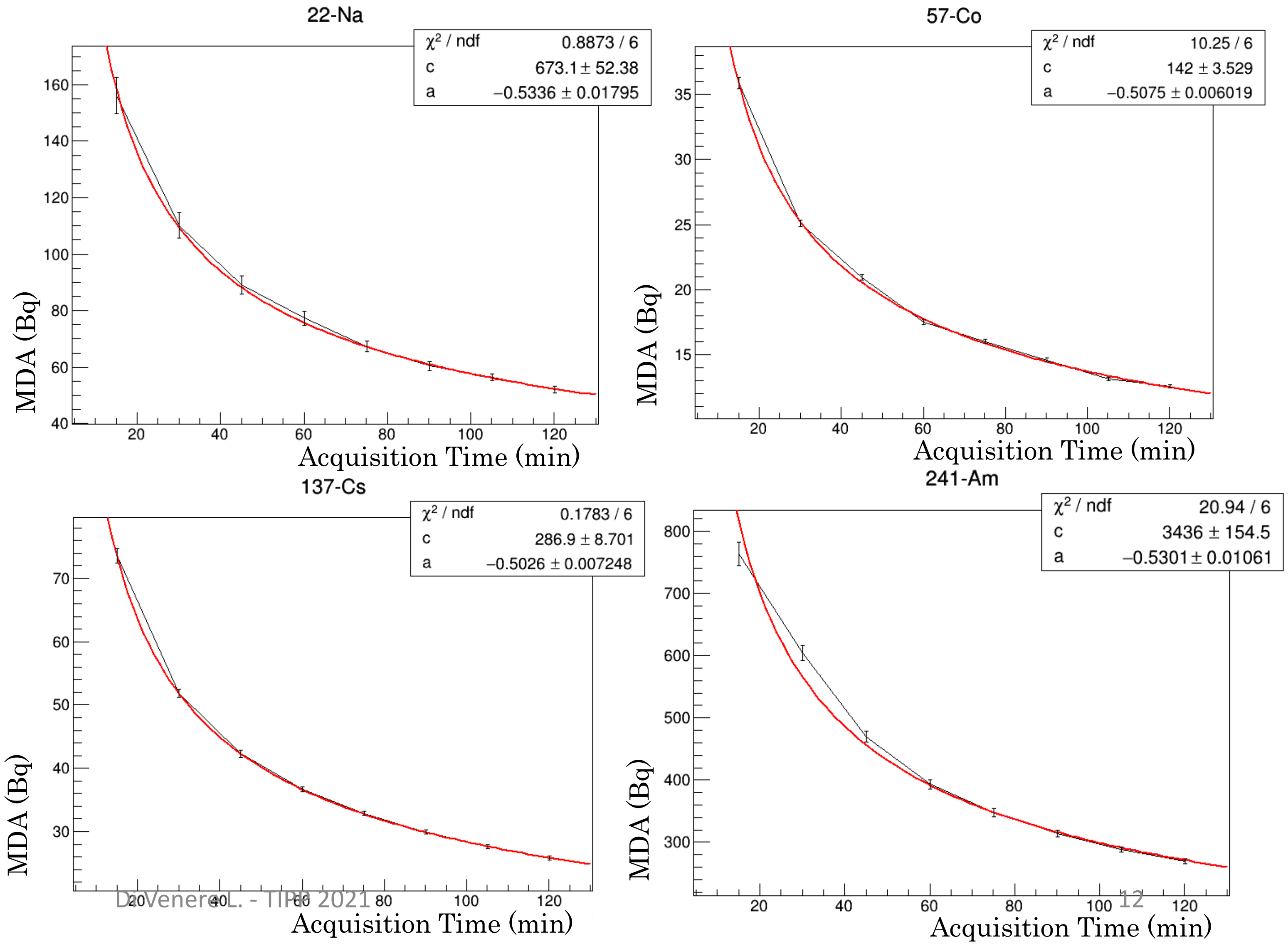
$R_b(s^{-1})$ → Background count rate
$t_m(s)$ → Source acquisition time
ε → Source detection efficiency
b → branching ratio

- Efficiency is measured as the ratio between detected and emitted photons



Minimum detectable activity (MDA)

- MDA was measured as a function of the acquisition time for four radionuclides: ^{241}Am, ^{57}Co, ^{137}Cs, ^{22}Na



Conclusions

- A gamma-ray detector with imaging capability developed
- Camera based on a CsI(Tl) crystal array coupled to PMTs and a coded mask reconstruction technique
- Position reconstruction measured at *mrad* levels
- Low MDA thanks to the large active volume
- Future improvements:
  - PMTs replaced with SiPMs to make the camera more compact
  - Improvement of camera geometry
  - Improvement of position reconstruction algorithms with machine learning techiques