Liquid Argon Detectors for GeV Neutrinos

Alessandro Montanari INFN BOLOGNA

INFN Workshop on Future Detectors – 18 Oct 2022

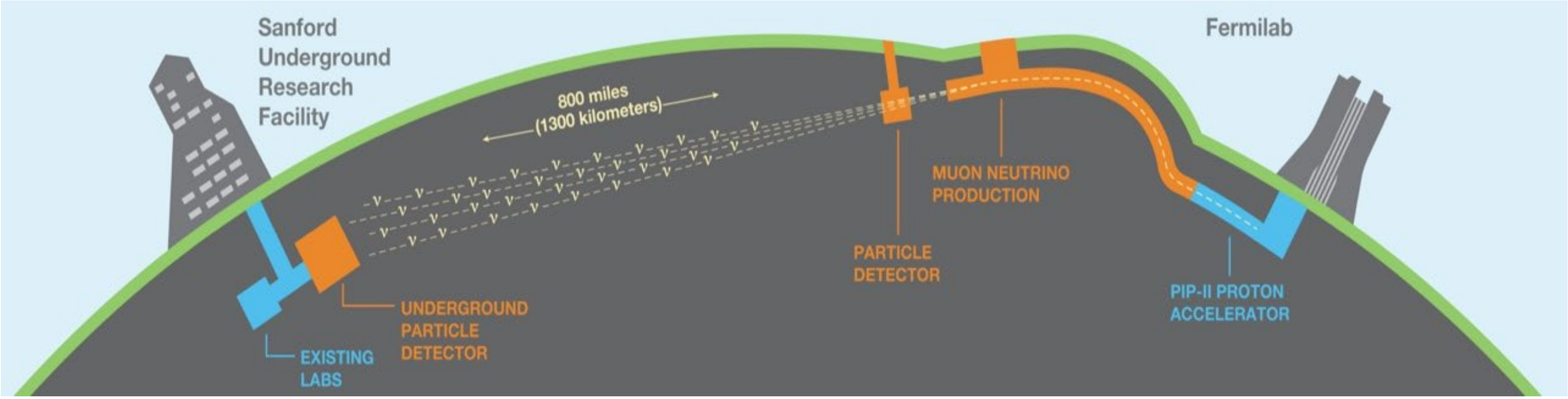
OUTLINE

DUNE experiment will exploit 4 different technologies:

- TPC Horizontal Drift (à la ICARUS) → Consolidated Technology (anode: wires)
- TPC Vertical Drift → Simplified Technology (anode: PCB)

- TPC Horizontal Drift Modular → High occupancy (anode: pixel)
- Scintillation light for imaging → Innovative (use only scintillation light)

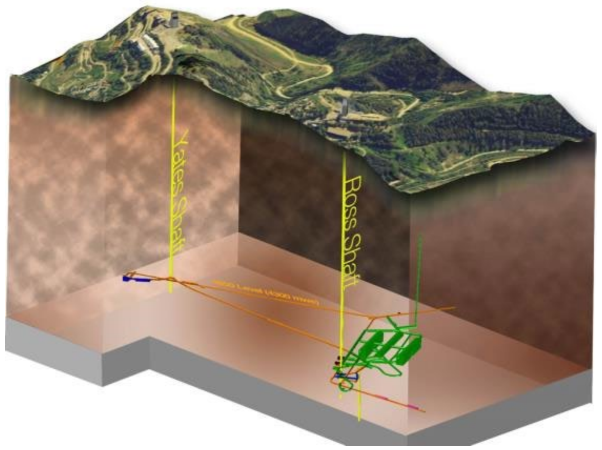
The Deep Underground Neutrino Experiment

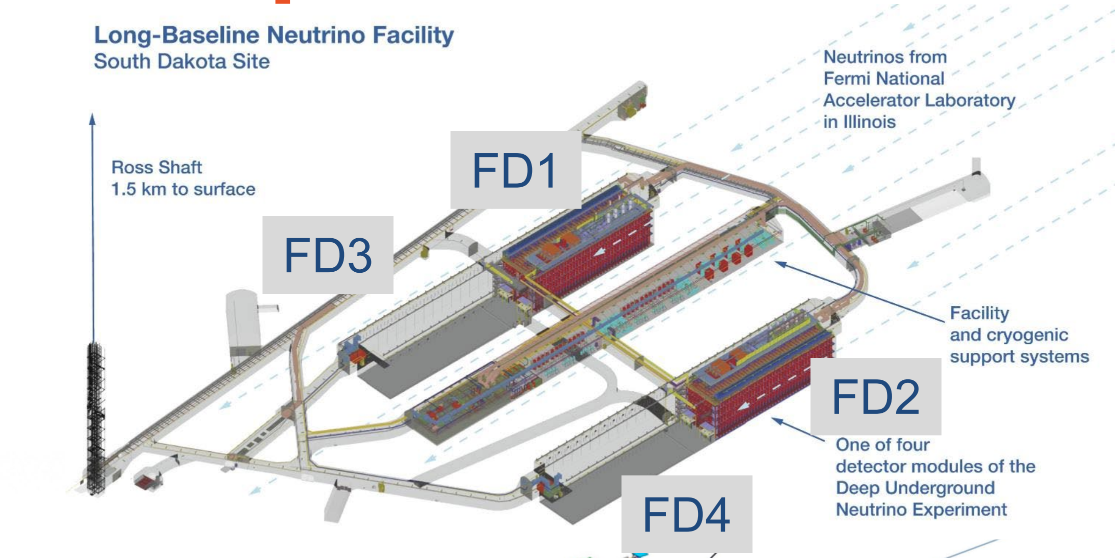


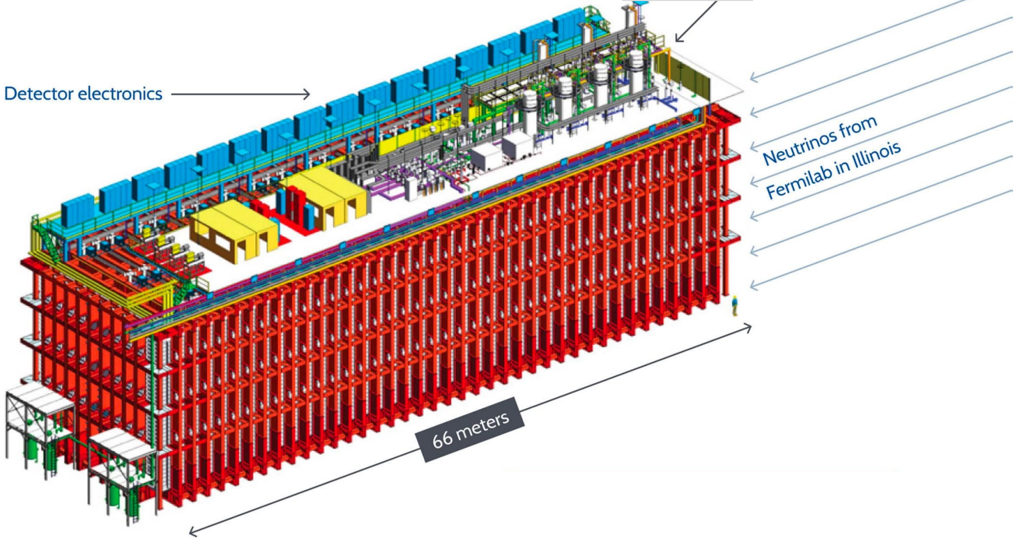
- Next generation long baseline neutrino experiment: 1300 km from Fermilab to SURF (South Dakota), 4300 m water equivalent depth
- Very intense wide band ν_μ / anti-ν_μ beam (0.5 – 7 GeV): 1.2 MW, upgradable to 2.4 MW
- Two detectors locations, Near/Far
- Giant Liquid Argon (LAr) TPC detectors as Far Detector (FD, total 70 kTons)
- Near Detector (ND) is a complex including a Segmented LAr (67 kTons) + Small LAr (1 kT)
- Worldwide Collaboration: 1300+ people, 200+ institutions including CERN, 34 countries

The DUNE Far Detector complex

- Four independent detector modules:
  - **Single Phase LAr-TPC** modules, 17 kT mass each module (62x14x15 m^3)
    - FD1: Horizontal Drift (HD)
    - FD2: Vertical Drift (VD)
    - FD3: Ongoing R&D
    - FD4: Ongoing R&D





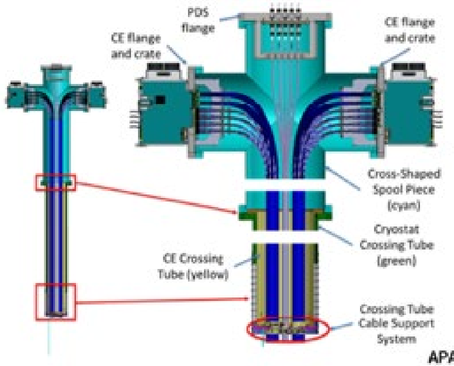


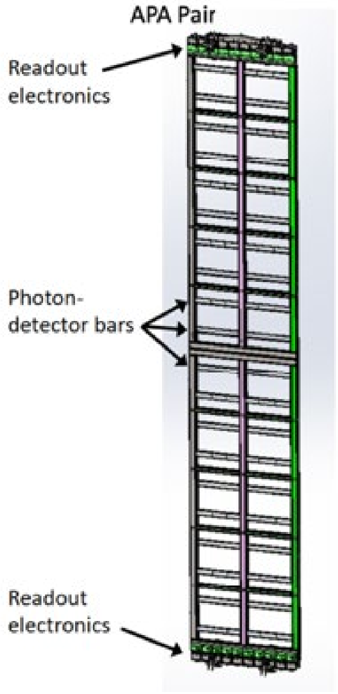
FD1

FD1: LAr-TPC Horizontal Drift technology

- Alternate Anode and Cathode Planes Assemblies (APA/CPA)
  - Segmented: 4 drift volumes, drift distance: 3.5 m
  - Electric field = 500 V/cm (HV= -175 kV)
  - High resistivity CPAs to prevent fast discharges
  - Anode: 150 APAs (6x2.3 m^2) 4 wire planes each grid, 2x Induction, Collection
  - Wire pitch 4.7 mm
  - Full cryogenic readout chain (analogue FE+ Digitizer) – 385000 channels

- Photon Detectors:
  - X-ARAPUCA SiPM based light traps integrated into APA frame





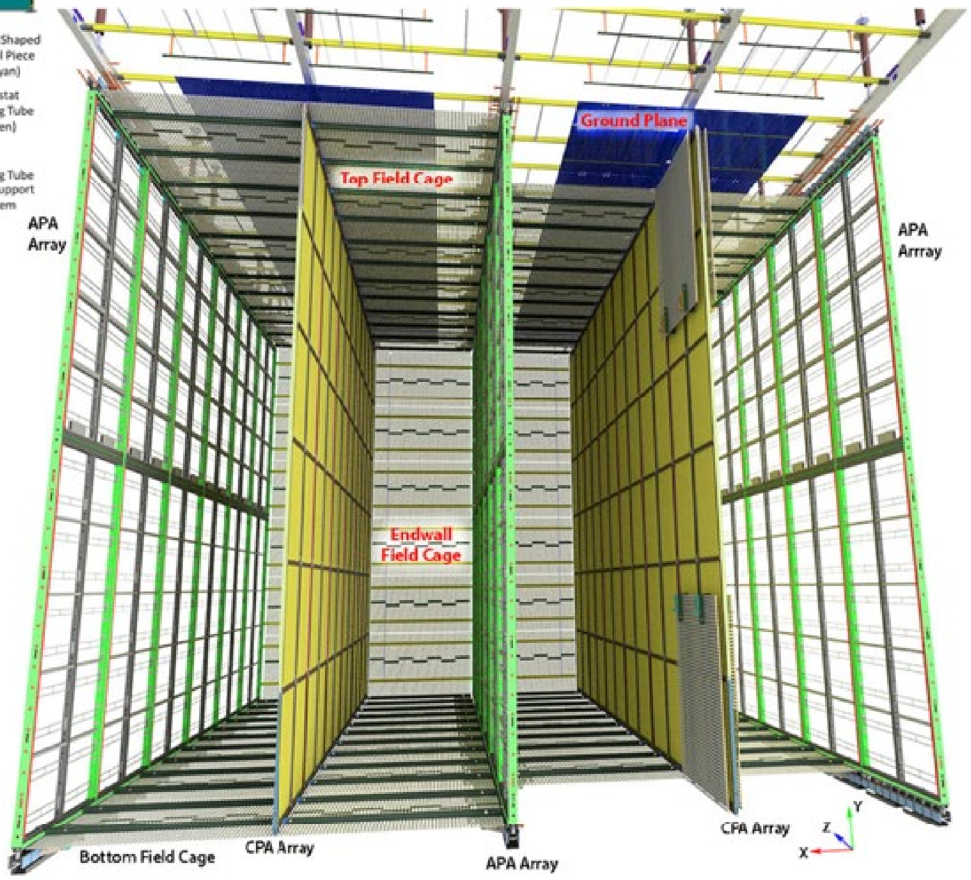
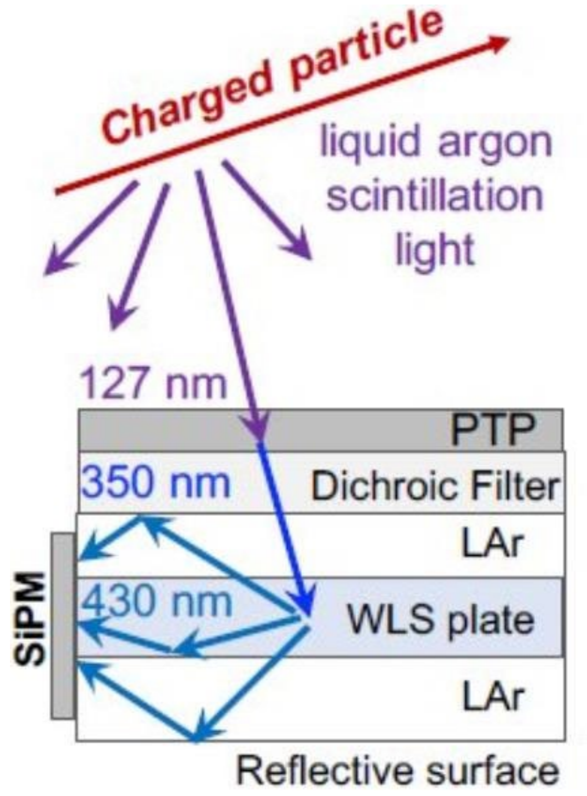


Photo Detector System: X-Arapuca

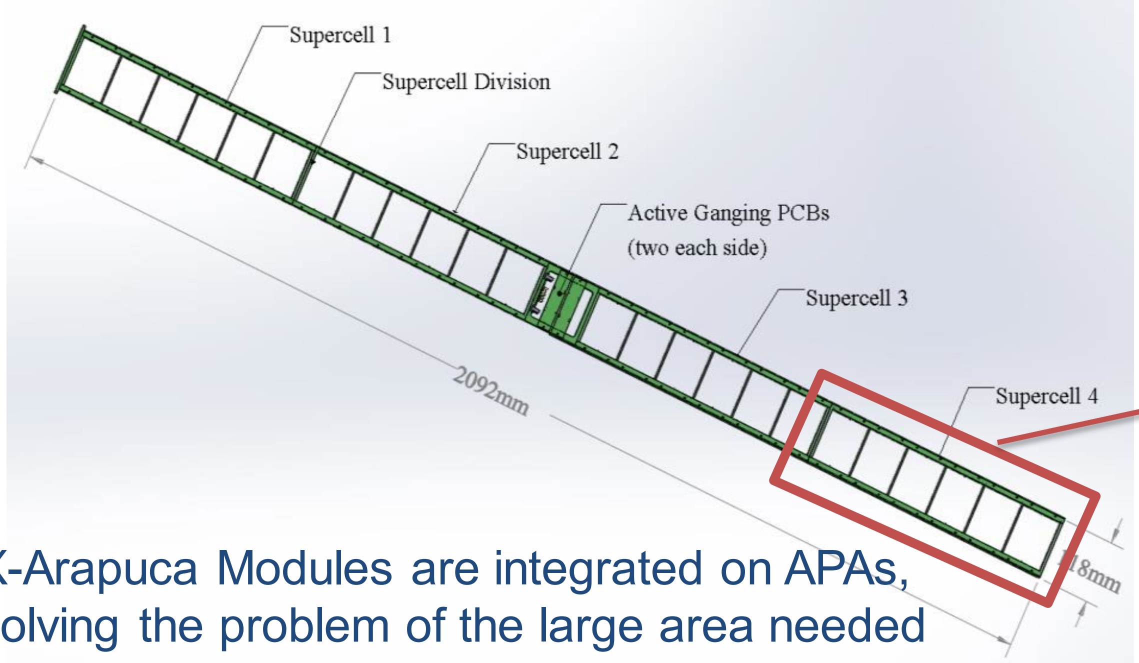
- **Challenges**
  - Emitted photon wavelength 128 nm
    - Difficult detection
    - Easily absorbed by impurities
  - Large detection area is needed but there is not available space for large area Photomultipliers

- **X-Arapuca advantages**
  - It traps the light and shift photons' wavelength to ~128nm
  - More light opens additional physics opportunities like calorimetry and triggering

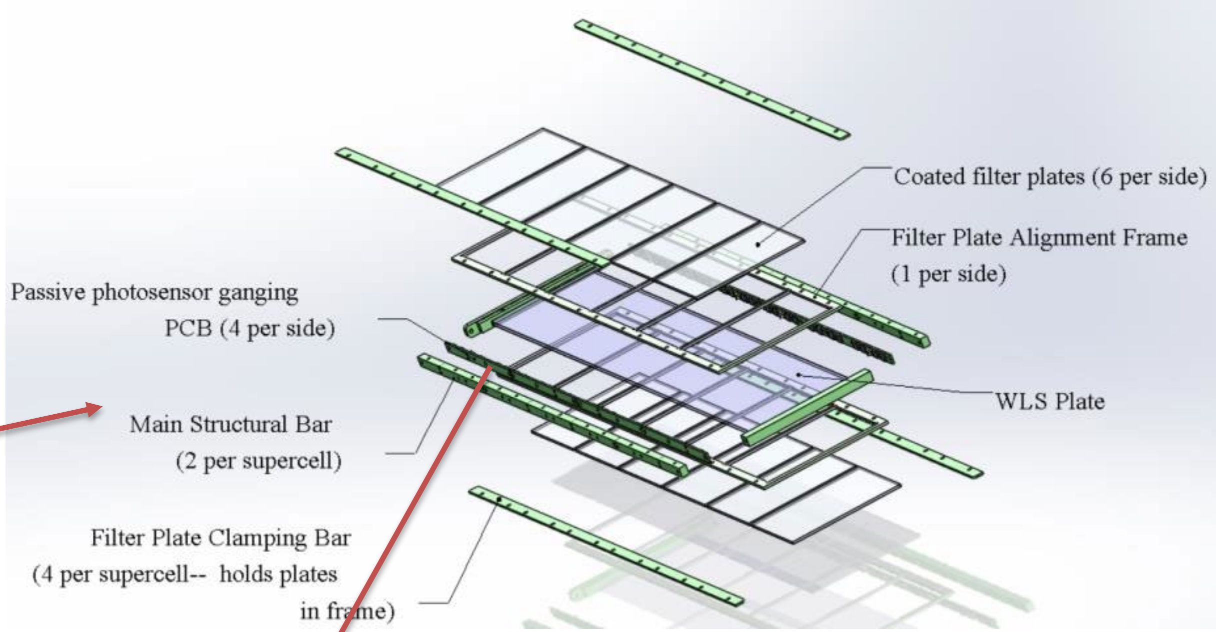


Photon Detection System (HD): X-Arapuca

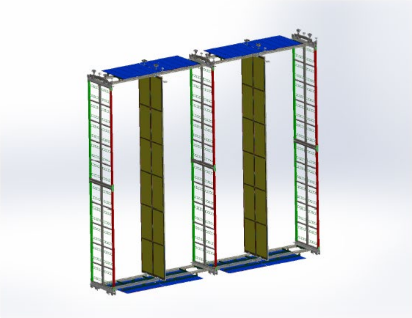
X-Arapuca Module

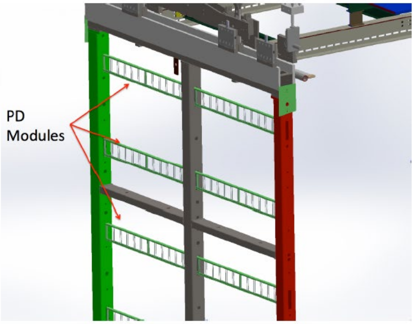


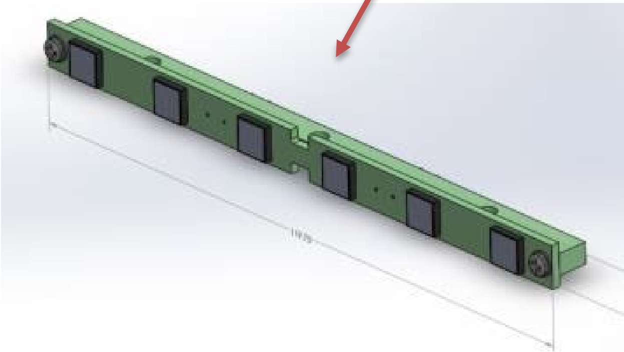
X-Arapuca Assembly



X-Arapuca Modules are integrated on APAs, solving the problem of the large area needed (10 modules x APA)



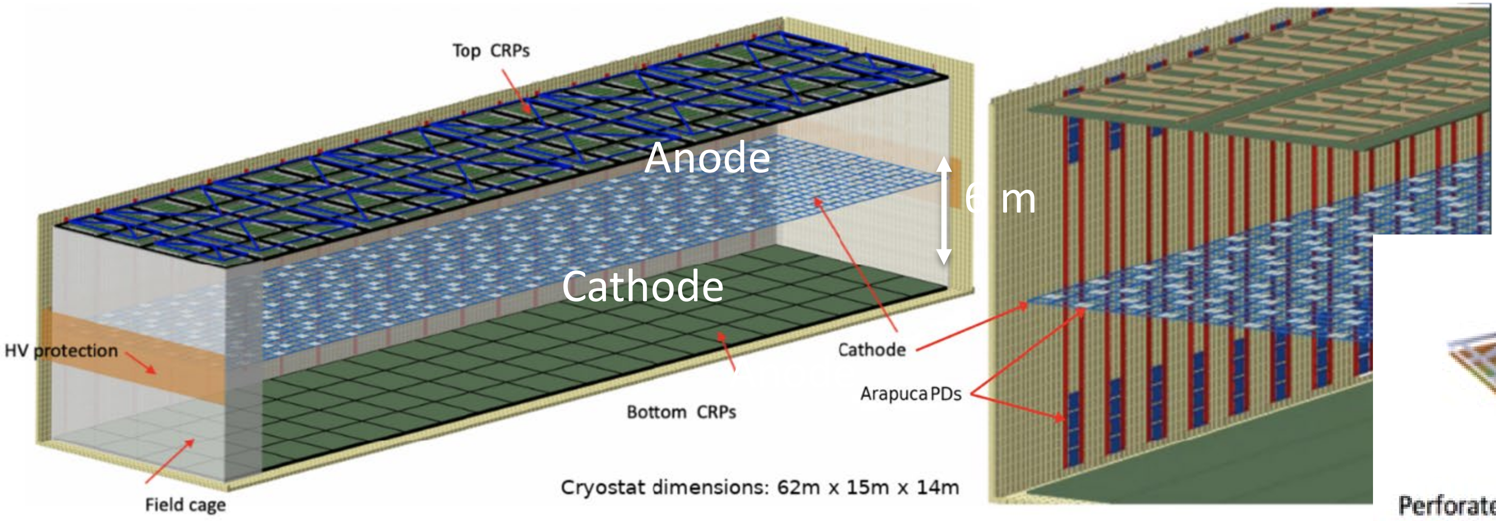


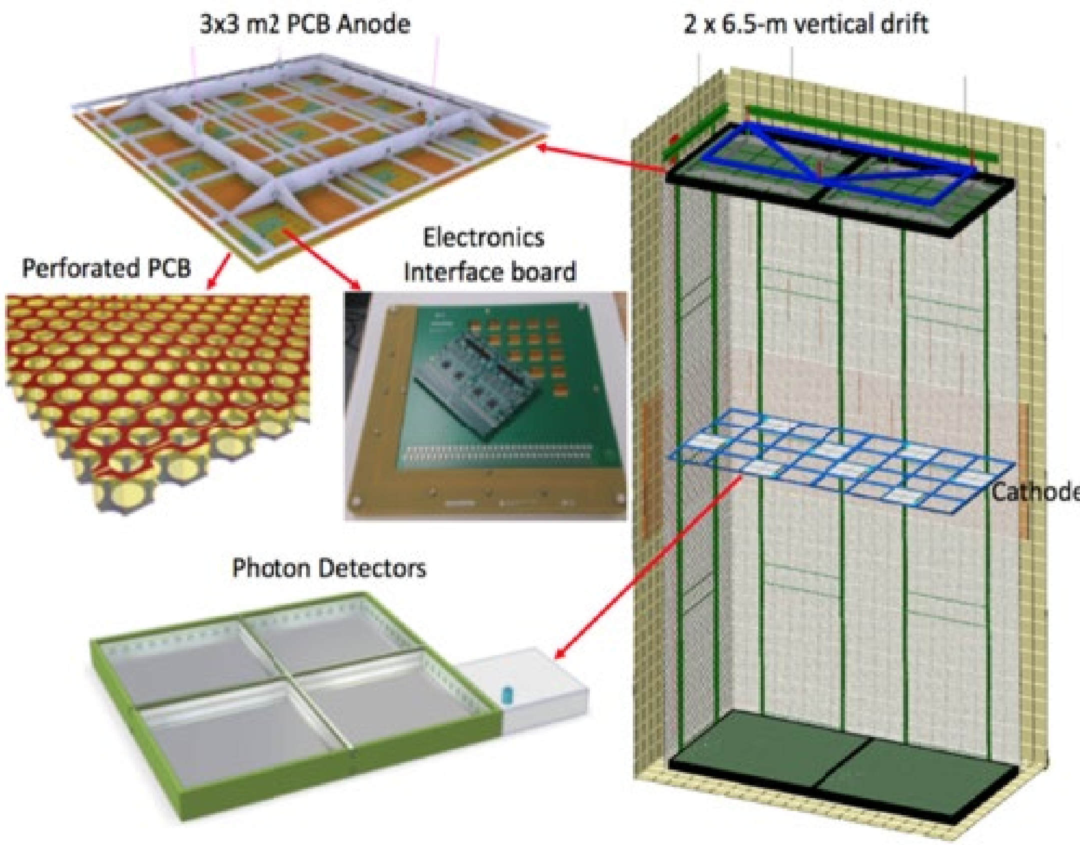


Photosensors:
6x6 mm^2 SiPMs

FD2

FD2 Vertical Drift technology



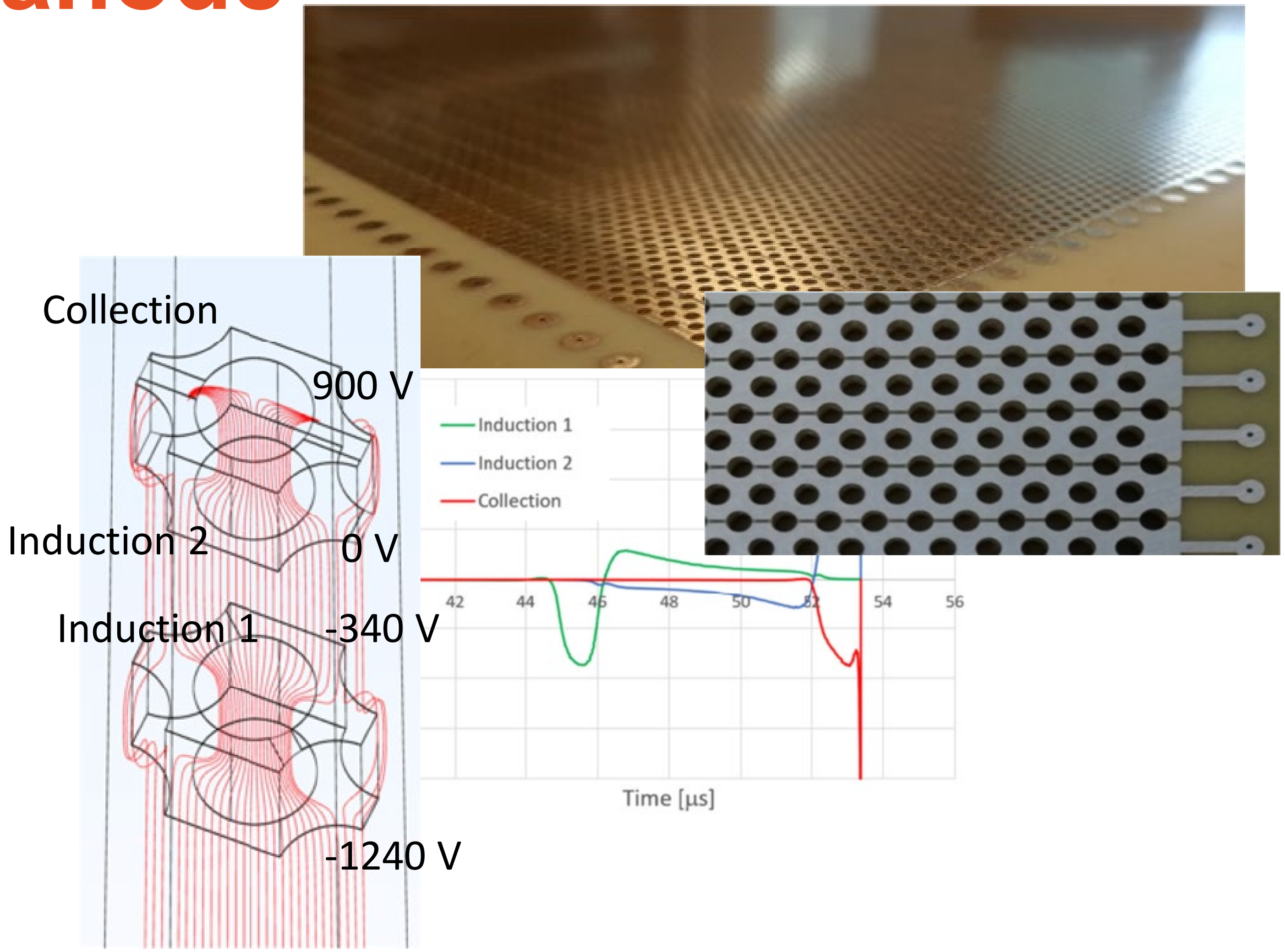


From experience on the R&D with ProtoDUNE, new solution for the FD2 design:

- Outstanding LAr purity → Long drift possible
- Excellent S/N for electronics → amplification in gas not needed
- Vertical Drift layout simpler to install, PCB boards for anodes exportable to industry → reduce cost and time
- Xenon doping improves light yield more uniform light collection over large distances

Perforated PCB anode

- LAr TPC readout with perforated multilayer Printed Circuit Boards
  - Electrons are 2D focused in the PCB holes
  - Signals are induced on the strips on both sides as electrons approach and leave
- Improvements wrt wires:
  - Most components can be mass produced commercially
  - No risk of breaking wires, simple mechanics
  - Integration of FE electronics/cable connectors on interface PCBs
- The design took advantages of large area Thick GEMs

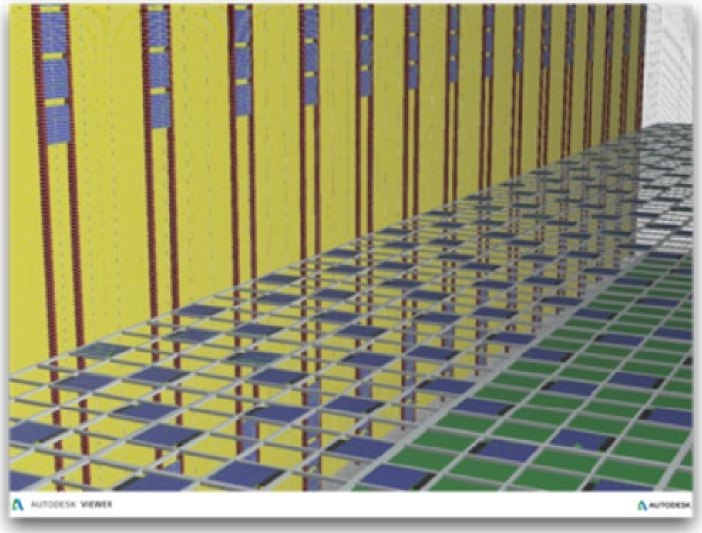


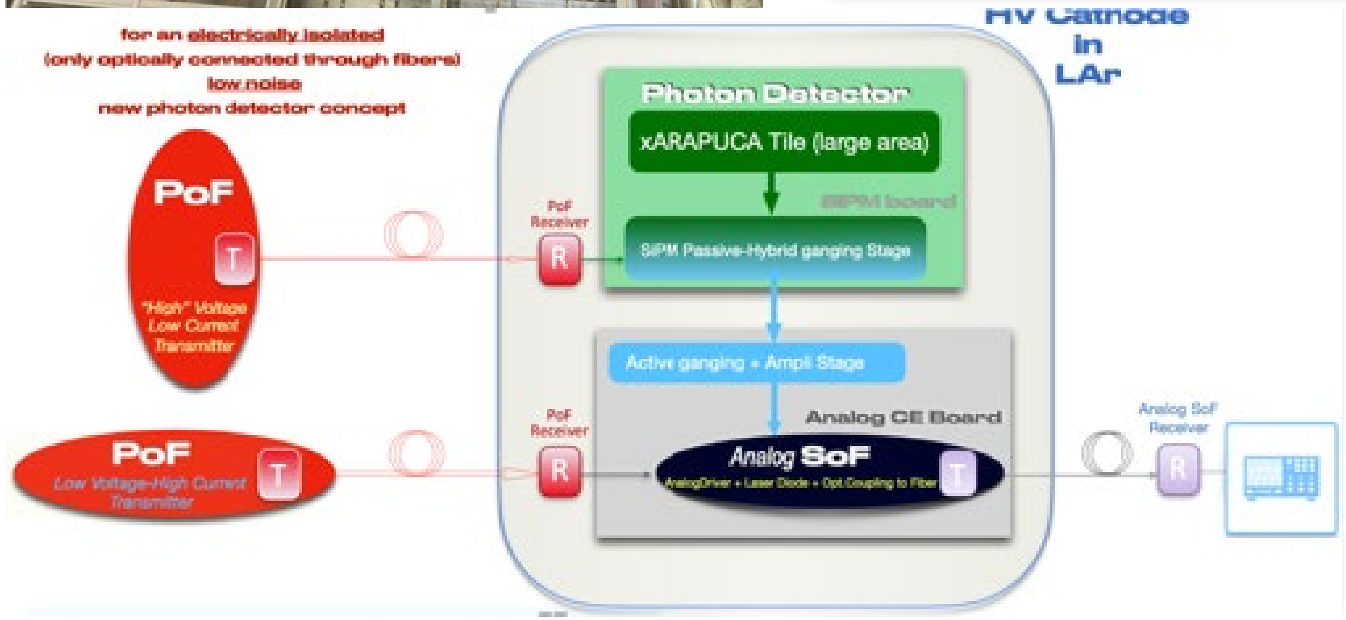
2 PCB stack, 3 views

PCB thickness 3.2 mm, distance 85 mm

Photon Detection System for VD

- PD modules (60 cm x 60 cm) based on X-Arapuca concept of HD
  - Placed on cathode and long walls
  - Xe doping (min Rayleigh scatter)
- Electrically floating photosensors and electronics
  - Power IN and Signal OUT via optical fiber

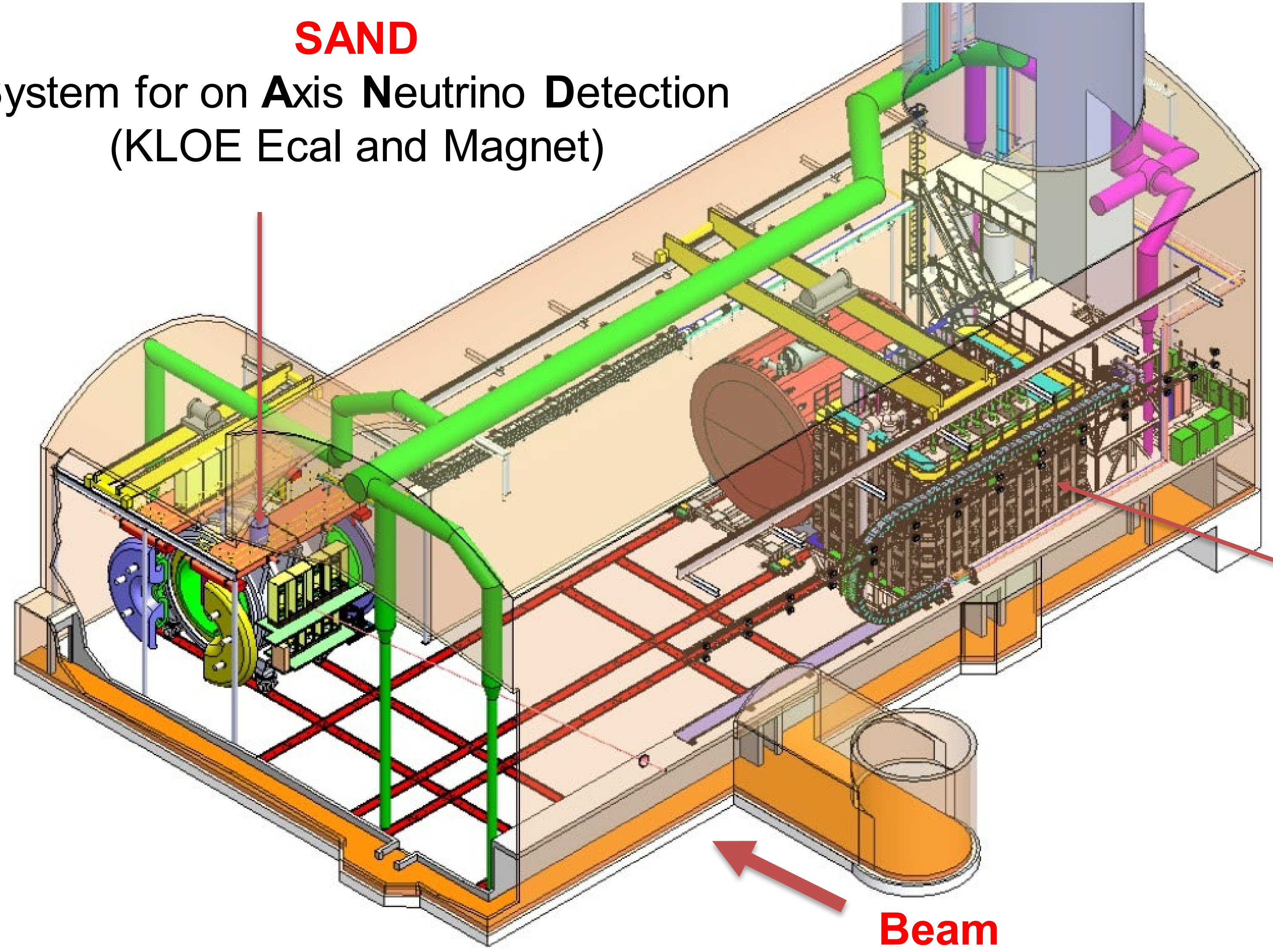




Near Detector Complex

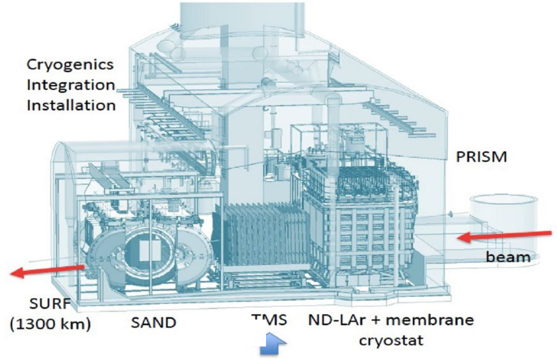
SAND

System for on **A**xis **N**eutrino **D**etection
(KLOE Ecal and Magnet)



ND-LAr

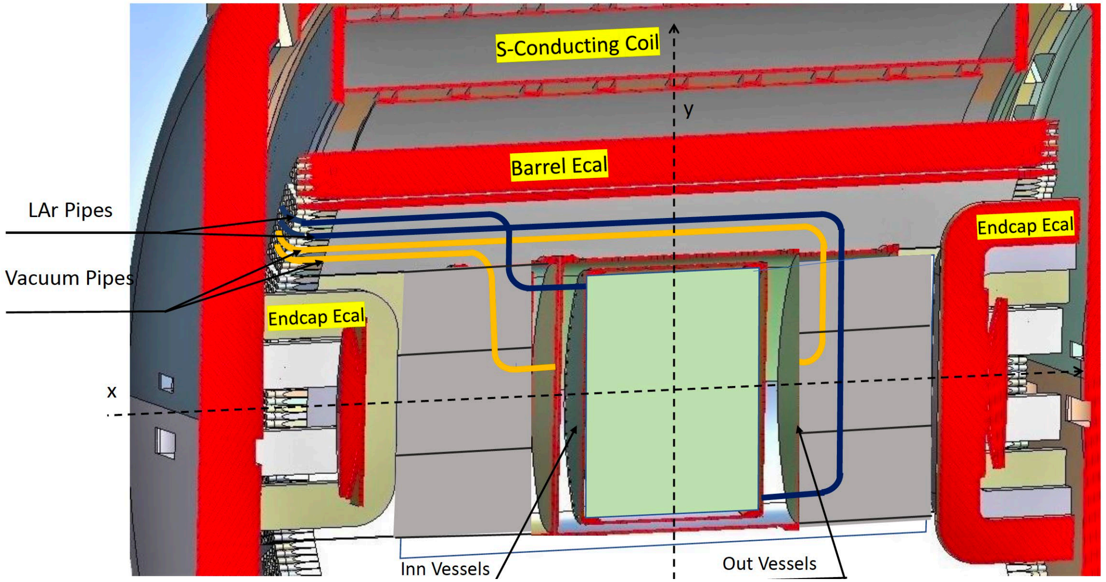
Beam

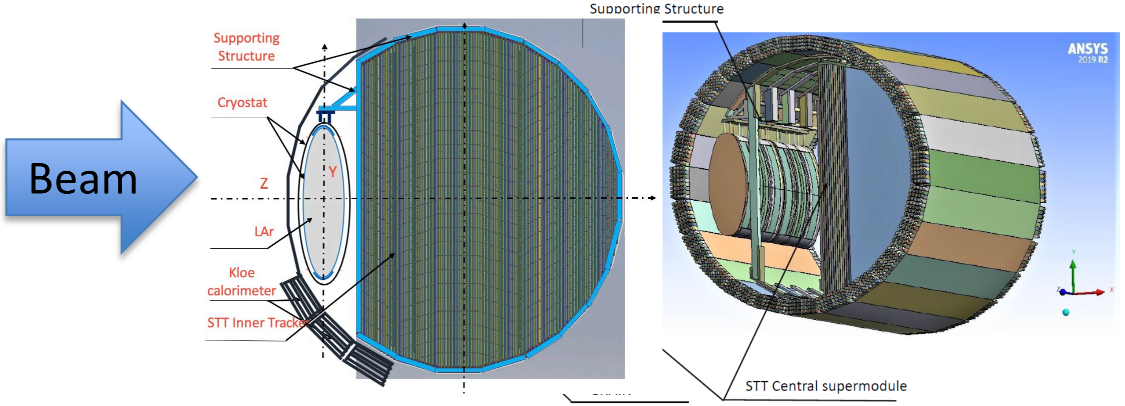


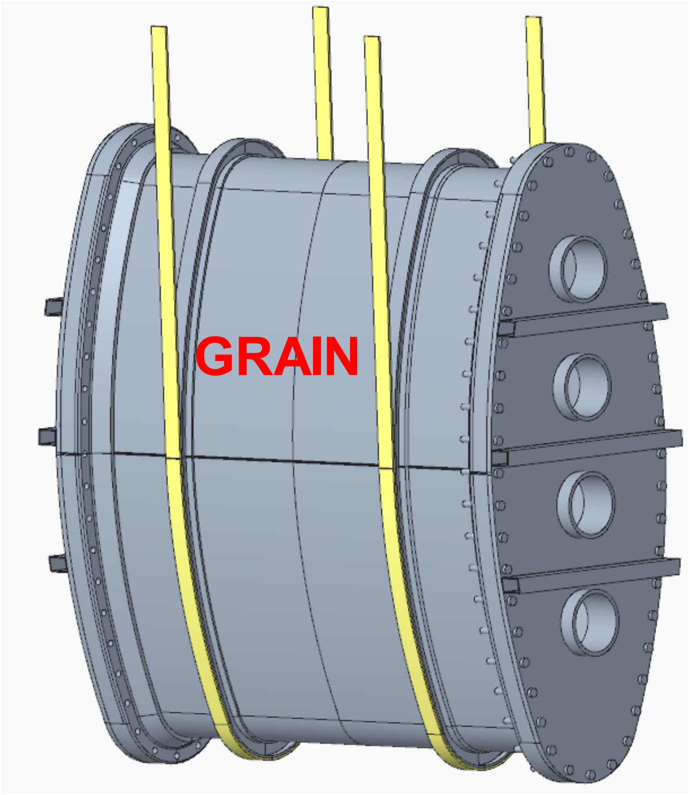
GRAIN

GRanular Argon for Interaction of Neutrinos

Inside ECAL: 1kton LAr + STraw Tubes for tracking







Innovative LAr imaging

Use only scintillation light to reconstruct tracks, we need:

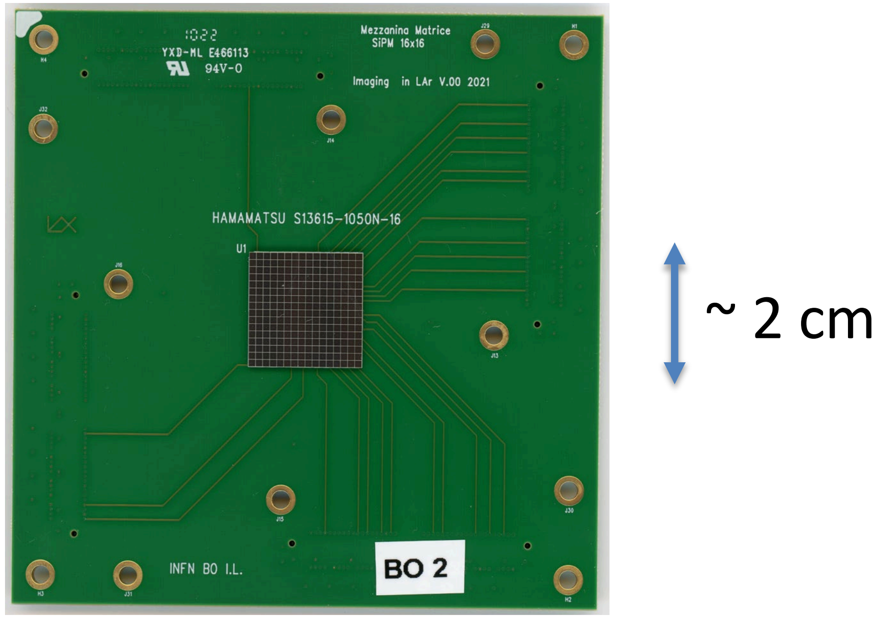
- Optics working at 128 nm:
  - **Coded Aperture Masks**
  - **Lens**

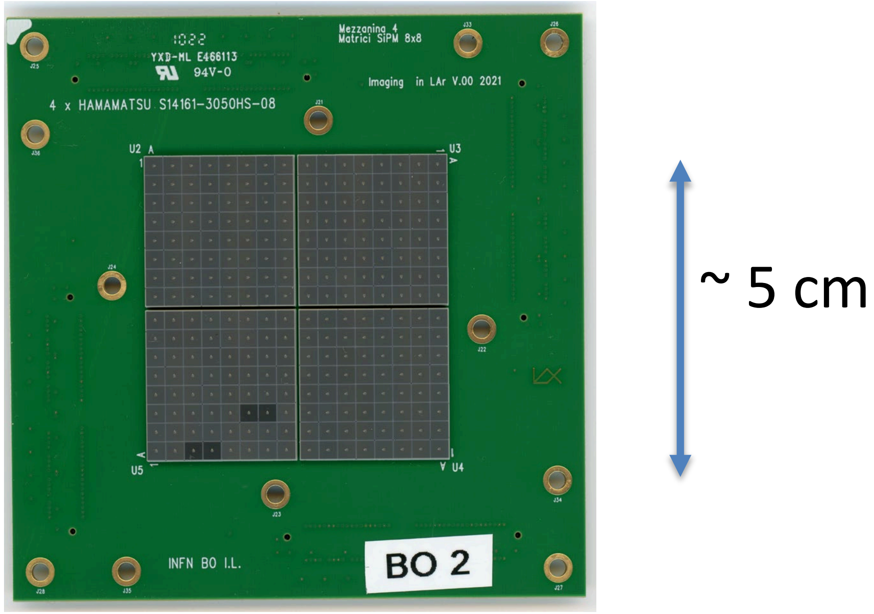
- Single Photon Photosensors:
  - **VuV sensitive SiPMs matrices** (TPB coating for WLS, Backside Illuminated??)

- LowPower crygenic electronics for High density channels:
  - **Cryogenic ASIC for SiPMs** (critical path !!!)

Photosensors for a demonstrator

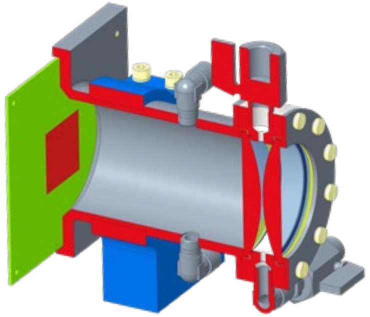
- Matrices of Silicon PhotoMultipliers
  - From Hamamatsu different models and sizes (to be coated with WLS)
  - Choose to work now with 16x16 matrices of 1x1 mm^2 or 3x3 mm^2 SiPM
  - 256 is the maximum channel count we can afford with presently available electronics (ASIC)



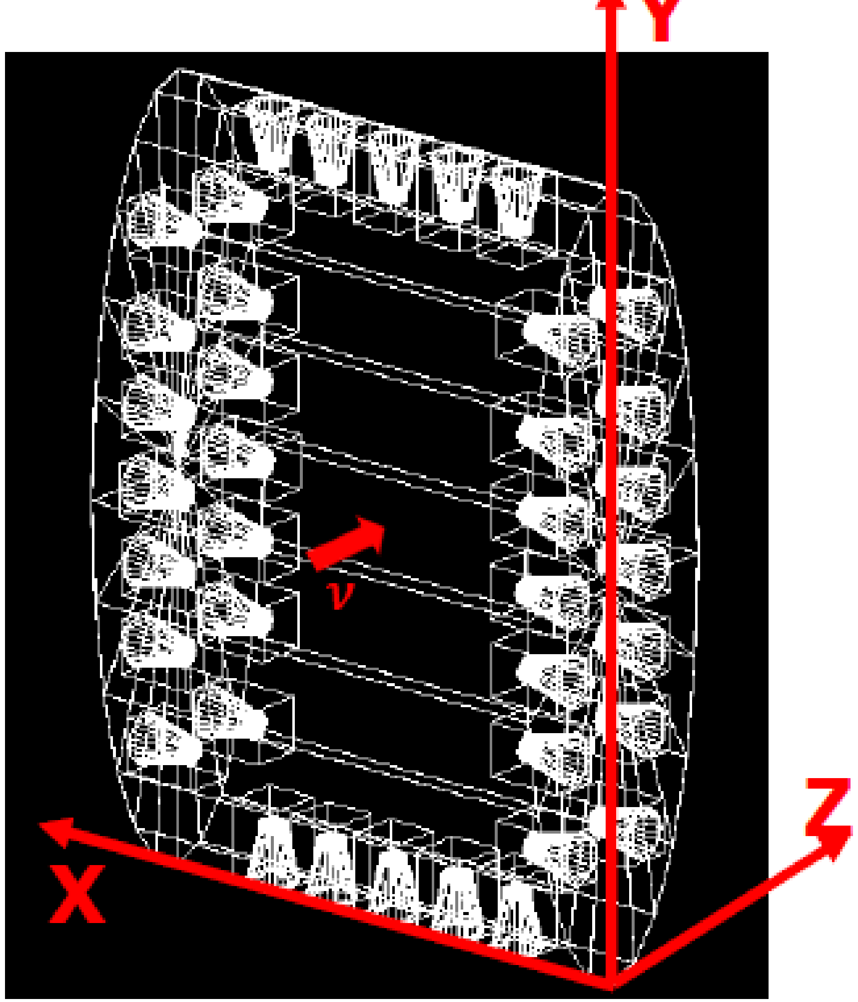


Lenses for demonstrator

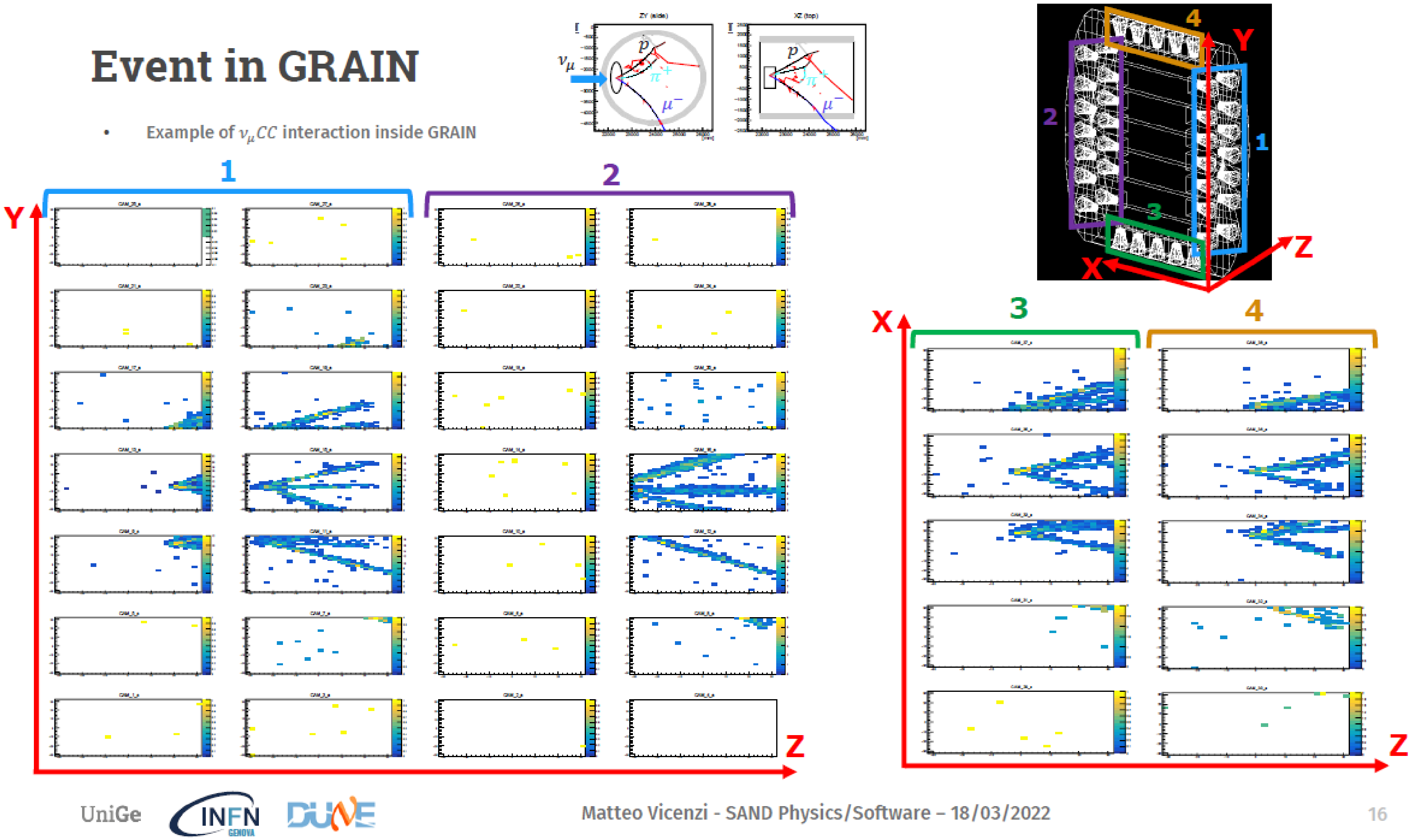
- Lens cameras inside the LAr volume
- 38 cameras, for maximum coverage
  - 14 pairs on the sides
  - 5 pairs on top/bottom
- Assume 32x32 matrix sensor, with 2 mm pixels and 20 % QE



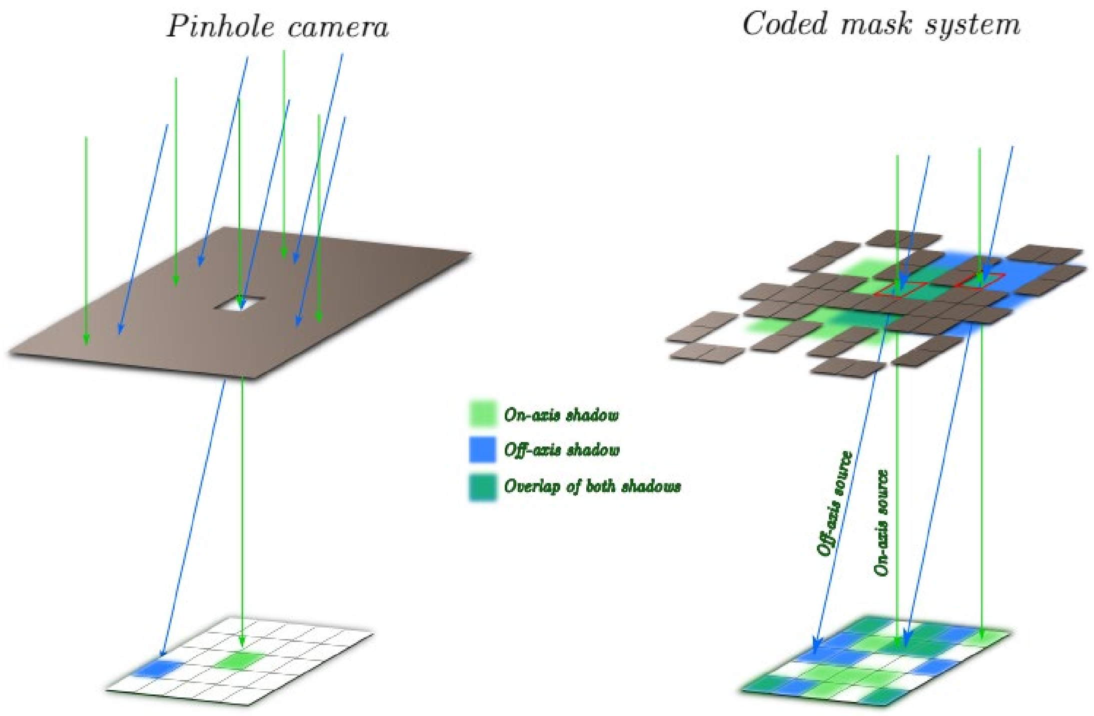
GDML:

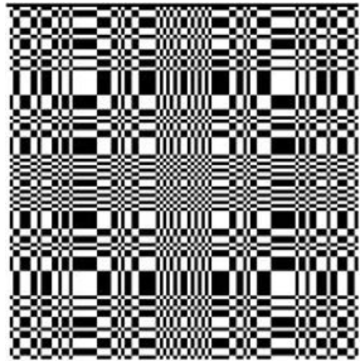


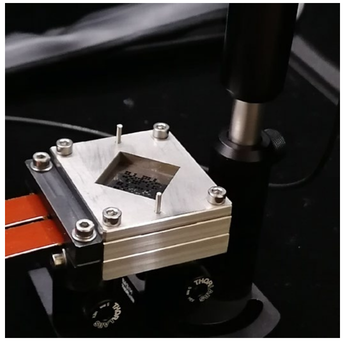
Simulation of lens imaging



Coded aperture masks







Coded aperture mask techniques were developed as the evolution of a single pinhole camera

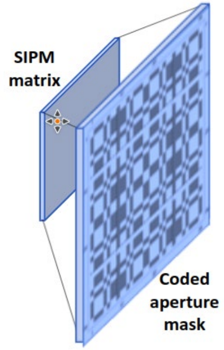
- matrix of multiple pinholes to improve light collection and reduce exposure time

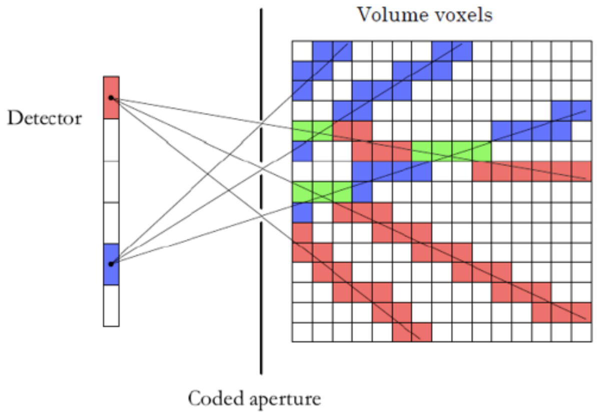
Image formed on sensor is the superimposition of multiple pinhole images.

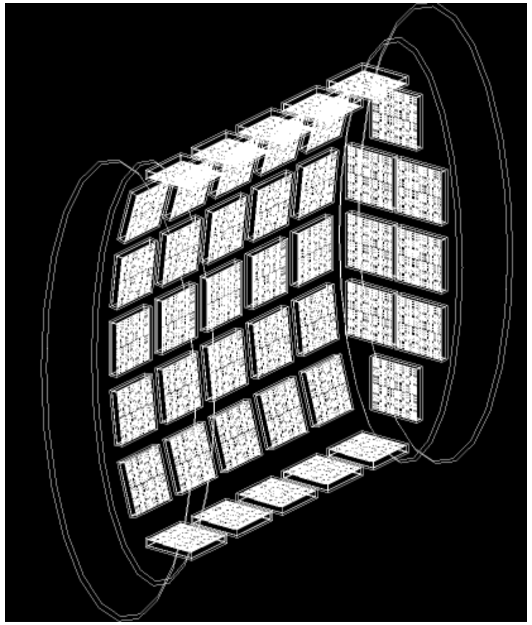
Advantages:

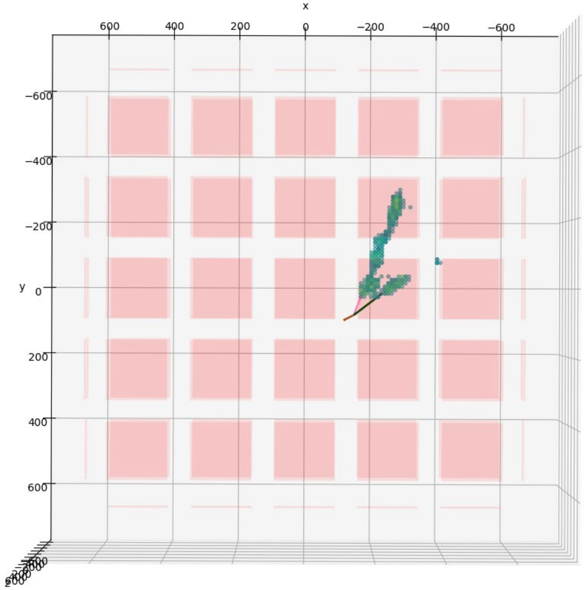
- Good light transmission (50%)
- Good depth of field
- Small required volume

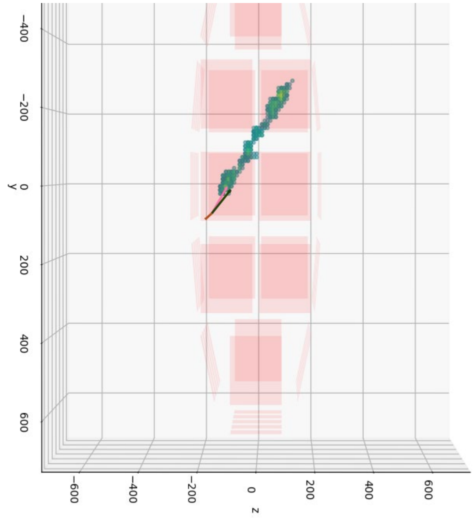
3D reconstruction with masks





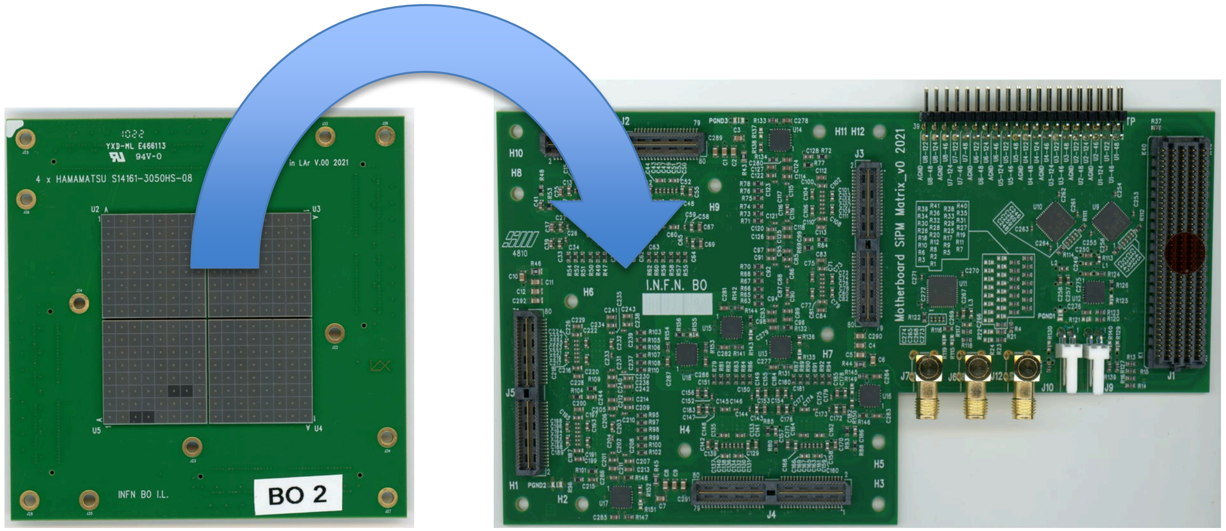






- Volume divided in voxels
- Search for the most probable light sources compatible with sensor response (number of photons for each SiPM in the matrix)
- O(10k) channels

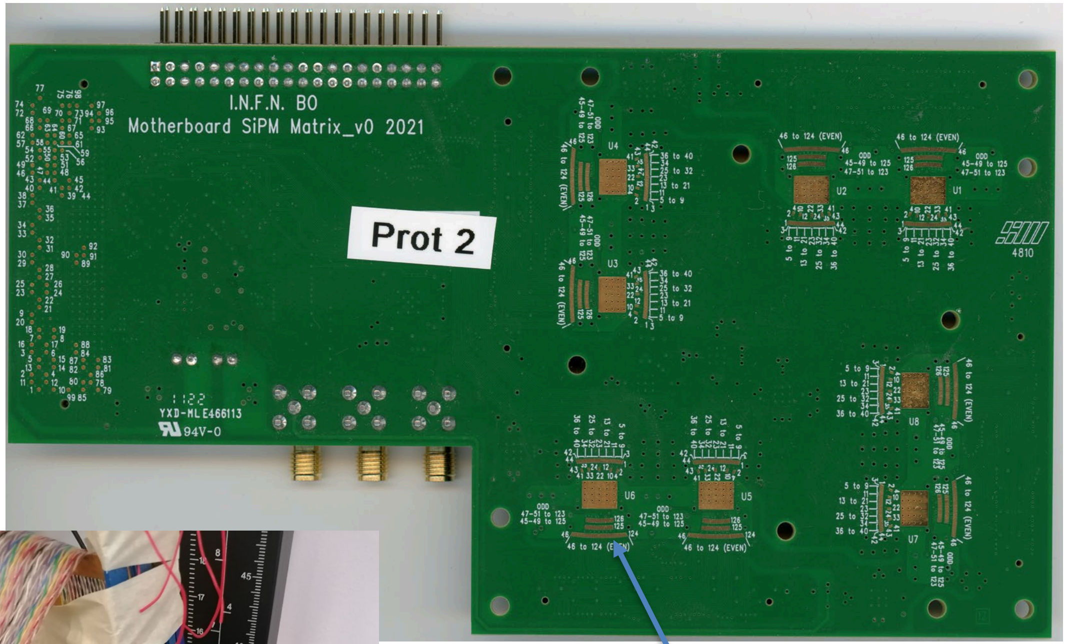
Camera demonstrator



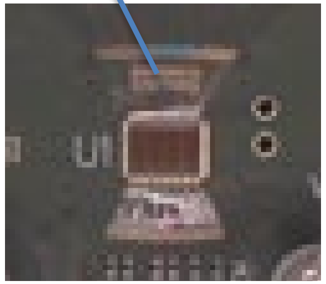
- Matrix of SiPMs mounted on a mezzanine board
- Motherboard contains 8 ASIC (256 ch in total)
- DAQ with FPGA on demo board
- To couple with the optics (lenses or masks)

Considerations on ASIC

- For this prototype we used the already available ASIC (“**Alcor**”) developed by **INFN-Torino** for other target applications (test in LN2 ongoing)
- It features Time Over Threshold frontend and High Rate capability (that implies high power consumption)
- This ASIC as it is now, does not fit perfectly with our needs: dynamic range starting from few photons, lower rate, high multiplicity of channels, but hopefully will allow to start dealing with real data.
- **ASIC development for our specific case is critical..**



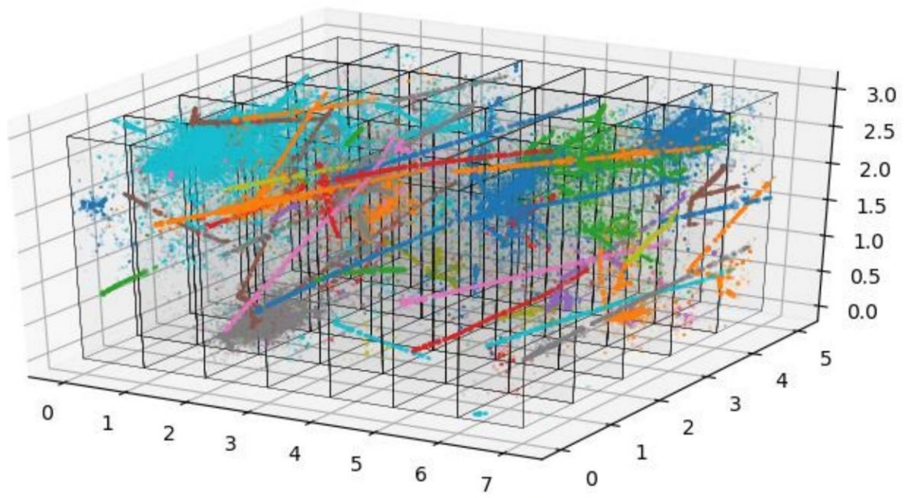
8 ASIC
Wire-bonded



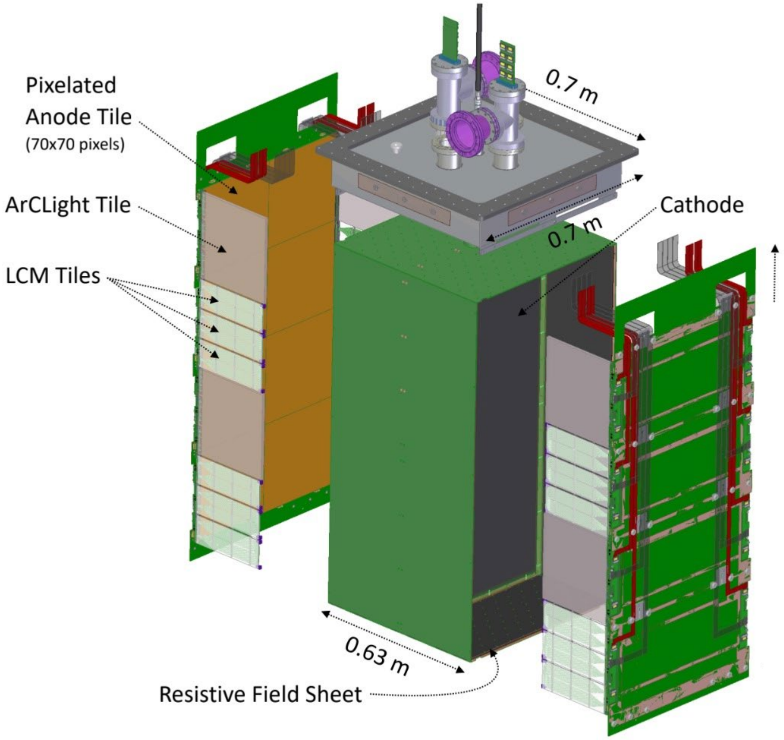
ND-LAr

ND-LAr modular design

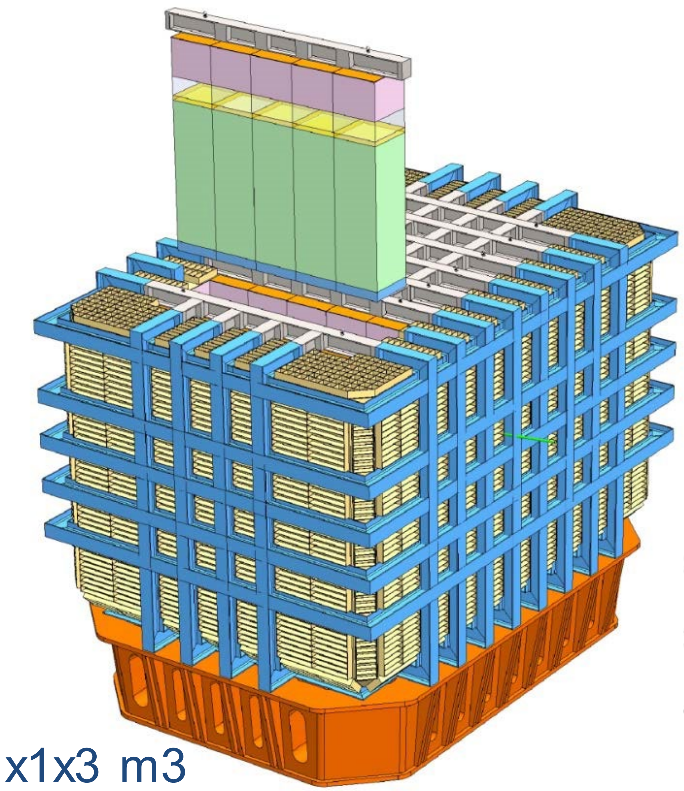
- Modular design to cope with high track multiplicity in a spill
- Pixelated charge readout
- High Photodetector coverage



Geant4 simulation of a spill at 1.2 MW



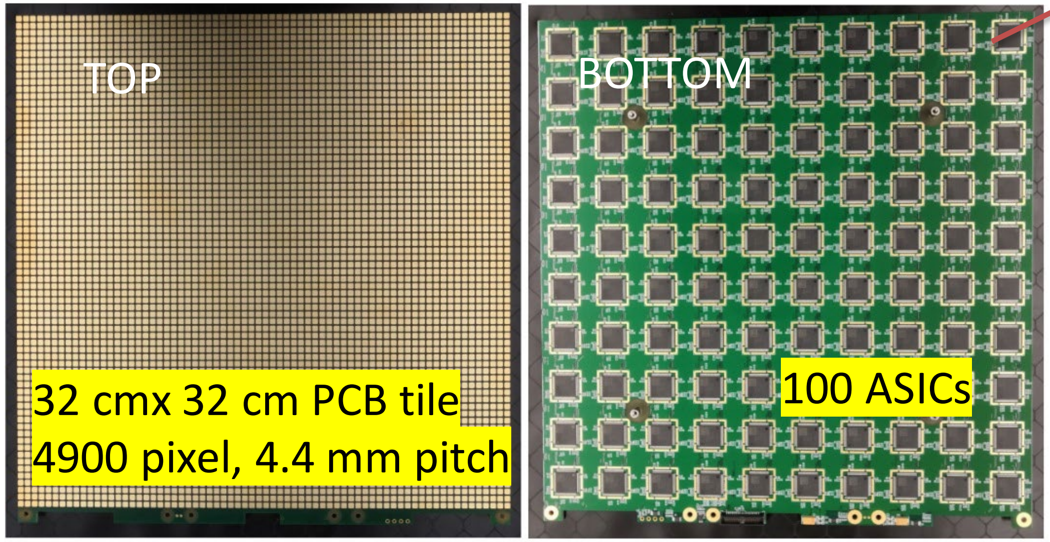
Single module

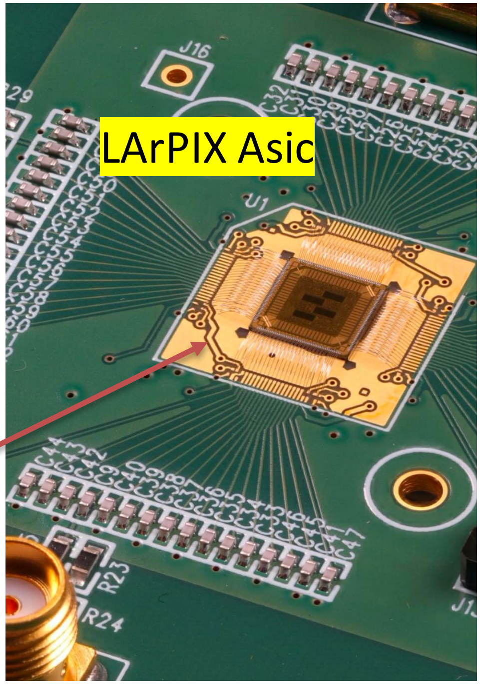


ND LAr
7x5 modules 1x1x3 m3

ND-Lar pixelated readout

- Provides unumbiguous 3D tracking of charged particles
- Low-power, low-noise integrating amplifier with self-triffered digitization and readout
- Charge stays on pixel until digitization and/or reset
- Always active – continuous self-triggering

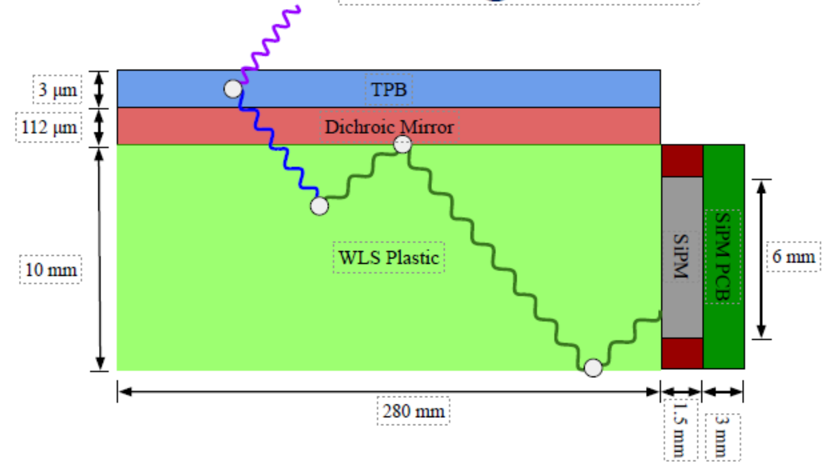


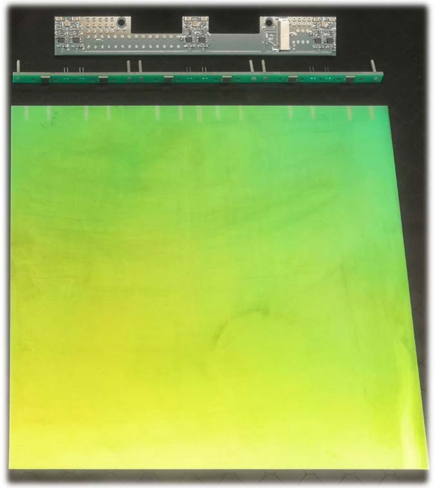


ND-LAr light collection

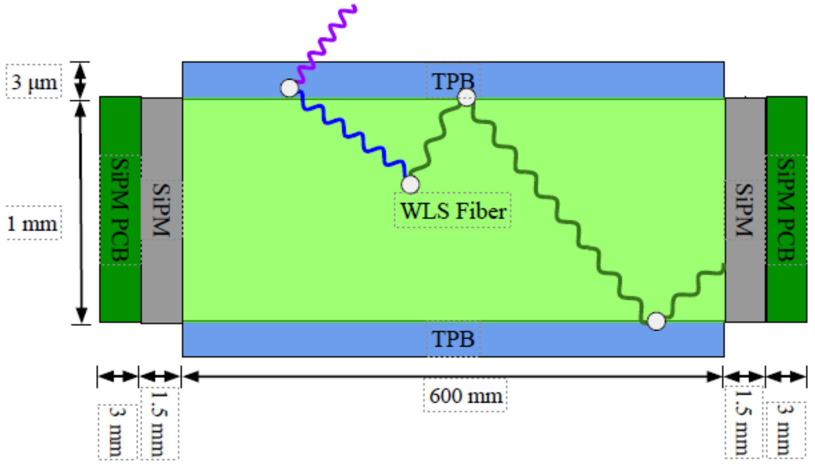
- High coverage
- Fast readout
- High rate capability

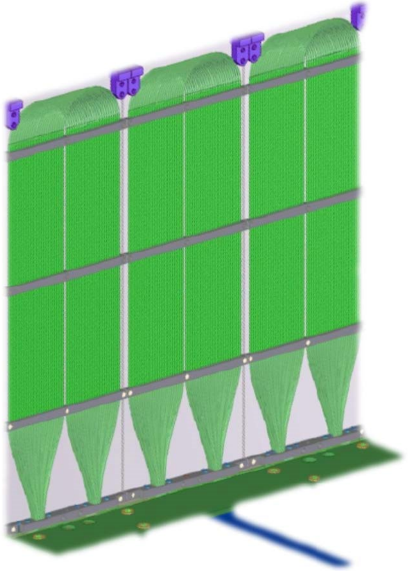
ArCLight Tiles





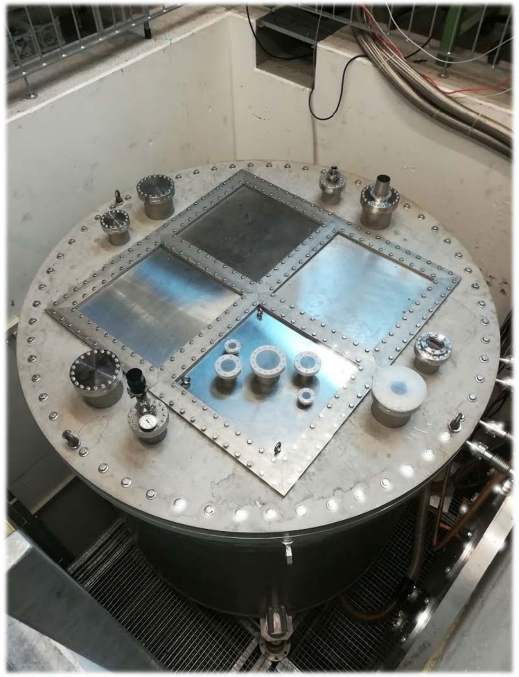
LCM Tiles

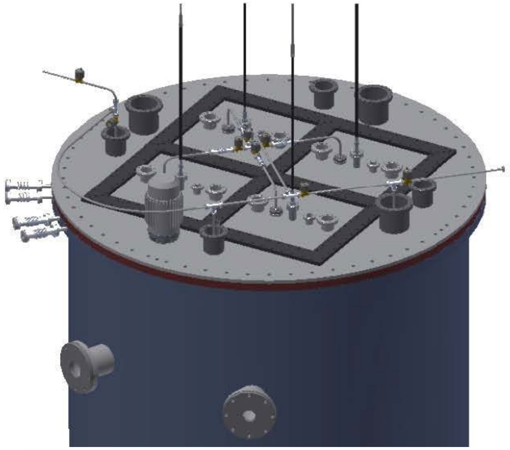


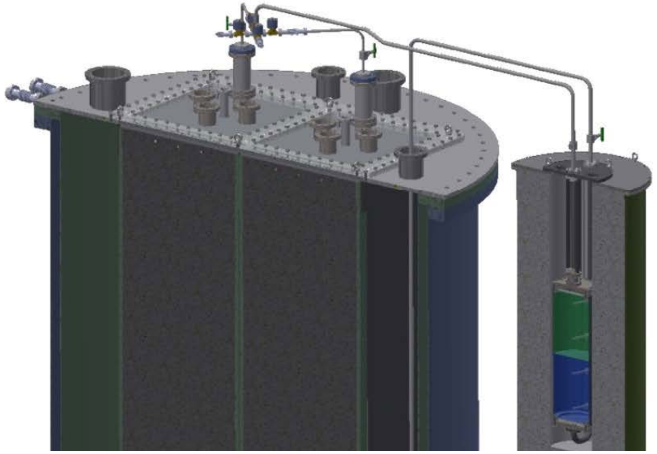


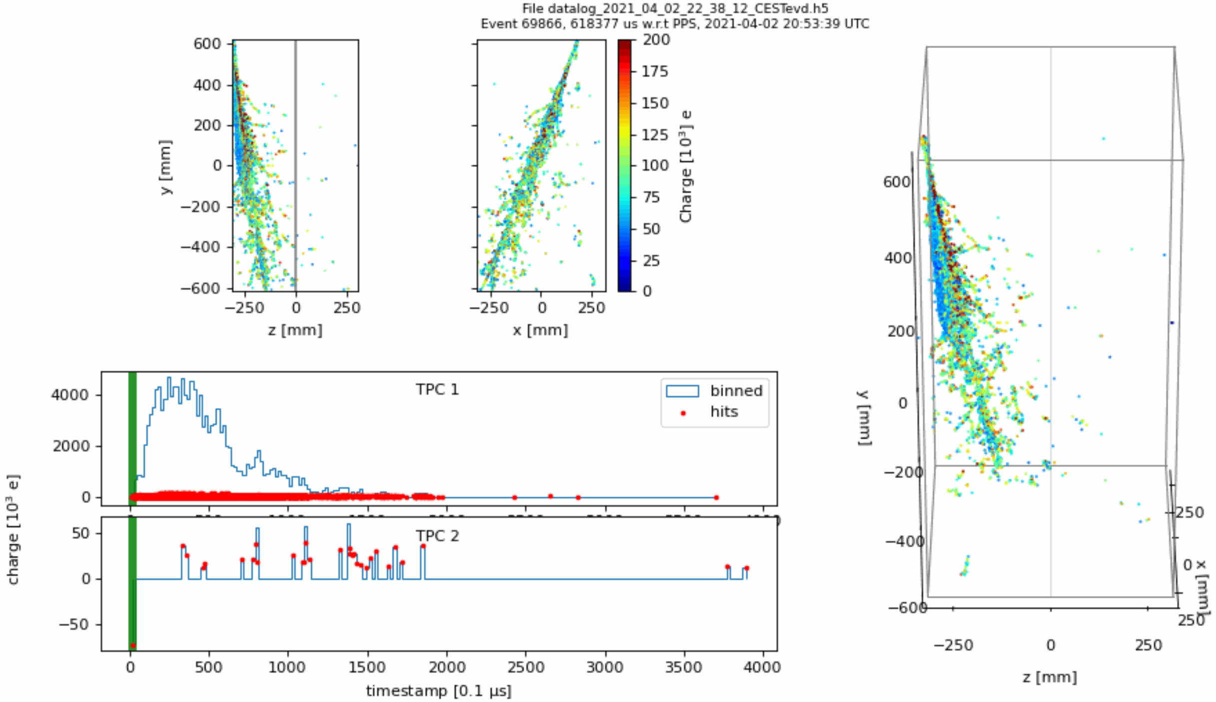
ND-LAr 2x2 prototype

- Single module already tested
- 4 module prototype going to be tested..







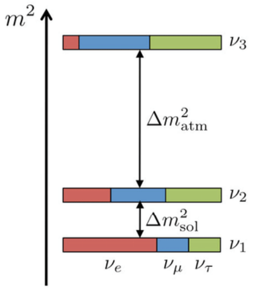


INFN DUNE

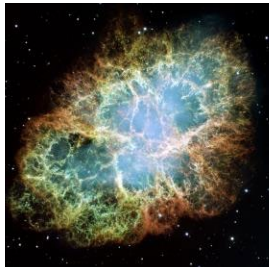
BACKUP

The DUNE experimental program

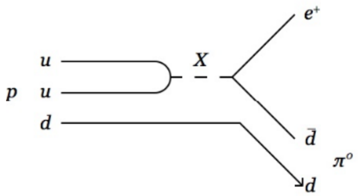
- Three-flavour Long-Baseline neutrino oscillation
  - Precise neutrino oscillation parameters for $\boldsymbol{\nu}_e$ / anti-$\boldsymbol{\nu}_e$ appearance , $\boldsymbol{\nu}_\mu$ / anti-$\boldsymbol{\nu}_\mu$ disappearence searches, CP violation, mass hierarchy in the $\boldsymbol{\nu}$ sector



- Supernovae Neutrino Burst
  - Large sample of neutrinos for SNB in our galacy flavour content, spectra, time evolution of SNB neutrinos



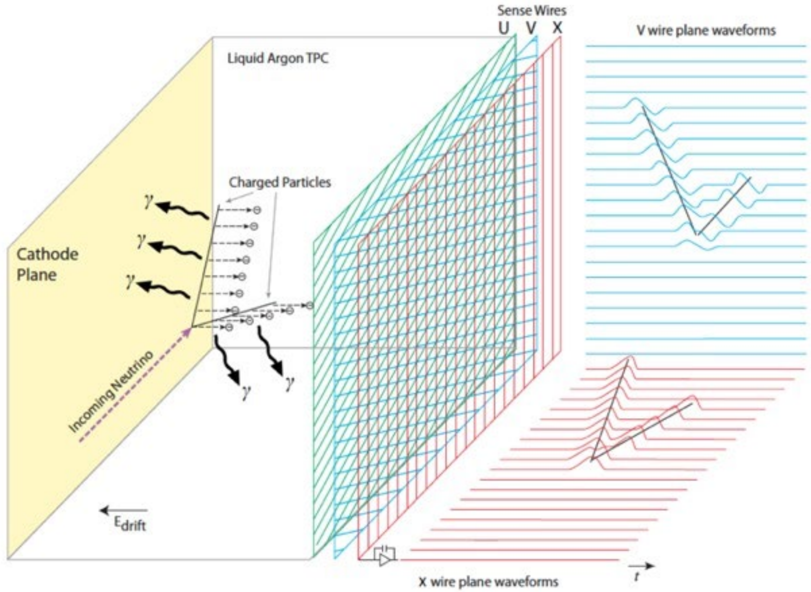
- Beyond Standard Model
  - Proton decay, baron number violation, sterile neutrinos, non-standard interactions and more



Detector requirements:

- LARGE detector mass (70 kt)
- Long baseline (1300 km)
- Good energy resolution up to GeV (TPC)
- Efficient particle identification ($K^\pm$, e^-, v_i)
- Low cosmic ray background (underground)
- Timing for non-beam events (PD system)
- Low energy threshold (good S/N + high LAr purity)

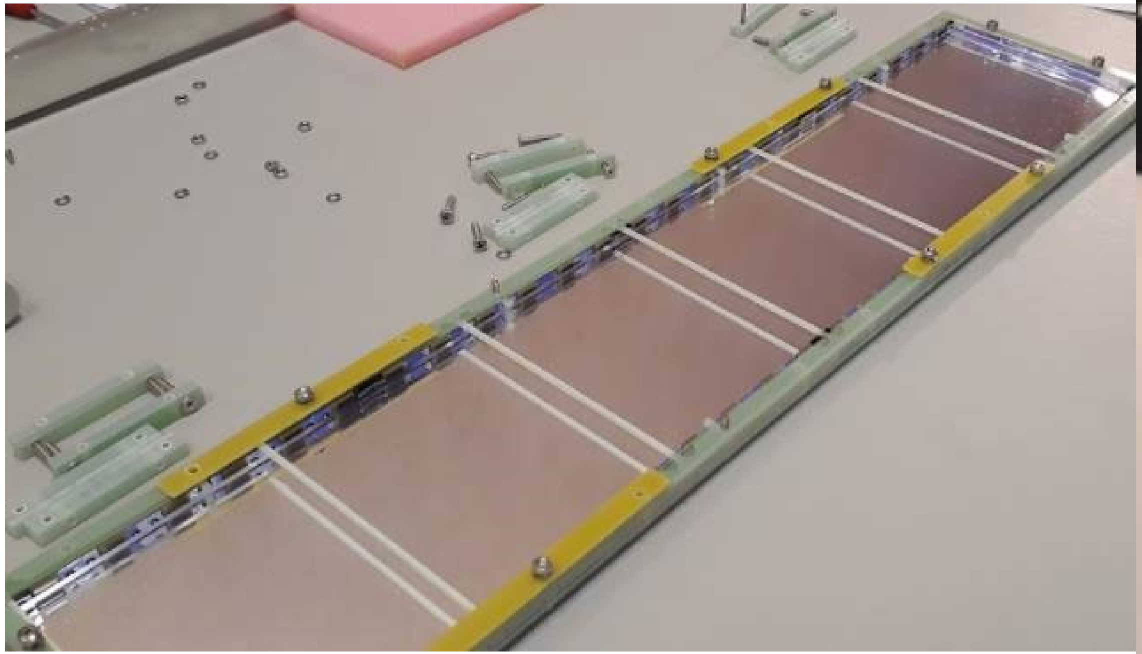
The Single-Phase LAr-TPC



- Ionization electrons [5fC/cm] drift to the anode in pure LAr & uniform E-field (500 V/cm)
  - Few mm pitch and MHz sampling frequency
  - 3D via multiple 2D views (wire vs drift time)
  - High imagin capabilities, kinematic reconstruction with mm scale spatial resolution
  - Intrinsecally excellent Calorimetry and particle identification (dE/dX) capability
- Prompt scintillating light (@128 nm)
  - T=0, trigger, calorimetry

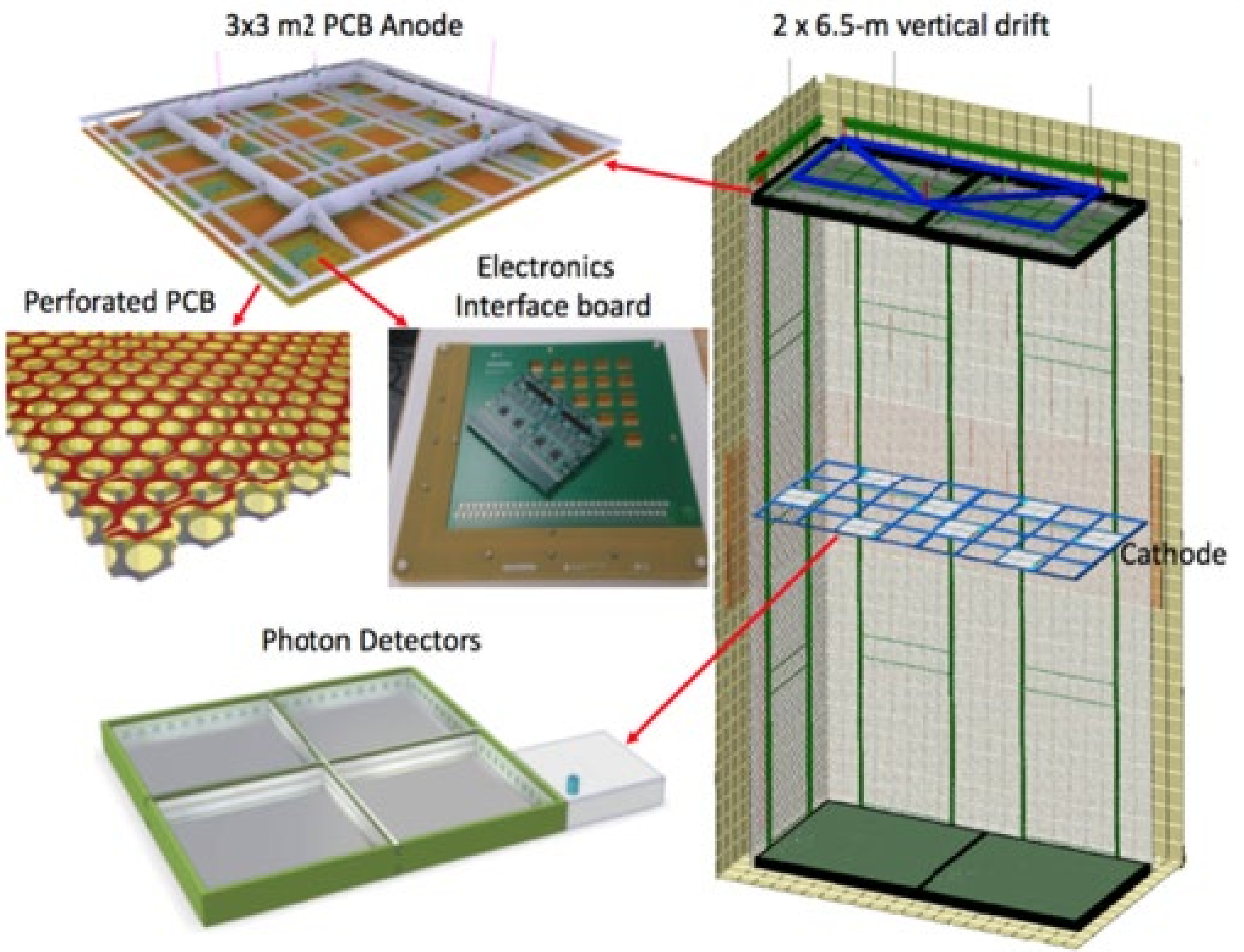
- **LAr as radiation medium**
  - Dense: 40% more than water
  - Abundant primary ionization: 42k e^- / MeV
  - High electron lifetime if purified, long drifts
  - High ligth yield: 40k γ / MeV
  - Easy available: 1% of the atmosphere
  - Cheap: 2$/L (3000$/L for Xe, 500$/L for Ne)
- **Technological challenges**
  - LAr purification <<0.1 ppt O2 eq (>> 3 ms electron lifetime) long drift
  - Imaging & anode planes
  - Very low noise frontend amplifiers to detect fC primary charge deposition
  - Large area photon detectors sensitive to 128 nm wavelength
  - HV system to provide uniform/stable E-field in large drift volume
- **Pionered by ICARUS** and adopted in present and next generation neutrino experiments (µBone, SBND, DUNE)

X-Arapuca Supercell



Vertical Drift architecture

- **Designed to maximize active volume**
  - Readout units cole to LAr surfave and cryostat floor
  - Catode at middle height: better HV stability due to LAr hydrostatic pressure
  - 6.5 m drift, 450 V/cm, 300 kV on Cathode
- **Perforated PCBs with segmented electrodes (strips) as readout units**
  - Good planarity (lightweight) and robust
  - Optimizable strip orientation, pitch, lenght
- **Modular supporting structures for readout planes**
  - Derived from CRP design of DP
  - Incorporates cathode hanging system
- **Single Field Cage surrounding entire active volume**
  - Derive from DUNE-DP design
- **Photon Detectors based on X-Arapuca technology (DUNE-SP)**
  - Integrated on cathode plane and cryostat walls
  - Decoupling from HV achieved with optical fibers for signal and power transmission

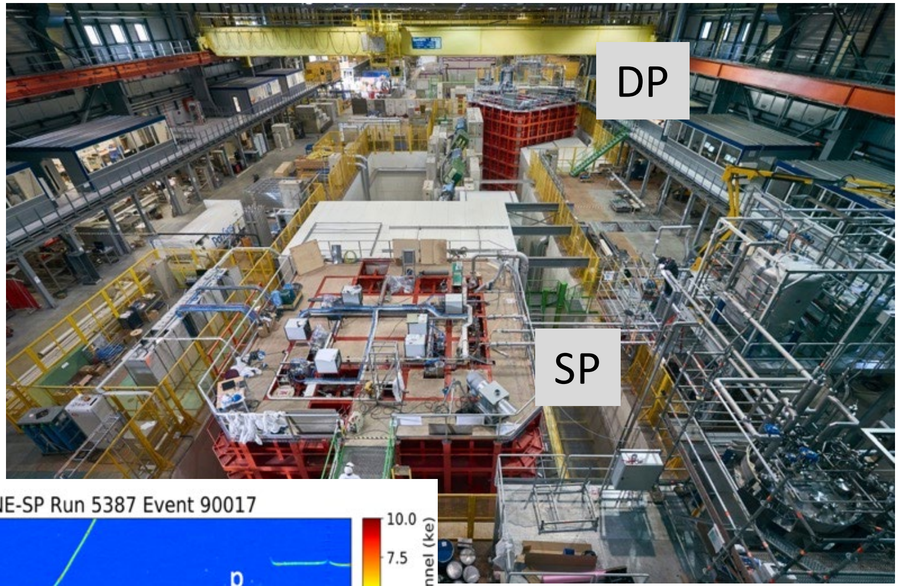


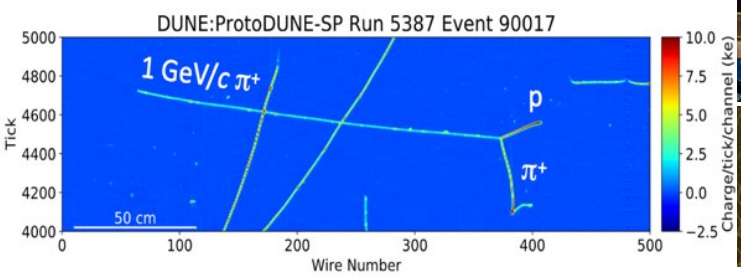
DUNE prototypes at CERN

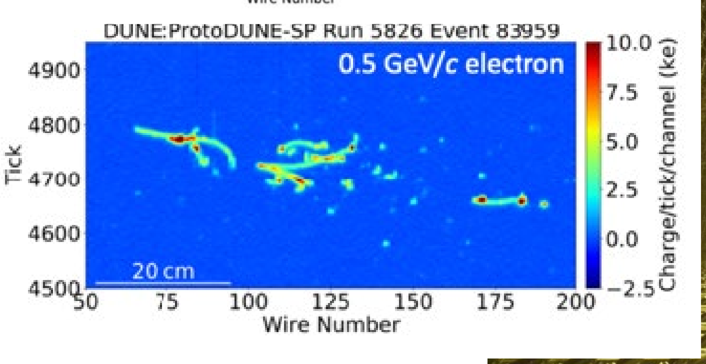
Two 750 t prototypes 8x8x8 m^3 at Neutrino Platform

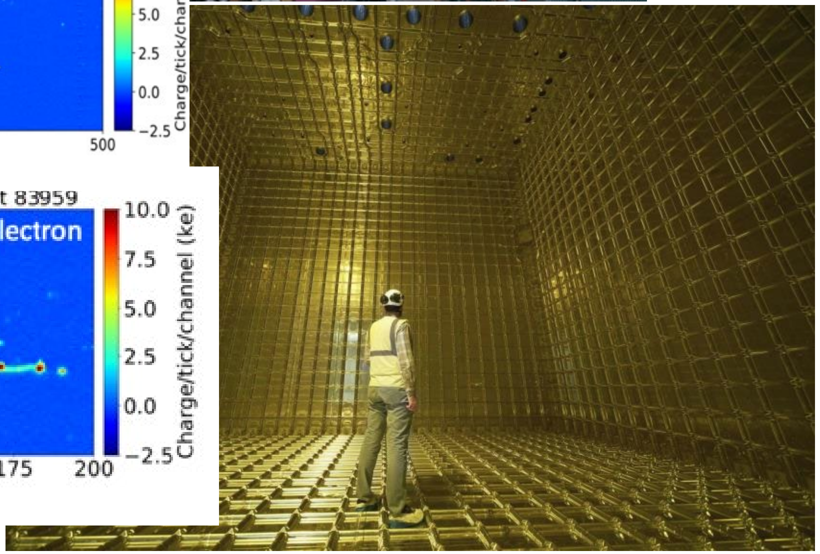
- **ProtoDUNE phase 1**
  - ProtoDUNE SP took data 2018-2020
    - Charged particles beam of 0.3-7 GeV (e^+, π, μ ,K, p^+)
  - ProtoDUNE DP took data 2019-2020
    - Very high voltage and large drift studies
    - Evolved into Vertical Drift technology

- **ProtoDUNE phase 2**
  - It was expected to start in early 2023 but delay Argon availability
  - Improve with lesson learned from Phase 1
  - Validate technology of 1° FD module (HD)
  - Baseline design for 2° FD module (VD)



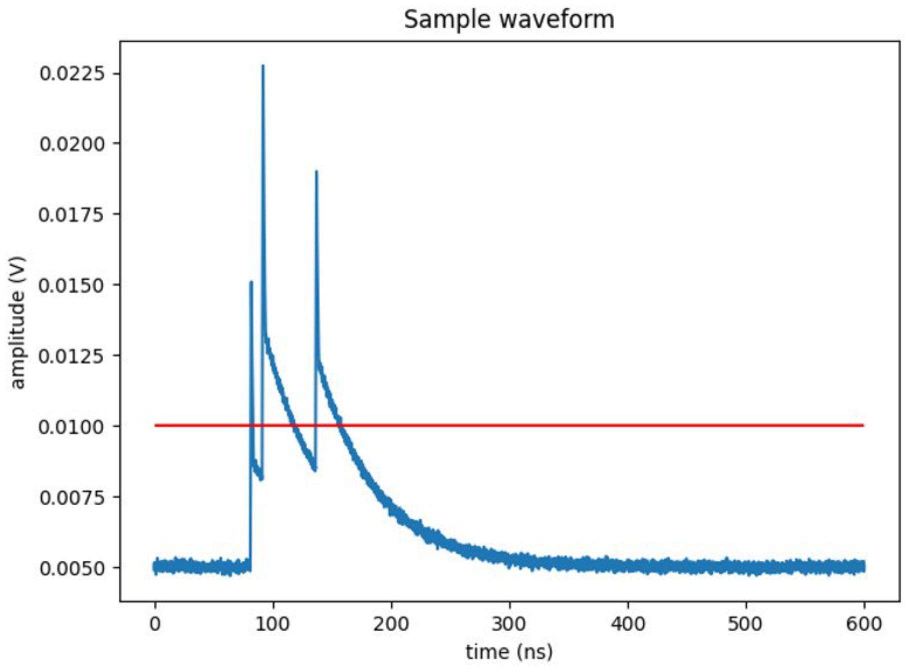






Summary on Simulation

- We setup a suite based on Geant4 that can simulate the time of arrival of all photons on the SiPM sensistive area, taking into account:
  - Fast and Slow component of scintillation process
  - Response of the detector and the FE electronics
  - Simulation of the whole 10 usec spill, including all possible sources of background
- Work is going on (limited by computing time) to use this information to define the requirements for the ASIC:
  - Charge integration or TDCs or …._?
  - Output data rates
  - Inner vessel feedthroughs,,,



Results expected in short time !!!