Enhanced Particle Identification in WbLS

Applied Antineutrino Physics Workshop

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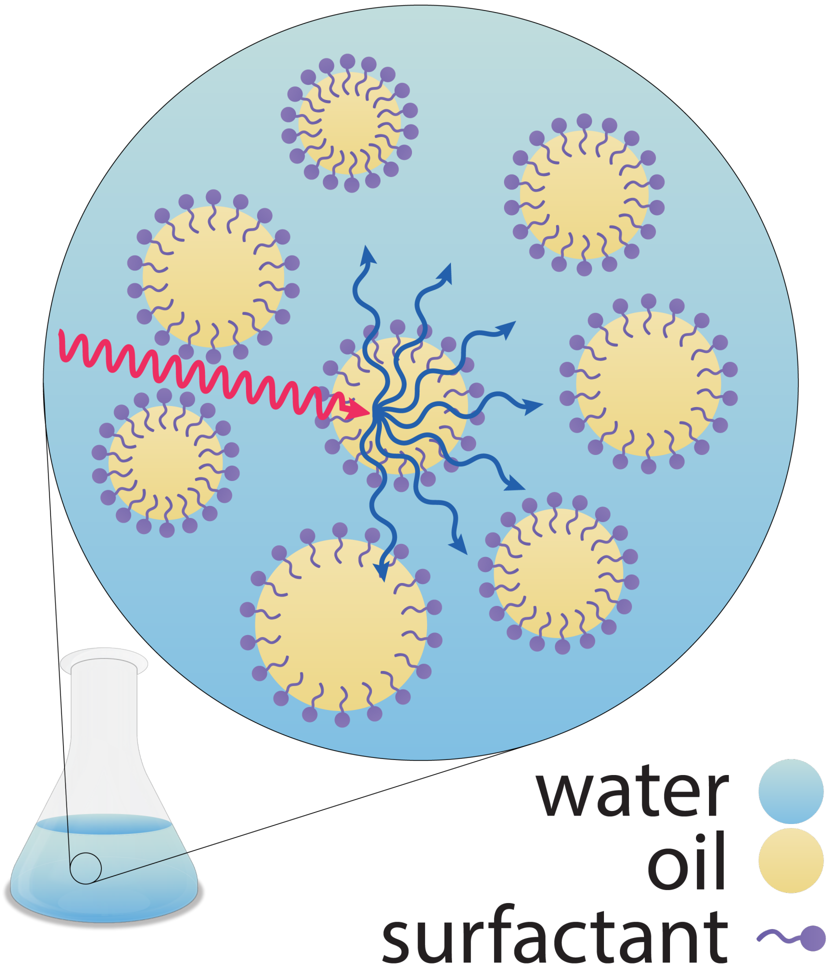
Lawrence Livermore National Laboratory

Overview

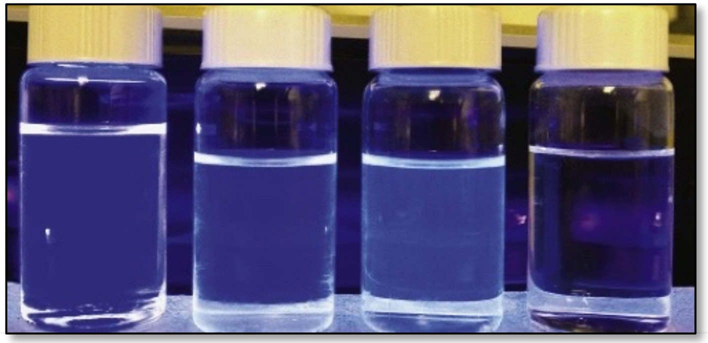
- Chemists at LLNL developed a new formulation of WbLS* with pulse-shaped discrimination for better particle identification.
- We are utilizing existing LLNL capabilities to characterize and reiterate on formulations for scaling to larger scale detectors.

*In this talk we define WbLS as a majority water complex.

Water-based Liquid Scintillator Developed by Brookhaven



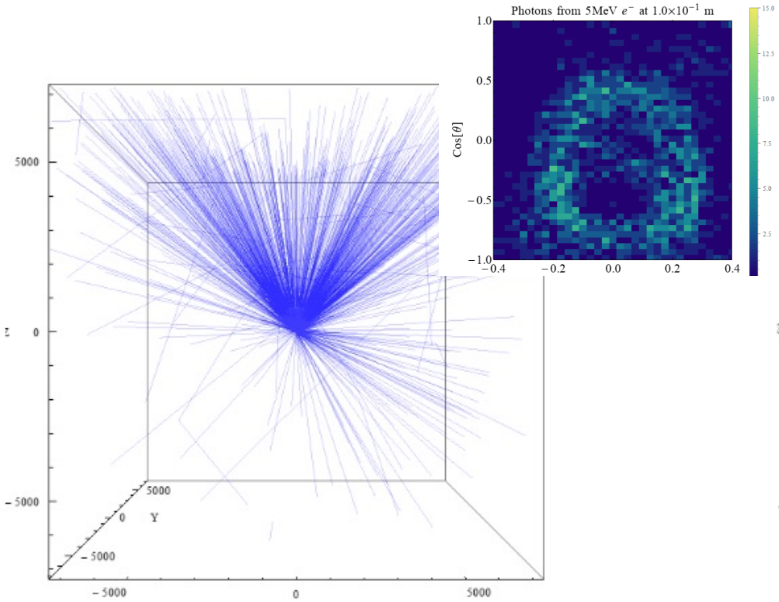
- Water-based liquid scintillator (WbLS) contains a scintillation phase (oil) dispersed in water, stabilized by a surfactant.
- This has already been demonstrated and developed by BNL and characterized by U.C. Berkeley and others over the past decade.



M. Yeh et al., **NIMA**, *2011*

WbLS Best of Both Worlds

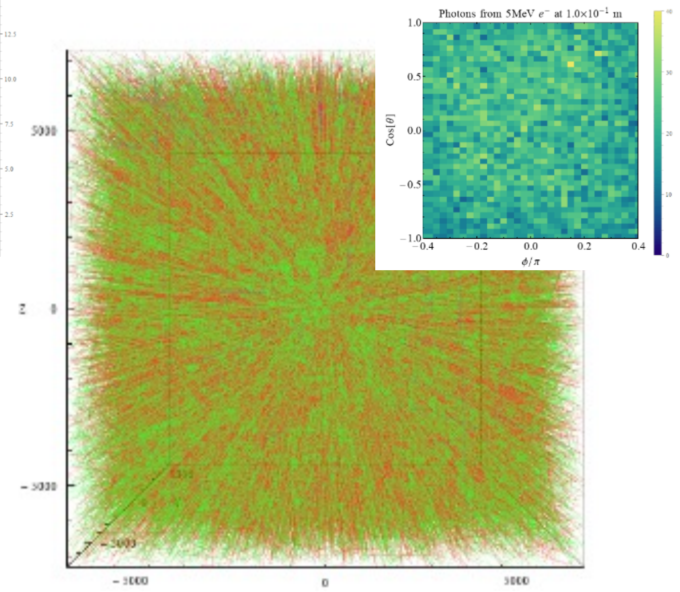
Water-Cherenkov Detectors



Advantages of Pure Water:

- Low attenuation
- Direction reconstruction
- Low Cost and Toxicity
- Scalability

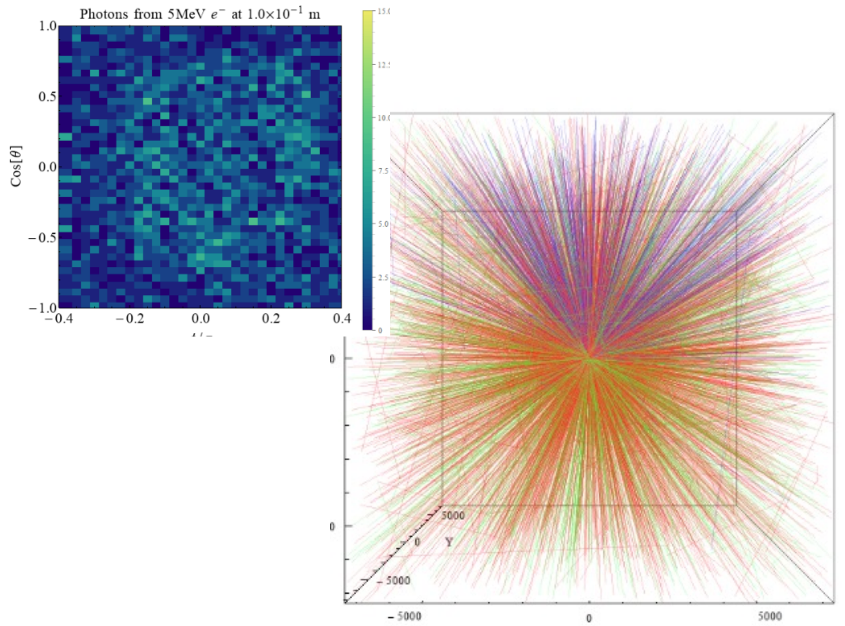
Scintillator Detectors



Advantages of Liquid Scintillator:

- High Light Yield
- Low Threshold Detection

Water-based Liquid Scintillator Detector



Cherenkov   Scintillation   Reemission

Best of both Worlds

Images taken from Ben Land at U.Penn

Current Particle Identification in Large-Scale Detectors

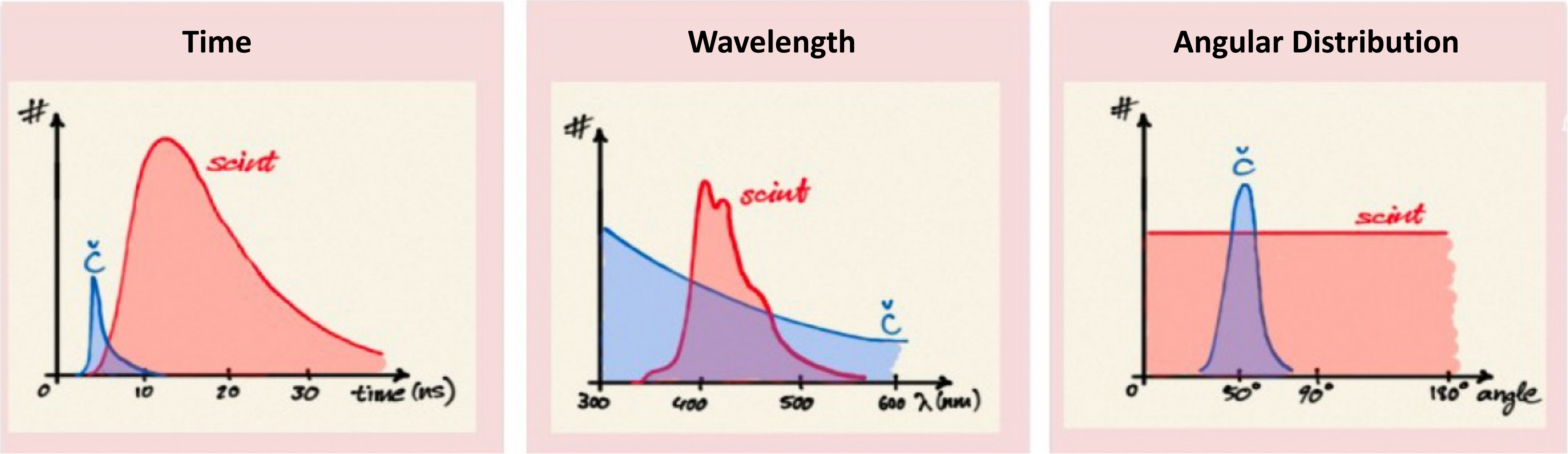


Image from Dr. Michael Wurm Johannes Gutenberg University Mainz

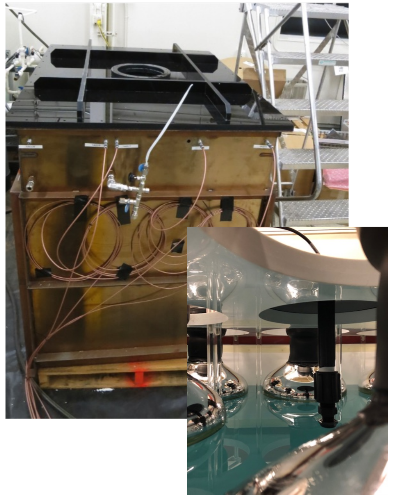
WbLS development at LLNL seeks to expand on PID techniques

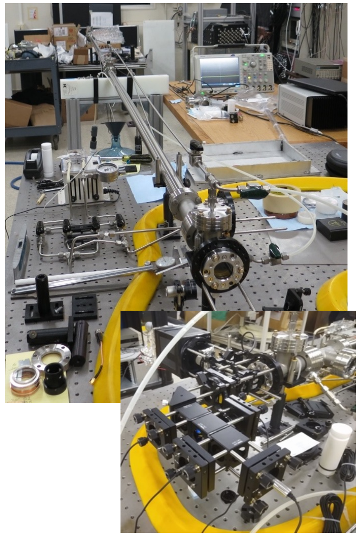
Why LLNL for WbLS Development

Extensive Scintillator Experience

- LLNL is home to some of the best scintillator chemists in the world.
- LLNL has developed Li loaded plastics, Stilbene arrays, slow-liquid scintillators, and more.

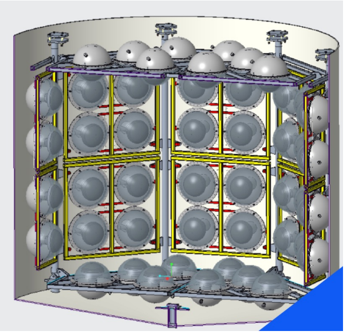
Existing Equipment



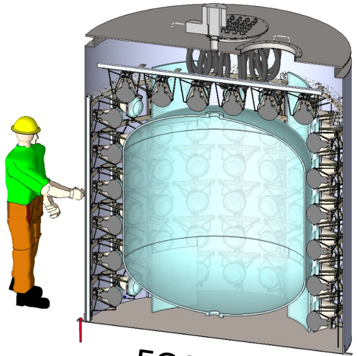


- LLNL has an existing 1-ton media testbed for small scale studies.
- LLNL is also home to an attenuation and scattering arm (LASE) that has been validated with DI water.

Collaborative Interface with other interest groups



BUTTON

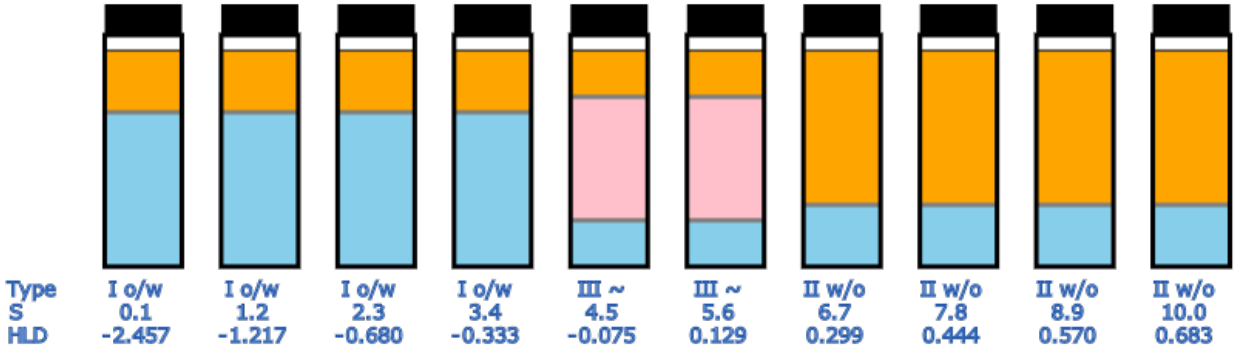


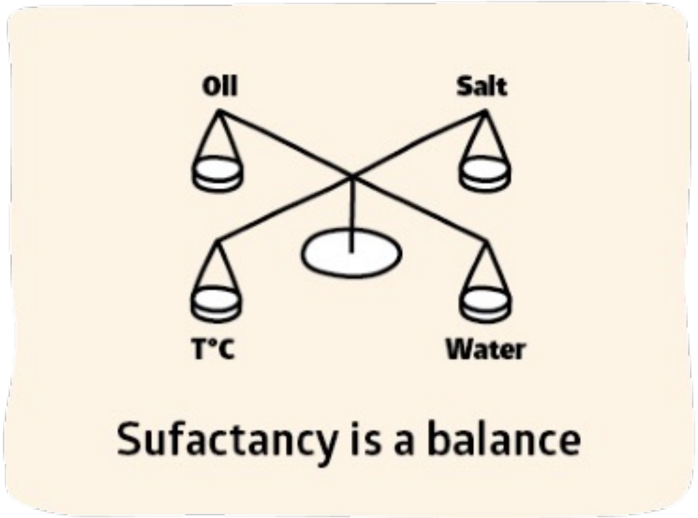
EOS

- We share collaborators between this effort and that of EOS and BUTTON.
- Members of the local LLNL team are observers on the THEIA interest group.

Hydrophilic-Lipophilic Difference (Michael Ford)

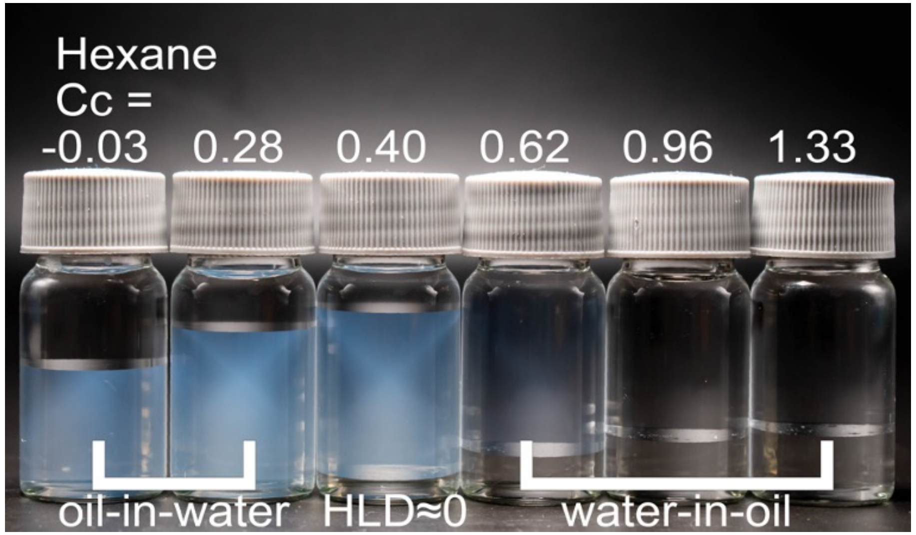
orange = oil phase (lower density); blue = water phase; pink = balanced

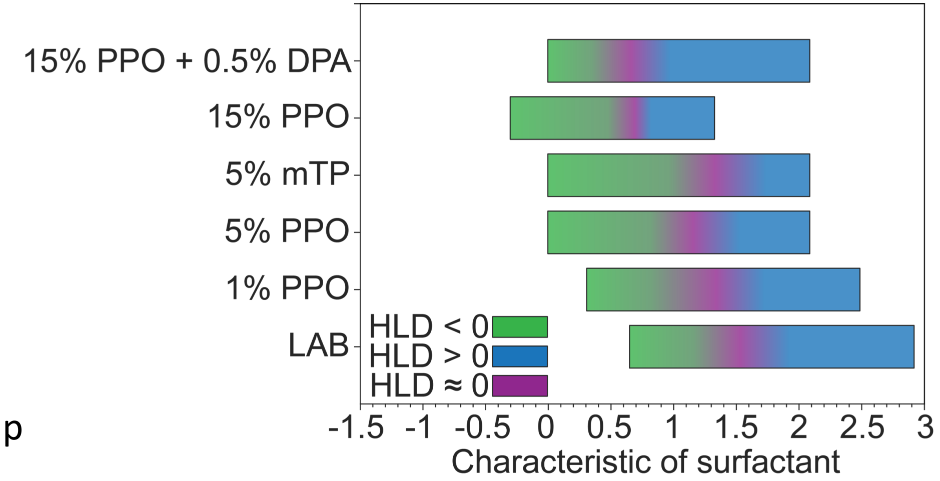




Each part of emulsion can be given a value:

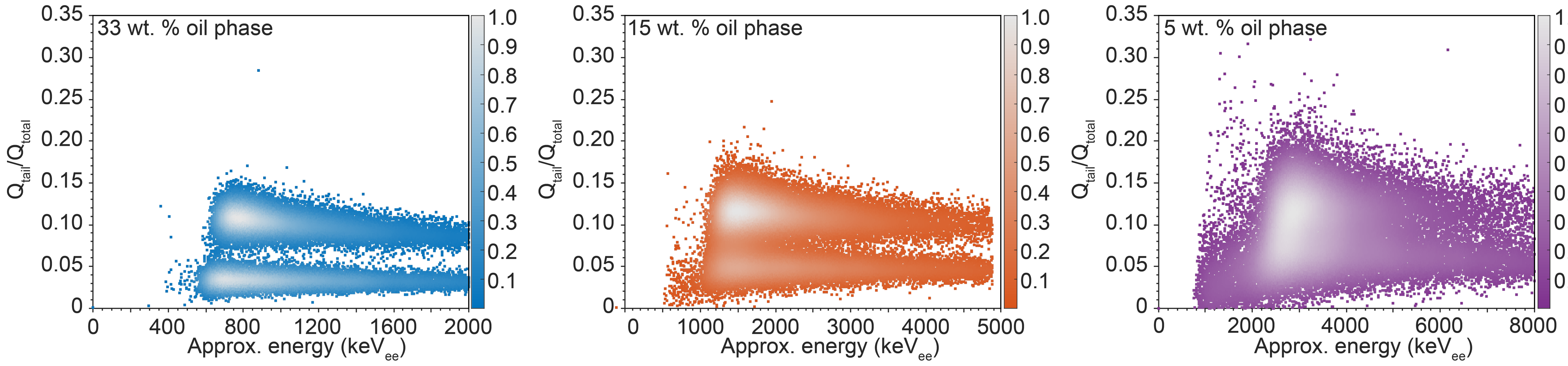
- Characteristic of **surfactant**, Cc
- Effective characteristic of **oil**, EACN
- **Salt** concentration, S
- **Temperature**, T





"Practical Surfactant Science" https://www.stevenabbott.co.uk/practical-surfactants/index.php
Ford, Michael J., et al. NIMA (2022): 166854.

First Demonstration of PSD in Scintillation Light using WbLS



- Through this work we have developed water-based liquid scintillator with pulse-shape discrimination capability in the scintillation profile.
- This formulation has the capability to distinguish fast-neutrons or proton recoils from electronic recoils which has implications for signal identification and backgrounds reduction in antineutrino detectors.
- This approach can be combined with Cherenkov/Scintillation separation at higher water content values or used as a lower flammability option to other scintillators.

Fully Dissolved ^{6}Li-Doped PSD Liquid Scintillator

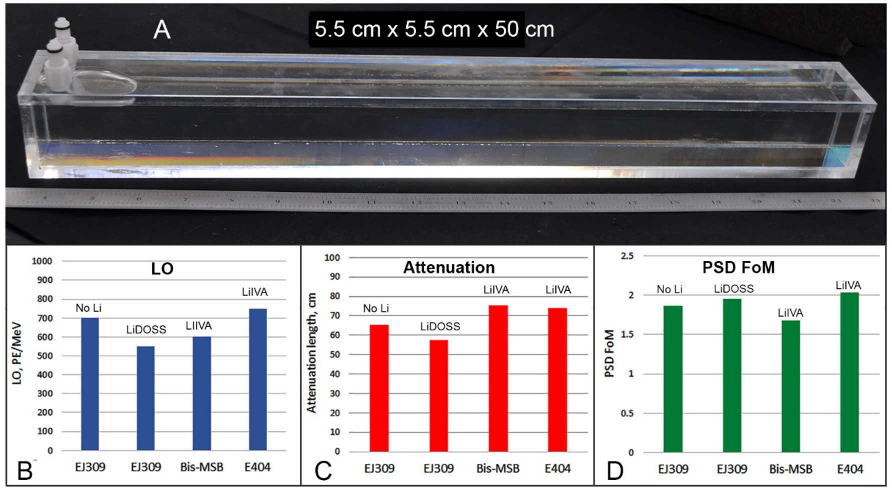
<u>New formulations of ^{6}Li-doped PSD liquid scintillator (Natalia Zaitseva and Michael Ford, LDRD funded work at LLNL)</u>
(Submitted to Nucl. Inst. And Meth. A – March, 2023)

- Fully dissolved ^{6}Li in organic solvent, in turn dissolved in PSD liquid scintillator
- PSD and light output performance is competitive with EJ-309
- Long term stability tests are ongoing. Good reason to believe these formulations might be more stable than the PROSPECT version.

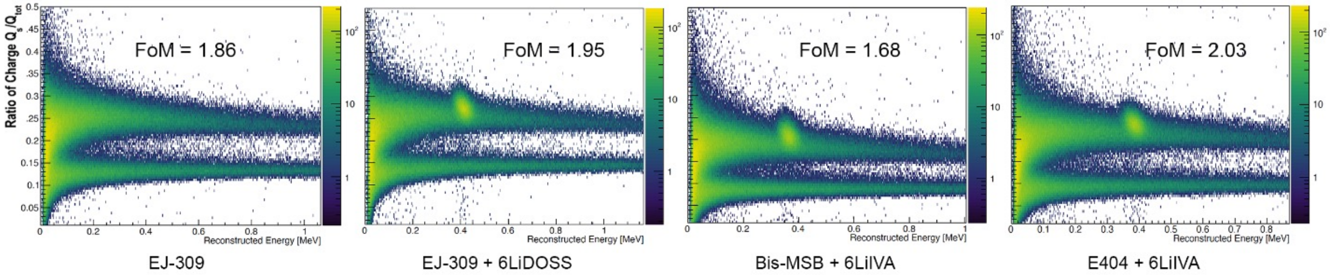
<u>Note: This work is motivated by stability issues with PROSPECT liquid scintillator</u>

- The PROSPECT experiment – PSD capable, doped with ^{6}Li
- However, ^{6}Li-doped water was suspended (using reverse micelle emulsion) in PSD capable (EJ-309) liquid scintillator
- Micelle formations proved to be only stable over ~<1 year

N. P. Zaitseva, M. L. Carman, M. J. Ford, et al., Submitted to NIMA, March (2023)

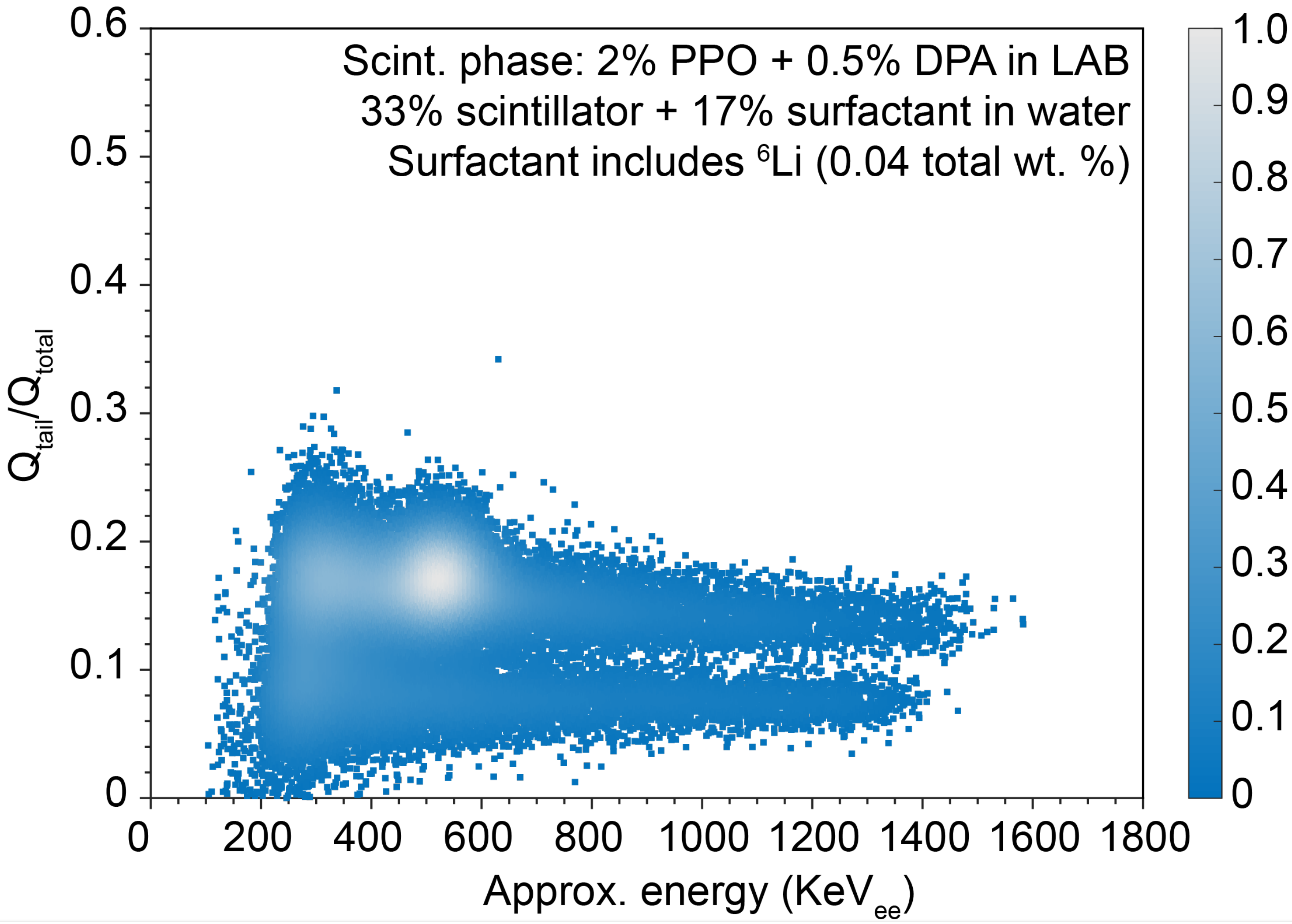


Light output and PSD performance of new liquids are competitive with EJ-309 standard.



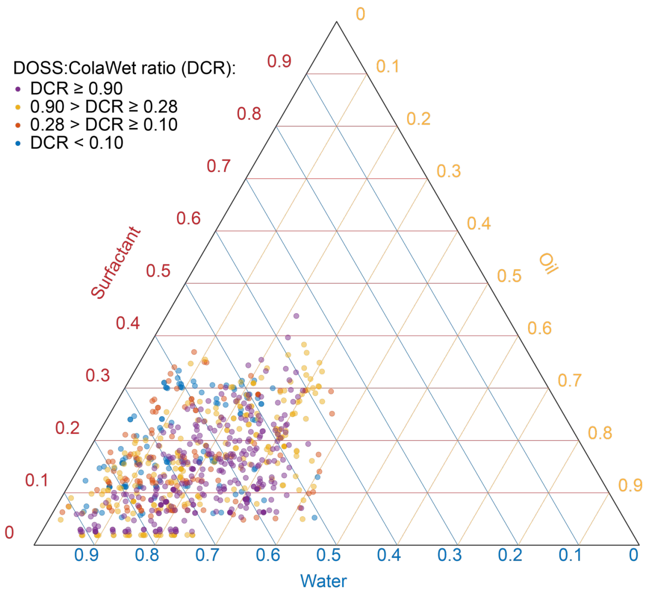
Lithium Doping in "WbLS"

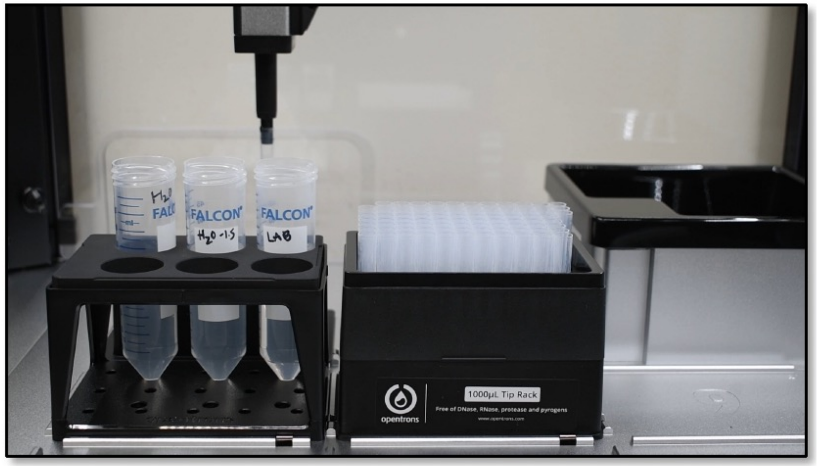
- As part of the work on WbLS formulations we are developing WbLS with Lithium doping.
- These formulations provide a promising progression to a majority water formulation by utilizing Li in the surfactant which can reduce the purification constraints.
- The alpha-triton signature also provides insight to the response to (alpha, n) backgrounds.
- Lithium doping can also allow for better particle reconstruction due to the localization of the event.

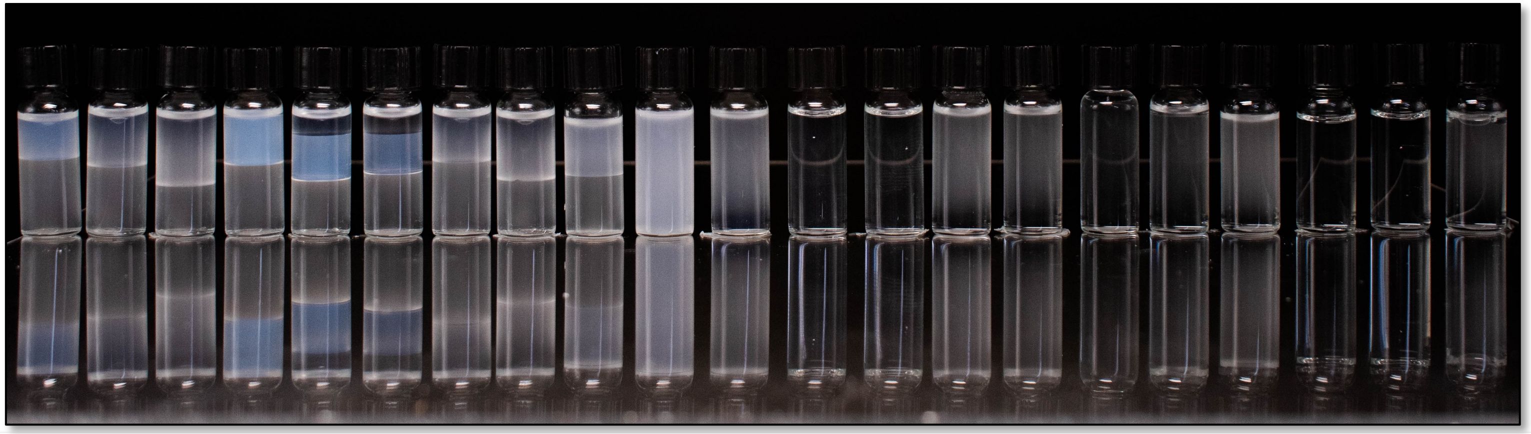


Water-based Liquid Scintillator Automation

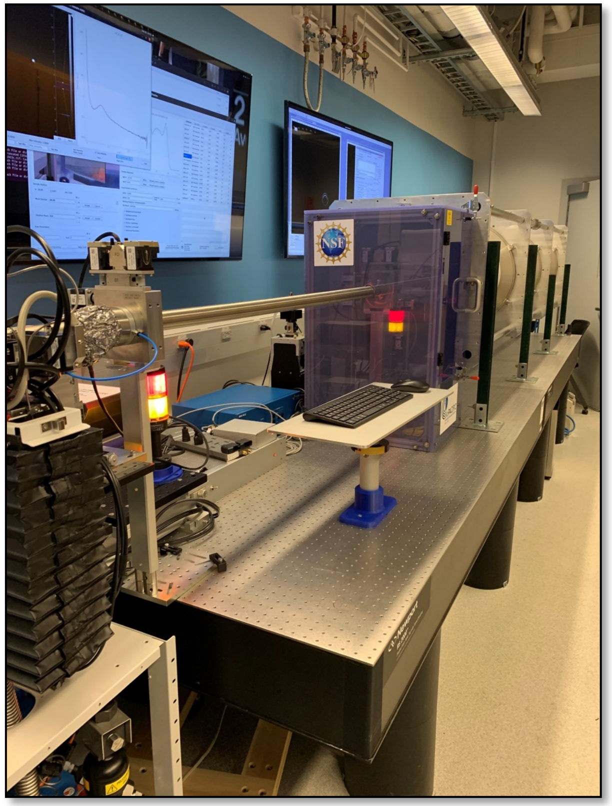
- Chemical automation has been used to generate WbLS to sample a large range of formulations.
- We use an iterative approach to synthesis along a large phase space and testing.
- We currently have enough samples to begin applying predictive models for informing future synthesis.

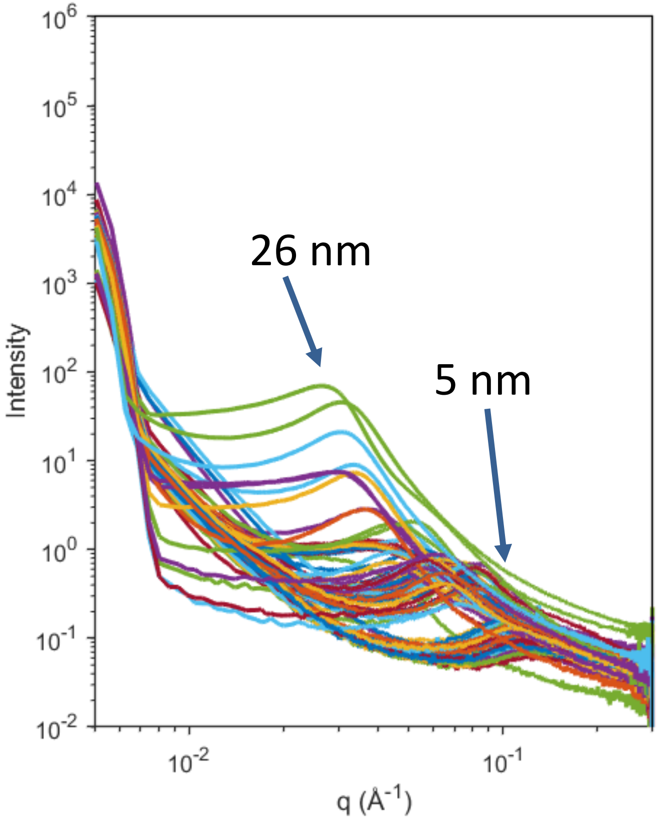


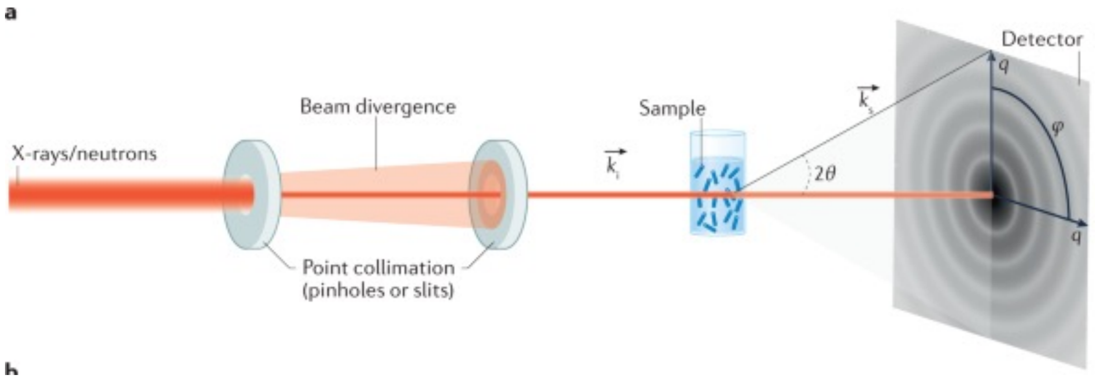




Micelle Size Characterization







- X-Ray diffraction measurements were performed at U.C. Santa Barbara to measure the size of the micelle in many of the formulations.
- The micelle ranged in size from 5-26 nm. Future work involved understanding what formulations lead to larger Micelles and the performance.

Livermore Attenuation and Scattering Experiment (LASE)

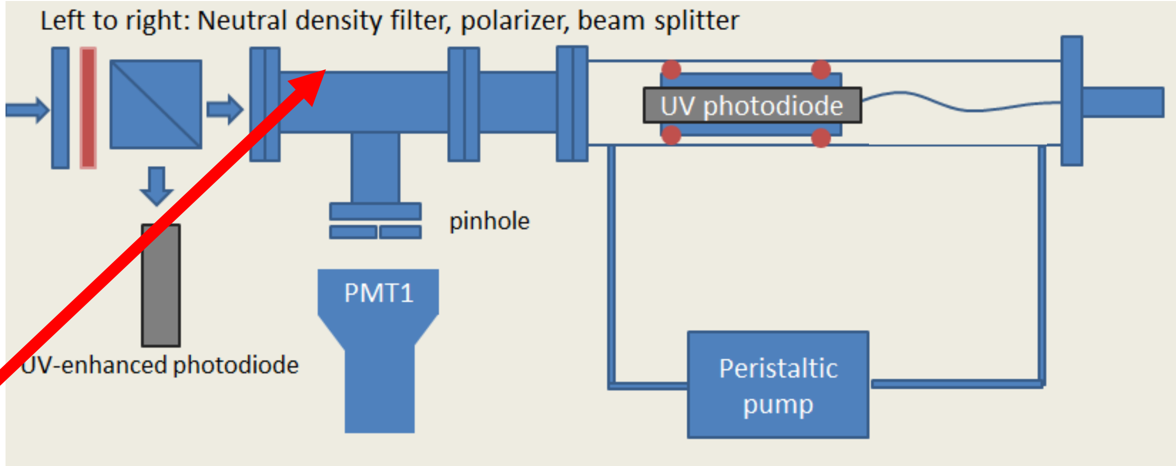
What: Attenuation and scattering

Why: A world standard instrument for measuring attenuation and scattering

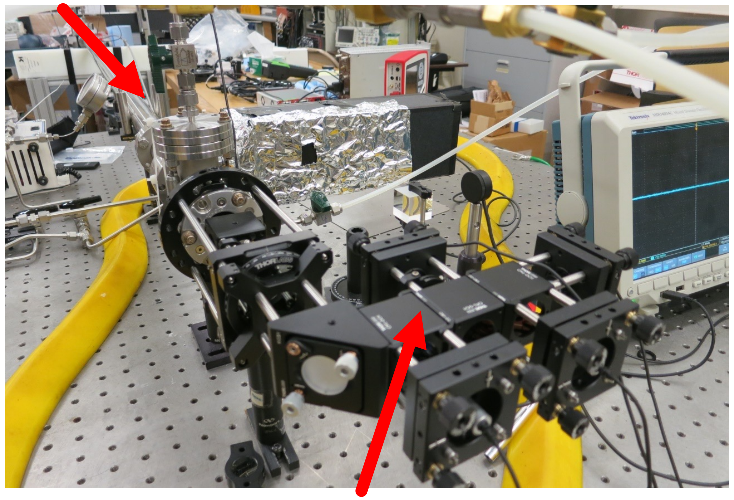
Status:

- 8 lasers spanning 405nm to 635nm
  - Horizontal, no liquid/air interface, small volume, stable, more accurate
- An identical instrument at the BNL 30-ton for in-situ measurements
- Two publications imminent

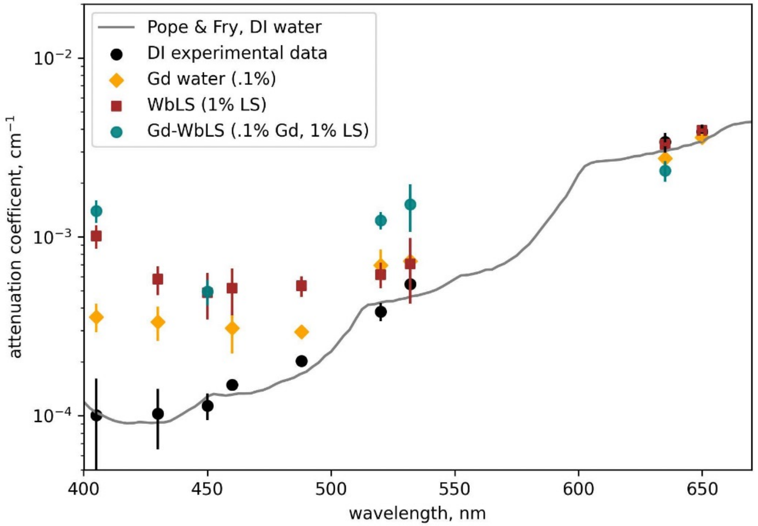
1. J. Hecla, et al. "Long Path-Length Optical Property Measurement Device for Highly Transparent Detector Media" – to be submitted to JINST
2. J. Hecla et al. "Measurements of Attenuation and Scattering properties of Water-Based Liquid Scintillator". To be submitted to PRD.



Liquid tube

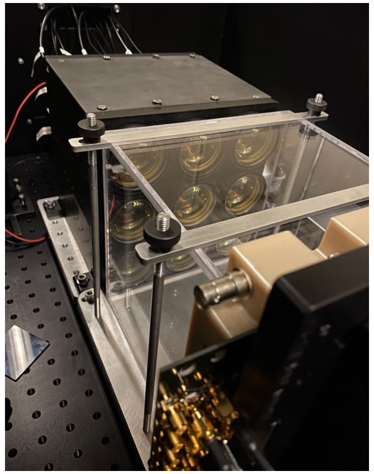


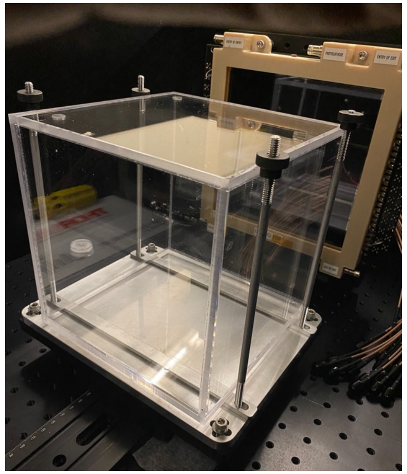
Mirror stack



Large Area Picosecond Photodetectors

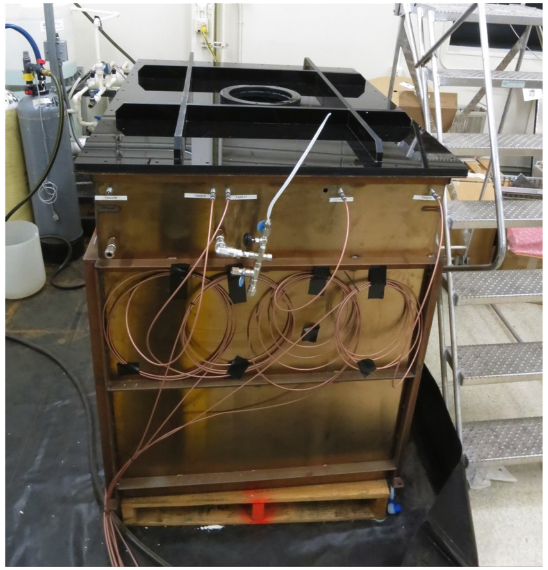
Testbed for comparing PMTs to LAPPDs for Scintillator and WbLS Comparatives





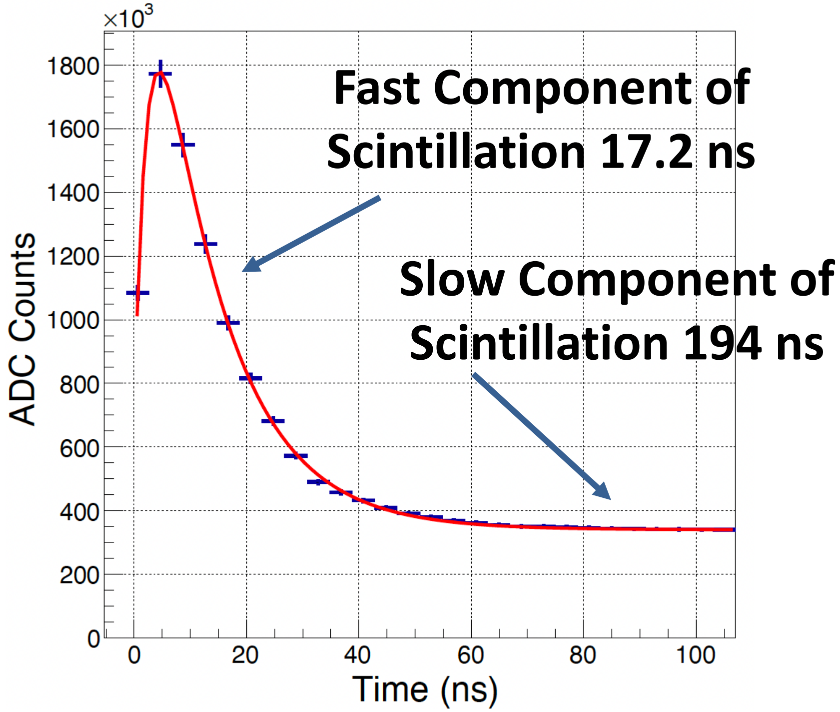
- Signal Processing Concerns (CAEN V1742) **:** 64 total channels, 5GHz sampling, 1024 record length, and significant limitations in commercial off the shelf electronics.
- Direct comparatives of traditional and advanced photosensors waveform by waveform to compare Cherenkov/Scintillation Separation to Pulse Shape Discrimination.
- In addition to fast timing, there are plans to investigate various bandwidth filters for separation of Cherenkov/scintillation by wavelength.

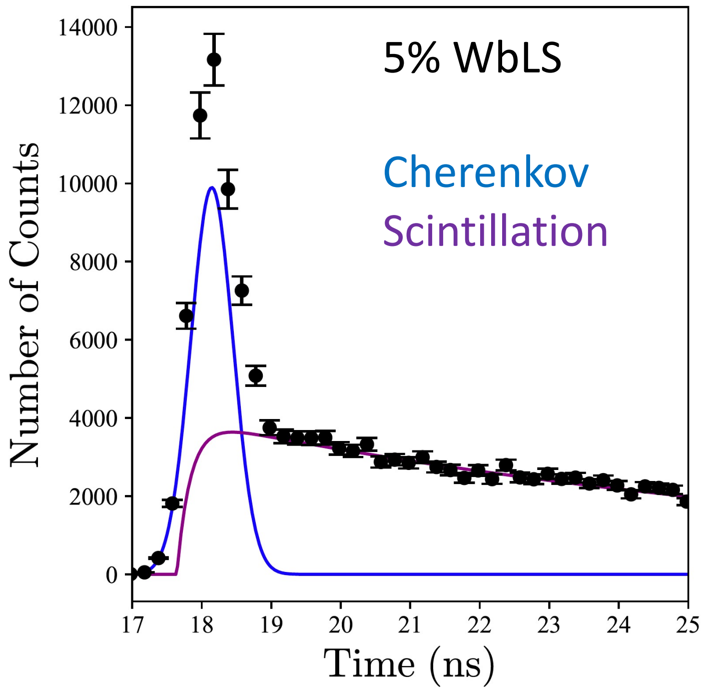
Eventual Scaling to 1-Ton

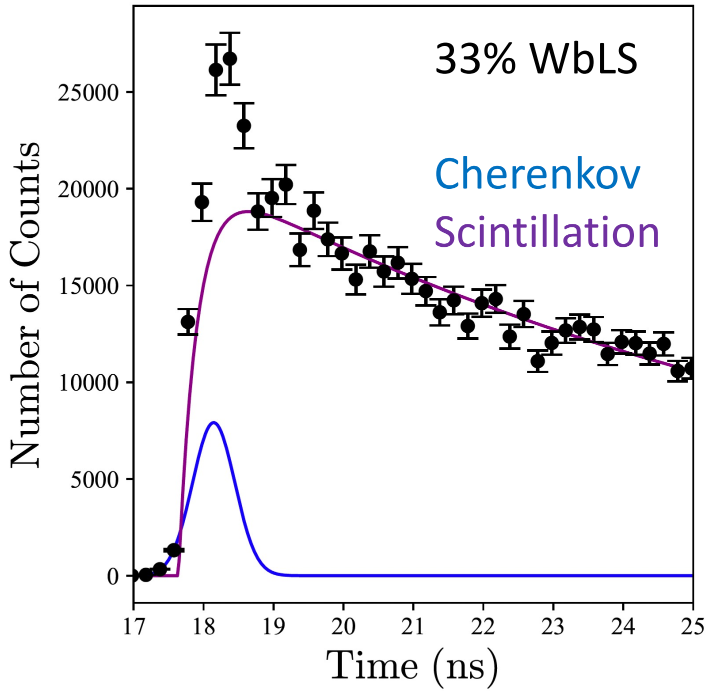


The testbed will provide experience with LAPPDs and WbLS before scaling formulations to the LLNL 1-ton detector.

WbLS Timing







- Some of our formulations showed significantly slower decay times than the state of the art. More work is ongoing to understand the decay time properties and how to formulate for them.
- Cherenkov/Scintillation separation can be performed on the order of 33% scintillation fraction. More work is needed to facilitate the appropriate electronics to make a comparison of Ch/S separation on the same waveform.

Conclusion

- LLNL has demonstrated PSD in water-based liquid scintillator using the scintillation light for the first time. Further development is ongoing to include lithium as a neutron dopant in a majority water formulation.
- Our formulation for WbLS also utilized the HLD method to ensure stable and empirical performance based on the constituent part.
- Experimental work is ongoing to define and validate the physical parameters to generate predictive formulations of water-based liquid scintillators.

Acknowledgements and Questions

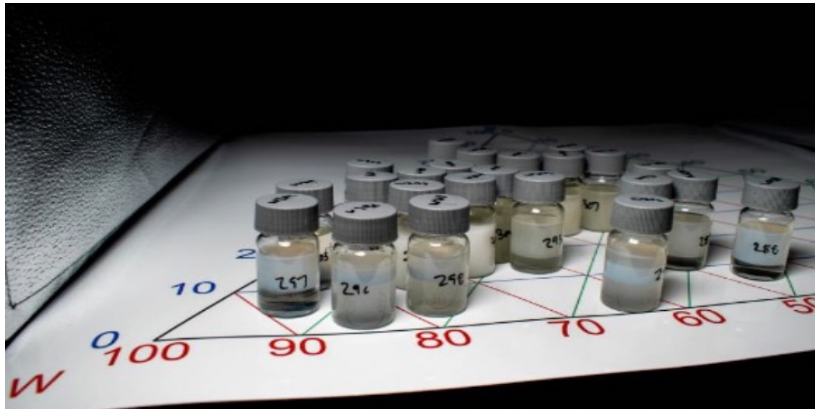
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT
WHERE INNOVATION BEGINS

NNSA
National Nuclear Security Administration

Lawrence Livermore National Laboratory

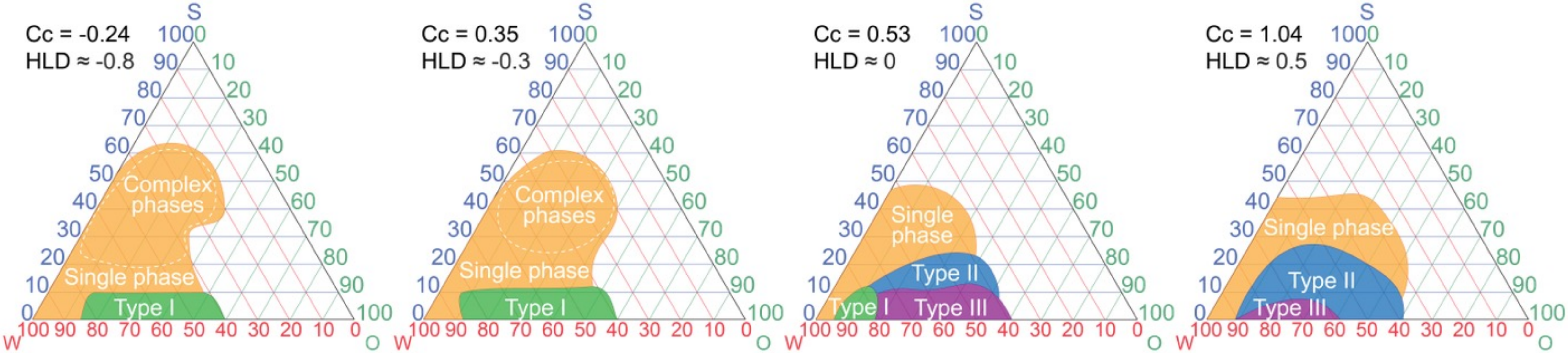
Backup Slides

An empirical approach to stabilize emulsions



- Through this work we have developed a way to fully characterize the stability of each sample by understanding the phase changes as a function of its constituent parts.

- This empirical formulation compared with experimental plans will pave the way for a ”tunable” WbLS depending on the required goals.



More Phase Spaces for Formulations