Spectral Photon Sorting for Neutrino Detectors

- Hybrid Cherenkov/Scintillation Neutrino Detection
- Spectral sorting with dichroicons
- Benchtop performance
- Deployment in Eos Demonstrator

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Breadth and Detectors

100 keV--10 Gev

Typically scintillator | Typically Cherenkov

keV — MeV — GeV

Solar νs

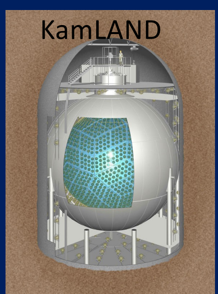
Reactor $\bar{\nu}$

SN burst νs

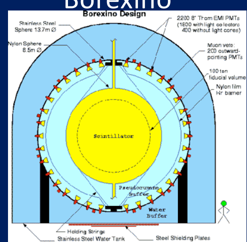
$0\nu\beta\beta$

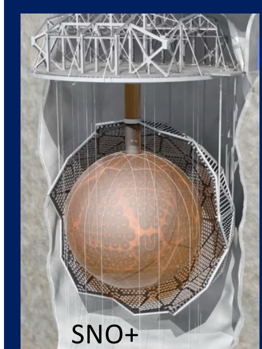
CP Violation

Atmospheric ν oscillations



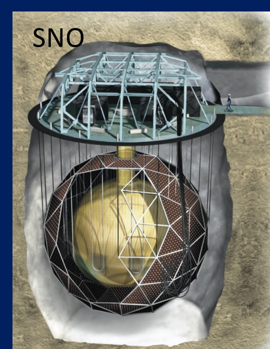
Borexino





Requirements:

- Low radio backgrounds
- Excellent energy resolution
- Directional information



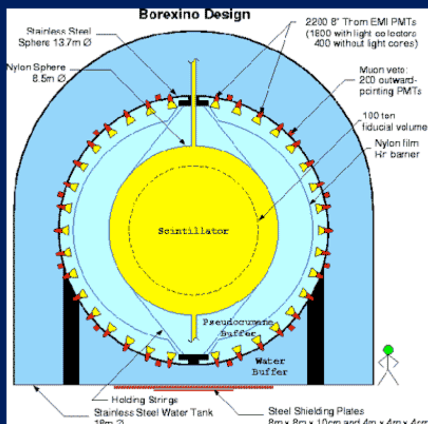
Requirements:

- Excellent particle ID
- Directional information
- Very big detector

Super-Kamiokande

Hybrid Detection

Why Not do Both?



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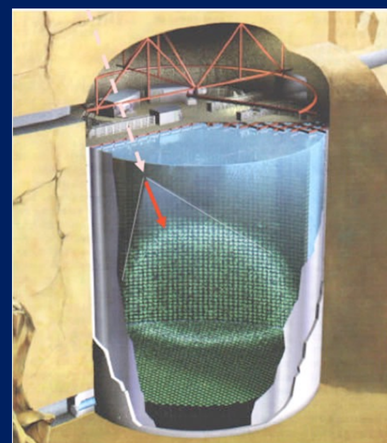

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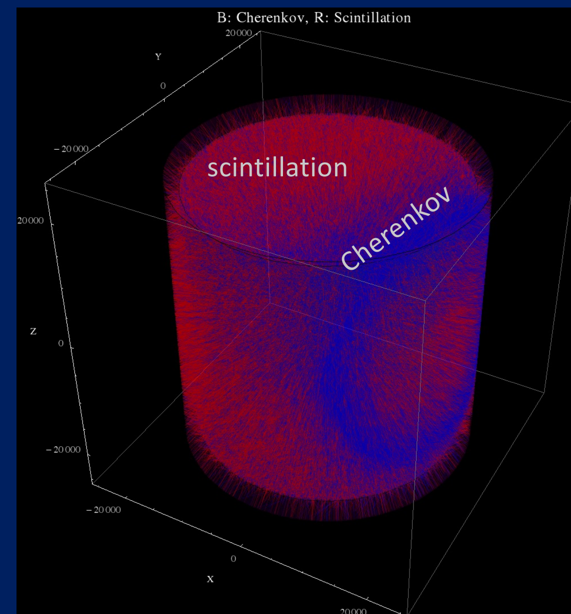
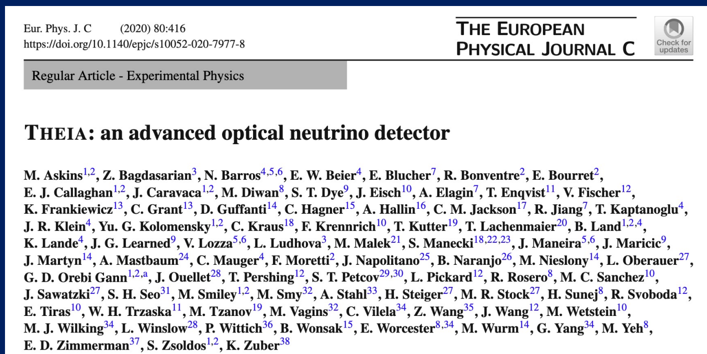


But:

- 100x more scintillation light in scintillator than Cherenkov light
- \`Chertons’ are buried by \`scintons’
- And need detector to be very big…

THEIA

- Low-energy physics using scintons
- High-energy with chertons
- Exploit *both* to do otherwise very difficult physics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THE EUROPEAN PHYSICAL JOURNAL C

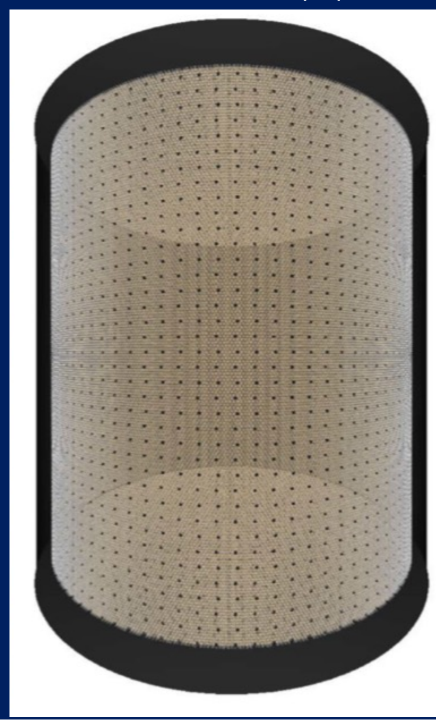
Regular Article - Experimental Physics

THEIA: an advanced optical neutrino detector

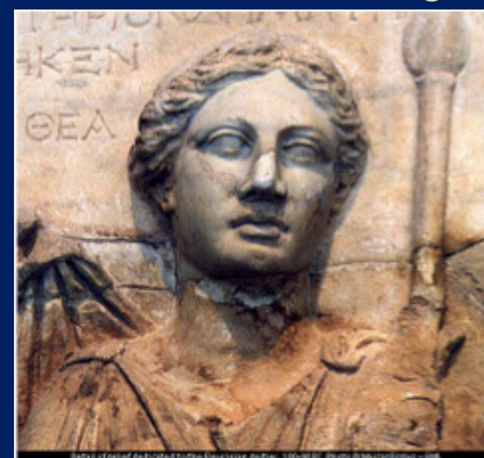
M. Askins[1,2], Z. Bagdasarian[3], N. Barros[4,5,6], E. W. Beier[4], E. Blucher[7], R. Bonventre[2], E. Bourret[2], E. J. Callaghan[1,2], J. Caravaca[1,2], M. Diwan[8], S. T. Dye[9], J. Eisch[10], A. Elagin[7], T. Enqvist[11], V. Fischer[12], K. Frankiewicz[13], C. Grant[13], D. Guffanti[14], C. Hagner[15], A. Hallin[16], C. M. Jackson[17], R. Jiang[7], T. Kaptanoglu[4], J. R. Klein[4], Yu. G. Kolomensky[1,2], C. Kraus[18], F. Krennrich[10], T. Kutter[19], T. Lachenmaier[20], B. Land[1,2,4], K. Lande[4], J. G. Learned[9], V. Lozza[5,6], L. Ludhova[3], M. Malek[21], S. Manecki[18,22,23], J. Maneira[5,6], J. Maricic[9], J. Martyn[14], A. Mastbaum[24], C. Mauger[4], F. Moretti[2], J. Napolitano[25], B. Naranjo[26], M. Nieslony[14], L. Oberauer[27], G. D. Orebi Gann[1,2,a], J. Ouellet[28], T. Pershing[12], S. T. Petcov[29,30], L. Pickard[12], R. Rosero[8], M. C. Sanchez[10], J. Sawatzki[27], S. H. Seo[31], M. Smiley[1,2], M. Smy[32], A. Stahl[33], H. Steiger[27], M. R. Stock[27], H. Sunej[8], R. Svoboda[12], E. Tiras[10], W. H. Trzaska[11], M. Tzanov[19], M. Vagins[32], C. Vilela[34], Z. Wang[35], J. Wang[12], M. Wetstein[10], M. J. Wilking[34], L. Winslow[28], P. Wittich[36], B. Wonsak[15], E. Worcester[8,34], M. Wurm[14], G. Yang[34], M. Yeh[8], E. D. Zimmerman[37], S. Zsoldos[1,2], K. Zuber[38]

See also:
"Advanced Scintillator Detector Concept," arXiv 1409.5864

THEIA-100 (kt)



Named for Titaness of Light



Mother of Eos (Dawn), Helios (Sun), and Selene (Moon)

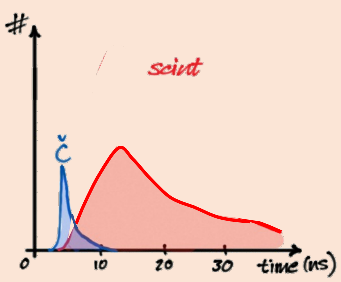
Hybrid Cherenkov/Scintillation Detectors

Many Ways of Doing This

Ratio

Add just a little scintillation

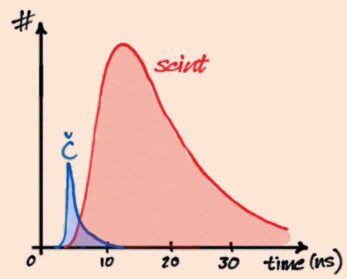
→ new materials/fluors



Timing

“instantaneous chertons” vs. delayed “scintons”

→ ns resolution or better

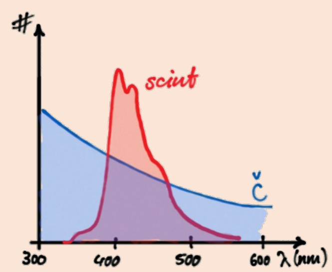


M. Wurm

Spectrum

UV/blue scintillation vs. blue/green Cherenkov

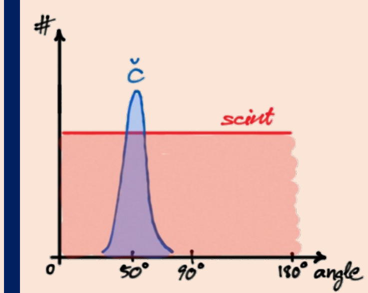
→ wavelength-sensitivity



Angular distribution

increased PMT hit density under Cherenkov angle

→ sufficient granularity

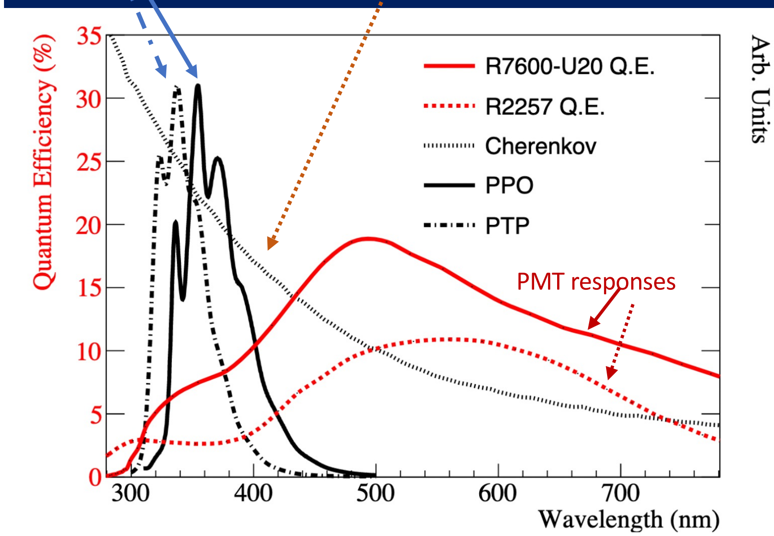


Past 5-10 years has seen rapid growth in exploring these approaches.

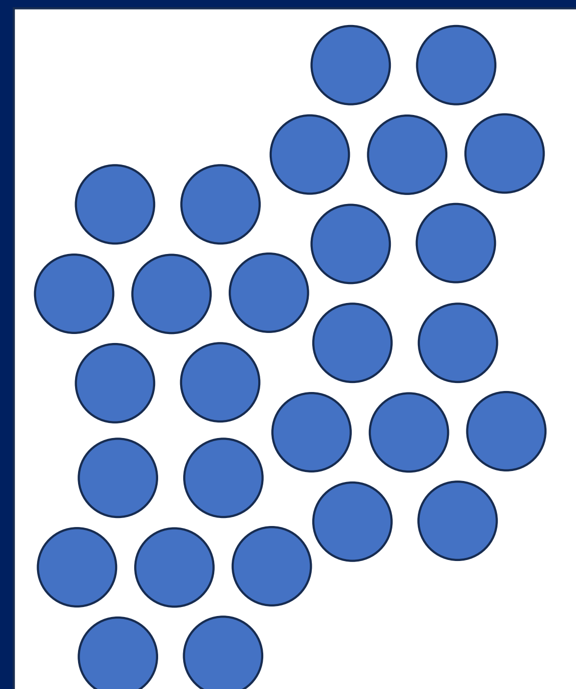
Spectral Sorting for Cher/Scint

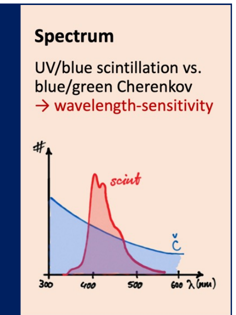
Scintillation emission

$N^{\gamma}_{cer} \sim 1/\lambda^2$

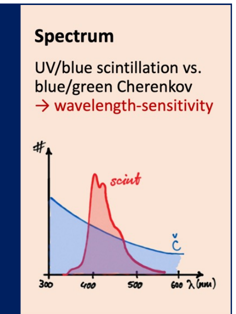


Spectral differences allow separation---
could use filters or red-sensitive PMTs:





Spectral Sorting for Cher/Scint



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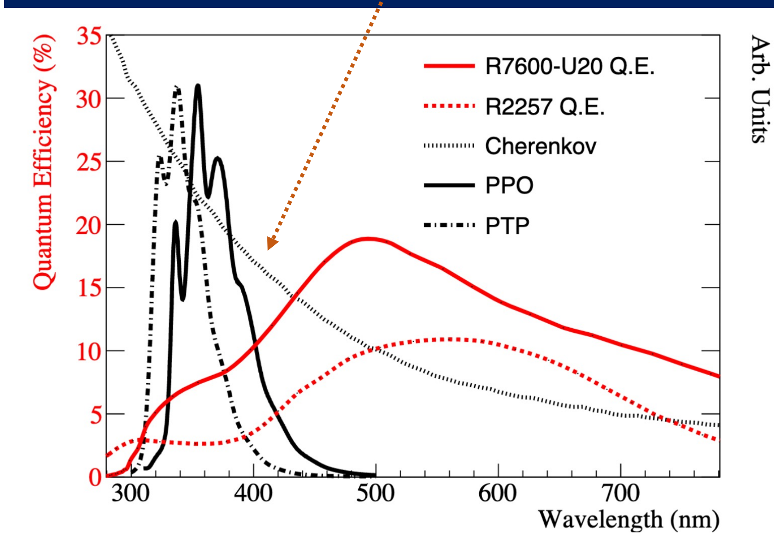
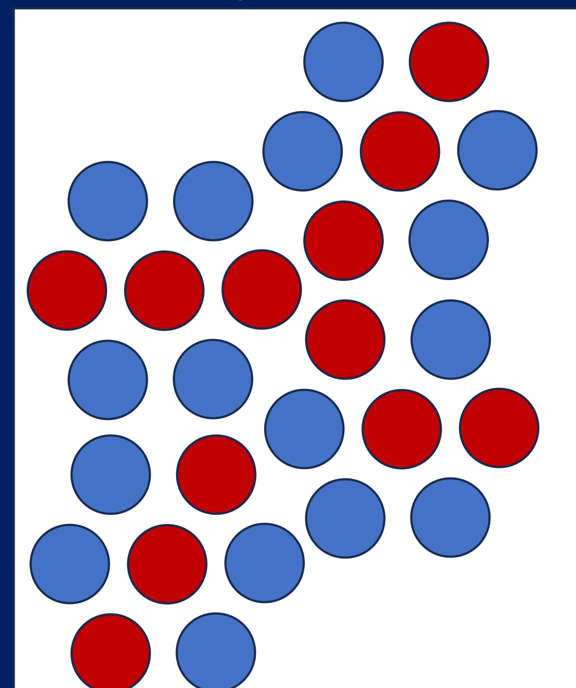


Spectral differences allow separation---could use filters and/or red-sensitive PMTs:



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

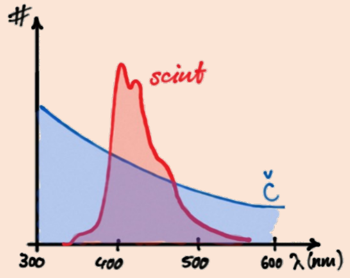
Spectral Photon Sorting

If we *sort* photons efficiently:

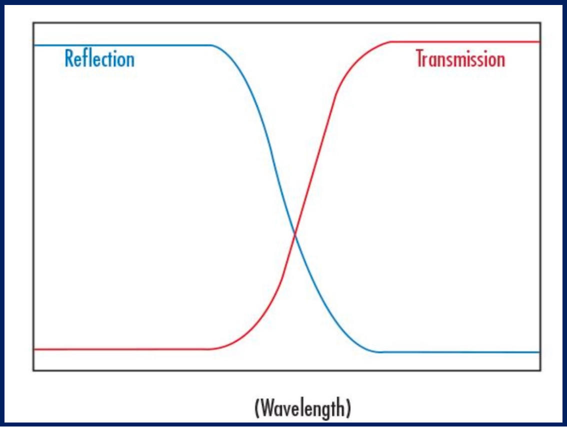
- Can preserve most of the different signals
- Possibly increase overall light yield by viewing a broad-band spectrum by relevant sensor

Spectrum

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

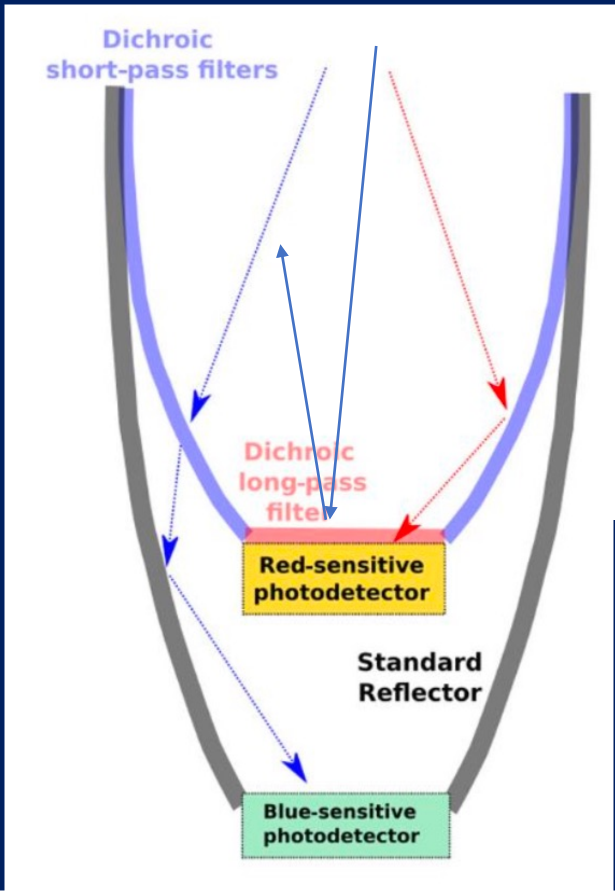


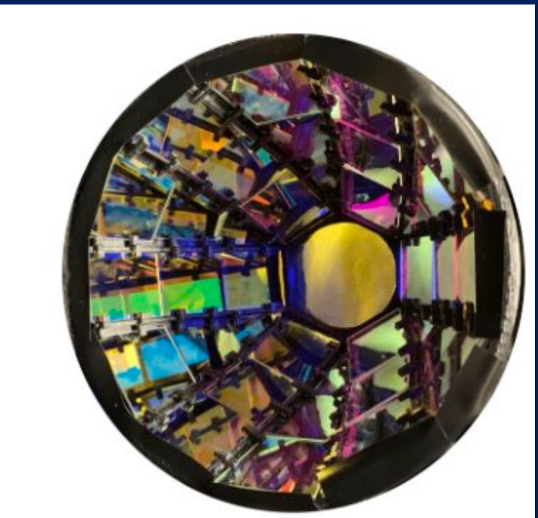
Dichroic filters provide a sorting mechanism---how do we use this in a large detector?



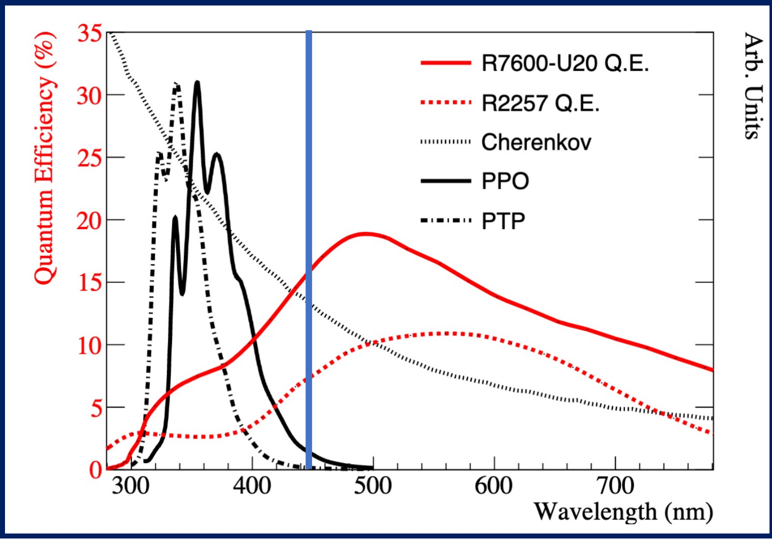
Dichroicons

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



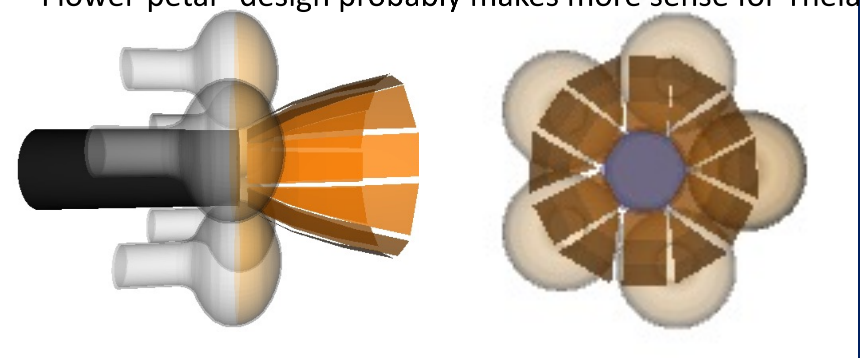


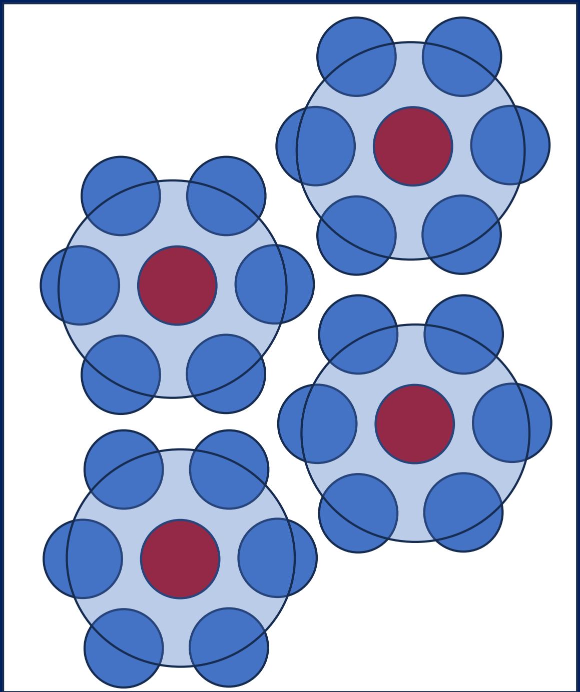
Cut-on wavelength depends on QE curve of sensors and emission of scintillation light and physics

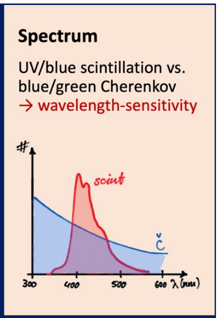


Spectrum

“Flower-petal” design probably makes more sense for Theia



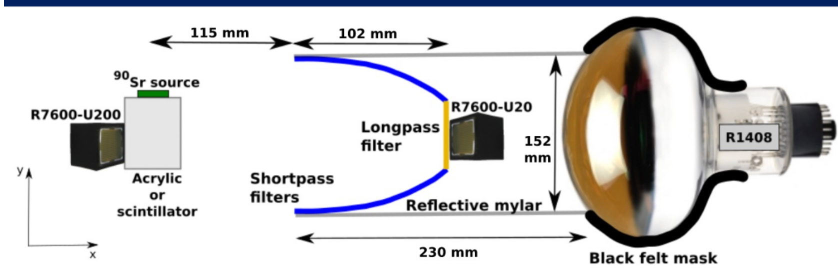


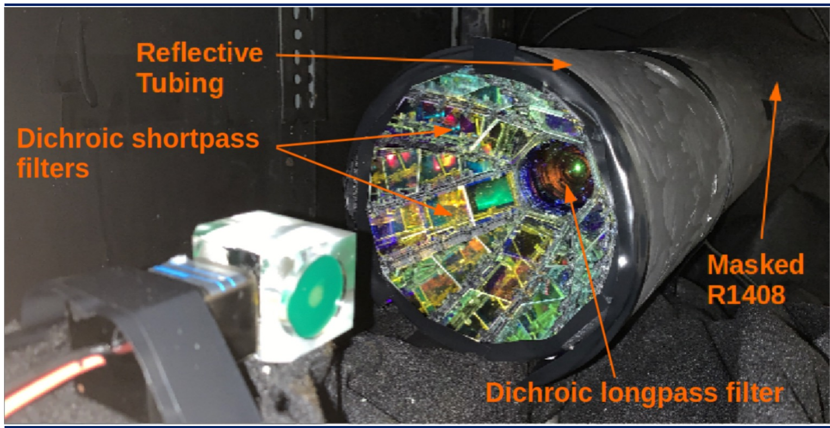


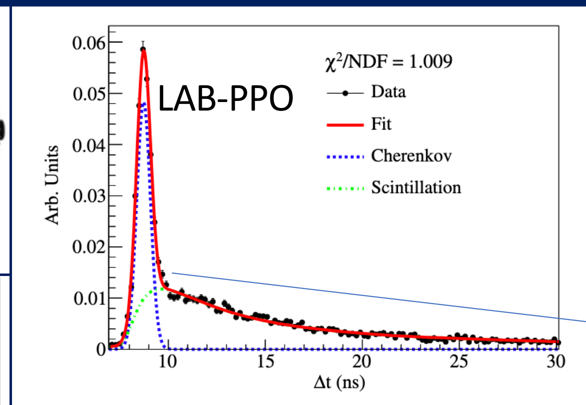
Dichroic filters at aperture also allow scintillation light to be reflected back into detector for improved calorimetry

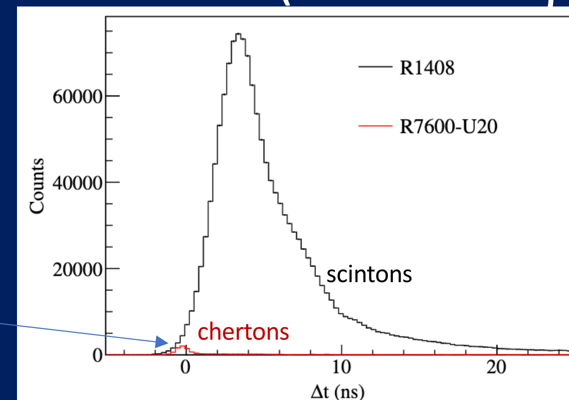
Dichroicons

$^{90}Sr/^{90}Y$ source (~2.3 MeV β)

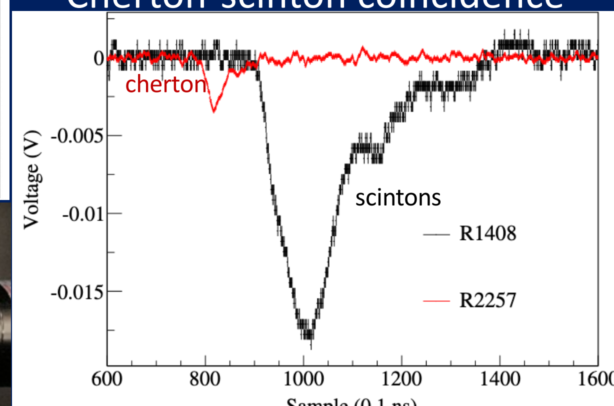




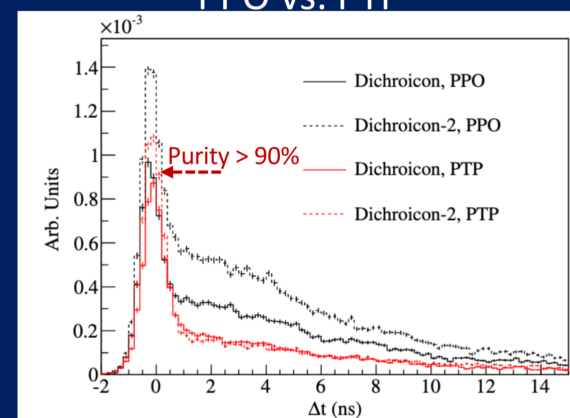




Cherton-scinton coincidence



PPO vs. PTP



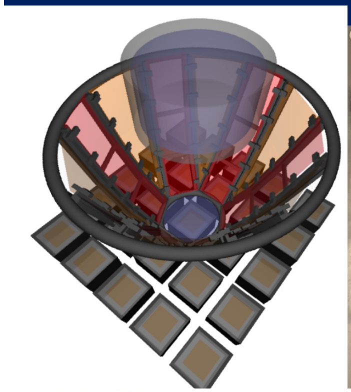
Phys. Rev. D 101, 072002

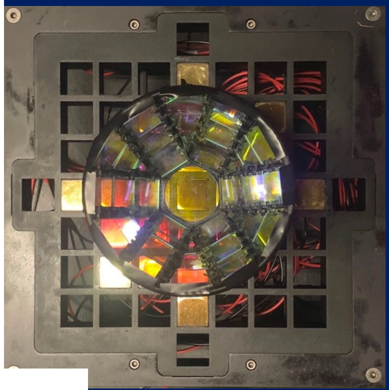
T. Kaptanoglu

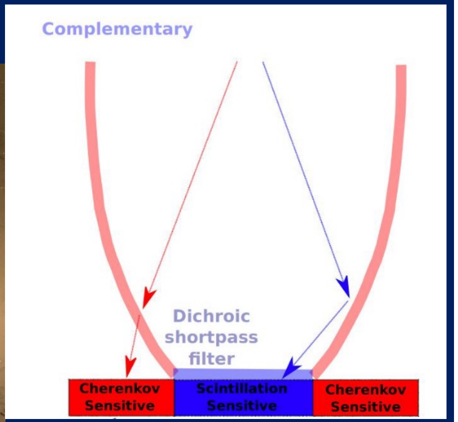
Dichroicons

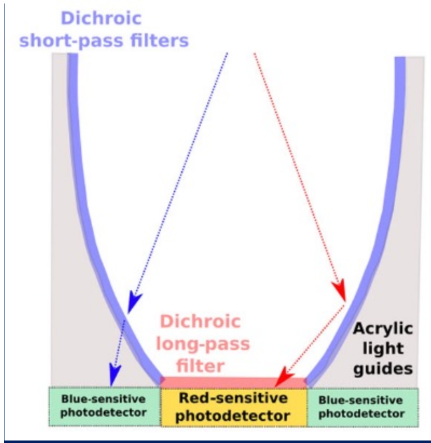
Pixellated sensors and high-energy source

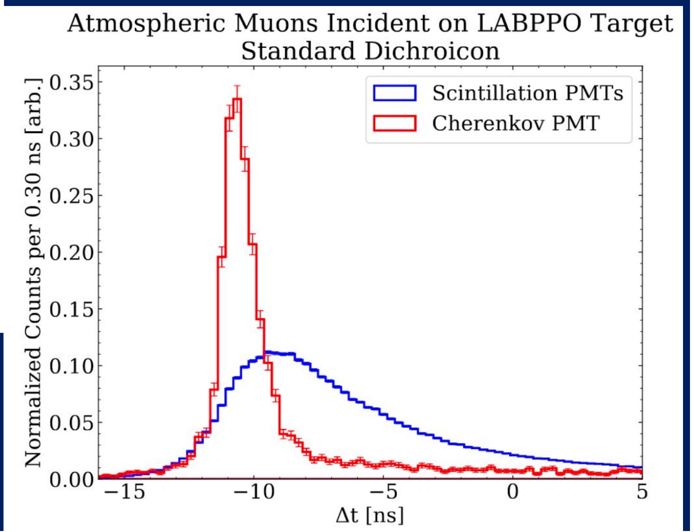
Dichroicon at CHESS (LBNL)

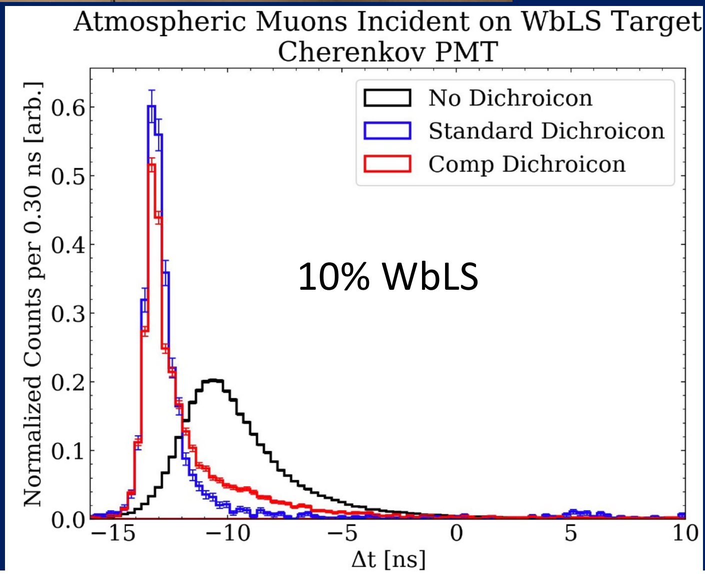










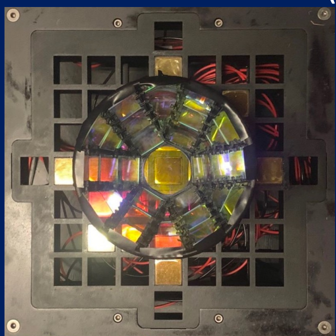


S. Naugle

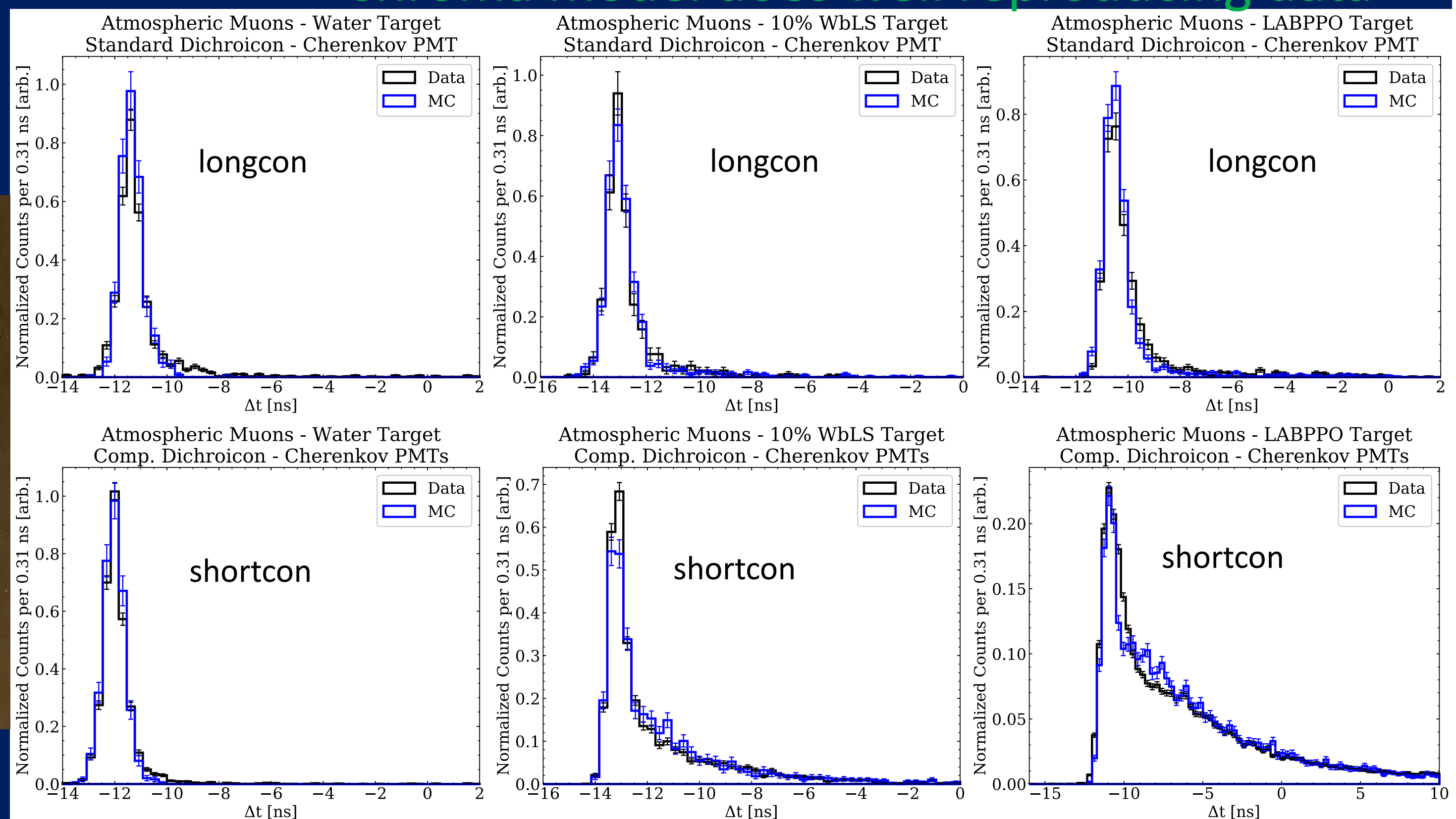
Dichroicons

Pixellated sensors and high-energy source

Dichroicon at CHESS (LBNL)



Chroma model does well reproducing data



S. Naugle

Dichroicons

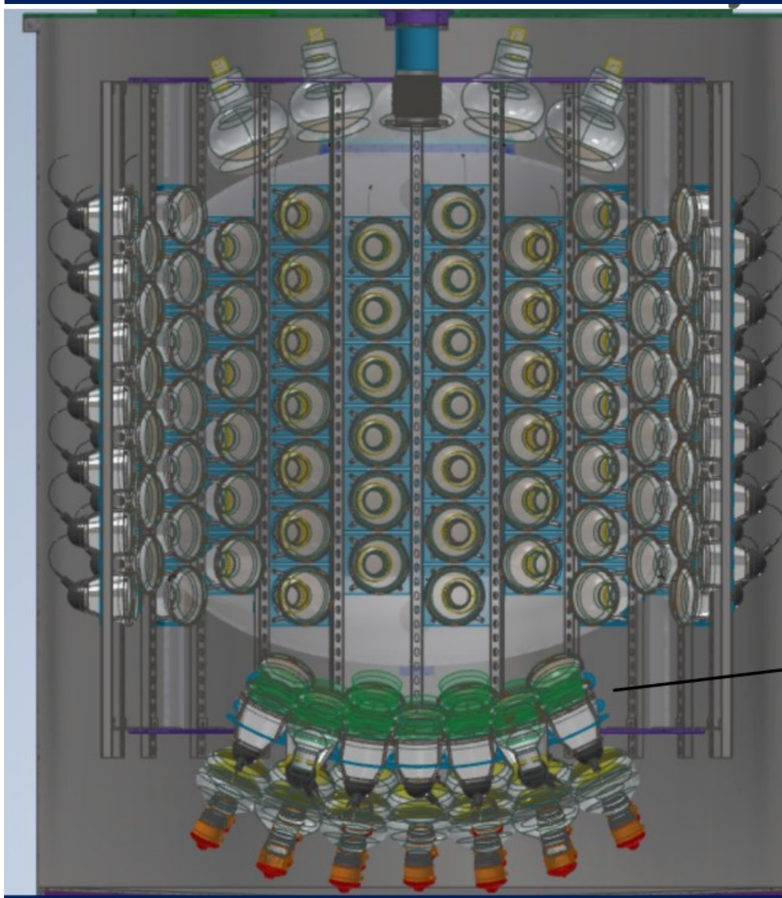
General Use Cases

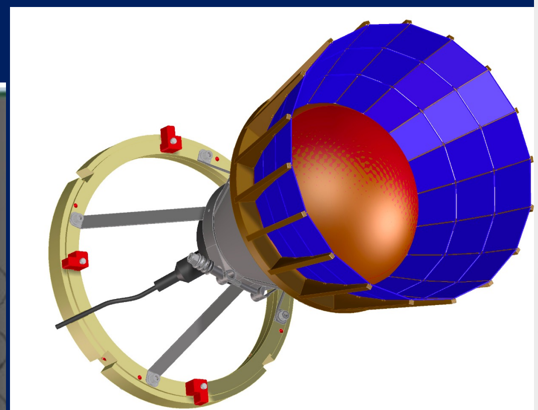
- Makes sense for high light-yield scintillator
- Make sense for fast scintillator
- Make sense when available area is constrained
  - More Cherenkov light than just filtered PMTs
  - With “small” loss of short-wavelength light
- Makes sense when scintillation light is narrow-band and short
  - Or has a giant Stokes shift and is very long---does this exist?
- In combination with fast timing, can use shorter cut-on wavelength
  - Tolerate more scintillation leakage, get more Cherenkov light
- Best when PMT does not shadow other PMTs (“flower petal” configuration)
- Or with planar/pixelated photon sensors

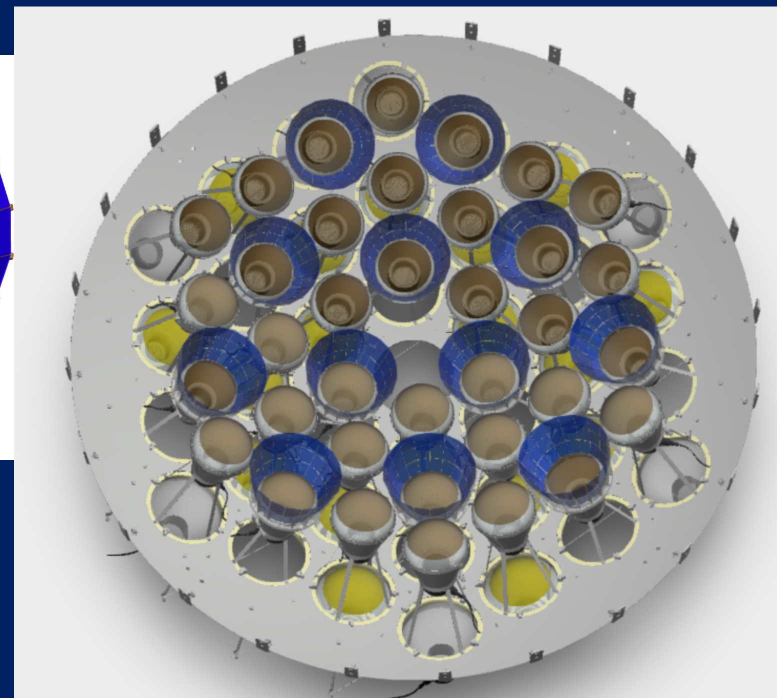
Dichroicons

Eos at LBNL

12 dichroicons at bottom





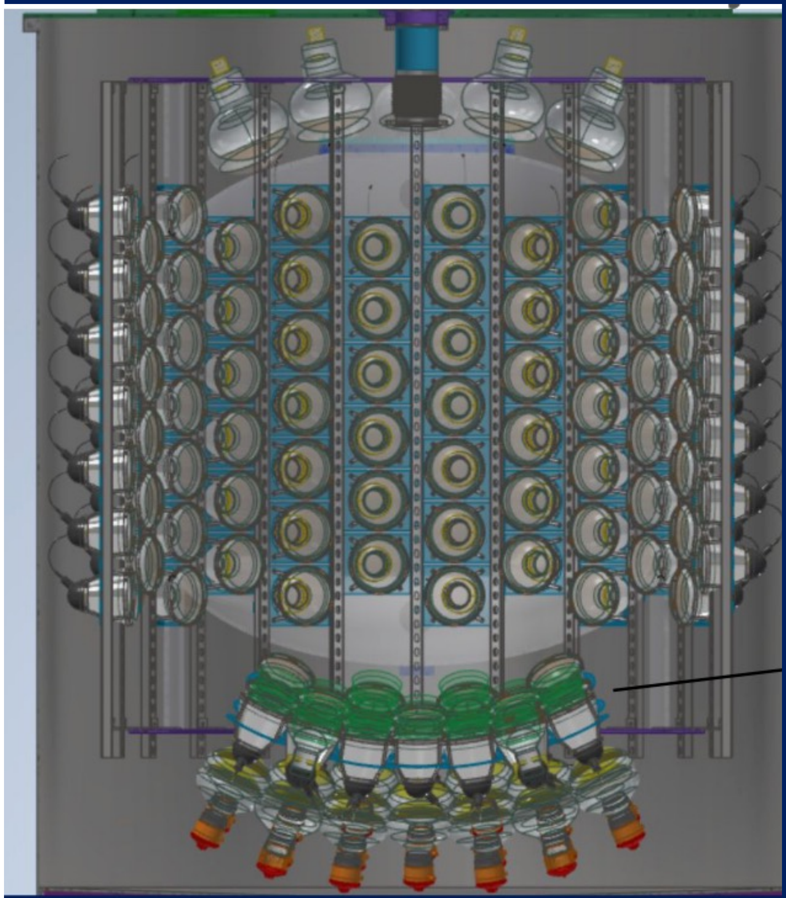


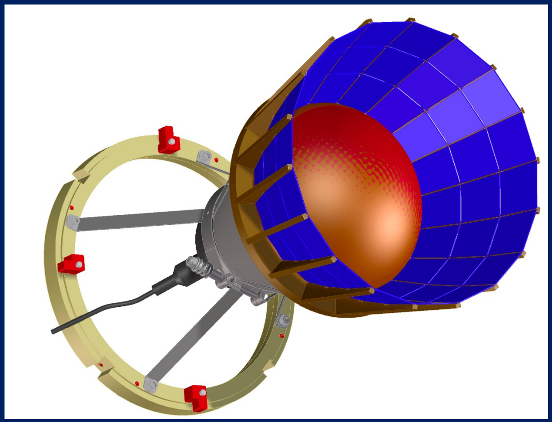
- Demonstrate Cherenkov/scintillation separation for variety of sources in tonne-scale detector
- Develop reconstruction methods leveraging scintons+chertons
- Test model of response

Dichroicons

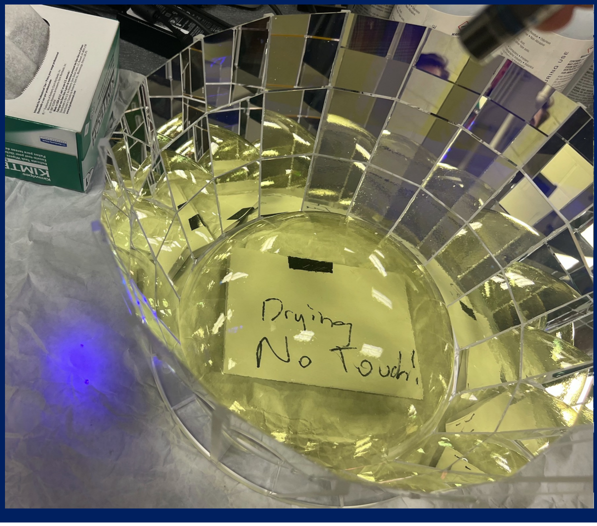
Eos at LBNL

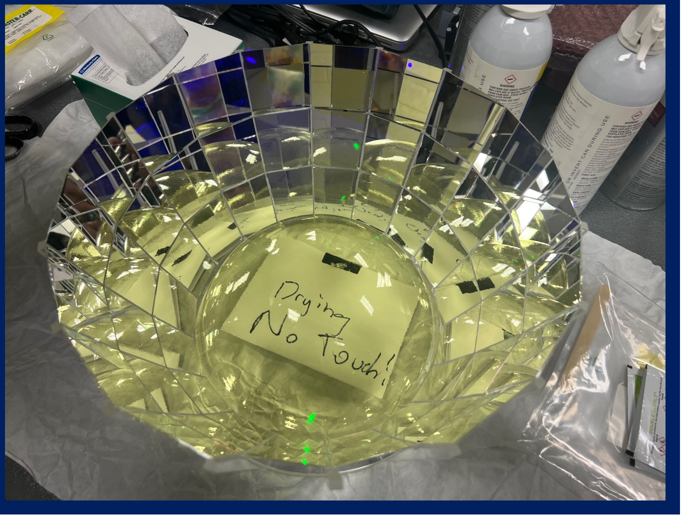
12 dichroicons at bottom





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

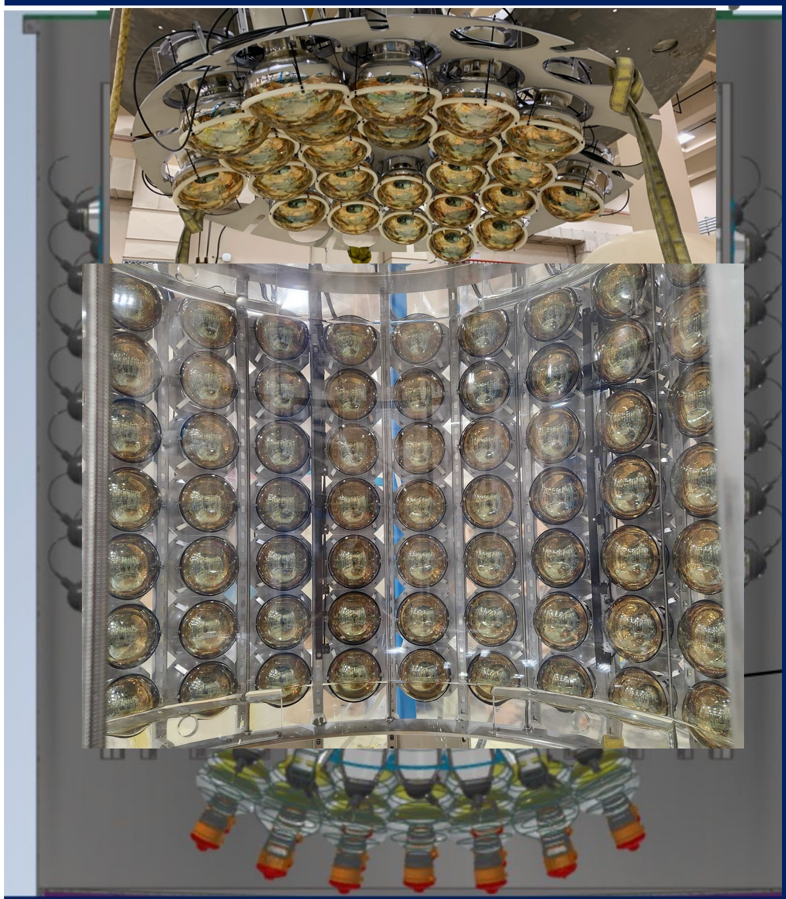


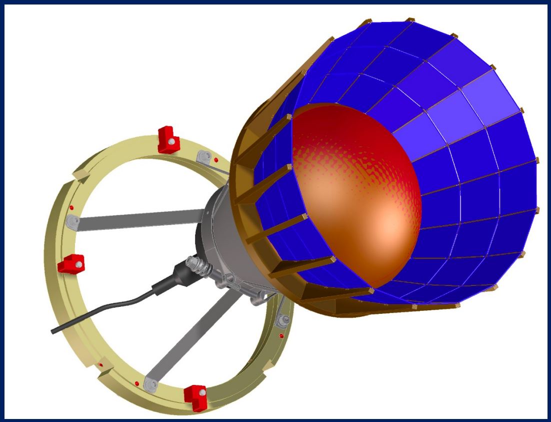


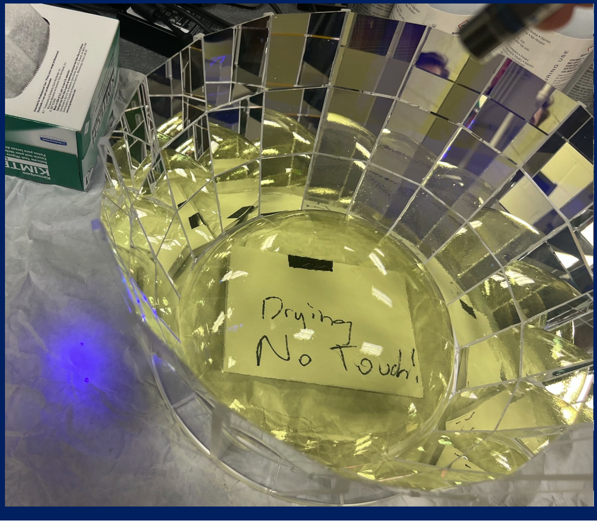
Dichroicons

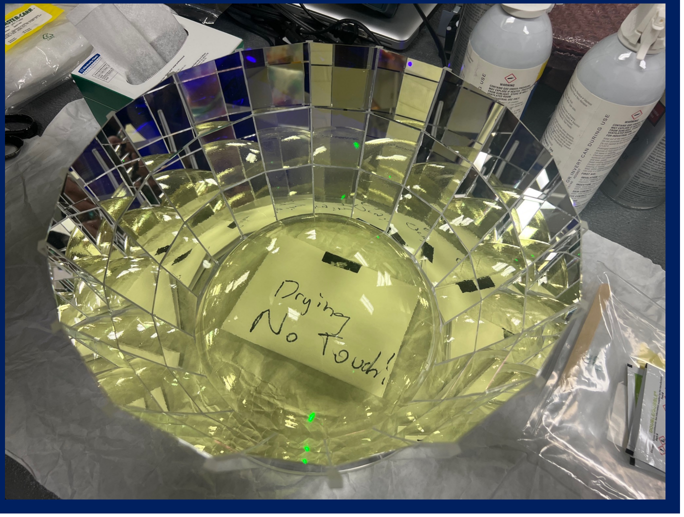
Eos at LBNL

12 dichroicons at bottom





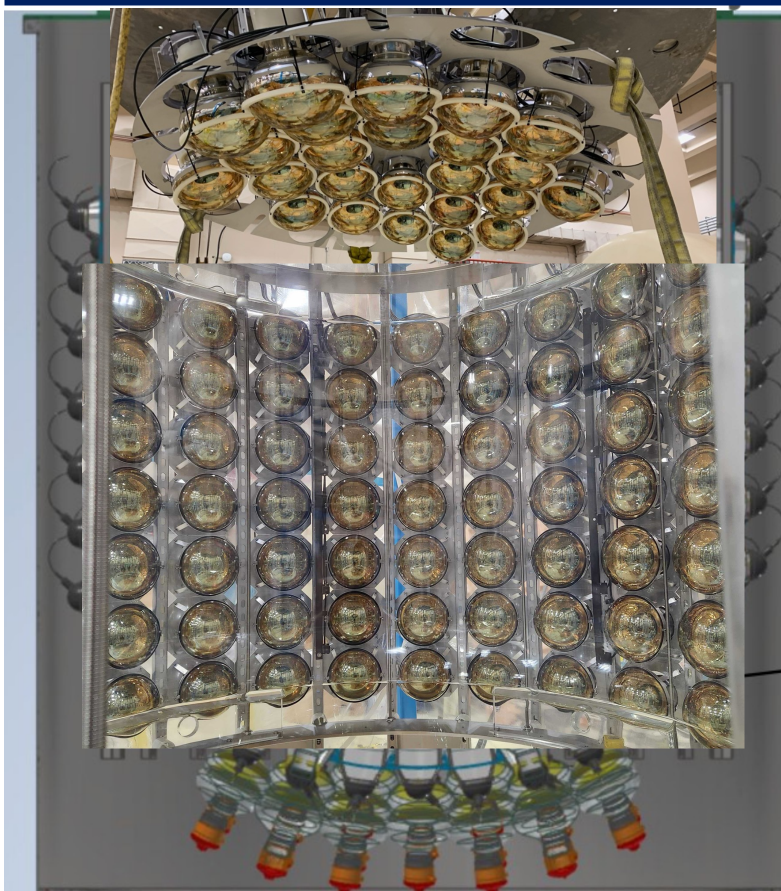




Dichroicons

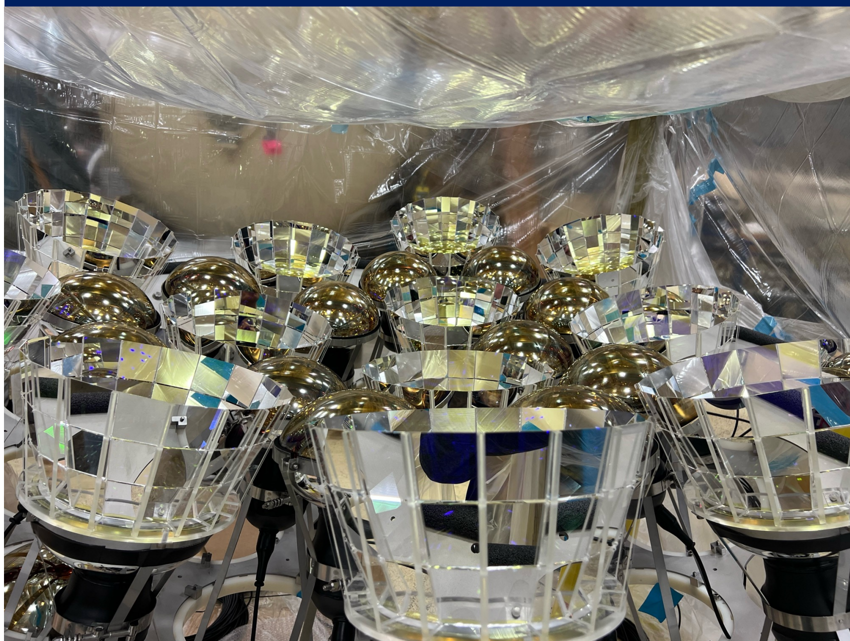
Eos at LBNL

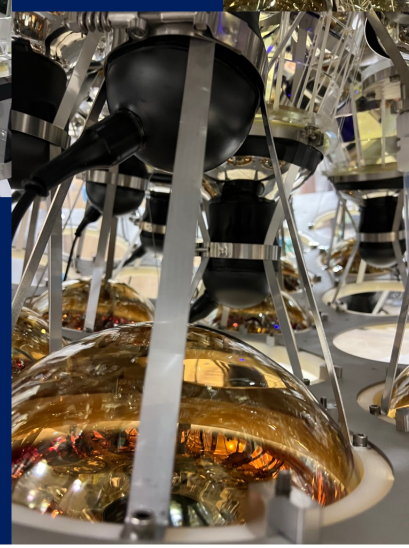
12 dichroicons at bottom

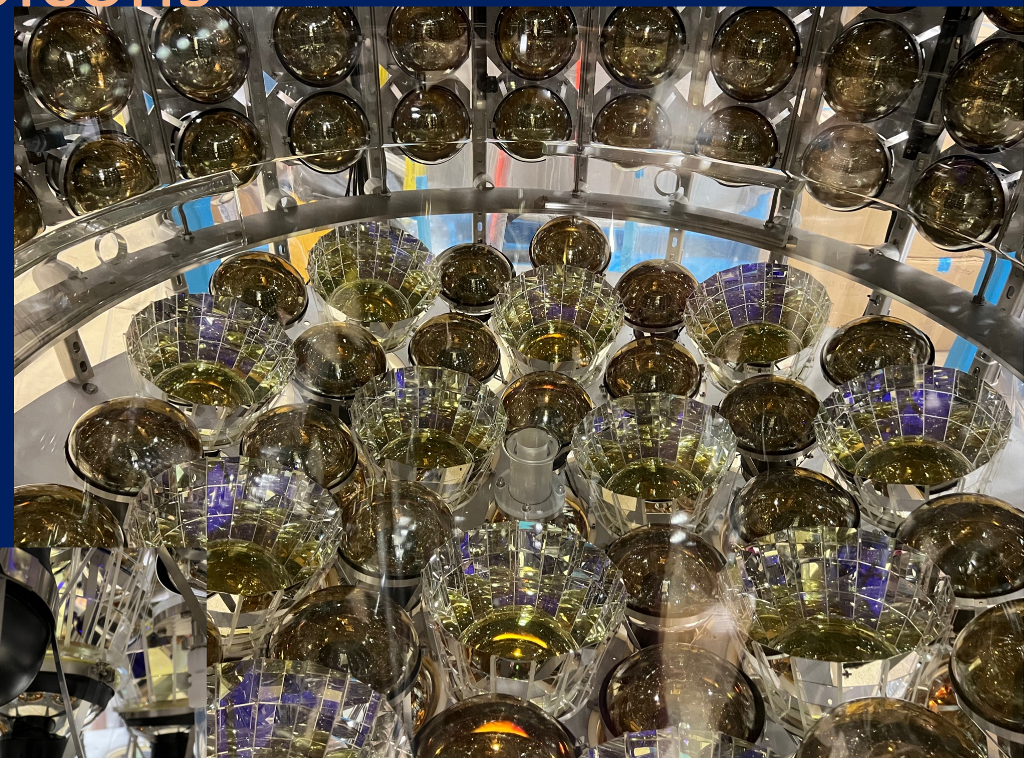


Dichroicons

Eos at LBNL



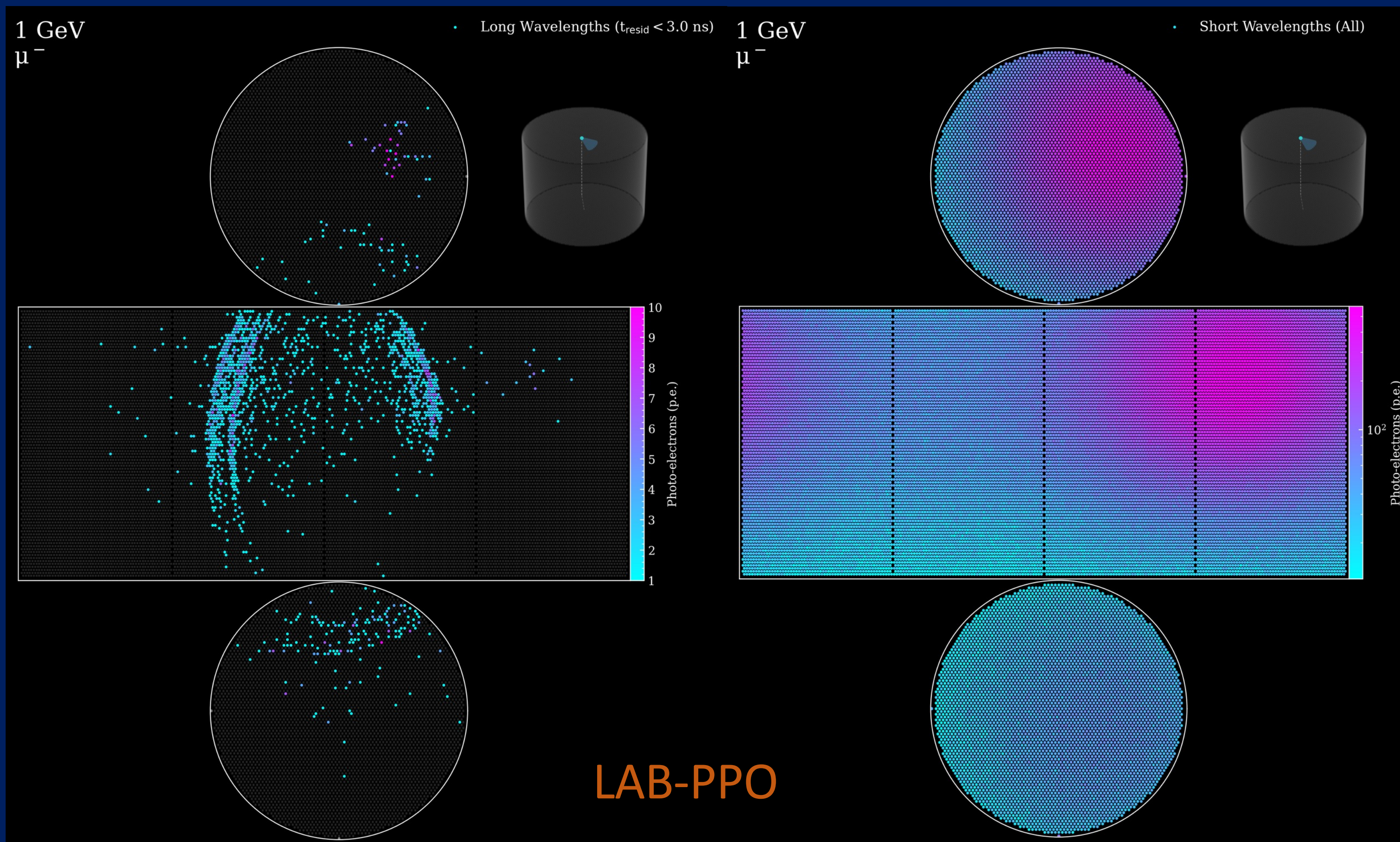




Dichroicons

Theia---Chroma simulation

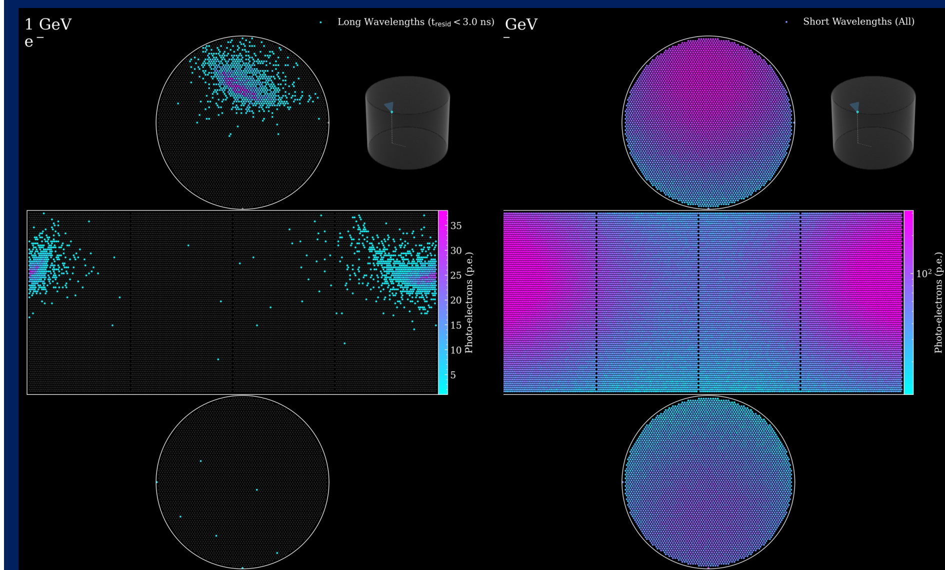
One Detector



S. Young

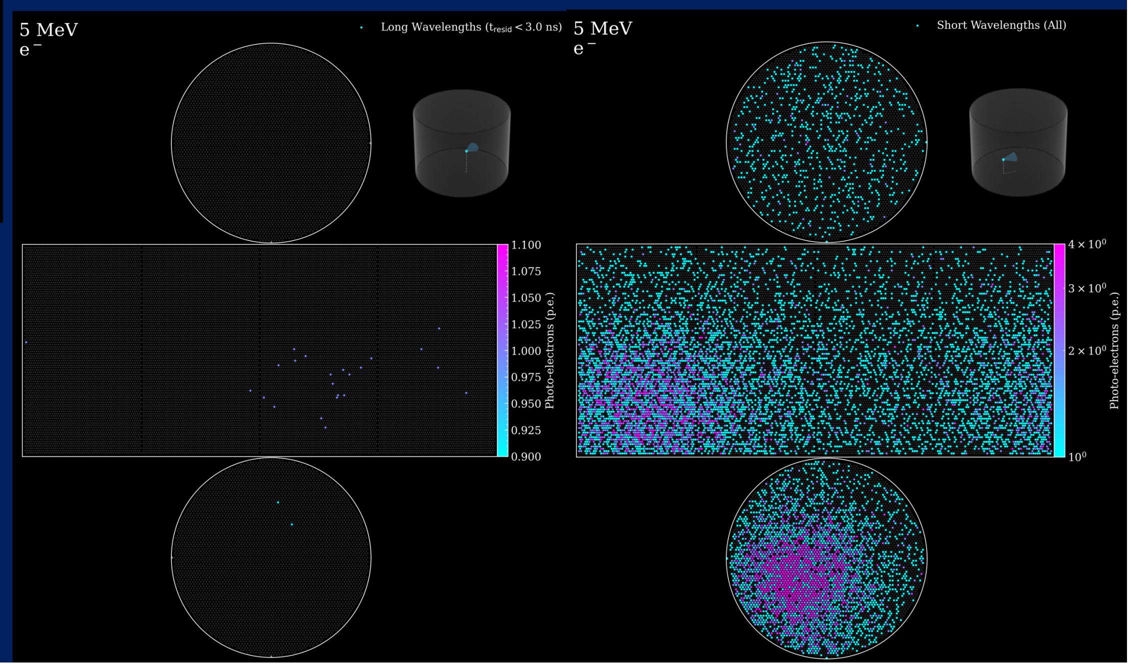
Dichroicons

Theia (100kt)



About 10,000pe≅
1% energy resolution
At 5 MeV

LAB-PPO, JUNO-level coverage



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

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

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

Summary

- Hybrid Cher/scint detectors are a new direction for neutrino physics
- Spectral sorting allows cherton/scinton discrimination even in bright scintillator
- Benchtop performance looks good!
- Performance tests at Eos coming very soon

Funded by: US DOE LBNL DE-AC02-05CH11231; DOE/NNSA/DNN R&D; DOE/HEP DE-SC0018974

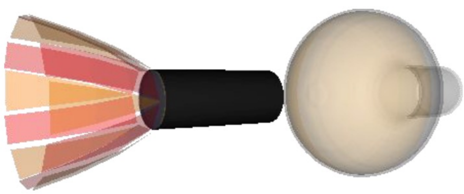
Backups

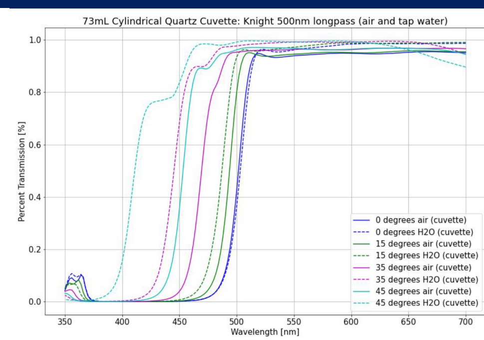
Dichroicons

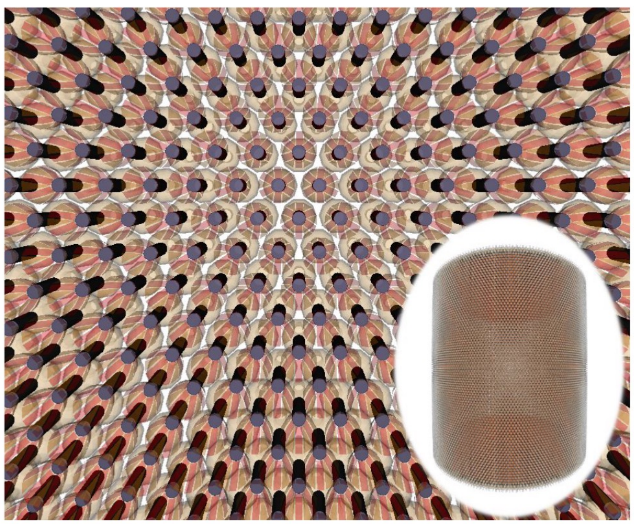
Theia

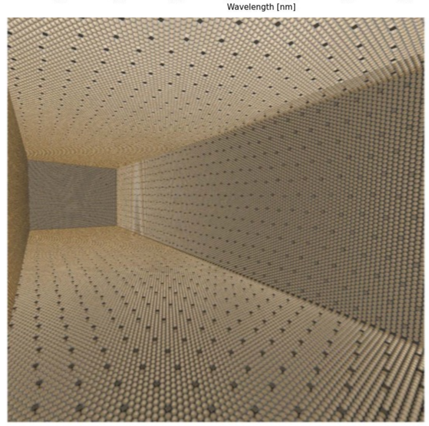
- Using full dichroicon model, implemented in Chroma GPU ray-tracer
- Developed simple timing and angular reconstruction for vertex and direction

A. Bacon







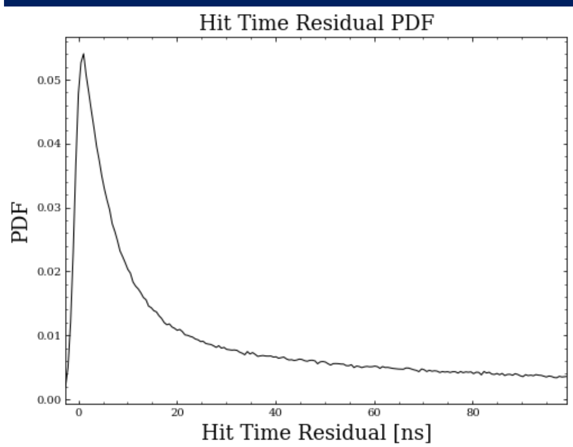


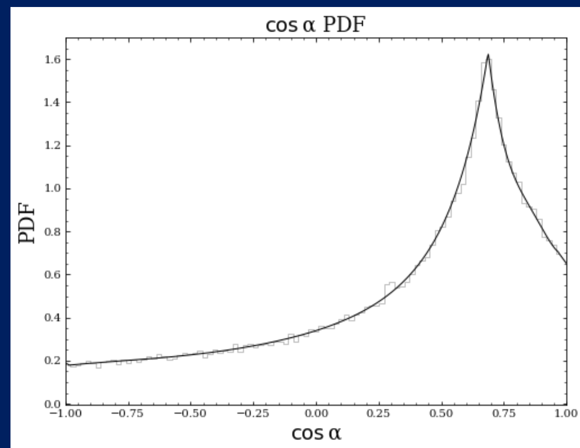
- *Implemented measured dichroic filter transmission and reflection curves in Chroma model*
- *Have full PMT QE curves*
- *Complete PMT timing response*
- *Optical isolation of long-wavelength PMT*

Dichroicons

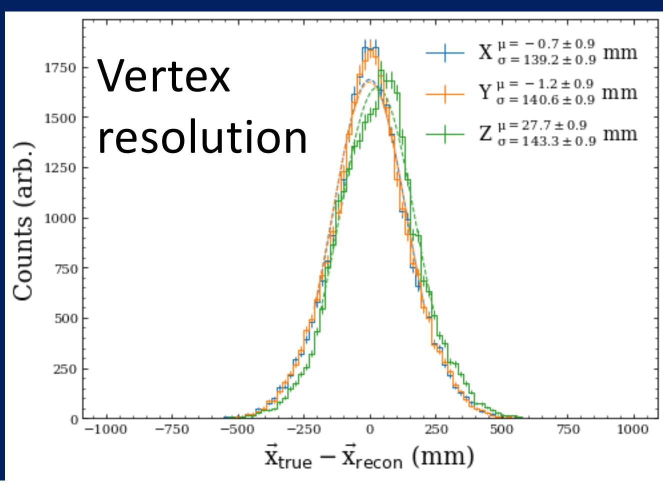
Reconstruction at 5 MeV

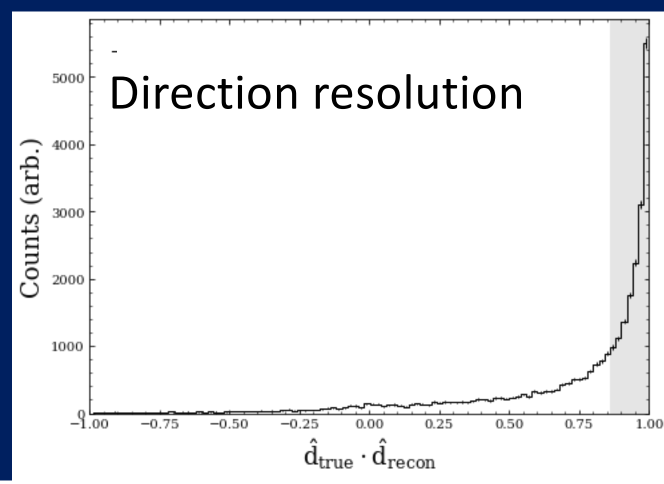
Simple likelihood-based reconstruction so far





- 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

Community Interest

8

Instrumentation Frontier

P. Barbeau, P. Merkel, J. Zhang

Dichroicons : Dichroicons, which are Winston-style light concentrators made from dichroic mirrors, allow photons to be sorted by wavelength thus directing the long-wavelength end of broad-band Cherenkov light to photon sensors that have good sensitivity to those wavelengths, while directing narrow-band short-wavelength scintillation light to other sensors. Dichroicons are particularly useful in high-coverage hybrid Cherenkov/scintillation detectors.

Snowmass Neutrino Frontier: NF10 Topical Group Report
Neutrino Detectors

3.1.4 Spectral Sorting and Dichroicons

One approach to separating Cherenkov and scintillation light is by discriminating photons by wavelength, as scintillation is typically within a narrow emission band, while Cherenkov is a broad spectrum of light, falling as roughly $1/\lambda^2$.

2

Photon Detectors

C. O. Escobar, J. Estrada, C. Rogan

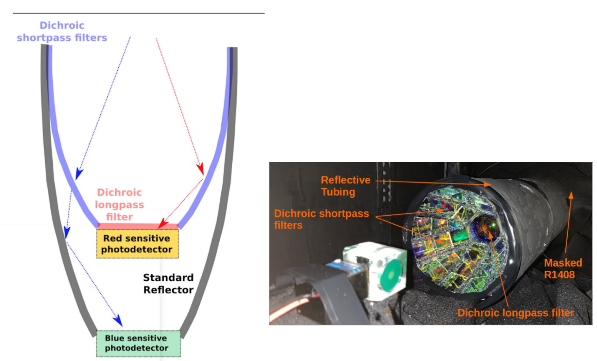
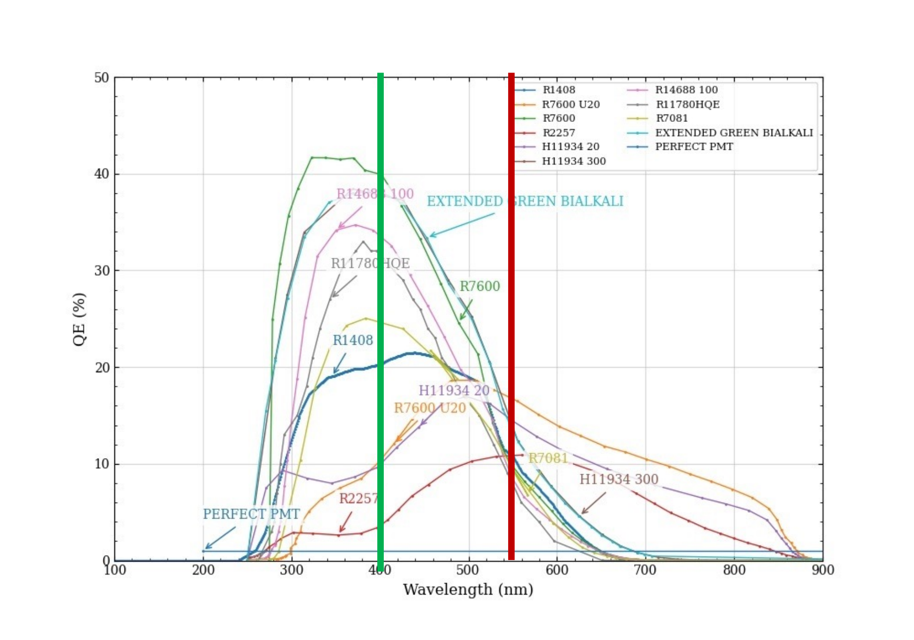
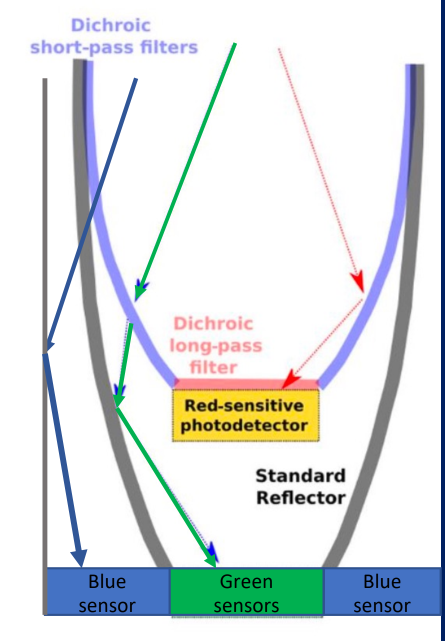


Figure 2-2. *Example of photon detector development for neutrinos: the dichroicon, from arXiv:2203.07479*

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)

Other Physics Use 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 H_2O
    - 5 ns for LAB-PPO
    - Could LAPPDs let us see dispersion even in ANNIE??
  - 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…?

Spectrum

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