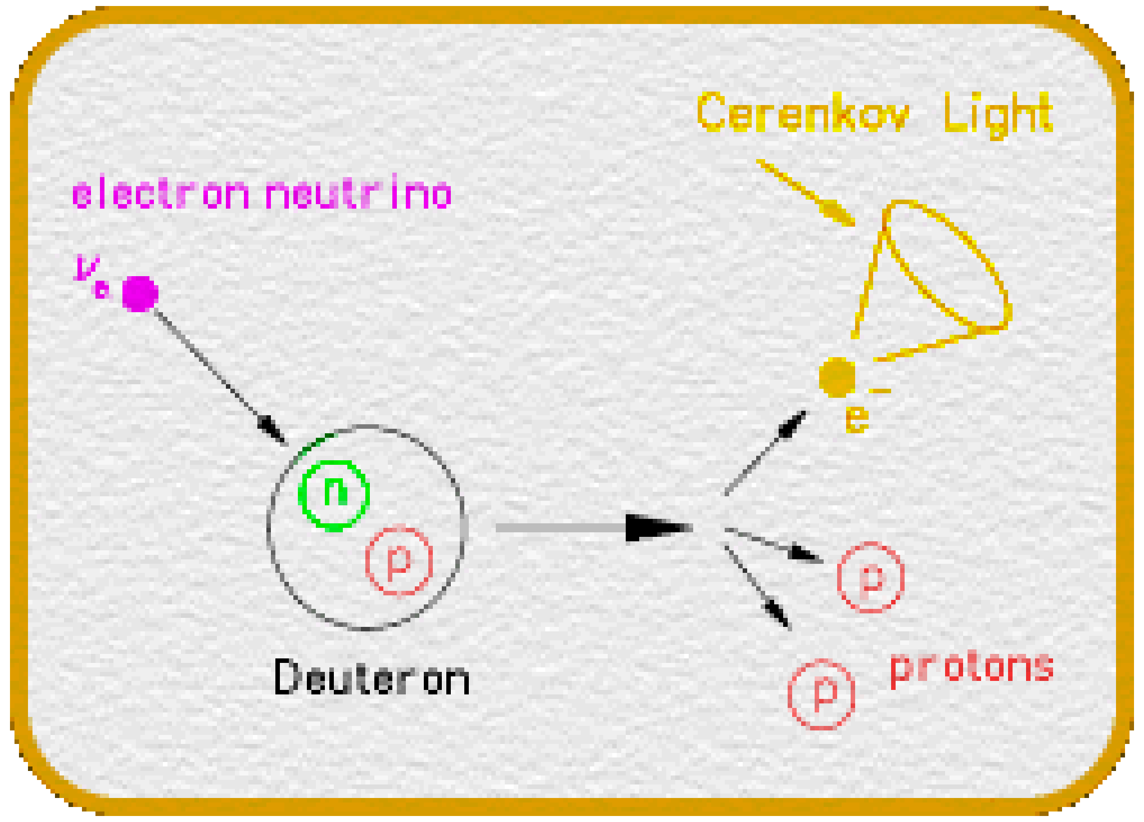
Liquid Detector Development

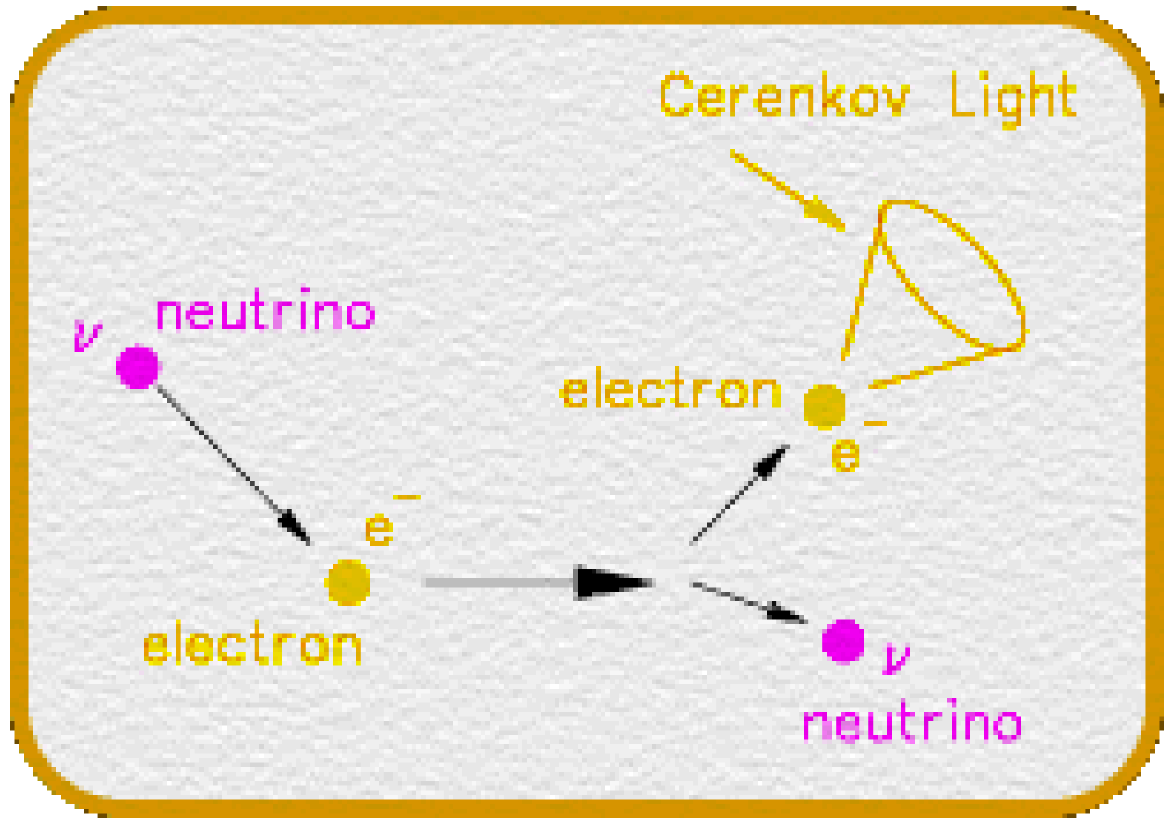
Water and/or Scintillator

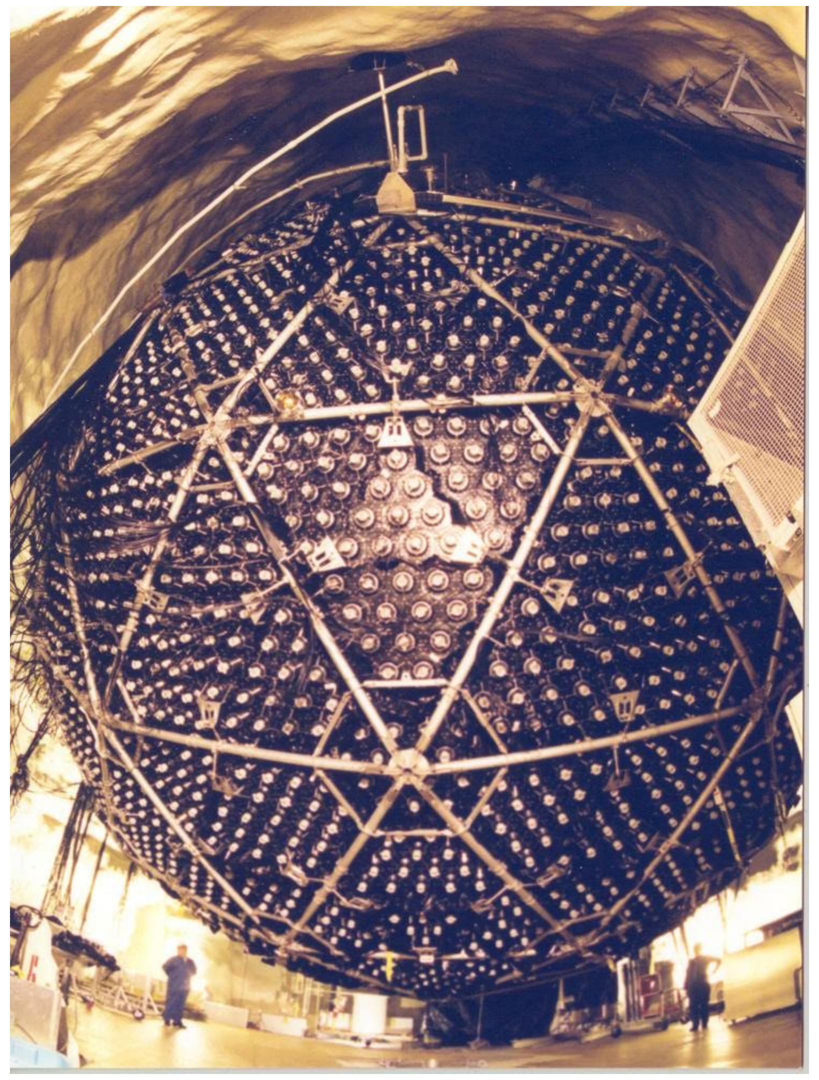
Minfang Yeh

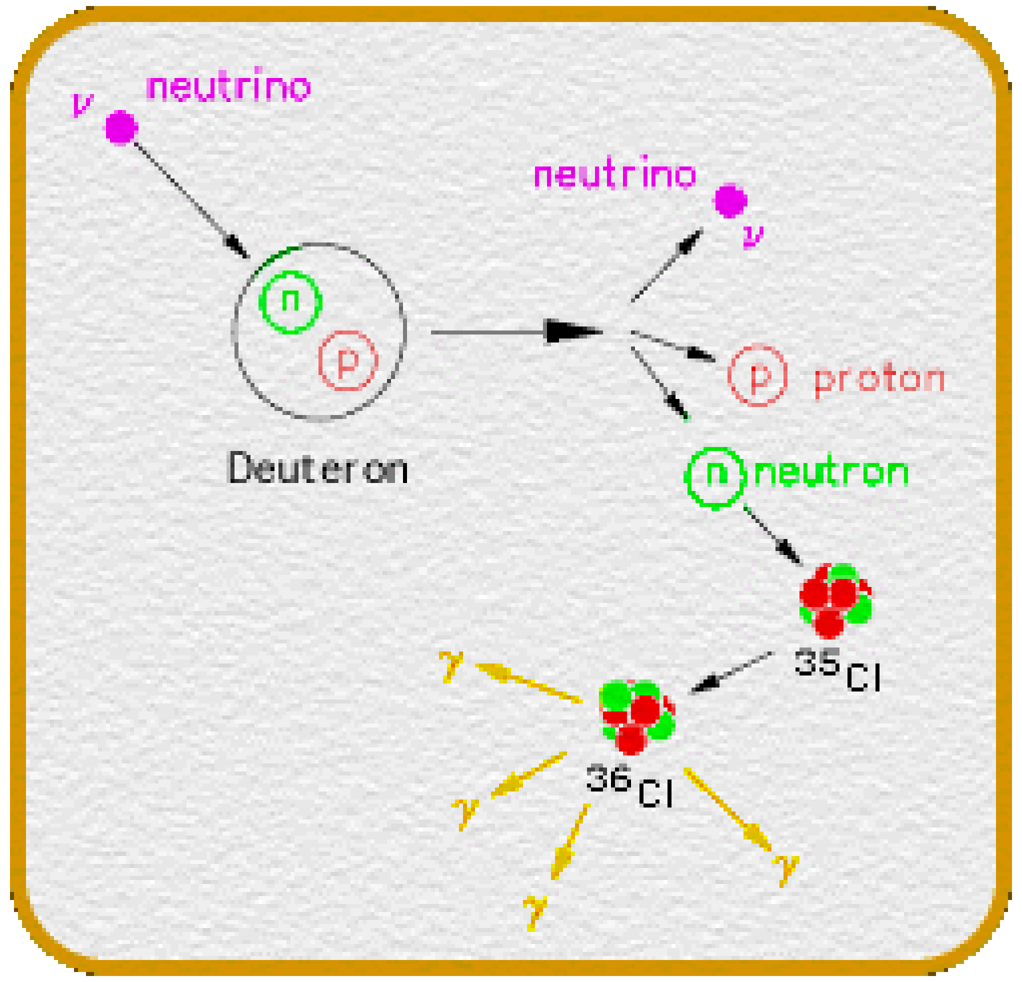
Hybrid Workshop, U. Penn., June 3-5, 2025

SNO Heavy Water Detector

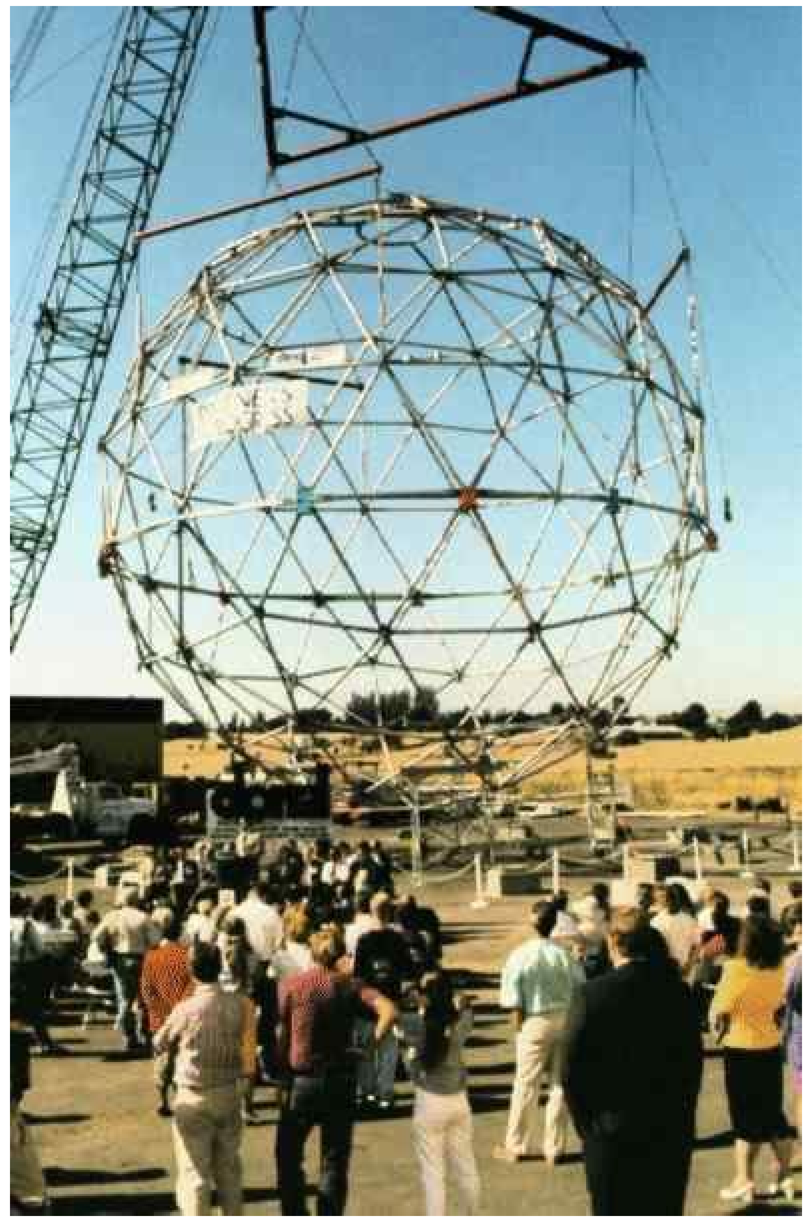






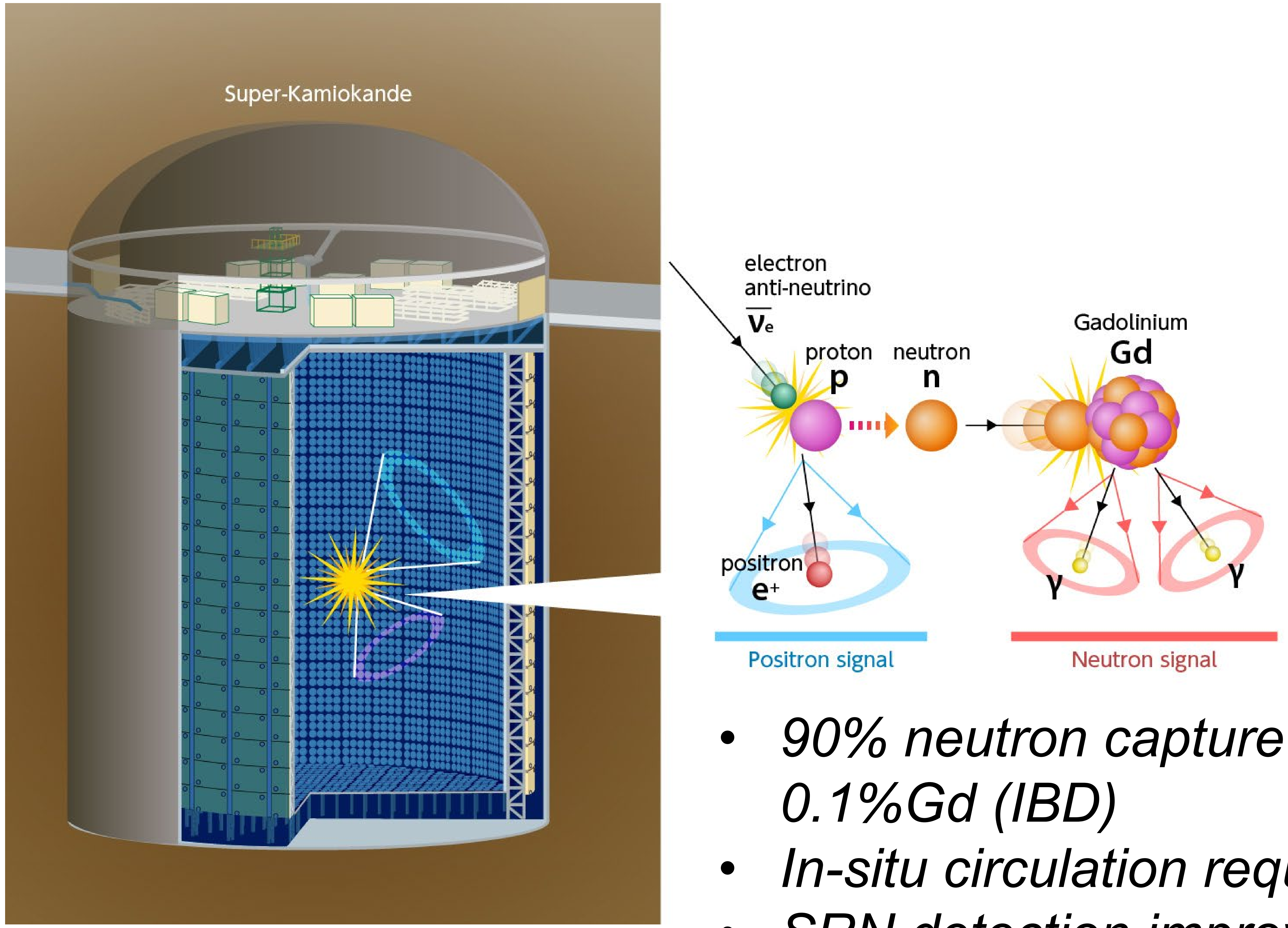


- *Effect of wavelength shifters in Cherenkov detectors*
- *Scarbostyril 124 (CS124) and Alexa Fluor 350 (AF350); water-soluble*
- *~x3 increase in light (from low-λ Cherenkov); however, might not be feasible due to optical for a large detector*



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

SK: physics enhancement with gadolinium



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

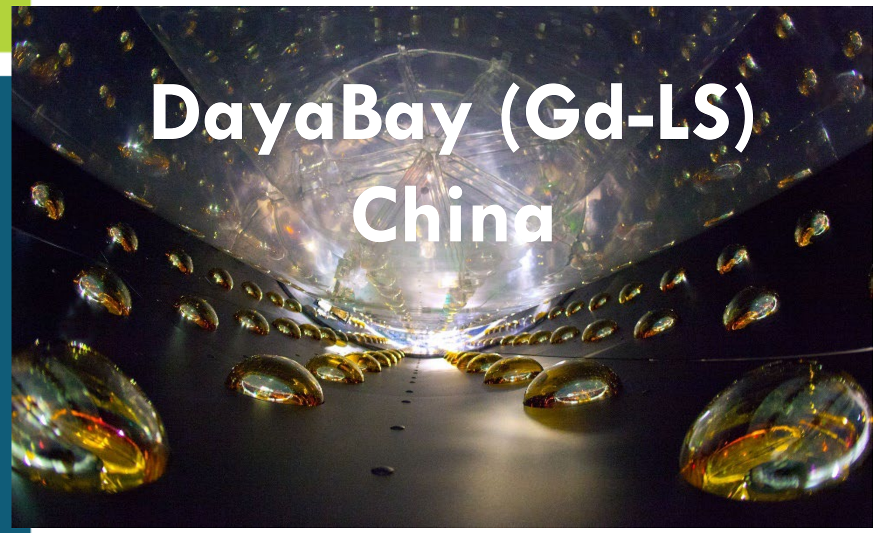
Ongoing Gd-loading for HK

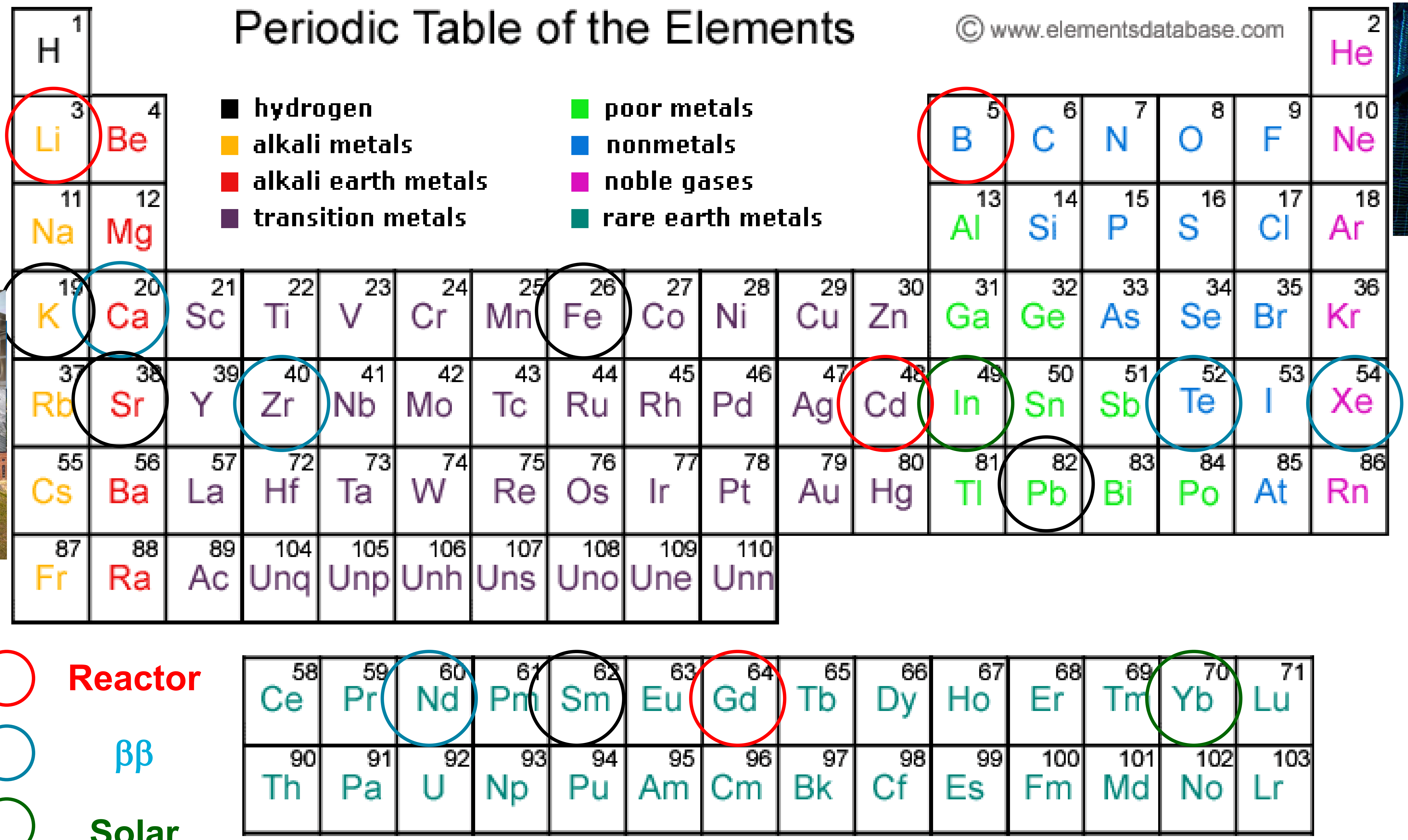
https://www-sk.icrr.u-tokyo.ac.jp/en/news/detail/309

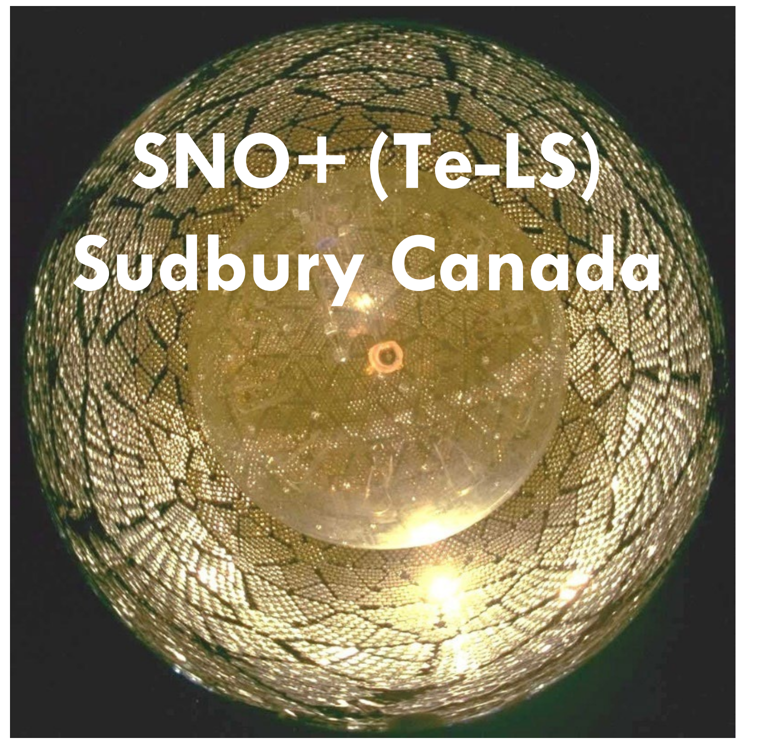
LS-based ν Experiments

Brookhaven National Laboratory

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







Reactor

ββ

Solar

Medical, calibration, LSC, etc

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

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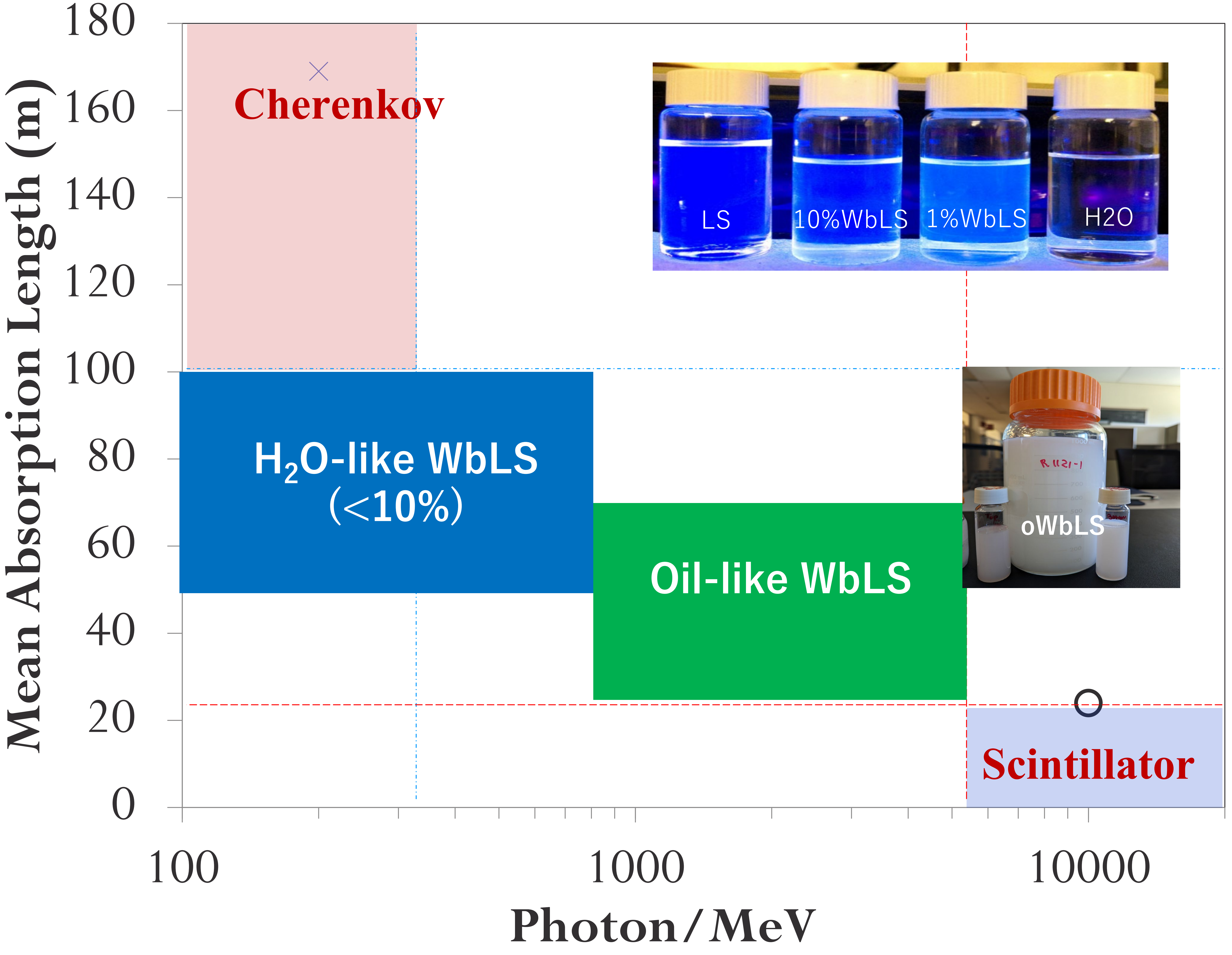
Water-based Liquid Scintillator (hybrid detection)

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



- ***Directionality*** *from Cherenkov photons.*
- ***Low energy threshold*** *from scintillation.*
- ***Particle ID*** *distinguishing particles using timing and pulse shape.*
- ***High metal loading capability***
- *Shares a similar scintillation mechanism with LS, as both rely on energy transfer from solvent excitation to dissolved fluors for light emission.*

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

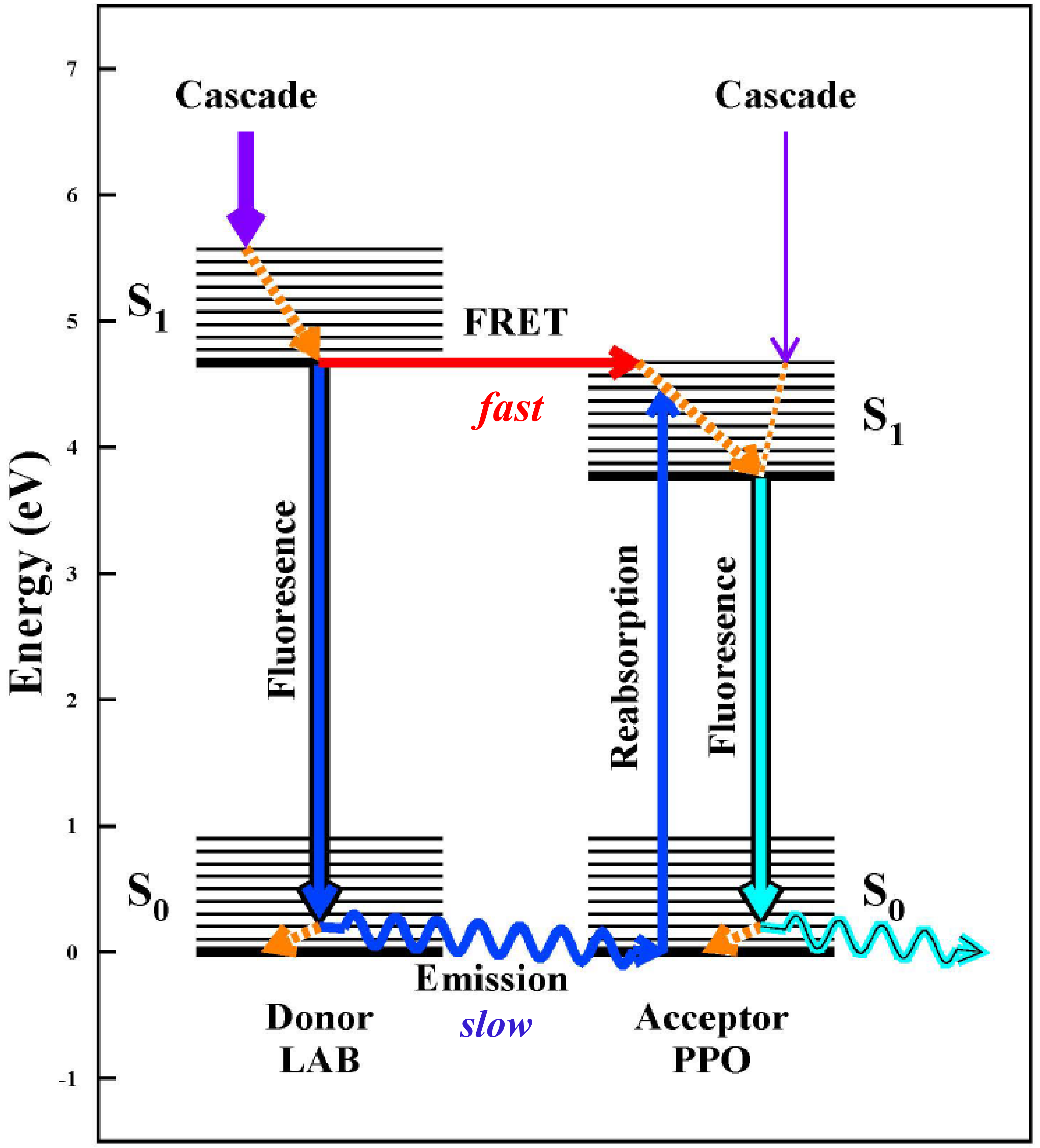
WbLS compared to LS

Factor	Cost
Base material	Primarily water (cheap, abundant)
Scintillator loading	Low concentration (1–10%) reduces cost
Large volumes feasible	Ideal for kiloton–megaton detectors
Scalable	Cheaper than oil-based LS for massive detectors

Factor	Safety
Flammability	Much lower — primarily water-based (not combustible)
Toxicity	Reduced; less volatile organic compounds (VOCs)
Environmental impact	Easier spill containment and cleanup
Handling and storage	Less restrictive than LS (especially underground or in public facilities)

We will review several liquid scintillator options in this talk

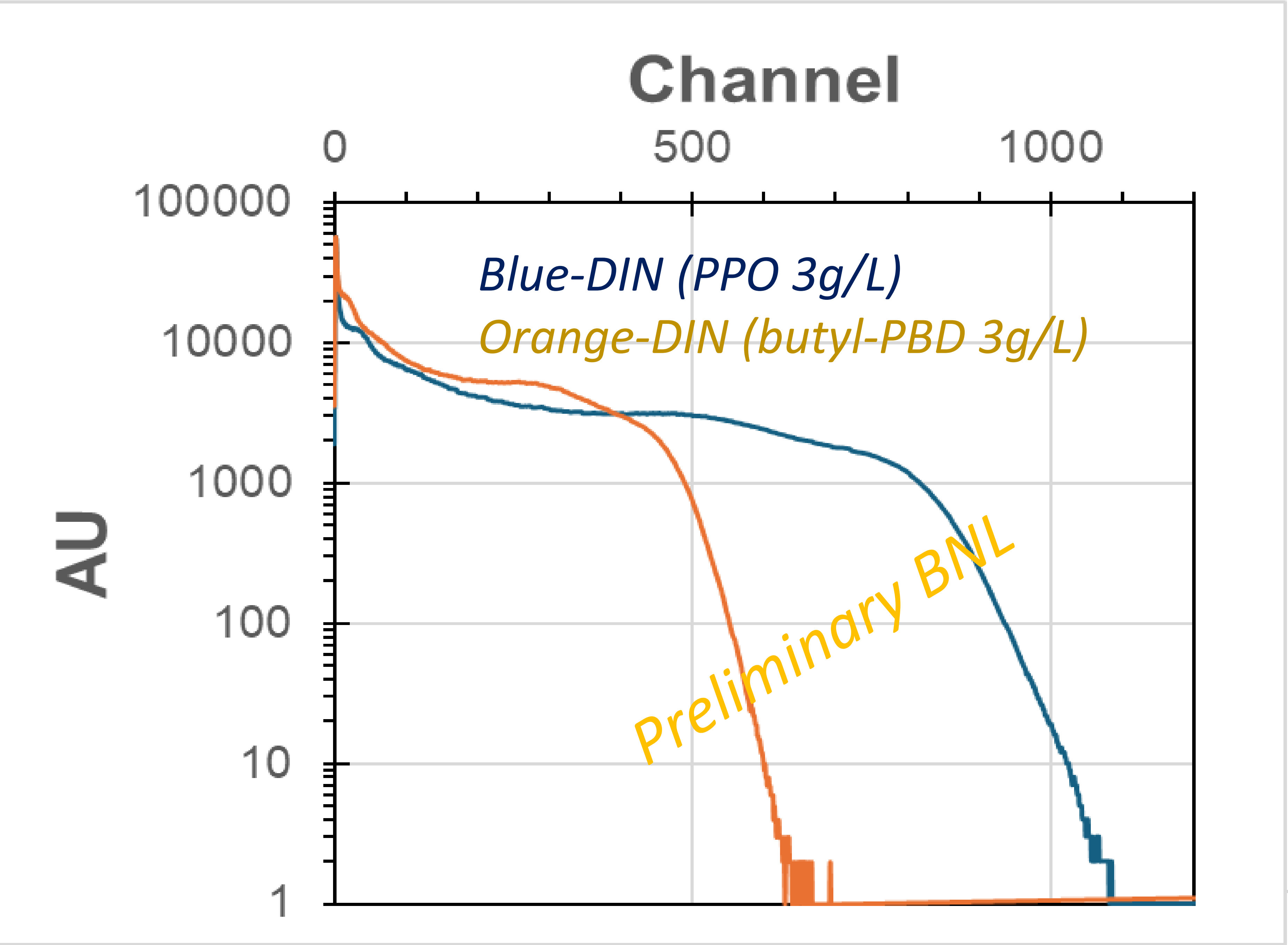
Energy Transfer Mechanism

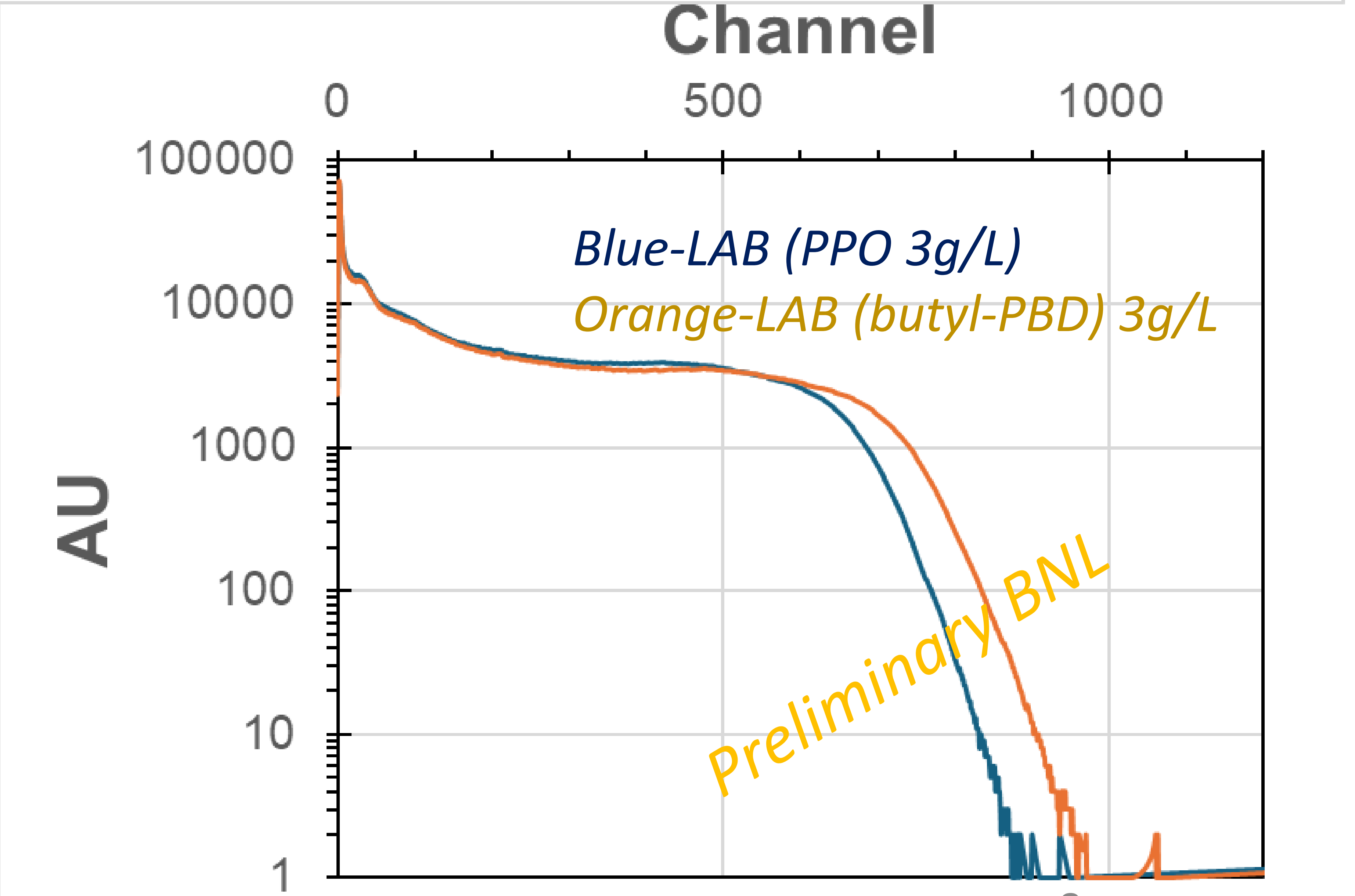


Solvent, fluor & WLS dictate the detector responses

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

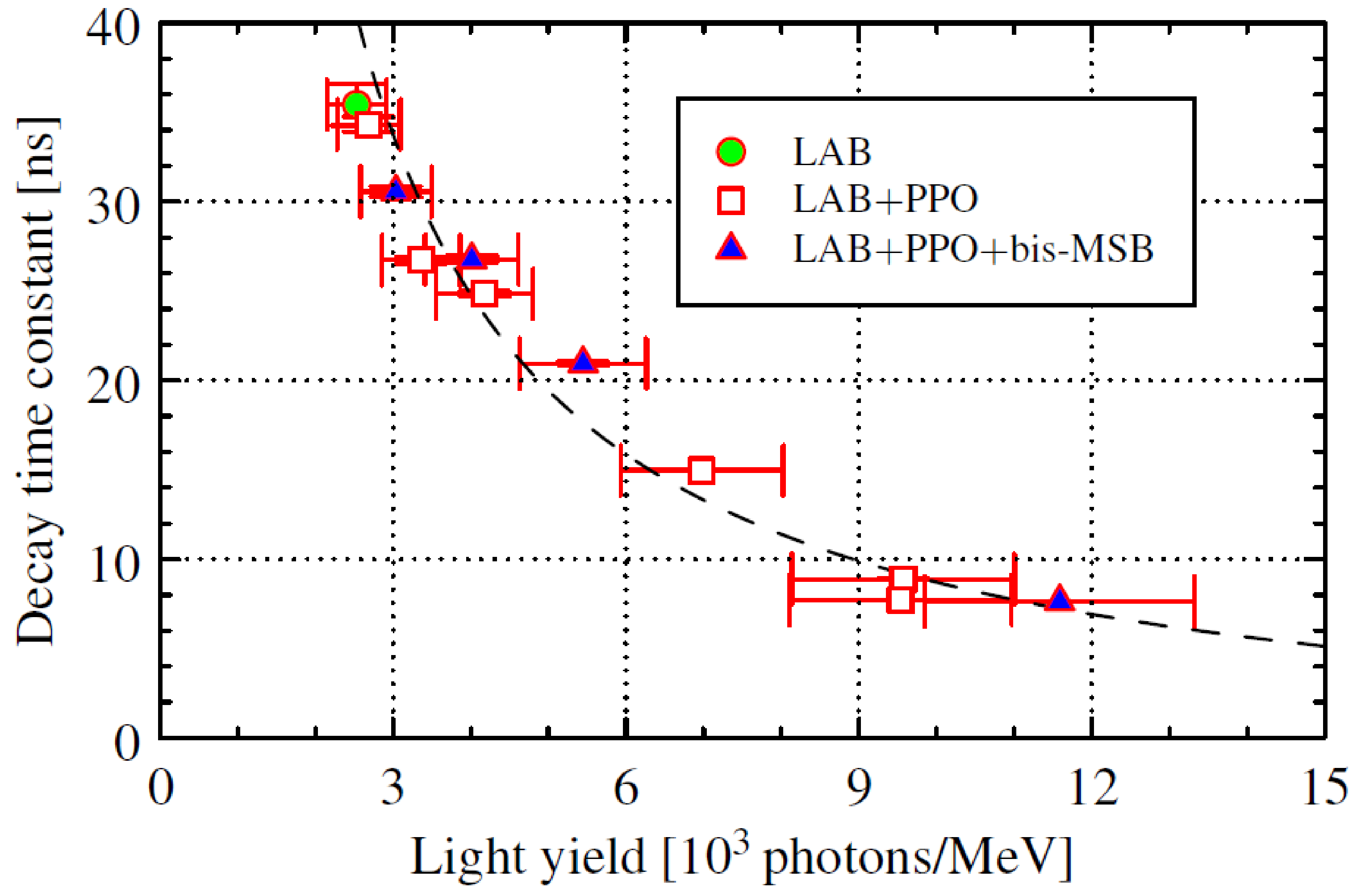
butyl-PBD could benefit LAB-based detectors



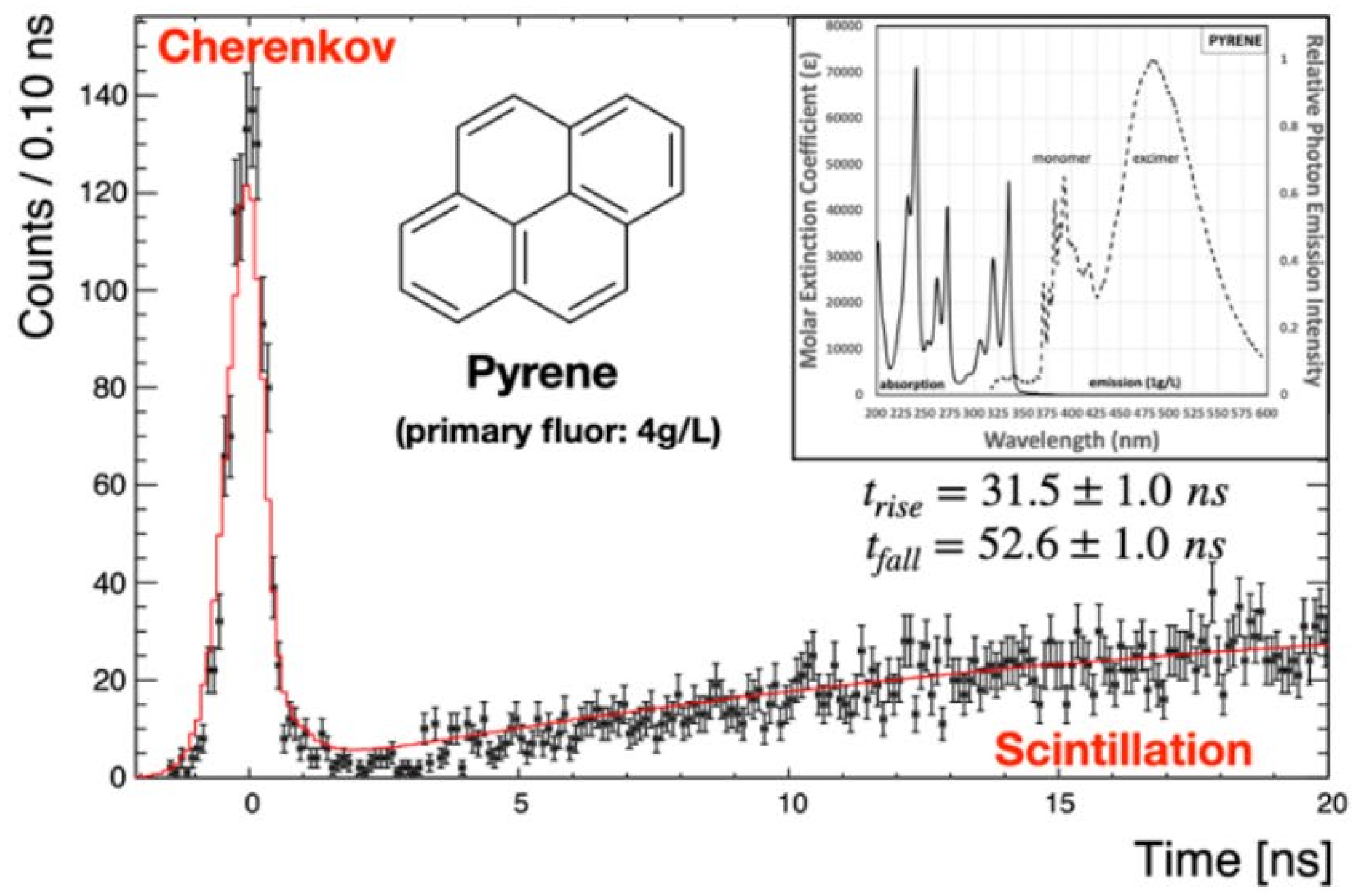


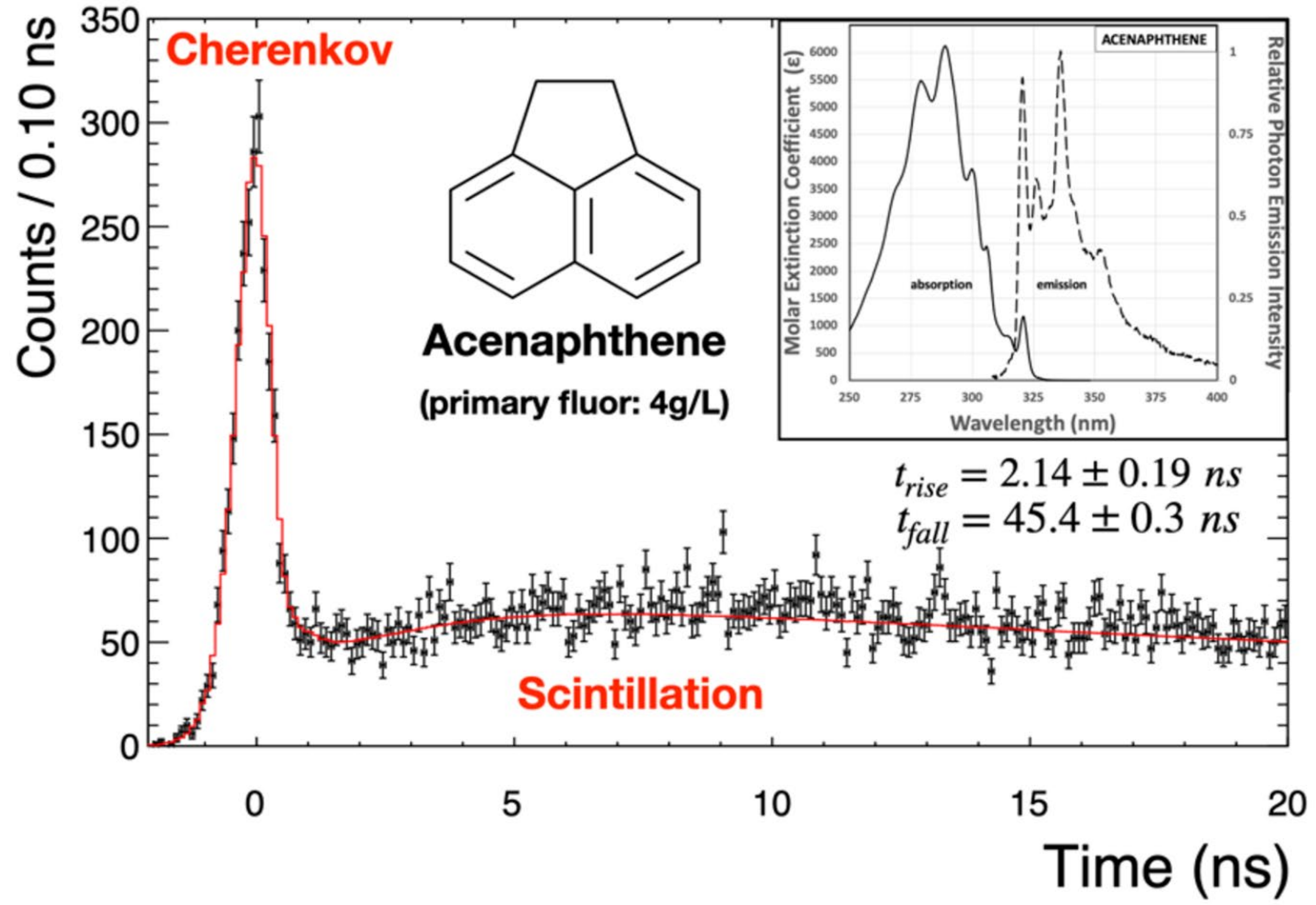
Christian Buck and Minfang Yeh 2016 J. Phys. G: Nucl. Part. Phys. 43 093001

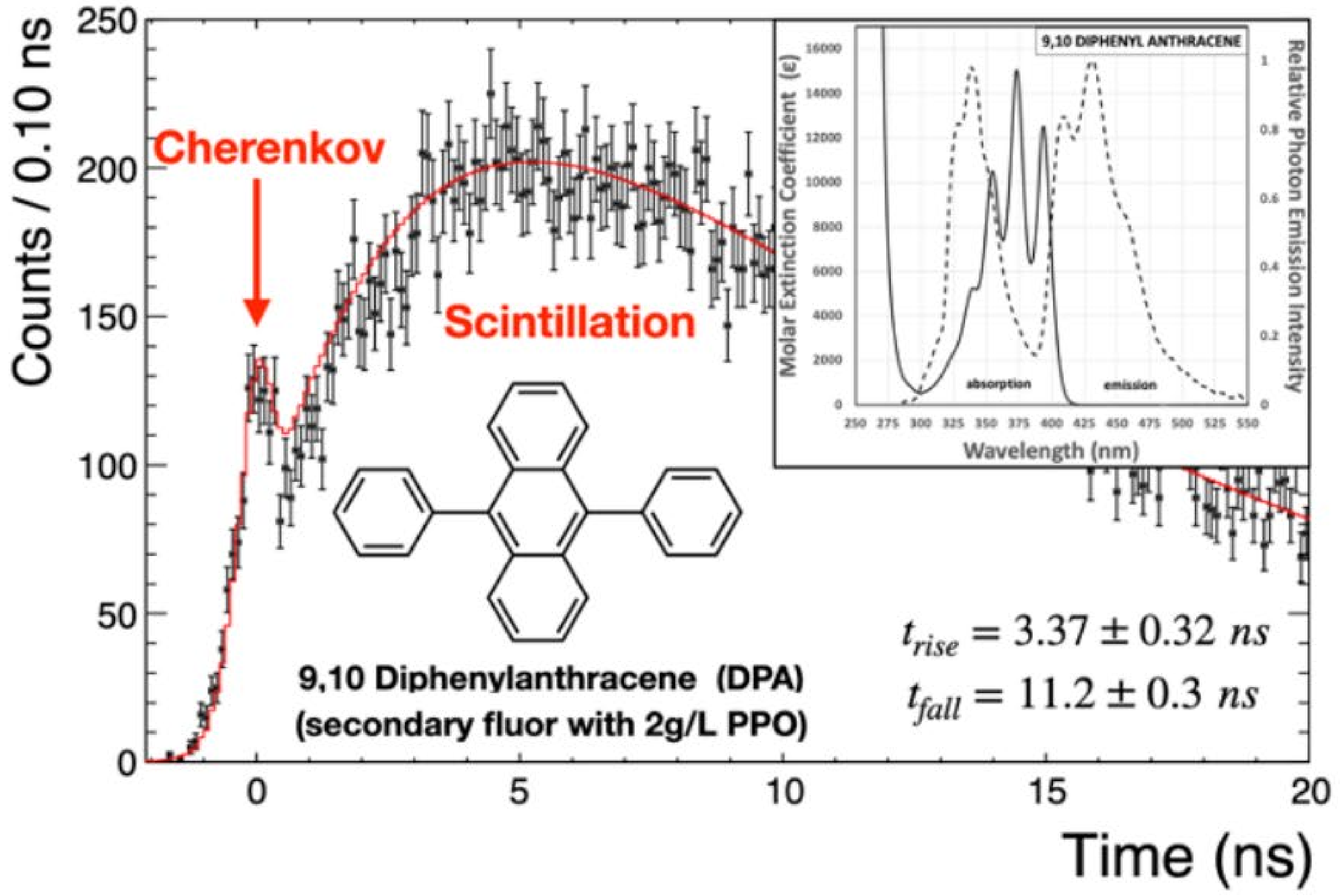
Slow Scintillator (fluor/WLS)
directionality & particle ID with good light yield

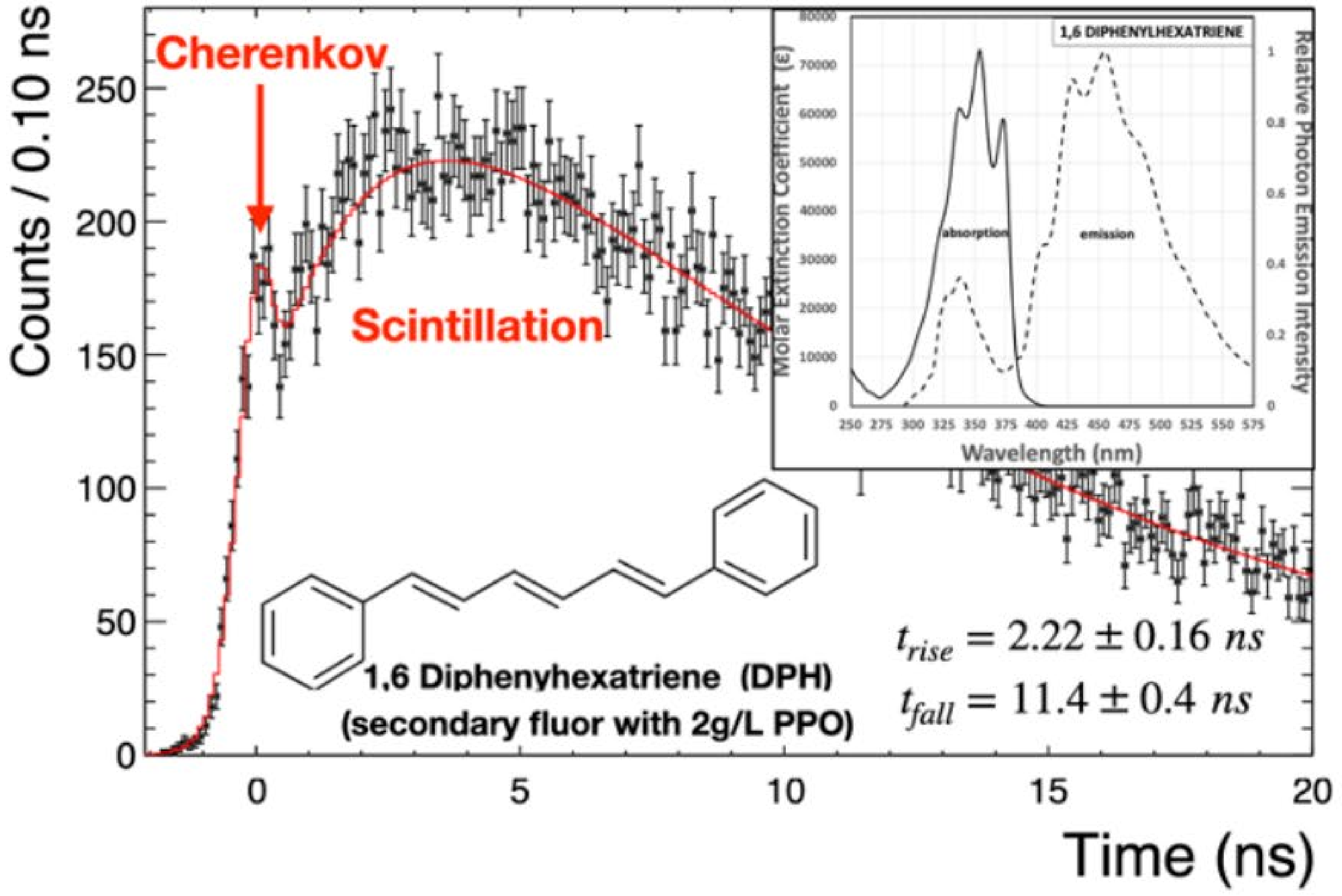


- *Adjust conc. of flour and shifters (Guo et. al., j.astropartphys.2019.02.001)*
- *Utilize slow fluor and WLS (Biller et. al., j.nima.2020.164106)*









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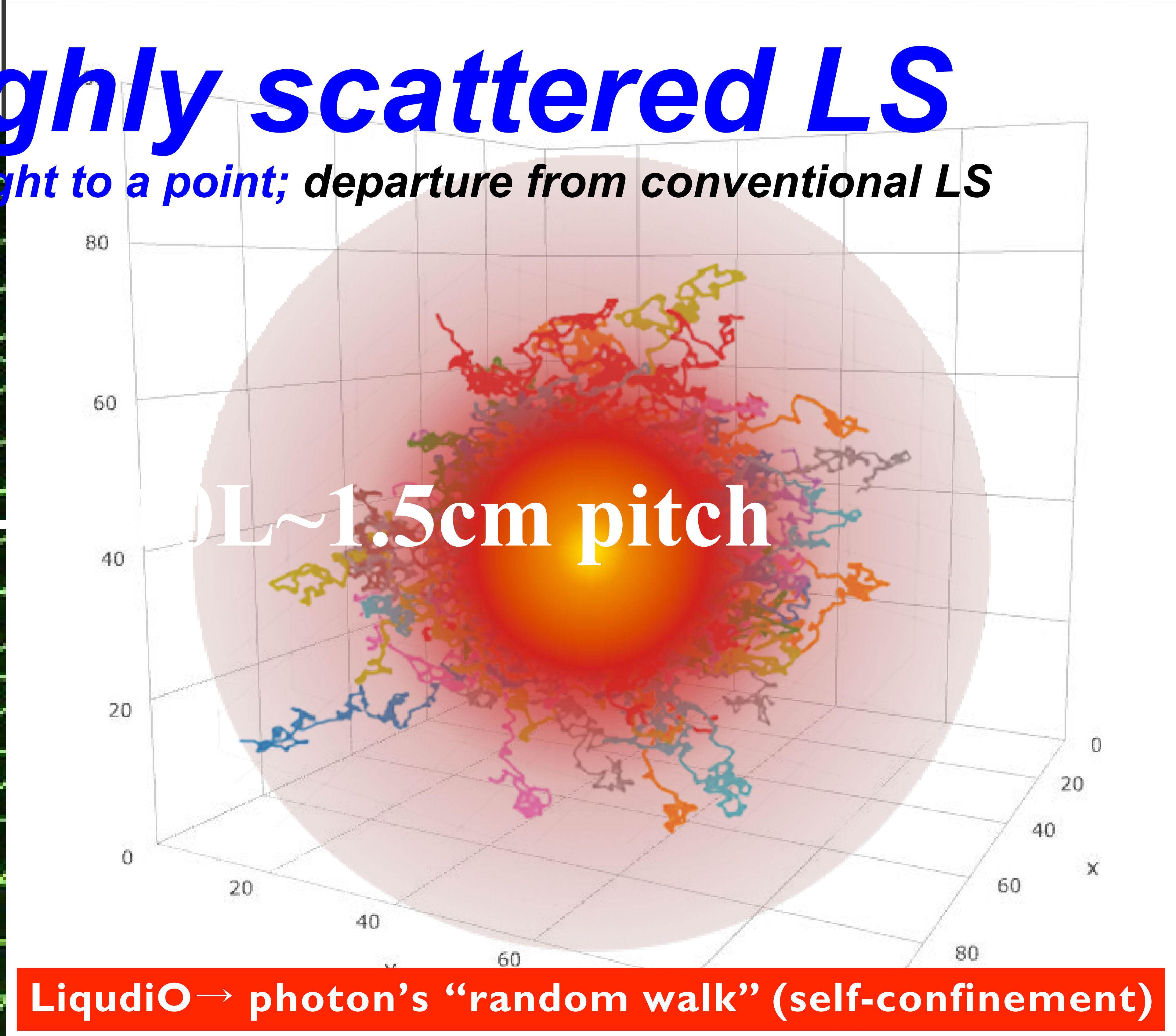
Large Stokes Shifts
emission beyond 450nm

Fluor/WLS	Absorption (nm)	Emission (nm)	Comment
DCM	470–500	600–650	Very large shift, red emission
Coumarin 6	430–450	500–530	Bright, efficient fluor
Nile Red	~520	~620–650	Solvent-sensitive
Bis-MSB	~345	~420–430	Standard secondary shifter
BODIPY	~400–500	520–600+	Customizable dyes
Oxazine	~600	~680–700	Red emission, niche use

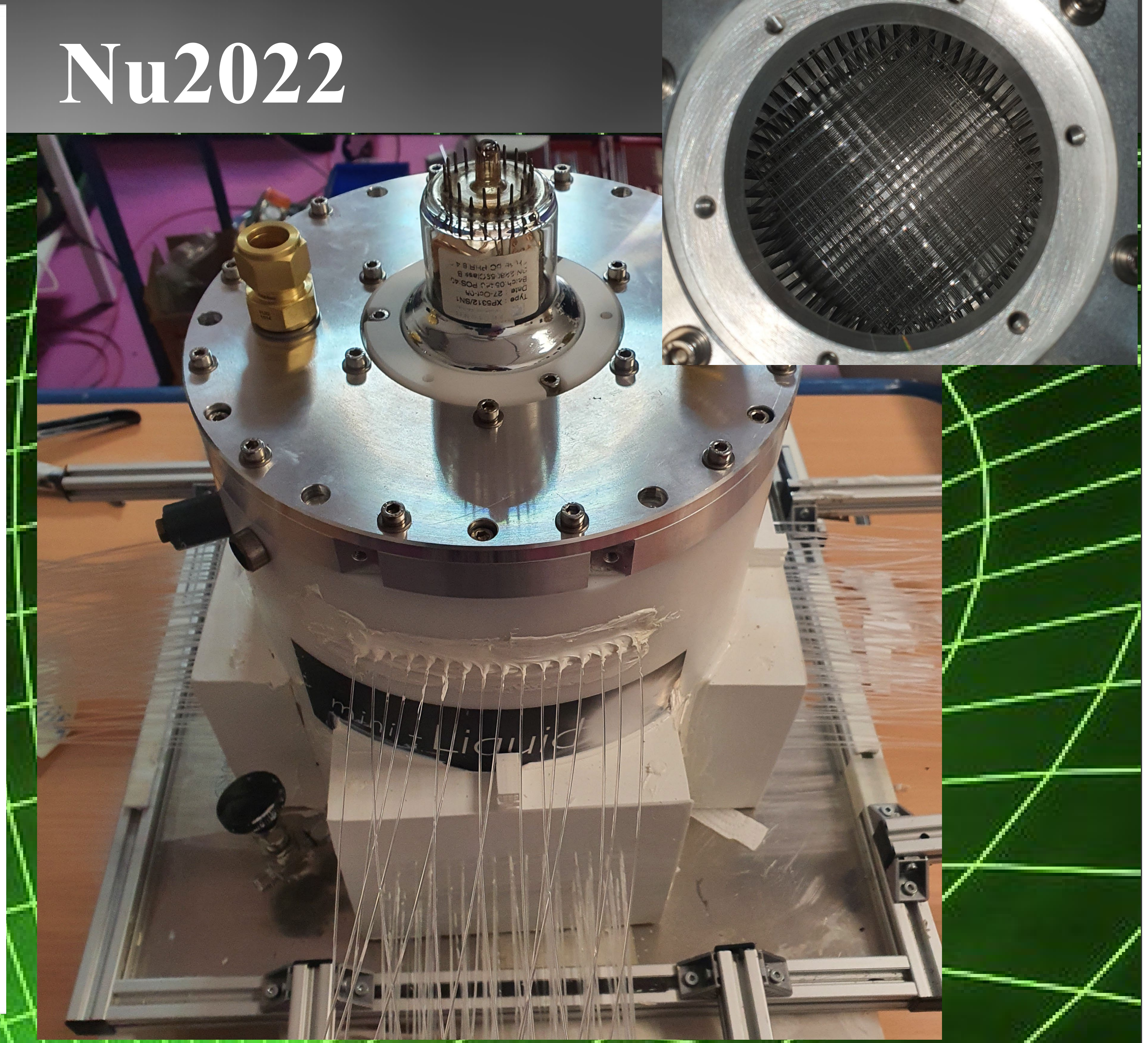
- Potential need for dual wavelength shifters, a two-step WLS scheme
- Impact on light-yield and optical properties
- Solubility and long-term stability in solvent
- Validation of spectral response and timing characteristics

A highly scattered LS

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



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



Transparency
λ(scattering)≥10m

Rayleigh & Mie Scattering
λ(scattering)≤1cm

LiquidO/CLOUD Consortium

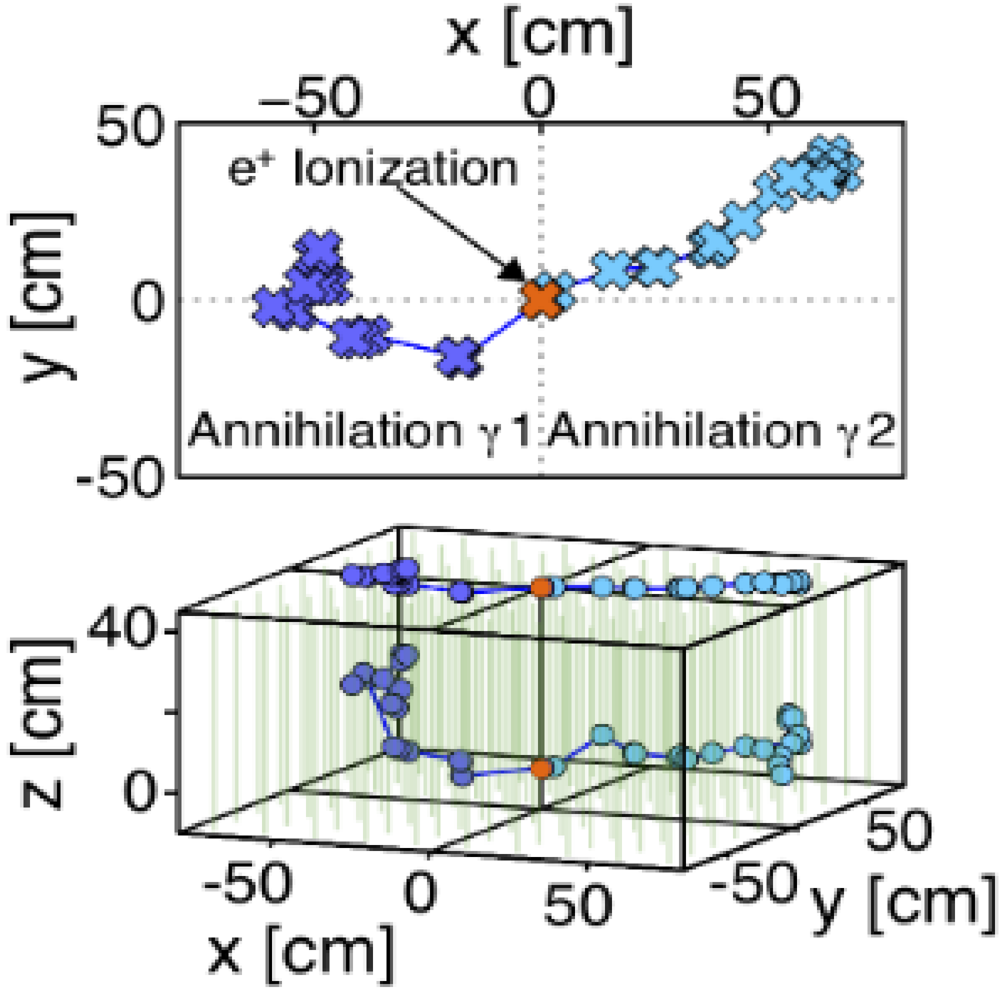
NoWaSH

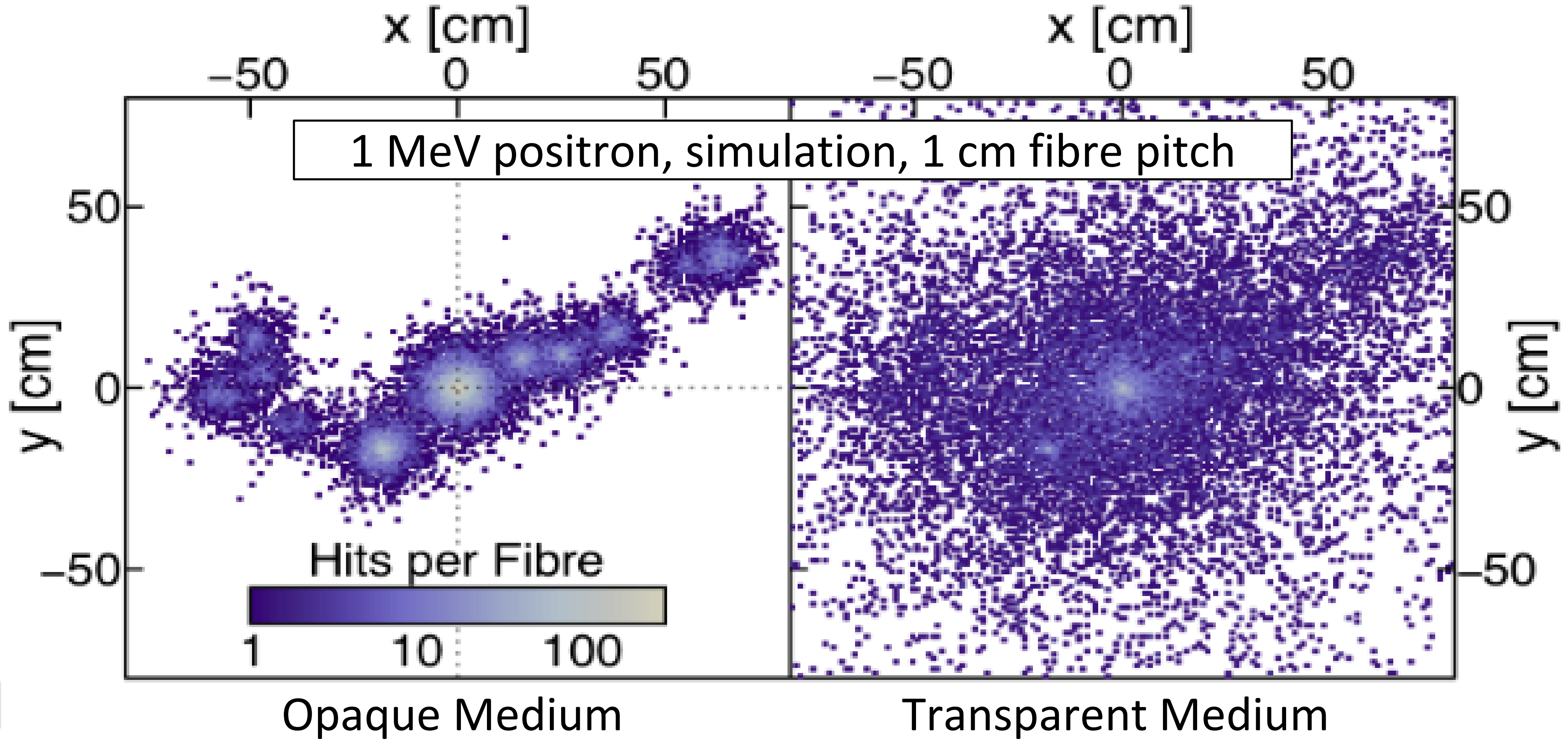
NoWaSH: wax-based opaque-white liquid scintillator

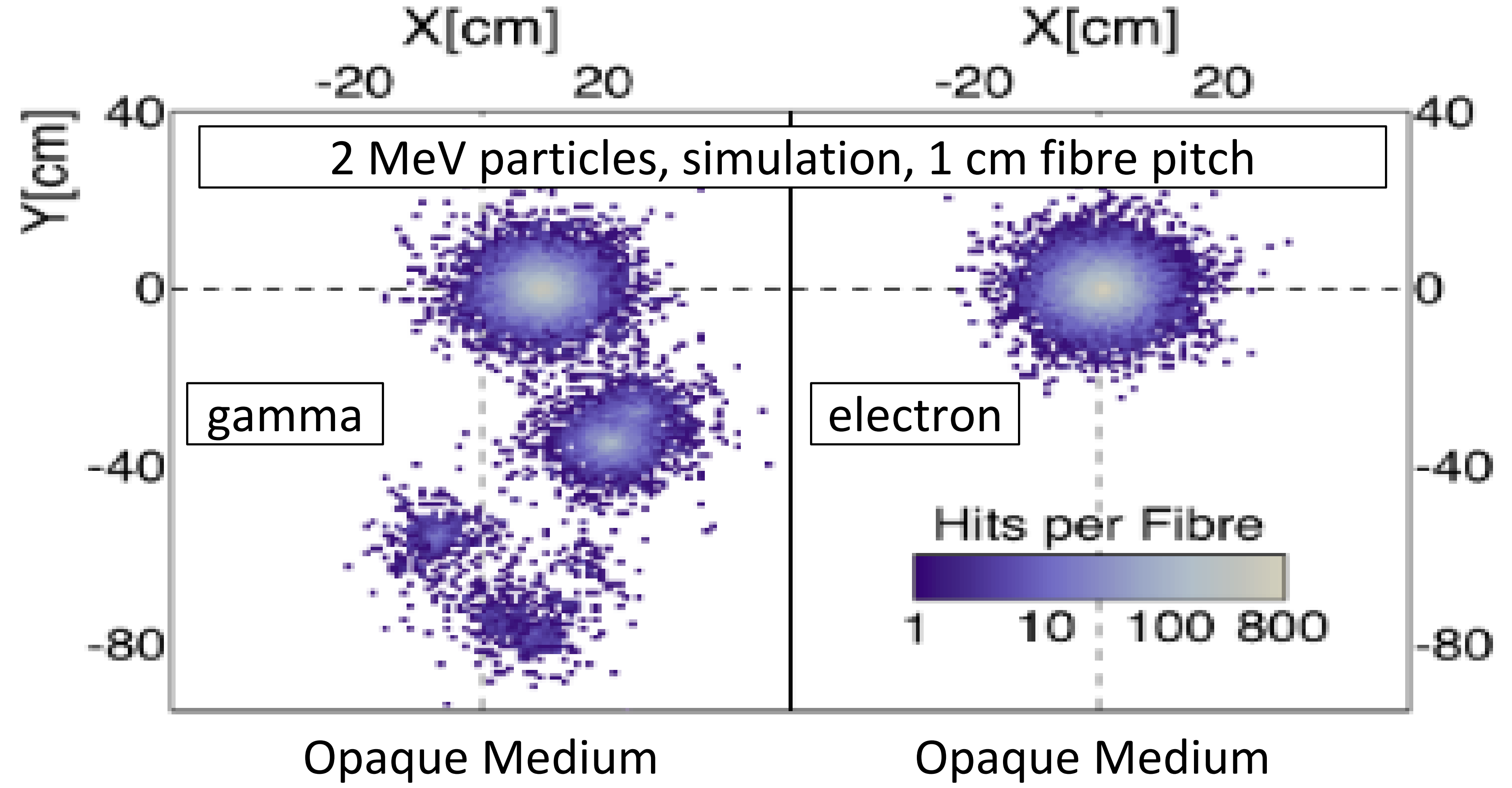
→ e.g. 98 wt.% solvent + 2 wt.% wax + primary and secondary wavelength shifters

→ opaqueness through scattering without absorption (Mie scattering)

→ particle-dependent morphology of confined light blobs:



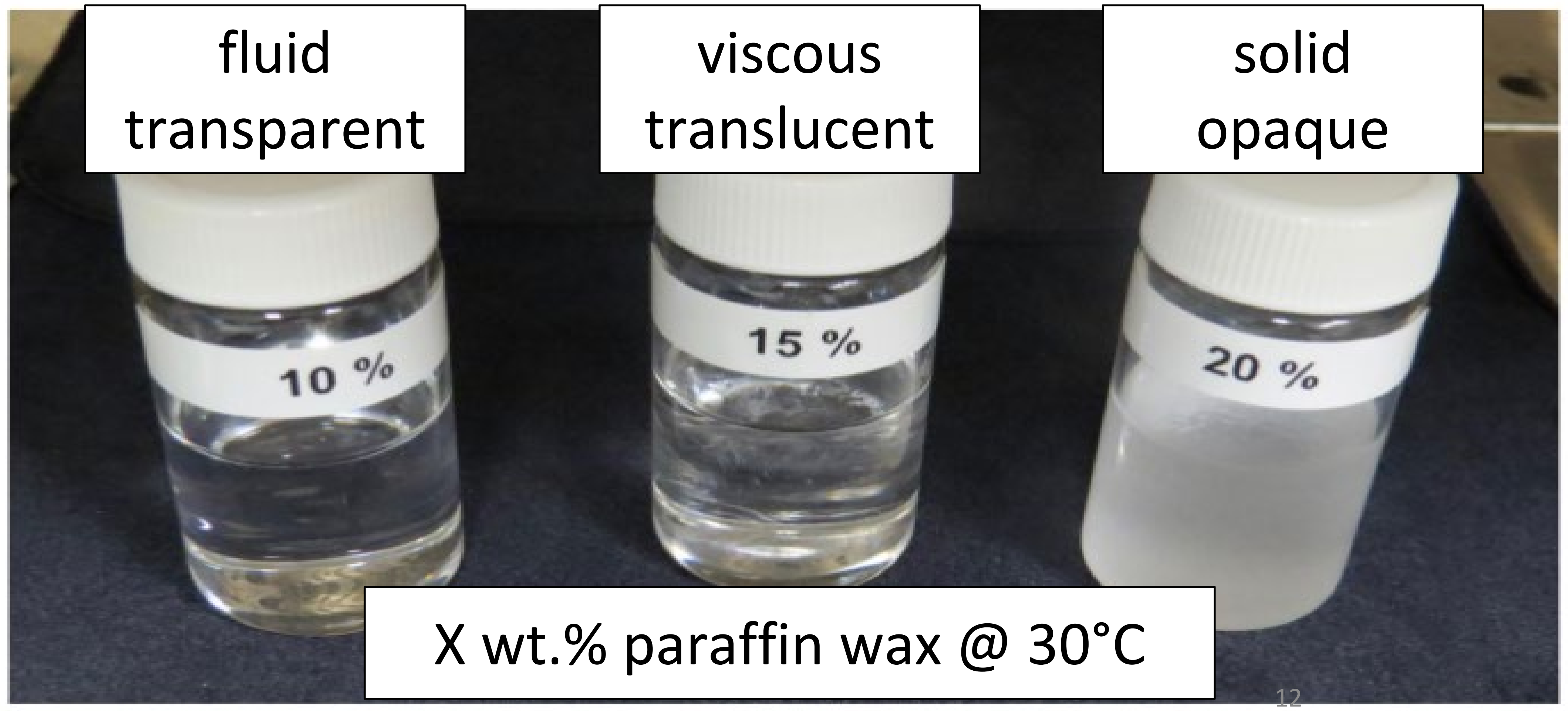




→ several options for solvents and waxes:

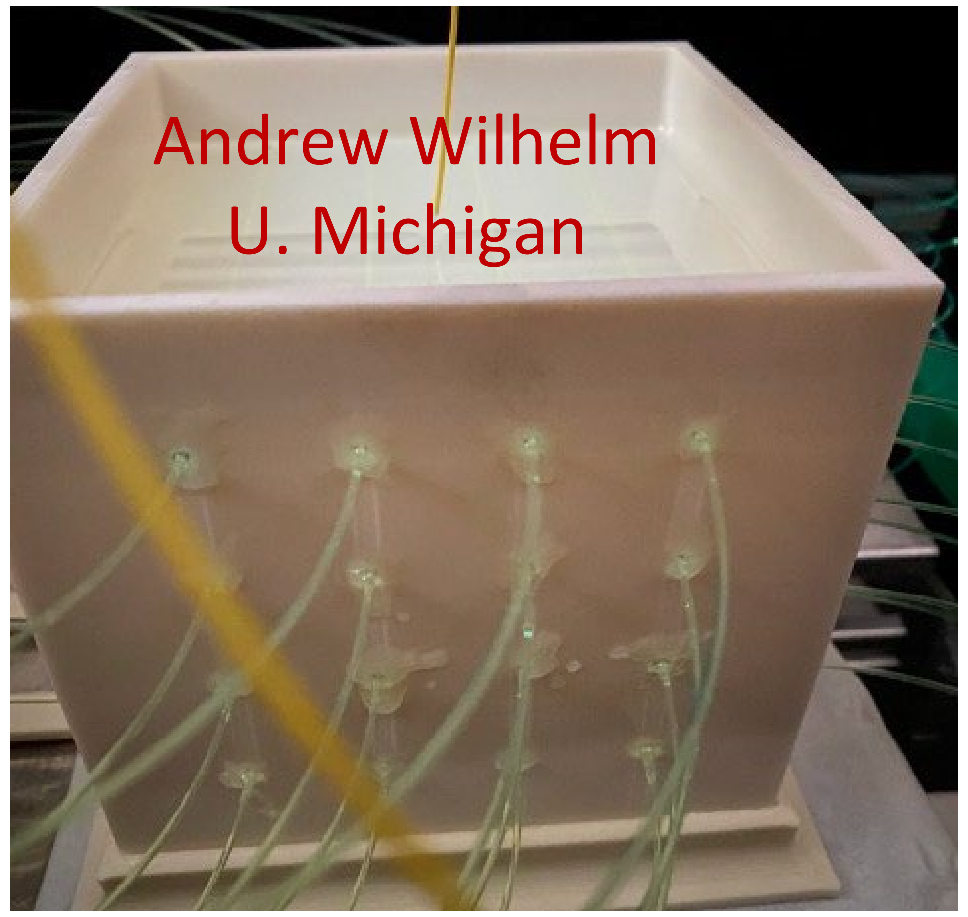
name	CAS number
LAB	67774-74-7
DIN	38640-62-9
o-PXE	6196-95-8
PC	95-63-6
xylene	1330-20-7
toluene	108-88-3

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

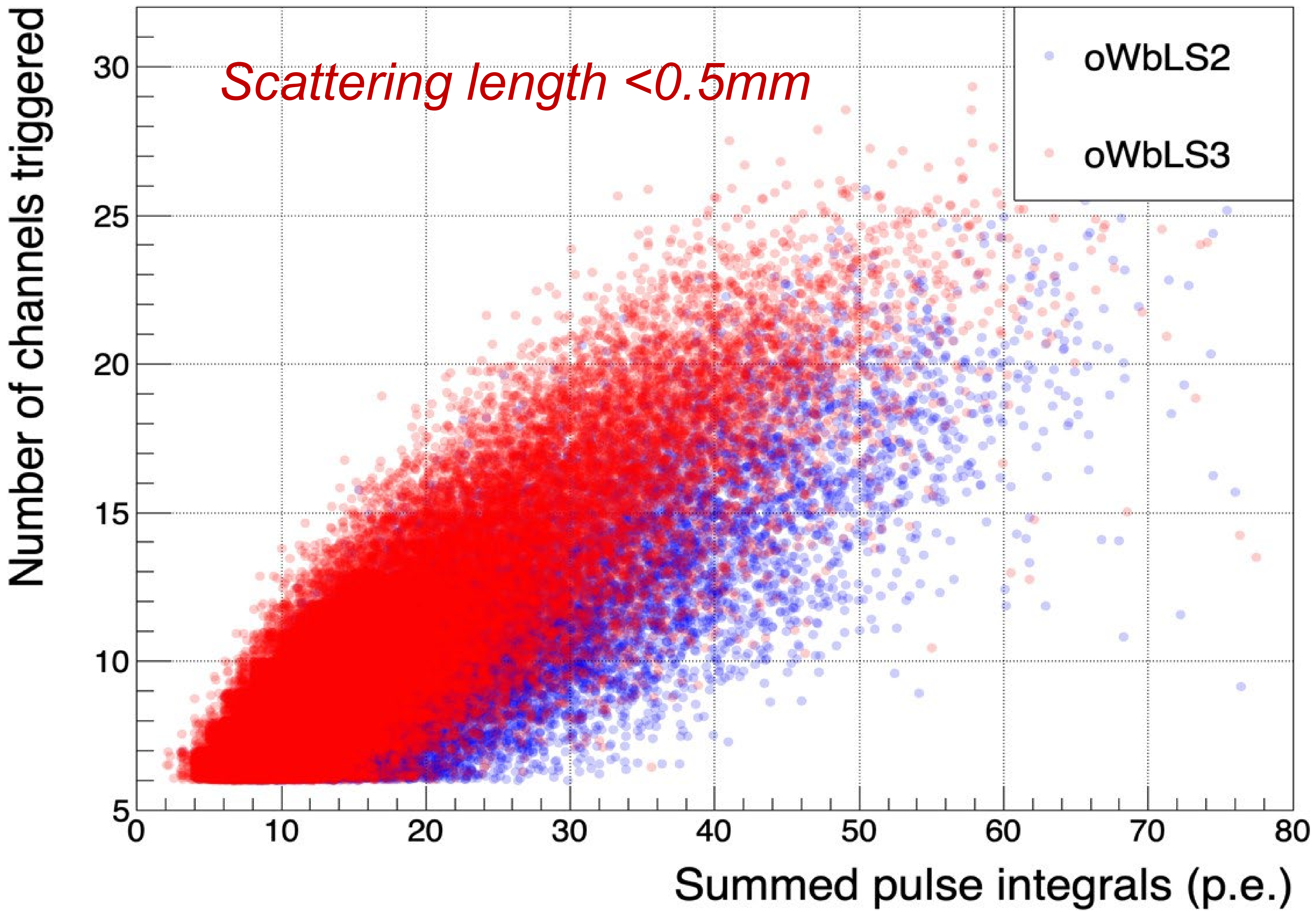


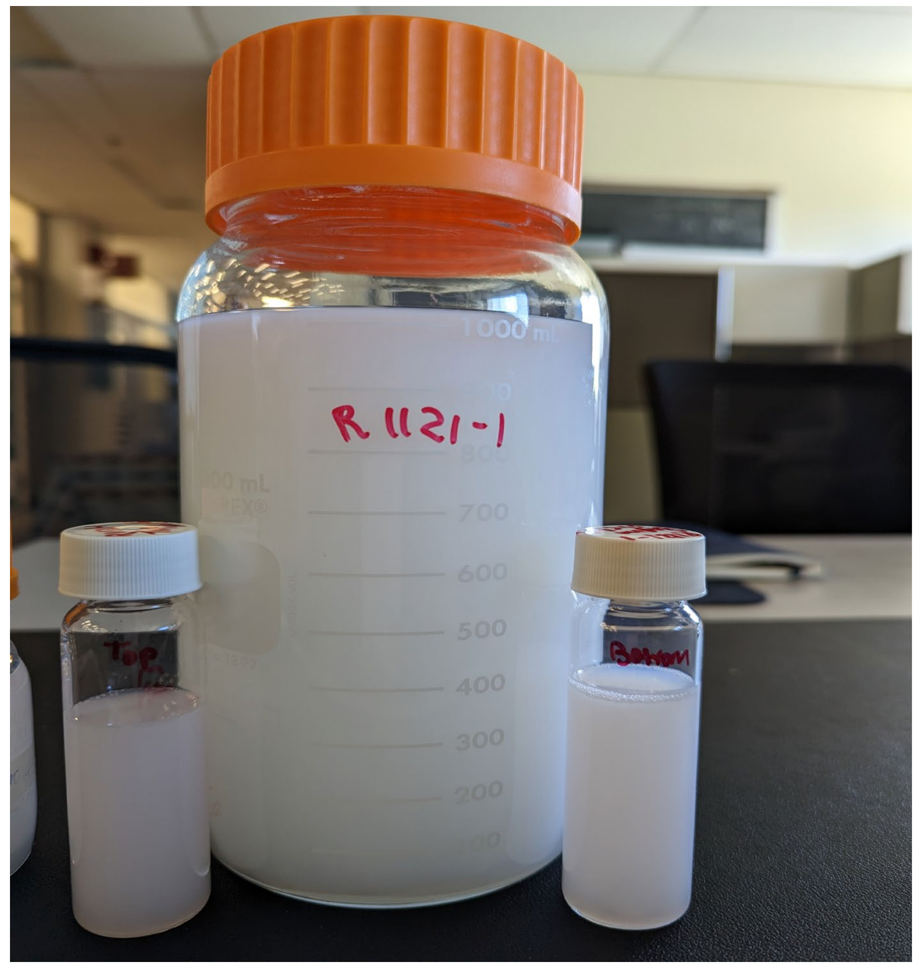
→ high metal loading possible

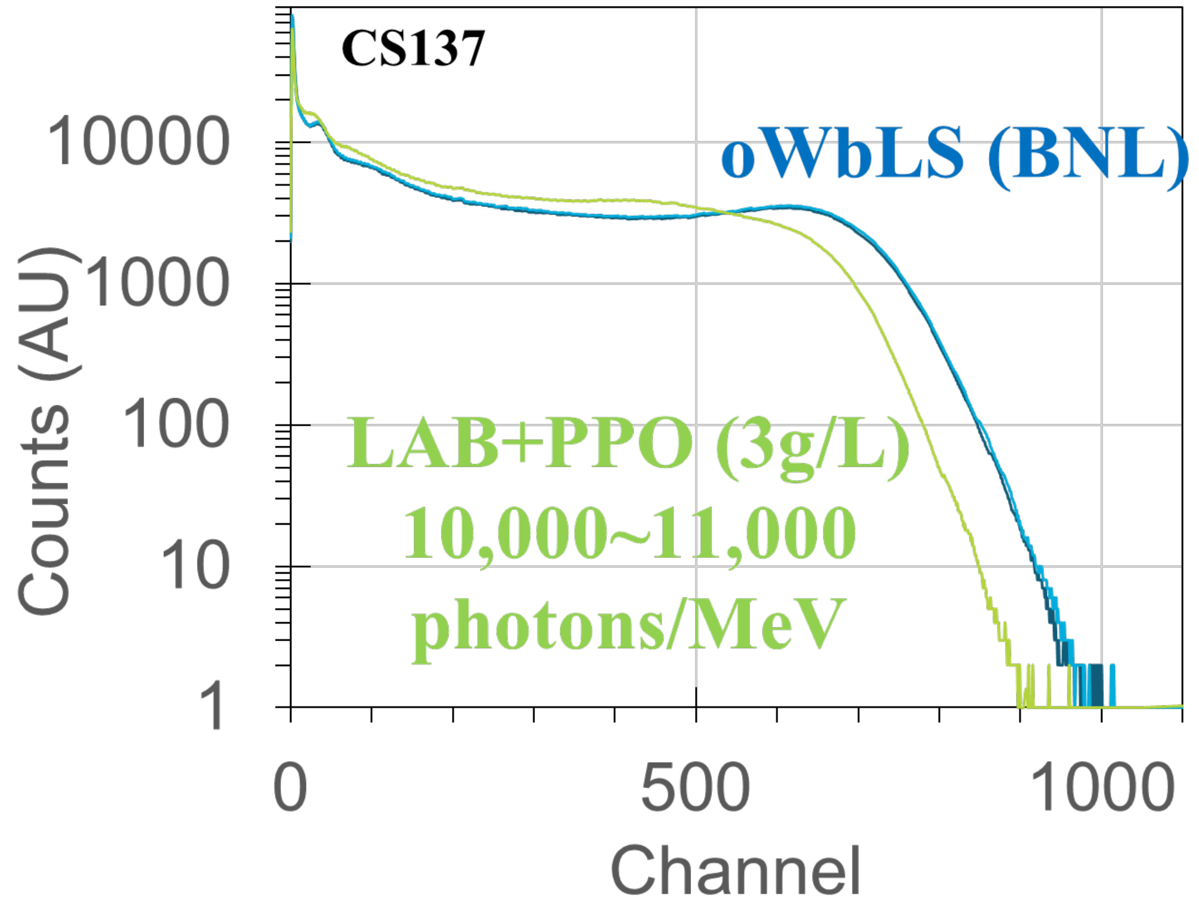
Oil-like WbLS (DIN- & LAB-based)



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*

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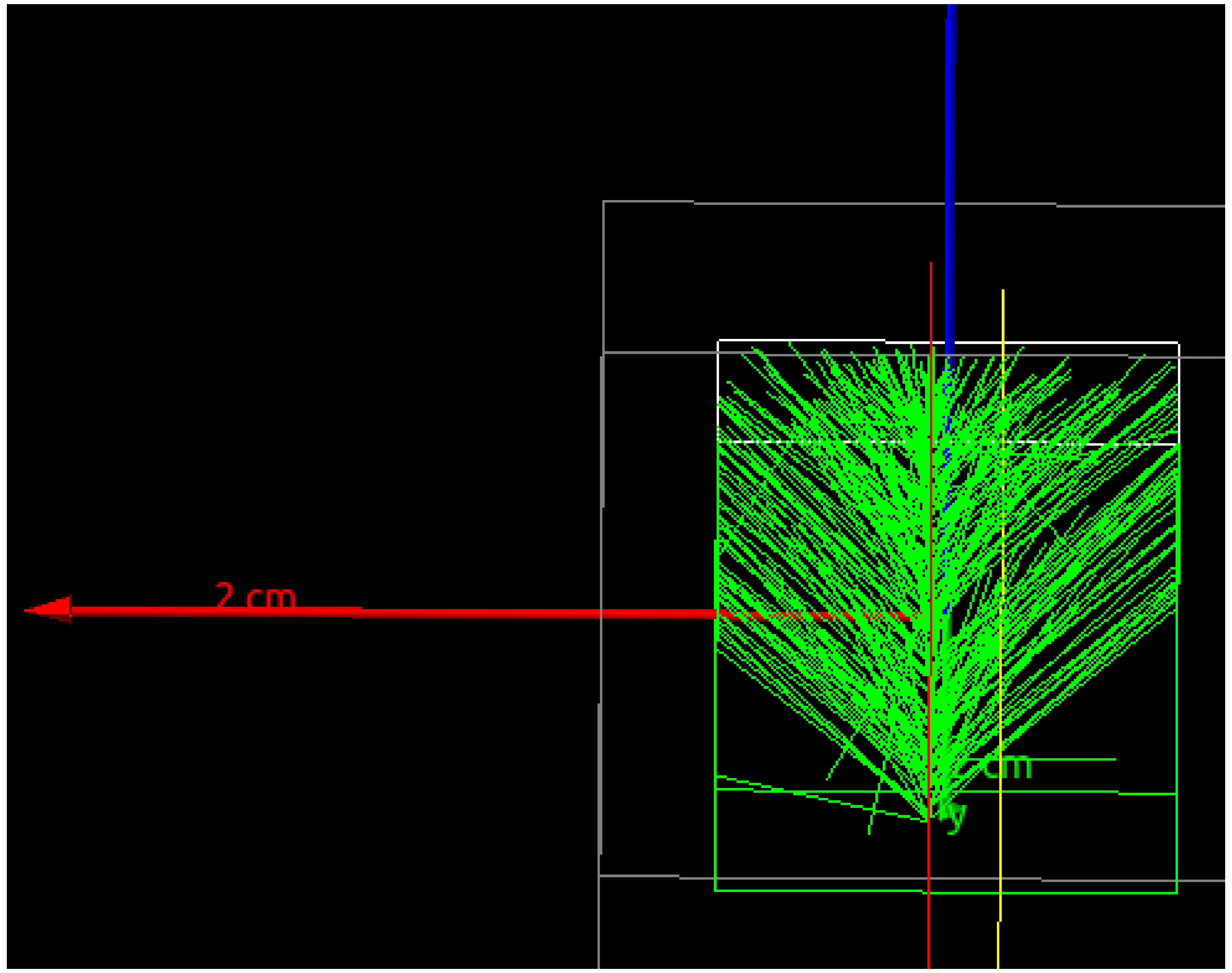
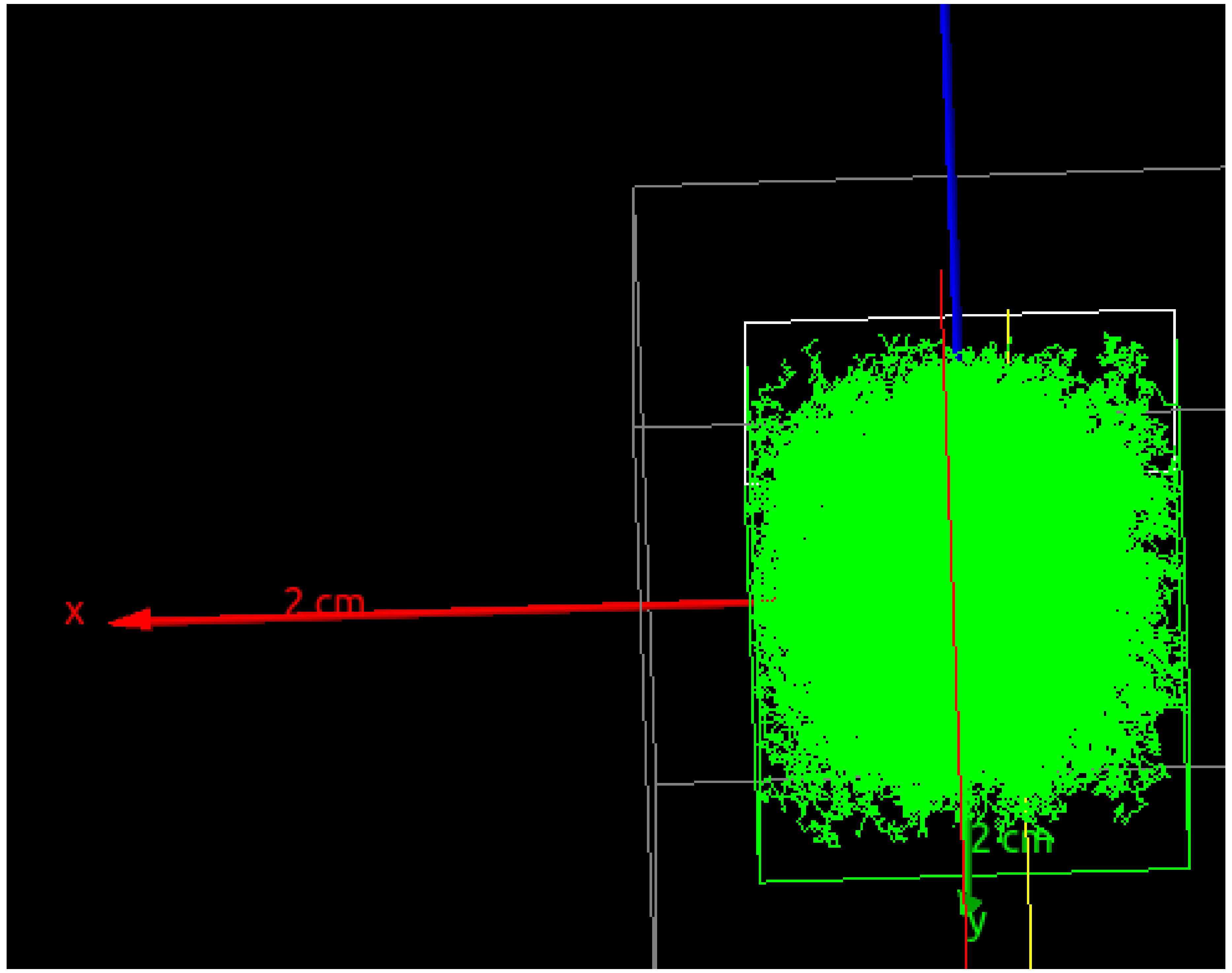
3D Opaque WbLS detector (3D-oWbLS)

Typical detector with long scattering length



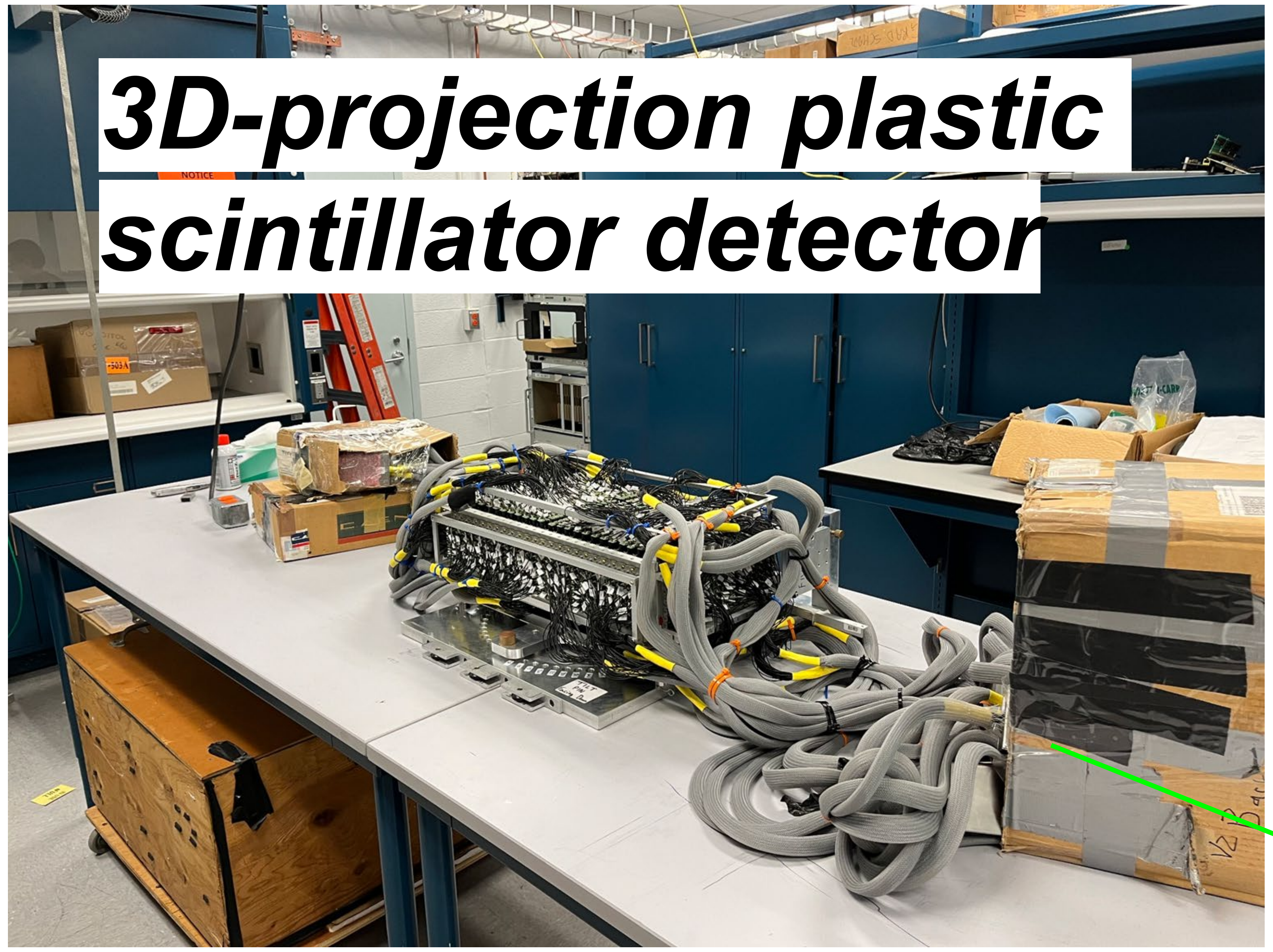
short scattering length (~ mm)

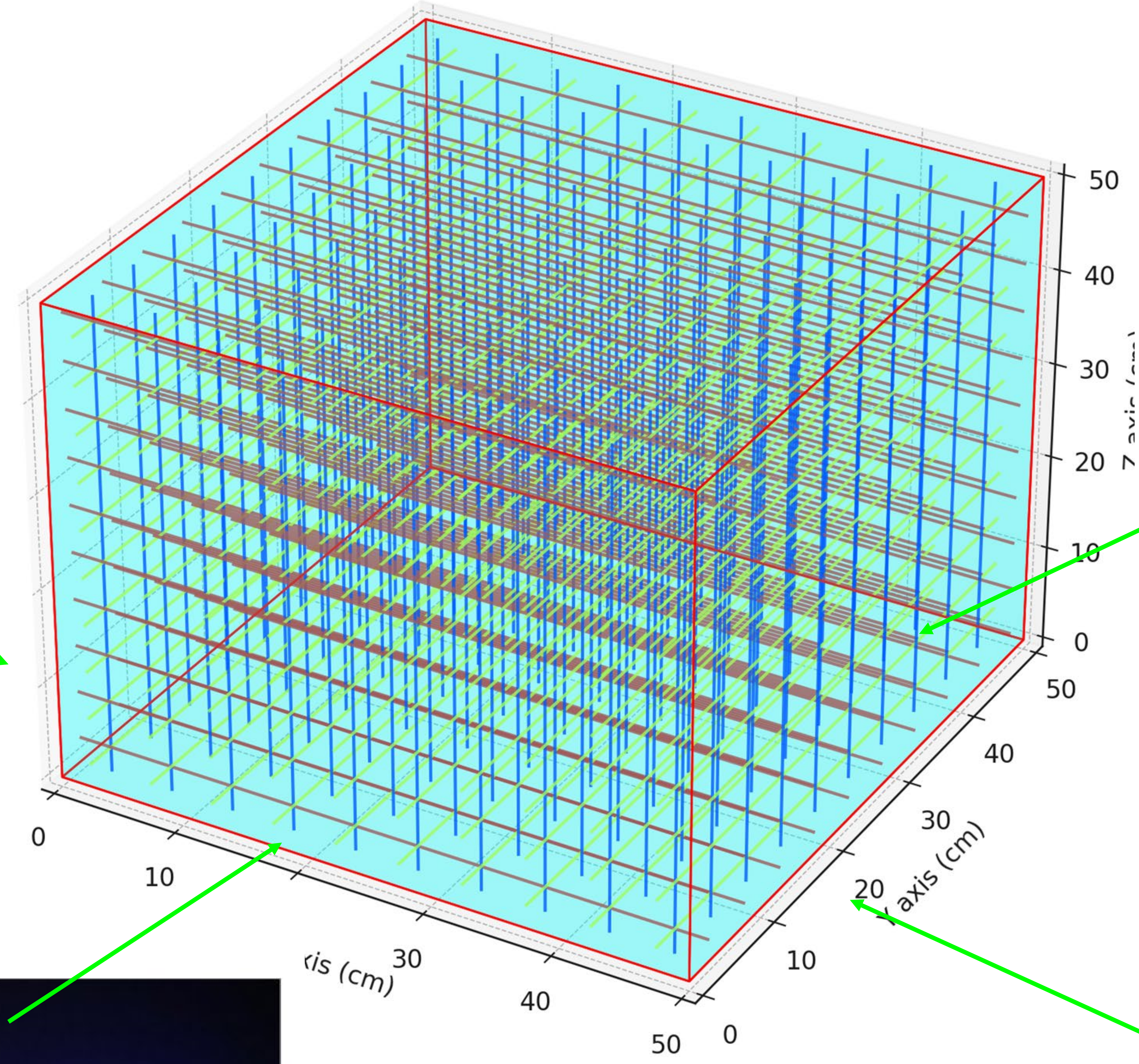


CPAD 2024 (Guang)

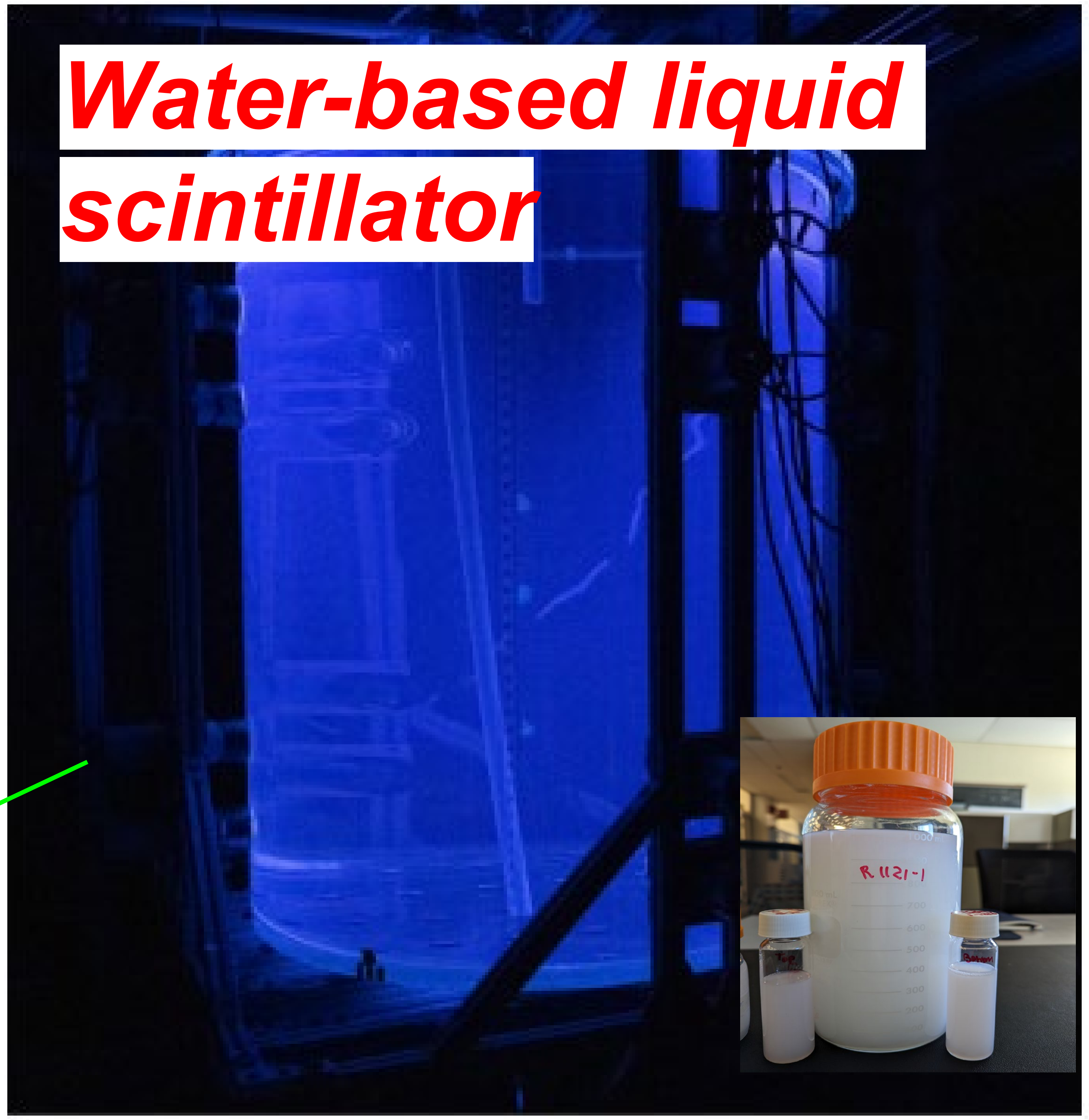
Large-scale 3D projection Calorimeter

3D-projection plastic scintillator detector

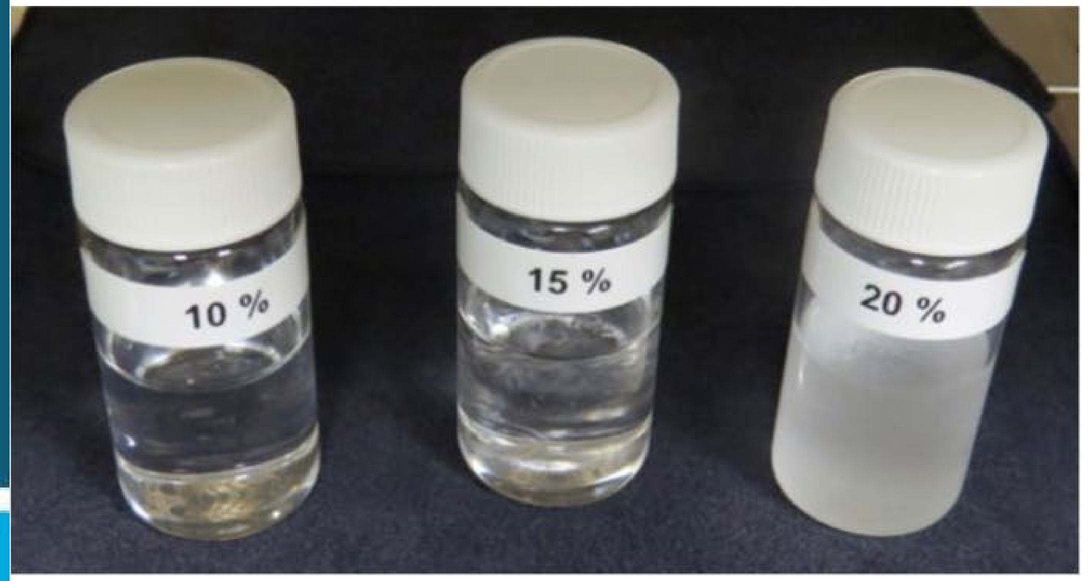


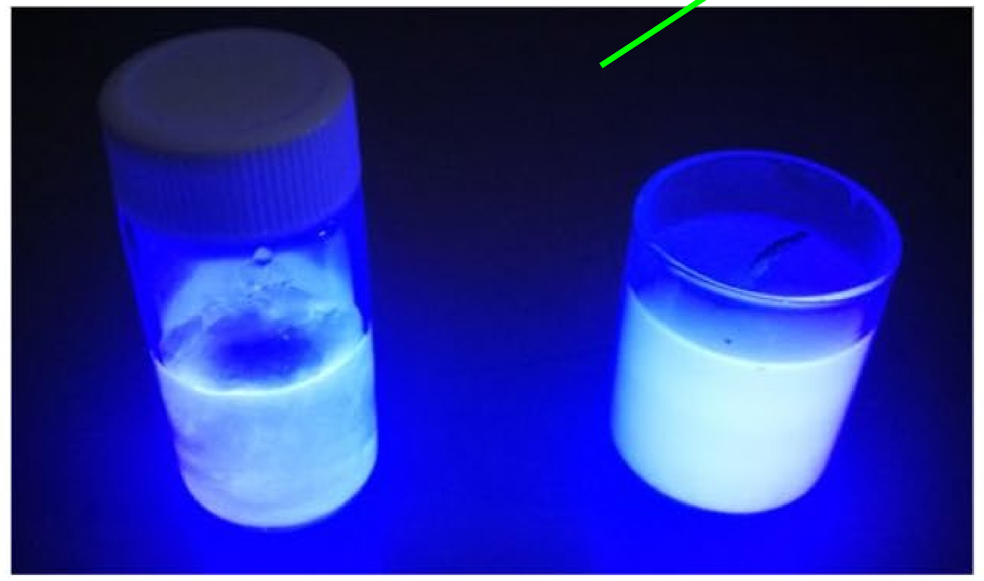


Water-based liquid scintillator



Liquid scintillator -> **Wax-added**

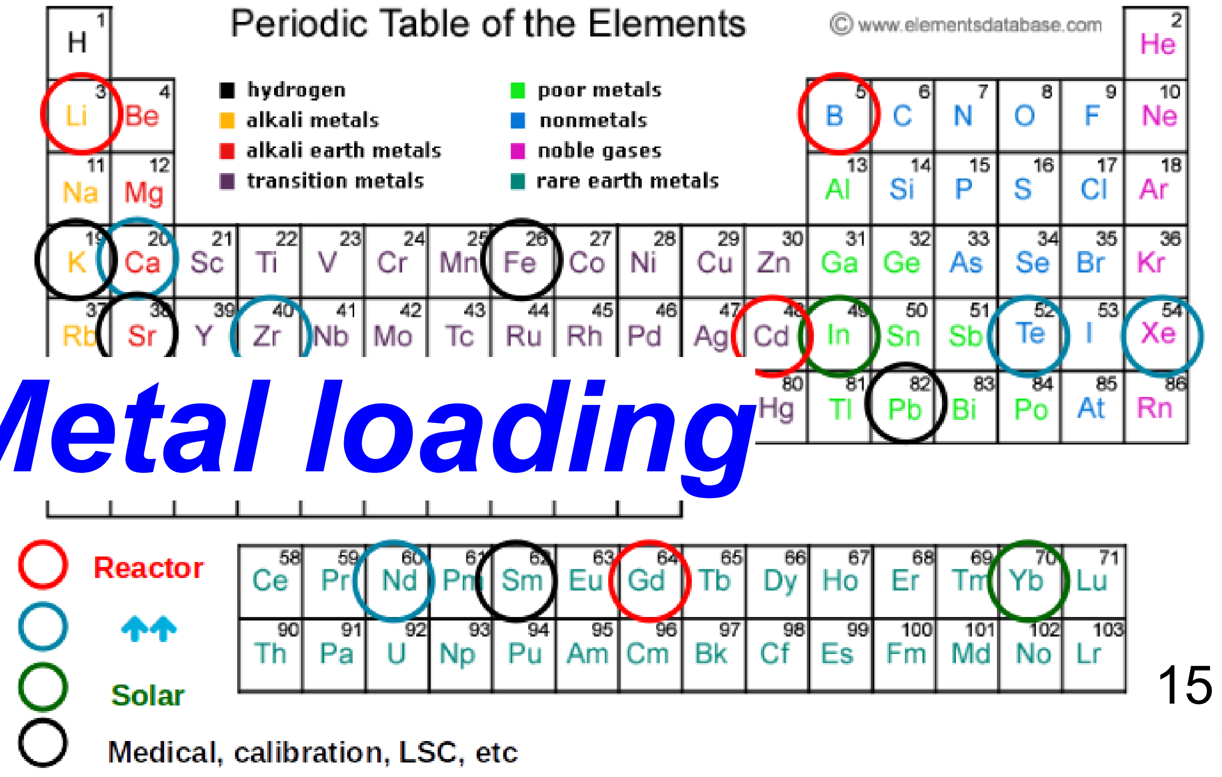




Short-scattering opaque detector

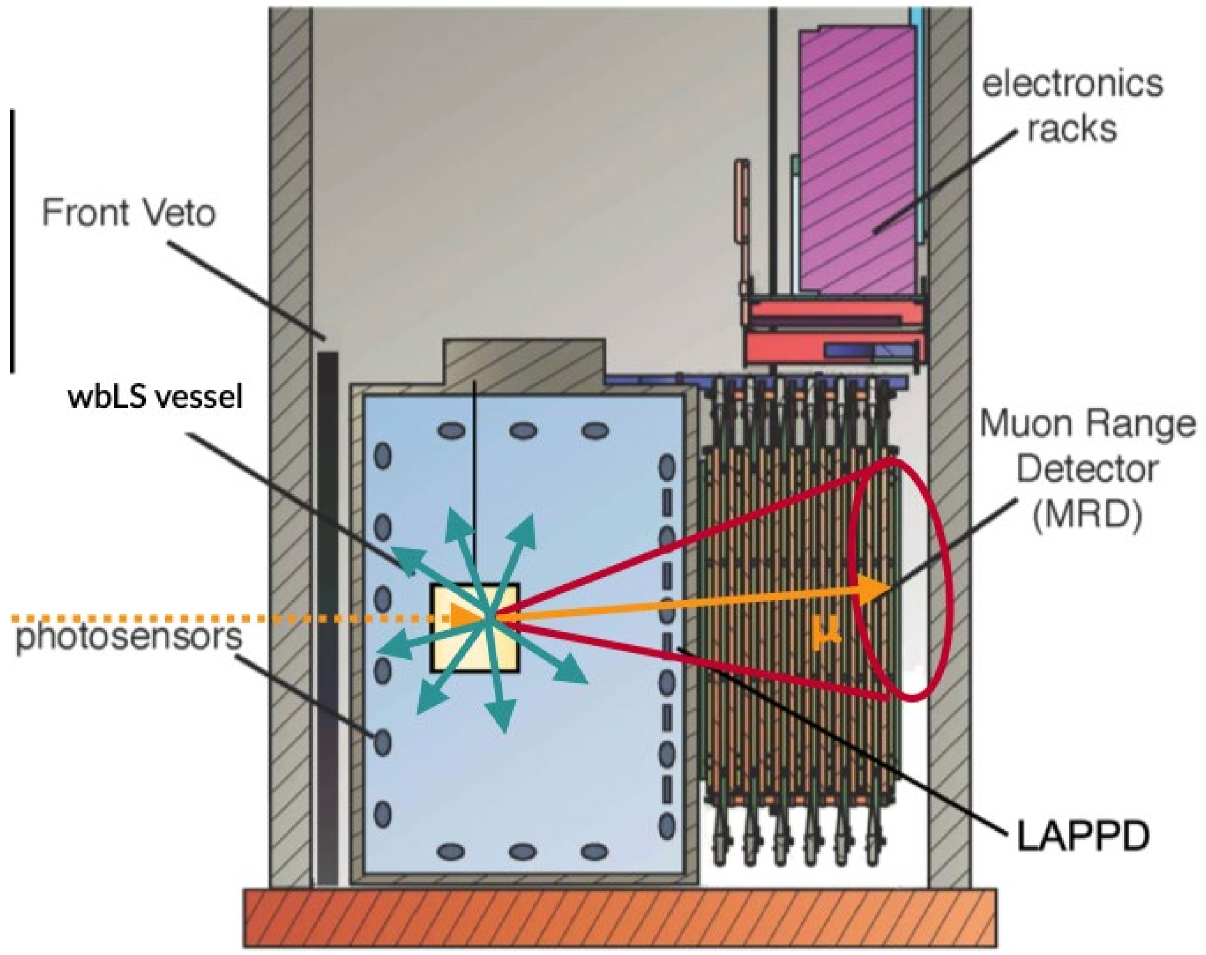
G.Yang

Metal-doped (Water-based) Liquid Scintillators for neutrino physics and other frontiers



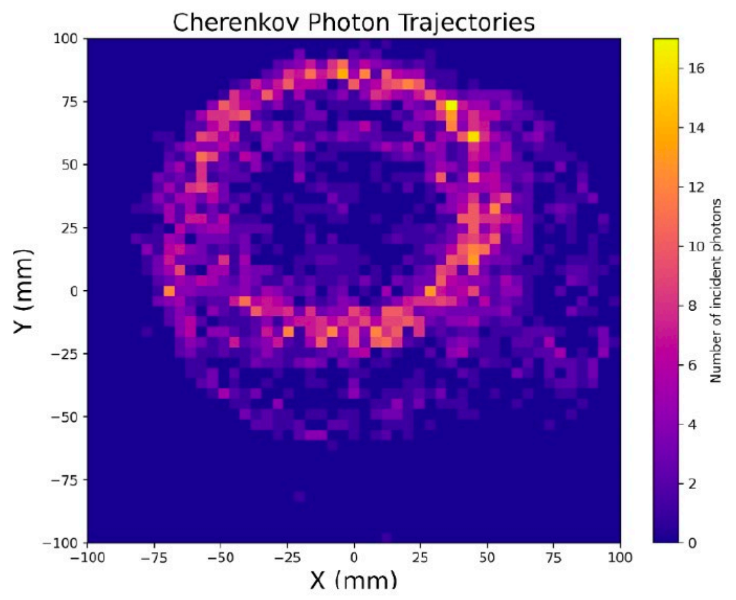
Metal loading

Path to a kiloton-scale Detector



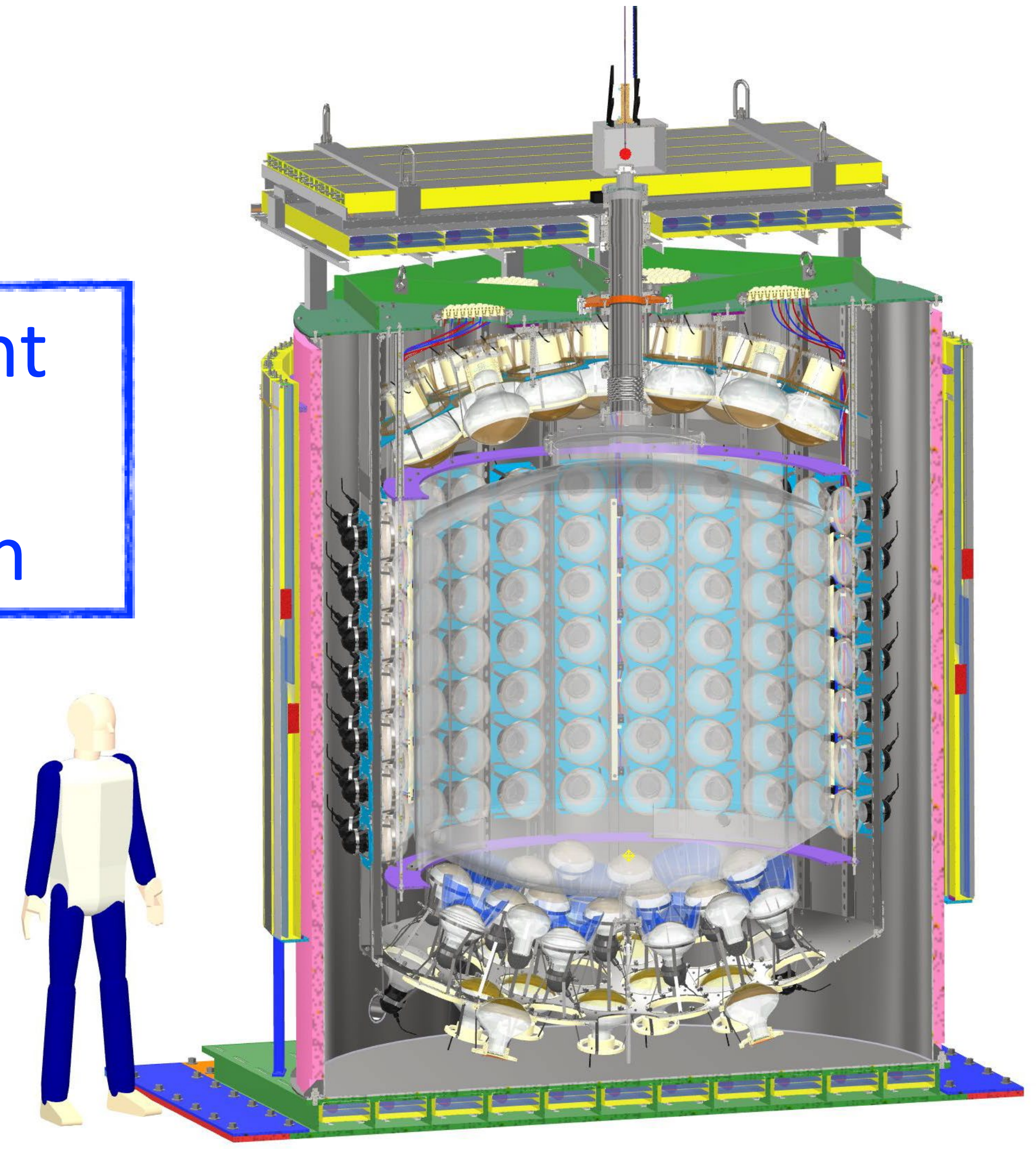
ANNIE: 365 kg

High-energy event reconstruction, neutrino detection

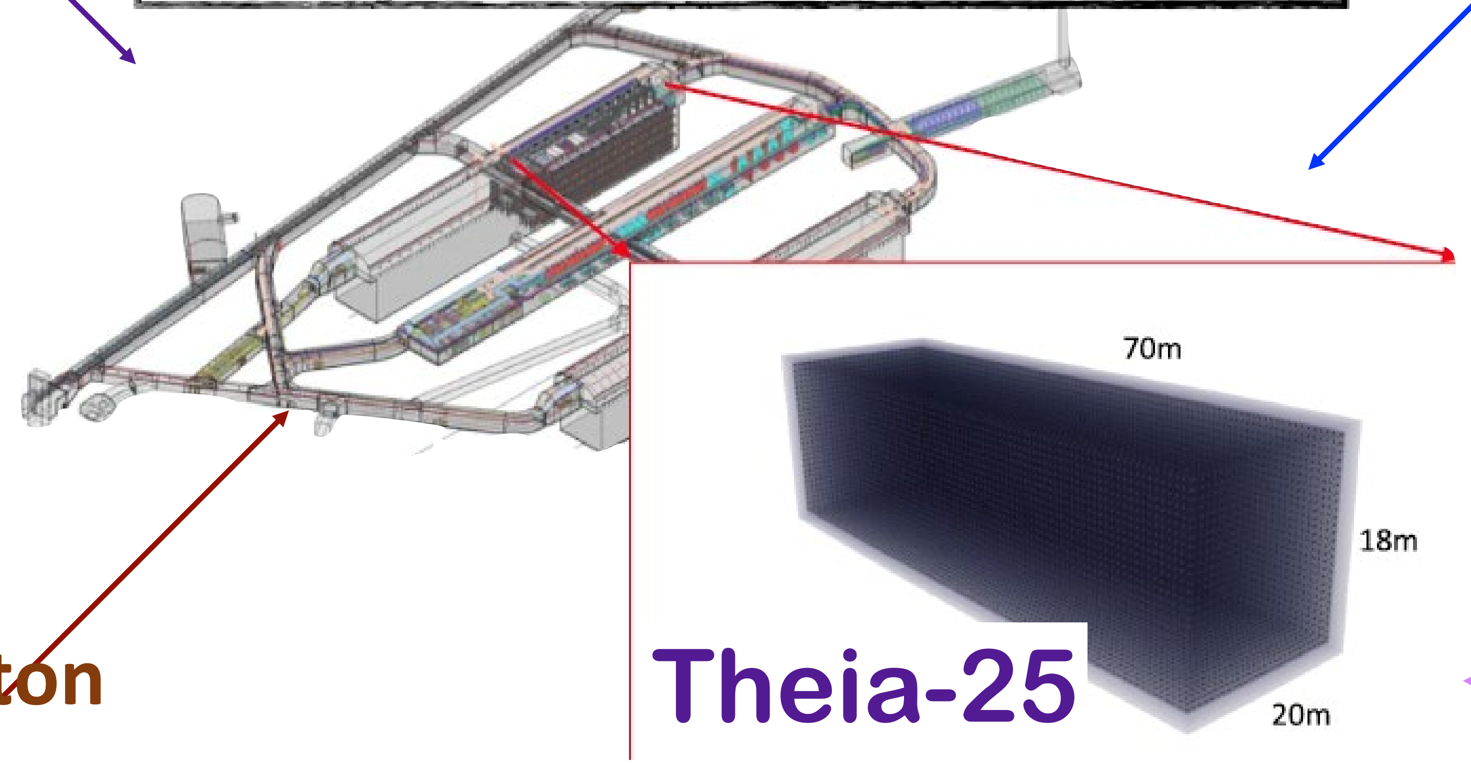


Eos: 20 ton

Low-energy event reconstruction, model validation



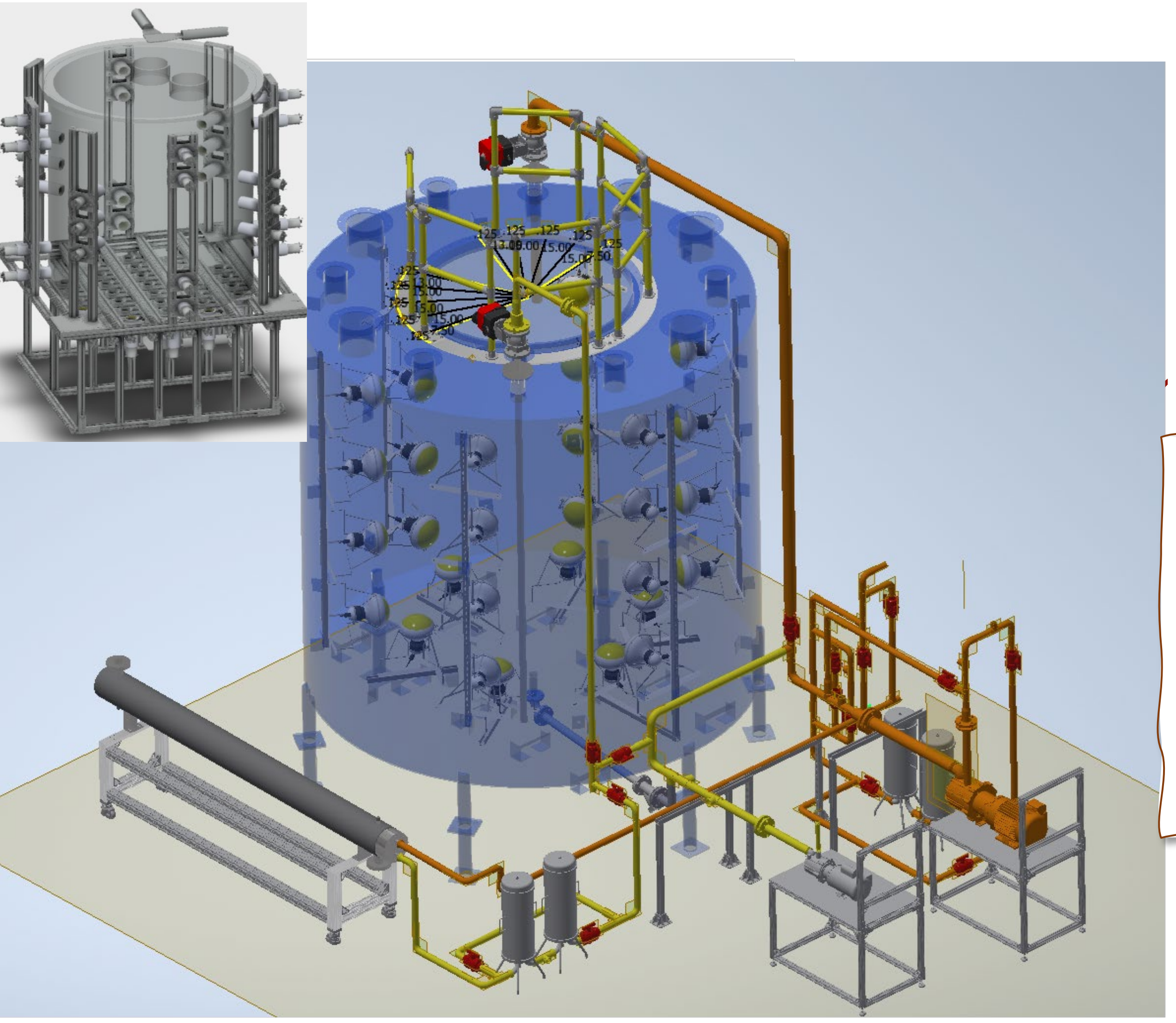
Building on a broad program of bench-top scale development



Theia-25

BNL: 1-and 30-ton

Deployment, purification, recirculation, transparency

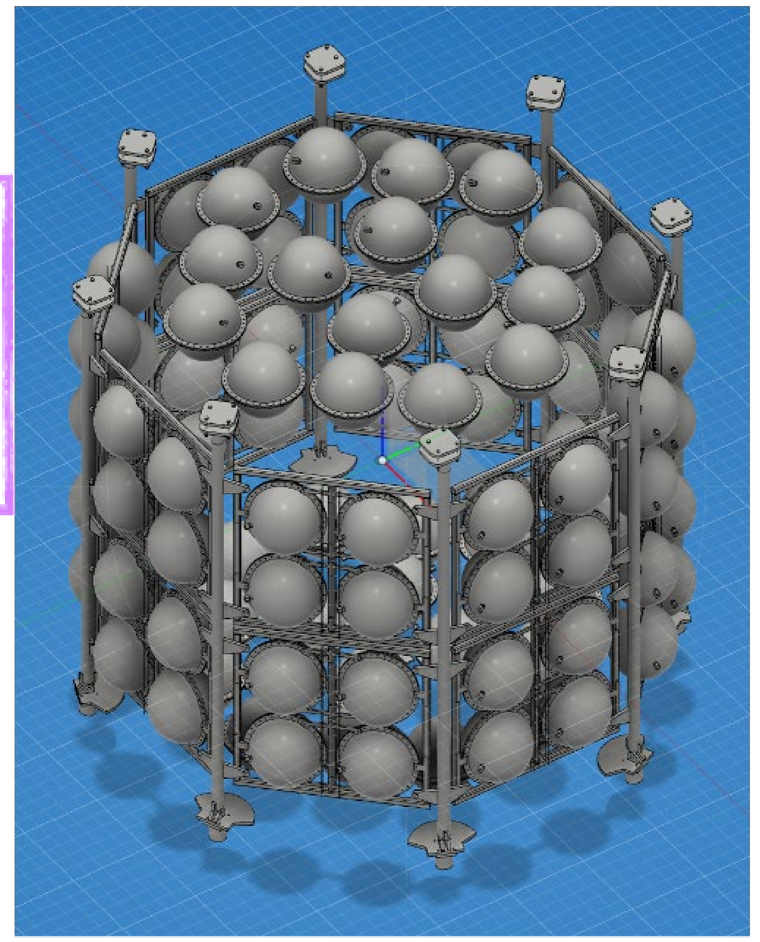


NuDot: 1 ton

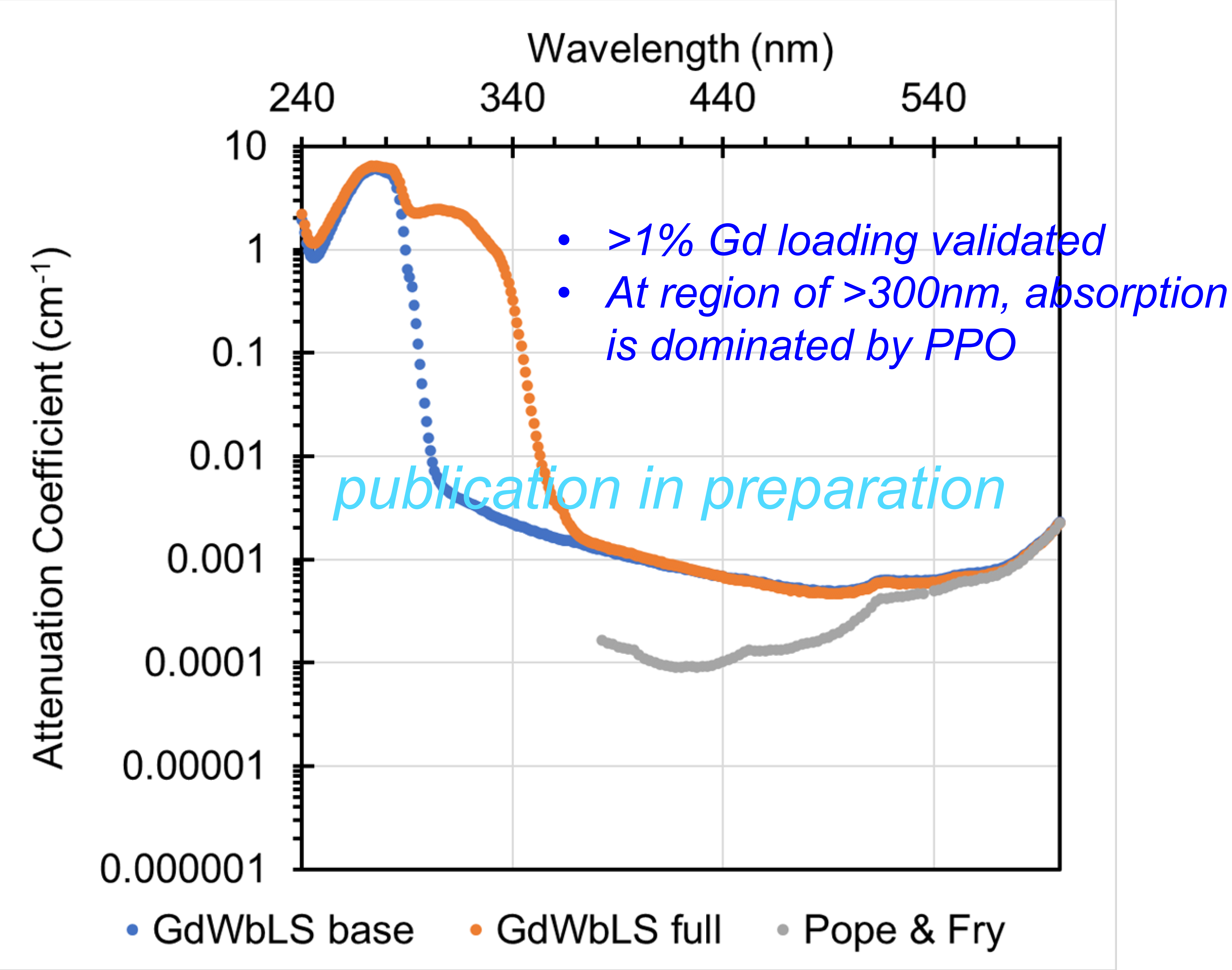
Isotope loading, NLDBD topology

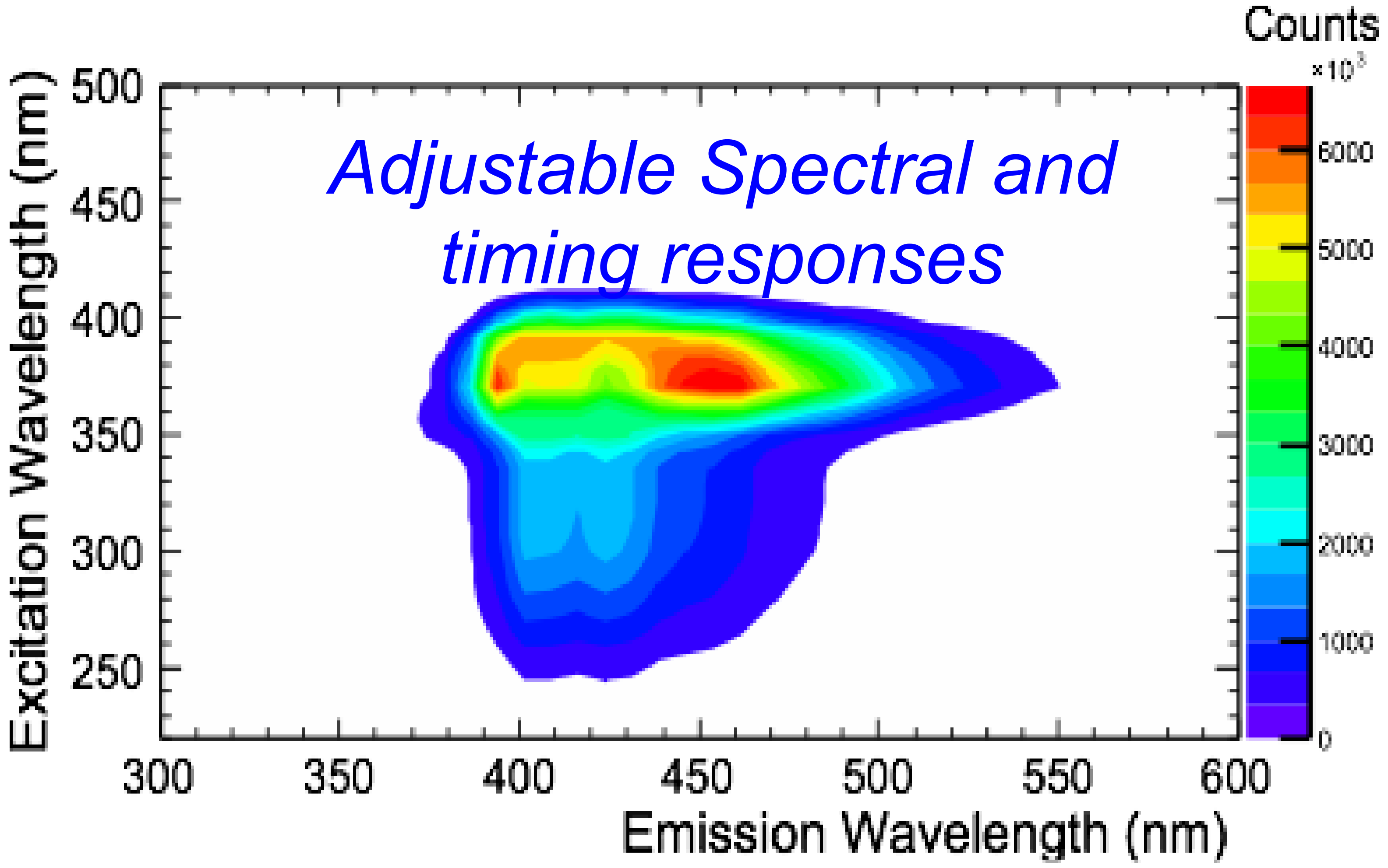
BUTTON: 30 ton

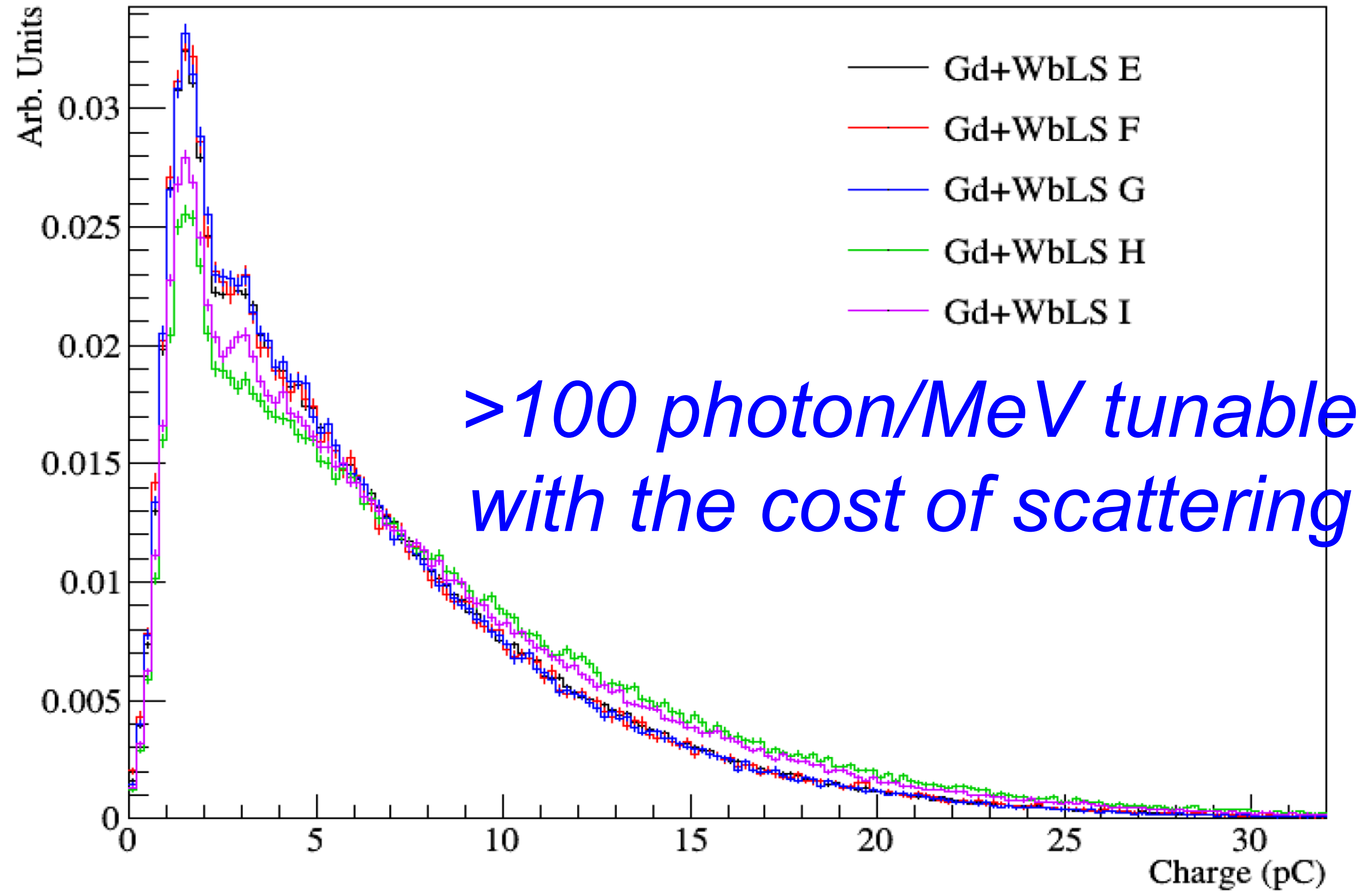
Underground deployment, low bkg verification



1% (Gd)WbLS 30-ton BNL, BUTTON, ANNIE







- *127.6 +/-17.6 (stat.) +/-19.8 (syst.); from 1-ton testbed, published in JINST 2024*
- *At 500nm, $\lambda_{scattering}$ ~ 50m and $\lambda_{absorption}$ > 60m*

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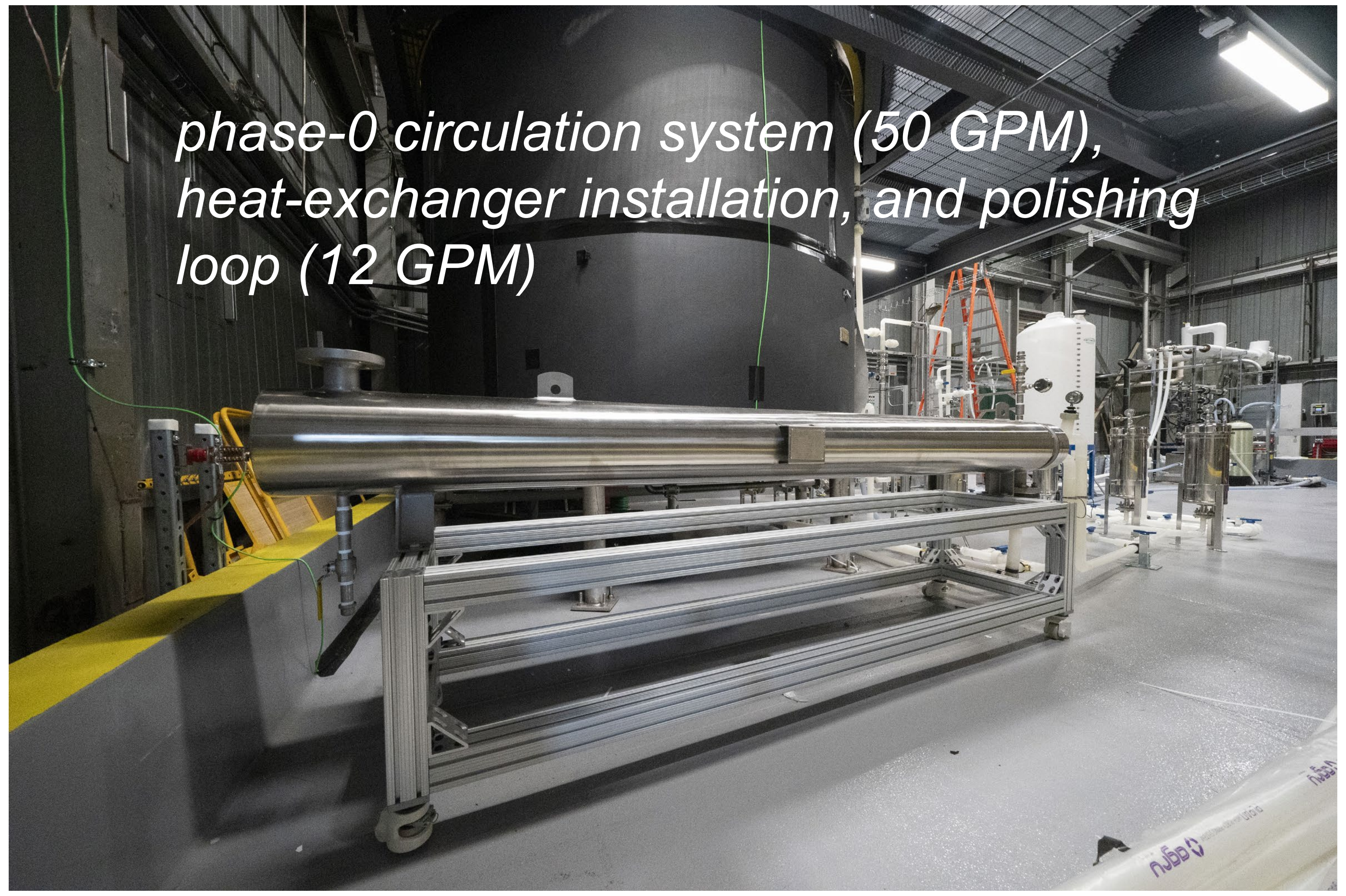
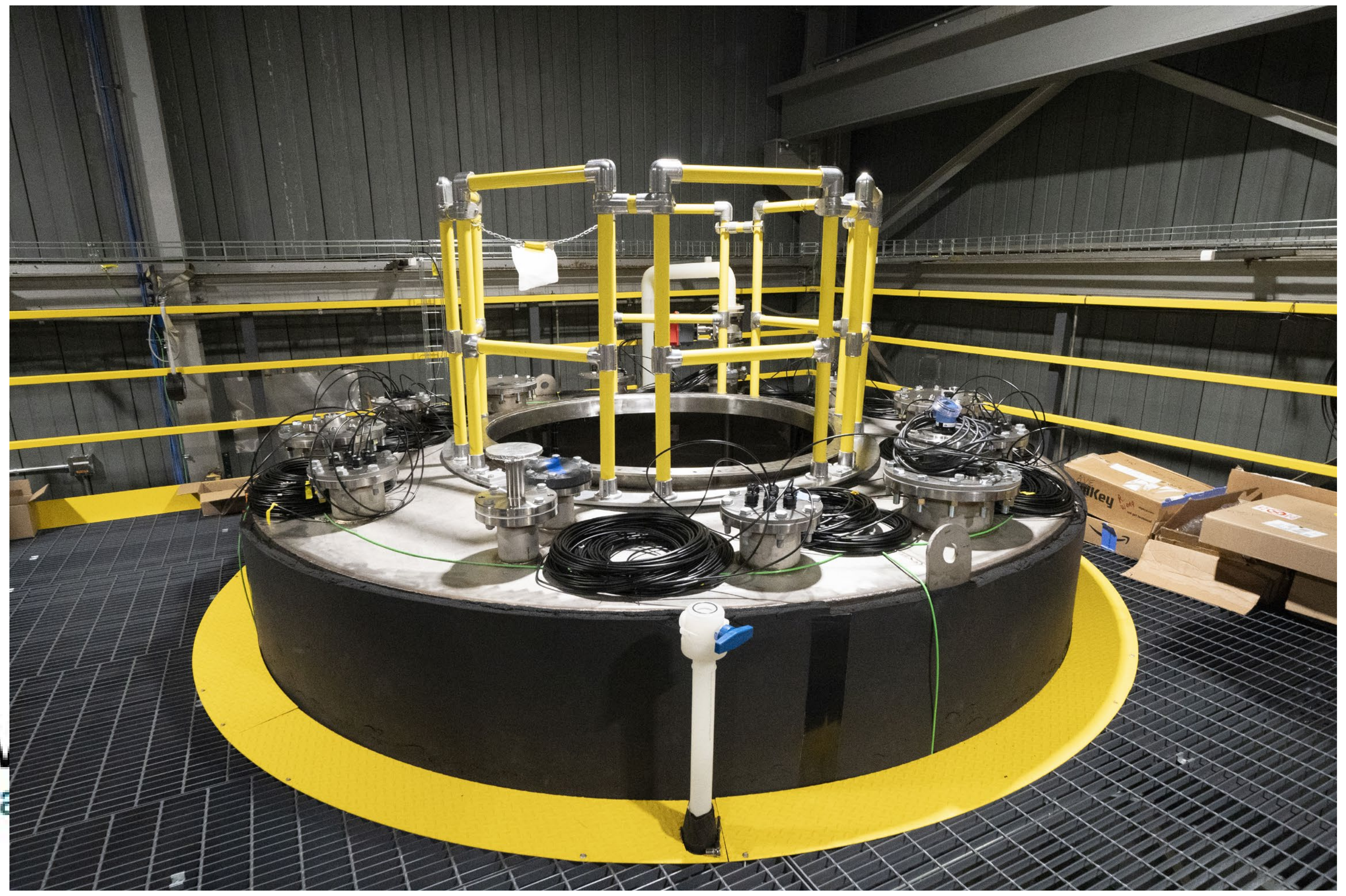
30-ton Demonstrator in 2024

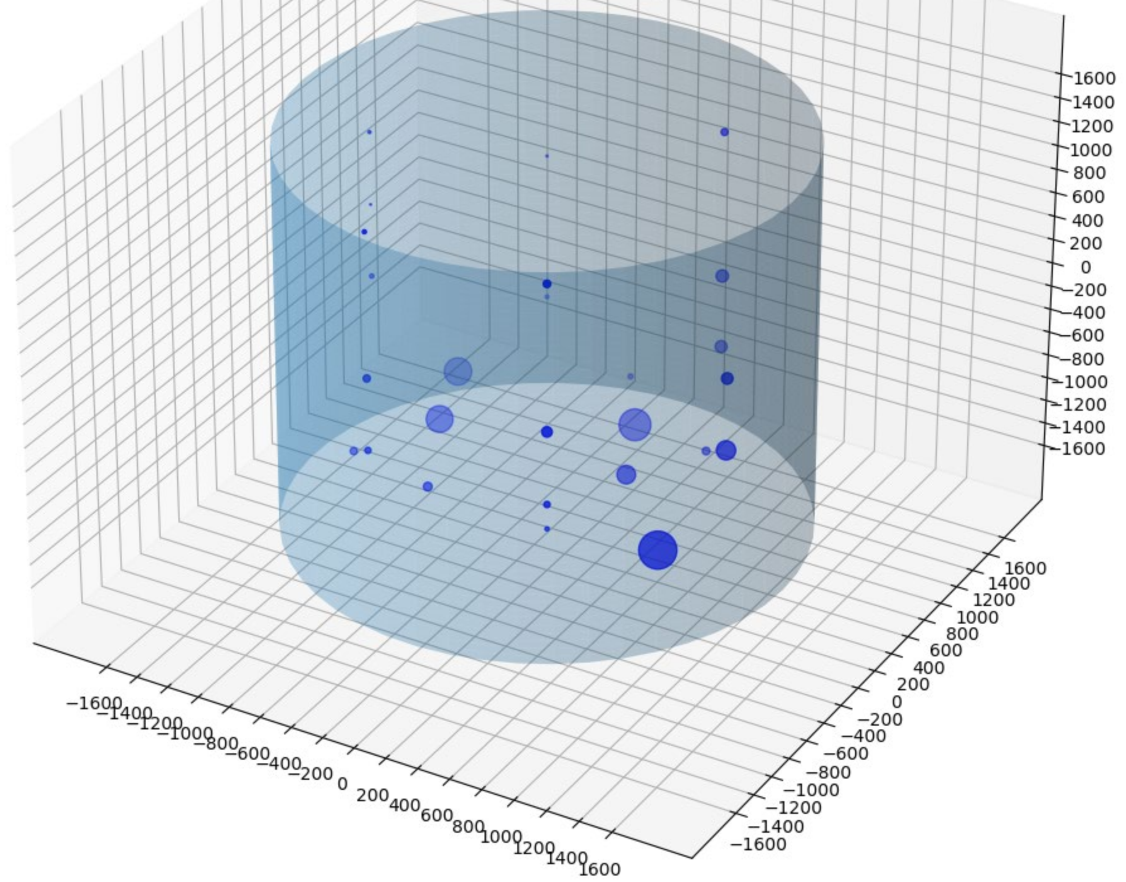
✓ commissioned in summer 2024

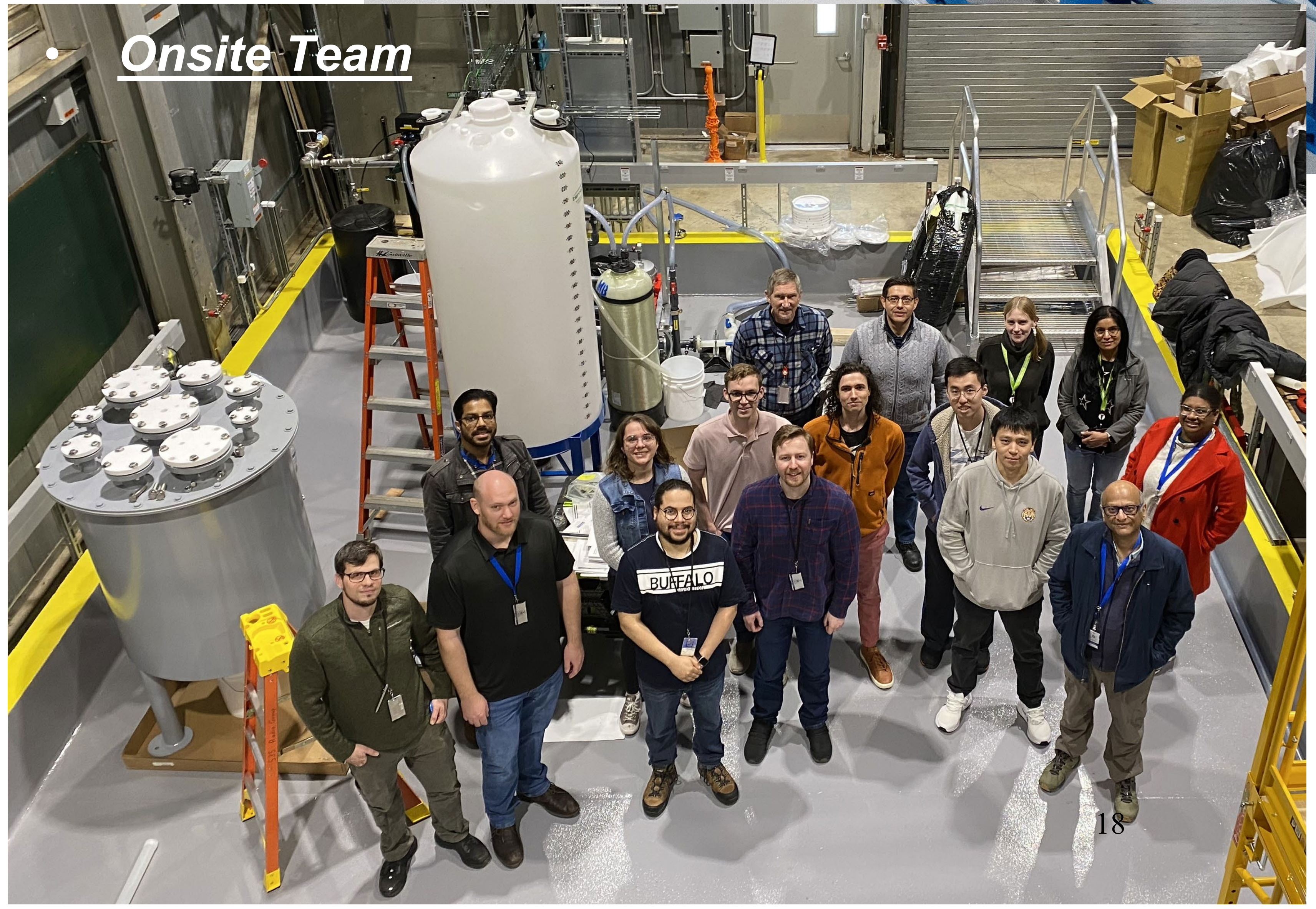


phase-0 circulation system (50 GPM), heat-exchanger installation, and polishing loop (12 GPM)

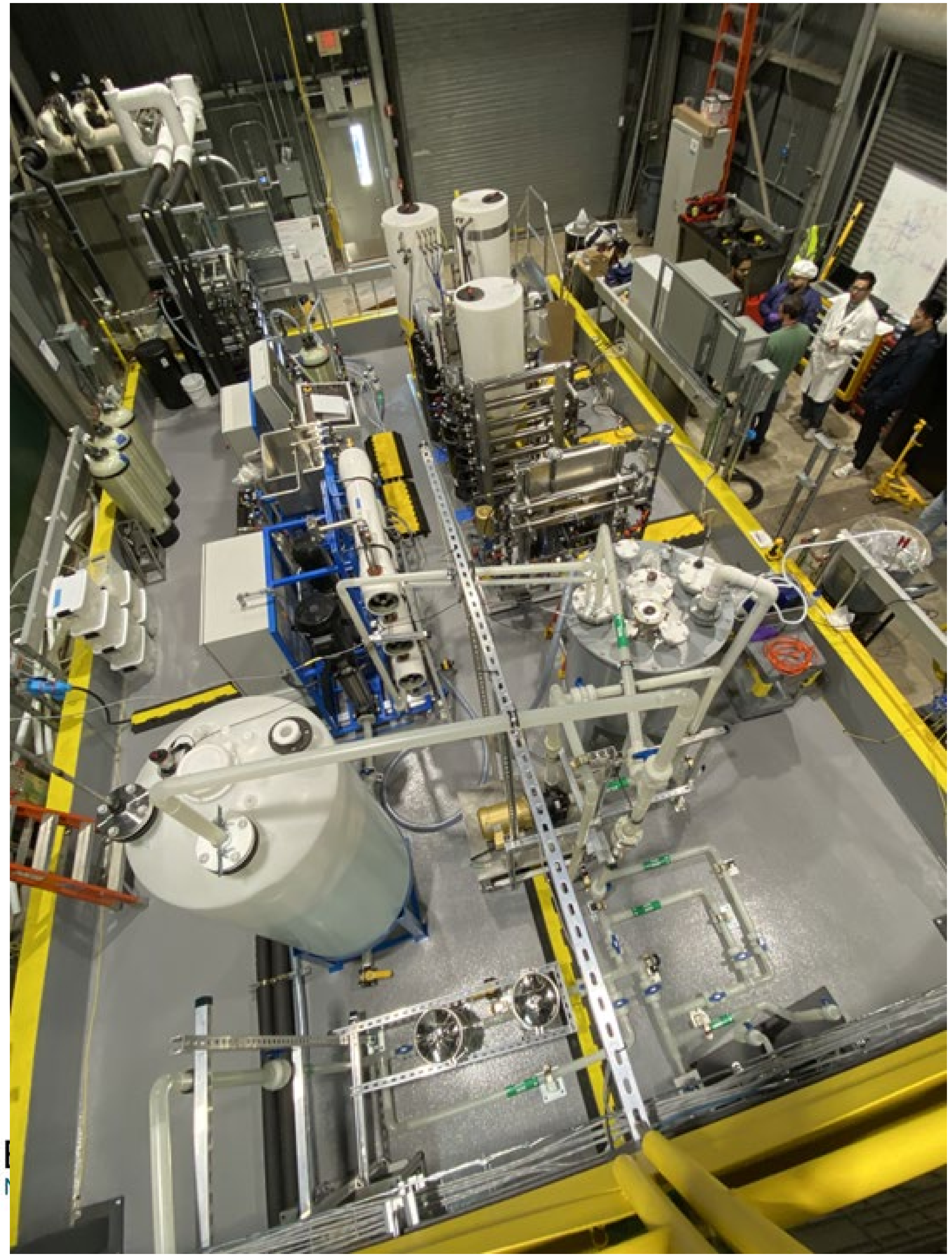


first paddle-triggered muon events in water (06/05/24)

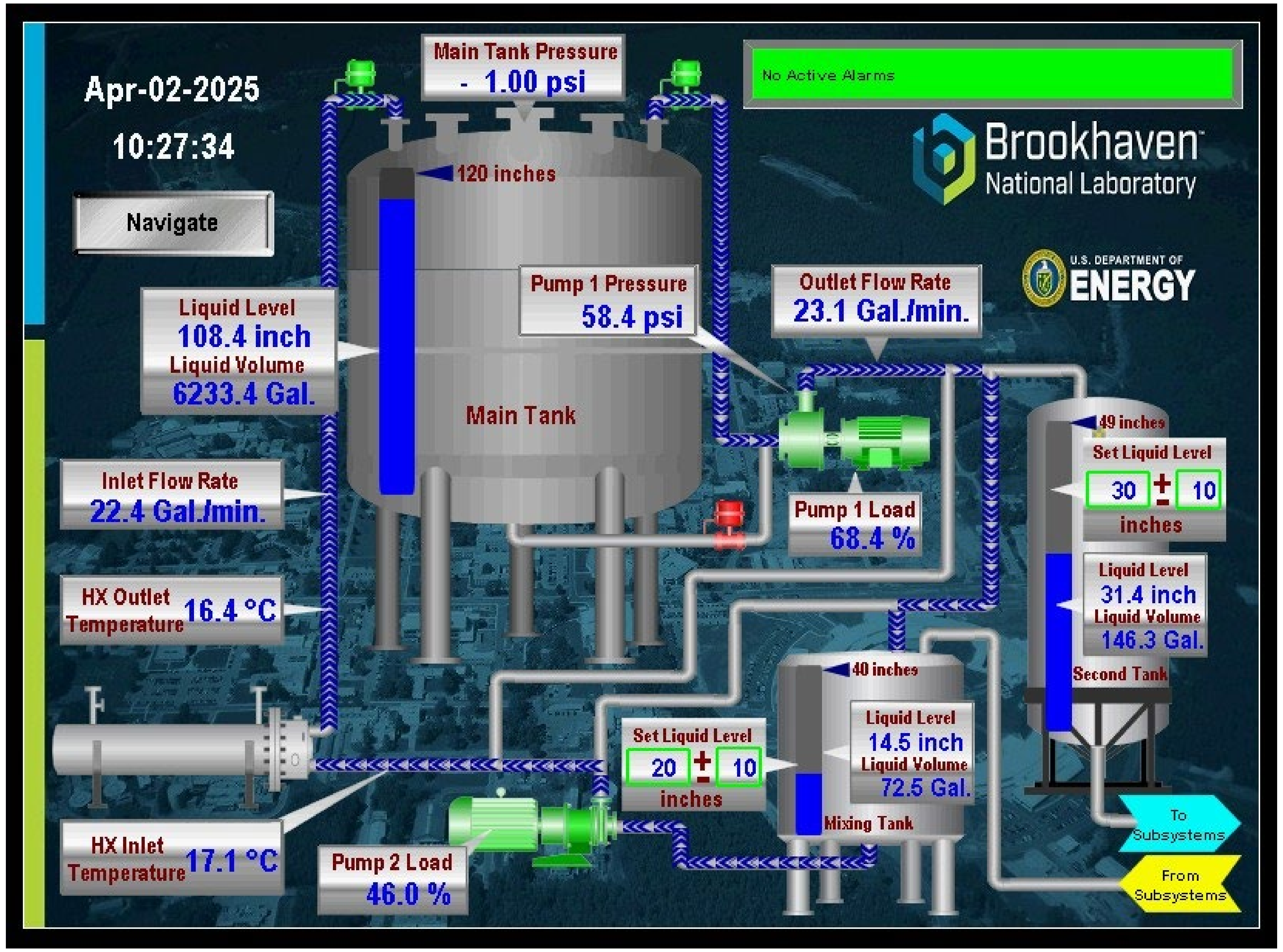




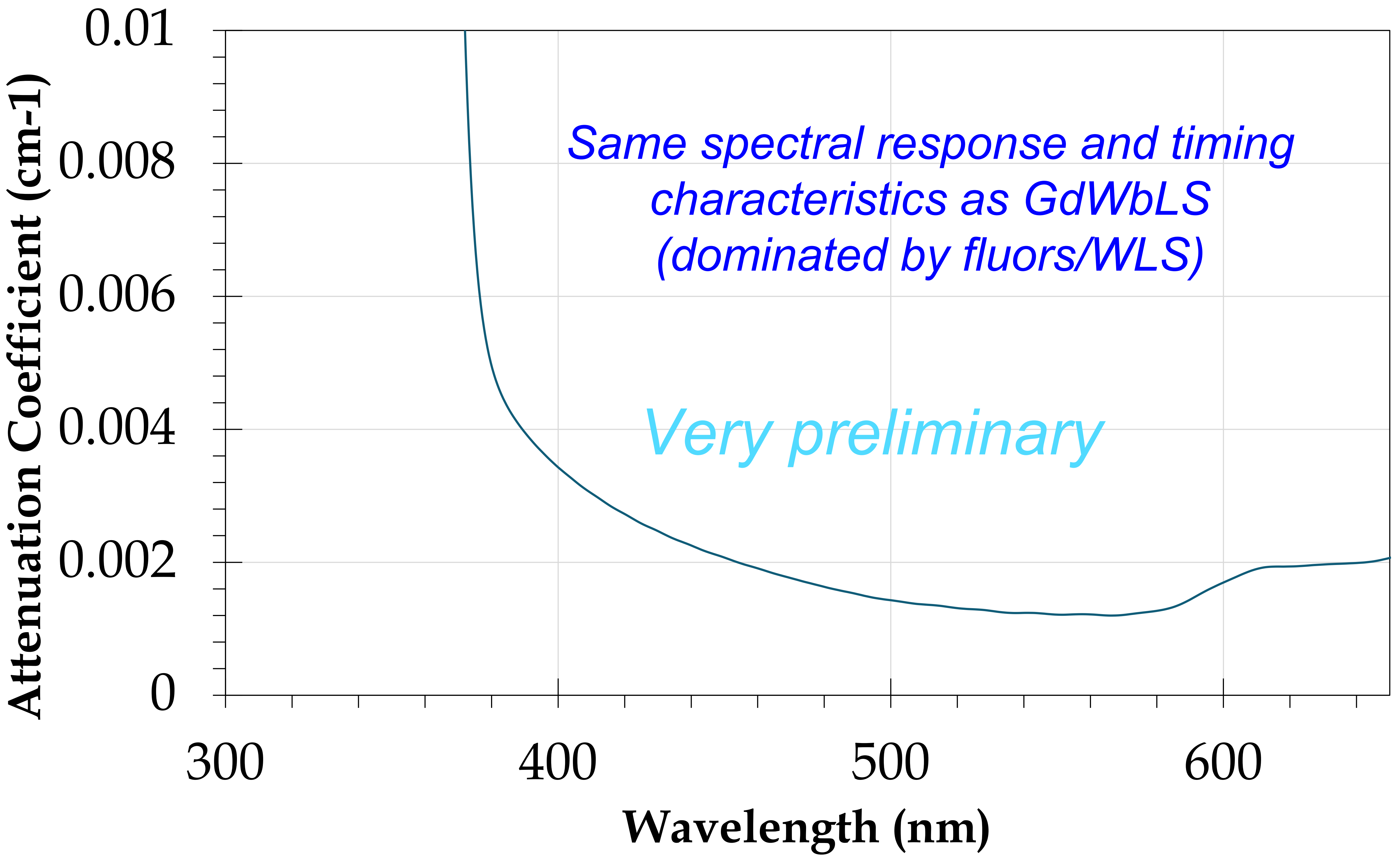
BNL30T today



executed in sequential injection modes from 0.35% to 1% WbLS with slow control system and Sequential Exchange Array only



1% WbLS (Eos)



- *~250 ph/MeV*
- *At 500nm, $\lambda_{scattering}$ ~ 10m and $\lambda_{absorption}$ > 30m (in process)*

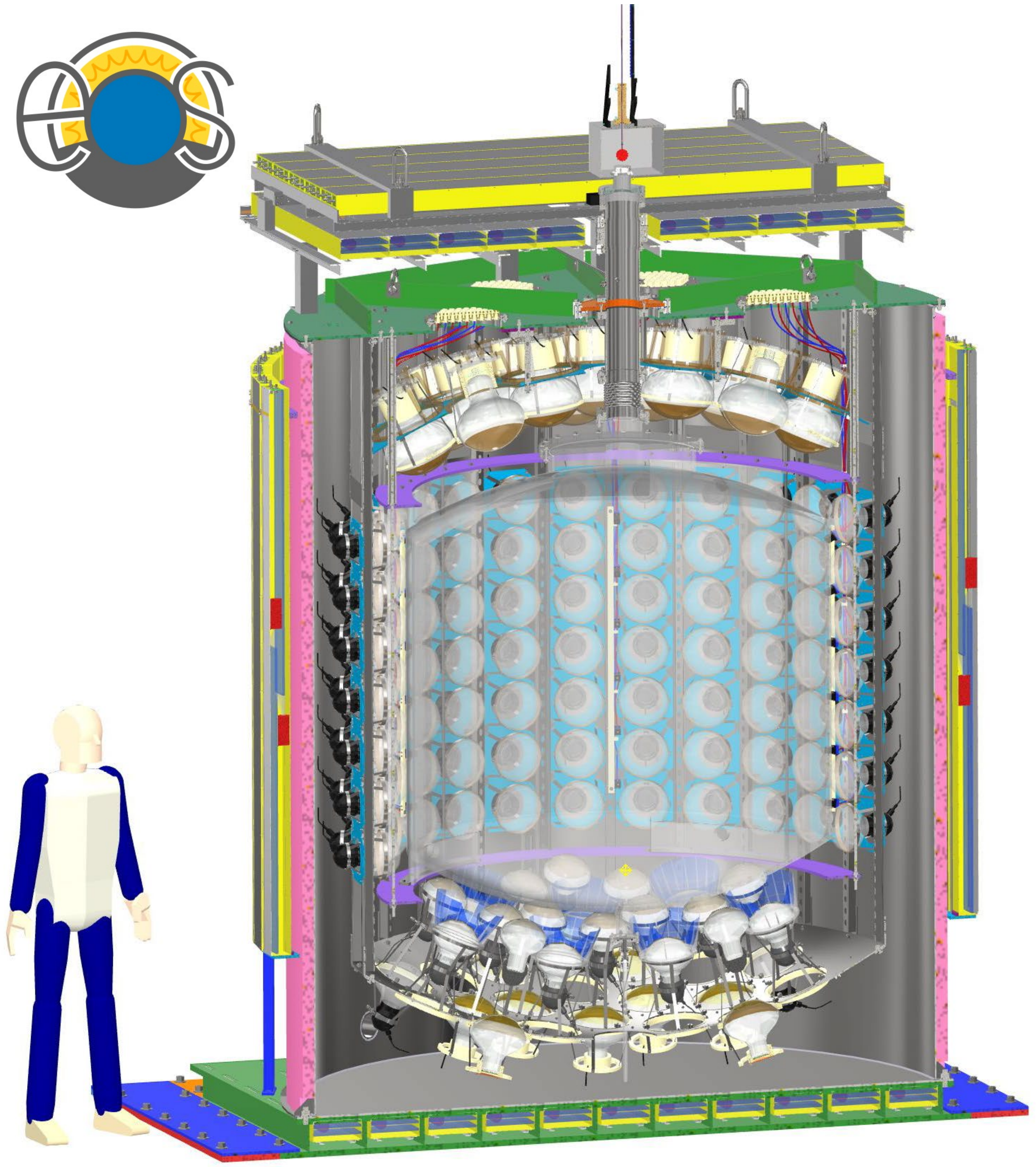
Eos: performance demonstrator

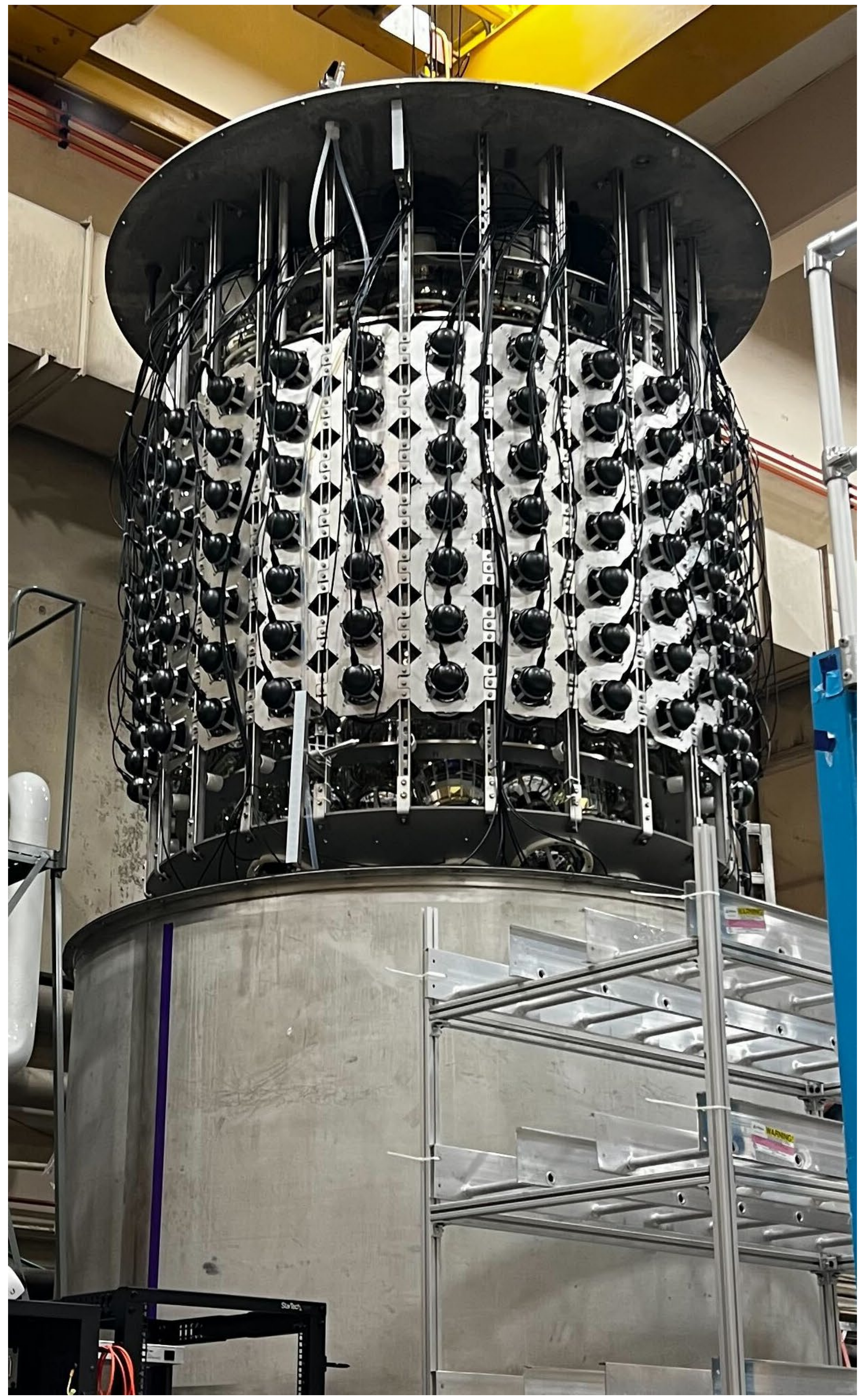
Approach: *design, construct and operate an integrated testbed to demonstrate the performance of novel technology*

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*

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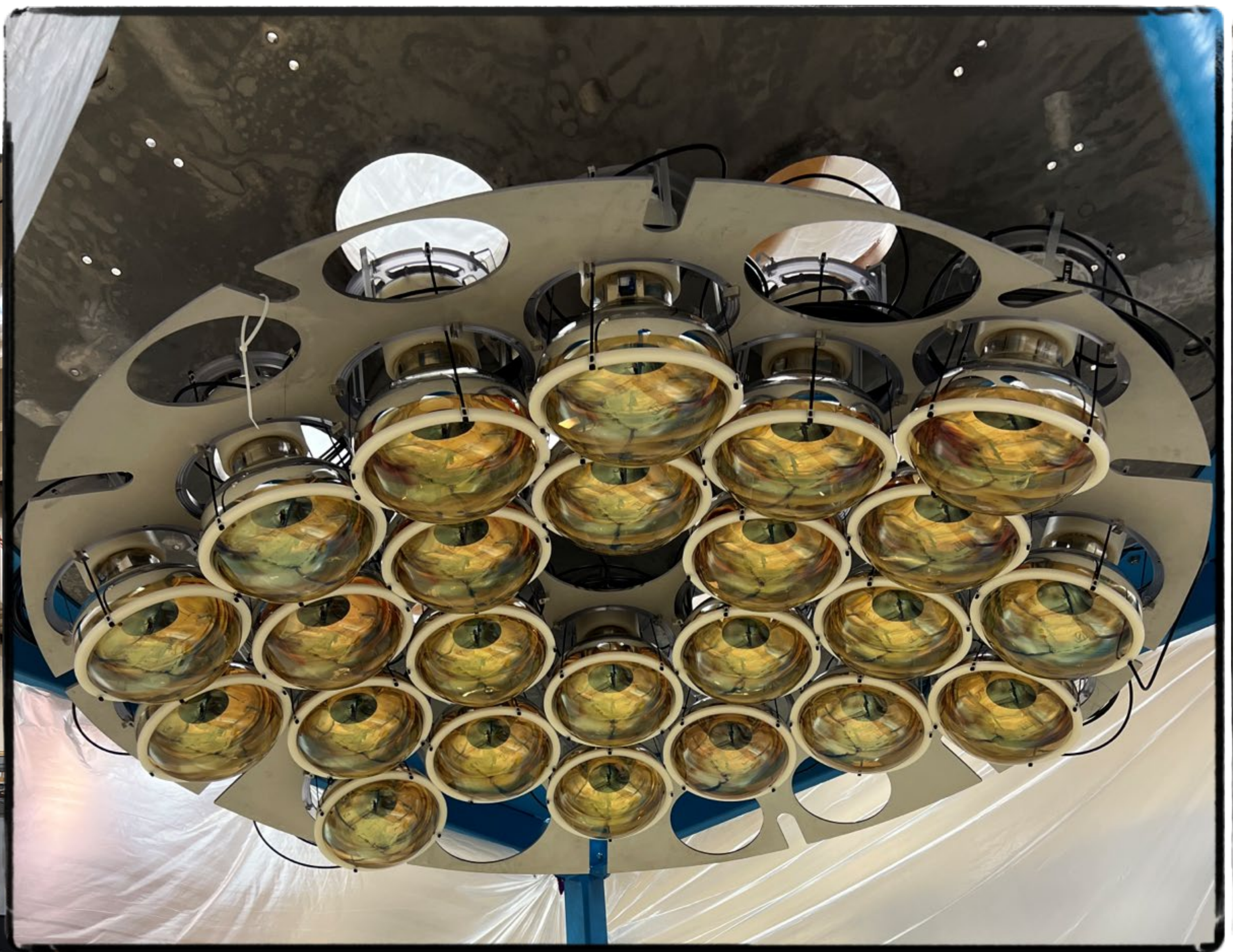
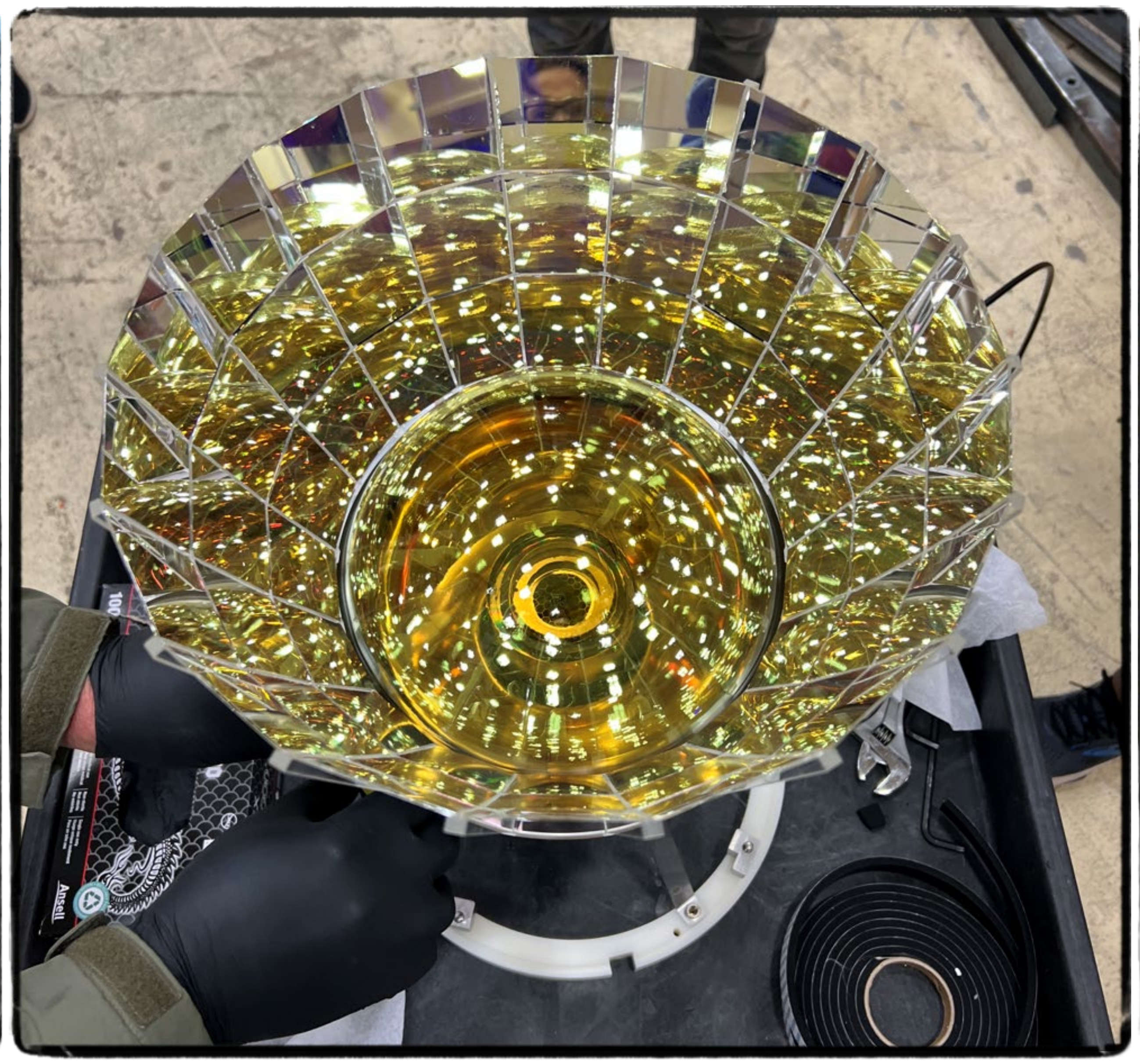
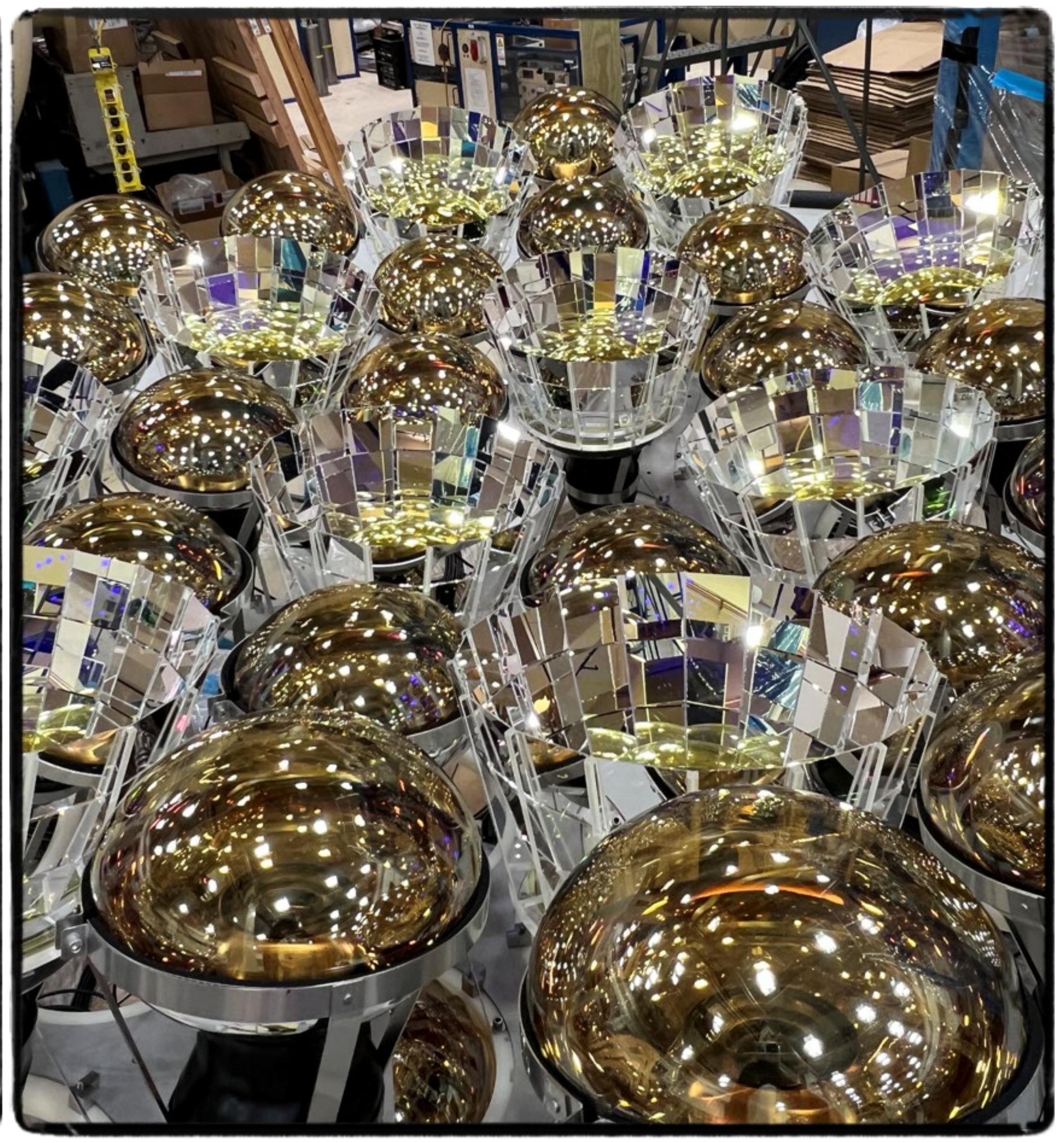
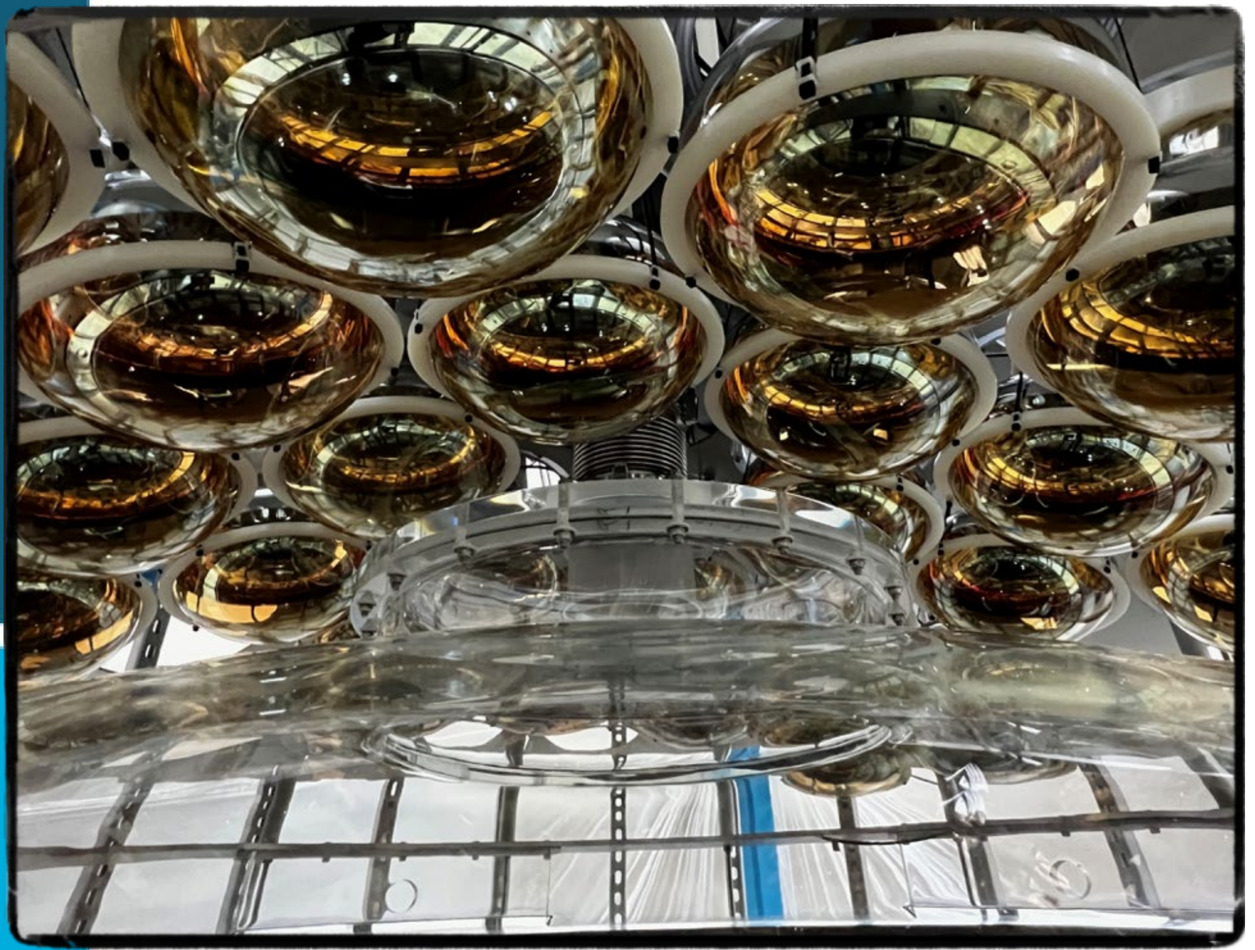
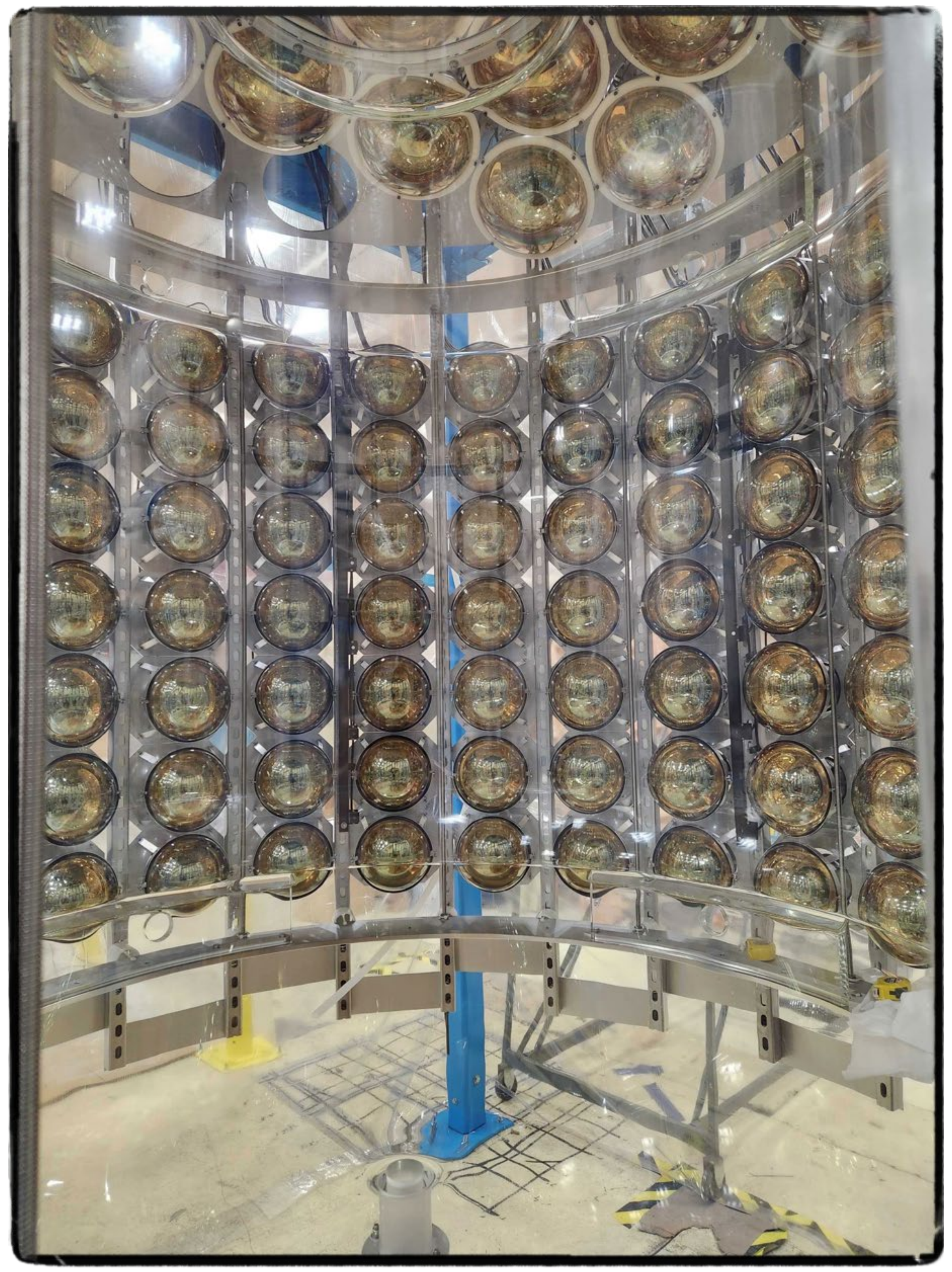
National Nuclear Security Administration

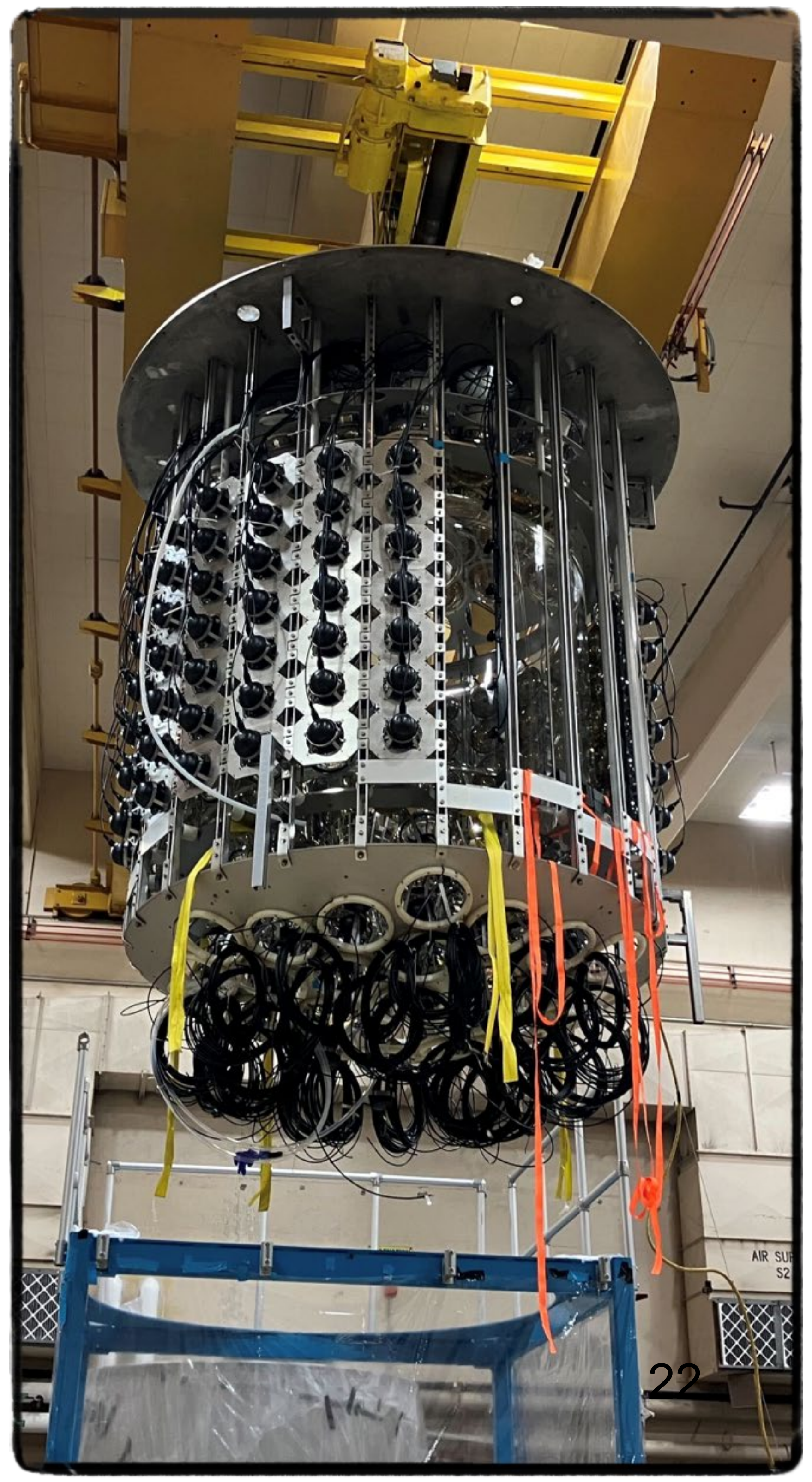












Eos today

- *1st WbLS injected in early 2025*
  - *Cherenkov ring from scintillation **demonstrated***
- *2nd WbLS injection in process*

USA

Germany

Portugal

Finland

Turkey

Canada

National Laboratory

Deuterated Liquid Detectors

A D_2O-based Liquid Scintillator (HbLS)

$$\pi^+ \to \mu^+ + \nu_\mu$$

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

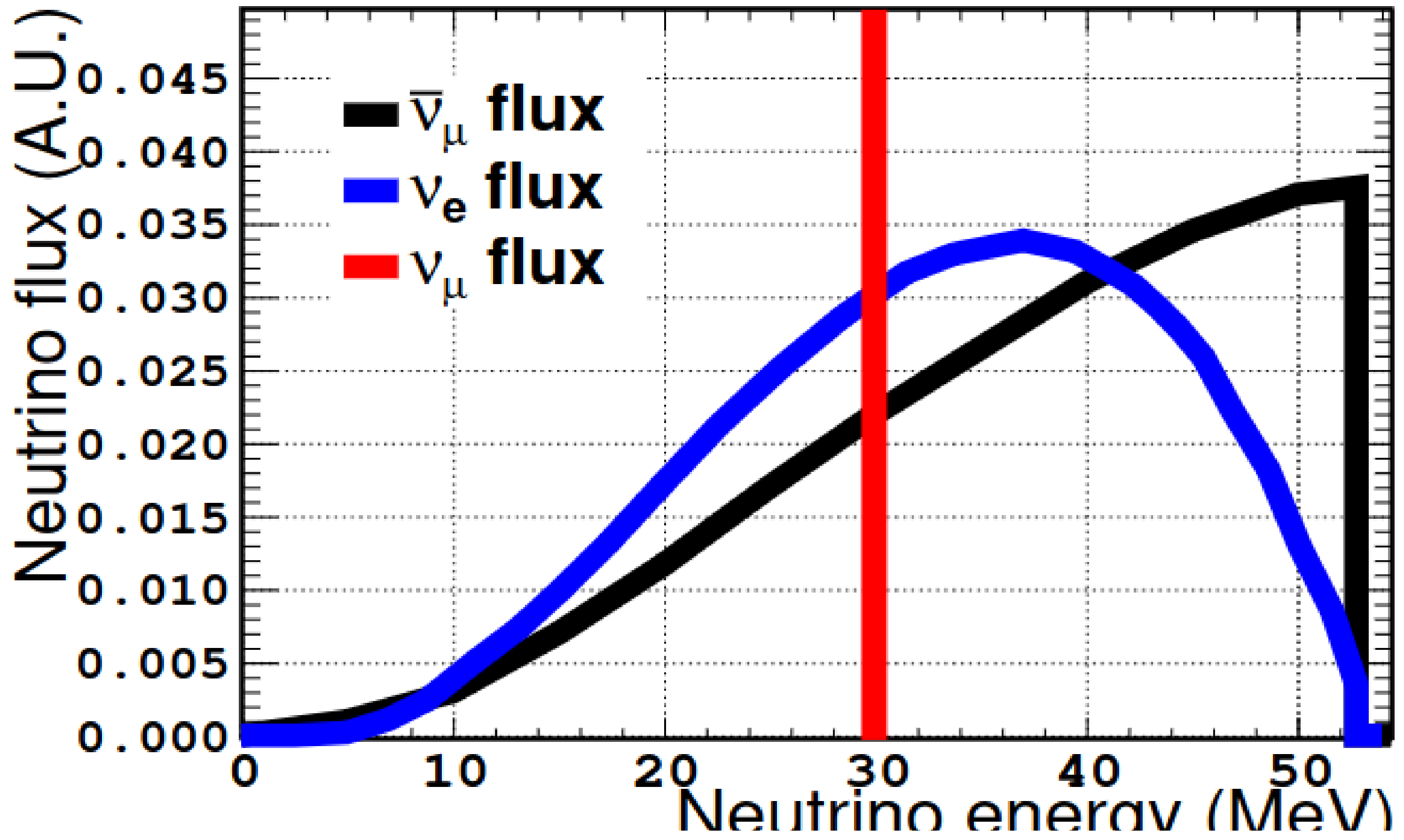
- Free neutrinos from Spallation Neutron Sources (COHERENT)
  - Measure three neutrinos from pion decay-at-rest
  - Measure sterile neutrinos
- Triple coincidence reducing background towards a near surface detector (IBD) & cleaner Cherenkov region (>450nm)
- A few liters of HbLS fabricated for evaluation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

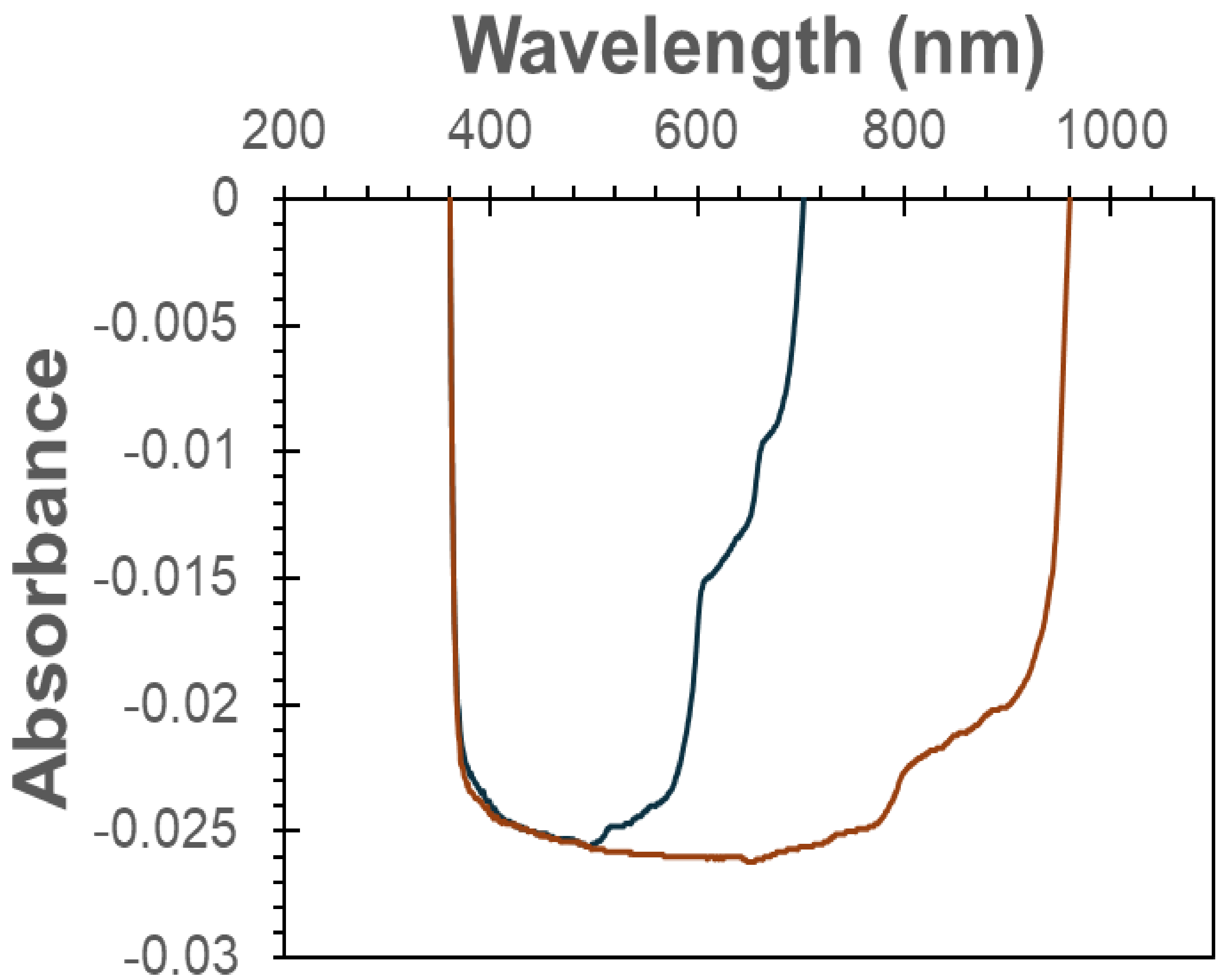
Interaction channel for neutrons from SNS

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

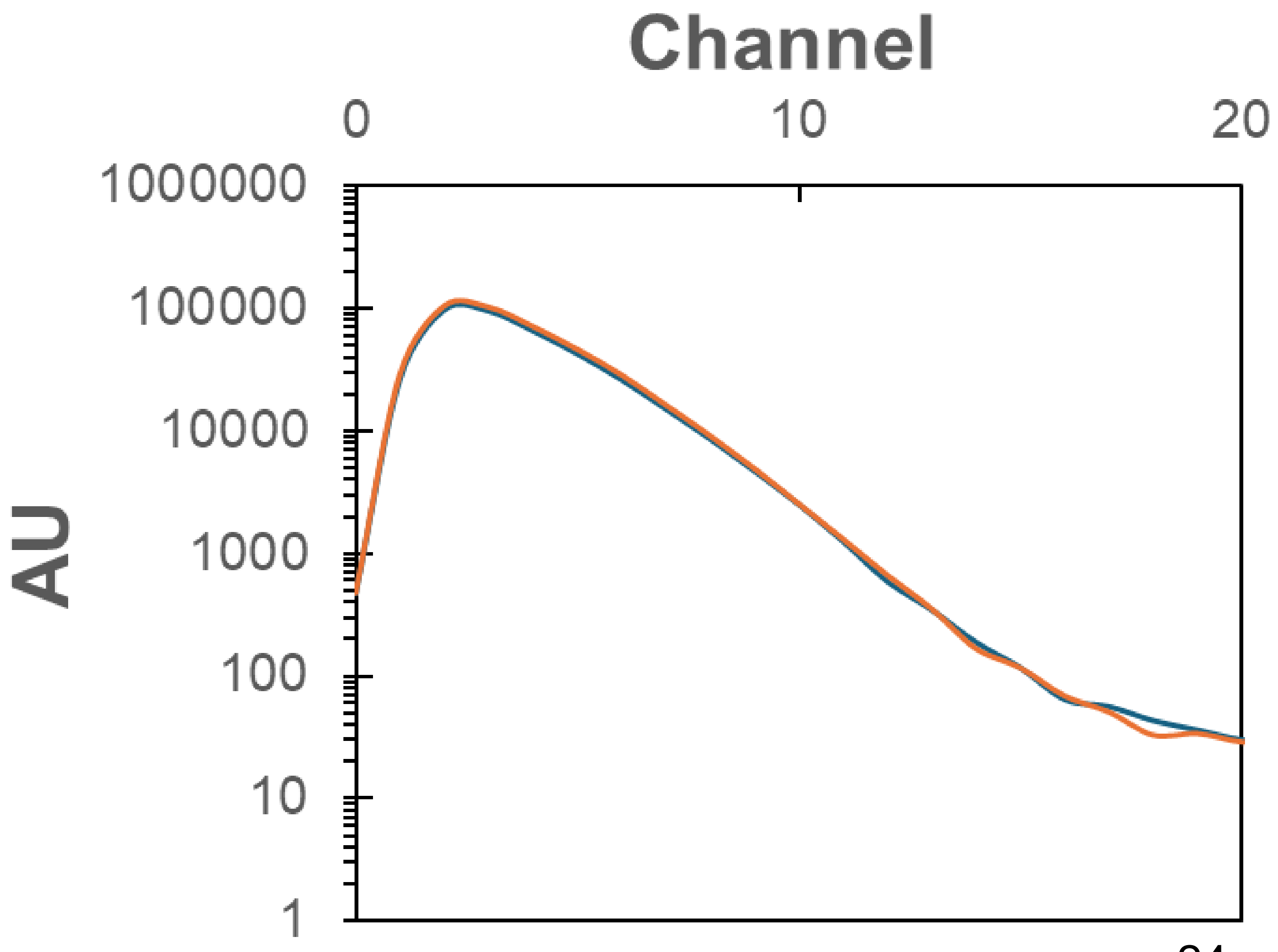
Chauhan et. al., JCAP, 11:005, 2021

Neutrino flux from SNS





10-cm UV (WbLS vs HbLS)



Compton Scattering (137Cs)

Brookhaven National Laboratory

WbLS Lesson-learned

- Performance proven at multiple ton-scale prototypes; focusing on in-situ circulation system deployment (Sequential Exchange Array, Nanofiltration and Gd-water system). **The 1%WbLS in BNL 30-ton has been stable with SEA only (over a month).**
- Homogeneous mixing can be achieved, with careful engineer control, in a few hours after injection (observed in 1-ton and 30-ton scale).
- Sequential injection is a stepwise introduction of detector media; enabling modular commissioning and early physics data-taking before full detector deployment is completed (incremental validation of system components).
- WbLS is flexible with staged upgrades, such as from Cherenkov to various LS and/or metal loading. This supports a phased scientific program that physics output begins while further capabilities are still being deployed.

Summary

- Advances in timing resolution (e.g., LAPPDs, fast PMTs) and interference coating (e.g., dichroic filters) allow event separation from isotropic light.
- Opaque liquid scintillator creates a diffuse, high-contrast optical response. Scintillation light is confined to local photodetectors, enhancing topological reconstruction.
- Engineer scintillator mixtures, an optimization of secondary WLS, multi-fluor combinations, and heavy element loading, to custom-tailored light yield, emission spectra, and decay time with 3D readout for HEP optical detectors & scalable calorimeters.
- Hybrid WbLS is a cost-effective detection medium that enables simultaneous Cherenkov and scintillation light detection, with tunable light yield, timing, and spectral response. It is a promising technology for next-generation multi-physics and nuclear nonproliferation experiments.

Brookhaven National Laboratory