

Development of a Muon Veto System for the CUORE Double Beta Decay Experiment

L.E. Fagan¹, P. Macías López², K. M. Heeger², R. H. Maruyama², D. Tozzi², T. Johnson², T.D. Gutierrez¹

¹ California Polytechnic State University, San Luis Obispo CA, ² Yale University, New Haven CT



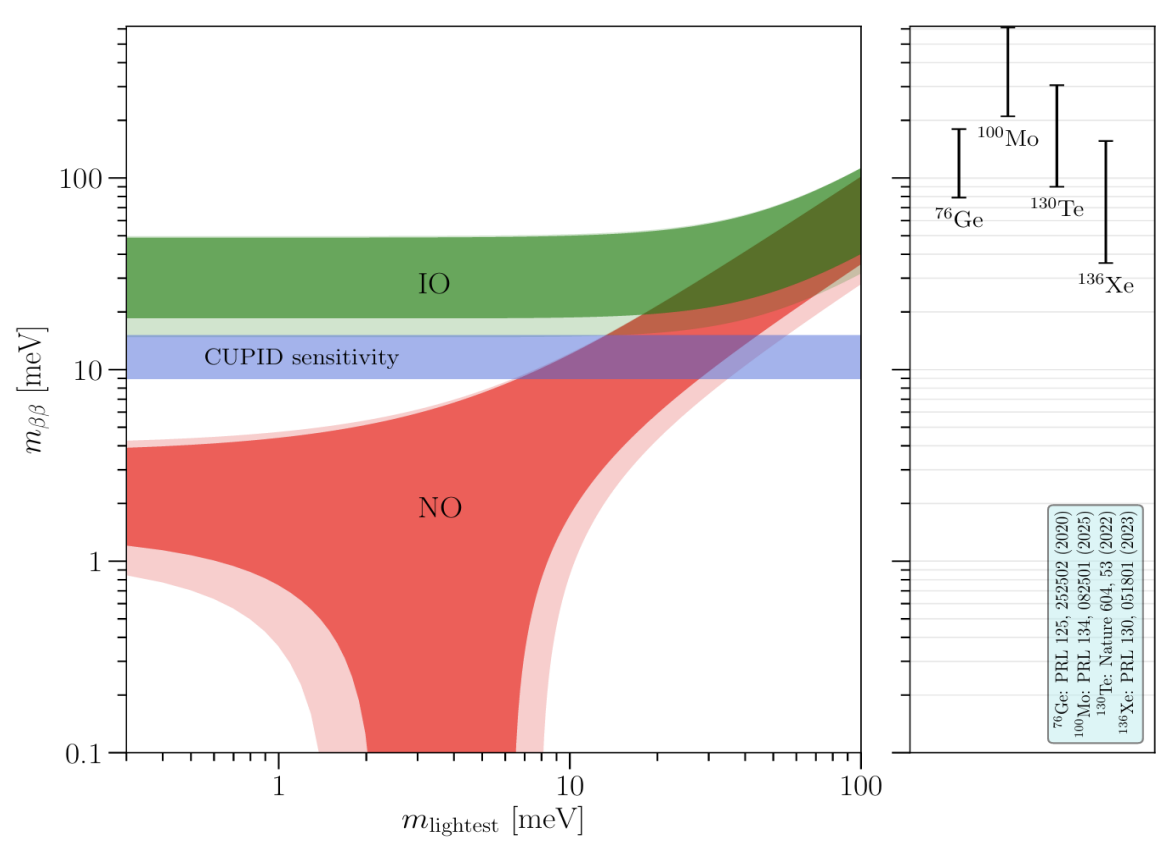
Introduction

The **CUORE (Cryogenic Underground Observatory for Rare Events)** experiment and its successor, **CUPID (CUORE Upgrade with Particle IDentification)**, are located in Italy's Gran Sasso National Laboratory and search for **neutrinoless double beta decay ($0\nu\beta\beta$)**.

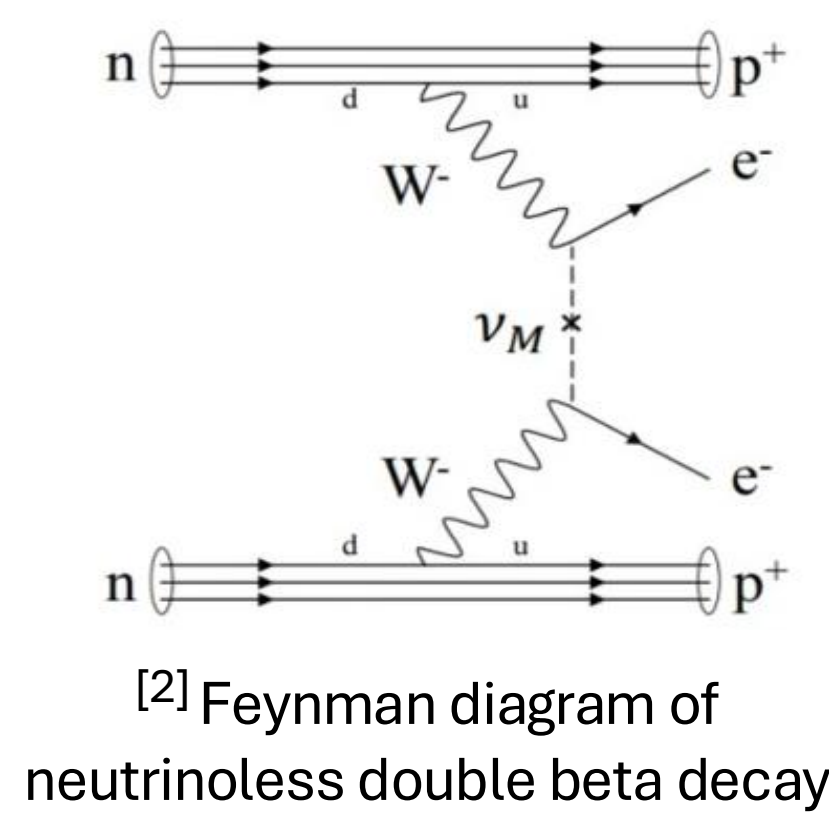
Due to a muon background in CUORE's region of interest (ROI), CUPID will implement a muon veto system to decrease the background. This work focuses on the development, design, and efficiency characterization of scintillating muon veto panel prototypes.

Background

- Neutrinoless double beta decay ($0\nu\beta\beta$)** is an ultra-rare, hypothetical radioactive decay process where two simultaneous beta decays don't emit antineutrinos.^[1] The decay contains net lepton number $\Delta L = 2$, violating lepton-number conservation in the Standard Model.



^[1] Inverted Ordering (IO) and Normal Ordering (NO) of neutrino masses



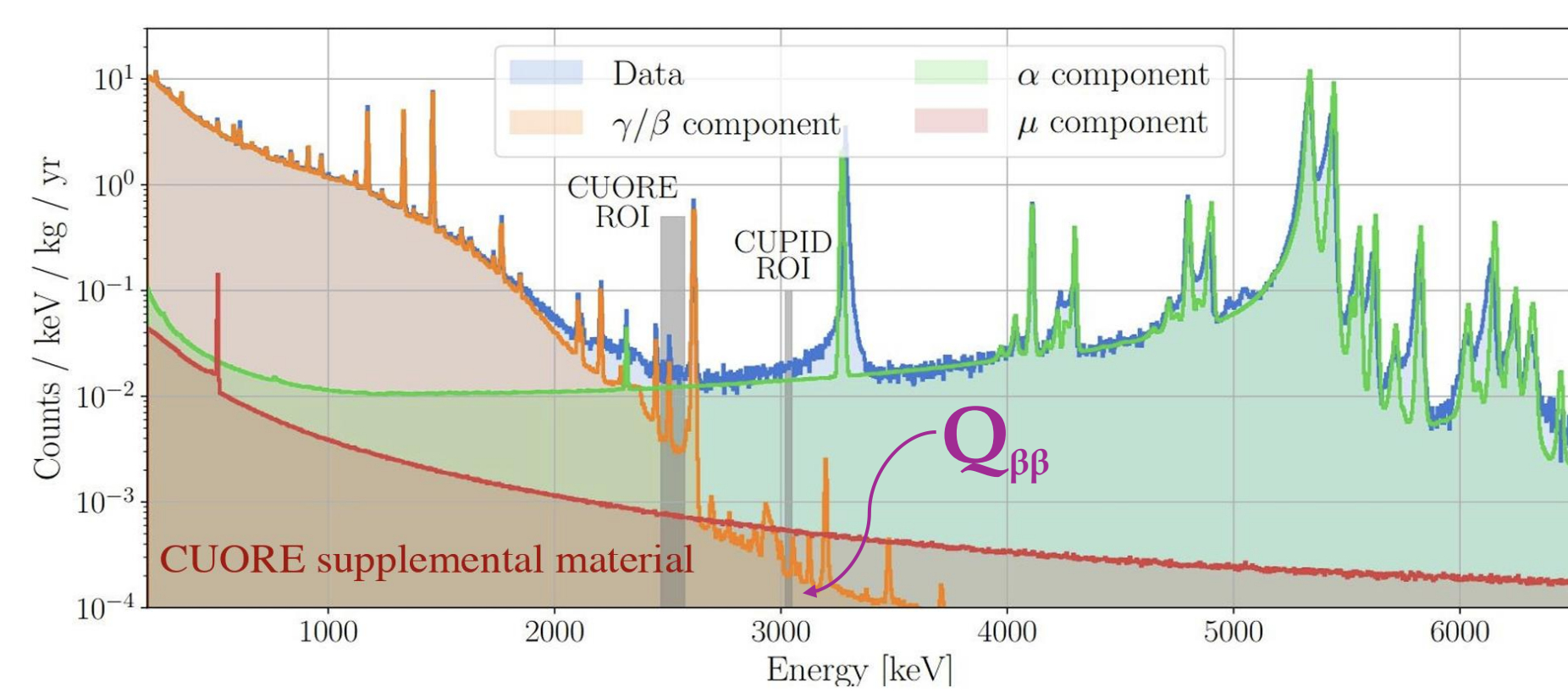
^[2] Feynman diagram of neutrinoless double beta decay

An Observation of $0\nu\beta\beta$

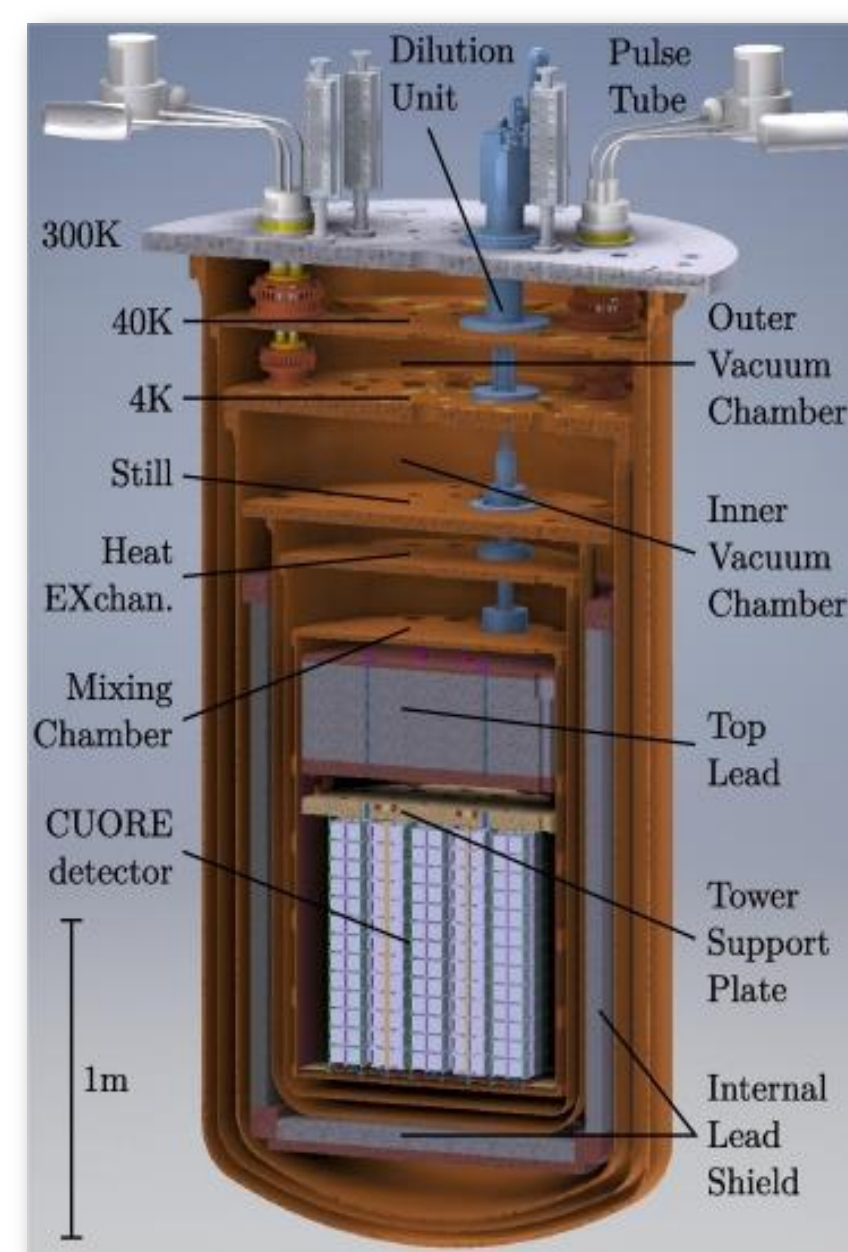
- Proves the **Majorana nature** of the neutrino
- Constrains the neutrino mass hierarchy
- Probes the **matter-antimatter asymmetry problem** in the universe

CUORE/CUPID Experiment

- CUORE uses TeO_2 crystals to search for $0\nu\beta\beta$ by detecting heat signatures. The 2 tonne-year data has set the best lower limit of $0\nu\beta\beta$ in ^{130}Te at 3.5×10^{25} yrs.
- CUPID's cryostat, set to ~ 10 mK, contains 57 towers of $1,596 \text{ Li}_2\text{MoO}_4$ scintillating crystals that collect thermal signals, and $\sim 2,500$ germanium light detectors for light signatures of decay events.^[3]
- ^{100}Mo crystal Q-value ($Q_{\beta\beta} = 3,034$ keV) is above most β/γ and α backgrounds, dramatically increasing sensitivity and doubly enables Particle IDentification (PID).
- Muon-induced events comprise background yield of 10^{-4} counts (keV/kg/yr) in CUPID's $0\nu\beta\beta$ ROI; oversaturating its background.**^[4]
- Aim to reject at least $\sim 98\%$ of muon-induced events!**



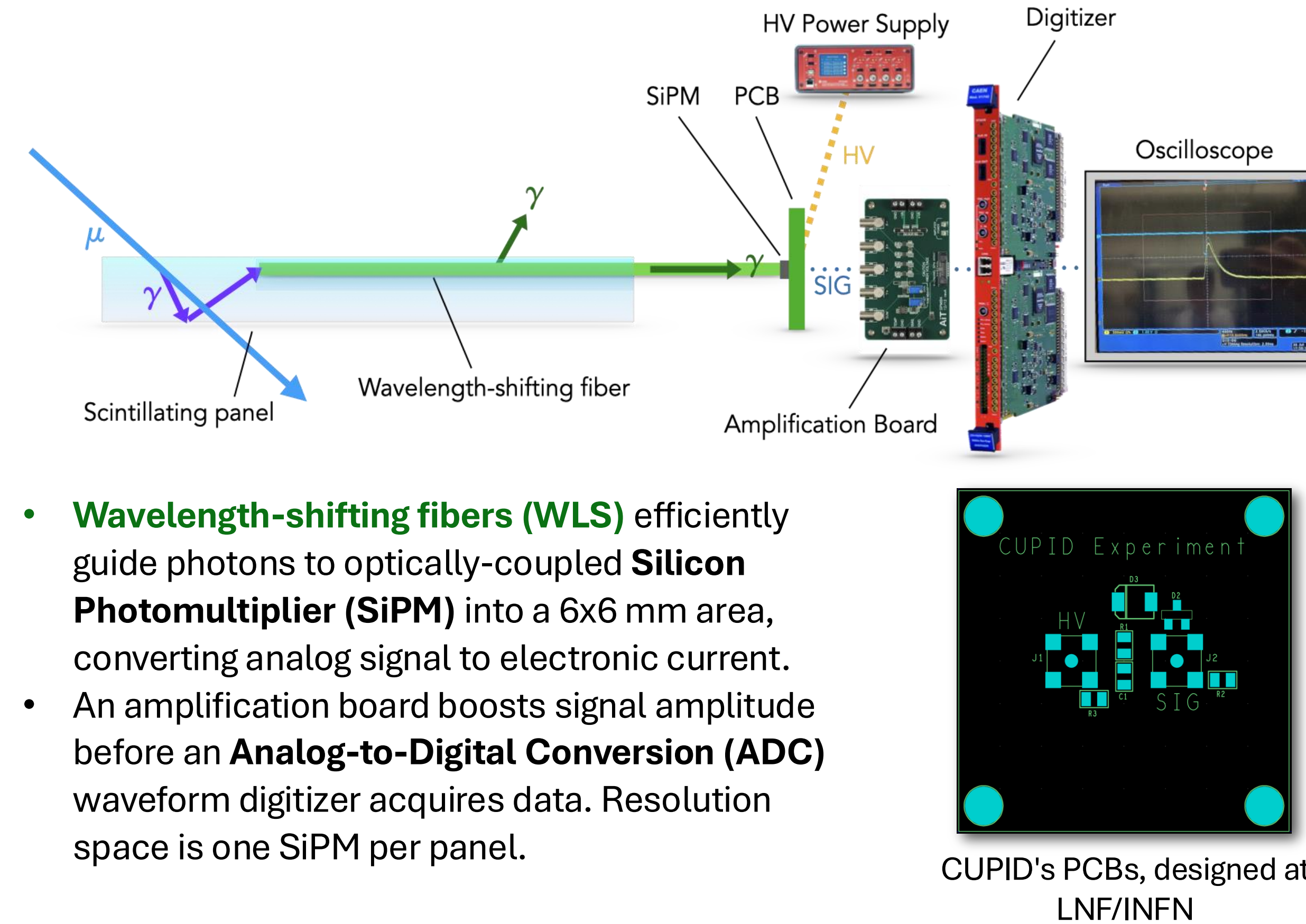
^[5] CUORE/CUPID Background Spectrum with $Q_{\beta\beta} = 3,034$ keV



^[6] CUORE's Cryostat

Muon Veto System

- Monolith structure comprising **80+ plastic scintillating panels** will surround CUPID. Muons deposit energy and produce light via scintillation effect.

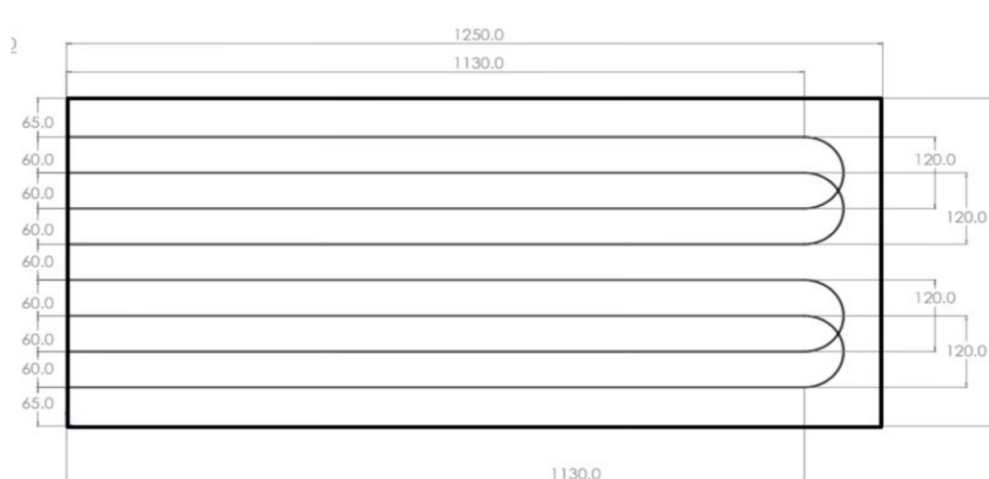


- Wavelength-shifting fibers (WLS)** efficiently guide photons to optically-coupled **Silicon Photomultiplier (SiPM)** into a 6×6 mm area, converting analog signal to electronic current.
- An amplification board boosts signal amplitude before an **Analog-to-Digital Conversion (ADC)** waveform digitizer acquires data. Resolution space is one SiPM per panel.

Prototype Construction

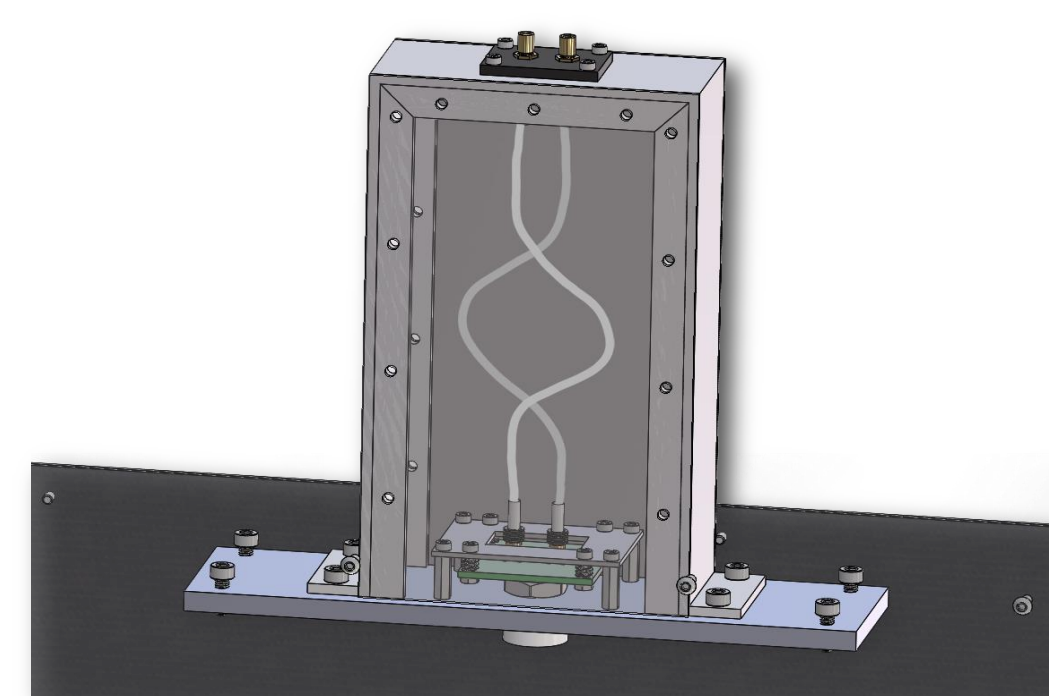
Design

- Prototyped **three EJ-200 scintillating panels**: 3.8m optical attenuation length, efficiency of 10,000 photons/MeV, max emission $\lambda = 425 \text{ nm}$
- Straight fiber groove exits provide higher light yield.

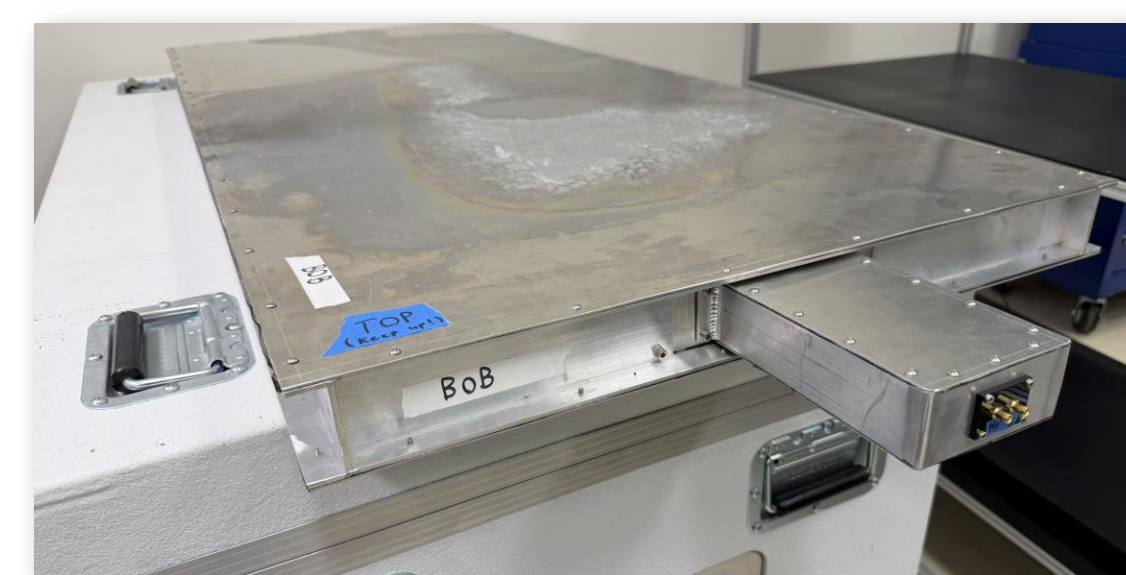


Electronics Box

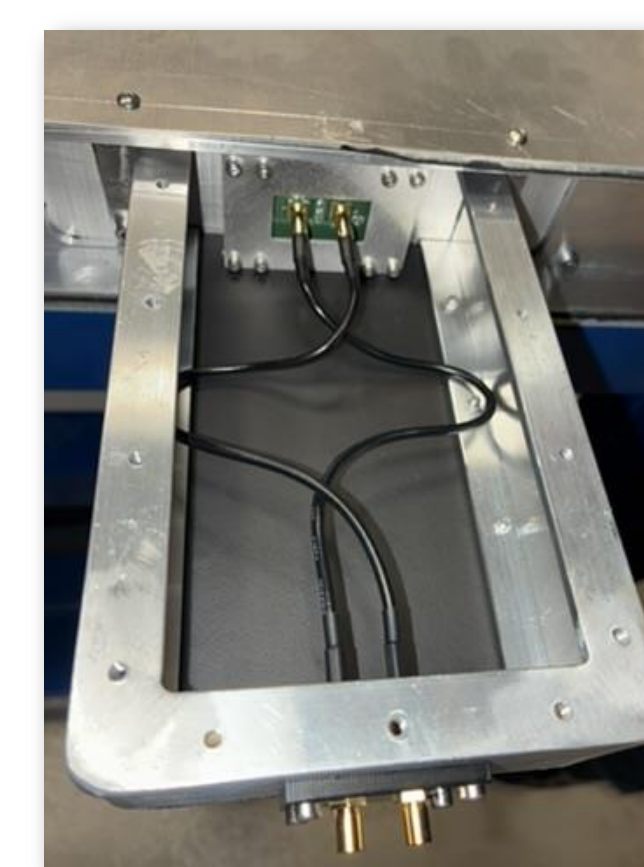
- WLS fibers are coupled to SiPM with glue, PCB is connected via MCX cables to DAQ.
- Aluminum cup designed in SolidWorks.
- Neoprene foam as light-leak proof seal for maximum light yield.



EJ-200 panel with WLS fibers



Assembled aluminum housing



Electronics box assembly

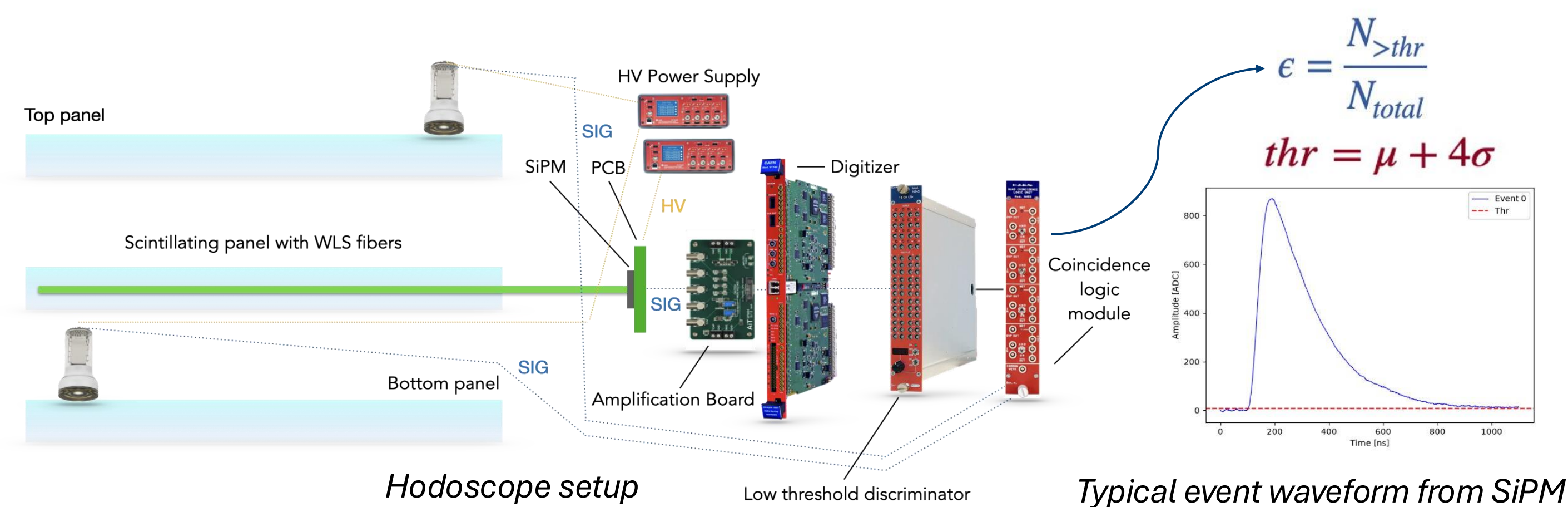
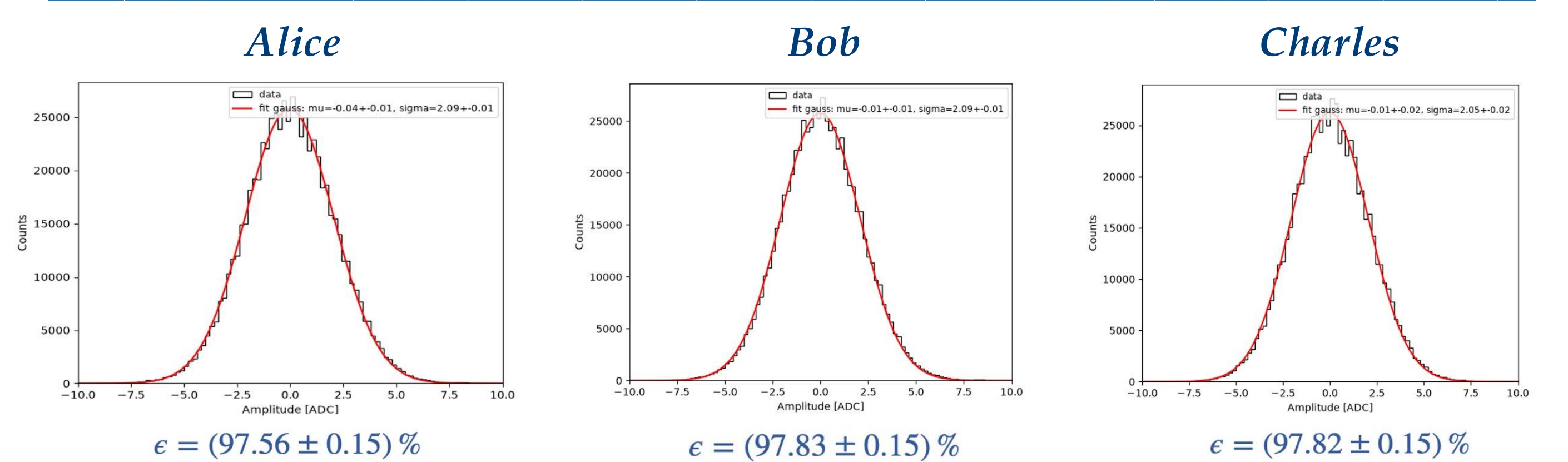
Build

- WLS fiber bundle polished and cured in template stand, fibers glued into panels.
- Panels are wrapped in 3 layers of **DuPont Tyvek S-10680** for reflectivity, one layer of **high-density polyethylene (HDPE)** to suppress ambient-light backgrounds.^[4]
- Aluminum U-channels/sheets form protective layer, internal foam layer for shocks.

Results & Testing

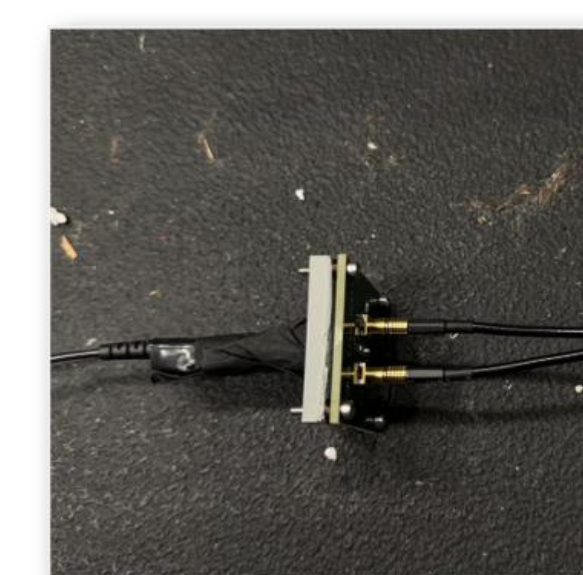
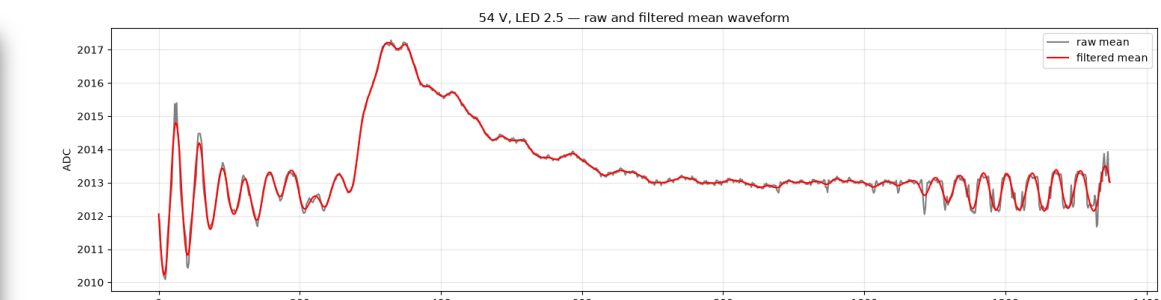
Hodoscope Efficiency Testing

- All prototypes were individually characterized in hodoscope setup using **Hamamatsu R6091 PMTs** and a **CAEN V1742 Waveform Digitizer**.



SiPM Characterization

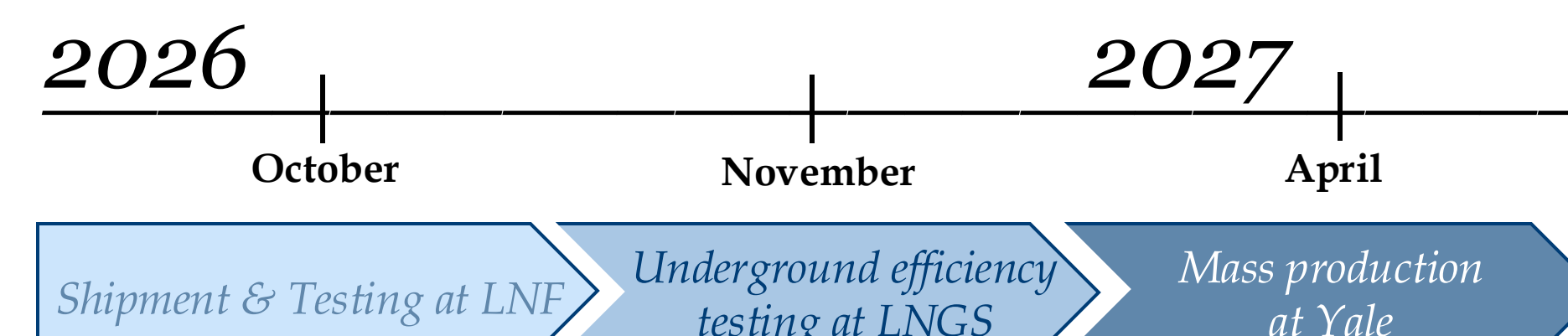
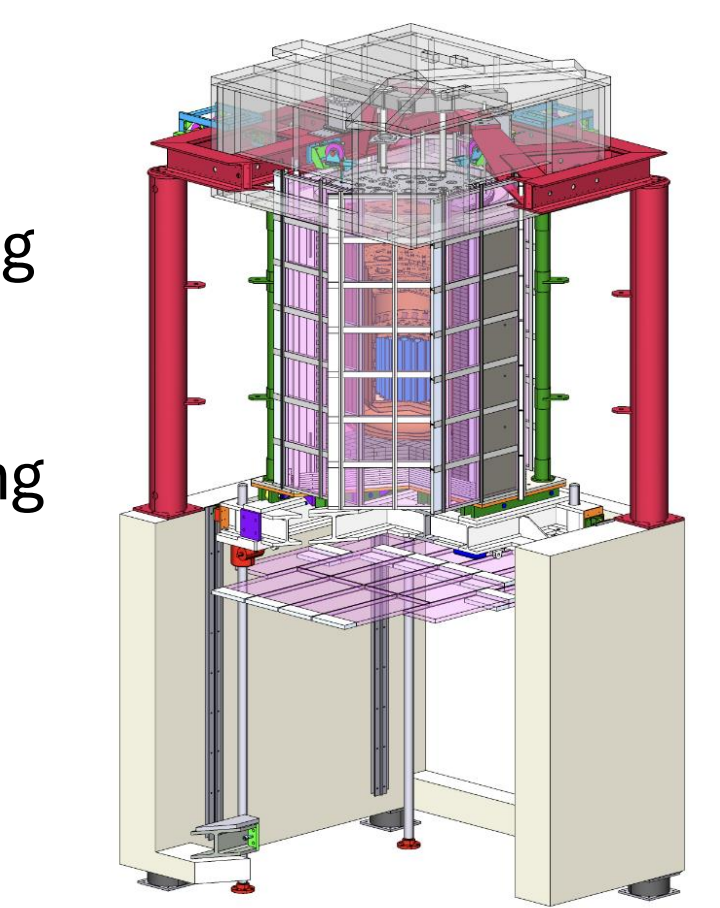
- S13360-6075PE Hamamatsu SiPM** in dark box, coupled with an LED peaked at **400 nm**. Sweep intervals from 52 V $\rightarrow$ 57 V.



(Left) LED-SiPM setup to test gain, dark count rate, and crosstalk. (Above) SiPM waveform from LED trigger

Future Directions

- Build SiPM characterization dark box module, rotating fiber gluing jig, Tyvek & HDPE acrylic cutout templates.
- Begin mass production of **~ 100 total muon veto panels** in spring 2027, supporting CUPID data collection into **early 2030s**.



CUPID monolith structure with panels in CAD

References & Acknowledgments

- ^[1] CUPID Collaboration (2025). CUPID, the Cuore upgrade with particle identification. *The European Physical Journal C* 85(737).
^[2] Cao, G., & EXO-200 and nEXO collaborations (2018). Search for $0\nu\beta\beta$ decay with EXO-200 and nEXO. *Proceedings of XIV International Conference on Heavy Quarks and Leptons*.
^[3] CUPID Collaboration (2026). Sensitivity of the CUPID experiment to $0\nu\beta\beta$ decay of ^{100}Mo . *The European Physical Journal C* 86(6).
^[4] Moore, M., Pagan, S., Pottebaum, E. G., Torres, J. A., Chizhik, A., Garcia, R. N., ... & Wilhelm, J. (2025). Performance of a SiPM-based, plastic scintillator muon veto prototype for CUPID. *Journal of Instrumentation*, 20(08), P08020.
^[5] Nutini, I. (2025). The CUPID neutrinoless double-beta decay experiment [Conference presentation]. *TAUP 2025: XIX International Conference on Topics in Astroparticle and Underground Physics, Xichang, China*.
^[6] CUORE Collaboration (2019). The CUORE cryostat: An infrastructure for rare event searches at millikelvin temperatures. *Cryogenics*, 102, 9-21.



We thank the CUORE/CUPID Collaborations, INFN, LNF, Wright Laboratory, and the National Science Foundation for their generous support (NSF-1913374 and NSF-2412377).

