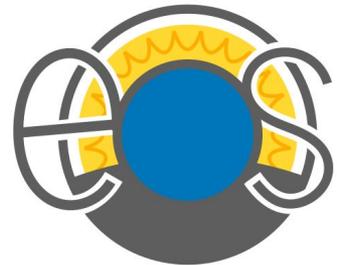


Spectral Photon Sorting Using Dichroicons in Large Optical Neutrino Detectors

James Shen
Department of Physics and Astronomy
University of Pennsylvania

CPAD 2025 (UPenn)



Outline

- Motivations for a hybrid optical detector
- Dichroicon and enabling technologies
- Benchtop measurements
- Dichroicons at EOS
- Future applications in kton-scale detectors (THEIA)



Particle Detectors using Light

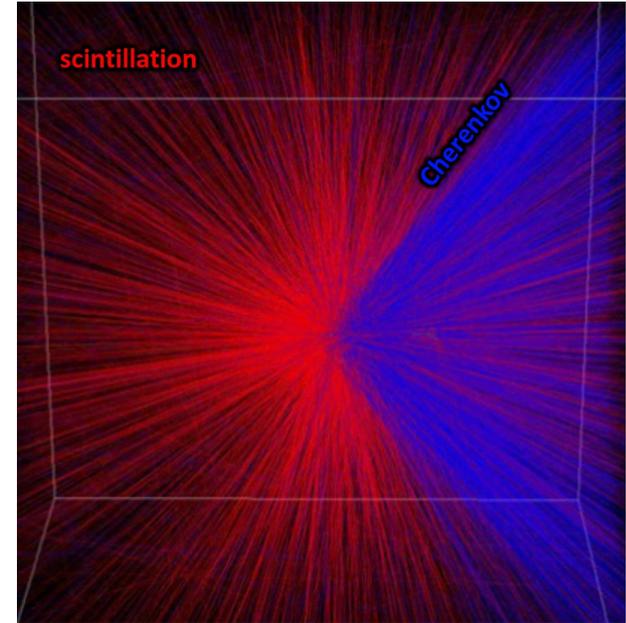
Optical Detectors have a long history of important discoveries

- SNO, Super-K, etc..

Generally utilize one type of light:

- Water Cherenkov Detectors:
 - Good direction resolution
 - Poor position and energy resolution due to low light yield ($\sim O(10)/\text{MeV}$)
- Liquid Scintillator Detectors:
 - Isotropic emission, but much higher light yield ($\sim 12\text{k photons/MeV}$ for 2g/L LAB+PPO)
 - Good resolution in energy, position
 - Lower energy threshold
 - No directional information

The ideal particle detector combines both types of light...

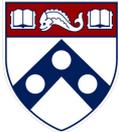
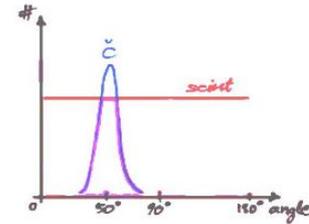
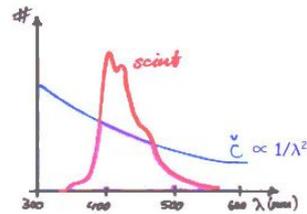
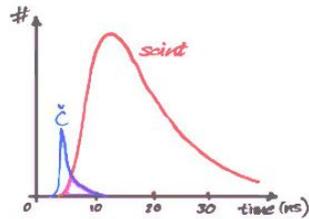


B. Land



Separate Cherenkov and Scintillation Light

Goal: Maintain high cherenkov purity while losing as few photons as possible

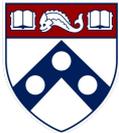
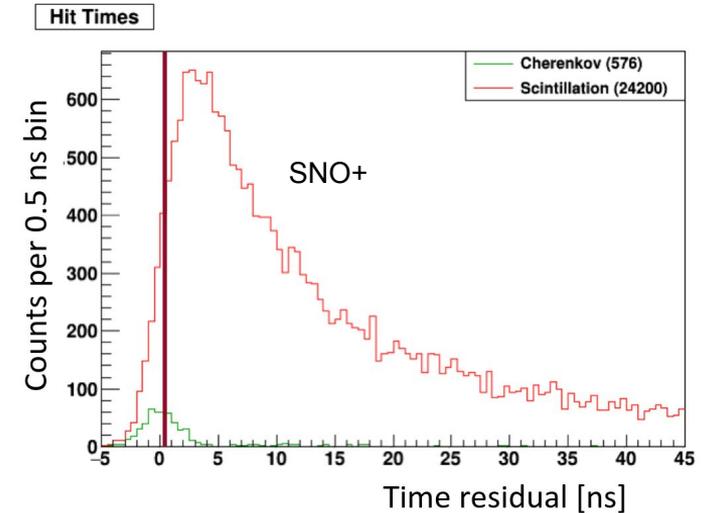
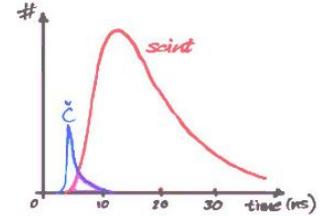


Separate Cherenkov and Scintillation Light

Goal: Maintain high cherenkov purity while losing as few photons as possible

Using Timing:

- Hard in large optical detectors
- Scintillation light is orders of magnitude more intense
- Fast photodetectors are expensive!



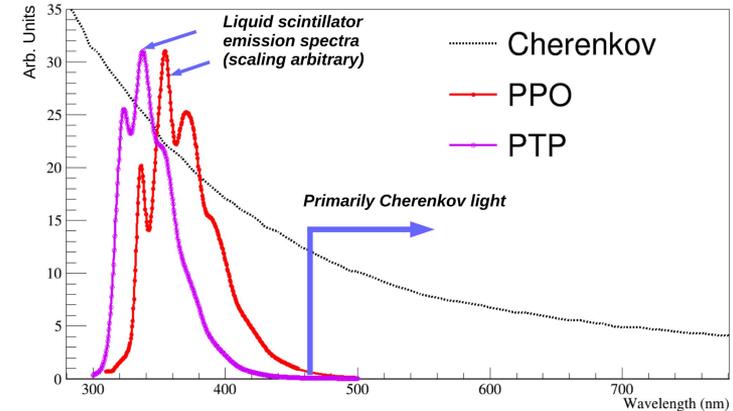
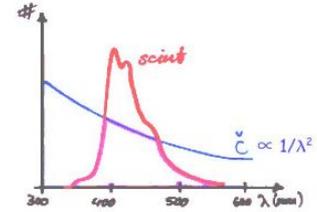
Separate Cherenkov and Scintillation Light

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Spectral Sorting: Using photon difference in wavelength

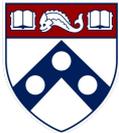
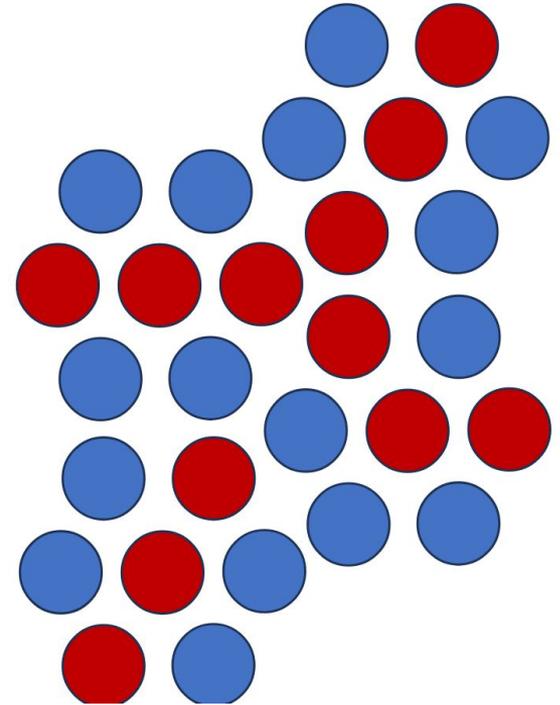


T. Kaptanoglu et al 2019 *JINST* 14 T05001



Spectral Sorting – The Naive Approach

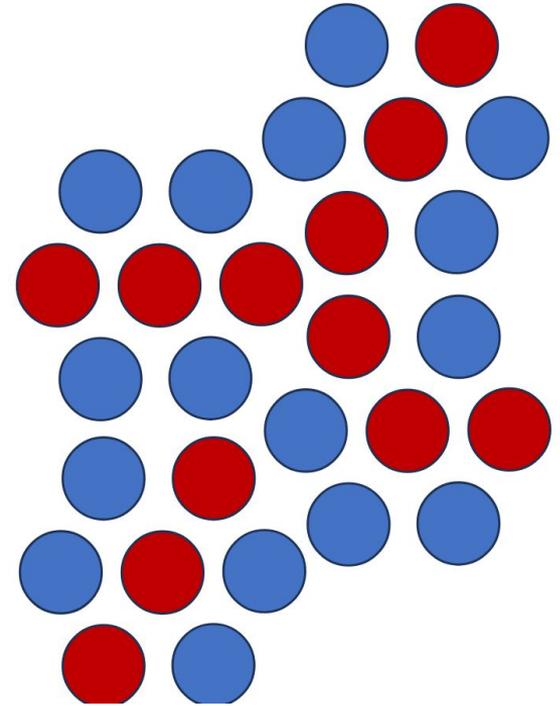
Cover half of the PMTs using red filters,
or with red-sensitive PMTs



Spectral Sorting – The Naive Approach

Cover half of the PMTs using red filters,
or with red-sensitive PMTs

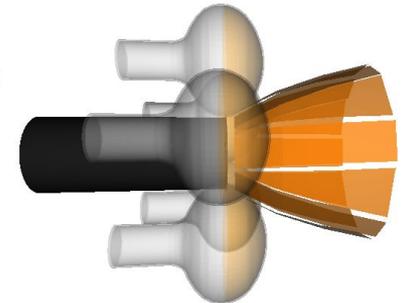
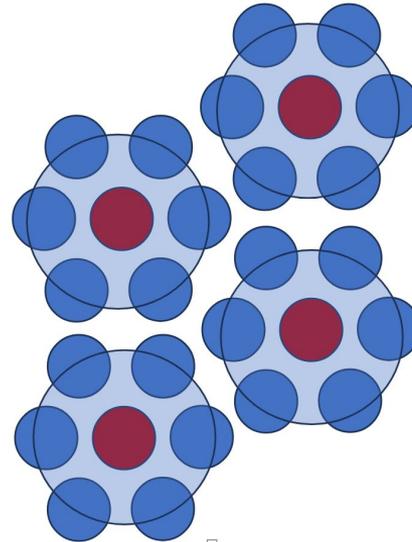
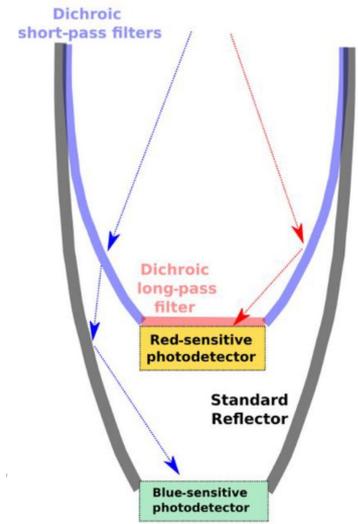
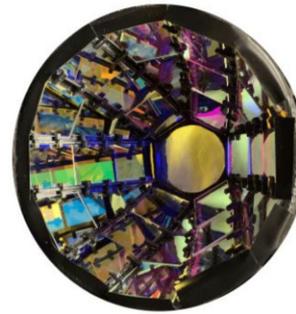
- Effective coverage $\times \frac{1}{2}$
- Dollar per coverage $\times 2$



The Dichroicon

Combines Dichroic filters and Winston cone concentrators

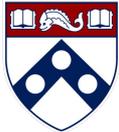
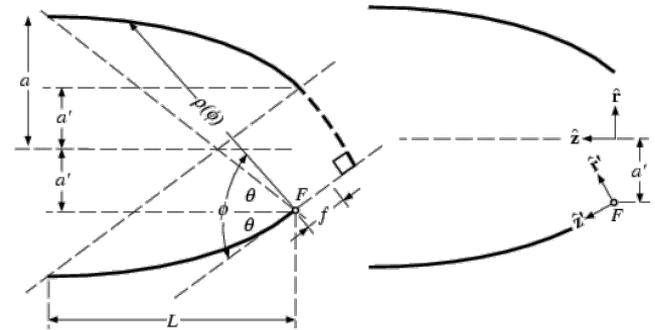
- One detector sits at the barrel of the dichroic concentrator – detects long-wavelength Cherenkov light
- Other detectors behind the barrel, collecting scintillation light
- Concentrator remains “transparent” to Scintillation light



Dichroicon Design Concerns

Concentrator Shape:

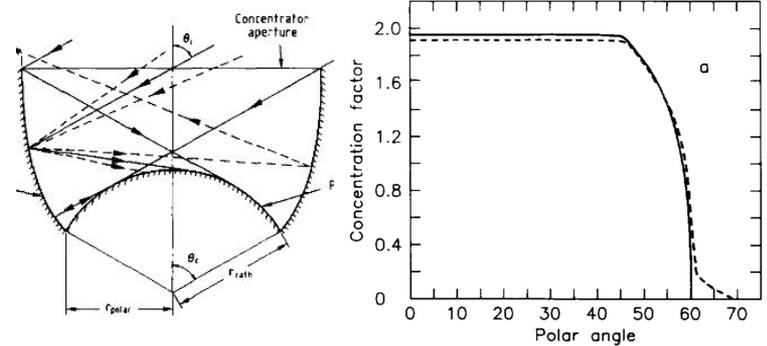
- “Winston Cone” – optimal non-imaging light collector developed by R. Winston in the 70s



Dichroicon Design Concerns

Concentrator Shape:

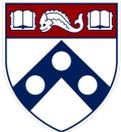
- “Winston Cone” – optimal non-imaging light collector developed by R. Winston in the 70s
- Further optimization in large detectors for SNO
 - Optimize for spherical collector surface (PMTs)
 - Truncated cone for wider angle
 - “Pixelate” to use flat panels for ease of construction



G. Doucas et al., 10.1016/0168-9002(95)00840-3



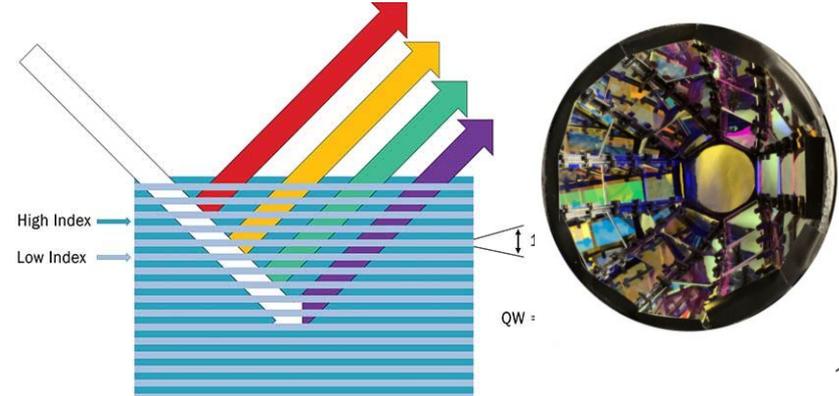
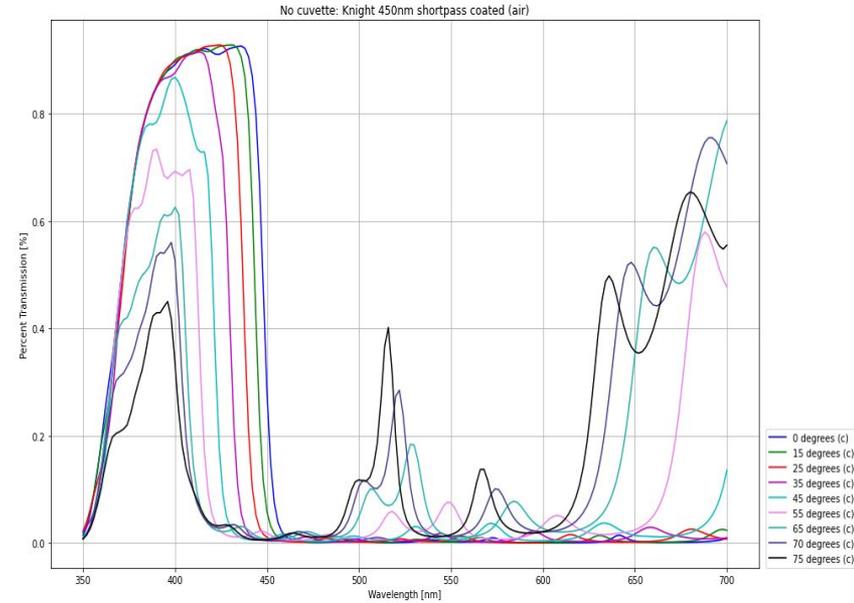
SNO+, <https://doi.org/10.1016/j.phpro.2014.12.087>



Dichroicon Design Concerns

Dichroic filters

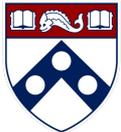
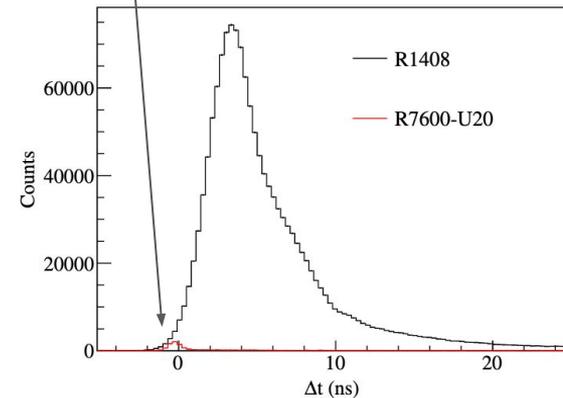
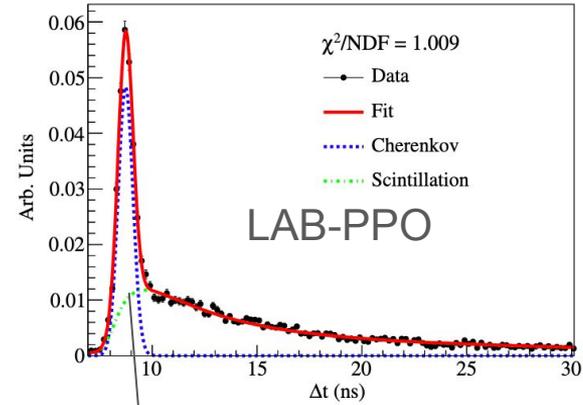
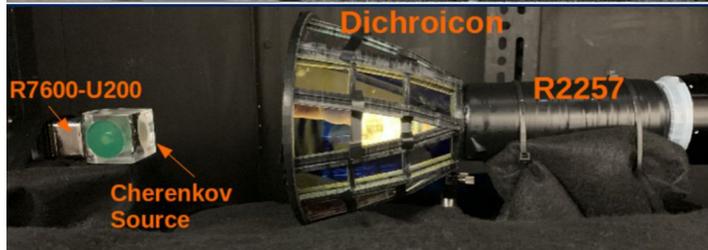
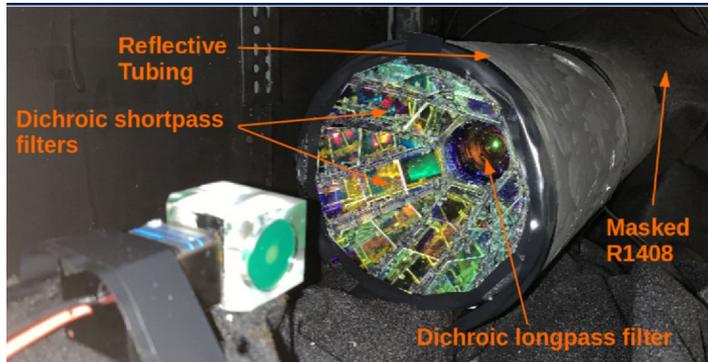
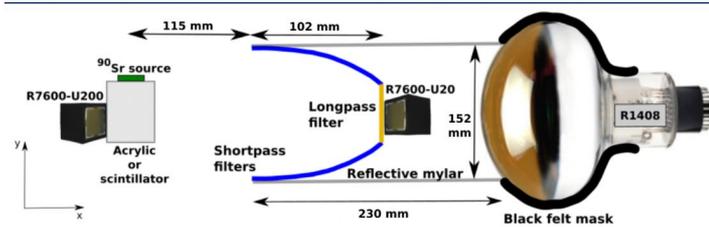
- Combination of many thin-film interference layers
- Wavelength response depends strongly on angle of incidence
 - complex to model in simulation and design
- Continuous efforts to fully characterize and optimize the angular response
 - See [A. Bacon's Talk](#)



Benchttop measurements

T. Kaptanoglu (2020)

Phys. Rev. D 101, 072002



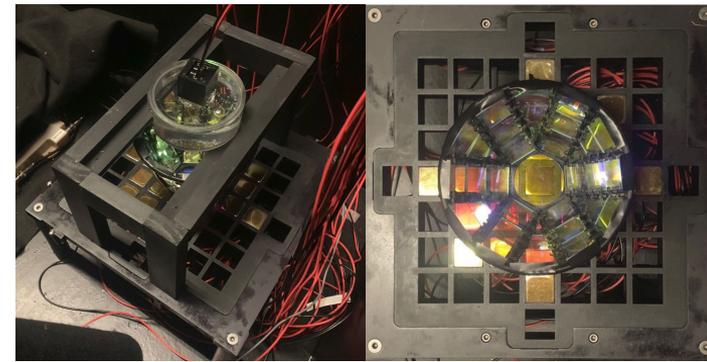
Benchtop Measurements (CHESS)

Target: Water-based liquid scintillator (WbLS), LAB+PPO, Water

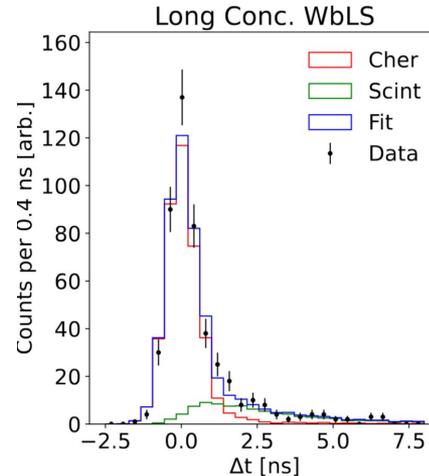
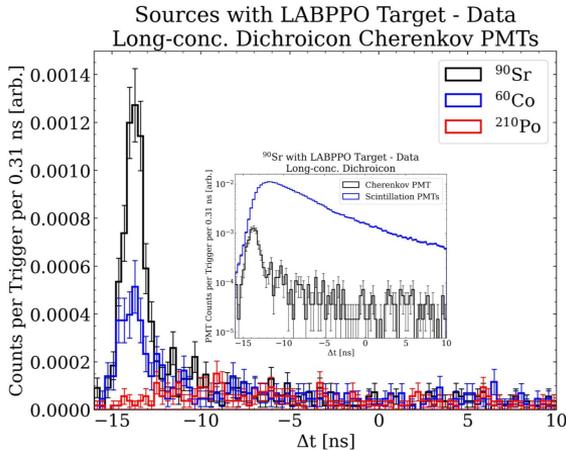
Taken data for:

- Cosmic Muons: Measured a purity of 95+% for Cherenkov photons.
- Deployed Sources: Demonstrated PID capabilities.

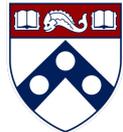
Ongoing measurements with fast photosensors (LAPPDs)



S. Naugle

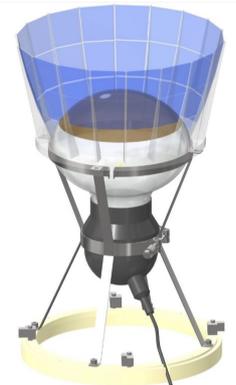
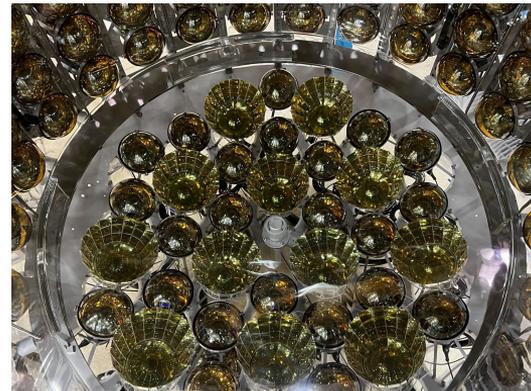
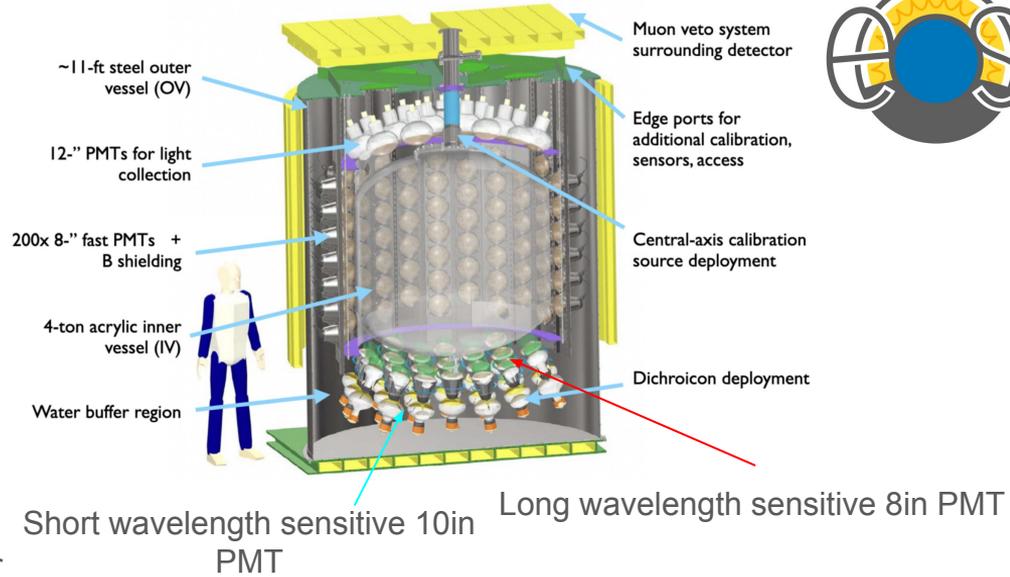


Cherenkov Purities	
10% WbLS	0.978 ± 0.004
LAB+PPO (2g/L)	0.990 ± 0.001



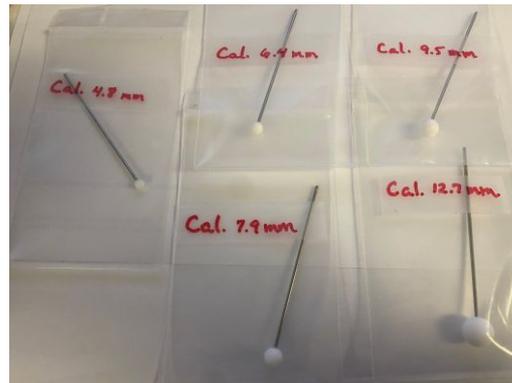
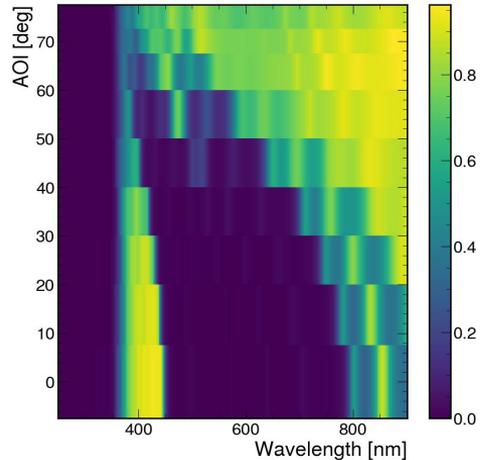
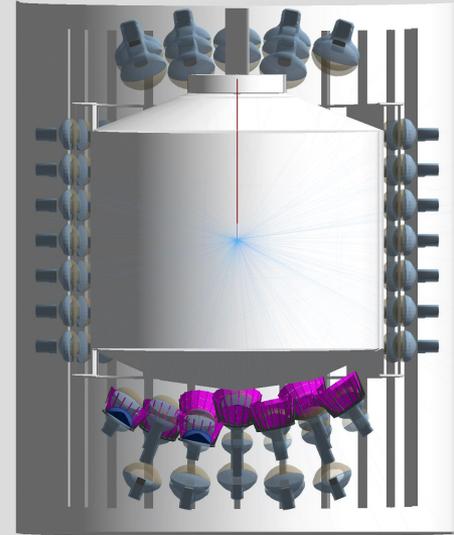
Eos @ LBNL

- 20-ton testbed for hybrid Cherenkov & Scintillation technologies
- 12 Dichroicons installed at the space-constrained bottom
 - Equipped with curved, acrylic, longpass absorbing filters.
 - Shortpass dichroic filters as concentrator
 - Cut-on frequency of 450nm.
- Commissioned and installed early 2024
- Started taking water data May 2024.
 - See [T. Kaptanoglu](#)
- WbLS data-taking ongoing
 - See [L. Pickard](#)



Dichroicon Efficiency Characterization

- Laser is injected down the center of the detector at various heights, diffused by a PTFE sphere.
- Full detector simulation performed using [RAT-PAC2](#)
- Data / MC Comparison:
 - Both longpass/shortpass filters modeled based on [spectrophotometer measurements done at Penn.](#)

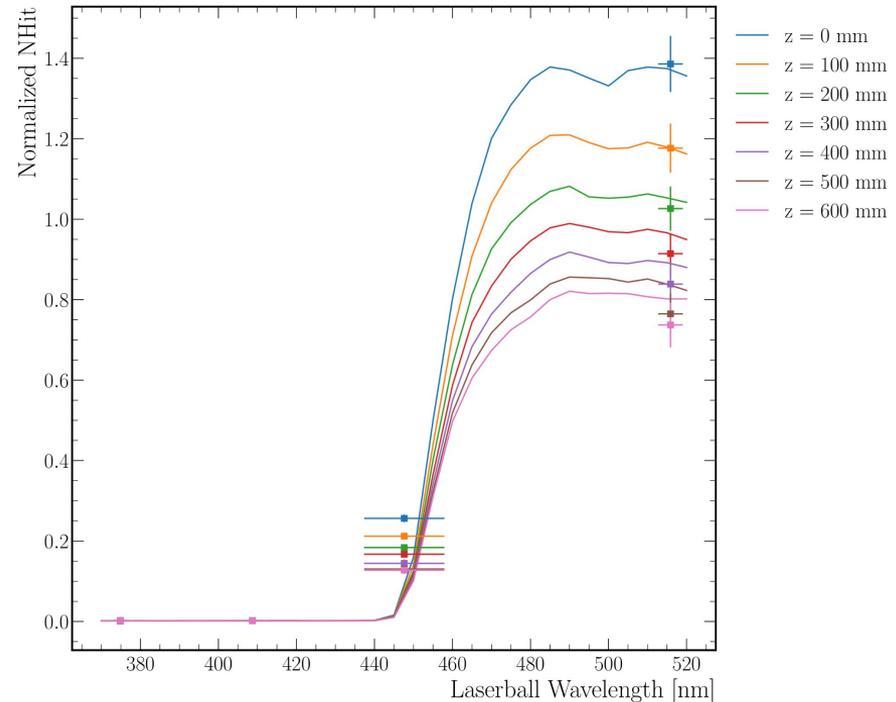


Dichroicon Laserball Calibration

Comparison between data (points) and MC wavelength scan (lines).

Comparing average light yield of dichroicon PMTs vs. other PMTs in the detector

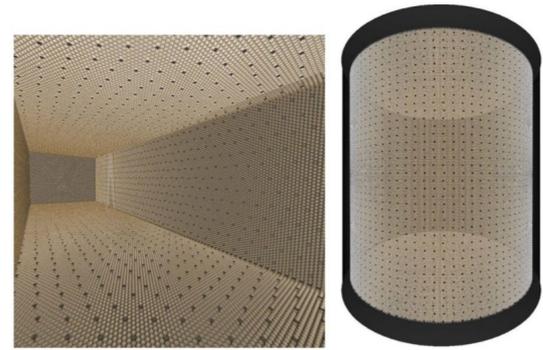
- Light yield below 450 nm is heavily suppressed
- light yield above 450 nm is higher than other adjacent PMTs
 - *Improved effective coverage due to Concentrators.*
- Ongoing MC Calibration on angle of incidence



Looking ahead – THEIA

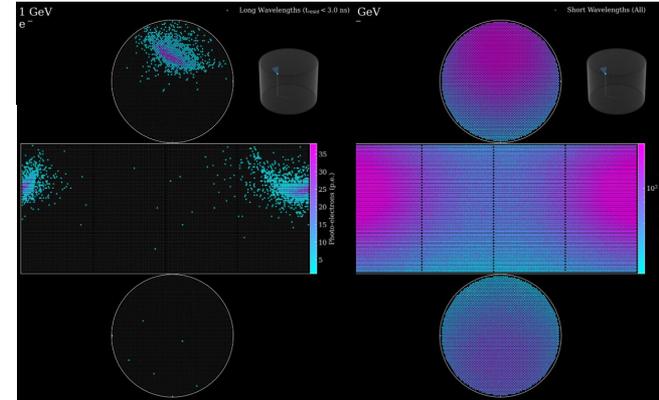
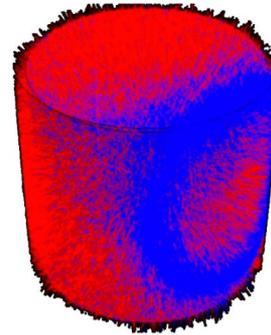
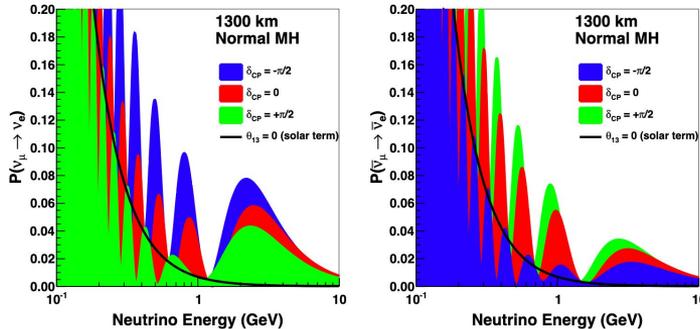
Working towards THEIA: 10kton+ hybrid cherenkov-scintillation detector

- DUNE's 4th cavern could house THEIA
- Probe electron antineutrino appearance, complementary to electron neutrino in LAR
- Place constraints on neutrino-N interactions
- Potentially enable additional low-energy physics goals
- Dichroicons would:
 - Improve effective coverage per dollar
 - Provide crucial information about event topology.

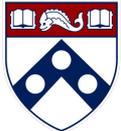


THEIA 25kt

THEIA 100kt

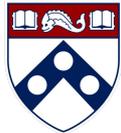
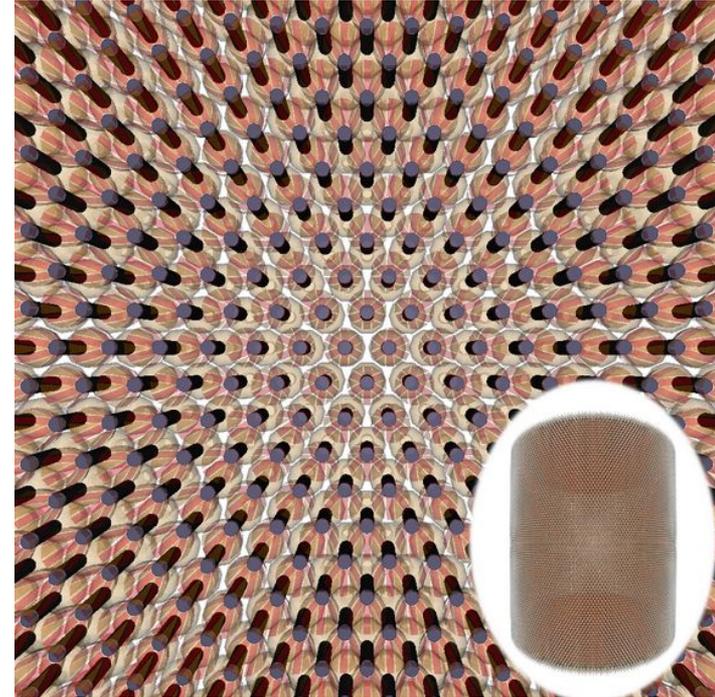


1 GeV electron in Theia



Conclusion

- The dichroicon is a good candidate for achieving cherenkov / scintillation separation in future hybrid optical detectors via spectral sorting.
- Mature design process, benchtop measurements that demonstrate C/S separation
- Successful deployment in Eos, with preliminary calibration results showing an increase in effective coverage compared to absorber designs
- Future applications in kiloton-scale hybrid optical detectors such as THEIA



Thanks for your attention!

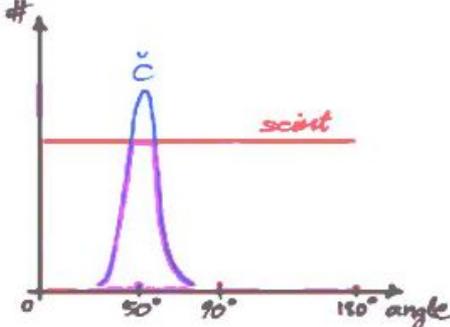
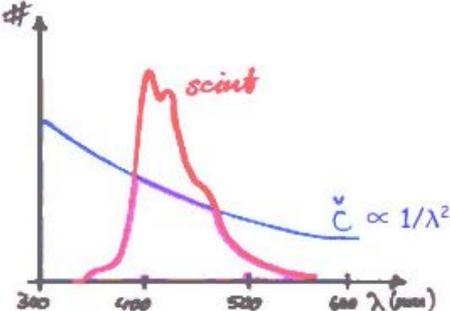
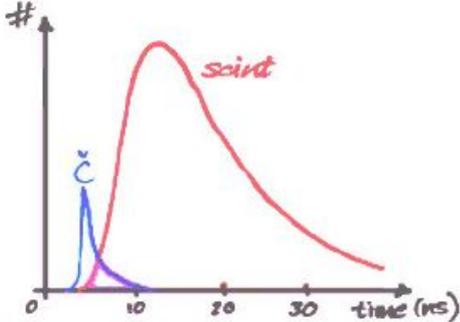
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Berkeley National Laboratory under Contract DE-AC02-05CHI 1231.

The project was funded by the U.S. Department of Energy, National Nuclear Security Administration, Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D). This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC0018974.



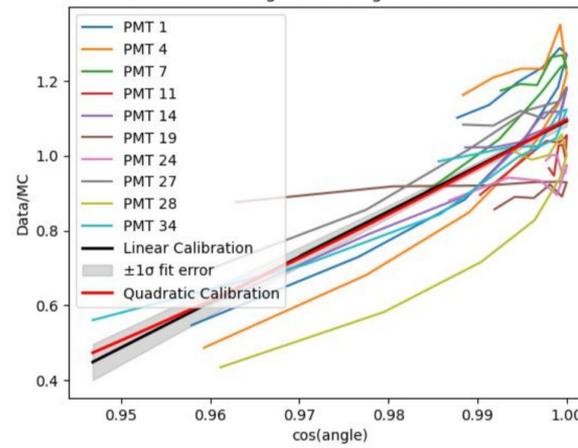
Backup

Cherenkov/scintillation separation

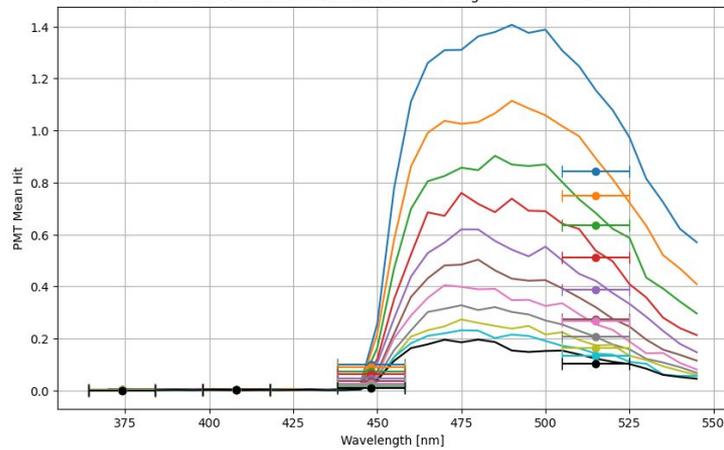




Data / MC PMT Average Hit vs Angle with Calibration Fits



Normalized Dichroic PMT Mean Hit vs Wavelength at Different Positions



Normalized Dichroic PMT Mean Hit vs Wavelength at Different Positions

