Imaging of scintillation light with Coded Aperture masks

An update on Project PRIN2022KJZSYB

L. Basiricò[1], V. Cicero[2], E. Colantoni[1],
L. Martina[3], N. Mauri[1], V. Pia[2], N. Tosi[2]

[1] Università di Bologna
[2] INFN sezione di Bologna
[3] Università del Salento

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Scintillation imaging

In most experiments **scintillation light** is collected without optical elements to form **images**

This project aims to develop a "**camera**" consisting of **SiPM matrices** paired to **Coded Aperture masks** to perform **particle tracking** in homogeneous volumes of scintillators, using only the signal of scintillation light

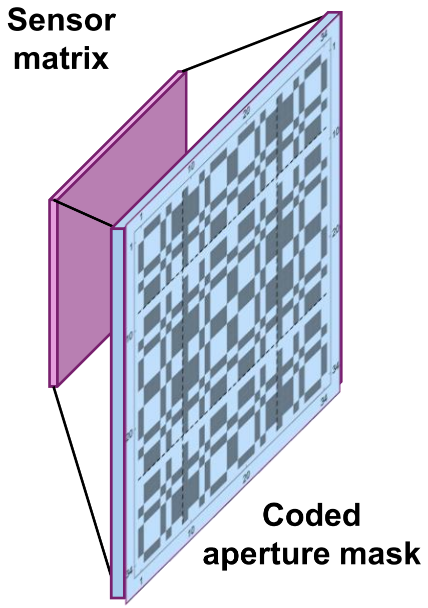
This tenchnique can be particularly suitable with LAr and LXe as a medium:

- ☑ High photon yield per unit energy and per unit length
- ☑ Fast prompt emission
- ☑ Cryogenic operation negates SiPM noise
- ⚠ Spectrum is peaked in the VUV →

need optics not affected by wavelength
→ Coded Aperture masks
Many R&D efforts focused on improving VUV sensitivity

Coded Aperture imaging

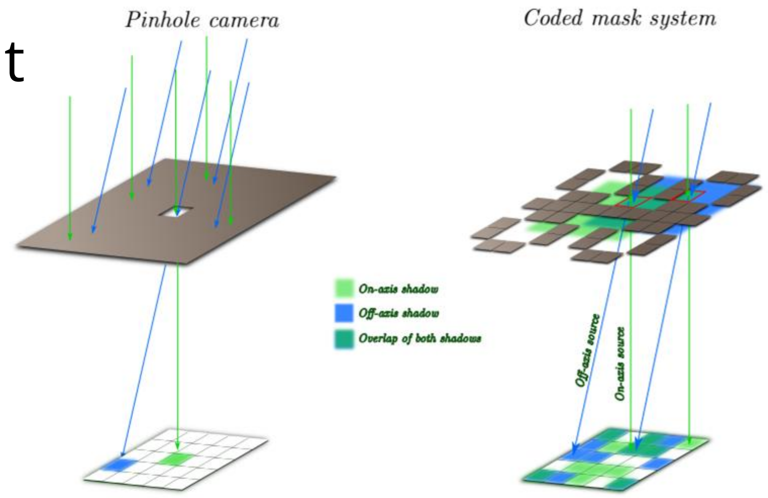
A **Coded Aperture (CA) mask** is a sheet of opaque material with a grid of holes placed at a fixed distance in front of an array of photon sensors.



Evolution of a *pinhole camera*:

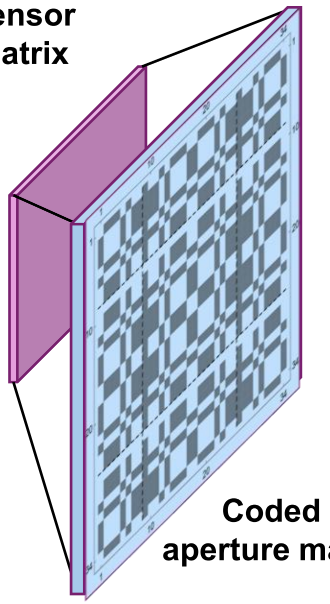
- A matrix of multiple holes improves light collection
- Light transmission depends only on hole/surface area
- The image formed on the sensor is the superimposition of multiple pinhole images

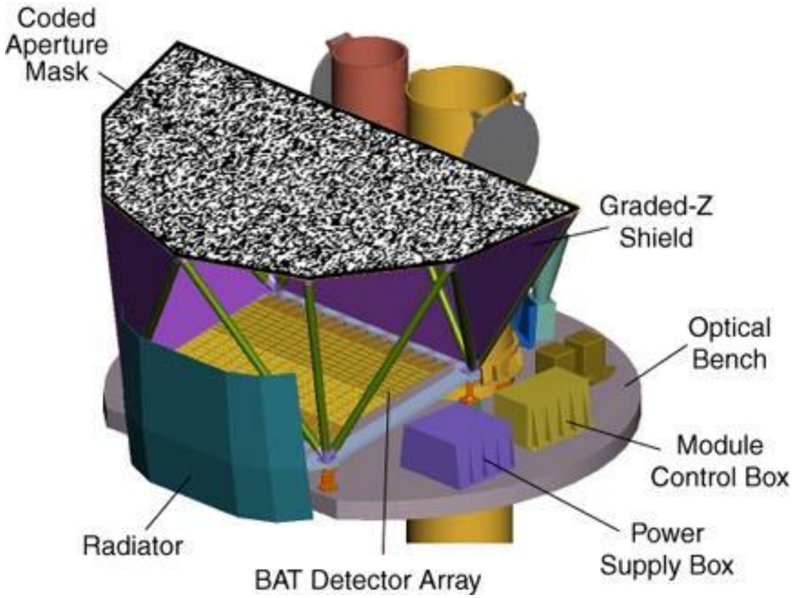
- Depending on the recostruction technique the mask pattern may matter



Coded Aperture imaging

A **Coded Aperture mask** is a sheet of opaque material with a grid of holes placed at a fixed distance in front of the sensor plane.

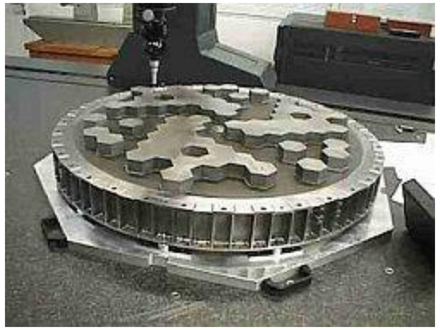




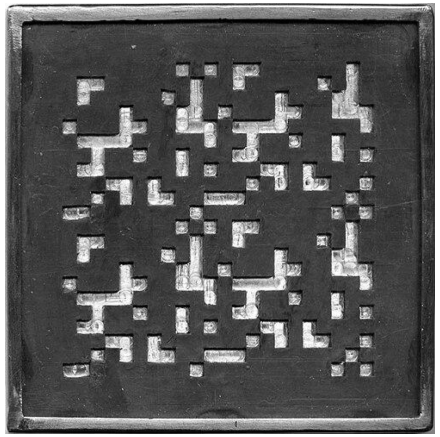
Burst Alert Telescope
(Swift Gamma-Ray Burst Mission)

Technique developed for X and γ rays:

- Cannot be refracted or reflected
- Used in astrophysics and medical imaging



SPI mask (INTEGRAL)



Reconstruction techniques

For **FAR field** imaging (e.g. in Astrophysics):

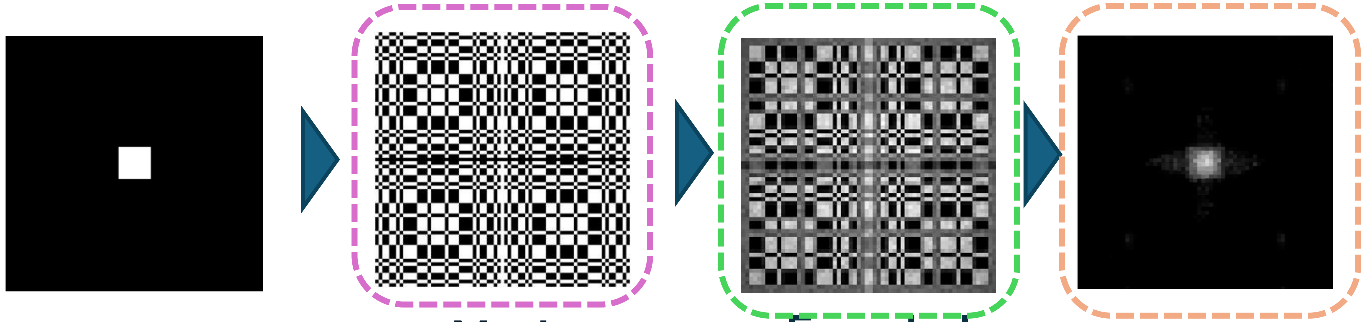
- the original image is obtained with a **deconvolution** process where the decoding matrix is derived from the mask pattern [2]
- Different mask patterns exhibit different image resolutions, sensitivities and background-noise rejection.

$$O'(x,y) = I\,(x,y) \otimes H\,(x,y)$$

reconstructed image — detected image — decoding matrix

$$M(x,y) \otimes H(x,y) = \delta(x,y)$$

mask



Source — Mask — Encoded image — Reconstructed image

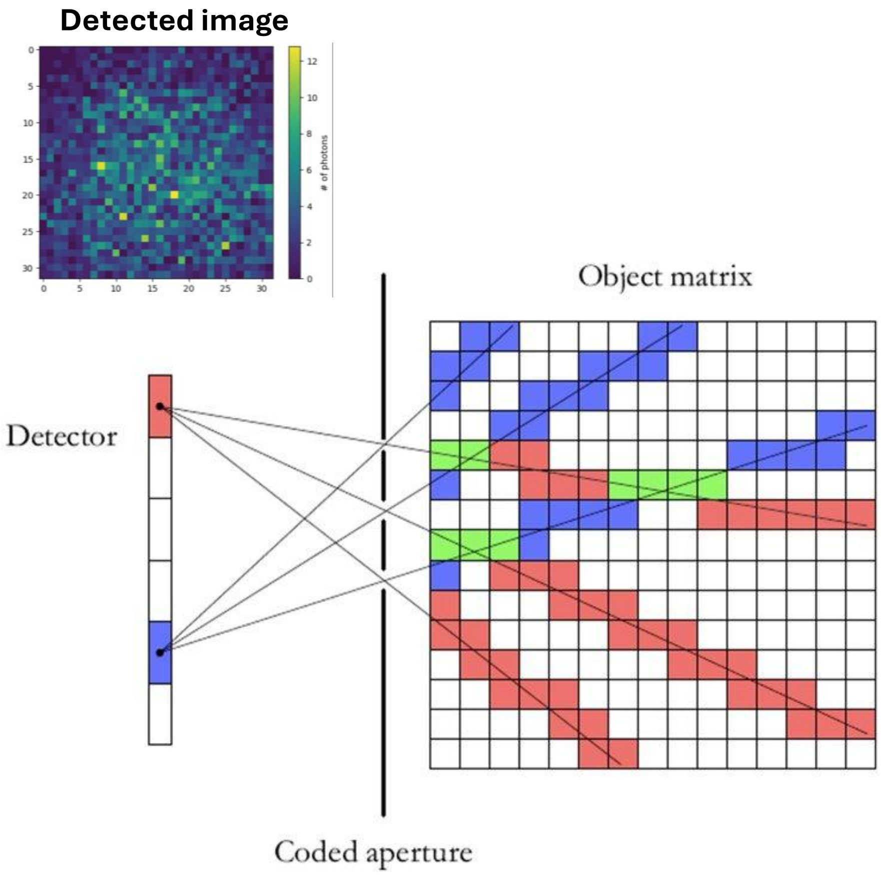
In **NEAR field** imaging more complex and computationally intensive algorithms are typically implemented

- Filtered back-projection, Maximum Likelihood Expectation Maximization…

ML-EM reconstruction algorithm

Directly reconstructs in 3D the initial photon source distribution in a segmented volume (voxels)

- measured photons from all cameras are propagated back into the fiducial volume with an appropriate **weight**, which is added to the voxel value
- this weight represents the **Bayesian probability** of the voxel to be a source of the detected photons
- the likelihood of the resulting photon source distribution having produced the raw data is maximized through an iterative process



ML-EM algorithm

Photon counting is described by a Poissonian pdf:

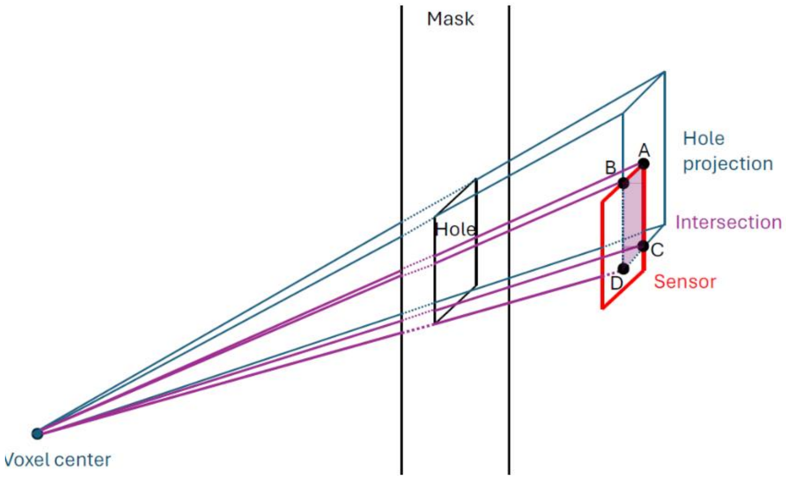
$$f(H_s \mid [\lambda_s]) = e^{-[\lambda_s]} \frac{[\lambda_s]^{H_s}}{H_s!}$$

H_s number of photons detected on sensor *s*
$[\lambda_s]$ expectation value of the detected photons

$$[\lambda_s] = \sum_j \lambda_j w(j,s)$$

λ_j (unknown) photon emission in voxel *j*
w(j,s) probability for a photon with origin in voxel j to be detected by sensor s

The weights describe detector geometry, the photon propagation in the medium and detection process



*w (j,s) = P geometry (j,s) * P mat (j,s) * P sensor (s)*

- P geometry (j,s): Solid angle subtendend by sensor area visible through mask holes
- P mat (j,s): Photon absorbption in the material + scattering
- P sensor (s): SiPM PDE

the weights can be precomputed for a detector geometry

ML-EM algorithm

The likelihood for all sensors is maximized iteratively [3]

$$\prod_s e^{-[\lambda s]} \frac{[\lambda_s]^{H_s}}{H_s!} \quad \longrightarrow \quad \lambda_j^{k+1} = \lambda_j^k \cdot \sum_s \frac{H_s \cdot w(j,s)}{\sum_j w(j,s) \cdot \lambda_j^k}$$

k iteration number

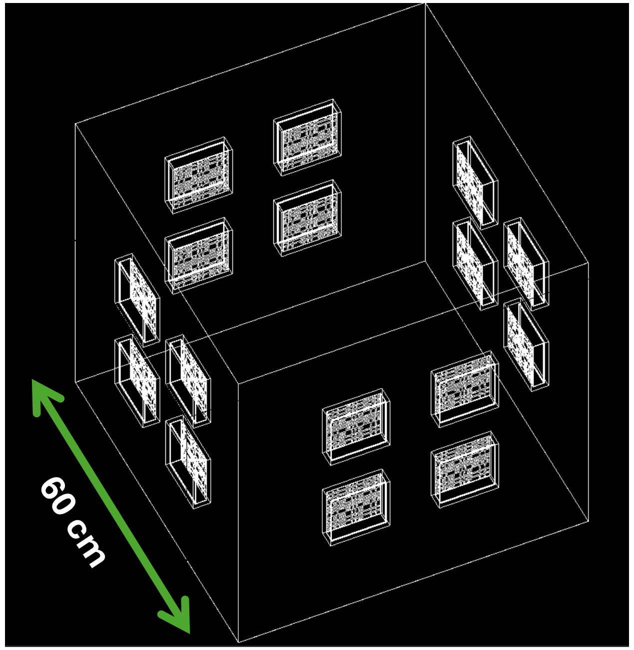
- The starting voxel distribution λ^0 can include prior information on the event otherwise is assumed to be uniform
- At every iteration $\sum_j \lambda_j$ is conserved

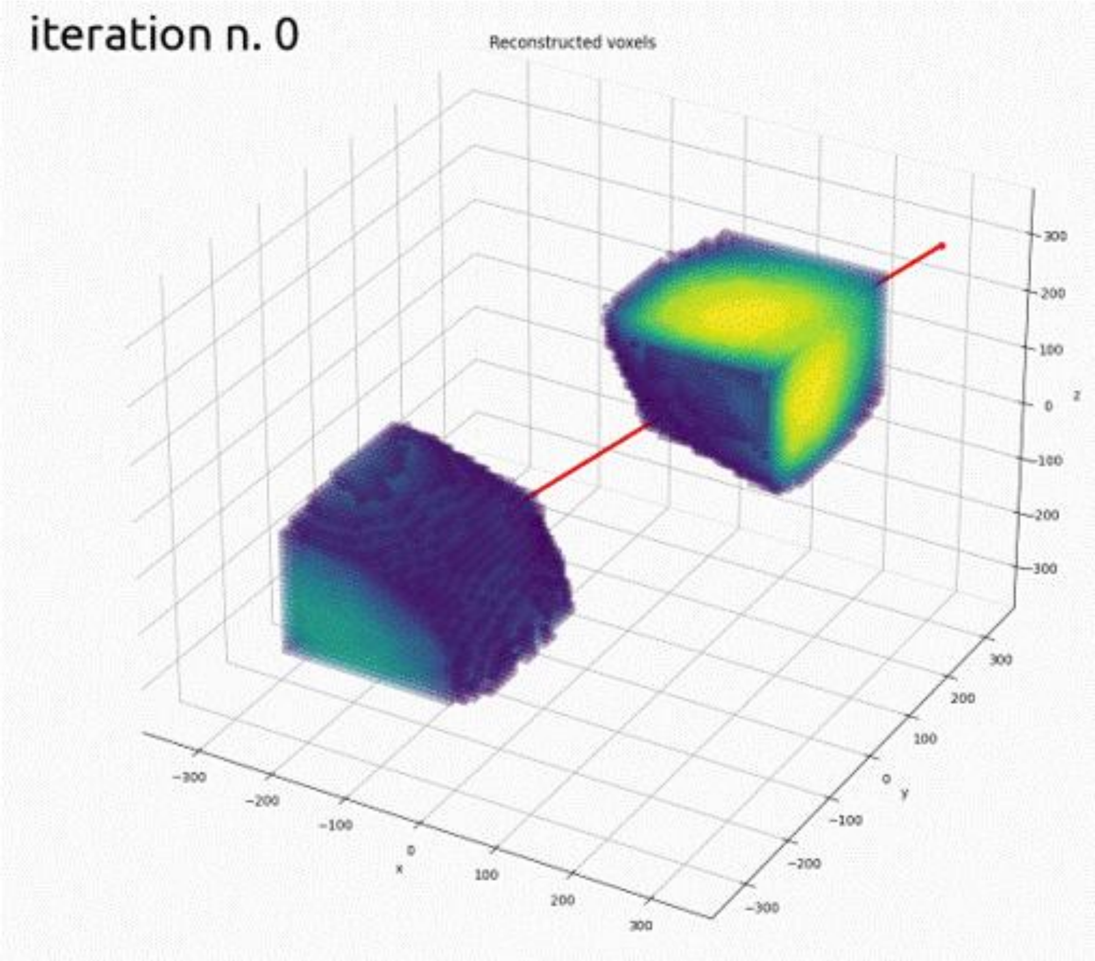
Computationally intensive algorithm → parallel impementation on GPU

ML-EM in action

Simulated 0.33 t LAr volume

- 16 x 1024 channel cameras
- 3x3 mm^2 SiPM with TPB (PDE 20%)
- 1 GeV muon track





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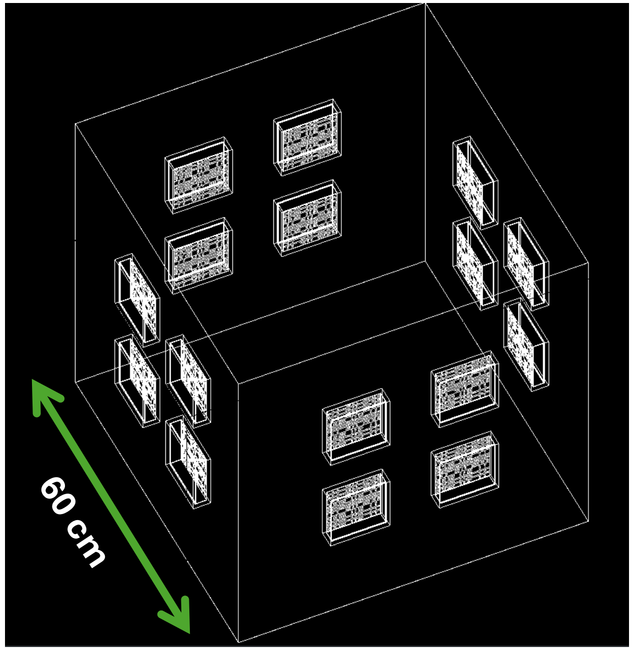

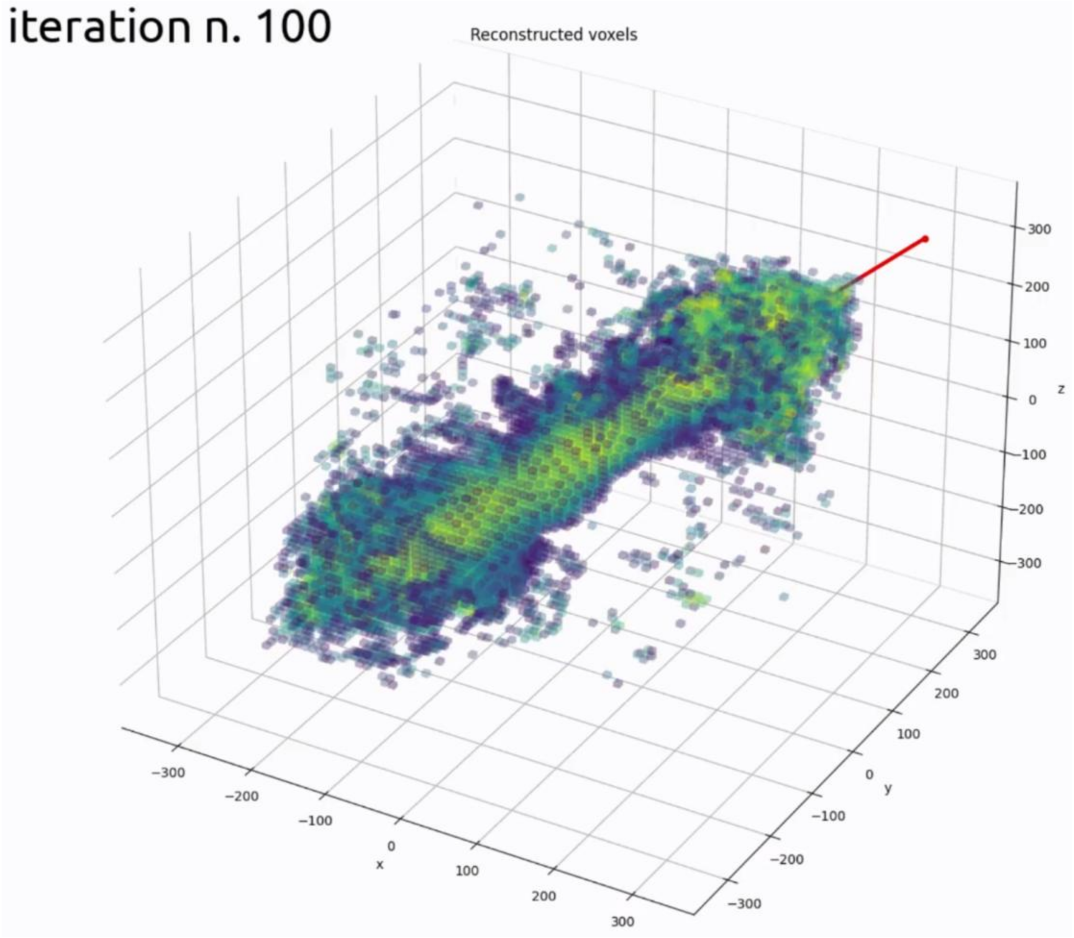

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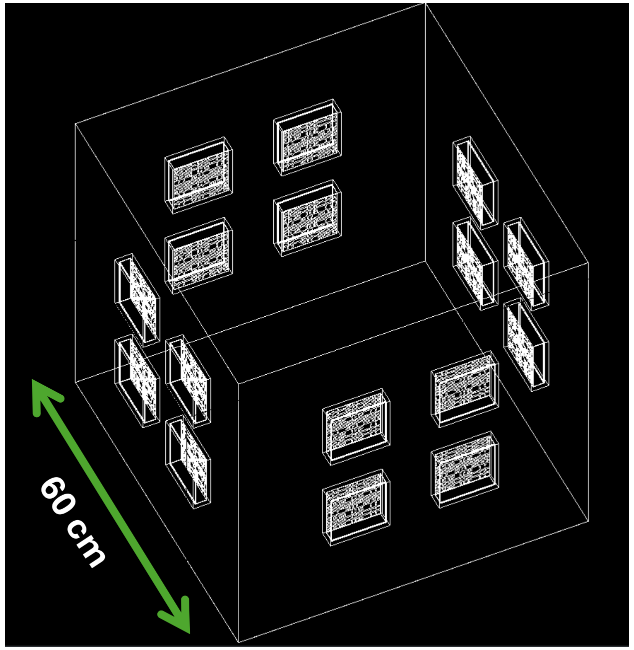
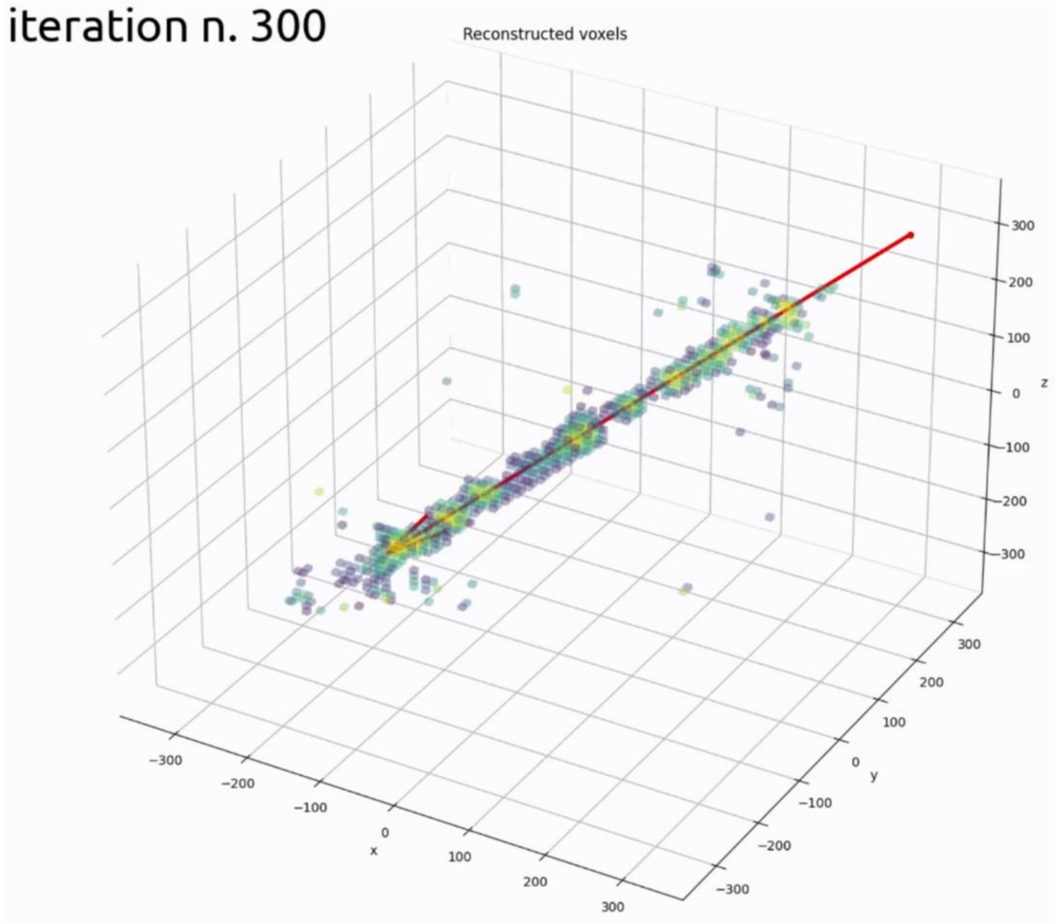




Applications

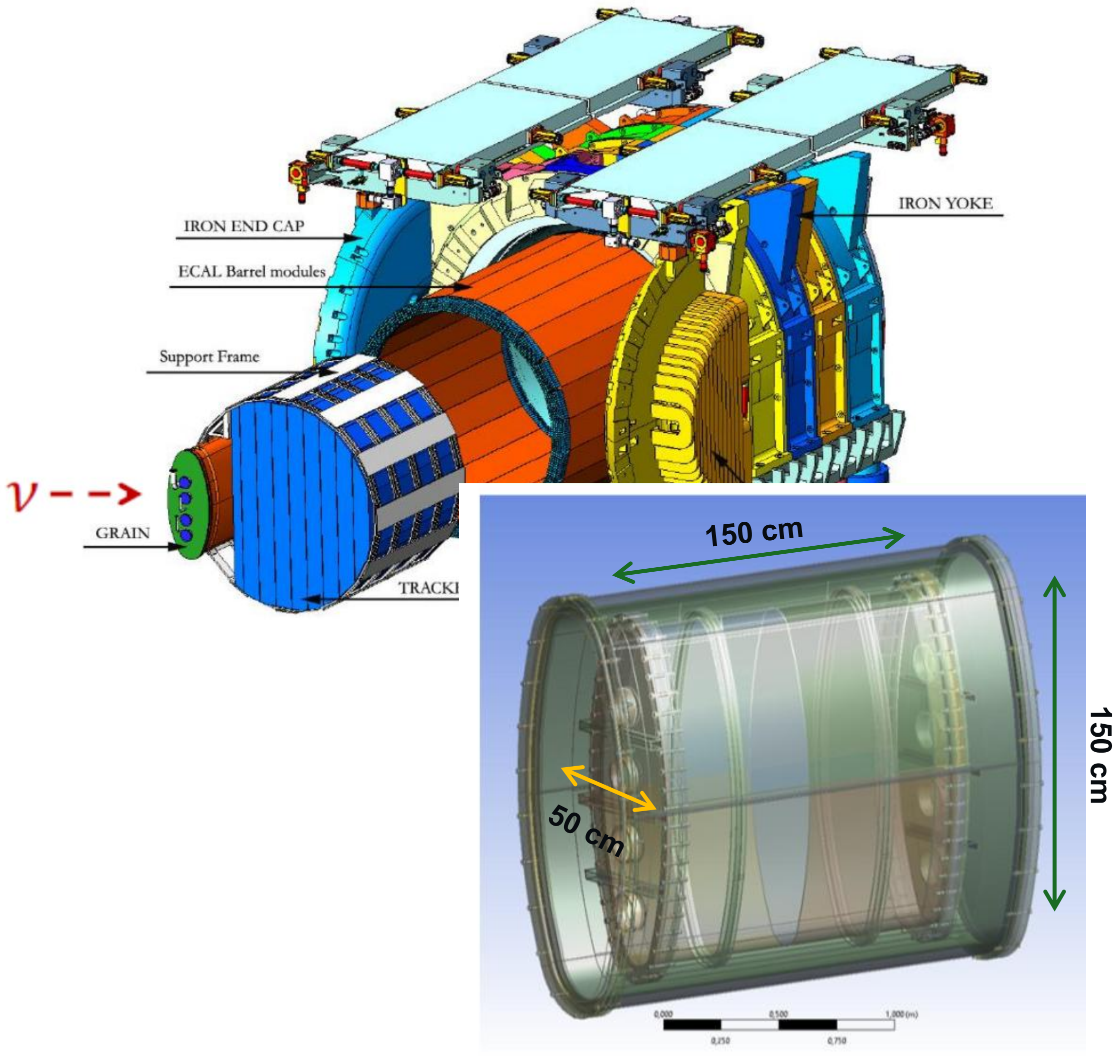
A Coded Aperture Imaging system can be an alternative approach to TPCs (or a complimentary one) :

- 3D tracking with 2D projections, from the periphery
- Good scaling to large volumes. Channel count only grows with $size^2$
- Only scintillator in the active volume, no passive material
- Drift time vs light propagation → a different compromised between rate and resolution
- No HV, no field cage, potentially more robust in operation

Potential applications:

- Neutrino physics
- Readout of LAr based "tracking" calorimeters, including proposed LAr PETs
- Direct coupling to solid scintillators for high resolution calorimetry

GRAIN detector

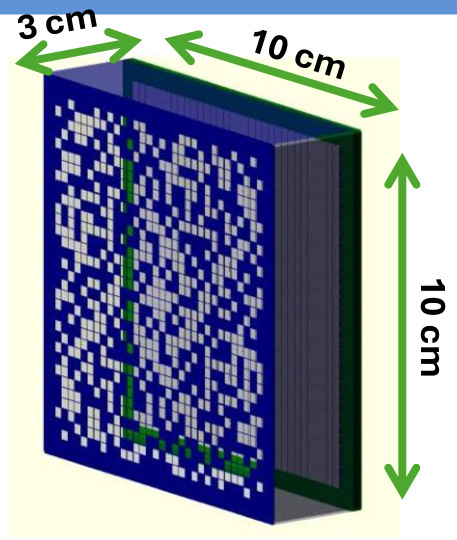


- A **1-ton LAr target** in a “thin” cryostat in the upstream magnetized volume of the **SAND** detector of DUNE Near Detector [3]
  - Optical readout for rate
  - Several tracks per 10μs spill

- Main motivations:
  - constrain nuclear effects on Ar
  - Perform cross-calibration with other detectors of the DUNE ND.

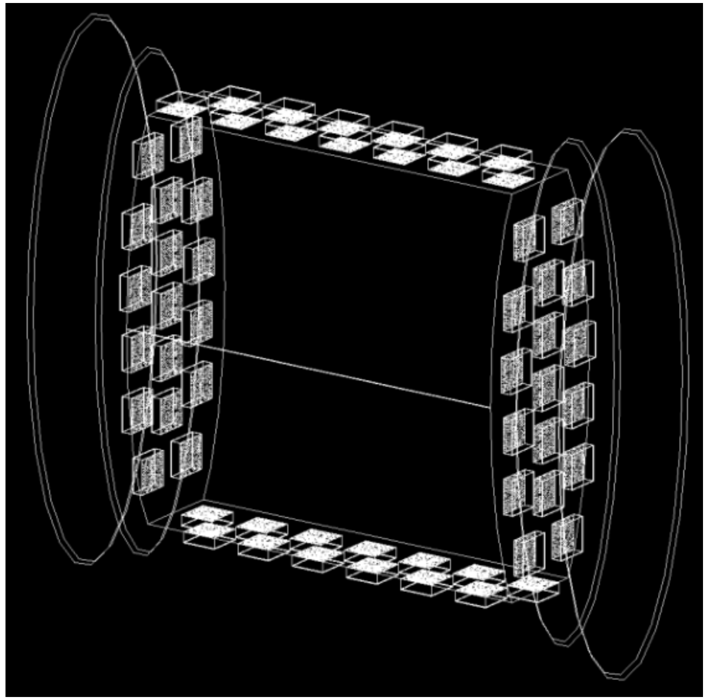
GRAIN CA imaging system

[4]

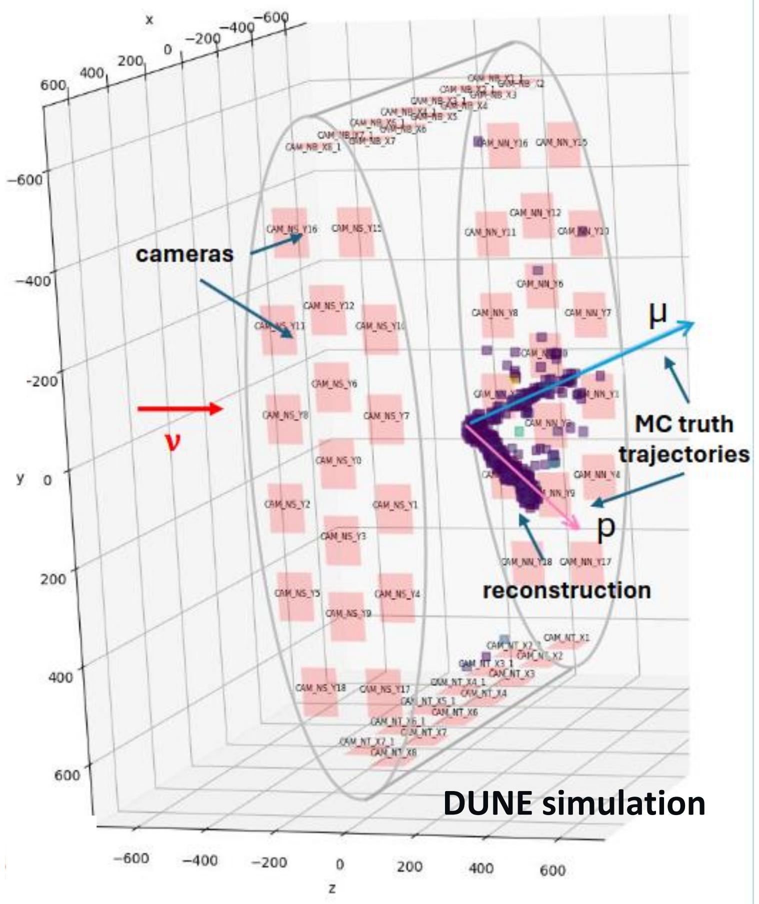


One of the proposed methods for readout

60 cameras in GRAIN



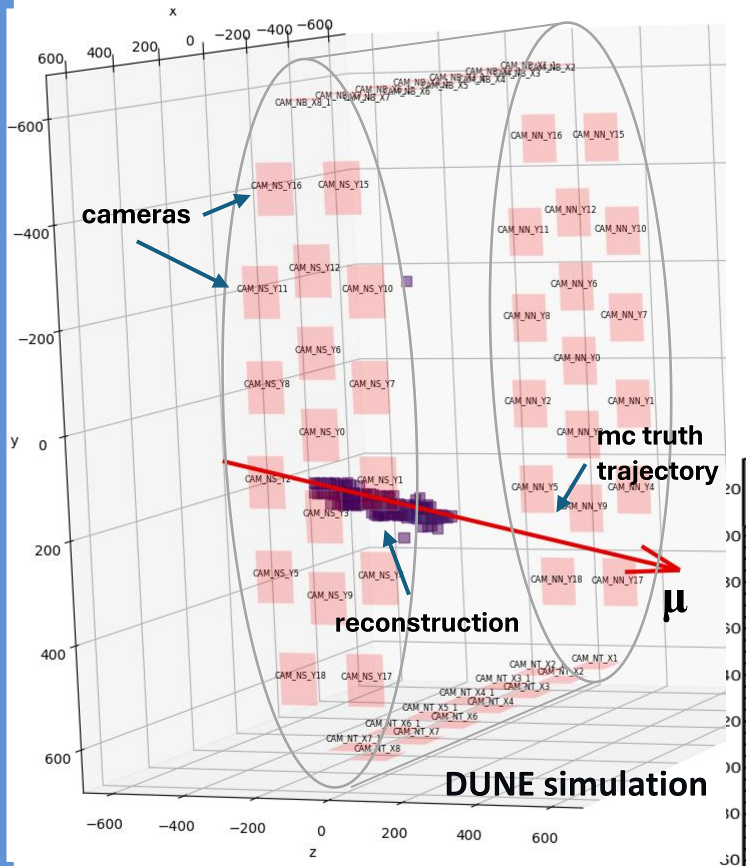
Reconstruction of a ν – Ar CCQE event



1024 pixel camera:

- 3x3 mm^2 SiPM
- Mask with 50% filled area
- Holes aligned to sensors with random uniform distribution
- LAr flows through the holes, filling the camera inner volume

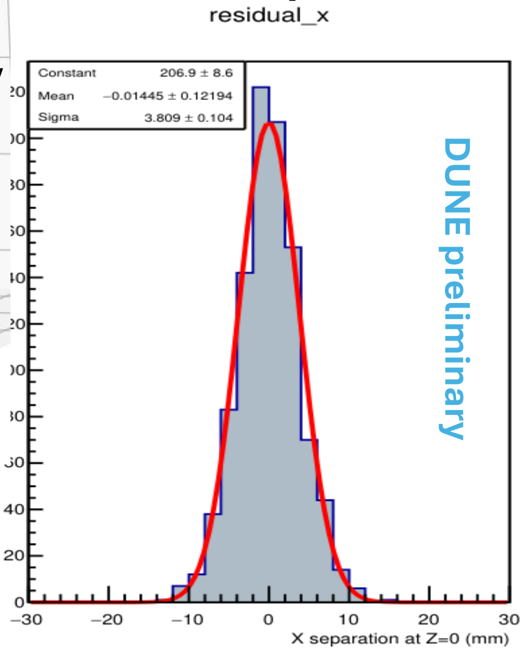
Track reconstruction in GRAIN

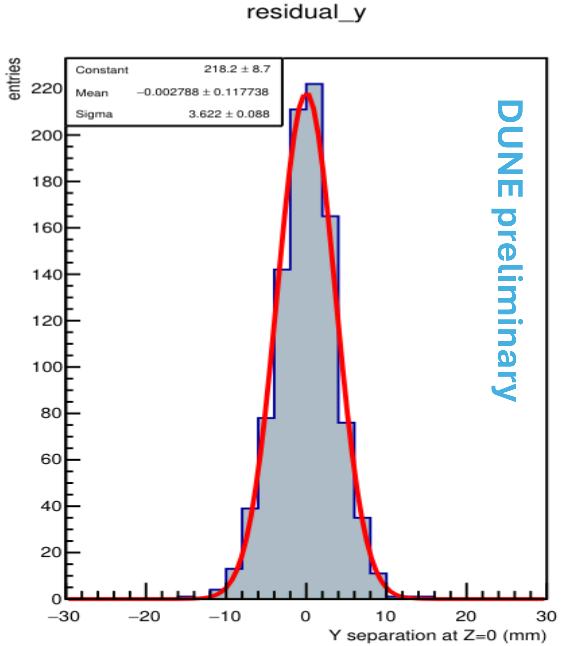


1000 **muons** in GRAIN

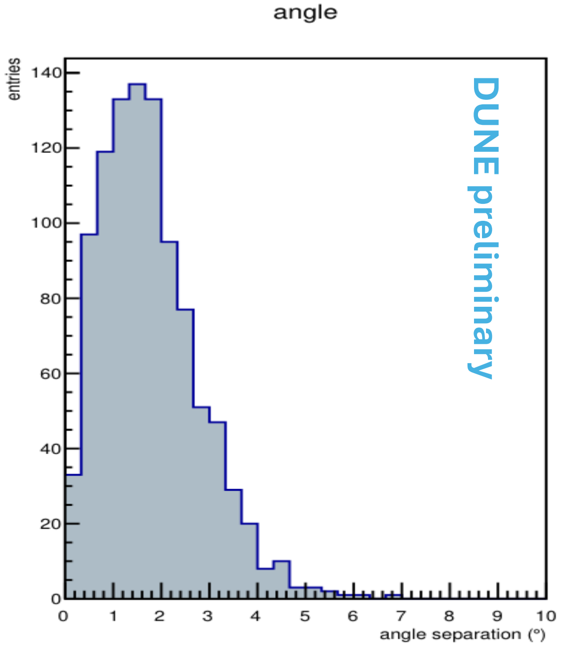
- E =1 ± 0.3 GeV
- Reconstruction with 18 mm voxel size
- 200 algorithm iterations

Track position at z=0 residual distribution



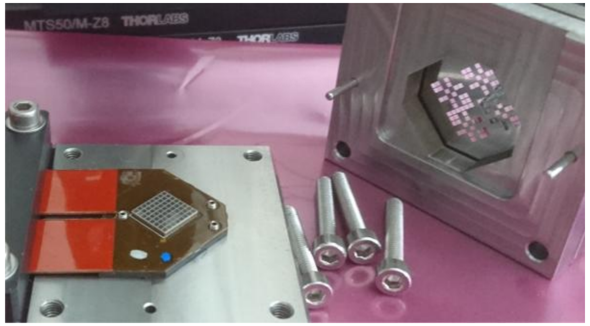


Angle separation

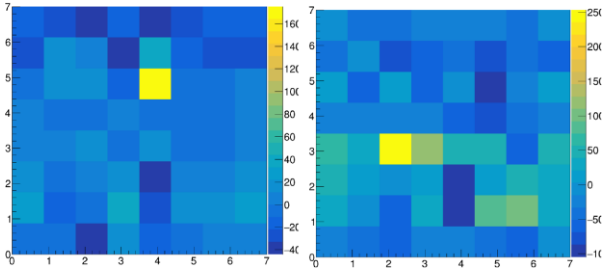


Camera prototypes

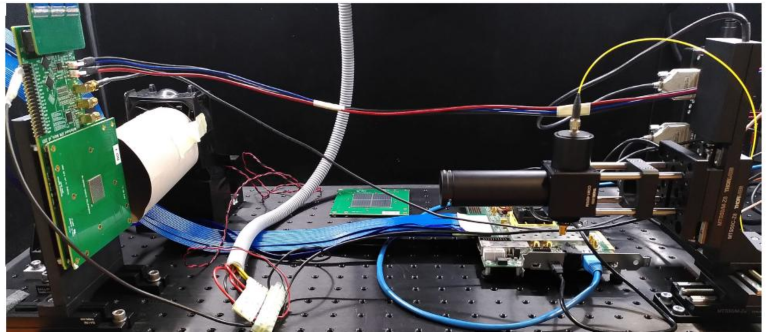
- early "warm" demonstrator with 64 pixels

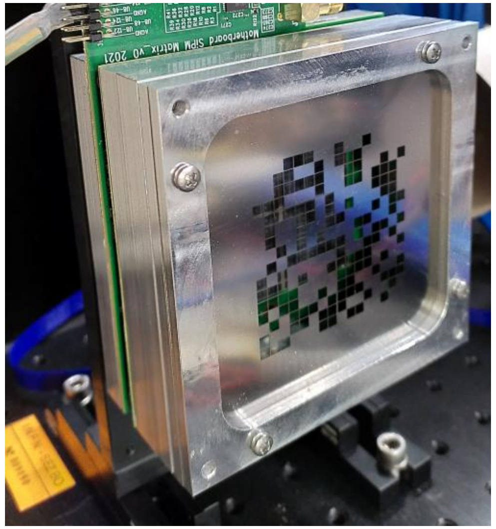


- 1x1 mm^2 SiPM
- warm electronics (TRIROC ASIC)
- achieved reconstruction of point sources



- "cold" demonstrator with 265 pixels
  - 3x3 mm^2 SiPM
  - Front-end board with cryogenic ASIC ALCOR (8 x 32 channels)
  - Calibration and testing is in progress

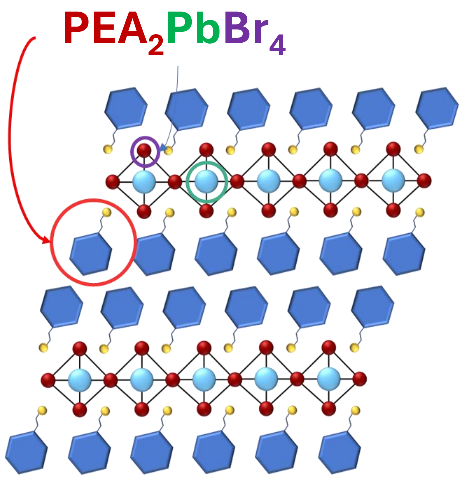




R&D for VUV sensitivity : WLS

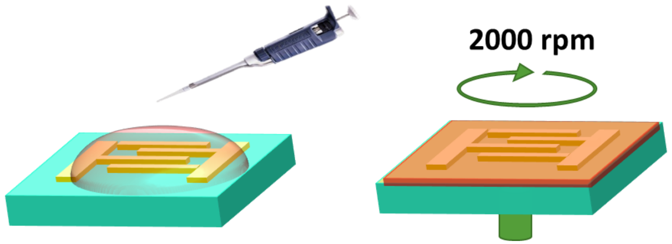
Wavelength shifter-based solutions

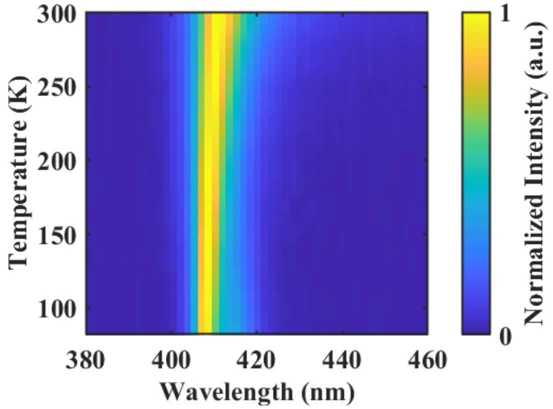
- SiPM matrices coated with TPB are considered as baseline
- **Perovskite**-based WLS materials are being investigated :

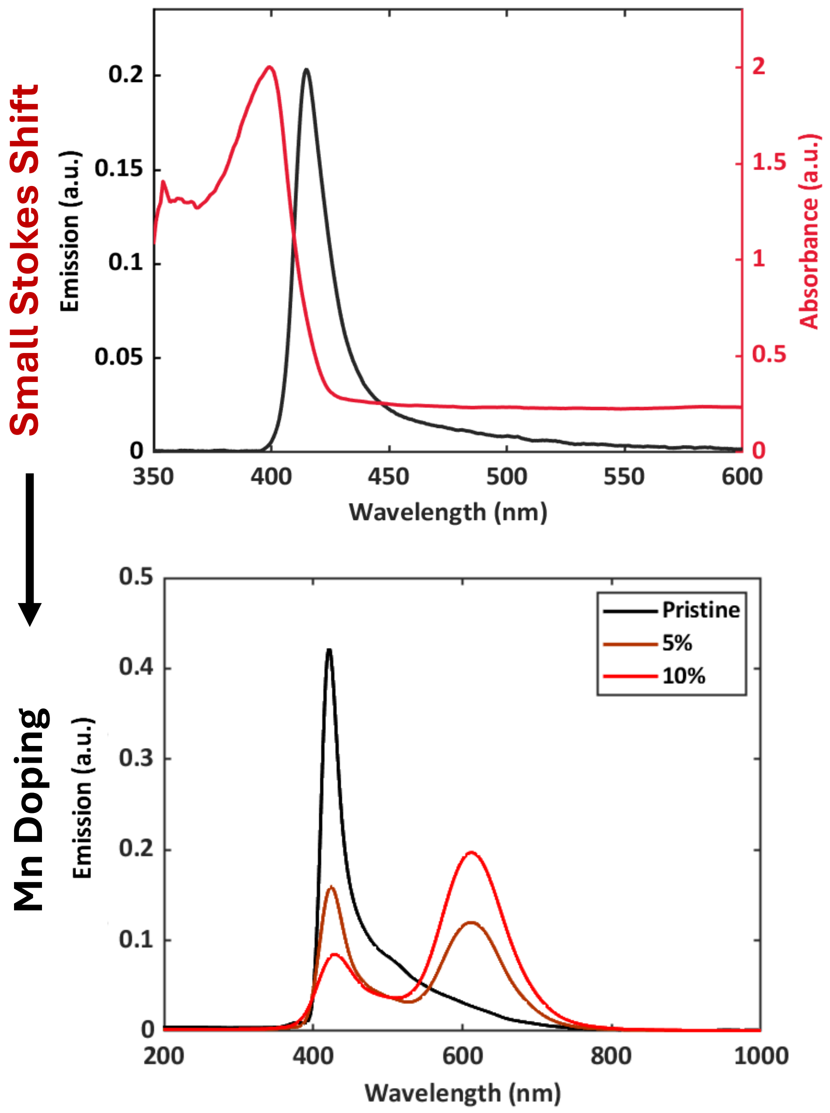


2D Lead Halide Perovskite:
Mn Doped PEA_2PbBr_4

- Large area coverage and uniformity
- Processed by liquid phase (spin coating, bar coating)
- Good stability in temperature







Outlook and Acknowledgements

- Scintillation imaging with Coded Aperture cameras shows promise in simulation, with prototypes nearing completion
- Reaching maturity for application in GRAIN, part of the Near Detector complex of the DUNE experiment, is presently our main goal
- Additional applications are undergoing early studies

- Funding for this work was provided in part by PRIN 2022KJZSYB
  - Early work on scintillation imaging was funded by PRIN 2017KC8WMB, now concluded
  - A parallel effort, PRIN 2022M7RRKK, is exploring gas-filled lenses as an optical system

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References

[1] Andreotti, M., et al. (NU@FNAL). "Coded masks for imaging of neutrino events", Eur. Phys. J. C 81 (2021) 1011. doi:10.1140/epjc/196 s10052-021-09798-y.

[2] Vardi, Y., L. A. Shepp, and L. Kaufman. (1985). “A Statistical Model for Positron Emission Tomography.” *Journal of the American Statistical Association* 80 (389): 8–20. doi:10.1080/01621459.1985.10477119.

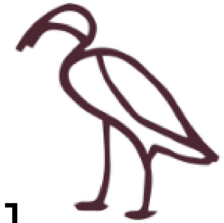
[3] A. Abed Abud et al. "DUNE Near Detector Conceptual Design Report" https://arxiv.org/abs/2103.13910

[4] V. Cicero. "Imaging neutrino interactions with liquid Argon scintillation light at the DUNE near detector complex", *Nuclear Instruments and Methods in Physics Research A* 1080 (2025) 170801. doi: 10.1016/j.nima.2025.170801

[5] A. Gola. "FBK roadmap towards the next-generation of 3D-integrated SiPM and SPAD technologies"(2024) talk at 6th International Workshop on Photon Detectors https://indico.cern.ch/event/1404192/contributions/6112094/

Backup slides

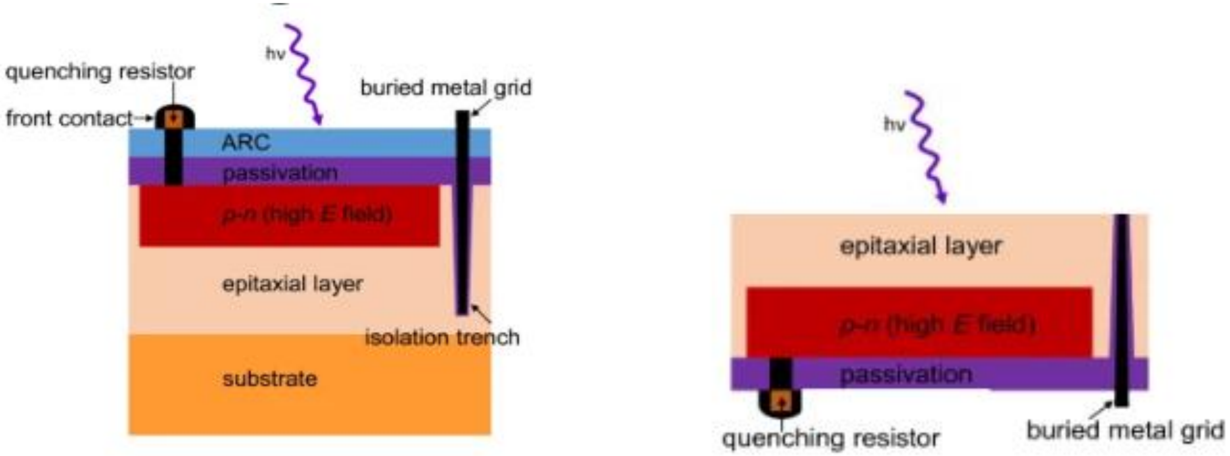
R&D for VUV sensitivity : SiPM



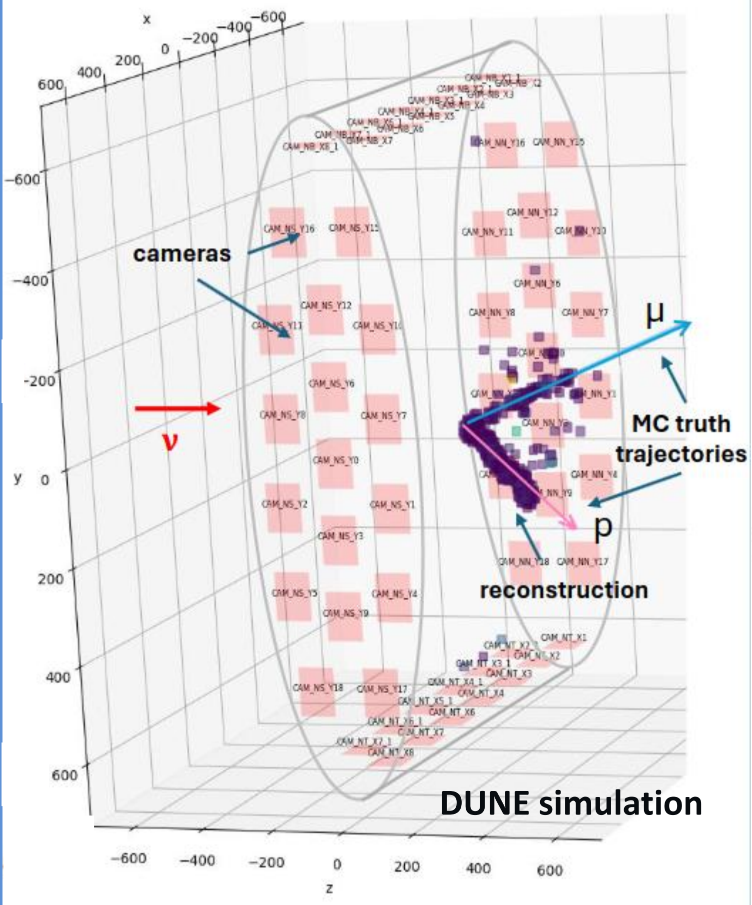
Innovative Backside Illumitaded Single-Photon detector (IBIS)

- An upside-down SiPM, with the substrate removed, developed with **FBK** [5]
- Clean, flat entrance window, suitable for advanced processing to enhance VUV efficiency → **Higher PDE**
- Back contact allows high density wafer-level bonding to a readout ASIC

  → more, smaller pixels for **better resolution**, without sacrificing Fill Factor



Track reconstruction in GRAIN



4000 ***ν* – Ar** Charged Current Quasi-Elastic scattering

- Reconstruction with 18 mm voxel size
- 200 algorithm iterations

Iteraction vertex position residual distribution [4]