

From Novel to Mature: Water-based Liquid Scintillator (WbLS) for Neutrinos and Beyond

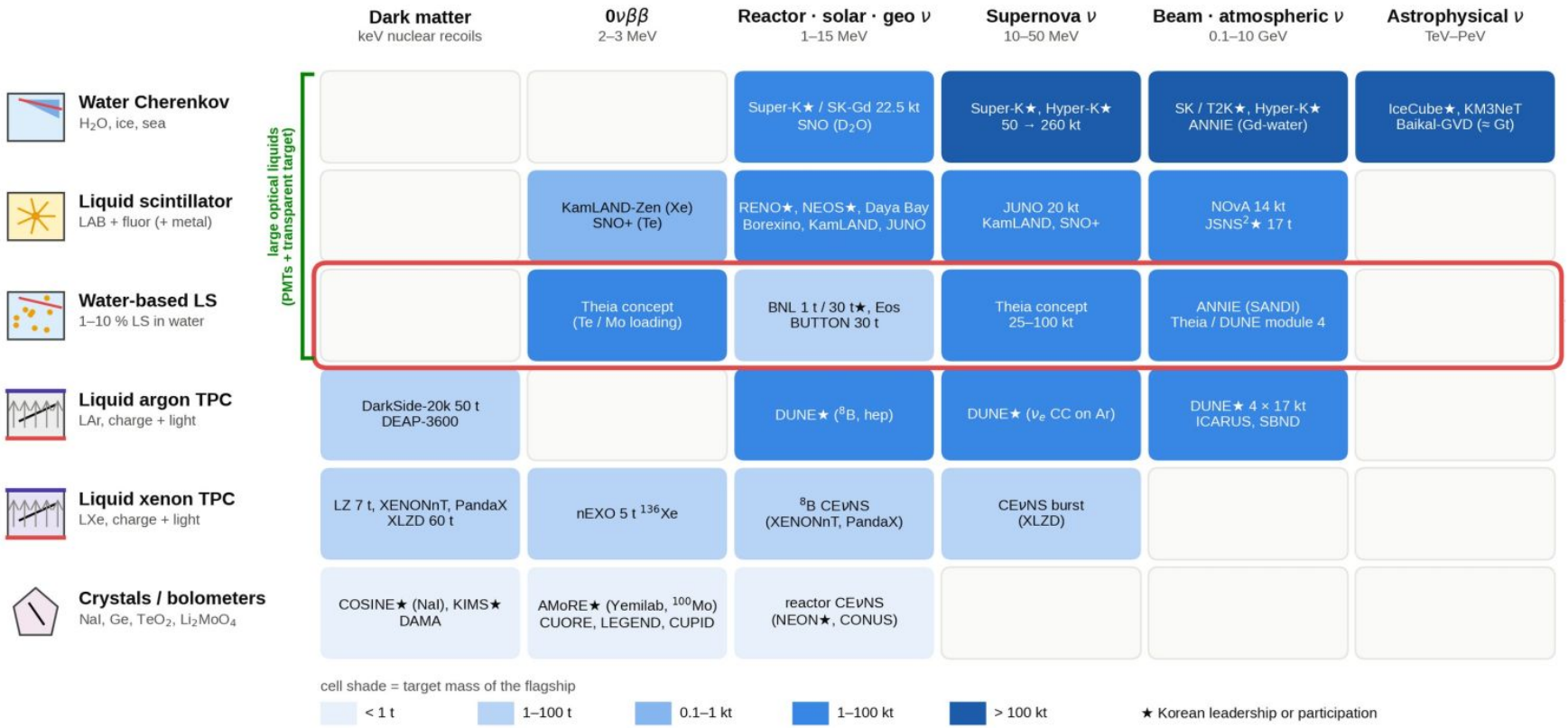
Guang Yang (Brookhaven National Lab)

October 2026

Chung-Ang University K-neutrino workshop

*Special thanks to **Milind Diwan and Minfang Yeh***

Neutrino/dark matter detector matrix



Designing a large-scale neutrino detector

Depending on the source intensity at the location of interest, the detector can be massive/large -> statistics is critical in neutrino detection.

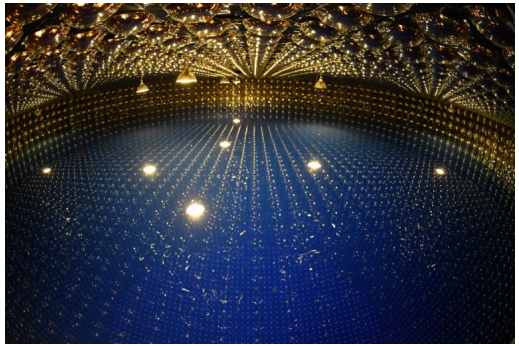
Installing large-scale detectors in liquid phase could be easier and likely cheaper.

The most straightforward material is water but a high particle detection threshold presents.

Optical detector with photomultiplier as the sensor was commonly used, thus the reliability was thoroughly proved.

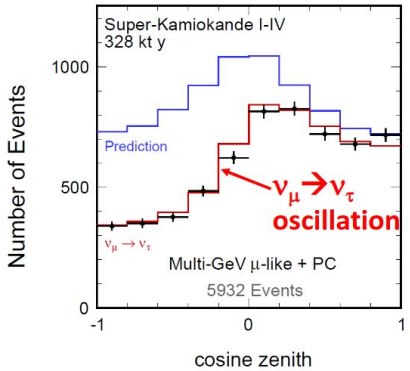
Operating/funded 10 kt scale OPTICAL neutrino detector

Super-K (22.5 kt)

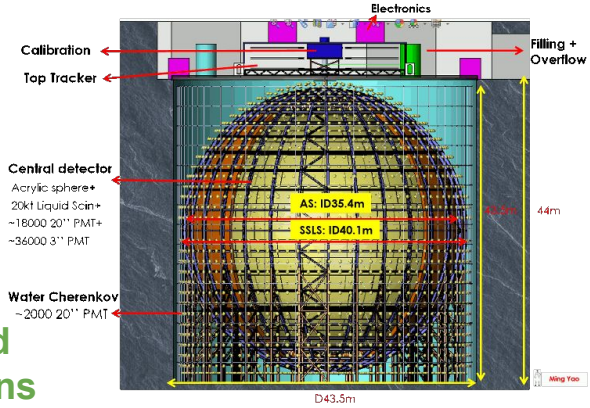


- Excellent Transparency
- Directionality
- Particle ID
- Cheap
- Potential for large Isotopic Loading

- No access to physics below the Cherenkov threshold
- Low light yield

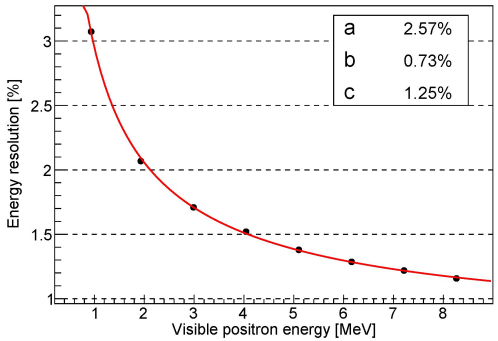


JUNO (20 kt)



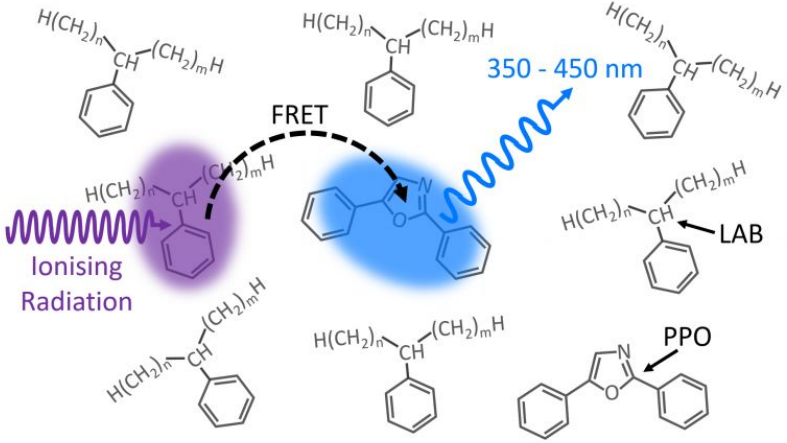
- High light yield
- Low energy threshold
- Good energy and position resolutions
- Can be radiologically very clean

- Costy
- High absorption
- Limited directionality

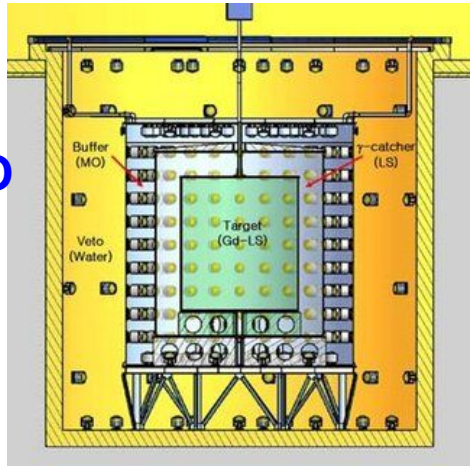


Target at different energy range

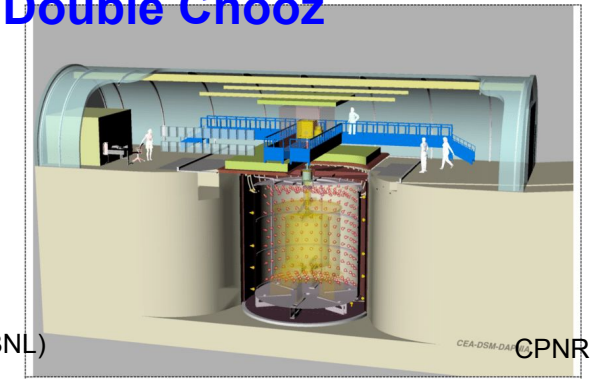
Welcome to the world of Benzene



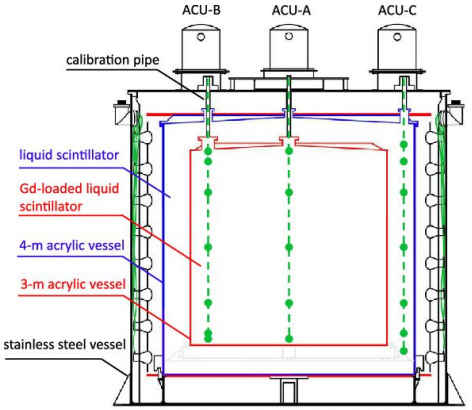
RENO



Double Chooz

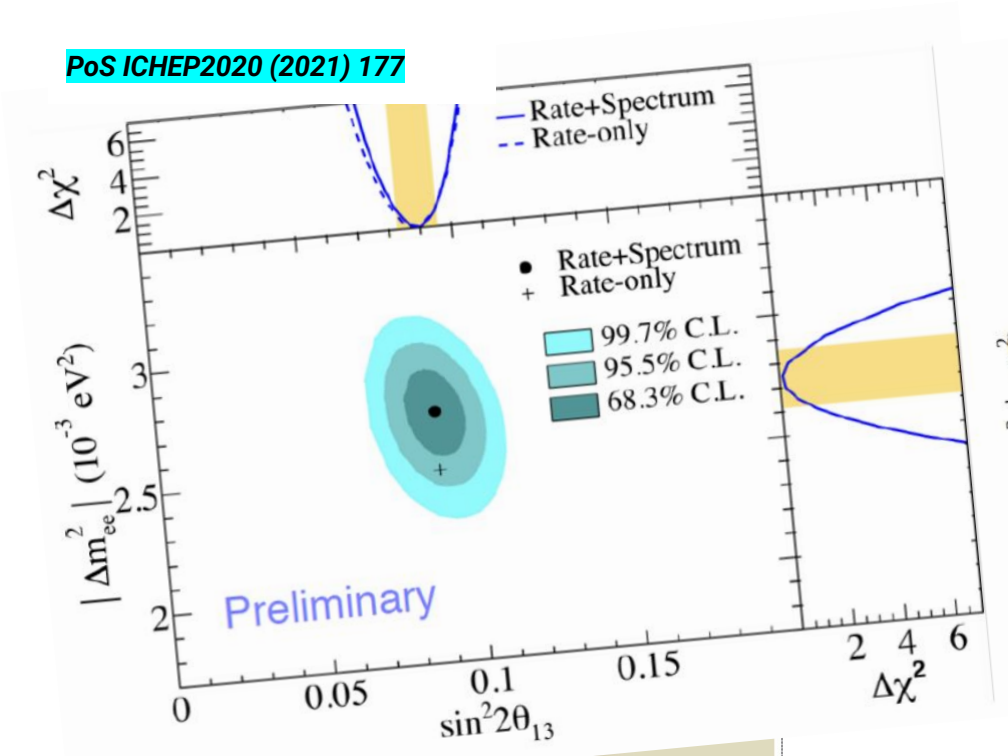


Daya Bay

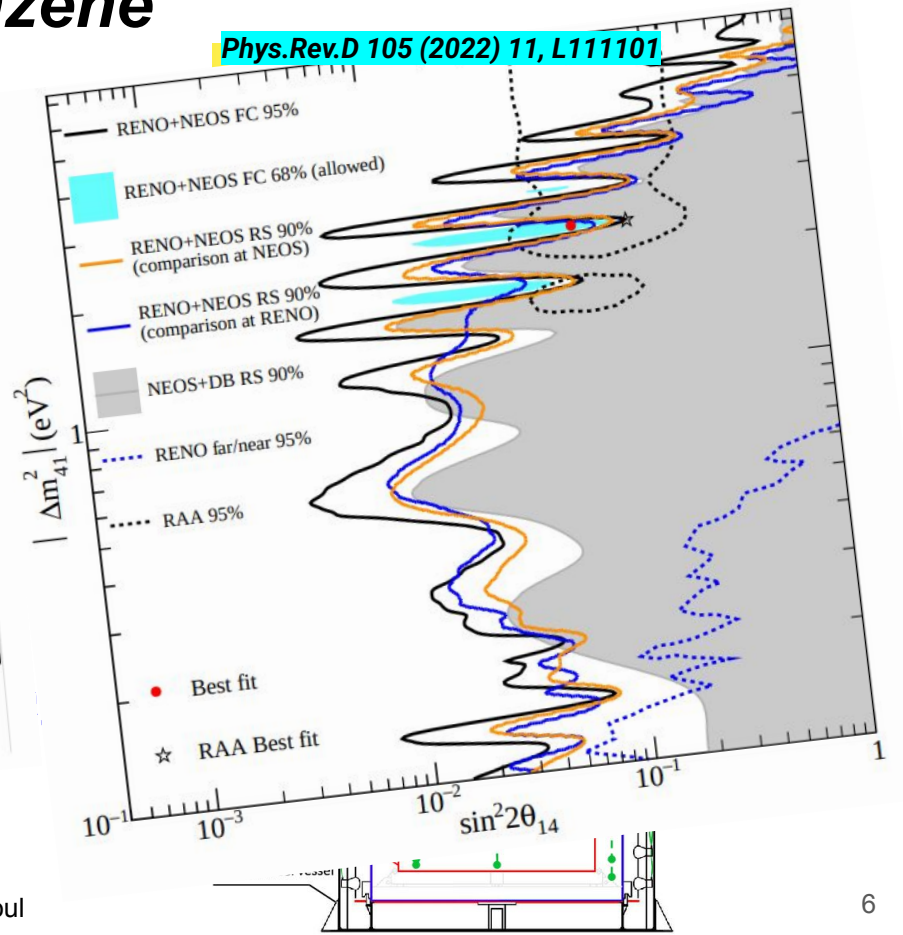


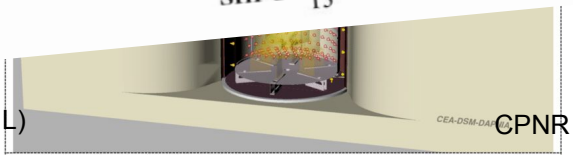
Welcome to the world of Benzene

PoS ICHEP2020 (2021) 177



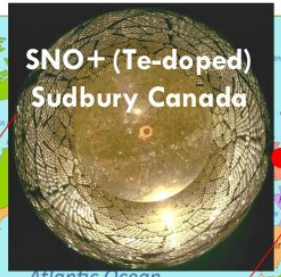
Phys.Rev.D 105 (2022) 11, L111101





LS-based ν Experiments

























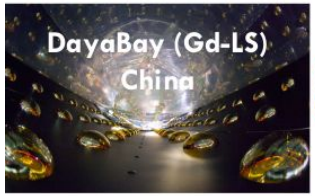




Guang Yang (BNL)

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

Brookhaven National Laboratory













Periodic Table of the Elements © www.elementsdatabase.com

H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	Ac 89	Unq 104	Unp 105	Unh 106	Uns 107	Uno 108	Une 109	Unn 110								

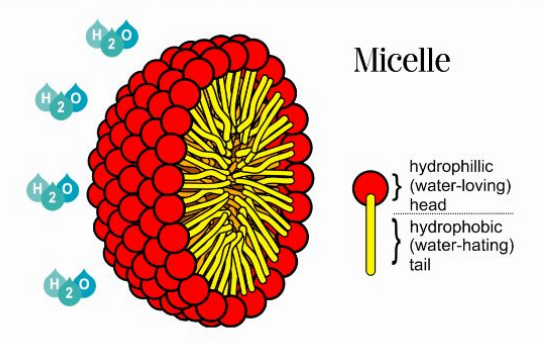
Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

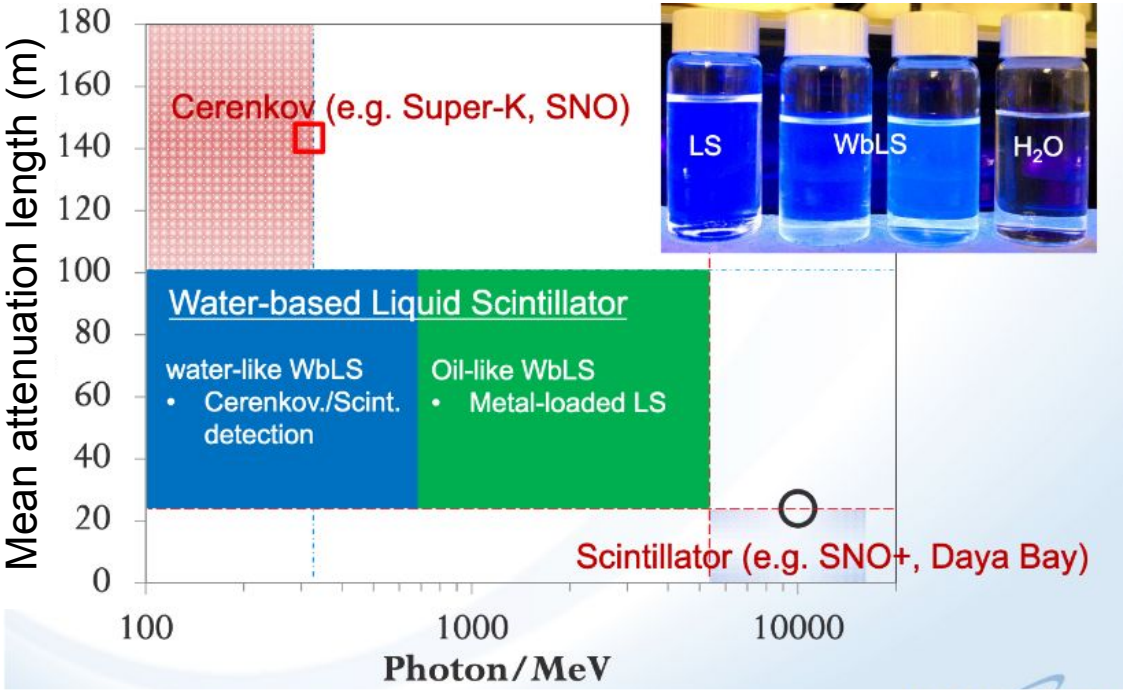
- **Reactor**
- **ββ**
- **Solar**
- **Medical, calibration, LSC, etc**

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

Next-generation: Combining water and LS

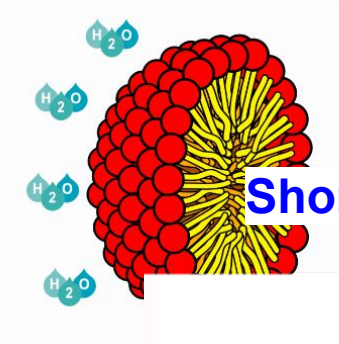






Next-generation: Combining water and LS

Attenuation length includes scattering and absorption





Short scattering length



Short absorption length

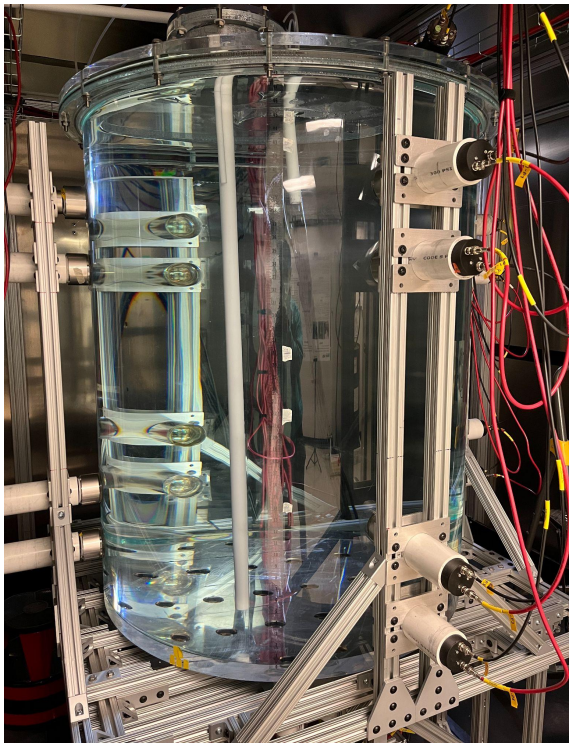


, Daya Bay)

BNL demonstrators

1ton

Acrylic tank
PMT coupled to the tank



30ton

Stainless steel tank
PMT inside the tank

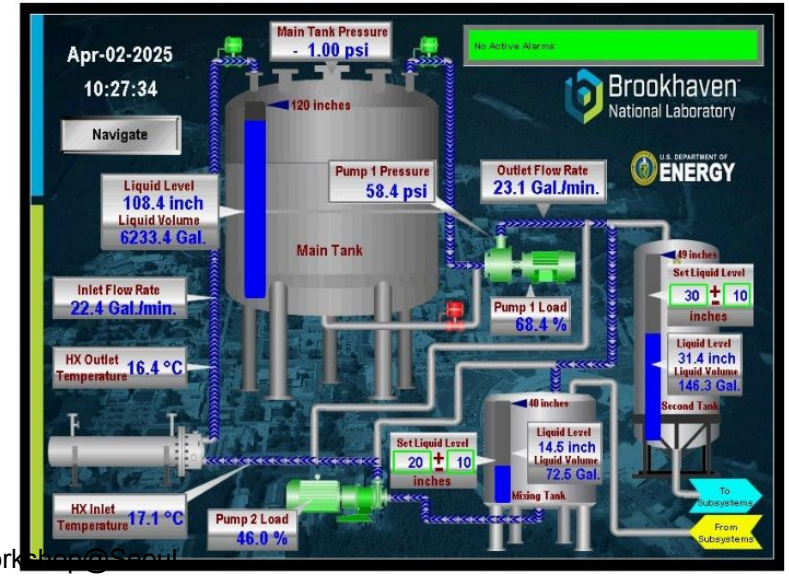


BNL 30ton demonstrator





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



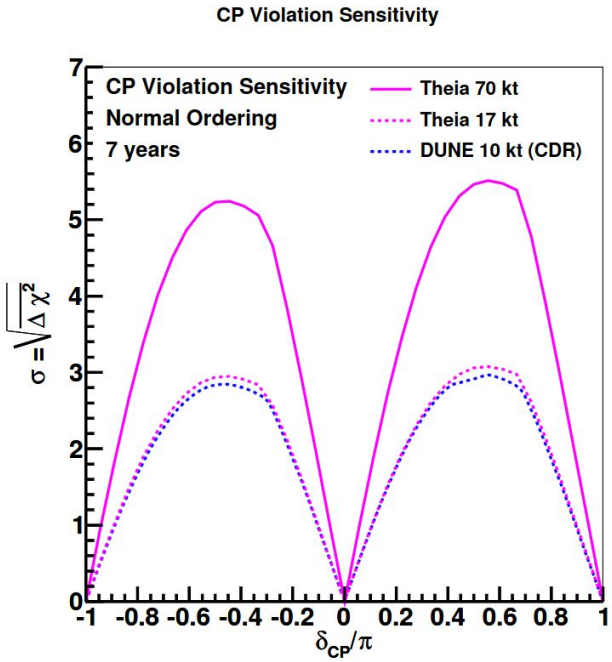
Running for 3 years

The 1-ton detector was starting running at the same year I joined BNL.

Historically, driven by the direct comparison between WbLS and Water detector for the DUNE fourth FD module, BNL has three questions in mind.

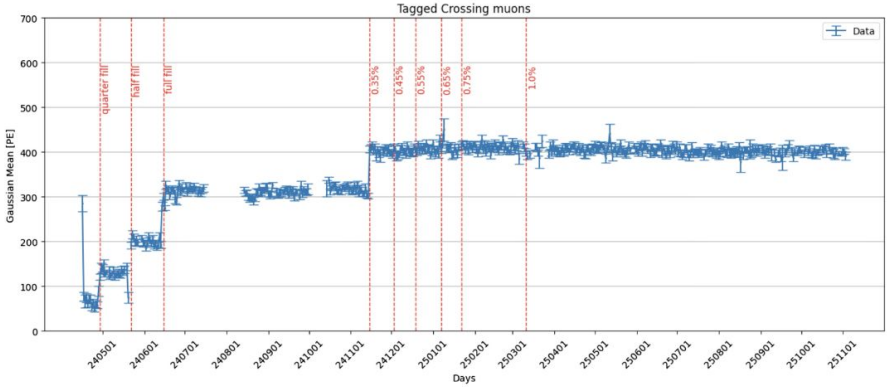
They are all answered at 10-ton level:

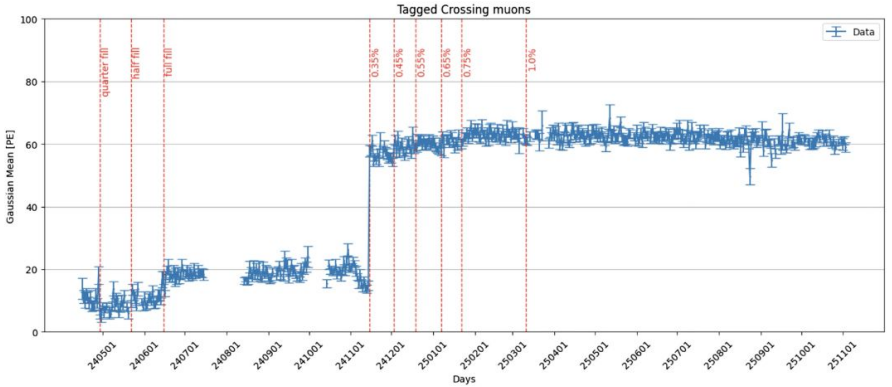
- What is the scintillation light yield at all?
- Is this whole thing stable?
- Is it clear to get the water performance?

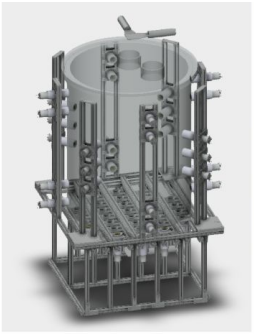


arXiv 1911.03501, Cited by 230 to date

Liquid stability









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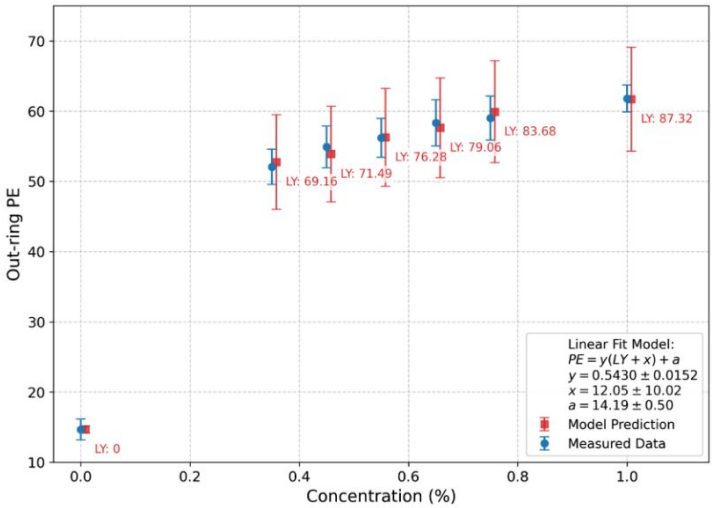
Design, construction, and operation of a 1-ton Water-based Liquid scintillator detector at Brookhaven National Laboratory

X. Xiang,[a,b] G. Yang,[a,c,d,*] S. Andrade,[a] M. Askins,[c,d] D.M. Asner,[a] A. Baldoni,[e] D.F. Cowen,[e] M.V. Diwan,[a] S. Gokhale,[a] S. Hans,[a,f] J. Jerome,[a] G. Lawley,[g] S. Linden,[a] G.D. Orebi Gann,[c,d] C. Reyes,[a] R. Rosero,[a] N. Seberg,[a] M. Smiley,[c,d] N. Speece-Moyer,[a] B. Walsh,[a] J.J. Wang,[h] M. Wilking[i] and M. Yeh[a]

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[e]Physics Department, The Pennsylvania State University, State College, PA 16801, U.S.A.
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[i]School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, U.S.A.

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Scintillation light yield



For 1.0% WbLS, the intrinsic scintillation light yield is measured as 87.3 ph/MeV and the re-emission light yield as 12.0 ph/MeV.

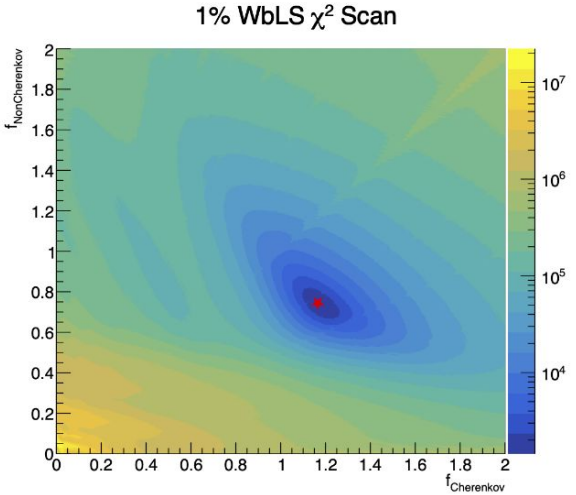
PHYSICAL REVIEW D **113,** 092015 (2026)

Measurement of the light yield response of the Gd-compatible water-based liquid scintillator with the Brookhaven one-ton testbed

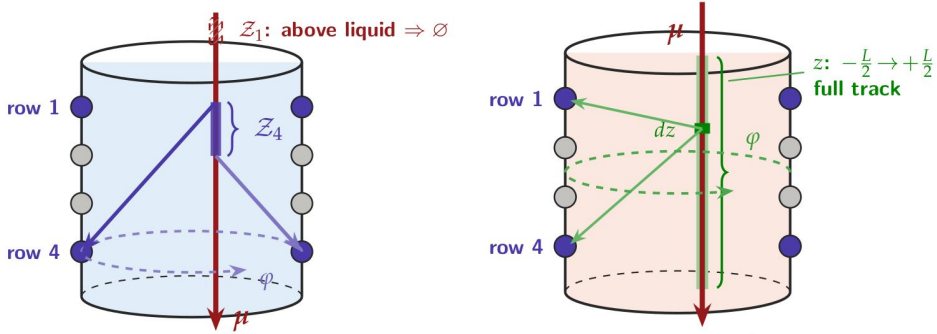
S. Gwon,[1] M. Askins,[2,3] D. M. Asner,[4] A. Baldoni,[5] D. F. Cowen,[5] R. Diaz Prerez,[4] M. V. Diwan,[4] S. Gokhale,[4] S. Hans,[4,6] P. Kumar,[7] G. Lawley,[8] S. Linden,[4] G. D. Orebi Gann,[2,3] J. Park,[1] C. Reyes,[4] R. Rosero,[4] K. Siyeon,[1] M. Smiley,[2,3] J. J. Wang,[7] M. Wilking,[9] G. Yang,[4,*] and M. Yeh[4]

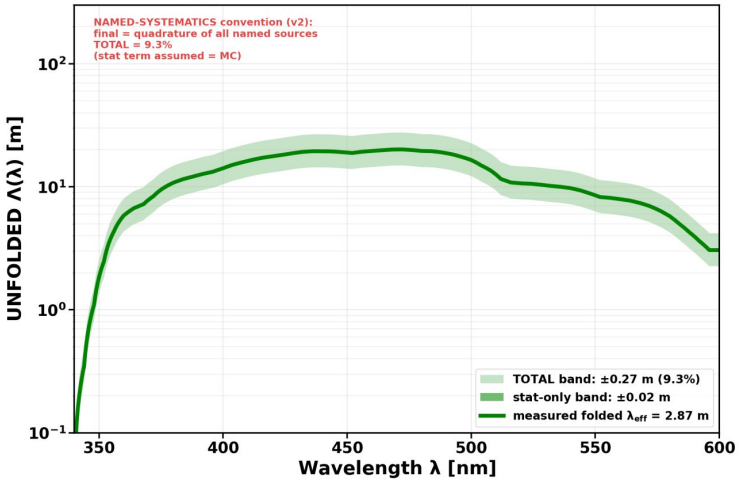
[1]*Chung-Ang University, Seoul, South Korea*
[2]*Physics Department, University of California at Berkeley, Berkeley, California 94720-7300, USA*
[3]*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720-8153, USA*
[4]*Brookhaven National Laboratory, Upton, New York, USA*
[5]*Physics Department, The Pennsylvania State University, State College, Pennsylvania 16801, USA*
[6]*Bronx Community College, Bronx, New York 10453, USA*
[7]*Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487, USA*
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Liquid transparency





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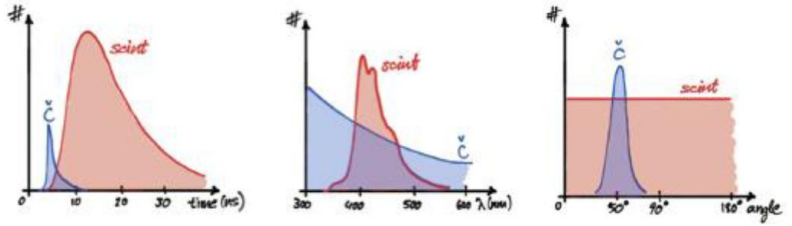
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[j] *Department of Physics and Astronomy, University of California, Irvine, Irvine, CA 92697, U.S.A.*
[k] *School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, U.S.A.*
E-mail: jwang214@ua.edu, gyang1@bnl.gov

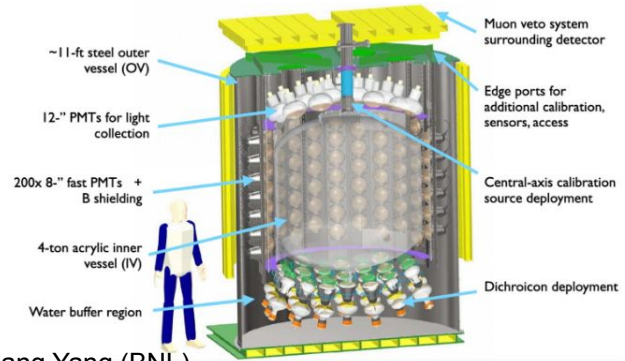
What else happening - Eos

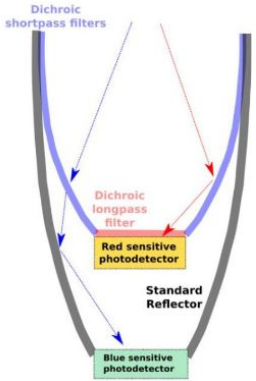
Low-energy performance demonstration

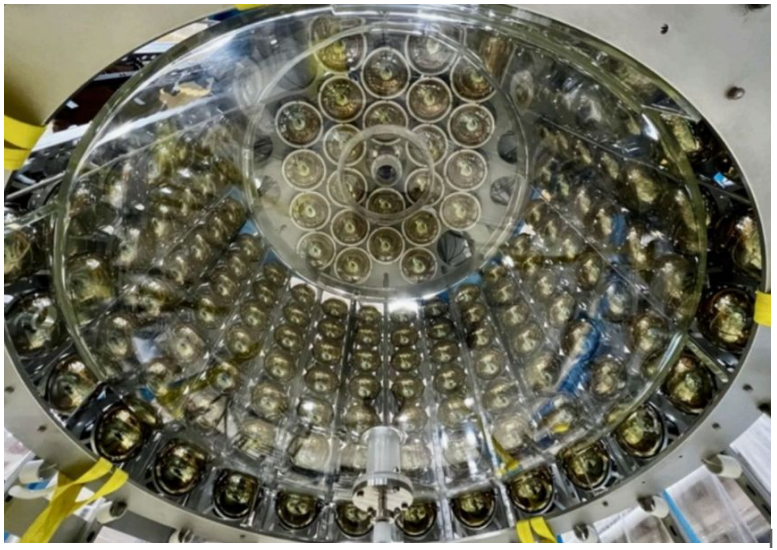
- Energy, angular and position resolution
- Cherenkov/Scintillation separation through wavelength and timing



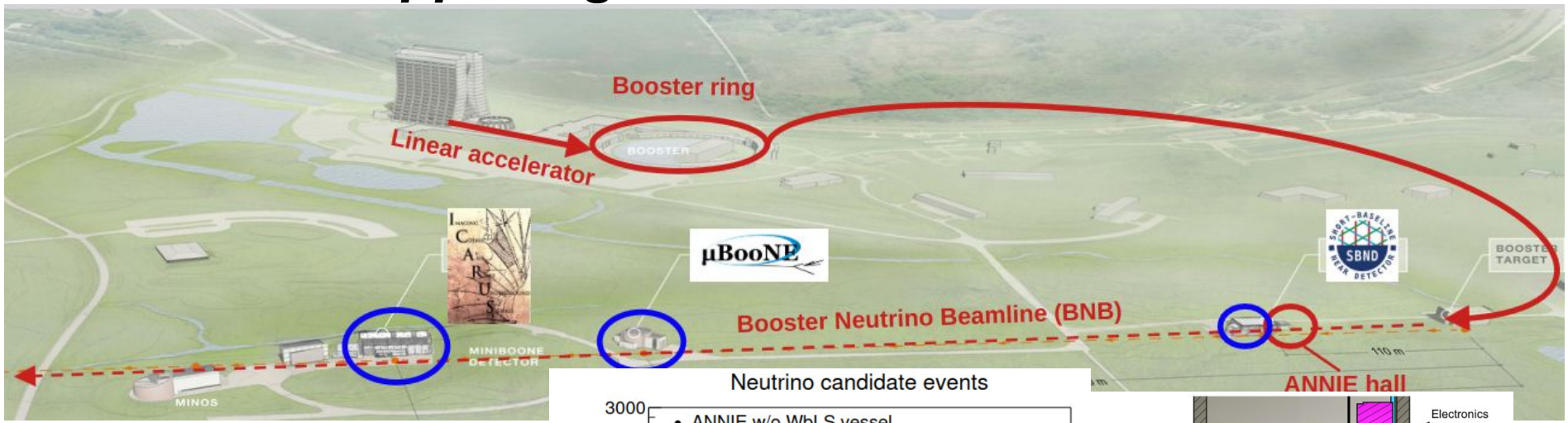
50% photo coverage





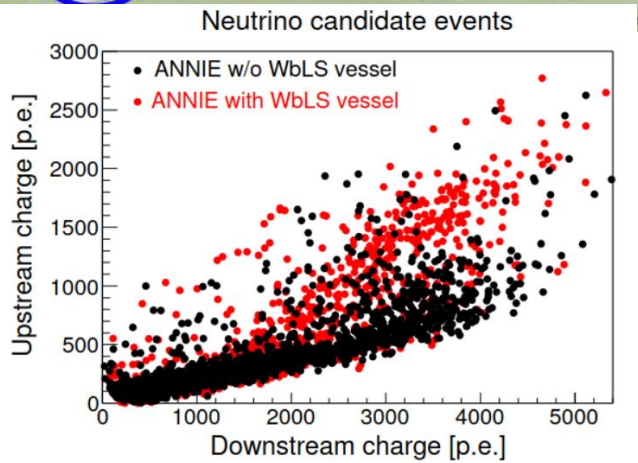


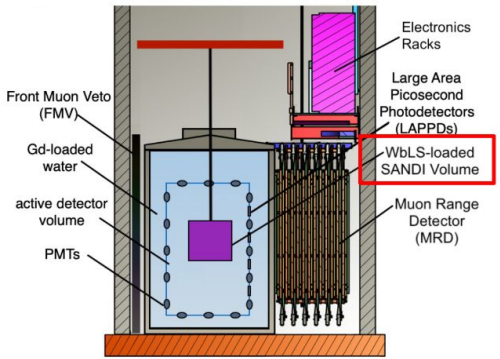
What else happening - ANNIE



Get the high-energy neutrinos

- **Cherenkov/scintillation separation with timing**
- **Neutron tagging with Gd**



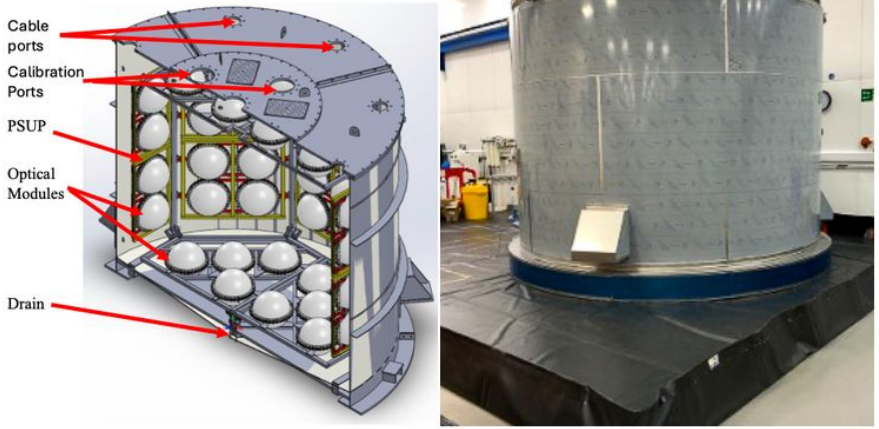


Ref: JINST 19 (2024) 05, P05070

What else happening - BUTTON and XLZD

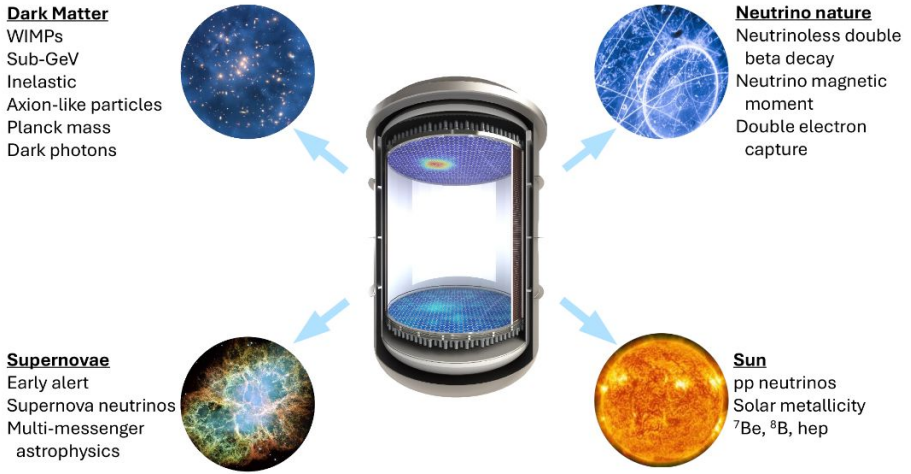
BUTTON 30ton mass in Boulby mine

- 15.5 miles away reactor neutrinos
- MeV neutrino detection with neutron tagging



Potential veto material for XLZD

(in Europe, not with DOE yet)



Getting mature for physics discovery

Let's recap the situation:

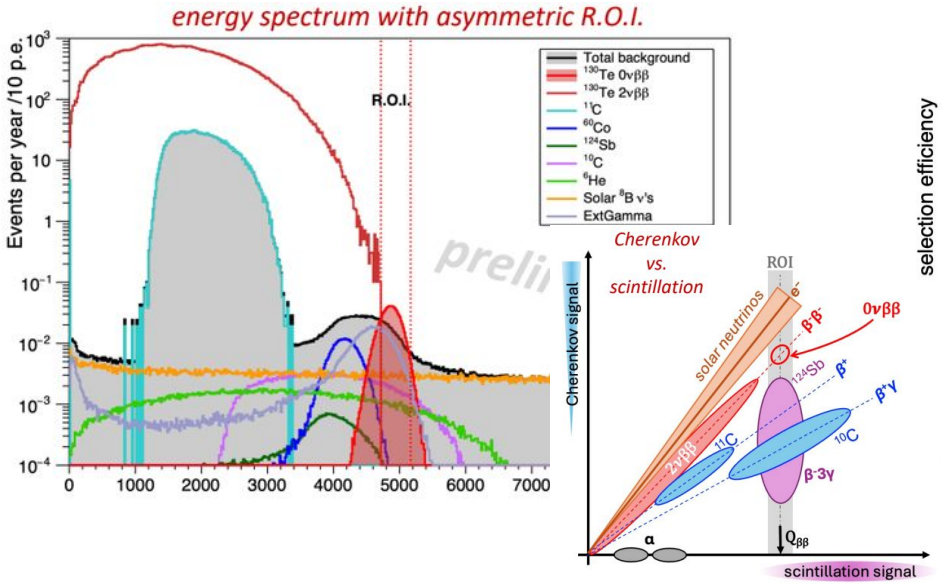
We have built demonstrators at 10-ton scales aiming to cover:

- Optical stability, scintillation yield and transparency. All seem decent. Done.
- Low-energy particle reconstruction performance demonstration. Ongoing.
- GeV neutrino detection demonstration. Ongoing.
- MeV neutrino detection demonstration. Ongoing.

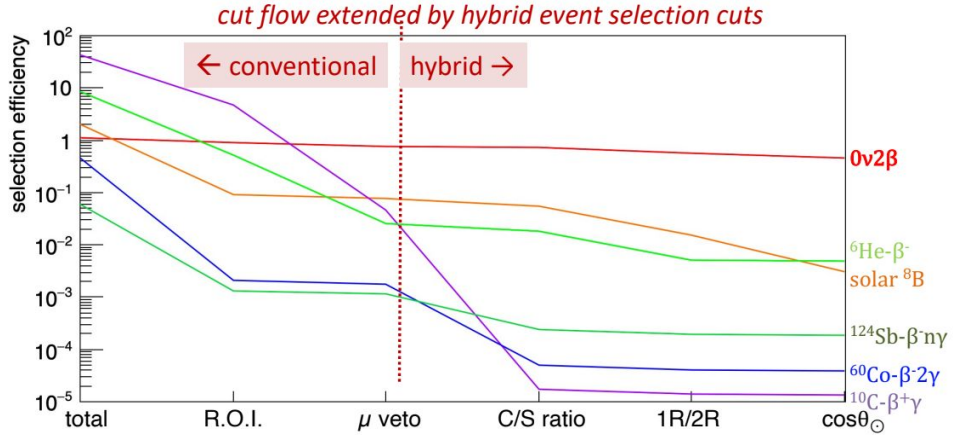
We need to find real physics discoveries with this brilliant technology as it gets mature. **Korea can do things!**

Getting mature for physics discovery

A large-scale WbLS scientific station deep underground would do all low-energy physics including reactor, geo, reactor, solar, and in particular **double beta decay**.



From Michi Wurm



https://physics.berkeley.edu/physics-opportunities-large-liquid-scintillator-detectors

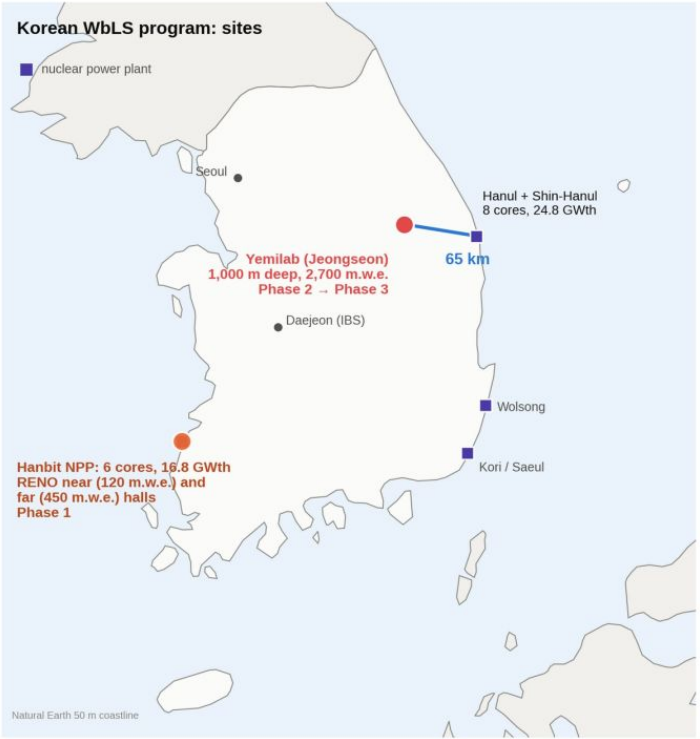
Possible WbLS in Korea

Three phases:

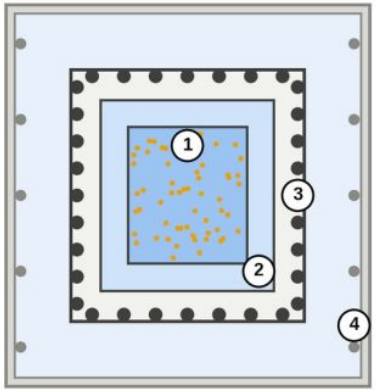
1. ***Reactor neutrinos***
2. ***Solar + Supernova + Geoneutrinos***
3. ***Double beta decay***

Why Korea:

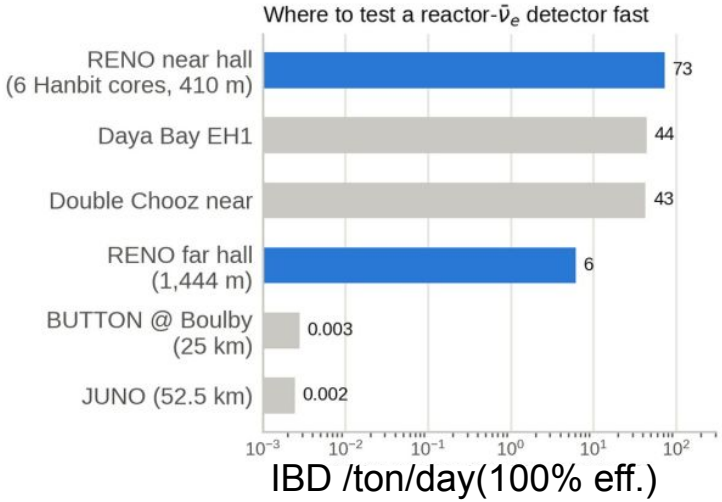
- RENO: two instrumented 16-t detectors and their halls, idle since March 2023, at the most intense reactor-$\bar{\nu}_e$ site available anywhere.
- Yemilab: the 20 m × 20 m pit at 2,700 m.w.e. is excavated
- Hanul: 24.8 GWth at 65 km, the strongest reactor source next to any deep laboratory (JUNO: 26.6 GWth at 52.5 km).
- CAU and CNU already collaborators the BNL 1-ton and 30-ton
- RENO, NEOS and JSNS² give Korea deep reactor-$\bar{\nu}_e$ expertise.

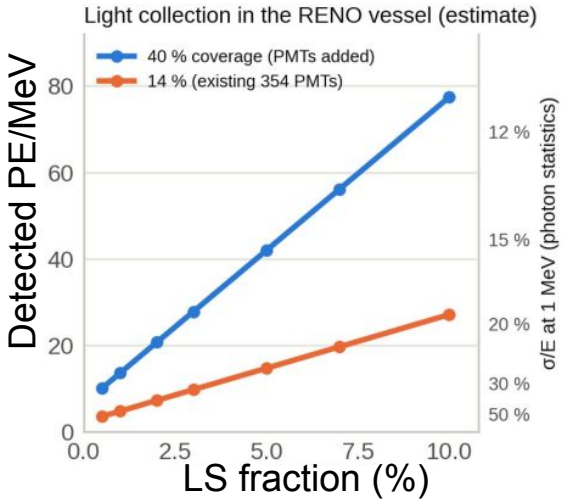


Phase 1 - reactor demonstration



1 Target: 16 t Gd-WbLS, acrylic 2.75 × 3.15 m
2 γ-catcher: 30 t WbLS, acrylic 4.0 × 4.4 m
3 Buffer: water (or oil), SS 5.4 × 5.8 m, 354 × 10″ PMTs
4 Veto: 350 t water, 67 PMTs, concrete 8.4 × 8.8 m

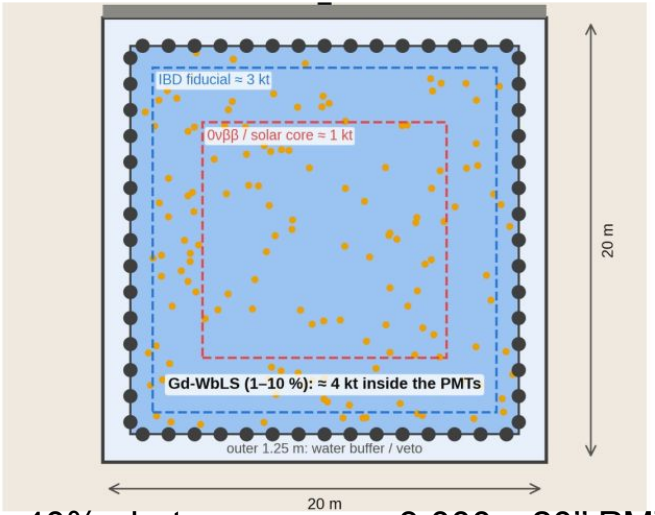




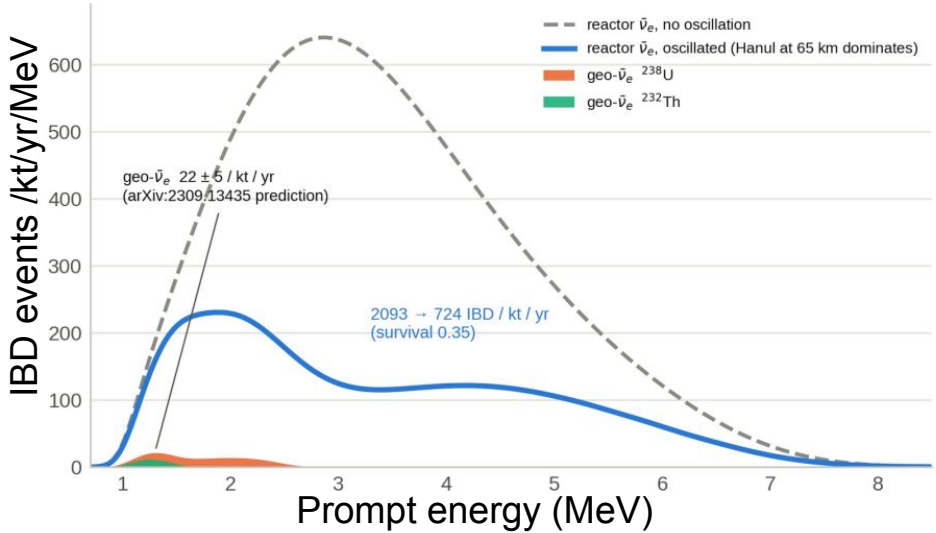
Even better with higher photo coverage
16 t Gd-WbLS at RENO near hall => 1,200 IBD/day

Phase 2 - large-scale detector deep underground

Yemilab pit: 20 m x 20 m
100 m of rock (2,700 m.w.e.)



Yemilab sits near Δm^2_{21} maximum of Hanul



40% photocoverage: ~3,000 x 20” PMTs

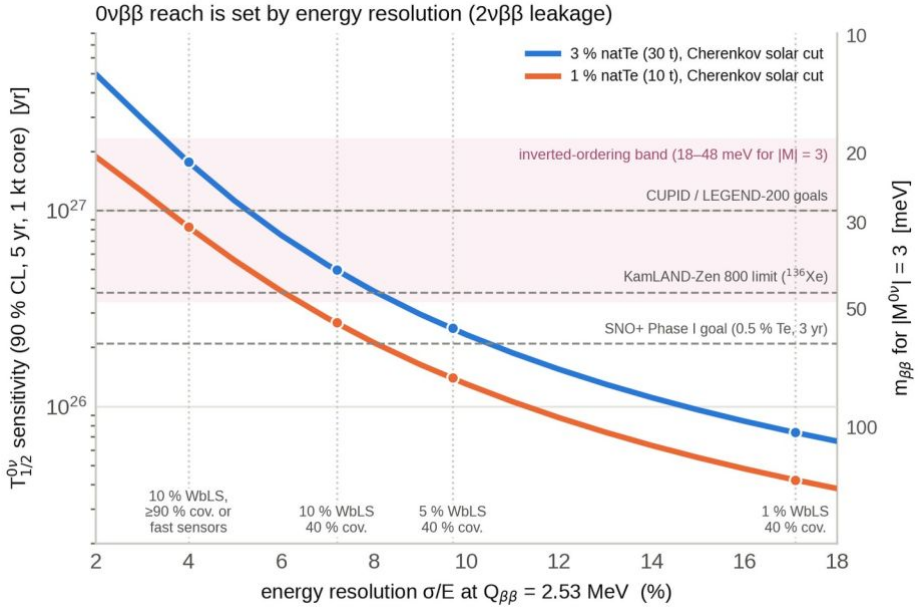
≈2,200 / yr
IBD in 3kt fiducial

≈65 ± 15 / yr
Geo-nue in 3kt

≈1,650 / yr
B8 solar nue above 3 MeV recoil in 2 kt

≈1,400 events
Supernova at 10 kpc in 4 kt (950 IBD + 390 vp and 45 ve)

Phase 3 - Double beta decay



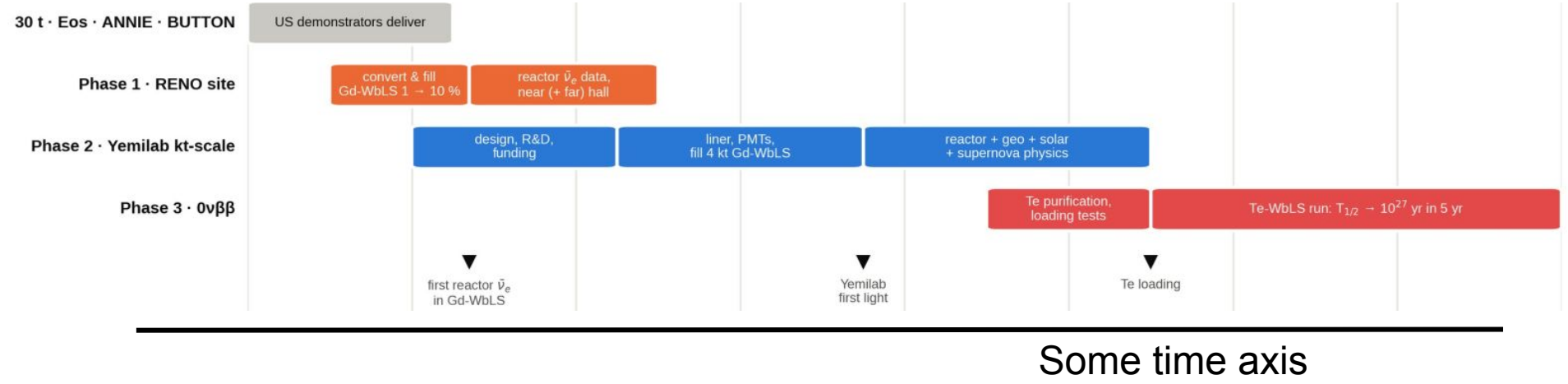
$$T^{0\nu}_{1/2} > \frac{\ln 2\, N_{\beta\beta}\, \varepsilon_{\rm tot}\, t}{N_{90}(B)}, \qquad m_{\beta\beta} = \frac{m_e}{g_A^2 \left|M^{0\nu}\right| \sqrt{G^{0\nu}\, T^{0\nu}_{1/2}}}$$

Isotope	Q (MeV)	nat. ab.	2νββ T½ (yr)	water-soluble form	verdict for WbLS
^{130}Te	2.53	34 %	7.7×10^{20}	$Te(OH)_6$, ≈300 g/L	baseline
^{100}Mo	3.03	9.7 %	7.1×10^{18}	Na_2MoO_4, ≈840 g/L	AMoRE synergy; needs σ/E ≲ 2 %
^{150}Nd	3.37	5.6 %	9.3×10^{18}	$Nd(NO_3)_3$	high Q; low abundance
^{136}Xe	2.46	8.9 %	2.2×10^{21}		not water-soluble

Extend the reach (10 % WbLS, ≥90 % coverage → σ/E ≈ 6 % at 3 % natTe; core 0.65–1 kt): T½ ≈ 6–7×10²⁶ yr in 5 yr and ≈ 8–10×10²⁶ yr in 10 yr, i.e. mββ ≈ 13–80 meV.

Reaching 2–3×10²⁷ yr (mββ 7–33 meV) needs a Te-LS balloon inside the WbLS.

Dreamline


30 t · Eos · ANNIE · BUTTON
US demonstrators deliver
Phase 1 · RENO site
convert & fill Gd-WbLS 1 → 10 %
reactor $\bar{\nu}_e$ data, near (+ far) hall
Phase 2 · Yemilab kt-scale
design, R&D, funding
liner, PMTs, fill 4 kt Gd-WbLS
reactor + geo + solar + supernova physics
Phase 3 · 0νββ
Te purification, loading tests
Te-WbLS run: $T_{1/2} \rightarrow 10^{27}$ yr in 5 yr
first reactor $\bar{\nu}_e$ in Gd-WbLS
Yemilab first light
Te loading
Some time axis

Summary

WbLS is moving from a novel technology to something that bring scientific results.

BNL has proved that WbLS can be useful for neutrino detection through:

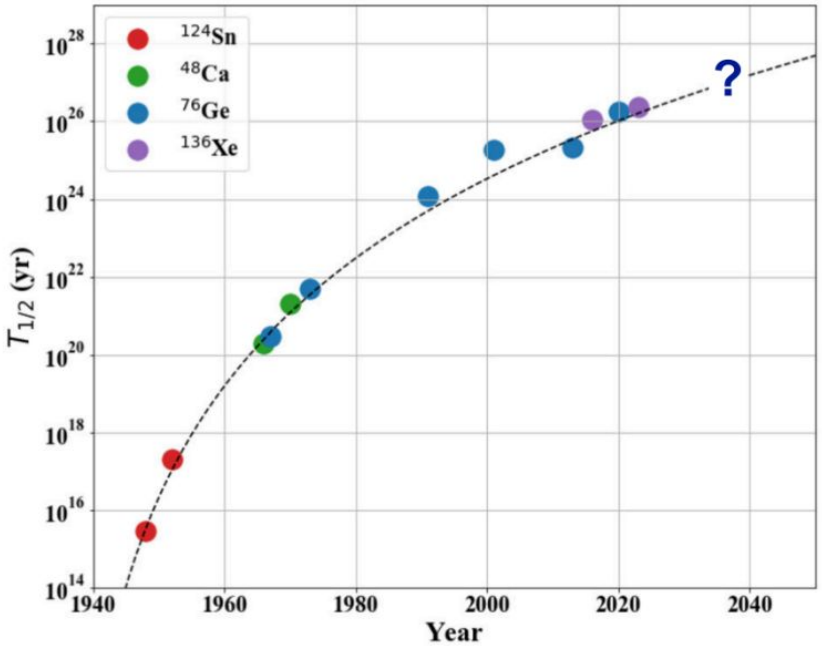
- Light yield, stability and Clarity. It will perform better than water while opening a whole new window for low-energy detection.

BNL and partners are working on various demonstrations.

- Particular with MeV and GeV neutrino detection, Cherenkov/Scintillation separation and n-Gd tagging.

It is great opportunity to work something out in Korea!

Backup



Gomez-Cadenas et al
Riv. Nuovo Cim. 46, 619–692 (2023).

Backup

assumption	value used on slide 25	basis	realistic?	consequence
Te loading	1–3 % natTe by mass, dissolved in the water phase (10–30 t)	$Te(OH)_6$ solubility ≈300 g/L; SNO+ purification chemistry	✓ chemically; (!) optical transparency after loading is unmeasured	test in the BNL 1-ton and in Phase 1
Core (fiducial)	1 kt: r < 5.5 m, |z| < 5.3 m → 3.25 m of liquid to the PMTs	geometry of the 20 m pit	✗ external ^{208}Tl needs ≥ 4.25 m shielding or low-activity glass (part 2)	core 0.65 kt (r < 4.5 m) → T½ × 0.8
Energy resolution σ/E at Q	6 % (main case); 4.5 % and 3 % also shown	photon statistics only: 99 ph/MeV per % LS × coverage × QE 0.28 × 0.64; Cherenkov 6.5 p.e./MeV at 40 %	10 % WbLS, 90 % cov. → 5.8 % incl. SPE 35 %, Te light ×0.8, 1.5 % constant: 6 % is realistic. 4.5 % needs the LBNL light yield and no Te loss; 3 % is LS-like (balloon)	6 %: as on slide; 8.6 % (40 % cov.): T½ × 0.45
Angular resolution (solar cut)	keep 30 % of ^8B ν–e at 85 % signal efficiency (cut cos ψ_sun < 0.7)	Monte-Carlo: kinematic angle 25° at 2.5 MeV ⊕ detector resolution; ×0.3 ↔ 35° rms	(!) Theia/Eos target 25–45° with 10 % WbLS + fast photosensors; not yet demonstrated at 2.5 MeV. 50° gives ×0.5	×0.5 instead of ×0.3: T½ −3 % at 6 % resolution
Muon flux at Yemilab	5×10^{-8} cm^{-2} s^{-1} (Mei–Hime, flat overburden)	arXiv:2309.13435 Table 1: 8.2×10^{-8} (Kamioka 1.3×10^{-7}, Boulby 4.8×10^{-8})	(!) use 8.2×10^{-8} → ≈0.3 Hz through the 20 m tank (≈26,000 μ/day)	spallation veto dead time ≈10 %
Analysis	efficiency 0.9; ROI [Q+aσ, Q+2σ] with a optimised; median Bayesian 90 % CL (flat prior)	standard counting analysis	✓ Feldman–Cousins gives similar medians; a spectral fit would gain 10–20 %	—
mββ conversion	$G^{0\nu} = 14.22\times10^{-15}$ yr^{-1}, $g_A = 1.27$, $\|M^{0\nu}\| = 1.4$–6.4	Kotila–Iachello 2012; NME compilation RMP 2023	✓ (quenched g_A would weaken all experiments alike)	—

light-collection configuration	p.e./MeV	photon statistics	+ SPE 35 %	+ Te light × 0.8	+ 1.5 % constant = σ/E at Q
1 % WbLS, 40 % cov.	14	17.1 %	18.1 %	20.2 %	20.3 %
5 % WbLS, 40 %	42	9.7 %	10.3 %	11.5 %	11.6 %
10 % WbLS, 40 %	77	7.1 %	7.6 %	8.5 %	8.6 %
5 % WbLS, 90 %	94	6.5 %	6.9 %	7.7 %	7.8 %
10 % WbLS, 90 %	174	4.8 %	5.0 %	5.6 %	5.8 %
10 % WbLS, 90 %, LBNL LY (128 ph/MeV/%)	220	4.2 %	4.5 %	5.0 %	5.2 %
LS balloon (10,000 ph/MeV), 90 %	1621	1.6 %	1.7 %	1.9 %	2.4 %

Backup

background (ROI ≈ [Q+0.5σ, Q+2σ] at 6 %)	in the slide model	realistic estimate (30 t natTe, 1 kt core, Yemilab)	requirement / handle
2νββ of ^{130}Te	4.3×10^{7} decays / yr; ≈110 / yr in ROI at 6 %	same; the tail is not exactly Gaussian (non-Gaussian tails would add)	resolution; measure the tail in situ
^{8}B solar ν–e	≈15 / yr after ×0.3	≈25 / yr with a 50° direction cut (×0.5); SNO+ table implies rates 1.5× higher	Cherenkov direction at 2.5 MeV (Eos)
Muon spallation β emitters (^{16}N g.s., ^{8}Li, ^{8}B, ^{12}B, ^{11}Be…)	inside the flat 5 / yr	170 / kt·yr in ROI before cuts (Li & Beacom yields × 8.2×10^{-8} cm^{-2} s^{-1}) → ≈8 / yr after shower-cylinder veto + Gd neutron tag, ≈10 % dead time	muon tracking, Gd neutron tagging
Cosmogenic activation of Te (^{60}Co, ^{110m}Ag, ^{22}Na, ^{124}Sb, ^{88}Y)	inside the flat 5 / yr	SNO+ Phase I estimate (0.5–2 / yr for 3.9 t Te after purification + ~6 months underground) × 8 in Te mass → 4–15 / yr	Te purification underground; longer cool-down (^{60}Co 5.3 yr is the hard one)
Internal ^{214}Bi (U chain)	inside the flat 5 / yr	≈8 / yr for U = 10^{-16} g/g with 99 % Bi–Po tagging (or 10^{-15} g/g with 99.9 %); 80 / yr at 10^{-15} g/g and 99 %. SNO D_2O reached 3×10^{-15}; SNO+ LS targets 10^{-16}–10^{-17}	water-phase purification (RO, ion exchange, Rn control); α tagging needs ≥ 5–10 % WbLS (^{214}Po α ≈ 40 p.e.)
Internal ^{208}Tl (Th chain)	inside the flat 5 / yr	≲ 0.5 / yr for Th = 10^{-16} g/g with 99 % ^{212}Bi–Po tagging (visible energy mostly above the ROI)	as above
External ^{208}Tl 2.615 MeV γ from 2,000 PMTs	not modelled	the line sits inside every ^{130}Te ROI: 720 / yr at r < 5.5 m with SK-like glass (0.5 Bq/PMT), 72 / yr with low-background glass; 9 / yr at r < 4.5 m (0.65 kt), 0.9 / yr with both	≥ 4.25 m of shielding (core 0.65 kt) or low-activity photosensors, as SNO+ (5 m)
Pile-up, ^{130}I, (α, n), ^{10}C from the 10 % carbon	not modelled	2νββ pile-up 0.6 / yr total (≈0 in ROI); ^{10}C ≈ 1/10 of an LS detector's rate; ^{130}I small at this depth	—
Sum of 'other' backgrounds	5 / yr	≈ 20–40 / yr (spallation 8, cosmogenic Te 4–15, U/Th 8, external 1–9) once the requirements above are met; 2νββ (110 / yr) still dominates at 6 %	T½ −3 % at 6 %; −25 % at 3 %

scenario (3 % natTe, direction cut)	core	σ/E	live time	other bkg in ROI	T½ (90 % CL)	mββ (meV)
slide model	1 kt	6 %	5 yr	2 / yr	7.5×10^{26}	15–69
realistic bkg + 50 deg direction (x0.5)	1 kt	6 %	5 yr	15 / yr	7.0×10^{26}	16–72
realistic + core 0.65 kt for external gammas	0.65 kt	6 %	5 yr	10 / yr	5.6×10^{26}	17–80
same, 10 yr	0.65 kt	6 %	10 yr	9 / yr	8.0×10^{26}	15–67
realistic bkg, 1 kt (low-bkg glass), 6 %, 10 yr	1 kt	6 %	10 yr	14 / yr	1.0×10^{27}	13–60
40 % coverage (sigma 8.6 %), 1 kt, 5 yr, 30/yr	1 kt	8.6 %	5 yr	11 / yr	3.2×10^{26}	23–106
LS-like light (3 %), 1 kt, 10 yr, other 30/yr	1 kt	3 % (balloon)	10 yr	29 / yr	3.2×10^{27}	7–33

Backup