Dichroic Winston Cones (‘Dichroicons’) for Cherenkov and Scintillation Light Separation in Large-Scale Neutrino Detectors

Tanner Kaptanoglu
University of Pennsylvania

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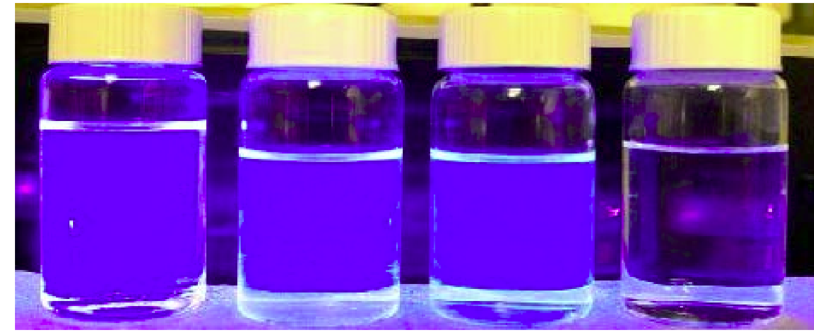
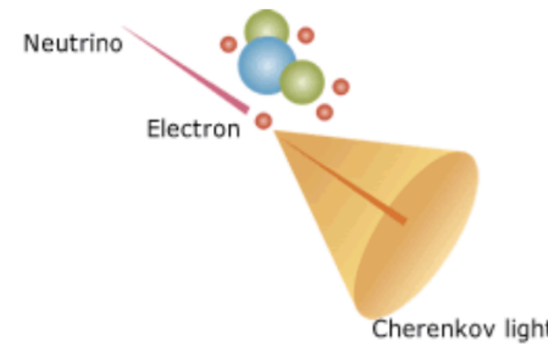
Detecting Cherenkov Light in a Scintillation Detector

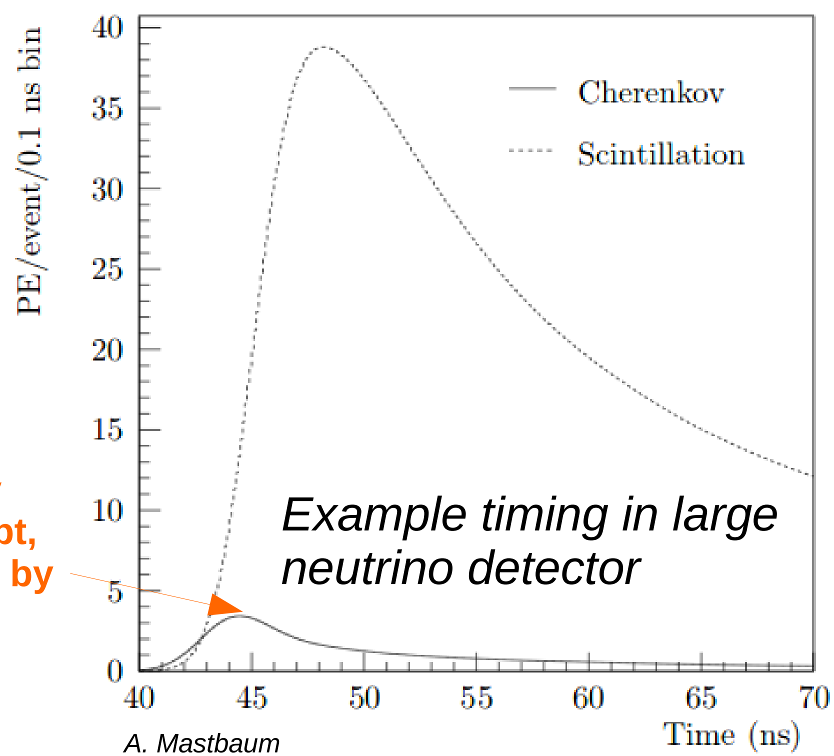
- Charged particle traveling through liquid scintillator creates *both* scintillation (~10,000 photons/MeV) *and* Cherenkov light (~100 photons/MeV)
- Challenge is to detect the Cherenkov light, which provides the direction of the traveling particle
- Cherenkov light is emitted promptly, scintillation light delayed and emitted with slower time-profile



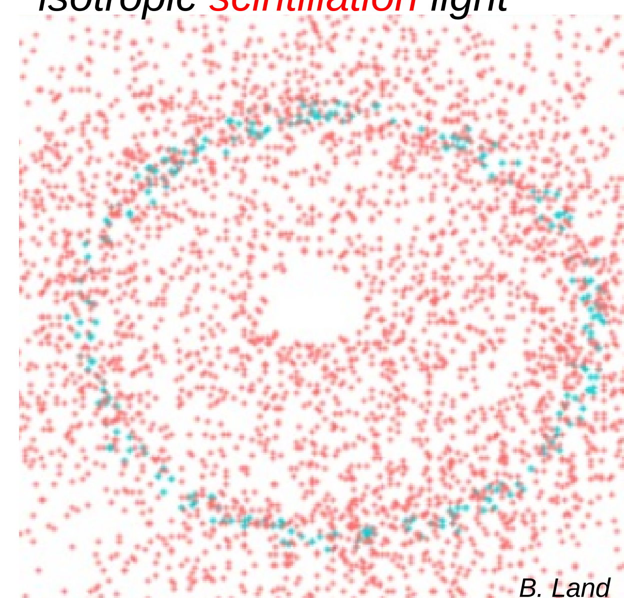
Cherenkov light emitted in a cone around particle direction



Cherenkov light prompt, but spread by detector response



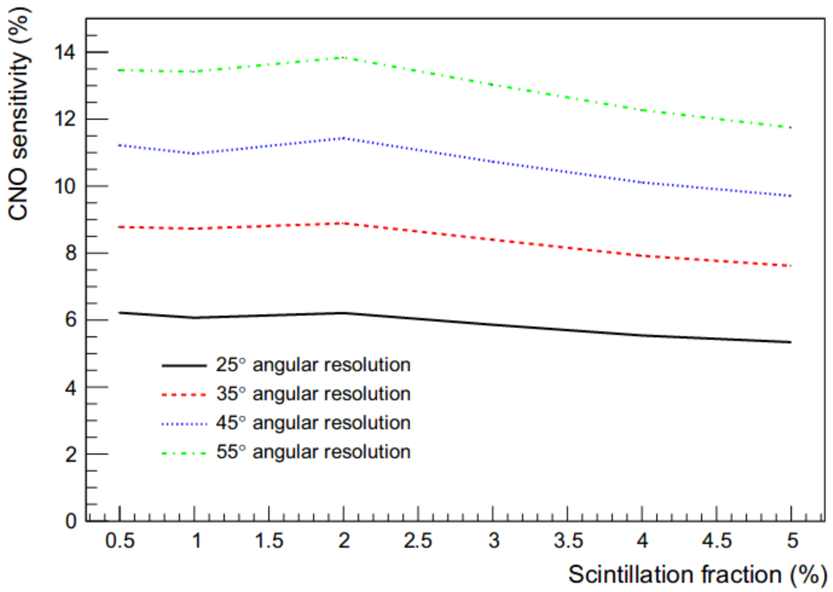
Cherenkov ring on top of isotropic scintillation light



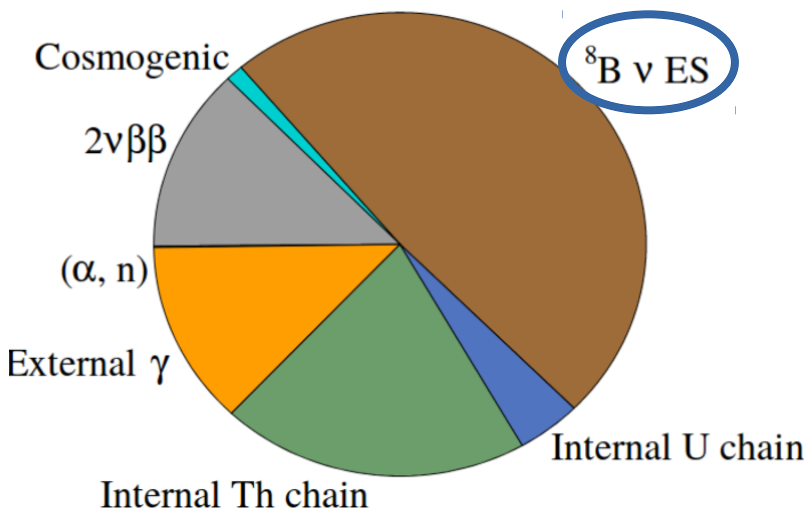
Why Cherenkov / Scintillation Separation?

- Recent trend in large monolithic neutrino detectors to move toward scintillator targets (Borexino, kamLAND-Zen, SNO+, JUNO, etc.)
- High light yield from scintillator provides excellent energy / position resolution, low energy thresholds **Neutrinoless double beta decay, low energy solar neutrinos, reactor & geo antineutrinos**
- Cherenkov light allows one to reconstruct direction, improve particle ID
- Allow scintillator-based solar neutrino experiments to suppress backgrounds
- Largest expected backgrounds for SNO+ is solar neutrinos, which can be rejected by detecting the Cherenkov light
- Has not been demonstrated in an existing liquid scintillator detector
- R&D work will be focus of this talk

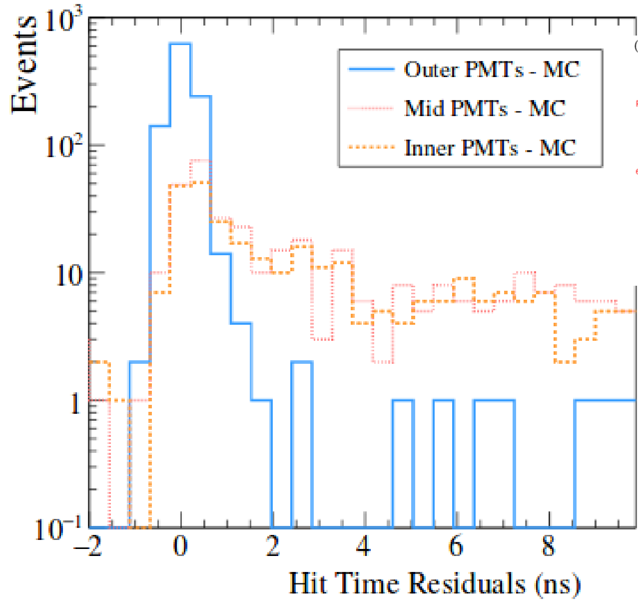
R. Bonventre, G.D. Orebi Gann, Eur. Phys. J. C (2018) 78:435

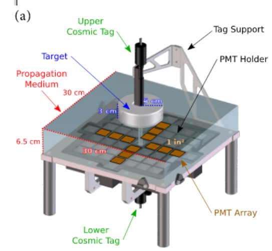


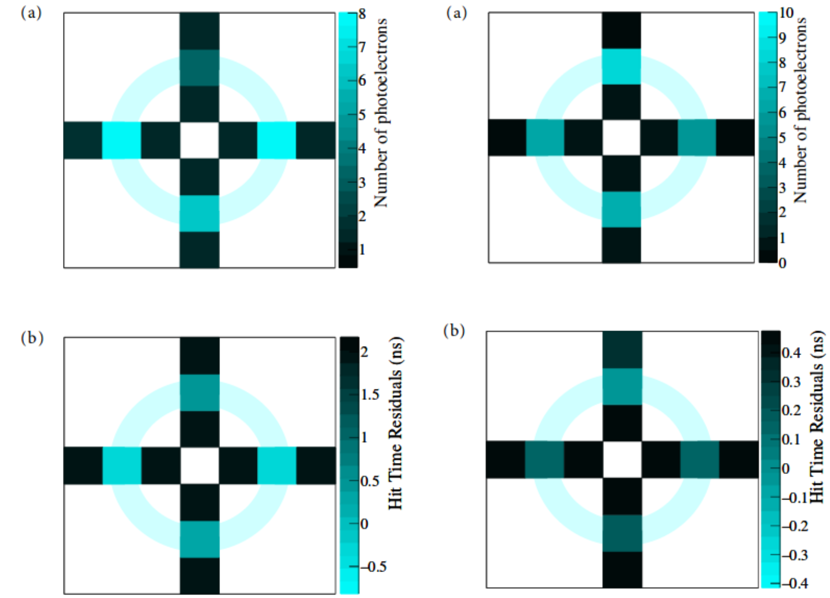
Expected background for SNO+ 0νββ



Ongoing R&D For Cherenkov / Scintillation Separation

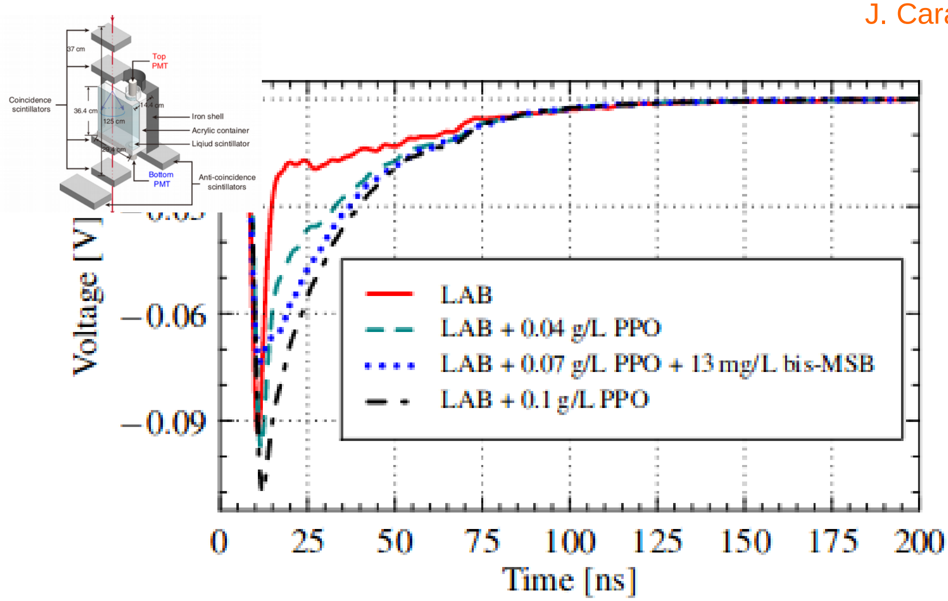






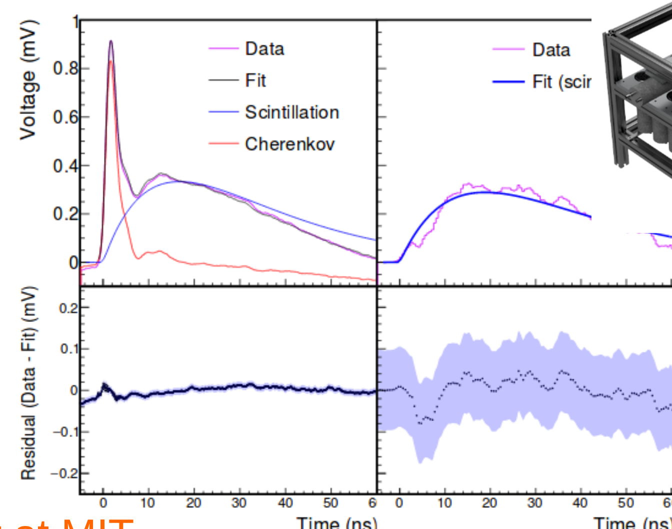
CHESS setup at LBNL

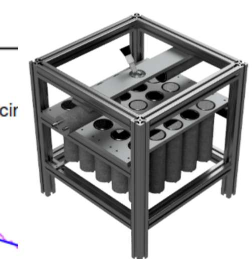
J. Caravaca et. al, 10.1103/PhysRevC.95.055801



Slow scintillator characterization for Jinping

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



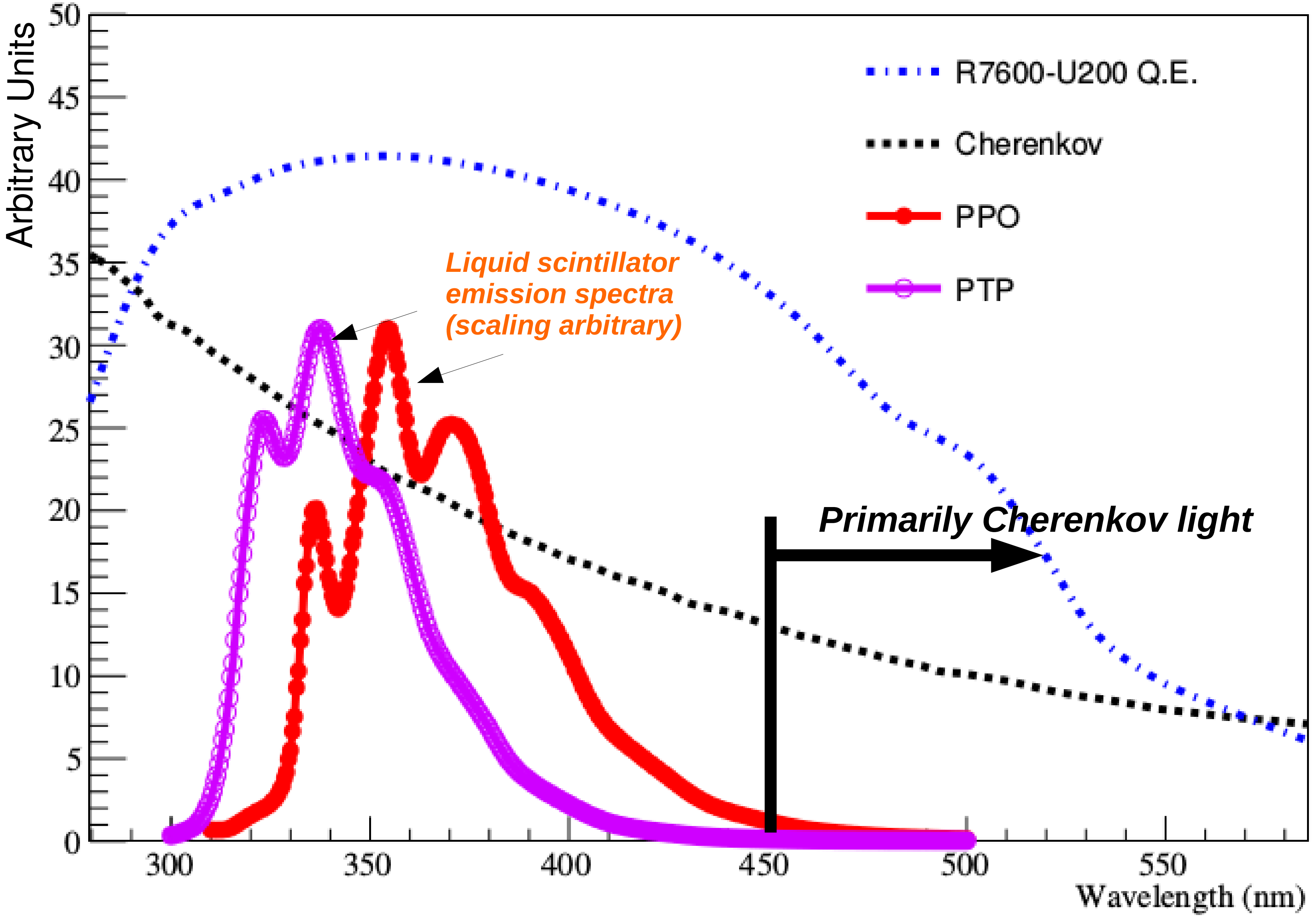


FlatDot at MIT

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

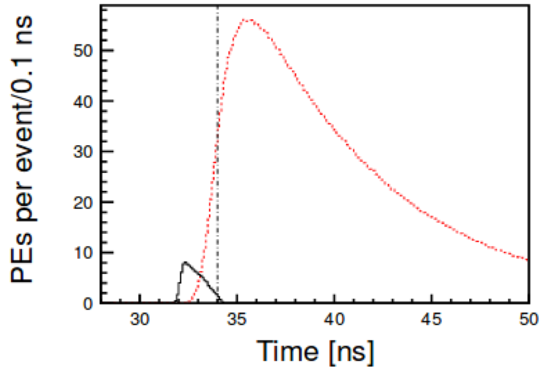
Only timing and isotropy used to identify the Cherenkov light.

Can we additionally use wavelength?

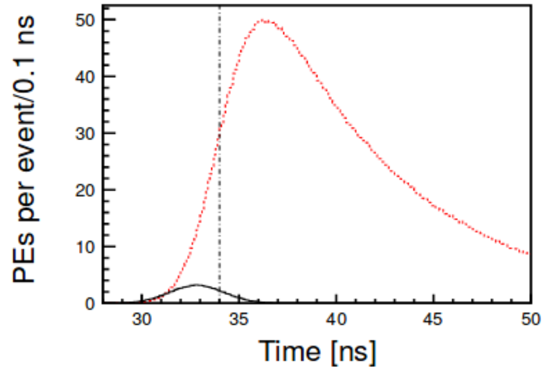


Ultimately we want to achieve Cherenkov and scintillation separation while losing as few total photons as possible.

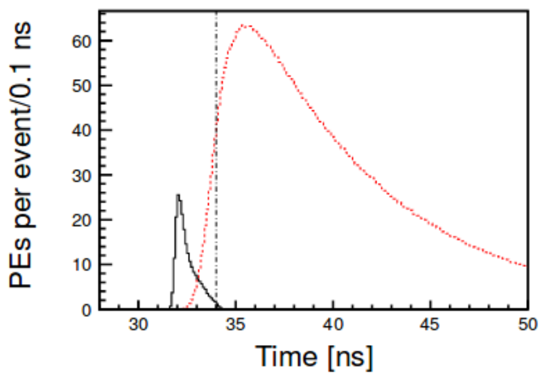
L. Winslow et. al, 10.1088/1748-0221/9/06/P06012



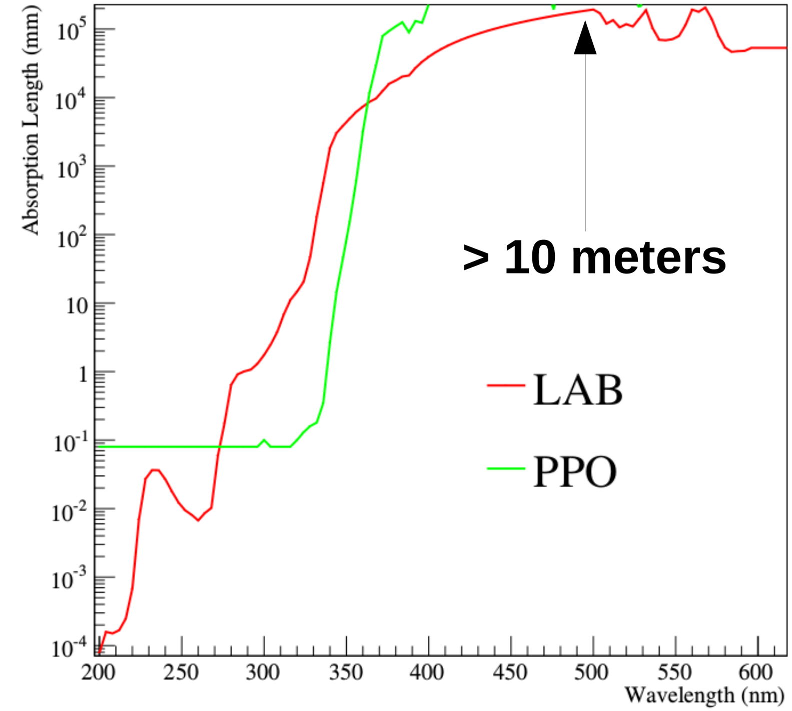
(a) Default simulation.

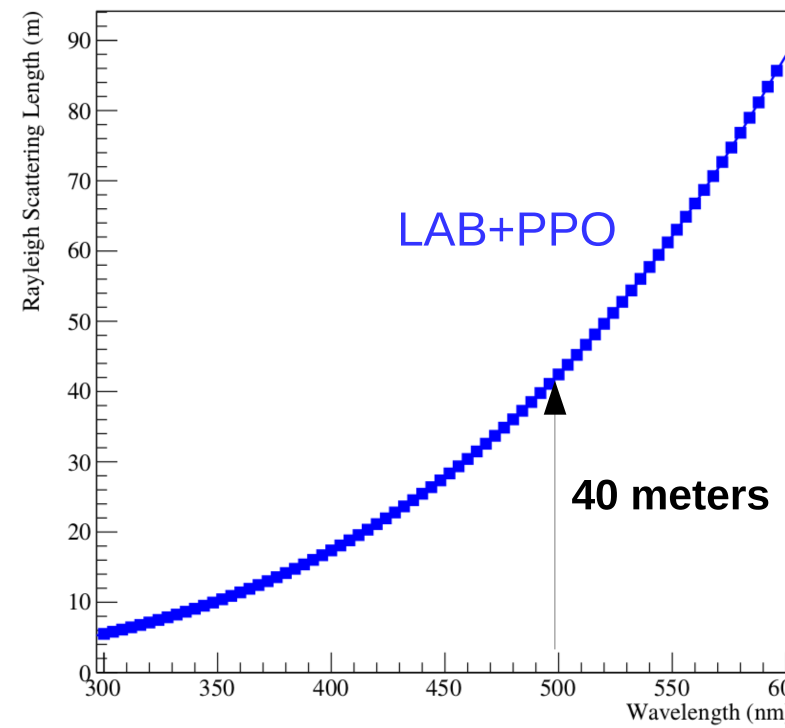


(b) Increased TTS (1.28 ns).



(c) Red-sensitive photocathode.

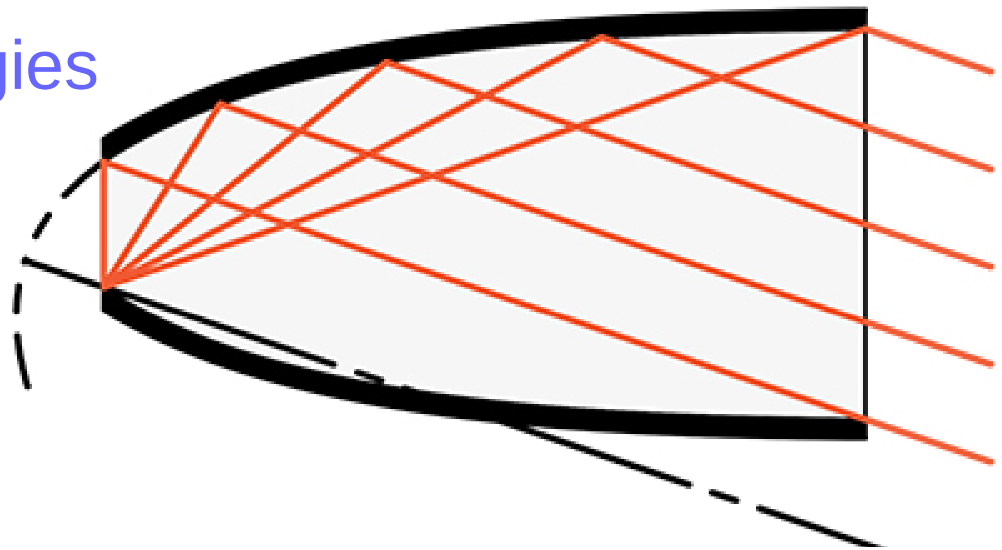




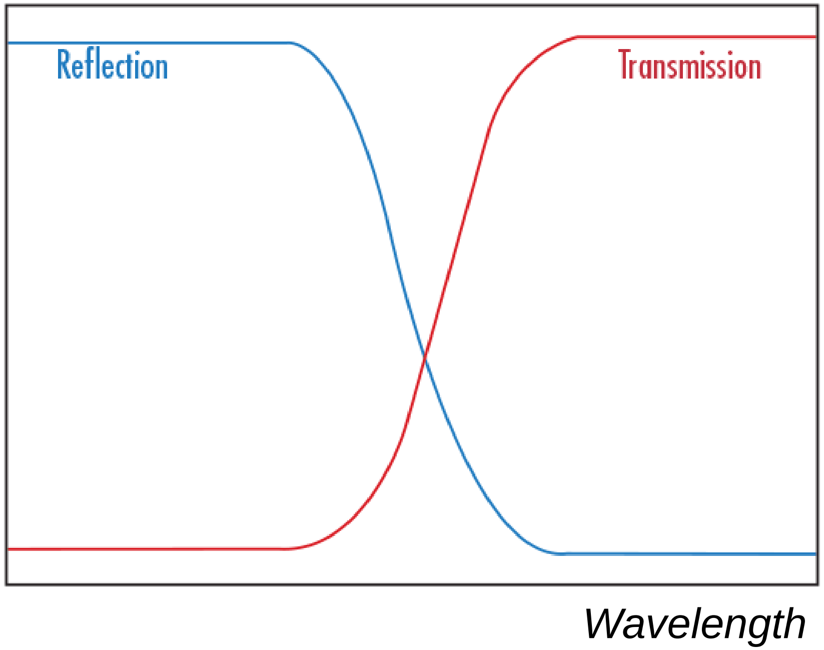
- Simulations of kamLAND-like detector show red-sensitive photocathodes improve Ch/Sc separation
- Absorption and scattering length increases with wavelength
- Cherenkov light that reaches the PMTs with its original direction is primarily long-wavelength

Dichroic Winston Cones:
The Dichroicon

Combining Two Technologies



Winston Cones

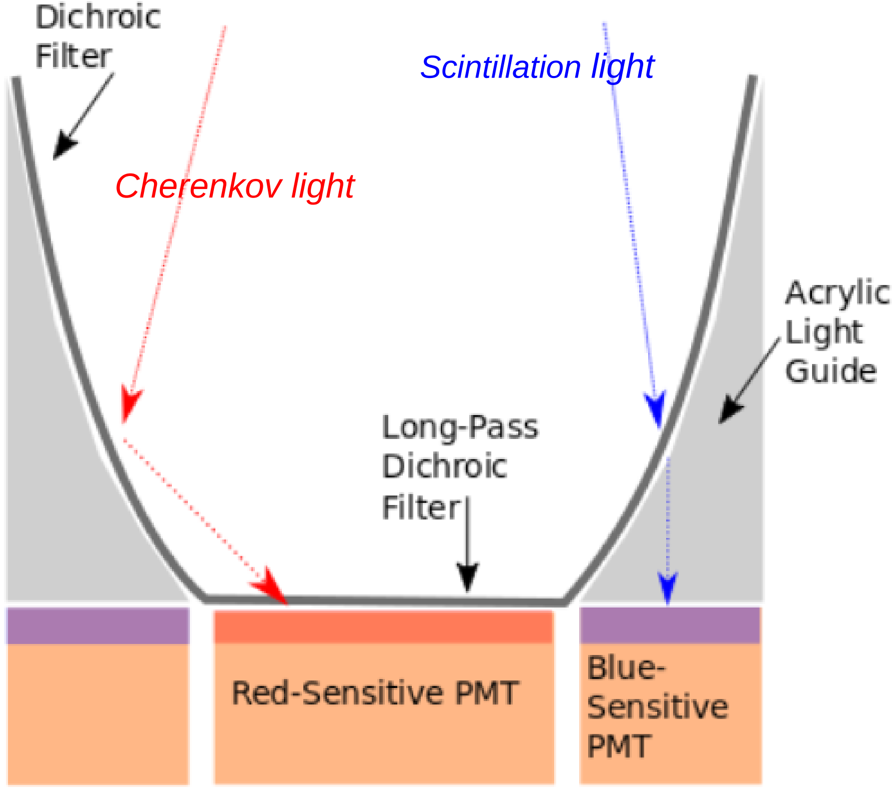


And Dichroic Filters

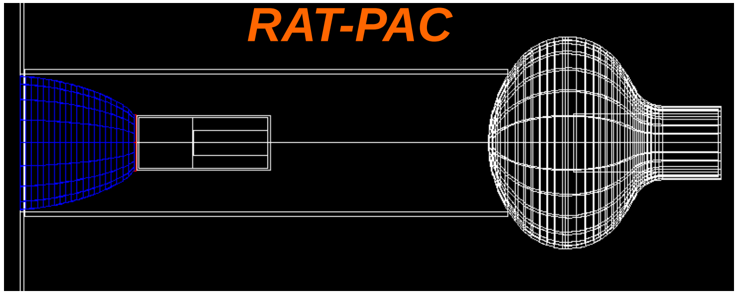
Dichroic Winston Cones:
The Dichroicon

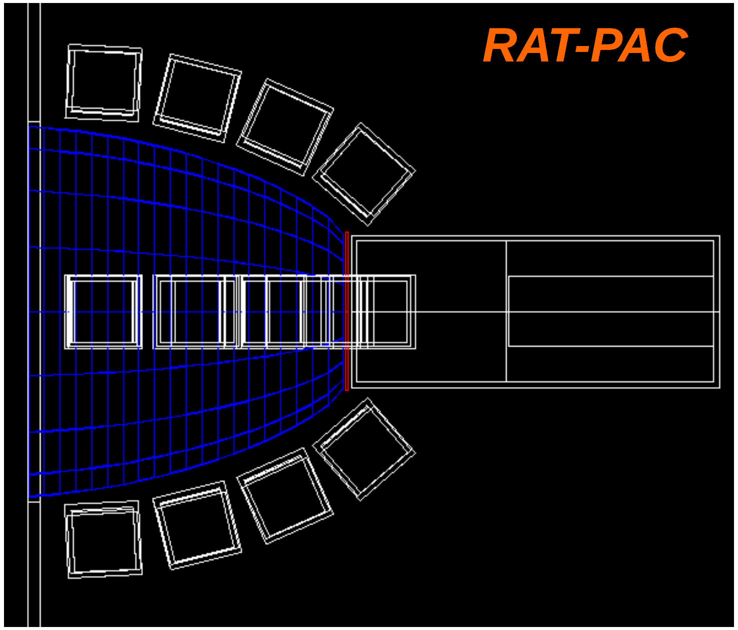
Sorting the scintillation and Cherenkov light towards different PMTs in order to achieve separation while maintaining a high detection efficiency for the scintillation light

Example full-scale design



Visualizations from M. Luo

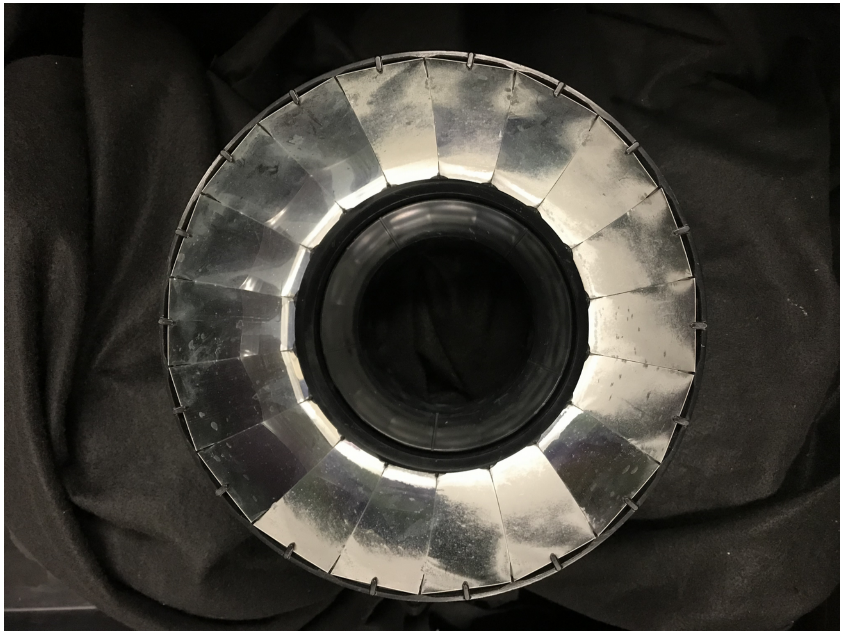




Complimentary to WbLS, slow scintillator, etc.

Familiar Technologies

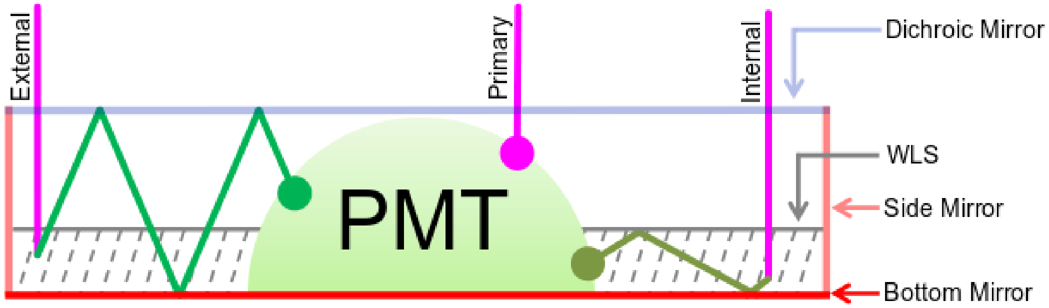
SNO Winston Concentrator



Borexino Winston Concentrator

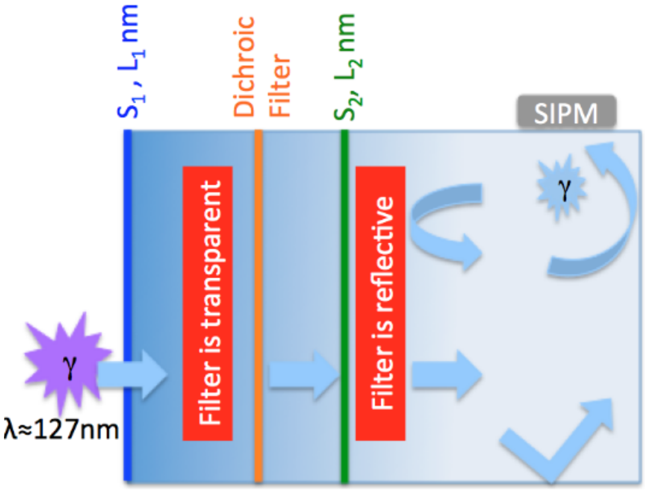
https://arxiv.org/pdf/physics/0310076.pdf

Photon trap using dichroic filters proposed for Hyper-K



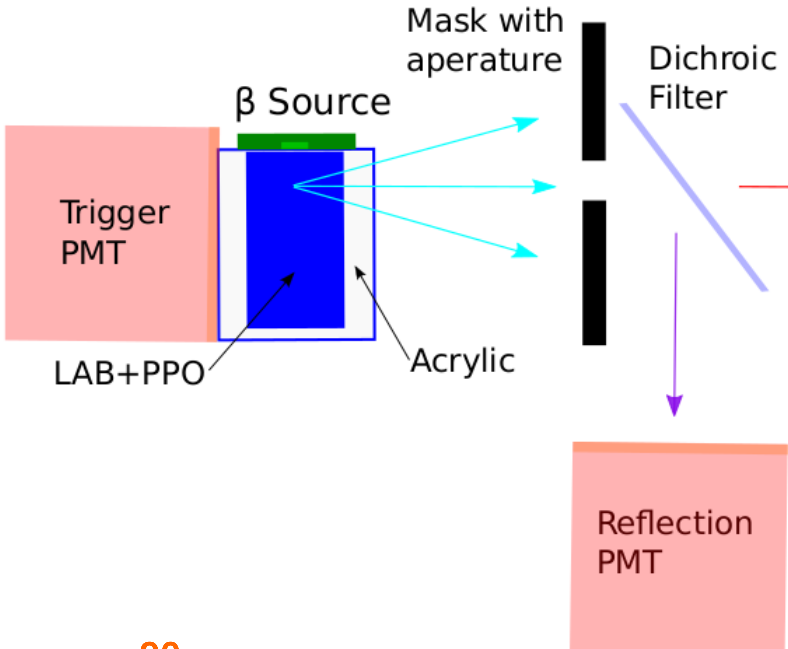
C. Rott et al. JINST 12 (2017)

ARAPUCA design for DUNE/protoDUNE



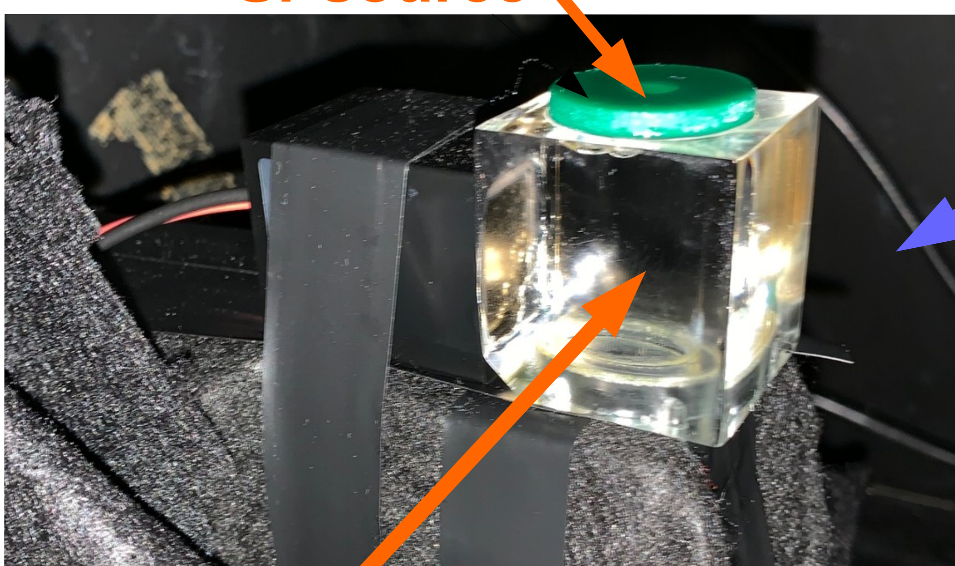
E. Segreto et al., JINST 13 (2018)

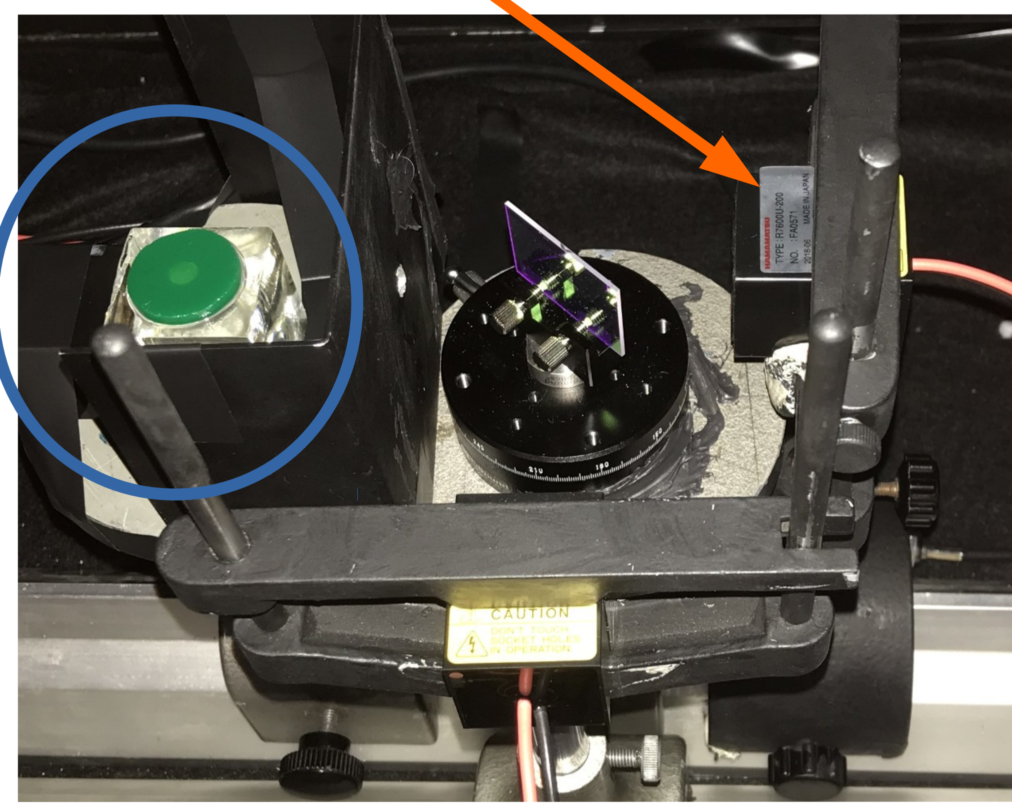
Cherenkov and Scintillation Separation With Dichroic Filters



"Photon Sorting"

^{90}Sr source

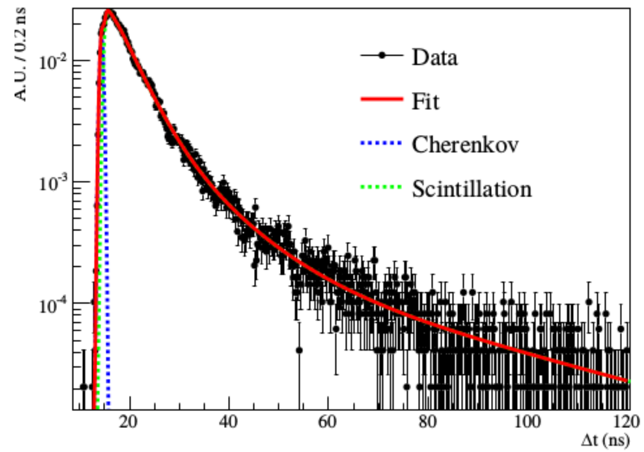




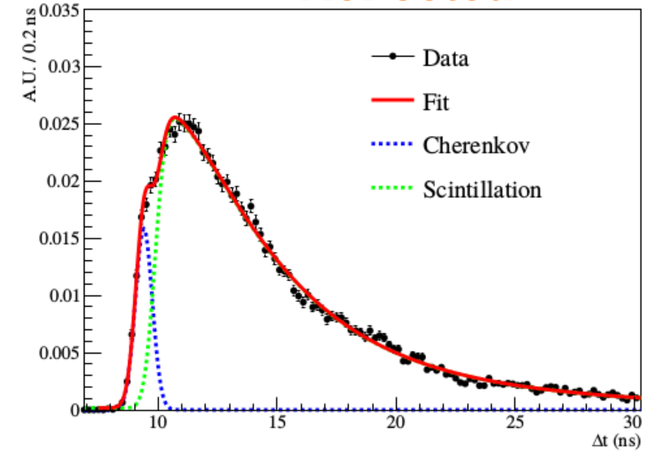
LAB+PPO inside UVT acrylic

LAB+PPO, 500 nm short-pass dichroic filter

Transmitted

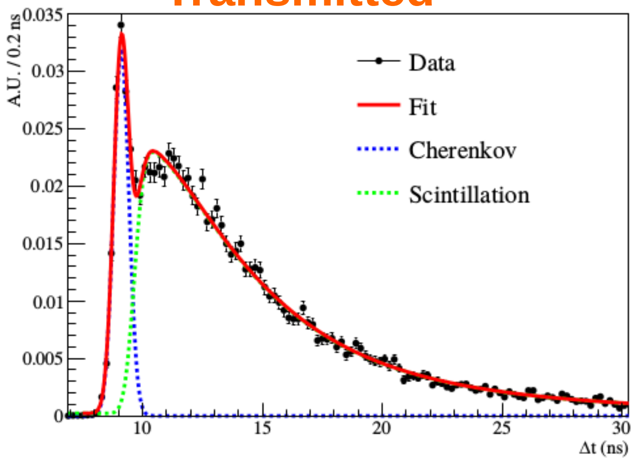


Reflected

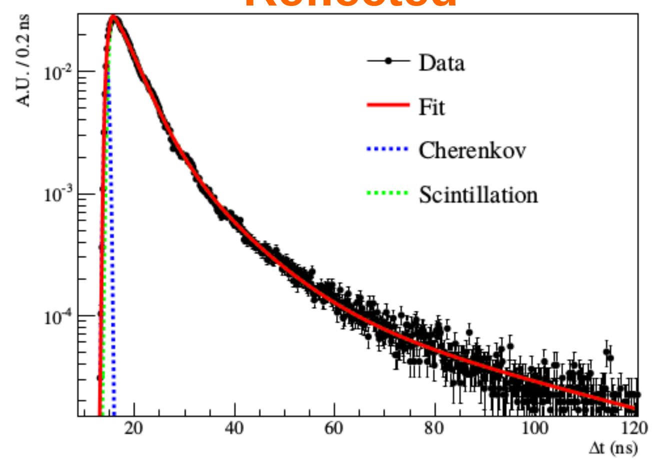


LAB+PPO, 500 nm long-pass dichroic filter

Transmitted

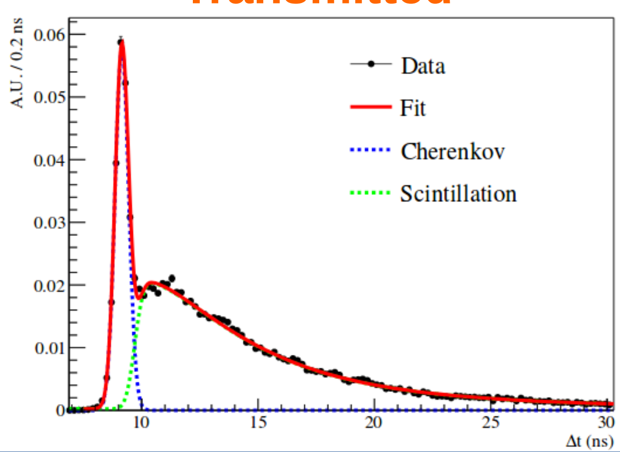


Reflected

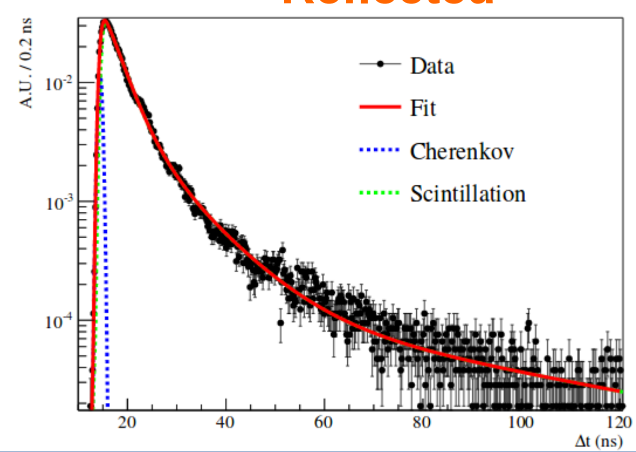


LAB+PTP, 450 nm long-pass dichroic filter

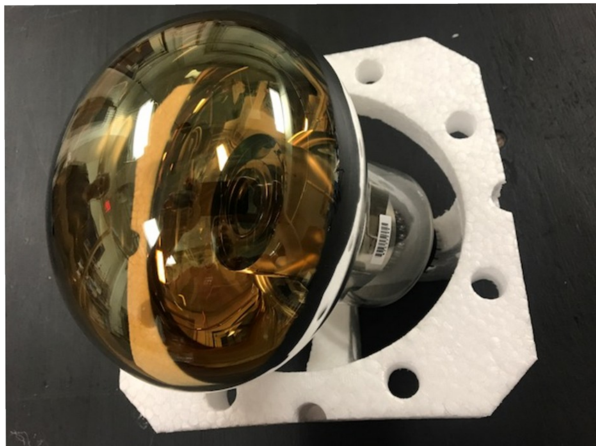
Transmitted



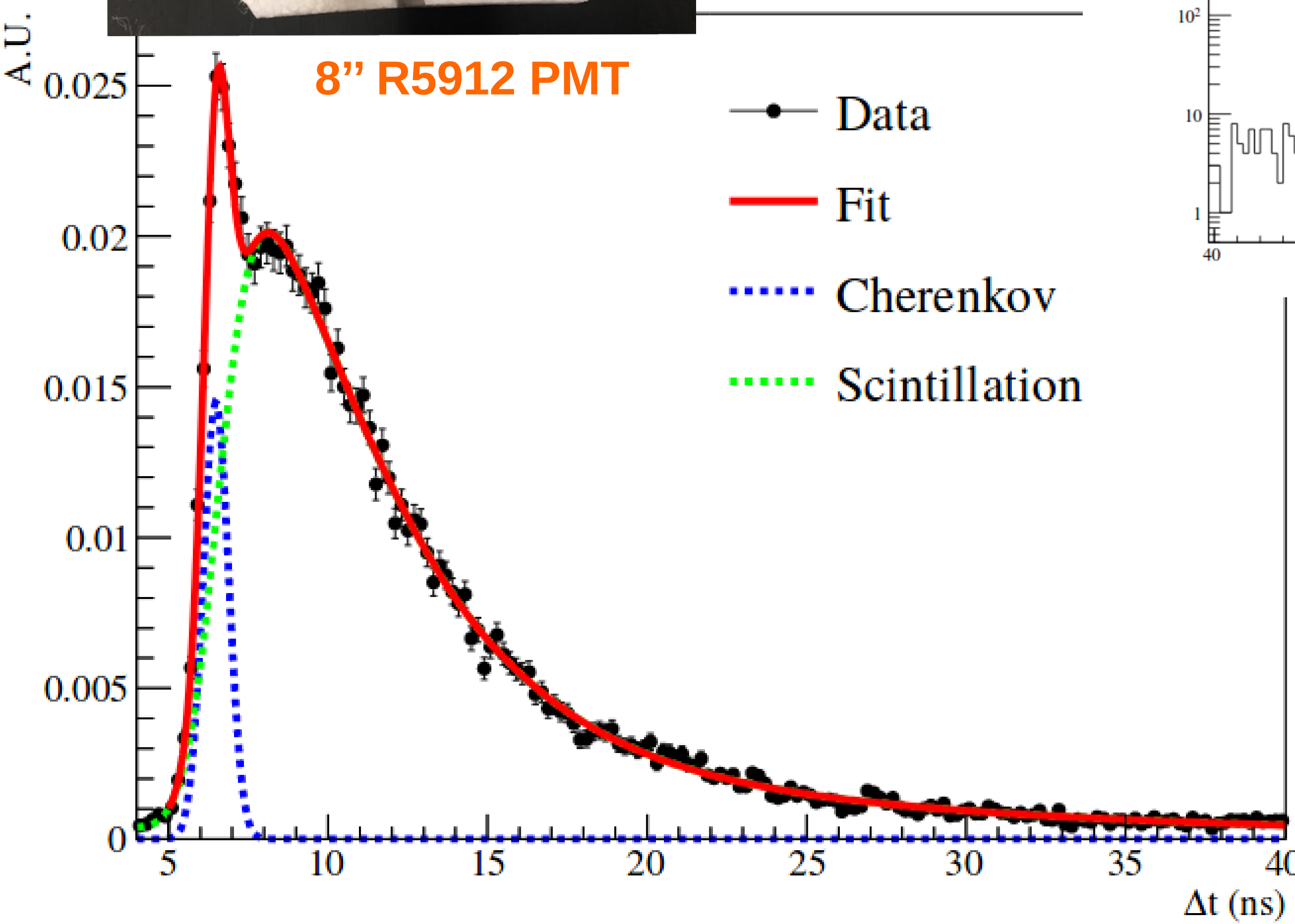
Reflected



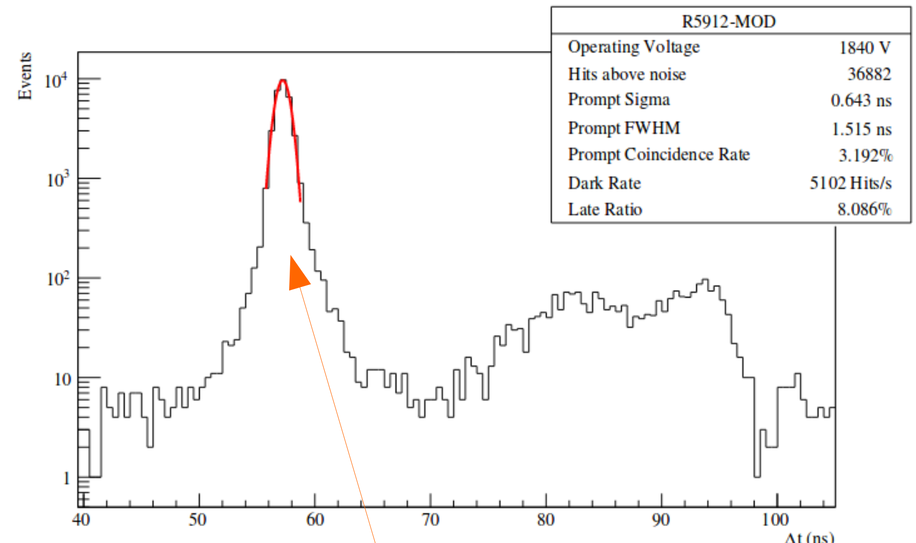
Cherenkov/Scintillation Separation With a Large-Area PMT



8” R5912 PMT



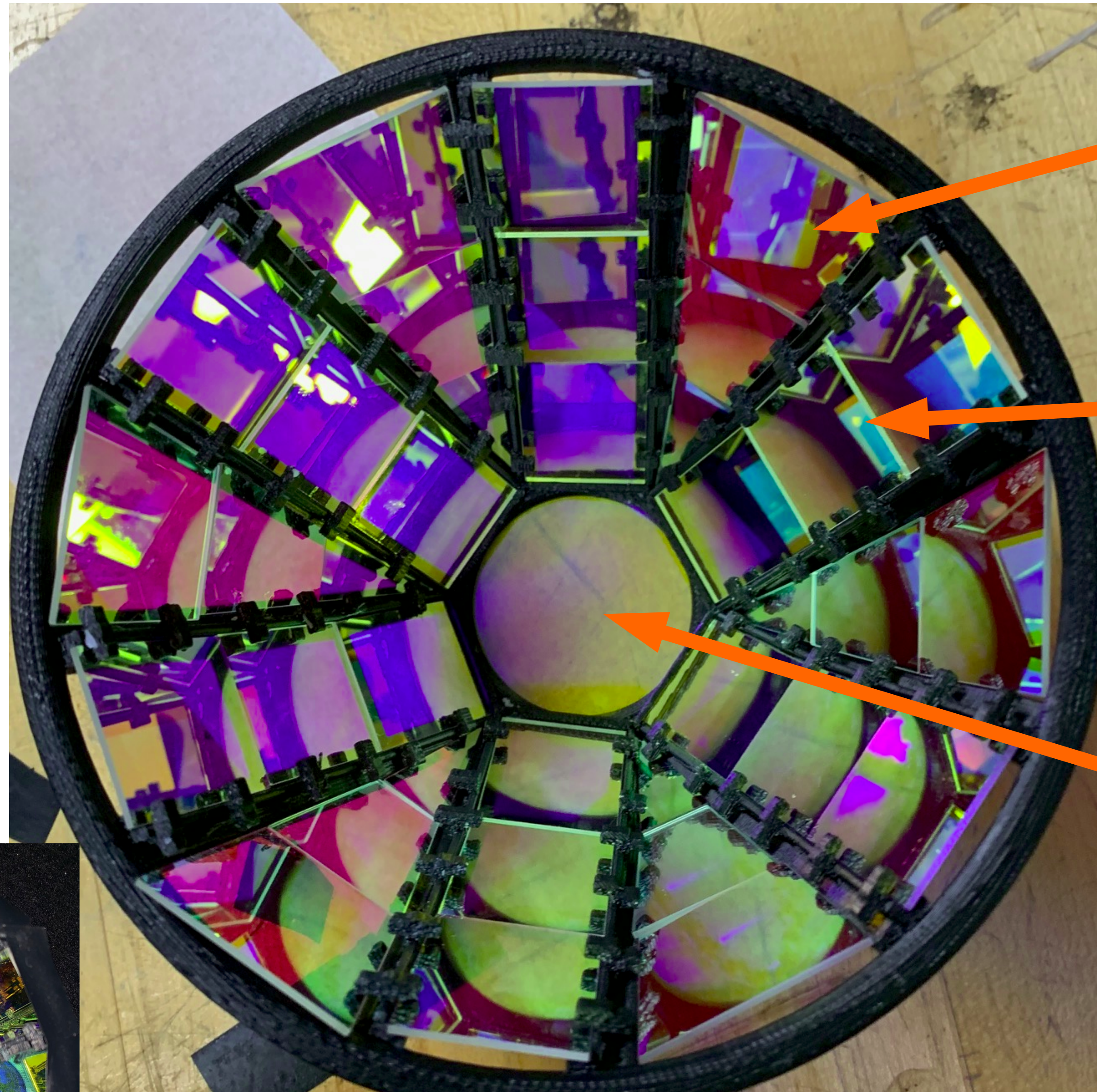
T. Kaptanoglu, Nucl.Instrum.Meth. A889 (2018) 69-77

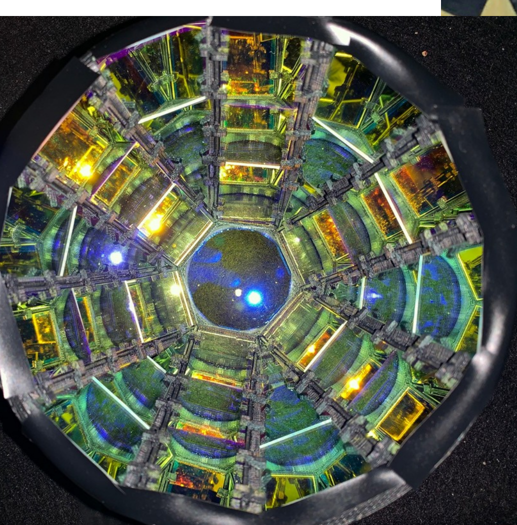


Transit time spread ~ 640ps

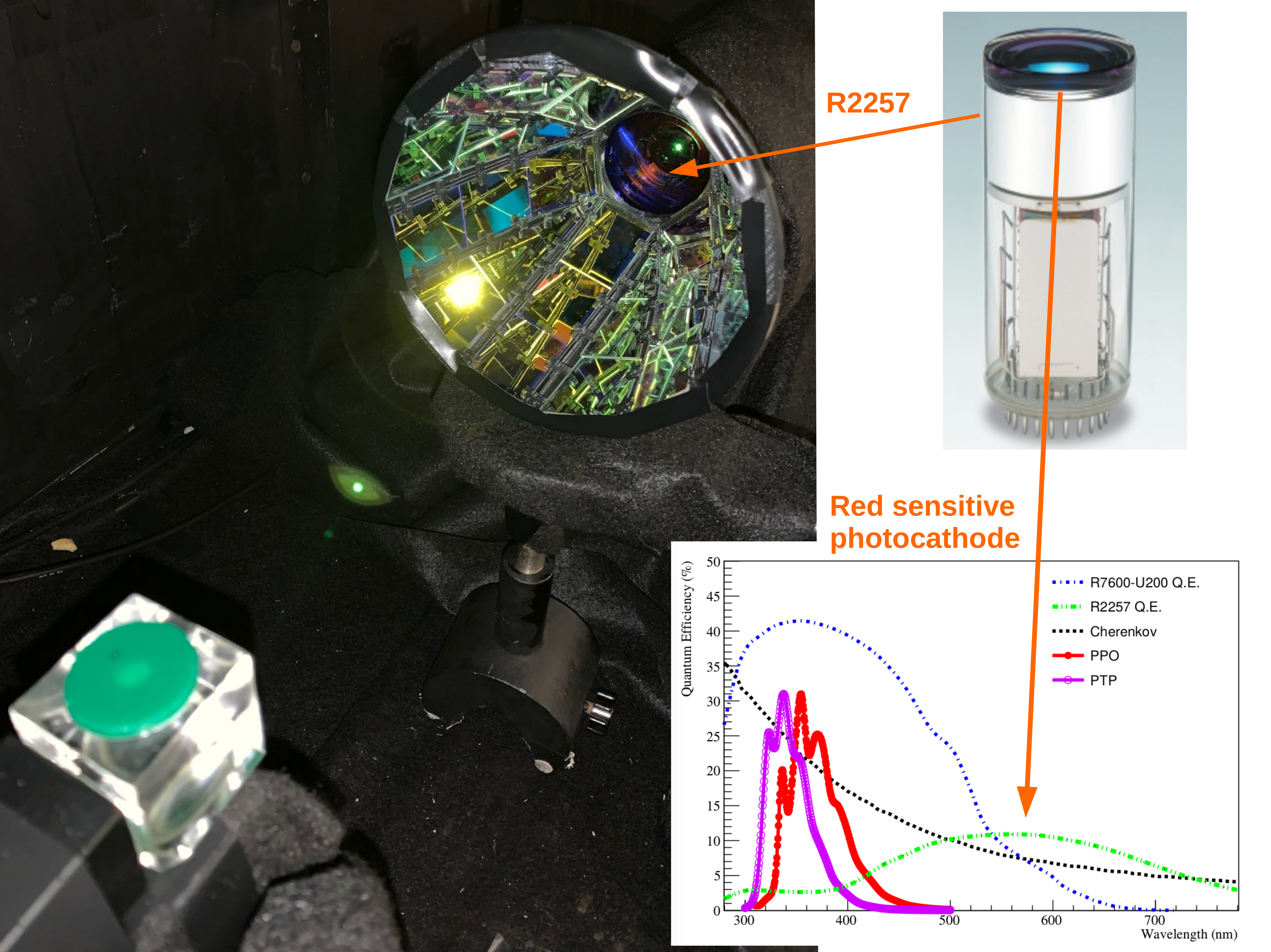
First demonstration of Cherenkov and scintillation separation using a large-area PMT!

3D Printed Prototype

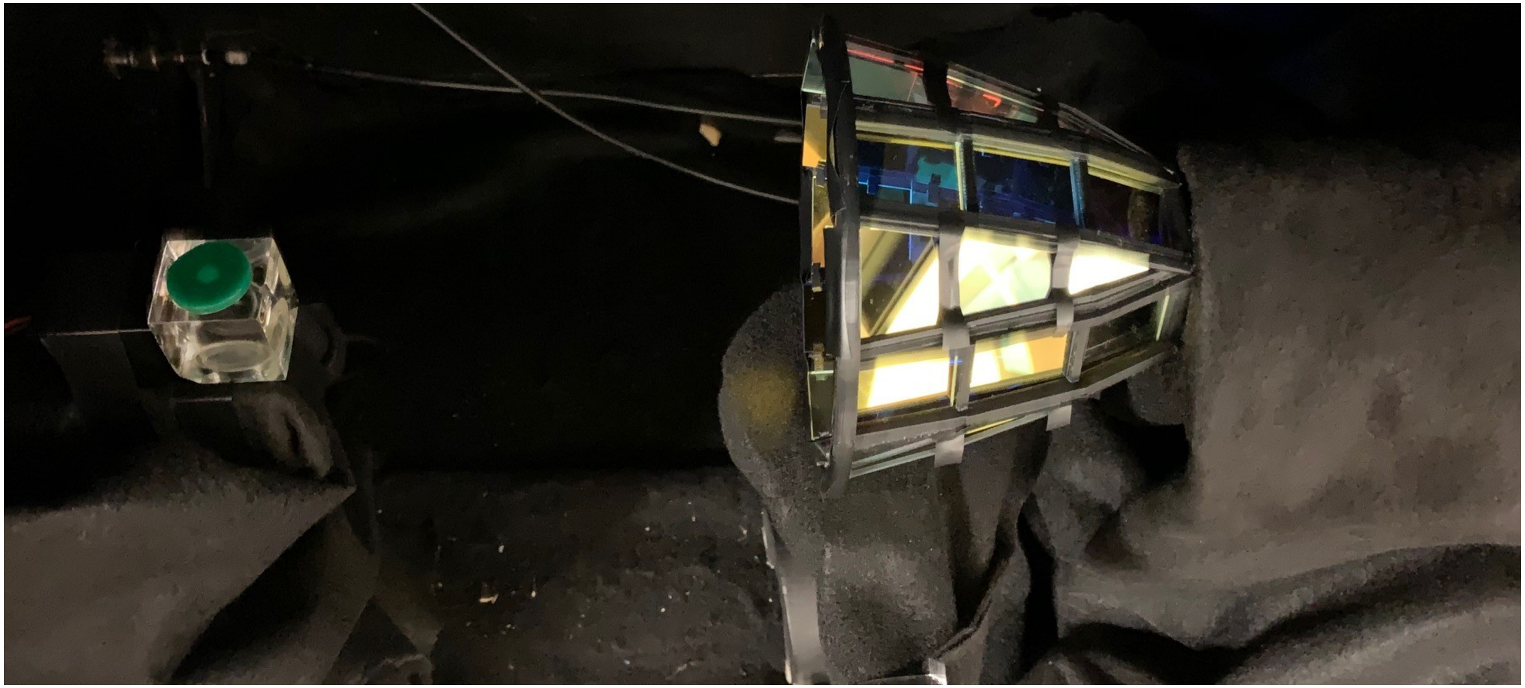


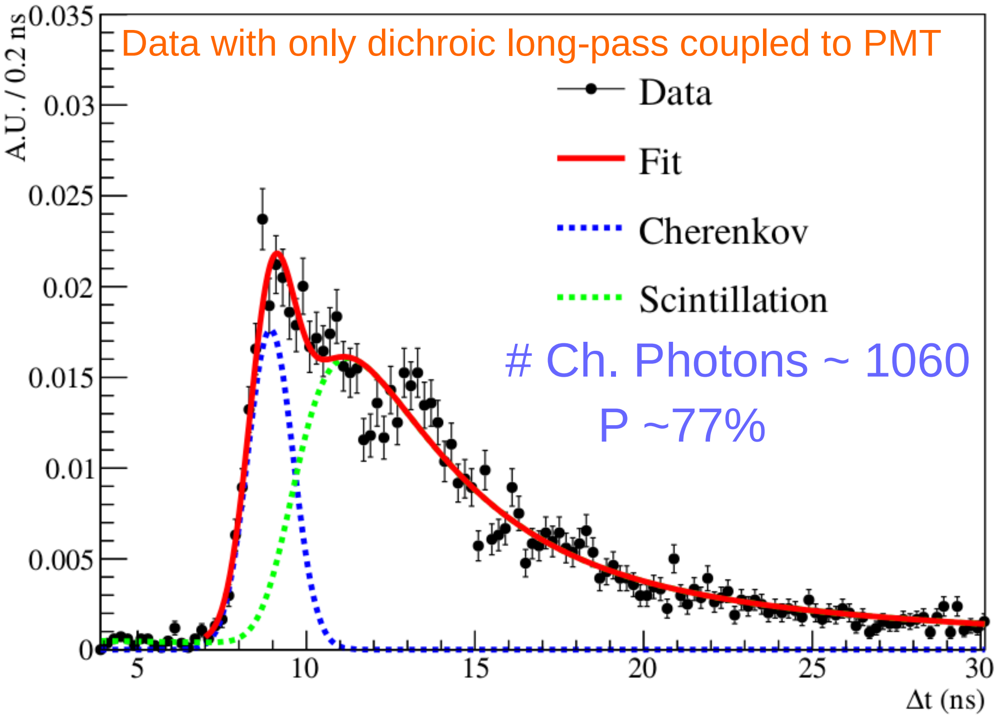


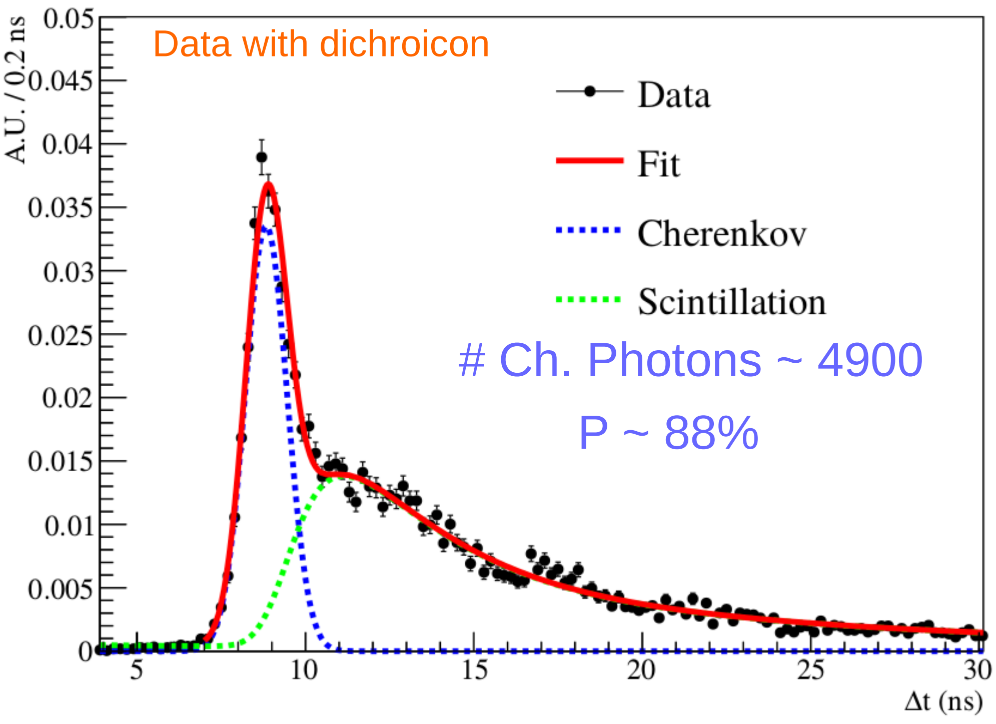
Measurements shown made with this prototype


R2257
Red sensitive
photocathode
Quantum Efficiency (%)
Wavelength (nm)
R7600-U200 Q.E.
R2257 Q.E.
Cherenkov
PPO
PTP
0
5
10
15
20
25
30
35
40
45
50
300
400
500
600
700

Dichroicon Data

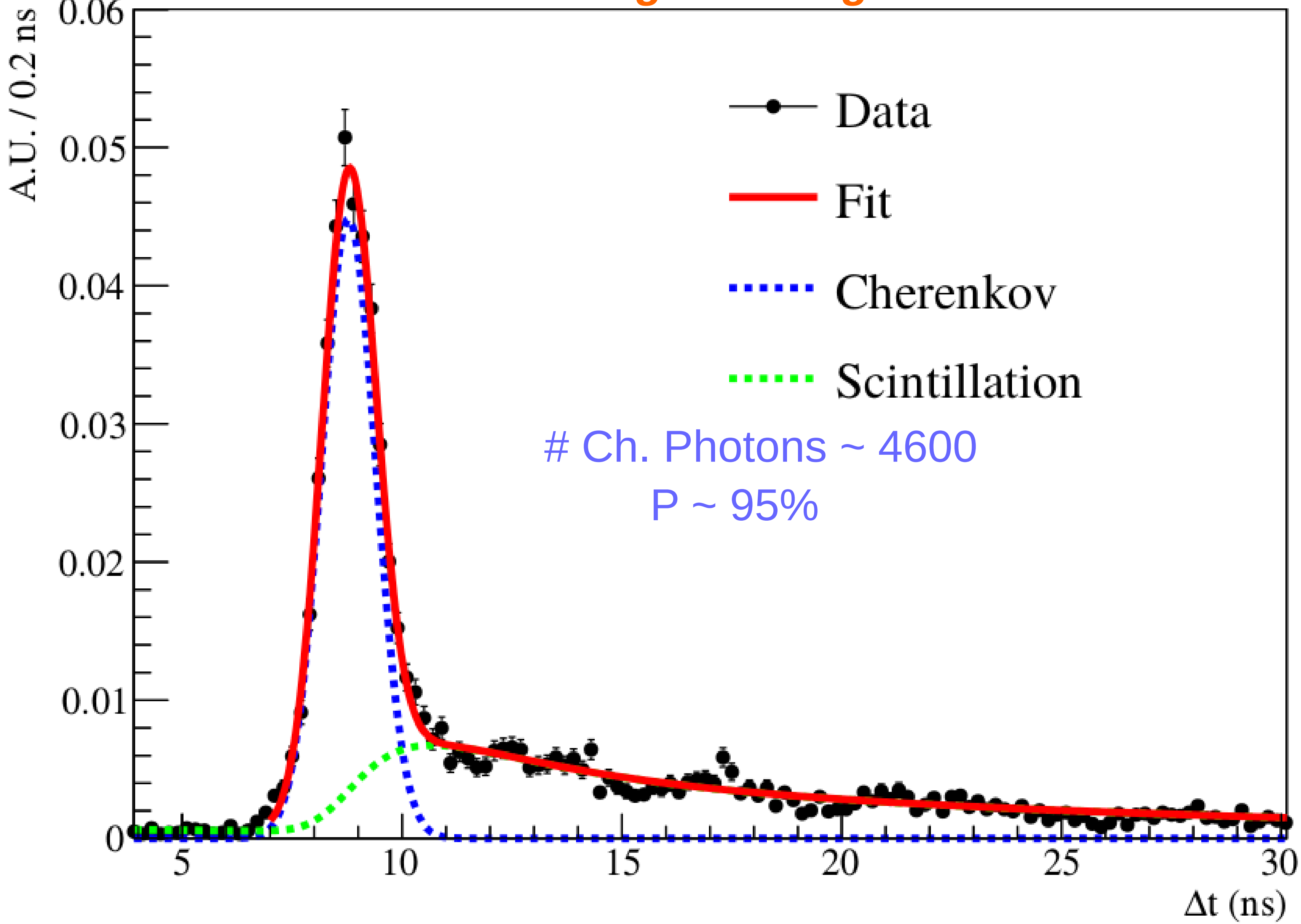




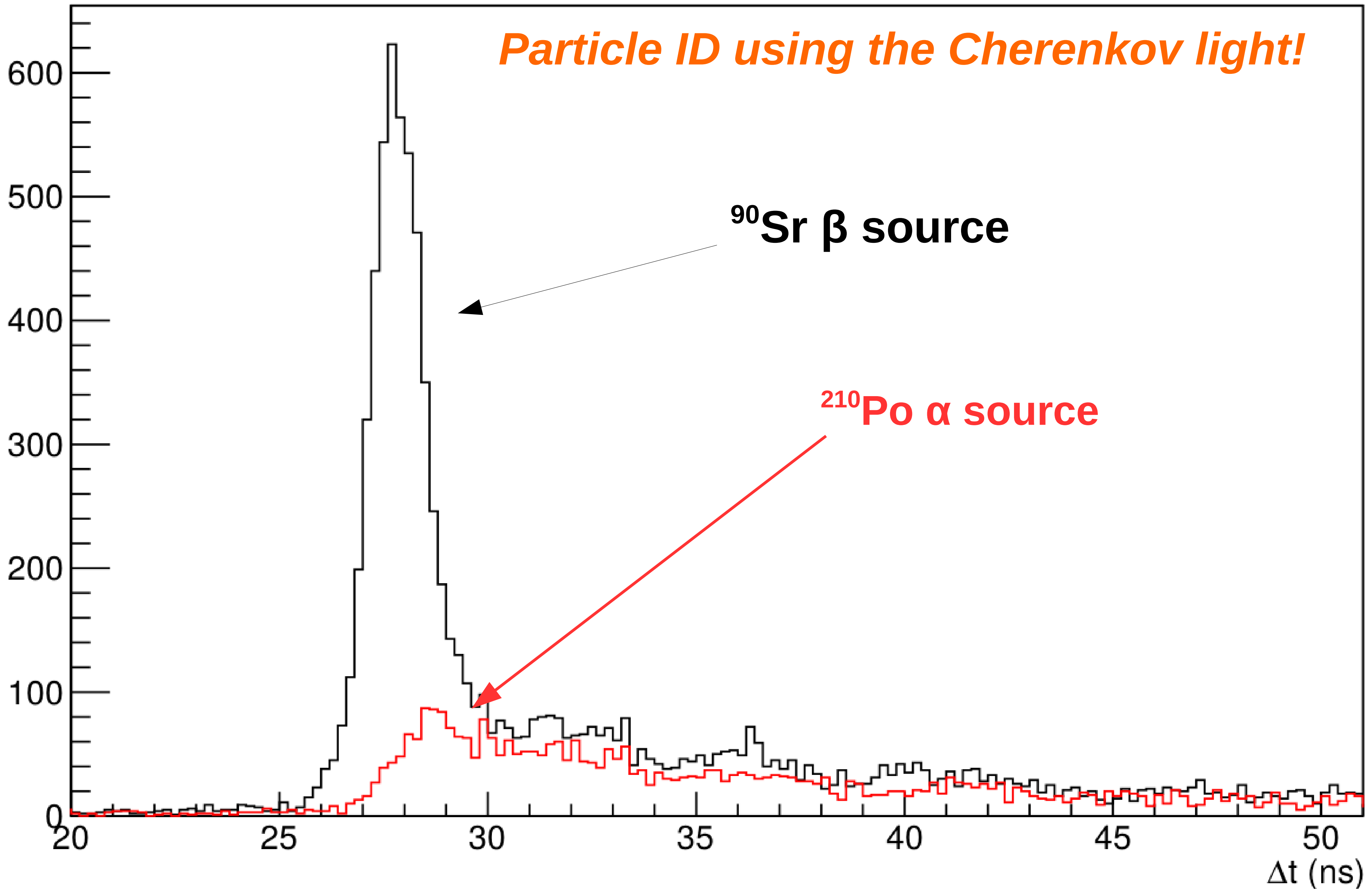


Dichroicon Data

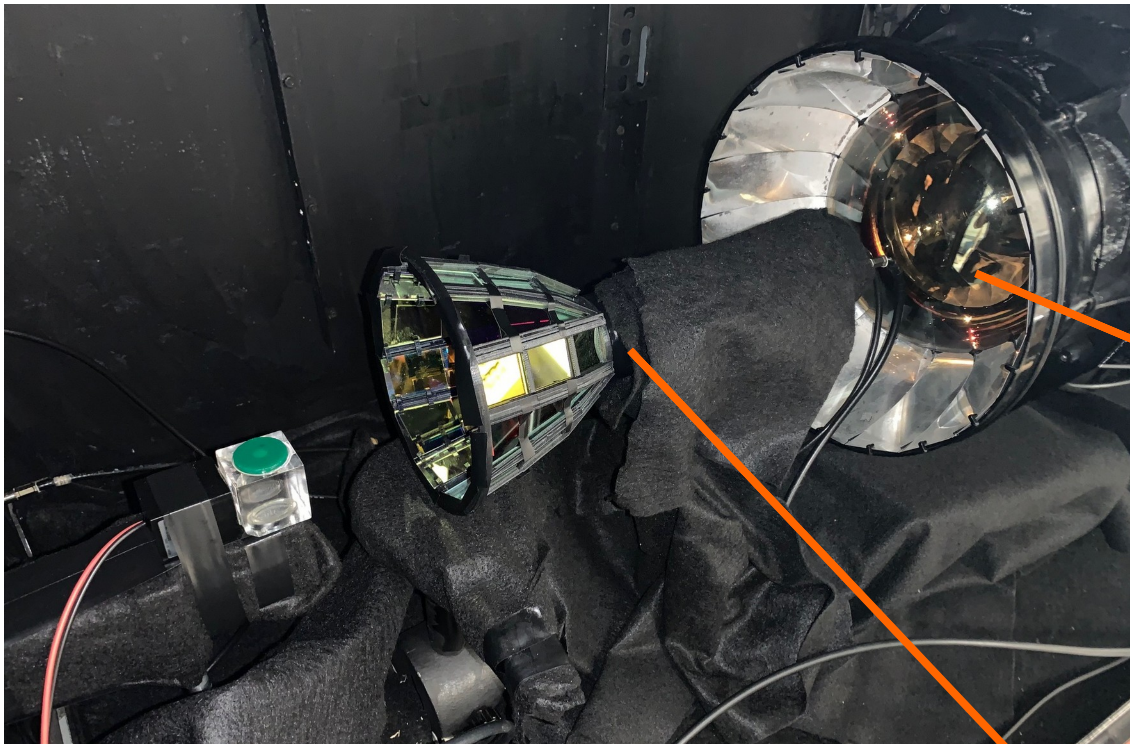
Introducing additional long-pass filter reduces scintillation light "background"



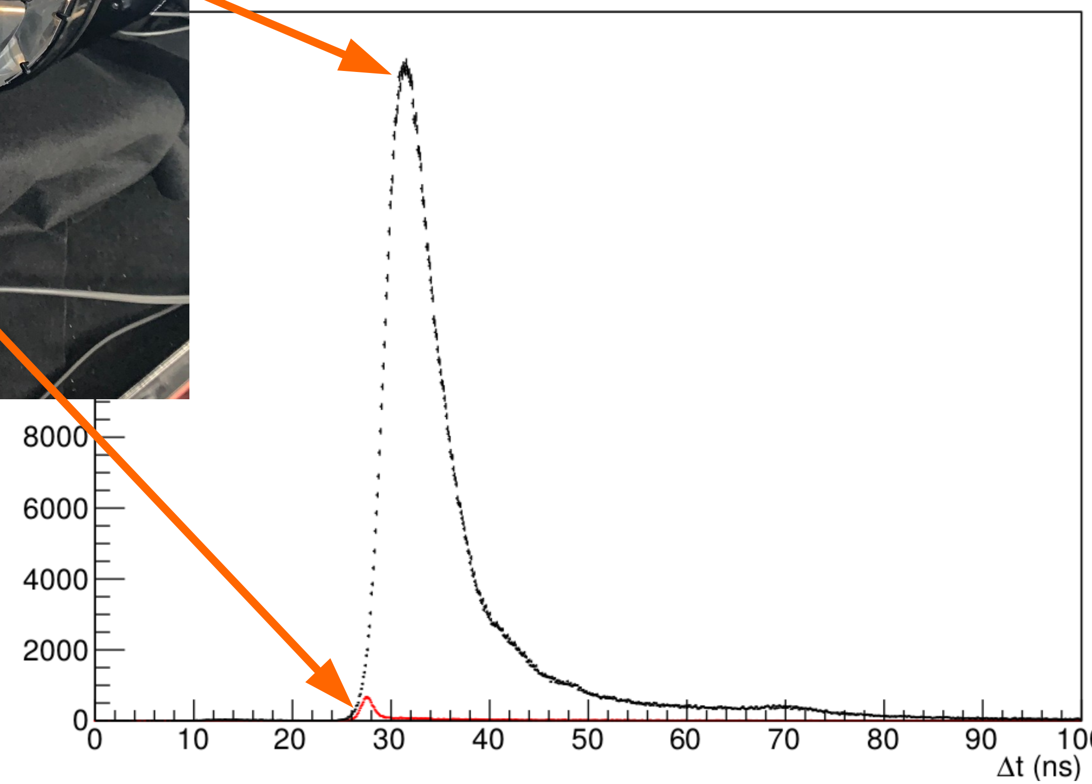
Dichroicon Data



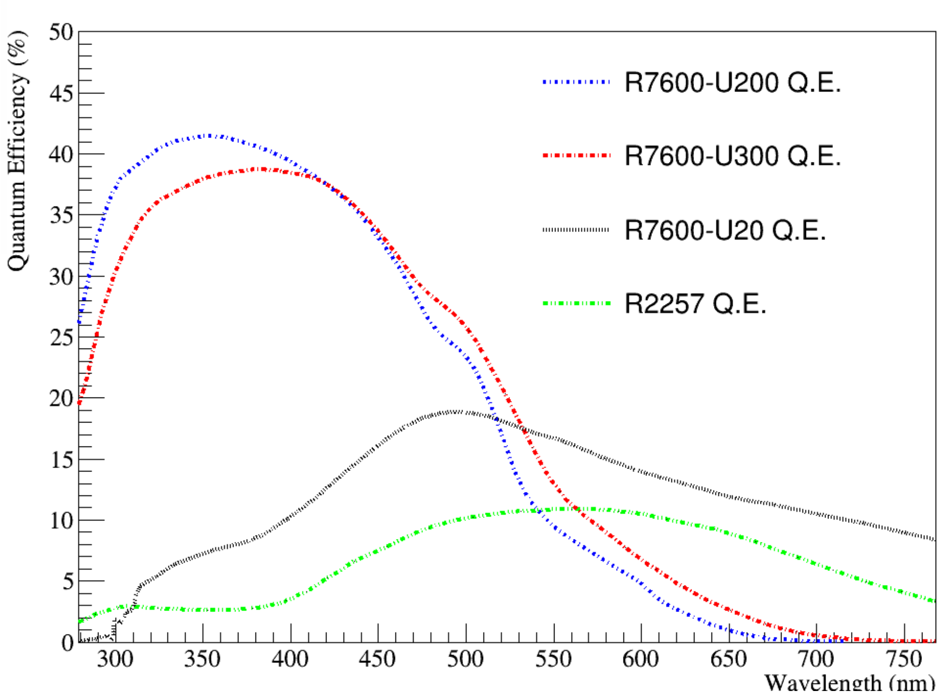
Dichroicon Data



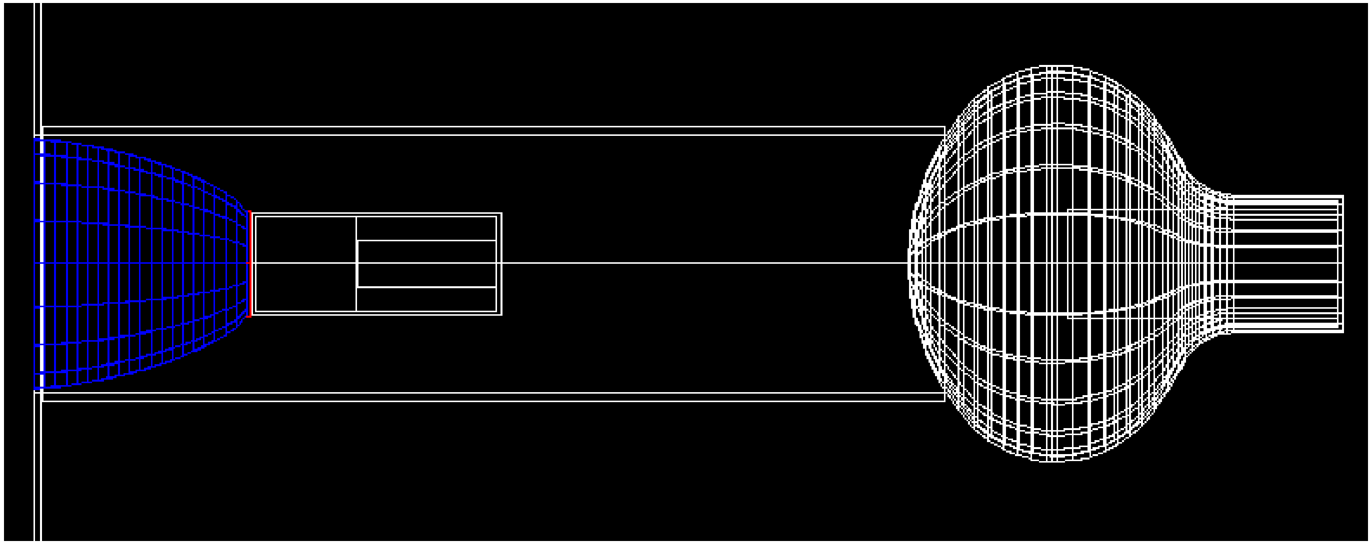
Scintillation light drowns the Cherenkov, but we've identified it by sorting the photons!



Future Measurements



- Transmission and reflections in water/oil
- Measurements with more PMTs
- Simulation studies using RAT-PAC
- Engineering of "monolithic" design
- Scintillation readout design
- Measurements with different fluors and filters



Conclusions

- Cherenkov / scintillation separation at the center of a lot of interesting R&D work
- Applications for many future experiments: THEIA, ANNIE, WATCHMAN, Jinping, JUNO
- Bench-top measurements of single dichroic filter demonstrated the potential for “photon-sorting”
- Cherenkov / scintillation separation demonstrated with first prototype dichroicon
- 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

Interest in this topic has developed from our experience working on SNO+

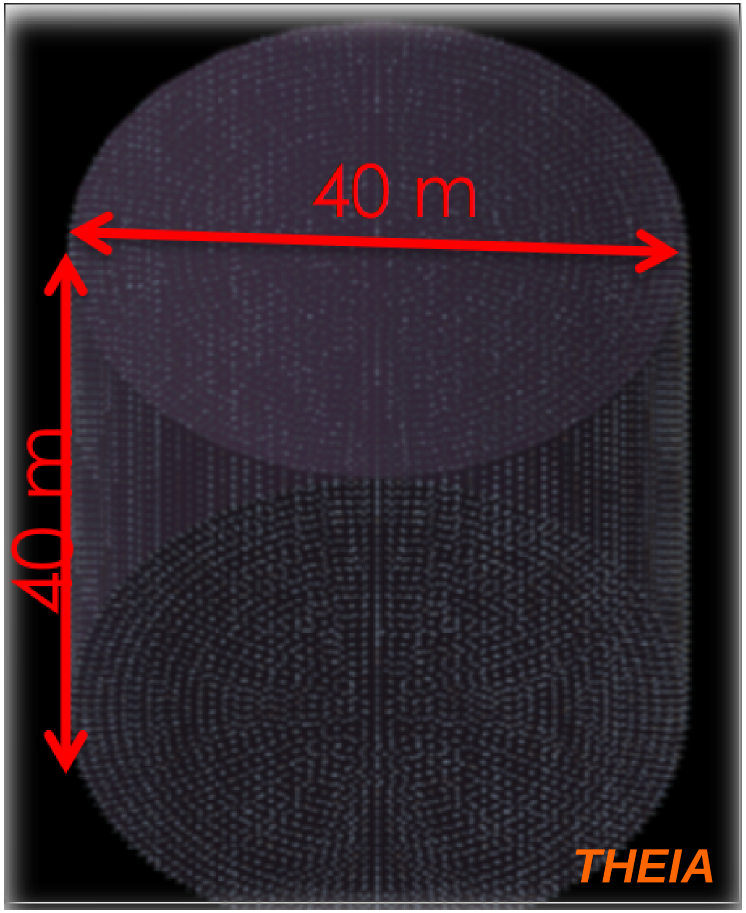
SNO+ in a unique position of having phases as a water Cherenkov detector and liquid scintillator detector.

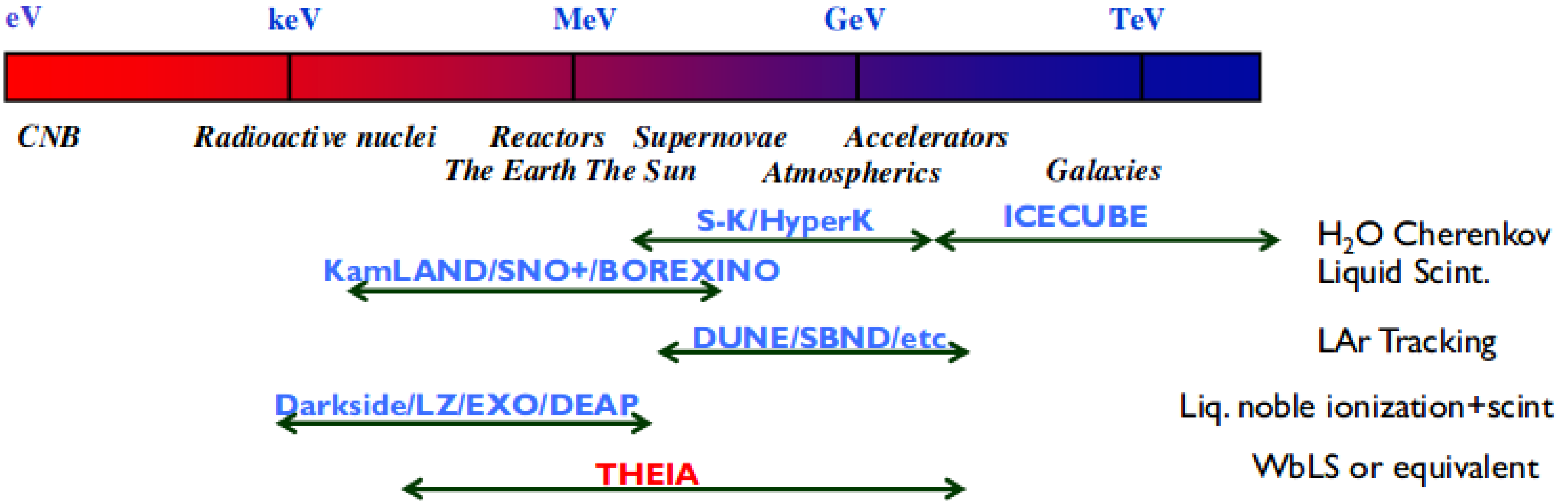
Expertise in running a water Cherenkov detector, but also lots of experience with scintillator (bench-top measurements, modeling in simulation, etc.)

Neck fill with LAB+PPO ongoing!

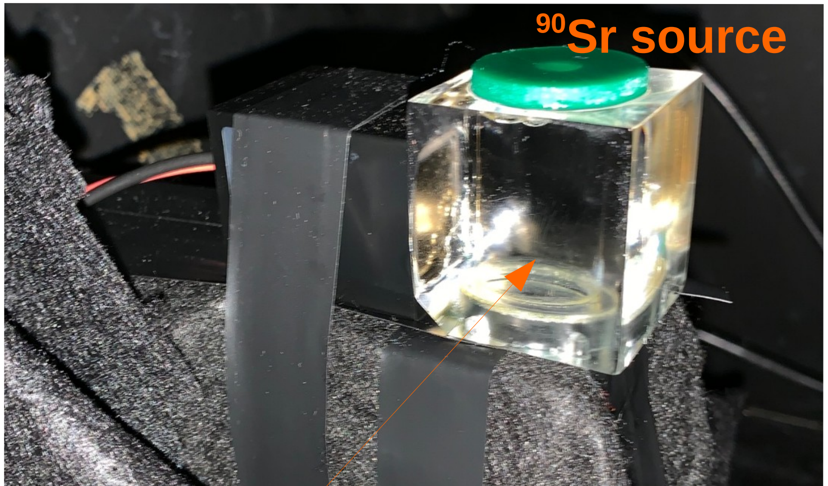
Future Experiments

- 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*

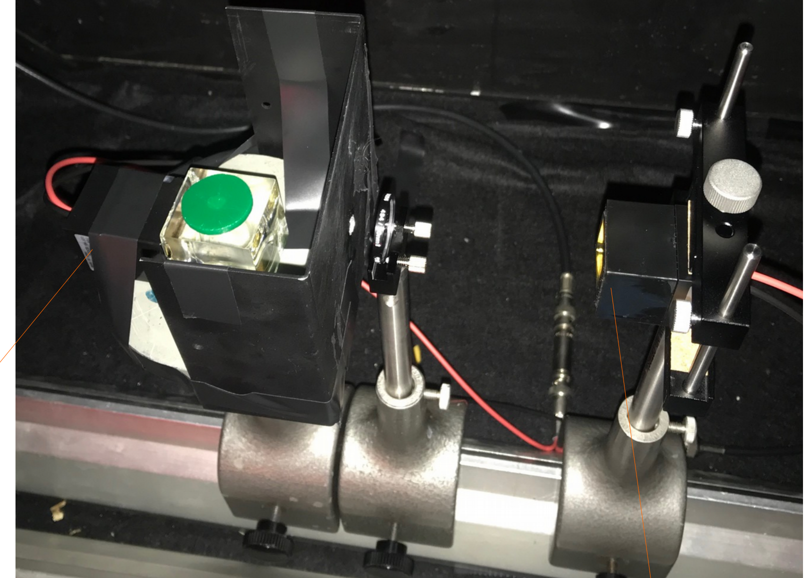


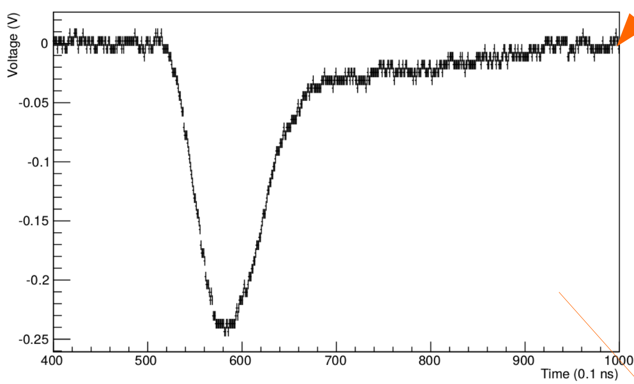


Schematic from J. Klein

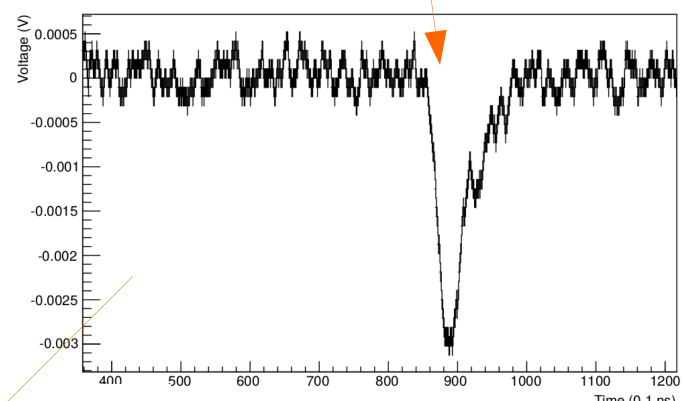


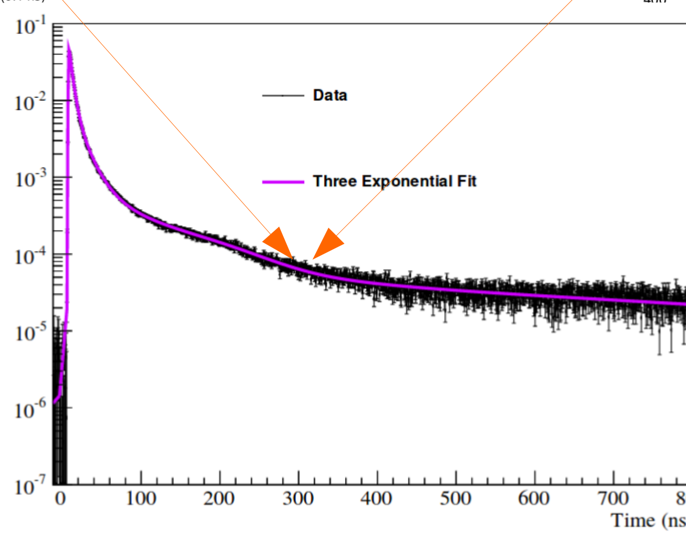
LAB+PPO inside UVT acrylic





Calculate Δt between the two waveforms





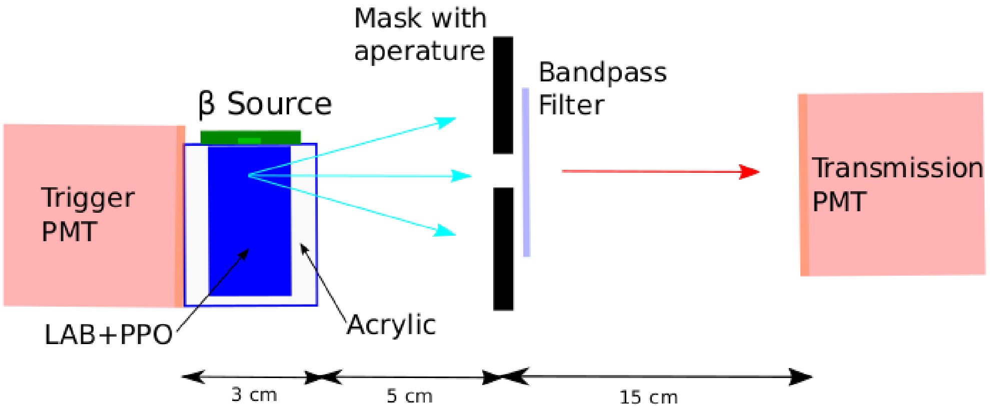
Data with no bandpass filter shows typical scintillation spectrum

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

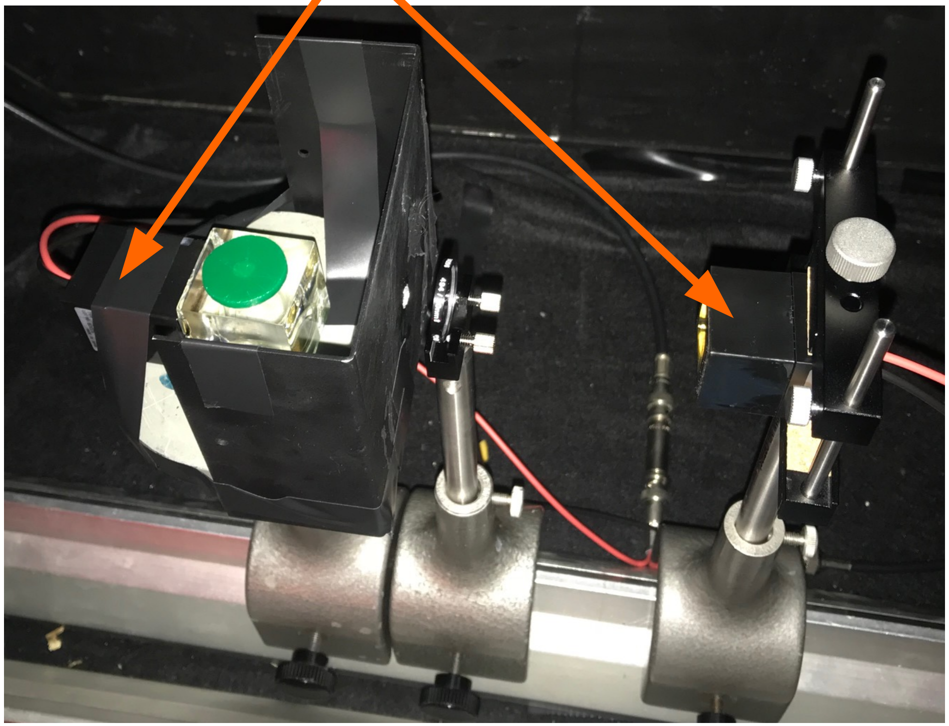
Cherenkov / Scintillation Separation With Bandpass Filters

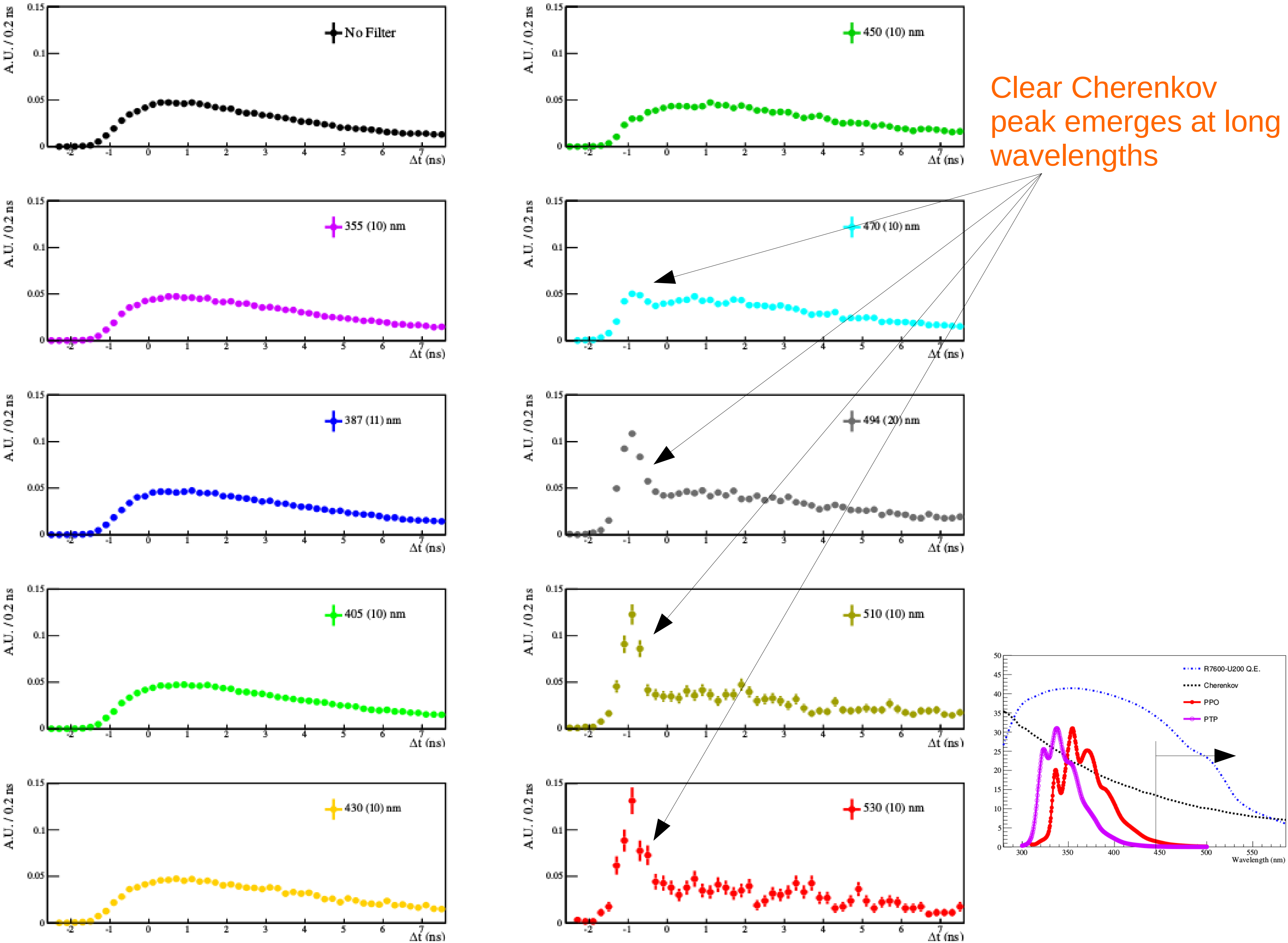
Using a set of bandpass filters to span emission spectrum of LAB+PPO

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
470 (10) nm
494 (20) 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

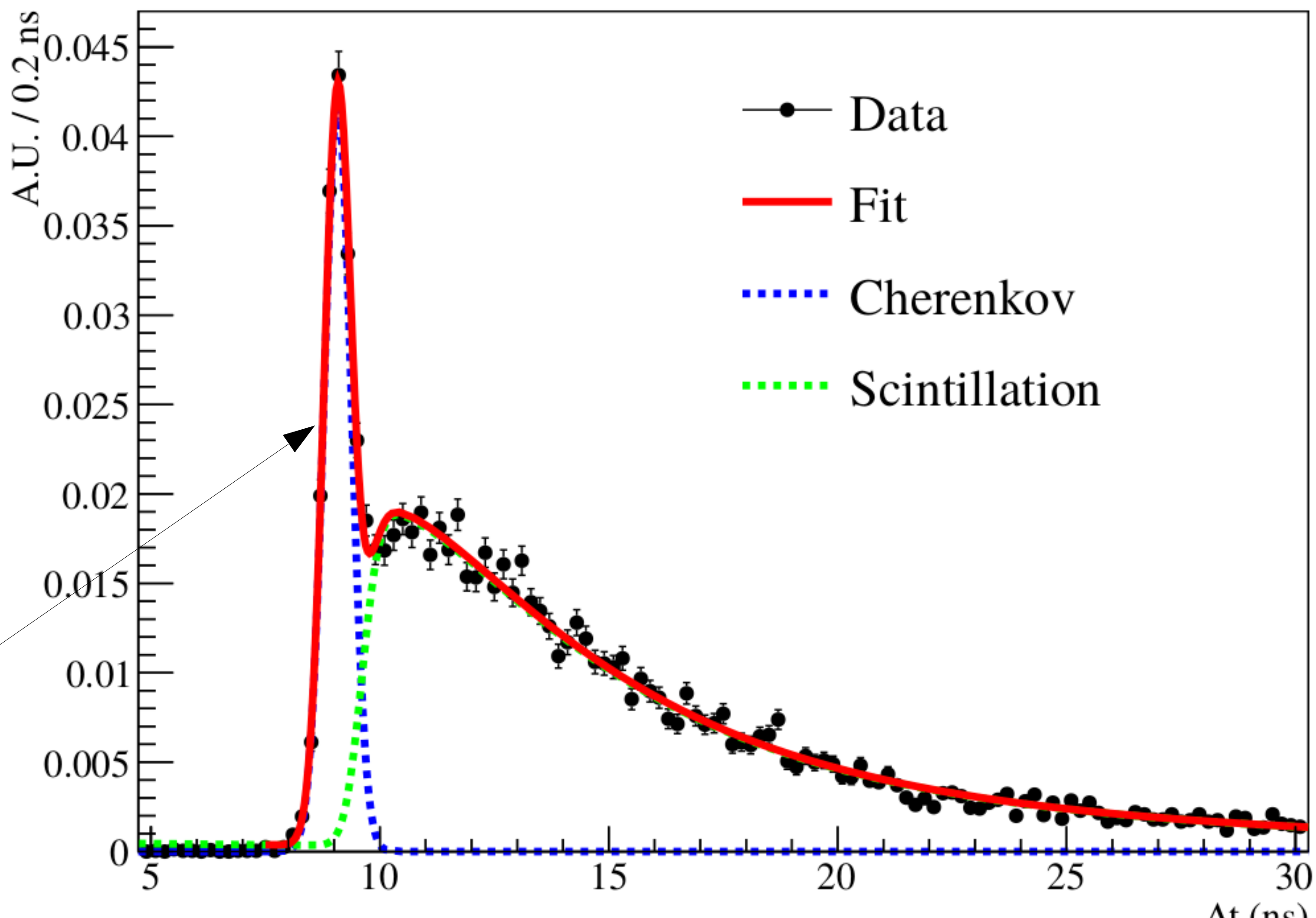
$$F = C \times f_{PMT}(t - t') + (1 - C) \times \sum_{i=1}^{2} \frac{A_i \times (e^{-t/\tau_i} - e^{-t/\tau_R})}{(\tau_i - \tau_R)} * f_{PMT}(t - t')$$

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

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

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

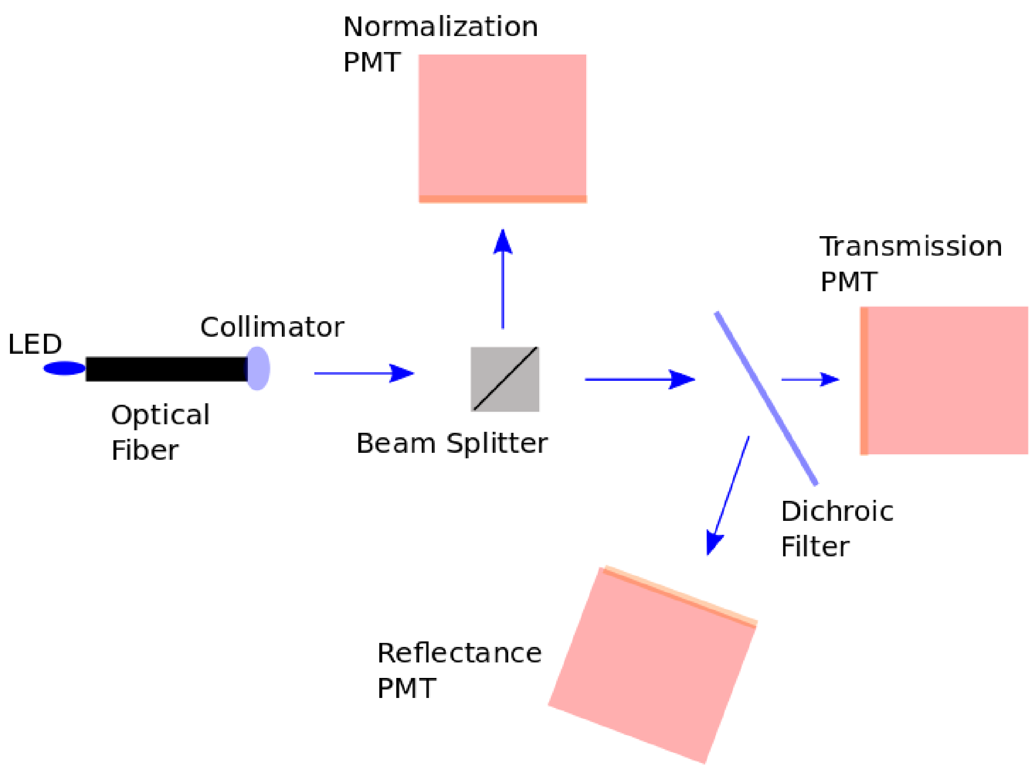
> 90% of prompt light is Cherenkov light!



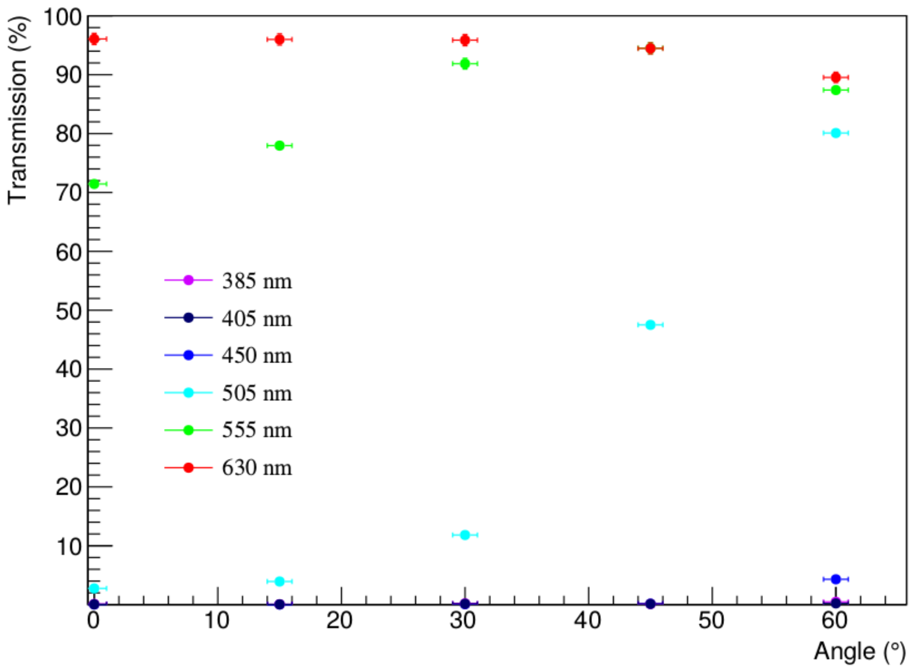
T. Kaptanoglu, M. Luo, J. Klein, JINST 14 (2019) no.05, T05001

Measuring T(λ, θ) and R(λ, θ)

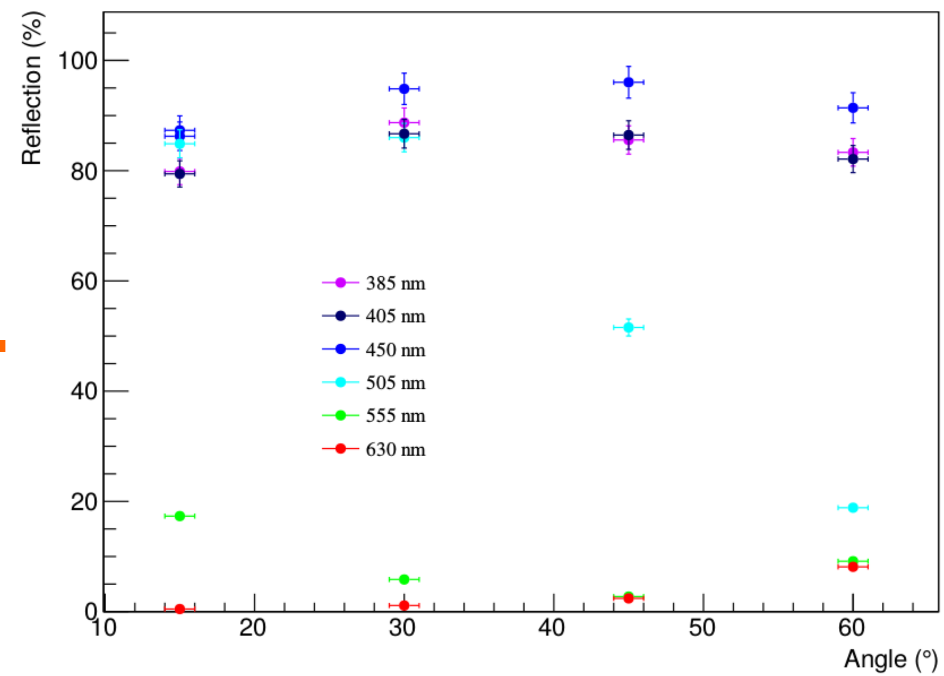
Characterize the transmission and reflection of the dichroic filters as a function of wave
and incident angle



Measurements for a 500 nm long-pass dichroic filter



+



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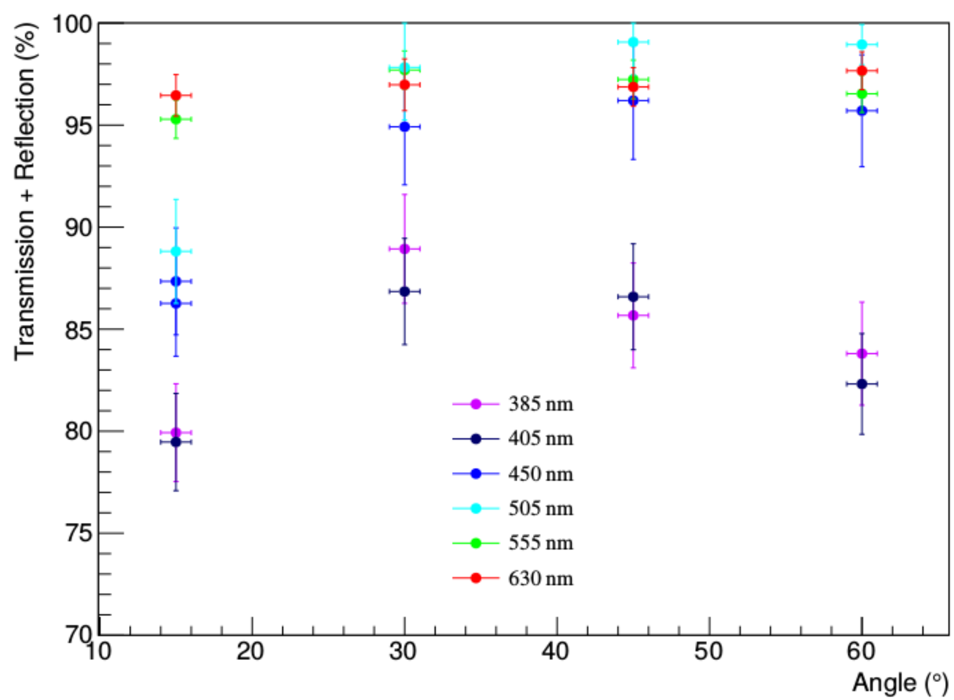
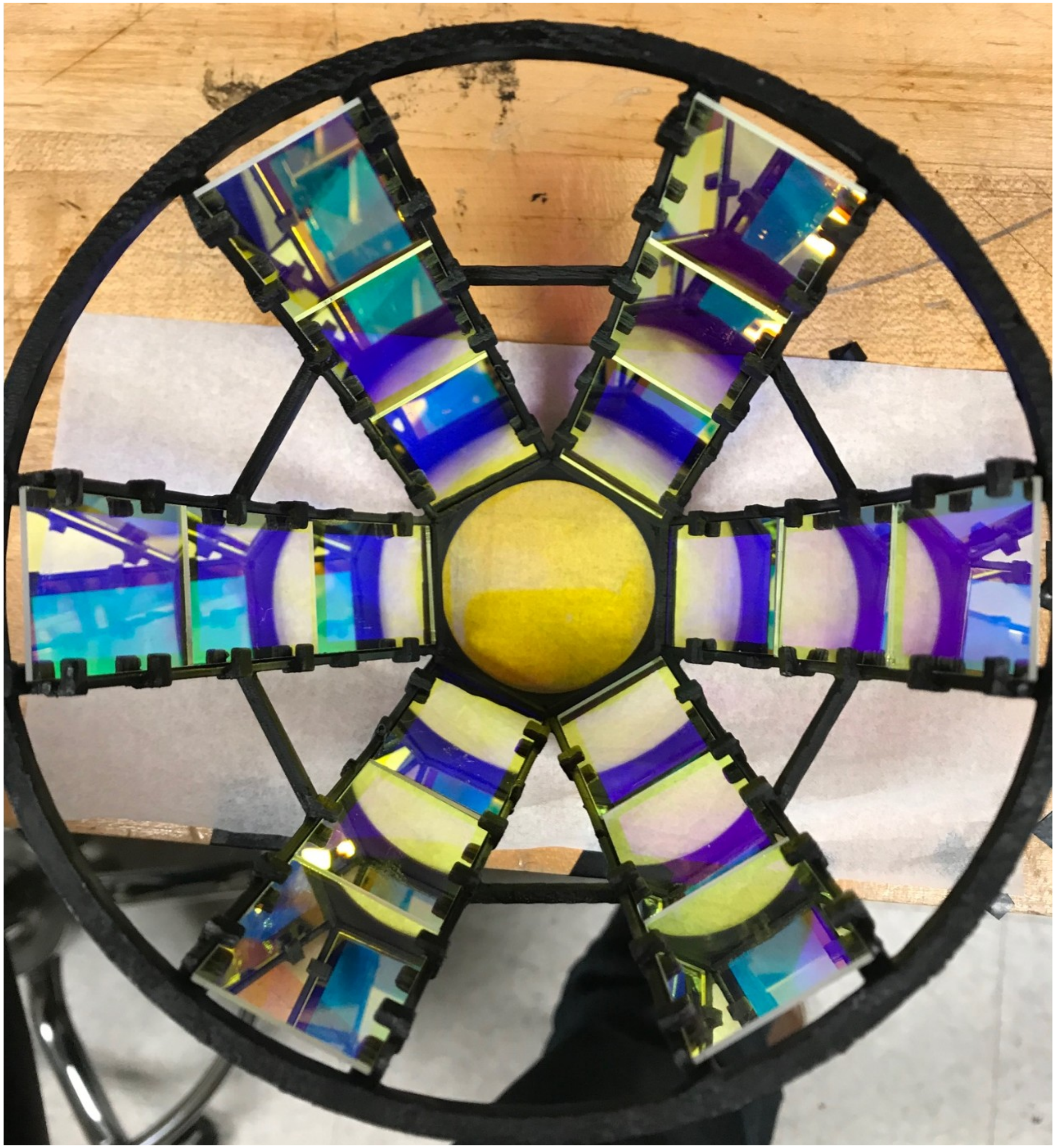


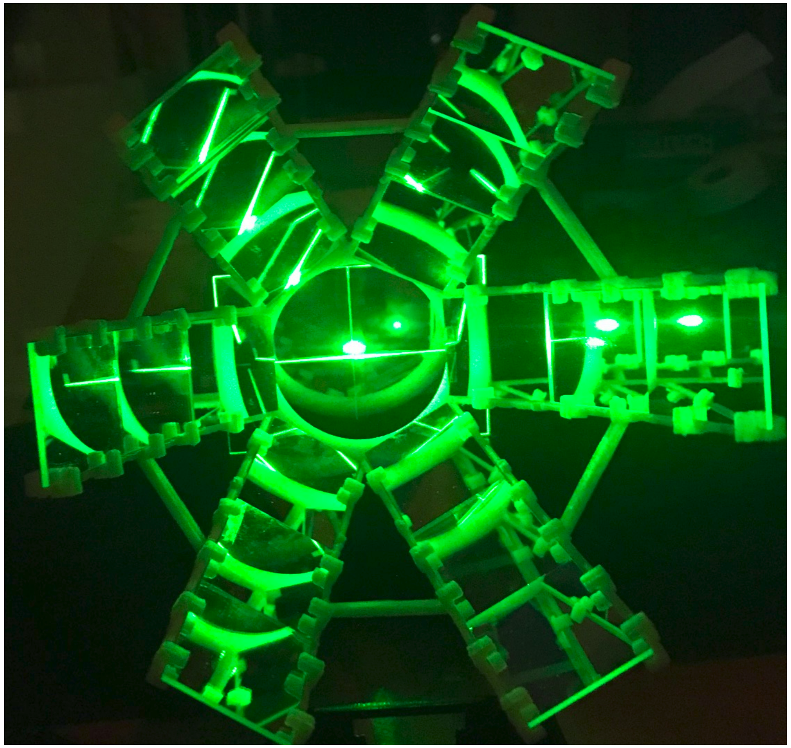
Very little light lost to the dichroic filter over range of wavelengths and incident angles

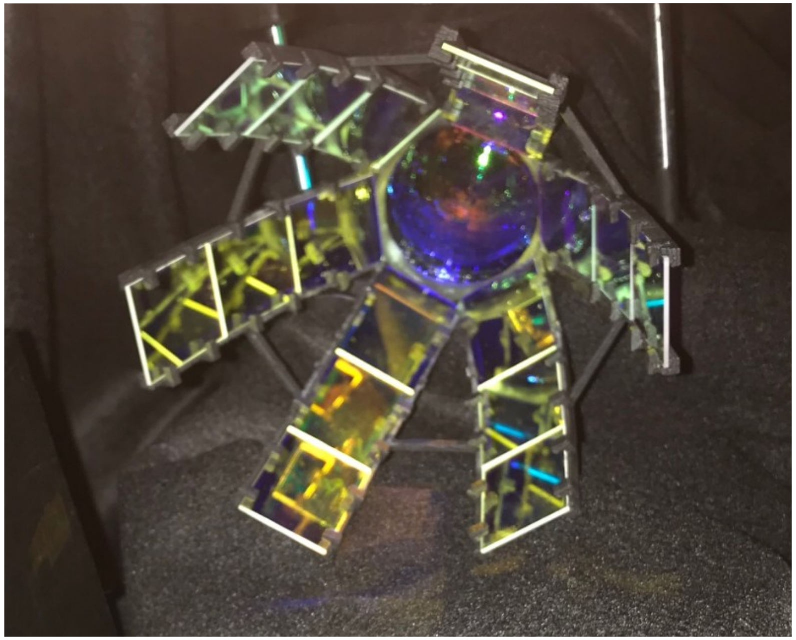
Used for input into our simulation model

Prototype 1

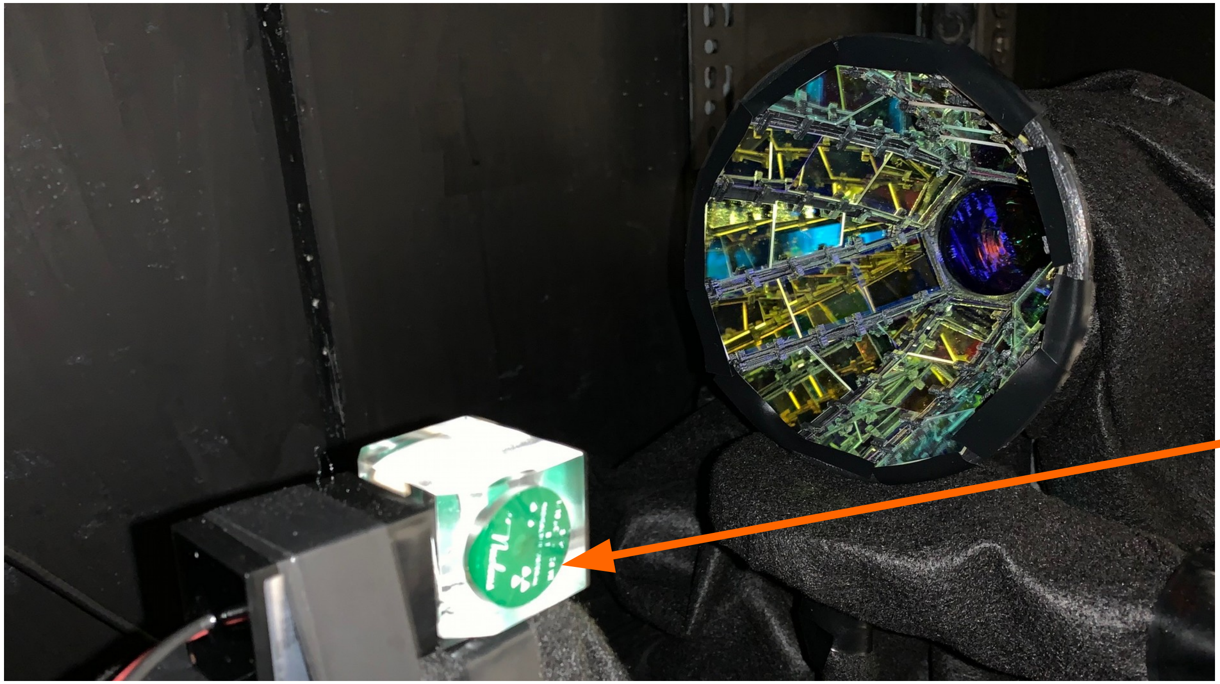
3D printed holder for dichroic filters







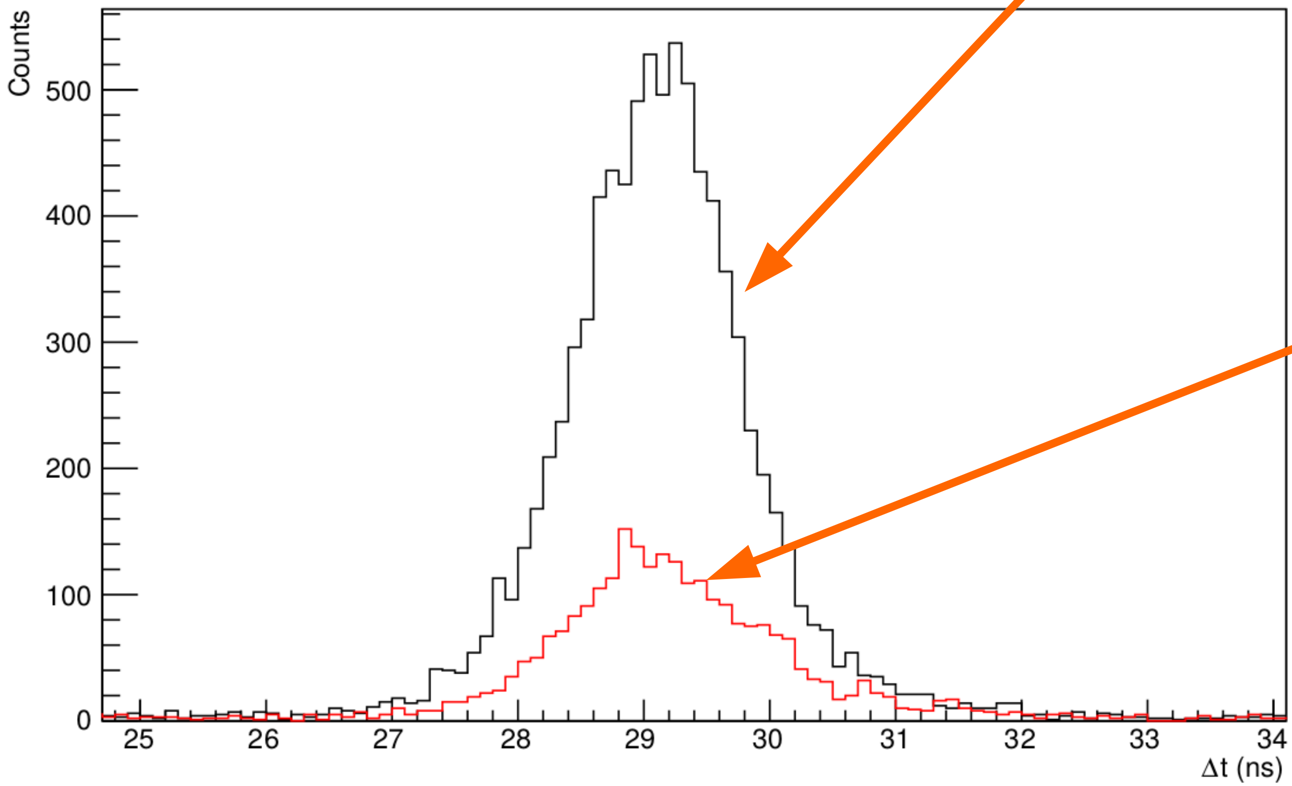
Dichroicon Data



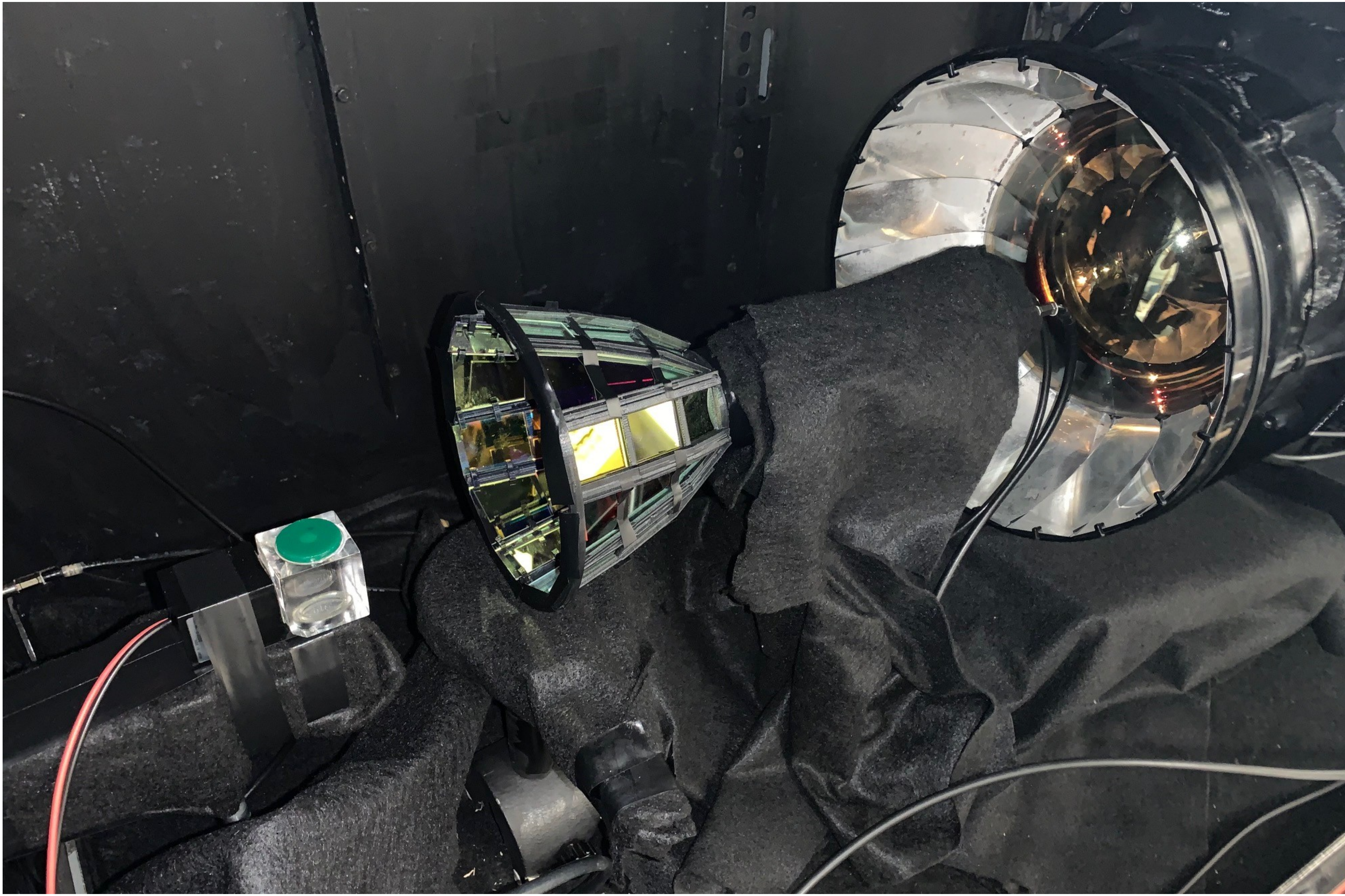
Acrylic Cherenkov source

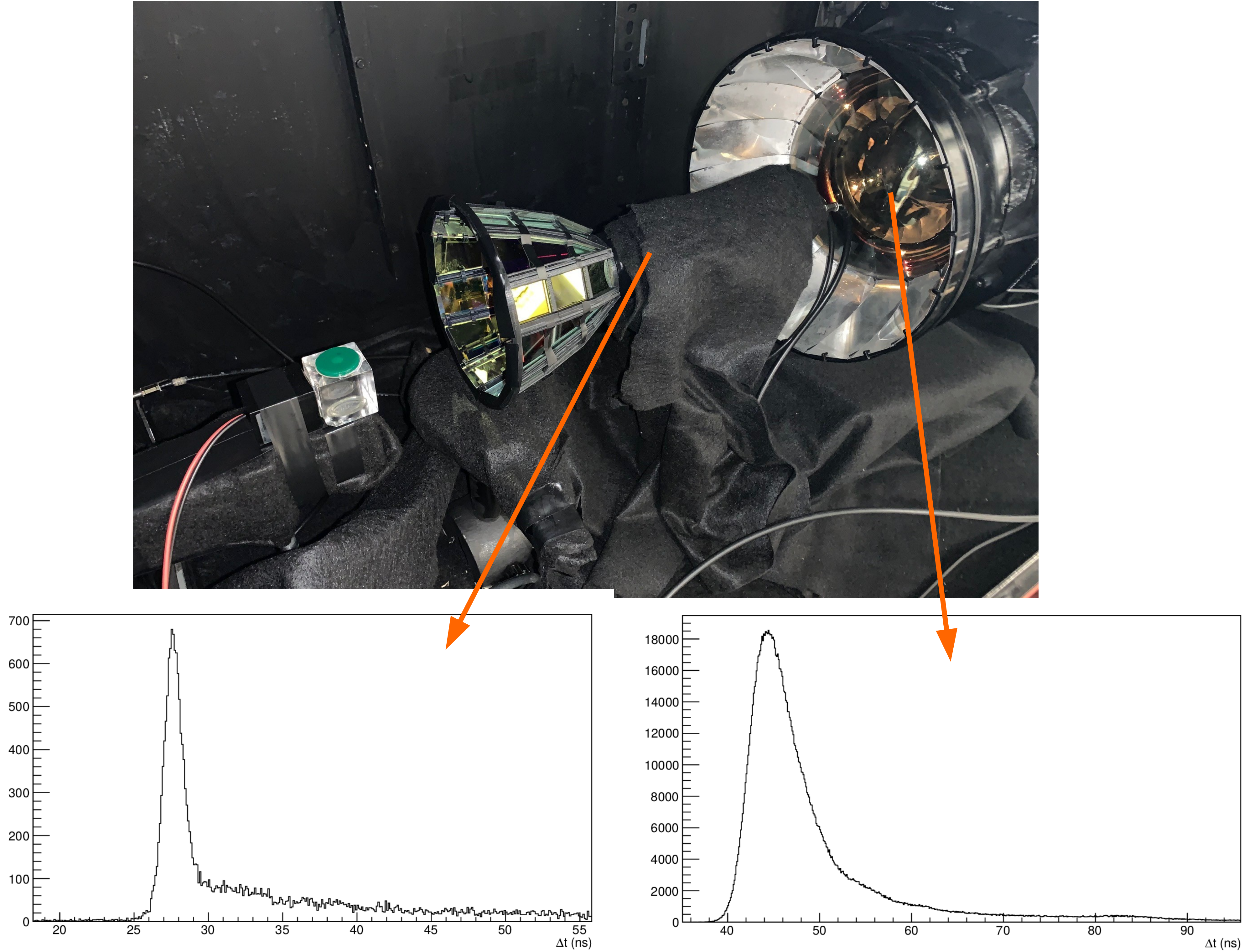
With dichroic Winston cone!

No Winston cone



Dichroicon Data




700
600
500
400
300
200
100
0
20
25
30
35
40
45
50
55
Δt (ns)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
40
50
60
70
80
90
Δt (ns)