Enhancing Angular Sensitivity of Segmented Antineutrino Detectors

for Reactor Monitoring

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Localization of IBD Source

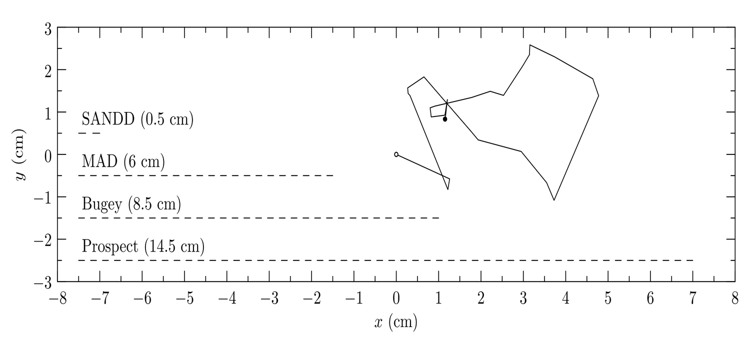
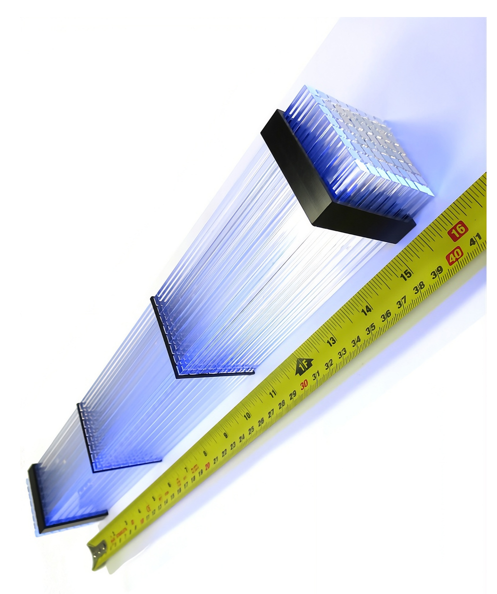


Figure 1: Characteristic neutron xy-trajectory at true scale (IBD vertex to capture) against the segment dimensions of four 2D-segmented detectors: SANDD, MAD, Bugey, PROSPECT.

- Directional method for segmented Inverse Beta Decay (IBD) detectors, measuring:
  $$\bar{\nu}_e + p \to e^+ + n$$
- Positron (e^+) gets most of the energy, and annihilation marks prompt vertex
- Neutron (n) gets momentum direction, and capture marks delayed vertex
- Lithium^6 dopant localizes n capture with $^3_1$H and $^4_2$He depositing energy within $\sim 10\ \mu$m of capture
- Direction to source inferred from n direction with enough events



SANDD

Our Approach to Simulation Design

- IBD simulation designed with RATPAC-2 with 1M generated events
- Simplified monolithic detector geometry using 0.1%-wt ^{6}Li-doped plastic scintillator
- Modeled in 5 mm, 50 mm and 150 mm segmentation regimes using grid overlays as binning matrices

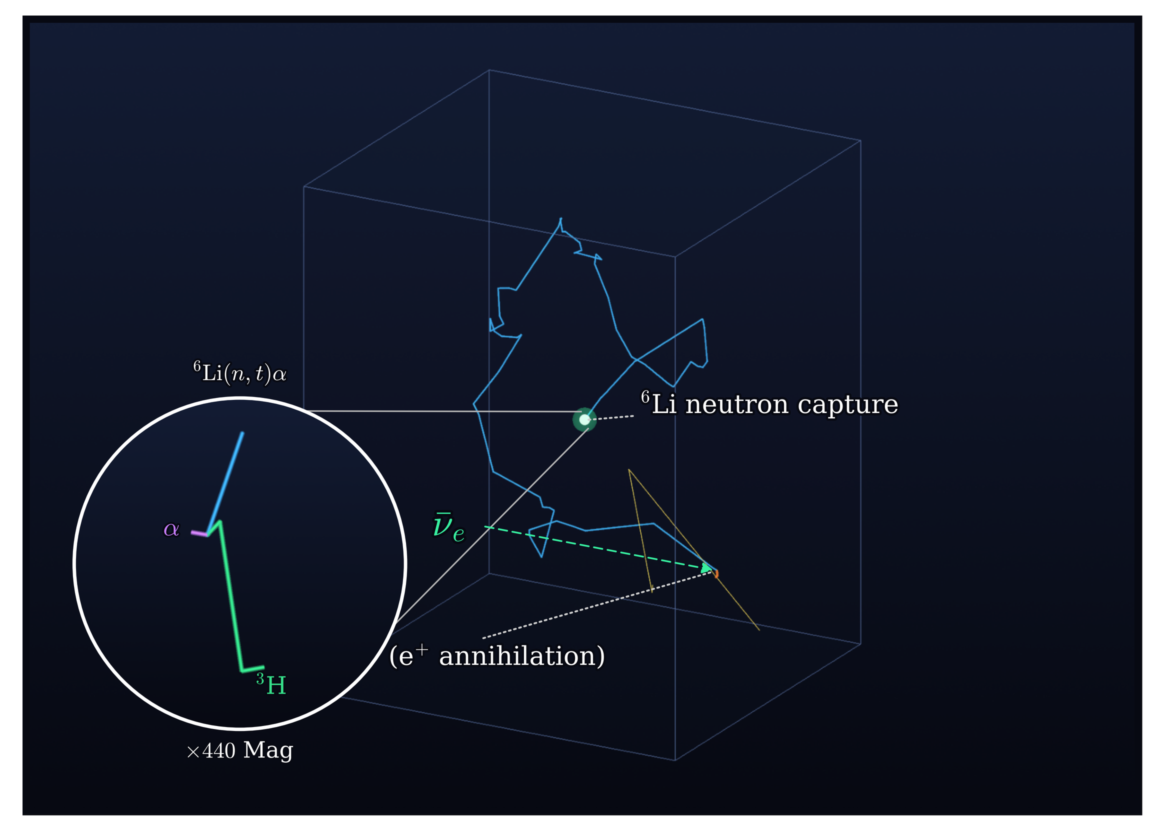


Figure 4: Simulated IBD event (RAT-PAC 2). The dashed $\bar{\nu}_e$ arrow follows the prompt-vertex-to-^{6}Li-capture displacement; the magnifier shows the ^{6}Li$(n,t)\alpha$ capture star.

★ Conclusions, Findings, and Future Work

Key findings:

- Sufficiently many events reconstructs neutrino direction to point source
- Realistic reproduction of achievable uncertainty in low-event regimes
- Suggests that there exists an optimal Geometry for determining directionality

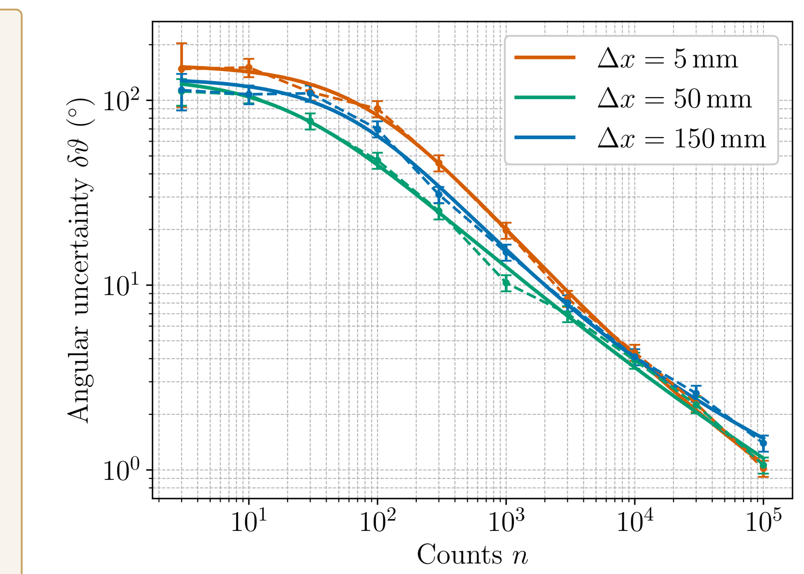
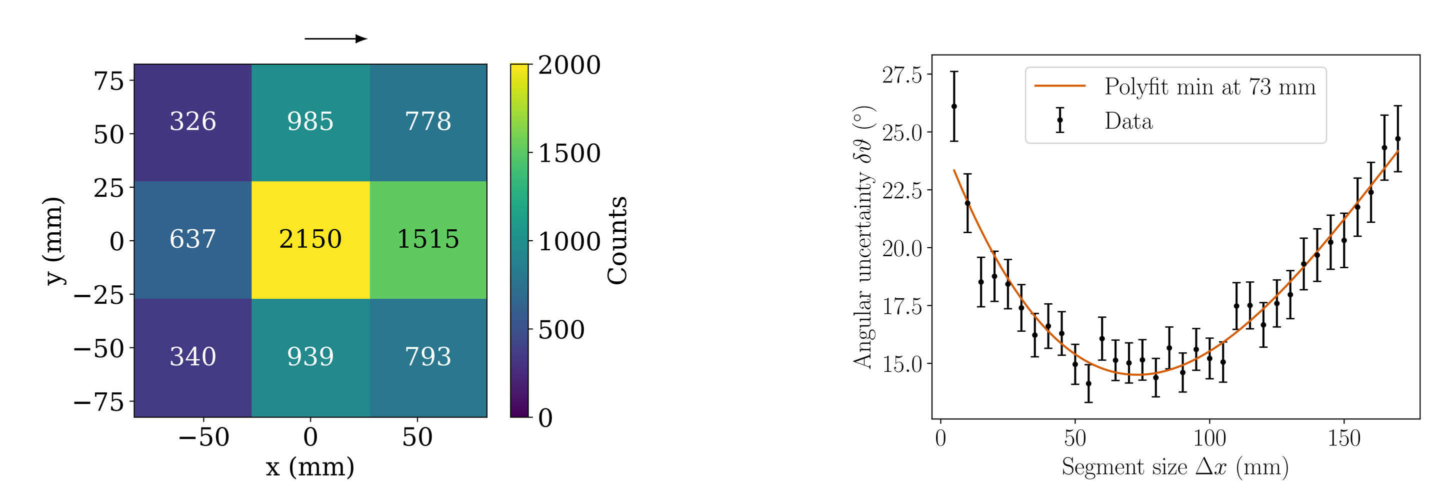


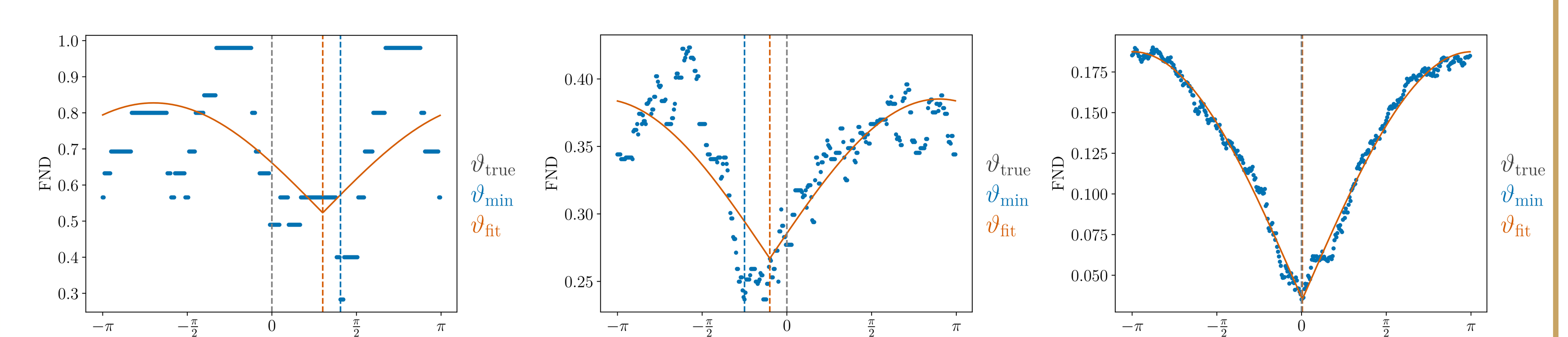
Figure 6: Angular uncertainty $\delta\vartheta$ versus event count n for square segment sizes of 5, 50, and 150 mm.

Optimal segment size: $\Delta x \approx 73$ mm



(a) binning distribution, $\vartheta_\nu = 0°$ (b) angular uncertainty vs. segment size

Figure 7: (a) Binning distribution at $\vartheta_\nu = 0°$ (0.1 wt% ^{6}Li; arrow marks the antineutrino direction); other incoming angles rotate the pattern. (b) Angular uncertainty versus segment size Δx, with a polynomial fit minimizing near $\Delta x \approx 73$ mm.



(a) $n = 10$ (b) $n = 100$ (c) $n = 1000$

Figure 8: FND versus reference angle ϑ at $n = 10, 100, 1000$ (50 mm segments, RAT-PAC 2 capture data). As n grows, the minimum ϑ_{min} and arctan fit ϑ_{fit} approach the true angle ϑ_{true}.

Future work:

- Implementing to mantle geoneutrino searches
- Developing methods to take advantage of machine learning
- Generalizing approach to three dimensionally segmented detectors
- Investigating applications within varying geometries such as monolithic detectors

Traditional Approach

Conventional "Chooz" method:

- Error propagation on prompt–delayed separation, l
- Position resolution, P
- Event count, N

$$\Delta\varphi = \arctan\left(\frac{P/l}{\sqrt{N}}\right) \quad (1)$$

Two shortcomings:

- $P \to 0 \Rightarrow \Delta\varphi \to 0$: unphysical finite capture spread
- Ignores intrinsic neutron spread

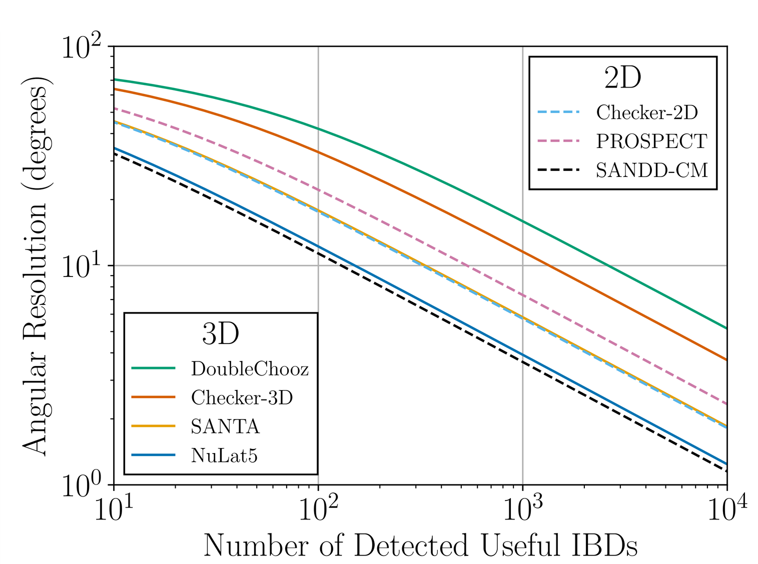


Figure 2: "Chooz" uncertainty vs. useful IBDs .

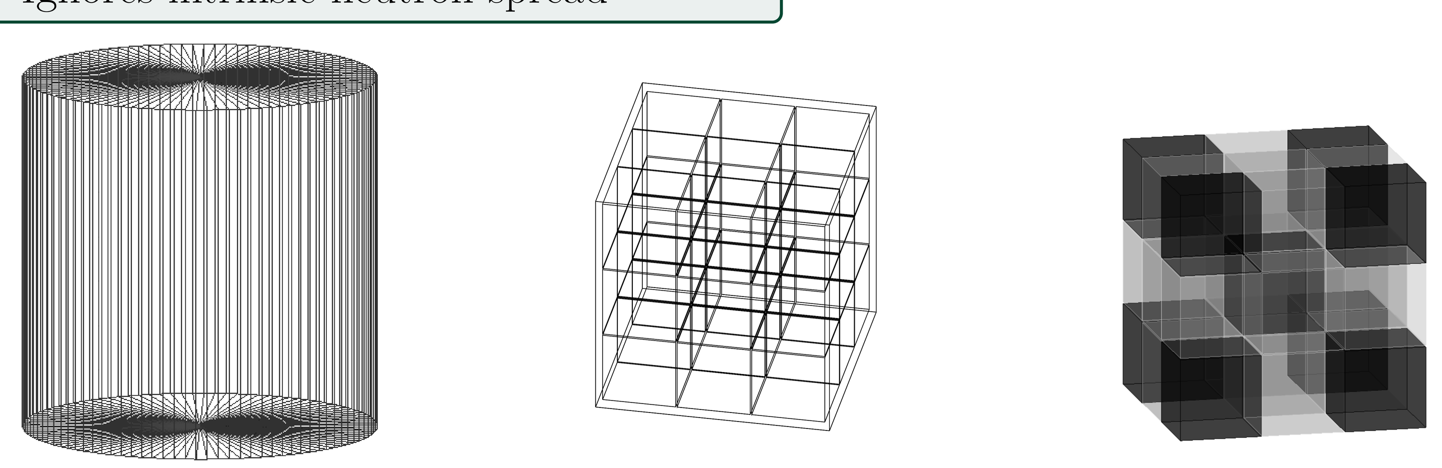
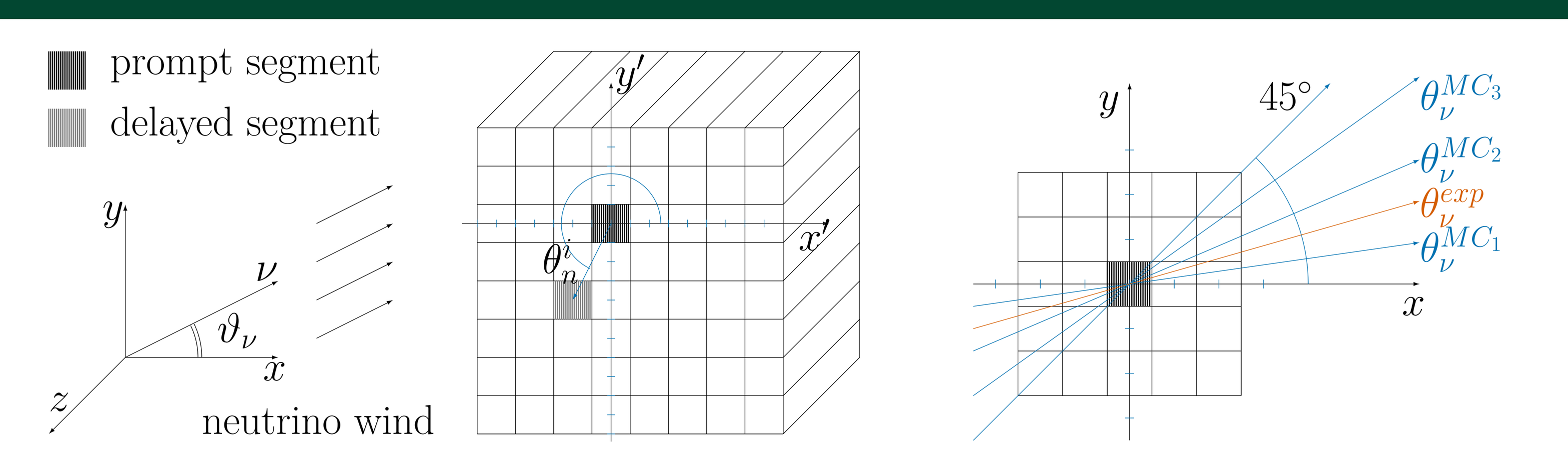


Figure 3: Geometries from Fig. 2: Double Chooz, NuLat, Checker-3D (not to scale).

Novel Algorithm for Segmented Detectors



(a) segment geometry (b) reference-angle comparison

Figure 5: (a) Prompt–delayed segment geometry, with the neutrino "wind" at angle ϑ_ν in the xy plane. (b) Reference sets at known angles $\theta_\nu^{MC_i}$ compared against data at unknown θ_ν^{exp}.

Source Localization Procedure:

1. Generate Monte Carlo reference dataset for every incident angle
2. Bin prompt–delayed displacement vectors into normalized voxels
3. Construct and normalize the truth dataset
4. Compute the L^2 norms of the difference between datasets at each reference angle ϑ:
   $$L_i^2(\vartheta) = \sqrt{\textstyle\sum_{k,j} (x_{kj})_i^2} \qquad (x_{kj})_i \in [\text{DifferenceSet}_i](\vartheta) \quad (2)$$
5. Fit $\alpha \left|\sin\left(\frac{\vartheta-\vartheta_0}{2}\right)\right|$ to the L^2 norms as a function of angle
6. Minimum of fit function reconstructs the source direction ϑ_0

References

[1] Crow *et al.*, in prep. (2026), *arXiv: 2603.03561*

[2] Duvall *et al.*, Phys. Rev. Applied **22**, 054030 (2024), *arXiv: 2402.01636*

[3] Yepez *et al.*, AIP Adv. **16**, 025110, *arXiv: 2506.17360* (2026)

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Ref. [1]: