Low Energy Performance and Physics Reach of Hybrid Neutrino Detectors

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Main Aims

1. Demonstrate position, direction and energy reconstruction performance in hybrid optical neutrino detectors using most complete simulation model to date and full reconstruction, compared with standard optical detectors [1]
2. Assess physics impact for CNO solar neutrino and $0\nu\beta\beta$ searches for proposed next generation hybrid detector experiments such as Theia [1-2]

Hybrid Optical Neutrino Detectors

- Typical optical detectors rely on one of two production processes: Cherenkov radiation and scintillation emission
- Each process has characteristic distributions (angular, timing, wavelength)
- Hybrid detectors aim to fully leverage properties of both to extract as much information as possible about particle interactions
- Potential use of novel scintillating media, fast photosensors, dichroic filters

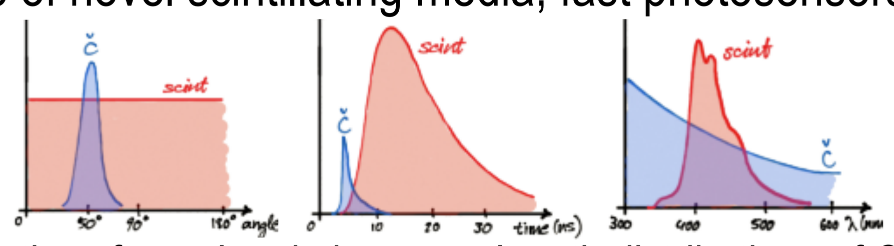

Fig. 1: Schematics of angular, timing, wavelength distributions of Cherenkov (blue), scintillation (red) emission

Theia

- Proposed multi-purpose, multi-kiloton, hybrid optical neutrino detector
- Two proposed scales, 25 kt and 100 kt, at depth of Sanford Underground Research Facility (SURF), 4300 mwe with 90% PMT coverage

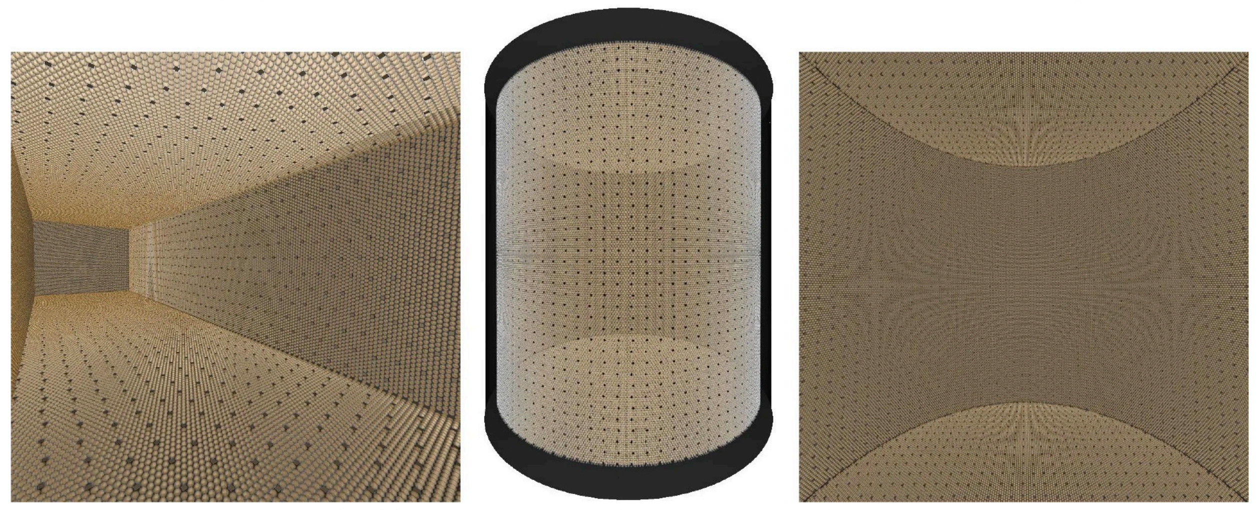

Fig. 2: Potential 25 kt (left) and 100 kt (center, right) detector configurations [2]

Water-based Liquid Scintillator Model

- Class of novel scintillating liquids combining benefits of directional Cherenkov light, exploited in experiments like Super-Kamiokande and SNO, and high yield scintillation light, used in experiments like Borexino [3]
- WbLS in this work: mixtures of water and linear alkyl benzene loaded with 2,5-diphenyloxazole (LAB+PPO)
- Measured simulation inputs: scintillation light yield [4], spectra and timing [5]
- Refractive index, absorption length, reemission probability, scattering length assumed as combinations of water, LAB+PPO

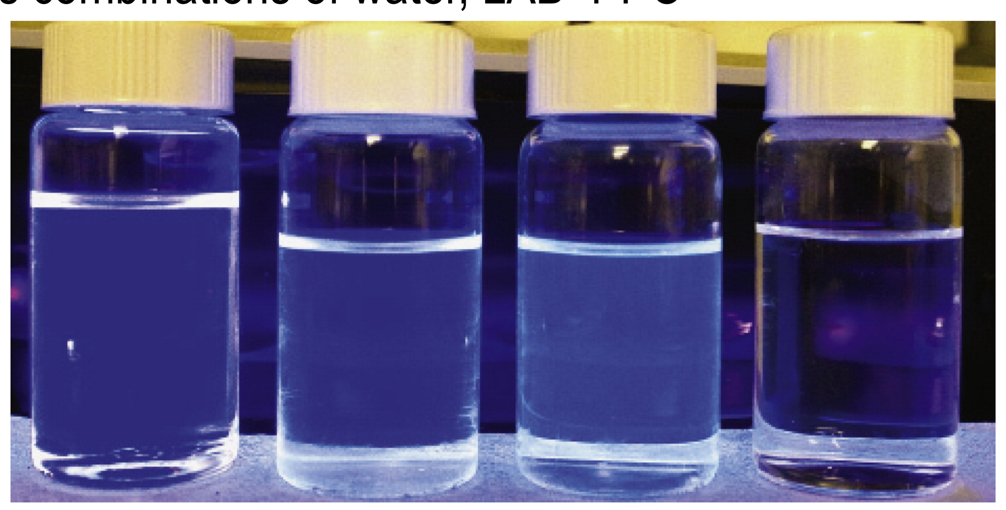

Fig. 3: Water-based liquid scintillator cocktails displaying scintillation [3]

Detector Simulation and Event Reconstruction

- Flexible simulation framework based on Geant4, GLG4 and RAT-PAC designed to efficiently produce results in variety of configurations
- Interactions simulated in large target volume with full photon tracking stored
- Hypothetical photodetector surface applied with specified quantum efficiency (QE), transit time spread (TTS), coverage
- Ignores reflections, physical photodetector size, photodetector noise
- Event vertex reconstruction performed using hit time residuals
- Direction reconstruction performed by using $\cos\theta$ between reconstructed position & hit locations for prompt photons to isolate Cherenkov component
- Energy reconstruction performed using number of detected hits

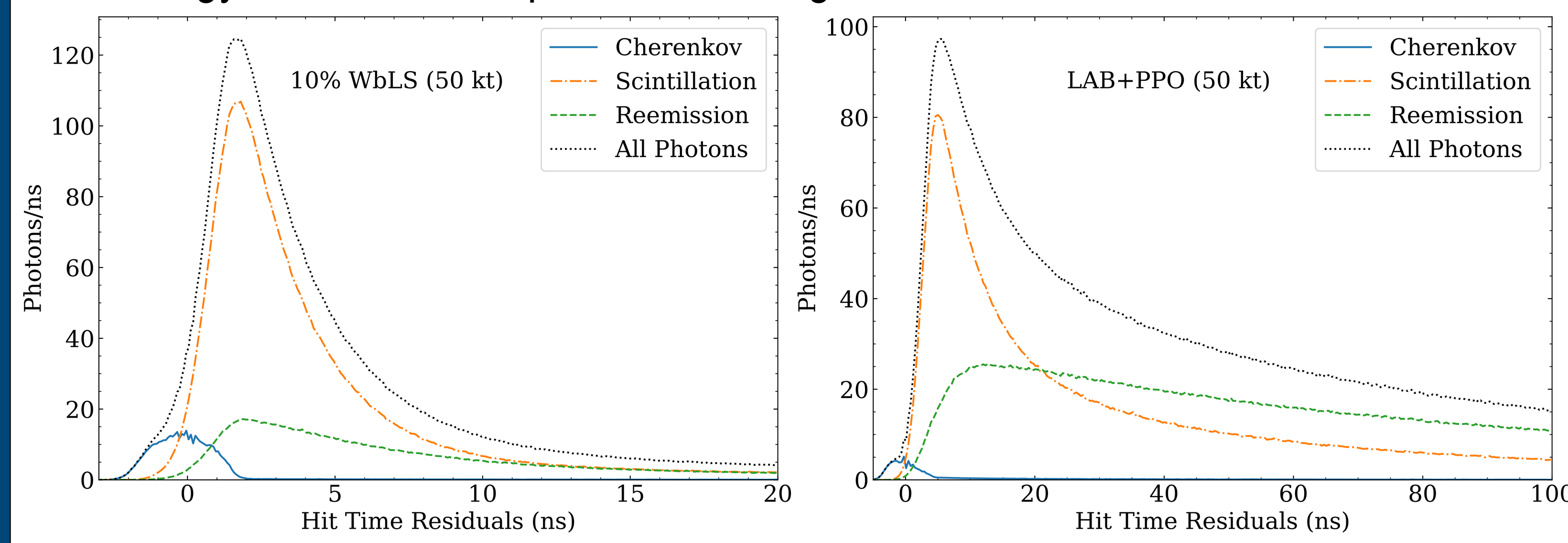

Fig. 3: True time residual distributions of detected hits (QE applied) for 50 kt detectors with 10% WbLS (left), LAB+PPO (right) for different photon production mechanisms

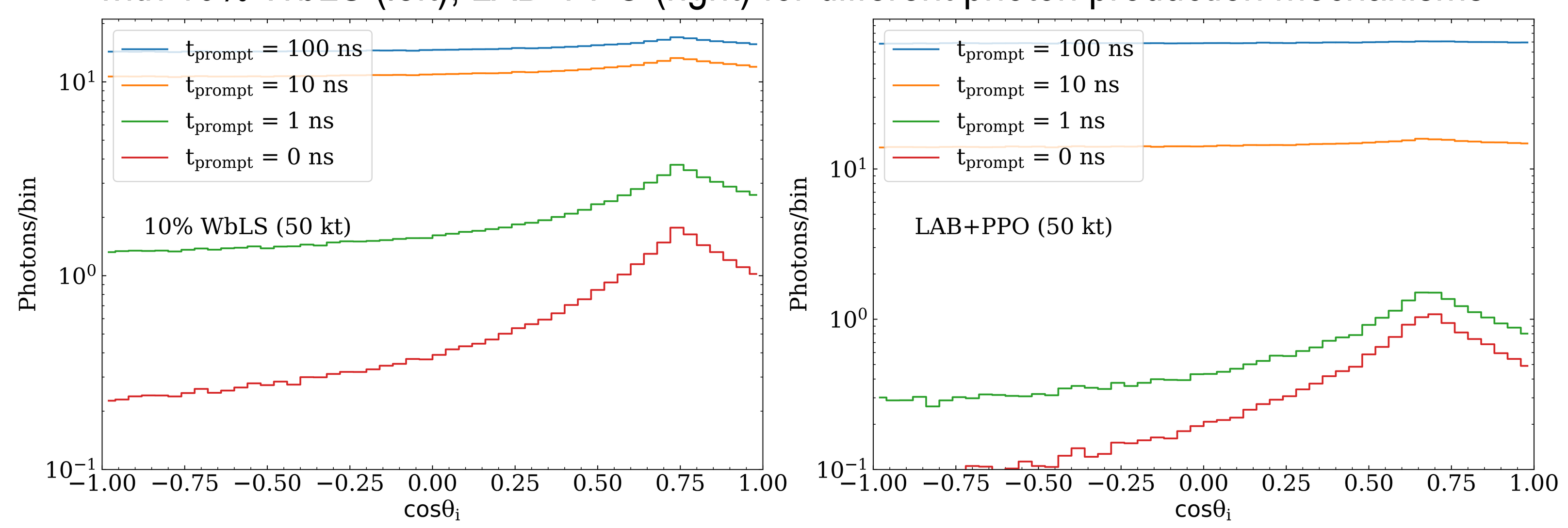

Fig. 4: True photon direction distributions of detected hits (QE applied) for 50 kt detectors with 10% WbLS (left), LAB+PPO (right) with different time cuts

Detector Performance

- Centrally-generated electrons at 2.6 MeV used to assess performance across configurations (target, size, photodetector timing), 90% coverage
- Scans over rise, decay times performed to understand response to emission profile in different materials from those currently measured

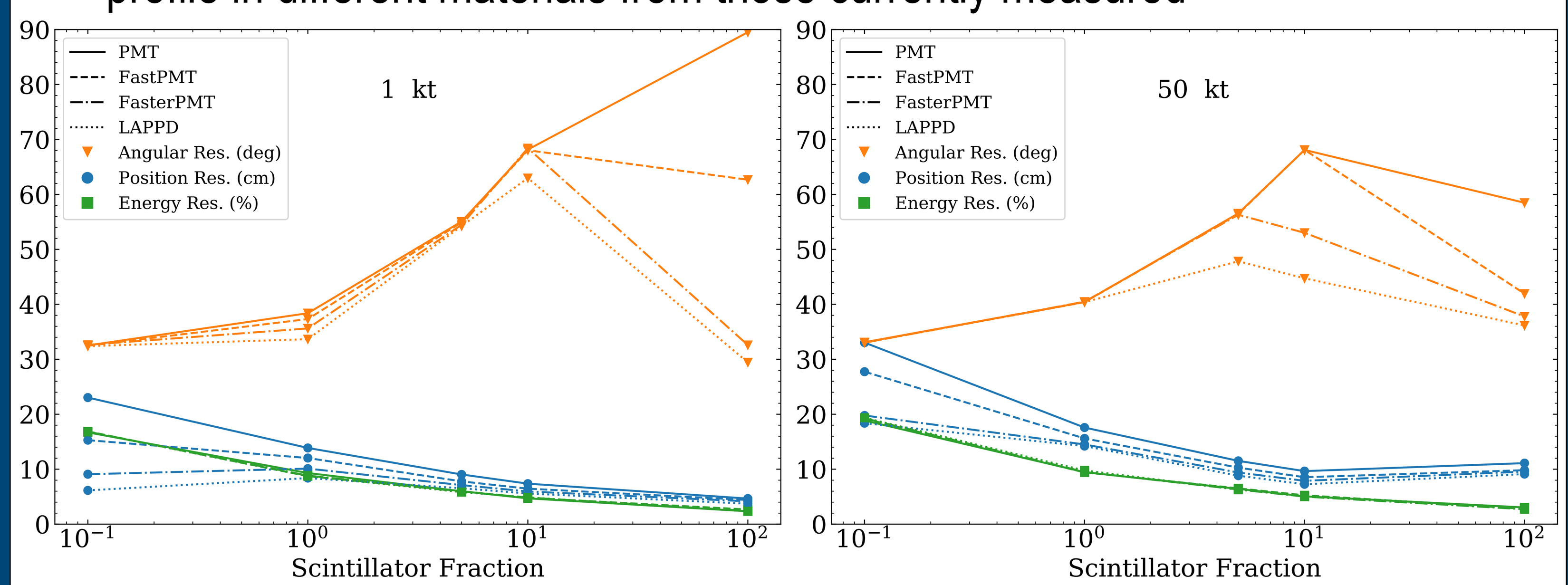

Fig. 5: Directional, position, energy reconstruction performance for 1 kt (left) and 50 kt (right) hybrid detectors with LS fraction (%, entries at 10^{-1} represent performance in water)

Detector Performance (contd.)

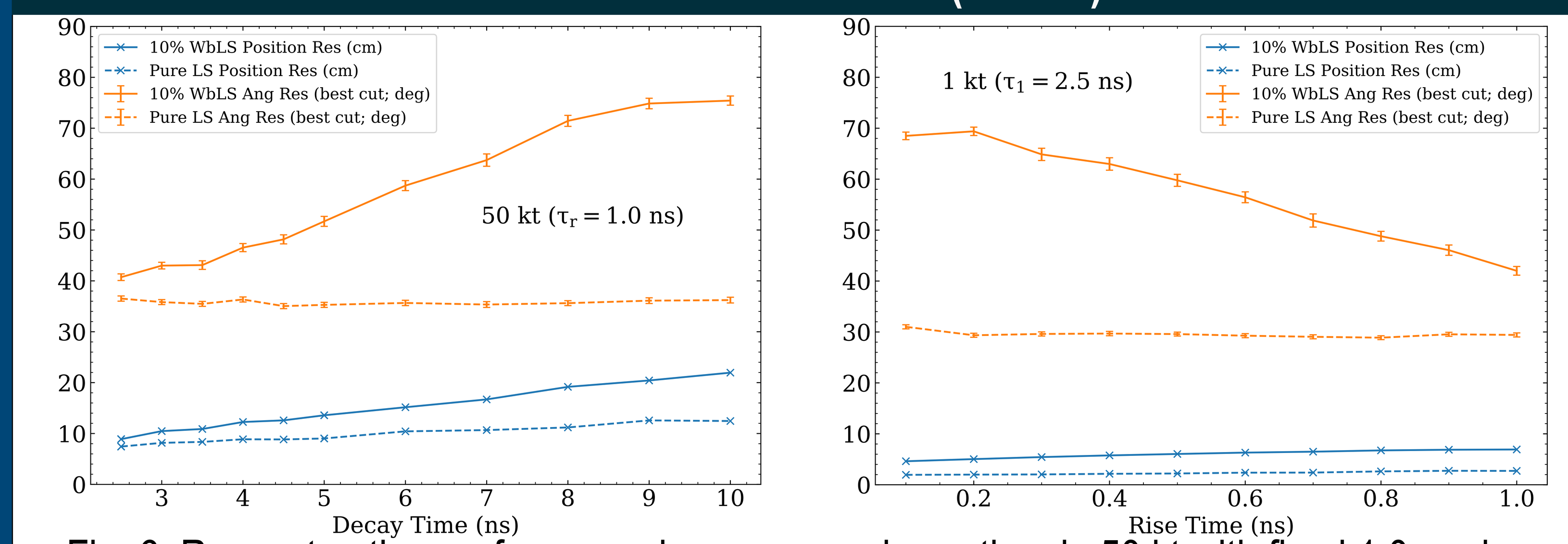

Fig. 6: Reconstruction performance in scan over decay time in 50 kt with fixed 1.0 ns rise time (left) and rise time in 1 kt with fixed 2.5 ns decay time (right) for LS and 10% WbLS

Physics Impacts

- CNO solar neutrino study like [2,6] performed by simulating signals, backgrounds and smearing truth information by energy and direction resolution (from performance for 1 MeV electrons)

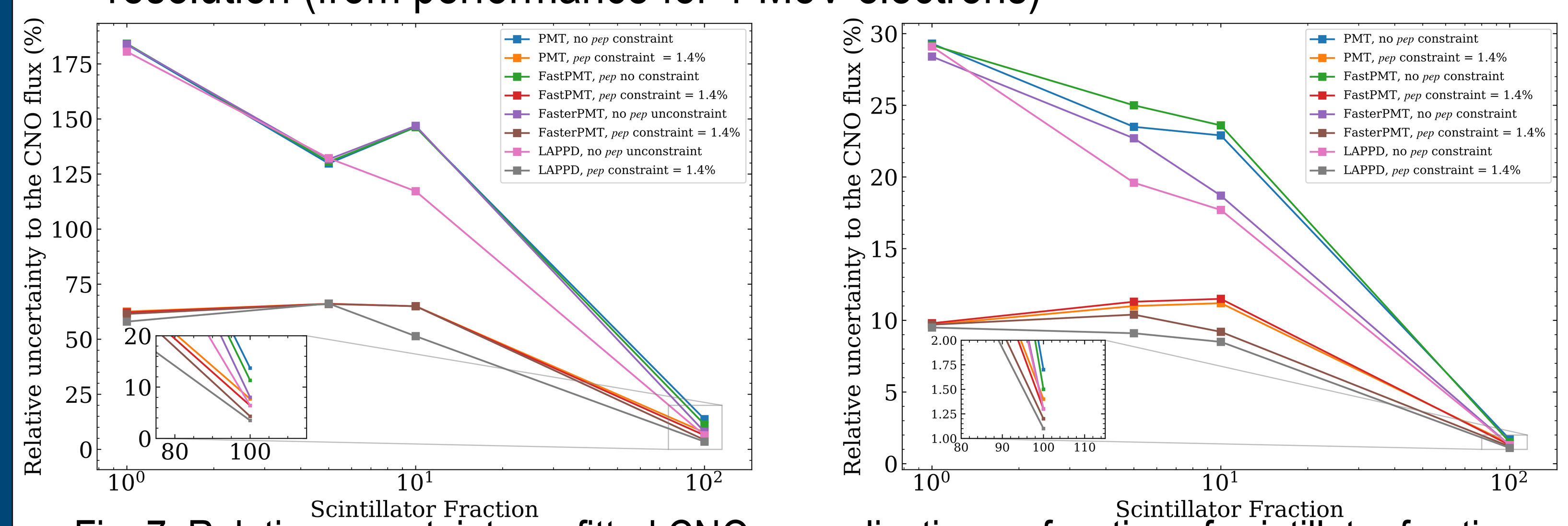

Fig. 7: Relative uncertainty on fitted CNO normalization as function of scintillator fraction (%) and photodetector TTS, w/ and w/o constraint on *pep* flux from theory in 5 yr exposure for 1 kt (left) and 50 kt (right)

- Assessed impact of simple ^{8}B solar neutrino rejection via direction reconstruction in LS on $0\nu\beta\beta$ study as in [2] (10 years exposure)

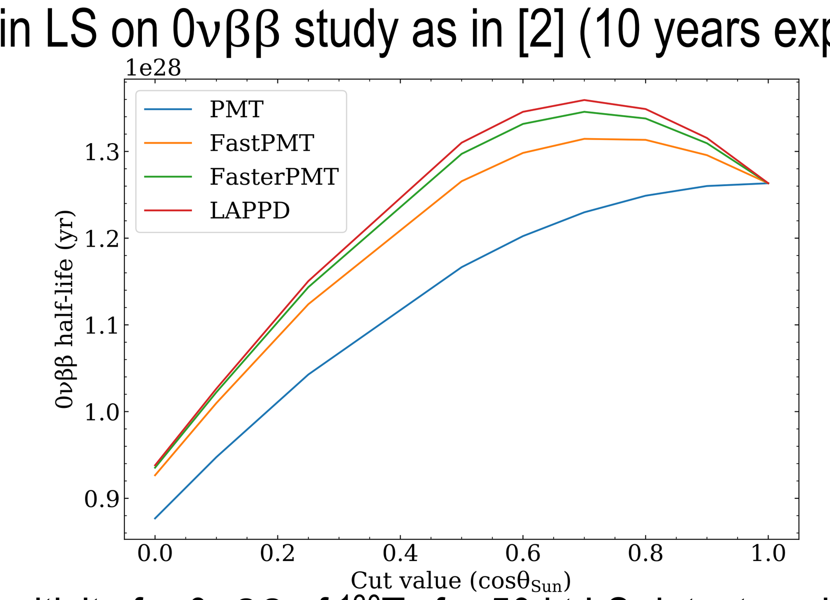

Fig. 8: Half-life sensitivity for $0\nu\beta\beta$ of ^{130}Te for 50 kt LS detector with 8m Te-loaded LS balloon deployment as function of cut on solar angle for various photodetector timings

Conclusions

- Hybrid detectors at kt, multi-kt scale allow for robust reconstruction at low energies relevant for many neutrino physics applications
- Potential for competitive CNO solar neutrino measurement, enhanced $0\nu\beta\beta$ measurement via hybrid technology

References and Acknowledgements

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