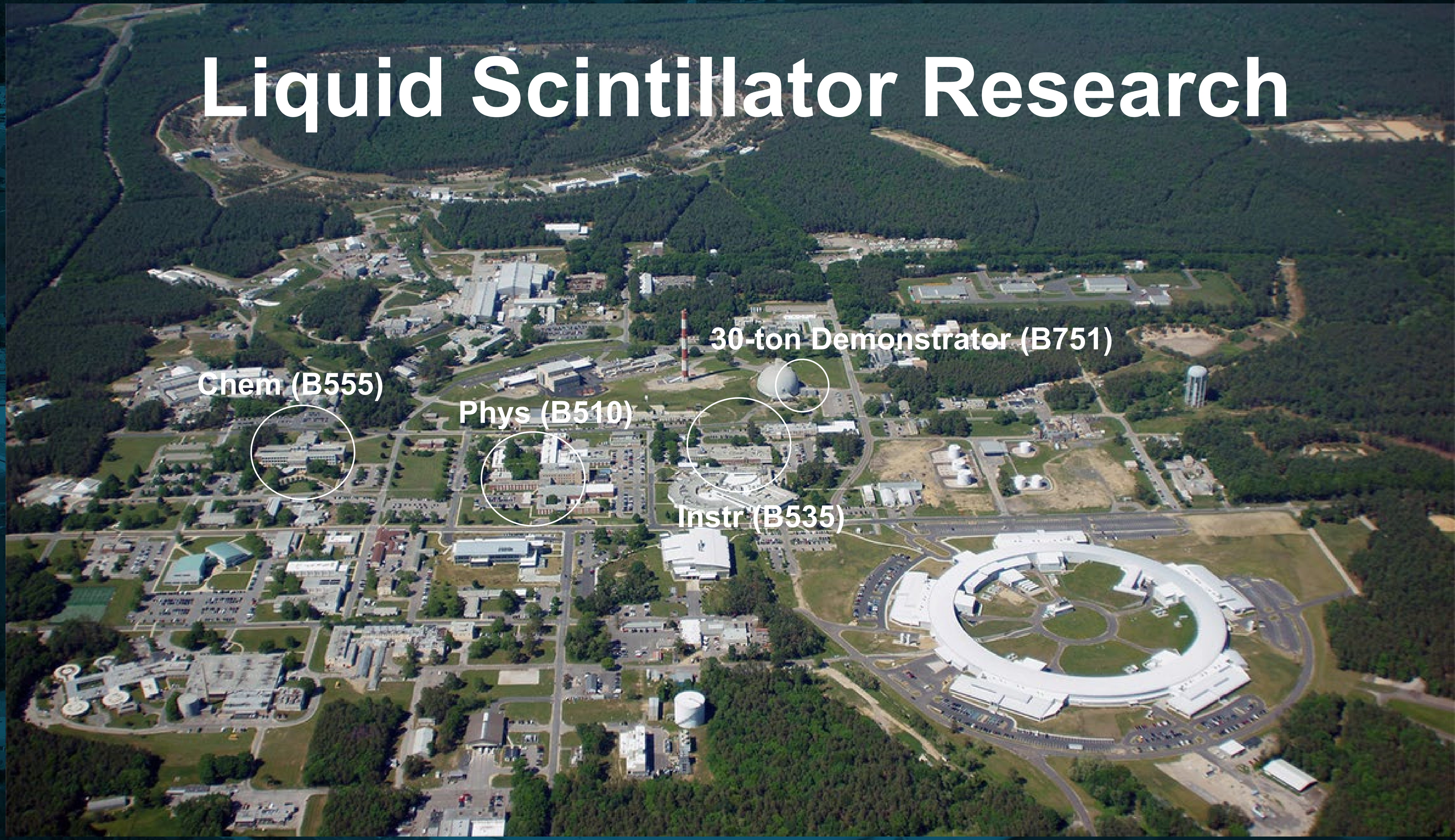
Liquid Scintillator based Experiments



Minfang Yeh

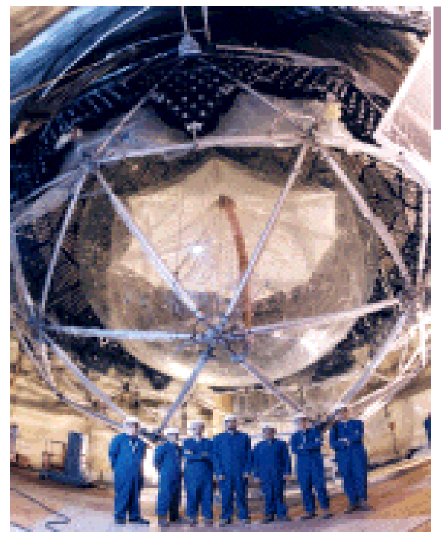
EDIT, BNL, 10/2023

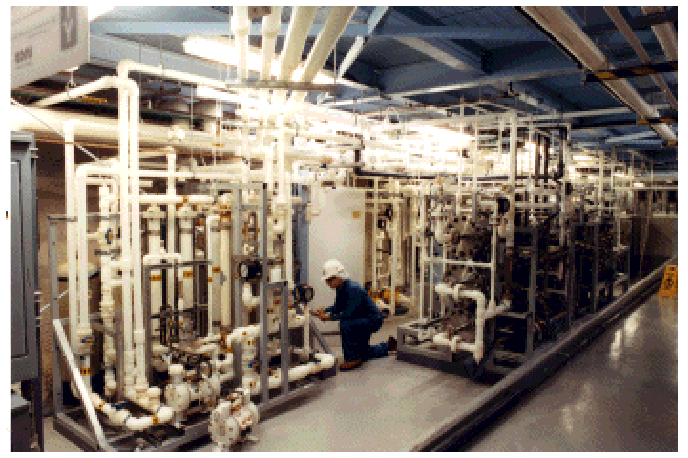
BNL Neutrino and Nuclear Chemistry since 1960
(*chemistry, physics, and instrumentation*)

SNO Nobel Prize in Physics 2015

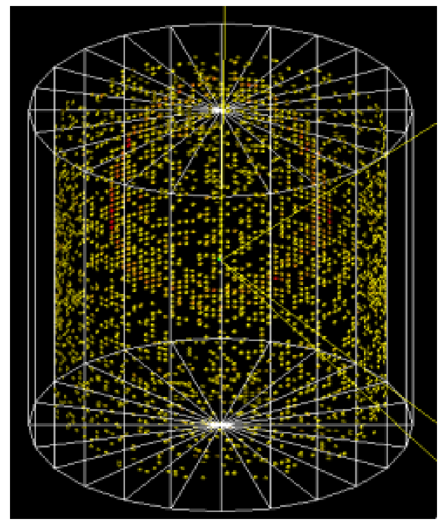
SNO & Daya Bay received The 2016 Breakthrough Prize in Fundamental Physics

Numerous APS and ACS awards over the past decades







HOMESTAKE — 615t $^{37}Cl + \nu_e \rightarrow ^{37}Ar + e^-$

Gallex — 30-t $^{71}Ga + \nu_e \rightarrow ^{71}Ge + e^-$

SNO — 780t D_2O CC/NC

200-kt H_2O or 37-kt LAr — *LBNF (DUNE)*

120-t 8% In-LS — *LENS*

200-t 0.1% Gd-LS — *Daya Bay*

780t 0.3% Nd/Te-LS — *SNO+*

^{6}Li, ^{10}B or Gd doped LS — *PROSPECT/LZ*

(Metal-doped) WbLS — *0νββ, dark-matter, medical, nonproliferation*

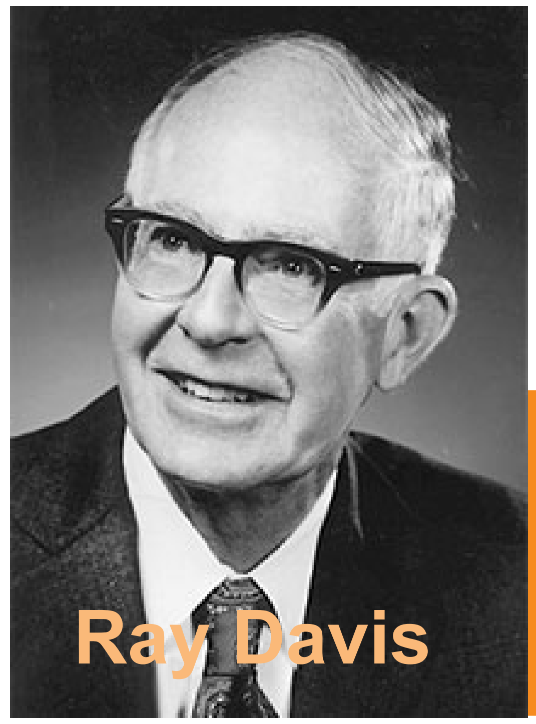
Water-based LS

Scintillator

Radiochemical

Cherenkov

1960 1970 1980 1990 2000 2010 2020



Nobel Prize in Physics 2002

Brookhaven National Laboratory

Liquid Scintillator (LS) Detectors

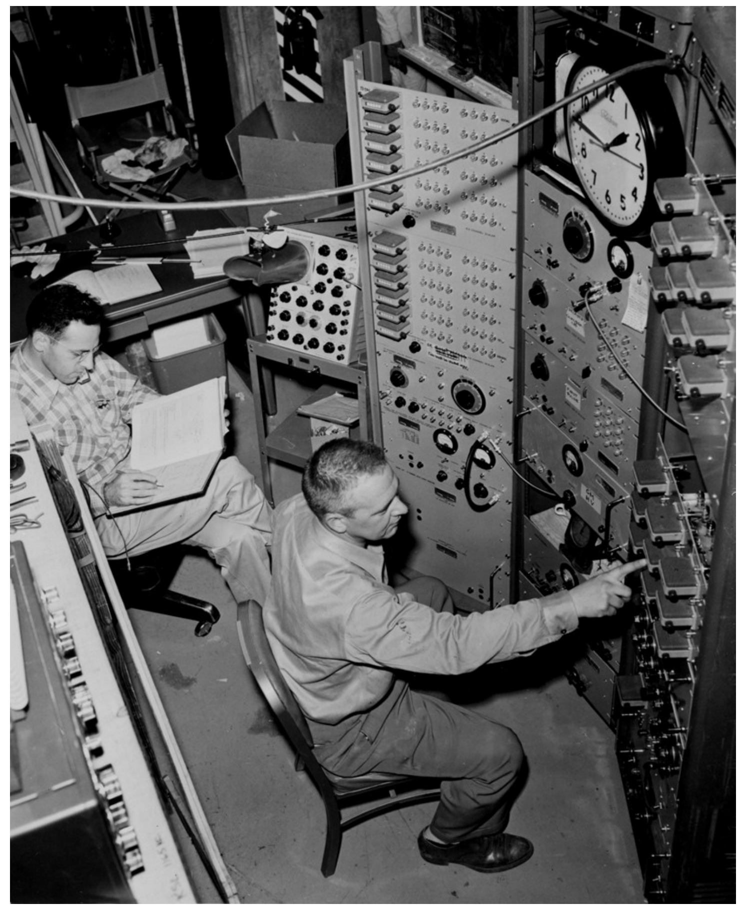
- $\bar{\nu}_e + p \rightarrow n + e^+;\ n + p \rightarrow d + \gamma$
- $\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B \rightarrow {}^{12}C + e^- + \bar{\nu}_e$
- $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N \rightarrow {}^{12}C + e^+ + \nu_e$
- $\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^* \rightarrow {}^{12}C + \gamma$
- $\nu_x + e^- \rightarrow \nu_x + e^-$
- $\nu_x + p \rightarrow \nu_x + p$

Large Liquid Scintillation Detectors*

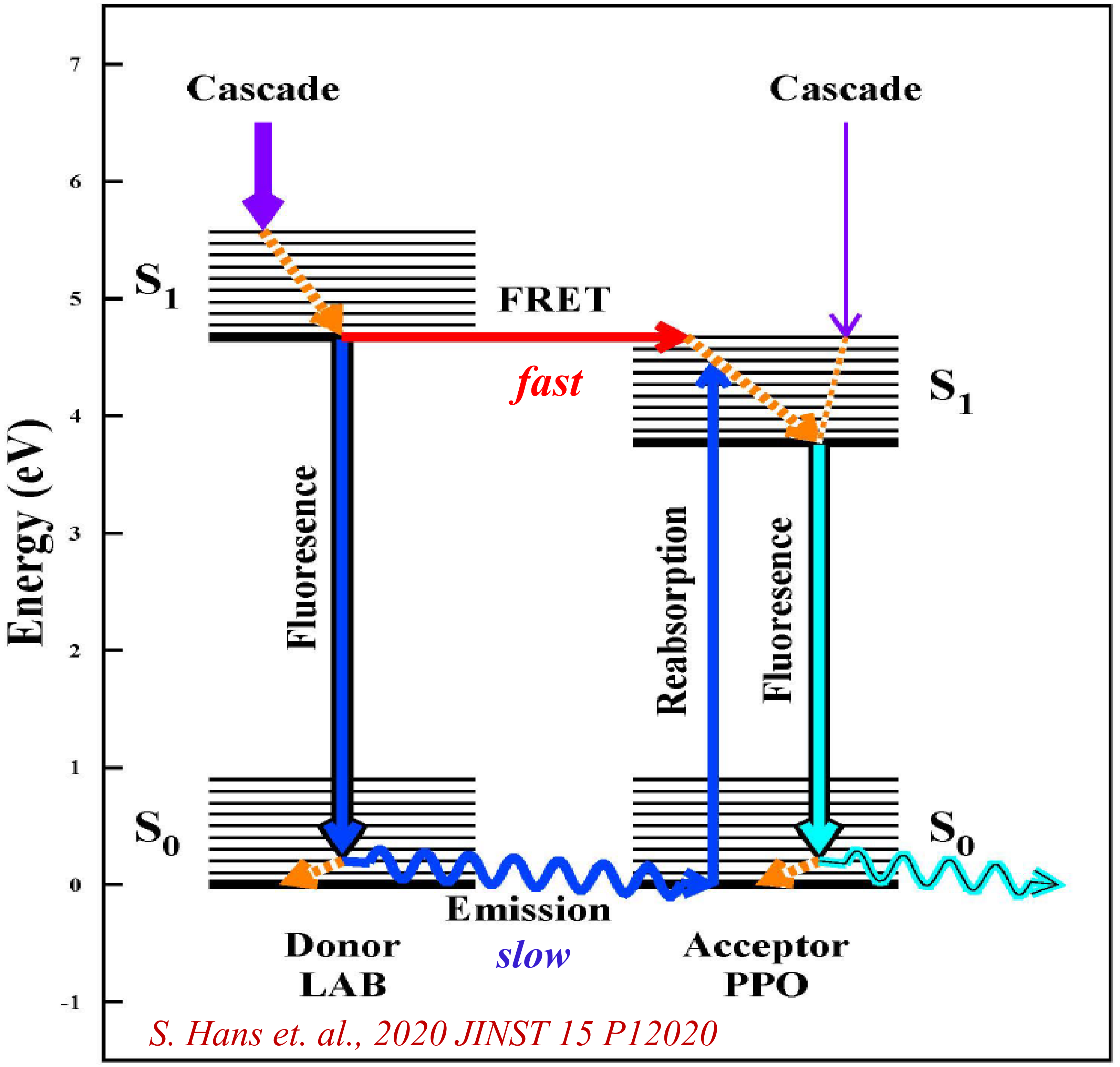
C. L. Cowan, Jr., F. Reines, F. B. Harrison, E. C. Anderson, and F. N. Hayes

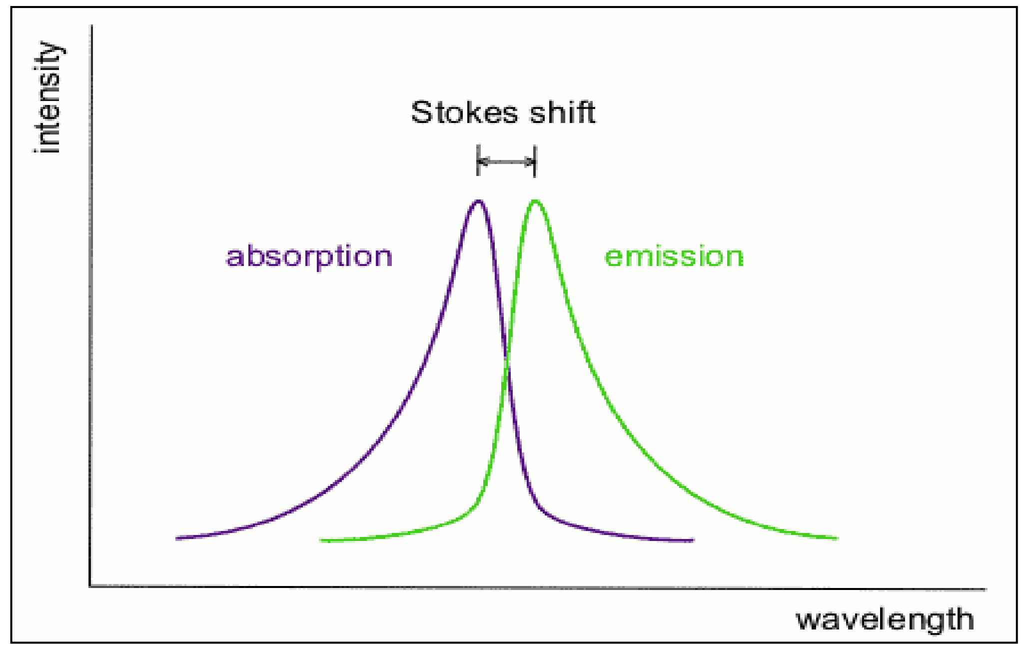
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

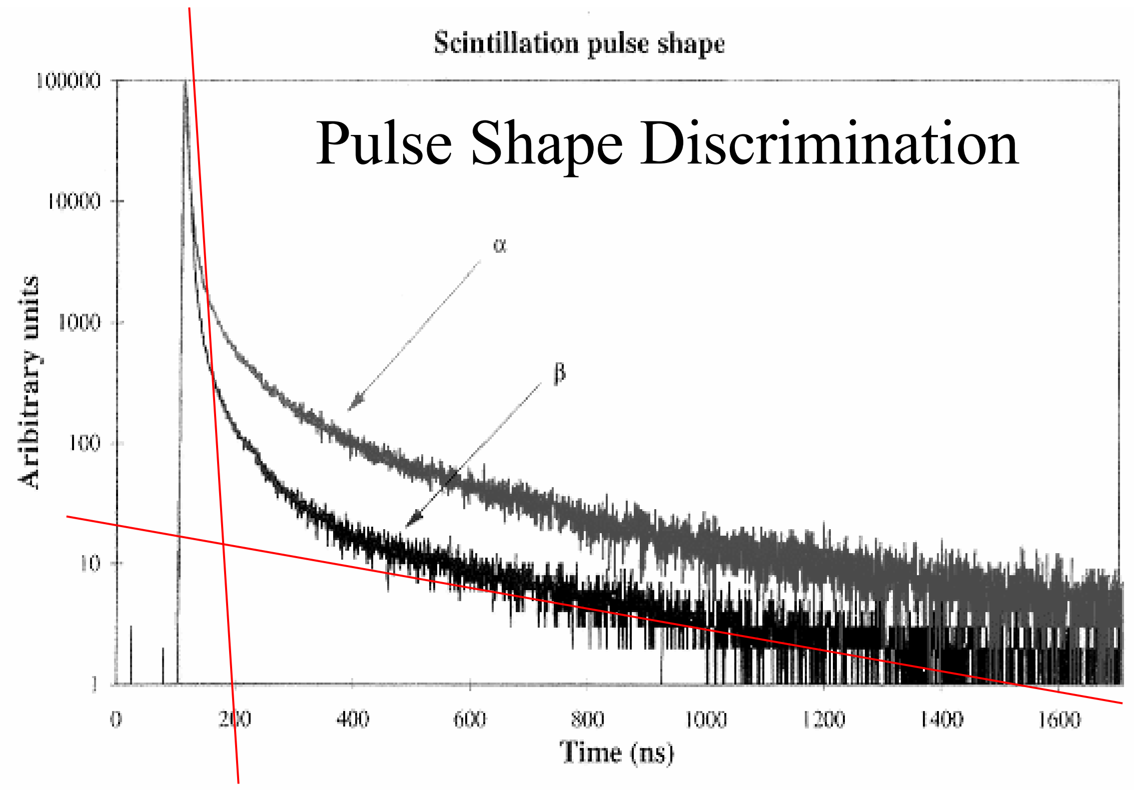
(Received February 24, 1953)



Aromatic solvent at $3-4k per ton







From understanding of our Universe to applications in nonproliferation, medical physics, nuclear material detection, LSC, etc.

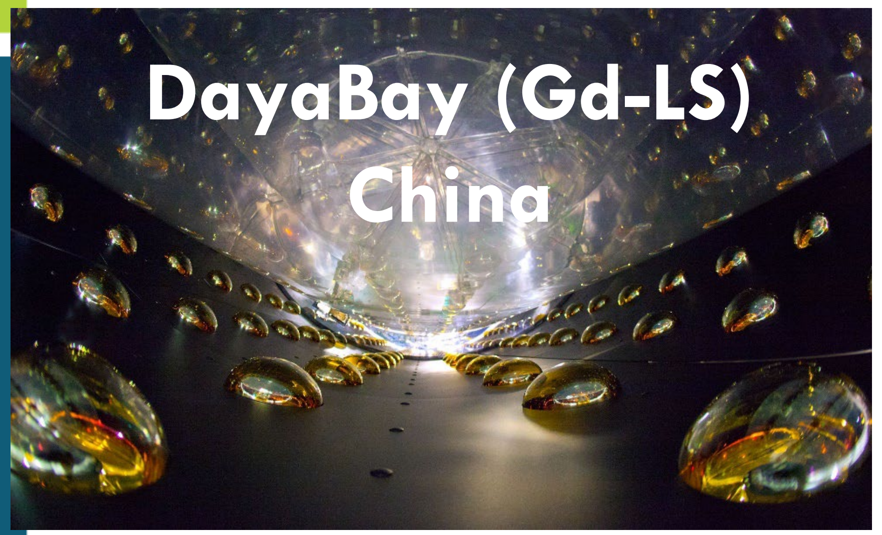
Stokes-shift, photon-yield, timing structure, and C/H density determine scintillator responses (modern LS is high fp, low toxicity, and compatible with most detector vessels)

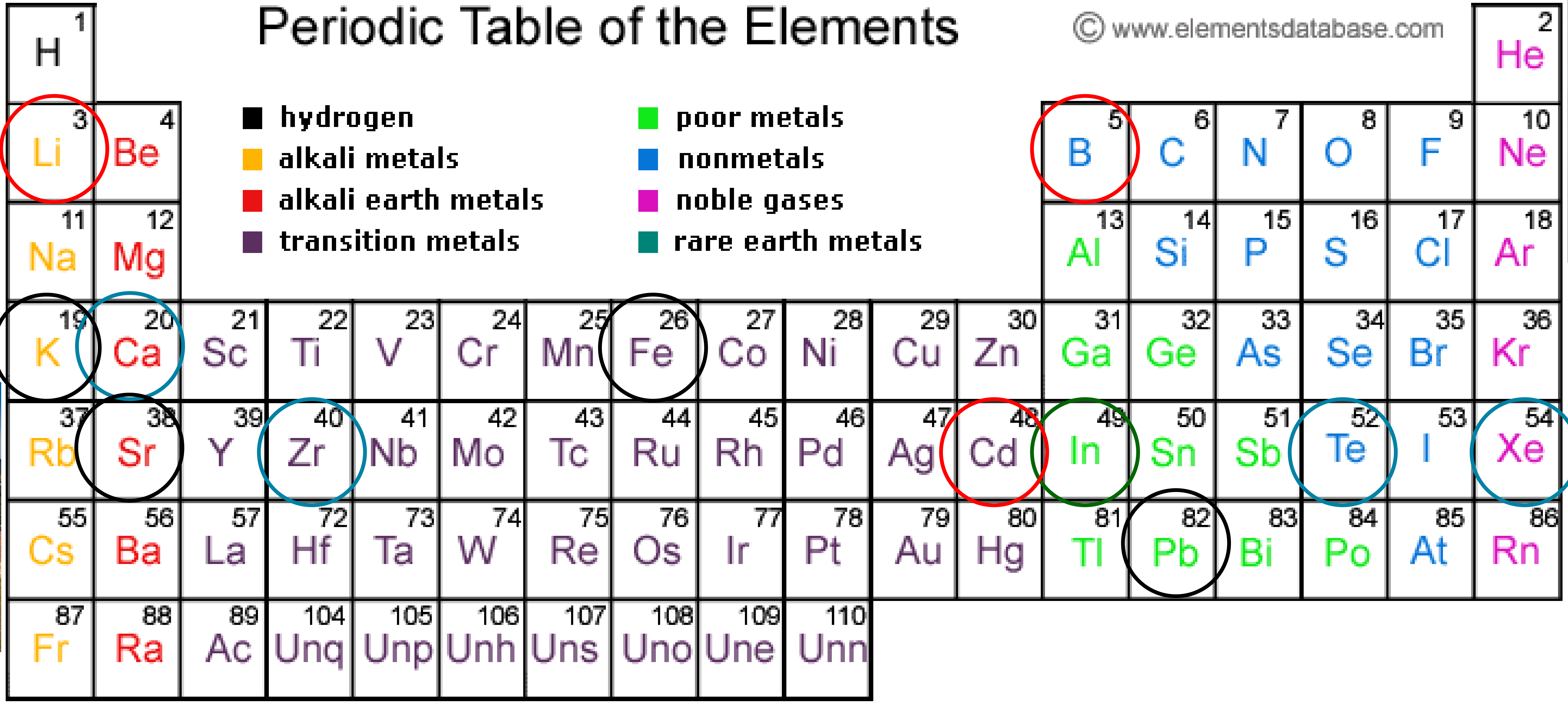
Brookhaven National Laboratory

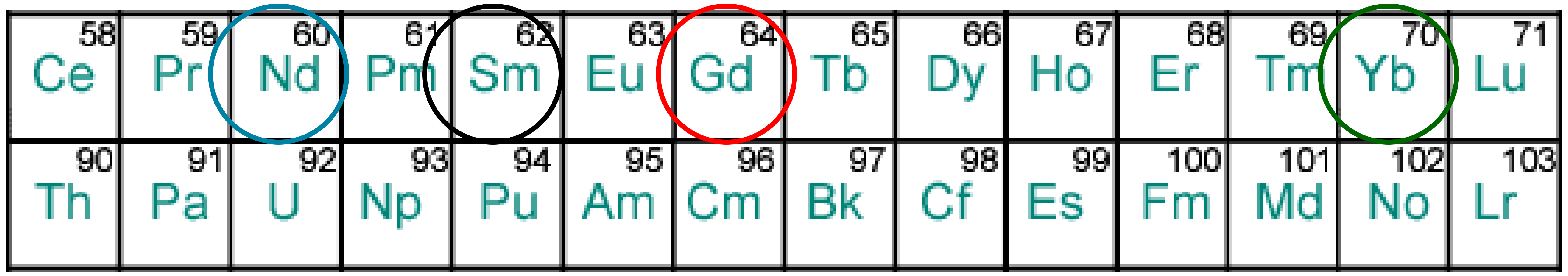
LS-based ν Landscape

Metal-doped Liquid Scintillators

for neutrino physics and other frontiers since 2000





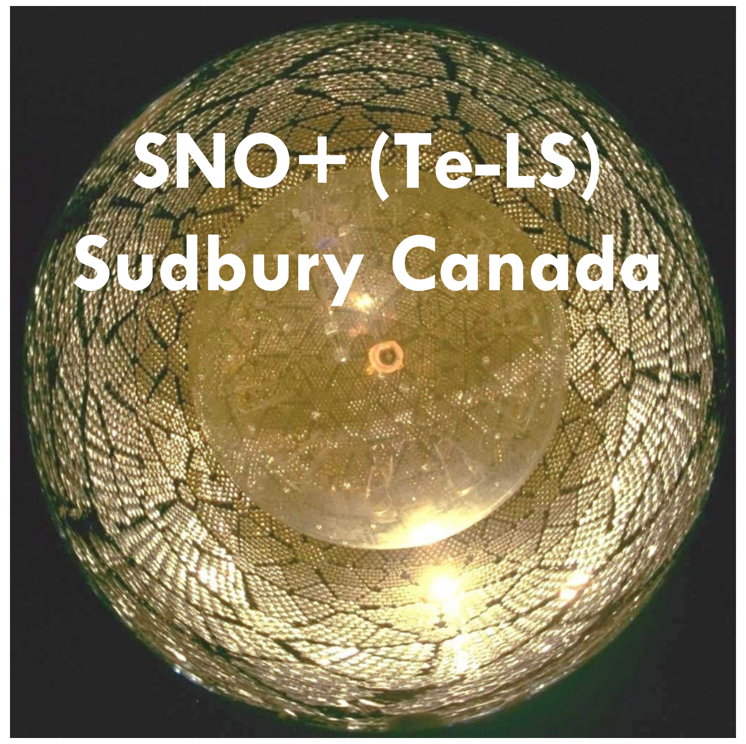


Reactor

ββ

Solar

Medical, calibration, LSC, etc



Brookhaven National Laboratory

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

Focus on reactor antineutrinos on this lecture

Neutrino Oscillation and Nuclear Fuel

Three types of Neutrinos. We can only detect these. They are grouped together with charged partners.

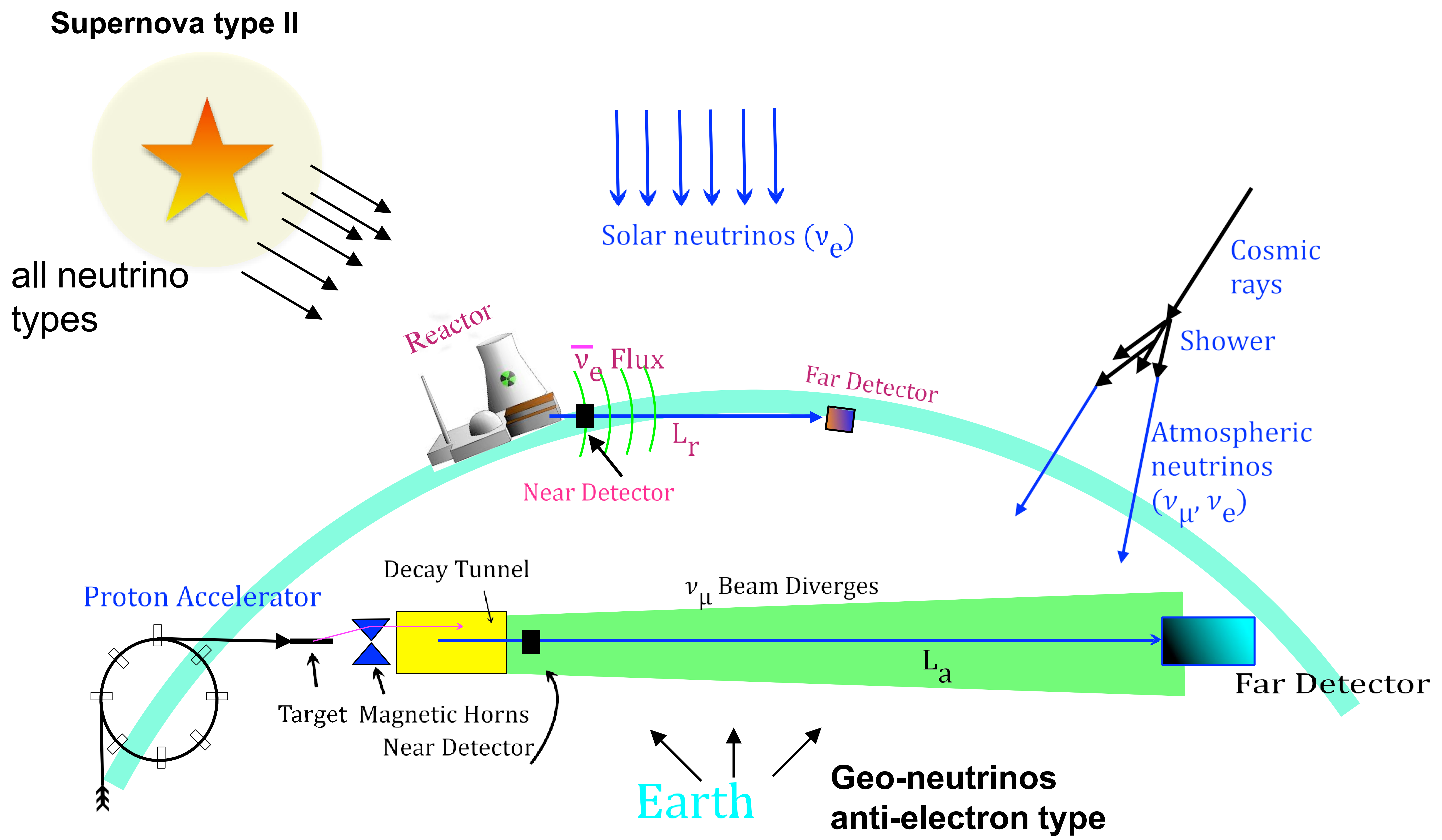
Particles in this table are called leptons (Greek root: leptos)

Particle	Symbol	Charged Mass	Associated Neutrino	Also Anti-neutrino
Electron	e	1	ν_e	$\bar{\nu}_e$
Muon	μ	200	ν_μ	$\bar{\nu}_\mu$
Tau	τ	3500	ν_τ	$\bar{\nu}_\tau$
	Negative Electrical Charged		Neutral	

- **The neutrino has no charge and so it is invisible as it enters a detector. Only very rarely it interacts and leaves charged particles that can be detected.**
- **The electron, muon, tau have very different signatures in a detector.**
- **Neutrino collision on atoms in detectors produces a charged lepton (Charged Current).**
- **Neutrino can also collide and scatter away leaving observable energy (Neutral Current).**

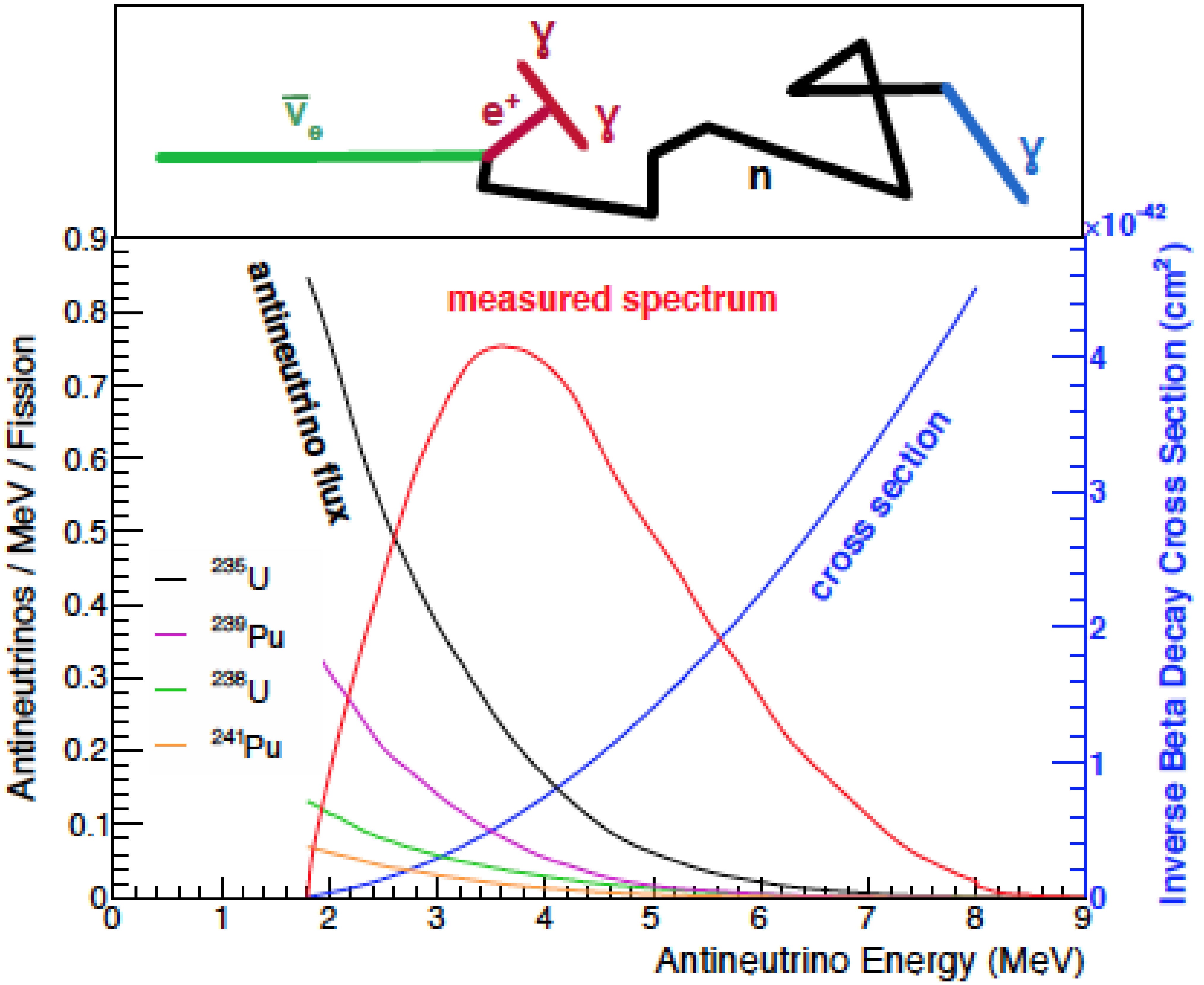
Fundamental Neutrinos: https://www.phy.bnl.gov/~diwan/

Neutrino Sources



Natural and manmade sources of led us to understand the properties of neutrinos in much greater detail. Annual Rev. 66, 2016.

Nuclear Reactor Events and Spectrum



Typical Power reactors produce 3 GW of thermal energy.

Each fission has ~200 MeV.

Each fission leads to 6 beta decays.

Beta decays produce electron antineutrinos.

These anti-neutrinos have inverse beta decay reactions on protons in a detector.

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$Neutrinos/\sec = 6\frac{3\times10^{9}\,J/\sec}{1.6\times10^{-13}\,J/MeV \bullet 200\,MeV} = 6\times10^{20}/sec$$

for 3 GW Thermal power.

Find how to calculate the spectrum from literature. (P. Vogel et al.)

Detector mass needed for 1000 reactor evts/yr ?

- Detector distance d = 100000 cm. (1 km)
- Yield = 2×10^{20} /sec for GW
- Flux = 1.6×10^{9} /cm^2/sec (assuming 4 pi)
- Protons = (2/3) x 10^{29} /ton
- Fraction above 2 MeV ~ 0.1
- Cross section ~ 0.9×10^{-42} cm^2
- 1 year = 3×10^{7} sec
- N = Flux* Fraction*cross section*Protons/ton*1 year
- N = 290 per ton per year for 1 GW reactor at 1 km.

Reactor Antineutrino Scintillator Detection

$\nu_e + {}^{115}\mathrm{In} \rightarrow {}^{115}\mathrm{Sn} + e^-$ prompt

$\tau = 4{,}76\ \mu s$ → delay

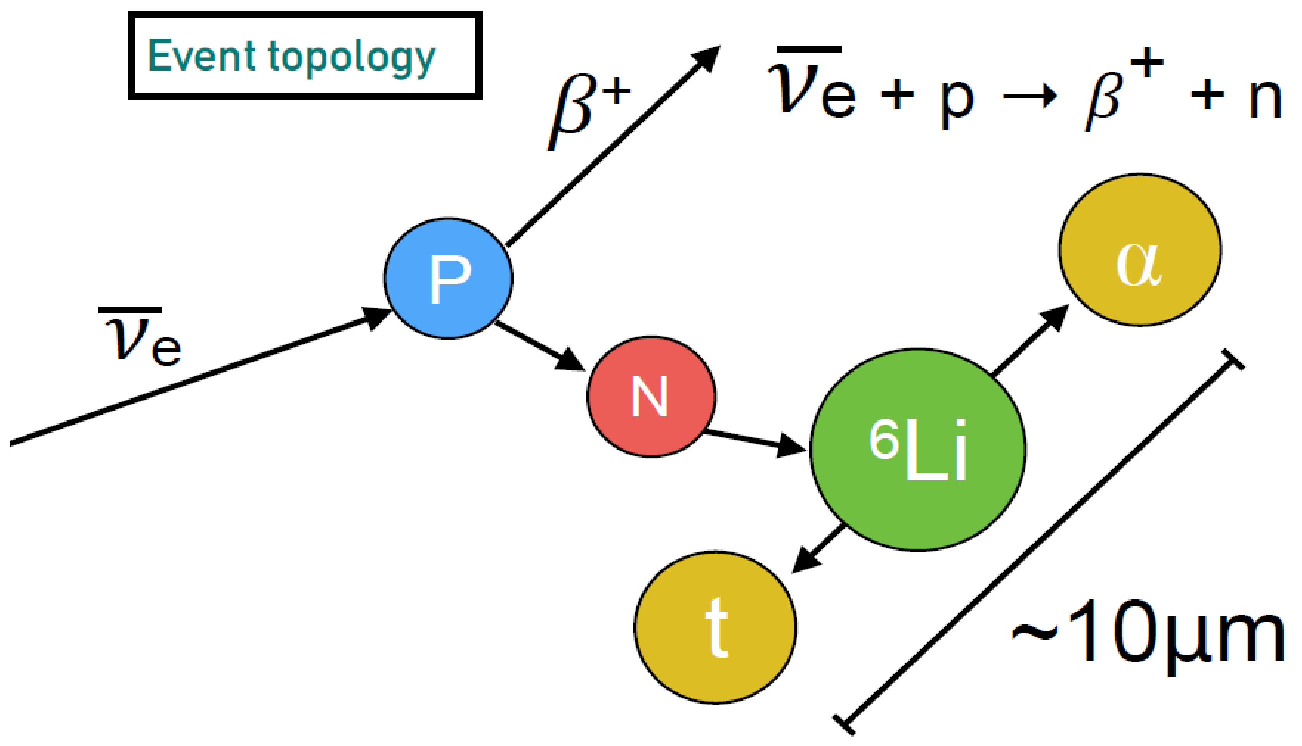
e_1^-/γ_1 E = 116 keV $(e/\gamma)=0.96$

+

γ_2 E = 497 keV

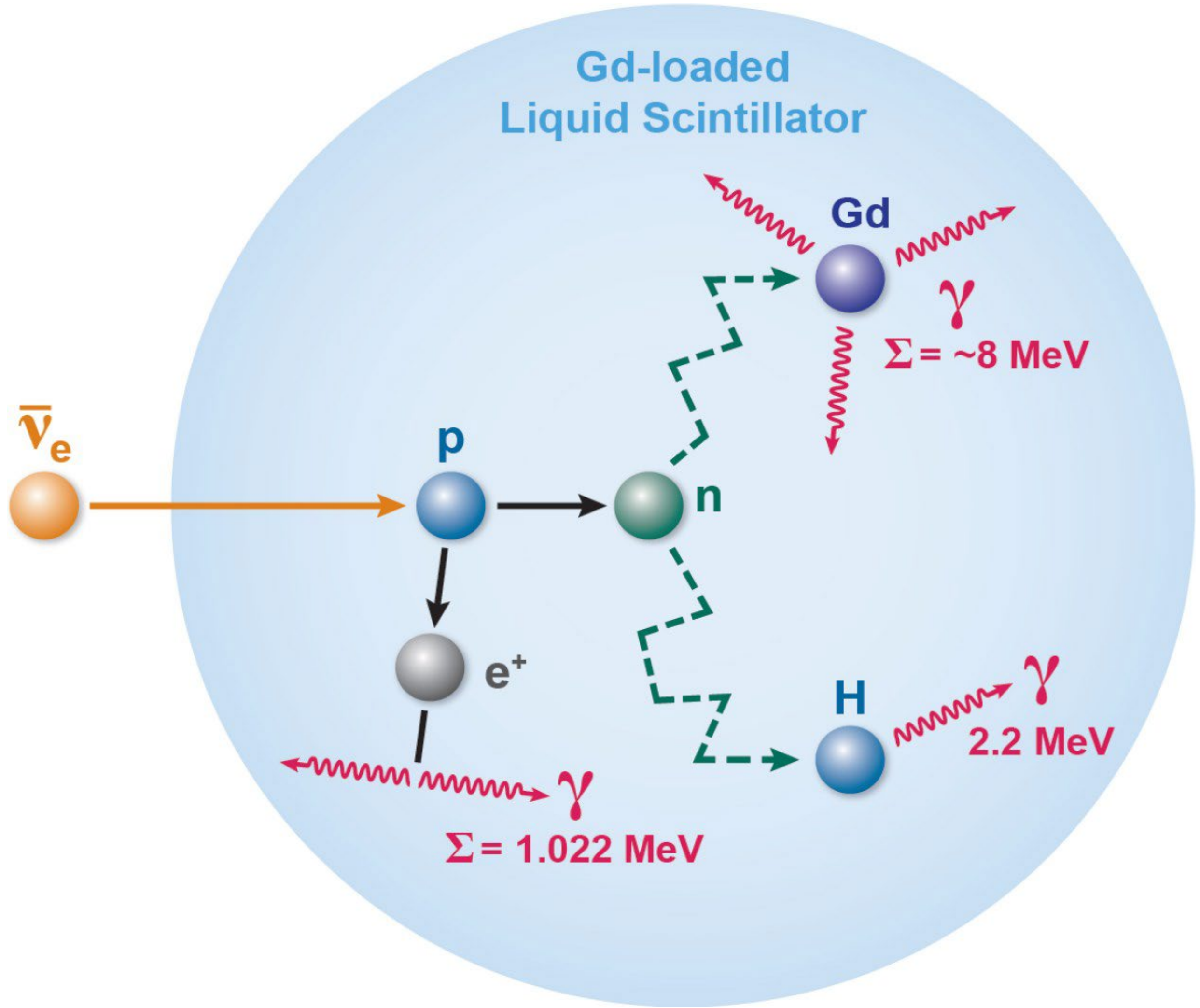
coincidence of two consecutive events (prompt and delayed)

- Enhance neutrino detection efficacy
- Reduce accidental background)



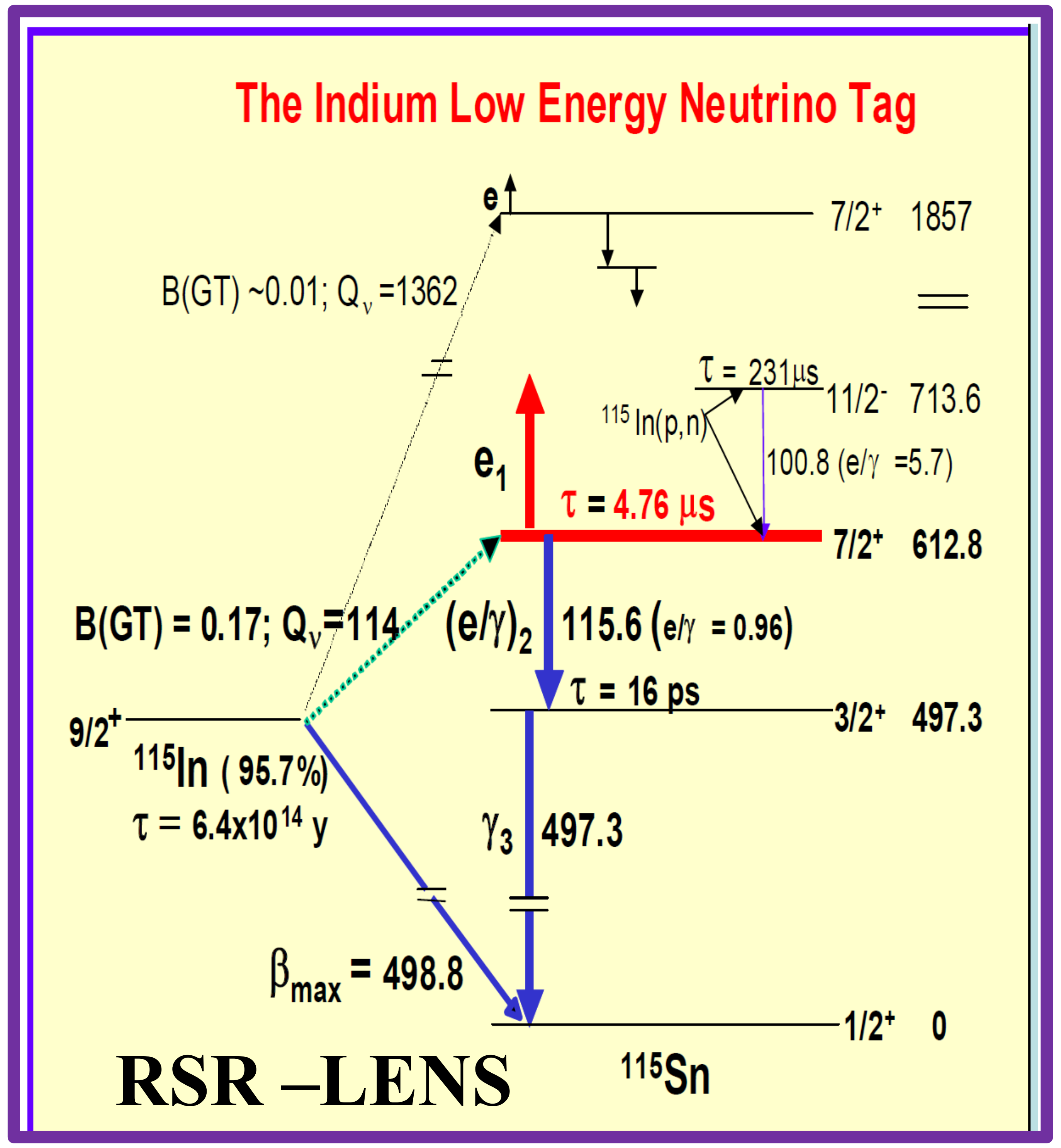
A segmented detector

Li loaded using Water-based Liquid Scintillator



A monolithic detector

Gd loaded with organo-metallic complexation



>10% In-doped WbLS

Brookhaven National Laboratory

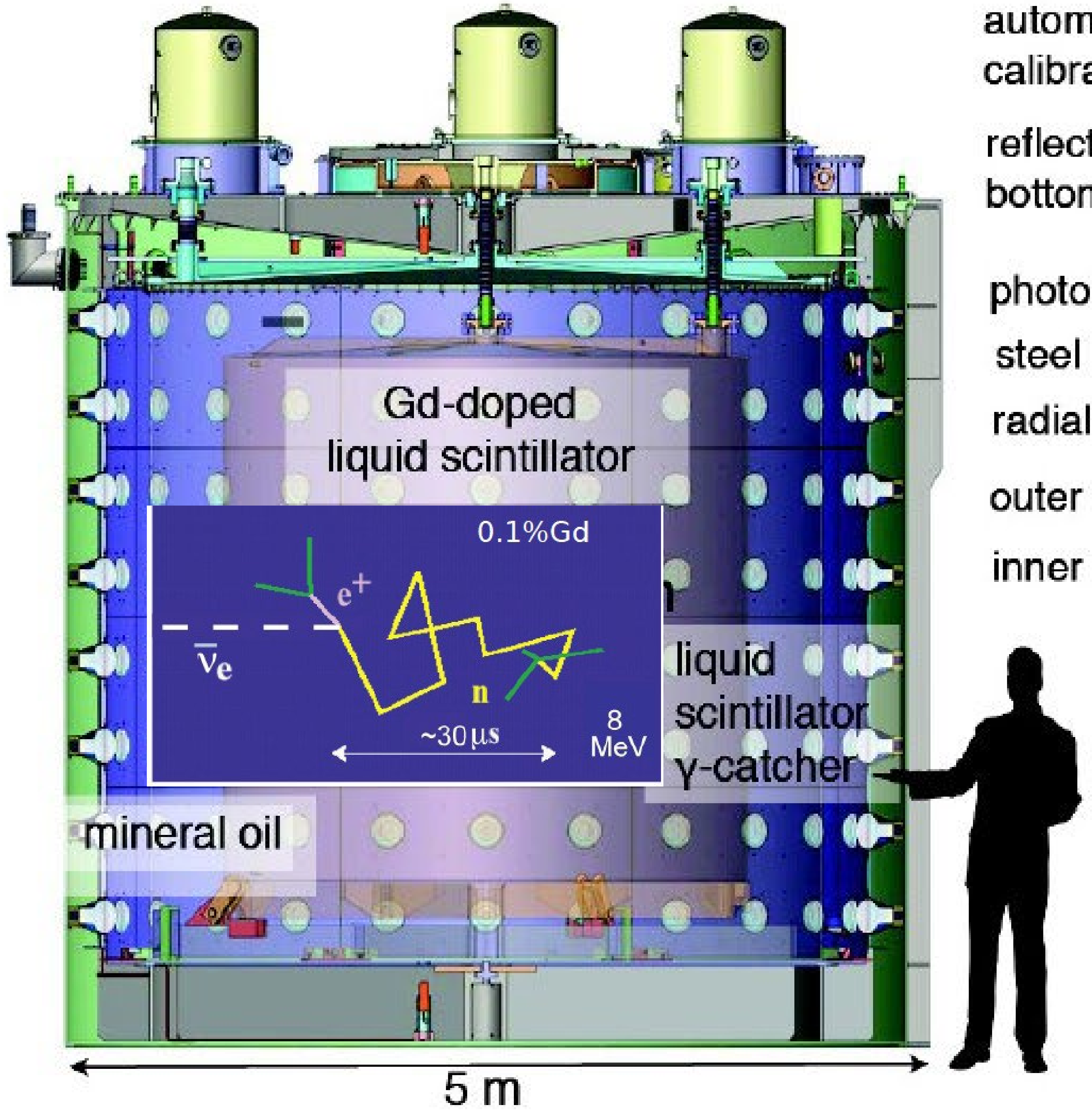
To build a neutrino detector

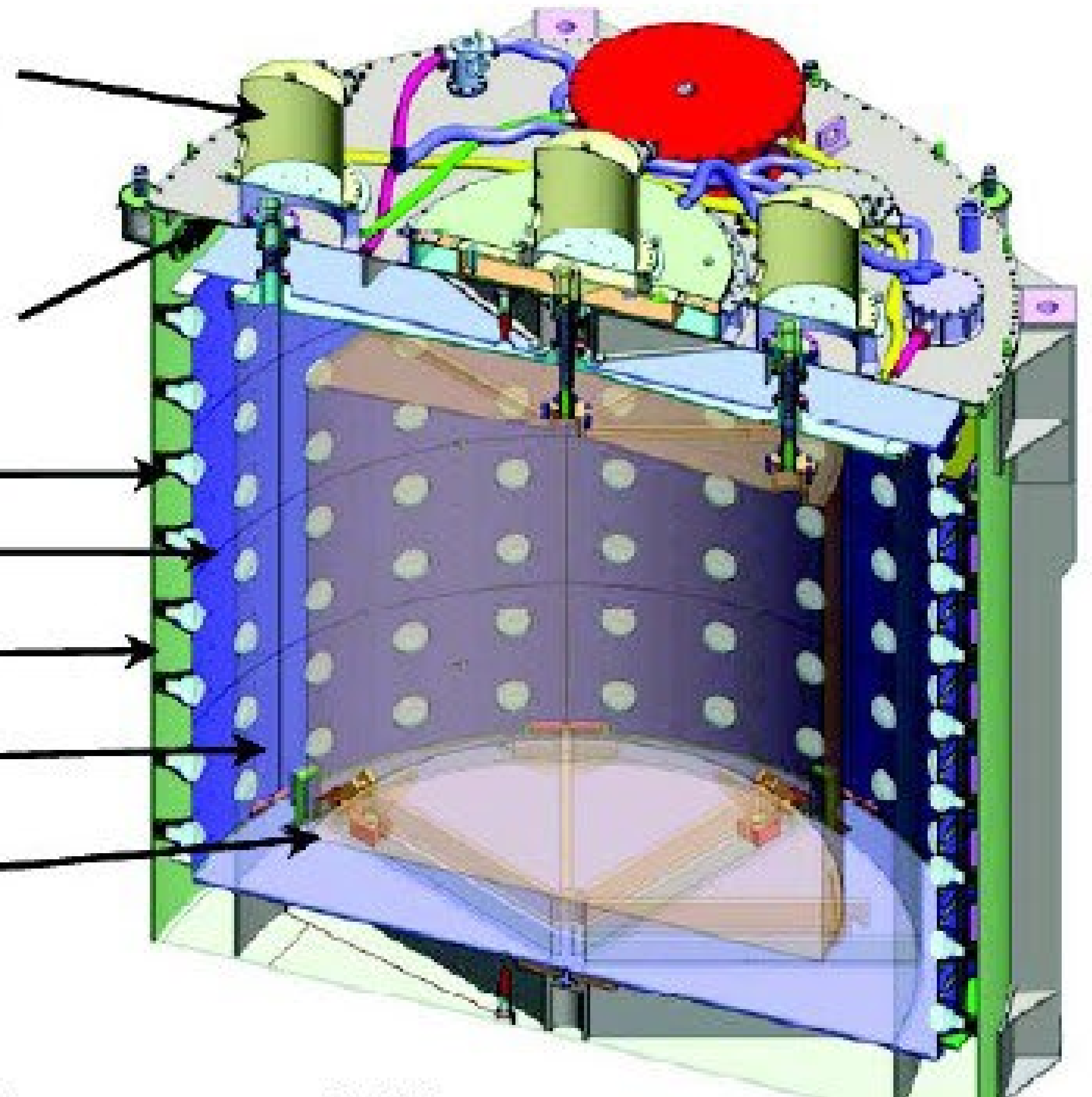
- Weak interaction requires large detector mass + many photosensors from 10s to 1000s of tons (physics target and instrumentation design)
- Enhanced s/b ratio needs a clean environment and well-defined detector (underground and calibration)
- Long experimental lifetime necessitates a highly stable and transparent detector liquid (chemical development)
- Expertise from multi-frontiers
- benchtop R&D → prototype → scale-up experiment

Daya Bay Experiment

- Daya Bay has 6 cores each 2.9 GW
  - ➜ 17.4 GW total
- The geography is ideal with hills rising away from the bay.
- We placed several detectors close to the reactors and several far away to understand neutrino physics called oscillations.
- Location is northeast of Hong Kong (10s of 16-hr flights from NYC to HK since 2007)

Daya Bay Antineutrino Detectors (AD)





total detector mass: ~ 110t
- inner: 20 tons Gd-doped LS (d=3m)
- mid: : 22 tons LS (d=4m)
- outer: 40 tons mineral oil buffer (d=5m)

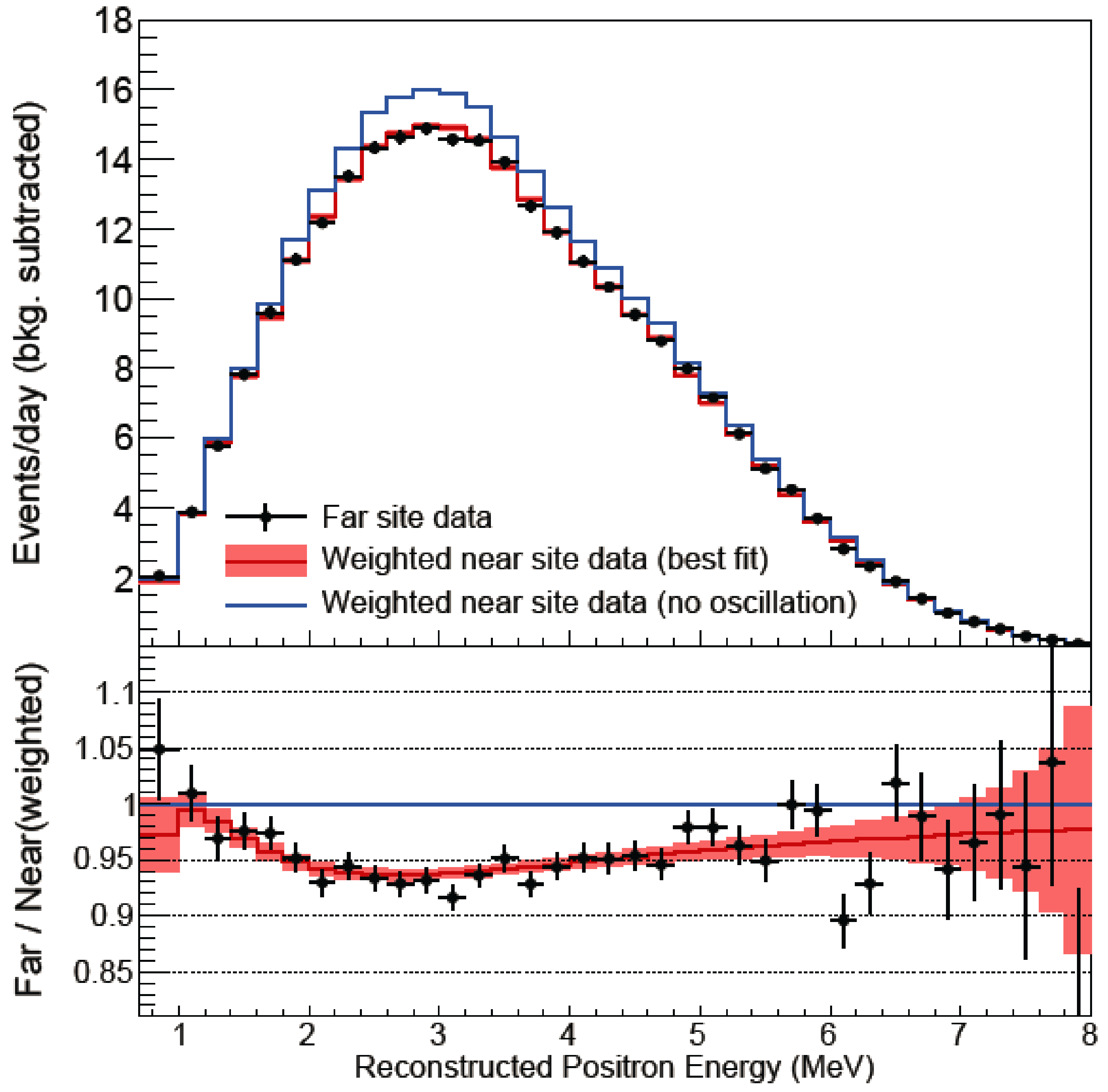
photosensors: 192 8"-PMTs

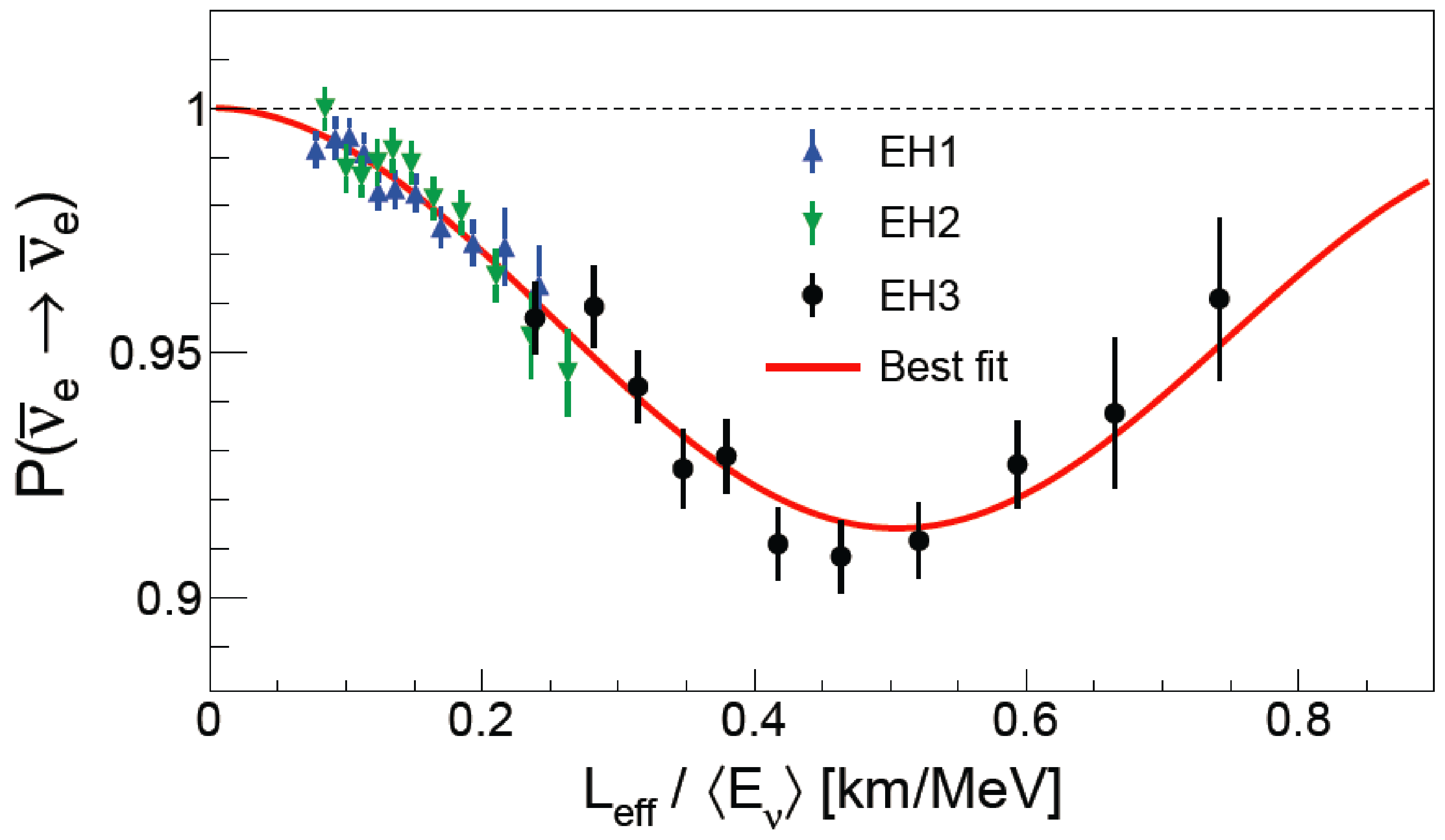
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right]$$

8 "functionally identical", 3-zone detectors reduce systematic uncertainties.

Very well defined target region

Result From Daya Bay with data up to Nov 2013.

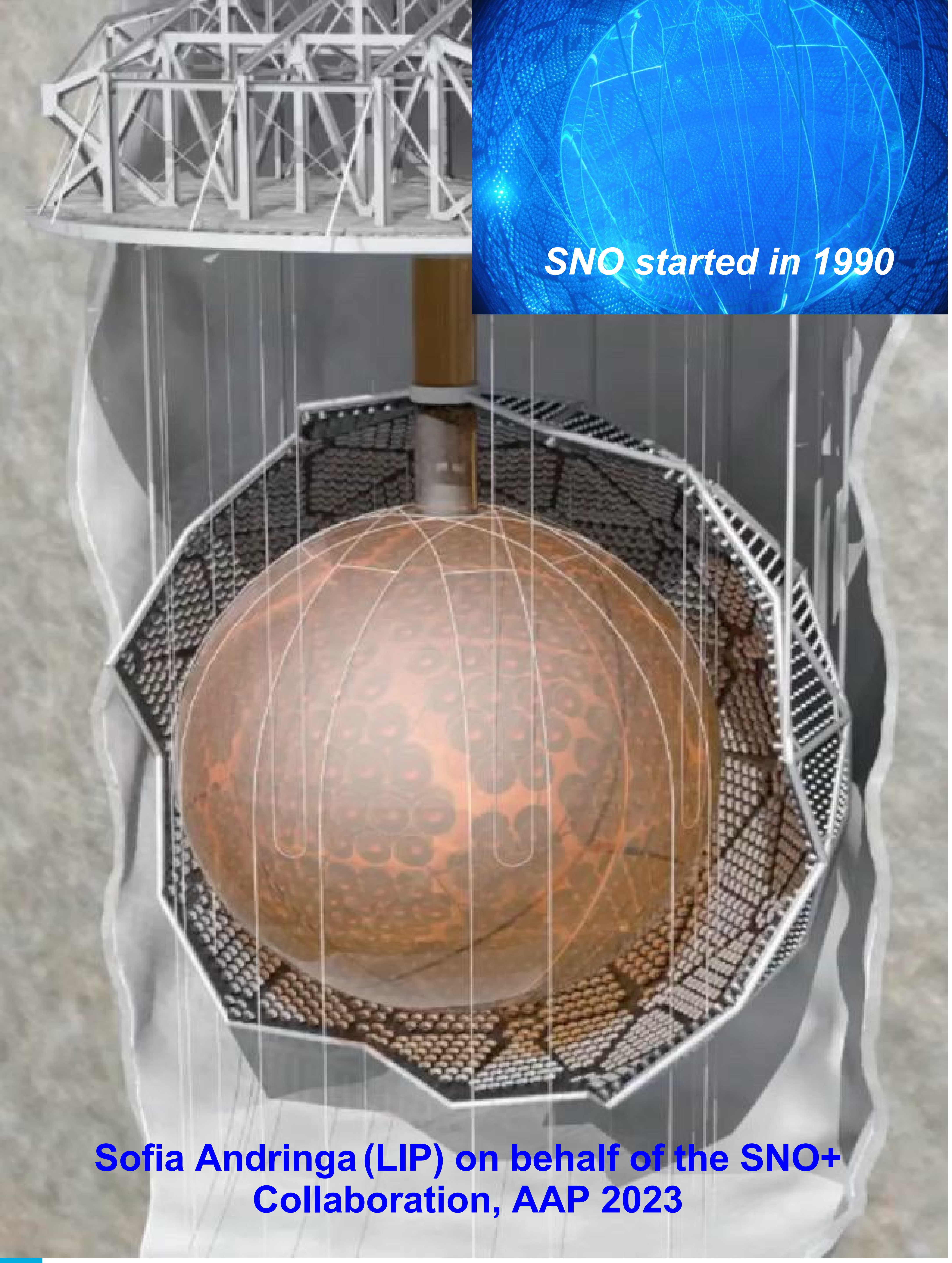




$\sin^2 2\theta_{13} = 0.084 \pm 0.005$

$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \mathrm{eV}^2$

- Using 217 days of 6 AD data and 404 days of 8 AD data.
- Total of 1.2 M events
- Best precision of mixing parameter measurements!



Sofia Andringa (LIP) on behalf of the SNO+ Collaboration, AAP 2023

the SNO+ detector

2070 m underground (can veto ~ 3 muons / hour)

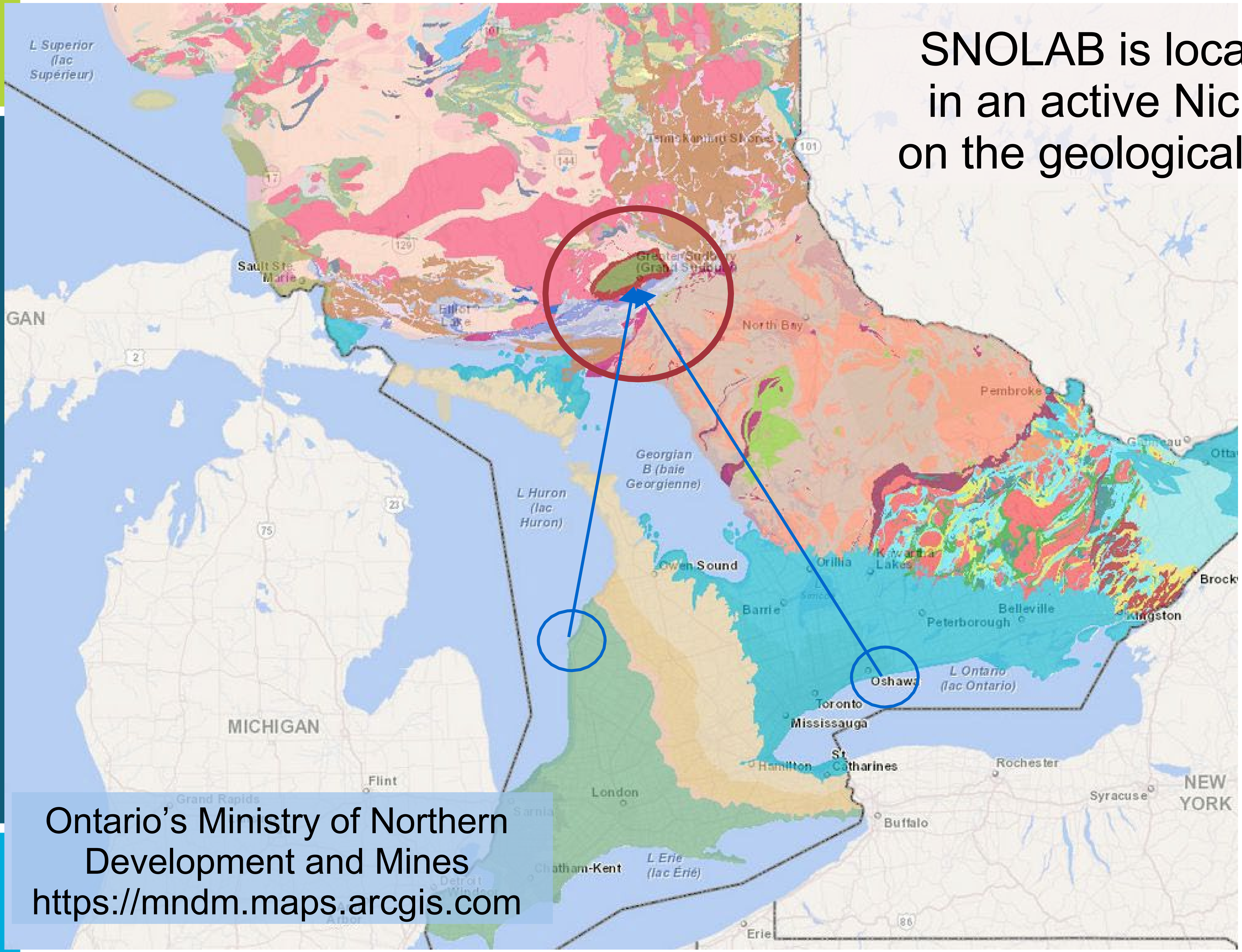
>9000 PMTs @ 8.5 m (50% optical coverage)

changing active medium H_2O to liquid scintillator
inside 6.0 m radius (5.5 cm thick) acrylic vessel

1. Water Phase (from September 2017 to July 2019)
   2.2 MeV gamma Cherenkov O(10 PMT hits)
2. Partial Fill (from March to October 2020)
3. Scintillator Phase (from May 2021)
   2.2 MeV gamma Scintillation O(1000 PMT hits)

^{130}Te $\beta\beta$

antineutrinos at SNOLAB



Ontario's Ministry of Northern Development and Mines
https://mndm.maps.arcgis.com

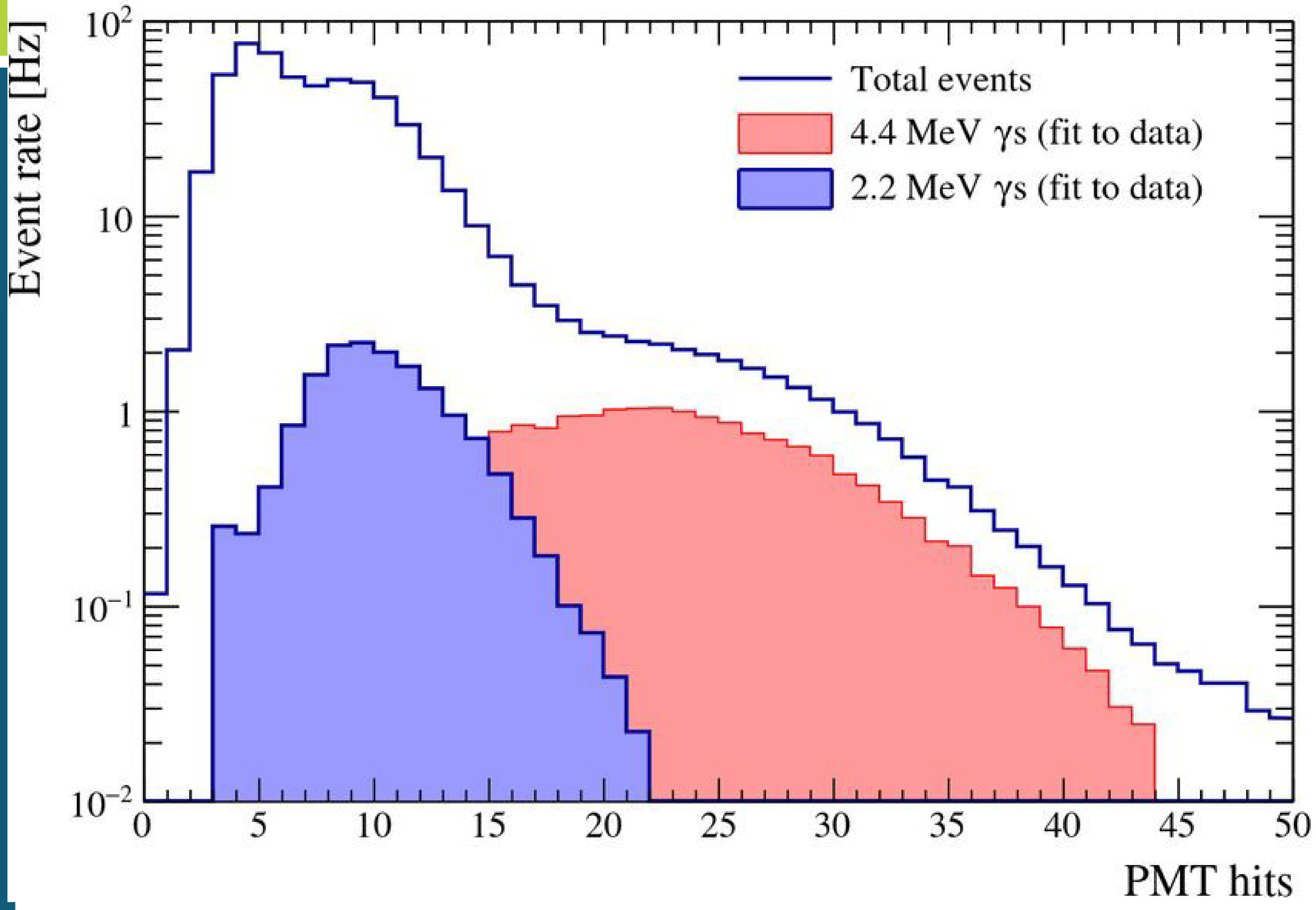
SNOLAB is located 2 km underground (6 km w.e.)
in an active Nickel mine (also Co, Cu, Pt, Pa, Au)
on the geologically interesting Sudbury impact basin

Geoneutrinos from the thick crust
of the North–American plate
a new location to add to
KamLAND (Japan) + Borexino (Italy)

Antineutrino from CANDU - Pressurized Heavy Water Reactors (can it be seen using a water Cherenkov detector?)

with clear oscillation features
to add more precision to Δm^2_{12}
from KamLAND + solar neutrinos

2.2 MeV and 4.4 MeV in Water



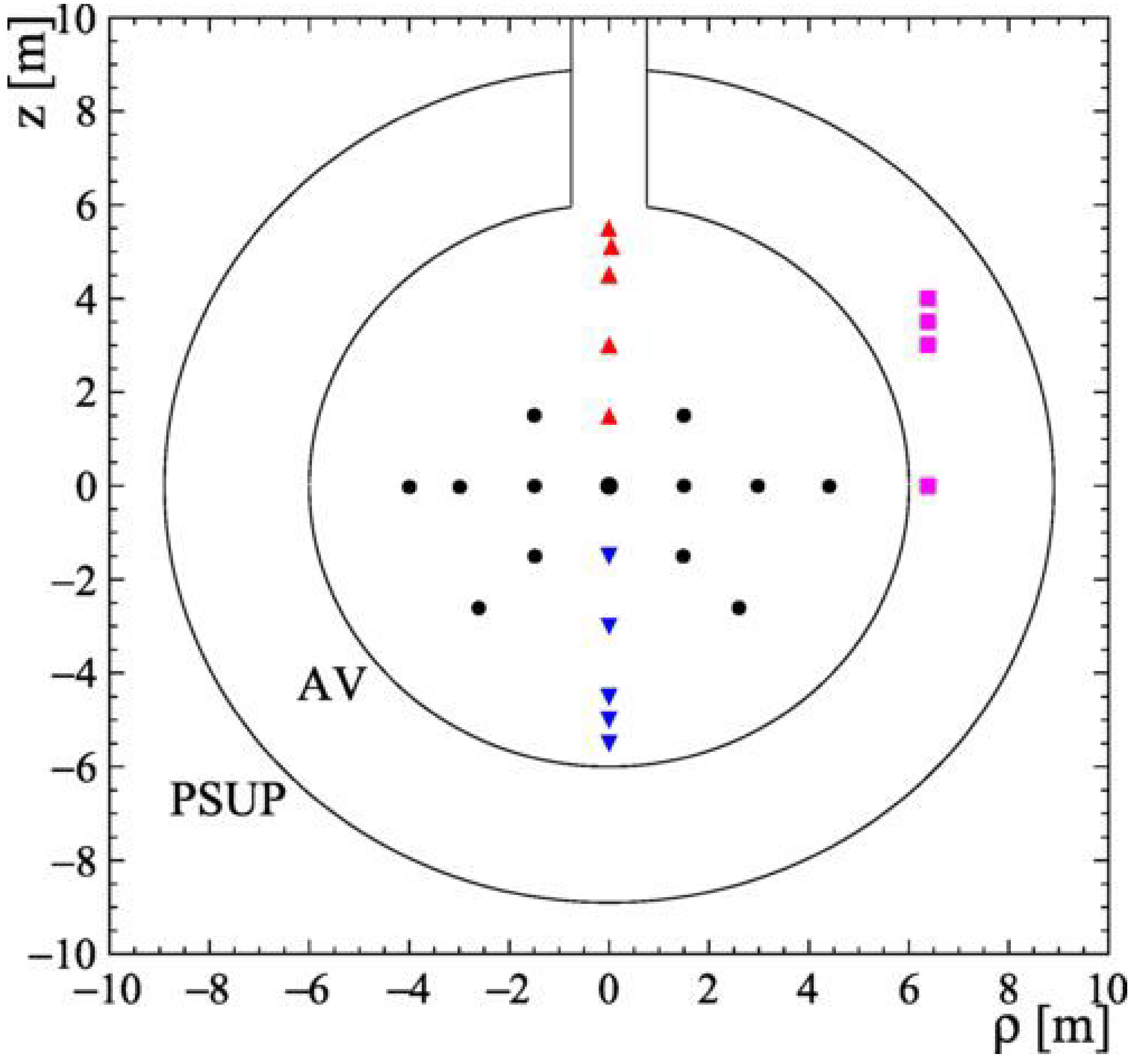
AmBe:
~60 Hz anti-neutrino calibration source!

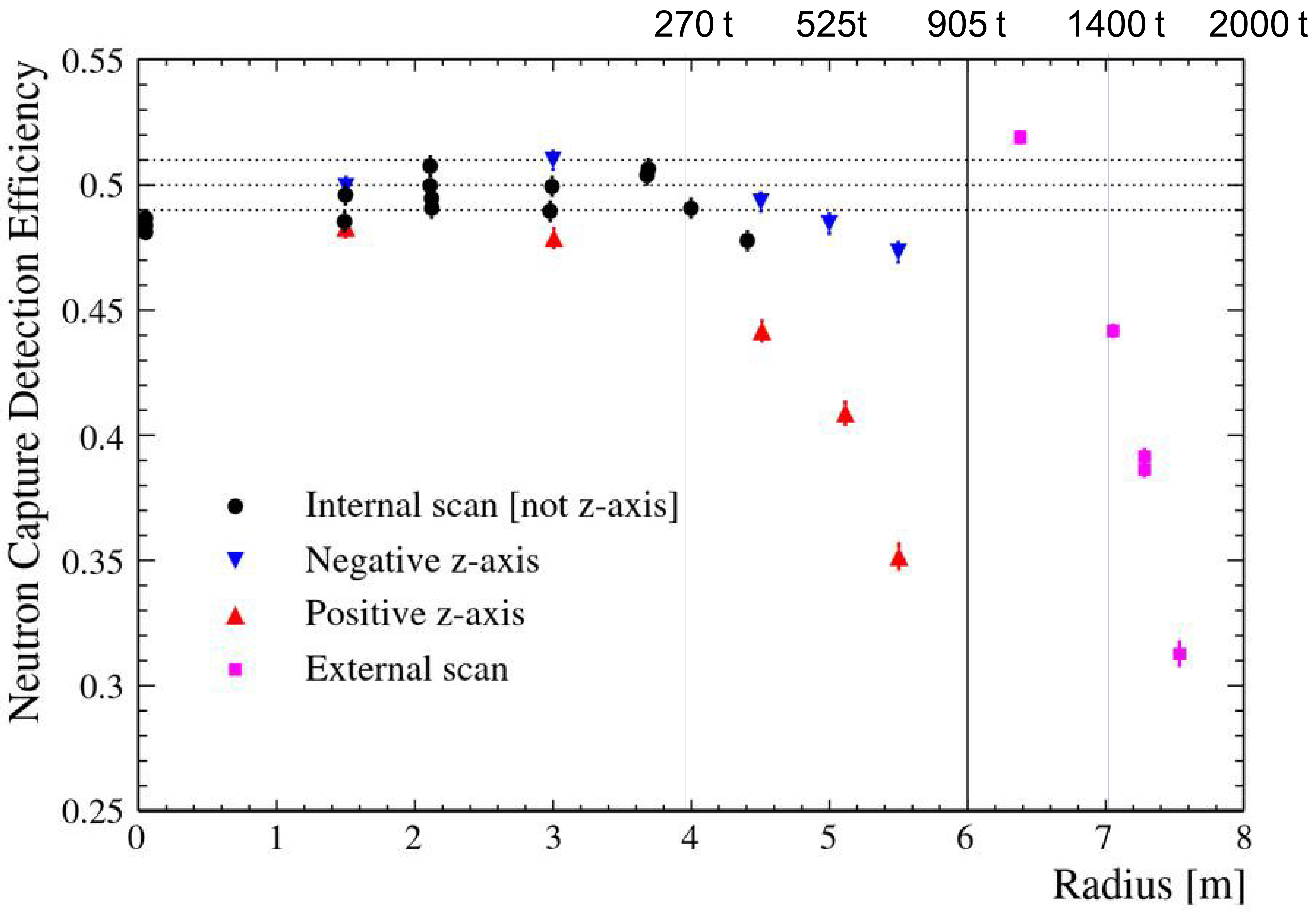
Prompt 4.4 MeV gamma (Eff ~100%)
Delayed 2.2 MeV gamma (at threshold)
- calibration of the trigger efficiency

Delayed coincidences in time and space
- calibration of the neutron propagation
- measurement of the p-n cross-section

Both signals can be *statistically* seen

highest efficiency in pure water





Phys. Rev. C 102, 014002 (2020)

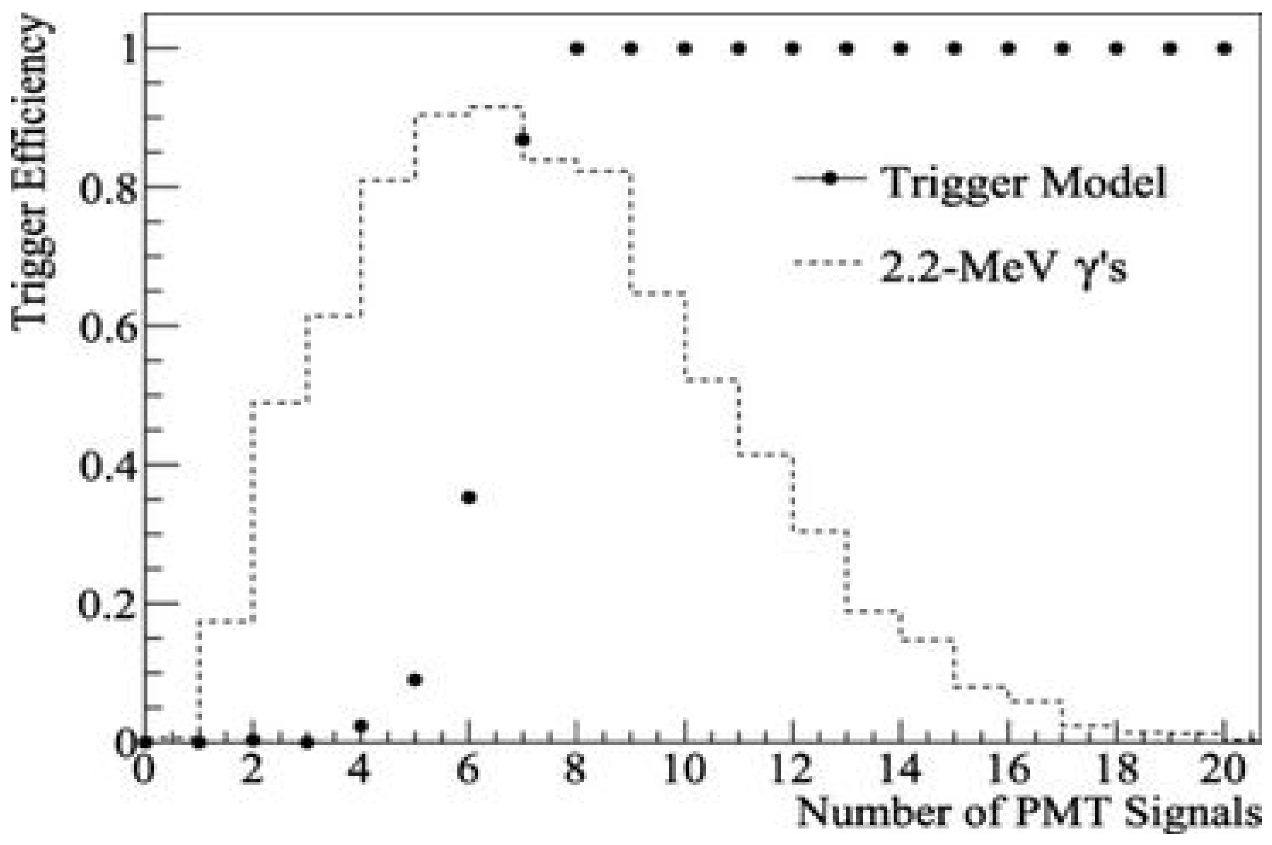
(49.08 ± 0.39)% efficiency for triggering on a neutron capture signal at detector center

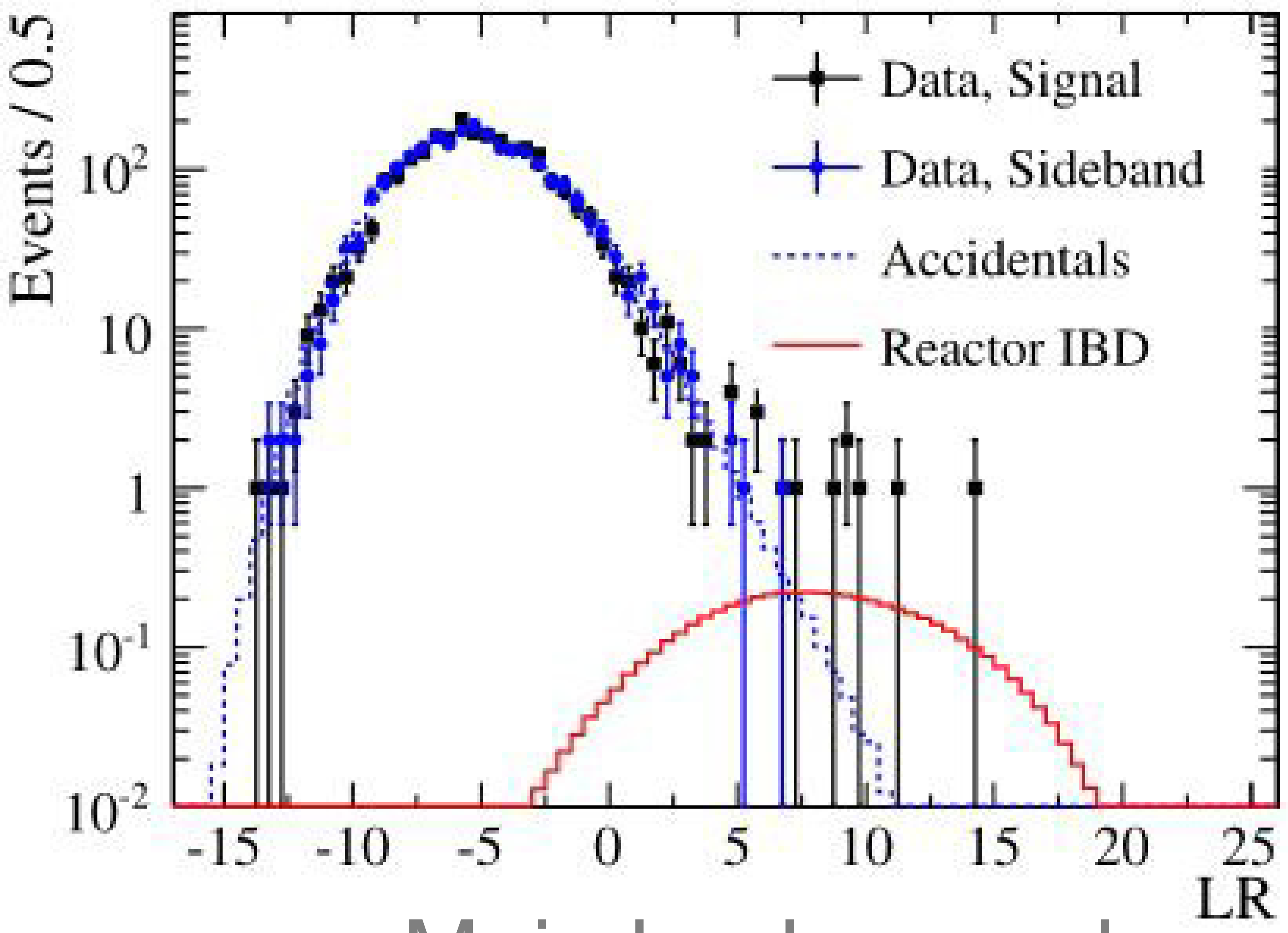
extended fiducial mass for neutron capture based analyses including external water

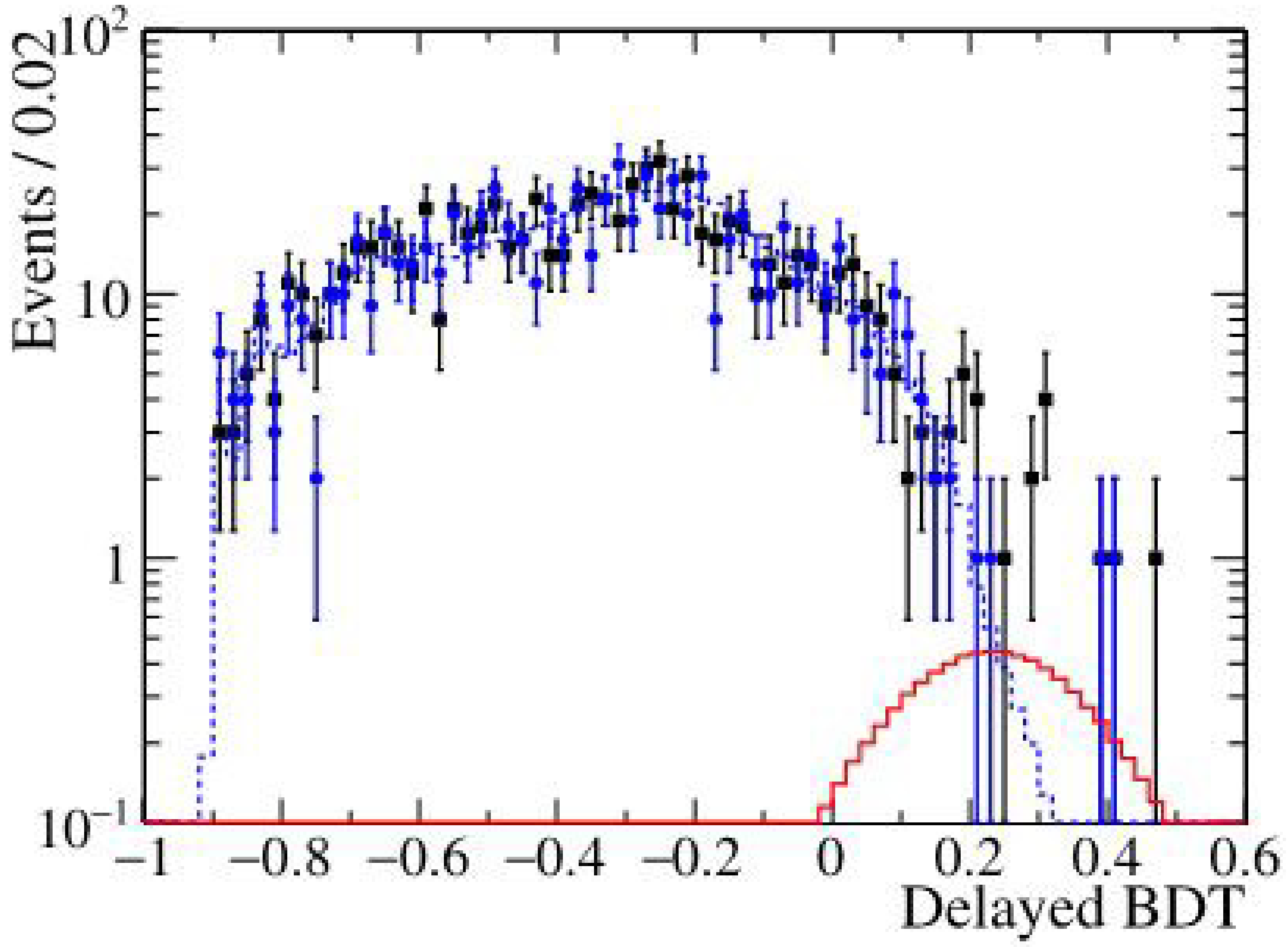
Antineutrinos in pure water

neutron capture coincidence signal down from ~10 Hz (calibration) to ~10 nHz (reactors)

imagine a scaling up of the red lines if reactors were closer!







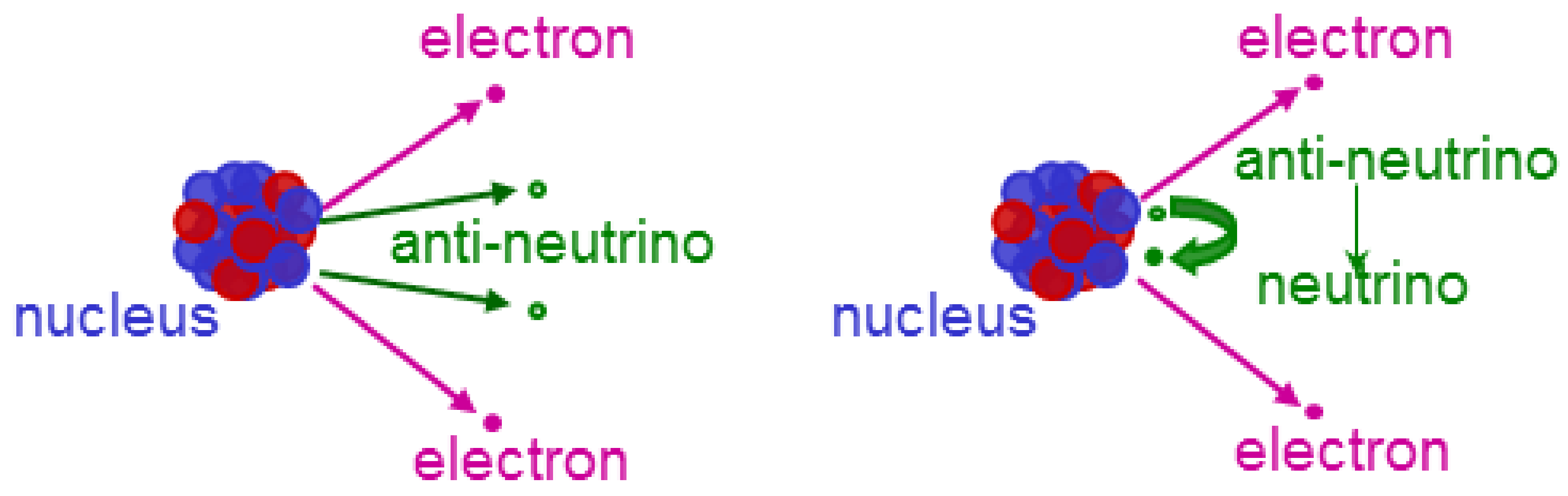
Main backgrounds:
accidental coincidences, C(α,n)O* interactions, atmospheric neutrinos...

Evidence of Antineutrinos from Distant Reactors Using Pure Water at SNO+ Physical Review Letters (130) 091801, 2023

3.5 sigma observation, from 14 candidates (for 3.2 ± 1.0 bkg events expected)
seen by two independent blind analyses (each ~ 3.0 σ)

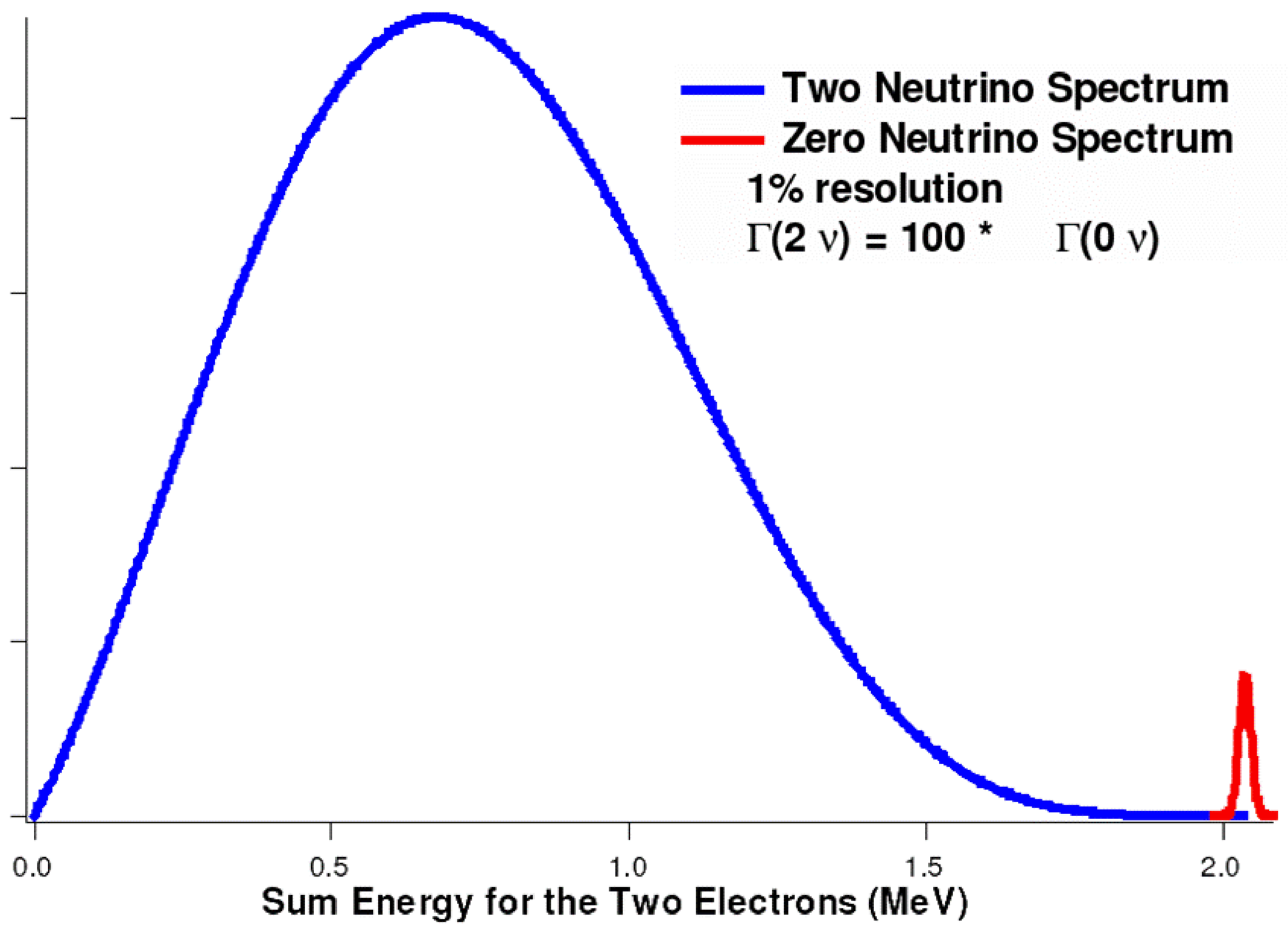
Brookhaven National Laboratory

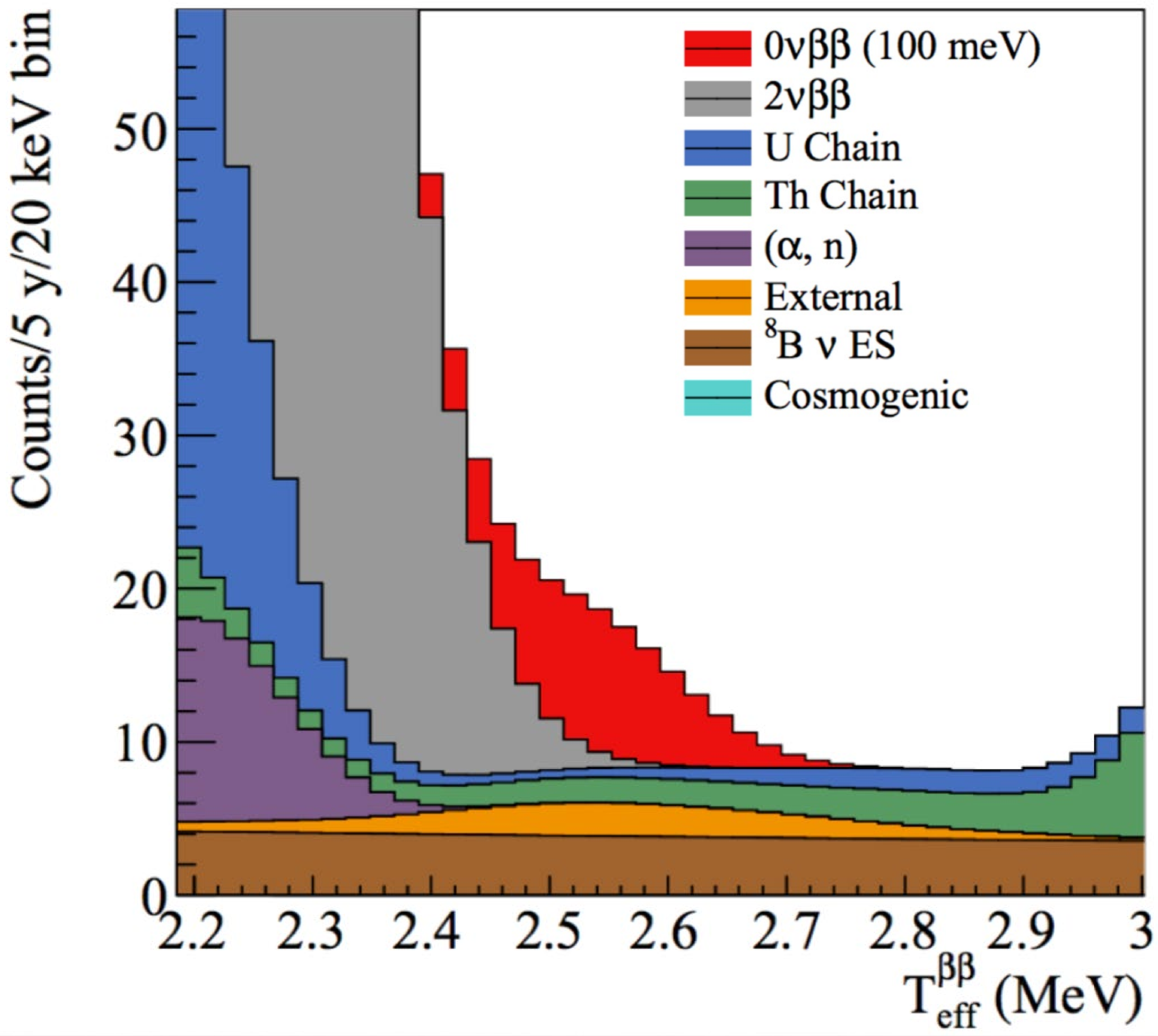
Neutrinoless double beta decay search: 0νββ



Two neutrino double beta decay

Neutrino-less double beta decay





antineutrinos in SNO+

First observation of reactor antineutrinos in a large Pure Water Cherenkov Detector (PRL 2023)

H_2O

SNO+ isolated a very small flux of antineutrinos from reactors at O(100 km)
proton-neutron captures seen with 50% efficiency in Pure Water volume

Confirmation of long base line antineutrino oscillation from CANDU reactors

SNO+ prepared to deal with significant amounts of the dominant (α,n) background

All components of antineutrino energy spectrum visible after full scintillator fill

LS

Sensitivity to Δm^2_{12} to be improved with larger statistics in the near future

Observation of geoneutrinos in a new geological setting (north american plate)

Will continue to measure antineutrinos throughout Tellurium phase

Te

Full potential will be achieved by adding all data together

Thank you!

LIP Coimbra
LIP Lisboa

SNOLAB
TRIUMF
University of Alberta
Queen's University
Laurentian University

TU Dresden

UNAM

Boston University
BNL
University of California Berkeley
LBNL
University of Chicago
University of Pennsylvania
UC Davis

Oxford University
Kings College London
University of Liverpool
University of Sussex
University of Lancaster

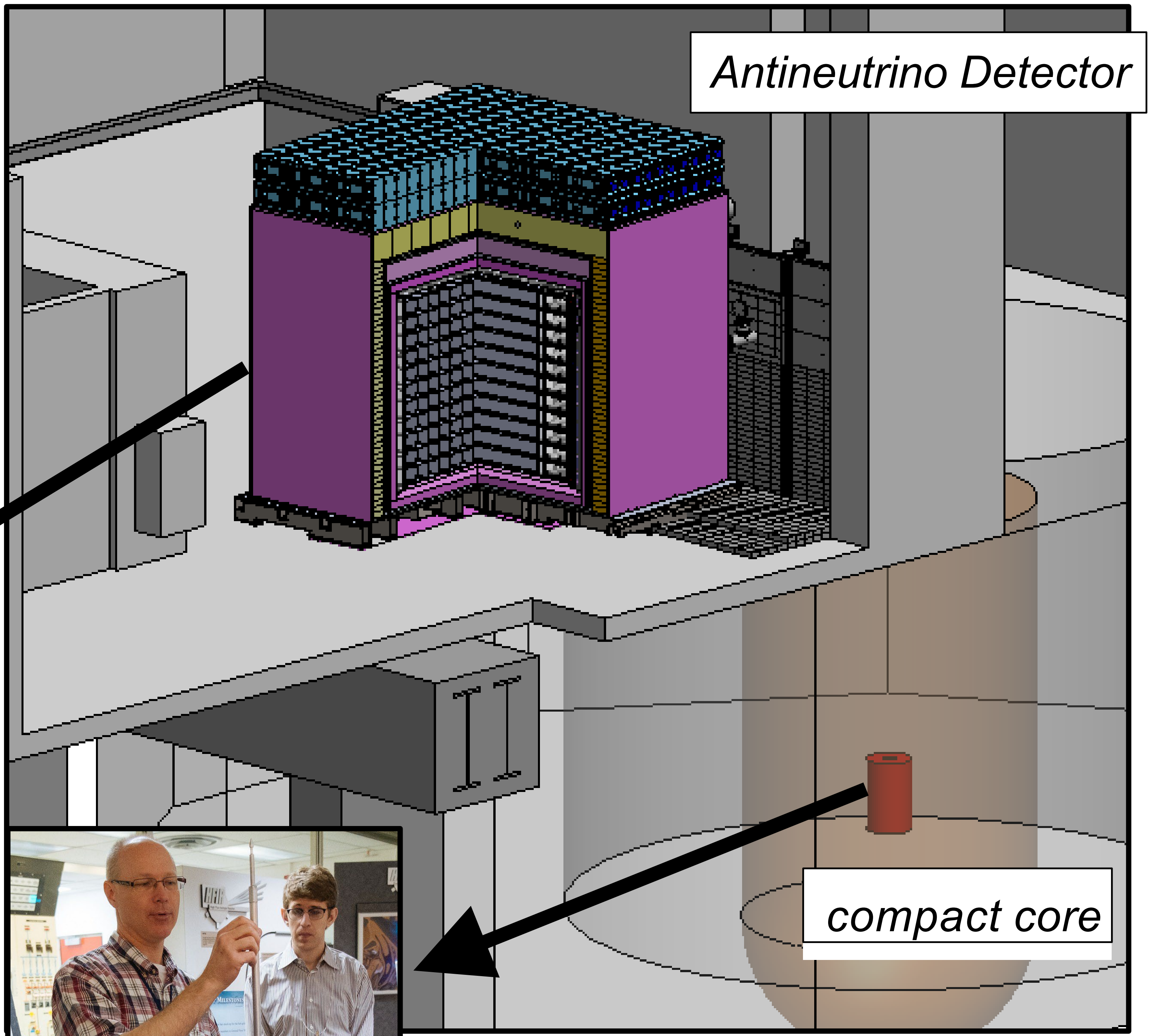
Shandong University

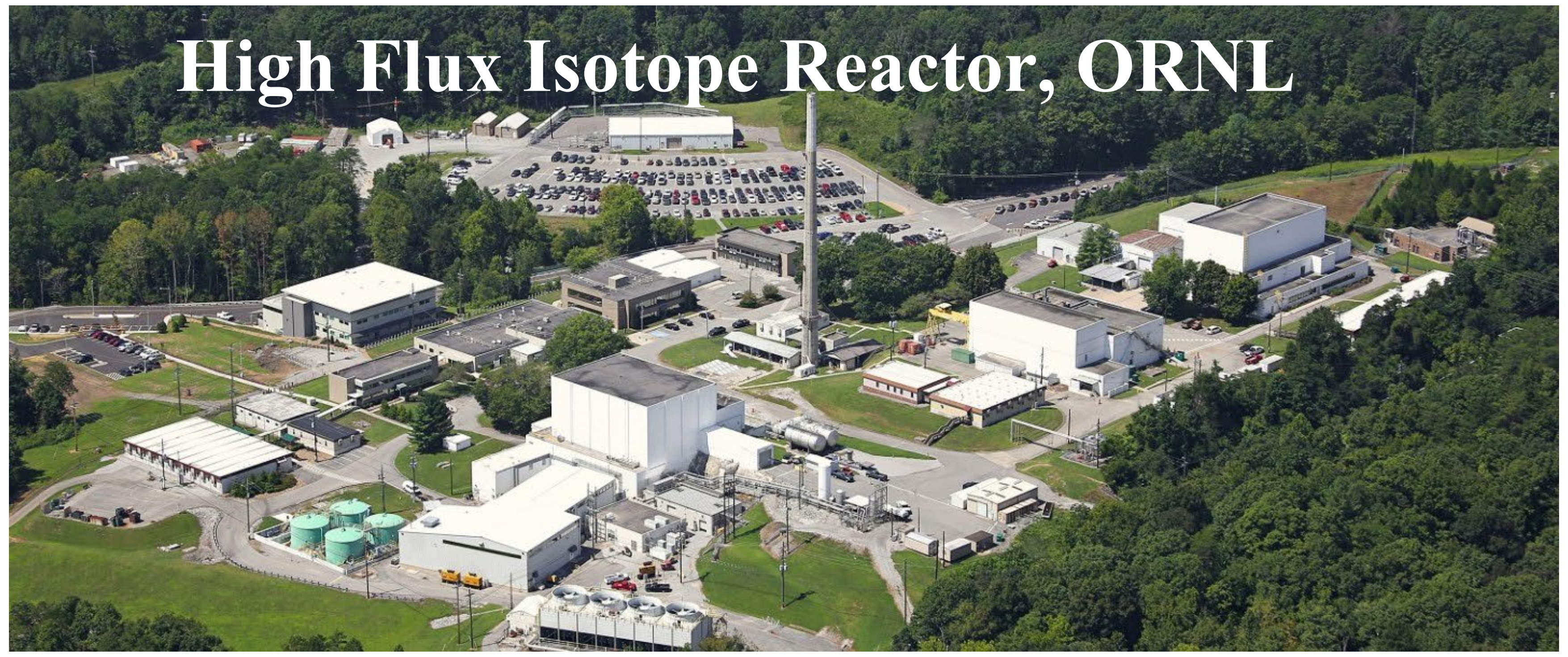
fct Fundação para a Ciência e a Tecnologia

OE, FCT-Portugal,
CERN/FIS-INS/0028/2021

PROSPECT Experiment

A 4-ton, segmented ^{6}Li-doped PSD LS detector at the HFIR research reactor (ORNL)





Bryce Littlejohn (LIT), on behalf of the PROSPECT Collaboration, AAP 2023

PROSPECT Physics Motivations

- Probe short-baseline neutrino oscillations

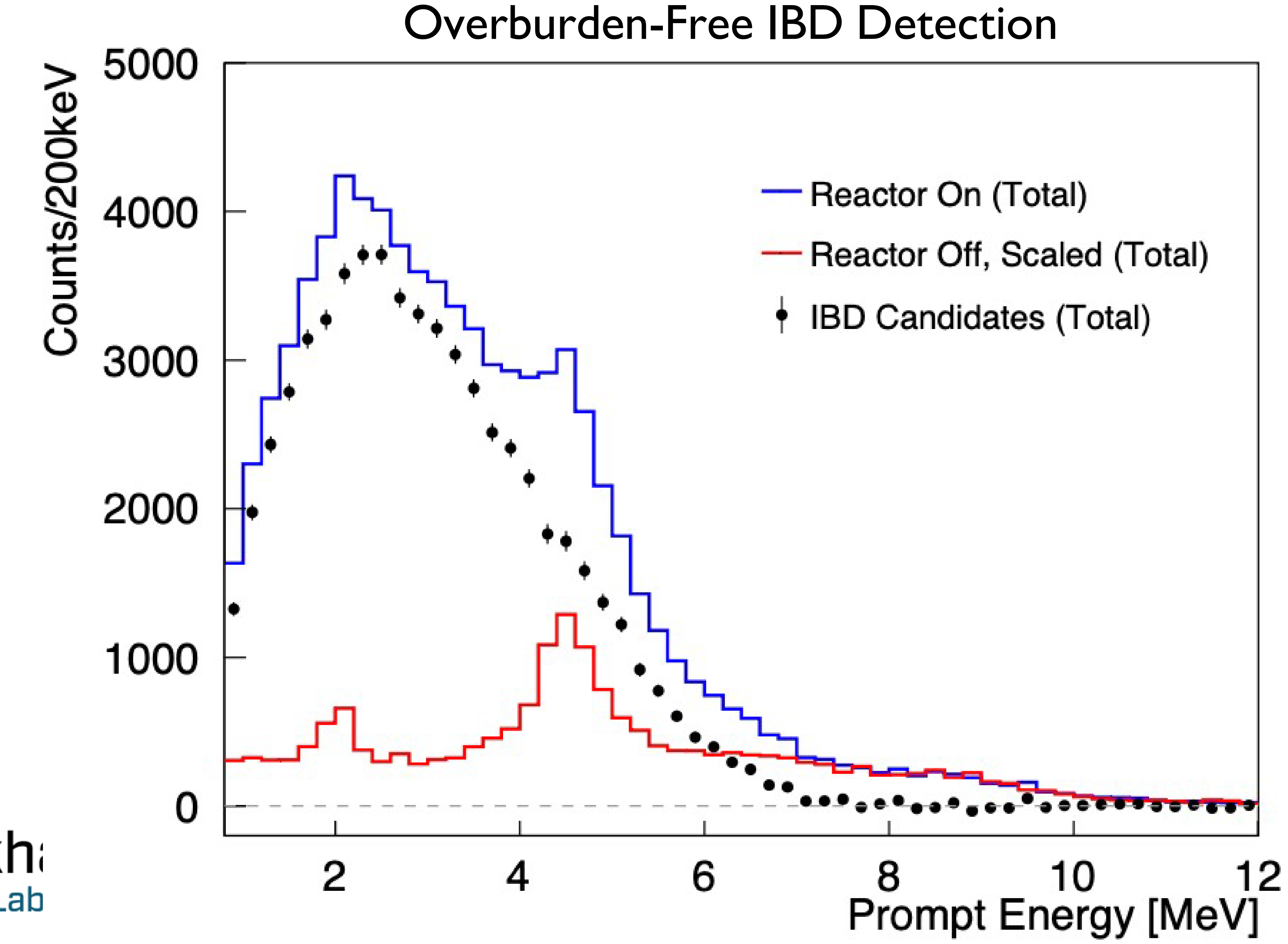
  PROSPECT, PRL 121 (2018) PROSPECT, PRD 103 (2021) TBD (2023) TBD (2024)

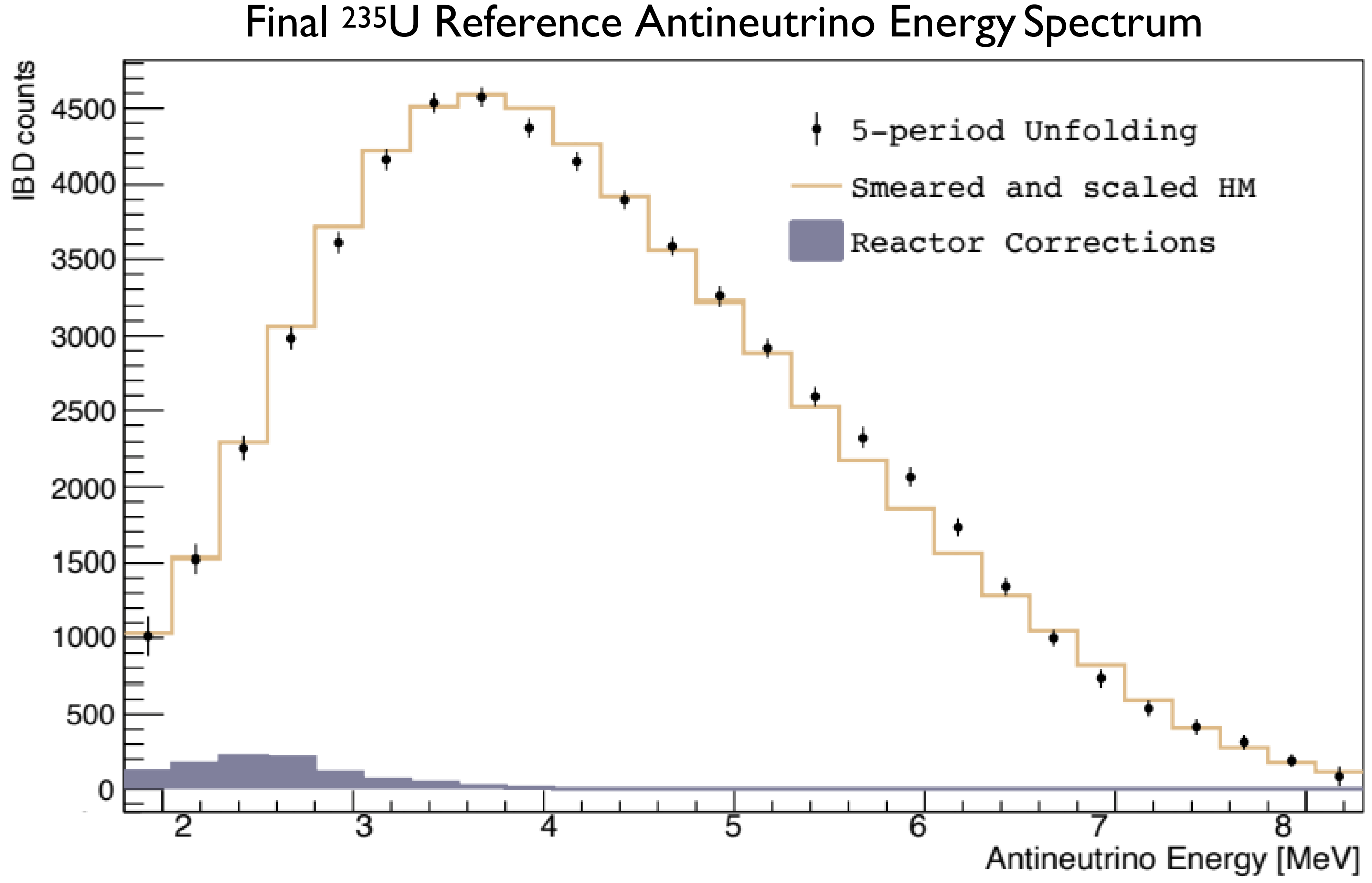
- Measure reference antineutrino spectrum and flux for ^{235}U

  PRL 122 (2019) PRD 103 (2021) PRL 128 (2022) PRL 128 (2022) PRL 131 (2023) TBD (2024)

- Develop/demonstrate on-surface IBD detection technology

  NIM A 922 (2018) JINST 13 (2018) JINST 14 P04014 (2019) JINST 14 P03026 (2019) TBD (2023) TBD (2024)

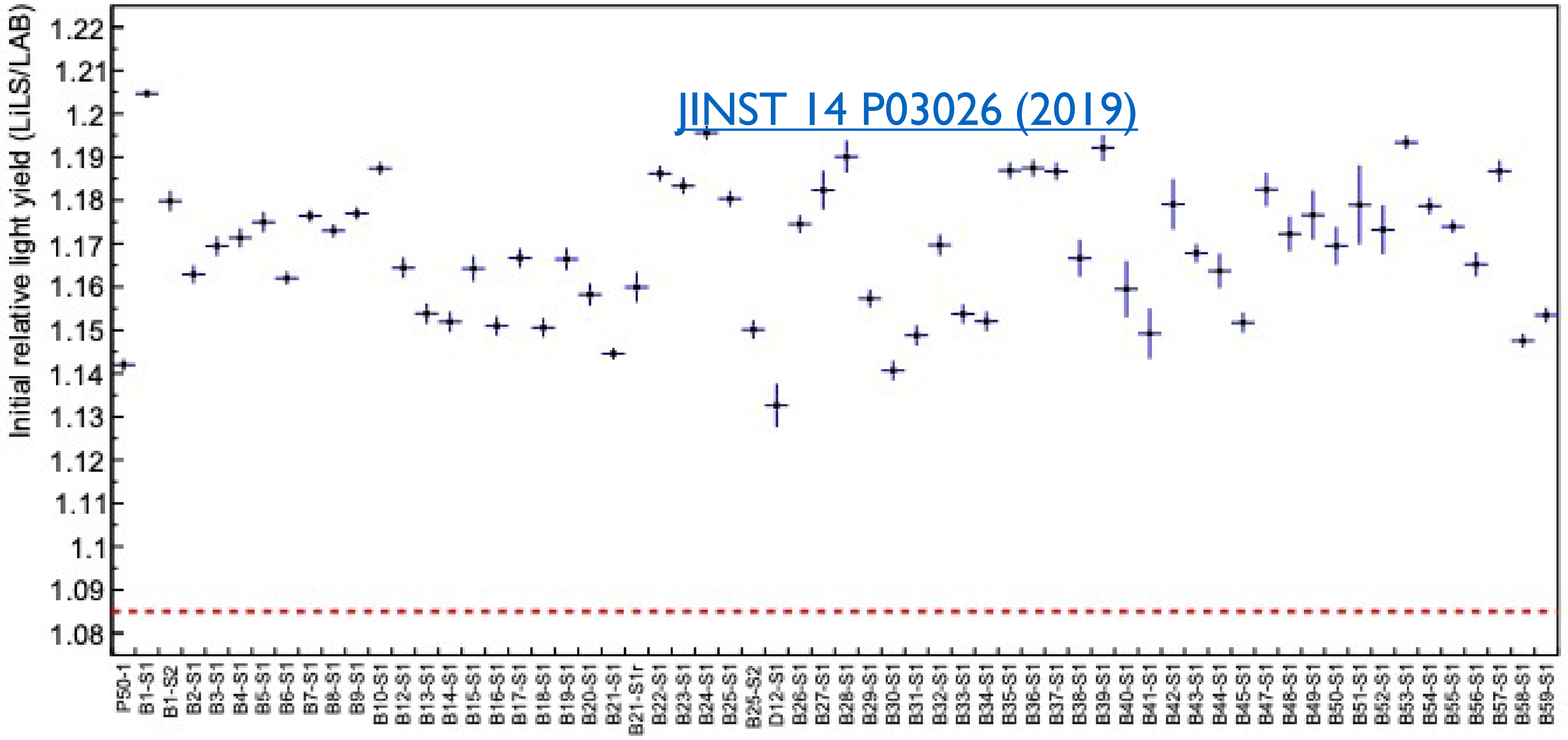


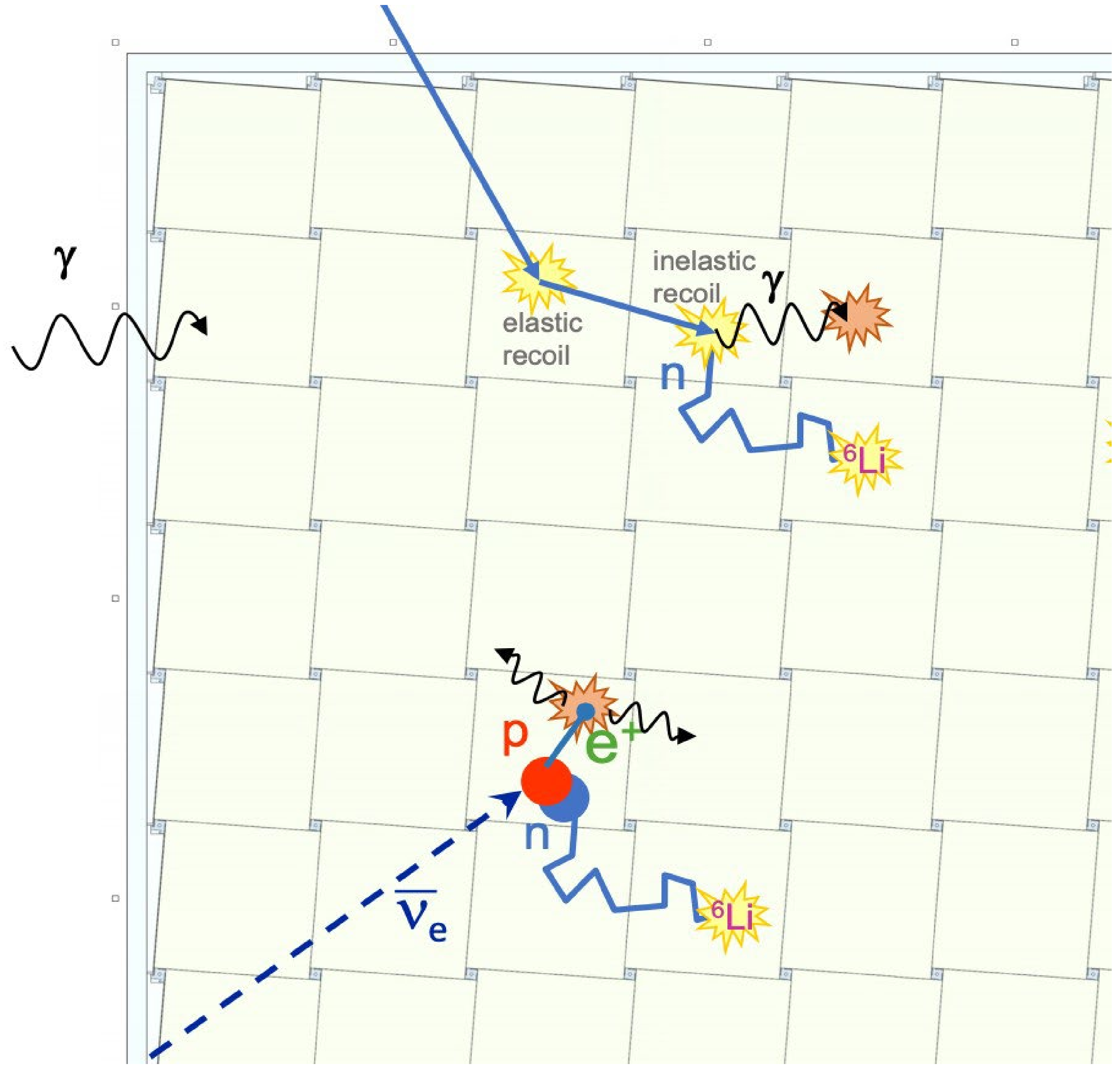


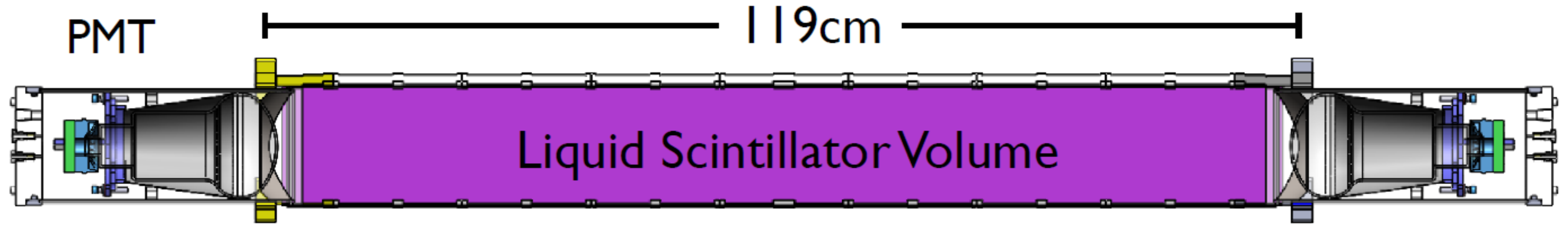
Brookhaven National Lab

^{6}Li-doped Liquid PSD Scintillator

- Essential R&D achievement for PROSPECT success: PSD-capable ^{6}Li-loaded LS
  - BNL-produced formulation based on commercial EJ-309
  - Higher scintillation yield than LAB-based scintillator with PSD (FOM > 2 at 0.53MeV$_{ee}$ nLi peak)





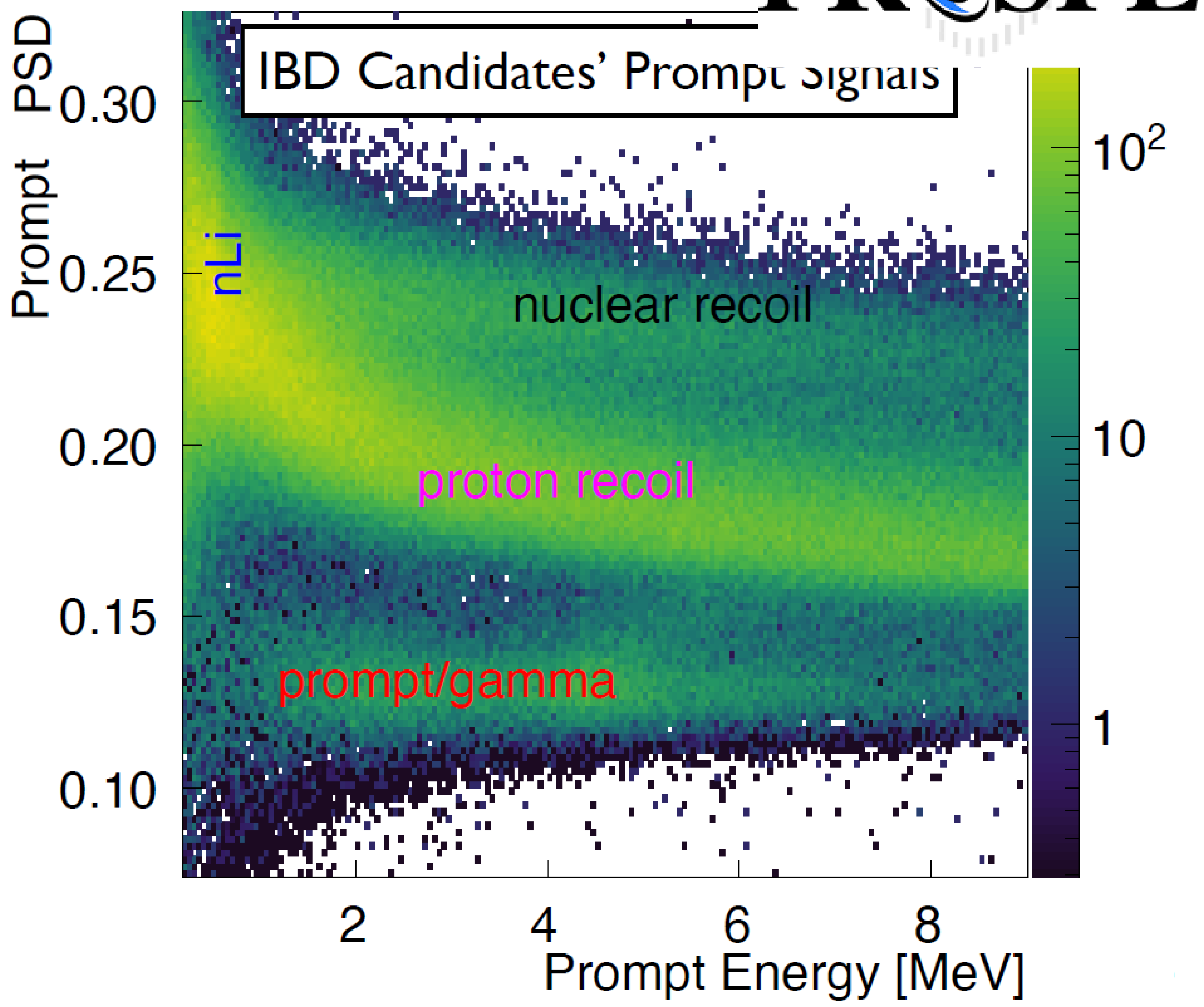


Double-end PMT readout and segmentation allows XYZ reco and topology cuts

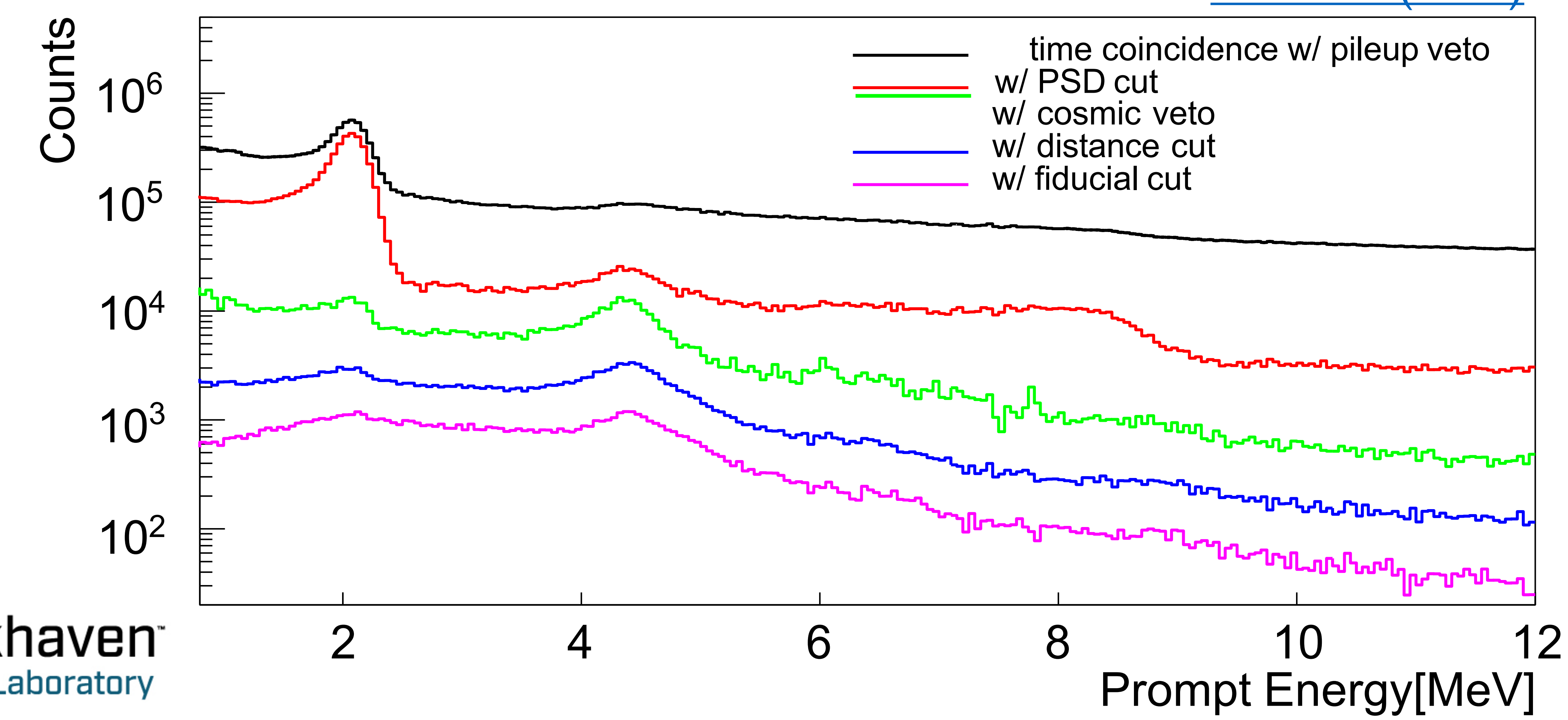
Brookhaven National Laboratory

IBD Selection Illustration

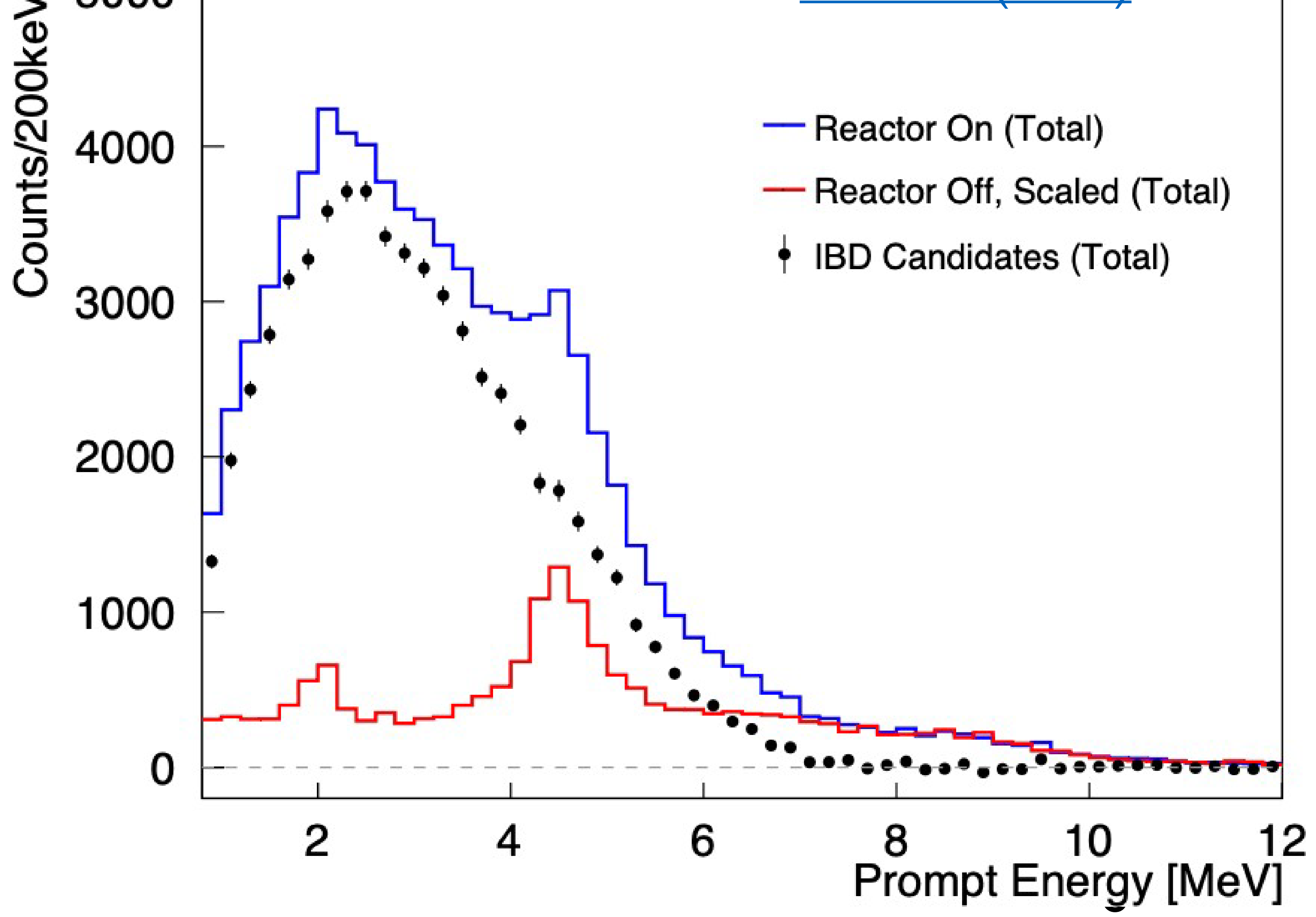
- IBD selection techniques described in last slide enable high signal:background despite near-total lack of overburden
  - S:B >1 at all energies below 6 MeV E_{prompt}, >10:1 for some energies
  - Achieved best-ever S:B for an overburden-free reactor IBD experiment despite an increasing number of non-functioning PMTs during operations



PRD 103 (2021)



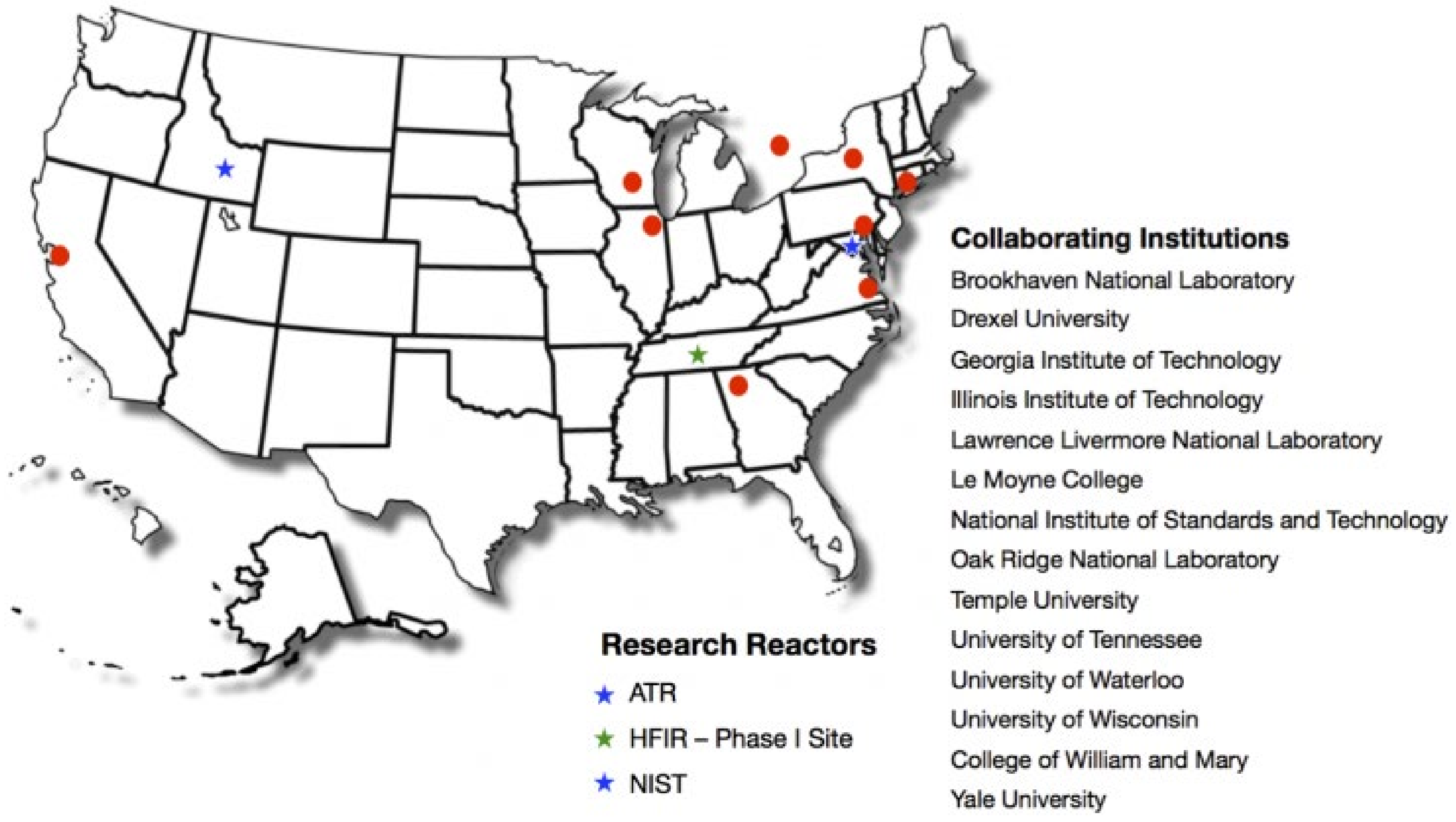
PRL 131 (2023)



Brookhaven National Laboratory

Conclusions and PROSPECTs

- PROSPECT has demonstrated >>1 S:B in an overburden-free reactor IBD experiment: a major achievement for AAP
- Along the way, we've developed tech, tools, and knowledge:
  - Leading sterile oscillation limits and reference ^{235}U spectra
  - Li-doped PSD-capable LiLS and supporting IBD detector design concepts
  - Versatile and reliable cosmic background simulations
  - A user-friendly US-based reactor neutrino lab at HFIR
- Working towards a multi-site deployment of PROSPECT-II

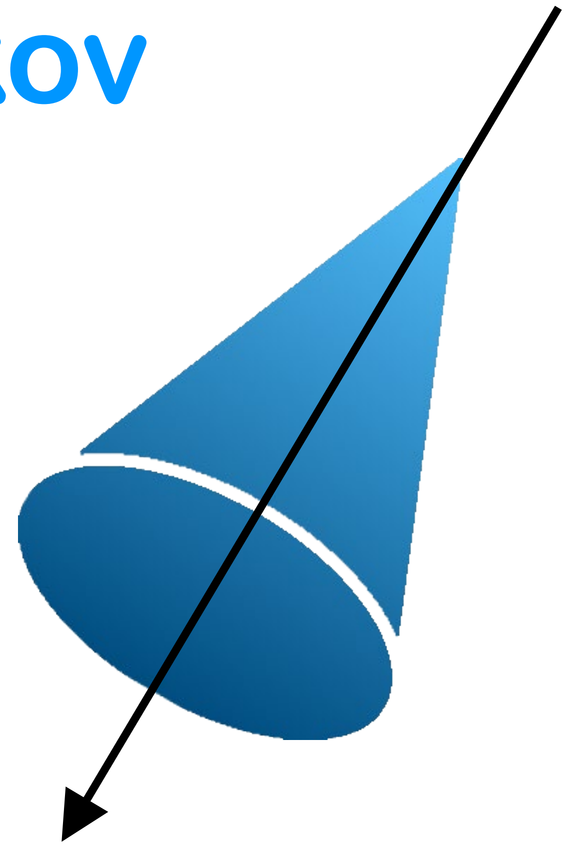


Next-generation liquid scintillator detectors

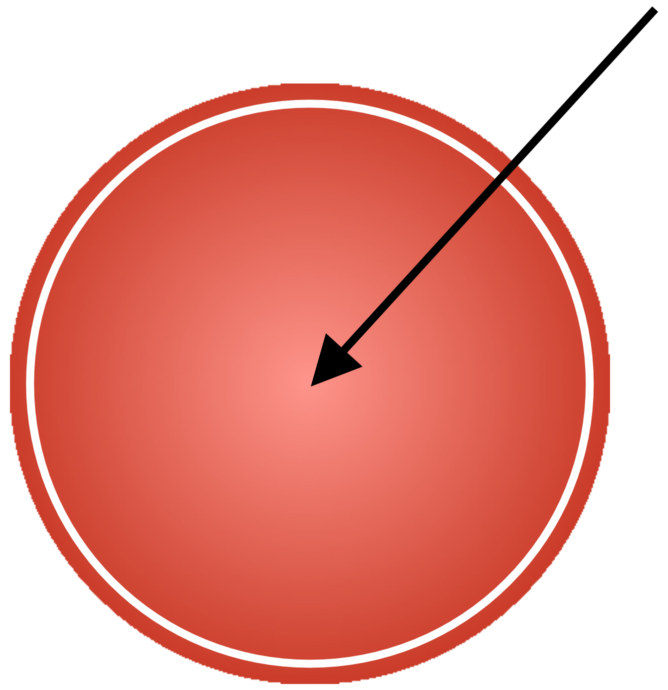
Directionality – A hybrid Cherenkov and Scintillation Optical Detector

How to see Cherenkov from “massive” scintillation?

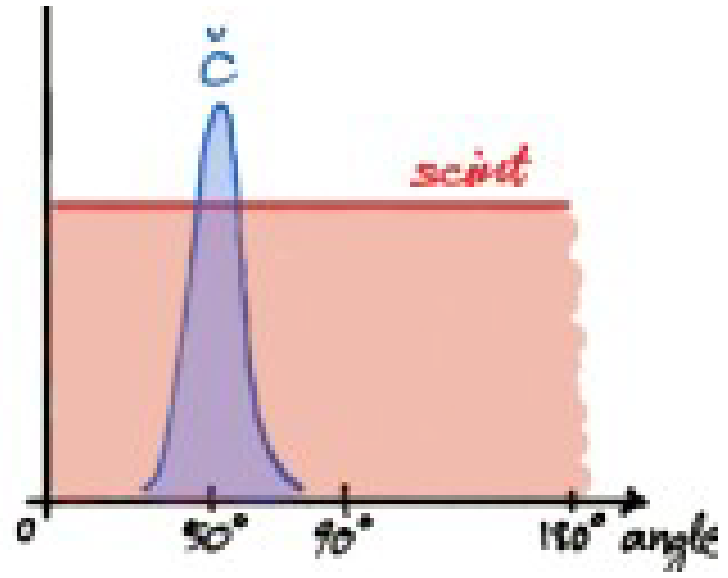
Cherenkov



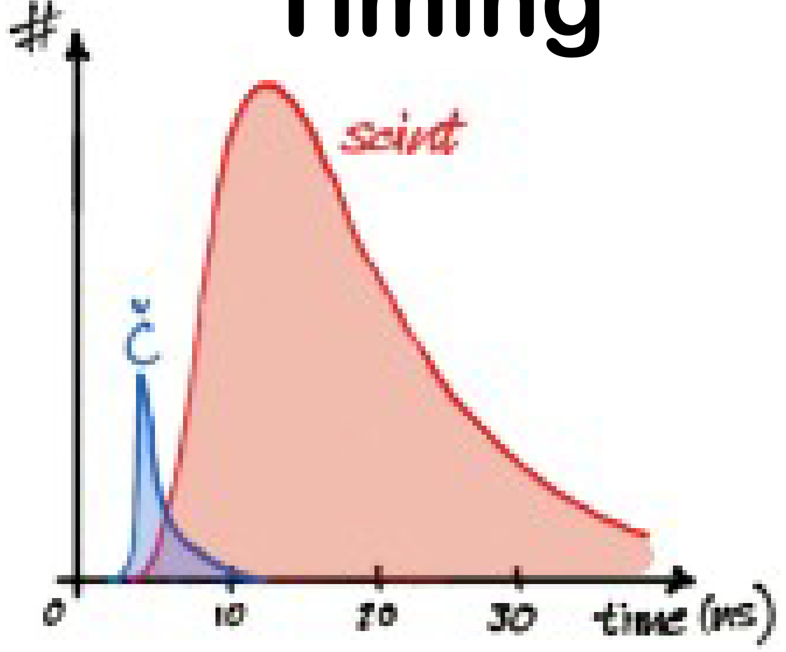
Scintillation



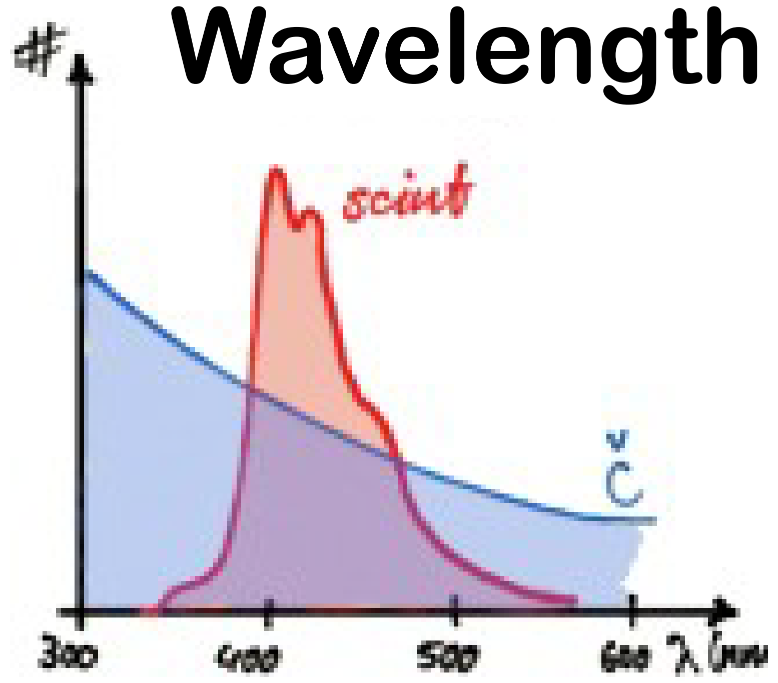
Angular distribution

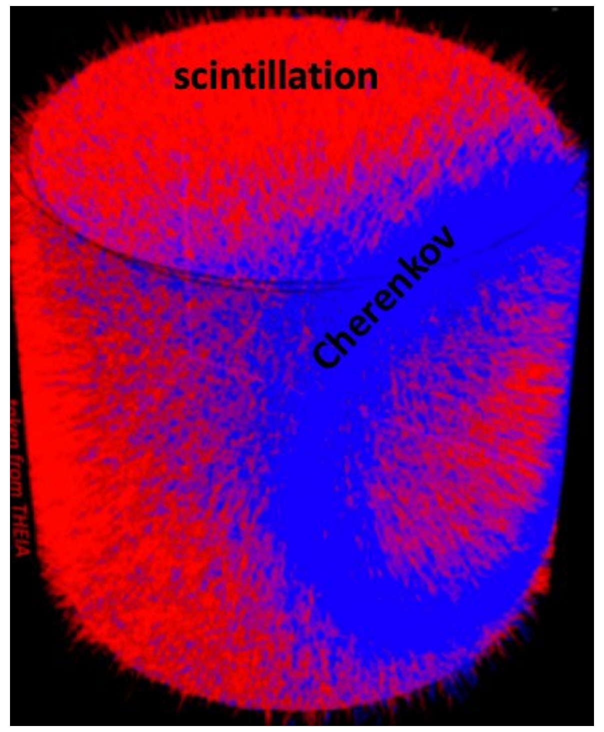


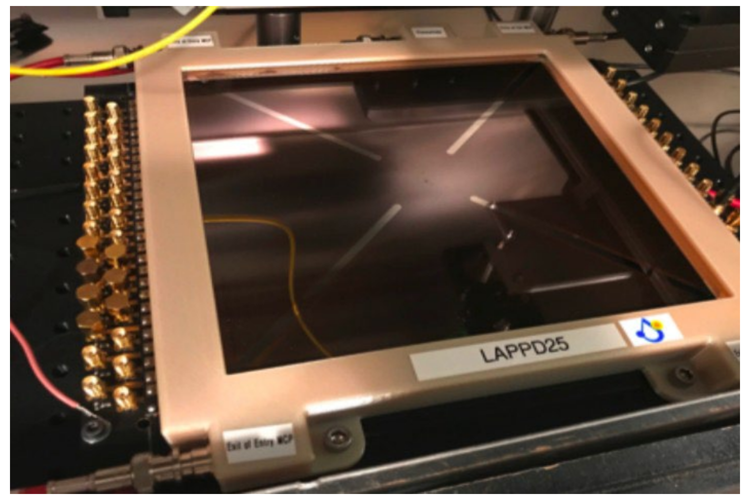
Timing



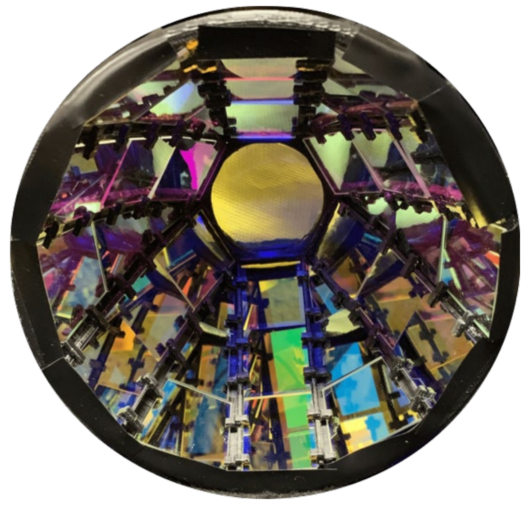
Wavelength







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



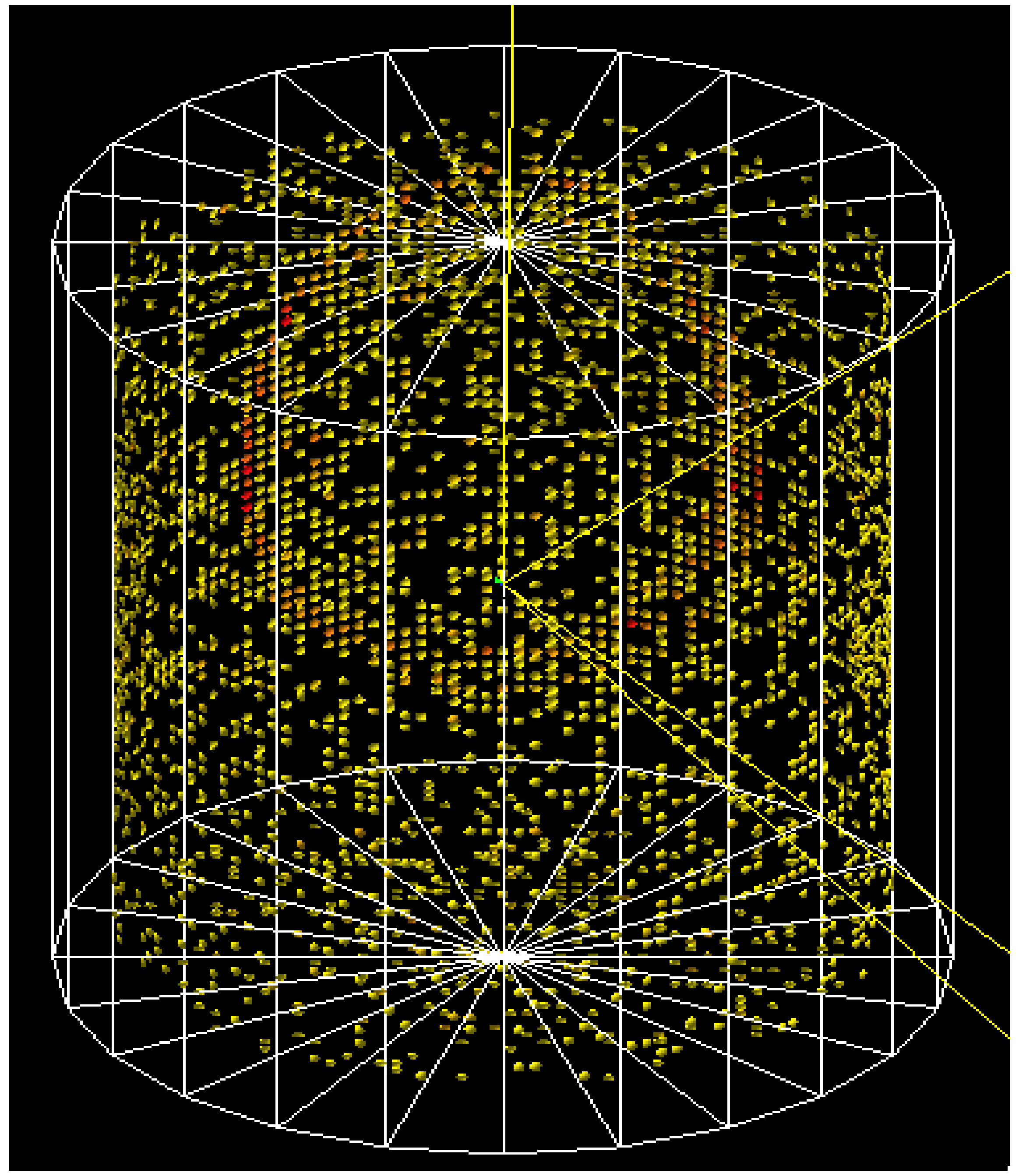
T. Kaptanoglu et al.
Phys. Rev. D 101, 072002 (2020)

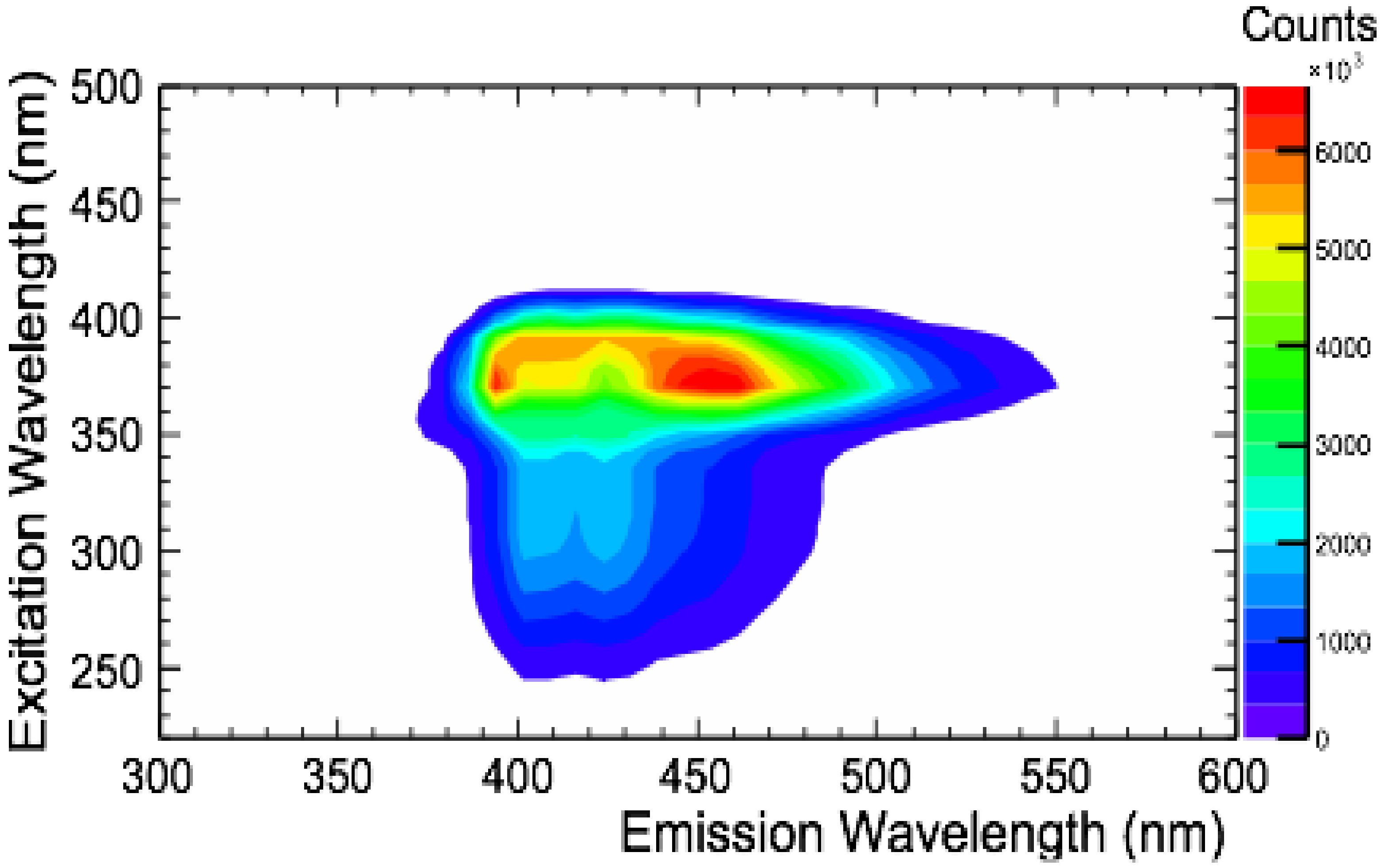
Water-based Liquid Scintillator

If you always do what you always did, you will always get what you always got. -Albert Einstein

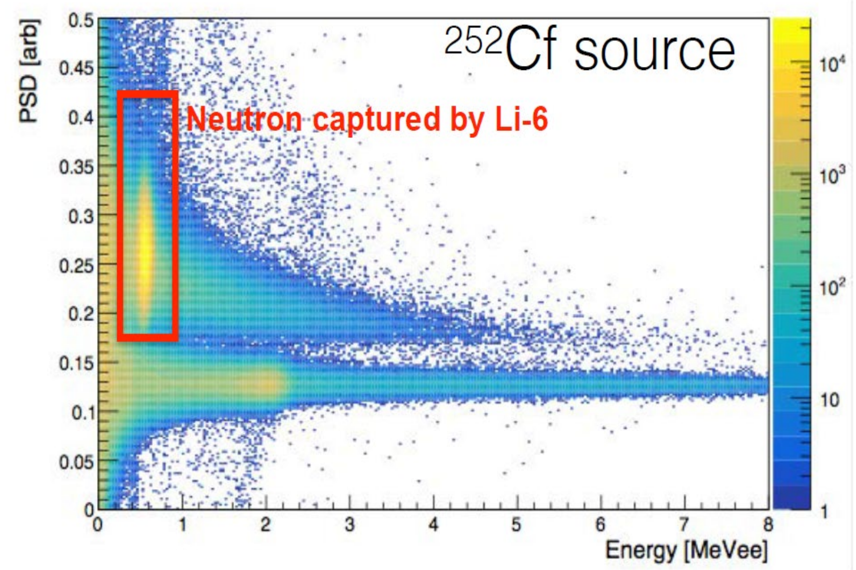
National Nuclear Security Administration

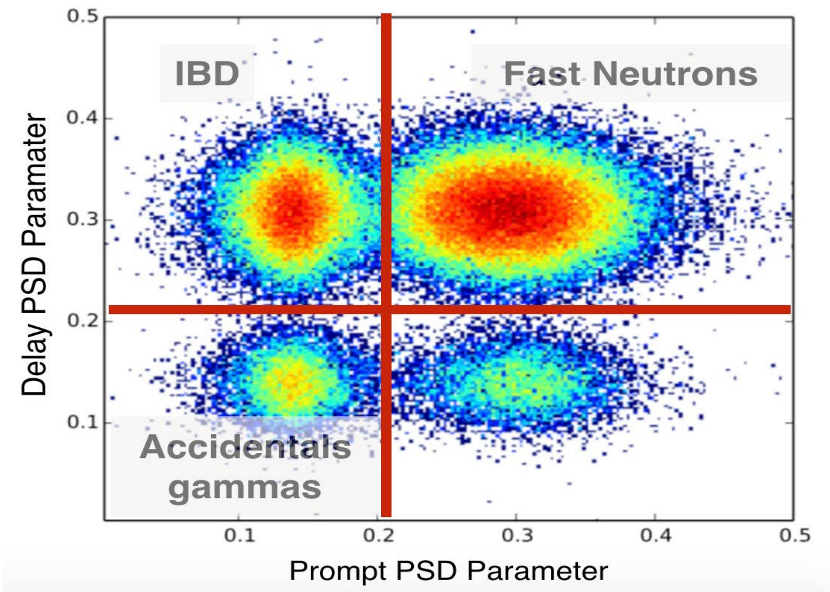
- A novel low-energy threshold detection medium, bridging scintillator and water.
- Tunable scintillation light from ~pure water to ~organic.
- Environment-friendly, noncombustible, and excellent material compatibility; feasible for **field study**.
- A particle detector capable of <u>Cherenkov and Scintillation detections</u>
- Viable to load a variety of metallic isotopes for varied particle detections (**neutron-enhanced**)

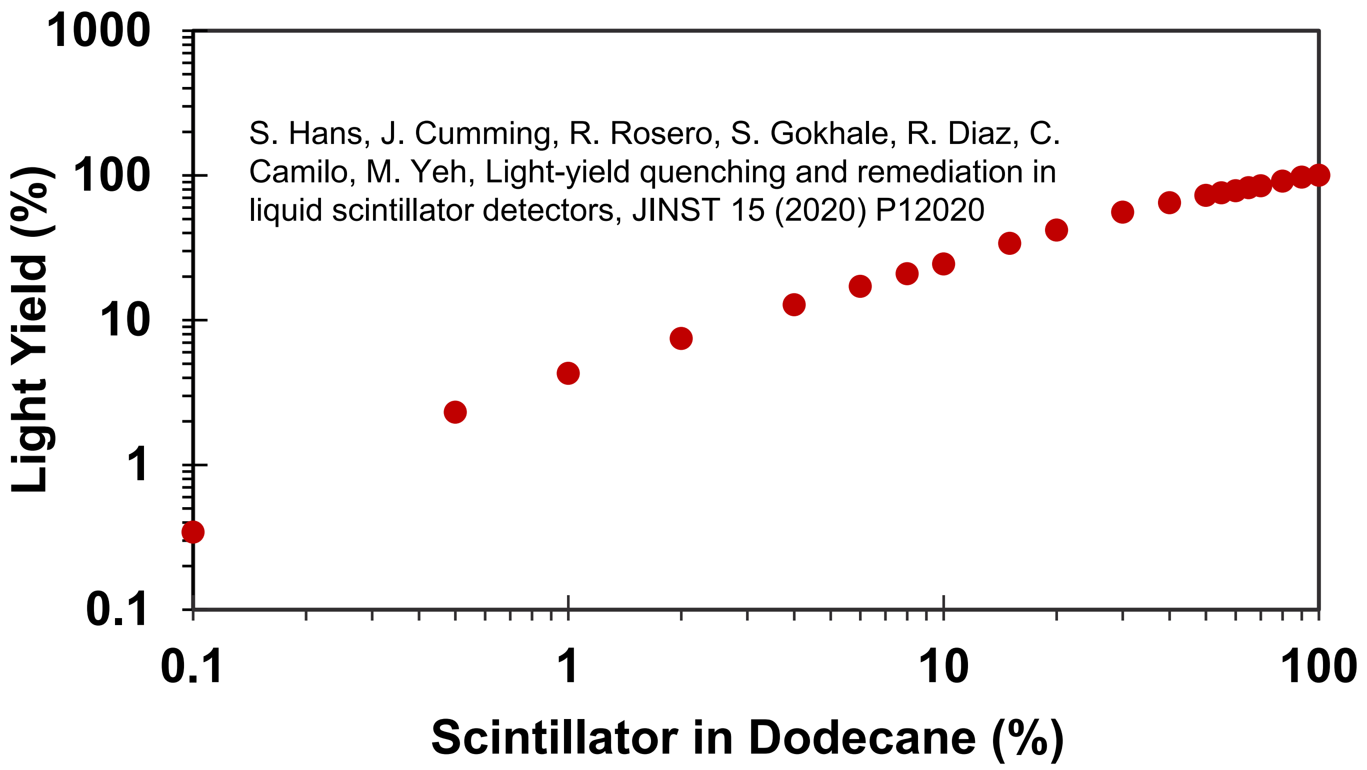


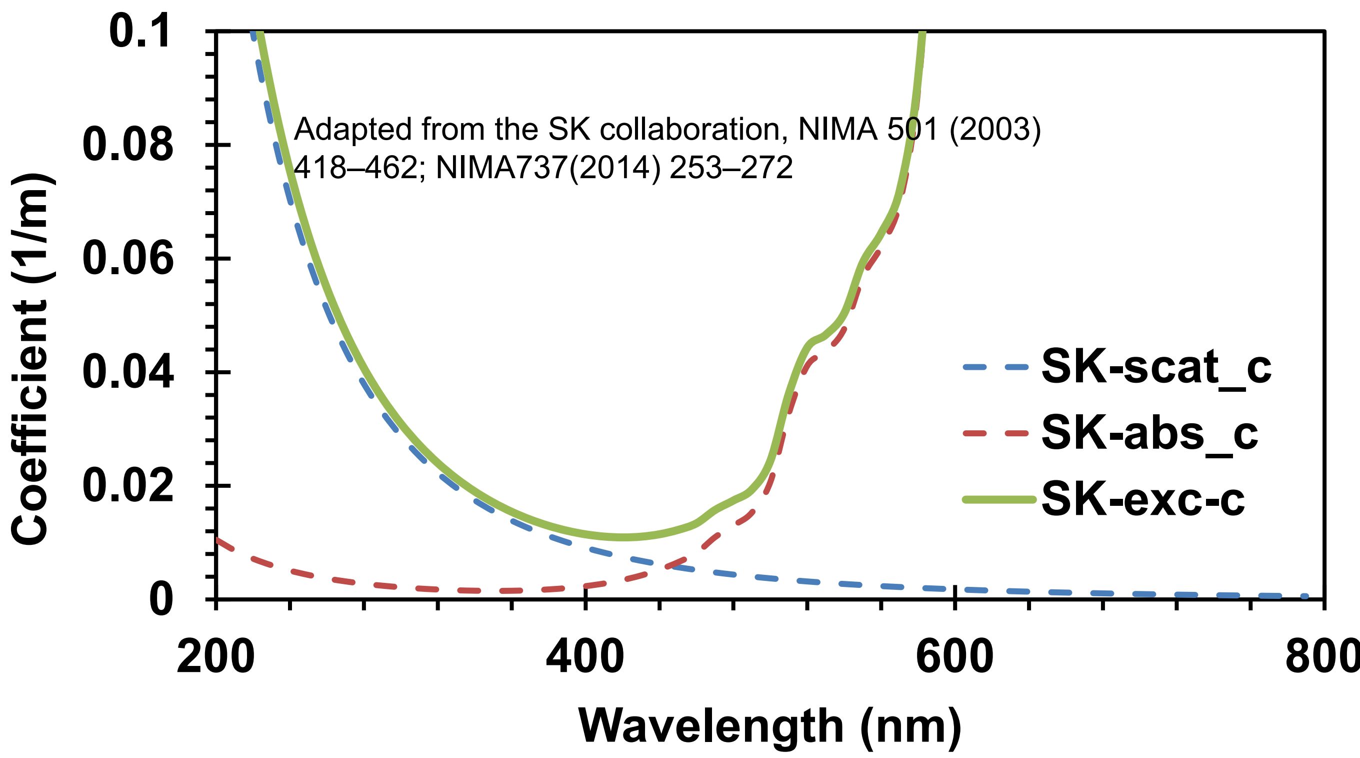


Tunable LS%, timing and emission









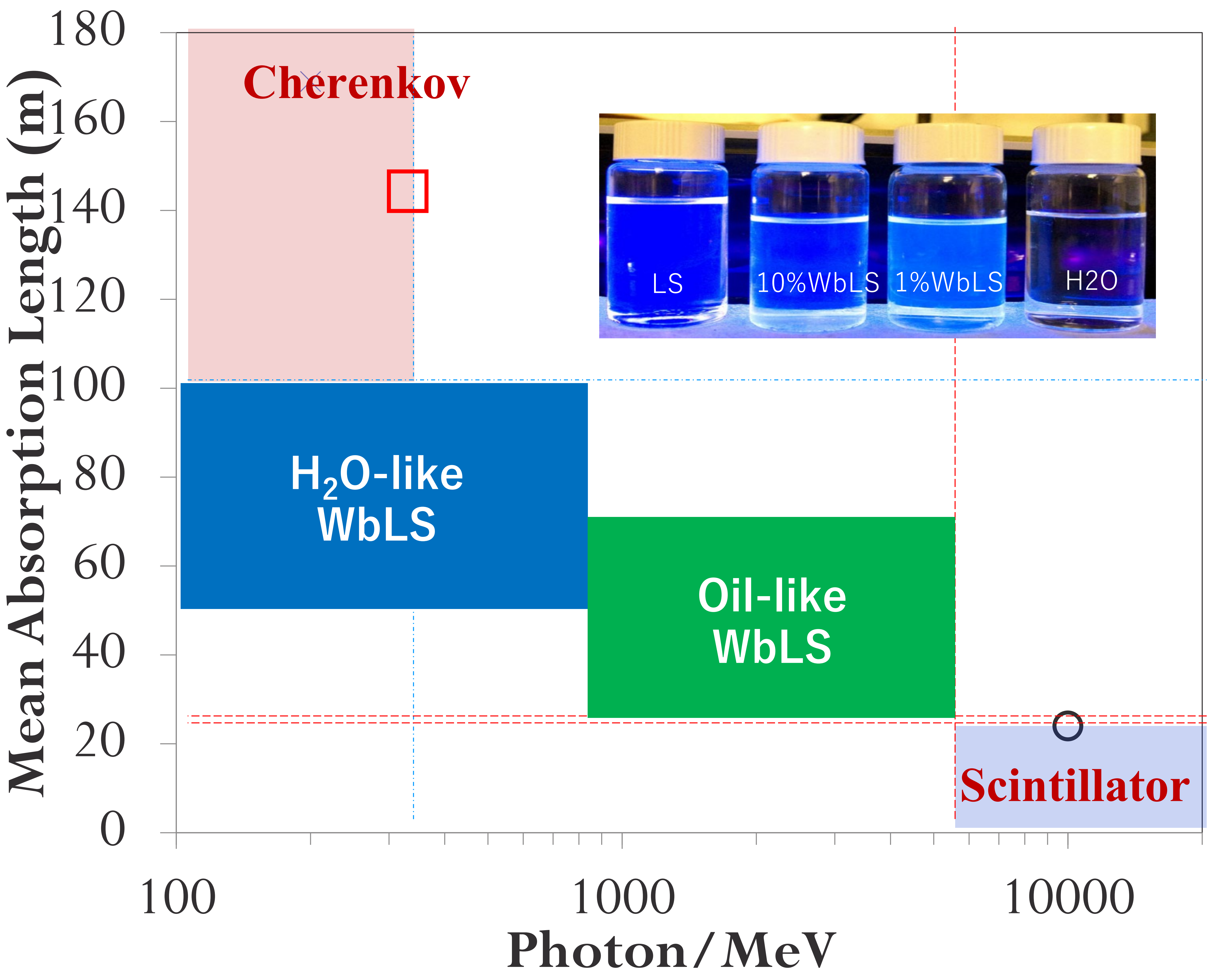
Brookhaven National Laboratory

4 tons of (PROSPECT) ^{6}Li-doped LS production for at BNL in 2019

Oil vs H_2O based LS

Water-like WbLS

- 1000s ton-scale detectors
- Long scattering length (>25m at 450nm)
- In-situ circulation feasible
- 1-10% LS loading in water (100-1200 phs/MeV)
- Metal-dope (~all elements)
- 30TBNL, Eos, ANNIE, BUTTON, THEIA



Oil-like WbLS

- 1-10s ton-scale detectors
- High light-yield
- PSD capability
- Not necessary for in-situ circulation
- >90% LS with water (>10,000 phs/MeV)
- Metal-doped (~all elements)
- PROSPECT, (G3)DM, LiquidO

First WbLS concept introduced in 2010ANT (Santa Fe) and A new water-based liquid scintillator and potential applications, NIMA, 2011

Brookhaven National Laboratory

What can WbLS do?

National Nuclear Security Administration

To demonstrate the feasibility of nuclear reactor monitoring (100s -1000s tons of a WbLS detector); technologies developed can be transitioned to diverse research fields

- **A scintillator R&D program with ton-scale testbeds for nonproliferation science**
  - A **homogeneously** **segmented** or **monolithic** optical detector for capture-gated fast neutron spectrum and detection of nuclear fuels and fissile materials
  - An ultrapure scintillator cocktail/material: enhancement of assay sensitivity (PNNL/SRNL/BNL)
    - *Water-based liquid scintillator is a drop-in substitute for LSC cocktail*
    - *Metal-doped liquid scintillator is a transformative technique for conventional LSC method → **improved current LSC sensitivity by an order of magnitude (Fe55 and other elements)***
- **A multipurpose physics program (THEIA) → OHEP, ONP**
  - Neutrino (oscillation and reactor), $0\nu\beta\beta$, dark matter
  - An Accelerator Neutrino Neutron Interaction Experiment (ANNIE) → OHEP, ONP (2019–)
  - Snowmass, module of opportunity at DUNE, CPAD-RDC, ECFA-RDR
- **A novel QA/QC device for radiotherapy: 2 patents in medical physics**

Brookhaven National Laboratory

Whole-Body Scintillator Counter in 1950s

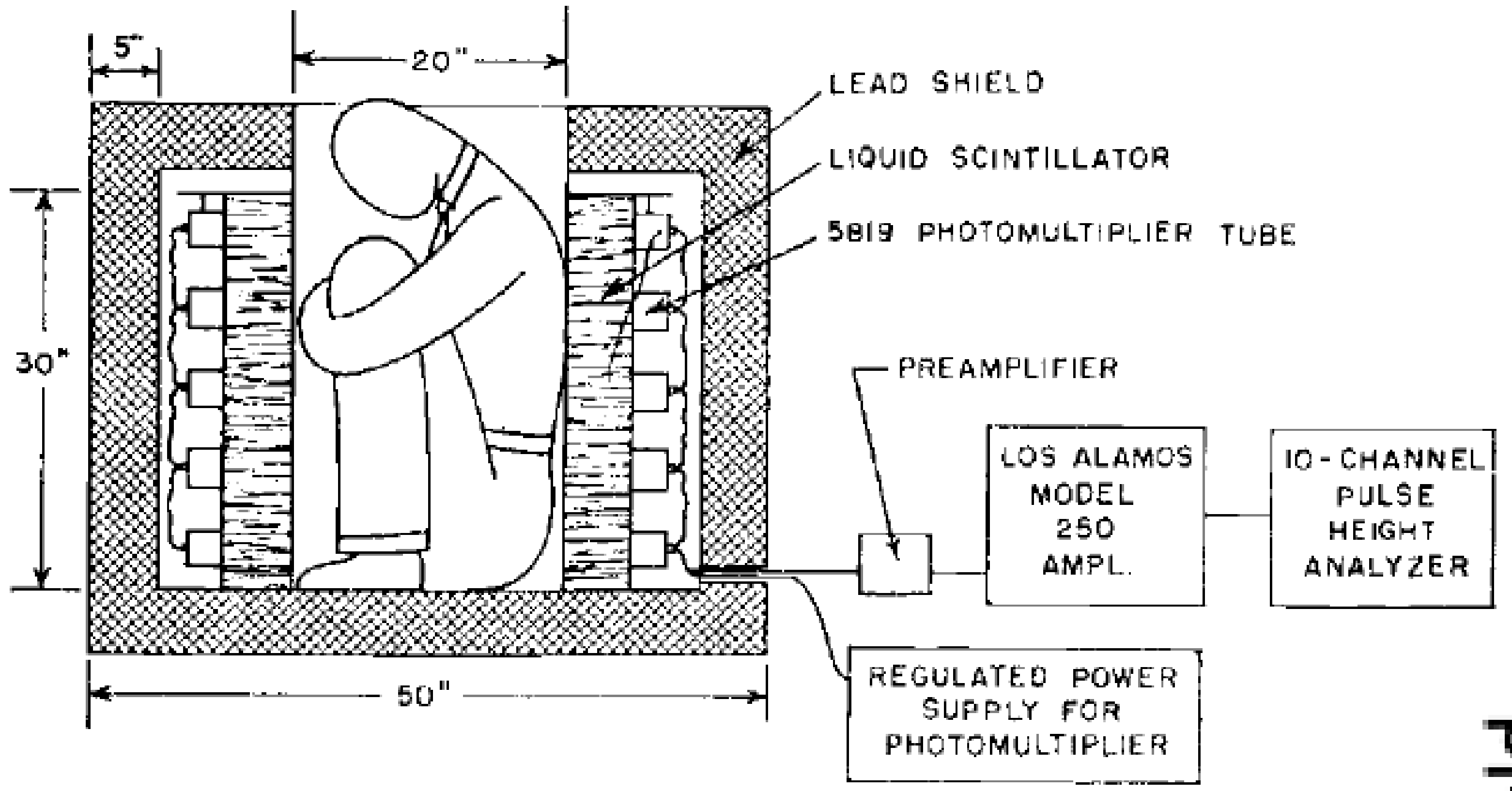
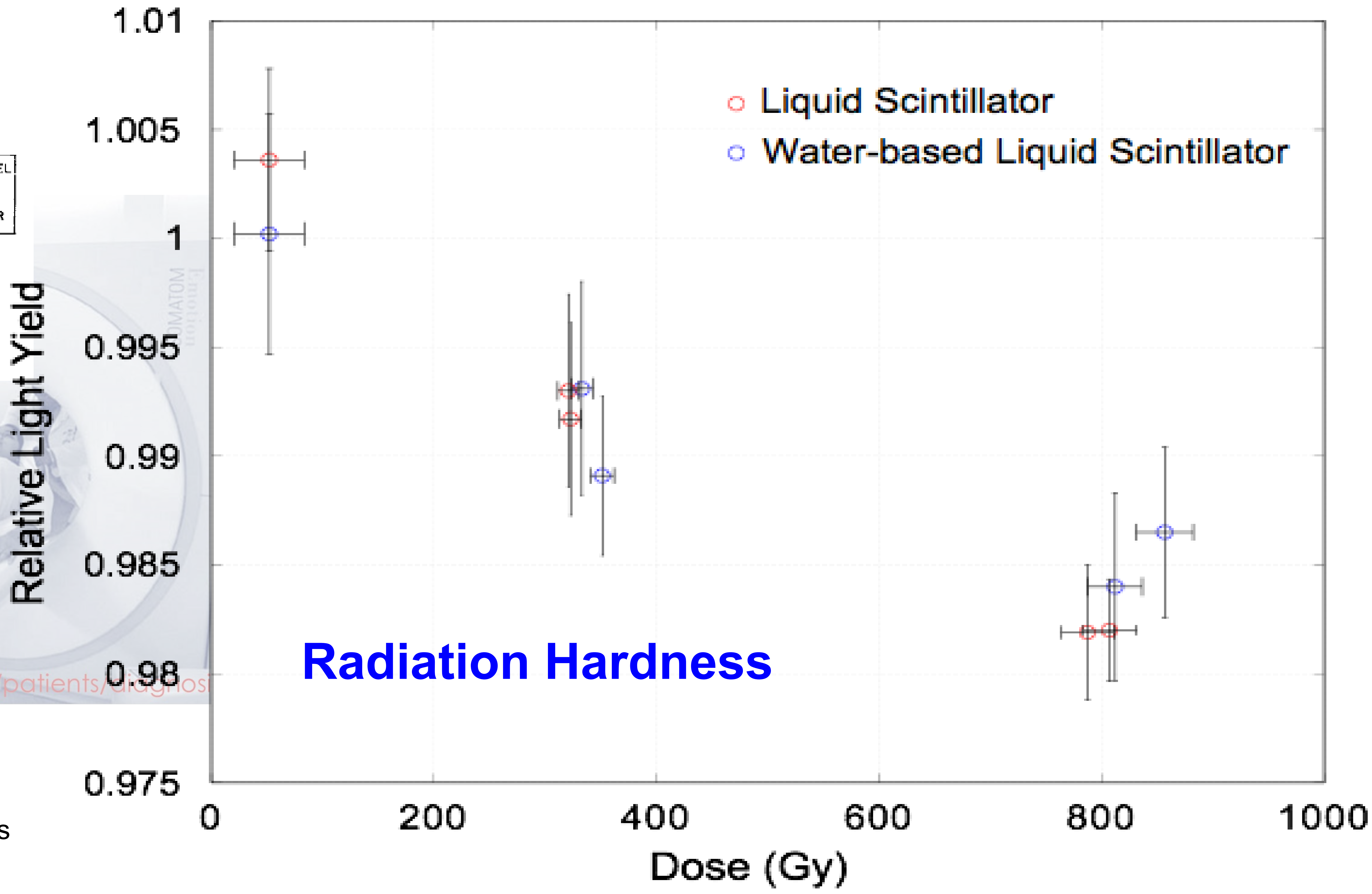


Fig. 8. Schematic view of first human counter (1953).



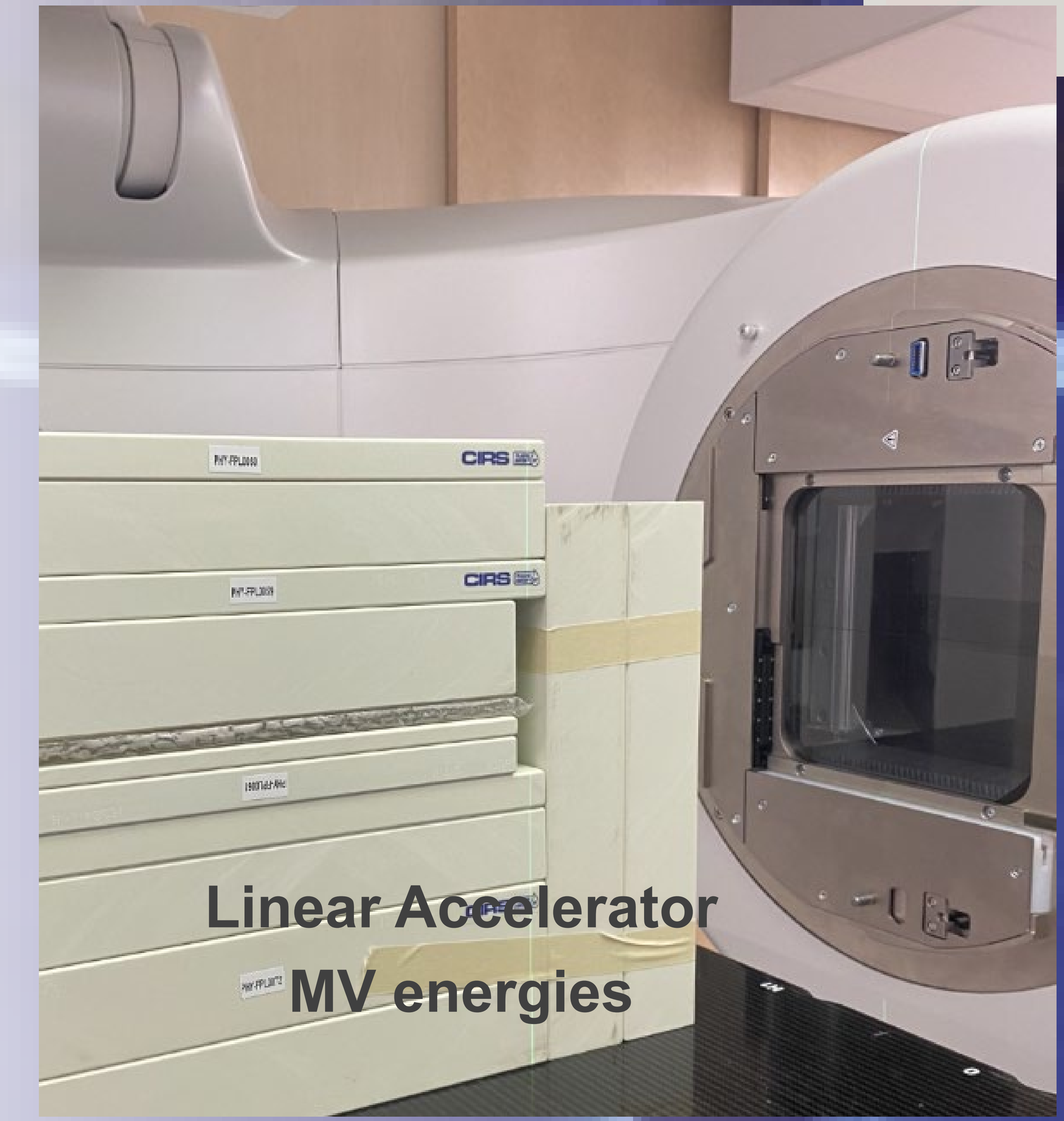
HUMCO I: Ernest Anderson, Robert Schuch, James Perrings, and Langham Wright, 1956

Brookhaven National Laboratory

Characterization of water-based liquid scintillators for use in scintillation dosimetry

- Human body has ~55-60% water.
- Seeking a detector that is as close to water as possible since the reference medium in radiotherapy is water → thus the dose measured in the detector is representative of the dose deposited in water and no correction factors are needed.

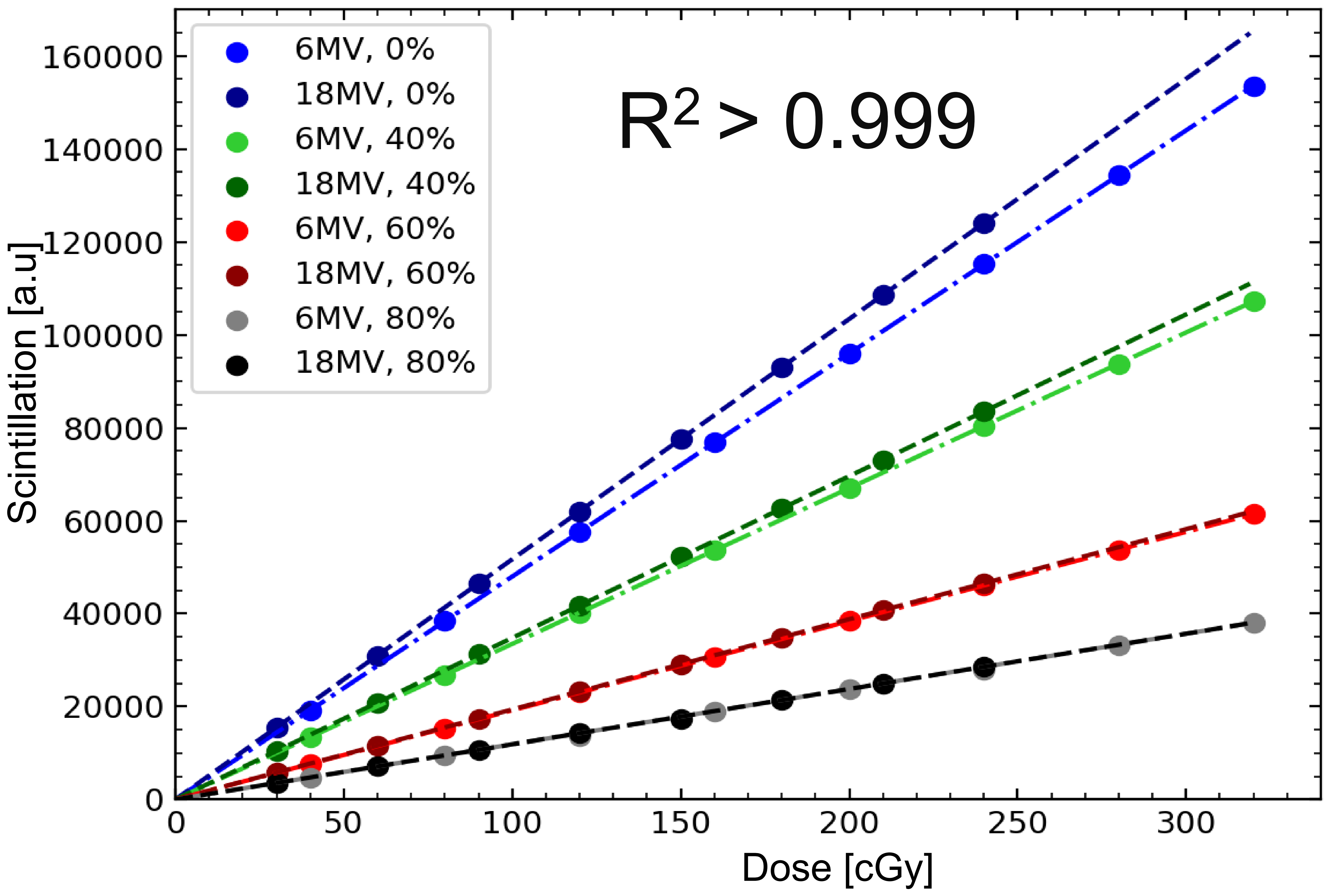
Orthovoltage Xstrahl 200
KV energies

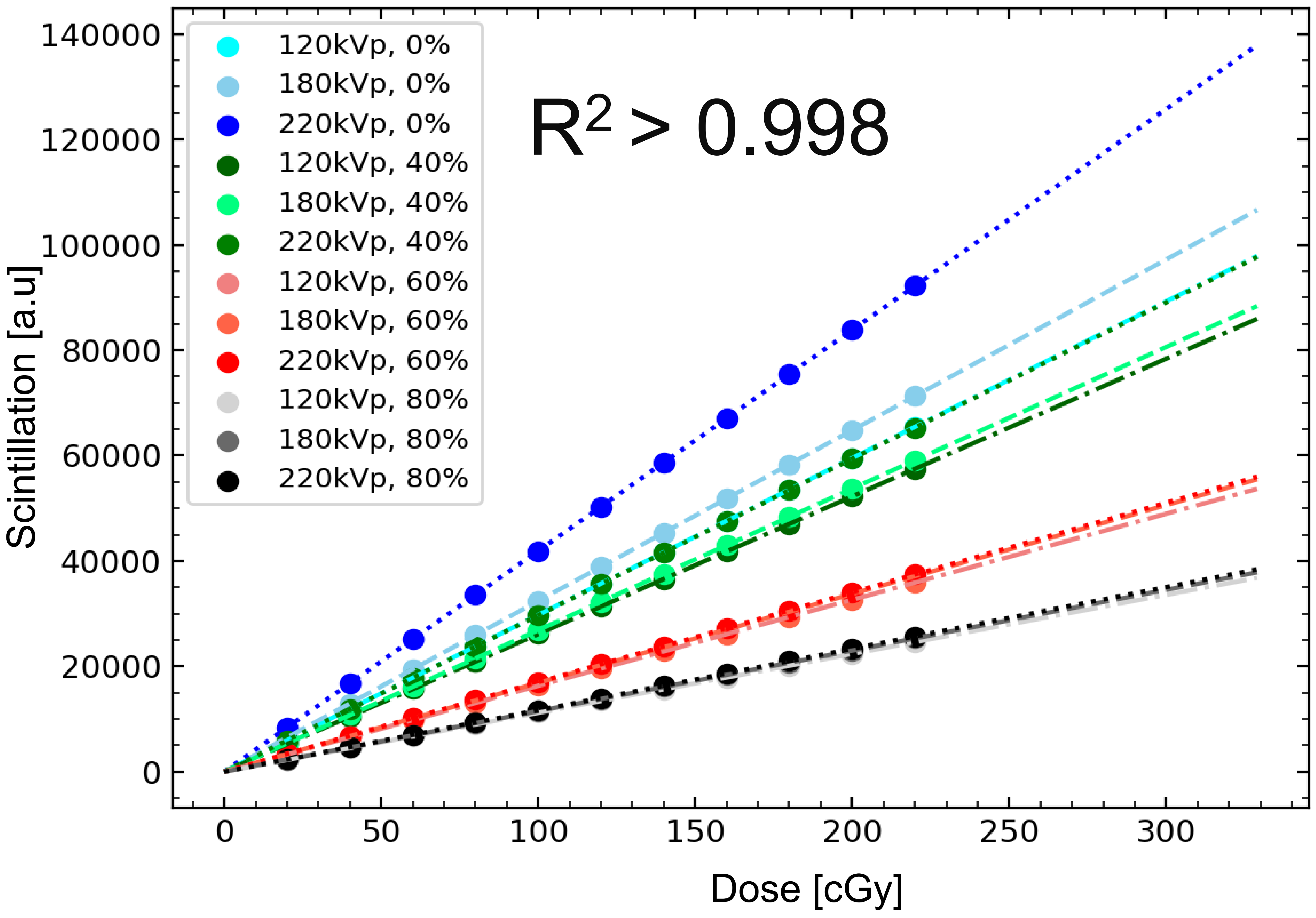


Linear Accelerator
MV energies

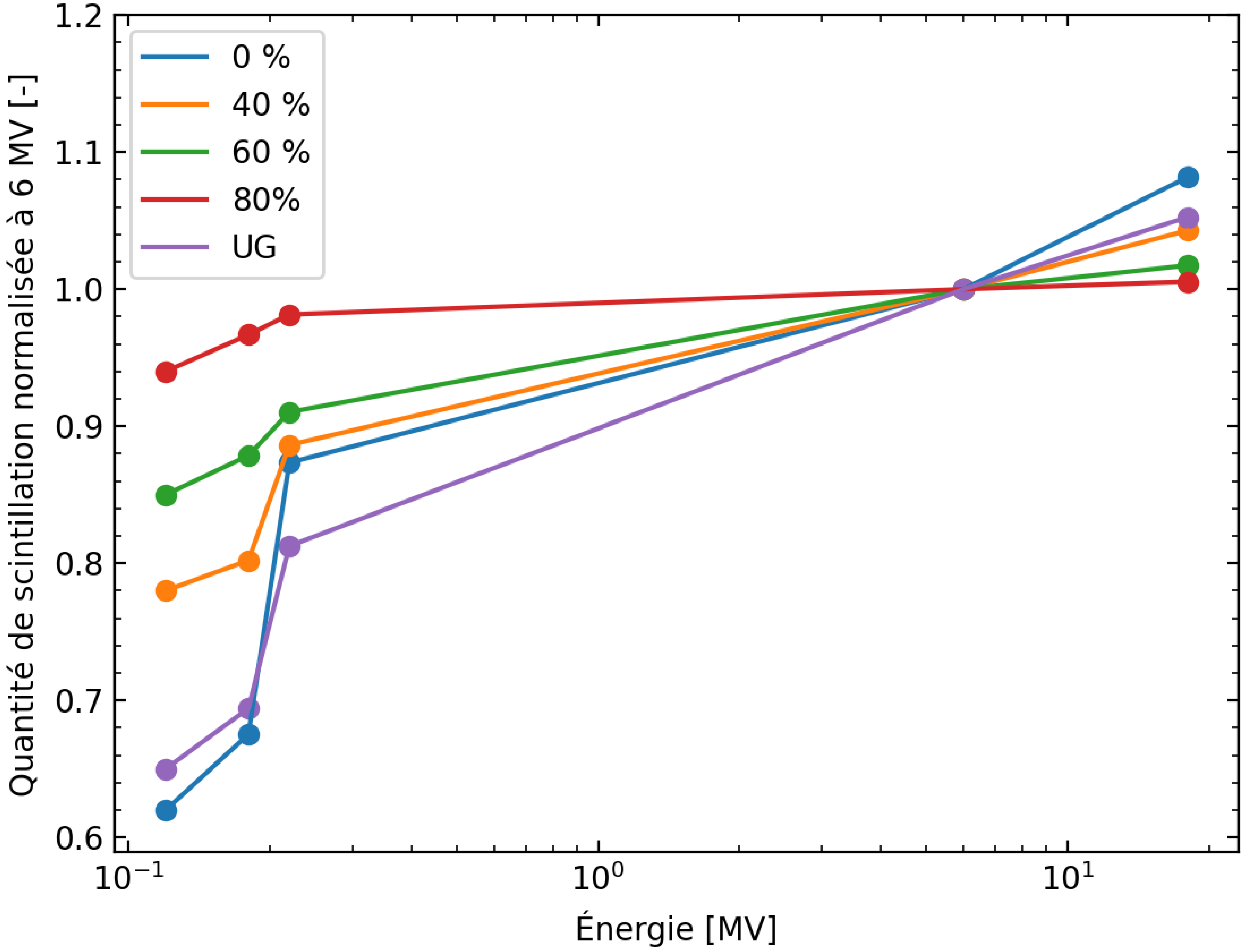
Daphnée Bernier-Marceau

Linearity of the WbLS response with the dose in KV and MV energies





Energy response of WbLS for a same dose deposited in water in KV and MV energies



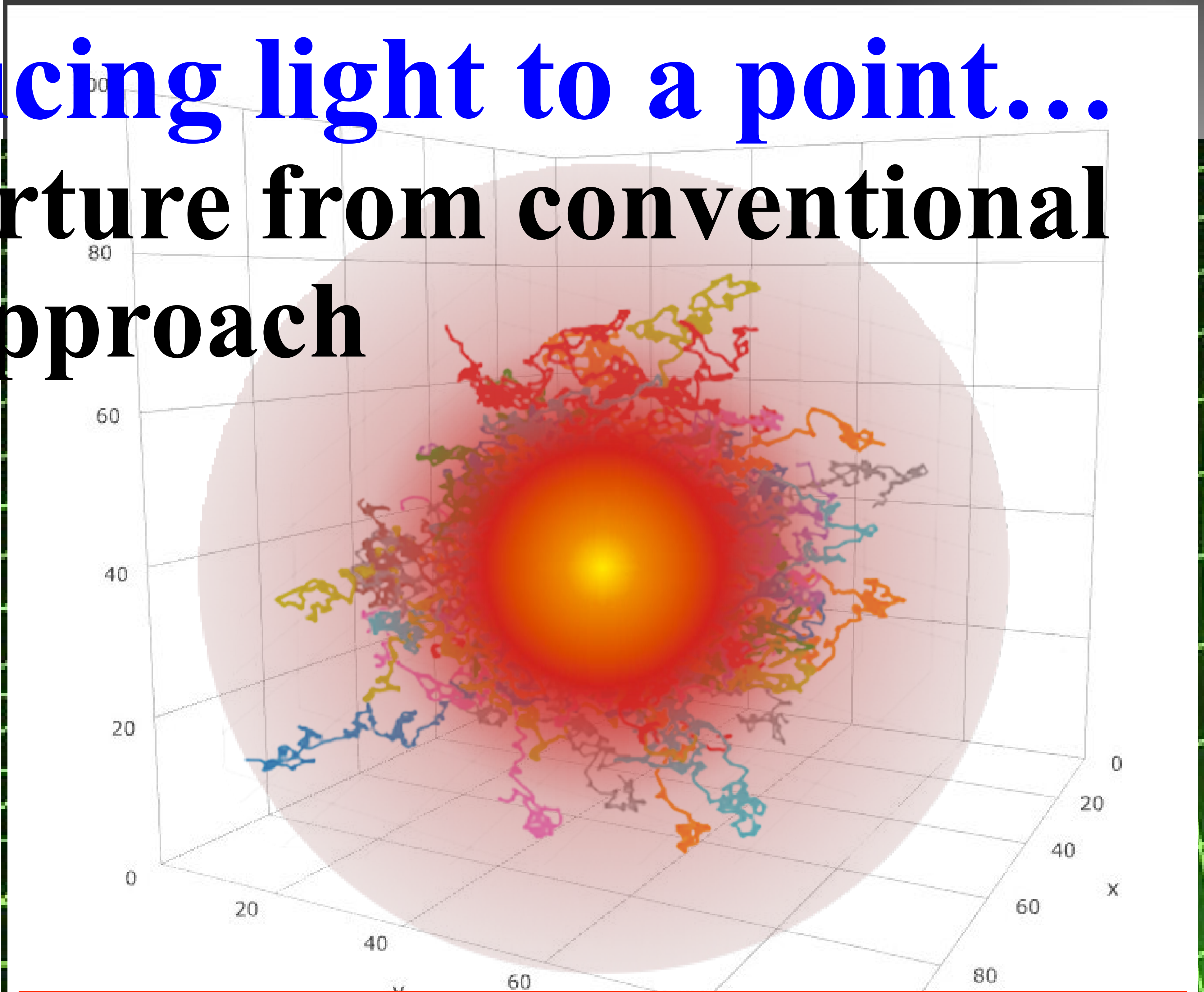
- WbLS performance is feasible for scintillator dosimetry
- The WbLS 80 has the lowest energy dependence and properties close to that of water
- Define path-forwards

Brookhaven National Laboratory

Daphnée Bernier-Marceau

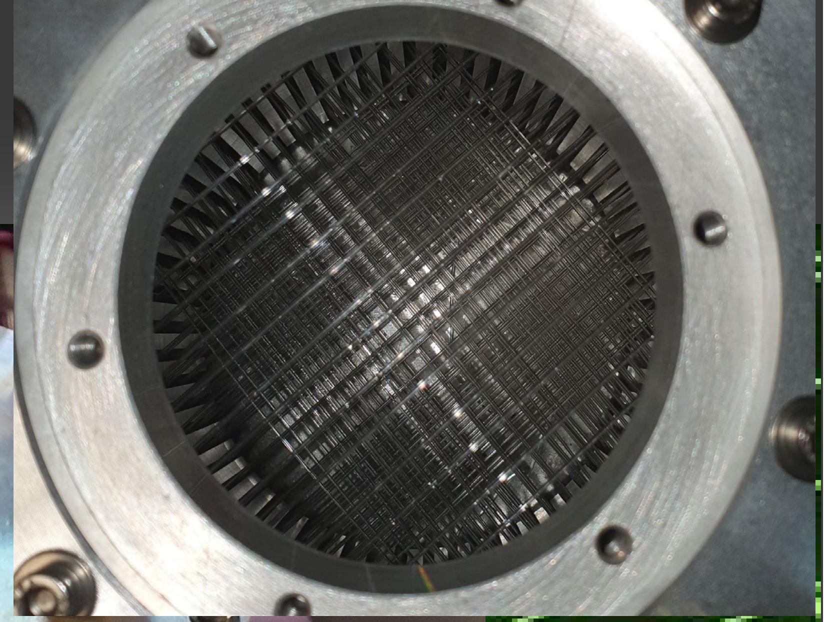
Inducing light to a point…

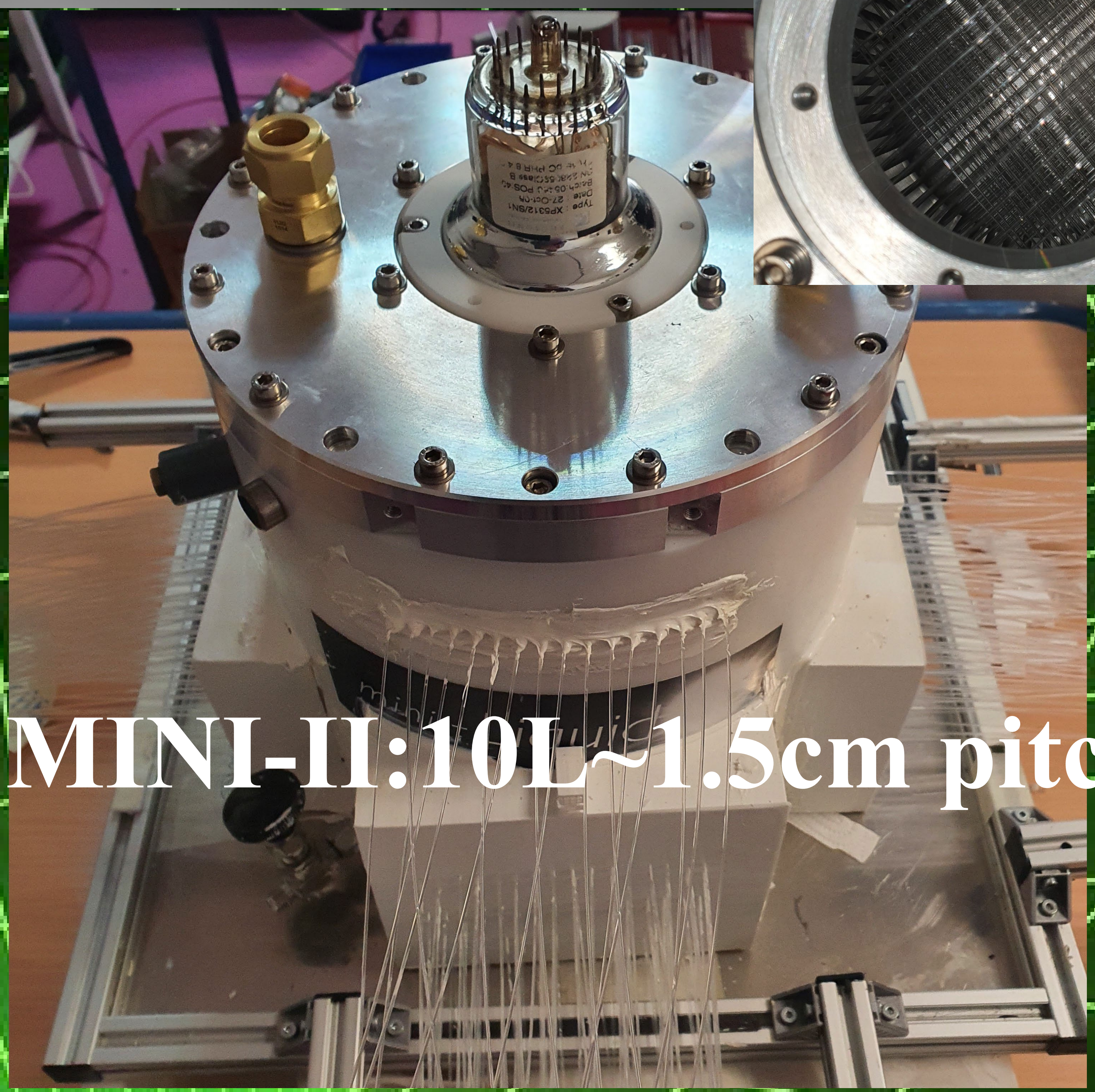
departure from conventional LS approach



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

Nu2022





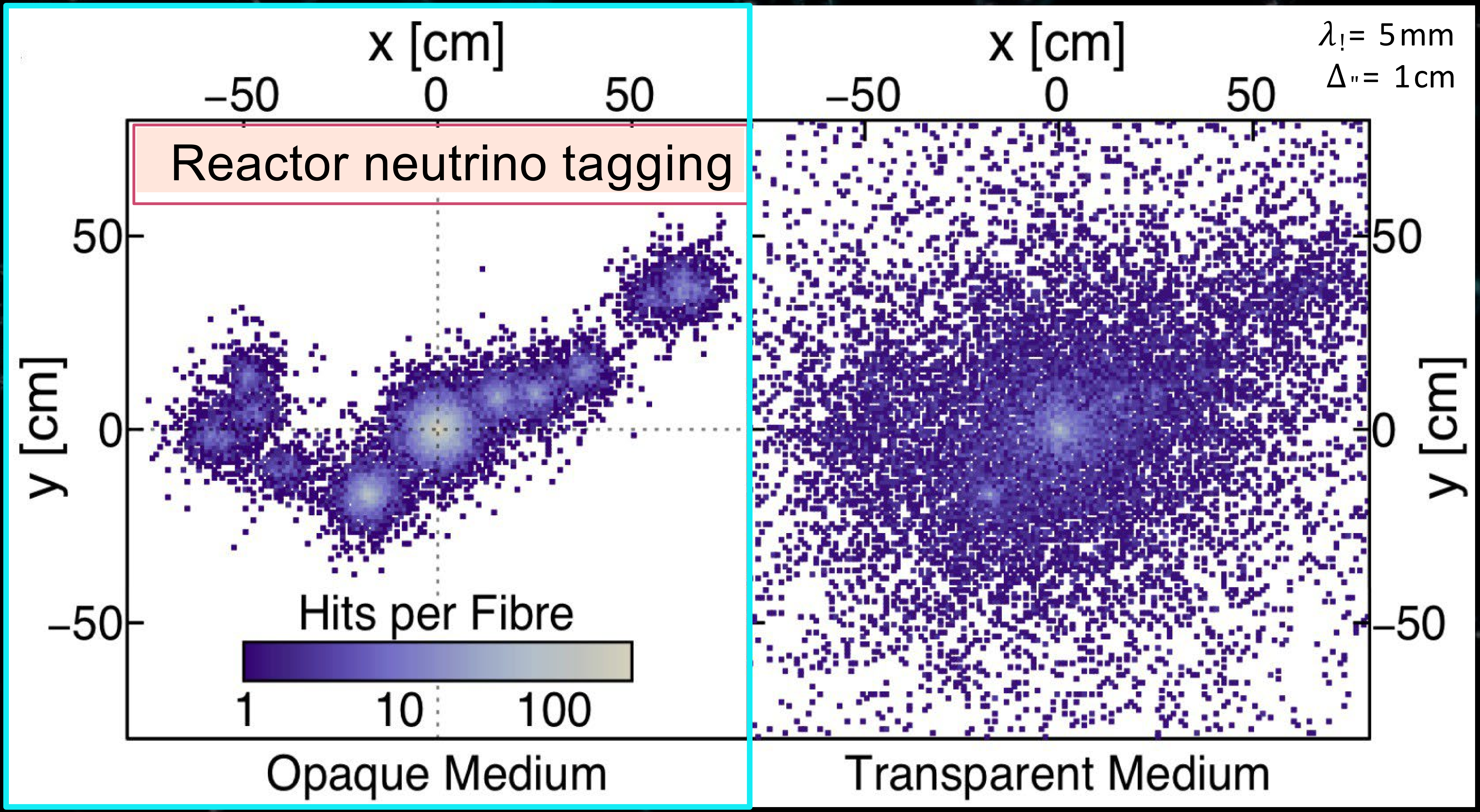
Transparency
λ(scattering)≥10m

Rayleigh & Mie Scattering
λ(scattering)≤1cm

LiquidO/CLOUD concept

Unprecedent Imaging Capabilities

Energy deposition 1MeV e^+



- ★ Particle Identification (PID) is a major challenge in MeV neutrino detection
- ★ Confinement of light into sphere around each ionization point
- ★ A self-segmented detector! (no need to introduce dead material for segmentation)

Article | Open Access | Published: 21 December 2021

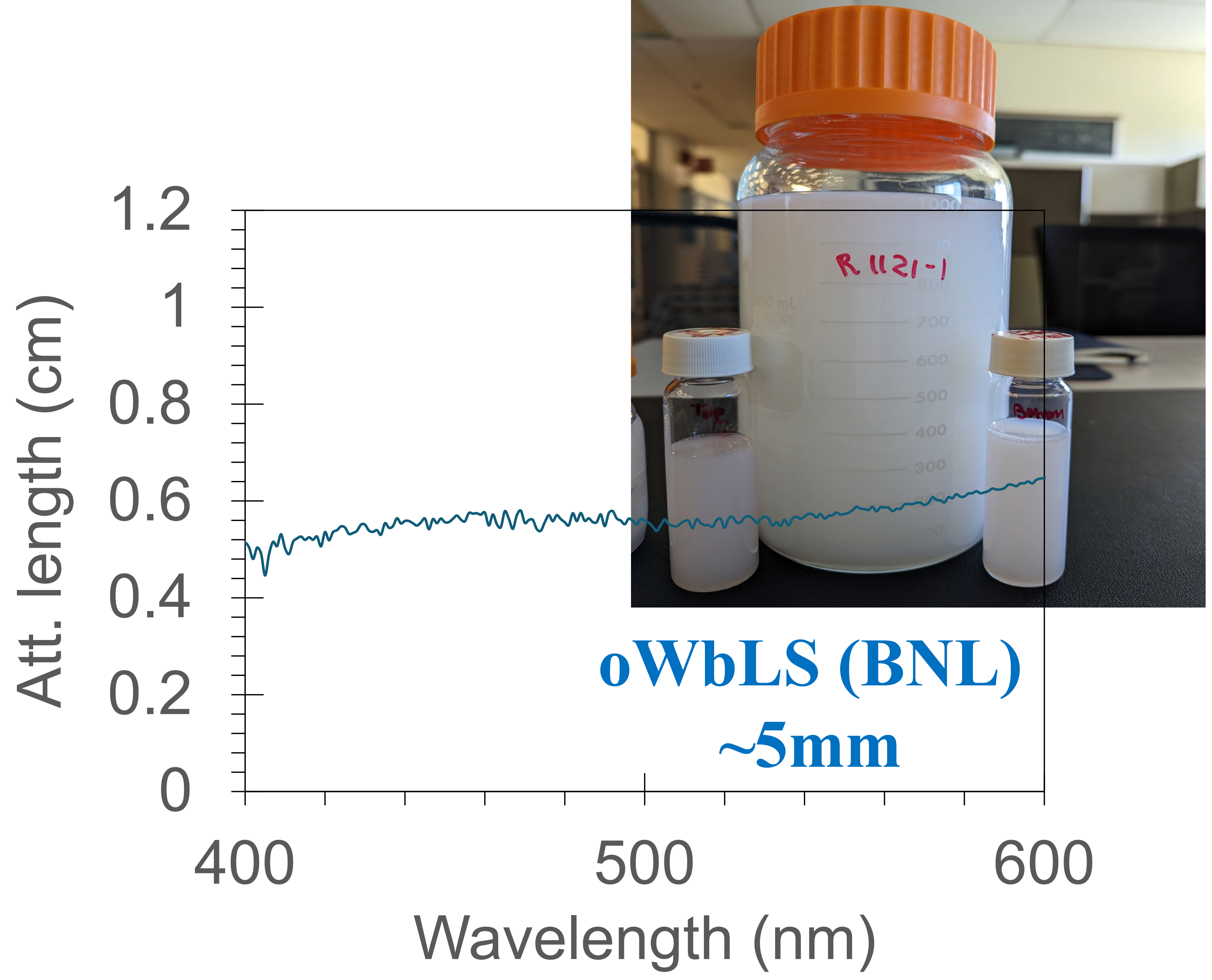
Neutrino physics with an opaque detector

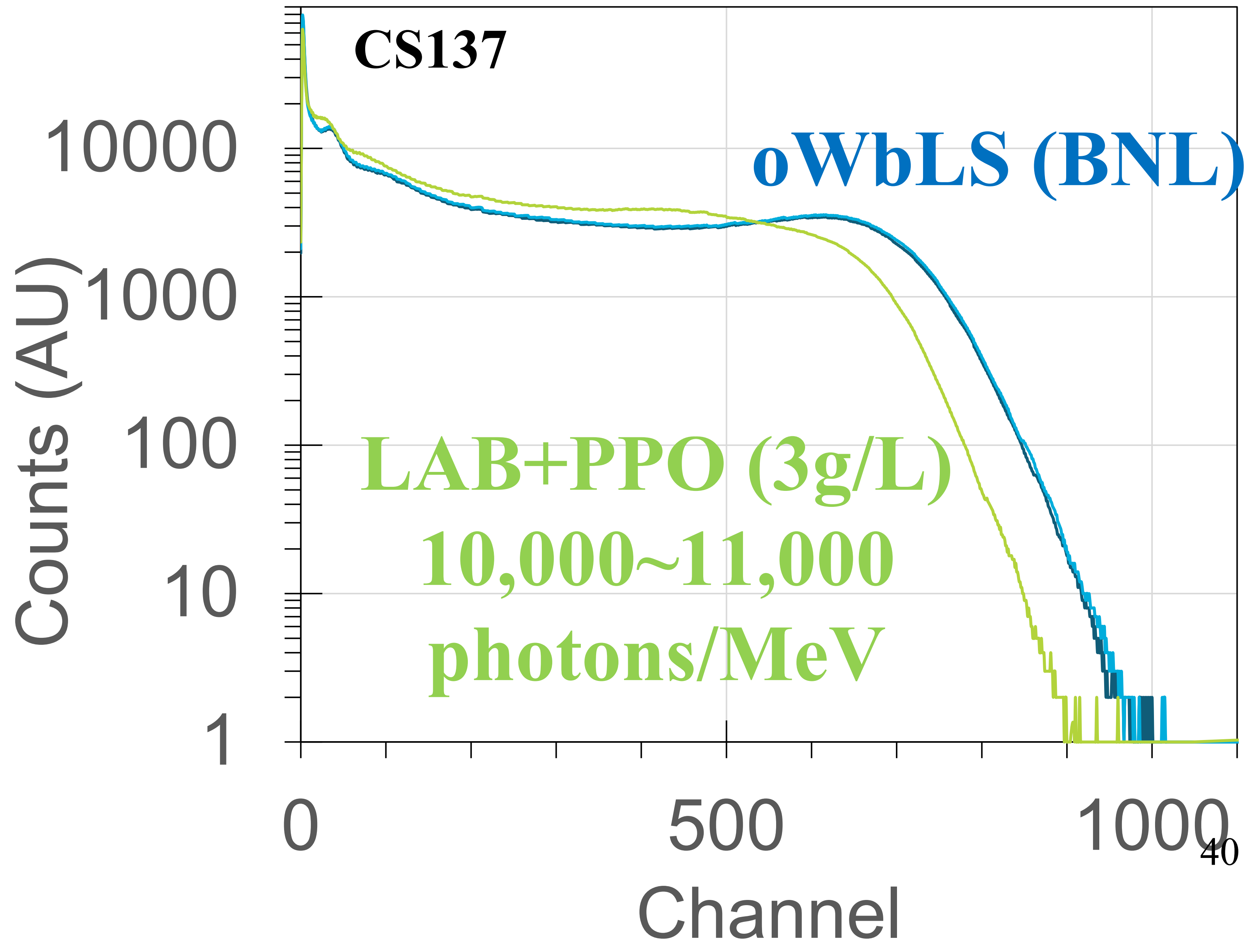
LiquidO Consortium

Communications Physics **4**, Article number: 273 (2021) | Cite this article

Opaque WbLS (BNL)

- Highly scattered WbLS (highly pixelized) feasible for near surface detection: **potential applications in off-the-fence monitoring, test-site transparency, etc.**
- Capability of loading metallic ions demonstrated at >10% (w) level
- High light-yield (>11000 ph/MeV)
- High stability with superior PSD as demonstrated by PROSPECT
- Tunable timing structure and emission range and compatible with WLS, SS, PP, Teflon, acrylic
- Stable at room temperature (>1-year since preparation)
- **Started detector development with LiquidO Consortium (liquid development and ton-scale facilities); working with UM and PSU**

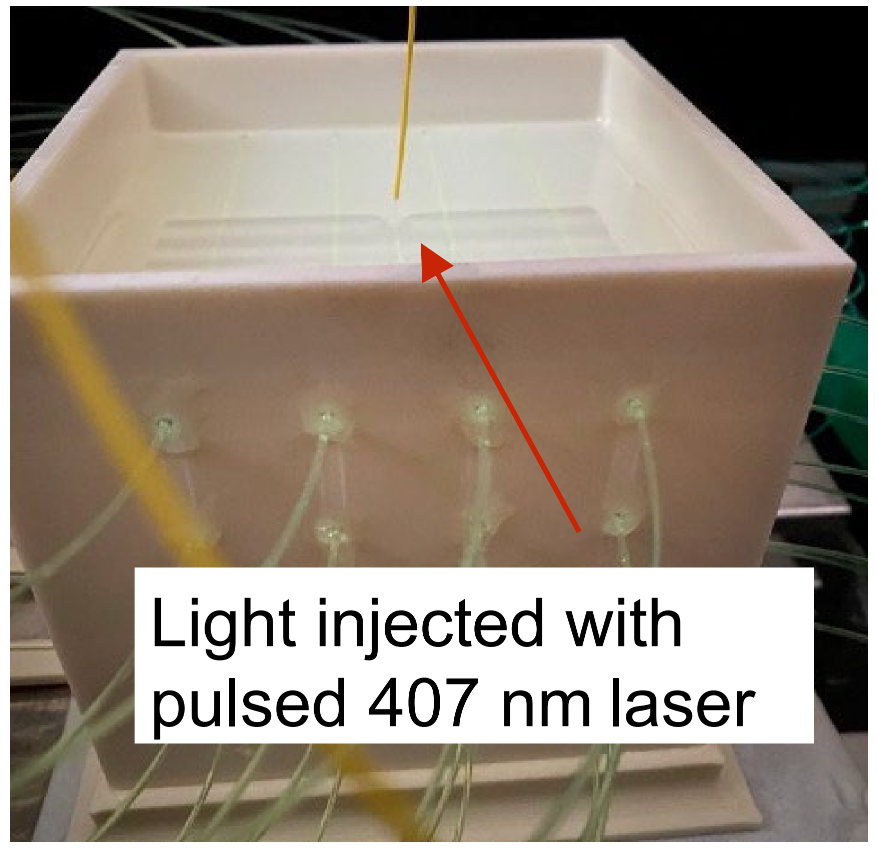


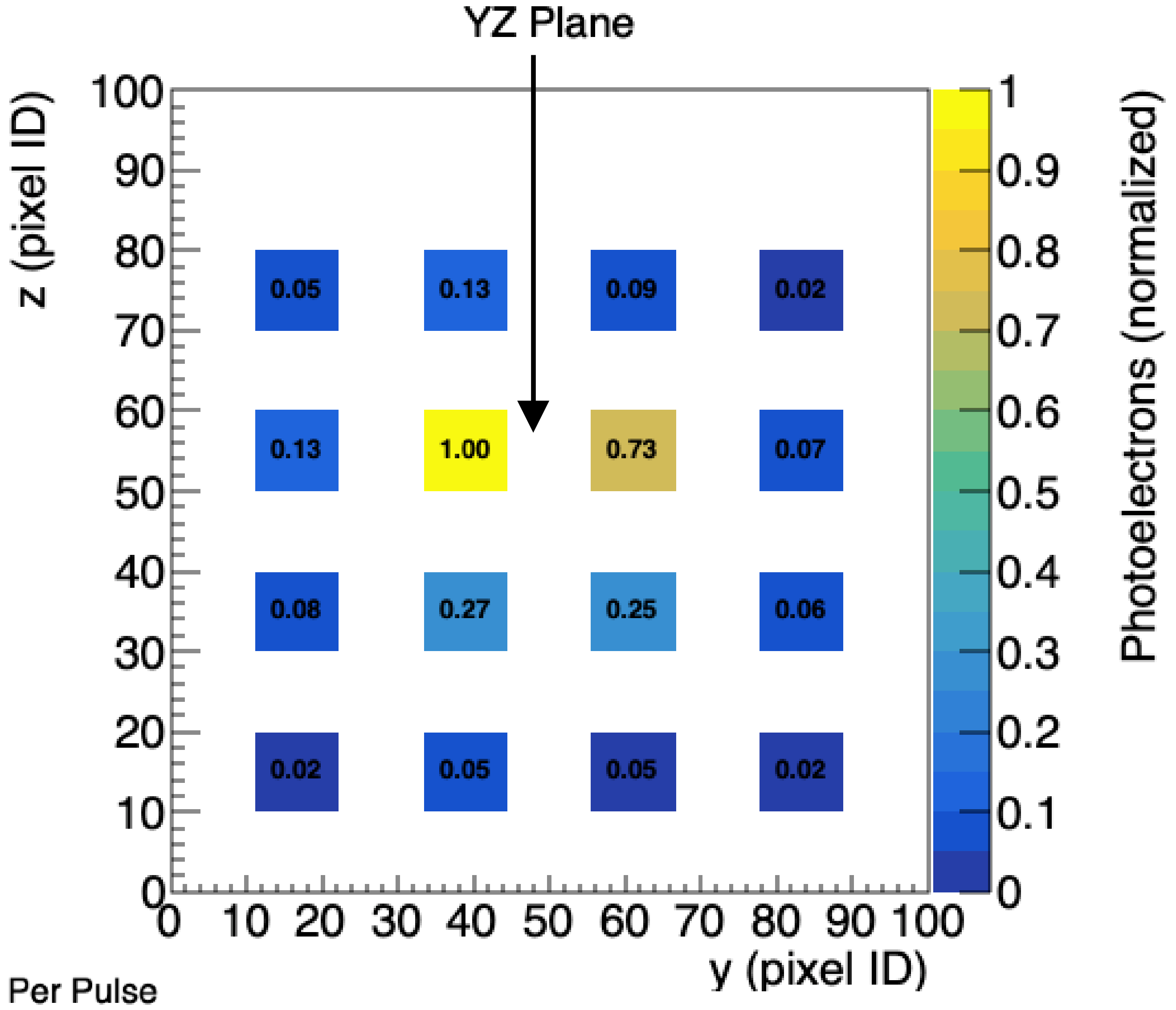


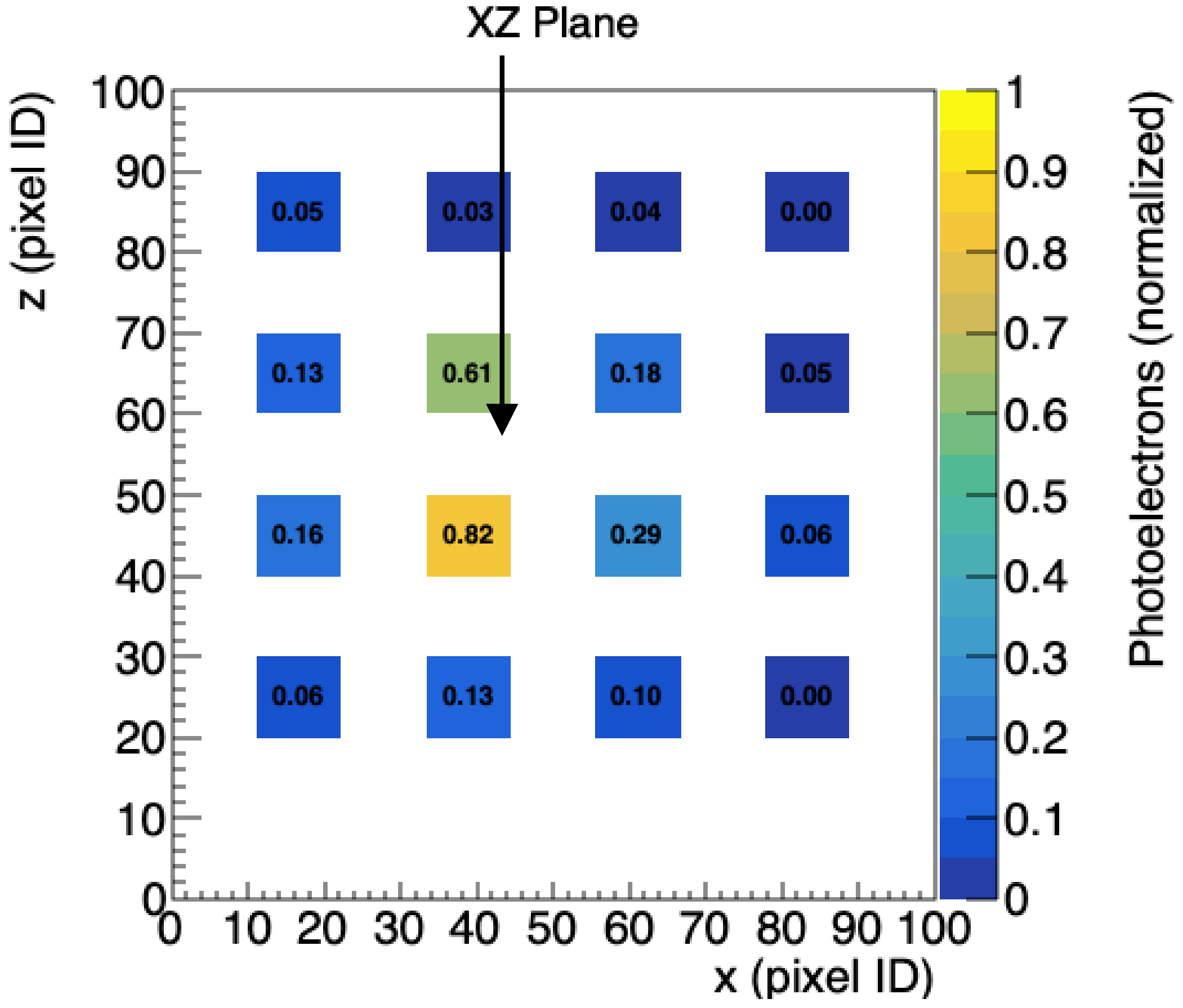
Brookhaven National Laboratory

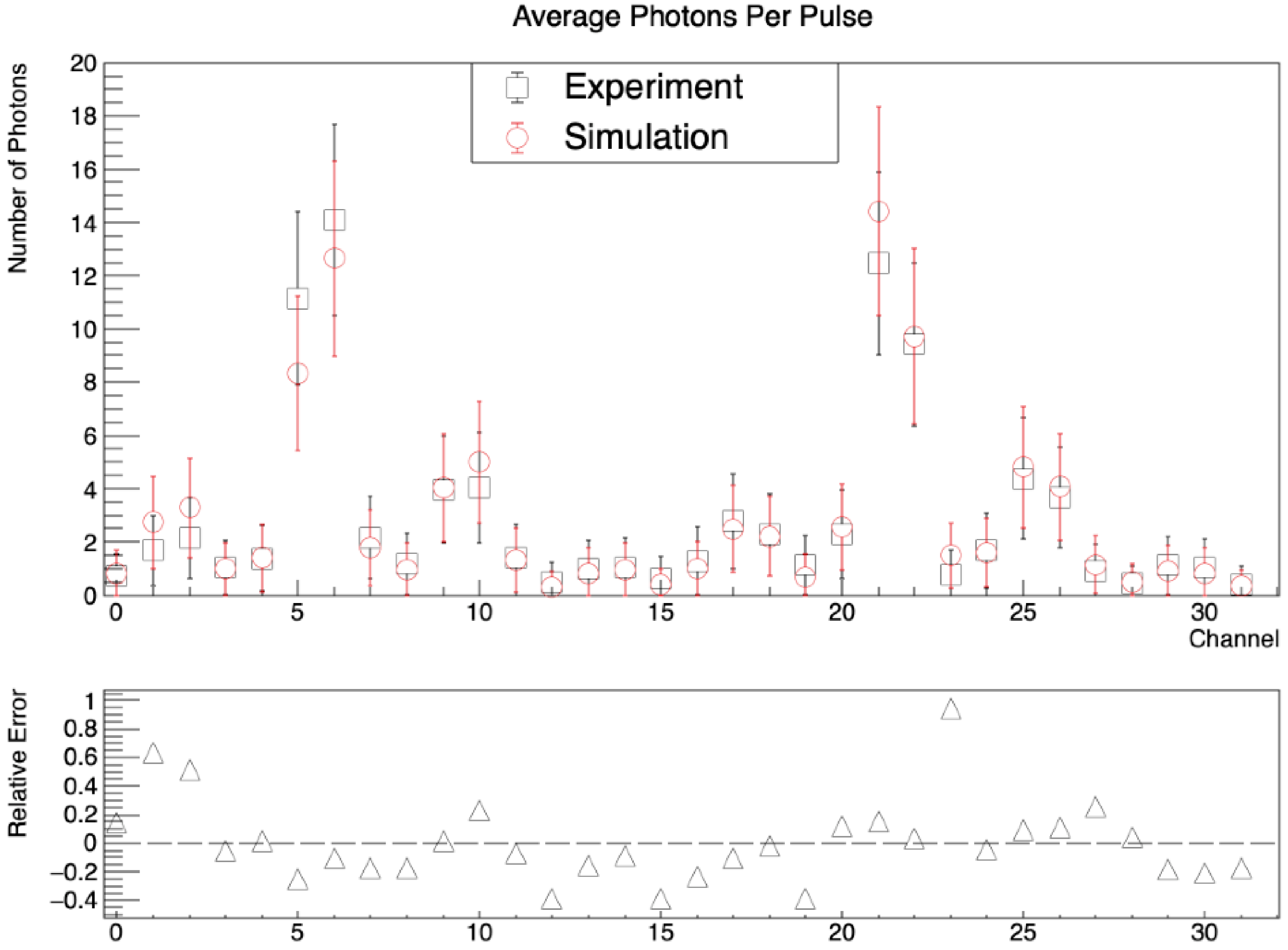
Scattering and Absorption (oWbLS2)

Andrew Wilhelm
U. Michigan





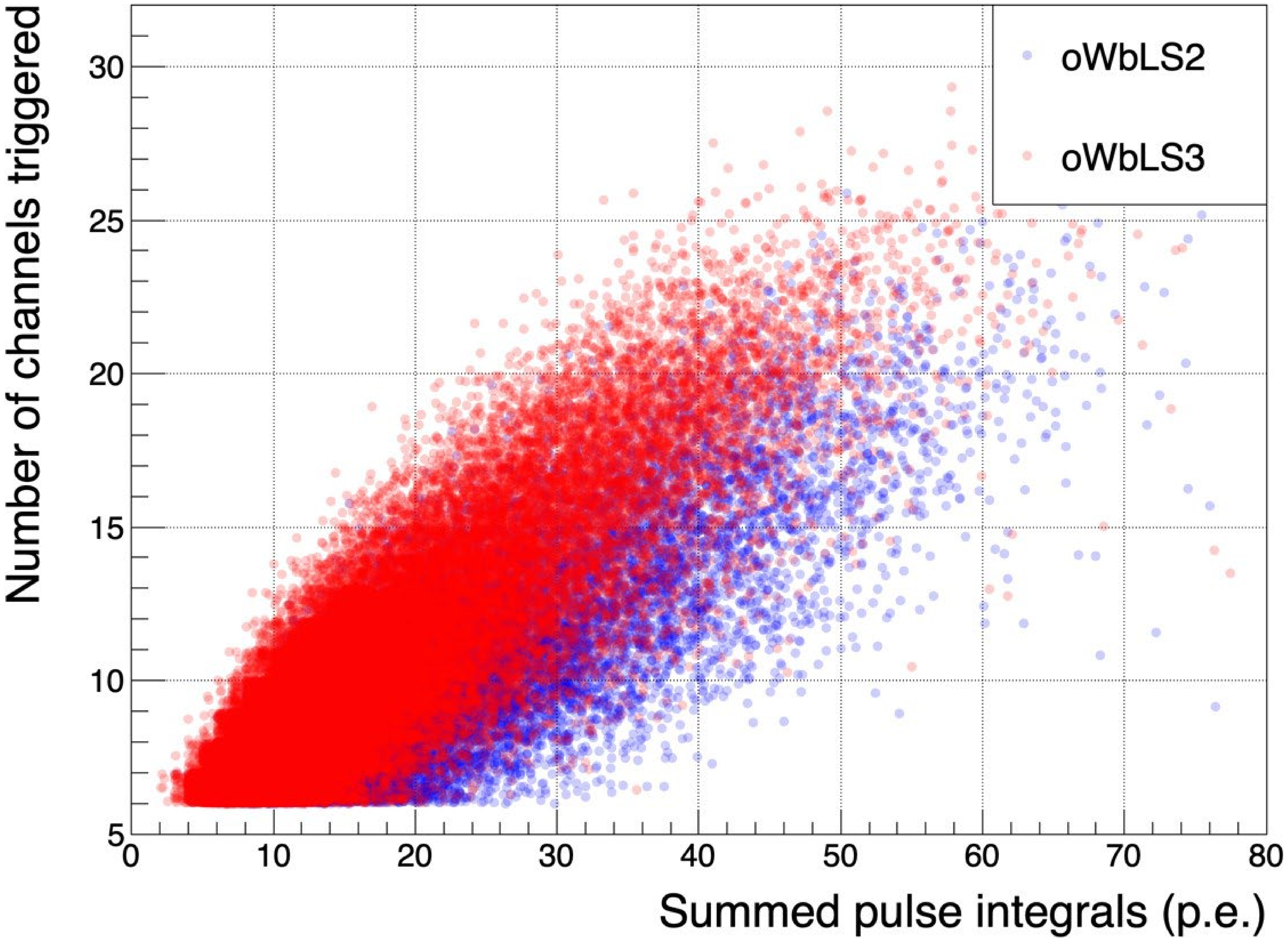




Parameter	Best fit
x,y,z (mm)	43.7, 48.1, 57.3
Scat. length (mm)	5.1
Abs. length (mm)	186.2
Reflectivity	0.008

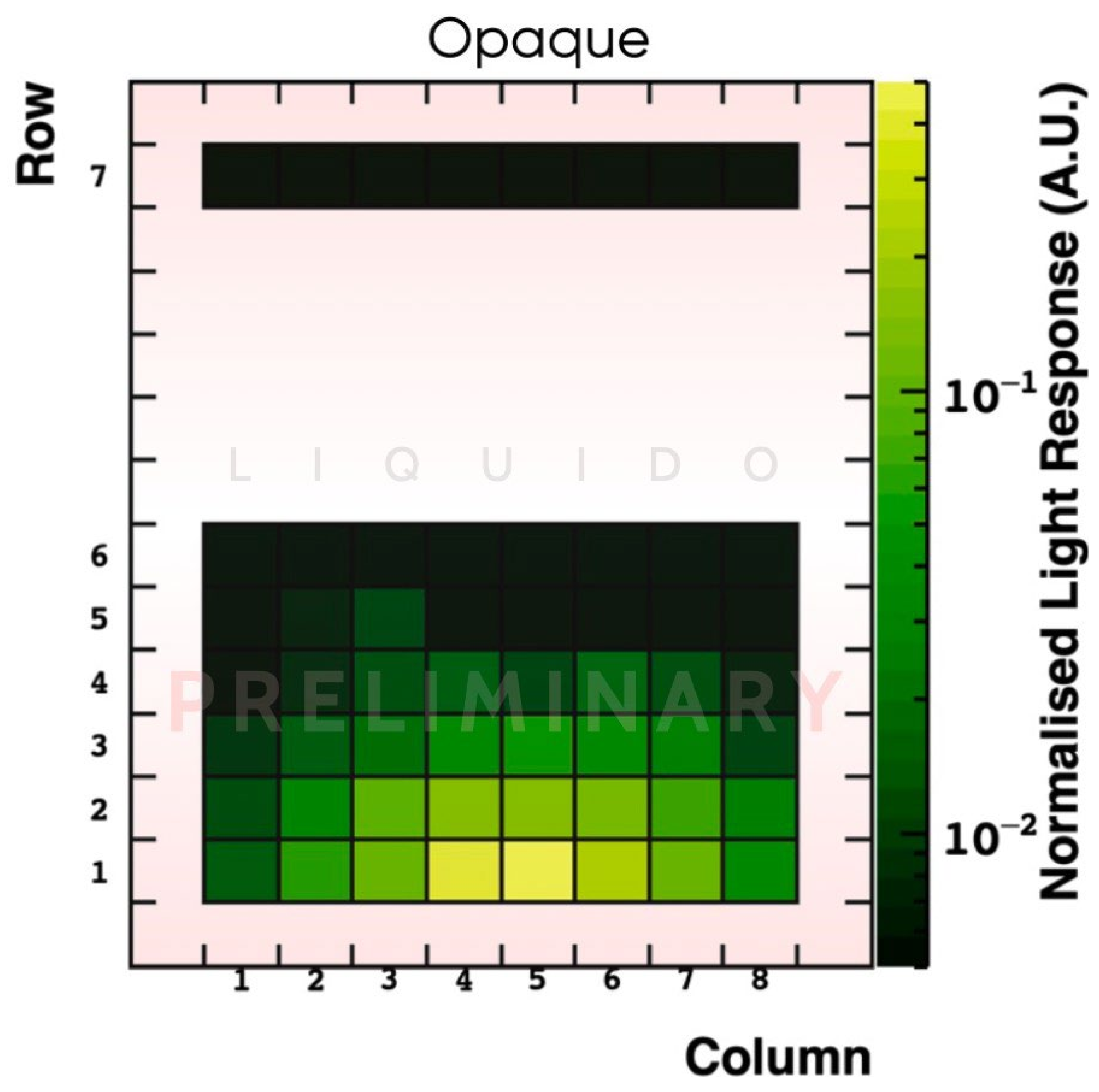
Andrew Wilhelm
U. Michigan

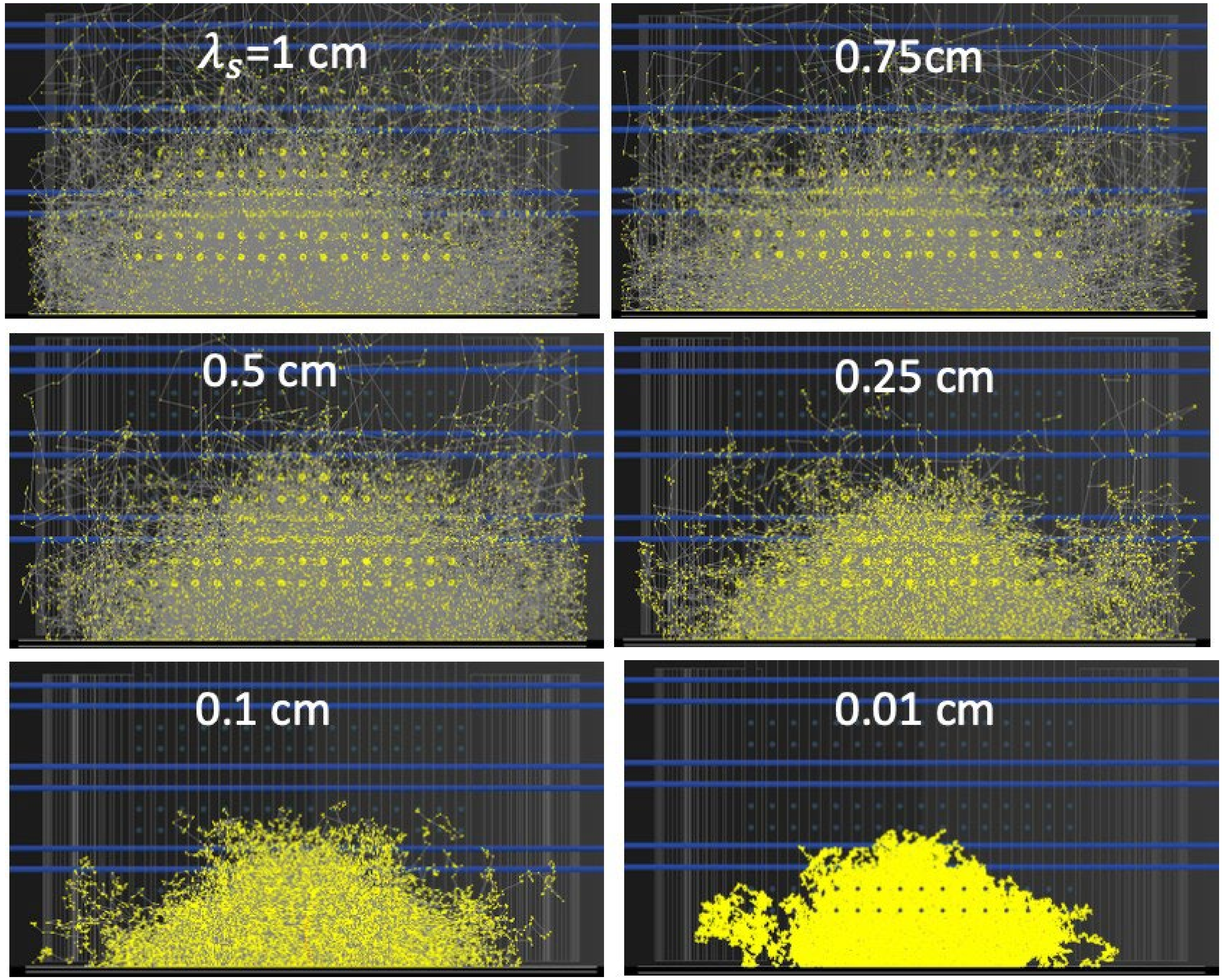
Comparison of Light Confinement of oWbLS2 and 3



MINI-LiquidO Prototype: Results

Opacity → Scattering length





WbLS for nonproliferation

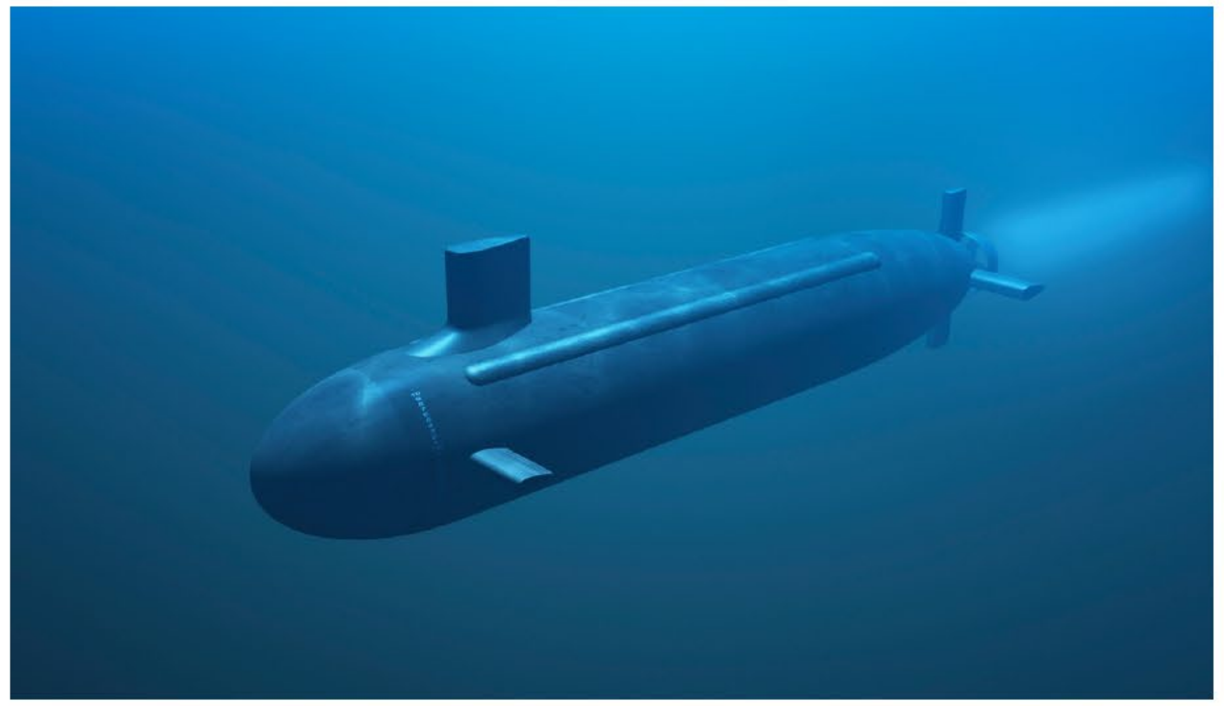
A kiloton-scale WbLS with in-situ circulation system

- *Deployment feasibility: formulation and scale-up*
- *In-situ purification (Water-purification, Gd-purification & Nanofiltration)*

Antineutrino Applications

Cooperative reactor monitoring
for NPT & regional agreements

Submarine tracking
& core verification



Long-range reactor
discovery & surveillance

Spent fuel & reprocessing
waste analysis

Nuclear explosion
monitoring

Communications

and other ideas…

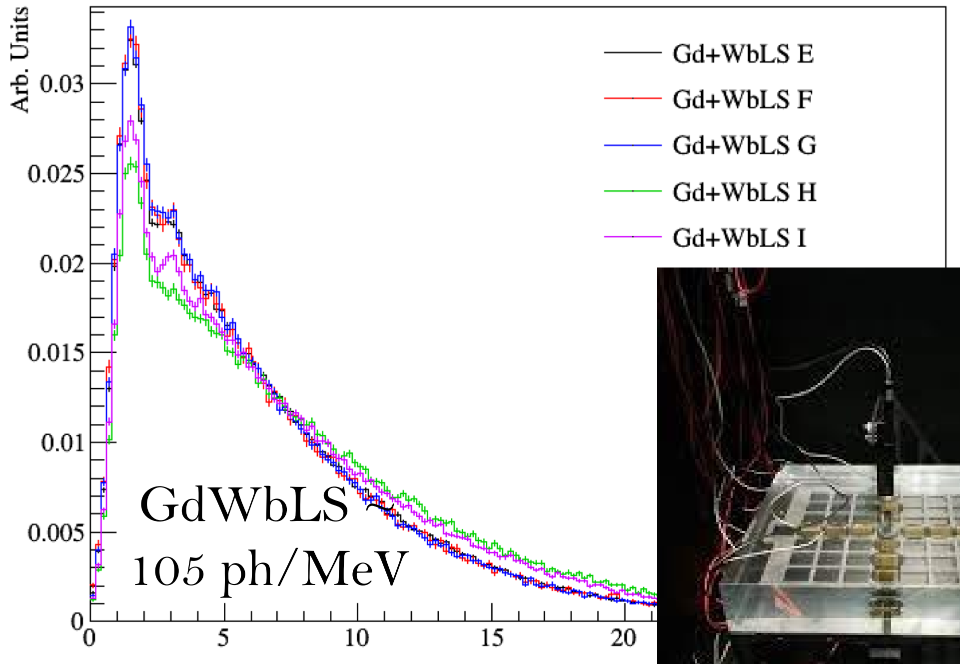
To build a neutrino detector

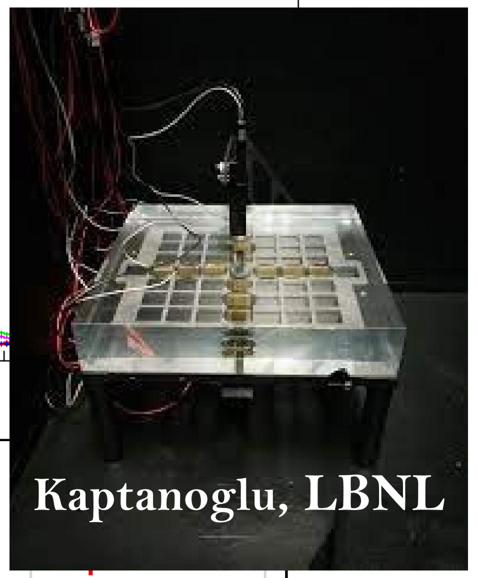
- Weak interaction requires large detector mass + many photosensors from 10s to 1000s of tons (physics target and instrumentation design)
- Enhanced s/b ratio needs a clean environment and well-defined detector (underground and calibration)
- Long experimental lifetime necessitates a highly stable and transparent detector liquid (chemical development)
- Expertise from multi-frontiers
- benchtop R&D → prototype → scale-up experiment

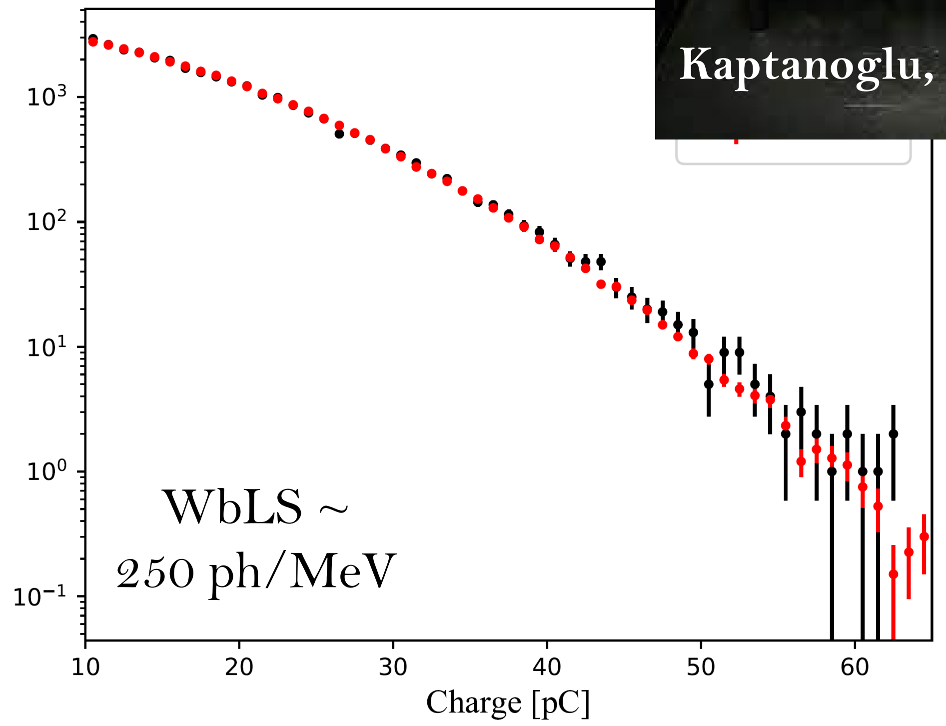
Brookhaven National Laboratory

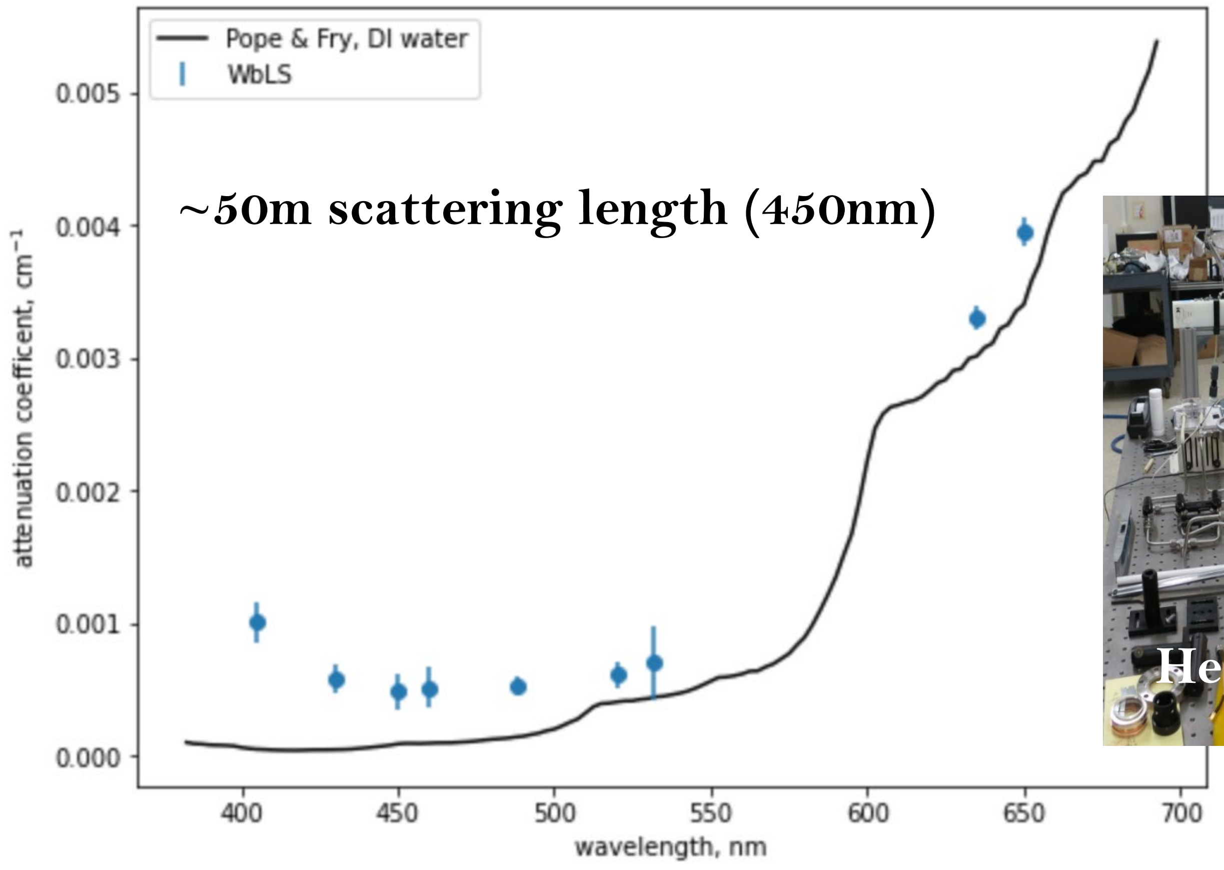
Laboratory Development

- Developed and characterized a variety of WbLS formulas for multiple frontiers; all liquids stable since production (~years).
- Demonstrated Gd-, Li-, and B-doped WbLS with projected performances.
- New initiates in XbLS (triple-coincident)
- Established material compatibility program to qualify detector construction.
- **Education and Training Program held student visits from SPINS, MTV consortiums, and DOE education programs; host 3~4 students/yr**

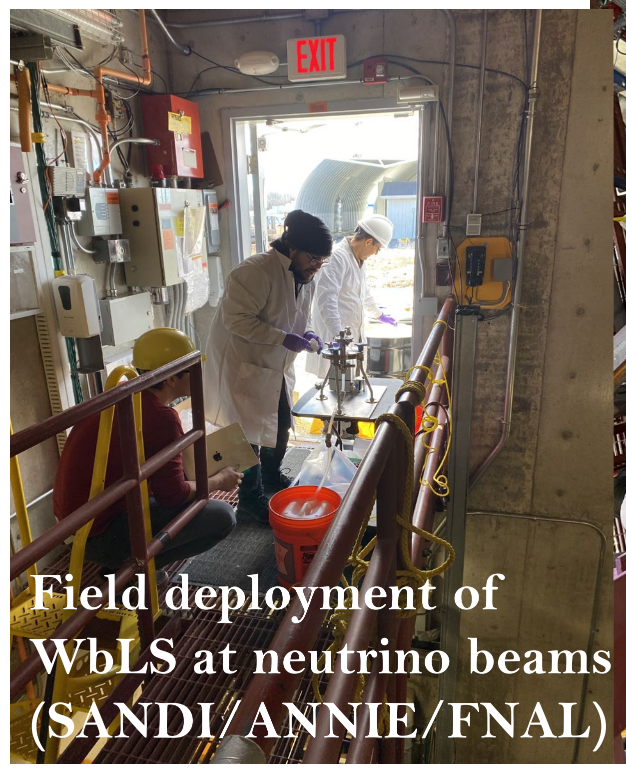


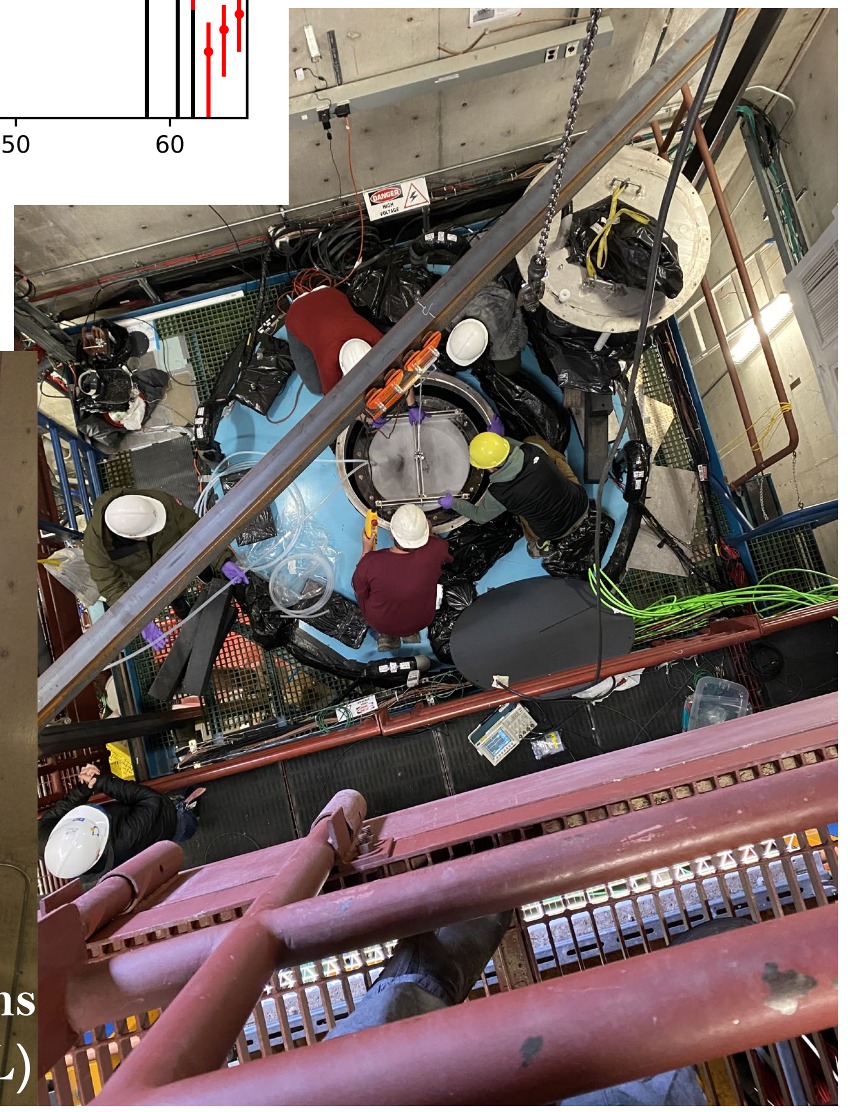


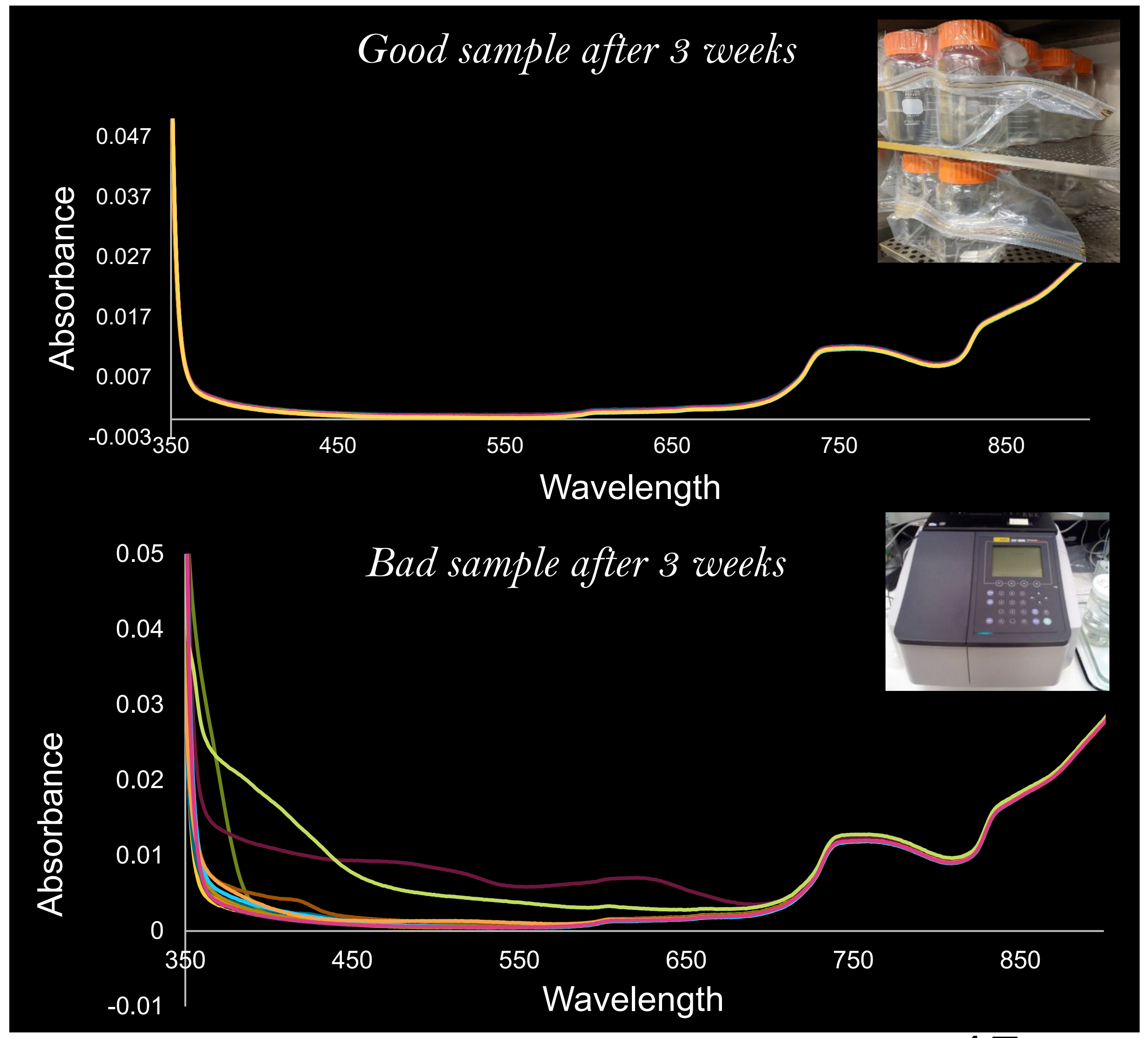




Orcid.org/0000-0003-2244-0499







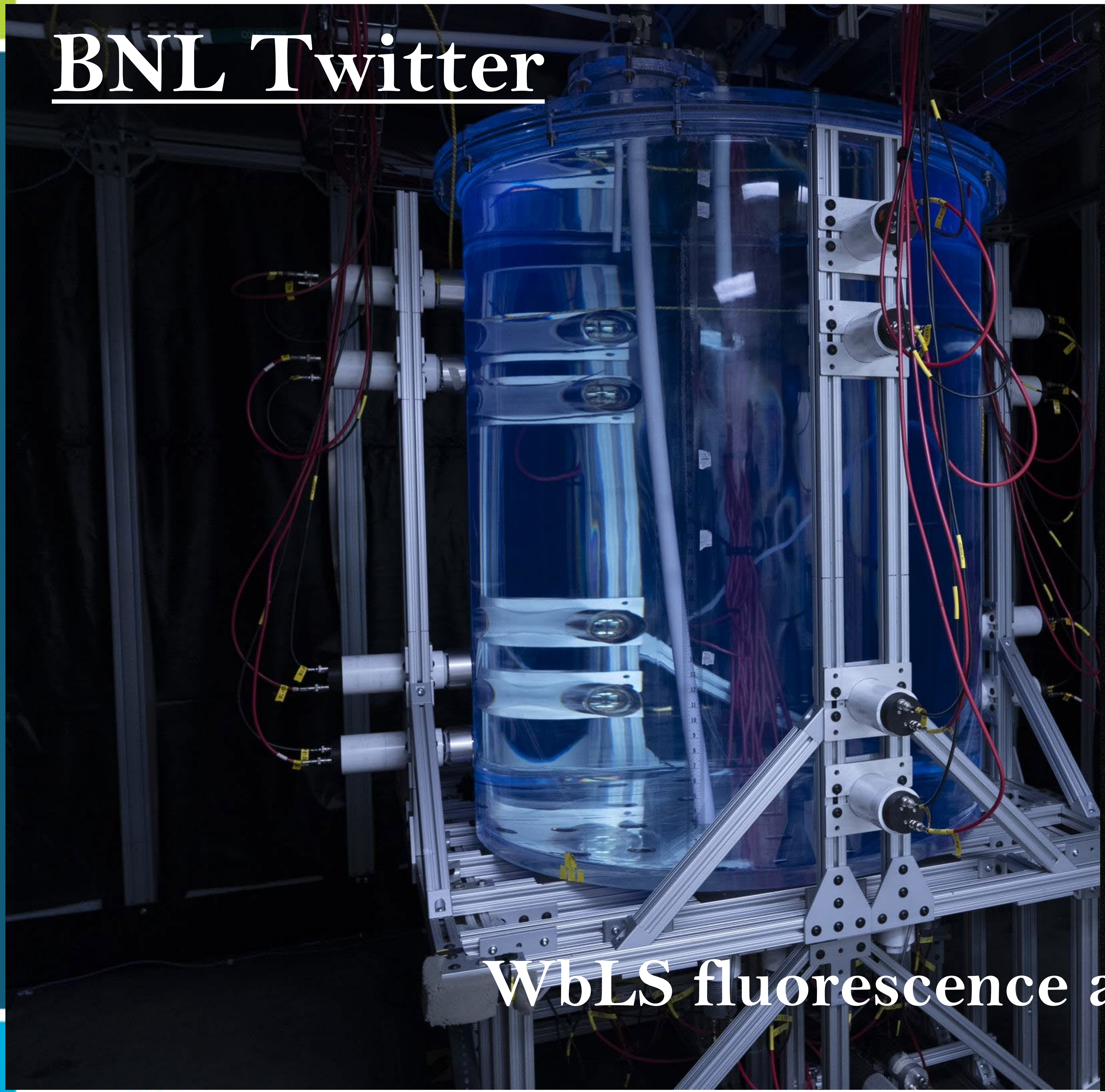
Brookhaven National Laboratory

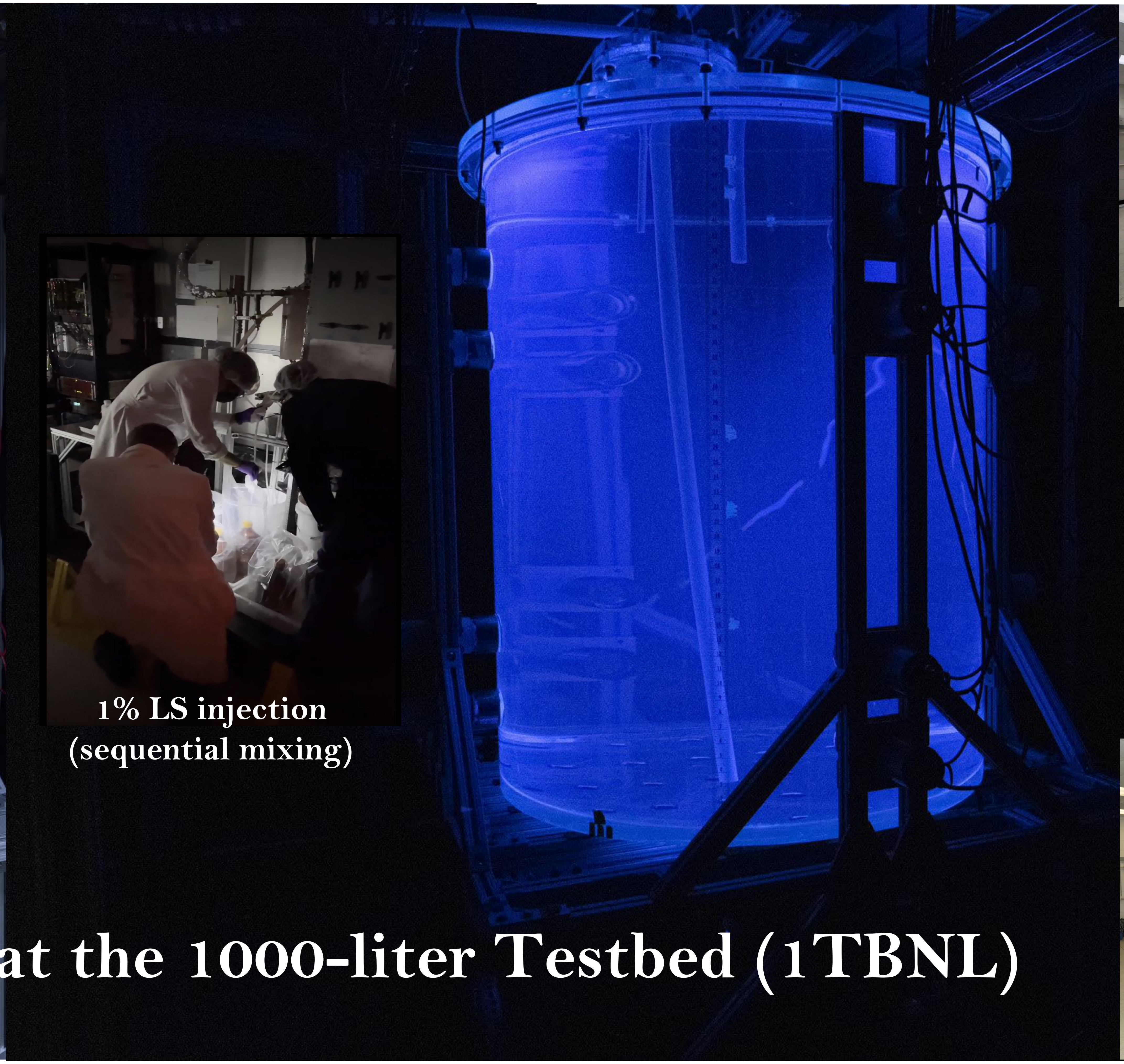
National Nuclear Security Administration

Scale-up Development: 1-ton Testbed (1TBNL)

National Nuclear Security Administration

BNL Twitter





1% LS injection
(sequential mixing)

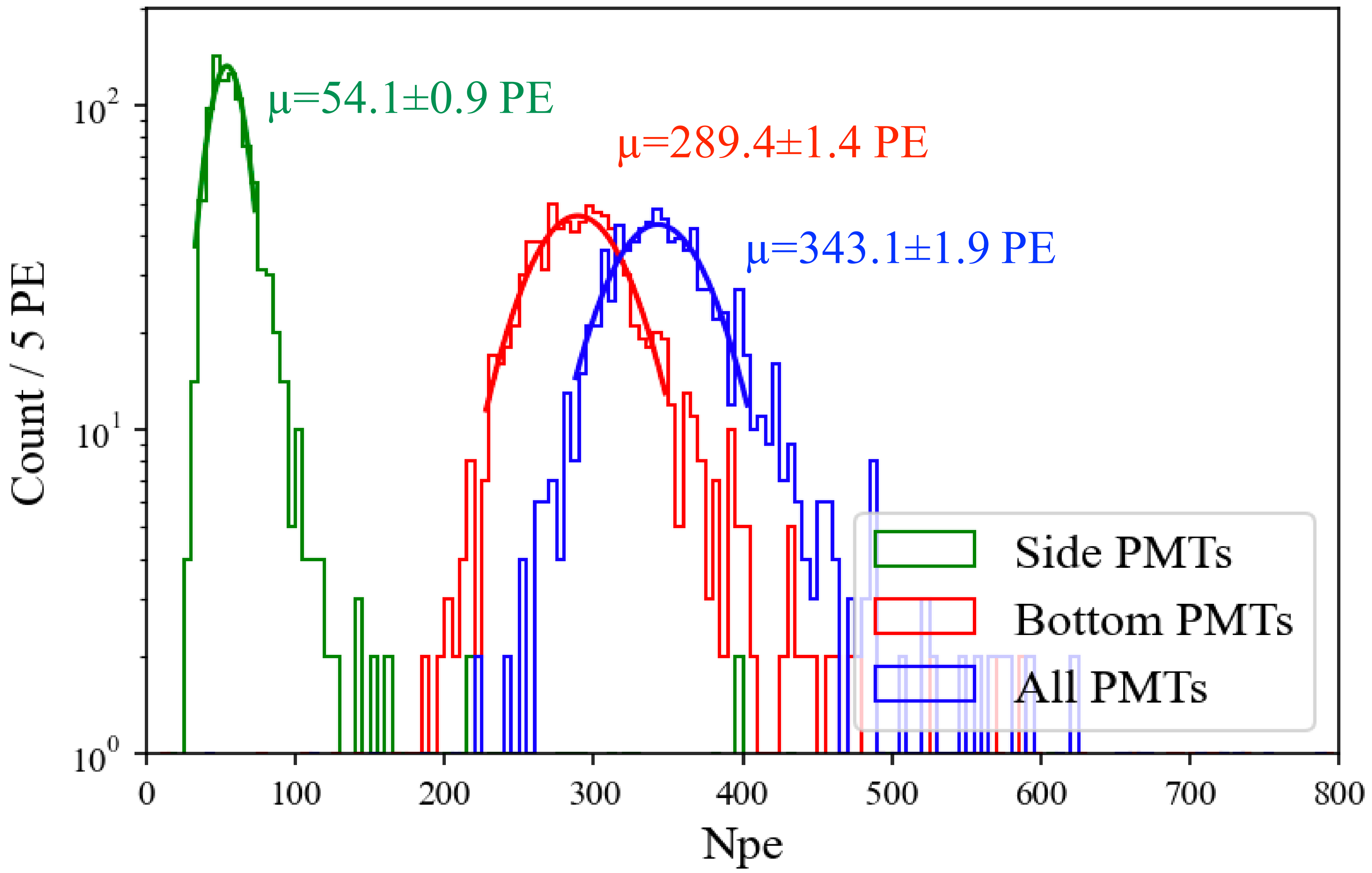
WbLS fluorescence at the 1000-liter Testbed (1TBNL)

Brookhaven National Laboratory

Progress at 1TBNL

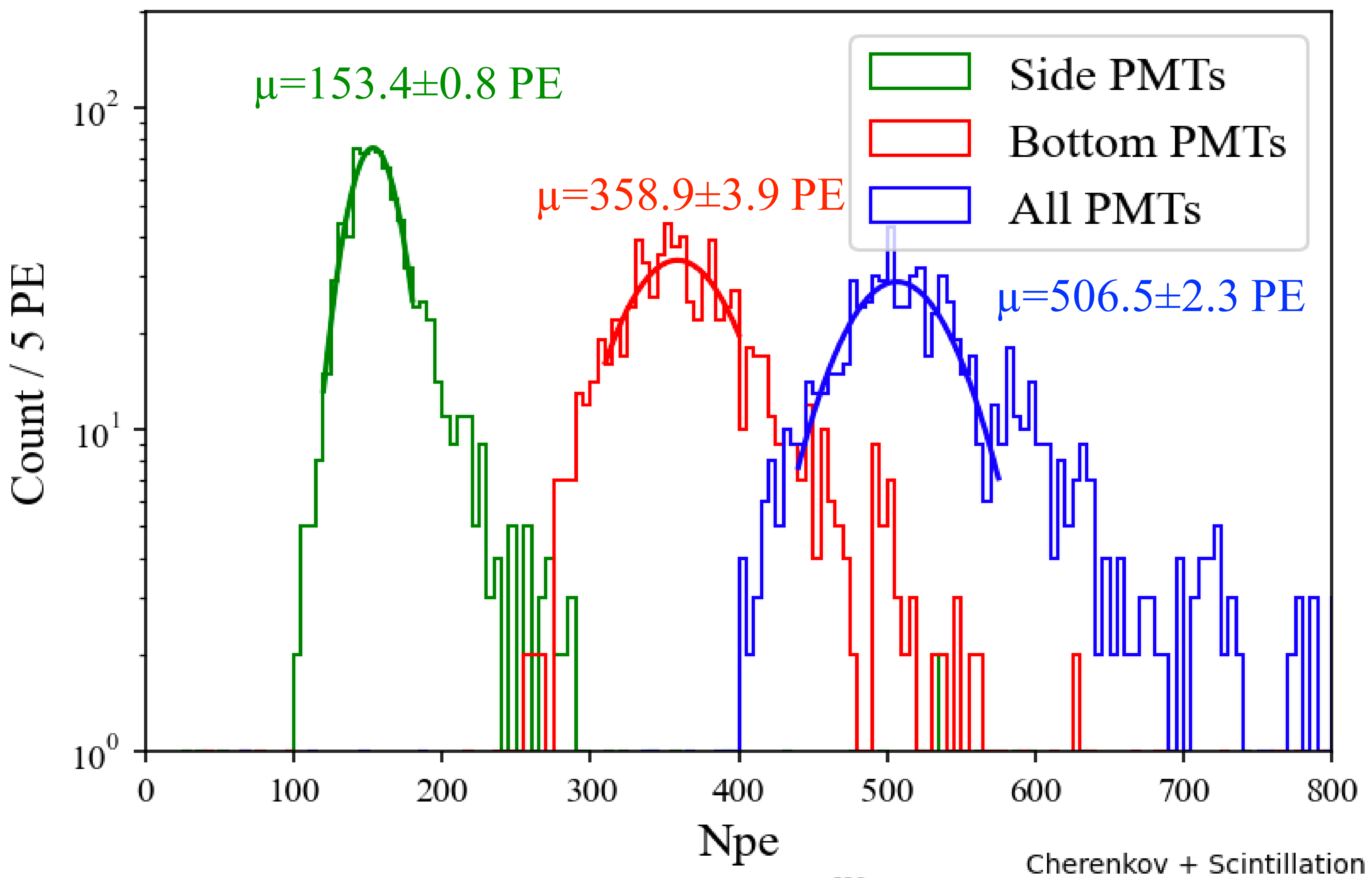
National Nuclear Security Administration

Tagged crossing muons in **water**

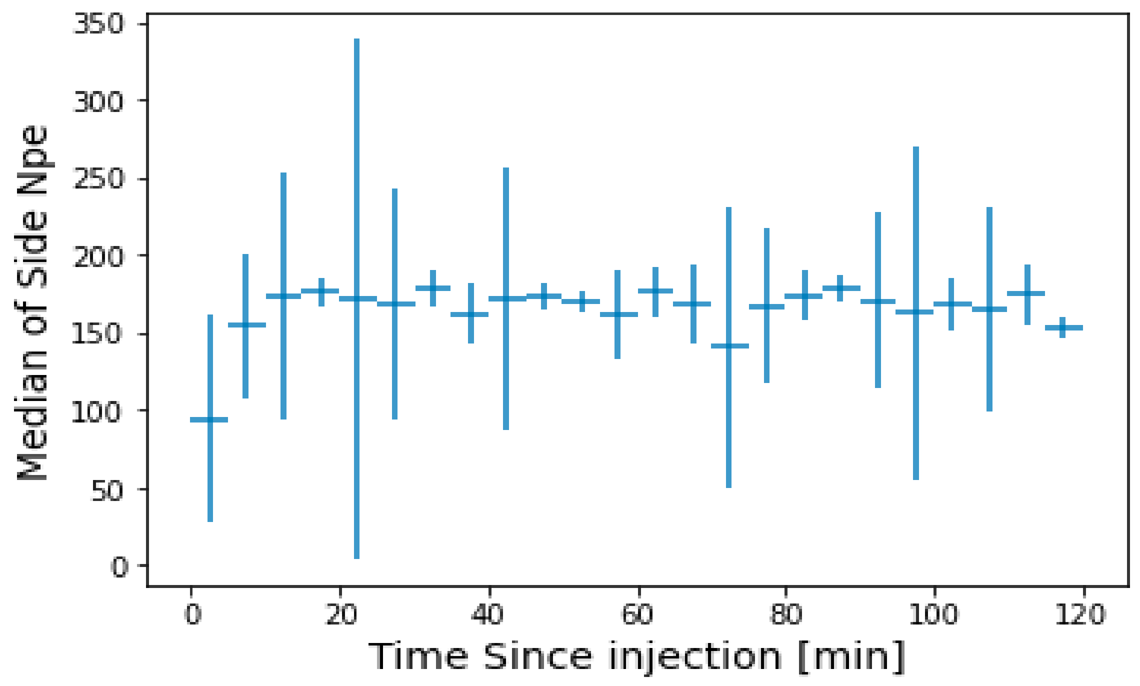


1% LS injection

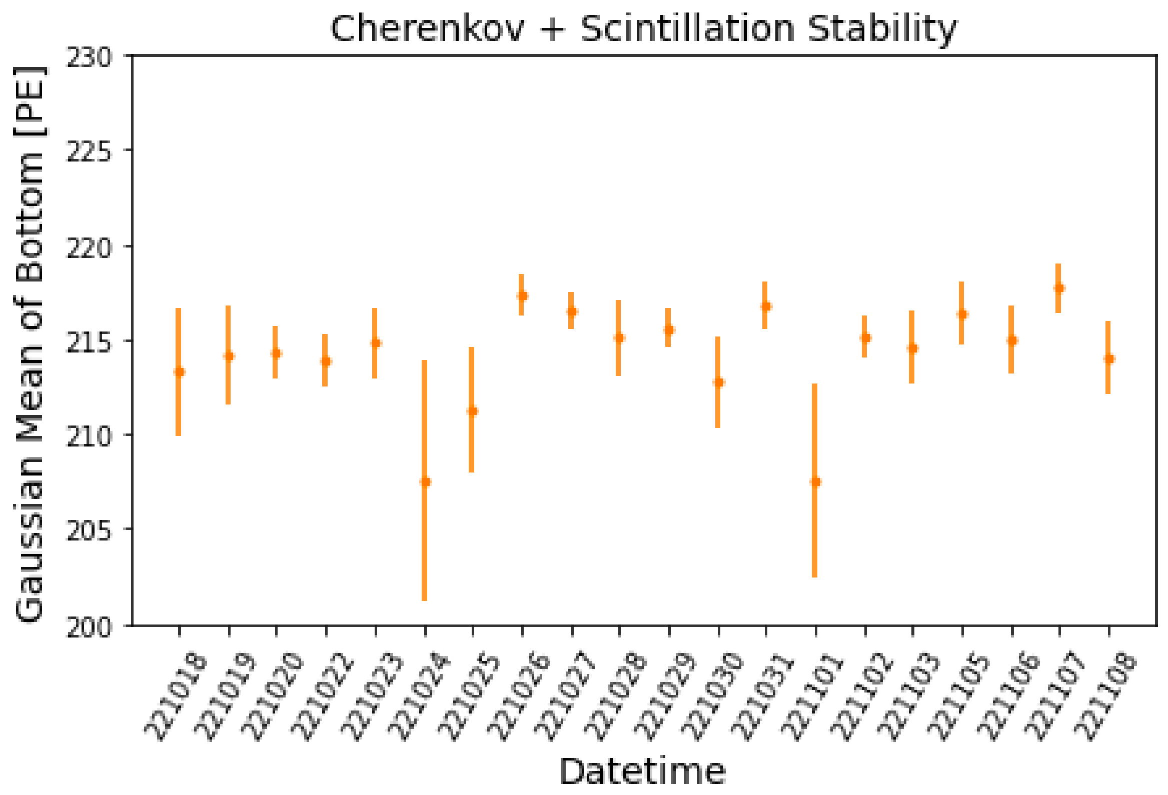
Tagged crossing muons in **WbLS (1%)**



- 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** (cost-effective with minimum labor)
- WbLS stability observed over months of operation



Homogeneity observed 20mins after injection



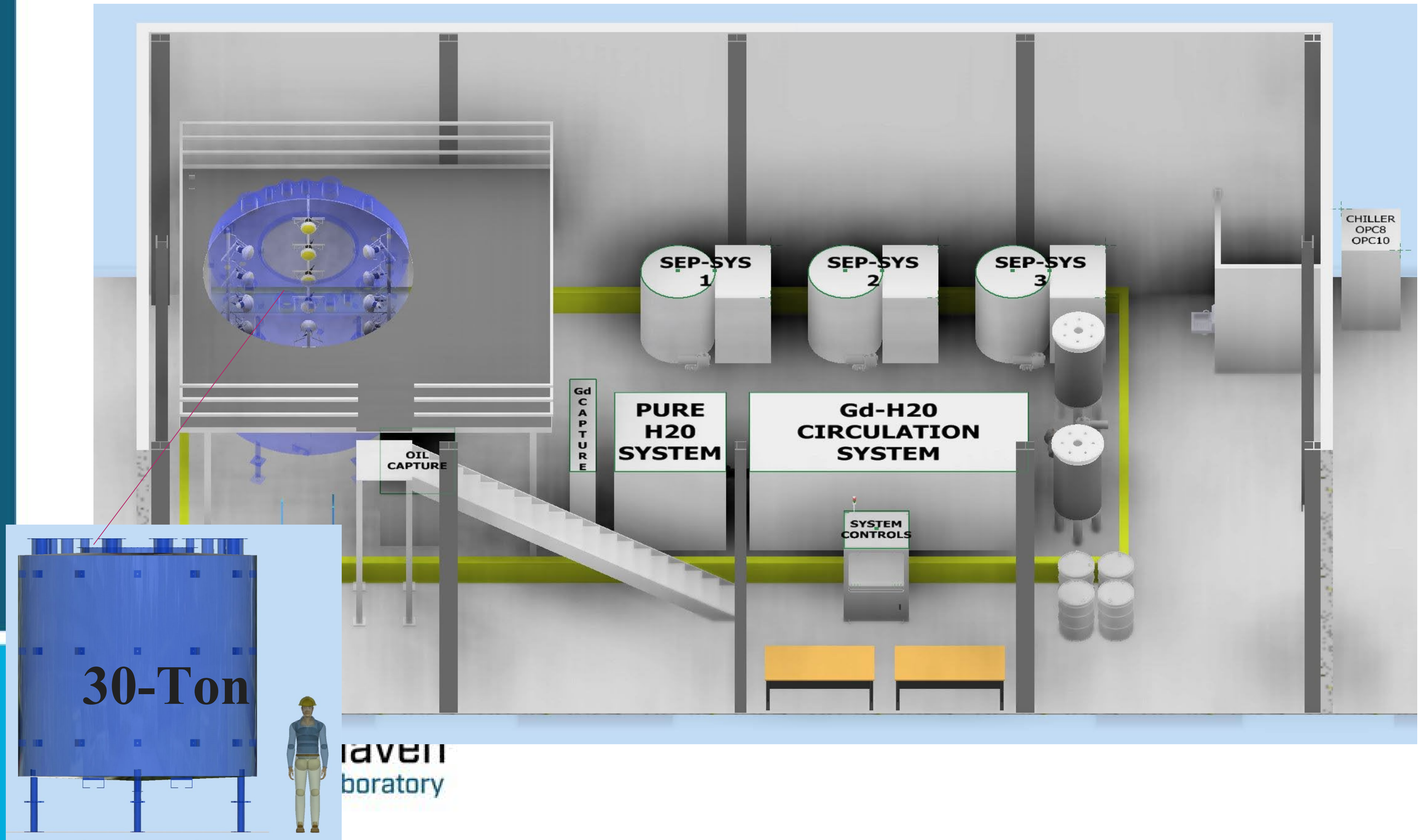
Stability of 1%WbLS observed

Brookhaven National Laboratory

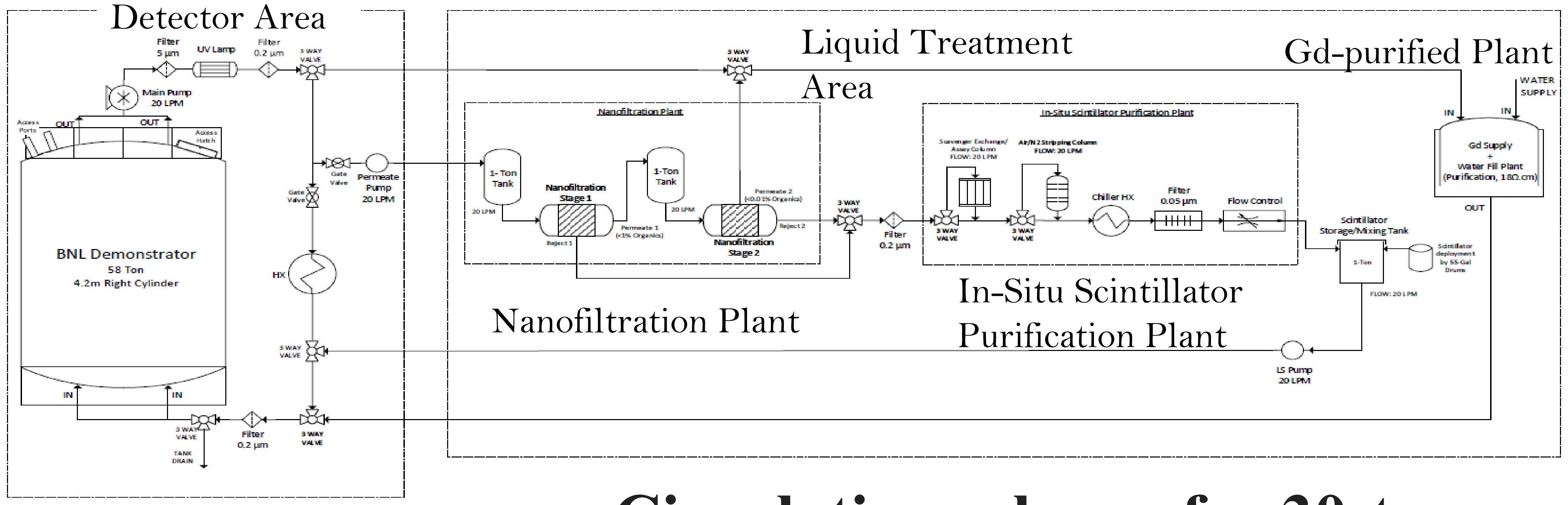
Scale-up Development: 30-ton Demonstrator (30TBNL)

National Nuclear Security Administration

- To demonstrate a large WbLS deployment at 100s-1000s tons-scale
- Engineering detector operation with scale-up systems and performance stability
- Capable of adding an inner tank



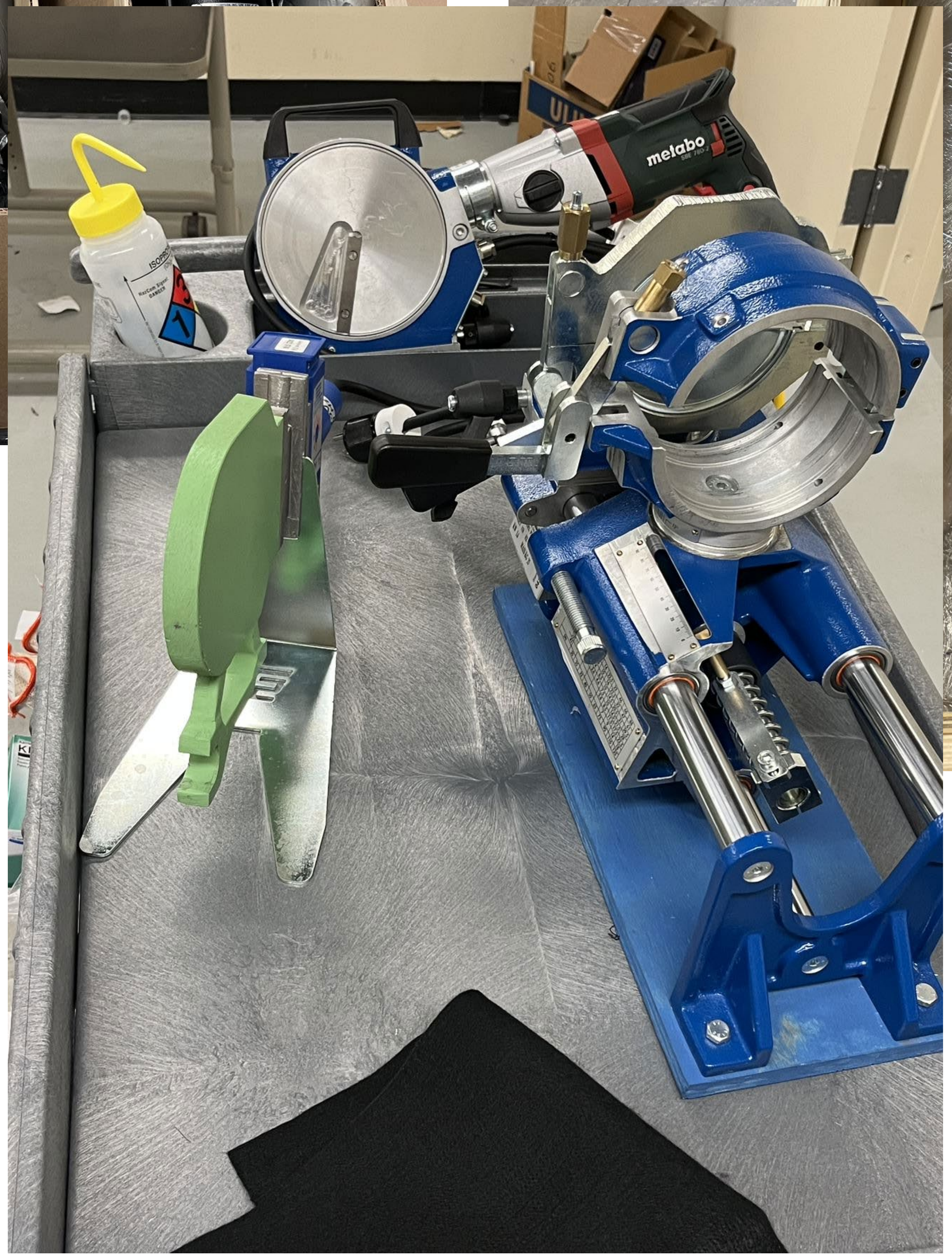
- **Milestones: PMT (10″), tank (30T), pumps (32GPM), HVAC, heat-exchanger, chiller, circulation system, DAQ, deployment system.**
- **Critical paths: Gd-system, nanofiltration system, slow-control, mezzanine, integration.**



Circulation scheme for 30-ton

Parts and Equipment arrived at BNL

NNSA National Nuclear Security Administration



30TBNL Installation

National Nuclear Security Administration

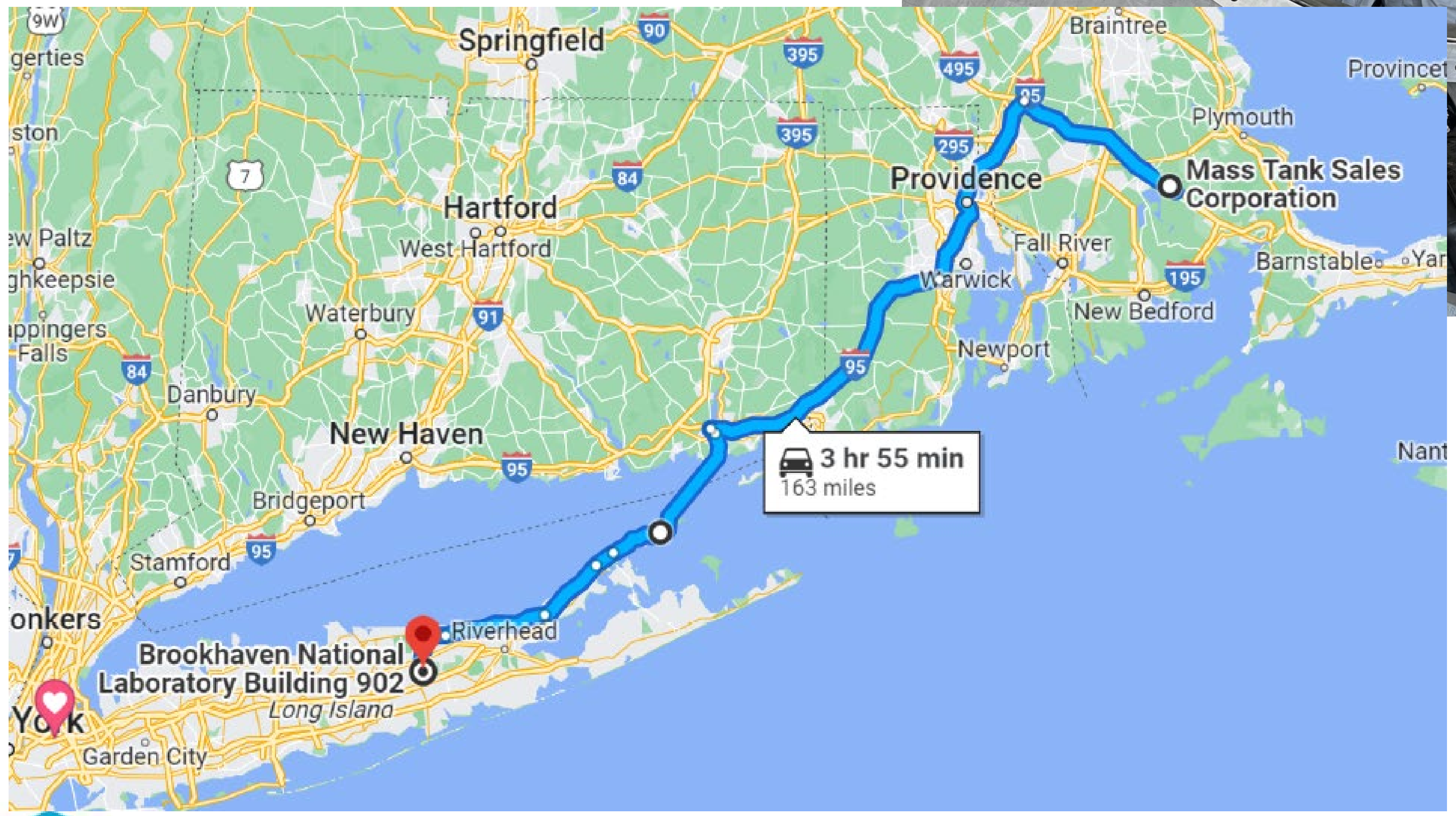
Started in FY22

A collaborative effort between multiple universities and other labs

30-ton Tank

National Nuclear Security Administration

Delivered to BNL on July 21, and moved into Facility on July 25, 2023



Milestone!

Preparing for cleaning and water fill

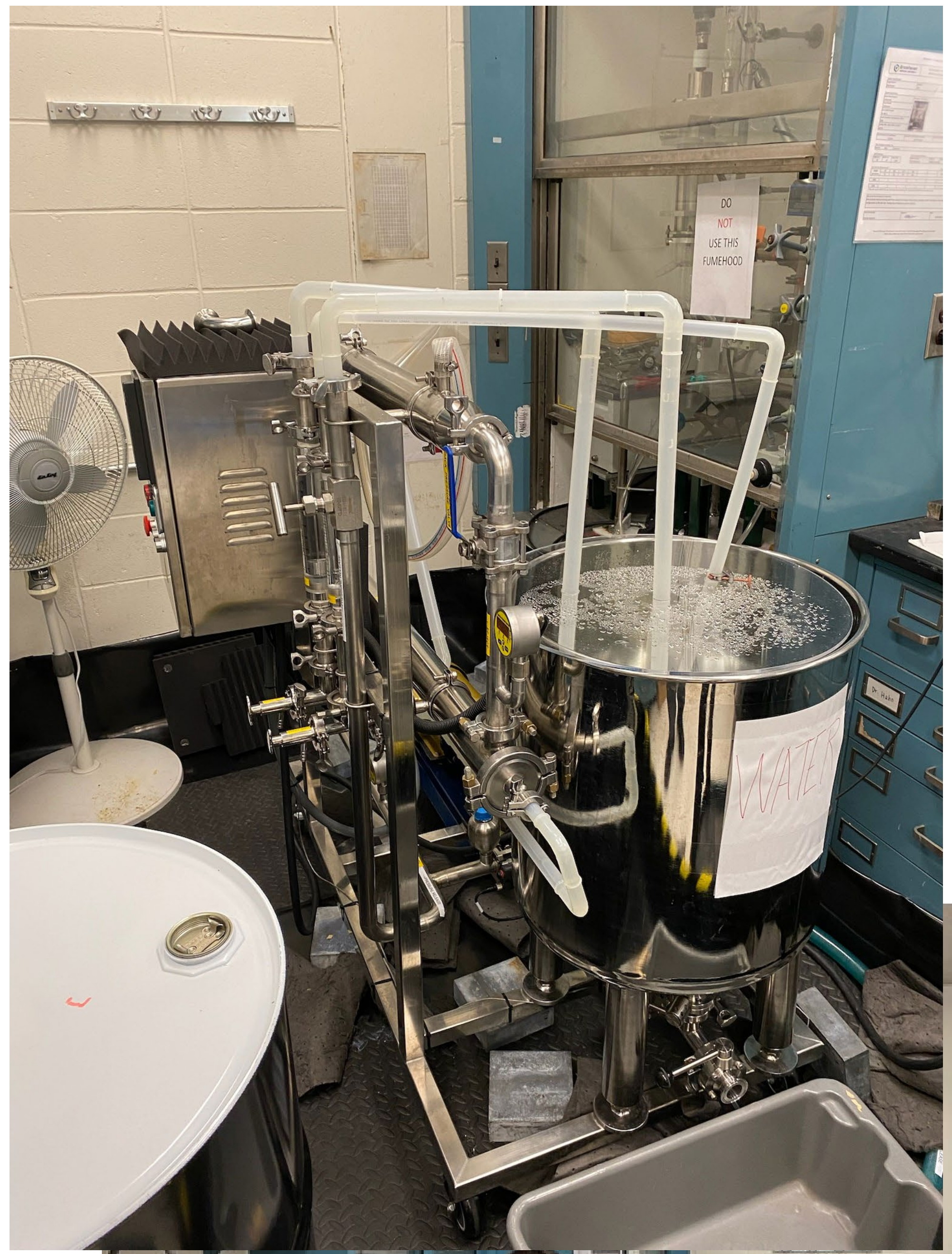
Brookhaven National Laboratory

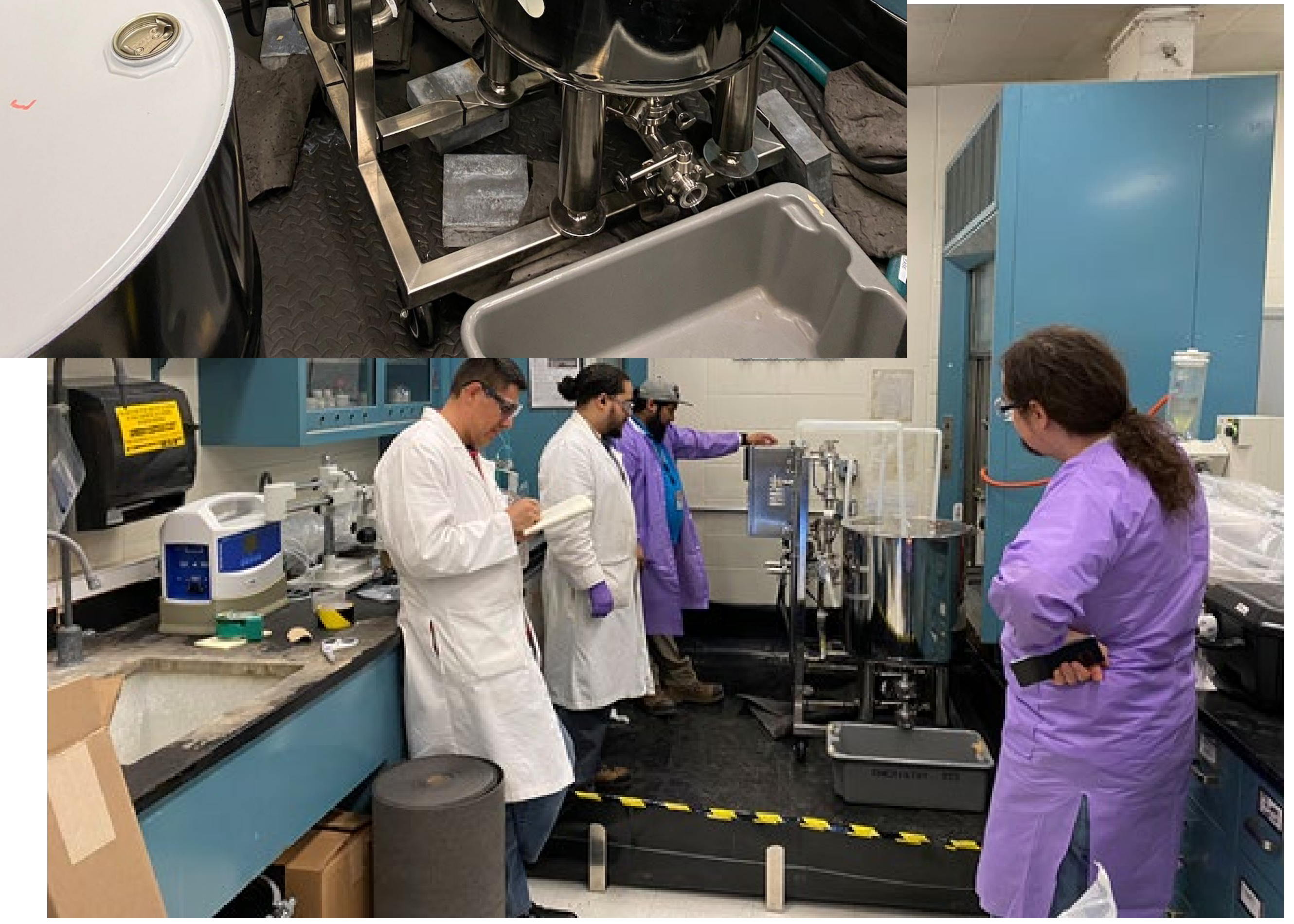
Nanofiltration System

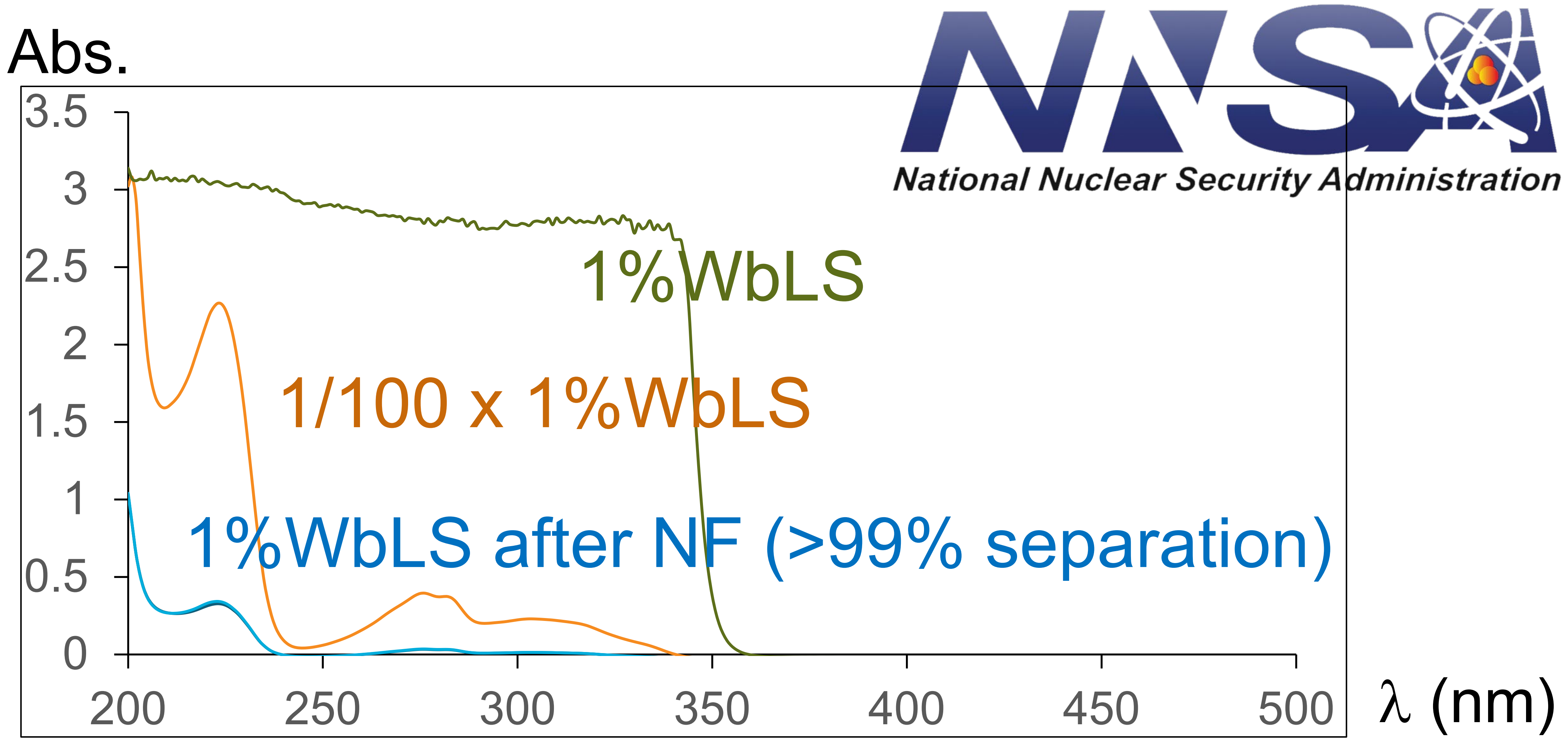
National Nuclear Security Administration

MaxiMem (0.5 GPM)

2540-pilot (6 GPM)







30T-NF (30 GPM, under RFQ)

A bandpass technology to separate oil and water for in-situ purification (largely used in industry); collective activity UC Davis, BNL and UK

Brookhaven National Laboratory

Alternative In-situ Purification (Exchange Column)

- Many industrial resins/scavengers (technologies developed from nuclear waste processing and enrichments) pose metal selectivity
- For Gd-WbLS, searching to remove radioactive/colored leaches from SS tank, PMTs, etc. (i.e. $Fe^{2+,3+}$); maintaining a clean optical detector
- A testbed with mixed resins showed promising results from multiple spiked tests (>80%Fe removal without Gd loss per pass)

One-step sequential extraction

WbLS Timeline

National Nuclear Security Administration

Sampling

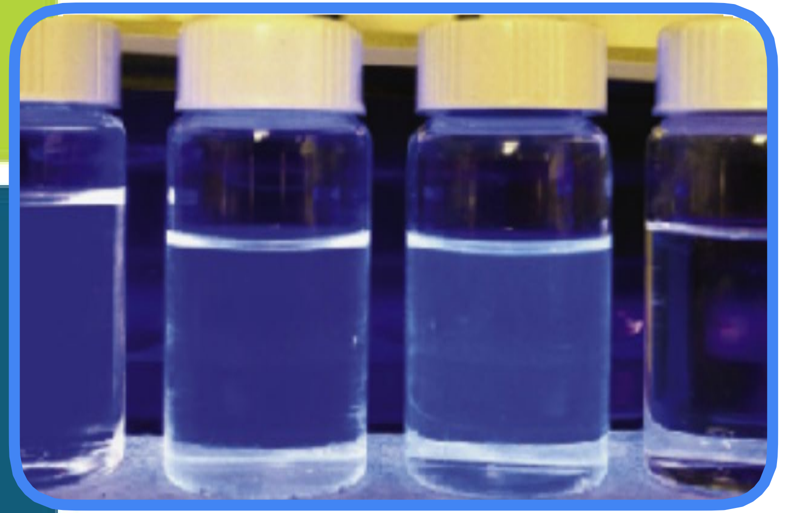
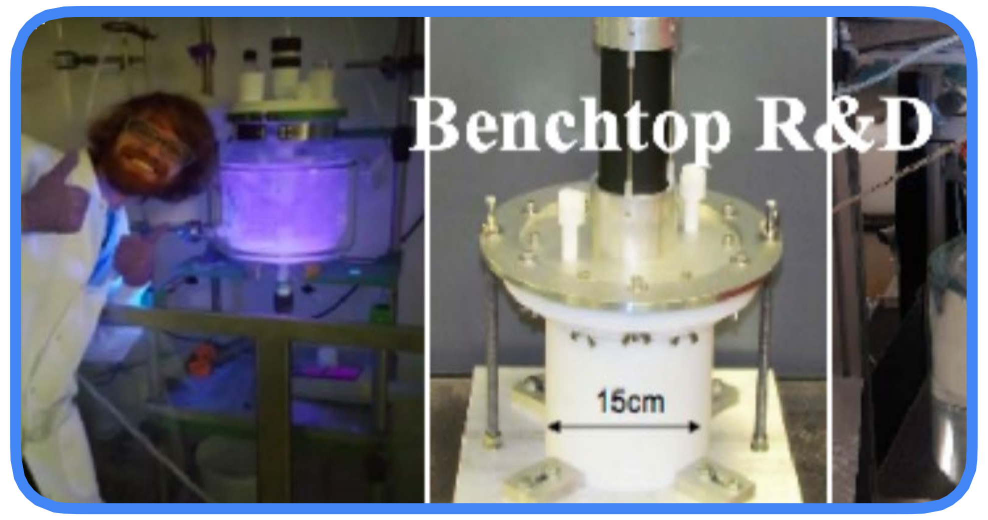
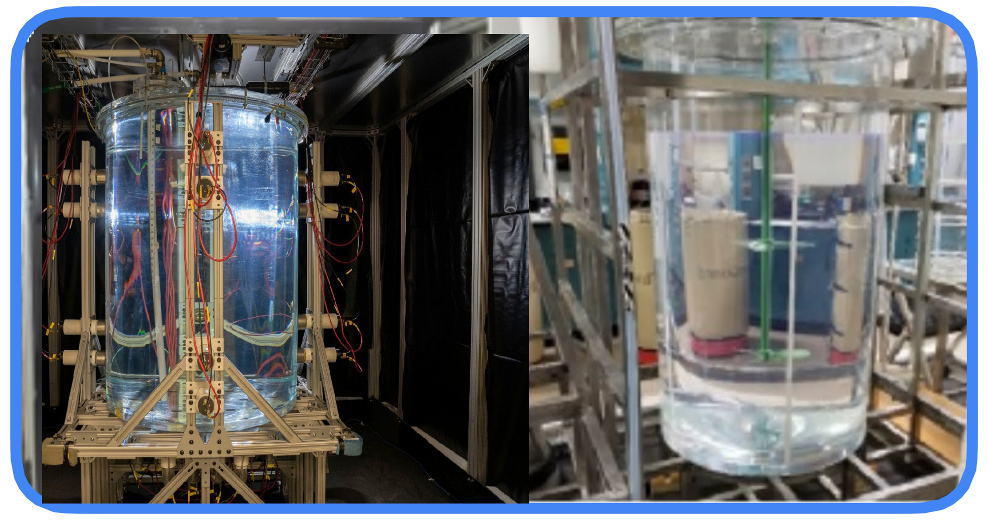


Table top R&D



Early prototype

Current 1-ton detector



30-ton demonstrator

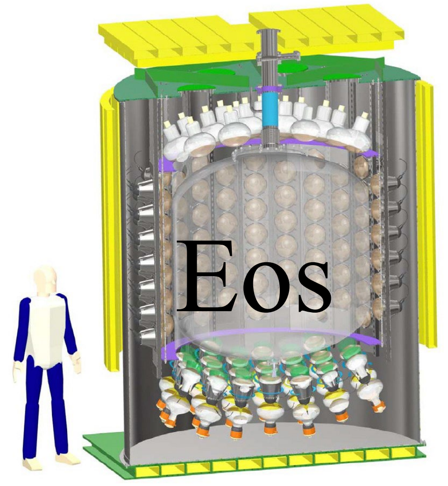
2011 2014 2016 2022 2023 2024

A new water-based liquid scintillator and potential applications

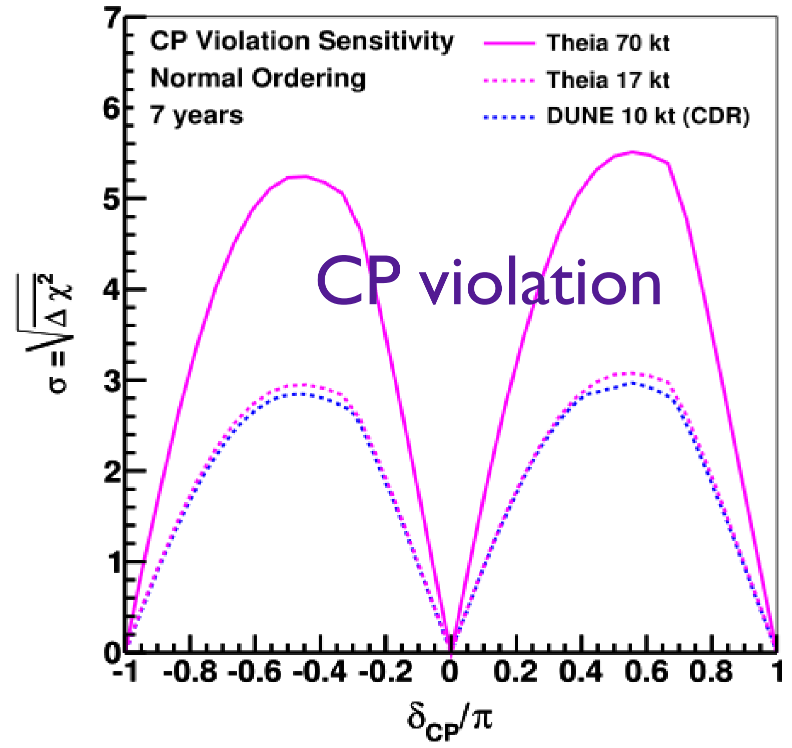
M. Yeh[a,*], S. Hans[a], W. Beriguete[a], R. Rosero[a], L. Hu[a], R.L. Hahn[a], M.V. Diwan[b], D.E. Jaffe[b], S.H. Kettell[b], L. Littenberg[b]

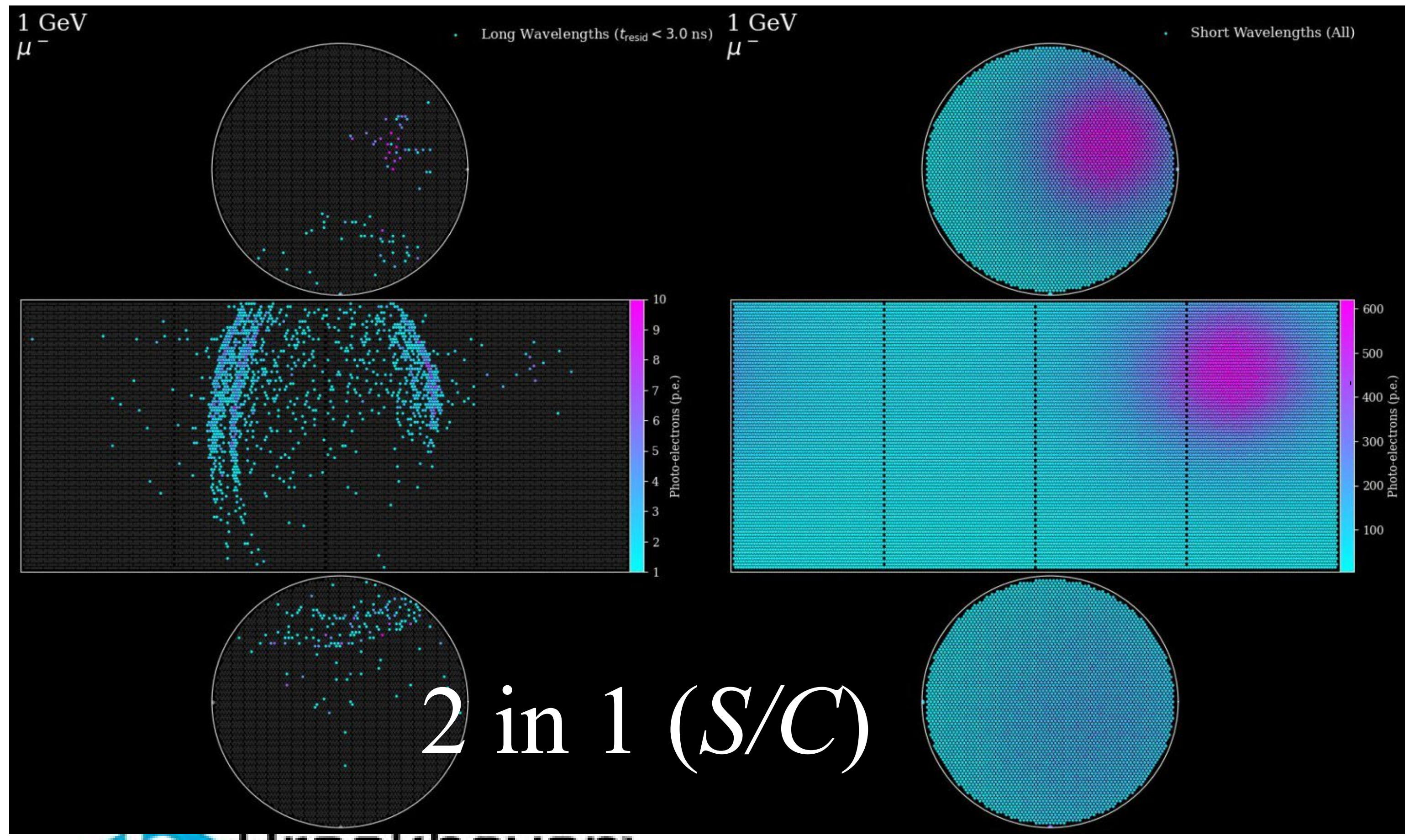
[a] Chemistry Department, Brookhaven National Laboratory[1], Upton, NY 11973, USA
[b] Physics Department, Brookhaven National Laboratory[1], Upton, NY 11973, USA

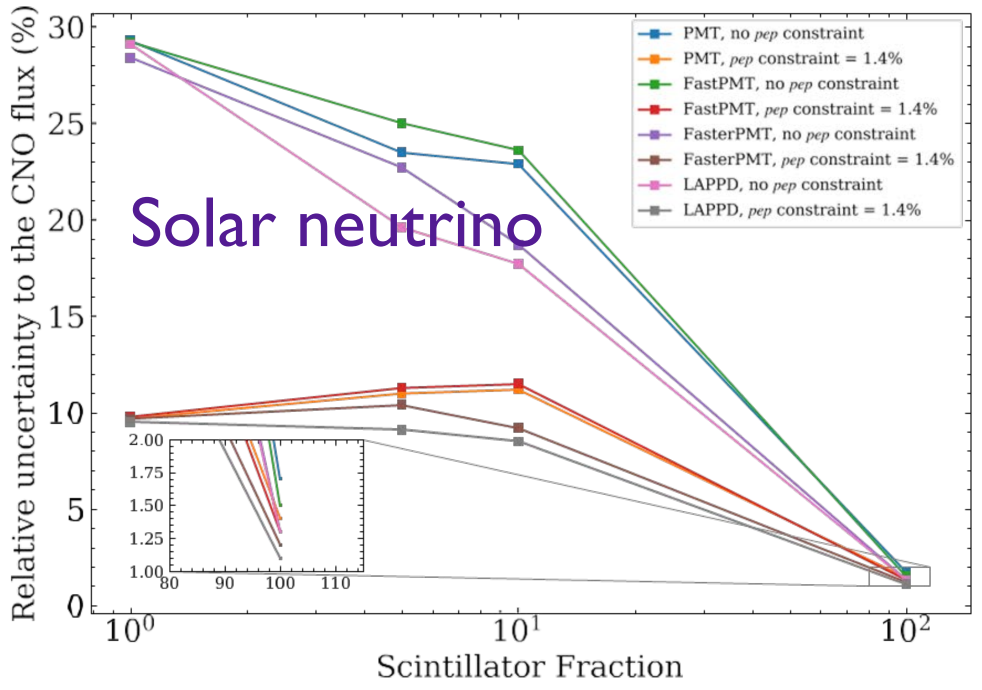
First Proposal

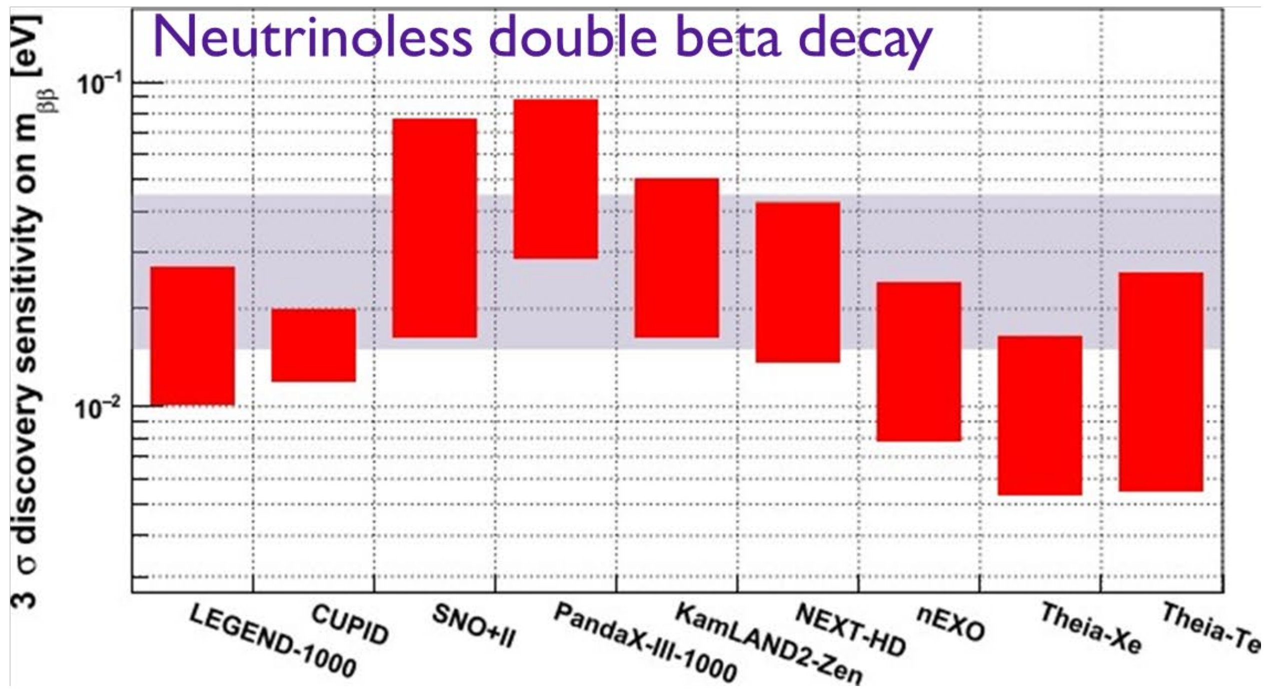


A cost-effective *C/S* hybrid detector capable of PSD, metal-doping, sequential mixing, etc. for multiple physics applications







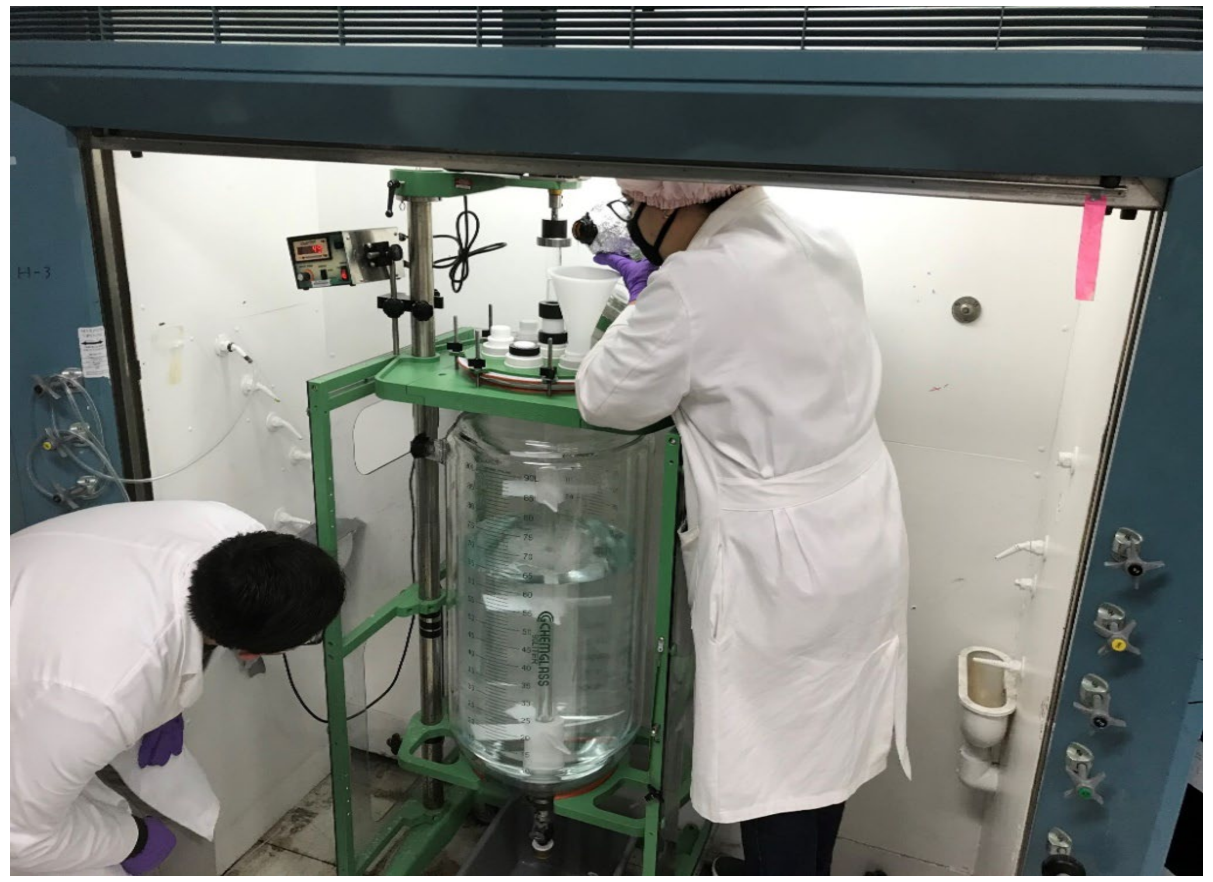


Brookhaven National Laboratory

To build a neutrino detector

- Weak interaction requires large detector mass + many photosensors from 10s to 1000s of tons (physics target and instrumentation design)
- Enhanced s/b ratio needs a clean environment and well-defined detector (underground and calibration)
- Long experimental lifetime necessitates a highly stable and transparent detector liquid (chemical development)
- Expertise from multi-frontiers
- benchtop R&D → prototype → scale-up experiment

In-house Scintillator R&D and Scale-up at BNL



- Expertise across chemistry, physics and instrumentation with strong collaborations with universities, other national labs, and international partners

Brookhaven National Laboratory

The work conducted at Brookhaven National Laboratory was supported by the U.S. Department of Energy under Contract No. DE-SC0012704. The material was based upon work supported by DNN/HEP/NP

Liquid Scintillator Laboratory Sessions

7 students in each session				Benchtop (B555) and 1-ton Testbed (B535)							
				10-Oct	11-Oct	12-Oct	13-Oct	16-Oct	17-Oct	18-Oct	19-Oct
LS benchtop and measurement (Richard, Sasmit, Chris)				group 2		group 4		group 6			
30	1:30	2:00	LS preparation								
60	2:00	3:00	LS mixing; 1T production and equipment introduction								
60	3:00	4:00	UV and LY								
30	4:00	4:30	Emission & timing								
60	4:30	5:30	data and Q&A								
1T testbed (Guang, Gannon)					group 3		group 5			group 7	group 1
30	1:30	2:00	Introduction detector and objects								
30	2:00	2:30	PMT, calibration and readout system								
30	2:30	3:00	DAQ and data-taking								
30	3:00	3:30	walk to B751								
120	3:30	5:30	data analysis								

Brookhaven National Laboratory