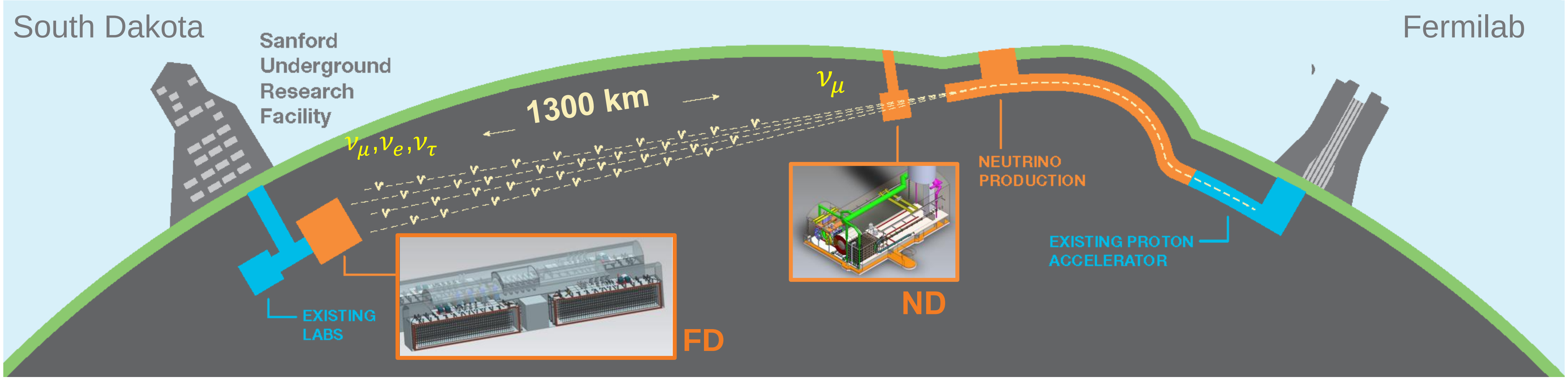
Imaging Neutrino interactions with Liquid Argon scintillation light at the DUNE Near Detector Complex

Valentina Cicero (INFN Bologna)
for the DUNE Collaboration

17th Vienna Conference on Instrumentation
Vienna, 20/02/2025

DUNE: Deep Underground Neutrino Experiment

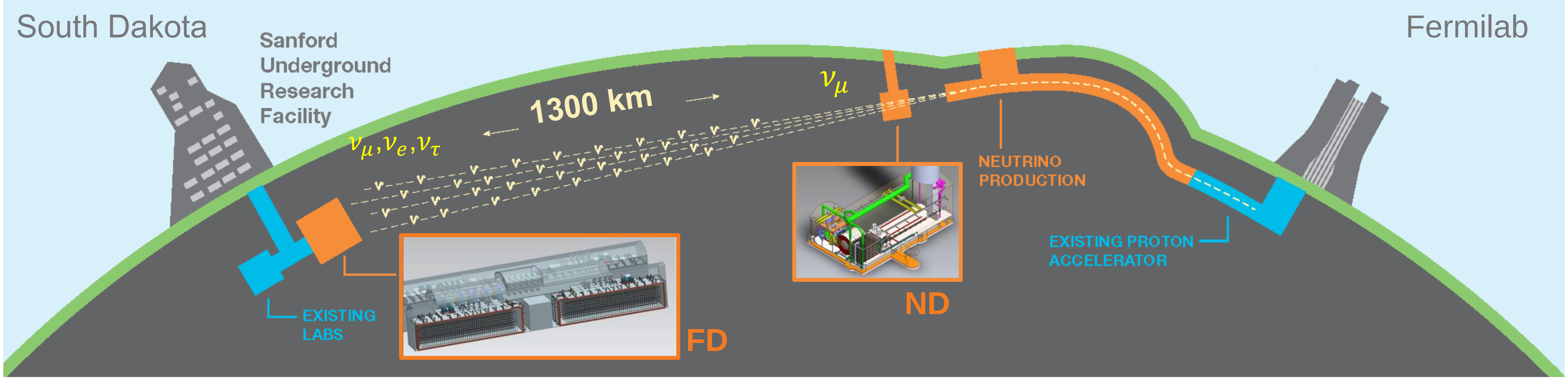


DUNE is a next generation Long Baseline neutrino oscillation experiment.

Physics Goals:

- High precision measurements of the neutrino oscillation parameters: δ_{CP}, mass ordering, θ_{23}
- Supernova and solar neutrinos detection
- Beyond the Standard Model Searches

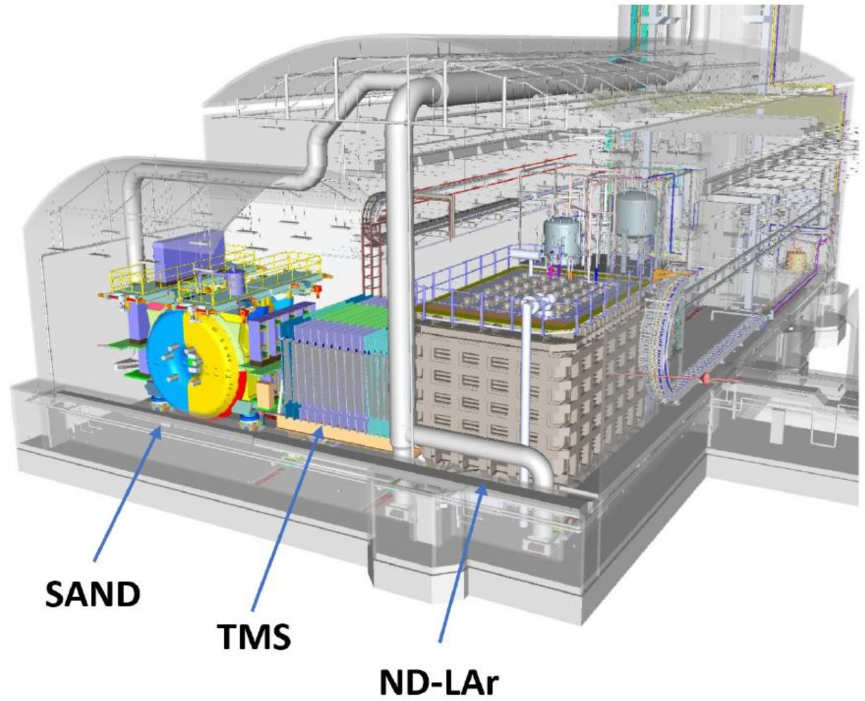
DUNE: Deep Underground Neutrino Experiment



- An intense **wide band $\nu/\bar{\nu}$ neutrino beam** produced at Fermilab, peak flux at 2.5 GeV $\rightarrow$ high intensity 1.2 MW upgradable to 2.4 MW
- Two detector complexes:
    - a **Far Detector (FD)** in South Dakota, with 3 modules of LArTPCs 17 kton fiducial mass each and one Module of Opportunity [1].
    - a **Near Detector (ND)** at Fermilab

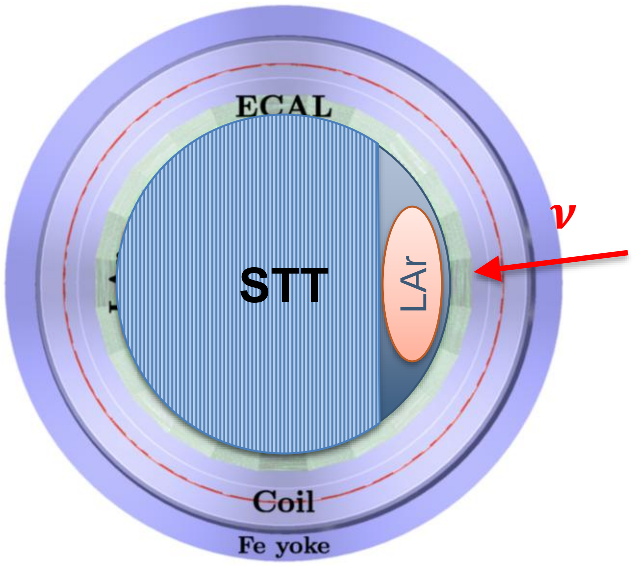
SAND at the Near Detector

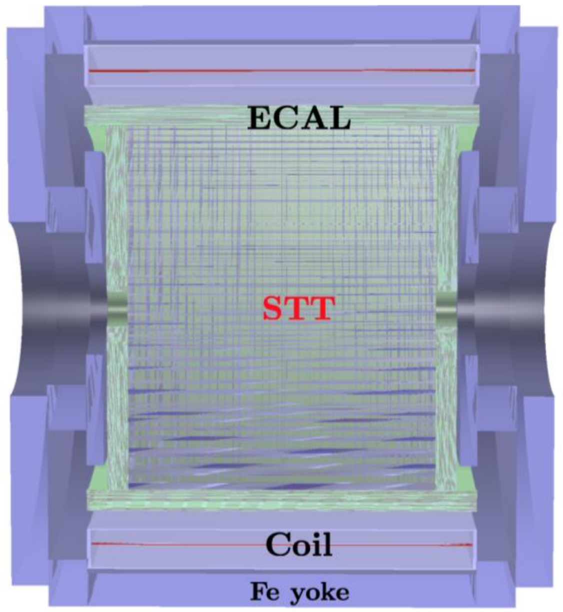
See N. Tosi talk on 17/02



SAND will be permanently located on axis to:

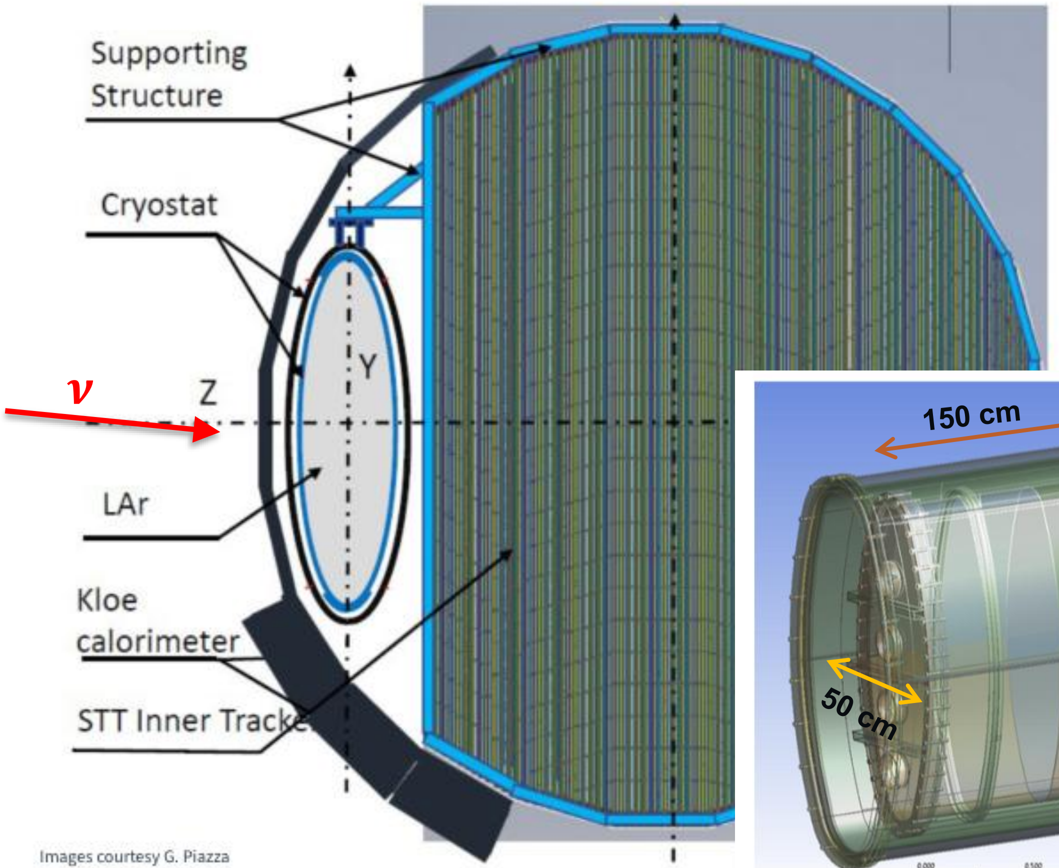
- measure the $\nu/\overline{\nu}$ flux and energy spectrum
- perform cross-section measurements on different nuclear targets



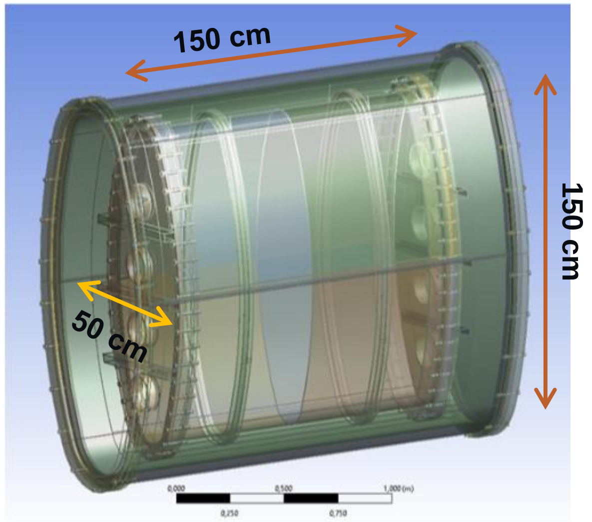


The **ND complex** will characterize the beam and reduce systematics uncertainties associated with detector and nuclear effects.

GRAIN



Images courtesy G. Piazza



A **1-ton LAr target** in a thin cryostat:

- Inner steel vessel at 1.5 bar
- Vacuum vessel made of composite materials at 10^{-5} bar

Main motivations:

- Constrain on systematics for ν-LAr cross sections
- Complementary Ar target for cross-calibration with ND-LAr

ACTIVE TARGET with optical readout

Imaging of scintillation light

LAr scintillation light properties:

- ✓ High photon yield per unit energy
- ✓ Emission time fast component 6-8 ns
- ✗ Spectrum peaked at 128 nm

We can **«take pictures» of particle tracks** using a segmented sensors coupled to an optical device

Comparison with a LAr-TPC
- Drift time vs photon propagation
- A different trade-off between timing and reconstruction resolution
- No HV or field cage, potentially more robust operation

Sensors: SiPM matrices
Cryogenic operation reduces noise
active R&D to improve sensitivity to VUV

«Optics» under study:
- UV lenses
- Coded Aperture Masks

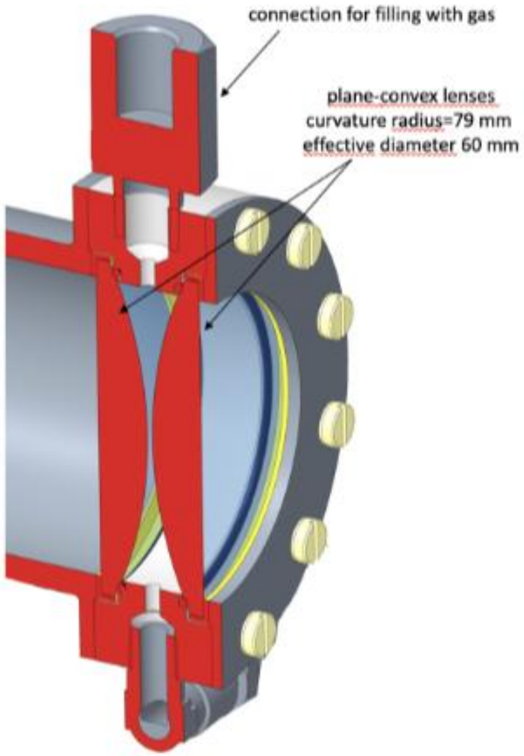
Lenses

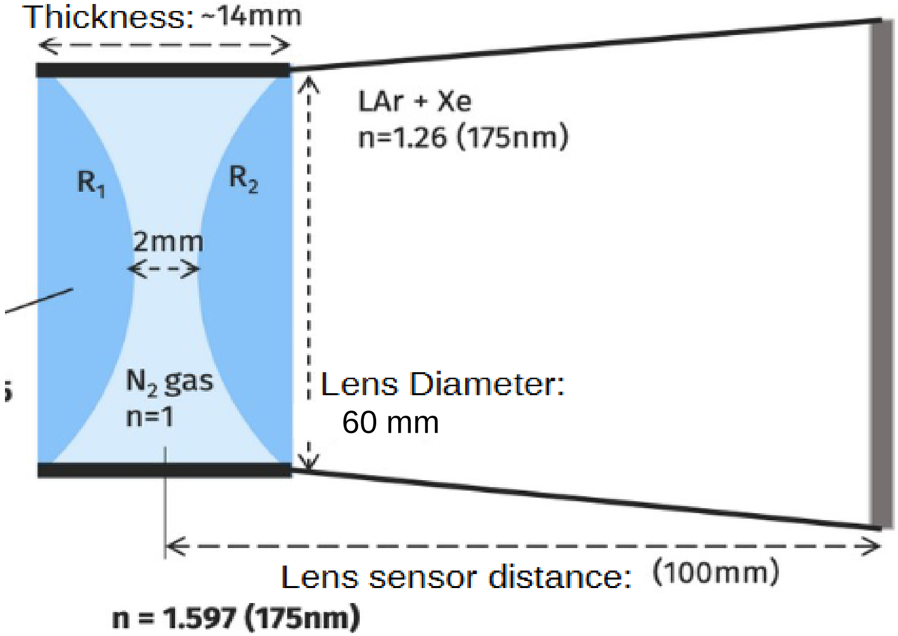
Typical imaging device but challenging (and innovative) for:

- Cryogenic condition
- Transmissivity of UV
- refraction index with LAr

Different materials under investigation:

- **MgF_2 , CaF_2** → mechanical and thermal stability of large lenses to be demonstrated
- **UV-silica** → need Xenon doping to shift wavelength to 175 nm for better transmissivity



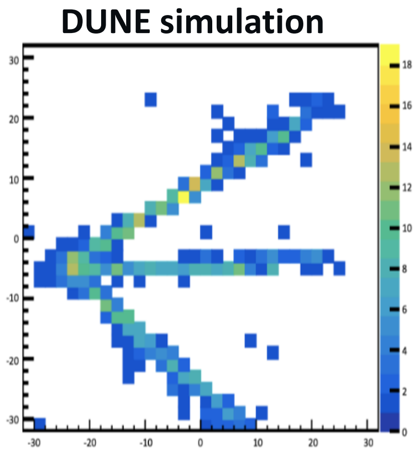


UV silica lens design:

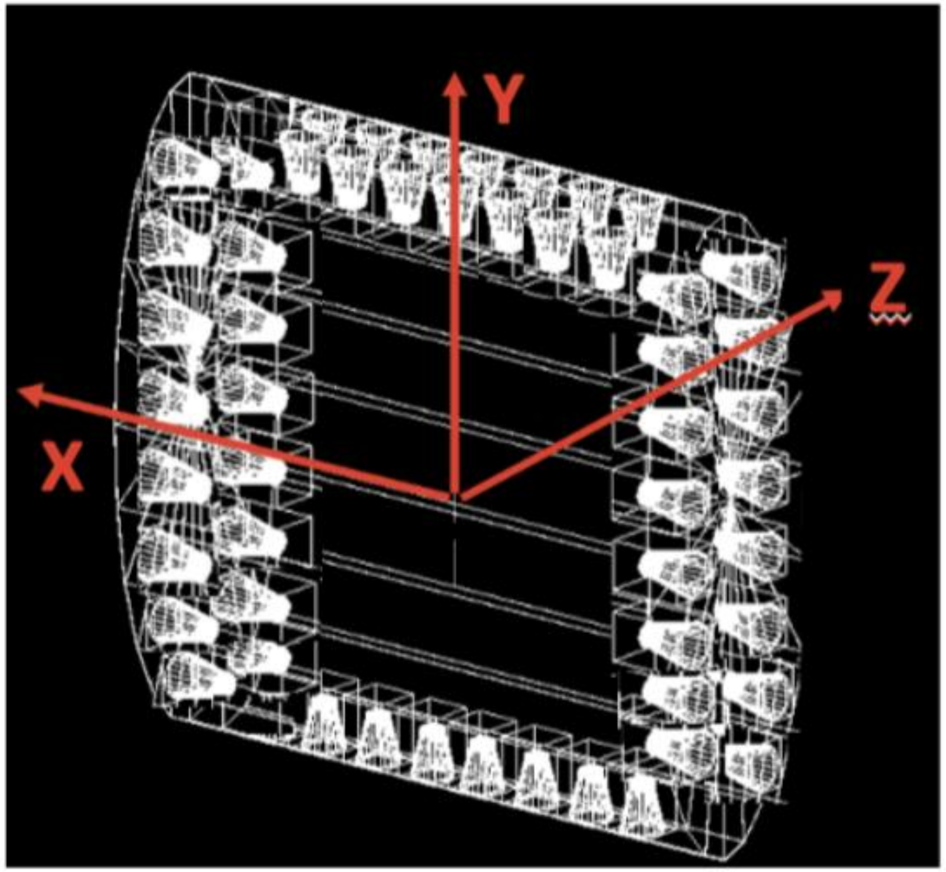
- Two biconvex lenses with N_2 gas between
- Depth of field optimized between 40 and 120 cm
- Angular aperture 35.5°

GRAIN lens imaging system

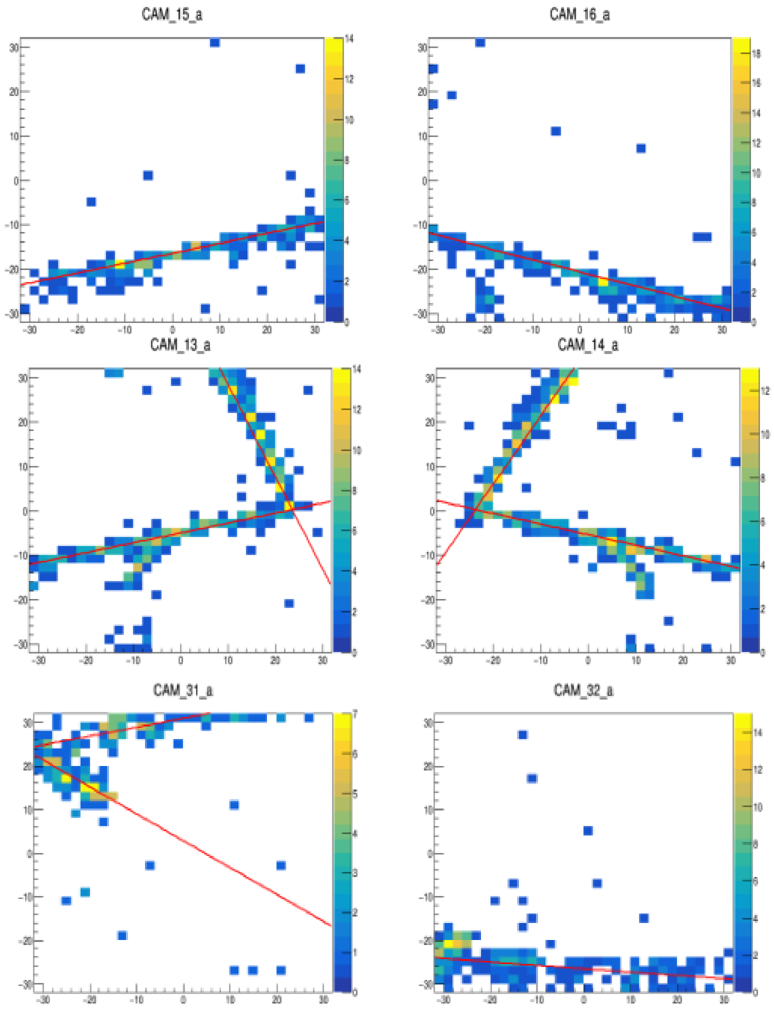
- Lens coupled to a 32 x 32 SiPM matrix
- SiPM area: 1x1 mm^2
- 53 lens cameras inside GRAIN
- no blind spaces at 40 cm from the inner walls



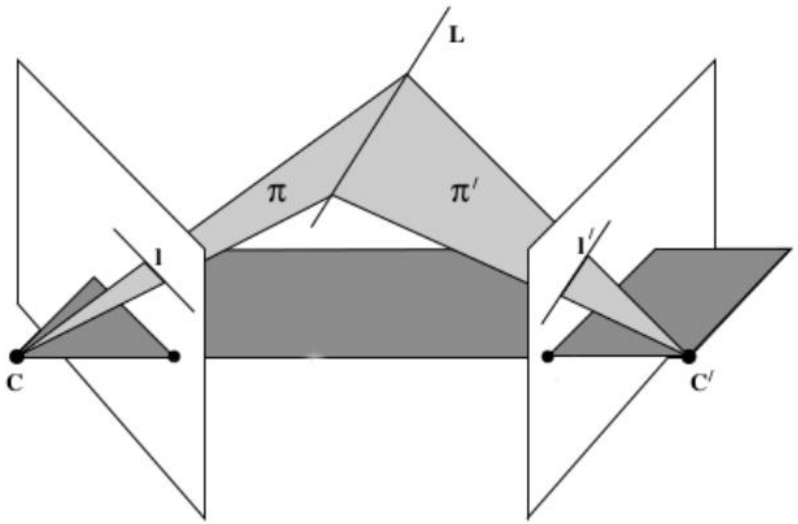
typical image for
well-focused tracks



Reconstruction



DUNE simulation



3D reconstruction using **projective geometry:**

- Find lines, vertexes, endpoints on images
- Combine 2 or more projections

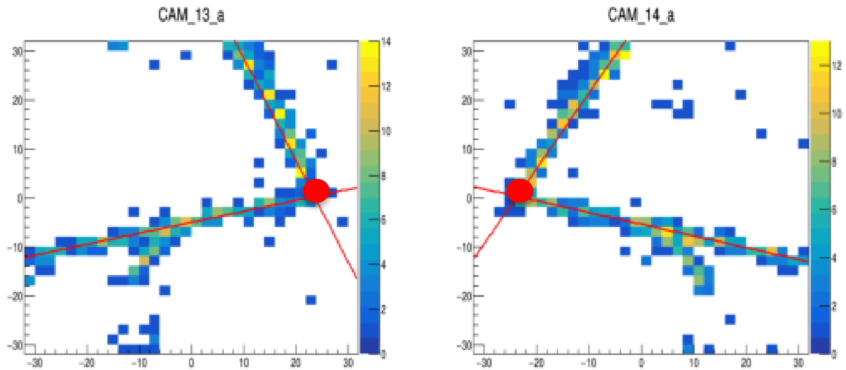
Challenges:

- Find correct matches between tracks on different images

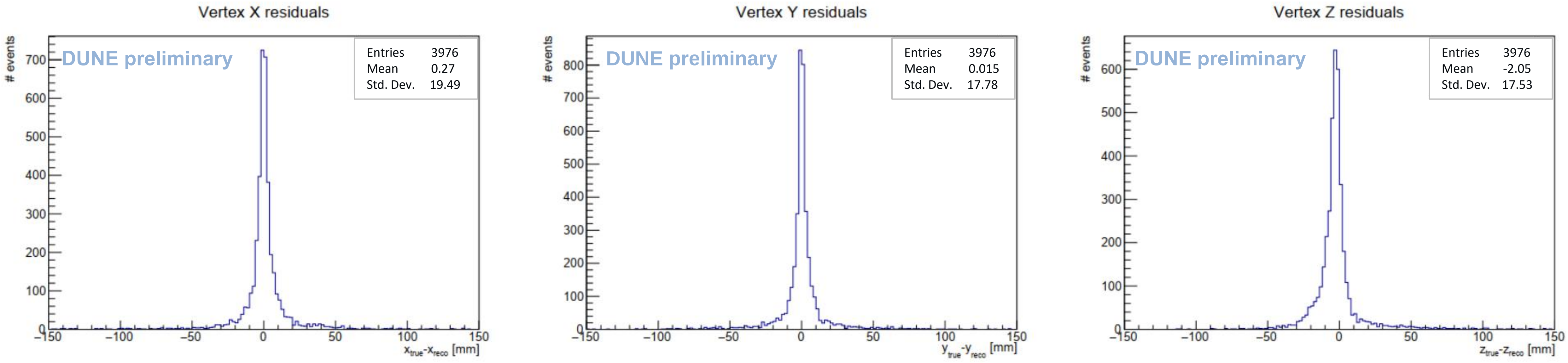
Simulated performances - vertex reconstruction [3]

Simulated sample:

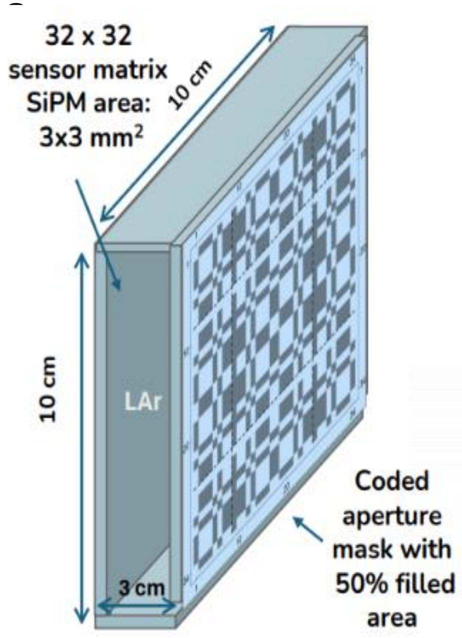
- 4000 ν_μ Charged Current interactions in LAr with DUNE beam spectrum
- vertex projection in at least 2 images



Vertex position residual distributions [2]

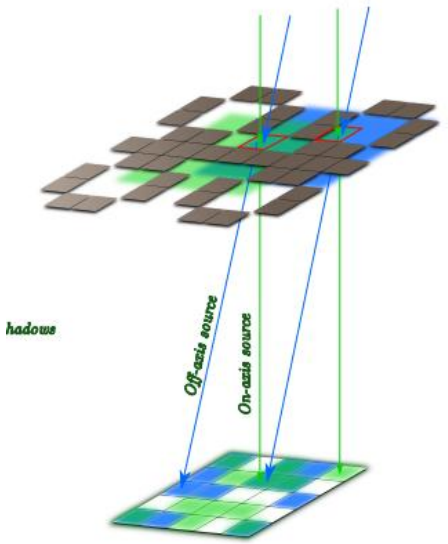


Coded aperture (CA) masks

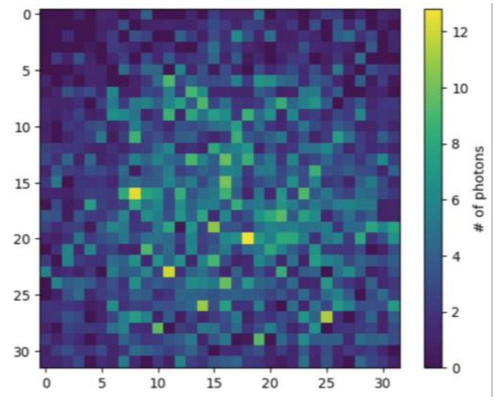


- A Coded aperture mask is a thin sheet of opaque material with a well-defined pattern of holes placed at a fixed distance from a sensor plane.
- conceptually the evolution of a single pinhole camera
  - A matrix of multiple pinholes improves light collection
- Advantages:
  - Light transmission (depends on mask pattern/holes size, usually ~50%)
  - Compact design
  - Robust and easy to build

concept



DUNE simulation



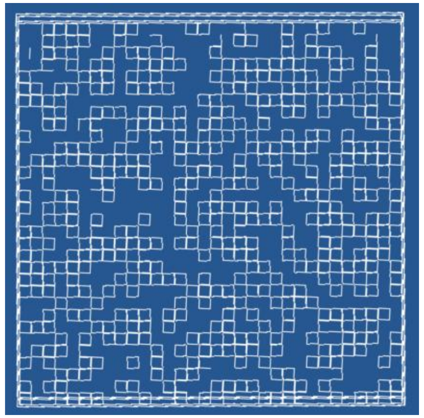
The image formed on the sensor is the superimposition of multiple pinhole images

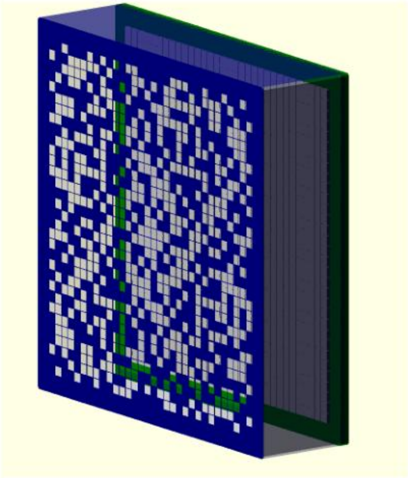
GRAIN CA imaging system

- **Sensor matrix:**
  - 32 x 32 SiPM
  - SiPM active area: 3x3 mm^2
- **Coded aperture mask**:
  - Random uniform pattern of holes
  - Holes aligned to SiPMs, area: 3x3 mm^2
  - Distance from sensors: 3 cm

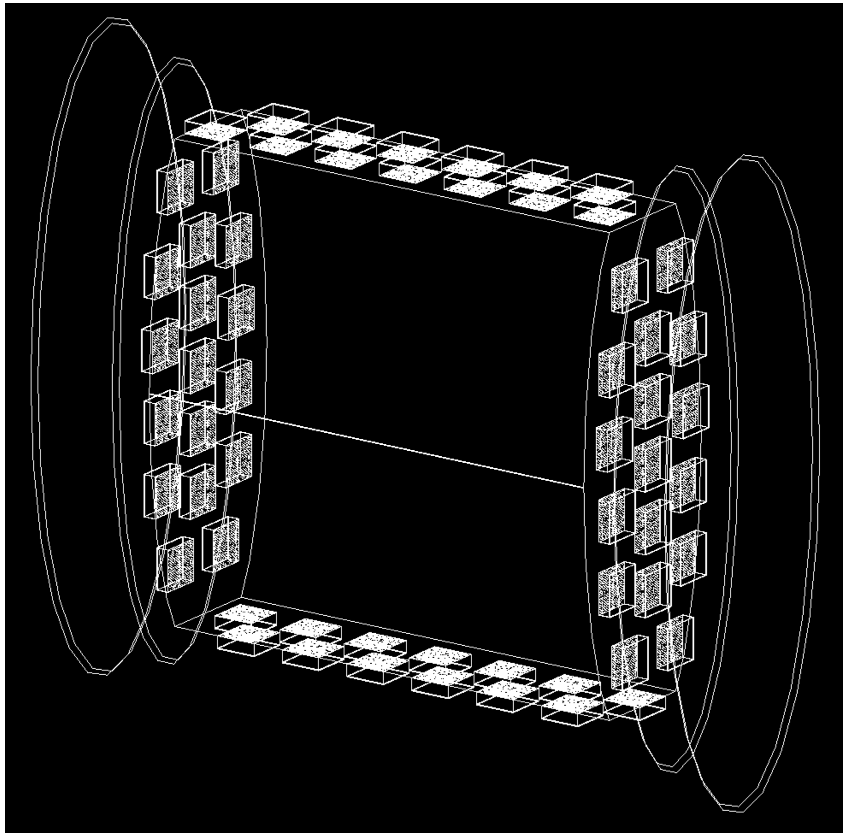
- 60 cameras in GRAIN

Mask pattern



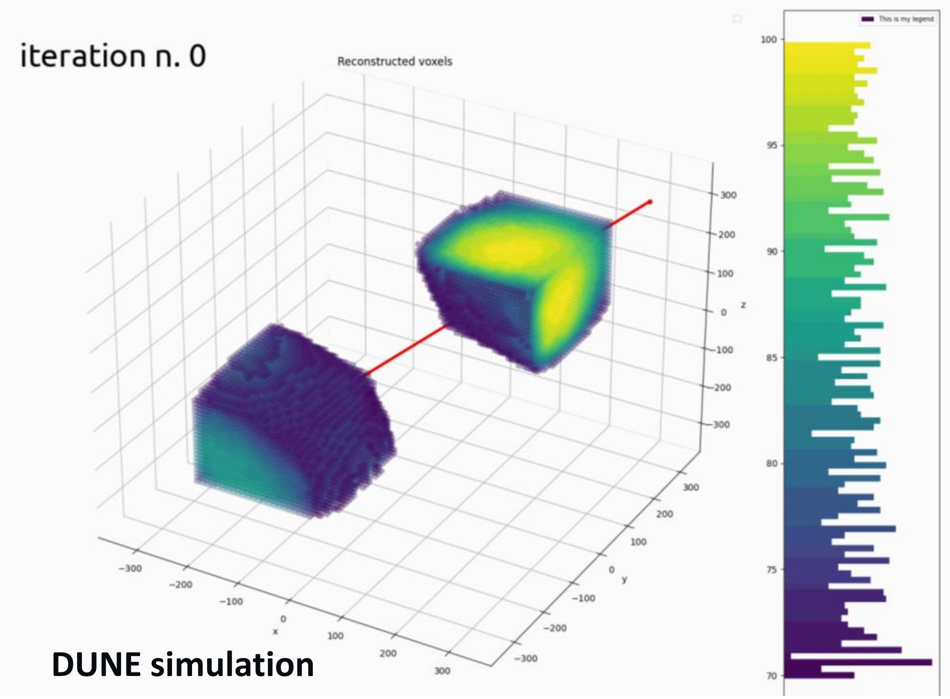


Camera design was optimized with simulations in simplified geometry [3]

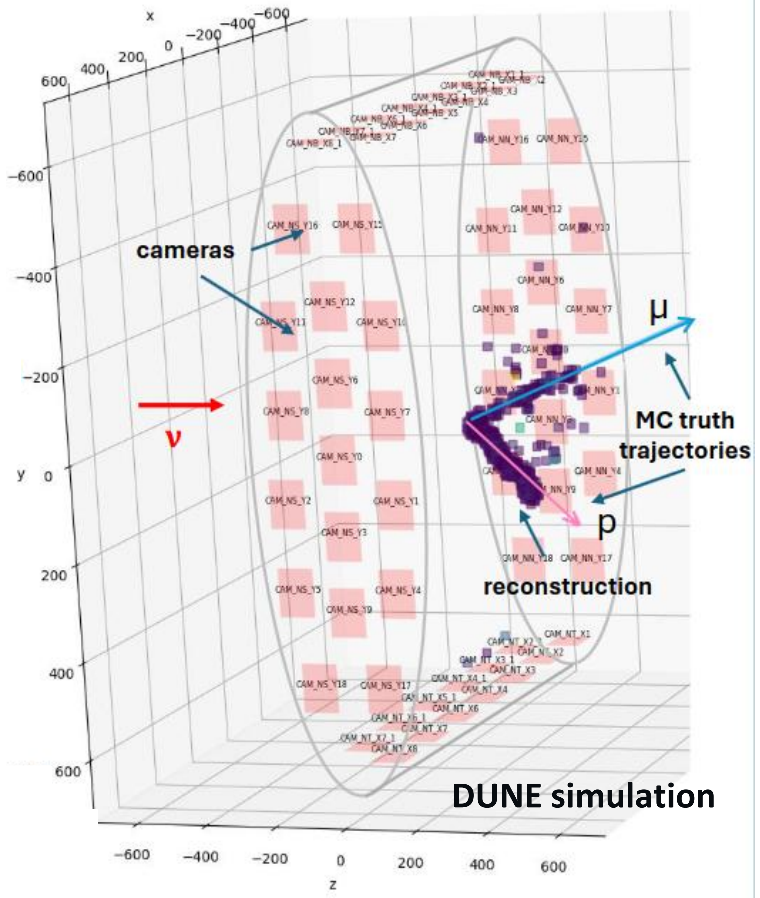


GRAIN CA reconstruction algorithm

- 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



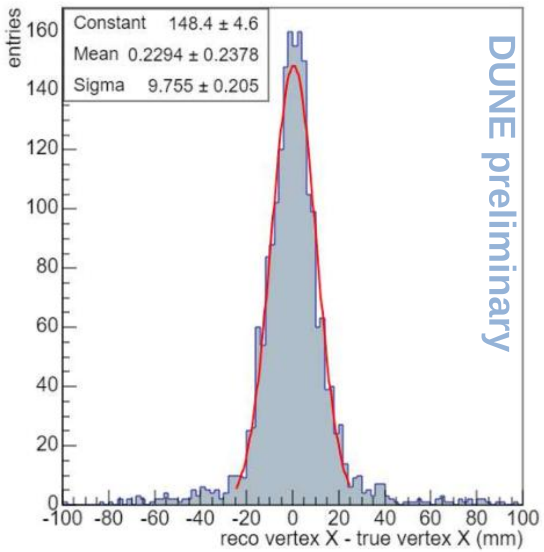
CA performances – CCQE events

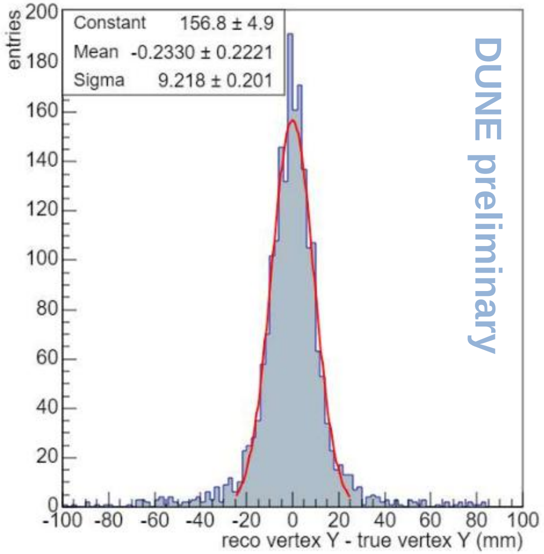


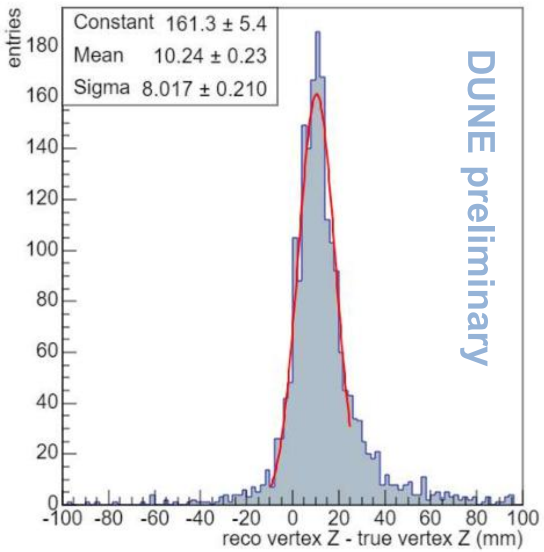
18 mm voxel size
200 algorithm iterations

Simulated sample:
4000 ν – Ar Charged Current Quasi-Elastic scattering in LAr

Challenges:
Identifying clusters of voxels as tracks





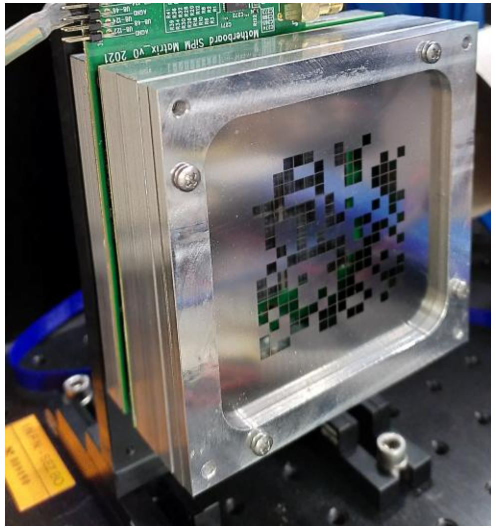


Camera prototypes

- Built 2 camera prototypes:
  - 16 x 16 channels
  - Interchangeable SiPM matrices: 1x1 and 3x3 mm^2

- Front end electronics with 8 ALCOR ASIC [4]
- DAQ with a Xilinx FPGA board
- to be tested in LAr at ARTIC facility at Genoa with artificial light sources and cosmic rays

CA mask



Lens

FPGA

SiPM matrix
(3 mm pitch)

Front–end board
with 8 ALCOR

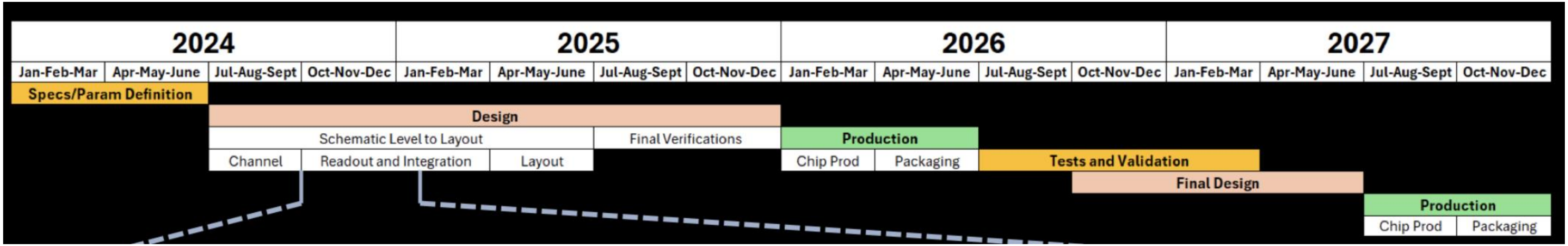
Enabling technology: readout ASIC

Cryogenic ASIC Requirements:

- 1024 channels
- Power consumption limits: **5 mW per channel**
    - considering 50 x10^3 channels as baseline and beam duty cycle
- Measure detected charge and time of arrival of photons
    - Must be able of separating pulses more than *O*(100)ns apart

DENEB ASIC
(*DUNE Integrated Electronics for Neutrino Beams*)
is currently under development by INFN Torino group

Timeline:



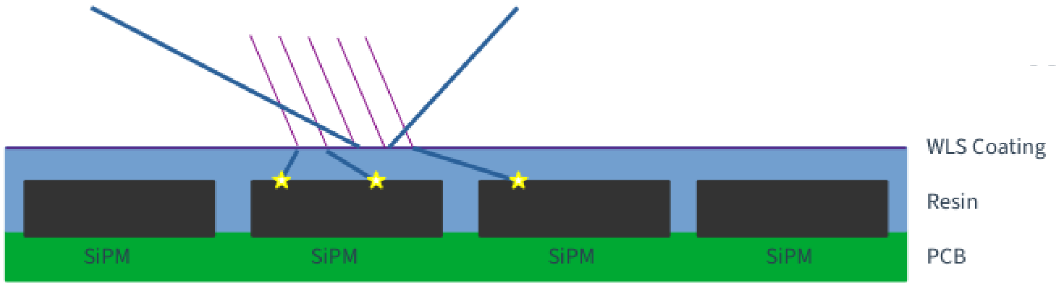
Related developments: VUV sensitivity

WLS based solutions for VUV sensitivity

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

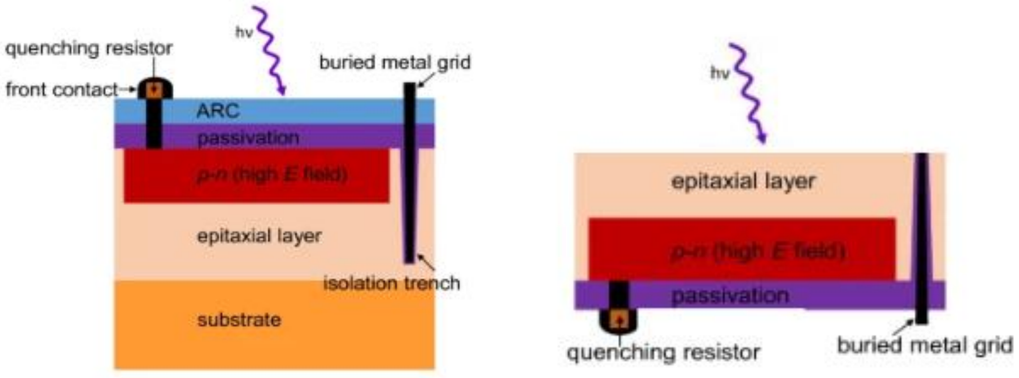
BUT

WSL coatings on the sensor re-emit light isotropically, which adds noise to the image data



Innovative Backside Illumitaded 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 →**Higher PDE**
- Back contact allows high density wafer-level bonding to a readout ASIC → more, smaller pixels for **better resolution**, without sacrificing Fill Factor



Summary and outlook

- SAND will **monitor and characterize** DUNE neutrino beam while also performing a rich physics program besides oscillations
- It will include **GRAIN,** an **innovative detector,** which will **exploit the argon scintillation light** to perform track and energy reconstructions.
- Two optical systems are being developed**: lens- and coded aperture-based cameras**
- A Cryogenic demonstrator with 2x256 pixel cameras is almost ready
- Cameras and a ASIC with 1024 pixel are under development

Bibliography

[1] B. Abi *et al.* (DUNE Collaboration), "DUNE TDR volume III. Dune far detector technical coordination", *JINST* 15 T08009 (2020)

[2] M. Vicenzi, "A Grain of SAND for DUNE: Development of simulations and reconstruction algorithms for the liquid Argon target of the SAND detector in DUNE", PhD Thesis, University of Genova (2023).

[3] V. Cicero, "Study of the tracking performance of a liquid Argon detector based on a novel optical imaging concept", PhD Thesis, University of Bologna (2023)

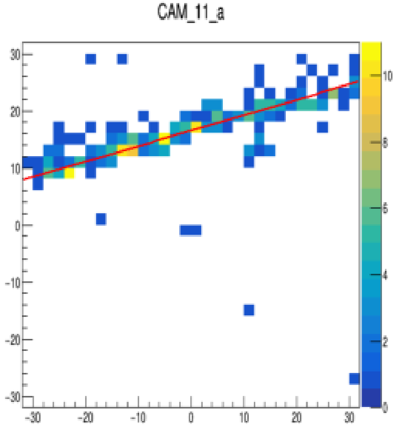
[4] F. Cossio et al. "ALCOR: A mixed-signal ASIC for the dRICH detector of the ePIC experiment at the EIC" Nuclear Instruments and Methods in Physics Research A 1096 (2024)

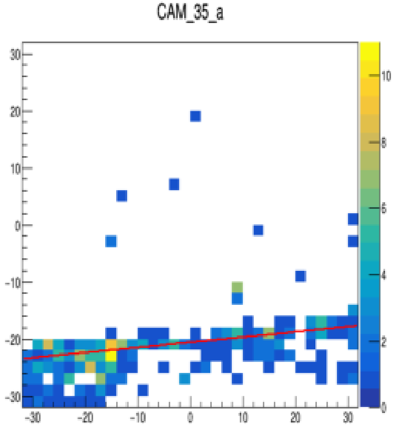
Backup slides

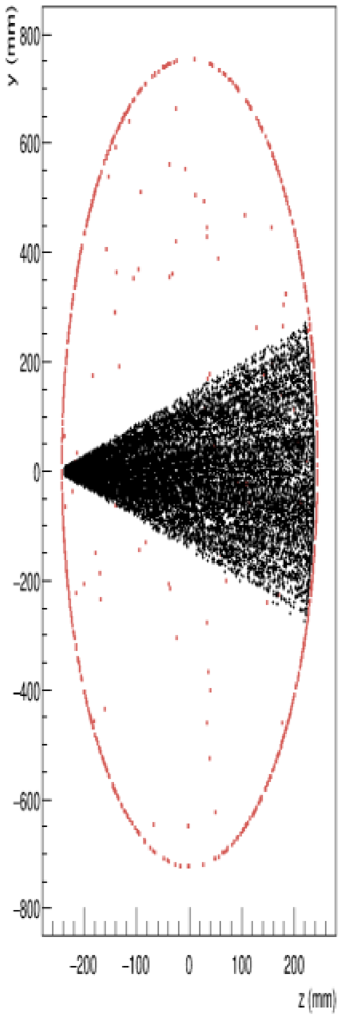
Lens simulated performances – muon tracks

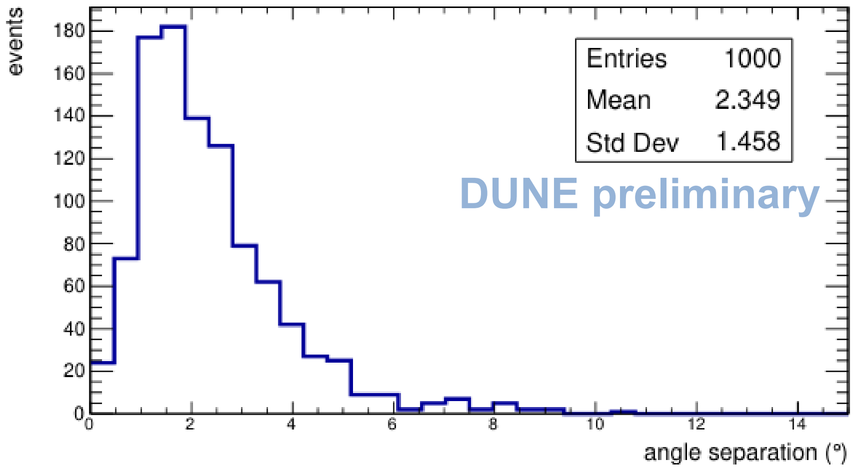
Simulated sample:

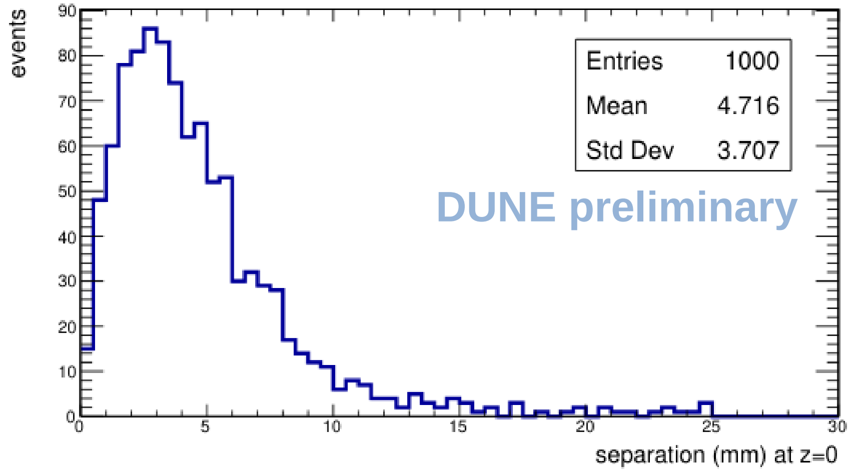
- 1000 muons in GRAIN volume
- Energy = 1 GeV
- Entry point (0,0,-25) cm with angle 0-30° w.r.t. Z axis











MLEM in numbers

Photon counting is described by a Poissonian pdf:

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

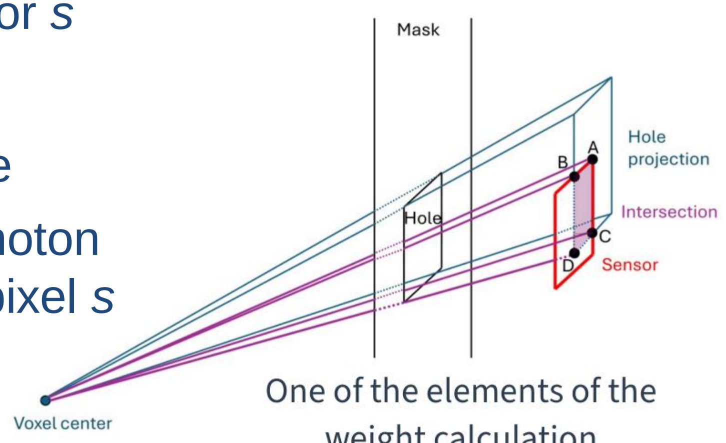
$$[\lambda_s] = \sum_j \lambda_j\, w(j,s)$$

H_s number of detected photons by sensor *s*

λ_j unknown photon emission in voxel ***j***

$[\lambda_s]$ detected photons expectation value

w(j,s) is the weight → probability of a photon that originated in voxel *j* is detected by pixel *s*



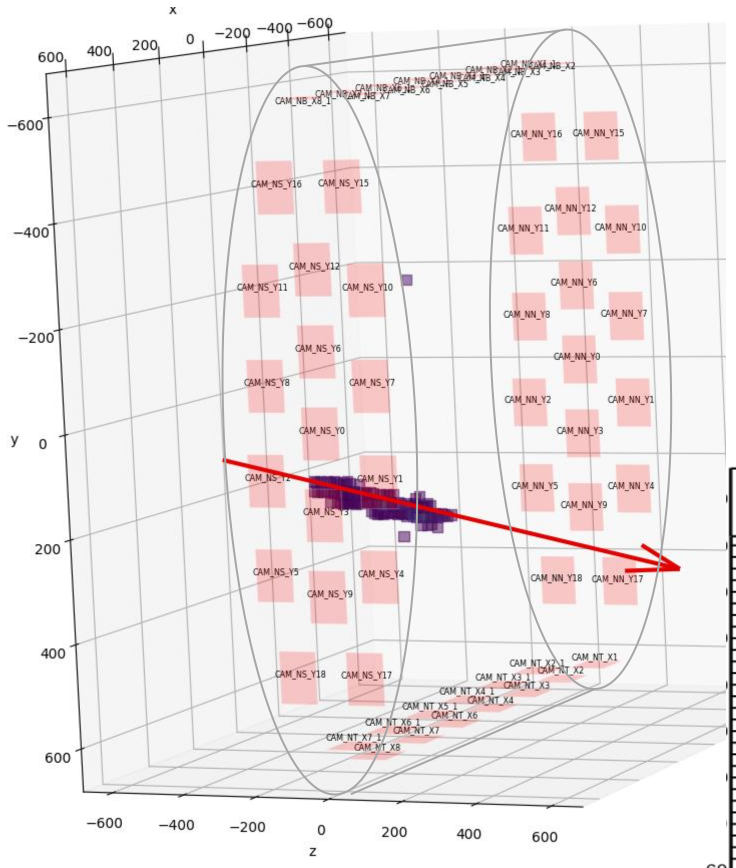
One of the elements of the weight calculation

The likelihood for all sensors must be **maximized iteratively:**

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

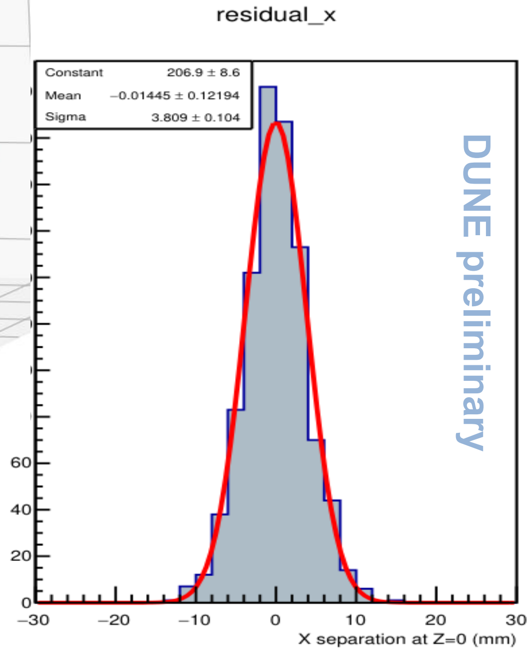
k iteration number

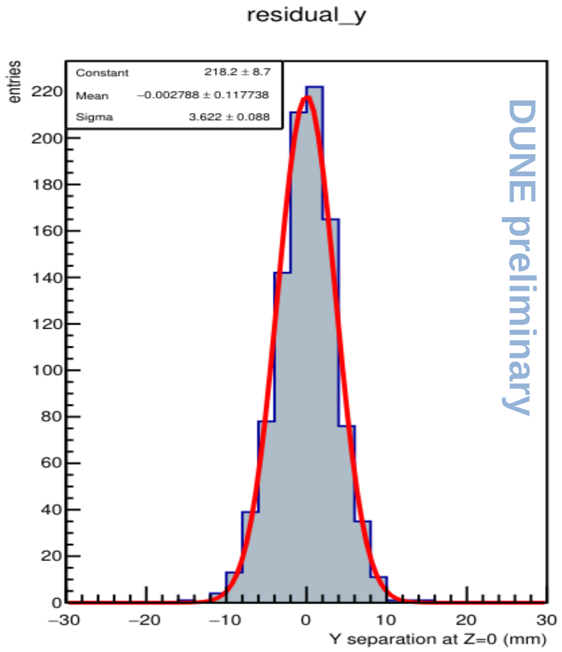
CA Simulated performances – muon tracks

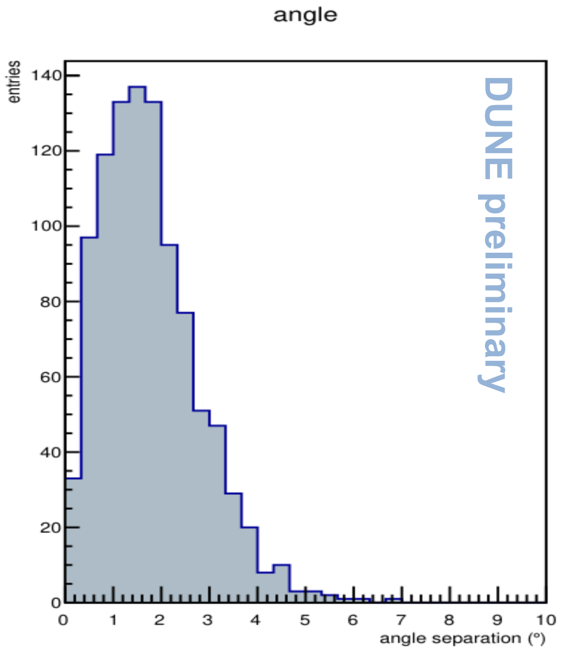


Simulated sample:
- 1k muons crossing GRAIN along the neutrino beam direction
- E = 1.0 ± 0.3 GeV, Gaussian distributed
- origin ([-30, + 30], [-30, + 30], -50) cm
- Direction: θ = 0°-20° w.r.t z axis

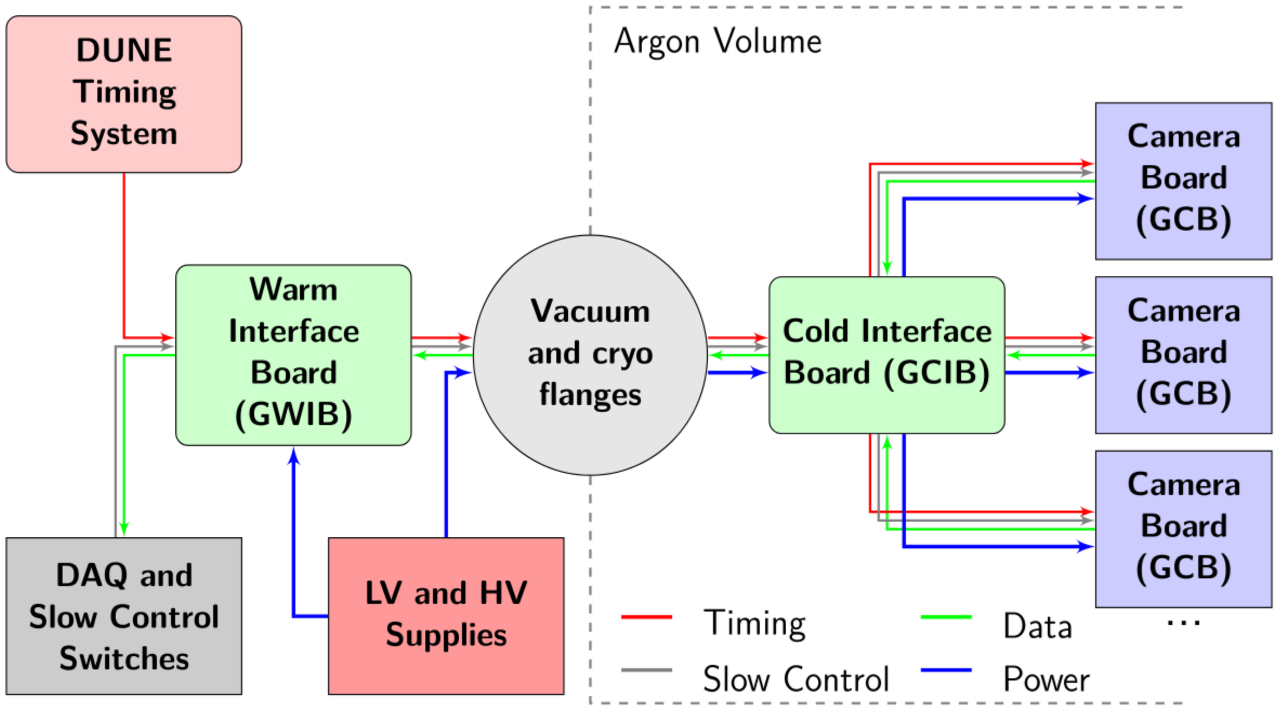
18 mm voxel size
200 algorithm iterations

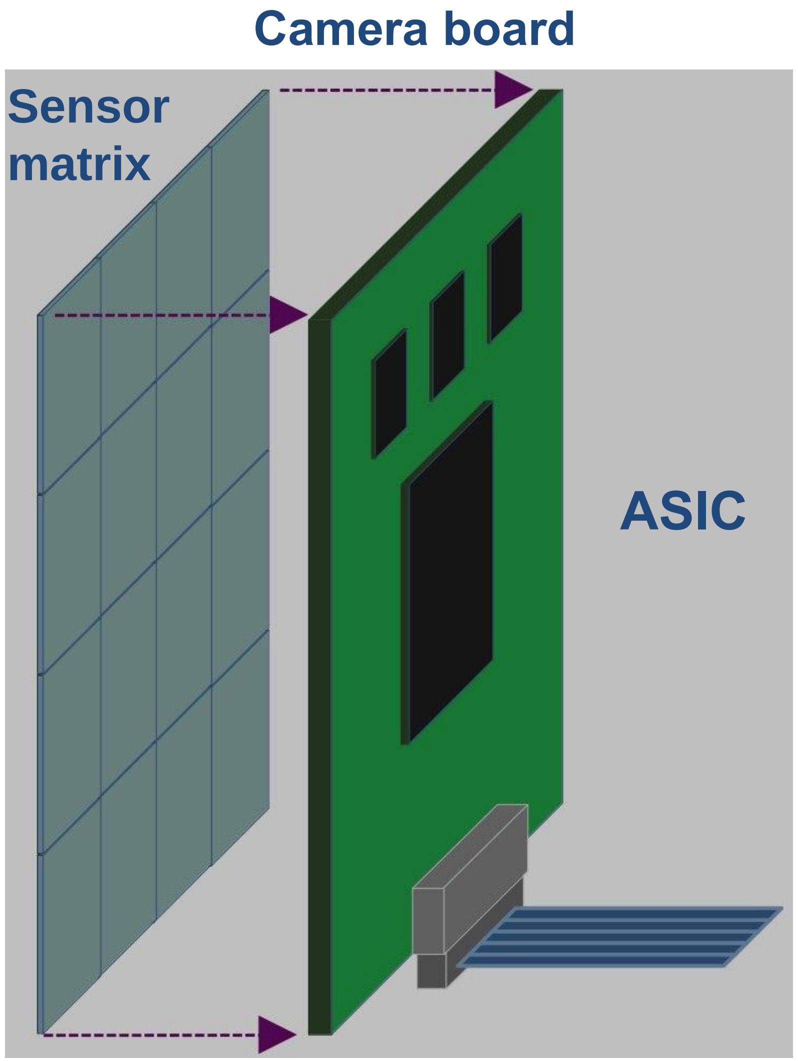






GRAIN readout and DAQ





- Camera board: ASIC and SiPMs
- Cold Interface: reduce connections
- Warm interface: DAQ and Timing endpoint

Expected interactions in GRAIN