WP1/WP4 - Development of Water-based Liquid Scintillator : Results from 1-ton and 30-ton Demonstrator at BNL

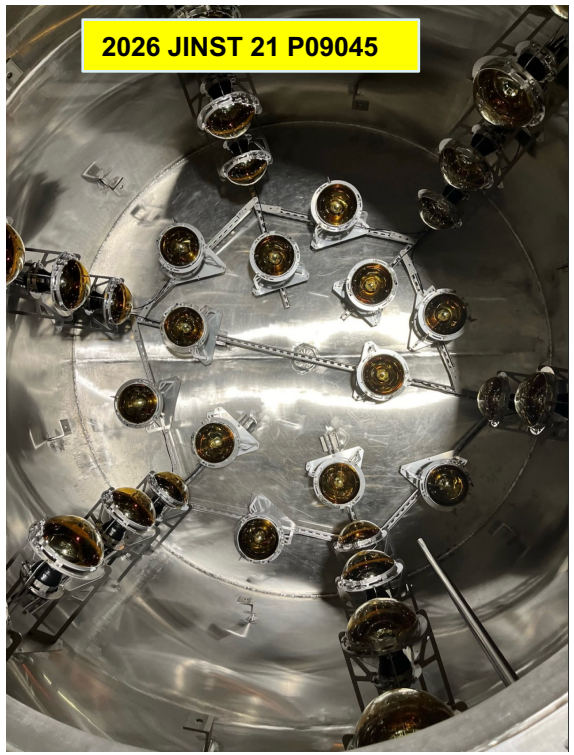
Praveen Kumar (for the WbLS team)
The University of Alabama, Tuscaloosa, USA

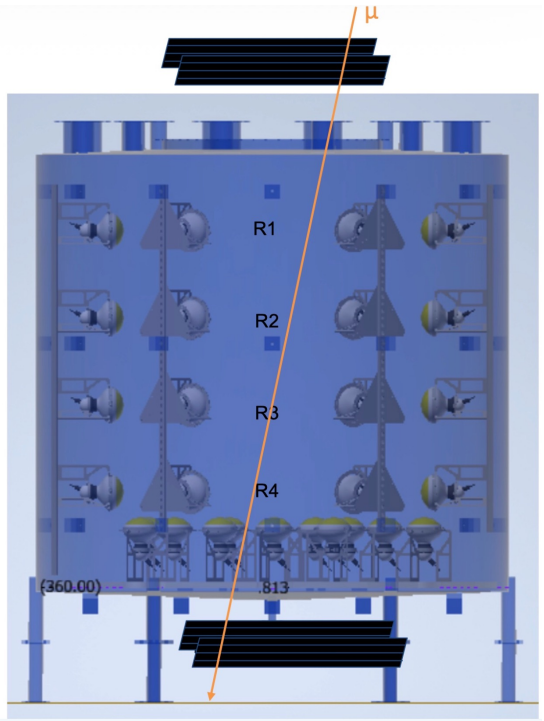
CPAD 2026
University of Washington, Seattle
Oct. 20 – 23, 2026

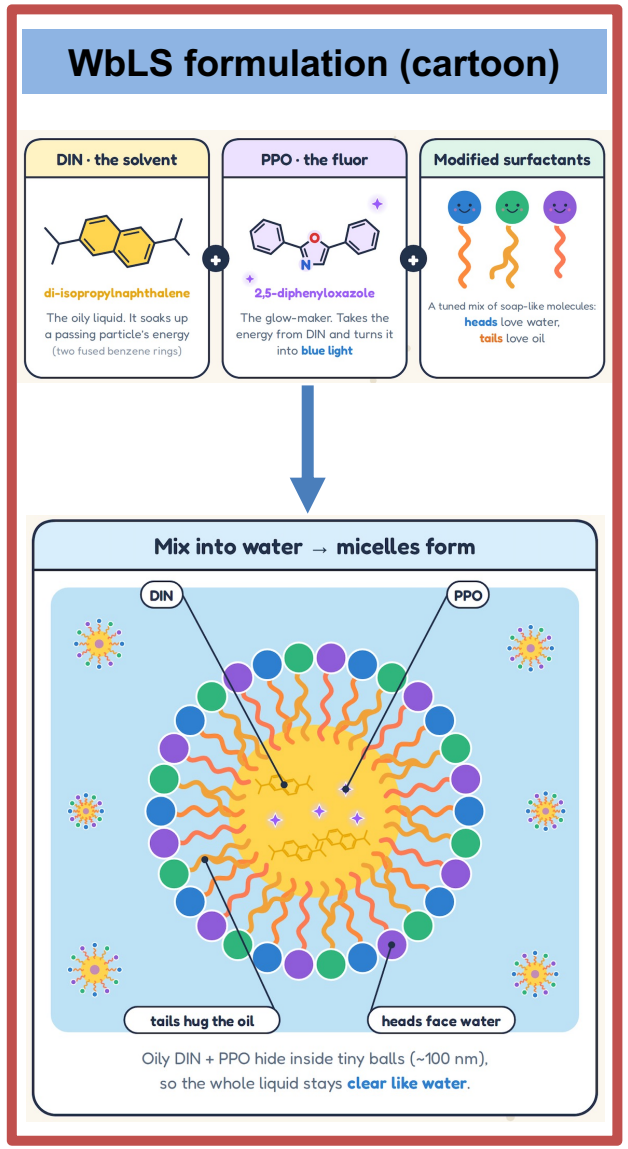
NNSA Slide Index: BNL-5687581

BNL WbLS experiments

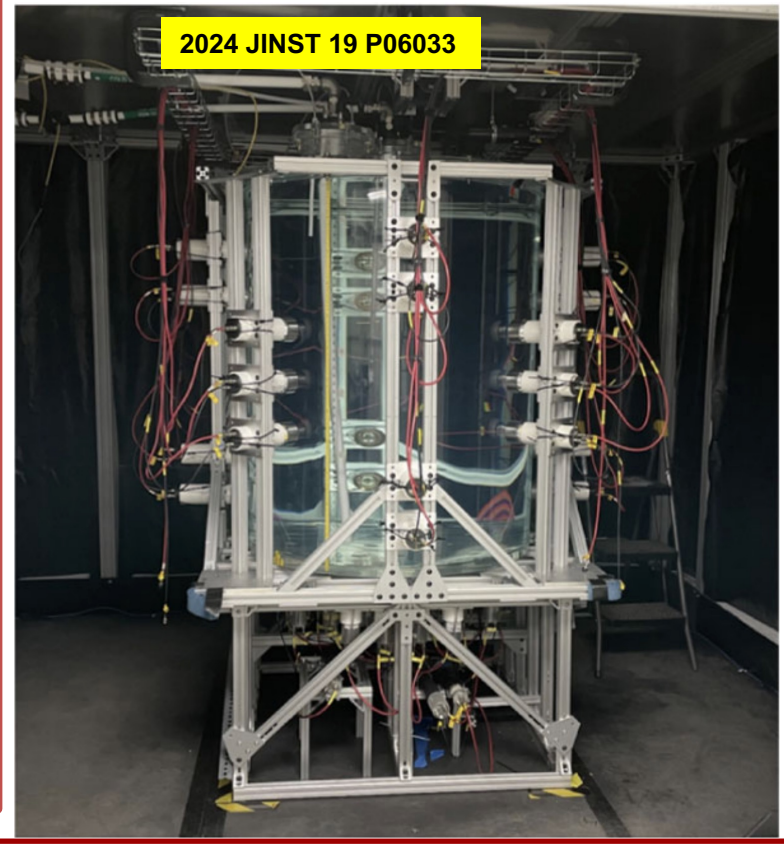
- **BNL 30T**
  - Stainless steel tank holding 30 tons of WbLS
  - Total 36 Hamamatsu R16367 PMTs of 10-inch size; compatible with WbLS
  - PMTs are fully submerged in the liquid
  - Commissioning in summer 2024







- **BNL 1T**
  - Acrylic tank holding 1 ton of WbLS
  - Total 58 2-inch size PMTs coupled to acrylic tank
  - Commissioning in summer 2023



WbLS advantages and experiment goals

- **Advantages of WbLS**
  - **Hybrid light**: Simultaneous Cherenkov and scintillation light
    - Directionality with low energy threshold
  - **Gd compatible**: Aqueous base allows metal loading for neutron tagging
  - **Tuneable and scalable**: Concentration can be adjusted in-situ; cost effective, kton scale (THEIA, BUTTON 1kton)
  - **Physics potential**: CP-phase sensitivity in long-baseline oscillations, low energy solar and supernova neutrinos, neutrinoless double beta decay

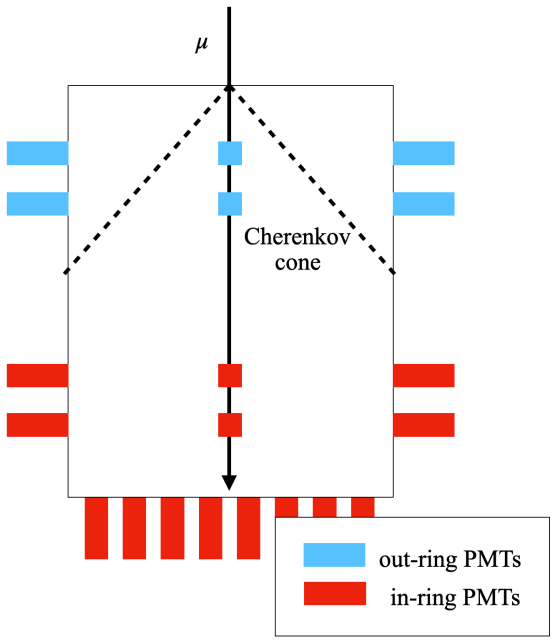
- **Goals**
  - Feasibility study of large-scale water-based liquid scintillator detectors with integrated calorimetry and topological tracking
  - Testing the full capacity of kt scale particle detector
  - Characterizing the optical properties of WbLS
  - Evaluating neutron capture performance in Gd-loaded WbLS
  - Assessing long-term stability of the system and detector medium

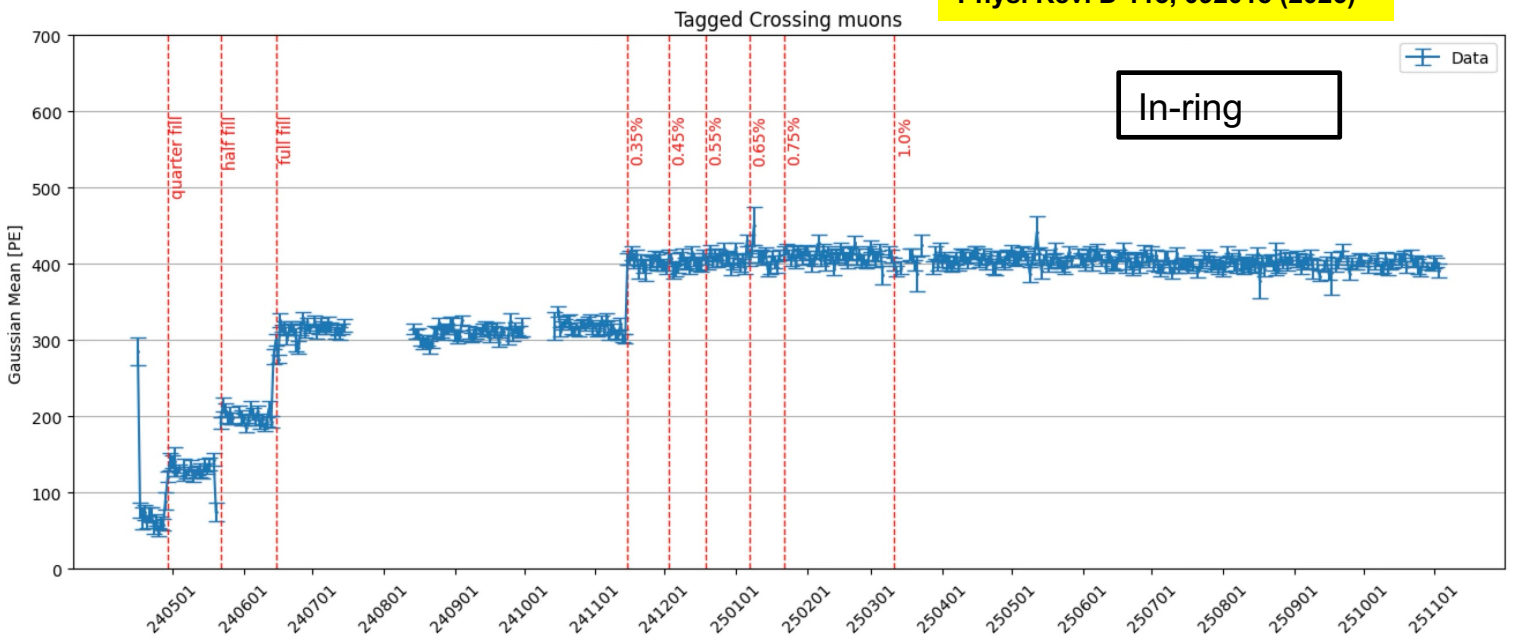
	BNL 1-ton	BNL 30-ton
WbLS stability	X	X
Light yield	X	X
Optical modelling	X	X
Scalability		X
Metal loading capability		X

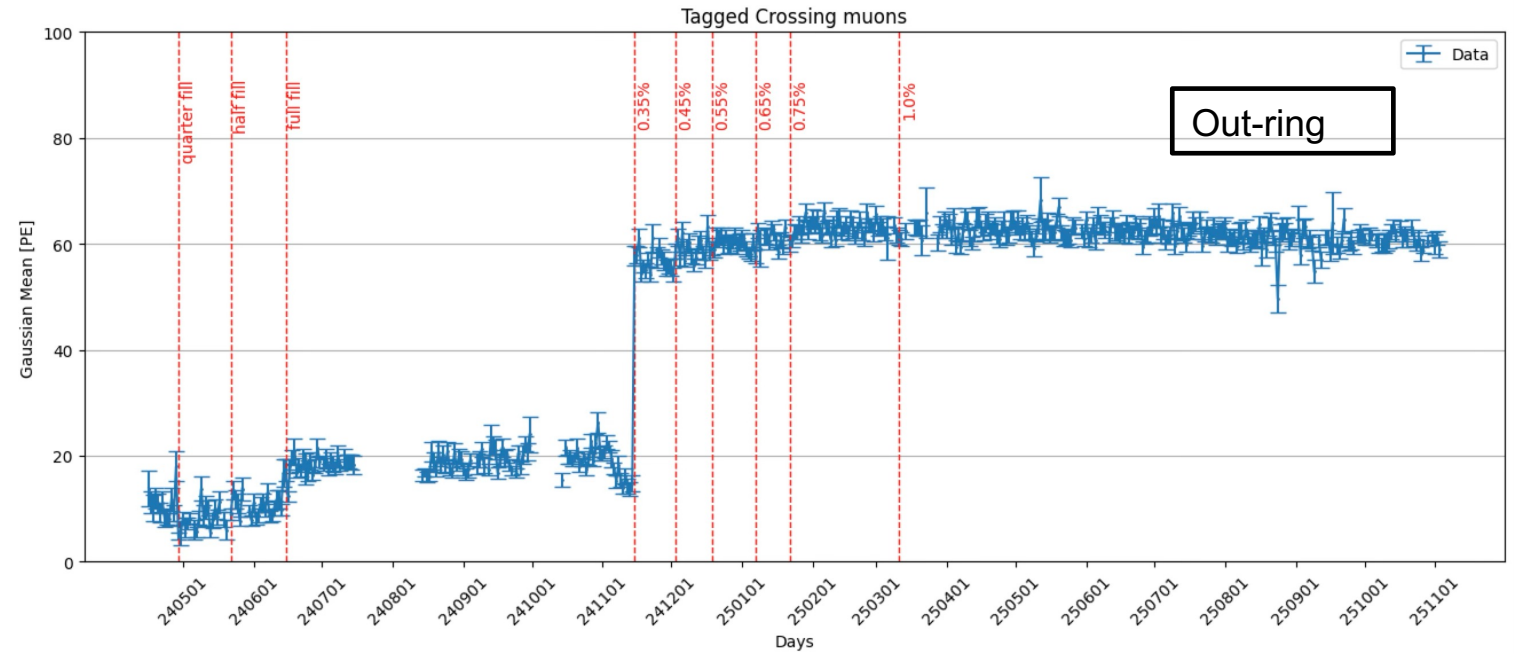
1-ton results

Phys. Rev. D 113, 092015 (2026)

- **Stepwise injection and light yield stability**
  - **Through going muons**
    - **Selecting upper and bottom paddle for muon trigger**
    - **Bottom PMTs majority**





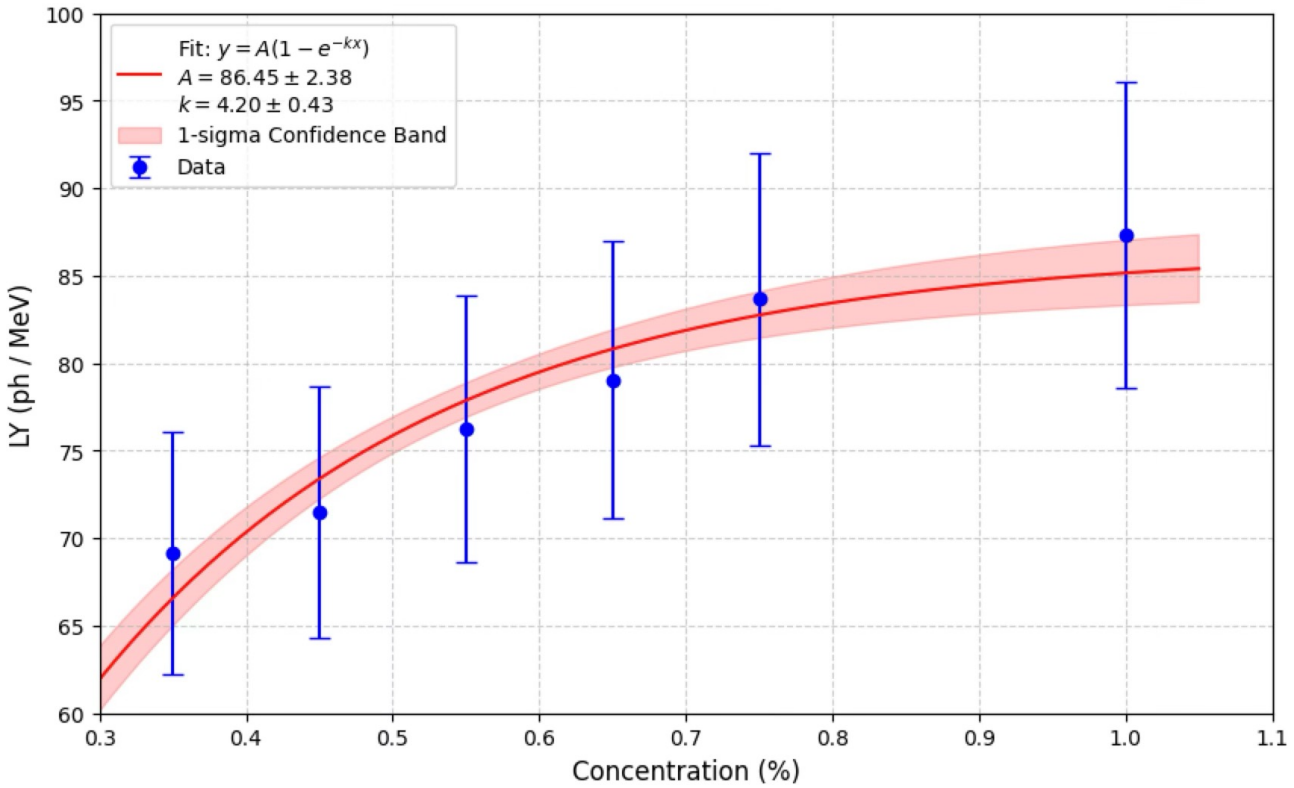


1-ton results

Phys. Rev. D 113, 092015 (2026)

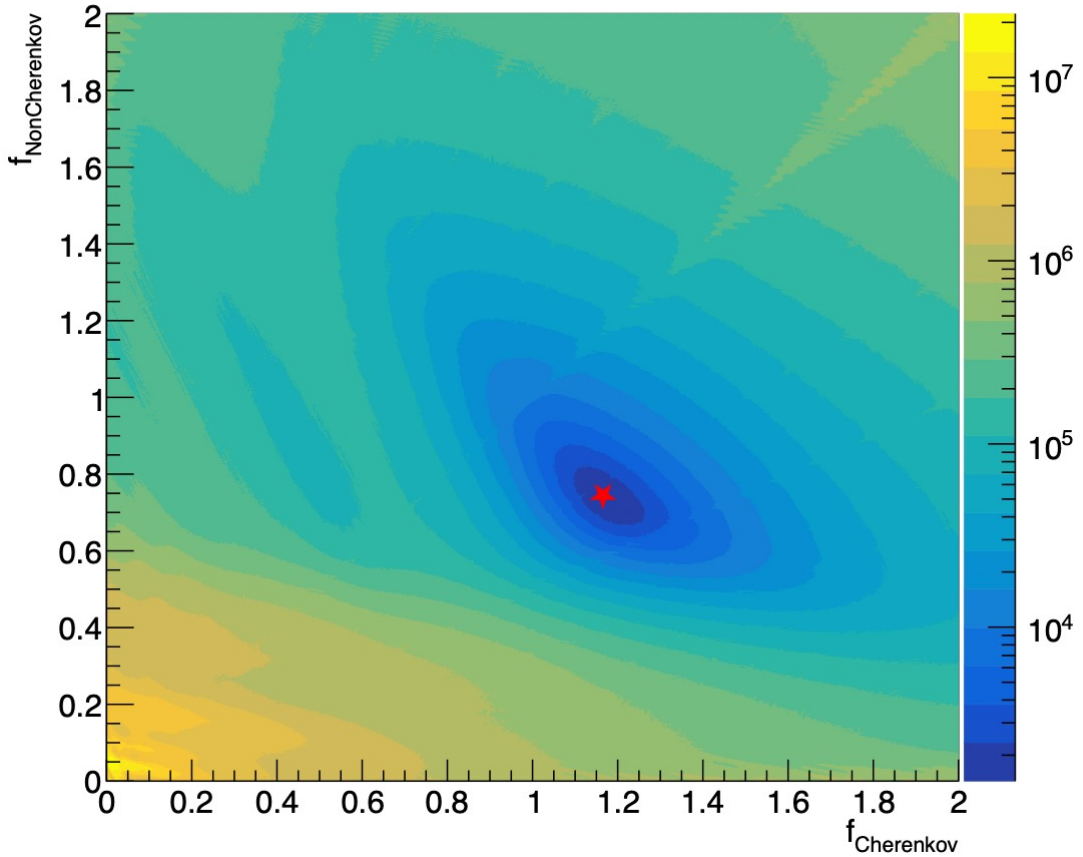
- **Absolute scintillation light yield**
  - Benchtop measurement of Gd compatible WbLS, 0.35-1.0 % by mass
  - 87.3 ph/MeV at 1 % WbLS

(Does not include re-emission, which is saturated at 0.35%, ~ 30 ph/Mev)



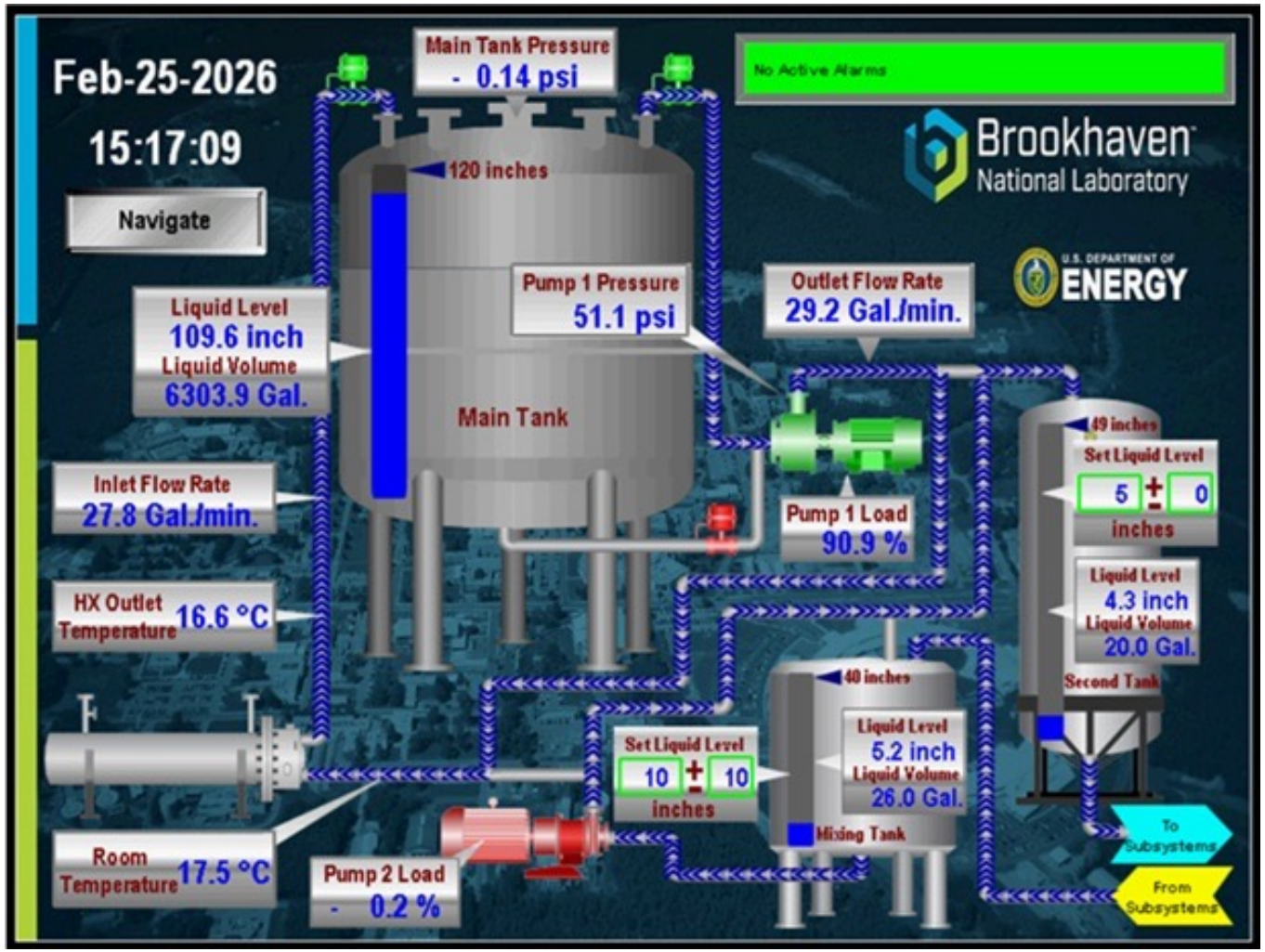
- **Cherenkov vs. non-Cherenkov light**
  - Crossing cosmic muons
  - 2D χ^2 scan: Cherenkov and non-Cherenkov light cleanly separated
  - Modelling is robust

1% WbLS χ^2 Scan

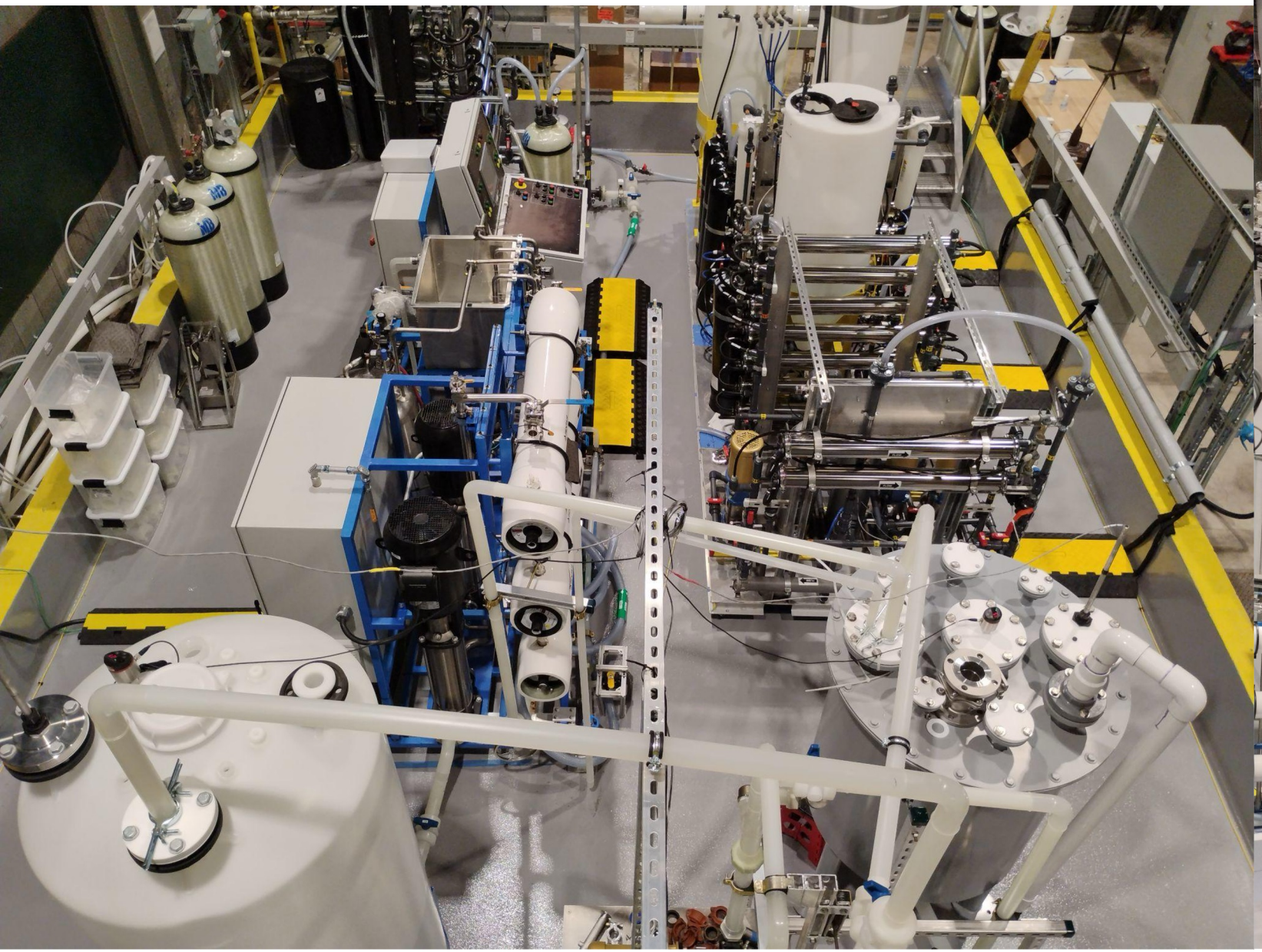


Circulation and online control system

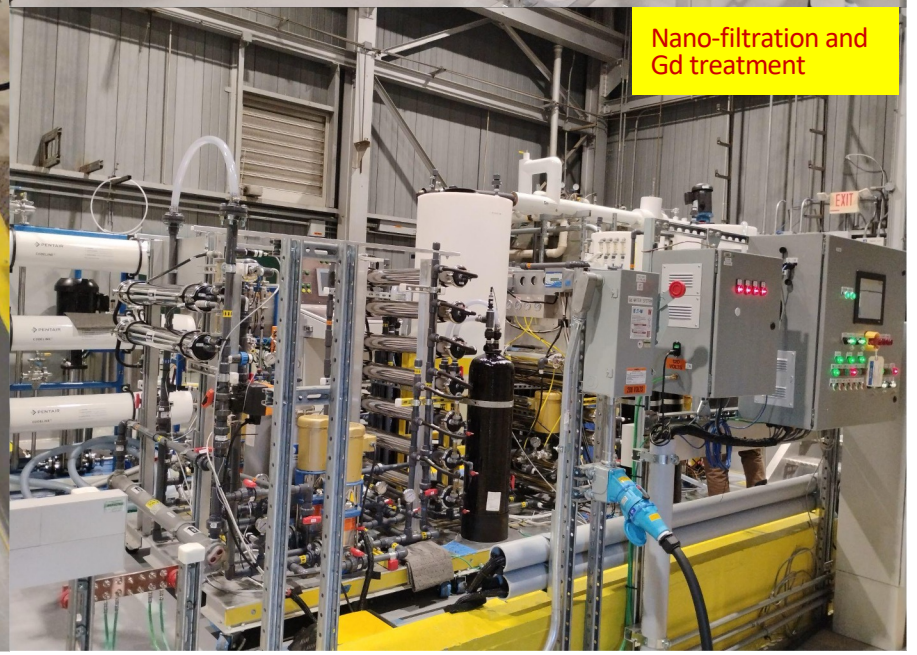
- **In-situ purification**
  - Ultrapure-water circulation system
  - Microfiltration: removes microparticles such as pipe shavings
  - Nanofiltration: removes nanoparticles such as iron ions
  - Gd-water circulation performance
- **Programmable logic controller (PLC)**
  - Monitors temperature, pressure, liquid level, etc.
  - Provides active control to maintain stability of these parameters
  - Real-time process monitoring of the 30T detector
- Optimize operational parameters based on physics-driven requirements



Circulation and filtration system



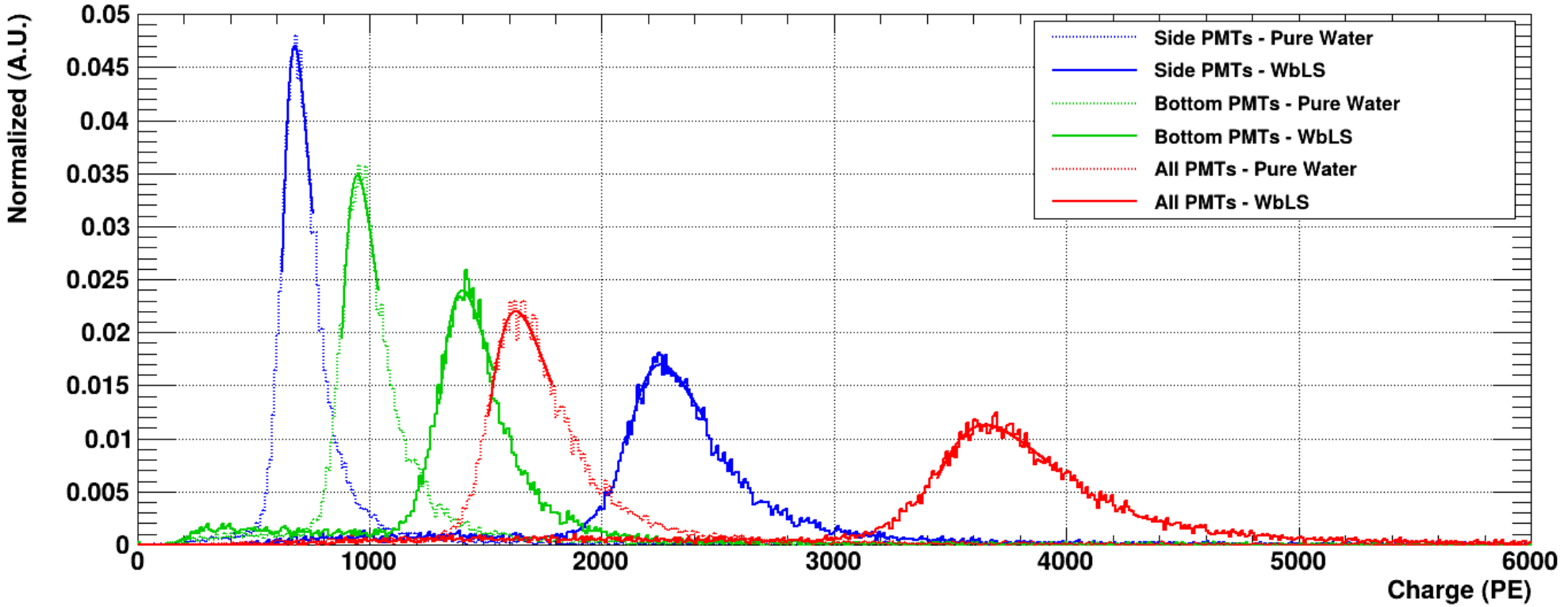


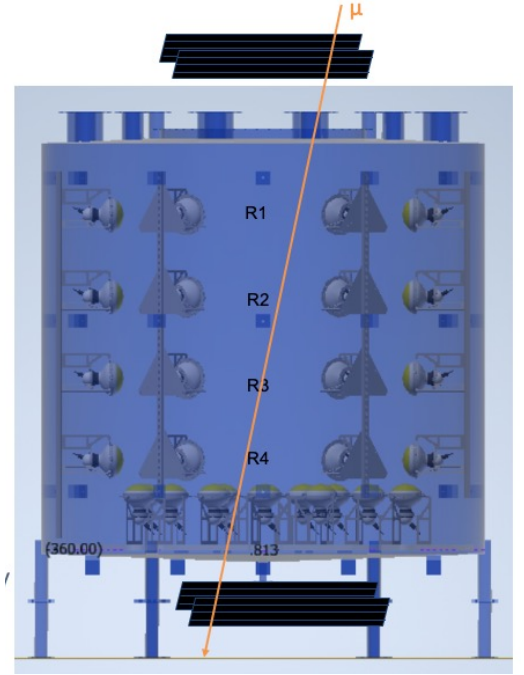


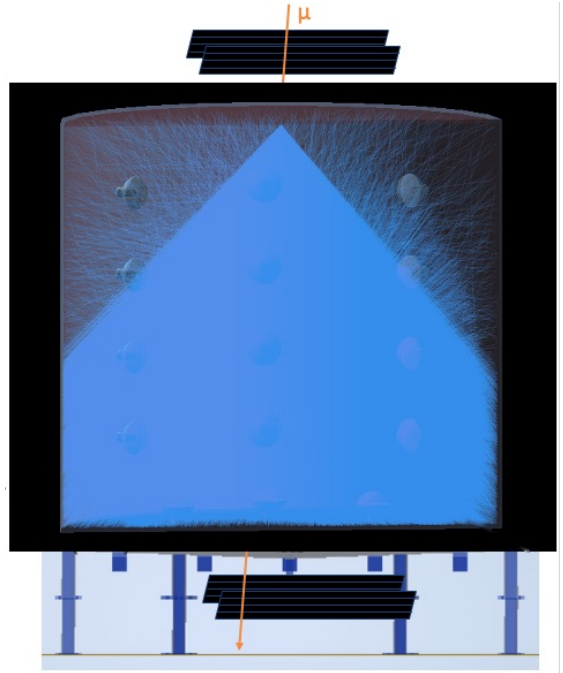
30-ton results

2026 JINST 21 P09045

- Light yield transition
  - Through going muons
    - Selecting upper and bottom paddle for muon trigger
    - Bottom PMTs majority







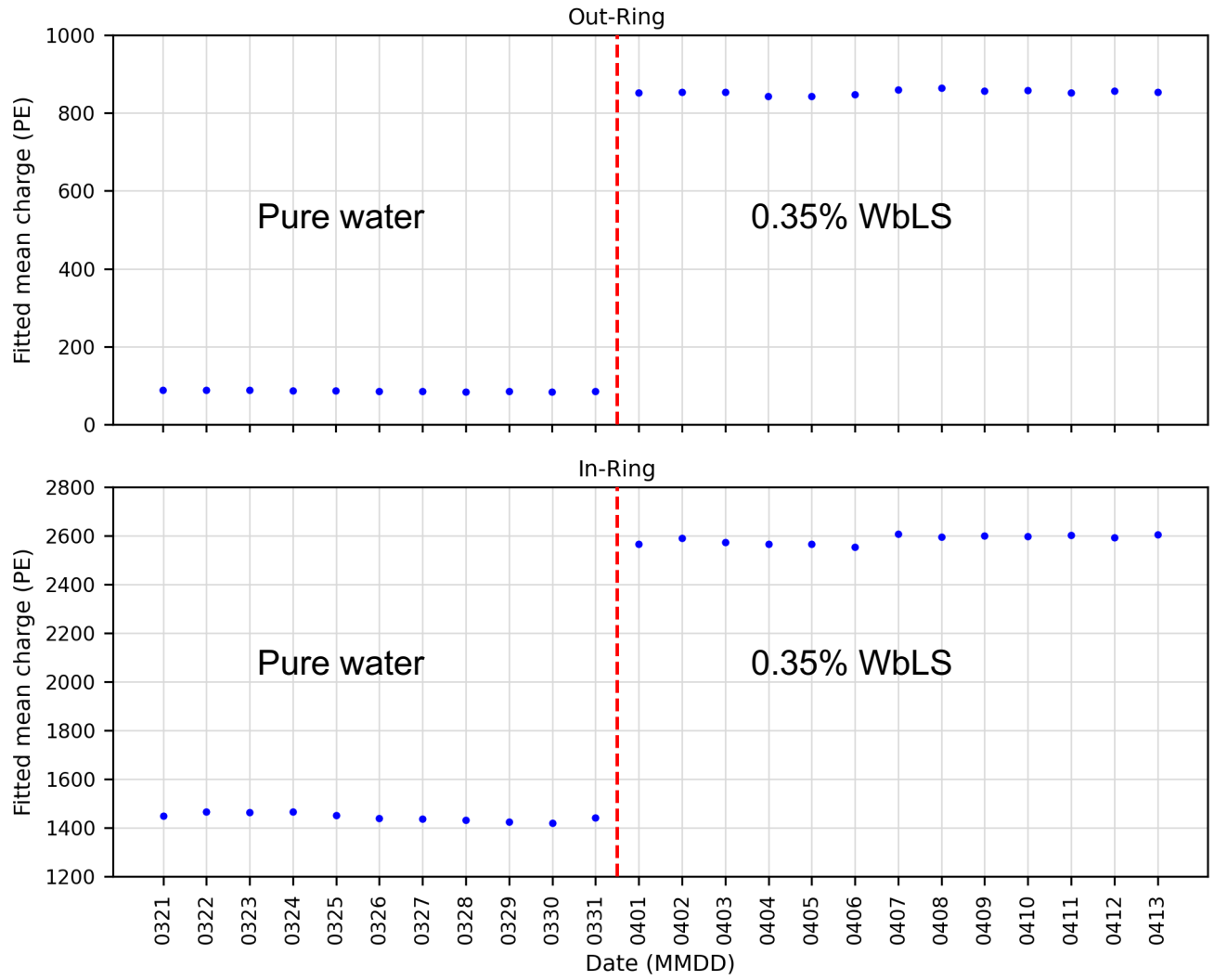
The light yield ratio with 1% WbLS increased by 3.31 ,1.48 and 2.23 times for side bottom and all PMTs

30-ton results

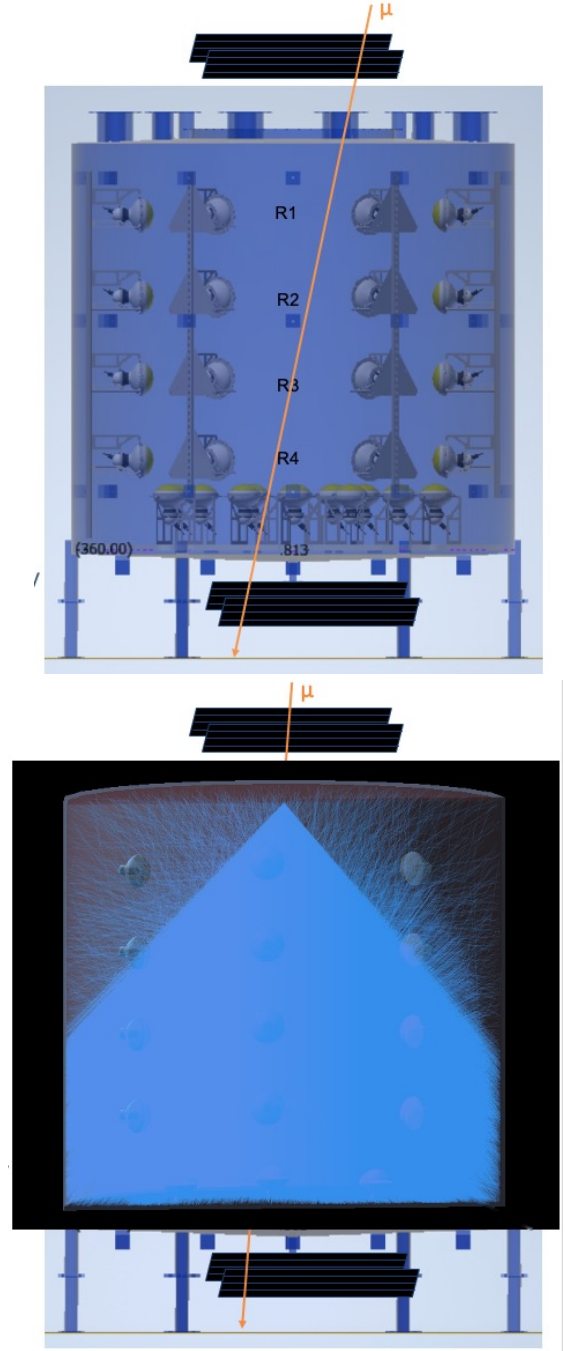
2026 JINST 21 P09045

- **Light yield monitor during injection**
  - **Pure water to 0.35% WbLS**

- Out-ring is out of the Cherenkov cone
- ~725 PE increase



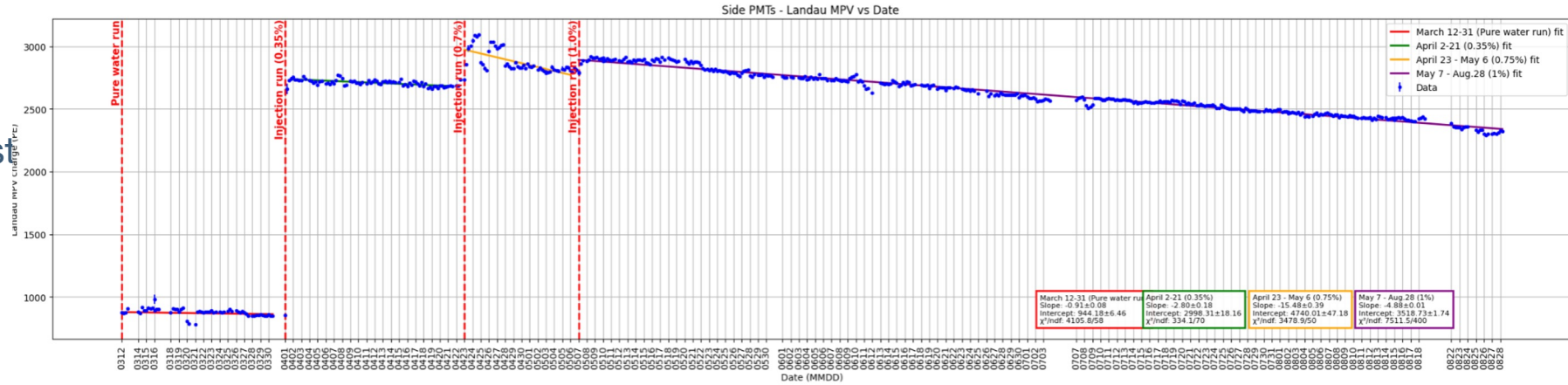
- In-ring inside the Cherenkov cone
- ~1200 PE increase



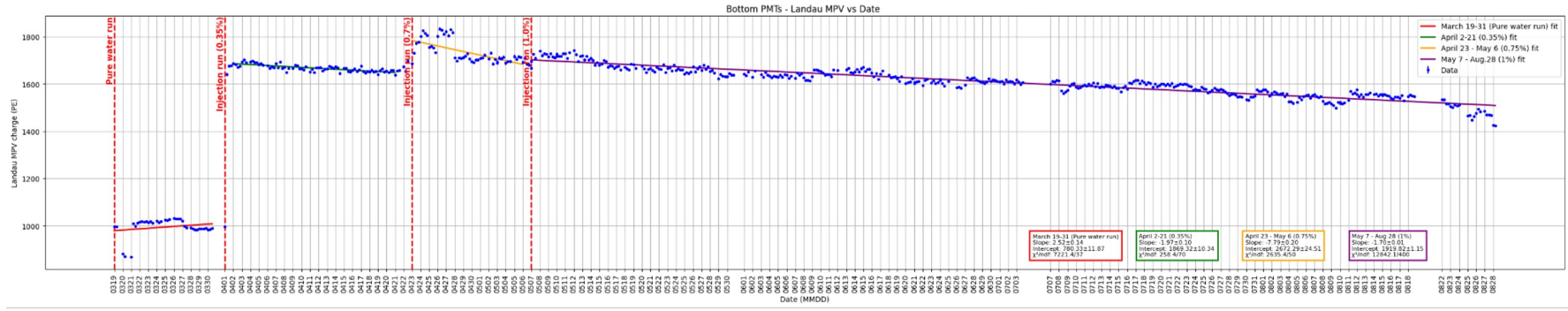
Light yield from through-going muons without in-situ purification

- **Three injections**
  - Pure water to 0.35% WbLS
  - 0.35% to 0.7% WbLS
  - 0.7% to 1% WbLS
- Significant gain in light yield in the first injection
- Increased light yield in subsequent injections
- Data suggest the saturation of Cherenkov light conversion–study in progress
- **Factors may affect light yield**
  - Oxygen presence
    - Strong photo quencher
    - Nitrogen system was off (now running)
  - Material leaching (PMTs, supportive structure, cables, etc.)
    - Evidence of iron rusting (from tank)
    - Potential additional quenching/contamination

Side PMTs



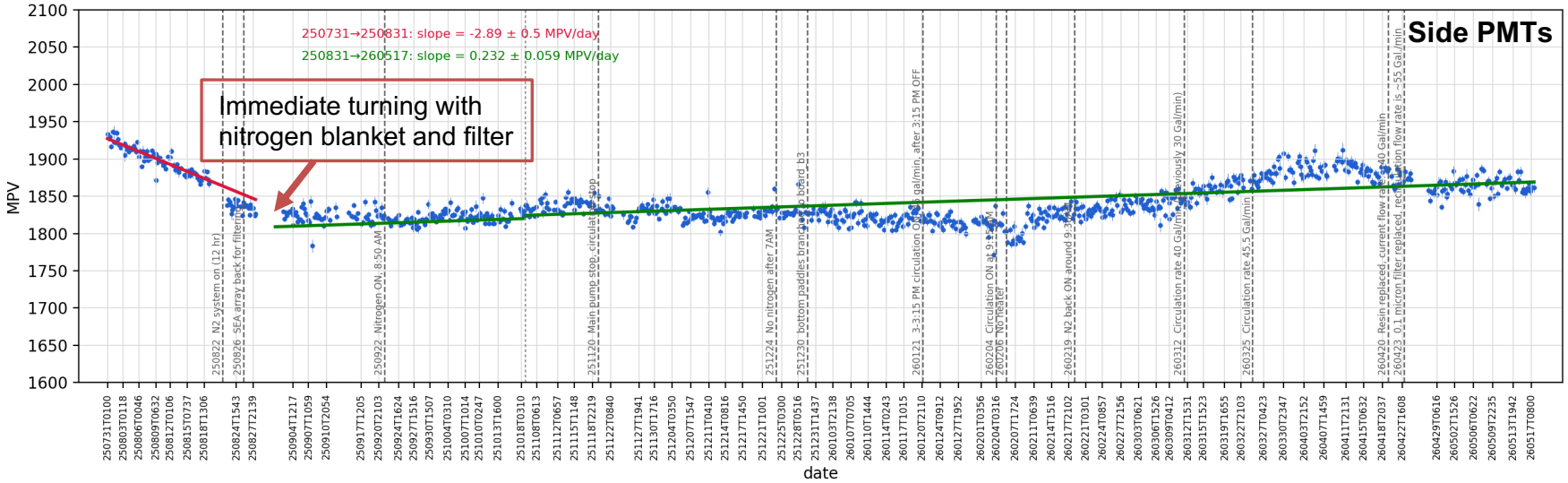
Bottom PMTs

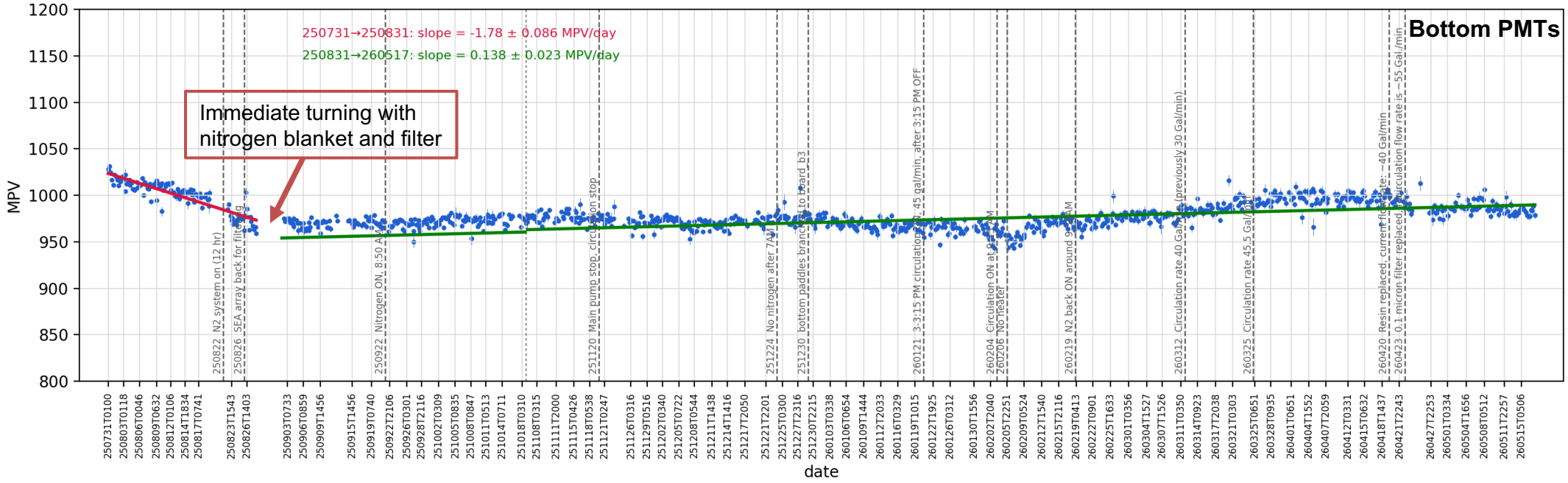


Recent data shows more stable light yield

Stability after replacing SEA resins

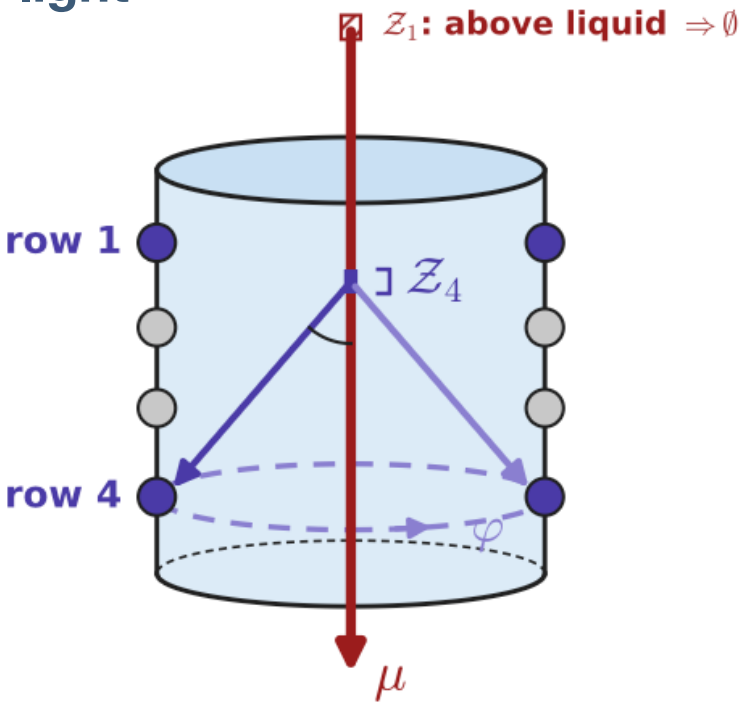
- Replaced SEA resins
  - Replaced after 8 months
- We have nitrogen blanket now
- Look more stable now
  - ~9 months data after SEA replacement





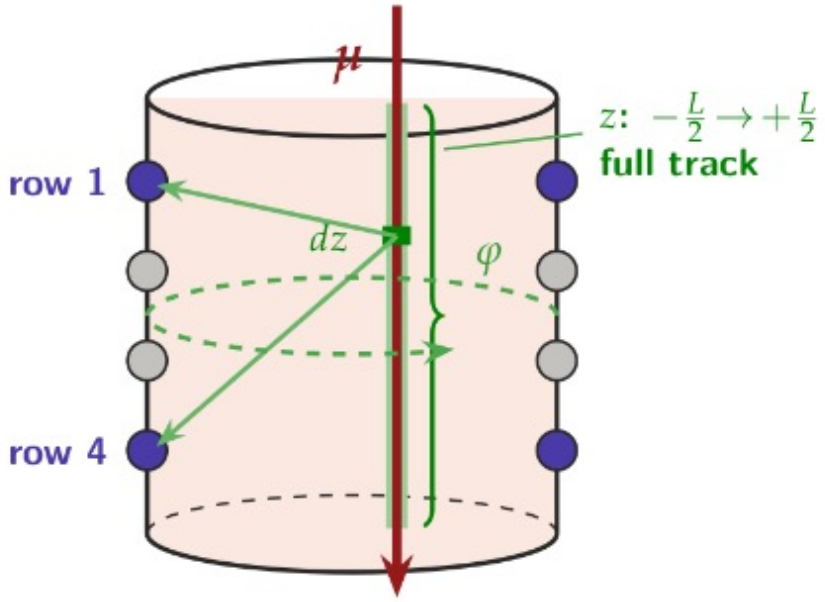
Attenuation length measurements of 1% WbLS in 30-ton

- **Cherenkov light**



- Vertical cosmic muons tagged by paddles above and below the tank
- Cherenkov light reaches **only the lower row**, from a short track segment
- Segment feeding the upper row lies above the liquid: **no direct Cherenkov** there

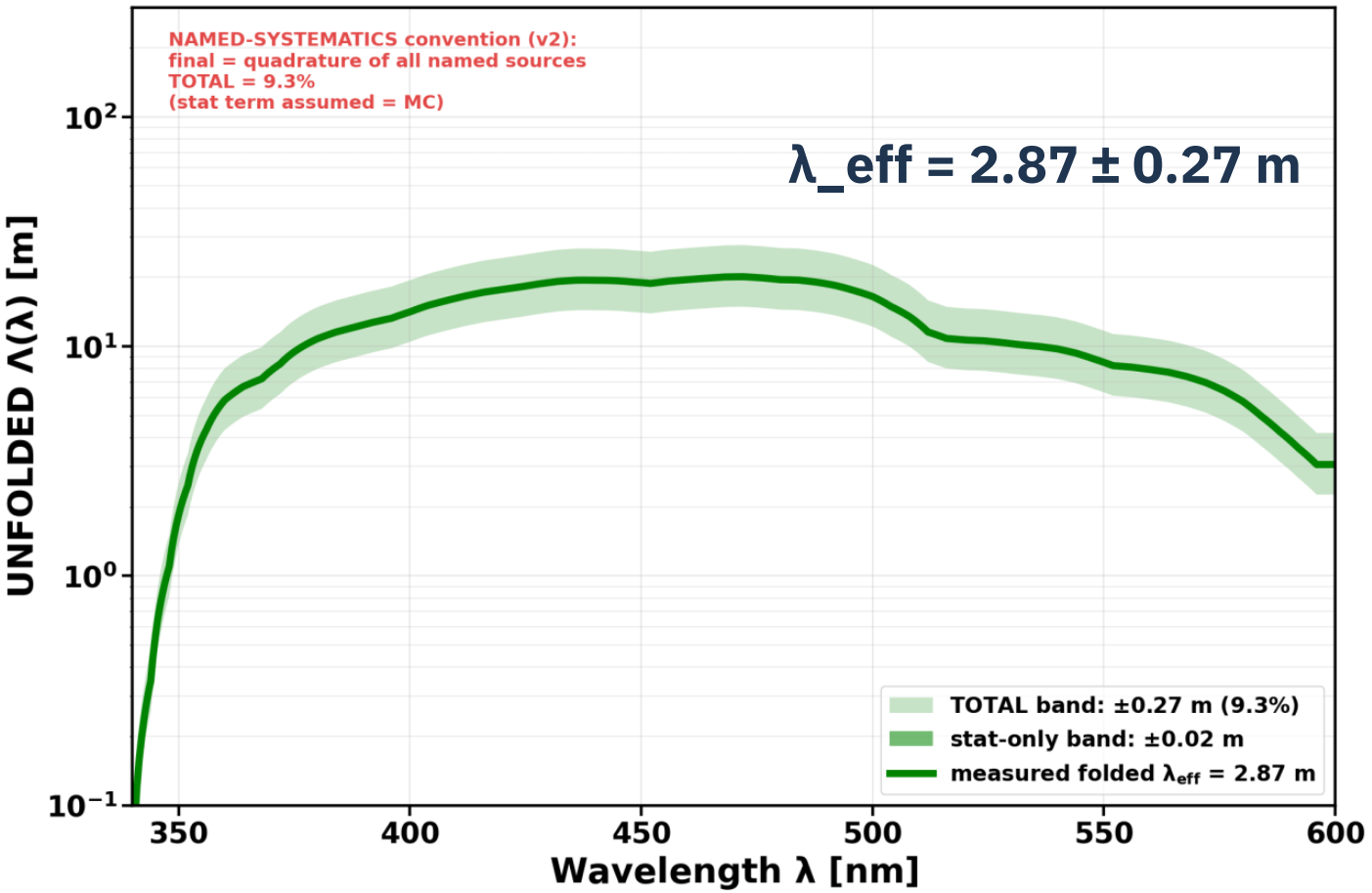
- **Isotropic light (scintillation + re-emission)**



- Emitted along the **full track**, reaches both rows equally (mirror symmetry)
- Row difference **D = PE(lower) – PE(upper)** cancels isotropic light
- Analysis uses mirror pair rows

Ratio D_{water} / D_{WbLS} gives the Cherenkov attenuation over 1.64 m: time cut removes reflected light

Attenuation length measurements of 1% WbLS in 30-ton



- 114 water/WbLS run pairs (6 water and 19 WbLS); 9.3% syst., dominated by muon angle (8.2%)
- Nominal optical model folds to 3.35 m
- Unfolded attenuation length: **19.5 m at 450 nm.**

- **First in-situ, metre-scale attenuation measurement of 1% WbLS**

Summary

- Platform for **performance, circulation & engineering** studies
- **Feasibility testbed** for kiloton-scale WbLS detector
- **Remote slow-control** with integrated safety features
- **No major technical obstacles** identified
- **Published two papers on 30 ton and 1 ton:** JINST 21 P09045 (2026) and Phys. Rev. D 113, 092015 (2026)

- **Conclusion: first set of goals completed with 1% WbLS**
  - Demonstrated stability
  - Demonstrated transparency
  - Demonstrated scintillation yield

Next: metal (Gd) loading and neutron tagging using AmBe neutron source

- **30T sets the stage for next-generation WbLS detector**

Collaboration

Key Collaboration Institutes (in alphabetical order):

- Brookhaven National Laboratory
- Bronx Community College
- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- Penn State University
- Stony Brook University
- University of Alabama
- University of California, Berkeley
- University of California, Davis
- University of California, Irvine



And other US/UK WATCHMAN/THEIA collaborators

Research supported by NNSA (DNN) and Office of Science (OHEP/ONP).

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

Brookhaven National Laboratory

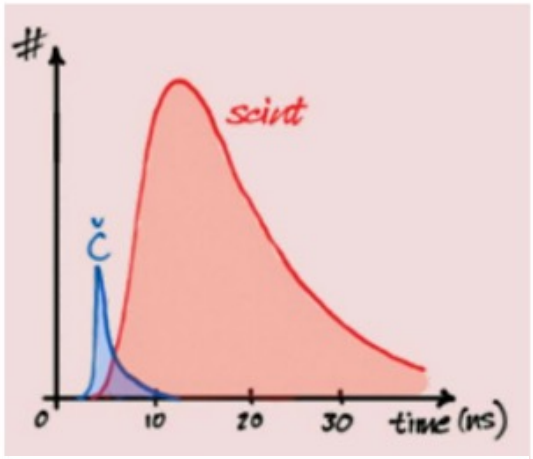
THE UNIVERSITY OF ALABAMA

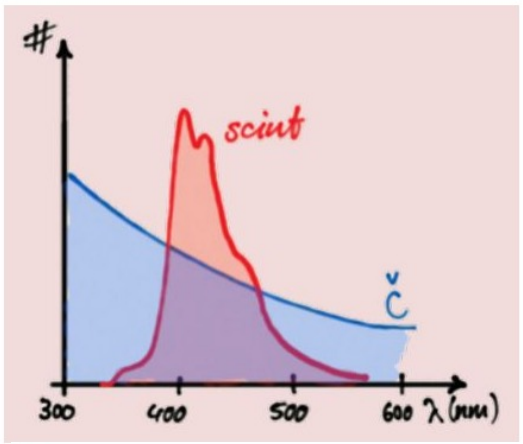
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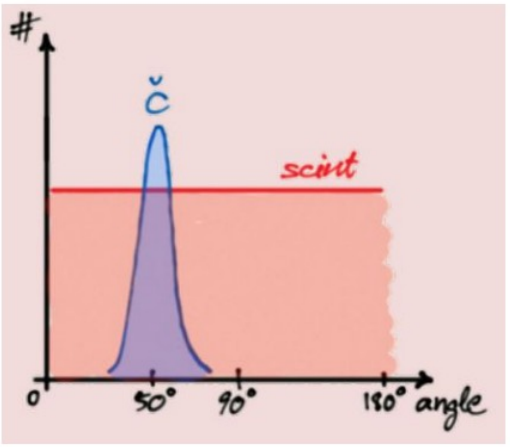
Backup slides!

WbLS performance and advantages

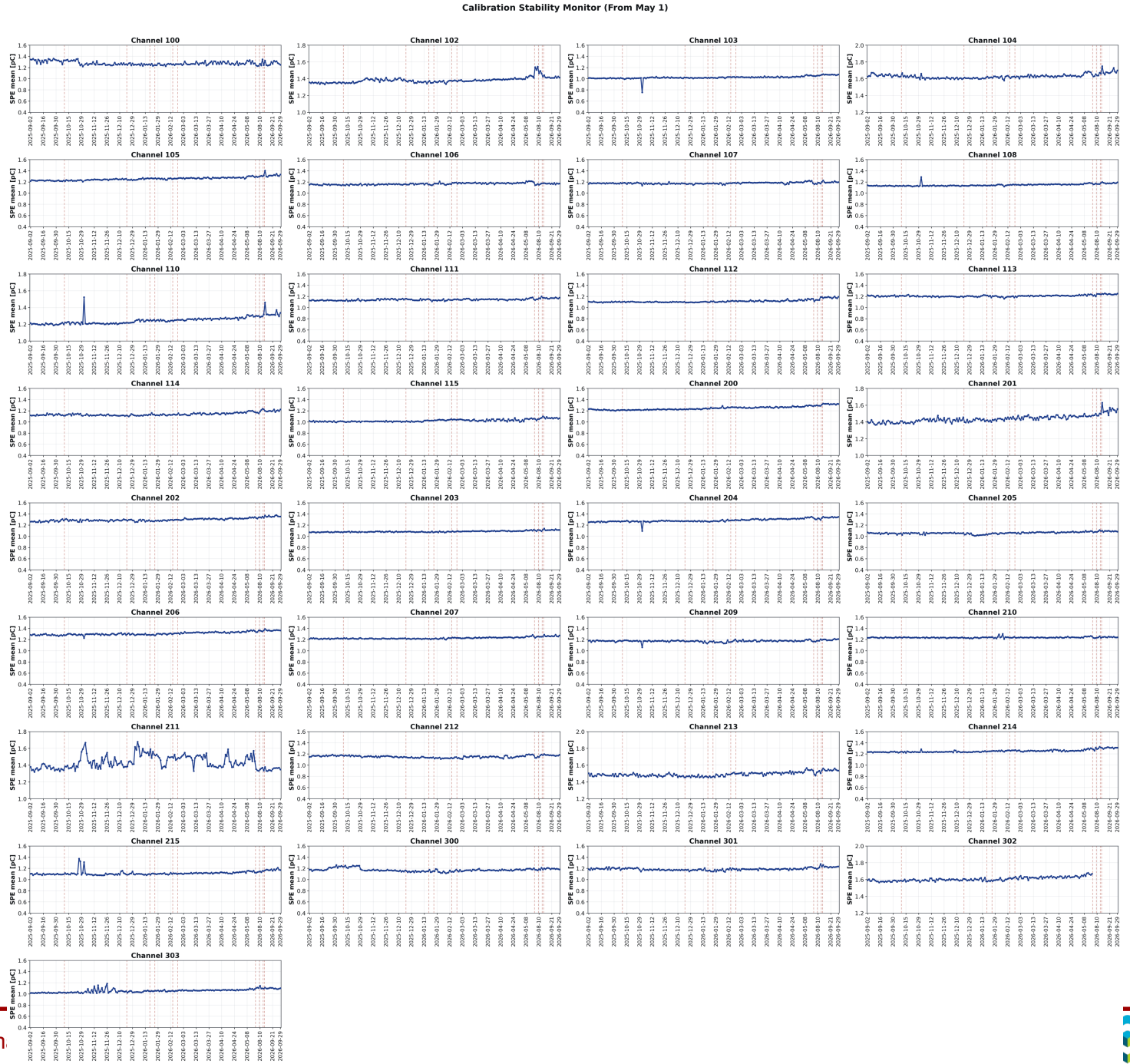
- Developed and characterized a variety of WbLS formulas for multiple frontiers
- In the context of neutrino physics, Cherenkov and Scintillation light separation is a key feature.
  - **Cherenkov** → direction, particle identification (e.g. separating electron vs muon tracks), timing.
  - **Scintillation** → energy resolution, event localization, sensitivity to low-energy interactions.
- Features:
  - Scintillation light yield proportional to WbLS concentration
  - Scintillation light later than Cherenkov light
  - Scintillation light with a narrower wavelength distribution than Cherenkov light
  - Scintillation light generated isotropically
- Combining **Cherenkov** (directionality) + **Scintillation** (energy resolution):
  - Allows identification of solar, reactor, atmospheric, and supernova neutrinos across broad energy ranges.
  - Enhances **background rejection** (since directional Cherenkov light can tag neutrino vs. radioactive background).
  - Key for **neutrinoless double beta decay**, **neutrino oscillations**, and **supernova burst neutrinos**, where both energy and topology matter.







Calibration monitor from source all PMTs



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