Spectral Photon Sorting with the Dichroicon in Large Neutrino Detectors

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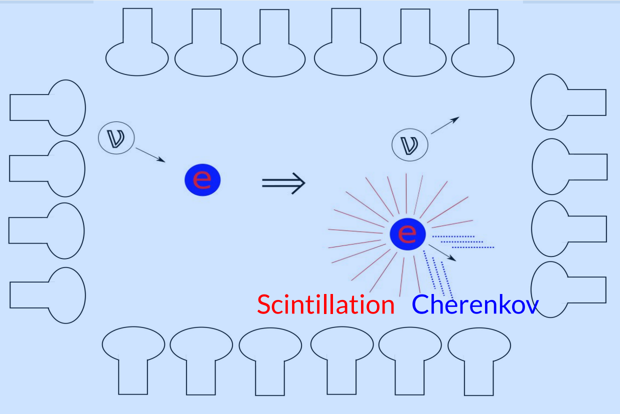
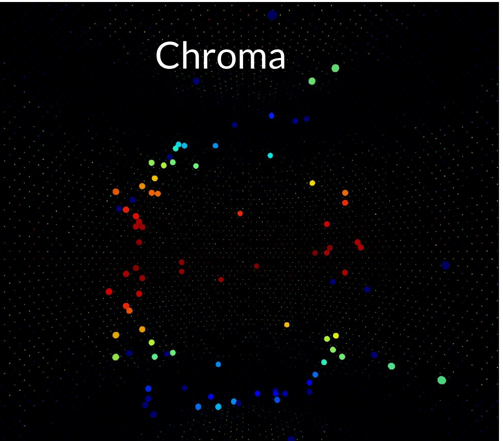
Outline

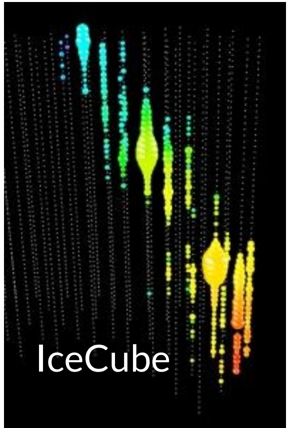
- Optical Neutrino Detection Overview
- Combined Cherenkov and Scintillation Detection
  - Spectral Photon Sorting
  - The Dichroicon
- Chroma Dichroicon Simulations
  - Cherenkov/Scintillation separation in pure liquid scintillator
  - Direction reconstruction in pure liquid scintillators
  - Particle identification for background rejection

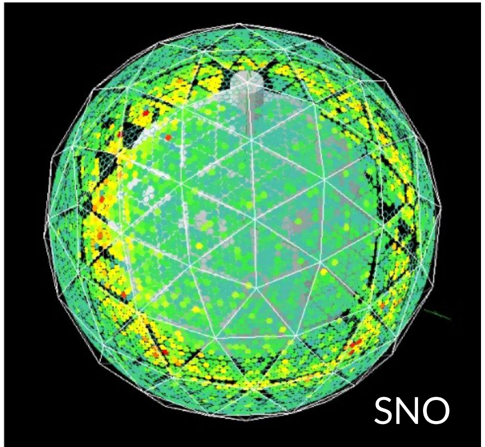
Optical Neutrino Detectors

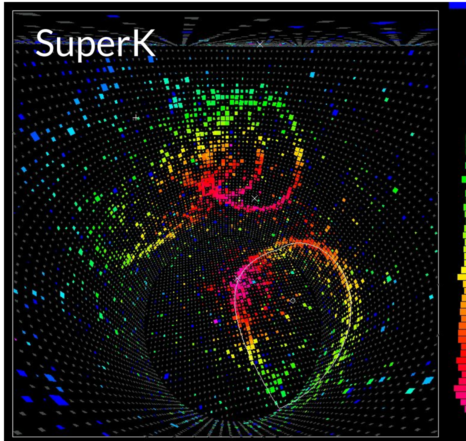


- Photons carry information about the interaction
  - Number / intensity - energy reconstruction
  - Hit time - position reconstruction
  - Hit topology - direction reconstruction (Cherenkov)
- Other properties that could be measured
  - Polarization - random for Scintillation, has topology with Cherenkov
  - **Wavelength - different spectra for Cherenkov/Scintillation**





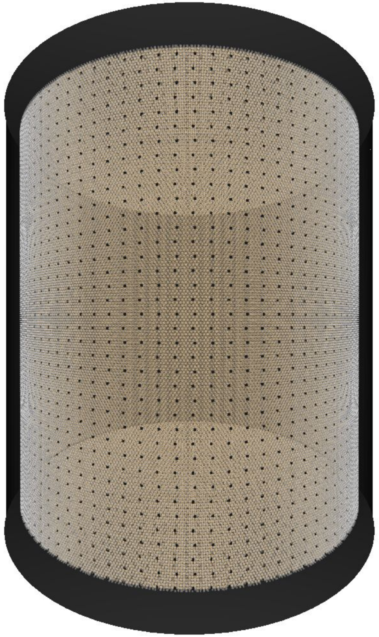


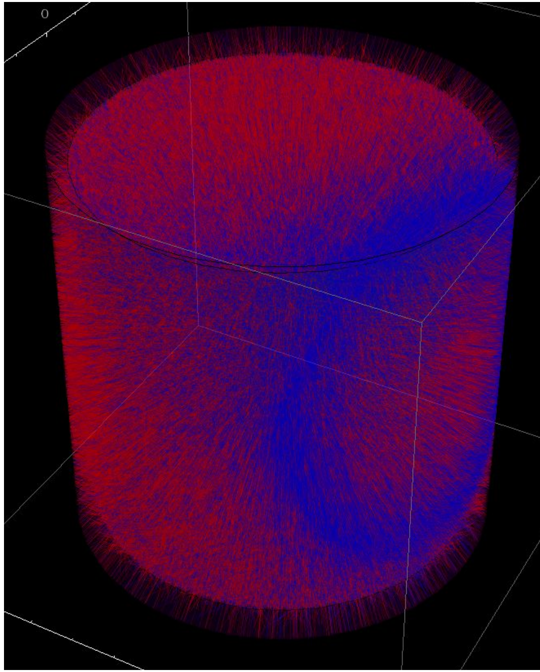


Cherenkov + Scintillation

- Cherenkov light occurs in all scintillating media
  - Typically much dimmer (~10 p.e./MeV)
  - Hidden under scintillation (> 100s-1000s p.e./MeV)
- Detecting both combines advantages
  - Cherenkov ring imaging → directionality
  - Scintillation light yield → low energy thresholds
- Also provides additional information
  - Cherenkov/Scintillation ratio → particle identification
- Detectors like THEIA are exploring combined detection [*Eur. Phys. J. C* **80**, 416 (2020)] (see Morgan's Theia talk next!)

THEIA100

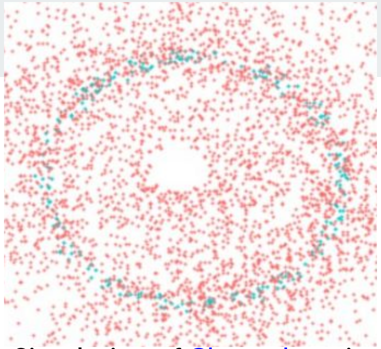




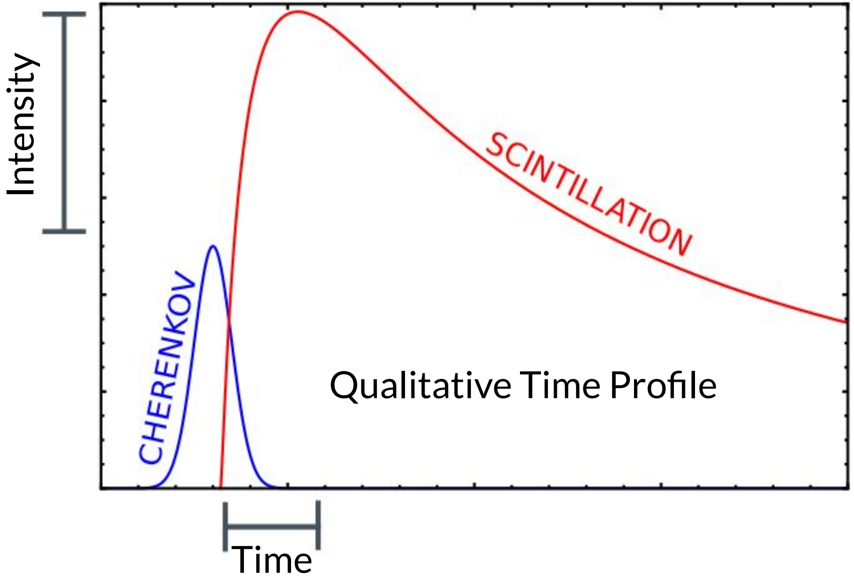
1 GeV electron simulation
10% WbLS

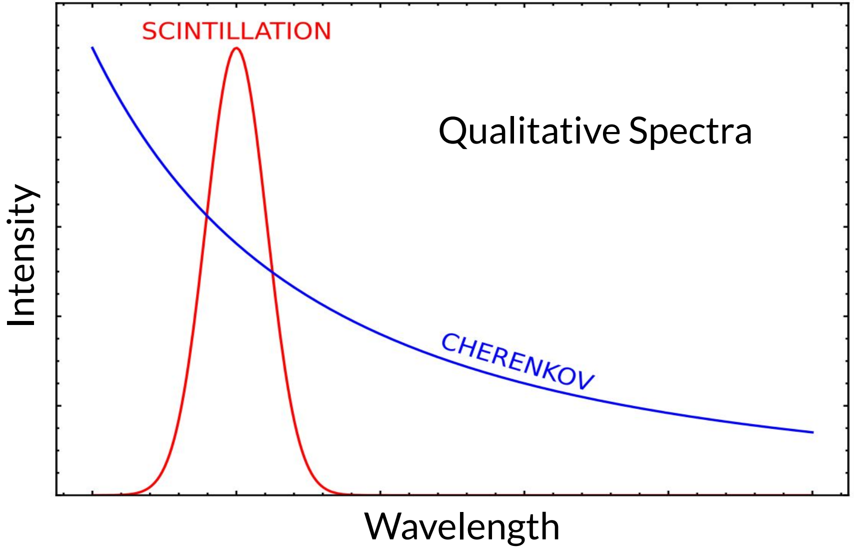
Identifying Cherenkov in Scintillation

- Several methods being explored by the community
  - Intensity - reduce scintillation light yield (e.g. WbLS)
  - Time - slow scintillators, fast photodetectors (e.g. LAPPD)
  - **Wavelength - spectral photon sorting**



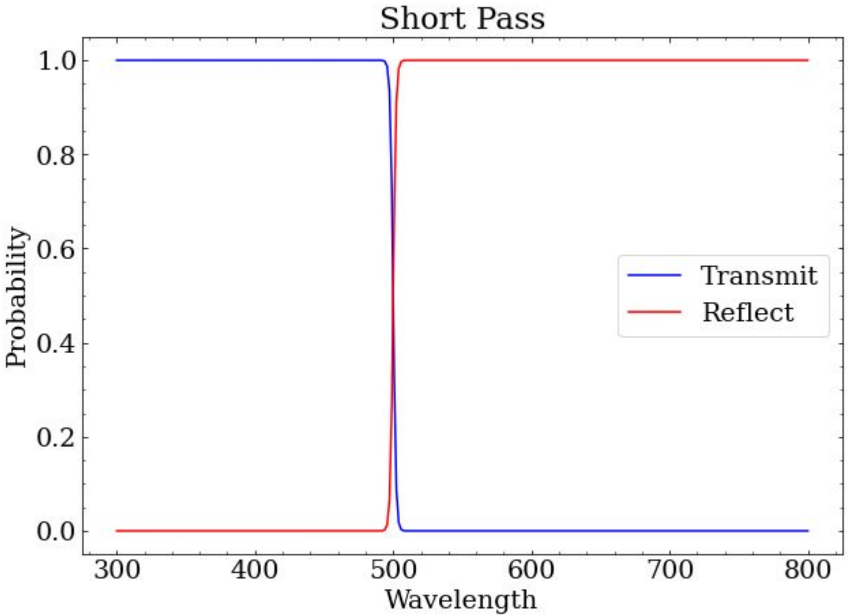
Simulation of Cherenkov ring in scintillation light in CHESS
Eur. Phys. J. C **80**, 867 (2020)

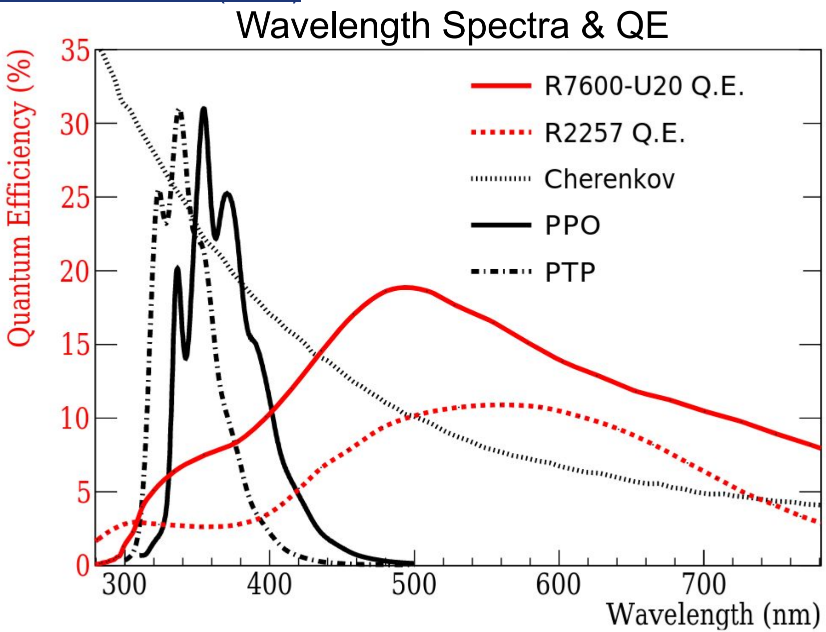




Spectral Photon Sorting

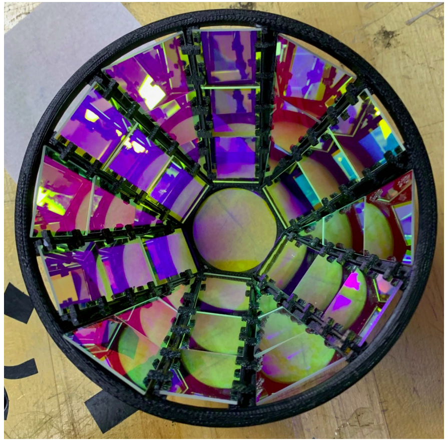
- Cherenkov is broad spectrum / Scintillation light typically narrow band
- Filter out Cherenkov with dichroic filters
  - Divert longer wavelengths (mostly Cherenkov) to one red-sensitive PMT
  - Pass short wavelength photons to blue-sensitive PMT
  - Testbench demonstrations with LAB+PPO in *JINST* **14** T05001 (2019)





The Dichroicon

- Implements spectral photon sorting
  - Winston cone of dichroic filters
  - Long wavelengths diverted to front PMT
  - Short wavelengths pass to rear PMT
- Benchtop model designed and tested
  - Demonstrated C/S separation with dichroicon prototype
    [*Phys. Rev. D* **101**, 072002 (2020)]



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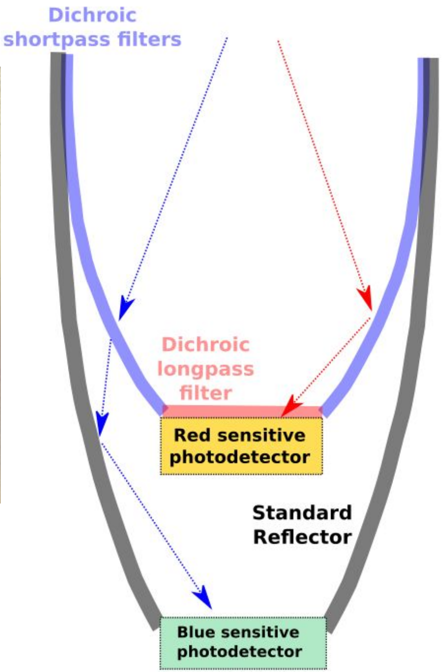
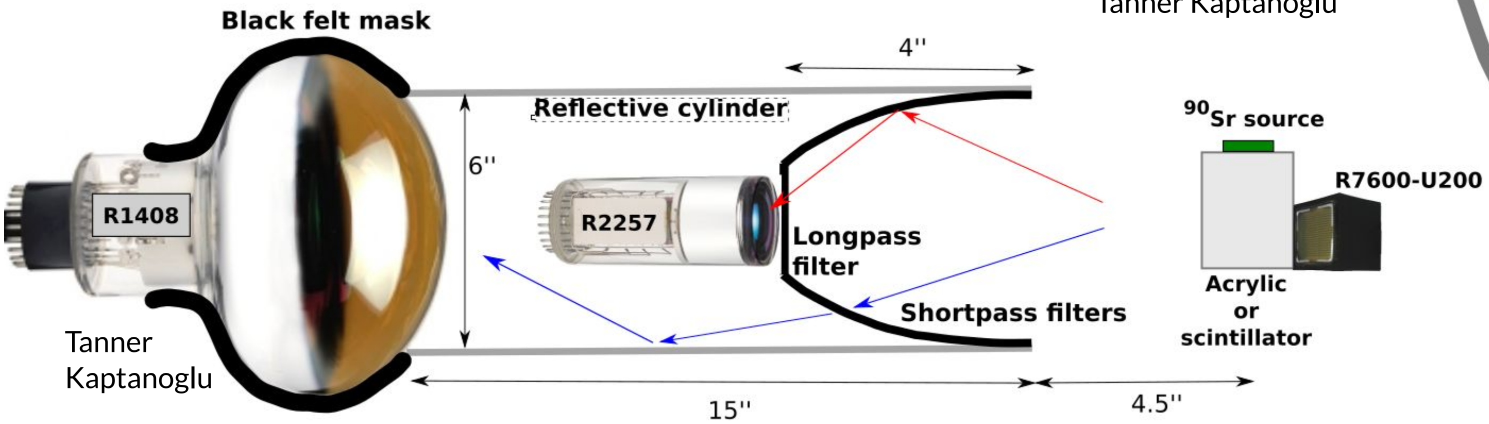


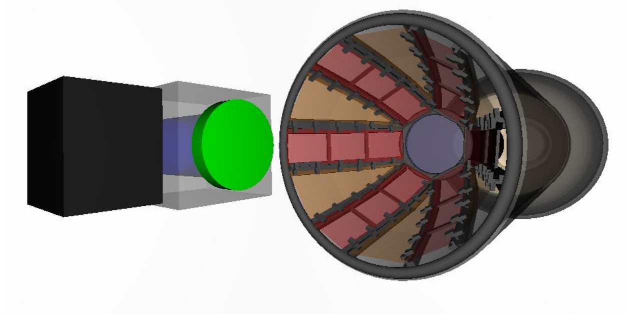


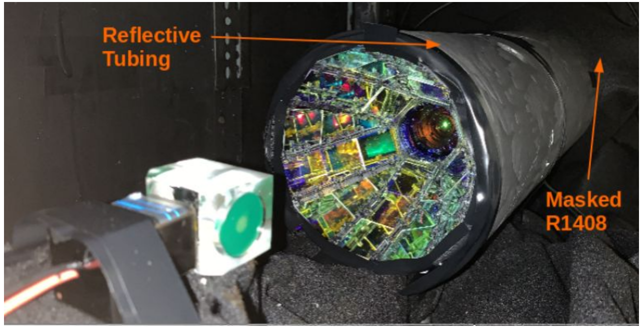
Tanner Kaptanoglu

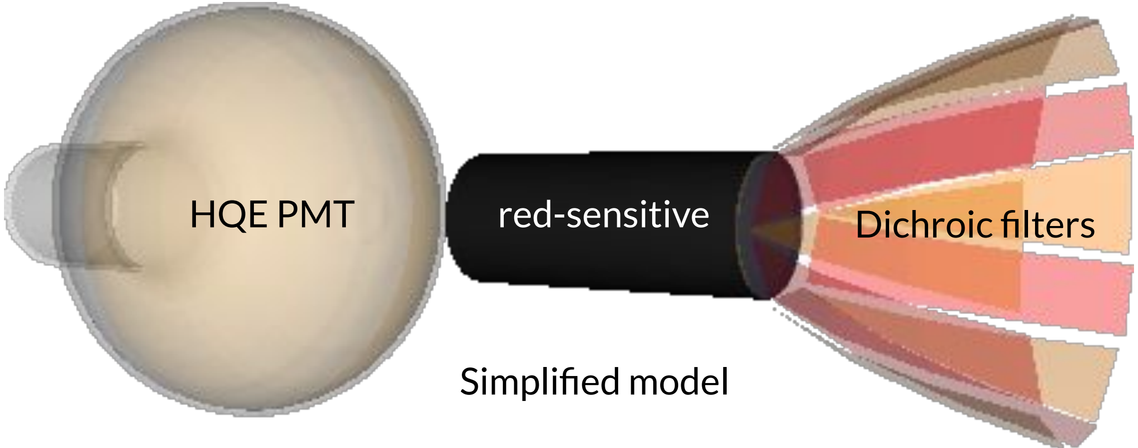
Dichroicon Chroma Simulation

- Full simulation model validated with benchtop data using Chroma in [*Phys. Rev. D* **101**, 072002 (2020)]
    - Chroma available at https://github.com/BenLand100/chroma (SNOWMASS LOI)
- Simplified model created for large scale simulations
    - 20" large area high QE PMTs
    - 5" cylindrical red-sensitive PMTs
    - Dichroic filters to concentrate long wavelength light

Benchtop setup Chroma model

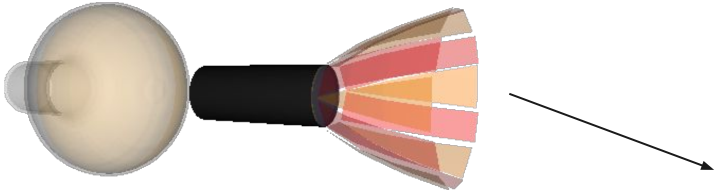


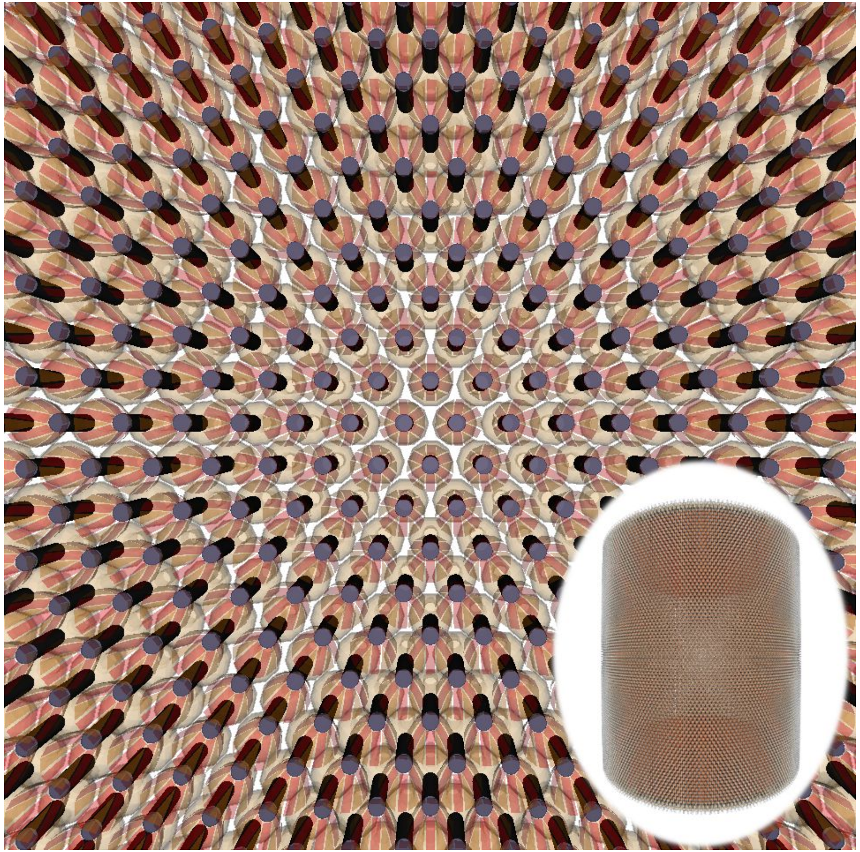




Simplified model

Large-Scale Chroma Simulations

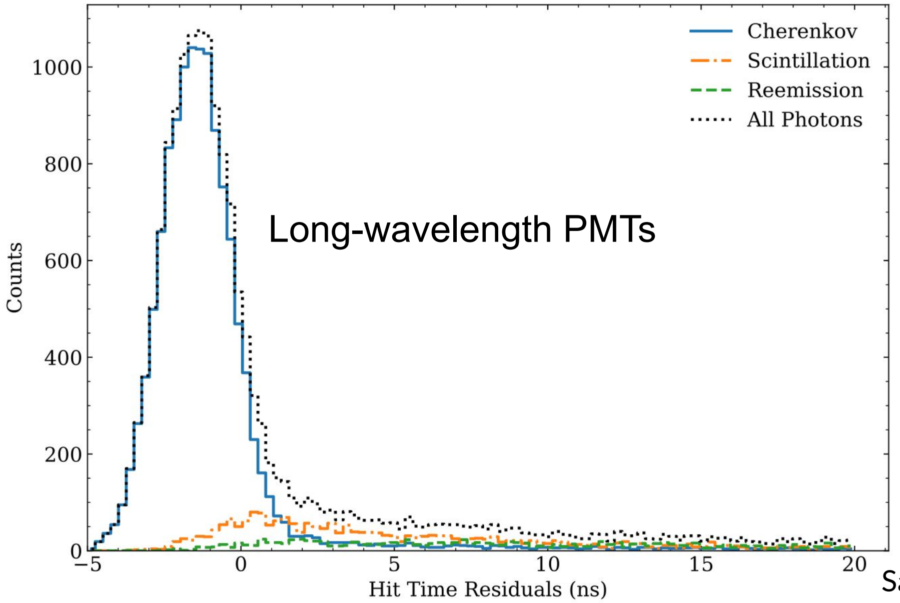


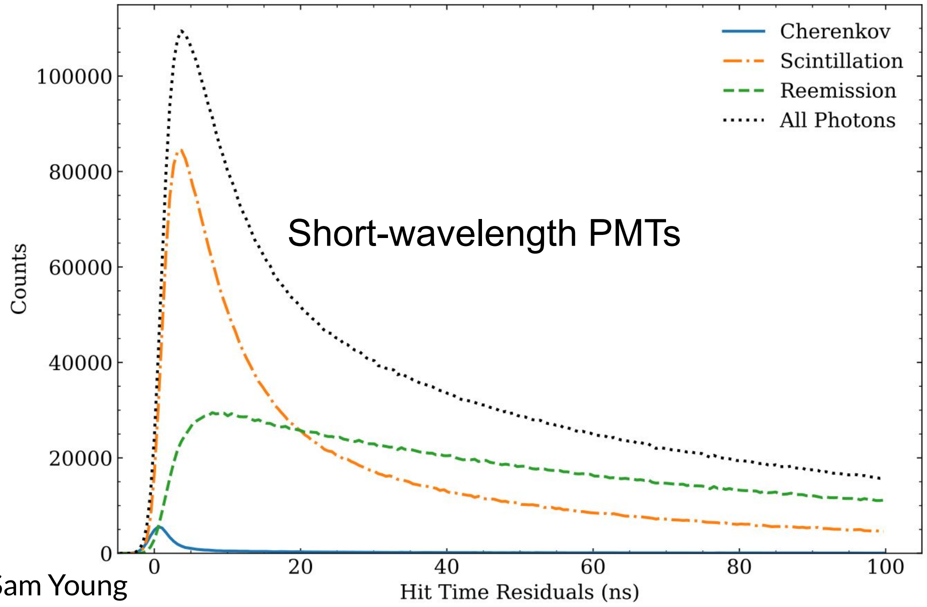


- Simulated next-generation detector
  - Compare to Theia geometries
  - 50 kt of LAB + 2g/L PPO scintillator
  - Right cylinder target volume
  - High coverage of simplified dichroicons
- Exploring impact of Cherenkov / Scintillation separation with dichroicons in next-generation neutrino detectors
  - Demonstration with MC truth
  - Direction reconstruction
  - Particle identification

Cherenkov/Scintillation Separation in MC Truth

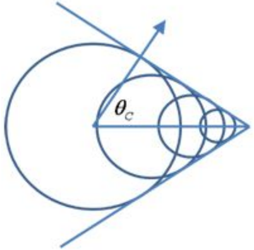
- Simulated 5 MeV electrons at center of detector
- Detected photon time residuals shown by photon creation process
- Clear Cherenkov signal on long-wavelength PMTs





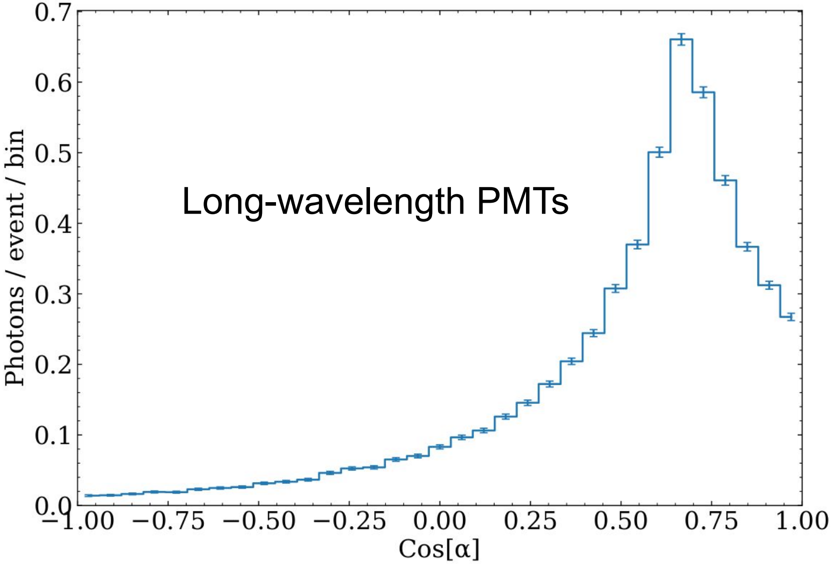
Sam Young

Direction Reconstruction in Pure Scintillator



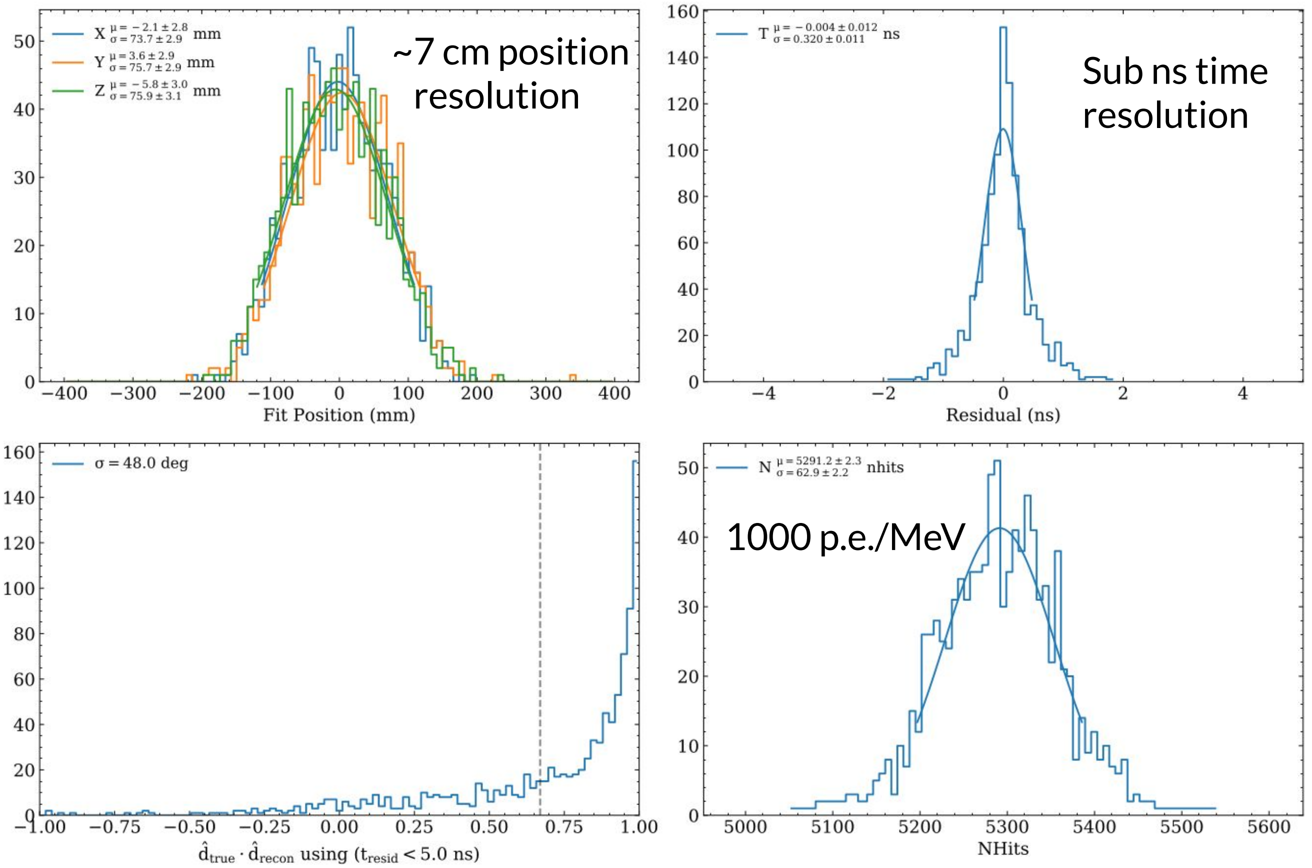
$$\theta_C = \cos^{-1}\left(\frac{1}{\beta n}\right)$$

- Long wavelength hits show Cherenkov topology
  - α is angle between direction of detected photon and initial electron direction
- Can be used to reconstruct electron direction
  - Use true Cos[α] distribution as PDF
- Adapted a two-stage reconstruction Algorithm from *Phys. Rev. D* **103**, 052004 (2021)
  - Reconstruct event position with time-residual based position fitter
    - Uses all PMT hits
  - Maximize likelihood of direction with Cos[α] angular PDF
    - Only long wavelength PMT hits



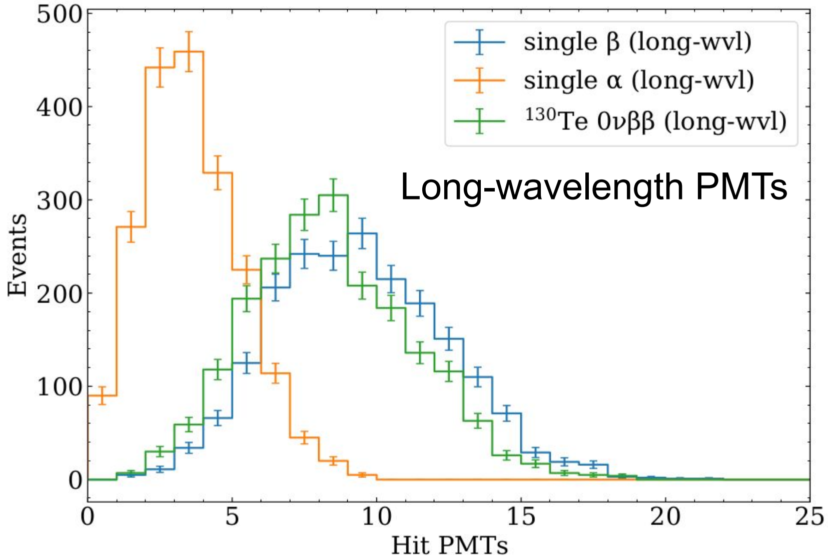
Direction Reconstruction in Pure Scintillator

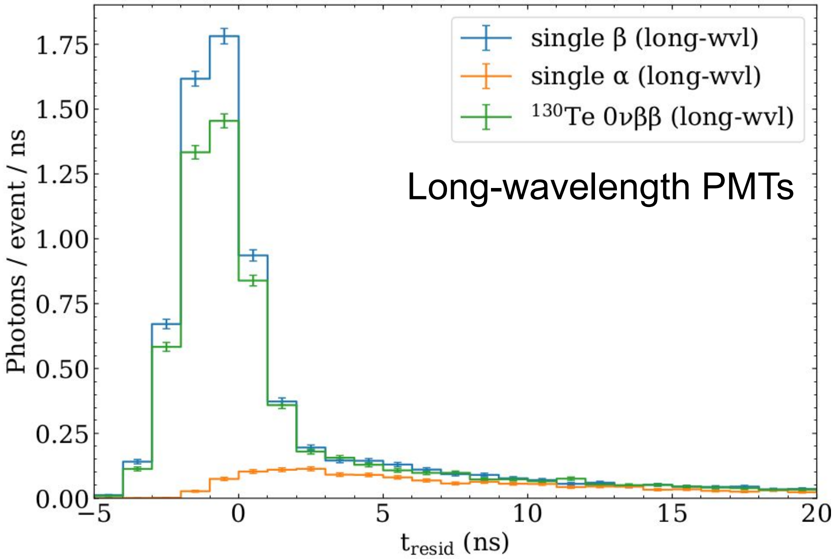
- Reconstruction results from two-stage fit
  - Again with 5 MeV center generated electrons
- 48deg angular resolution at 5 MeV in pure scintillator
- Ongoing work to optimize dischroicon design to improve results



Particle Identification using Spectral Sorting

- Simulated single β, single α, and 0νββ, all with the same visible energy
- Looking at long wavelength PMT hits below
  - β and α clearly different (could optimize design to reduce scintillation leakage)
  - β and 0νββ slightly different





Conclusions

- Simulation of large next-generation neutrino detectors possible in Chroma
- Model of 50 kt detector instrumented with dichroicons developed
  - Demonstrates Cherenkov/scintillation separation
  - Developing analyses to exploit information provided from spectral sorting
- Direction reconstruction possible in pure scintillators with spectral sorting
  - Enhanced capabilities to reduce directional backgrounds
  - e.g. solar neutrinos in $0\nu\beta\beta$ experiments
- Particle identification possible with spectral sorting
  - Rejecting alpha backgrounds relevant to many experiments
  - Slight handle on single vs double beta events
- Ongoing work to optimize dichroicon design to improve performance