# Hybrid Optical Neutrino Detectors: R&D toward EOS and THEIA

## 2023 MTV Workshop

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# Hybrid optical neutrino detection

Large-volume optical neutrino detectors have a long history
Traditionally,

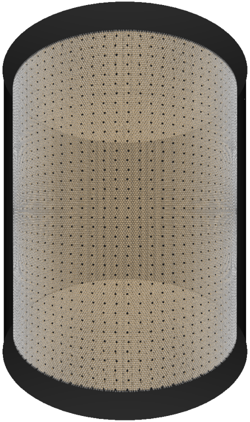
- Cherenkov detectors have directional reconstruction
- Scintillator detectors have precision energy reconstruction

Decades of work leading to *hybrid* technology:

- Low energy threshold
- Balance between directionality and calorimetry

Our design: THEIA at 10-100 kt scale

- Solar neutrinos and DSNB
- Fundamental physics topics
- Geo- and reactor antineutrinos



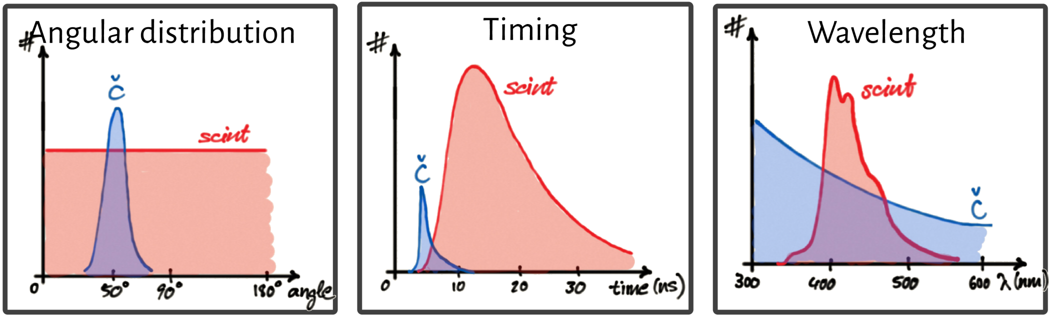
EPJC **80** 416 (2020) arXiv:1911.03501

# R&D for hybrid optical detectors

Need to reconstruct the neutrino interaction from "hits"

- Energy resolution improves with # of hits
- Position resolution improves with # of hits
- Direction resolution improves with *purity of Cherenkov hits*

Cartoons from Michi Wurm



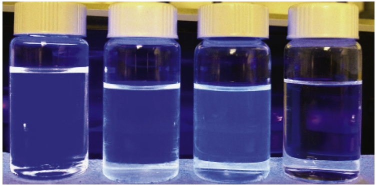
# R&D for hybrid optical detectors at Berkeley

Expansive campaign to make use of:

- Modern chemical synthesis techniques
- State-of-the-art photodetectors
- Novel spectral sorting technology

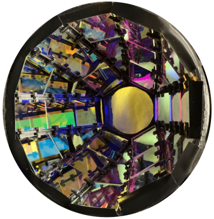
...to achieve high-purity Cherenkov selection

WbLS



LAPPDs


Dichroicons



# Mission relevance

Facilitates new capabilities for nuclear reactor discovery and exclusion
Development of new technologies for monitoring and verification of reactor operations for proliferation detection

Preventing nuclear weapons **proliferation** and reducing the threat of nuclear and radiological terrorism around the world are key U.S. national security strategic objectives that require constant vigilance.
NNSA's Office of Defense Nuclear Nonproliferation works globally to prevent state and non-state actors from **developing nuclear weapons** or acquiring weapons-usable nuclear or radiological materials, equipment, technology, and expertise.

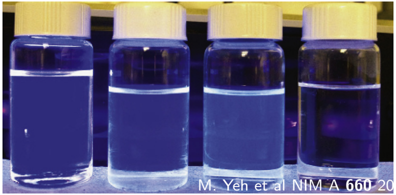
# Water-based liquid scintillator

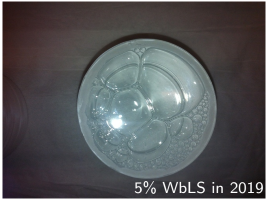
Hybrid reconstruction has been utilized by e.g. LSND and MiniBooNE
But energy range was much higher (more favorable C/S ratio), and there are hurdles to scalability:

- Scintillator is relatively costly
- Optical effects play a larger role

To go larger, go WbLS: start with water, mix in scintillator as needed

- But need to know optical properties, timing, light yield...



# Proton light yield measurement

Fast neutrons constitute inverse $\beta$-decay background via elastic *np* scattering

"Double time-of-flight" method: Pulsed deuteron beam on Be target + PID-capable secondary detectors

Collaboration with Bay Area Neutron Group (BANG — UCB/LBNL)

- Brown et al, Jour. Appl. Phys. 124, 045101 (2018)

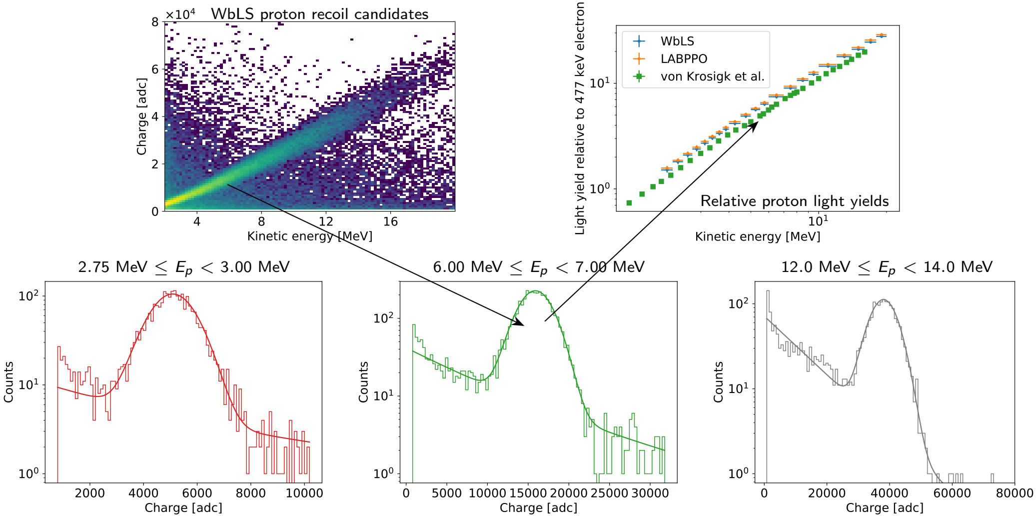
Protons excited via n-p elastic scattering internal to measurement sample

Two kinematic measures of neutron energy (before/after scattering)

- Three measures of proton energy (under single-scatter hypothesis)
- Enforce consistency with beam-neutron hypothesis

# Proton light yield measurements - Results

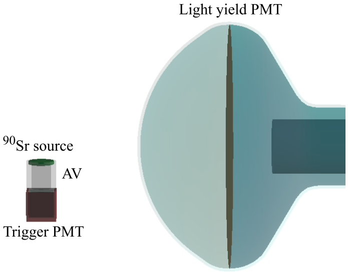
EPJC **83** 134 (2023) `arXiv:2210.03876`

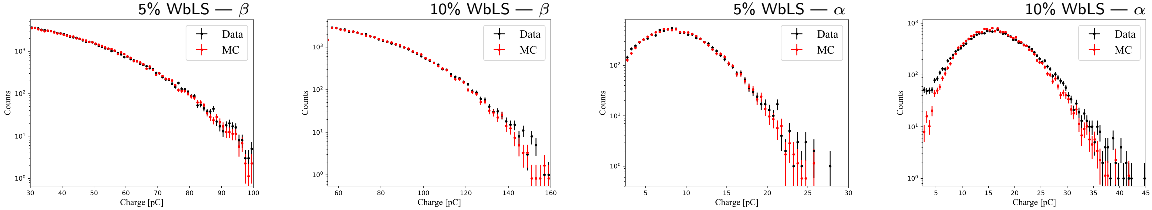


# Electron / $\alpha$ light yields

Benchtop light-yield setup

- GEANT4-based Monte Carlo assuming Birks' law
- Global detection efficiency calibrated used Cherenkov light
- Model parameters found via MC-data matching



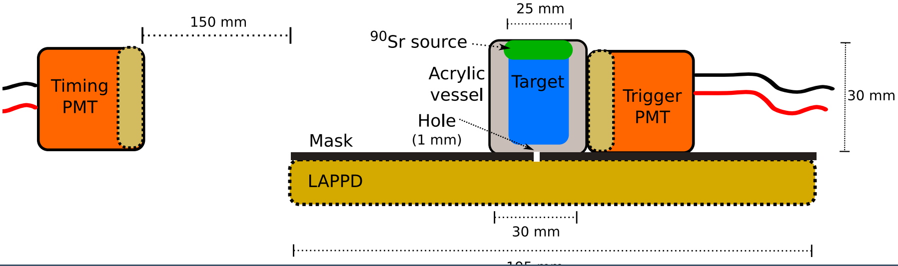

Paper in preparation

# Time profile measurements

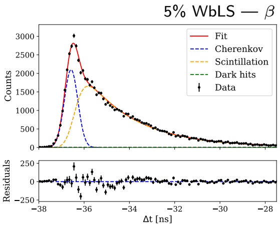
Radioactive source deployed above sample, contained in acrylic vessel
Vessel is coupled to LAPPD, forced-operating in single-photon regime

Joint measurement with conventional PMT

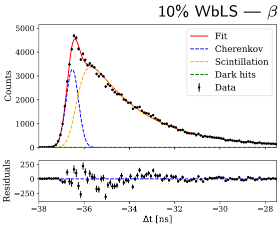
Signals digitized via CAEN V1742 @ 5 GHz and processed offline



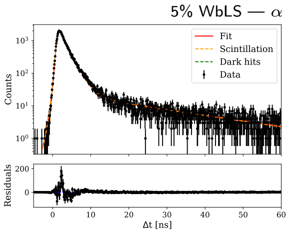
# Time profile measurements - Results

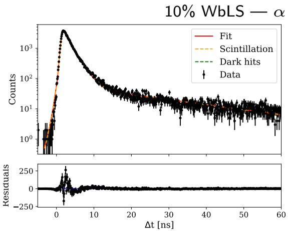



EPJC **82** 169 (2022)




`arXiv:2110.13222`




Paper in preparation

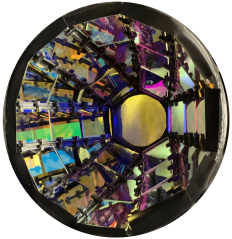
| | $\beta$s | | $\alpha$s | |
|---|---|---|---|---|
| | 5% WbLS | 10% WbLS | 5% WbLS | 10% WbLS |
| $\tau_1$ [ns] | $2.25^{+0.01}_{-0.01}$ | $2.36^{+0.01}_{-0.01}$ | $1.82^{+0.01}_{-0.01}$ | $1.92^{+0.01}_{-0.01}$ |
| $\tau_2$ [ns] | $23.5^{+1.0}_{-0.9}$ | $22.8^{+0.7}_{-0.7}$ | $24.7^{+0.8}_{-0.8}$ | $26.1^{+0.5}_{-0.5}$ |
| $A_1$ [%] | $94.8^{+0.1}_{-0.1}$ | $94.9^{+0.1}_{-0.1}$ | $89.7^{+0.2}_{-0.2}$ | $86.6^{+0.1}_{-0.1}$ |

*These numbers feed directly into particle-ID studies — paper in preparation!*

# Dichroicon deployment

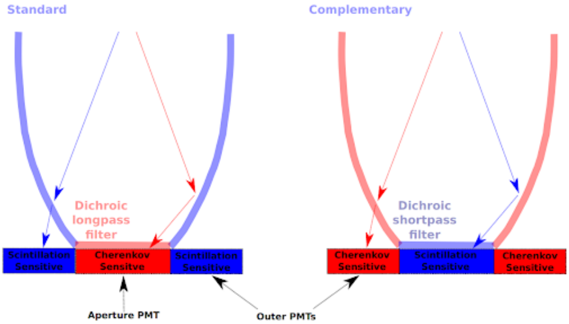
A different approach: use dichroic filters to manually affect cuts on wavelength

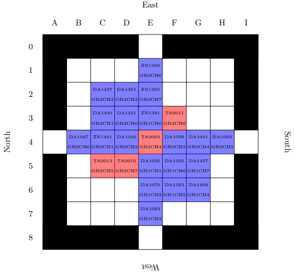
In CHESS, demonstrate different C/S proportions for different radiation sources

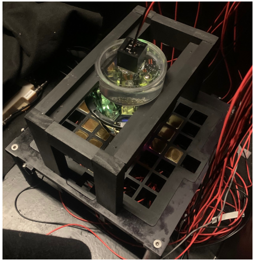


Kaptanoglu et al. Phys. Rev. D **101** 072002 (2020)

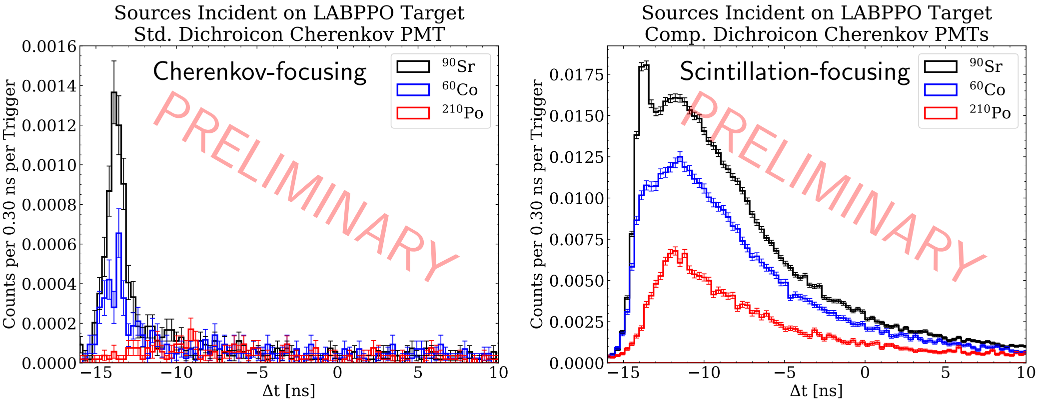
`arXiv:1912.10333`



# Dichroicon deployment



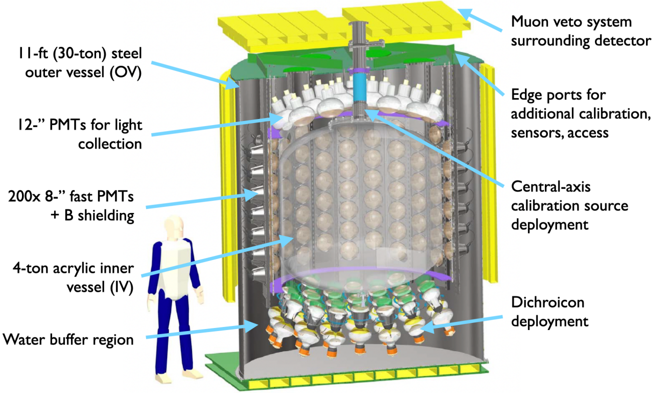

*Paper in preparation. Figures courtesy of S. Naugle.*

# The Eos Project

Solid R&D foundation, but need demonstration in a real detector

Eos: `https://nino.lbl.gov/eos/`, JINST **18** P02009 (2023). `arXiv:2211.11969`

- Explicit demonstration of reconstruction in a hybrid detector
- Validate Monte Carlo model to support simulations at larger scales
- Act as testbed for new and novel technologies




- Multi-ton targets
- Water, WbLS, pure LS
- Fast PMTs + dichroicons
- Full waveform digitization ← *Extension of CHESS DAQ*

# MTV impact and Conclusion

Professional advancements:

- Exposure to electronic, chemical, software technologies
- Regular collaboration with LBNL, BNL scientists
- Development of technical skills necessary within NNSA enterprise

Technical advancements:

- WbLS emission time profile
- WbLS light yield, and $\alpha$,*p* quenching
- LAPPD characterization
- EOS demonstrator funded and under construction

National Nuclear Security Administration

# Acknowledgements

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