Omnidirectional Photon Time Projection with Large Liquid Neutrino Detectors

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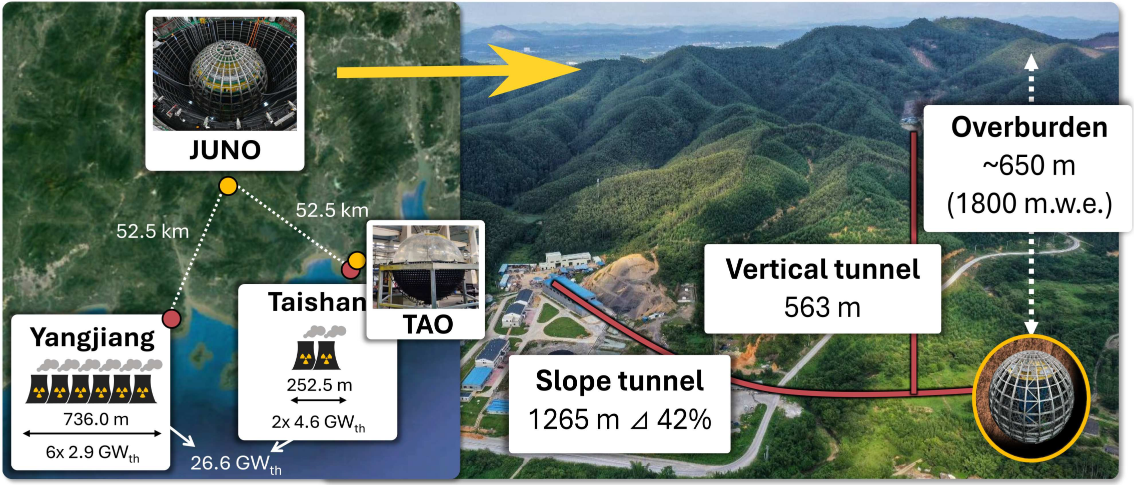
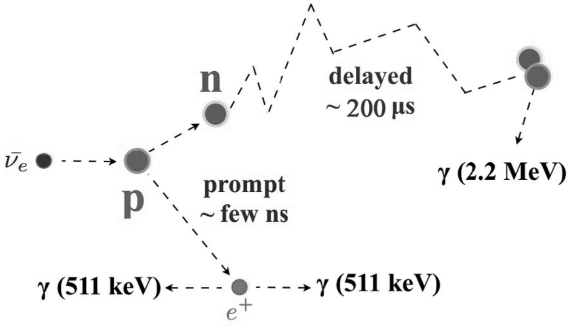
Jiangmen Underground Neutrino Observatory

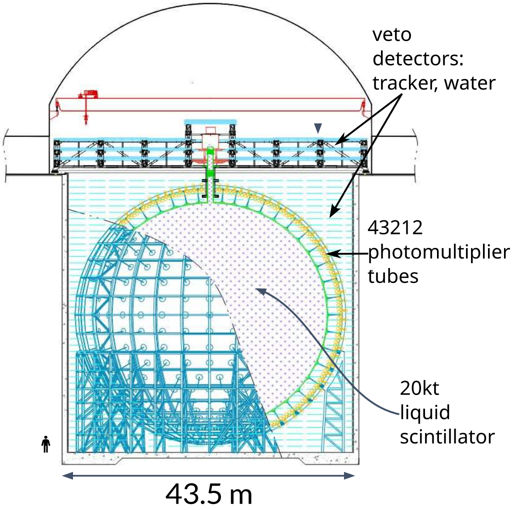


- 52.5 km is the sweet spot for ν oscillation.

$\bar{\nu}$ Inverse Beta Decay

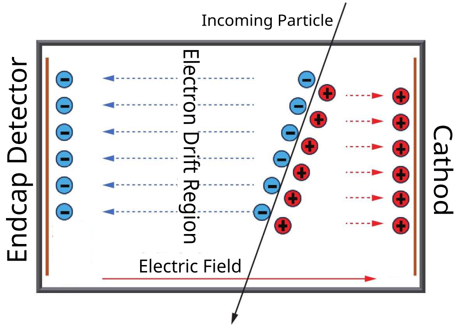
$$\bar{\nu}_e + \mathrm{p} \longrightarrow \mathrm{e}^+ + \mathrm{n}$$



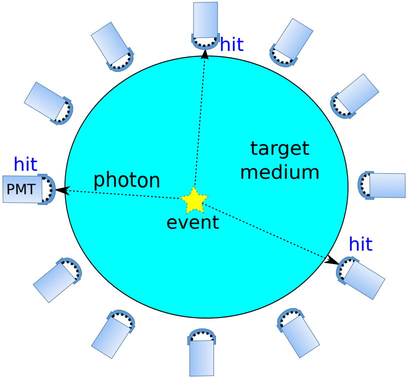


- e^+/γ scintillation light are collected by photomultipliers.

Photon Time Projection at Liquid Scintillation Detectors



$\rightarrow$

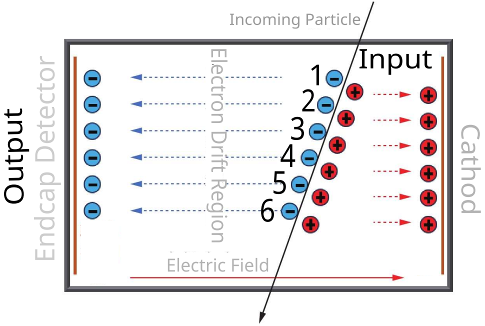


From drift electrons to omnidirectional photons

- Speed from drift $1\,$cm/ţs to intrinsic $20\,000\,$cm/ţs, needing faster readout.
- Photons travel in all directions, needing stronger algorithm and computing.

$$\text{1D} \quad \Delta z = v\Delta t \quad \rightarrow \quad \vec{r} = \vec{v}\Delta t \quad \text{3D}$$

Green's Function Analog for a TPC



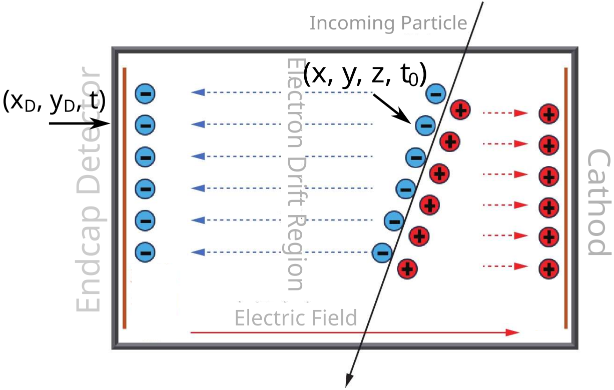
- Linear superposition of outputs.
- $\mathcal{D}_{\text{TPC}}(\cdot)$ is the linear detection operator.
- linear differential operator has Green's function.

$$\mathcal{D}_{\text{TPC}}(i_i + i_2 + i_3 + \ldots + i_6) = \mathcal{D}_{\text{TPC}}(i_i) + \mathcal{D}_{\text{TPC}}(i_2) + \ldots + \mathcal{D}_{\text{TPC}}(i_6)$$

The Trivial Green's Function

$$G(x_D, y_D, t; x, y, z, t_0) = \delta(x - x_D)\delta(y - y_D)\delta(z - v(t - t_0))$$

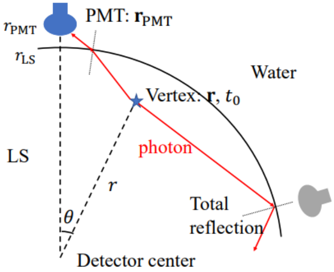
- $\delta(\cdot)$ is the Dirac delta function, in reality replaced with finite-resolution Gaussian.



Green's Function for Monolithic Liquid Scintillator Detector

$$G(\boldsymbol{r}_{\mathsf{PMT}}, t; \boldsymbol{r}, t_0) \xrightarrow{\text{PMT location symmetry}} R(t - t_0; \boldsymbol{r} - \boldsymbol{r}_{\mathsf{PMT}})$$: probe function

A non-trivial function that exhibits an asymptotic inverse-square dependence.



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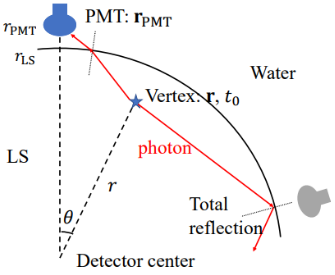
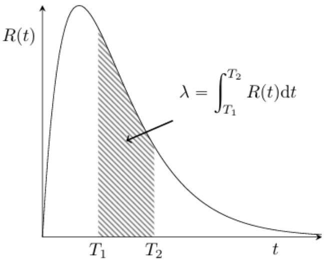
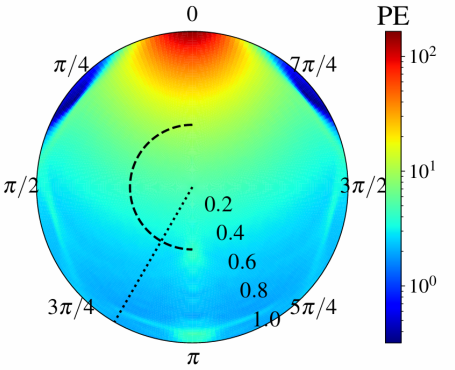
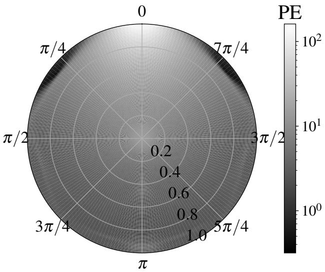






Characterization of the Probe



- The deficits at $\frac{\pi}{4}$ is from the total internal reflection of acrylic-water interface.

NIM A 1057(2023)168692

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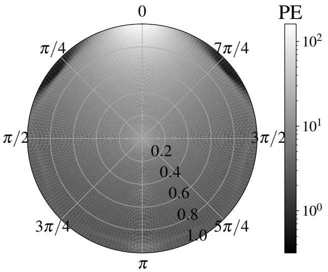

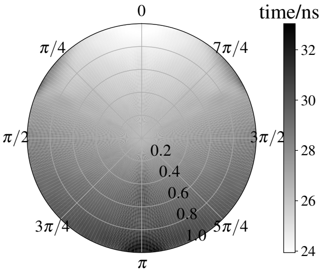

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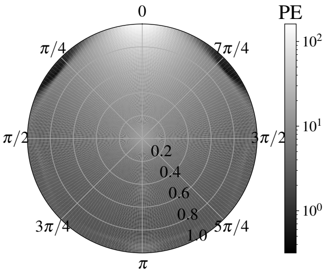

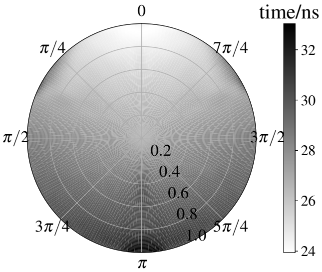

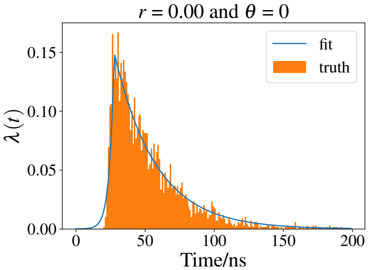

- The deficits at $\frac{\pi}{4}$ is from the total internal reflection of acrylic-water interface.
- Photon time of flight from all directions, modified by refraction, reflection and scattering.
- Shape approximates scintillation time profile. $\lambda(t) = R(t; \boldsymbol{r})$ for a specific (r, θ).

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The Quantum Nature of Photon Detection

- A sample of photo-electrons on a PMT is from a time-dependent poisson process $ER_j(t;\vec{r},t_0)$, its intensity function is superposition of multiple probes.

$$R(t) = \sum_k \left[R_k^{\text{scintillation}}(t) + R_k^{\text{Cherenkov}}(t)\right] + R^{\text{Dark Count}}(t)$$

First-Principle Bottom-Up Event Reconstruction

$$\begin{aligned}\mathcal{L}(\{\boldsymbol{w}_i\}|E,t_0,\boldsymbol{r}) &= \prod_i p[\boldsymbol{w}_i|ER_i(t;t_0,\boldsymbol{r}) + b_i] \\ &= \prod_i \sum_j p(\boldsymbol{w}_i|\boldsymbol{z}_j)p[\boldsymbol{z}_j|ER_i(t;t_0,\boldsymbol{r}) + b_i]\end{aligned}$$

waveform

dark noise

total probability

all PE times (sampled)

SPE charge spectrum embedded

Chuang Xu, Contribution #260; Novel MCP-PMT response NIM A 1055(2023)168506, NIM A 1066(2024)169626.

High-Resolution Waveform Analysis for Particle Detection

PEs follow an inhomogeneous Poisson process with intensity $\lambda\phi(t - t_0)$.

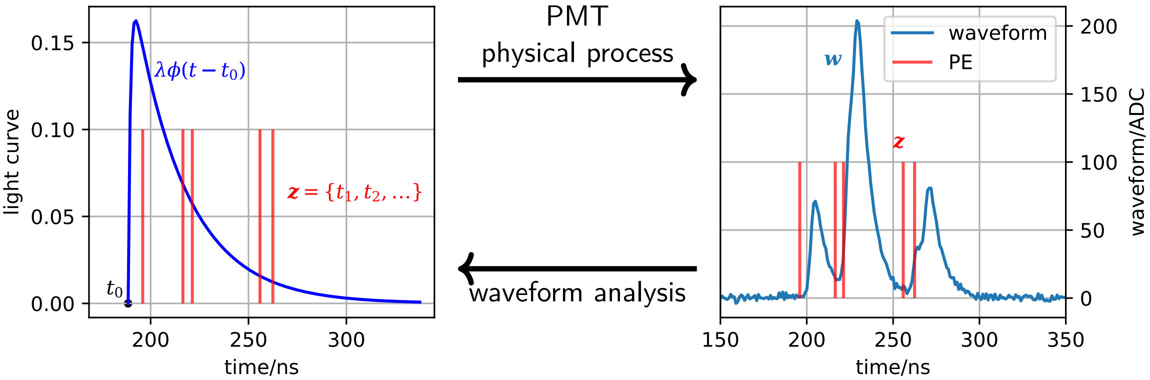


Figure: Sample PEs from Poisson process

Figure: Convolve PEs into a waveform

Yuyi Wang, Contribution #191; arXiv:2403.03156

Calibration of the Probe

Neural network as universal functional approximation $\leftrightarrow$ non-parametric statistics

Calibration of the detector response

- Time-dependent Poission point process model as a surrogate to the optical process.
- Its intensity function is statistically learned non-parametrically.

From generalized linear model (GLM) to generalized additive model (GAM)

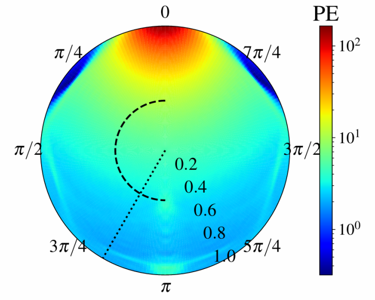
$$g\left(\mathbb{E}[y|\boldsymbol{x}]\right) = \beta_0 + \sum_{j=1}^{p} \beta_j x_j$$

$$\rightarrow g\left(\mathbb{E}[y|\boldsymbol{x}]\right) = \beta_0 + \sum_{j=1}^{p} f_j(x_j)$$

- f_j are the smooth basis functions.
- Basis are expanded with cartesian products.

Generalized Additive Model on Histograms

x	y	t	nEV	nPE
...	...	...	...	...



- x average x-coordinate of a bin
- y average y-coordinate of a bin
- t t central value of a bin
- nEV number of events
- nPE number of PEs

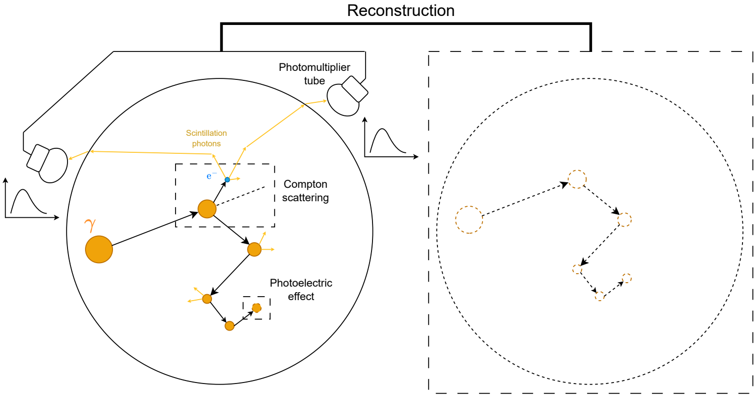
Regression formula

$$\mathrm{nPE} \sim \pi(\lambda), \log\lambda = \mathrm{te}(x(r,\theta), y(r,\theta), t) + \log(\mathrm{nEV})$$

$\to$ Learn $R_j(t - t_0; r, \theta)$, extensible to boosted decision trees and neural networks.

Chuanhui Hao, Contribution #96

Monolithic Liquid Scintillator as a Compton Camera



- Reconstructed gamma-ray trajectory from Compton and photoelectric electrons.

EPJ C 85, 4 (2025): 438, track effect expected for MeV β at JUNO-TAO

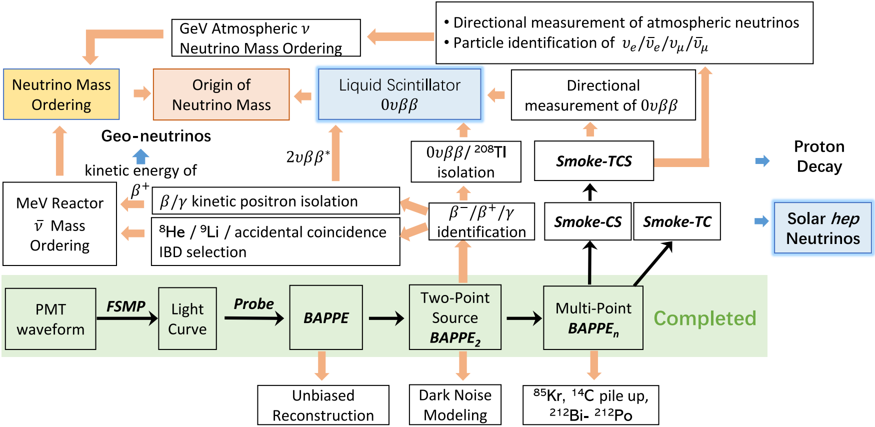
Summary

- With faster readout and powerful algorithms, large liquid neutrino detectors could gain omnidirectional photon time projection tracking capabilities.
- Stochastic model by classical statistics, deterministic impulse response by machine learning (universal functional approximation).

Next

- Calibrating the probe by mitigating the effects of PMT dark noise, non-uniform photon detection efficiency, and transit time spread (TTS).
- Promoting cross-experiment collaboration to enhance event reconstruction capabilities for the DUNE (LArTPC), Hyper-K (water Cherenkov), and JUNO (liquid scintillator) neutrino detectors.

Low and high hanging fruits



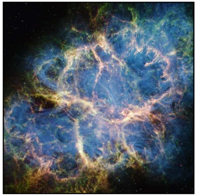
- **FSMP:** fast stochastic matching pursuit algorithm
- **BAPPE:** Bayesian probe for point-like events
- **TCS:** tracking Cherenkov scintillation
- **Probe:** response function
- **Smoke:** luminescence field

Principal scientific objectives (orange arrow)
Potential technological applications (blue arrow)
Technology development (black arrow)

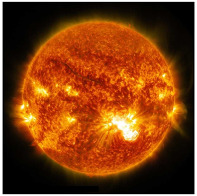
ν research enabled by large $20\,$kt target

Reactor

Supernovae

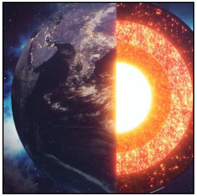


Sun



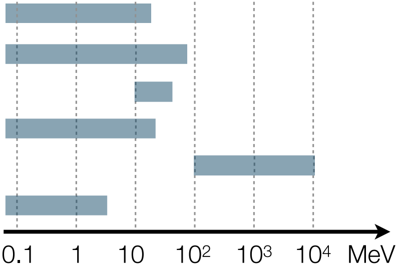
Atmosphere

Earth Interior



Neutrino source	Expected signal
Reactor	45 evts / day
Supernova burst	10^4 evts at 10 kpc
Diffuse supernova background	2-4 evts/ year
Sun ^{8}B (^{7}Be)	16 (490) / day
Atmosphere	100+ / year
Earth crust & mantle	400 / year

Energy Region



Spline Approximation

Cubic Spline

$$f_j(x_j) = \sum_{k=1}^{m_j} \beta_{jk} B_k(x_j) \quad \Rightarrow \quad \boldsymbol{f}_j = \boldsymbol{X}_j \boldsymbol{\beta}_j$$

- $\boldsymbol{X}_j$: $n \times m_j$ design matrix
- $\boldsymbol{\beta}_j$: $m_j \times 1$ parameter vector

$$\int [f_j''(x_j)]^2 dx_j = \boldsymbol{\beta}_j^T \boldsymbol{S}_j \boldsymbol{\beta}_j$$

Ambiguity of direction in 3D

$$\vec{r} = \vec{v}\Delta t.$$

1. Hardware approach: measure the direction of incoming photon
   - development of lenses for liquid scintillation and Cherenkov detectors
2. Solve the inverse problem with machine learning, in light of computational imaging.
   - extract particle interaction tracks from data analysis.
   - invertible full probabilistic modeling a.k.a. probabilistic programming

Super-KamiokaNDE

- time projection

Integration of the intensity function gives a Poisson field.

$$\int R_j(t - t_0; r, \theta)\mathrm{d}t = \lambda_j(r, \theta)$$