IFIC R&D on photon collection for noble-element detectors

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MOTIVATION

Goal

Enhance scintillation-light detection efficiency to

- Lower energy threshold
- Improve energy resolution
- Enhance background rejection

Key challenges

- Light emitted in the VUV (<200 nm) ➜ most materials opaque; sensors costly and inefficient
- Large detector volumes ➜ need scalable, cost-effective photon collectors
- Cryogenic and mechanical constraints: integration with TPC field cages and charge readout

Context

- Participation in several neutrino experiments: DUNE, NEXT, COLINA
- R&D aligned with DRD2 objectives
- Collaboration with Spanish and international groups

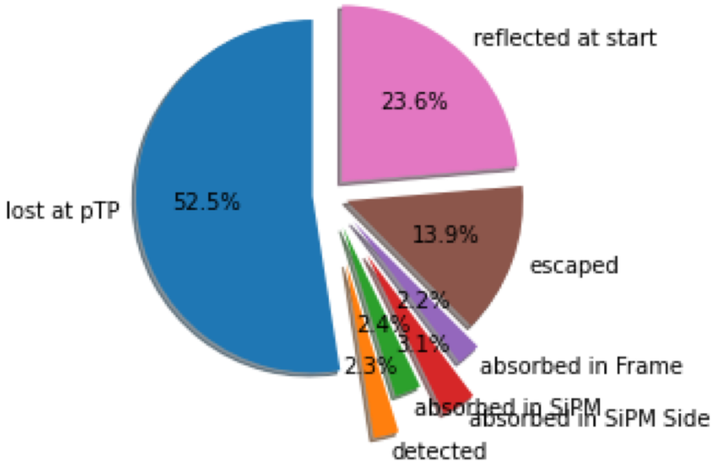
CURRENT PERFORMANCE — DUNE AS EXAMPLE

LAr scintillation yield: ~25000 photons/MeV at 500 V/cm.

But only a small fraction is detected:

- Photon transport losses: <10% reach a photon collector surface
- Collection and detection losses: only a few percent are finally detected by photosensors

Effective detection: O(10^{-3}) of produced light.





R&D LINES TO IMPROVE PHOTON DETECTION

Photon transport to collectors

- Xenon doping of liquid argon (spectral changes and Rayleigh scattering)
- Characterization of detector materials: VUV reflectivity and transparency

Photon collector optimization

- Novel collector geometries and technologies
- Optical performance in the VUV (wavelength shifting, trapping, transport)

Photosensor characterization & improvement

- Photon detection efficiency (PDE), noise, timing
- VUV sensitivity
- Readout electronics and integration

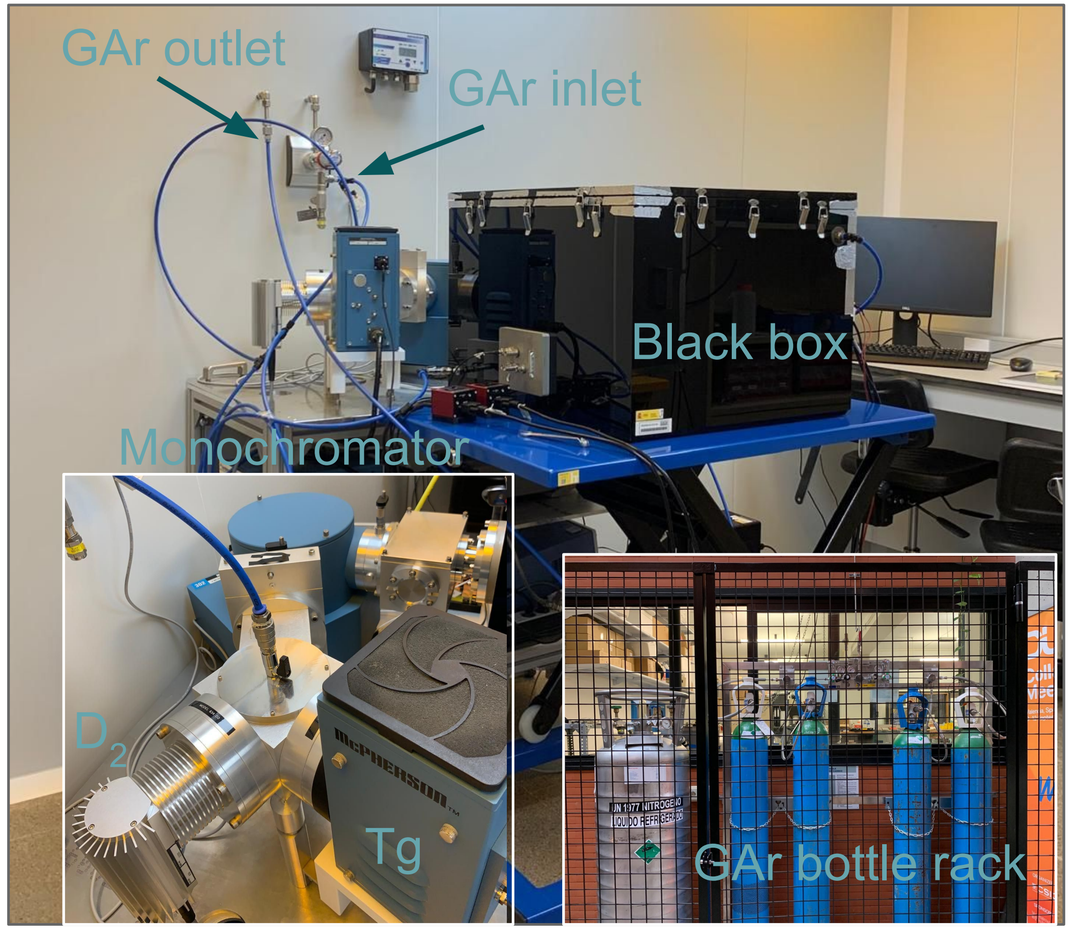
PHOTON TRANSPORT: VUV CHARACTERIZATION OF MATERIALS

Setup for the measurement of optical properties in the vacuum ultraviolet:

- D_2 lamp coupled to a monochromator which is connected to a GAr system in a dedicated dark room.
- Measurements are conducted in a pure GAr atmosphere to enable light transmission in the VUV region.

The use of a GAr atmosphere:

- Protects the monochromator from outgassing.
- Provides the flexibility to fully instrument the black box.



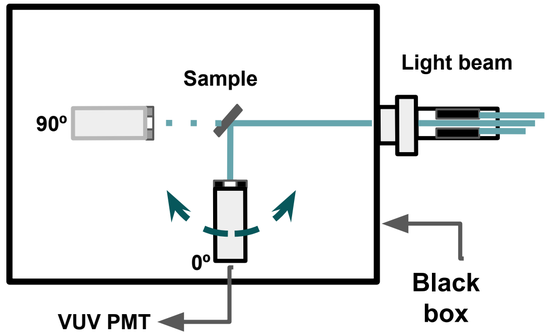
PHOTON TRANSPORT: VUV CHARACTERIZATION OF MATERIALS

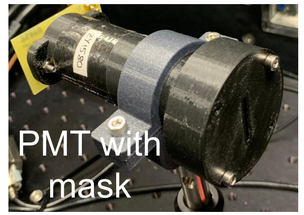
A 3D-printed assembly that incorporates two Thorlabs rotary stages and a motorized sample holder:

- Motor 1 facilitates sample exchange.
- Motor 2 rotates a calibrated, VUV-sensitive PMT
  ➜ selection of the reflected angle
- Motor 3 controls the rotation of the sample holder
  ➜ selection of the incident angle

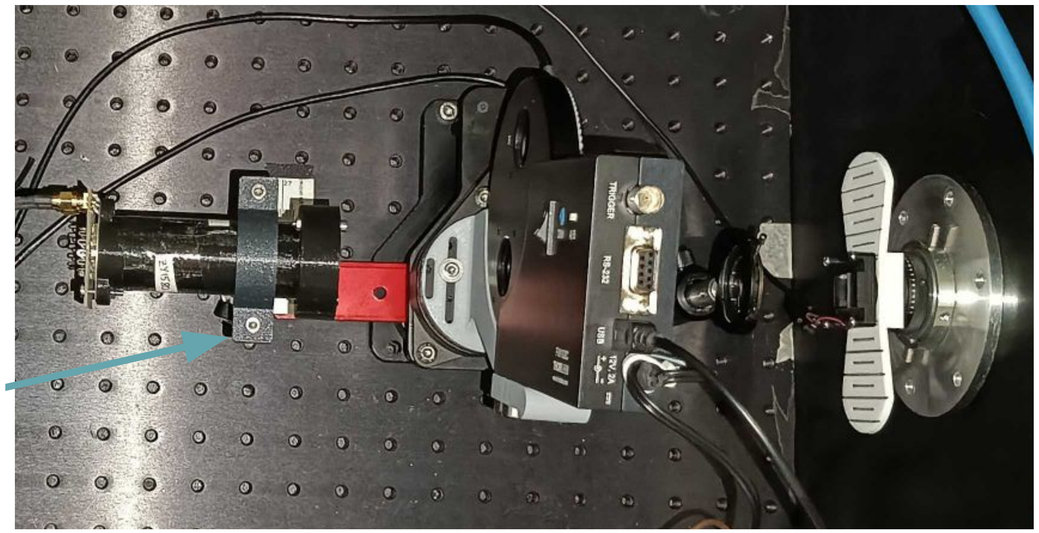
An iris and shutter collimate and control the exposure to the beam.

A rectangular mask (aperture of 0.8°) is placed over the PMT to enhance angular resolution.

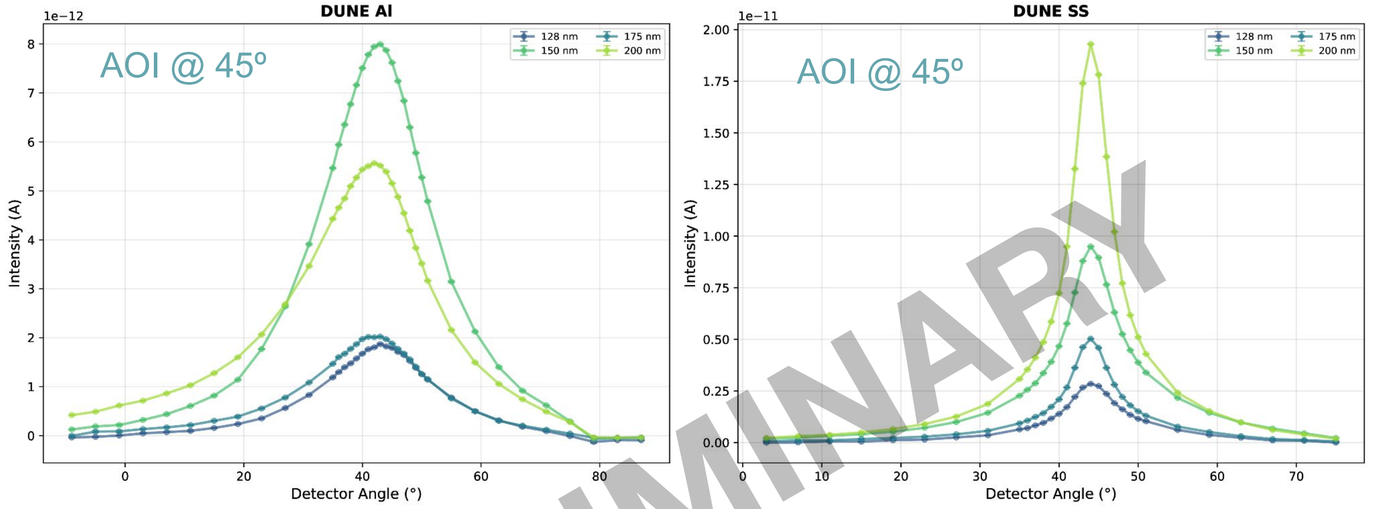




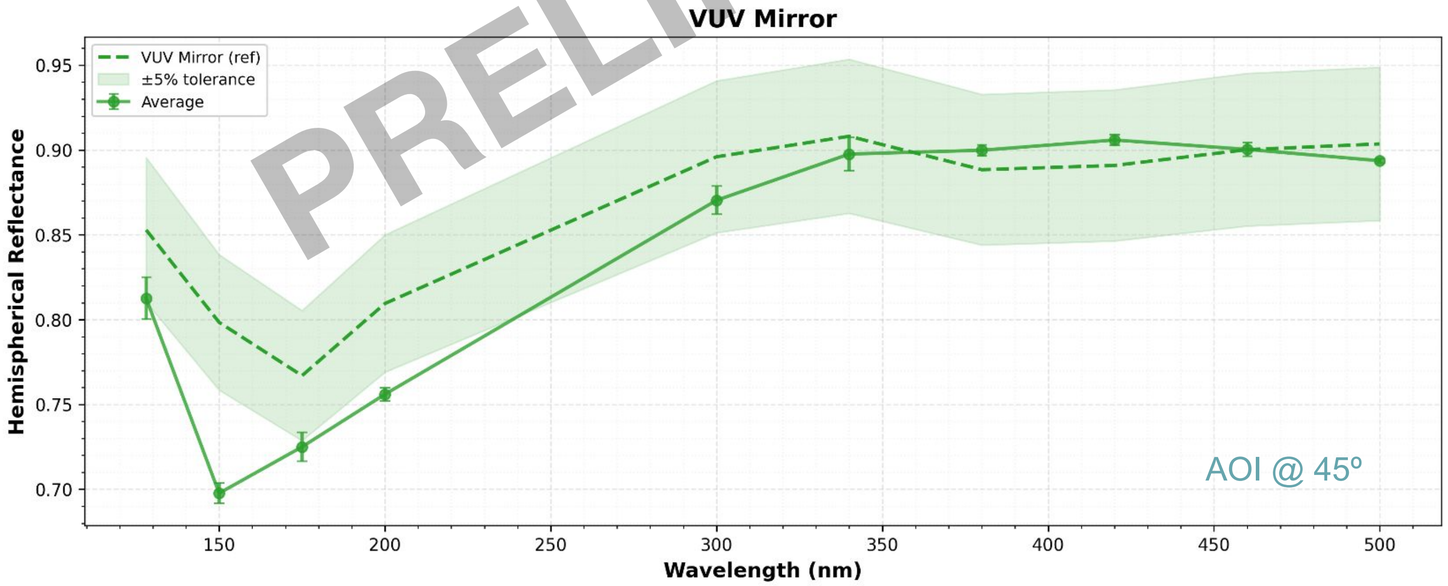




PHOTON TRANSPORT: VUV CHARACTERIZATION OF MATERIALS



PRELIMINARY

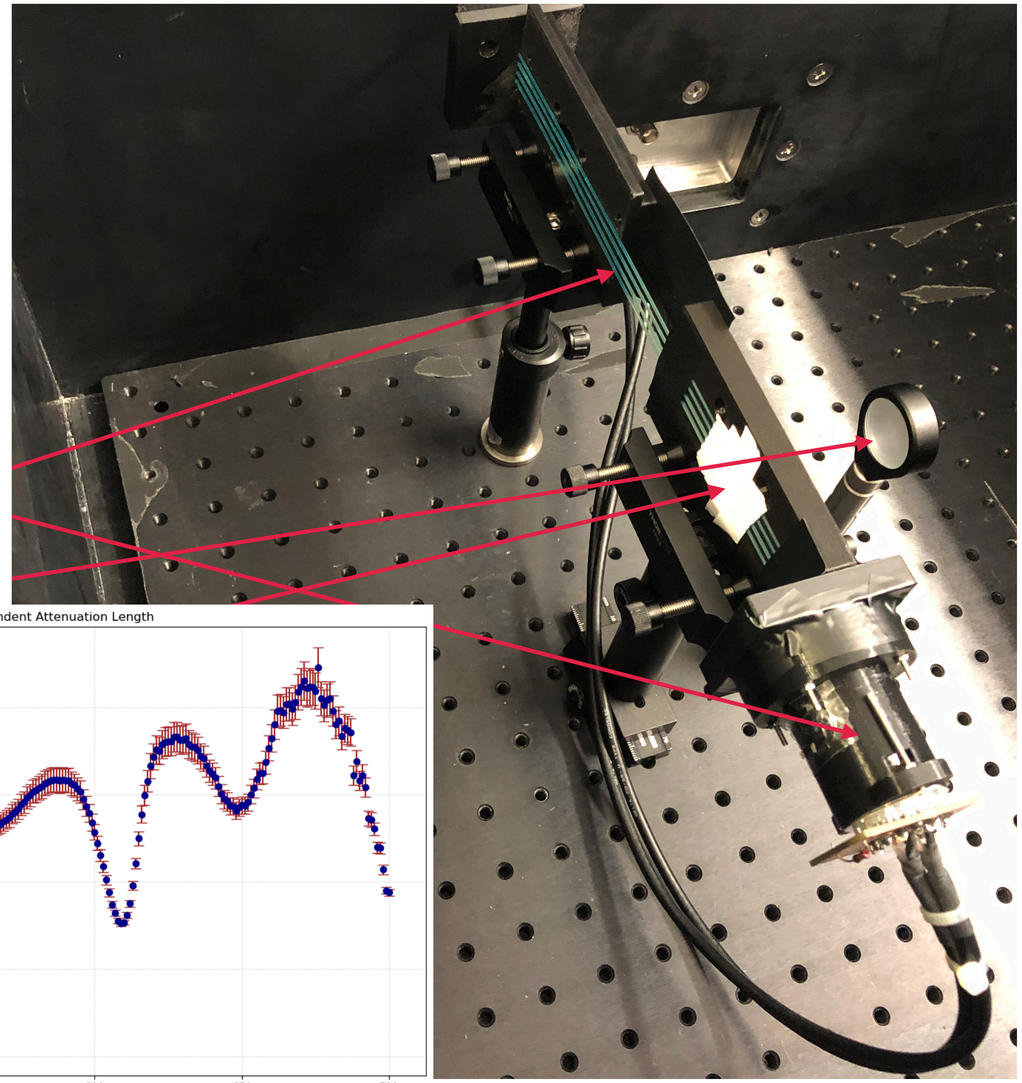


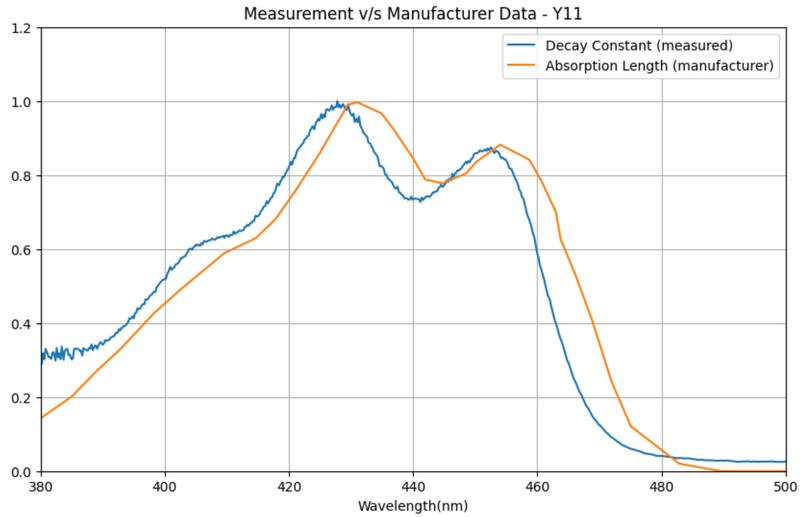
PHOTON COLLECTION: CHARACTERIZATION OF WLS FIBERS

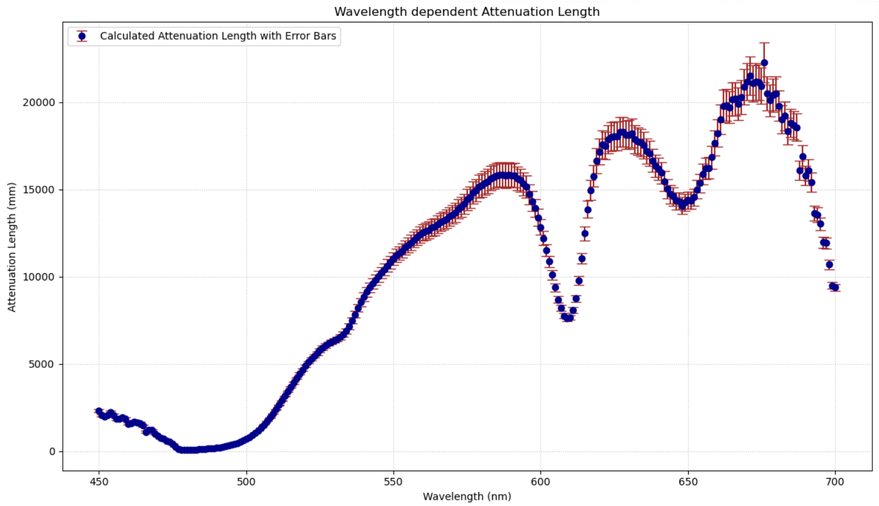
Goal: detailed characterization of wavelength-shifting optical fibers for their use in high-resolution applications

Measurements:

- WLS efficiency and absorption length
- Attenuation length
- Photon collection efficiency







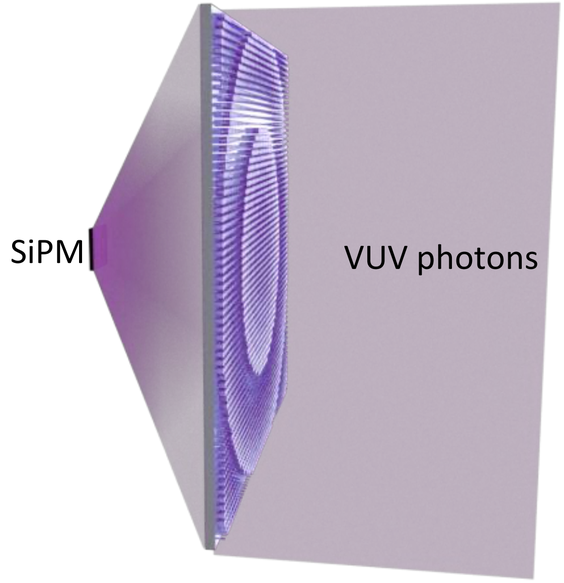
PHOTON COLLECTION: METALENSES

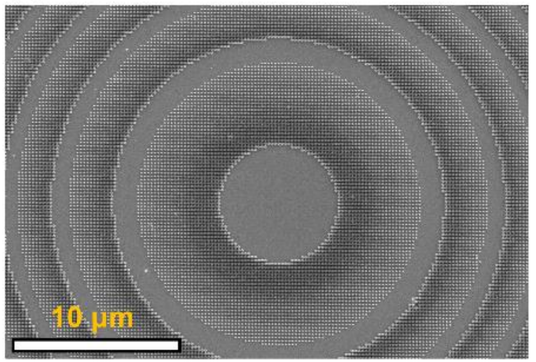
Designed and manufactured several large-area VUV-transparent metalenses (first ever!), measuring an average efficiency of ~53%:

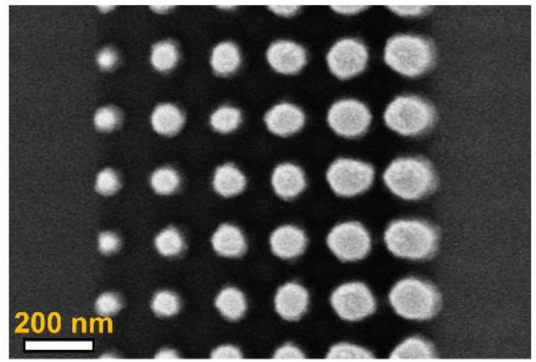
- A. Martins et al. *"High efficiency glass-based VUV metasurfaces"*, Optical 12 (2025) 1681–1688.

Design process considered aspects such as:

- highly efficient VUV operation;
- large area;
- wide field of view;
- easily tuneable focal length;
- low cost and high throughput fabrication methods.







PHOTON COLLECTION: SIMULATION

Geant4-based optical simulation framework for photon collectors.

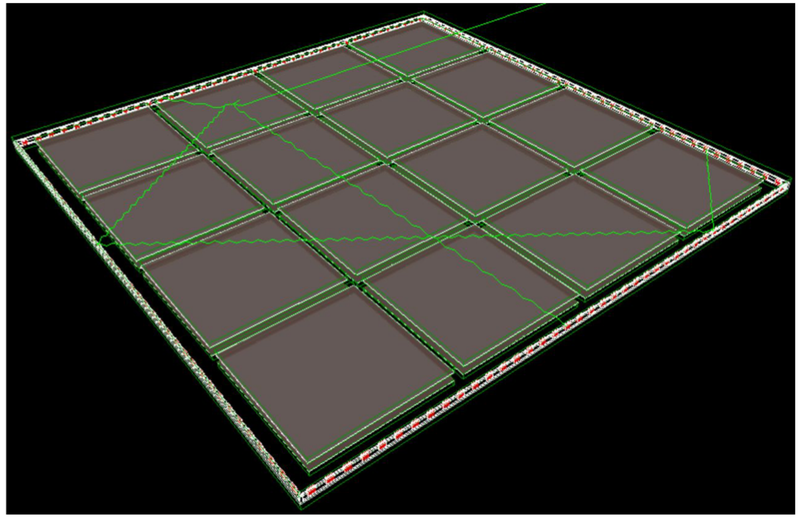
- Fully configurable: geometry, materials, optical properties

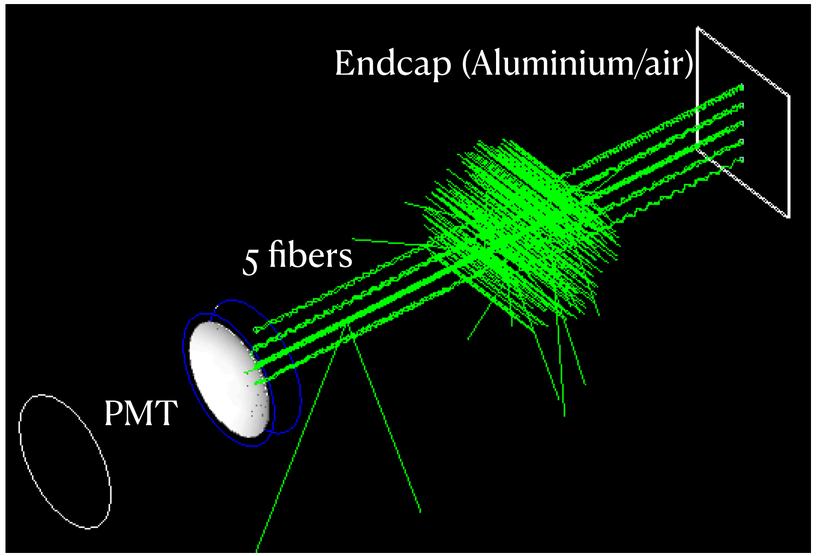
Goal: validated model delivering absolute photon collection efficiency (PCE).

Ongoing tuning of VUV optical parameters.

- Reflectivity, transmission, absorption, WLS, surface effects
- Contrained with laboratory measurements

Current agreement: simulation within ~10% of measured PCE.





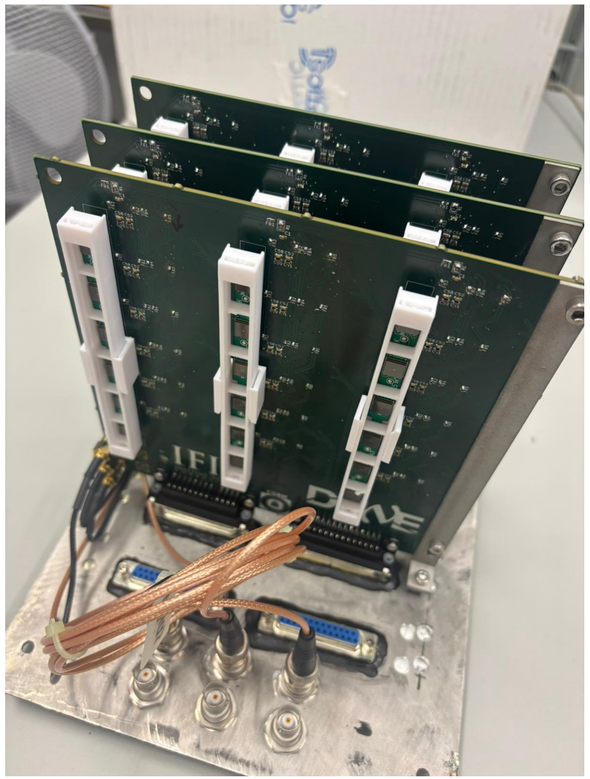
PHOTOSENSORS: MASS CHARACTERIZATION FOR DUNE

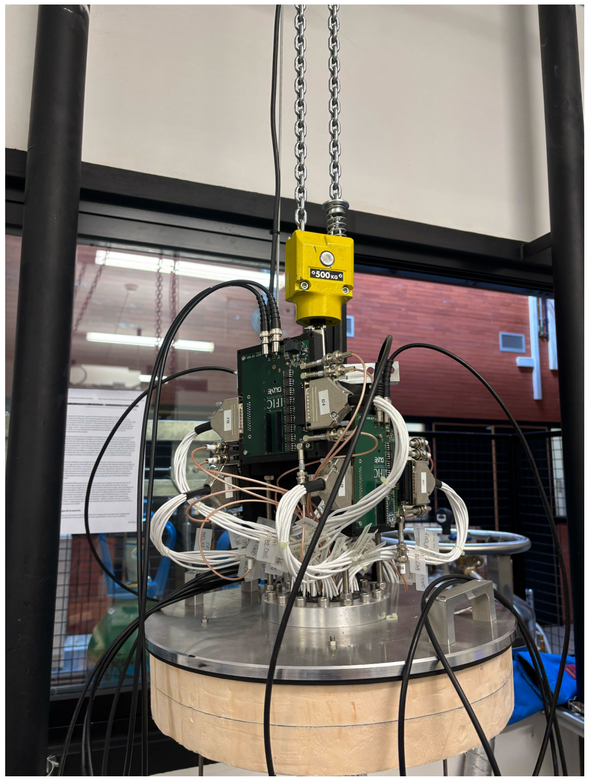
System objectives:

- Breakdown voltage vs. overvoltage in cryogenic conditions
- Key noise parameters: DCR, optical cross talk, afterpulsing
- Quality control and performance uniformity assessment

Methodology:

- Statistical sampling of the full sensor production for the DUNE far detector
- Automated data taking and analysis





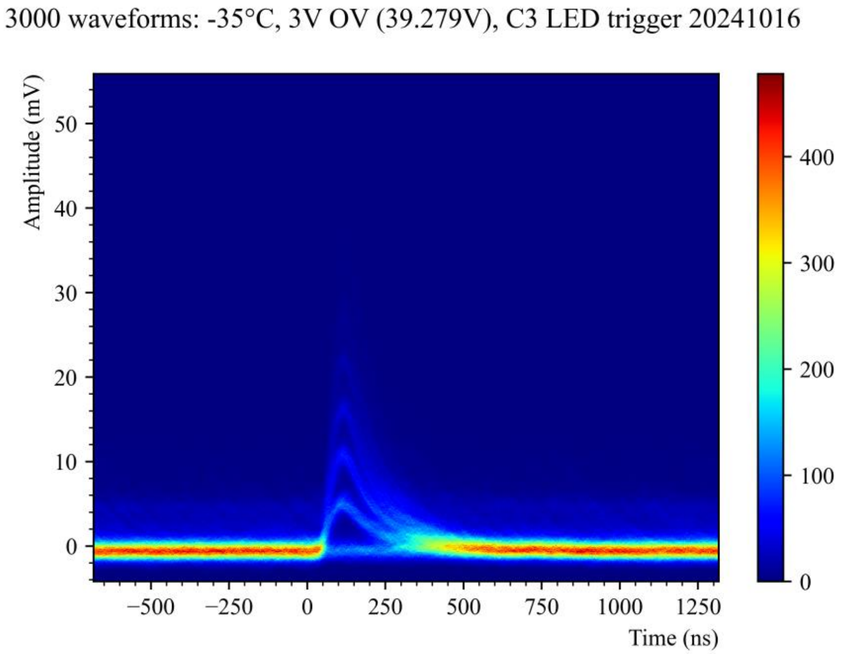
ELECTRONICS: SIPM GANGING

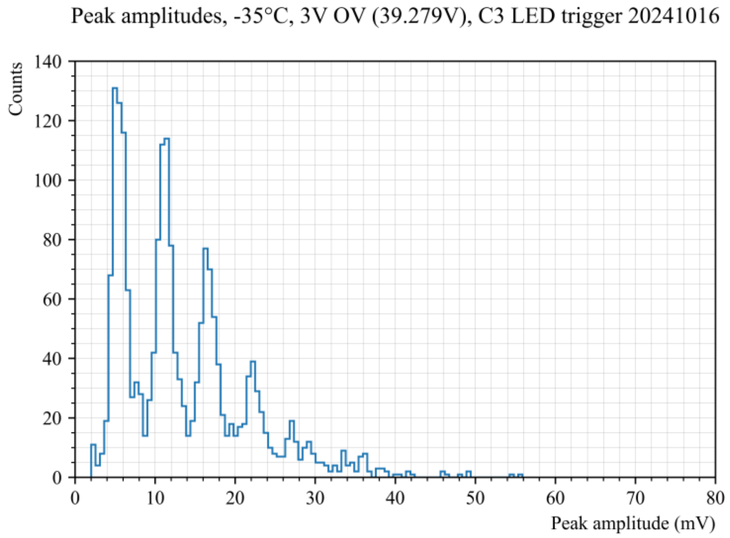
Developed electronics to gang and amplify groups of SiPMs

- SiPM array of 16 SiPMs of 6×6 mm^2 each, model Hamamatsu S14161-6050HS-04.
- Current prototype uses parallel ganging with a double amplification stage.

Achieved performance:

- Good signal-to-noise ratio (7–10)
- Time resolution of 5–10 ns





SUMMARY

Interdisciplinary R&D to enhance photon collection in large noble-element TPCs for next-generation neutrino experiments

- Improving light transport through highly reflective and VUV-transparent detector materials
- Increasing photon collection efficiency beyond the few-percent level using optimized components and novel technologies.
- Exploring new VUV-sensitive photosensors and improved readout electronics.

This R&D is

- Aligned with DRD2 objectives.
- In collaboration with Spanish and international groups.

ACKNOWLEDGMENTS

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