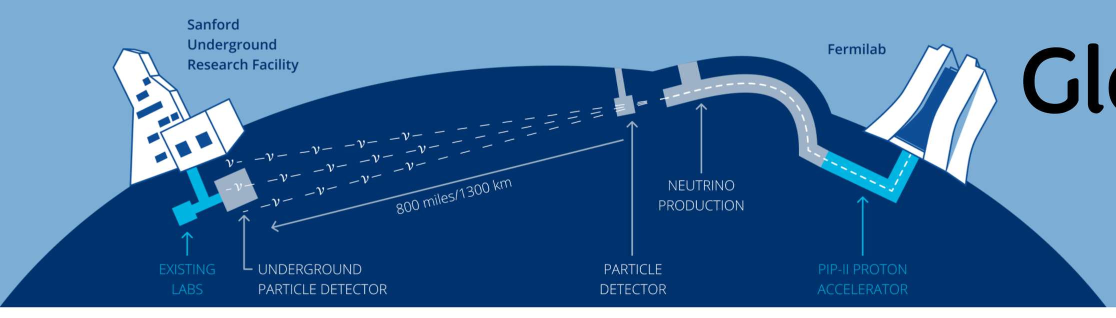
International Neutrino Summer School (INSS) 2026 – UC Santa Barbara (CA)

# Xenon doping of Liquid Argon in ProtoDUNE-VD

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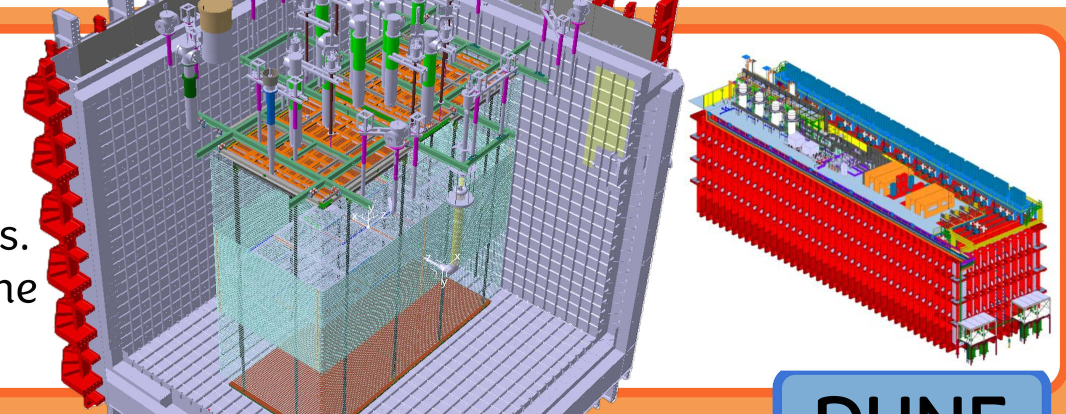
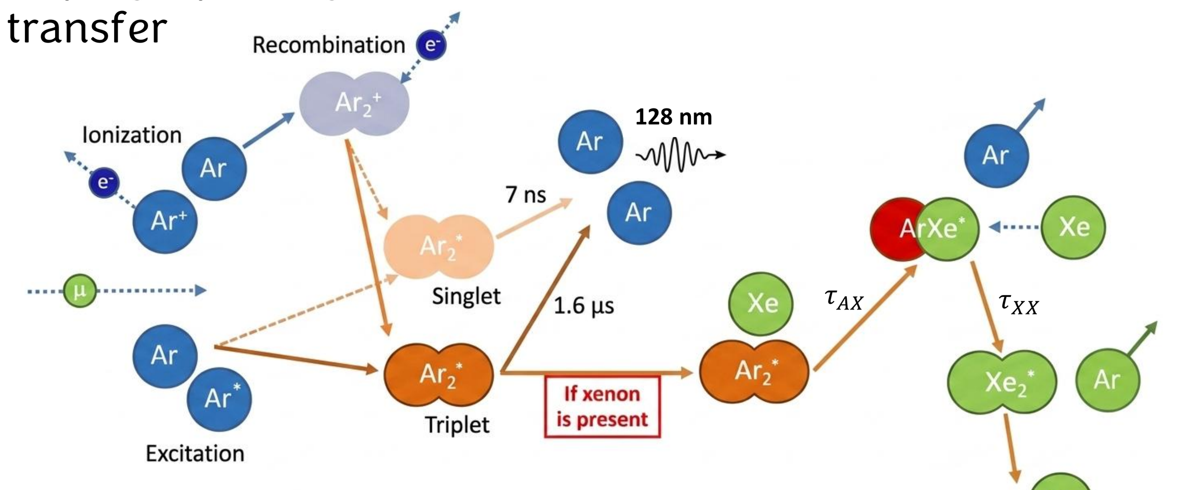
The Deep Underground Neutrino Experiment is a next-generation long-baseline neutrino-oscillation experiment.
Its Far Detectors are massive Liquid Argon Time Projection Chambers (LArTPCs) equipped with a high-performance Photon Detection System (PDS) for timing neutrino events.
The Neutrino Platform at CERN hosts and operates two 770-ton prototype modules to test the technologies for the DUNE Far Detectors.
ProtoDUNE-VD implements a Vertical Drift configuration with the Photon Detection Modules installed on the central cathode and on the membrane walls, behind the field cage.



DUNE

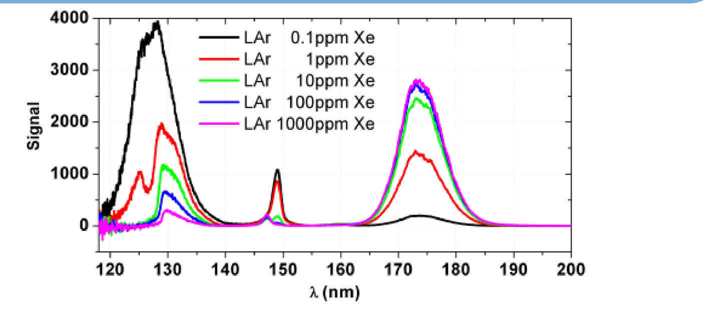
## XENON DOPING

Doping liquid argon with xenon shifts the scintillation emission from 128 nm to 178 nm via energy transfer




Key benefits of Xe doping [3]:

- Longer wavelenght
- Longer Rayleigh scattering length: more uniform response
- Faster scintillation and higher light yield



Energy transfer of dimer $Ar_2^* \rightarrow ArXe^* \rightarrow Xe_2^*$

- Time constant of transition processes ($\tau_{AX}$, $\tau_{XX}$) depend on Xenon concentration
- No FAST and SLOW component, decay time < 23 ns

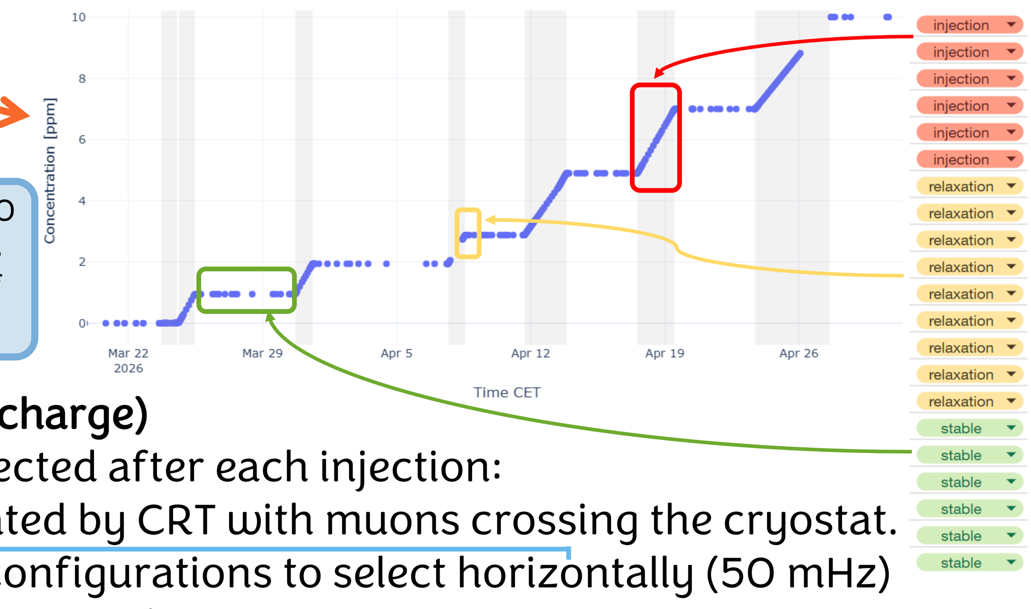
ArAr* scintillation at 128 nm and shifting to ArXe*
ArXe* scintillation at 150 nm and shifting to XeXe*
XeXe* scintillation at 178 nm

## CAMPAIGN

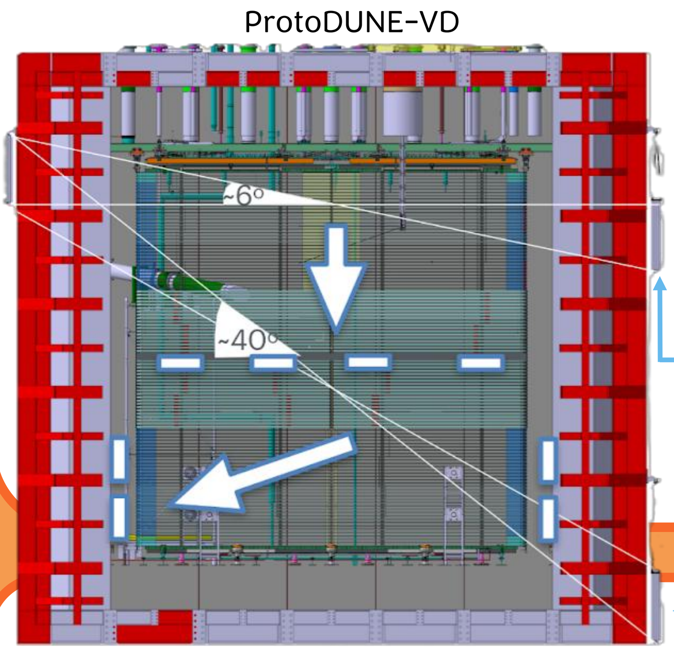
| Injection | Start | Duration | Injected [kg] | [ppm] |
|---|---|---|---|---|
| 1 | 23/03/2026 | 19h | 0.011 | 0.015 |
| 2 | 24/03/2026 | 20h | 0.702 | 0.953 |
| 3 | 30/03/2026 | 22h | 0.744 | 1.948 |
| 4 | 07/04/2026 | 21h | 0.697 | 2.880 |
| 5 | 11/04/2026 | 52h | 1.516 | 4.906 |
| 6 | 17/04/2026 | 47h | 1.572 | 7.008 |
| 7 | 23/04/2026 | 93h | 2.245 | 10.009 |

Reached the target concentration of 10 ppm!

Data acquisition modes:
**1) PDS**: using DAPHNE self-trigger we collected 5-minutes runs every 30 min, 2h or 3h during injection and whenever possible outside injection periods. In each run there are ~2-5 million waveforms for cathode and membrane modules.



ProtoDUNE-VD



Collected more than 400 PDS runs, 400h of CRTs data and 350k events of random trigger

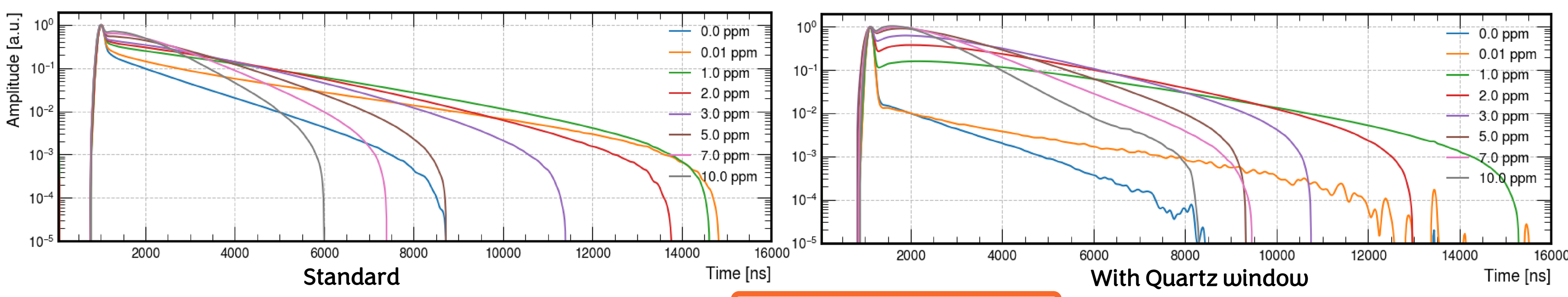
**2) PDS+TPC (light+charge)**
Different runs collected after each injection:

- Trigger generated by CRT with muons crossing the cryostat. Two possible configurations to select horizontally (50 mHz) or vertically (150 mHz) crossing muons
- Random trigger at 2-4 Hz to acquire cosmic data

## FIRST RESULTS

### Signal Shape evolution

Clear modification of scintillation waveform shape with increasing xenon concentration observed in all modules. The presence of a Quartz window suppress pure liquid argon light.

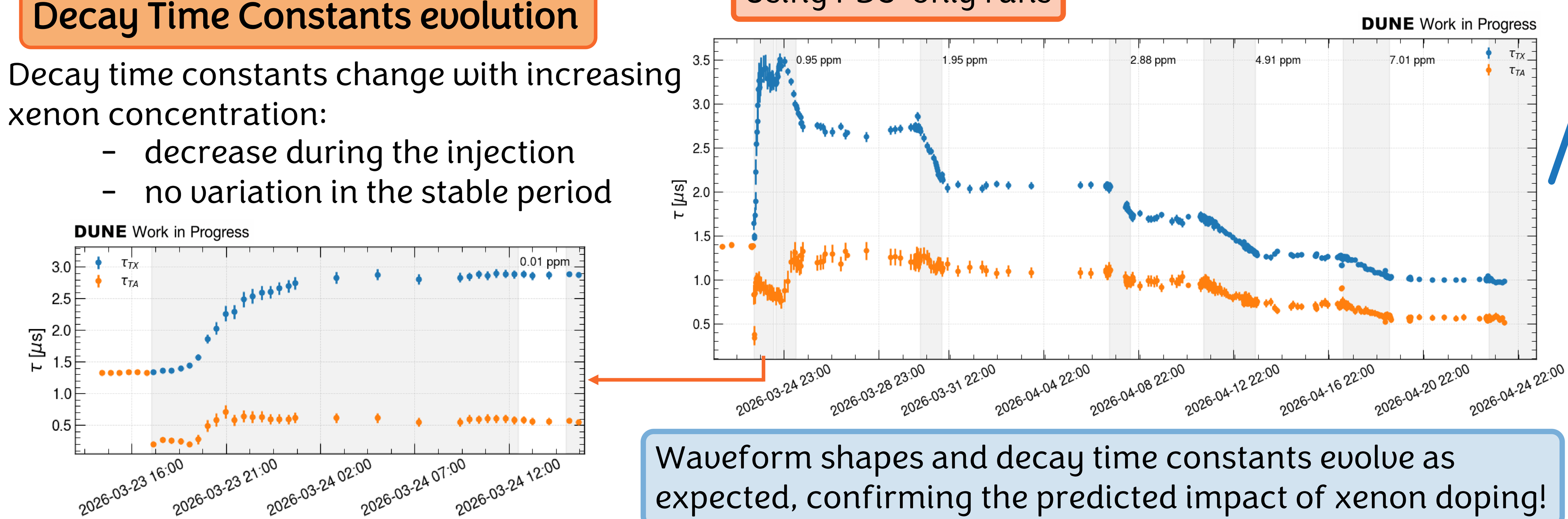



### Decay Time Constants evolution

Decay time constants change with increasing xenon concentration:

- decrease during the injection
- no variation in the stable period

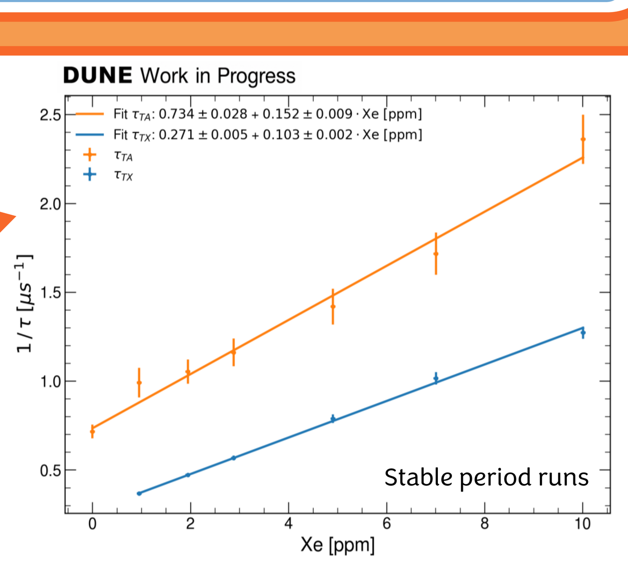
Using PDS-only runs



Waveform shapes and decay time constants evolve as expected, confirming the predicted impact of xenon doping!

## NEXT STEPS

- **Decay time constant estimation** using PDS runs and global fit results (ONGOING)
- Investigation of **light-collection uniformity** using CRT-reconstructed tracks. Quantify the light yield as a function of the distance between the track and the photosensor and evaluate the impact of xenon doping on the detector response uniformity
- Check the impact on **charge collection**



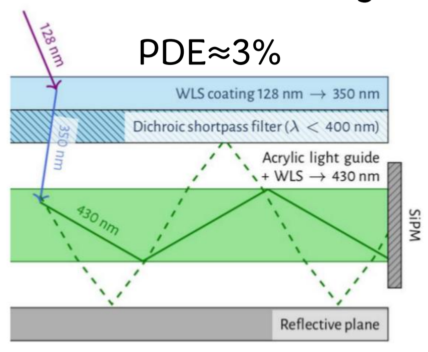
Still a lot of data to analyze!

## PDS MODULES

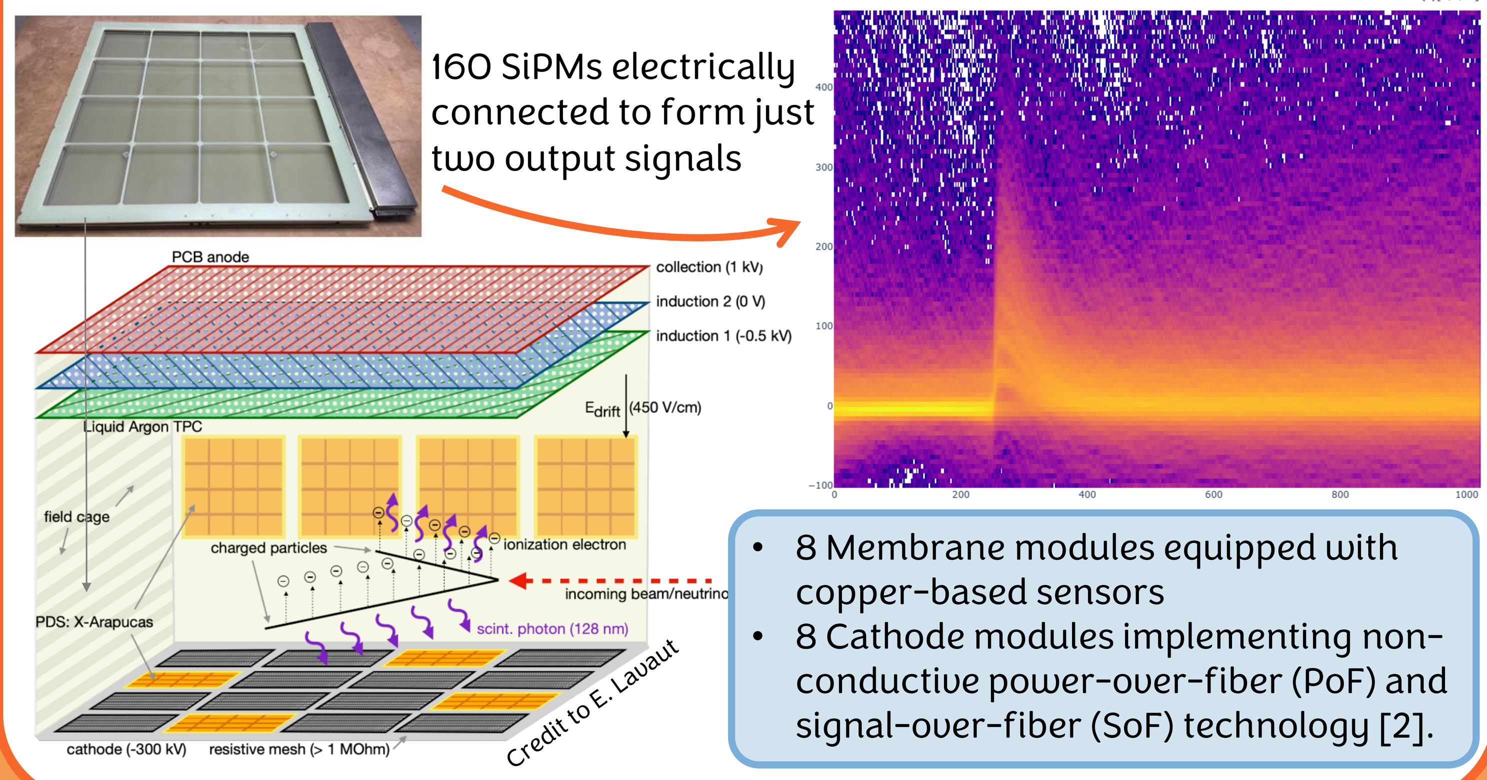
The DUNE PDS consists of a large number of photon detection units, X-ARAPUCAs [1], that act as light-traps capturing wavelength-shifted photons inside boxes with highly reflective internal surfaces until they are eventually detected by silicon photomultipliers.

- Shifts the 127 nm VUV light in the visible region (430 nm)
- Optimizes the ratio of light-collecting area to SiPM area
- Same compact structure for both cathode and membrane modules.

PDE≈3%



Light collecting area of $\sim 600 \times 600\ mm^2$



160 SiPMs electrically connected to form just two output signals

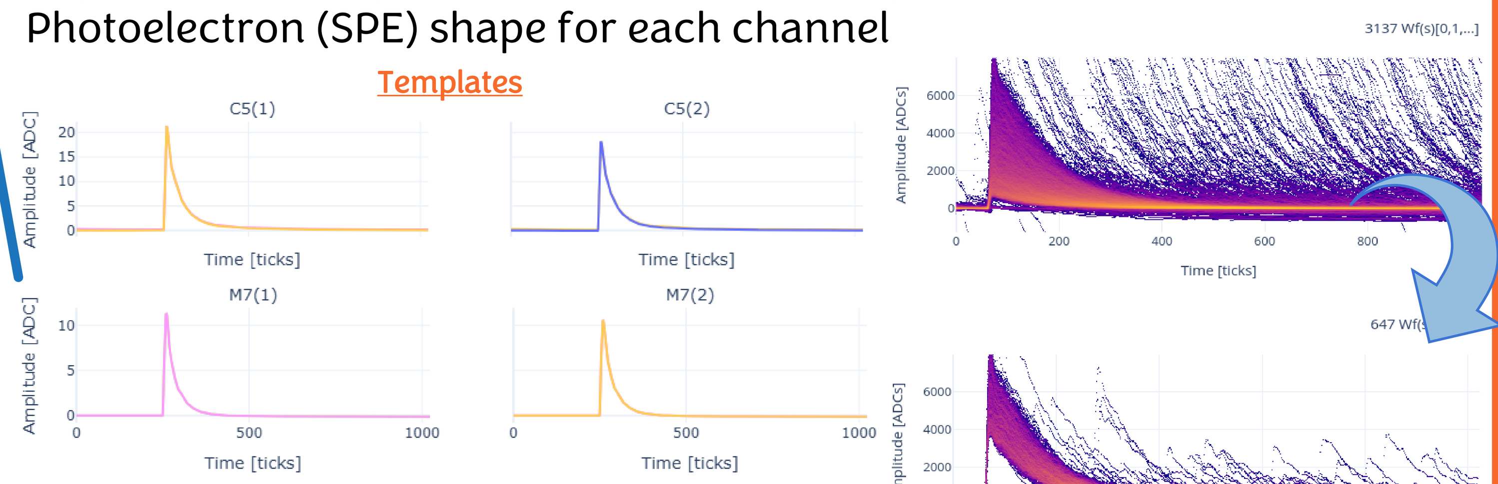
Credit to E. Lavaut

- 8 Membrane modules equipped with copper-based sensors
- 8 Cathode modules implementing non-conductive power-over-fiber (PoF) and signal-over-fiber (SoF) technology [2].

## ANALYSIS METHOD

### Average response & Templates

Choose minimal cuts to clean our signals and implemented template that describe the Single Photoelectron (SPE) shape for each channel

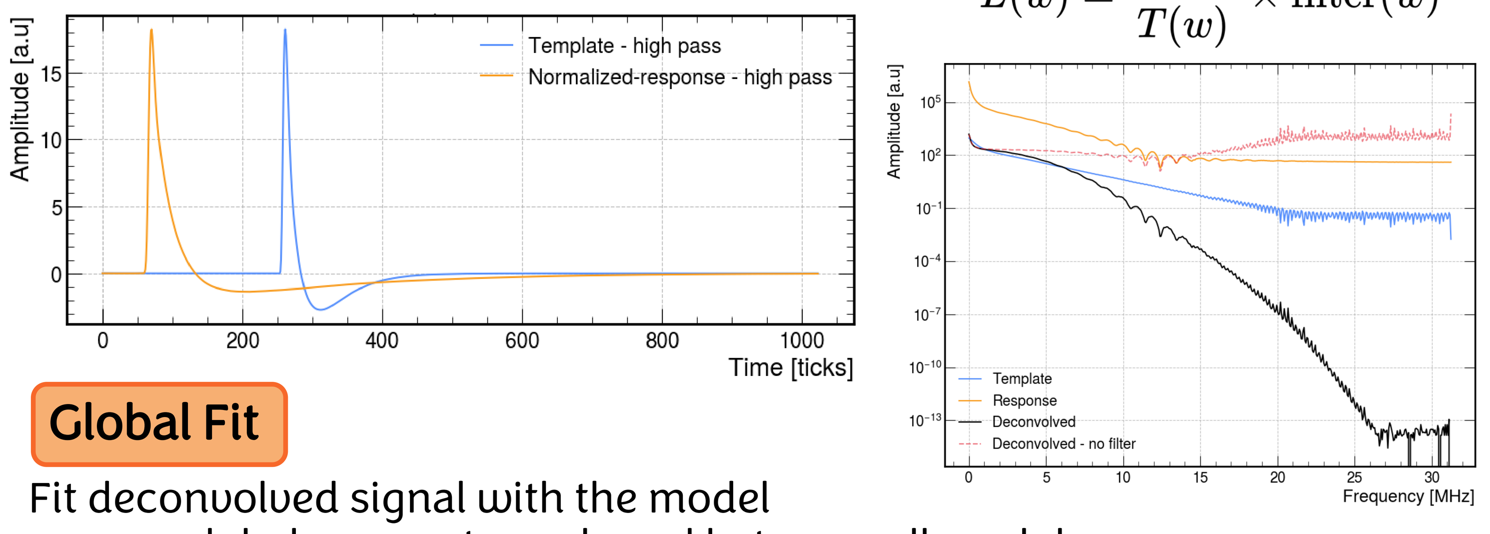



### Deconvolution

Remove the electronics and photosensor response from the raw waveforms to recover the genuine scintillation light time-profile

$$\mathrm{Response}(t) = \mathrm{Template}(t) \circledast L(t)$$

$$L(w) = \frac{R(w)}{T(w)} \times \mathrm{filter}(w)$$

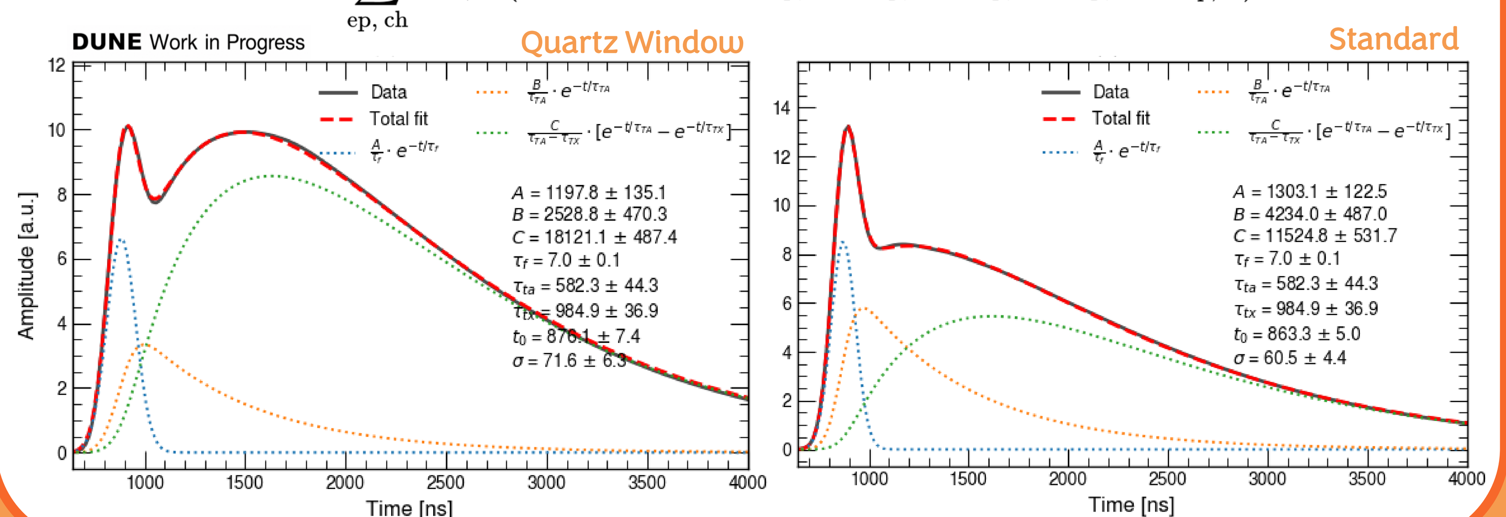


### Global Fit

Fit deconvolved signal with the model
$\tau_{TA}$, $\tau_{TX}$: global parameters, shared between all modules
The quartz window module helps to constrain $\tau_{TA}$ and $\tau_{TX}$

$$f(t_i;\, \tau_{\mathrm{fast}}, \tau_{TA}, \tau_{TX}, A, B, C) = \frac{A}{\tau_{\mathrm{fast}}} \times e^{-t_i/\tau_{\mathrm{fast}}} + \frac{B}{\tau_{\mathrm{TA}}} \times e^{-t_i/\tau_{\mathrm{TA}}} + \frac{C}{\tau_{\mathrm{TA}} - \tau_{\mathrm{TX}}} \times \left(e^{-t_i/\tau_{\mathrm{TA}}} - e^{-t_i/\tau_{\mathrm{TX}}}\right)$$

$$\chi^2 = \sum_{\mathrm{ep,\,ch}} \chi^2_{\mathrm{ar+xe}}\left(\tau_{\mathrm{fast}}, \tau_{TA}, \tau_{TX}, A_{\mathrm{ep,ch}}, B_{\mathrm{ep,ch}}, C_{\mathrm{ep,ch}}, \sigma_{\mathrm{ep,ch}}, t_{0\,\mathrm{ep,ch}}\right)$$





[1] Machado, A. A., et al. "The X-ARAPUCA: An improvement of the ARAPUCA device." Journal of instrumentation 13.04 (2018): C04026-C04026.
[2] Arroyave, M. A., et al. "Characterization and novel application of power over fiber for electronics in a harsh environment." Journal of Instrumentation 19.10 (2024): P10019.
[3] Abed Abud, Adam, et al. "Doping liquid argon with xenon in ProtoDUNE Single-Phase: effects on scintillation light." Journal of instrumentation 19.08 (2024): P08005.