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

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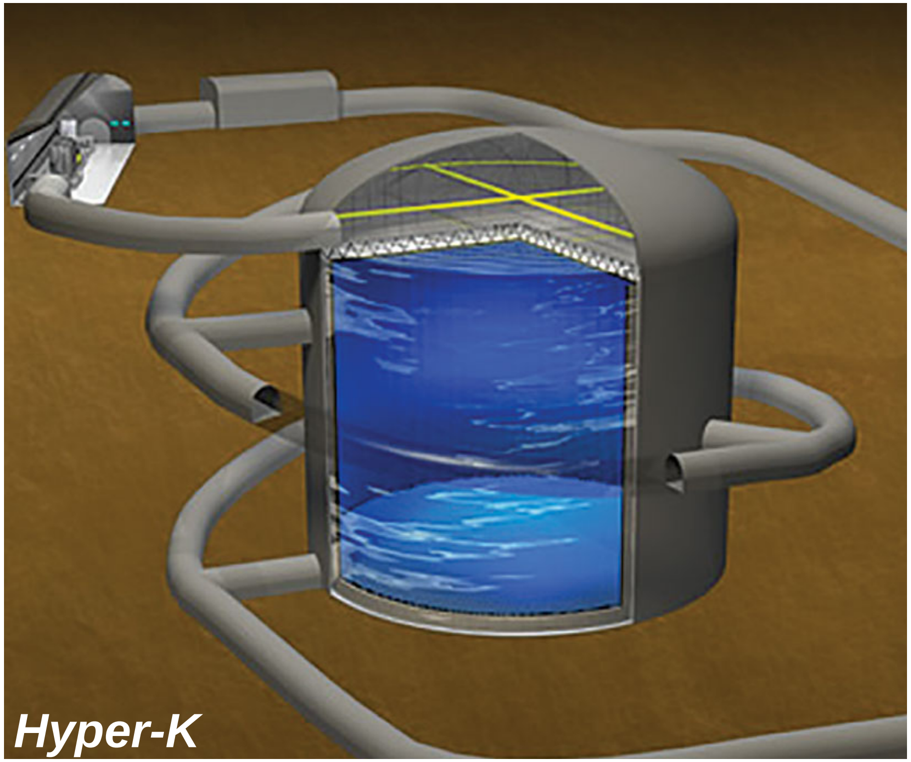
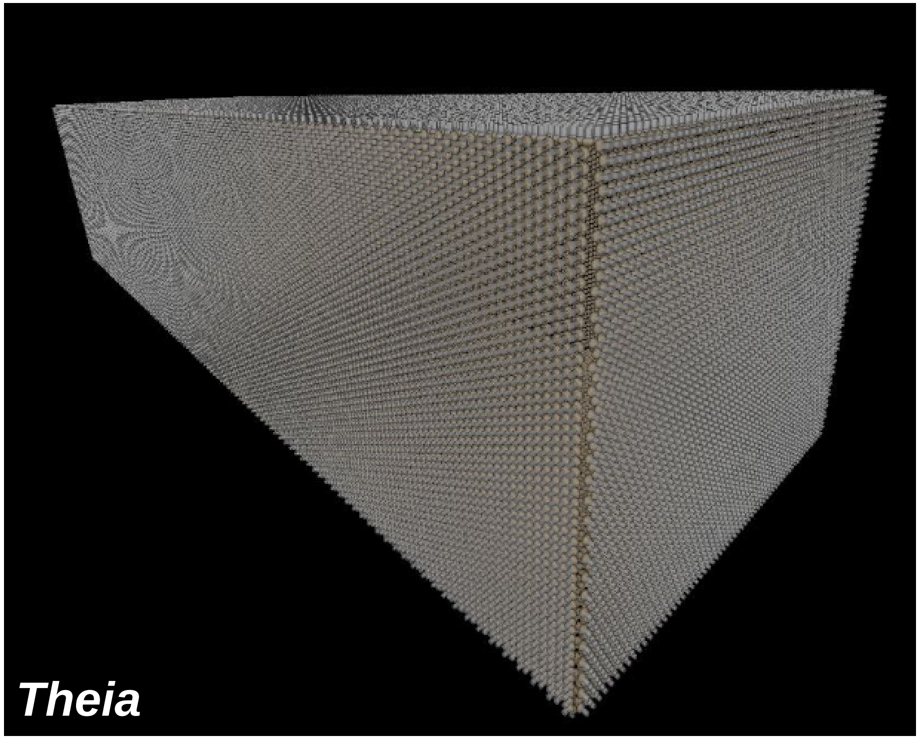
Provide Photon Wavelength Information for Large-Scale Neutrino Detectors

For water Cherenkov detectors the scale of Hyper-K, 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)

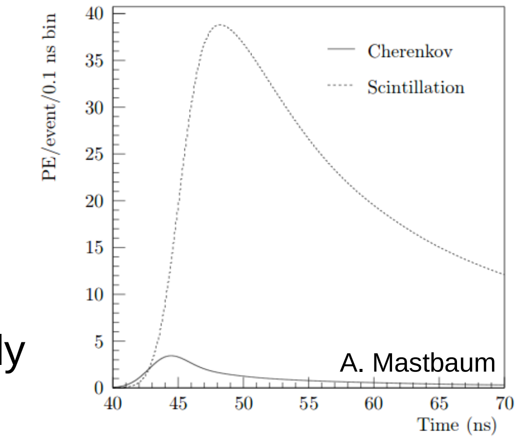




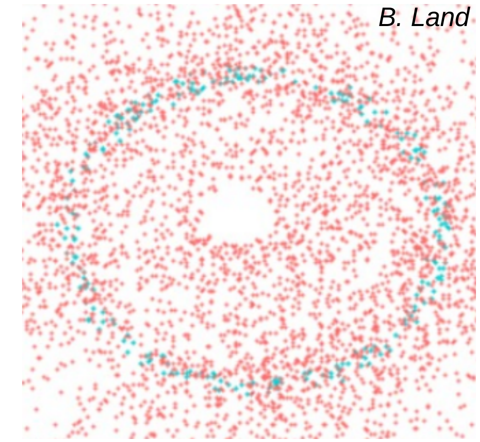
Cherenkov Light in a Liquid Scintillator Detector

- 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*

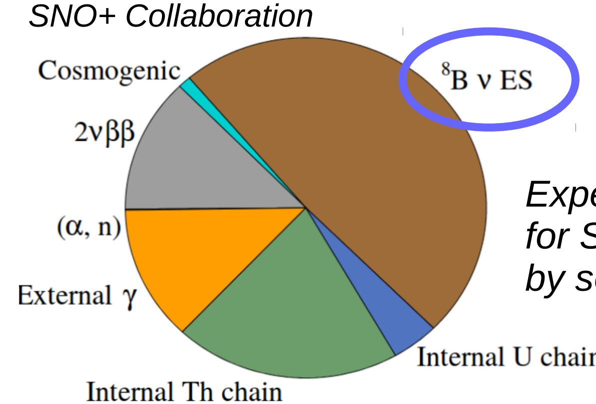
Example timing in large neutrino detector



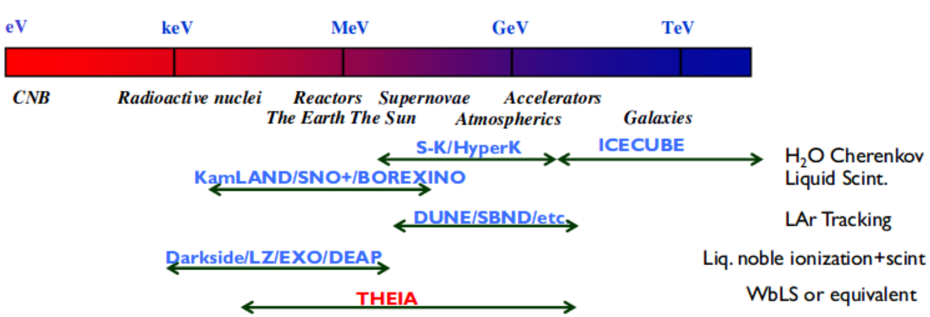
Cherenkov ring on top of isotropic scintillation light



SNO+ Collaboration



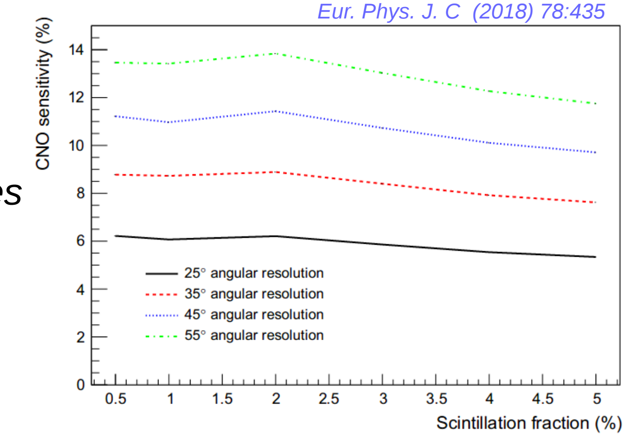
Expected background for SNO+ 0νββ dominated by solar neutrinos



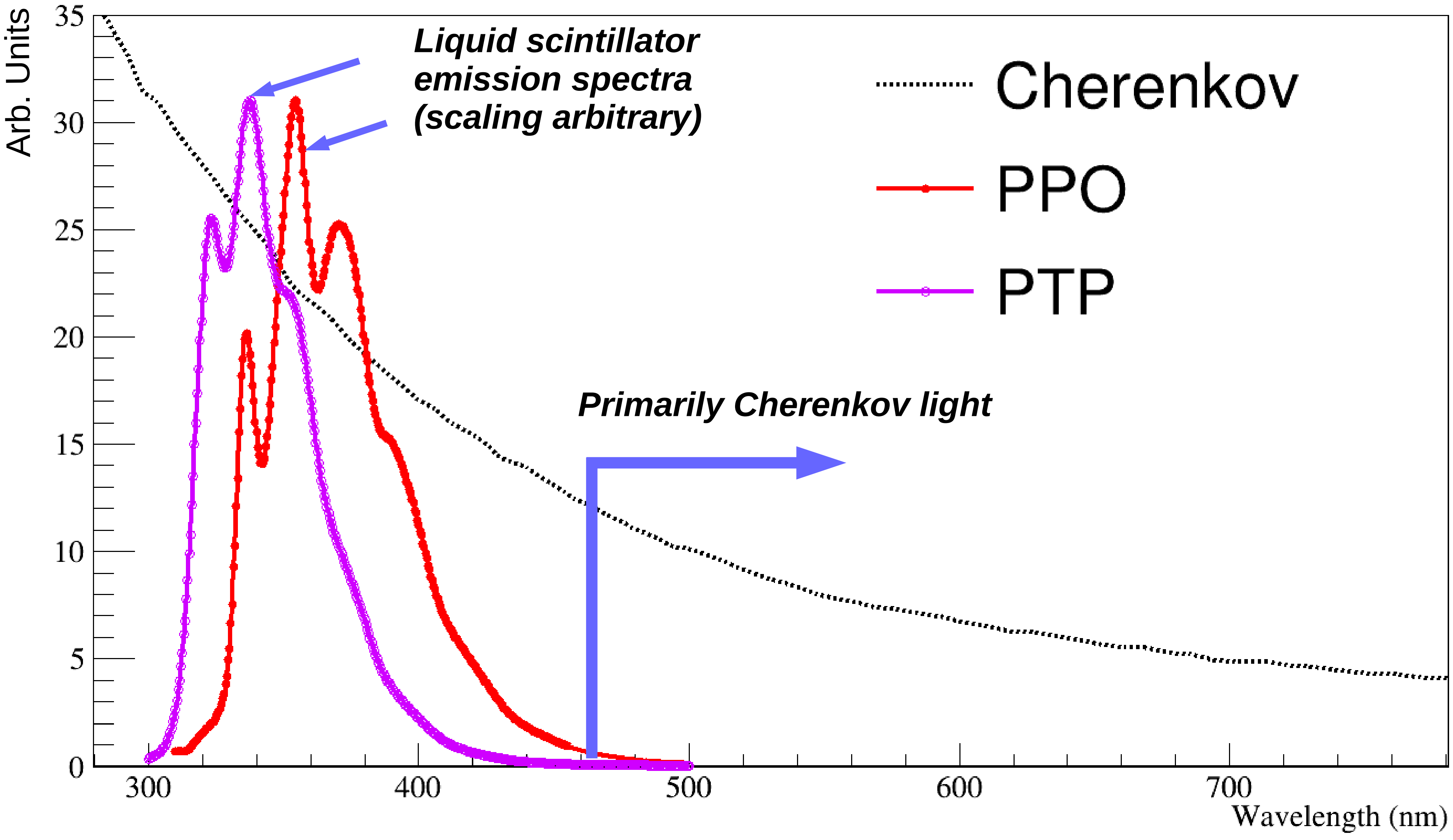
Schematic from J. Klein

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

CNO sensitivity improves with improved direction reconstruction

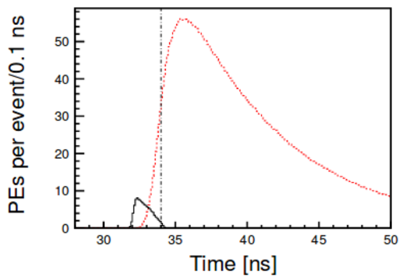


Separating Cherenkov and Scintillation Light Using Wavelength

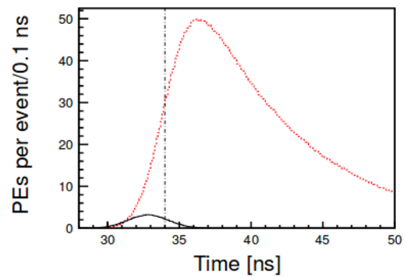


Goal is to achieve Cherenkov and scintillation separation while losing as few total photons as possible.

Advantages of Long Wavelength Light



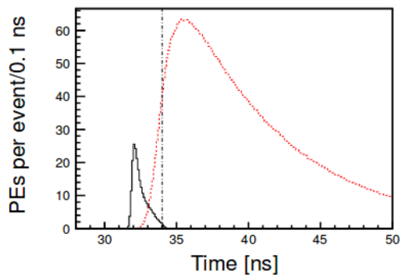
(a) Default simulation.



(b) Increased TTS (1.28 ns).

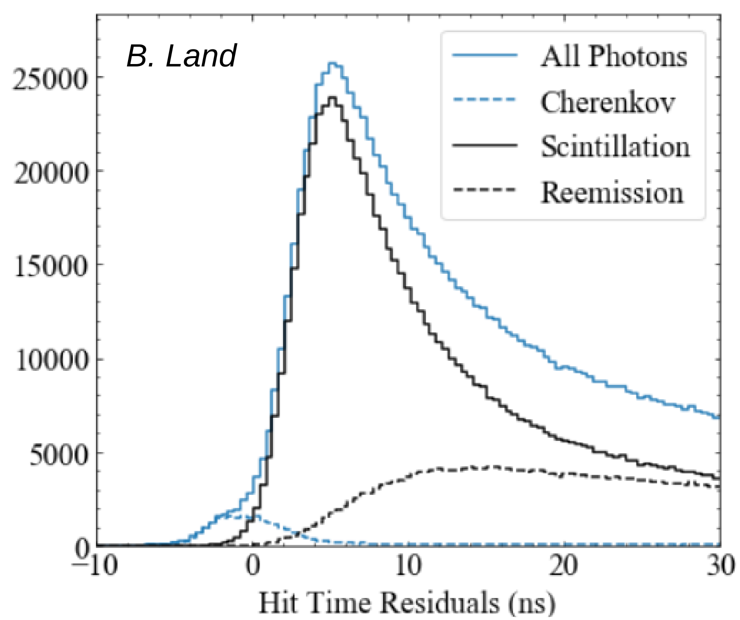
L. Winslow et. al,
10.1088/1748-0221/9/06/P06012

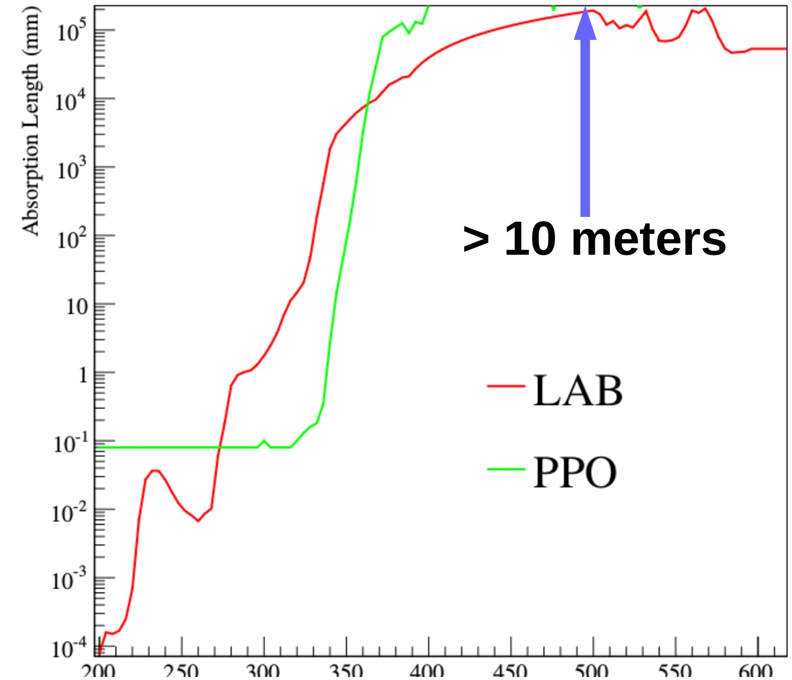
Using red-sensitive photocathodes improves separation

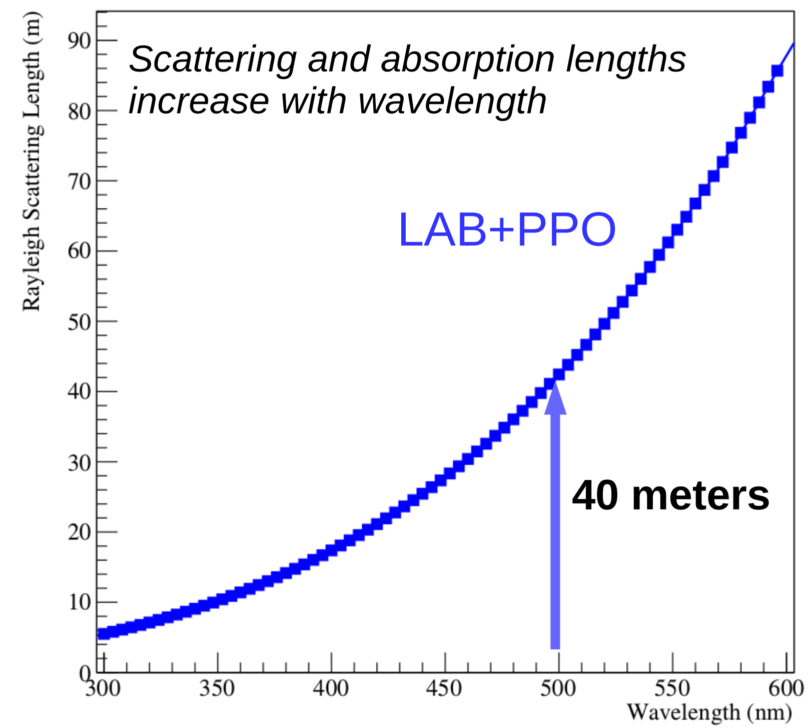


(c) Red-sensitive photocathode.

In 50kT THEIA, dispersion already gives some separation

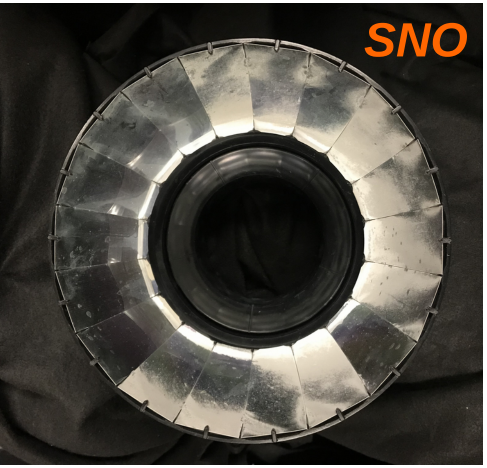


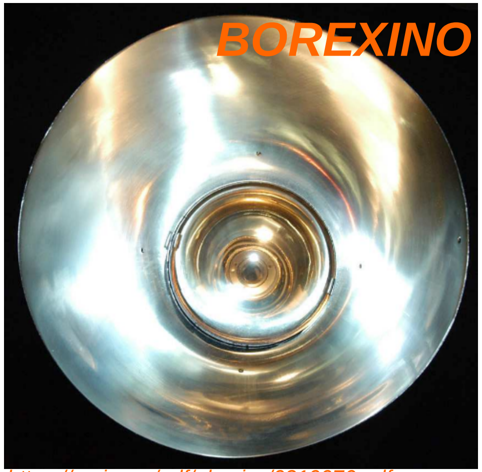




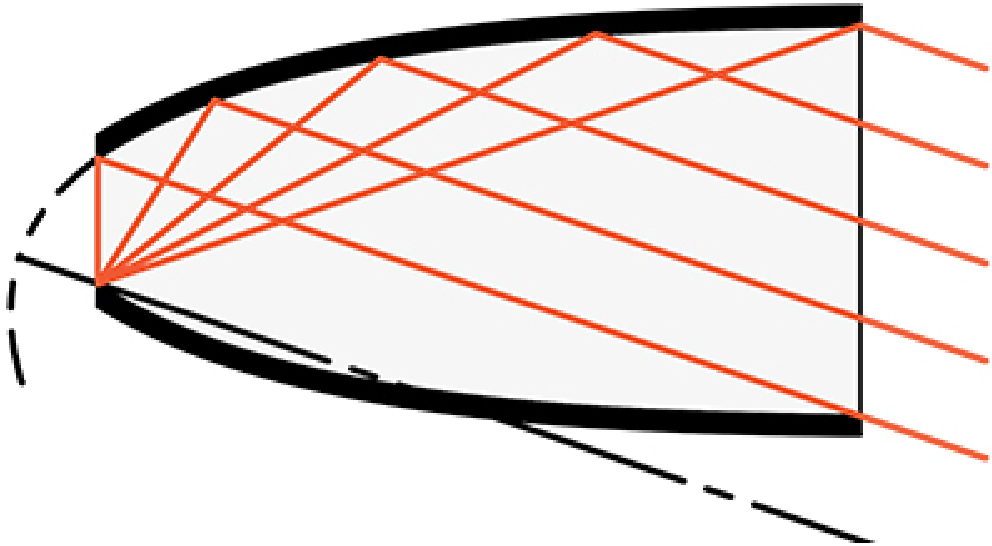
Our device combines two technologies

Winston Cones

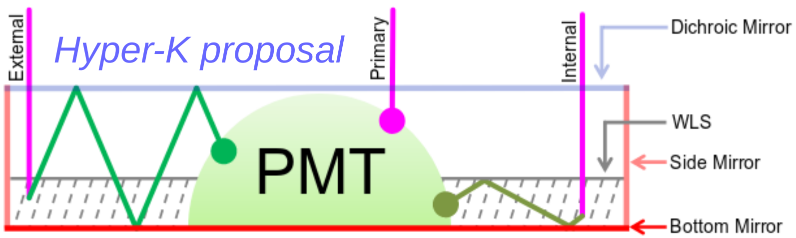




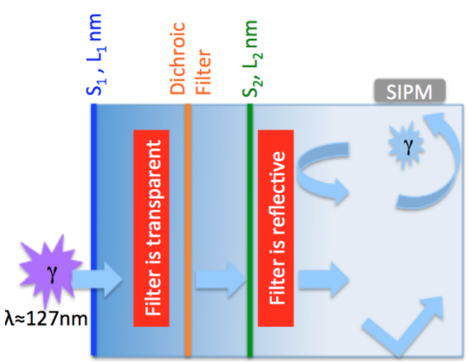
https://arxiv.org/pdf/physics/0310076.pdf



Dichroic Filters

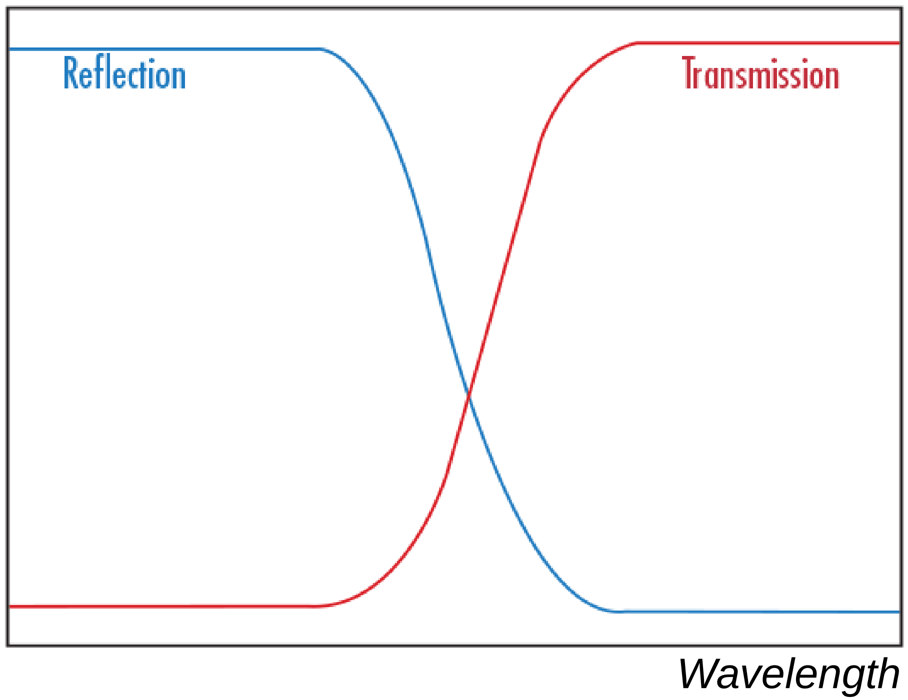


C. Rott et al. JINST 12 (2017)

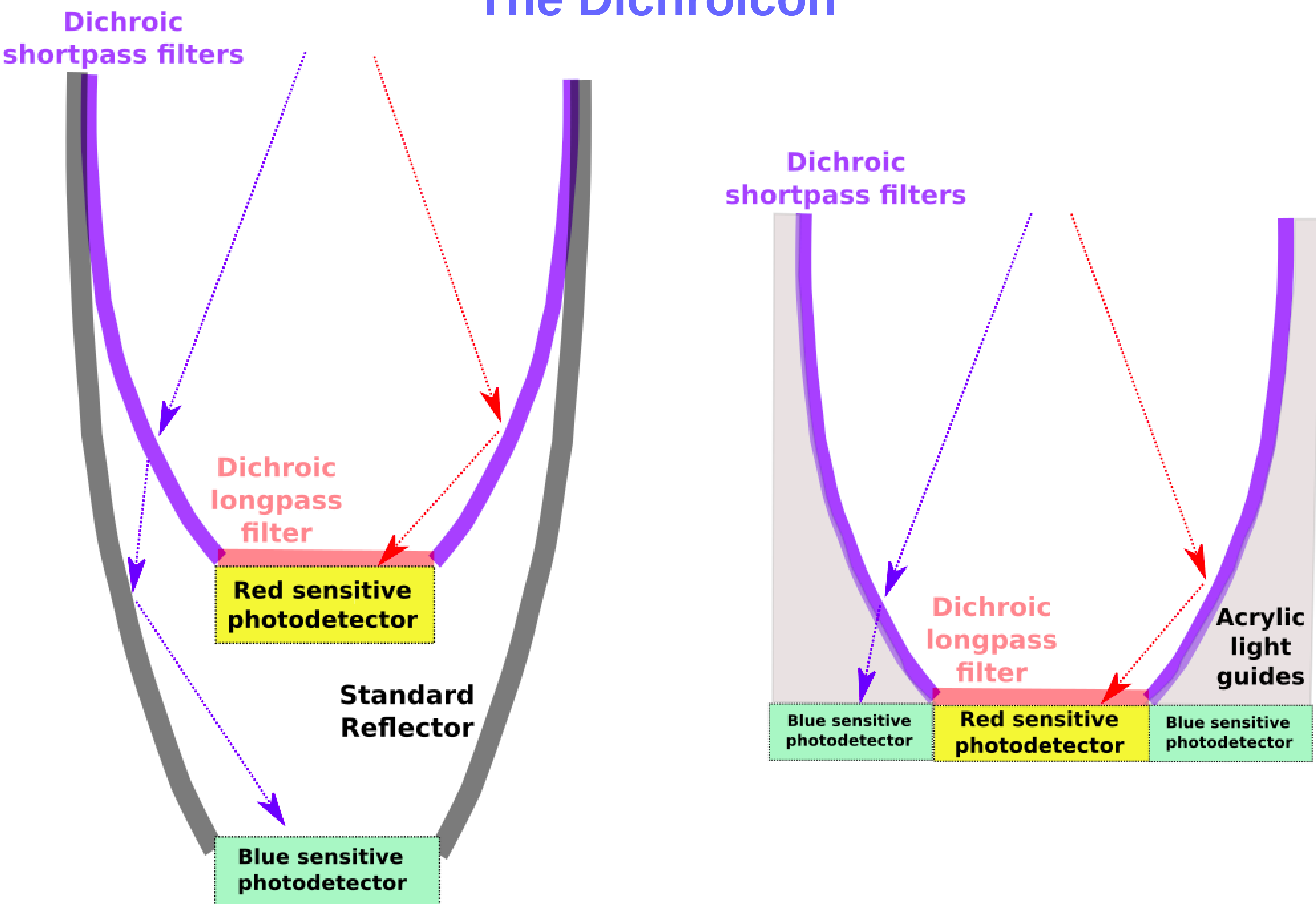


ARAPUCA for DUNE

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

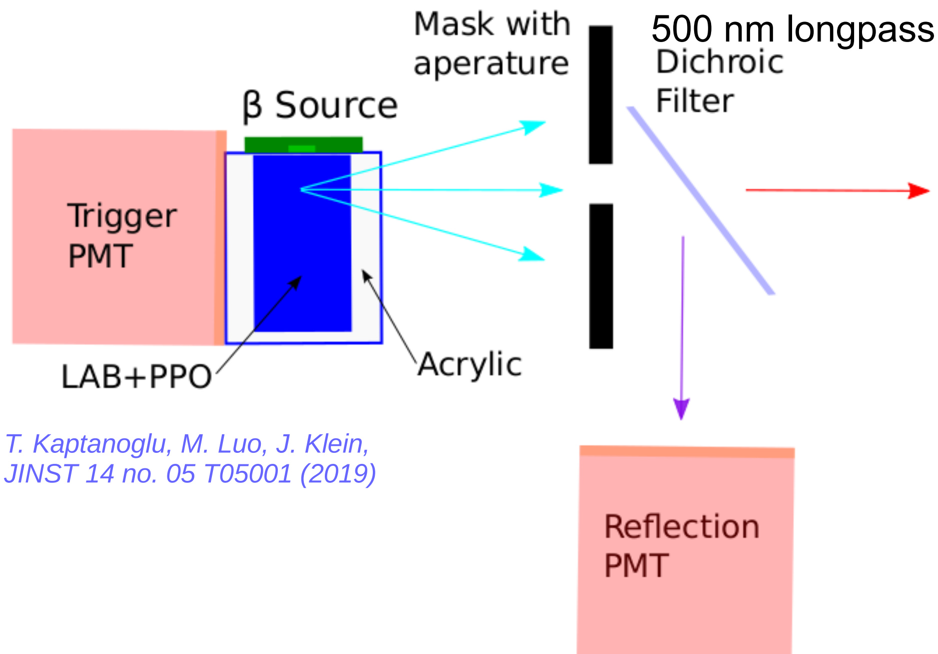


The Dichroicon



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

Spectral Sorting with Dichroic Filters

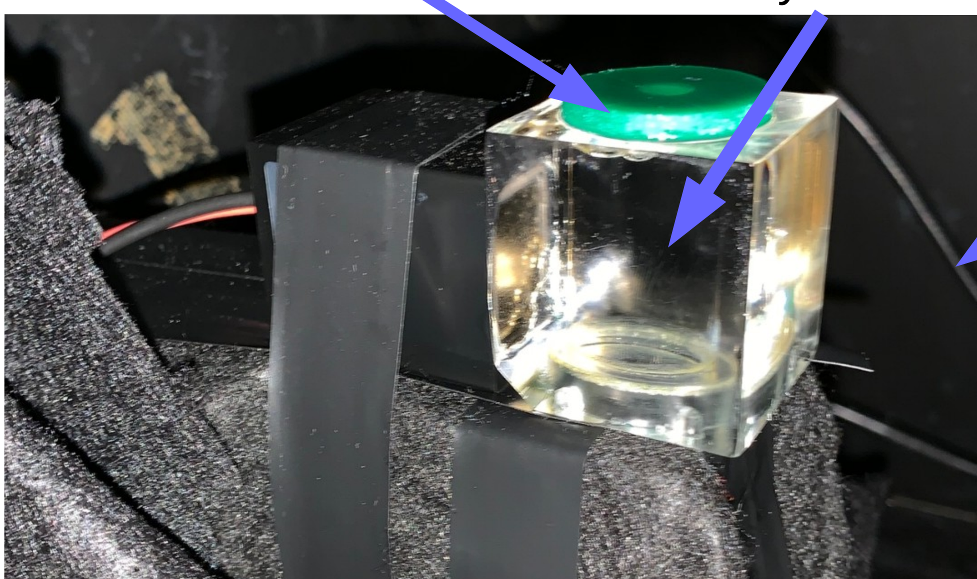


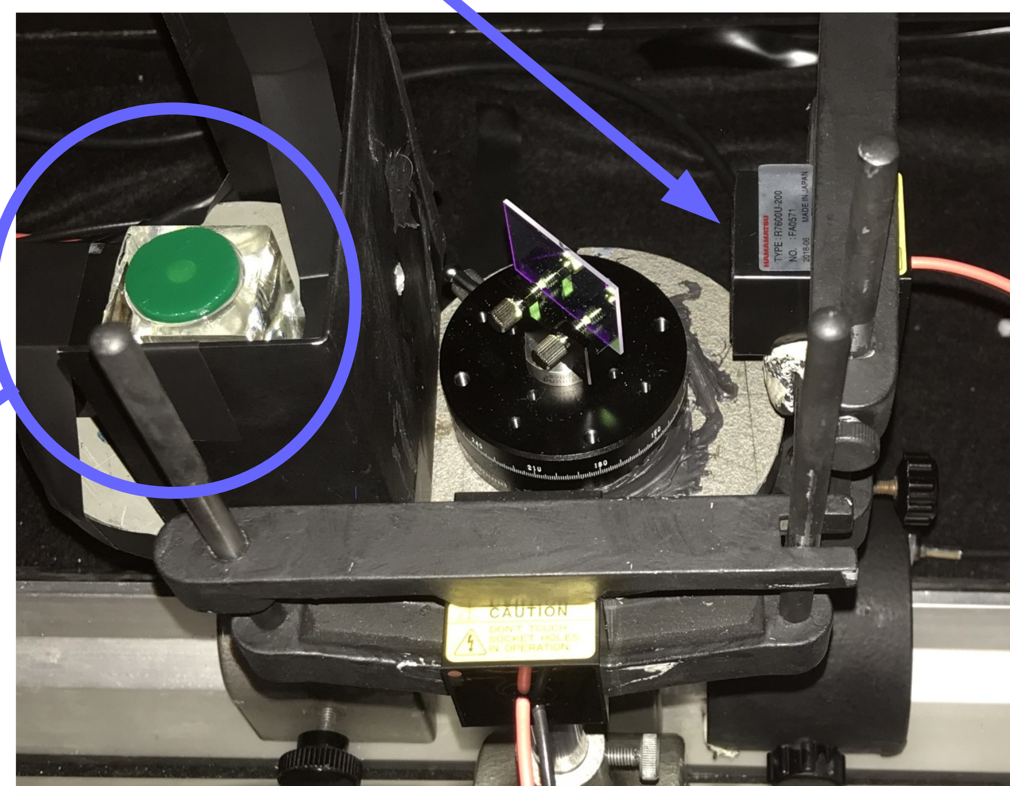
T. Kaptanoglu, M. Luo, J. Klein, JINST 14 no. 05 T05001 (2019)

Demonstration of technology with single dichroic filter

^{90}Sr source

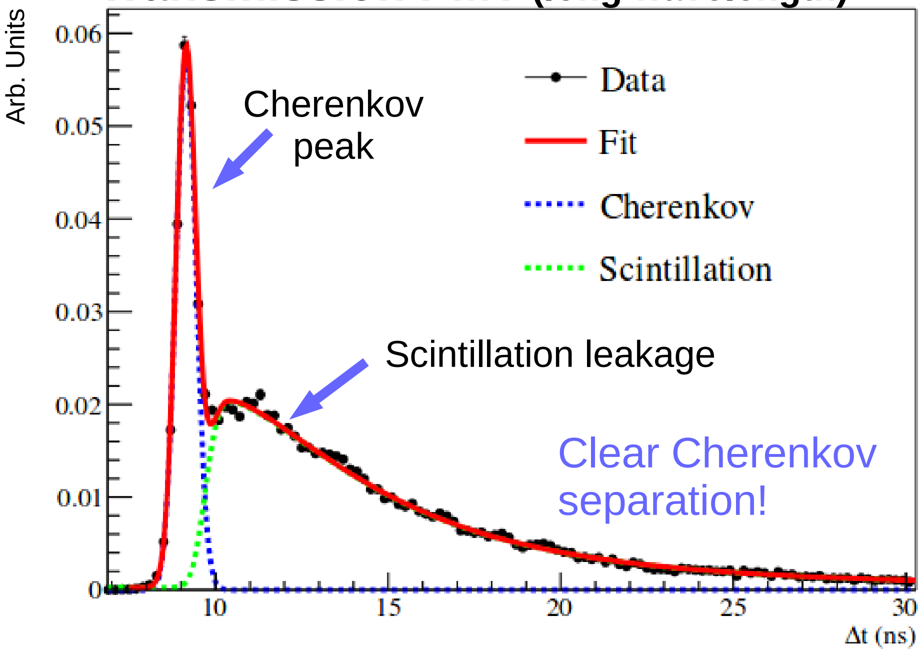
LAB+PPO in UVT acrylic



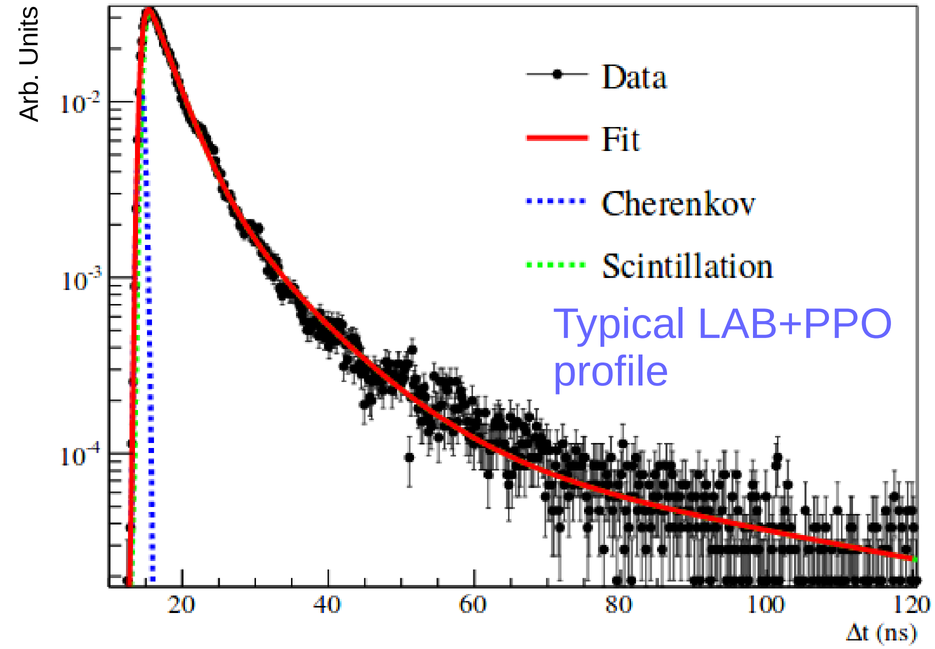


Spectral Sorting with Dichroic Filters

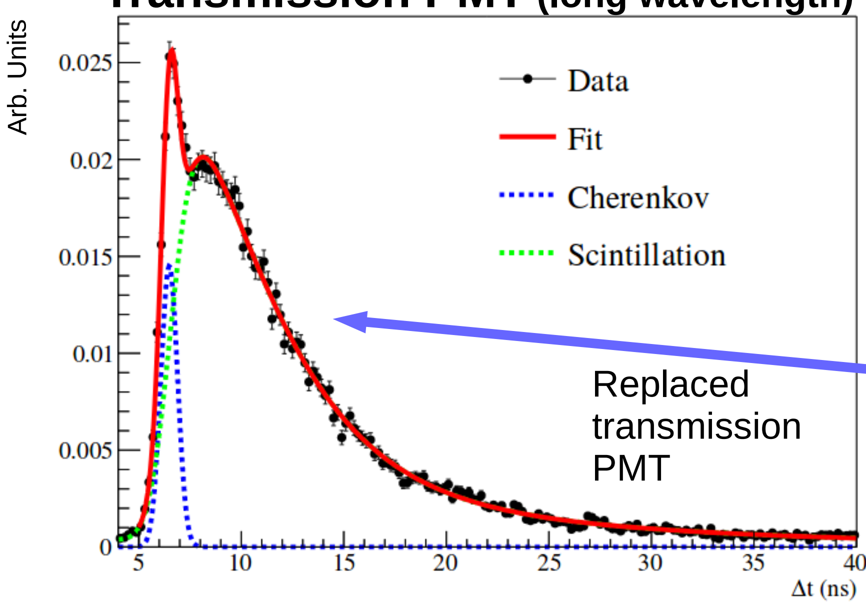
Transmission PMT (long wavelength)



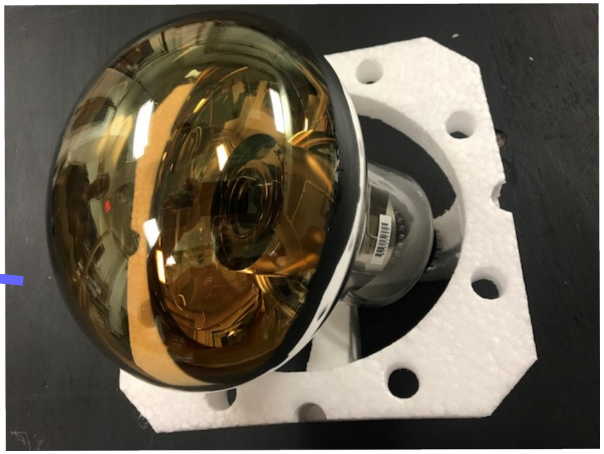
Reflection PMT (short wavelength)



Transmission PMT (long wavelength)



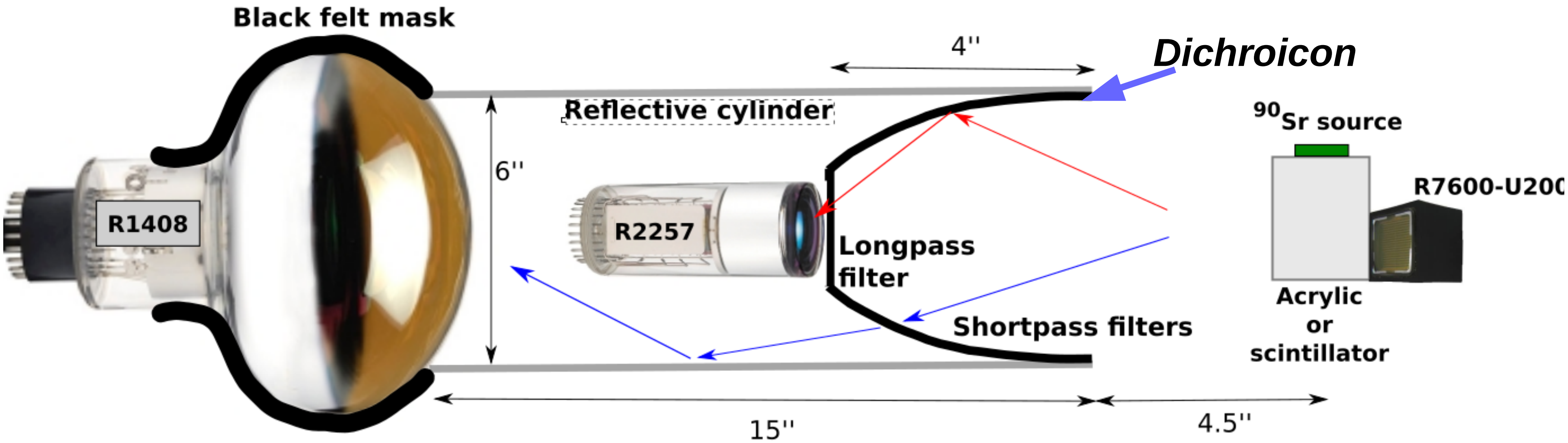
Photon sorting allows Cherenkov and scintillation separation with high efficiency collection of scintillation light

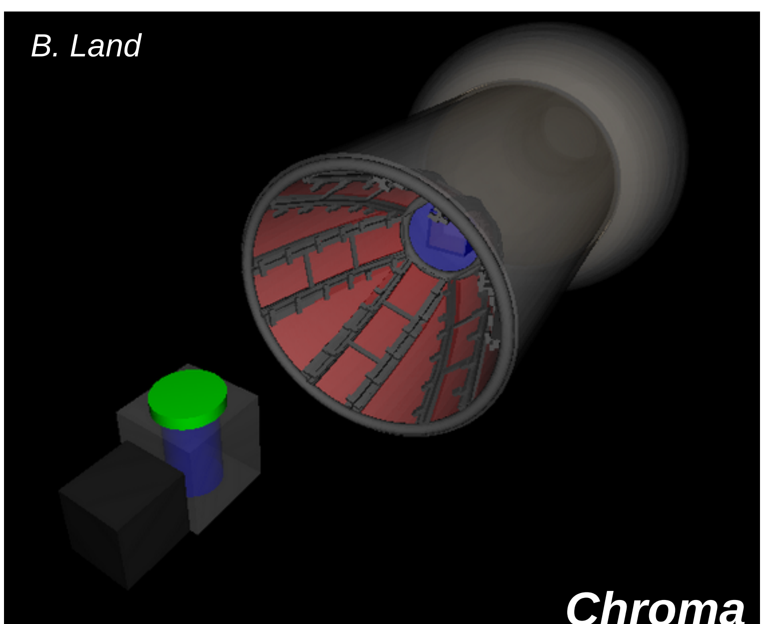


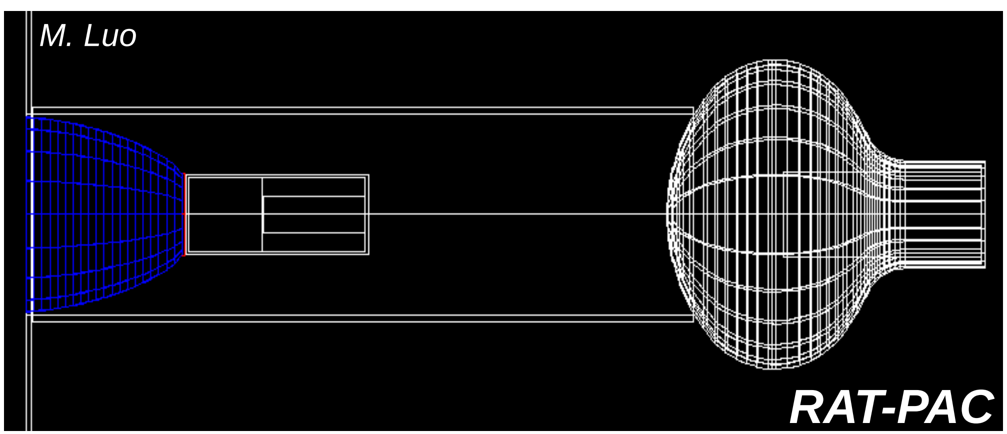
First demonstration of Cherenkov / scintillation separation using large-area PMT!

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

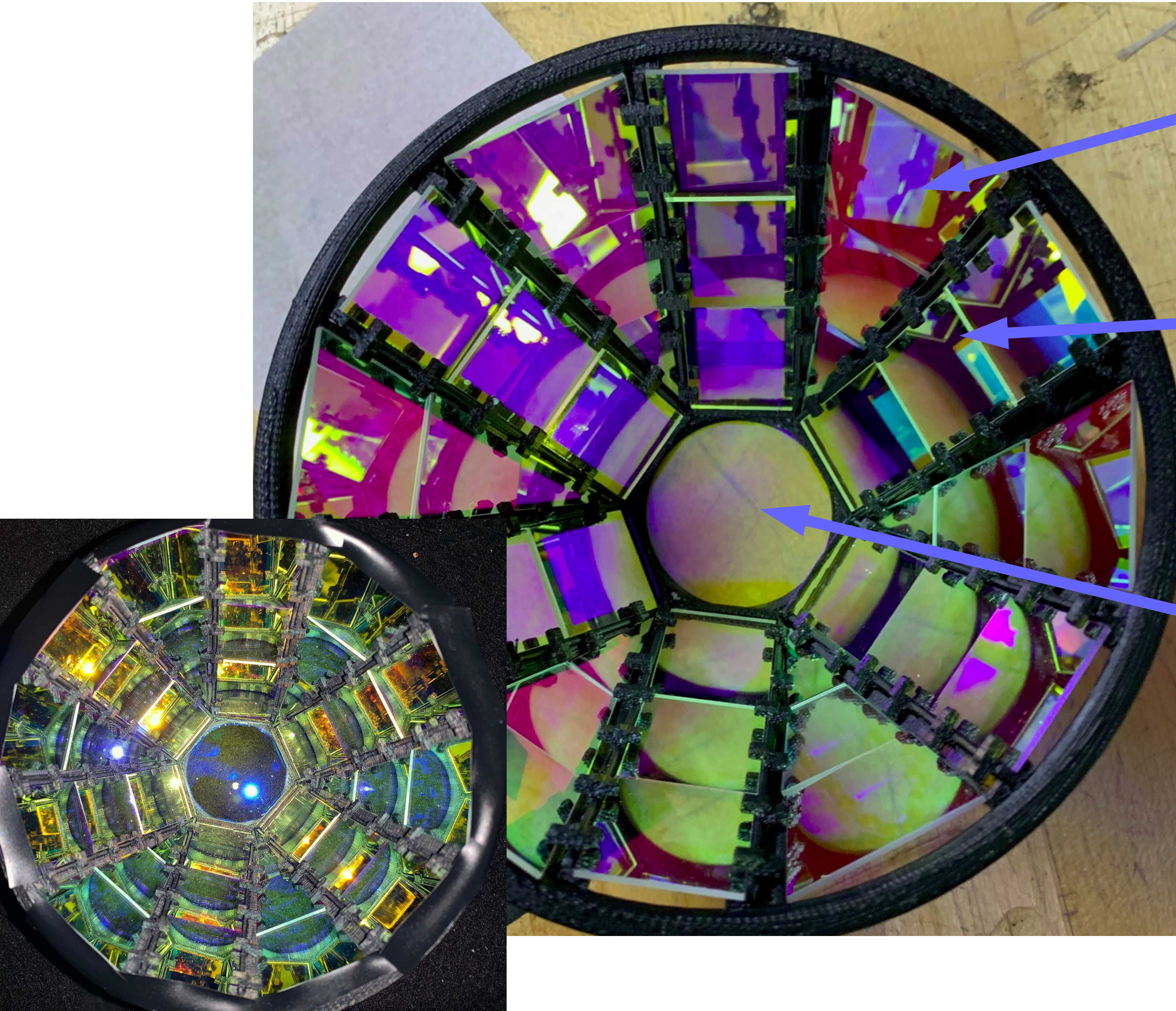
Bench-Top Setup and Simulation Models







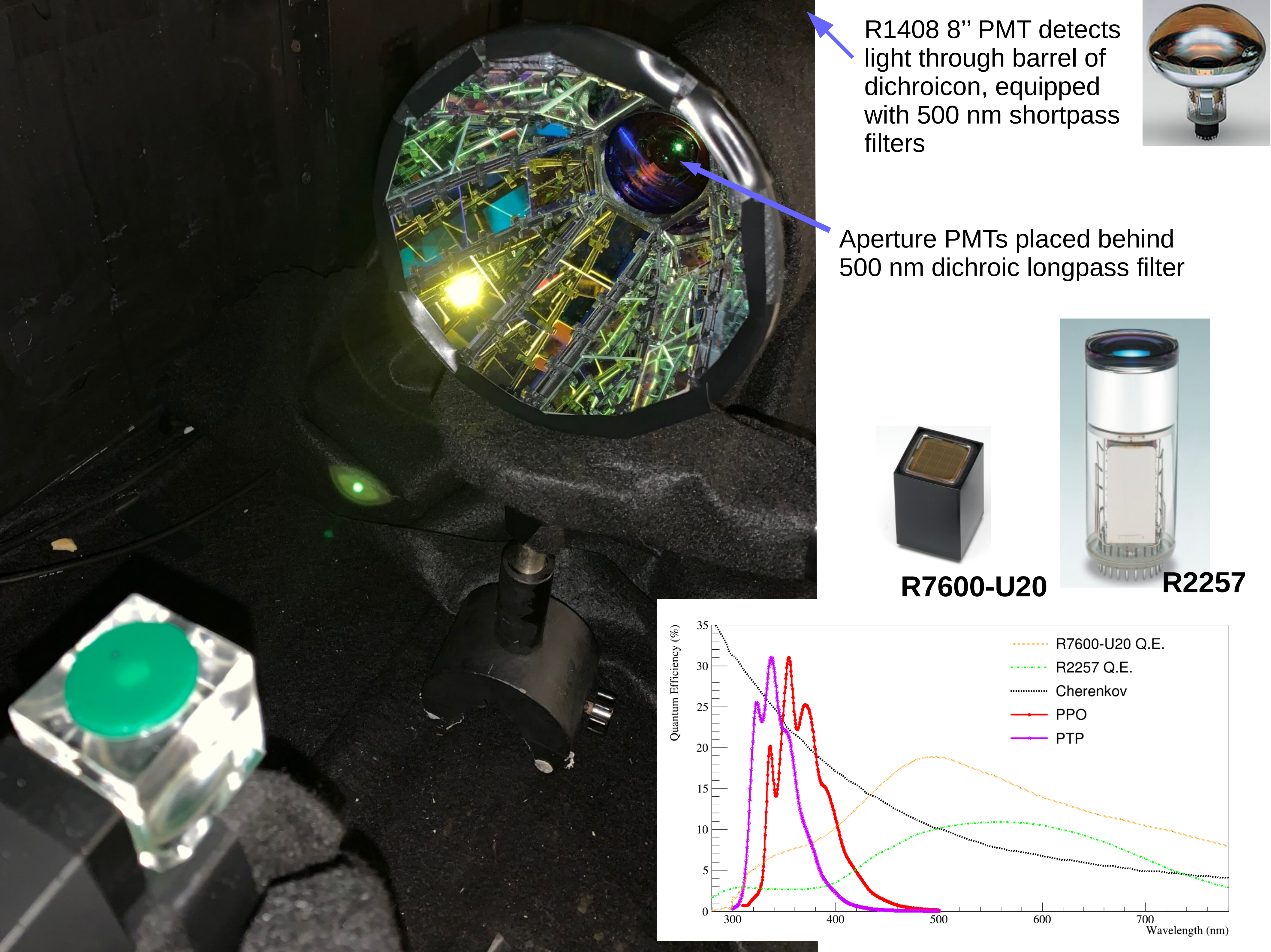
3D Printed Filter Holder



Custom cut short-pass filters from Knight Optical to fill out full 3D printed design

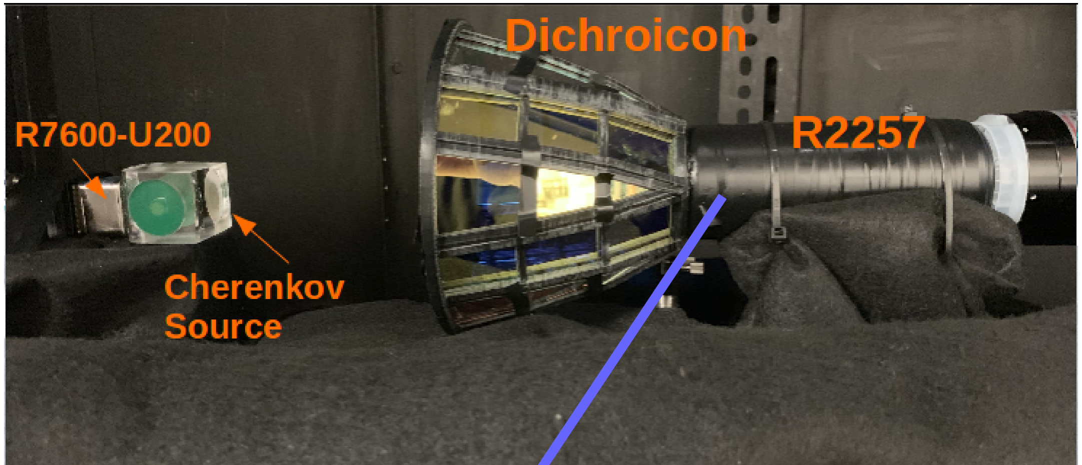
High performance short-pass dichroic filters from Edmund Optics

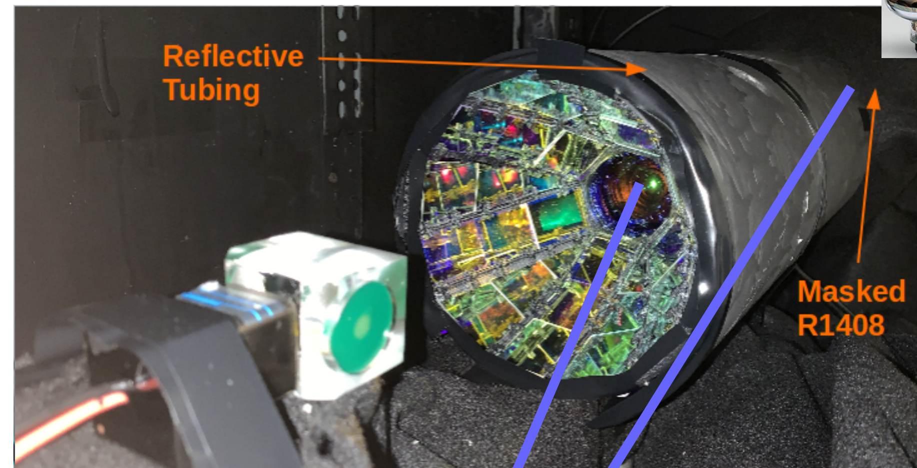
Custom cut long-pass filter from Knight Optical to fit the aperture

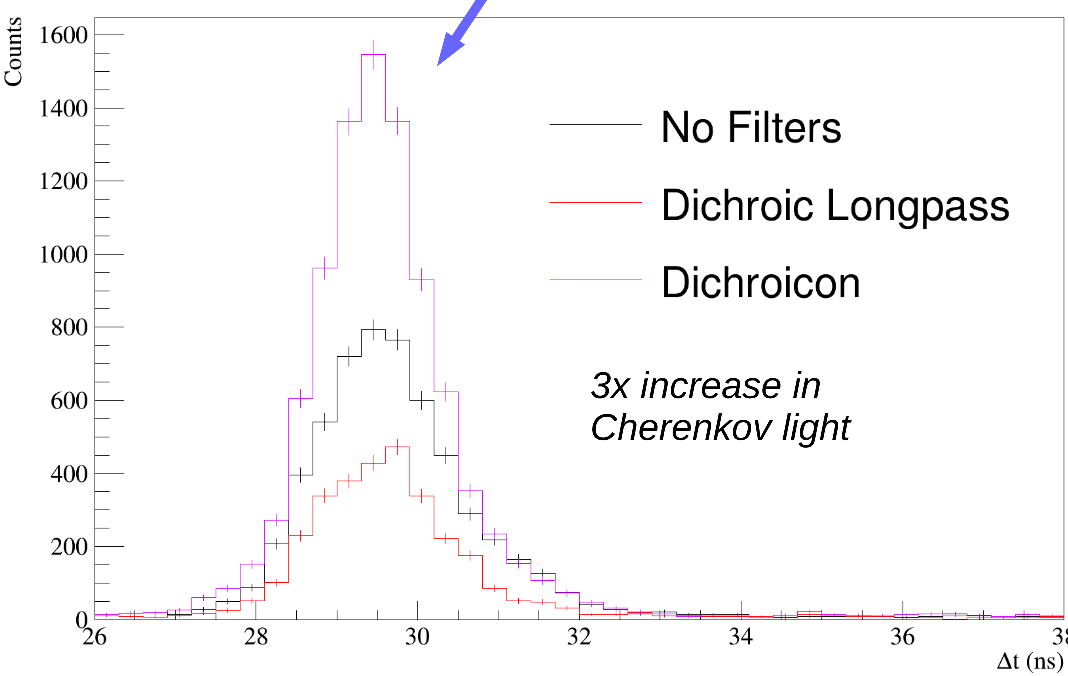


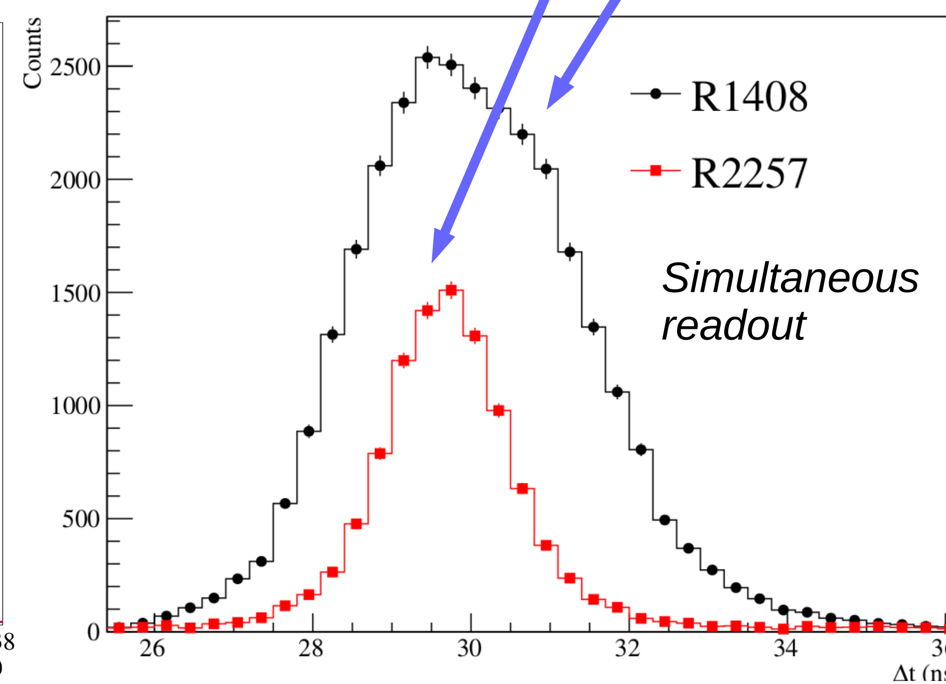
R1408 8'' PMT detects light through barrel of dichroicon, equipped with 500 nm shortpass filters
Aperture PMTs placed behind 500 nm dichroic longpass filter
R7600-U20
R2257
Quantum Efficiency (%)
Wavelength (nm)
R7600-U20 Q.E.
R2257 Q.E.
Cherenkov
PPO
PTP
0
5
10
15
20
25
30
35
300
400
500
600
700

Dichroicon Data with a Cherenkov Source

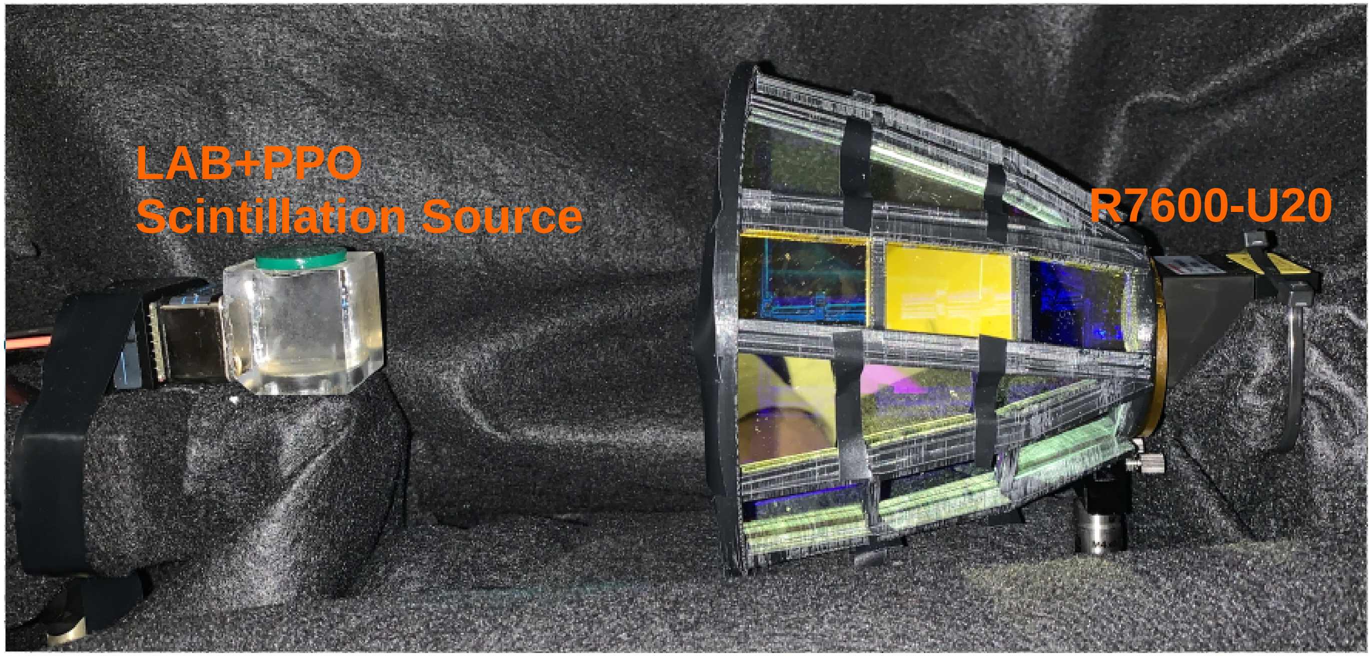


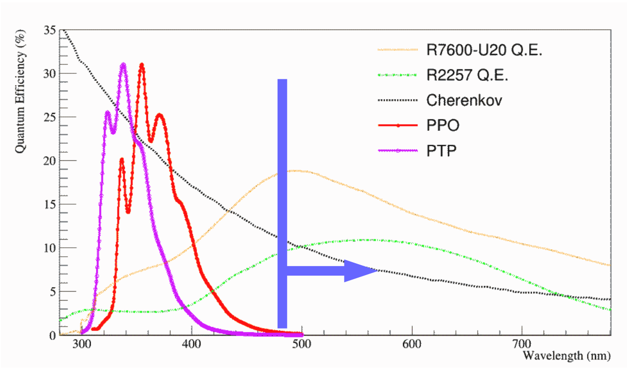


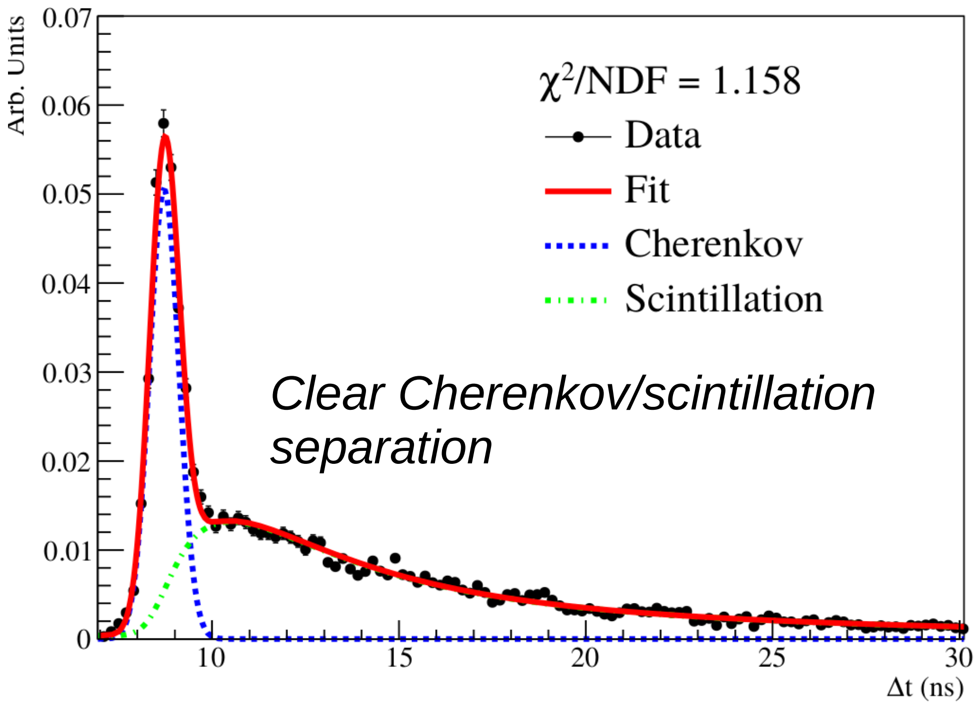




Dichroicon Data with a LAB+PPO Target



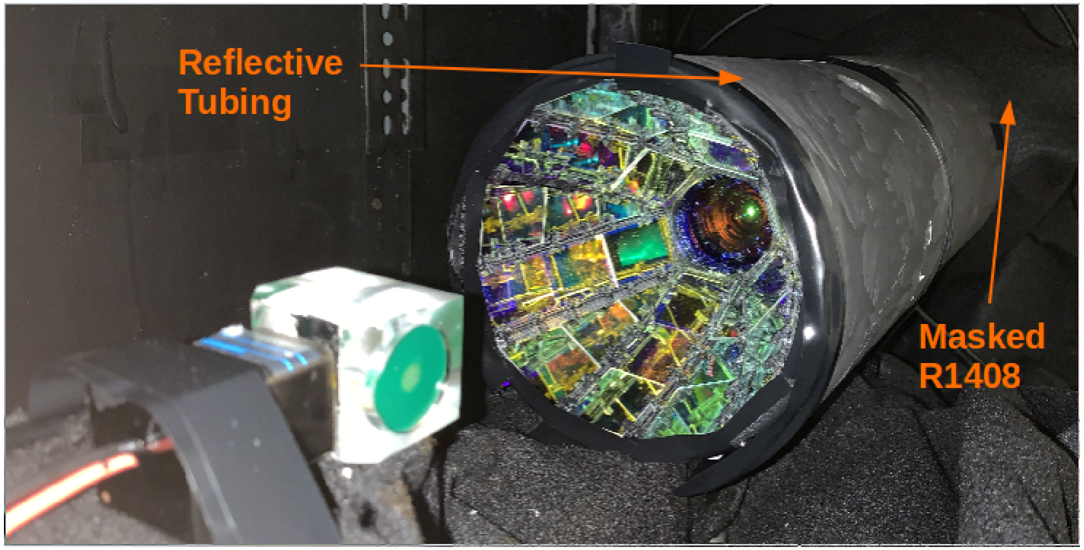




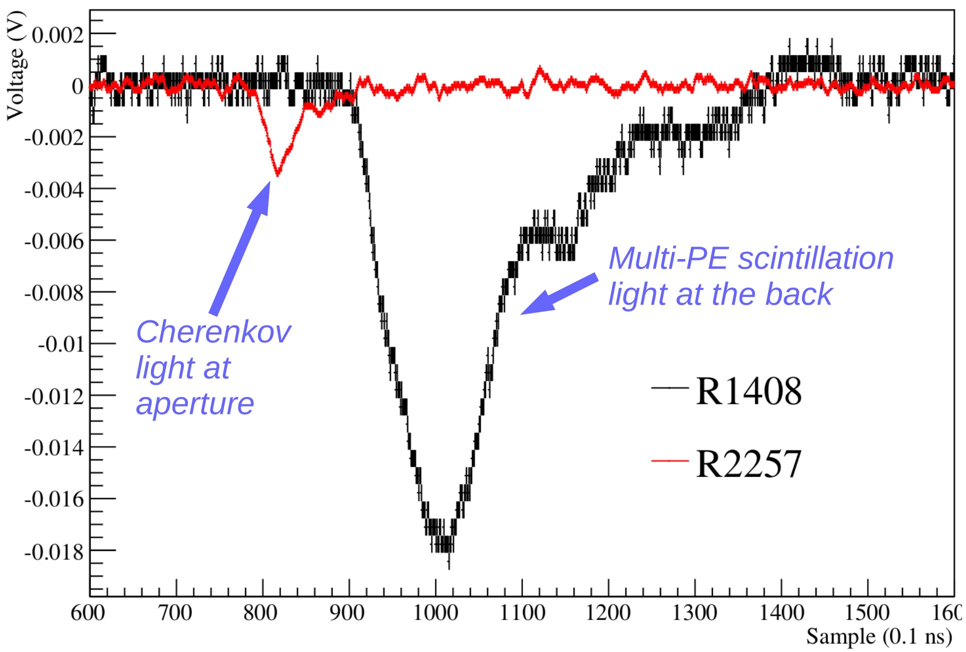
Clear Cherenkov/scintillation separation

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

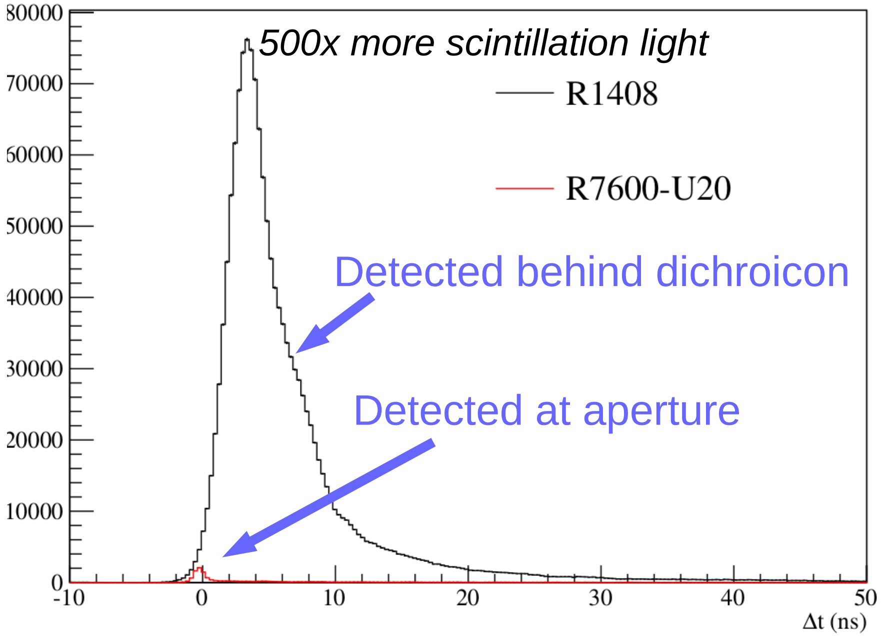
Simultaneous Detection of Cherenkov and Scintillation Light



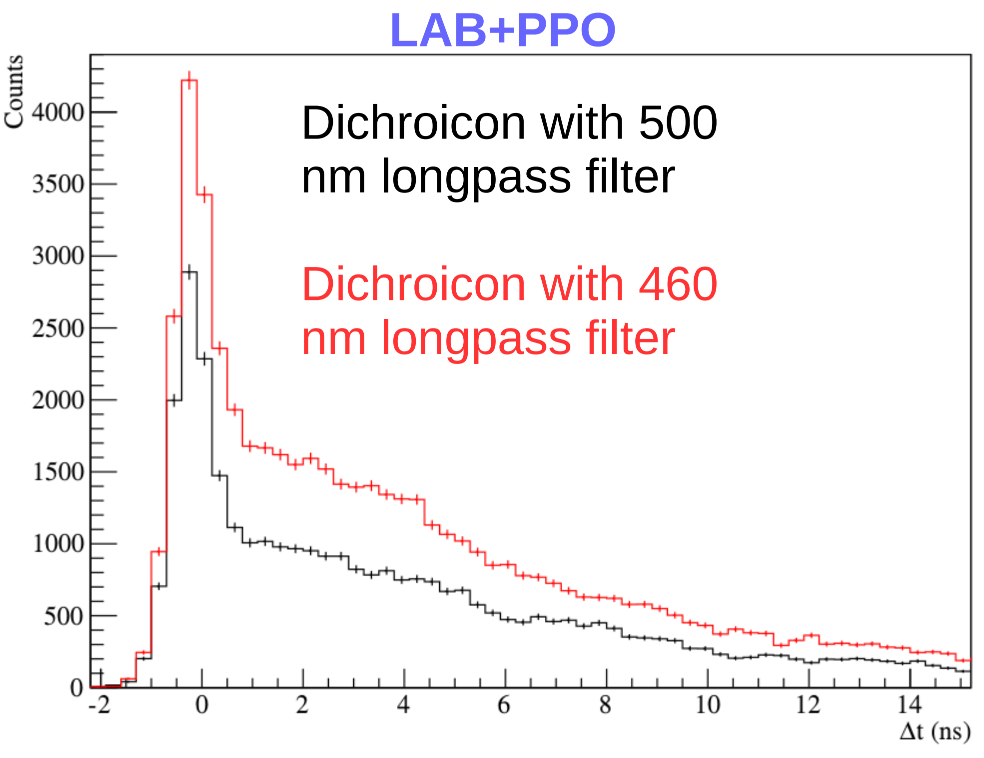
Photon sorting allows you to detect Cherenkov light with one PMT and scintillation light with the other, even with overwhelming scintillation light yield

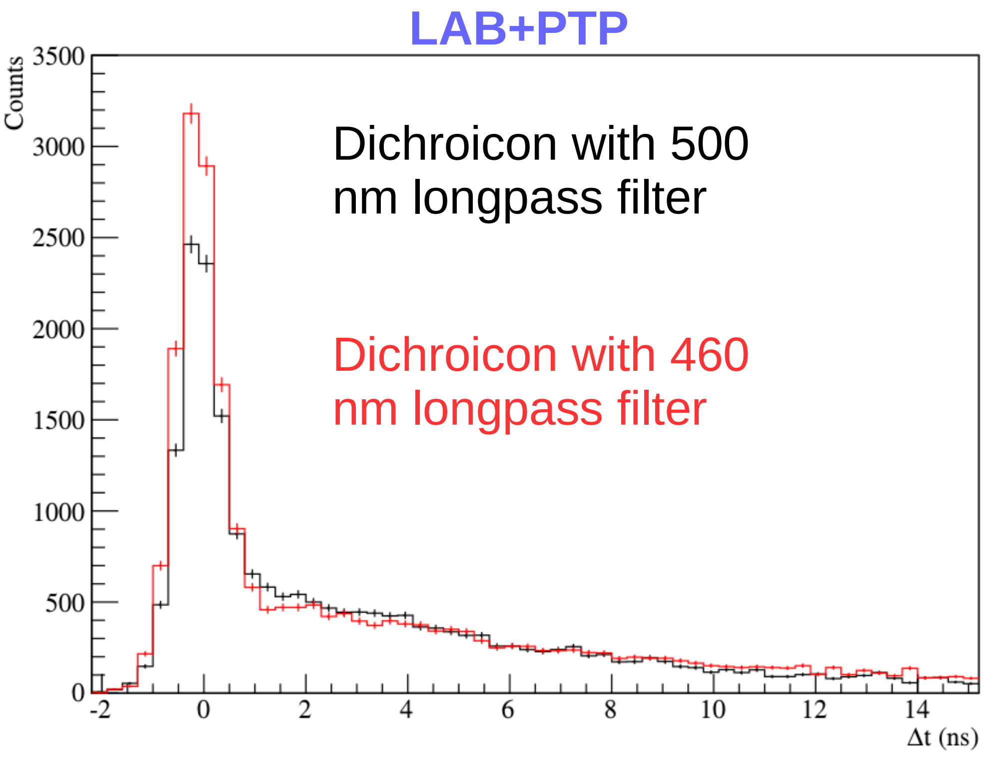


Identify Cherenkov and scintillation light in the same event

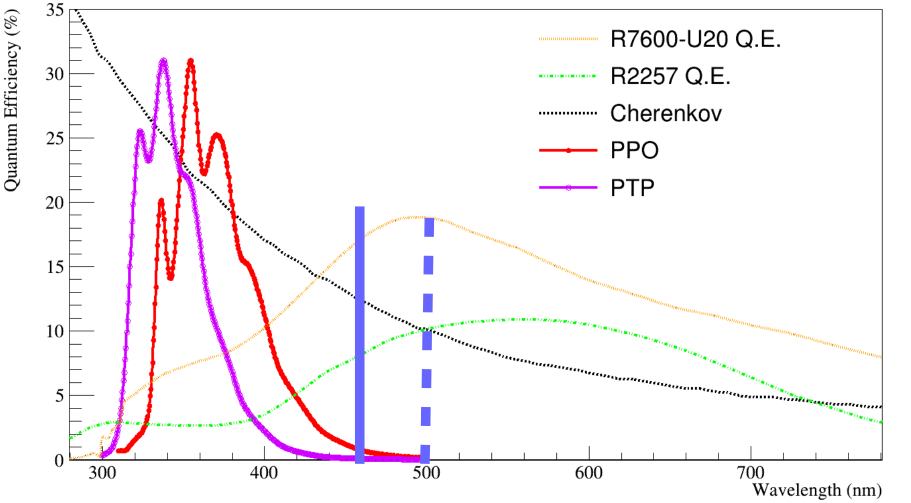


Dichroicon Data with Liquid Scintillator Targets and Two Different Central Dichroic Filters



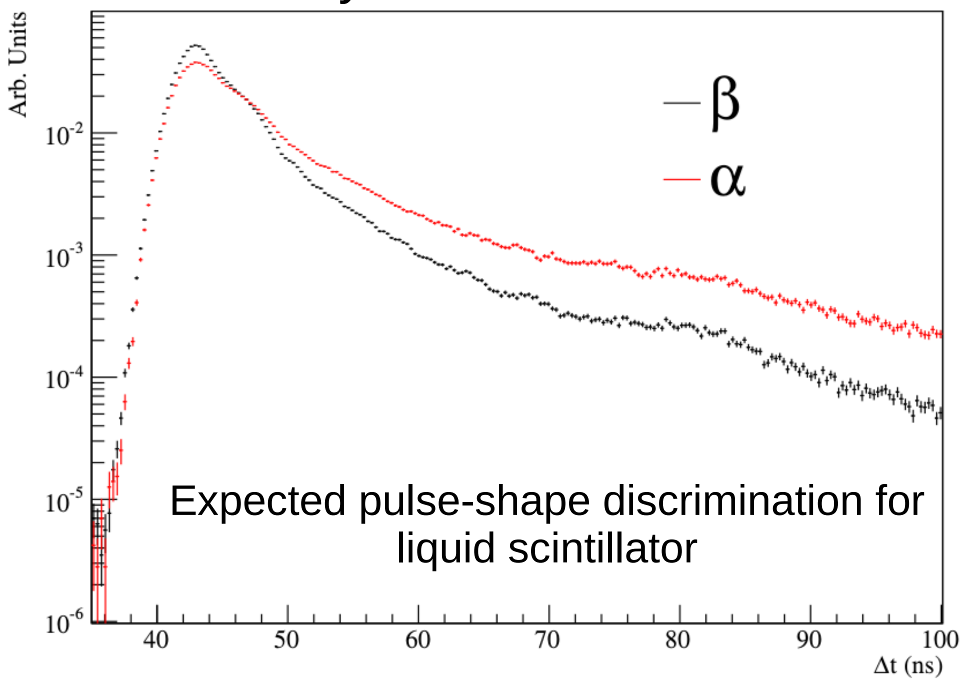


Dichroicon filters should be carefully tuned to emission spectrum of scintillator

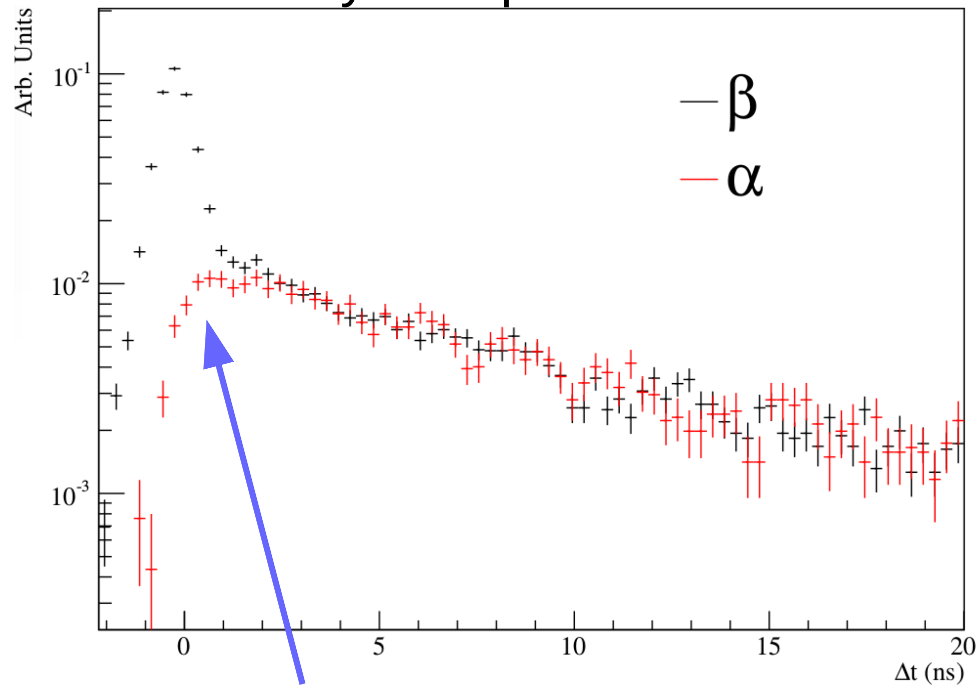


Dichroicon Data with an Alpha Source

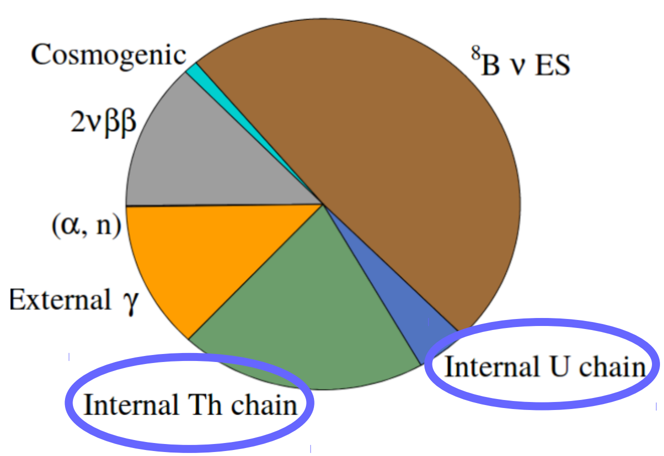
Short wavelength light
detected by the R1408 PMT



Long wavelength light
detected by the aperture PMT

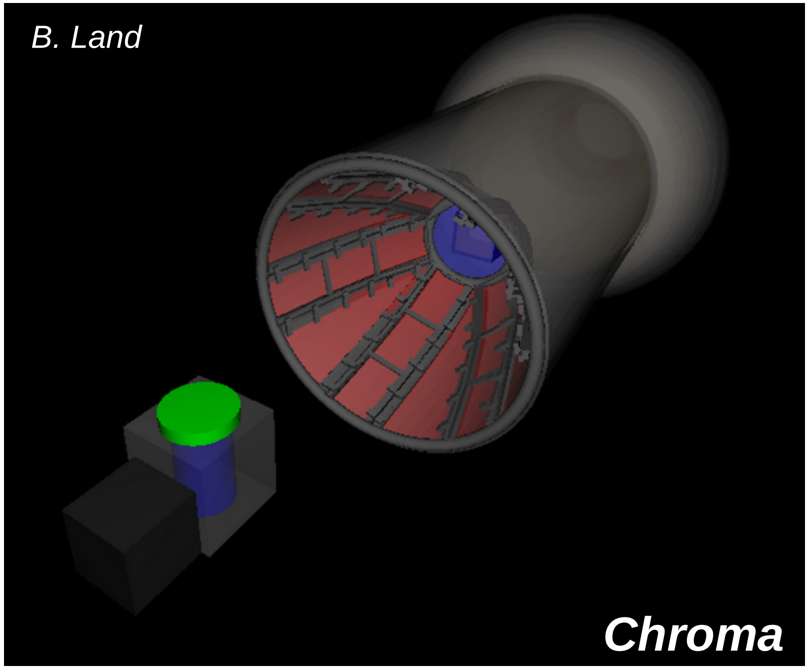


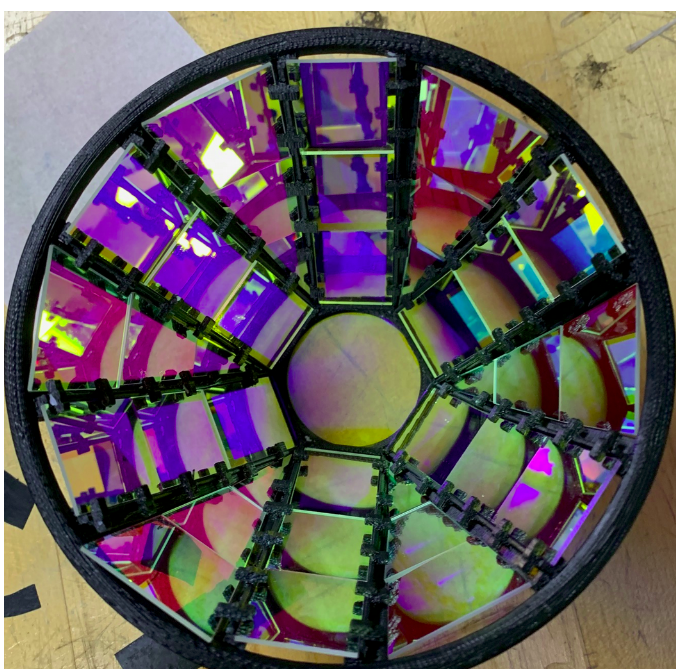
Additional Particle ID using the Cherenkov light!

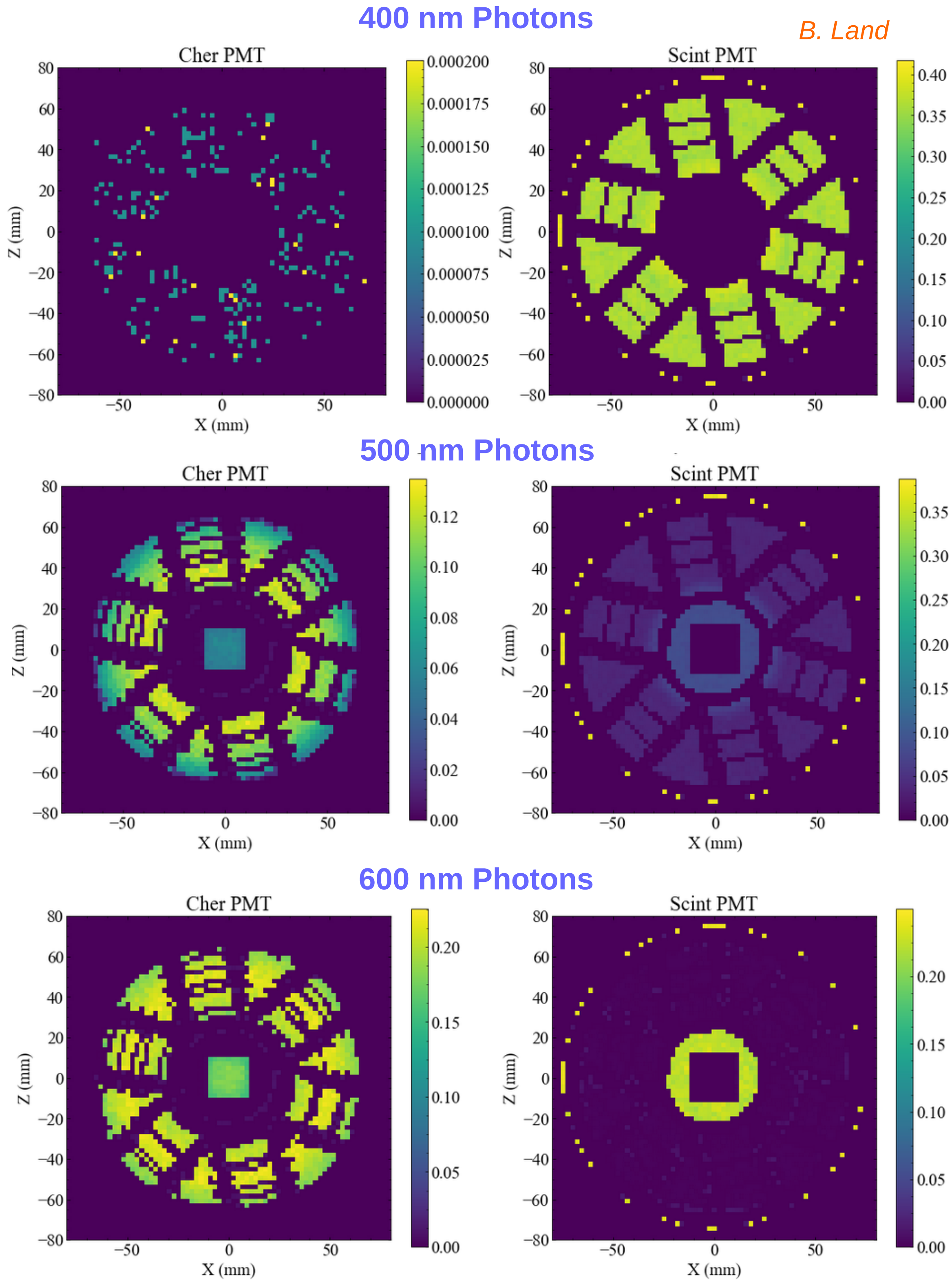


Improved α/β separation particularly important for background reduction for the low energy program

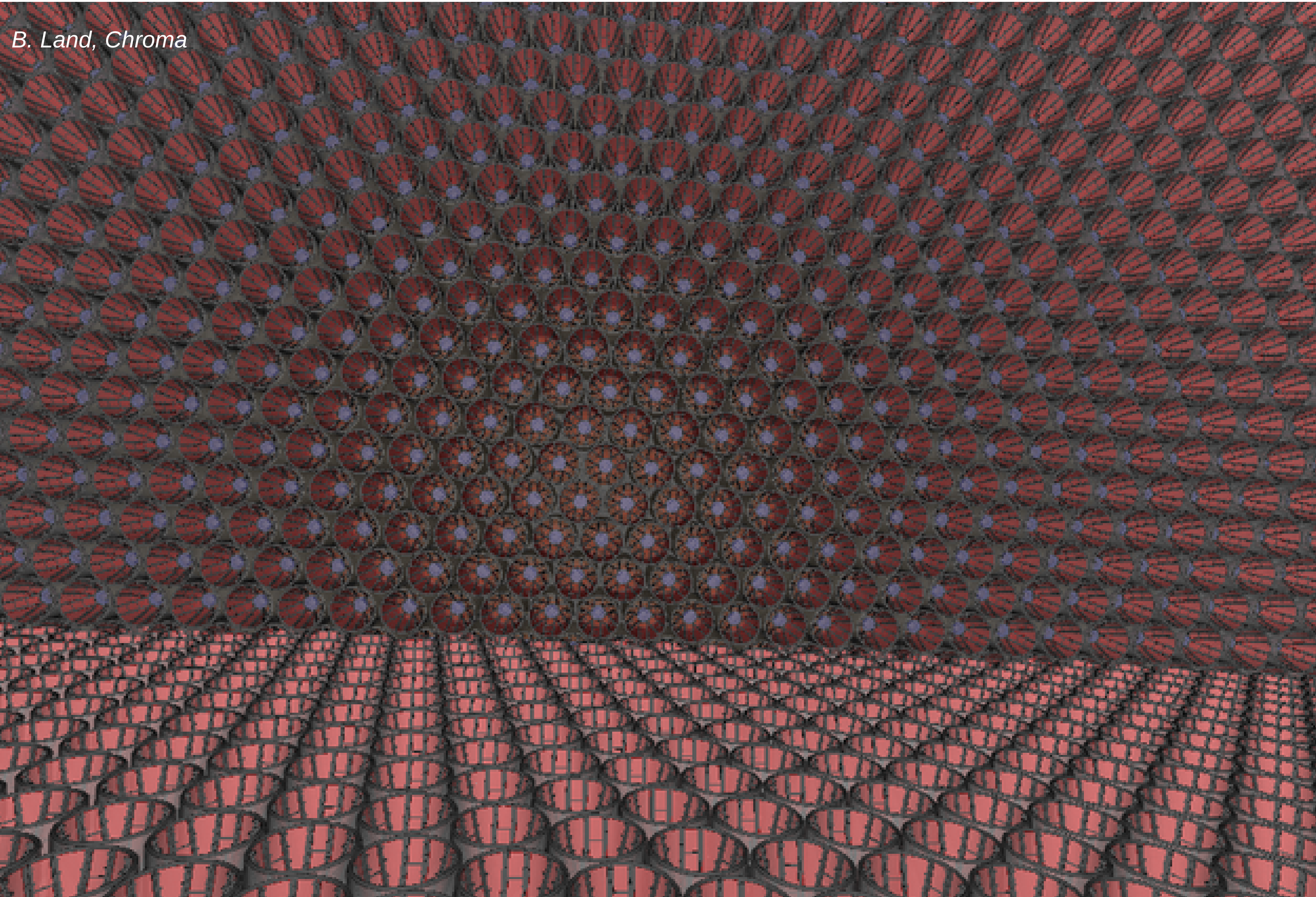
Dichroicon Simulations







Simulations of Large-Scale Detectors With Dichroicons

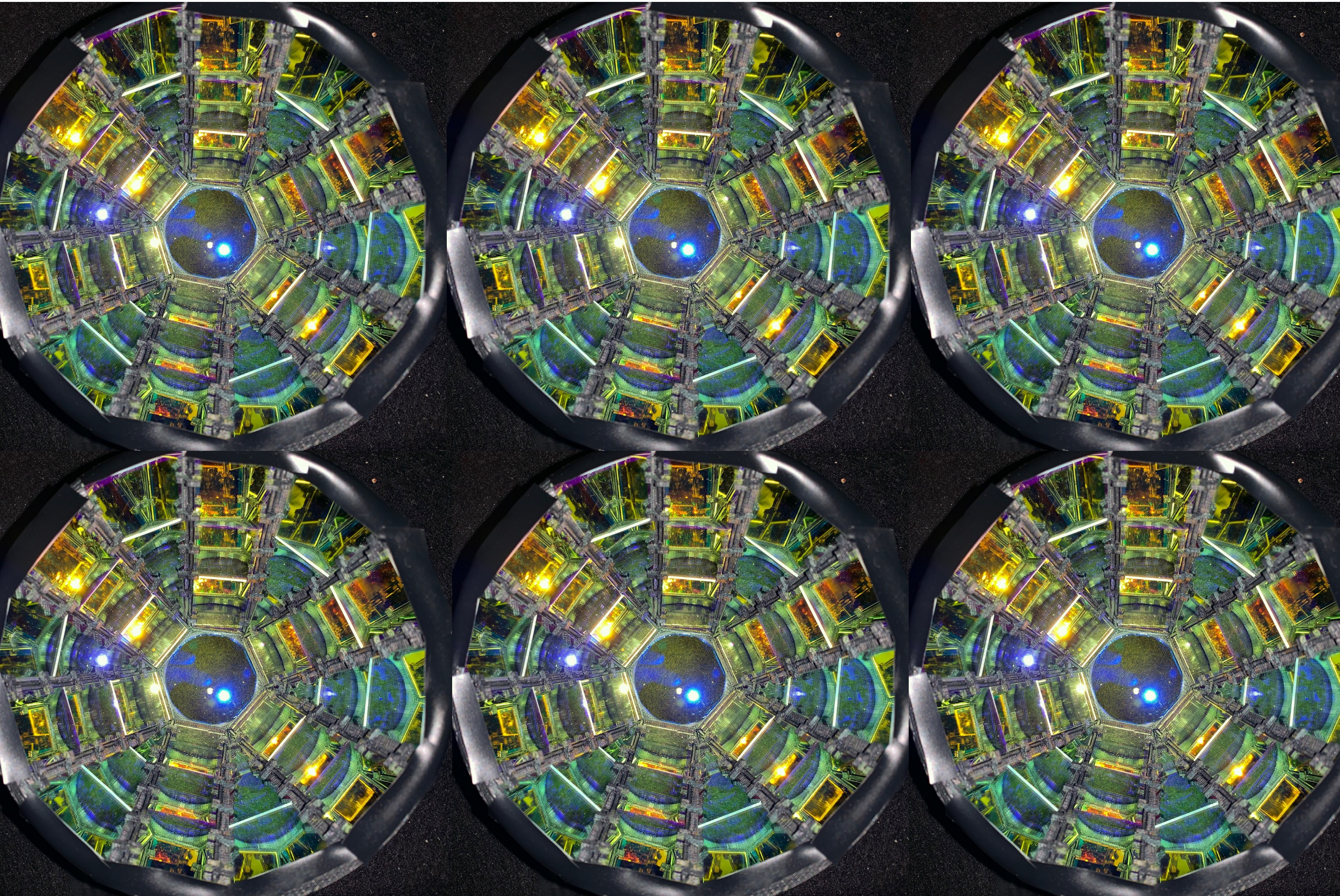


Conclusions

- 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

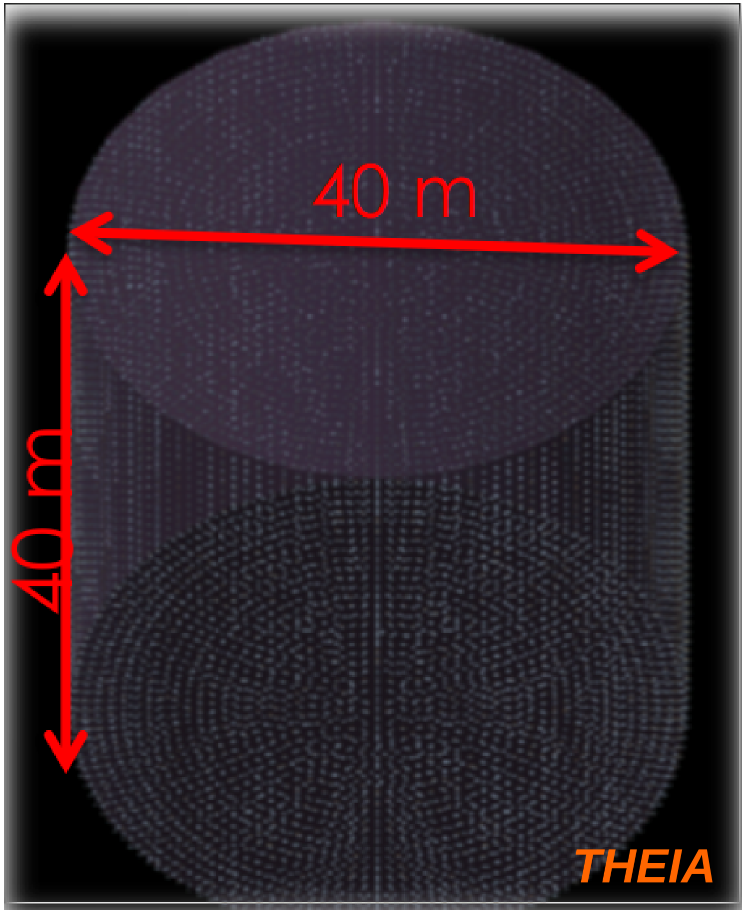
Work supported by Department of Energy Office of High Energy Physics Advanced Detector R&D

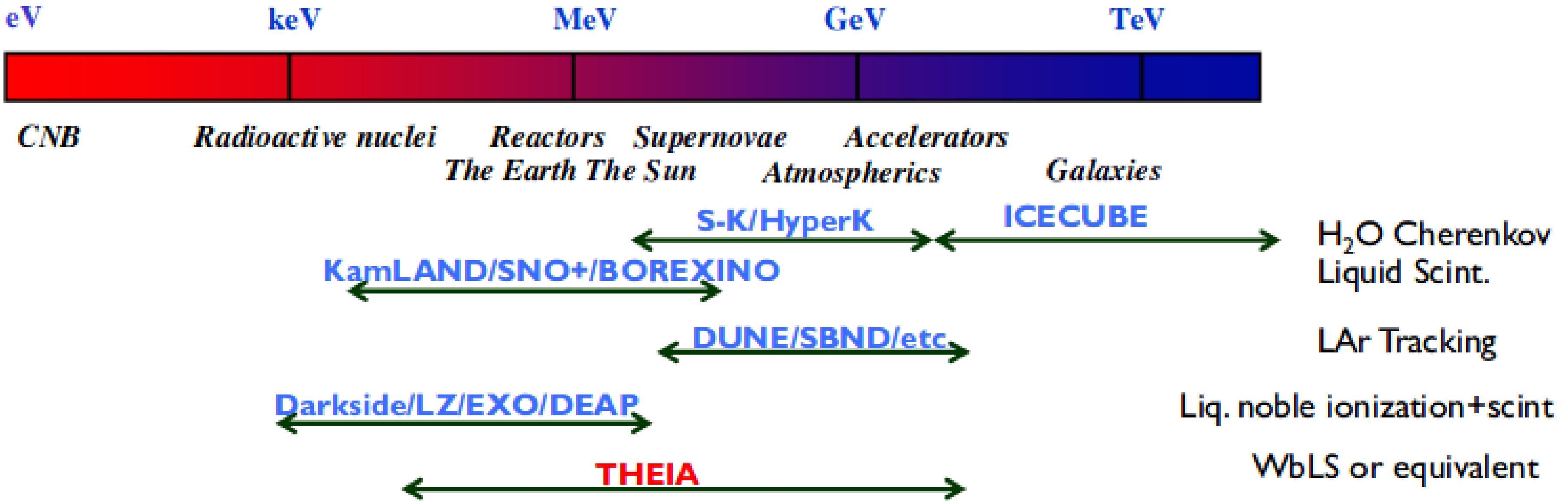
Backup Slides



Future Experiments

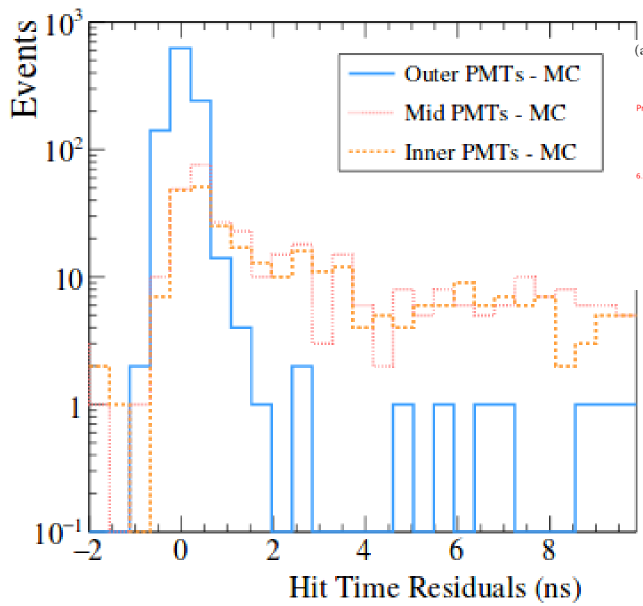
- Several proposed WbLS detectors hoping to achieve Cherenkov and scintillation separation
- THEIA is a proposed 50kT WbLS (or equivalent technology) detector, potentially complimentary to DUNE
- ANNIE is 26-ton water-based detector measuring neutrino-nucleus interactions. Future phases will likely include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

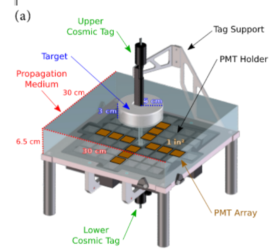


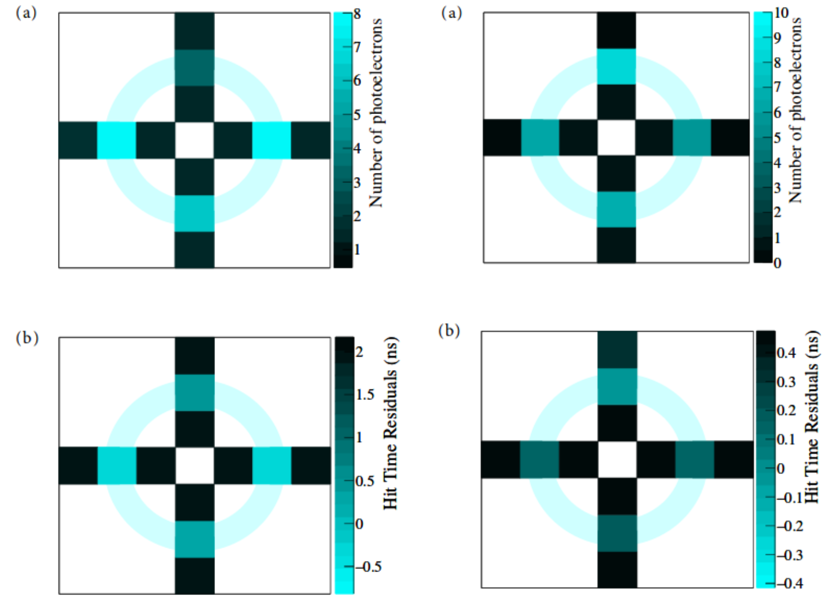


Schematic from J. Klein

Ongoing R&D For Cherenkov / Scintillation Separation

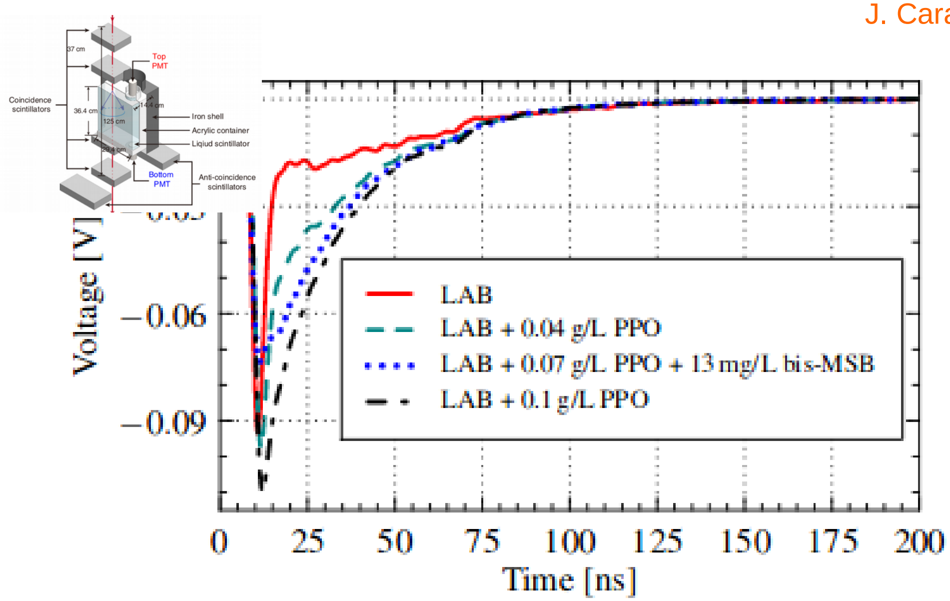






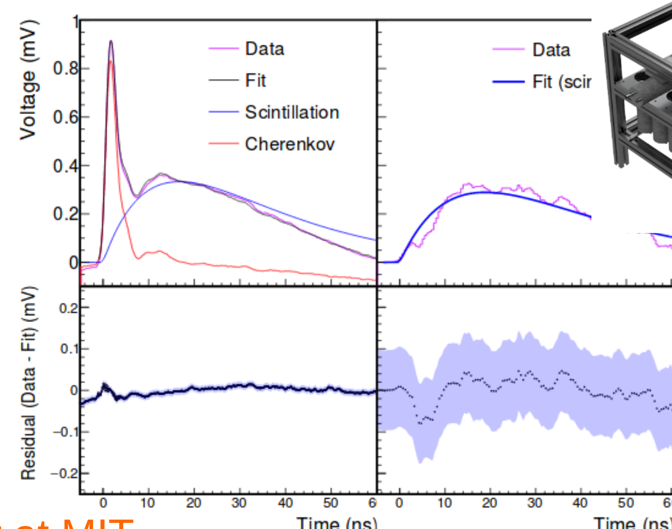
CHESS setup at LBNL

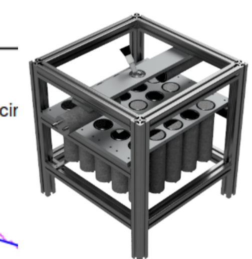
J. Caravaca et. al, 10.1103/PhysRevC.95.055801



Slow scintillator characterization for Jinping

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

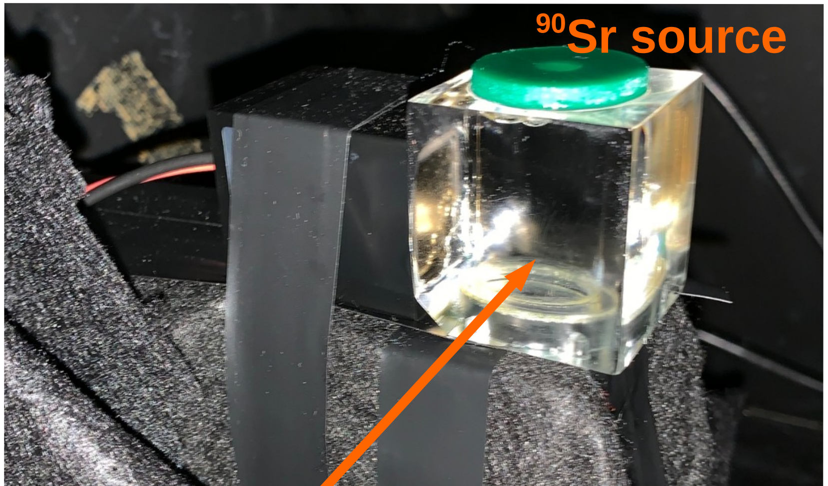




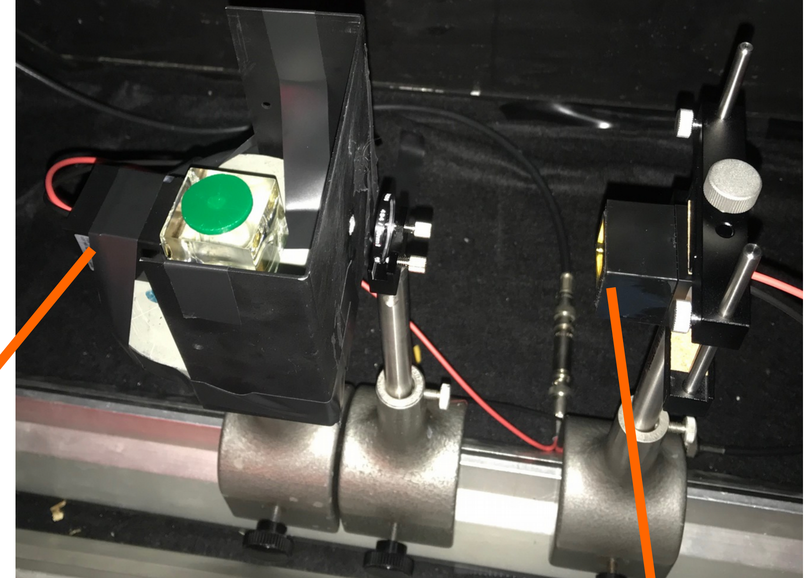
FlatDot at MIT

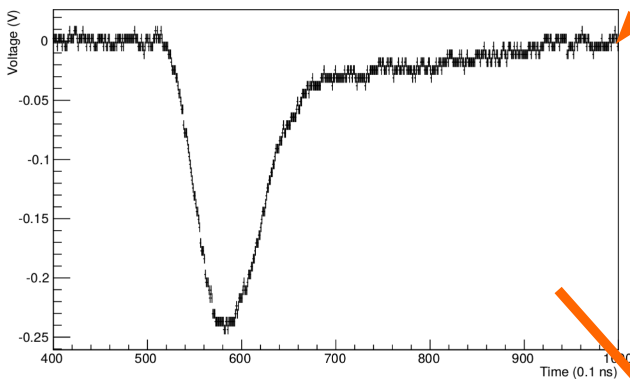
J. Gruszko, et. al, 10.1088/1748-0221/14/02/P02005

Only timing and isotropy used to identify the Cherenkov light.

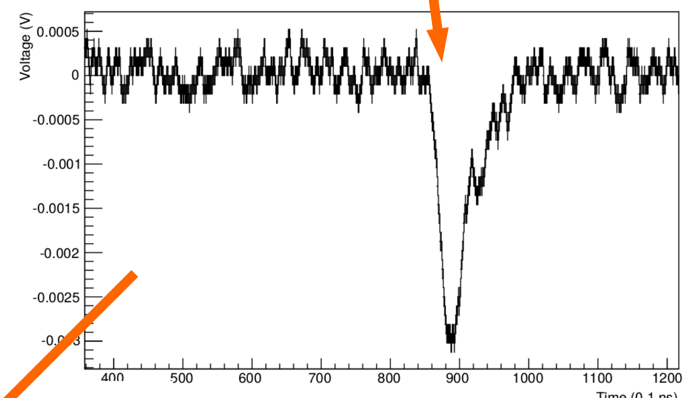


LAB+PPO inside UVT acrylic

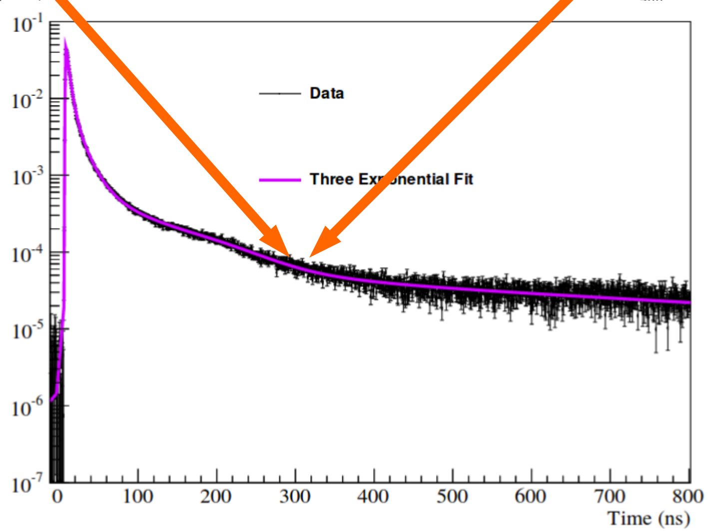




Calculate Δt between the two waveforms



Data with no bandpass filter shows typical scintillation spectrum

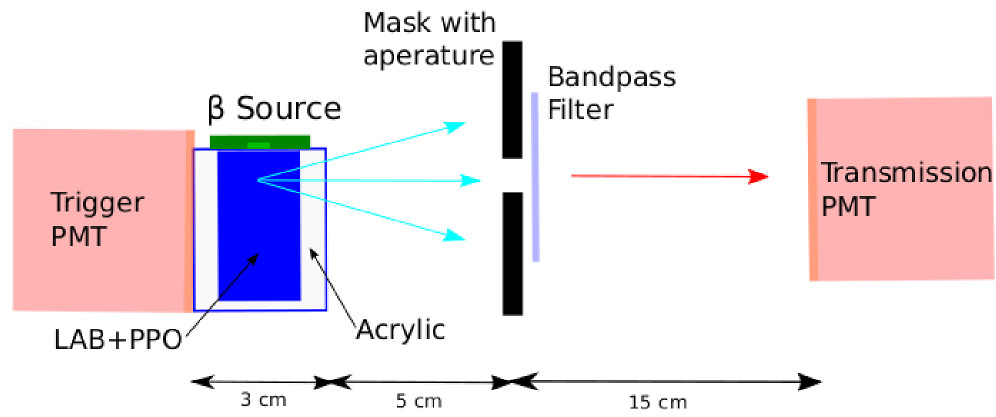


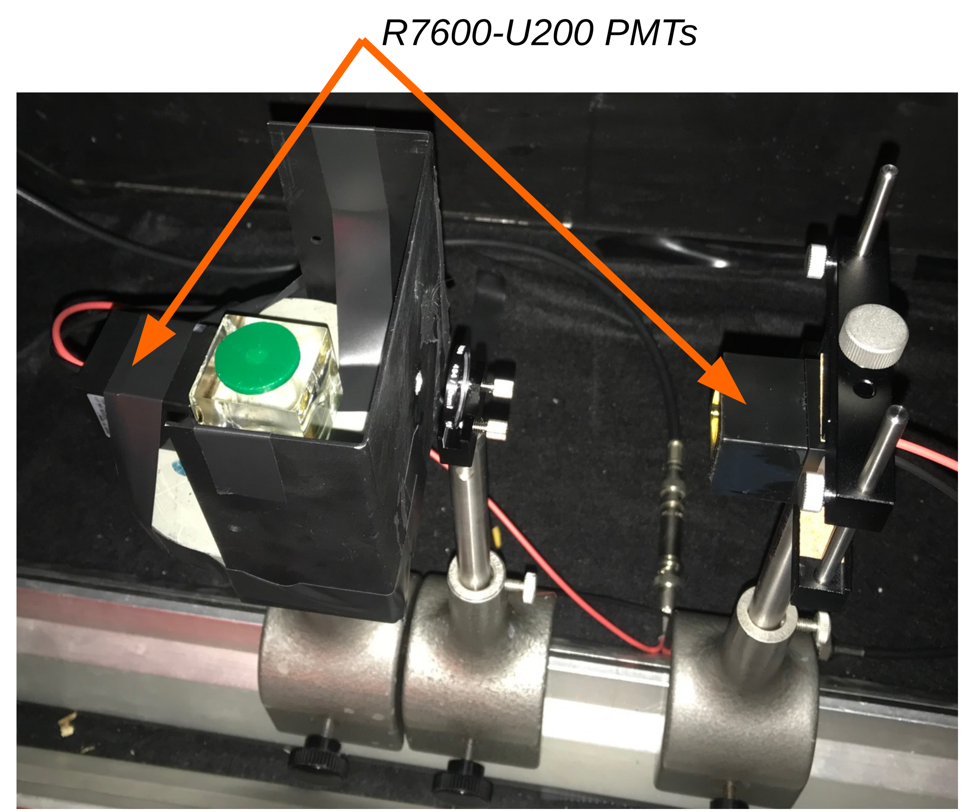
Characterized by intrinsic rise τ_r ~1ns followed by exponential decay with $\tau_{1,2,3}$ ~5ns, ~20ns, ~400ns

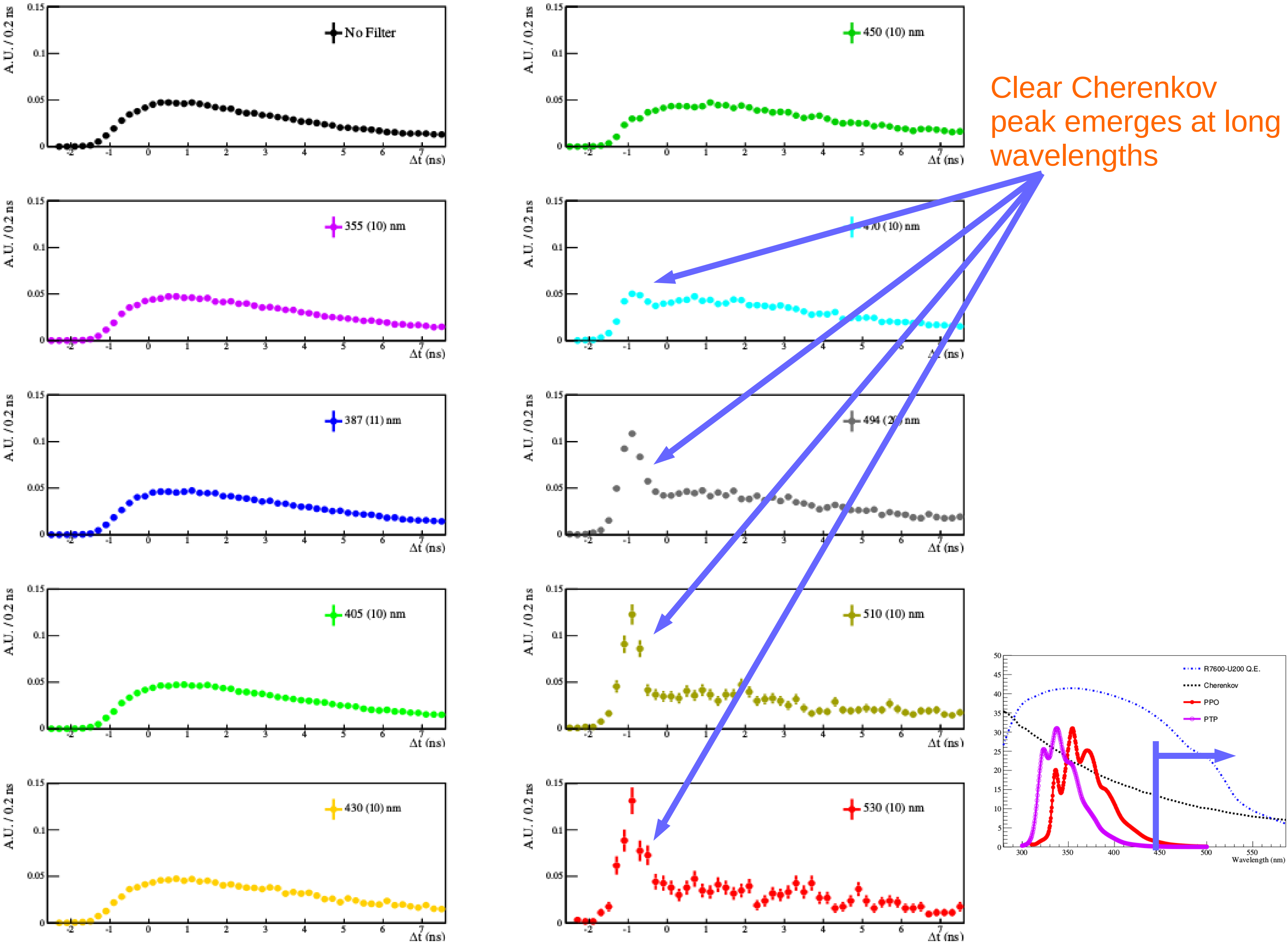
Cherenkov / Scintillation Separation With Bandpass Filters

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







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

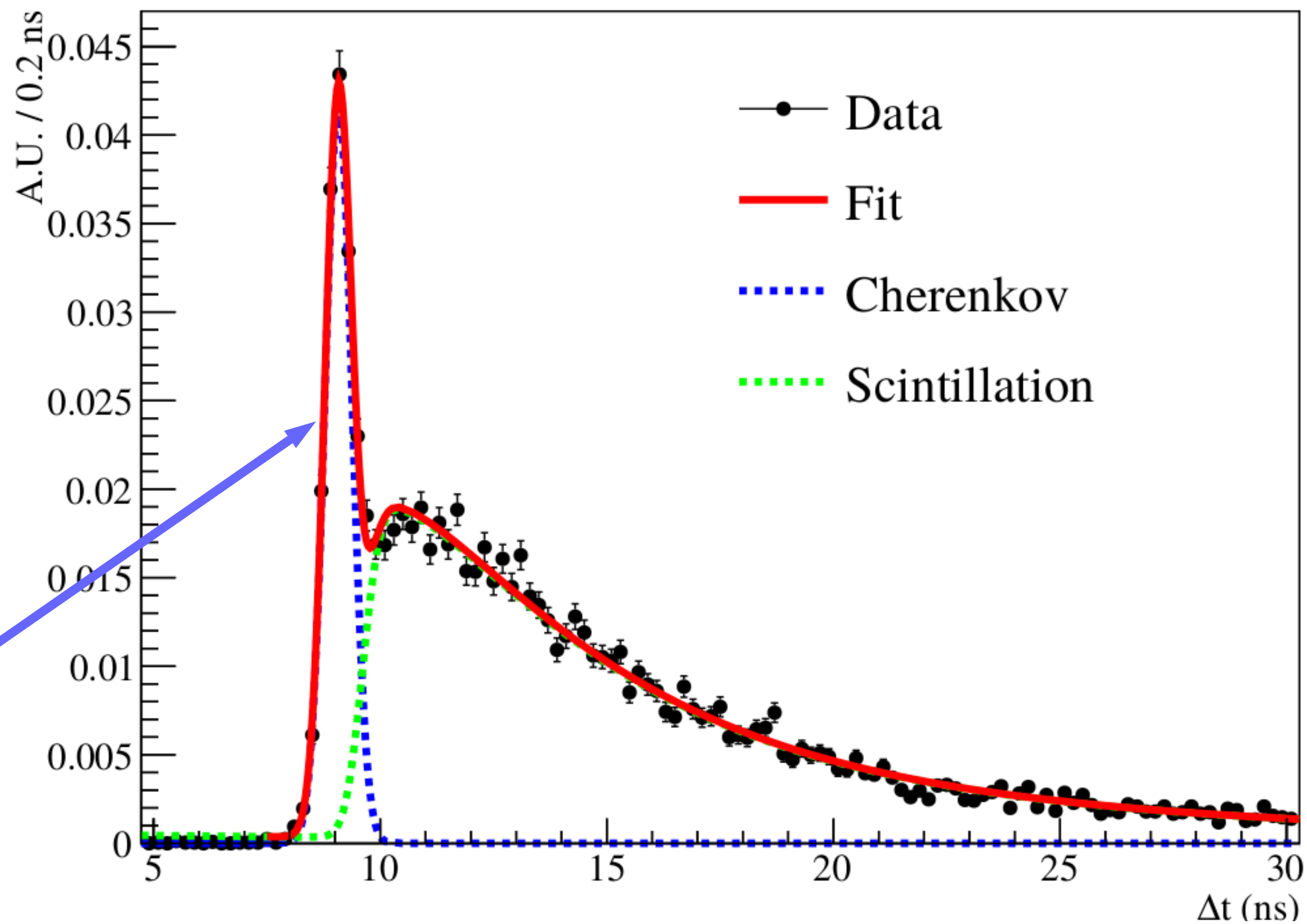
Fitting the Spectrum

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

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

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

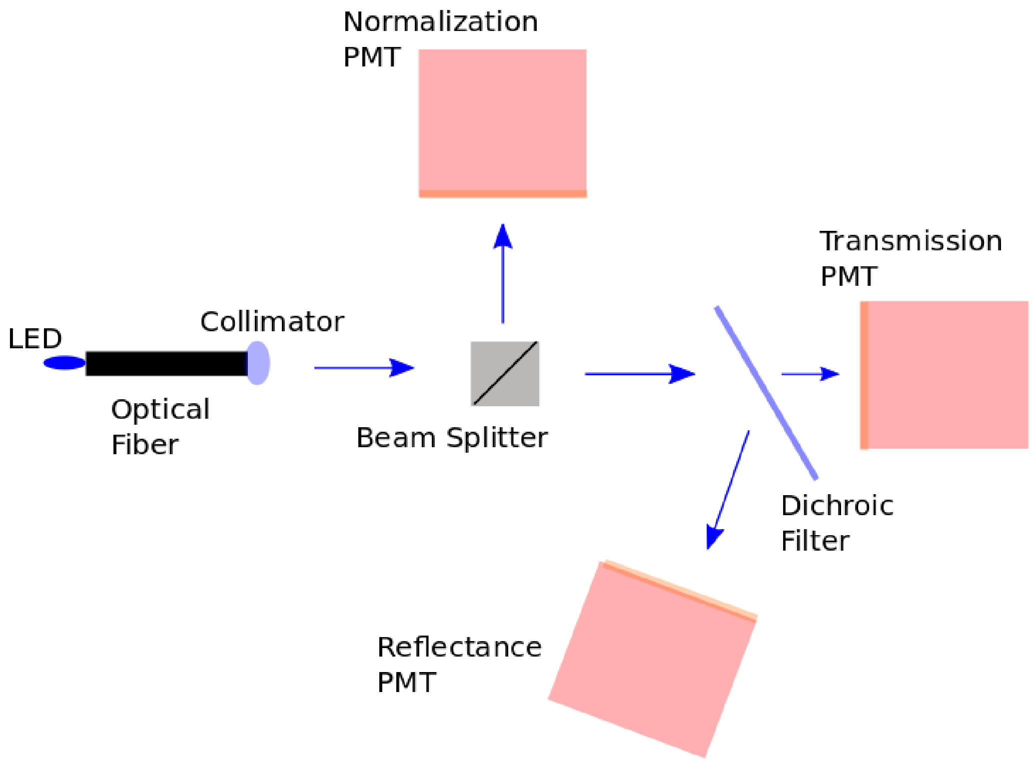
Purity, *P*, of the Cherenkov light in a prompt window



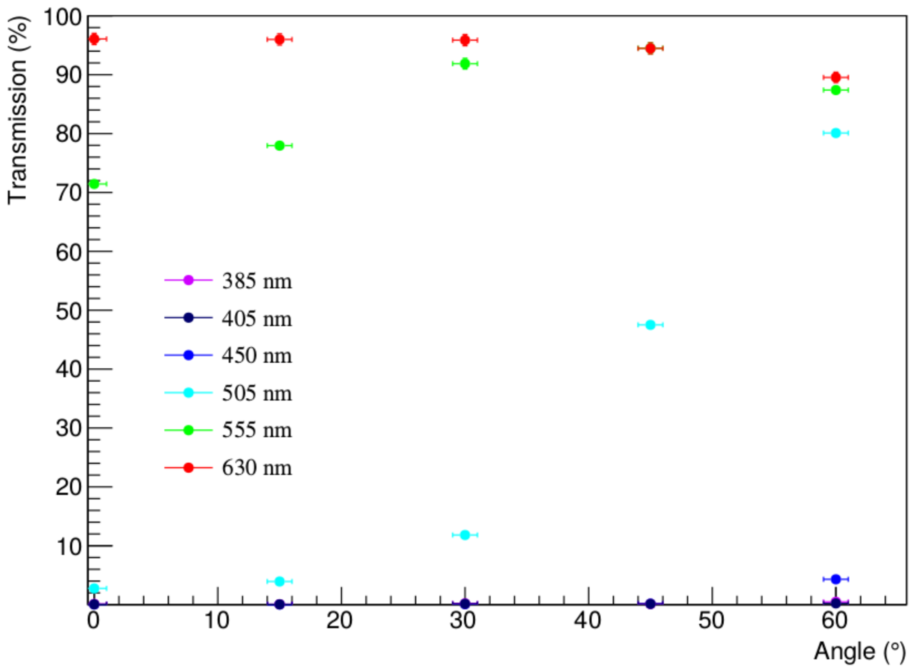
> 90% of prompt light is Cherenkov light!

Measuring T(λ, θ) and R(λ, θ)

Characterize the transmission and reflection of the dichroic filters as a function of wave
and incident angle



Measurements for a 500 nm long-pass dichroic filter



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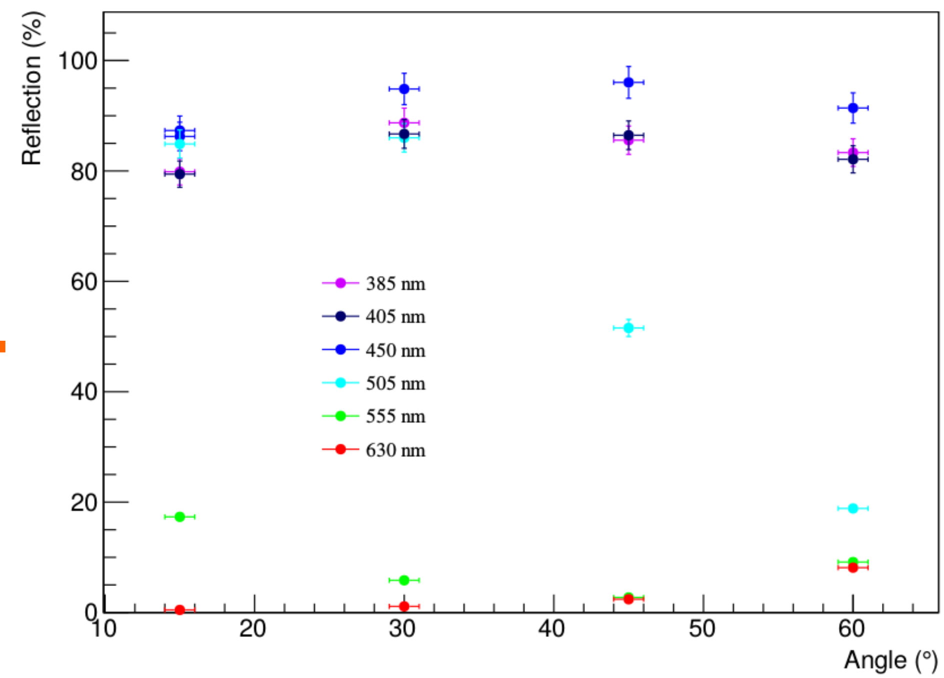

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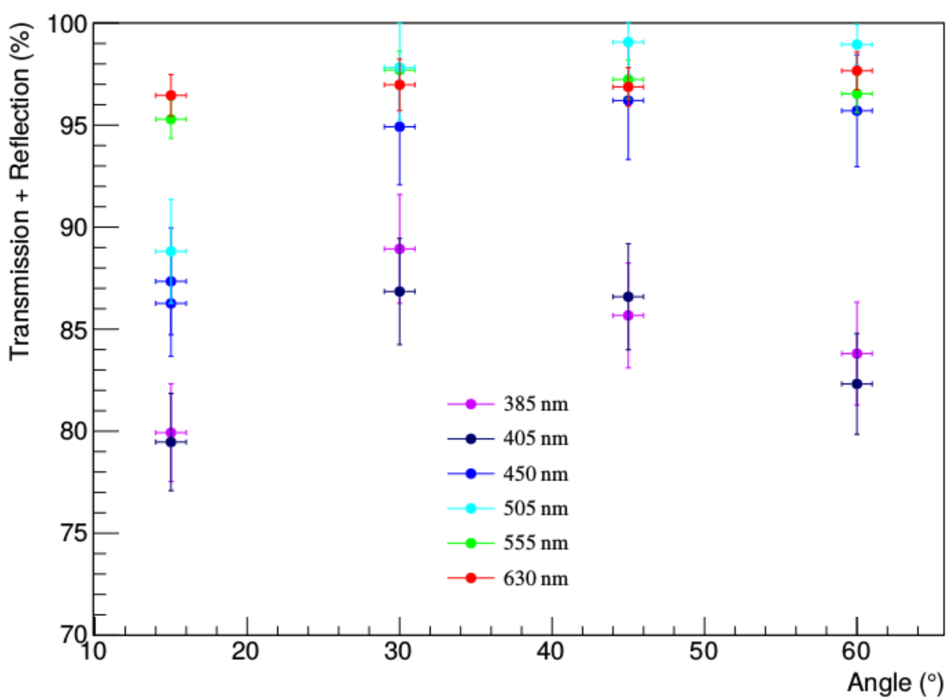

Very little light lost to the dichroic filter over range of wavelengths and incident angles

Used for input into our simulation model