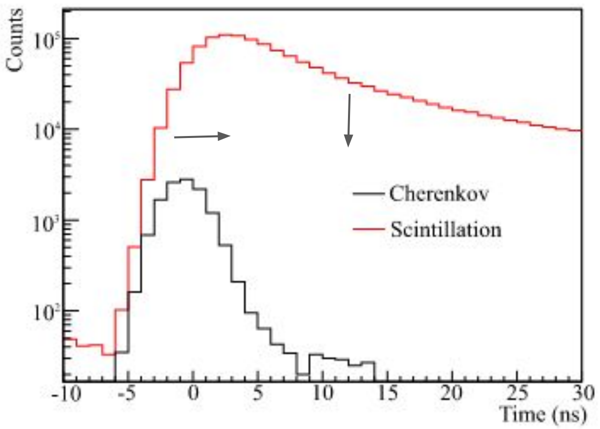
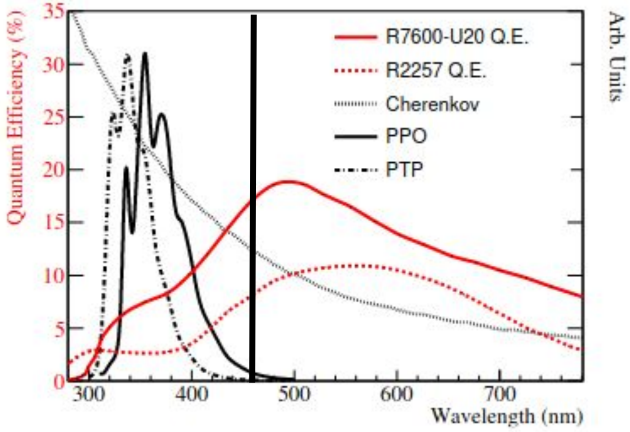
Spectral Photon Sorting with Dichroicons

Hybrid Detector Workshop
June 4th, 2025
Samuel Naugle

Hybrid Cherenkov and Scintillation Detectors

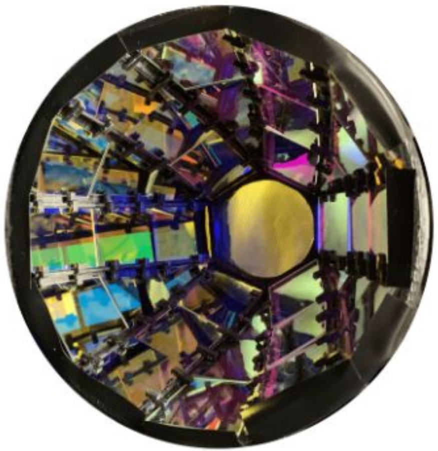
– A hybrid detector provides many advantages, but with some difficulties
– Four distinct approaches to hybrid detection
  – Reduce intensity of scintillation light (WbLS)
  – Utilize time separation between Cherenkov and scintillation light (fast sensors/slow scintillators)
  – Use the angular distribution of Cherenkov photons
  – Use wavelength information (dichroicons)

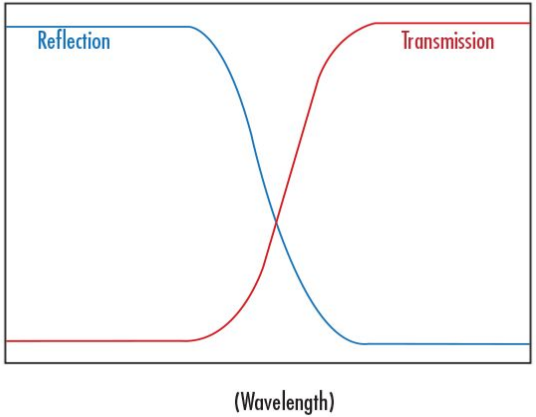


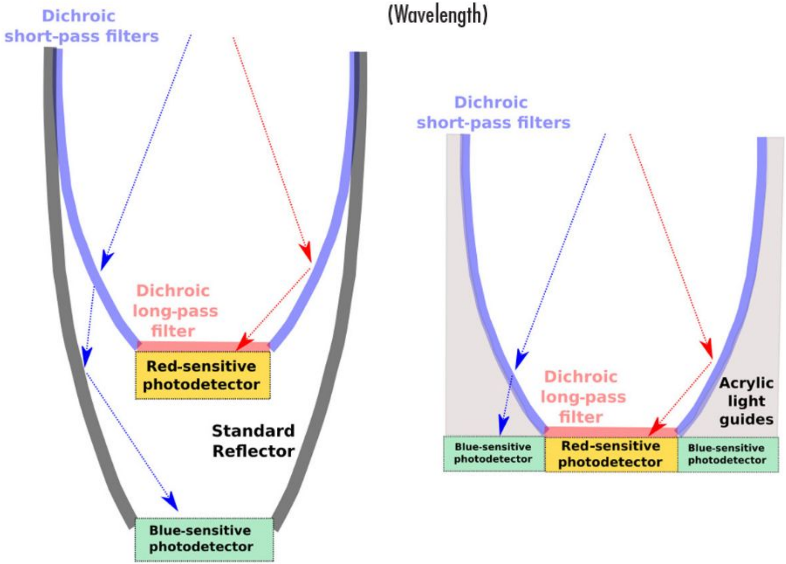


The Dichroicon

- Dichroic filters sort photons by wavelength
  - Sort Cherenkov and scintillation light to detect both simultaneously and separately

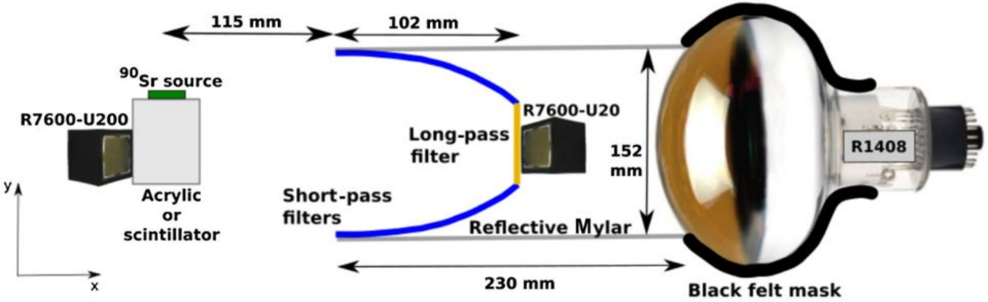


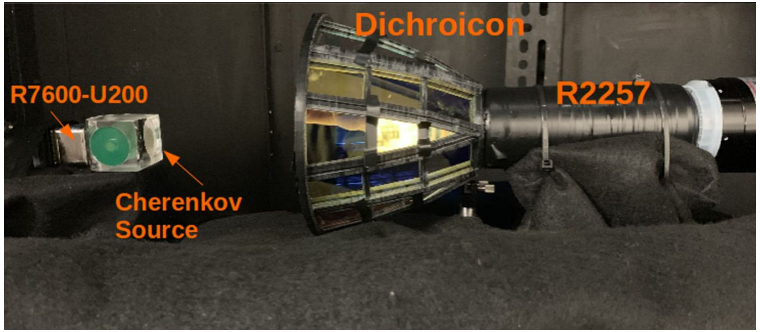


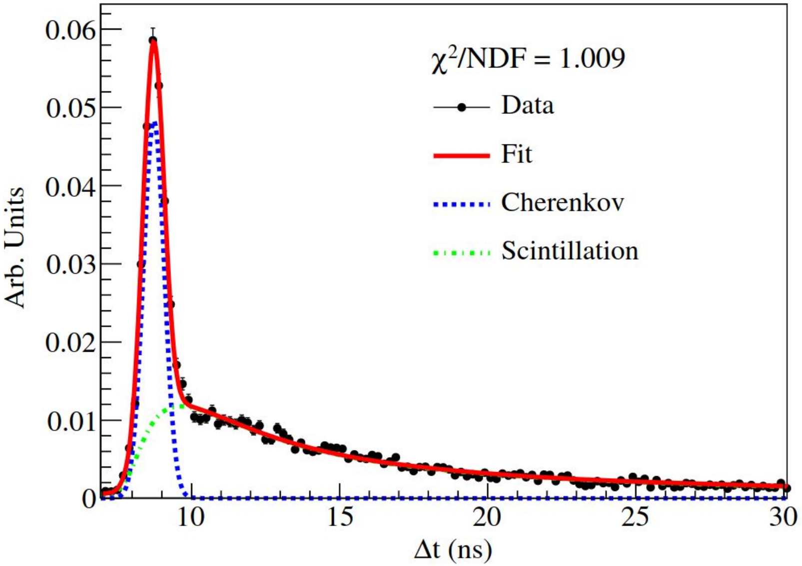


First Demonstration

– First demonstrations showed clear separation of Cherenkov and scintillation light







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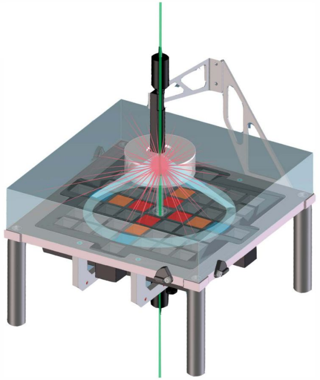
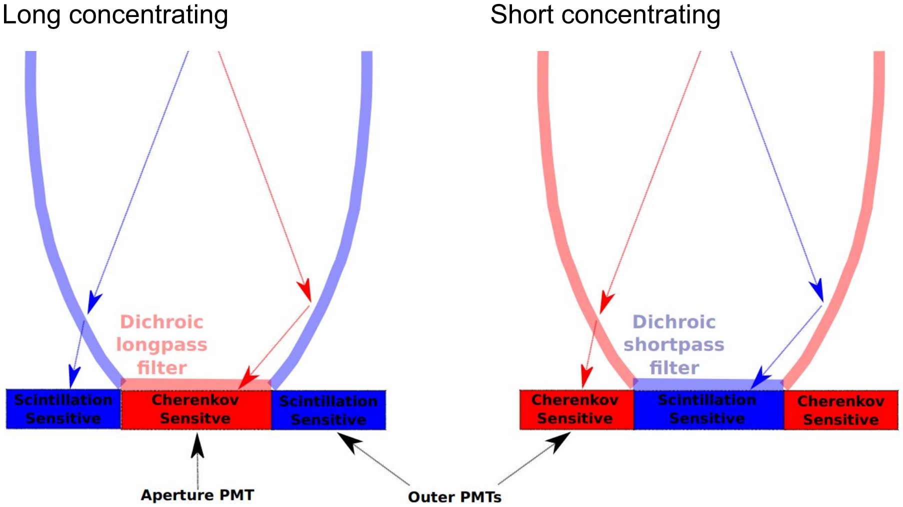
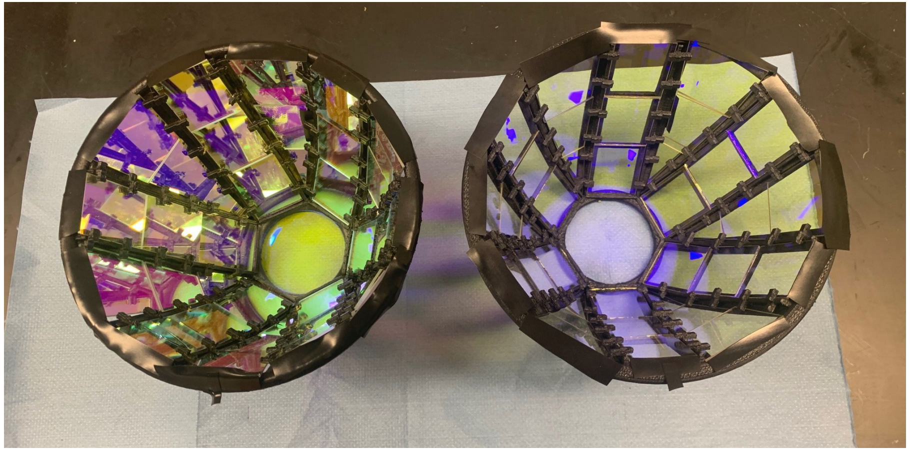
Benchtop Scale Testing of the Dichroicon

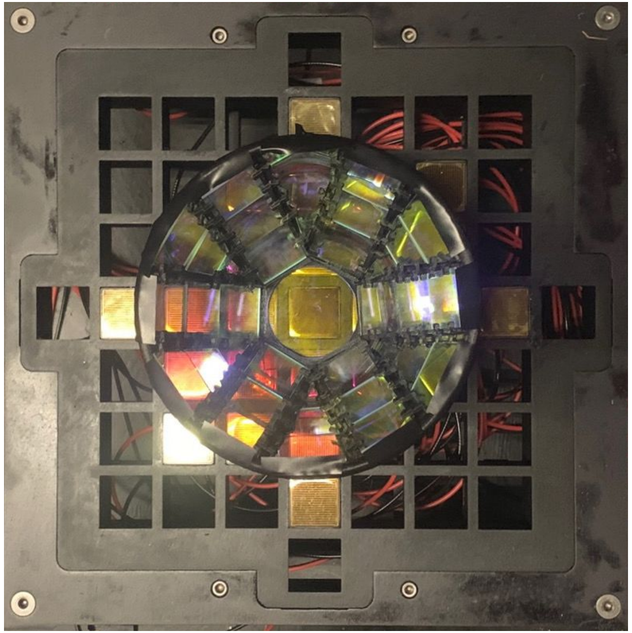
- The performance of the dichroicon was measured at the CHESS experiment
  - Sources: Atmospheric muons, ^{60}Co, ^{90}Sr, and ^{210}Po
  - Targets: Water, 10% WbLS, LAB with 2 g/L PPO
  - Dichroicon layouts: Long and short concentrating

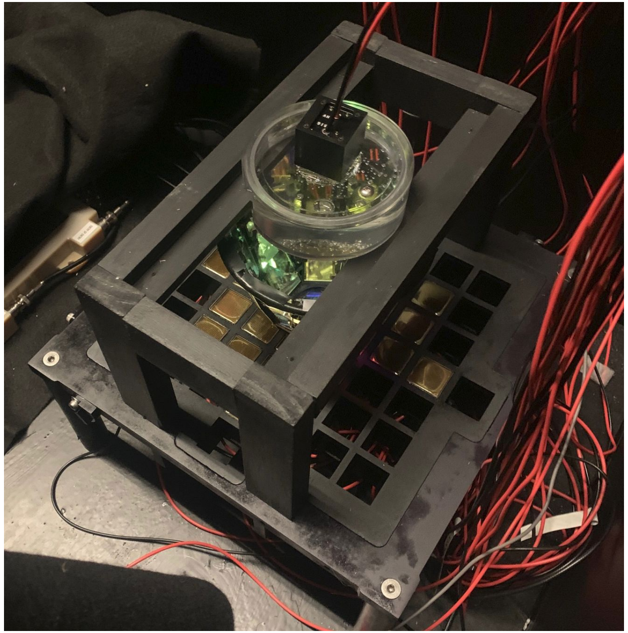






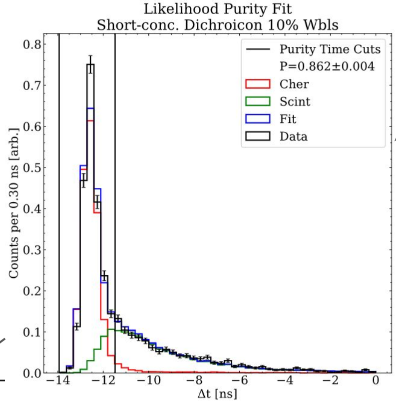
Benchtop Scale Testing of the Dichroicon

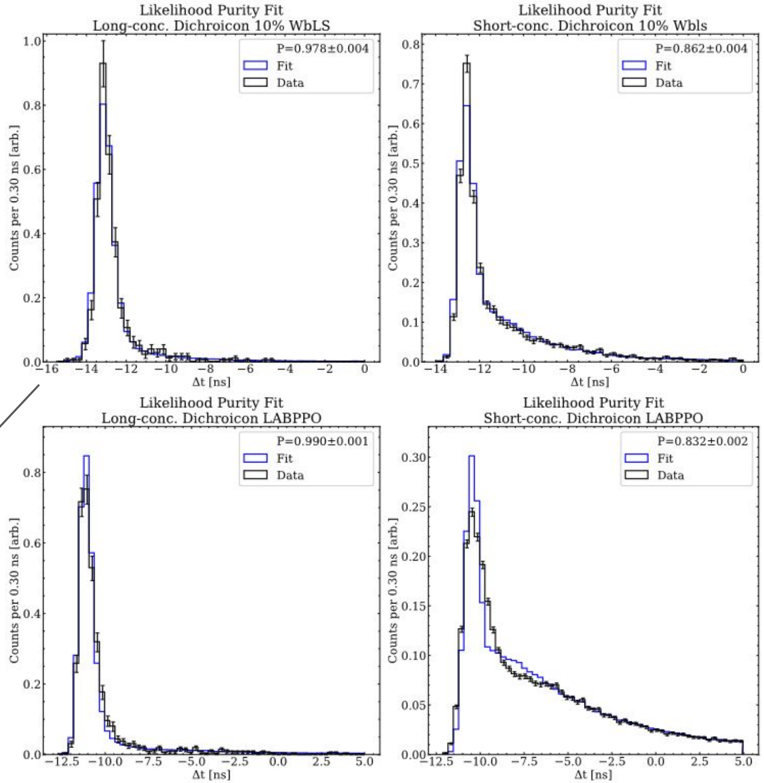




Benchtop Scale Testing of the Dichroicon

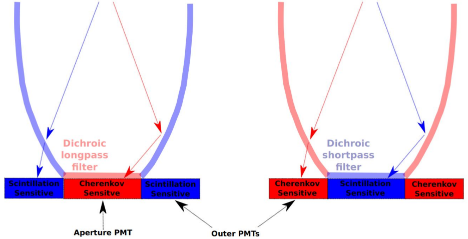
- Cosmic muon datasets were used to estimate the Cherenkov and scintillation hit time contributions
  - Measure the “purity” using a model
  - The purity is the ratio of Cherenkov photons to all photons in a prompt time window



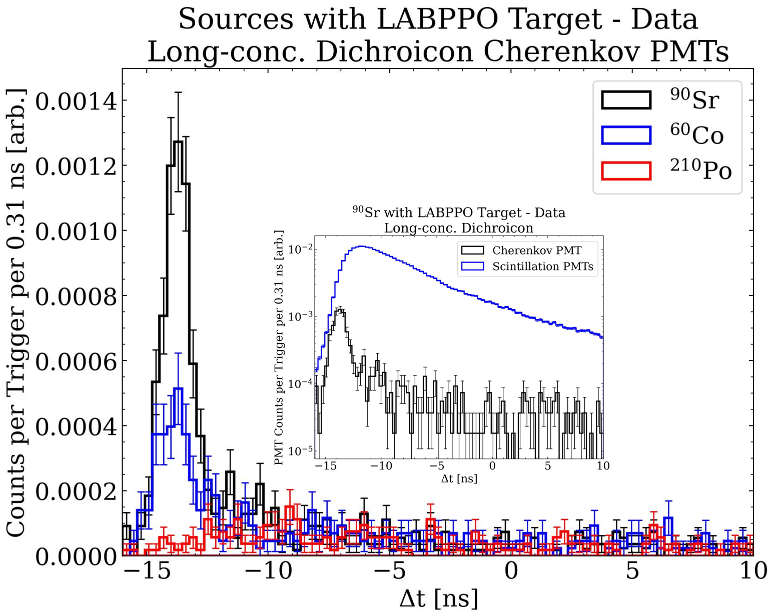


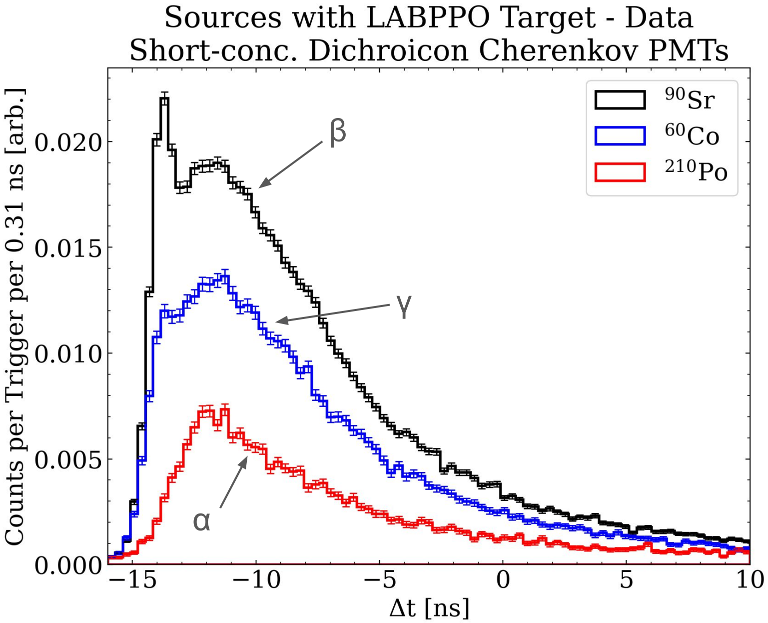
Purities		
	Long-conc.	Short-conc.
10% WbLS	0.978 ± 0.004	0.862 ± 0.004
LABPPO	0.990 ± 0.001	0.832 ± 0.002

Benchtop Scale Testing of the Dichroicon



– Deployed source also demonstrated particle ID capabilities of the dichroicon





Benchtop Scale Testing of the Dichroicon

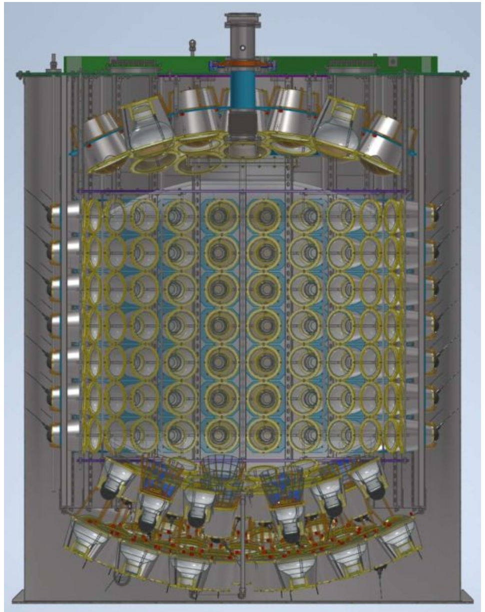
- Charge collection measurements show that the advantage of the Winston cone for photon collection

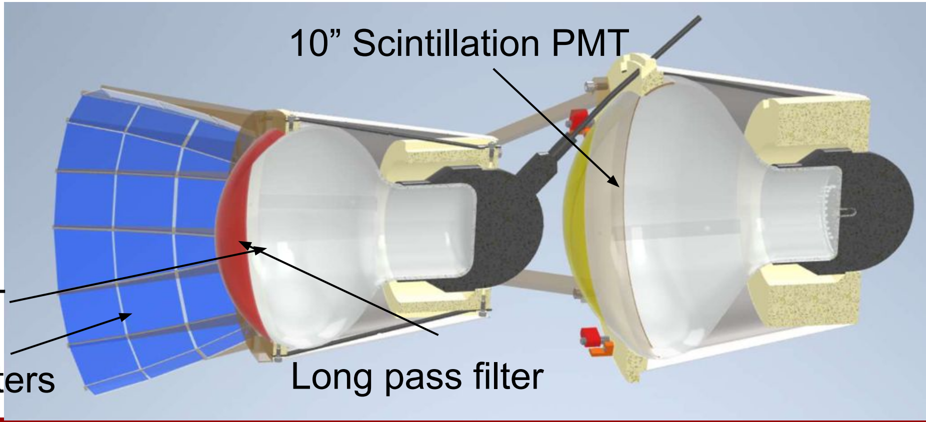
	Scintillation Yield	Cherenkov Yield
	Charge/Event/PMT [pC]	C_{hits}/PMT
Aperture Filter	10.2 ± 0.1	0.023 ± 0.007
Long-conc. Dichroicon	4.35 ± 0.04	0.066 ± 0.009
Short-conc. Dichroicon	19.2 ± 0.3	0.077 ± 0.002

- The dichroicon is not filtering light, rather it **sorts** the photons
- Due to optics of Winston cones, the long concentrating dichroicon is not optimal for setups with close photon sources
  - This is not necessarily an issue in large detectors
  - Still both do “better” than aperture only design

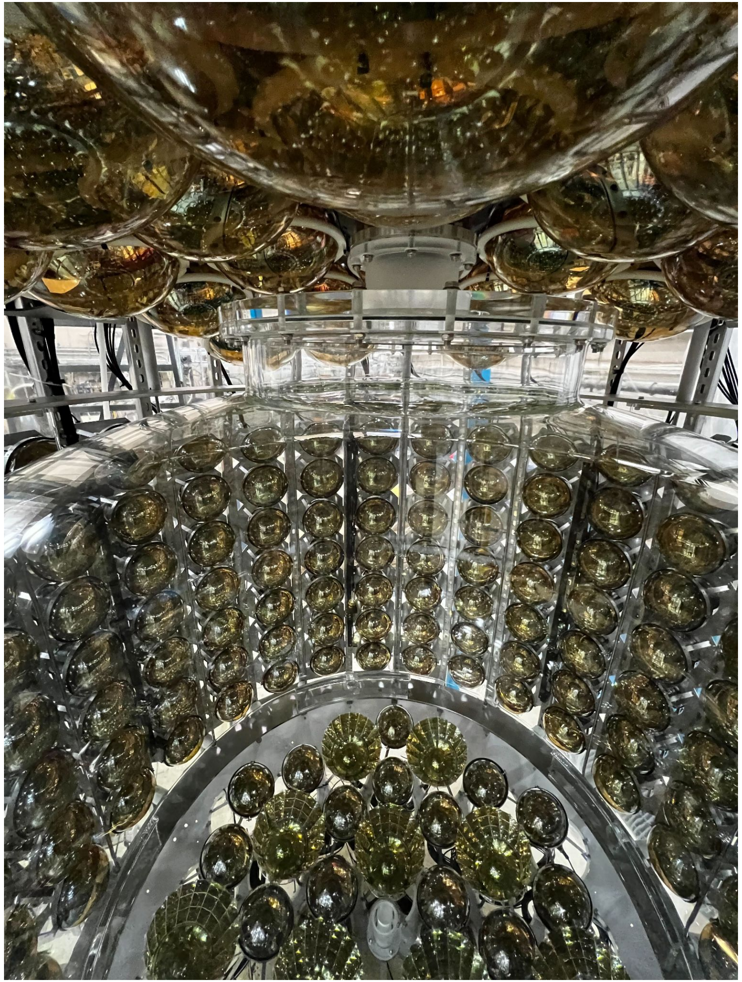
Eos Deployment

- 12 monolithic dichroicons deployed in the Eos detector
  - Eos is a 30 ton experiment whose goal is to demonstrate hybrid Cherenkov and scintillation utilization
  - Involves many new technologies and will scan over multiple WbLS loadings
- First test of a monolithic, kiloton scale dichroicon design
- Cost of filters per dichroicon is ~$2000

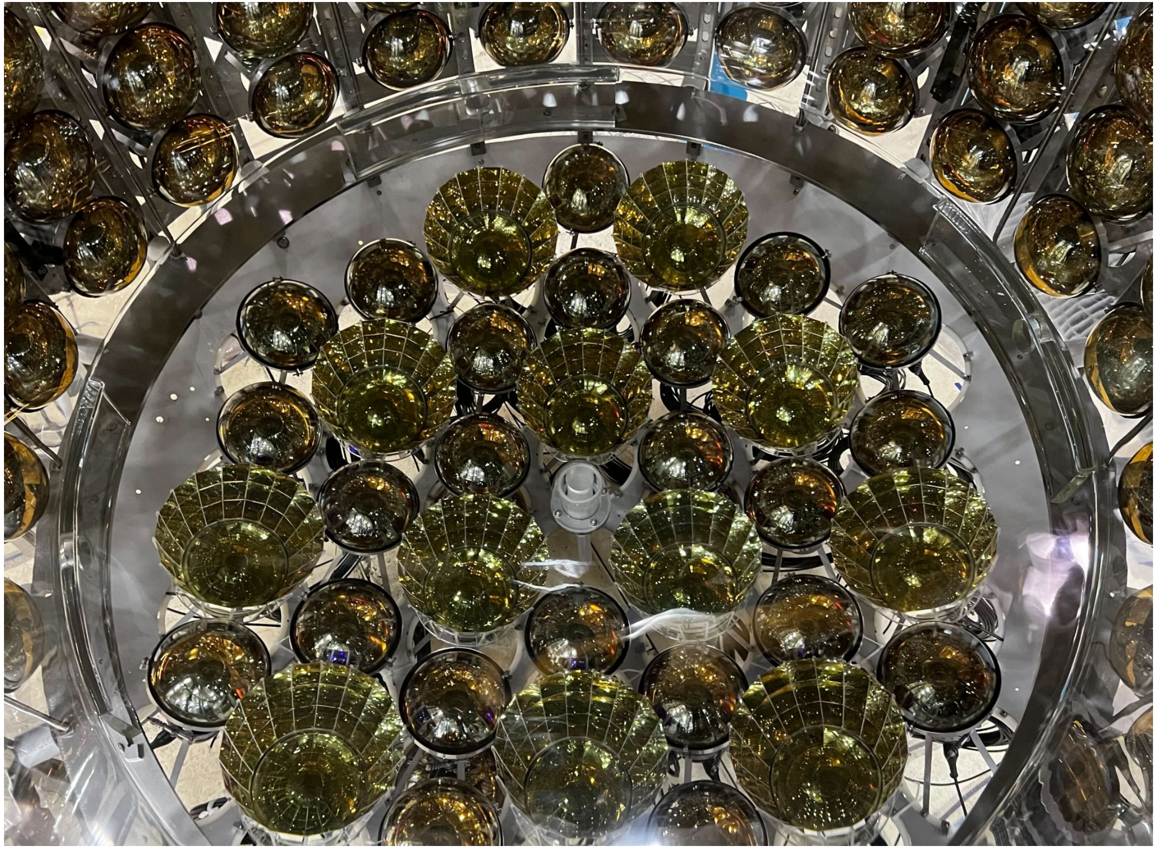




Eos Deployment

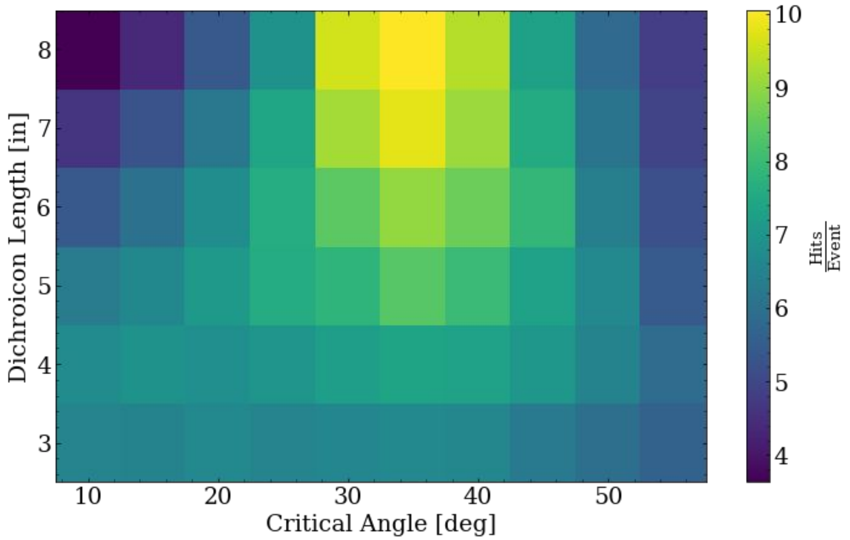


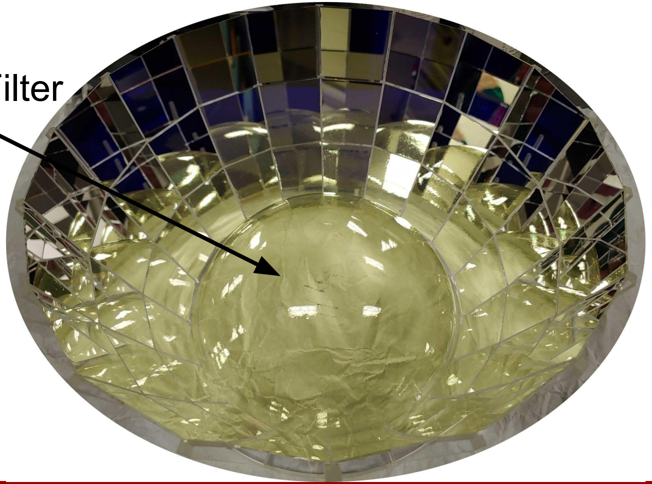
Eos Deployment



Eos Considerations

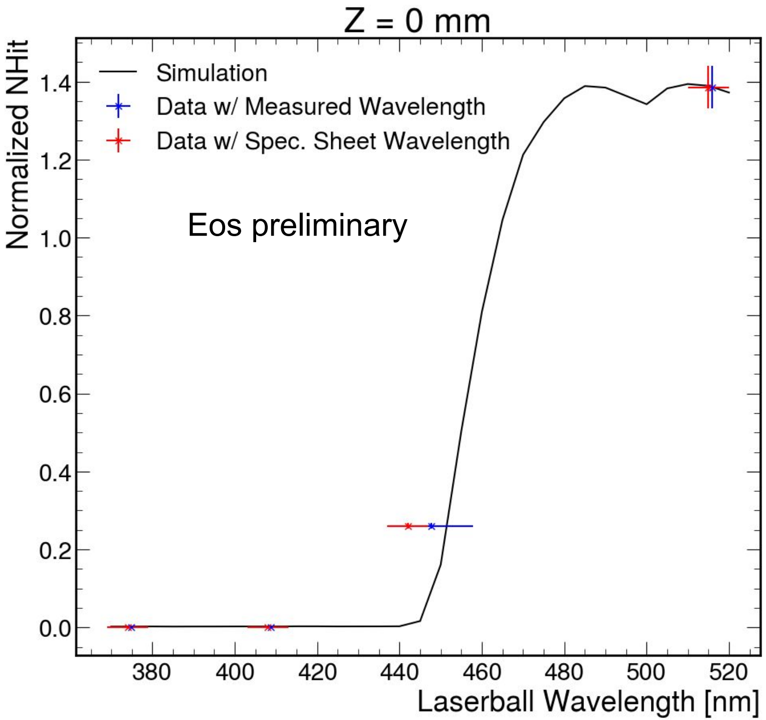
- A large amount of effort was put into optimizing this new, larger dichroicon design
- Simulated various Winston cone shapes to find maximum collection efficiency
- Custom molded longpass filter allows PMT photocathode to fit through aperture of Winston cone
  - Improves collection efficiency by ~50% relative to design with PMT pushed through aperture





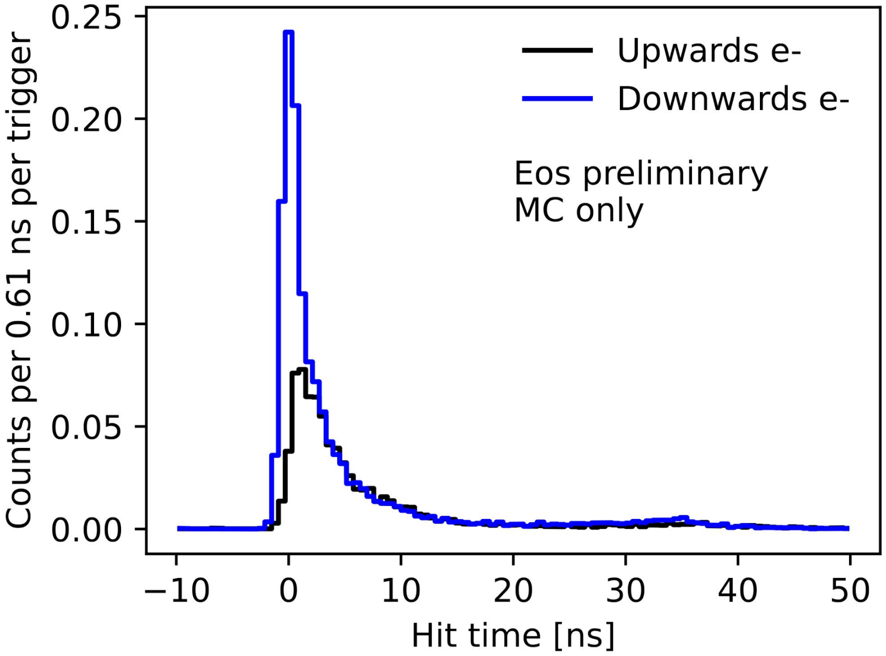
Eos Demonstrations

- Eos has collected water data and preliminary WbLS data
  - Many sources deployed, including β's, neutrons, γ's, calibration lasers
- Currently taking 1% WbLS data
- Plot on right shows data MC agreement for "laserball" runs at different wavelengths
  - No leakage at short wavelengths!



Planned Eos Demonstrations

- Appearance and disappearance of Cherenkov cone using directional source
  - Includes measurement of Cherenkov purity with different WbLS fractions
- α/β/γ particle ID with dichroicons
- Reconstruction which intelligently leverages information from dichroicons
- Plot on right shows hit times on dichroicons from 2 MeV electrons in 10% WbLS



Optimization Parameters

Planning for the Eos deployment made one thing clear, optimization parameter space for dichroicons is vast

A few considerations:

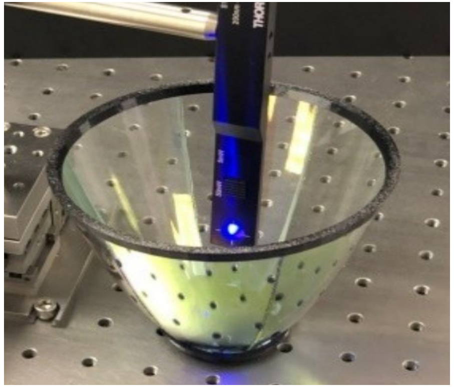
- Cut on wavelengths of filters
  - Increase Cherenkov yield at the cost of purity on the Cherenkov PMT
  - Decreases the scintillation yield
- Shape and style of dichroicon
  - Each detector and use case has a slightly different optimal shape
- Photon detectors
  - Improvements to QE and timing will aid in Cherenkov collection and purity
- Placement of dichroicons
  - How many and where?

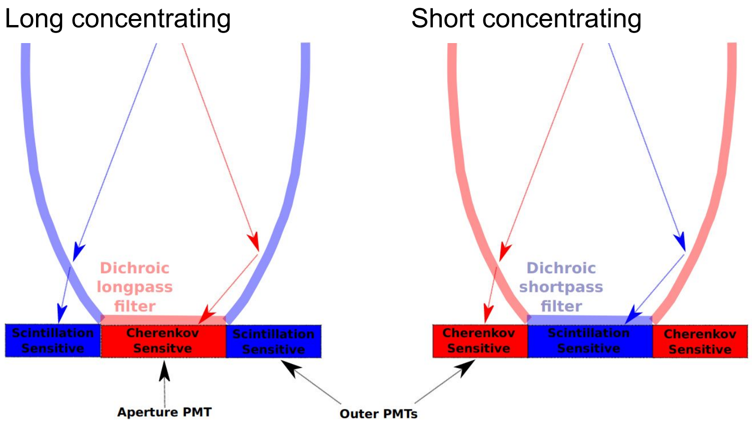
Dichroicon niche

- In large scintillator detectors, vertex of physics events are unknown
  - PMT hit times do not directly translate to photon emission times
  - Analysis must reconstruct photon emission times, called hit time residuals
- Hit time residuals are sensitive to optics and detector effects that may be hard to understand
  - Faster timing alone may not help if there are large systematic errors on scintillator model or position reconstruction
- Dichroicon photon sorting efficiency does not* depend on position of events in the detector, so it won't be affected by systematics on reconstruction or optics
- Additionally, dichroicons could be used as a calibration tool since they probe distinct wavelength bands that standard PMTs integrate over

Looking Ahead - Near Term

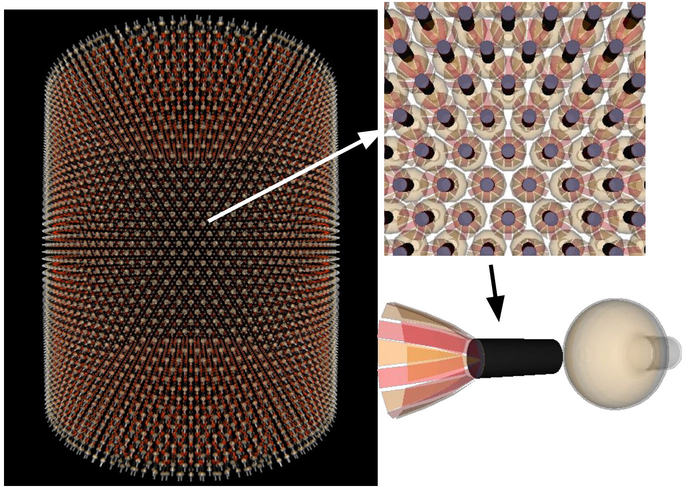
- Current focus is the initial Eos deployment
- But there are many ideas that still need to be explored
  - Large scale short concentrating dichroicon
  - New photodetectors like SiPMs and LAPPDs
  - The "trichroicon"
  - New dichroic filter technology including atomic layer deposition (ALD) techniques
  - Novel scintillators

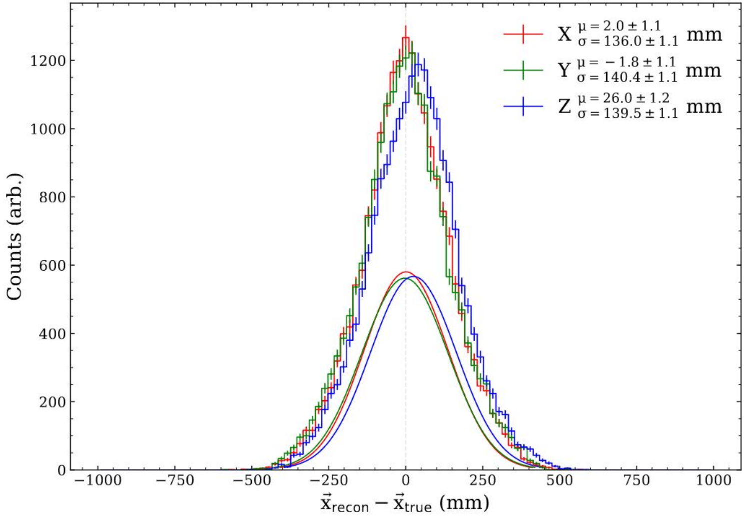


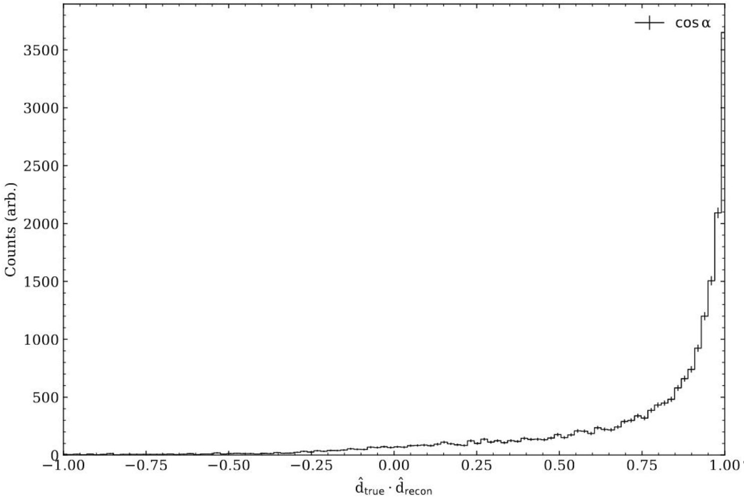


Looking Ahead - Long Term

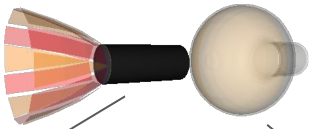
- Long term goal of dichroicons deployed in next generation kiloton-scale neutrino detectors, like Theia (50kT)
  - Below are preliminary simulation results using 5 MeV electrons in a detector filled with 2g/L LABPPO



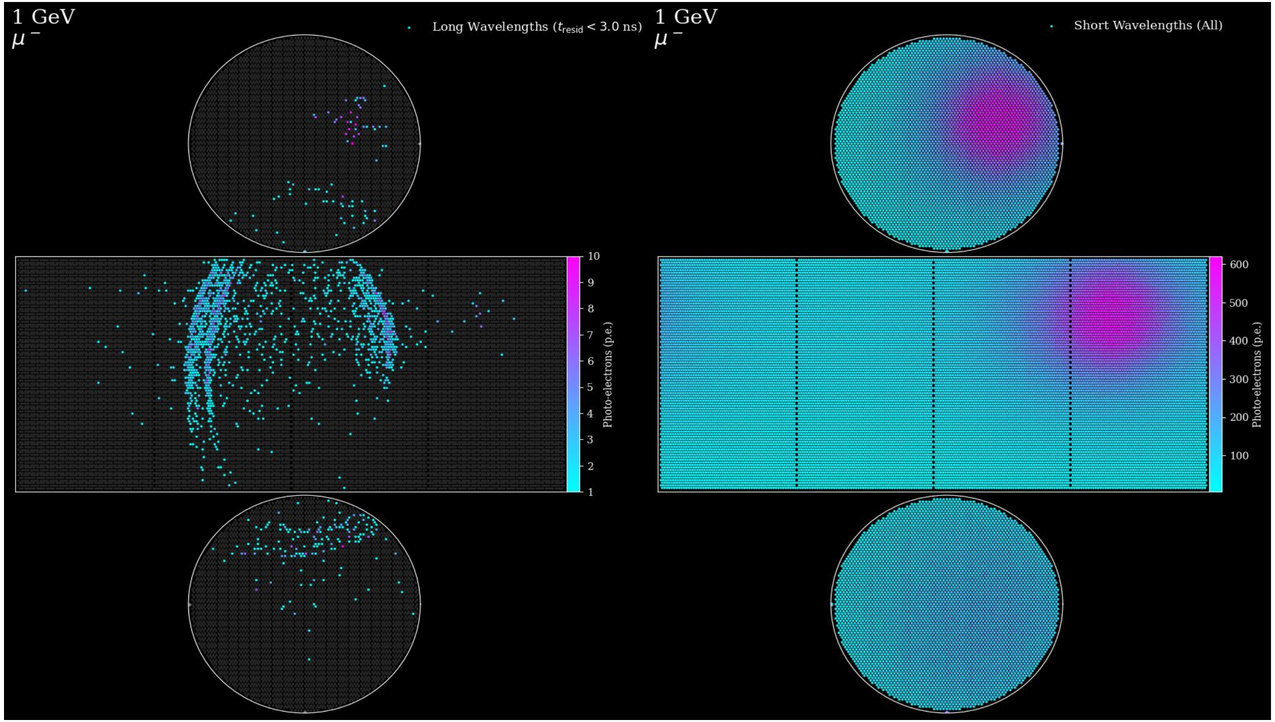




Questions?



Thanks for listening!



Backup

Angular dependence