Material Development and 30-ton WbLS Demonstrator at BNL

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Minfang Yeh

Engineering, technical and project supports for 1T & 30T Prototypes

Ton-scale production and purification facilities

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AAP, The Guildhall York, September 18-21, 2023

Liquid Scintillator (LS) Detectors

- $\bar{\nu}_e + p \rightarrow n + e^+ ; n + p \rightarrow d + \gamma$
- $\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B \rightarrow {}^{12}C + e^- + \bar{\nu}_e$
- $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N \rightarrow {}^{12}C + e^+ + \nu_e$
- $\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^* \rightarrow {}^{12}C + \gamma$
- $\nu_x + e^- \rightarrow \nu_x + e^-$
- $\nu_x + p \rightarrow \nu_x + p$

Large Liquid Scintillation Detectors*

C. L. Cowan, Jr., F. Reines, F. B. Harrison, E. C. Anderson, and F. N. Hayes

Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received February 24, 1953)

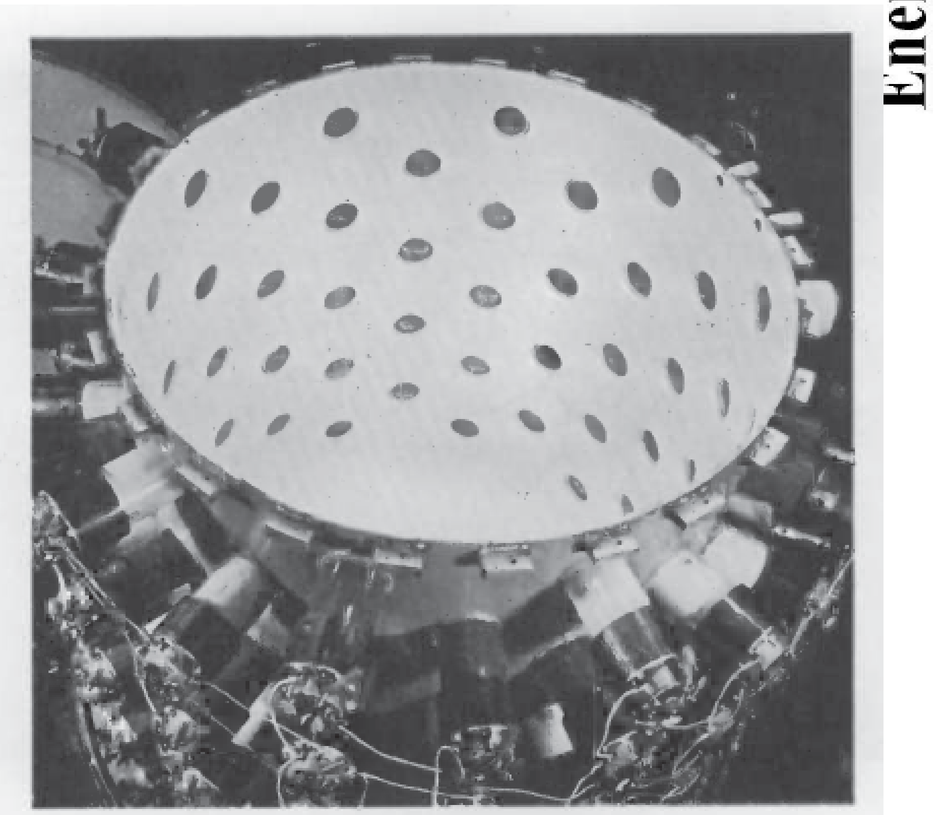
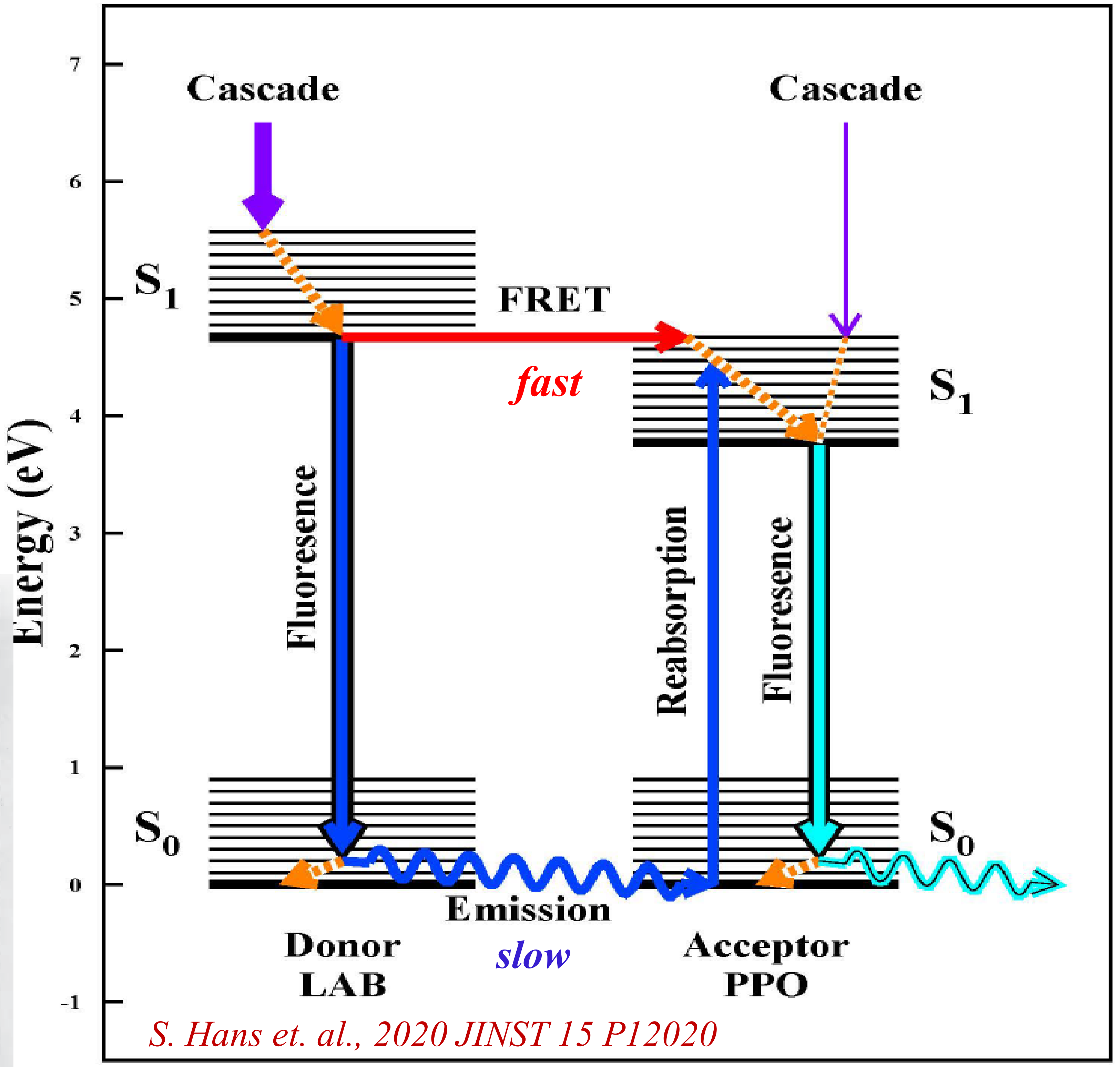
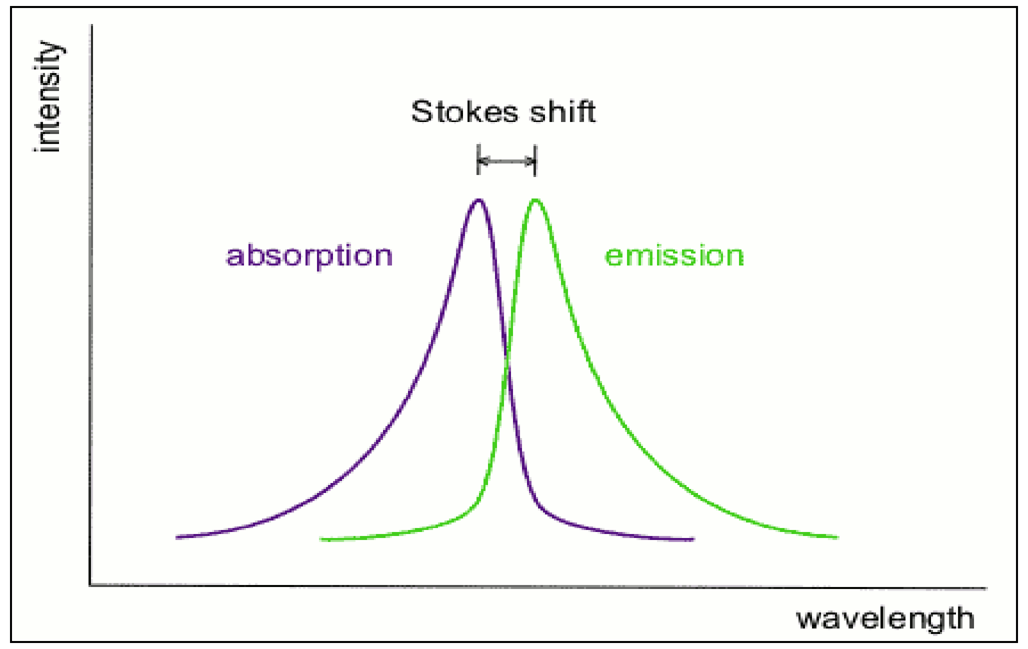
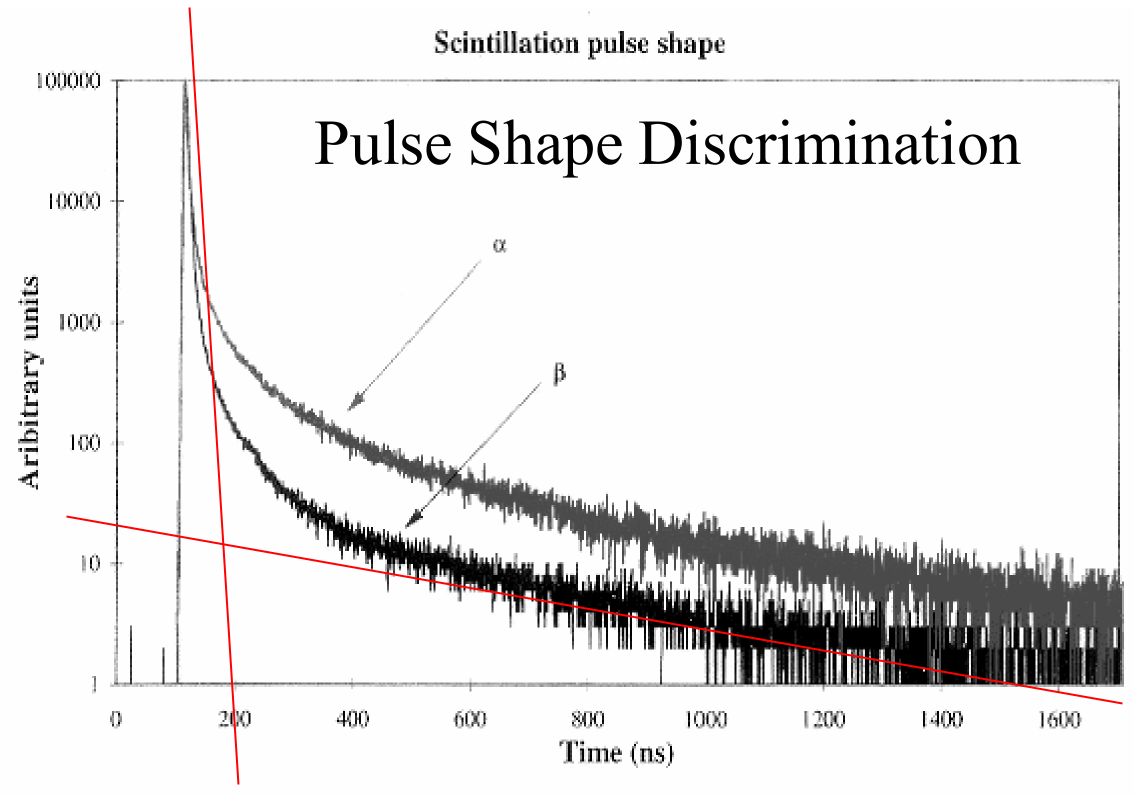


Fig. 2. The Hanford neutrino detector (1953).

Aromatic solvent at $3-4k per ton







From understanding of our Universe to applications in nonproliferation, medical physics, nuclear material detection, LSC, etc.

Stokes-shift, photon-yield, timing structure, and C/H density determine scintillator responses (modern LS is high fp and low toxicity; compatible with detector vessel)

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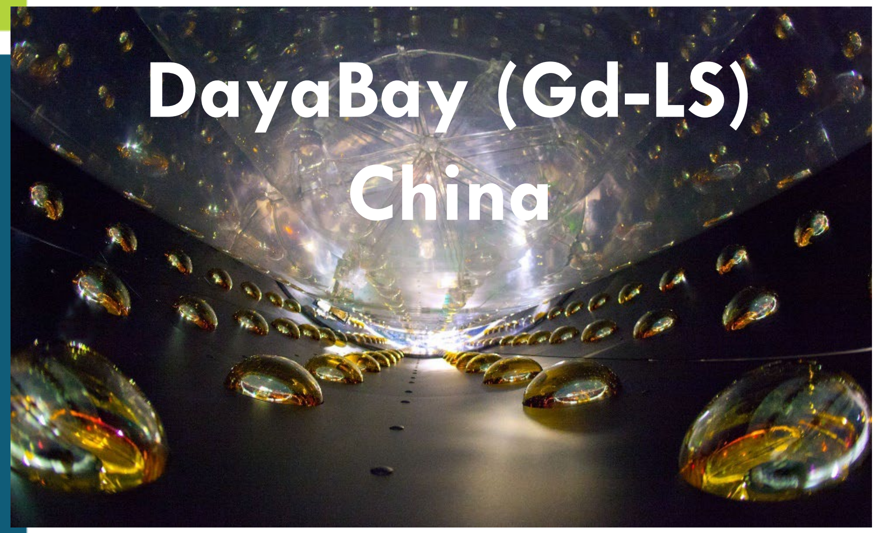
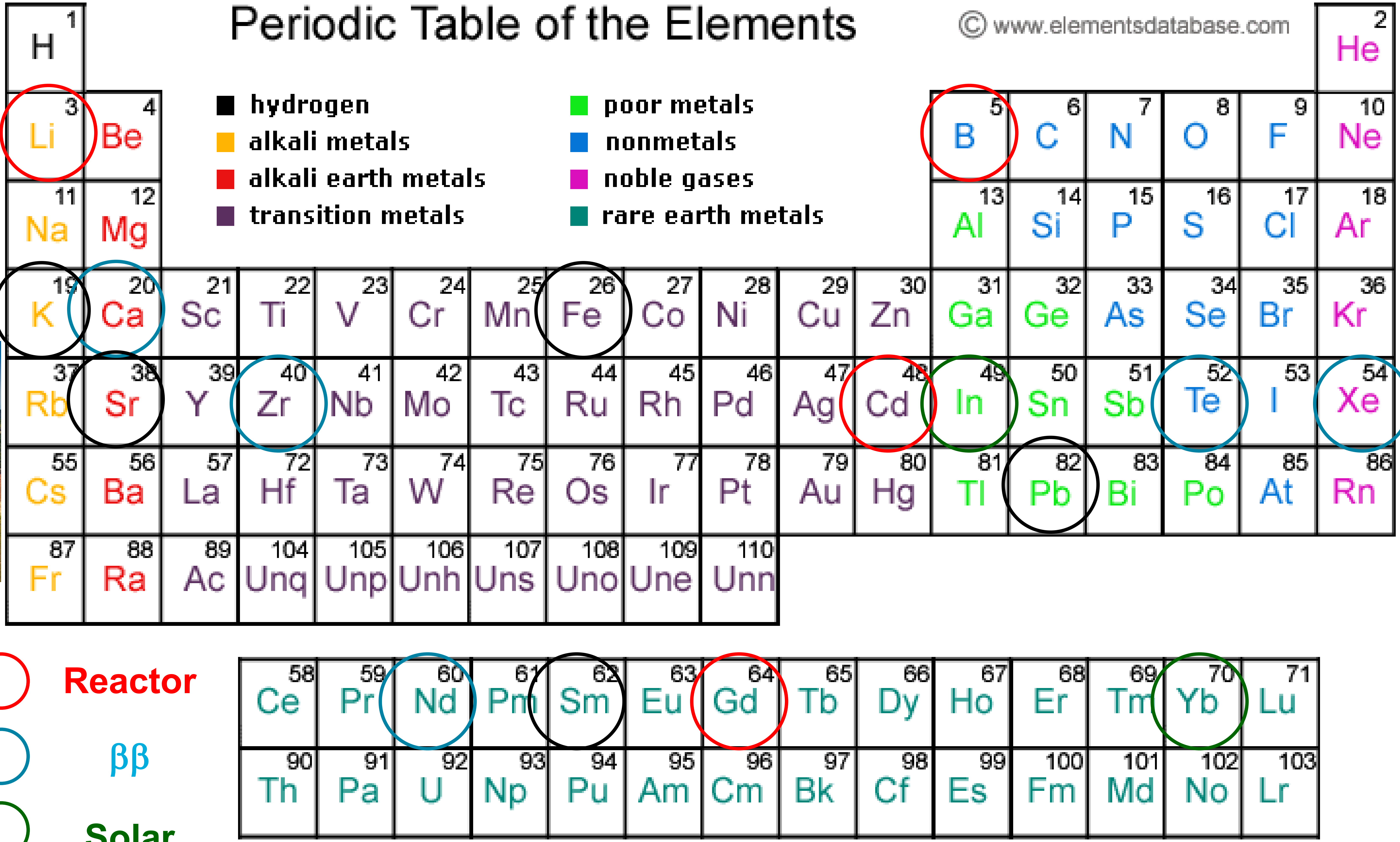
Metal-doped Liquid Scintillators

for neutrino physics and other frontiers since 2000





Reactor

ββ

Solar

Medical, calibration, LSC, etc

Started from LENS R&D

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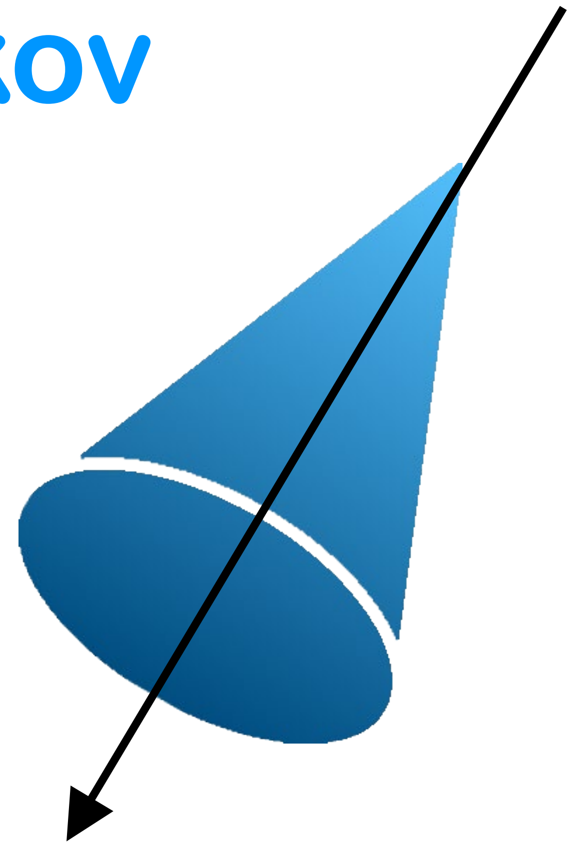
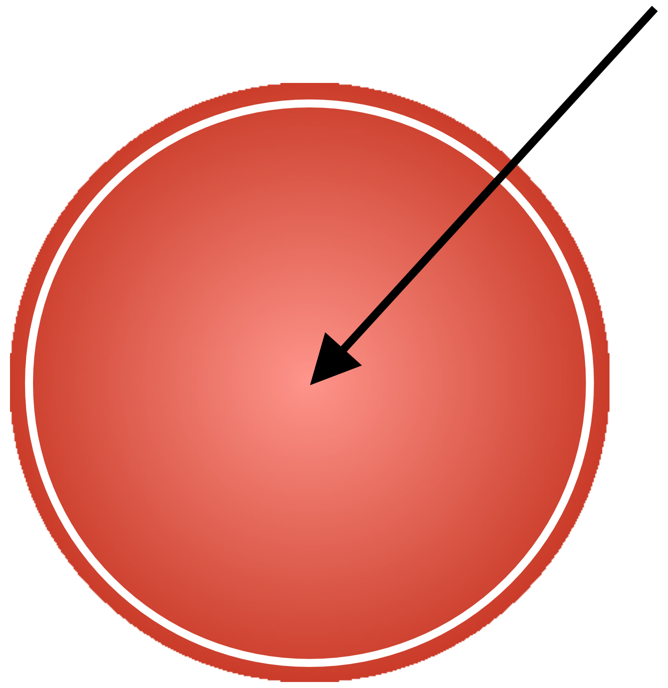
Next Generation Liquid Scintillator Detectors → Directionality

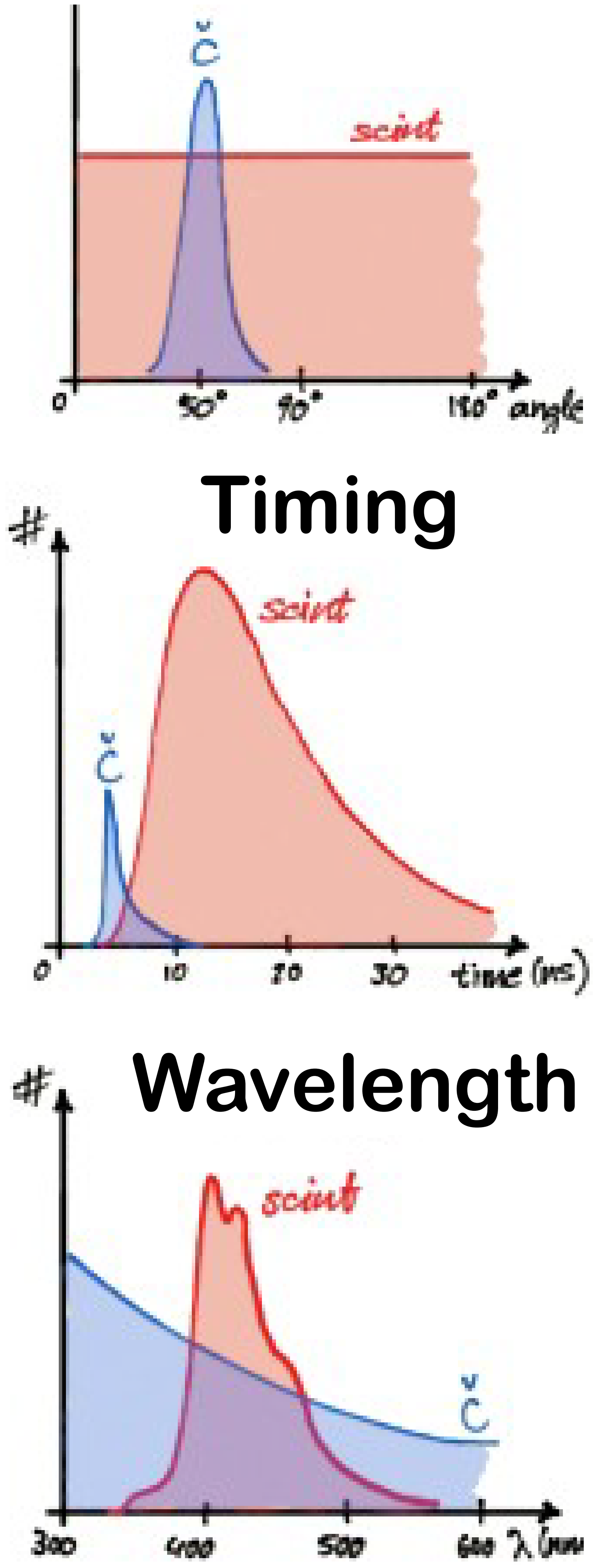
Cherenkov



Scintillation



Angular distribution



Materials:

- Water-based Liquid Scintillator: Cherenkov and scintillation detection
- Slow Scintillator (sWbLS ~10ns): timing separation of slow(er) scintillation from fast Cherenkov
- LiquidO: stochastic light confinement; lossless scattering

Instrumentation:

- LAPPD, dichroicon

Water-based Liquid Scintillator

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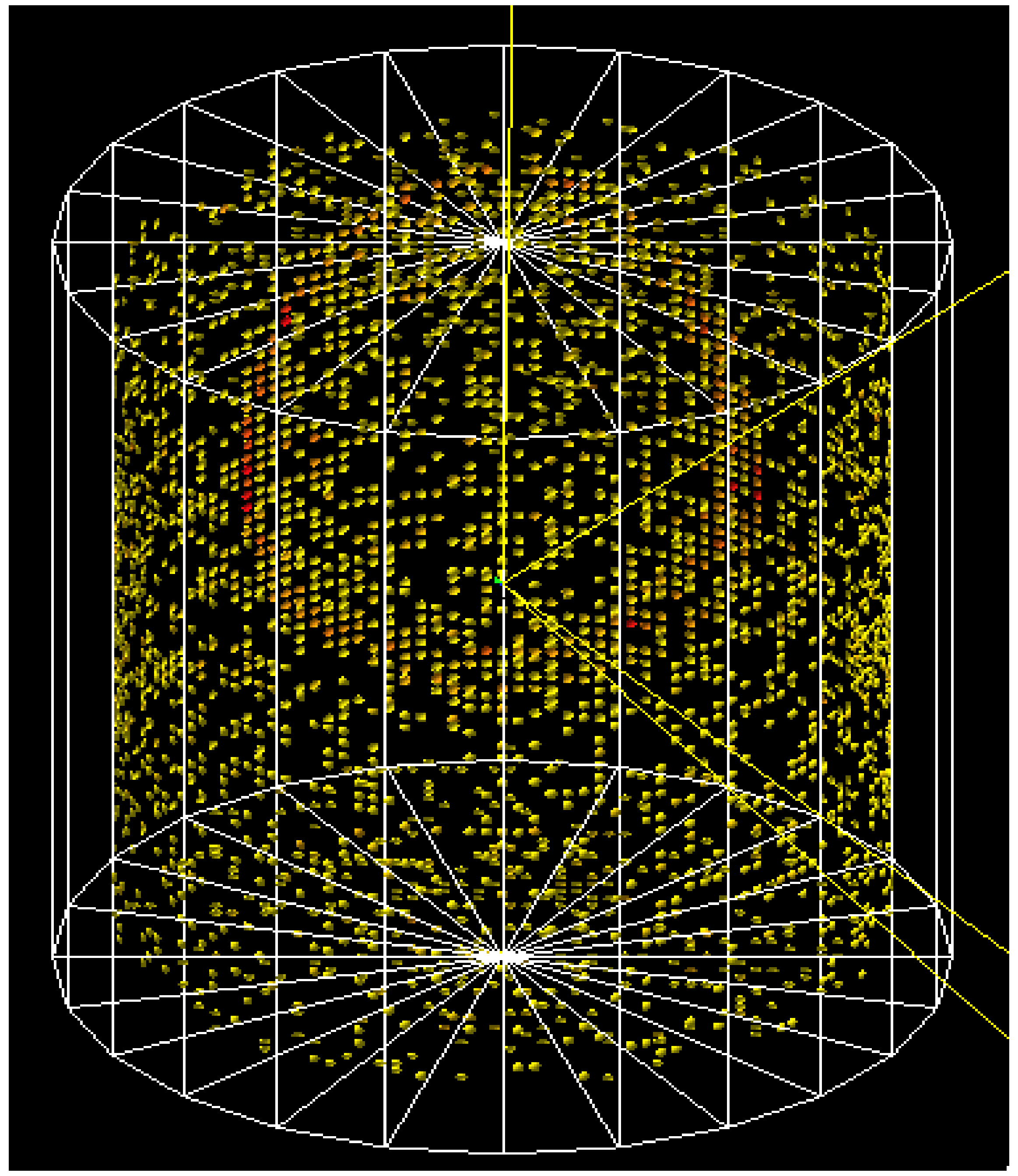
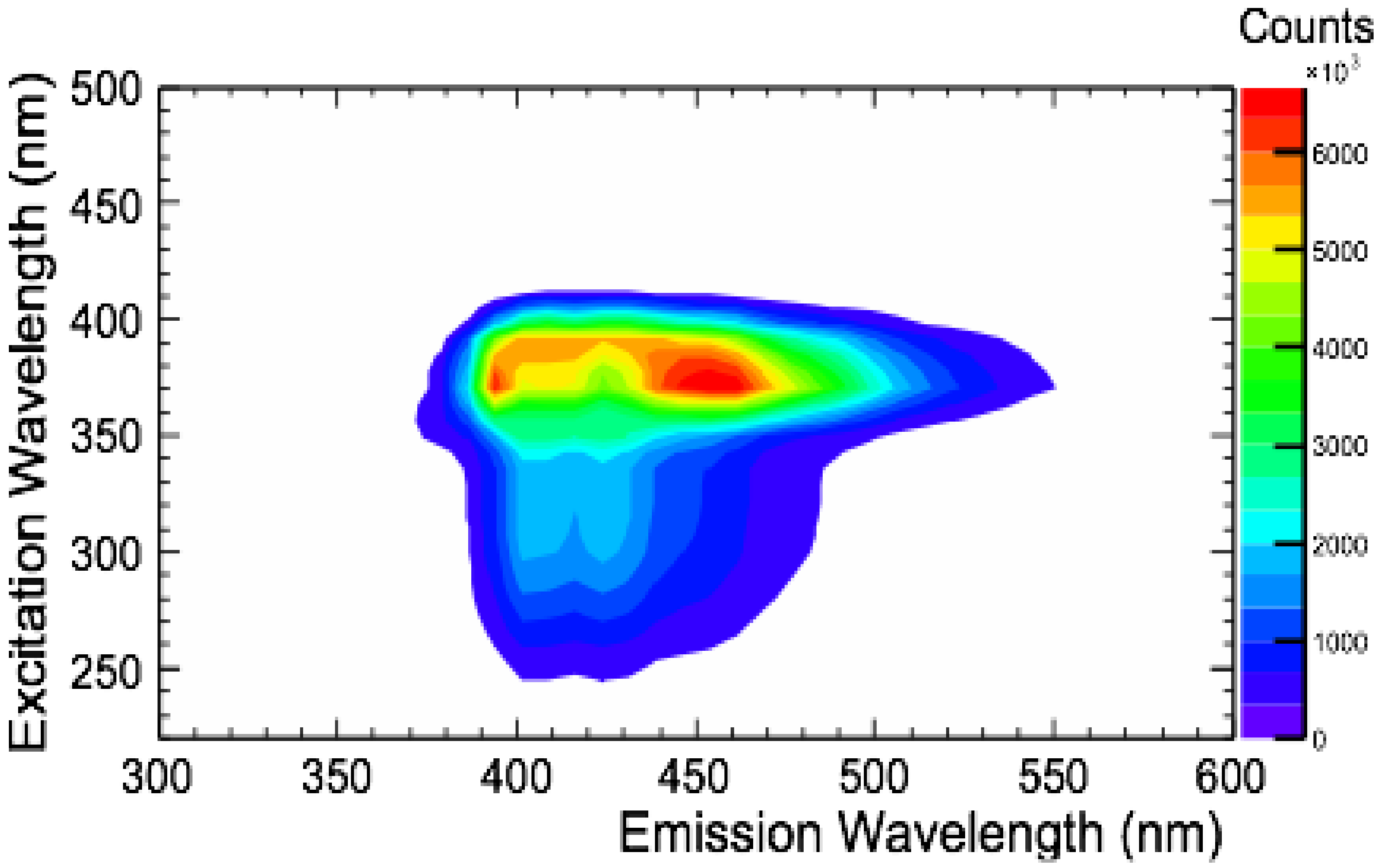
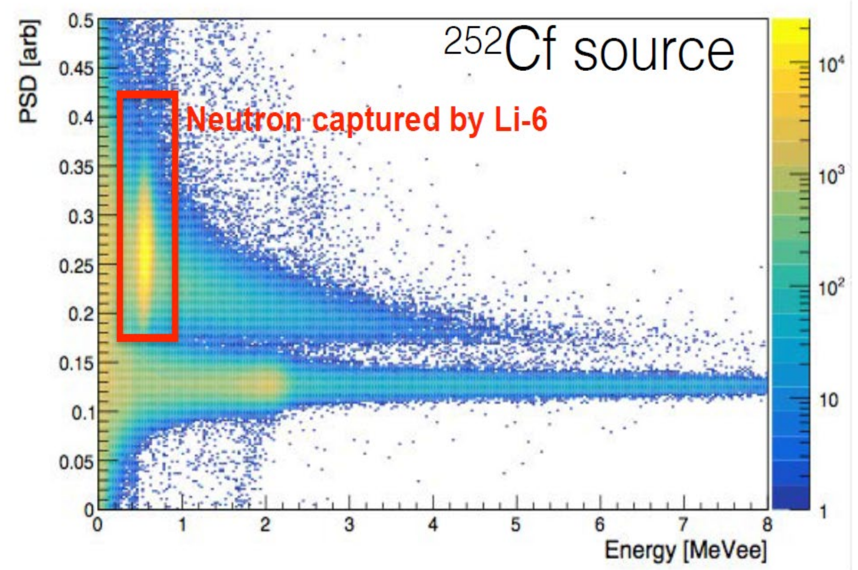
If you always do what you always did, you will always get what you always got. -Albert Einstein

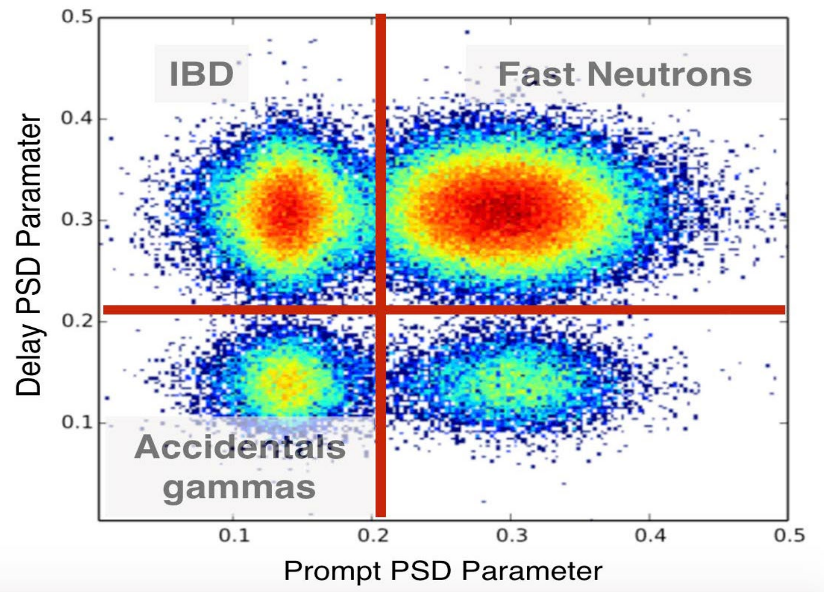
- A novel low-energy threshold detection medium, bridging scintillator and water.
- Tunable scintillation light from ~pure water to ~organic.
- Environment-friendly, noncombustible, and excellent material compatibility; feasible for **field study**.
- A particle detector capable of Cherenkov and Scintillation detections
- Viable to load a variety of metallic isotopes for varied particle detections (**neutron-enhanced**)





Tunable LS%, timing and emission





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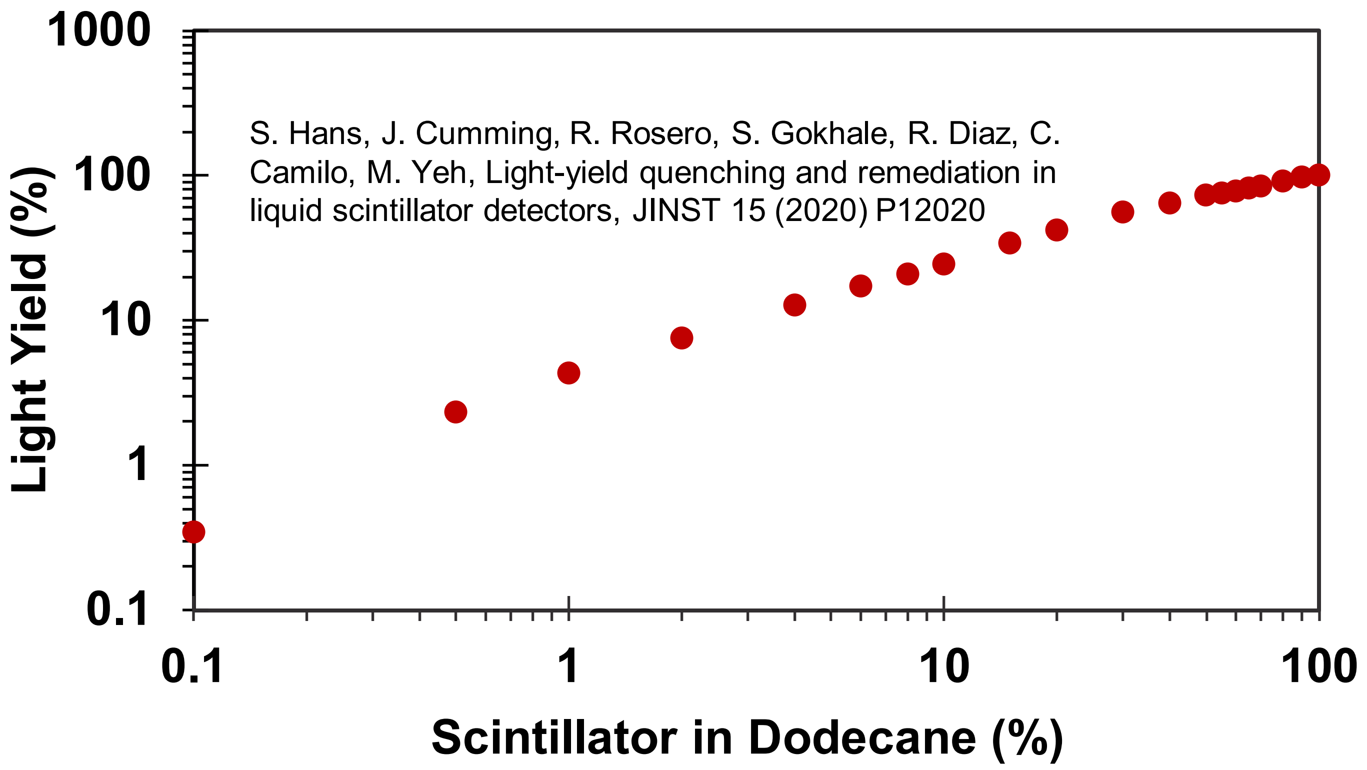
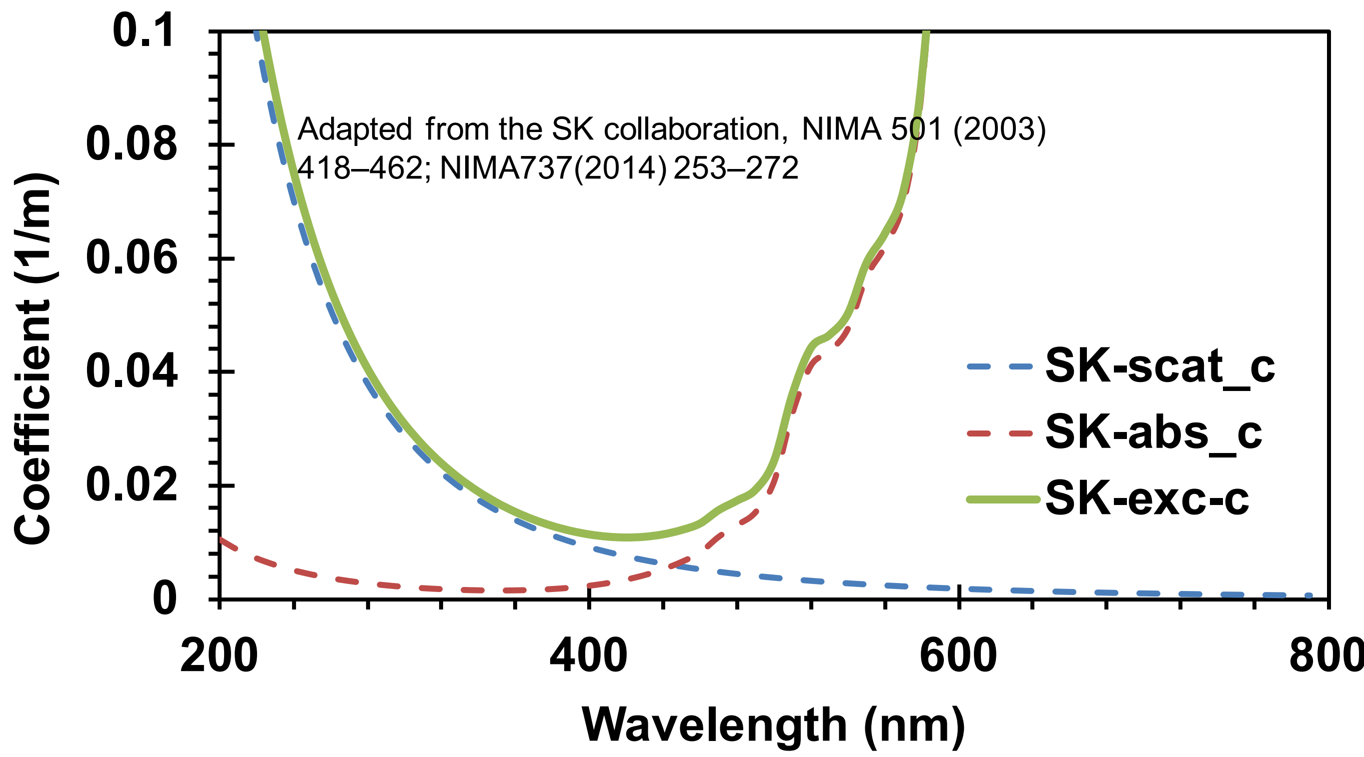
4 tons of (PROSPECT) ^{6}Li-doped LS production for at BNL in 2019

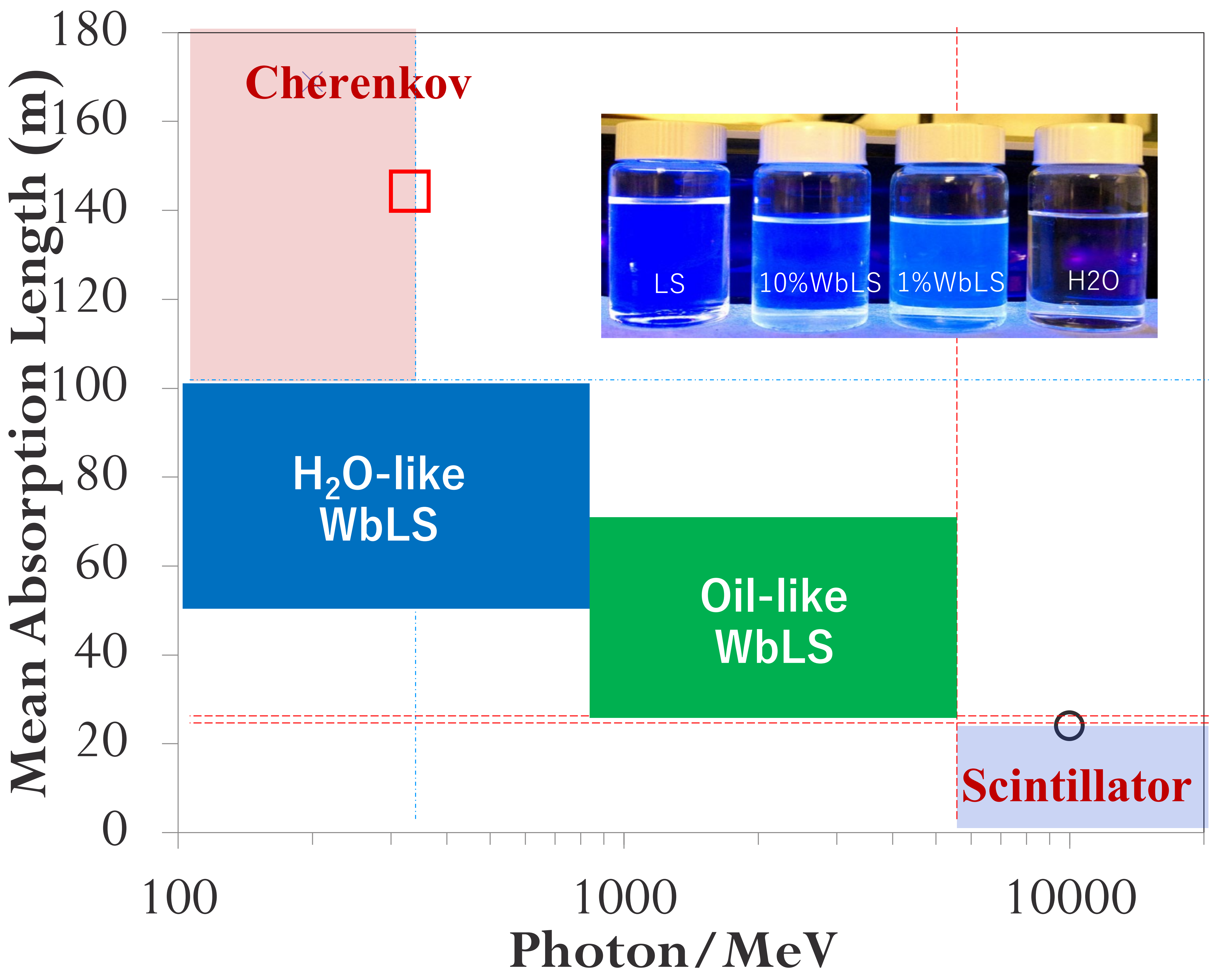




Oil vs H_2O

Water-like WbLS

- 1000s ton-scale detectors
- Long scattering length (>25m at 450nm)
- In-situ circulation feasible
- 1-10% LS loading in water (100-1200 phs/MeV)
- Metal-dope (~all elements)
- 30TBNL, Eos, ANNIE, BUTTON, THEIA



Oil-like WbLS

- 1-10s ton-scale detectors
- High light-yield
- PSD capability
- Not necessary for in-situ circulation
- >90% LS with water (>10,000 phs/MeV)
- Metal-doped (~all elements)
- PROSPECT, (G3)DM, LiquidO

First WbLS concept introduced in 2010ANT (Santa Fe) and A new water-based liquid scintillator and potential applications, NIMA, 2011

Yeh at AAP2023

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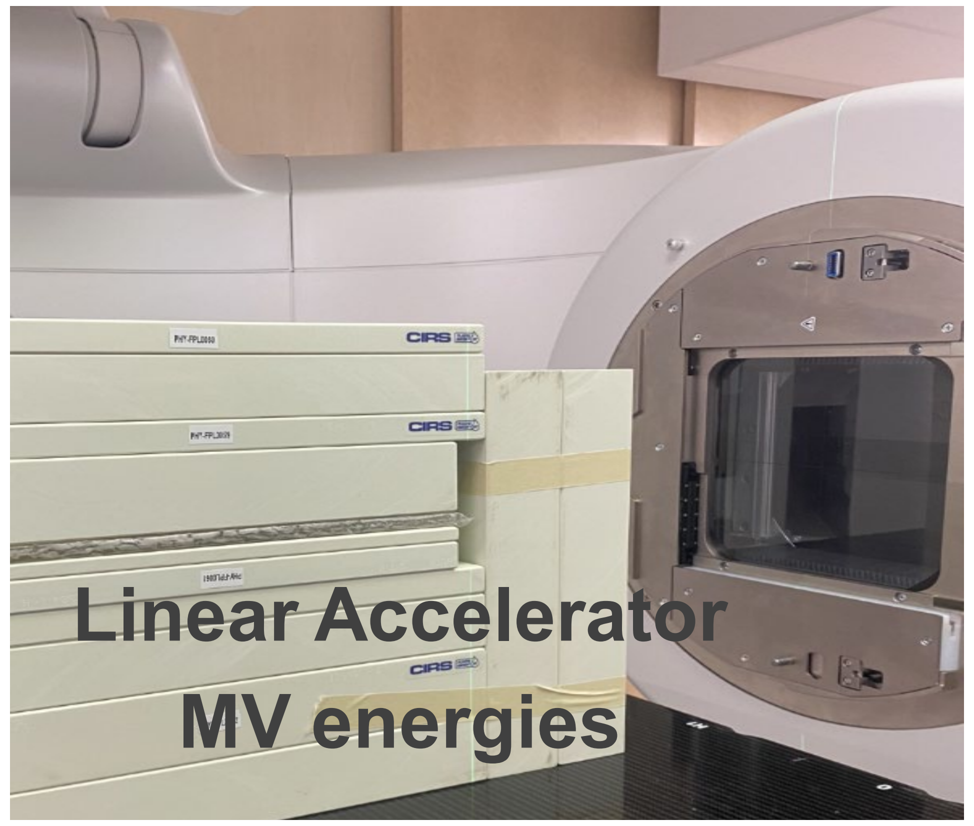
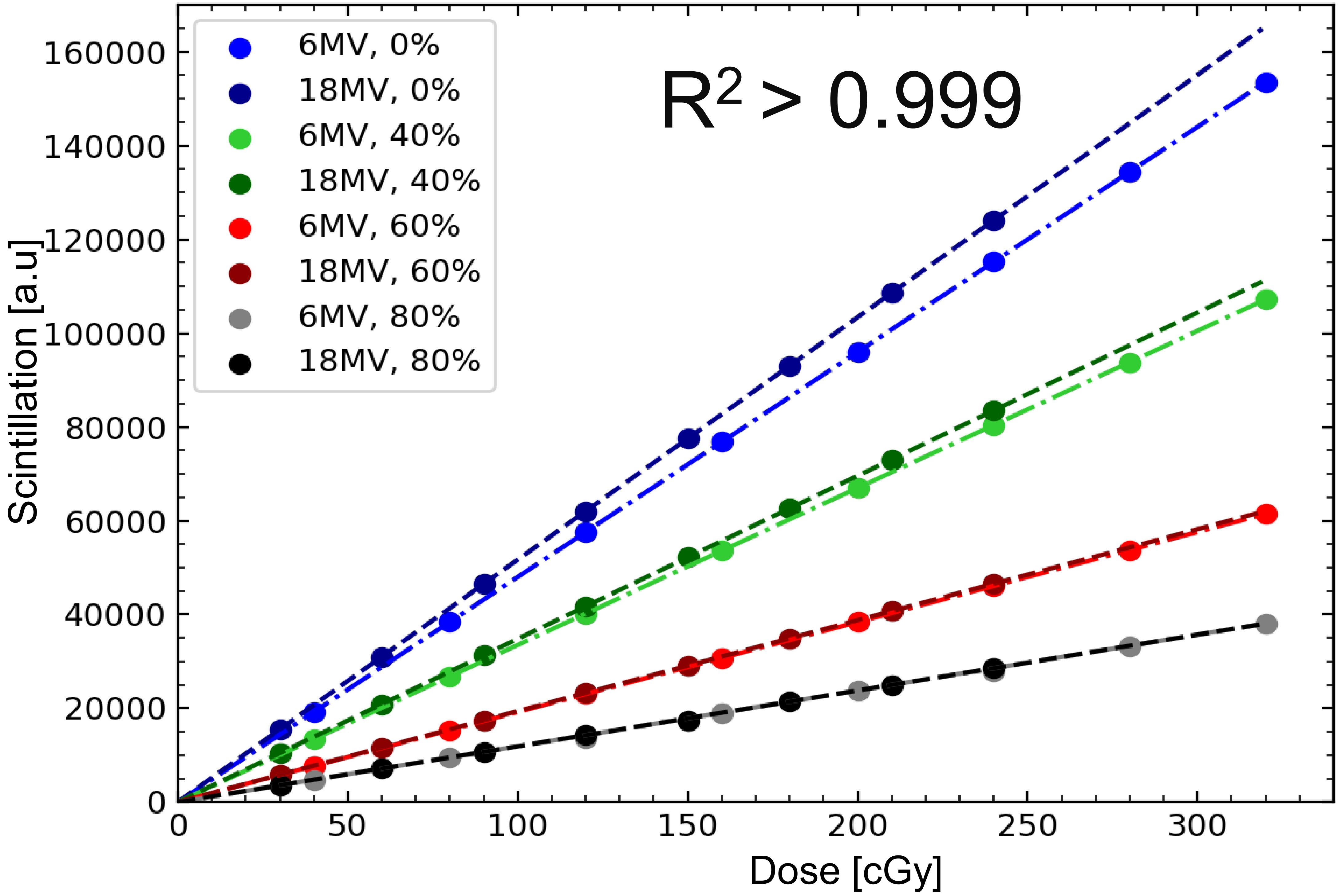
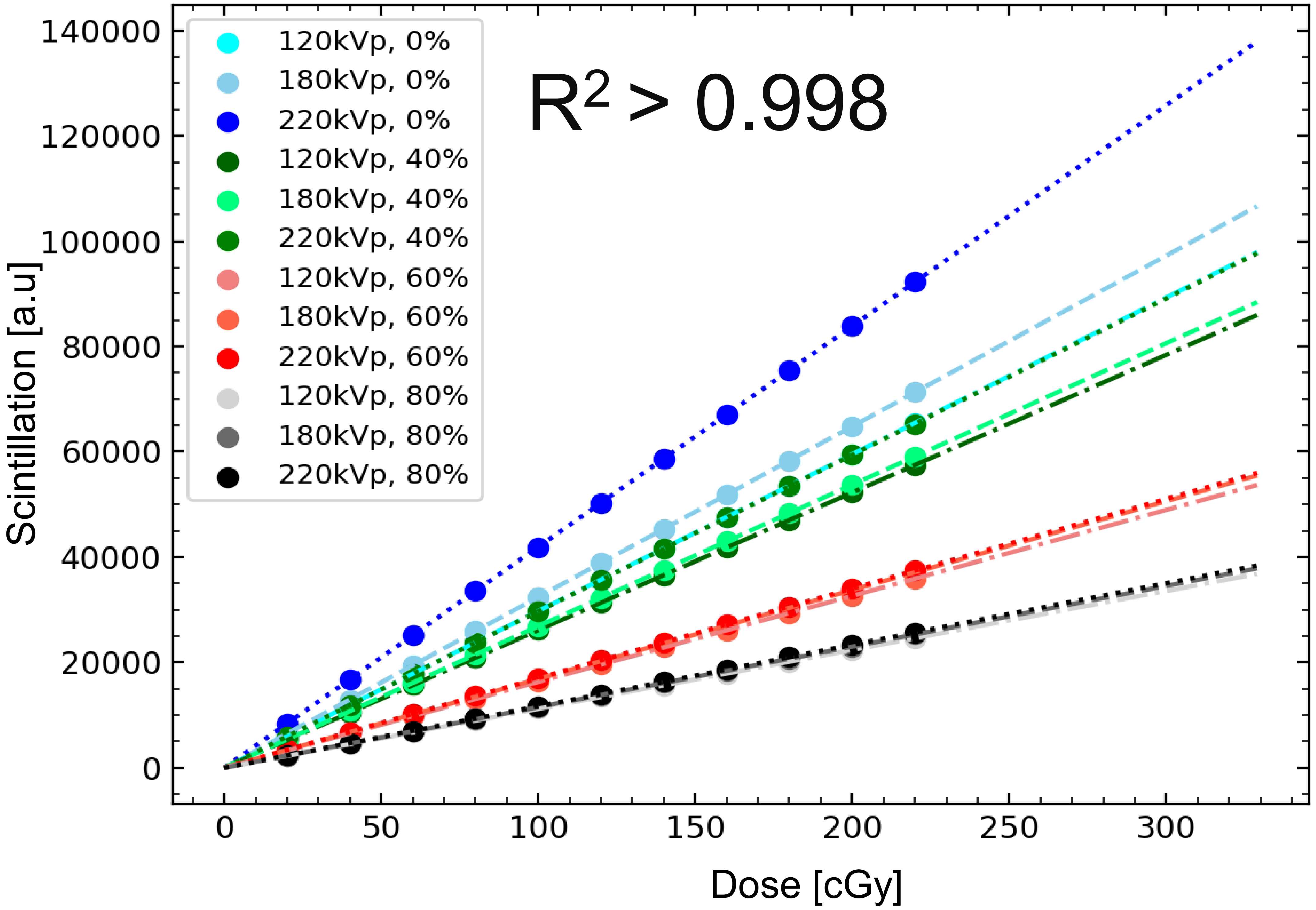
Linearity of the WbLS response with the dose in KV and MV energies







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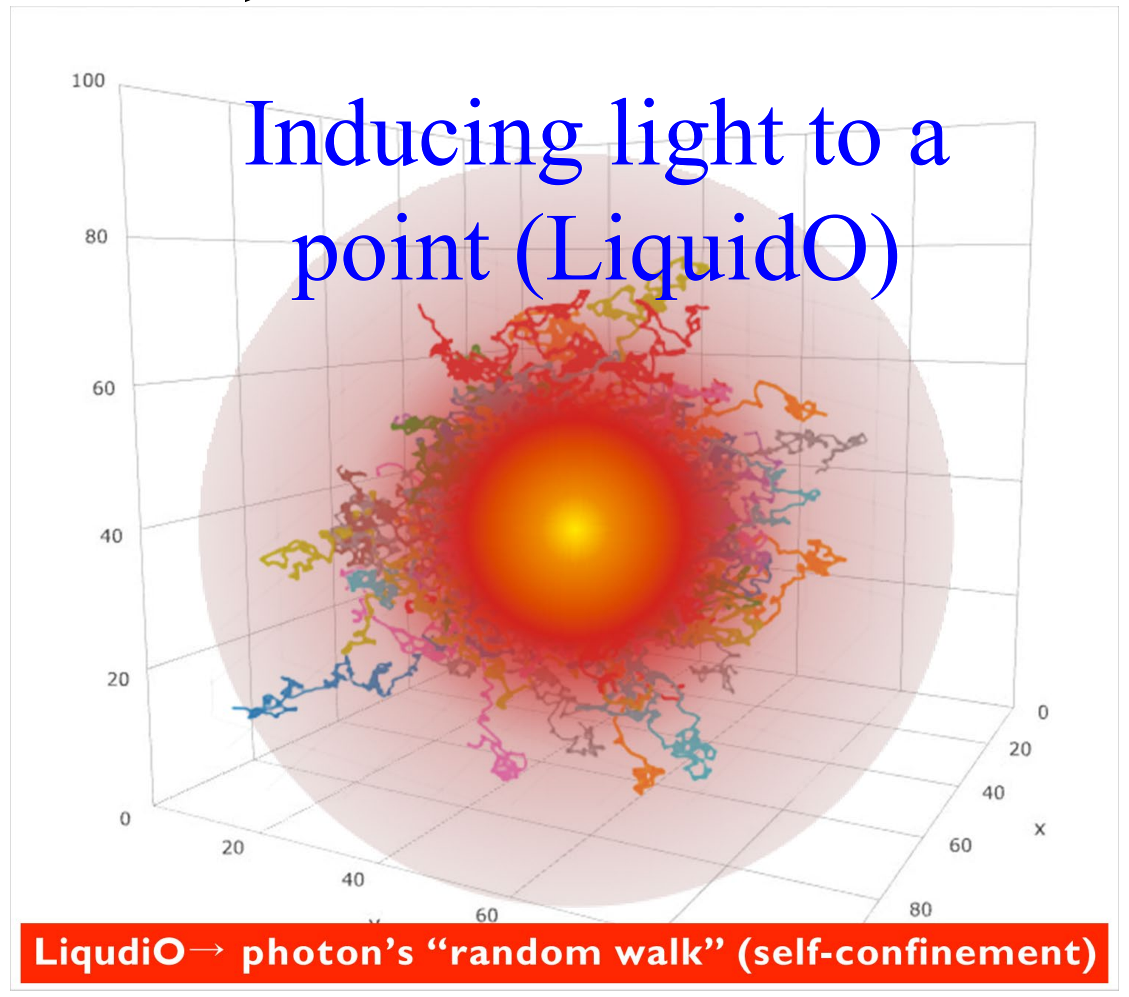
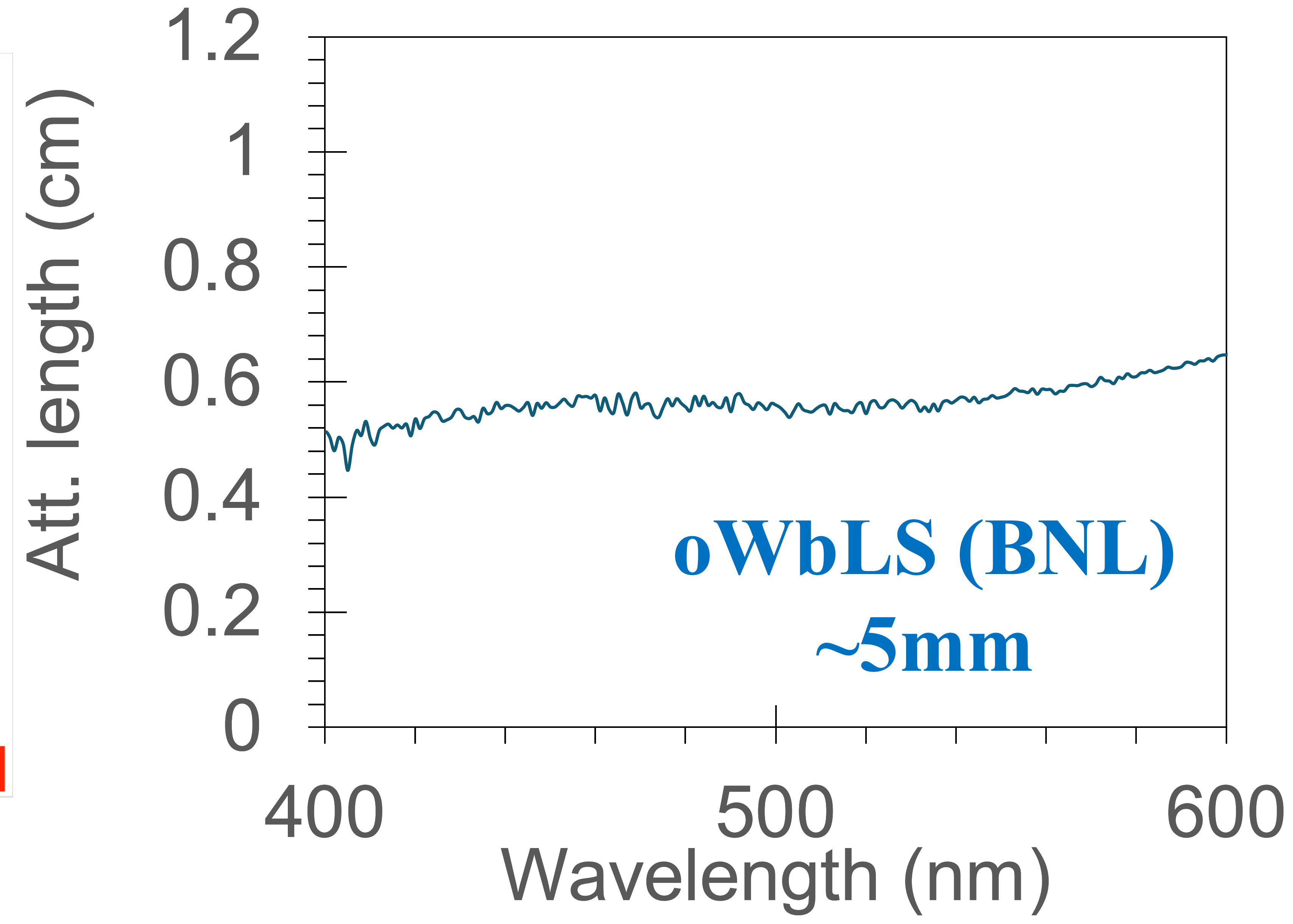
Dosimetry (~60% water)

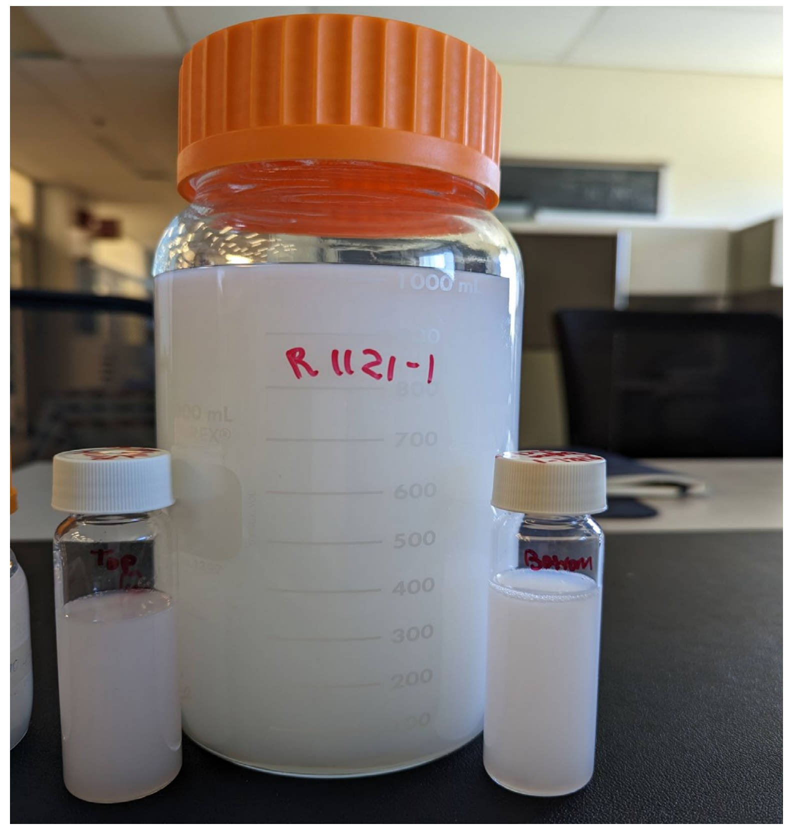
Daphnée Bernier-Marceau

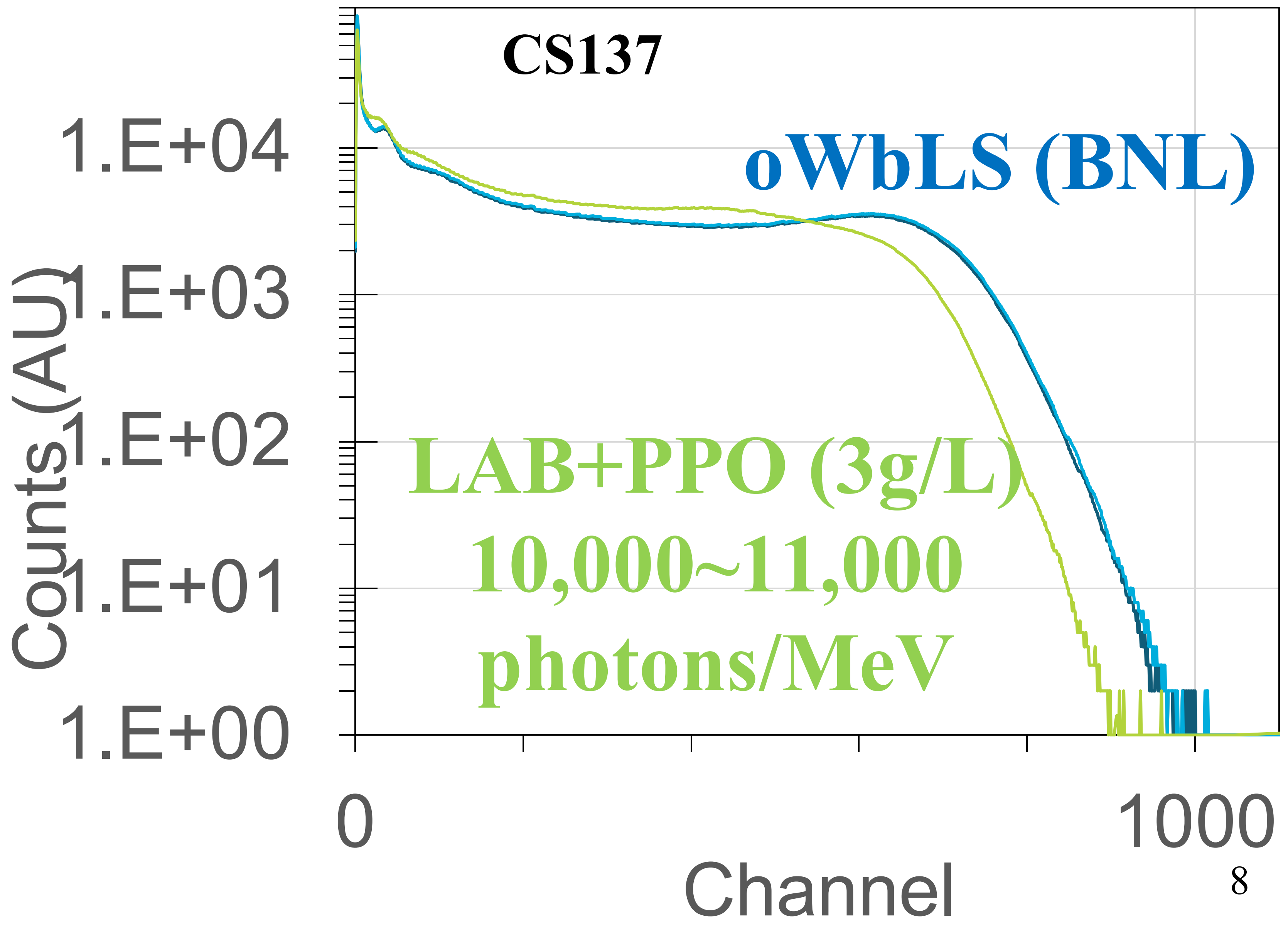
Opaque WbLS (*>90%LS*)

- Highly scattered WbLS (highly pixelized) feasible for near surface detection: potential applications in off-the-fence monitoring, test-site transparency, etc.
- High light-yield (>11000 ph/MeV) and superior PSD Tunable timing structure and emission range
- Capability of loading metallic ions demonstrated at >10% (w) level
- Started detector development with CLOUD & LiquidO (liquid development and ton-scale facilities); prototype data taking with Michigan and PennState









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A water-like WbLS for kiloton-scale optical detector: GdWbLS vs (1~5%)WbLS

- Benchtop and Prototype developments
- Ton-scale production facility

Benchtop Development

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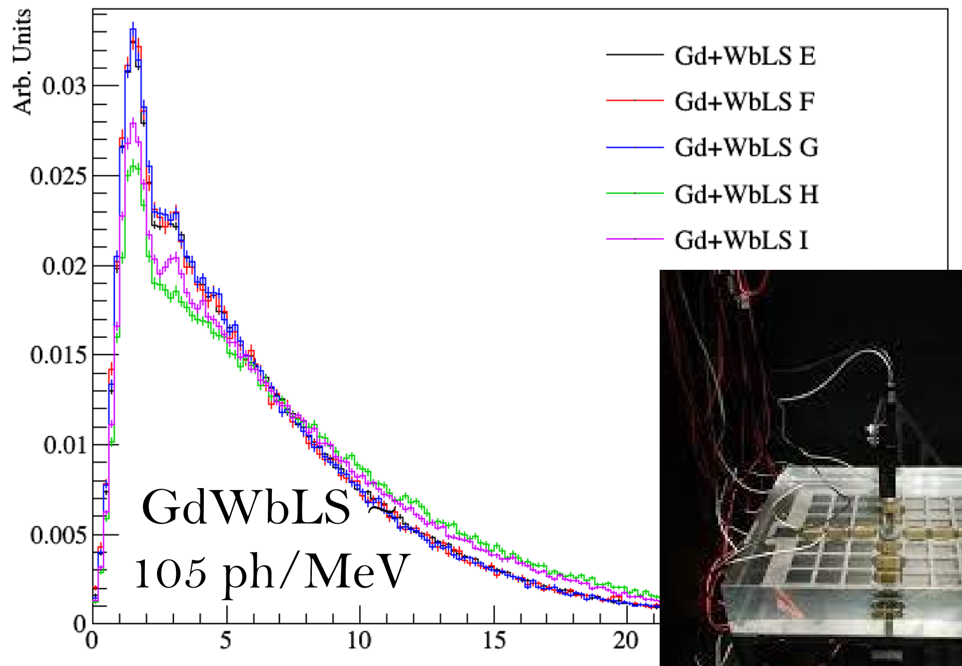
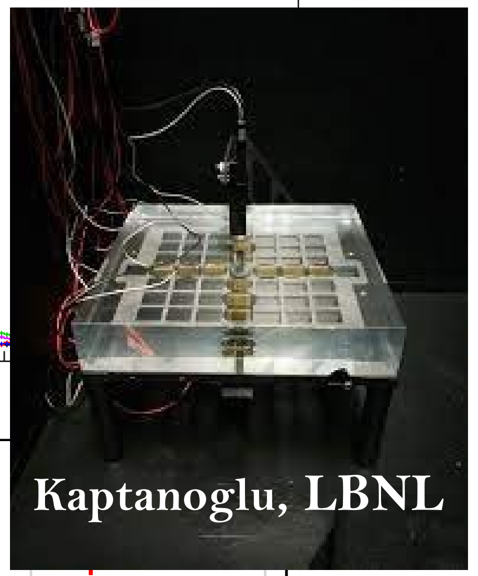
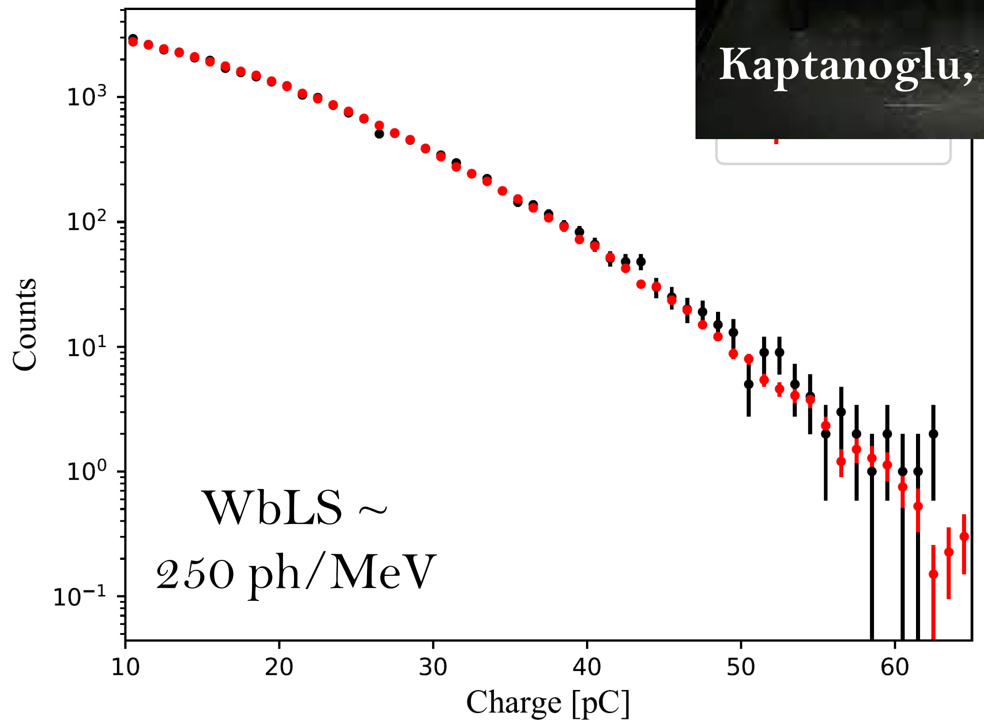
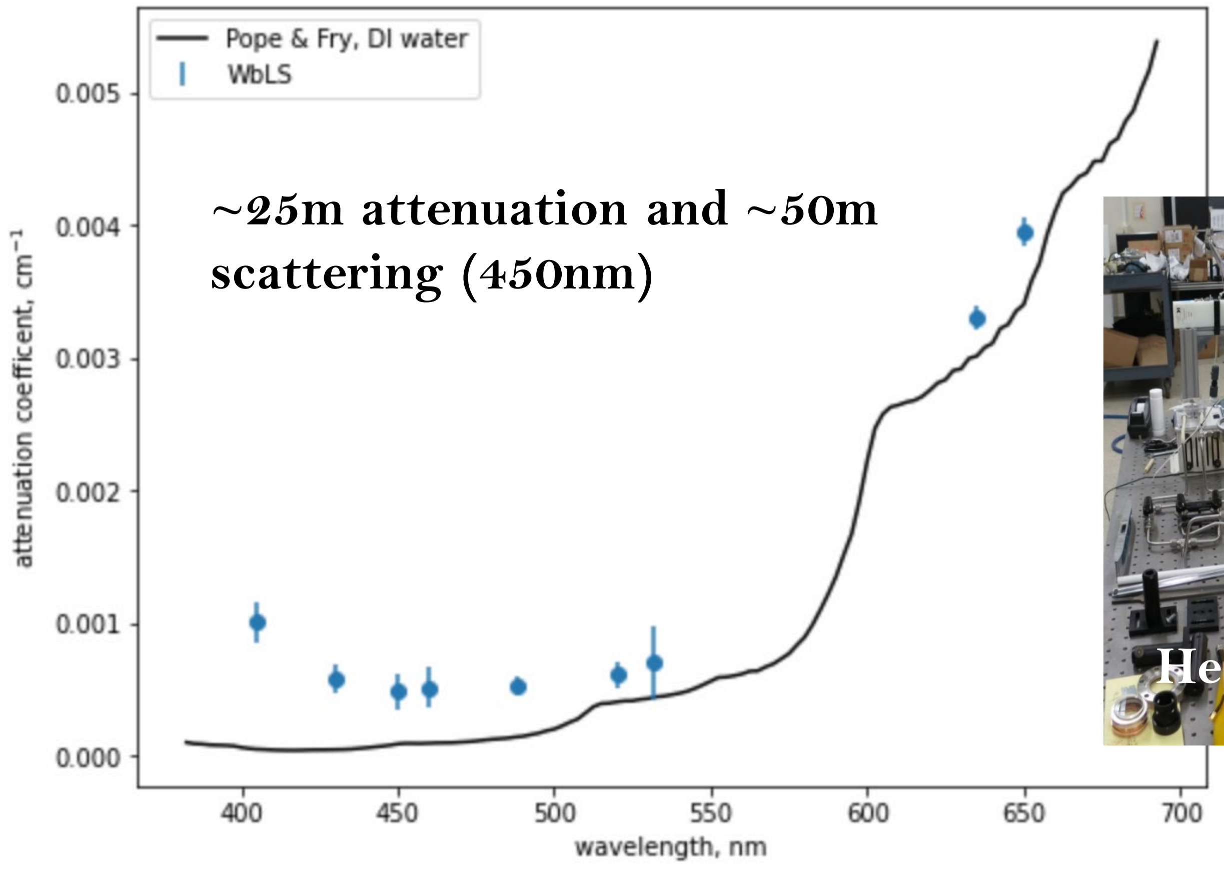
- Developed and characterized a variety of WbLS formulas for multiple frontiers; all liquids stable since production (~years).
- Demonstrated Gd-, Li-, and B-doped WbLS with projected performances.
- New initiates in XbLS (triple-coincident)
- Established material compatibility program to qualify detector construction.

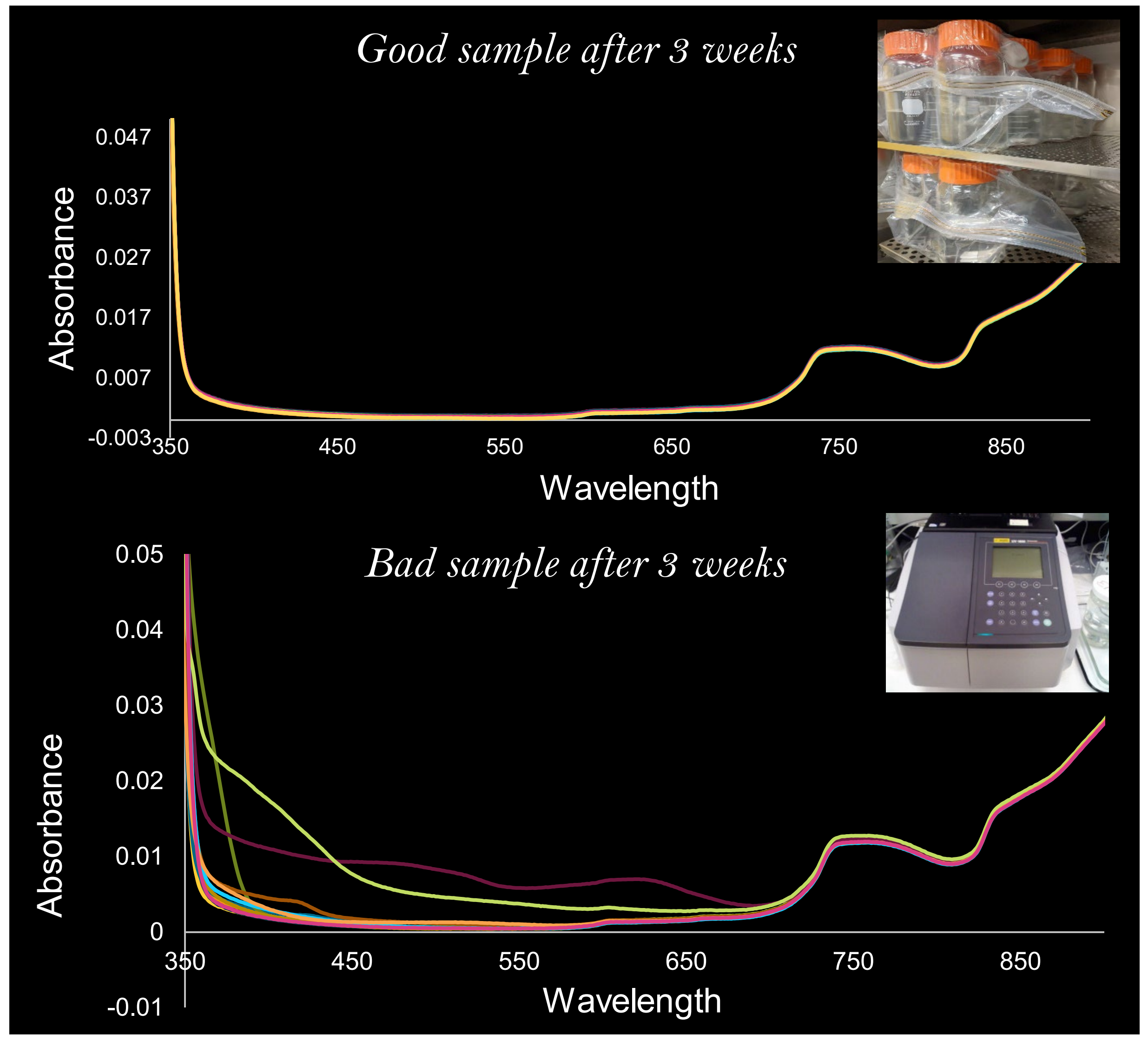








orcid.org/0000-0003-2244-0499

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Scale-up Development: 1-ton Testbed (1TBNL)

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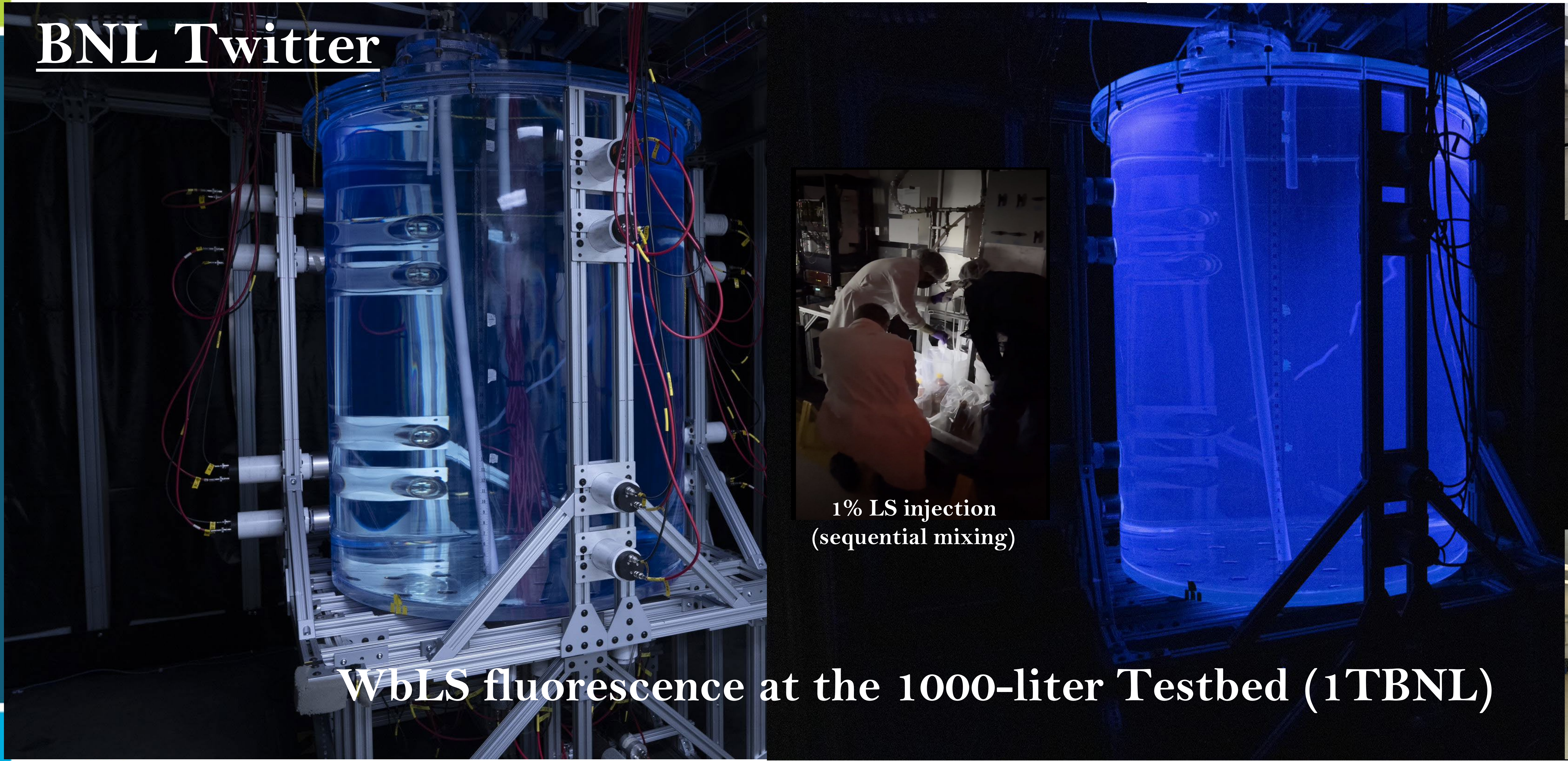
BNL Twitter



1% LS injection
(sequential mixing)

WbLS fluorescence at the 1000-liter Testbed (1TBNL)

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Progress at 1TBNL

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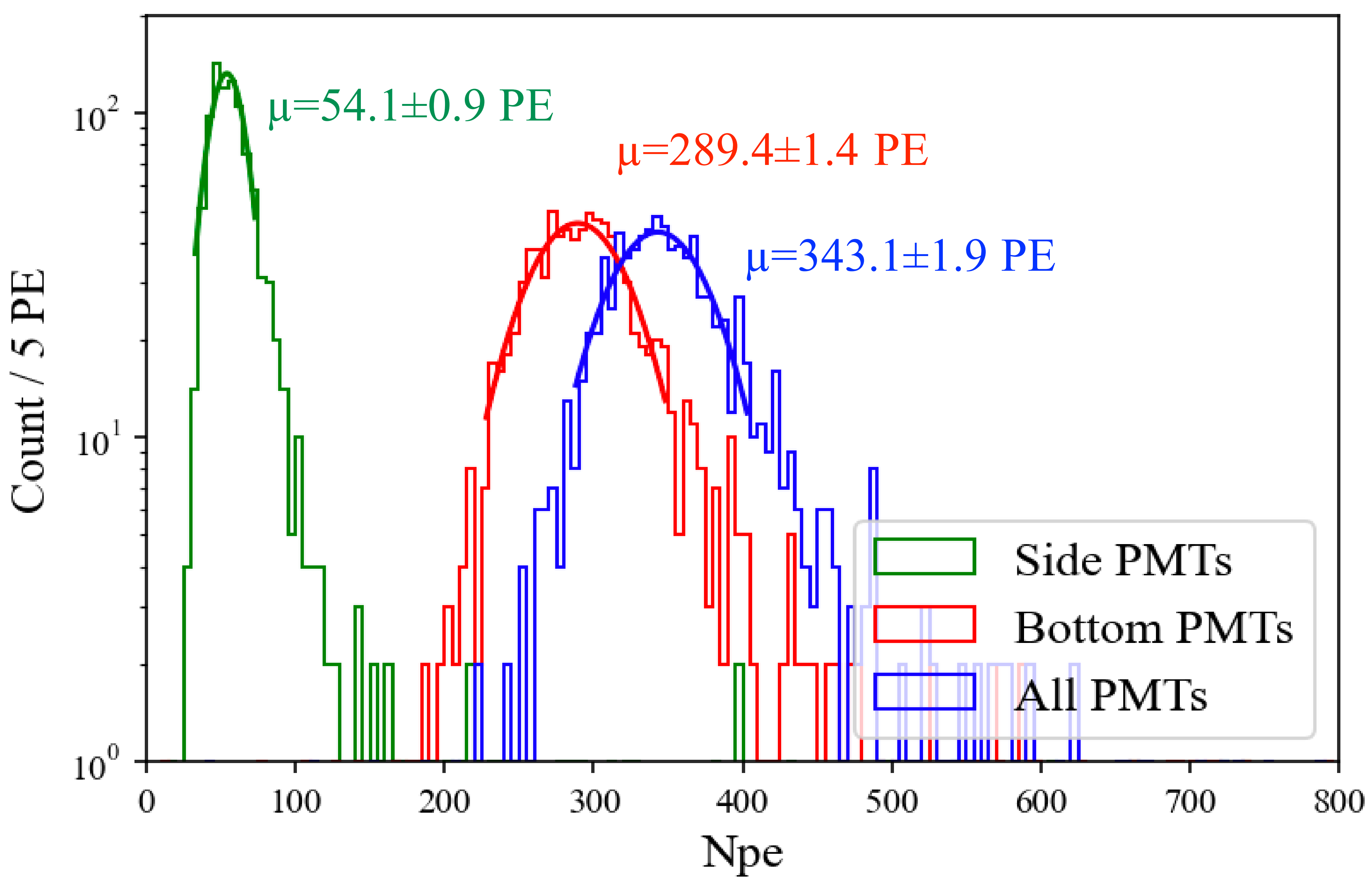
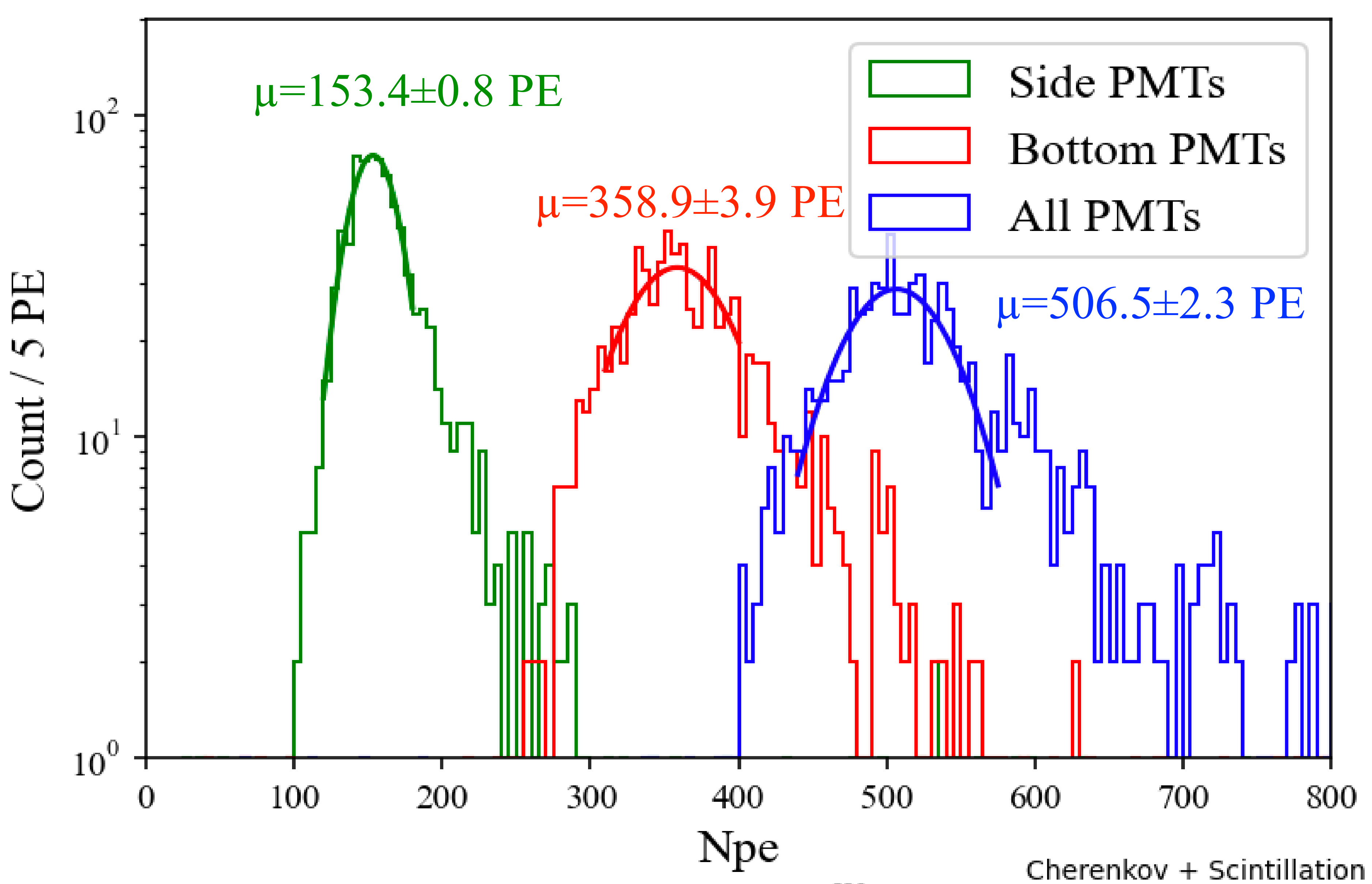
Tagged crossing muons in **water**

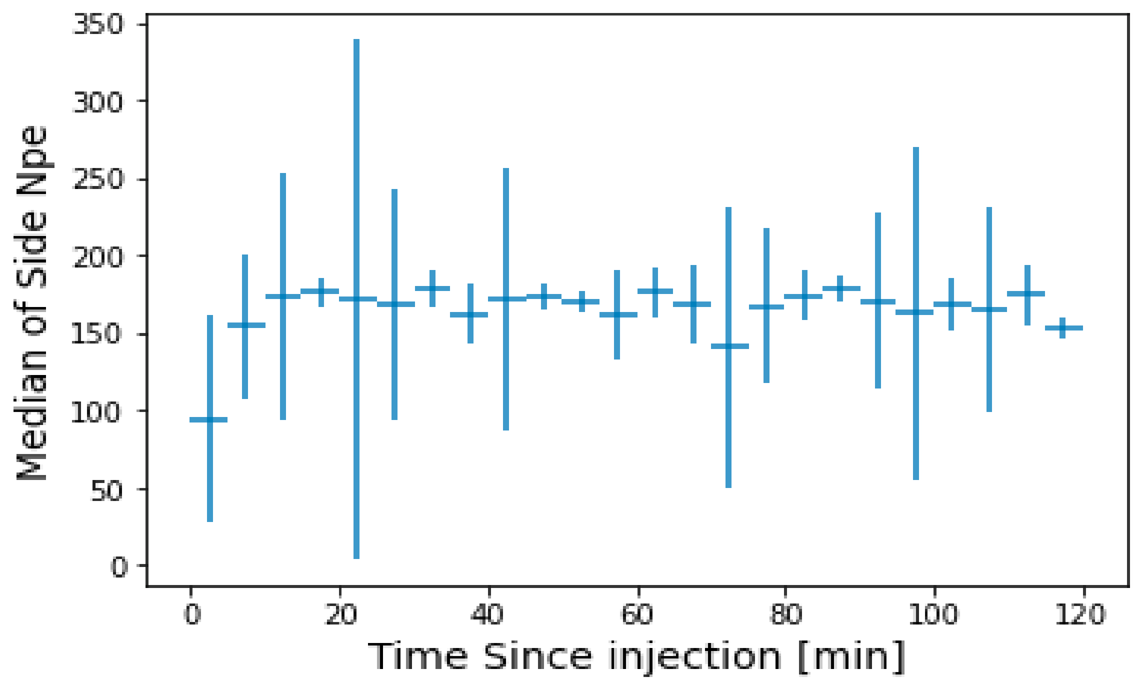


1% LS injection

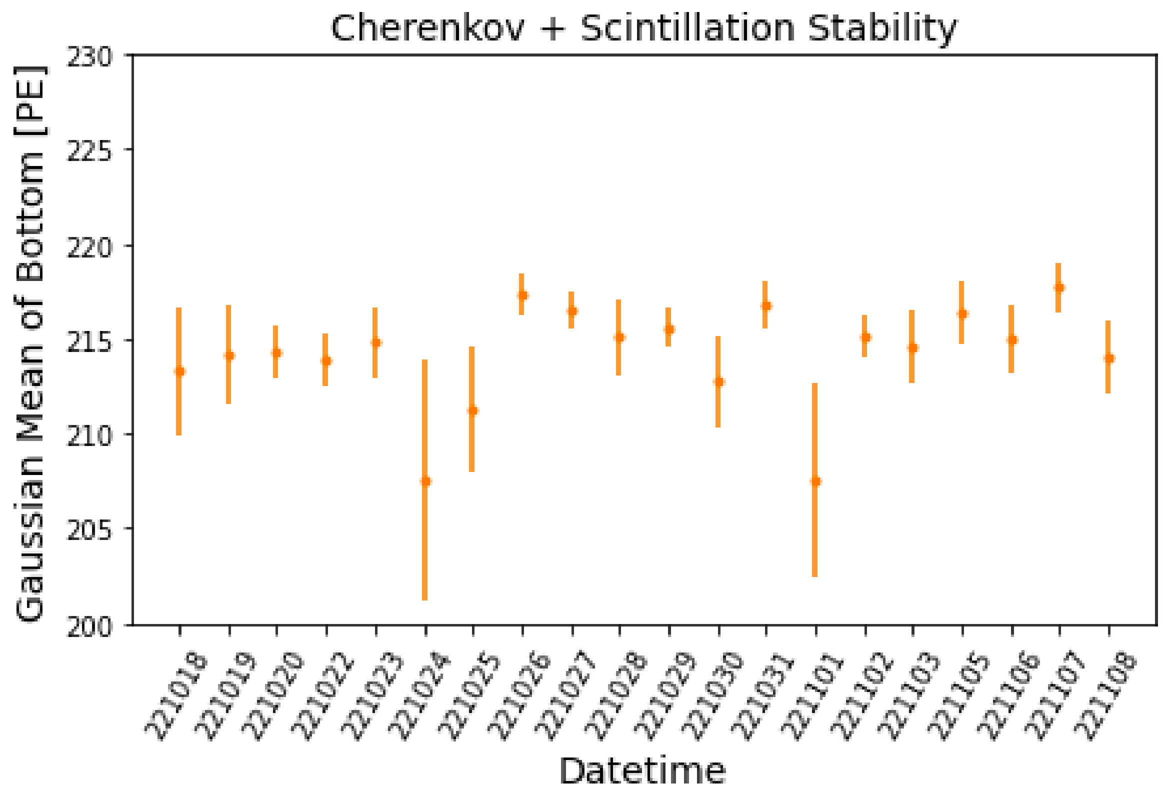
Tagged crossing muons in **WbLS (1%)**



- Light enhancement (scintillation) from the tagged crossing muons with only 1% LS in water
- Successful demonstration of transforming a water Cherenkov detector to a WbLS detector by **sequential mixing technology** (cost-effective with minimum labor)
- WbLS stability observed over months of operation (cont.)



Homogeneity observed 20mins after injection



Stability of 1%WbLS observed

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30-ton Demonstrator (30TBNL)

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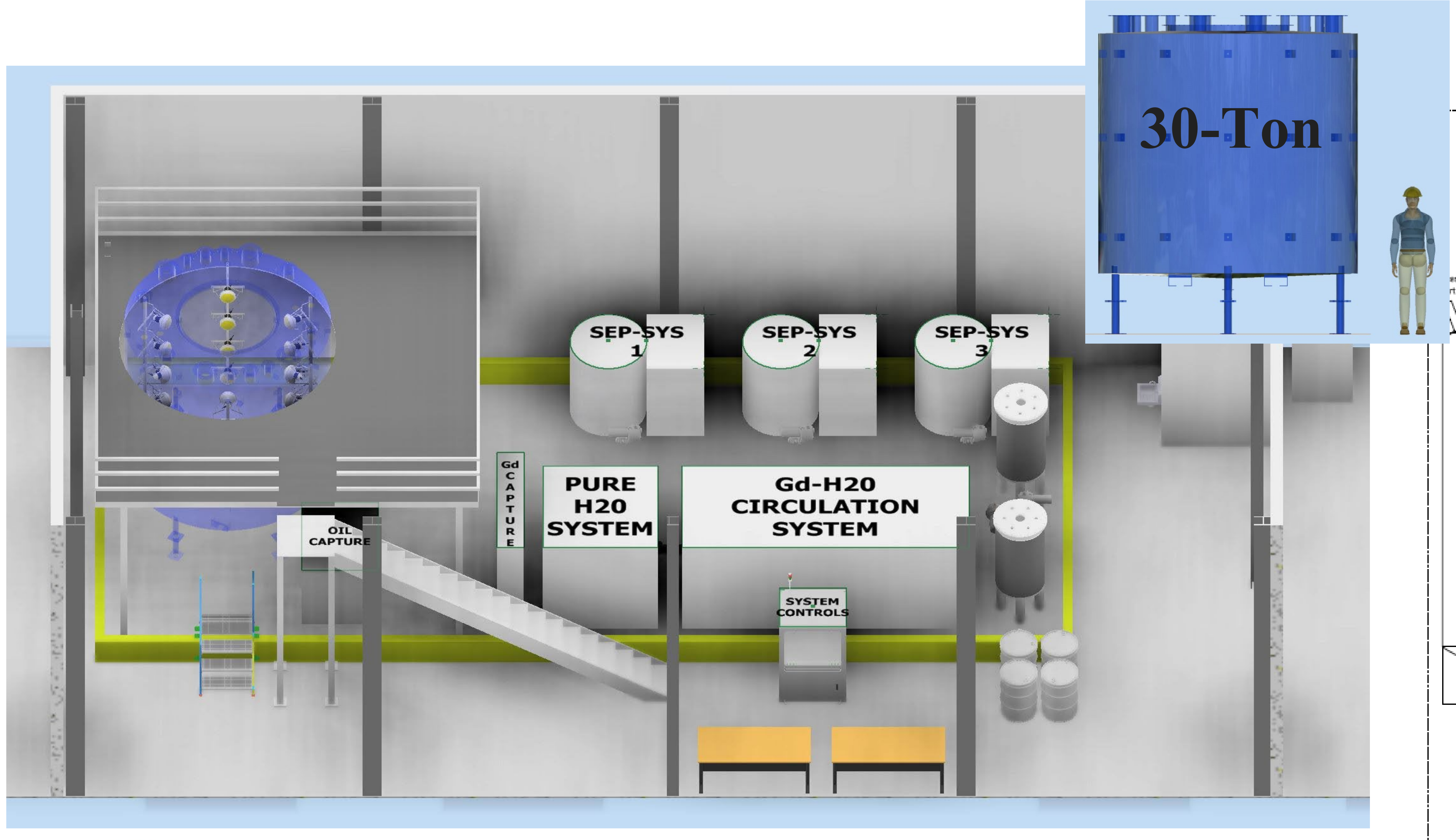
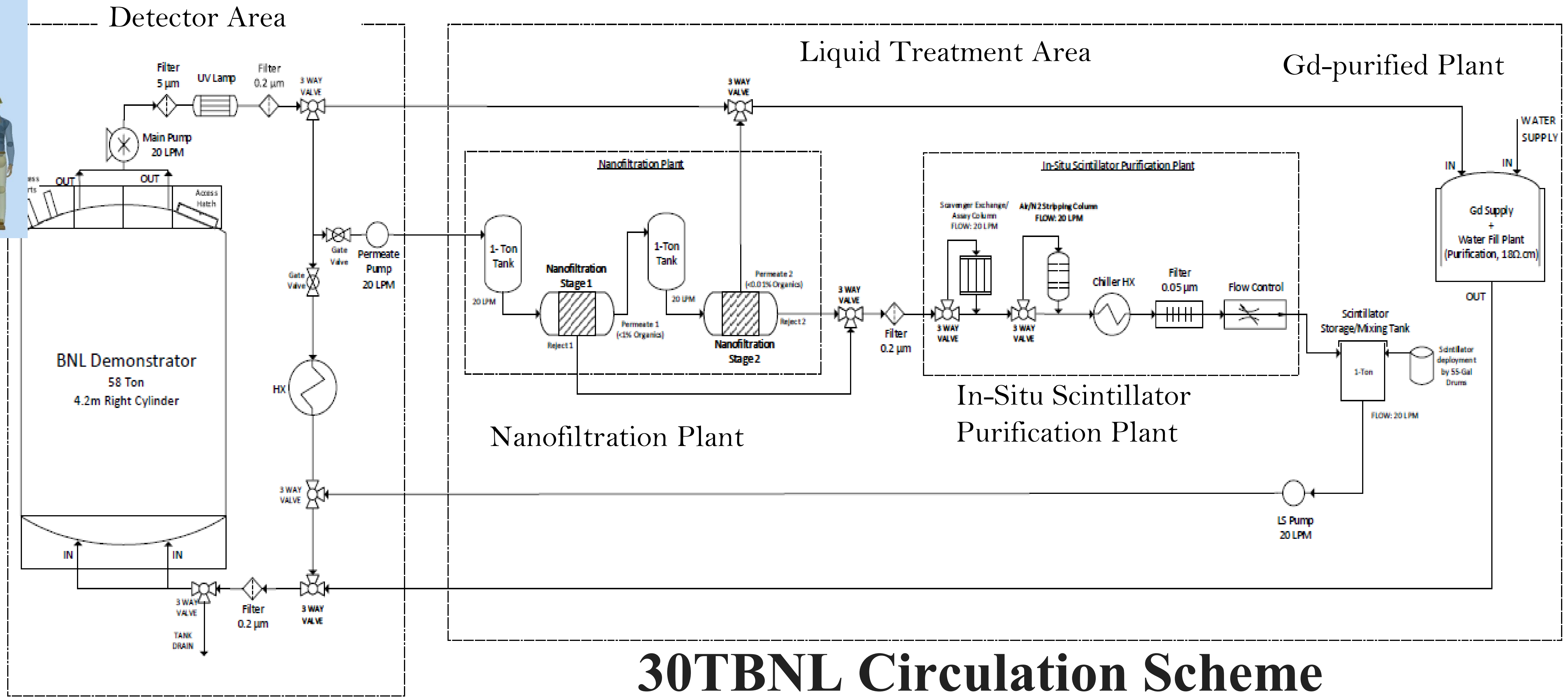
- **A fully-equipped 30-ton optical detector with in-situ circulation system to demonstrate large-scale WbLS deployment**
- engineering and integration studies with Gd-water system and nanofiltration system (in-situ purification)
- Performance stability, interface, and slow-control
- Capable of adding an Inner Vessel (IV)





30TBNL Circulation Scheme

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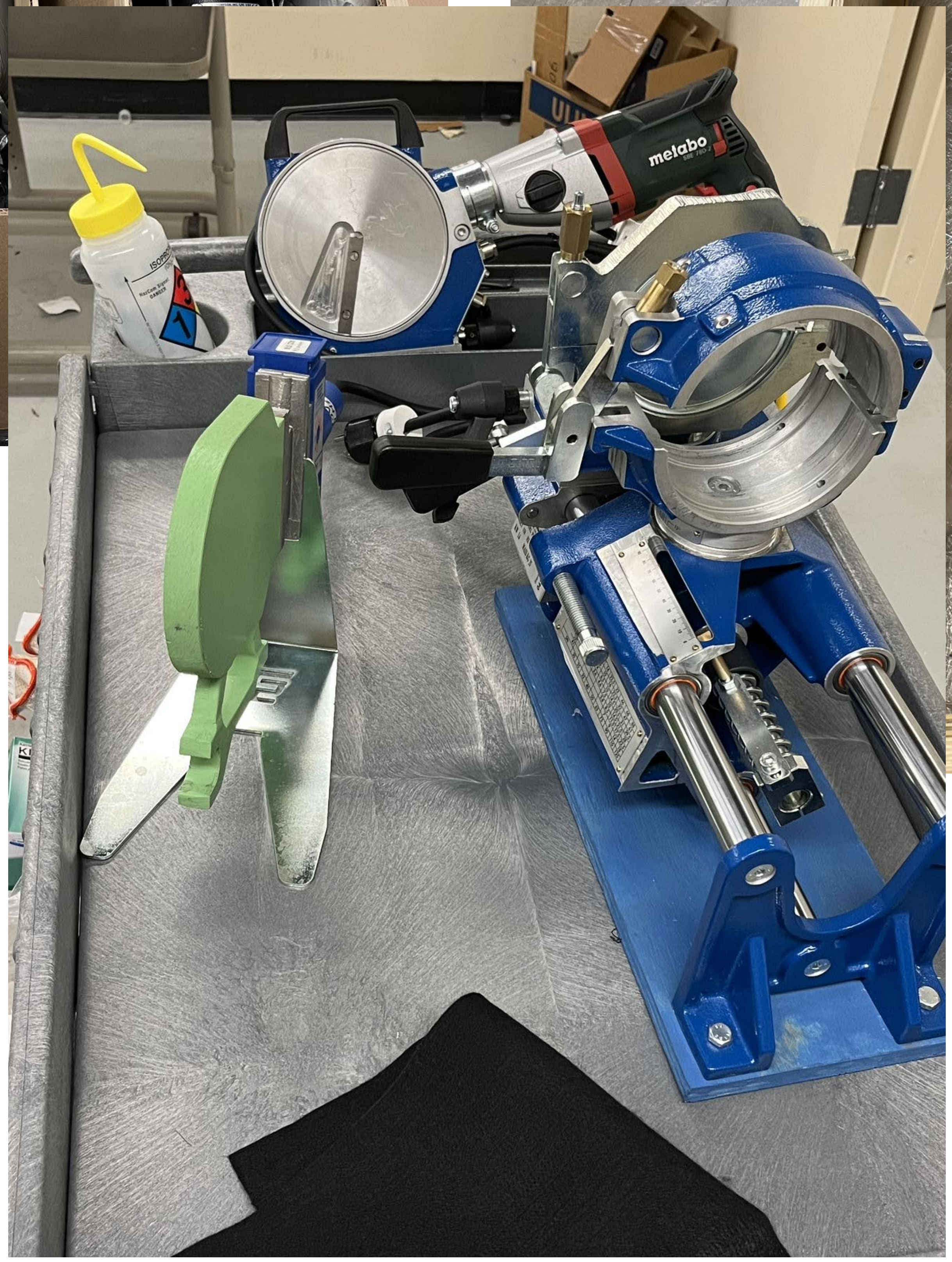
Parts and Equipment arrived at BNL



NNSA
National Nuclear Security Administration

30TBNL Installation

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Started in FY22

A collaborative effort between multiple universities and other labs

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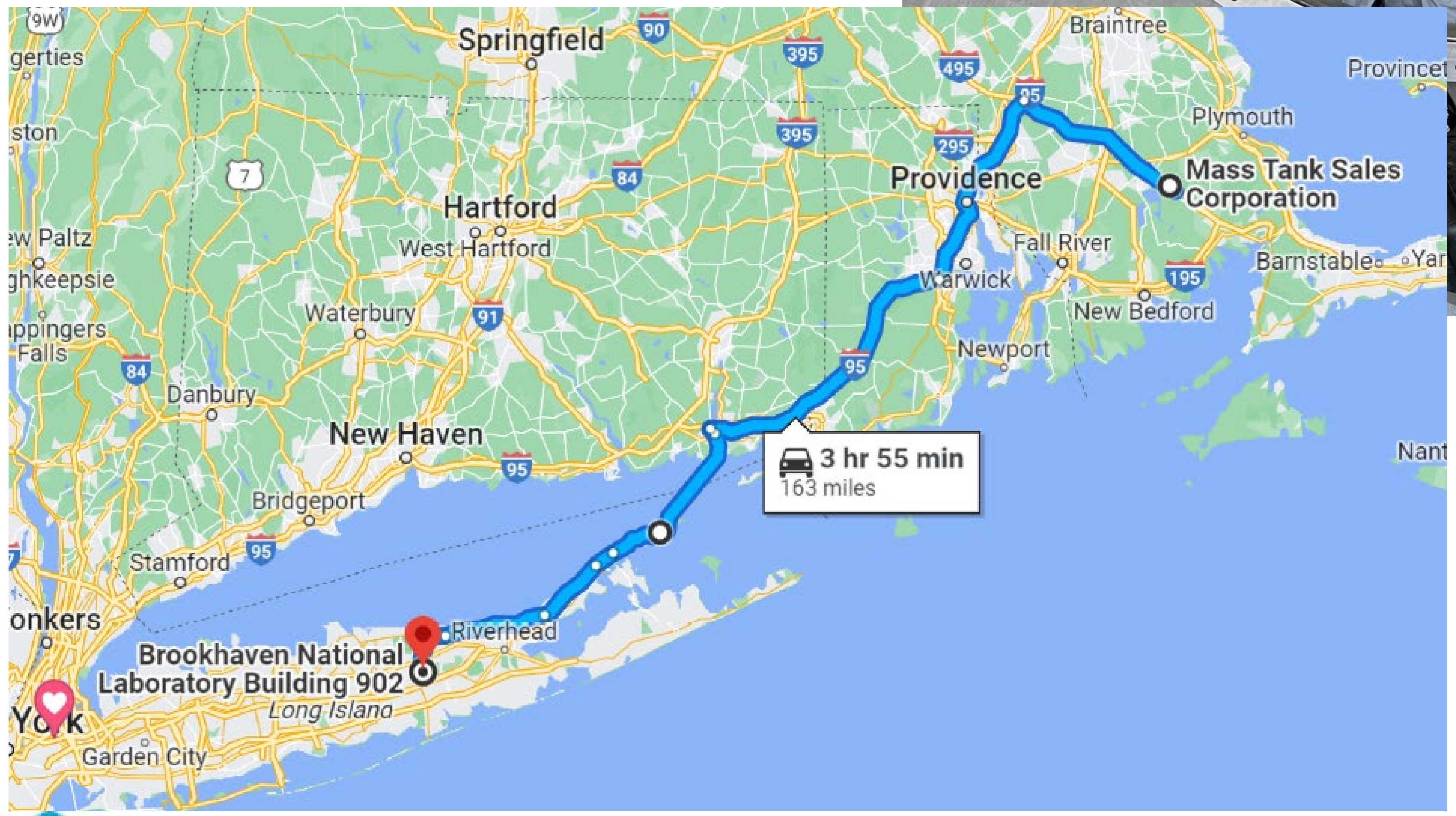
30-ton Tank

Delivered to BNL on July 21, and moved into Facility on July 25, 2023



Milestone!

Preparing for cleaning and water fill

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Technical Challenges

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- ~~Formula development to optimize Rayleigh Scattering Length~~
  - ~~Mitigated by early investment to develop various anti-scattering agents to minimize the impact of inhomogeneous electronic clouds; and by an iterative R&D approach, to characterize and verify property, and to provide feedback for optimization~~
- Scalability for In-situ Filtration
  - Mitigated by two prototyping studies (1000-L testbed and 30-Ton demonstrator) to exercise various deployment and filtration schemes to minimize unknown cost and schedule risks associated with technology development → nanofiltration system scale-up
- ~~Simulation~~
  - ~~Mitigated by forming a WbLS working group to define the requirement and performance of target medium for a kiloton-scale detector~~

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Nanofiltration System

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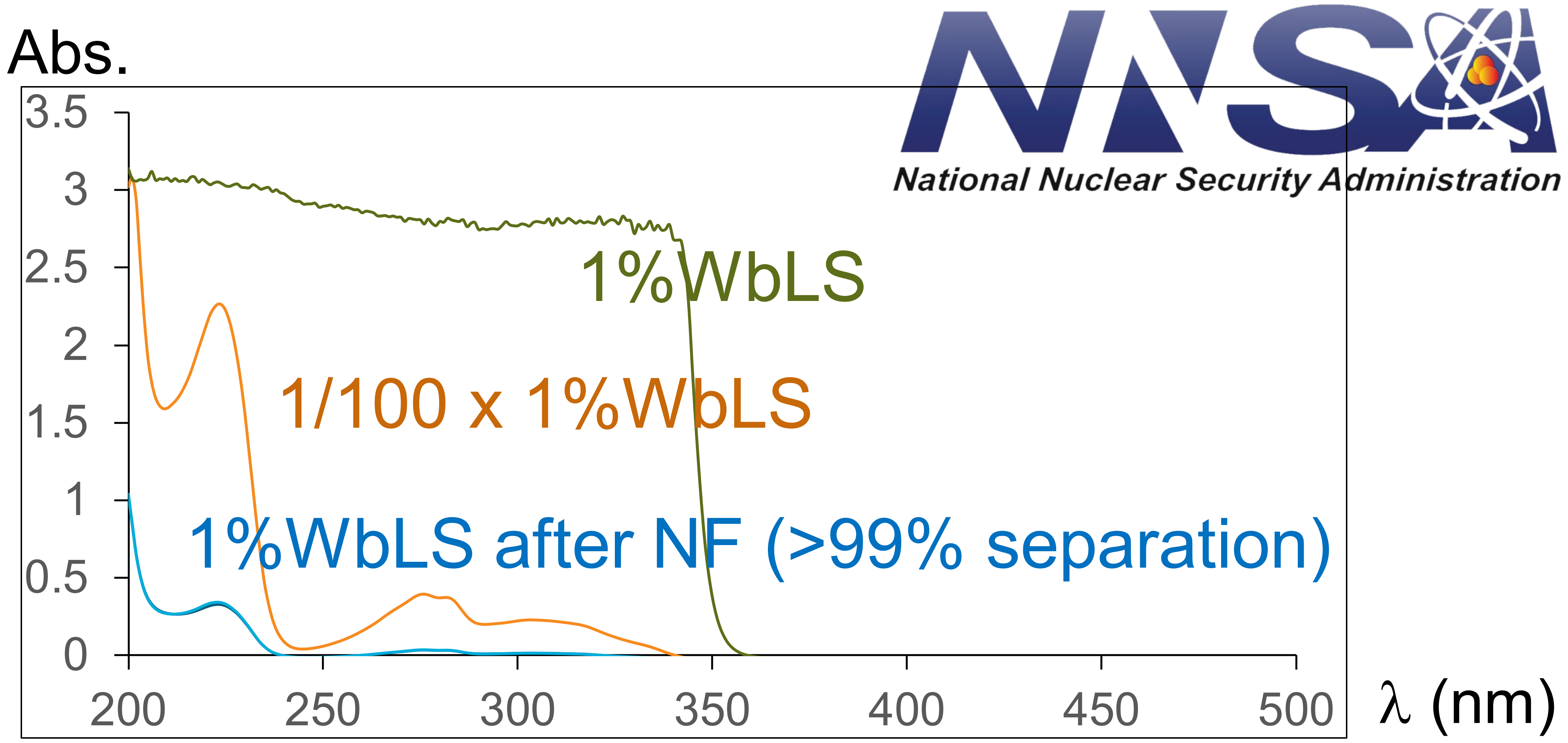
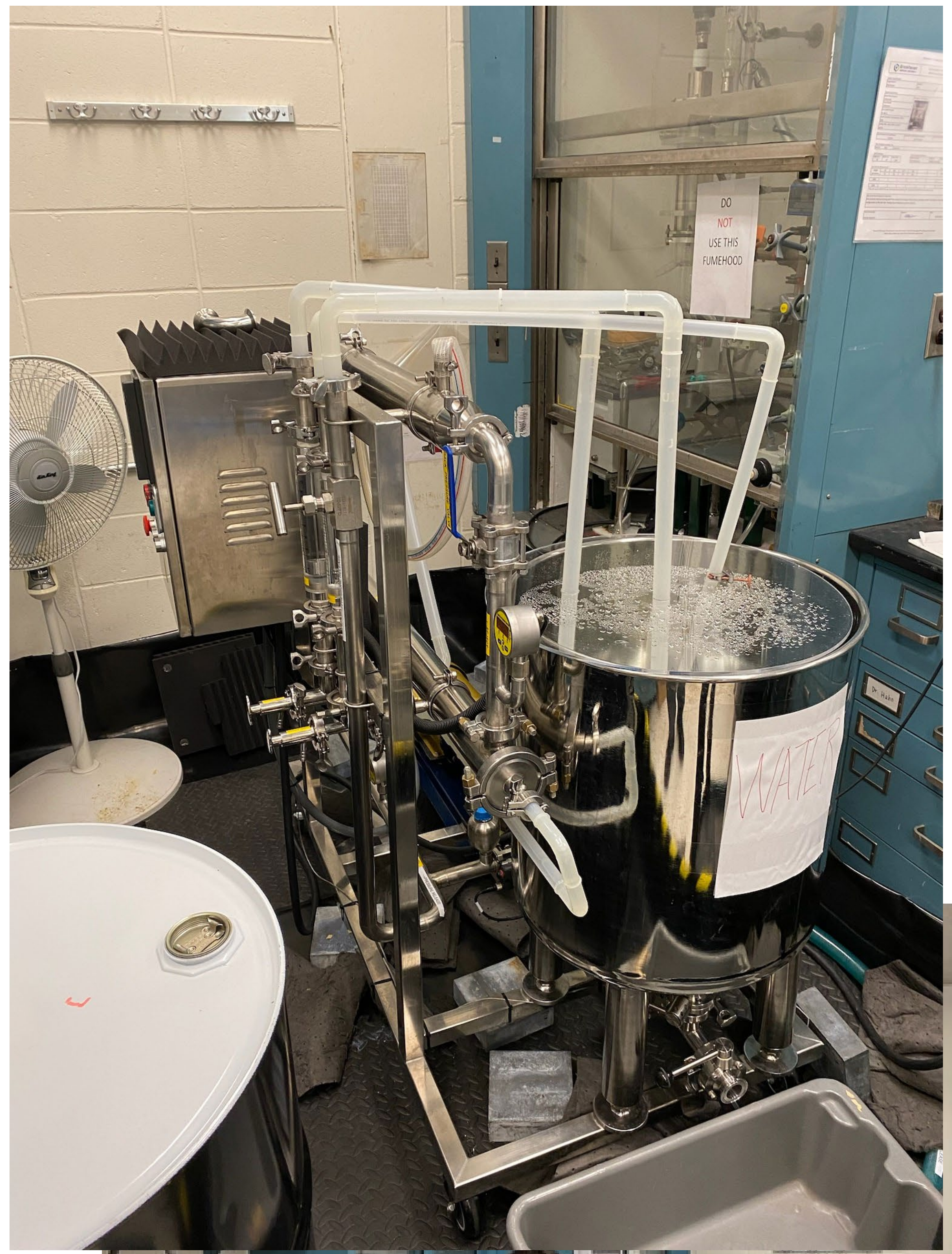
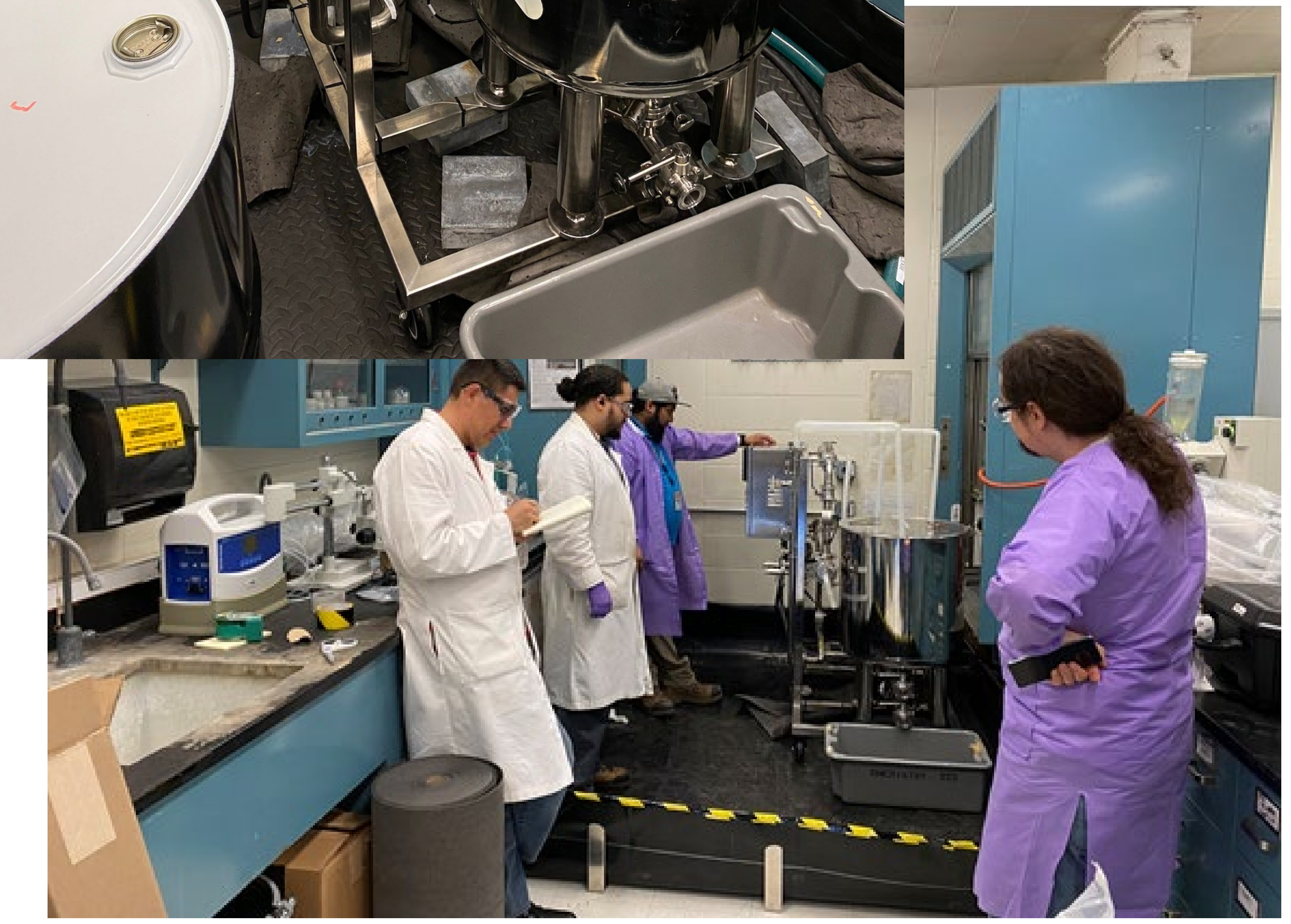


MaxiMem (0.5 GPM)

2540-pilot (6 GPM)





30T-NF (30 GPM, under RFQ)

A bandpass technology to separate oil and water for in-situ purification (largely used in industry); collective activity UC Davis, BNL and UK

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Alternative In-situ Purification (Exchange Column)

- Many industrial resins/scavengers (technologies developed from nuclear waste processing and enrichments) pose metal selectivity
- For Gd-WbLS, searching to remove radioactive/colored leaches from SS tank, PMTs, etc. (i.e. $Fe^{2+,3+}$); maintaining a clean optical detector
- A testbed with mixed resins showed promising results from multiple spiked tests (>80%Fe removal without Gd loss per pass)

One-step sequential extraction

Summary

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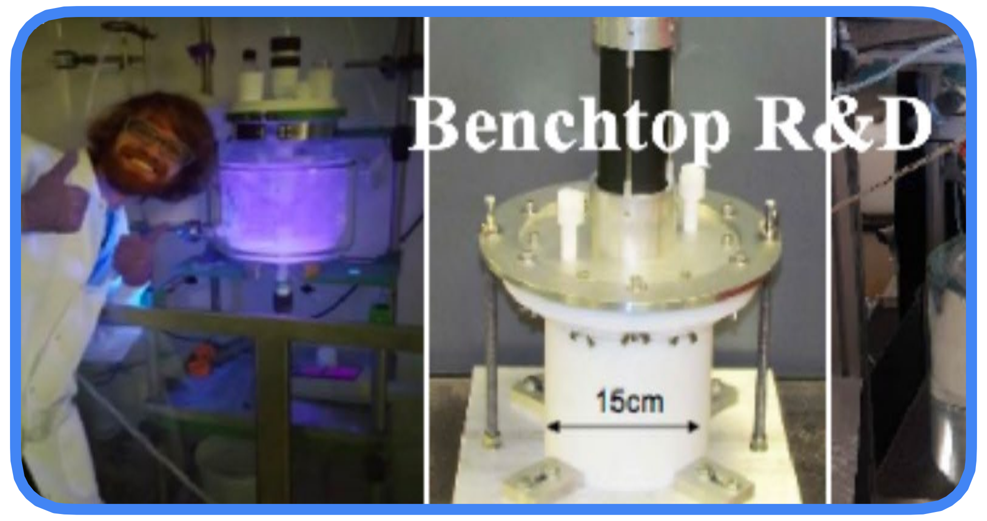
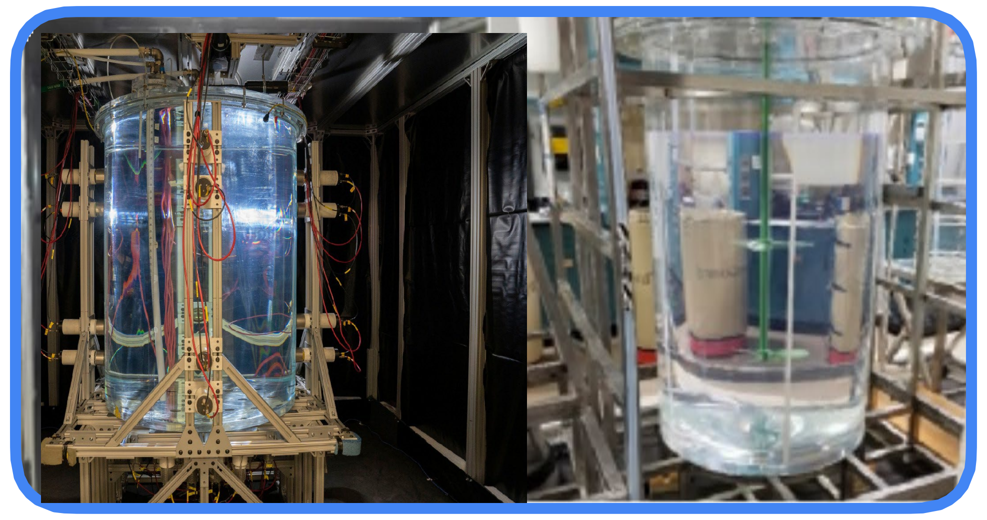
Sampling

Tabletop R&D



Early prototype

Current 1-ton detector

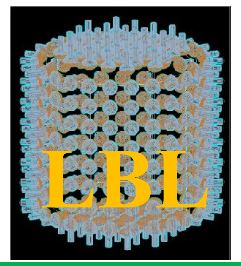


30-ton demonstrator

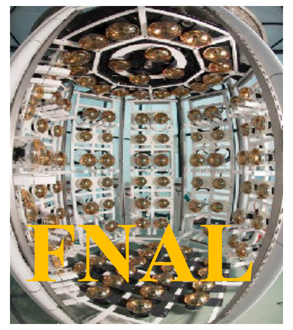
2011 | 2014 | 2016 | 2022 | 2023 | 2024

Synergy

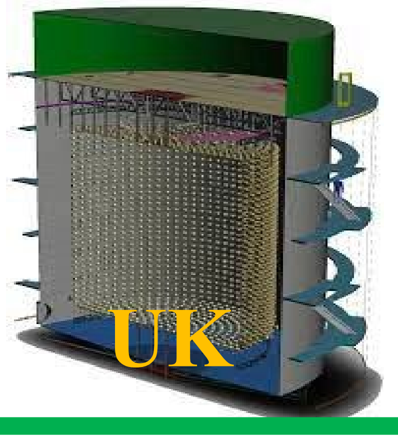
Eos



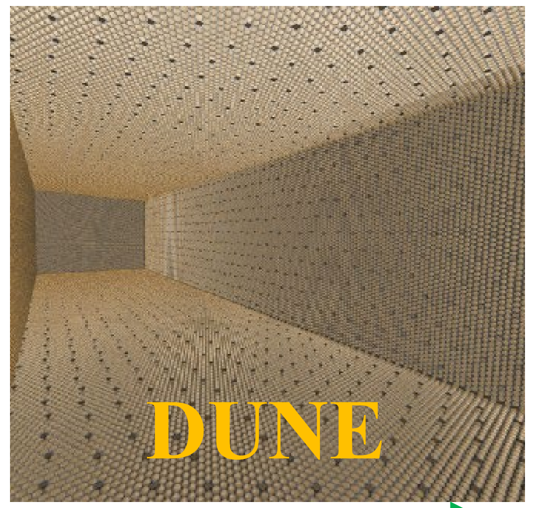
ANNIE



BUTTON



THEIA



1t | *10t* | *100t* | *1000t*

Continue research in new detector mediums and technologies

- Good progress towards technical developments on benchtop and prototyping studies
- Commissioned 1T Testbed; data-taking and analysis ongoing
- Ton-scale production facility ready in Q1/2024
- 30-ton Demonstrator in Q2/2024
- Start with water, Gd-H_2O, Gd-WbLS (1%); followed by testing different WbLS and alternative purification schemes

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