The Dichroicon: Spectral Photon Sorting For Large-Scale Cherenkov and Scintillation Detectors

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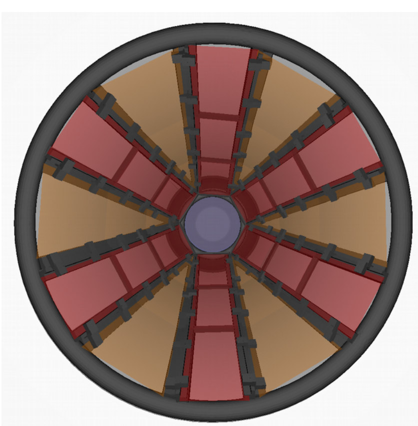
CPAD INSTRUMENTATION FRONTIER WORKSHOP 2019
University of Wisconsin-Madison



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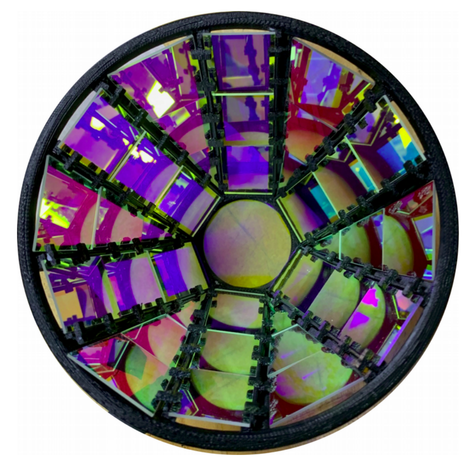
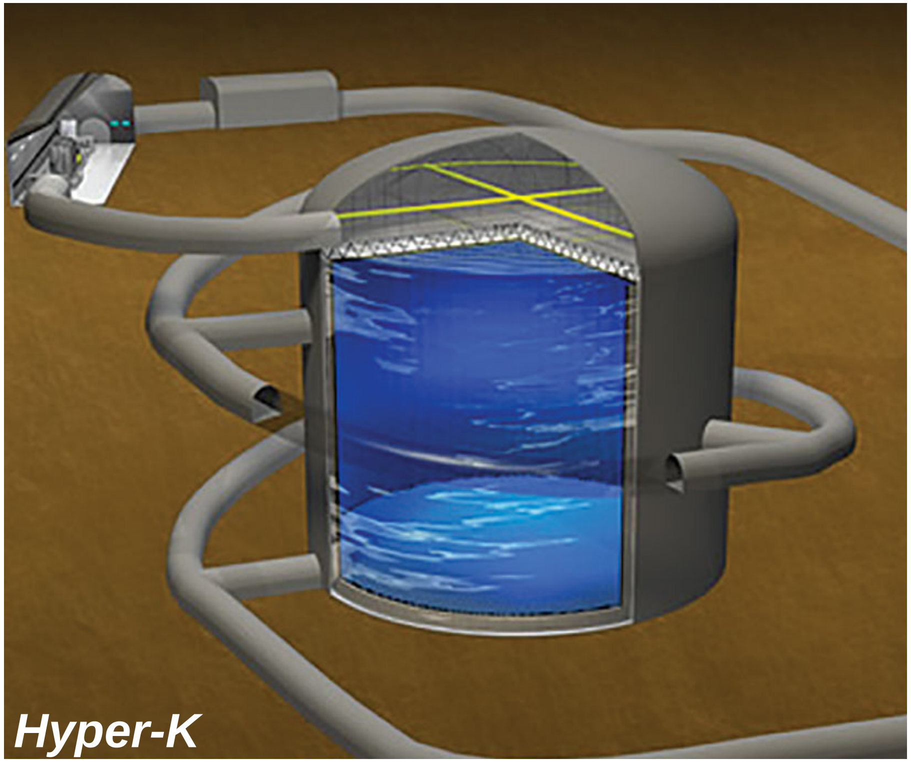


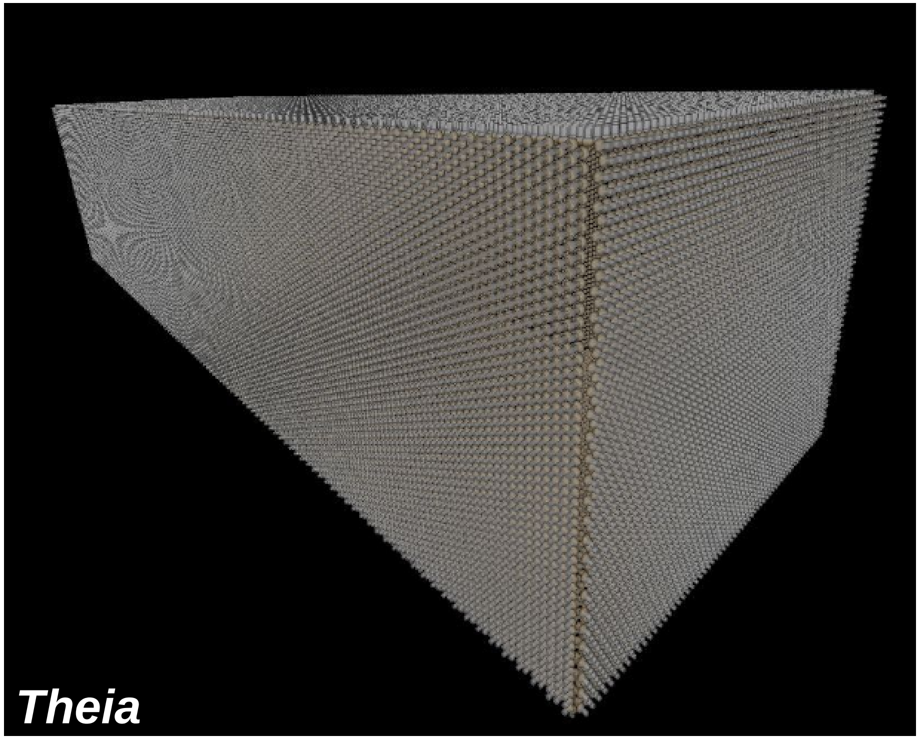
December 2019

Goal:
Provide Photon Wavelength Information for Large-Scale Neutrino Detectors

For water/ice Cherenkov detectors the scale of Hyper-K or Icecube, dispersion can spread photon arrival times by > 2 ns. Measuring time between long and short wavelength photons provides information about event position

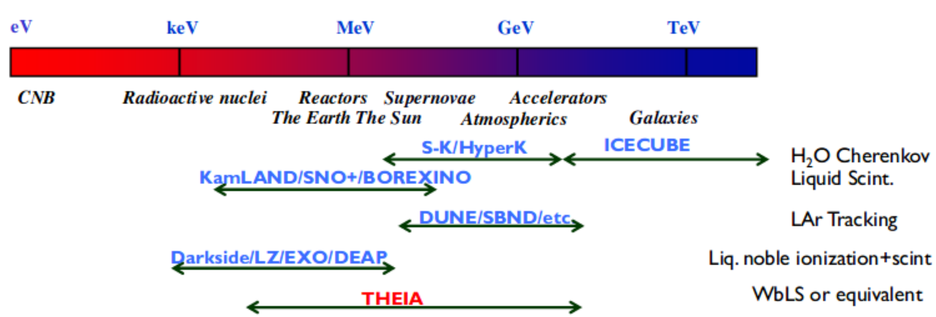
For scintillator or water-based scintillator detectors, measuring wavelength provides information about the process that created the photon (Cherenkov or scintillation)





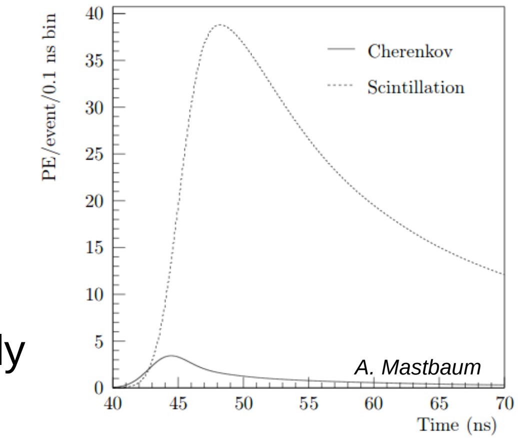
Cherenkov Light in a Liquid Scintillator Detector

- Charged particle traveling through liquid scintillator creates *both* scintillation (~10,000 photons/MeV) *and* Cherenkov light (~100 photons/MeV)
- Challenge is to detect the Cherenkov light, which provides the direction of the traveling particle. Typically use *timing* and *directionality.*
- High light yield from scintillator provides excellent energy and position resolution and low energy thresholds
- Cherenkov light allows one to reconstruct direction, improve particle ID
- Many applications towards future experiments: *Neutrinoless double beta decay, low energy solar neutrinos, reactor and geo antineutrinos, atmospheric neutrinos, long baseline physics*

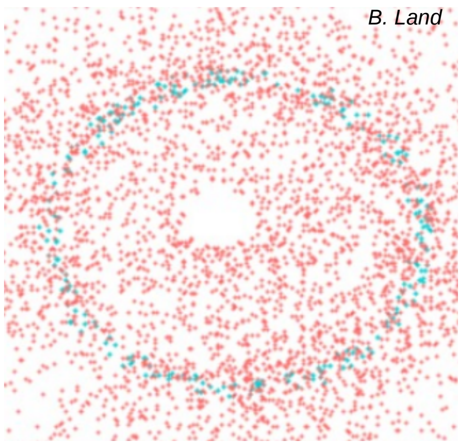


Schematic from J. Klein

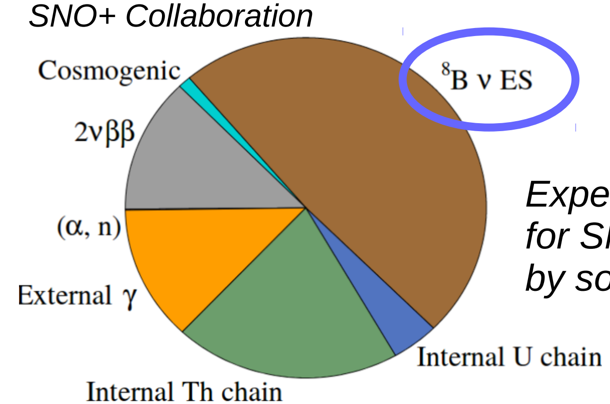
Example timing in large neutrino detector



Cherenkov ring on top of isotropic scintillation light

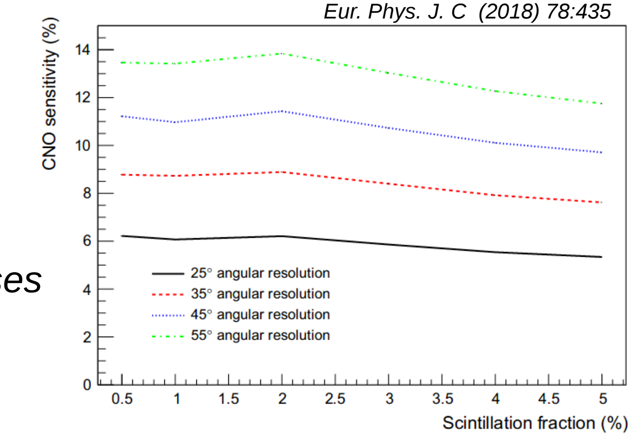


SNO+ Collaboration



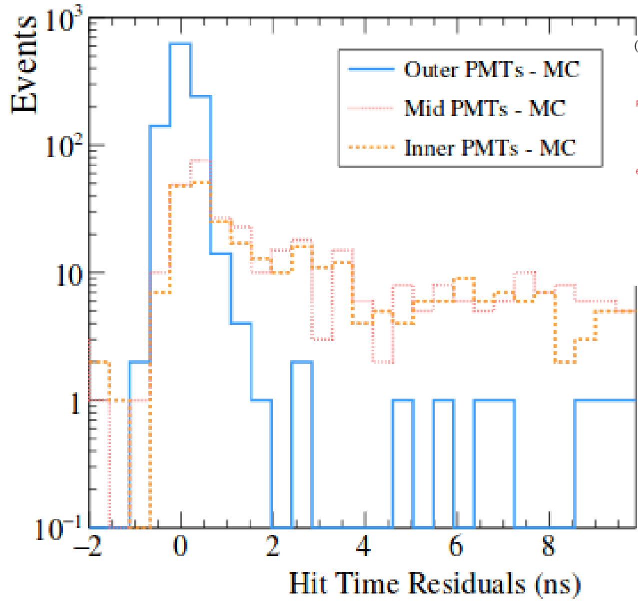
Expected background for SNO+ $0\nu\beta\beta$ dominated by solar neutrinos

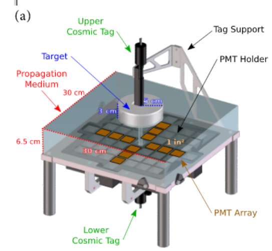
R. Bonventre, G.D. Orebi Gann, Eur. Phys. J. C (2018) 78:435

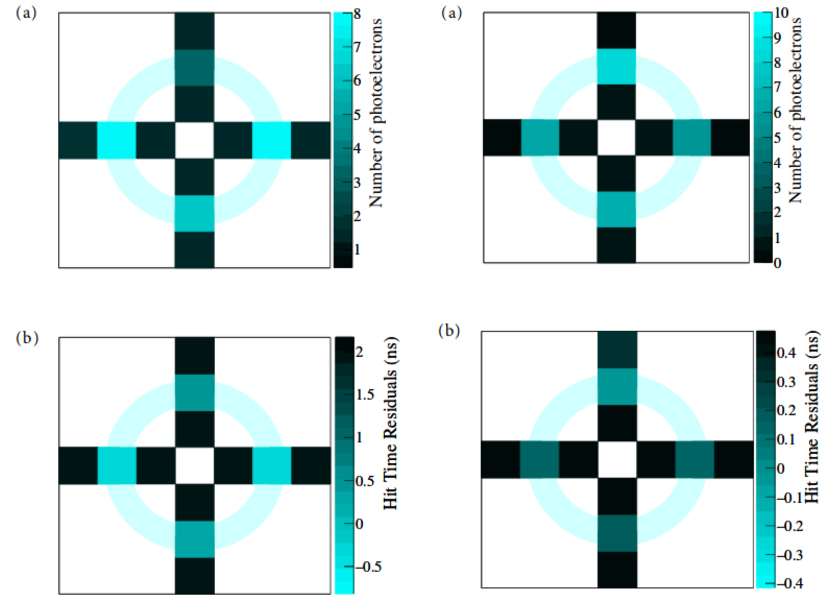


CNO sensitivity increases with improved direction reconstruction

Ongoing R&D for Cherenkov / Scintillation Separation

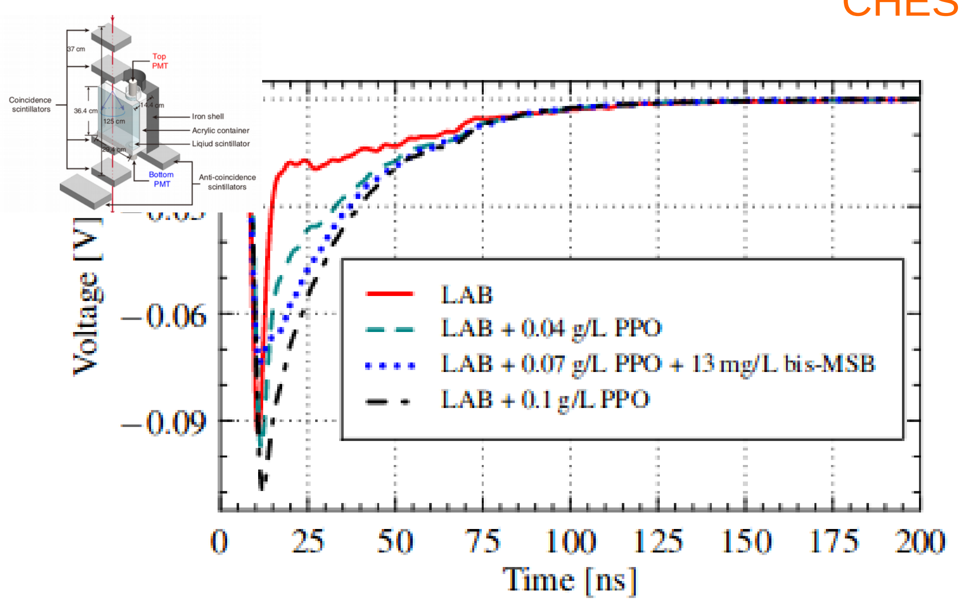






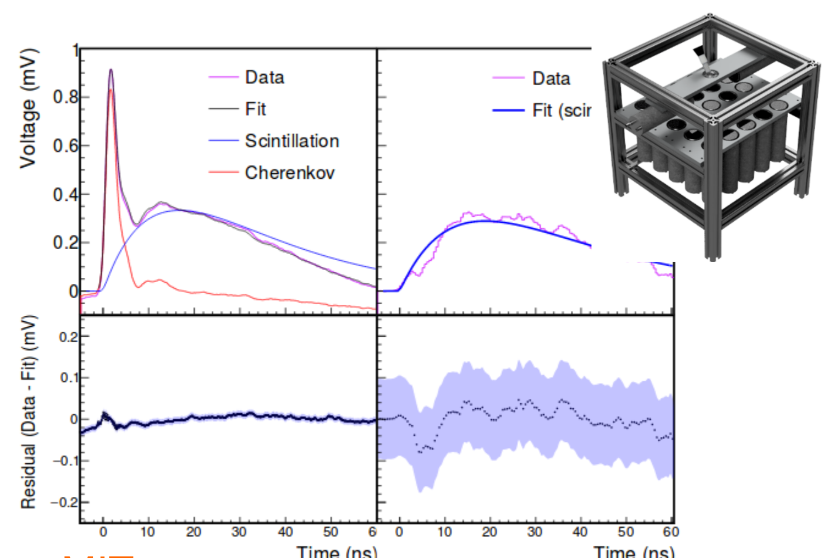
CHESS setup at LBNL

J. Caravaca et. al, 10.1103/PhysRevC.95.055801



Slow scintillator characterization for Jinping

Z. Guo et. al, 10.1016/j.astropartphys.2019.02.001

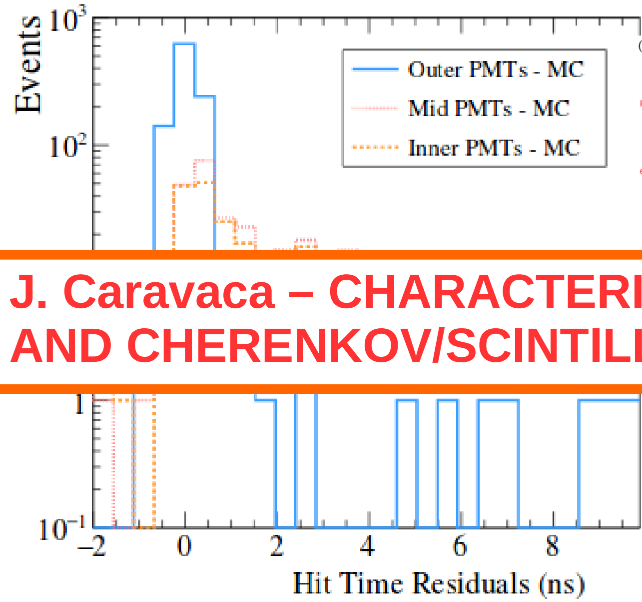


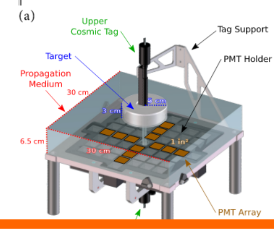
FlatDot at MIT

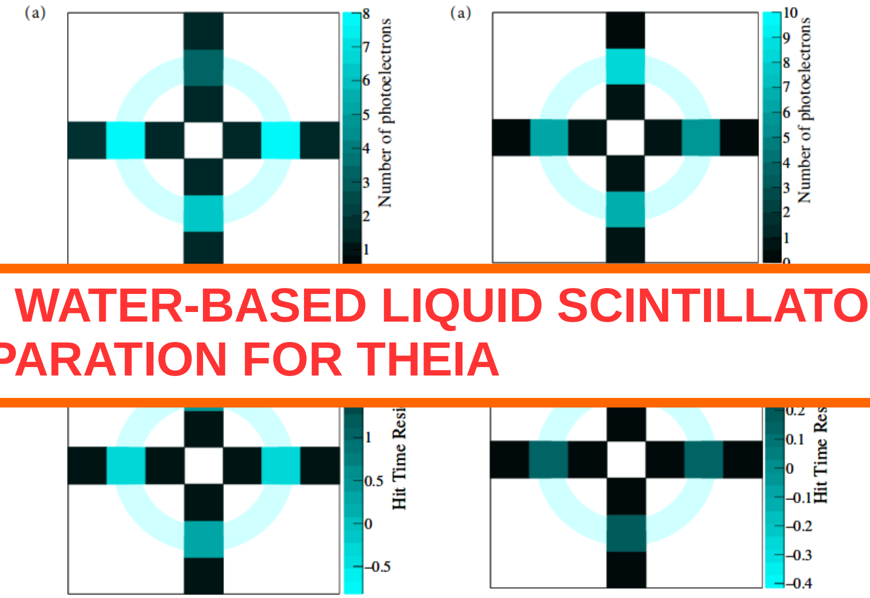
J. Gruszko, et. al, 10.1088/1748-0221/14/02/P02005

Only timing and isotropy used to identify the Cherenkov light.

Ongoing R&D for Cherenkov / Scintillation Separation



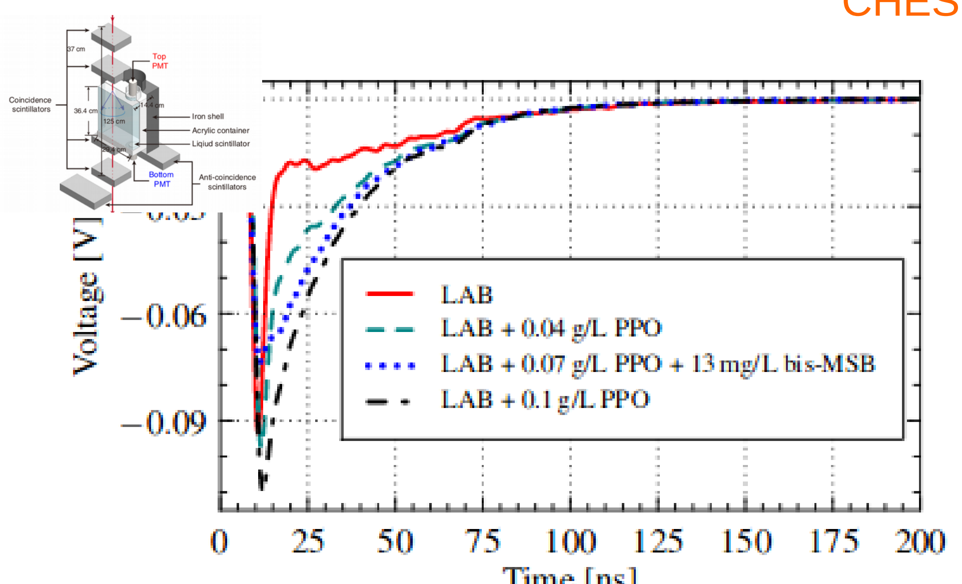




J. Caravaca – CHARACTERIZATION OF WATER-BASED LIQUID SCINTILLATOR AND CHERENKOV/SCINTILLATION SEPARATION FOR THEIA

CHESS setup at LBNL

J. Caravaca et. al, 10.1103/PhysRevC.95.055801



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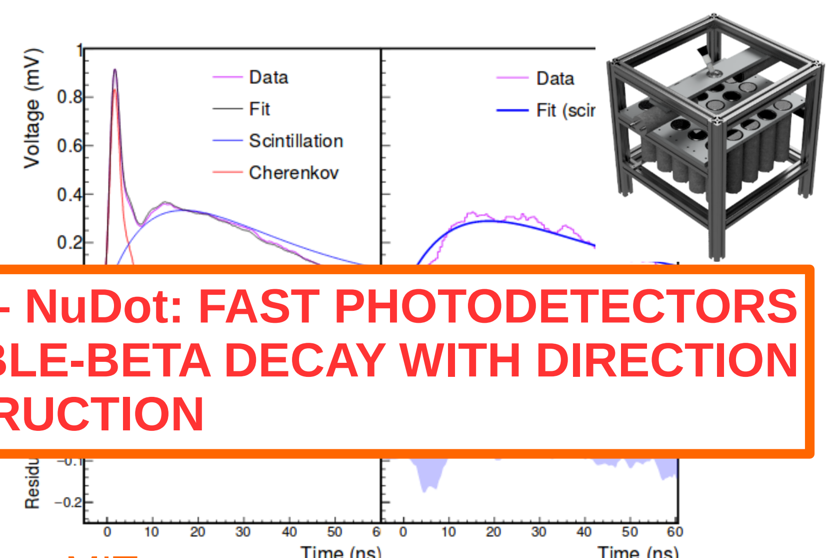


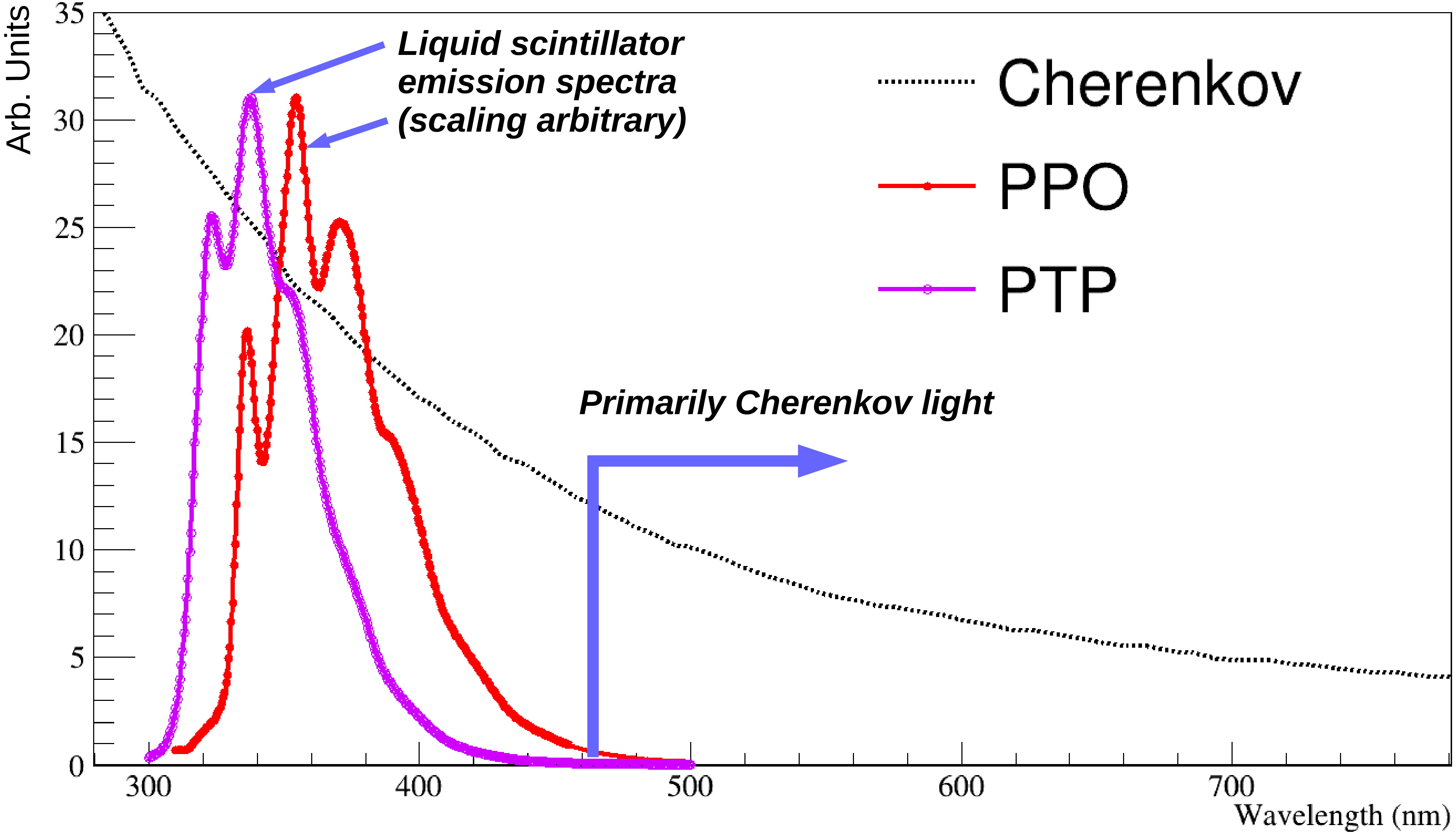
J. Gruzko – NuDot: FAST PHOTODETECTORS FOR DOUBLE-BETA DECAY WITH DIRECTION RECONSTRUCTION

FlatDot at MIT

J. Gruszko, et. al, 10.1088/1748-0221/14/02/P02005

Only timing and isotropy used to identify the Cherenkov light.

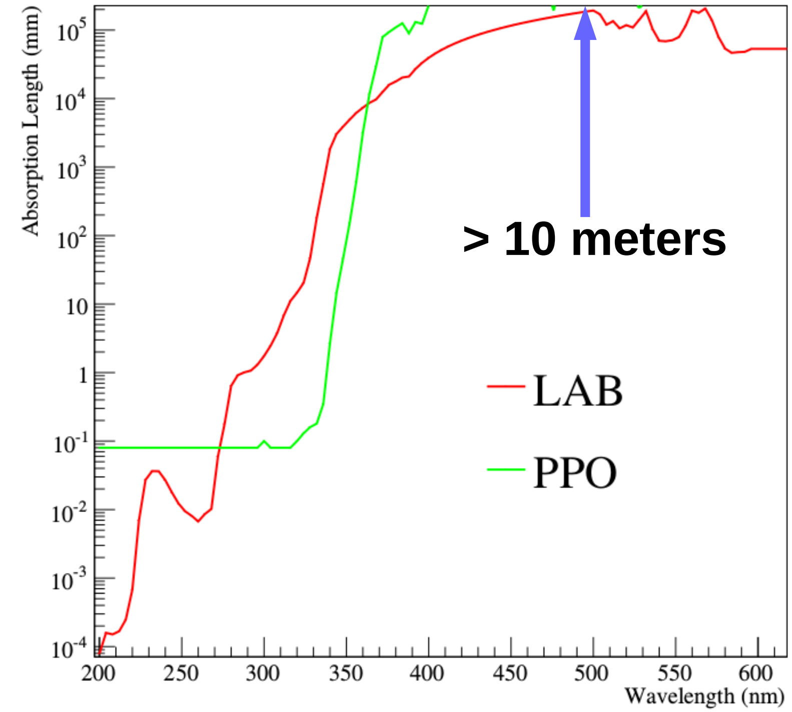
Separating Cherenkov and Scintillation Light Using Wavelength

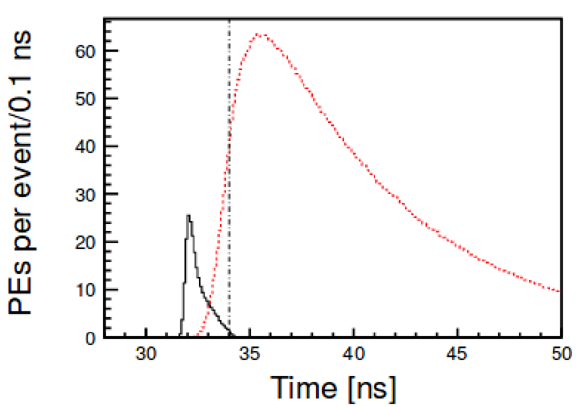


Goal is to achieve Cherenkov and scintillation separation while losing as few total photons as possible.

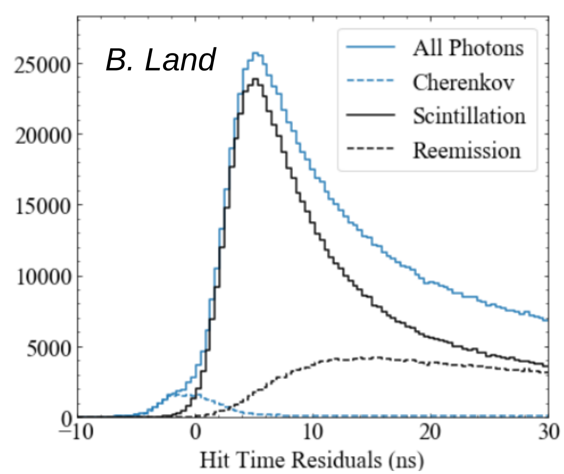
Advantages of Long-Wavelength Light

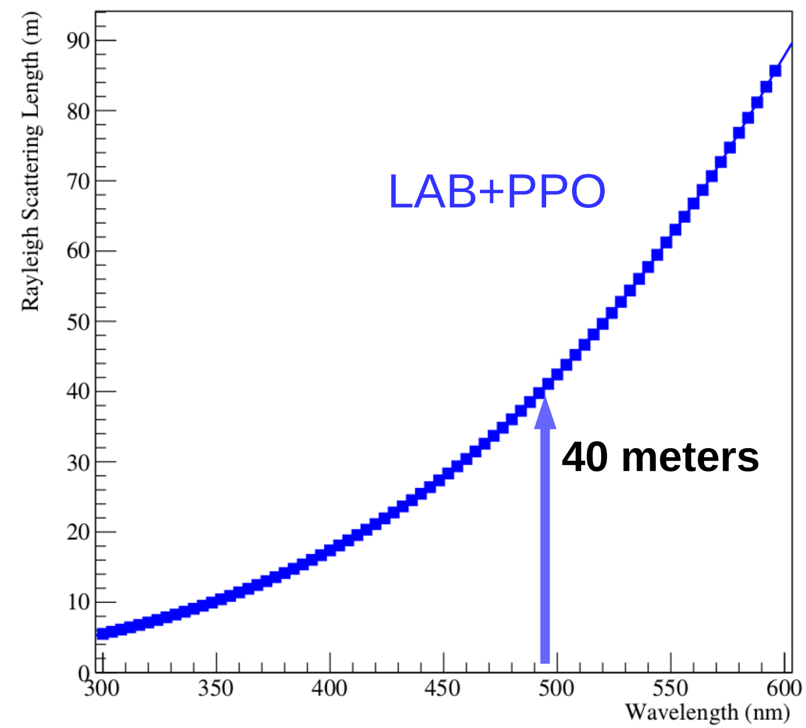
- Raleigh scattering length and absorption length increase with wavelength → the longer wavelength Cherenkov light maintains its directionality
- Simulations of KamLAND-like detector showed ability to separate Cherenkov and scintillation using red-sensitive photocathodes and fast-timing
- In even larger detectors, chromatic dispersion starts to help separate the components further





(c) Red-sensitive photocathode.

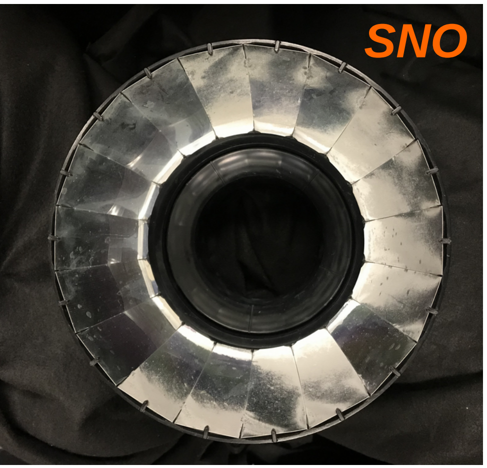


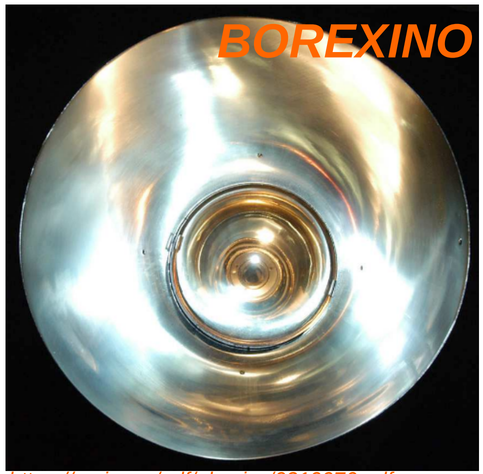


L. Winslow et. al, 10.1088/1748-0221/9/06/P06012

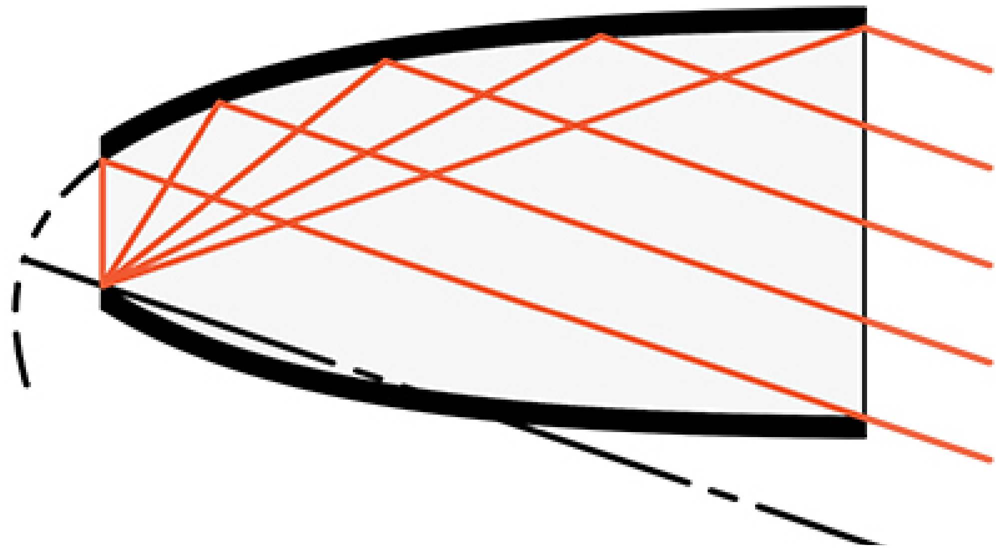
Combining Two Technologies

Winston Cones

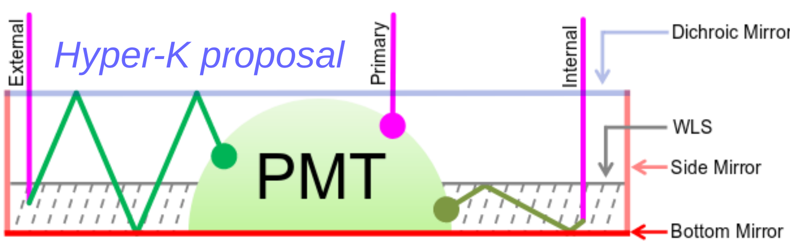




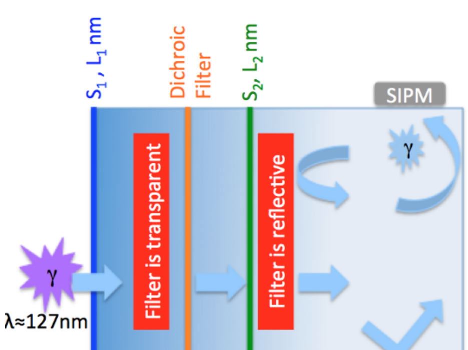
https://arxiv.org/pdf/physics/0310076.pdf



Dichroic Filters

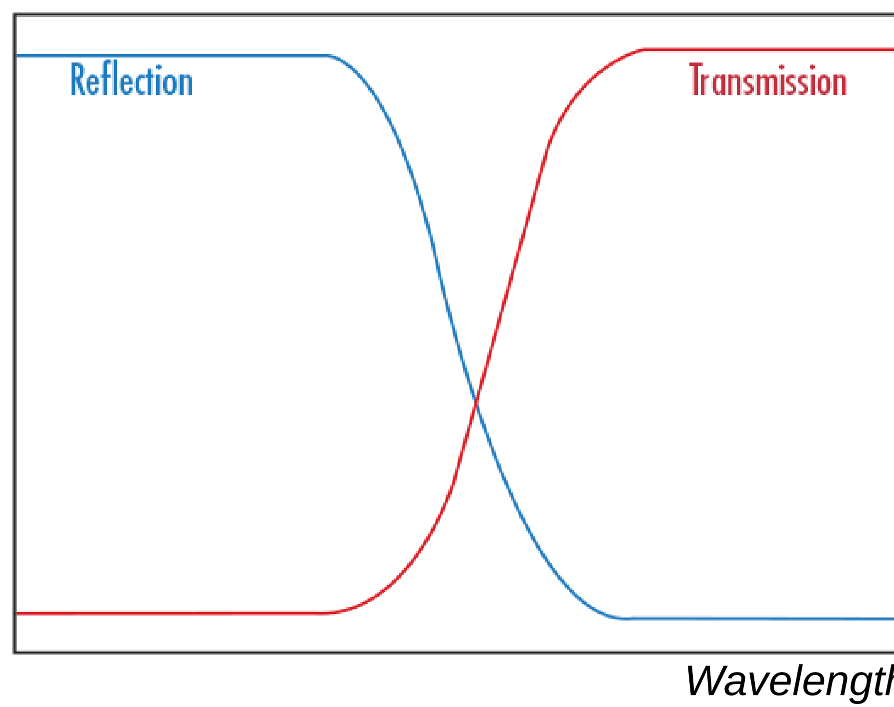


C. Rott et al. JINST 12 (2017)

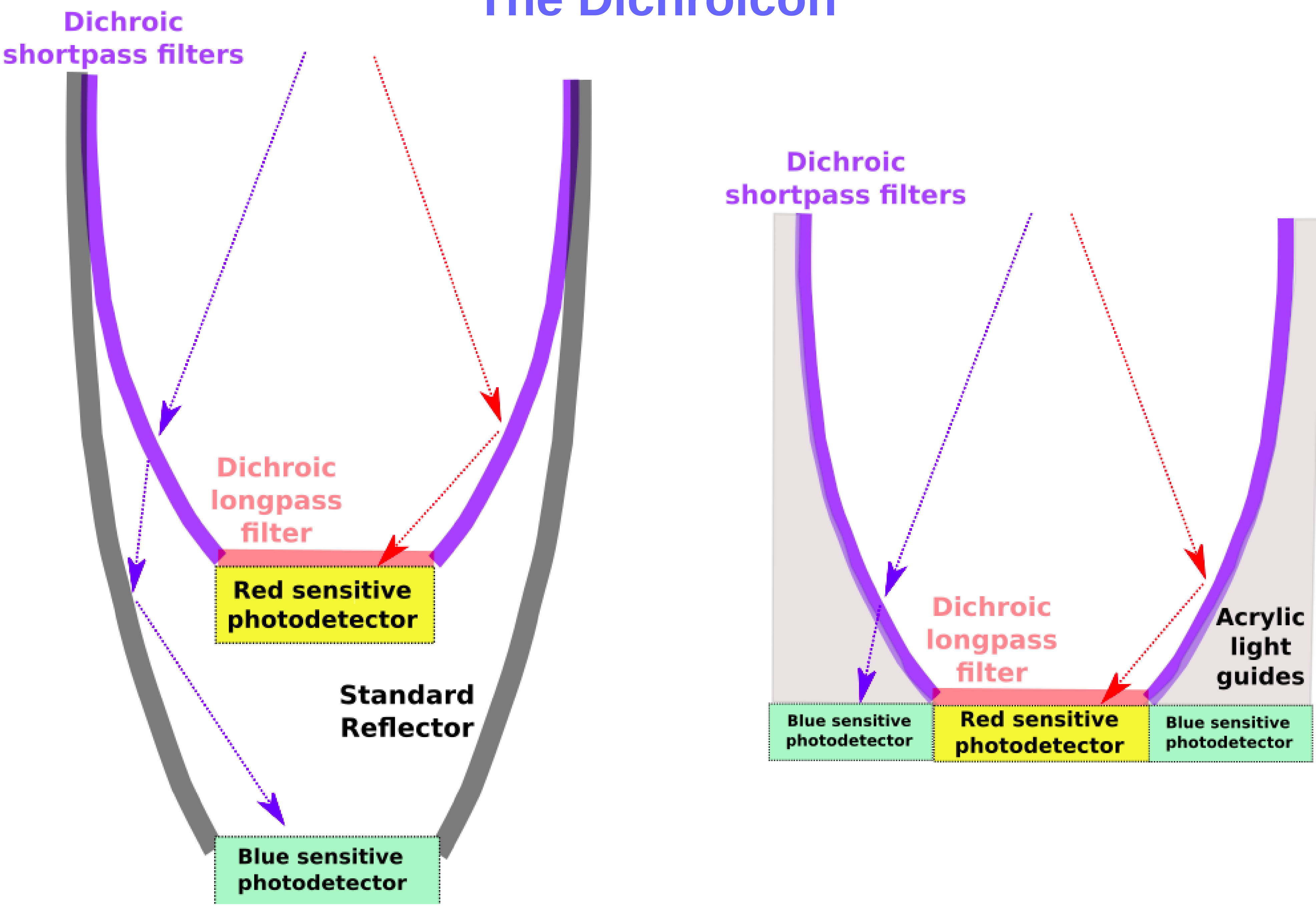


ARAPUCA for DUNE

E. Segreto et al., JINST 13 (2018)

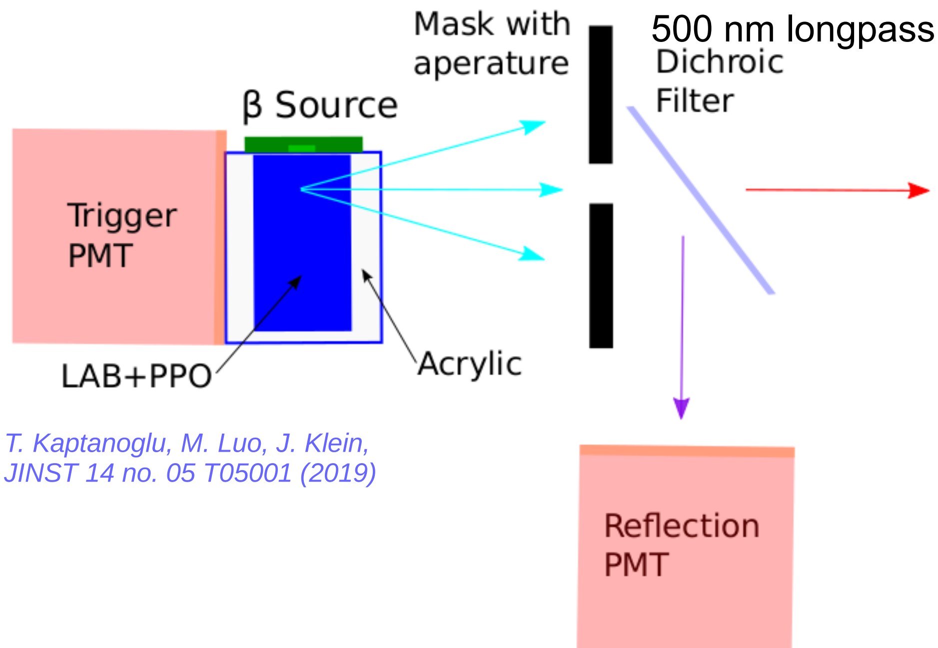


The Dichroicon



Complementary to WbLS, slow scintillator, fast photdetectors, etc.

Spectral Sorting with Dichroic Filters

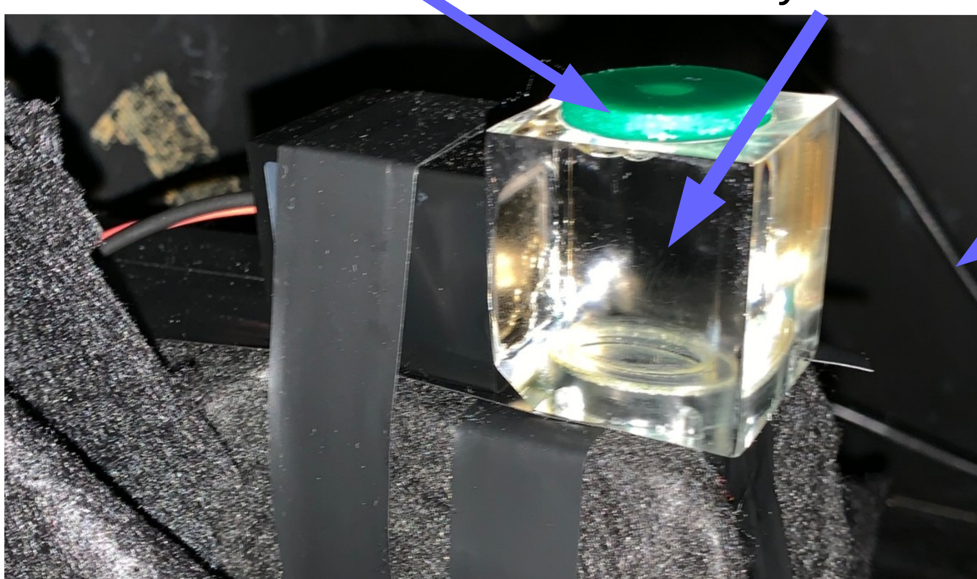


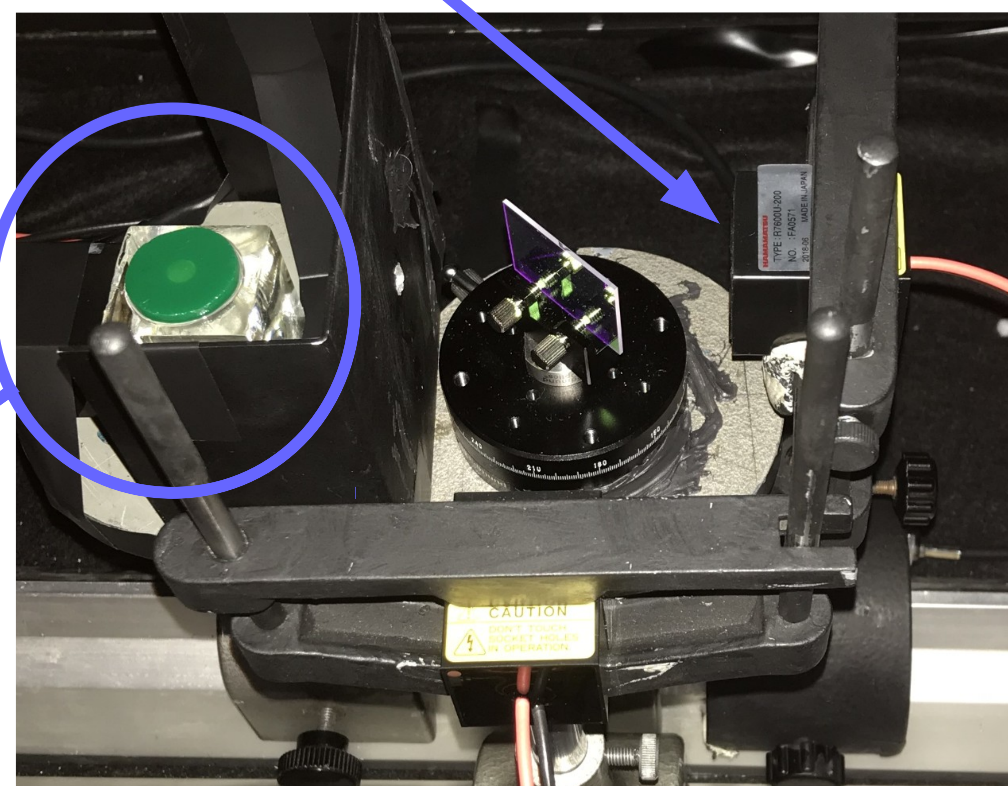
T. Kaptanoglu, M. Luo, J. Klein, JINST 14 no. 05 T05001 (2019)

Demonstration of technology with single dichroic filter

^{90}Sr source

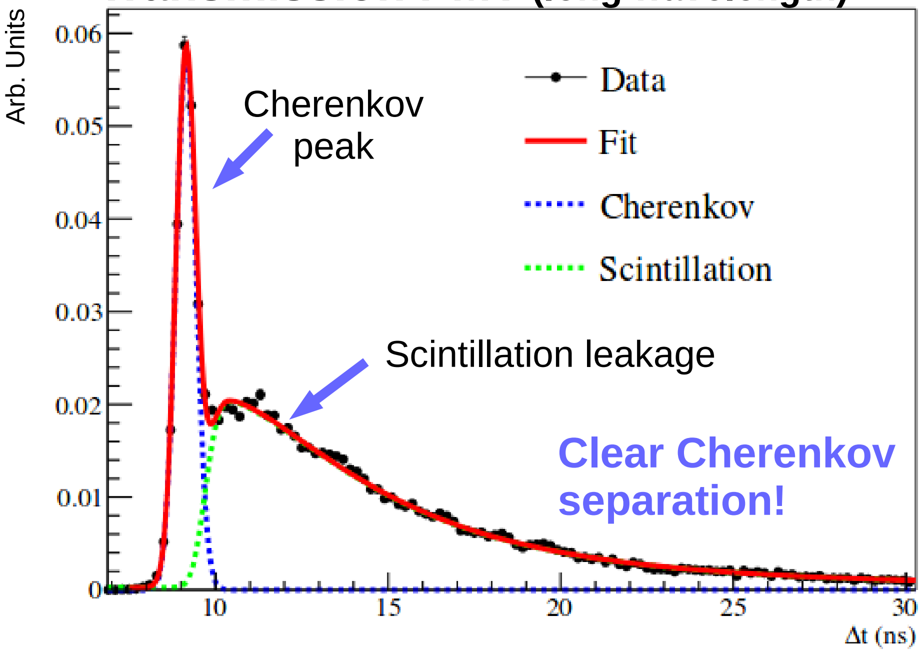
LAB+PPO in UVT acrylic



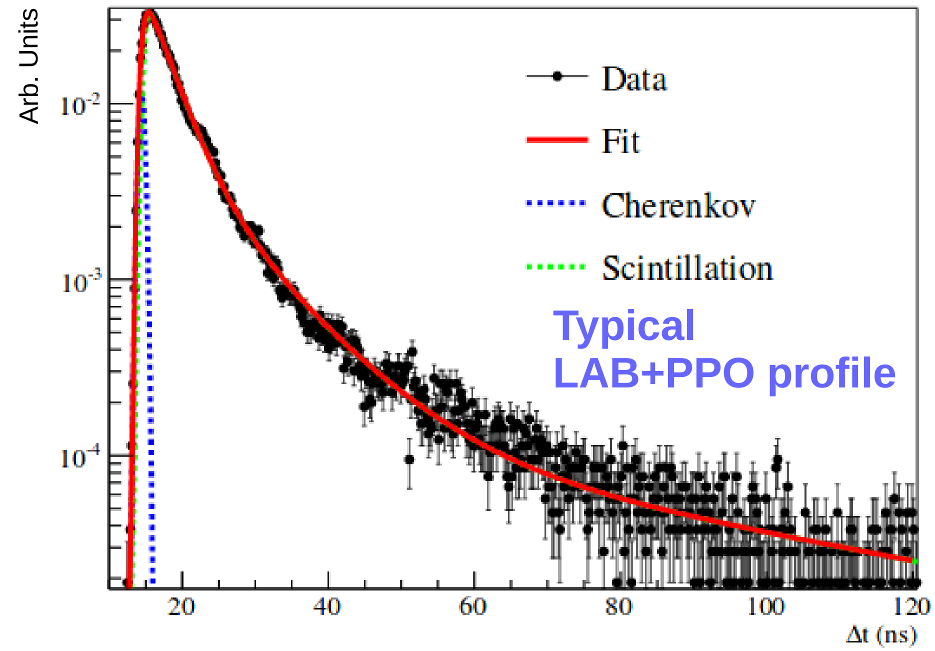


Spectral Sorting with Dichroic Filters

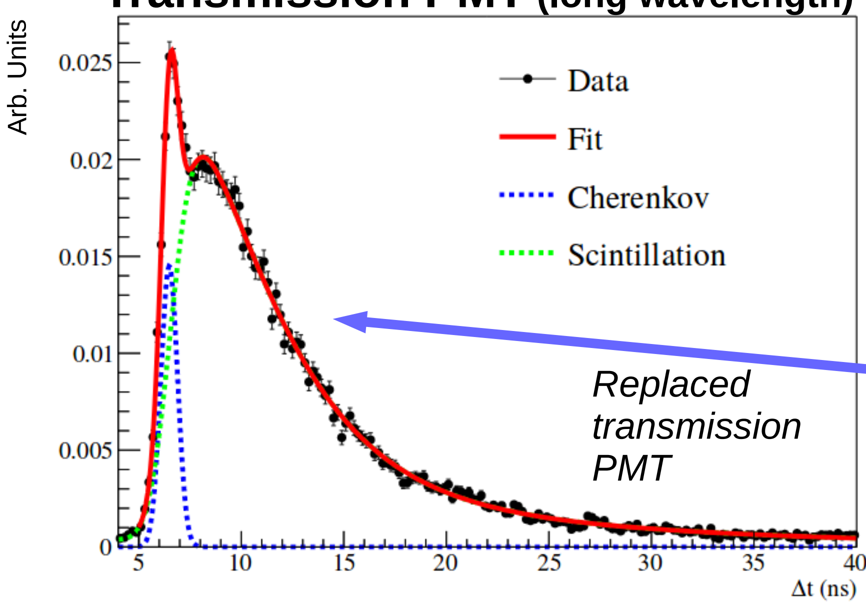
Transmission PMT **(long wavelength)**



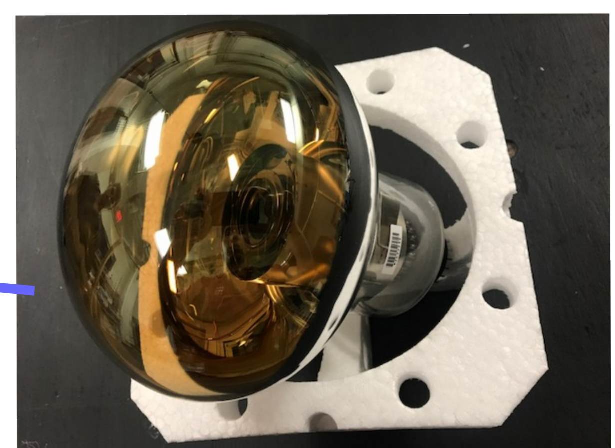
Reflection PMT **(short wavelength)**



Transmission PMT **(long wavelength)**



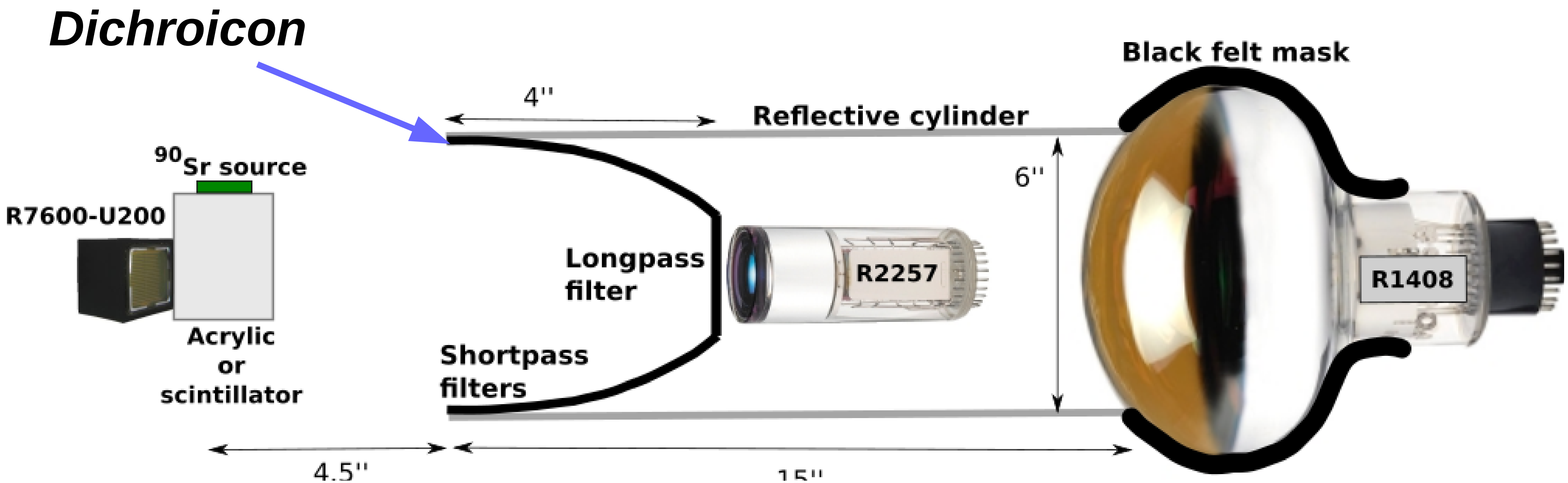
Photon sorting allows Cherenkov and scintillation separation with high efficiency collection of scintillation light

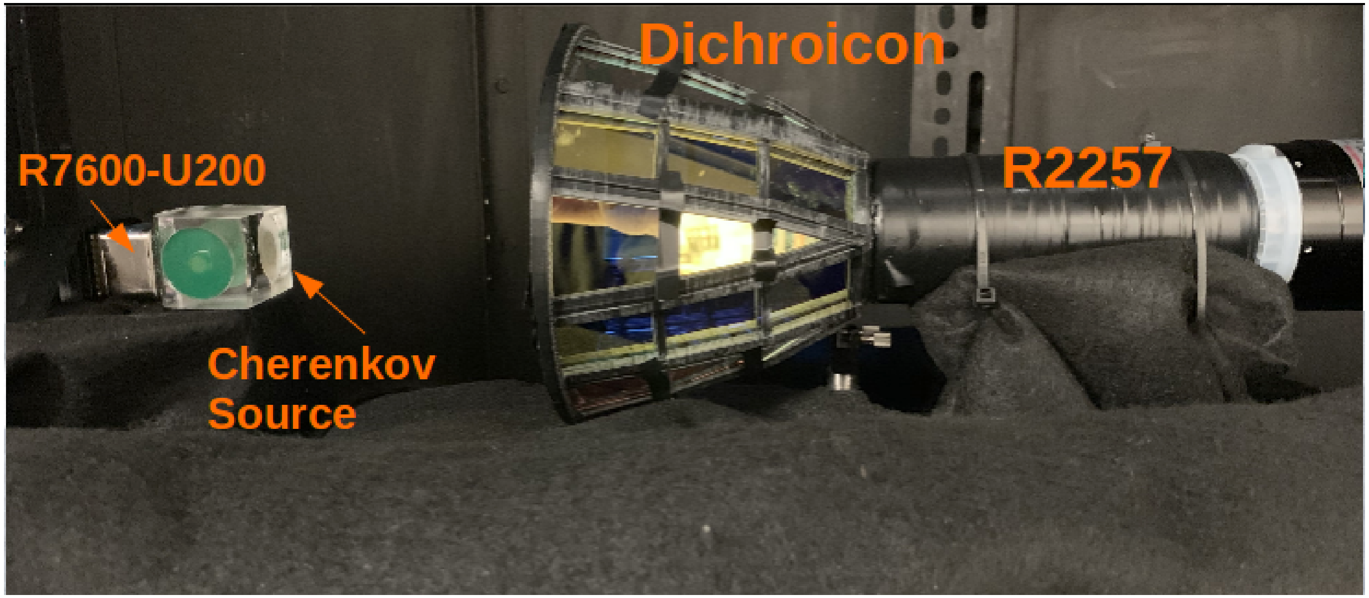


First demonstration of Cherenkov / scintillation separation using large-area PMT!

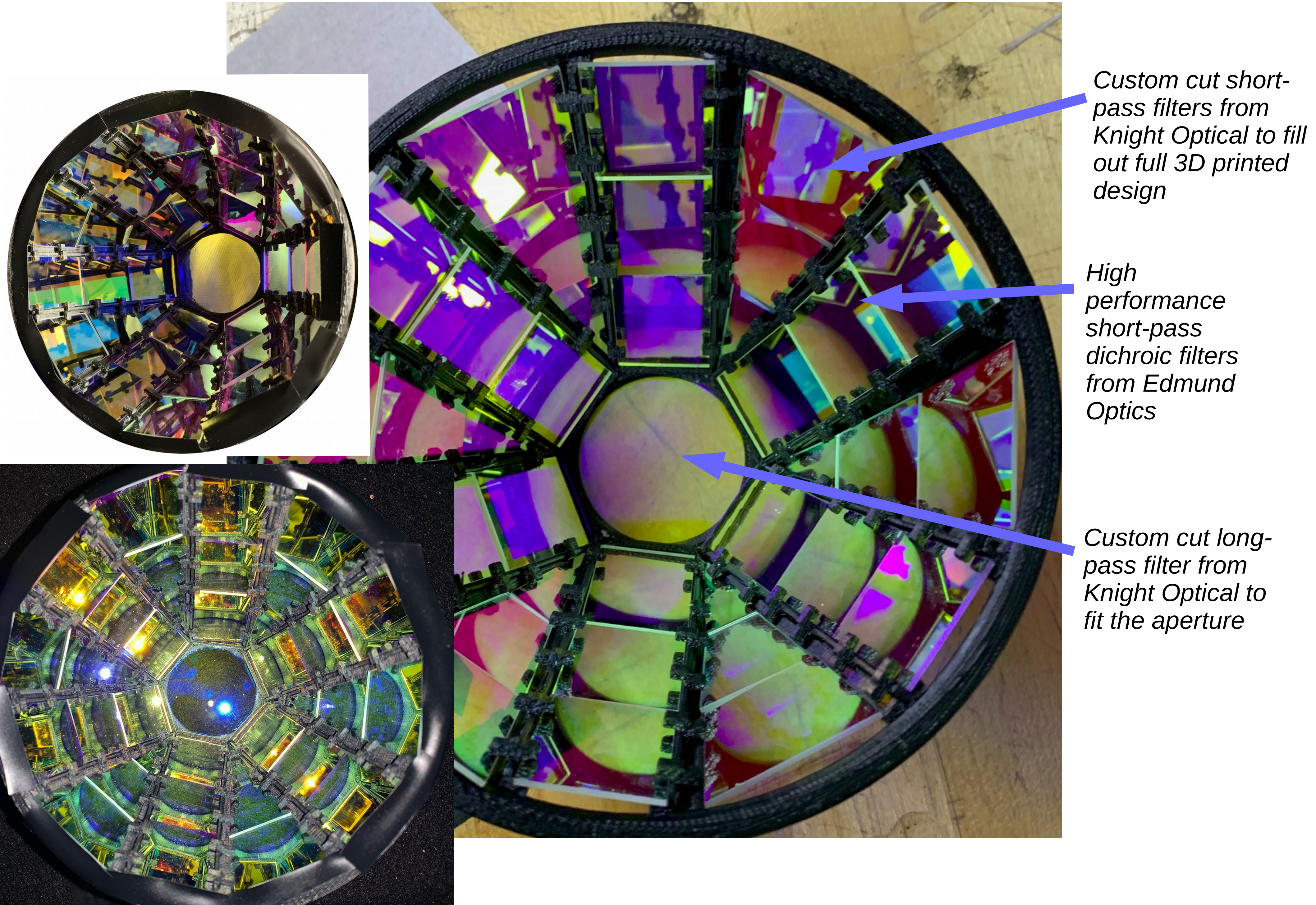
T. Kaptanoglu, Nucl. Instrum. Meth. A889 (2018) 69-77
T. Kaptanoglu, M. Luo, J. Klein, JINST 14 no. 05 T05001 (2019)

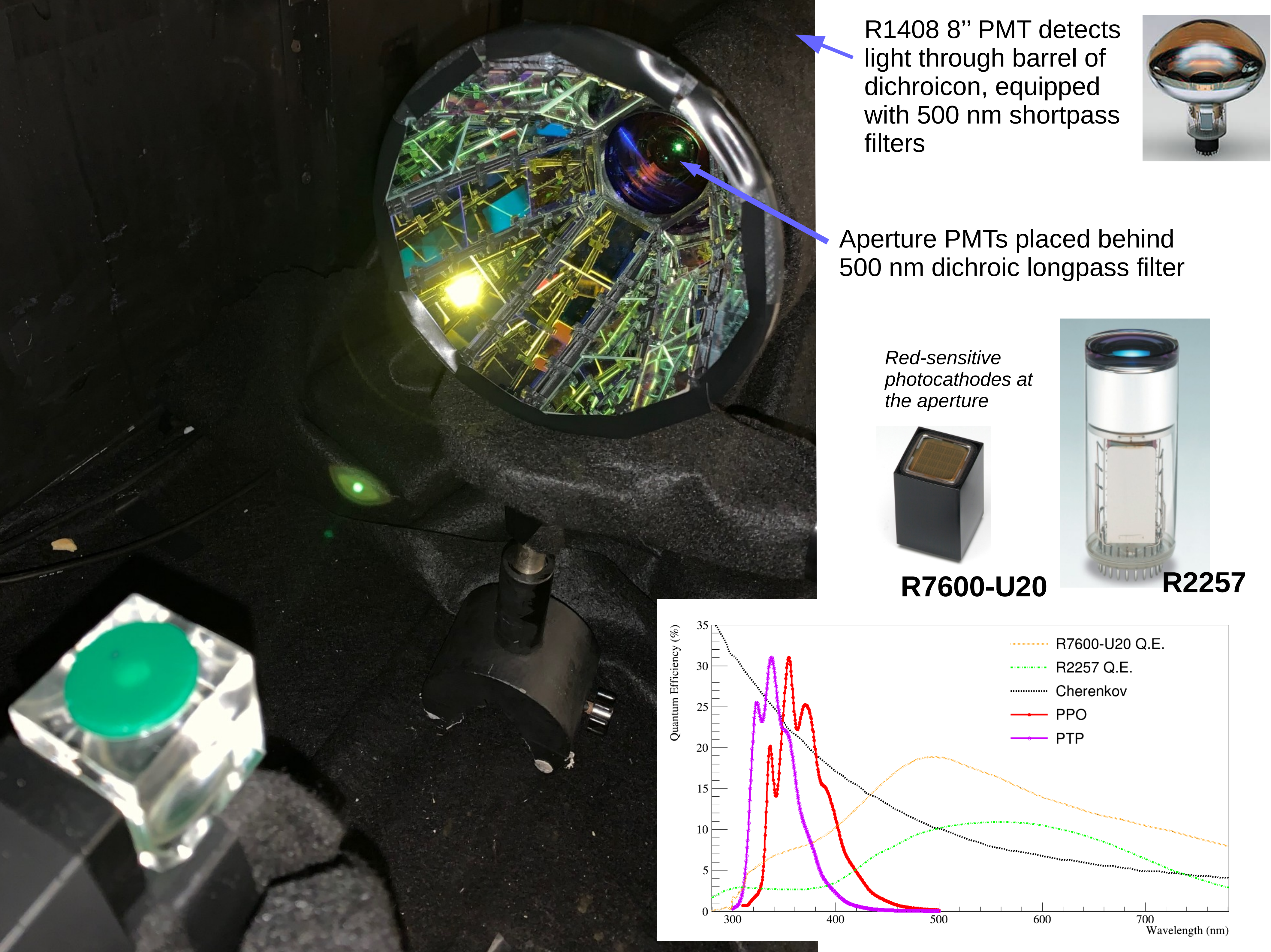
Bench-Top Setup



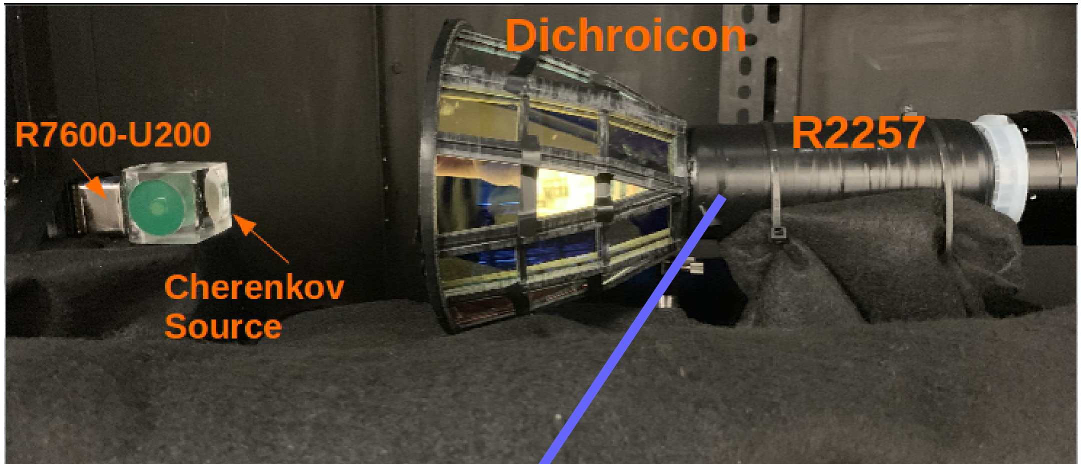


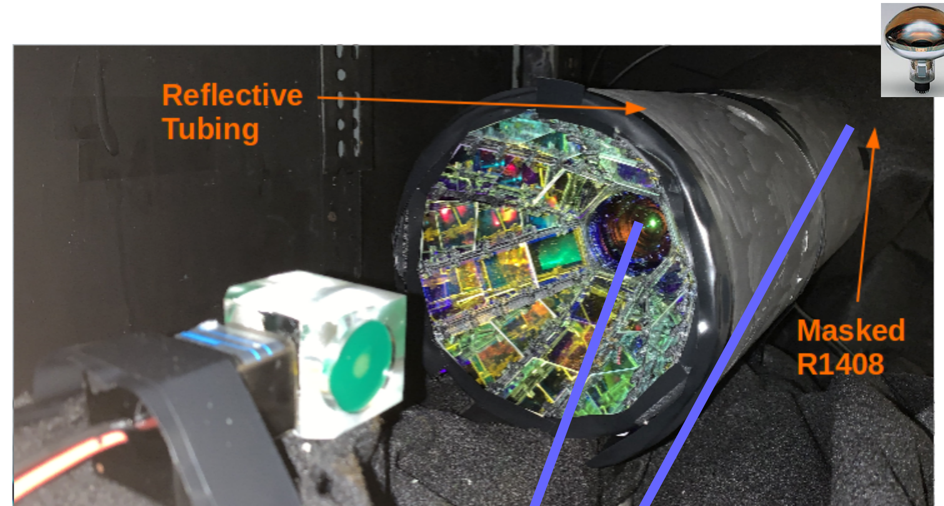
3D Printed Filter Holder

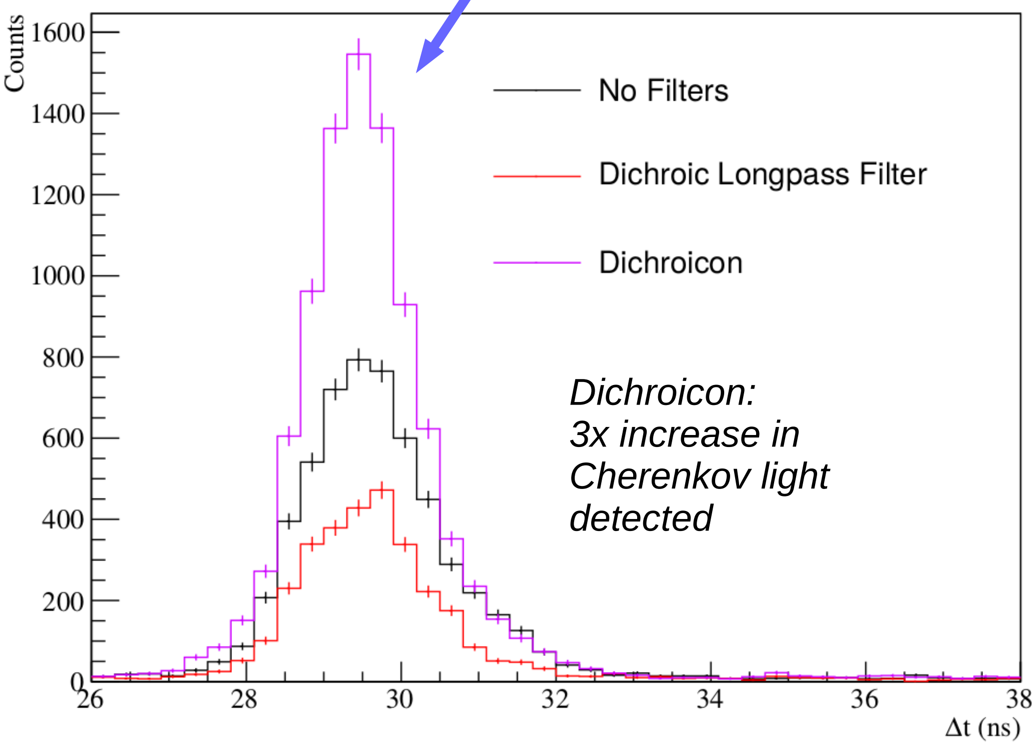


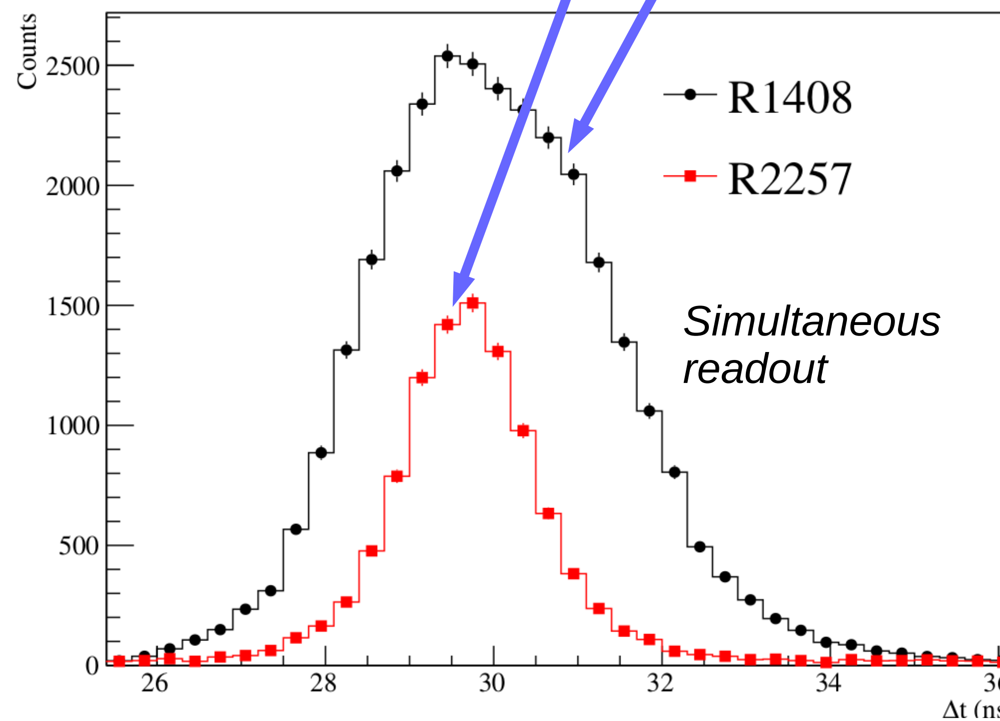

R1408 8'' PMT detects light through barrel of dichroicon, equipped with 500 nm shortpass filters
Aperture PMTs placed behind 500 nm dichroic longpass filter
Red-sensitive photocathodes at the aperture
R7600-U20
R2257
Quantum Efficiency (%)
Wavelength (nm)
R7600-U20 Q.E.
R2257 Q.E.
Cherenkov
PPO
PTP
0
5
10
15
20
25
30
35
300
400
500
600
700

Dichroicon Data with a Cherenkov Source

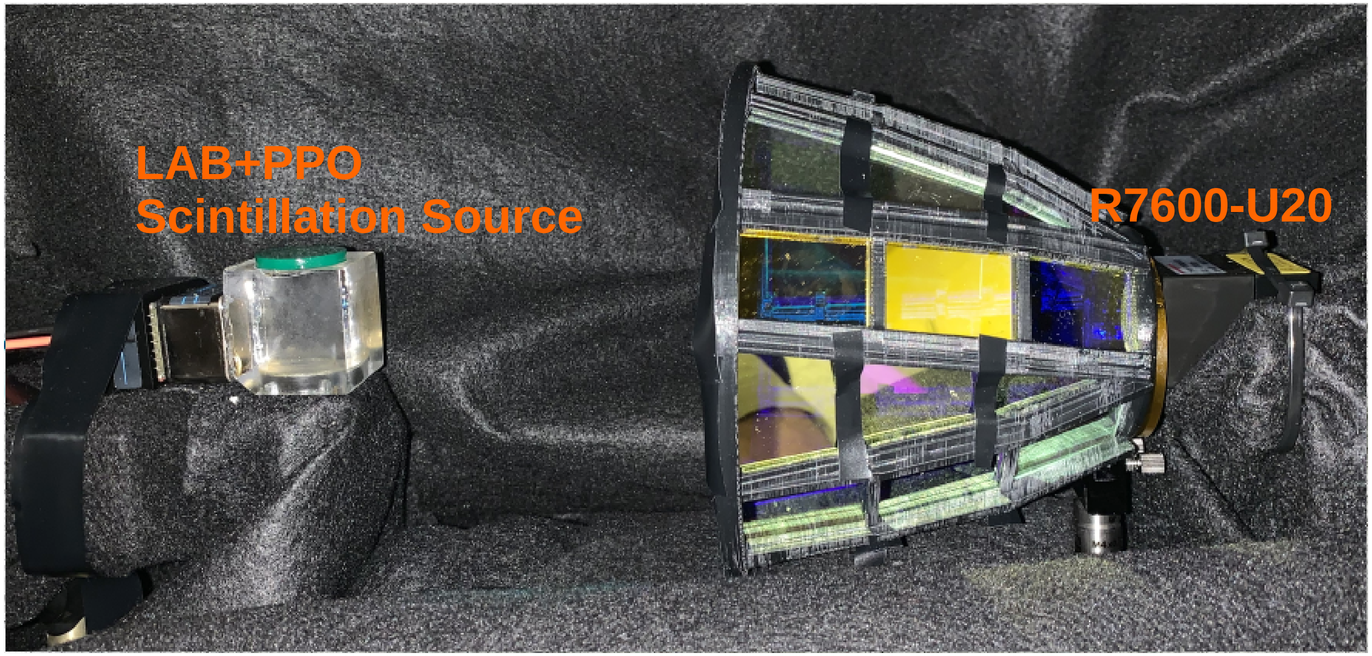


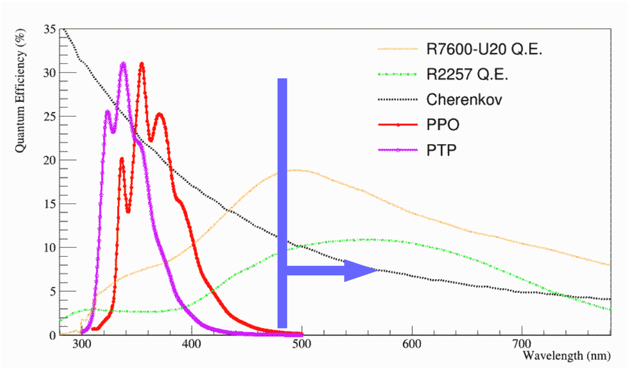


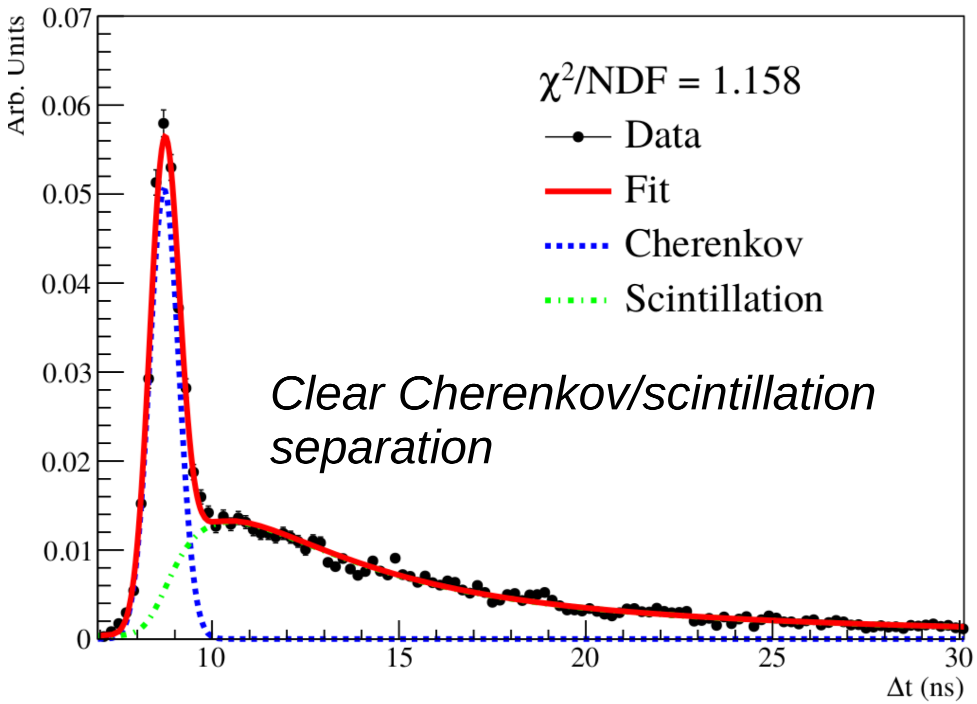




Dichroicon Data with a LAB+PPO Target

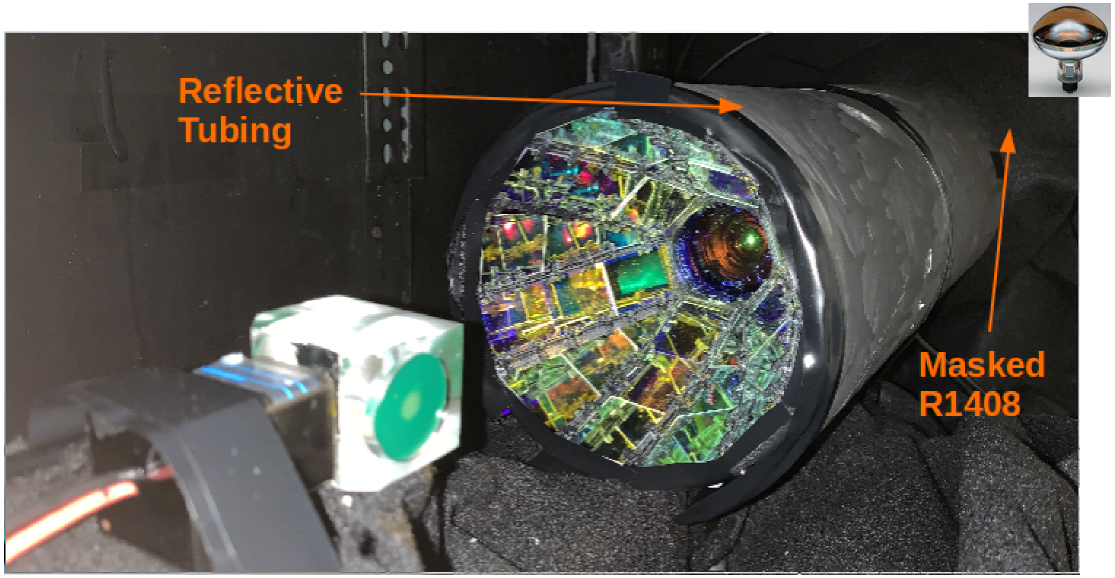




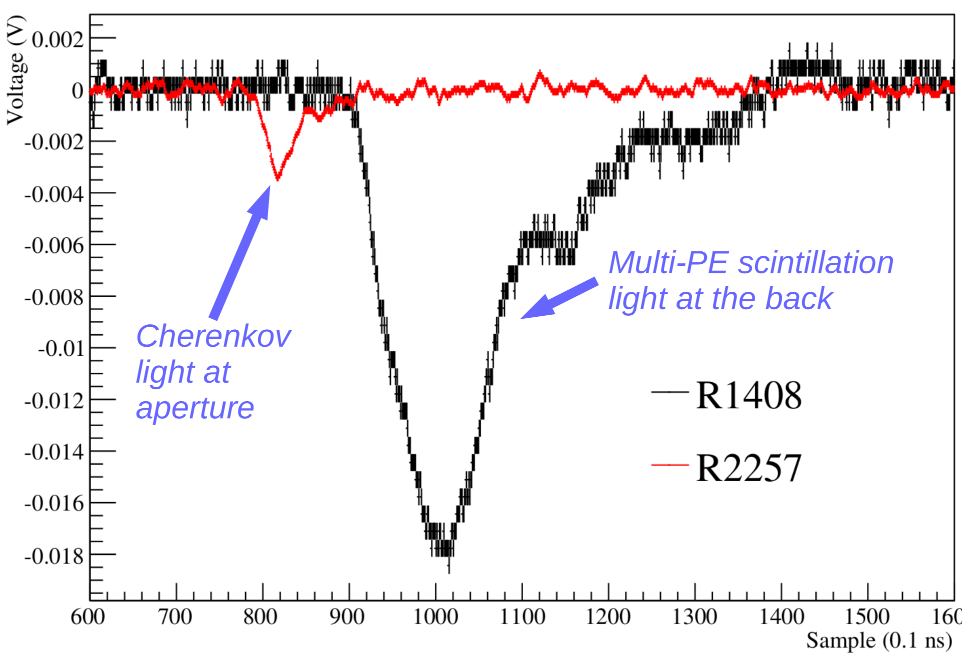


- Total Cherenkov light collected (extracted from the fit) is consistent with Cherenkov source data
- Purity of Cherenkov light in prompt window > 90%

Simultaneous Detection of Cherenkov and Scintillation Light

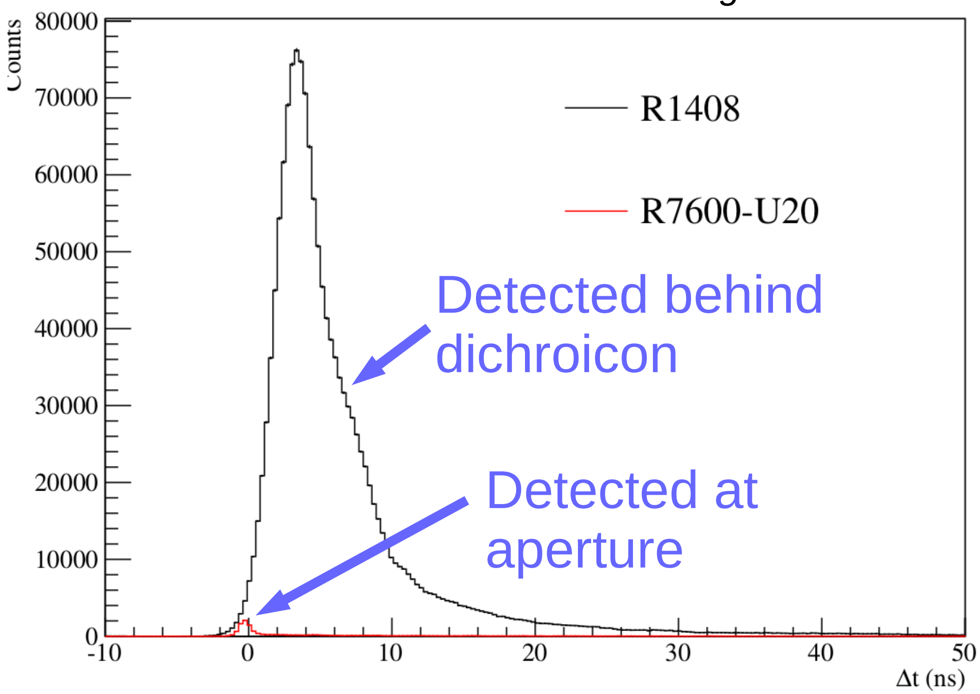


Photon sorting allows you to detect Cherenkov light with one PMT and scintillation light with the other, even with overwhelming scintillation light yield



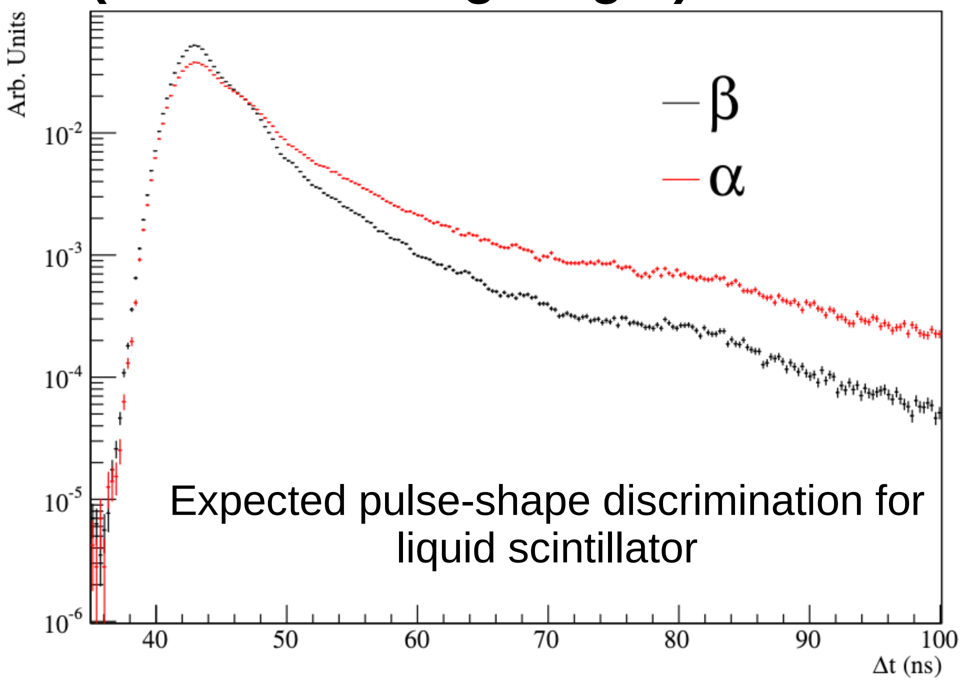
Identify Cherenkov and scintillation light in the same event

500x more scintillation light than Cherenkov light

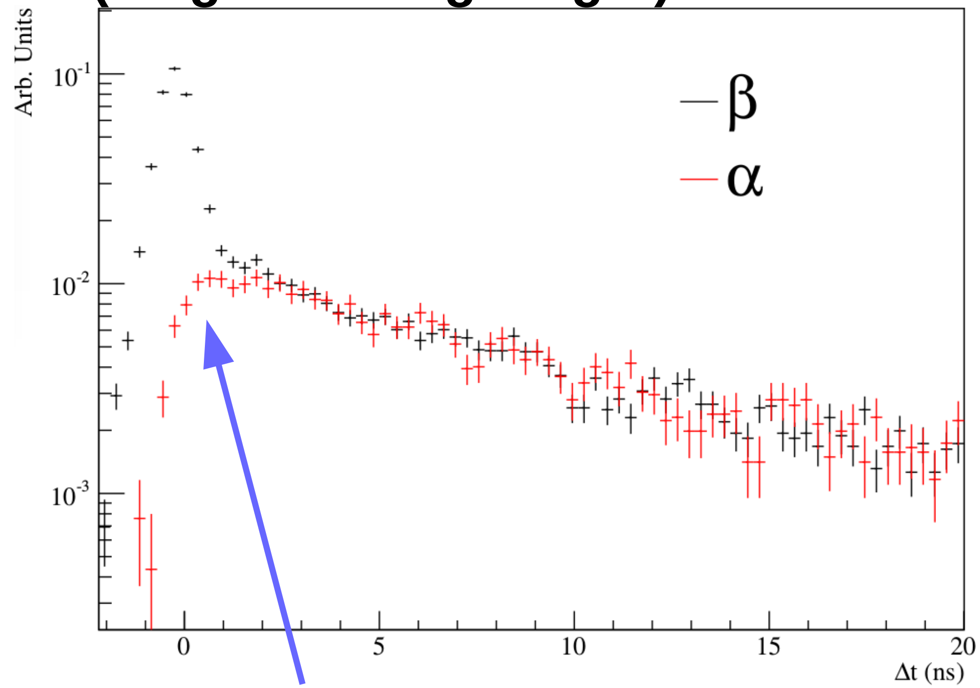


Dichroicon Data with an Alpha Source

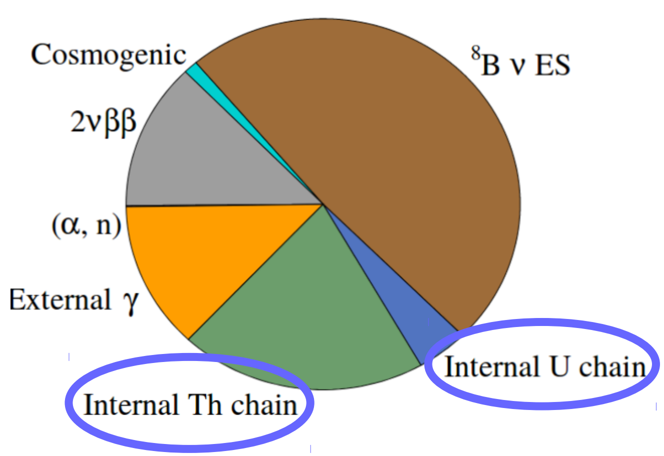
Detected by the R1408 PMT
(short wavelength light)



Detected by PMT at aperture
(long wavelength light)



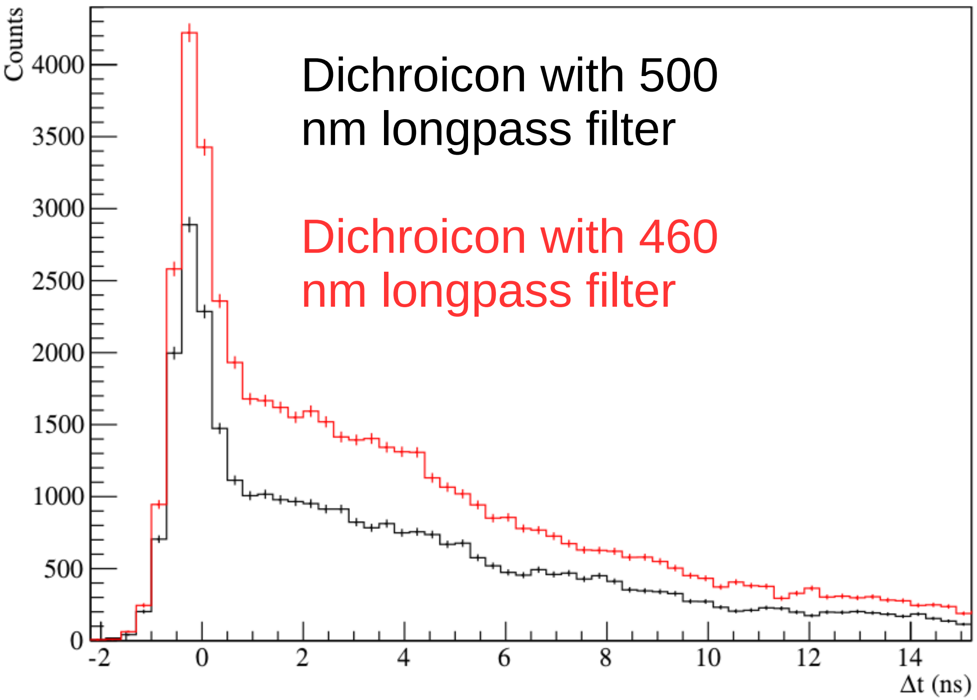
Additional Particle ID using the Cherenkov light!



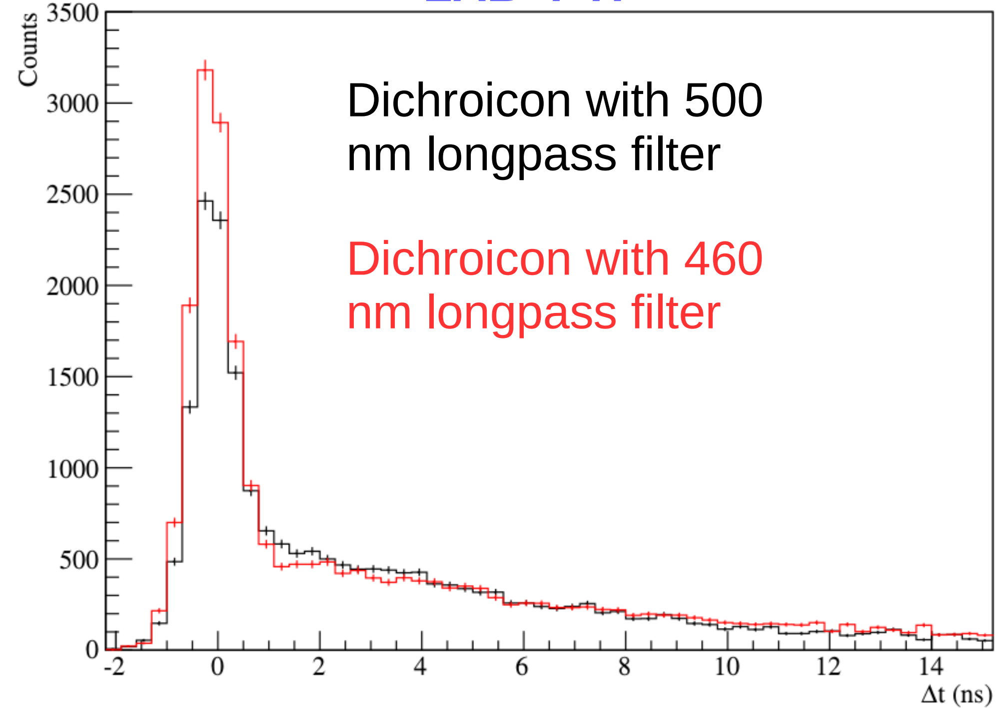
Improved α/β separation particularly important for background reduction for the low energy program

Dichroicon Data with Liquid Scintillator Targets and Two Different Central Dichroic Filters

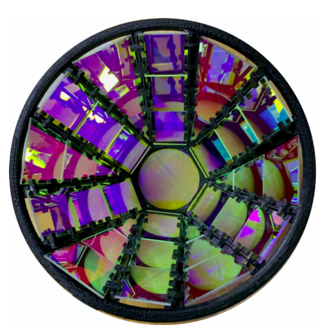
LAB+PPO

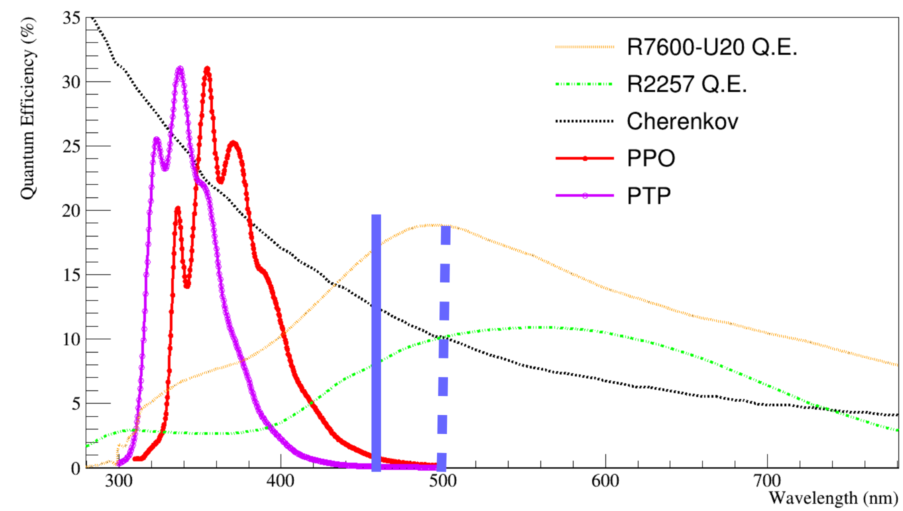


LAB+PTP



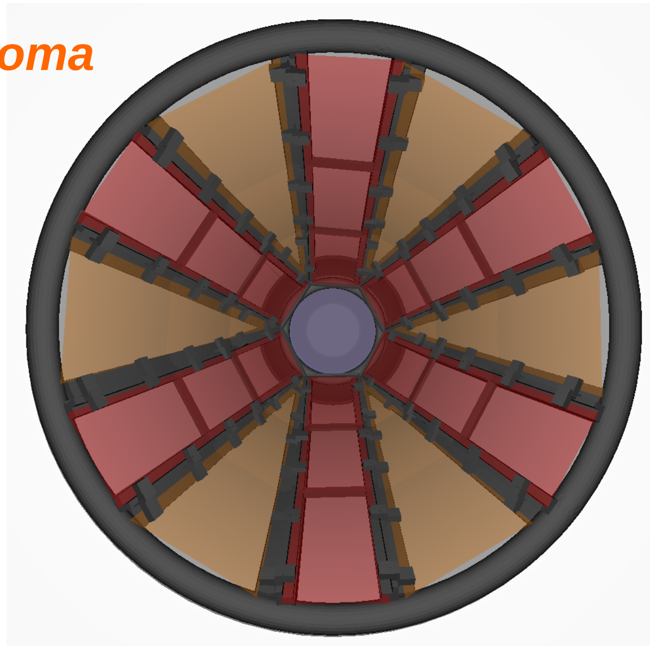
Filters used in the dichroicon should be carefully based on detector and target material. Detailed study ongoing using Chroma and RAT-PAC.

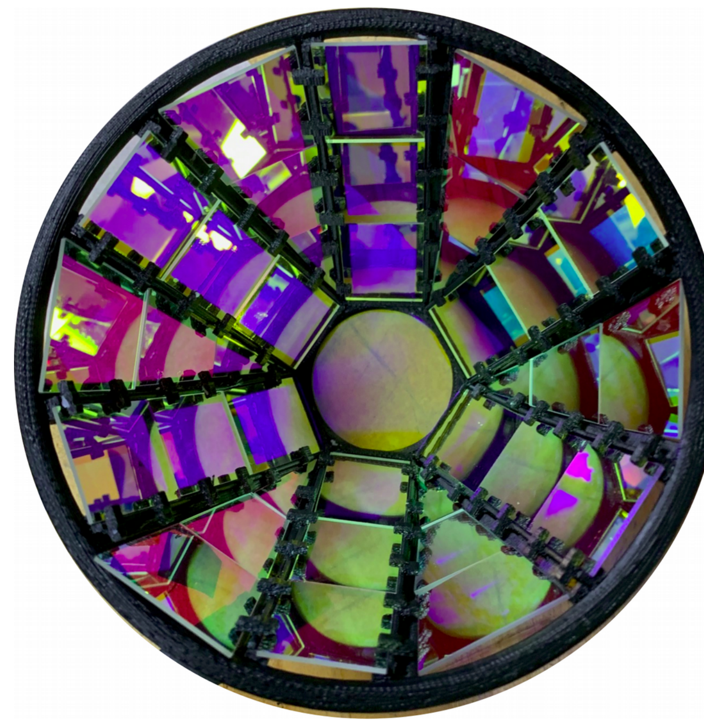


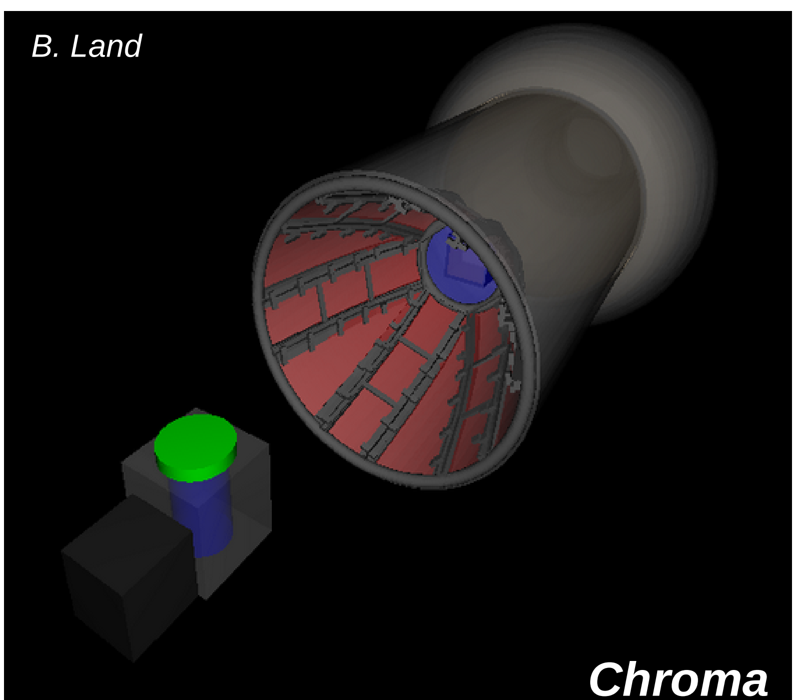


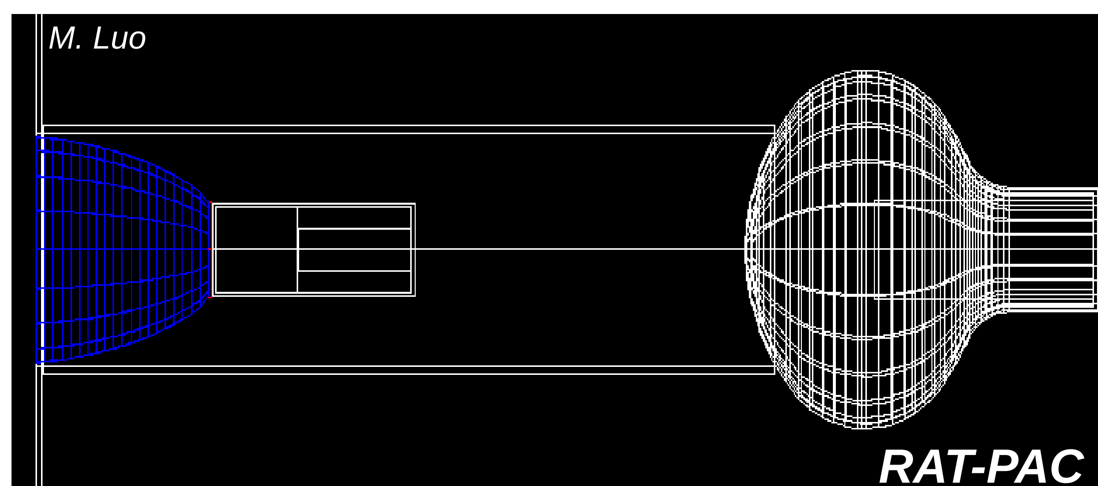
Simulation Models of Bench-top Setup

Chroma

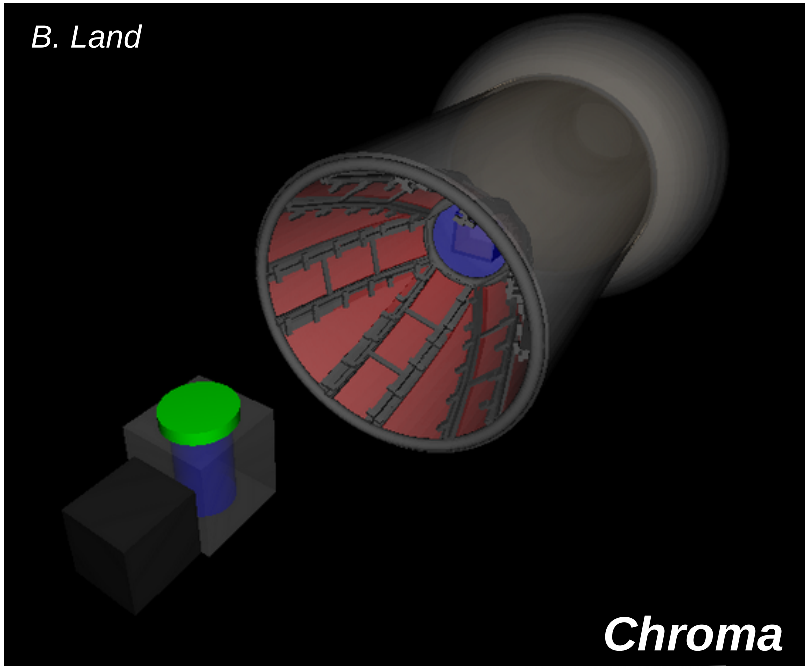


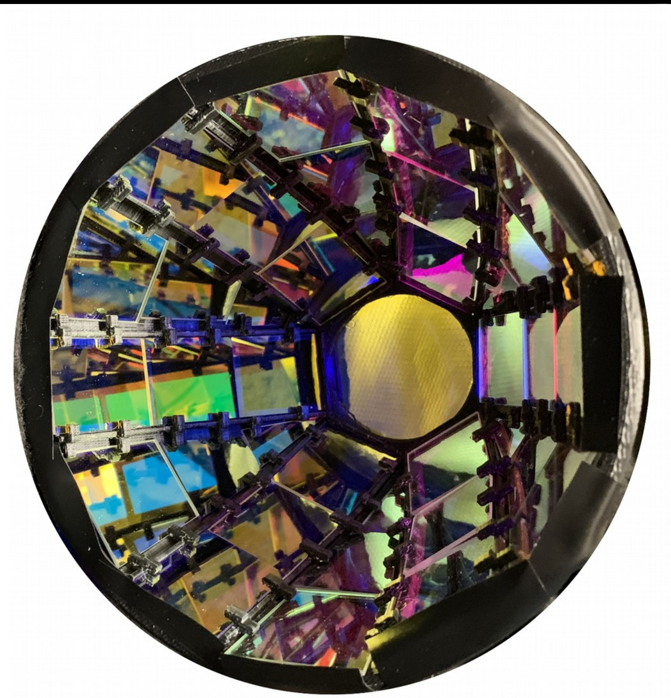






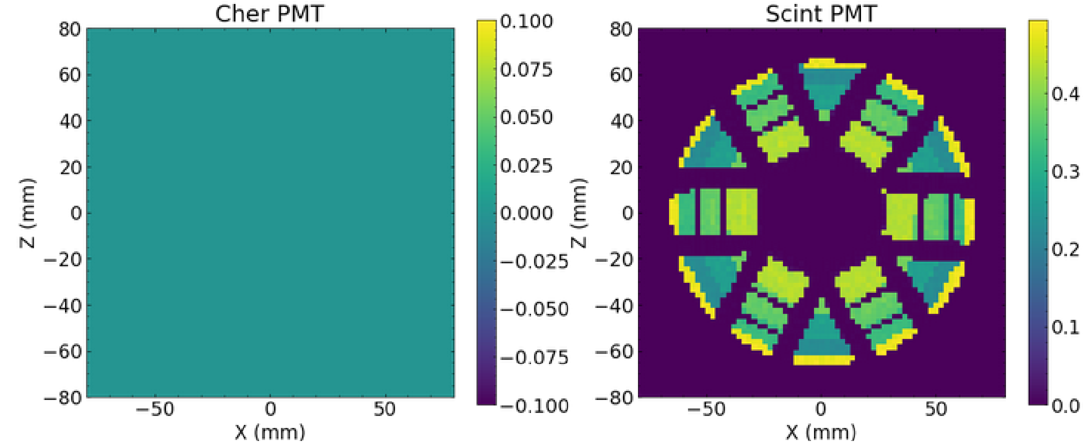
Dichroicon Simulations



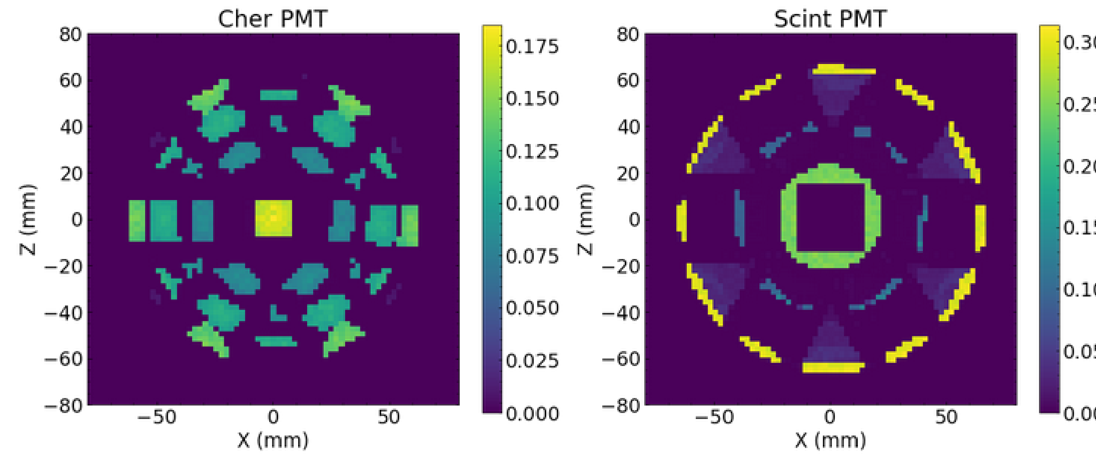


B. Land

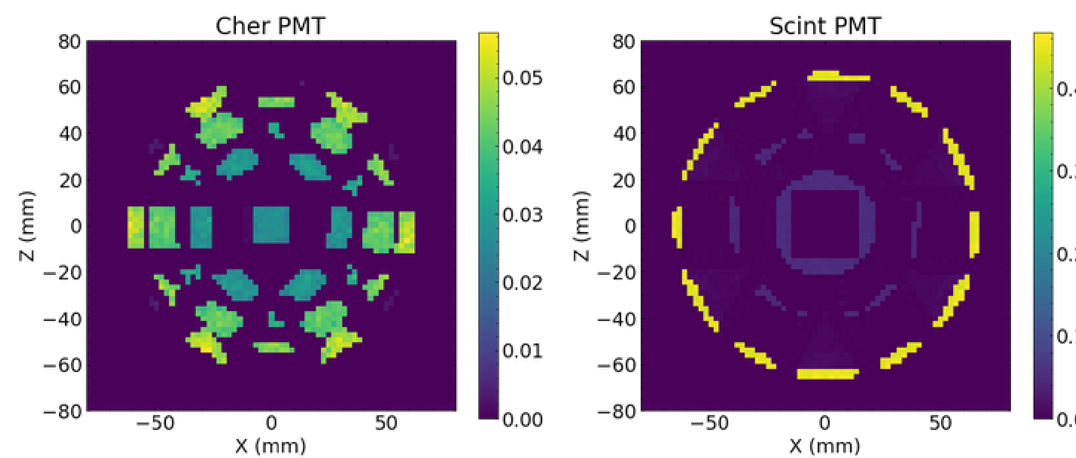
420 nm Photons



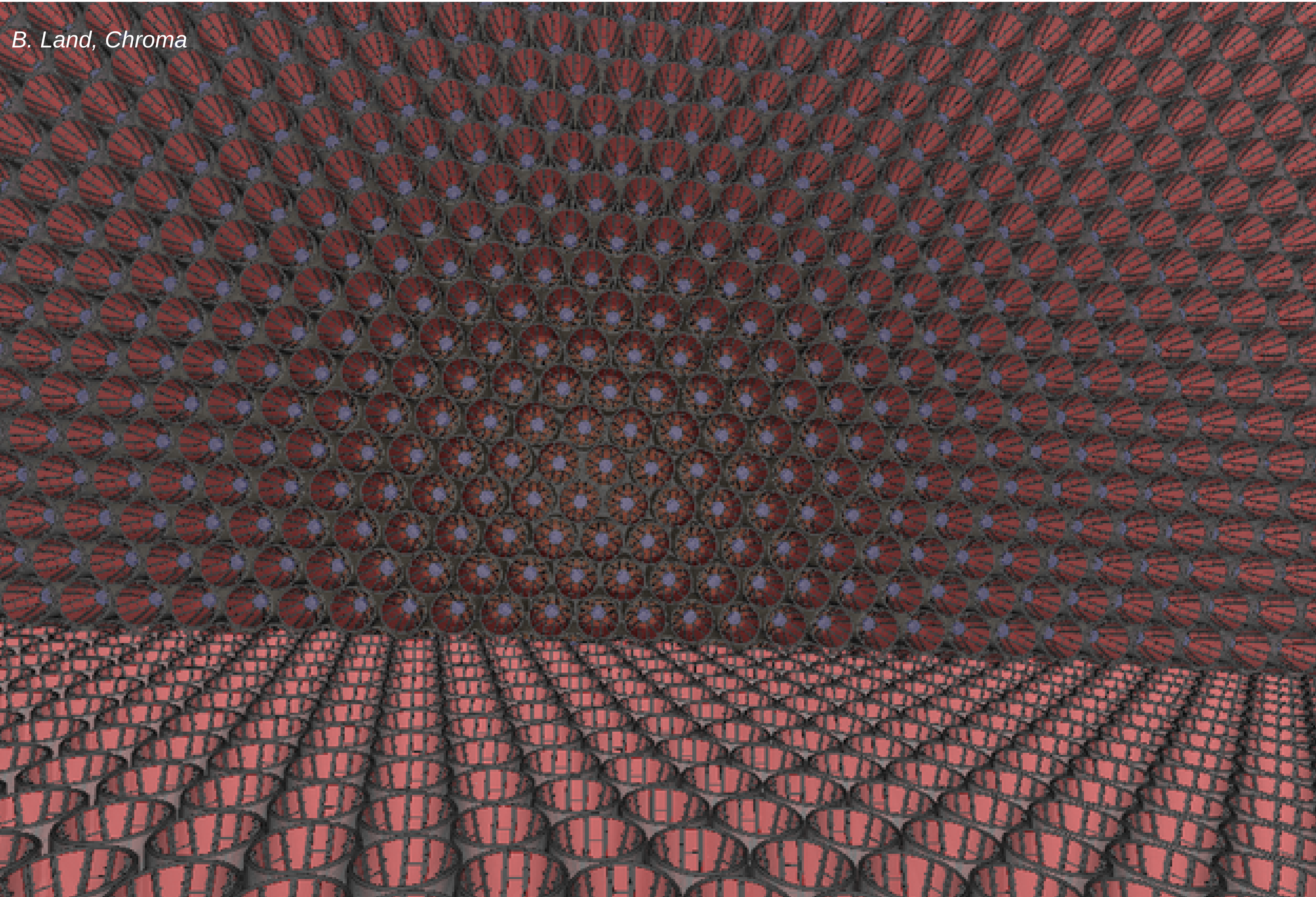
500 nm Photons



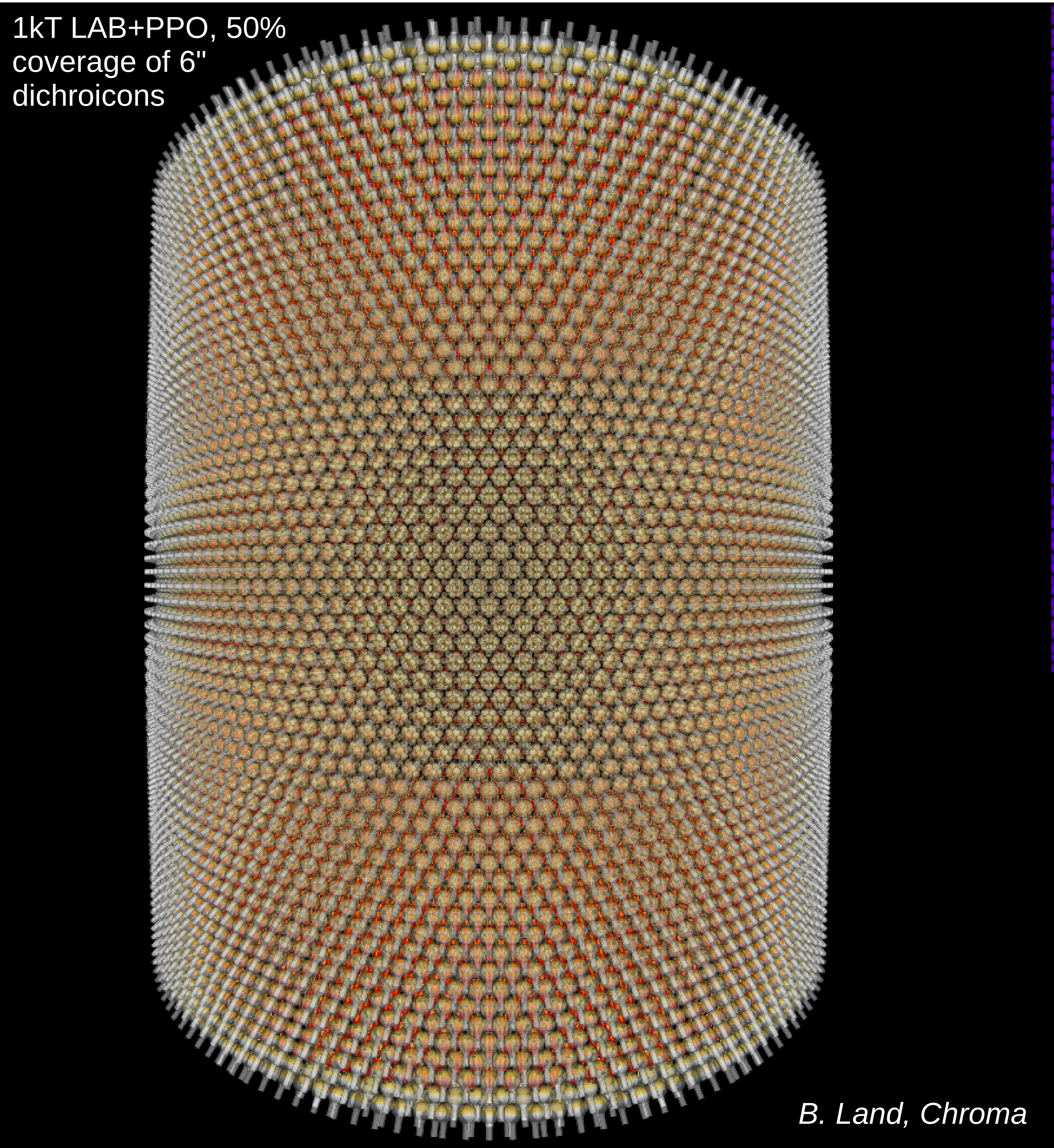
550 nm Photons

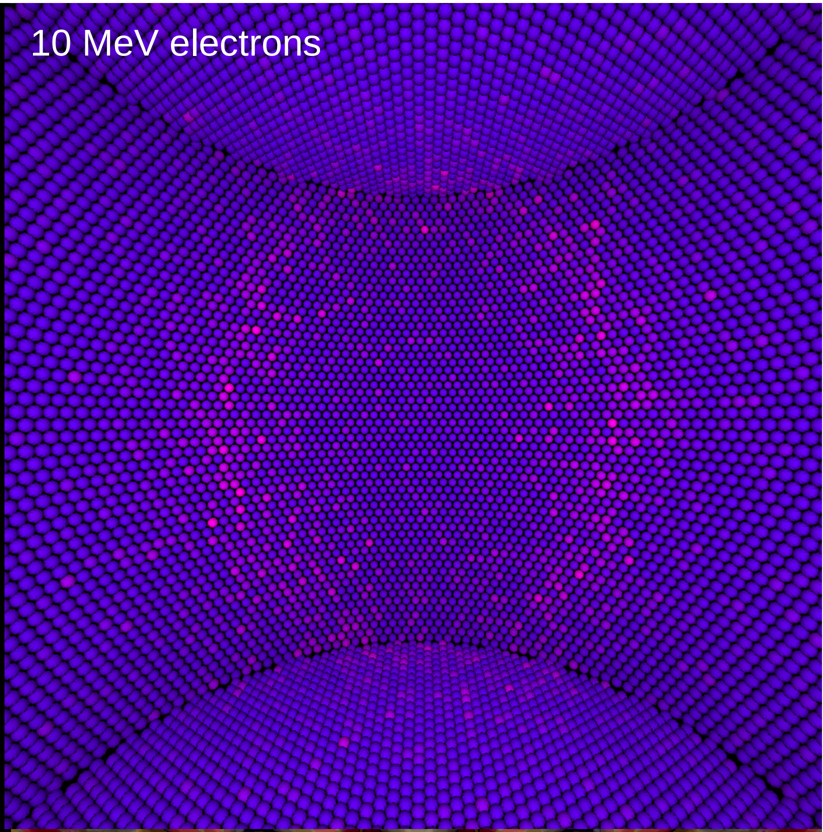


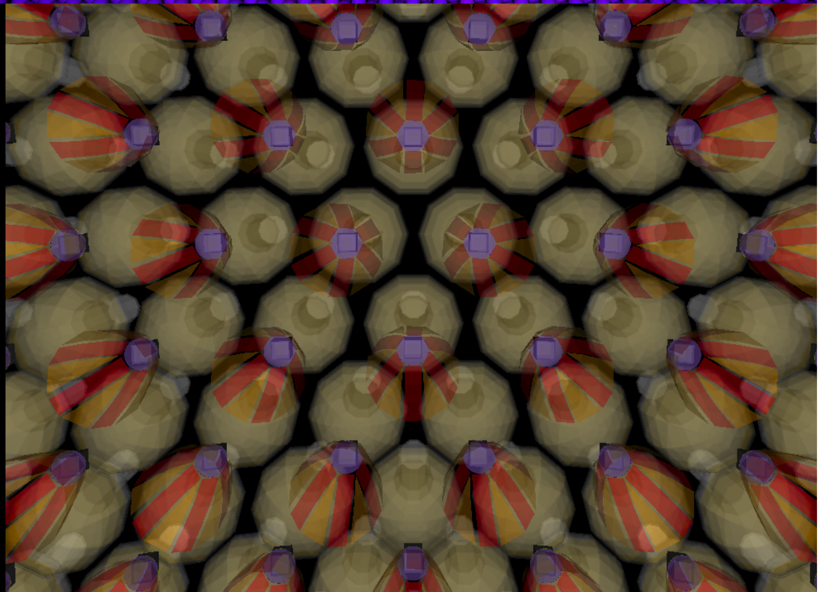
Simulations of Large-Scale Detectors With Dichroicons



Simulations of Large-Scale Detectors With Dichroicons





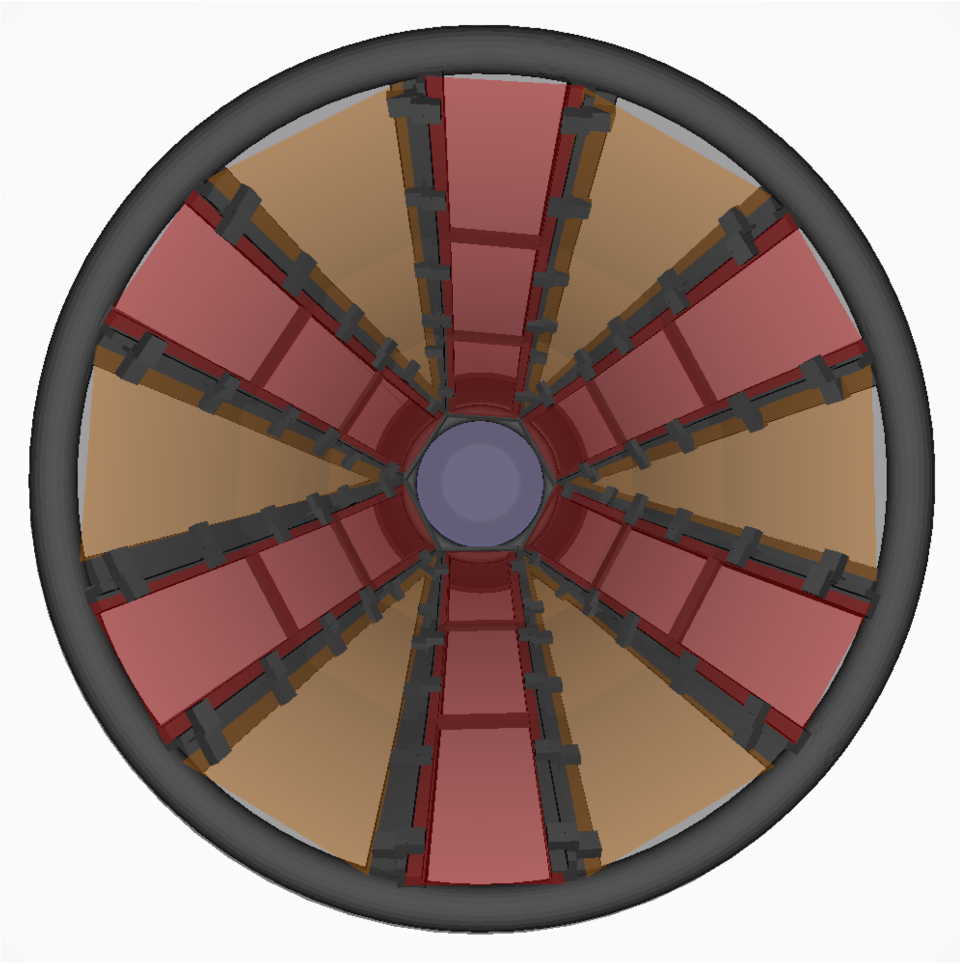


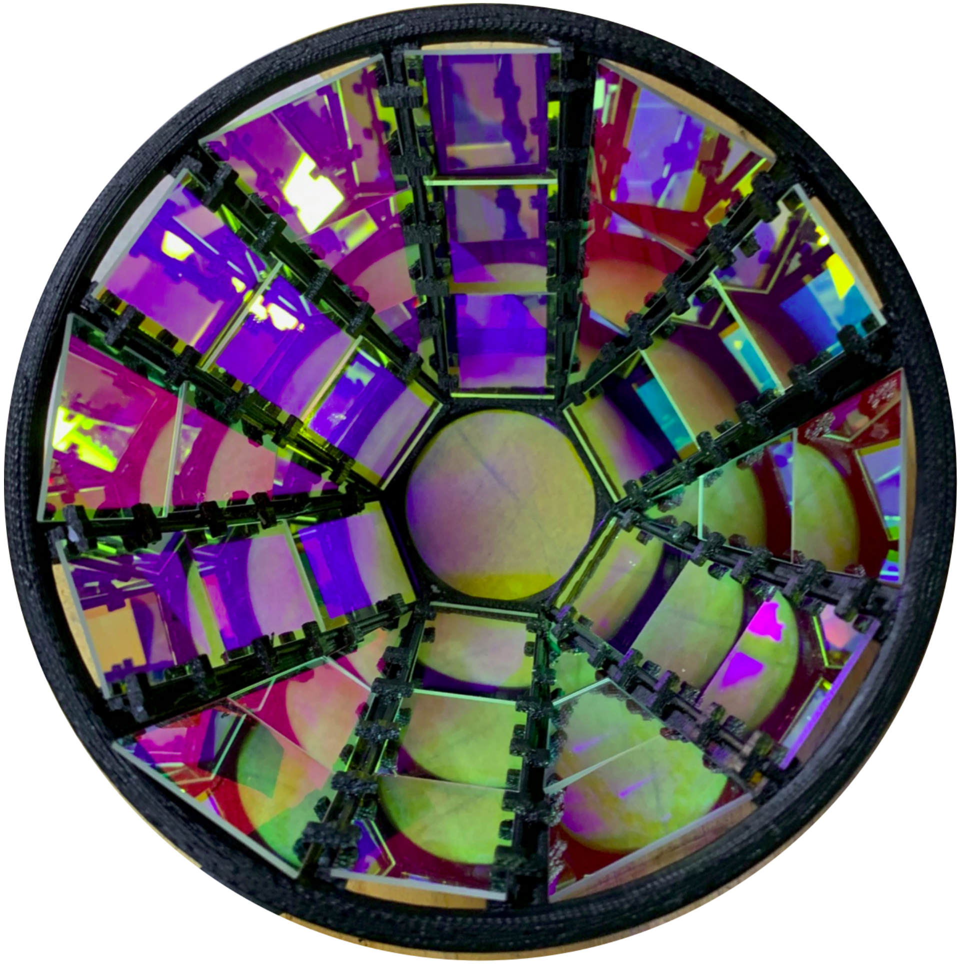
Conclusions

- Spectral sorting of photons has interesting applications for future large-scale water Cherenkov and scintillator detectors, with the potential to improve reconstruction and particle ID
- Bench-top measurements of single dichroic filter demonstrated photon-sorting technique
- Dichroicon with a Cherenkov source showed photon sorting working as expected
- Dichroicon with a scintillation source demonstrated Cherenkov / scintillation separation
- Lots of interesting measurements and simulations forthcoming with dichroicons

Work supported by Department of Energy Office of High Energy Physics Advanced Detector R&D

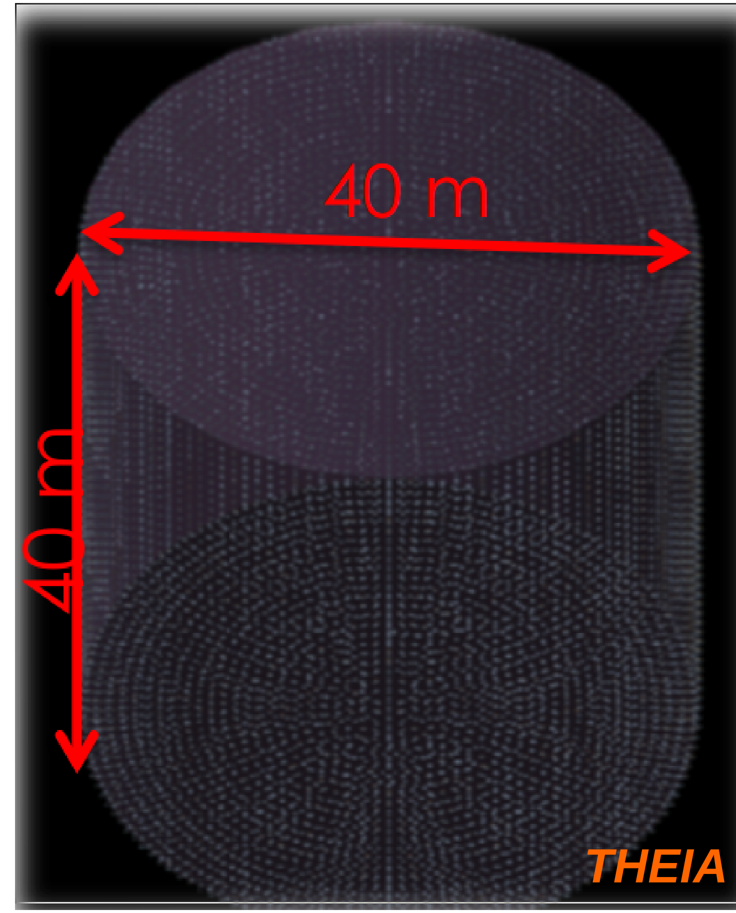
Backup Slides

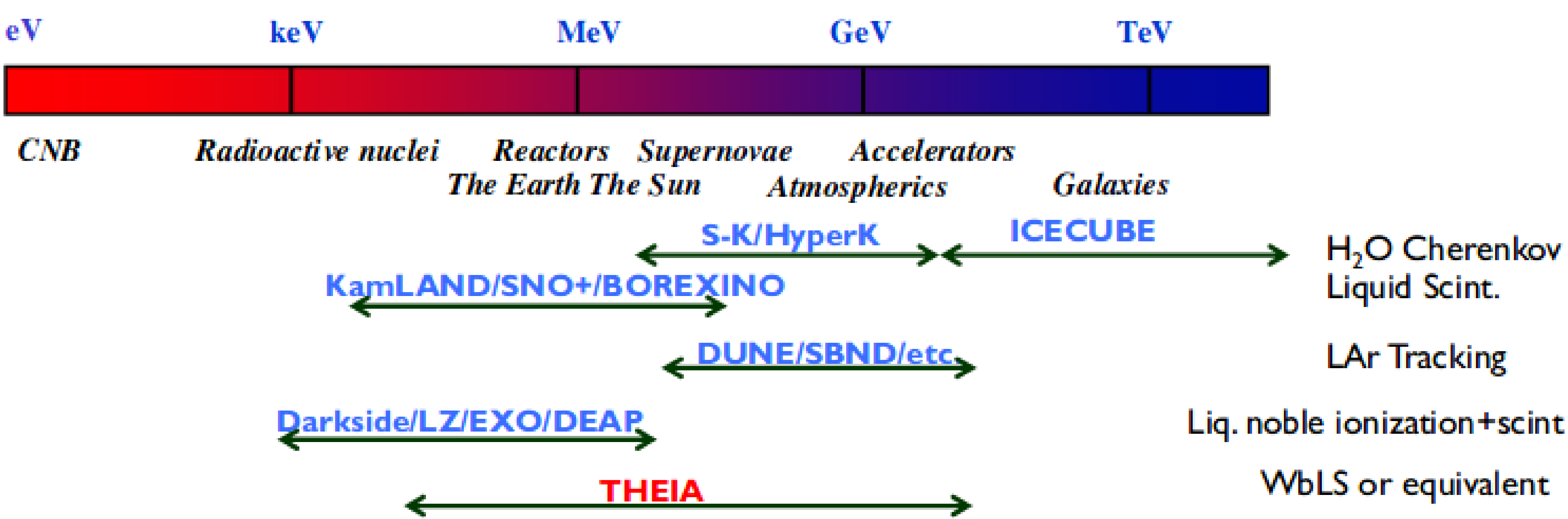




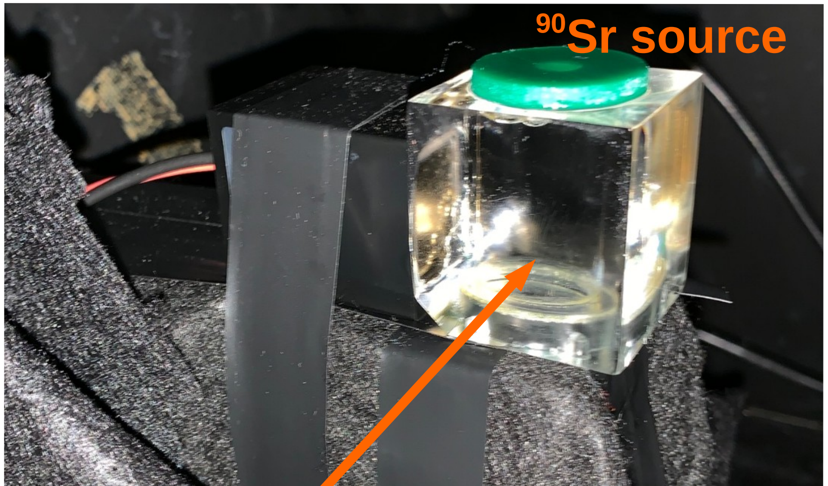
Future Experiments

- Several proposed WbLS detectors hoping to achieve Cherenkov and scintillation separation
- THEIA is a proposed 50kT WbLS (or equivalent technology) detector, potentially complimentary to DUNE
- ANNIE is 26-ton water-based detector measuring neutrino-nucleus interactions. Future phases will likely include LAPPDs and WbLS
- WATCHMAN hot-bed for future technologies – WbLS, LAPPDs, fast PMTs, *dichroicons*

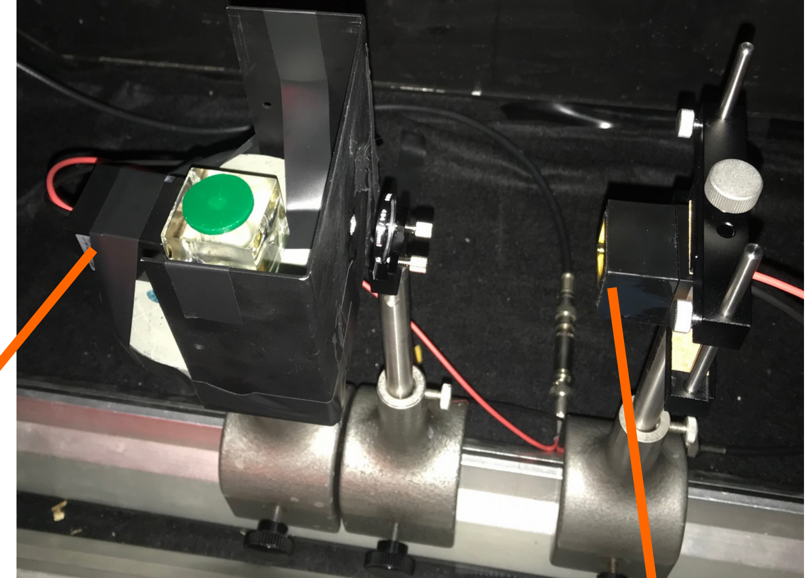


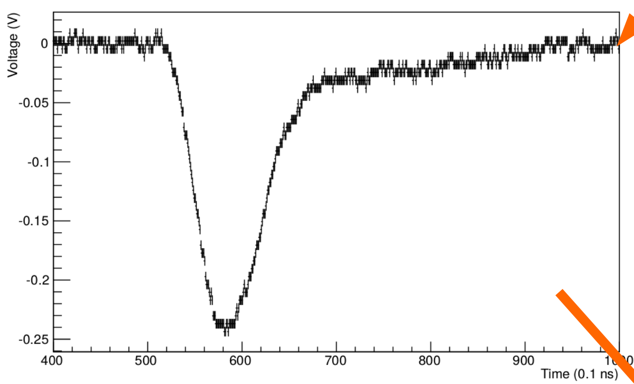


Schematic from J. Klein

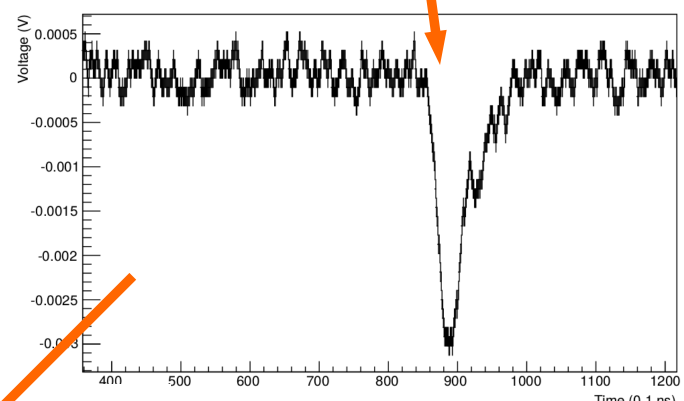


LAB+PPO inside UVT acrylic

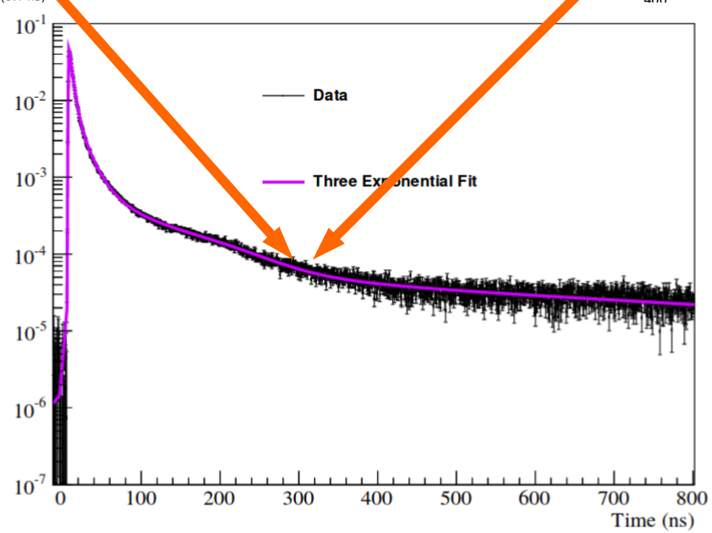




Calculate Δt between the two waveforms



Data with no bandpass filter shows typical scintillation spectrum

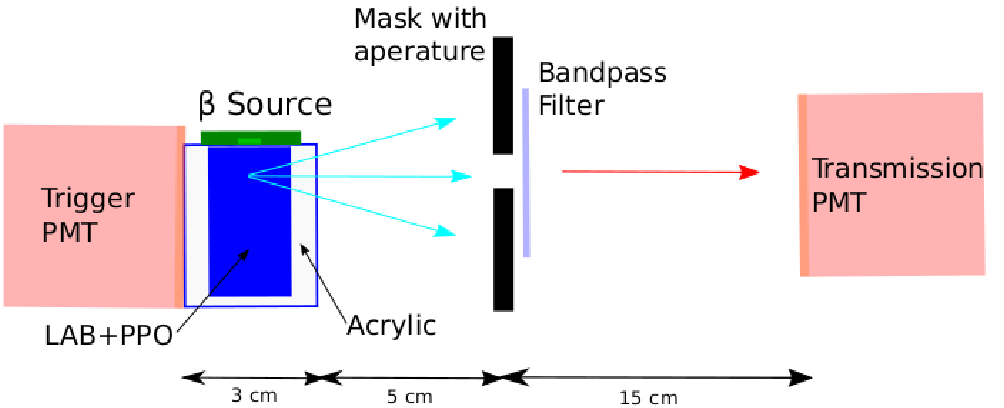


Characterized by intrinsic rise τ_r ~1ns followed by exponential decay with $\tau_{1,2,3}$ ~5ns, ~20ns, ~400ns

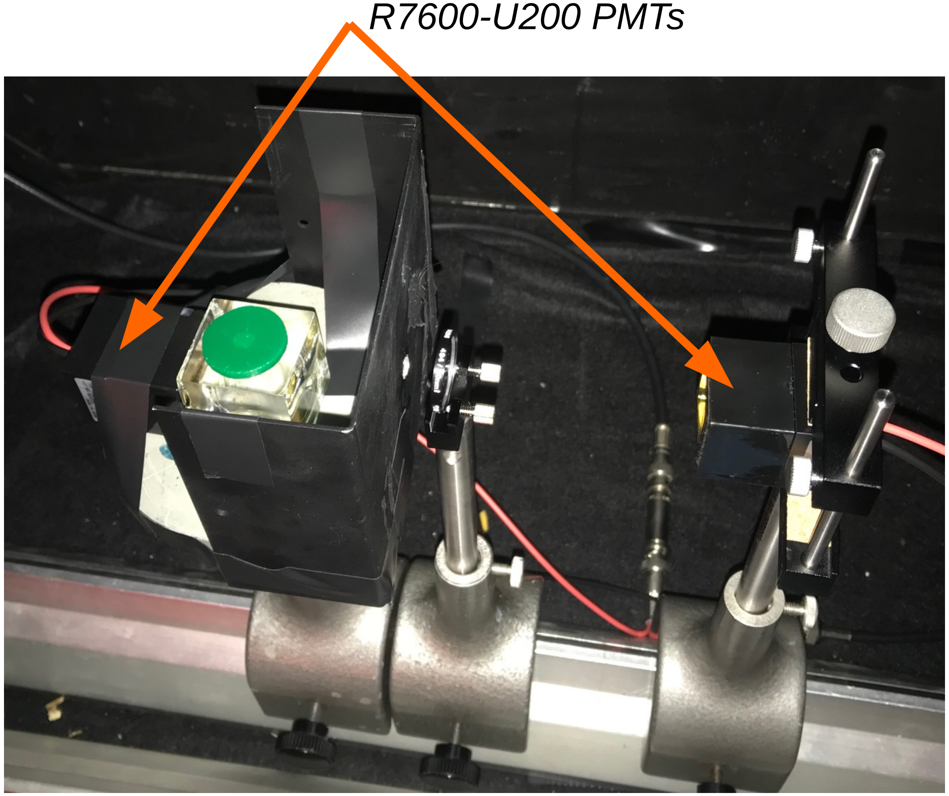
Cherenkov / Scintillation Separation With Bandpass Filters

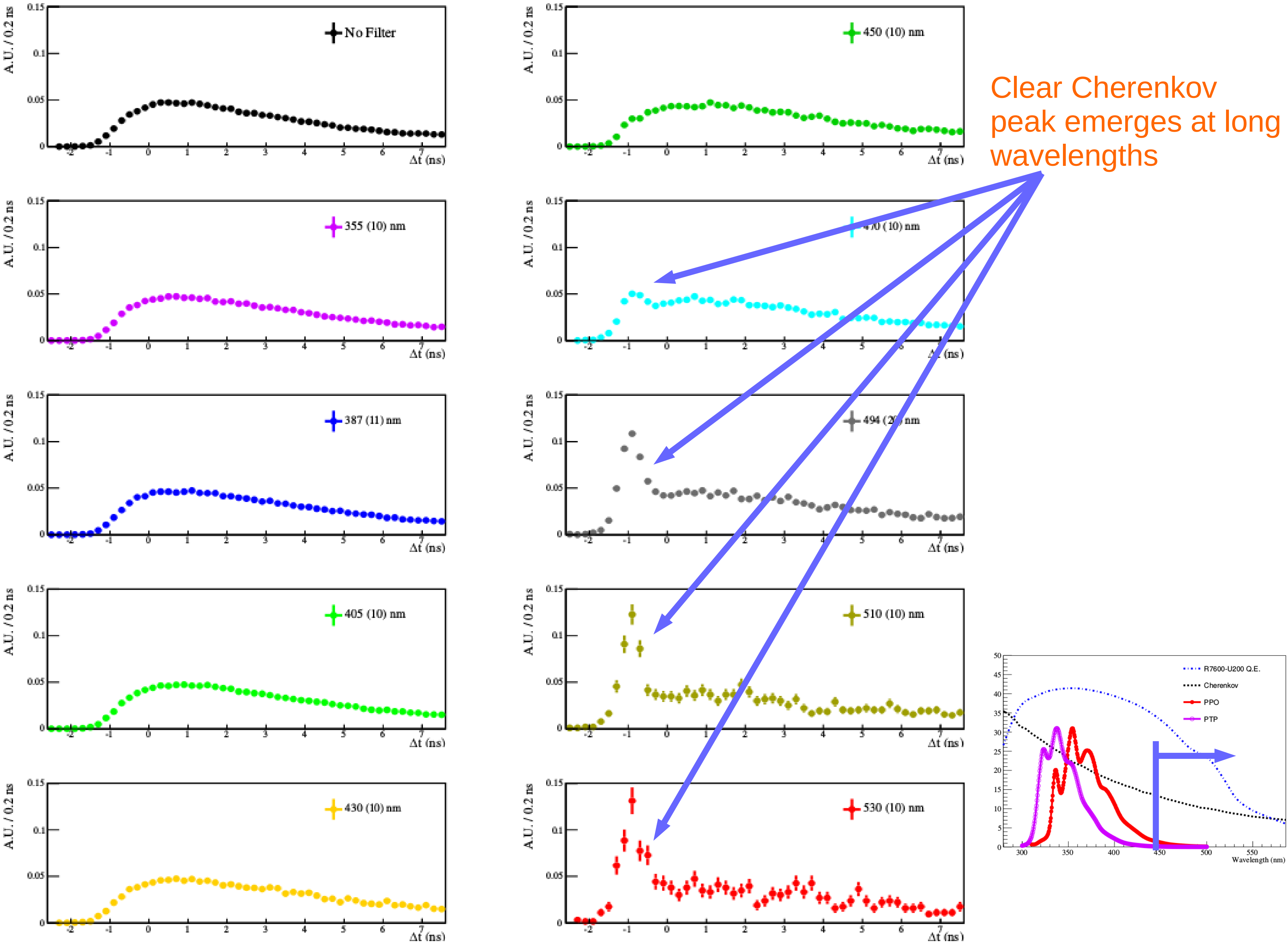
Using a set of bandpass filters to span emission spectrum of LAB+PPO

Center (nm)	FWHM (nm)	Peak Transmission (%)
355	10	95
387	11	95
405	10	96
430	10	46
450	10	98
470	10	53
494	20	95
510	10	60
530	10	54



R7600-U200 PMTs





Clear Cherenkov peak emerges at long wavelengths
No Filter
355 (10) nm
387 (11) nm
405 (10) nm
430 (10) nm
450 (10) nm
510 (10) nm
530 (10) nm
A.U. / 0.2 ns
Δt (ns)
R7600-U200 Q.E.
Cherenkov
PPO
PTP
Wavelength (nm)

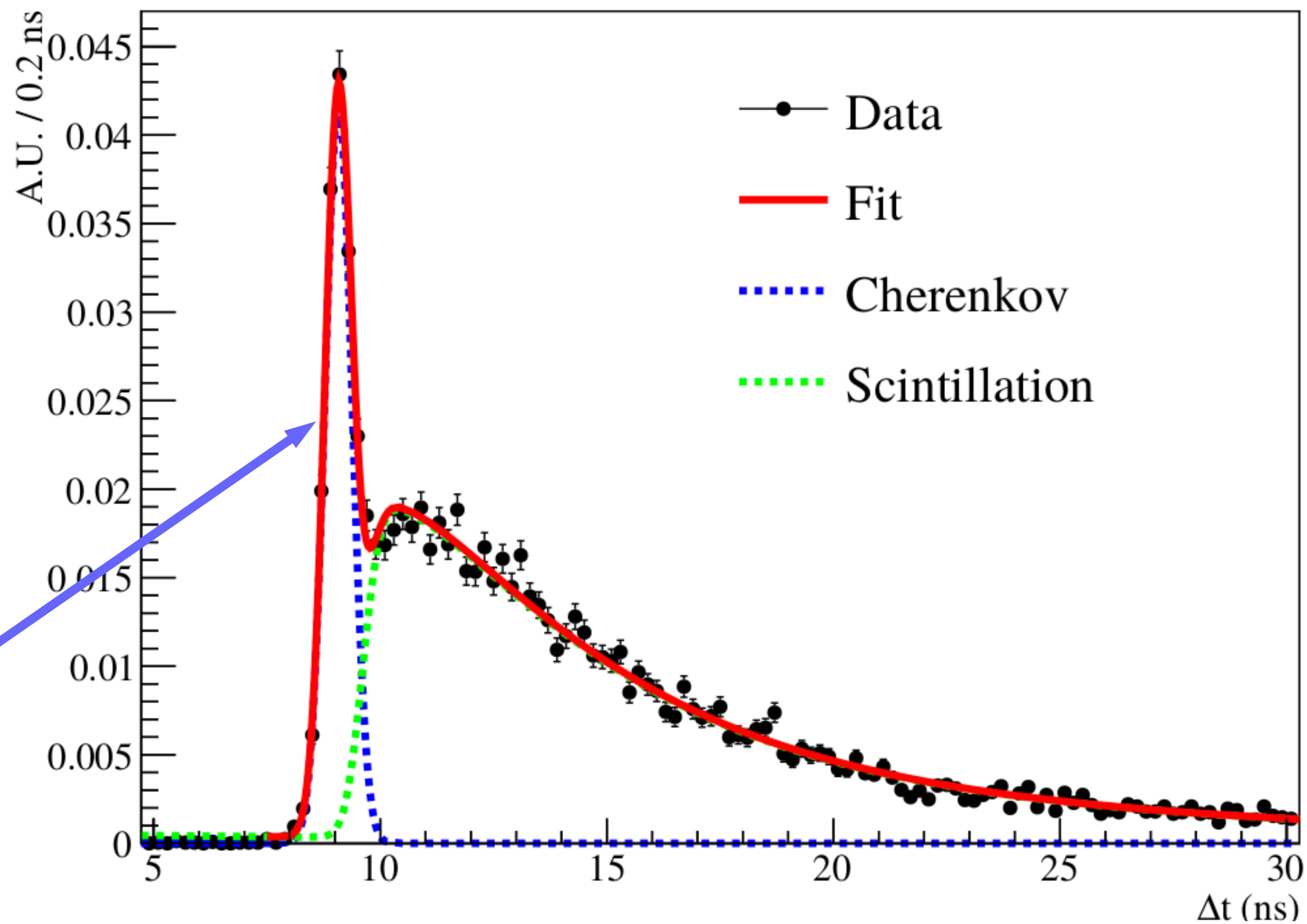
Fitting the Spectrum

$$F = C \times f_{PMT}(t-t') + (1-C) \times \sum_{i=1}^{2} \frac{A_i \times (e^{-t/\tau_i} - e^{-t/\tau_R})}{(\tau_i - \tau_R)} * f_{PMT}(t-t')$$

$$P = \int_{8.0}^{9.5} \frac{F_C}{F} dt$$

Simultaneously fit both the Cherenkov and scintillation components of the timing profile

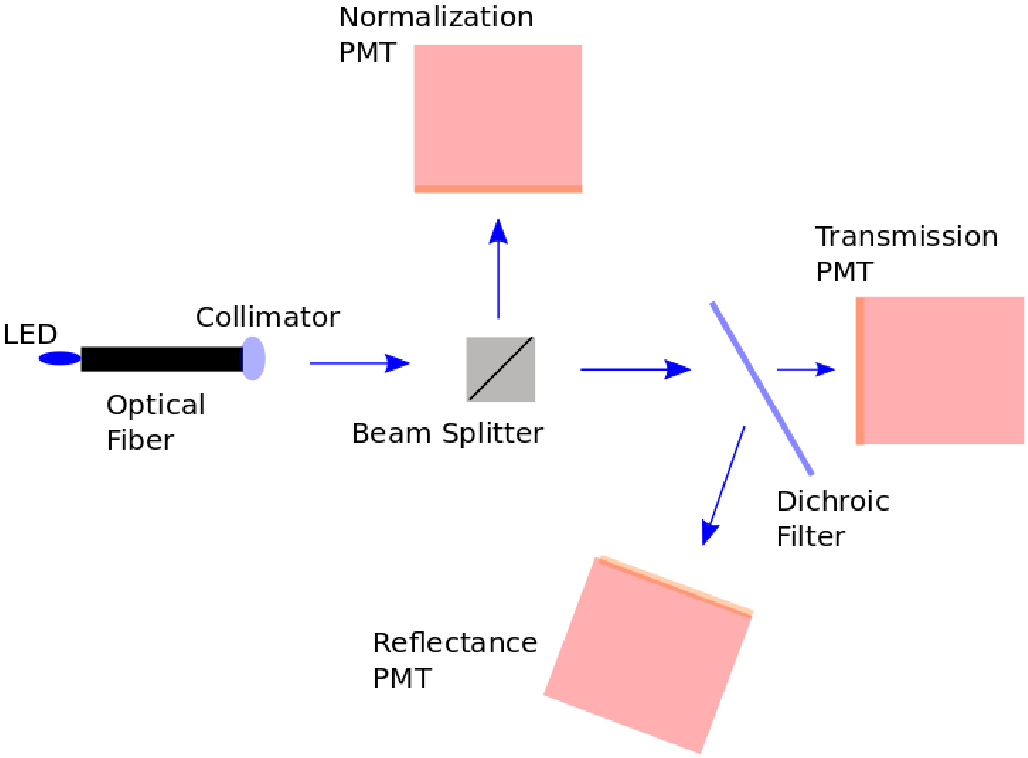
Purity, *P*, of the Cherenkov light in a prompt window



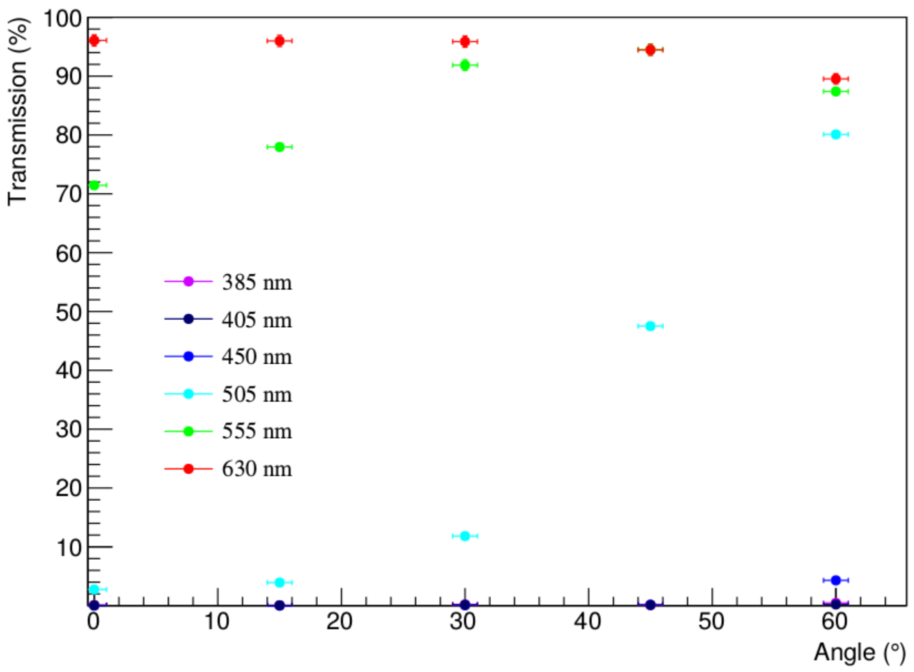
> 90% of prompt light is Cherenkov light!

Measuring T(λ, θ) and R(λ, θ)

Characterized the transmission and reflection of the dichroic filters as a function of wavelength and incident angle in to ways



Measurements for a 500 nm Longpass Dichroic Filter



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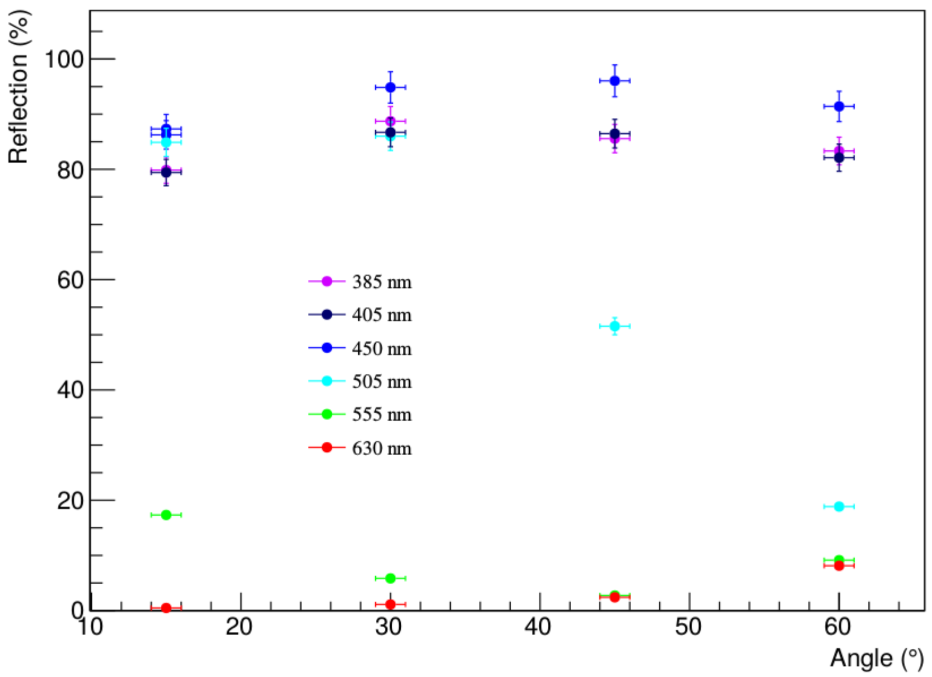

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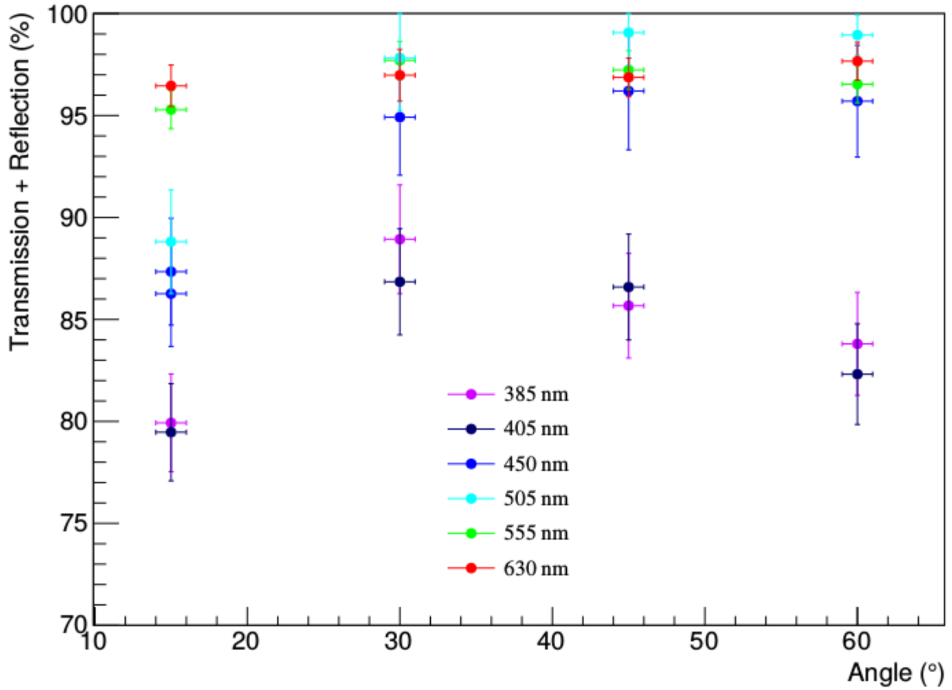

Very little light lost to the dichroic filter over range of wavelengths and incident angles

Measurements for a 500 nm Longpass Dichroic Filter

Using a spectrometer to measure transmission as function of wavelength and incident angle