Scintillation Imaging with Coded Aperture Masks

A Report on Project PRIN2022KJZSYB

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LIDINE 2024

Finanziato dall'Unione europea
NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

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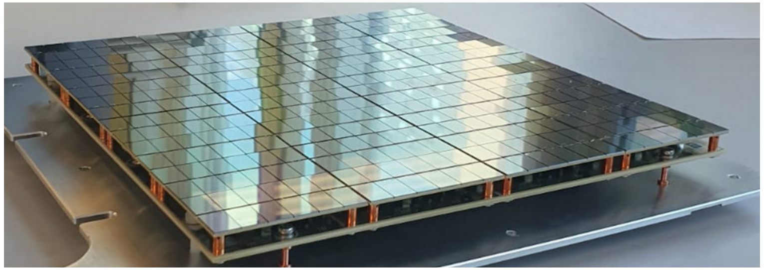
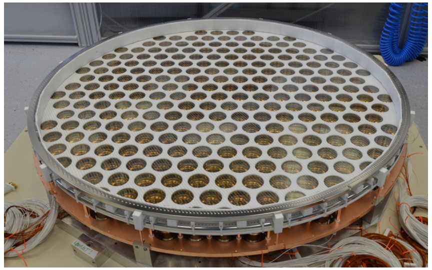
Scintillation without imaging

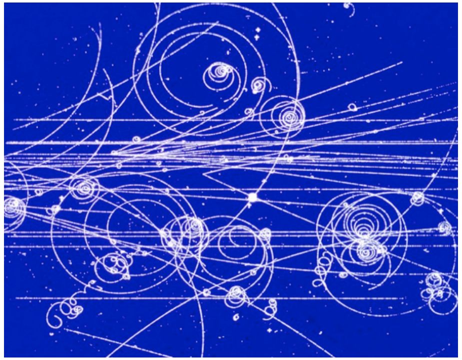
- In the vast majority of scintillation detectors, light is collected *without* optical elements capable of forming *images*

- Many experiments only use the amplitude and/or the timing of the scintillation signal. None *takes pictures* of the tracks.*

*Several other prototypes and proposals exist, see for example [1], [2]. Also, one could argue Cherenkov detectors take pictures of tracks via the rings.

Scintillation without imaging



- **Why is scintillation imaging not used?**
  - Taking pictures (of bubbles) is how we started...
  - However, with scintillation *"light is not enough"*

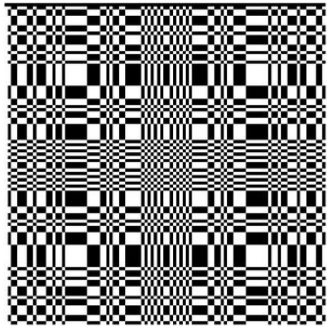
- **Technological developments are now challenging this assumption:**
  - More efficient, large area SiPMs detect more light on a broader spectrum
  - More advanced ASICs enable higher channel densities
  - More computing power allows for more complex reconstruction algorithms

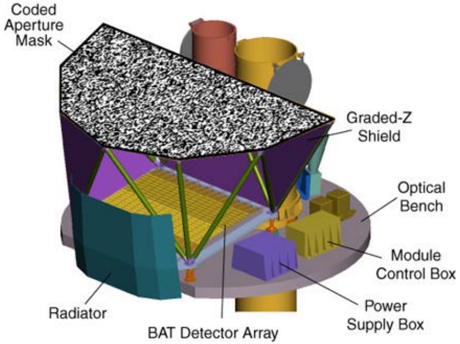
Scintillation imaging – the case for liquid Argon

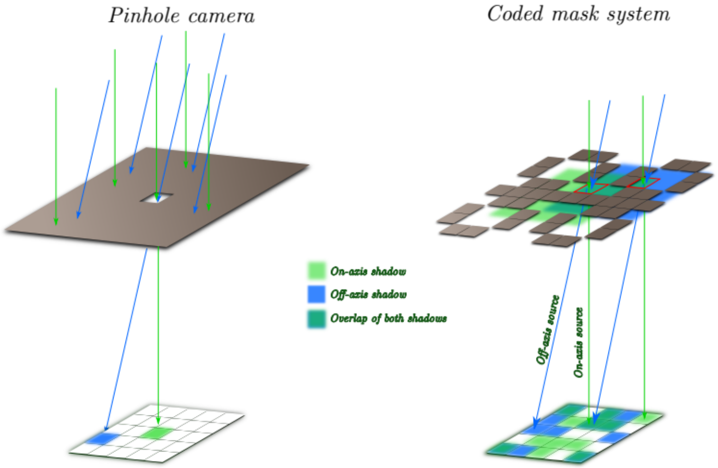
- High photon yield per unit energy and especially per unit length
- Cryogenic operation is challenging, but negates SiPM noise
- VUV spectrum is a problem for optics and sensors
  - Coded aperture imaging ignores wavelength
  - Many R&D efforts focused on improved VUV sensitivity

What is coded aperture imaging?

- A technique developed for X and γ photons
  - These cannot be refracted or reflected
  - in astrophysics and in medical imaging







- An extension of the pinhole camera which captures more light

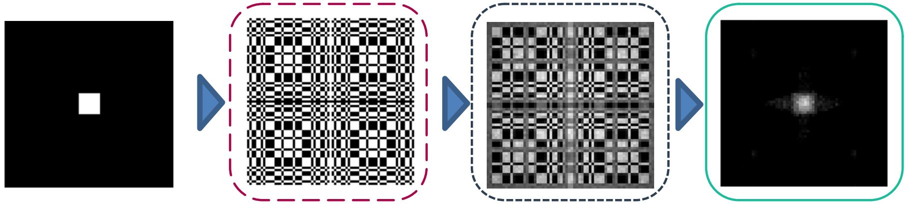
Reconstruction Algorithms

- For *far* field imaging (i.e. astrophysics):
  - the original image can be obtained with a deconvolution process where the decoding matrix is derived from the mask pattern. The pattern matters here.

$$\overset{\text{Reconstructed Image}}{\boxed{O'(x,y)}} = \overset{\text{Raw Image}}{\boxed{I(x,y)}} \otimes H(x,y)$$

Where H is the “inverse” of M, such that

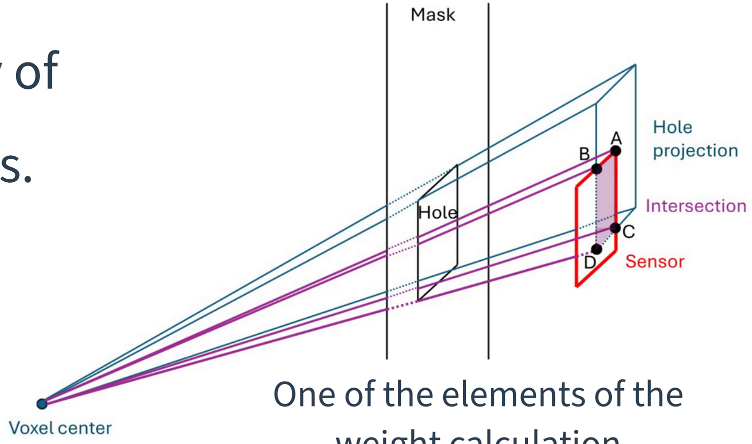
$$\text{Mask} \quad \boxed{M(x,y)} \otimes H(x,y) = \delta(x,y)$$


Source Mask Raw Image Reconstructed Image

- For *near* field imaging:
  - more complex and computationally intensive algorithms can be implemented: Filtered Back Projection, Maximum Likelihood Expectation Maximization. Pattern can be random.

Maximum Likelihood Expectation Maximization (MLEM)

- Directly reconstructs in 3D the initial *photon source distribution* in a segmented volume (voxel array):
  - *measured photons* from all cameras are *propagated back* into the LAr 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.



One of the elements of the weight calculation

MLEM in numbers

- **Photon counting is described by a Poissonian pdf:**

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

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

H_s	is the number of photons detected on sensor *s* (raw data)
λ_i	is the (unknown) photon source value in voxel *j*
$[\lambda_s]$	is the expectation value of the detected photons
$w(j,s)$	is the weight (a very large precalculated matrix)

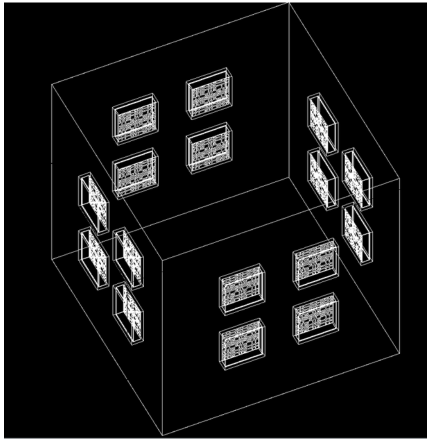
- **The likelyhood for all sensors must be maximized (iteratively) [3]**

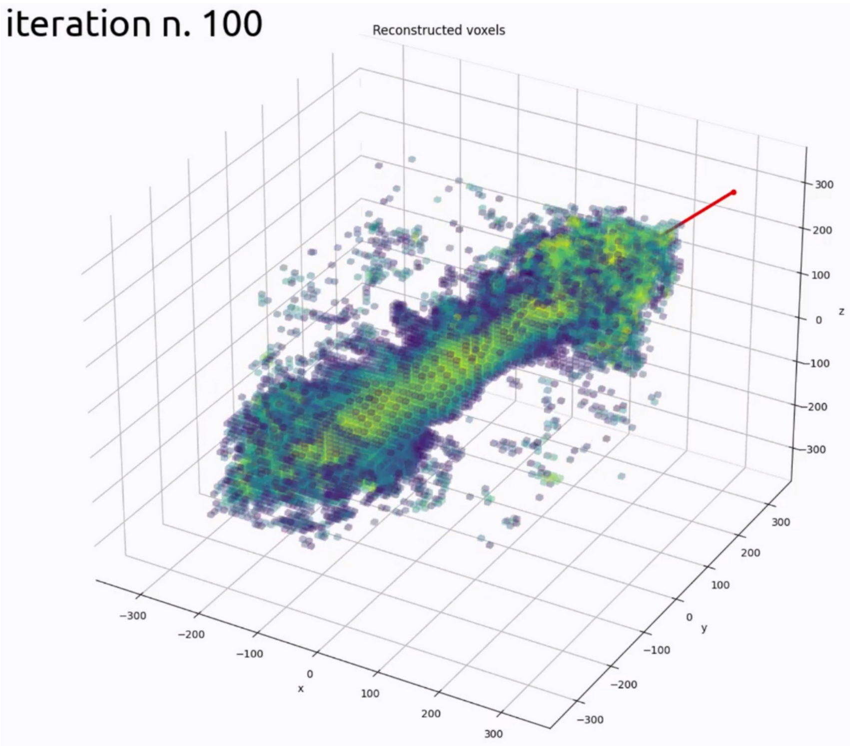
$$\prod_s e^{-[\lambda s]}\frac{[\lambda_s]^{H_s}}{H_s!}$$

$$\lambda_j^{k+1}=\frac{\lambda_j^k}{\sum_s w(j,s)}\cdot\sum_s\frac{H_s\cdot w(j,s)}{\sum_j w(j,s)\cdot\lambda_j^k}$$

MLEM in action

- **Simulated 0.33 t LAr volume**
  - 16 x 1024 channel cameras
  - 3x3 mm SiPM with TPB





Images courtesy V. Cicero

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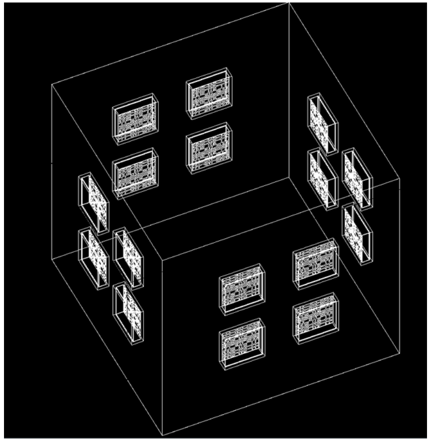
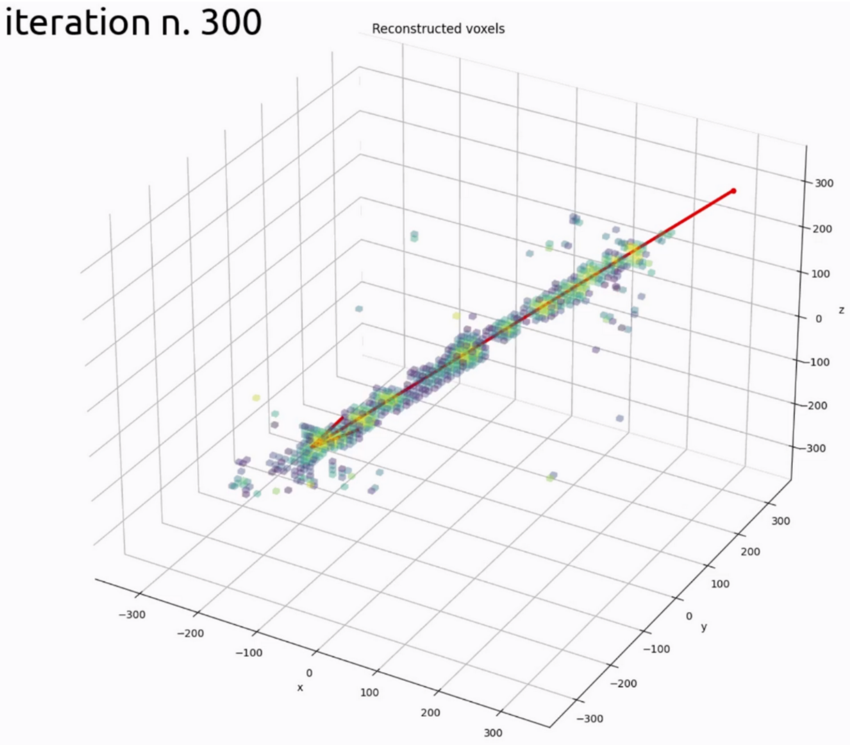




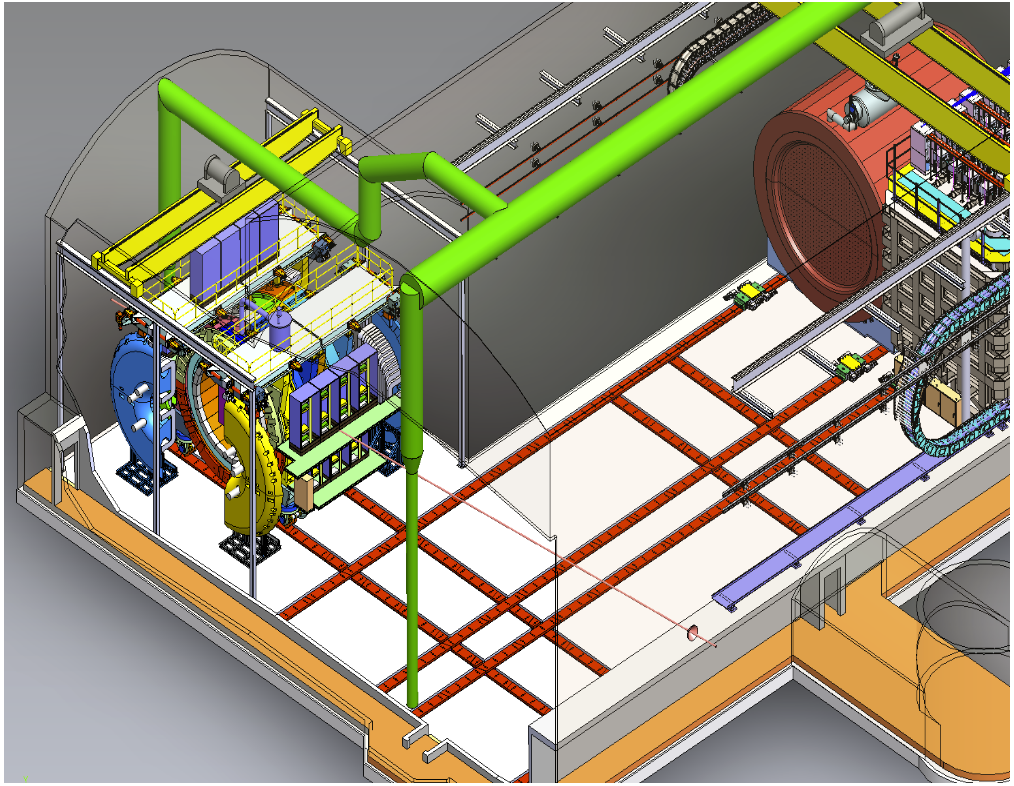
Images courtesy V. Cicero

Applications of scintillation light imaging

- **Achieving 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

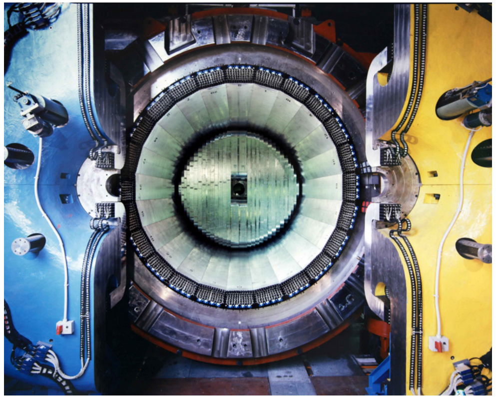
- **This could also be said of a TPC, where is the advantage then?**
  - ~µs vs ~ms. A different compromise between rate and resolution
  - No HV, no field cage, potentially somewhat more robust in operation.

A real use case in the DUNE Experiment

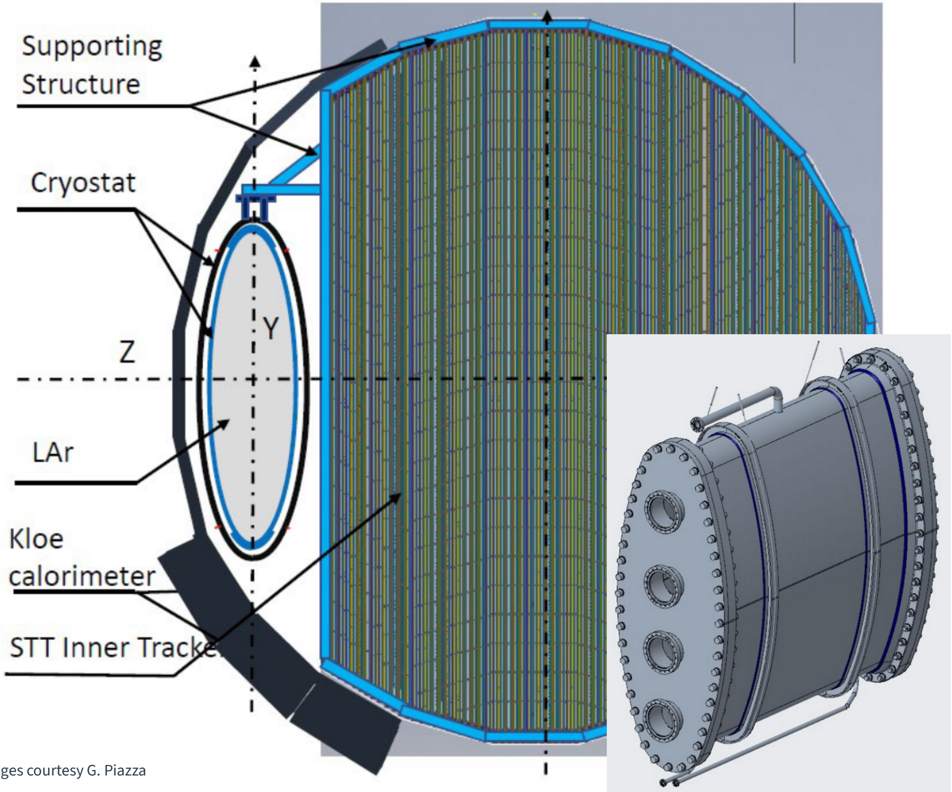


SAND is one of the three elements of the DUNE Near Detector complex [4]

- Re-use of the *KLOE* magnet and ECAL
- New gas Target Tracker and LAr “active target”



GRAIN, the Active Argon Target in SAND

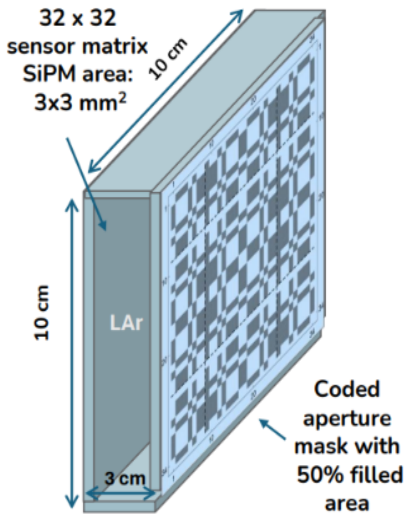


Images courtesy G. Piazza

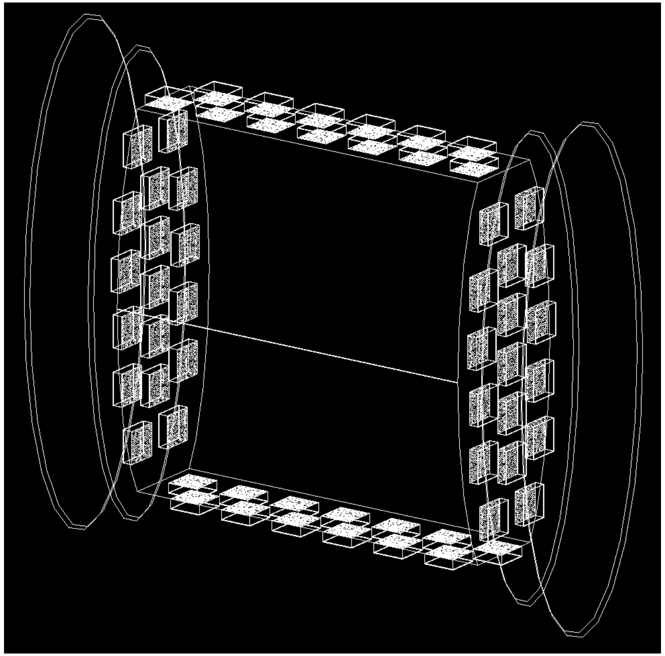
- **A 1-ton target in a “thin” cryostat**
  - Optical readout for rate
  - Several tracks/spill
- **Main motivations:**
  - constrain nuclear effects on Ar
  - have a complementary (to ND-LAr) target permanently located on-axis for cross-calibration

GRAIN read out with Coded Aperture cameras

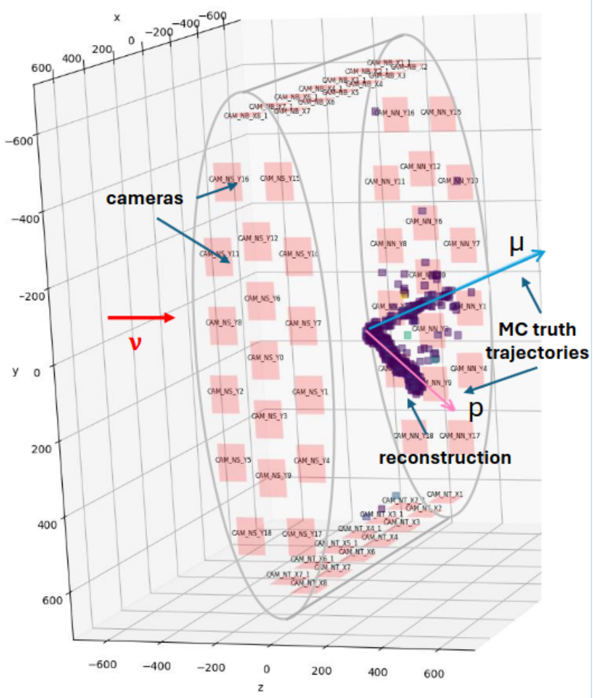
1024 pixel camera



60 cameras in GRAIN



MLEM reconstruction of ν_μ-CC event



Images courtesy V. Cicero

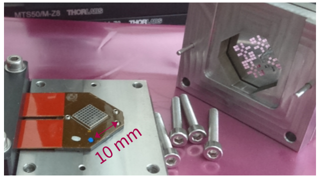
Other potential applications

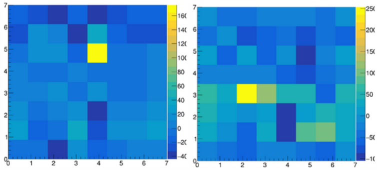
- **Coded aperture cameras can be used for near field imaging with compact (flat) detectors in fields other than neutrino physics**
  - Direct coupling to solid scintillators for high resolution calorimetry
  - Readout of LAr based “tracking” calorimeters, including proposed LAr PETs

- **Coded aperture cameras can still be coupled with charge readout**
  - Enhance the rate capability of TPCs, aid in event reconstruction
  - The mask does not have to be passive

Related developments: SiPM matrix readout systems

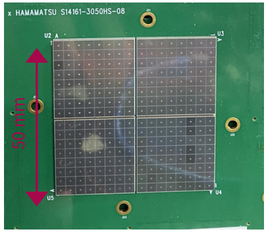
- **Readout systems of increasing performance have been developed:**
  - Early warm demonstrator, 64 channels, 1x1 mm SiPMs, warm ASIC (TRIROC)

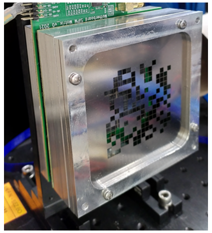


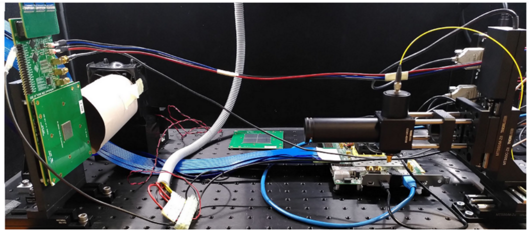


- could reconstruct point sources

  - Cold demonstrator: 256 channels, 3x3 mm SiPMs, 8 x cryo ASIC (ALCOR)







- laser calibration in progress

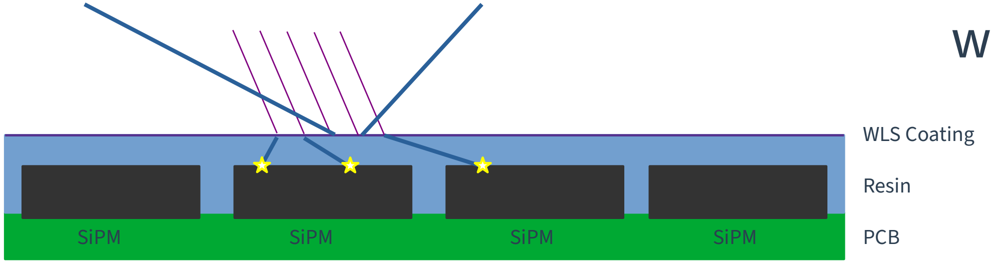
  - Future development: a 1024 channel cryo ASIC for GRAIN

Related developments: VUV sensitivity

- **This project is investigating WLS based solutions for VUV sensitivity**
  - SiPM Matrices with coated with TPB are considered as baseline
  - Perovskite-based WLS materials are being investigated (sorry no results yet)

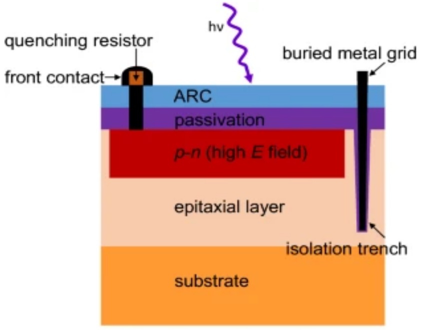
BUT

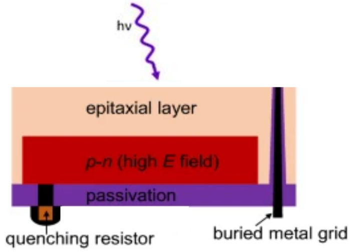
  - WLS coatings on the sensor do not re-emit all light in the “correct” direction which adds noise to the image data



Related developments: VUV sensitivity

- Innovative Backside Illuminated Single-photon detector (IBIS)
  - An upside-down SiPM,
    with the substrate removed,
    developed with FBK





  - Clean, flat entrance window, suitable for advanced processing to enhance VUV efficiency (decreased reflection/absorption) → Higher PDE
  - Back contact allow high density *wafer-level bonding* to a readout ASIC → more, smaller pixels for *better resolution*, without sacrificing Fill Factor

IBIS Project: multiple paths being worked on

- Redesigned SiPM cell
  - Optimized for backside illumination, blind at the top
  - Internal charge focusing effect

- Substrate removal
  - Grinding
  - Doping selective etching

- First samples being characterized now

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

Most funding for this work was provided 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

Bibliography

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