

Dichroicons

- The spectral sorting approach
- Dichroicon Designs
- Challenges and Opportunities with Dichroicons

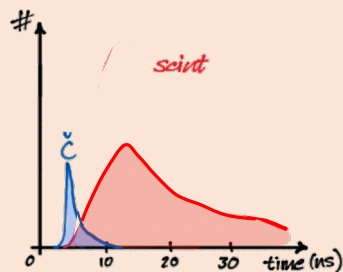
Josh Klein
University of Pennsylvania
Mainz LS Town Hall

Hybrid Cherenkov/Scintillation Detectors

Ratio

Add just a little scintillation

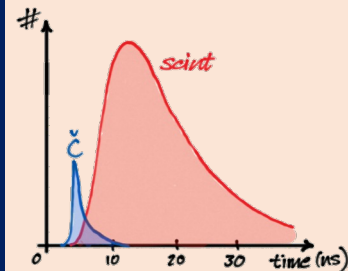
→ new materials/fluors



Timing

"instantaneous chertons"
vs. delayed "scintons"

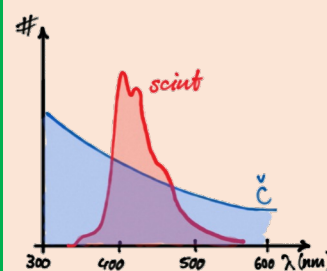
→ ns resolution or better



M. Wurm

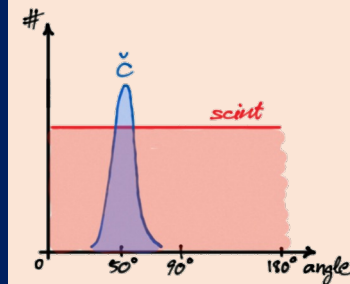
Spectrum

UV/blue scintillation vs.
blue/green Cherenkov
→ wavelength-sensitivity



Angular distribution

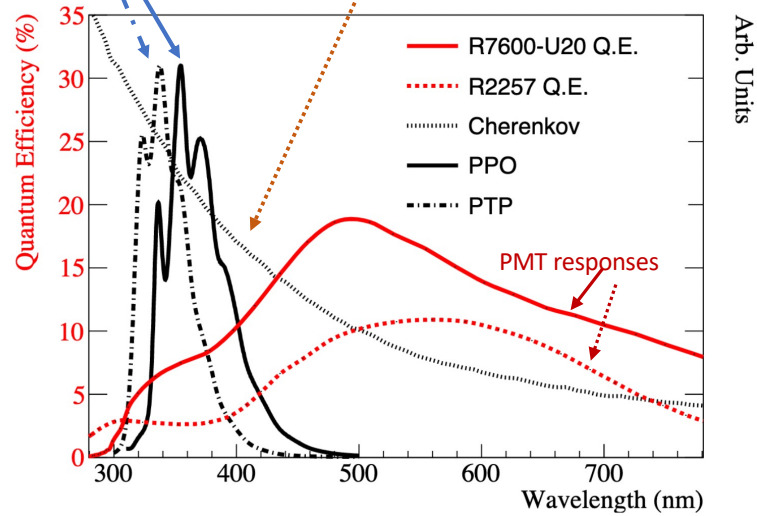
increased PMT hit density
under Cherenkov angle
→ sufficient granularity



Spectral separation has advantages even for fast scintillator

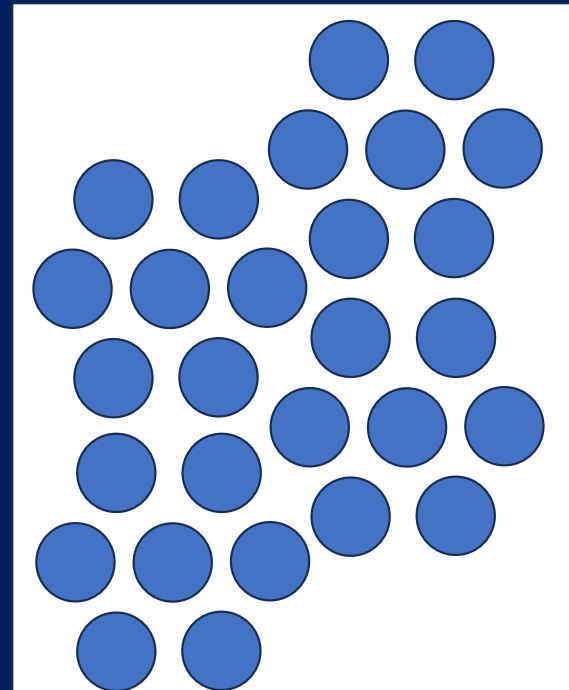
Scintillation
emission

$$N_{\text{cer}}^{\gamma} \sim 1/\lambda^2$$



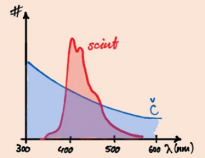
Spectrum

Spectral differences allow separation---
could use filters or red-sensitive PMTs:



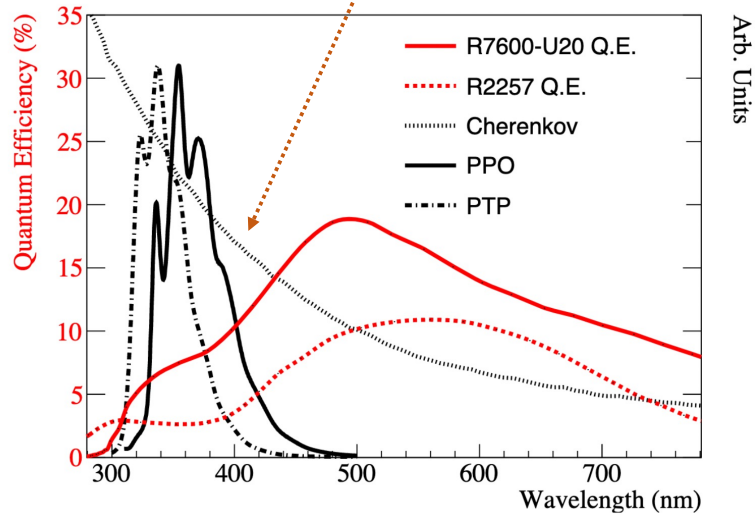
Spectrum

UV/blue scintillation vs.
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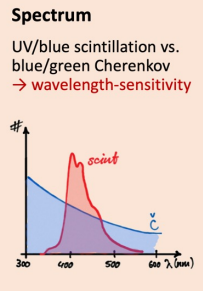


Spectrum

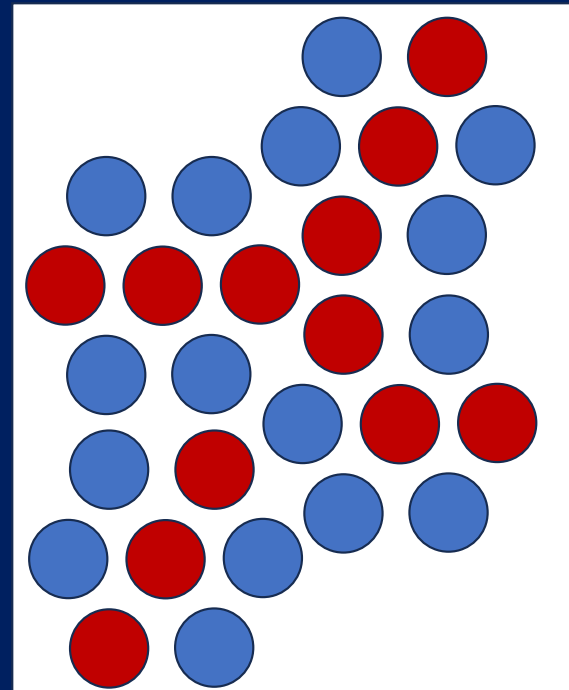
$$N_{\text{cer}}^{\gamma} \sim 1/\lambda^2$$



Spectral differences allow separation---
could use filters or red-sensitive PMTs:



But now we have lost a lot of our
scintillation photons---can we instead
sort the photons so they go to the
right sensors...?



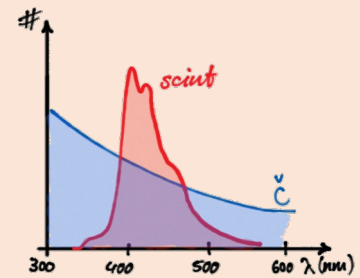
Spectral Photon Sorting

If we sort photons efficiently:

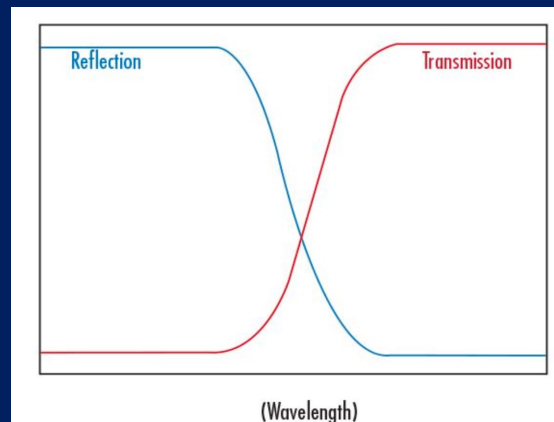
- Can preserve most of the different signals
- Possibly increase overall light yield by viewing a broad-band spectrum by relevant sensor

Spectrum

UV/blue scintillation vs.
blue/green Cherenkov
→ wavelength-sensitivity

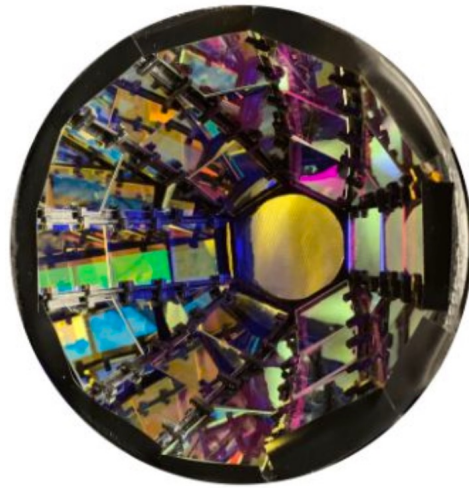
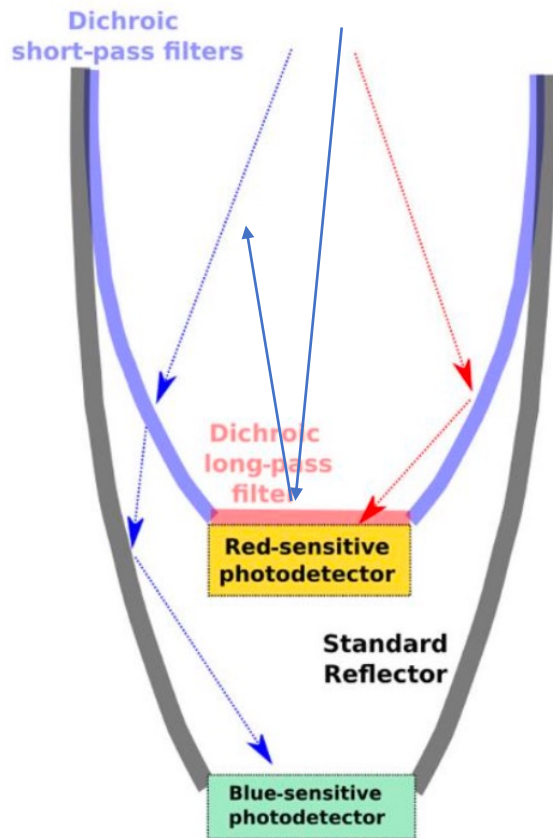


Dichroic filters provide a sorting mechanism---how do we use this in a large detector?

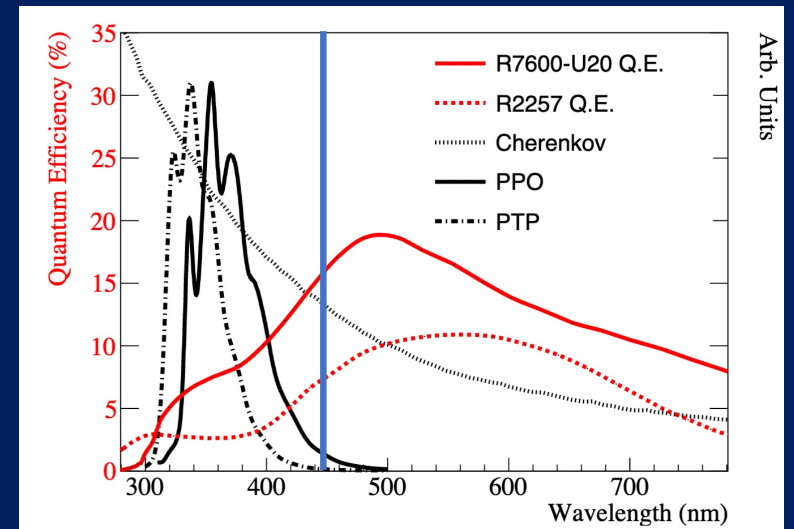


Dichroicons

Winston-style light concentrator made out of dichroic mirrors can concentrate long-wavelength and pass short wavelength light (a “dichroicon”)

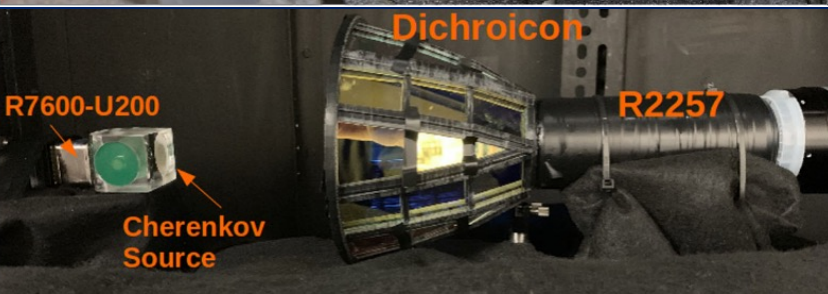
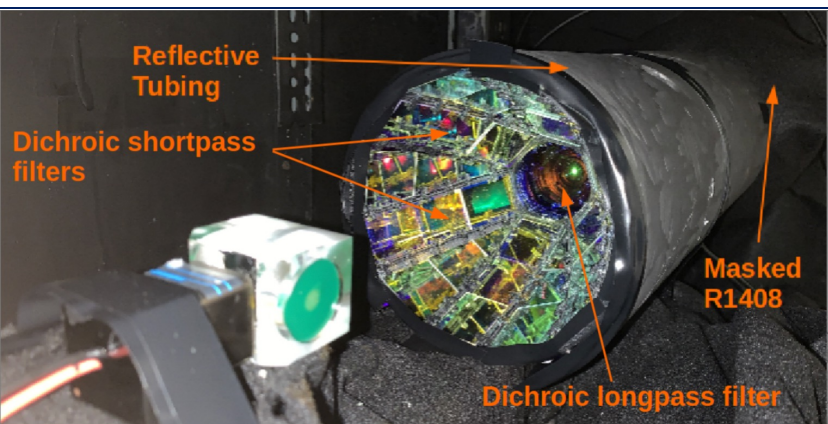
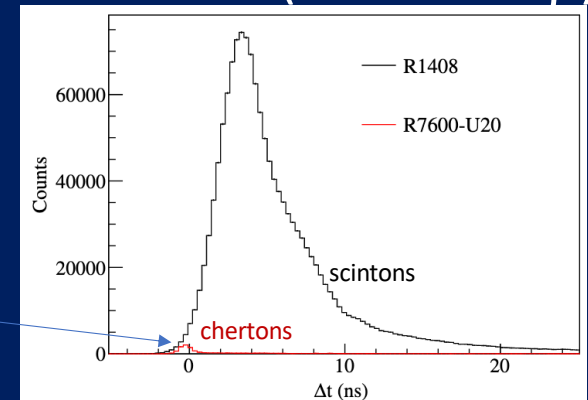
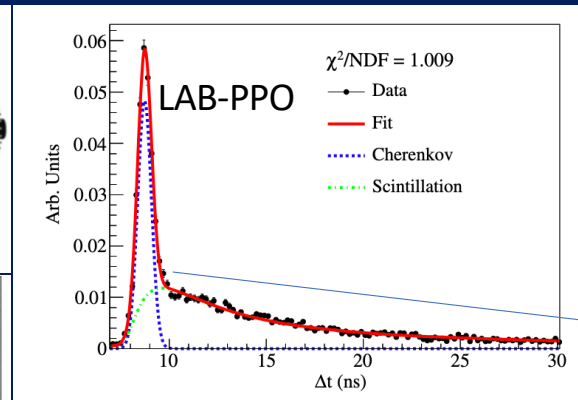
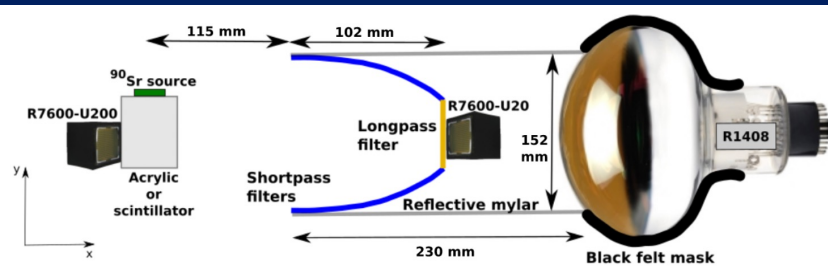


Cut-on wavelength depends on QE curve of sensors and emission of scintillation light and physics

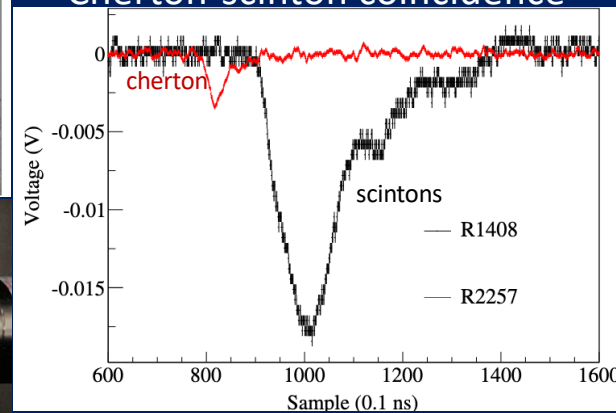


Benchtop Performance

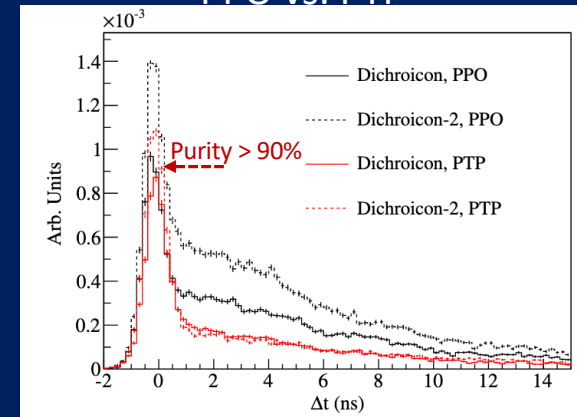
$^{90}\text{Sr}/^{90}\text{Y}$ source ($\sim 2.3 \text{ MeV } \beta$)



Cherton-scinton coincidence



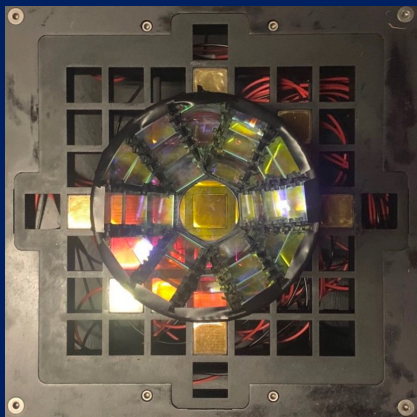
PPO vs. PTP



Phys. Rev. D 101, 072002

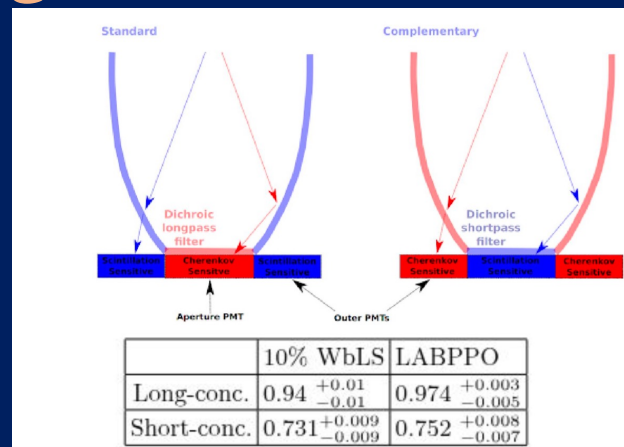
T. Kaptanoglu

Dichroicon at CHES (LBNL)

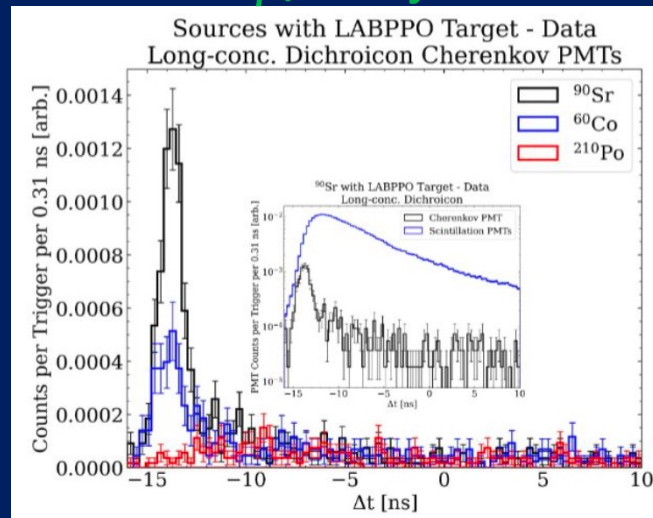
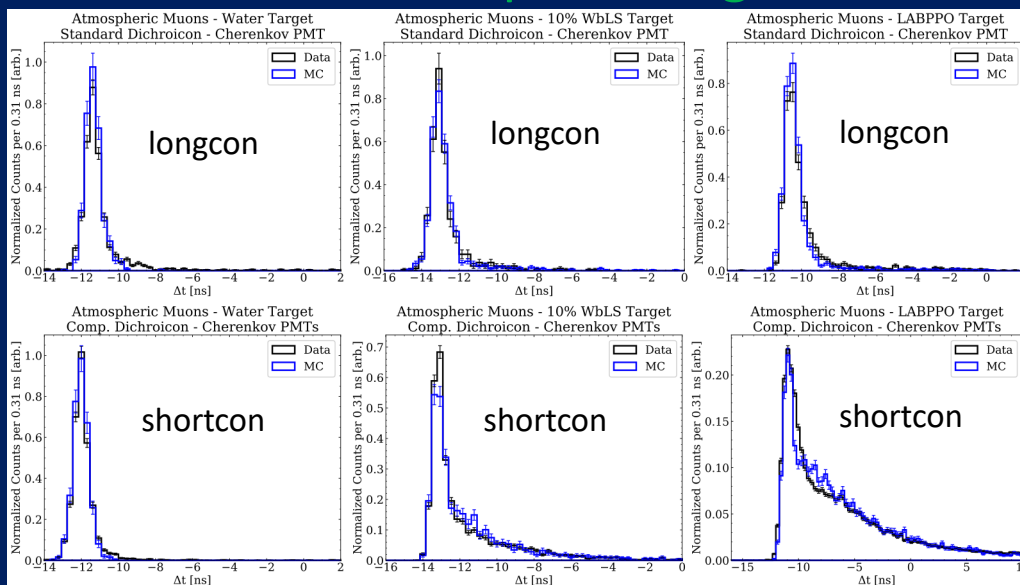


Benchtop Performance (Flat) Pixellated sensors

Model does well reproducing data



Great β/α rejection

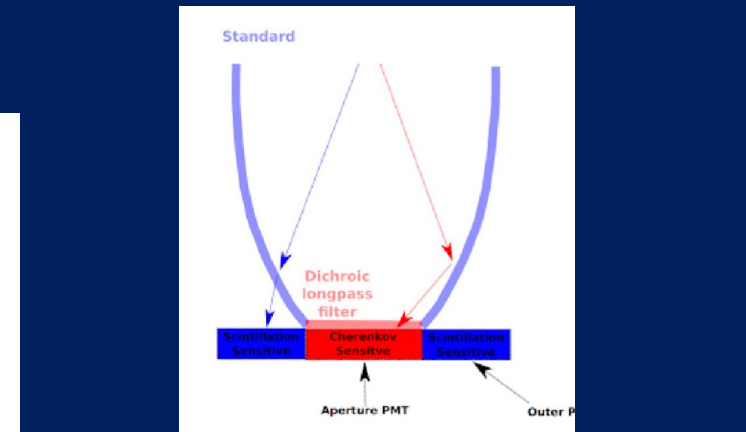
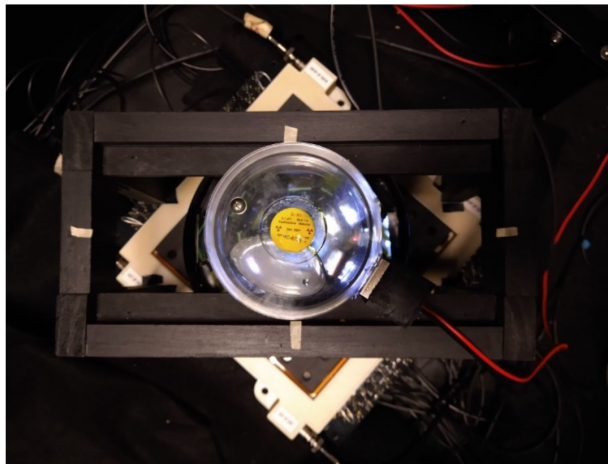
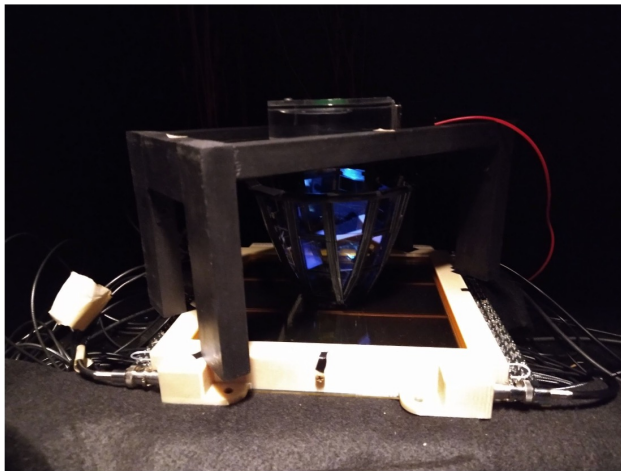


S. Naugle

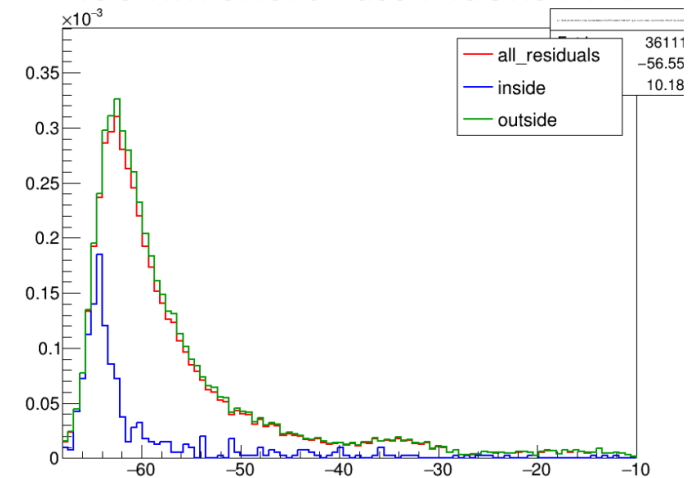
Benchtop Performance

(Flat) Pixellated sensors

Dichroicon with LAPPD at LBNL

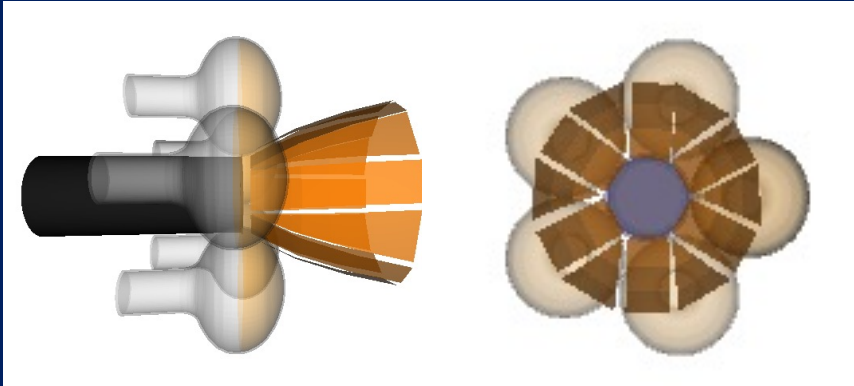


450 nm Short Pass Muons in LAB



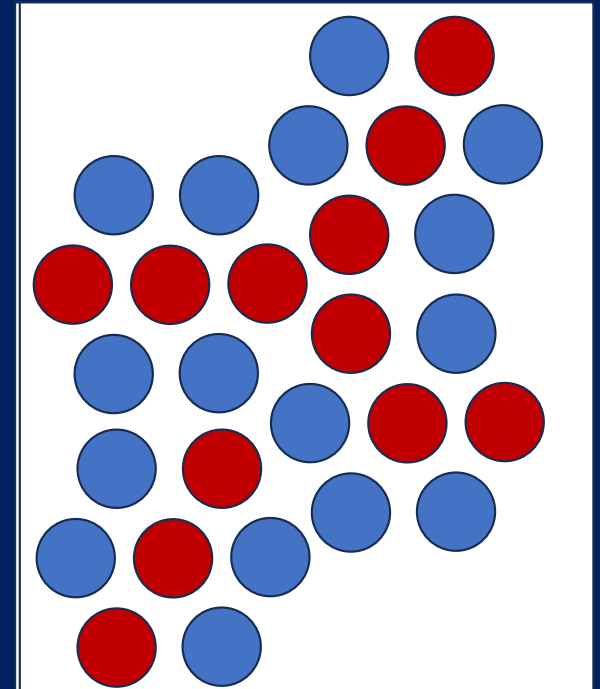
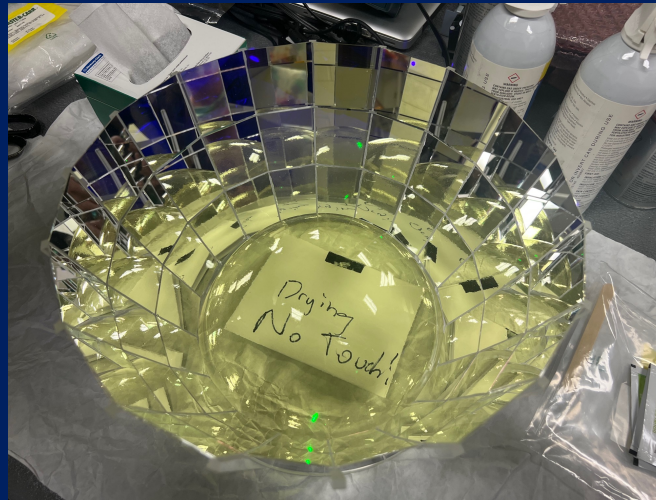
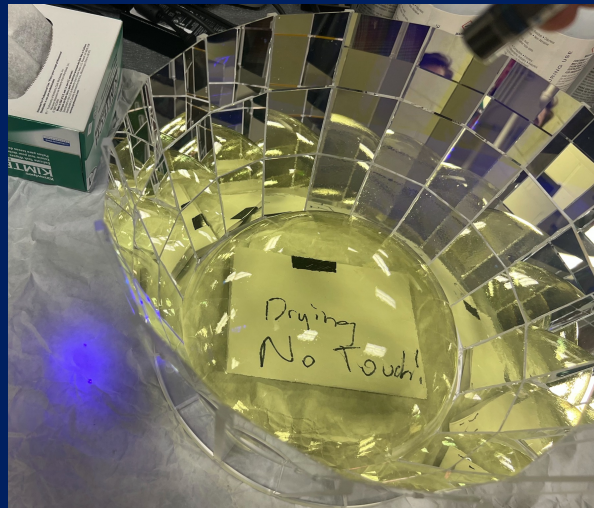
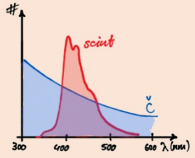
Spectrum

“Flower-petal” design probably makes more sense for big detector



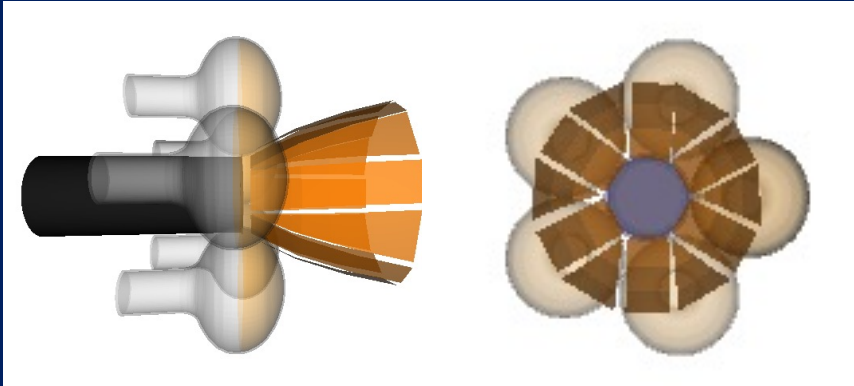
Spectrum

UV/blue scintillation vs.
blue/green Cherenkov
→ wavelength-sensitivity



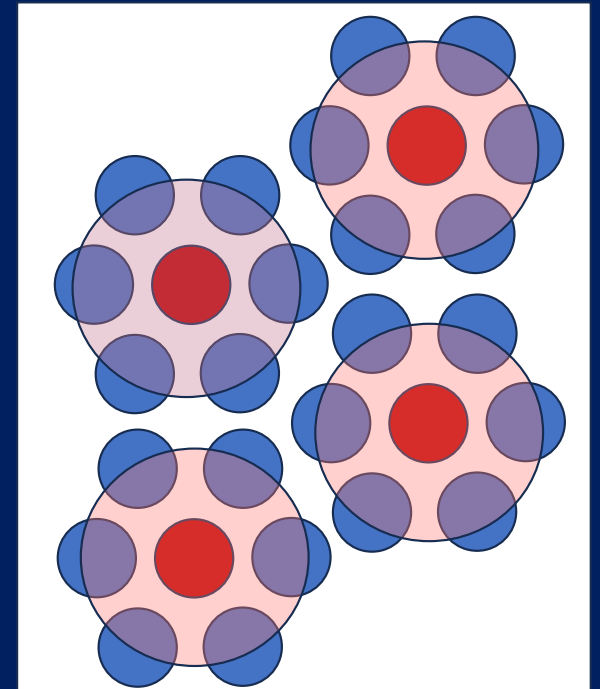
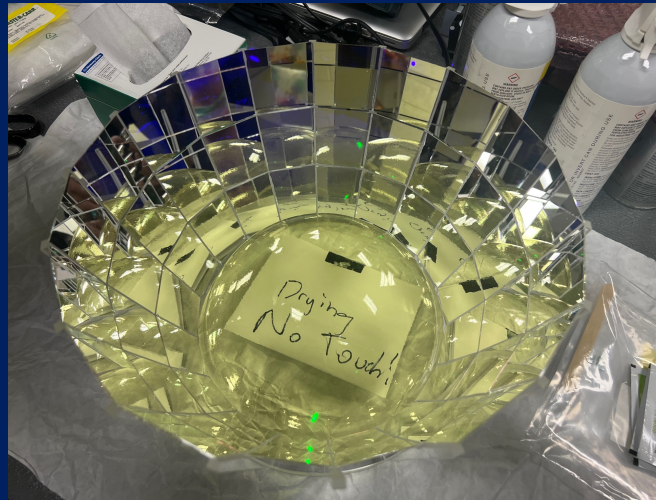
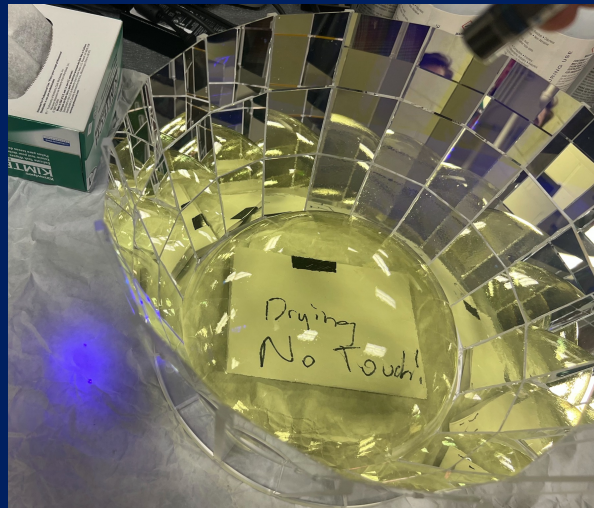
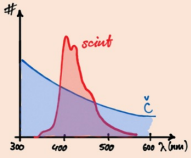
Spectrum

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Spectrum

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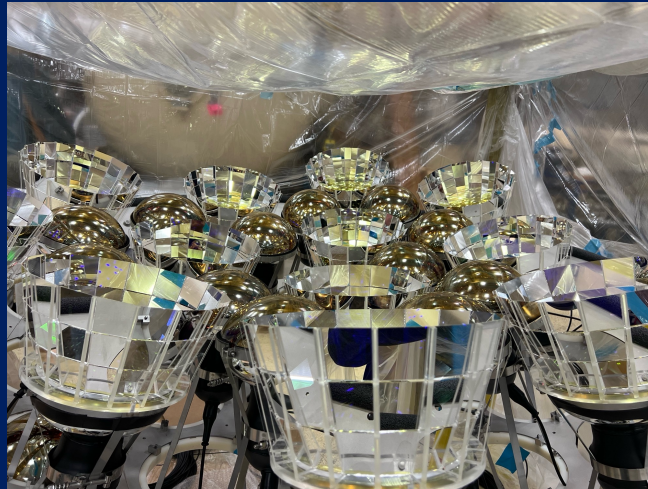
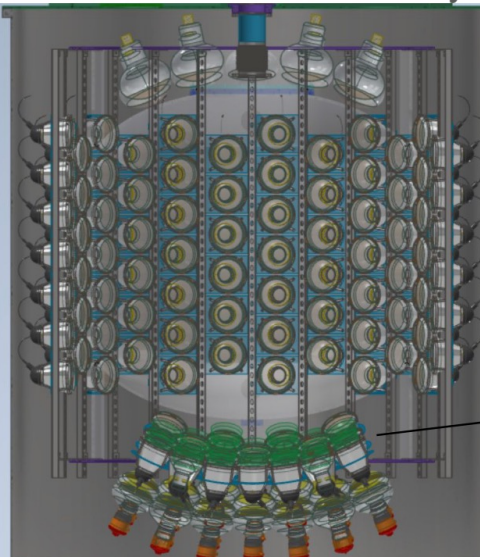
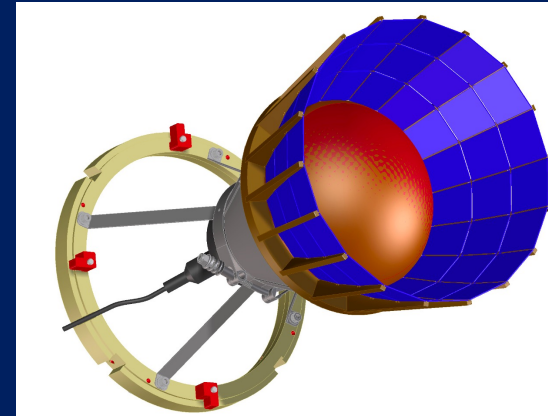


Eos at UCB/LBNL

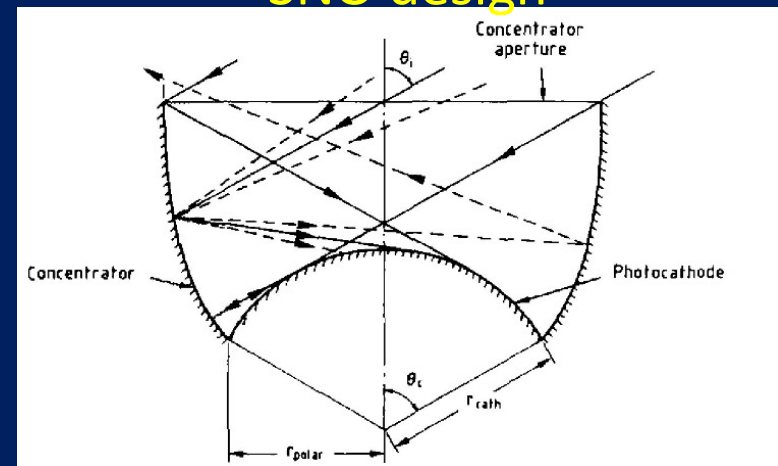
12 dichroicons at bottom

Eos Deployment

- Note: PMT hemisphere inside cone doubles Cherenkov yield
- No curved dichroic filters exist yet: use a longpass absorbing filter
- (Means we lose scintons that hit PMT bulb)



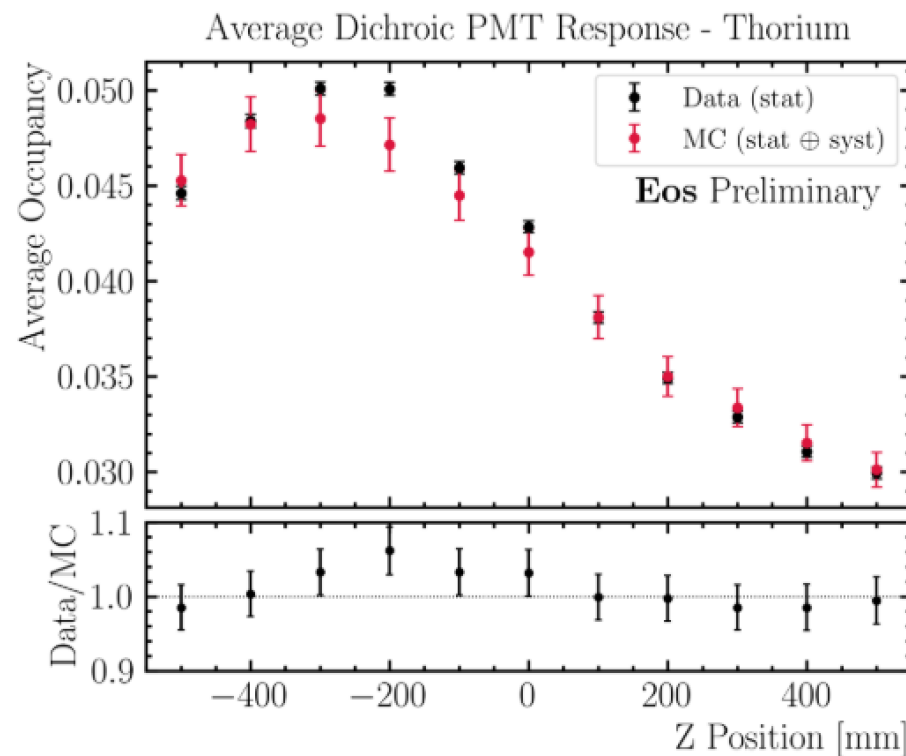
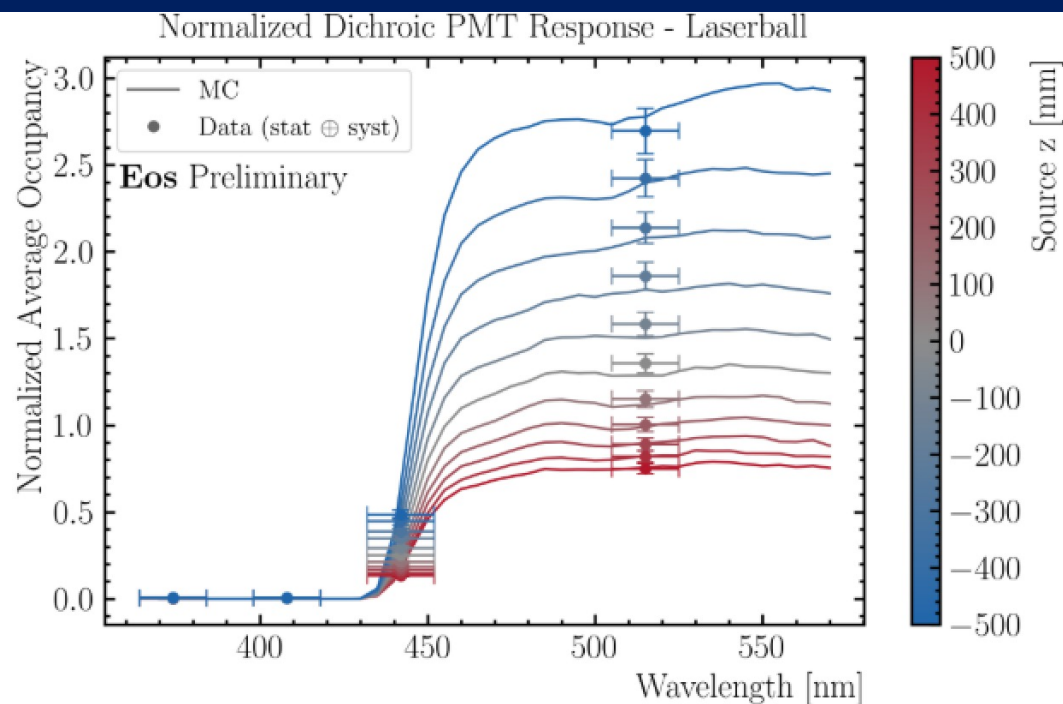
SNO design



Eos Deployment

Complete RATPAC2 Model

Water



M. Dubnowski

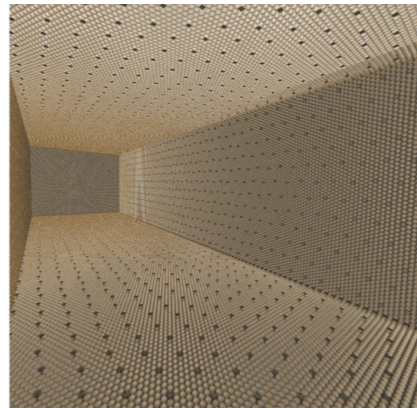
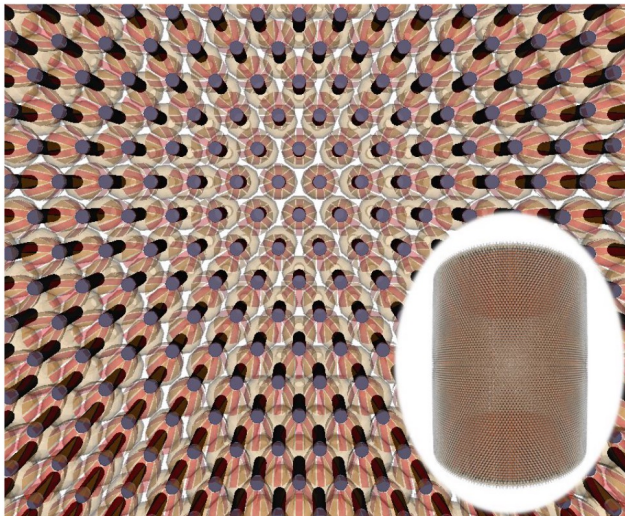
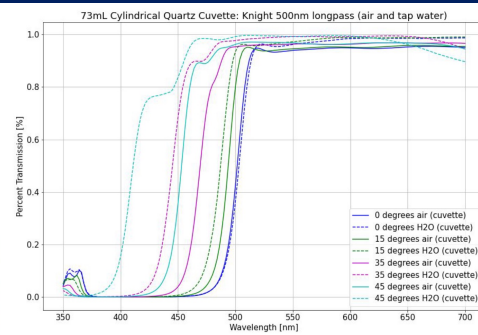
Data/MC comparisons look good after calibration

Theia

Large Detector

- Using full dichroicon model, implemented in Chroma GPU ray-tracer
- Developed simple timing and angular reconstruction for vertex and direction

A. Bacon

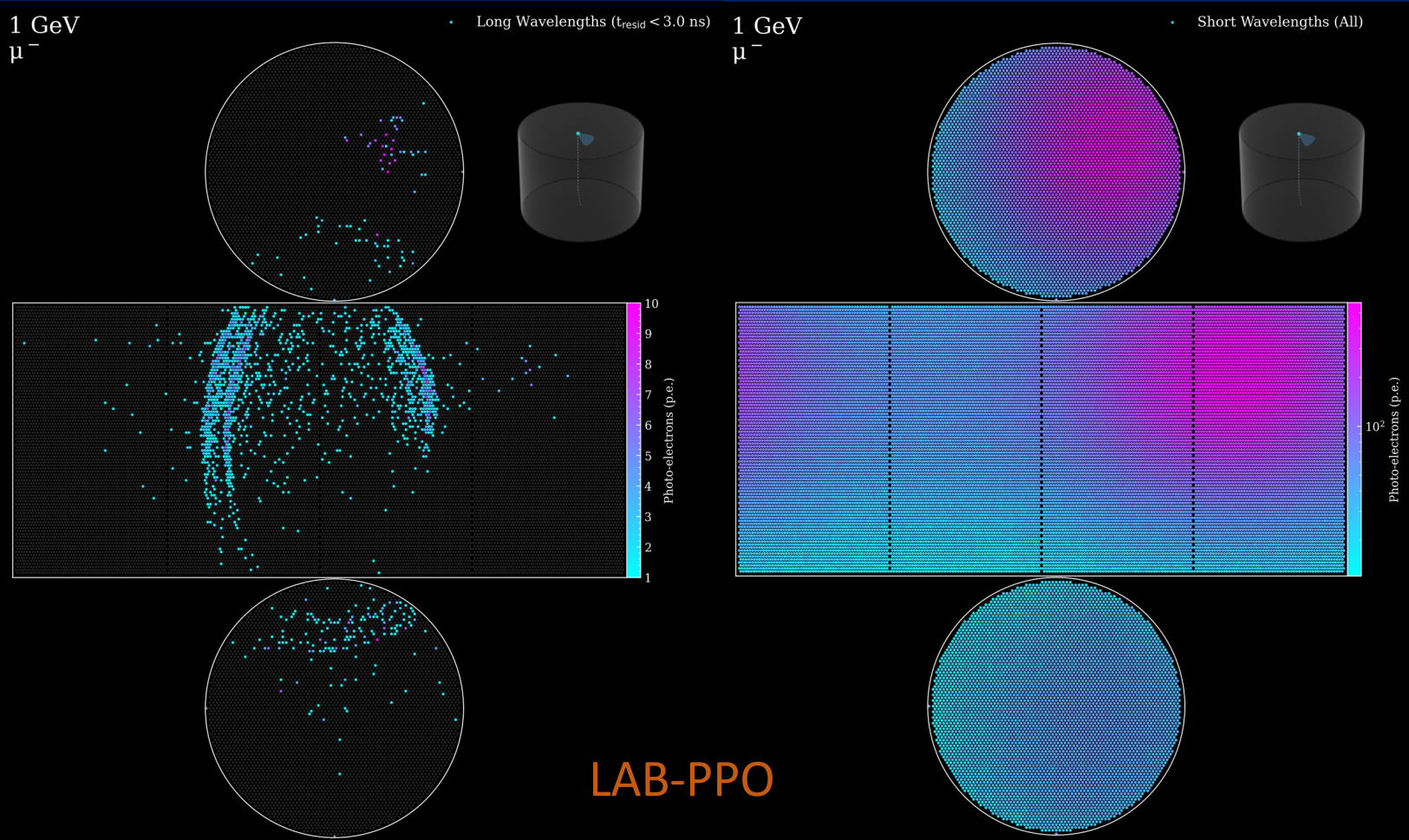


- *Implemented measured dichroic filter transmission and reflection curves in Chroma model*
- *Have full PMT QE curves*
- *Complete PMT timing response*
- *Optical isolation of long-wavelength PMT*

Theia

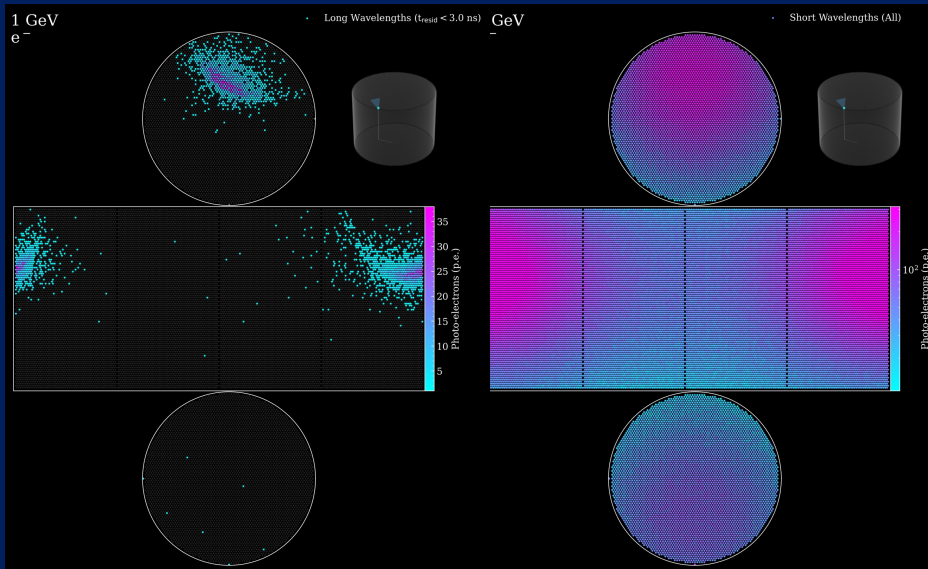
Large Detector with LAB-PPO

One Detector



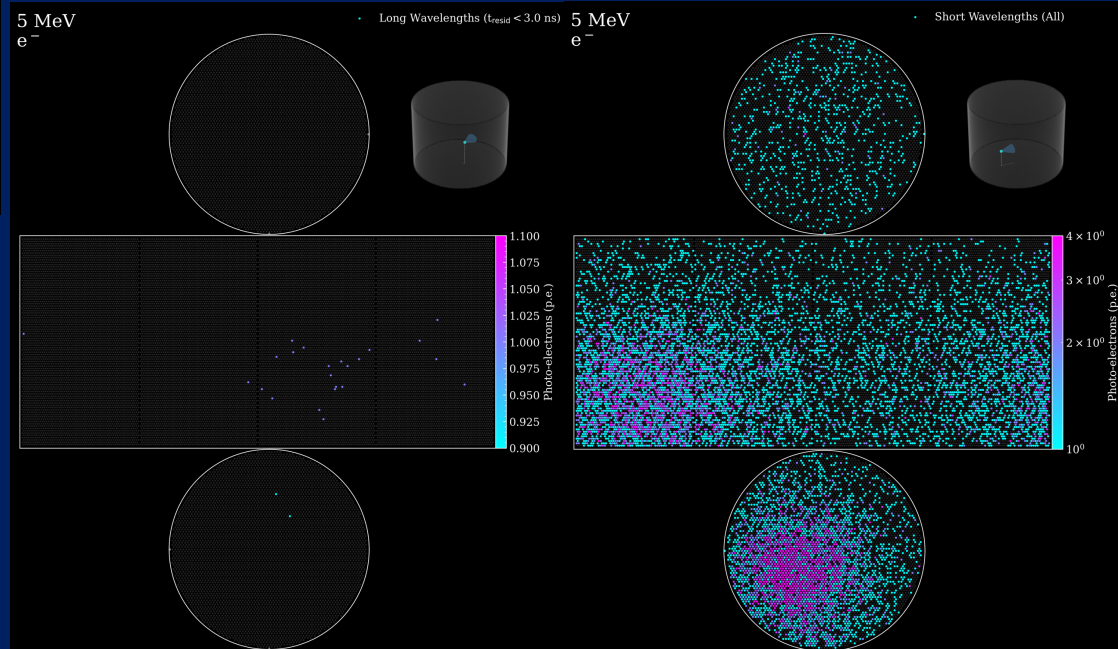
S. Young

Theia (100kt) Large Detector with LAB-PPO



LAB-PPO, JUNO-level coverage

About $10,000 p.e. \cong$
1% energy resolution
At 5 MeV



$$\cos\theta_{\text{ch}} = 1/\beta n$$

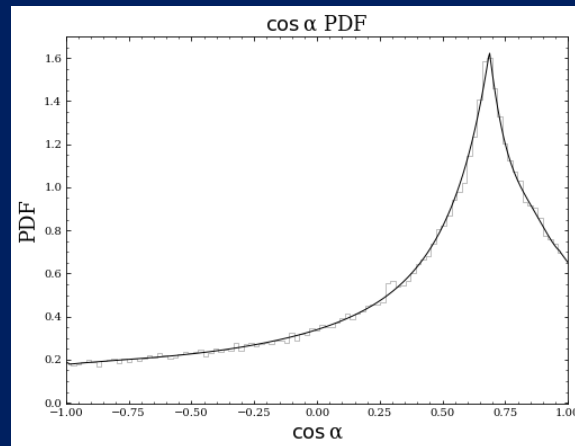
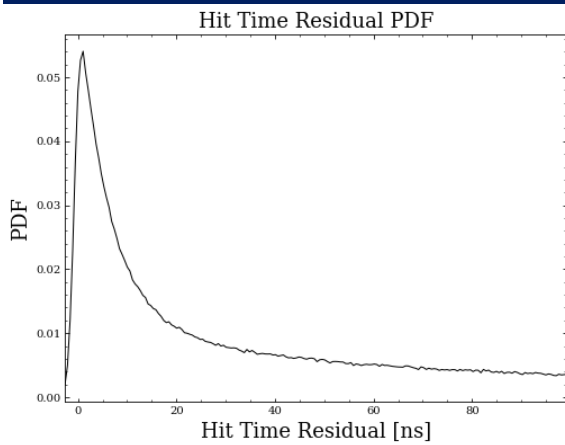
$$\text{So } m = E \frac{\sqrt{n^2 \cos^2 \theta - 1}}{n \cos \theta}$$

→ New PID handle if uncertainty on $\cos\theta_{\text{ch}}$ is small enough (~ 1 degree can do e, μ, K, p but not μ/π)

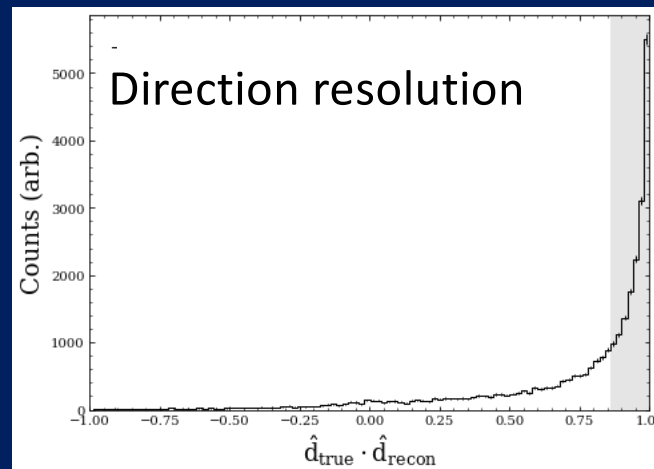
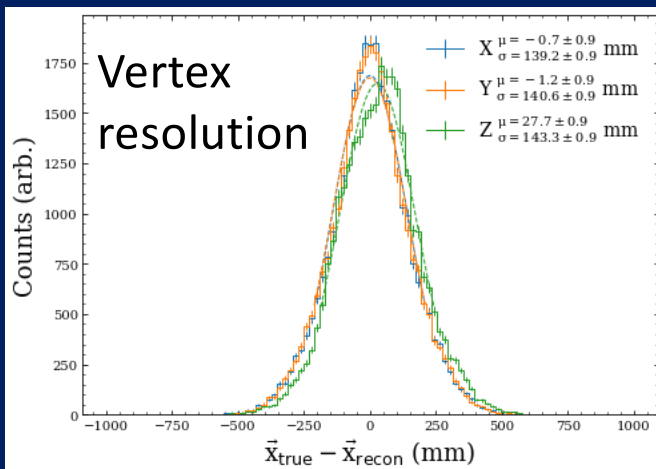
Large Detector LAB-PPO

Reconstruction at 5 MeV

Simple likelihood-based reconstruction so far



- 2D PDFs for both chertons and scintons will do better
- Energy should be included, too
- Bayesian approach may help with scintillation leakage
- Machine learning?

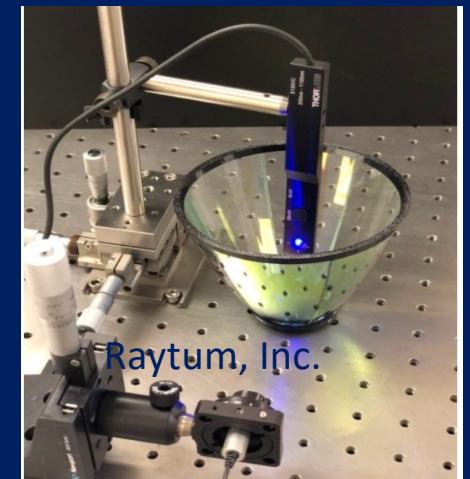
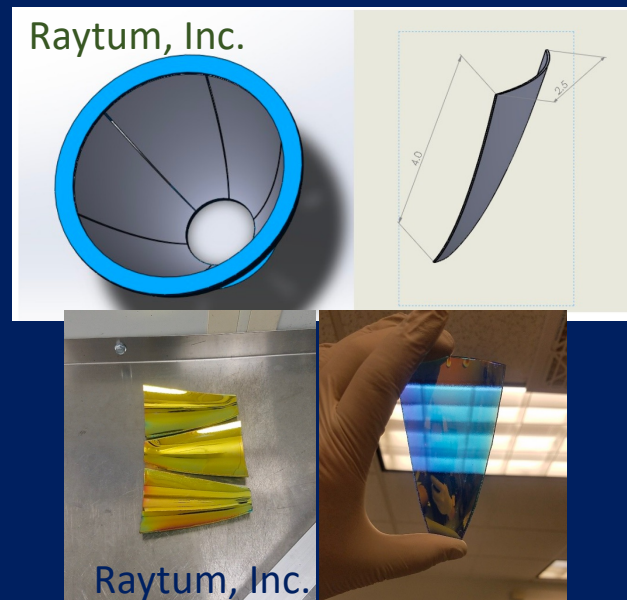
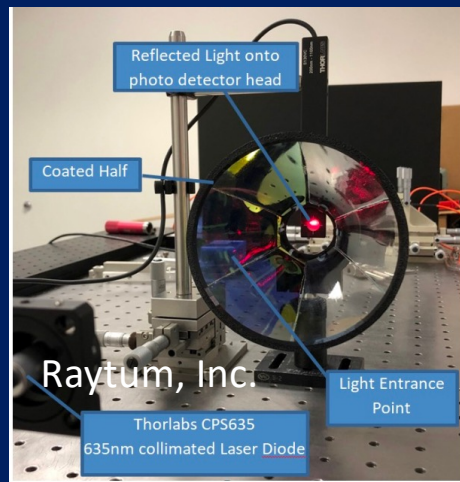


Only the surface has been scratched here---many other interesting problems

S. Young

Challenges

1. **Cost:** Filters are not cheap! (Full dichroicon for a 5" PMT is ~cost of PMT)
 - But costs vary by x10 between vendors
 - New approach by Raytum Inc+Brookhaven SBIR grant using atomic-layer deposition may lead to much cheaper and better filters
 - With dichroic layers on non-flat surfaces!

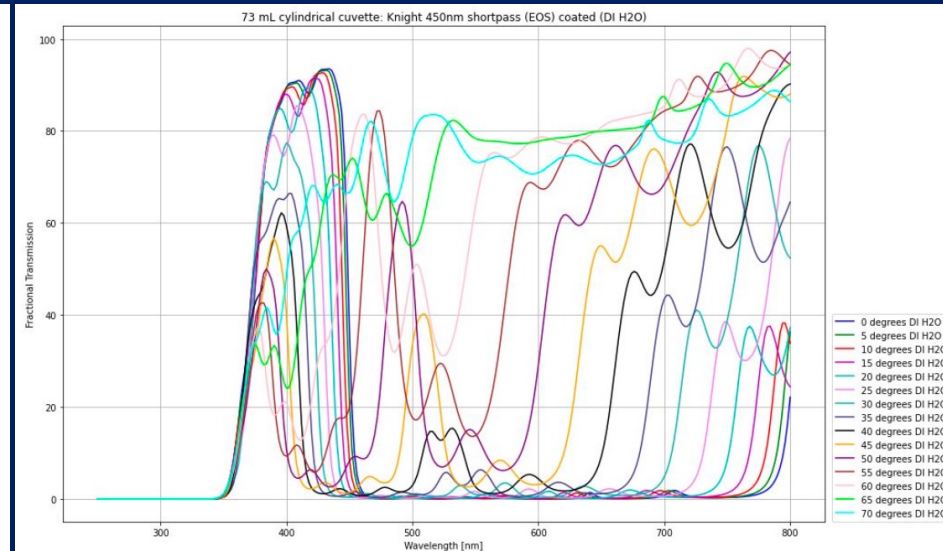
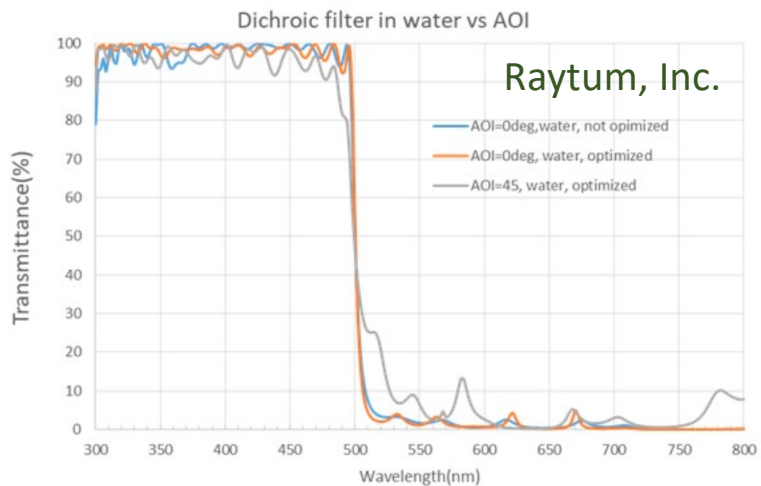


Challenges

2. Filter response (in media): Dichroicon has high-incidence illumination And cut-on wavelength shifts in media

- But can design (e.g. Raytum) better matched angular response
- And tune critical angle for better illumination

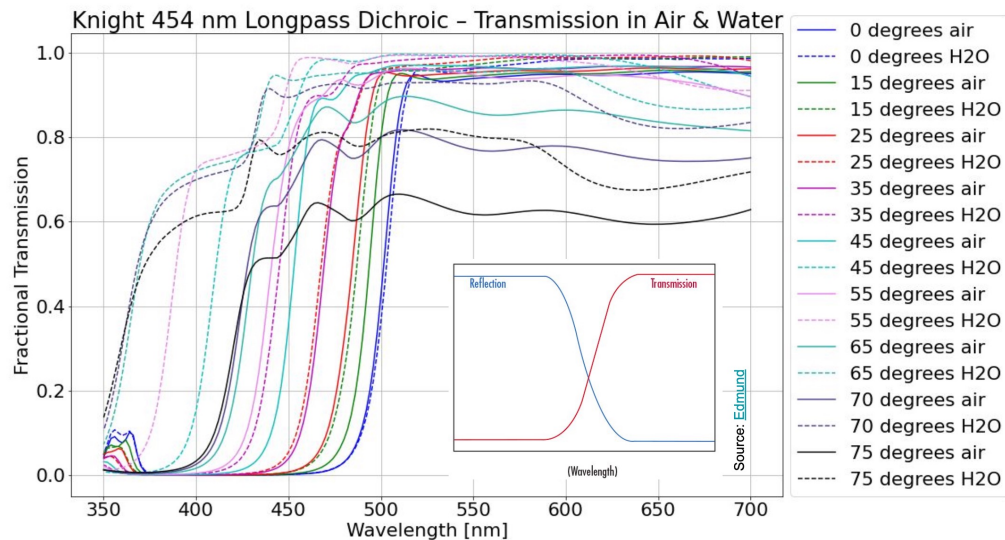
Dichroic filter optimized in water at AOI=0° and 45°



A. Bacon et al,
JINST 20
P09012 (2025)

Challenges

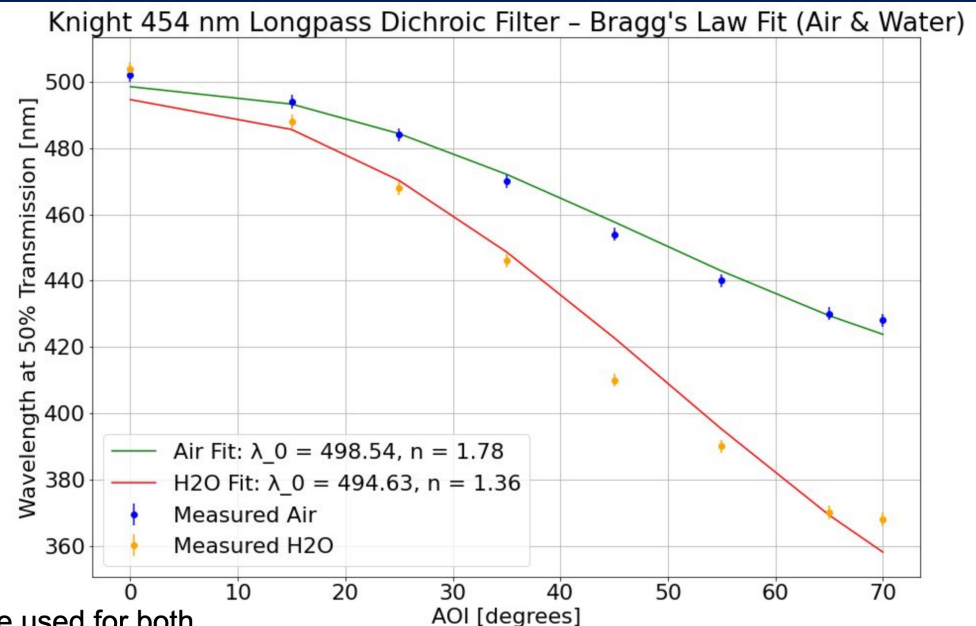
Filter response is complex:



Angle of incidence+different media
RAT-PAC2 model now includes full behavior

A. Bacon et al, JINST 20 P09012 (2025)

Bragg's Law does a good job for modeling different media

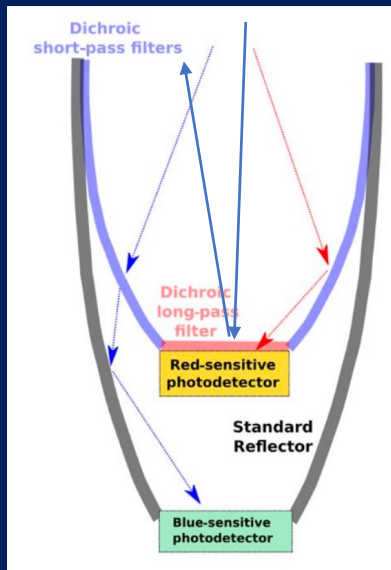


the used for both

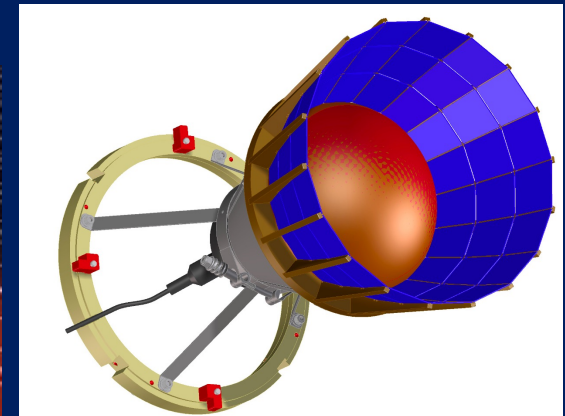
Challenges

Challenges

3. **Field-of-view:** Winston sees only part of the volume in a cylinder/shoebox
- “Truncated” Winston cone like SNO loses few% light but much better FOV
 - Insertion of PMT into cone doubles Cherenkov yield



But this makes short-wavelength bounce harder to implement--- need a curved filter

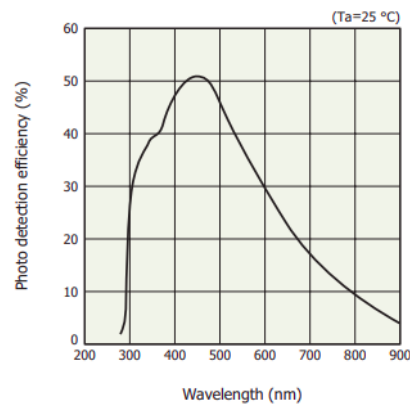


Challenges

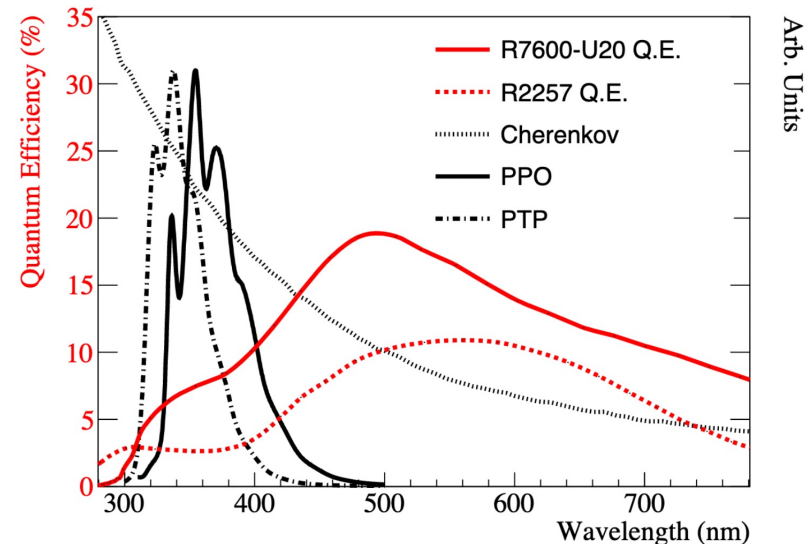
3. Long-wavelength sensors: Vendors do not make green or red PMTs in >5" sizes with good timing yet

- 8" SBA PMTs are already pretty good
- SiPMs have almost "ideal" response
- But they have high dark rates and are small

Photon detection efficiency vs. wavelength (typical example)

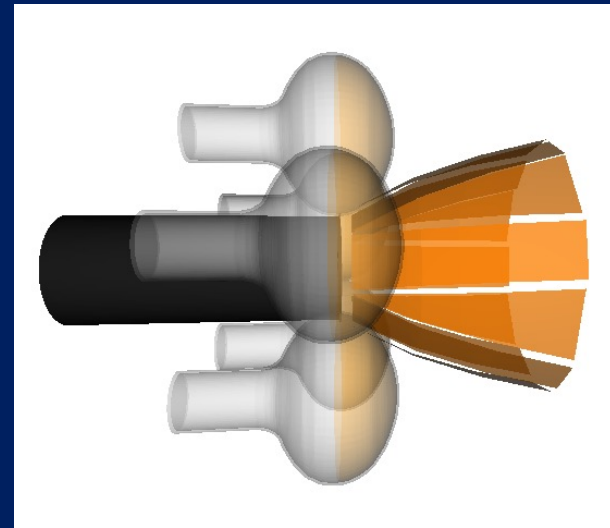
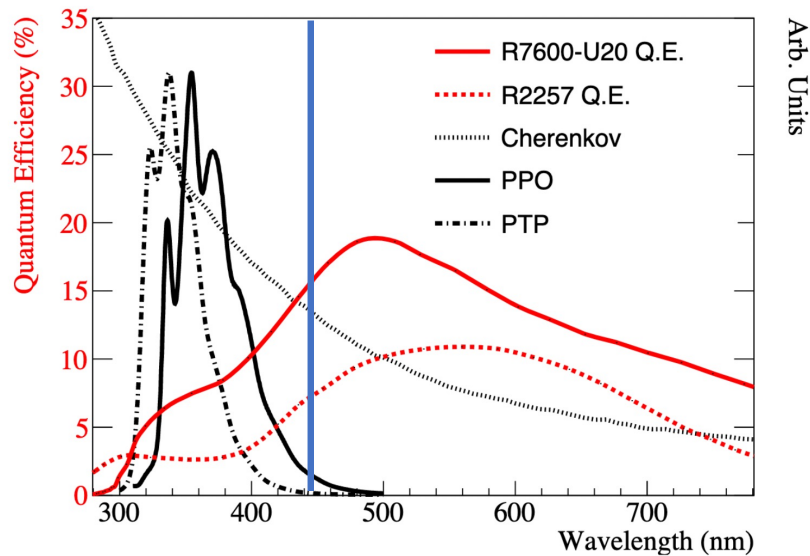


Photon detection efficiency does not include crosstalk and afterpulses.



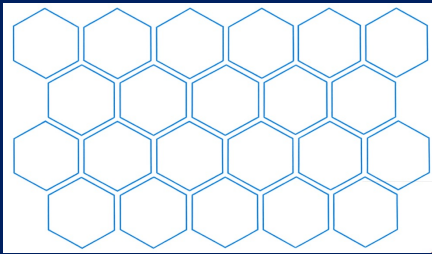
Challenges

5. Cherenkov yield: Cut-off wavelengths at 450 nm miss plenty of chertons
- Development of narrow-band fluor (perovskites? quantum dots?) would allow lower cut-offs, increasing chertons without leaking scintons
 - Shadowing may limit scintillation collection

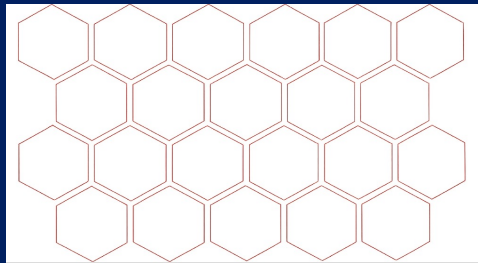


Hex-Dichroicons

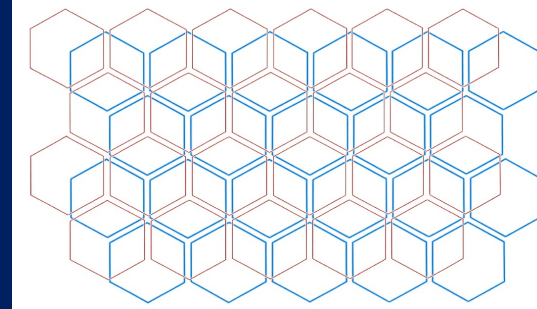
In principle, can get full sorting by intersecting hex pattern:



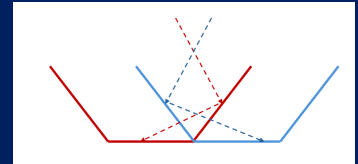
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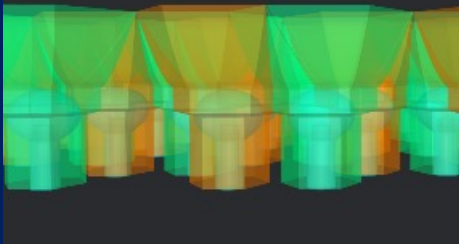
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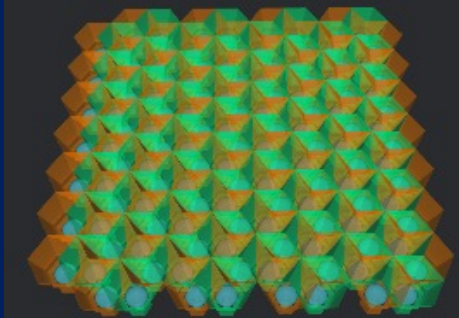
Side view



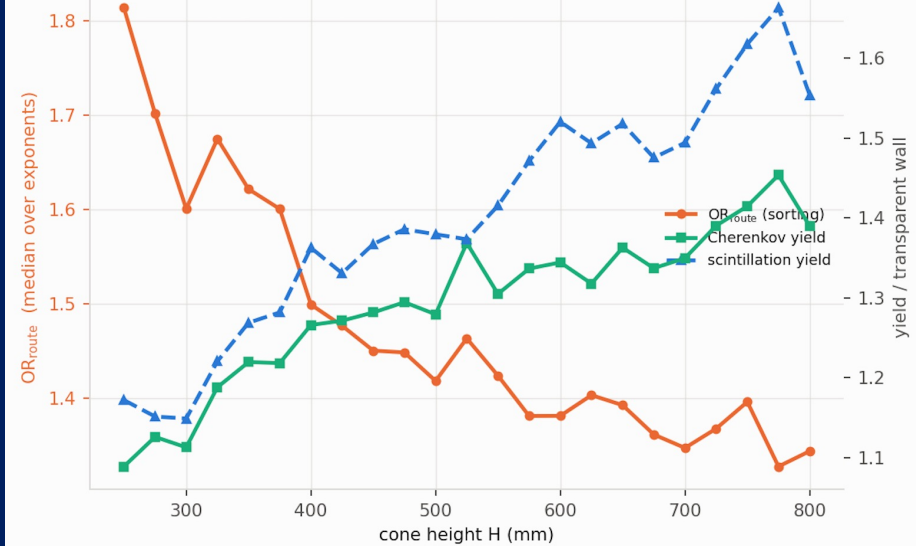
View from the side



View from above

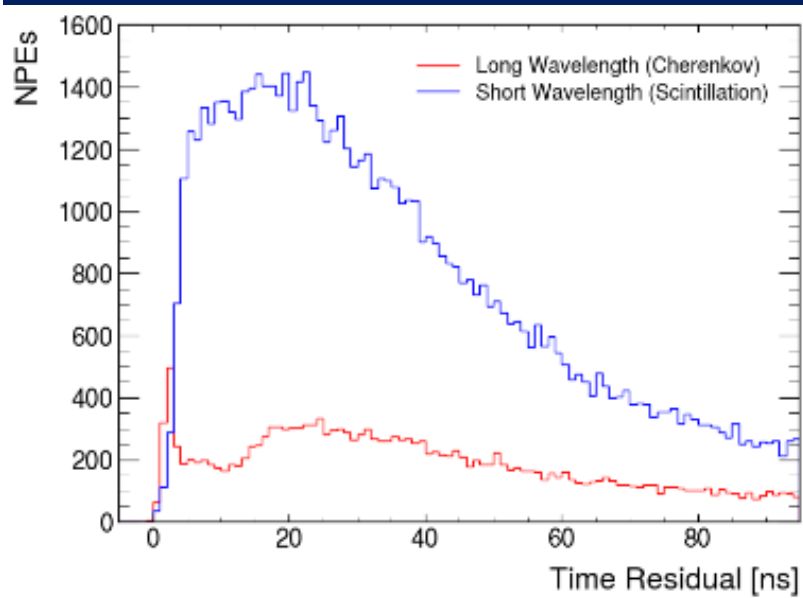
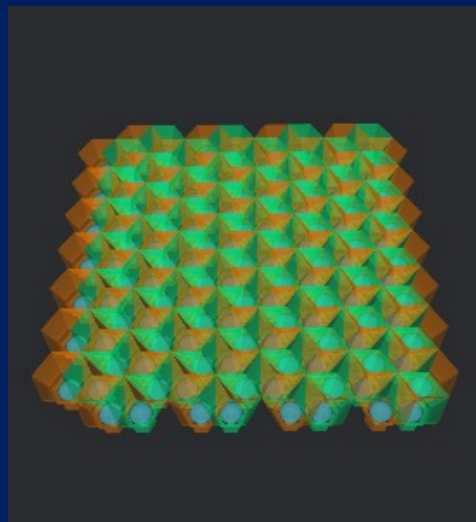
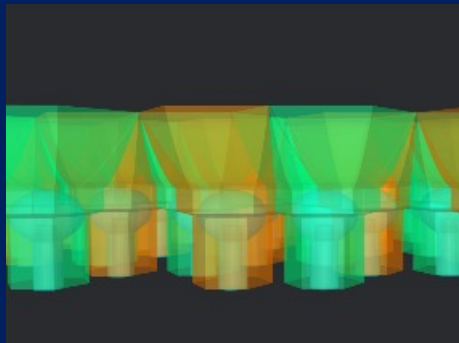


F. Sorting and both yields versus height



Hex-Dichroicons

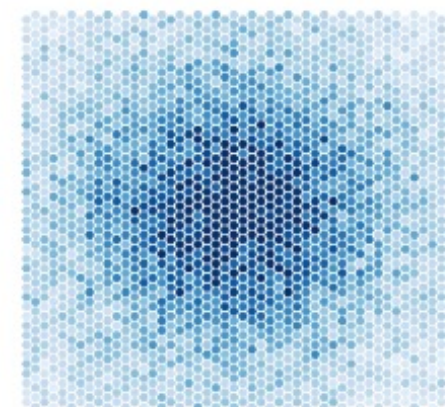
1 GeV Muon



Long Wavelength (Cherenkov)



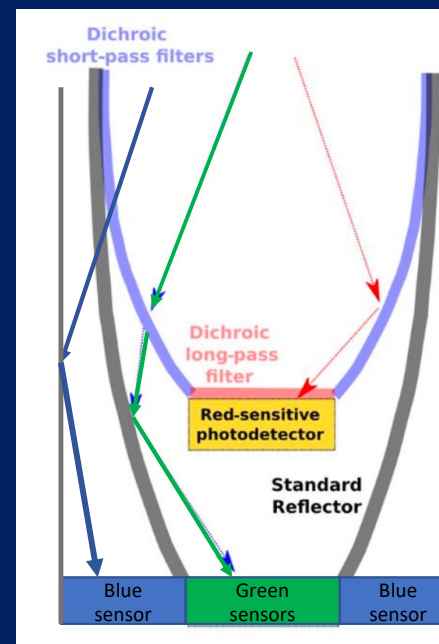
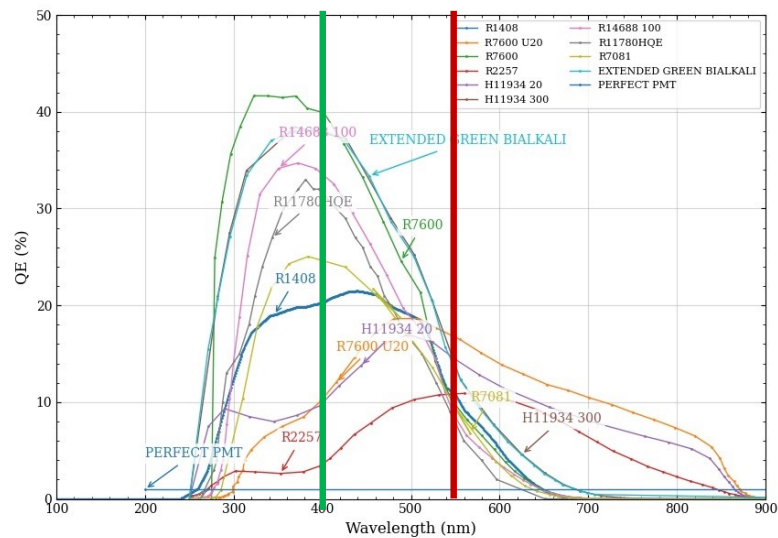
Short Wavelength (Scintillation)



Trichroicons...?

Three distinct QE regimes---blue, green, red

Can stack dichroicons to direct photons to best collector



Increases light yield in a broadband, very photon-starved detector
(e.g, low-energy Cherenkov)

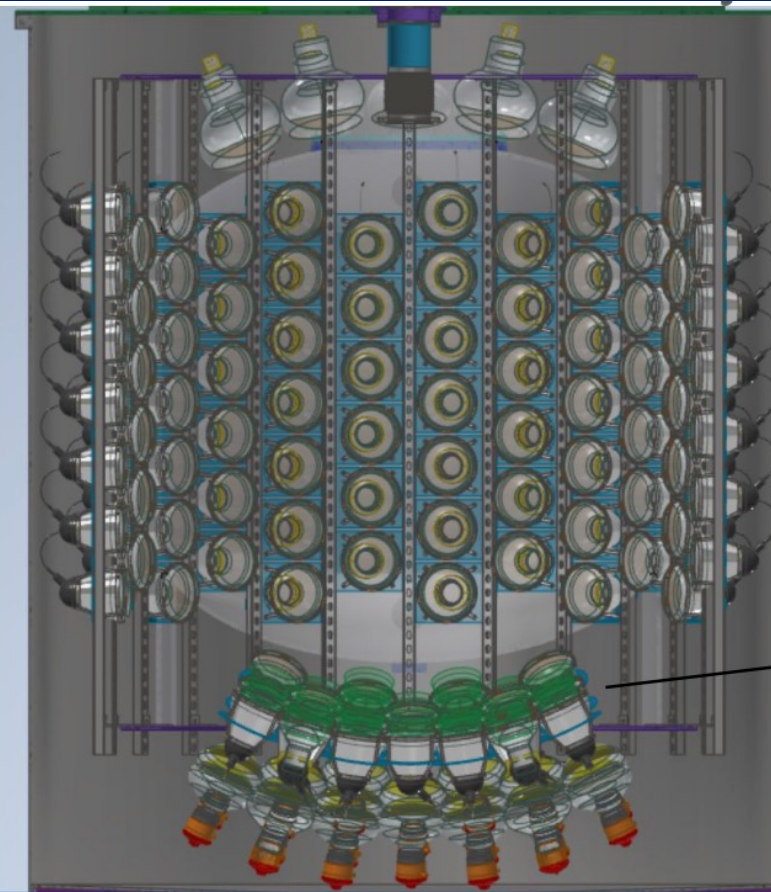
Summary

- Dichroicons provide excellent separation even for fast scintillator
- Cherenkov and scintillation yield is better than just filtered/"red" PMTs
- Combined with fast timing, cut-on wavelength can move shorter
- Would be better if paired with narrow-band (e.g., PTP) fluor
- Filters are not cheap right now---but seem to be dropping in price
- Filter response is very complex! Can dichroicon-specific designs be made?
- Field-of-view may be a challenge in any non-spherical geometry
- "Hex-dichroicons" in principle provide best coverage+best sorting

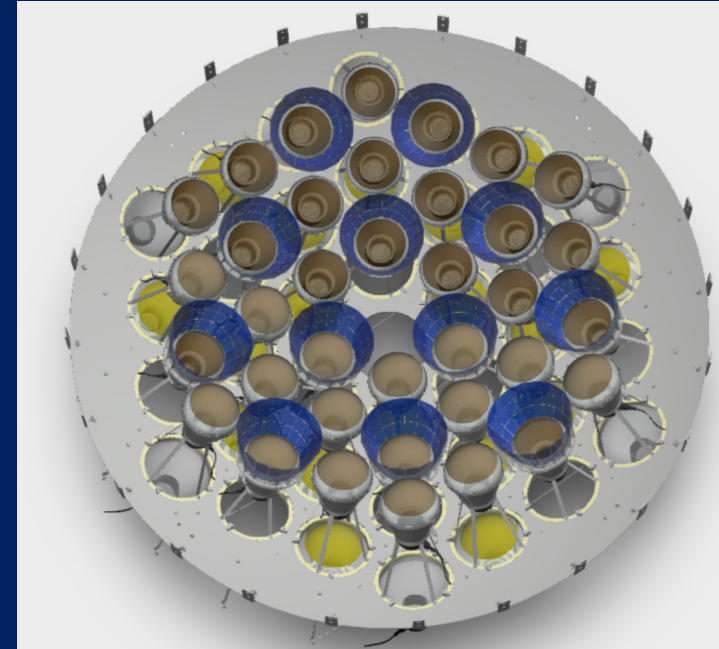
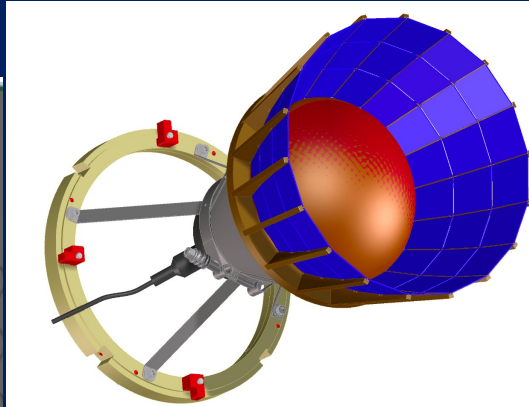


Eos at UCB/LBNL

12 dichroicons at bottom



Eos Deployment

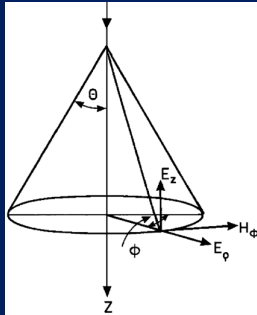


- Demonstrate Cherenkov/scintillation separation for variety of sources in ton-scale detector
- Develop reconstruction methods leveraging scintons+chertons
- Test model of response

Photon Information

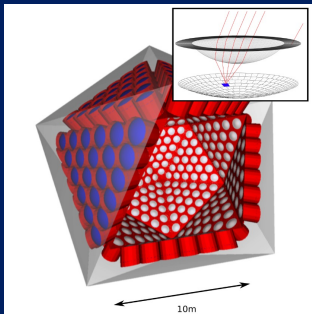
Photons also have:

- Polarization



These have never been exploited in a large-scale detector---

- Direction



Distributed Imaging for Liquid Scintillation Detectors

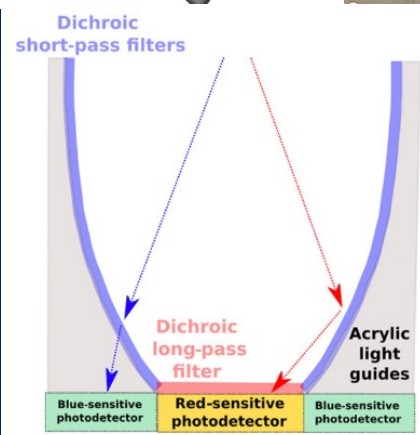
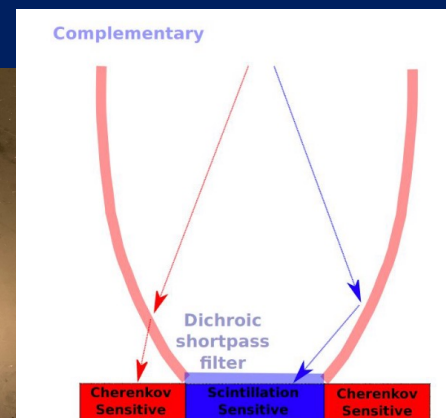
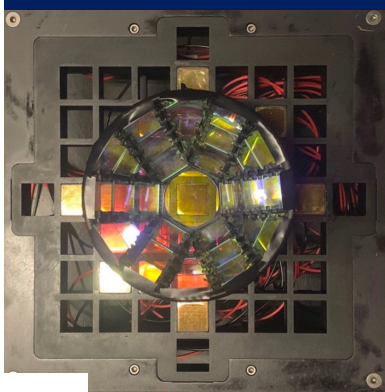
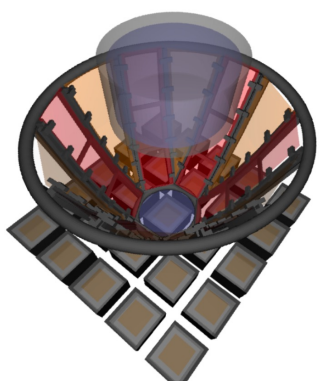
J. Dalmasson,¹ G. Gratta,¹ A. Jamil*,^{1,2} S. Kravitz^{†,1} M. Malek,¹ K. Wells,¹ J. Bentley,³ S. Steven,³ and J. Su⁴

- Wavelength

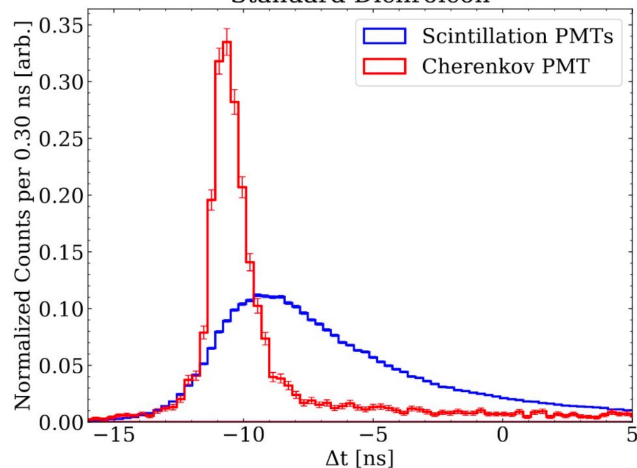
Dichroicons

Dichroicon at CHESS (LBNL)

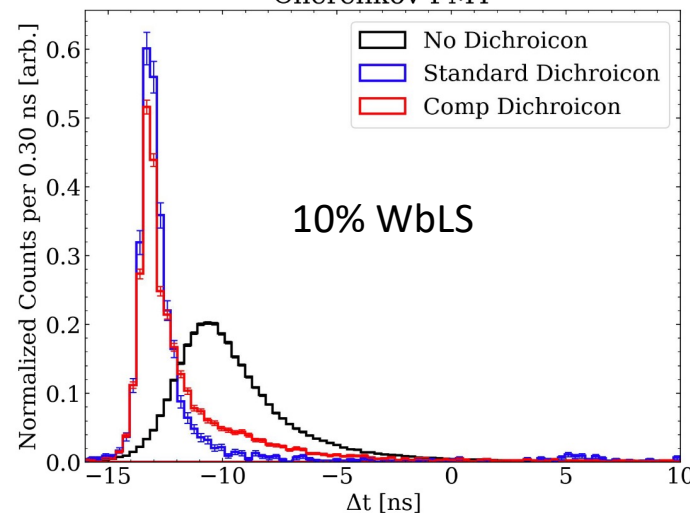
Pixellated sensors and high-energy source



Atmospheric Muons Incident on LABPPO Target
Standard Dichroicon



Atmospheric Muons Incident on WbLS Target
Cherenkov PMT



S. Naugle

Photon Information

To date nearly all these detectors use only

- Photon time-of-arrival
- Photon sensor position
- Total photon count

These allow reconstruction of

- (x,y,z,t) for vertex
- (u,v,w) usually for Cherenkov detectors
- Energy from calorimetry and/or Cherenkov angle
- Particle ID at high energy (ring imaging)
- Particle ID at low energy (scintillation time profile)

But photons carry a lot more information...

Physics Cases

- **Photon Dispersion**

- Time-of-flight difference between 400 nm and 600 nm over 60 m is
 - 0.5 ns for LAr
 - 1.5 ns for H₂O
 - 5 ns for LAB-PPO
- Measuring difference allows new handle on position reconstruction
- And more precise timing

- **Photon Collection**

- Trapping (e.g. ARAPUCAs)
- Detecting broader spectrum than single device can see

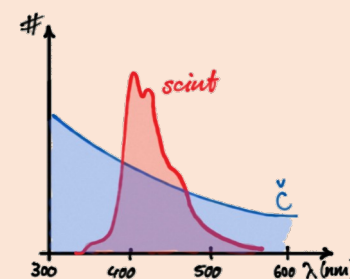
- **Particle ID**

- LAr triplet state re-emitted by Xe
- Wavelength dependence of LS tail...?

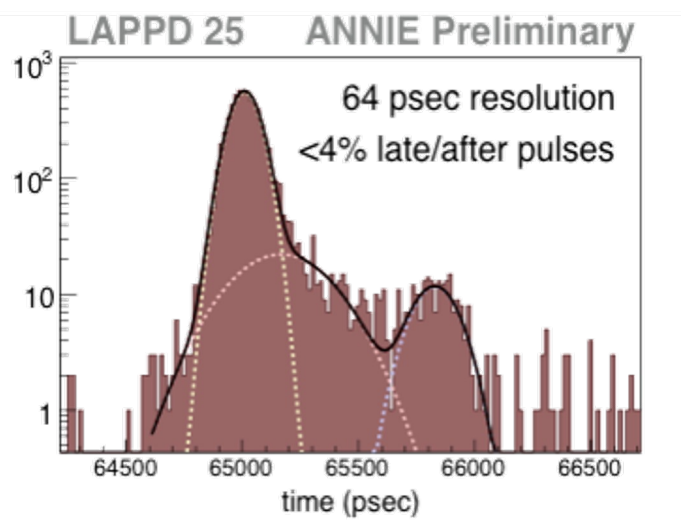
- **Cherenkov/scintillation separation (e.g., Theia)**

Spectrum

UV/blue scintillation vs.
blue/green Cherenkov
→ wavelength-sensitivity

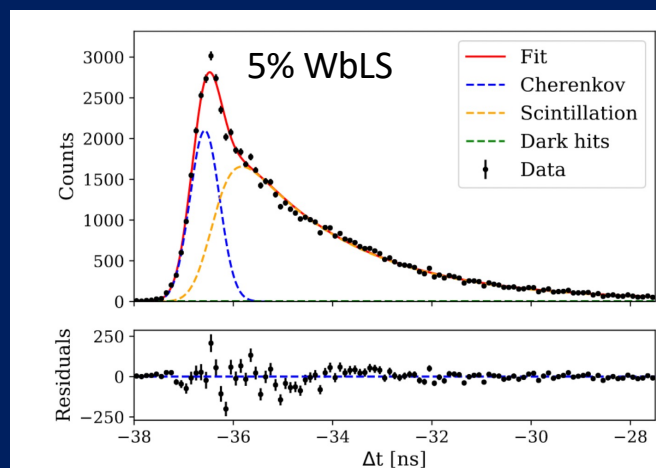
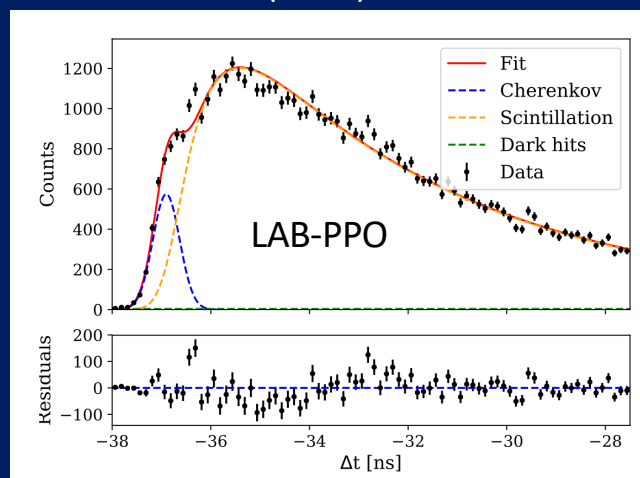


Fast(er) Sensors



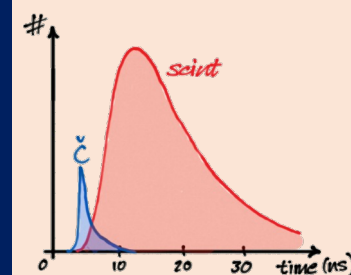
Timing

CHESS (LBNL)

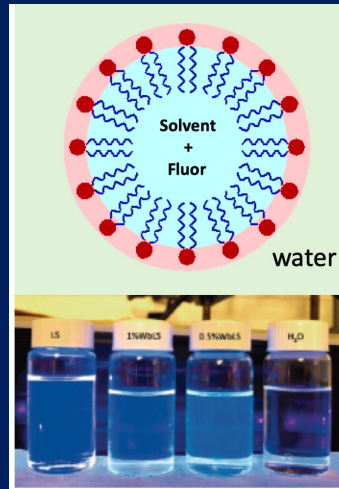
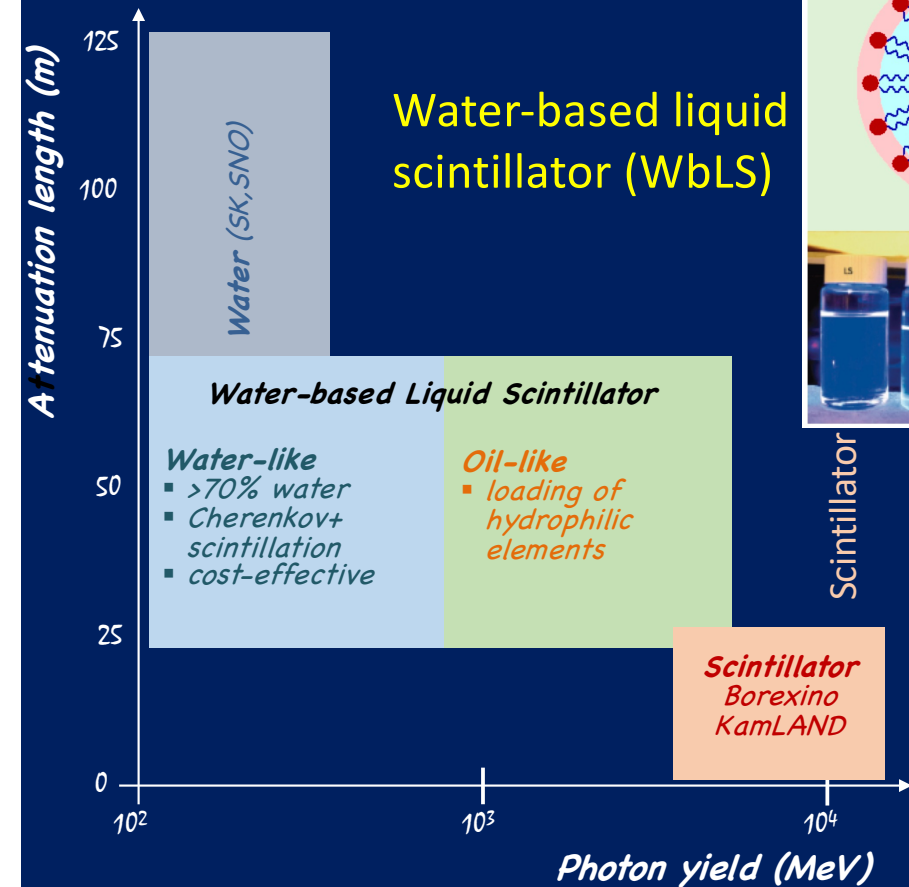


Timing

“instantaneous chertons”
vs. delayed “scintons”
→ ns resolution or better



Adjust Cher/Scint Ratio

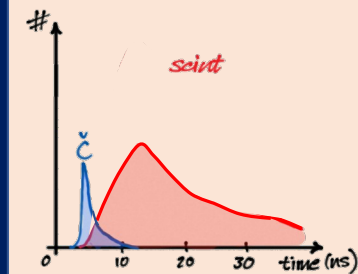


Scintillator
1% WbLS
0.5% WbLS
H₂O

Ratio

Reduce number of scintons

→ new materials/fluors



Other possibilities:

- LAB with “thin” PPO (Jinping)
- Vanilla mineral oil (MiniBooNE)
- Oil+a little scintillator
- Water+WLS?

Target can be adjusted for different physics goals

Spectral Sorting in LAr?

Probably not necessary...

Scintillation light in LAr is such a different band, Cherenkov/scintillation separation comes for "free"

ArCherS=Argon Cherenkov and Scintillation

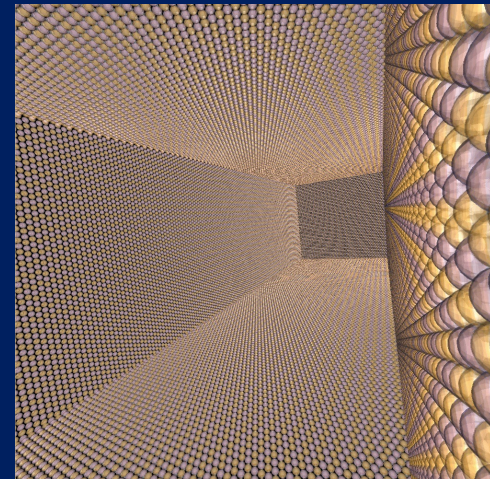


- LAr all-photon detector (DEAP, MiniCLEAN, CCM)
- Chertons detected by "bare" PMTs (e.g., SBND)
- UV scintillation via ARAPUCAs or TPB-covered PMTs
- Scinton yield with no E-field is 40,000 photons/MeV (produced)
- With $\frac{1}{4}$ of scinton sensors still competitive with LS detectors
- Remaining "60%" of space can be used for Cherenkov detection
- Only need spectral sorting if WLS is dissolved in LAr (Xe?)
- Cherenkov light gives excellent timing

But:

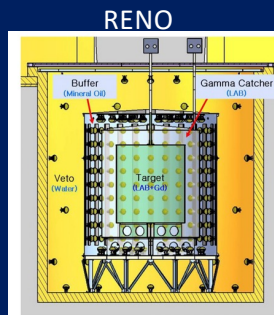
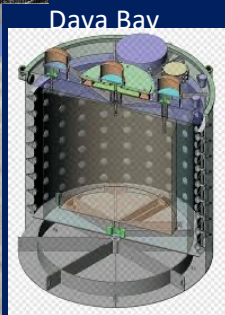
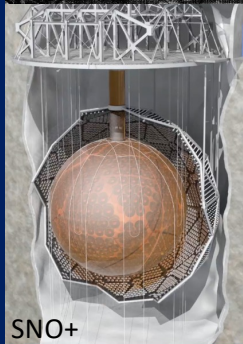
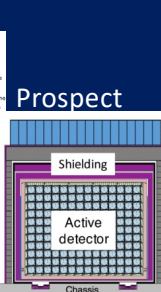
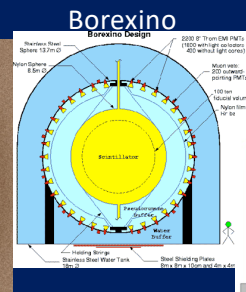
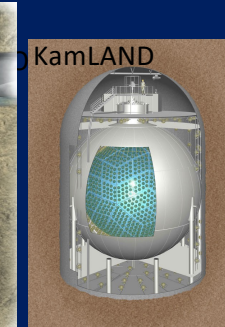
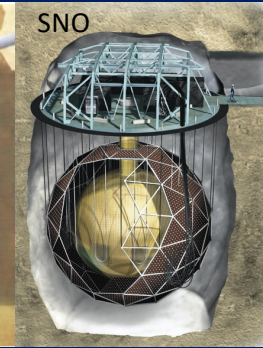
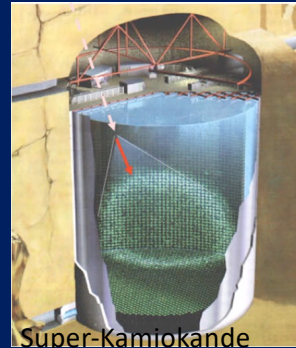
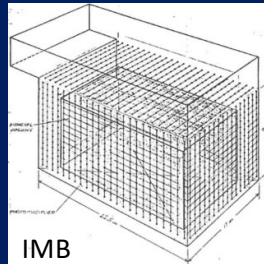
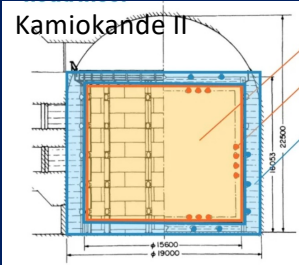
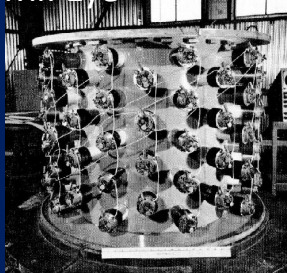
- For low-energy physics, still need to shield neutrons and use u/g argon
- "High"-Z nucleus increases multiple scattering, affecting direction resolution
- "High"-Z nucleus lowers crit. energy, affecting energy resolution (see Michel paper)
- "High"-Z nucleus has complex neutrino interactions (e.g., neutrons)
- High-ish density shortens tracks at low-energies

Logan Lebanowski, LBNL

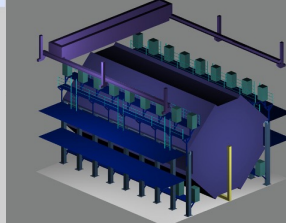


“Photon-Based” “Photon-based Neutrino Detector” is almost redundant

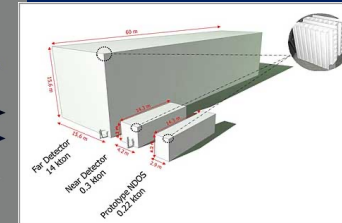
Mr. Eye



MINOS



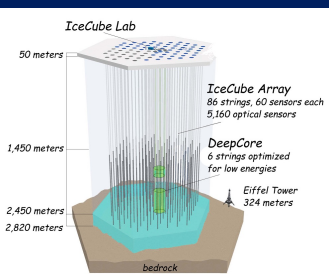
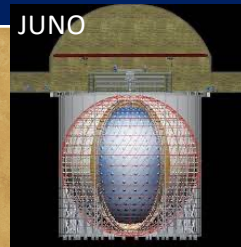
NOvA



Discoveries/Measurements:

- The neutrino
- Neutrino oscillations
- Resolution of Solar Neutrino Problem
- LMA mixing
- θ_{12} , Δm^2_{12} , δm^2_{23} , θ_{23} , θ_{13}
- Supernova neutrinos
- (Exclusive) ^8B , pep , ^7Be , pp solar
- Extragalactic vs

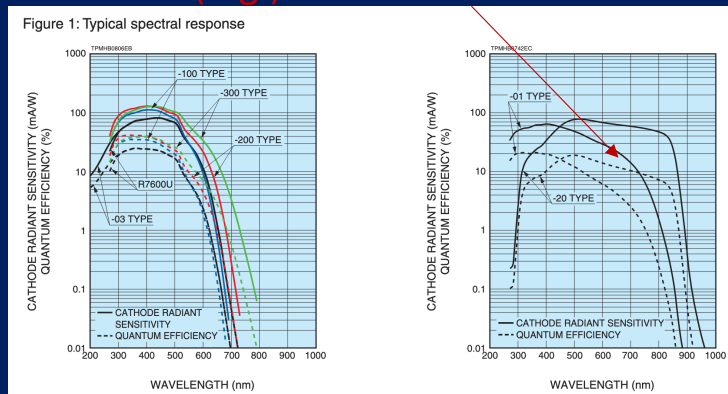
Coming soon:



Cherenkov/Scintillation Separation with Wavelength

- “Obvious” solution would just filter x% of photon sensors

And use (e.g.) red sensitive devices



- But low-energy physics is photon-starved! Don't want to lose x% of light
- And what if sensor coverage is already very high?
- Or what if detection area is already constrained (e.g., segmented like PROSPECT)

Spectrum

UV/blue scintillation vs.
blue/green Cherenkov
→ wavelength-sensitivity

