Scintillation Imaging in GRAIN Liquid Argon Detector

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LAr readout: state of the art

- The state of the art readout technique (*Time Projection Chamber*), pionered by ICARUS detector, uses both ionization charges and scintillation light produced by charged particles in LAr:

  - Ionization electrons are drifted in a uniform electric field to a segmented (wires or pads) anode, allowing the 2D reconstruction of the track
  - The drift time, calculated from the reference time of scintillation light, allows to reconstruct the third coordinate, knowing the drift velocity

- The LAr TPC is the technique with the best tracking capability but has some limitation:

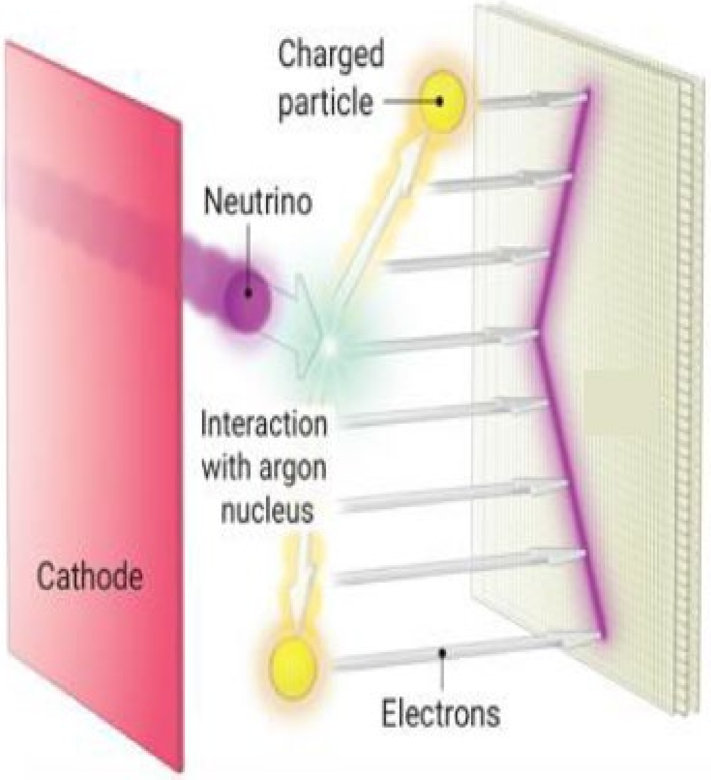
  - The rate capability is low due to a drift time O(msec)
  - High Voltage is needed for a uniform drift field in big volume

An innovative technique

- Scintillation of Argon produces about 40 ph / KeV for m.i.p. (1000 ph / 100um):

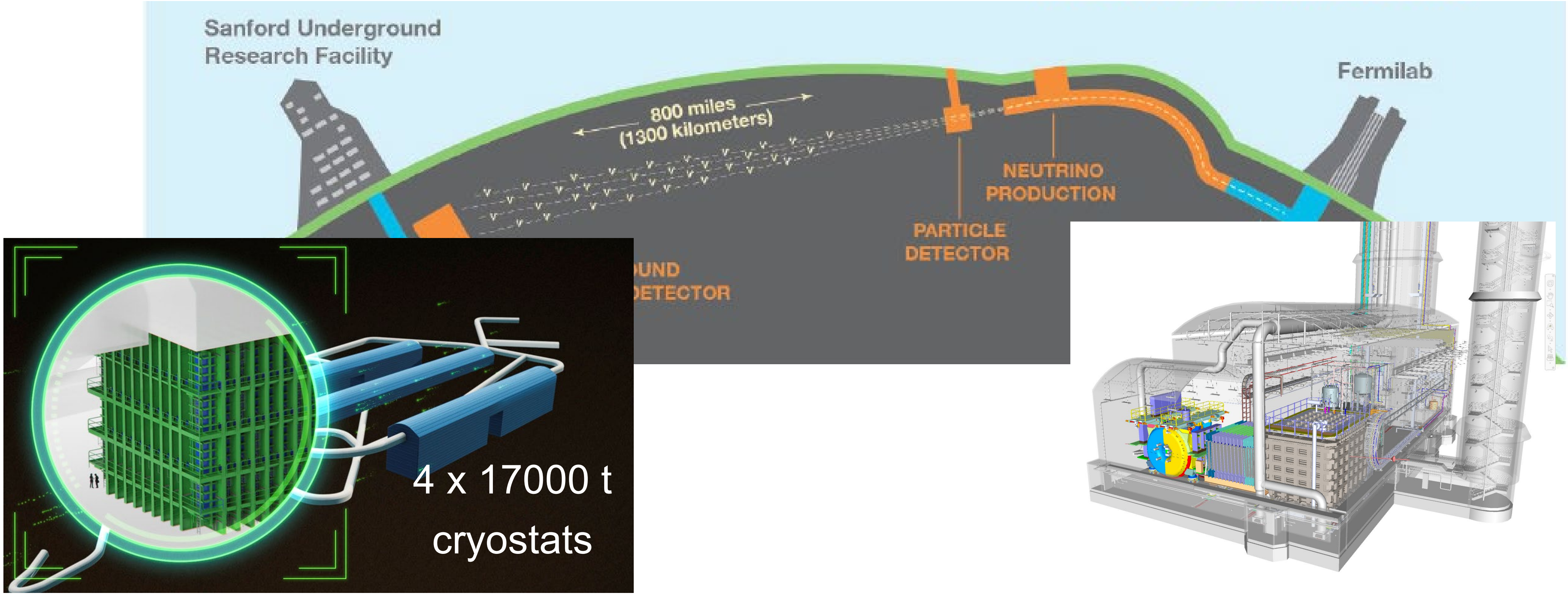
Can we use only scintillation light for track imaging??

- Challanges:
  - Liquid Argon scintillation is in the VuV (128 nm)
    - Need a new kind of camera with VuV optics
    - The photon detector must be sensive to VuV
    - The camera has to operate at 87 K
- Advantages:
  - High rate capability (μsec)
  - Insensitive to magnetic field
  - Simple and robust



DUNE experiment

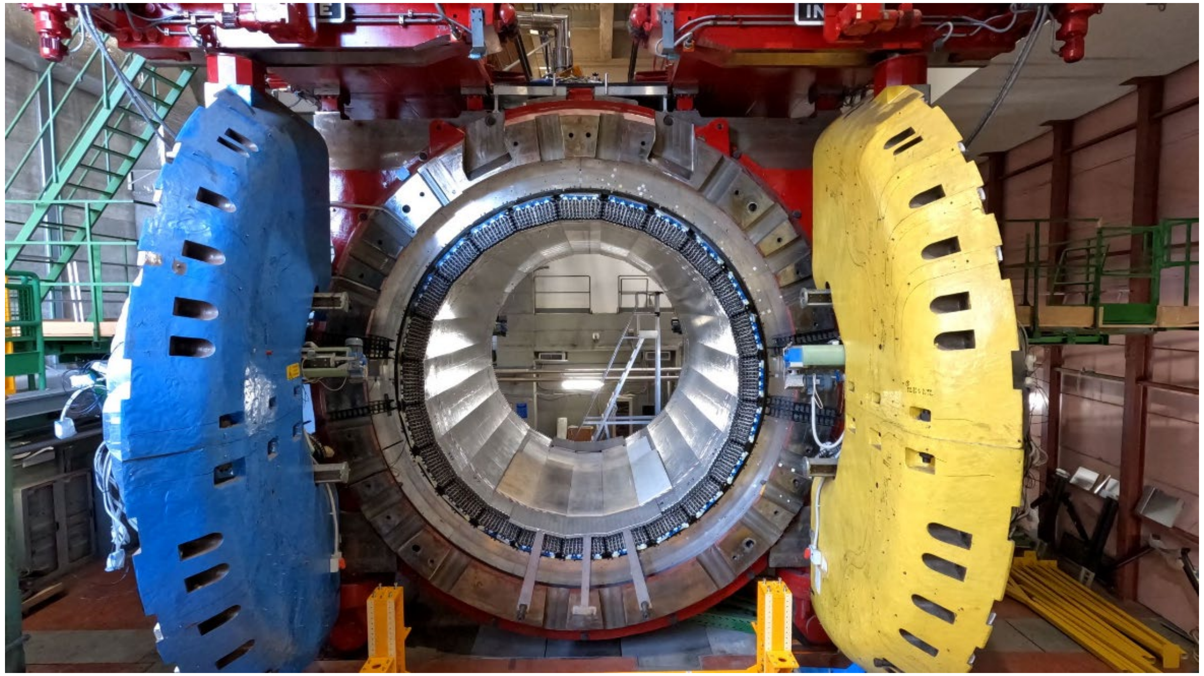
- High intensity neutrino beam from Fermilab
- Near Detector at 575 m + Far Detector at 1500 km (in gold mine 1300 m deep)

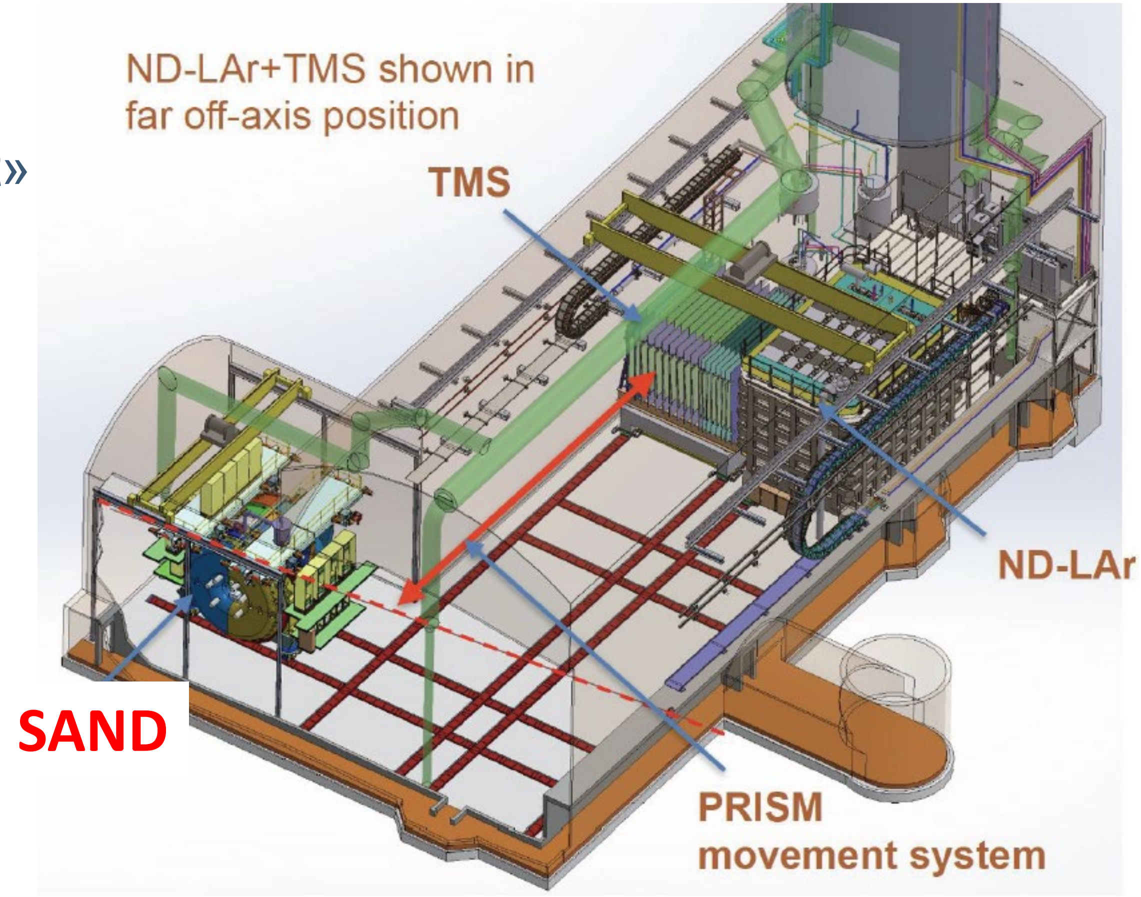


Physics program: mass hierarchy, ν oscillations, CP violation, Supernova, BSM

The SAND Detector

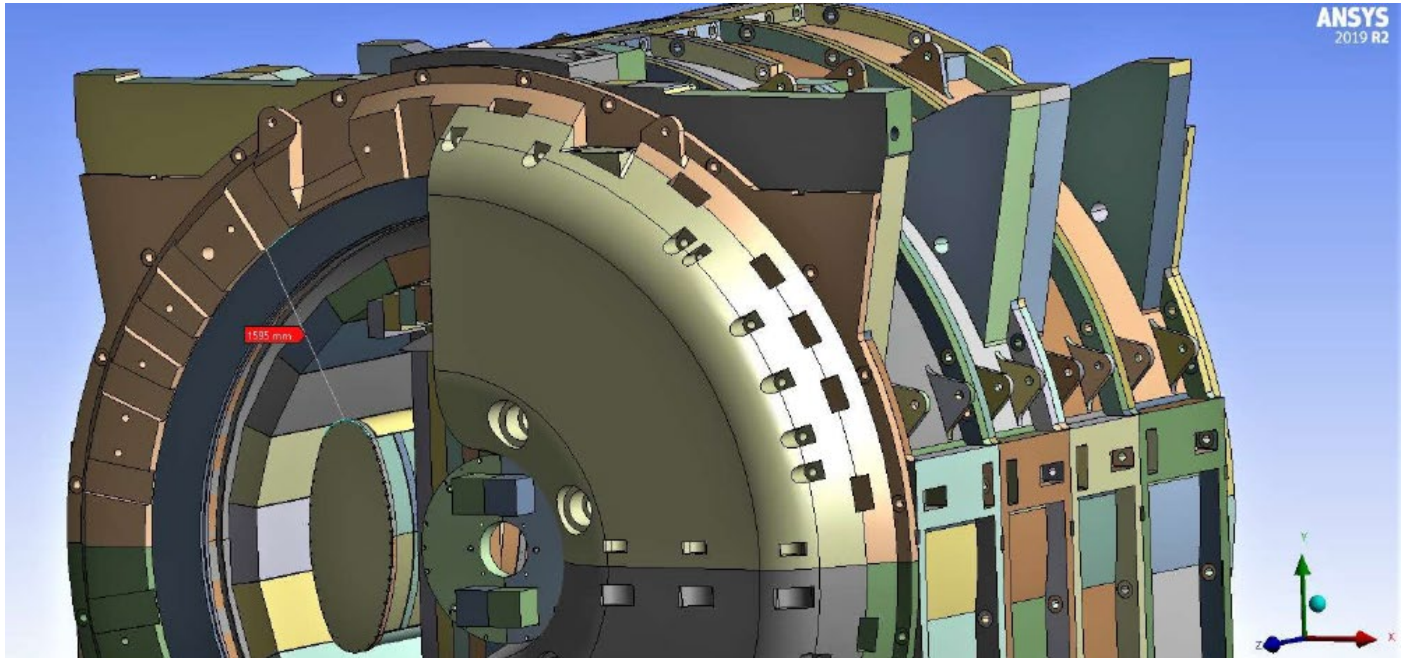
- It is one of three elements of the DUNE Near Detector Complex:
  - Re-use of KLOE Magnet and ECAL
  - New Gas Tracker and Liquid Argon «active target»

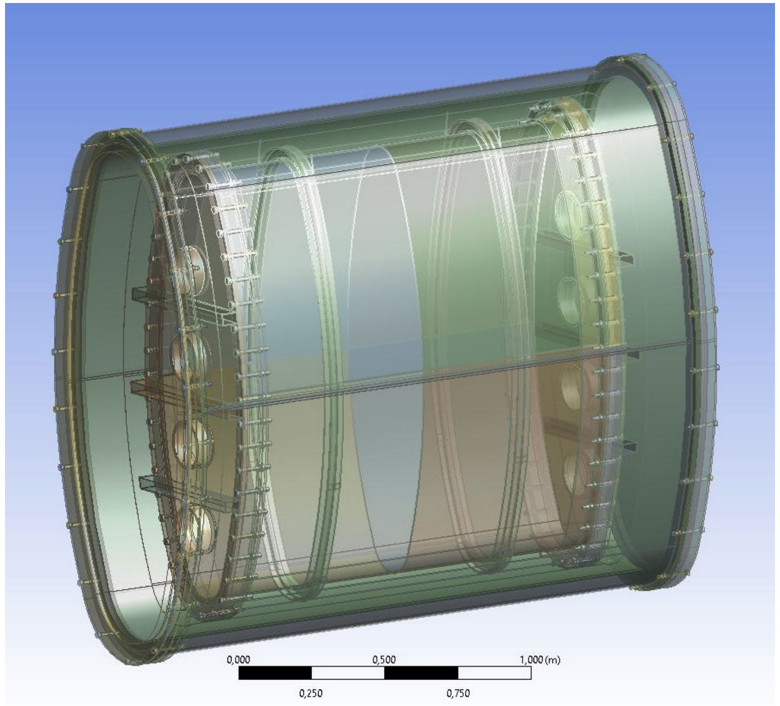




GRAIN, the active Liquid Argon target in SAND

- A 1 ton target in light cryostat
  - Constrain nuclear effects on Argon
  - Argon target permanently located on-axis for cross-calibration, complementary to NDLAr,





Imaging in GRAIN

- *Coded Aperture Masks* or VuV lenses for the *optics*
- Matrices of *Silicon PhotoMultipliers* as *single photon sensor* with high dinamic range
- Wave Length Shifter coating of SiPM entrance window (TPB)
- New *cryogenic ASIC*, low power and high density of channels (1024)
- R&D for a new generation of *Backside Illuminated SiPMs*

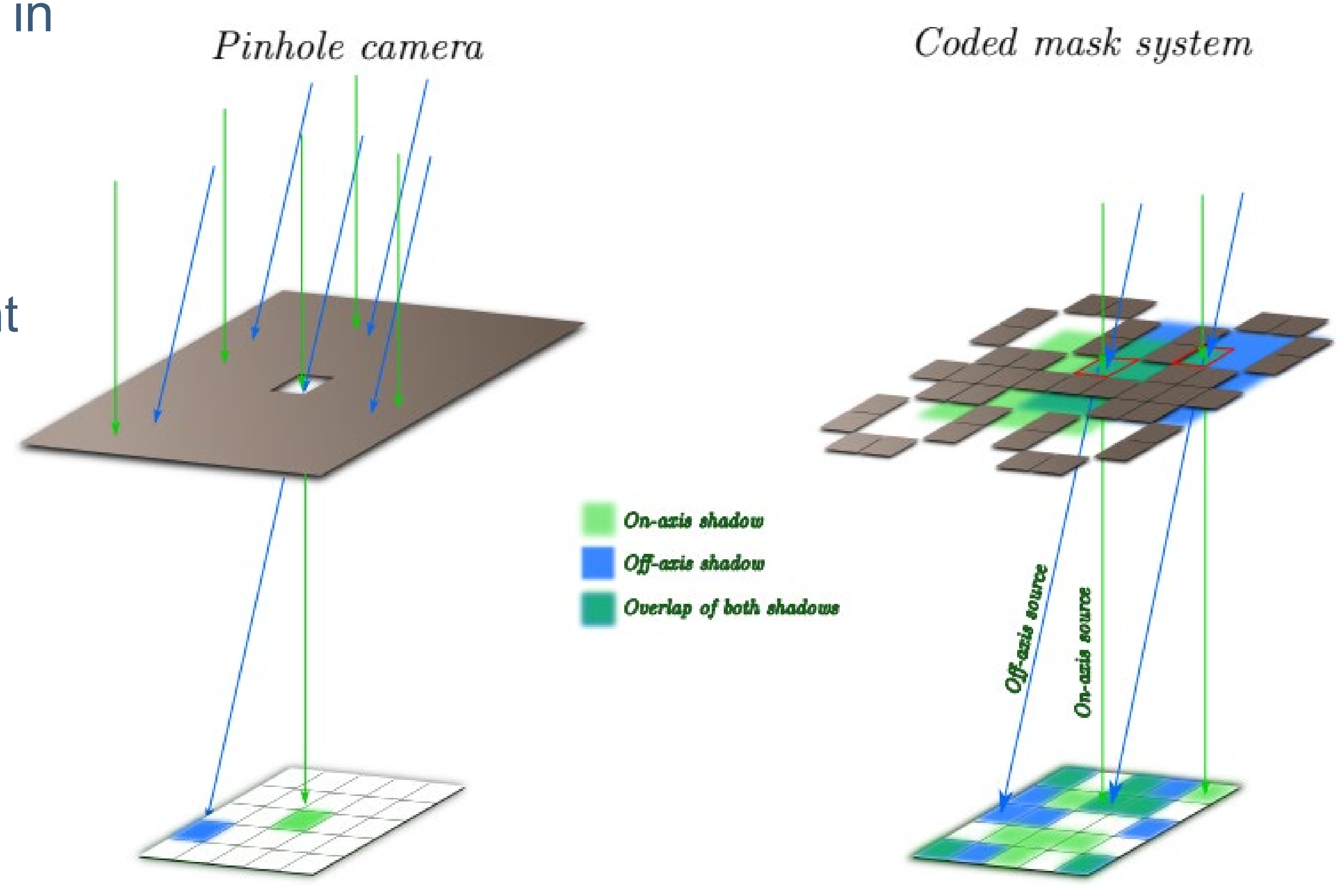
Coded Aperture Masks

- A technique developed for X and γ photons in astrophysics

- An evolution of a single pinhole camera:
  - a matrix of multiple pinholes to improve light collection and reduce exposure time

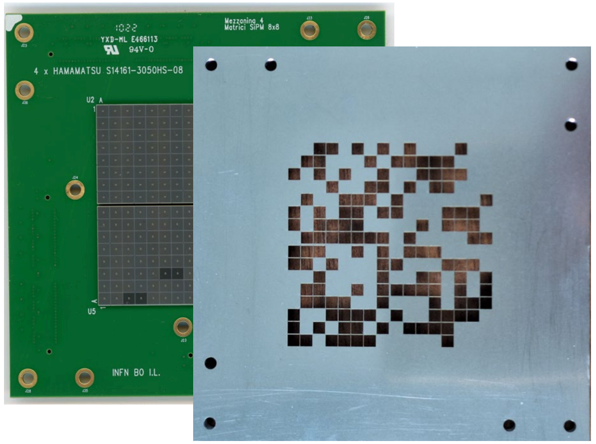
- The image formed on sensor is the superimposition of multiple pinhole images

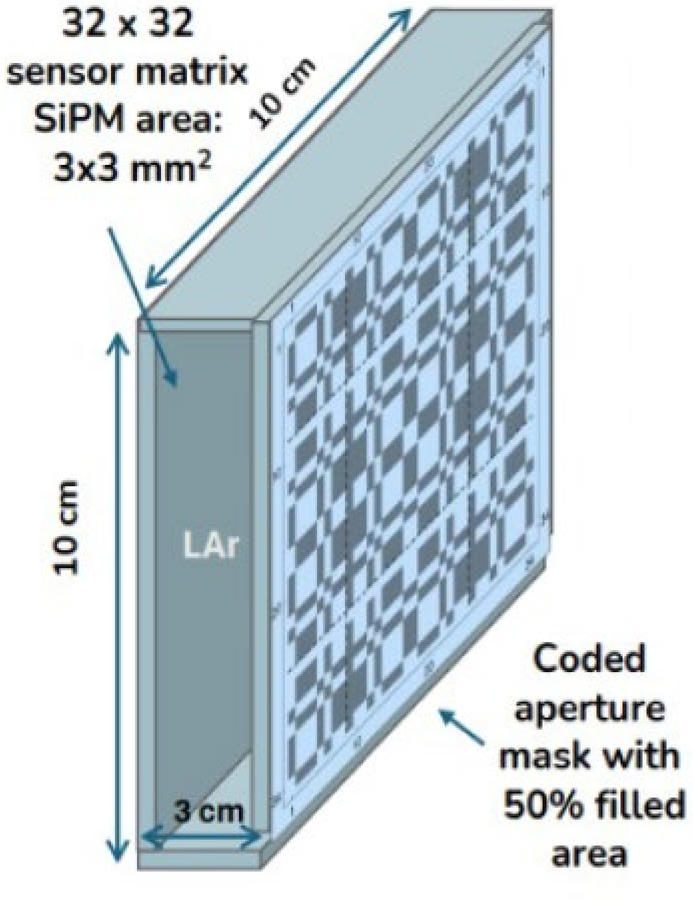
  - 50% light transmission
  - Good depth of field
  - Small dimension

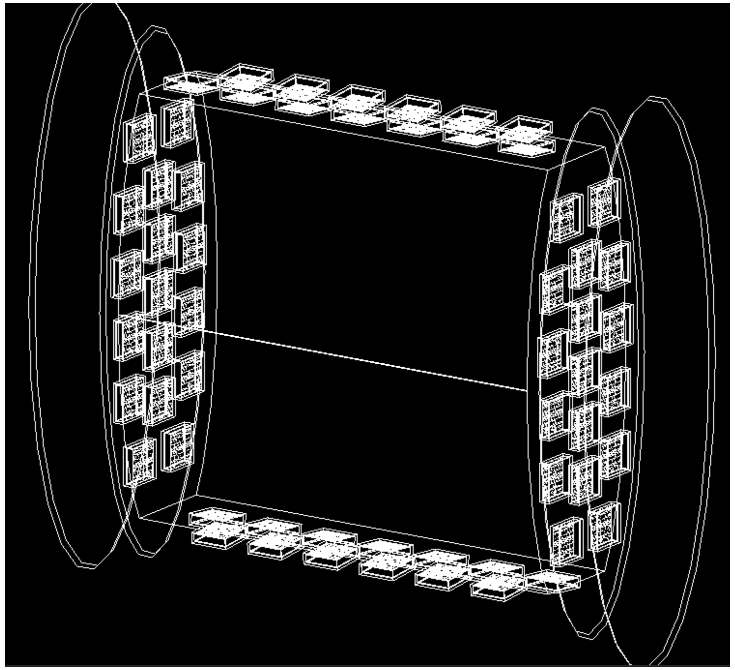


The VUV camera

- 32x32 matrix of SiPMs (3x3 mm^2)
- Mask with 50% holes
- 60 cameras in GRAIN

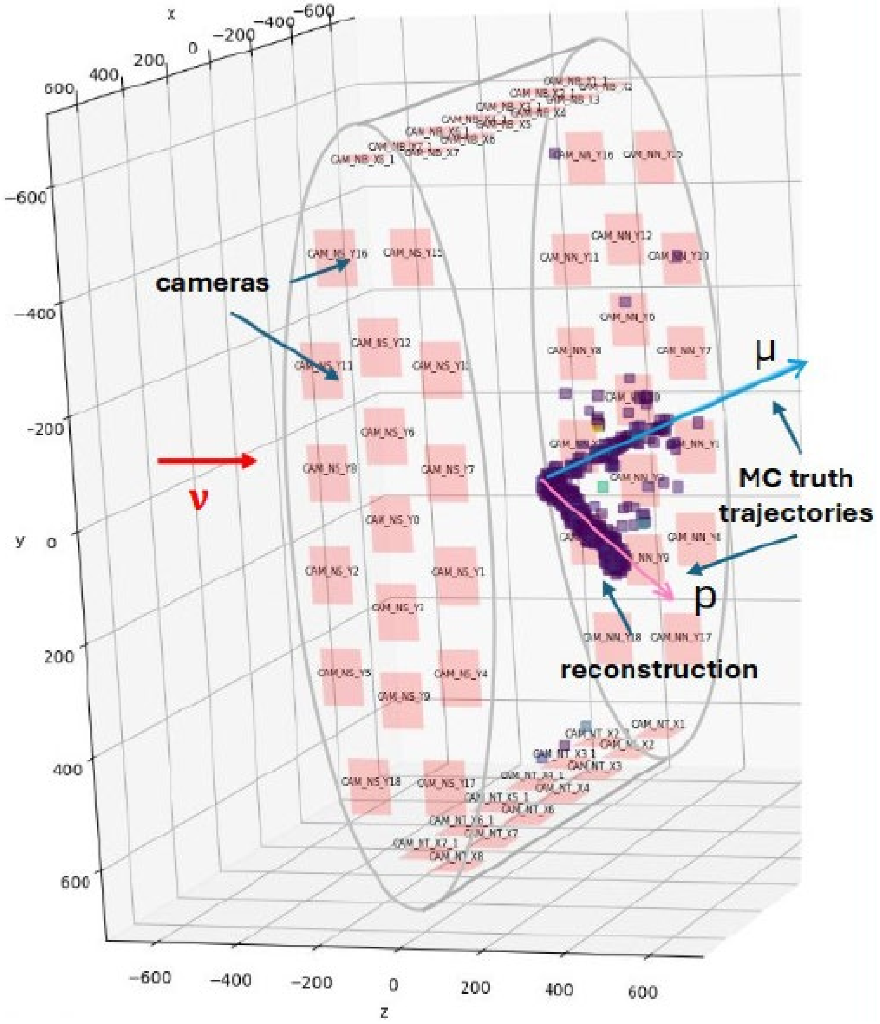






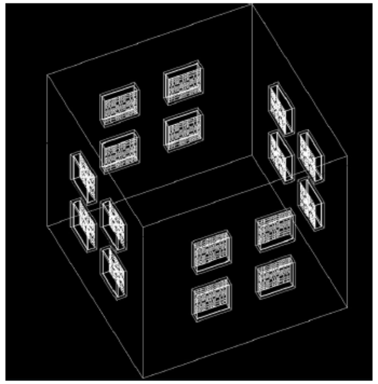
Track reconstruction

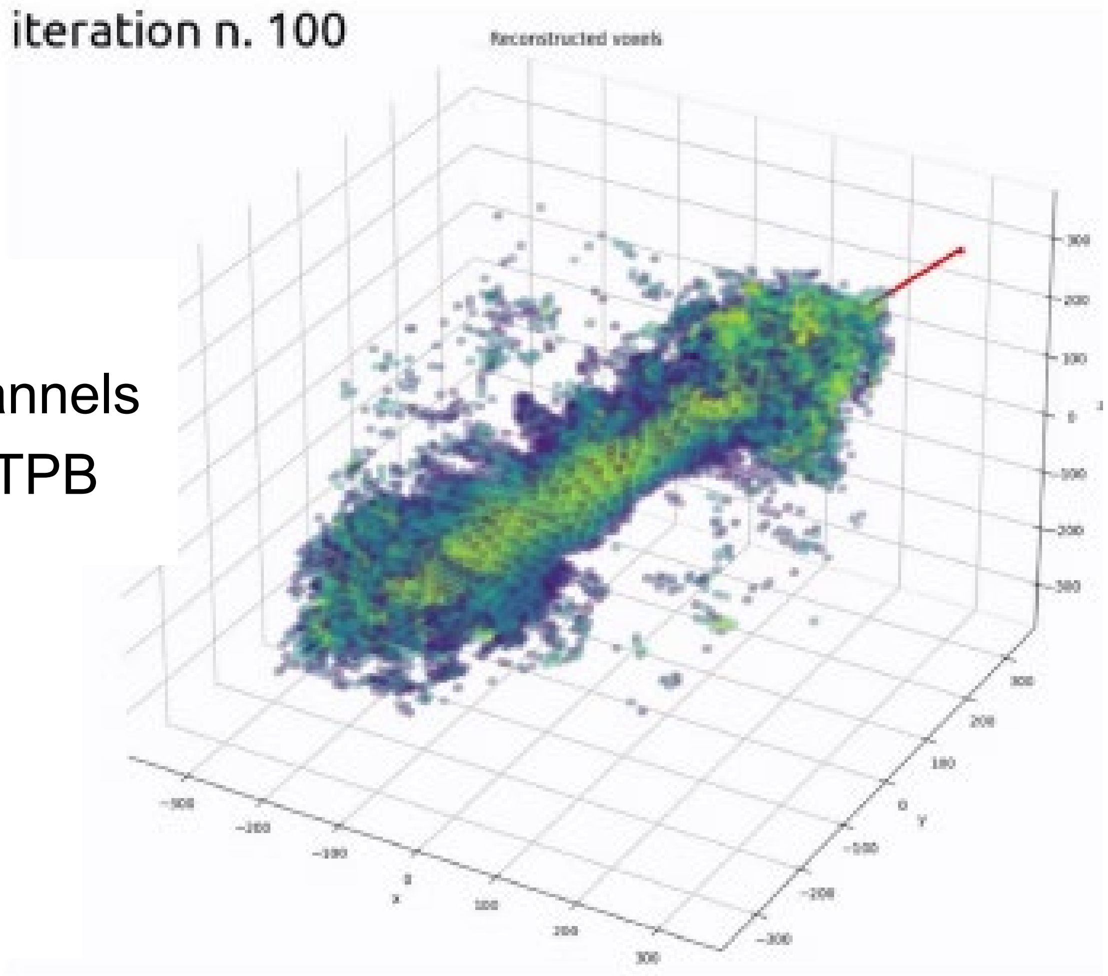
- Directly reconstructs in 3D dimensions the initial photon source distribution in a segmented volume (voxels)
- Combines information of multiple cameras at once
- Maximum Likelihood Expectation Maximization (MLEM) algorithm:
  - Iteratively converges to the photon source distribution that maximizes the likelihood of detecting the observed images
- Implemented for execution on (multiple) GPUs



Vertex resolution ~20 mm

- Simulated 0.3 t LAr
  - 16 cameras x 1024 channels
  - SiPMs (3x3 mm^2) with TPB





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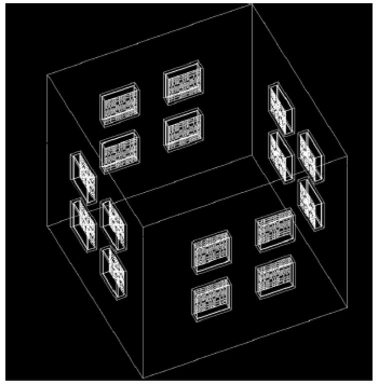
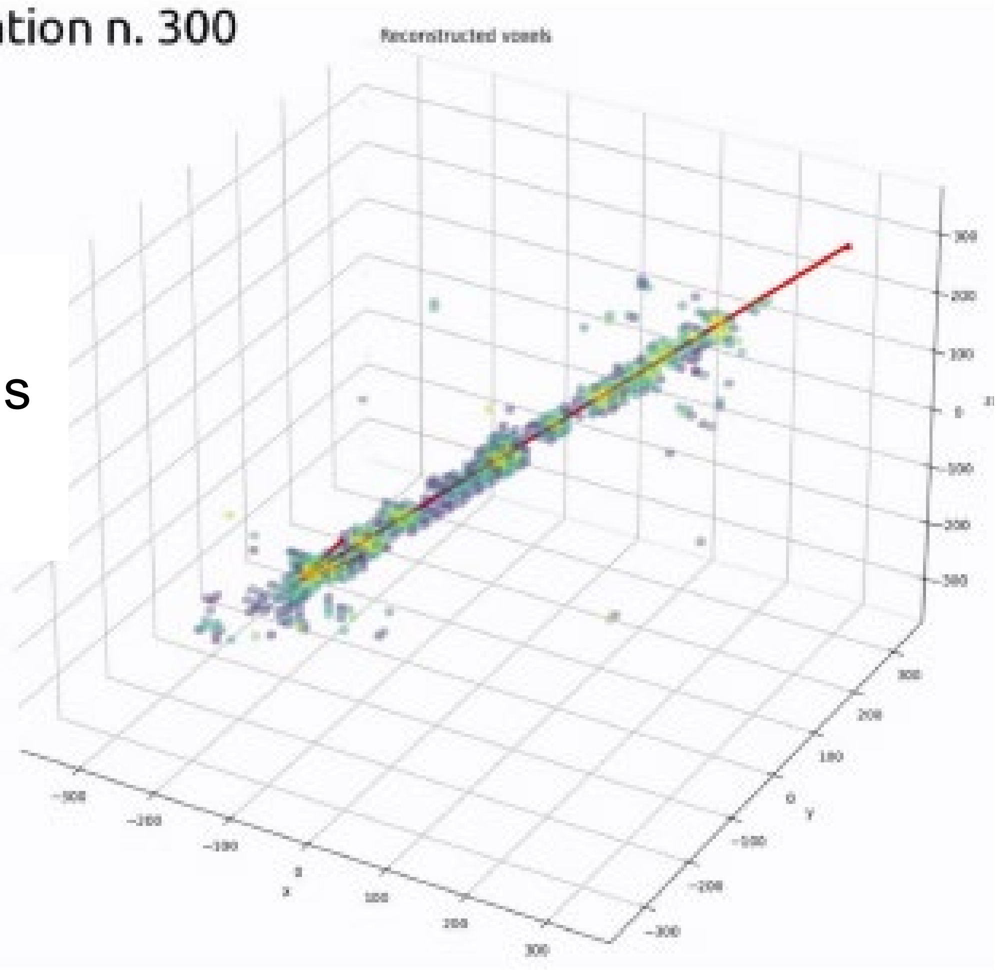
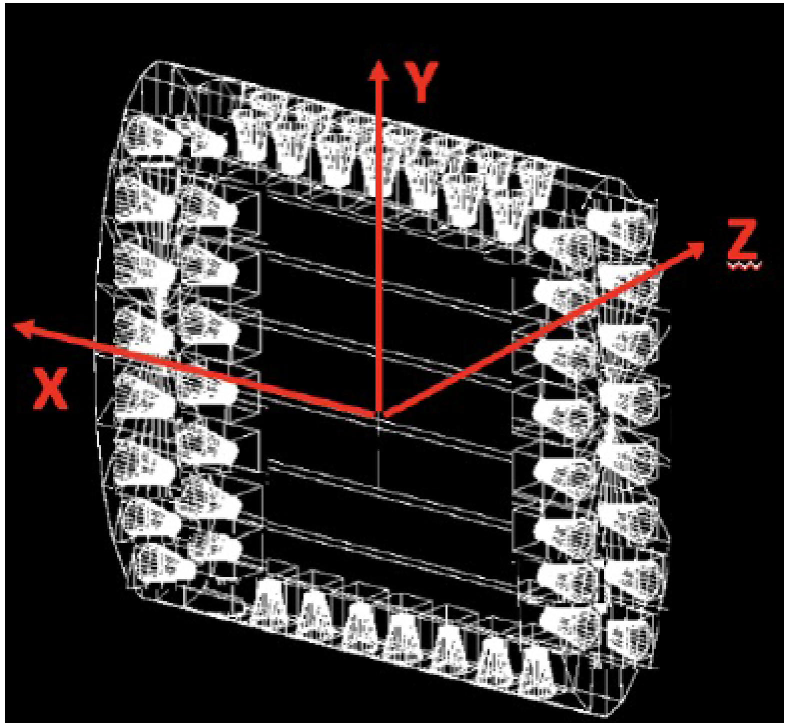
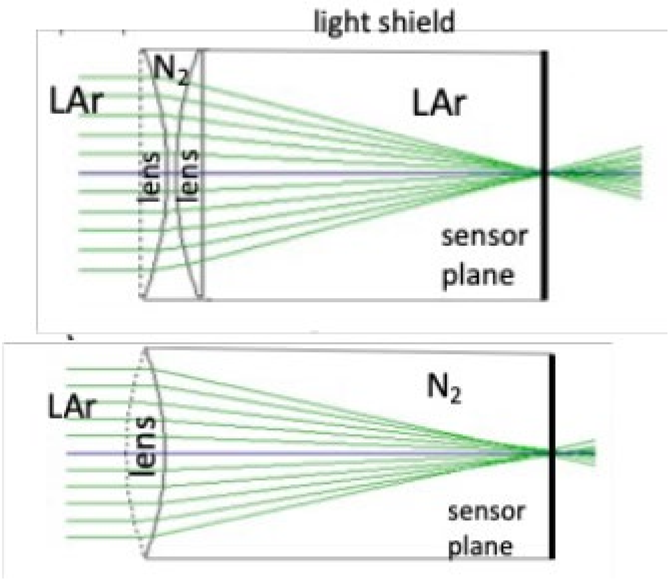


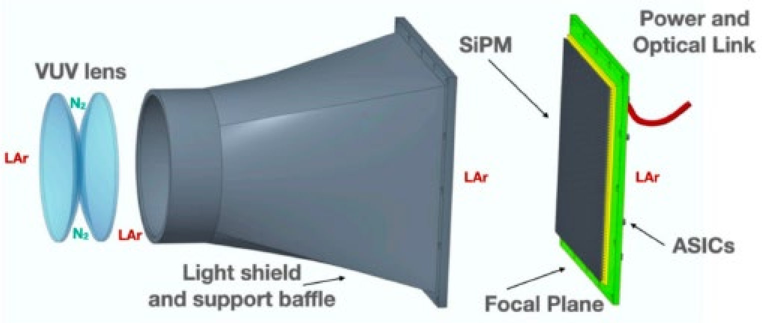


Optics with lenses

- Two types of lenses (Fused Silica or MgF2)
- SiPM (2x2 mm^2) matrix rank 32x32







Reconstrution with lenses

- 2 steps algorithm
- 2D analysis of the camera images
- 3D matching of the different tracks based on projective geometry

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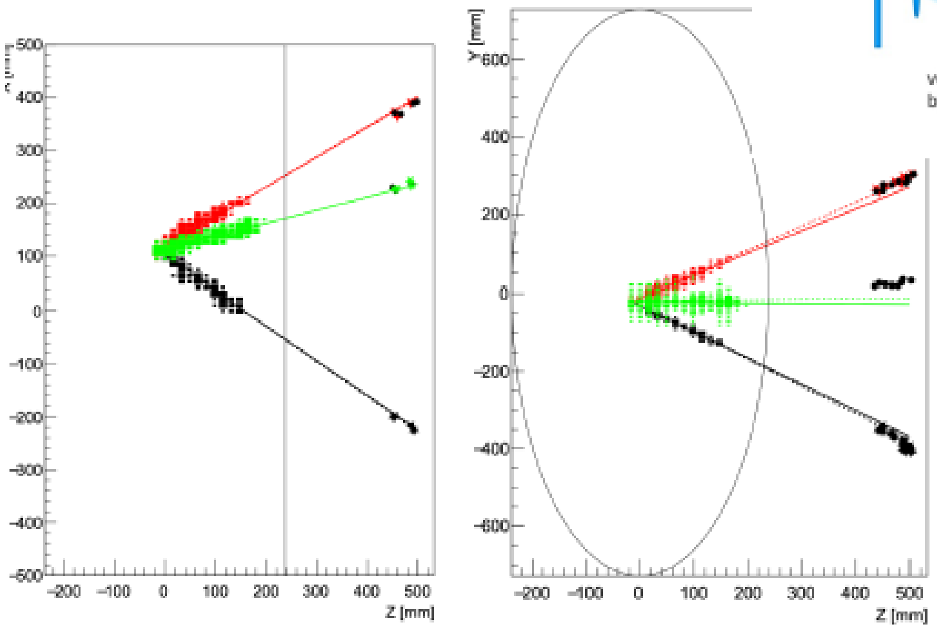
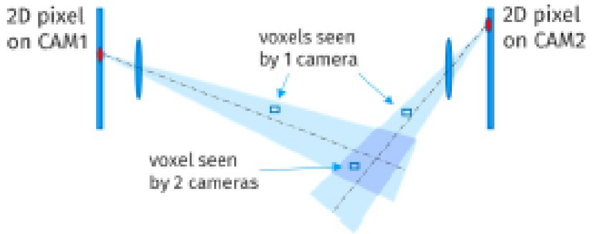
- Vertex resolution ~20 mm
- Energy resolution ~18%



(a) ZX (top)   (b) ZY (side)

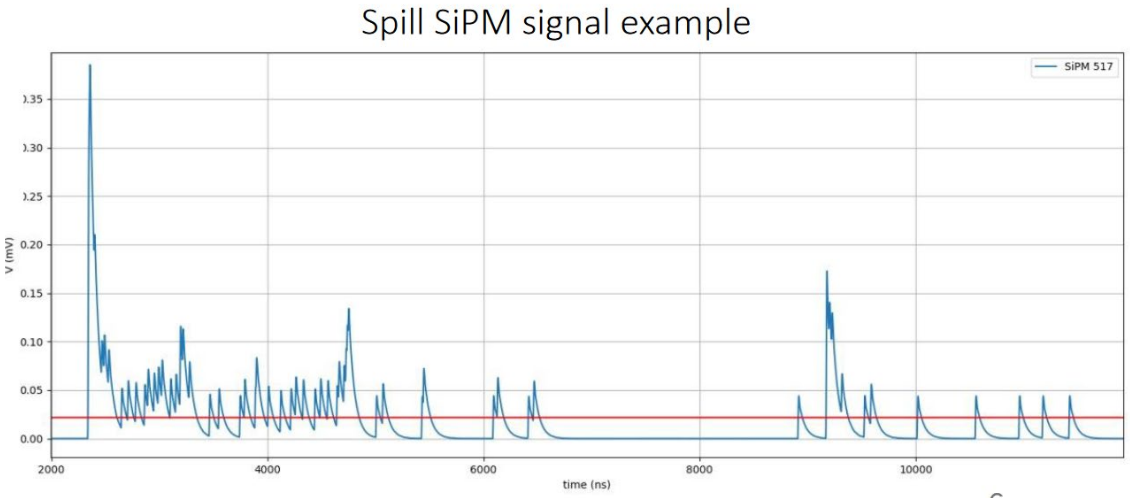


The new ASIC

- We need an ASIC with *1024 channels*, measure *time* and *charge*, *low power*
- Reuse modules of ALCOR chip as much as possible

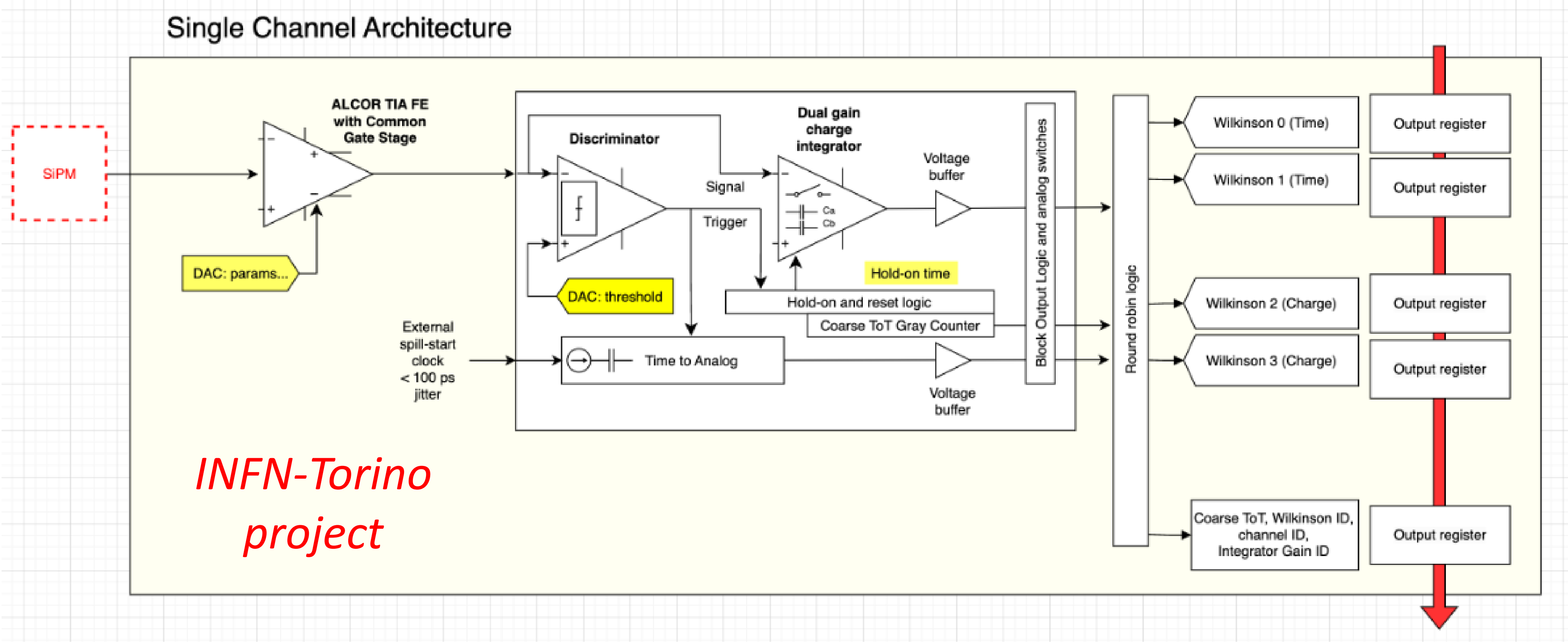
Parameter	Value
SiPM Size	2 x 2 mm^2 (140 pF) 3 x 3 mm^2 (500 pF)
# Channels/ASIC	1024
Operating Temperatures	300 K – 77 K
<Power Consumption>	5 W / cm^2 ◊
Duty Cycle	On ≥ 9.6 μs (50 μs) Off ◊◊ < 0.1 s
Measurements:	**Q – ToA - ToT**
Integrator Dynamic Range	> 100 PE
RMS_{ToA} (first PE)	100 ÷ 150 ps / 1PE
RMS_{ToT}	≈ ns
Threshold	0.5 x 1PE
SNR	30

INFN-Torino project



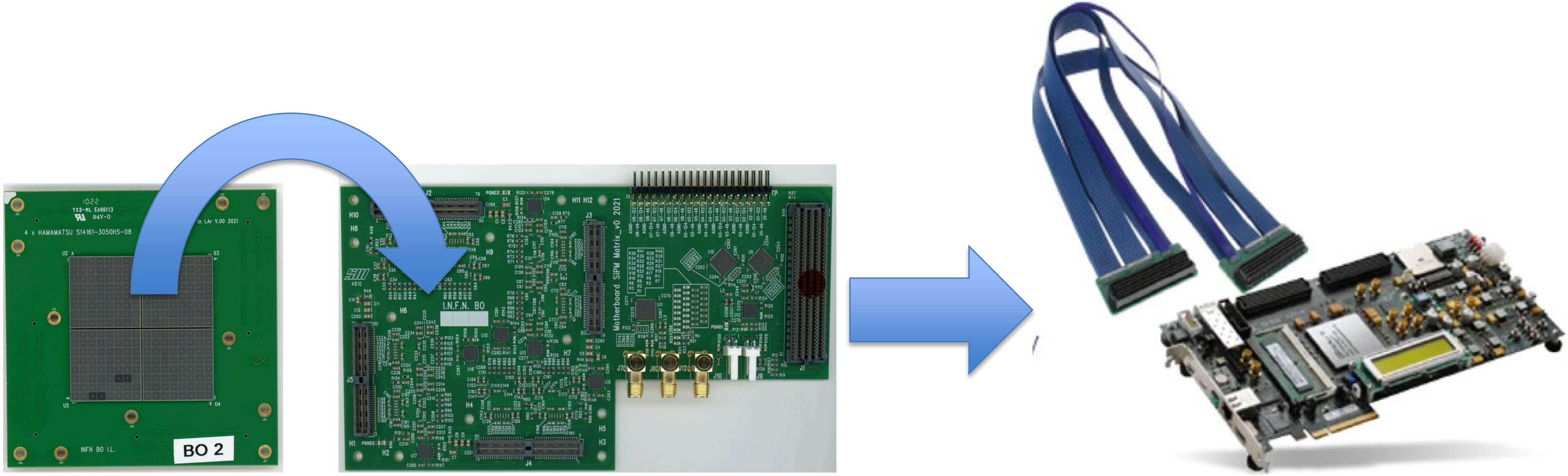
New ASIC architecture

- Architecture under evaluation:
  - Python model of Front-end fed with photons expected in a spill
  - Working chip in 2027



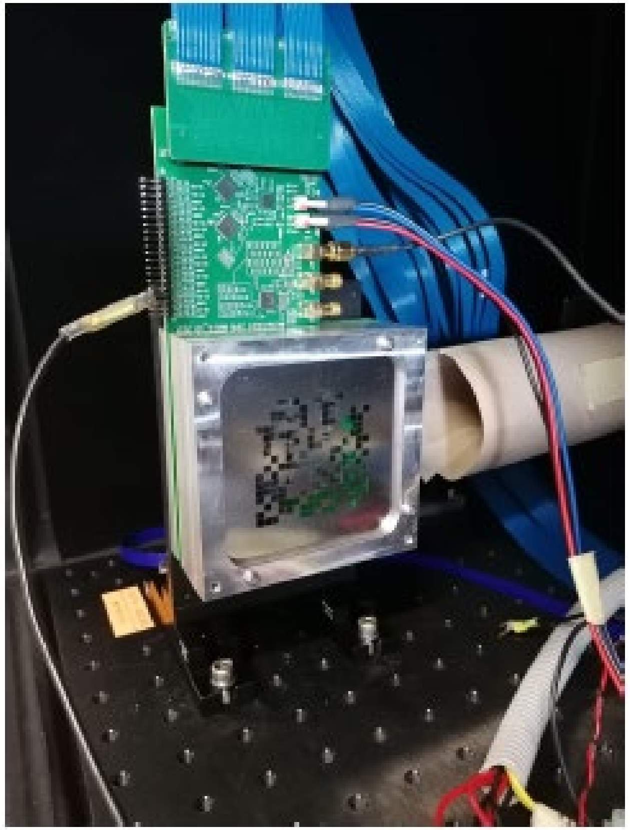
Demonstrator

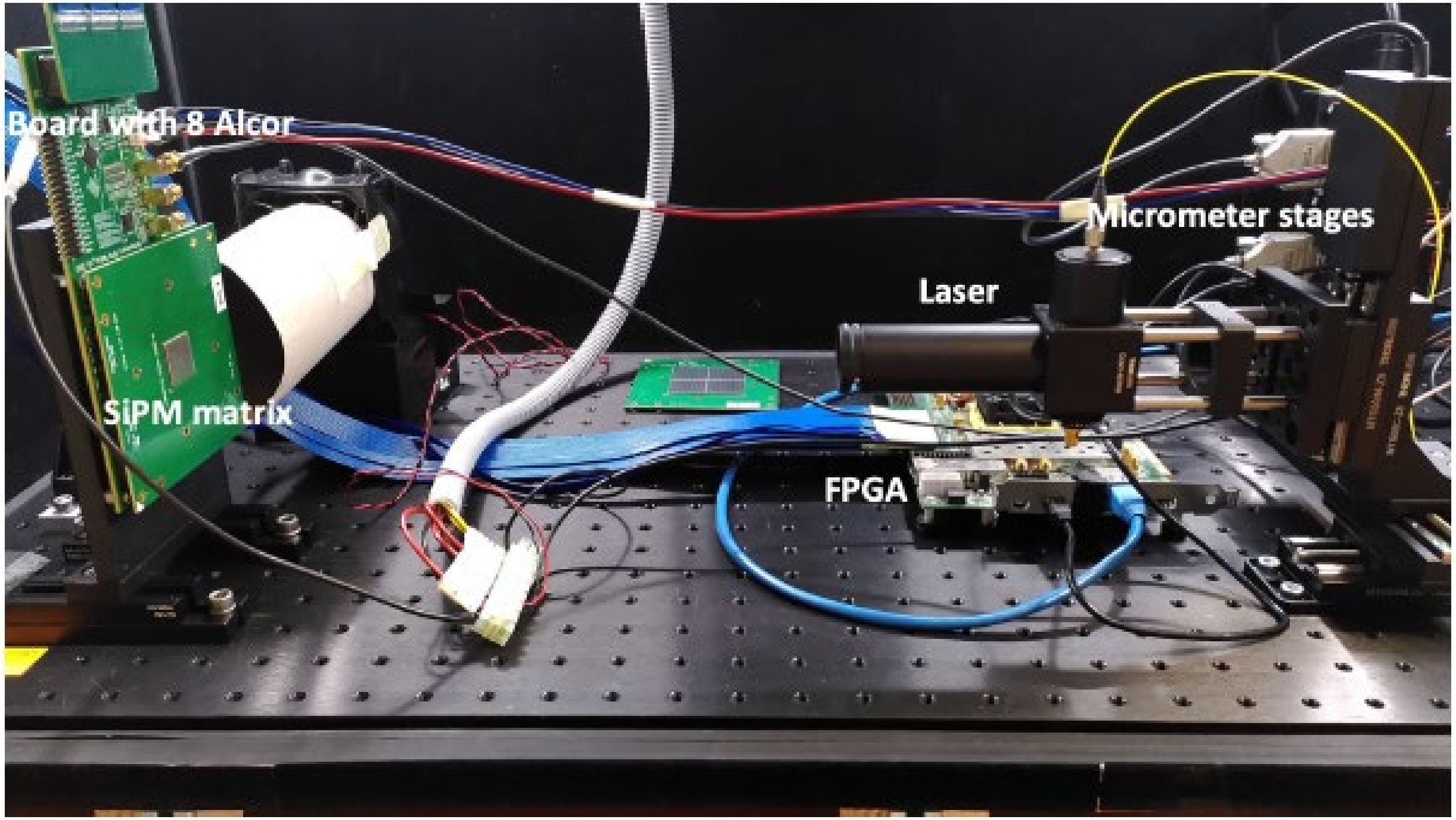
- SiPM matrix *16x16*
- Readout board with *8 x ASIC 32 ch* ("ALCOR" from INFN-Torino)
- RO board can be coupled to Lens or Mask



Tests on Demonstrator

- Verification of firmware, control, daq
- Calibration using a laser source





Test of Demonstrator in LAr

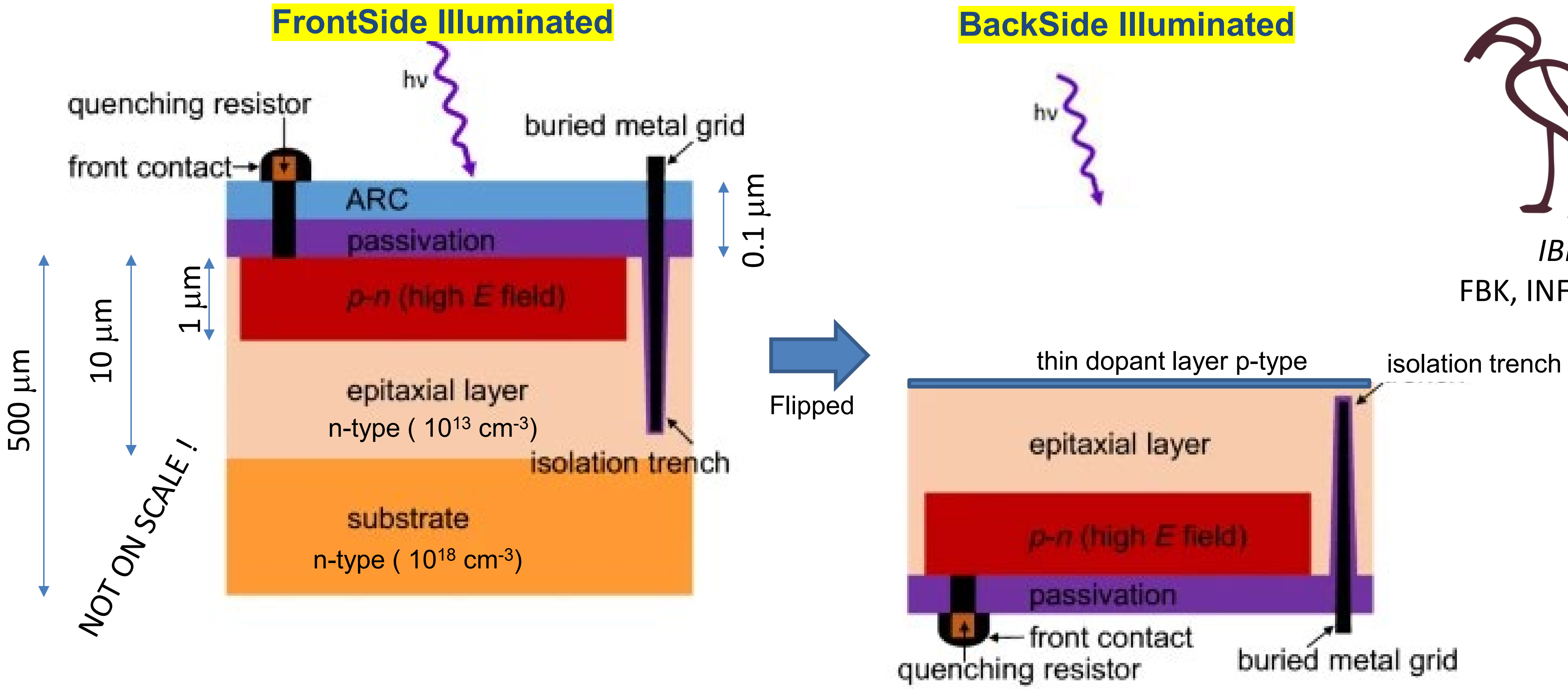
- Test demonstrator with artificial light sources and cosmics, in a small volume of Lar
- Test final cameras (1024 channels) in 2027

INFN-Genova
"ARTIC" facility

INFN-Lecce
Cosmic Trigger

Backside Illuminated SiPM

- INFN has a joint project ("IBIS") with FBK-Trento for the development of BSI SiPM

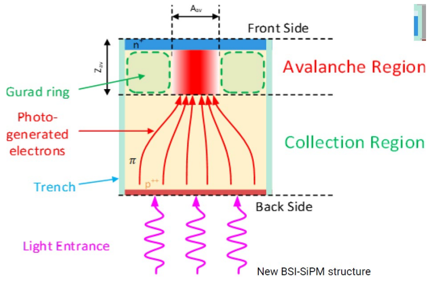


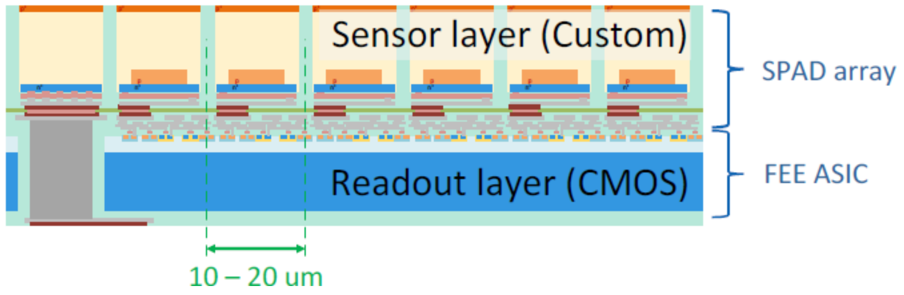
IBIS
FBK, INFN-CSN5

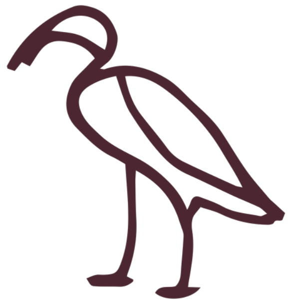
BSI premium features

- In our application we are interested in improving *VUV efficiency* and *integration* with high density ASIC:

  - no metallizations are on the Back Side: better Fill Factor
  - clean, flat entrance window, suitable for advanced processing to enhance PDE (decreased reflection/absorption)
  - all contact are on the Front Side allowing high density wafer-level bonding to a readout ASIC, smaller pixels for better resolution (if needed)







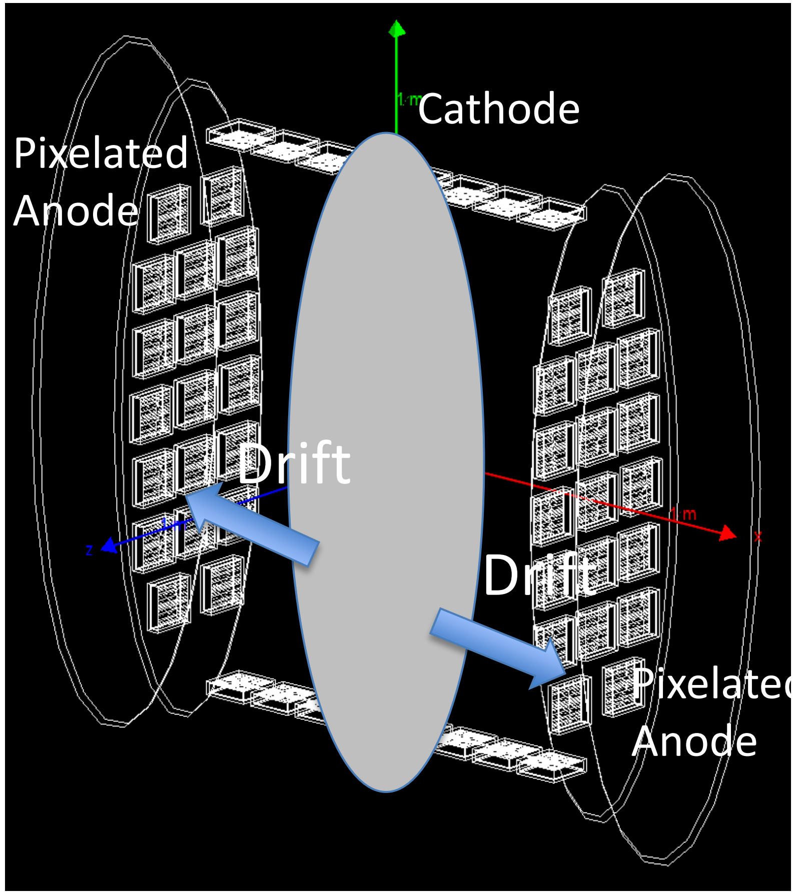
IBIS
FBK, INFN-CSN5

- First BSI SiPM prototypes expected in Spring 2025

Thanks

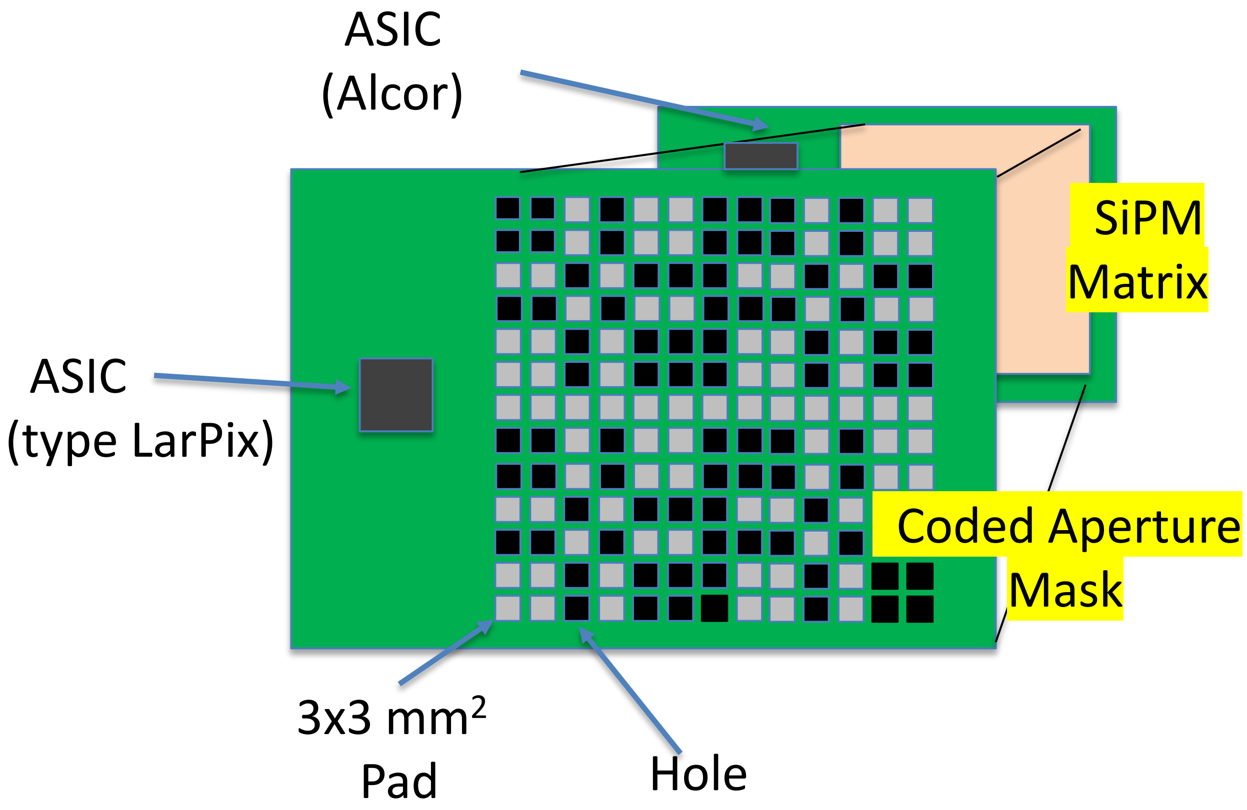
Ideas for ND Phase II: charge + light readout

- Coded Aperture Masks are pixelated and form the anode.
- A Cathode grid is added in the middle to form a TPC with horizontal drift.
- Standard mask on top and bottom
- Combined reconstruction of tracks by scintillation light and charge readout allows to solve superimposed events
- Charge identification thanks to magnetic field



Dual Purpose Camera

- Holes in a FR4 (or else) form the Coded Aperture Mask
- 3x3 mm^2 metallic pads are placed in the mask positions free from holes (50% surface)
- Dedicated ASICs read the charge and SiPM response to 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.

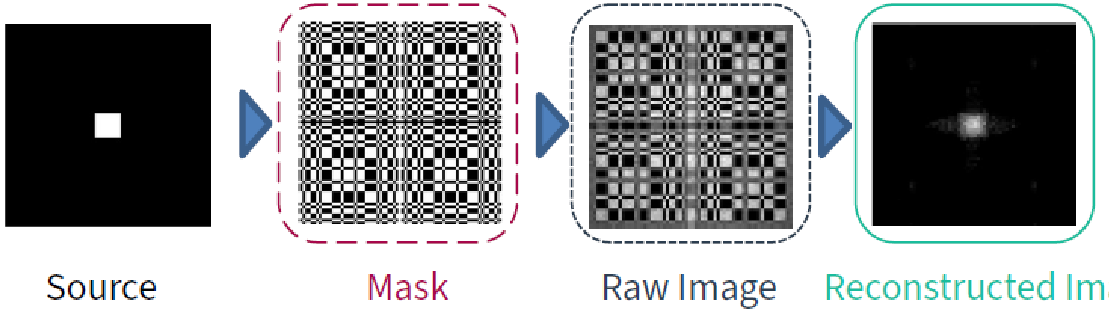
Reconstructed Image   Raw Image

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

Where H is the "inverse" of M, such that

Mask

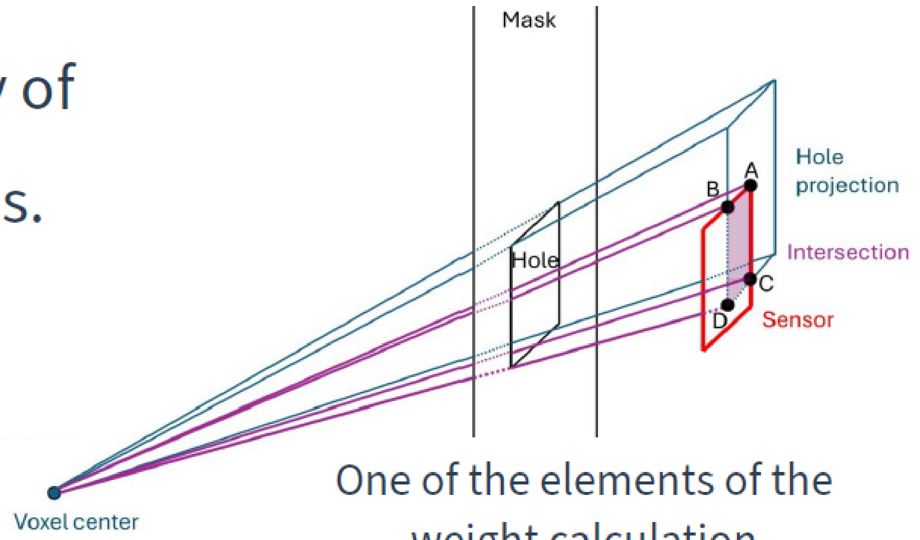
$$M(x,y) \otimes H(x,y) = \delta(x,y)$$



- **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 technique

- **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_j	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]**

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

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