



Hybrid Light Detection in ANNIE: In-Beam Studies of Water-based Liquid Scintillator



By Amala Augusthy, Johann Martyn, Noah Goehlke, Johannes Gutenberg-University Mainz
Presented by Bruno Gelli[†], UC Davis - on behalf of the ANNIE collaboration

ANNIE Experiment

- 26 tonnes Gd-loaded water cherenkov detector
- Upstream (FMV) and downstream (MRD) muon detectors
- On axis, 100m from the BNB target at Fermilab → high $\nu\mu$ flux!

Rich science program and detector R&D:

- Neutron multiplicity on $\nu\mu$ - nuclei interaction
- CC/NC cross-section in Oxygen and relative to Argon
- Multiple Large Area Picosecond Photodetectors (LAPPD)
- Water-based Liquid Scintillators (WbLS)

SANDI Deployment

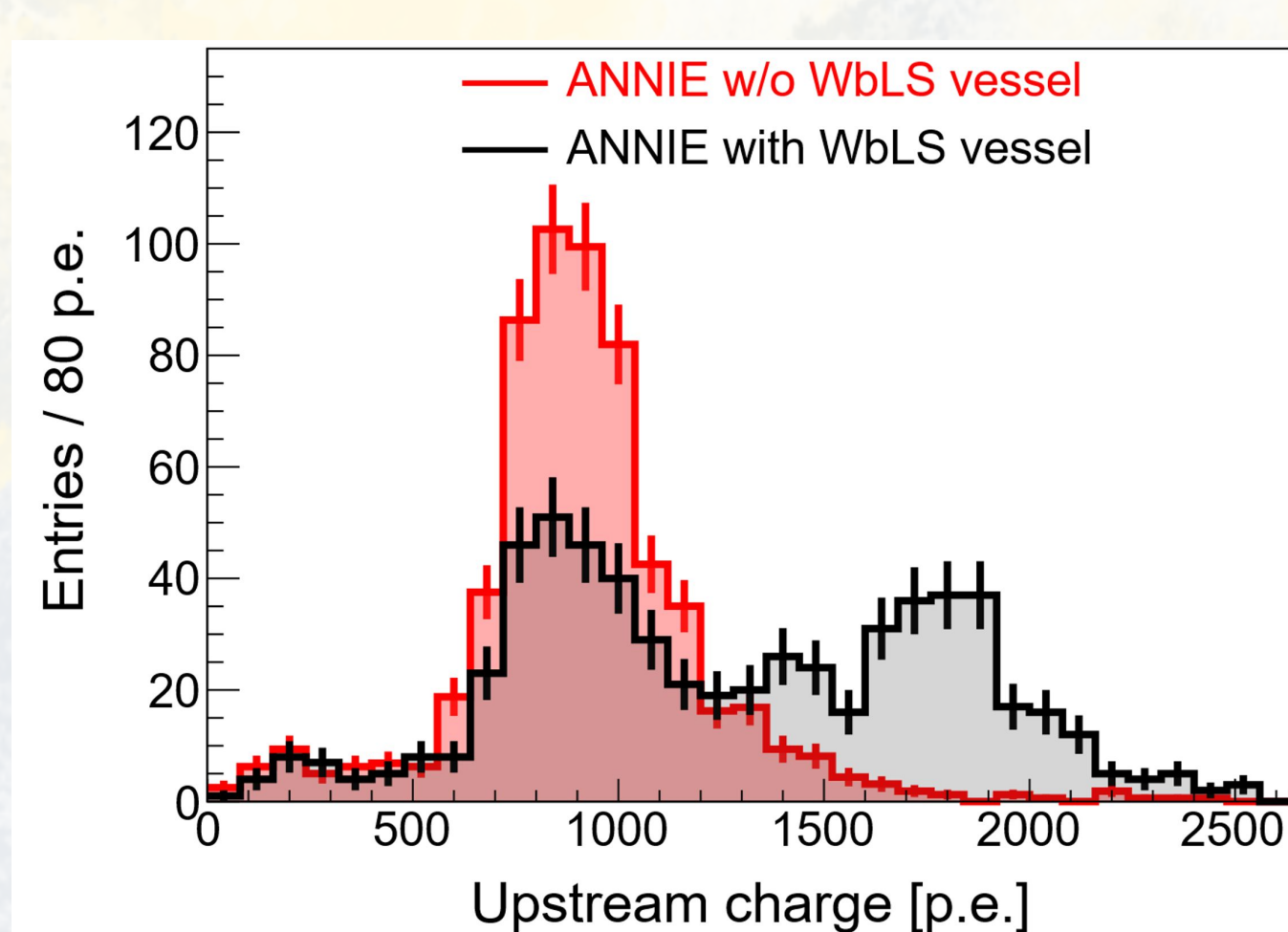
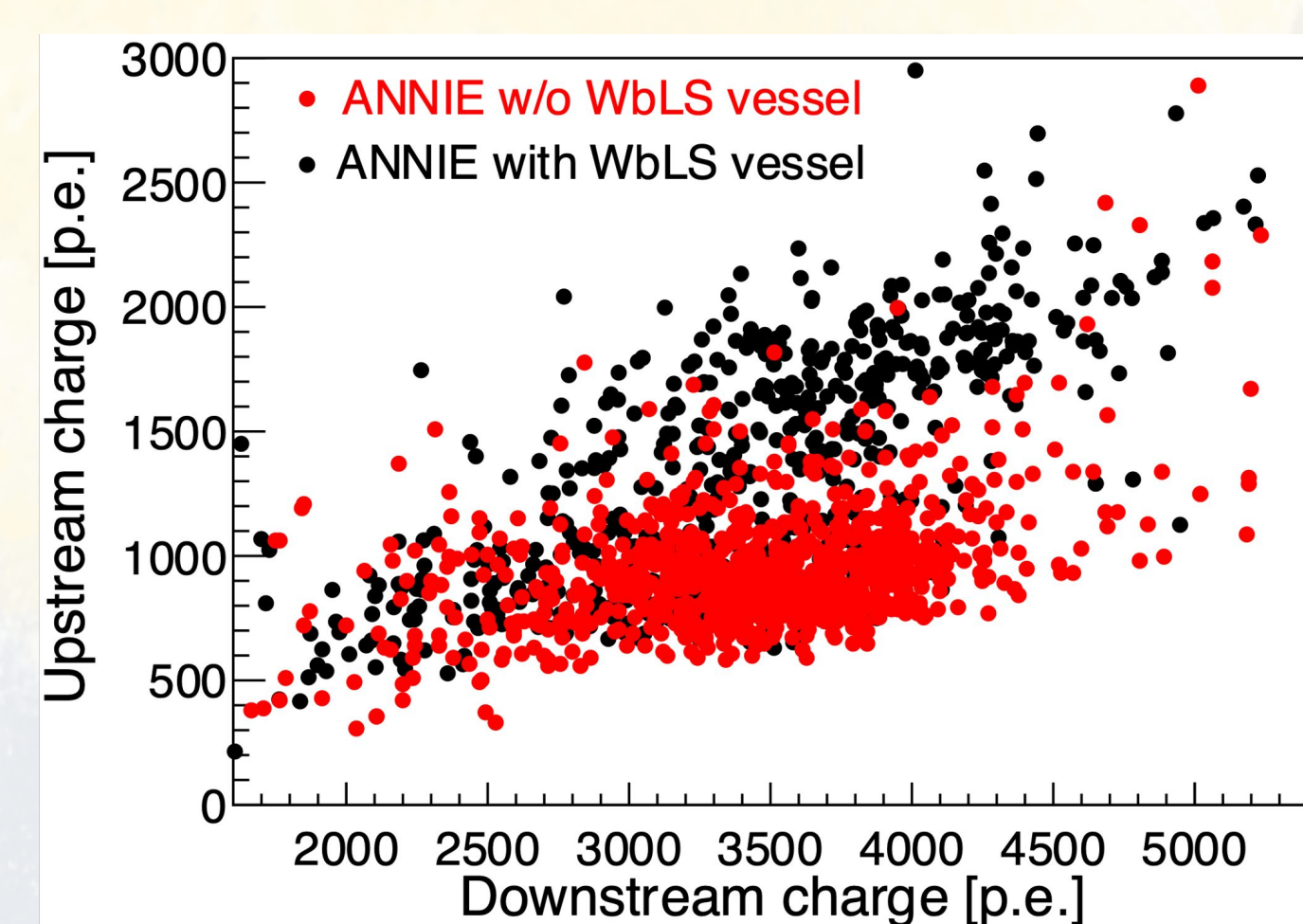
- ANNIE WbLS is composed of

- **Surfactant:** polyethylene glycol-based
- **Liquid Scintillator:** diisopropyl naphthalene (DIN)
- **Fluor:** 2,5-diphenyloxazole (PPO)

- Produced at BNL and shipped to Fermilab
- 366 L of WbLS deployed in UVT acrylic cylinder: SANDI
- Enhanced neutron detection capability at Run 2 with **Gd-loaded WbLS**

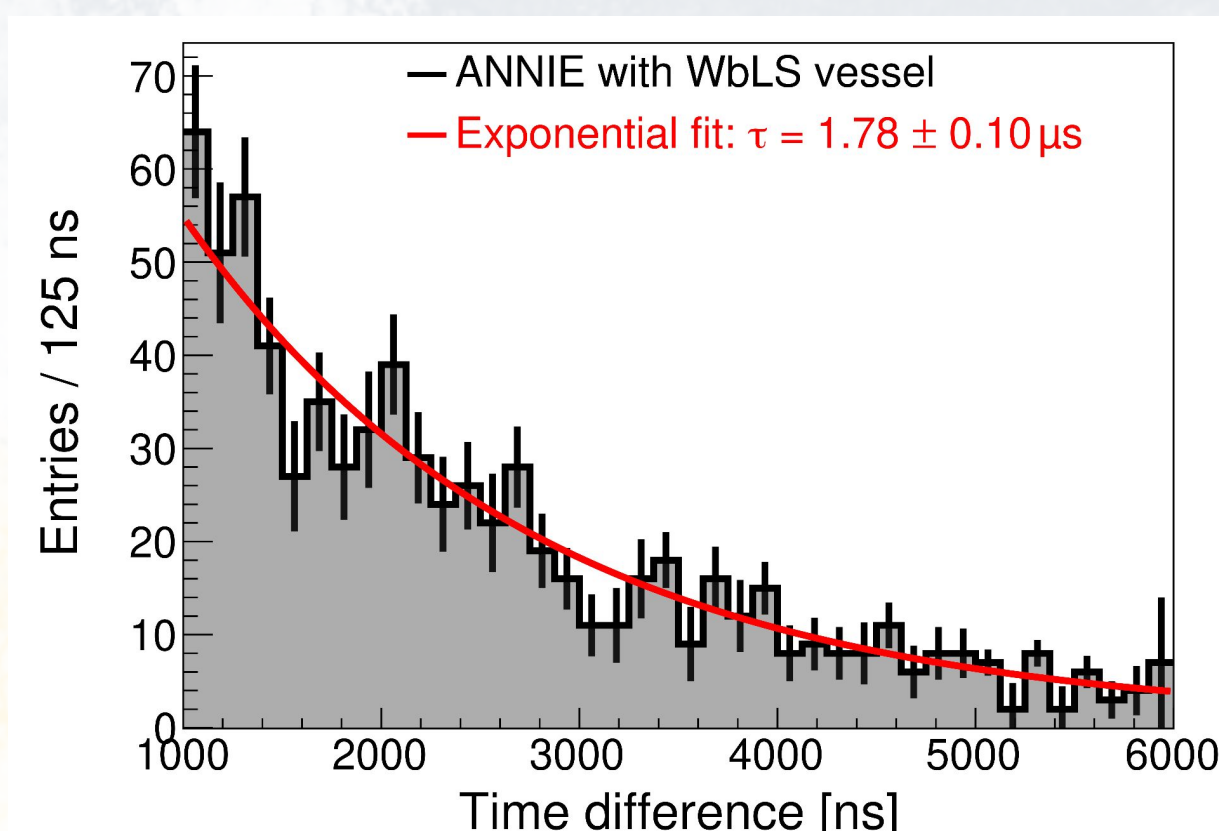
Run 1 - Scintillation from muons

Known MIP deposition from triple-tagged through-going rock muons
Events on WbLS volume produce both Cherenkov and scintillation

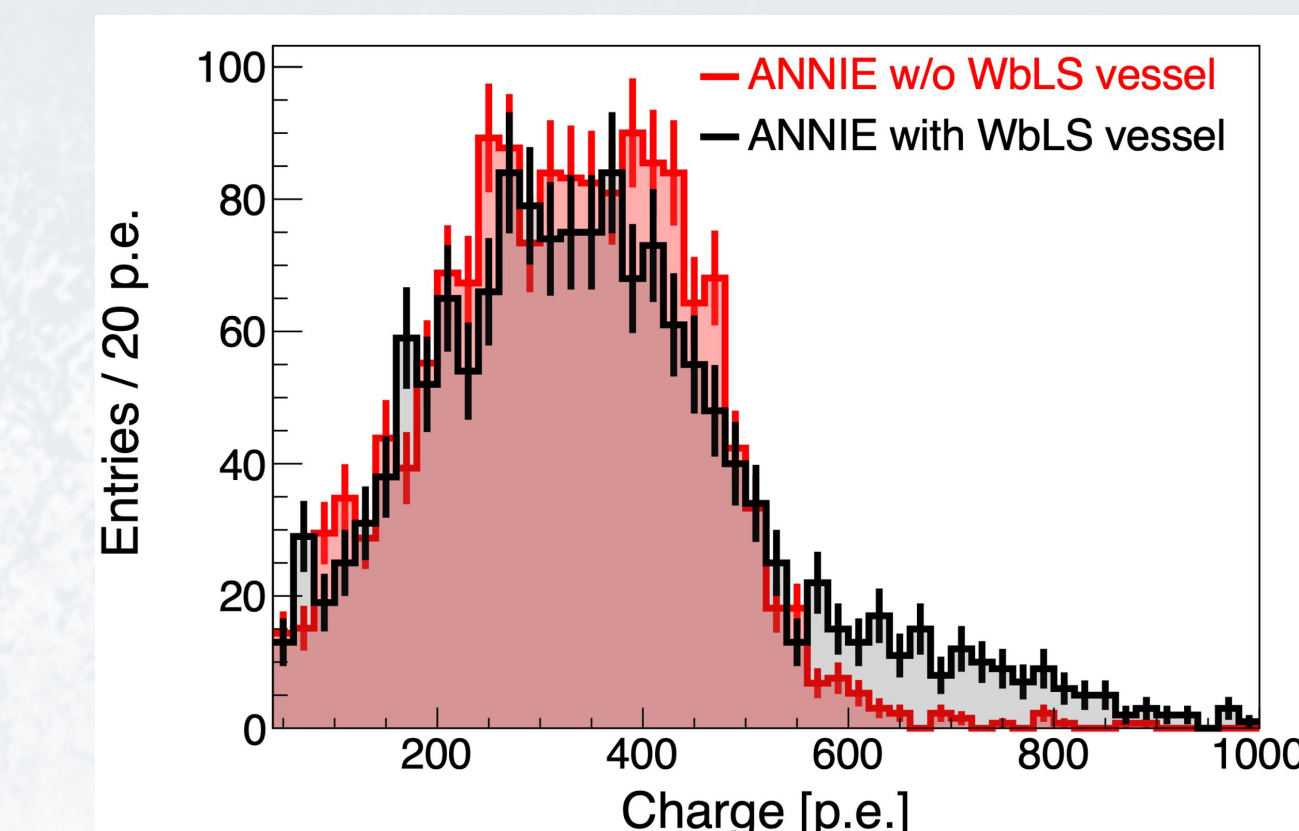


Charge of Through Going Muon Events in the Tank

- Cherenkov light:
 - Direct Cherenkov light detected by downstream PMTs
 - Indirect Cherenkov reflections detected by upstream PMTs
- Scintillation light is isotropic:
 - Detected by both Upstream and Downstream PMTs



Michel Electron Detection time

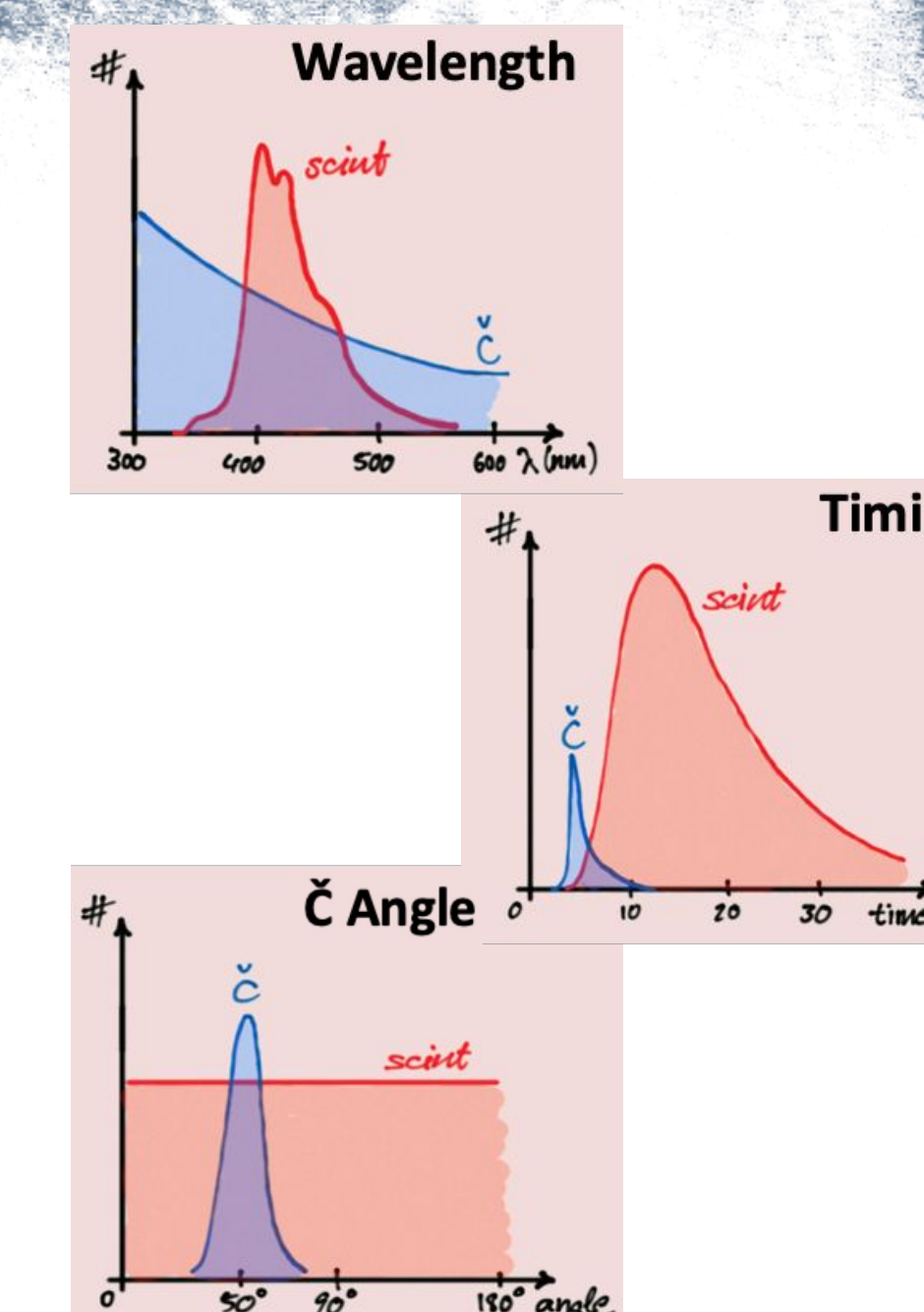
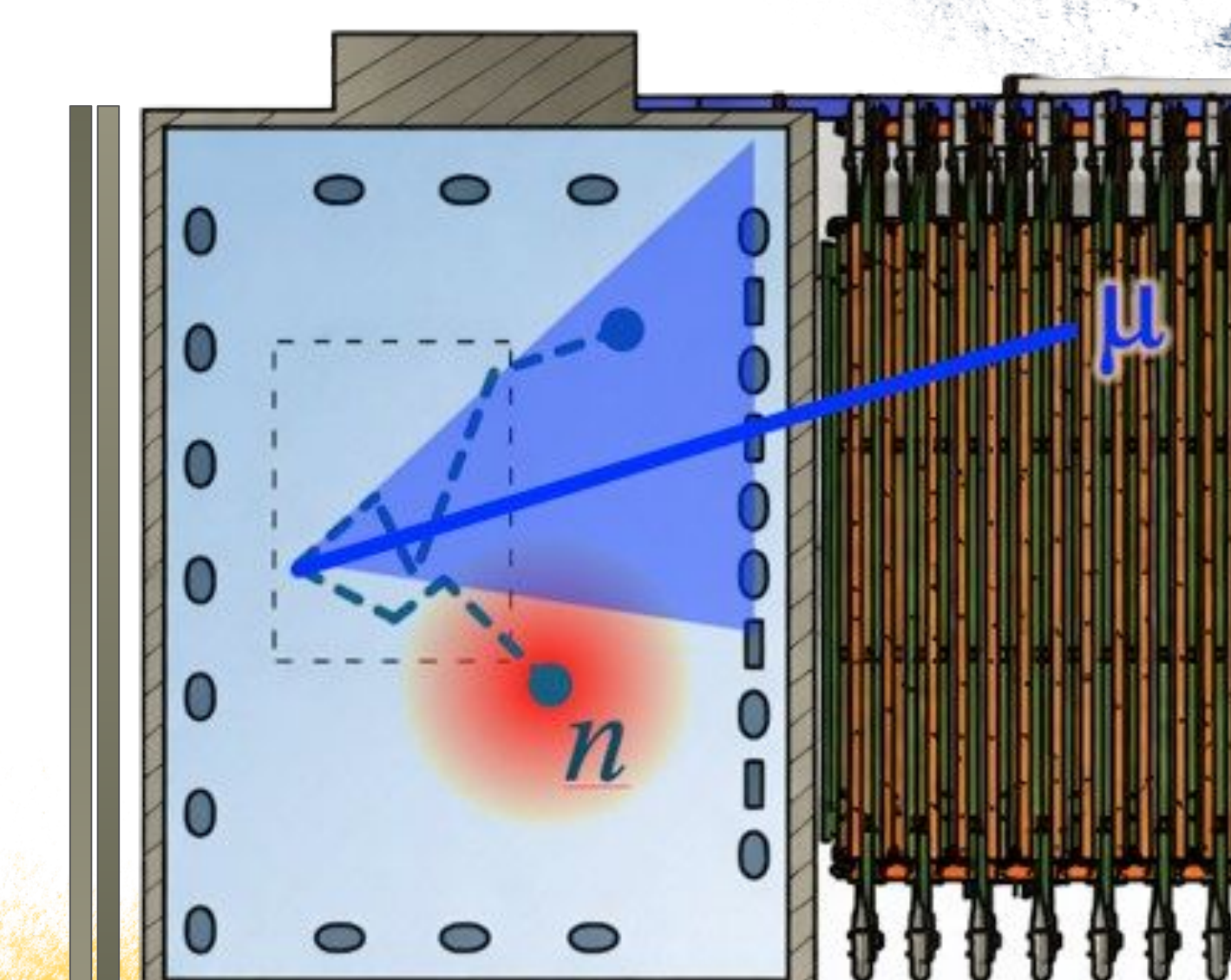
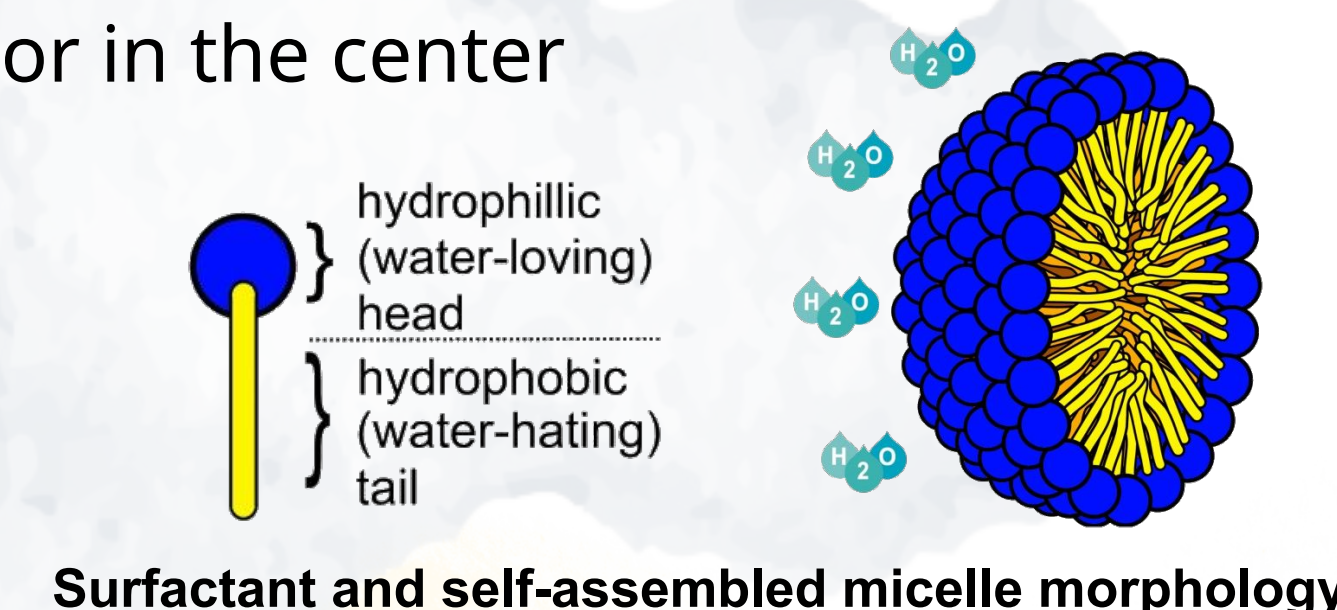


Charge of selected michel electron events

Water-based liquid scintillator (WbLS)

- Novel enhanced detection medium capable of adding Scintillation to Cherenkov-like detectors.
- Mixture of water and scintillator with tunable light yield and timing profile
- Micelles of surfactant with liquid scintillator in the center
- Hybrid event detection:

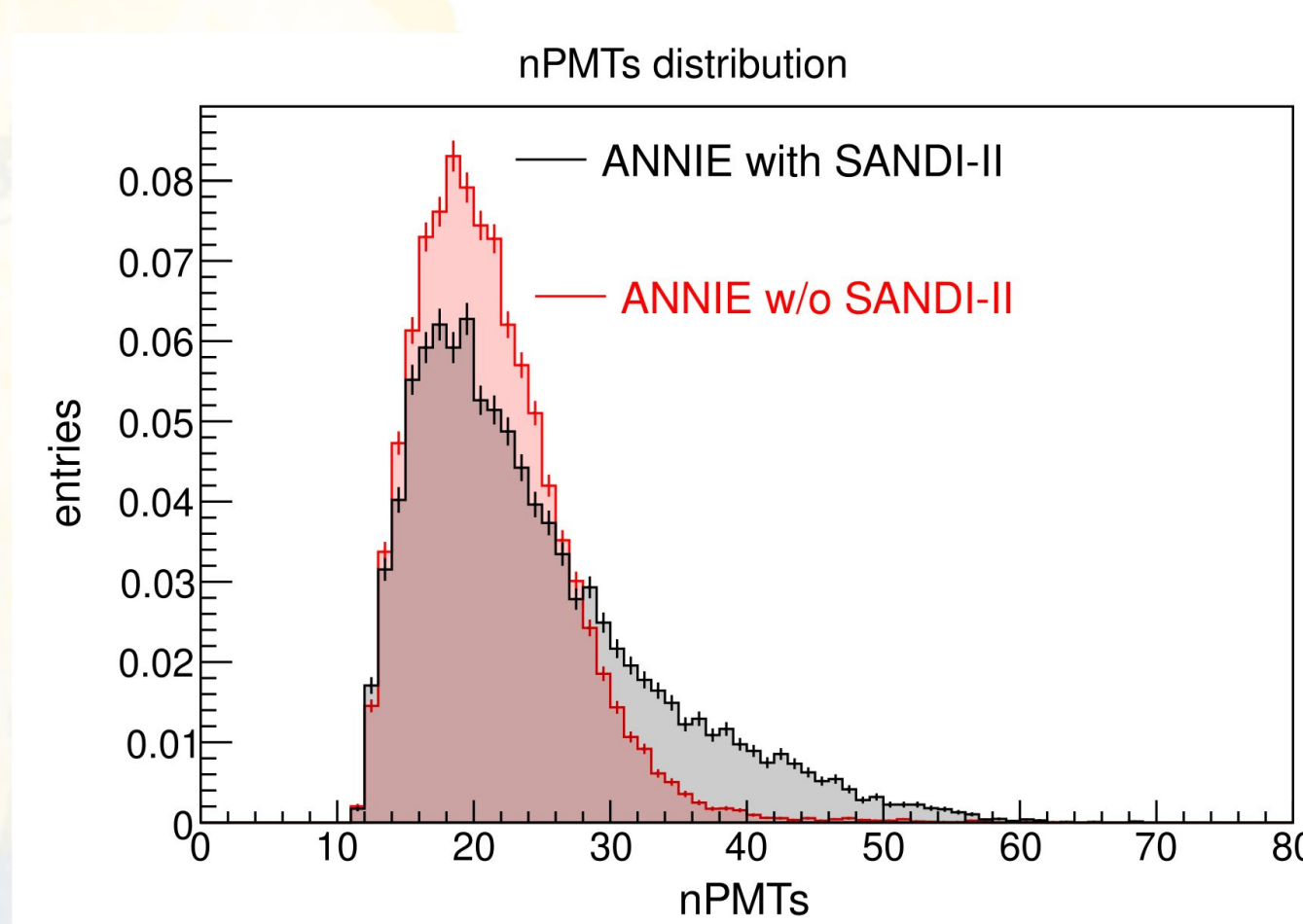
- Good energy resolution + directionality
- Sensitive to low energy particles
- Background rejection
- Scalable due to high transparency



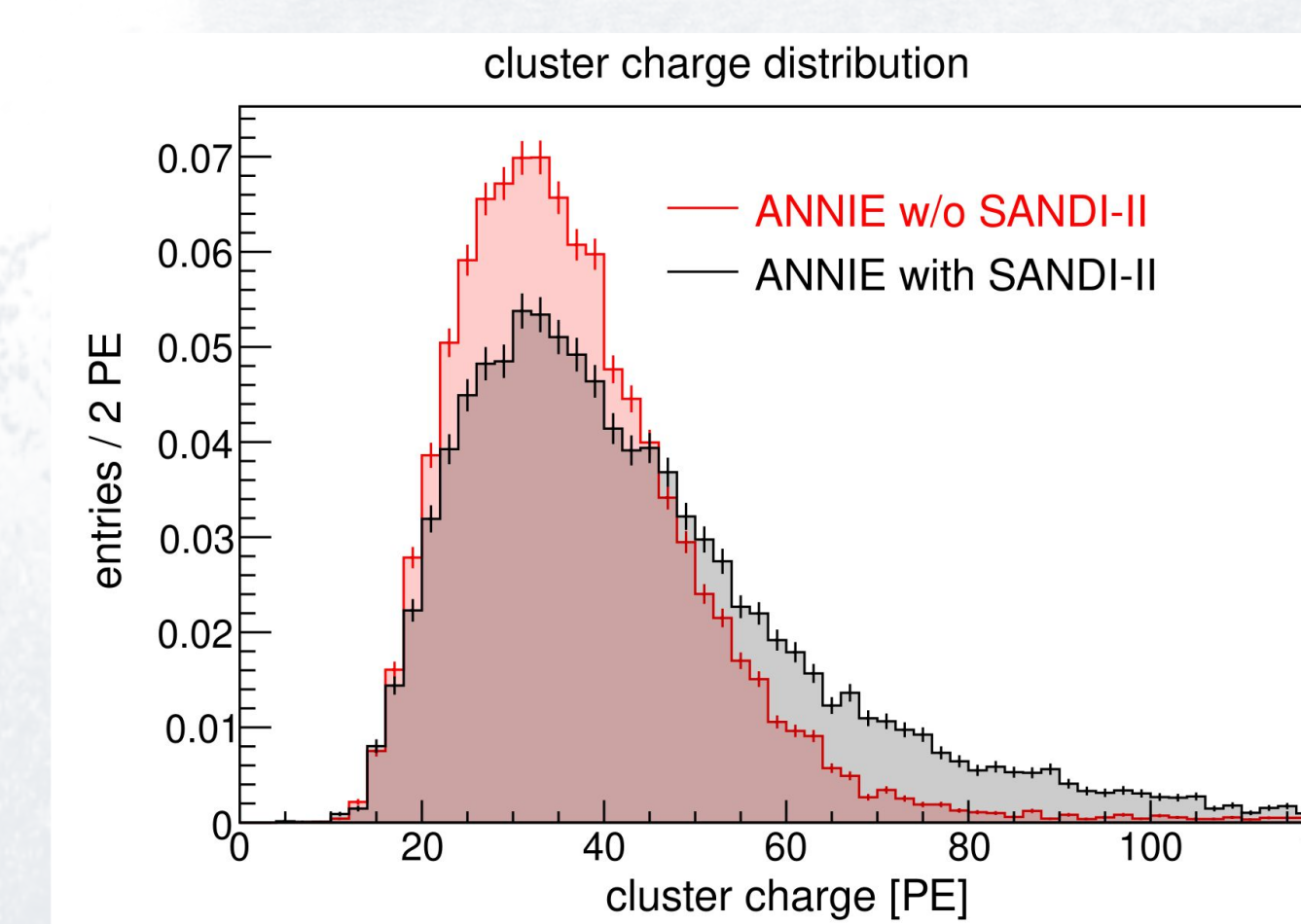
Run 2 - Gadolinium Loaded WbLS

SANDI-II redeployed the acrylic vessel with Gd-loaded WbLS
The Gadolinium Loading enhanced the Neutron-Detection capability

- AmBe source was used as source of tagged neutrons:
 - Coincident gamma to tag neutron emission
 - Direct comparison to Gd-Water filled vessel



Number of PMT hits per Neutron Cluster



Total Neutron Cluster Charge

Comparison with AmBe data shows increased cluster charge and more hit PMTs

- Full capture efficiency extraction still requires simulation
- Brighter Events!

Run 1 - Scintillation from Michel electrons

Very well known energy spectrum for direct comparison
Direct comparison energy spectrum Water-WbLS

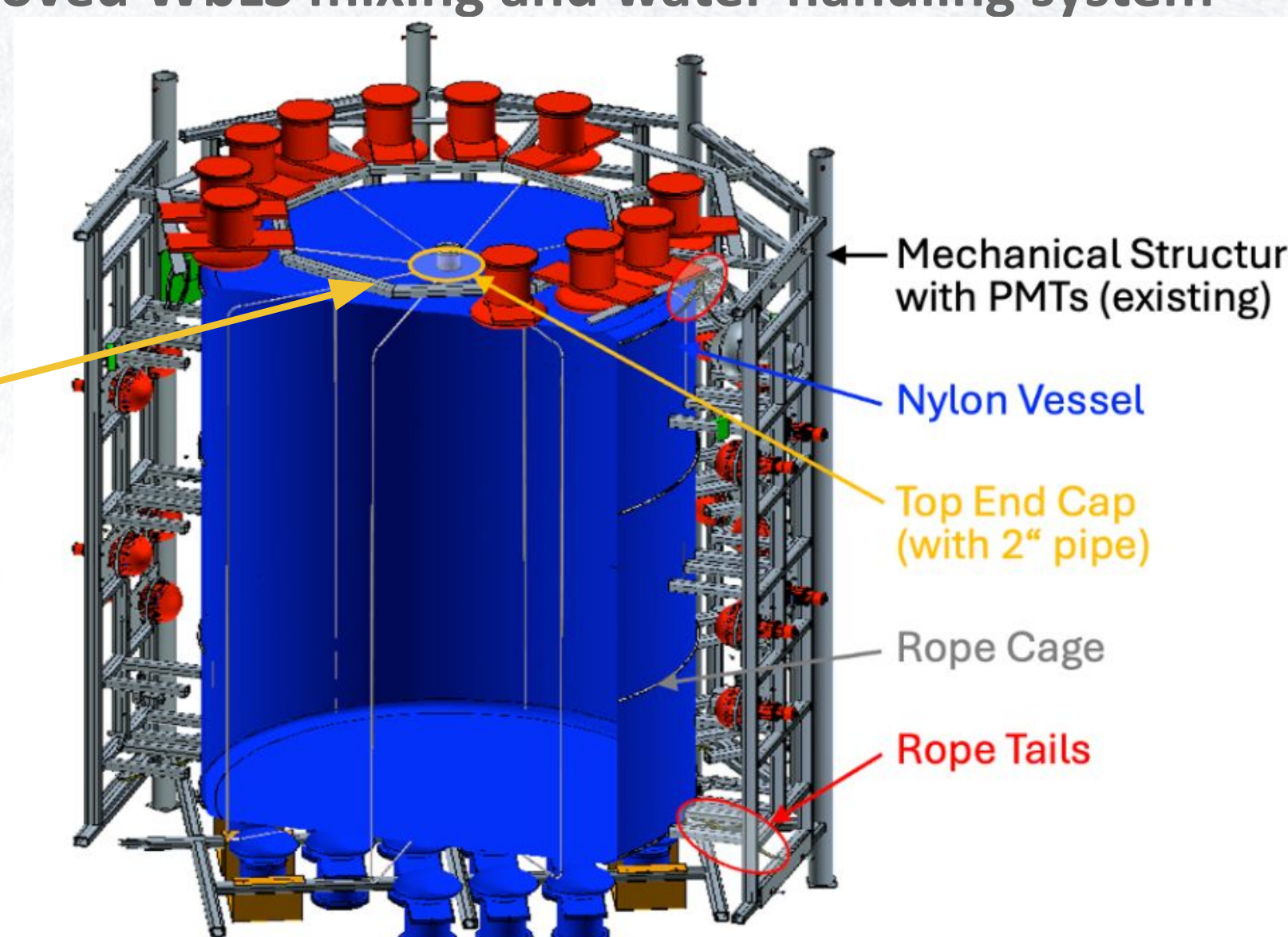
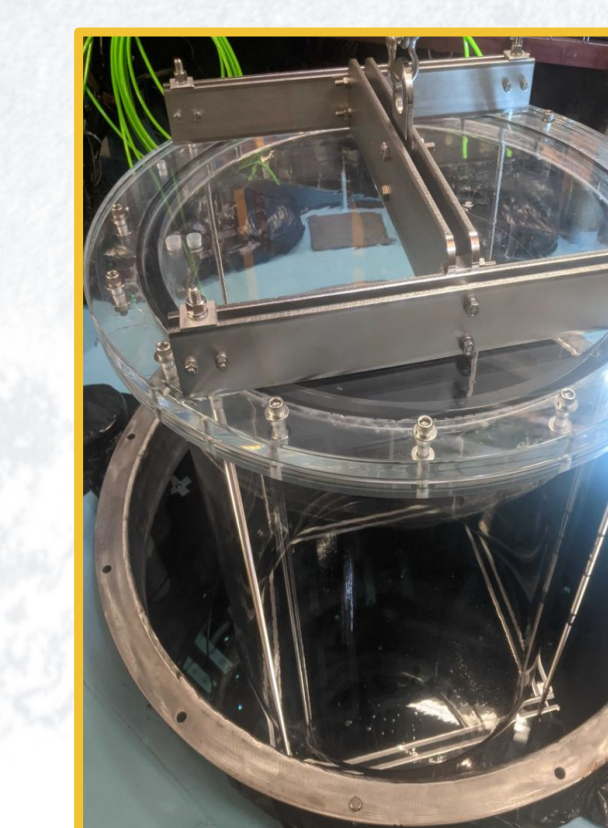
- Event selection: prompt muon event followed by an electron
Electron clusters timing showed good agreement with the expected muon lifetime, indicating good purity
- Two types of michel electron events:
 - WbLS volume events (Cherenkov + Scintillation)
 - Pure Water events (Cherenkov photons only)
- Increase in photoelectrons (PE) detected for Michel electrons created inside SANDI:
 - Relative increase in detected PE estimated using the ratio of the mean number of detected PE by the two event types

WbLS produced a measured increase in detected light: (77 ± 8)% for Michel electrons

SuperSANDI

After the successful deployment of the SANDI vessel, a new larger WbLS deployment is planned - SuperSANDI!

- New vessel will be 8 tonnes, roughly 22x bigger than SANDI
- One whole beam year of exposure, starting Fall 2026
- New and improved WbLS mixing and water-handling system



Comparison between the SANDI and SuperSANDI

Conclusion and Takeaways

ANNIE successfully demonstrated the capabilities of novel WbLS detection media

- Demonstrated the detection of both cherenkov and scintillation light
- Two independent analyses to estimate the increase in light production
- Demonstrated WbLS stability over the full deployment period

Rich R&D program ahead

- SuperSANDI deployment with Gd-loaded WbLS for neutron capture
- Timing separation of scintillation and Cherenkov signal with LAPPDs

This document was prepared by the ANNIE collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics HEP User Facility. Fermilab is managed by Fermi Forward Discovery Group, LLC, acting under Contract No. 89243024CSC000002.

This work was supported in part by the Deutsche Forschungsgemeinschaft, grants 490717455 and 460377837. And by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC0009999.

[†] Bruno Gelli: bgelli@ucdavis.edu

More information at DOI 10.1088/1748-0221/19/05/P05070 →

