

Exploring Physics with Liquid Scintillator Detectors

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NNN2026, Chung-Ang University, Seoul (Korea), October 28-30, 2026

THE PLATFORM

Why liquid scintillator remains broad

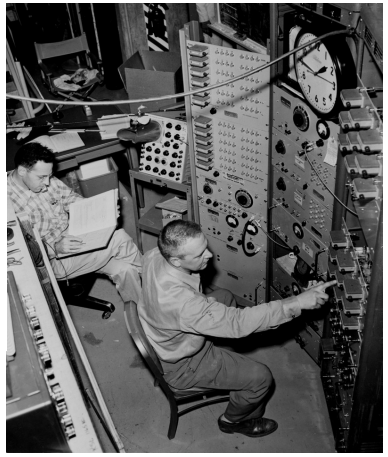
Trade threshold, directionality, loading, and topology against the physics goal.

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)



Low threshold

Solar and supernova neutrinos

Large target mass

Long-baseline oscillations

Radiopure loading

0vββ and rare-event searches

Fine segmentation

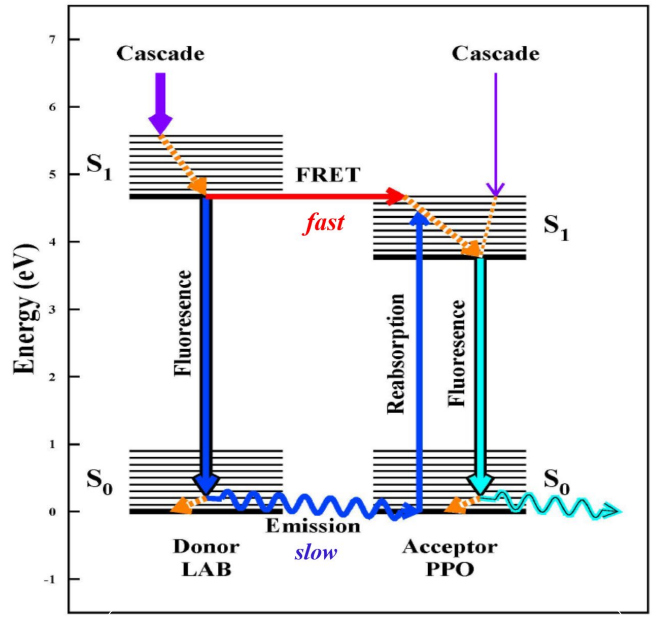
Charged-particle calorimetry

The medium is valuable because its response can be engineered around the observable.

OPTICAL FOUNDATION

Detected light determines the physics reach

The useful quantity is photoelectrons with the right timing and topology.



1

Excitation & transfer

Solvent to primary fluor

2

Emission spectrum

Fluor and wavelength shifter

3

Transport

Absorption, scattering, re-emission

4

Detection

Coverage, PDE, and timing

At detector scale, transparency and spectral matching can matter more than modest gains in intrinsic light yield.

LS-based ν Landscape



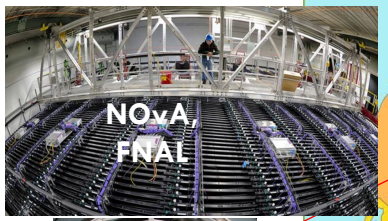






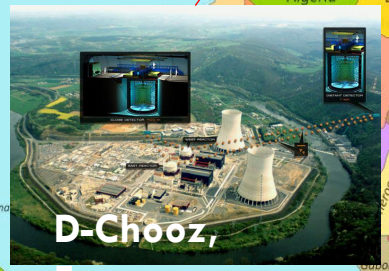




















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HYBRID MEDIA

Water-based liquid scintillator (WbLS) adds new handles

WbLS combines a water-rich target with tunable scintillation (First introduced at ANT 2010 (Santa Fe); published in NIMA, 2011.

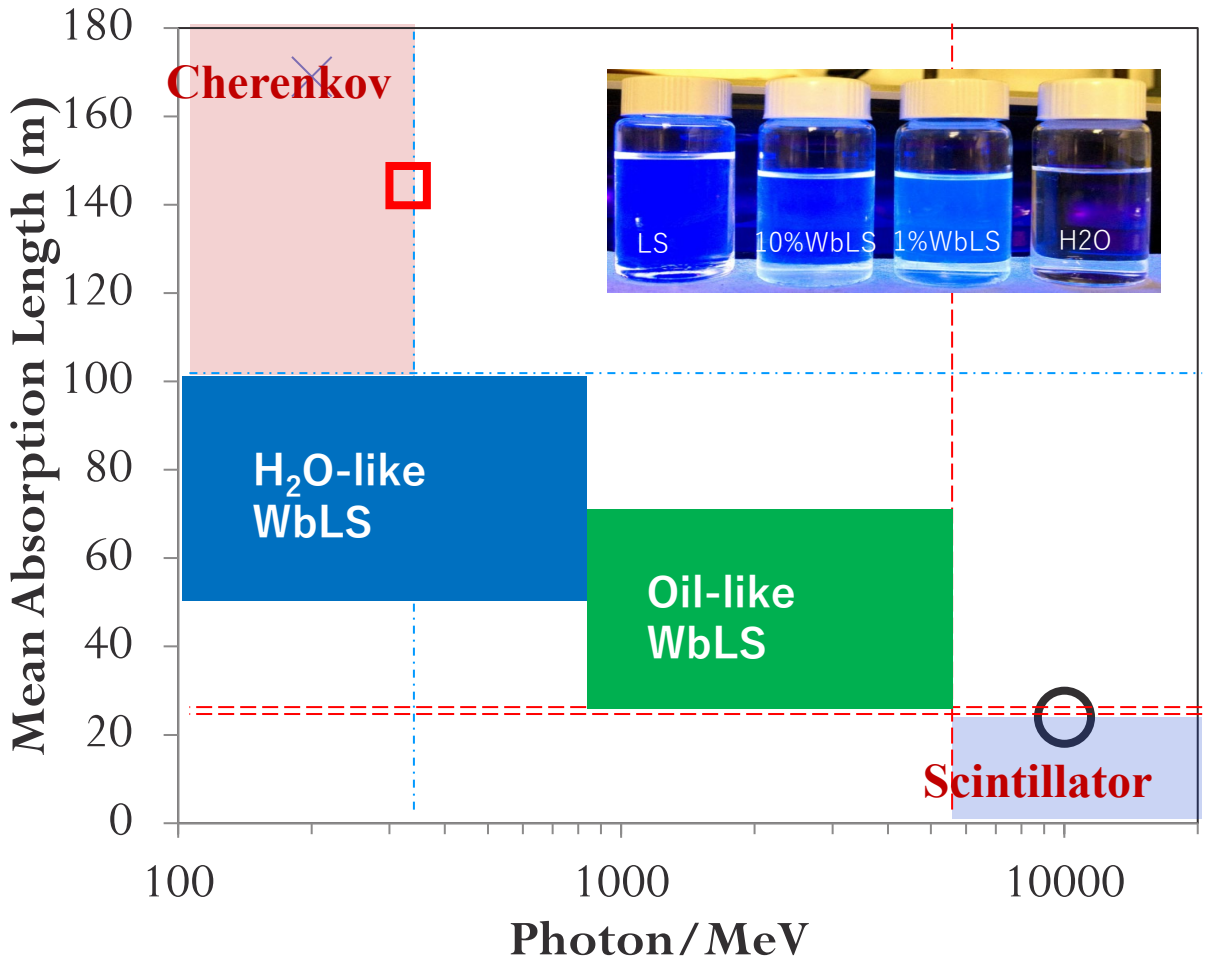
Cherenkov + scintillation	Early directional photons plus low-energy scintillation
Aqueous metal loading	A route to neutron tagging and isotope deployment
Water-rich scalability	A potentially practical path toward large targets
Tunability	Adjust threshold, directionality, and chemistry

WbLS is an enabling thread across several physics programs — not the entire story.

Oil- vs. Water-like WbLS performances

Depends on experimental needs

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



Oil-like WbLS
- <100 ton-scale detectors
- High light-yield
- Not necessary for in-situ circulation
- >90% LS with water (>10,000 phs/MeV)
- Metal-doped (selected elements)
- PROSPECT, (G3)DM, LiquidO

PHYSICS MAPPING

The medium opens specific observables

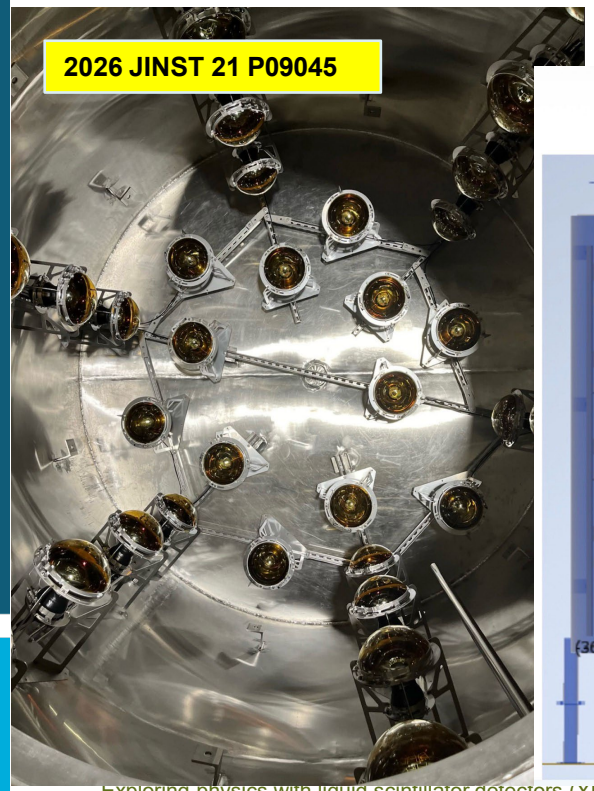
Capabilities should be selected because they enable an observable, not as a technology end point.

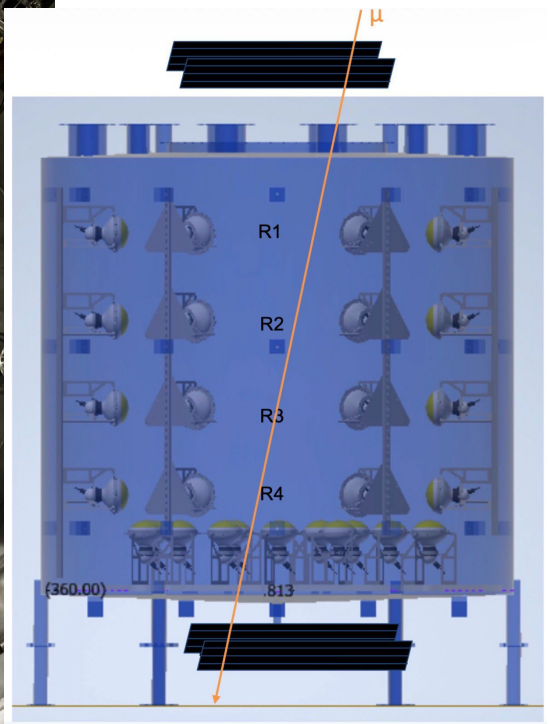
CAPABILITY	OBSERVABLE	PHYSICS OPPORTUNITY
Early Cherenkov photons	Direction and topology	Oscillations; solar and supernova neutrinos
Scintillation photons	Low threshold and calorimetry	Solar neutrinos; energy reconstruction
Neutron-tagging chemistry	Delayed coincidence	Antineutrino and background rejection
Local light confinement	Track shape and particle ID	Hadronic and charged-particle calorimetry
Metal loading	Candidate isotope mass	0νββ searches

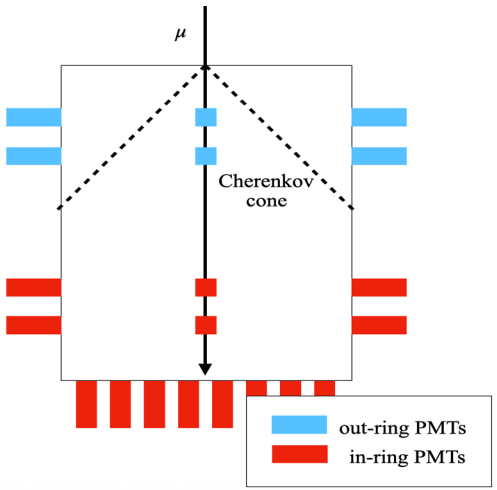
Paths to a large-scale optical detector: BNL1T/30T, ANNIE, Eos, BUTTON

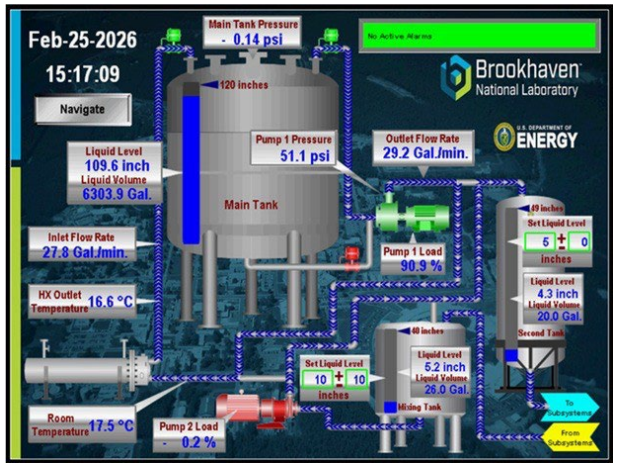
BNL 30T (Commissioning in summer 2024)

- 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





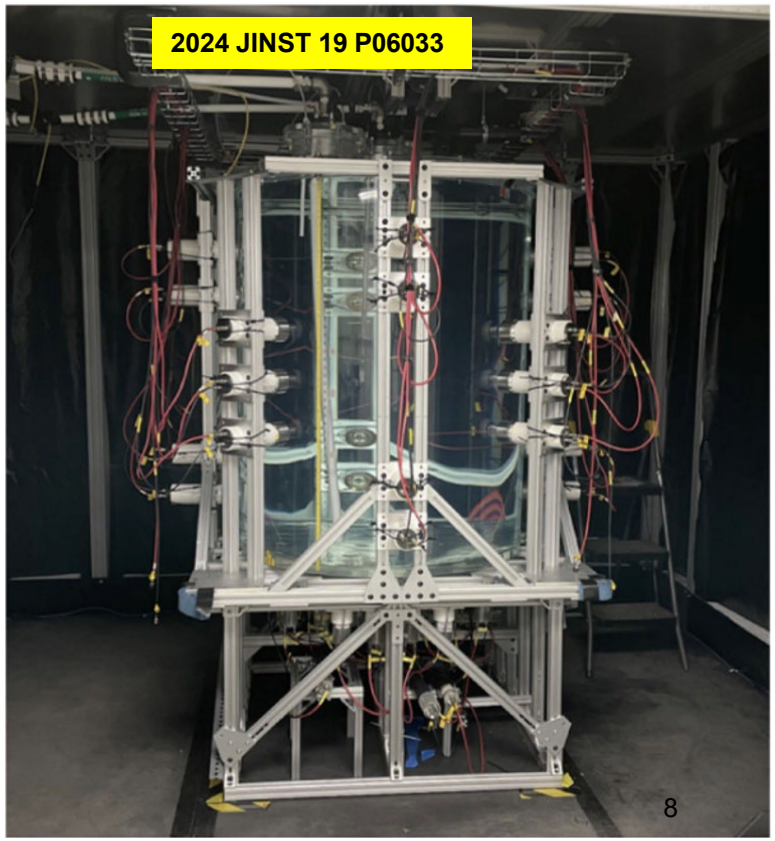




Automated control system

BNL 1T (Commissioning in summer 2023)

- Acrylic tank holding 1 ton of WbLS
- Total 58 2-inch size PMTs coupled to acrylic tank



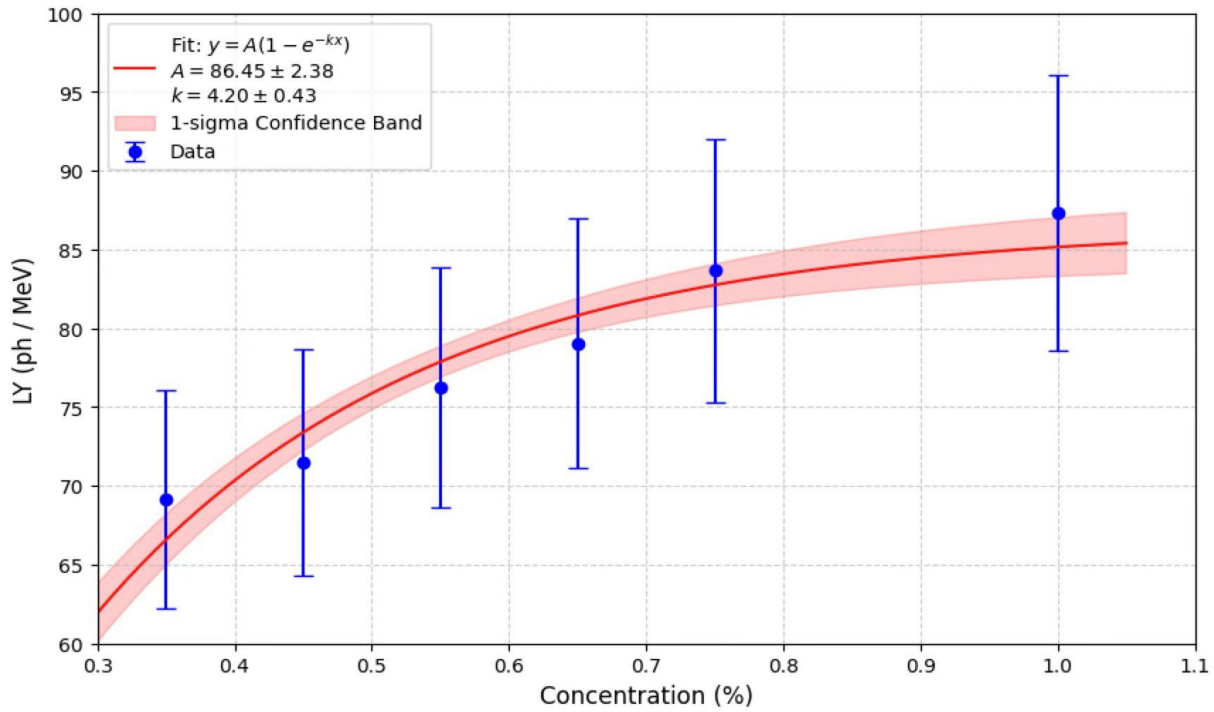
Phys. Rev. D 113, 092015 (2026)

1-ton results

Absolute scintillation light yield

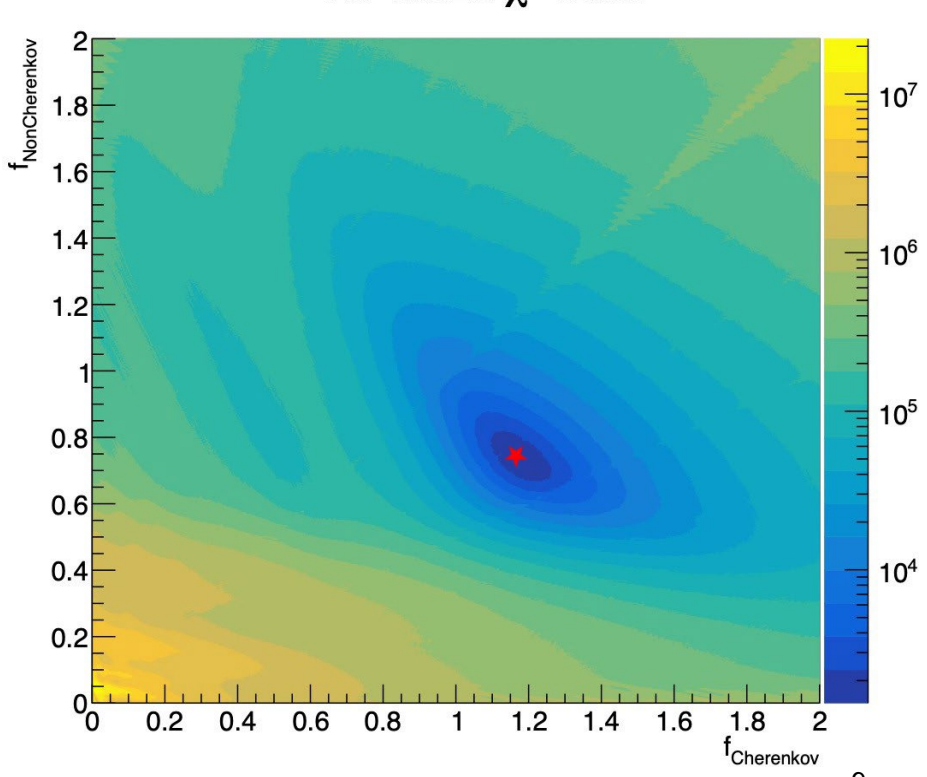
- Benchtop measurement of Gd compatible WbLS, 0.35-1.0 % by mass
- 87.3 ph/MeV at 1 % WbLS

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

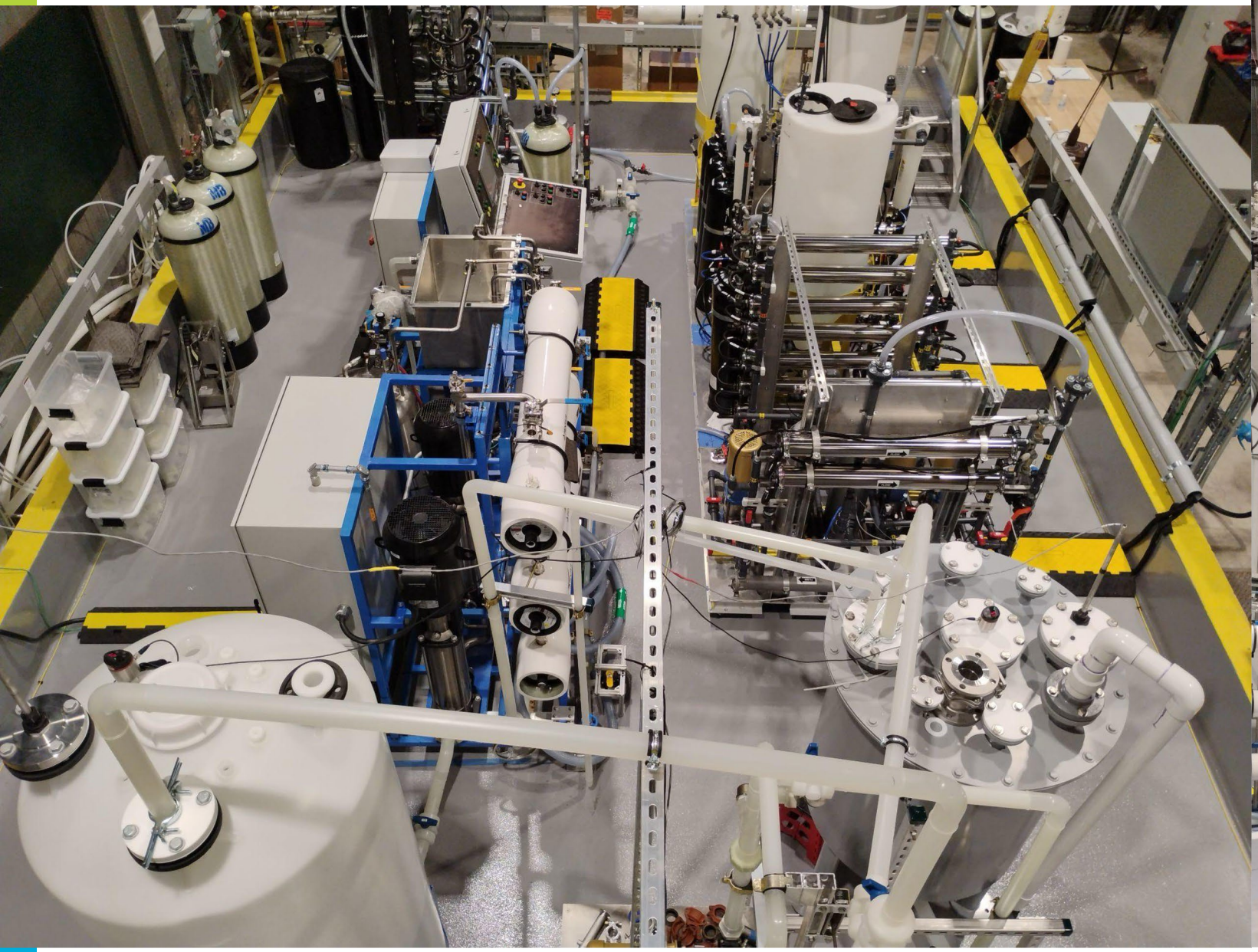


Cherenkov vs. non-Cherenkov light

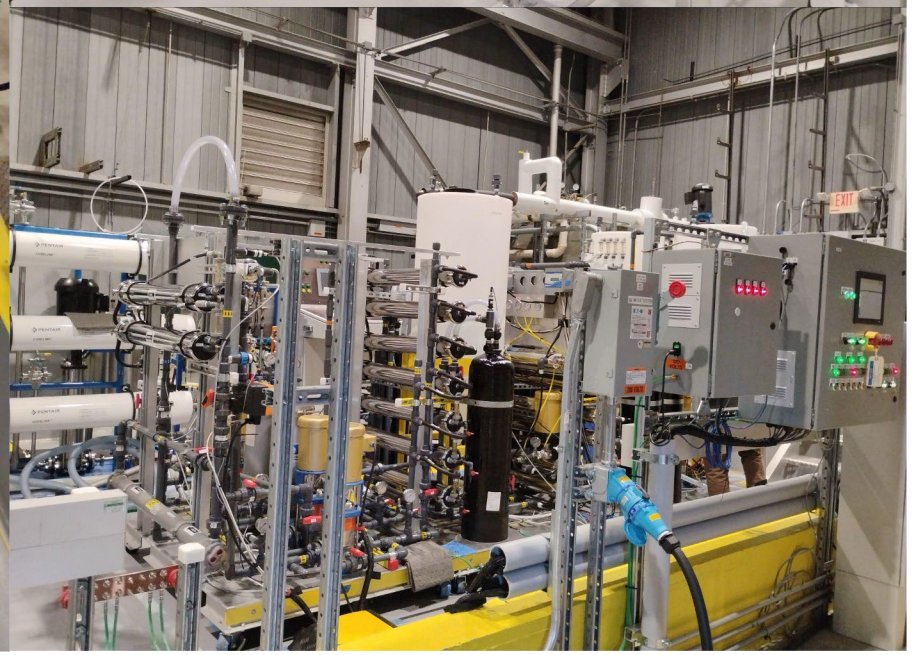
- Crossing cosmic muons
- 2D χ^2 scan: Cherenkov and non-Cherenkov light cleanly separated
- Modelling is robust



30-ton Facility with circulation and filtration system (JINST accepted)



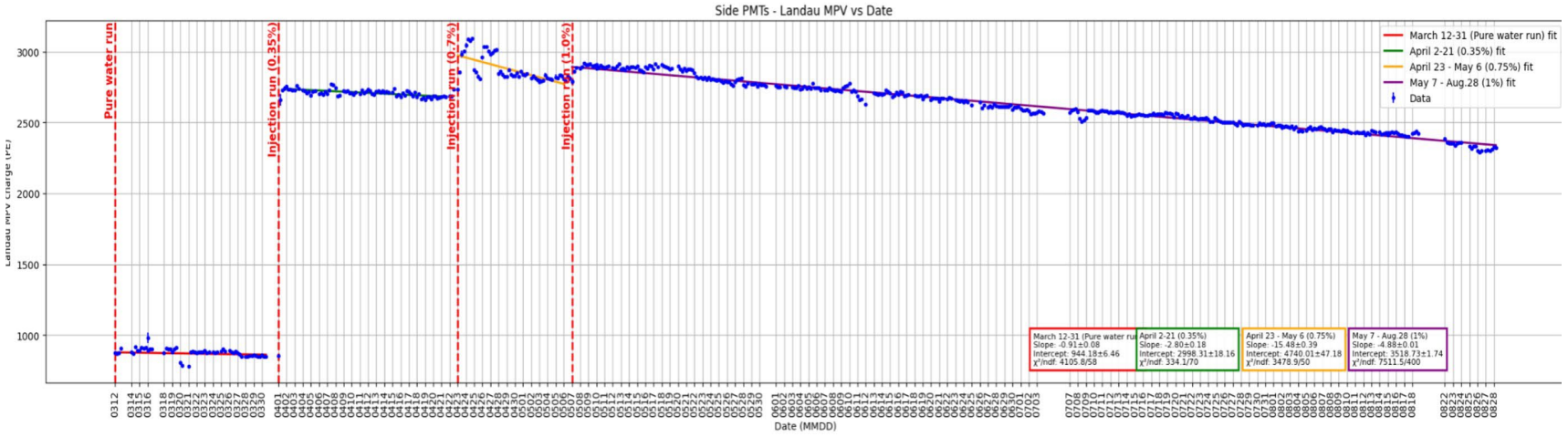




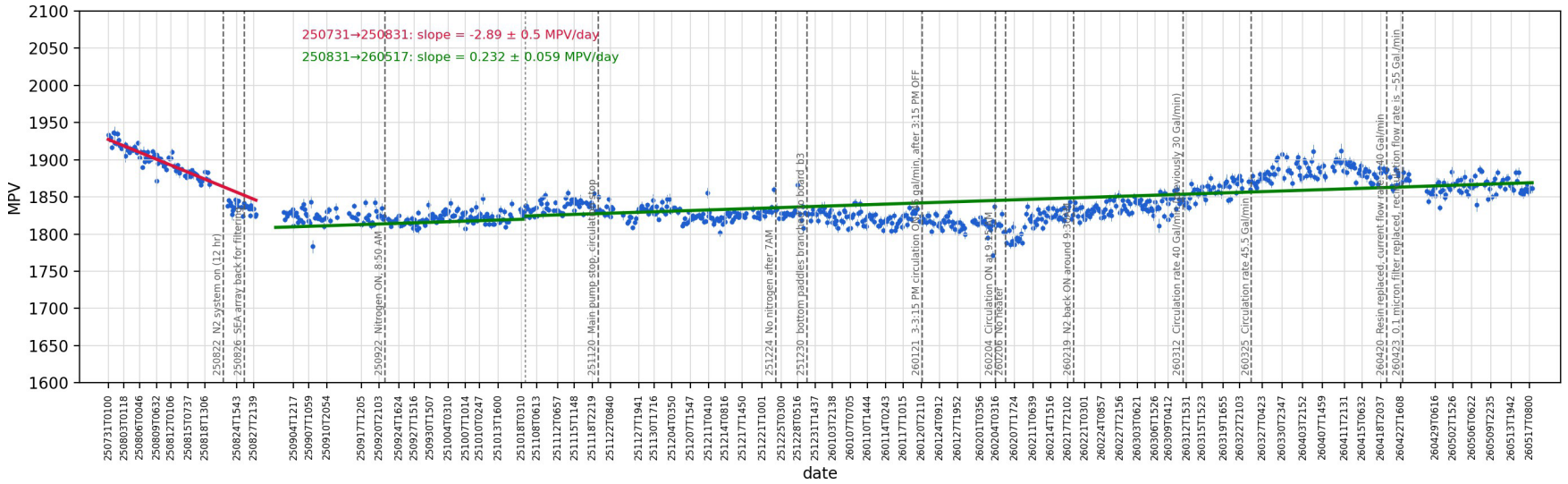
3-ton results

stability after installing Sequential Exchange Array (SEA) and nitrogen buffer

Before



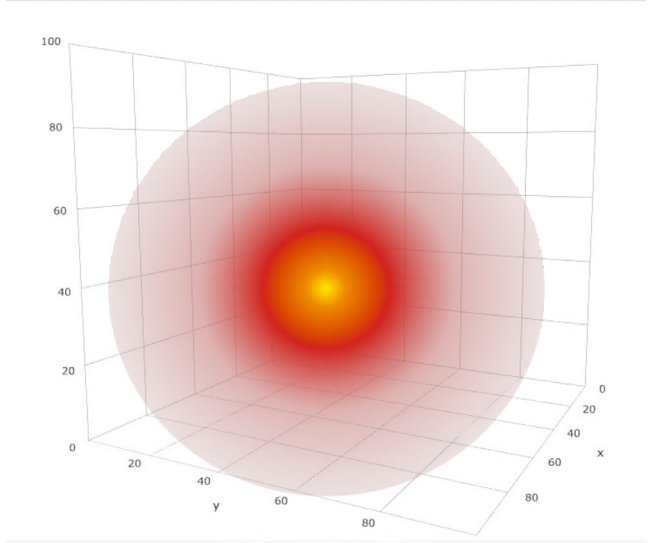
After



TOPOLOGY

Opaque WbLS points toward a 3D projection calorimeter

Local light confinement can make a homogeneous liquid an imaging detector.



Inducing light to a point (LiquidO)

Chemistry

Tune scattering and local confinement

Readout

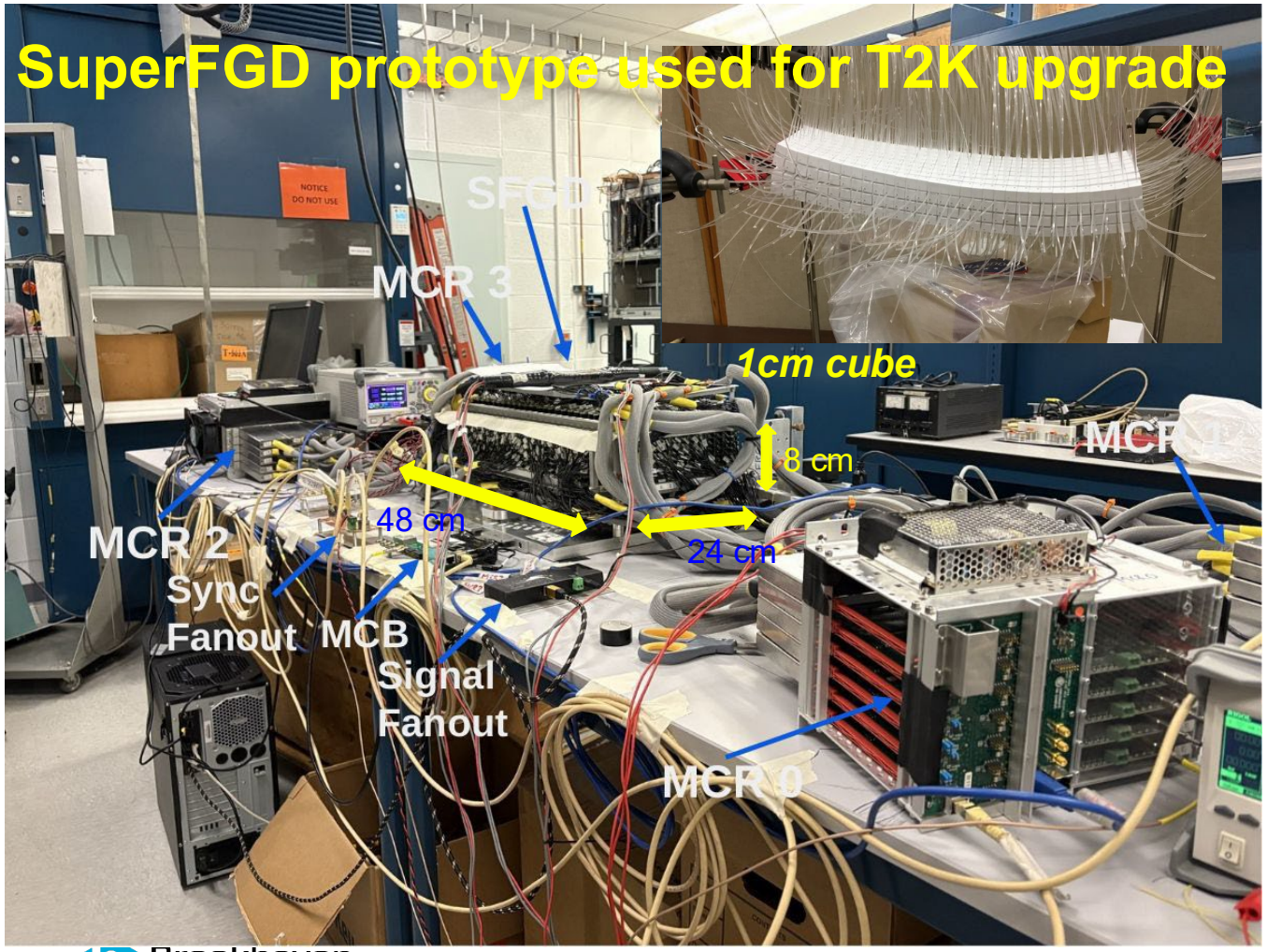
Three orthogonal WLS-fiber views

Evidence

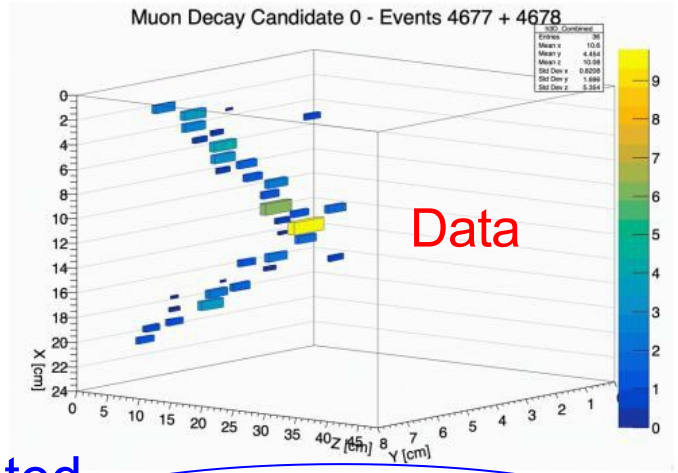
3D proton imaging; >90% light confinement in a voxel

The physics test: can local imaging improve particle ID and hadronic energy reconstruction?

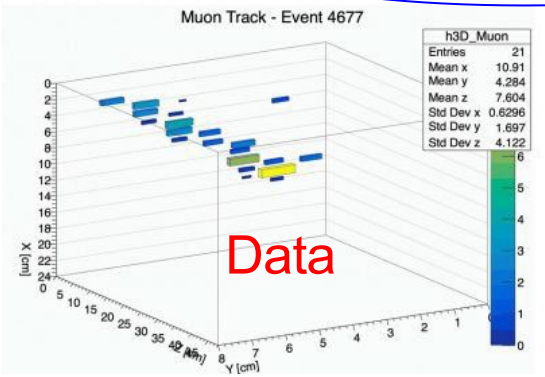
From 1 cm³ Cubes to oWbLS: The Next Step in Detector Innovation

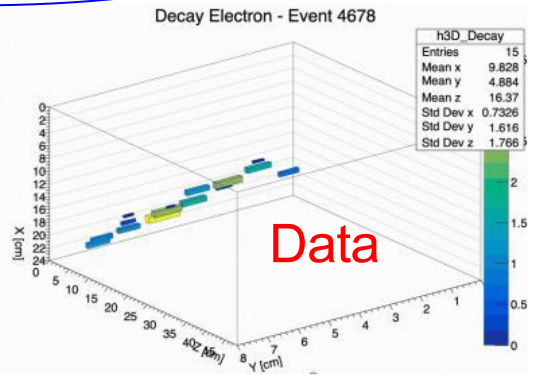


Fully calibrated



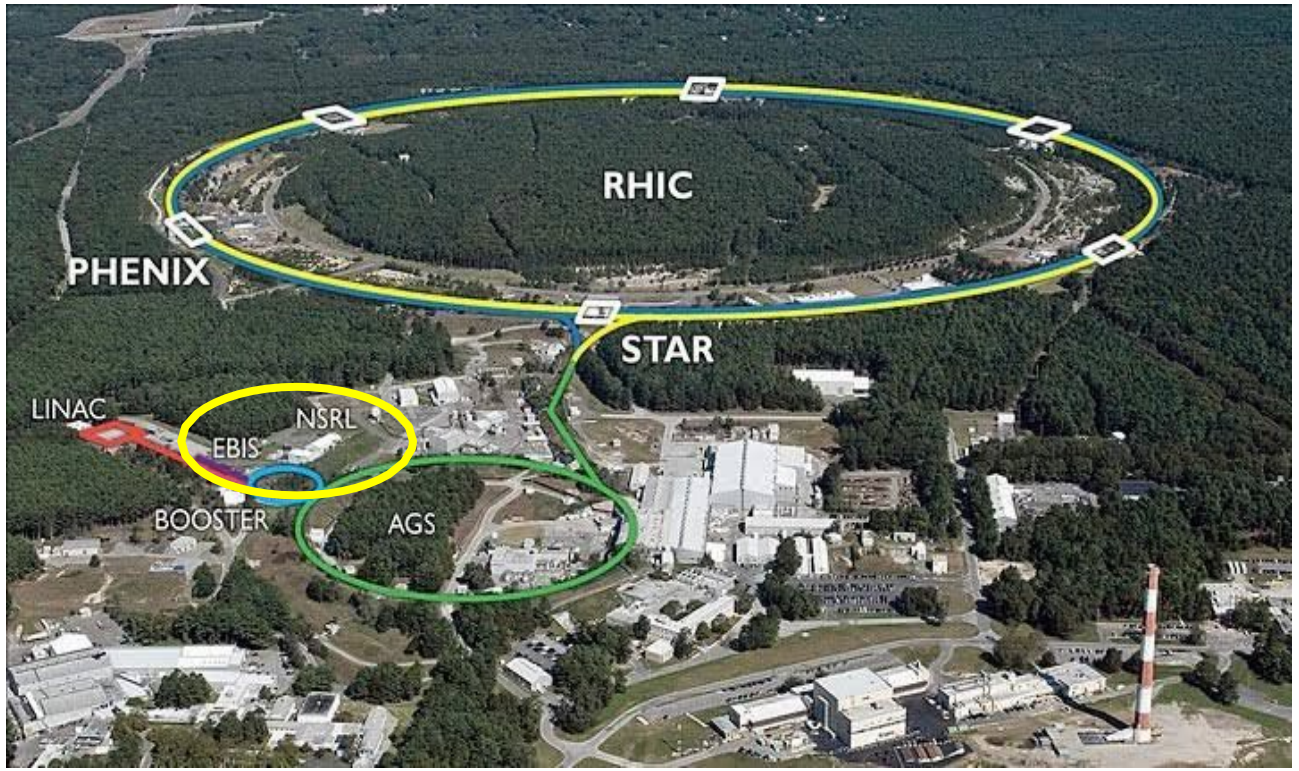
Muon Decay; ΔT=1.445μs

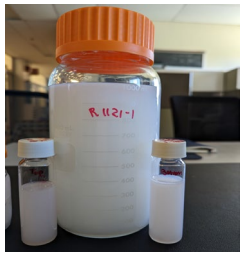




Beamtest at NASA Space Radiation Lab (NSRL)

Beyond 1 cm³ Cubes: Unlocking a seamless, fully active oWbLS detector



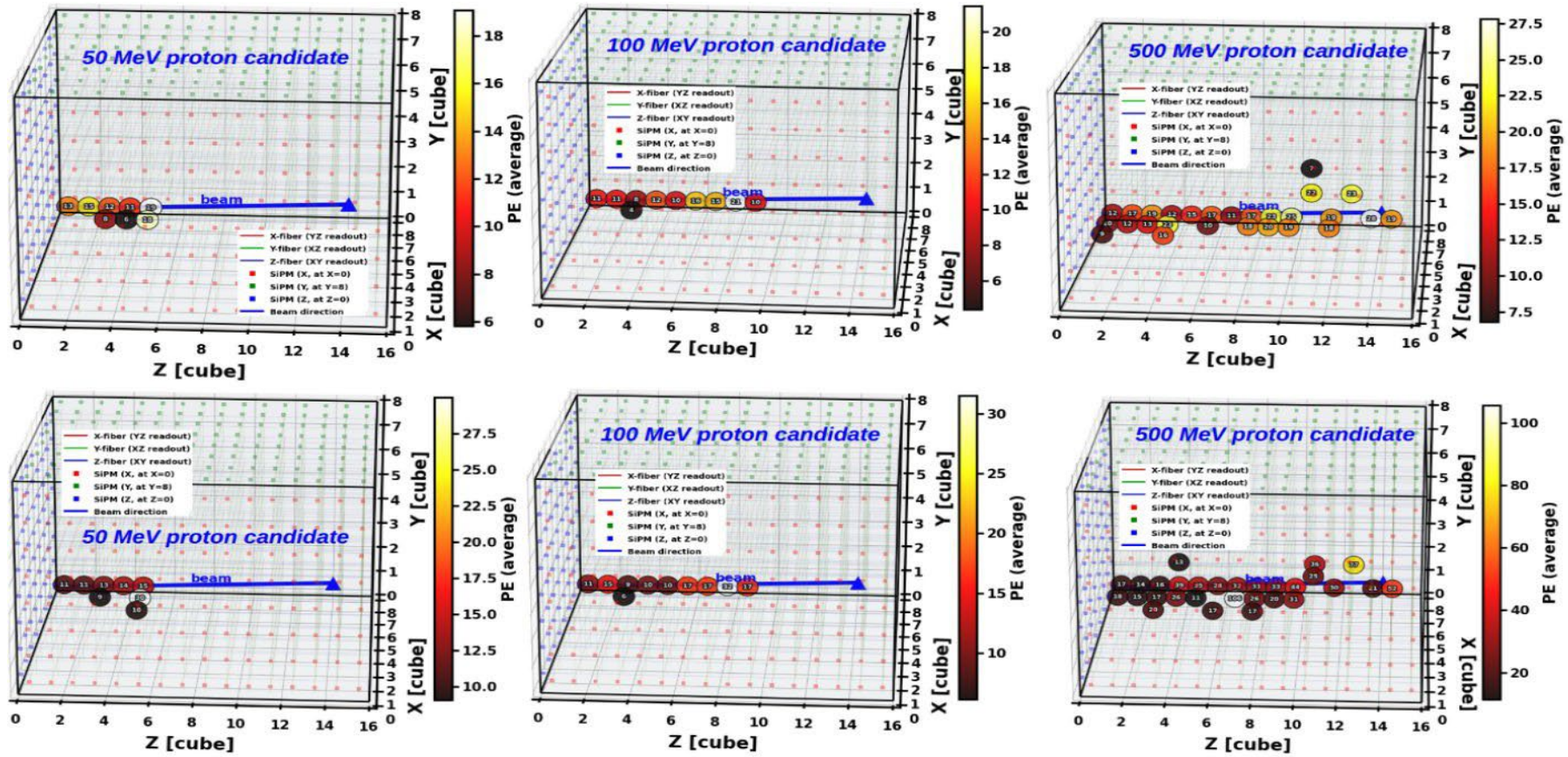


- **Light-yield ~12,000 ph's/MeV**
- **$\lambda_{scattering}$ ~ <5mm**





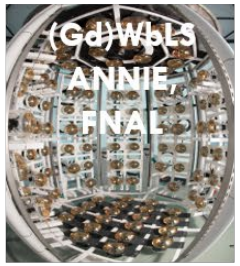
3D particle tracking with oWbLS

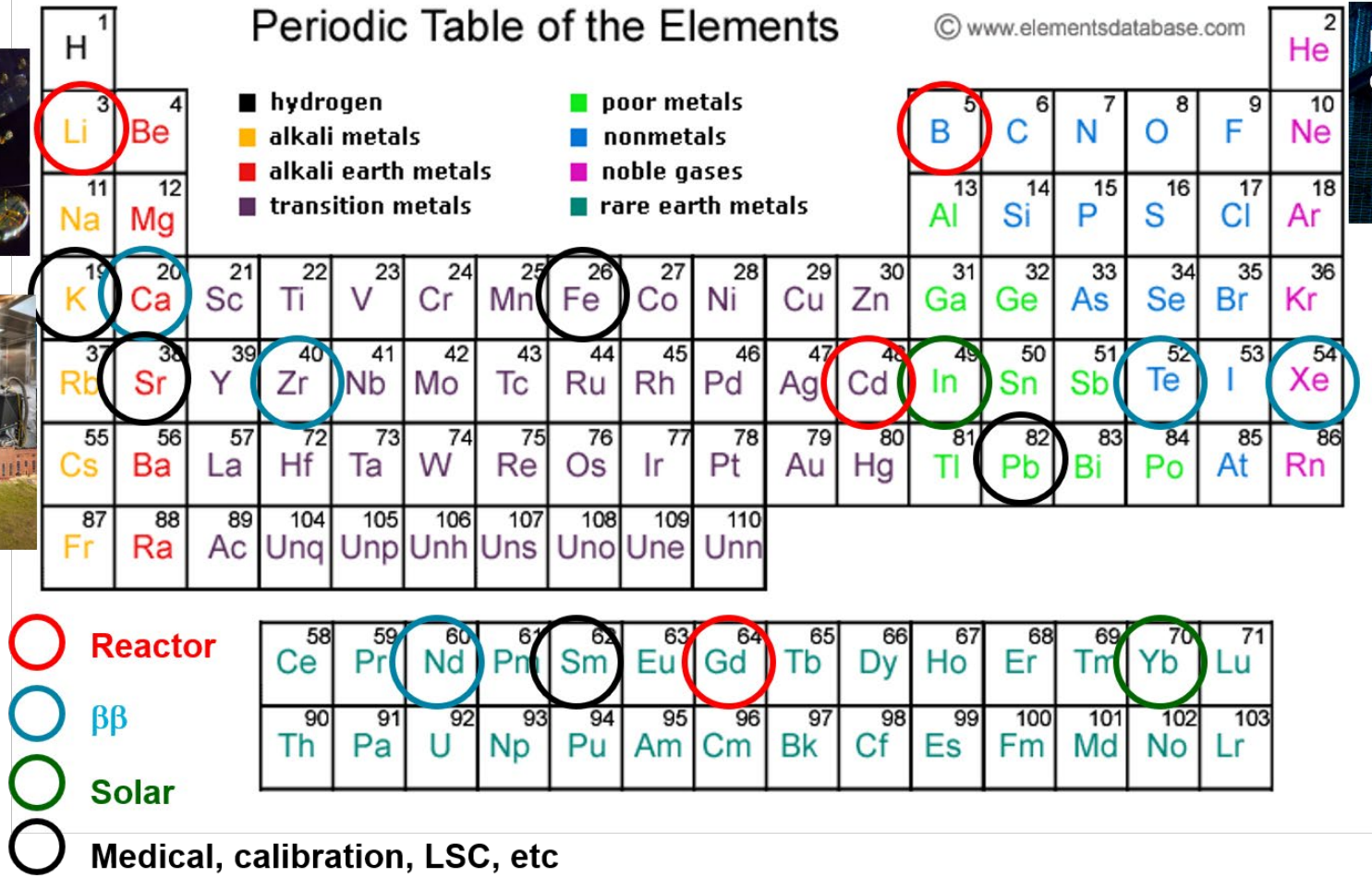


Metal-Doped LS: Expanding Physics Reach and Opening New Frontiers















Metal-loaded organic scintillators for neutrino physics, Christian Buck & Minfang Yeh, J. Phys. G: Nucl. Part. Phys, 43, 093001 (2016).

0νββ Isotopes and Experimental Approaches

The isotope choice is determined by Q-value, natural abundance, enrichment cost, achievable loading, radiopurity, light yield, attenuation length and chemical stability.

DBD isotope	Q_{bb} (MeV)	Natural abundance	Major experiments / projects	Detector approach
48Ca	4.268	0.19%	CANDLES, ELEGANT VI	CaF_2 crystal scintillator
76Ge	2.039	7.8%	LEGEND, GERDA, Majorana Demonstrator	HPGe semiconductor
82Se	2.998	8.8%	SuperNEMO, NEMO-3, CUPID-0	Source foil / ZnSe bolometer
96Zr	3.356	2.8%	NEMO-3	Source foil
100Mo	3.034	9.7%	CUPID-Mo, AMoRE, NEMO-3	Mo-containing bolometer / source foil
116Cd	2.813	7.5%	Aurora, COBRA	$CdWO_4$ / CdZnTe
130Te	2.528	34.1%	SNO+, CUORE, JUNO	Te-loaded LS / TeO_2 bolometer
136Xe	2.458	8.9%	KamLAND-Zen, EXO-200, nEXO, NEXT	Xe-loaded LS / Xe TPC
150Nd	3.371	5.6%	NEMO-3; original SNO+ program	Source foil / Nd-loaded LS R&D

RARE-EVENT OPPORTUNITY

0νββ isotope choice ties physics directly to chemistry

Nuclear properties, isotope availability, loading chemistry, radiopurity, and optics form one system.

ISOTOPE	IMPLEMENTATION	DESIGN QUESTION
136Xe	Physically dissolved	Benchmark noble-gas option
130Te	Chemical loading	High natural abundance; mature LS path
100Mo / 82Se	Chemical or aqueous routes	High-Q exploratory opportunities
96Zr / 48Ca	Specialized chemistry	High-Q, harder materials constraints

WbLS-type loading capability may widen the design space.

CONCLUSION

Parting thoughts

Liquid scintillator is a configurable physics platform

Optics, chemistry, and readout together set the reach.

WbLS adds valuable handles

Directional Cherenkov light, water-rich scale, and aqueous metal loading.

Opaque WbLS points toward topology

Local light confinement can make a homogeneous liquid an imaging calorimeter.

0νββ needs a chemistry-first view

New media can make new isotope choices worth pursuing.

Physics questions should choose the medium.

Not the reverse.