R&D on neutrino LAr TPCs: Photon collection

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Instrumentation for the future of particle, nuclear and astroparticle physics
and medical applications in Spain ▪ Barcelona, 7 March 2023

Goals and challenges

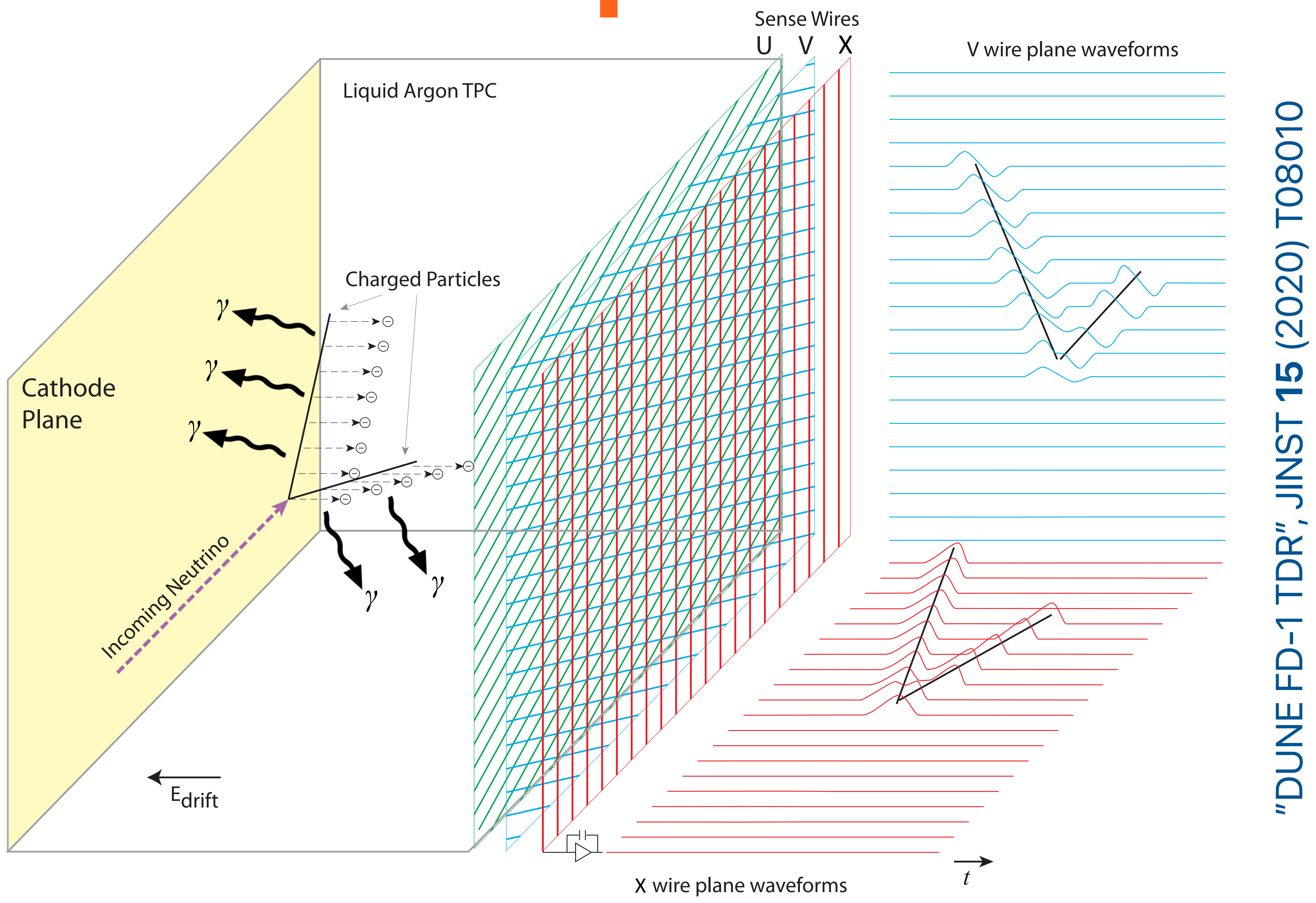
We aim at **enhancing the detection efficiency of scintillation light** in DUNE to:

- **Lower energy thresholds** to extend the sensitivity of DUNE to the few-MeV region.
- **Improve detector performance** for triggering, timing, calorimetry and background rejection.

This R&D poses **several challenges**:

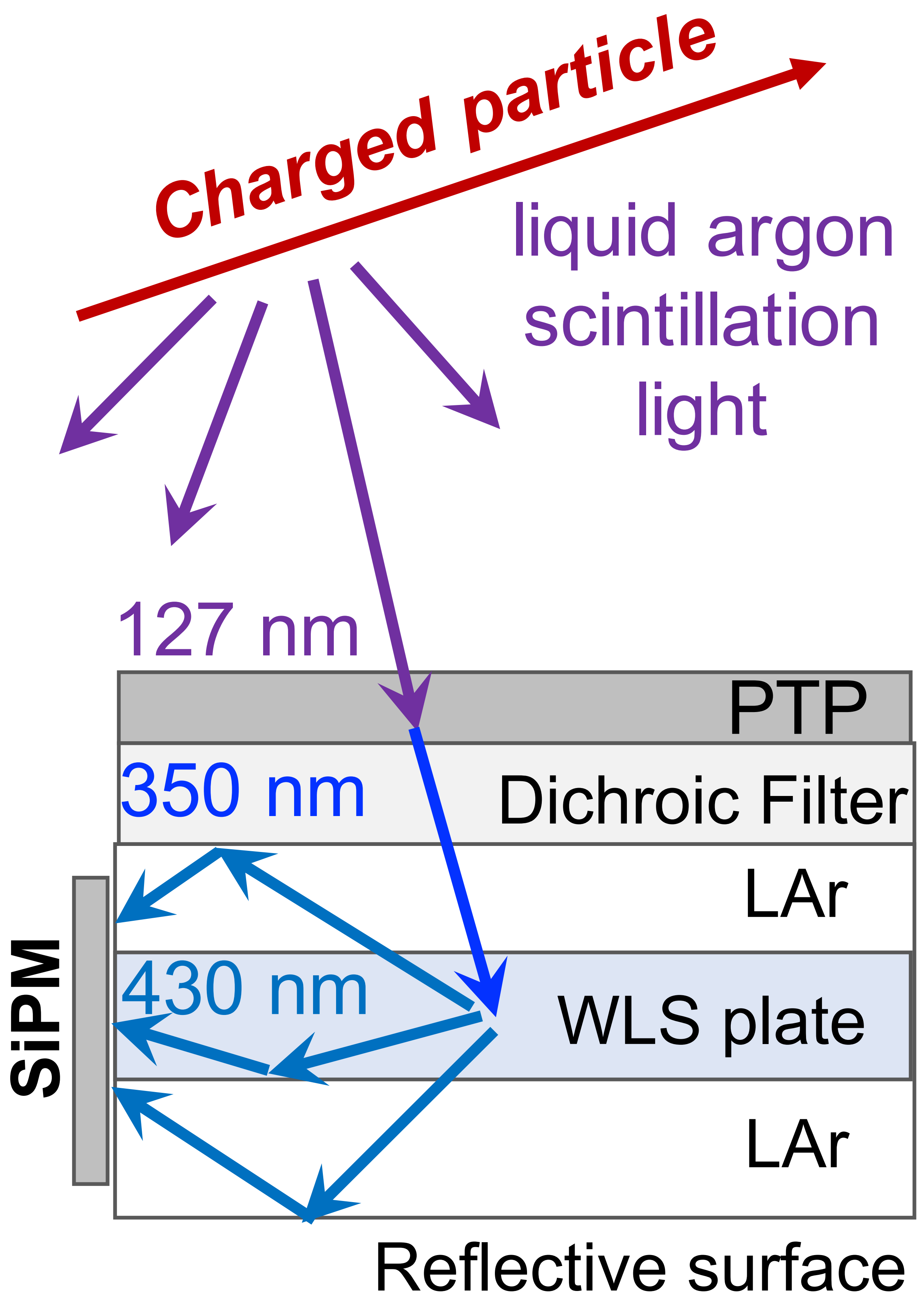
- The **scintillation light from LAr is emitted in the vacuum ultraviolet** (VUV) region of the spectrum, around 128 nm, where most materials are not transparent/reflective and photosensors are expensive and not very efficient.
- **Large volume** of the DUNE LArTPCs, requiring cost-effective photon collectors.
- **Integration** of the photon detectors with the LArTPC field cage and charge readouts.

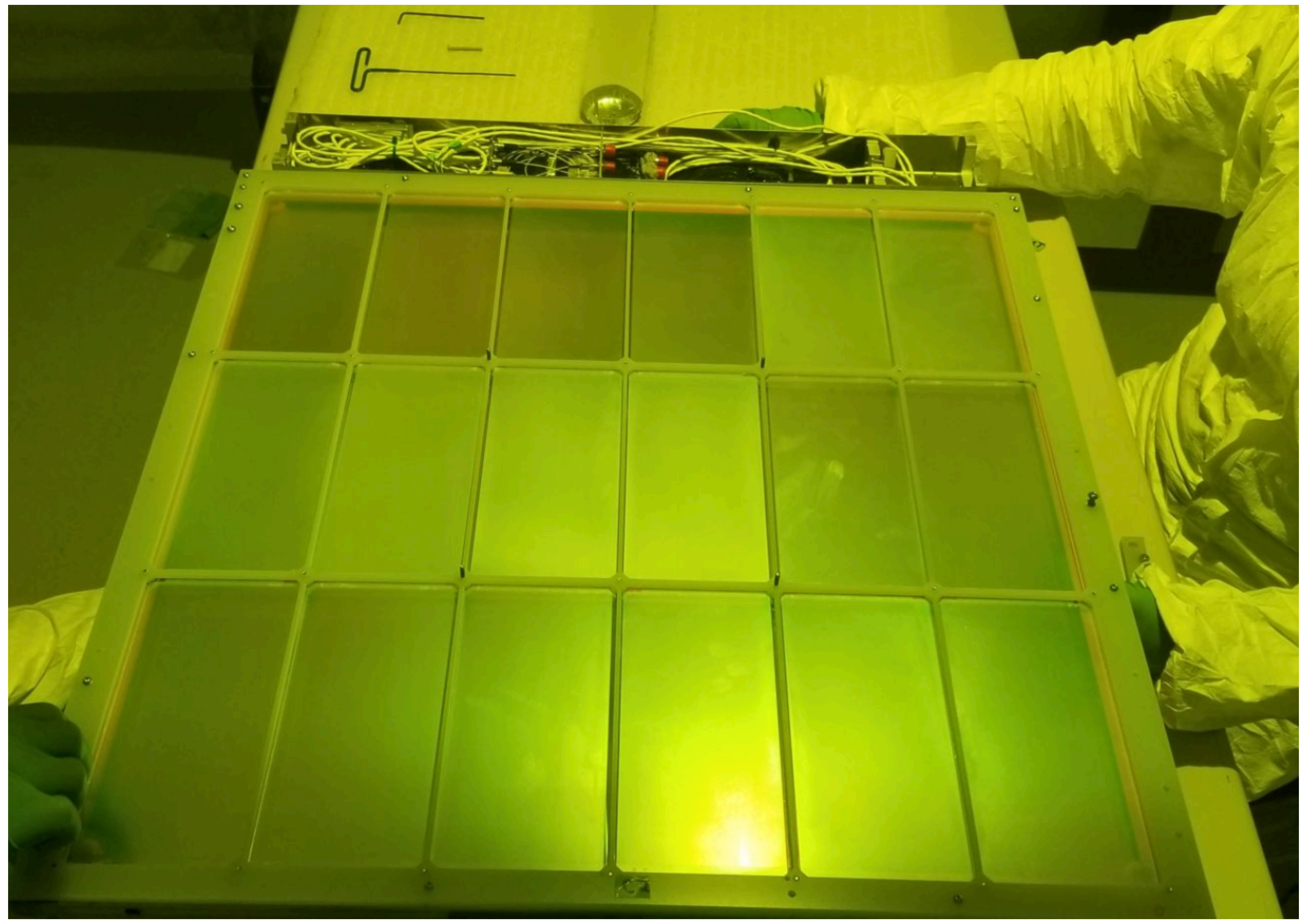
LArTPC detector concept

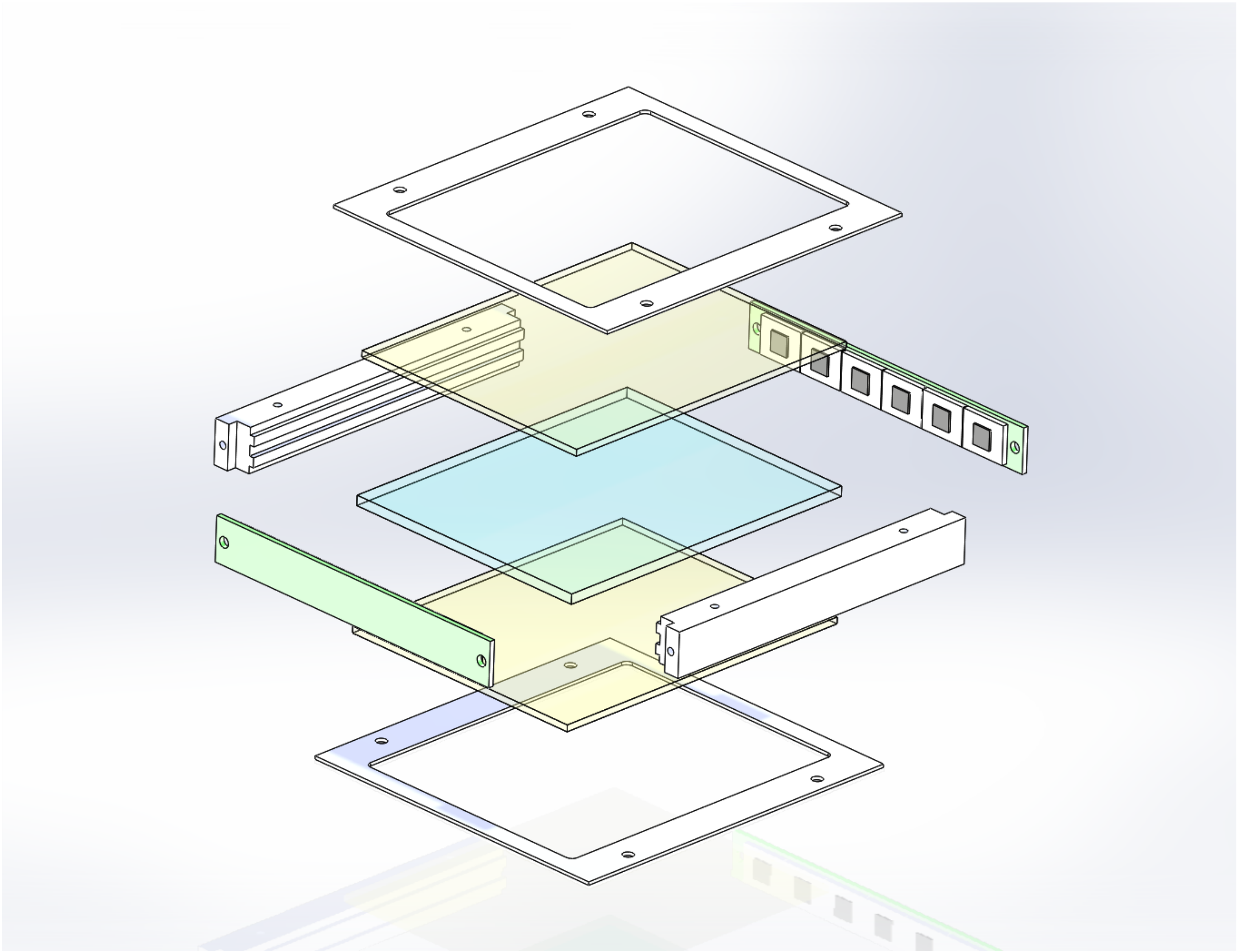


Interacting particles in the LAr produce scintillation and ionisation. The detection of the scintillation light by photon detectors signals the start time of the interaction. The ionisation electrons drift in an electric field towards the anode, where they are read out.

DUNE photon collectors: X-ARAPUCA







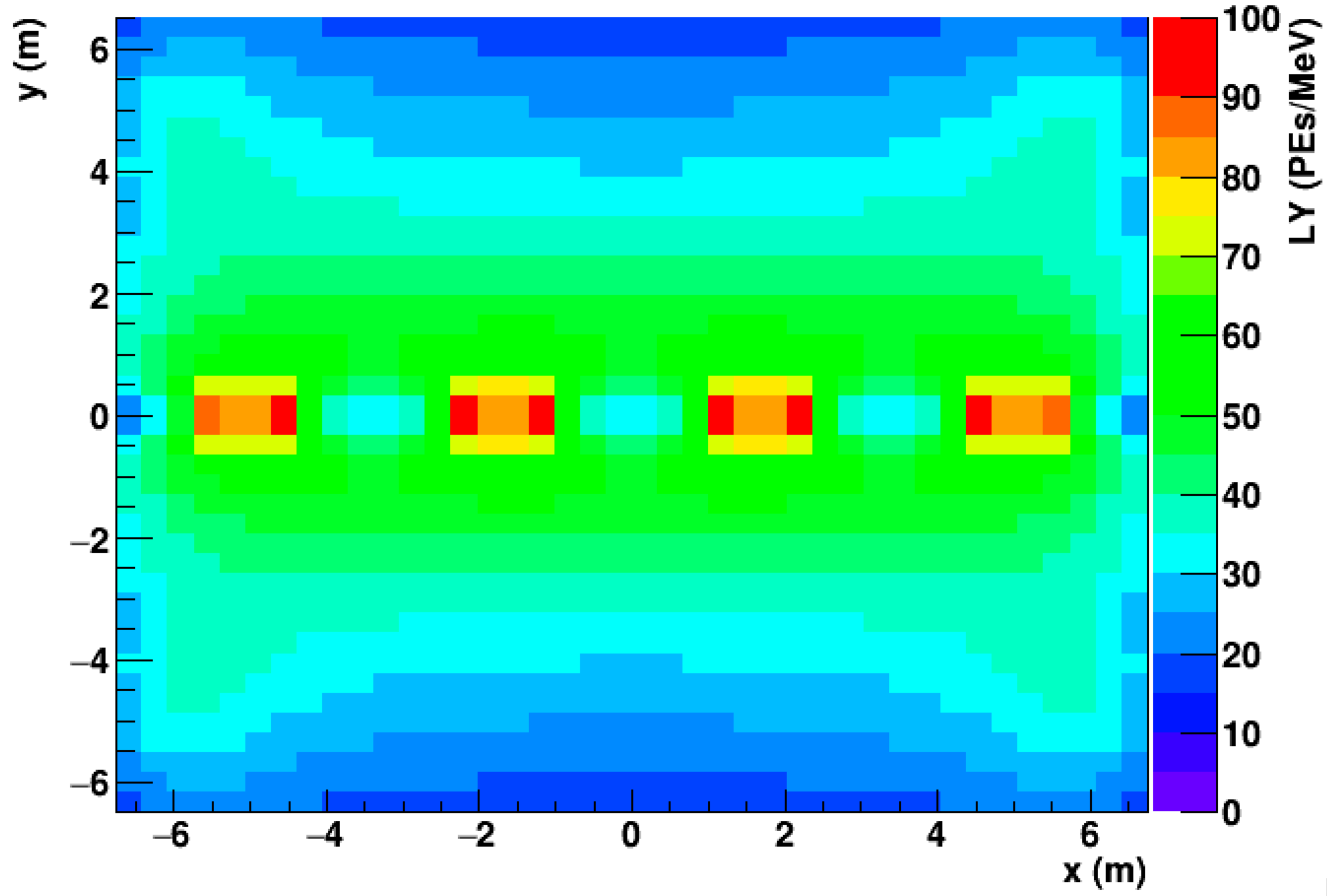
"DUNE FD-1 TDR", JINST **15** (2020) T08010

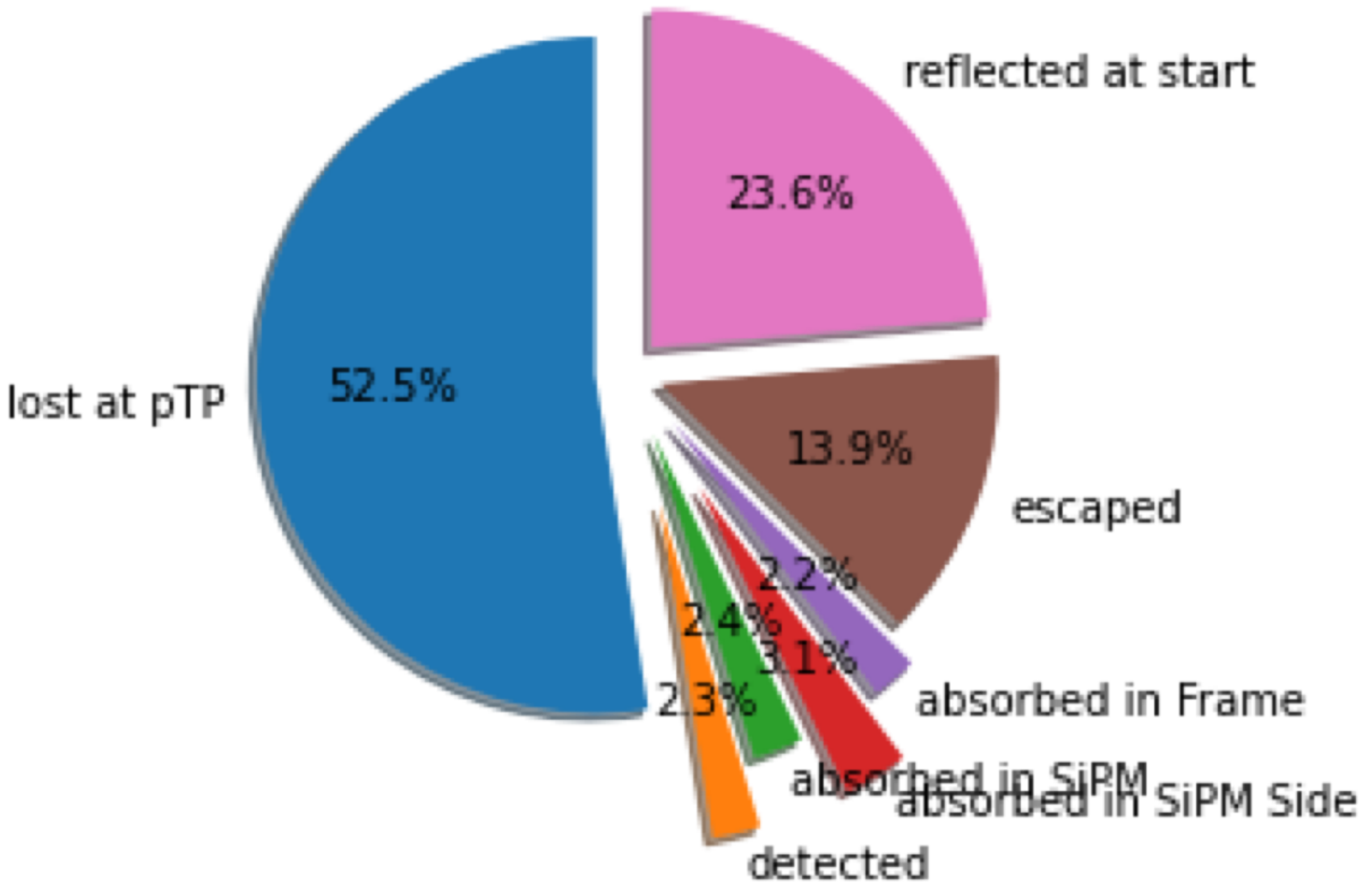
Current performance

About 25000 photons/MeV are produced in LAr (in the presence of a 500 V/cm drift electric field). Only a tiny fraction are actually detected:

- On average, less than 10% of the photons reach the surface of an X-ARAPUCA.
- Of those, only 2–3% are eventually detected by the SiPMs.

”DUNE FD-2 TDR”, in preparation.



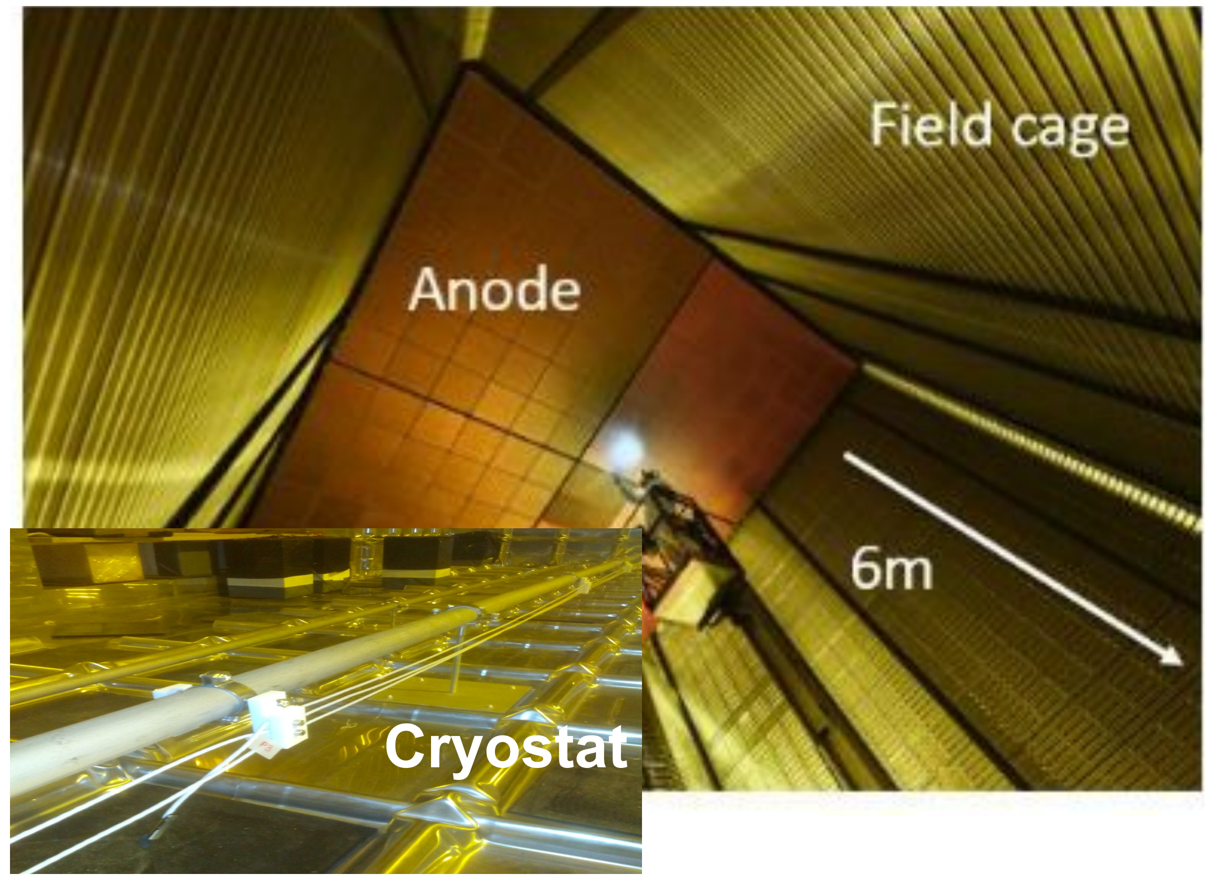


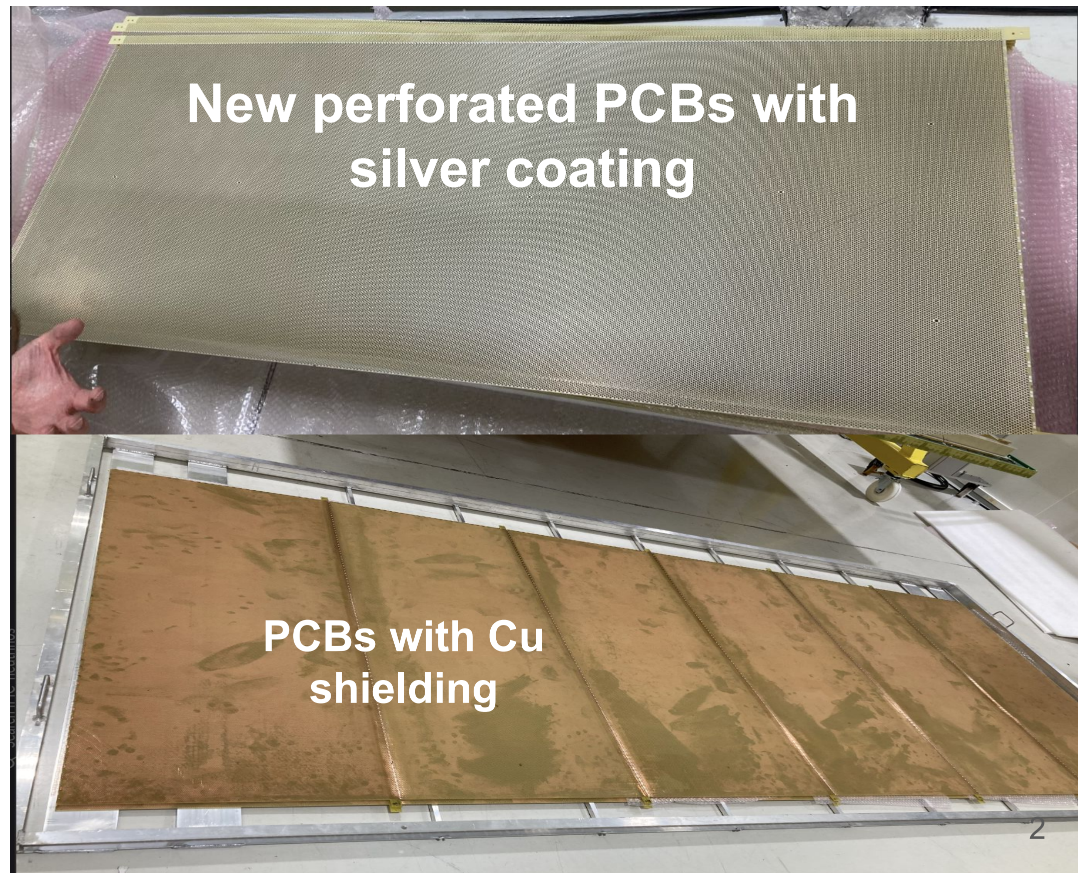
Optical characterisation of materials

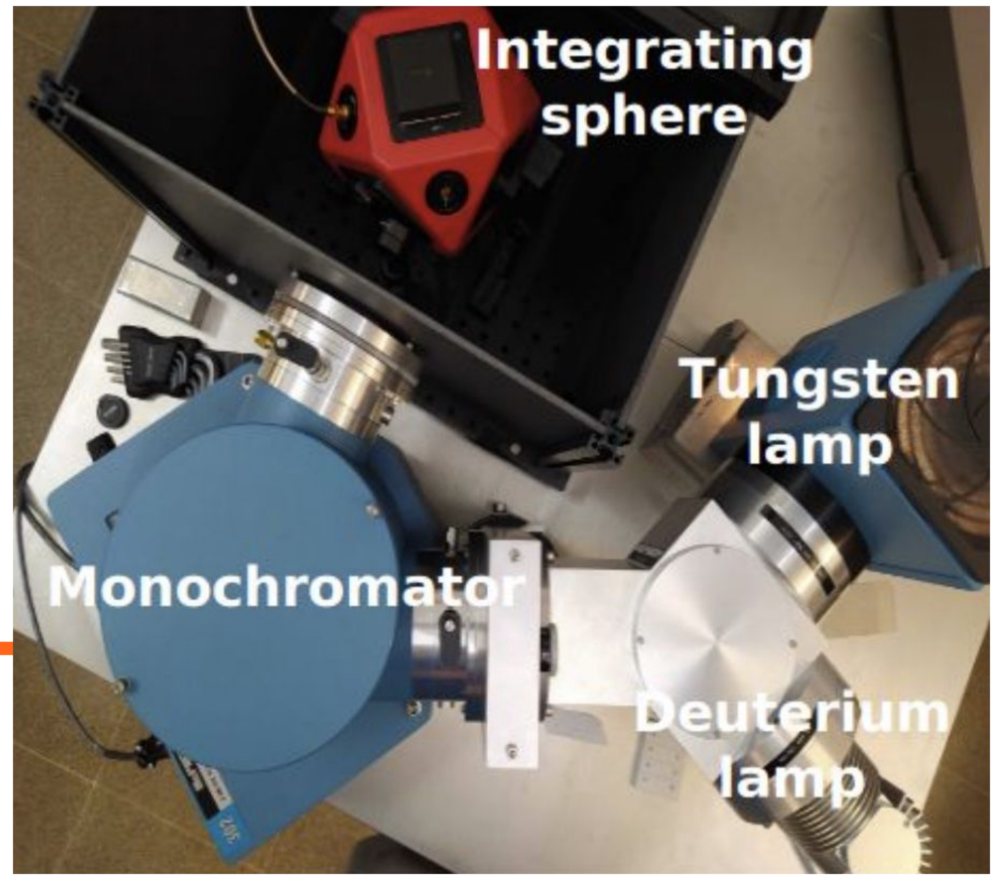
We are working on the identification and characterisation of materials that would increase photon collection in the DUNE LAr TPCs, including:

- Highly reflective metals in the VUV for the field cage, readout planes and cryostat.
- Highly reflective/transmissive materials for the X-ARAPUCA photon collectors.

Our labs are equipped with the necessary equipment (lamps, monochromator, etc.) to measure optical reflectance, transmission and absorption from the visible to the VUV. In particular, measurements in the VUV are difficult, since they require high vacuum or LN_2/GAr atmospheres. We have established links with other European groups specialised in this type of measurements.





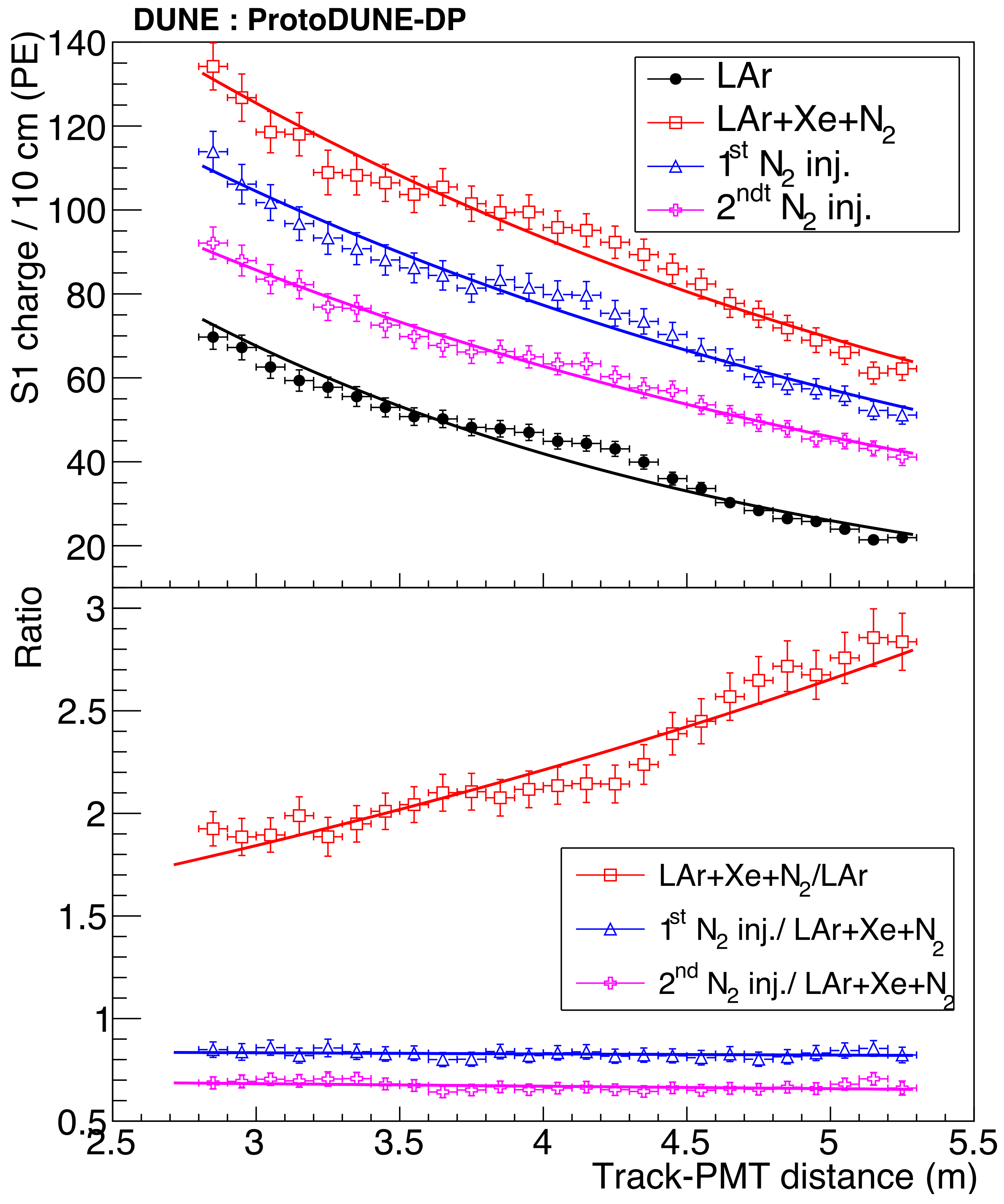


Xe doping

Doping the liquid argon with small amounts of xenon (~10 ppm) shifts the long-lived component of the Ar scintillation (~75% of the total) to the Xe emission wavelength (~175 nm), with several advantages:

- **Reduction of the Rayleigh scattering rate** of the wavelength-shifted light, increasing collection efficiency for light emitted at a far distance photon collectors.
- The 175-nm photons are easier to collect and detect, as **highly transparent or reflective materials are available** for that wavelength.
- Mitigation of the light suppression due to the presence of N_2 impurities.

First results are promising, but further studies are required to understand, for example, long-term stability or whether the reduction of the fast signal amplitude could compromise the performance of the light-based trigger.



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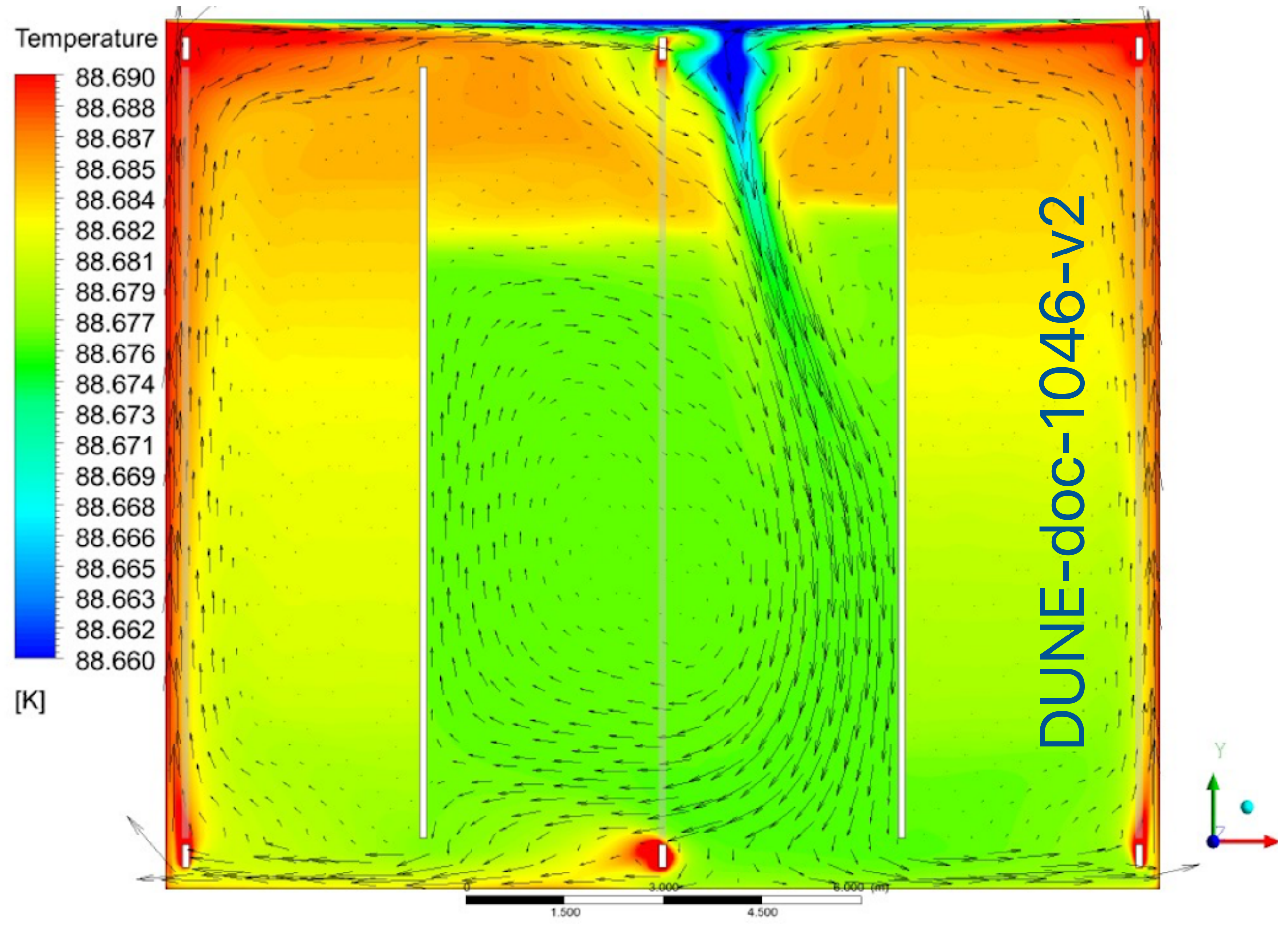
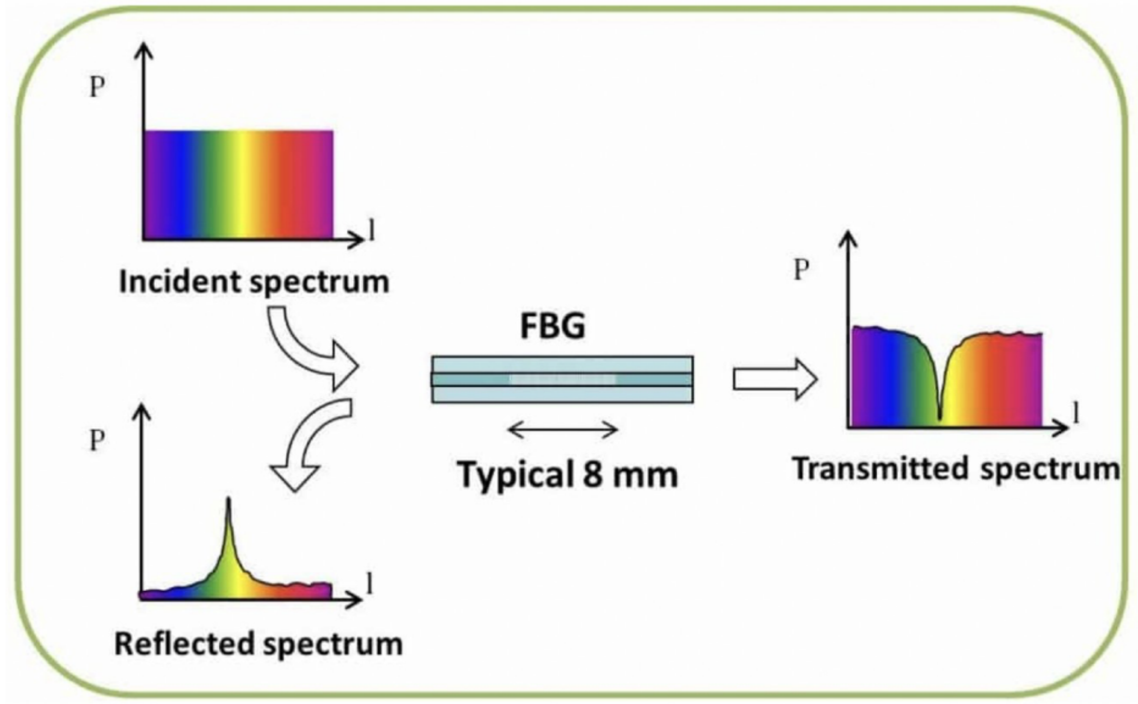
LAr temperature monitoring system

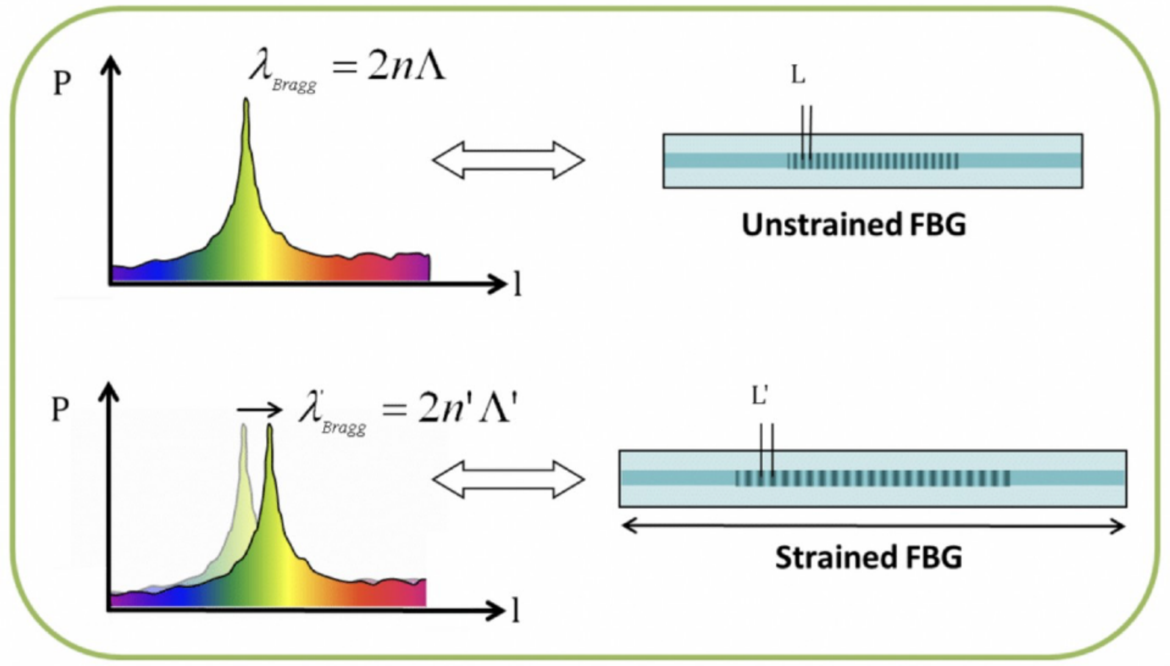
Precise 3D LAr temperature maps constrain the fluid dynamic simulations (top figure) that predict **important parameters for detector performance** such as impurity levels (which have an effect on the intensity of the scintillation signal).

We are developing temperature sensors for the DUNE LAr TPCs based on the **fibre Bragg grating** (FBG) technology, which uses the changes in the reflected/transmitted spectral response of an optical fibre to measure strain and temperature.

Our application has requirements (e.g. **relative precision of 2 mK**) beyond the typical commercial specs of FBG.

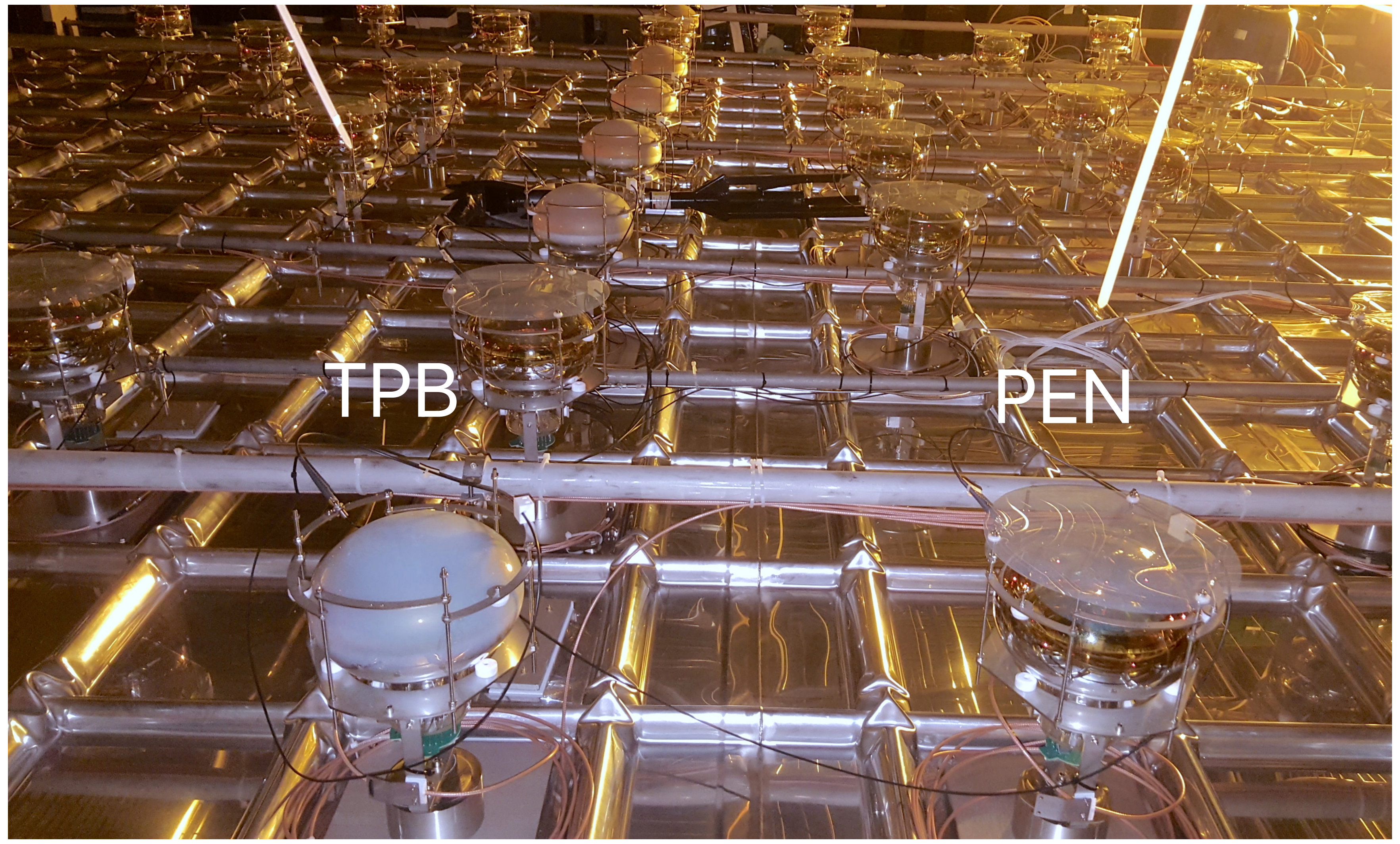






Photon collectors: Wavelength shifters

WLS compounds are a crucial element of the X-ARAPUCA, and although the last decade has brought huge progress in understanding the behaviour, performance and stability of the most commonly used WLS, significant room for further R&D still remains:



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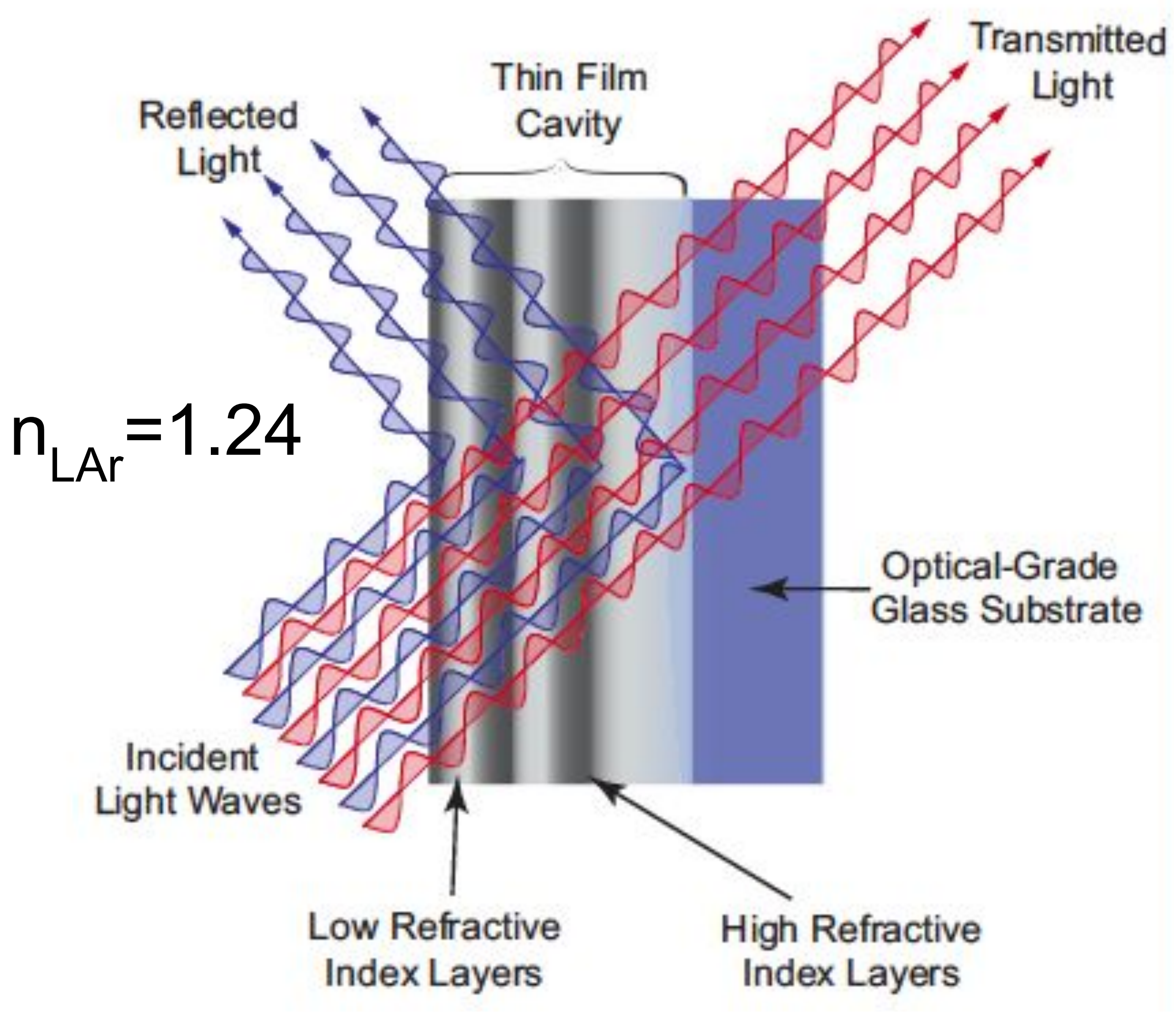
- Coating of extremely large surfaces may be difficult to achieve on a reasonable timescale with vacuum evaporation. Other techniques (such as spin-coating) or films could provide a solution.
- Achieving higher WLS efficiency through nanotechnologies such as quantum dots or metasurfaces.
- Long-term stability.

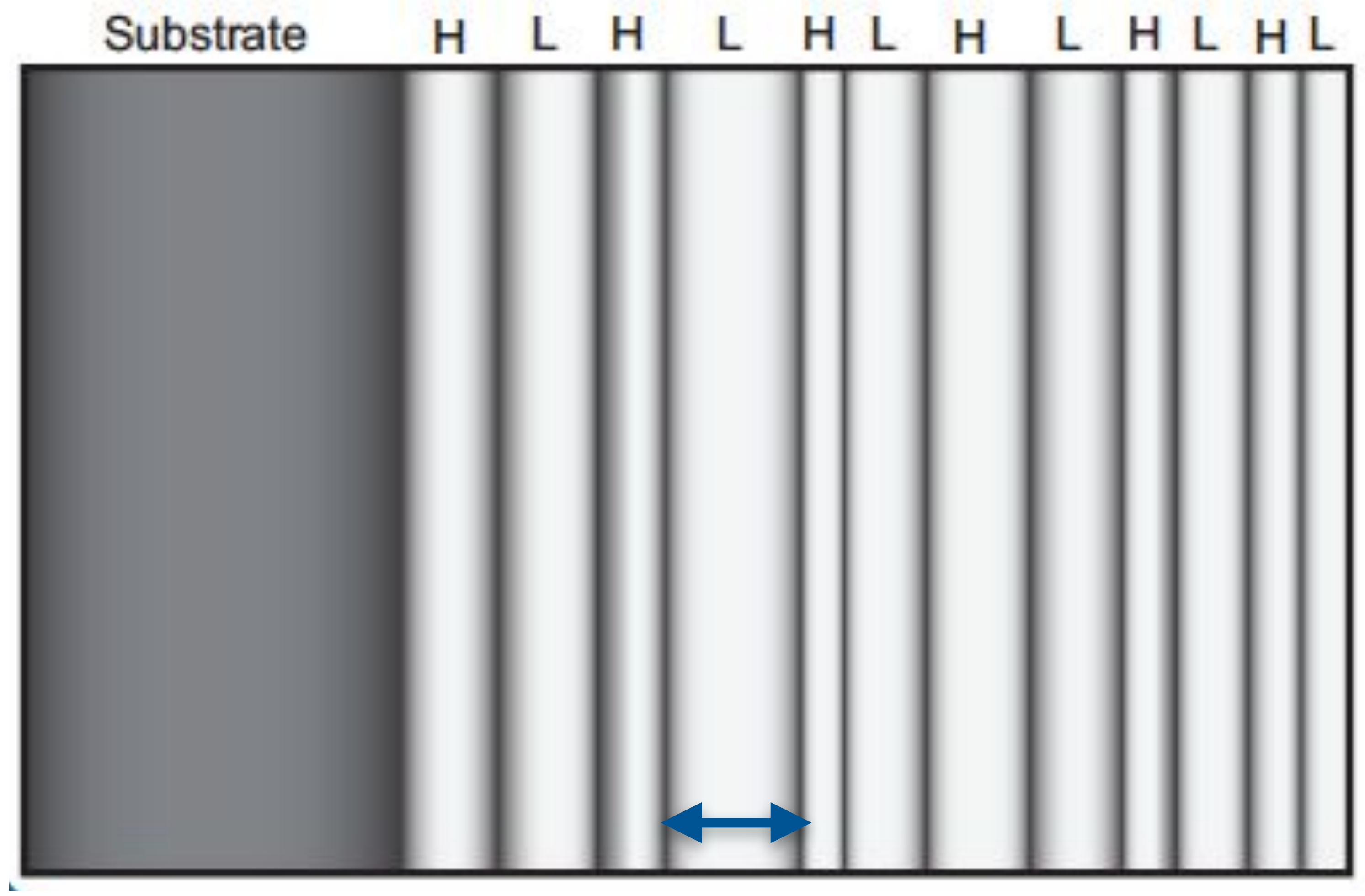
Our groups are acquiring equipment (e.g. vacuum evaporators) to push this R&D line.

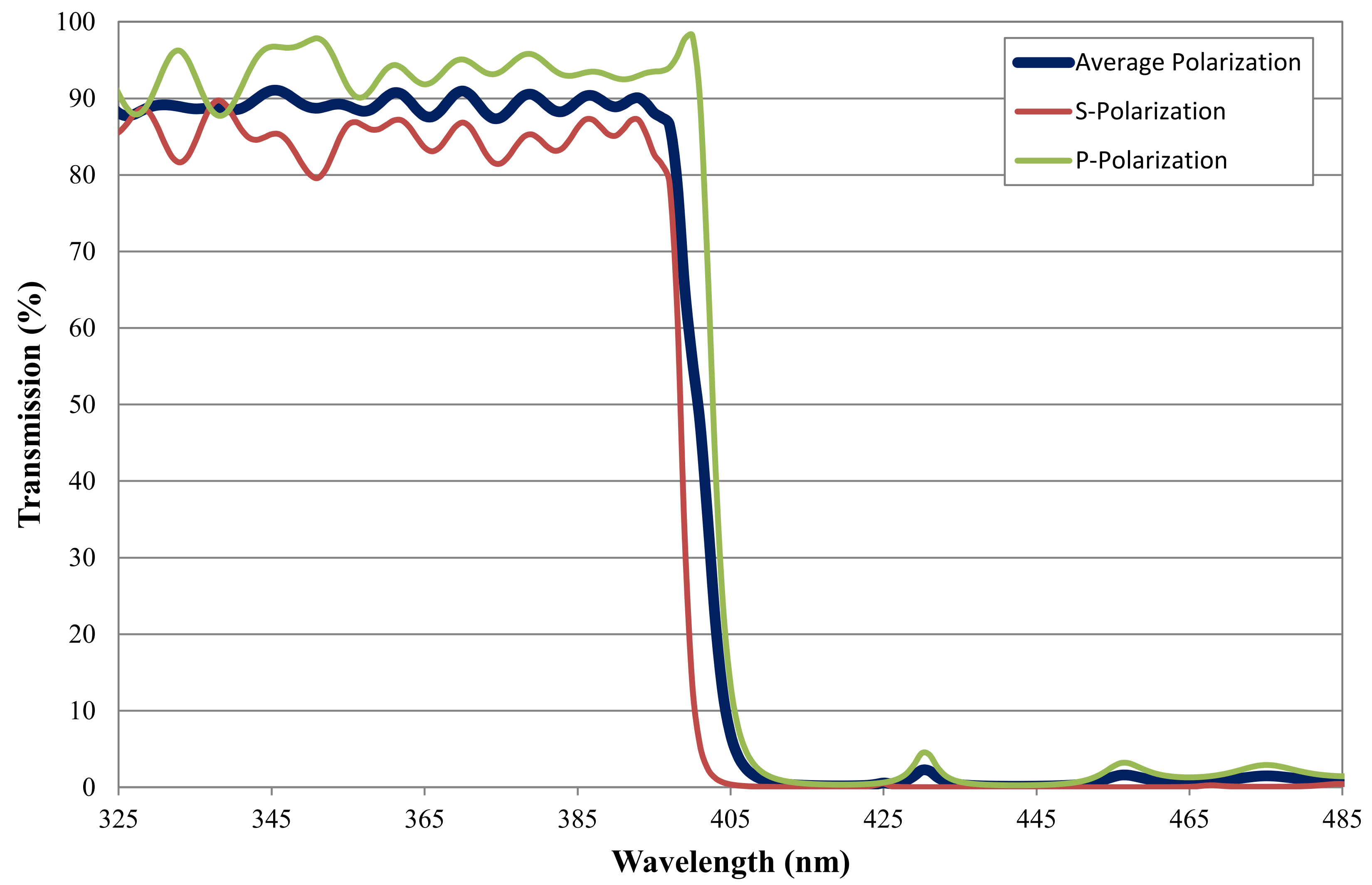
Photon collectors: Dichroic filters

They are interference filters (consisting of a thin-film multilayer structure) that are highly transparent to photons with wavelengths in the range between the VUV and a cut-off, yet almost perfectly reflective to photons with wavelengths above the cut-off.

They trap the LAr scintillation photons (shifted already to the soft UV) within the volume of the X-ARAPUCA.



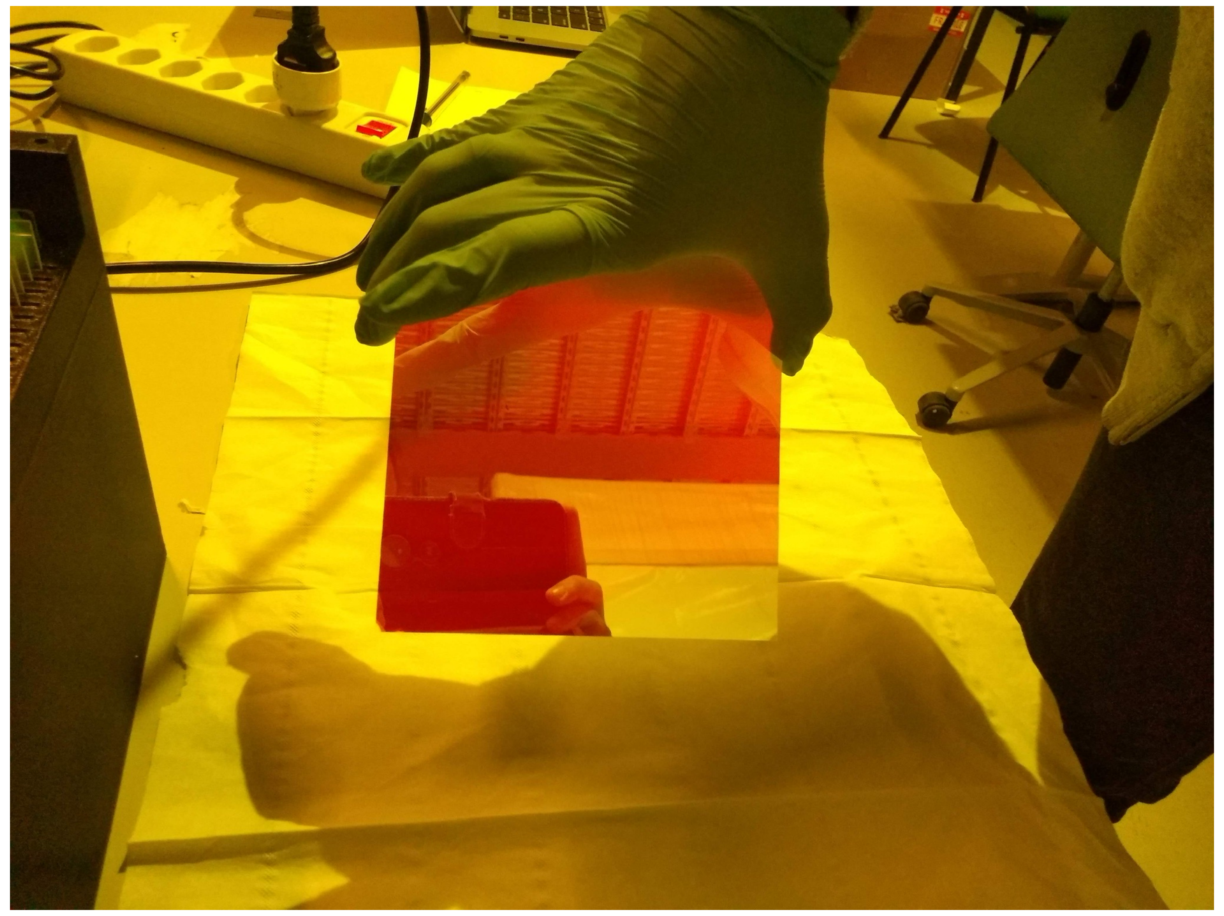


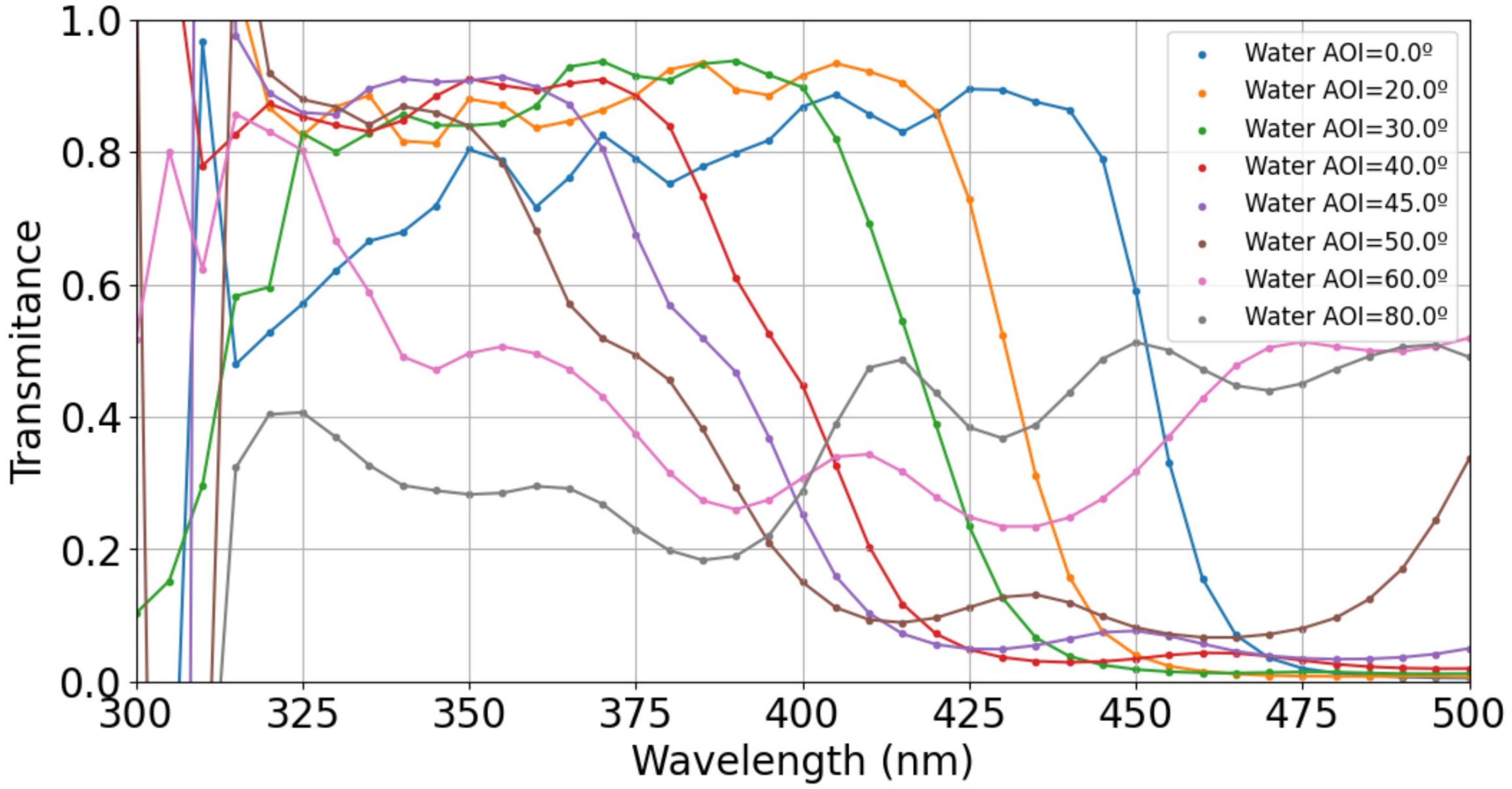


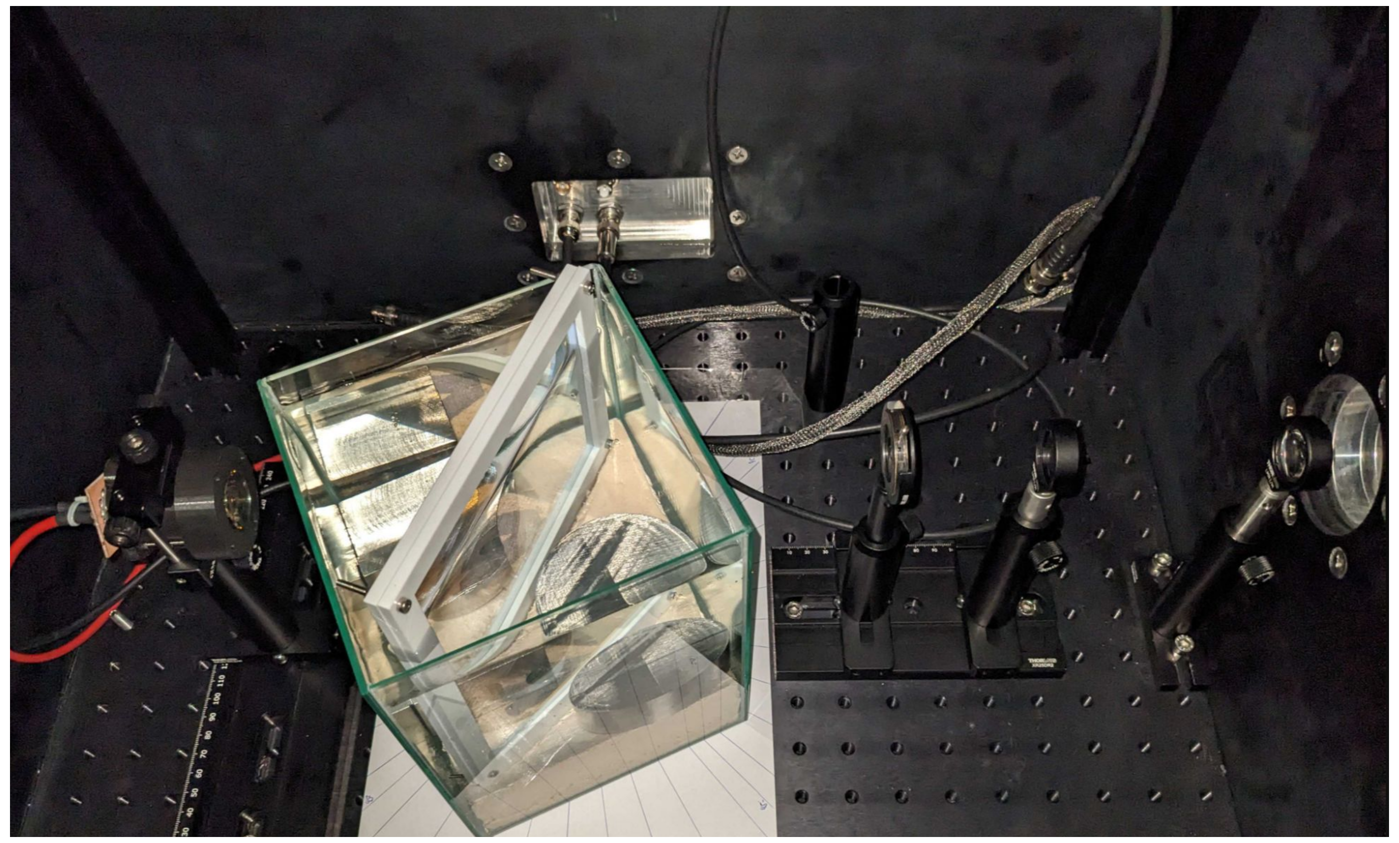
Photon collectors: Dichroic filters

We are developing **more efficient filters** in collaboration with Italian and Brazilian groups (Milano-Bicocca and UNICAMP) and the Spanish industry (PhotonExport) to:

- Find material with high refractive index and good transparency in order to reduce the angular dependence of the cutoff (plot below).
- Develop thin-film coatings on large surfaces and with different shapes.







Photon collectors: Light guides

Polymethyl methacrylate (PMMA) slabs doped with a WLS compound. They trap the photons that enter the X-ARAPUCA, shift them to the blue region of the spectrum and transport them to the SiPMs.

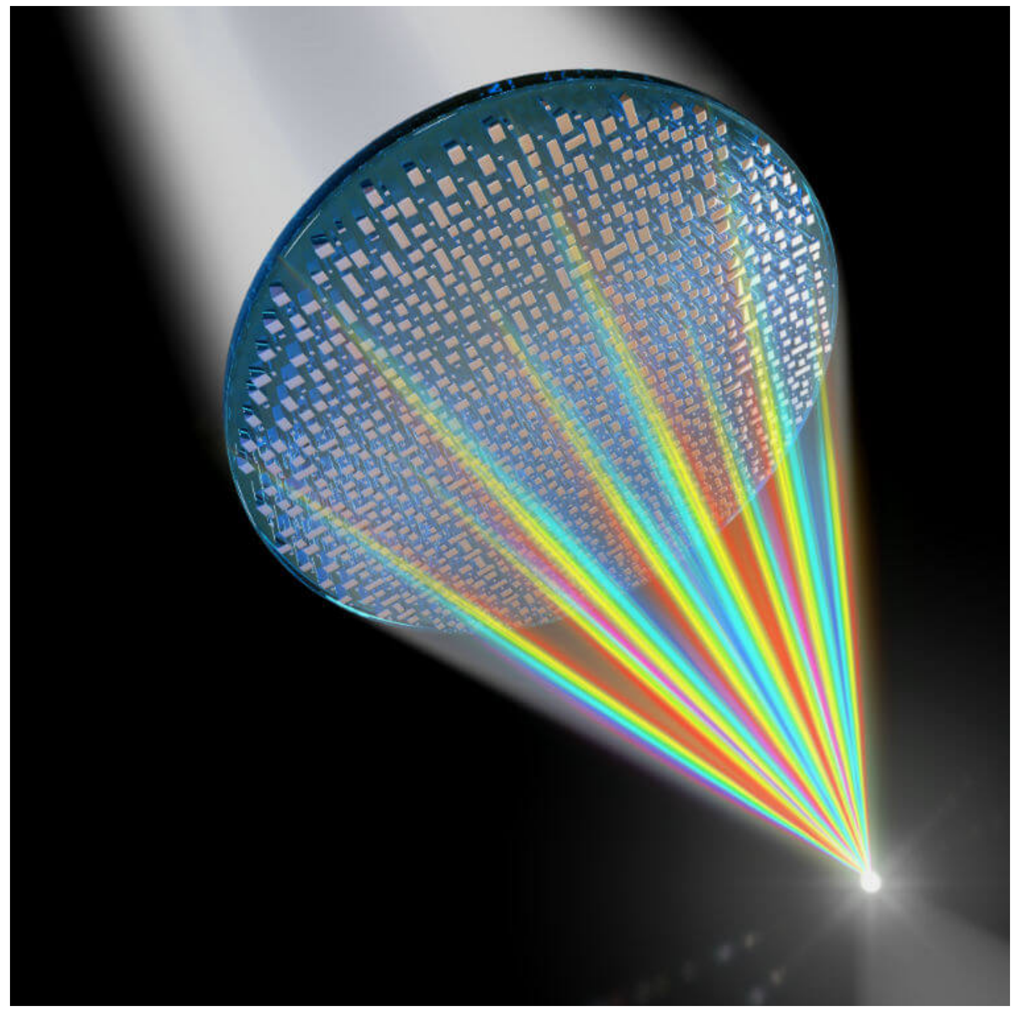
Our R&D, in collaboration with Italian groups and industry, addresses issues such as:

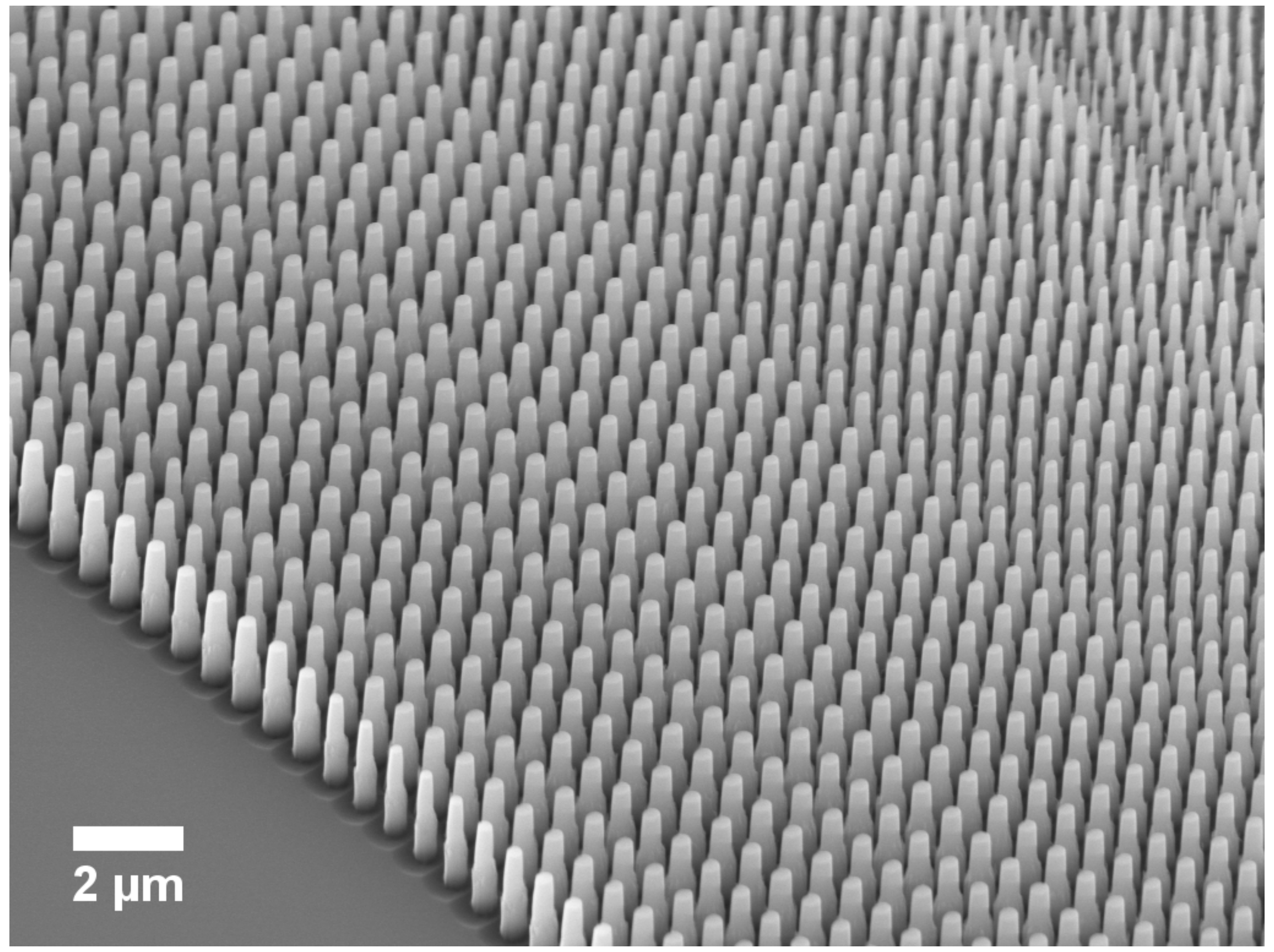
- Longer attenuation lengths for shifted (blue) photons.
- Coupling between light guide and SiPMs (e.g. lensing via dimples).
- Behaviour and long-term stability under cryogenic temperatures.

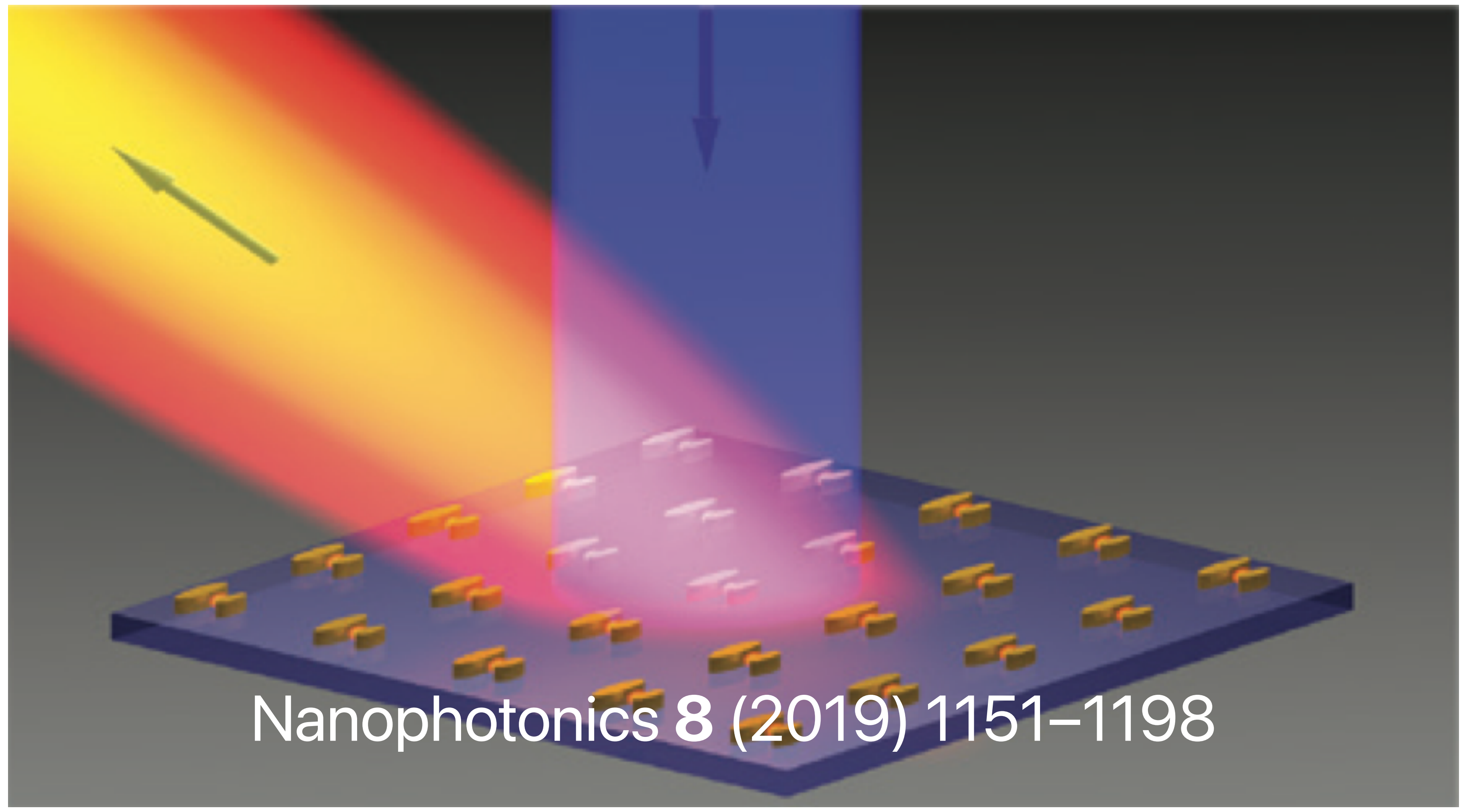
Photon collectors: Metasurfaces

Optical metasurfaces are two-dimensional arrays of scattering elements with sub-wavelength dimensions and periodicity that allow accurate and efficient manipulation of light.

They can realise flat, lightweight and inexpensive optical components, including blazed gratings, lenses, beam shapers or polarizing filters. They can also resonantly capture light and re-emit it with a defined phase, polarization, modality and spectrum.







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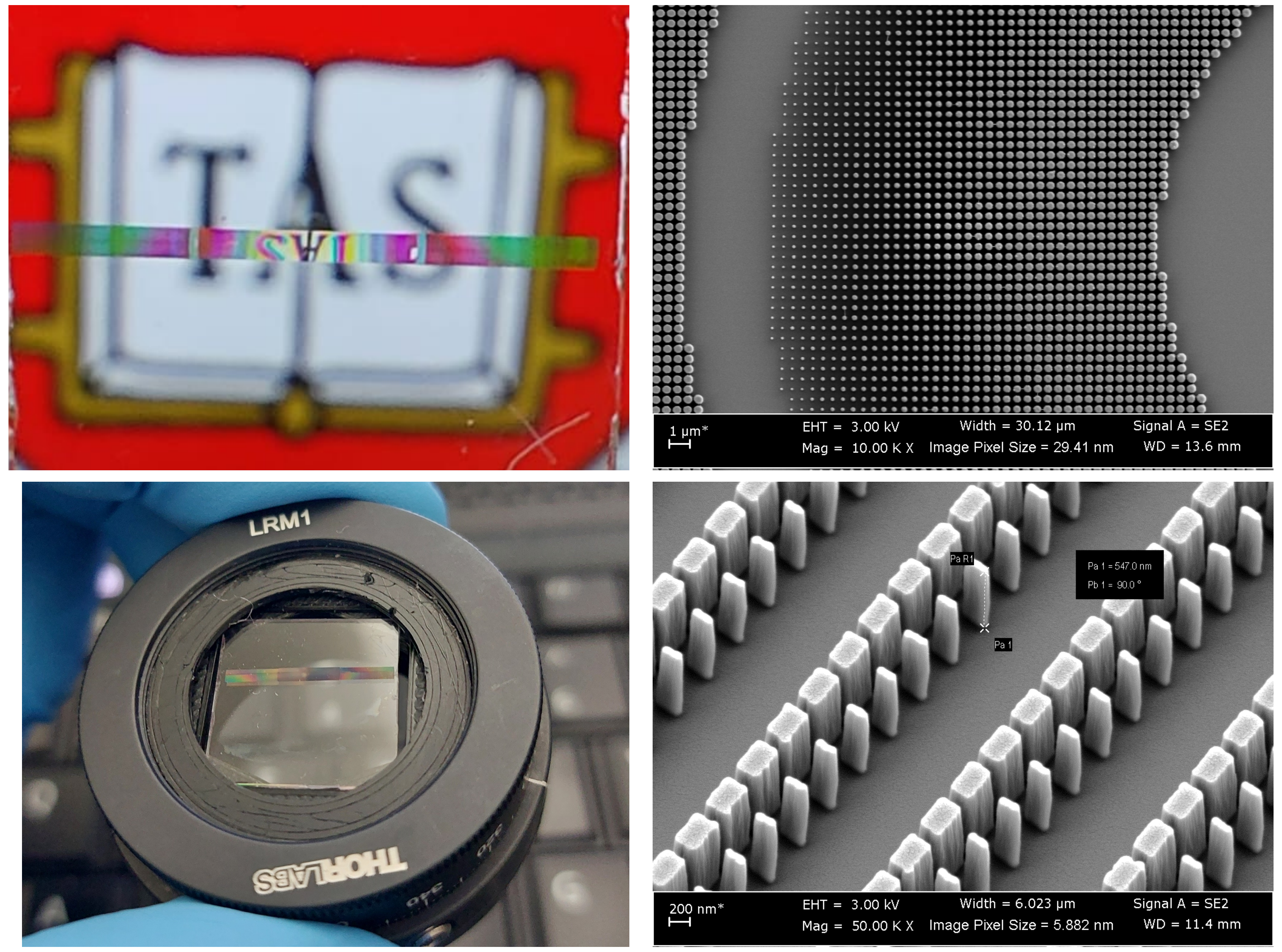
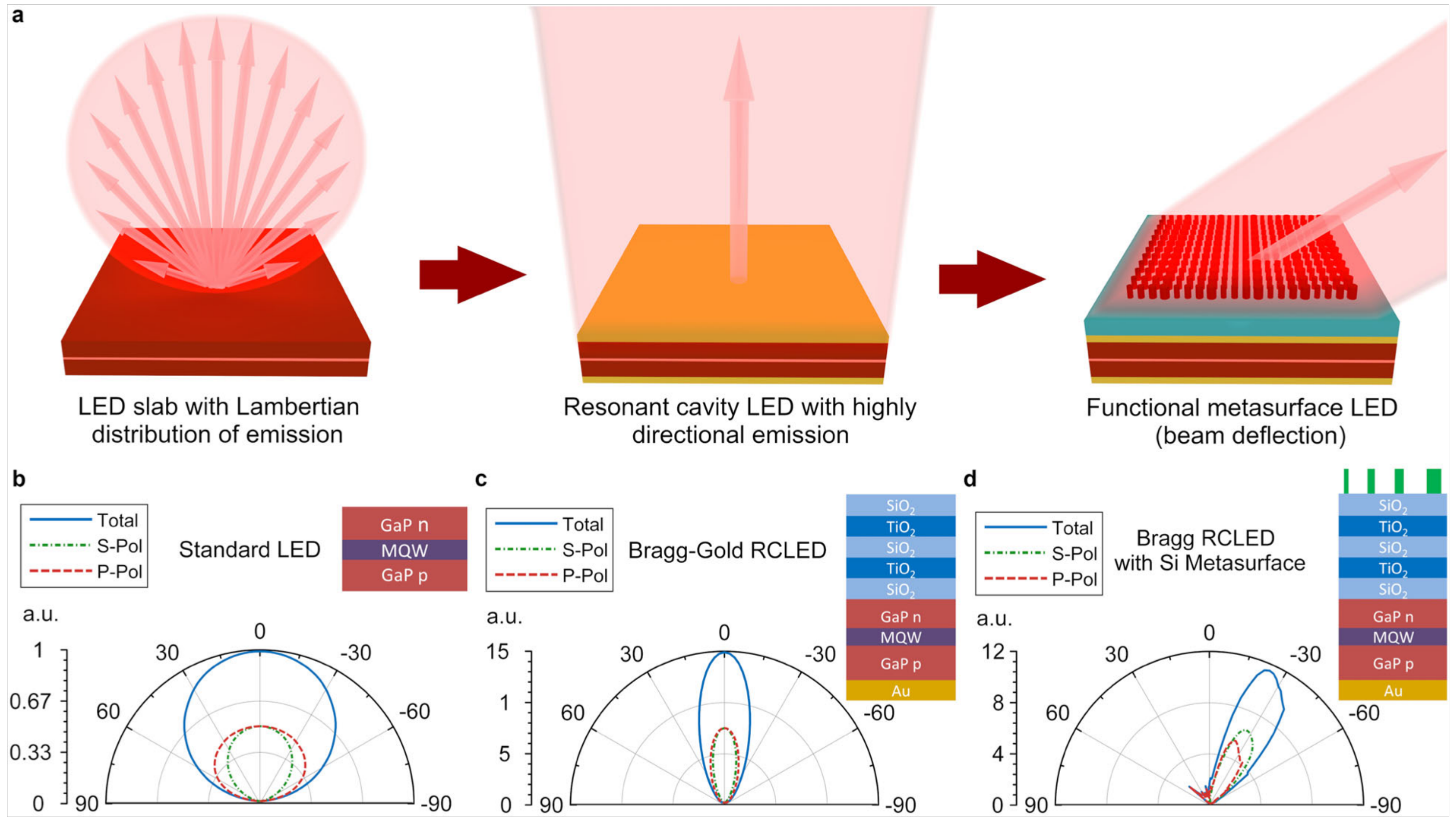
Photon collectors: Metasurfaces

In collaboration with the U. of Manchester, Harvard U. and Fermilab, we are doing research and development on metasurfaces to improve photon collection in LAr TPCs (and other noble element detectors), exploring concepts such as VUV metalenses coupled to SiPMs (left image) or WLS metasurfaces (right image).





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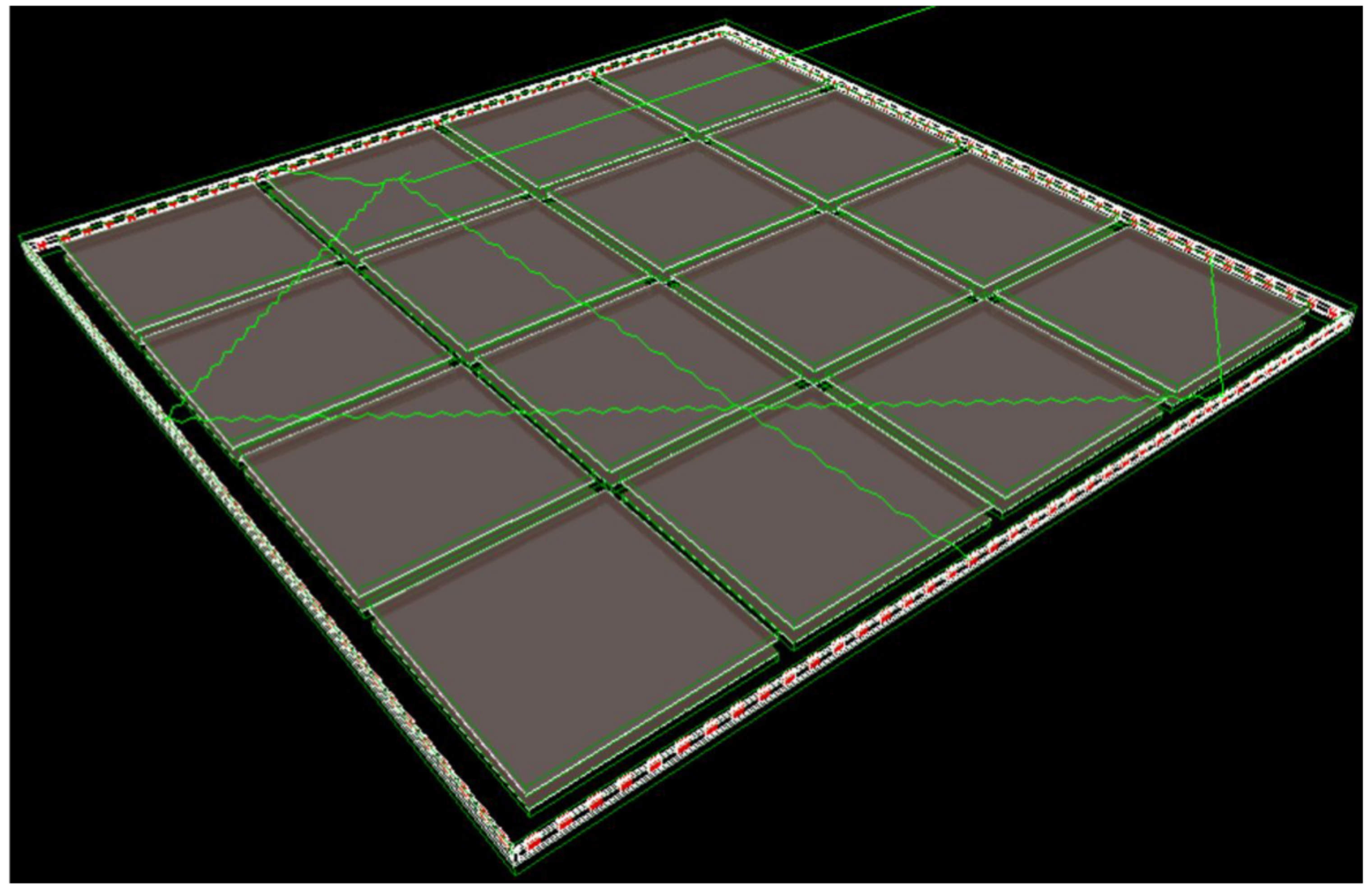
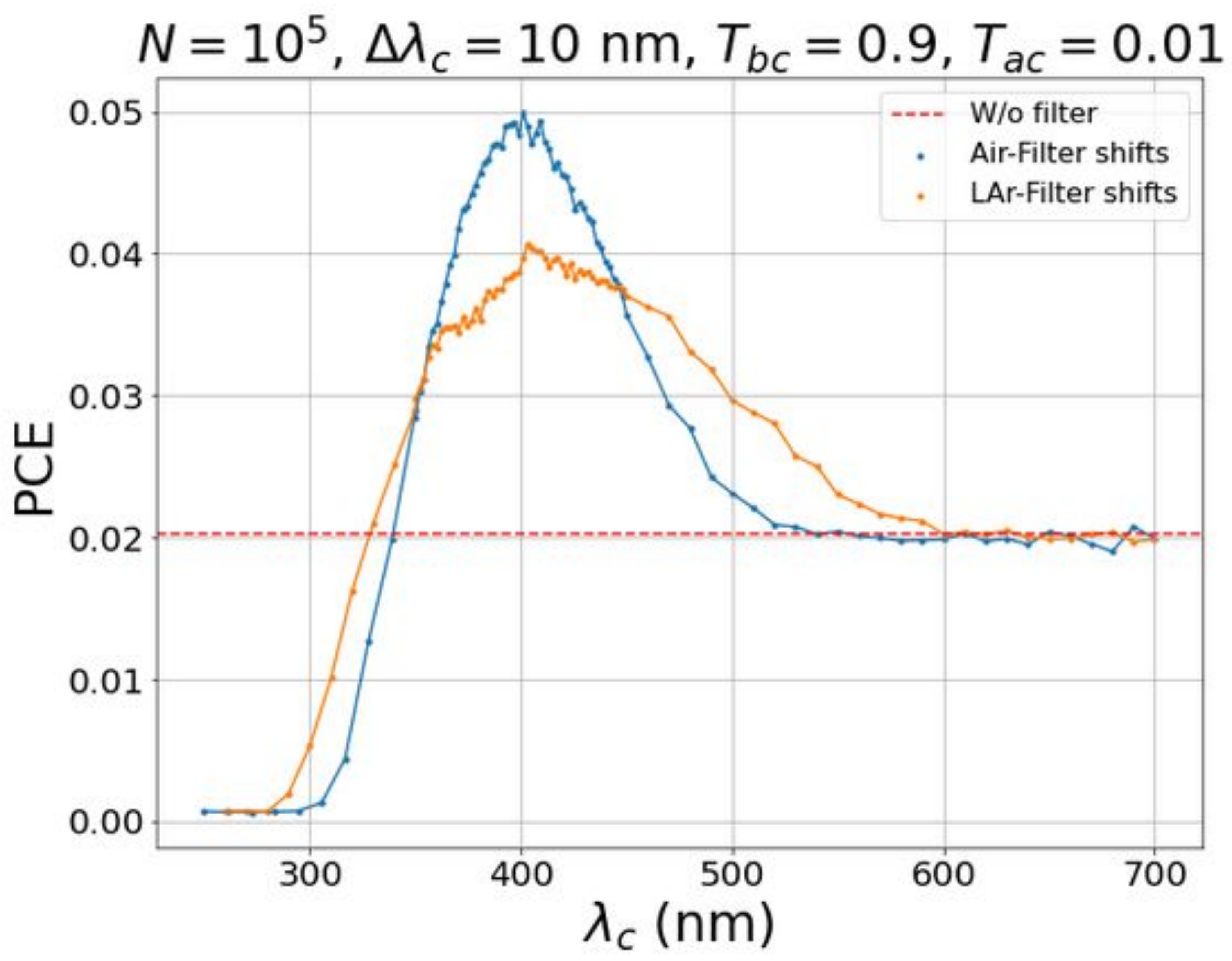
Photon collectors: Simulation

We have developed a Geant4 simulation of the X-ARAPUCA to guide our R&D work. The software can be easily configured to simulate different geometries and optical properties for each component.

Realistic fine tuning of all of the optical properties that come into the simulation is still work in progress. Our goal is to eventually converge on a simulation that outputs reliable, absolute estimations of the X-ARAPUCA photon detection efficiency.





Cut-off position at 45° (DAOI)

Summary

Our groups are carrying out a focused, interdisciplinary R&D to optimise and enhance photon collection in the large liquid argon (LAr) TPCs of the DUNE far detector; namely:

- Improving light propagation via highly reflective detector materials and xenon doping of the LAr.
- Improving the detection efficiency of the X-ARAPUCA beyond the few-percent level using optimised components (dichroic filters, light guides…) or new technologies (e.g. metasurfaces).

While this R&D has DUNE at its center, other applications (in particle physics or medical imaging, for example) may be explored as well.