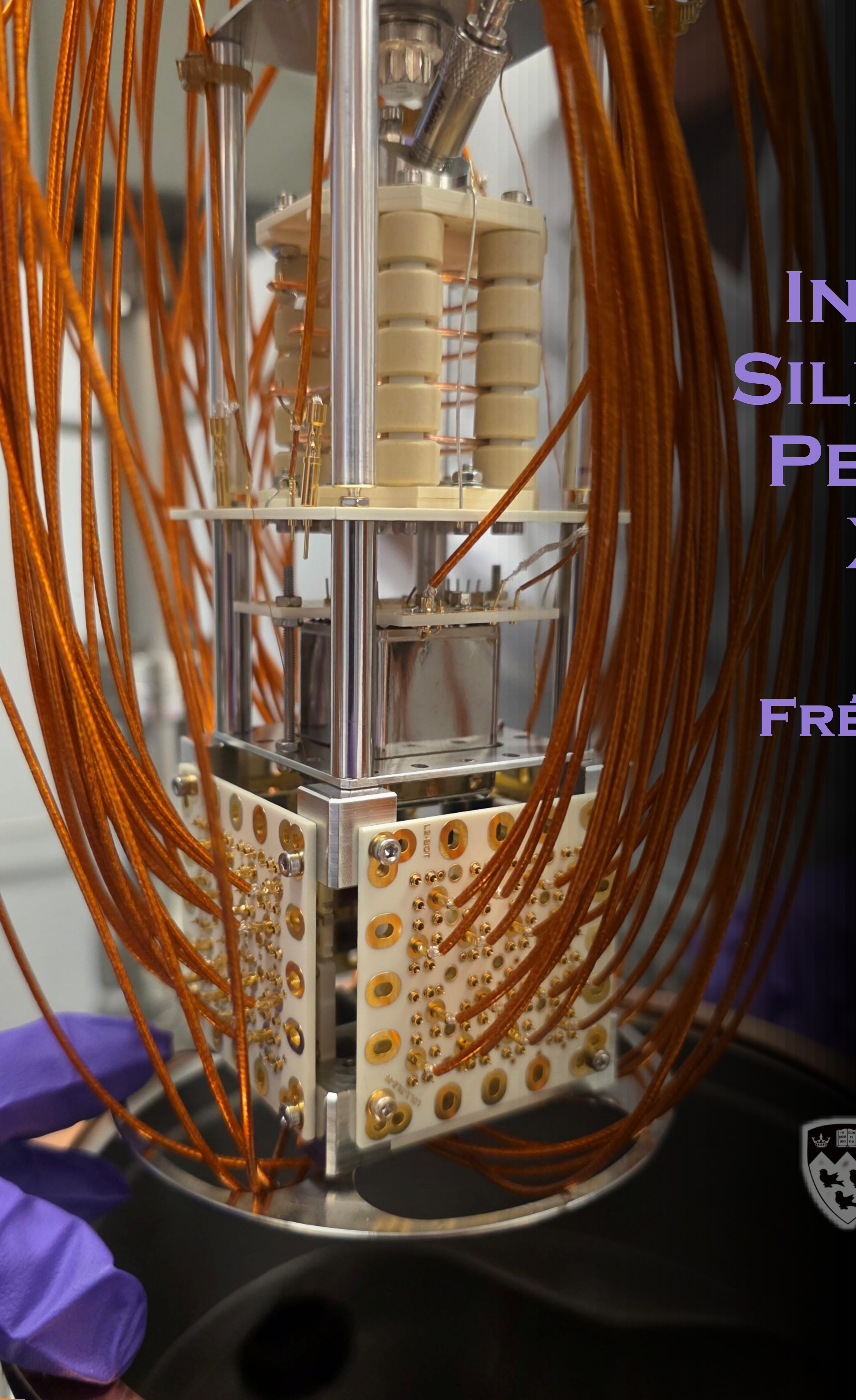


In Situ Comparison of Silicon Photomultiplier Performance in Liquid Xenon with LoLX 2

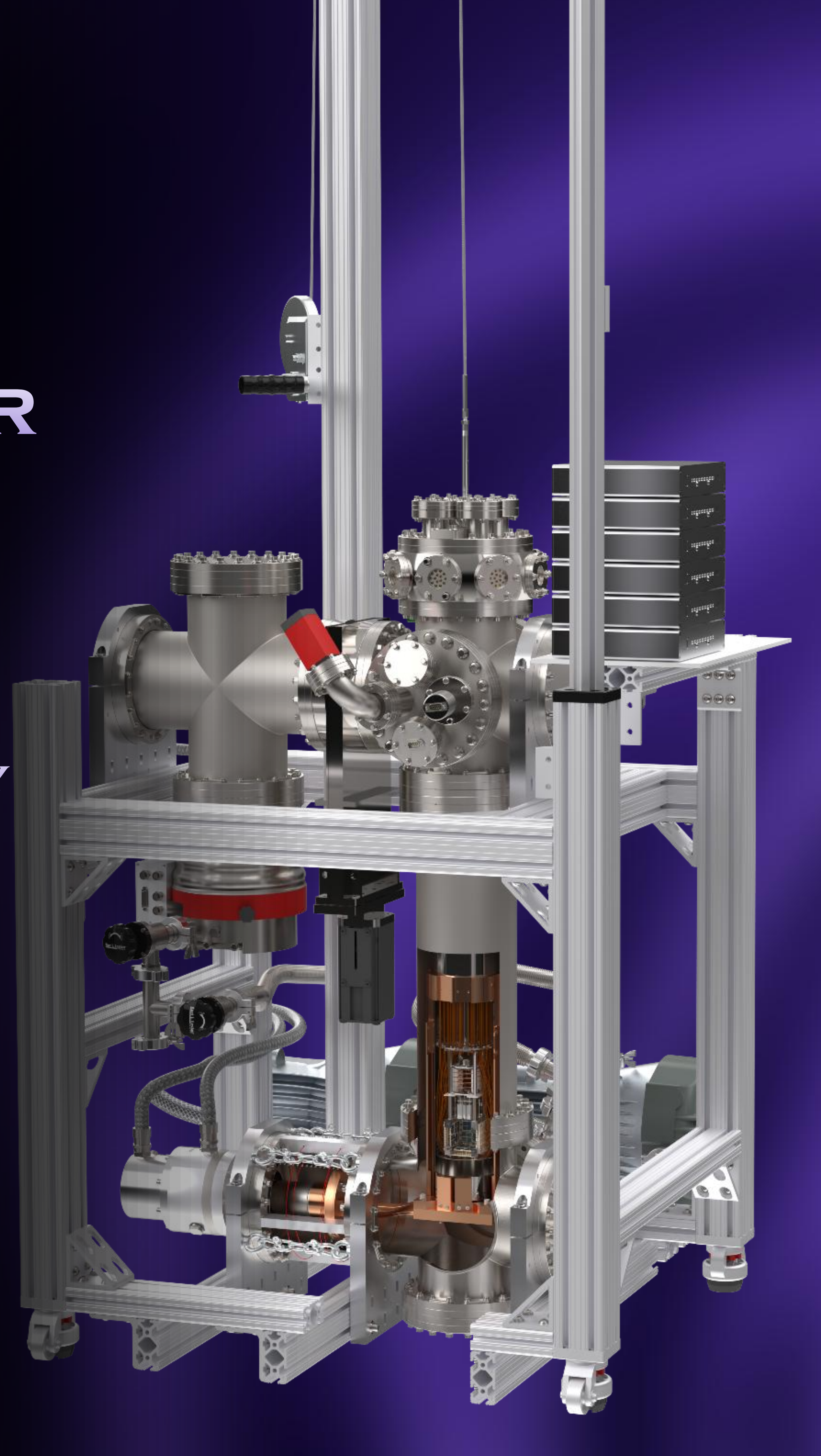
Frédéric Girard, McGill University

On behalf of the LoLX collaboration

2026 CAP Congress

McGill University

Canadian Association of Physicists
Association canadienne des physiciens et physiciennes



Light-only Liquid Xenon Collaboration

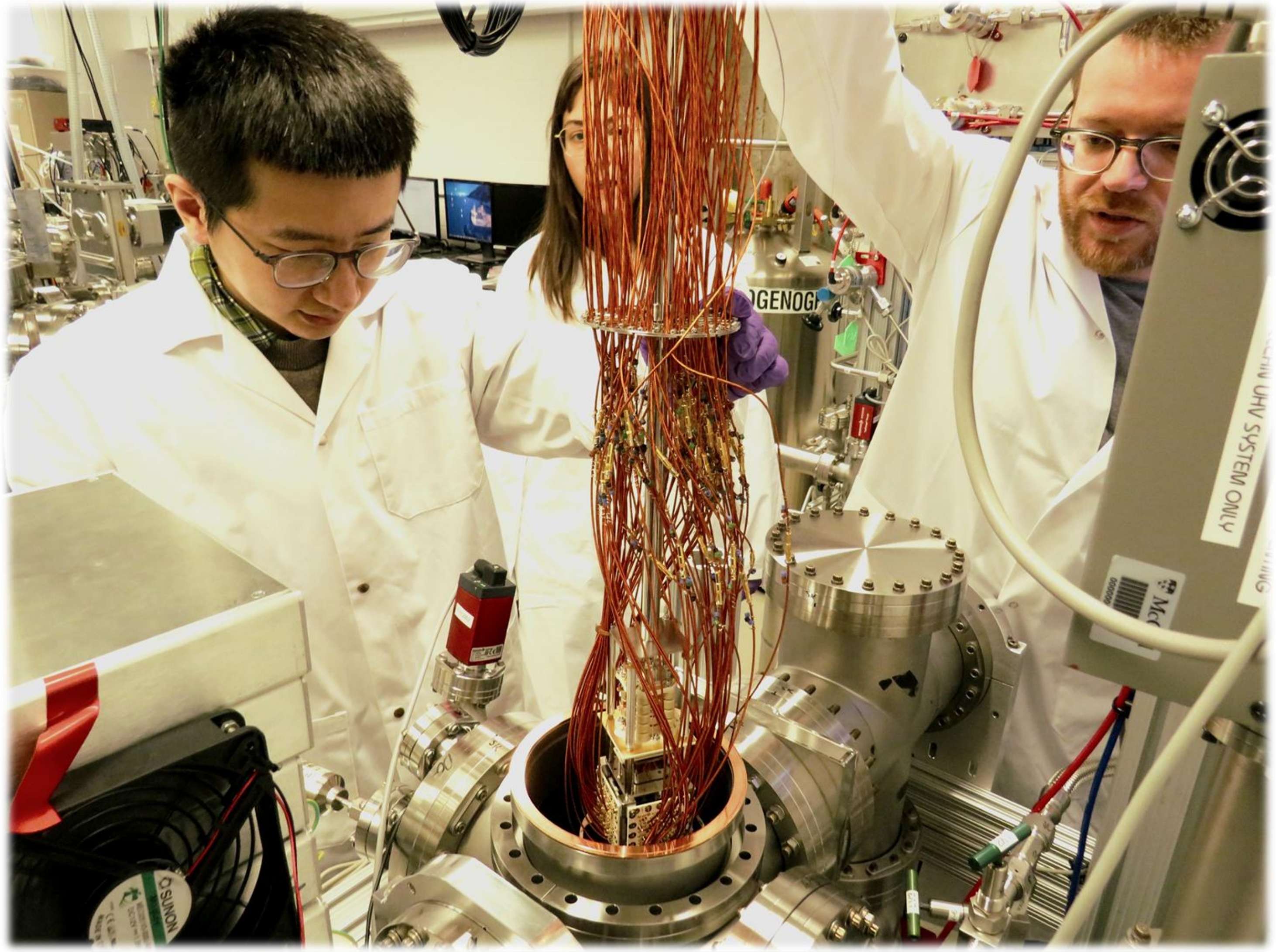
- Detector located at McGill University, Montréal, Canada
- Design, development, operation and analysis: McGill and TRIUMF
- Photosensor development: U. Sherbrooke and TRIUMF
- DAQ: TRIUMF and INFN
- Simulations: Carleton, TRIUMF, McGill

LoLX

TRIUMF McGill UNIVERSITY

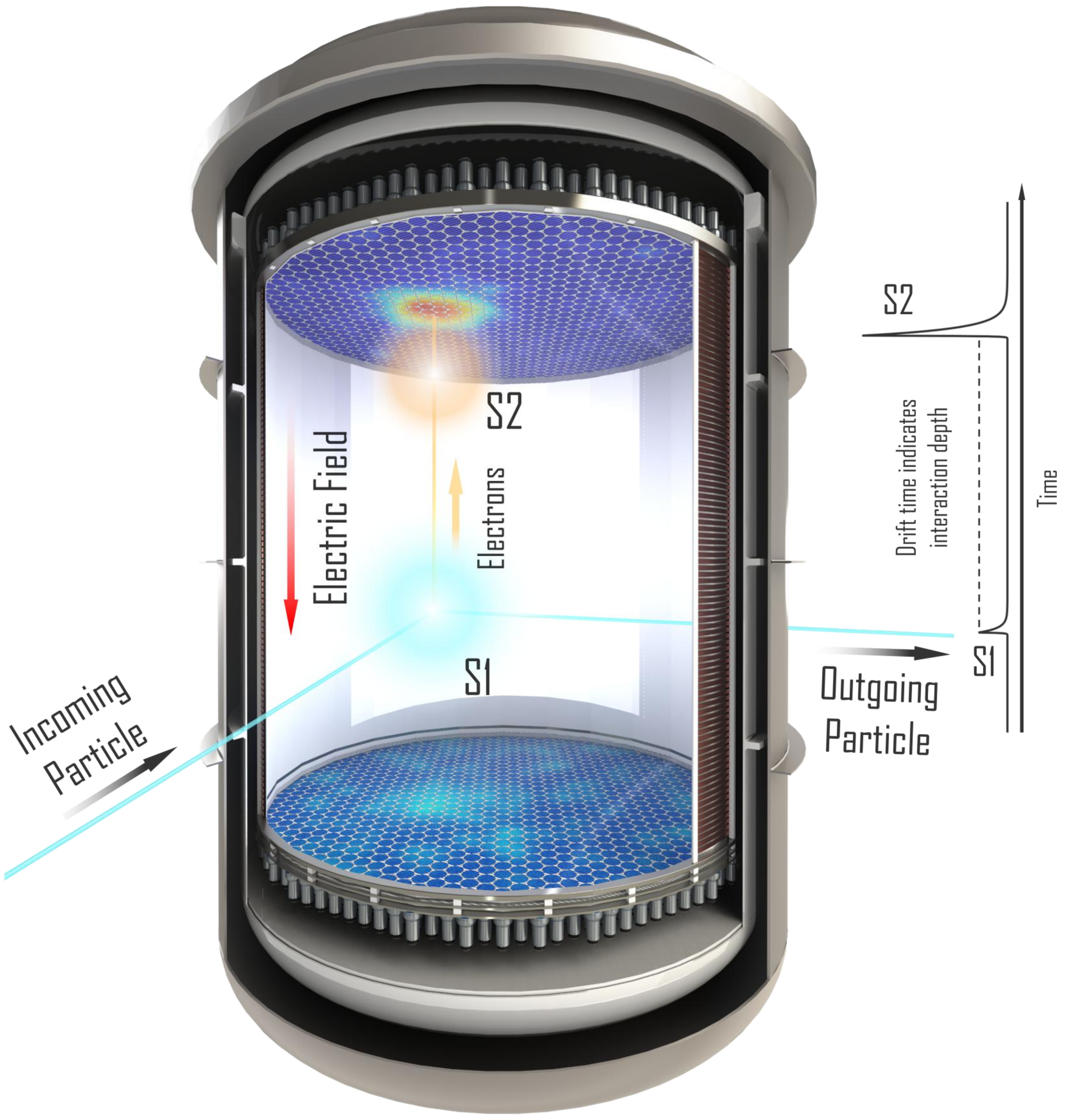
UNIVERSITÉ DE SHERBROOKE Carleton University

INFN



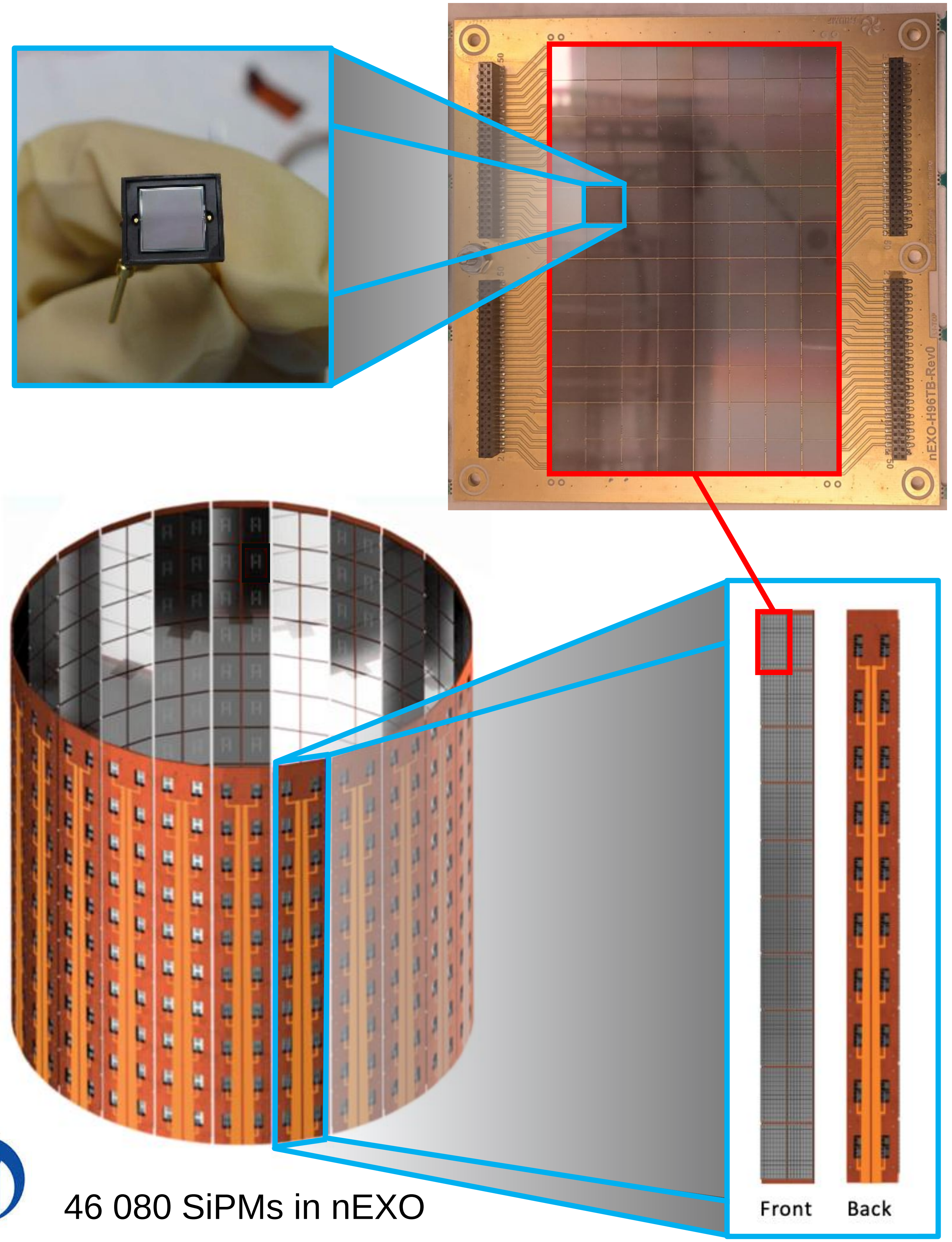
Xenon Time Projection Chamber

- Detection of prompt scintillation (S1) and delayed ionization signal (S2)
  - Vacuum Ultra-Violet photons, λ = 178 nm
  - Photosensors at the top, bottom, or side walls
- 3D position reconstruction
  - X-Y from hit pattern
  - Z from S1-S2 time delay
- Electronic recoil/Nuclear recoil discrimination based on S1/S2 ratio



LoLX 2 Goals

- Photosensor R&D for next-generation low background experiments (nEXO, PIONEER, XLZD)
  - **Direct comparison of SiPM performance in LXe**
  - Study of external crosstalk
  - Long-term photosensor stability at cryogenic temperature
- Study of optical properties of LXe and validation of simulations
  - LXe scintillation
  - Cherenkov radiation in LXe



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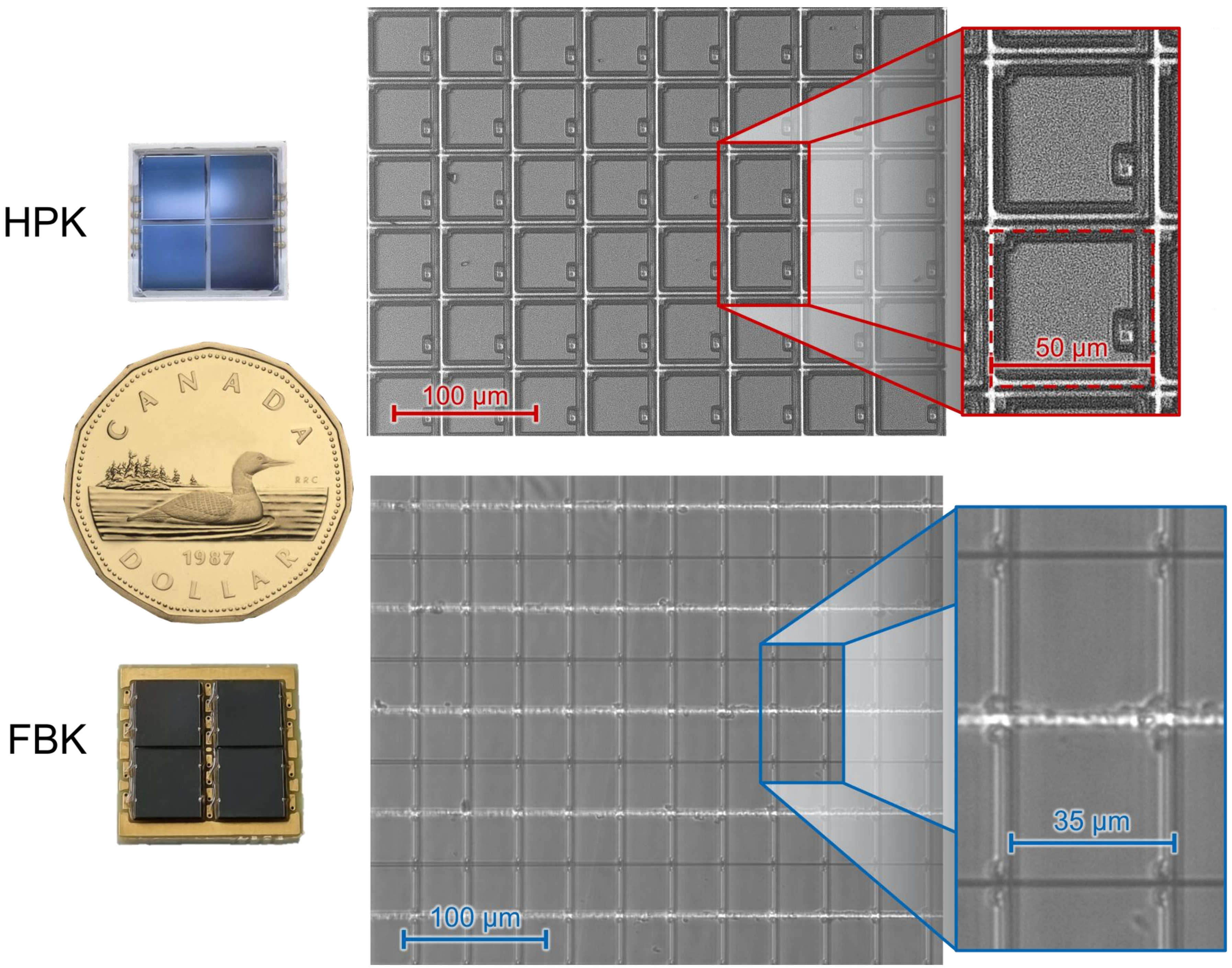
  - LXe scintillation
  - Cherenkov radiation in LXe

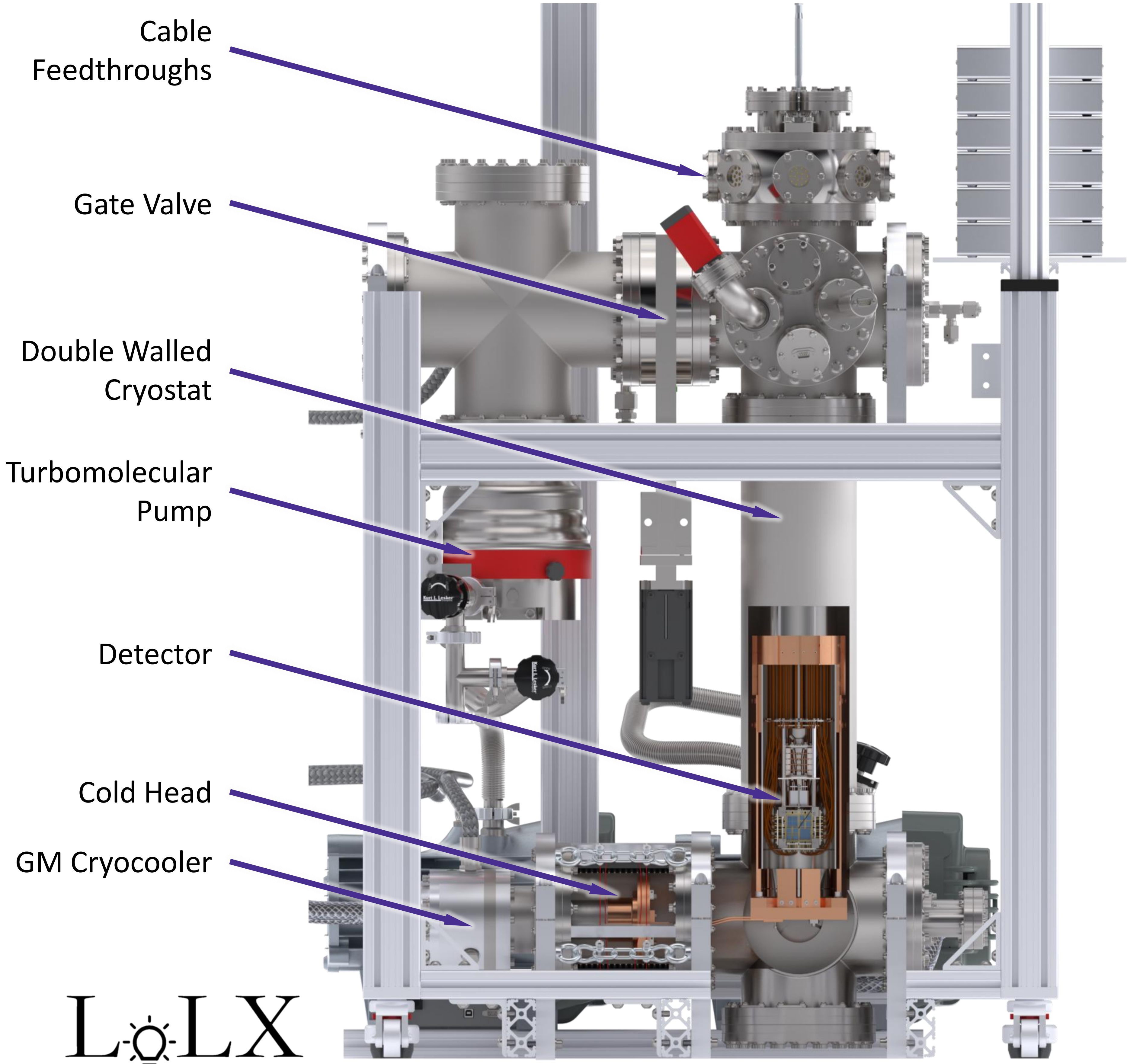
Fill Factor: 60%



Fill Factor: 80%

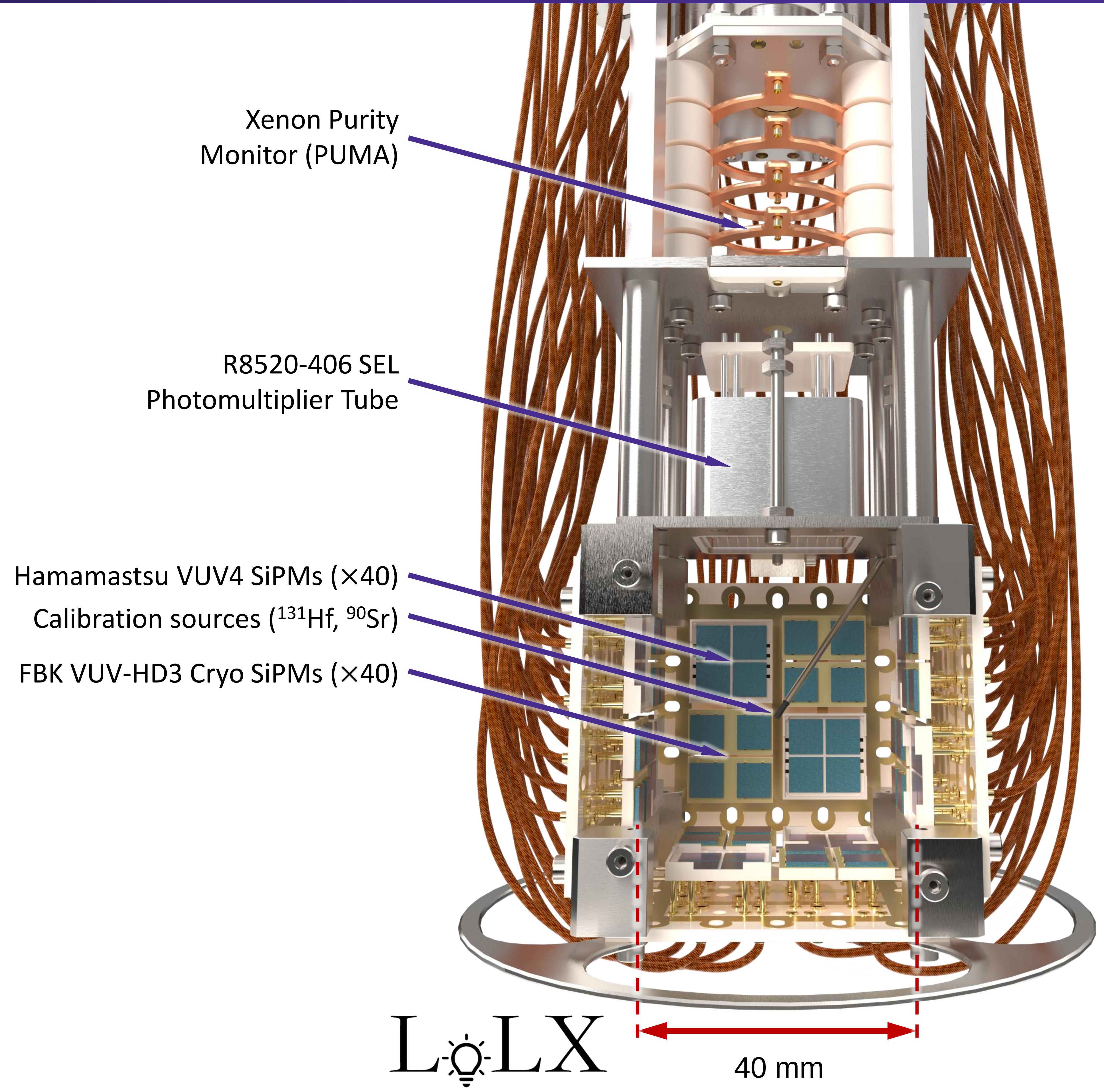
LoLX 2 Overview

- Double-walled cryostat
  - 5 kg LXe total
  - Hosts the detector at 165 K
  - Detector inserted from the top
- Cooling from Gifford-McMahon cryocooler
  - Copper cooling plates surround the inner vessel
- Gas handling system
  - Purification during filling with hot metal getter (MonoTorr PS3-MT3)
  - Storage in stainless steel cylinders
  - Xe recuperation with cryopumping



LoLX 2 Detector

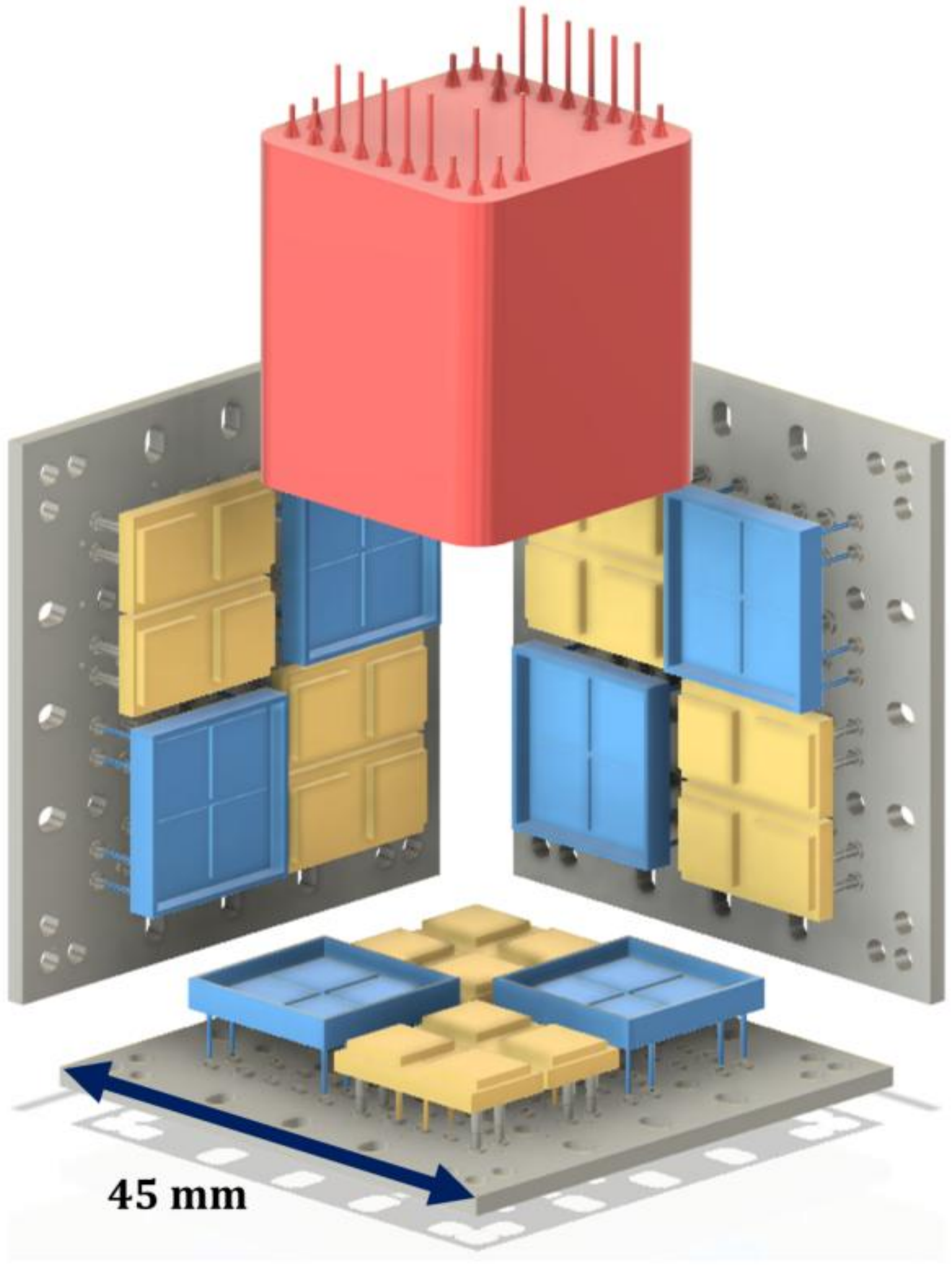
- 42 x 42 x 45 mm^3 cubic volume of LXe instrumented with:
  - 40× 6 × 6 mm^2 Hamamatsu VUV4 SiPMs
  - 40× 6 × 6 mm^2 FBK VUV-HD3 Cryo SiPMs
  - 1× 1'' Hamamatsu Photomultiplier Tube
- Purity Monitor (PUMA)
  - Continuous monitoring of the electron drift lifetime
- Calibration sources:
  - External (^{22}Na, ^{133}Ba, ^{137}Cs)
  - Internal (^{127}Xe (Gaseous), ^{181}Hf, ^{90}Sr)
  - Visible-light laser



Performance of FBK VUV-HD3 and HPK VUV4 SiPMs in the Light-only Liquid Xenon (LoLX) Detector

arXiv:2510.15270 (submitted to JINST)

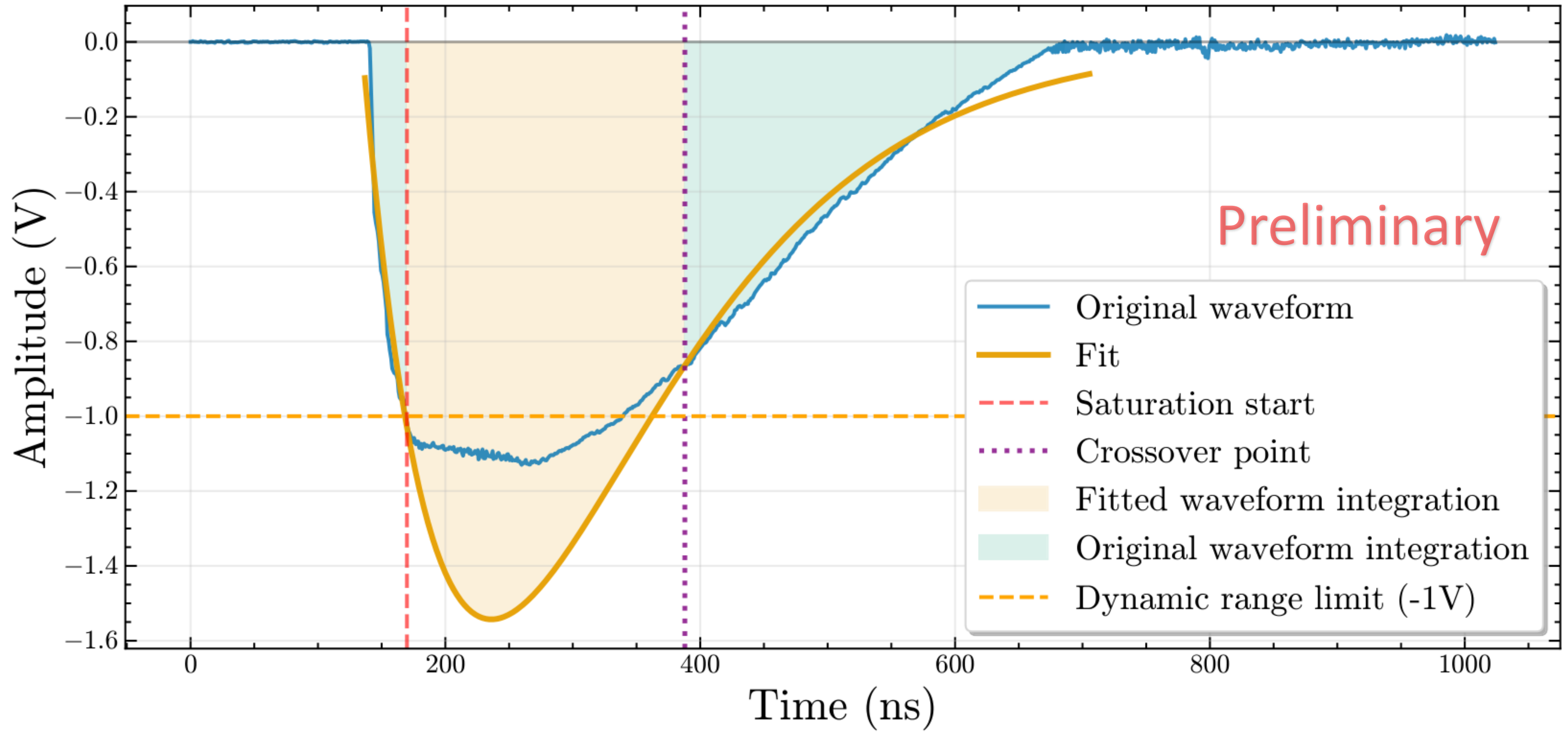
- Direct comparison of photodetector performance in LXe
- SiPM calibration using visible-light laser and external gamma source
- Operational overvoltage: 3 V_{OV}
  - Optimized for correlated-avalanche noise and energy resolution for nEXO [Eur. Phys. J. C (2022) 82 :1125]
- Active photosensors in this study
  - 34 FBK SiPMs (yellow)
  - 35 HPK SiPMs (blue)
  - 1 HPK PMT (red)



External Source Measurements

- Two external sources, with main γ lines:
  - ^{133}Ba: 356 keV
  - ^{137}Cs: 662 keV
- Global trigger from the PMT
  - Trigger independent from vendor
- Event position distribution introduces solid angle variations
  - Accounted for with Monte Carlo simulations
- DAQ saturated at least one channel for ~30% of events
  - Mitigated with pulse fitting saturation correction algorithm (adapted from NIM A, 940 (2019) 371–379)
  - Fit used only in the saturated region

$$V(t) = -\frac{A}{\tau_D}\left[\exp\left(-\frac{t-t_0}{\tau_D+\tau_R}\right) - \exp\left(-\frac{t-t_0}{\tau_R}\right)\right]$$

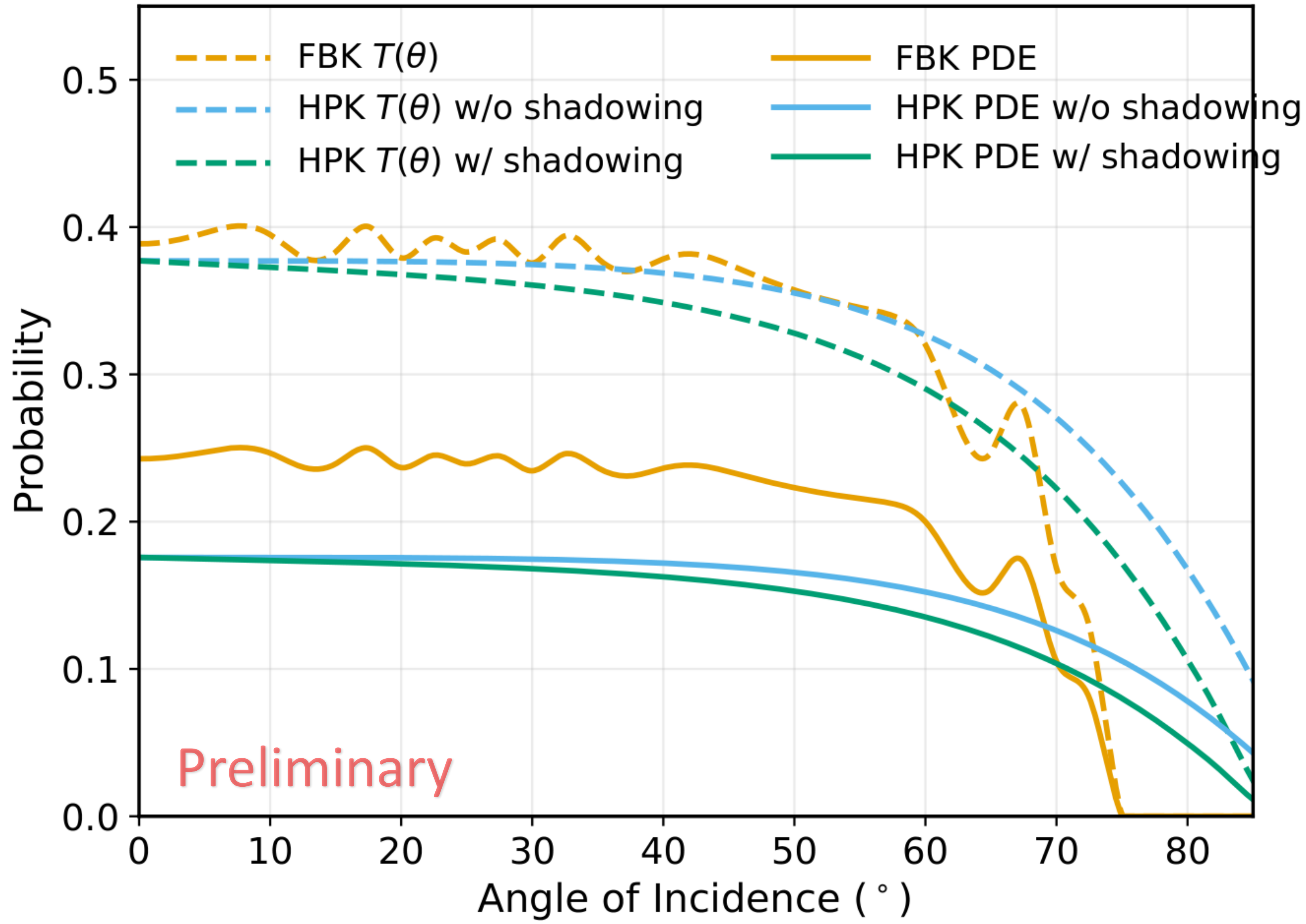


Example of the pulse fitting saturation correction

arXiv:2510.15270 (submitted to JINST)

Simulation pipeline

- Detector response modeled with multi-stage simulation pipeline
  - Geant4: Particle interaction and energy deposition
  - NEST: LXe scintillation
  - CHROMA: GPU-based light transport See talk by Xiang Li!
- PDE offset governed by geometric fill factor
  - FBK: 0.8
  - HPK: 0.6
- FBK optical transmission probability cut-off caused by thin-film interference
- HPK shadowing caused by surface topology
- HPK quartz window treated separately in CHROMA



Angular dependence of optical transmission probability and photodetection efficiency

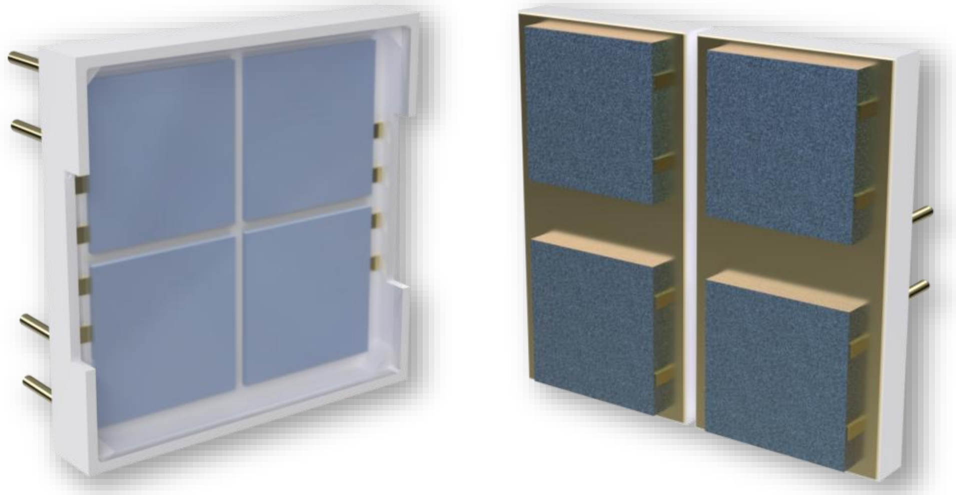
arXiv:2510.15270 (submitted to JINST)

Experimental and Simulations Comparison of SiPM Response to LXe Scintillation

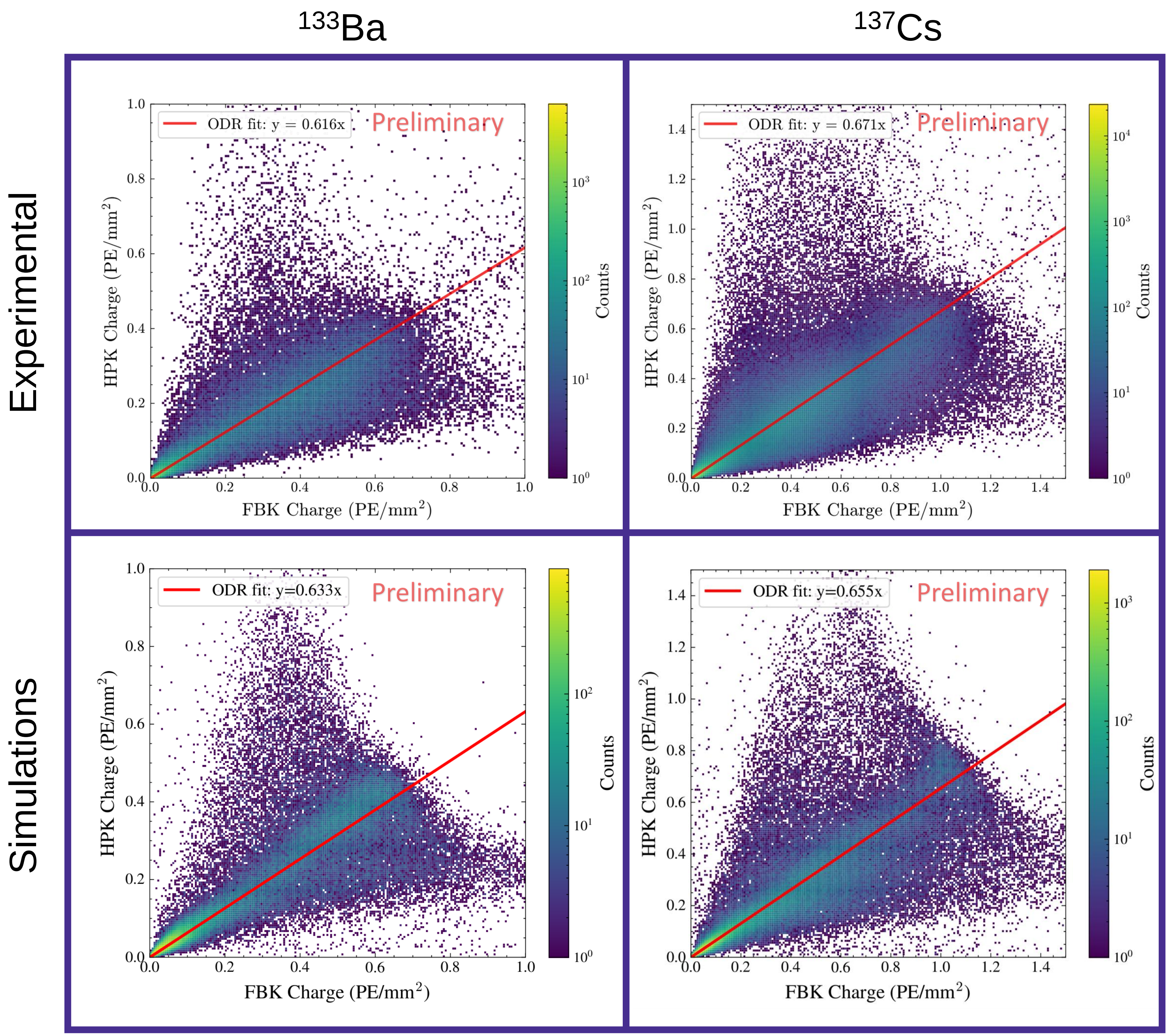
- Collected charge normalized to the total nominal active area

Method	HPK/FBK Photon Detection Ratio	
	^{133}Ba	^{137}Cs
Vacuum measurement (0° AOI) [15]	0.84 ± 0.01	
PDE model extrapolation in LXe (0° AOI) [17]	0.72 ± 0.03	
Experimental Data (This work)		
LoLX2 data	$0.62^{+0.03}_{-0.04}$	$0.67^{+0.03}_{-0.05}$
Simulation Model		
Full simulation (with HPK shadowing)	$0.63^{+0.03}_{-0.04}$	$0.66^{+0.04}_{-0.05}$
Simulation w/o HPK shadowing	$0.68^{+0.04}_{-0.05}$	$0.71^{+0.04}_{-0.05}$
Full + excess absorption	$0.55^{+0.03}_{-0.04}$	$0.58^{+0.03}_{-0.04}$

HPK



FBK



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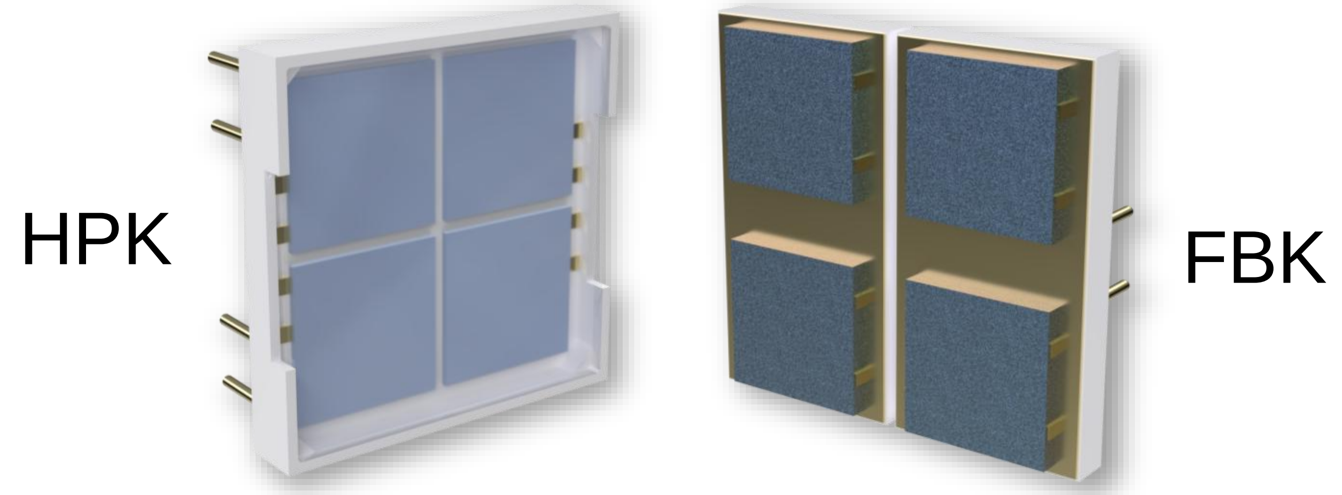
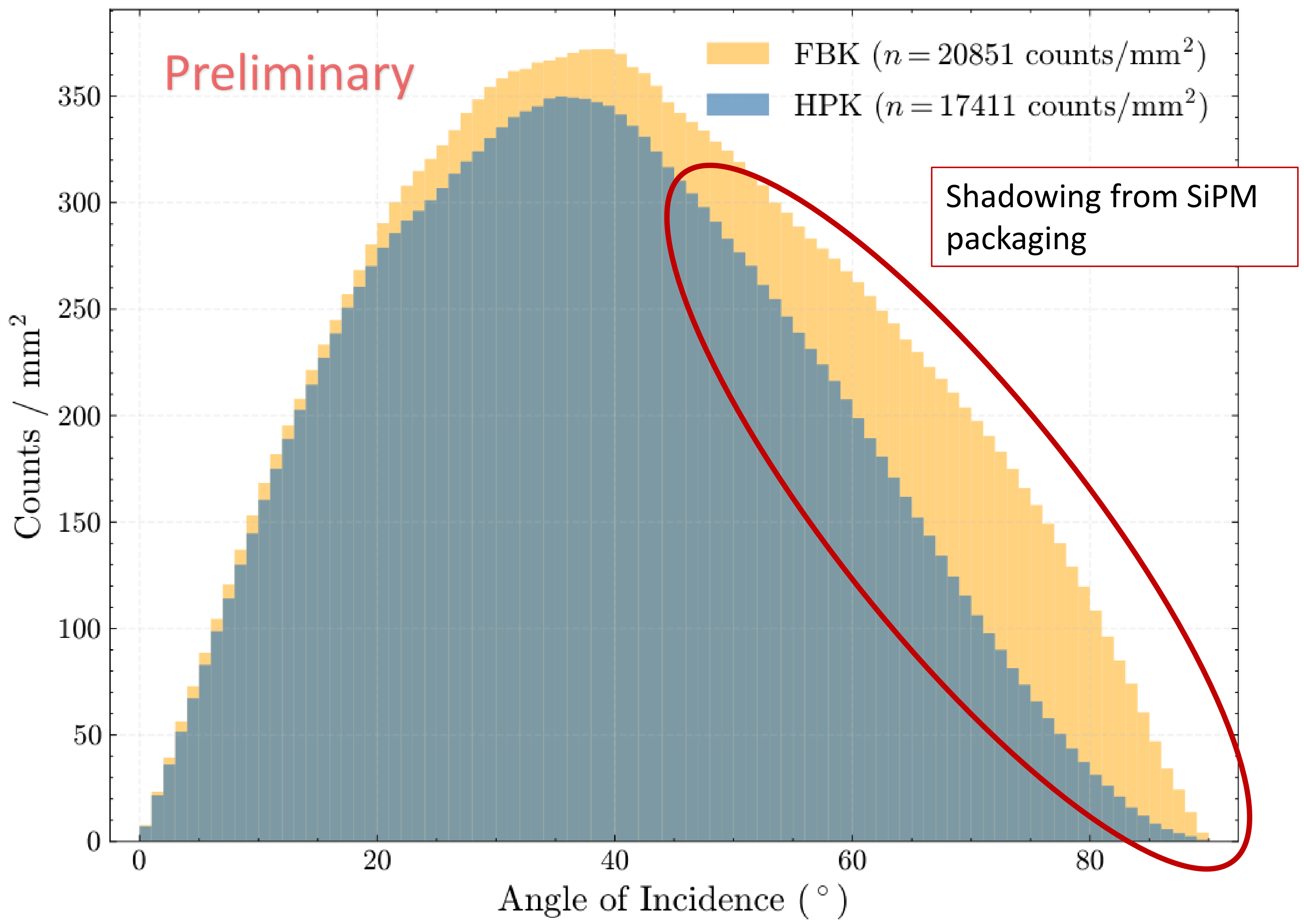




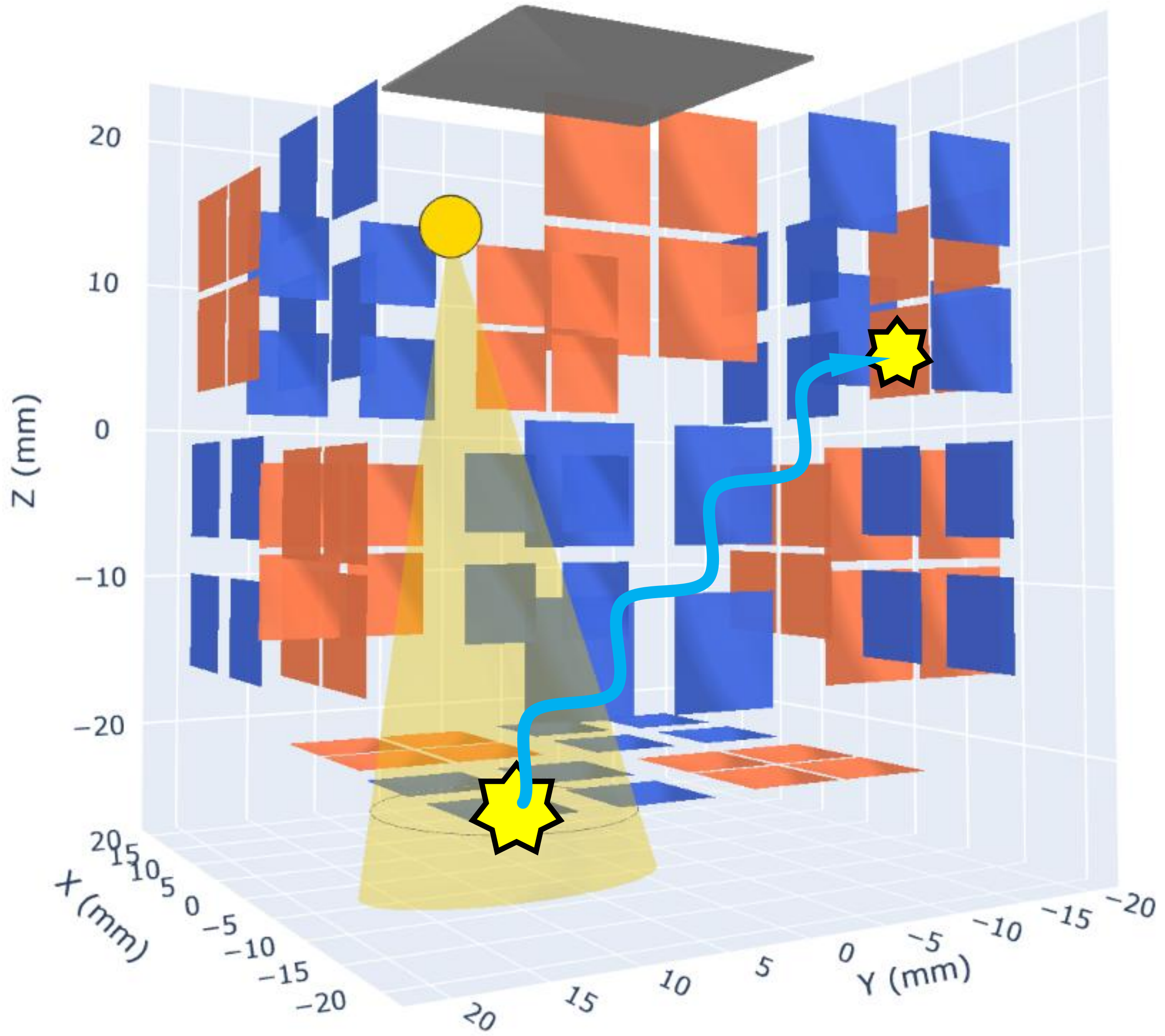
- The effective photon detection ratio is a convolution of:
  - the intrinsic angle dependent efficiency of the SiPMs
  - system-level photon transport

arXiv:2510.15270 (submitted to JINST)

What’s next for LoLX?

Angle-Dependent External Crosstalk Measurements in LXe

- Illuminate a single SiPM with pulsed visible-light laser
  - 99% of light seen by source SiPM
- Measure correlated events in other SiPMs produced by IR photons produced during the initial photo-avalanche
  - With vs. Without source SiPM active
- Estimate the probability of photons produced in the photo-avalanche process to be detected in a different SiPM
- Measurement in Progress - Stay tune!

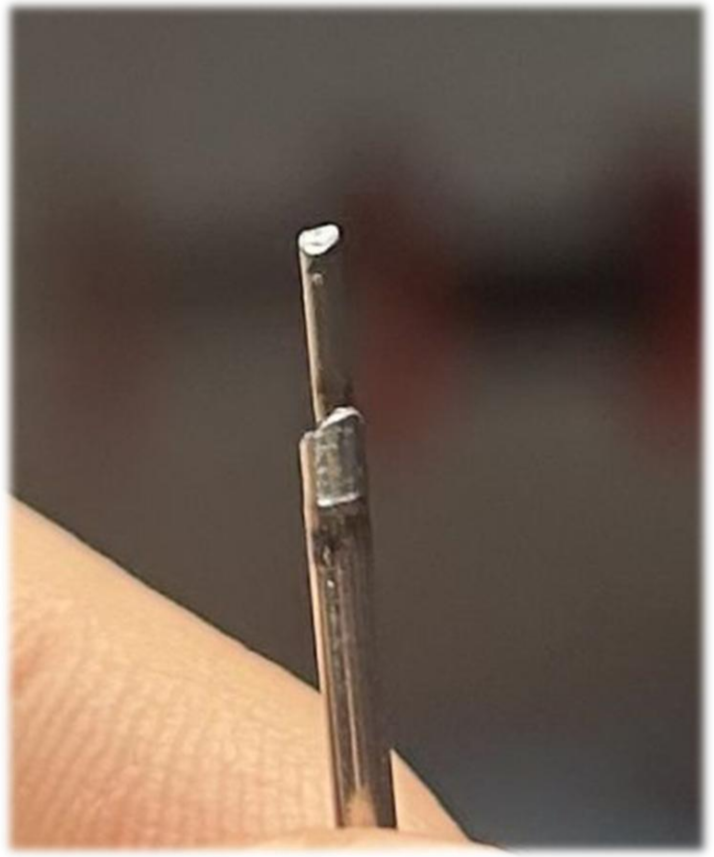


External crosstalk principle

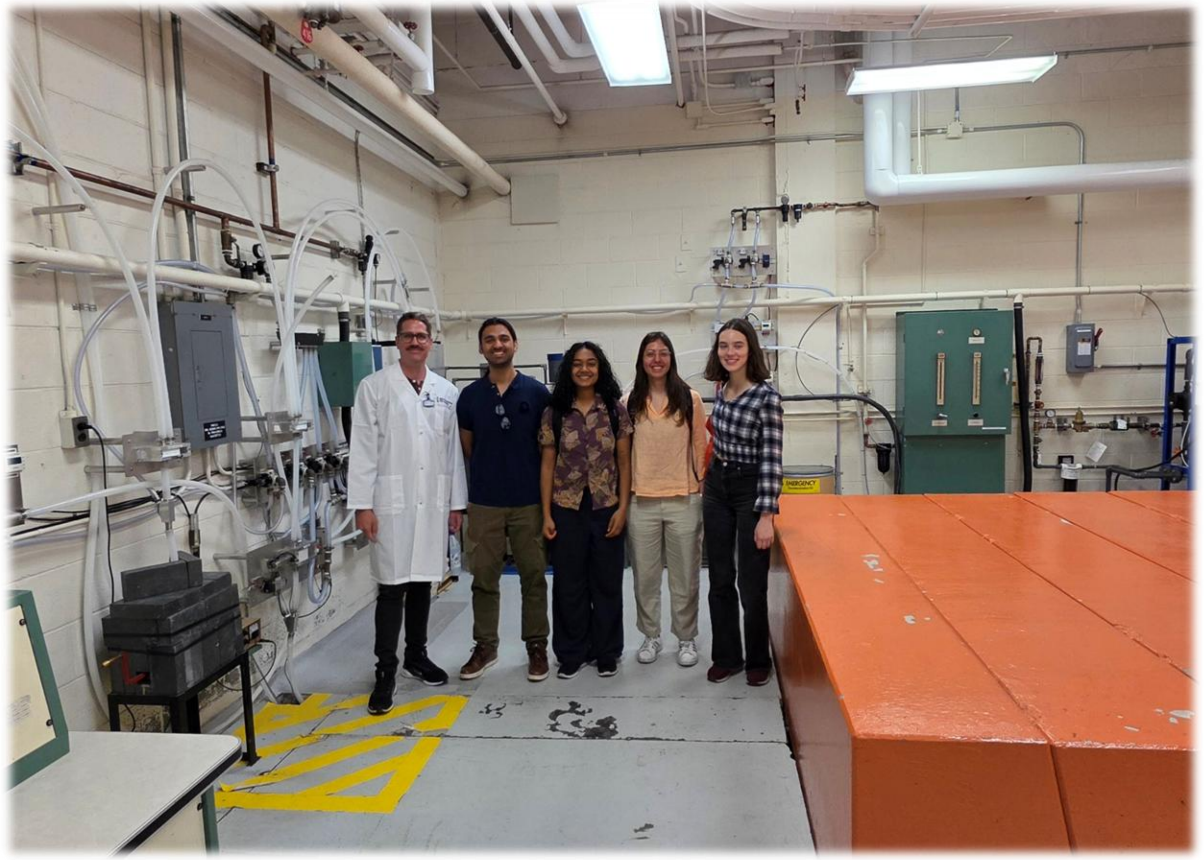

Source SiPM illuminated by light from optical fiber

^{181}Hf Source Activation

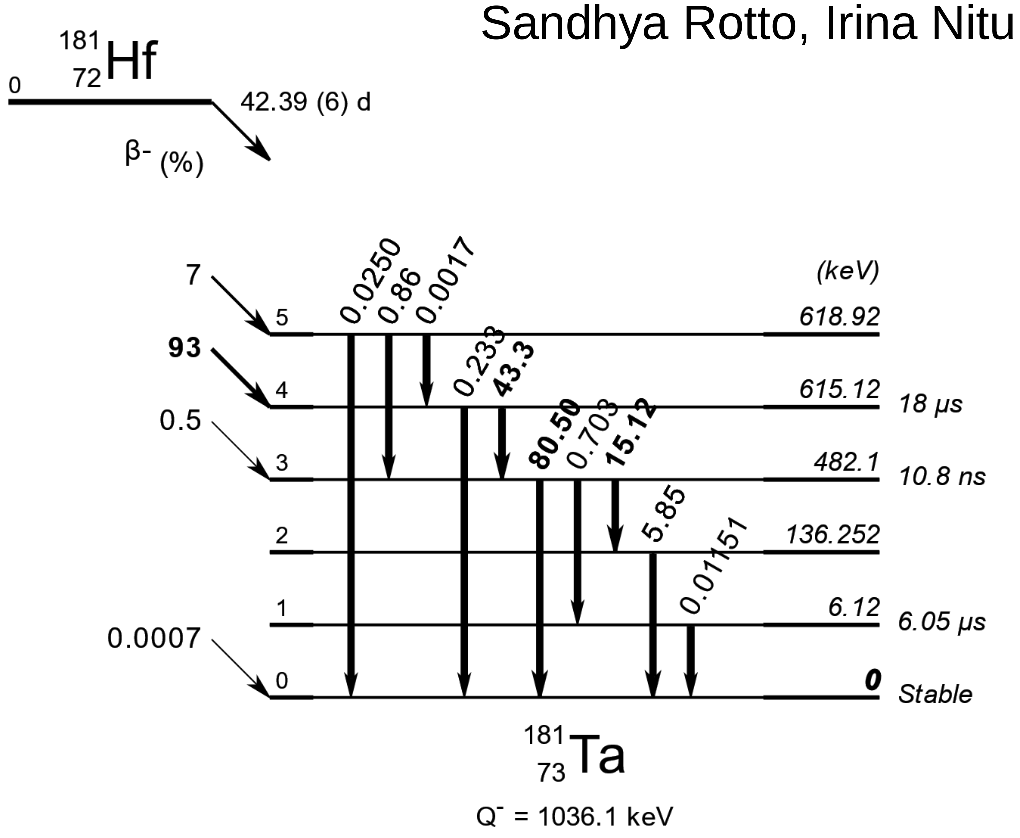
- Half-life: 42.39 days
- Main γ lines: 133 and 482 keV
- Target Activity: 1 kBq
- Centrally located in the LoLX active volume
- Collaboration with SLOWPOKE-II Laboratory of *École Polytechnique de Montréal*
    - Neutron activation of natural Hafnium
- Hafnium sample spot-welded at McGill to natural zirconium rod
- Cryogenically tested at 77 K with LN_2 for structural integrity
- Activation <u>Summer 2026</u>



^{nat}Hf welded to a Zn rod

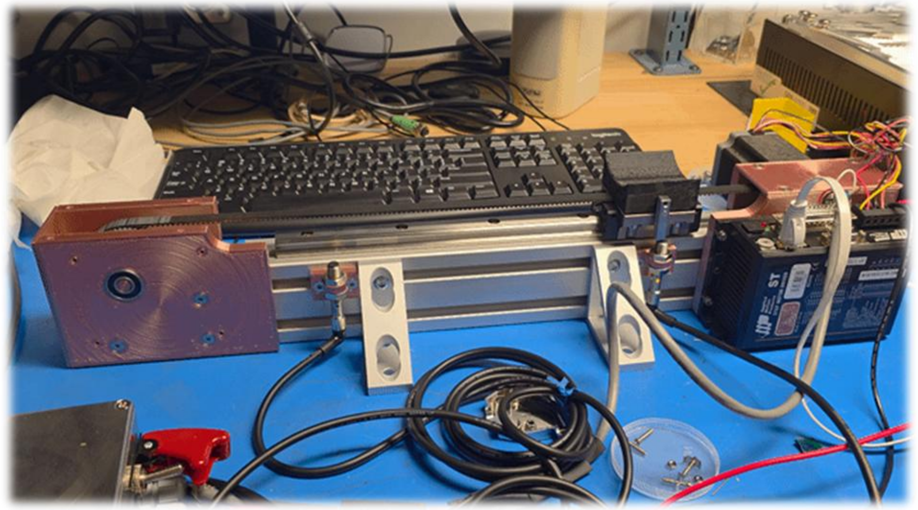


Visit of the SLOWPOKE-II reactor. Darren Hall (SLOWPOKE-II Lab Director), Naman Walia, Sandhya Rotto, Irina Nitu, Eleanor Allen

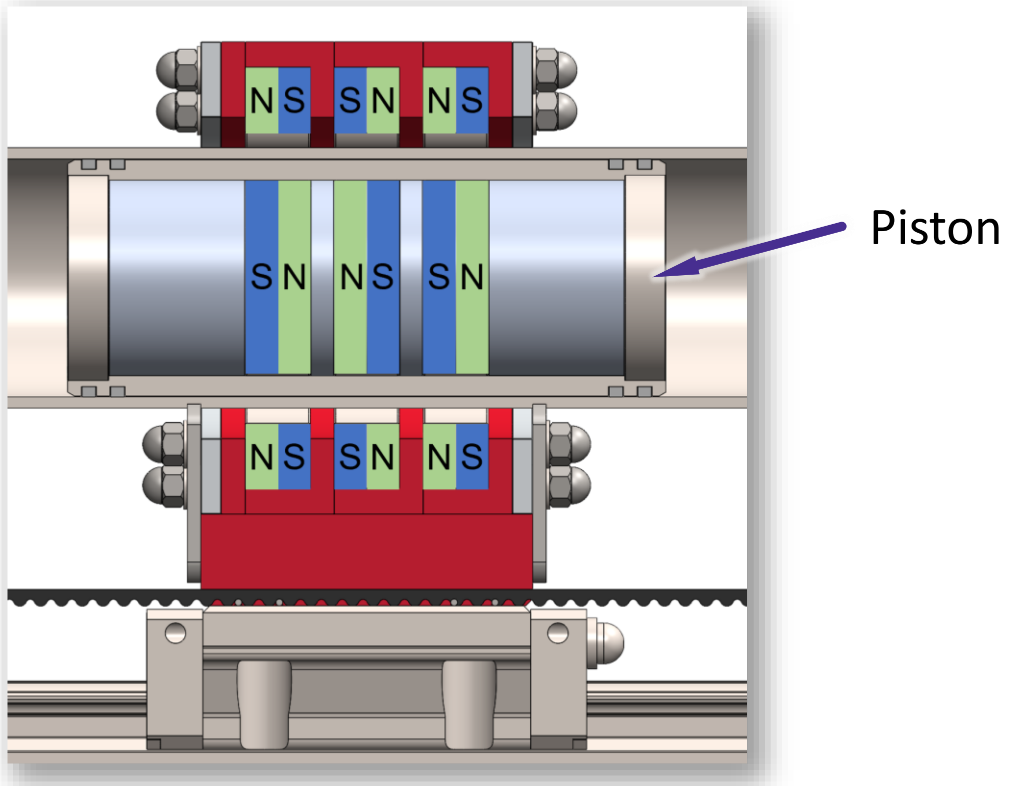


Purification System Upgrade: Xenon Gas Magnetic Pump

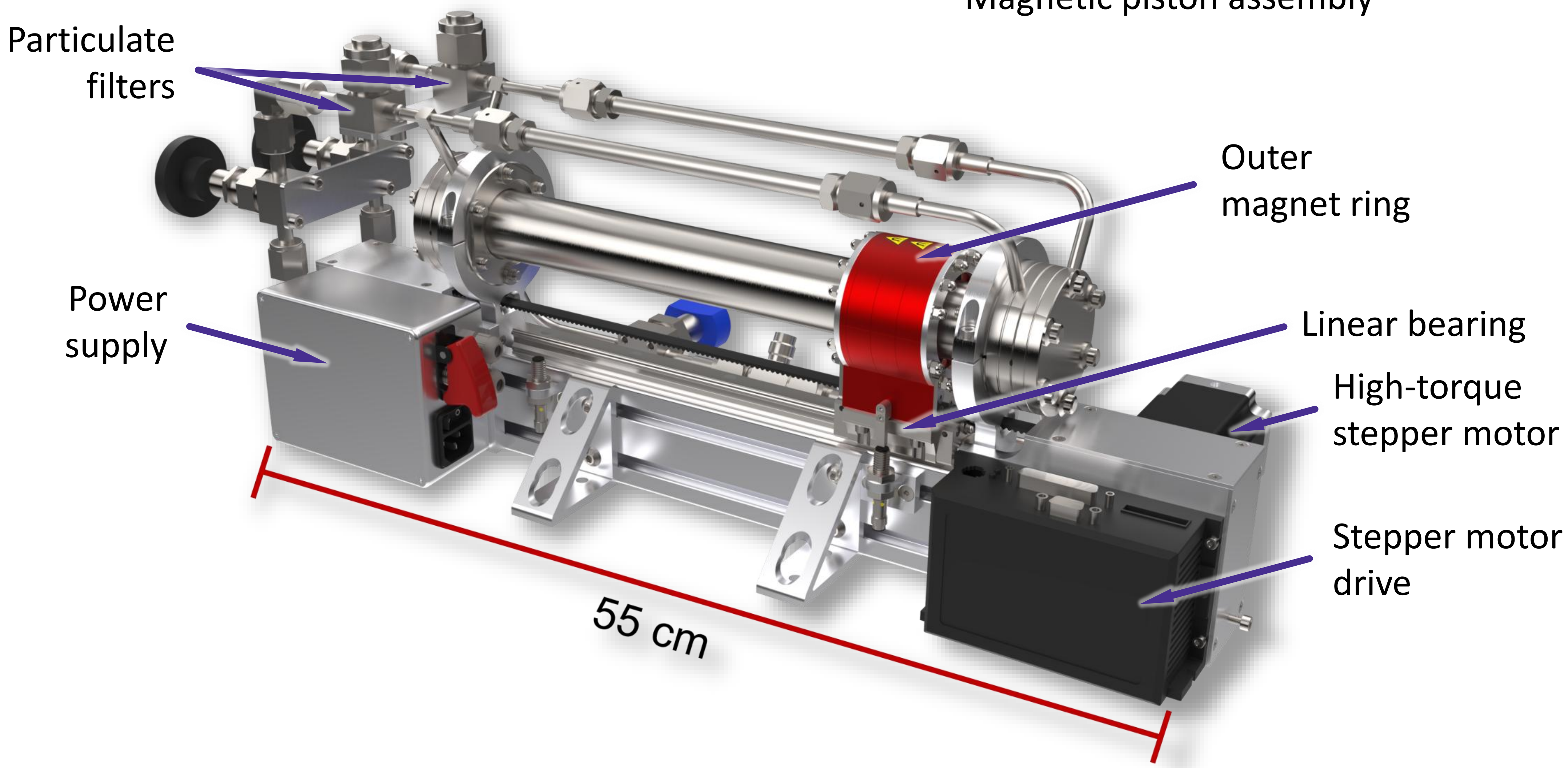
- We are designing a low-cost, high-purity magnetically driven piston pump
- Inspired by similar pumps designs built by the EXO-200 [Rev. Sci. Instrum. 82, 105114 (2011)] and XENON [Eur. Phys. J. C (2018) 78:604] experiments, and design from nEXO collaborators at SLAC
- Target Xe flow: 5 slpm
- All wetted surfaces 316L stainless steel
- Ultra-high molecular weight polyethylene piston rings
- High-toque stepper motor with programable drive unit
- Will allow for the continuous purification of xenon in LoLX



First motion tests



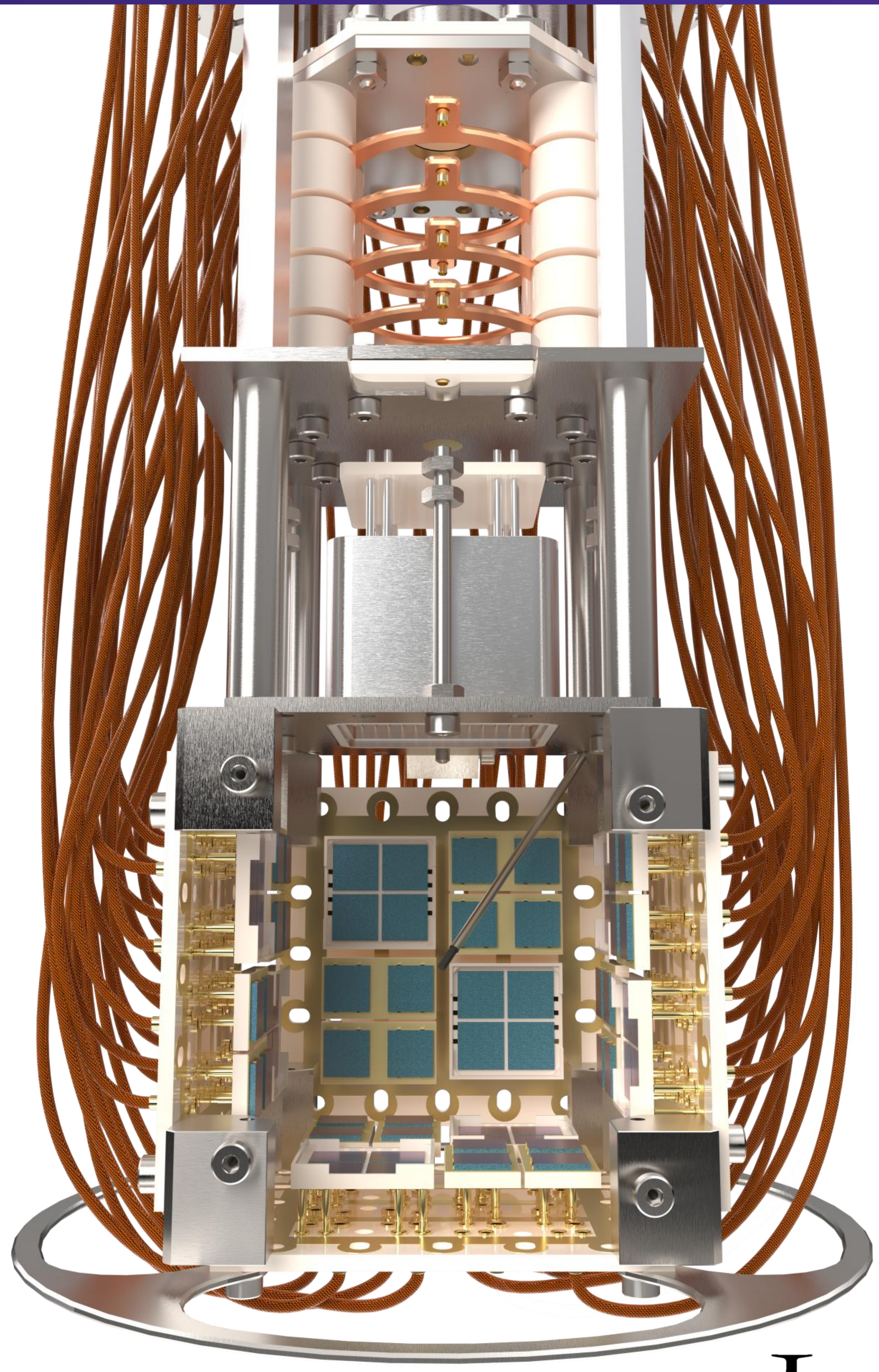
Magnetic piston assembly



Summary

- We have measured the relative photon detection efficiency of Hamamatsu VUV4 and FBK VUV-HD3 Cryo in LXe
- We observed a PDE 33-38% lower for the HPK SiPMs compared to the FBKs
  - Discrepancy much bigger than from normal incidence vacuum measurements
  - Lower fill factor
  - Shadowing effects for low grazing angles
- We successfully reproduced these PDE ratios with comprehensive optical simulations
- This discrepancy with normal incidence vacuum measurements highlights the need for complete simulations for large scales experiments

Thank you!

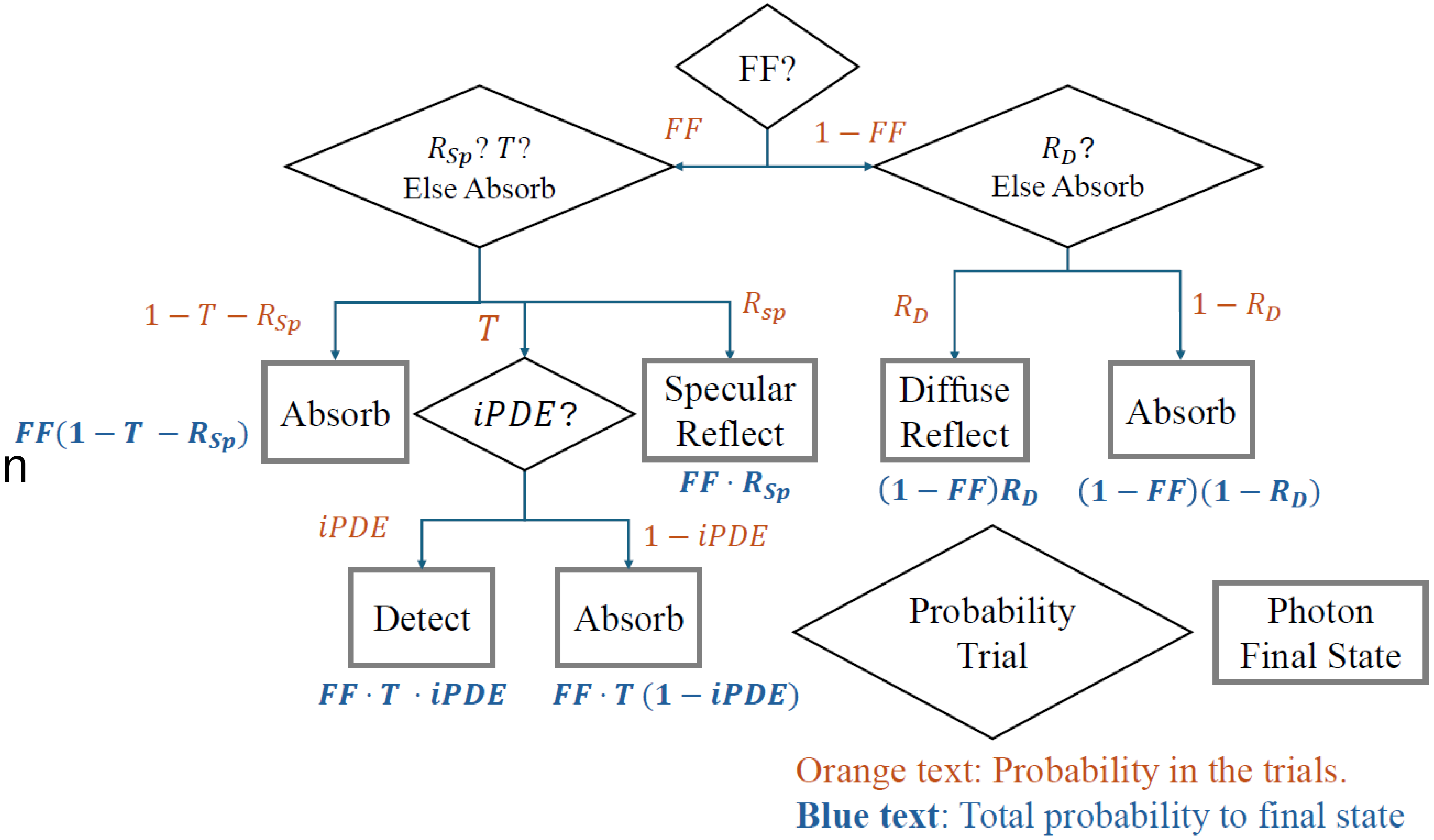


LoLX

LoLX

Bernouli trial photon detection scheme

- FF: Fill Factor
- $R_{Sp}(\lambda, \theta)$: Specular Reflection
- R_D: Diffuse Reflection
- $iPDE(\lambda, V_{OV})$: internal Photon Detection Efficiency
- $T(\lambda, \theta)$: Transmission Probability



$$PDE(\lambda, \theta, V_{OV}) = FF \cdot T(\lambda, \theta) \cdot iPDE(\lambda, V_{OV})$$

arXiv:2510.15270 (submitted to JINST)