NuDot: Research & development platform for liquid scintillator detectors and single photon sensing

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Neutrinoless double beta decay

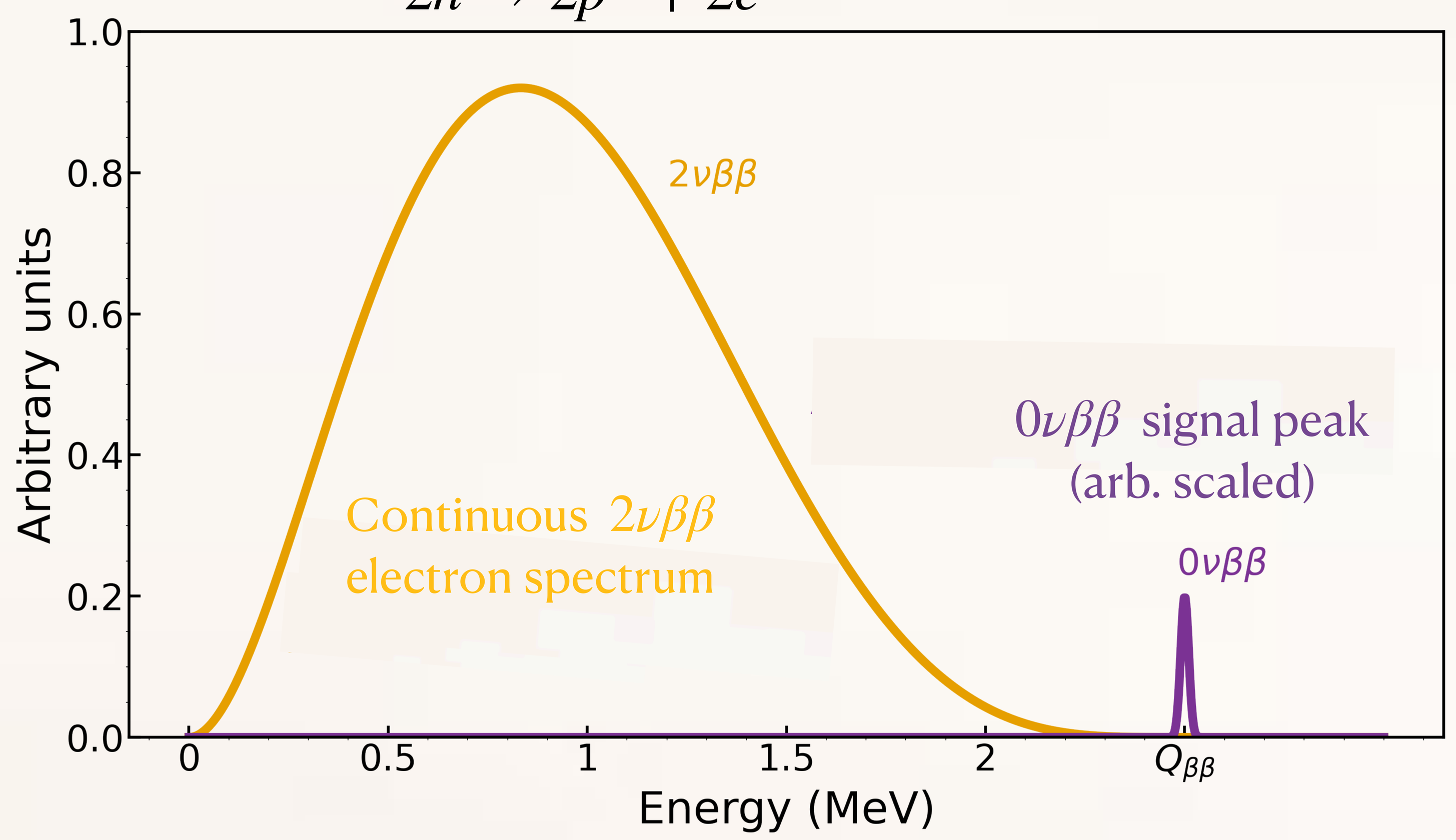
Neutrinoless double beta decay ($0\nu\beta\beta$) is the key to revealing whether neutrinos are their own antiparticles (Majorana particles) and observing this decay would reshape our understanding of fundamental physics.

$2\nu\beta\beta$: Observed rare decay with a lifetime of $\approx 10^{19}$ yrs

$$2n \rightarrow 2p^+ + 2e^- + 2\bar{\nu}_e$$

$0\nu\beta\beta$: Ultra-rare hypothesized decay with a lifetime of $\geq 10^{26}$ yrs

$$2n \rightarrow 2p^+ + 2e^-$$

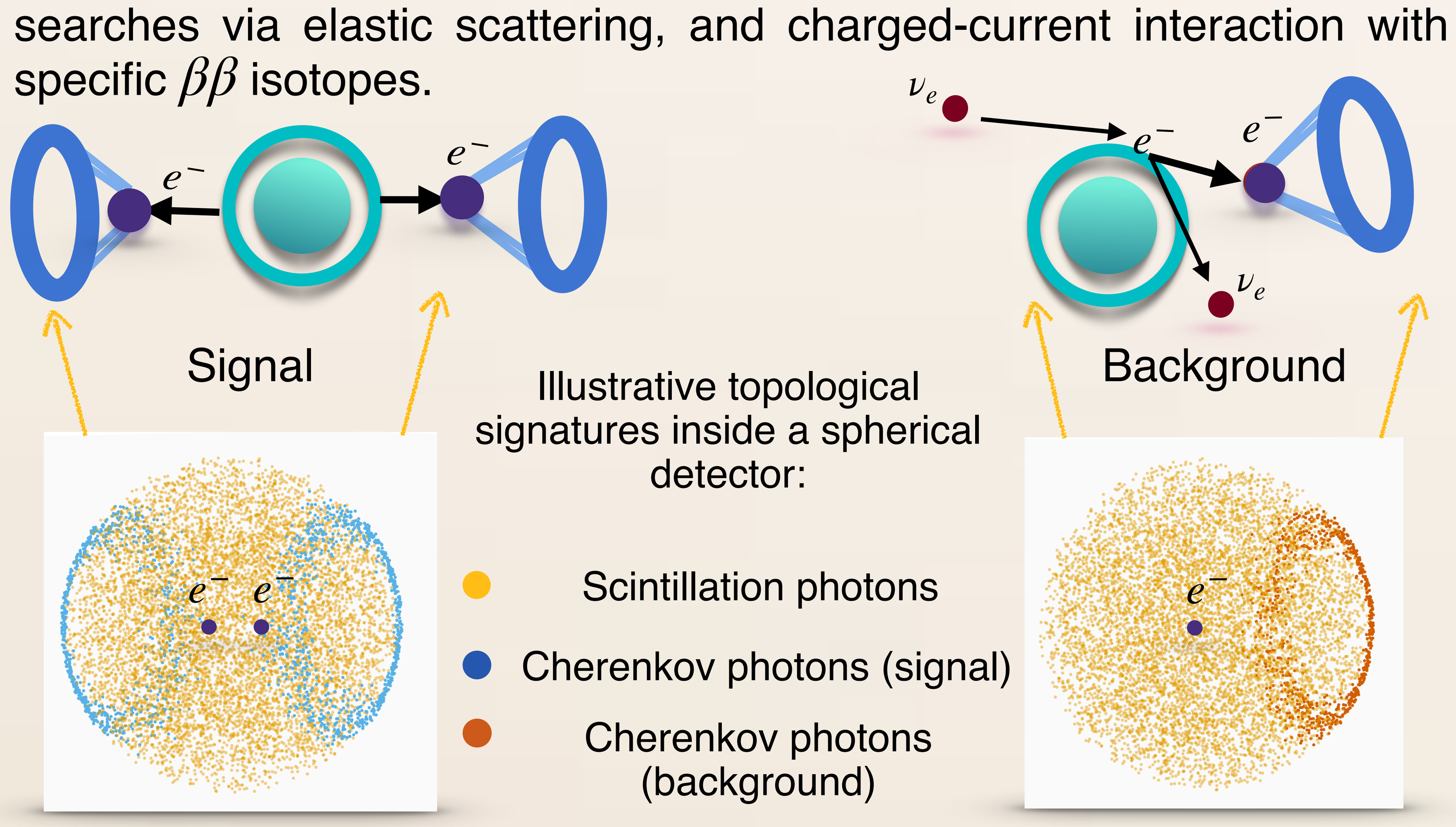


Current and future prospects for large liquid scintillator detectors

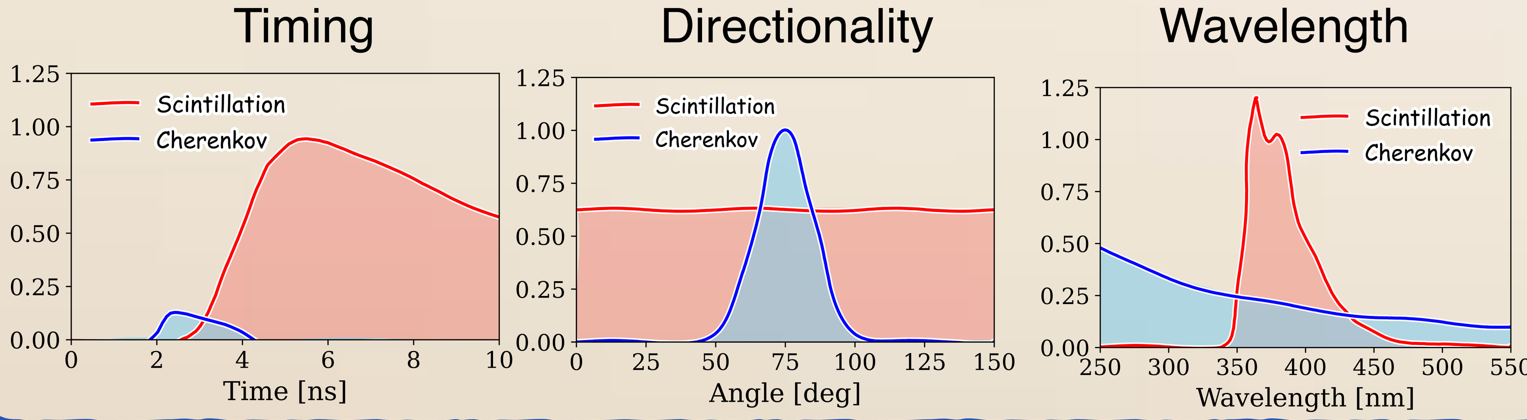
KamLAND-Zen has established the world's leading lower limit on the half-life of $0\nu\beta\beta$ for Xe-136, with $T_{1/2} > 4.3 \times 10^{26}$years at 90% confidence level (published in PRL) [1].

Solar neutrino background

^7Be solar neutrinos constitute a dominant background in the $0\nu\beta\beta$ searches via elastic scattering, and charged-current interaction with specific $\beta\beta$ isotopes.

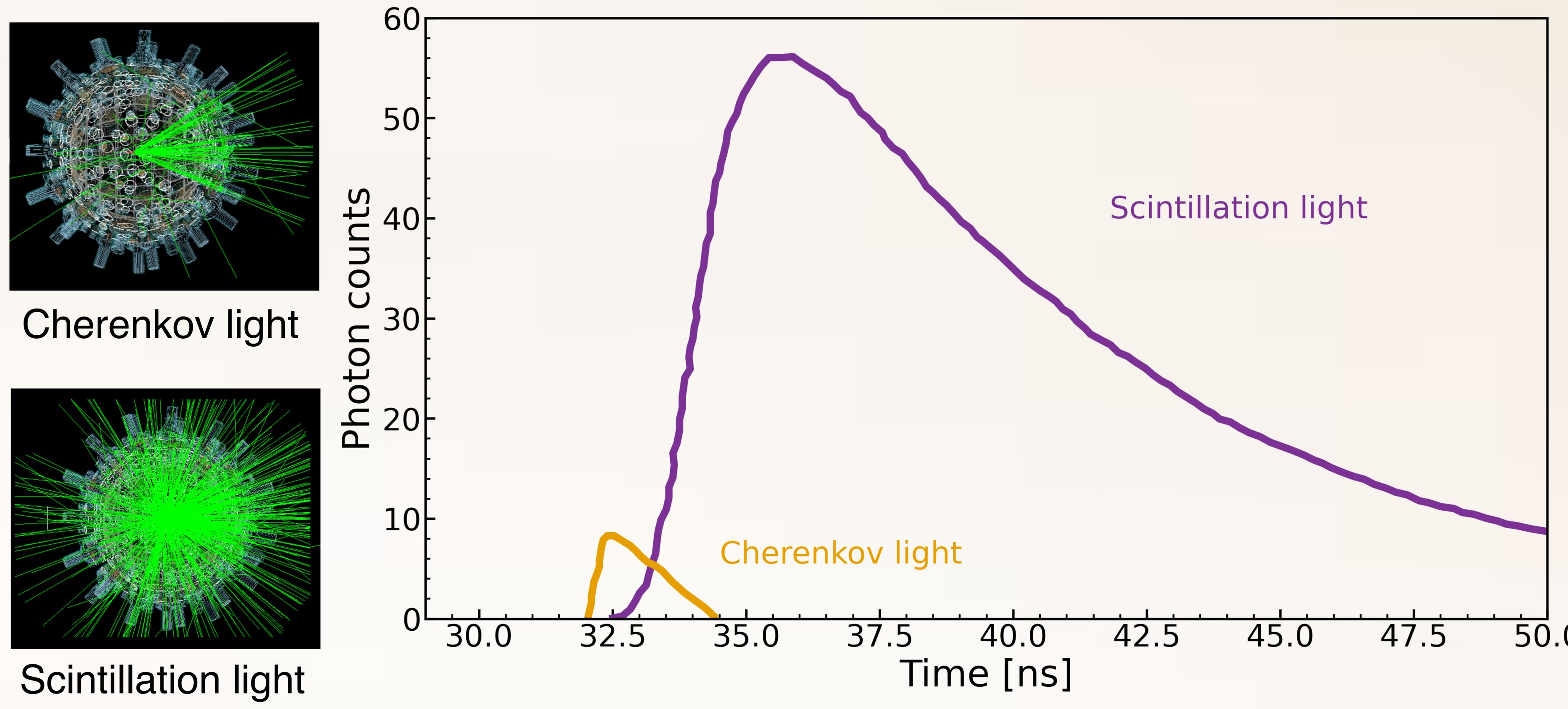


Single electron events resulting from solar neutrino interactions can deposit energy near $Q_{\beta\beta}$, mimicking $0\nu\beta\beta$ signals and motivating the need for Cherenkov scintillation separation. There are several ways to adopt for the separation:



Scientific goal:

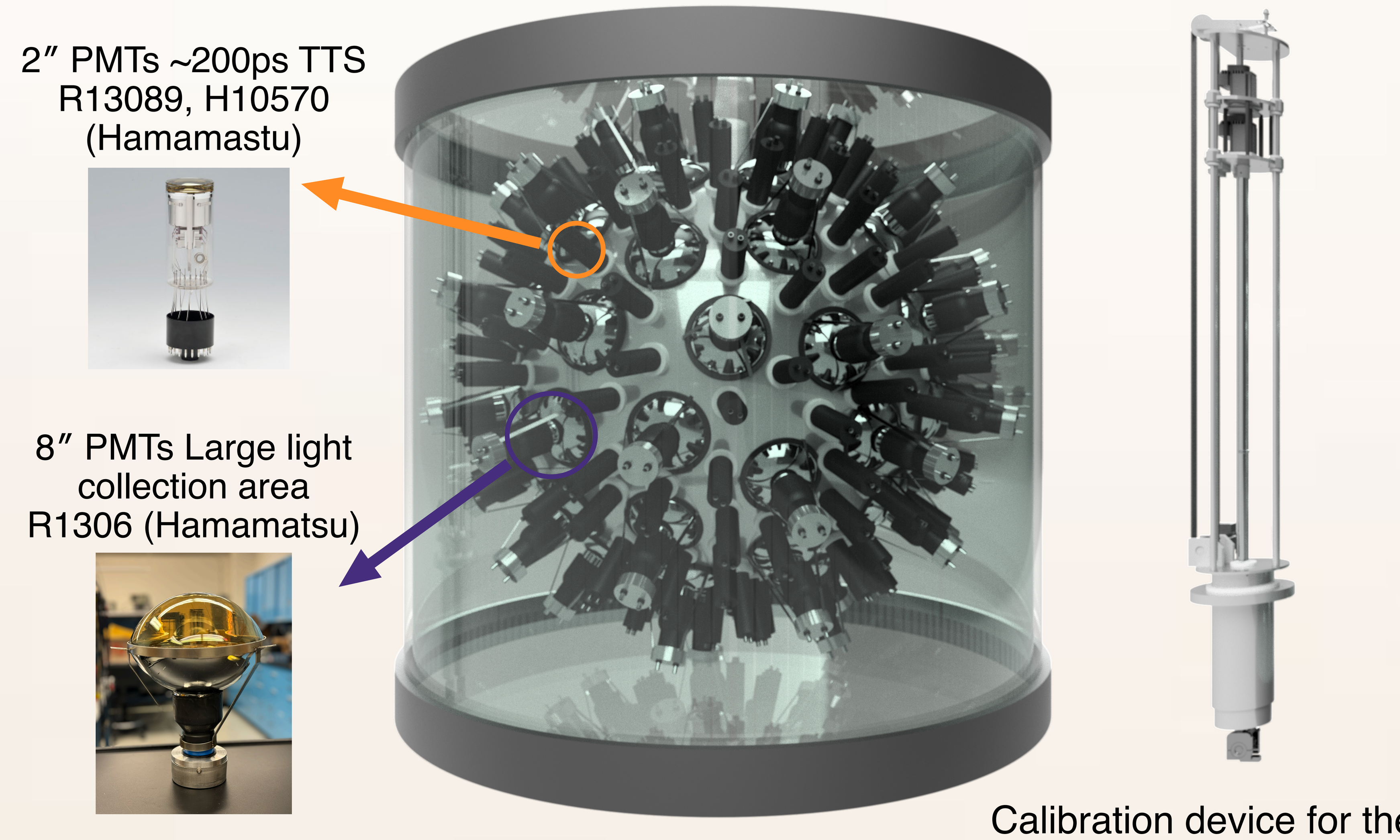
NuDot's primary goal is to demonstrate, at ton scale, **separation of prompt Cherenkov and delayed scintillation light**, enabling clearer identification of solar neutrino signals through timing and directionality with photomultiplier tubes (PMTs).



Simulation of KamLAND-Zen type detector for separating prompt Cherenkov from scintillation emission [2].

NuDot detector

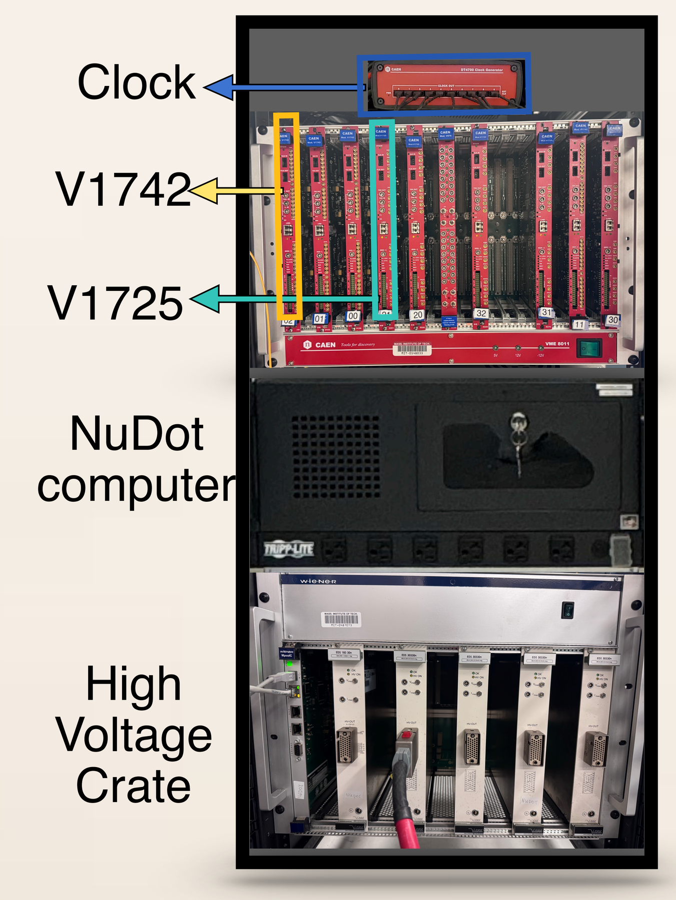
NuDot is a 1m diameter acrylic vessel that is surrounded by 4π array of high precision, low time-transit spread (TTS) and, large light collection PMTs located at UD.



Calibration device for the detector from UNC

Data acquisition system (DAQ)

- The DAQ system comprise of two different types of digitizer boards:
  - CAEN V1742 (5 GSa/s) digitizers for 2″ PMTs
  - CAEN V1725 (250 MSa/s) digitizers for 8″ PMTs
- CAEN V976 trigger fan-in/fan-out
- CAEN DT4700 clock to synchronize timing of all channels.
- Custom DAQ firware is being developed at UD.

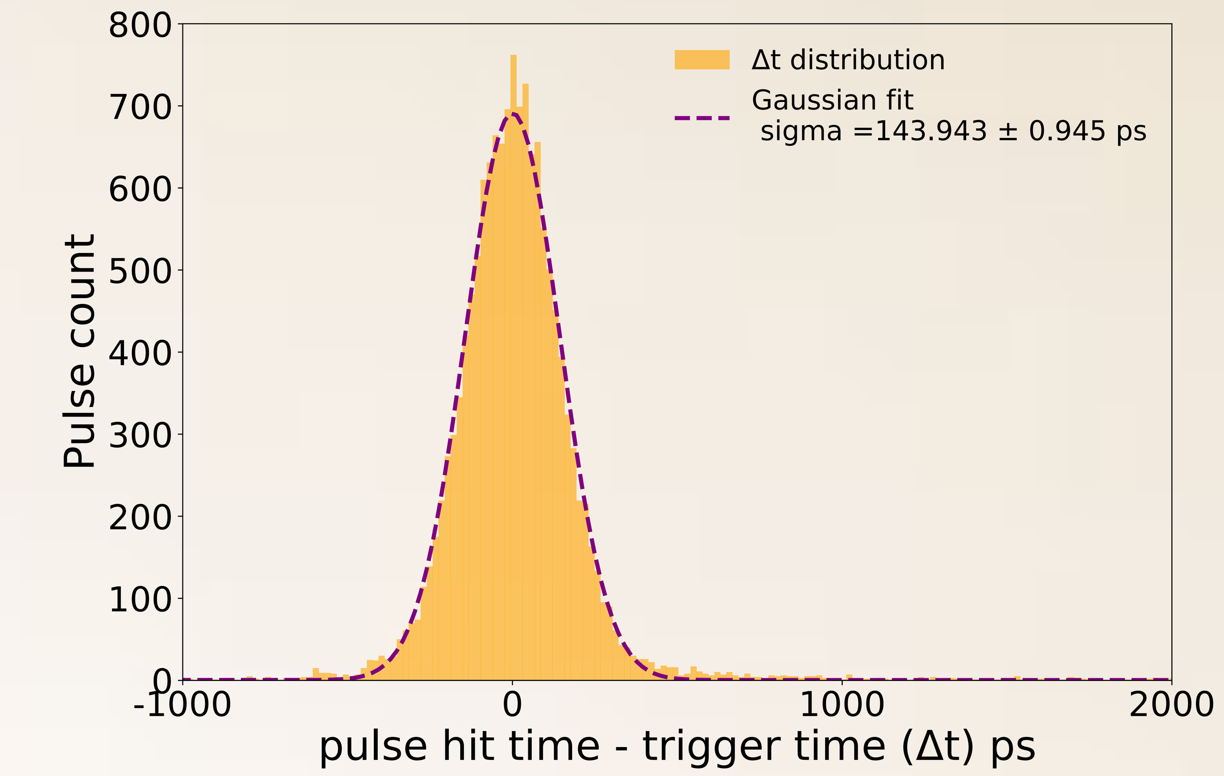


Calibration system is designed by the collaborators from UNC.

- A mechanical arm supports the source assembly.
- A collimated double-beta point source is coupled to a quartz cuvette filled with liquid scintillator.
- Three motors control the position and orientation of the cuvette.

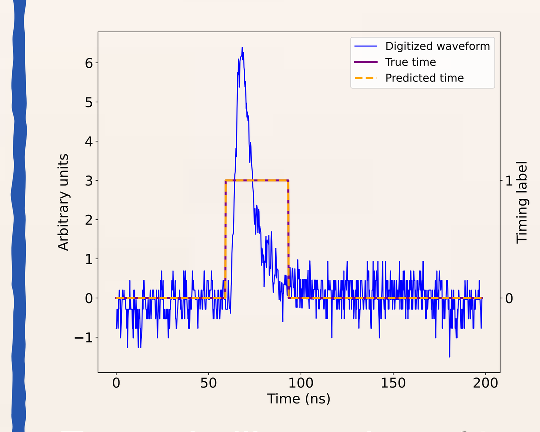
First look at single photons from the 2″ PMTs

- **Template fitting** enables sub-nanosecond timing resolution for 2″ PMTs (**~144 ps**).
- Used a pico-second laser with triggers to record data (waveforms and trigger pulses)
- For each event, the trigger rise time and associated pulse hit time are extracted, and their difference (Δt) is used to characterize the TTS."

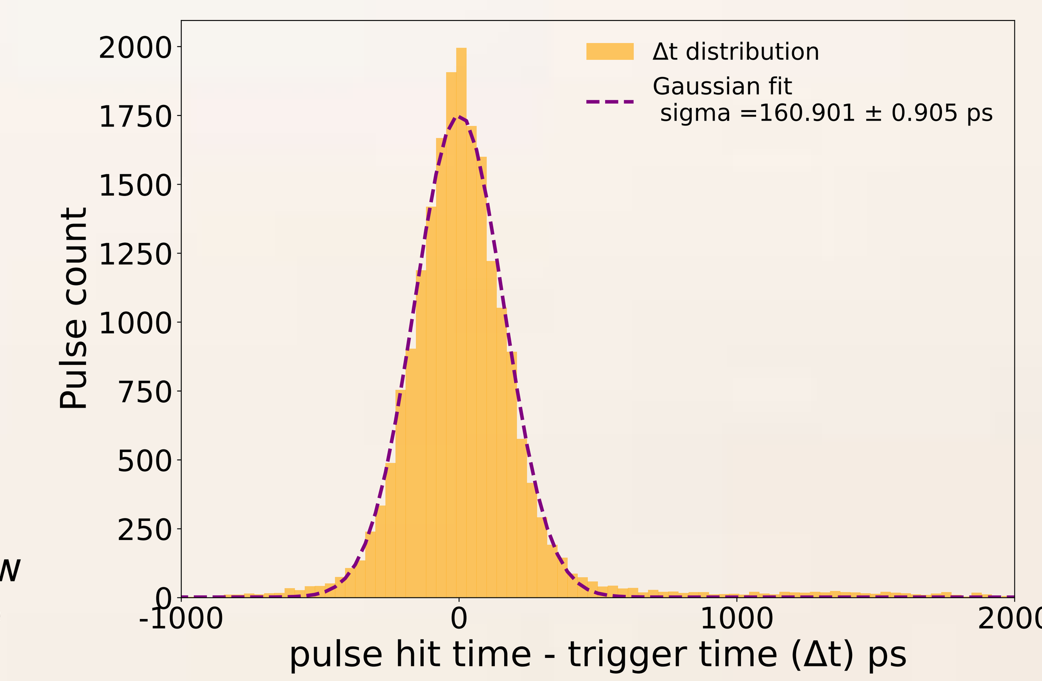


- Using **Machine learning** technique:
  - A 1D U-Net architecture is employed for pulse time extraction and waveform denoising, achieving < 200 ps timing resolution, comparable to traditional template fitting.
  - U-Net is a Convolutional Neural Network (CNN) that captures both local and global features, making it effective for waveform denoising and timing extraction.

The U-Net model achieves a timing resolution of **~161 ps** for single-pulse waveforms, approaching the 144 ps resolution obtained with template fitting. Development of a multi-pulse timing framework is underway.



Example illustration of how UNet classifies the pulse rise time from the noise



What's coming next

- This summer aiming to take data only in water to verify Cherenkov timing using muon tagger.
- Next step is to replace water with a scintillator for combined Cherenkov + scintillation reconstruction
- Extension to lower energy regimes with ^{90}Sr β source using calibration device from UNC, and a high light yield scintillator.

References

[1] KamLAND-Zen Collaboration, *Phys. Rev. Lett.* 135, 262501 (2025).
[2] C. Aberle et al., JINST 9, P06012 (2014).

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