Novel Liquid Technology

Brookhaven National Laboratory

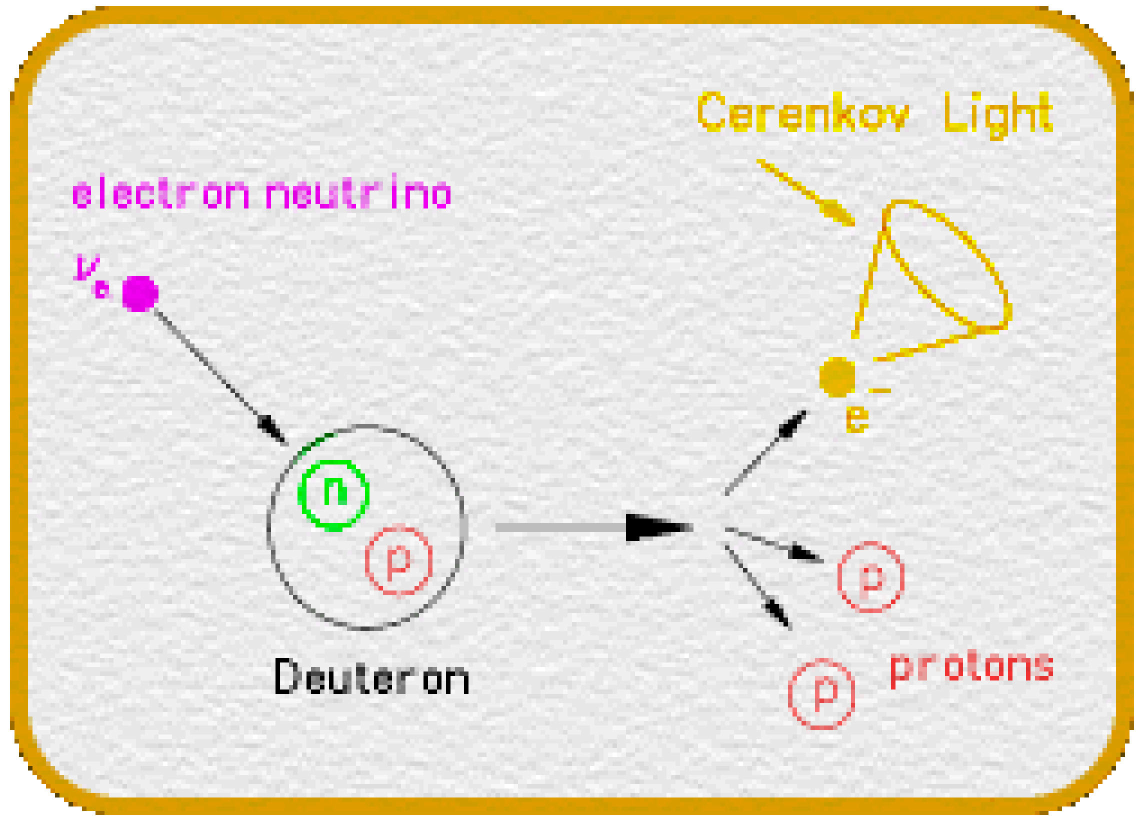
U.S. DEPARTMENT OF ENERGY

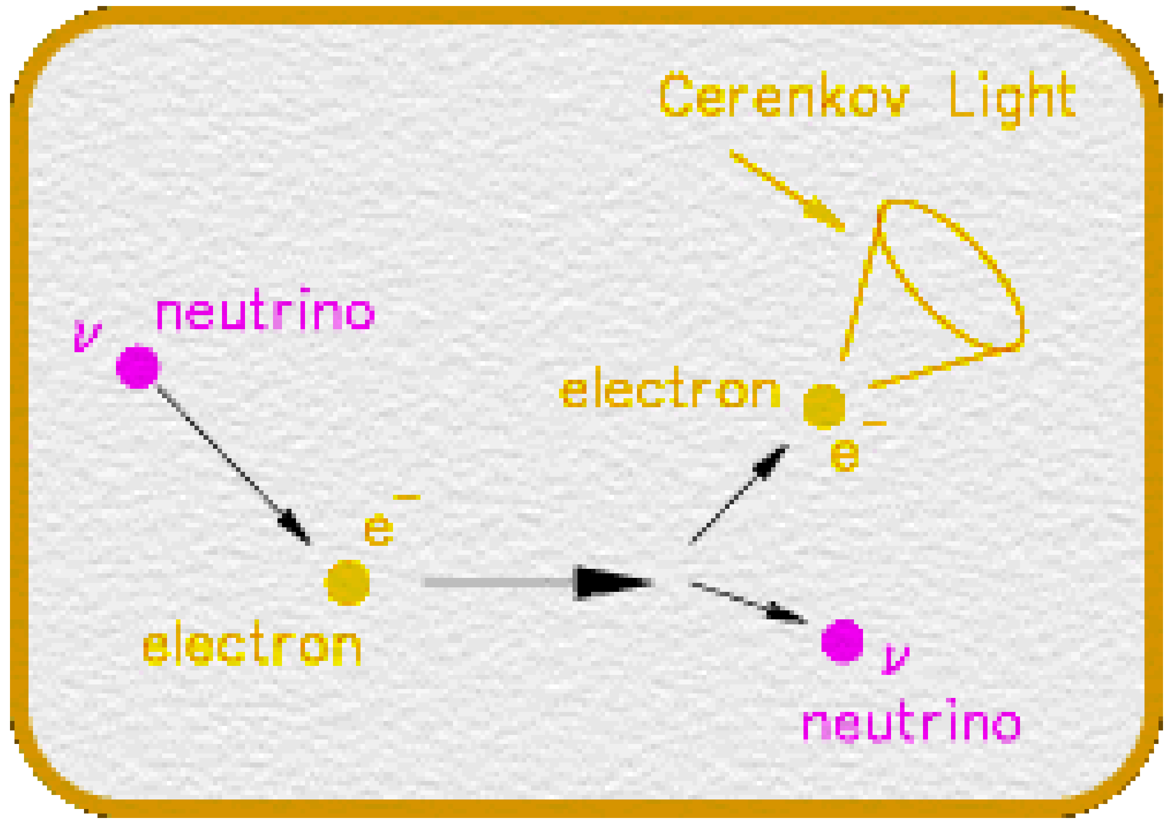
Minfang Yeh

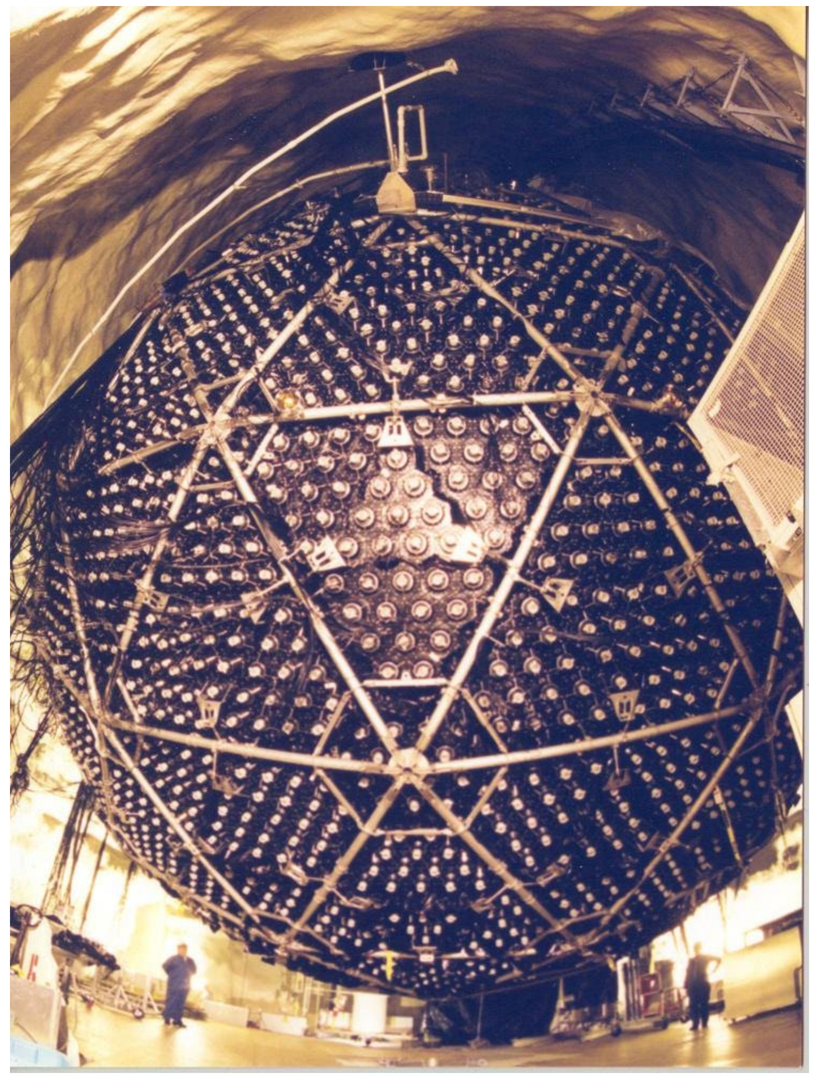
- *Water-based (Cherenkov)*
- *Oil-based (Scintillation)*
- *(Water+Oil)-based (Cher.+Scin.)*
- *Noble liquid (Ar, Xe)*

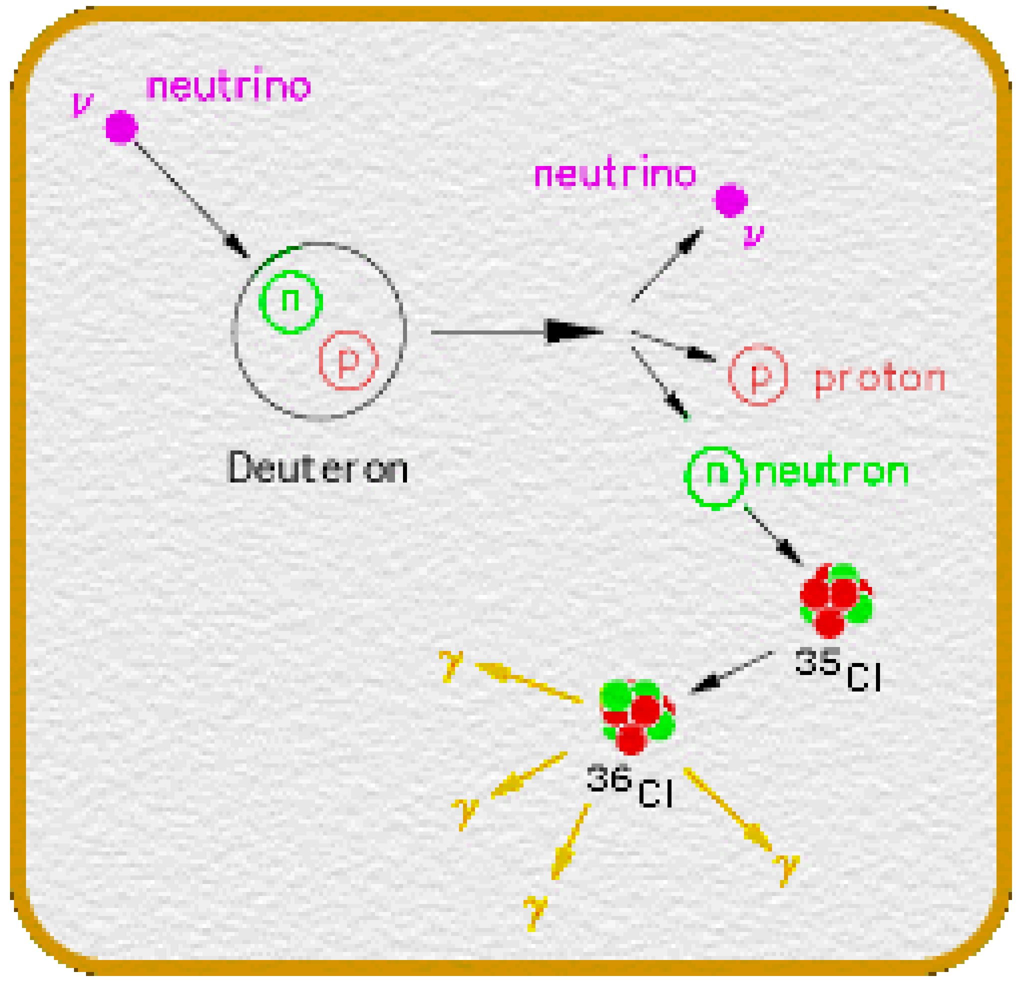
XXXI International Conference on Neutrino Physics and Astrophysics, Milan, Italy 06/16-22/2024

SNO Heavy Water Detector



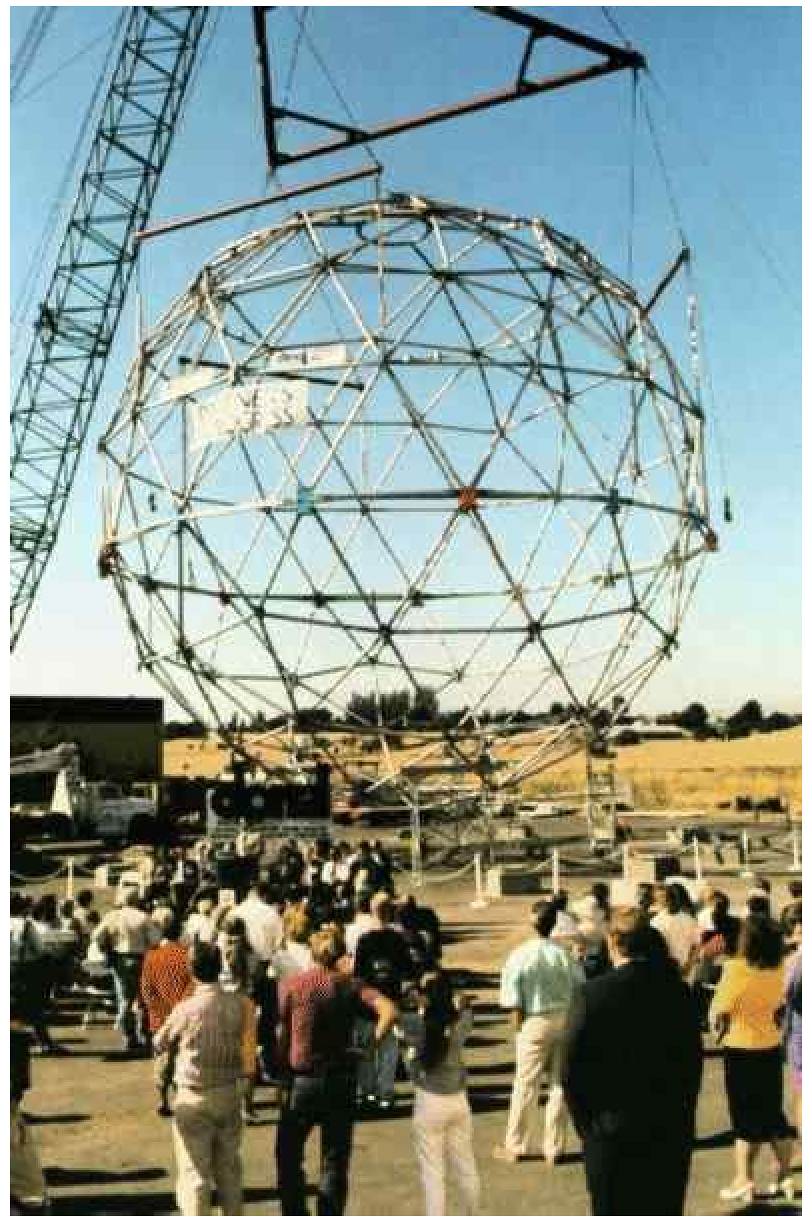






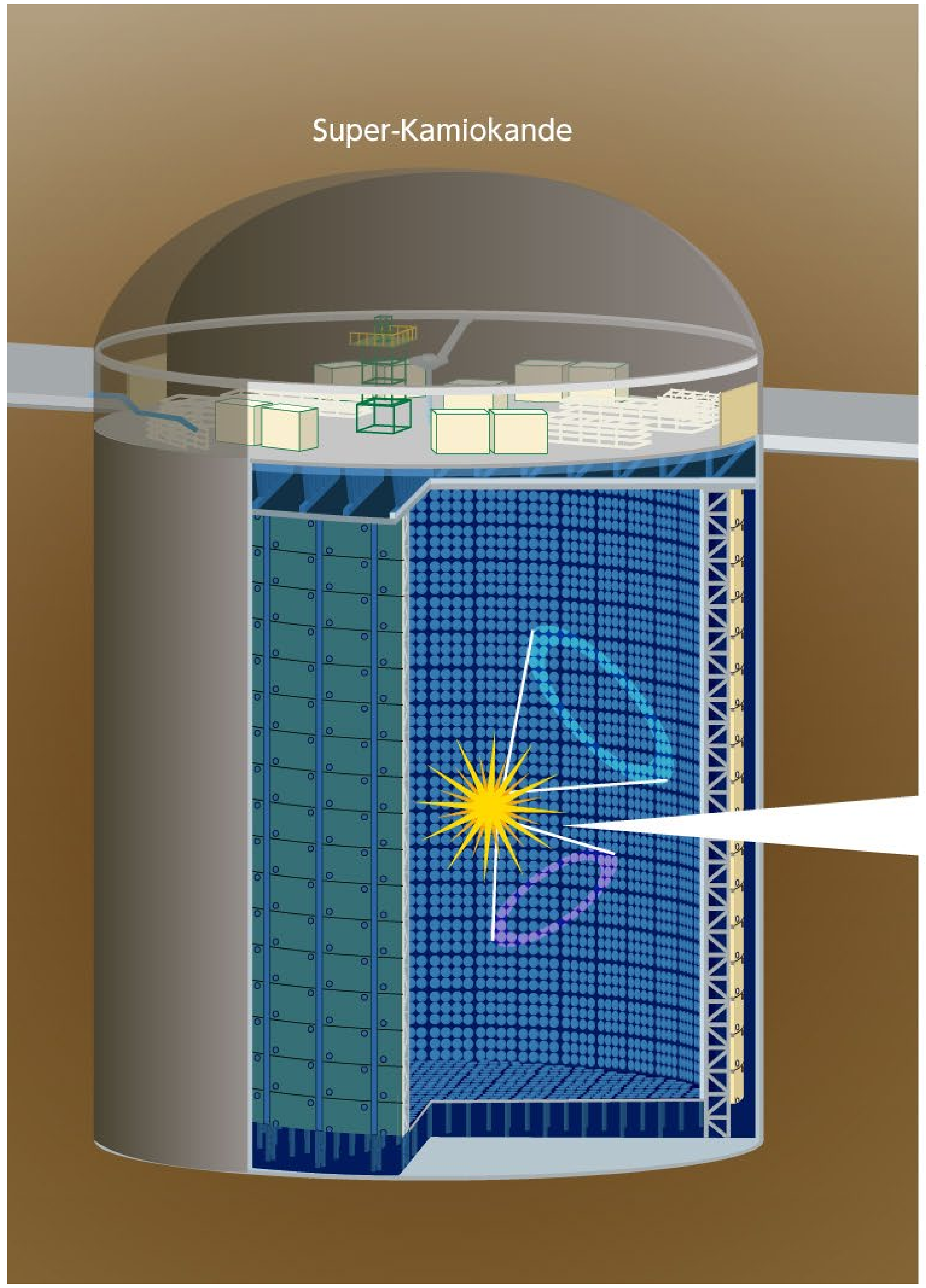
- *Effect of wavelength shifters in Cherenkov detectors*
- *Scarbostyril 124 (CS124) and Alexa Fluor 350 (AF350); water-soluble*
- *~x3 increase in light (from low-λ Cherenkov); however, might not be feasible due to optical for a large detector*

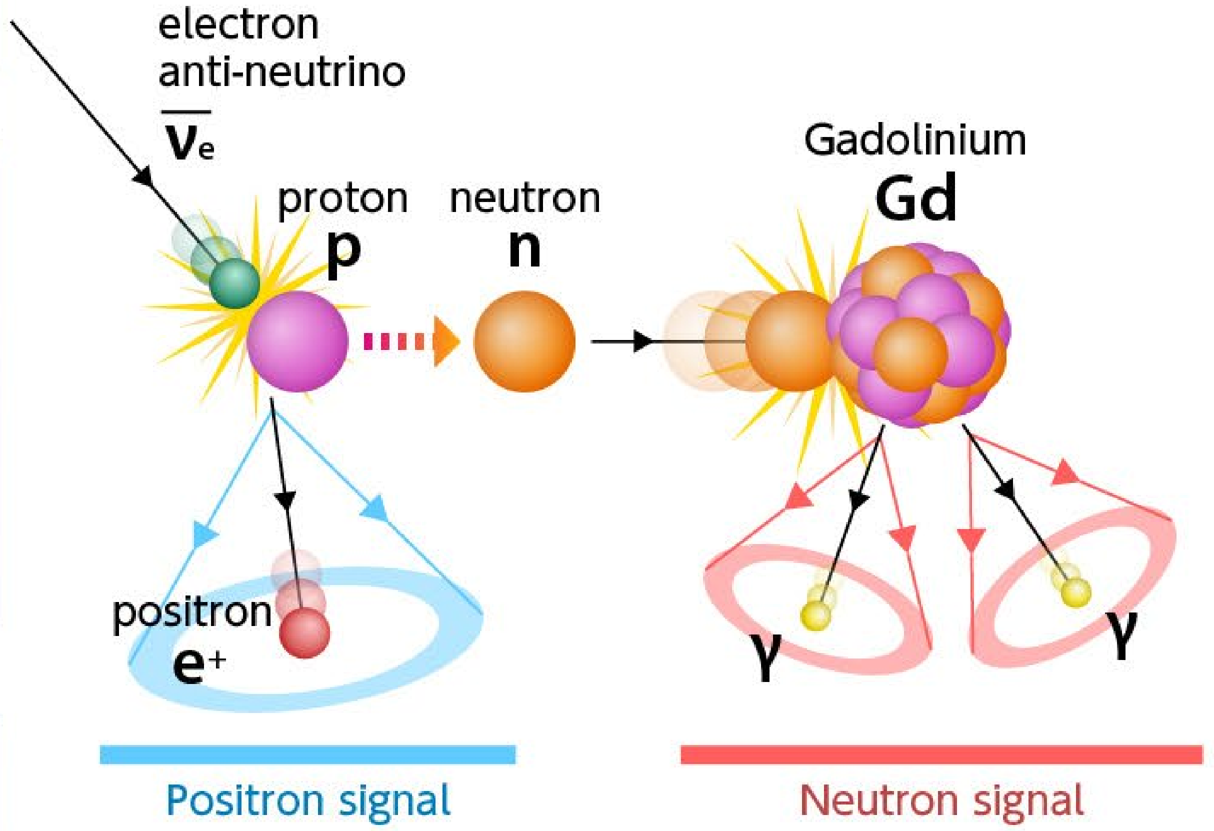
Dai et. al., Nucl.Instrum.Meth.A 589 (2008) 290-295



Brookhaven National Laboratory

SK: physics enhancement with gadolinium





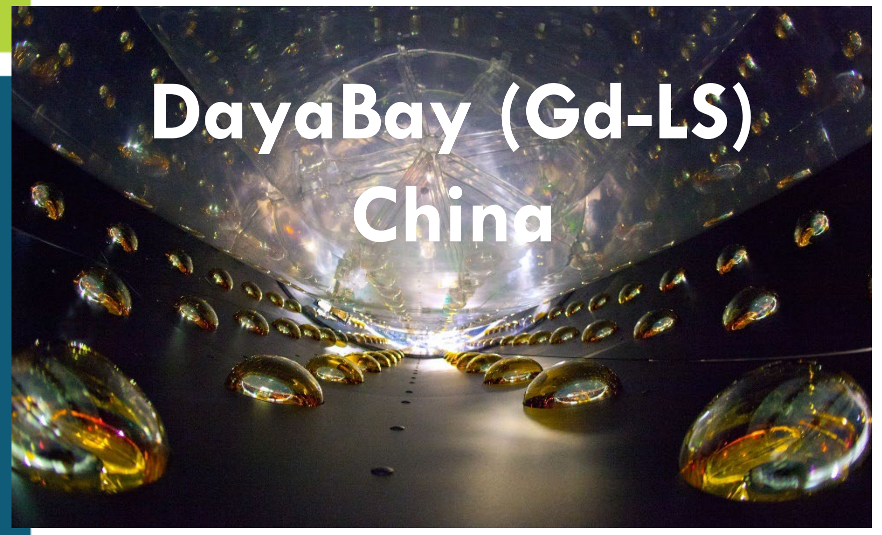
- *90% neutron capture by 0.1%Gd (IBD)*
- *In-situ circulation required*
- *SRN detection improvement*
- *Ongoing Gd-loading in SK*

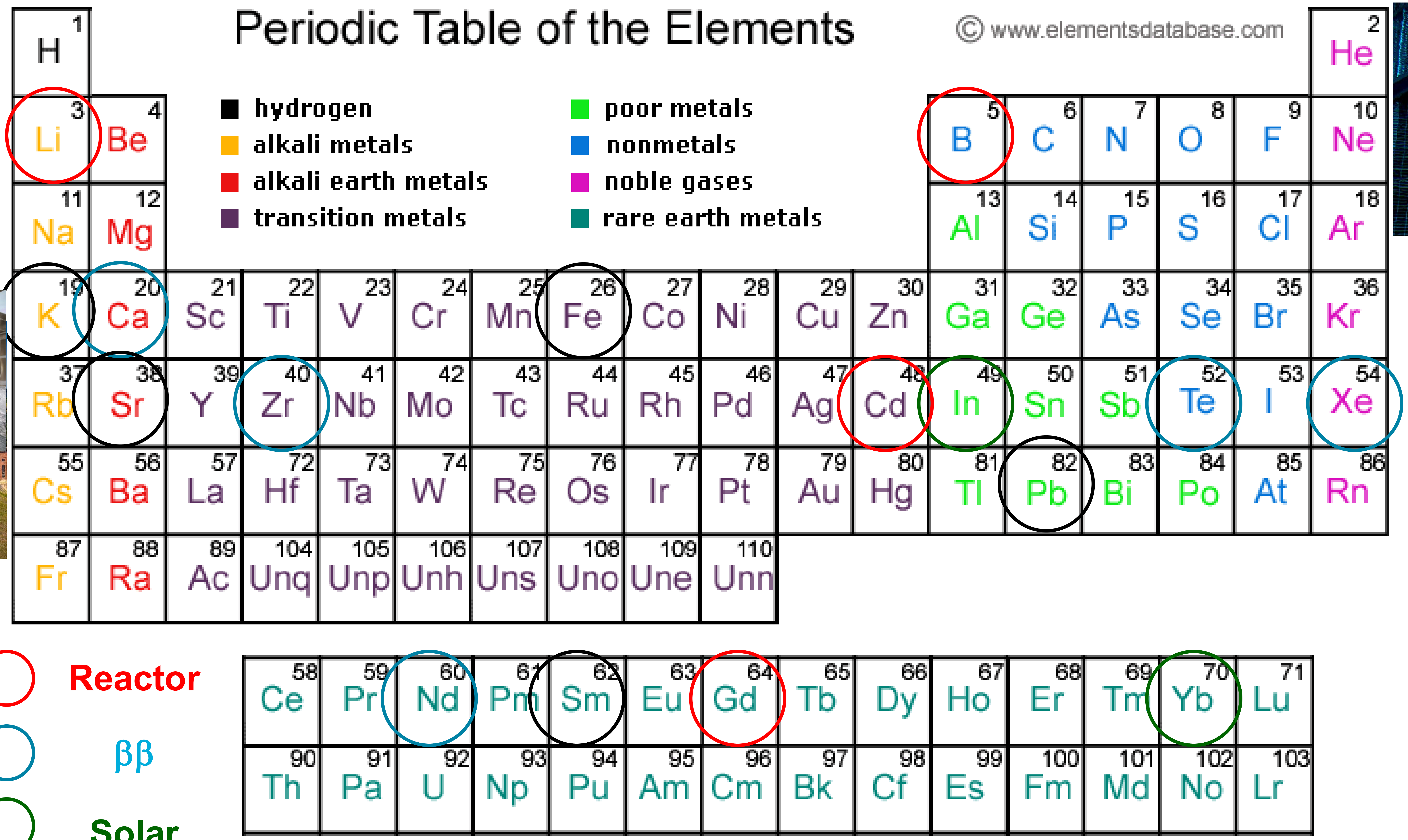
https://www-sk.icrr.u-tokyo.ac.jp/en/news/detail/309

LS-based ν Landscape

Brookhaven National Laboratory

Metal-doped Liquid Scintillator
for neutrino physics and other frontiers since 2000



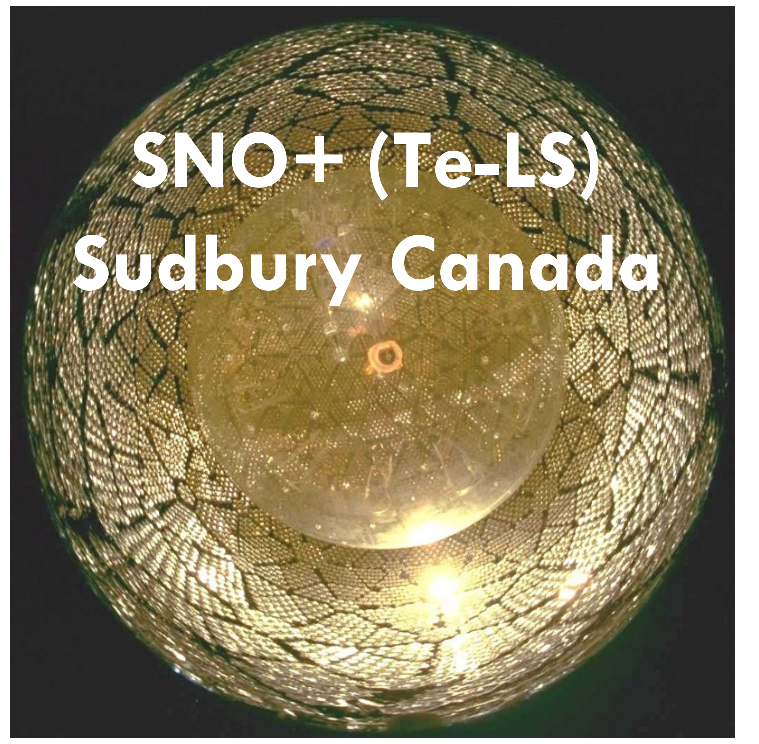


Reactor

ββ

Solar

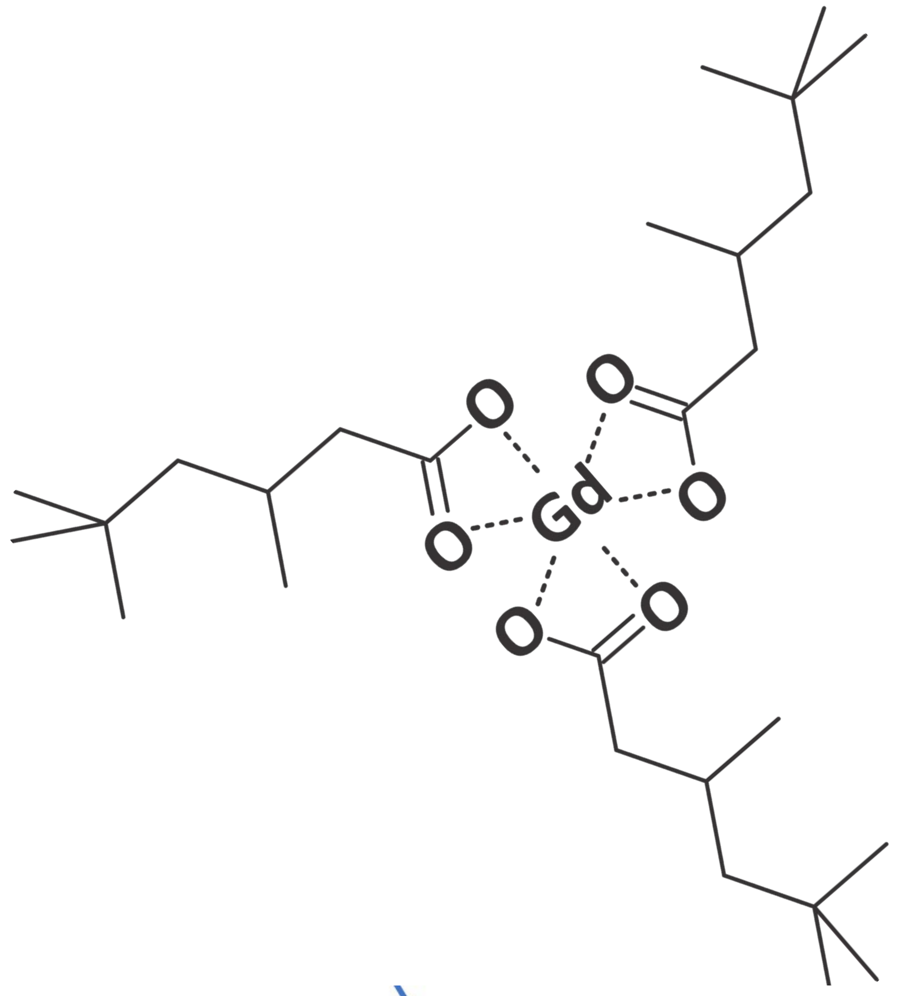
Medical, calibration, LSC, etc

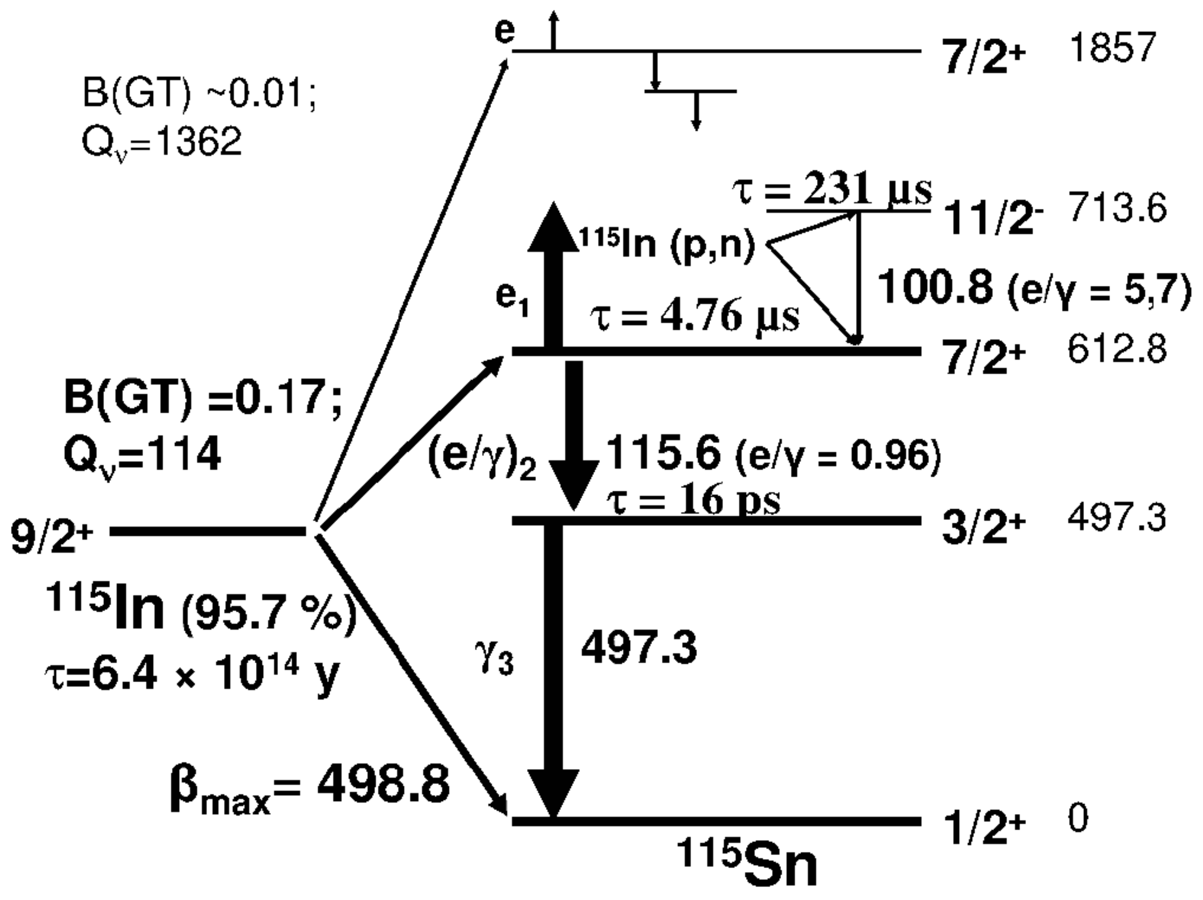


Brookhaven National Laboratory

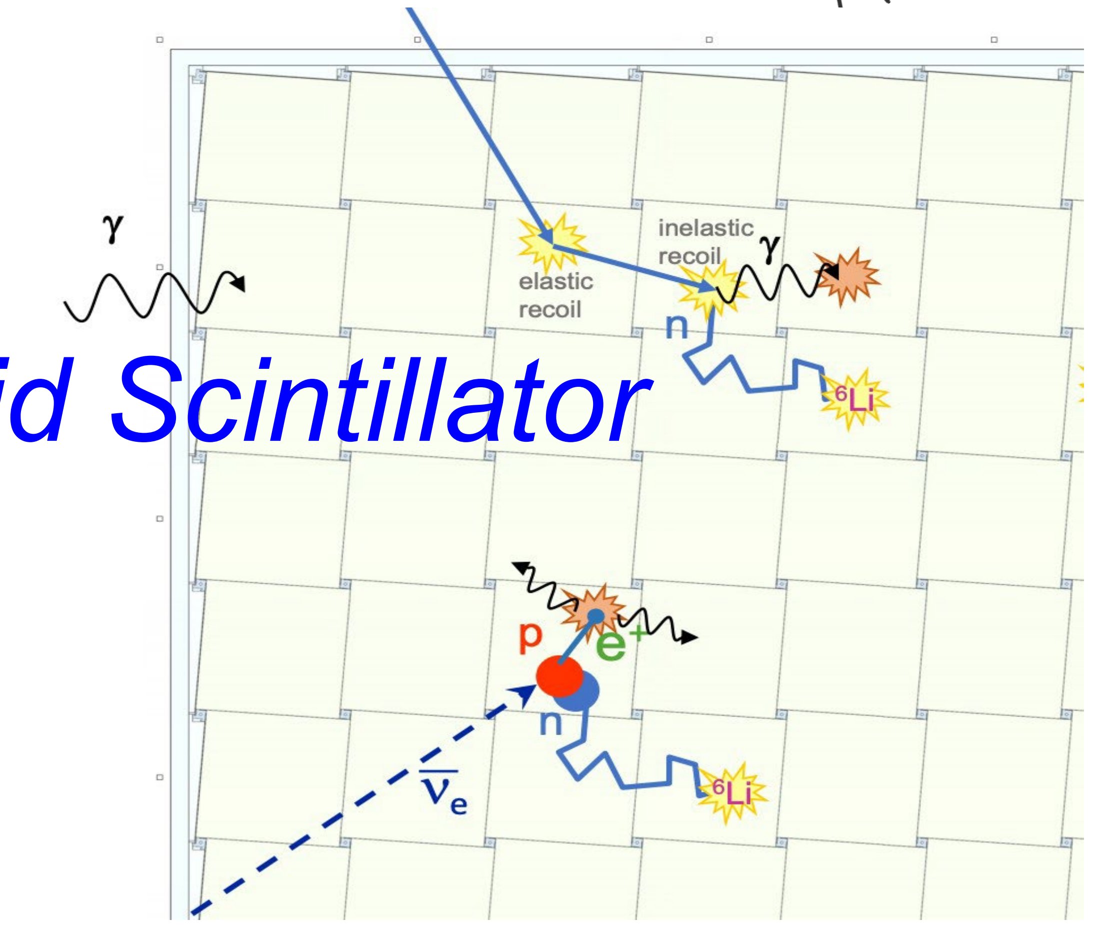
Buck & Yeh, Metal-loaded organic scintillators for neutrino physics, J. Phys. G: Nucl. Part. Phys, 43, 093001 (2016).

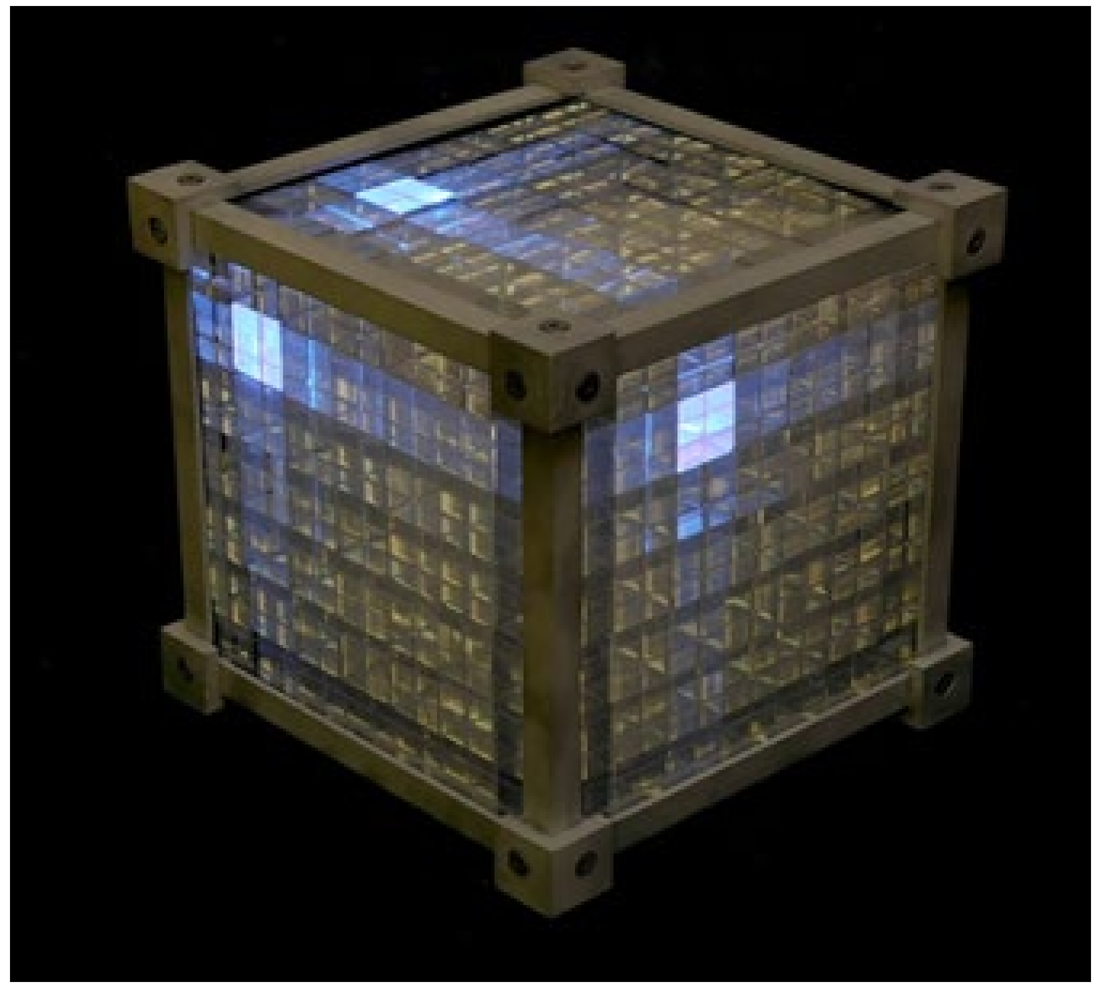
Metal-doped LS Technology

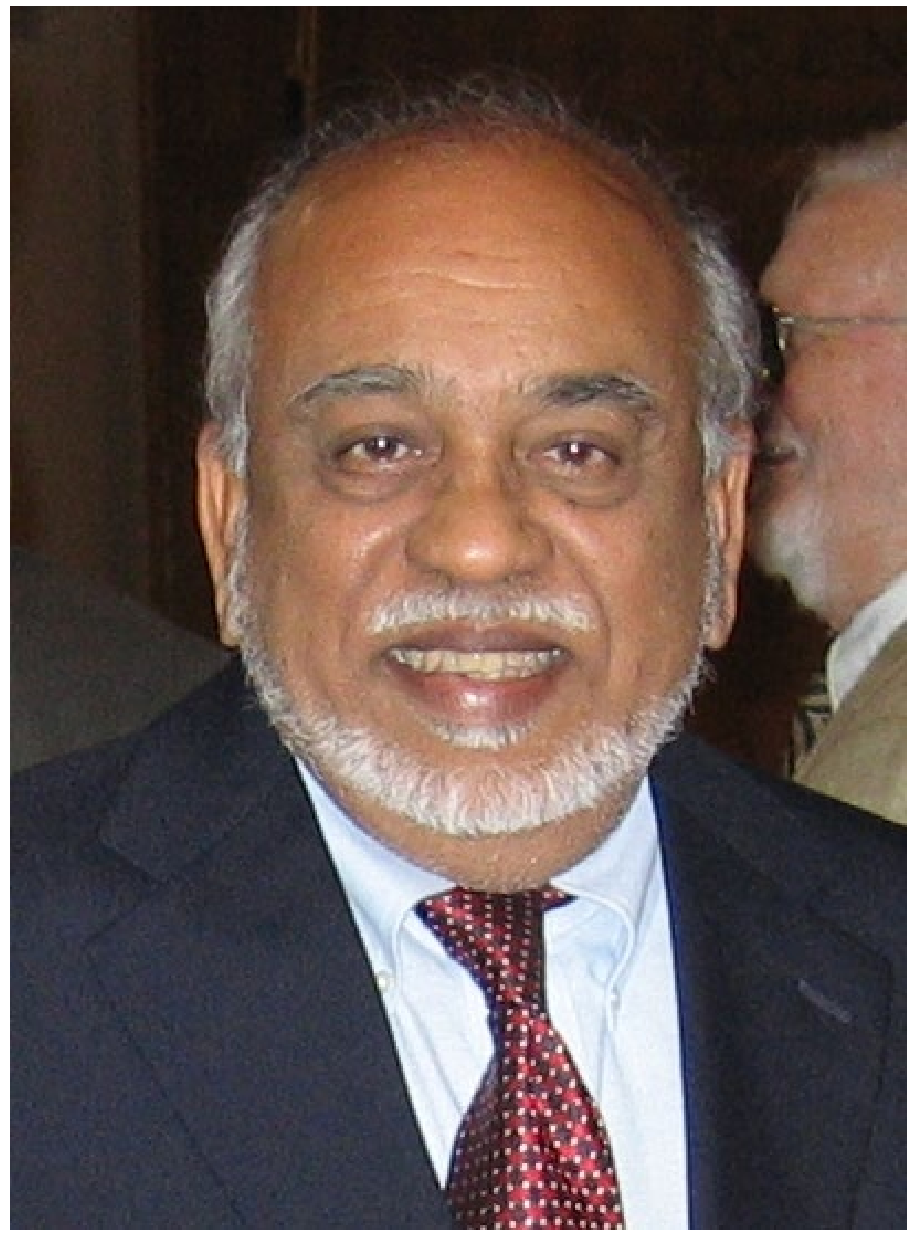




- *Carboxylic acid*
- *Beta-diketone*
- *Organic alcohol*
- *Quantum dots*
- *Water based Liquid Scintillator*





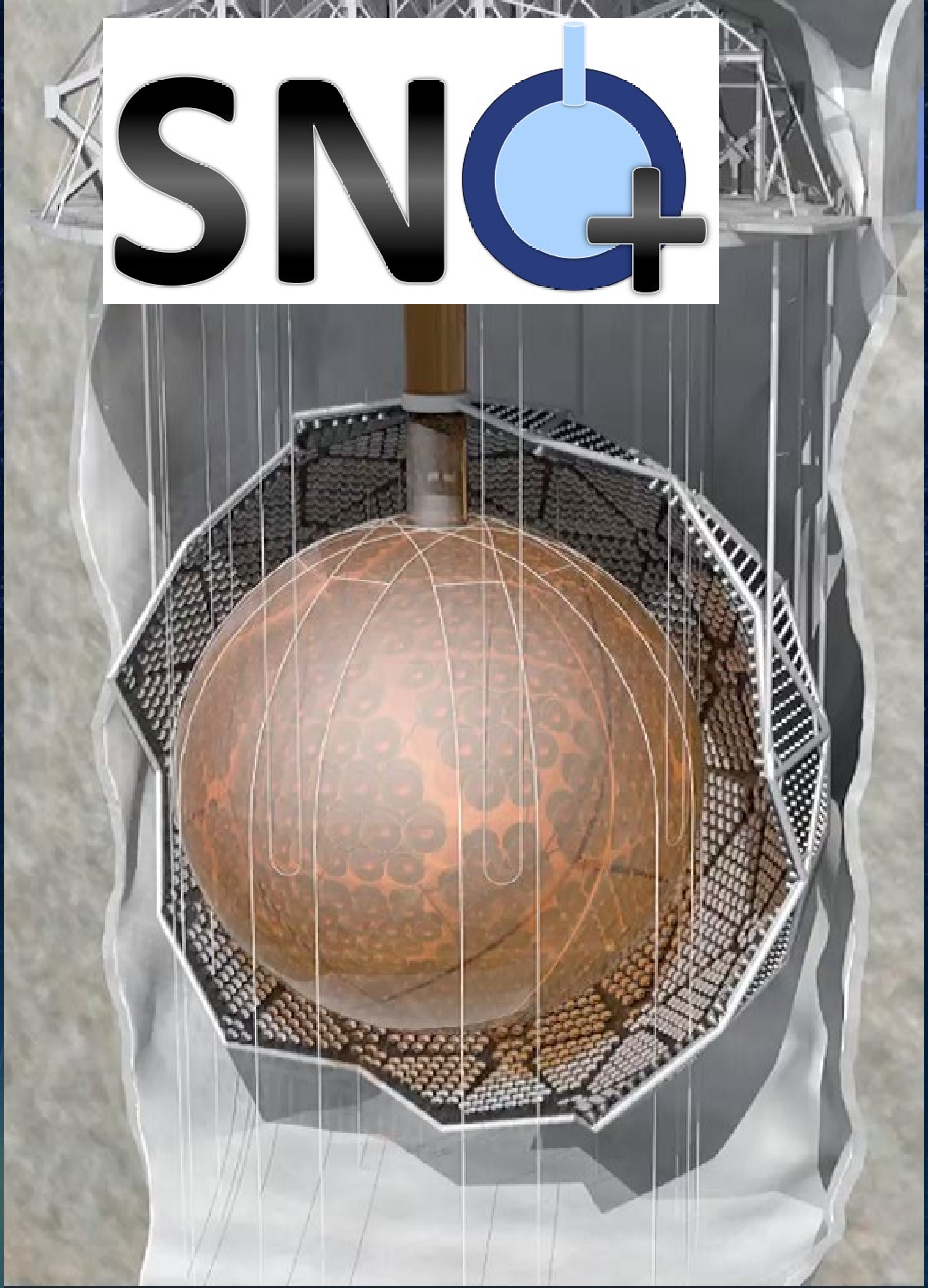


1937 -2011

LENS started with three $0\nu\beta\beta$ candidates, 176Yb, 160Gd and 82Se, with Q-values low enough allowing the detection of pp-neutrinos via inverse -decay. Later focus on 115In (2000): ***metal-doped technology & lattice design****.*

The SNO+ 0νββ Strategy

- Improve sensitivity through a high isotope mass
- ^{130}Te chosen as isotope
  - High natural abundance → expensive enrichment unnecessary
  - Q-value of 2.53 MeV



Purification

Four chemical plants to treat the various internal and external media

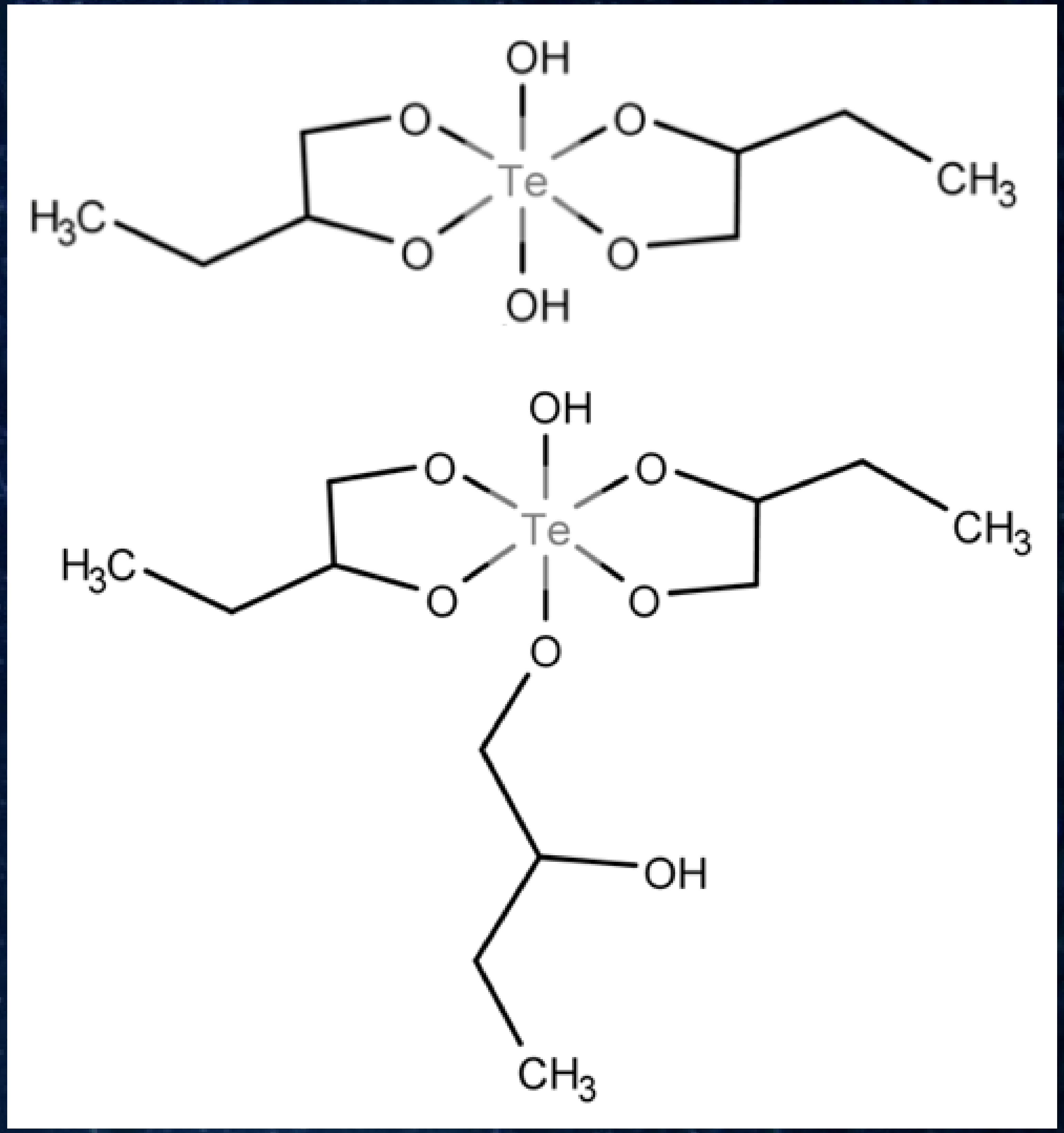
Vigorous QA campaign: hourly chemical analysis during operations

Recirculation and repurification capabilities for internal and external media

Detector Hardware: JINST 16 P08059

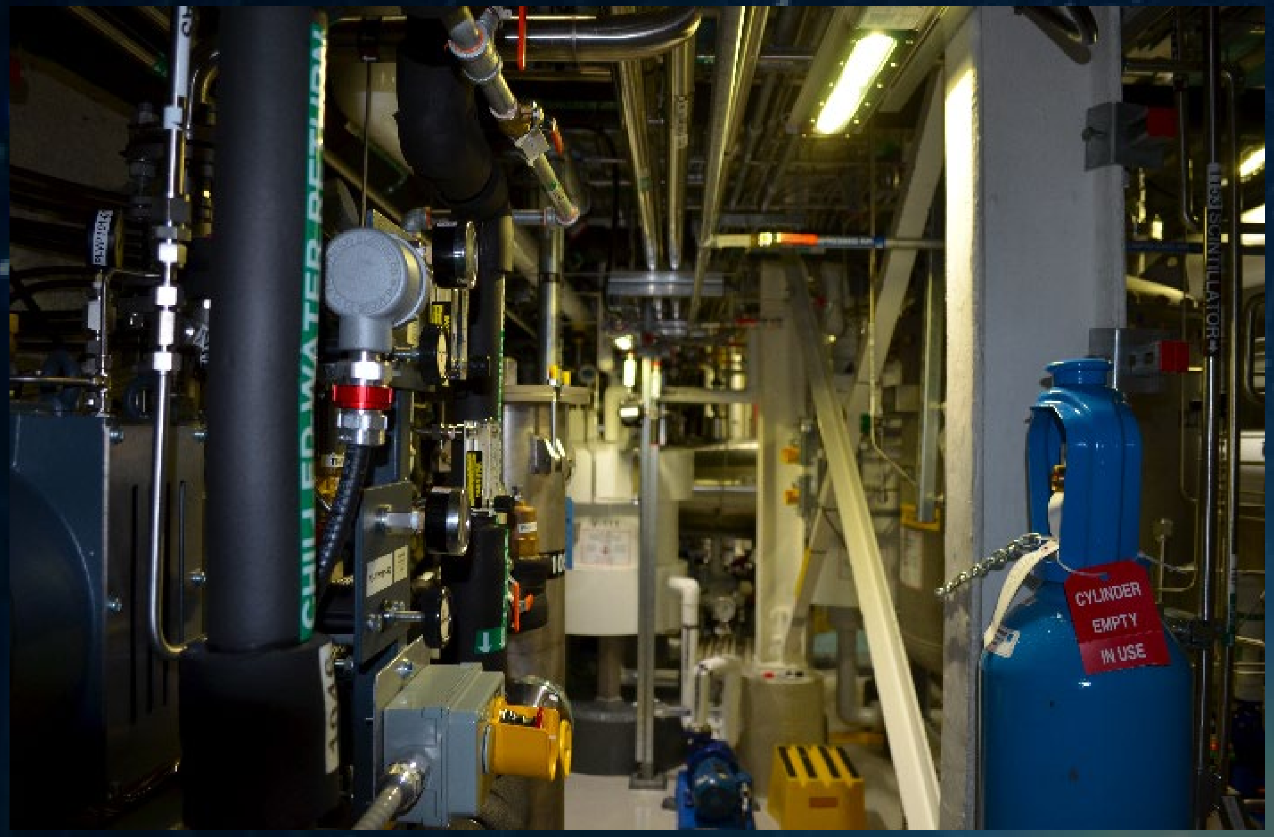
Tellurium Loading of Scintillator

- Novel metal-loading technique to dope SNO+ LS with Te
  - Achieved by diolising telluric acid (TeA), forming Tellurium Butanediol (TeBD) that readily dissolves in LAB
  - Additives introduced to scintillator to improve light yield and stability
    - 1,4-Bis(2-methylstyryl)benzene (Bis-MSB)
    - Butylated Hydroxytoluene (BHT)
    - N,n-dimethyldodecylamine (DDA)



Final Detector Medium Composition:

904,000 L LAB (first identified by SNO+)



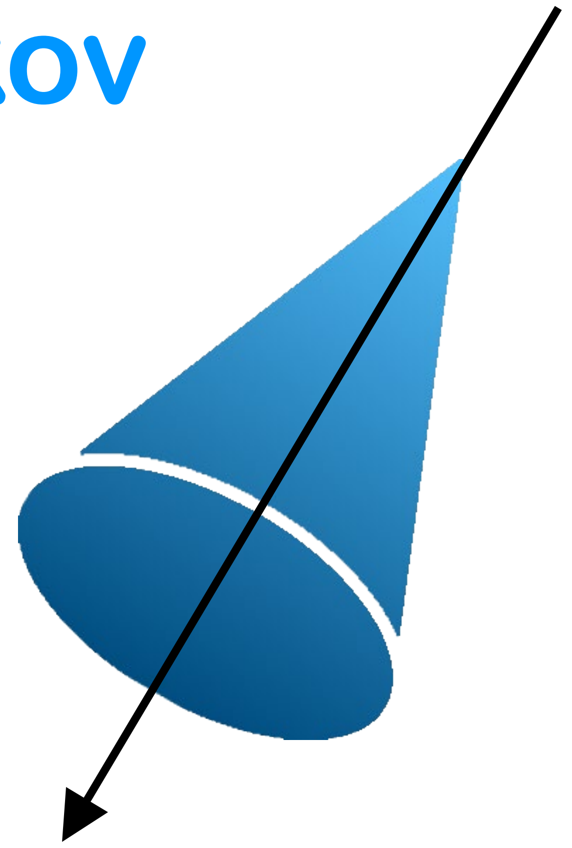
+ 2.2 g/L PPO
+ 2.2 mg/L bis-MSB
+ 6.5 mg/L BHT
+ DDA
+ TeBD

Tellurium Loading Technique: NIM A 1051:168204

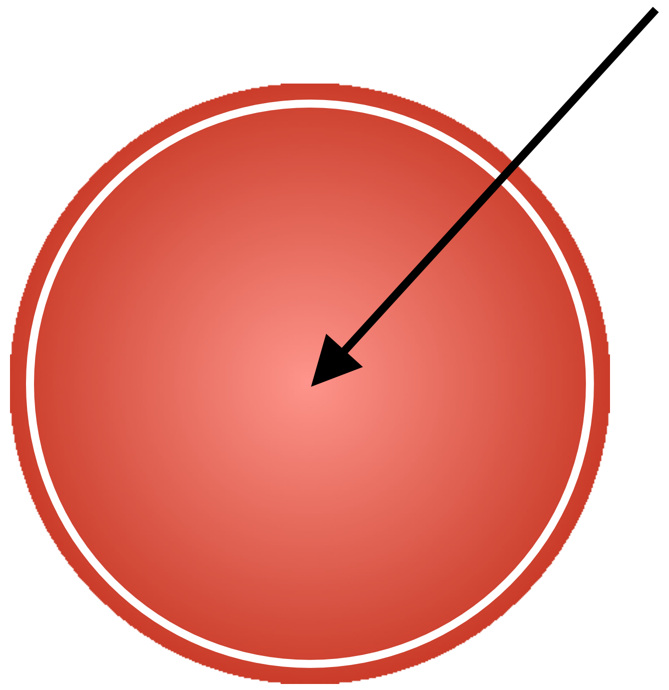
Hybrid Cherenkov & Scintillation Detection

Material and Instrumentation Development

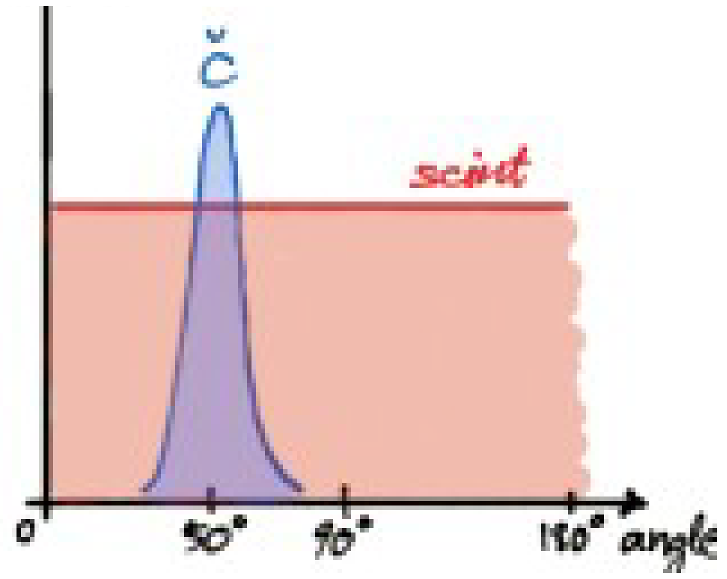
Cherenkov



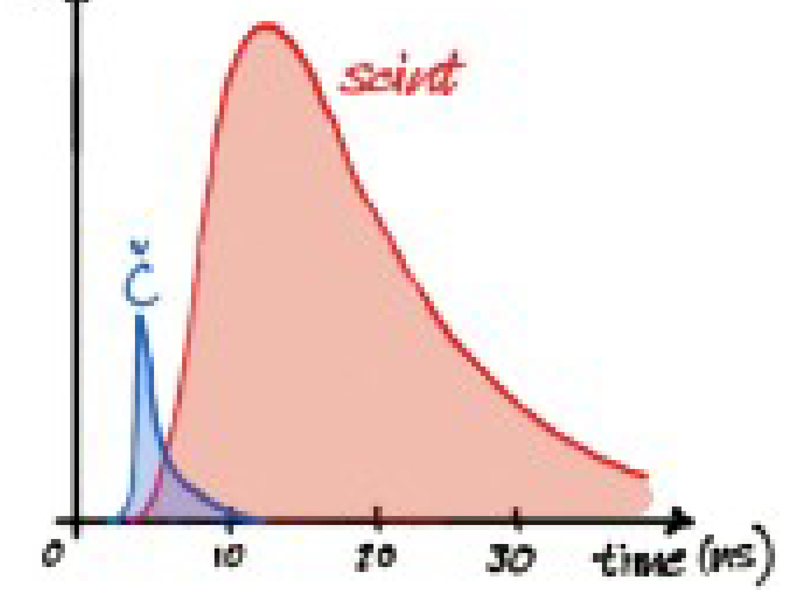
Scintillation



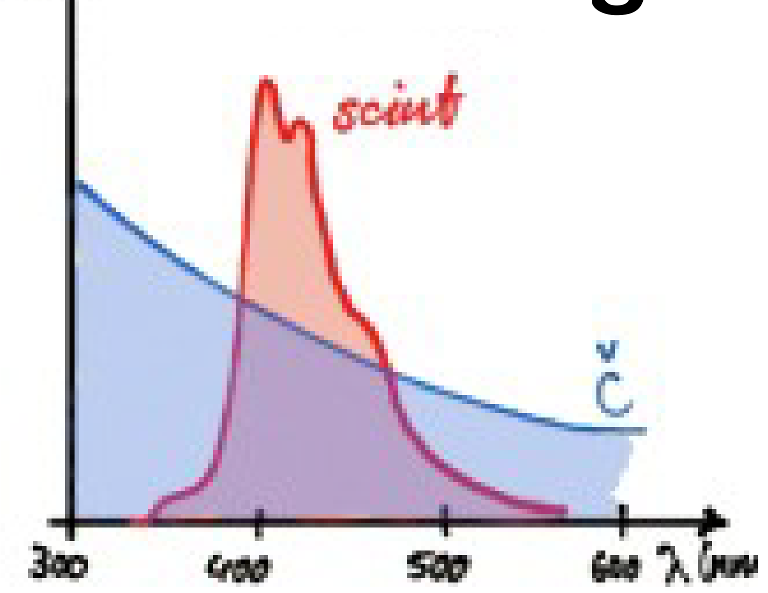
Angular distribution

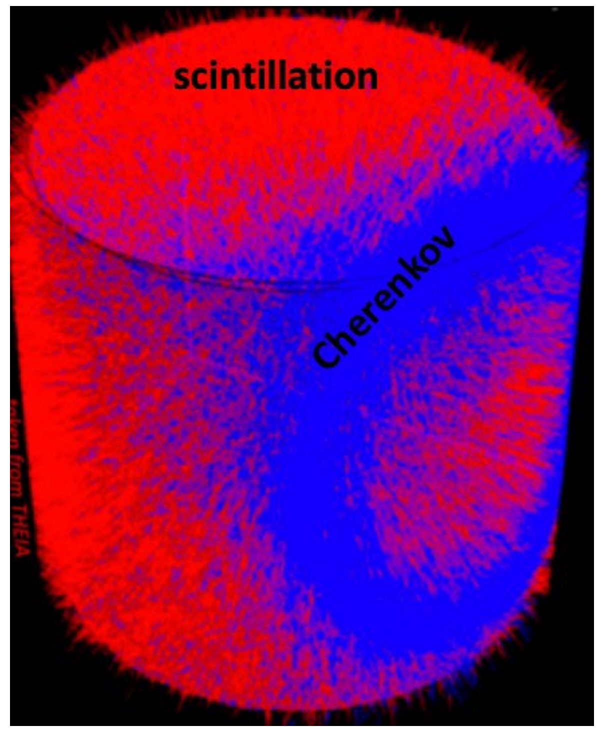


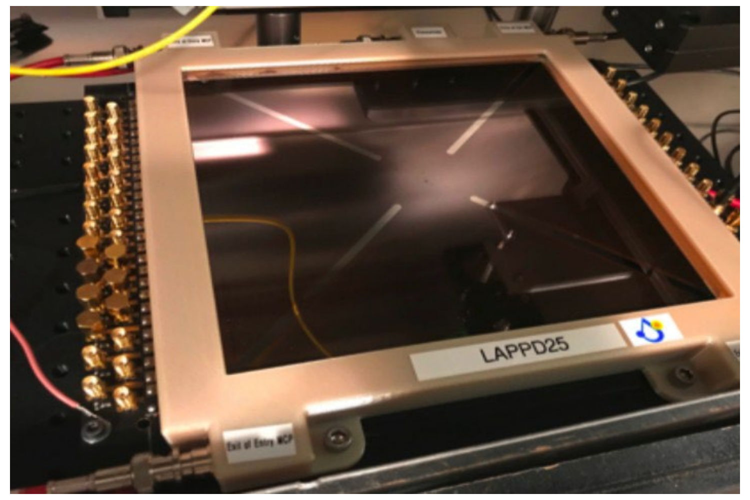
Timing



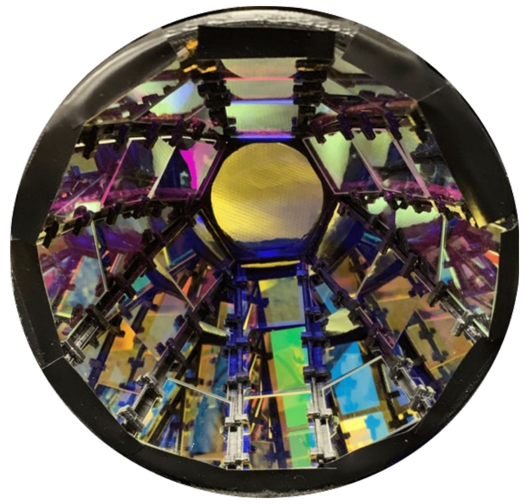
Wavelength







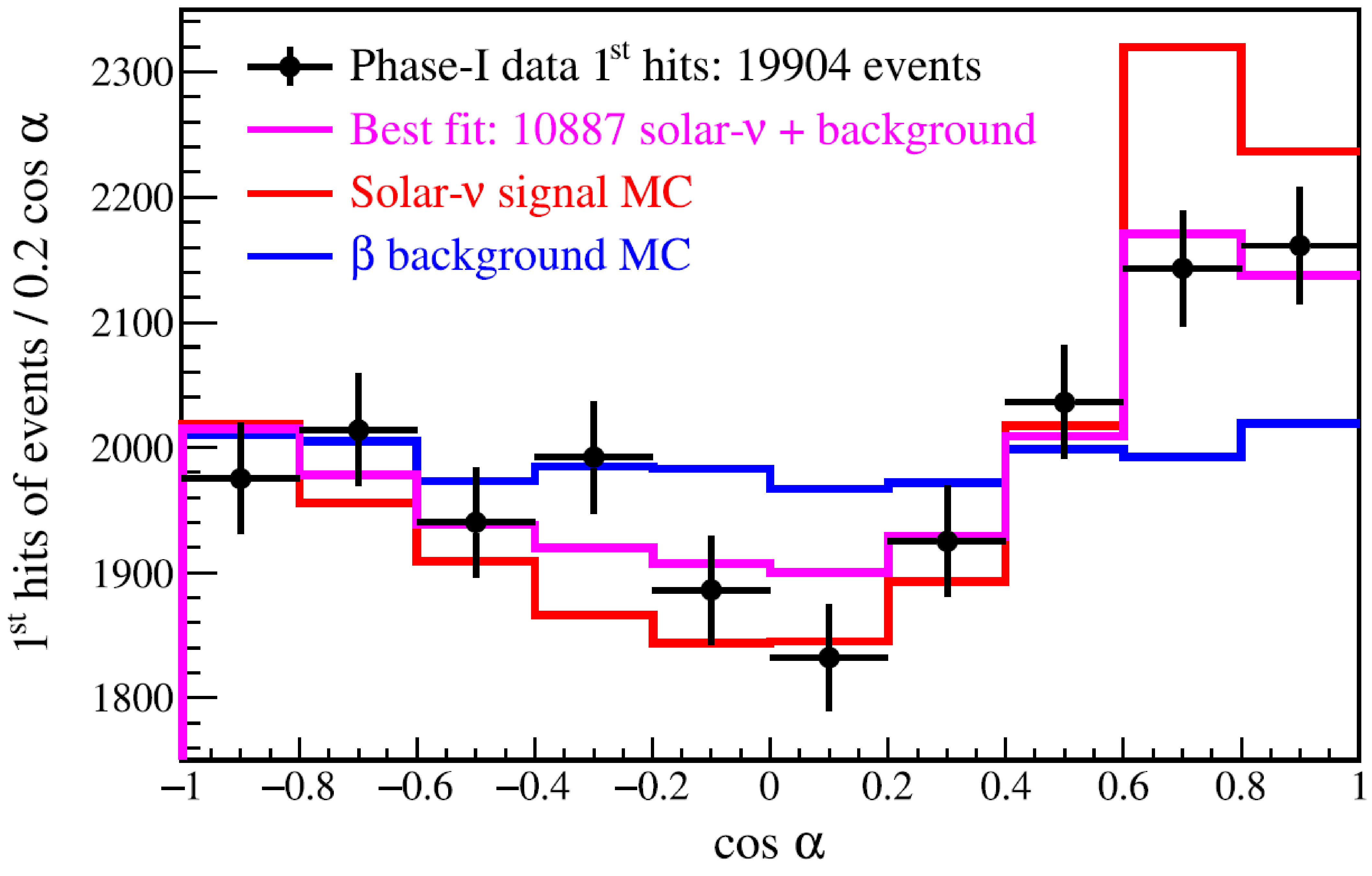
B.W.Adams et al. NIM A Volume 795, 1 (2015)



T. Kaptanoglu et al.
Phys. Rev. D 101, 072002 (2020)

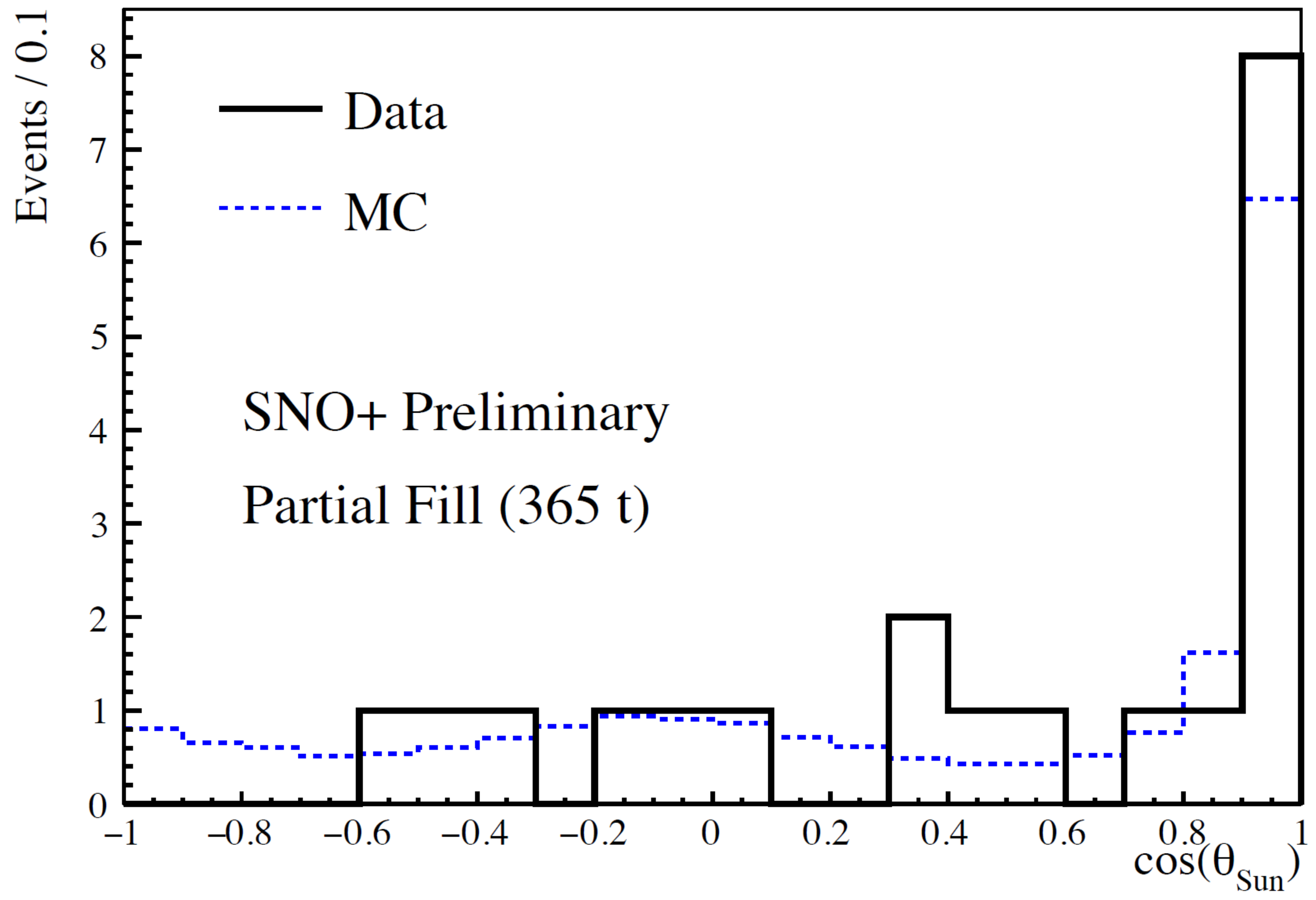
Michi Wurm

Successful hybrid detection in experiments



Borexino has achieved the statistical evidence for solar neutrino directionality by using the first detected photons in each event.

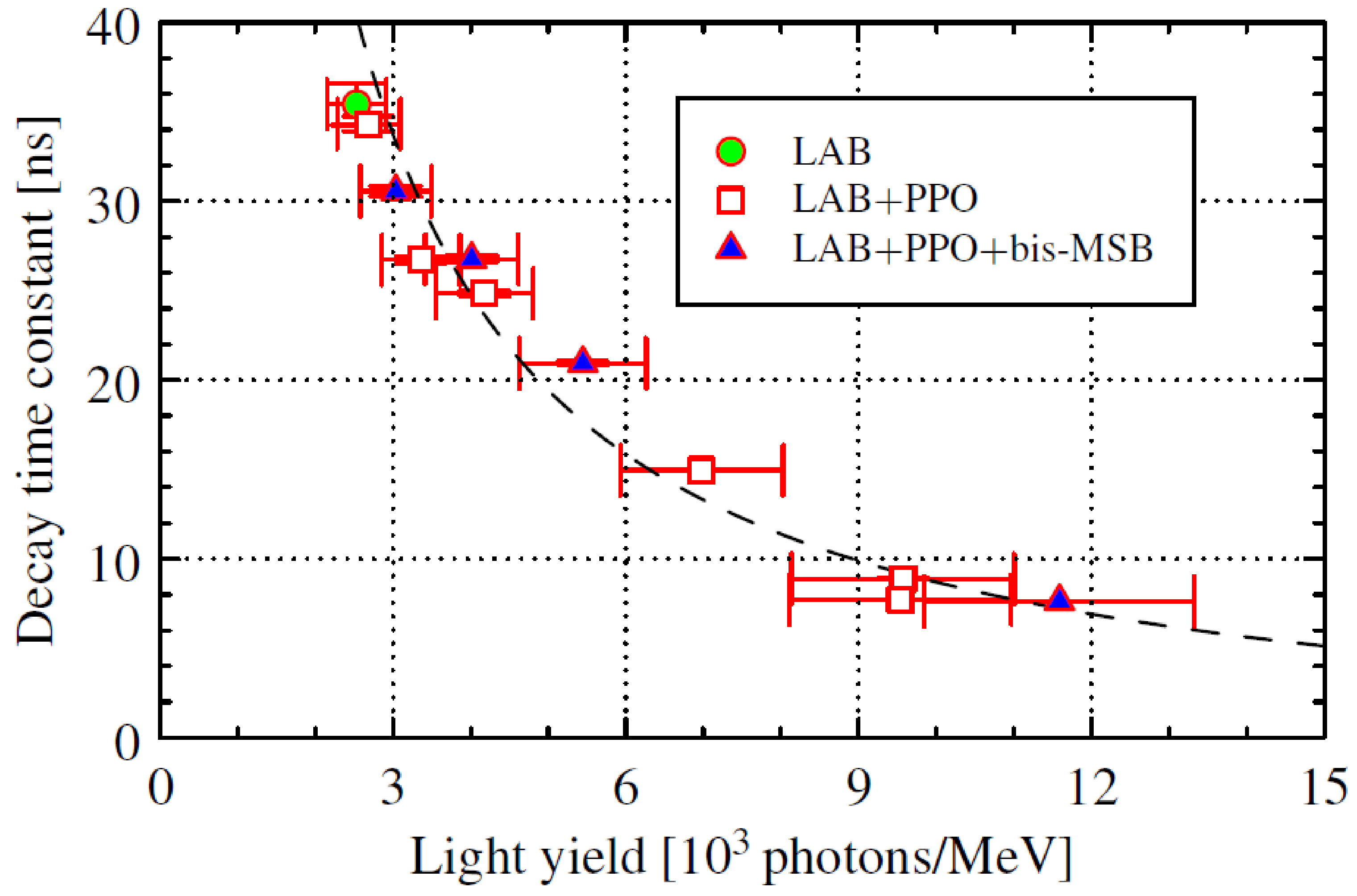
BOREXINO Collaboration, Phys. Rev. Lett. 128 no. 9, (2022) 091803

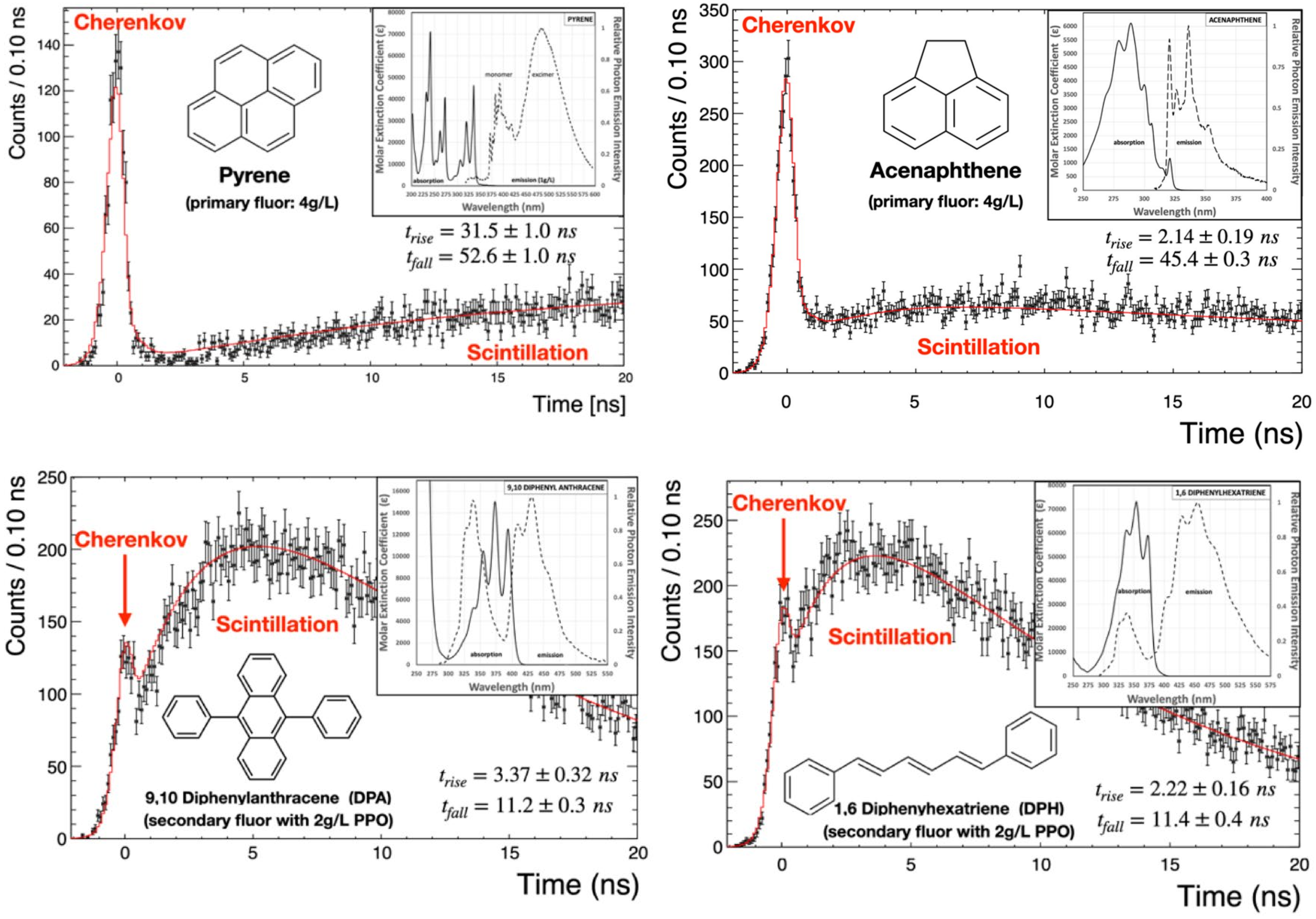


SNO+ has achieved the first event-by-event directional reconstruction by using diluted liquid scintillator (*a.k.a*. LSND & MiniBooNE)

SNO+ collaboration, arXiv:2309.06341

Slow Scintillator (fluor/WLS)
directionality & particle ID with good light yield

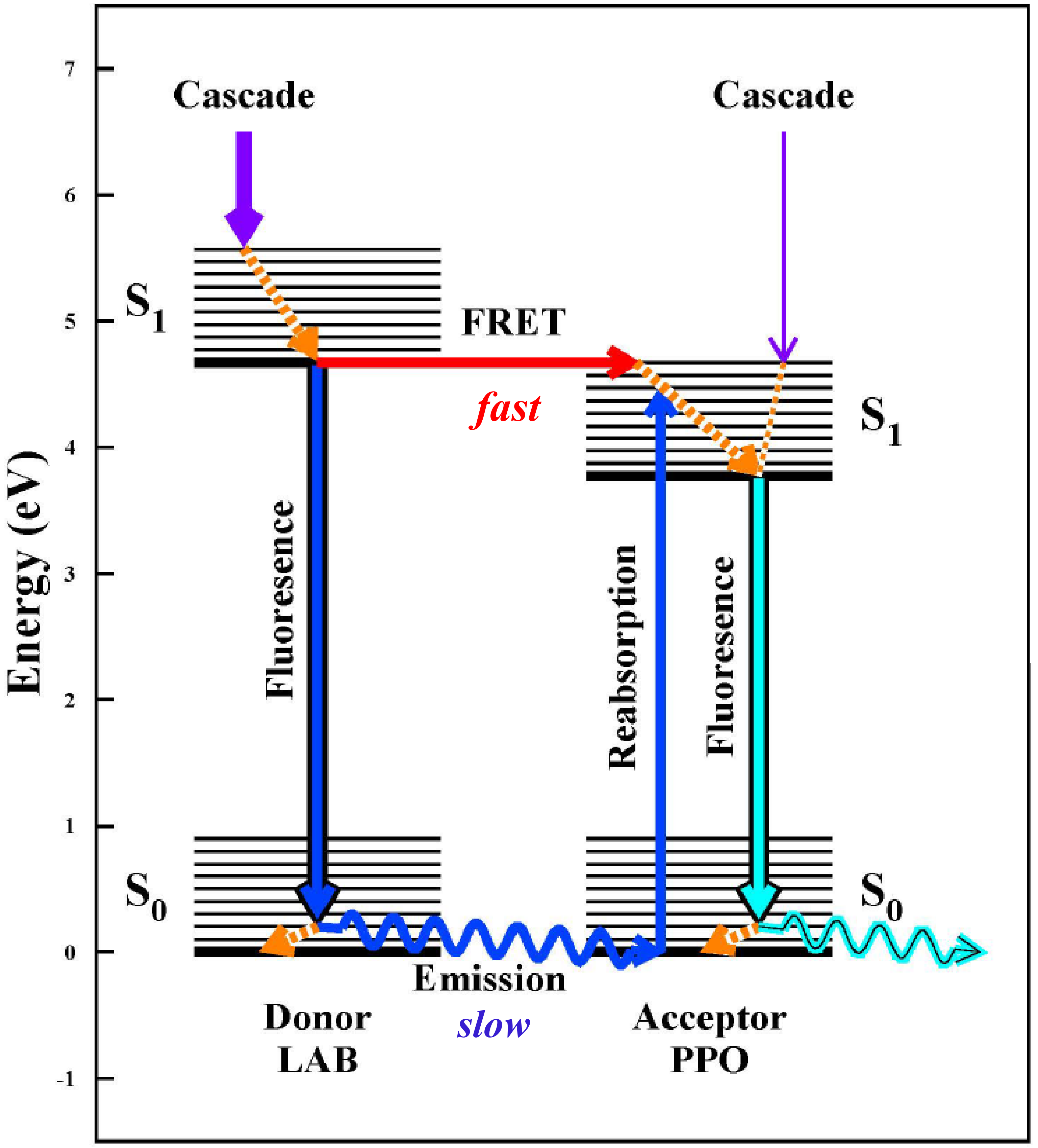




- *Adjust conc. of flour and shifters (Guo et. al., j.astropartphys.2019.02.001)*
- *Utilize slow fluor and WLS (Biller et. al., j.nima.2020.164106)*

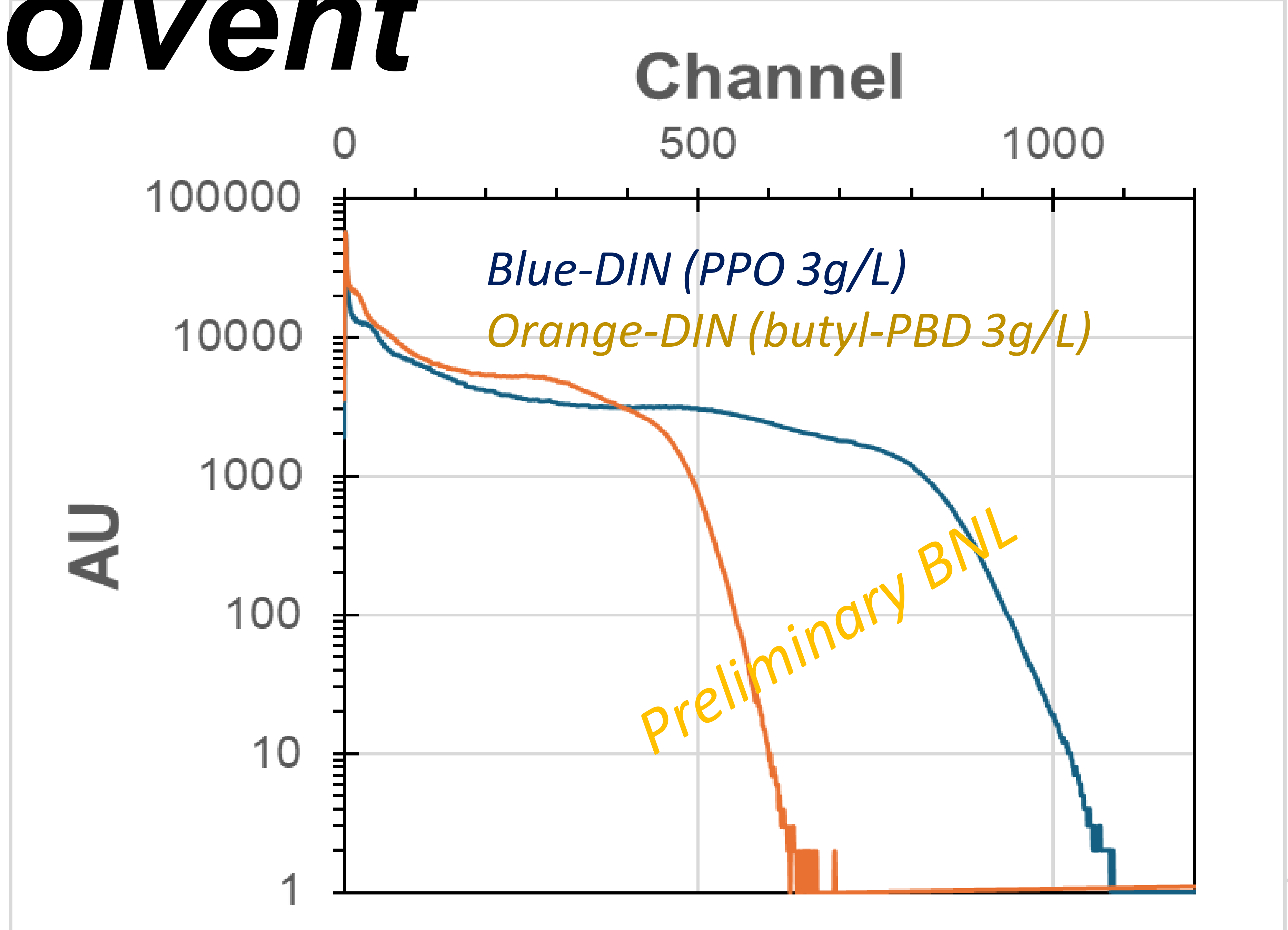
Energy transfer mechanism in solvent

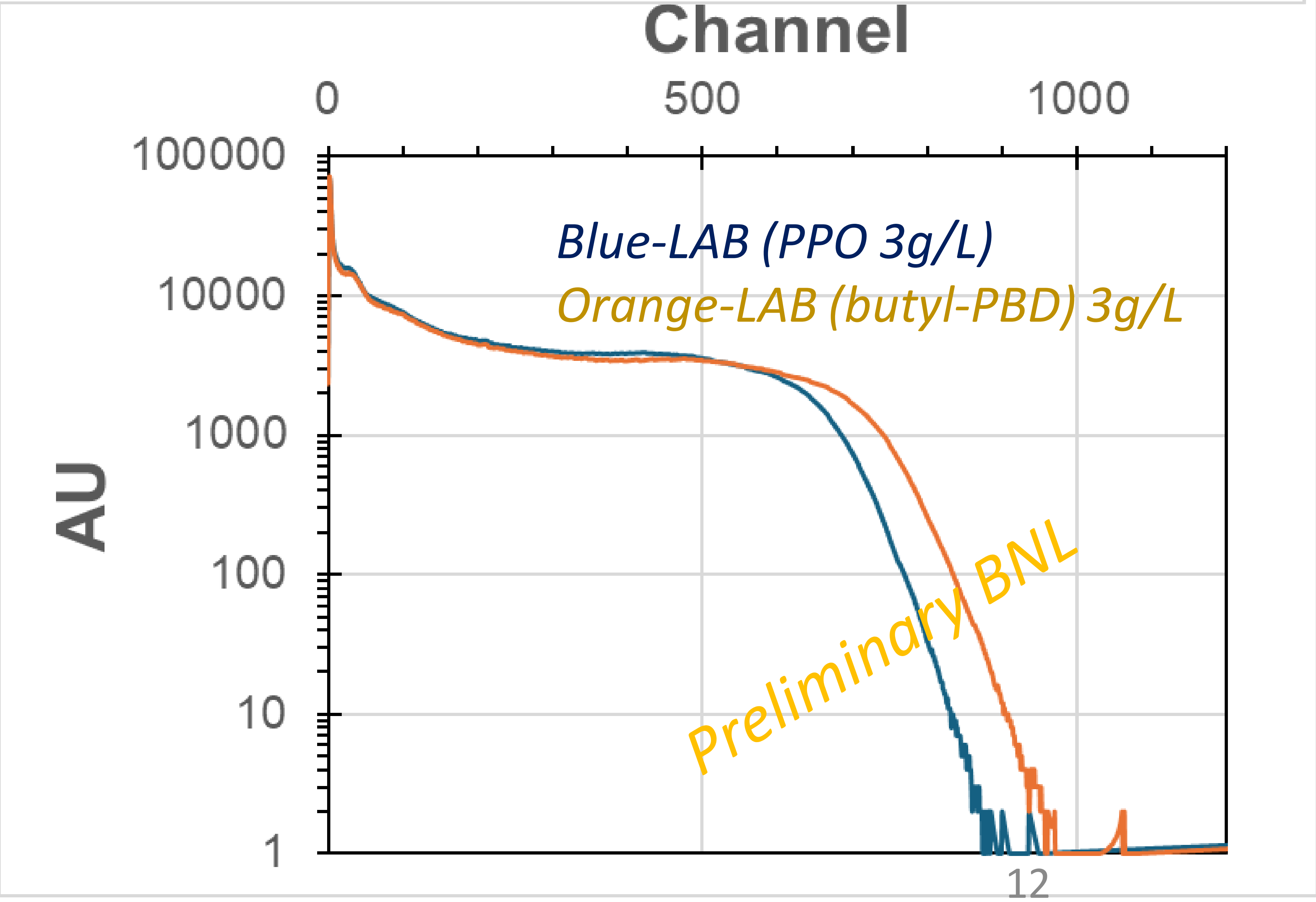
Radiative vs. Nonradiative



Molecule	chemical formula	abs. max.	em. max.
PPO	$C_{15}H_{11}NO$	303 nm	358 nm
PBD	$C_{20}H_{14}N_2O$	302 nm	358 nm
butyl-PBD	$C_{24}H_{22}N_2O$	302 nm	361 nm
BPO	$C_{21}H_{15}NO$	320 nm	384 nm
p-TP	$C_{18}H_{14}$	276 nm	338 nm
TBP	$C_{28}H_{22}$	347 nm	455 nm
bis-MSB	$C_{24}H_{22}$	345 nm	418 nm
POPOP	$C_{24}H_{16}N_2O_2$	360 nm	411 nm
PMP	$C_{18}H_{20}N_2$	295 nm	425 nm

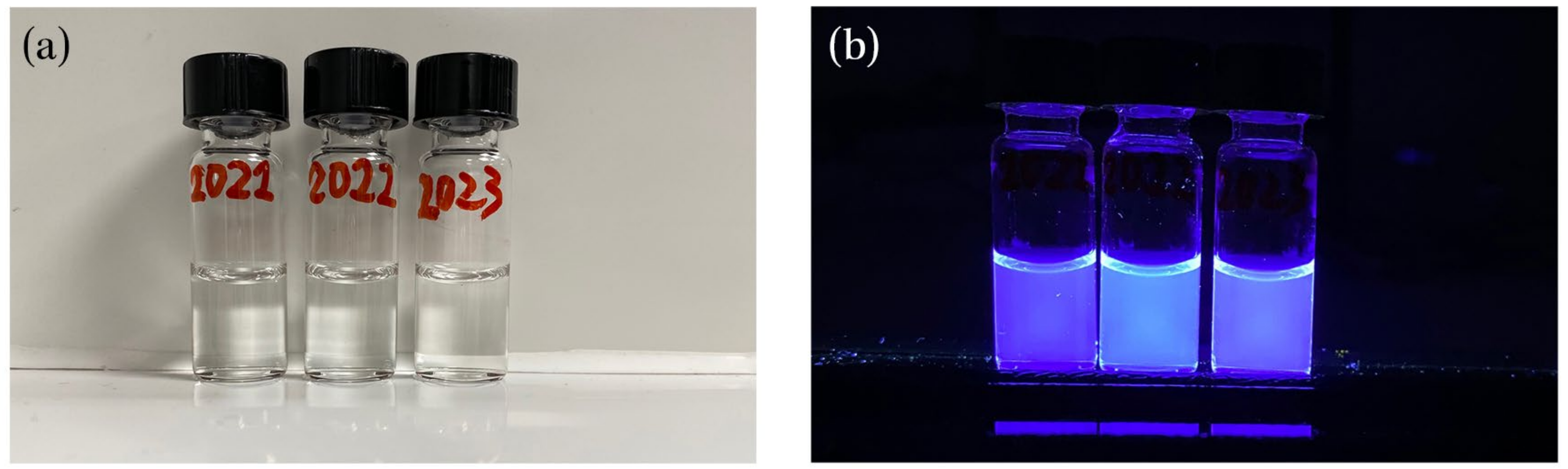
Christian Buck and Minfang Yeh 2016 J. Phys. G: Nucl. Part. Phys. 43 093001





butyl-PBD could benefit LAB-based detectors, such as SNO+ and JUNO https://arxiv.org/abs/2403.10122

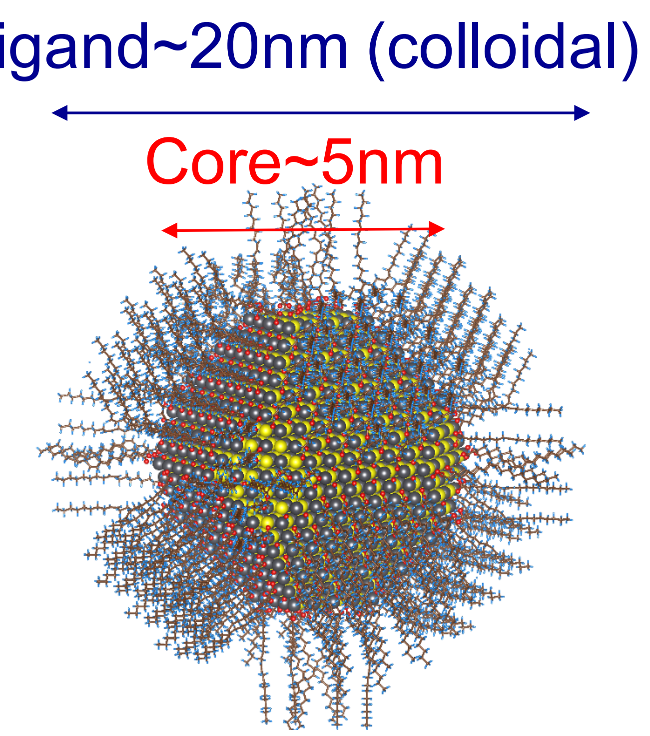
Water-based Quantum Dots Liquid Scintillator for Particle Physics

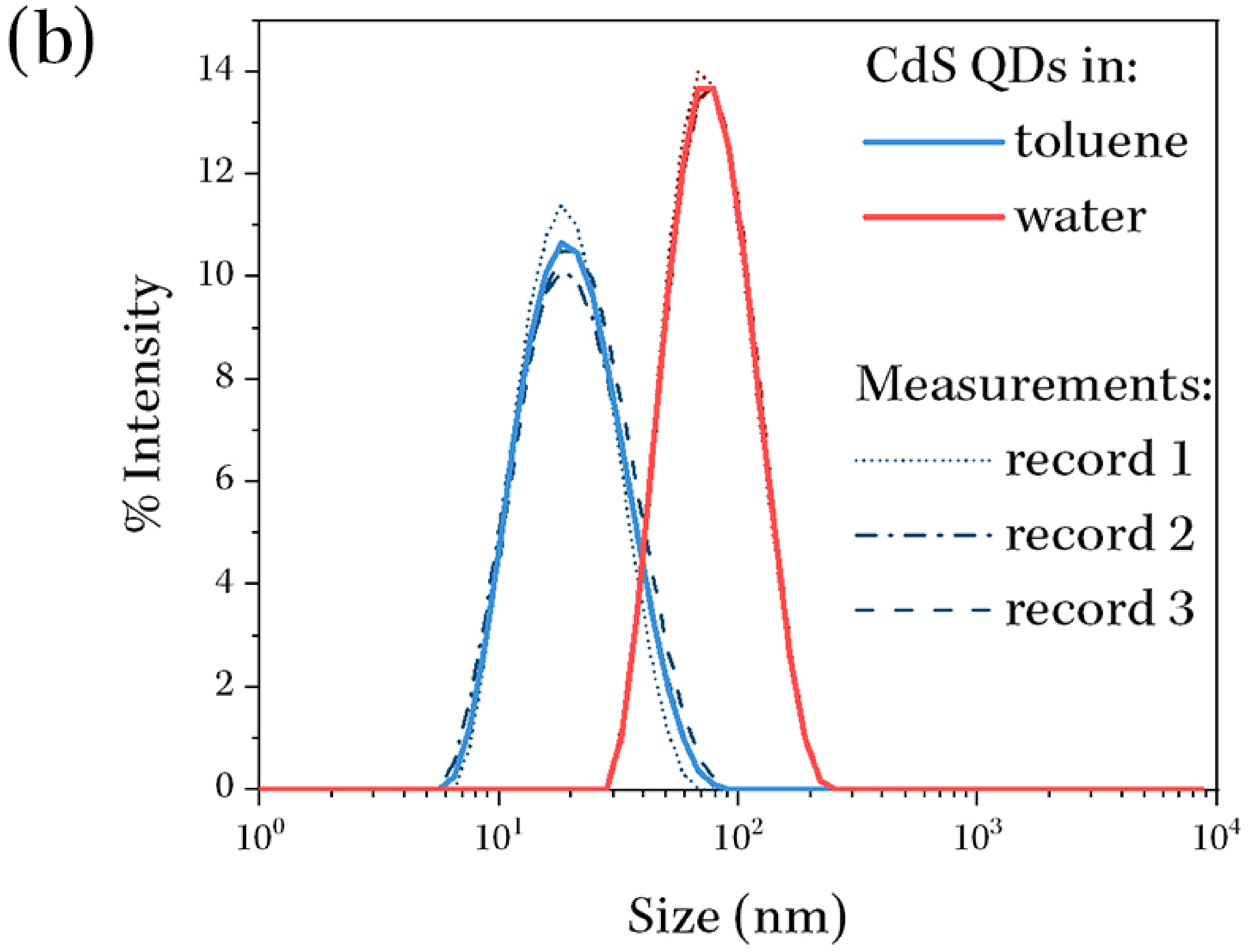


Semiconductor nano-crystal
- Emission spectrum is tunable (core type, size)
- Surface layers to change chemical properties

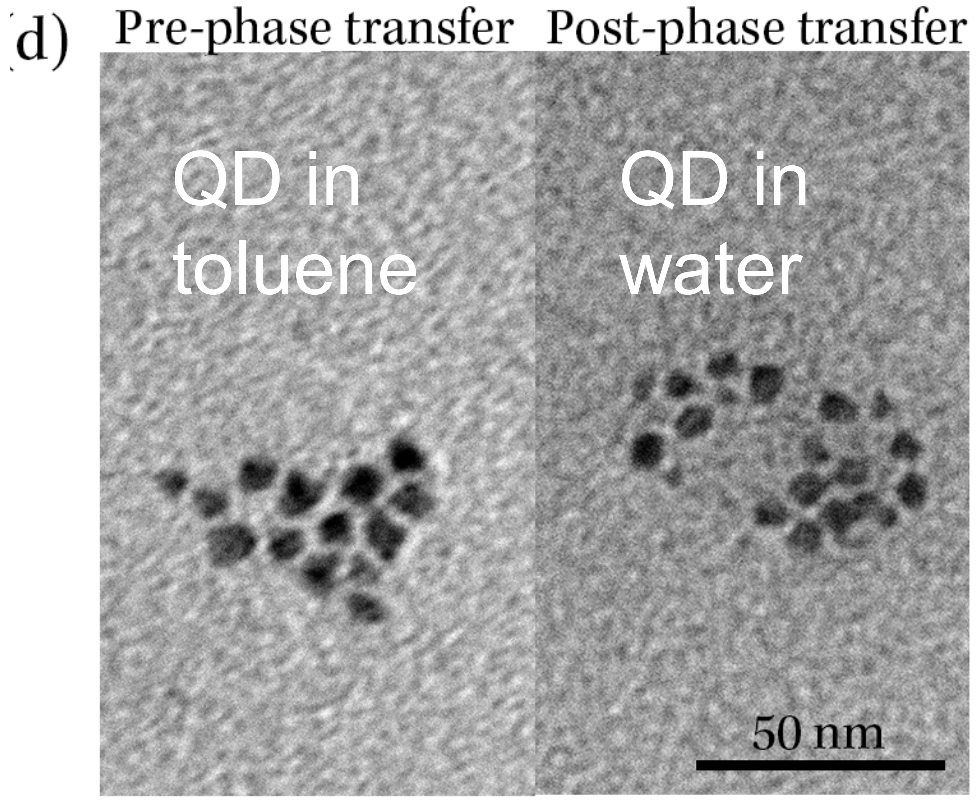
Water-based quantum dots (WbQD) liquid scintillator
- Hydrophilic layer to make water solution
- Use quantum dots as primary fluor

Hydrodynamic diameter of WbQD is ~70nm. WbQD is moving by dragging many water molecules

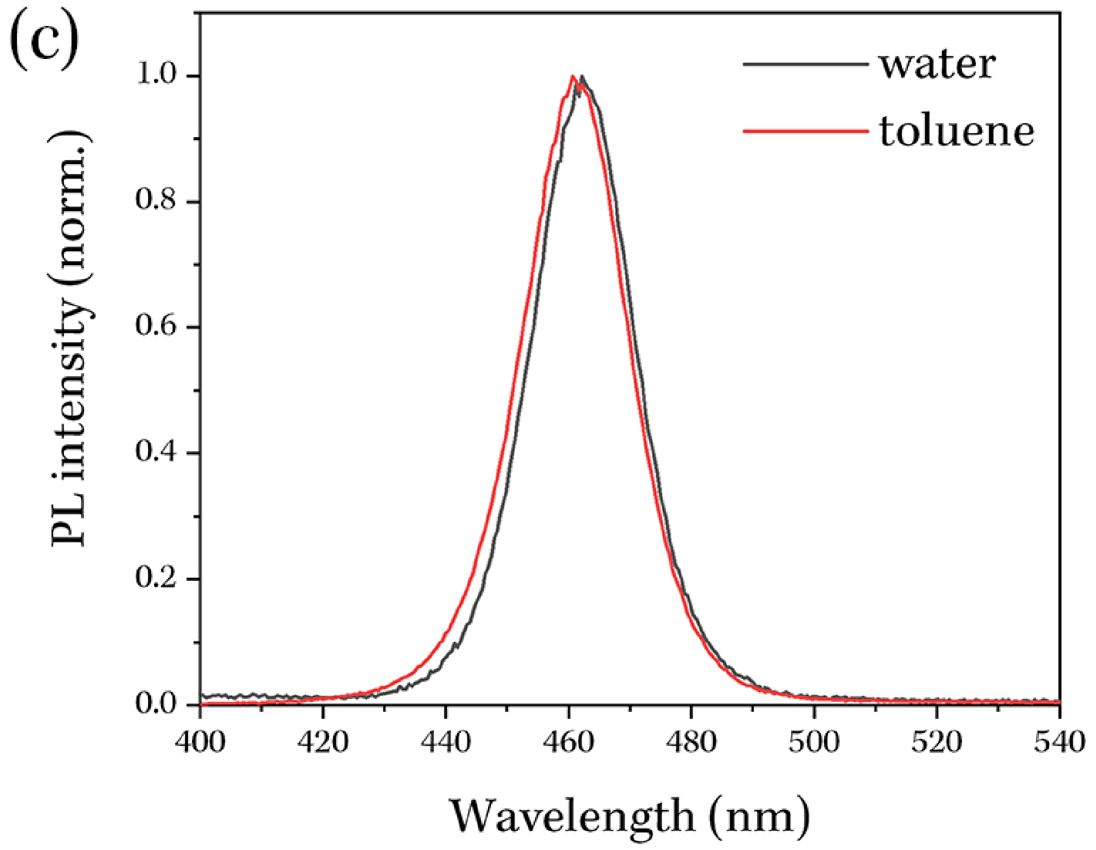




Core size is preserved (TEM image)



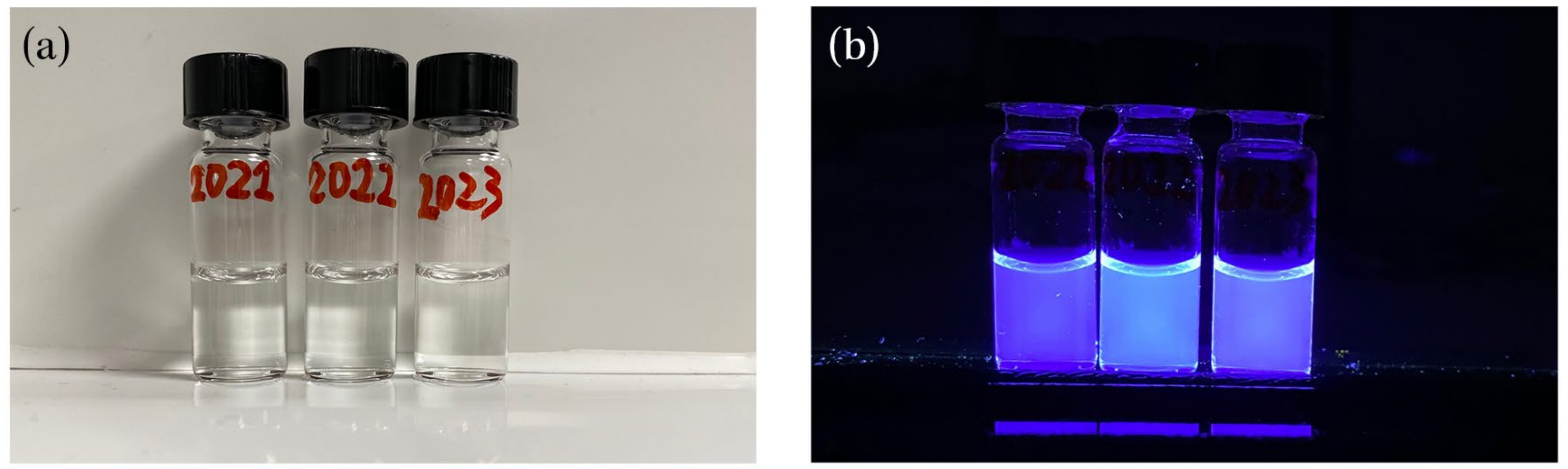
Emission spectrum is preserved



Teppei Katori

https://arxiv.org/abs/2403.10122

Water-based Quantum Dots Liquid Scintillator for Particle Physics

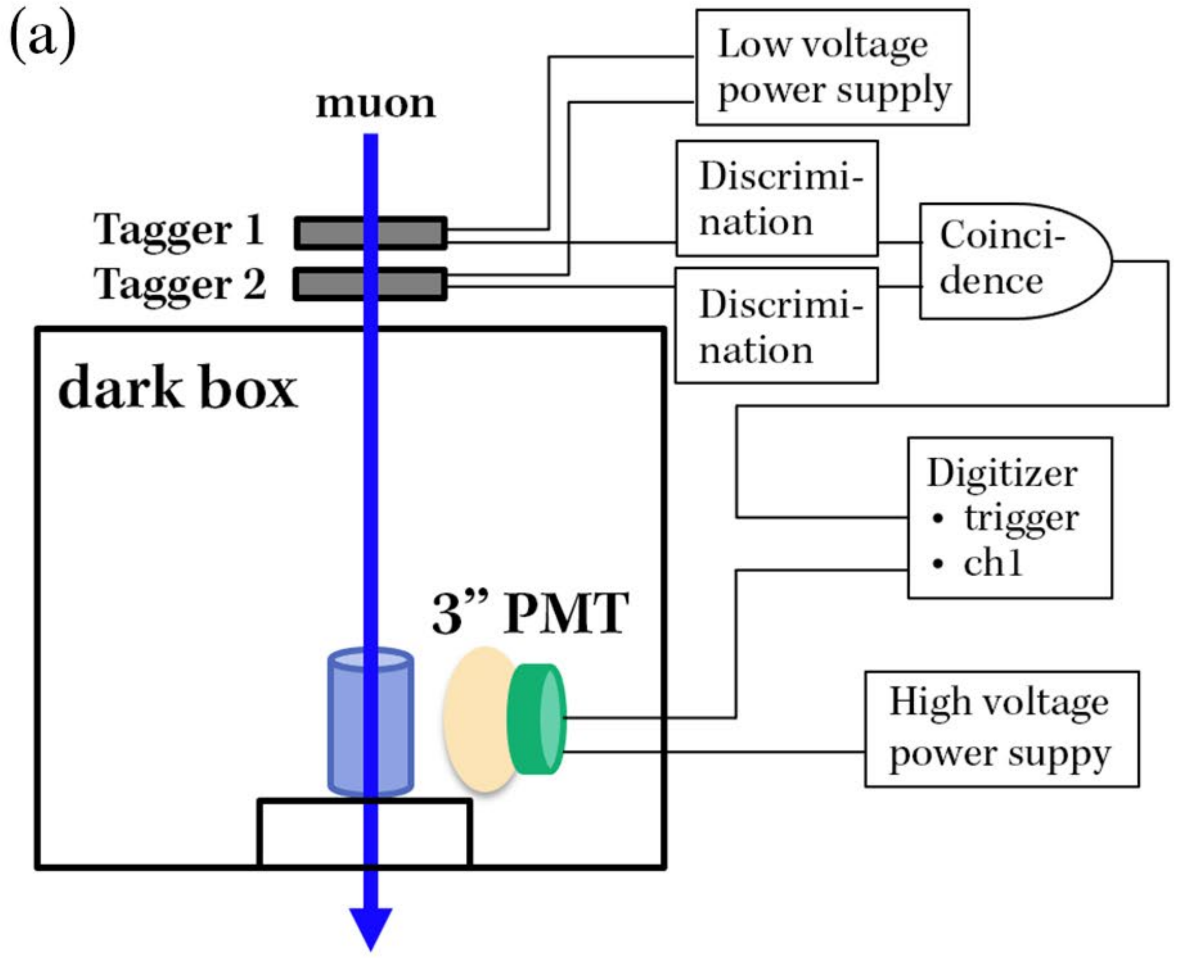


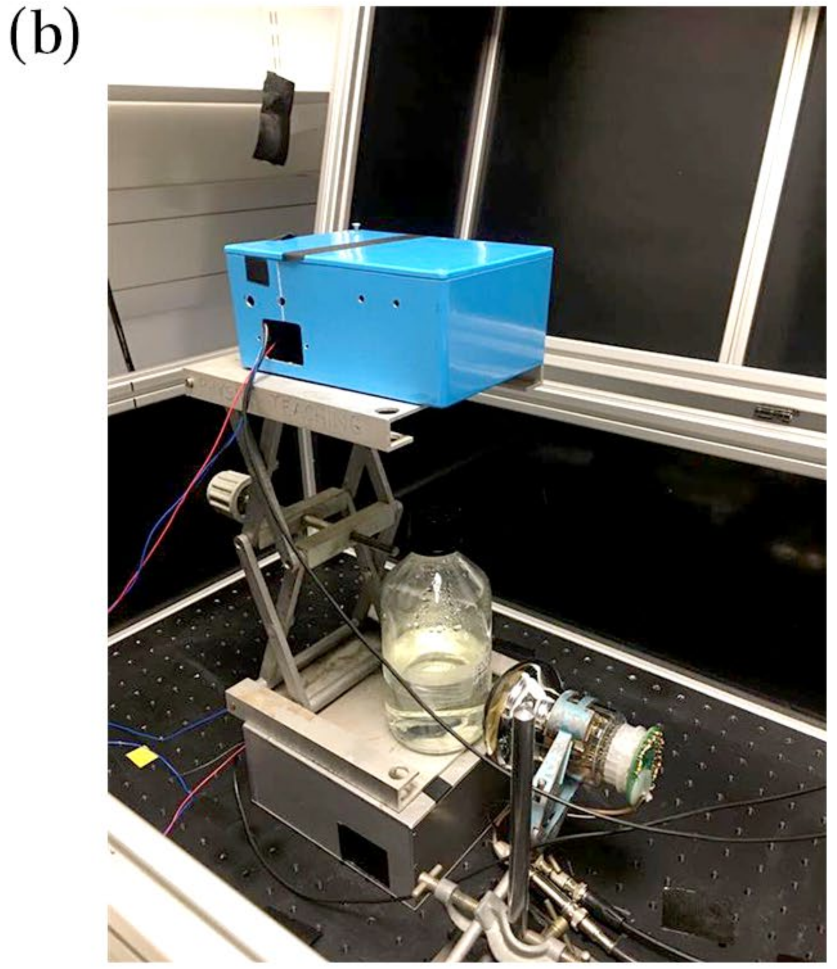
Semiconductor nano-crystal
- Emission spectrum is tunable (core type, size)
- Surface layers to change chemical properties

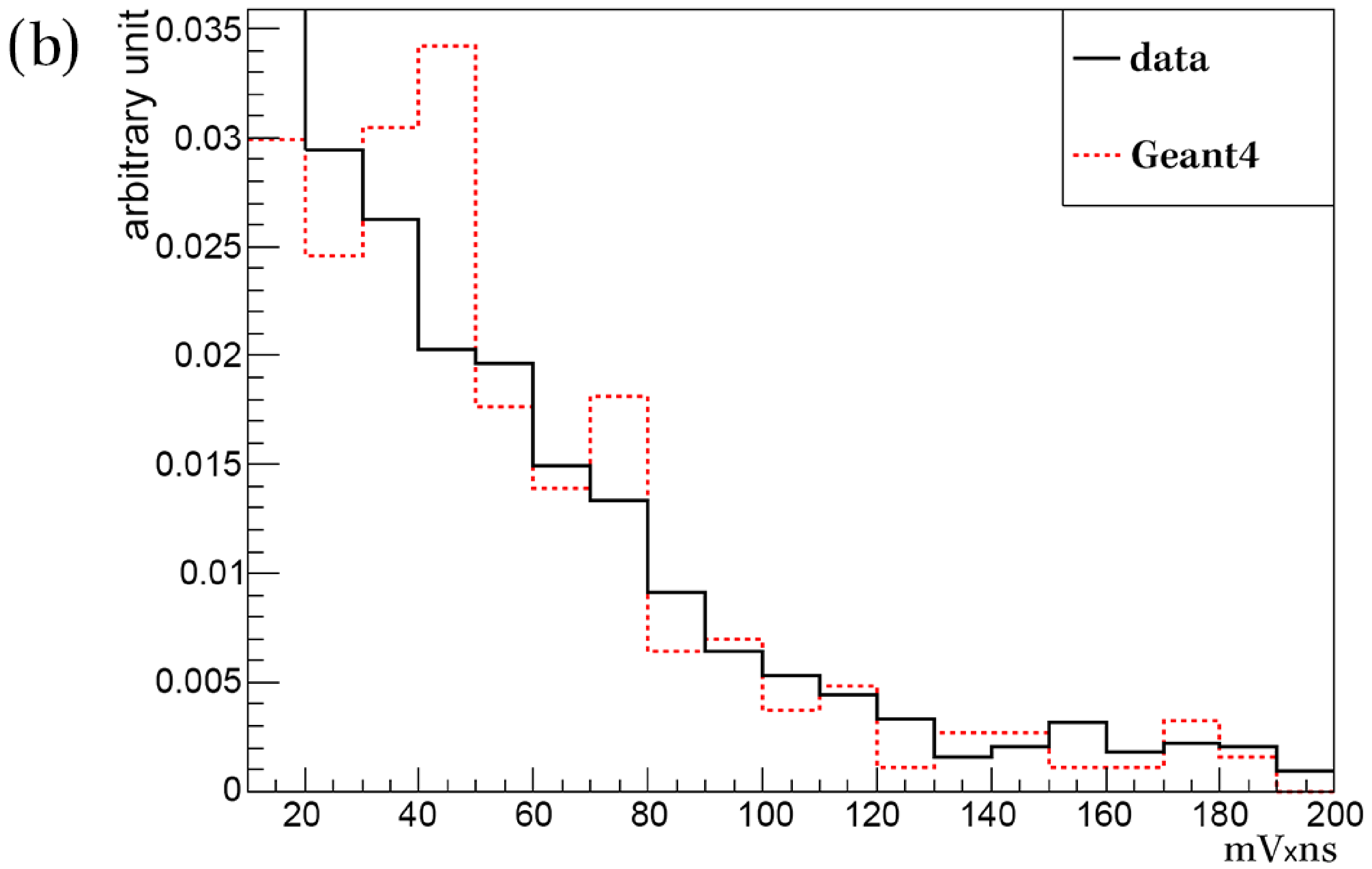
Water-based quantum dots (WbQD) liquid scintillator
- Hydrophilic layer to make water solution
- Use quantum dots as primary fluor

Hydrodynamic diameter of WbQD is ~70nm. WbQD is moving by dragging many water molecules

WbQD cosmic ray test
- First scintillation measurement by quantum dots with MIPs
- Pave the road for future quantum-dots-based detector
- Future R&D includes neutron tagging, beam test, etc



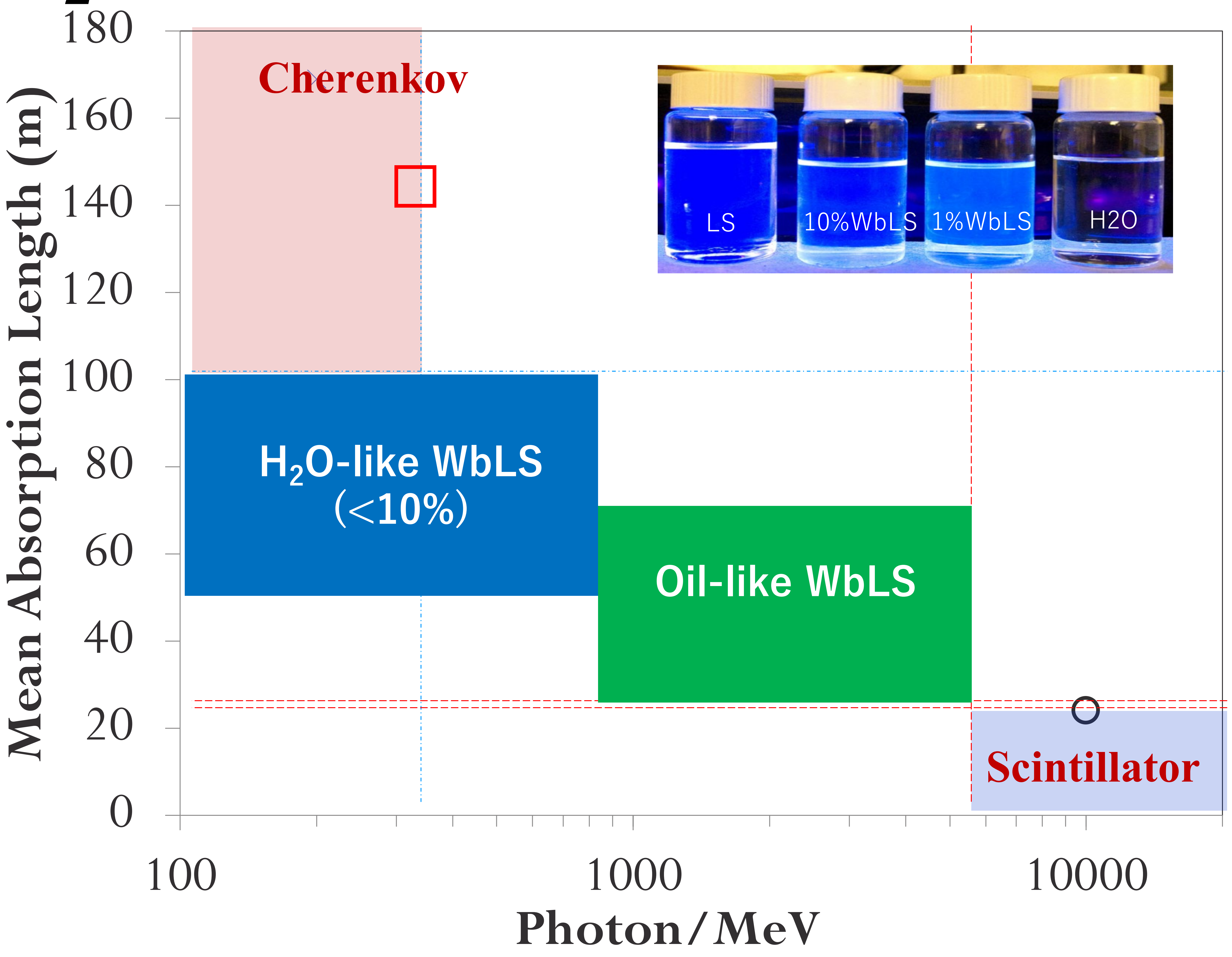




Teppei Katori

Water-based Liquid Scintillator

Oil- vs. H_2O-like WbLS for different detection concepts



Loading vs. light-yield vs. optical model

Yeh et. al., A new water-based liquid scintillator and potential applications, j.nima.2011.08.040.

Deuterated liquid detectors

A D_2O-based Liquid Scintillator (HbLS)

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

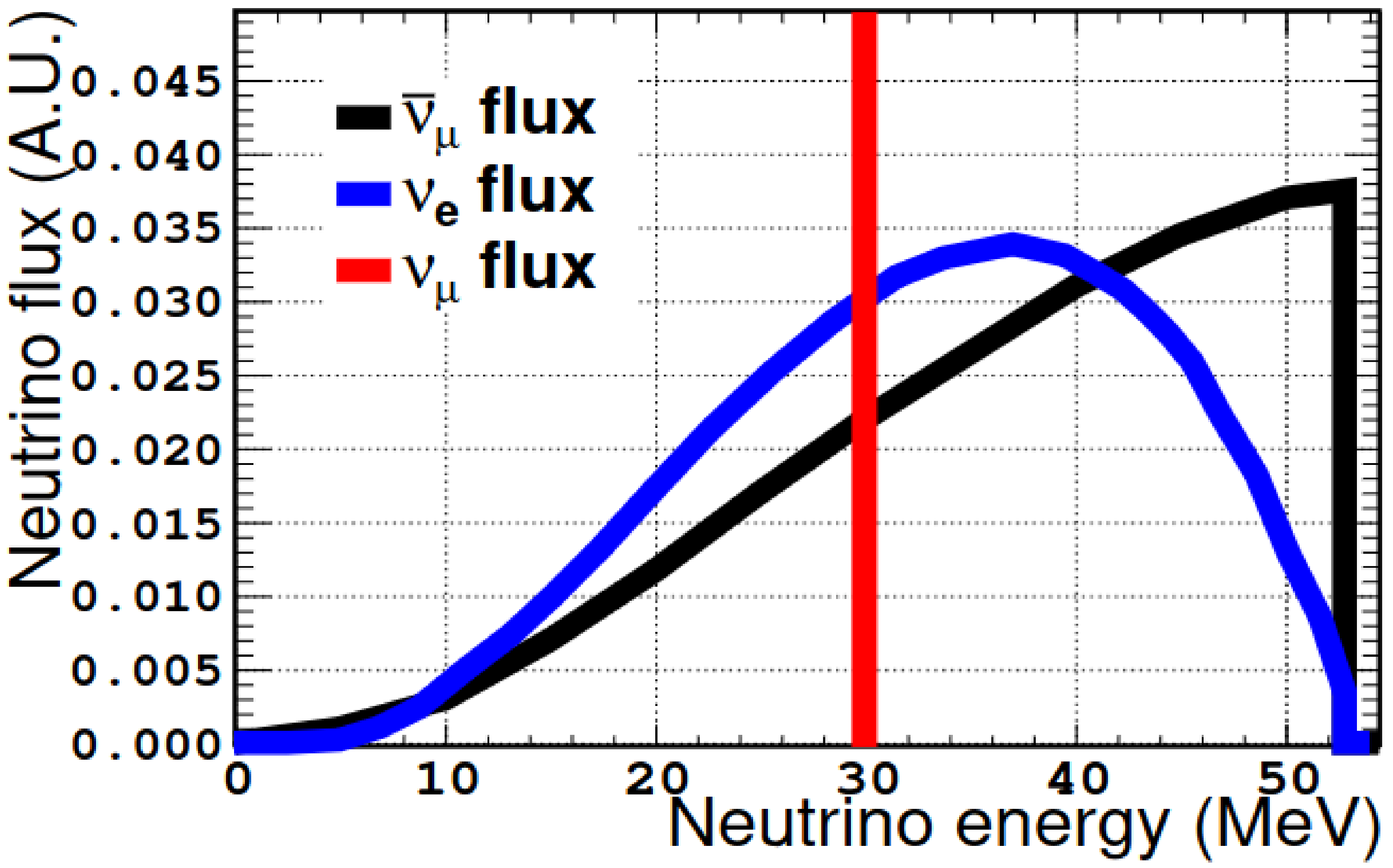
- Free neutrinos from Spallation Neutron Sources (COHERENT)
  - Measure three neutrinos from pion decay-at-rest
  - Measure sterile neutrinos
- Triple coincidence reducing background towards a near surface detector (IBD) & cleaner Cherenkov region (>450nm)
- A few liters of HbLS fabricated for evaluation (pub. in prep.)

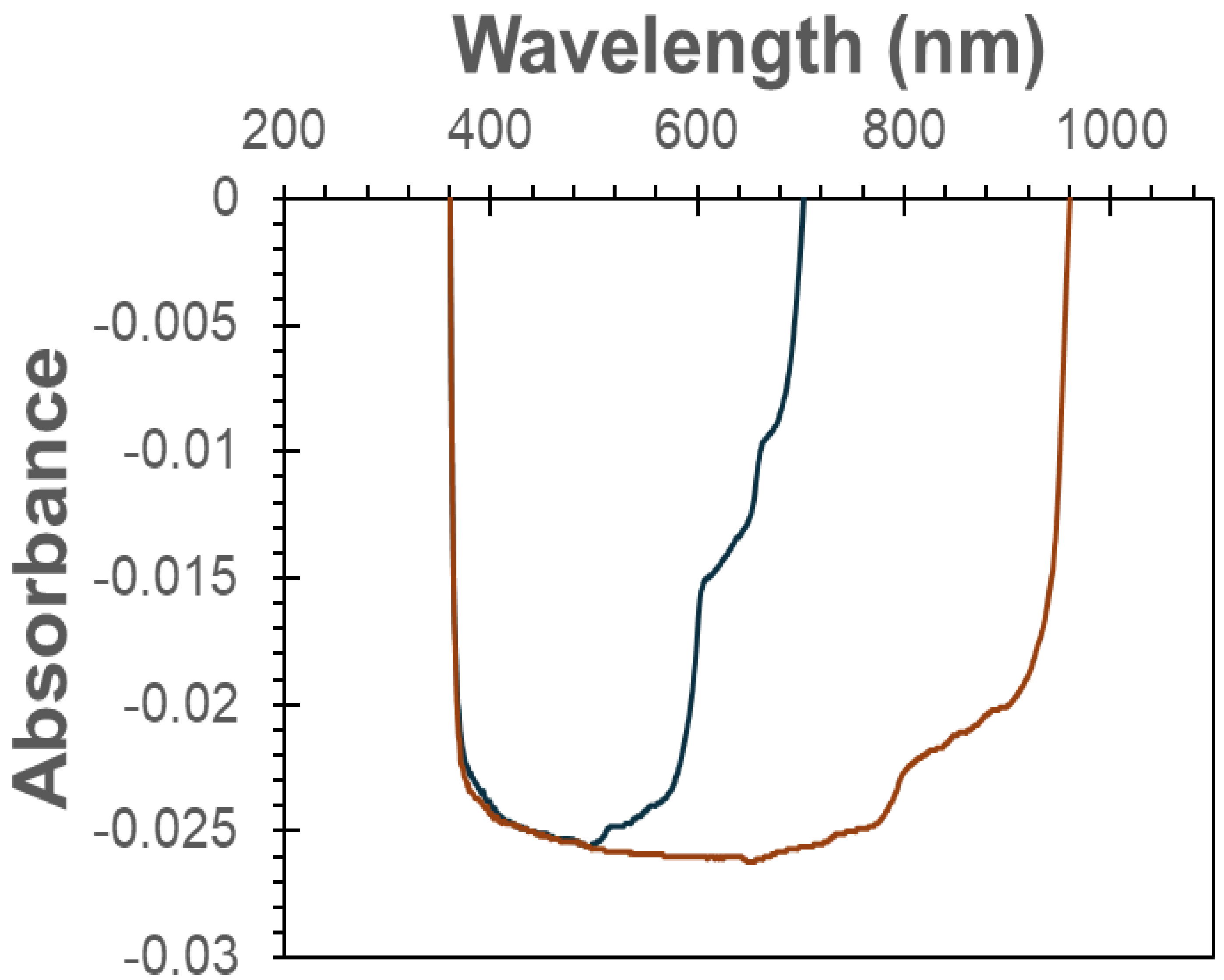
Interaction channel for neutrons from SNS

Interaction	Channel	-Q(MeV)	Cross section E_ν = 10 MeV (cm^2)
$\nu + d \rightarrow \nu + n + p$	NC	2.224	1.10×10^{-42}
$\bar{\nu} + d \rightarrow \bar{\nu} + n + p$	NC	2.224	1.05×10^{-42}
$\nu_e + d \rightarrow e^- + p + p$	CC	1.442	2.69×10^{-42}
$\bar{\nu}_e + d \rightarrow e^+ + n + n$	CC (DIBD)	4.028	1.23×10^{-42}
$\nu_e + e^- \rightarrow \nu_e + e^-$	ES	0.	9.19×10^{-44}
$\nu_x + e^- \rightarrow \nu_x + e^-$	ES	0.	3.77×10^{-44}
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	ES	0.	1.64×10^{-44}
$\bar{\nu}_x + e^- \rightarrow \bar{\nu}_x + e^-$	ES	0.	1.320×10^{-44}
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC (IBD)	1.8	6.7×10^{-42}

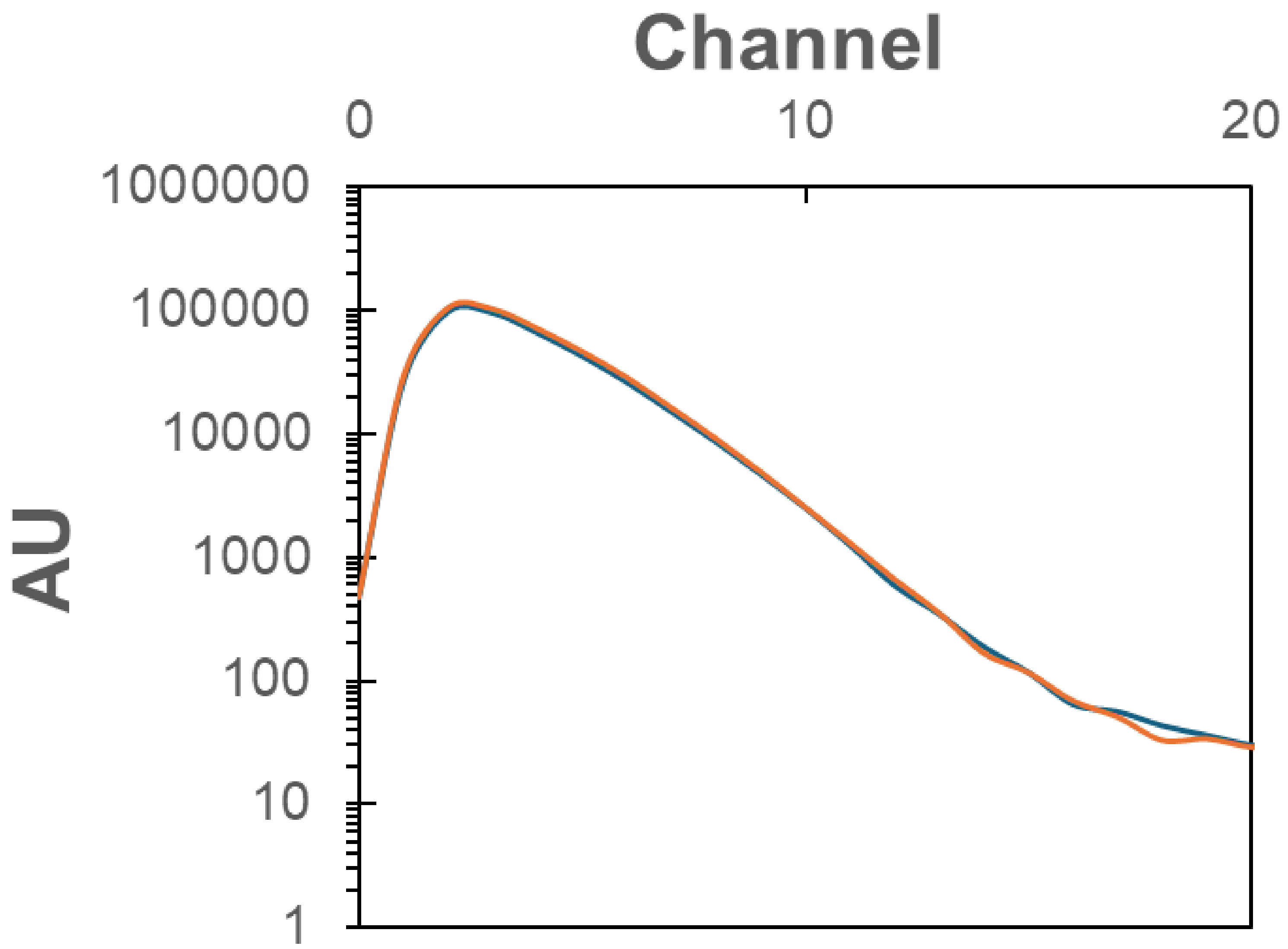
Chauhan et. al., JCAP, 11:005, 2021

Neutrino flux from SNS





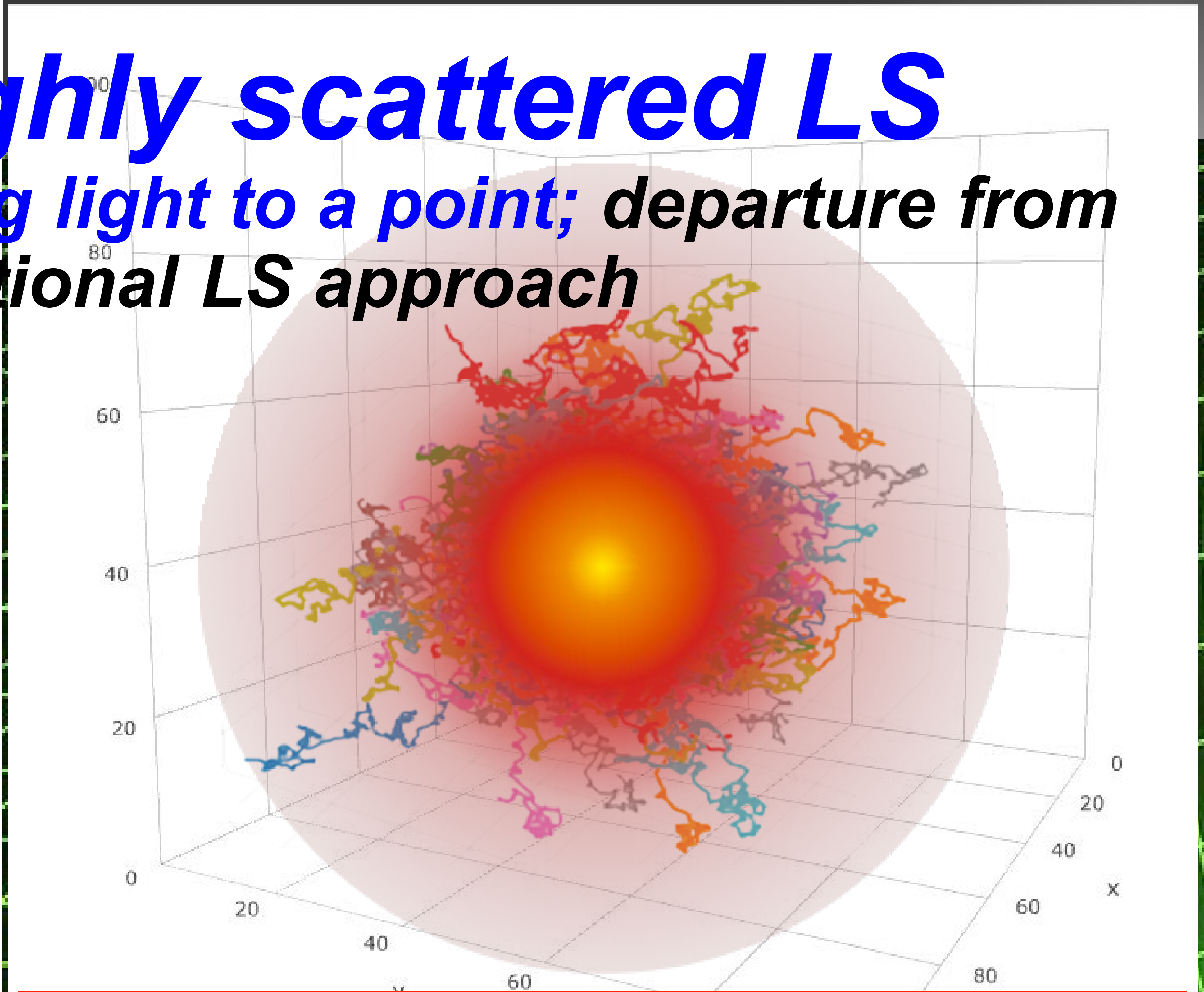
10-cm UV (WbLS vs HbLS)



Compton Scattering (137Cs)

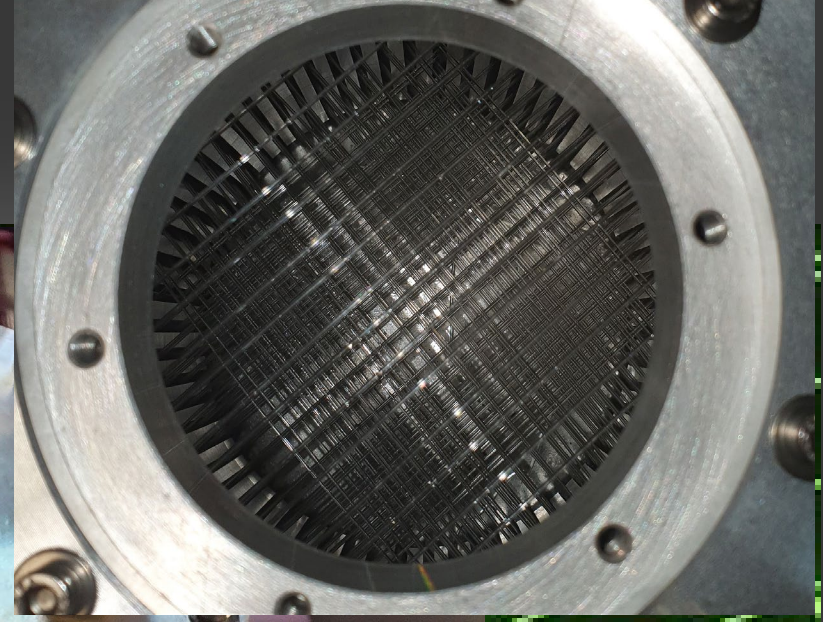
A highly scattered LS

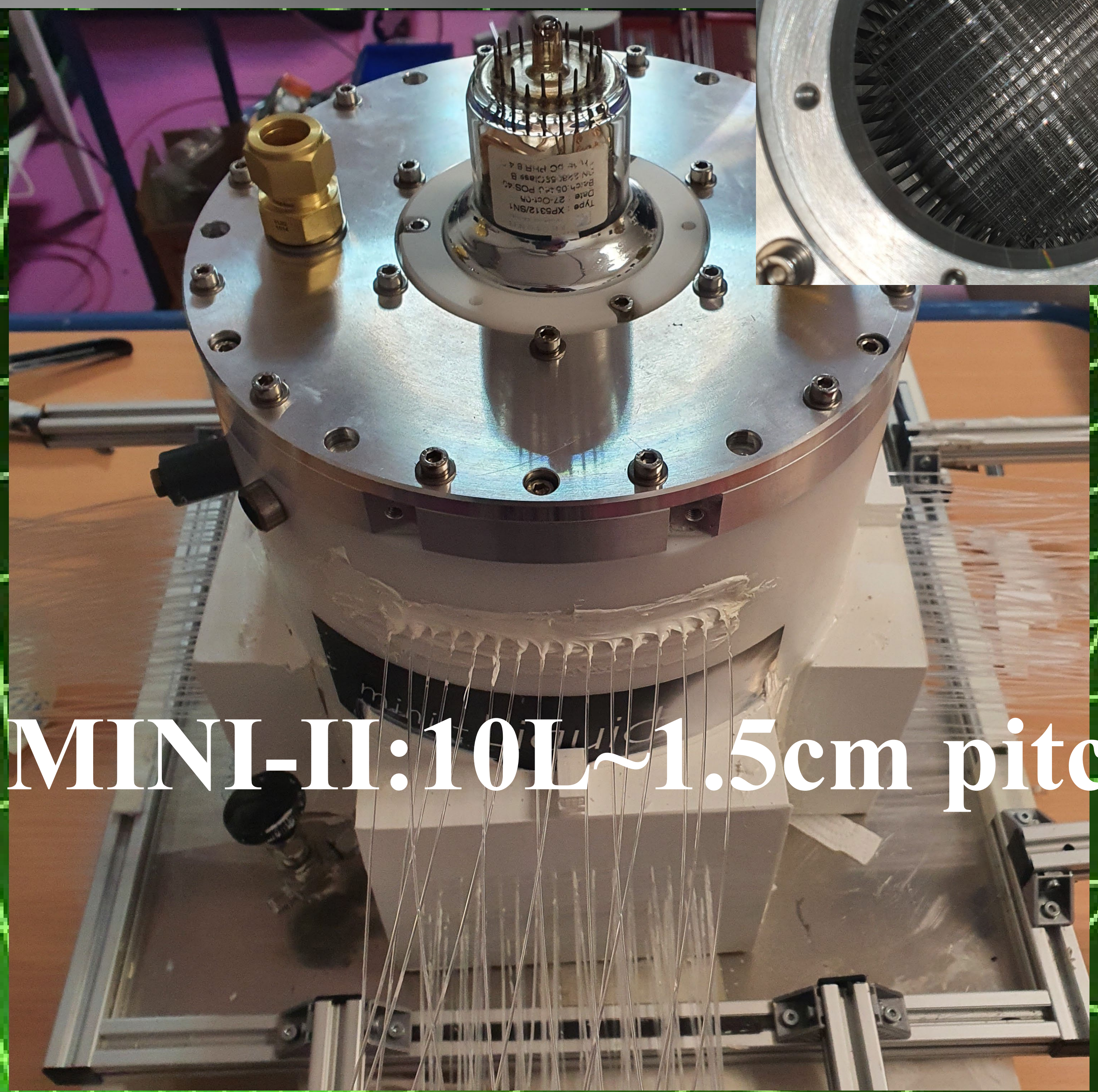
Inducing light to a point; ***departure from conventional LS approach***



Liqudi O→ photon's "random walk" (self-confinement)

Nu2022





MINI-II:10L~1.5cm pitch

Transparency
λ(scattering)≥10m

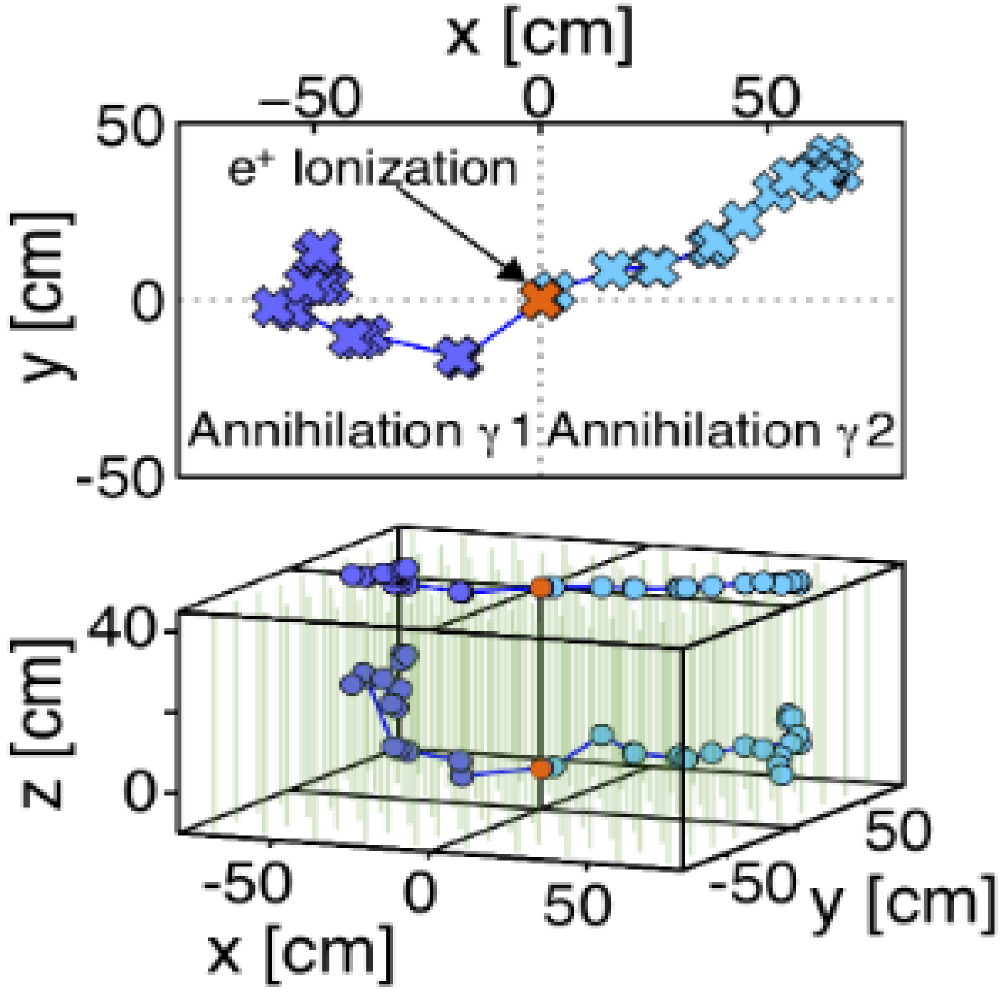
Rayleigh & Mie Scattering
λ(scattering)≤1cm

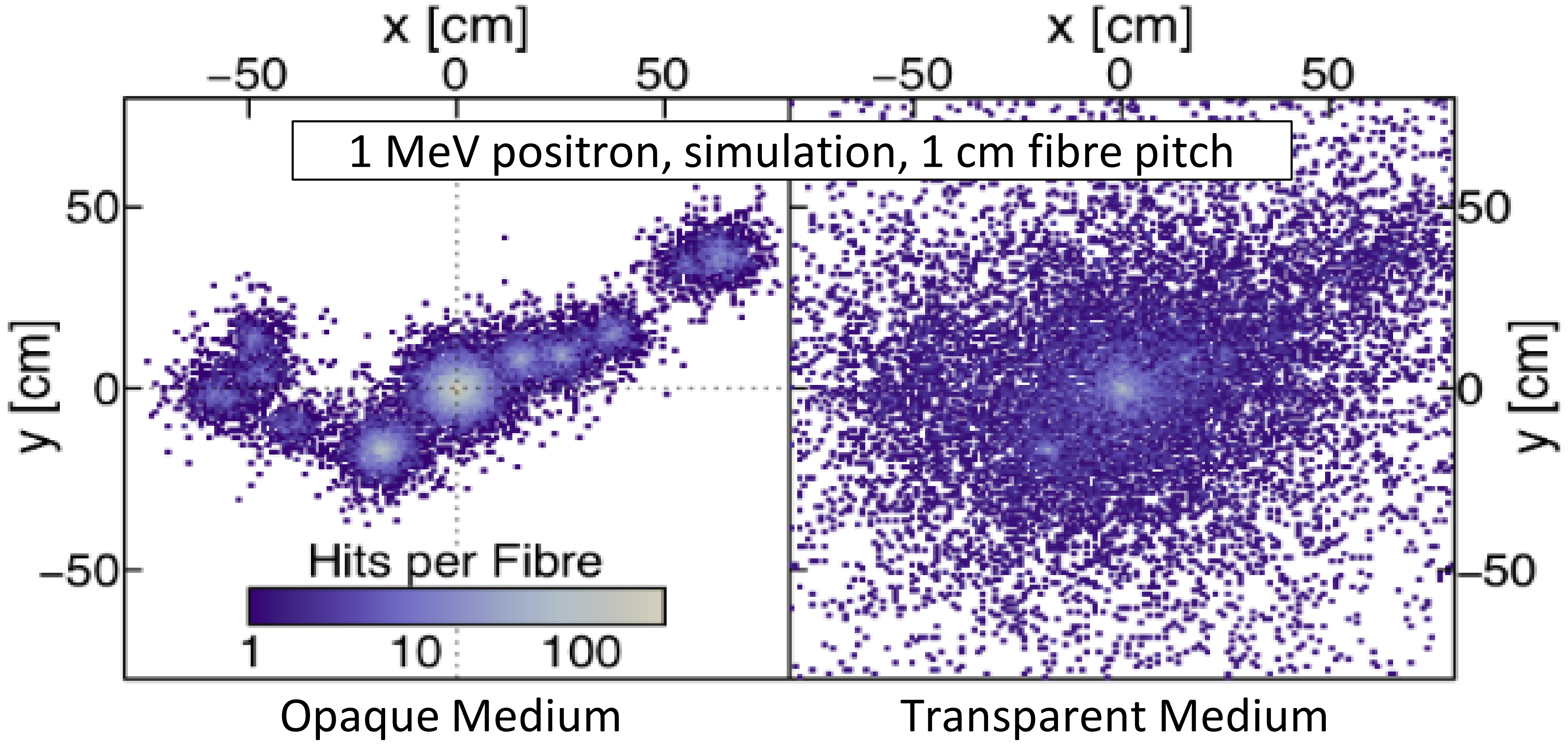
LiquidO/CLOUD Consortium

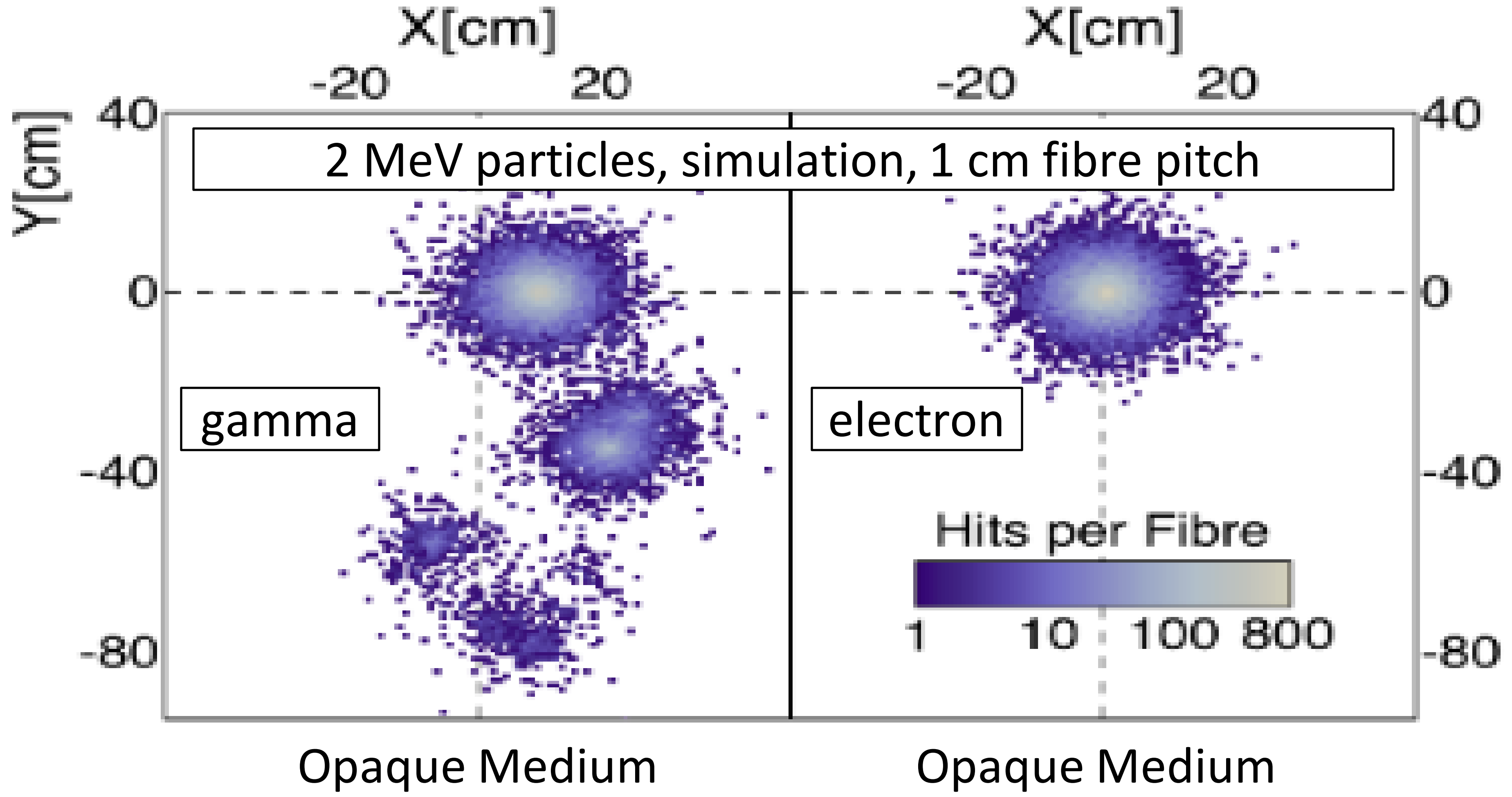
Brookhaven National Laboratory

NoWaSH

NoWaSH: wax-based opaque-white liquid scintillator
→ e.g. 98 wt.% solvent + 2 wt.% wax + primary and secondary wavelength shifters
→ opaqueness through scattering without absorption (Mie scattering)
→ particle-dependent morphology of confined light blobs:



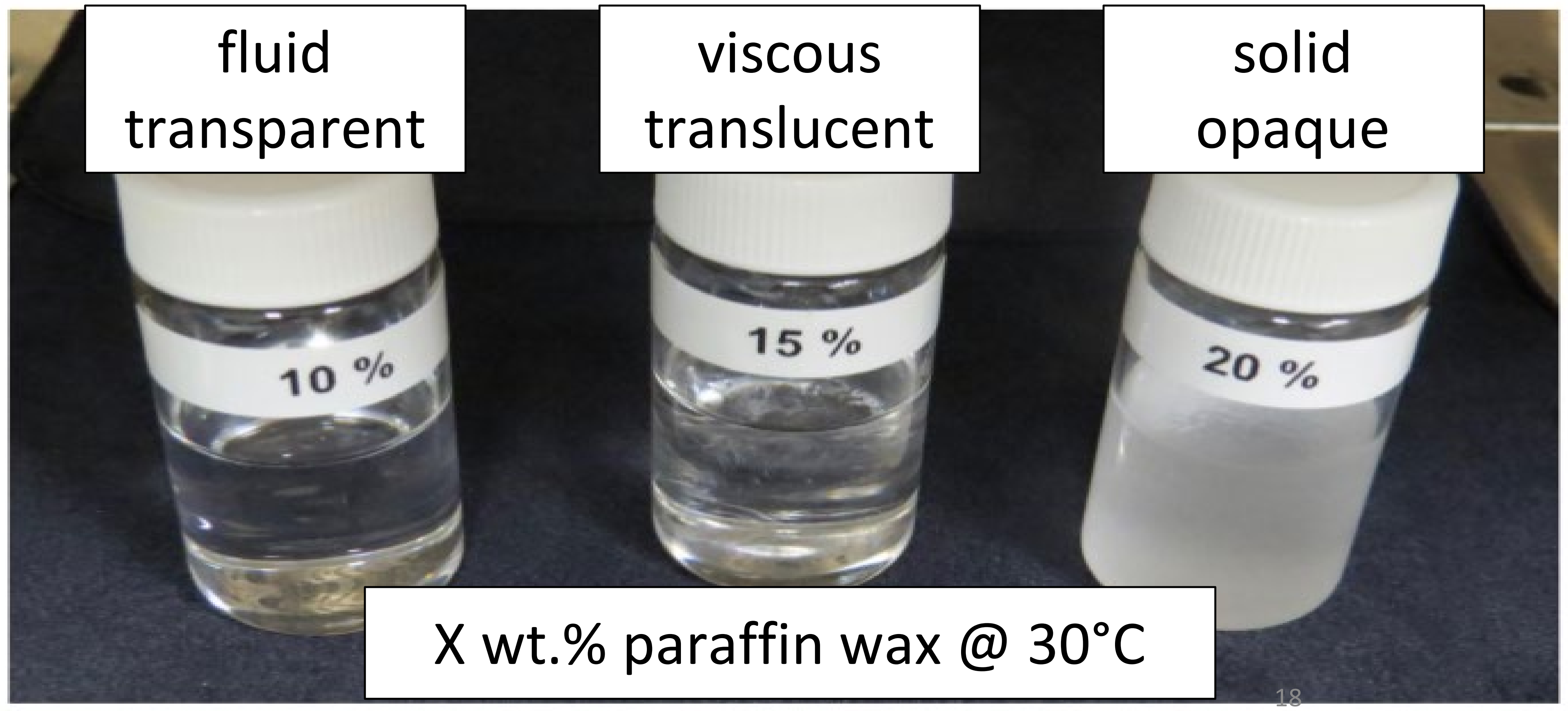




→ several options for solvents and waxes:

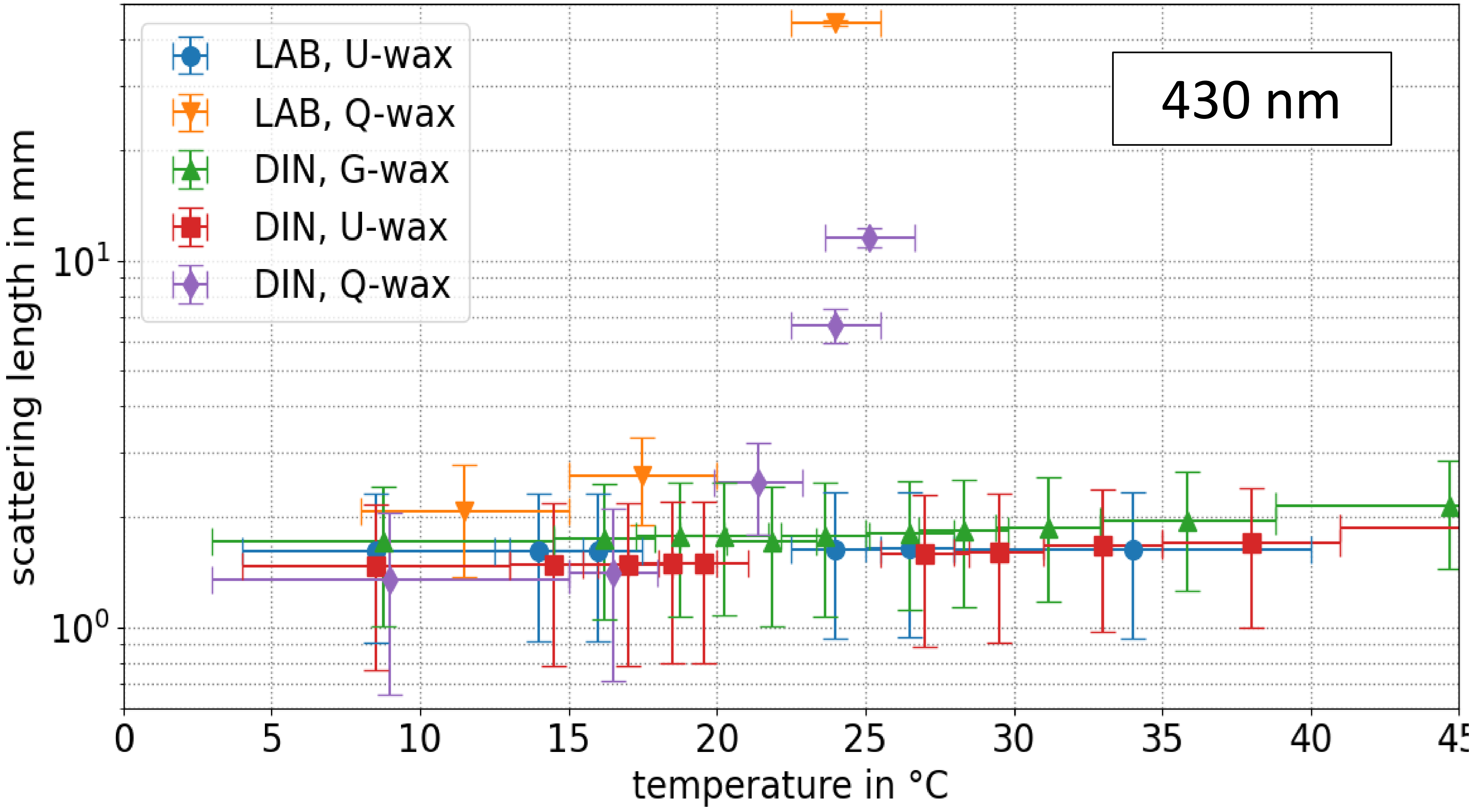
name	CAS number
LAB	67774-74-7
DIN	38640-62-9
o-PXE	6196-95-8
PC	95-63-6
xylene	1330-20-7
toluene	108-88-3

ID	wax type	CAS number
G	non-polar PE	9002-88-4
H	EBS	110-30-5
O	oxidised PE	68441-17-8
Q	paraffin	8002-74-2
U	FT	8002-74-2
X	EBS	110-30-5



→ high metal loading possible

Properties of NoWaSH

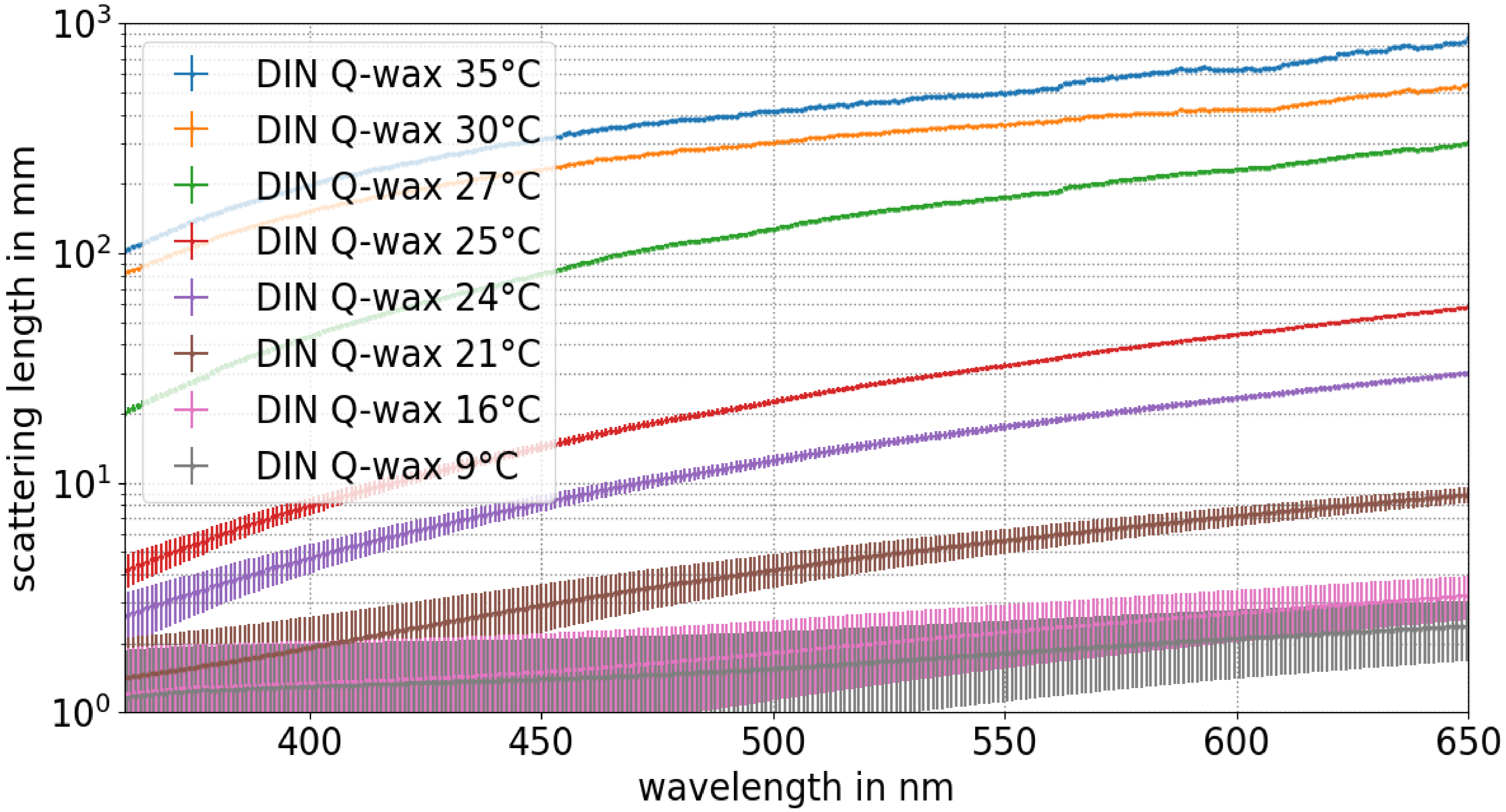


→ only ~ 2 wt.% wax loading required

→ same properties as transparent scintillator with respect to:
→ light yield
→ absorption length
→ emission spectrum
→ refractive index
→ density

→ scattering length of O(1mm)
→ NoWaSH formulations with temperature dependent and independent scattering length available

→ low and high viscosity NoWaSH formulations available

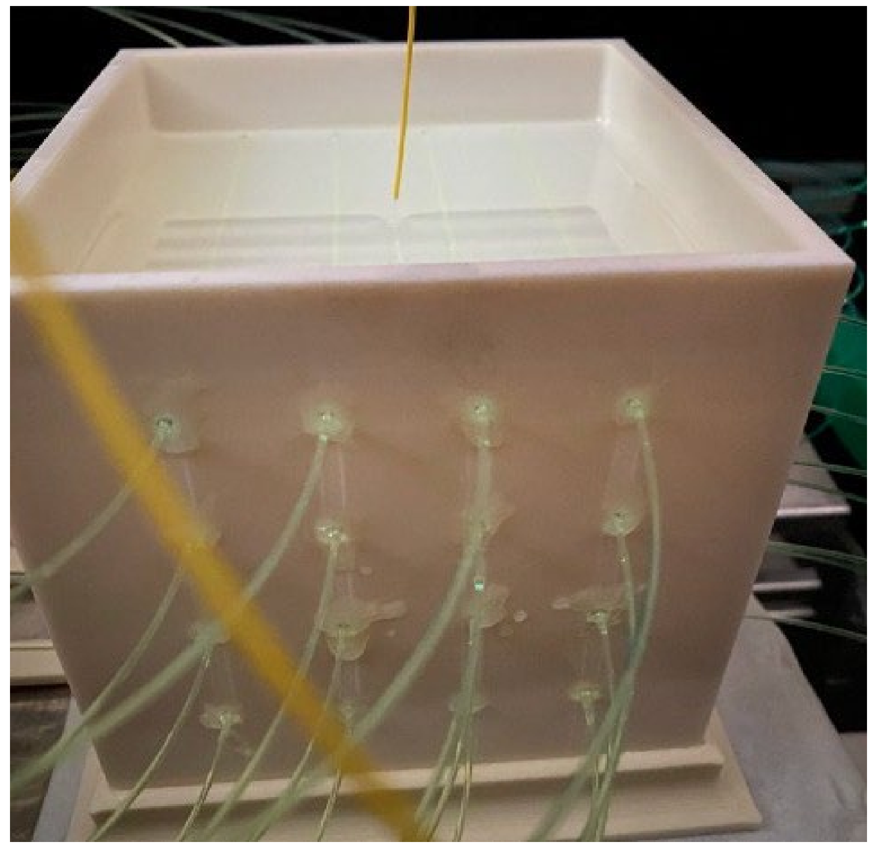


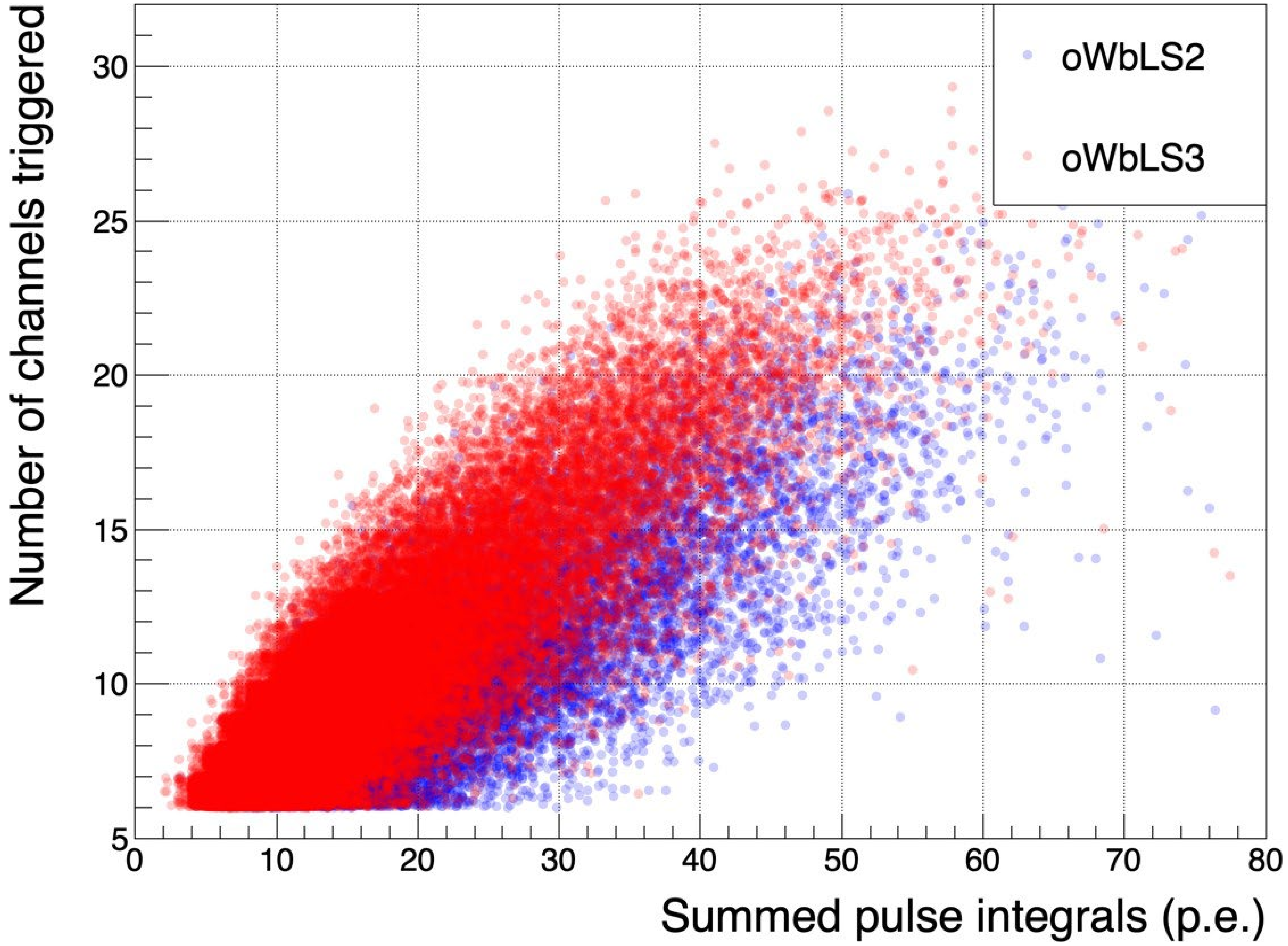
→ C. Buck, B. Gramlich, S. Schoppmann, Novel Opaque Scintillator for Neutrino Detection, JINST 14 (2019) P11007
→ S. Schoppmann, Improved Opaque Scintillator for Neutrino Detection, Symmetry (2024) to be published

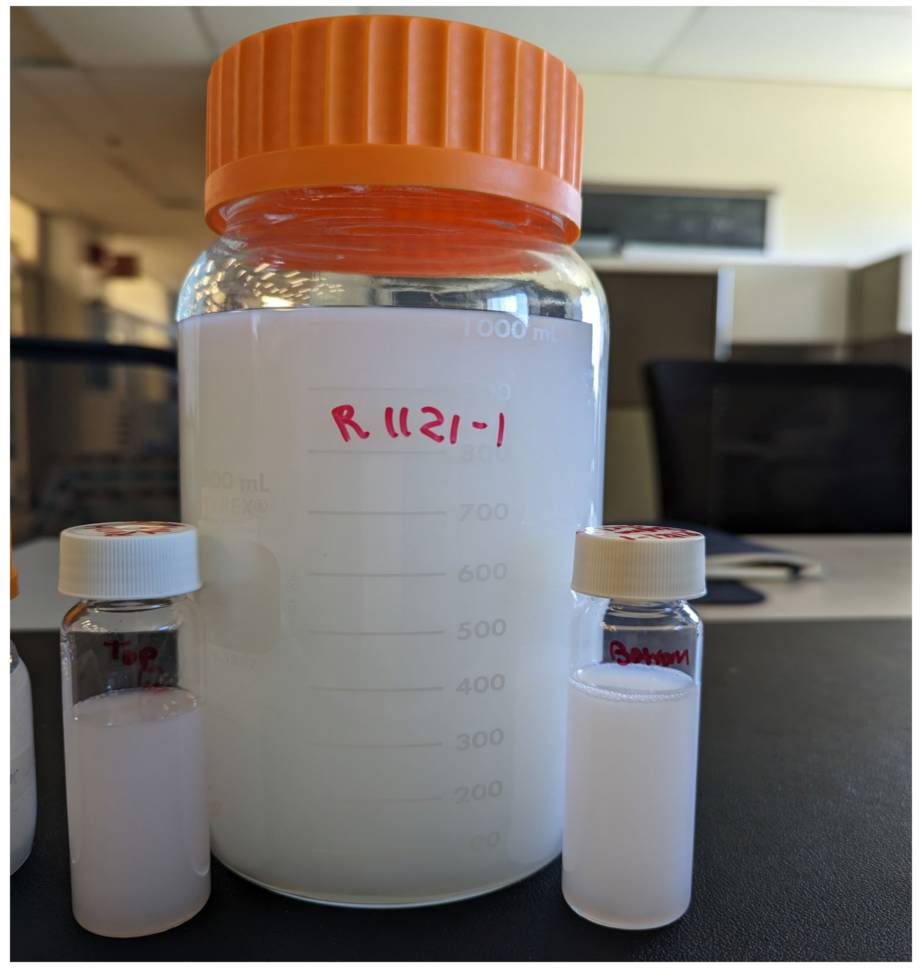
Light Confinement of oWbLS

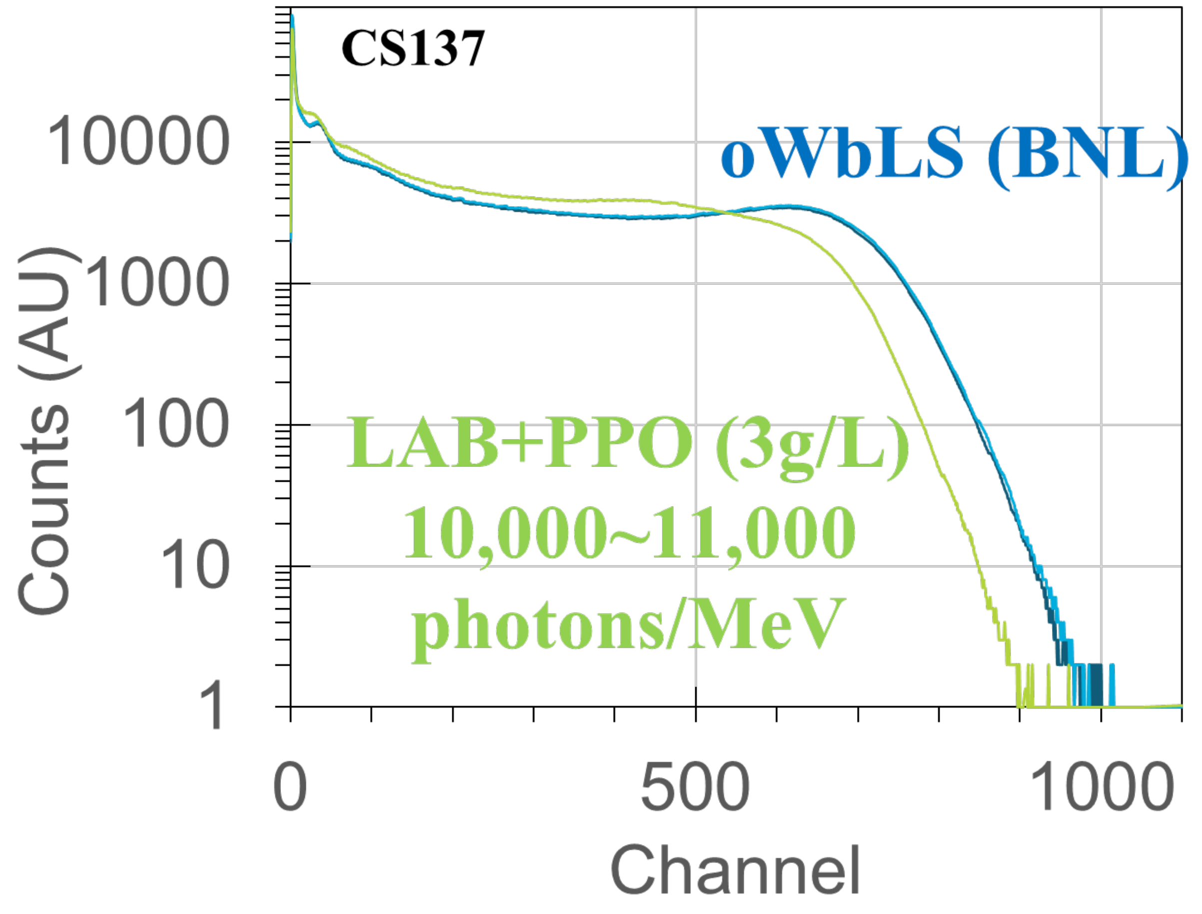
Andrew Wilhelm
U. Michigan

An opaque WbLS (oil-like) with high light-yield for self-imaging







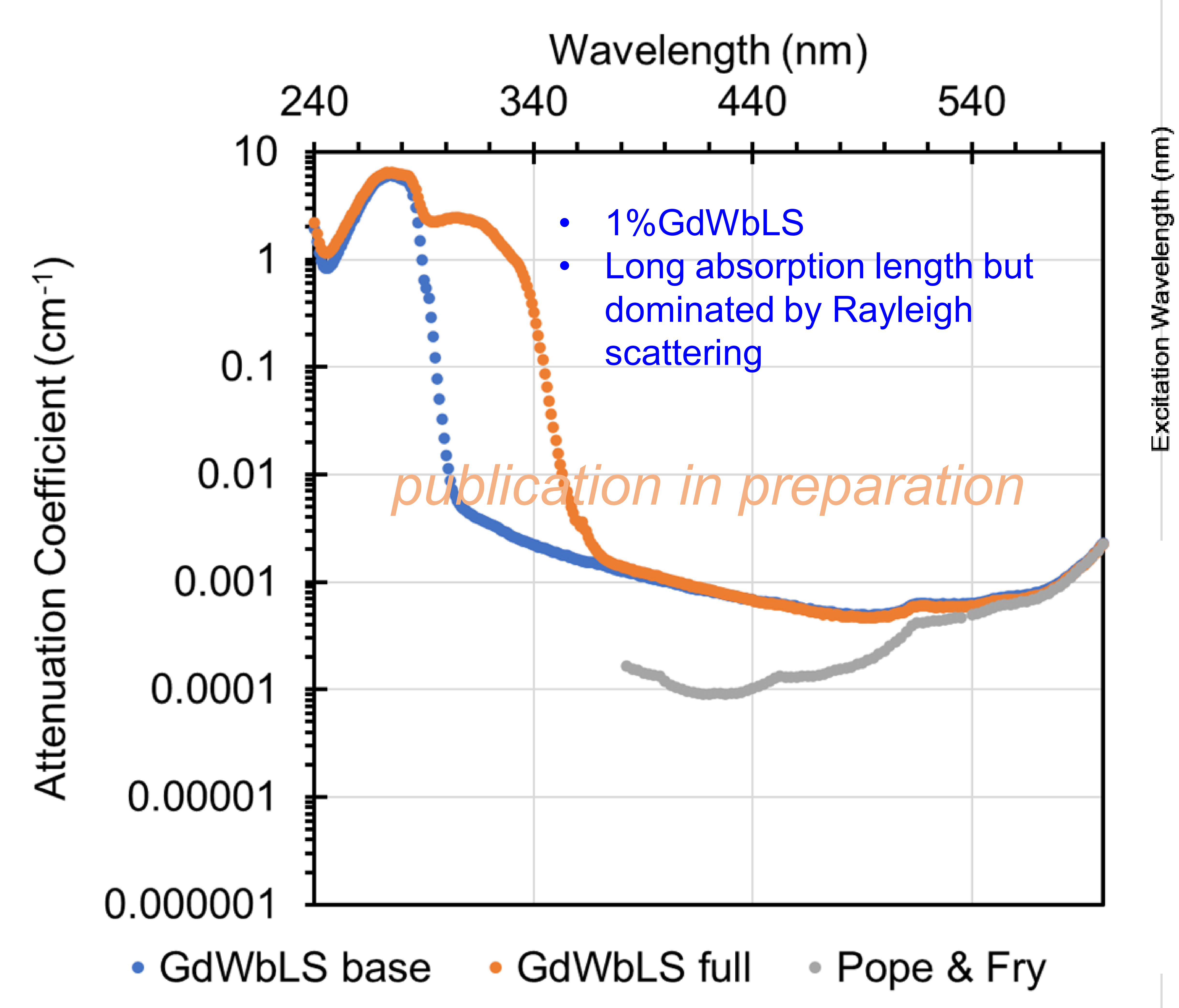


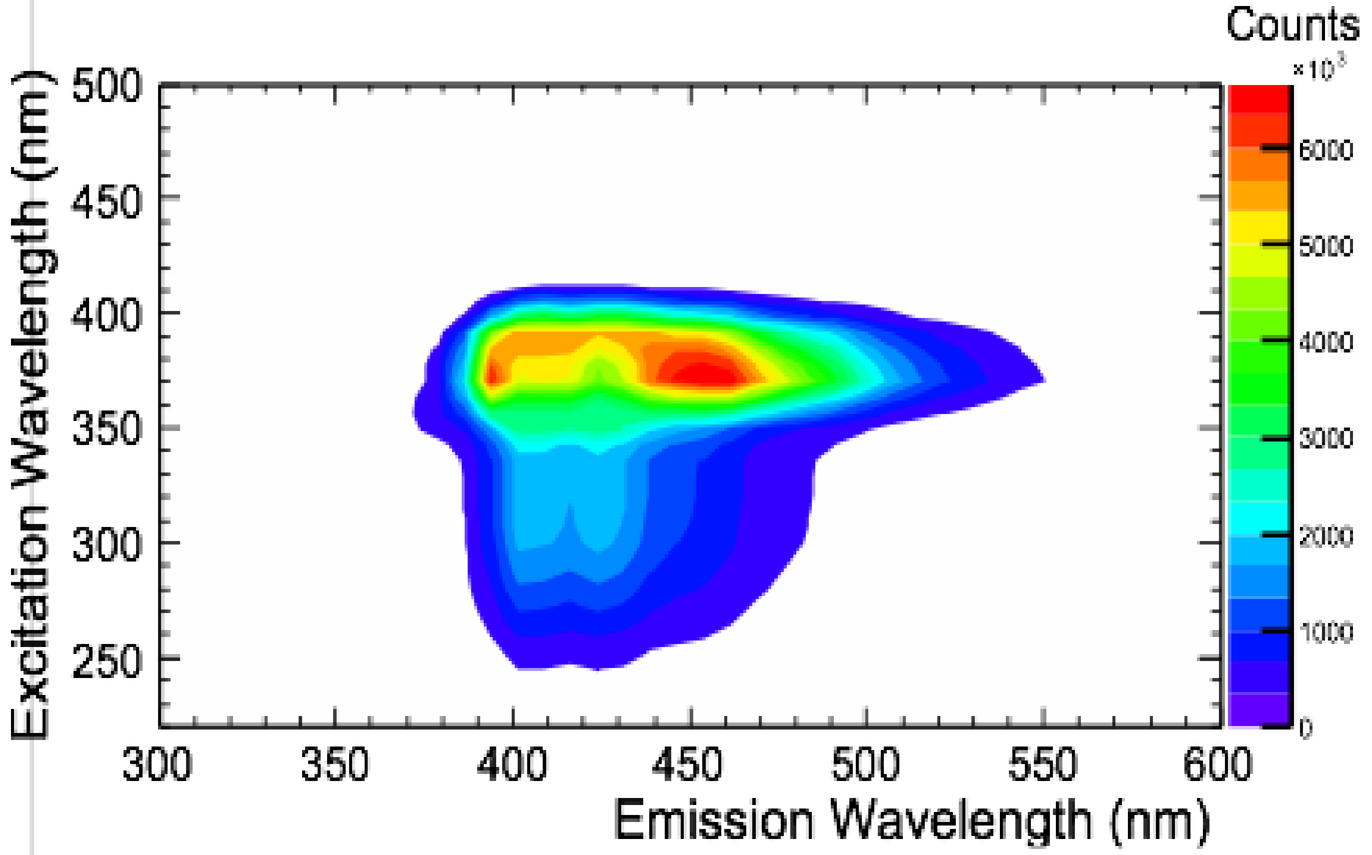
- *developed for near surface deployment within LiquidO/CLOUD consortium (UM, PSU, and BNL)*
- *Capability of loading metallic ions demonstrated at a few % (w) level*

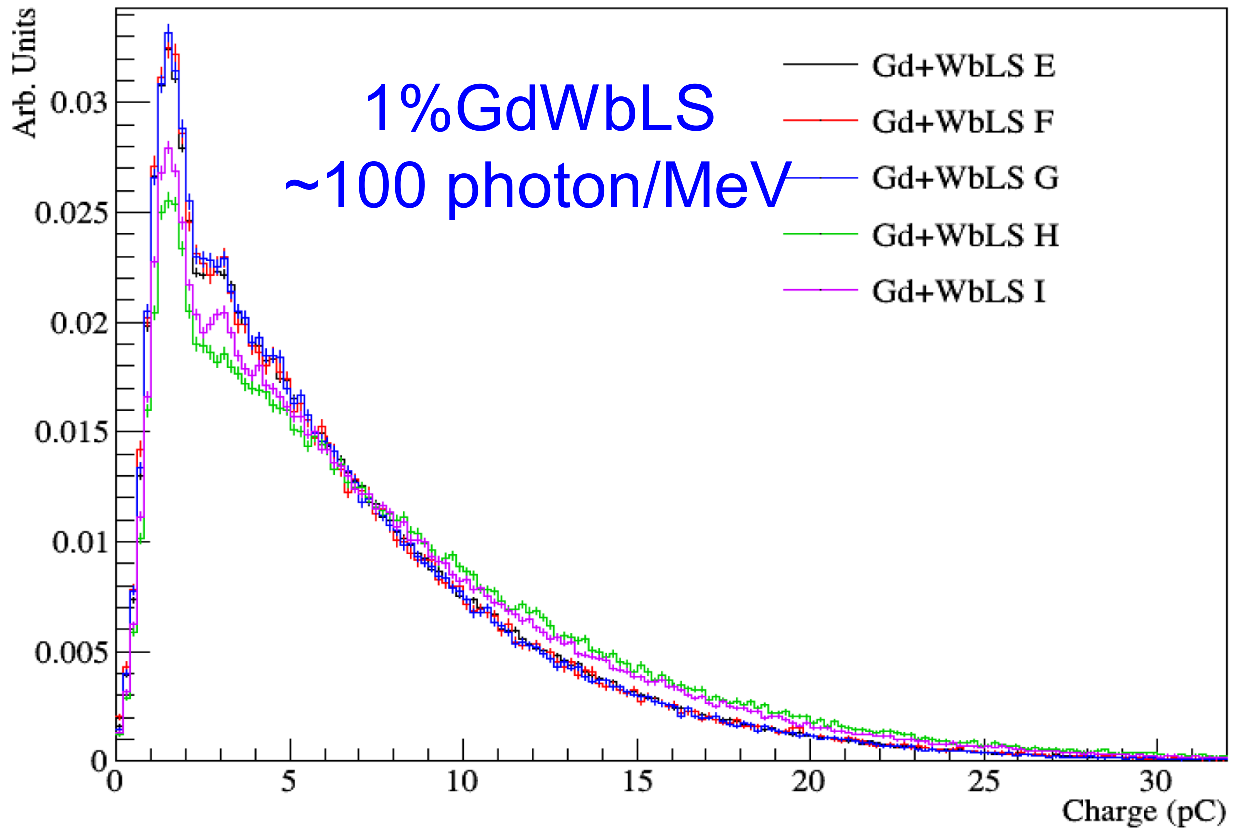
A large-scale (10s of tons) neutrino detector

cost vs. safety vs. performance

- ✓ *Isotope-loading (Gd, Li tested)*
- ✓ *Tunable excitation and emission range and timing structure (fast vs. slow)*
- ✓ *Well-characterized at different scales*



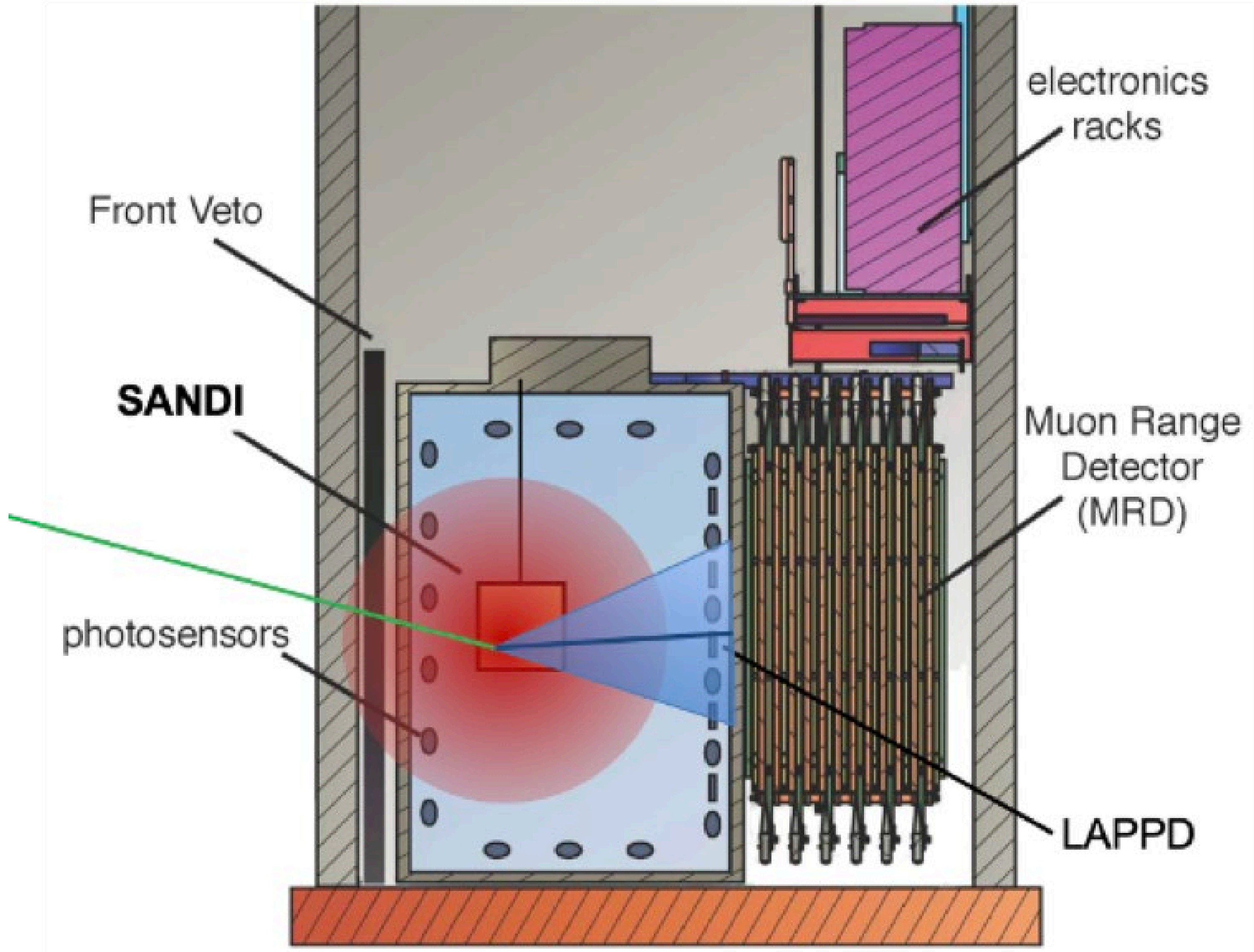


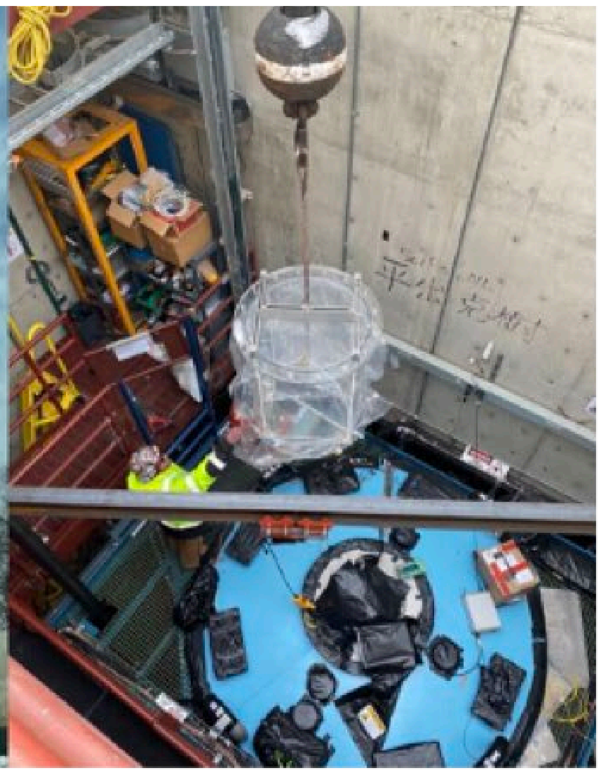


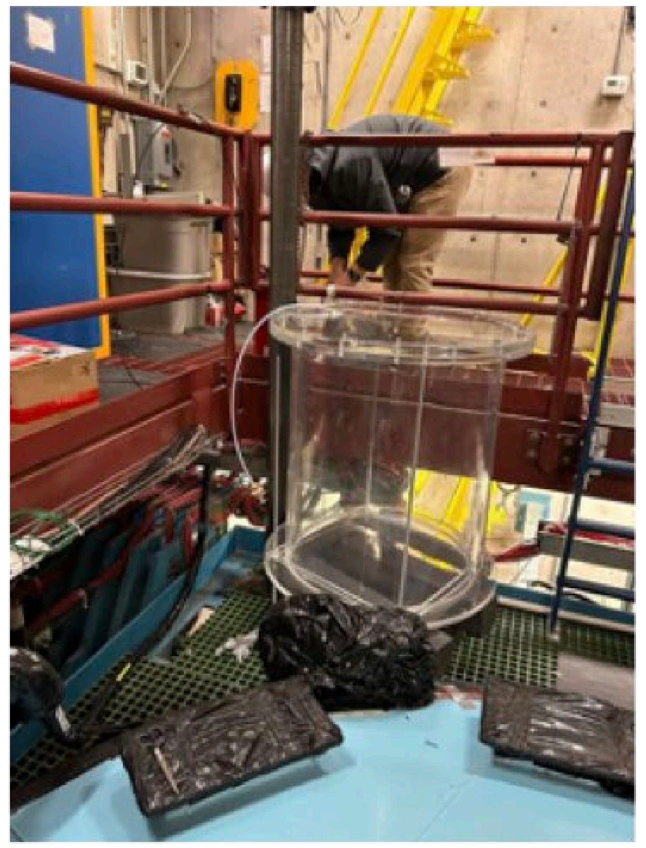
Deployed & planning demonstrators: ANNIE, Eos, BNL1T&30T and BUTTON

WbLS deployment in ANNIE (2023)

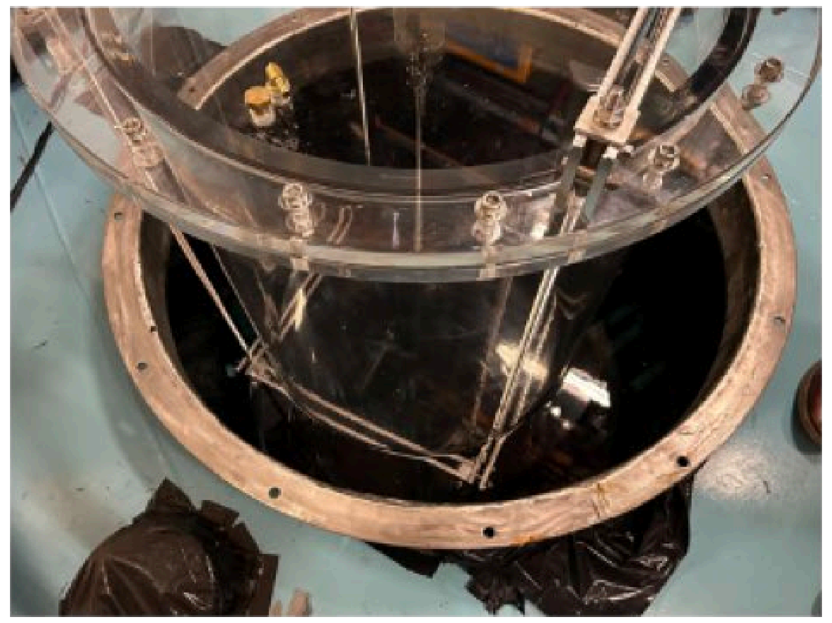
- deployed SANDI acrylic vessel filled with 365 kg of WbLS
- WbLS produced by BNL: “thin“, i.e. 1% organics → expect scintillation light output cf. Cherenkov yield
- took data for two months → few 1000 events





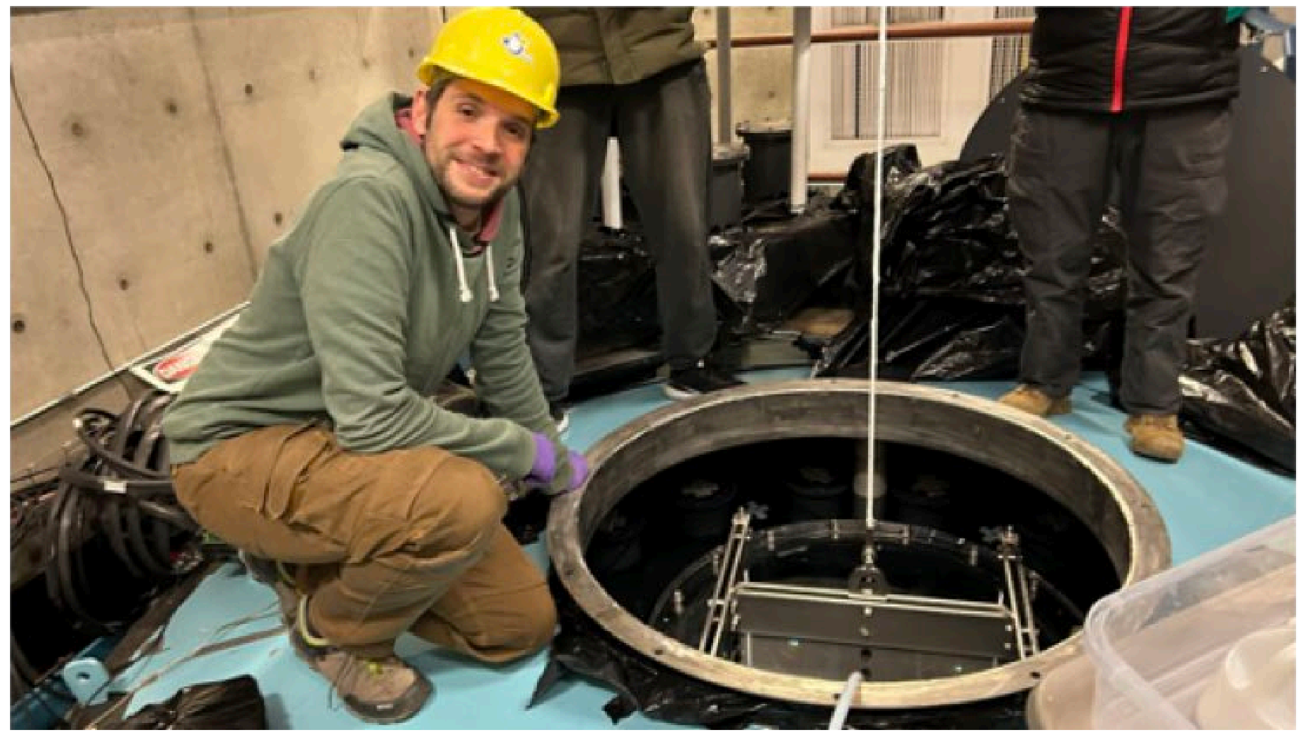


removed in May after taking 2 months worth of beam data

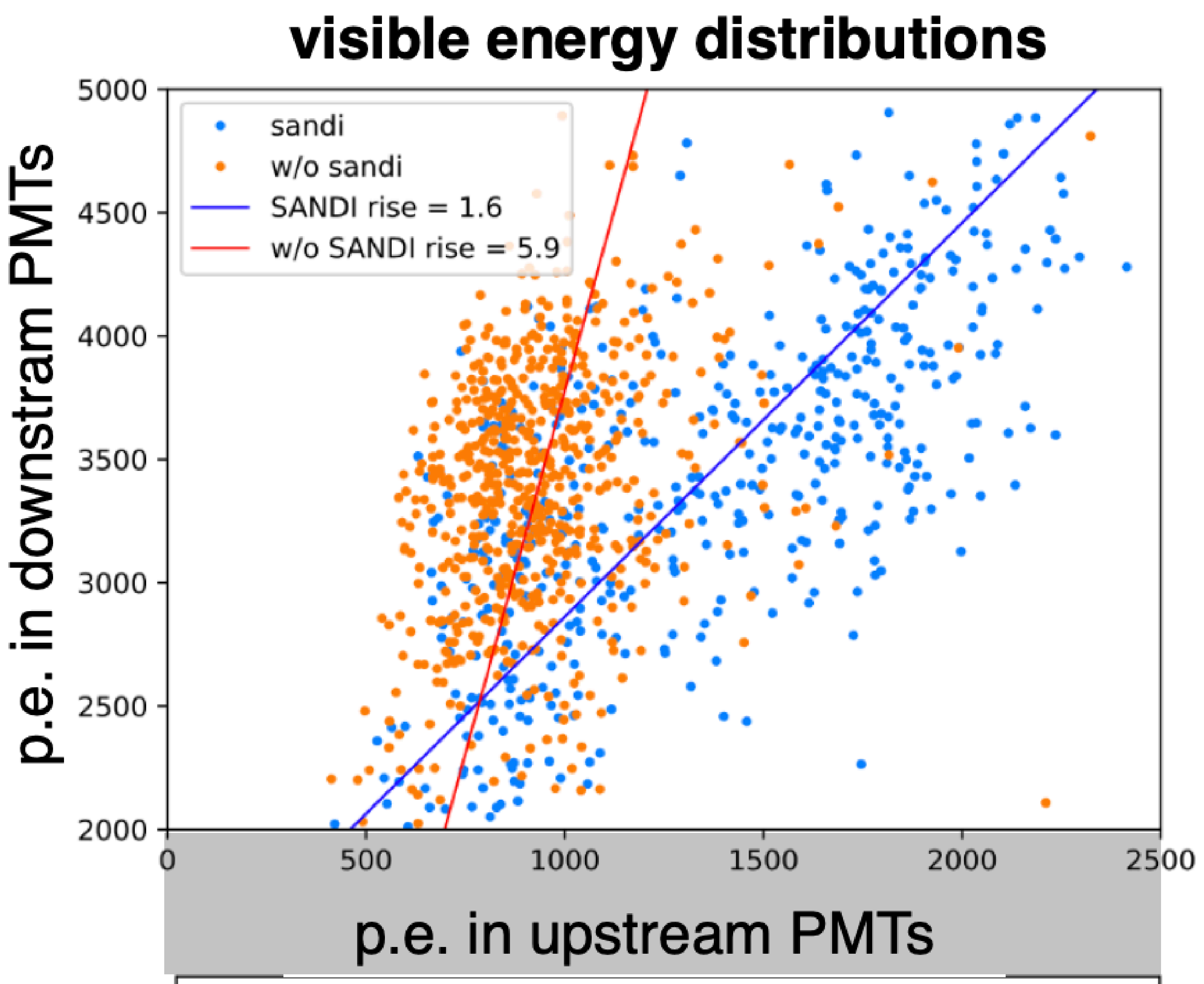


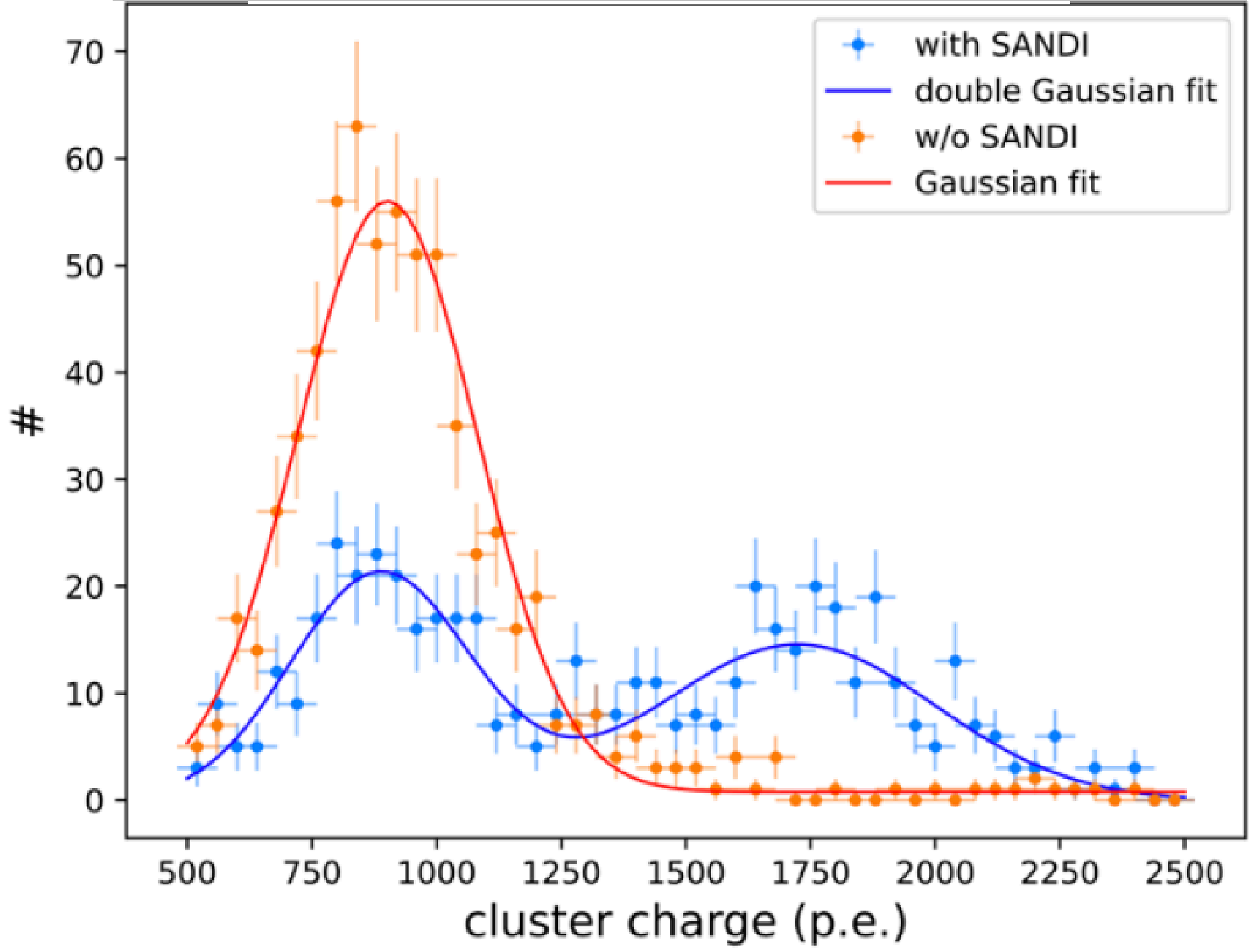
SANDI vessel & support frame inserted in Jan

Insertion of vessel inside ANNIE tank in March



First Neutrinos Detected with WbLS

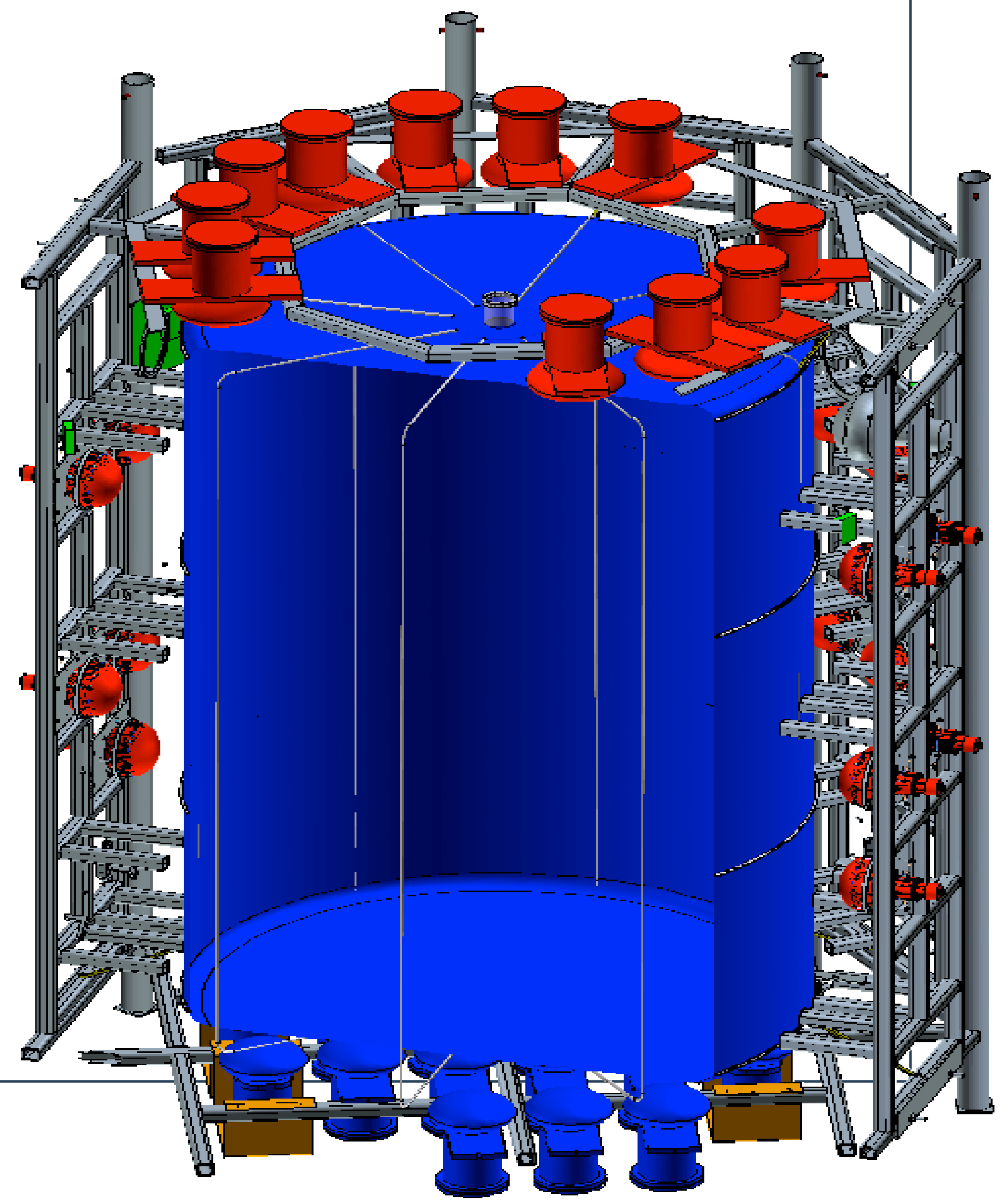




- comparison of pure water (orange) and SANDI WbLS data (blue)
- additional population of SANDI events with higher light output
- best visible in upstream (“back“) PMTs that see mostly scintillation photons
- effective scintillation light ouput ~80% of Cherenkov (from Michel electrons)

What‘s next?

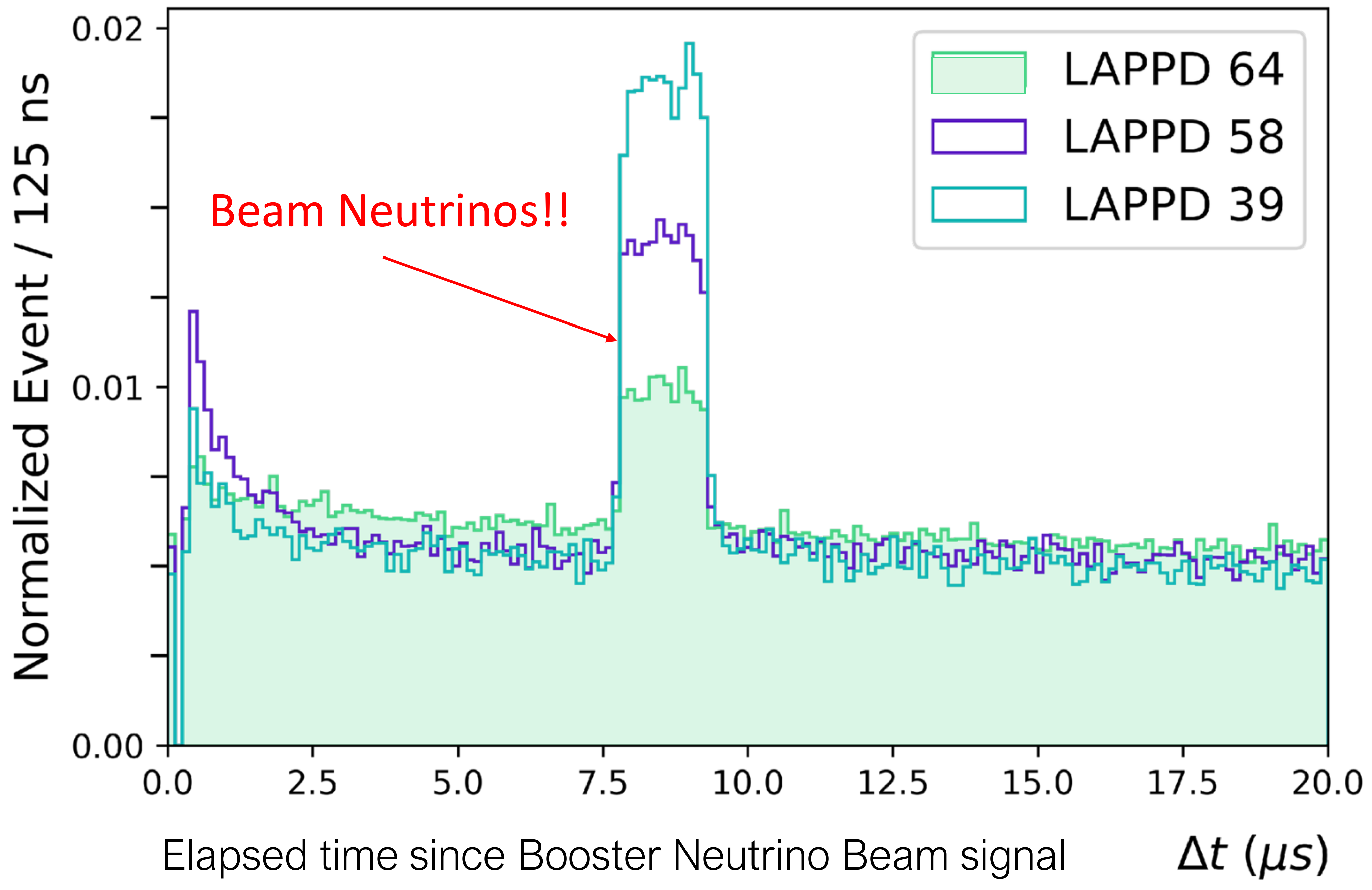
- 2nd SANDI deployment with Gd-loaded WbLS (end of this year)
- prepare to deploy full-volume (8t WbLS) nylon vessel
  → full event reco
  → hadronic recoils
  → neutron ranging

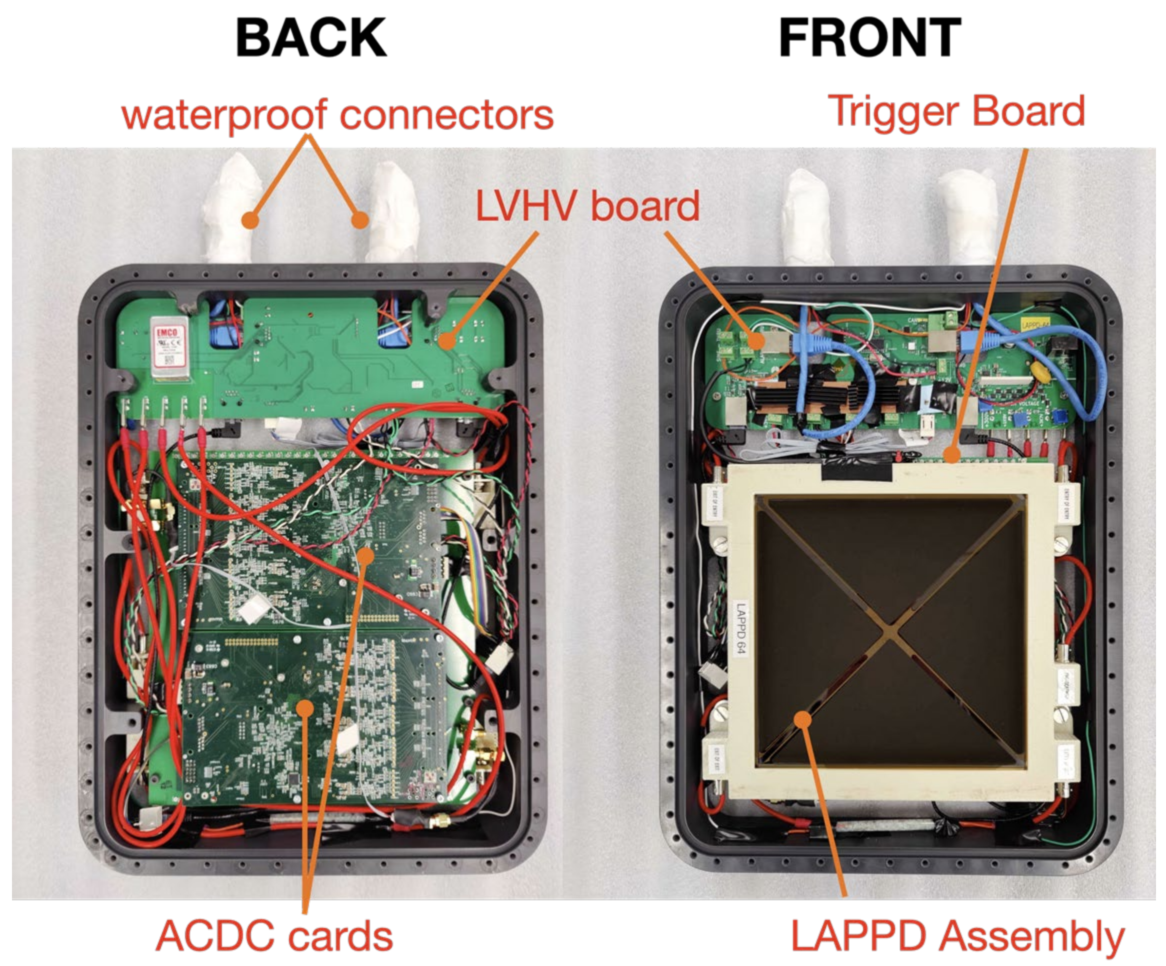


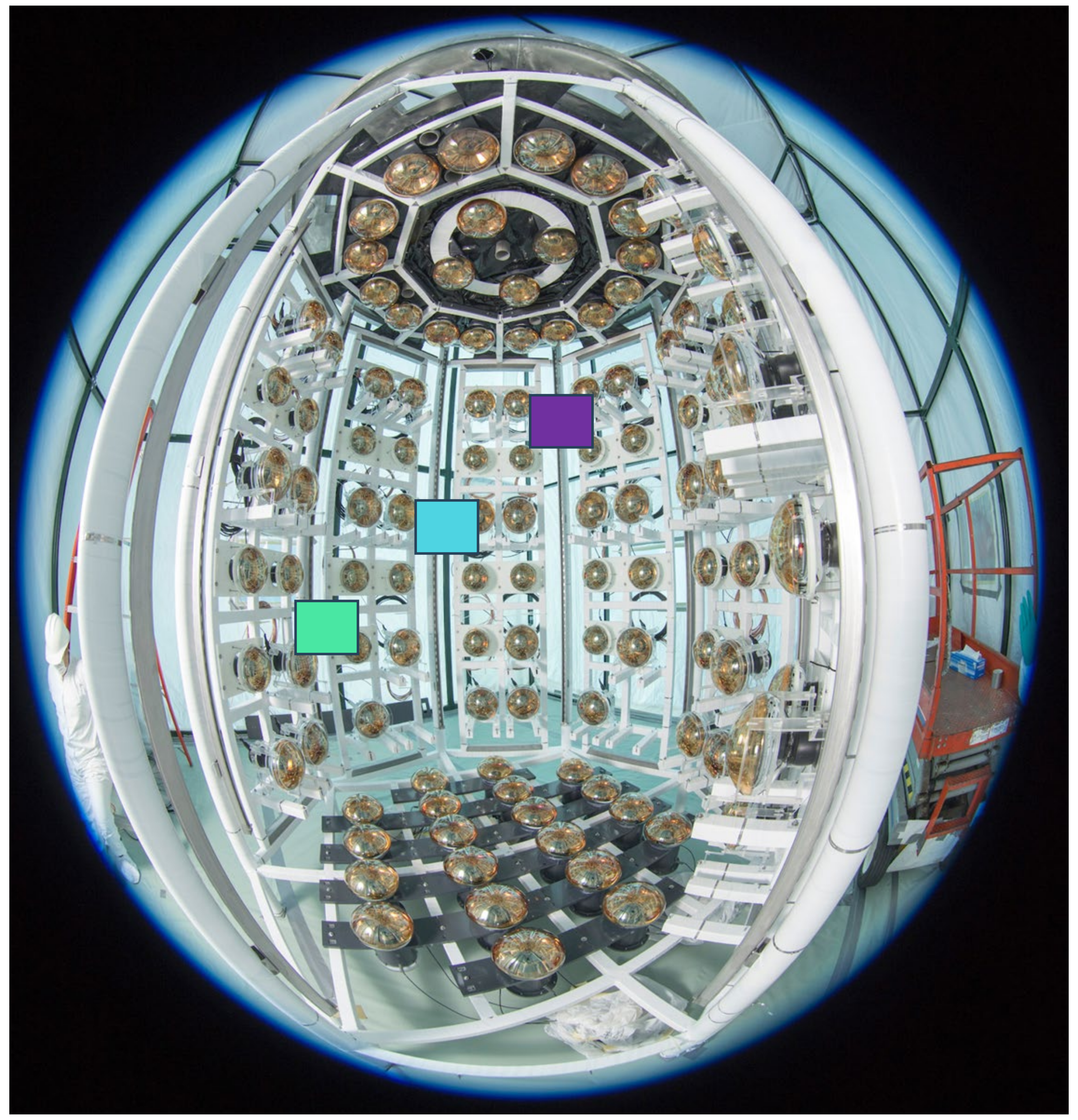
JINST 19 (2024) 05, P05070 [arXiv:2312.09335] → Poster 518

First Neutrinos Detected with LAPPDs at ANNIE

- ANNIE sees beam neutrinos with 3 Large Area Picosecond Photodetectors (LAPPDs) with custom readout electronics and housing
    - LAPPDs are commercially available (Incom, Inc.) microchannel plate-based photosensors







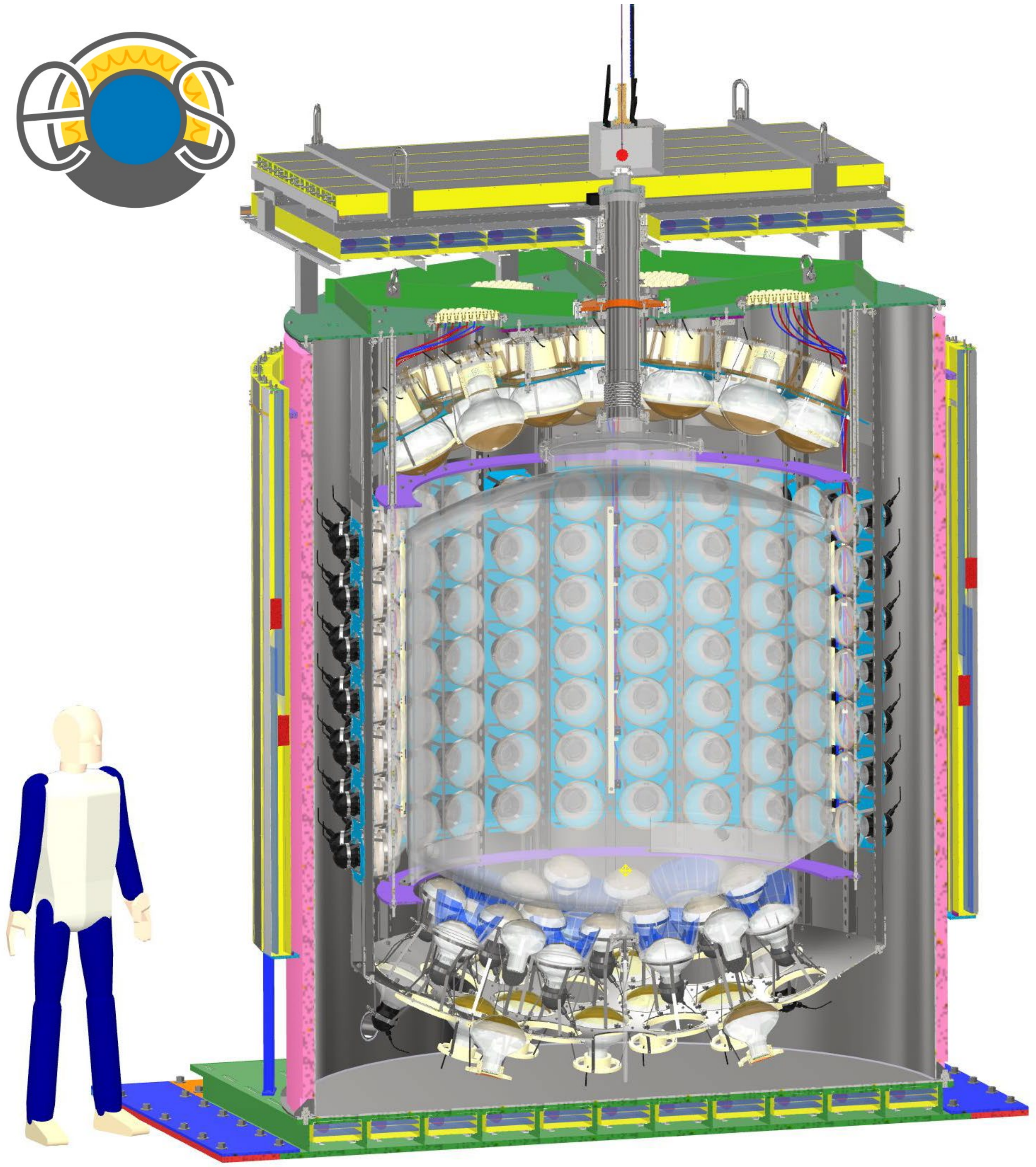
EOS: performance demonstrator

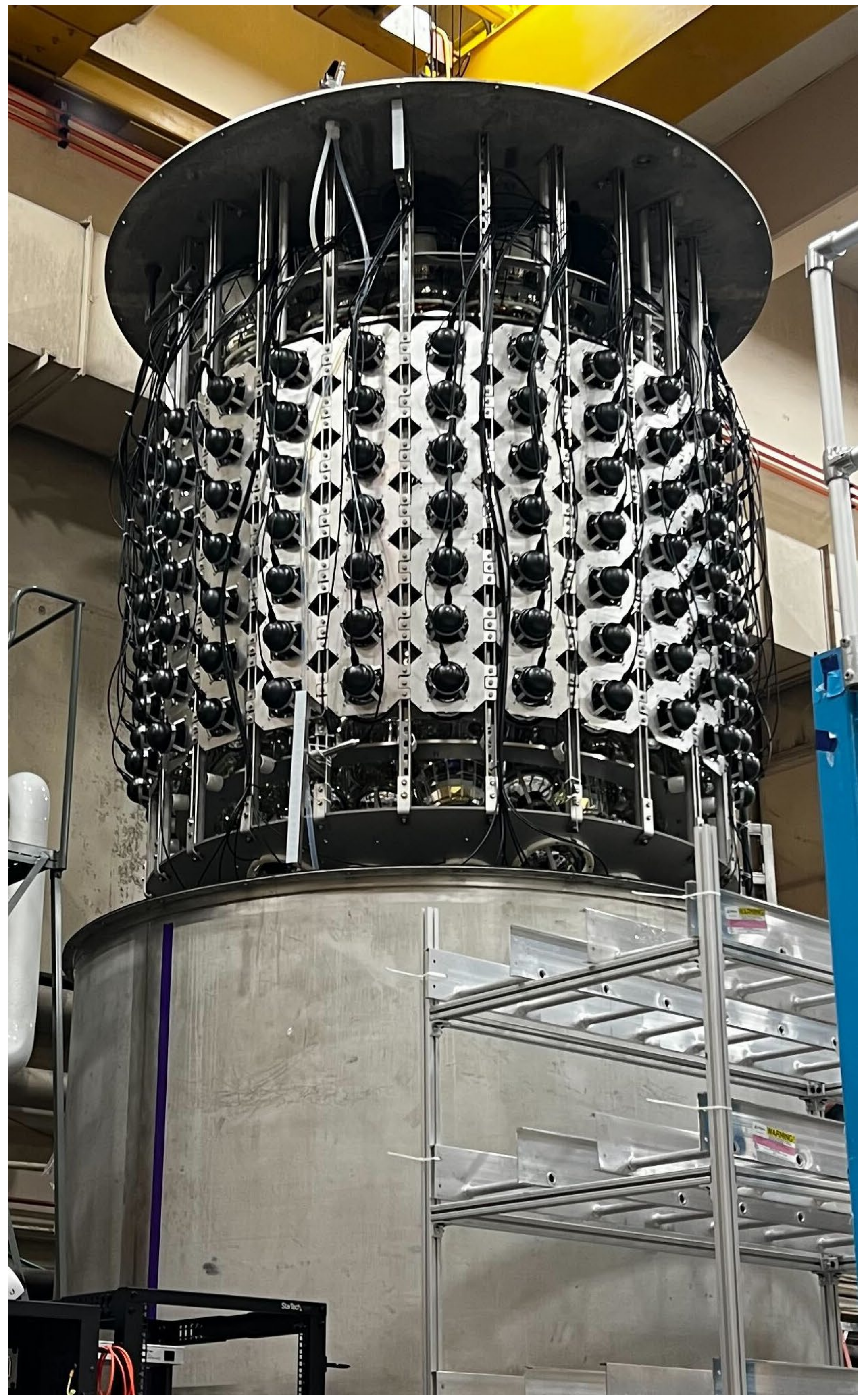
Approach: *design, construct and operate an integrated testbed to demonstrate the performance of novel technology*

Novelty / technology:

- Novel scintillating liquids — water-based scintillator, slow scintillator
- Ultra-fast photon detectors — novel 8” PMTs (200 8” PMTs: R14688-100, 900ps FWHM)
- “Quantum chromatic sorting”: dichroicons for spectrally sensitive photon detection
- AI/ML-based analysis techniques
- Deployable sources for studies of vertex, energy, direction reconstruction & PID
- 36-fiber 4-wavelength picosecond laser light injection system for optical and timing calibration

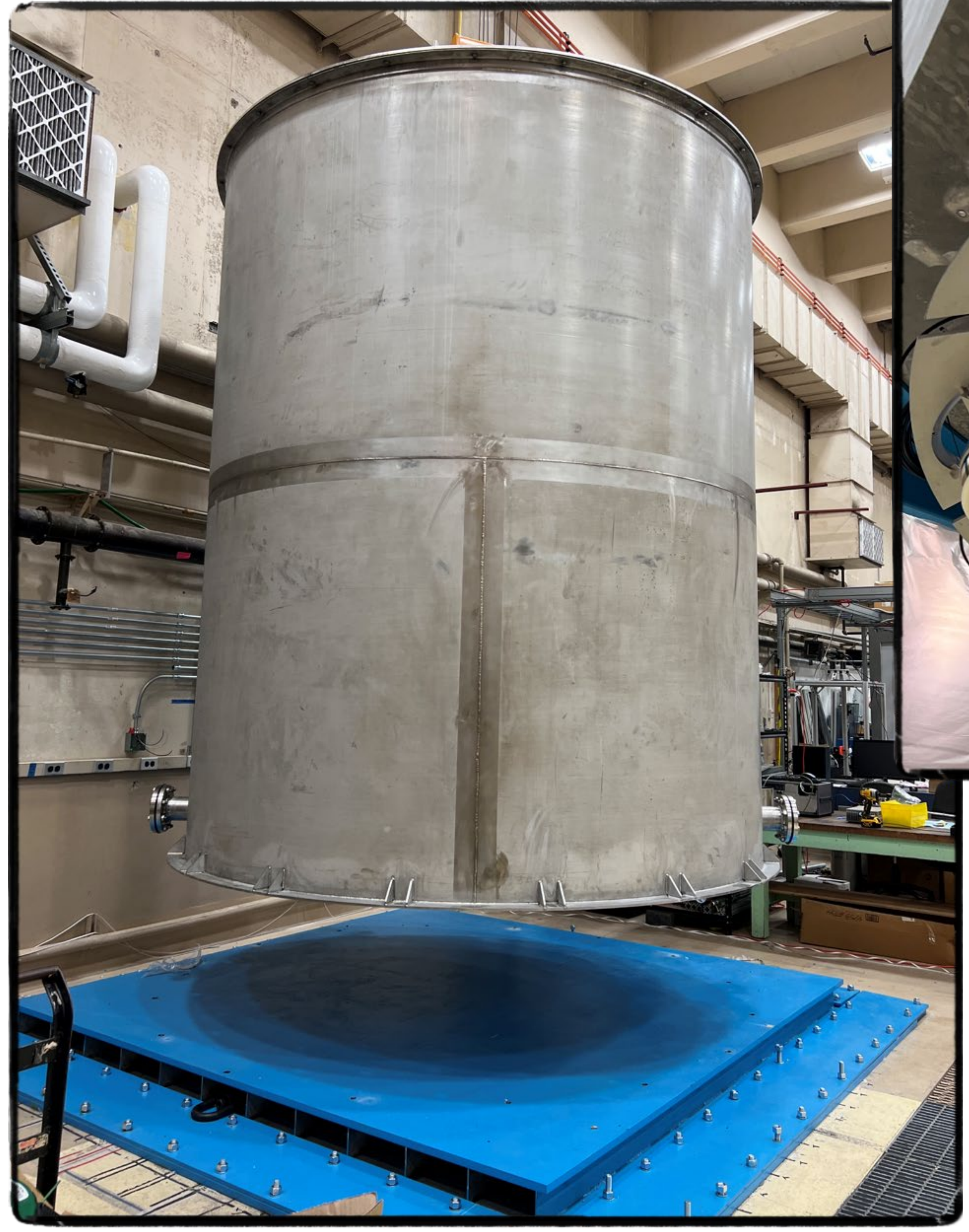
Designed for flexible upgrade paths & to be redeployed at a neutrino source → demonstrate viability of future applications

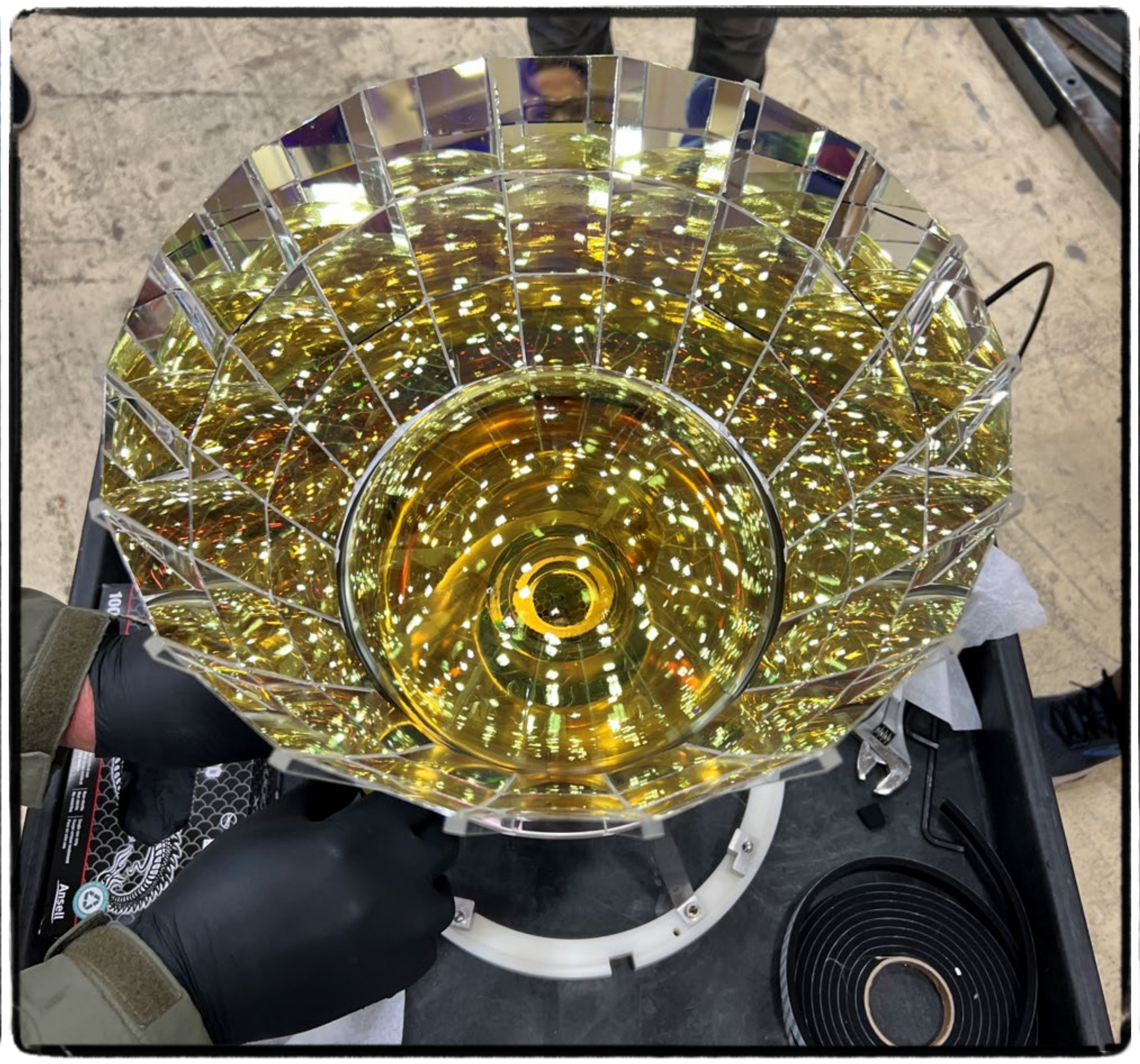
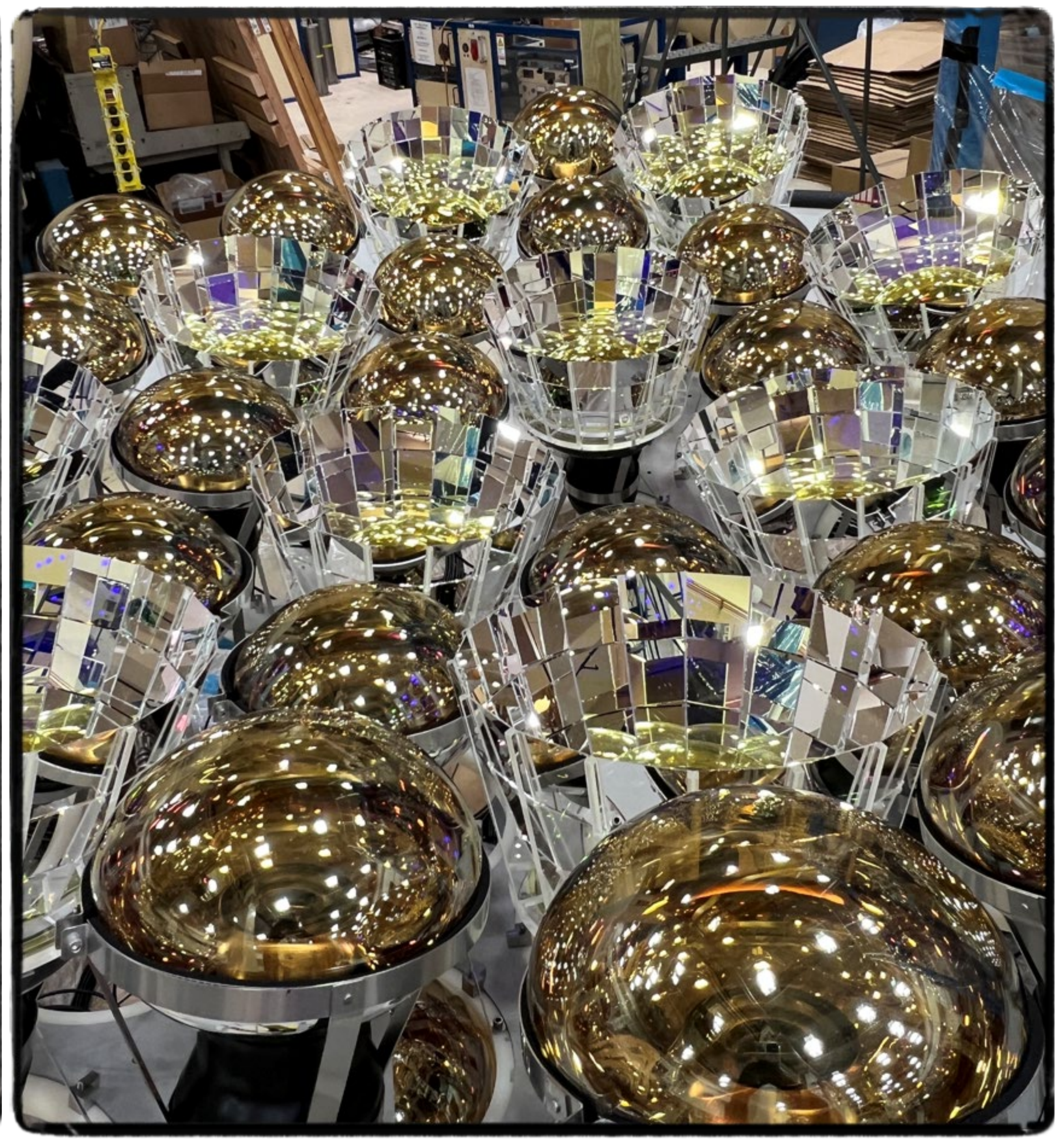
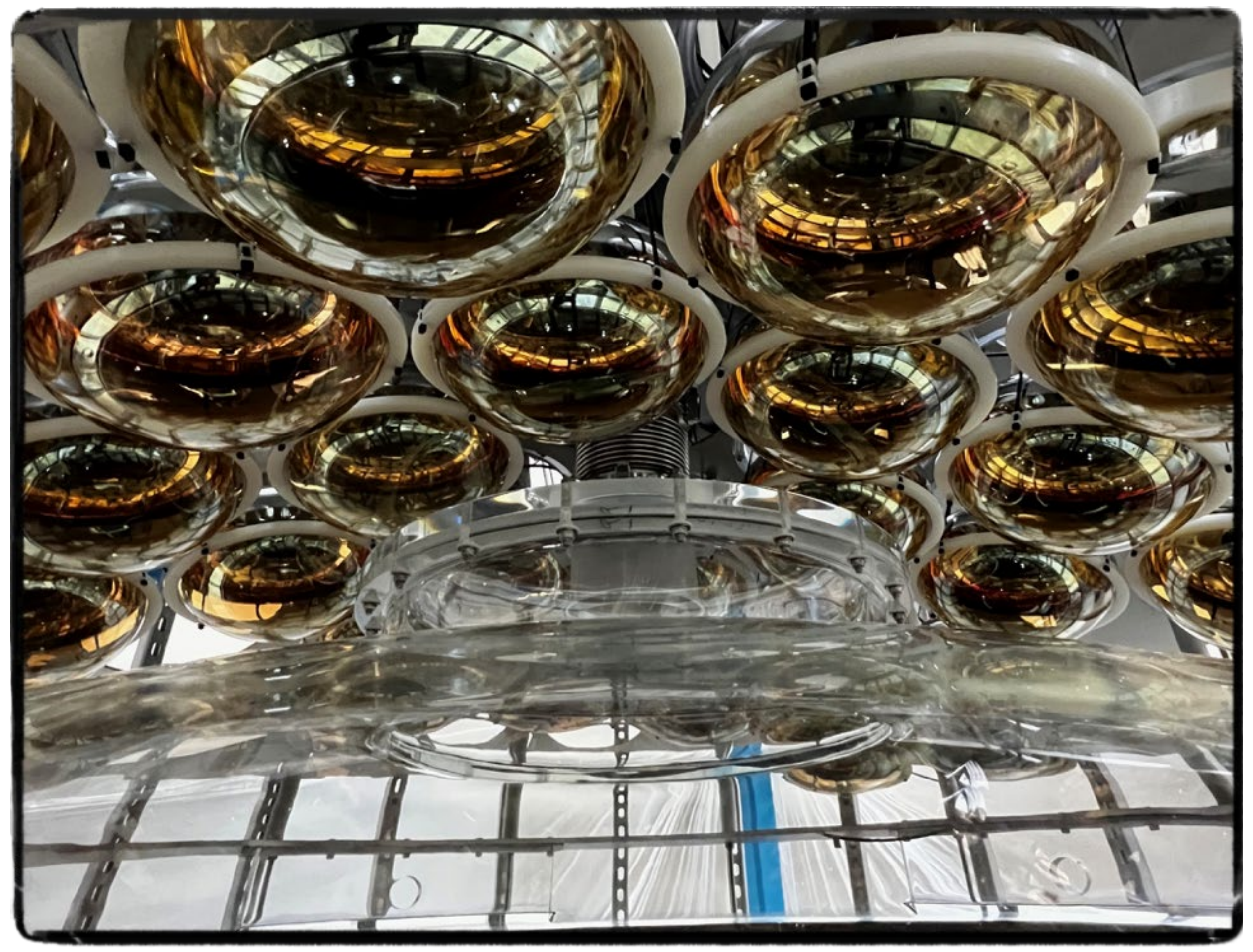
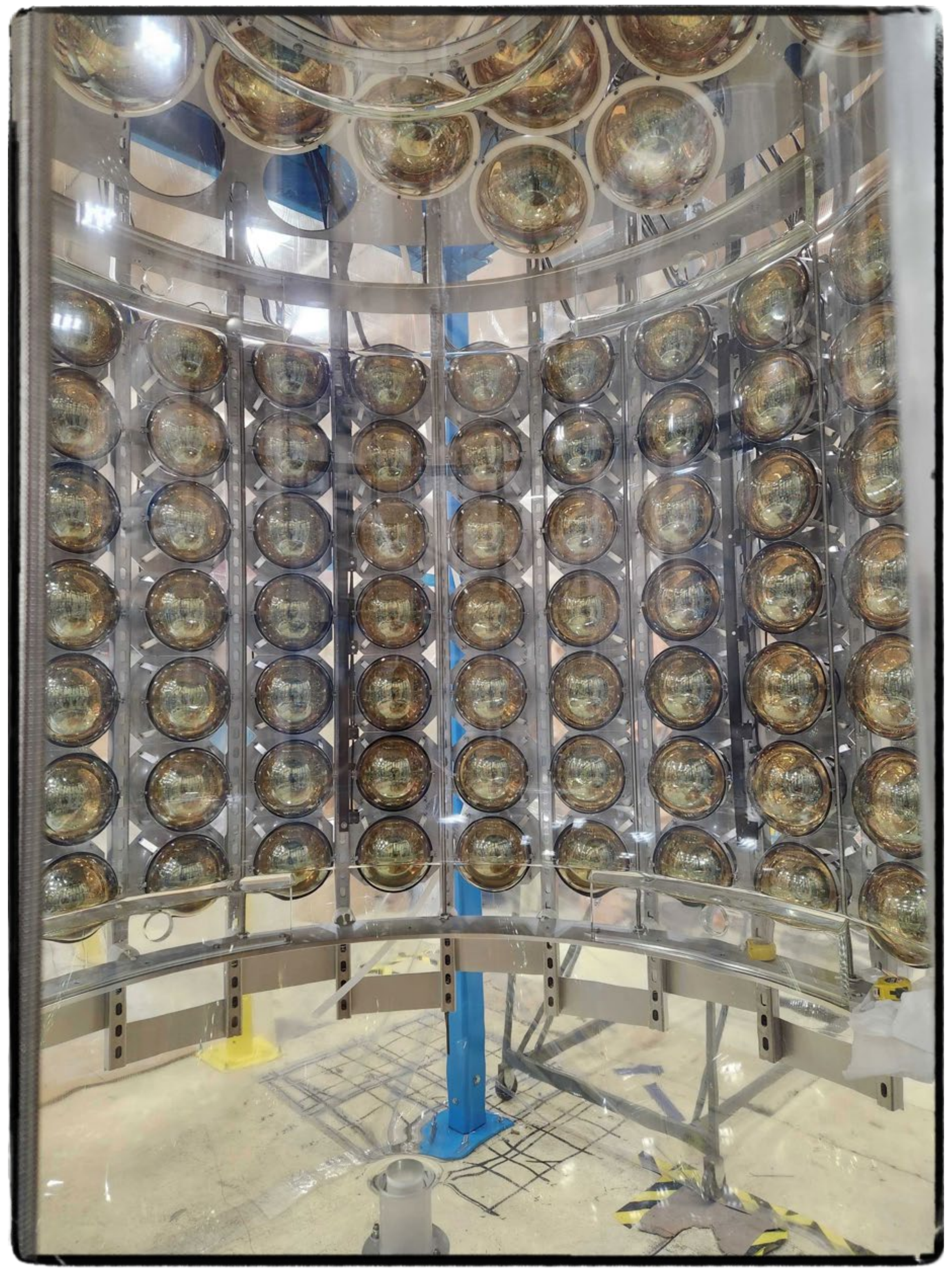


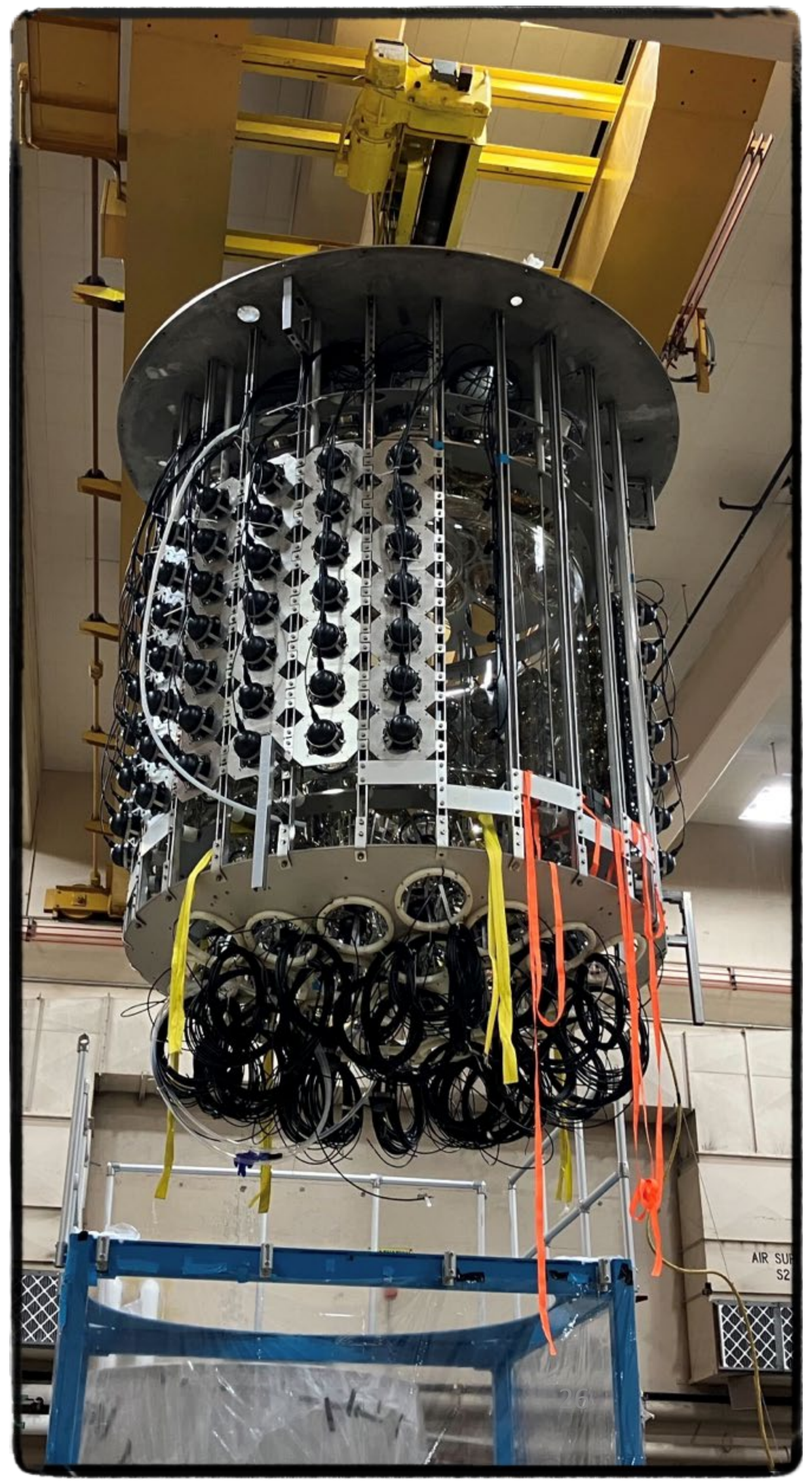


- Sited on UC Berkeley campus, in Nuclear Engineering (NE) department

EOS concept paper published: *JINST 18 P02009 (2023), https://doi.org/10.1088/1748-0221/18/02/P02009*





Eos status

- Detector performance currently being evaluated with water target
- Plan to inject first WbLS this summer
- Hope to fully explore WbLS phase space, and pure LS, in following years
- Evaluate energy / vertex / direction reconstruction

USA

Germany

Portugal

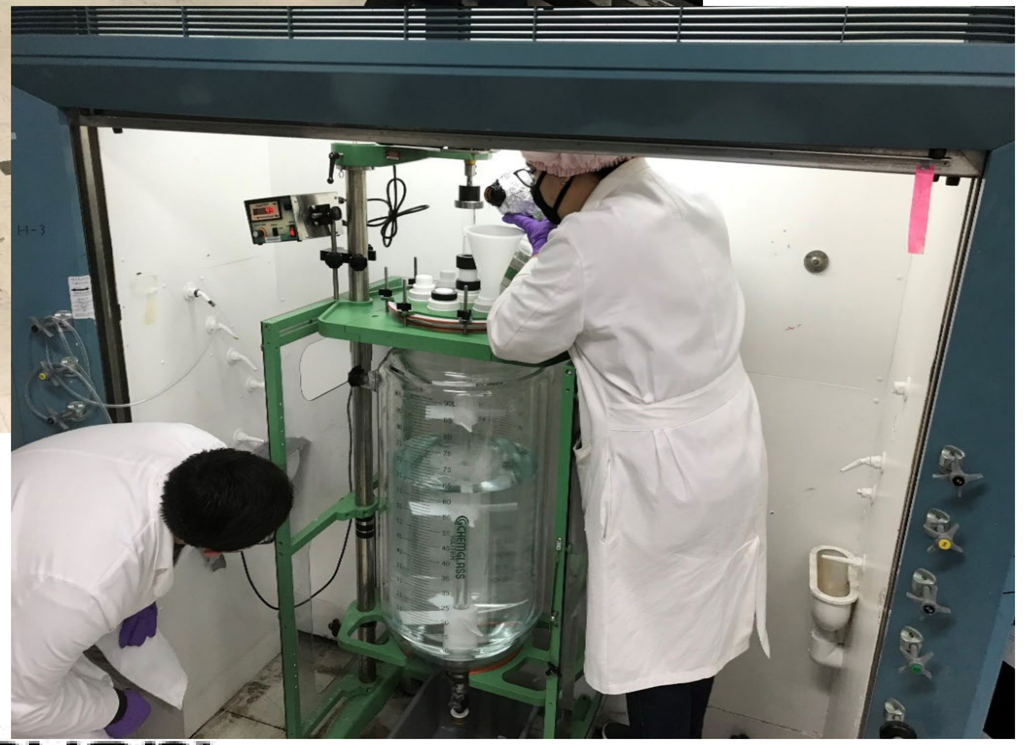
Finland

Turkey

Canada

Scale-up Program

available to support collaborative research



- **1-ton Testbed** to develop deployment scheme and measure intrinsic property (universitas and other labs)
- **30-ton demonstrator** to prove the feasibility of kiloton-scale hybrid optical detectors (universitas and other labs)
- **ton-scale production facility** capable of scale-up (Wb)LS fabrication in use for benchtop, prototype, and experiment.

Brookhaven National Laboratory

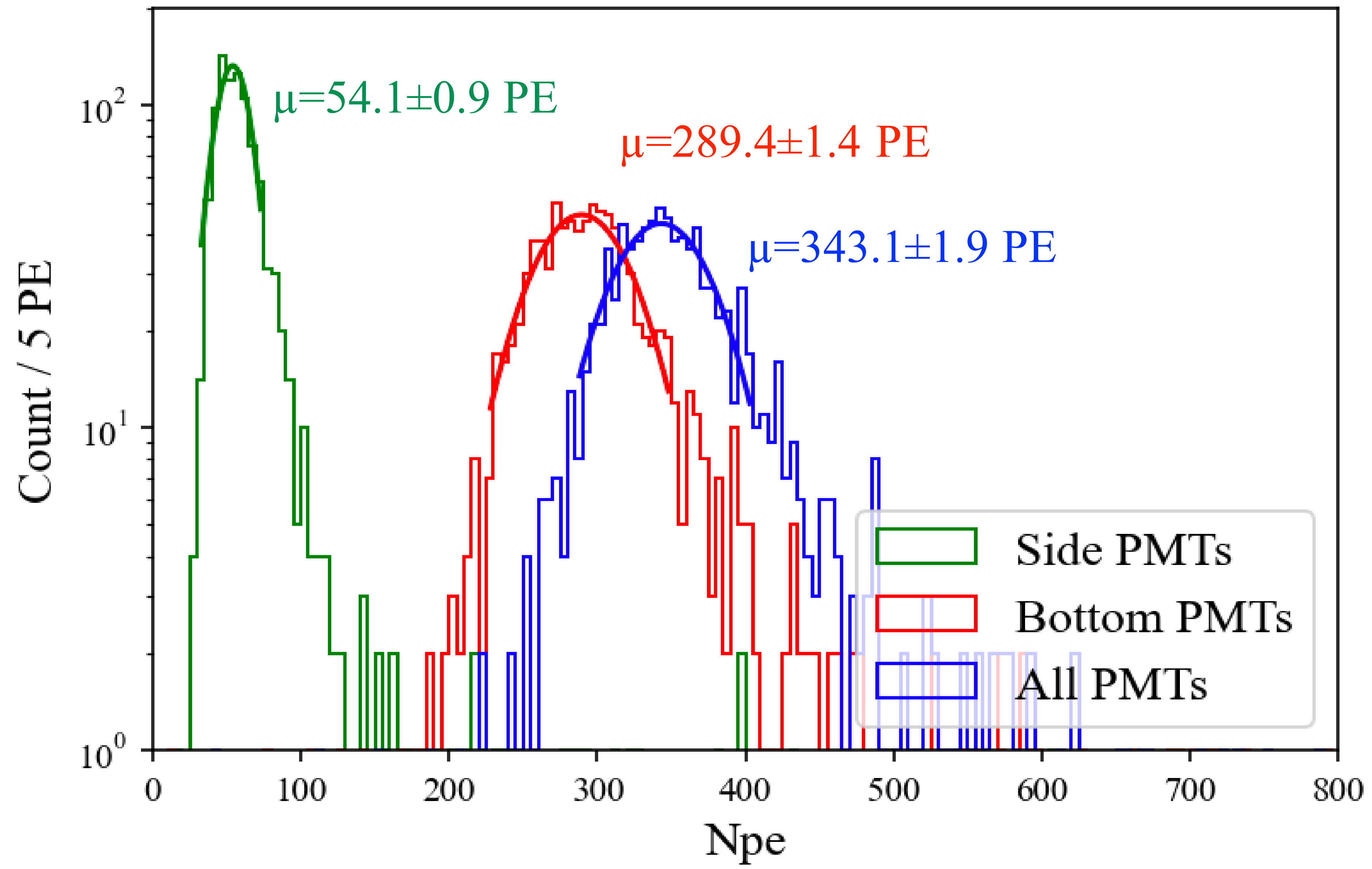
National Nuclear Security Administration


WbLS (1%) deployment in 1-ton Testbed (2023)
Image taken with UV light
(BNL twitter)

1-ton Testbed deployment
demonstrated mixing feasibility and stability

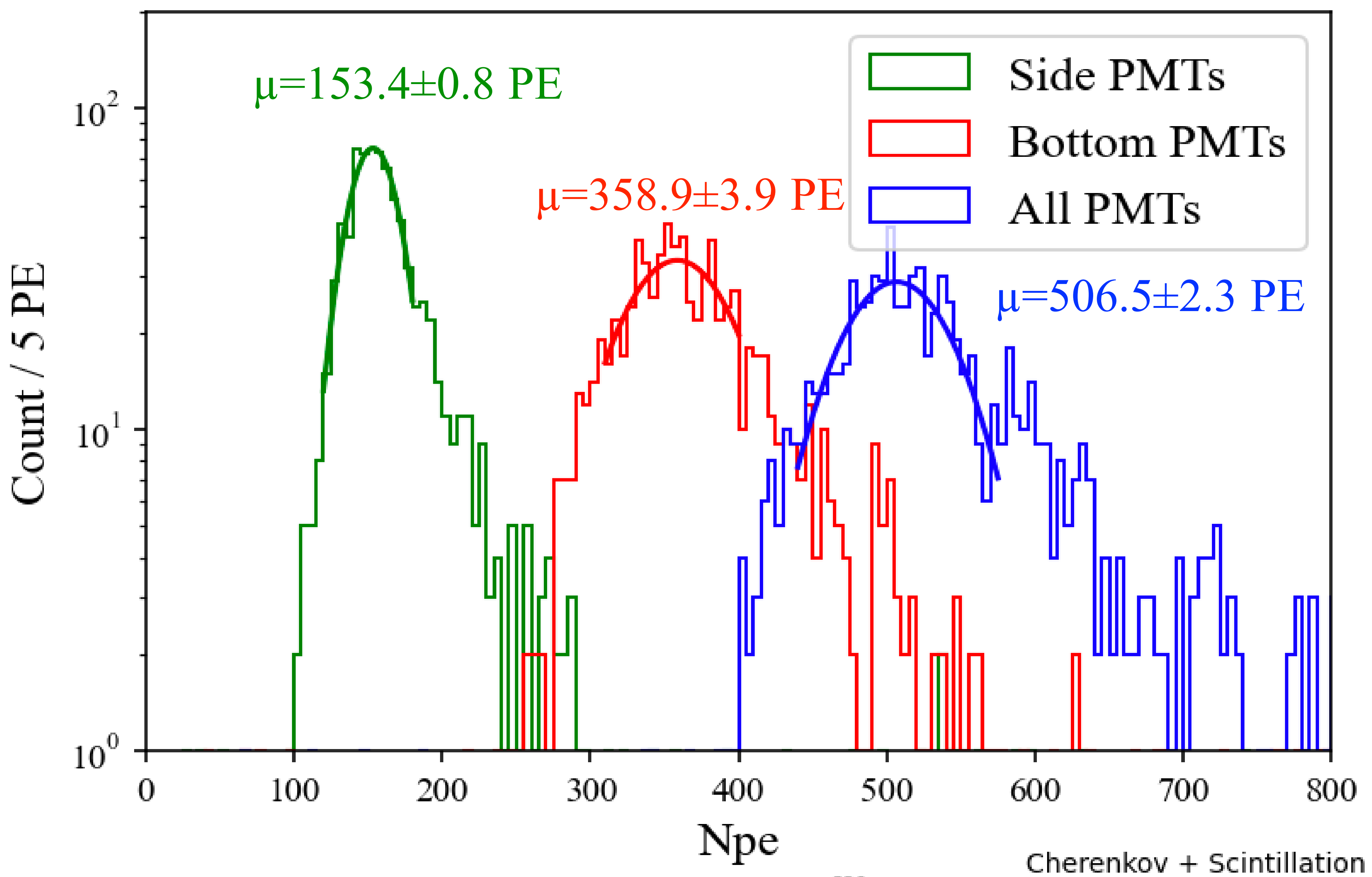
National Nuclear Security Administration

Tagged crossing muons in **water**

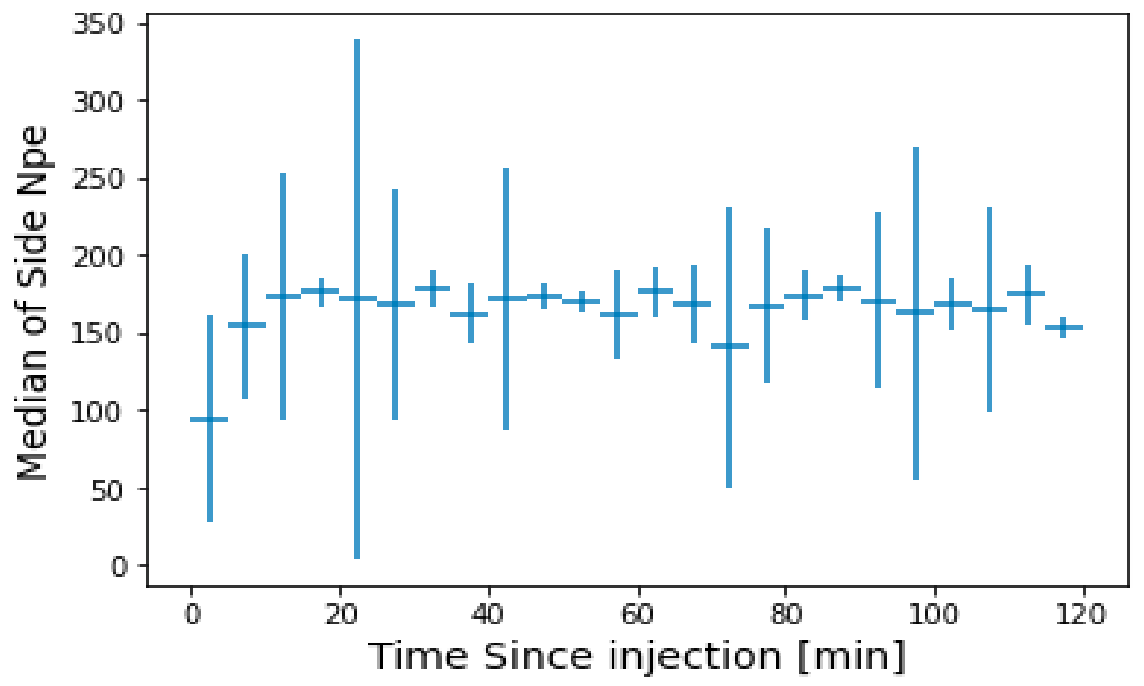


1% LS injection

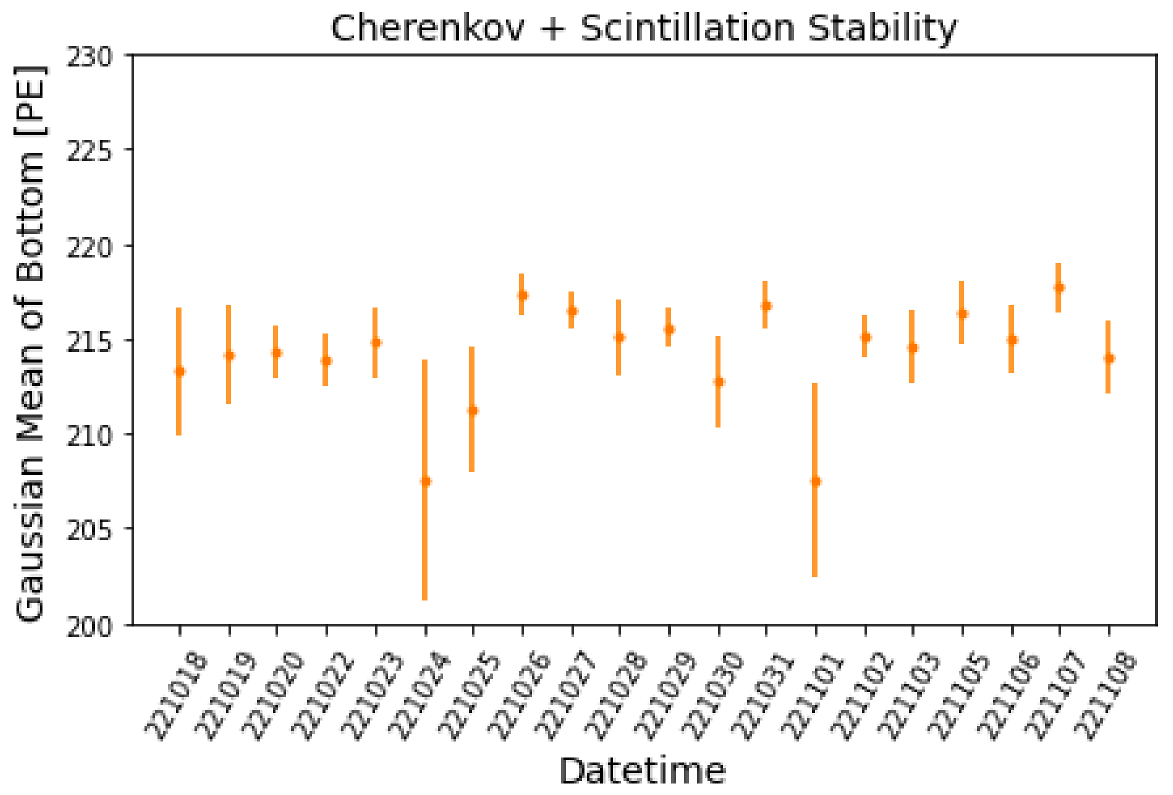
Tagged crossing muons in **WbLS (1%)**



- Much enhanced light production 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**



Homogeneity observed 20mins after injection



Stability of 1%WbLS observed

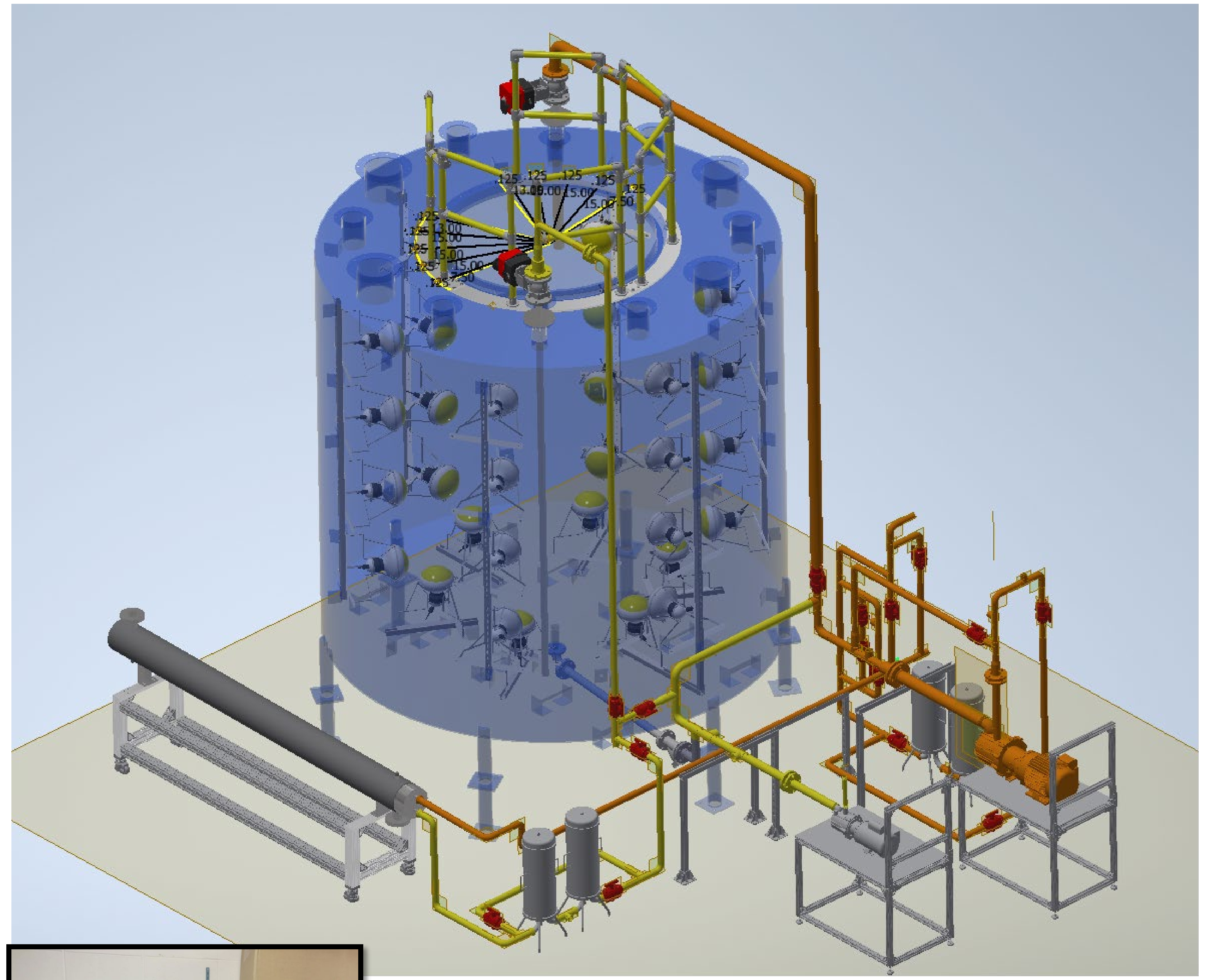
arXiv:2403.13231 (JINST)

Brookhaven National Laboratory

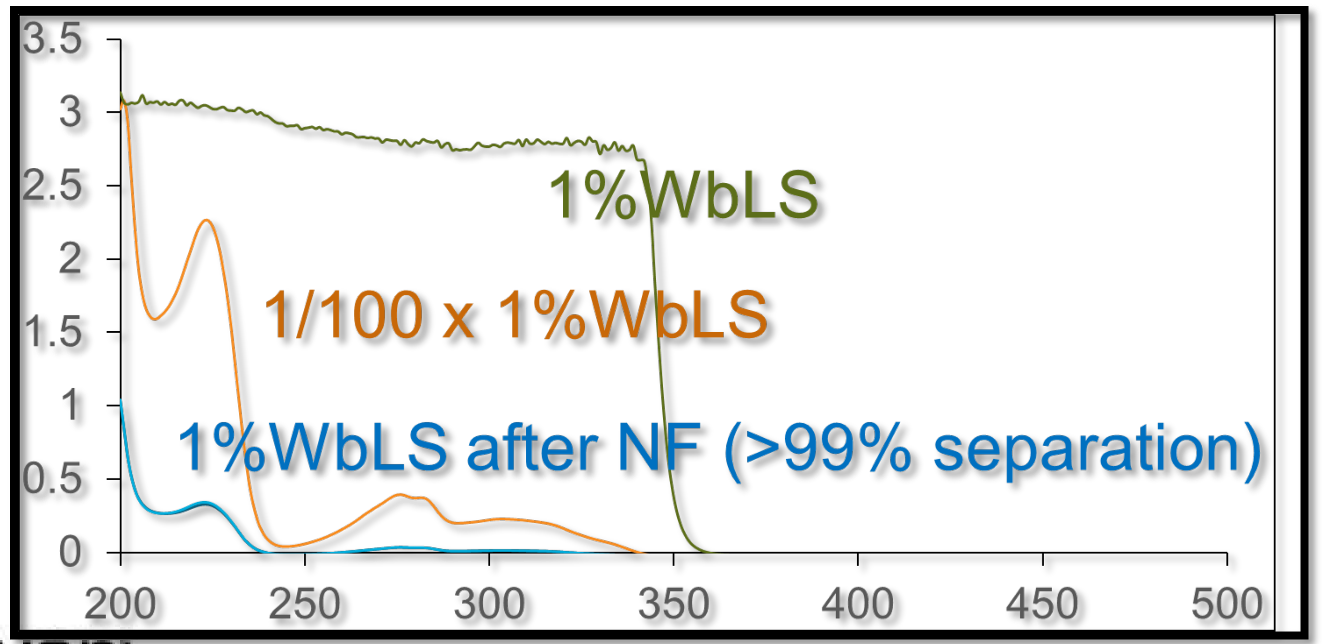
30-ton Demonstrator

to demonstrate scale-up stability and feasibility

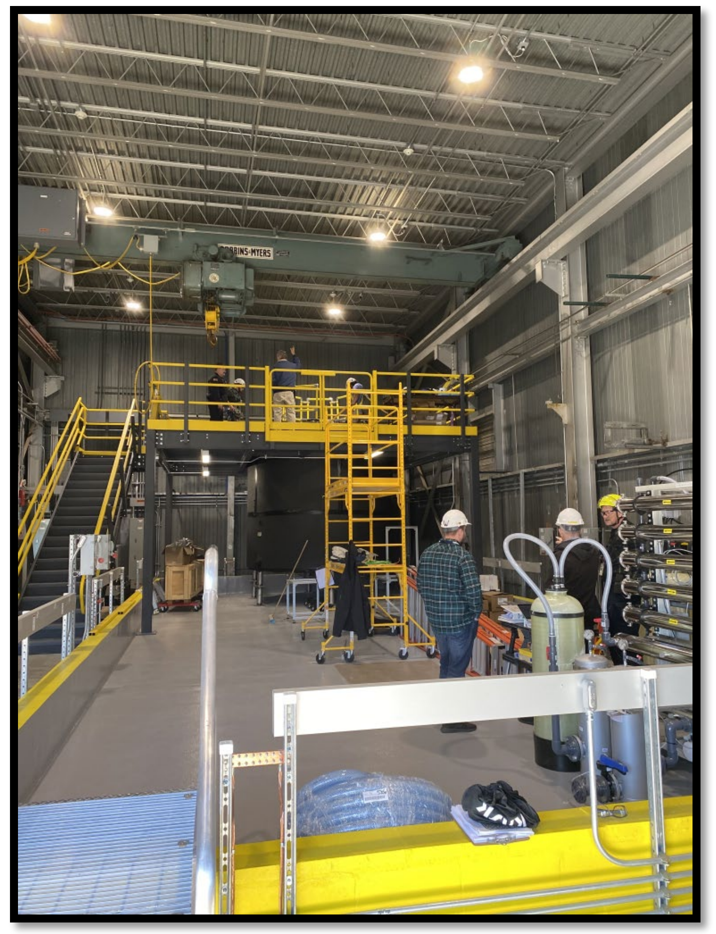
National Nuclear Security Administration



- *30-ton SS tank & 10” PMTs*
- *WbLS deployment (in-situ sequential mixing) system*
- *In-situ purification systems*
  - *Nanofiltration system*
  - *Gd-water system*
  - *Sequential Exchange Array (SEA)*
- *Slow control (PLC)*



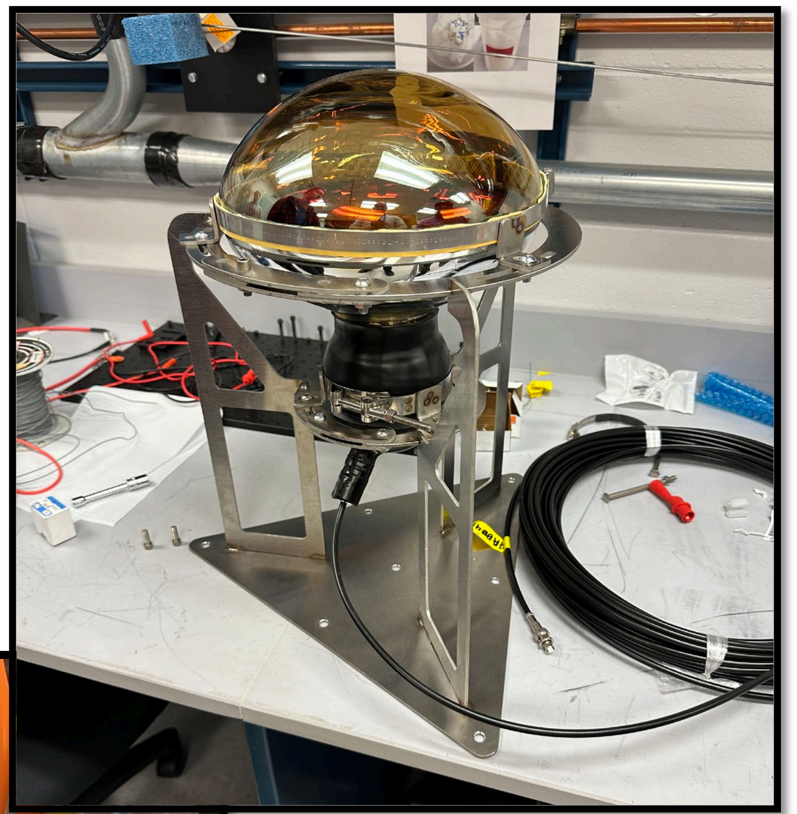
National Laboratory

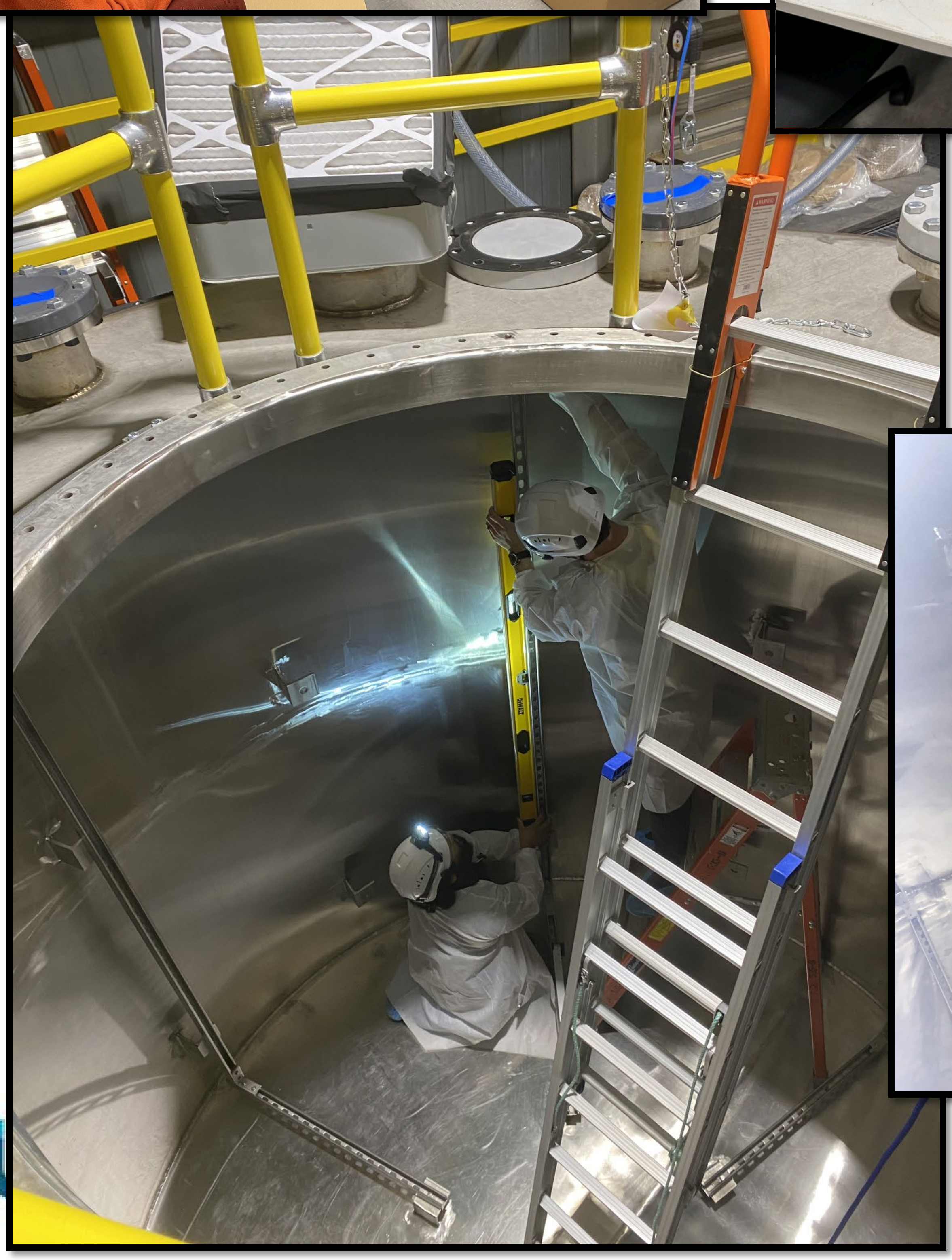


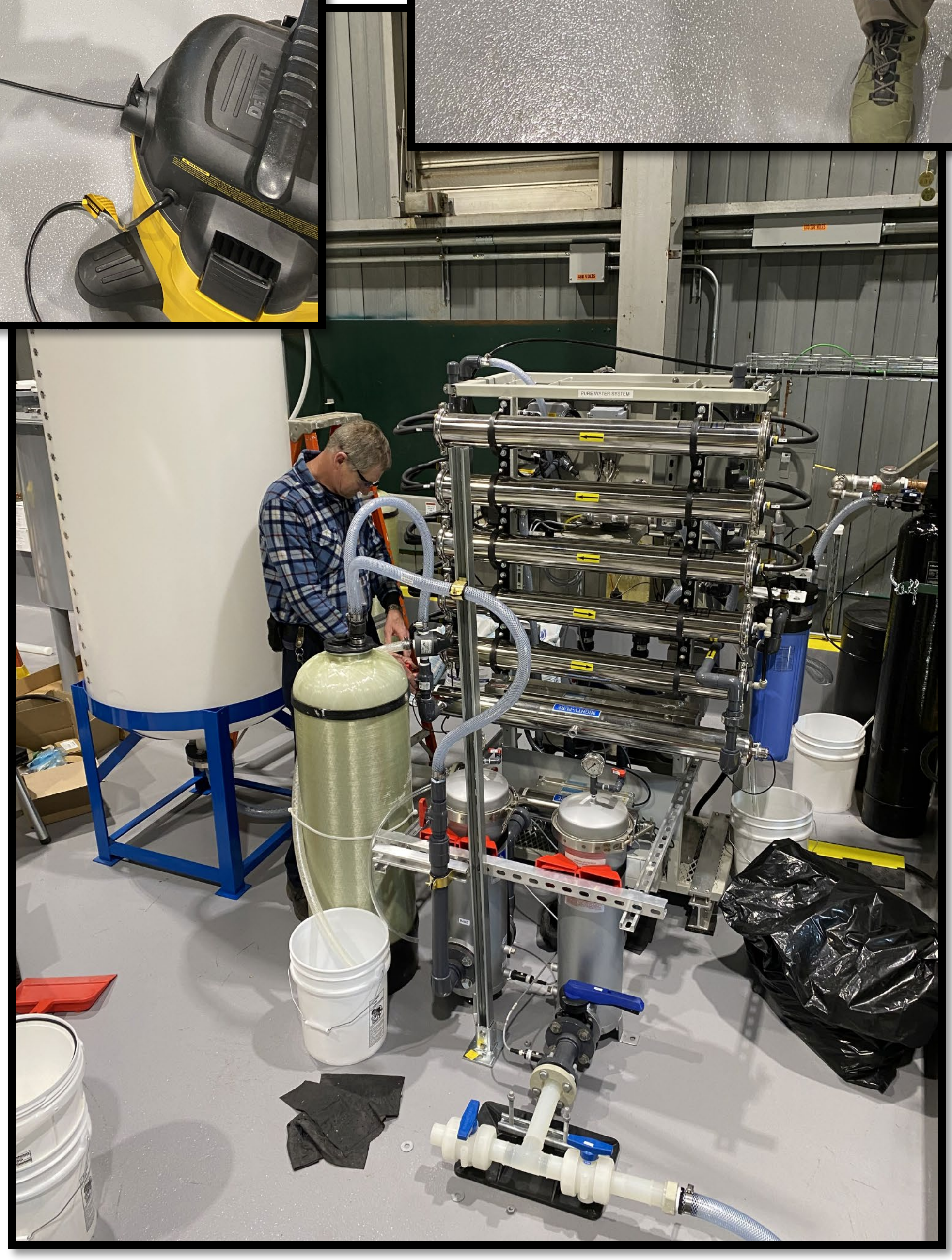
30-ton Demonstrator

installation & prefill exercises

National Nuclear Security Administration

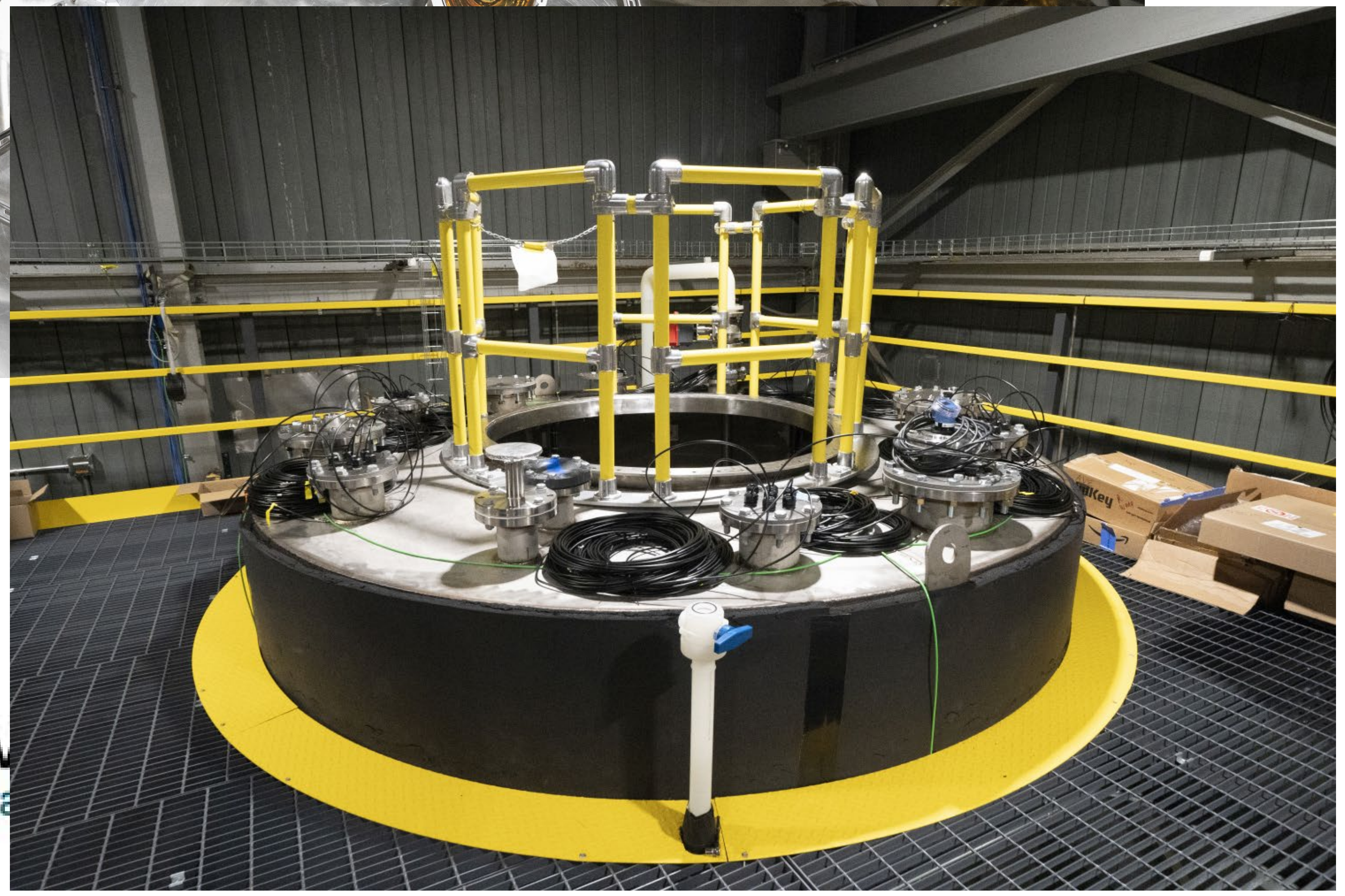


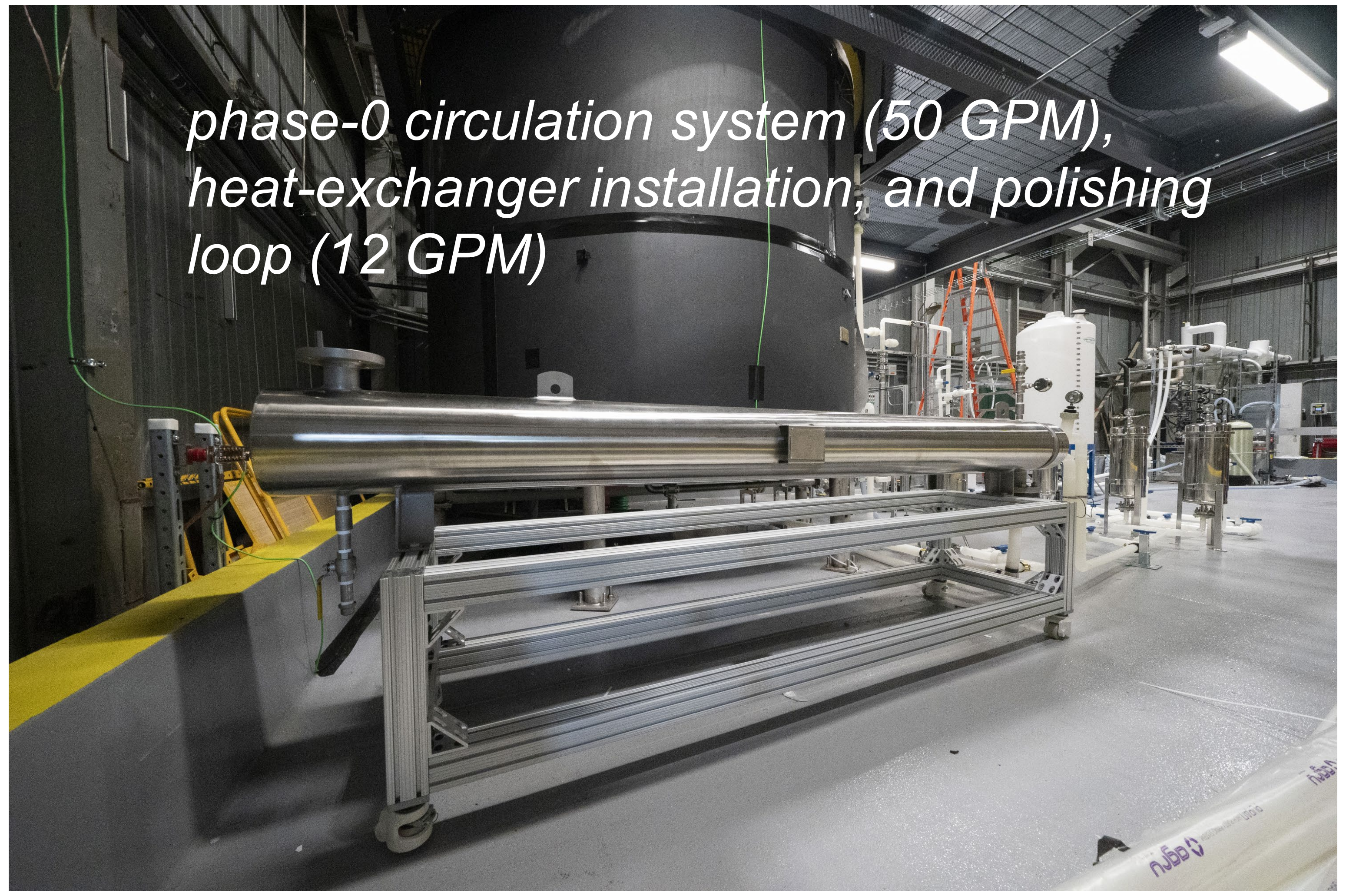




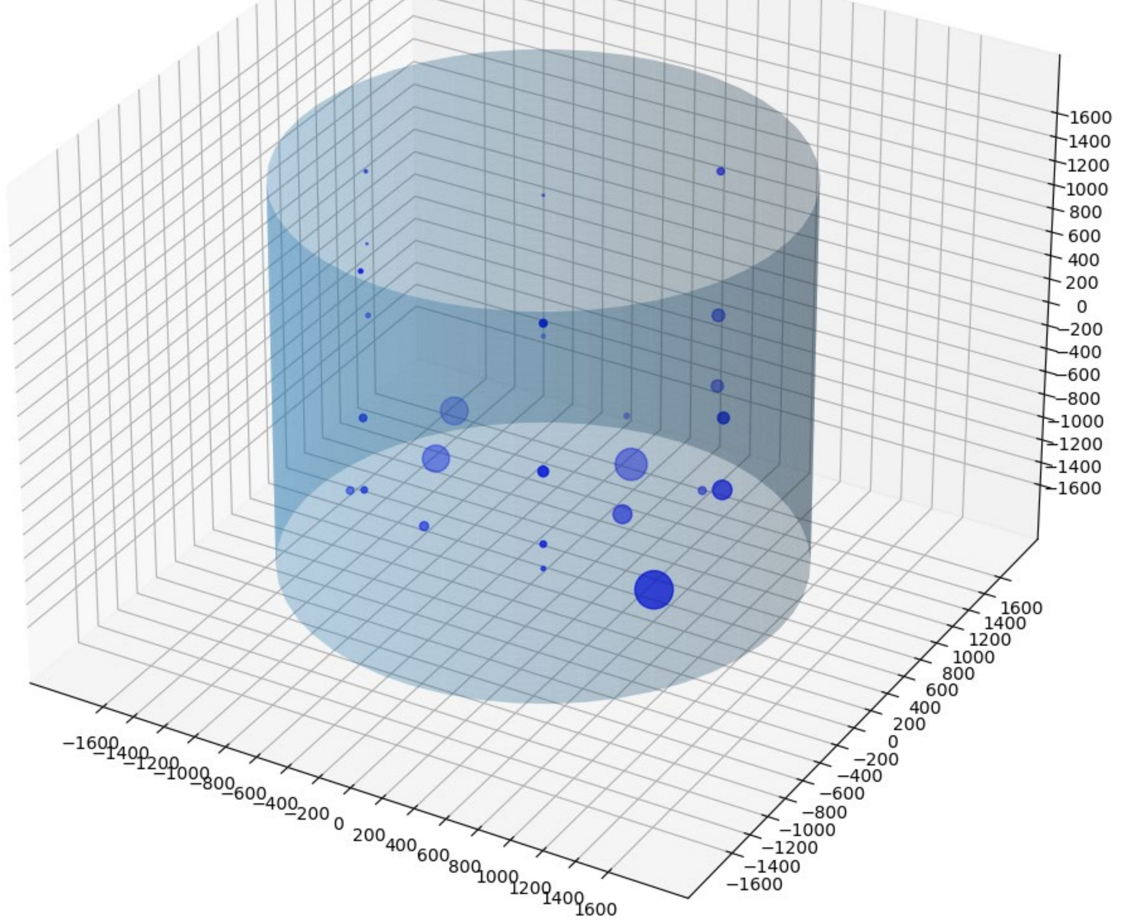
30-ton Demonstrator Status

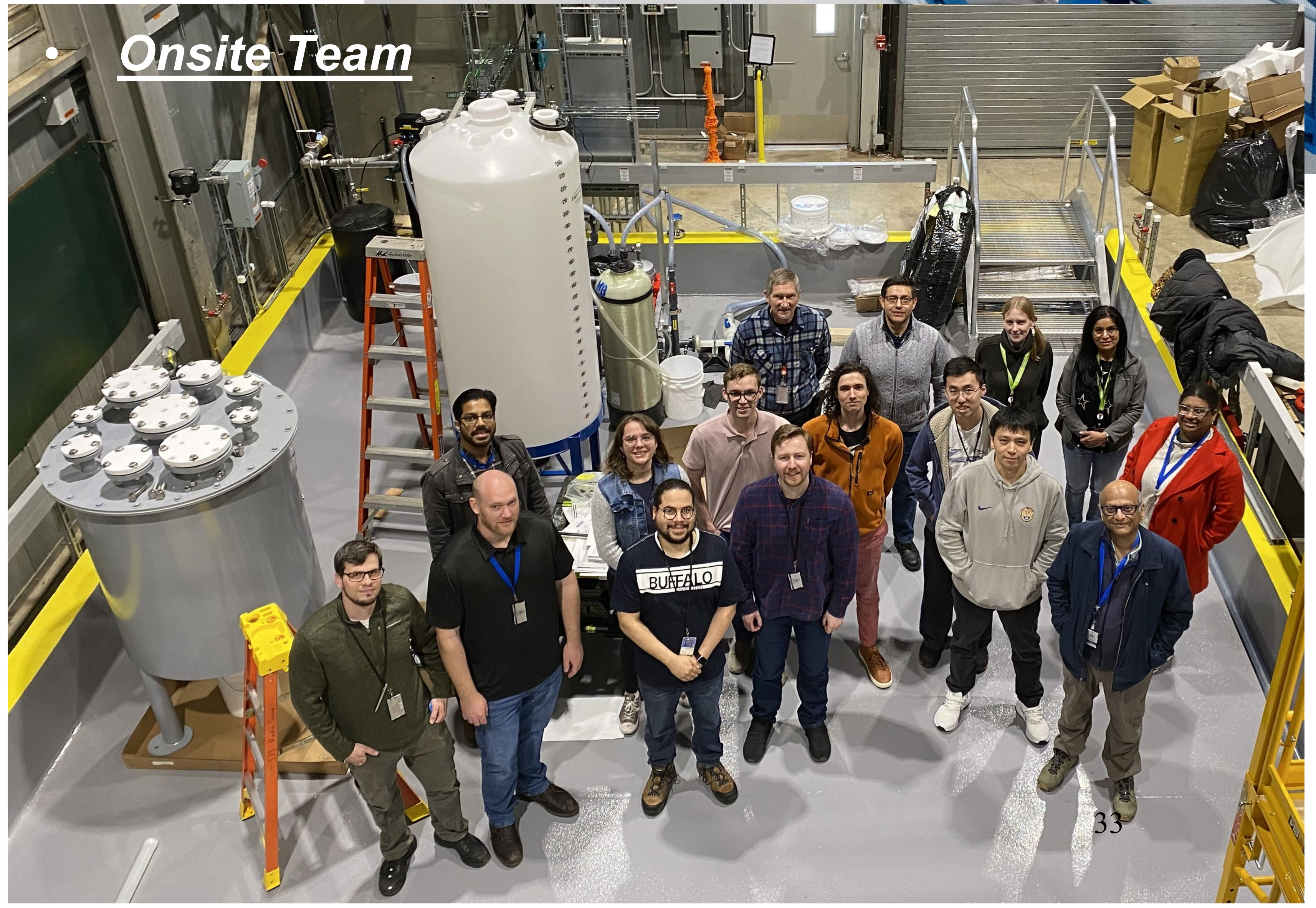
- ✓ *Commissioned in 06/2024*
- ✓ *Started phase-0 operation (water target)*
- *Plan to inject LS & in-situ circulation in 2024*
- *Full deployment with different detector configurations in following years*



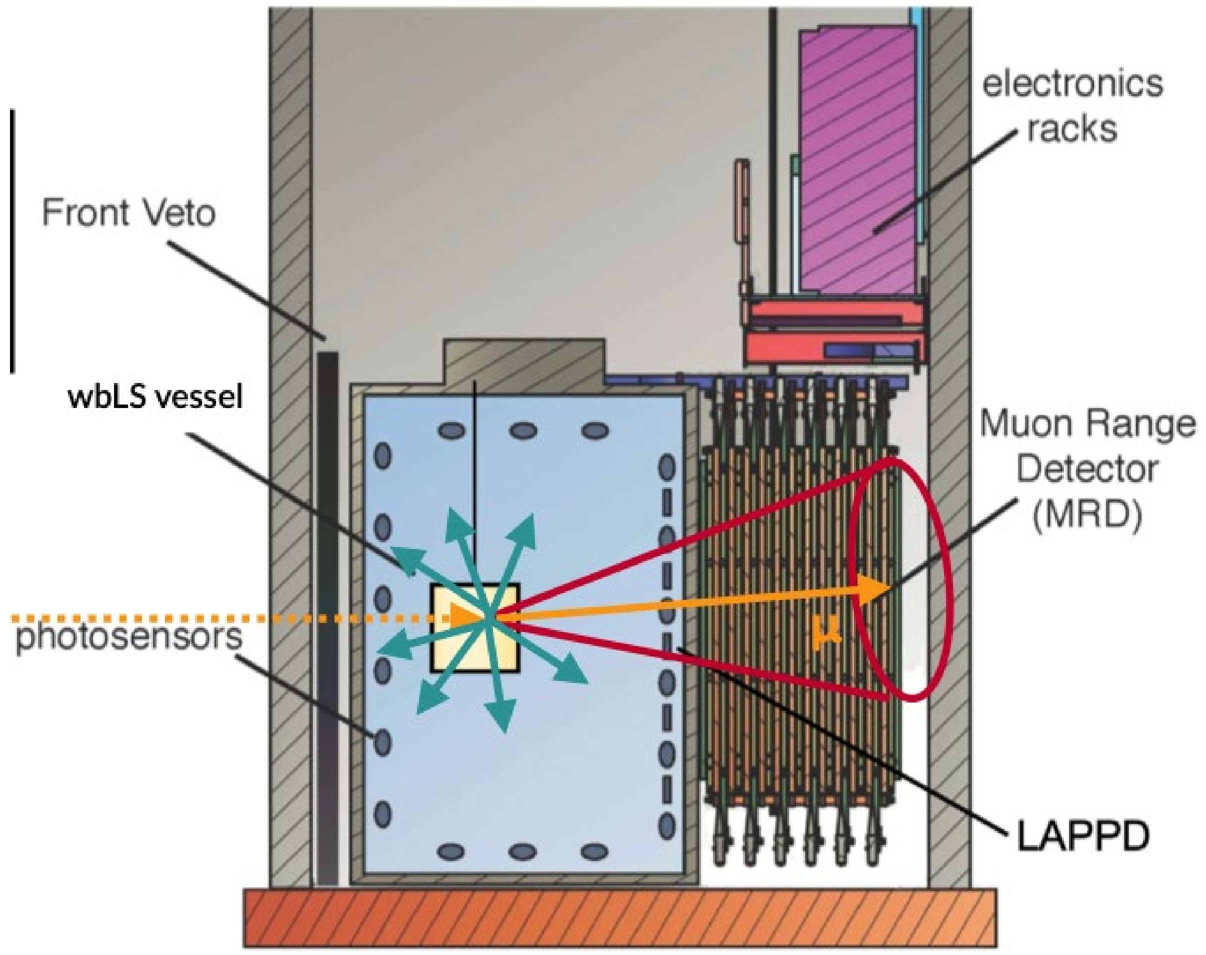

phase-0 circulation system (50 GPM), heat-exchanger installation, and polishing loop (12 GPM)

first paddle-triggered muon events in water (06/05/24)



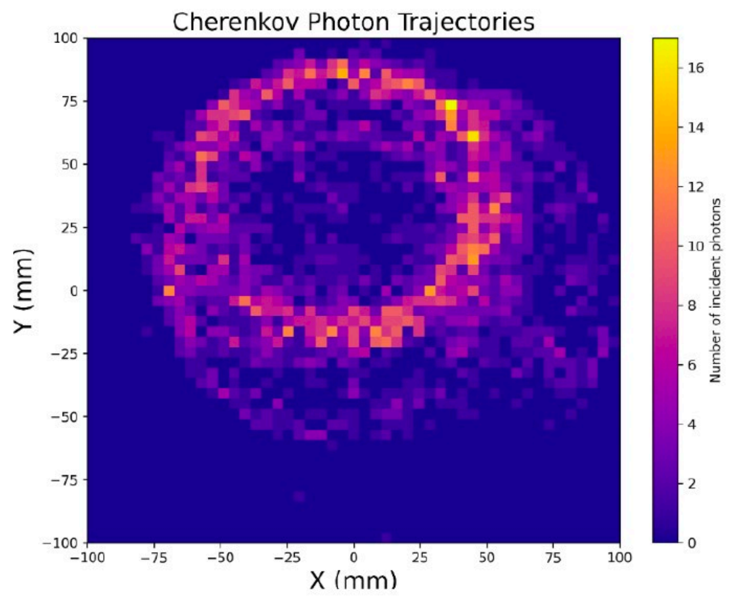


A large-scale (10s of tons) neutrino detector



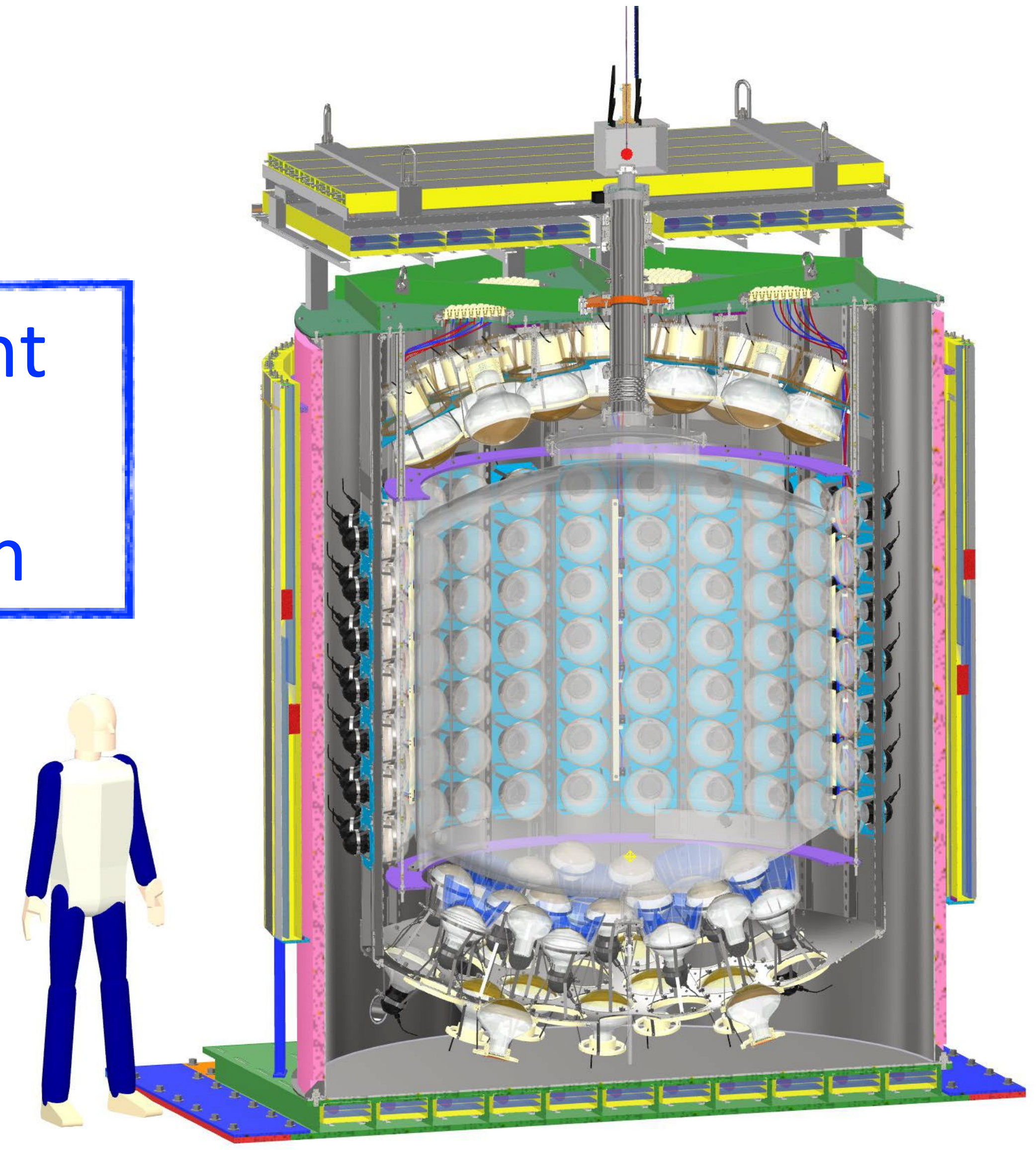
ANNIE: 365 kg

High-energy event reconstruction, neutrino detection

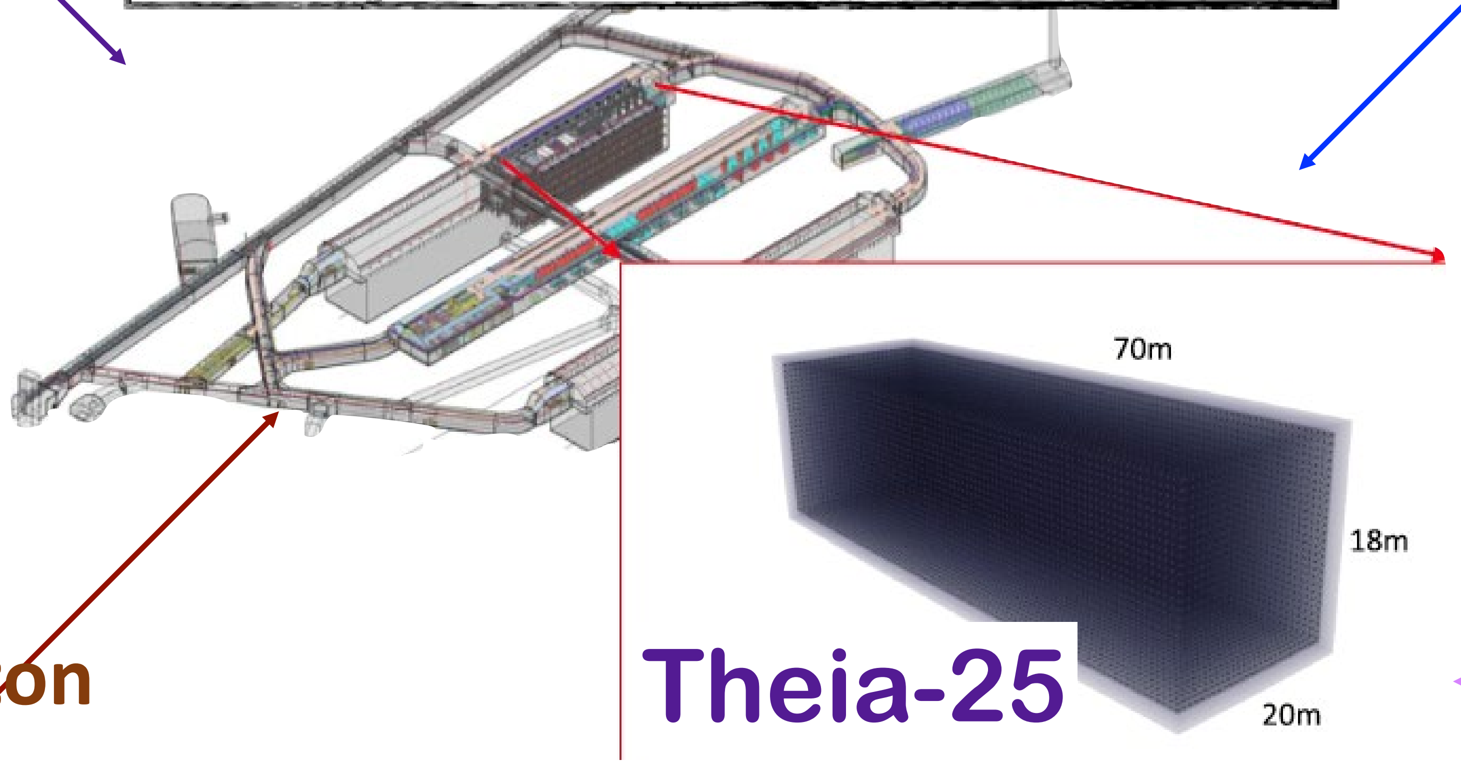


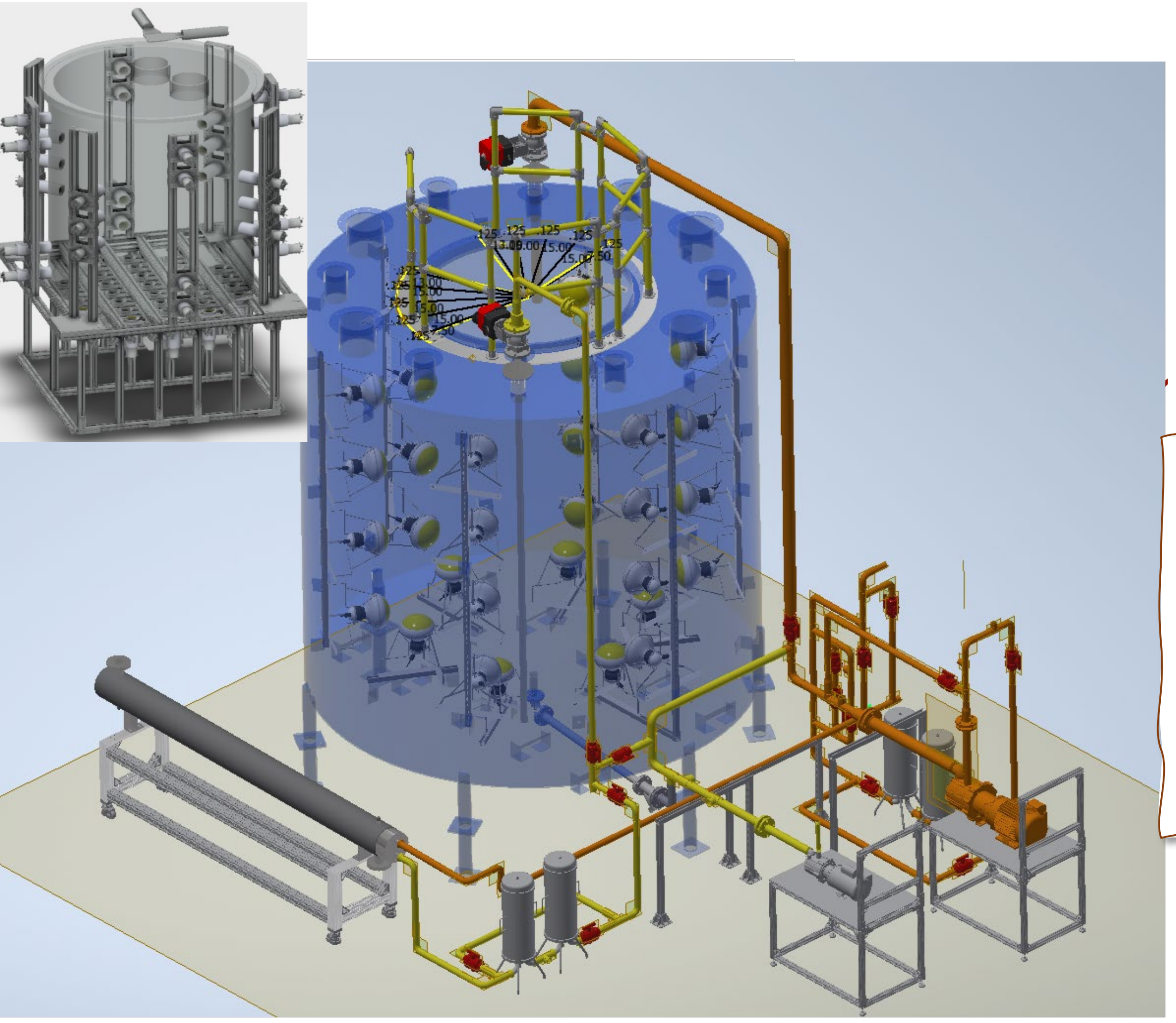
Eos: 20 ton

Low-energy event reconstruction, model validation



Building on a broad program of bench-top scale development





BNL: 1-and 30-ton

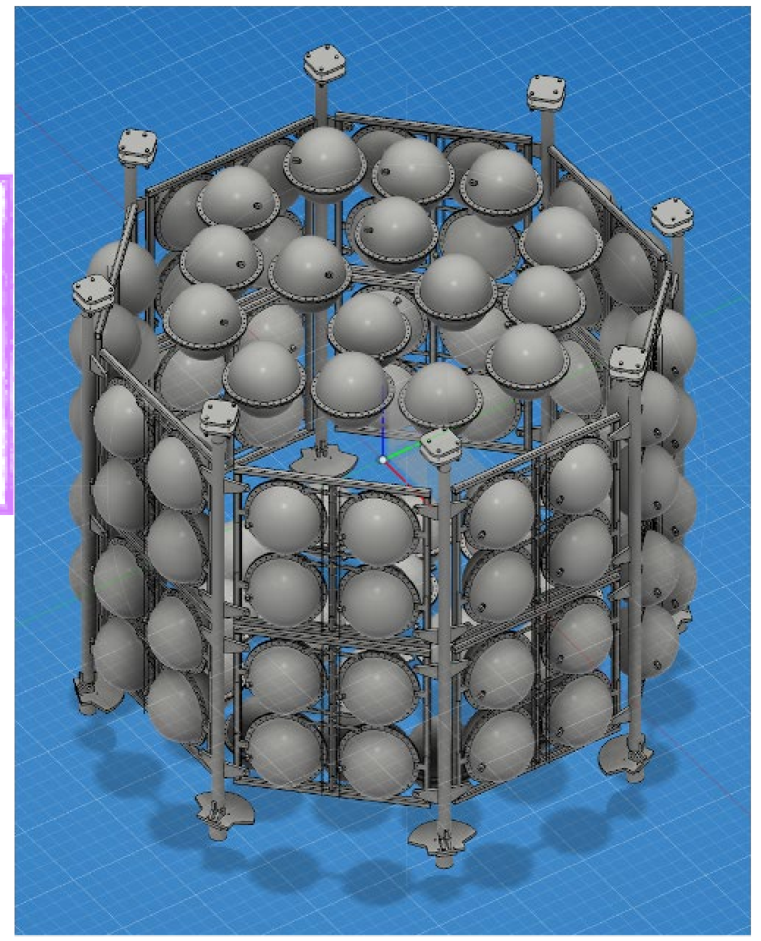
Deployment, purification, recirculation, transparency

NuDot: 1 ton

Isotope loading, NLDBD topology

BUTTON: 30 ton

Underground deployment, low bkg verification



Summary

- Liquid technology can cater to specific needs in different physics areas
  - Transparent vs. Opaque vs. Isotope-loading
- A cost-effective large-scale hybrid detector with tunable light level, timing, and emission property
  - allows staging deployment (loading) to extract different physics frontiers to fully exploit the investment
- Diverse R&D program & Scale-up facility available for community
  - encourage collaboration in detector and material development

Brookhaven National Laboratory